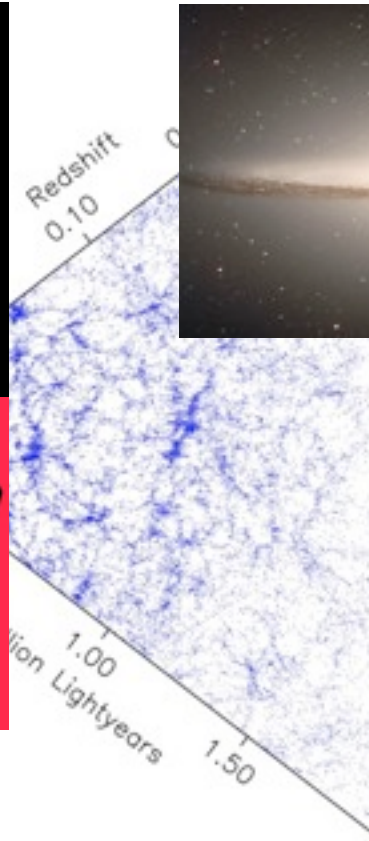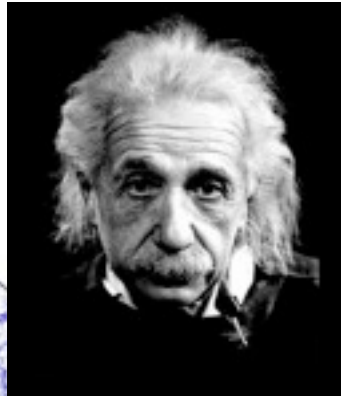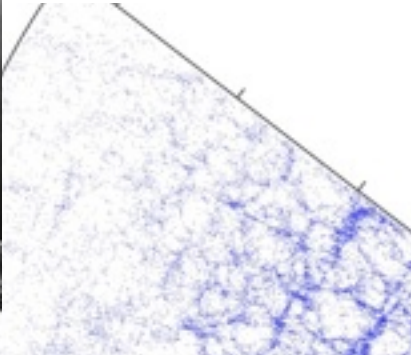# Introduction to Cosmology:
Lifestyles in an Expanding Universe

Brian Fields
University of Illinois
TALENT Summer School in Nuclear Astrophysics
MSU/NSCL | June 2, 2014

Syllabus: Part I

★ **Cosmology Primer**

▶ **evidence for an expanding universe**

▶ **life in an expanding universe**

▶ **dynamics of an expanding universe**

★ **The Cosmic Microwave Background (CMB)**

★ **Cosmic Acceleration**

Cosmology 101

Cosmology

Structure, Origin, Evolution of the Universe

⭐ **today: stars organized into galaxies**

⭐ **ex: Solar Sytem is part of Milky Way**

Typical galaxy: 100 billion stars

Andromeda galaxy

Sombrero galaxy

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galaxies are building blocks

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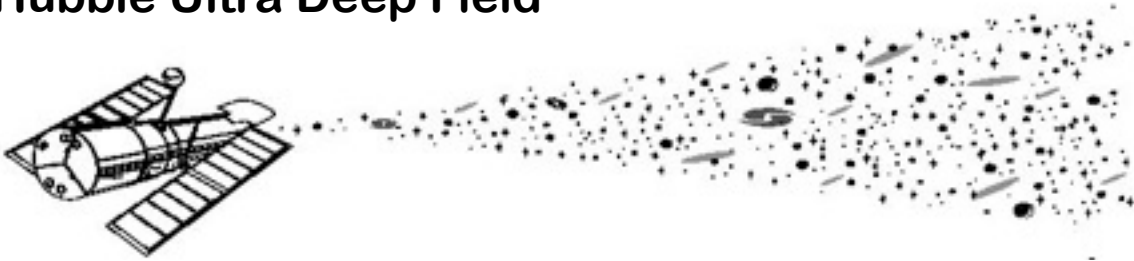⭐ **today: stars organized into galaxies**
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**far away = long ago
telescopes are time machines!**
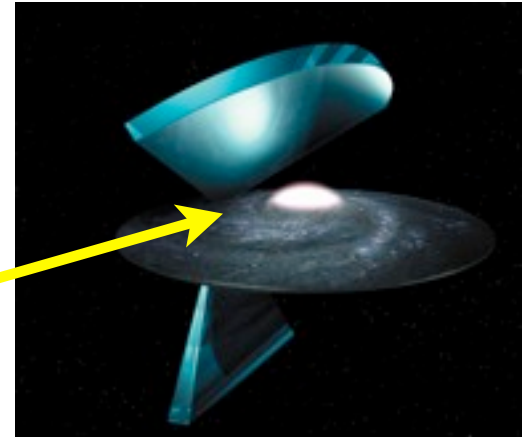
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Cosmic Matter Distribution

**Measure cosmic structure:
map galaxies in space**

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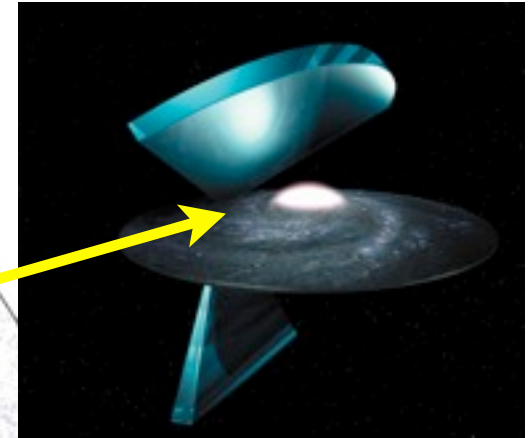
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Impressions?

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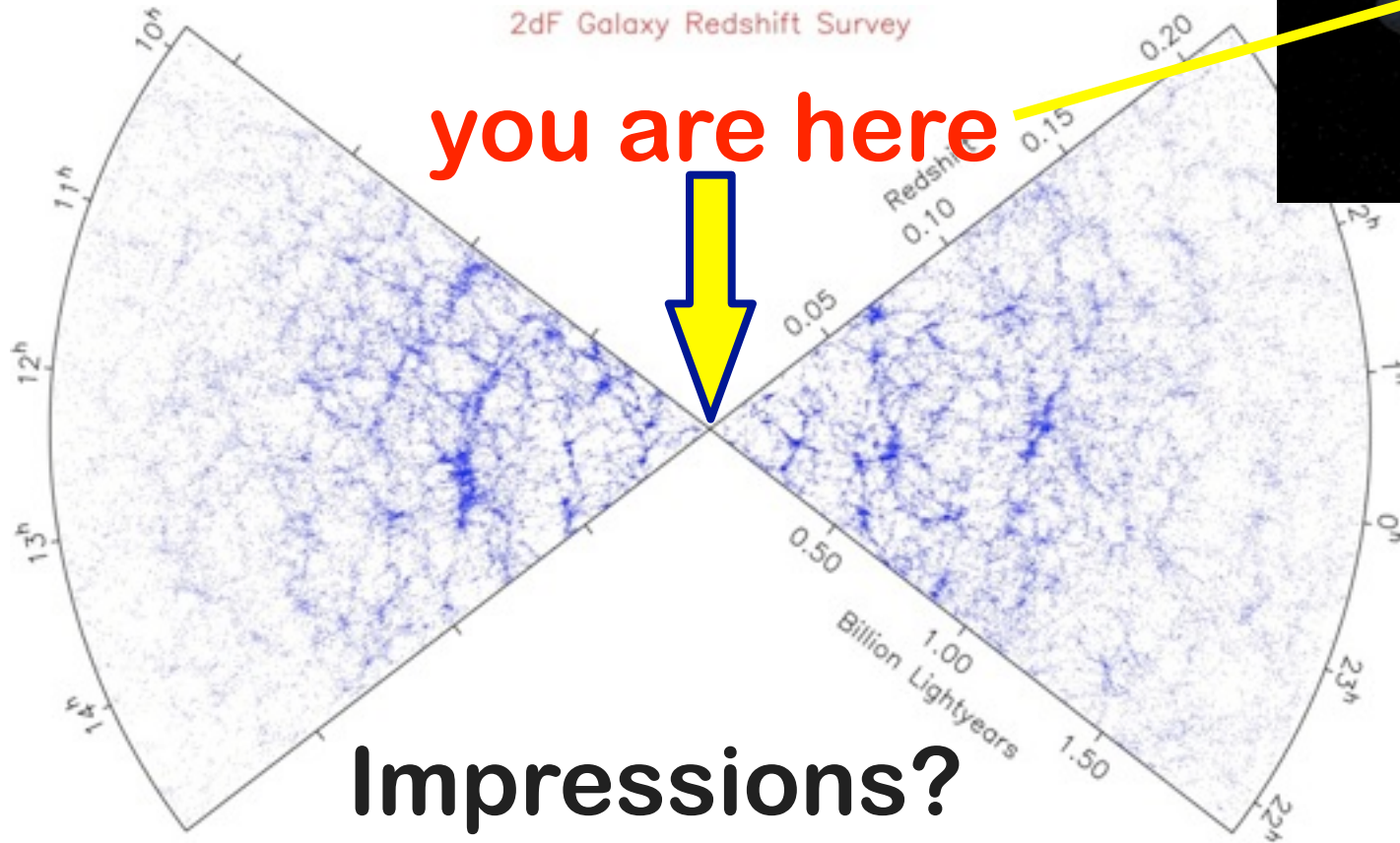
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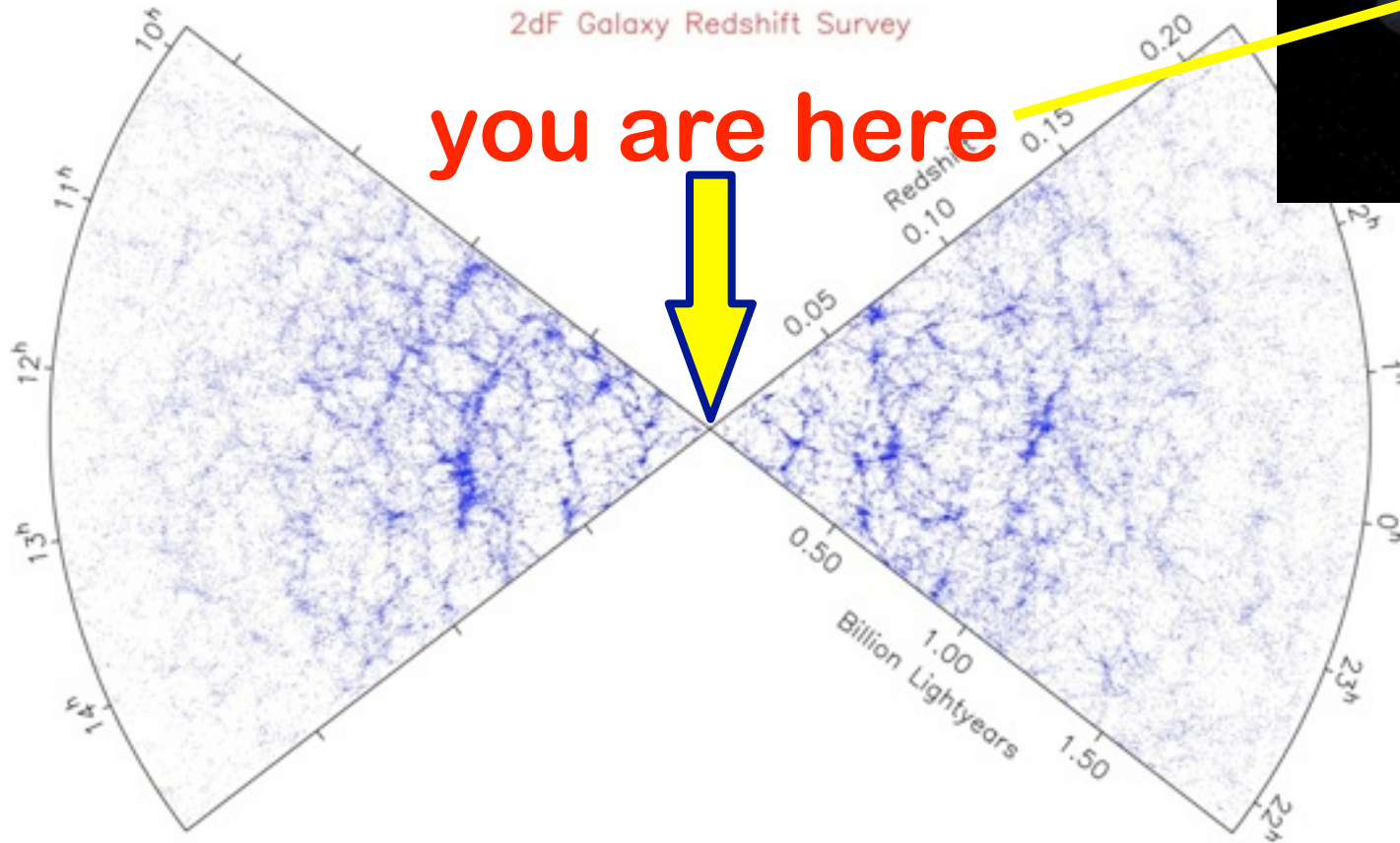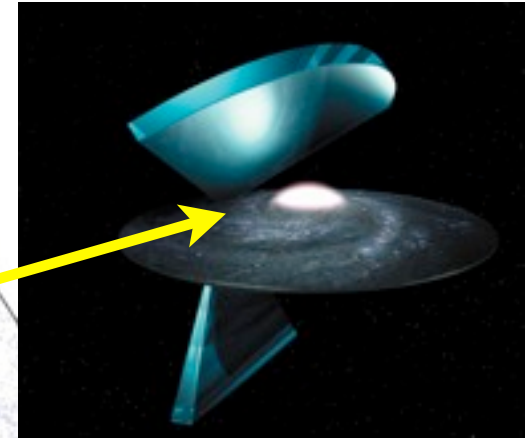
On small scales: galaxies clumpy

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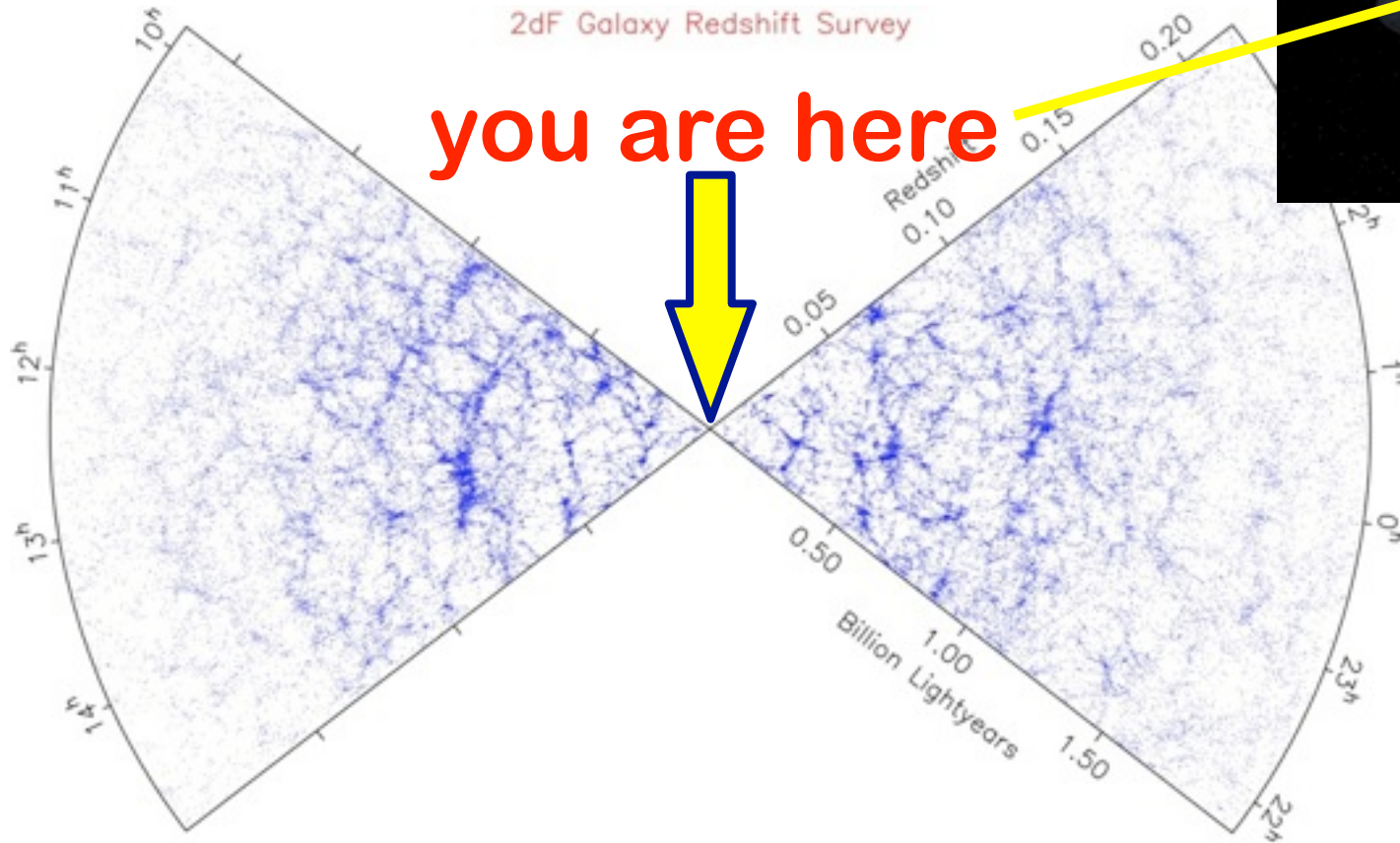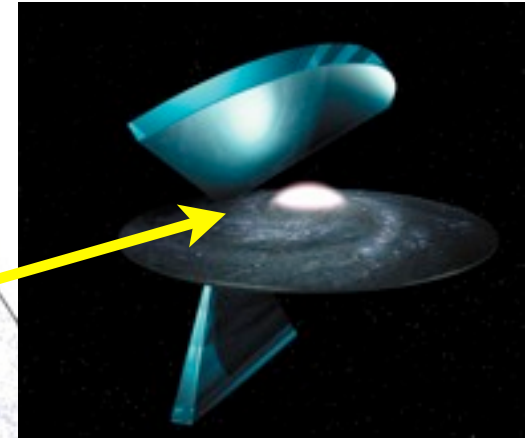
**On large scales: galaxies smoothly fill universe:
homogeneous + isotropic = "Cosmological Principle"**

Cosmic Kinematics:
Hubble's Law and its Meaning

Edwin Hubble (1929):

- measured galaxy motions, distances

- all galaxies redshifted: move away from us

- farther   faster:

- that is,

- Q: units of H? velocity pattern in space?

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**Qualitative trend?
Quantitative?**

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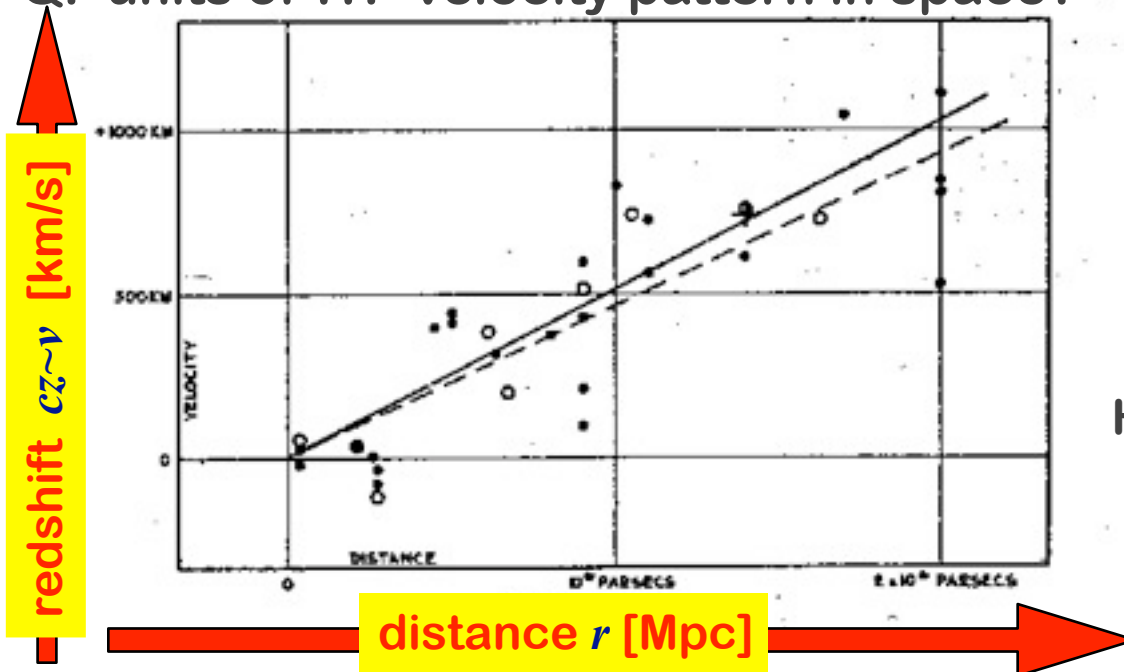

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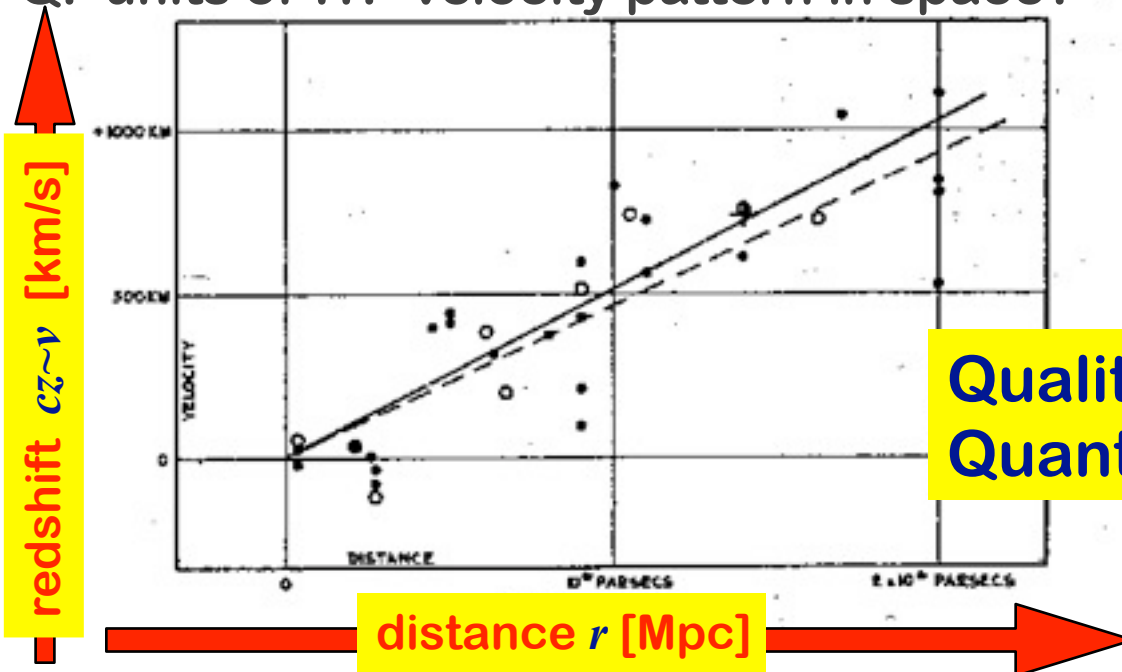
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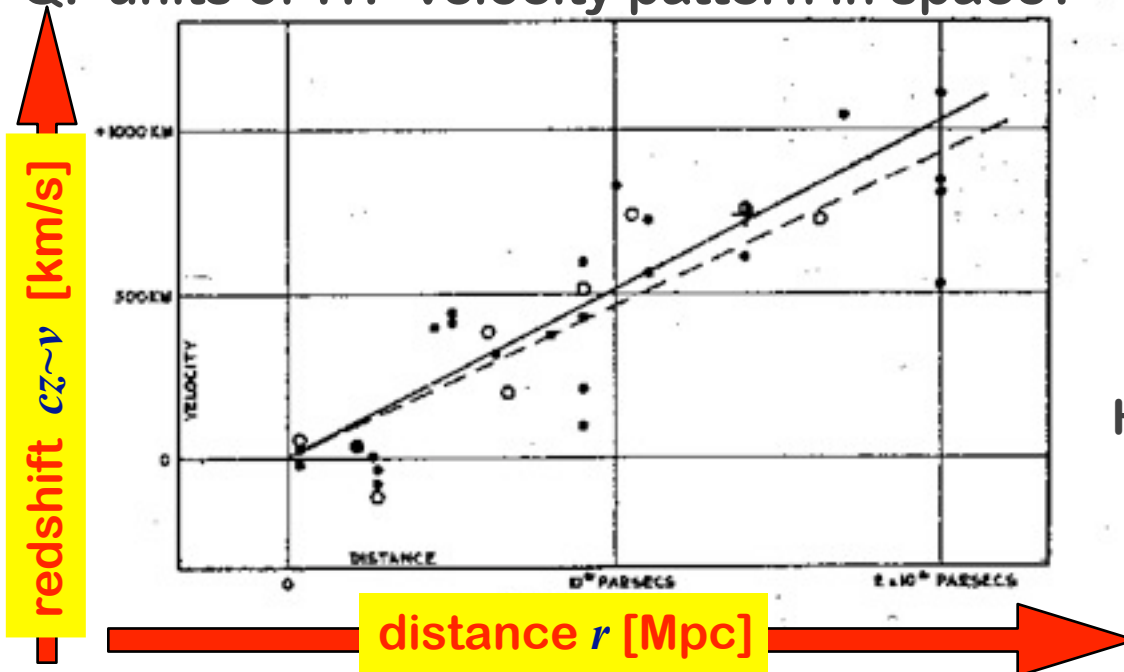redshift $cz \sim v$ [km/s]

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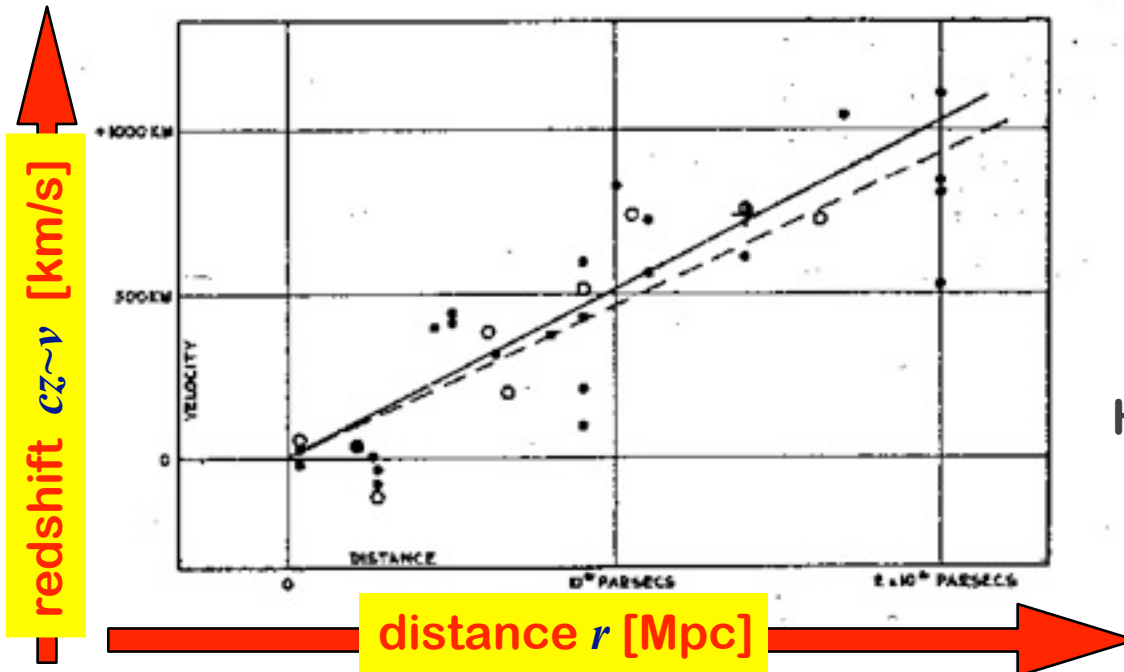
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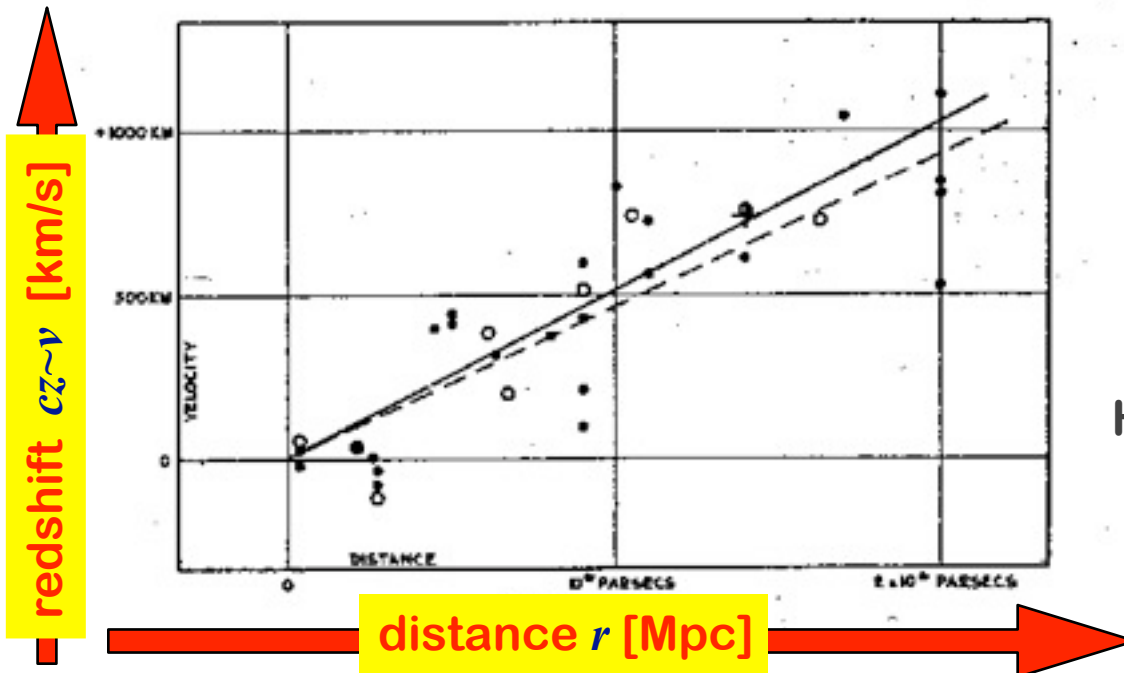redshift $cz\sim v$ [km/s]

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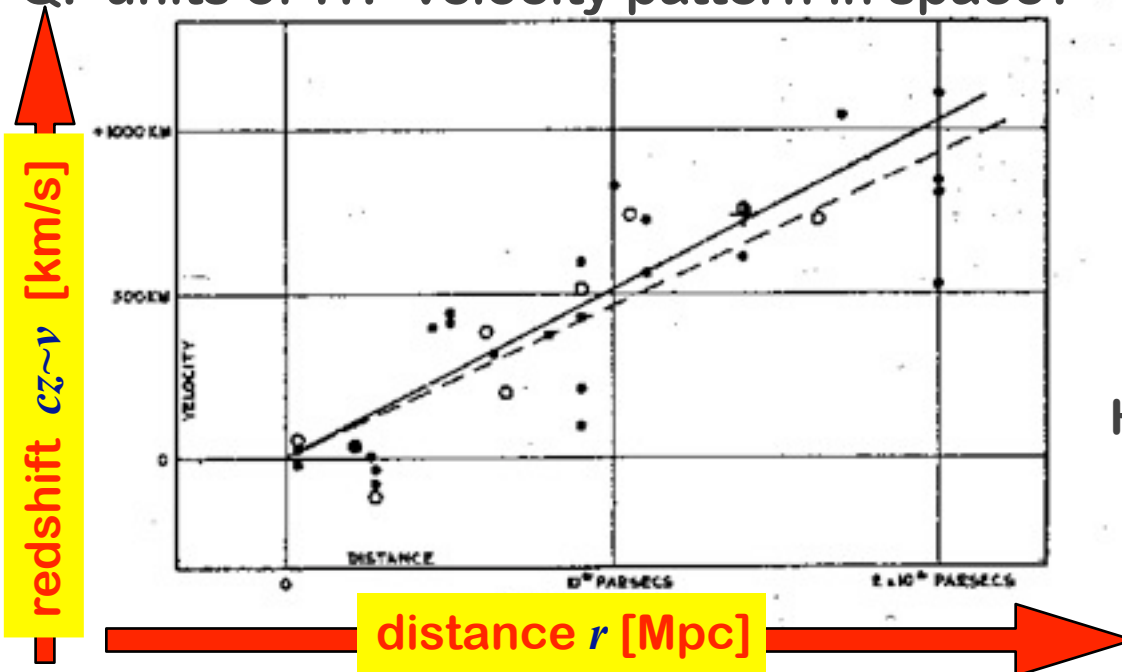GALAXY MOTION: ARTIST'S CONCEPTION

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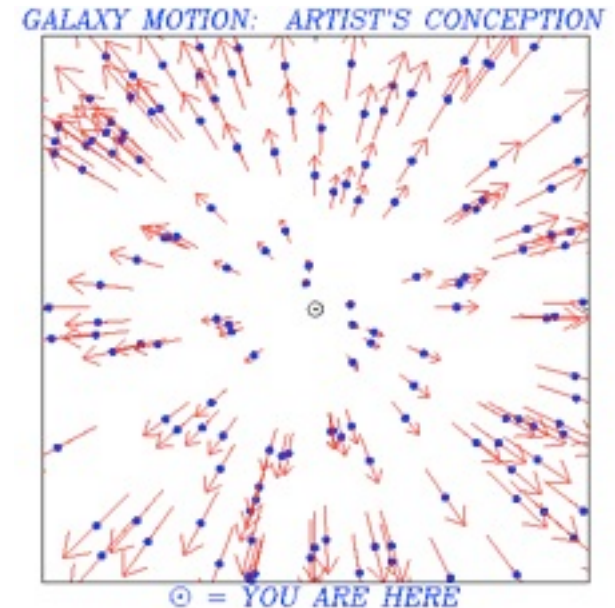
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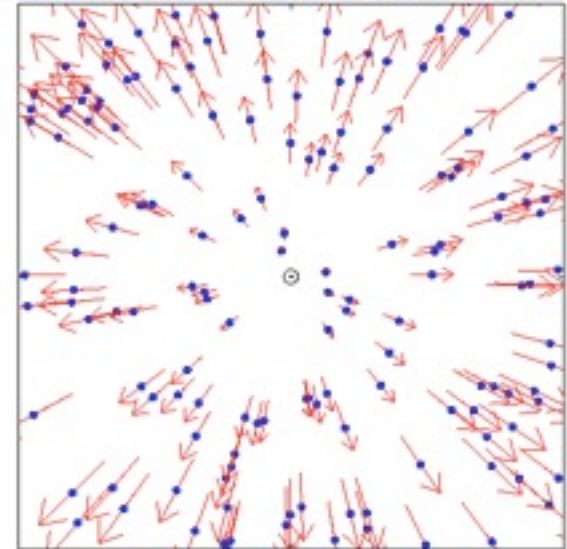
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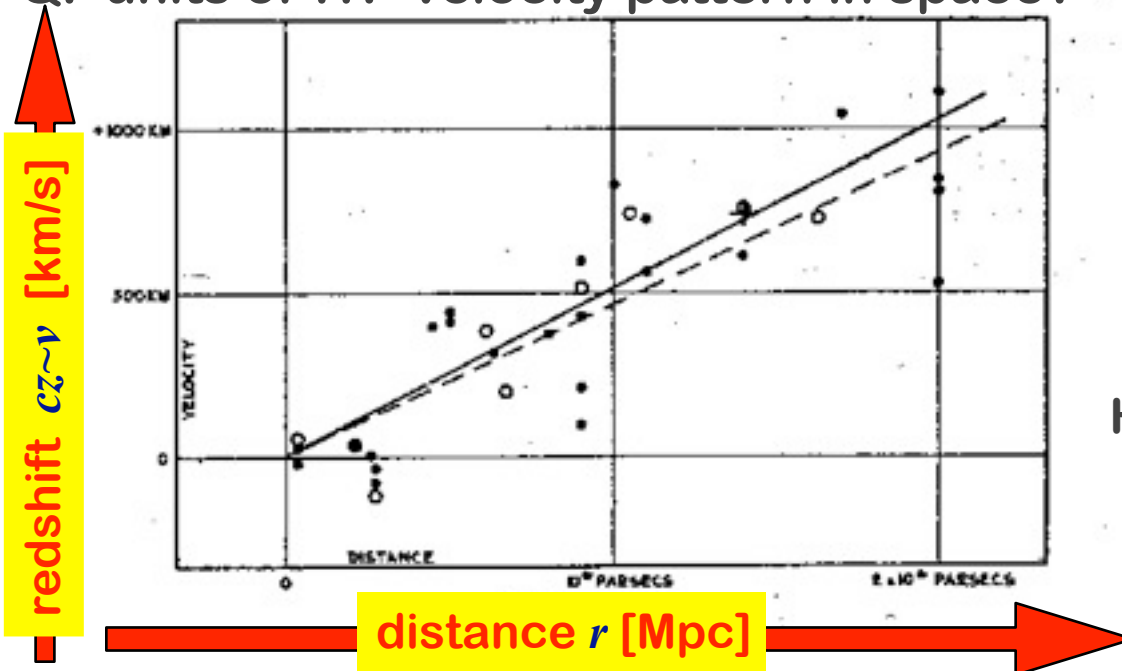
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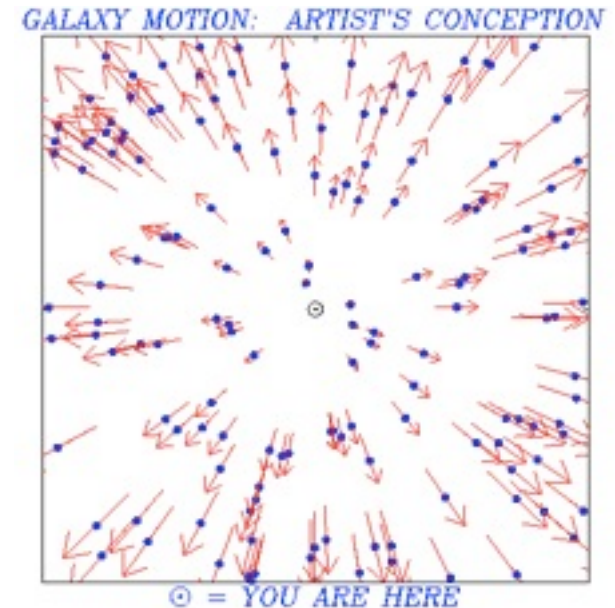
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We are at center of Universe

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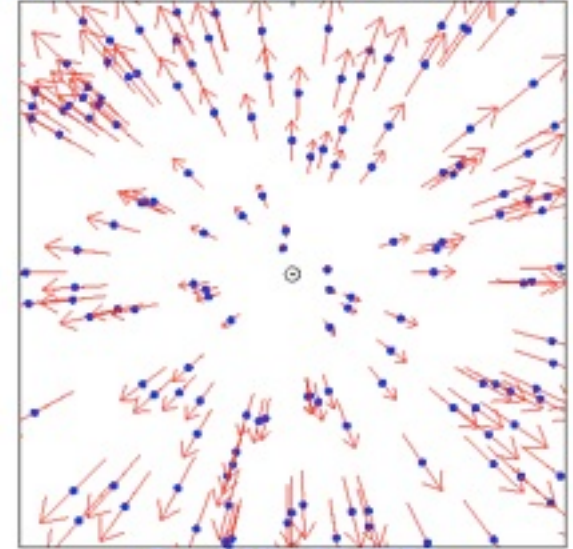GALAXY MOTION: ARTIST'S CONCEPTION
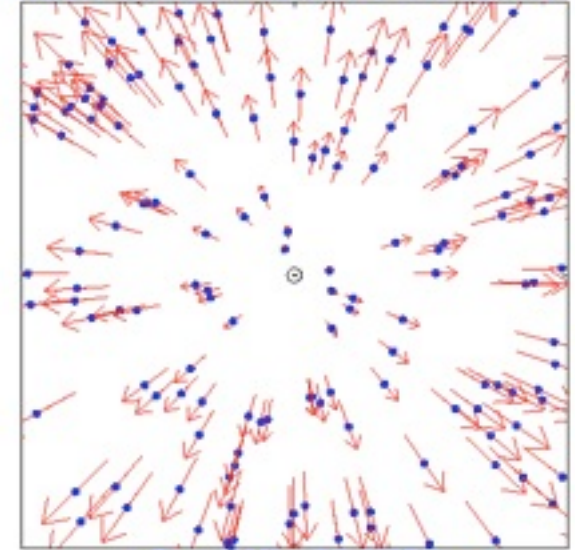
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➢ **Einstein view**

Universe is expanding! No center!
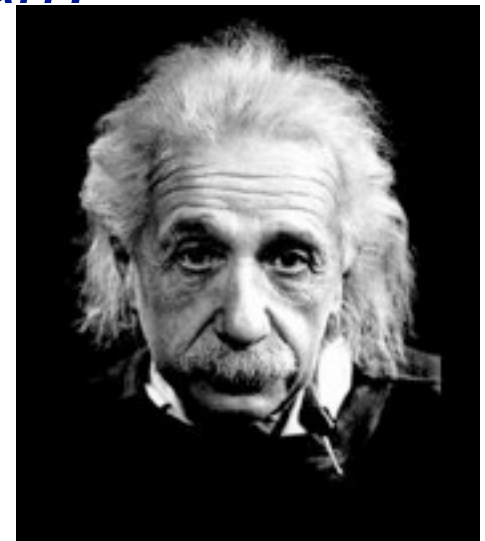
Explaining Hubble:
Kinematic Model of Milne (1933)

imagine an explosion at $t = 0$

- let galaxies all start in region of size $\ll ct_{\text{today}}$
  fly away with uniform distribution speeds v_{gal}
- but we remain at $r = 0$ until now: $t_{\text{today}} = t_0$

after explosion, let each galaxy *coast*
maintaining its initial velocity

after time $\Delta t = t_0$:

- $\vec{r}_{\text{gal}} \to \vec{v}_{\text{gal}}\, t_0$ fastest $\to$ farthest!
- so $\vec{v}_{\text{gal}} \to \vec{r}_{\text{gal}}/t_0 \equiv H_0 \vec{r}_{\text{gal}} \propto \vec{r}_{\text{gal}}$: recover Hubble's law!
- solve for cosmic age

$$t_{0,\text{Milne}} = \frac{1}{H_0}$$

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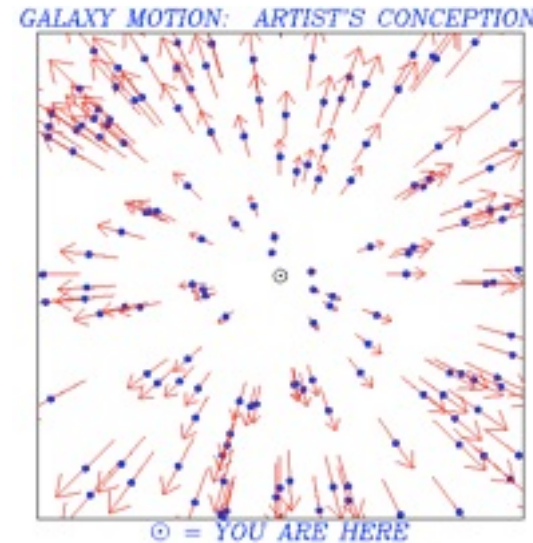
Hubble Flow: Characteristic Scales

Hubble's law today: $\vec{v} = H_0 \vec{r}$

introduces Hubble parameter $H_0 = 100 \, h$ km s^{-1} Mpc^{-1}

  with $h \approx 0.7$

Hubble time

$$t_{\mathsf{H}} \equiv \frac{1}{H_0} = 9.778 \, h^{-1} \text{ Gyr} = 13.97 \text{ Gyr} \left(\frac{0.70}{h}\right)$$

where 1 Gyr $= 10^9$ years

$\Rightarrow$ sets $\sim$ scale of "expansion age" of Universe

Hubble length

$$d_{\mathsf{H}} \equiv \frac{c}{H_0} = c t_{\mathsf{H}} = 2.998 \, h^{-1} \text{ Gpc} = 4.283 \text{ Gpc} \left(\frac{0.70}{h}\right)$$

sets $\sim$ size of *observable* Universe

Kinematic/Egoist/Explosion Model (Milne) is logically possible!

- i.e., can fit basic cosmo structure, kinematic data

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Q: give a philosophical reason why we don't believe this?

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Q: give an **observational** reason why we don't believe this?

Critiques of Cosmic Egoism

We are at the center of the universe?

Philosophically:
- not Copernican ("principle of mediocrity")

Physically:
- haven't included gravity!

Observationally:
- Milky Way, Local Group don't look special
- not what expect from center of explosion
- compare supernova → neutron star, black hole
- …yet radial v pattern makes us look special…

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Einstein & General Relativity

Einstein (1915): General Relativity:

- **spacetime warped by matter: "stretches like rubber sheet"**

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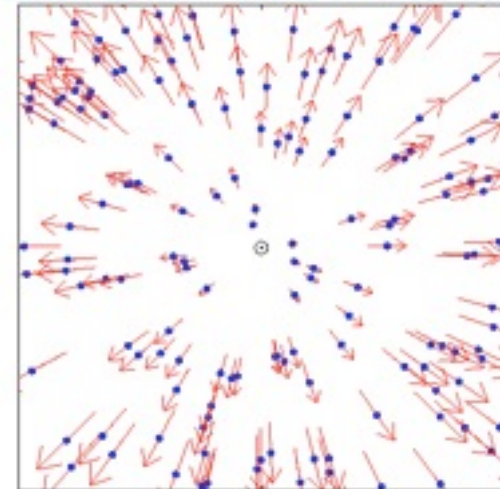## Einstein & General Relativity
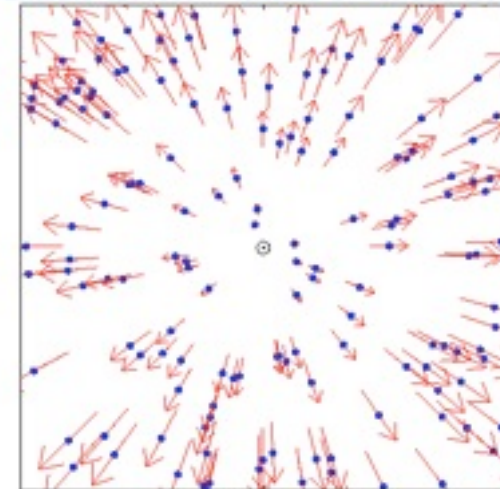
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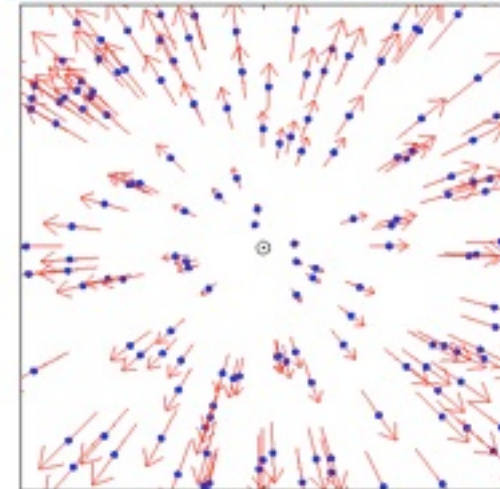
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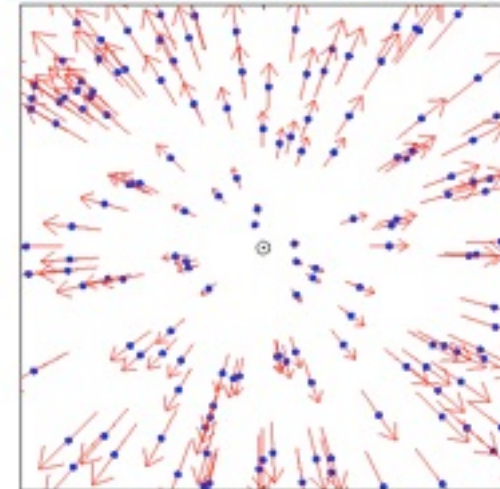
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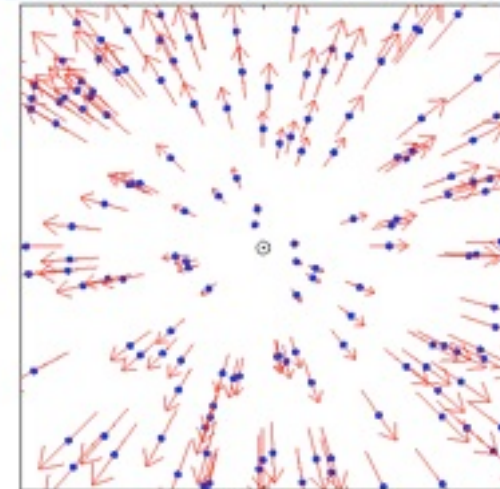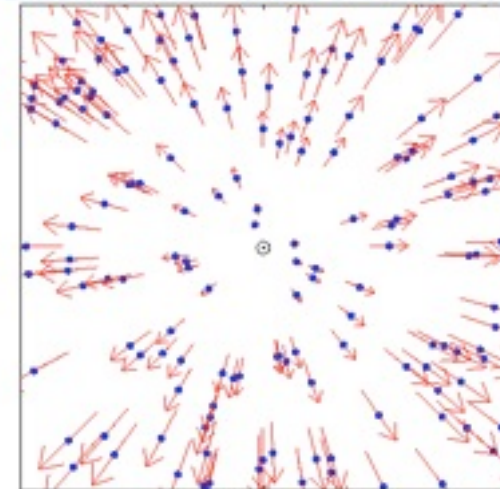
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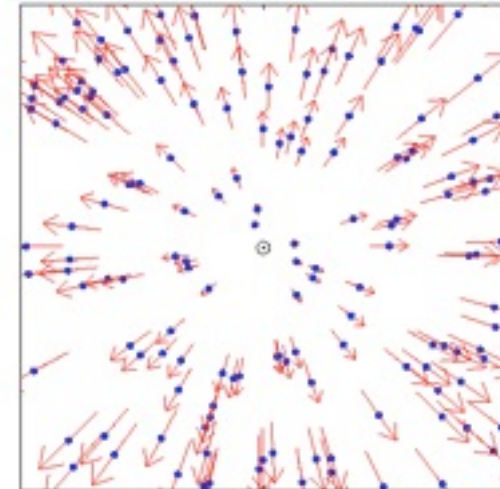- i.e., spacetime is dynamic

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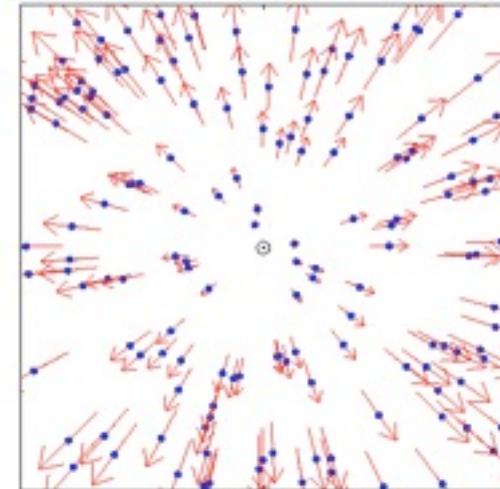
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Expansion and Dynamics
What do observers see in expanding universe?
galaxies at t
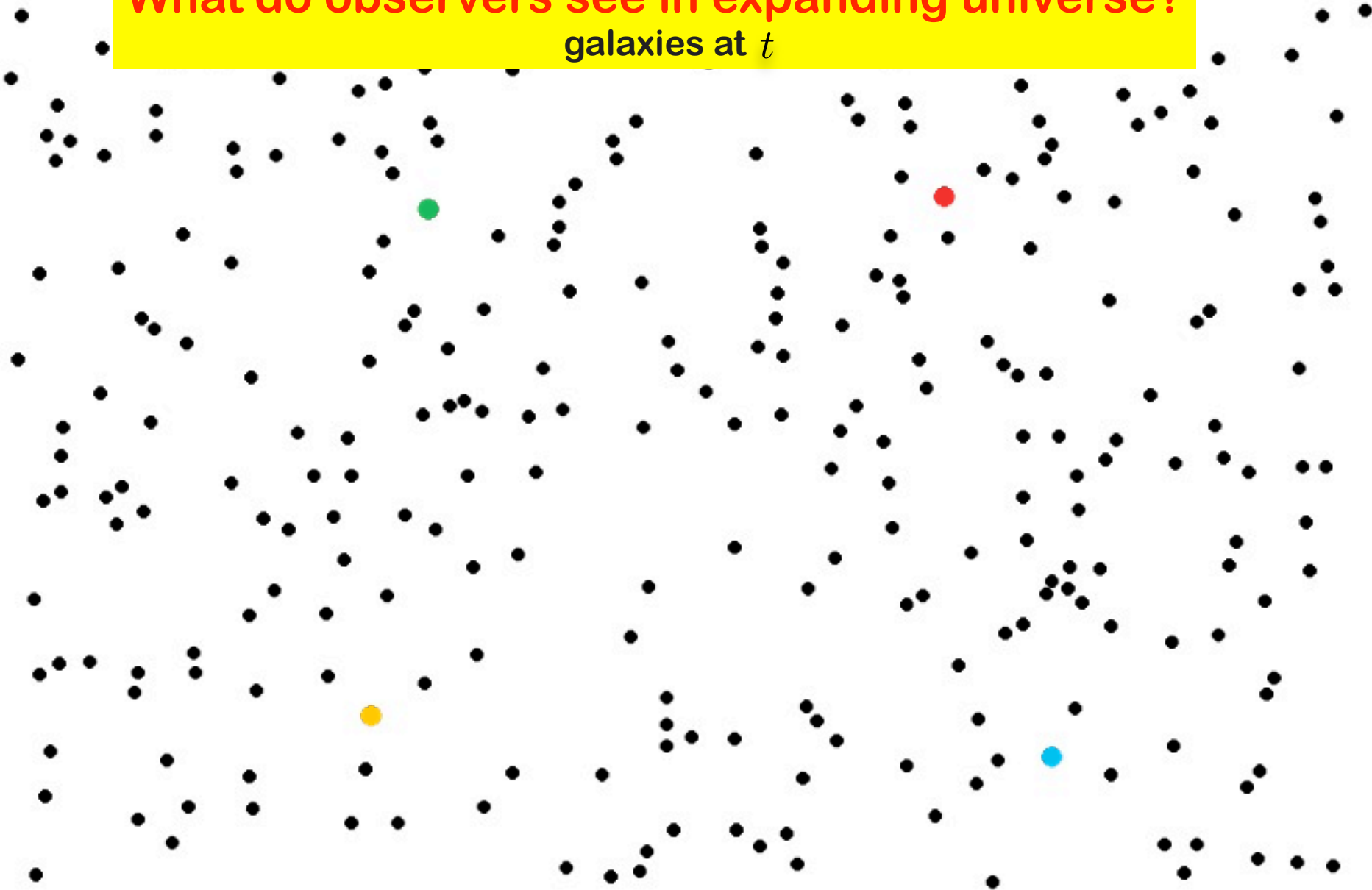
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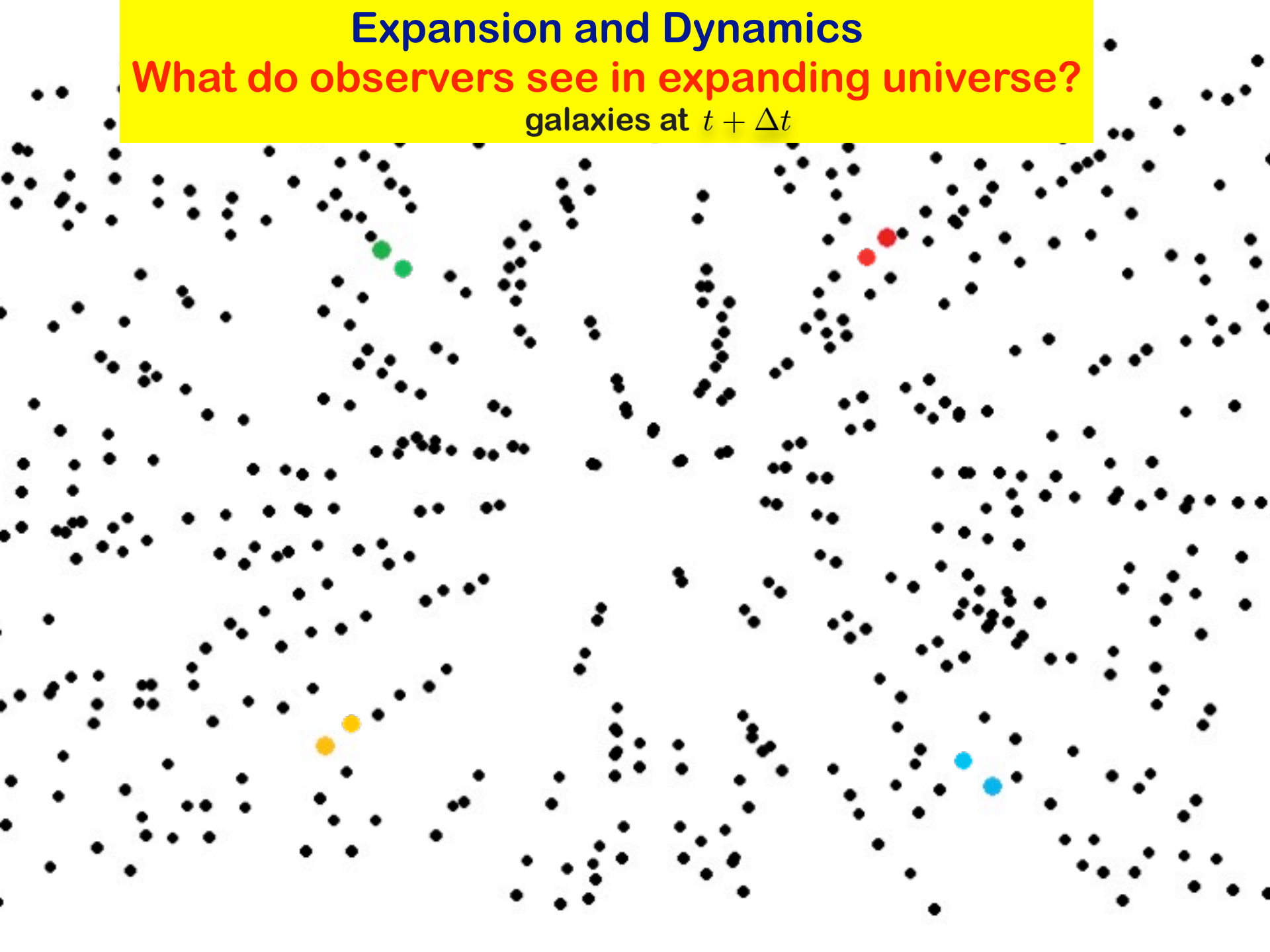
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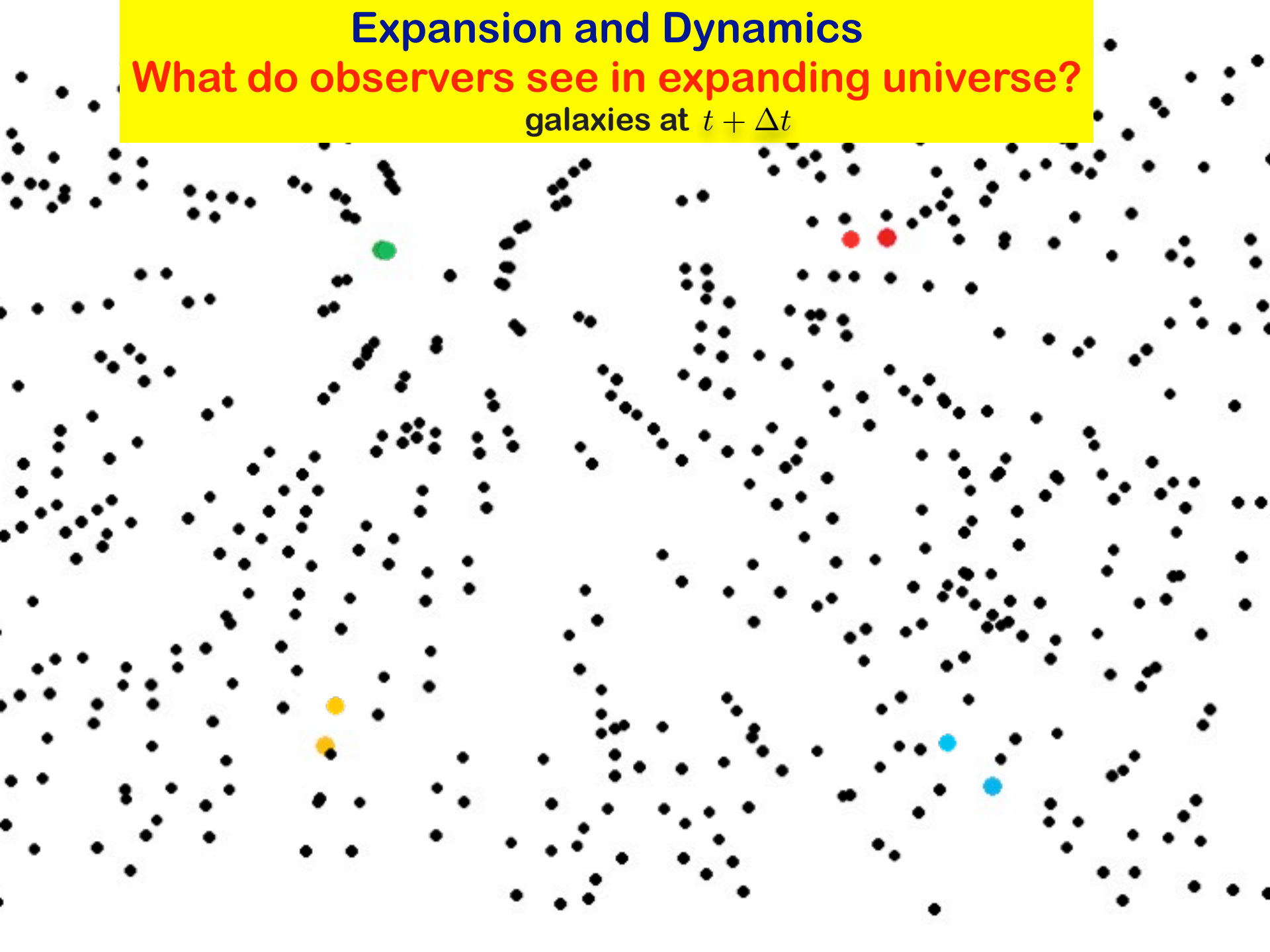
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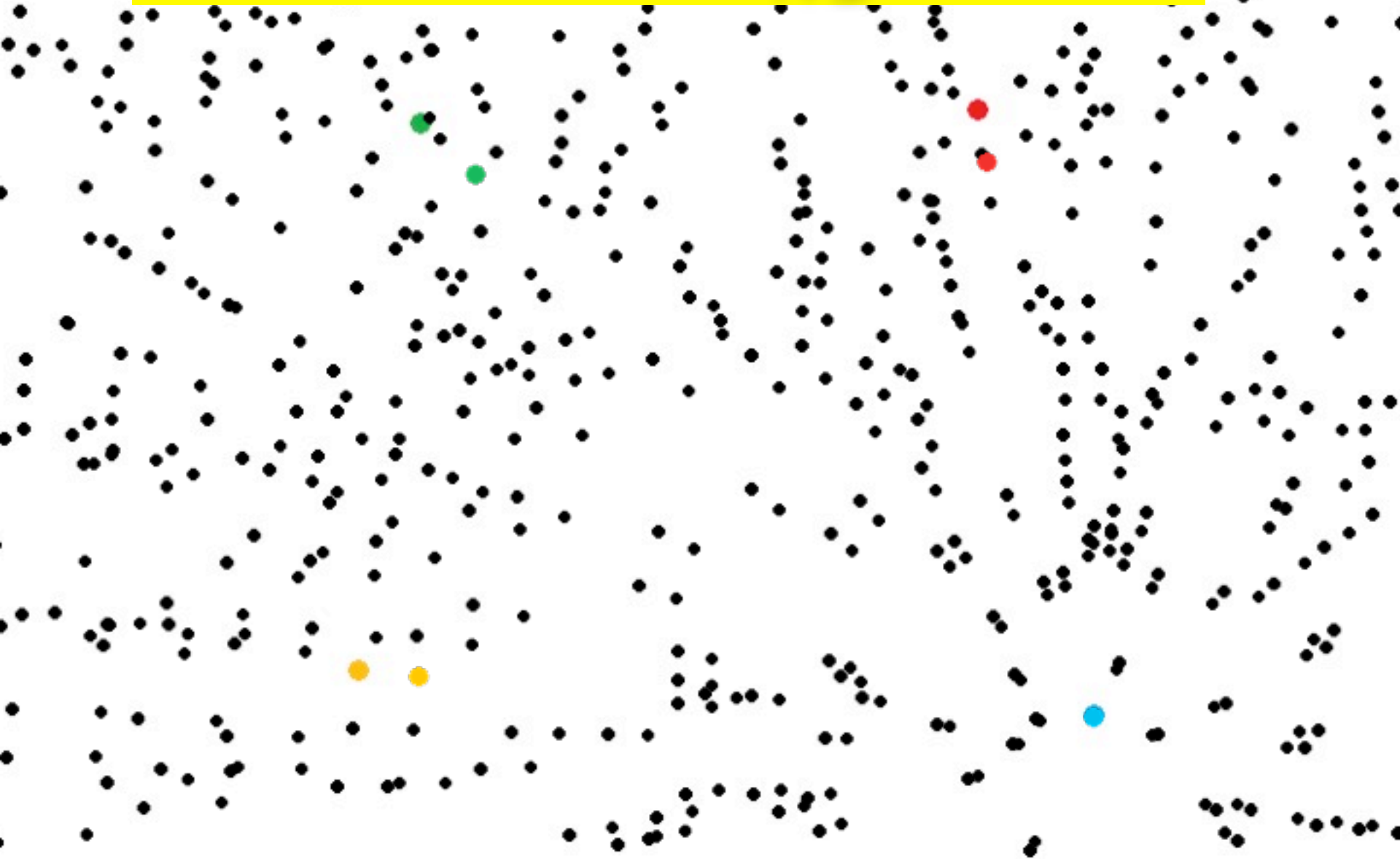
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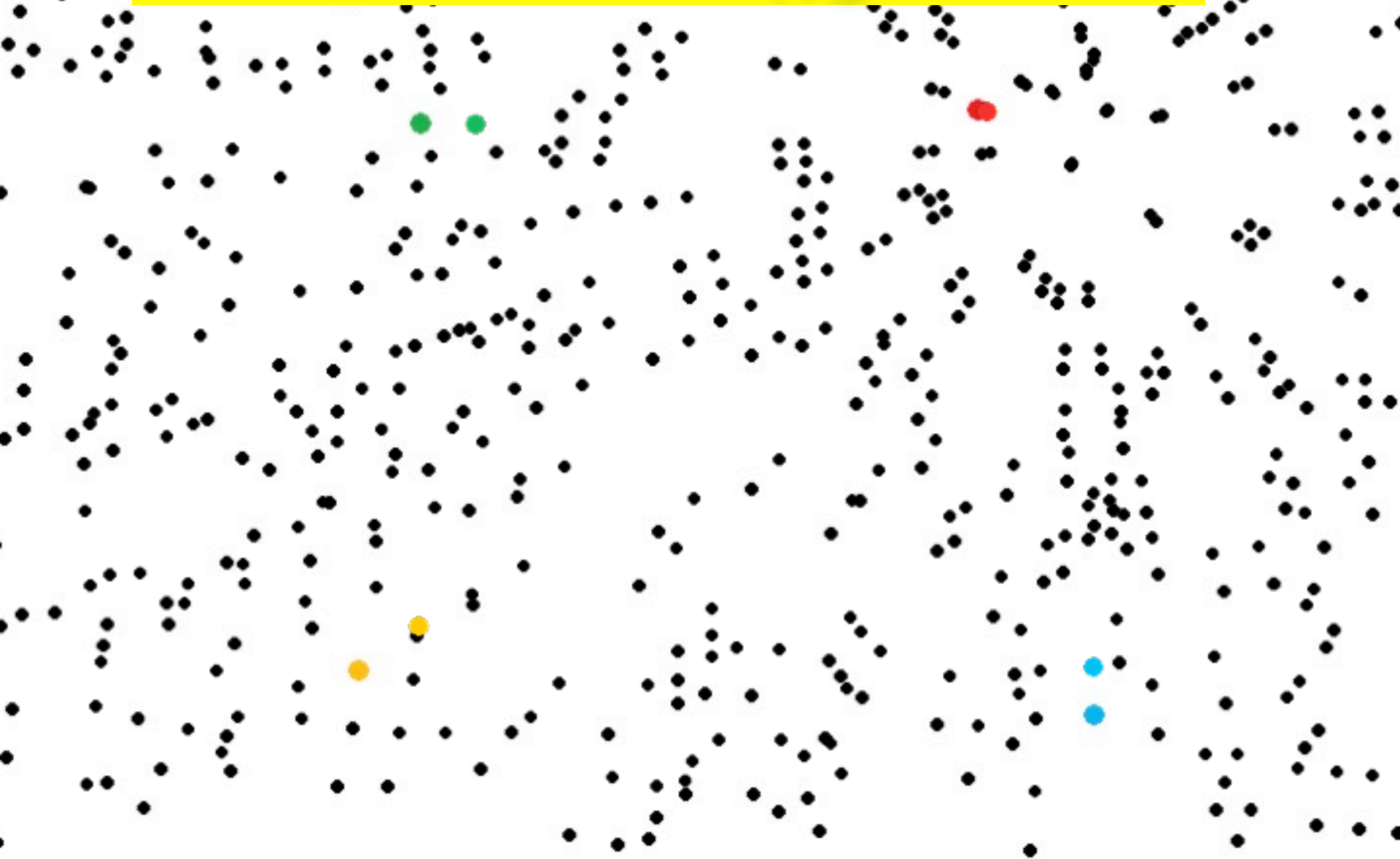
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Lesson?

What do observers see in expanding universe?
galaxies at $t + \Delta t$

in expanding universe:
all observers
see Hubble's Law!
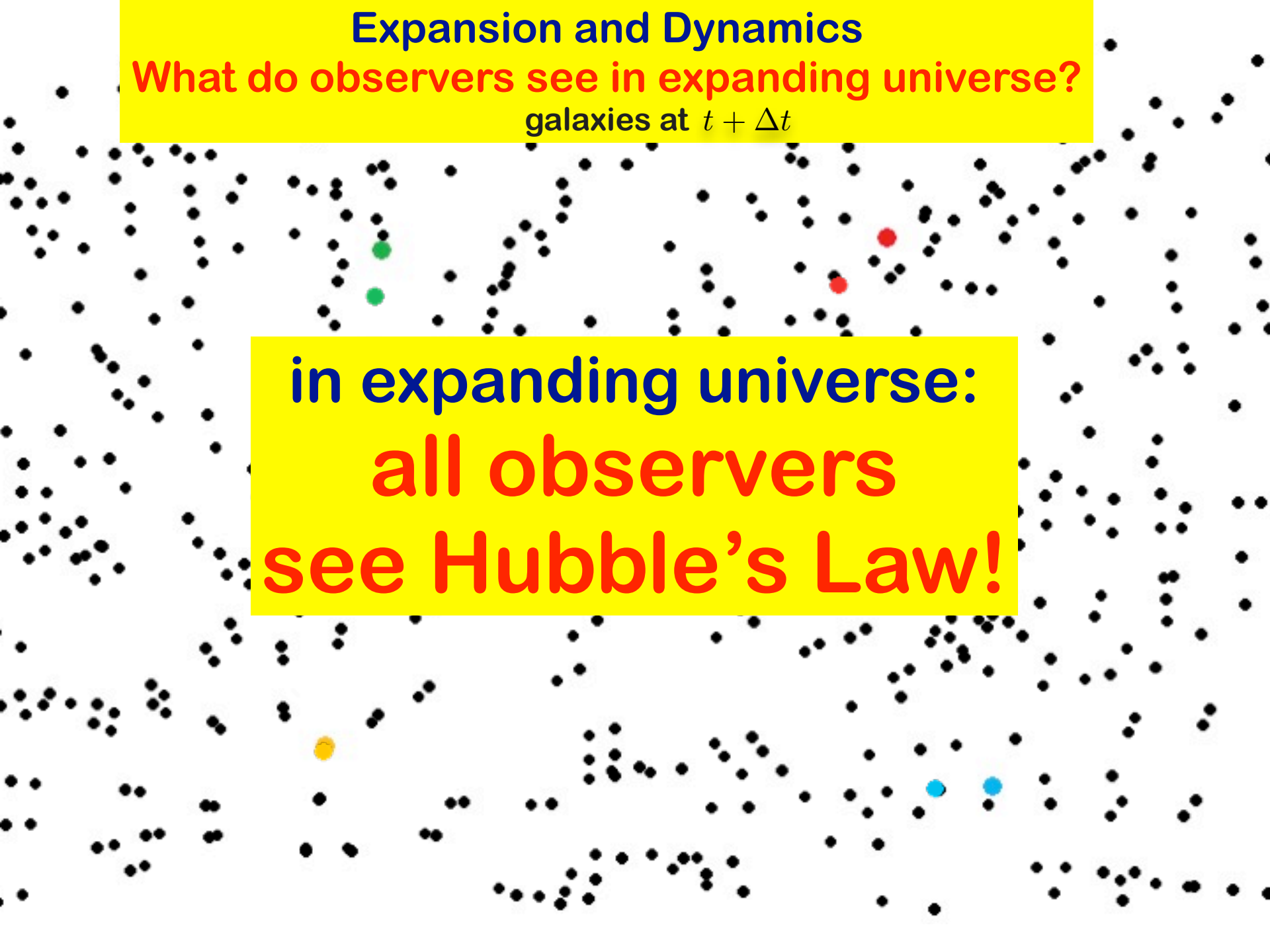
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recover Hubble's law! with Hubble "constant"

$$H(t) = \frac{\dot{a}}{a} \qquad \text{cosmic expansion rate}$$

Expansion and Redshifts: I

quick-n-dirty: wavelengths are lengths! ..it's right there in the name!

$\rightarrow$ expansion stretches photon λ

$$\lambda \propto a$$

if *emit* photon at t_{em}, then at later times

$$\lambda(t) = \lambda_{\text{emit}} \frac{a(t)}{a(t_{\text{em}})}$$

if *observe* later, $\lambda_{\text{obs}} = \lambda_{\text{em}} \, a_{\text{obs}}/a_{\text{em}}$

measure redshift today:

$$z \;=\; \frac{\lambda_{\text{obs}} - \lambda_{\text{em}}}{\lambda_{\text{em}}} = \frac{1 - a_{\text{em}}}{a_{\text{em}}}$$

high z $\leftrightarrow$ small a $\leftrightarrow$ distant past

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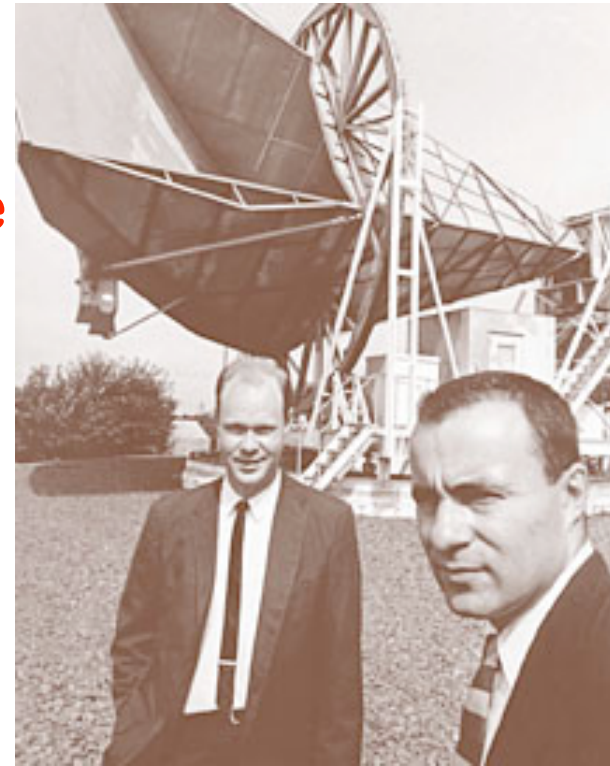
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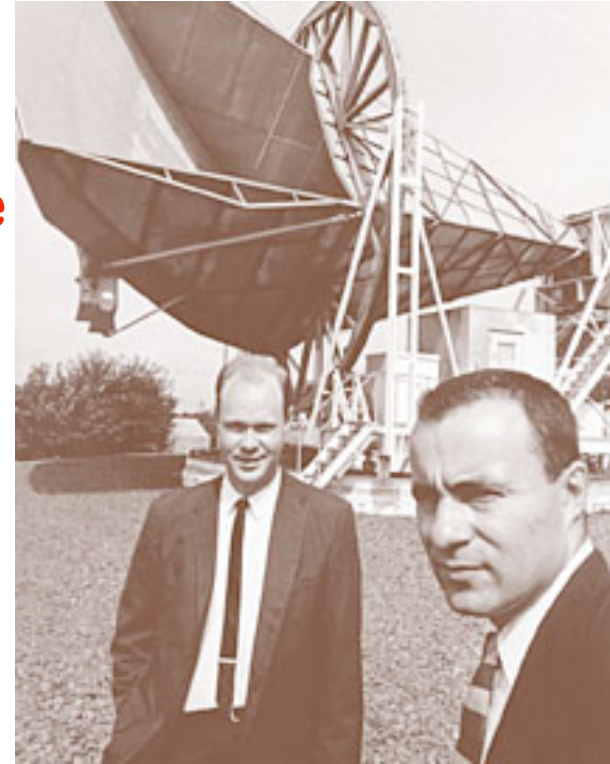
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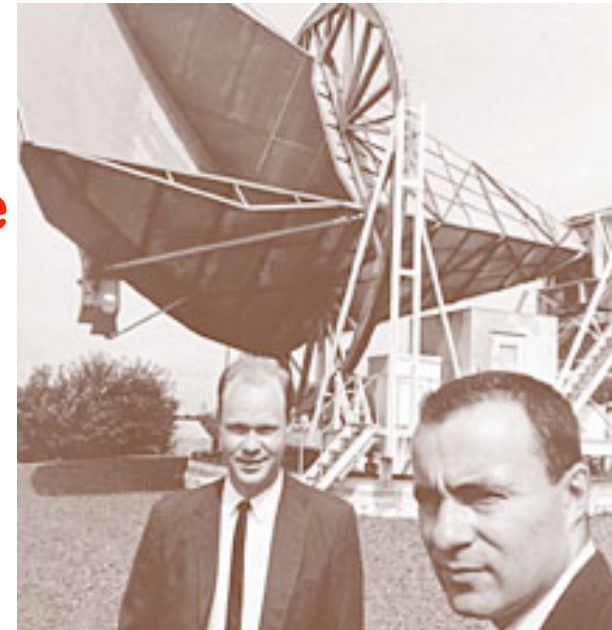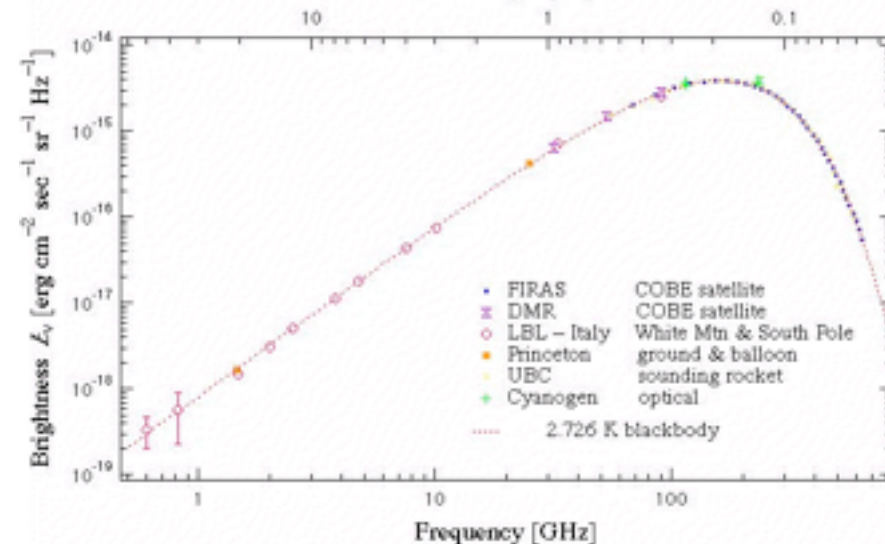
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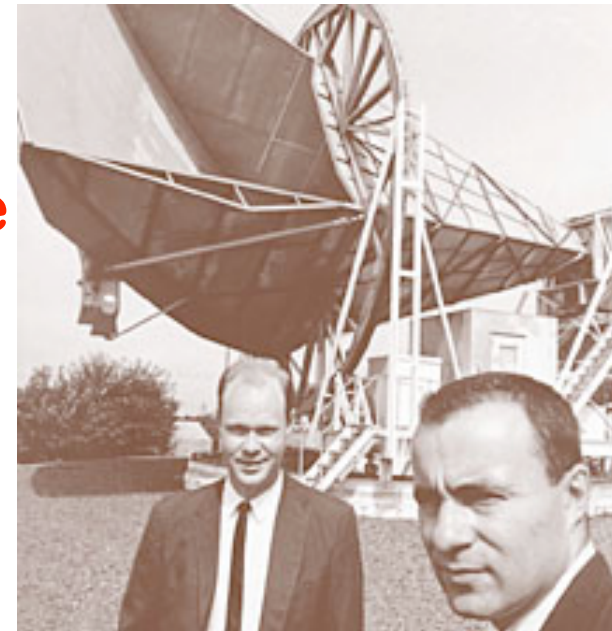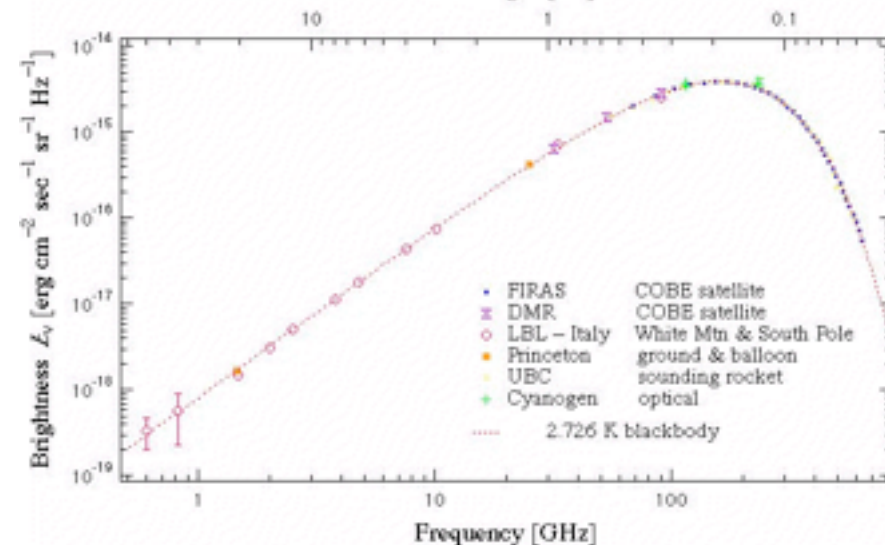
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Newtonian Cosmodynamics:

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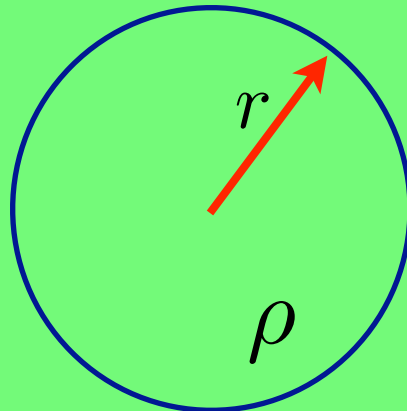expansion rate of the universe depends on the contents of the universe

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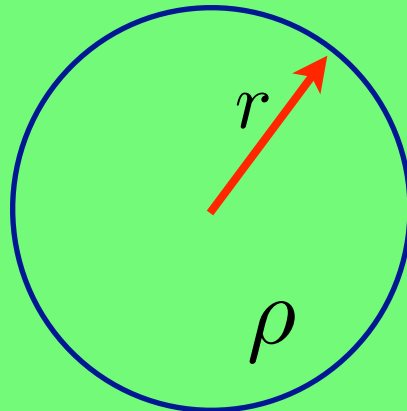
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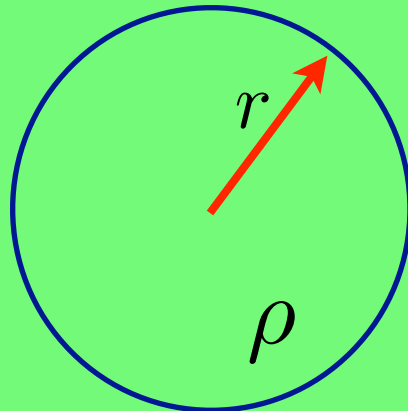consider arbitrary point, in homogeneous U of density ρ

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Cosmic dynamics: expansion.

- **Friedmann says**

spoiler alert: curvature term is zero

- **thanks, CMB!**

- **Q: so if we measure expansion history H(z)…?**
- **trace evolution of cosmic contents!**

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- **quick and dirty: Hubble law**

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Consider a <mark>standard candle</mark>

- **object with known, fixed luminosity L = light power output**

In non-expanding, Euclidean (uncurved) U:

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- object with known, fixed luminosity **L** = light power output

In non-expanding, Euclidean (uncurved) U:

- observer at distance **D** sees energy flux: $F = \dfrac{L}{4\pi D^2}$
- and thus infers a "luminosity distance"

$$D_L \equiv \sqrt{\frac{L}{4\pi F}}$$

In the real, expanding Universe

- luminosity distance still well-defined
- determined by cosmic expansion history:

$$D_L(z) = (1+z)\int_0^z \frac{c\,dz'}{H(z')}$$

The Game:

- identify standard candle
- measure candle flux **F(z)** over large range of **z**
- determine cosmic expansion history **H(z)**

Q: requirements for a useful standard candle? Candidate(s)?
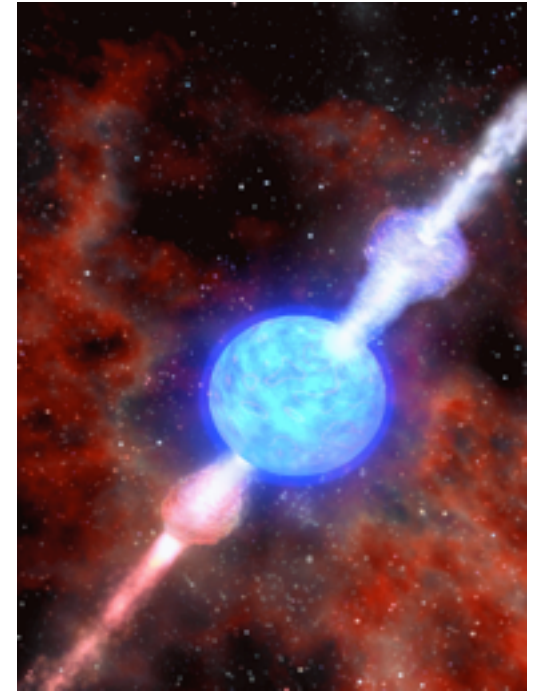
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- **known and fixed luminosity**

    must understand emitter well
    preferably candles identical at all cosmic time
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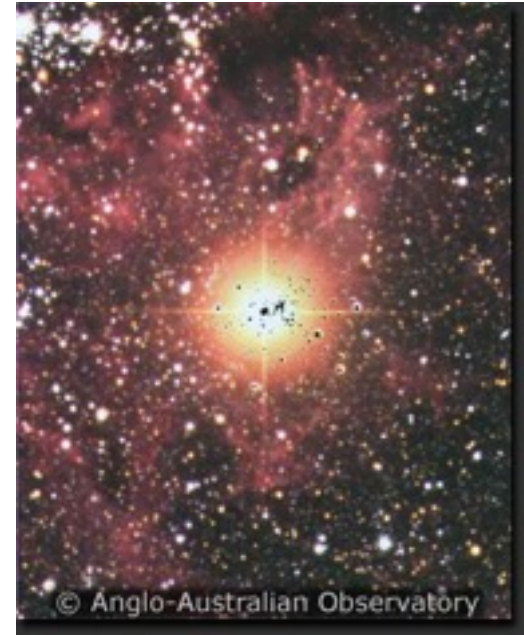

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© Anglo-Australian Observatory

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    - why? nuclear physics!
    - thermonuclear explosions of white dwarfs
    - all have similar composition and mass (Chandrasekhar limit)

Supernova Cosmology: Results

Supernovae show

★ **cosmic expansion slower in the past!?!?**

★ **the expansion rate is speeding up with time!**

★ **the universe is accelerating!**
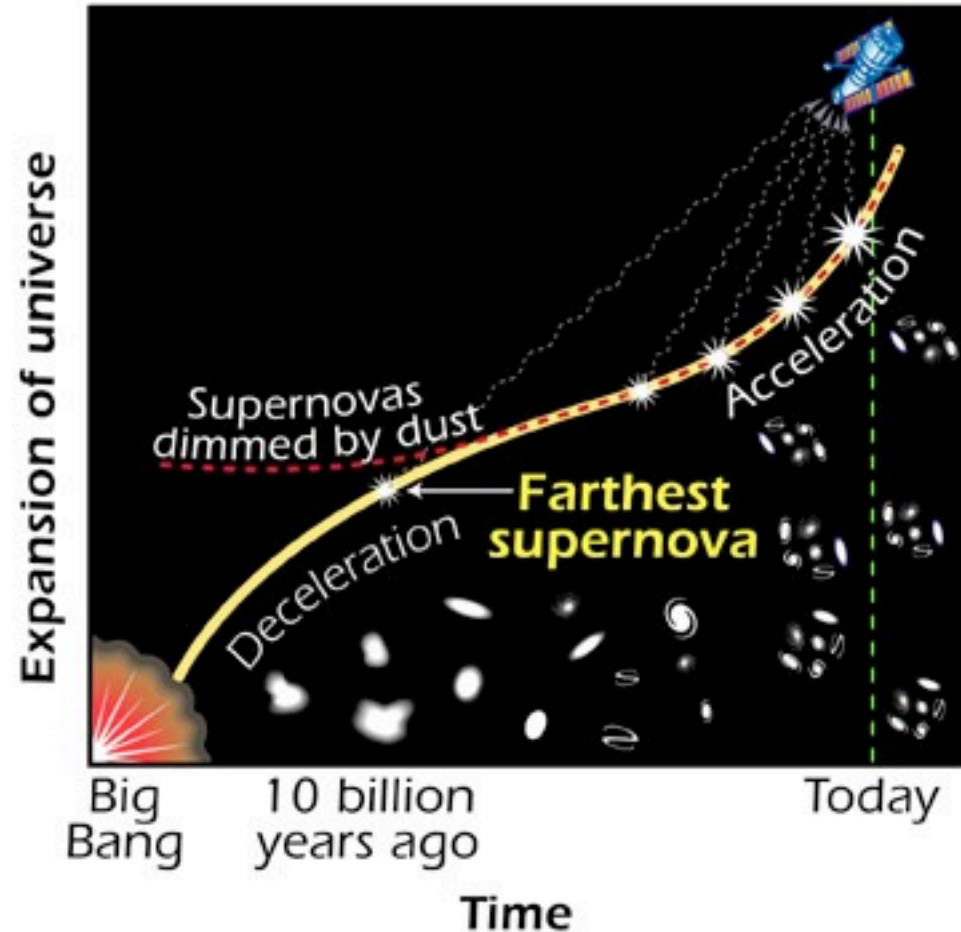
Cosmic Acceleration!?!
Implications

★ **ordinary matter and ordinary attractive gravity leads to deceleration**

★ **but observe acceleration!**

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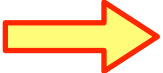   - for experts: need negative pressure $P < 0$

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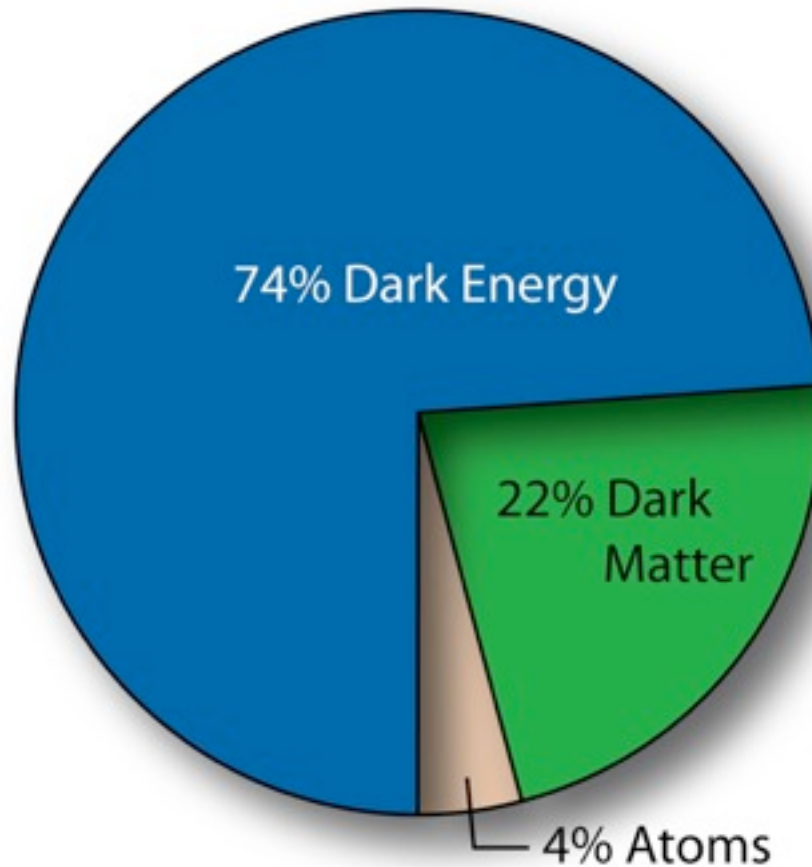
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★ **acceleration ⟹ "dark energy"**

Cosmic Ingredients
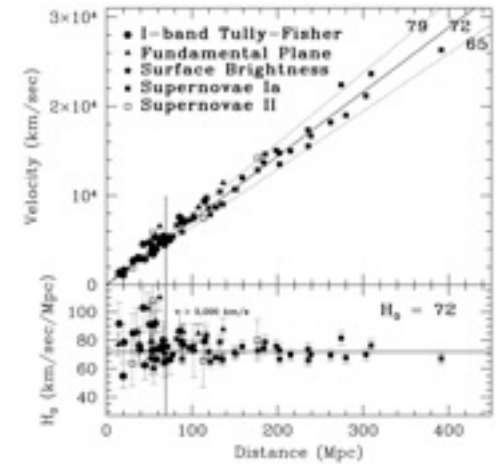## Who ordered that?
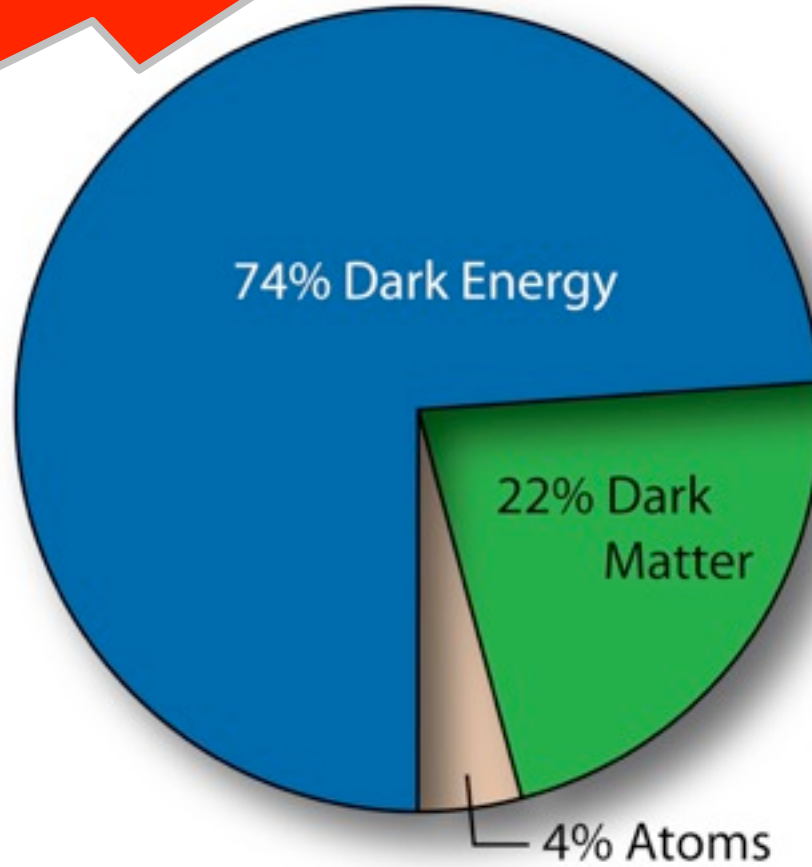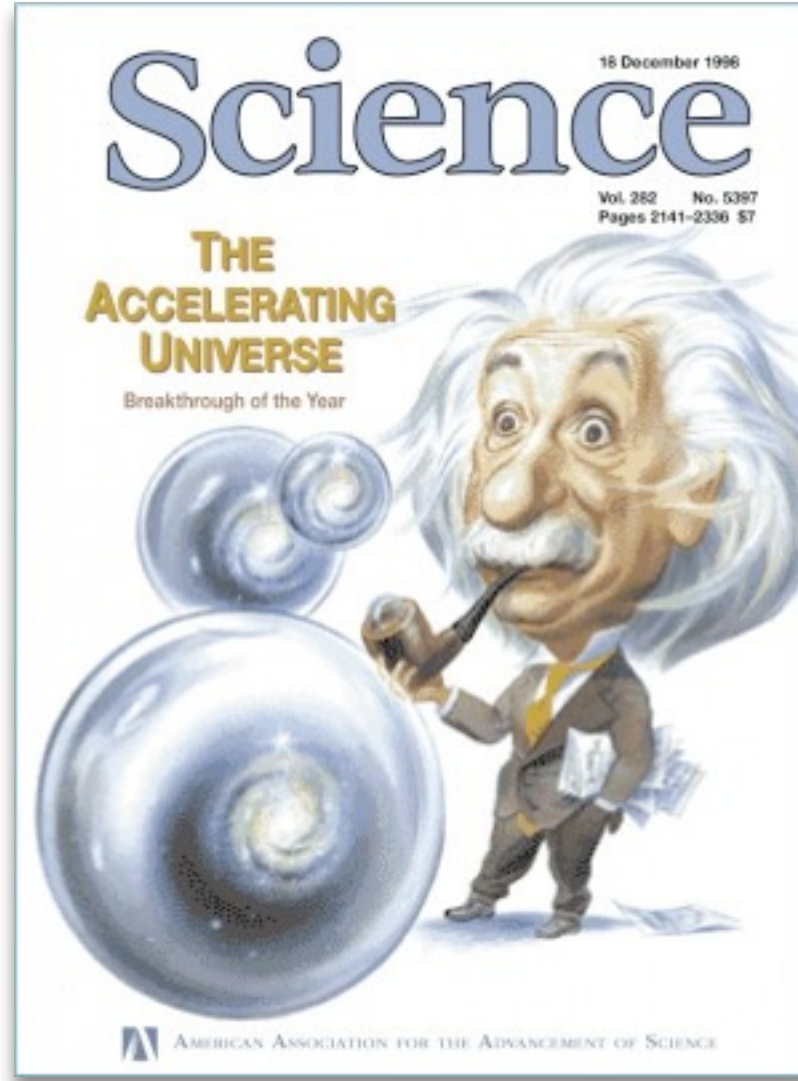
Science Magazine "Breakthrough of the year"
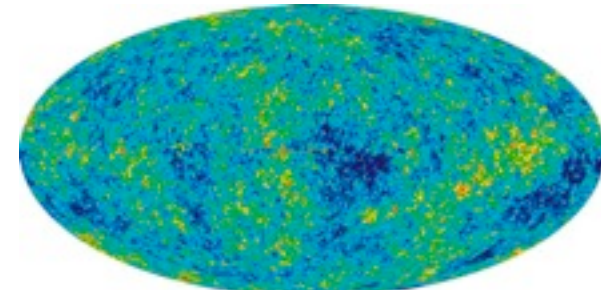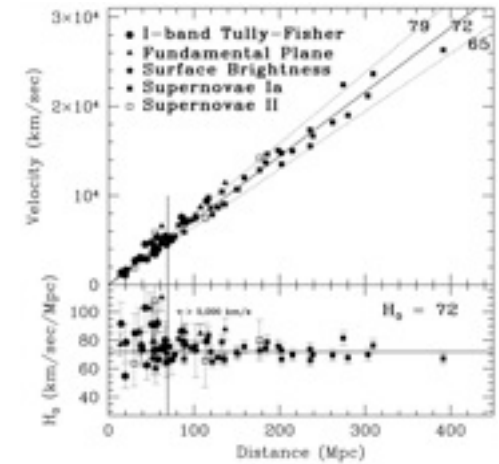
The Standard Cosmology:
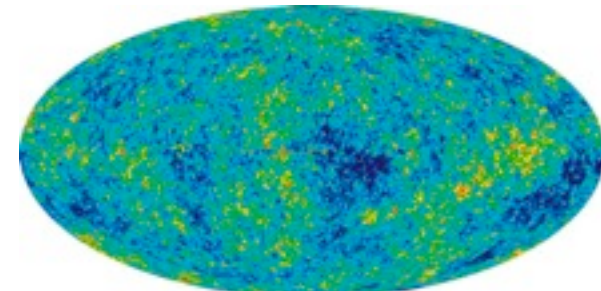## Hot Big Bang Model

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- **Expanding Universe**

   t~14 Gyr; T~10^{-4} eV

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   t~400,000 yr; T~1 eV   atomic physics

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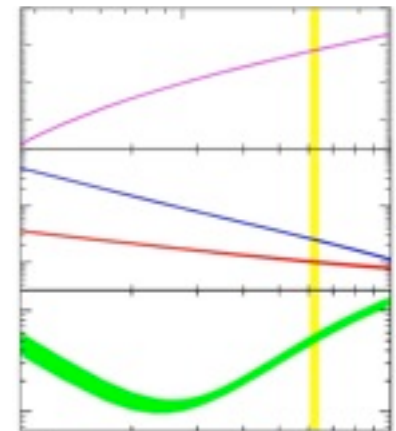**Space: Homogeneous & Isotropic**

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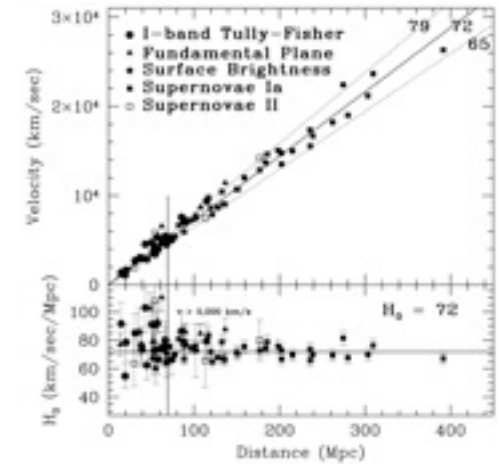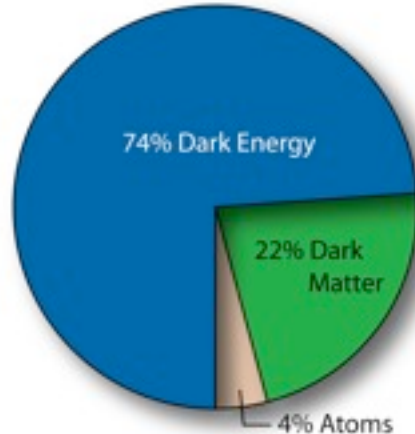
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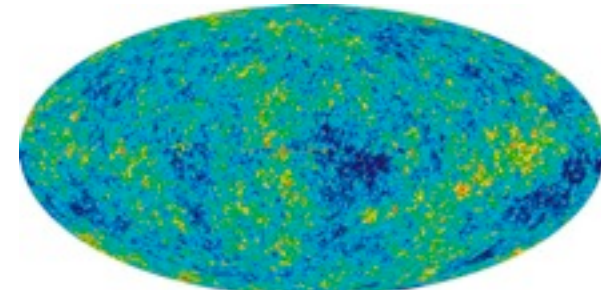## Hot Big Bang Model

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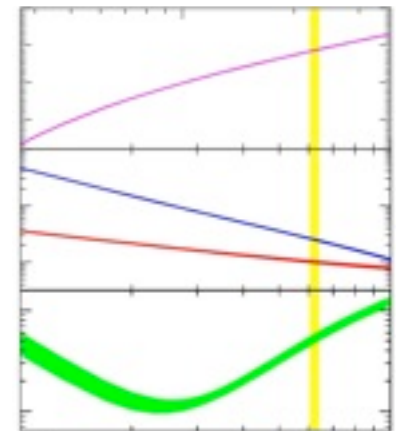 $t \sim 1$ sec, $T \sim 1$ MeV   nuclear physics

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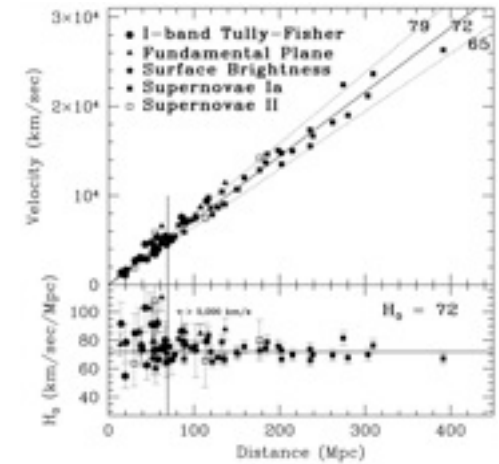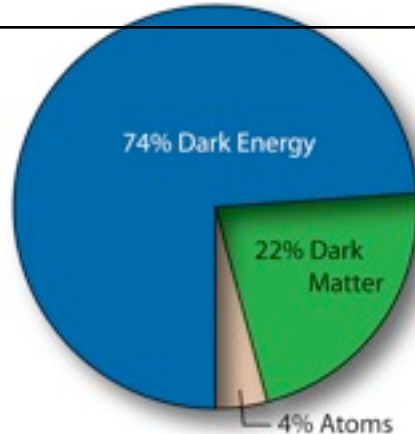Freedman et al 2001

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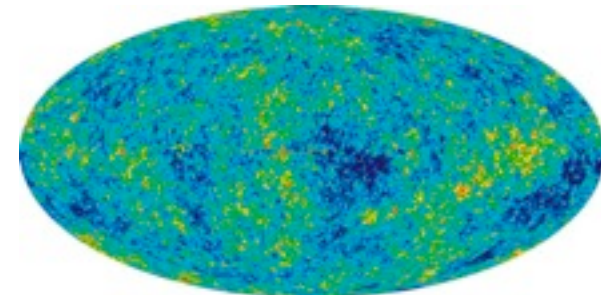## Hot Big Bang Model

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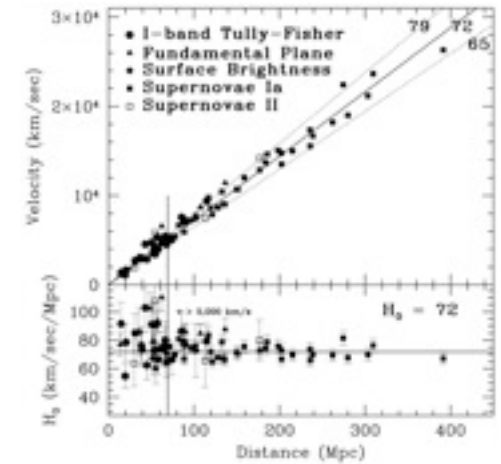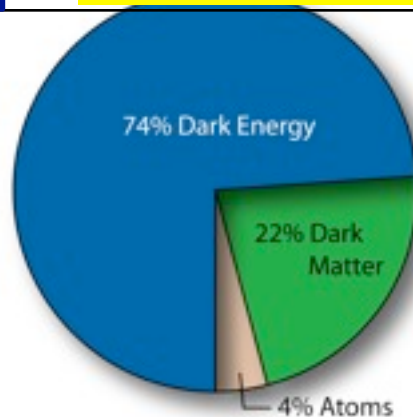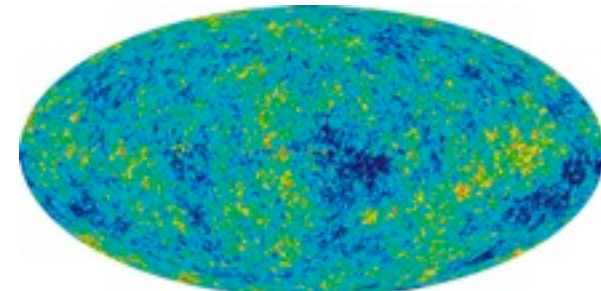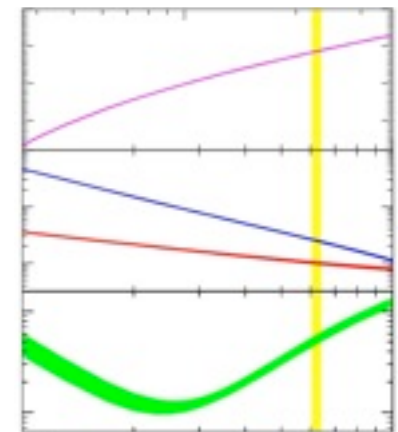
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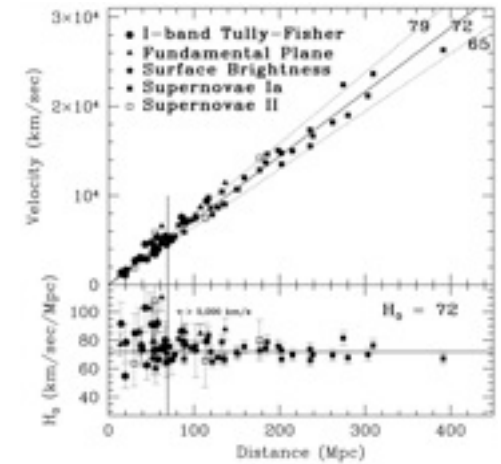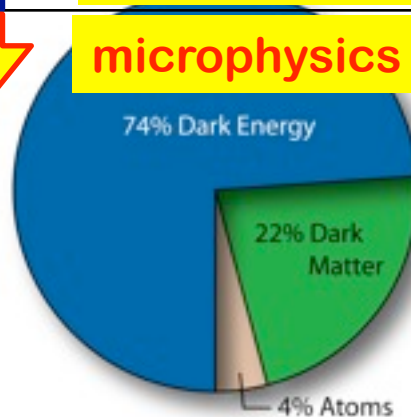   t~1 sec, T~Me   **microphysics known**

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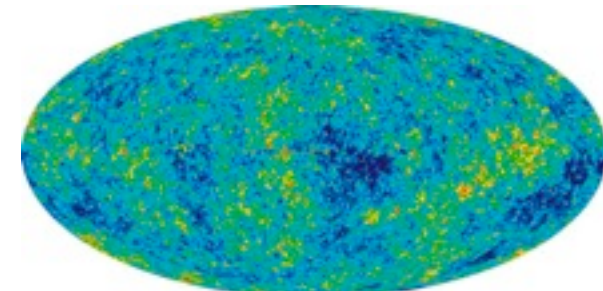- **Dark Matter**

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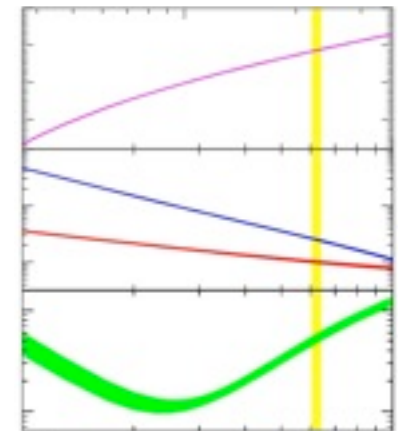4% Atoms

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Cosmic Job Security:
Precision Ignorance

▶ **What is the dark matter?**

    how is it produced?

    how does it interact?

    what was its role in the early universe?

▶ **What is the dark energy?**

    is it related to dark matter?

    does it evolve with time?

    what was its role in the early universe?

▶ **What sets** $\rho_{\mathrm{baryon}} \sim \rho_{\mathrm{matter}} \sim \rho_\Lambda$ **today?**

    compare: nuclear physics sets $\rho_{\mathrm{H}} \sim \rho_{\mathrm{He}}$

Expansion and Redshifts: II

slower-n-cleaner: non-relativistic Doppler

non-rel Doppler sez:

$$\frac{\delta\lambda}{\lambda} \equiv z = \frac{v}{c}$$

Hubble sez:

$$cz = Hr$$

Together

$$\frac{\delta\lambda}{\lambda} = \frac{Hr}{c}$$

But light travels distance r in time $\delta t = r/c$, so

$$\frac{\delta\lambda}{\lambda} = H\delta t = \frac{\dot{a}\delta t}{a} = \frac{\delta a}{a}$$

for arriving light, fractional λ change = fractional a change!

Worked Example: A Matter-Only Universe

consider a universe containing *only* non-relativistic matter
Friedmann:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{\kappa c^2}{R^2}\frac{1}{a^2}$$

$$= \frac{8\pi G}{3}\rho_0 a^{-3} - \frac{\kappa c^2}{R^2}a^{-2}$$

For $\kappa = 0$: "Einstein-de Sitter"

$$(\dot{a}/a)^2 = \frac{8\pi G}{3}\rho_0 a^{-3}$$

evaluate today: $H_0^2 = 8\pi G\rho_0/3$

$$a^{1/2}da = H_0\, dt$$
$$2/3\ a^{3/2} = H_0\, t$$

Q: implicit assumptions in solution?

Einstein-de Sitter:

$$t = \frac{2}{3}a^{3/2}H_0^{-1}$$

$$a = \left(\frac{3}{2}H_0 t\right)^{2/3} = \left(\frac{t}{t_0}\right)^{2/3}$$

Now unpack the physics:
- boundary condition: $a = 0$ at $t = 0 \rightarrow$ "big bang"
- $a \propto t^{2/3}$ *Q: interpretation?*
- evaluate Hubble parameter

$$H = \frac{\dot{a}}{a} = \frac{2}{3}\frac{1}{t}$$

Q: interpretation?
- present age:

$$t_0 = \frac{2}{3}\,H_0^{-1} = \frac{2}{3}\,t_H$$

Hubble time t_H sets scale
Q: note that $t_0 < t_H$: why?

Other Einstein-de Sitter fun facts:

- U. half its present age at $a = 2^{-2/3} = 0.63$
- objects half present separation (and $8\times$ more compressed) at $t = 2^{-3/2}t_0 = 0.35t_0$
- using measured value of H_0, calculate $t_0 = 8.9$ Gyr but know globular clusters have ages $t_{gc} \gtrsim 12$ Gyr *Q: huh?*

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A: Einstein--de Sitter model is not the correct description of our Universe!

- **EdS assumes matter only, and no curvature**
- **turns out: no curvature is correct assumption**
- **...but there is stuff other than matter (and radiation!) out there!**