Large-scale Universe

B.F. Roukema

2020-09-30
DOI:10.5281/zenodo.4060261

Introduction

basic cosmology model:

- GR: curvature = matter-energy content

Introduction

basic cosmology model:

- GR: curvature = matter-energy content
- verbal averaging: homogeneous, isotropic spatial slices

Introduction

basic cosmology model:

- GR: curvature = matter-energy content
- verbal averaging: homogeneous, isotropic spatial slices
- shape of space (curvature + topology)

Introduction

basic cosmology model:

- GR: curvature = matter-energy content
- verbal averaging: homogeneous, isotropic spatial slices
- shape of space (curvature + topology)

\+ observations of expansion ⇒ hot big bang

Introduction

basic cosmology model:

- GR: curvature = matter-energy content
- verbal averaging: homogeneous, isotropic spatial slices
- shape of space (curvature + topology)

\+ observations of expansion ⇒ hot big bang

⇒ black body radiation, nucleosynthesis

Introduction

basic cosmology model:

- GR: curvature = matter-energy content
- verbal averaging: homogeneous, isotropic spatial slices
- shape of space (curvature + topology)

\+ observations of expansion $\Rightarrow$ hot big bang

$\Rightarrow$ black body radiation, nucleosynthesis

- but: $\exists$ galaxies $\Rightarrow$ inhomogeneous, anisotropic spatial slices

Introduction

basic cosmology model:

- GR: curvature = matter-energy content
- verbal averaging: homogeneous, isotropic spatial slices
- shape of space (curvature + topology)

\+ observations of expansion $\Rightarrow$ hot big bang

$\Rightarrow$ black body radiation, nucleosynthesis

- but: $\exists$ galaxies $\Rightarrow$ inhomogeneous, anisotropic spatial slices
- standard model: density perturbations (anisotropy)

Introduction

basic cosmology model:

- GR: curvature = matter-energy content
- verbal averaging: homogeneous, isotropic spatial slices
- shape of space (curvature + topology)

+ observations of expansion ⇒ hot big bang

⇒ black body radiation, nucleosynthesis

- but: ∃ galaxies ⇒ inhomogeneous, anisotropic spatial slices
- standard model: density perturbations (anisotropy)
- verbal averaging: can we do better?

Introduction

basic cosmology model:

- GR: curvature = matter-energy content
- verbal averaging: homogeneous, isotropic spatial slices
- shape of space (curvature + topology)

\+ observations of expansion $\Rightarrow$ hot big bang

$\Rightarrow$ black body radiation, nucleosynthesis

- but: $\exists$ galaxies $\Rightarrow$ inhomogeneous, anisotropic spatial slices
- standard model: density perturbations (anisotropy)
- ~~verbal averaging~~

Introduction

basic cosmology model:

- GR: curvature = matter-energy content
- verbal averaging: homogeneous, isotropic spatial slices
- shape of space (curvature + topology)

$+$ observations of expansion $\Rightarrow$ hot big bang

$\Rightarrow$ black body radiation, nucleosynthesis

- but: $\exists$ galaxies $\Rightarrow$ inhomogeneous, anisotropic spatial slices
- standard model: density perturbations (anisotropy)
- scalar (GR) averaging: statistically homogeneous spatial slices

verbal averaging

- w:Cosmological principle

verbal averaging

- w:Cosmological principle
- practical meaning:

verbal averaging

- w:Cosmological principle
- practical meaning:
  1. assume homogeneity and isotropy

verbal averaging

- w:Cosmological principle
- practical meaning:
  1. assume homogeneity and isotropy
  2. find the (differential 4-pseudo-manifold, metric) pairs $(M, \mathbf{g})$ that solve $\mathbf{G} = 8\pi\mathbf{T}$

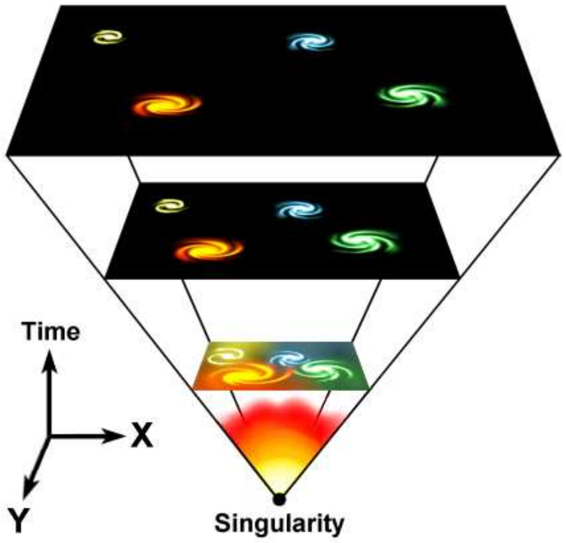
verbal averaging

- w:Cosmological principle
- practical meaning:
  1. assume homogeneity and isotropy
  2. find the (differential 4-pseudo-manifold, metric) pairs $(M, \mathbf{g})$ that solve $\mathbf{G} = 8\pi\mathbf{T}$
  3. assume that $(M, \mathbf{g})$ remains unchanged if we add density perturbations to an early time slice

verbal averaging

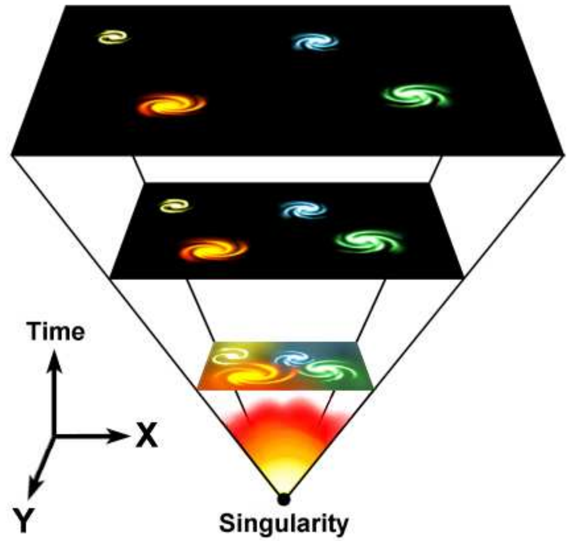
- w:Comoving coordinates

verbal averaging



- w:Comoving coordinates

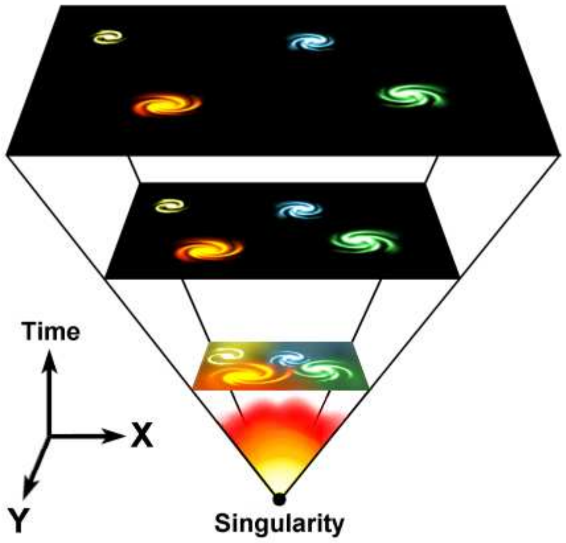
verbal averaging



- w:Comoving coordinates
-

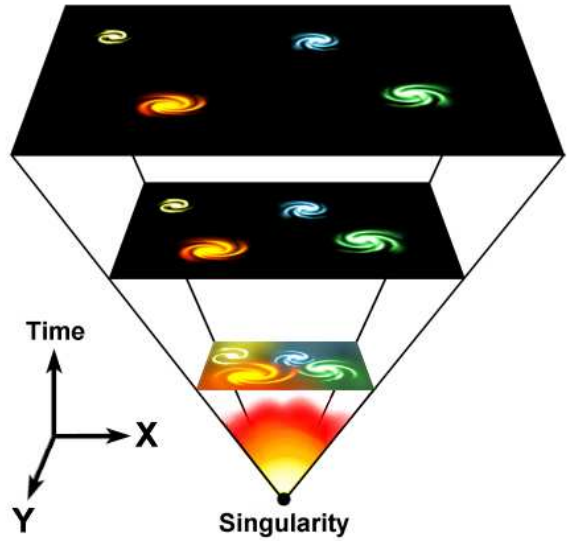
$$\Delta x(t) = a(t)\Delta r$$

verbal averaging



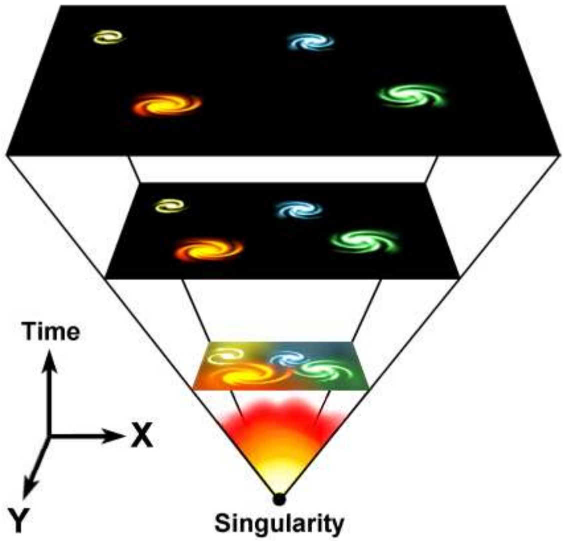
- w:Comoving coordinates
- $$\Delta x(t) = a(t)\Delta r$$
- spherical coordinates for spatial slice

verbal averaging



- w:Comoving coordinates
- $$\int_{(t,r_1,\theta,\phi)}^{(t,r_2,\theta,\phi)} \mathrm{d}s = a(t)\Delta r = a(t)|r_2 - r_1|$$

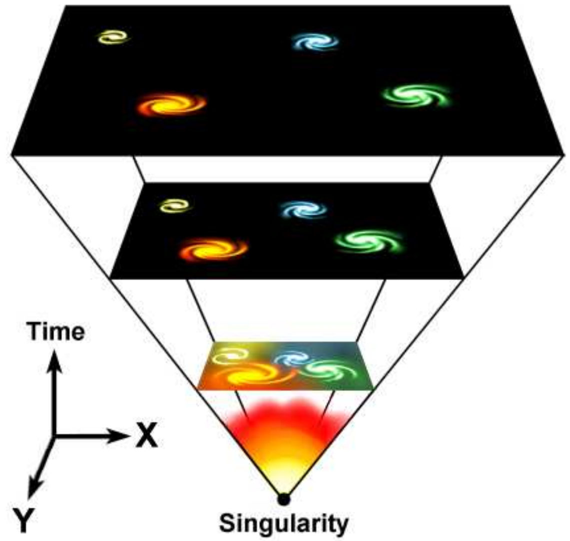
verbal averaging



- w:Comoving coordinates
- $$\int_{(t,r_1,\theta,\phi)}^{(t,r_2,\theta,\phi)} \mathrm{d}s = a(t)\Delta r = a(t)|r_2 - r_1|$$

where all expansion/contraction $\rightarrow$ w:scale factor $a(t)$

verbal averaging



- w:Comoving coordinates
-

$$\int_{(t,r_1,\theta,\phi)}^{(t,r_2,\theta,\phi)} \mathrm{d}s = a(t)\Delta r = a(t)|r_2 - r_1|$$

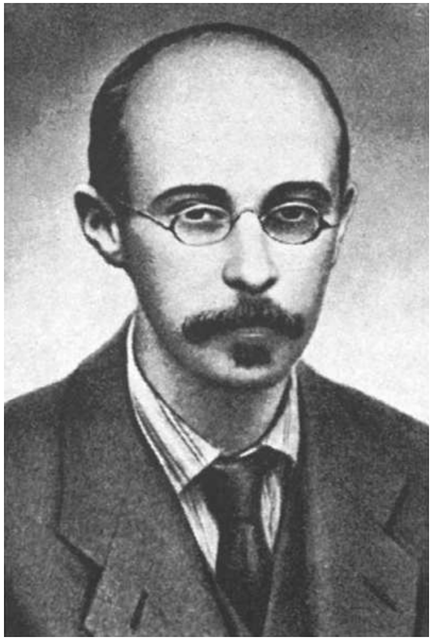
where all expansion/contraction $\rightarrow$ w:scale factor $a(t)$

- universe is static in comoving coordinates (r, θ, ϕ)

FLRW metric

- w:Friedmann–Lemaître–Robertson–Walker metric

FLRW metric

- w:Friedmann–Lemaître–Robertson–Walker metric
- w: w:
  w:Howard Percy Robertson
  w:Arthur Geoffrey Walker

FLRW metric

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + \ldots$$

FLRW metric

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\,[\ldots]$$

FLRW metric

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\left[\mathrm{d}r^2 + \ldots\right]$$

FLRW metric

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\left[\mathrm{d}r^2 + r_\perp^2(\ldots)\right]$$

FLRW metric

$$\boxed{\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\left[\mathrm{d}r^2 + r_\perp^2(\mathrm{d}\theta^2 + \cos^2\theta\mathrm{d}\phi^2)\right]}$$

FLRW metric

$$\boxed{\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\left[\mathrm{d}r^2 + r_\perp^2(\mathrm{d}\theta^2 + \cos^2\theta \mathrm{d}\phi^2)\right]}$$

- *aside:* conformal coordinates: may define

$$u := \int \frac{\mathrm{d}t}{a(t)}$$

FLRW metric

$$\boxed{\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\left[\mathrm{d}r^2 + r_\perp^2(\mathrm{d}\theta^2 + \cos^2\theta \mathrm{d}\phi^2)\right]}$$

- *aside:* conformal coordinates: may define

$$u := \int \frac{\mathrm{d}t}{a(t)}$$

$\Rightarrow$

$$\mathrm{d}s^2 = a^2(u)\left[-\mathrm{d}u^2 + \mathrm{d}r^2 + r_\perp^2(\mathrm{d}\theta^2 + \cos^2\theta \mathrm{d}\phi^2)\right]$$

FLRW metric

$$\boxed{\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\left[\mathrm{d}r^2 + r_\perp^2(\mathrm{d}\theta^2 + \cos^2\theta \mathrm{d}\phi^2)\right]}$$

- *aside:* conformal coordinates: may define

$$u := \int \frac{\mathrm{d}t}{a(t)}$$

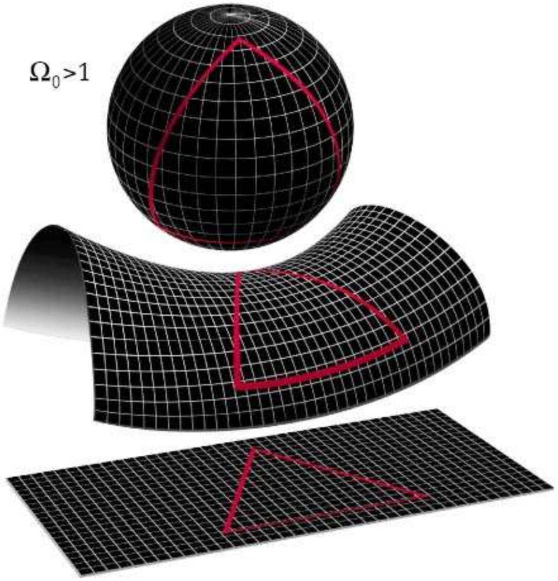
$\Rightarrow$

$$\mathrm{d}s^2 = a^2(u)\left[-\mathrm{d}u^2 + \mathrm{d}r^2 + r_\perp^2(\mathrm{d}\theta^2 + \cos^2\theta \mathrm{d}\phi^2)\right]$$

- but $\int \mathrm{d}u \neq$ proper time; *more:* arXiv:astro-ph/0707.2106

FLRW metric

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\left[\mathrm{d}r^2 + r_\perp^2(\mathrm{d}\theta^2 + \cos^2\theta\,\mathrm{d}\phi^2)\right]$$

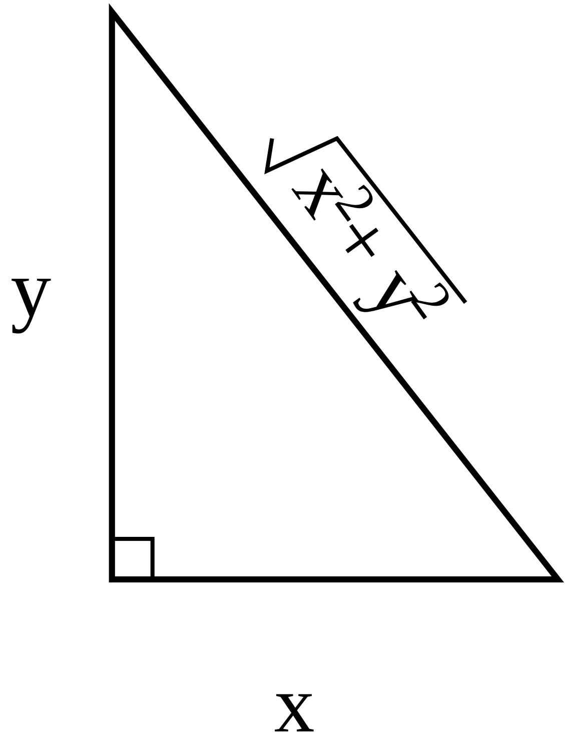


where $$r_\perp := \begin{cases} R_\mathrm{C}\sinh\frac{r}{R_\mathrm{C}} & k<0 \\ r & k=0 \\ R_\mathrm{C}\sin\frac{r}{R_\mathrm{C}} & k>0 \end{cases}$$

for a comoving radius of curvature R_C and curvature of sign k

curvature

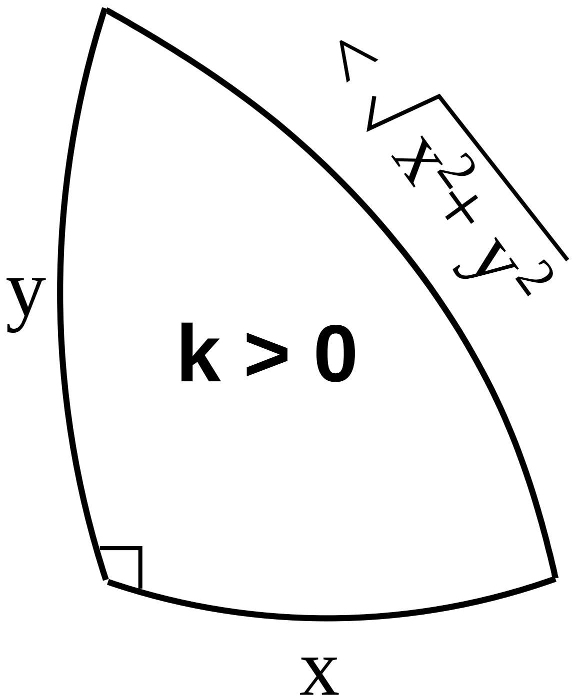
- on a spatial slice (fixed value of t):



$k = 0$

curvature

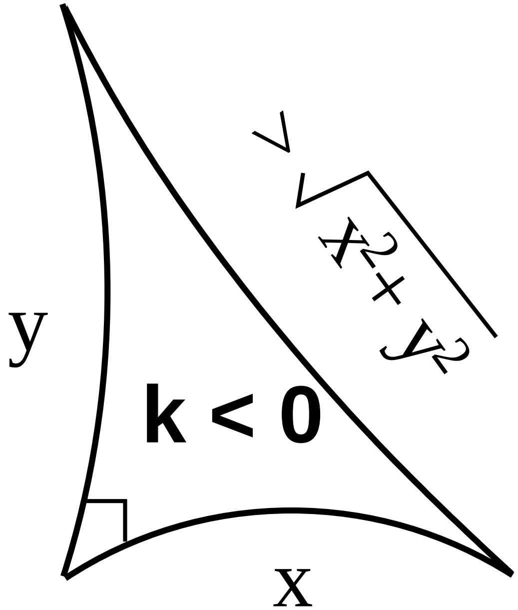
- on a spatial slice (fixed value of t):



$$k > 0$$

curvature

- on a spatial slice (fixed value of t):



$$k < 0$$

2D curvature intuition: $k > 0$

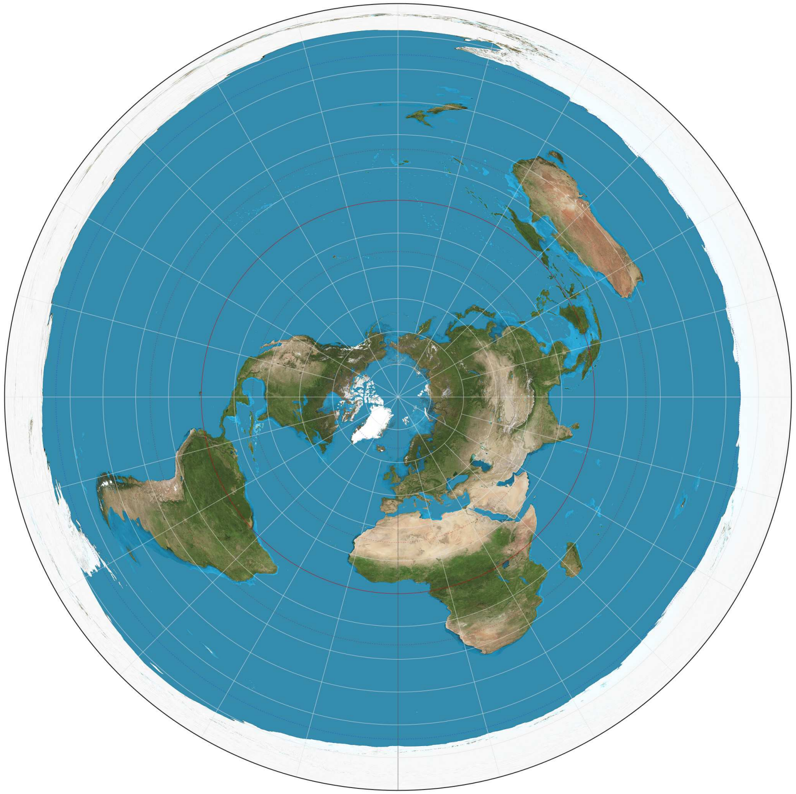
$$\mathrm{d}s^2|_{\phi=\mathrm{const},a=1} = \mathrm{d}r^2 + r_\perp^2 \mathrm{d}\theta^2,$$

2D curvature intuition: $k > 0$

$$\mathrm{d}s^2|_{\phi=\mathrm{const},a=1} = \mathrm{d}r^2 + r_\perp^2 \mathrm{d}\theta^2, \text{ where } r_\perp := R_\mathrm{C} \sin \frac{r}{R_\mathrm{C}}$$

2D curvature intuition: $k > 0$

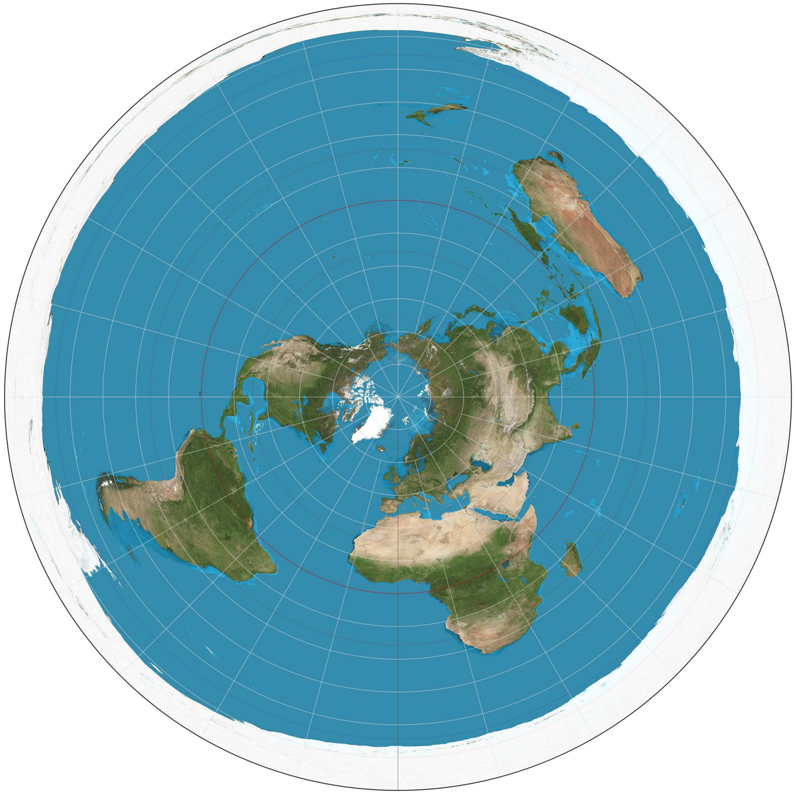
$\mathrm{d}s^2|_{\phi=\mathrm{const}, a=1} = \mathrm{d}r^2 + r_\perp^2 \mathrm{d}\theta^2$, where $r_\perp := R_\mathrm{C} \sin \frac{r}{R_\mathrm{C}}$



w: ________ (al-Biruni, c. 1000 CE)

2D curvature intuition: $k > 0$

$$\mathrm{d}s^2|_{\phi=\mathrm{const},a=1} = \mathrm{d}r^2 + r_\perp^2 \mathrm{d}\theta^2, \text{ where } r_\perp := R_\mathrm{C} \sin \frac{r}{R_\mathrm{C}}$$



w: ________ (al-Biruni, c. 1000 CE)

- intuition switch: S^2 easier vs S^3 more physical

2D topology intuition ($k = 0$)

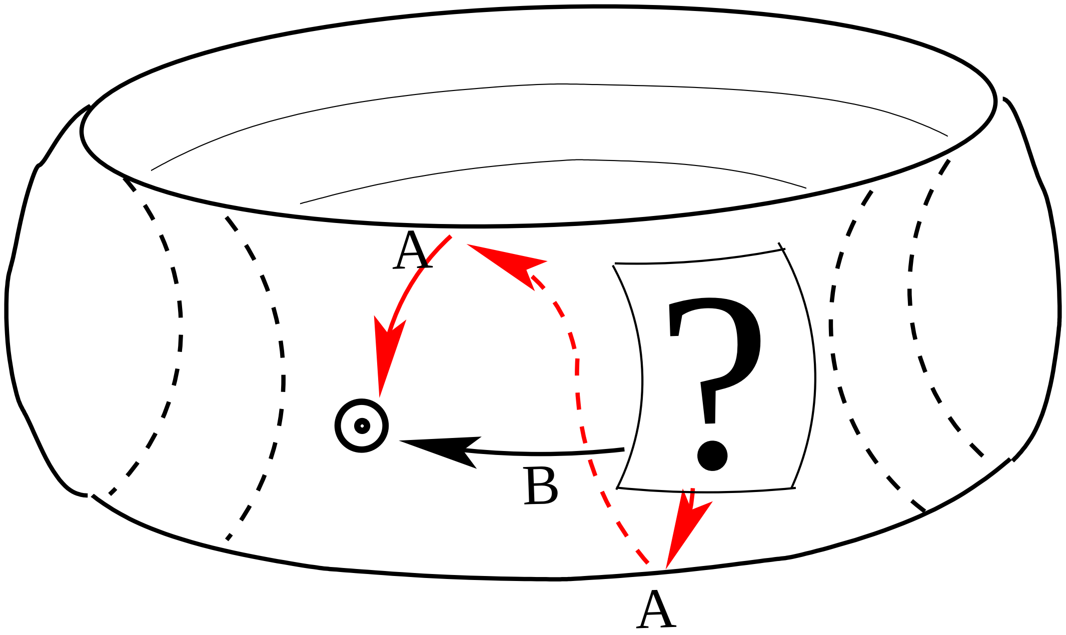
- w:

2D topology intuition ($k = 0$)

- intuition 1: embed in higher dim. space

2D topology intuition ($k = 0$)

- intuition 1: embed in higher dim. space

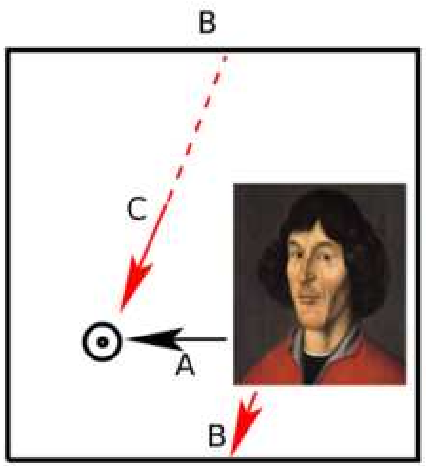


2D topology intuition ($k = 0$)

- intuition 1: embed in higher dim. space
- intuition 2: fundamental domain

2D topology intuition ($k = 0$)

- intuition 1: embed in higher dim. space
- intuition 2: fundamental domain

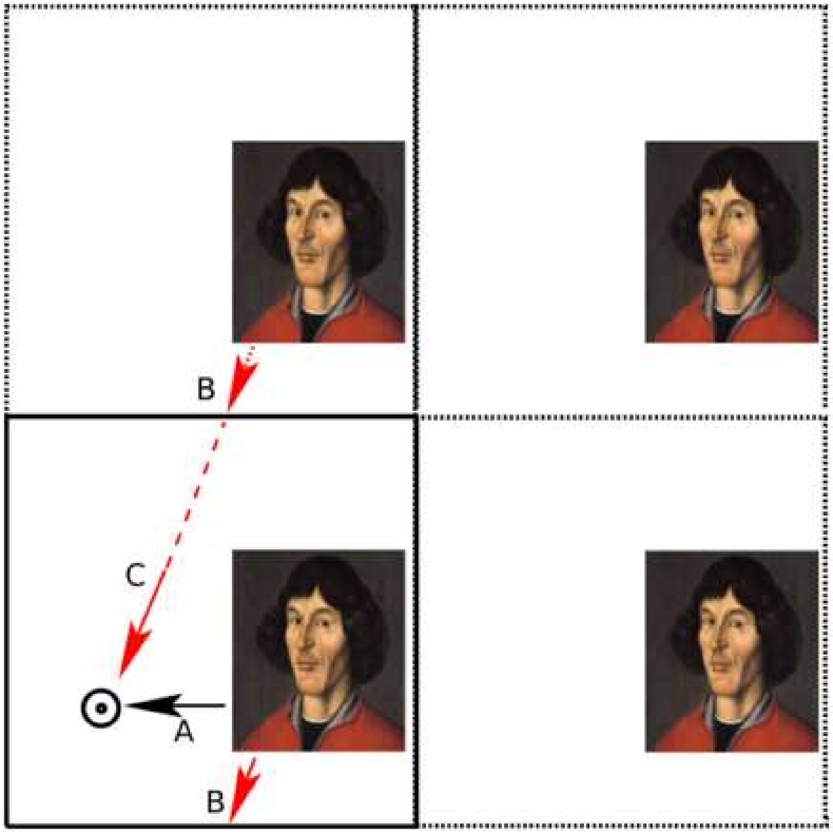


2D topology intuition ($k = 0$)

- intuition 1: embed in higher dim. space
- intuition 2: fundamental domain
- intuition 3: universal covering space

2D topology intuition ($k = 0$)

- intuition 1: embed in higher dim. space
- intuition 2: fundamental domain
- intuition 3: universal covering space



expansion

- Hubble law (Lemaître 1927; ADS:1927ASSB...47...49L): $\dot{a}(t_0)/a(t_0) \approx 600$ km/s/Mpc

expansion

- Hubble law (Lemaître 1927; ADS:1927ASSB...47...49L):
  $\dot{a}(t_0)/a(t_0) \approx 600$ km/s/Mpc > 0 (also Hubble 1929)

expansion

- Hubble law (Lemaître 1927; ADS:1927ASSB...47...49L):
  $\dot{a}(t_0)/a(t_0) \approx 600$ km/s/Mpc > 0 (also Hubble 1929)
- so what is the "Big Bang"?

expansion

- Hubble law (Lemaître 1927; ADS:1927ASSB...47...49L): $\dot{a}(t_0)/a(t_0) \approx 600$ km/s/Mpc > 0 (also Hubble 1929)
- so what is the "Big Bang"?
- it is: $\exists t_\mathrm{b}$ such that $t \to t_\mathrm{b}^+ \Rightarrow a(t) \to 0^+$

expansion

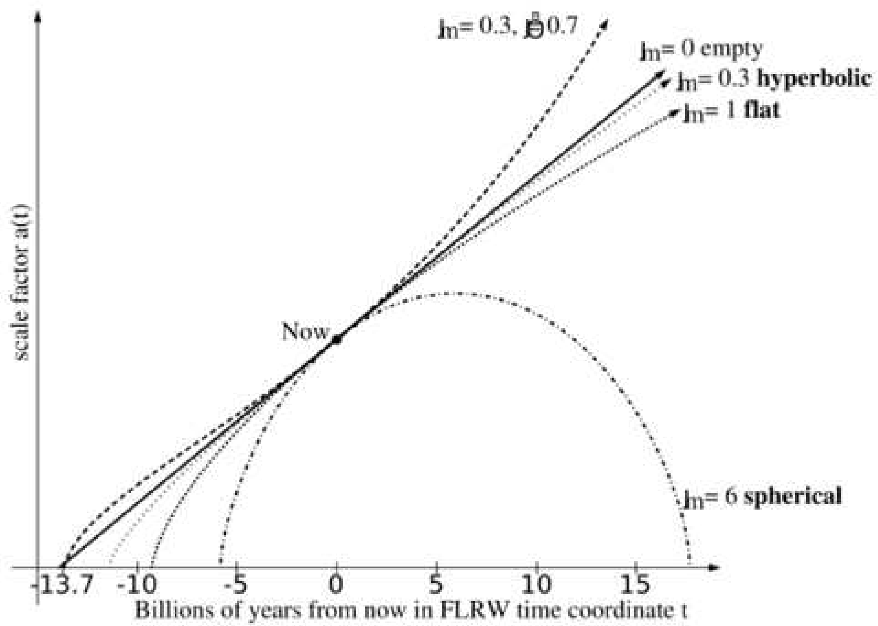
- Hubble law (Lemaître 1927; ADS:1927ASSB...47...49L):
  $\dot{a}(t_0)/a(t_0) \approx 600$ km/s/Mpc > 0 (also Hubble 1929)
- so what is the "Big Bang"?
- convention: $t_\mathrm{b} := 0$, giving $t \to 0^+ \Rightarrow a(t) \to 0^+$

expansion

- Hubble law (Lemaître 1927; ADS:1927ASSB...47...49L): $\dot{a}(t_0)/a(t_0) \approx 600$ km/s/Mpc > 0 (also Hubble 1929)
- so what is the "Big Bang"?
- it is: $\exists t_\mathrm{b}$ such that $t \to t_\mathrm{b}^+ \Rightarrow a(t) \to 0^+$

expansion

- Hubble law (Lemaître 1927; ADS:1927ASSB...47...49L): $\dot{a}(t_0)/a(t_0) \approx 600$ km/s/Mpc > 0 (also Hubble 1929)
- so what is the "Big Bang"?
- it is: $\exists t_\mathrm{b}$ such that $t \rightarrow t_\mathrm{b}^+ \Rightarrow a(t) \rightarrow 0^+$



w:

expansion

- matter density: $\rho_{\rm m} \propto a^{-3}$

expansion

- matter density: $\rho_{\rm m} \propto a^{-3}$
- wavelength: $\lambda \propto a$ [GR—transport four-velocity: Synge (1960); Narlikar (1994; ADS:1994AmJPh..62..903N)]

expansion

- matter density: $\rho_{\rm m} \propto a^{-3}$
- wavelength: $\lambda \propto a$ [GR—transport four-velocity: Synge (1960); Narlikar (1994; ADS:1994AmJPh..62..903N)]

$\Leftrightarrow$

$$\frac{\lambda_{\rm obs}}{\lambda_{\rm em}} = \frac{a_{\rm obs}}{a_{\rm em}}$$

expansion

- matter density: $\rho_{\rm m} \propto a^{-3}$
- wavelength: $\lambda \propto a$ [GR—transport four-velocity: Synge (1960); Narlikar (1994; ADS:1994AmJPh..62..903N)]
- $$\frac{\lambda_{\rm obs}}{\lambda_{\rm em}} = \frac{1}{a_{\rm em}}$$

  (Defn: $a_0 := 1$)

expansion

- matter density: $\rho_{\rm m} \propto a^{-3}$
- wavelength: $\lambda \propto a$ [GR—transport four-velocity: Synge (1960); Narlikar (1994; ADS:1994AmJPh..62..903N)]
- $$1 + z = \frac{1}{a_{\rm em}}$$

  (Defn of redshift z)

expansion

- matter density: $\rho_{\rm m} \propto a^{-3} = (1+z)^3$
- wavelength: $\lambda \propto a$ [GR—transport four-velocity: Synge (1960); Narlikar (1994; ADS:1994AmJPh..62..903N)]
- $$\boxed{1+z = a^{-1}}$$

  (light-cone convention: a often means $a_{\rm em}$)

expansion

- matter density: $\rho_\mathrm{m} \propto a^{-3} = (1+z)^3$
- wavelength: $\lambda \propto a$ [GR—transport four-velocity: Synge (1960); Narlikar (1994; ADS:1994AmJPh..62..903N)]
- $$\boxed{1 + z = a^{-1}}$$
  (light-cone convention: a often means a_em)
- radiation density: $E = h\nu \Rightarrow \rho_\mathrm{r} \propto a^{-4} = (1+z)^4$

Black body

- Planck's Law: $I(\nu, T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1}$

Black body

- Planck's Law: $I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1}$
- wavelength: $\lambda \propto a \Rightarrow$ frequency: $\nu \propto a^{-1} = (1+z)$

Black body

- Planck's Law: $I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1}$
- wavelength: $\lambda \propto a \Rightarrow$ frequency: $\nu \propto a^{-1} = (1 + z)$
- $\Rightarrow$ temperature: $kT \propto h\nu \propto (1 + z)$

Black body

- Planck's Law: $I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1}$
- wavelength: $\lambda \propto a \Rightarrow$ frequency: $\nu \propto a^{-1} = (1+z)$
- $\Rightarrow$ temperature: $kT \propto h\nu \propto (1+z)$
- $z \gg 1 \Rightarrow$ early Universe dominated by hot, dense plasma = protons, electrons, photons

Black body

- Planck's Law: $I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1}$
- wavelength: $\lambda \propto a \Rightarrow$ frequency: $\nu \propto a^{-1} = (1+z)$
- $\Rightarrow$ temperature: $kT \propto h\nu \propto (1+z)$
- $z \gg 1 \Rightarrow$ early Universe dominated by hot, dense plasma = protons, electrons, photons
- $\Rightarrow$ black body

Black body

- Planck's Law: $I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1}$
- wavelength: $\lambda \propto a \Rightarrow$ frequency: $\nu \propto a^{-1} = (1+z)$
- $\Rightarrow$ temperature: $kT \propto h\nu \propto (1+z)$
- $z \gg 1 \Rightarrow$ early Universe dominated by hot, dense plasma = protons, electrons, photons
- $\Rightarrow$ black body + primordial nucleosynthesis

CMB discovery: McKellar 1941

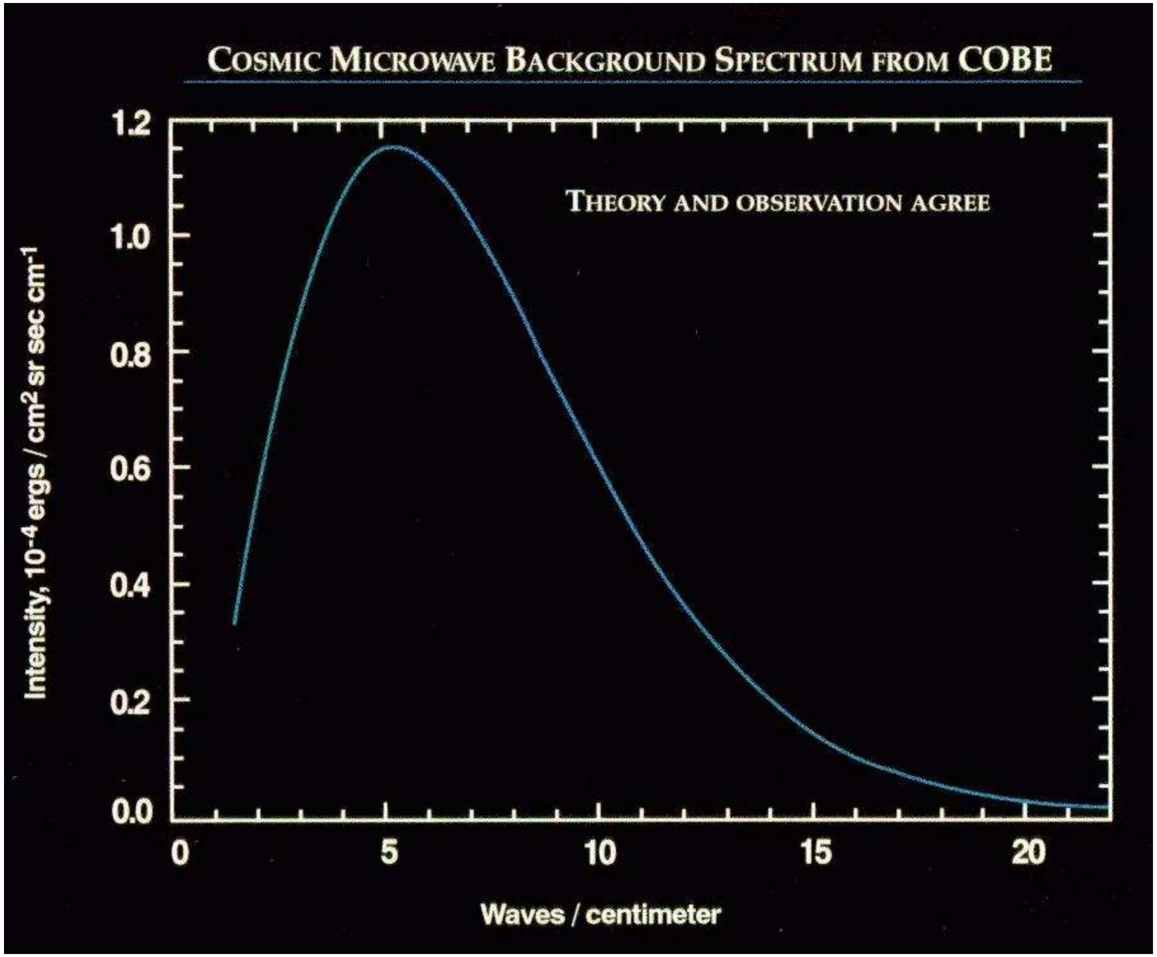
- $T \approx 2.3$ K — Andrew McKellar (1941; ADS:1941PDAO....7..251M) from observations by Walter S. Adams (1941; ADS:1941ApJ....93...11A)
- Penzias & Wilson rediscovery (1965 + Nobel prize)

Black body: COBE (~ 1992)

- COBE /FIRAS (Far Infrared Absolute Spectrophotometer)

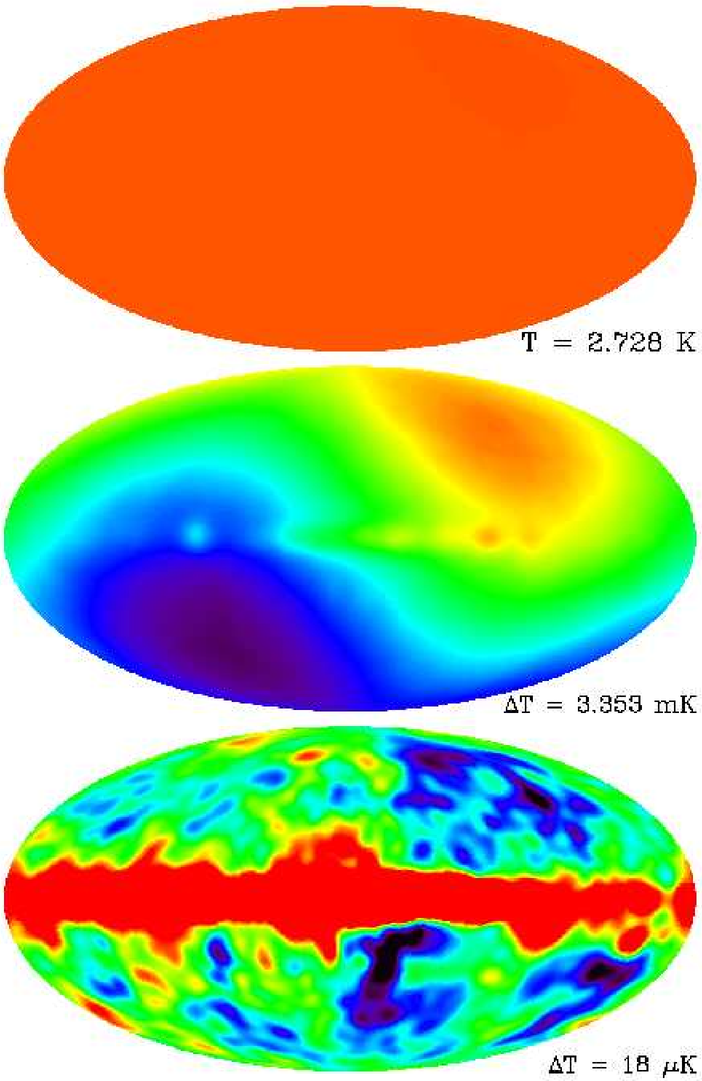
Black body: COBE (~ 1992)

- COBE /FIRAS (Far Infrared Absolute Spectrophotometer)



Black body: COBE (~ 1992)

- COBE /DMR (Differential Microwave Radiometer)



BBN: Big bang nucleosynthesis

- Alpher, Bethe, & Gamow (1948; ADS:1948PhRv...73..803A)

BBN: Big bang nucleosynthesis

- Alpher, Bethe, & Gamow (1948; ADS:1948PhRv...73..803A)

  main reactions of varying probability:

$$\begin{aligned}
\mathrm{p} + \mathrm{n} &\rightarrow {}^{2}\mathrm{H} + \gamma \\
\mathrm{p} + {}^{2}\mathrm{H} &\rightarrow {}^{3}\mathrm{He} + \gamma \\
{}^{2}\mathrm{H} + {}^{2}\mathrm{H} &\rightarrow {}^{3}\mathrm{He} + \mathrm{n} \\
{}^{2}\mathrm{H} + {}^{2}\mathrm{H} &\rightarrow {}^{3}\mathrm{H} + \mathrm{p} \\
{}^{3}\mathrm{He} + {}^{2}\mathrm{H} &\rightarrow {}^{4}\mathrm{He} + \mathrm{p} \\
{}^{3}\mathrm{H} + {}^{2}\mathrm{H} &\rightarrow {}^{4}\mathrm{He} + \mathrm{n}
\end{aligned}$$

BBN: Big bang nucleosynthesis

- Alpher, Bethe, & Gamow (1948; ADS:1948PhRv...73..803A)

  main reactions of varying probability:

$$\begin{aligned}
\mathrm{p} + \mathrm{n} &\rightarrow {}^{2}\mathrm{H} + \gamma \\
\mathrm{p} + {}^{2}\mathrm{H} &\rightarrow {}^{3}\mathrm{He} + \gamma \\
{}^{2}\mathrm{H} + {}^{2}\mathrm{H} &\rightarrow {}^{3}\mathrm{He} + \mathrm{n} \\
{}^{2}\mathrm{H} + {}^{2}\mathrm{H} &\rightarrow {}^{3}\mathrm{H} + \mathrm{p} \\
{}^{3}\mathrm{He} + {}^{2}\mathrm{H} &\rightarrow {}^{4}\mathrm{He} + \mathrm{p} \\
{}^{3}\mathrm{H} + {}^{2}\mathrm{H} &\rightarrow {}^{4}\mathrm{He} + \mathrm{n}
\end{aligned}$$

  w:Big Bang nucleosynthesis

FLRW: $a(t) =?$

- second choice FLRW coord system: $r :=$ w:orthographic projection of radial comoving distance (cf $r :=$ radial comoving distance)

FLRW: $a(t) =?$

- second choice FLRW coord system: $r :=$ w:orthographic projection of radial comoving distance (cf $r :=$ radial comoving distance)

$\Rightarrow$ coord singularity at equator ($:= \pi/2$ from centre) if $k > 0$

FLRW: $a(t) = ?$

- second choice FLRW coord system: $r :=$ w:orthographic projection of radial comoving distance (cf $r :=$ radial comoving distance)

$\Rightarrow$ coord singularity at equator ($:= \pi/2$ from centre) if $k > 0$

FLRW: $a(t) =?$

- second choice FLRW coord system: $r :=$ w:orthographic projection of radial comoving distance (cf $r :=$ radial comoving distance)

$\Rightarrow$ coord singularity at equator ($:= \pi/2$ from centre) if $k > 0$

- $$ds^2 = -dt^2 + a^2(t) \left[\frac{dr^2}{1 - kr^2} + r^2 (d\theta^2 + \cos^2\theta d\phi^2) \right]$$

FLRW: $a(t) =?$

- $$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \cos^2\theta d\phi^2)\right]$$

- universe content: $\mathrm{diag}(\mathbf{T}) = (-\rho, p, p, p)$

FLRW: $a(t) =?$

- $$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\left[\frac{\mathrm{d}r^2}{1-kr^2} + r^2(\mathrm{d}\theta^2 + \cos^2\theta\,\mathrm{d}\phi^2)\right]$$
- universe content: $\mathrm{diag}(\mathbf{T}) = (-\rho, p, p, p)$
- MAXIMA: calculate $\mathbf{G}$ and $\mathbf{G} = 8\pi\mathbf{T}$ and simplify: https://cosmo.torun.pl/Cosmo/FLRWEquationsGR

FLRW: $a(t) =?$

- $$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \cos^2\theta d\phi^2)\right]$$

- universe content: $\mathrm{diag}(\mathbf{T}) = (-\rho, p, p, p)$
- MAXIMA: calculate $\mathbf{G}$ and $\mathbf{G} = 8\pi\mathbf{T}$ and simplify: https://cosmo.torun.pl/Cosmo/FLRWEquationsGR
- Friedmann Eqn: $$\frac{c^2\,k}{a^2} + \frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3}$$

FLRW: $a(t) =?$

- $$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\left[\frac{\mathrm{d}r^2}{1-kr^2} + r^2(\mathrm{d}\theta^2 + \cos^2\theta\,\mathrm{d}\phi^2)\right]$$

- universe content: $\mathrm{diag}(\mathbf{T}) = (-\rho, p, p, p)$
- MAXIMA: calculate $\mathbf{G}$ and $\mathbf{G} = 8\pi\mathbf{T}$ and simplify: https://cosmo.torun.pl/Cosmo/FLRWEquationsGR
- Friedmann Eqn: $$\frac{c^2\,k}{a^2} + \frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3}$$
- acceleration Eqn: $$\frac{\ddot{a}}{a} = -\frac{4\,\pi\,G\,(\rho + 3\,p/c^2)}{3}$$

FLRW matter-dominated epoch

- Friedmann Eqn: $$\boxed{\frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3} - \frac{c^2\,k}{a^2}}$$

FLRW matter-dominated epoch

- Friedmann Eqn: $$\boxed{\frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3} - \frac{c^2\,k}{a^2}}$$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}}$

FLRW matter-dominated epoch

- Friedmann Eqn: $$\boxed{\frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3} - \frac{c^2\,k}{a^2}}$$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$

FLRW matter-dominated epoch

- Friedmann Eqn: $$\boxed{\frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho_{\rm m0}}{3\,a^3} - \frac{c^2\,k}{a^2}}$$
- matter-dominated epoch: $\rho = \rho_{\rm m} = \rho_{\rm m0}\,a^{-3}$

FLRW matter-dominated epoch

- Friedmann Eqn: $\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k}$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$

FLRW matter-dominated epoch

- Friedmann Eqn: $$\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k}$$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$
- $k = 0$ case: $\dot{a}^2 \propto a^{-1}$

FLRW matter-dominated epoch

- Friedmann Eqn: $$\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m}0}}{3\,a} - c^2\,k}$$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m}0}\,a^{-3}$
- $k = 0$ case: $\dot{a} \propto a^{-1/2}$ for $a > 0$

FLRW matter-dominated epoch

- Friedmann Eqn: $\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m}0}}{3\,a} - c^2\,k}$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m}0}\,a^{-3}$
- $k = 0$ case: $\mathrm{d}a \propto a^{-1/2}\mathrm{d}t$ for $a > 0$

FLRW matter-dominated epoch

- Friedmann Eqn: $$\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k}$$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$
- $k = 0$ case: $a^{1/2}\mathrm{d}a \propto \mathrm{d}t$

FLRW matter-dominated epoch

- Friedmann Eqn: $$\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k}$$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$
- $k = 0$ case: $(2/3)a^{3/2} \propto t$

FLRW matter-dominated epoch

- Friedmann Eqn: $\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k}$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$
- $k = 0$ case: $a \propto t^{2/3}$

FLRW matter-dominated epoch

- Friedmann Eqn: $$\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k}$$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$
- $k = 0$ case: $$\boxed{a = \left(\frac{t}{t_0}\right)^{2/3}}$$ Einstein–de Sitter model (EdS)

FLRW matter-dominated epoch

- Friedmann Eqn: $\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k}$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$
- $k = 0$ case: $\boxed{a = \left(\frac{t}{t_0}\right)^{2/3}}$ Einstein–de Sitter model (EdS)

Defn: $\boxed{\text{Hubble parameter } H := \dot{a}/a}$

FLRW matter-dominated epoch

- Friedmann Eqn: $\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m}0}}{3\,a} - c^2\,k}$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m}0}\,a^{-3}$
- $k = 0$ case: $\boxed{a = \left(\frac{t}{t_0}\right)^{2/3}}$ Einstein–de Sitter model (EdS)

Defn: $\boxed{\text{Hubble parameter } H := \dot{a}/a}$

$\Rightarrow$ Hubble constant $H_0 := H(z = 0)$

FLRW matter-dominated epoch

- Friedmann Eqn: $\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k}$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$
- $k = 0$ case: $\boxed{a = \left(\frac{t}{t_0}\right)^{2/3}}$ Einstein–de Sitter model (EdS)

Defn: Hubble parameter $H := \dot{a}/a$

$\Rightarrow$ Hubble constant $H_0 := H(z = 0)$

$\Rightarrow$ $k = 0$ case: $\frac{\dot{a}}{a} = \frac{2}{3t}$

FLRW matter-dominated epoch

- Friedmann Eqn: $$\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k}$$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$
- $k = 0$ case: $$\boxed{a = \left(\frac{t}{t_0}\right)^{2/3}}$$ Einstein–de Sitter model (EdS)

Defn: $\boxed{\text{Hubble parameter } H := \dot{a}/a}$

$\Rightarrow$ Hubble constant $H_0 := H(z=0)$

$\Rightarrow$ $k = 0$ case: $\frac{\dot{a}}{a} = \frac{2}{3t}$

$\Rightarrow$ $H(t) = \frac{2}{3t}$;

FLRW matter-dominated epoch

- Friedmann Eqn: $$\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k}$$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$
- $k = 0$ case: $$\boxed{a = \left(\frac{t}{t_0}\right)^{2/3}}$$ Einstein–de Sitter model (EdS)

Defn: $\boxed{\text{Hubble parameter } H := \dot{a}/a}$

$\Rightarrow$ Hubble constant $H_0 := H(z=0)$

$\Rightarrow$ $k = 0$ case: $\frac{\dot{a}}{a} = \frac{2}{3t}$

$\Rightarrow$ $H(t) = \frac{2}{3t}$; $H_0 = H(t_0) = \frac{2}{3t_0}$

FLRW matter-dominated epoch

- Friedmann Eqn: $$\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m}0}}{3\,a} - c^2\,k}$$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m}0}\,a^{-3}$
- $k = 0$ case: $$\boxed{a = \left(\frac{t}{t_0}\right)^{2/3}}$$ Einstein–de Sitter model (EdS)

$\Rightarrow$ $H(t) = \frac{2}{3t}$; $H_0 = H(t_0) = \frac{2}{3t_0}$

- convenient conversion: 1 km/s ≈ 1.04 kpc/Gyr ≈ 1 kpc/Gyr

FLRW matter-dominated epoch

- Friedmann Eqn: $\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k}$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$
- $k = 0$ case: $\boxed{a = \left(\frac{t}{t_0}\right)^{2/3}}$ Einstein–de Sitter model (EdS)

$\Rightarrow$ $H(t) = \frac{2}{3t}$; $H_0 = H(t_0) = \frac{2}{3t_0}$

- Lemaître (1927) ADS:1927ASSB...47...49L: $H_0 \approx 600$ km/s/Mpc

FLRW matter-dominated epoch

- Friedmann Eqn: $\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k}$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$
- $k = 0$ case: $\boxed{a = \left(\frac{t}{t_0}\right)^{2/3}}$ Einstein–de Sitter model (EdS)

$\Rightarrow$ $H(t) = \frac{2}{3t}$; $H_0 = H(t_0) = \frac{2}{3t_0}$

- Lemaître (1927) ADS:1927ASSB...47...49L: $H_0 \approx 600$ kpc/Gyr/Mpc

FLRW matter-dominated epoch

- Friedmann Eqn: $\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k}$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$
- $k = 0$ case: $\boxed{a = \left(\frac{t}{t_0}\right)^{2/3}}$ Einstein–de Sitter model (EdS)

$\Rightarrow$ $H(t) = \frac{2}{3t}$; $H_0 = H(t_0) = \frac{2}{3t_0}$

- Lemaître (1927) ADS:1927ASSB...47...49L: $H_0 \approx$ 0.6 Gyr^{-1}

FLRW matter-dominated epoch

- Friedmann Eqn: $\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k}$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$
- $k = 0$ case: $\boxed{a = \left(\frac{t}{t_0}\right)^{2/3}}$ Einstein–de Sitter model (EdS)

$\Rightarrow$ $H(t) = \frac{2}{3t}$; $H_0 = H(t_0) = \frac{2}{3t_0}$

- Lemaître (1927) ADS:1927ASSB...47...49L: $H_0 \approx$ 0.6 Gyr^{-1}
- Hubble (1929) ADS:1929PNAS...15..168H: $H_0 \approx$ 500 km/s/Mpc

FLRW matter-dominated epoch

- Friedmann Eqn: $\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k}$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$
- $k = 0$ case: $\boxed{a = \left(\frac{t}{t_0}\right)^{2/3}}$ Einstein–de Sitter model (EdS)

$\Rightarrow$ $H(t) = \frac{2}{3t}$; $H_0 = H(t_0) = \frac{2}{3t_0}$

- Lemaître (1927) ADS:1927ASSB...47...49L: $H_0 \approx 0.6$ Gyr^{-1}
- Hubble (1929) ADS:1929PNAS...15..168H: $H_0 \approx 500$ kpc/Gyr/Mpc

FLRW matter-dominated epoch

- Friedmann Eqn: $$\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k}$$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$
- $k = 0$ case: $\boxed{a = \left(\frac{t}{t_0}\right)^{2/3}}$ Einstein–de Sitter model (EdS)

$\Rightarrow$ $H(t) = \frac{2}{3t}$; $H_0 = H(t_0) = \frac{2}{3t_0}$

- Lemaître (1927) ADS:1927ASSB...47...49L: $H_0 \approx 0.6$ Gyr^{-1}
- Hubble (1929) ADS:1929PNAS...15..168H: $H_0 \approx 0.5$ Gyr^{-1}

FLRW matter-dominated epoch

- Friedmann Eqn: $$\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k$$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$
- $k = 0$ case: $$a = \left(\frac{t}{t_0}\right)^{2/3}$$ Einstein–de Sitter model (EdS)

$\Rightarrow$ $H(t) = \frac{2}{3t}$; $H_0 = H(t_0) = \frac{2}{3t_0}$

- Lemaître (1927) ADS:1927ASSB...47...49L: $H_0 \approx$ 0.6 Gyr^{-1}
- Hubble (1929) ADS:1929PNAS...15..168H: $H_0 \approx$ 0.5 Gyr^{-1}

$\Rightarrow$ EdS would give $t_0 = \frac{2}{3H_0}$

FLRW matter-dominated epoch

- Friedmann Eqn: $\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m}0}}{3\,a} - c^2\,k}$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m}0}\,a^{-3}$
- $k = 0$ case: $\boxed{a = \left(\frac{t}{t_0}\right)^{2/3}}$ Einstein–de Sitter model (EdS)

$\Rightarrow$ $H(t) = \frac{2}{3t}$; $H_0 = H(t_0) = \frac{2}{3t_0}$

- Lemaître (1927) ADS:1927ASSB...47...49L: $H_0 \approx 0.6$ Gyr^{-1}
- Hubble (1929) ADS:1929PNAS...15..168H: $H_0 \approx 0.5$ Gyr^{-1}

$\Rightarrow$ EdS would give $t_0 = \frac{2}{3H_0} \approx 1.3$ Gyr

FLRW matter-dominated epoch

- Friedmann Eqn: $$\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m}0}}{3\,a} - c^2\,k$$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m}0}\,a^{-3}$
- $k = 0$ case: $$a = \left(\frac{t}{t_0}\right)^{2/3}$$ Einstein–de Sitter model (EdS)

$\Rightarrow$ $H(t) = \frac{2}{3t}$; $H_0 = H(t_0) = \frac{2}{3t_0}$

- Lemaître (1927) ADS:1927ASSB...47...49L: $H_0 \approx 0.6$ Gyr^{-1}
- Hubble (1929) ADS:1929PNAS...15..168H: $H_0 \approx 0.5$ Gyr^{-1}

$\Rightarrow$ EdS would give $t_0 = \frac{2}{3H_0} \approx 1.3$ Gyr $< t_{\mathrm{Earth}} \approx 4.5$ Gyr

FLRW matter-dominated epoch

- Friedmann Eqn: $$\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k}$$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$
- $k = 0$ case: $$\boxed{a = \left(\frac{t}{t_0}\right)^{2/3}}$$ Einstein–de Sitter model (EdS)

$\Rightarrow$ $H(t) = \frac{2}{3t}$; $H_0 = H(t_0) = \frac{2}{3t_0}$

- Lemaître (1927) ADS:1927ASSB...47...49L: $H_0 \approx 0.6$ Gyr^{-1}
- Hubble (1929) ADS:1929PNAS...15..168H: $H_0 \approx 0.5$ Gyr^{-1}

$\Rightarrow$ EdS would give $t_0 = \frac{2}{3H_0} \approx 1.3$ Gyr $< t_{\mathrm{Earth}} \approx 4.5$ Gyr

- 1980's: $H_0 \approx 50$ or 100 km/s/Mpc

FLRW matter-dominated epoch

- Friedmann Eqn: $$\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m0}}}{3\,a} - c^2\,k}$$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m0}}\,a^{-3}$
- $k = 0$ case: $\boxed{a = \left(\frac{t}{t_0}\right)^{2/3}}$ Einstein–de Sitter model (EdS)

$\Rightarrow$ $H(t) = \frac{2}{3t}$; $H_0 = H(t_0) = \frac{2}{3t_0}$

- Lemaître (1927) ADS:1927ASSB...47...49L: $H_0 \approx$ 0.6 Gyr^{-1}
- Hubble (1929) ADS:1929PNAS...15..168H: $H_0 \approx$ 0.5 Gyr^{-1}

$\Rightarrow$ EdS would give $t_0 = \frac{2}{3H_0} \approx 1.3$ Gyr $< t_{\mathrm{Earth}} \approx 4.5$ Gyr

- 1980's: $H_0 \approx 50$ or 100 kpc/Gyr/Mpc

FLRW matter-dominated epoch

- Friedmann Eqn: $$\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m}0}}{3\,a} - c^2\,k}$$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m}0}\,a^{-3}$
- $k = 0$ case: $\boxed{a = \left(\frac{t}{t_0}\right)^{2/3}}$ Einstein–de Sitter model (EdS)

$\Rightarrow$ $H(t) = \frac{2}{3t}$; $H_0 = H(t_0) = \frac{2}{3t_0}$

- Lemaître (1927) ADS:1927ASSB...47...49L: $H_0 \approx$ 0.6 Gyr^{-1}
- Hubble (1929) ADS:1929PNAS...15..168H: $H_0 \approx$ 0.5 Gyr^{-1}

$\Rightarrow$ EdS would give $t_0 = \frac{2}{3H_0} \approx 1.3$ Gyr $< t_{\mathrm{Earth}} \approx 4.5$ Gyr

- 1980's: $H_0 \approx 0.05$ or 0.1 Gyr^{-1}

FLRW matter-dominated epoch

- Friedmann Eqn: $\boxed{\dot{a}^2 = \frac{8\,\pi\,G\,\rho_{\mathrm{m}0}}{3\,a} - c^2\,k}$
- matter-dominated epoch: $\rho = \rho_{\mathrm{m}} = \rho_{\mathrm{m}0}\,a^{-3}$
- $k = 0$ case: $\boxed{a = \left(\frac{t}{t_0}\right)^{2/3}}$ Einstein–de Sitter model (EdS)

$\Rightarrow$ $H(t) = \frac{2}{3t}$; $H_0 = H(t_0) = \frac{2}{3t_0}$

- Lemaître (1927) ADS:1927ASSB...47...49L: $H_0 \approx 0.6$ Gyr^{-1}
- Hubble (1929) ADS:1929PNAS...15..168H: $H_0 \approx 0.5$ Gyr^{-1}

$\Rightarrow$ EdS would give $t_0 = \frac{2}{3H_0} \approx 1.3$ Gyr $< t_{\mathrm{Earth}} \approx 4.5$ Gyr

- 1980's: $H_0 \approx 0.05$ or 0.1 Gyr^{-1} $\Rightarrow t_0(\mathrm{EdS}) \approx 13.0$ or 6.5 Gyr, resp.

FLRW: ρ_{crit}

- Friedmann Eqn: $$\frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3} - \frac{c^2\,k}{a^2}$$

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $H^2 = \frac{8\,\pi\,G\,\rho}{3} - \frac{c^2\,k}{a^2}$

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $H^2 = \frac{8\,\pi\,G\,\rho}{3} - \frac{c^2\,k}{a^2}$
- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $H^2 = \frac{8\,\pi\,G\,\rho}{3} - \frac{c^2\,k}{a^2}$
- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc
  - $\rho_{\rm m0} = \frac{3H_0^2}{8\pi G} \Leftrightarrow k = 0$

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $H^2 = \frac{8\,\pi\,G\,\rho}{3} - \frac{c^2\,k}{a^2}$
- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc
  - $\rho_{\rm m0} = \frac{3H_0^2}{8\pi G} \Leftrightarrow k = 0$ flat

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $H^2 = \frac{8\,\pi\,G\,\rho}{3} - \frac{c^2\,k}{a^2}$
- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc
  - $\rho_{\rm m0} = \frac{3H_0^2}{8\pi G} \Leftrightarrow k = 0$ flat
  - $\rho_{\rm m0} > \frac{3H_0^2}{8\pi G} \Leftrightarrow k > 0$

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $H^2 = \frac{8\,\pi\,G\,\rho}{3} - \frac{c^2\,k}{a^2}$
- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc
  - $\rho_{\rm m0} = \frac{3H_0^2}{8\pi G} \Leftrightarrow k = 0$ flat
  - $\rho_{\rm m0} > \frac{3H_0^2}{8\pi G} \Leftrightarrow k > 0$ spherical

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $H^2 = \frac{8\,\pi\,G\,\rho}{3} - \frac{c^2\,k}{a^2}$
- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc
  - $\rho_{\rm m0} = \frac{3H_0^2}{8\pi G} \Leftrightarrow k = 0$ flat
  - $\rho_{\rm m0} > \frac{3H_0^2}{8\pi G} \Leftrightarrow k > 0$ spherical
  - $\rho_{\rm m0} < \frac{3H_0^2}{8\pi G} \Leftrightarrow k < 0$

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $H^2 = \frac{8\,\pi\,G\,\rho}{3} - \frac{c^2\,k}{a^2}$
- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc
  - $\rho_{\rm m0} = \frac{3H_0^2}{8\pi G} \Leftrightarrow k = 0$ flat
  - $\rho_{\rm m0} > \frac{3H_0^2}{8\pi G} \Leftrightarrow k > 0$ spherical
  - $\rho_{\rm m0} < \frac{3H_0^2}{8\pi G} \Leftrightarrow k < 0$ hyperbolic

FLRW: ρ_{crit}

- Friedmann Eqn: $$H^2 = \frac{8\,\pi\,G\,\rho}{3} - \frac{c^2\,k}{a^2}$$

FLRW: ρ_{crit}

- Friedmann Eqn: $H^2 = \frac{8\,\pi\,G\,\rho}{3} - \frac{c^2\,k}{a^2}$

Defn: $\boxed{\rho_{\mathrm{crit}} := \frac{3H^2}{8\pi G}}$ critical density

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $H^2 = \frac{\rho H^2}{\rho_{\rm crit}} - \frac{c^2\, k}{a^2}$

Defn: $\boxed{\rho_{\rm crit} := \frac{3H^2}{8\pi G}}$ critical density

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $$H^2 = \frac{\rho H^2}{\rho_{\rm crit}} - \frac{c^2\, k}{a^2}$$

Defn: $\boxed{\rho_{\rm crit} := \frac{3H^2}{8\pi G}}$ critical density

Defn: $\boxed{\Omega_{\rm m} := \frac{\rho}{\rho_{\rm crit}}}$ matter density parameter

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $H^2 = \Omega_{\rm m} H^2 - \frac{c^2\,k}{a^2}$

Defn: $\boxed{\rho_{\rm crit} := \frac{3H^2}{8\pi G}}$ critical density

Defn: $\boxed{\Omega_{\rm m} := \frac{\rho}{\rho_{\rm crit}}}$ matter density parameter

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $H^2 = \Omega_{\rm m} H^2 - \frac{c^2\, k}{a^2}$

Defn: $\boxed{\rho_{\rm crit} := \frac{3H^2}{8\pi G}}$ critical density

Defn: $\boxed{\Omega_{\rm m} := \frac{\rho}{\rho_{\rm crit}}}$ matter density parameter

Defn: $\boxed{\Omega_k := -\frac{c^2 k}{a^2 H^2}}$ curvature density parameter

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $H^2 = \Omega_{\rm m} H^2 - \frac{c^2\, k}{a^2}$

Defn: $\boxed{\rho_{\rm crit} := \frac{3H^2}{8\pi G}}$ critical density

Defn: $\boxed{\Omega_{\rm m} := \frac{\rho}{\rho_{\rm crit}}}$ matter density parameter

Defn: $\boxed{\Omega_k := -\frac{c^2 k}{a^2 H^2}}$ curvature density parameter (sign reversal!)

FLRW: ρ_{crit}

- Friedmann Eqn: $H^2 = \Omega_{\mathrm{m}} H^2 + \Omega_k H^2$

Defn: $\boxed{\rho_{\mathrm{crit}} := \frac{3H^2}{8\pi G}}$ critical density

Defn: $\boxed{\Omega_{\mathrm{m}} := \frac{\rho}{\rho_{\mathrm{crit}}}}$ matter density parameter

Defn: $\boxed{\Omega_k := -\frac{c^2 k}{a^2 H^2}}$ curvature density parameter (sign reversal!)

FLRW: ρ_{crit}

- Friedmann Eqn: $\boxed{1 = \Omega_{\mathrm{m}} + \Omega_k}$

Defn: $\boxed{\rho_{\mathrm{crit}} := \frac{3H^2}{8\pi G}}$ critical density

Defn: $\boxed{\Omega_{\mathrm{m}} := \frac{\rho}{\rho_{\mathrm{crit}}}}$ matter density parameter

Defn: $\boxed{\Omega_k := -\frac{c^2 k}{a^2 H^2}}$ curvature density parameter (sign reversal!)

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $\boxed{1 = \Omega_{\rm m} + \Omega_k}$

Defn: $\boxed{\rho_{\rm crit} := \frac{3H^2}{8\pi G}}$ critical density

Defn: $\boxed{\Omega_{\rm m} := \frac{\rho}{\rho_{\rm crit}}}$ matter density parameter

Defn: $\boxed{\Omega_k := -\frac{c^2 k}{a^2 H^2}}$ curvature density parameter (sign reversal!)

- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $\boxed{1 = \Omega_{\rm m} + \Omega_k}$

Defn: $\boxed{\rho_{\rm crit} := \frac{3H^2}{8\pi G}}$ critical density

Defn: $\boxed{\Omega_{\rm m} := \frac{\rho}{\rho_{\rm crit}}}$ matter density parameter

Defn: $\boxed{\Omega_k := -\frac{c^2 k}{a^2 H^2}}$ curvature density parameter (sign reversal!)

- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc
  - $\Omega_{\rm m0} = 1 \Leftrightarrow k = 0$

FLRW: ρ_{crit}

- Friedmann Eqn: $$\boxed{1 = \Omega_{\mathrm{m}} + \Omega_k}$$

Defn: $\boxed{\rho_{\mathrm{crit}} := \frac{3H^2}{8\pi G}}$ critical density

Defn: $\boxed{\Omega_{\mathrm{m}} := \frac{\rho}{\rho_{\mathrm{crit}}}}$ matter density parameter

Defn: $\boxed{\Omega_k := -\frac{c^2 k}{a^2 H^2}}$ curvature density parameter (sign reversal!)

- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc
  - $\Omega_{\mathrm{m}0} = 1 \Leftrightarrow k = 0$ flat

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $\boxed{1 = \Omega_{\rm m} + \Omega_k}$

Defn: $\boxed{\rho_{\rm crit} := \frac{3H^2}{8\pi G}}$ critical density

Defn: $\boxed{\Omega_{\rm m} := \frac{\rho}{\rho_{\rm crit}}}$ matter density parameter

Defn: $\boxed{\Omega_k := -\frac{c^2 k}{a^2 H^2}}$ curvature density parameter (sign reversal!)

- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc
  - $\Omega_{\rm m0} = 1 \Leftrightarrow k = 0$ flat
  - $\Omega_{\rm m0} > 1 \Leftrightarrow k > 0$

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $\boxed{1 = \Omega_{\rm m} + \Omega_k}$

Defn: $\boxed{\rho_{\rm crit} := \frac{3H^2}{8\pi G}}$ critical density

Defn: $\boxed{\Omega_{\rm m} := \frac{\rho}{\rho_{\rm crit}}}$ matter density parameter

Defn: $\boxed{\Omega_k := -\frac{c^2 k}{a^2 H^2}}$ curvature density parameter (sign reversal!)

- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc
  - $\Omega_{\rm m0} = 1 \Leftrightarrow k = 0$ flat
  - $\Omega_{\rm m0} > 1 \Leftrightarrow k > 0$ spherical

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $\boxed{1 = \Omega_{\rm m} + \Omega_k}$

Defn: $\boxed{\rho_{\rm crit} := \frac{3H^2}{8\pi G}}$ critical density

Defn: $\boxed{\Omega_{\rm m} := \frac{\rho}{\rho_{\rm crit}}}$ matter density parameter

Defn: $\boxed{\Omega_k := -\frac{c^2 k}{a^2 H^2}}$ curvature density parameter (sign reversal!)

- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc
  - $\Omega_{\rm m0} = 1 \Leftrightarrow k = 0$ flat
  - $\Omega_{\rm m0} > 1 \Leftrightarrow k > 0$ spherical
  - $\Omega_{\rm m0} < 1 \Leftrightarrow k < 0$

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $\boxed{1 = \Omega_{\rm m} + \Omega_k}$

Defn: $\boxed{\rho_{\rm crit} := \frac{3H^2}{8\pi G}}$ critical density

Defn: $\boxed{\Omega_{\rm m} := \frac{\rho}{\rho_{\rm crit}}}$ matter density parameter

Defn: $\boxed{\Omega_k := -\frac{c^2 k}{a^2 H^2}}$ curvature density parameter (sign reversal!)

- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc
  - $\Omega_{\rm m0} = 1 \Leftrightarrow k = 0$ flat
  - $\Omega_{\rm m0} > 1 \Leftrightarrow k > 0$ spherical
  - $\Omega_{\rm m0} < 1 \Leftrightarrow k < 0$ hyperbolic

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $\boxed{1 = \Omega_{\rm tot} + \Omega_k}$

Defn: $\boxed{\rho_{\rm crit} := \frac{3H^2}{8\pi G}}$ critical density

Defn: $\boxed{\Omega_{\rm m} := \frac{\rho}{\rho_{\rm crit}}}$ matter density parameter

Defn: $\boxed{\Omega_k := -\frac{c^2 k}{a^2 H^2}}$ curvature density parameter (sign reversal!)

- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc
  - $\Omega_{\rm m0} = 1 \Leftrightarrow k = 0$ flat
  - $\Omega_{\rm m0} > 1 \Leftrightarrow k > 0$ spherical
  - $\Omega_{\rm m0} < 1 \Leftrightarrow k < 0$ hyperbolic

- $\Omega_{\rm tot} :=$

FLRW: ρ_{crit}

- Friedmann Eqn: $\boxed{1 = \Omega_{\mathrm{tot}} + \Omega_k}$

Defn: $\boxed{\rho_{\mathrm{crit}} := \frac{3H^2}{8\pi G}}$ critical density

Defn: $\boxed{\Omega_{\mathrm{m}} := \frac{\rho}{\rho_{\mathrm{crit}}}}$ matter density parameter

Defn: $\boxed{\Omega_k := -\frac{c^2 k}{a^2 H^2}}$ curvature density parameter (sign reversal!)

- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc
  - $\Omega_{\mathrm{m}0} = 1 \Leftrightarrow k = 0$ flat
  - $\Omega_{\mathrm{m}0} > 1 \Leftrightarrow k > 0$ spherical
  - $\Omega_{\mathrm{m}0} < 1 \Leftrightarrow k < 0$ hyperbolic

- $\Omega_{\mathrm{tot}} := \Omega_{\mathrm{m}} +$

FLRW: ρ_{crit}

- Friedmann Eqn: $\boxed{1 = \Omega_{\mathrm{tot}} + \Omega_k}$

Defn: $\boxed{\rho_{\mathrm{crit}} := \frac{3H^2}{8\pi G}}$ critical density

Defn: $\boxed{\Omega_{\mathrm{m}} := \frac{\rho}{\rho_{\mathrm{crit}}}}$ matter density parameter

Defn: $\boxed{\Omega_k := -\frac{c^2 k}{a^2 H^2}}$ curvature density parameter (sign reversal!)

- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc
  - $\Omega_{\mathrm{m}0} = 1 \Leftrightarrow k = 0$ flat
  - $\Omega_{\mathrm{m}0} > 1 \Leftrightarrow k > 0$ spherical
  - $\Omega_{\mathrm{m}0} < 1 \Leftrightarrow k < 0$ hyperbolic
- $\Omega_{\mathrm{tot}} := \Omega_{\mathrm{m}} + \Omega_{\mathrm{r}} +$

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $\boxed{1 = \Omega_{\rm tot} + \Omega_k}$

Defn: $\boxed{\rho_{\rm crit} := \frac{3H^2}{8\pi G}}$ critical density

Defn: $\boxed{\Omega_{\rm m} := \frac{\rho}{\rho_{\rm crit}}}$ matter density parameter

Defn: $\boxed{\Omega_k := -\frac{c^2 k}{a^2 H^2}}$ curvature density parameter (sign reversal!)

- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc
  - $\Omega_{\rm m0} = 1 \Leftrightarrow k = 0$ flat
  - $\Omega_{\rm m0} > 1 \Leftrightarrow k > 0$ spherical
  - $\Omega_{\rm m0} < 1 \Leftrightarrow k < 0$ hyperbolic

- $\Omega_{\rm tot} := \Omega_{\rm m} + \Omega_{\rm r} + \Omega_\Lambda$

FLRW: $\rho_{\rm crit}$

- Friedmann Eqn: $\boxed{1 = \Omega_{\rm tot} + \Omega_k}$

Defn: $\boxed{\rho_{\rm crit} := \frac{3H^2}{8\pi G}}$ critical density

Defn: $\boxed{\Omega_{\rm m} := \frac{\rho}{\rho_{\rm crit}}}$ matter density parameter

Defn: $\boxed{\Omega_k := -\frac{c^2 k}{a^2 H^2}}$ curvature density parameter (sign reversal!)

- consider a fixed observation, e.g. $H_0 = 100$ km/s/Mpc
  - $\Omega_{\rm m0} = 1 \Leftrightarrow k = 0$ flat
  - $\Omega_{\rm m0} > 1 \Leftrightarrow k > 0$ spherical
  - $\Omega_{\rm m0} < 1 \Leftrightarrow k < 0$ hyperbolic

- $\Omega_{\rm tot} := \Omega_{\rm b} + \Omega_{\rm nbDM} + \Omega_{\rm r} + \Omega_\Lambda$

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_{C}

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_C
  - orthographic coords: k

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_{C}
  - orthographic coords: k
- orthographic: $1 - kr^2 = 0$ coord singularity at equator

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_{C}
  - orthographic coords: k
- orthographic: $1 - kr^2 = 0$ coord singularity at equator
- $\Rightarrow kR_{\mathrm{C}}^2 = 1$

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_{C}
  - orthographic coords: k
- orthographic: $1 - kr^2 = 0$ coord singularity at equator
- $\Rightarrow kR_{\mathrm{C}}^2 = 1 \Rightarrow k = 1/R_{\mathrm{C}}^2$

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_{C}
  - orthographic coords: k
- orthographic: $1 - kr^2 = 0$ coord singularity at equator
- $\Rightarrow kR_{\mathrm{C}}^2 = 1 \Rightarrow k = 1/R_{\mathrm{C}}^2$
- Defn: $\Omega_k := -\frac{c^2 k}{a^2 H^2}$

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_{C}
  - orthographic coords: k
- orthographic: $1 - kr^2 = 0$ coord singularity at equator
- $\Rightarrow kR_{\mathrm{C}}^2 = 1 \Rightarrow k = 1/R_{\mathrm{C}}^2$
- Defn: $\Omega_k := -\frac{c^2 k}{a^2 H^2} \ \Rightarrow \ \Omega_{k0} = -\frac{c^2 k}{H_0^2}$

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_{C}
  - orthographic coords: k
- orthographic: $1 - kr^2 = 0$ coord singularity at equator
- $\Rightarrow kR_{\mathrm{C}}^2 = 1 \Rightarrow k = 1/R_{\mathrm{C}}^2$
- Defn: $\Omega_k := -\frac{c^2 k}{a^2 H^2} \;\Rightarrow\; k = -\frac{\Omega_{k0} H_0^2}{c^2}$

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_{C}
  - orthographic coords: k
- orthographic: $1 - kr^2 = 0$ coord singularity at equator
- $\Rightarrow kR_{\mathrm{C}}^2 = 1 \Rightarrow k = 1/R_{\mathrm{C}}^2$
- Defn: $\Omega_k := -\frac{c^2 k}{a^2 H^2} \;\Rightarrow\; R_{\mathrm{C}}^2 = -\frac{c^2}{\Omega_{k0} H_0^2}$

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_{C}
  - orthographic coords: k
- orthographic: $1 - kr^2 = 0$ coord singularity at equator
- $\Rightarrow kR_{\mathrm{C}}^2 = 1 \Rightarrow k = 1/R_{\mathrm{C}}^2$
- Defn: $\Omega_k := -\frac{c^2 k}{a^2 H^2} \;\Rightarrow\; R_{\mathrm{C}}^2 = -\frac{c^2}{H_0^2}\frac{1}{\Omega_{k0}}$

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_C
  - orthographic coords: k
- orthographic: $1 - kr^2 = 0$ coord singularity at equator
- $\Rightarrow kR_\mathrm{C}^2 = 1 \Rightarrow k = 1/R_\mathrm{C}^2$
- Defn: $\Omega_k := -\frac{c^2 k}{a^2 H^2}$ $\Rightarrow$ $R_\mathrm{C}^2 = -\frac{c^2}{H_0^2}\frac{1}{1-\Omega_{\mathrm{tot}\,0}}$

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_{C}
  - orthographic coords: k
- orthographic: $1 - kr^2 = 0$ coord singularity at equator
- $\Rightarrow kR_{\mathrm{C}}^2 = 1 \Rightarrow k = 1/R_{\mathrm{C}}^2$
- Defn: $\Omega_k := -\frac{c^2 k}{a^2 H^2}$ $\Rightarrow$ $\boxed{R_{\mathrm{C}} = \frac{c}{H_0} \frac{1}{\sqrt{\Omega_{\mathrm{tot}0} - 1}}}$

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_C
  - orthographic coords: k
- orthographic: $1 - kr^2 = 0$ coord singularity at equator
- $\Rightarrow kR_\mathrm{C}^2 = 1 \Rightarrow k = 1/R_\mathrm{C}^2$
- Defn: $\Omega_k := -\frac{c^2 k}{a^2 H^2}$ $\Rightarrow$ $\boxed{R_\mathrm{C} = \frac{c}{H_0} \frac{1}{\sqrt{\Omega_{\mathrm{tot}0} - 1}}}$
- $\Omega_{\mathrm{tot}0} > 1$

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_{C}
  - orthographic coords: k
- orthographic: $1 - kr^2 = 0$ coord singularity at equator
- $\Rightarrow kR_{\mathrm{C}}^2 = 1 \Rightarrow k = 1/R_{\mathrm{C}}^2$
- Defn: $\Omega_k := -\frac{c^2 k}{a^2 H^2}$ $\Rightarrow$ $\boxed{R_{\mathrm{C}} = \frac{c}{H_0} \frac{1}{\sqrt{\Omega_{\mathrm{tot}0} - 1}}}$
- $\Omega_{\mathrm{tot}0} > 1$ *spherical*

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_{C}
  - orthographic coords: k

- orthographic: $1 - kr^2 = 0$ coord singularity at equator
- $\Rightarrow kR_{\mathrm{C}}^2 = 1 \Rightarrow k = 1/R_{\mathrm{C}}^2$
- Defn: $\Omega_k := -\frac{c^2 k}{a^2 H^2}$ $\Rightarrow$ $\boxed{R_{\mathrm{C}} = \frac{c}{H_0} \frac{1}{\sqrt{\Omega_{\mathrm{tot}0} - 1}}}$
- $\Omega_{\mathrm{tot}0} > 1$ *spherical* R_{C} real

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_{C}
  - orthographic coords: k
- orthographic: $1 - kr^2 = 0$ coord singularity at equator
- $\Rightarrow kR_{\mathrm{C}}^2 = 1 \Rightarrow k = 1/R_{\mathrm{C}}^2$
- Defn: $\Omega_k := -\frac{c^2 k}{a^2 H^2}$ $\Rightarrow$ $\boxed{R_{\mathrm{C}} = \frac{c}{H_0} \frac{1}{\sqrt{\Omega_{\mathrm{tot}0} - 1}}}$
- $\Omega_{\mathrm{tot}0} > 1$ *spherical* R_{C} real
- $\Omega_{\mathrm{tot}0} = 1$

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_{C}
  - orthographic coords: k
- orthographic: $1 - kr^2 = 0$ coord singularity at equator
- $\Rightarrow kR_{\mathrm{C}}^2 = 1 \Rightarrow k = 1/R_{\mathrm{C}}^2$
- Defn: $\Omega_k := -\frac{c^2 k}{a^2 H^2}$ $\Rightarrow$ $\boxed{R_{\mathrm{C}} = \frac{c}{H_0} \frac{1}{\sqrt{\Omega_{\mathrm{tot}0} - 1}}}$
- $\Omega_{\mathrm{tot}0} > 1$ *spherical* R_{C} real
- $\Omega_{\mathrm{tot}0} = 1$ *flat*

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_{C}
  - orthographic coords: k
- orthographic: $1 - kr^2 = 0$ coord singularity at equator
- $\Rightarrow kR_{\mathrm{C}}^2 = 1 \Rightarrow k = 1/R_{\mathrm{C}}^2$
- Defn: $\Omega_k := -\frac{c^2 k}{a^2 H^2}$ $\Rightarrow$ $\boxed{R_{\mathrm{C}} = \frac{c}{H_0} \frac{1}{\sqrt{\Omega_{\mathrm{tot0}} - 1}}}$
- $\Omega_{\mathrm{tot0}} > 1$ *spherical* R_{C} real
- $\Omega_{\mathrm{tot0}} = 1$ *flat* R_{C} undefined

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_{C}
  - orthographic coords: k
- orthographic: $1 - kr^2 = 0$ coord singularity at equator
- $\Rightarrow kR_{\mathrm{C}}^2 = 1 \Rightarrow k = 1/R_{\mathrm{C}}^2$
- Defn: $\Omega_k := -\frac{c^2 k}{a^2 H^2}$ $\Rightarrow$ $\boxed{R_{\mathrm{C}} = \frac{c}{H_0} \frac{1}{\sqrt{\Omega_{\mathrm{tot}0} - 1}}}$
- $\Omega_{\mathrm{tot}0} > 1$ *spherical* R_{C} real
- $\Omega_{\mathrm{tot}0} = 1$ *flat* R_{C} undefined
- $\Omega_{\mathrm{tot}0} < 1$

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_{C}
  - orthographic coords: k
- orthographic: $1 - kr^2 = 0$ coord singularity at equator
- $\Rightarrow kR_{\mathrm{C}}^2 = 1 \Rightarrow k = 1/R_{\mathrm{C}}^2$
- Defn: $\Omega_k := -\frac{c^2 k}{a^2 H^2}$ $\Rightarrow$ $\boxed{R_{\mathrm{C}} = \frac{c}{H_0} \frac{1}{\sqrt{\Omega_{\mathrm{tot}0} - 1}}}$
- $\Omega_{\mathrm{tot}0} > 1$ *spherical* R_{C} real
- $\Omega_{\mathrm{tot}0} = 1$ *flat* R_{C} undefined
- $\Omega_{\mathrm{tot}0} < 1$ *hyperbolic*

FLRW curvature constant

- metric in
  - azimuthal equidistant coords: R_{C}
  - orthographic coords: k
- orthographic: $1 - kr^2 = 0$ coord singularity at equator
- $\Rightarrow kR_{\mathrm{C}}^2 = 1 \Rightarrow k = 1/R_{\mathrm{C}}^2$
- Defn: $\Omega_k := -\frac{c^2 k}{a^2 H^2}$ $\Rightarrow$ $\boxed{R_{\mathrm{C}} = \frac{c}{H_0} \frac{1}{\sqrt{\Omega_{\mathrm{tot}0} - 1}}}$
- $\Omega_{\mathrm{tot}0} > 1$ *spherical* R_{C} real
- $\Omega_{\mathrm{tot}0} = 1$ *flat* R_{C} undefined
- $\Omega_{\mathrm{tot}0} < 1$ *hyperbolic* R_{C} imaginary (or use $|R_{\mathrm{C}}|$)

Einstein's free parameter: Λ

- Einstein: prevent expansion/contraction via Λ
  ADS:1917SPAW.......142E

Einstein's free parameter: Λ

- Einstein: prevent expansion/contraction via Λ
  ADS:1917SPAW.......142E
- MAXIMA: calculate $\mathbf{G}$ and $\mathbf{G} + \mathbf{g}\Lambda = 8\pi\mathbf{T}$ and simplify:
  https://cosmo.torun.pl/Cosmo/FLRWEquationsGR

Einstein's free parameter: Λ

- Einstein: prevent expansion/contraction via Λ
  ADS:1917SPAW.......142E
- MAXIMA: calculate $\mathbf{G}$ and $\mathbf{G} + \mathbf{g}\Lambda = 8\pi\mathbf{T}$ and simplify:
  https://cosmo.torun.pl/Cosmo/FLRWEquationsGR
- *hint:* mixed index form of $\mathbf{g}$ is easy

Einstein's free parameter: Λ

- Einstein: prevent expansion/contraction via Λ
  ADS:1917SPAW.......142E

  Friedmann Eqn ($\Lambda \neq 0$): $$\frac{c^2\,k}{a^2} + \frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3} + \frac{c^2\,\Lambda}{3}$$

Einstein's free parameter: Λ

- Einstein: prevent expansion/contraction via Λ
  ADS:1917SPAW.......142E

Friedmann Eqn ($\Lambda \neq 0$):

$$\frac{c^2\,k}{a^2} + \frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3} + \frac{c^2\,\Lambda}{3}$$

acceleration Eqn ($\Lambda \neq 0$):

$$\frac{\ddot{a}}{a} = -\frac{4\,\pi\,G\,(\rho + 3\,p/c^2)}{3} + \frac{c^2\,\Lambda}{3}$$

Einstein's free parameter: Λ

- Einstein: prevent expansion/contraction via Λ
  ADS:1917SPAW.......142E

Friedmann Eqn ($\Lambda \neq 0$):
$$\frac{c^2\,k}{a^2} + \frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3} + \frac{c^2\,\Lambda}{3}$$

acceleration Eqn ($\Lambda \neq 0$):
$$\frac{\ddot{a}}{a} = -\frac{4\,\pi\,G\,(\rho + 3\,p/c^2)}{3} + \frac{c^2\,\Lambda}{3}$$

Defn: "dust solution": $p(t) = 0$

Einstein's free parameter: Λ

- Einstein: prevent expansion/contraction via Λ
  ADS:1917SPAW.......142E

Friedmann Eqn ($\Lambda \neq 0$):
$$\frac{c^2\,k}{a^2} + \frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3} + \frac{c^2\,\Lambda}{3}$$

acceleration Eqn ($\Lambda \neq 0$):
$$\frac{\ddot{a}}{a} = -\frac{4\,\pi\,G\,(\rho + 3\,p/c^2)}{3} + \frac{c^2\,\Lambda}{3}$$

Defn: "dust solution": $p(t) = 0$

Defn: $\Omega_\Lambda := \frac{c^2\,\Lambda}{3\,H^2}$

Einstein's free parameter: Λ

- Einstein: prevent expansion/contraction via Λ
  ADS:1917SPAW.......142E

  Friedmann Eqn ($\Lambda \neq 0$): $$\frac{c^2\,k}{a^2} + \frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3} + \frac{c^2\,\Lambda}{3}$$

Defn: "dust solution": $p(t) = 0$

Defn: $\Omega_\Lambda := \frac{c^2\,\Lambda}{3\,H^2}$

acceleration Eqn ($\Lambda \neq 0$): $$\frac{\ddot{a}}{a} = -\frac{4\,\pi\,G\,\left(\rho + 3\,p/c^2\right)}{3} + \Omega_\Lambda\,H^2$$

Einstein's free parameter: Λ

- Einstein: prevent expansion/contraction via Λ
  ADS:1917SPAW.......142E

Friedmann Eqn ($\Lambda \neq 0$): $$\frac{c^2\,k}{a^2} + \frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3} + \frac{c^2\,\Lambda}{3}$$

Defn: "dust solution": $p(t) = 0$

Defn: $\Omega_\Lambda := \frac{c^2\,\Lambda}{3\,H^2}$

acceleration Eqn ($\Lambda \neq 0$): $$\frac{\ddot{a}}{a} = -\frac{H^2}{2}\frac{\rho}{\rho_{\mathrm{crit}}} + \Omega_\Lambda\,H^2$$

Einstein's free parameter: Λ

- Einstein: prevent expansion/contraction via Λ
  ADS:1917SPAW.......142E

Friedmann Eqn ($\Lambda \neq 0$): $$\frac{c^2\,k}{a^2} + \frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3} + \frac{c^2\,\Lambda}{3}$$

Defn: "dust solution": $p(t) = 0$

Defn: $\Omega_\Lambda := \frac{c^2\,\Lambda}{3\,H^2}$

acceleration Eqn ($\Lambda \neq 0$): $$\frac{\ddot{a}}{a} = -\frac{H^2\,\Omega_\mathrm{m}}{2} + \Omega_\Lambda\,H^2$$

Einstein's free parameter: Λ

- Einstein: prevent expansion/contraction via Λ
  ADS:1917SPAW.......142E

Friedmann Eqn ($\Lambda \neq 0$): $$\frac{c^2\,k}{a^2} + \frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3} + \frac{c^2\,\Lambda}{3}$$

Defn: "dust solution": $p(t) = 0$

Defn: $\Omega_\Lambda := \frac{c^2\,\Lambda}{3\,H^2}$

acceleration Eqn ($\Lambda \neq 0$): $$\frac{\ddot{a}}{a}\frac{a^2}{\dot{a}^2} = -\frac{\Omega_{\mathrm{m}}}{2} + \Omega_\Lambda$$

Einstein's free parameter: Λ

- Einstein: prevent expansion/contraction via Λ
  ADS:1917SPAW.......142E

Friedmann Eqn ($\Lambda \neq 0$): $$\frac{c^2\,k}{a^2} + \frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3} + \frac{c^2\,\Lambda}{3}$$

Defn: "dust solution": $p(t) = 0$

Defn: $\Omega_\Lambda := \frac{c^2\,\Lambda}{3\,H^2}$

acceleration Eqn ($\Lambda \neq 0$): $$\frac{\ddot{a}}{a}\frac{a^2}{\dot{a}^2} = -\frac{\Omega_{\mathrm{m}}}{2} + \Omega_\Lambda$$

Defn: $q := -\frac{\ddot{a}a}{\dot{a}^2}$

Einstein's free parameter: Λ

- Einstein: prevent expansion/contraction via Λ
  ADS:1917SPAW.......142E

Friedmann Eqn ($\Lambda \neq 0$):
$$\frac{c^2\,k}{a^2} + \frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3} + \frac{c^2\,\Lambda}{3}$$

Defn: "dust solution": $p(t) = 0$

Defn: $\Omega_\Lambda := \frac{c^2\,\Lambda}{3\,H^2}$

Defn: $q := -\frac{\ddot{a}a}{\dot{a}^2}$ "deceleration parameter"

acceleration Eqn ($\Lambda \neq 0$):
$$q = \frac{\Omega_{\rm m}}{2} - \Omega_\Lambda$$

Einstein's free parameter: Λ

- Einstein: prevent expansion/contraction via Λ
  ADS:1917SPAW.......142E

  Friedmann Eqn ($\Lambda \neq 0$): $$\frac{c^2\,k}{a^2} + \frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3} + \frac{c^2\,\Lambda}{3}$$

Defn: "dust solution": $p(t) = 0$

Defn: $\Omega_\Lambda := \frac{c^2\,\Lambda}{3\,H^2}$

Defn: $q := -\frac{\ddot{a}a}{\dot{a}^2}$ "deceleration parameter"

- $$\boxed{q = \frac{\Omega_\mathrm{m}}{2} - \Omega_\Lambda}$$

Einstein's free parameter: Λ

- Einstein: prevent expansion/contraction via Λ
  ADS:1917SPAW.......142E

Friedmann Eqn ($\Lambda \neq 0$): $$\frac{c^2\,k}{a^2} + \frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3} + \frac{c^2\,\Lambda}{3}$$

Defn: "dust solution": $p(t) = 0$

Defn: $\Omega_\Lambda := \frac{c^2\,\Lambda}{3\,H^2}$

Defn: $q := -\frac{\ddot{a}a}{\dot{a}^2}$ "deceleration parameter"

- $\boxed{q = \frac{\Omega_{\mathrm{m}}}{2} - \Omega_\Lambda}$ acceleration equation
- if $\Lambda = 0$ and $\Omega_{\mathrm{m}} > 0$ then $\frac{\ddot{a}}{a} < 0$, i.e. $q > 0$

Einstein's free parameter: Λ

- Einstein: prevent expansion/contraction via Λ
  ADS:1917SPAW.......142E

Friedmann Eqn ($\Lambda \neq 0$): $$\frac{c^2\,k}{a^2} + \frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3} + \frac{c^2\,\Lambda}{3}$$

Defn: "dust solution": $p(t) = 0$

Defn: $\Omega_\Lambda := \frac{c^2\,\Lambda}{3\,H^2}$

Defn: $q := -\frac{\ddot{a}a}{\dot{a}^2}$ "deceleration parameter"

- $\boxed{q = \frac{\Omega_{\mathrm{m}}}{2} - \Omega_\Lambda}$ acceleration equation
- if $\Lambda = 0$ and $\Omega_{\mathrm{m}} > 0$ then $\frac{\ddot{a}}{a} < 0$, i.e. $q > 0$ *deceleration*

Einstein's free parameter: Λ

- Einstein: prevent expansion/contraction via Λ
  ADS:1917SPAW.......142E

  Friedmann Eqn ($\Lambda \neq 0$): $$\frac{c^2\,k}{a^2} + \frac{\dot{a}^2}{a^2} = \frac{8\,\pi\,G\,\rho}{3} + \frac{c^2\,\Lambda}{3}$$

Defn: "dust solution": $p(t) = 0$

Defn: $\Omega_\Lambda := \frac{c^2\,\Lambda}{3\,H^2}$

Defn: $q := -\frac{\ddot{a}a}{\dot{a}^2}$ "deceleration parameter"

- $\boxed{q = \frac{\Omega_\mathrm{m}}{2} - \Omega_\Lambda}$ acceleration equation
- if $\Omega_\Lambda > \Omega_\mathrm{m}/2$ then $\frac{\ddot{a}}{a} > 0$, i.e. $q < 0$ *acceleration*

distances in FLRW cosmology

- azimuthal equidistant r:

distances in FLRW cosmology

- azimuthal equidistant r: proper distance at t_0 $\equiv$ comoving radial distance $r = \int_t^{t_0} \frac{c\,\mathrm{d}t'}{a(t')}$

distances in FLRW cosmology

- azimuthal equidistant r: proper distance at t_0 $\equiv$ comoving radial distance $r = \int_t^{t_0} \frac{c\,\mathrm{d}t'}{a(t')}$
- Friedmann Eq: $1 = \Omega_\mathrm{m} + \Omega_k + \Omega_\Lambda$

distances in FLRW cosmology

- azimuthal equidistant r: proper distance at t_0 $\equiv$ comoving radial distance $r = \int_t^{t_0} \frac{c\,\mathrm{d}t'}{a(t')}$
- Friedmann Eq: $1 = \Omega_\mathrm{m} + \Omega_k + \Omega_\Lambda$
- $\Omega_\mathrm{m} = \frac{\rho}{\rho_\mathrm{crit}}$

distances in FLRW cosmology

- azimuthal equidistant r: proper distance at $t_0 \equiv$ comoving radial distance $r = \int_t^{t_0} \frac{c\,\mathrm{d}t'}{a(t')}$
- Friedmann Eq: $1 = \Omega_\mathrm{m} + \Omega_k + \Omega_\Lambda$
- $\Omega_\mathrm{m} = \frac{\rho}{\rho_\mathrm{crit}} = \frac{\rho_0\, a^{-3}}{\rho_{\mathrm{crit}\,0}\,(H^2/H_0^2)}$

distances in FLRW cosmology

- azimuthal equidistant r: proper distance at $t_0 \equiv$ comoving radial distance $r = \int_t^{t_0} \frac{c\,\mathrm{d}t'}{a(t')}$
- Friedmann Eq: $1 = \Omega_\mathrm{m} + \Omega_k + \Omega_\Lambda$
- $\Omega_\mathrm{m} = \frac{\rho}{\rho_\mathrm{crit}} = \frac{\rho_0\, a^{-3}}{\rho_{\mathrm{crit}\,0}\,(H^2/H_0^2)} = \Omega_{\mathrm{m}0}\, H_0^2 a^{-1} \dot{a}^{-2}$

distances in FLRW cosmology

- azimuthal equidistant r: proper distance at $t_0 \equiv$ comoving radial distance $r = \int_t^{t_0} \frac{c\,\mathrm{d}t'}{a(t')}$
- Friedmann Eq: $1 = \Omega_\mathrm{m} + \Omega_k + \Omega_\Lambda$
- $\Omega_\mathrm{m} = \frac{\rho}{\rho_\mathrm{crit}} = \frac{\rho_0\, a^{-3}}{\rho_{\mathrm{crit}\,0}\,(H^2/H_0^2)} = \Omega_{\mathrm{m}0}\, H_0^2 a^{-1} \dot{a}^{-2}$
- $\Omega_k = \Omega_{k0}\, \dot{a}^{-2} H_0^2$

distances in FLRW cosmology

- azimuthal equidistant r: proper distance at $t_0 \equiv$ comoving radial distance $r = \int_t^{t_0} \frac{c\,\mathrm{d}t'}{a(t')}$
- Friedmann Eq: $1 = \Omega_\mathrm{m} + \Omega_k + \Omega_\Lambda$
- $\Omega_\mathrm{m} = \frac{\rho}{\rho_\mathrm{crit}} = \frac{\rho_0\, a^{-3}}{\rho_{\mathrm{crit}\,0}\,(H^2/H_0^2)} = \Omega_{\mathrm{m}0}\, H_0^2 a^{-1} \dot{a}^{-2}$
- $\Omega_k = \Omega_{k0}\, \dot{a}^{-2} H_0^2$
- $\Omega_\Lambda = \Omega_{\Lambda 0} a^2 \dot{a}^{-2} H_0^2$

distances in FLRW cosmology

- azimuthal equidistant r: proper distance at t_0 $\equiv$ comoving radial distance $r = \int_t^{t_0} \frac{c\,\mathrm{d}t'}{a(t')}$
- Friedmann Eq: $1 = \Omega_\mathrm{m} + \Omega_k + \Omega_\Lambda$
- $\Omega_\mathrm{m} = \frac{\rho}{\rho_\mathrm{crit}} = \frac{\rho_0\, a^{-3}}{\rho_{\mathrm{crit}\,0}\,(H^2/H_0^2)} = \Omega_{\mathrm{m}0}\, H_0^2 a^{-1} \dot{a}^{-2}$
- $\Omega_k = \Omega_{k0}\, \dot{a}^{-2} H_0^2$
- $\Omega_\Lambda = \Omega_{\Lambda 0} a^2 \dot{a}^{-2} H_0^2$
- $1 = \Omega_{\mathrm{m}0} H_0^2 a^{-1} \dot{a}^{-2} + \Omega_{k0} \dot{a}^{-2} H_0^2 + \Omega_{\Lambda 0} a^2 \dot{a}^{-2} H_0^2$

distances in FLRW cosmology

- azimuthal equidistant r: proper distance at $t_0 \equiv$ comoving radial distance $r = \int_t^{t_0} \frac{c\,\mathrm{d}t'}{a(t')}$
- Friedmann Eq: $1 = \Omega_\mathrm{m} + \Omega_k + \Omega_\Lambda$
- $\Omega_\mathrm{m} = \frac{\rho}{\rho_\mathrm{crit}} = \frac{\rho_0\, a^{-3}}{\rho_{\mathrm{crit}\,0}\,(H^2/H_0^2)} = \Omega_{\mathrm{m}0}\, H_0^2 a^{-1} \dot{a}^{-2}$
- $\Omega_k = \Omega_{k0}\, \dot{a}^{-2} H_0^2$
- $\Omega_\Lambda = \Omega_{\Lambda 0} a^2 \dot{a}^{-2} H_0^2$
- $1 = \Omega_{\mathrm{m}0} H_0^2 a^{-1} \dot{a}^{-2} + \Omega_{k0} \dot{a}^{-2} H_0^2 + \Omega_{\Lambda 0} a^2 \dot{a}^{-2} H_0^2$

$\Rightarrow$ $\dot{a}^2 = H_0^2 \left(\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2\right)$

distances in FLRW cosmology

- azimuthal equidistant r: proper distance at $t_0 \equiv$ comoving radial distance $r = \int_t^{t_0} \frac{c\,\mathrm{d}t'}{a(t')}$
- Friedmann Eq: $1 = \Omega_\mathrm{m} + \Omega_k + \Omega_\Lambda$
- $\Omega_\mathrm{m} = \frac{\rho}{\rho_\mathrm{crit}} = \frac{\rho_0\, a^{-3}}{\rho_{\mathrm{crit}\,0}\,(H^2/H_0^2)} = \Omega_{\mathrm{m}0}\, H_0^2 a^{-1}\dot{a}^{-2}$
- $\Omega_k = \Omega_{k0}\,\dot{a}^{-2} H_0^2$
- $\Omega_\Lambda = \Omega_{\Lambda 0} a^2 \dot{a}^{-2} H_0^2$
- $1 = \Omega_{\mathrm{m}0} H_0^2 a^{-1}\dot{a}^{-2} + \Omega_{k0}\dot{a}^{-2} H_0^2 + \Omega_{\Lambda 0} a^2 \dot{a}^{-2} H_0^2$

$\Rightarrow$ $\mathrm{d}a = H_0 \sqrt{\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2}\,\mathrm{d}t$ if $\dot{a}, a, H_0 > 0$

distances in FLRW cosmology

- azimuthal equidistant r: proper distance at $t_0 \equiv$ comoving radial distance $r = \int_t^{t_0} \frac{c\,\mathrm{d}t'}{a(t')}$
- Friedmann Eq: $1 = \Omega_\mathrm{m} + \Omega_k + \Omega_\Lambda$
- $\Omega_\mathrm{m} = \frac{\rho}{\rho_\mathrm{crit}} = \frac{\rho_0\, a^{-3}}{\rho_{\mathrm{crit}\,0}\,(H^2/H_0^2)} = \Omega_{\mathrm{m}0}\, H_0^2 a^{-1} \dot{a}^{-2}$
- $\Omega_k = \Omega_{k0}\, \dot{a}^{-2} H_0^2$
- $\Omega_\Lambda = \Omega_{\Lambda 0} a^2 \dot{a}^{-2} H_0^2$
- $1 = \Omega_{\mathrm{m}0} H_0^2 a^{-1} \dot{a}^{-2} + \Omega_{k0} \dot{a}^{-2} H_0^2 + \Omega_{\Lambda 0} a^2 \dot{a}^{-2} H_0^2$

$\Rightarrow$ $\mathrm{d}a = H_0 \sqrt{\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2}\,\mathrm{d}t$ if $\dot{a}, a, H_0 > 0$

$\Rightarrow$ $\mathrm{d}t = \frac{\mathrm{d}a}{H_0 \sqrt{\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2}}$ if $\dot{a}, a, H_0 > 0$

distances in FLRW cosmology

- azimuthal equidistant r: proper distance at $t_0 \equiv$ comoving radial distance $r = \int_t^{t_0} \frac{c\,\mathrm{d}t'}{a(t')}$
- Friedmann Eq: $1 = \Omega_\mathrm{m} + \Omega_k + \Omega_\Lambda$
- $\Omega_\mathrm{m} = \frac{\rho}{\rho_\mathrm{crit}} = \frac{\rho_0\, a^{-3}}{\rho_{\mathrm{crit}\,0}\, (H^2/H_0^2)} = \Omega_{\mathrm{m}0}\, H_0^2 a^{-1} \dot{a}^{-2}$
- $\Omega_k = \Omega_{k0}\, \dot{a}^{-2} H_0^2$
- $\Omega_\Lambda = \Omega_{\Lambda 0} a^2 \dot{a}^{-2} H_0^2$
- $1 = \Omega_{\mathrm{m}0} H_0^2 a^{-1} \dot{a}^{-2} + \Omega_{k0} \dot{a}^{-2} H_0^2 + \Omega_{\Lambda 0} a^2 \dot{a}^{-2} H_0^2$

$\Rightarrow$ $\mathrm{d}a = H_0 \sqrt{\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2}\, \mathrm{d}t$ if $\dot{a}, a, H_0 > 0$

$\Rightarrow$ $$\boxed{r = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\, \sqrt{\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2}}}$$

Low z limit Hubble law

- use r = comoving radial distance

Low z limit Hubble law

- use r = comoving radial distance
- consider $0 < z \ll 1$ limit $\Leftrightarrow 1 > a \gg 0.5$

Low z limit Hubble law

- use r = comoving radial distance
- consider $0 < z \ll 1$ limit $\Leftrightarrow 1 > a \gg 0.5$
- $a = \frac{1}{1+z}$

Low z limit Hubble law

- use $r =$ <u>comoving radial distance</u>
- consider $0 < z \ll 1$ limit $\Leftrightarrow 1 > a \gg 0.5$
- $a = \frac{1}{1+z} \Rightarrow \mathrm{d}a = -(1+z)^{-2}\mathrm{d}z$

Low z limit Hubble law

- use r = comoving radial distance
- consider $0 < z \ll 1$ limit $\Leftrightarrow 1 > a \gg 0.5$
- $a = \frac{1}{1+z} \Rightarrow \mathrm{d}a = -(1+z)^{-2}\mathrm{d}z = -a^2\mathrm{d}z$

Low z limit Hubble law

- use r = <u>comoving radial distance</u>
- consider $0 < z \ll 1$ limit $\Leftrightarrow 1 > a \gg 0.5$
- $a = \frac{1}{1+z} \Rightarrow \mathrm{d}a = -(1+z)^{-2}\mathrm{d}z = -a^2\mathrm{d}z$

$$r = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\,\sqrt{\Omega_{\mathrm{m}0}a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0}a^2}}$$

Low z limit Hubble law

- use $r =$ comoving radial distance
- consider $0 < z \ll 1$ limit $\Leftrightarrow 1 > a \gg 0.5$
- $a = \frac{1}{1+z} \Rightarrow \mathrm{d}a = -(1+z)^{-2}\mathrm{d}z = -a^2\mathrm{d}z$

$$\begin{aligned} r &= \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\sqrt{\Omega_{\mathrm{m}0}a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0}a^2}} \\ &= -\int_{z}^{0} \frac{c}{H_0} \frac{a^2\,\mathrm{d}z}{a\sqrt{\Omega_{\mathrm{m}0}a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0}a^2}} \end{aligned}$$

Low z limit Hubble law

- use $\underline{r = \text{comoving radial distance}}$
- consider $0 < z \ll 1$ limit $\Leftrightarrow 1 > a \gg 0.5$
- $a = \frac{1}{1+z} \Rightarrow \mathrm{d}a = -(1+z)^{-2}\mathrm{d}z = -a^2\mathrm{d}z$

$$\begin{aligned} r &= \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\sqrt{\Omega_{\mathrm{m}0}a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0}a^2}} \\ &= -\int_z^0 \frac{c}{H_0} \frac{a\,\mathrm{d}z}{\sqrt{\Omega_{\mathrm{m}0}a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0}a^2}} \end{aligned}$$

Low z limit Hubble law

- use $\underline{r = \text{comoving radial distance}}$
- consider $0 < z \ll 1$ limit $\Leftrightarrow 1 > a \gg 0.5$
- $a = \frac{1}{1+z} \Rightarrow \mathrm{d}a = -(1+z)^{-2}\mathrm{d}z = -a^2\mathrm{d}z$

$$r = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\sqrt{\Omega_{\mathrm{m}0}a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0}a^2}}$$

$$\approx -\int_{z}^{0} \frac{c}{H_0} \frac{1\,\mathrm{d}z}{\sqrt{\Omega_{\mathrm{m}0} + \Omega_{k0} + \Omega_{\Lambda 0}}}$$

Low z limit Hubble law

- use $\underline{r = \text{comoving radial distance}}$
- consider $0 < z \ll 1$ limit $\Leftrightarrow 1 > a \gg 0.5$
- $a = \frac{1}{1+z} \Rightarrow \mathrm{d}a = -(1+z)^{-2}\mathrm{d}z = -a^2\mathrm{d}z$

$$\begin{aligned} r &= \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\sqrt{\Omega_{\mathrm{m}0}a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0}a^2}} \\ &\approx -\int_z^0 \frac{c}{H_0} \frac{1\,\mathrm{d}z}{\sqrt{1}} \end{aligned}$$

Low z limit Hubble law

- use $r =$ comoving radial distance
- consider $0 < z \ll 1$ limit $\Leftrightarrow 1 > a \gg 0.5$
- $a = \frac{1}{1+z} \Rightarrow \mathrm{d}a = -(1+z)^{-2}\mathrm{d}z = -a^2\mathrm{d}z$

$$\begin{aligned} r &= \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\,\sqrt{\Omega_{\mathrm{m}0}a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0}a^2}} \\ &\approx -\int_z^0 \frac{c}{H_0}\frac{1\,\mathrm{d}z}{\sqrt{1}} \\ &= -\int_z^0 \frac{c}{H_0}\,\mathrm{d}z \end{aligned}$$

Low z limit Hubble law

- use $r =$ comoving radial distance
- consider $0 < z \ll 1$ limit $\Leftrightarrow 1 > a \gg 0.5$
- $a = \frac{1}{1+z} \Rightarrow \mathrm{d}a = -(1+z)^{-2}\mathrm{d}z = -a^2\mathrm{d}z$

$$\begin{aligned} r &= \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\sqrt{\Omega_{\mathrm{m}0}a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0}a^2}} \\ &\approx -\int_z^0 \frac{c}{H_0} \frac{1\,\mathrm{d}z}{\sqrt{1}} \\ &= -\int_z^0 \frac{c}{H_0}\,\mathrm{d}z \end{aligned}$$

$\Rightarrow \quad \frac{\mathrm{d}r}{\mathrm{d}z} \approx \frac{c}{H_0}$

Low z limit Hubble law

- use $\underline{r = \text{comoving radial distance}}$
- consider $0 < z \ll 1$ limit $\Leftrightarrow 1 > a \gg 0.5$
- $a = \frac{1}{1+z} \Rightarrow \mathrm{d}a = -(1+z)^{-2}\mathrm{d}z = -a^2\mathrm{d}z$

$$
\begin{aligned}
r &= \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\sqrt{\Omega_{\mathrm{m}0}a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0}a^2}} \\
&\approx -\int_z^0 \frac{c}{H_0}\frac{1\,\mathrm{d}z}{\sqrt{1}} \\
&= -\int_z^0 \frac{c}{H_0}\,\mathrm{d}z
\end{aligned}
$$

$\Rightarrow \quad \frac{\mathrm{d}r}{\mathrm{d}z} \approx \frac{c}{H_0}$

$\Rightarrow \quad$ when $0 < z \ll 1$, $\beta := v/c$, $\; r \approx \dfrac{z\,c}{H_0}$

Low z limit Hubble law

- use $r =$ comoving radial distance
- consider $0 < z \ll 1$ limit $\Leftrightarrow 1 > a \gg 0.5$
- $a = \frac{1}{1+z} \Rightarrow \mathrm{d}a = -(1+z)^{-2}\mathrm{d}z = -a^2\mathrm{d}z$

$$\begin{aligned} r &= \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\sqrt{\Omega_{\mathrm{m}0}a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0}a^2}} \\ &\approx -\int_z^0 \frac{c}{H_0}\frac{1\,\mathrm{d}z}{\sqrt{1}} \\ &= -\int_z^0 \frac{c}{H_0}\,\mathrm{d}z \end{aligned}$$

$\Rightarrow \quad \frac{\mathrm{d}r}{\mathrm{d}z} \approx \frac{c}{H_0}$

$\Rightarrow$ when $0 < z \ll 1$, $\beta := v/c$, $r \approx \dfrac{z\,c}{H_0} \approx \dfrac{\beta\,c}{H_0}$

Low z limit Hubble law

- use $\underline{r = \text{comoving radial distance}}$
- consider $0 < z \ll 1$ limit $\Leftrightarrow 1 > a \gg 0.5$
- $a = \frac{1}{1+z} \Rightarrow \mathrm{d}a = -(1+z)^{-2}\mathrm{d}z = -a^2\mathrm{d}z$

$$\begin{aligned} r &= \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\sqrt{\Omega_{\mathrm{m}0}a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0}a^2}} \\ &\approx -\int_z^0 \frac{c}{H_0}\frac{1\,\mathrm{d}z}{\sqrt{1}} \\ &= -\int_z^0 \frac{c}{H_0}\,\mathrm{d}z \end{aligned}$$

$\Rightarrow \quad \frac{\mathrm{d}r}{\mathrm{d}z} \approx \frac{c}{H_0}$

$\Rightarrow \quad$ when $0 < z \ll 1$, $\beta := v/c$, $\boxed{r \approx \frac{z\,c}{H_0} \approx \frac{\beta\,c}{H_0} = \frac{v}{H_0}}$

EdS: radial comoving distance

- $r = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\,\sqrt{\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2}}$

EdS: radial comoving distance

- $r = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\,\sqrt{\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2}}$

  EdS: $\Omega_{\mathrm{m}0} = 1, \Omega_{k0} = 0, \Omega_{\Lambda 0} = 0$

EdS: radial comoving distance

- $r = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\,\sqrt{\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2}}$

  EdS: $\Omega_{\mathrm{m}0} = 1, \Omega_{k0} = 0, \Omega_{\Lambda 0} = 0$

$\Rightarrow$
$$r_{\mathrm{EdS}} = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\,\sqrt{a^{-1}}}$$

EdS: radial comoving distance

- $r = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\sqrt{\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2}}$

  EdS: $\Omega_{\mathrm{m}0} = 1, \Omega_{k0} = 0, \Omega_{\Lambda 0} = 0$

$$\Rightarrow \quad r_{\mathrm{EdS}} = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\sqrt{a^{-1}}} = \frac{c}{H_0} \int_{1/(1+z)}^{1} a^{-1/2} \mathrm{d}a$$

EdS: radial comoving distance

- $r = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a \sqrt{\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2}}$

  EdS: $\Omega_{\mathrm{m}0} = 1, \Omega_{k0} = 0, \Omega_{\Lambda 0} = 0$

$$\Rightarrow \quad r_{\mathrm{EdS}} = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a \sqrt{a^{-1}}}$$

$$= \frac{c}{H_0} \int_{1/(1+z)}^{1} a^{-1/2} \mathrm{d}a$$

$$= \frac{c}{H_0} \left[2a^{1/2} \right]_{1/(1+z)}^{1}$$

EdS: radial comoving distance

- $r = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\,\sqrt{\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2}}$

  EdS: $\Omega_{\mathrm{m}0} = 1, \Omega_{k0} = 0, \Omega_{\Lambda 0} = 0$

$\Rightarrow$

$$
\begin{aligned}
r_{\mathrm{EdS}} &= \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\,\sqrt{a^{-1}}} \\
&= \frac{c}{H_0} \int_{1/(1+z)}^{1} a^{-1/2} \mathrm{d}a \\
&= \frac{c}{H_0} \left[2a^{1/2} \right]_{1/(1+z)}^{1} \\
&= \boxed{\frac{2c}{H_0} \left(1 - \frac{1}{\sqrt{1+z}} \right)}
\end{aligned}
$$

EdS: radial comoving distance

- $r = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\,\sqrt{\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2}}$

  EdS: $\Omega_{\mathrm{m}0} = 1, \Omega_{k0} = 0, \Omega_{\Lambda 0} = 0$

$$\Rightarrow \quad \begin{aligned} r_{\mathrm{EdS}} &= \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\,\sqrt{a^{-1}}} \\ &= \frac{c}{H_0} \int_{1/(1+z)}^{1} a^{-1/2} \mathrm{d}a \\ &= \frac{c}{H_0} \left[2a^{1/2}\right]_{1/(1+z)}^{1} \\ &= \boxed{\frac{2c}{H_0}\left(1 - \frac{1}{\sqrt{1+z}}\right)} \\ &\approx 6h^{-1}\mathrm{Gpc}\left(1 - \frac{1}{\sqrt{1+z}}\right) \end{aligned}$$

distances in FLRW cosmology

- $r = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\, \sqrt{\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2}}$

distances in FLRW cosmology

- $r = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\sqrt{\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2}}$
- GPL numerical package: `cosmdist`
  https://codeberg.org/boud/cosmdist

distances in FLRW cosmology

- $r = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\sqrt{\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2}}$
- GPL numerical package: `cosmdist`
  https://codeberg.org/boud/cosmdist
- standard install to `/usr/local`:
  `./configure && make && make install`

distances in FLRW cosmology

- $r = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\,\sqrt{\Omega_{\mathrm{m}0}a^{-1}+\Omega_{k0}+\Omega_{\Lambda 0}a^2}}$
- GPL numerical package: `cosmdist`
  https://codeberg.org/boud/cosmdist
- standard install to `/usr/local`:
  `./configure && make && make install`
- command line pipe:
  `cat myredshifts.lis | cosmdist`

distances in FLRW cosmology

- $r = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\sqrt{\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2}}$
- GPL numerical package: `cosmdist`
  https://codeberg.org/boud/cosmdist
- standard install to `/usr/local`:
  `./configure && make && make install`
- command line pipe:
  `cat myredshifts.lis | cosmdist`
- command line options: `cosmdist --help`

distances in FLRW cosmology

- $r = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\sqrt{\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2}}$
- GPL numerical package: `cosmdist`
  https://codeberg.org/boud/cosmdist
- standard install to `/usr/local`:
  `./configure && make && make install`
- command line pipe:
  `cat myredshifts.lis | cosmdist`
- command line options: `cosmdist --help`
- static fortran or C library: link to `libcosmdist.a`

distances in FLRW cosmology

- $r = \int_{1/(1+z)}^{1} \frac{c}{H_0} \frac{\mathrm{d}a}{a\,\sqrt{\Omega_{\mathrm{m}0} a^{-1} + \Omega_{k0} + \Omega_{\Lambda 0} a^2}}$
- GPL numerical package: `cosmdist`
  https://codeberg.org/boud/cosmdist
- standard install to `/usr/local`:
  `./configure && make && make install`
- command line pipe:
  `cat myredshifts.lis | cosmdist`
- command line options: `cosmdist --help`
- static fortran or C library: link to `libcosmdist.a`
- high-level frontends (e.g. python) should be easy to write

tangential arc-lengths: $r_\perp$ vs d_A

- $r_\perp =:$ "proper motion" distance (Weinberg 1972)

tangential arc-lengths: $r_\perp$ vs d_{A}

- $r_\perp =:$ "proper motion" distance (Weinberg 1972)
- $\equiv$ **comoving** tangential arc-length for 1 radian

tangential arc-lengths: $r_\perp$ vs d_A

- $r_\perp$ =: "proper motion" distance (Weinberg 1972)
- $\equiv$ **comoving** tangential arc-length for 1 radian
- azimuthal equidistant coords: $r_\perp = \begin{cases} R_\mathrm{C} \sinh \frac{r}{R_\mathrm{C}} & k < 0 \\ r & k = 0 \\ R_\mathrm{C} \sin \frac{r}{R_\mathrm{C}} & k > 0 \end{cases}$

tangential arc-lengths: $r_\perp$ vs d_A

- $r_\perp =:$ "proper motion" distance (Weinberg 1972)
- $\equiv$ **comoving** tangential arc-length for 1 radian
- azimuthal equidistant coords: $r_\perp = \begin{cases} R_\mathrm{C} \sinh \frac{r}{R_\mathrm{C}} & k < 0 \\ r & k = 0 \\ R_\mathrm{C} \sin \frac{r}{R_\mathrm{C}} & k > 0 \end{cases}$ where

  $r =$ comoving radial distance
- angular diameter distance d_A

tangential arc-lengths: $r_\perp$ vs d_A

- $r_\perp =:$ "proper motion" distance (Weinberg 1972)
- $\equiv$ **comoving** tangential arc-length for 1 radian
- azimuthal equidistant coords: $r_\perp = \begin{cases} R_\mathrm{C} \sinh \frac{r}{R_\mathrm{C}} & k < 0 \\ r & k = 0 \\ R_\mathrm{C} \sin \frac{r}{R_\mathrm{C}} & k > 0 \end{cases}$ where

  $r =$ comoving radial distance
- angular diameter distance d_A
- $\equiv$ **physical**/

tangential arc-lengths: $r_\perp$ vs d_A

- $r_\perp =:$ "proper motion" distance (Weinberg 1972)
- $\equiv$ **comoving** tangential arc-length for 1 radian
- azimuthal equidistant coords: $r_\perp = \begin{cases} R_\mathrm{C} \sinh \frac{r}{R_\mathrm{C}} & k < 0 \\ r & k = 0 \\ R_\mathrm{C} \sin \frac{r}{R_\mathrm{C}} & k > 0 \end{cases}$ where

  $r =$ comoving radial distance
- angular diameter distance d_A
- $\equiv$ **physical/ metric /**

tangential arc-lengths: $r_\perp$ vs d_A

- $r_\perp =:$ "proper motion" distance (Weinberg 1972)
- $\equiv$ **comoving** tangential arc-length for 1 radian
- azimuthal equidistant coords: $r_\perp = \begin{cases} R_\mathrm{C} \sinh \frac{r}{R_\mathrm{C}} & k < 0 \\ r & k = 0 \\ R_\mathrm{C} \sin \frac{r}{R_\mathrm{C}} & k > 0 \end{cases}$ where

  $r =$ comoving radial distance
- angular diameter distance d_A
- $\equiv$ **physical/ metric / local**

tangential arc-lengths: $r_\perp$ vs d_A

- $r_\perp =:$ "proper motion" distance (Weinberg 1972)
- $\equiv$ **comoving** tangential arc-length for 1 radian
- azimuthal equidistant coords: $r_\perp = \begin{cases} R_\mathrm{C} \sinh \frac{r}{R_\mathrm{C}} & k < 0 \\ r & k = 0 \\ R_\mathrm{C} \sin \frac{r}{R_\mathrm{C}} & k > 0 \end{cases}$ where

  $r =$ comoving radial distance
- angular diameter distance d_A
- $\equiv$ **physical/ metric / local** arc-length for 1 radian

tangential arc-lengths: $r_\perp$ vs d_A

- $r_\perp =:$ "proper motion" distance (Weinberg 1972)
- $\equiv$ **comoving** tangential arc-length for 1 radian
- azimuthal equidistant coords: $r_\perp = \begin{cases} R_\mathrm{C} \sinh \frac{r}{R_\mathrm{C}} & k < 0 \\ r & k = 0 \\ R_\mathrm{C} \sin \frac{r}{R_\mathrm{C}} & k > 0 \end{cases}$ where

  $r =$ comoving radial distance
- angular diameter distance d_A
- $\equiv$ **physical/ metric / local** arc-length for 1 radian
- $d_\mathrm{A} = r_\perp \, a$ (scaled by the scale factor)

tangential arc-lengths: $r_\perp$ vs d_A

- $r_\perp =:$ "proper motion" distance (Weinberg 1972)
- $\equiv$ **comoving** tangential arc-length for 1 radian
- azimuthal equidistant coords: $r_\perp = \begin{cases} R_\mathrm{C} \sinh \frac{r}{R_\mathrm{C}} & k < 0 \\ r & k = 0 \\ R_\mathrm{C} \sin \frac{r}{R_\mathrm{C}} & k > 0 \end{cases}$ where

  $r =$ comoving radial distance
- angular diameter distance d_A
- $\equiv$ **physical/ metric / local** arc-length for 1 radian
- $$\boxed{d_\mathrm{A} = \frac{r_\perp}{1+z}}$$

luminosity distance

want to define d_L such that flux is $F = \frac{L}{4\pi d_L^2}$

luminosity distance

want to define d_L such that flux is $F = \frac{L}{4\pi d_L^2}$

- surface area of 2-sphere $= 4\pi r_\perp^2$ (comoving)

luminosity distance

want to define d_L such that flux is $F = \dfrac{L}{4\pi d_L^2}$

- $E = h\nu$ of photon:

luminosity distance

want to define d_L such that flux is $F = \frac{L}{4\pi d_L^2}$

- $E = h\nu$ of photon: emitter frame to observer frame $F \propto 1/\lambda \propto a_{\mathrm{em}}$

luminosity distance

want to define d_L such that flux is $F = \frac{L}{4\pi d_L^2}$

- $E = h\nu$ of photon: emitter frame to observer frame $F \propto 1/\lambda \propto a_{\rm em}$
- erg **per s**: time dilation:

luminosity distance

want to define d_L such that flux is $F = \frac{L}{4\pi d_L^2}$

- $E = h\nu$ of photon: emitter frame to observer frame $F \propto 1/\lambda \propto a_{\mathrm{em}}$
- erg **per s**: time dilation: emitter frame to observer frame $F \propto a_{\mathrm{em}}$

luminosity distance

want to define d_L such that flux is $F = \dfrac{L}{4\pi d_L^2}$

- $E = h\nu$ of photon: emitter frame to observer frame $F \propto 1/\lambda \propto a_{\rm em}$
- erg **per s**: time dilation: emitter frame to observer frame $F \propto a_{\rm em}$
- $\Rightarrow F = \frac{L}{4\pi r_\perp^2} a^2$

luminosity distance

want to define d_L such that flux is $F = \frac{L}{4\pi d_L^2}$

- $E = h\nu$ of photon: emitter frame to observer frame $F \propto 1/\lambda \propto a_{\rm em}$
- erg **per** s: time dilation: emitter frame to observer frame $F \propto a_{\rm em}$
- $\Rightarrow F = \frac{L}{4\pi r_\perp^2} a^2 = \frac{L}{4\pi r_\perp^2 (1+z)^2}$

luminosity distance

want to define d_L such that flux is $F = \frac{L}{4\pi d_L^2}$

- $E = h\nu$ of photon: emitter frame to observer frame $F \propto 1/\lambda \propto a_{\rm em}$
- erg **per** s: time dilation: emitter frame to observer frame $F \propto a_{\rm em}$
- $\Rightarrow F = \frac{L}{4\pi r_\perp^2} a^2 = \frac{L}{4\pi r_\perp^2 (1+z)^2}$
- $\Rightarrow$ luminosity distance $\boxed{d_L := r_\perp(1+z) = d_{\rm A}(1+z)^2}$

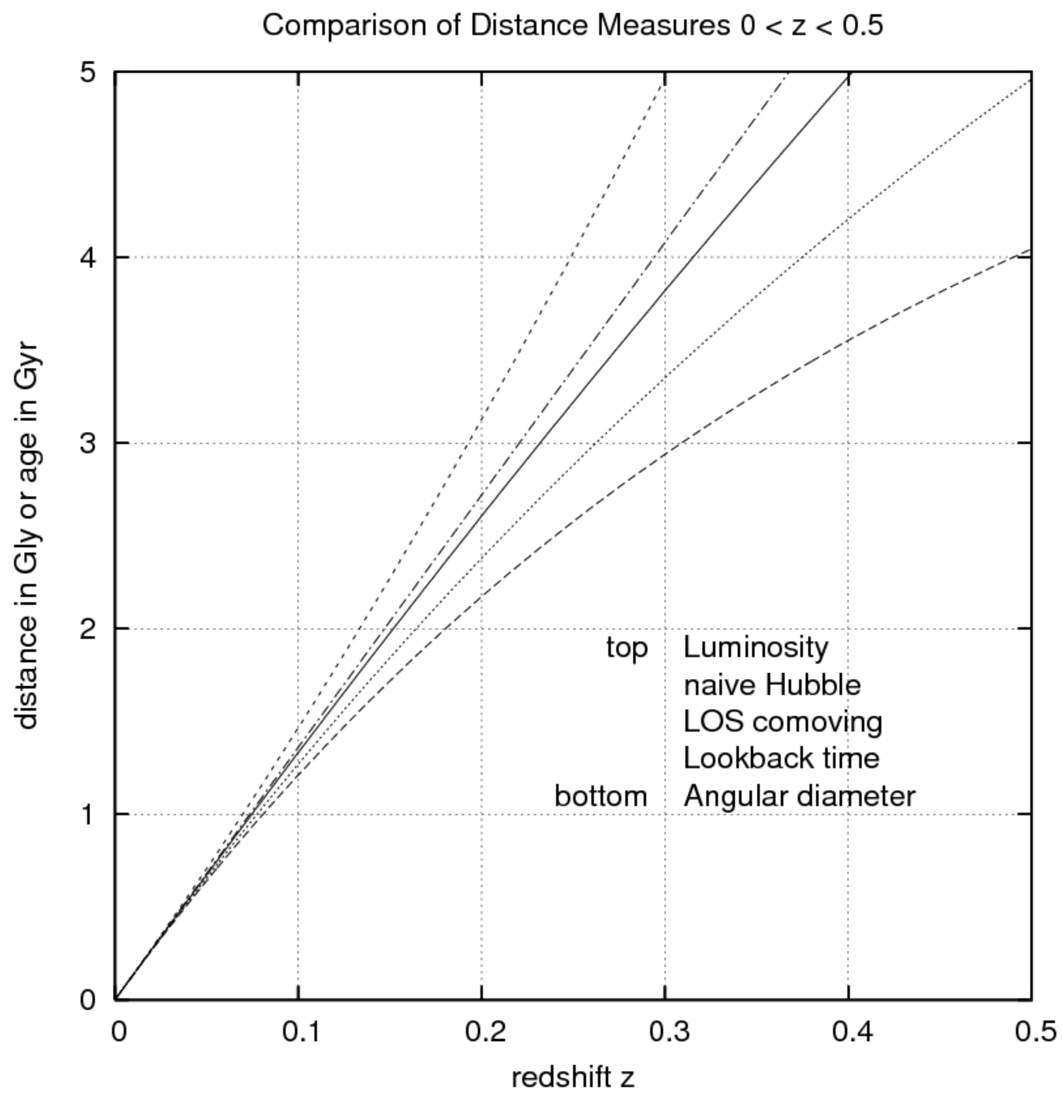
luminosity distance

want to define d_L such that flux is $F = \frac{L}{4\pi d_L^2}$

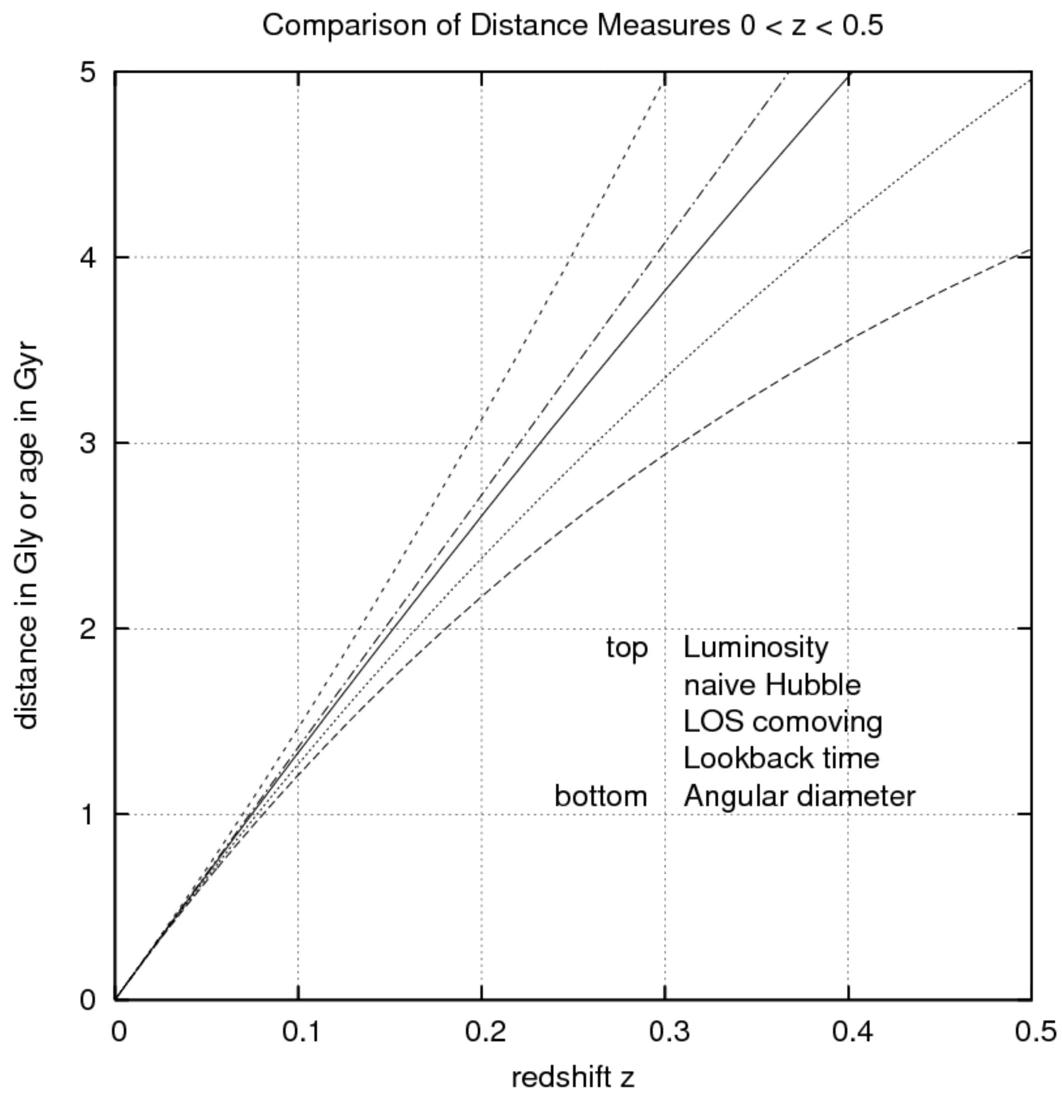
- $E = h\nu$ of photon: emitter frame to observer frame $F \propto 1/\lambda \propto a_{\rm em}$
- erg **per** s: time dilation: emitter frame to observer frame $F \propto a_{\rm em}$
- $\Rightarrow F = \frac{L}{4\pi r_\perp^2} a^2 = \frac{L}{4\pi r_\perp^2 (1+z)^2}$
- $\Rightarrow$ luminosity distance $\boxed{d_L := r_\perp (1+z) = d_{\rm A} (1+z)^2}$

- w:Distance measures (cosmology)

FLRW distances e.g. ΛCDM

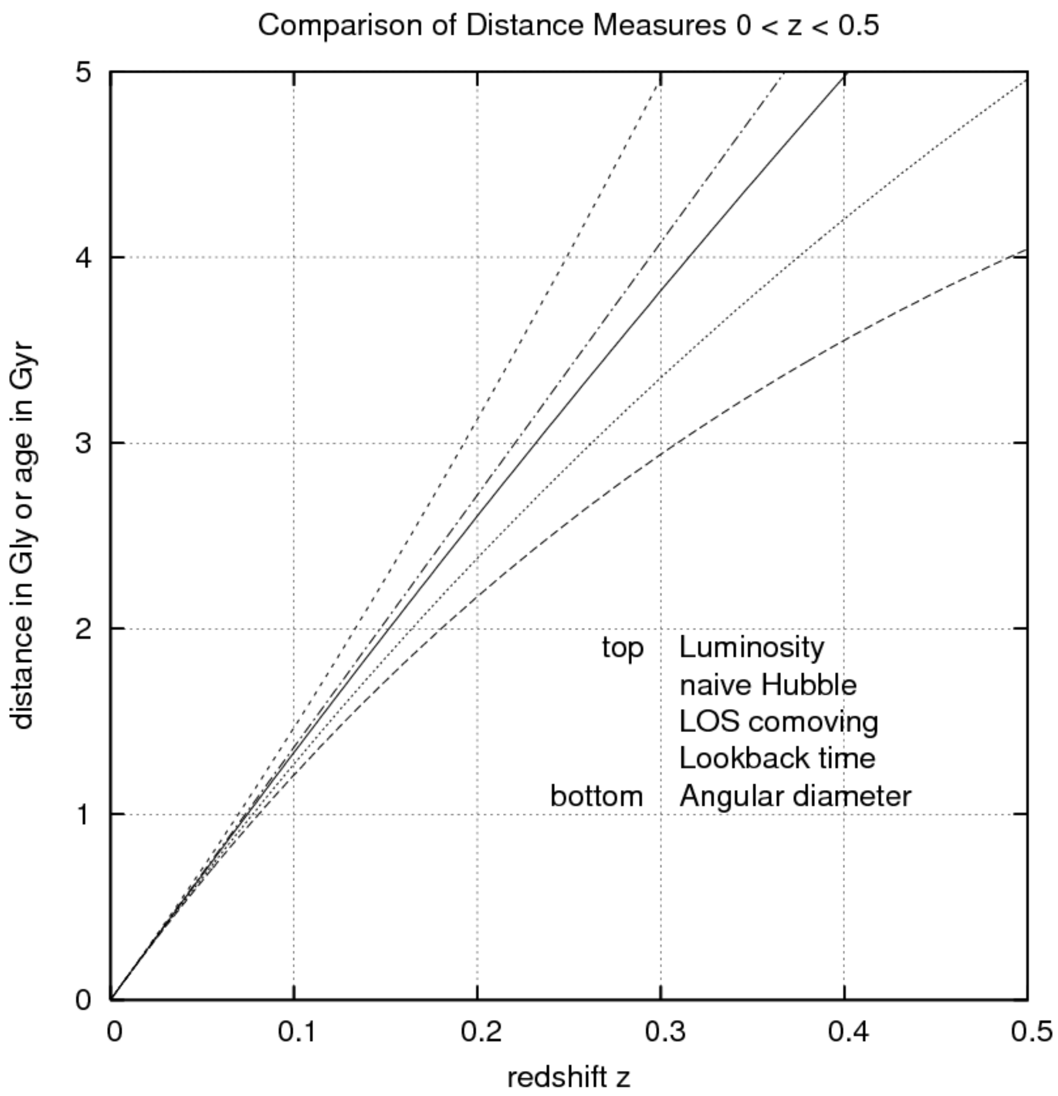


FLRW distances e.g. ΛCDM



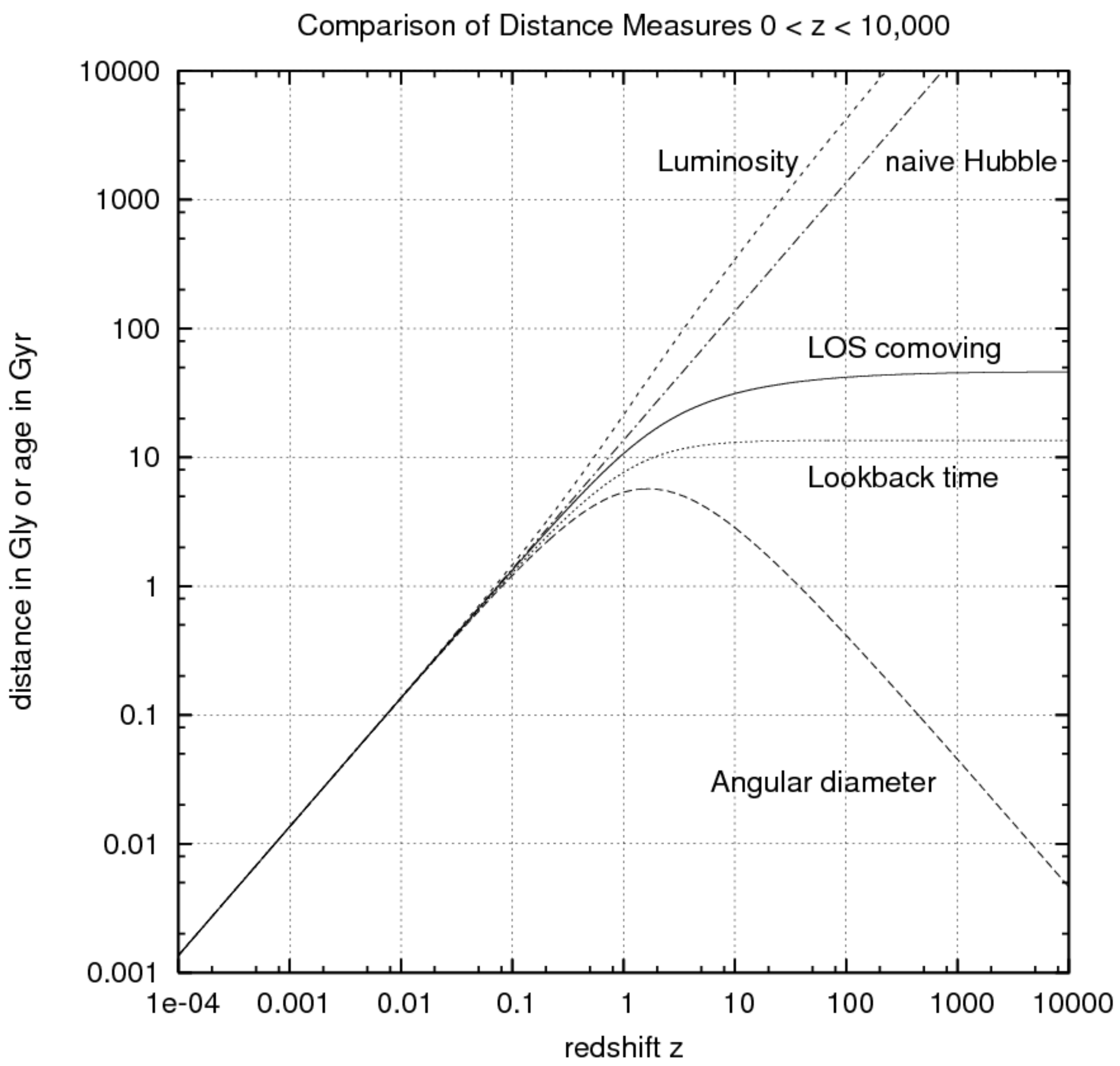
Defn: $\boxed{h := H_0/100\ \text{km/s/Mpc}}$ (without a “0” subscript on h)

FLRW distances e.g. ΛCDM



$$\Omega_{\mathrm{m}0} = 0.3,\ \Omega_{\mathrm{r}0} = 10^{-4},\ \Omega_{\Lambda 0} = 1.0 - (\Omega_{\mathrm{m}0} + \Omega_{\mathrm{r}0}),\ h = 0.7,\ \Omega_{k0} = 0$$

FLRW distances e.g. ΛCDM



$$\Omega_{\rm m0} = 0.3,\ \Omega_{\rm r0} = 10^{-4},\ \Omega_{\Lambda 0} = 1.0 - (\Omega_{\rm m0} + \Omega_{\rm r0}),\ h = 0.7,\ \Omega_{k0} = 0$$

"Velocity" $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?

"Velocity" $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of "velocity":
  1. galaxy as fundamental observer,

“Velocity” $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of “velocity”:
  1. galaxy as fundamental observer, local velocity $v_{\mathrm{gal}} = 0$ by defn of comoving coords,

“Velocity” $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of “velocity”:
  1. galaxy as fundamental observer, local velocity $v_{\mathrm{gal}} = 0$ by defn of comoving coords, or
  2. Hubble law assumes $\|$ transport of 4-velocity $\vec{u}_{\mathrm{gal}}$; then compare $\vec{u}_{\mathrm{obs}}, \vec{u}_{\mathrm{gal}}$ *locally* in Minkowski spacetime

“Velocity” $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of “velocity”:
  1. galaxy as fundamental observer, local velocity $v_{\mathrm{gal}} = 0$ by defn of comoving coords, or
  2. Hubble law assumes $\|$ transport of 4-velocity $\vec{u}_{\mathrm{gal}}$; then compare $\vec{u}_{\mathrm{obs}}, \vec{u}_{\mathrm{gal}}$ *locally* in Minkowski spacetime i.e. $1 + z = \sqrt{\frac{1+\beta}{1-\beta}}$ is *assumed* in derivation

"Velocity" $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of "velocity":
  1. galaxy as fundamental observer, local velocity $v_{\mathrm{gal}} = 0$ by defn of comoving coords, or
  2. Hubble law assumes $\|$ transport of 4-velocity $\vec{u}_{\mathrm{gal}}$; then compare $\vec{u}_{\mathrm{obs}}, \vec{u}_{\mathrm{gal}}$ *locally* in Minkowski spacetime i.e. $1 + z = \sqrt{\frac{1+\beta}{1-\beta}}$ is *assumed* in derivation $v_{\mathrm{gal}} < c$ by assumption ($\|$ transport + Mink.)

"Velocity" $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of "velocity":
  1. galaxy as fundamental observer, local velocity $v_{\mathrm{gal}} = 0$ by defn of comoving coords, or
  2. $v_{\mathrm{gal}} < c$ by assumption ($\|$ transport + Mink.) or
  3. define differential "global" comoving velocity $v_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\mathrm{d}\left(\int_0^r \mathrm{d}s|_{t,\theta,\phi}\right)}{\mathrm{d}t}$

“Velocity” $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of “velocity”:
  1. galaxy as fundamental observer, local velocity $v_{\mathrm{gal}} = 0$ by defn of comoving coords, or
  2. $v_{\mathrm{gal}} < c$ by assumption ($\|$ transport + Mink.) or
  3. define differential “global” comoving velocity $v_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\mathrm{d}\left(\int_0^r \mathrm{d}s|_{t,\theta,\phi}\right)}{\mathrm{d}t} = \frac{\mathrm{d}(ar)}{\mathrm{d}t}$

“Velocity” $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of “velocity”:
  1. galaxy as fundamental observer, local velocity $v_{\mathrm{gal}} = 0$ by defn of comoving coords, or
  2. $v_{\mathrm{gal}} < c$ by assumption ($\|$ transport + Mink.) or
  3. define differential “global” comoving velocity $v_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\mathrm{d}\left(\int_0^r \mathrm{d}s|_{t,\theta,\phi}\right)}{\mathrm{d}t} = \frac{\mathrm{d}(ar)}{\mathrm{d}t} = r\,\dot{a}$

"Velocity" $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of "velocity":
  1. galaxy as fundamental observer, local velocity $v_{\mathrm{gal}} = 0$ by defn of comoving coords, or
  2. $v_{\mathrm{gal}} < c$ by assumption ($\|$ transport + Mink.) or
  3. define differential "global" comoving velocity
     $v_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\mathrm{d}\left(\int_0^r \mathrm{d}s|_{t,\theta,\phi}\right)}{\mathrm{d}t} = \frac{\mathrm{d}(ar)}{\mathrm{d}t} = r\,\dot{a} = r\,\frac{\dot{a}}{a}\,a$

“Velocity” $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of “velocity”:
  1. galaxy as fundamental observer, local velocity $v_{\mathrm{gal}} = 0$ by defn of comoving coords, or
  2. $v_{\mathrm{gal}} < c$ by assumption ($\|$ transport + Mink.) or
  3. define differential “global” comoving velocity $v_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\mathrm{d}\left(\int_0^r \mathrm{d}s|_{t,\theta,\phi}\right)}{\mathrm{d}t} = \frac{\mathrm{d}(ar)}{\mathrm{d}t} = r\,\dot{a} = rH_0$

“Velocity” $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of “velocity”:
  1. galaxy as fundamental observer, local velocity $v_{\mathrm{gal}} = 0$ by defn of comoving coords, or
  2. $v_{\mathrm{gal}} < c$ by assumption ($\|$ transport + Mink.) or
  3. $v_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\mathrm{d}\left(\int_0^r \mathrm{d}s|_{t,\theta,\phi}\right)}{\mathrm{d}t} = \frac{\mathrm{d}(ar)}{\mathrm{d}t} = r\,\dot{a} = rH_0$ or
  4. define mean “global” comoving velocity $\langle v\rangle_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\int_0^r \mathrm{d}s|_{t,\theta,\phi}}{t_0}$

"Velocity" $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of "velocity":
  1. galaxy as fundamental observer, local velocity $v_{\mathrm{gal}} = 0$ by defn of comoving coords, or
  2. $v_{\mathrm{gal}} < c$ by assumption ($\|$ transport + Mink.) or
  3. $v_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\mathrm{d}\left(\int_0^r \mathrm{d}s|_{t,\theta,\phi}\right)}{\mathrm{d}t} = \frac{\mathrm{d}(ar)}{\mathrm{d}t} = r\,\dot{a} = rH_0$ or
  4. define mean "global" comoving velocity $\langle v \rangle_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\int_0^r \mathrm{d}s|_{t,\theta,\phi}}{t_0} = \frac{ar}{t_0}$

"Velocity" $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of "velocity":
  1. galaxy as fundamental observer, local velocity $v_{\mathrm{gal}} = 0$ by defn of comoving coords, or
  2. $v_{\mathrm{gal}} < c$ by assumption (∥ transport + Mink.) or
  3. $v_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\mathrm{d}\left(\int_0^r \mathrm{d}s|_{t,\theta,\phi}\right)}{\mathrm{d}t} = \frac{\mathrm{d}(ar)}{\mathrm{d}t} = r\,\dot{a} = rH_0$ or
  4. define mean "global" comoving velocity $\langle v \rangle_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\int_0^r \mathrm{d}s|_{t,\theta,\phi}}{t_0} = \frac{ar}{t_0} = \frac{r}{t_0}$

“Velocity” $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of “velocity”:
  1. galaxy as fundamental observer, local velocity $v_{\mathrm{gal}} = 0$ by defn of comoving coords, or
  2. $v_{\mathrm{gal}} < c$ by assumption ($\|$ transport + Mink.) or
  3. $v_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\mathrm{d}\left(\int_0^r \mathrm{d}s|_{t,\theta,\phi}\right)}{\mathrm{d}t} = \frac{\mathrm{d}(ar)}{\mathrm{d}t} = r\,\dot{a} = rH_0$ or
  4. $\langle v \rangle_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\int_0^r \mathrm{d}s|_{t,\theta,\phi}}{t_0} = \frac{ar}{t_0} = \frac{r}{t_0}$
- $v_{\mathrm{gal}}^{\mathrm{glob}} \geq c$ when

"Velocity" $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of "velocity":
  1. galaxy as fundamental observer, local velocity $v_{\mathrm{gal}} = 0$ by defn of comoving coords, or
  2. $v_{\mathrm{gal}} < c$ by assumption ($\|$ transport + Mink.) or
  3. $v_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\mathrm{d}\left(\int_0^r \mathrm{d}s|_{t,\theta,\phi}\right)}{\mathrm{d}t} = \frac{\mathrm{d}(ar)}{\mathrm{d}t} = r\,\dot{a} = rH_0$ or
  4. $\langle v \rangle_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\int_0^r \mathrm{d}s|_{t,\theta,\phi}}{t_0} = \frac{ar}{t_0} = \frac{r}{t_0}$
- $v_{\mathrm{gal}}^{\mathrm{glob}} \geq c$ when $r \geq c/H_0 \approx 3\mathrm{h}^{-1}$ Gpc

"Velocity" $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of "velocity":
  1. galaxy as fundamental observer, local velocity $v_{\mathrm{gal}} = 0$ by defn of comoving coords, or
  2. $v_{\mathrm{gal}} < c$ by assumption ($\|$ transport + Mink.) or
  3. $v_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\mathrm{d}\left(\int_0^r \mathrm{d}s|_{t,\theta,\phi}\right)}{\mathrm{d}t} = \frac{\mathrm{d}(ar)}{\mathrm{d}t} = r\,\dot{a} = rH_0$ or
  4. $\langle v \rangle_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\int_0^r \mathrm{d}s|_{t,\theta,\phi}}{t_0} = \frac{ar}{t_0} = \frac{r}{t_0}$
- $v_{\mathrm{gal}}^{\mathrm{glob}} \geq c$ when $r \geq c/H_0 \approx 3\mathrm{h}^{-1}$ Gpc
- $\langle v \rangle_{\mathrm{gal}}^{\mathrm{glob}} \geq c$ when $r/t_0 \geq c$

"Velocity" $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of "velocity":
  1. galaxy as fundamental observer, local velocity $v_{\rm gal} = 0$ by defn of comoving coords, or
  2. $v_{\rm gal} < c$ by assumption ($\|$ transport + Mink.) or
  3. $v^{\rm glob}_{\rm gal} := \frac{\mathrm{d}\left(\int_0^r \mathrm{d}s|_{t,\theta,\phi}\right)}{\mathrm{d}t} = \frac{\mathrm{d}(ar)}{\mathrm{d}t} = r\,\dot{a} = rH_0$ or
  4. $\langle v \rangle^{\rm glob}_{\rm gal} := \frac{\int_0^r \mathrm{d}s|_{t,\theta,\phi}}{t_0} = \frac{ar}{t_0} = \frac{r}{t_0}$
- $v^{\rm glob}_{\rm gal} \geq c$ when $r \geq c/H_0 \approx 3\mathrm{h}^{-1}$ Gpc
- $\langle v \rangle^{\rm glob}_{\rm gal} \geq c$ when $r \geq ct_0 \approx 4.5\mathrm{h}^{-1}$ Gpc

“Velocity” $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of “velocity”:
  1. galaxy as fundamental observer, local velocity $v_{\mathrm{gal}} = 0$ by defn of comoving coords, or
  2. $v_{\mathrm{gal}} < c$ by assumption ($\|$ transport + Mink.) or
  3. $v_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\mathrm{d}\left(\int_0^r \mathrm{d}s|_{t,\theta,\phi}\right)}{\mathrm{d}t} = \frac{\mathrm{d}(ar)}{\mathrm{d}t} = r\,\dot{a} = rH_0$ or
  4. $\langle v \rangle_{\mathrm{gal}}^{\mathrm{glob}} := \frac{\int_0^r \mathrm{d}s|_{t,\theta,\phi}}{t_0} = \frac{ar}{t_0} = \frac{r}{t_0}$
- $v_{\mathrm{gal}}^{\mathrm{glob}} \geq c$ when $r \geq c/H_0 \approx 3\mathrm{h}^{-1}$ Gpc
- $\langle v \rangle_{\mathrm{gal}}^{\mathrm{glob}} \geq c$ when $r \geq ct_0 \approx 4.5\mathrm{h}^{-1}$ Gpc
- $v_{\mathrm{gal}}^{\mathrm{glob}}$, $\langle v \rangle_{\mathrm{gal}}^{\mathrm{glob}}$ = theoretical, global $\neq$ velocity in tangent spacetime

"Velocity" $v > c$ in FLRW?

- low z Hubble law $r \approx \frac{\beta c}{H_0}$: $r > 3\mathrm{h}^{-1}$ Gpc $\Rightarrow \beta > 1$?
- possible definitions of "velocity":
  1. galaxy as fundamental observer, local velocity $v_{\mathrm{gal}} = 0$ by defn of comoving coords, or
  2. $v_{\mathrm{gal}} < c$ by assumption ($\|$ transport + Mink.) or
  3. $v^{\mathrm{glob}}_{\mathrm{gal}} := \frac{\mathrm{d}\left(\int_0^r \mathrm{d}s|_{t,\theta,\phi}\right)}{\mathrm{d}t} = \frac{\mathrm{d}(ar)}{\mathrm{d}t} = r\,\dot{a} = rH_0$ or
  4. $\langle v \rangle^{\mathrm{glob}}_{\mathrm{gal}} := \frac{\int_0^r \mathrm{d}s|_{t,\theta,\phi}}{t_0} = \frac{ar}{t_0} = \frac{r}{t_0}$
- $v^{\mathrm{glob}}_{\mathrm{gal}} \geq c$ when $r \geq c/H_0 \approx 3\mathrm{h}^{-1}$ Gpc
- $\langle v \rangle^{\mathrm{glob}}_{\mathrm{gal}} \geq c$ when $r \geq ct_0 \approx 4.5\mathrm{h}^{-1}$ Gpc
- $v^{\mathrm{glob}}_{\mathrm{gal}}$, $\langle v \rangle^{\mathrm{glob}}_{\mathrm{gal}}$ = theoretical, global $\neq$ velocity in tangent spacetime

$\Rightarrow$ no conflict with locally Lorentzian (SR) spacetime

Non-radial spatial geodesics

- What is the comoving distance between two objects at different celestial positions and different redshifts, for an arbitrary curvature $(+, 0, -)$?

Non-radial spatial geodesics

- distances on the 2-sphere, embedded in $\mathbb{R}^3$

Non-radial spatial geodesics

- distances on the 2-sphere, embedded in $\mathbb{R}^3$

$$
\begin{aligned}
x_i &= R_{\mathrm{C}} \cos\delta_i \cos\alpha_i \\
y_i &= R_{\mathrm{C}} \cos\delta_i \sin\alpha_i \\
w_i &= R_{\mathrm{C}} \sin\delta_i
\end{aligned}
$$

Non-radial spatial geodesics

- distances on the 2-sphere, embedded in $\mathbb{R}^3$

$$\begin{aligned} x_i &= R_\mathrm{C} \cos\delta_i \cos\alpha_i \\ y_i &= R_\mathrm{C} \cos\delta_i \sin\alpha_i \\ w_i &= R_\mathrm{C} \sin\delta_i \end{aligned}$$

$$\langle \mathbf{a}_1, \mathbf{a}_2 \rangle = x_1 x_2 + y_1 y_2 + w_1 w_2$$

Non-radial spatial geodesics

- distances on the 2-sphere, embedded in $\mathbb{R}^3$

$$\begin{aligned} x_i &= R_\mathrm{C} \cos\delta_i \cos\alpha_i \\ y_i &= R_\mathrm{C} \cos\delta_i \sin\alpha_i \\ w_i &= R_\mathrm{C} \sin\delta_i \end{aligned}$$

$$\langle \mathbf{a}_1, \mathbf{a}_2 \rangle = x_1 x_2 + y_1 y_2 + w_1 w_2$$

- but also:

$$\langle \mathbf{a}_1, \mathbf{a}_2 \rangle = R^2 \cos\theta_{12}.$$

Non-radial spatial geodesics

- distances on the 2-sphere, embedded in $\mathbb{R}^3$

$$\begin{aligned} x_i &= R_\mathrm{C} \cos\delta_i \cos\alpha_i \\ y_i &= R_\mathrm{C} \cos\delta_i \sin\alpha_i \\ w_i &= R_\mathrm{C} \sin\delta_i \end{aligned}$$

$$\langle \mathbf{a}_1, \mathbf{a}_2 \rangle = x_1 x_2 + y_1 y_2 + w_1 w_2$$

- but also:

$$\langle \mathbf{a}_1, \mathbf{a}_2 \rangle = R^2 \cos\theta_{12}.$$

- a distance in S^2 = arc-length in $\mathbb{R}^3$:

Non-radial spatial geodesics

- distances on the 2-sphere, embedded in $\mathbb{R}^3$

$$\begin{aligned} x_i &= R_{\mathrm{C}} \cos\delta_i \cos\alpha_i \\ y_i &= R_{\mathrm{C}} \cos\delta_i \sin\alpha_i \\ w_i &= R_{\mathrm{C}} \sin\delta_i \end{aligned}$$

$$\langle \mathbf{a}_1, \mathbf{a}_2 \rangle = x_1 x_2 + y_1 y_2 + w_1 w_2$$

- but also:

$$\langle \mathbf{a}_1, \mathbf{a}_2 \rangle = R^2 \cos\theta_{12}.$$

- a distance in S^2 = arc-length in $\mathbb{R}^3$:

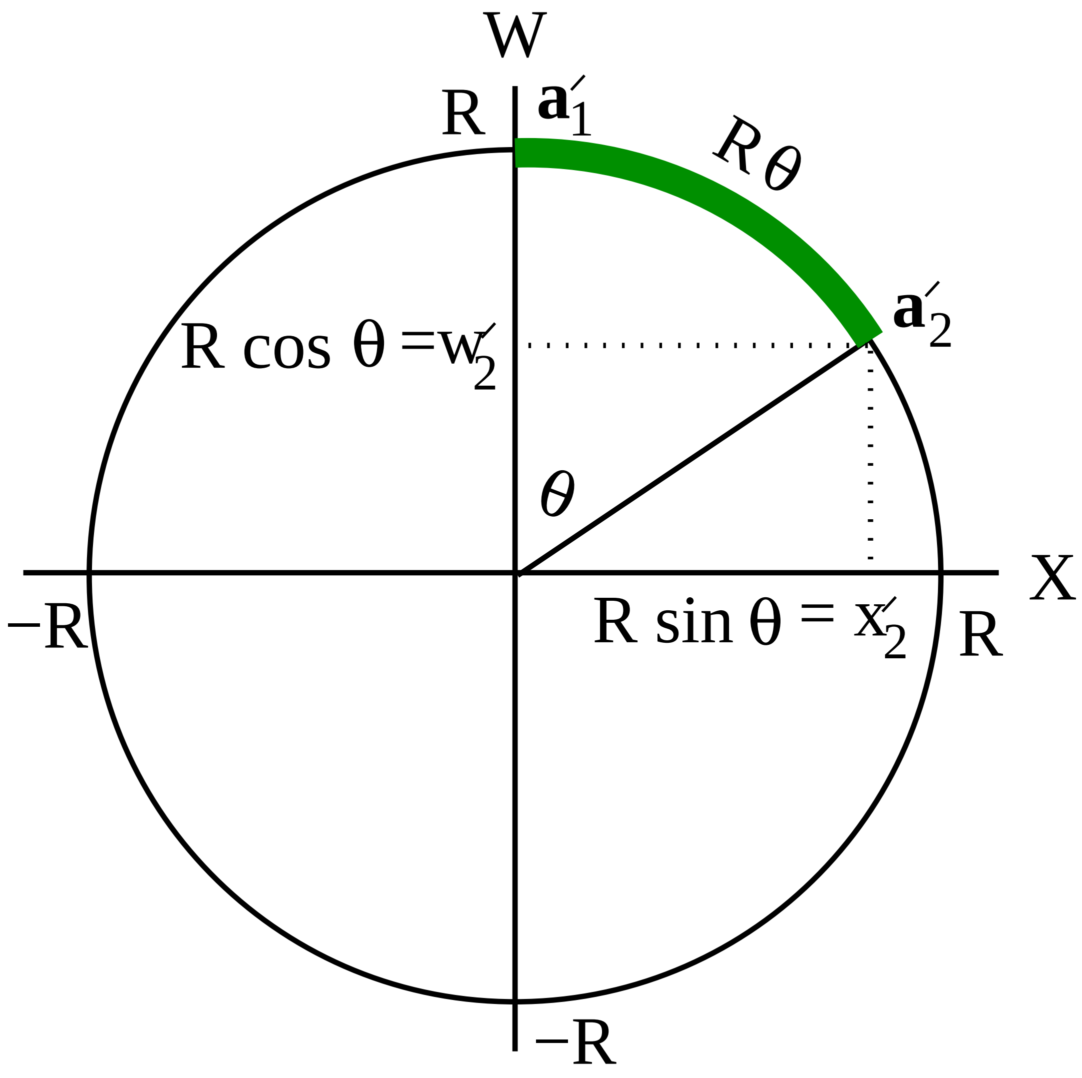
$$\chi_{12} = R_{\mathrm{C}}\, \theta_{12} = R_{\mathrm{C}}\ \cos^{-1}\left[\langle \mathbf{a}_1, \mathbf{a}_2 \rangle / R_{\mathrm{C}}^2\right]$$

Non-radial spatial geodesics

- positive curvature

Non-radial spatial geodesics

- positive curvature

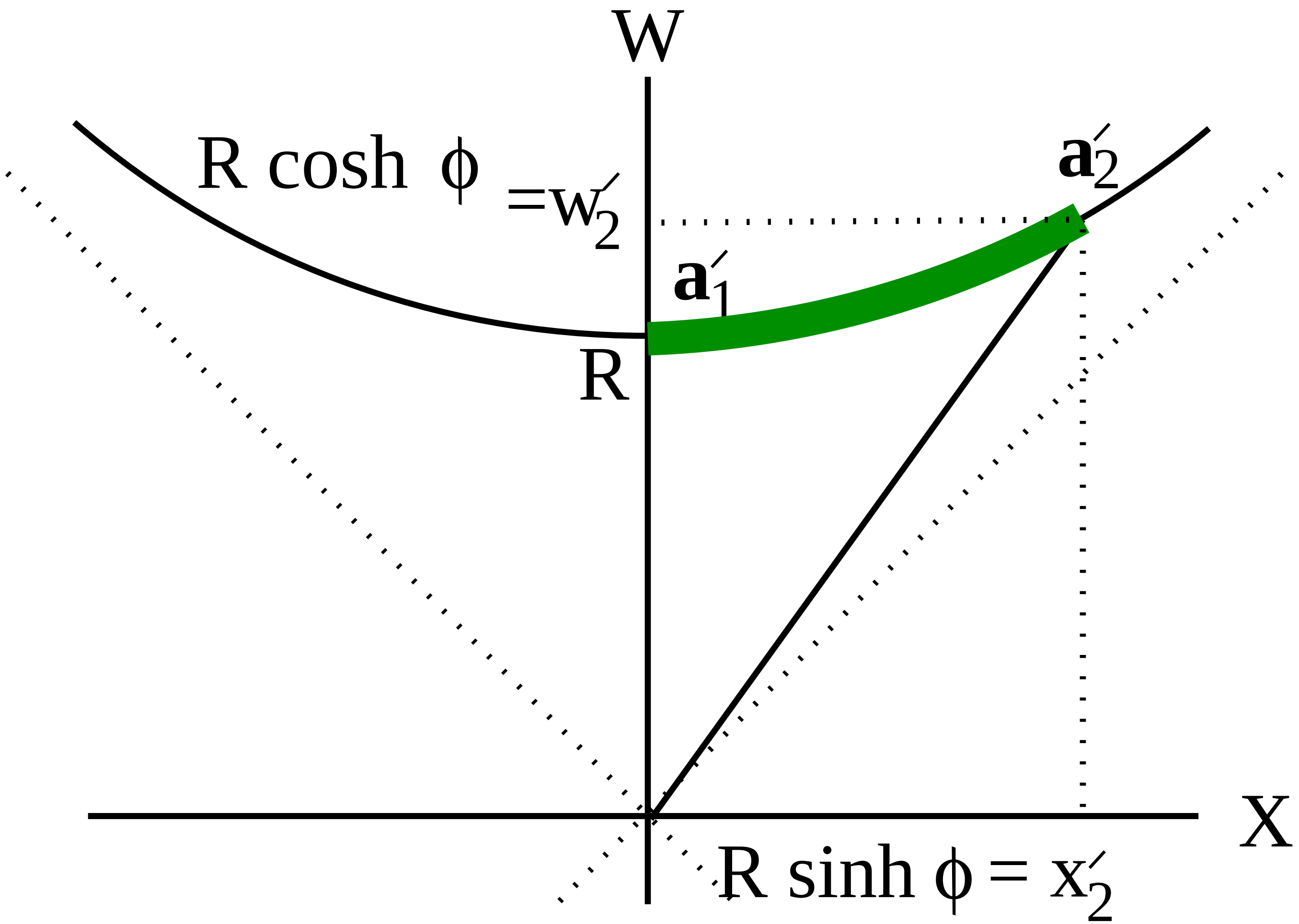


Non-radial spatial geodesics

- negative curvature

Non-radial spatial geodesics

- negative curvature



-

distances on $\mathsf{S}^3 \subset \mathbb{R}^4$ or $\mathsf{H}^3 \subset \mathsf{M}^4$

$$\Sigma(\chi_i) := \begin{cases} R_{\mathrm{C}} \, \sinh(\chi_i/R_{\mathrm{C}}) & k < 0 \\ \chi_i & k = 0 \\ R_{\mathrm{C}} \, \sin(\chi_i/R_{\mathrm{C}}) & k > 0 \end{cases}$$

distances on $\mathsf{S}^3 \subset \mathbb{R}^4$ or $\mathsf{H}^3 \subset \mathsf{M}^4$

- $$\Sigma(\chi_i) := \begin{cases} R_\mathrm{C}\ \sinh(\chi_i/R_\mathrm{C}) & k < 0 \\ \chi_i & k = 0 \\ R_\mathrm{C}\ \sin(\chi_i/R_\mathrm{C}) & k > 0 \end{cases}$$

- $$\begin{aligned} x_i &= \Sigma(\chi_i) \cos\delta_i \cos\alpha_i \\ y_i &= \Sigma(\chi_i) \cos\delta_i \sin\alpha_i \\ z_i &= \Sigma(\chi_i) \sin\delta_i \\ w_i &= \begin{cases} R_\mathrm{C}\ \cosh(\chi_i/R_\mathrm{C}) & k < 0 \\ 0 & k = 0 \\ R_\mathrm{C}\ \cos(\chi_i/R_\mathrm{C}) & k > 0 \end{cases} \end{aligned}$$

distances on $S^3 \subset \mathbb{R}^4$ or $H^3 \subset M^4$

- $$\Sigma(\chi_i) := \begin{cases} R_C \ \sinh(\chi_i/R_C) & k < 0 \\ \chi_i & k = 0 \\ R_C \ \sin(\chi_i/R_C) & k > 0 \end{cases}$$

- $$\begin{aligned} x_i &= \Sigma(\chi_i)\cos\delta_i\cos\alpha_i \\ y_i &= \Sigma(\chi_i)\cos\delta_i\sin\alpha_i \\ z_i &= \Sigma(\chi_i)\sin\delta_i \\ w_i &= \begin{cases} R_C \ \cosh(\chi_i/R_C) & k < 0 \\ 0 & k = 0 \\ R_C \ \cos(\chi_i/R_C) & k > 0 \end{cases} \end{aligned}$$

- metric on S^3 (or $\mathbb{R}^3$ or H^3):
$$\mathrm{d}s^2 = \begin{cases} (k/|k|)\ (\mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2) + \mathrm{d}w^2 & k \neq 0 \\ \mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2 & k = 0 \end{cases}$$

distances on $\mathsf{S}^3 \subset \mathbb{R}^4$ or $\mathsf{H}^3 \subset \mathsf{M}^4$

- $$\Sigma(\chi_i) := \begin{cases} R_\mathrm{C}\ \sinh(\chi_i/R_\mathrm{C}) & k < 0 \\ \chi_i & k = 0 \\ R_\mathrm{C}\ \sin(\chi_i/R_\mathrm{C}) & k > 0 \end{cases}$$

- $$\begin{aligned} x_i &= \Sigma(\chi_i)\cos\delta_i\cos\alpha_i \\ y_i &= \Sigma(\chi_i)\cos\delta_i\sin\alpha_i \\ z_i &= \Sigma(\chi_i)\sin\delta_i \\ w_i &= \begin{cases} R_\mathrm{C}\ \cosh(\chi_i/R_\mathrm{C}) & k < 0 \\ 0 & k = 0 \\ R_\mathrm{C}\ \cos(\chi_i/R_\mathrm{C}) & k > 0 \end{cases} \end{aligned}$$

- inner product:
$$\langle \mathbf{a}_1, \mathbf{a}_2 \rangle \equiv \begin{cases} (k/|k|)\ (x_1x_2 + y_1y_2 + z_1z_2) + w_1w_2 & k \neq 0 \\ x_1x_2 + y_1y_2 + z_1z_2 & k = 0 \end{cases}$$

distances on $\mathsf{S}^3 \subset \mathbb{R}^4$ or $\mathsf{H}^3 \subset \mathsf{M}^4$

- $$\Sigma(\chi_i) := \begin{cases} R_\mathrm{C}\ \sinh(\chi_i/R_\mathrm{C}) & k < 0 \\ \chi_i & k = 0 \\ R_\mathrm{C}\ \sin(\chi_i/R_\mathrm{C}) & k > 0 \end{cases}$$

- $$\begin{aligned} x_i &= \Sigma(\chi_i)\cos\delta_i\cos\alpha_i \\ y_i &= \Sigma(\chi_i)\cos\delta_i\sin\alpha_i \\ z_i &= \Sigma(\chi_i)\sin\delta_i \\ w_i &= \begin{cases} R_\mathrm{C}\ \cosh(\chi_i/R_\mathrm{C}) & k < 0 \\ 0 & k = 0 \\ R_\mathrm{C}\ \cos(\chi_i/R_\mathrm{C}) & k > 0 \end{cases} \end{aligned}$$

$\Rightarrow$

$$\chi_{12} = \begin{cases} R_\mathrm{C}\cosh^{-1}\left[\langle \mathbf{a}_1, \mathbf{a}_2\rangle / R_\mathrm{C}^2\right] & k < 0 \\ \sqrt{\langle \mathbf{a}_1 - \mathbf{a}_2, \mathbf{a}_1 - \mathbf{a}_2\rangle} & k = 0 \\ R_\mathrm{C}\cos^{-1}\left[\langle \mathbf{a}_1, \mathbf{a}_2\rangle / R_\mathrm{C}^2\right] & k > 0 \end{cases}$$

distances on $S^3 \subset \mathbb{R}^4$ or $H^3 \subset M^4$

$$
\begin{aligned}
x_i &= \Sigma(\chi_i) \cos\delta_i \cos\alpha_i \\
y_i &= \Sigma(\chi_i) \cos\delta_i \sin\alpha_i \\
z_i &= \Sigma(\chi_i) \sin\delta_i \\
w_i &= \begin{cases} R_\mathrm{C} \ \cosh(\chi_i/R_\mathrm{C}) & k < 0 \\ 0 & k = 0 \\ R_\mathrm{C} \ \cos(\chi_i/R_\mathrm{C}) & k > 0 \end{cases}
\end{aligned}
$$

$\Rightarrow$

$$
\chi_{12} = \begin{cases} R_\mathrm{C} \cosh^{-1} \left[\langle \mathbf{a}_1, \mathbf{a}_2 \rangle / R_\mathrm{C}^2 \right] & k < 0 \\ \sqrt{\langle \mathbf{a}_1 - \mathbf{a}_2, \mathbf{a}_1 - \mathbf{a}_2 \rangle} & k = 0 \\ R_\mathrm{C} \cos^{-1} \left[\langle \mathbf{a}_1, \mathbf{a}_2 \rangle / R_\mathrm{C}^2 \right] & k > 0 \end{cases}
$$

- a distance in S^3 is an arc-length in $\mathbb{R}^4$

distances on $S^3 \subset \mathbb{R}^4$ or $H^3 \subset M^4$

$$\begin{aligned} x_i &= \Sigma(\chi_i)\cos\delta_i\cos\alpha_i \\ y_i &= \Sigma(\chi_i)\cos\delta_i\sin\alpha_i \\ z_i &= \Sigma(\chi_i)\sin\delta_i \\ w_i &= \begin{cases} R_\mathrm{C}\ \cosh(\chi_i/R_\mathrm{C}) & k < 0 \\ 0 & k = 0 \\ R_\mathrm{C}\ \cos(\chi_i/R_\mathrm{C}) & k > 0 \end{cases} \end{aligned}$$

$\Rightarrow$

$$\chi_{12} = \begin{cases} R_\mathrm{C}\cosh^{-1}\left[\langle \mathbf{a}_1, \mathbf{a}_2\rangle / R_\mathrm{C}^2\right] & k < 0 \\ \sqrt{\langle \mathbf{a}_1 - \mathbf{a}_2, \mathbf{a}_1 - \mathbf{a}_2\rangle} & k = 0 \\ R_\mathrm{C}\cos^{-1}\left[\langle \mathbf{a}_1, \mathbf{a}_2\rangle / R_\mathrm{C}^2\right] & k > 0 \end{cases}$$

- a distance in S^3 is an arc-length in $\mathbb{R}^4$
- a distance in H^3 is an arc-length in M^4

distances on $S^3 \subset \mathbb{R}^4$ or $H^3 \subset M^4$

$$\begin{aligned} x_i &= \Sigma(\chi_i) \cos\delta_i \cos\alpha_i \\ y_i &= \Sigma(\chi_i) \cos\delta_i \sin\alpha_i \\ z_i &= \Sigma(\chi_i) \sin\delta_i \\ w_i &= \begin{cases} R_{\mathrm{C}} \ \cosh(\chi_i/R_{\mathrm{C}}) & k < 0 \\ 0 & k = 0 \\ R_{\mathrm{C}} \ \cos(\chi_i/R_{\mathrm{C}}) & k > 0 \end{cases} \end{aligned}$$

$\Rightarrow$

$$\chi_{12} = \begin{cases} R_{\mathrm{C}} \cosh^{-1}\left[\langle \mathbf{a}_1, \mathbf{a}_2 \rangle / R_{\mathrm{C}}^2\right] & k < 0 \\ \sqrt{\langle \mathbf{a}_1 - \mathbf{a}_2, \mathbf{a}_1 - \mathbf{a}_2 \rangle} & k = 0 \\ R_{\mathrm{C}} \cos^{-1}\left[\langle \mathbf{a}_1, \mathbf{a}_2 \rangle / R_{\mathrm{C}}^2\right] & k > 0 \end{cases}$$

- a distance in S^3 is an arc-length in $\mathbb{R}^4$ arXiv:astro-ph/0102099
- a distance in H^3 is an arc-length in M^4

Structure formation

- statistical description of perturbations $\delta(\mathbf{x})$ as w:gaussian random field either:

Structure formation

- statistical description of perturbations $\delta(\mathbf{x})$ as w:gaussian random field either:
  - 2-point autocorrelation function $\xi(d) := \langle \delta(\mathbf{x}), \delta(\mathbf{y}) \rangle$ where the mean $\langle\ ,\ \rangle$ is over pairs $(\mathbf{x}, \mathbf{y})$ separated by spatial geodesic distance d

Structure formation

- statistical description of perturbations $\delta(\mathbf{x})$ as w:gaussian random field either:
  - 2-point autocorrelation function $\xi(d) := \langle \delta(\mathbf{x}), \delta(\mathbf{y}) \rangle$ where the mean $\langle\ ,\ \rangle$ is over pairs $(\mathbf{x}, \mathbf{y})$ separated by spatial geodesic distance d
    valid: any curvature

Structure formation

- statistical description of perturbations $\delta(\mathbf{x})$ as w:gaussian random field either:
  - 2-point autocorrelation function $\xi(d) := \langle \delta(\mathbf{x}), \delta(\mathbf{y}) \rangle$ where the mean $\langle\ ,\ \rangle$ is over pairs $(\mathbf{x}, \mathbf{y})$ separated by spatial geodesic distance d
    valid: any curvature

    cf WMAP

Structure formation

- statistical description of perturbations $\delta(\mathbf{x})$ as w:gaussian random field either:
  - 2-point autocorrelation function $\xi(d) := \langle \delta(\mathbf{x}), \delta(\mathbf{y}) \rangle$ where the mean $\langle \;,\; \rangle$ is over pairs $(\mathbf{x}, \mathbf{y})$ separated by spatial geodesic distance d
    valid: any curvature
    OR
  - Fourier mode power spectrum $P(k)$

Structure formation

- statistical description of perturbations $\delta(\mathbf{x})$ as w:gaussian random field either:
  - 2-point autocorrelation function $\xi(d) := \langle \delta(\mathbf{x}), \delta(\mathbf{y}) \rangle$ where the mean $\langle\ ,\ \rangle$ is over pairs $(\mathbf{x}, \mathbf{y})$ separated by spatial geodesic distance d
    valid: any curvature
    OR
  - Fourier mode power spectrum $P(k)$
    valid: flat case only

Structure formation

- statistical description of perturbations $\delta(\mathbf{x})$ as w:gaussian random field either:
  - 2-point autocorrelation function $\xi(d) := \langle \delta(\mathbf{x}), \delta(\mathbf{y}) \rangle$ where the mean $\langle \; , \; \rangle$ is over pairs $(\mathbf{x}, \mathbf{y})$ separated by spatial geodesic distance d
    valid: any curvature
    OR
  - Fourier mode power spectrum $P(k)$
    valid: flat case only
- w:structure formation

Structure formation

- statistical description of perturbations $\delta(\mathbf{x})$ as w:gaussian random field either:
  - 2-point autocorrelation function $\xi(d) := \langle \delta(\mathbf{x}), \delta(\mathbf{y}) \rangle$ where the mean $\langle \;,\; \rangle$ is over pairs $(\mathbf{x}, \mathbf{y})$ separated by spatial geodesic distance d
    valid: any curvature
    OR
  - Fourier mode power spectrum $P(k)$
    valid: flat case only
- w:structure formation
  - qualitatively covers main standard arguments

Structure formation

- statistical description of perturbations $\delta(\mathbf{x})$ as w:gaussian random field either:
  - 2-point autocorrelation function $\xi(d) := \langle \delta(\mathbf{x}), \delta(\mathbf{y}) \rangle$ where the mean $\langle \;,\; \rangle$ is over pairs $(\mathbf{x}, \mathbf{y})$ separated by spatial geodesic distance d
    valid: any curvature
    OR
  - Fourier mode power spectrum $P(k)$
    valid: flat case only
- w:structure formation
  - qualitatively covers main standard arguments
  - omits key assumptions:

Structure formation

- statistical description of perturbations $\delta(\mathbf{x})$ as w:gaussian random field either:
  - 2-point autocorrelation function $\xi(d) := \langle \delta(\mathbf{x}), \delta(\mathbf{y}) \rangle$ where the mean $\langle\ ,\ \rangle$ is over pairs $(\mathbf{x}, \mathbf{y})$ separated by spatial geodesic distance d
    valid: any curvature
    OR
  - Fourier mode power spectrum $P(k)$
    valid: flat case only
- w:structure formation
  - qualitatively covers main standard arguments
  - omits key assumptions:
    flat space for $P(k)$

Structure formation

- statistical description of perturbations $\delta(\mathbf{x})$ as w:gaussian random field either:
  - 2-point autocorrelation function $\xi(d) := \langle \delta(\mathbf{x}), \delta(\mathbf{y}) \rangle$ where the mean $\langle \ , \ \rangle$ is over pairs $(\mathbf{x}, \mathbf{y})$ separated by spatial geodesic distance d
    valid: any curvature
    OR
  - Fourier mode power spectrum $P(k)$
    valid: flat case only
- w:structure formation
  - qualitatively covers main standard arguments
  - omits key assumptions:
    flat space for $P(k)$
    inhomogeneous epoch modelled under assumption of homogeneity