Introduction to Cosmology (in 3 lectures)

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Cosmology

Program:

- Introduction, lightening fast background review (homeworks in yellow background)
- Inflation
- Dark energy

Lectures and additional material will appear at
http://icc.ub.edu/~liciaverde/TAElectures.html

Cosmology

Cosmos= Universe, Order, beauty
-logy= study

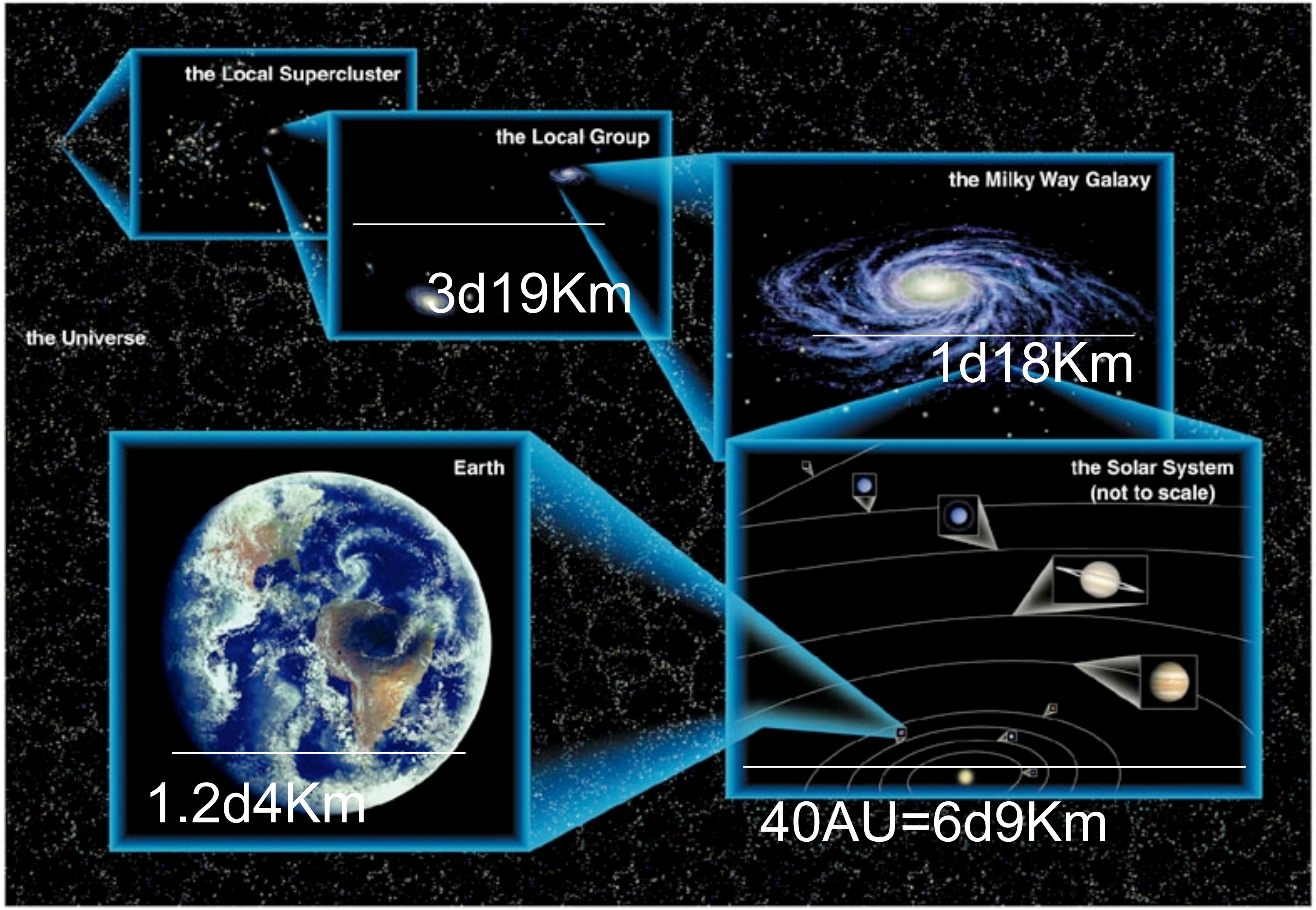
Greek!

Study of the Universe as a whole
Aim at getting an understanding of:

- its origin
- its structure and composition
(where do galaxies, stars, planets, people come from?)
- its evolution
- its fate

Deep connections to fundamental physics

Scales involved!



New units of measure

For distance, we use pc, Kpc & Mpc

$$1\ \mathrm{pc} = 3.086 \times 10^{16}\mathrm{m}$$

$$1\ \mathrm{Mpc} = 3.086 \times 10^{22}\mathrm{m}$$

For comparison, mean Earth-Sun distance (Astronomical Unit):

$$1\ \mathrm{AU} = 1.496 \times 10^{11}\mathrm{m}$$

$$1\ \mathrm{pc} = 2.1 \times 10^{5}\mathrm{AU}$$

- Cosmologists often express masses
- in units of the solar mass:

$$1\ \mathrm{M}_\odot = 1.99 \times 10^{30}\mathrm{kg}$$

Looking far away is looking back in time!

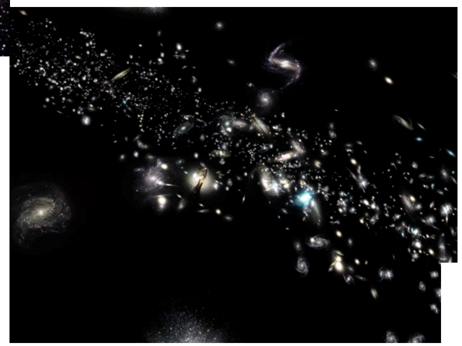
8 minutes ago

28000 years ago

Cosmic archeology

Andromeda, M31

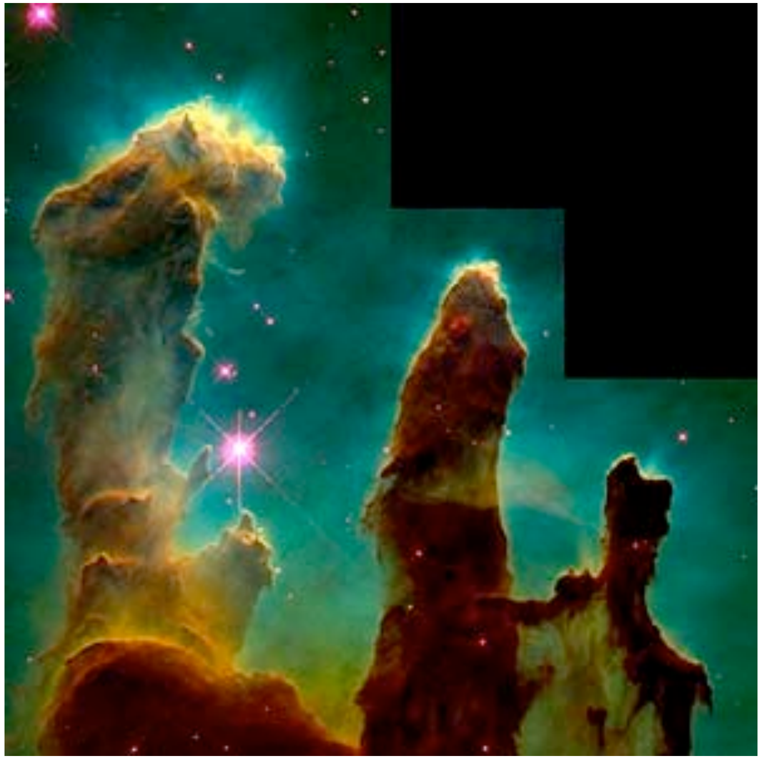
2.2 million years ago



3 billion years ago

Looking far away in space= looking back in time

stars

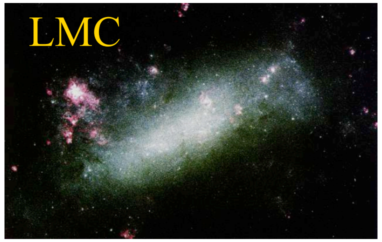


HST image of stars being born,
but it has no direct use
for Cosmology;
exploding stars (supernovae)
are very useful
(you’ll see later on)

By the way, we are star-dust

galaxies

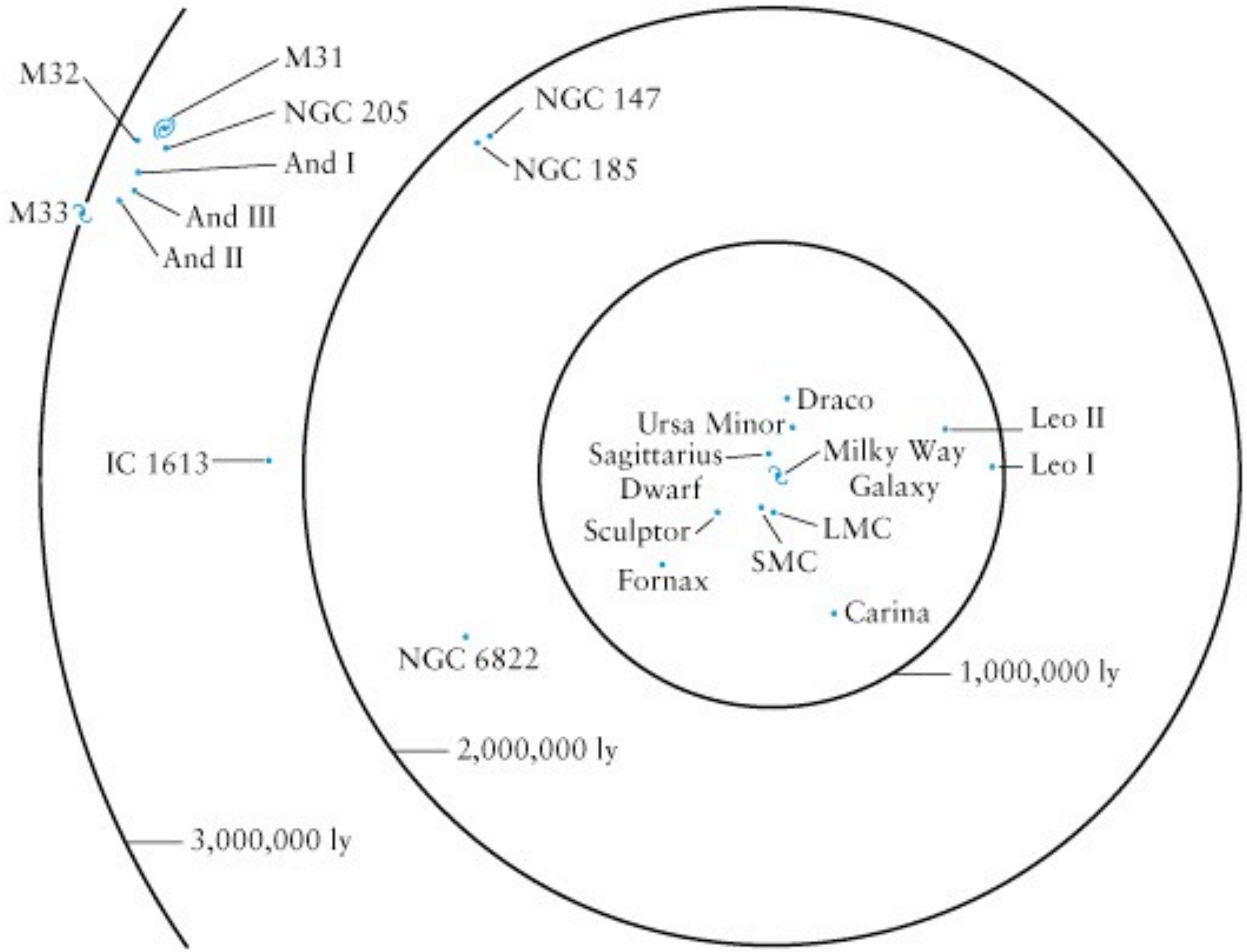
Collections of ~10^{11}~ 10^{12} Stars



galaxies

galaxies

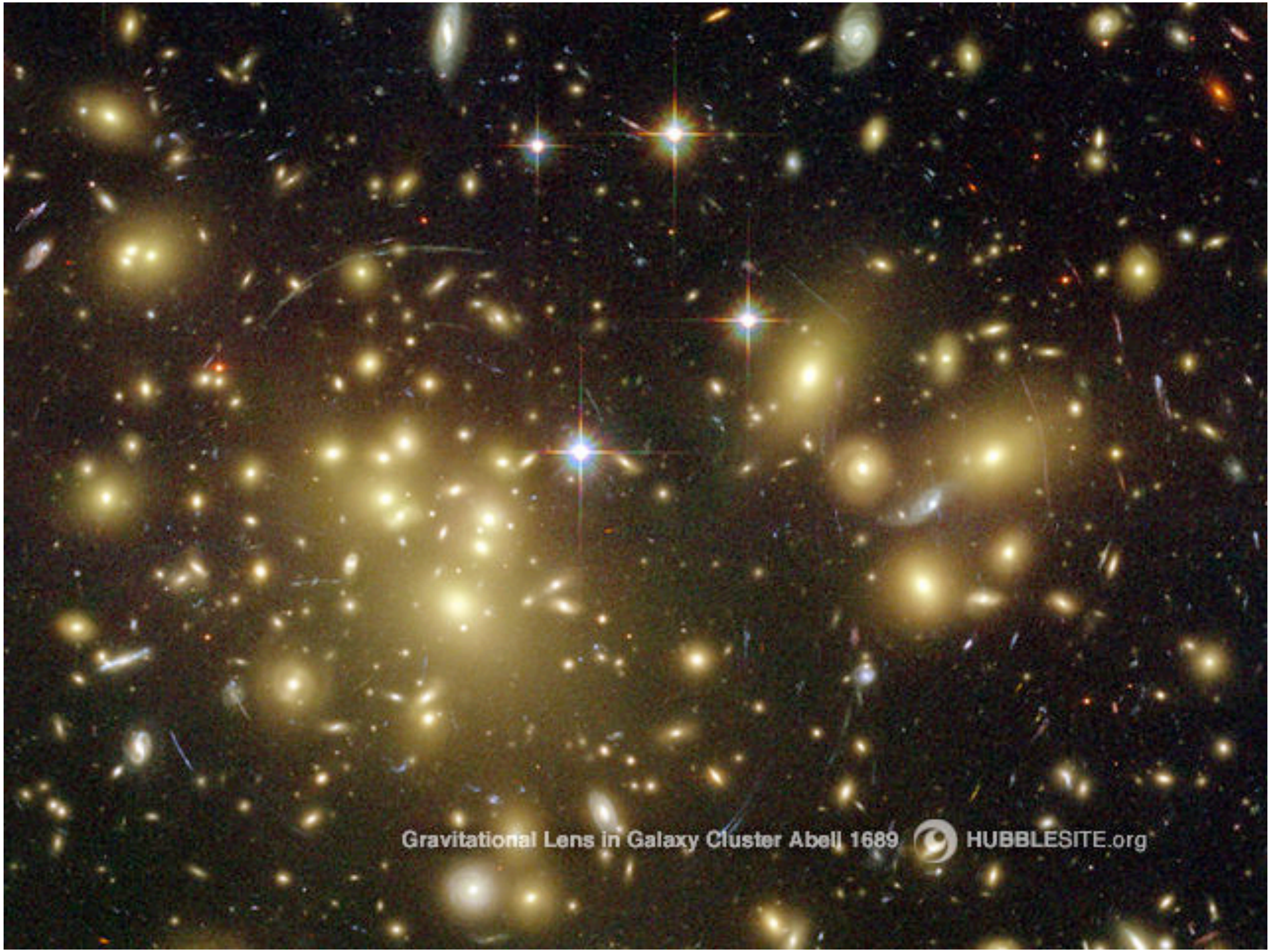
The local group



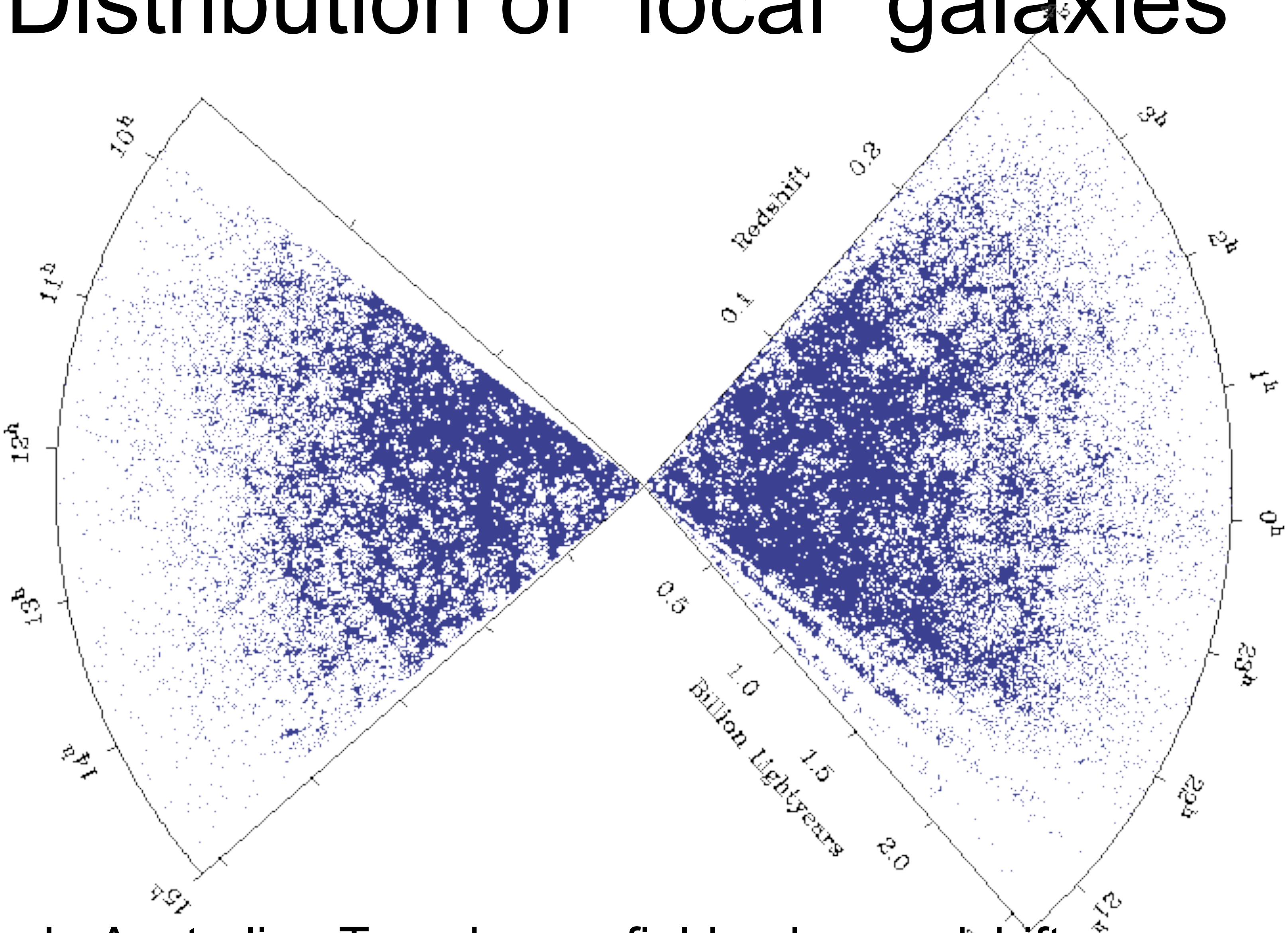
Entering the regime of cosmology….

groups

Groups and clusters

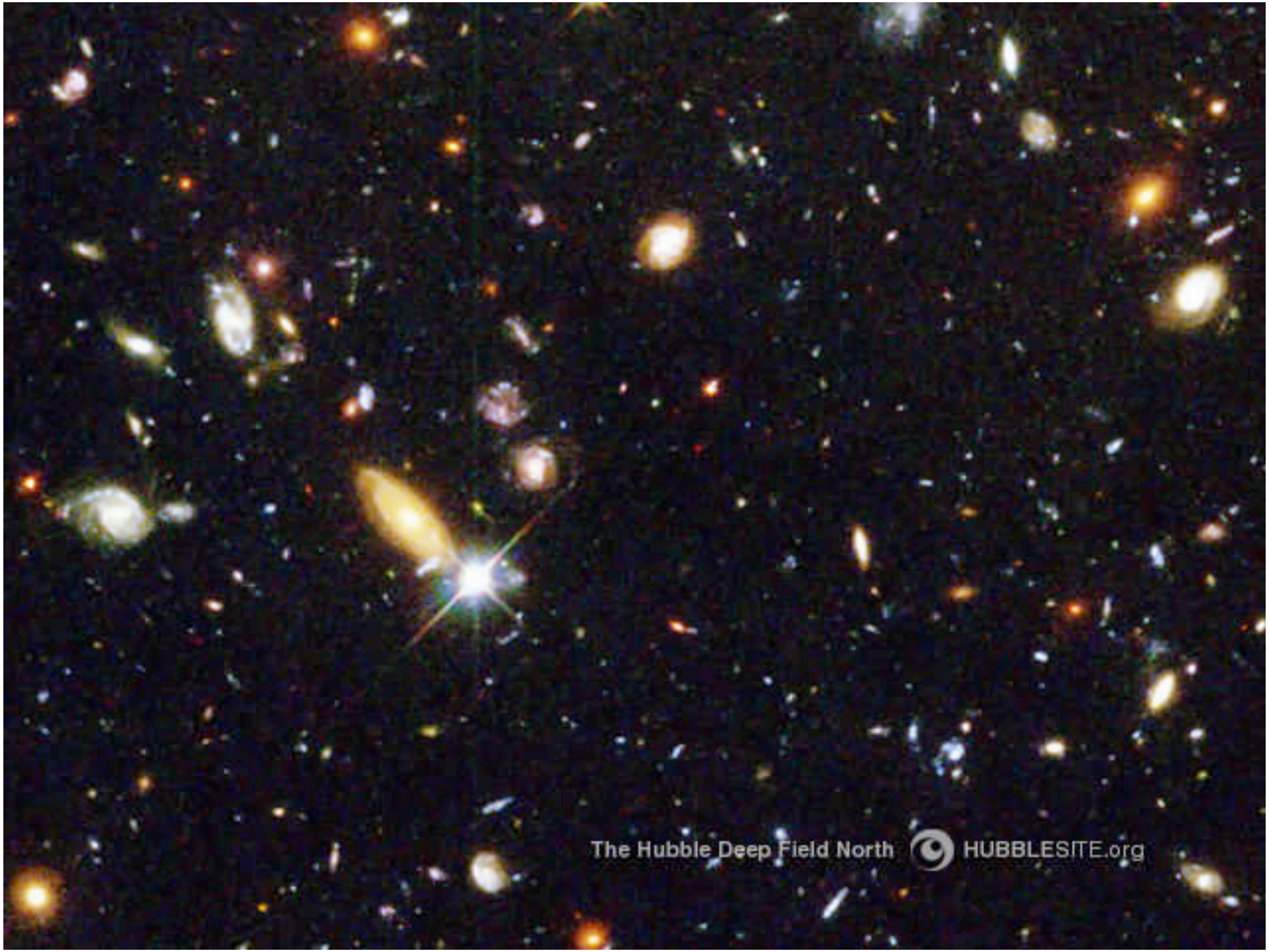


Distribution of “local” galaxies



Anglo Australian Two-degree field galaxy redshift survey

Hubble deep field



Not only pretty pictures

Nature is written in the mathematical language (Galileo)

The laws of physics are the same in the entire Universe

The universe is comprehensible (by us)

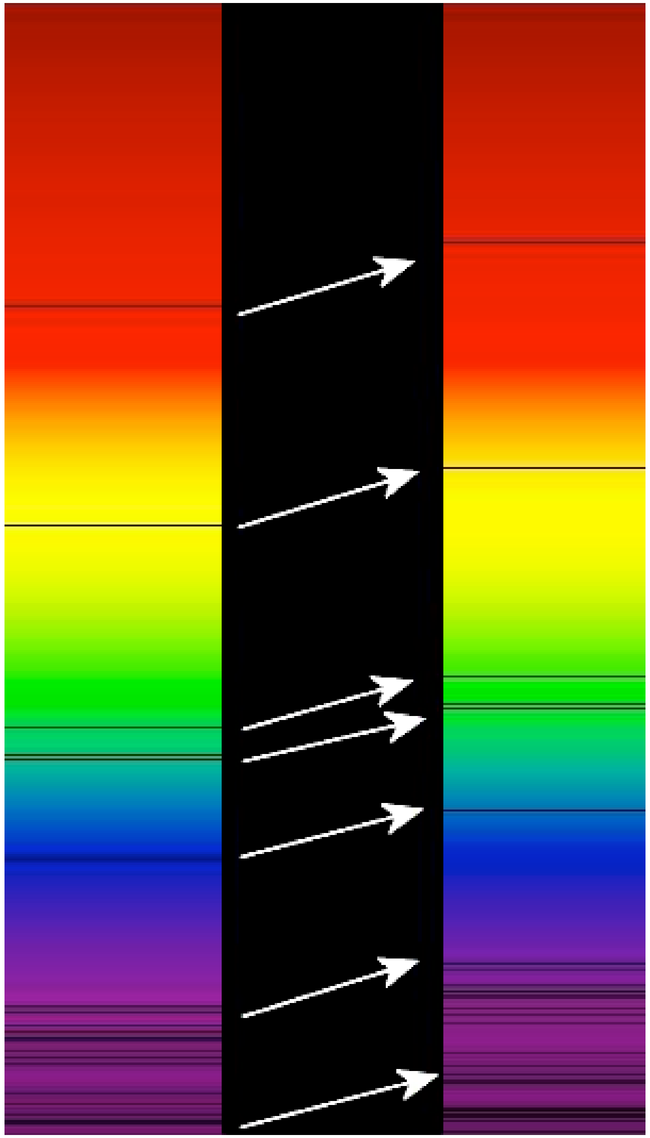
Deep connections to fundamental physics

FROW QUARKS TO THE COSMOS!

Distances are difficult: velocities are “easy” Thank you Edwin Hubble

REDSHIFT

$$z = \frac{\lambda_{\text{obsv}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}}$$ or $$1 + z = \frac{\lambda_{\text{obsv}}}{\lambda_{\text{emit}}}$$



In relativity:

$$1 + z = \gamma\left(1 + \frac{v_{||}}{c}\right)$$

$$z \approx \frac{v_{||}}{c}$$ For small velocity

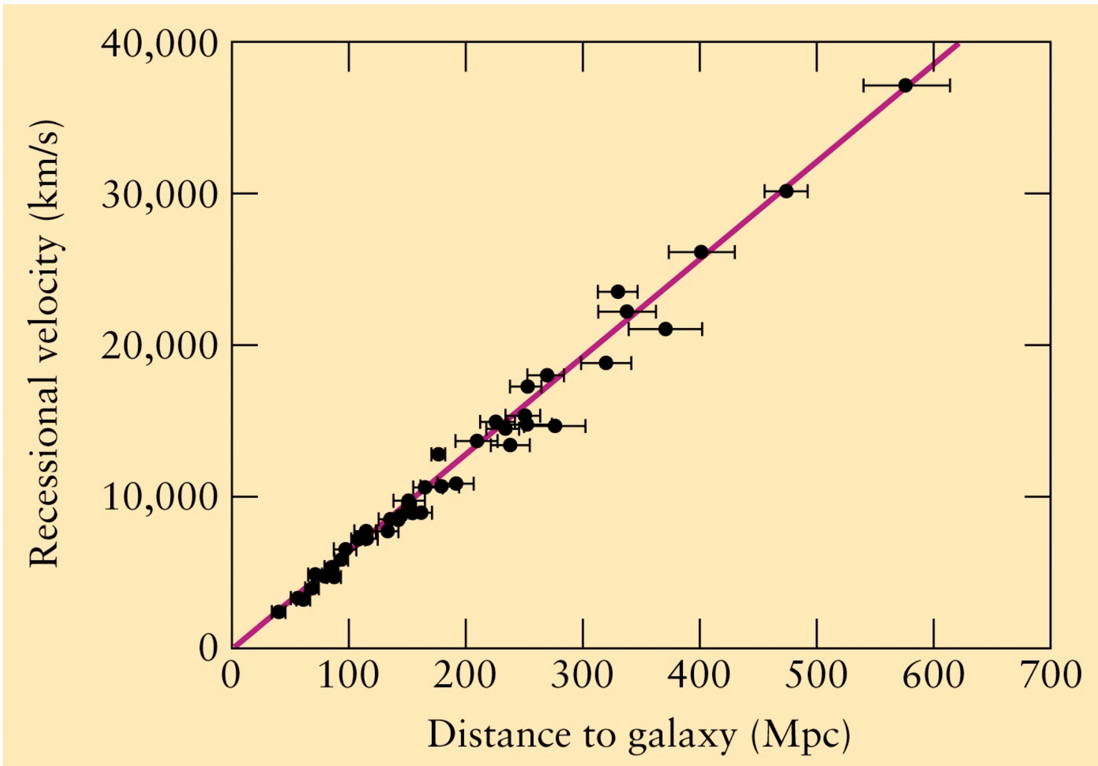
or $$1 + z = \frac{1 + v\cos(\theta)/c}{\sqrt{1 - v^2/c^2}}$$

Hubble's Law

$$cz = v = H_0 d$$

Ho=74.2 +- 3.8   km/s/Mpc

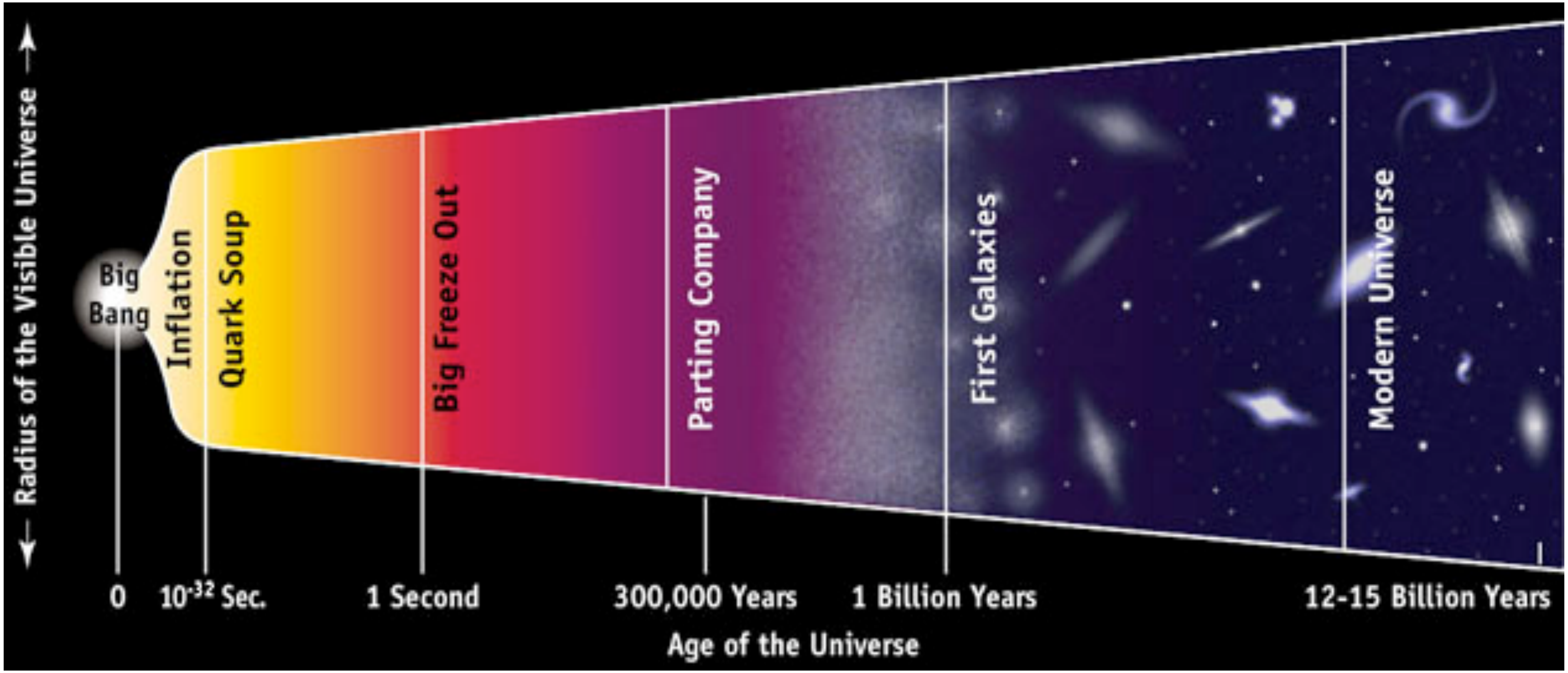
Hubble 1929
(PNAS vol 15)



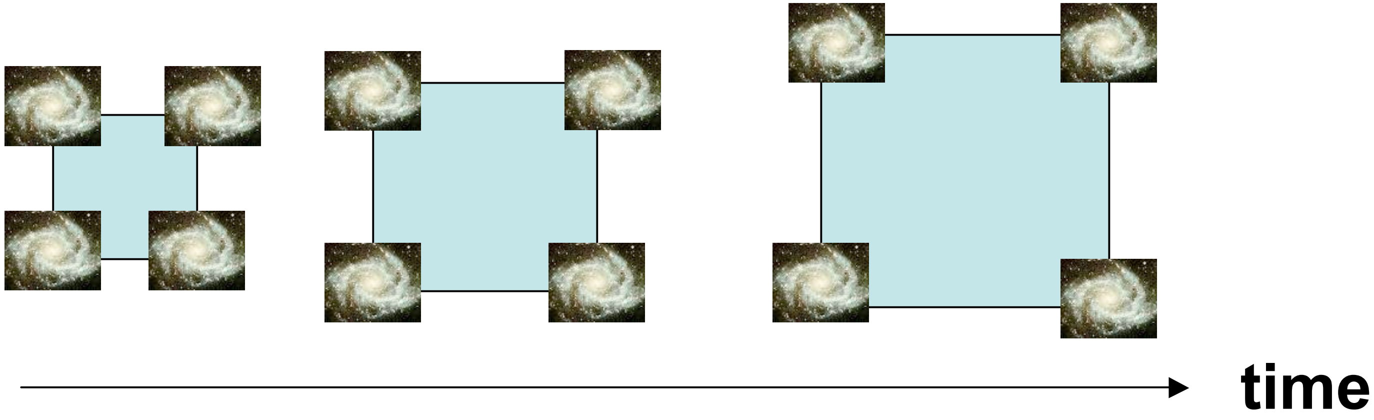
The universe is expanding!

The universe had a beginning!

The extremely successful BIG BANG theory!



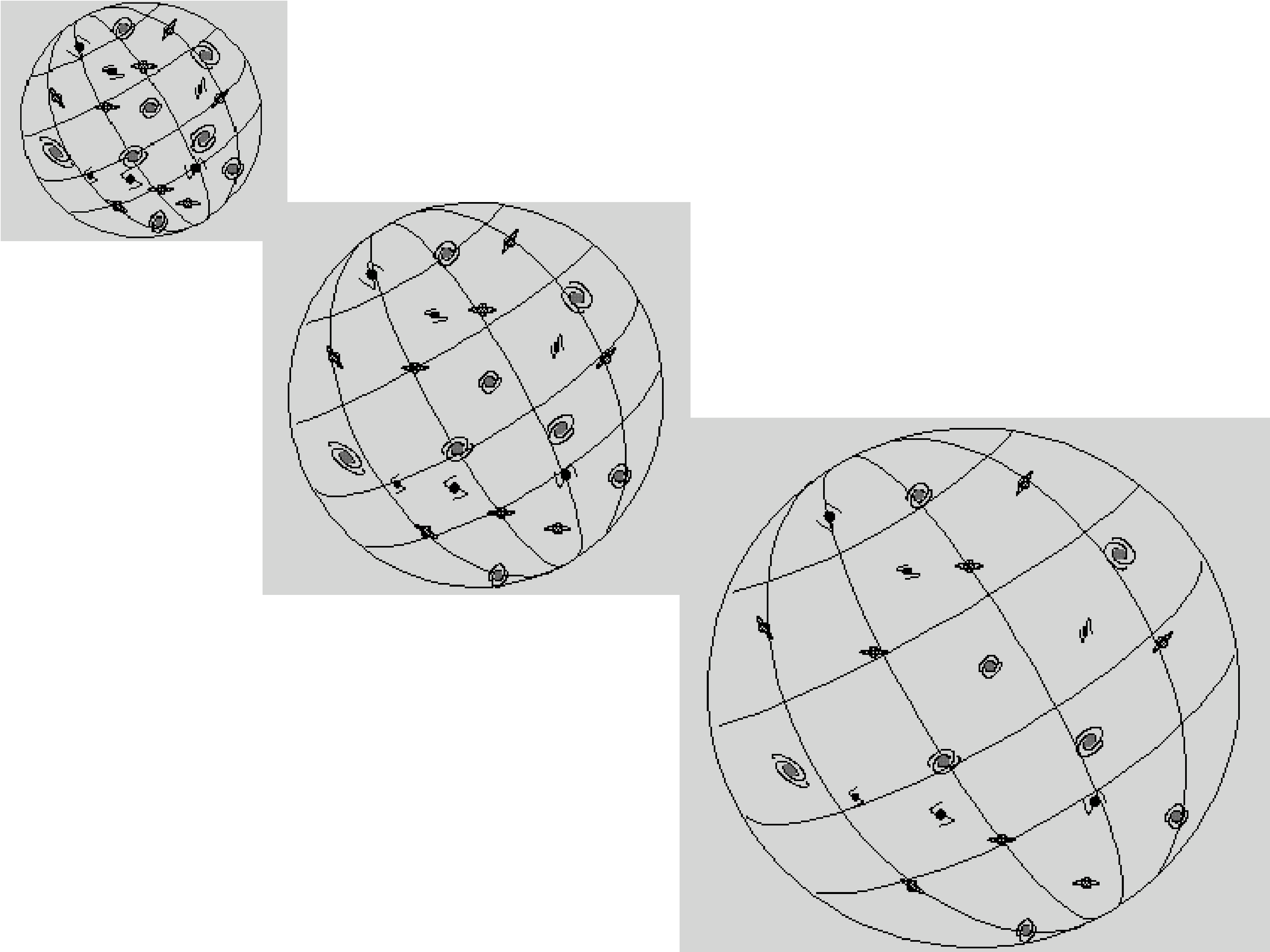
The scale factor a



$r(t)=r(t_0)\,a(t)$ **Comoving coordinates!**

$v_{12}=dr_{12}/dt=\dot{a}\,r_{12}(t_0)=\dot{a}/a\,r_{12}(t)$ Looks like Hubble law

$$H=\frac{\dot{a}}{a}$$ **Important!**



How old is the Universe?

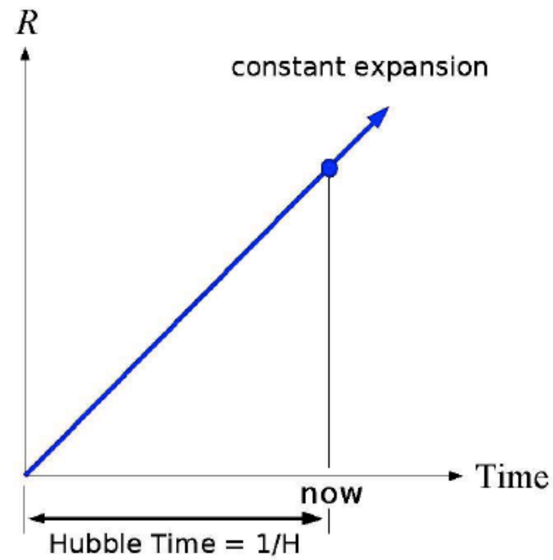
$t_0 = r/v = r/(H_0 r) = 1/H_0$

Hubble time

Hubble radius c/H_0
Also called Hubble horizon

The Hubble time is the age of the present day Universe assuming a constant expansion rate.

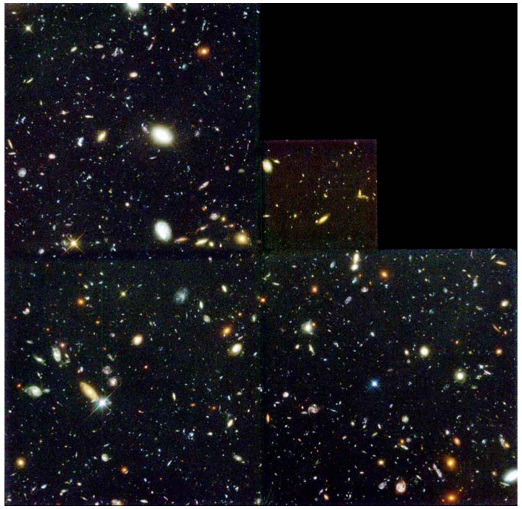
$$t_H = \frac{1}{H_0} = \frac{D_H}{c}$$



Exercise: compute numerical values.
Do they make sense? Why? Is that a coincidence?

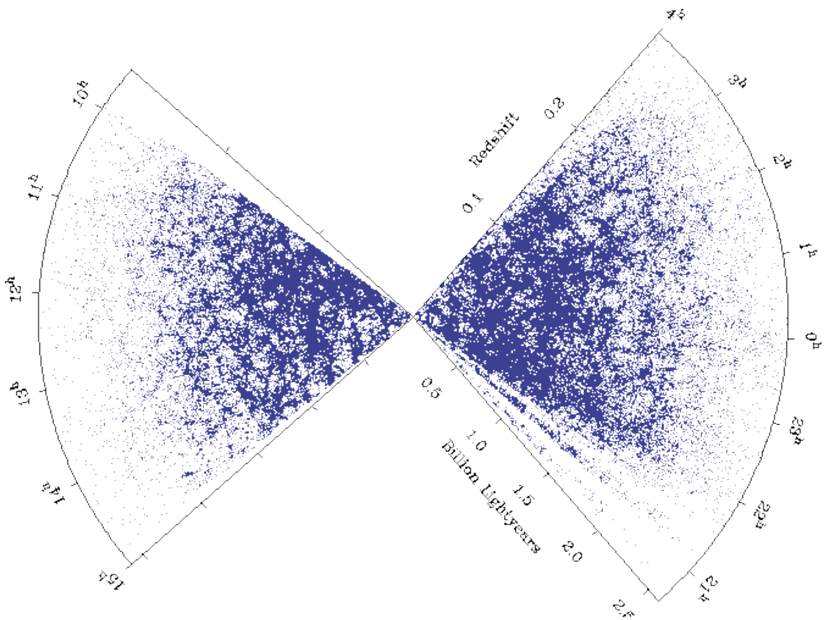
Some assumptions

The Universe is homogeneous and isotropic on large scales



This is supported by observations

HDF north and south

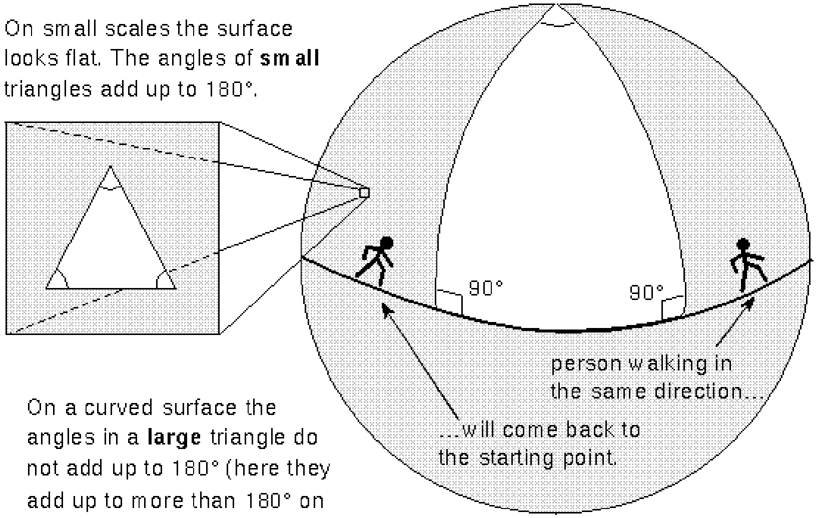


2dF GRS

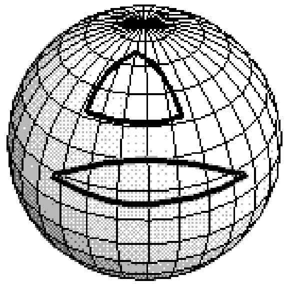
Large volumes of the sky in different directions, 100's of Mpc in size, look about the same.

Geometry

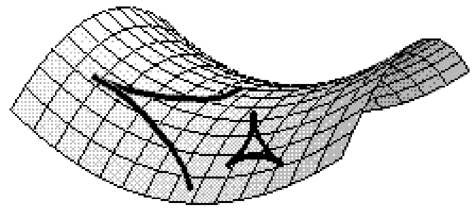
On small scales the surface looks flat. The angles of **small** triangles add up to 180°.



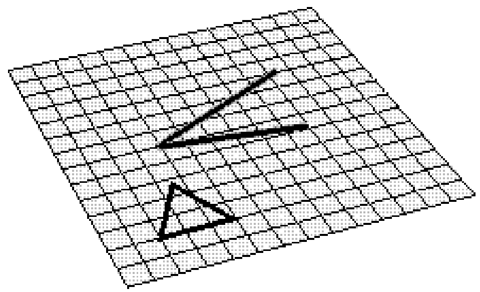
On a curved surface the angles in a **large** triangle do not add up to 180° (here they add up to more than 180° on this type of curved surface).



Universe with *positive* curvature. Diverging line converge at great distances. Triangle angles add to more than 180°.

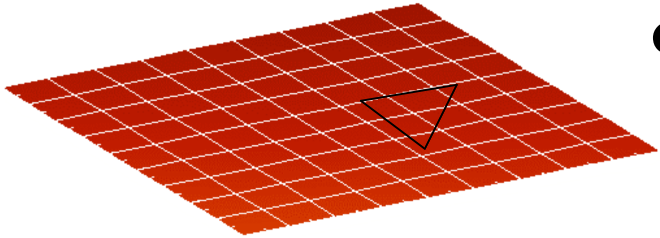


Universe with *negative* curvature. Lines diverge at ever increasing angles. Triangle angles add to less than 180°.



Universe with no curvature. Lines diverge at constant angle. Triangle angles add to 180°.

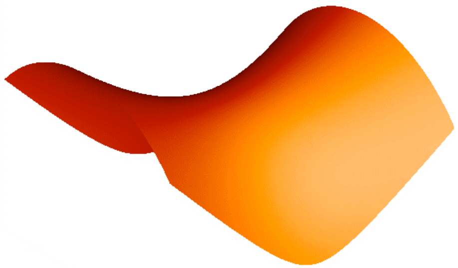
Geometry & Metrics



$\alpha+\beta+\gamma=\pi$

flat

$ds^2=dr^2+r^2d\theta^2$

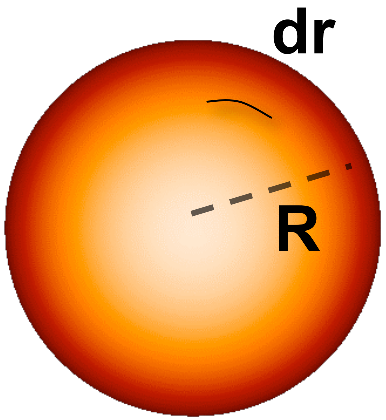


Area of triangle

$\alpha+\beta+\gamma=\pi-A/R^2$

Negatively curved

$ds^2=dr^2+R^2\sinh^2(r/R)d\theta^2$



$\alpha+\beta+\gamma=\pi+A/R^2$

Positively curved

Finite area, max separation

$ds^2=dr^2+R^2\sin^2(r/R)d\theta^2$

In 3D and in general…

$$d\theta^2 \longrightarrow d\theta^2 + \sin^2\theta \, d\phi^2 = d\Omega^2$$

R

$$ds^2 = dr^2 + S_k(r)^2 d\Omega^2$$

$$S_k(r) = \begin{cases} \sqrt{k}^{-1} \sin(r\sqrt{k}), & k > 0 \\ r, & k = 0 \\ \sqrt{|k|}^{-1} \sinh(r\sqrt{|k|}), & k < 0. \end{cases}$$

k may be taken to belong to the set {−1,0,+1}

Changing coordinate system $x=S_k(r)$:

$$ds^2 = \frac{dx^2}{1 - \kappa x^2/R^2} + x^2 d\Omega^2.$$

Freedman-Robertson Walker metric

In 4 dimensions and introducing back the scale factor

$$\boxed{ds^2 = dt^2 - a^2(t)\left[\frac{d\chi^2}{1 - k\chi^2} + \chi^2(d\theta^2 + \sin^2\theta d\phi^2)\right]}$$

c^2

If k=0 Minkowski

OR $$\boxed{ds^2 = -c^2 dt^2 + a(t)^2\left[dr^2 + S_\kappa(r)^2 d\Omega^2\right]}$$

Comoving coords again!

t is COSMIC TIME:
time seen by an observer who sees the universe expanding uniformly

Knowing a(t),k, and R_0 is "all" you need!

Compute distances:

At fixed time spatial geodesic (angles are fixed)

ds=a(t)dr

Proper distance:

$$d_p = a(t) \int_0^r dr = a(t)r = a(t)r(x) = a(t)S_k(r)^{-1}$$

Hubble law again:

$$\dot{d}_p = \dot{a}r = \frac{\dot{a}}{a} d_p$$

$$H_o = \left(\frac{\dot{a}}{a} \right)_{t=t_0}$$

$$v_p(t_0) = H_0 d_p(t_0)$$

Redshift, again

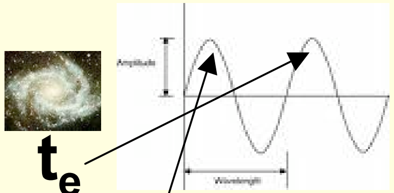
$$ds = 0 \longrightarrow c^2 dt^2 = a(t)^2 dr^2$$

Photons travel along null geodesics

$$c\frac{dt}{a(t)} = dr$$

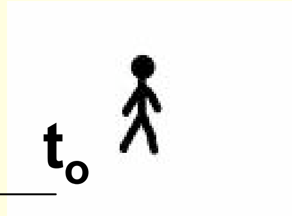
t only

r only



t_e

t_o



r

The next crest

$$c\int_{t_e}^{t_o} \frac{dt}{a(t)} = \int_0^r dr = r$$

$$c\int_{t_e+\lambda_e/c}^{t_o+\lambda_o/c} \frac{dt}{a(t)} = \int_0^r dr = r$$

$t_e \qquad t_e + \lambda_e/c \qquad t_o \qquad t_o + \lambda_o/c$

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

$$\frac{1}{a(t_e)}\int_{t_e}^{t_e+\lambda_e/c} dt = \frac{1}{a(t_o)}\int_{t_o}^{t_o+\lambda_o/c} dt \longrightarrow \frac{\lambda_e}{a(t_e)} = \frac{\lambda_o}{a(t_o)}$$

Should remind you of z

$$\boxed{\frac{\lambda_o - \lambda_e}{\lambda_e} = (1+z) = \frac{a(t_o)}{a(t_e)}}$$

If an object has z=3, what was the size of the Universe?

How do we measure the geometry then?

$$\alpha + \beta + \gamma = \pi + kA/R_0$$

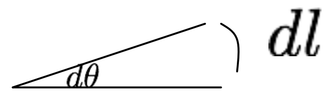
K=+1--> finite size: circumference $2\pi R_0$ In the past even smaller

If $2\pi R_0 << ct_0 \sim c/H_0$ **?????**

Angular size of objects

If I happen to know dl….

$$d\theta = \frac{dl}{a(t)S_k(r)}$$



Ah!

Standard ruler, angular diameter distance

brightness

Standard candle

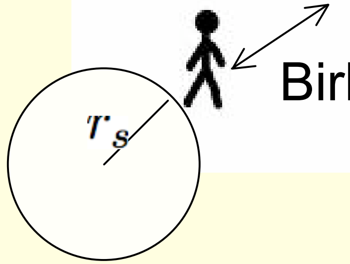
$$F = \frac{L}{4\pi r^2} \longrightarrow F = \frac{L}{4\pi S_k^2(1+z)^2}$$

Ah! ah!

- In GR space tells mass how to move, mass tells space how to curve.

- Suspicion: $a(t)$ related to content of Universe?
- Really need GR but we do Newton…

Friedmann equations (1)



Birkhoff theorem

$$a_{cc} = \frac{d^2 r_s(t)}{dt^2} = -\frac{GM_s}{r_s^2(t)}$$

$$\frac{dr_s}{dt}\frac{d^2 r_s(t)}{dt^2} = -\frac{GM_s}{r_s^2(t)}\frac{dr_s}{dt} = \frac{1}{2}\frac{d}{dt}\left(\frac{dr_s}{dt}\right)^2$$

integrate

$$\frac{1}{2}\left(\frac{dr_s}{dt}\right)^2 = \frac{GM_s}{r_s(t)} + U$$

kinetic potential

$$Ms = \frac{4\pi}{3}\rho(t) r_s^3(t) \equiv \frac{4\pi}{3}\rho(t) a^3(t) r_s^3$$

Substitute and divide each side by $\frac{r_s^2 a^2}{2}$

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

Symmetric under time reversal

Start with an expanding sphere:
How does it evolve of U>0 ?
How does it evolve of U<0 ?

Need GR
to go further

Friedmann equations 1

$$\boxed{H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho(t) - \frac{kc^2}{R_0^2 a^2}}$$

U was related to spatial curvature

ρ Total matter-energy density: ε/c^2

Make the Universe flat

$$\rho_{c,0} = \frac{3H_0^2}{8\pi G}$$

Today (and at any time using (t) for 0)

Define: $\Omega = \frac{\rho_{tot}}{\rho_c}$

Density parameter, gives curvature

$$\text{Mass-energy} \rightarrow \begin{cases} \text{gravity} \\ \text{curvature} \end{cases}$$

Friedmann equations 2

One eq.; 2 unknowns a(t) , ρ(t), need a relation between the two

$dQ = dE + PdV$ Expanding universe, adiabatic $\dot{E} + P\dot{V} = 0$

Consider a spherical chunk of Universe

$$\dot{V} = \frac{4\pi}{3}\frac{d}{dt}(ar_s)^3 = \frac{4\pi}{3}r_s^3 3a^2\dot{a} = V\left(3\frac{\dot{a}}{a}\right)$$

$$\dot{E} = \frac{d}{dt}\epsilon(t)V(t) = \dot{V}\epsilon + V\dot{\epsilon} = V\left(\dot{\epsilon} + 3\frac{\dot{a}}{a}\epsilon\right)$$

$$0 = \dot{E} + P\dot{V} = V\left(\dot{\epsilon} + 3\frac{\dot{a}}{a}\epsilon\right) + PV3\frac{\dot{a}}{a}$$

$$\boxed{\dot{\epsilon} + 3\frac{\dot{a}}{a}(\epsilon + P) = 0}$$

Fluid equation

Friedman and fluid equations are ENERGY CONSERVATION

Friedmann Equations 3

Let's combine the two to get a useful eqn

Multiply Friedmann by a^2
derive wrt t
Divide by $2\dot{a}a$

$$\dot{a}^2 = \frac{8\pi G}{3c^2}\epsilon a^2 - \frac{kc^2}{R_0^2}$$

$$2\dot{a}\ddot{a} = \frac{8\pi G}{3c^2}(2\epsilon a\dot{a} + \dot{\epsilon}a^2)$$

$$\frac{\ddot{a}}{a} = \frac{8\pi G}{3c^2}(\dot{\epsilon}\frac{a}{\dot{a}} + 2\epsilon)$$

Use fluid eq.

$$\dot{\epsilon}\frac{a}{\dot{a}} = -3\left(\epsilon + P\right)$$

$$\boxed{\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\epsilon + 3P)}$$

Acceleration equation!

If P=0 and ε>0 …

So if you start with an expanding Universe….

If the Universe started off expanding stuff should slow down the expansion!

And what would it take to make it accelerate?

Friedmann equations

NOT independent!

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho(t) - \frac{kc^2}{R_0^2 a^2}$$

$$\dot{\epsilon} + 3\frac{\dot{a}}{a}(\epsilon + P) = 0$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\epsilon + 3P)$$

$$\rho(t)c^2 = \epsilon(t)$$

If you want to solve for

$$a(t), \epsilon(t), P(t)$$

need more info…

$$P = P(\epsilon)$$

$$P = w\epsilon$$

Interesting cases:

Non-relativistic matter	$w \simeq 0$
Radiation	$w = 1/3$
Accelerating fluid	$w < -1/3$
Cosmological constant	$w = -1$

This is weird……
but looks like we are stuck with it

Einstein and the cosmological constant

$\nabla^2\Phi = 4\,\pi G\rho$ Poisson equation $a_{cc} = -\vec{\nabla}\Phi \equiv 0$

If static

If static $\rho = \frac{1}{4\pi G}\nabla^2\Phi = 0$ Empty… humm….. or $\nabla^2\Phi + \Lambda = 4\pi G\rho$

$\Lambda = 4\,\pi G\rho$

Einstein….

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho(t) - \frac{kc^2}{R_0^2 a^2} + \frac{\Lambda}{3}$$

$$\dot{\epsilon} + 3\frac{\dot{a}}{a}(\epsilon + P) = 0$$

Does not get diluted…

$$\epsilon_\Lambda = \frac{c^2}{8\pi G}\Lambda$$

$$w = -1, P_\Lambda = -\epsilon$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\epsilon + 3P) + \frac{\Lambda}{3}$$

Vacuum energy…

I told you it was weird….

The universe composition

Matter; radiation; curvature;etc…

$$H^2 = \frac{8\pi G}{c^2 3}\sum_i \epsilon_i$$

One for each component

$$\dot{\epsilon} + 3\frac{\dot{a}}{a}(\epsilon + P) = 0$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}\left(\sum_i \epsilon_i + 3\sum_i P_i\right)$$

$$\begin{aligned} \dot{\epsilon} &= -3(1+w)\epsilon\frac{\dot{a}}{a} \\ d\ln\epsilon &= -3(1+w)d\ln a \\ \boxed{\epsilon = \epsilon_0 a^{-3(1+w)}} \end{aligned}$$

Matter…
Radiation… (redshift is back)
Cosmological constant…

Use Friedmann equation

$$\dot{a}^2 = \frac{8\pi G}{3c^2}\epsilon_0 a^{-(1+3w)}$$

You can solve it!

If it was only one component

$$\dot{a}^2 = \frac{8\pi G}{3c^2}\epsilon_0 a^{-(1+3w)}$$ Ansatz: $a \sim t^q$ If $w \neq -1$ $q = \frac{2}{3(1+w)}$

$$a(t) = \left(\frac{t}{t_0}\right)^{\frac{2}{3(1+w)}}$$

$$t_0 = \sqrt{\frac{c^2}{6\pi G\epsilon_0}\frac{1}{(1+w)}}$$

$$H_0 = \left.\frac{\dot{a}}{a}\right|_{t_0} = t_0^{-1}\frac{2}{3(1+w)}$$

$$(1+z) = \frac{a(t_o)}{a(t_e)} = \left(\frac{t_o}{t_e}\right)^{\frac{2}{3(1+w)}} \longrightarrow t_e(t_o)$$

$$d_p(t_o, z) = c\int_{t_e}^{t_o}\frac{dt}{a(t)} = .. = \frac{c}{H_0}\frac{2}{1+3w}\left[1-(1+z)^{-(1+3w)/2}\right]$$

The farther object you can see…. Horizon! (we'll get back to this later)

If it was only Λ

$$\dot{a}^2 = \frac{8\pi G}{3c^2}\epsilon_0 a^{-(1+3w)}$$

$$H = \left(\frac{8\pi G\epsilon_\Lambda}{3c^2}\right)^{1/2} = H_0$$

$$\frac{\dot{a}}{a} = const \longrightarrow a(t) = \exp[H_0(t - t_0)]$$

$$PHYSICAL:\ d_p(t) = a(t)\int \frac{dt}{a(t)} = \exp(H_\Lambda t)\int_{t_i}^{t_f} \exp(-H_\Lambda t)dt$$
$$= H_\Lambda^{-1}(\exp(H_\Lambda(t - t_i)) - 1)$$

Grows exponentially and c/H<<dp!

Back to Friedmann

$$H(t)^2 = \frac{8\pi G}{3c^2}\epsilon - \frac{kc^2}{R_0^2 a^2} \longrightarrow (1-\Omega) = -\frac{kc^2}{R_0^2 a^2 H_0^2}$$

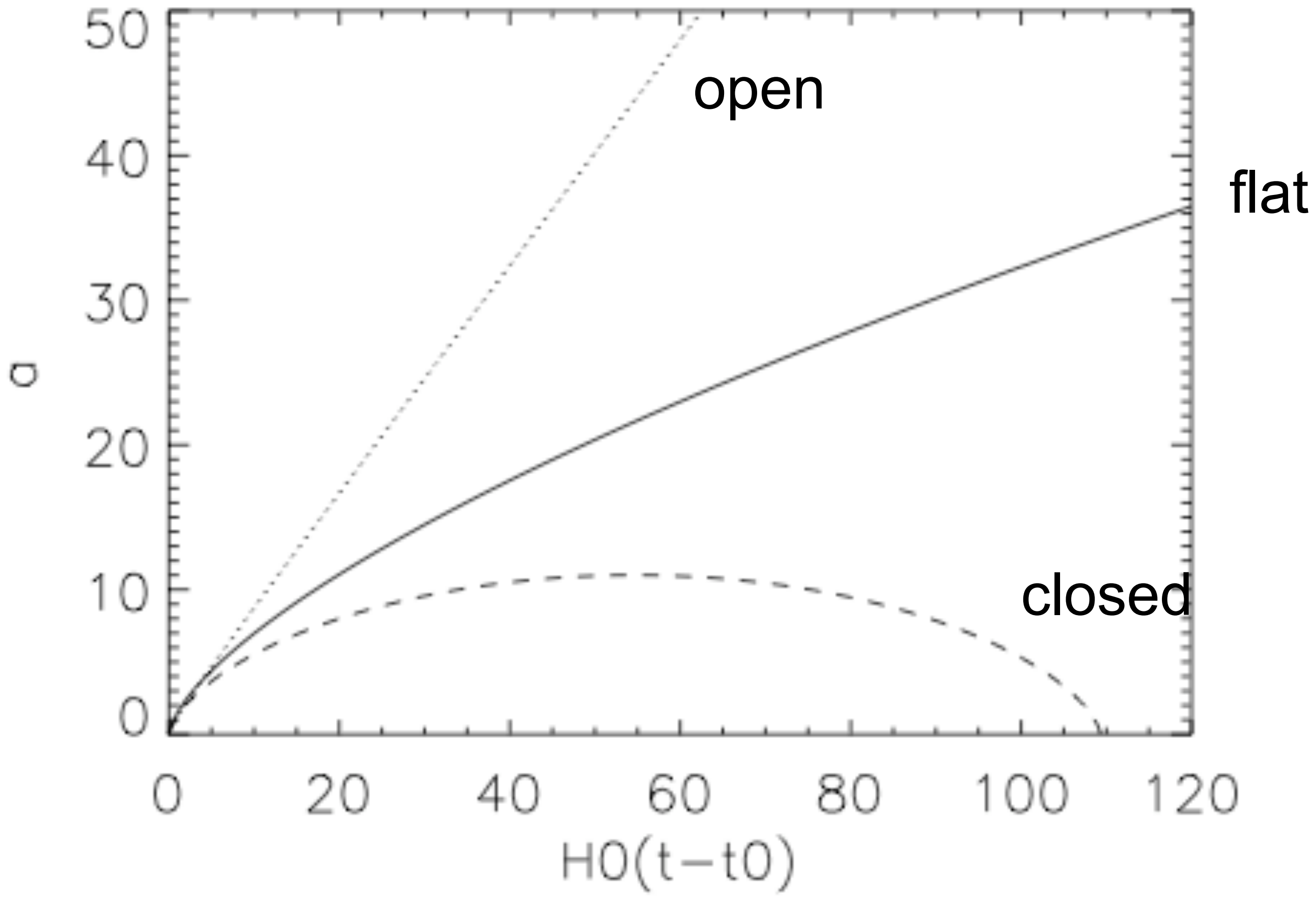
$$\rho_{c,0} = \frac{3H_0^2}{8\pi G} \qquad \Omega = \frac{\rho_{tot}}{\rho_c}$$

$$\frac{H(t)^2}{H_0^2} = \frac{8\pi G}{3c^2}\frac{\epsilon}{H_0^2} - \frac{(\Omega_0 - 1)}{a^2} = \frac{\Omega_{r,0}}{a^4} + \frac{\Omega_{m,0}}{a^3} + \Omega_{\Lambda_0} + \frac{\Omega_{k,0}}{a^2}; \qquad \Omega_k = 1 - \Omega$$

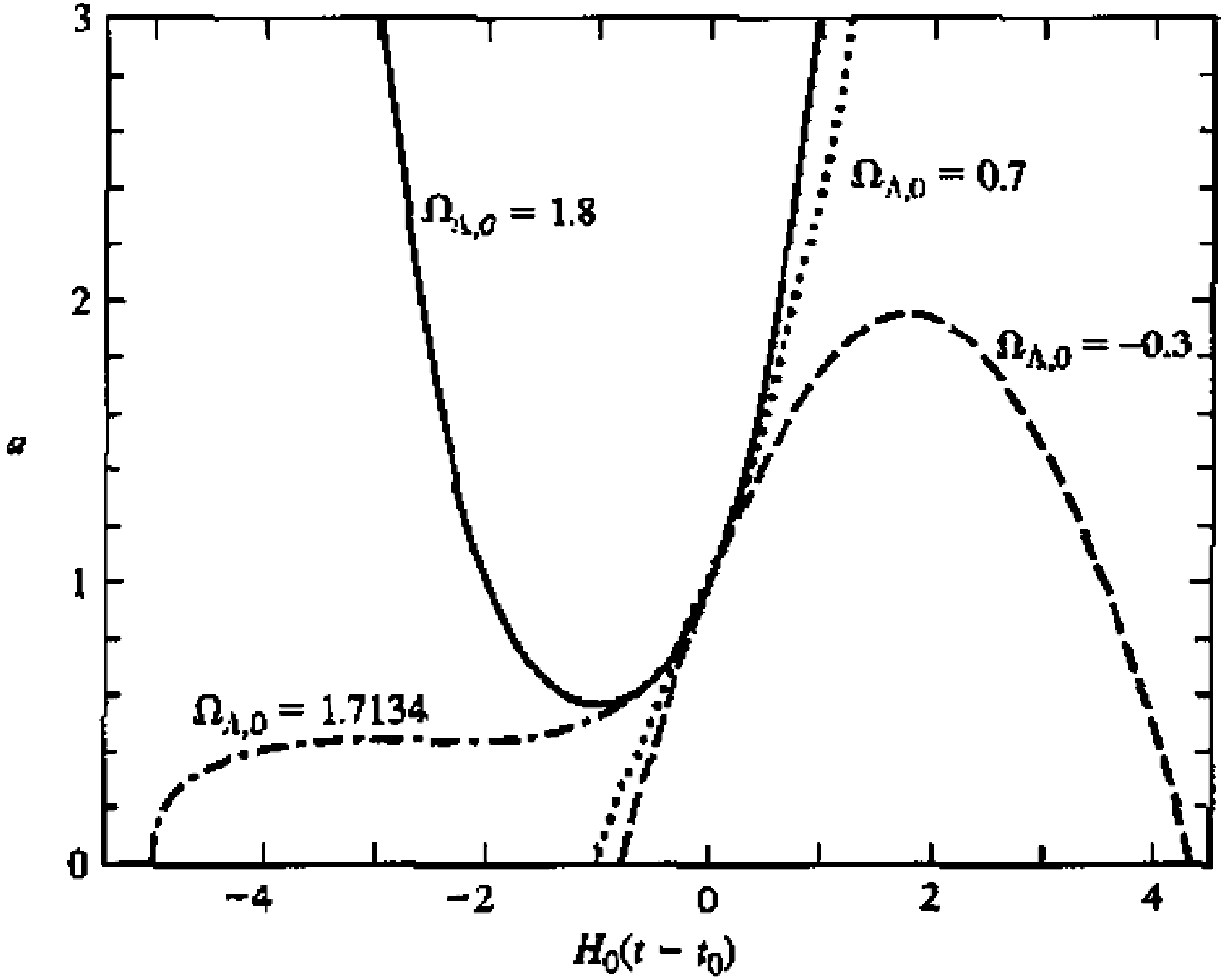
If you have a mix of components, chances are that at different times in the life of the Universe different components dominate

MATTER + CURVATURE ONLY

Density is destiny!!

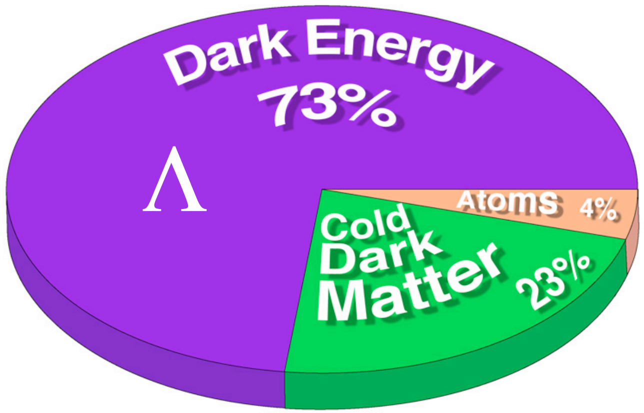


A ZOO OF POSSIBILITIES…..

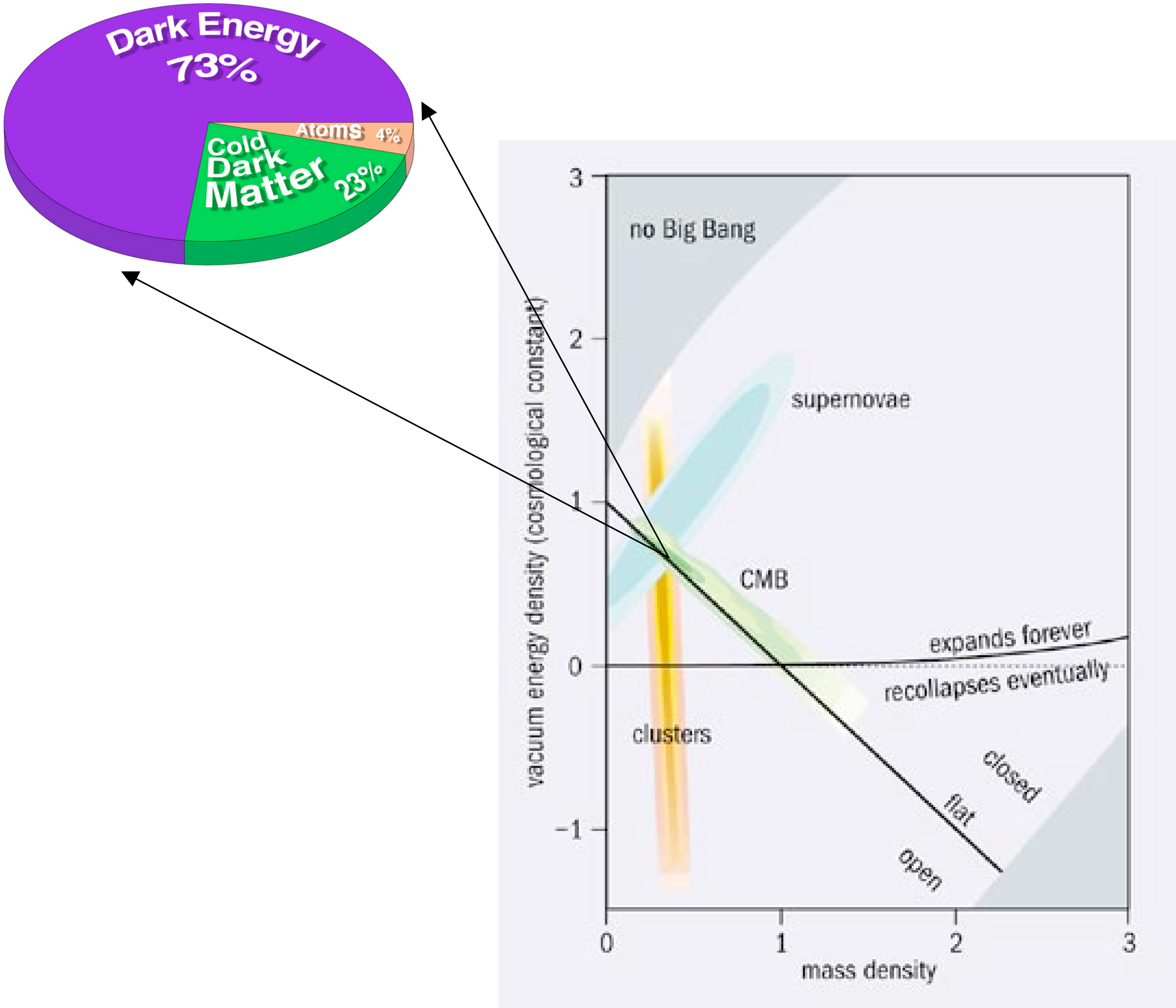


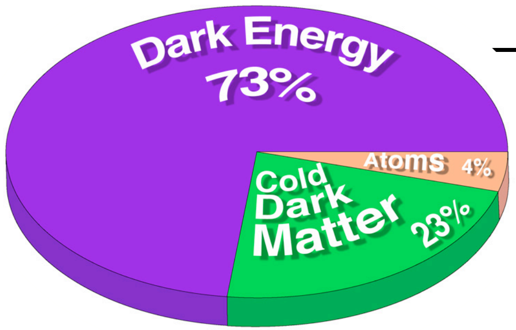
Make such a plot for yourself. PS try www.icosmo.org

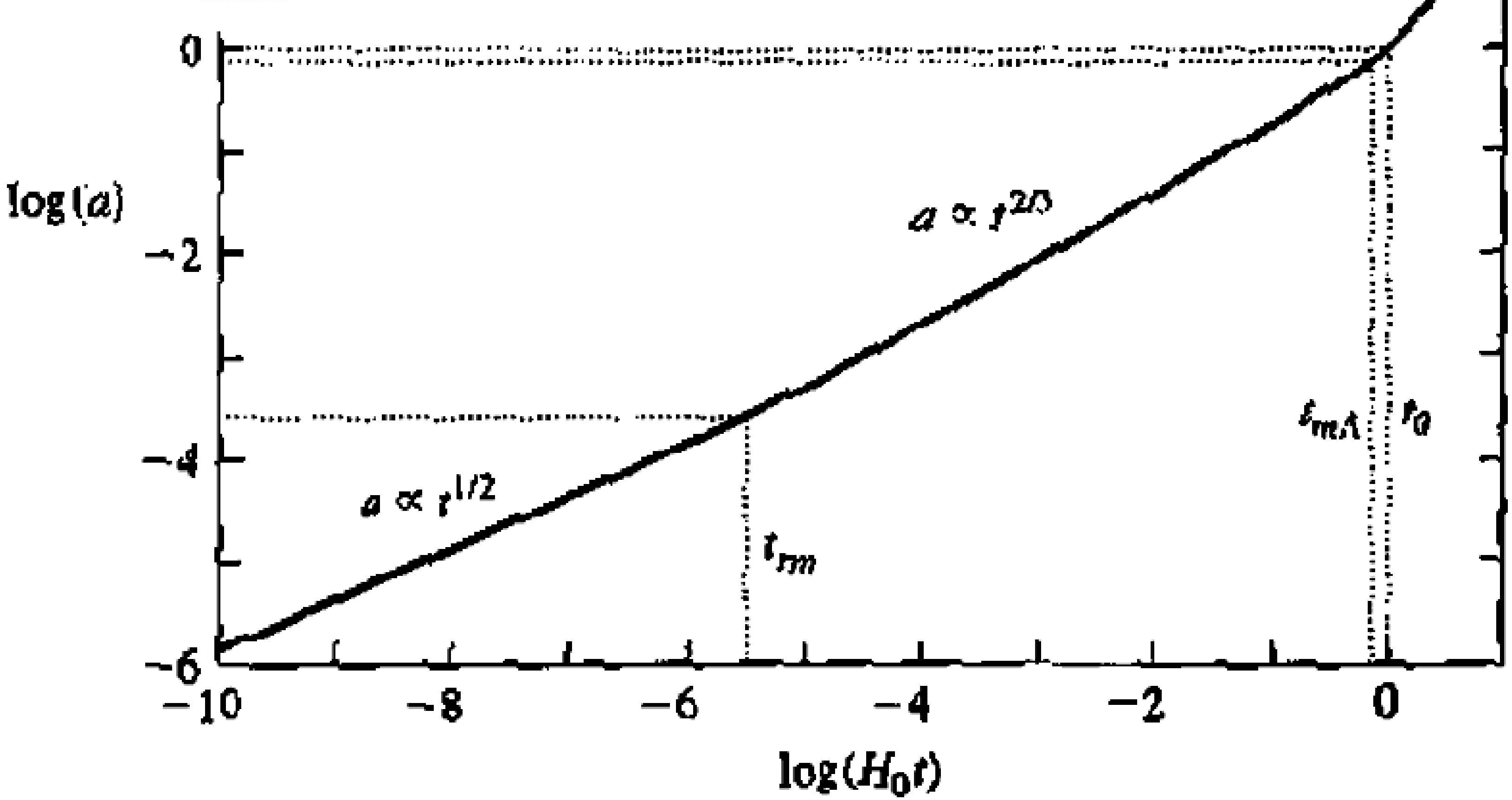
Composition of the Universe



Radiation…

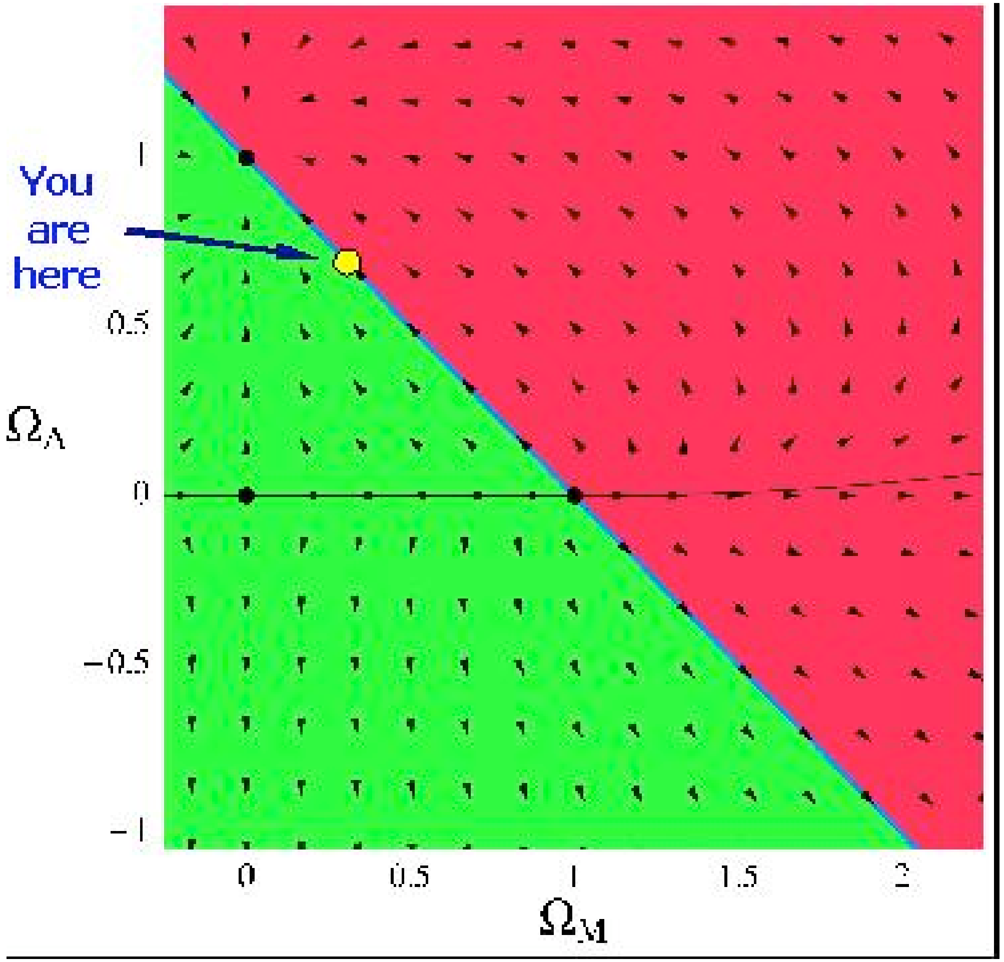

Dark Energy
73%
Atoms 4%
Cold
Dark
Matter
23%
no Big Bang
supernovae
CMB
expands forever
recollapses eventually
clusters
closed
flat
open
vacuum energy density (cosmological constant)
mass density
3
2
1
0
−1
0
1
2
3





Exercise: derive approximate curve analytically
PS assume one component universe at every epoch

Evolution….



Exercise: take a point in this plot and show that the arrow direction is OK

This is a BIG puzzle

Distances, for completeness

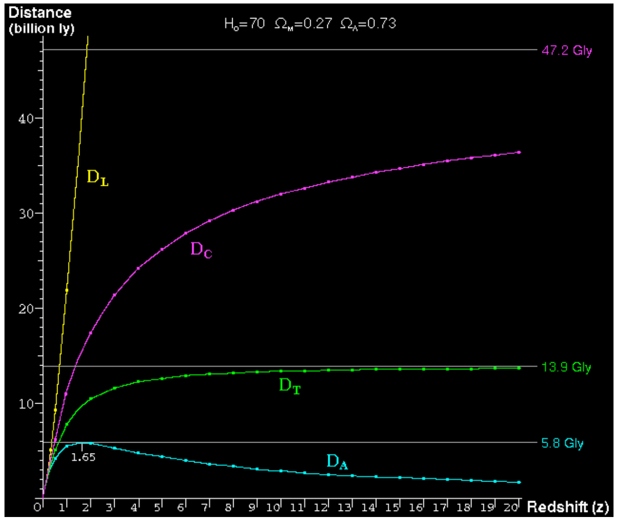
Luminosity distance: In an expanding universe, distant galaxies are much dimmer than you would normally expect because the photons of light become stretched and spread out over a wide area.

Angular diameter distance: In an expanding universe, we see distant galaxies when they were much younger and much closer to us

Comoving Distance is the opposite of the Angular Diameter Distance - it tells us where galaxies are now rather than where they were when they emitted the light that we now see

The Light Travel Time Distance represents the time taken for the light from distant galaxies to reach us

For small distances all four distance scales converge and become the same



Distances in useful format

$$1 + z = \frac{a(t_0)}{a(t)}$$

$$\frac{dz}{da} = -\frac{a_0}{a^2}$$

$$d_c = \int_{t_e}^{t_o} \frac{a_0}{a} dt$$

$$\frac{H(z)}{H_0} = E(z) = \left(\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right)^{\frac{1}{2}}.$$

$$\begin{aligned} \frac{dz}{E(z)} &= -\frac{da\, a_0}{a(t)^2} \frac{1}{E(z)} \\ &= -\frac{da\, a_0}{a(t)^2} \frac{a(t)}{\dot{a}(t)} H_0 \\ &= -\frac{a_0}{a(t)} H_0\, dt. \end{aligned}$$

Comoving, line-of-sight distance

$$d_c = D_c = D_H \int_0^z \frac{dz'}{E(z)}$$

$$D_H = \frac{c}{H_0}.$$

Comoving transverse distance

$$D_M = \begin{cases} D_H \frac{1}{\sqrt{\Omega_k}} \sinh\left[\sqrt{\Omega_k}\, D_C / D_H\right] & \text{for } \Omega_k > 0 \\ D_C & \text{for } \Omega_k = 0 \\ D_H \frac{1}{\sqrt{|\Omega_k|}} \sin\left[\sqrt{|\Omega_k|}\, D_C / D_H\right] & \text{for } \Omega_k < 0 \end{cases}$$

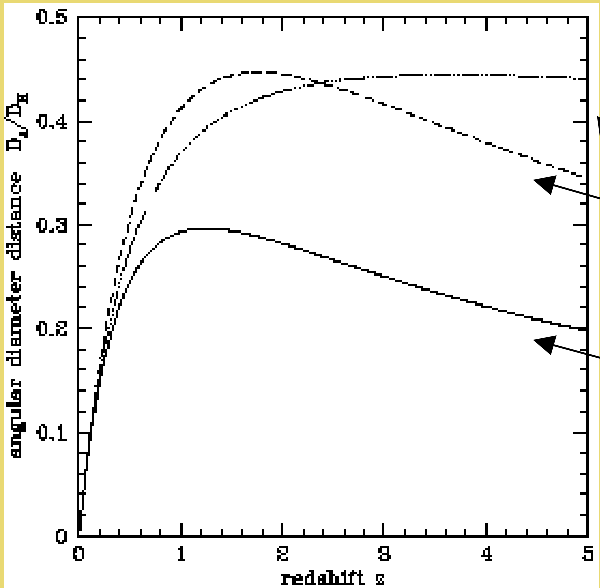
$$D_M = D_H \frac{2\left[2 - \Omega_M (1-z) - (2 - \Omega_M)\sqrt{1 + \Omega_M z}\right]}{\Omega_M^2 (1+z)} \quad \text{for } \Omega_\Lambda = 0$$

Distances, useful format

Angular diameter distance $$D_A = \frac{D_M}{(1+z)}$$

Warning: not additive!

$$D_{A12} = \frac{1}{1+z_2}\left[D_{M2}\sqrt{1+\Omega_k\frac{D_{M1}^2}{D_H^2}} - D_{M1}\sqrt{1+\Omega_k\frac{D_{M2}^2}{D_H^2}}\right]$$



$\Omega_m = 0.2; \quad \Omega_\Lambda = 0.8$

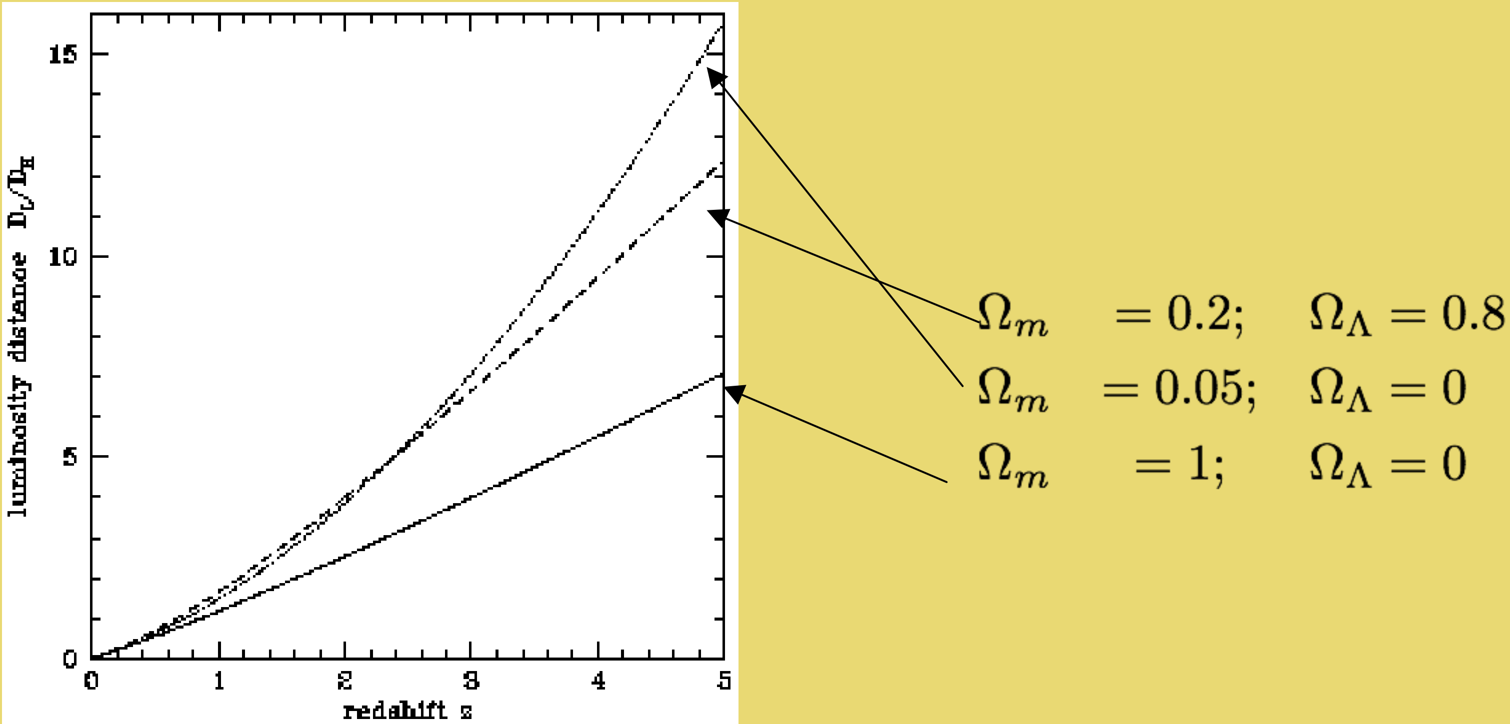
$\Omega_m = 0.05; \quad \Omega_\Lambda = 0$

$\Omega_m = 1; \quad \Omega_\Lambda = 0$

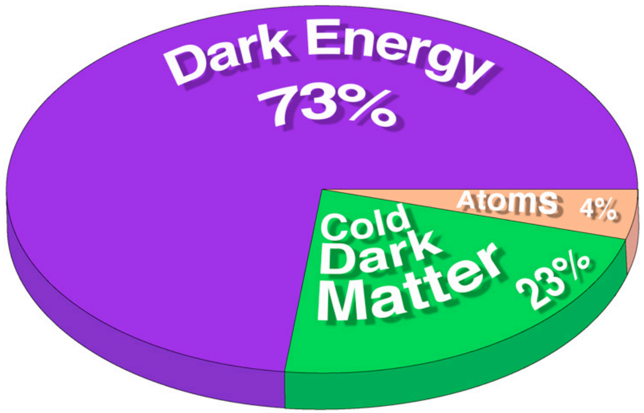
http://arxiv.org/pdf/astro-ph/9905116v4 http://www.icosmo.org/

Distances, useful format

Luminosity distance $$D_L = (1+z)D_M = (1+z)^2 D_A$$



Composition of the Universe



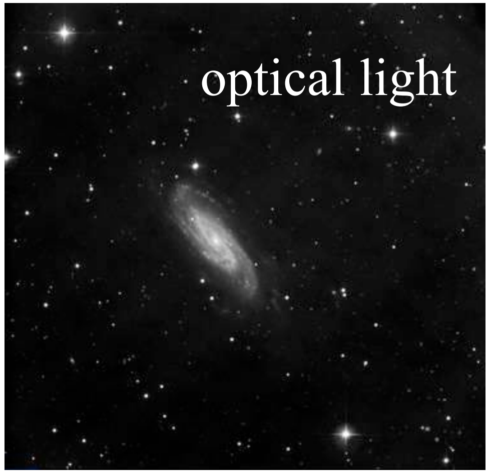
Radiation…

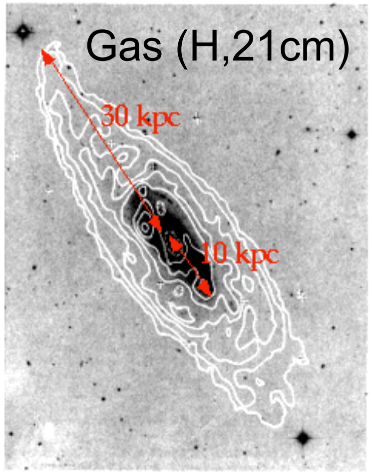
There is more than meets the eye

In the solar system sun + planets

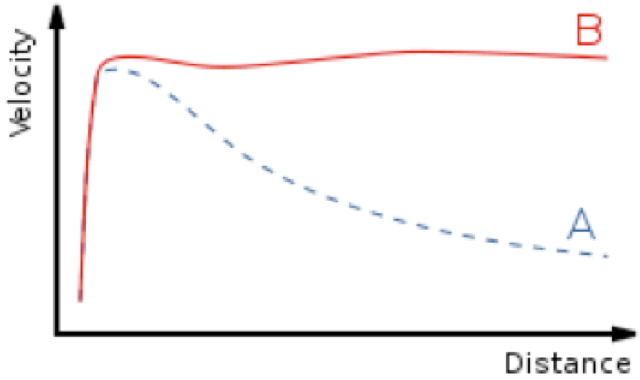
Mass-to-light ratio

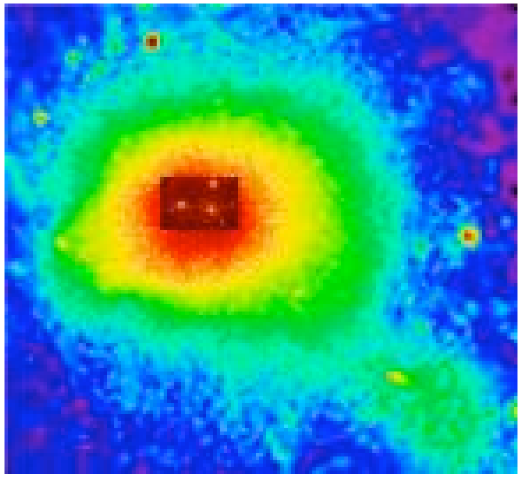
Let's consider galaxies





rotating





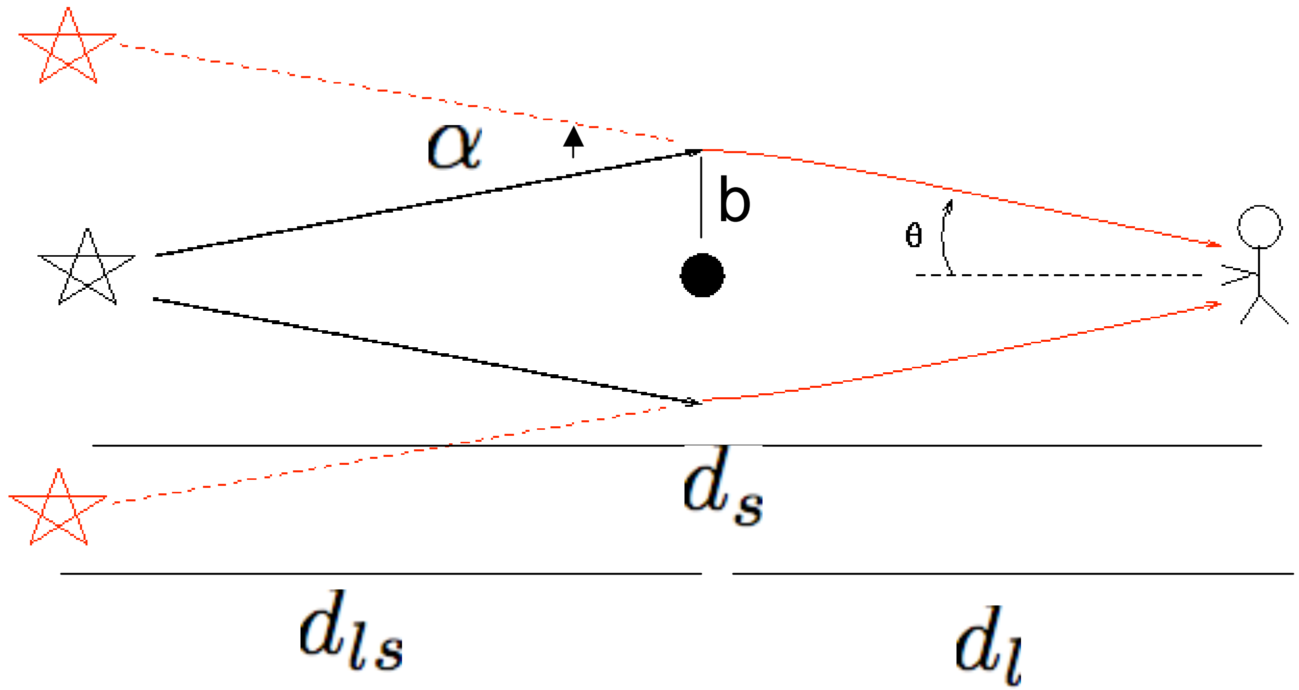
And clusters: Xrays

$$K.E. \sim \frac{3}{2}kT = \frac{3}{2}m_H\sigma_v^2$$

$$T \sim 6\times10^7 K; \lambda \sim \frac{c}{\nu} = \frac{ch}{KT}$$

Gravitational lensing

Gravitational lensing

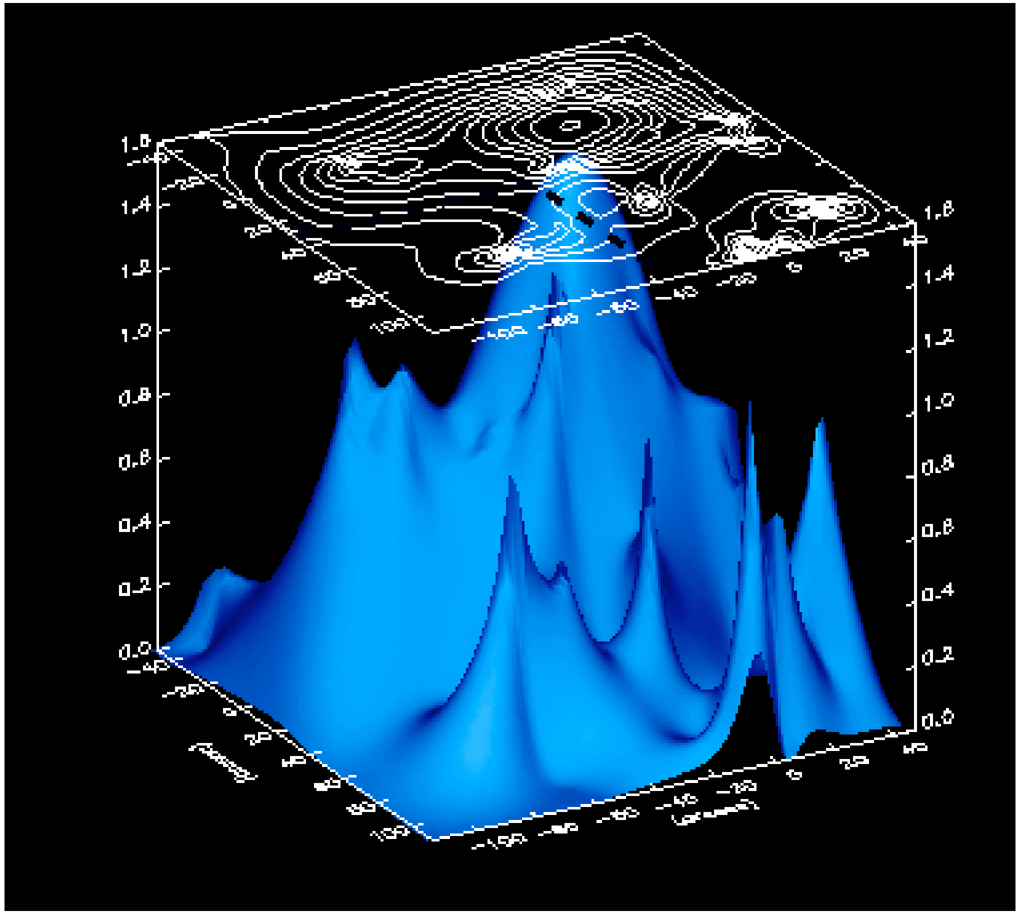


$$\alpha = \frac{4GM}{bc^2}$$

$$\begin{aligned} d_s\theta &= d_{ls}\alpha \\ b &= \theta d_l \\ \theta^2 &= \frac{4GM}{d_l c^2}\frac{d_{ls}}{d_s} \end{aligned}$$

HA!

Reconstructed dark matter distribution of cluster Abell 2218

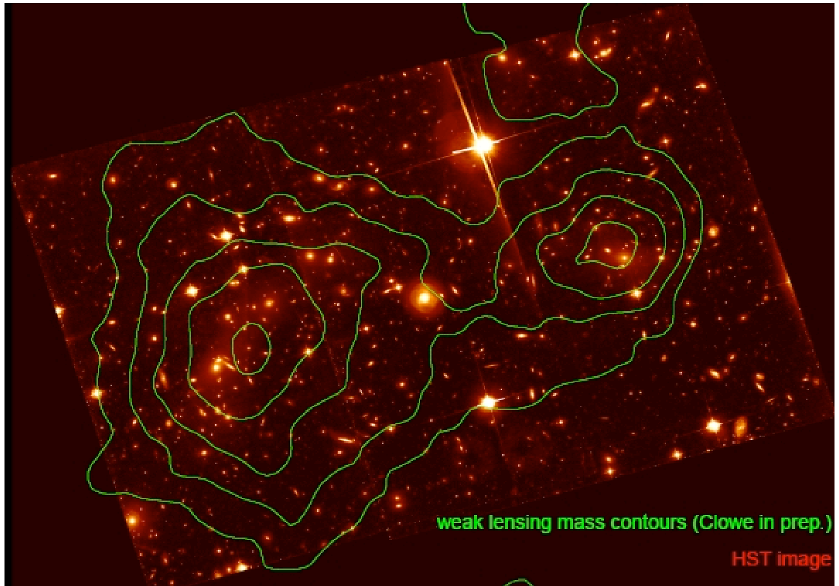


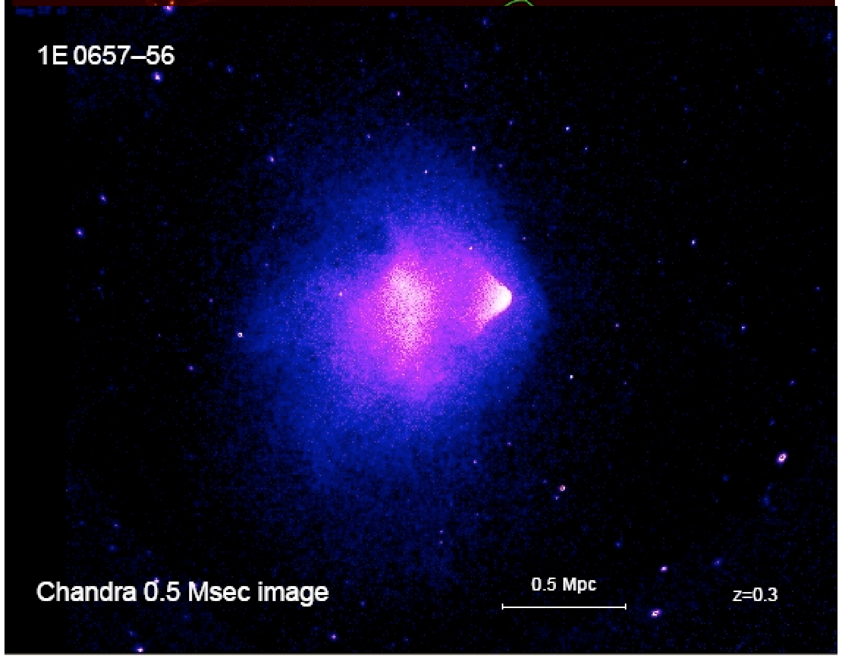
Abell 2218

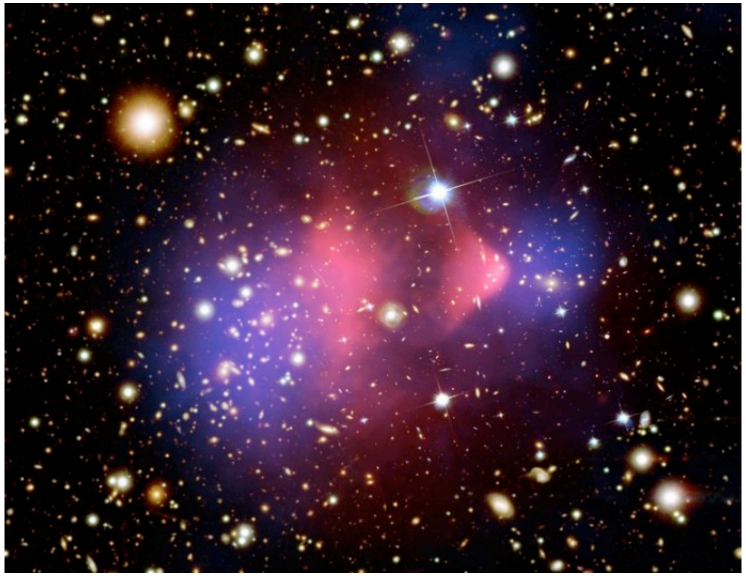
New evidence

REAL DATA!

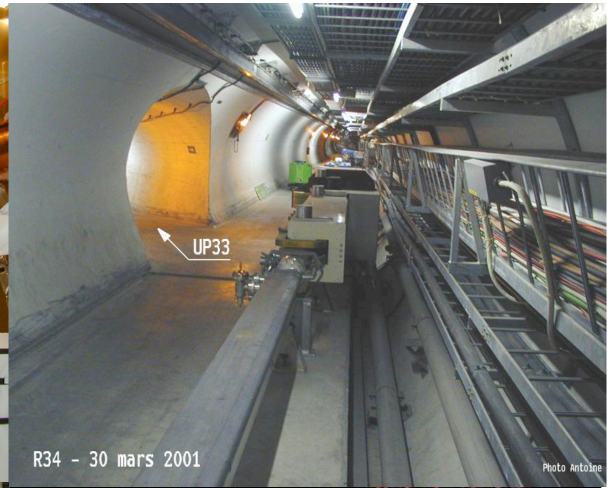
Bullet cluster

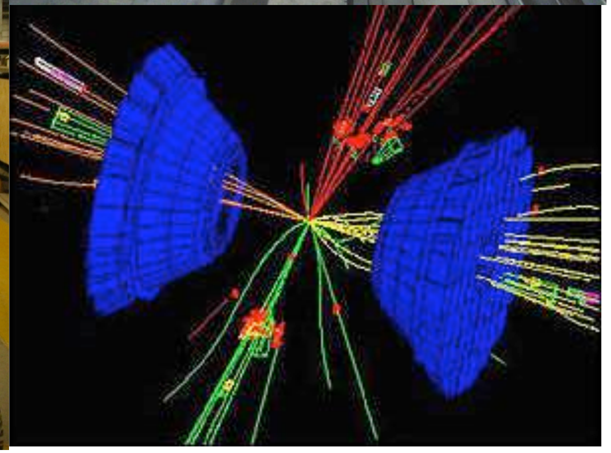


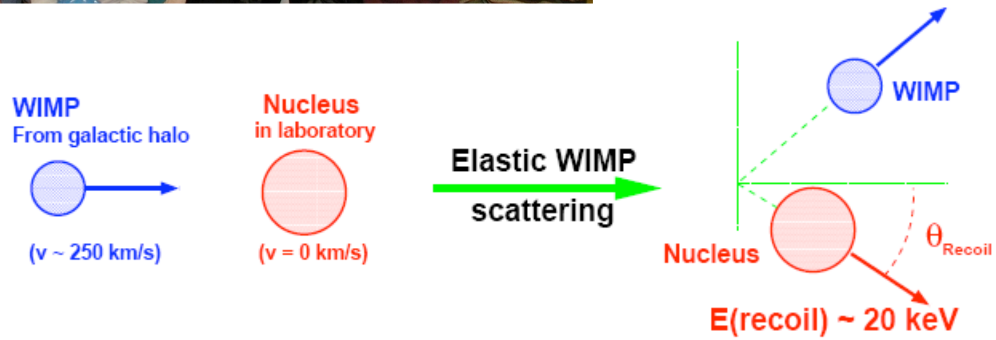




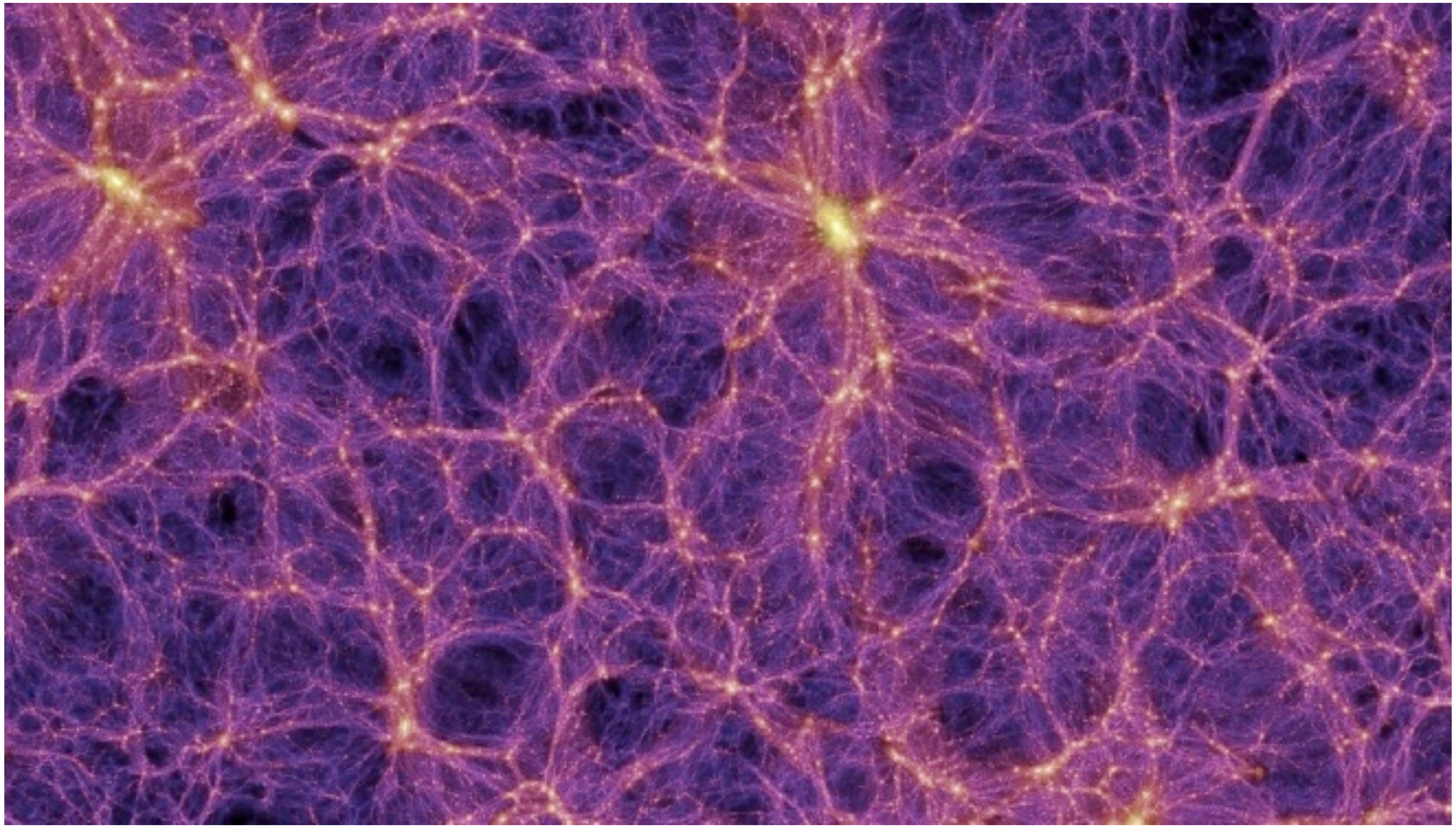
DIY dark matter

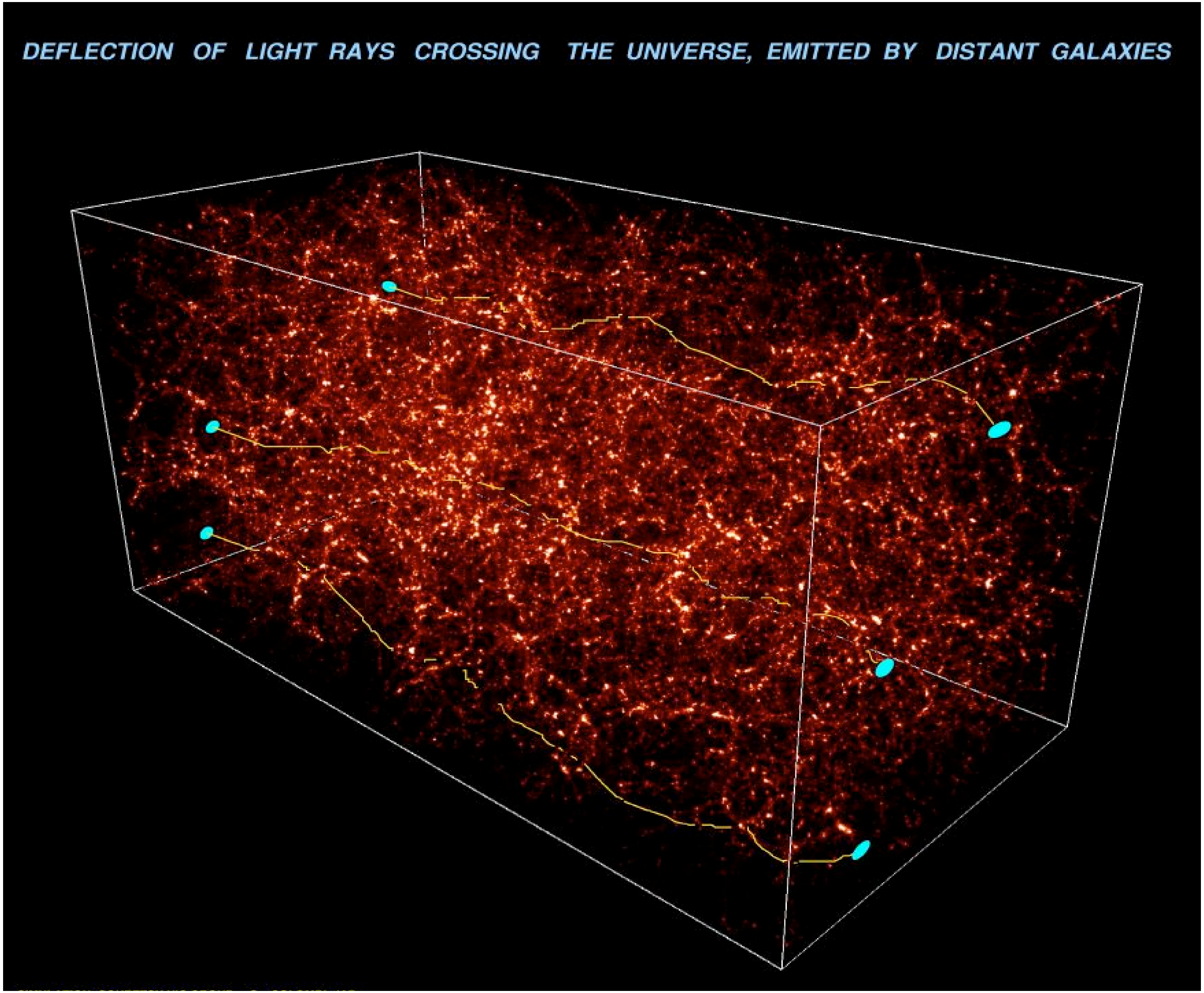




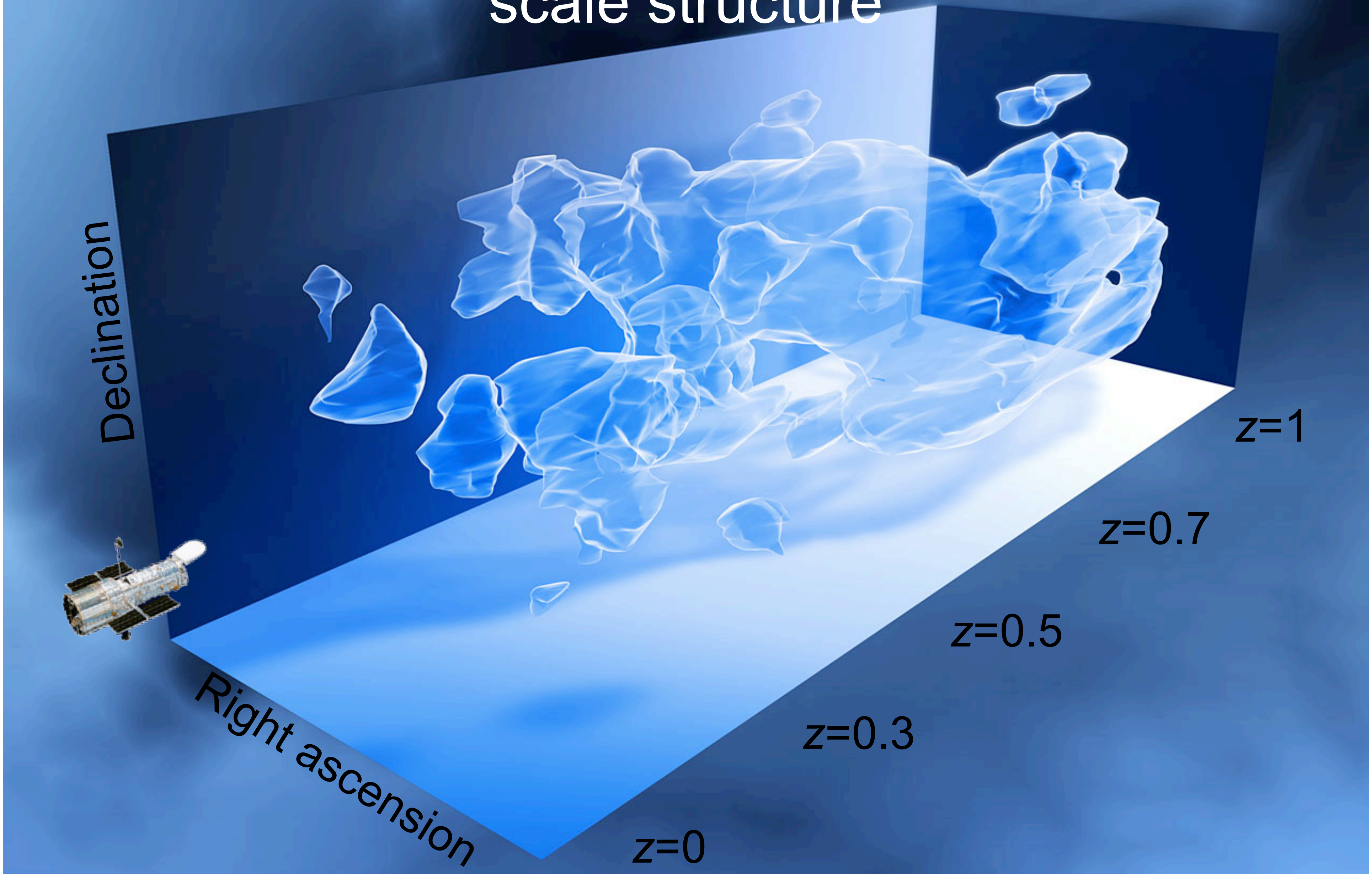


Computer simulation of dark matter distribution




DEFLECTION OF LIGHT RAYS CROSSING THE UNIVERSE, EMITTED BY DISTANT GALAXIES

Weak lensing reconstruction of dark matter large-scale structure



NASA, ESA and R. Massey (California Institute of Technology)

It gets worst!

- The universe is undergoing an accelerated expansion

- It may not have been the first time

Key concepts today

The expansion of the Universe
Hubble's Law
Redshift
Geometry
FRW metric
Universe composition and background evolution

Take a good look at: http://arxiv.org/pdf/astro-ph/9905116v4
Play with icosmo