Robertson Walker Metric

General Relativity (GR) and Special Relativity (SR) use coordinates in space-time to describe events.

ds^2 : interval between events

$$ds^2 = c^2 dt^2 - dx^2 - dy^2 - dz^2 \equiv \eta_{\mu\nu}\, dx^\mu\, dx^\nu$$

$\eta_{\mu\nu}$: Minkowsky metric $\quad \eta_{\mu\nu} = \begin{pmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{pmatrix} \quad dx^\mu = (c\,dt, d\vec{x})$

In SR $\rightarrow$ metric is fixed

In GR $\rightarrow$ dynamical field solution of Einstein equations.

Cosmological principle $\rightarrow$ homogeneity and isotropy ; functional form is fixed

$$ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu = c^2 dt^2 - a^2(t) \left[\frac{dr^2}{1-kr^2} + r^2 \left(d\theta^2 + \sin^2\theta\, d\phi^2 \right) \right]$$

"cosmic" time measured by comoving observers at fix position

scale factor overall time dep. due to expansion of Universe

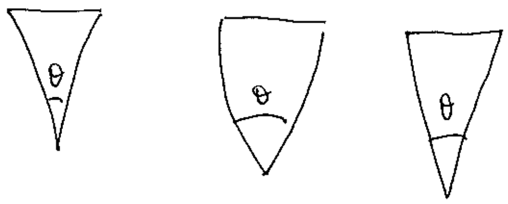
(r, θ, ϕ) : comoving coordinates.

$$k \begin{cases} 0 & \text{flat} \rightarrow \text{no spatial curvature} \\ +1 & \text{closed} \\ -1 & \text{open} \end{cases}$$

Conformal time $\quad dt^2 \equiv a^2 \, d\tau^2 \quad \rightarrow \quad d\tau = \dfrac{dt}{a(t)}$

Another way of writting the spatial part of the metric

$$\chi \equiv \int \frac{dr}{\sqrt{1-kr^2}} \quad \rightarrow \quad \begin{matrix} (\sin \chi)^2 \; d^3_x \\ (\sinh \chi)^2 \; d^3_x \\ \chi^2 \; d^3_x \end{matrix}$$



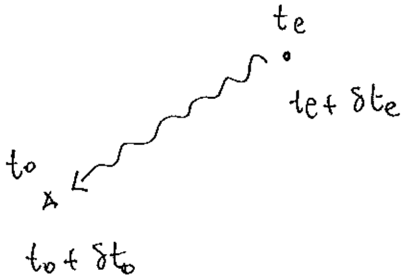
a given transverse distance subtends different angles. in different geometries.

Kinematics of RW metric

redshift:

Let's consider propagation of light $\rightarrow \; ds^2 = 0$

$$dt^2 = a^2(t) \, \frac{dr^2}{1-kr^2}$$



2

$$\int_{t_e}^{t_o} \frac{dt}{a(t)} = \int_0^{r_s} \frac{dr}{\sqrt{1-kr^2}}$$ first pulse

r_s : fixed comoving coord.

$$\int_{t_e+\delta t_e}^{t_o+\delta t_o} \frac{dt}{a(t)} = \int_0^{r_s} \frac{dr}{\sqrt{1-kr^2}}$$

so

$$\int_{t_e}^{t_o} \frac{dt}{a(t)} = \int_{t_e+\delta t_e}^{t_o+\delta t_o} \frac{dt}{a(t)} = \int_{t_e+\delta t_e}^{t_o} dt/a + \int_{t_o}^{t_o+\delta t_o} dt/a$$

$$= \int_{t_e}^{t_o} \frac{dt}{a} - \int_{t_e}^{t_e+\delta t_e} \frac{dt}{a} + \int_{t_o}^{t_o+\delta t_o} dt/a$$

so

$$\int_{t_e}^{t_e+\delta t_e} \frac{dt}{a(t)} = \int_{t_o}^{t_o+\delta t_o} \frac{dt}{a(t)}$$ $\rightarrow$ if we think on this as pulses with wavelength $\lambda \sim \Delta t$

$$\downarrow$$

$$\frac{\delta t_e}{a(t_e)} = \frac{\delta t_o}{a(t_o)}$$

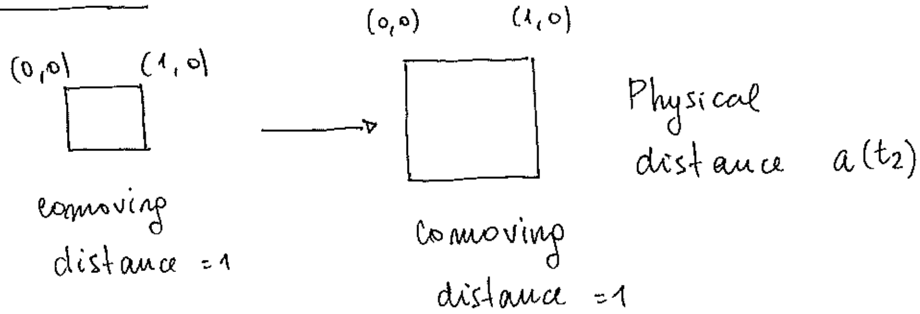
$$\frac{\lambda_{emitted}}{\lambda_{obs.}} = \frac{a_{emitted}}{a_{obs}}$$

"a" grows with time (universe expands) so wavelengths are stretched [i.e redshifted]

or

$$\frac{\lambda_{obs}}{\lambda_e} = \frac{a_{obs}}{a_e} \equiv 1 + z_e$$ $\leftarrow$ redshift

assuming $z=0$ at obs.



$$\lambda_{com} \cdot a = \lambda_{phys.}$$

Comoving distance that light can travel

$$\eta \equiv \int_0^t \frac{dt'}{a(t')} \qquad [c=1]$$

→ Regions separated by distances greater than η are NOT causally connected.

$$\eta \longleftrightarrow \text{comoving horizon}$$

η is also conformal time

$$\begin{cases} \eta \propto a^{1/2} & : \text{matter dominated Universe} \\ \eta \propto a & : \text{radiation dominated} \end{cases}$$

Comoving distance between a distant emitter and us

$$\chi(a) = \int_{t(a)}^{t_0} c\, \frac{dt'}{a(t')} = \int_a^1 \frac{da'}{a'^2 H(a')}$$

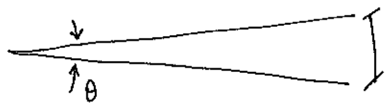
using $\frac{da}{dt} \equiv aH$

Typically we can see objects out to $z \lesssim 6$ so Universe is still matter dominated.

$$H \propto a^{-3/2}$$

$$\chi^{\text{Flat, MD}}(a) = \frac{2}{H_0}\left(1 - a^{1/2}\right) = \frac{2}{H_0}\left(1 - \frac{1}{\sqrt{1+z}}\right) \sim \frac{z}{H_0} \qquad (z \ll 1)$$

Angular Diameter Distance



ℓ : known physical size

$$d_A \equiv \frac{\ell}{\theta}$$

d_A in an expanding Universe

ℓ/a ← comoving size of object

$\chi(a)$ ← comoving distance

angle subtended

$$\theta = \frac{(\ell/a)}{\chi(a)} = \frac{\ell}{d_A} \quad \rightarrow \quad d_A^{\text{flat}} = a\,\chi(a) = \frac{\chi}{1+z}$$

Angular distance is equal to χ at low z but it decreases at high z. objects at large z appear larger than they would at intermediate z.

Non-zero curvature

$$d_A = \frac{a}{H_0\sqrt{|\Omega_k|}} \begin{cases} \sinh \sqrt{\Omega_k}\, H_0 \chi & \Omega_k > 0. \\ \sin \sqrt{-\Omega_k}\, H_0 \chi & \Omega_k < 0. \end{cases}$$

if $\Omega_k \rightarrow 0$ $\quad d_A \rightarrow a\chi$. $\qquad$ (d_A = physical distance?)

Distances - 2

$$d_A = \frac{S_k(\chi)}{1+z}$$

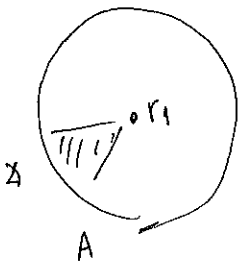
In the currently favoured cosmological model "angular diameter distance" is a good approx. to "proper distance" (i.e. distance when light left obj.)

2 objects of same size $\Rightarrow$ the one further out appears larger in an expanding universe

$$\theta_1 = \frac{l}{d_A(z_1)} \qquad \theta_2 = \frac{l}{d_A(z_2)}$$

because after $z \sim 1.5$ d_A decreases w/ redshift.

Luminosity distance



L : intrinsic luminosity $\quad \frac{\text{Energy}}{\text{time}}$

$$\frac{dt_e}{a_e} = \frac{dt_o}{a_{obs}}$$

$$P\Big|_{\text{detector}} = \frac{dE_{ob}}{dt_{ob}} \cdot \frac{A}{A_{full}}$$

A ↙ area of detector

$$E \sim \frac{1}{\lambda} \sim \frac{1}{a}$$

$$= \left(\frac{a_e}{a_{obs}}\right)^2 \underbrace{\frac{dE_e}{dt_e}}_{L} \cdot \frac{A}{4\pi \underbrace{r_1^2 a_0^2}_{\text{physical distance}}}$$

$$E_0 = E_e \cdot \frac{a_e}{a_0}$$

$$= \left(\frac{a_e}{a_0}\right)^2 L \, \frac{A}{4\pi \, a_0^2 r_e^2}$$

$$\frac{a_e}{a_0} = \frac{1}{1+z}$$

Flux at the detector

$$F = \frac{P}{A} = \frac{1}{(1+z)^2} \, \frac{1}{4\pi r_e^2} \, \frac{1}{a_0^2} = \frac{1}{4\pi \, d_L^2}$$

↑ source comoving distance.

luminosity distance $\boxed{d_L \equiv (1+z)\, a_0 \, r_s}$

Let's try to get rid of r_s

$$\int_0^{r_s} \frac{dr}{1-kr^2} = \int_{t_e}^{t_0} \frac{dt}{a(t)} = \begin{cases} \arcsin r_s \approx r_s + r_s^3/6 & k=+1 \\ r_s & k=0 \\ \operatorname{arcsinh} r_s \approx r_s - r_s^3/6 & k=-1 \end{cases}$$

Now we expand

Here $t = t_0 - \delta t$

$$a(t) = a_0 + \dot{a}_0 (t - t_0) + \ddot{a}_0 \frac{(t-t_0)^2}{2}$$

$$\frac{1}{1+z} = \frac{a(t)}{a_0} = 1 + H_0 (t - t_0) - \frac{q_0 H_0^2}{2} (t - t_0)^2 \qquad (*)$$

where $H = \frac{\dot{a}}{a}$ $\qquad q \equiv - \frac{\ddot{a}}{a H^2}$ ↖ it's called deceleration parameter

Going back to

$$d_L = 4\pi a_0 r_s^2$$

Recast $(*)$ as

$$\cancel{\frac{a(t_0)}{a(t_1)}} \qquad \frac{a(t_1)}{a(t_0)} = \frac{a(t_0 - \delta t)}{a(t_0)} = 1 - \frac{1}{a_0} \dot{a}\, \delta t + \frac{\ddot{a}}{a} \frac{\delta t^2}{2}$$

At the end

$$H_0 \delta t \simeq \frac{z}{1+z} - q_0 \frac{z^2}{(1+z)^2}$$

You can get to

$$\boxed{H_0 d_L = z + \frac{1}{2}(1 - q_0) z^2 + \dots}$$

* We need some kind of standard candle => objects of known L, measure F -> compute d_L as a function of their z

Dynamics

Evolution of scale factor will be given by the solution to

$$G_{\mu\nu} = \underbrace{R_{\mu\nu}}_{\text{Ricci tensor}} - \frac{1}{2} g_{\mu\nu} \underbrace{R}_{\text{Ricci scalar}} = 8\pi G \underbrace{T_{\mu\nu}}_{\text{stress-energy tensor}}$$

second derivatives of the potential

We can add a term $+ \Lambda g_{\mu\nu}$ for a cosmological constant so $T_{\mu\nu} \sim \rho_\Lambda$

$$\rho_\Lambda = \frac{\Lambda}{8\pi G}$$

Equivalent to $\nabla^2 \phi = 4\pi G \rho$. Poisson equation

- Here stress-energy conservation means $\nabla_\nu (T_{\mu\nu}) = 0$

Homogeneity and Isotropy impose

$$T^\mu{}_\nu = \begin{pmatrix} \rho & & & \\ & -p & & \\ & & -p & \\ & & & -p \end{pmatrix}$$

In general

$$T_{\mu\nu} = -p\, g_{\mu\nu} + (\rho + p)\, u_\mu u_\nu$$

for a perfect fluid (in our case at rest in com. coordinates so $u^0 = 1$ $u_i = 0$

From the conservation equation

$$d(\rho a^3) = - \underbrace{p\, da^3}_{\text{work}}$$

"change in Energy in com volume"

Now we need the equation of state

$$p(t) = w\,\rho(t)$$ with w some constant

$$d(\rho a^3) = -p\, da^3$$

$$\downarrow$$

$$\boxed{\rho = a^{-3(1+w)}}$$

Let's consider some special cases

1) Matter : $w \approx 0 \longrightarrow \rho \sim a^{-3}$ ✓ mass conservation

Recall this is relativistic pressure

$$\frac{p}{c^2} = w\rho$$ in a normal fluid $p = v^2\rho$

$$w \approx \left(v/c\right)^2 \approx 0.$$

2) Radiation

$$p = \frac{1}{3}\rho \longrightarrow \rho_R \sim \frac{1}{a^4}$$

3) Vacuum energy

$$p = -\rho \rightarrow w = -1 \rightarrow \rho_\Lambda = \text{constant}$$

Friedman equations (00 and ii components of Einstein eqs.)

$$\left(\frac{\dot a}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho$$

$$2\frac{\ddot a}{a} + \left(\frac{\dot a}{a}\right)^2 + \frac{k}{a^2} = -8\pi G p$$

which can of course be written as

(1) $$H \equiv \left(\frac{\dot a}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

$k = 0$ flat

$k = +1$ closed

$k = -1$ open

$\mapsto$ Gives the expansion rate H of the Universe

(2) $$\frac{\ddot a}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

$\mapsto$ Shows how the Universe accelerates, given by $\rho + 3p$ (in GR pressure exerts gravity). Negative pressure gives acceleration.

$$\frac{k}{a^2 H^2} = -1 + \frac{\rho}{\rho_{crit}} \qquad \rho_{crit} = \frac{3H^2}{8\pi G} \quad \text{critical density}$$

today this is $\rho_{crit} = \frac{3H_0}{8\pi G} = 1.87 \times 10^{-29}\, g\, \frac{h^2}{cm^3}$.

We define all densities w.r.t ρ_{crit}

$$\Omega_i = \frac{\rho_i}{\rho_{crit}}$$

Recall

$$\Omega_{TOT} = \sum_i \Omega_i$$

$$\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_{crit}} = \frac{\Lambda}{3H^2}$$

We can also write $\frac{k}{a^2H^2} = \Omega_{TOT} - 1$ $(*)$

$$\boxed{\rho_\Lambda = \frac{\Lambda}{8\pi G}}$$

$$-\Omega_k \equiv \frac{k}{a^2H^2} \quad (**)$$

From $(*)$ you get $\Omega_{TOT} = 1$ flat

$\Omega_{TOT} > 1$ closed.

$\Omega_{TOT} < 1$ open

From $(**)$ $\Omega_{TOT} + \Omega_k = 1$ always!

Going back to the deceleration parameter

$$q = -\frac{\ddot{a}}{aH^2} = +\frac{4\pi G}{3H^2}(\rho + 3p) =$$

$$\rho + 3p = \rho(1 + 3w) = \begin{cases} \rho_m \\ 2\rho_R \\ -2\rho_\Lambda \end{cases}$$

ii) Flatness Problem

Go back to $\quad -\Omega_k = \dfrac{k}{a^2H^2} = \Omega_{TOT} - 1$

At early times $\quad \dfrac{1}{a^2H^2} \sim \dfrac{1}{a^2\rho} \sim \{a, a^2\}$ so $\Omega_k \longrightarrow 0$, $t \to 0$, $a \to 0$.

curvature is negligible.

$\rho \leftarrow \dfrac{1}{a^3}$ or $\dfrac{1}{a^4}$

MAT $\quad$ RAD

$$\Omega_k \sim \begin{cases} a & \text{MAT} \\ a^2 & \text{RAD} \end{cases} \qquad \Omega_{TOT} \xrightarrow[a\to 0]{} 1.$$

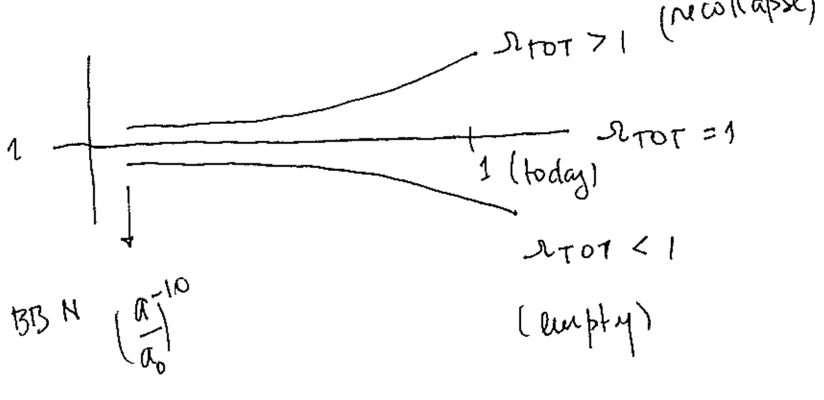
The other way around;

$$\Omega_{TOT}(a) - 1 = (\Omega^i_{TOT} - 1)\left(\frac{a}{a_i}\right) \quad \text{or} \quad (\Omega^i_{TOT} - 1)\left(\frac{a}{a_i}\right)^2$$

so

$$\Omega_{TOT}(a) - 1 \simeq (\Omega^i_{TOT} - 1)\left(\frac{a}{a_i}\right)^{1 \text{ or } 2}$$

Ω_{TOT} grows very fast with a, unless Ω^i_{TOT} was very close to 1. we would see large values of Ω_{TOT} $\gg 1$, $\ll 1$ today; but observationally we don't



its a fine tunning problem $\Rightarrow$ Universe is very close to flat

$$q = + \frac{4\pi G}{3H^2} (\rho_M + 2\rho_R - 2\rho_\Lambda) = + \frac{1}{2\rho_{crit}} (\rho_M + 2\rho_R - 2\rho_\Lambda)$$

$$= \frac{\Omega_M}{2} + \Omega_{RAD} - \Omega_\Lambda \underset{\uparrow}{\simeq} \frac{\Omega_M}{2} - (1 - \Omega_M) = \frac{3}{2}\Omega_M - 1$$

if that at

late time $\Omega_M + \Omega_\Lambda = 1$

$(\Omega_{TOT} = 1)$; $\Omega_{RAD} \sim 0$

$$q \approx \frac{3}{2}\Omega_M - 1$$

In general for one component $p = w\rho$ dominating the Universe

$$q = \frac{1}{2\rho_{crit}} (\rho + 3p) = \Omega_{TOT} \left(\frac{1+3w}{2}\right) > 0 \, !$$

Recall that $q \sim -\ddot{a}$ so Universe <u>accelerates</u> for $q < 0$ or

$w < -1/3$ (not for matter!)

<u>Static Universe</u> (if we were to tune the value of Λ)

$$H = 0 \longrightarrow \frac{8\pi G}{3}\rho = \frac{k}{a^2}$$

$$\ddot{a} = 0 \longrightarrow \rho + 3p = 0 \longrightarrow w = -1/3$$

$$\frac{3k}{8\pi G a^2} = \rho = -3p \underset{\uparrow}{=} -3p_\Lambda = 3\rho_\Lambda = \frac{3\Lambda}{8\pi G} \qquad \boxed{\Lambda = \frac{k}{a^2}}$$

only Λ has pressure

Unstable to perturbations!

Some solutions to the Friedman eqs

i) Flat, MATTER dominated Universe $k=0$, $\Omega_M=1$

$$H^2 = \frac{8\pi G}{3}\rho_M \sim a^{-3} \qquad \left(\frac{\dot a}{a}\right)^2 \sim a^{-3} \qquad \dot a \sim \frac{1}{\sqrt{a}}$$

$$\sqrt{a}\, da \sim dt \qquad d(a^{3/2}) \sim dt \qquad \boxed{a(t) \sim t^{2/3}}$$

ii) Flat, RAD dominated

$$H^2 = \frac{8\pi G}{3}\rho_R \sim a^{-4} \qquad \dot a \sim \frac{1}{a} \qquad a\, da \sim dt$$

$$\boxed{a(t) \sim t^{1/2}}$$

iii) General case $p = w\rho$

$$\boxed{a \sim t^{2/3(1+w)^{-1}}}$$

iv) Flat, Λ dominated

$$H = H_0 \qquad \dot a \sim a \qquad \boxed{a \sim e^{H_0 t}}$$

exponential expansion

Acceleration of the Universe : SN Ia results

- One way of measure the expansion of the Universe is to find standard variables ; in the case of SN Ia their luminosity can be standardized so you can then measure Flux and d_L

$$d_L \equiv \frac{L}{4\pi F} = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

$$H_0 = \dot{a}/a$$

$$q = -\ddot{a}/aH^2$$

$$d_L(z) = \frac{cz}{H_0}\left\{1 + \frac{1}{2}(1-q_0)z - \dots\right\} \qquad j_0 \simeq \dddot{a}$$

The acceleration gives a quadratic correction to Hubble's law (while a cubic term is change in acceleration

Let's move ~~mmm~~ to magnitudes

M : absolute magnitude ~ log L
m : apparent " ~ log F

M - m $\equiv$ distance modulo → log measurement of d_L

M = apparent magnitude an object would have at 10 pc

$$L(d) = \frac{L(10)}{(d/10)^2} \qquad m = -2.5\log_{10} L(d)$$

↑ luminosity at dist. d

$$m = -2.5 \log_{10} L(d) = -2.5 \log_{10}\left\{ L(10) \left(\frac{10}{d}\right)^2 \right\}$$

$$= \underbrace{-2.5 \log_{10} L(10)}_{M} - 5 \log_{10}(10/d_L)$$

$$\boxed{m - M = 5 \log_{10}(d_L/10)}$$

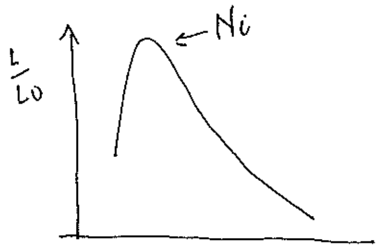
"standarizable candles".

Type Ia SN occur in binary systems (two stars orbiting each other). ~~The other star can be another~~ One star is a white ~~dwarf~~ dwarf; the other star can be another WD or a giant star or a smaller WD. Usually these WD are made of Carbon- and Oxygen. The WD accretes from the companion star until the core reaches the ignition temp. for carbon fusion.* at about $1.44\, M_\odot$ (sometimes refered as the Chandrasekhar limit).

(*) and undergoes a thermonuclear reaction triggering a SN explosion.

The peak luminosity in all these systems are very similar as they originate from the same physical process.

In reality there is a variance of about 40% at peak luminosity related to the amount of Ni in the progenitor.. But this is very correlated with the width of the light curve



decay → the integral is a measure of the bolometric mag. (total luminosity)

This brings the 40% scatter to about 15%.

Less Nickel decays faster.

Horizon

At $t = t_0$ (present time) is the 3D separating particles that have been already seen by an observer at t_0 from those that have not yet

"These are points that could have been in causal contact sometime in the life of the Universe"

ds^2 = null geodesic

"comoving distance" $= \int_0^r \frac{dr'}{\sqrt{1-kr'^2}} = c \int_0^{t_0} \frac{dt}{a}$ ← total comoving distance light could have traveled until t_0

"physical" horizon at t_0 is

$$d_H(t_0) = a(t_0) \int_0^{t_0} c \underbrace{\frac{dt}{a(t)}}_{\text{conformal time.}}$$

← Farthest that a particle could have traveled by time t_0.

if $a \sim t^n$ ($n = 2/3, 1/2$ for MAT, RAD) and $n < 1$

$$d_H(t_0) = \frac{ct}{1-n}$$

MAT = $d_H(t) = 3ct$.

RAD = $d_H(t) = 2ct$.

Notice this is larger than c.. But this is NOT the physical distance that light has travel but rather the physical position at t_0 of an object that sent a light ray at big bang arriving now at t_0
→ fartest object in the Universe for us.

Past light-cone:

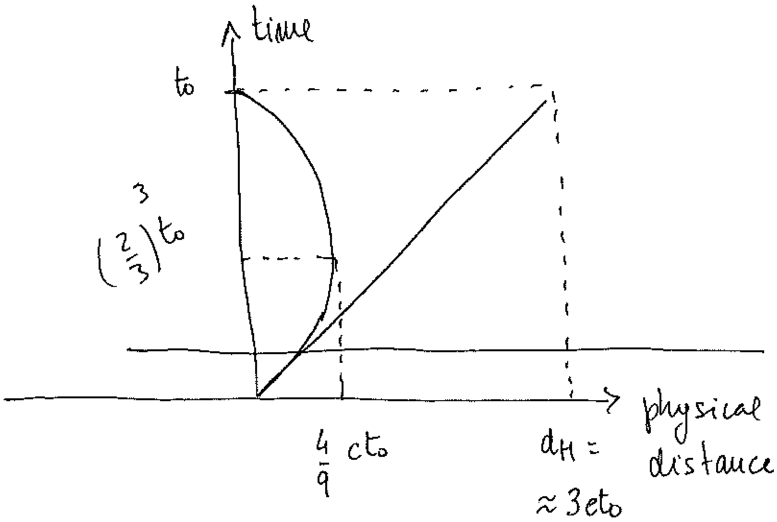
This is our standard idea of a past lightcone;

where are the objects that we see <u>now</u> at t_0

↓

at time $t < t_0$

As far as we can see now:



effectively this is cut by last scattering surface.

$$\ell(t) = a(t) \int_t^{t_0} c \frac{dt'}{a(t')} = 3c\left(t^{2/3} t_0^{1/3} - t\right)$$

for MAT $a = t^{2/3}$

convert to physical at t.

⇓

comoving distance to light emitted at t that gets to us at t_0.

Maximum $\frac{\partial \ell}{\partial t} = 0 \rightarrow \frac{t}{t_0} = \left(\frac{2}{3}\right)^3$ $\quad \ell_{max} = \frac{4}{9} c t_0$

<u>Hubble Radious</u> : cH^{-1} : is a local quantity ; not integrated

and note that $H \sim 1/t$ so H^{-1} is the local "time scale".

At time ~~the~~ t

$$v = H d \quad \text{so} \quad d \approx H^{-1} c$$

d_{Hubble} : surface at which recesion speed is equal to speed of light.

$$v_H = H d_H = \frac{2}{3t} \cdot 3ct = 2ct$$ recesion speed of the horizon.

Hubble radious shows up in equations of motion.

Physical distance of a wordline of an object with constant ~~speed~~ comoving position

$$\lambda_{phys} = a(t) \, \lambda_{comoving}$$

So

$$d_H(t) = \begin{cases} 3t & \text{MAT} \quad t \sim a^{3/2} \\ 2t & \text{RAD} \quad t \sim a^2 \end{cases}$$

$$H^{-1} = \begin{cases} \left(\frac{2}{3t}\right)^{-1} & \text{MAT} \quad t \sim a^{3/2} \\ \left(\frac{1}{2t}\right)^{-1} & \text{RAD} \quad t \sim a^2 \end{cases}$$

$\lambda_{phys} \sim a$ always.

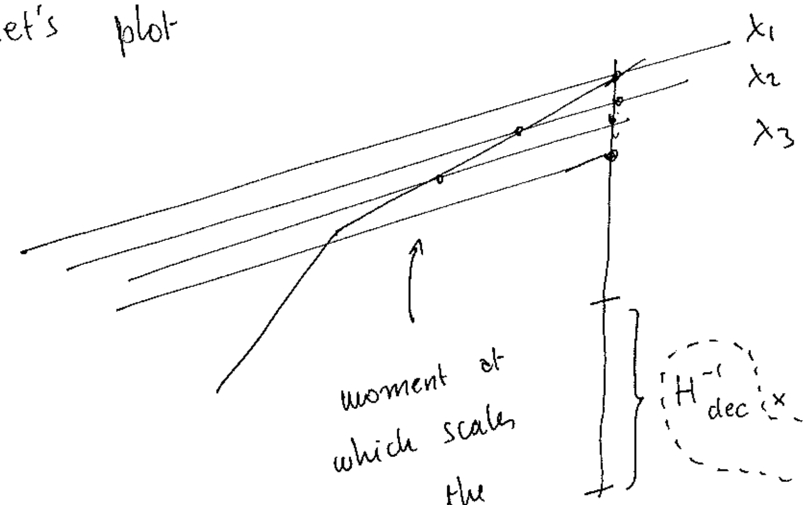
Note that if $a \sim t^n$

$$\lambda_{phys} \sim a \sim t^n \quad \text{with } n < 1$$

But d_H, $H^{-1} \sim t$ $\rightarrow$ so the horizon grows faster than physical scales ; this means that all scales "enter the horizon" eventually.

Horizon Problem.

Let's plot



$(\lambda_1 > \lambda_3)$

↑ increasing scales.

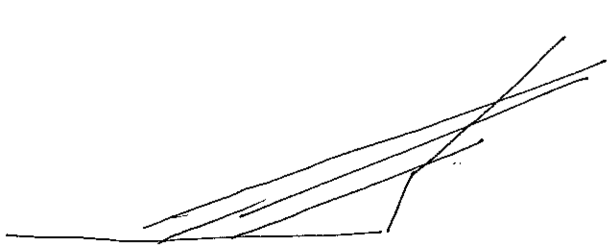
moment at which scales enter the horizon. ($\sim H^{-1}$).

$H^{-1}_{dec} \times \frac{a_0}{a_{dec}}$ back to comoving.

⇓

This should be the scales in causal contact! yet all are in same temperature

Problem with CMB temperature $\rightarrow$ H^{-1}_{dec}.



INFLATION

they enter causal contact ~~that~~ back then

$t_{dec} > t_{MAT=RAD}$

Matter - RAD equality happened before decoupling of photons (at $z \sim 2700$) ~ 2740

Particle horizon (Horizon) : maximum distance from which particles could have travel to the observer in the age of the Universe. Boundary between observable and unobservable Universe. It represents the furthest distance from which we can retrieve info from the past. (about 46 billion light years)