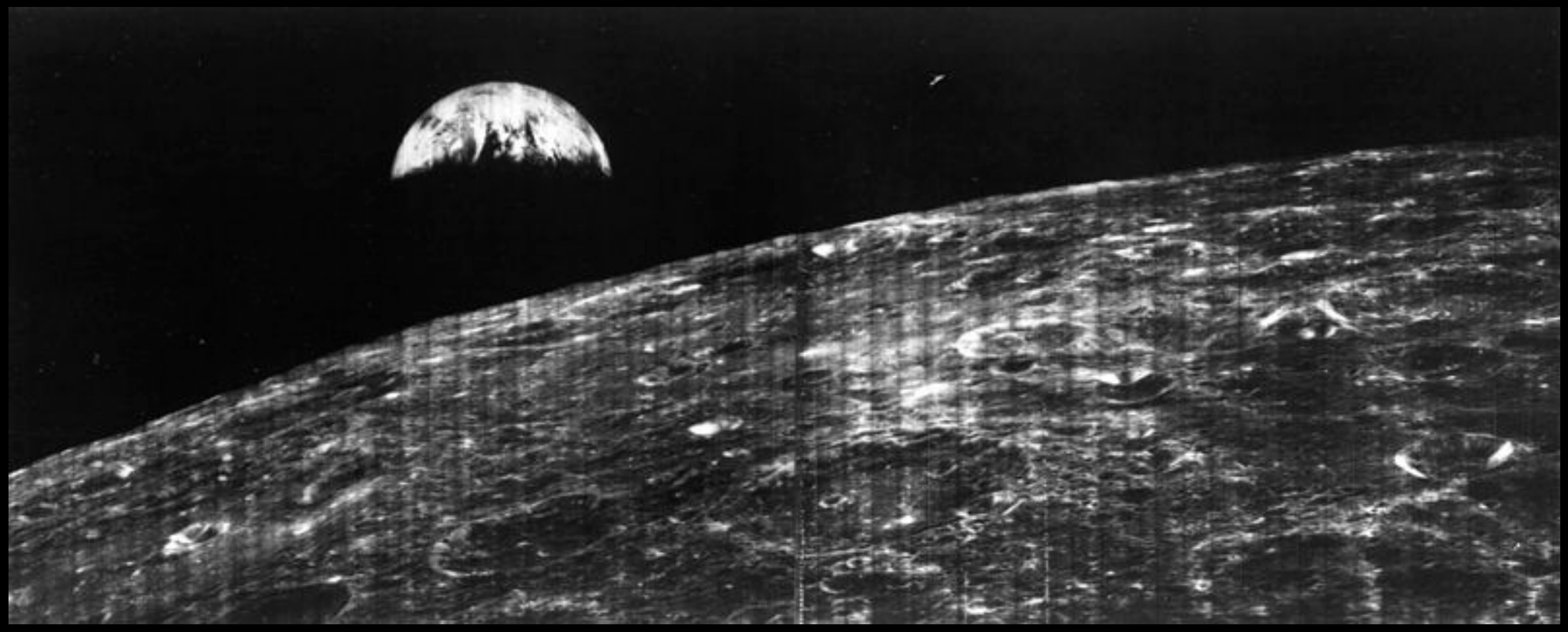
Cosmic Acceleration

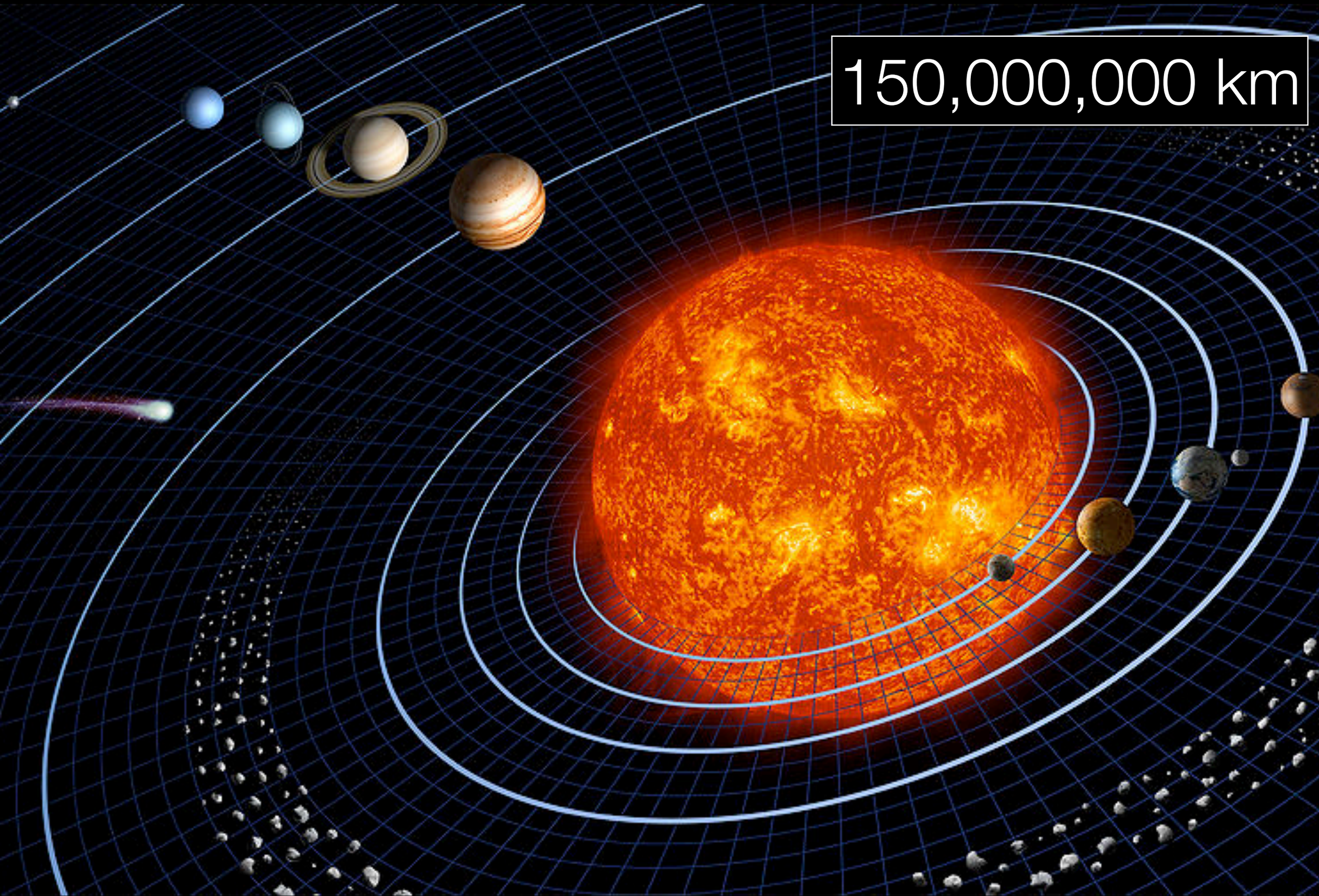
How the Universe is getting away from us

Brian Nord (nord@fnal.gov)
FNAL Summer Lecture Series
July 22, 2014


6,400 km

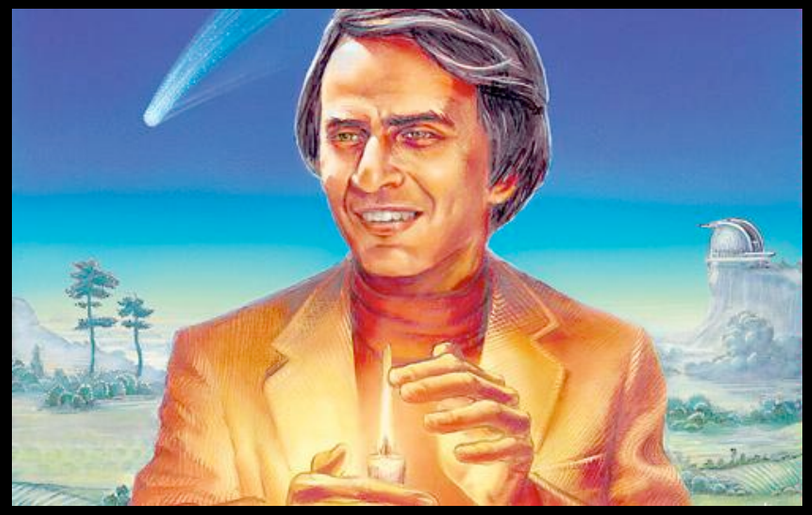
384,000 km




150,000,000 km

A ‘pale blue dot’

19,000,000,000 km

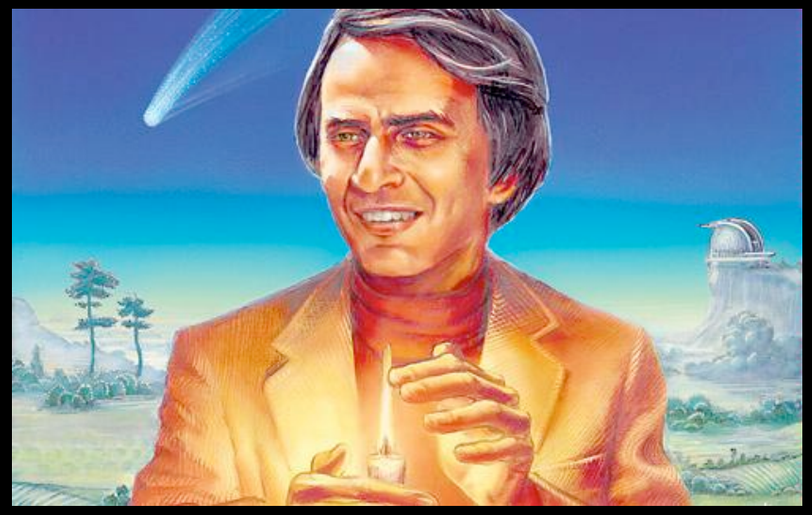


“That's here. That's home. That's us.

On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives.”

A ‘pale blue dot’

19,000,000,000 km



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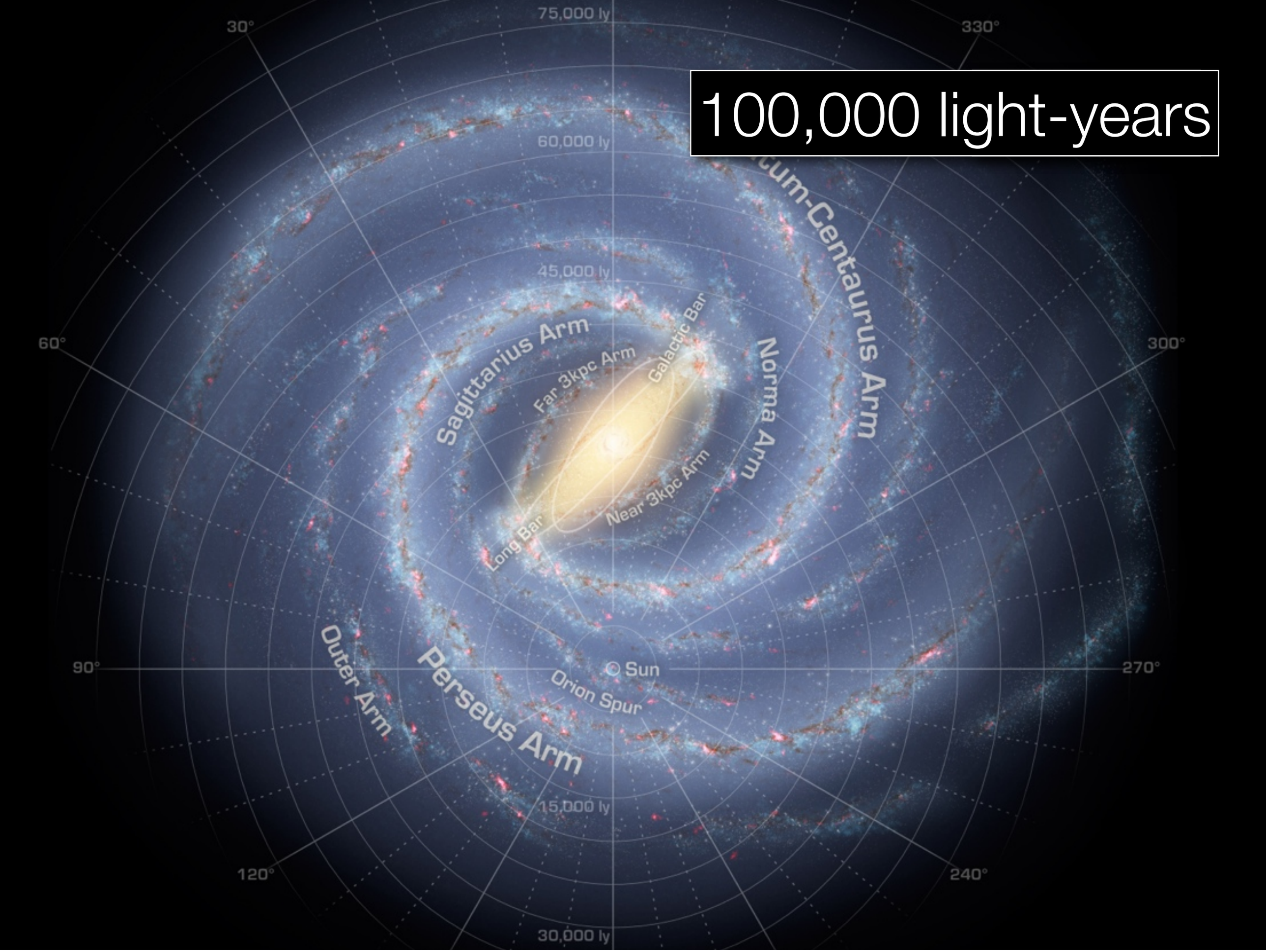
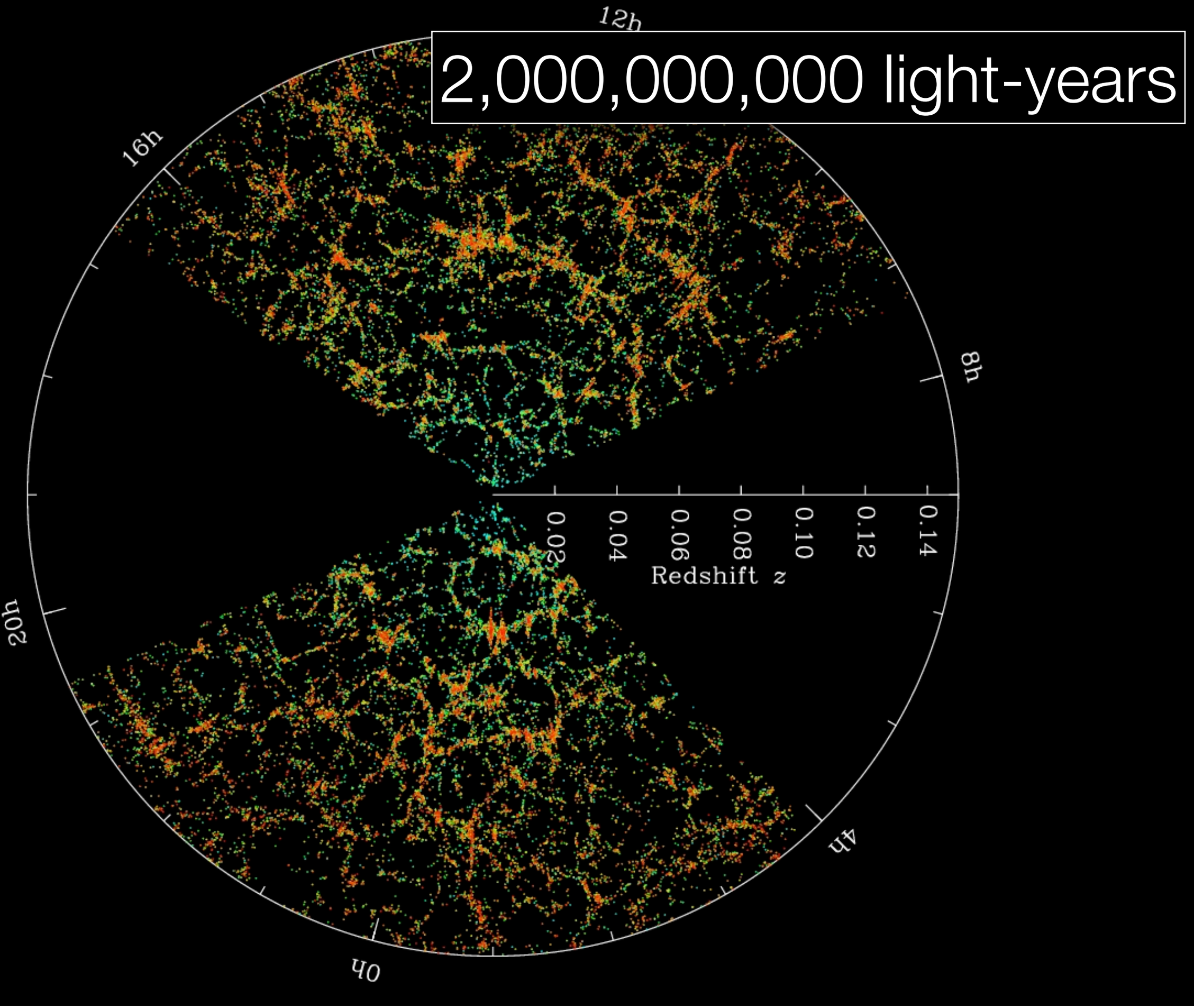

100,000 light-years
75,000 ly
60,000 ly
45,000 ly
30,000 ly
15,000 ly
30°
330°
60°
300°
90°
270°
120°
240°
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur

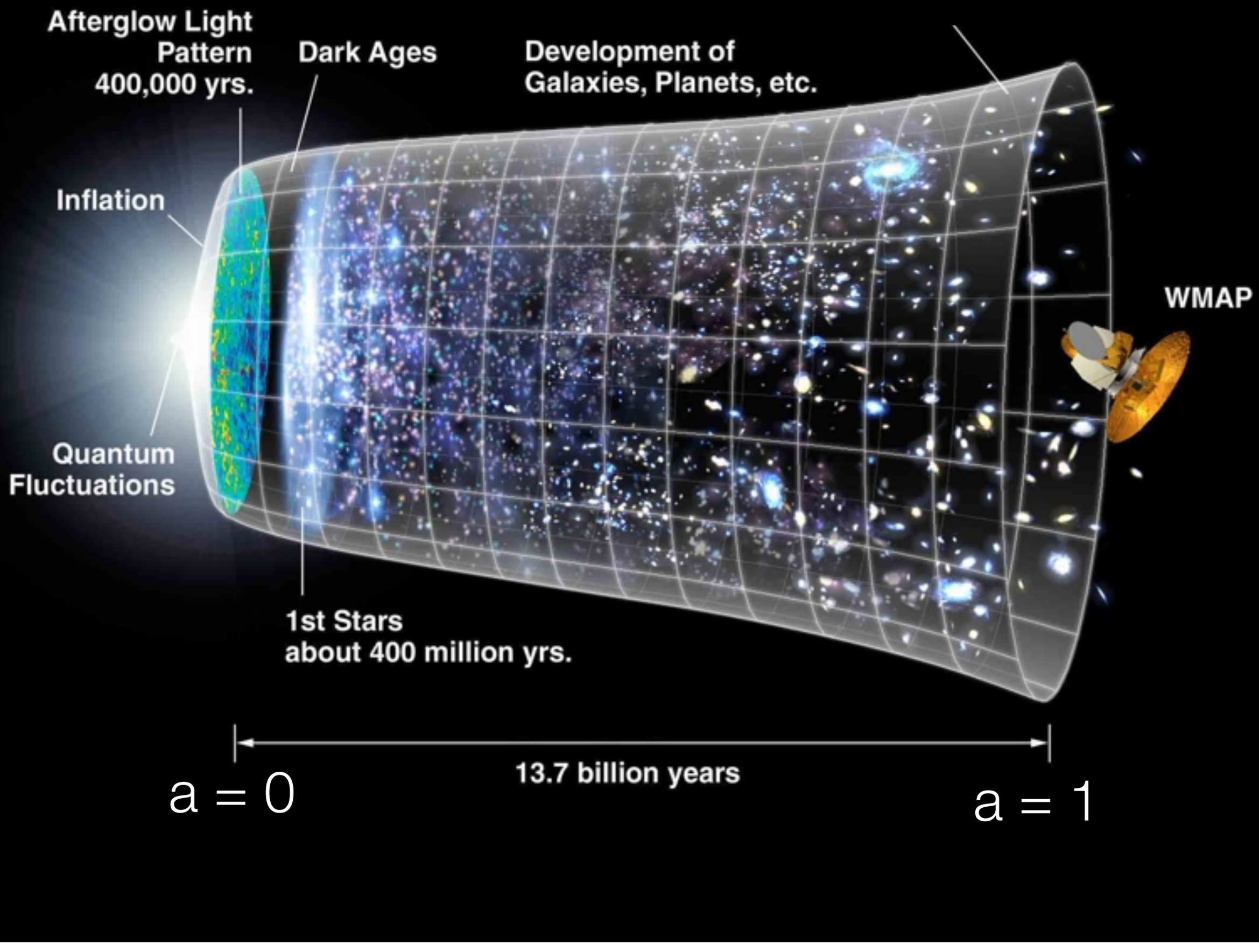

2,000,000,000 light-years
12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z

Parametrize the Cosmos

name	symbol	description
energy density	ρ (Ω)	How much energy [from stuff] is there in the universe?
Hubble Factor	H	How [fast] is the universe changing in size?
normalization of matter fluctuations	σ	How clumpy [vs. smooth] is the distribution of matter in the universe?
optical depth	τ	How easily can light pass through gas in the early universe?

(+ ~10 more parameters)

What is “everything”?
From where and from did it come?


Afterglow Light Pattern 400,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Inflation
WMAP
Quantum Fluctuations
1st Stars about 400 million yrs.
13.7 billion years
a = 0
a = 1

Recombination
[400,000 yrs]

Expansion leads to decreasing temperature

Dark Ages

[150 - 800 Myrs]

Dark Ages

[150 - 800 Myrs]

First Stars

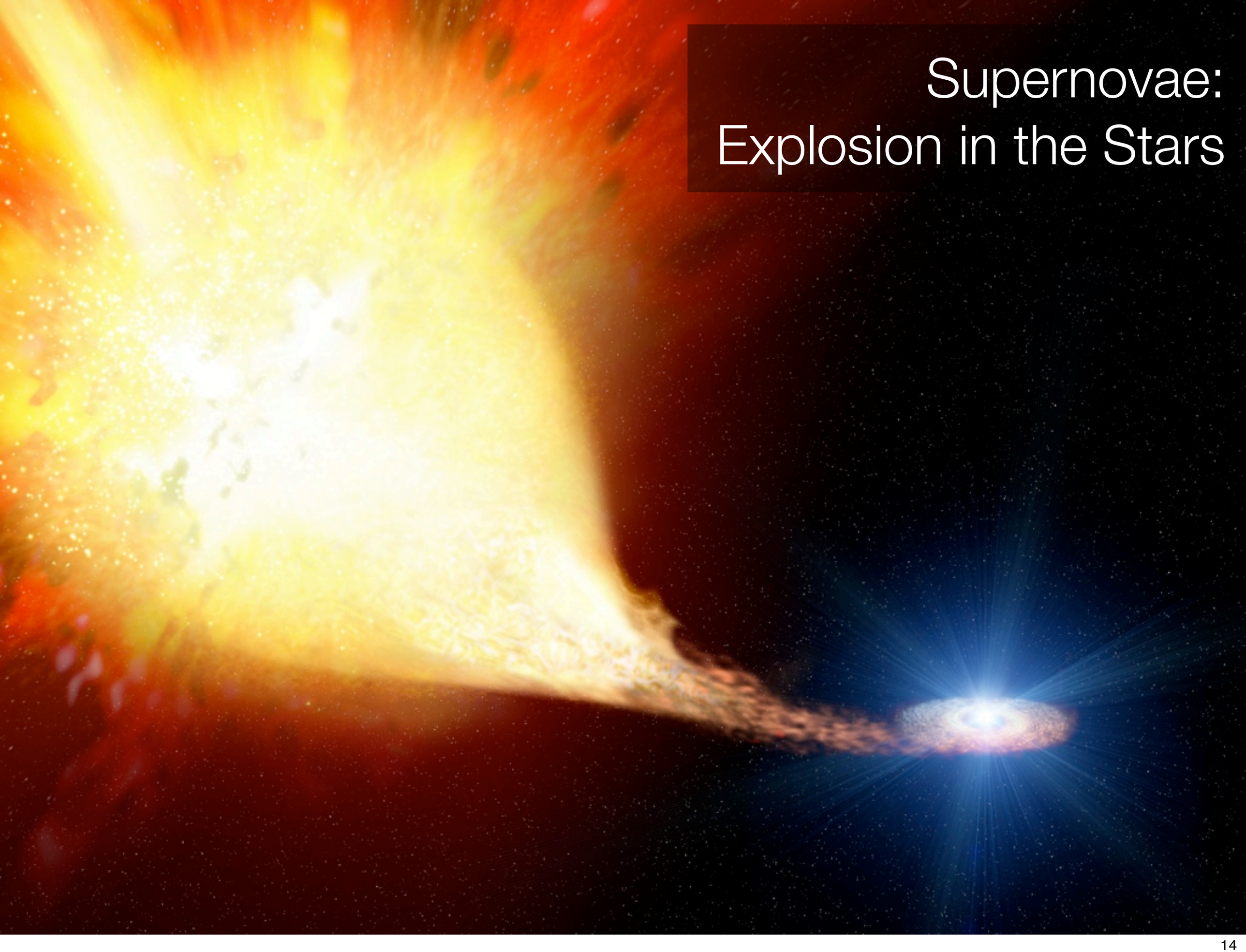
[~ 1 Gyr]

First Stars

[~ 1 Gyr]

Text

Supernovae: Explosion in the Stars



Stellar remnants…

… stellar nurseries

Star Stuff

Quarks

Leptons

Force Carriers

up

charm

top

photon

down

strange

bottom

gluon

electron neutrino

muon neutrino

tau neutrino

Z boson

electron

muon

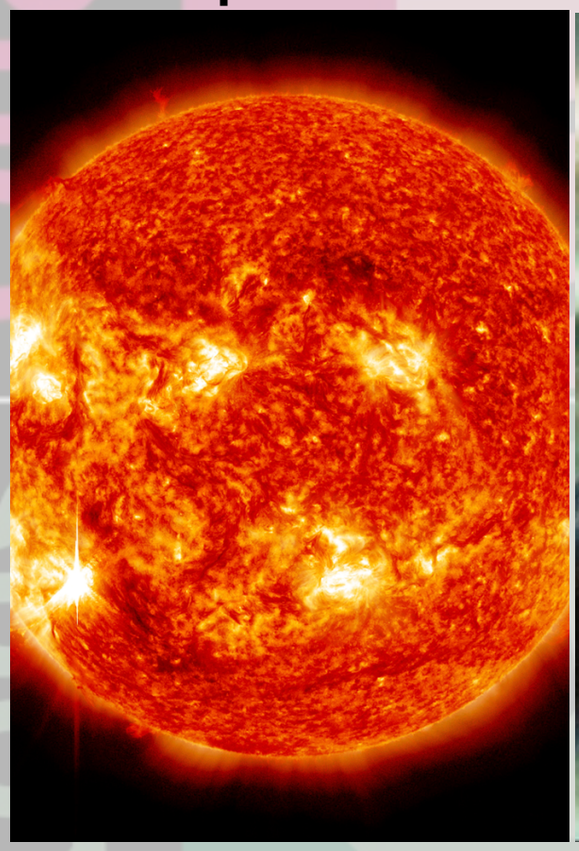
tau

W boson

$$\rho = \rho_b$$

16

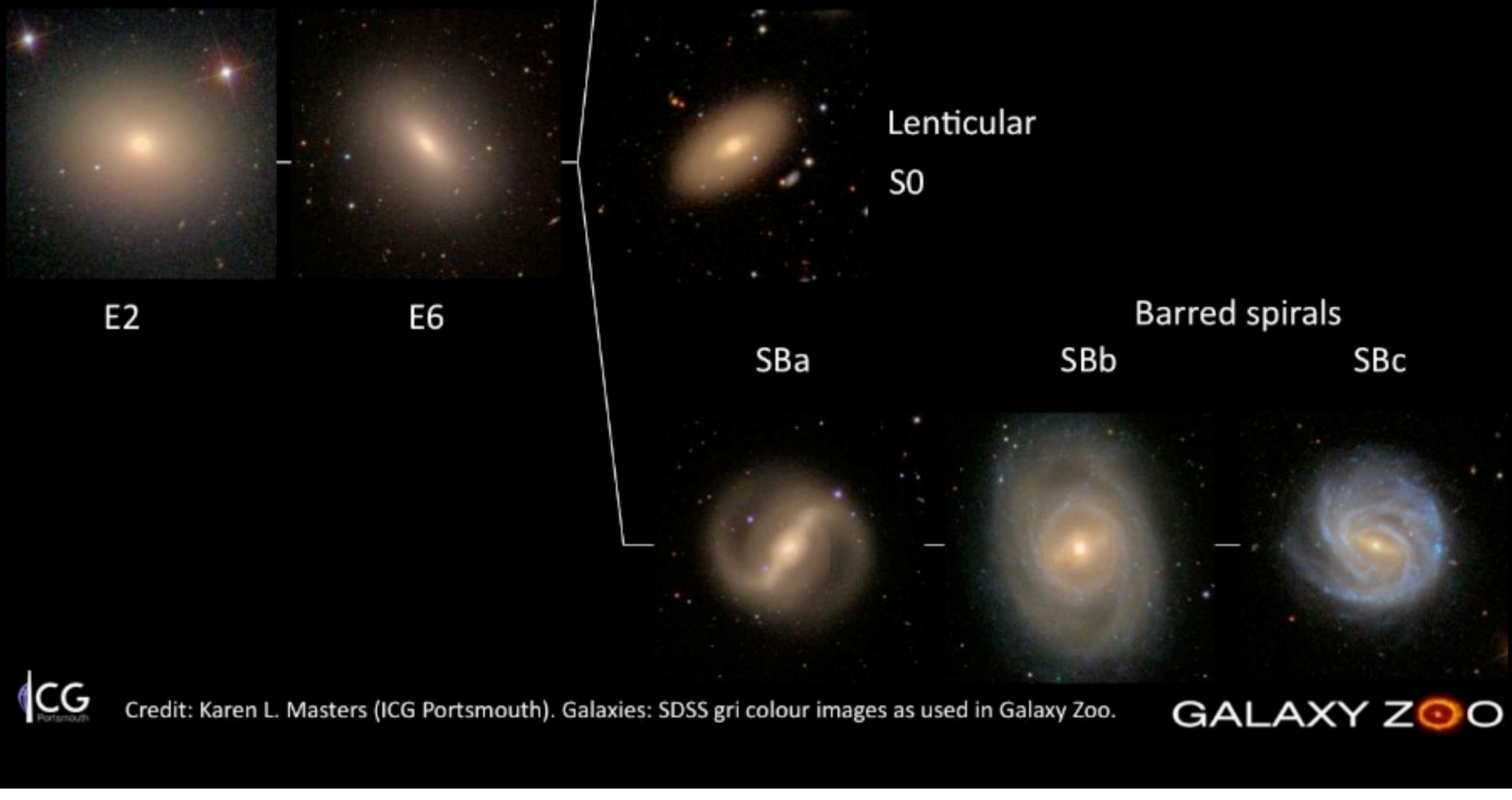
Star Stuff



$$\rho = \rho_b$$

16

The Hubble Tuning Fork



Credit: Karen L. Masters (ICG Portsmouth). Galaxies: SDSS gri colour images as used in Galaxy Zoo.

Fritz Zwicky

Virgo Cluster

$$\rho = \rho_{\rm b} + \rho_{\rm DM}$$

See Hugh Lippincott's talk for more on dark matter (last week)

How did the structures form?

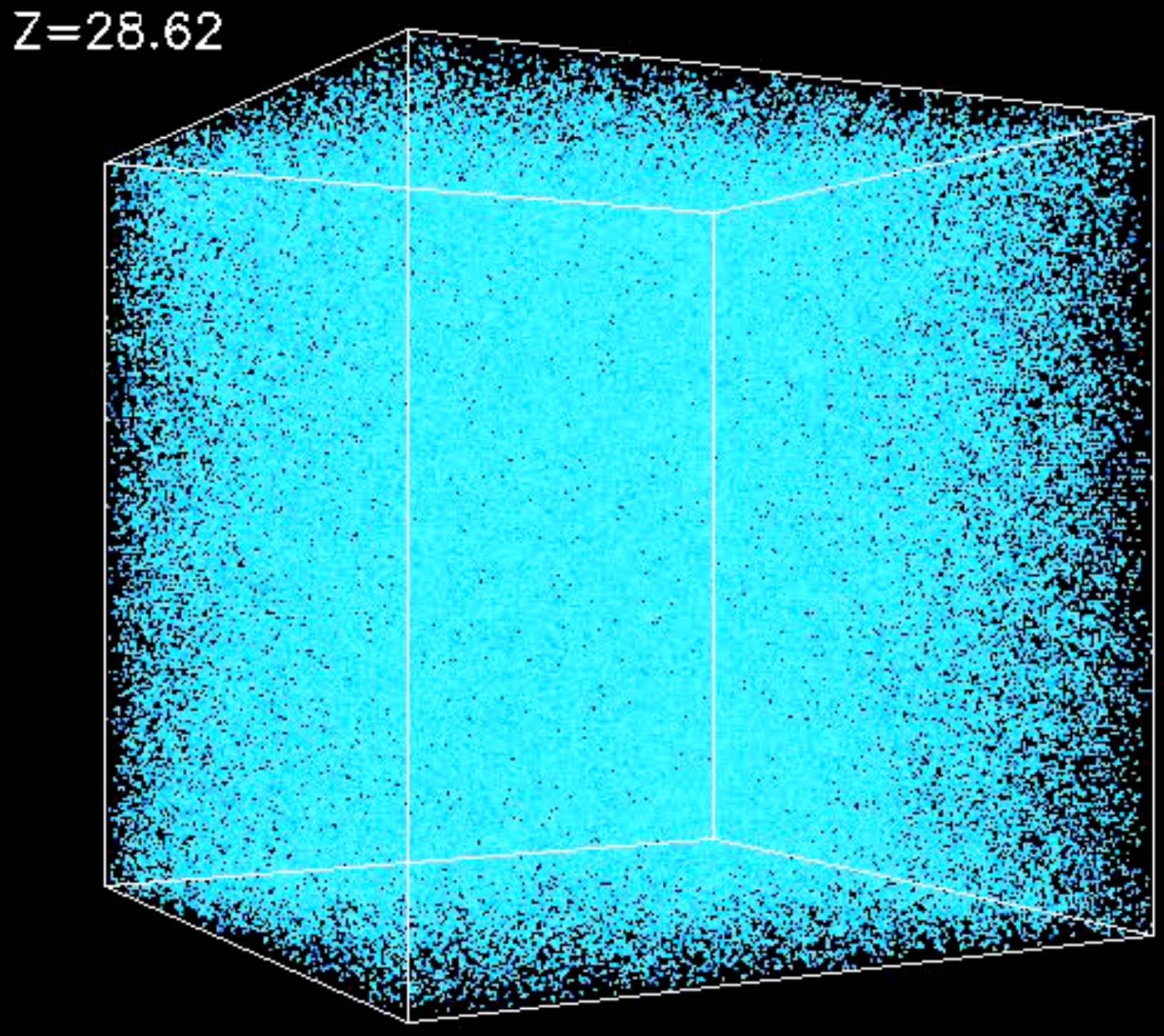
Recombination
[400,000 yrs]

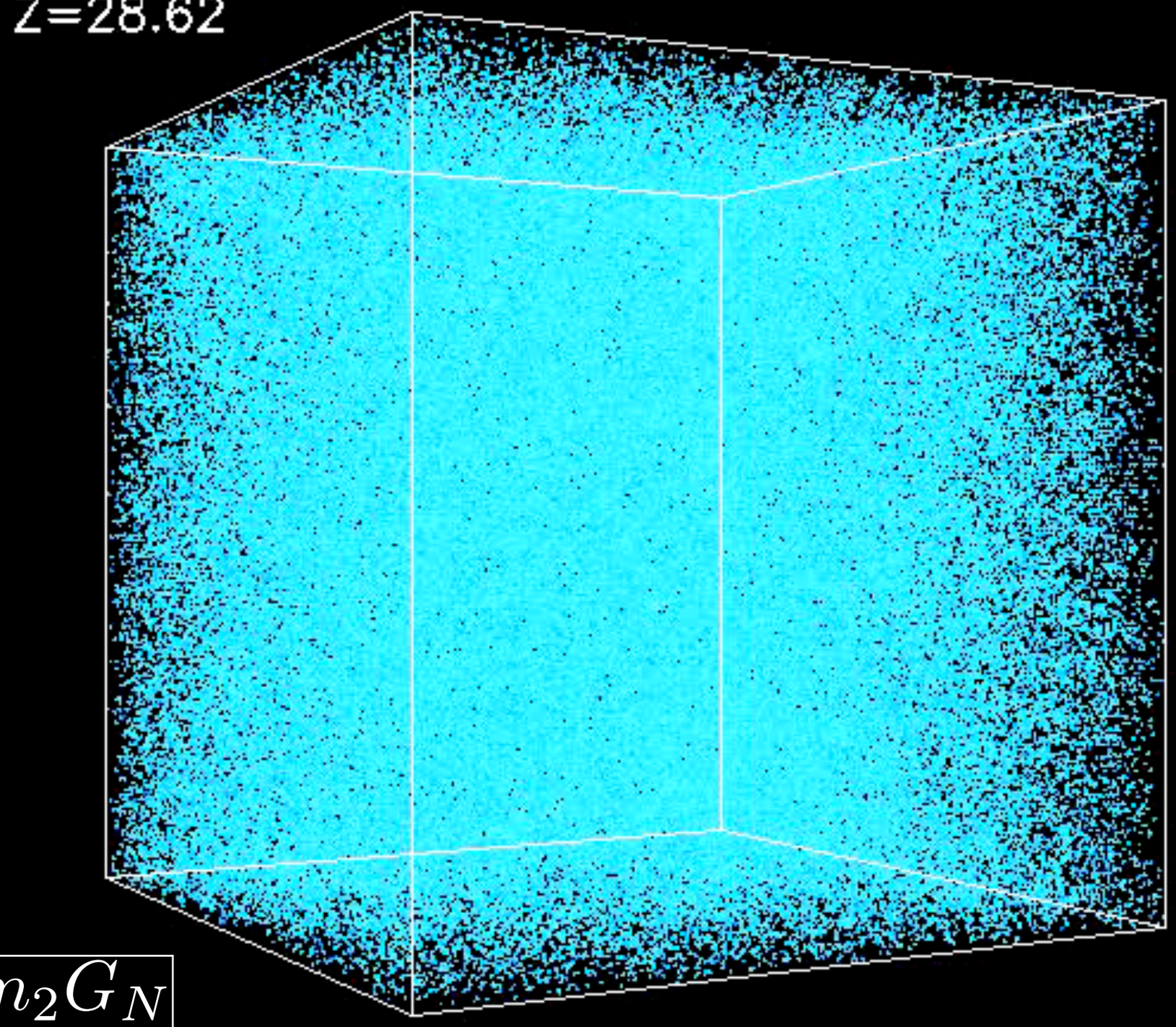
Expansion leads to decreasing temperature

Recombination

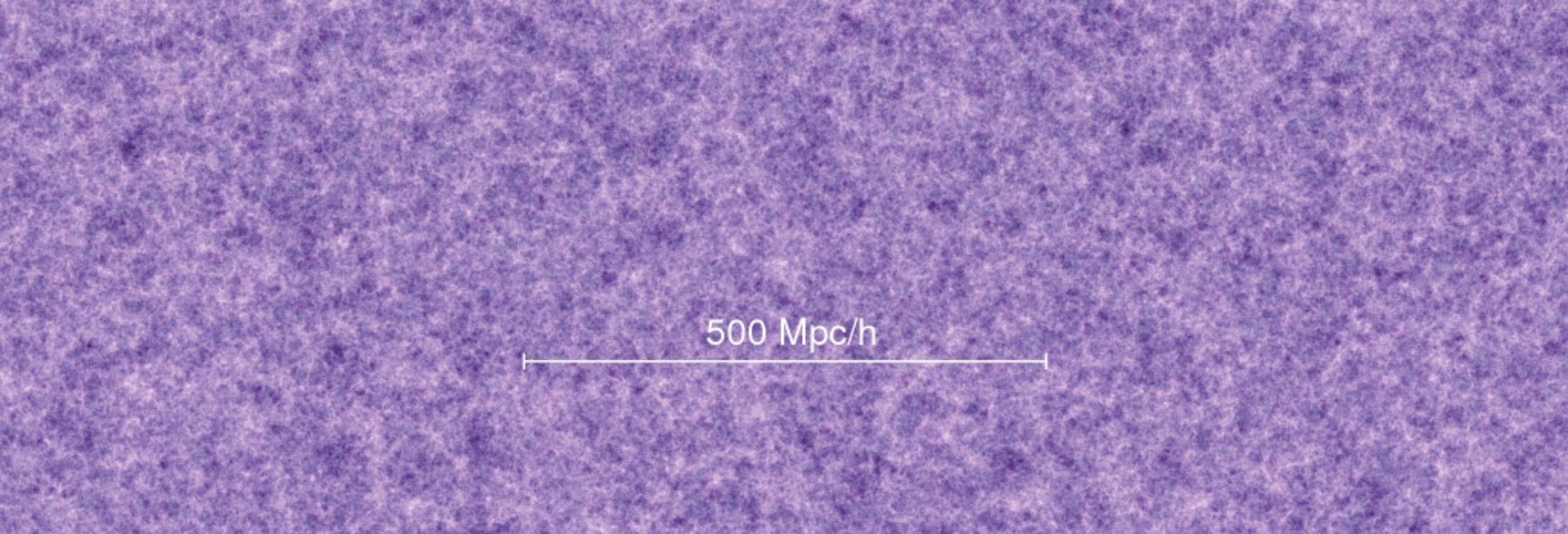
[today, 13.7 billion yrs]

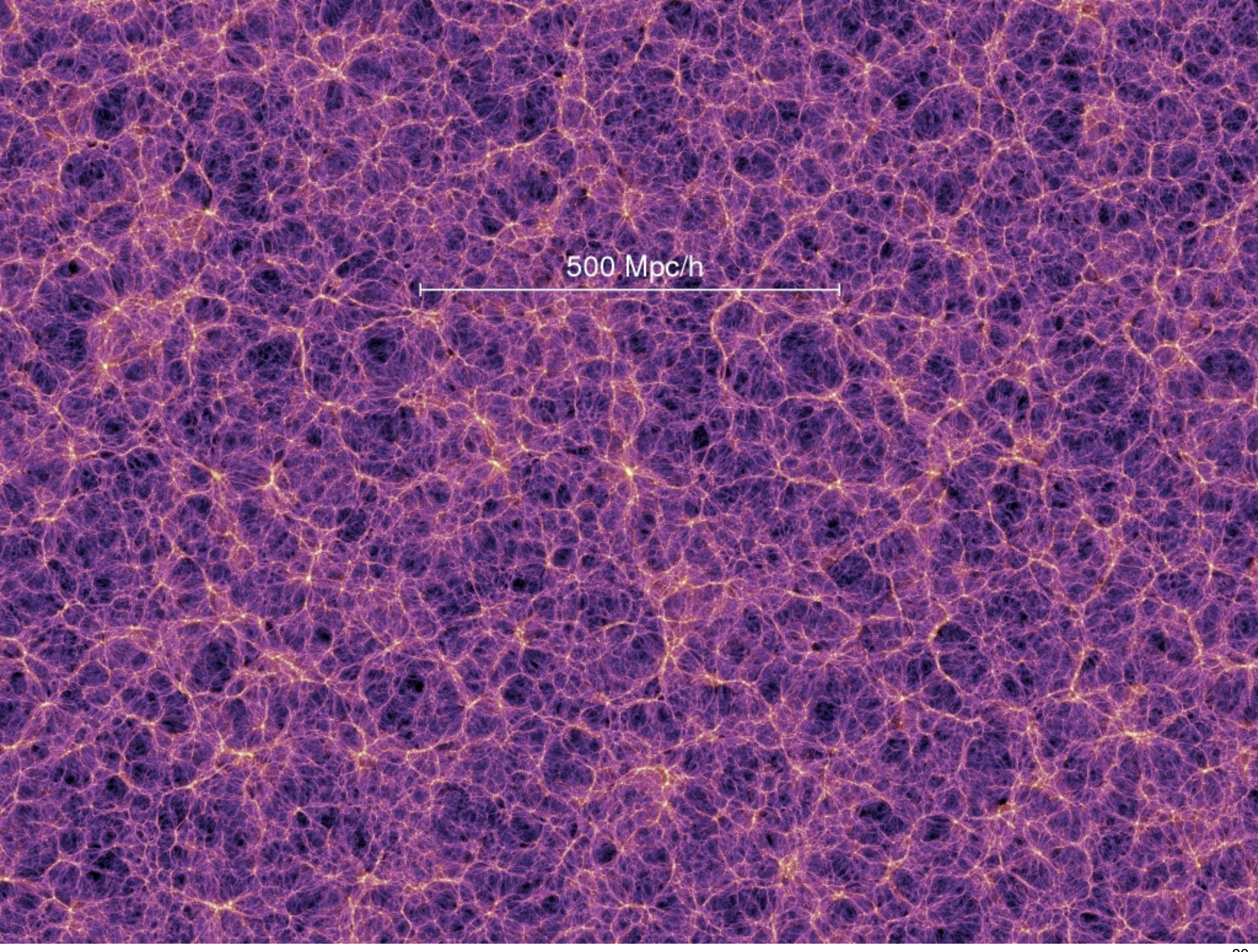
Temperature of empty space has very small spatial variation ($<10^{-5}$); very nearly a blackbody.


Z=28.62



$$F = \frac{m_1 m_2 G_N}{r^2}$$


500 Mpc/h

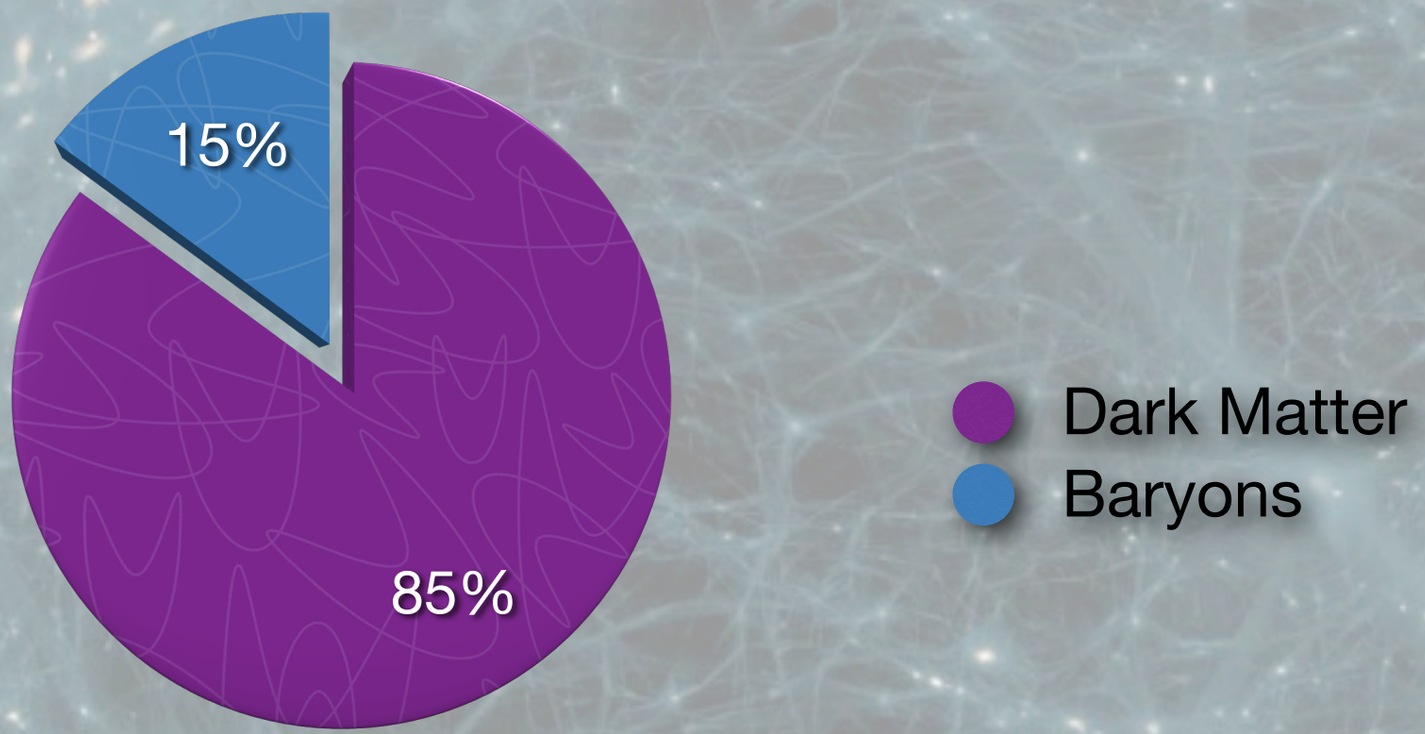

500 Mpc/h

Growth of Structure


The Contiguous United States
Visualized by distance to the nearest McDonald's
Created by Stephen Von Worley
http://www.weathersealed.com/tags/maps/
Location data courtesy of AggData
http://www.aggdata.com/

Our Cosmic Web

- regions of initially high density gather up the mass from less dense regions (and vice versa)
- Dark matter rules the day in recent epochs via gravitational attraction.



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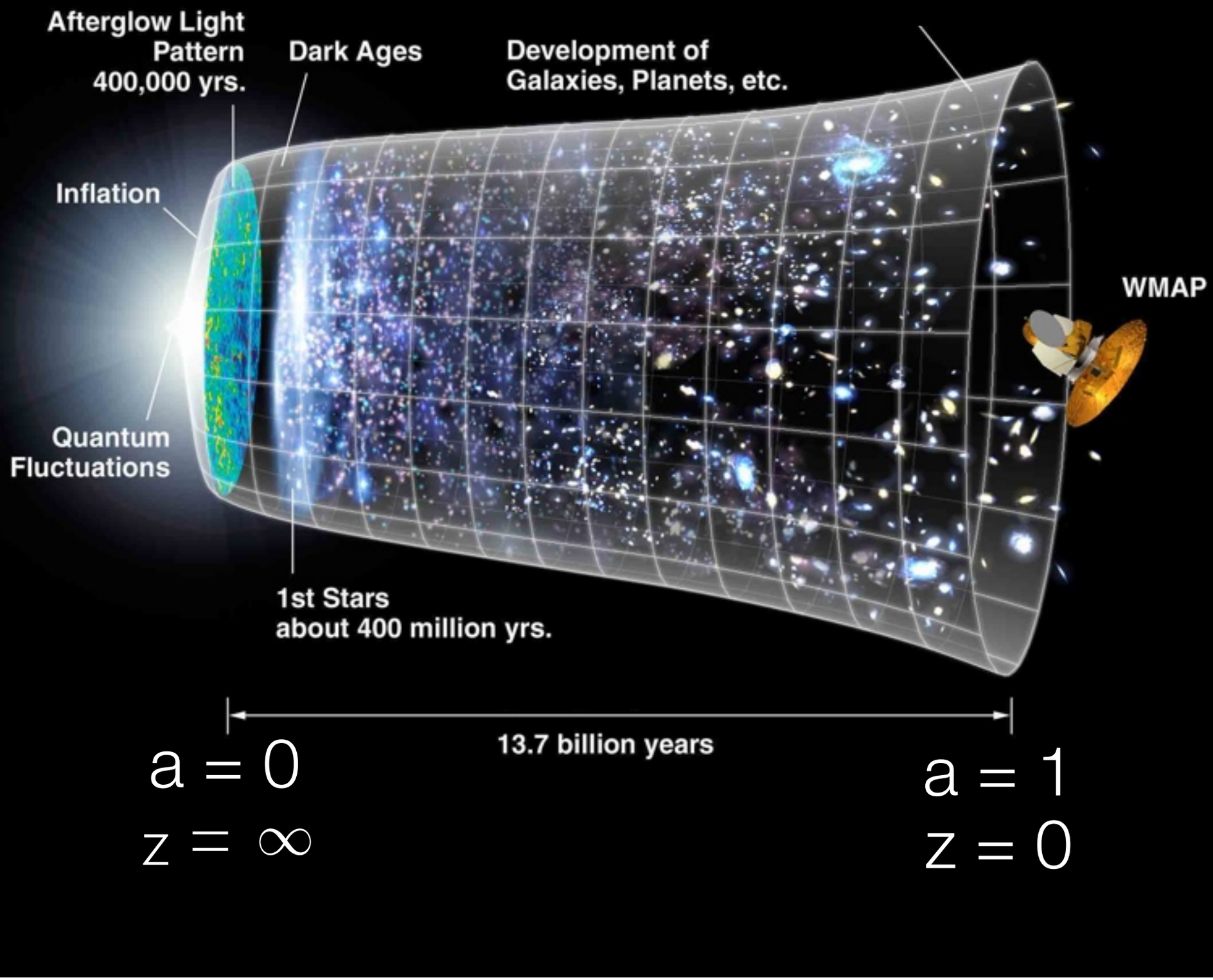
An Ancient Tug of War, a 100-year Puzzle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a = 0
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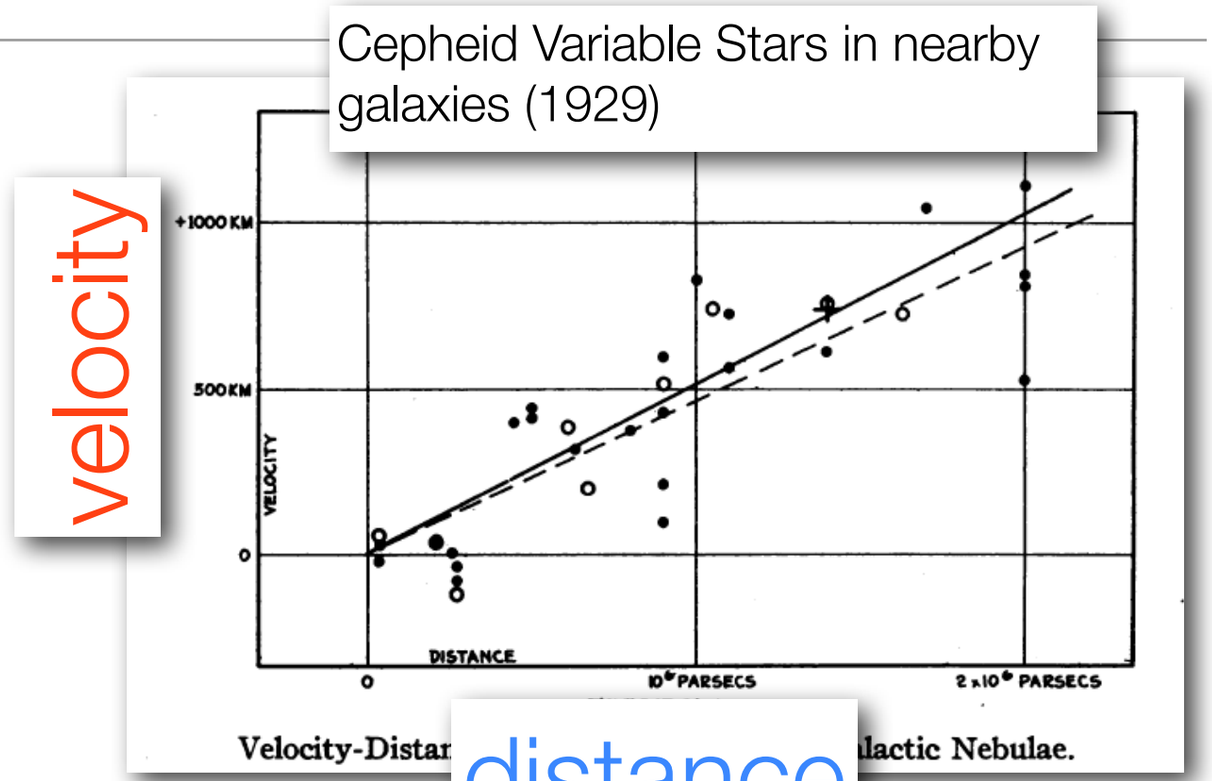
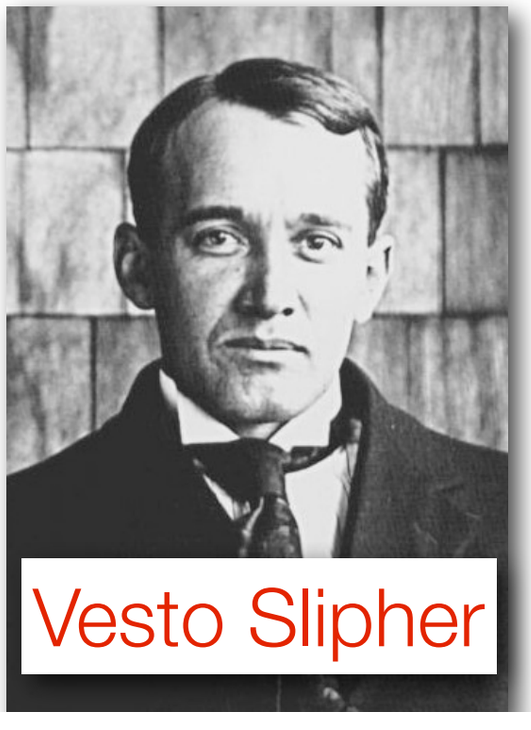
NASA/WMAP Science Team

A Tug of War
In an Expanding Universe

$$H = v / d$$

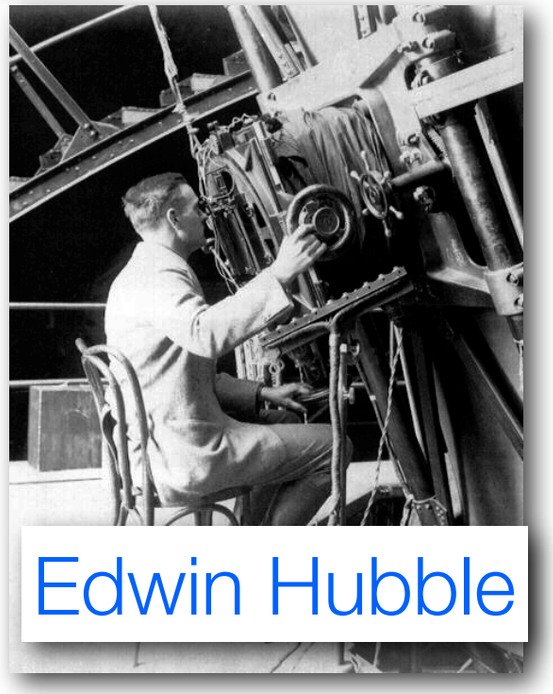
- Expansion of space-time:
  - a(t): scale factor is relative size of the universe at time, t
- Space Moves Matter
  - expansion carries galaxies away
  - redshifts light: $1+z = a(t_0)/a(t)$




Vesto Slipher

Cepheid variables in distant nebulae

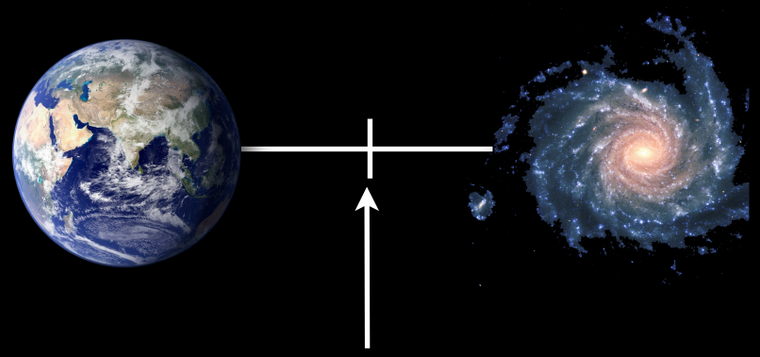
- Slipher performed spectroscopy to measure the velocities.
- Hubble measured distances and used Slipher's data (without reference to that work)


Edwin Hubble

Physical Effect of Hubble Expansion

$$H = v / d$$

[km / s / Megaparsec]



Example:

constant positive Hubble value

⇒ “stuff” is accelerating even when space isn’t.

Physical Effect of Hubble Expansion

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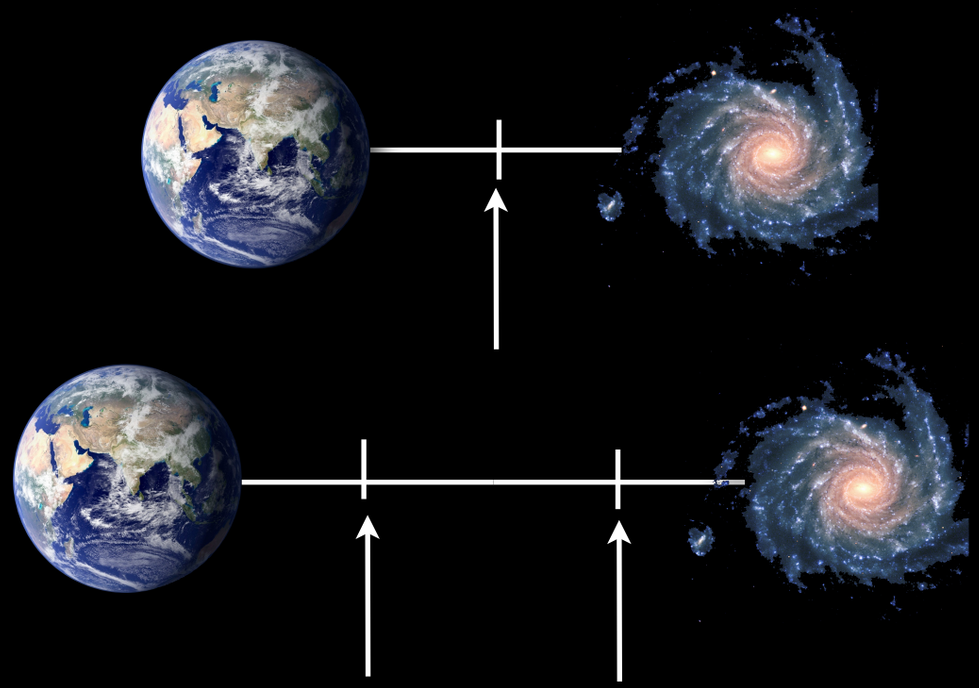
[km / s / Megaparsec]



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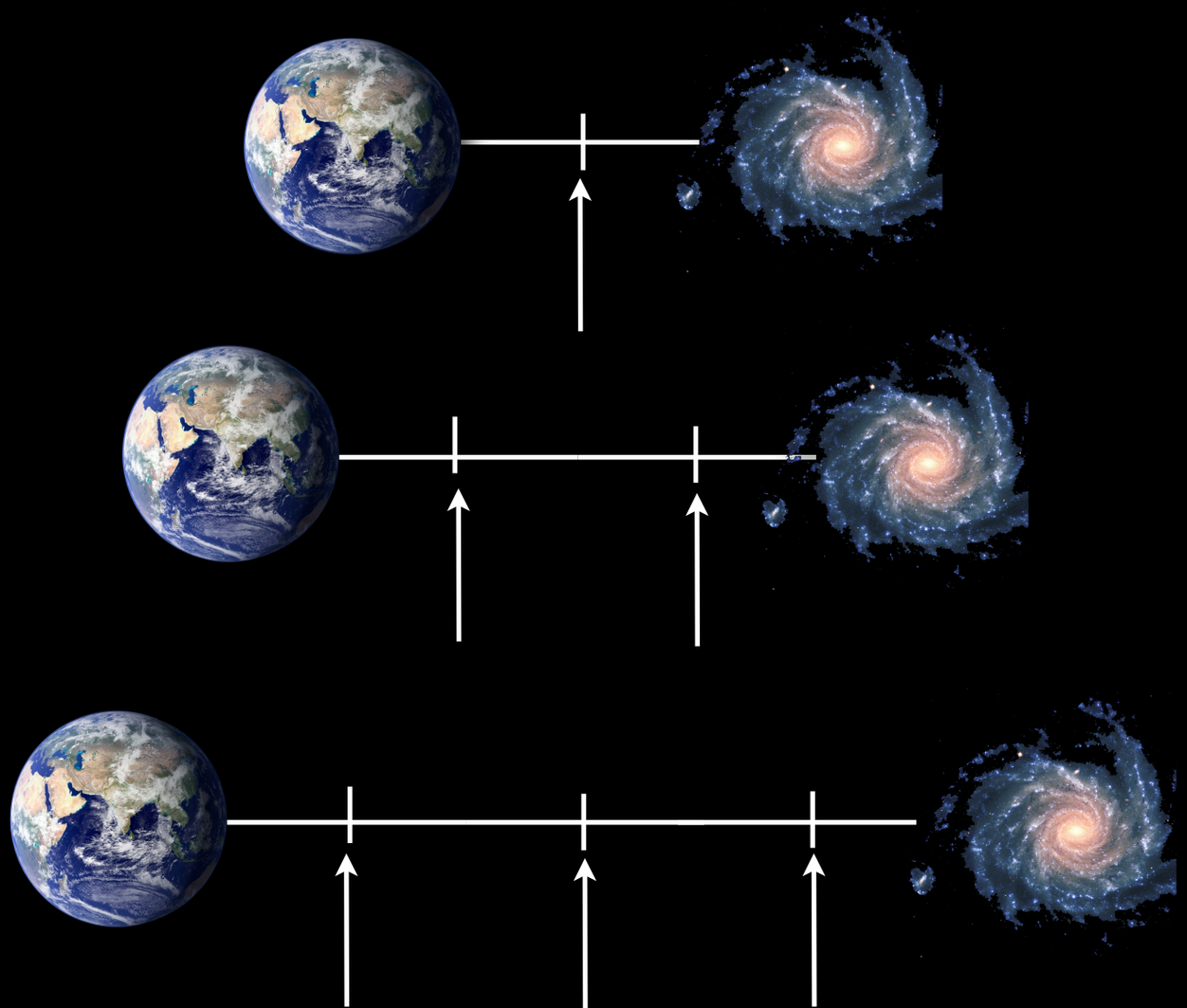

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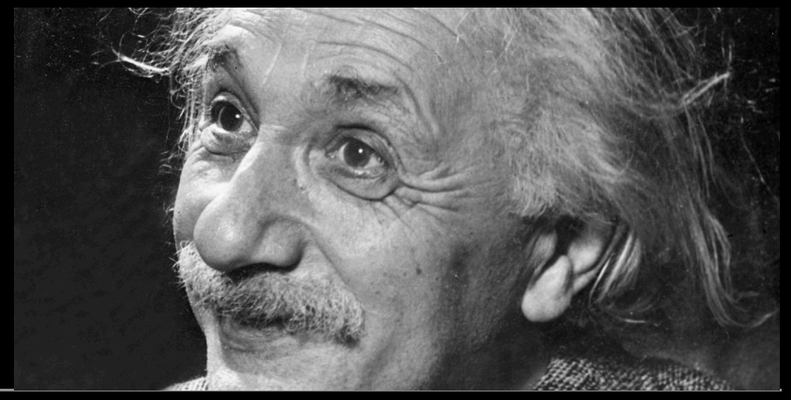
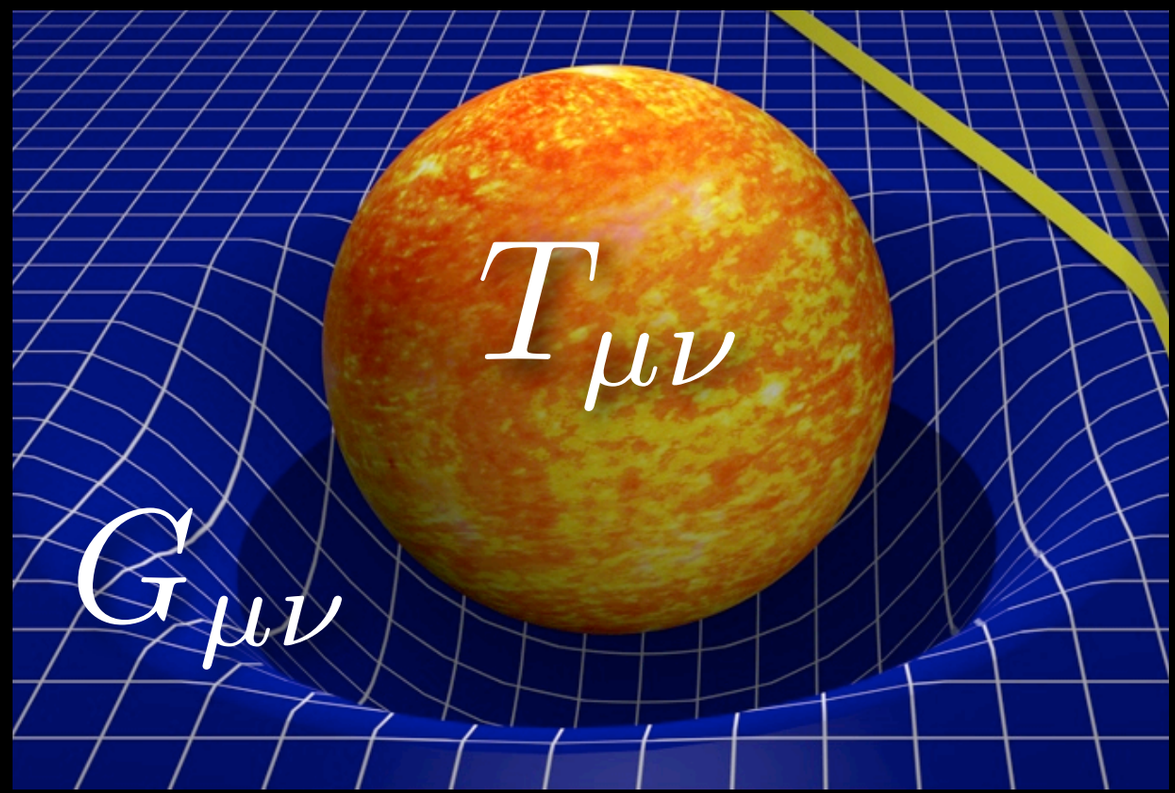
Tug of War:
Energy vs. Space-time



Energy tells space how to curve, and space tells energy how to move

$$G_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu}$$



μ, ν are indices that track the four dimensions of space and time

- (0,0) gives time/energy component
- others give spatial/pressure component

A Tug of War
Quantifying Matter-Energy Content

$$G_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu}$$

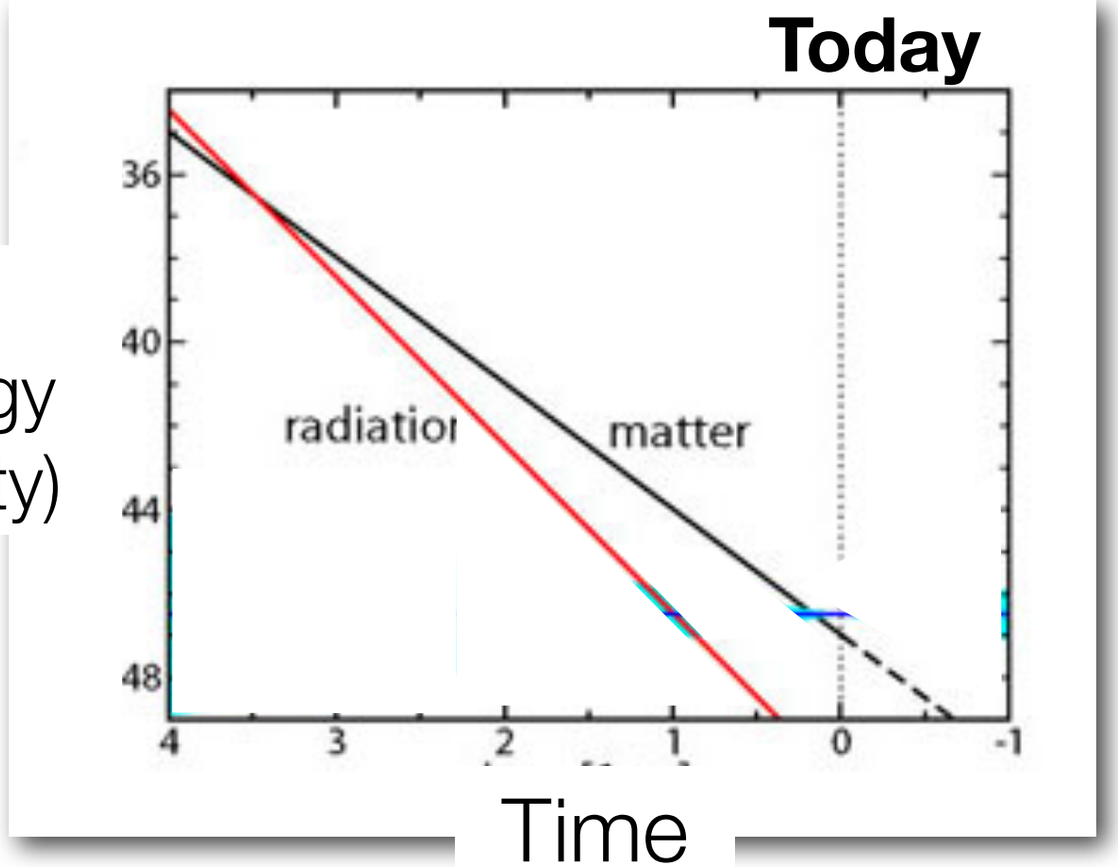
$$T_{\mu\nu} = \begin{bmatrix} \rho & 0 & 0 & 0 \\ 0 & p_x & 0 & 0 \\ 0 & 0 & p_y & 0 \\ 0 & 0 & 0 & p_z \end{bmatrix}$$

ρ_i : *density* of energy species

p_i : *pressure* of energy species

Types of energy:
matter: $\rho \propto a^{-3}$
radiation: $\rho \propto a^{-4}$

Equations of State ($w = p/\rho$)
matter: $w = 0$
radiation: $w = 1/3$



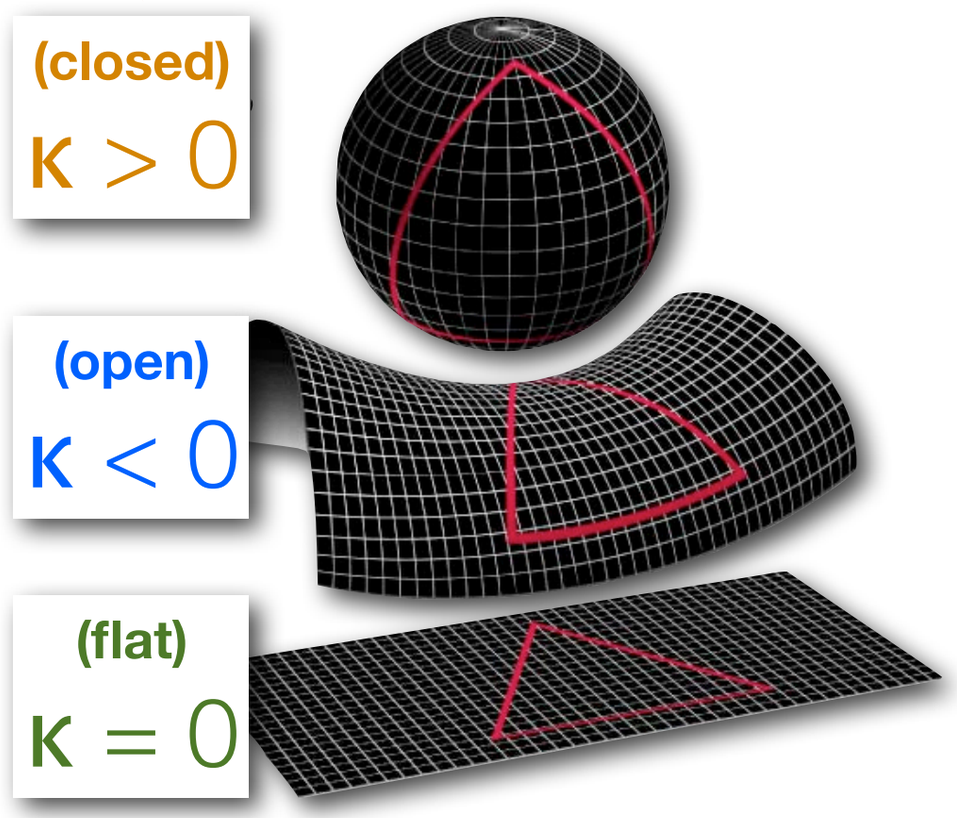
A Tug of War
Quantifying Local Geometry

$$G_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu}$$

Define a metric: a method for computing distances in **homogeneous, isotropic** space-time [FLRW metric tensor]

$$-c^2 \mathrm{d}\tau^2 = -c^2 \mathrm{d}t^2 + a(t)^2 \left[\frac{\mathrm{d}r^2}{1 - \kappa r^2} + r^2 \mathrm{d}\Omega^2 \right]$$

- $\mathbf{G_{\mu\nu}}$ defines the response of space-time to local energies and pressures
- Einstein curvature tensor ($\mathbf{G_{\mu\nu}}$) is a function then of r, a(t) and **K**



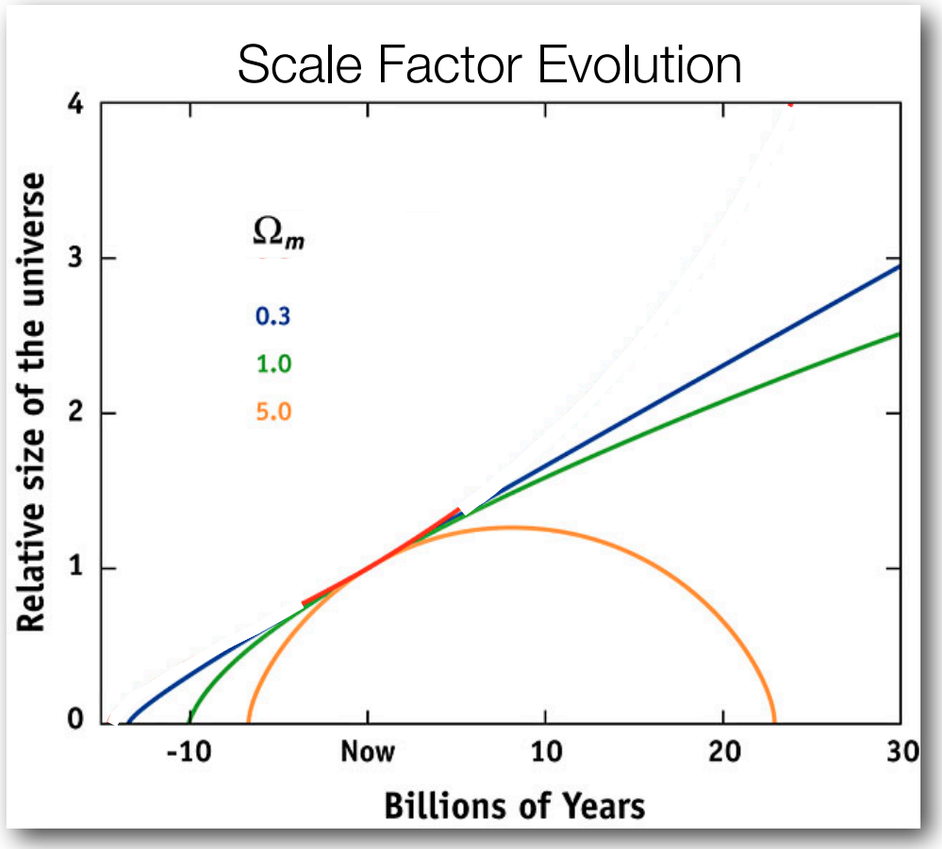
Cosmic Equations of Motion

$$G_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu}$$

Compare $G_{\mu\nu}$ and $T_{\mu\nu}$, *component by component*, to obtain equations of motion for scale of universe (a, ȧ, ä).

(speed) $$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\sum_i \rho_i - \frac{\kappa}{a^2}$$

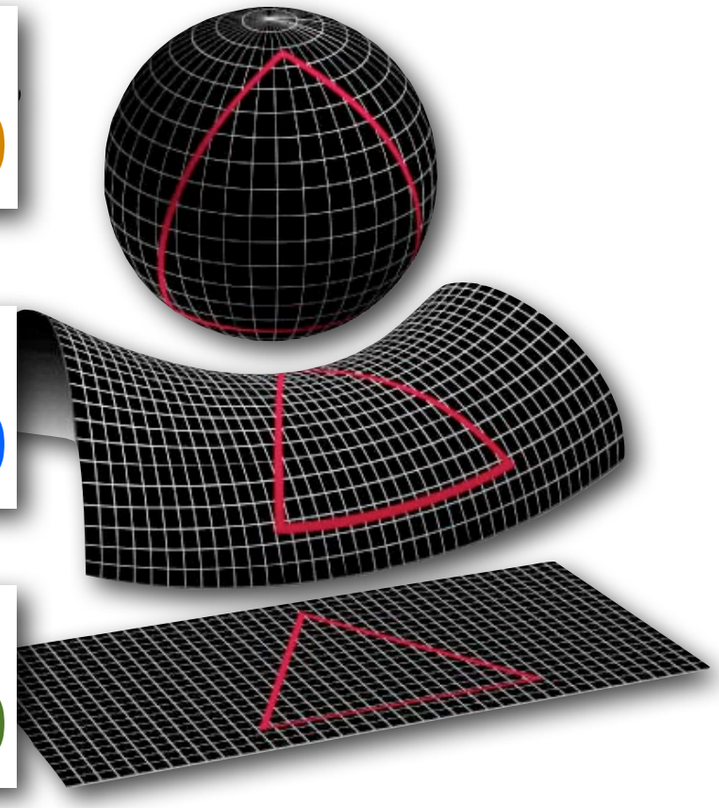
(acceleration) $$\frac{\ddot{a}}{a} = -\frac{-4\pi G_N}{3}\sum_i (\rho_i + 3p_i)$$



(closed) $\kappa > 0$

(open) $\kappa < 0$

(flat) $\kappa = 0$



The Consequences

The local geometry and the energy density are intimately linked.

$\rho_{crit} = 3H^2 / 8\pi G_N$ (critical density)

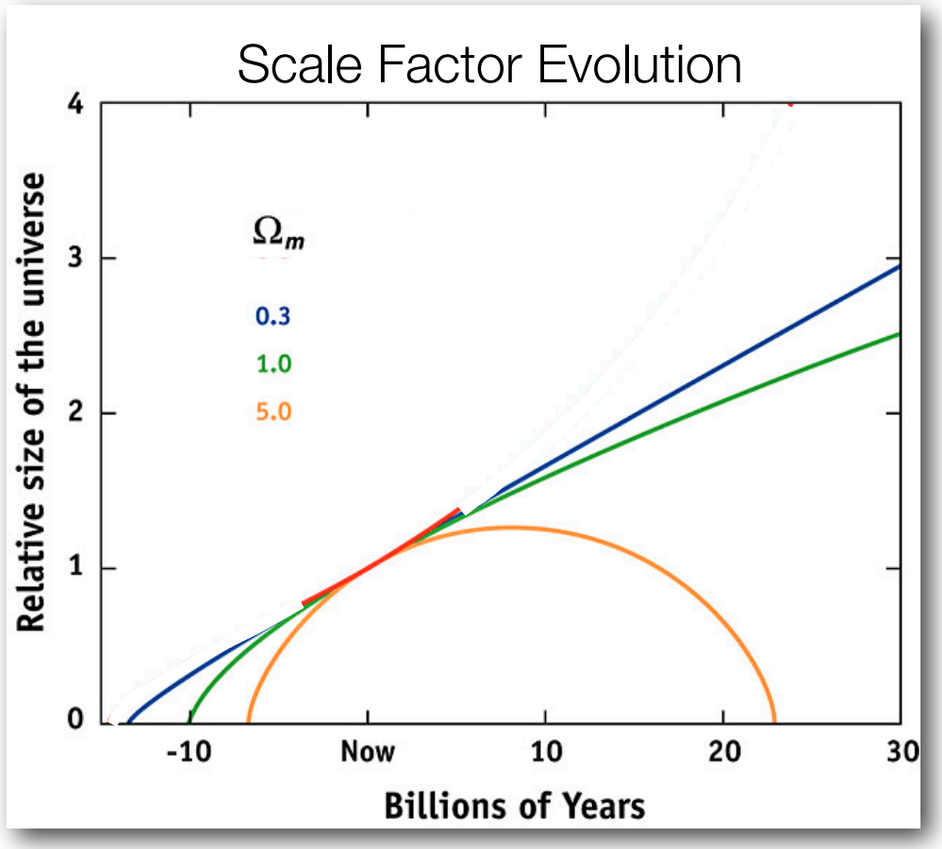
$\Omega_i = \rho_i / \rho_{crit}$

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

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\sum_i \rho_i - \frac{\kappa}{a^2}$$

$$\Downarrow$$

$$1 = \Omega_{\rm tot} - \Omega_\kappa$$



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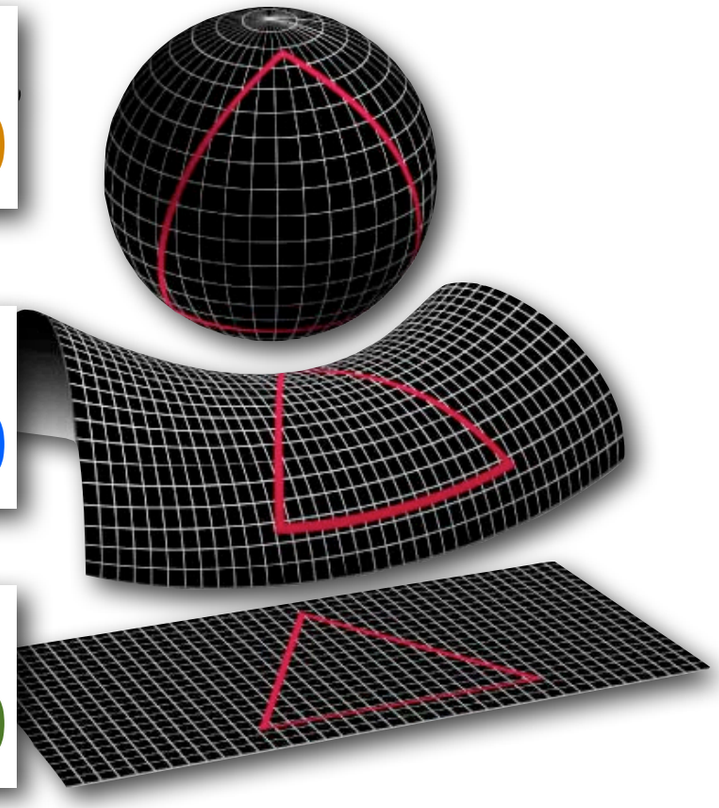
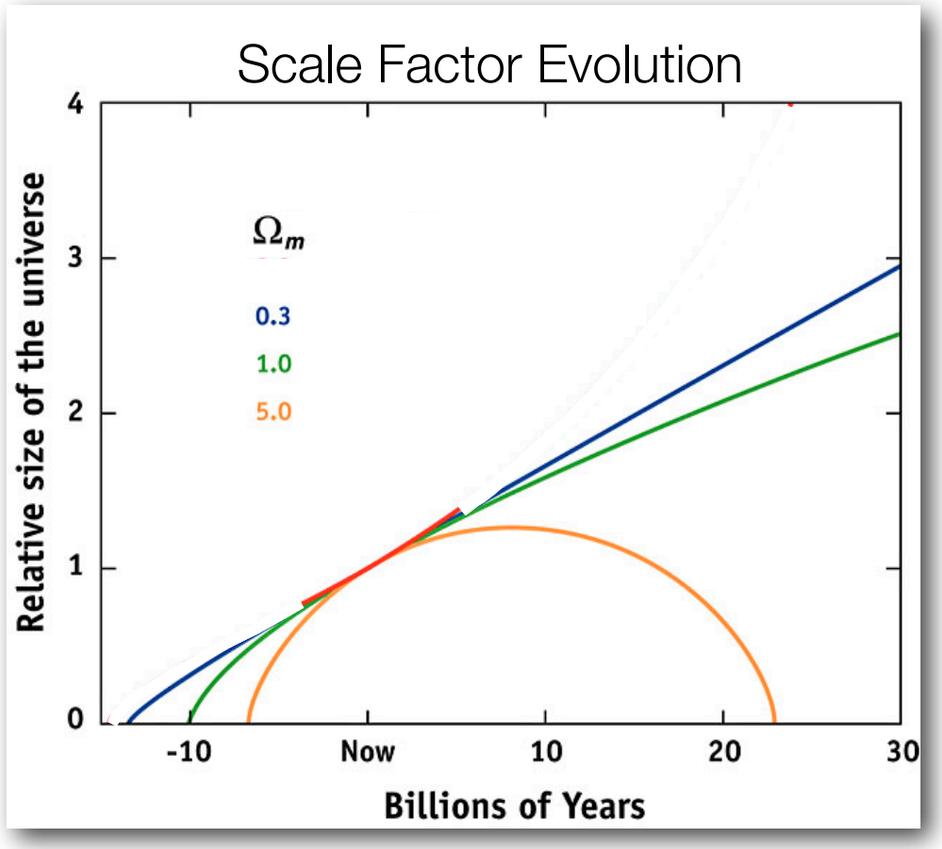
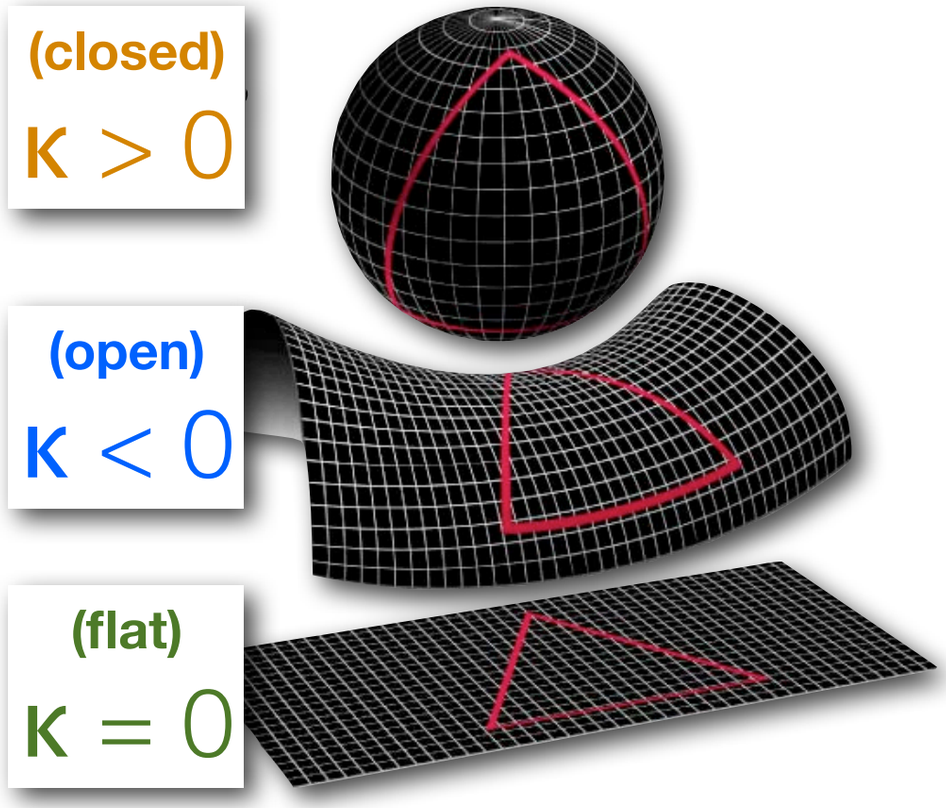


A Matter of Fate

Is there enough matter to close the universe, to cause the universe to re-collapse?

$$1 = \Omega_{\mathrm{tot}} - \Omega_{\kappa}$$





What will win the tug of war?

- Step 1: ‘Weigh’ the Universe.
- Step 2: Measure the shape of the universe.
- Step 3: Measure the speed of expansion.

36

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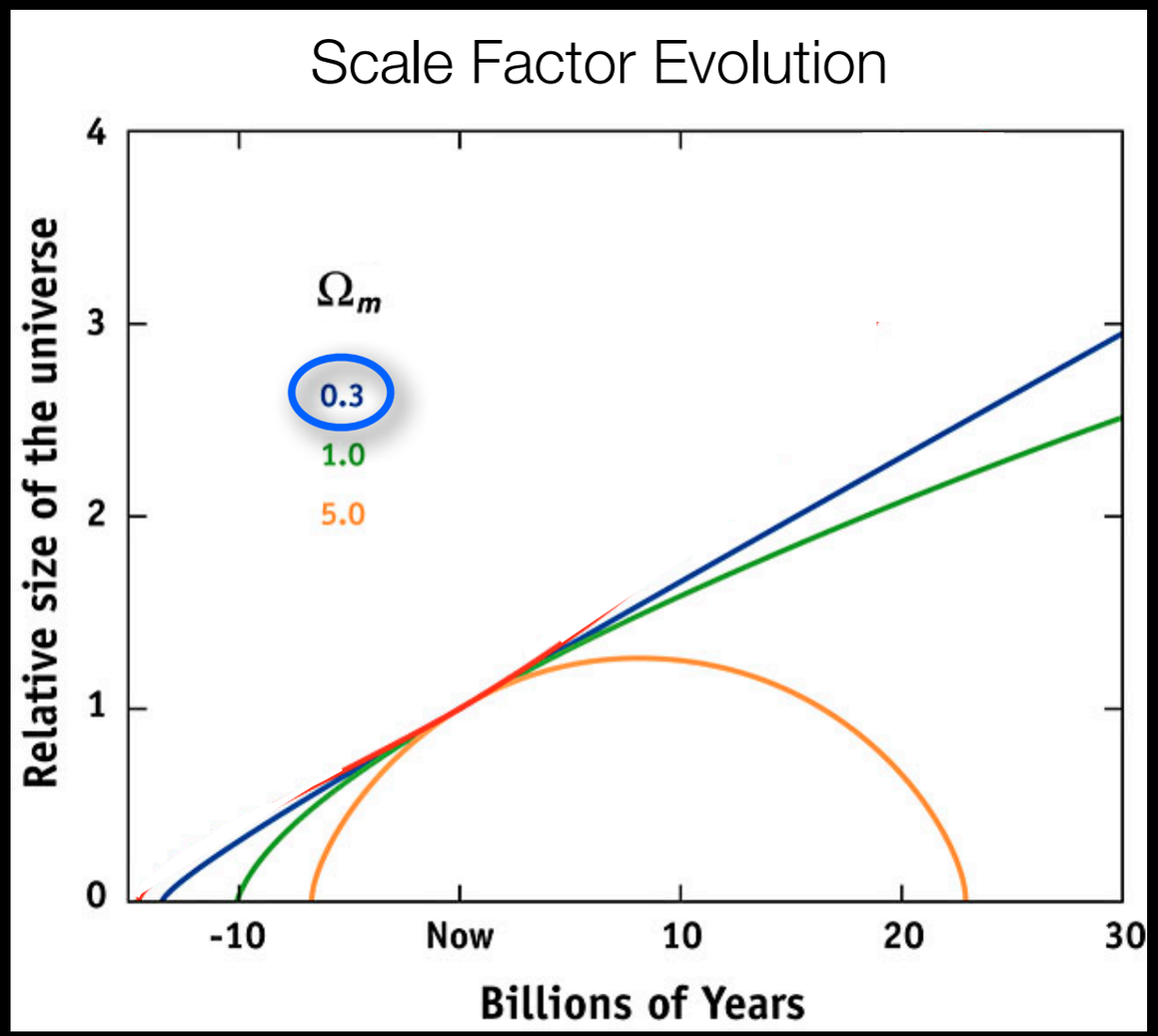
Galaxy Surveys
(e.g., Sloan Digital Sky Survey)

Use large-throughput optical telescopes to find and measure large galaxy samples



1. Find <u>all</u> galaxies in a spatial volume
2. Through other methods measure amount of dark matter per galaxy
3. Count total mass of baryonic and dark matter within the volume

$\Omega_{tot} \sim \Omega_M = 0.3$

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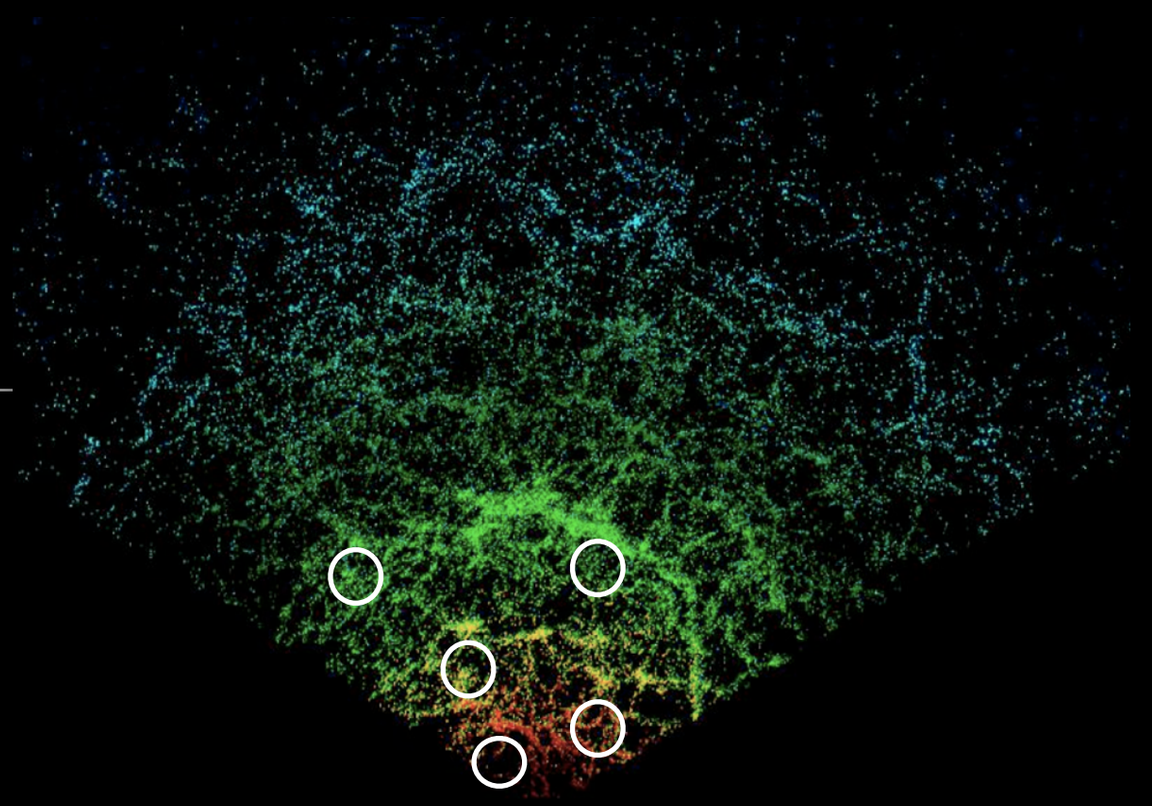

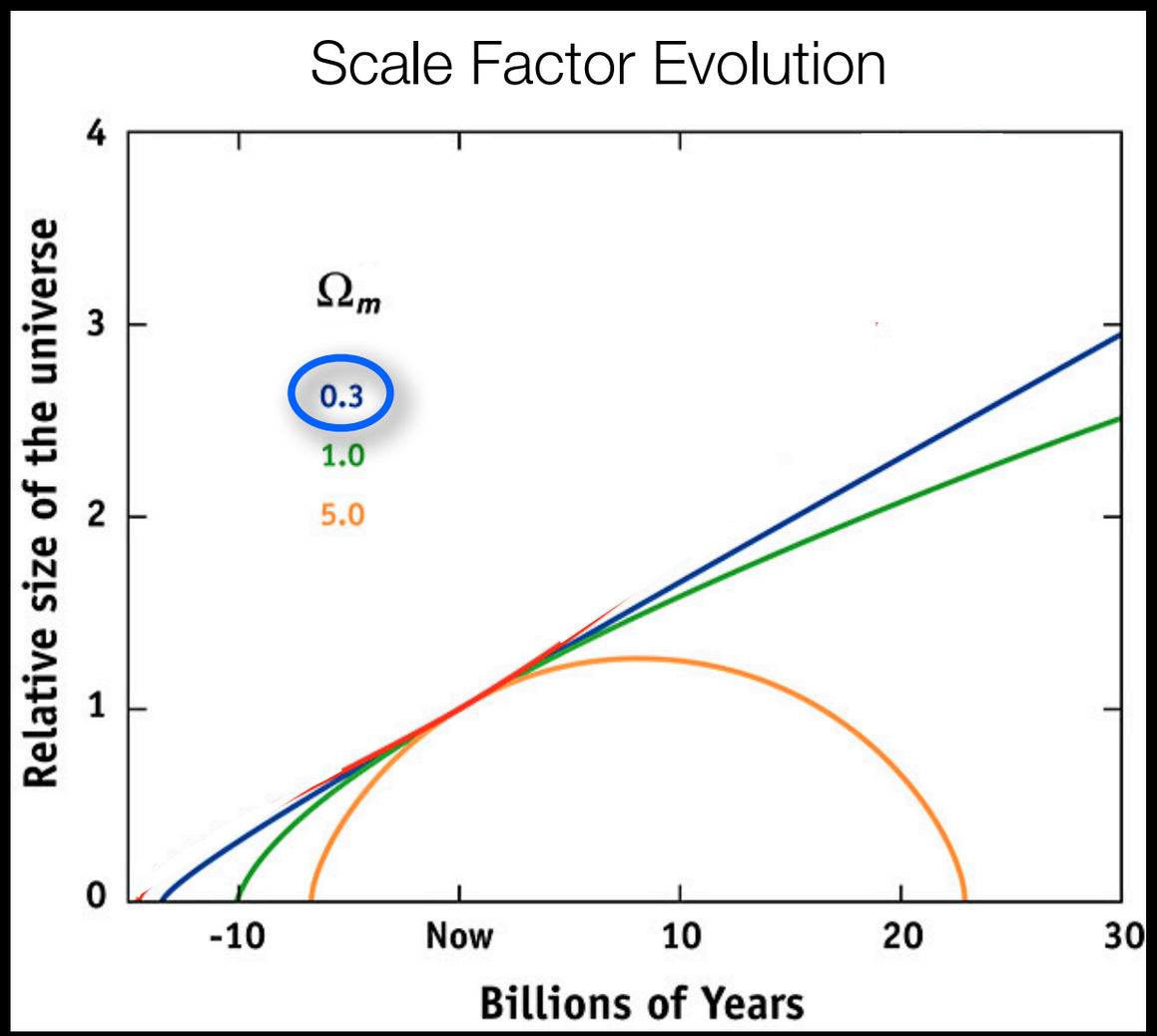

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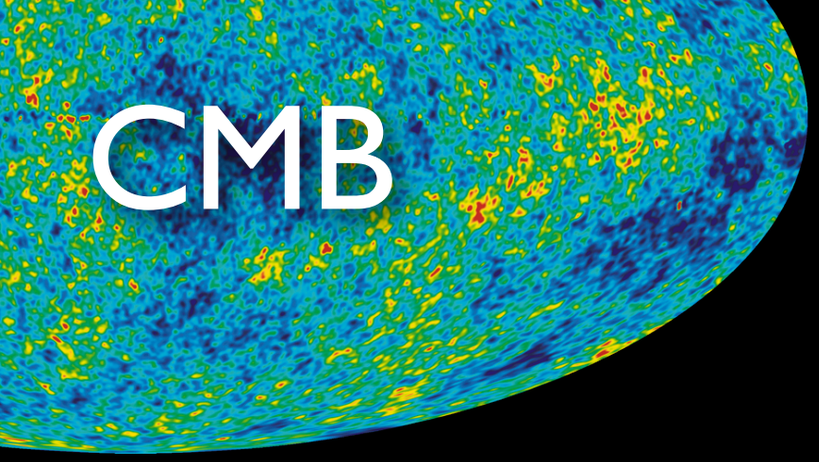
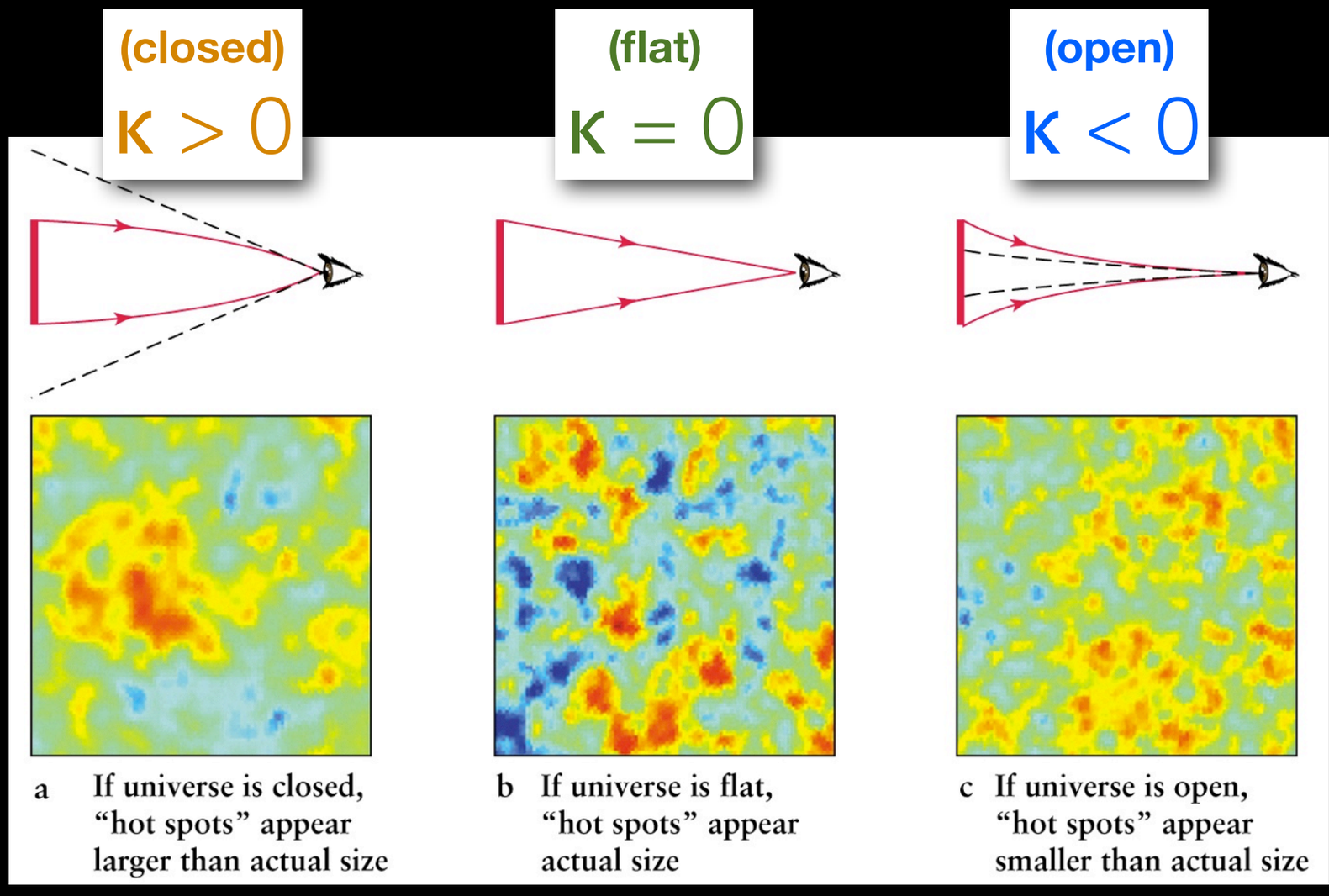


The baryon-photon fluid

- has characteristic length scale set by sound speed
- has known time (distance away) at which it occurred

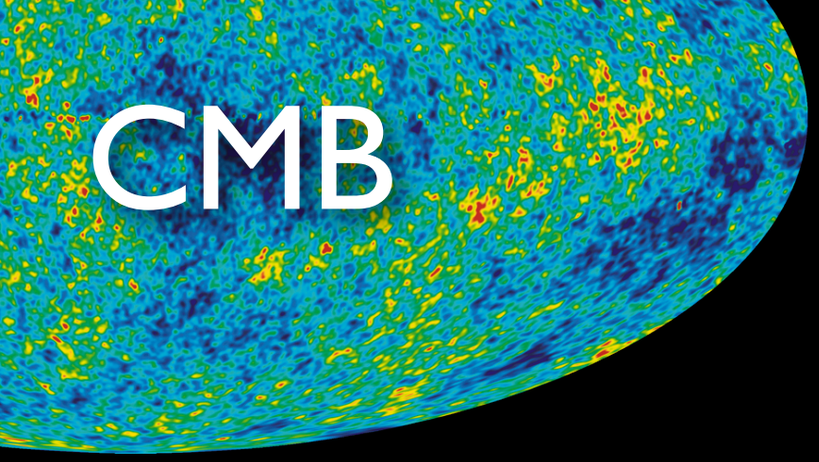
We measure the angle from those elements of the triangle (and thus curvature)



a If universe is closed, "hot spots" appear larger than actual size

b If universe is flat, "hot spots" appear actual size

c If universe is open, "hot spots" appear smaller than actual size



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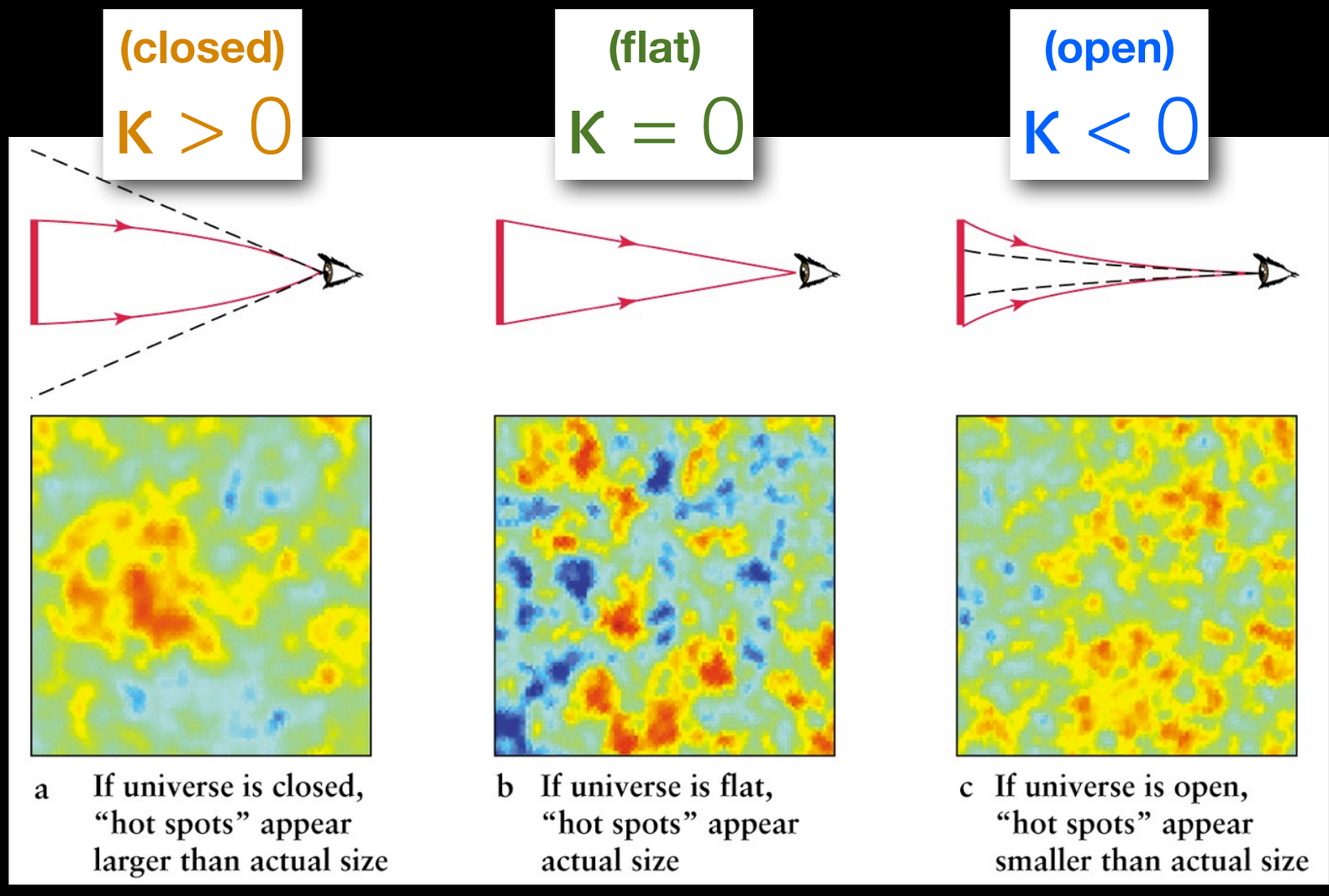
$$1 = \Omega_{\rm M} - \Omega_\kappa$$

$$\Omega_\kappa = 0$$

$$\Omega_{\rm M} = 0.3$$

$$\Downarrow$$

$$1 = \Omega_{\rm M} + ?$$



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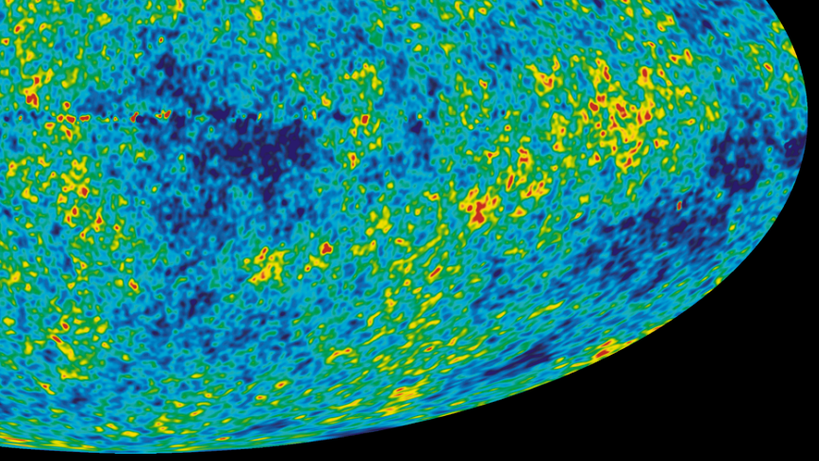
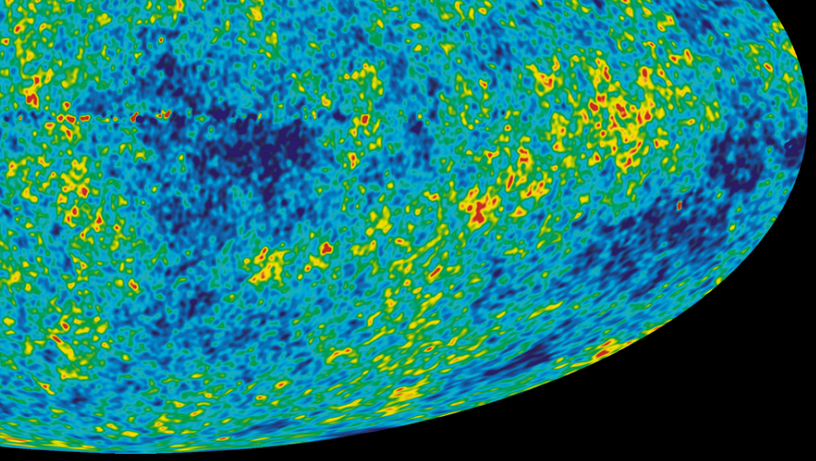
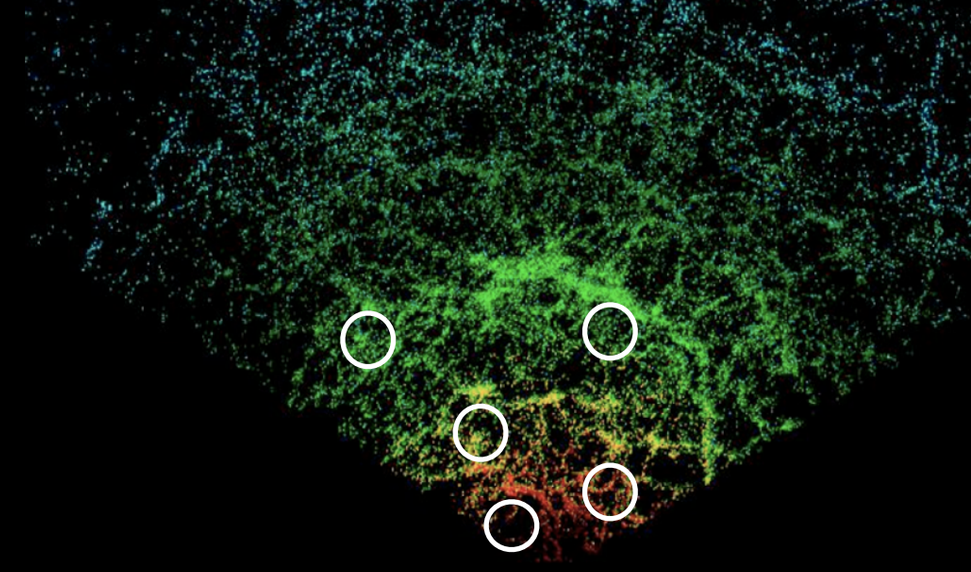


- The universe is under-dense (in matter).
- The geometry of the universe is flat.
- ... Is there an energy for which we have not yet accounted?





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What will win the tug of war?

- Step 1: ‘Weigh’ the Universe.
- Step 2: Measure the shape of the universe.
- Step 3: Measure the speed of expansion.

41

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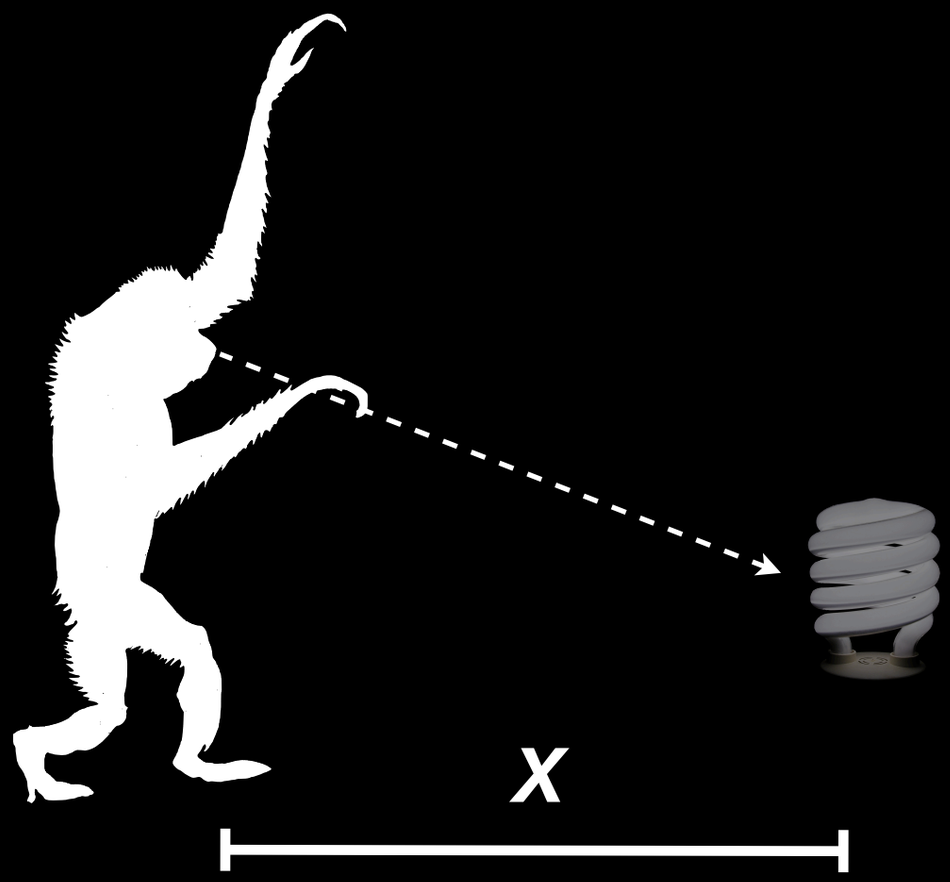
Measuring the Expansion Rate
with ‘standard candles’

start with bulb of intrinsic luminosity, $\mathbf{I_0}$ = **30W** bulb.

Observe bulb to have luminosity, **I.**
Assume distance is ***X***



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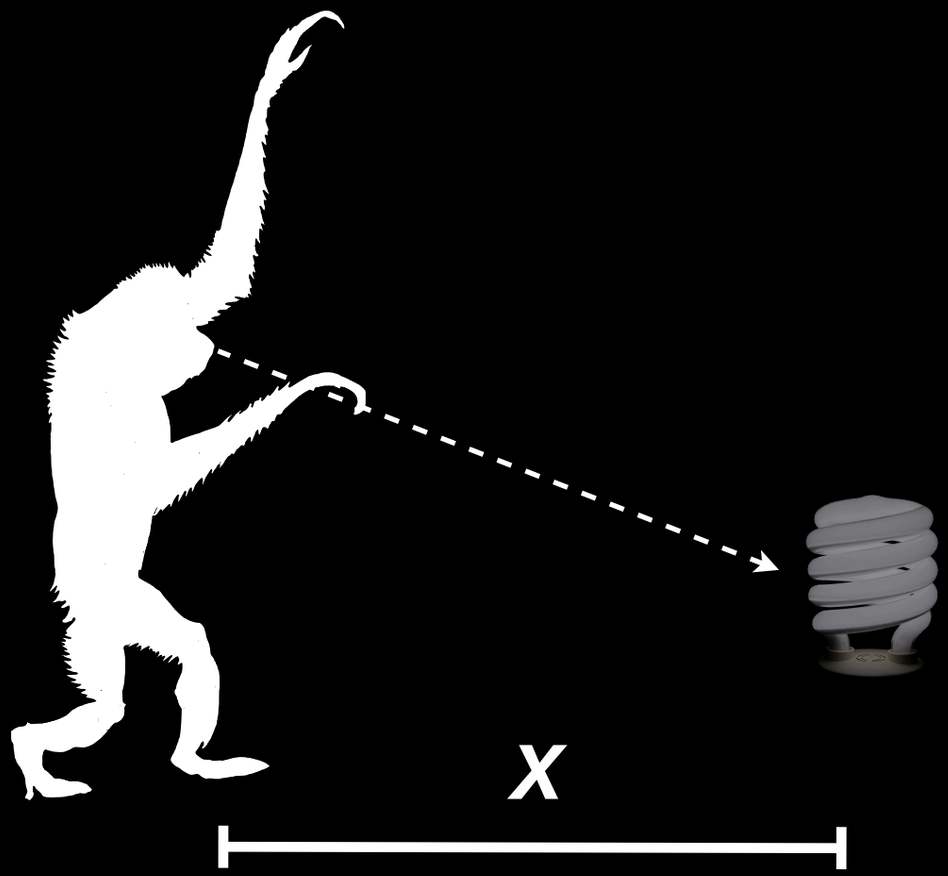
Using $I = I_0 / 4\pi X^2$, infer that I_0 = **25W**



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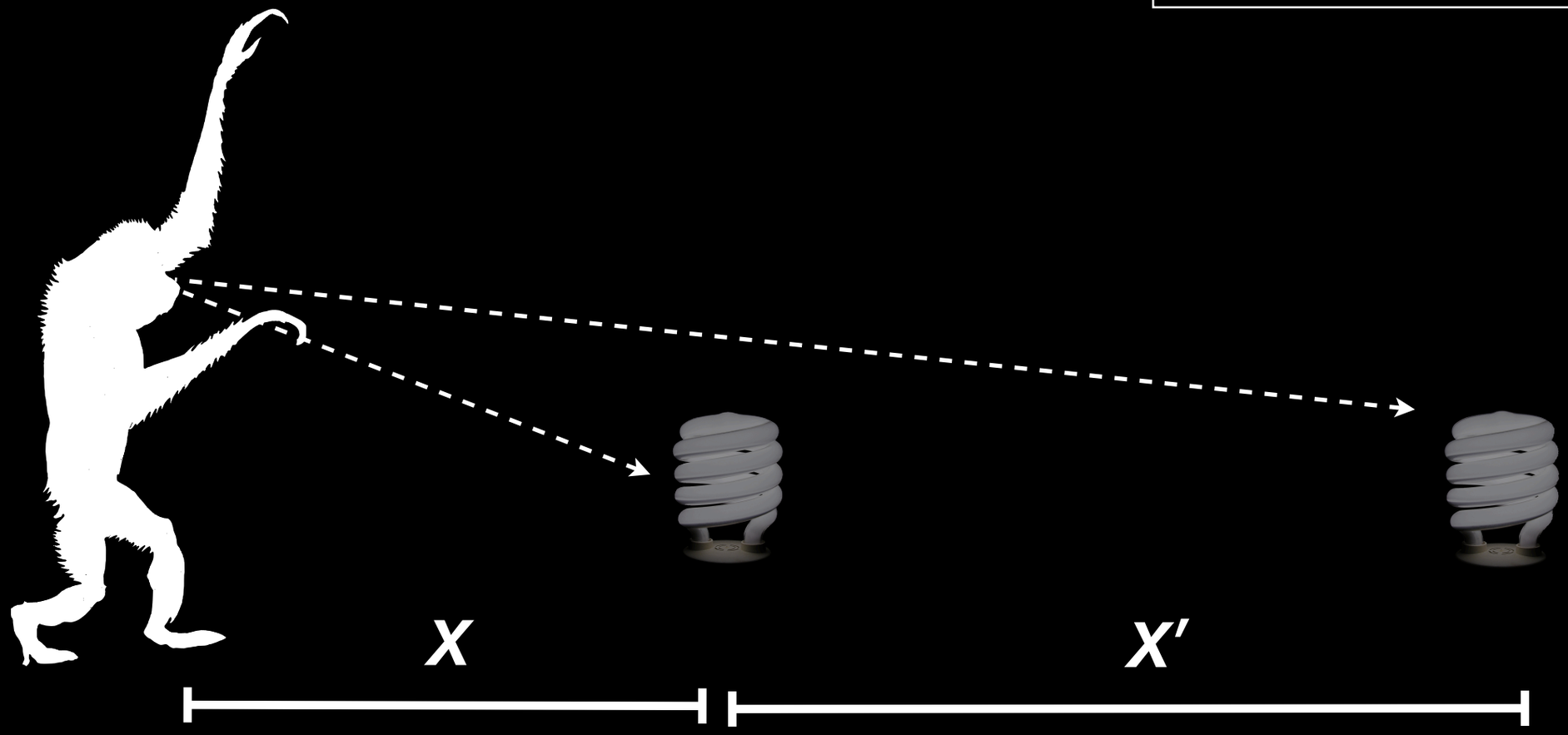
Contradiction! Bulb must then be located farther away at a distance ***X′***



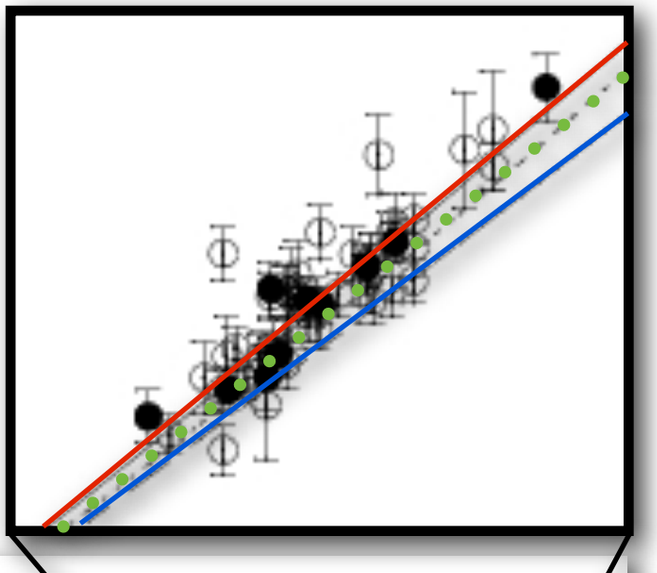
Supernovae:
Beacons in Spacetime

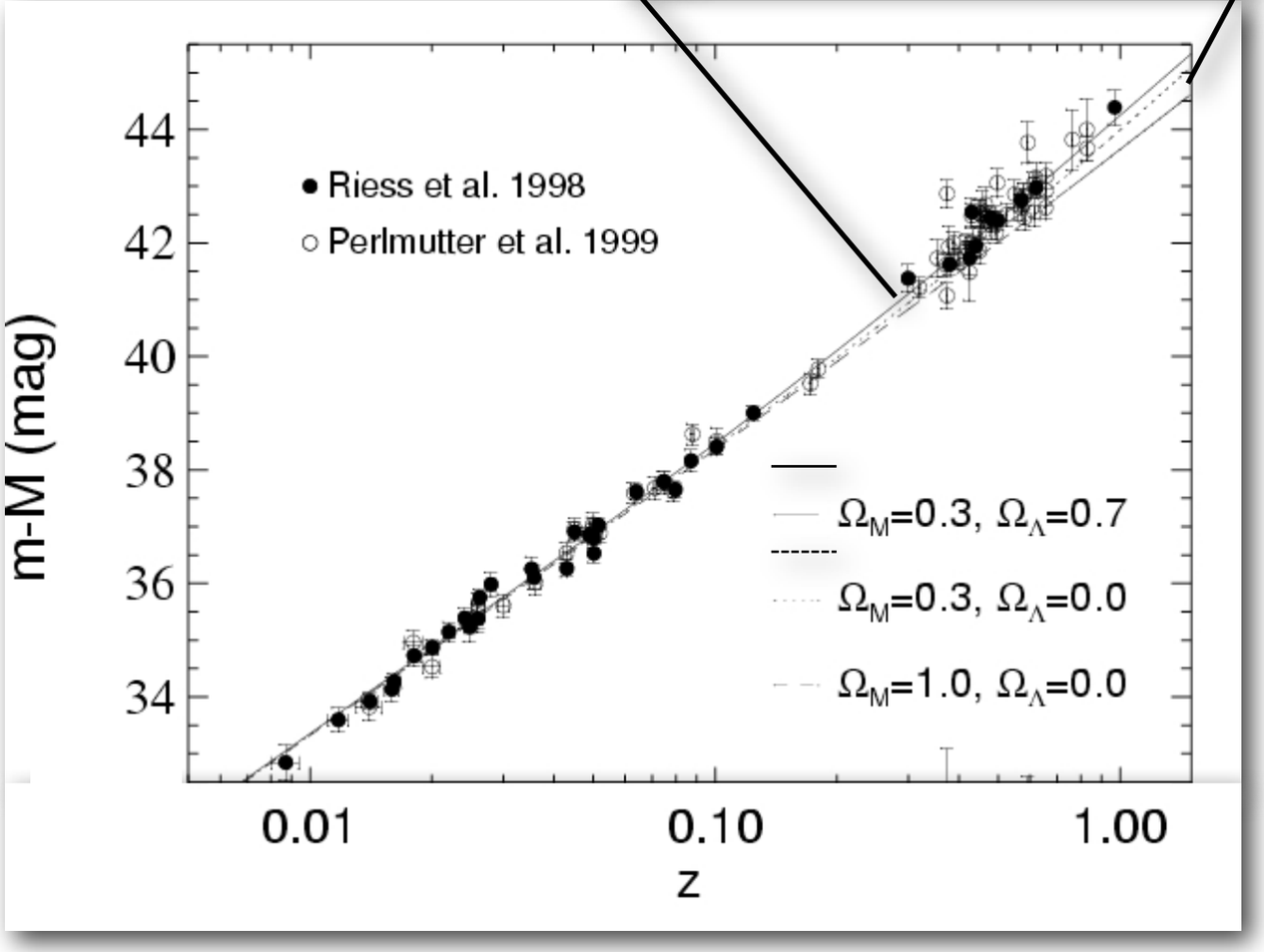
$$\Omega_M + \Omega_{DE} = 1$$

$\Omega_\Lambda = 0.7$

$\Omega_\Lambda = 0.0$

$\Omega_M = 1.0$





- Standard Candles:
  After some corrections, a type Ia SN is a "Standard Candle," and the brightness can be used to determine distances.

- 1998 Observations:
  Two teams measured distances and redshifts of Type Ia SNe using the the Mosaic Camera on the *Blanco 4m Telescope*.

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  SN are dimmer than expected for a universe that has matter only.

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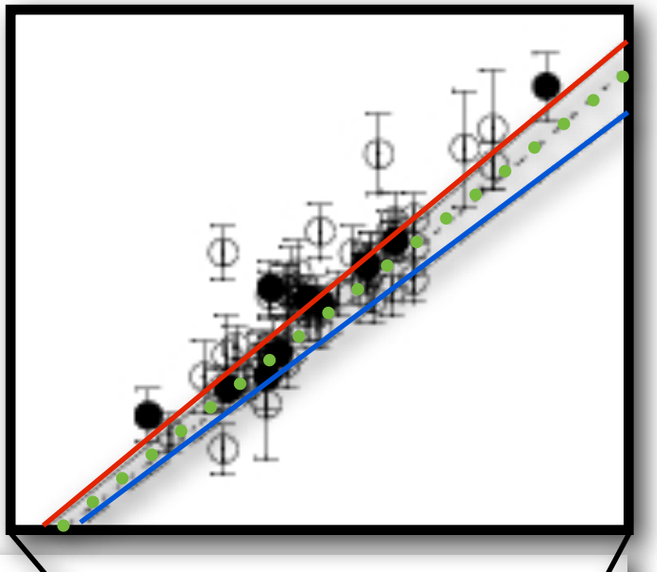

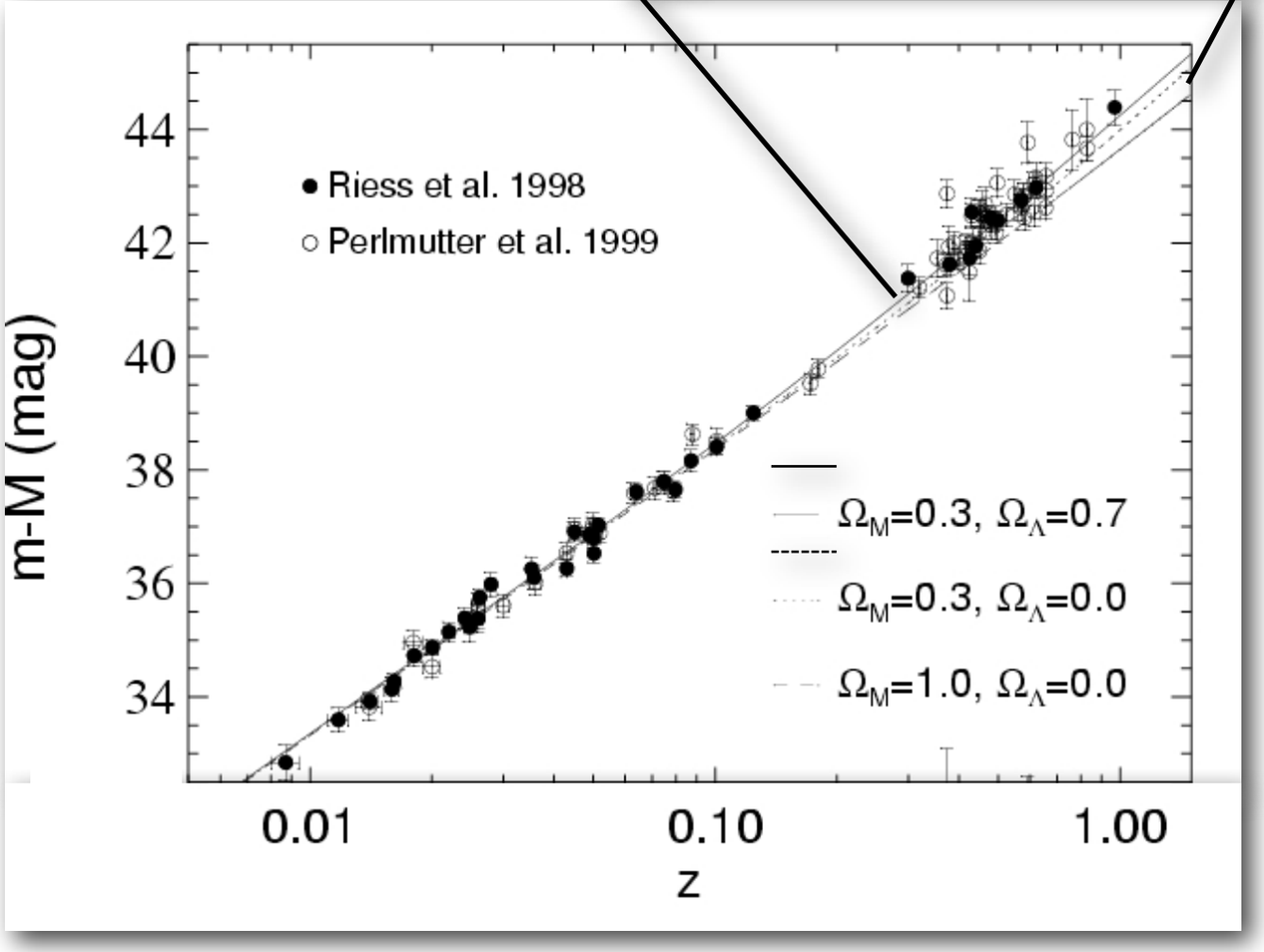

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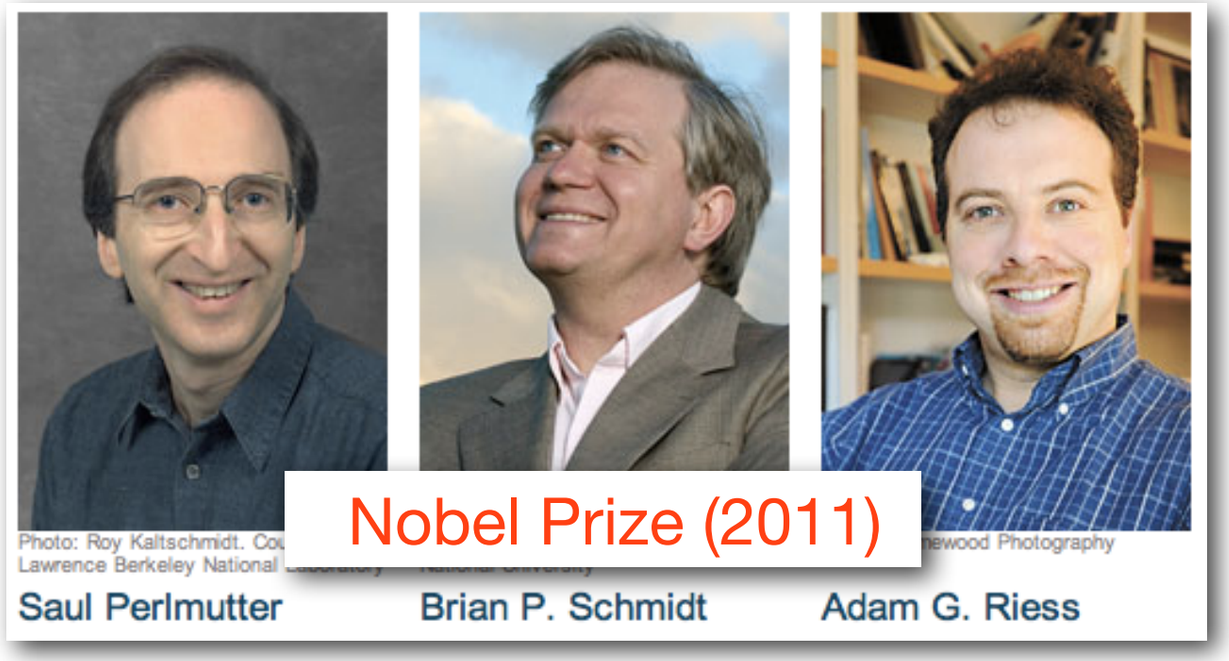
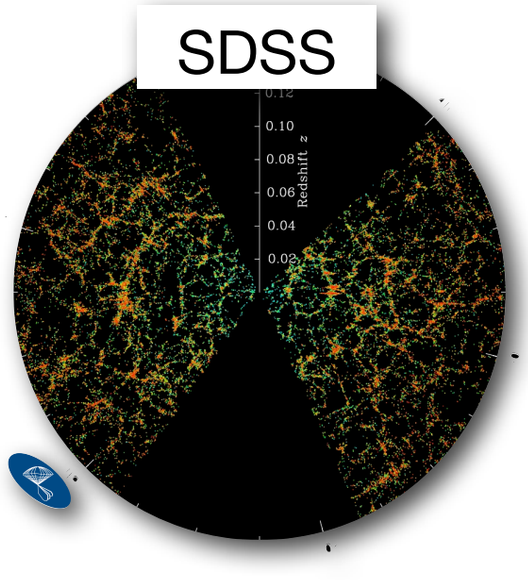


Nobel Prize (2011)

A Tug of War:
Key Results



<u>Total Matter Density:</u>

- Most matter is ‘dark’ (Zwicky and Rubin)
- Can measure total matter content within a galaxy survey volume.

➡ *Universe is matter under-dense*

$$\Omega_M \sim 0.3$$

A Tug of War:
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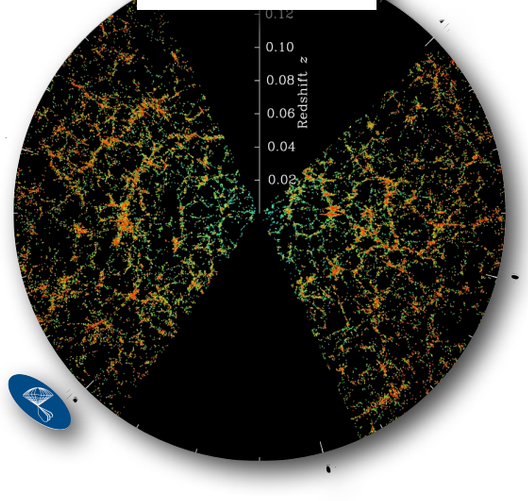
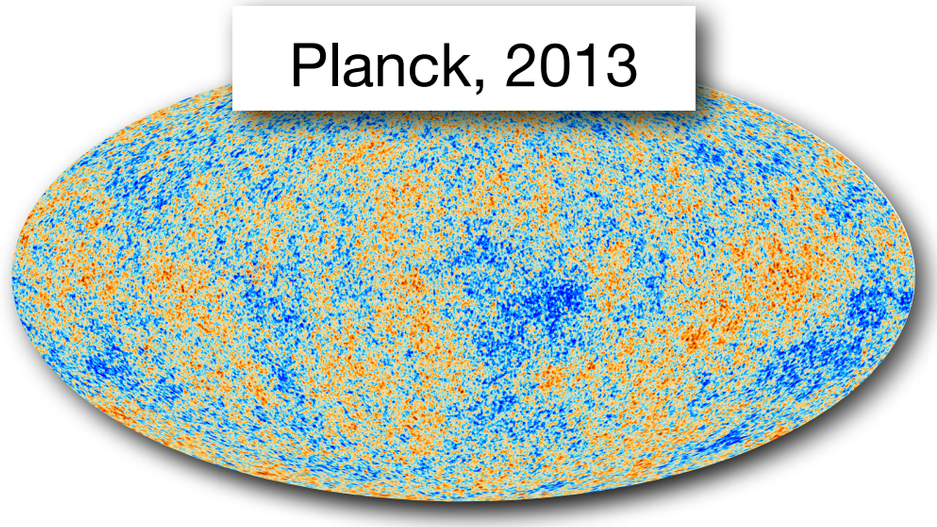
SDSS



Planck, 2013



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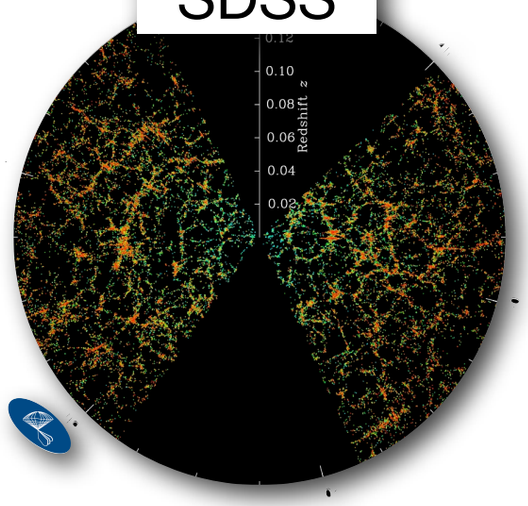

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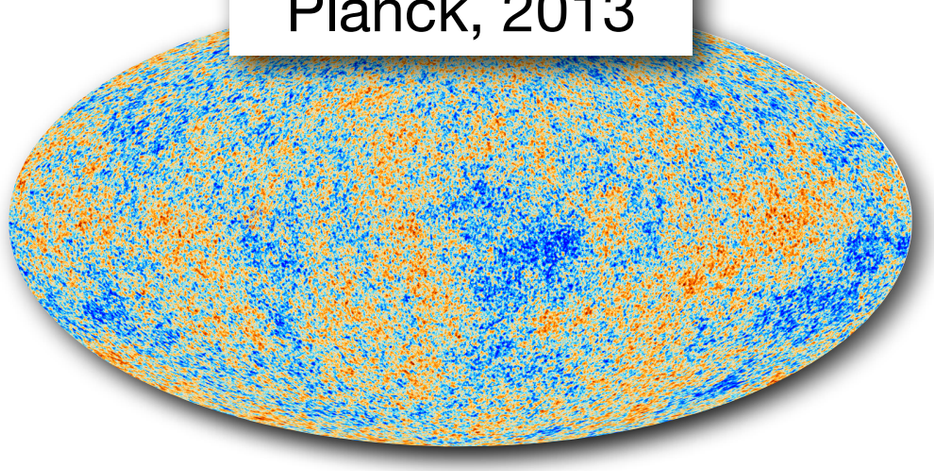
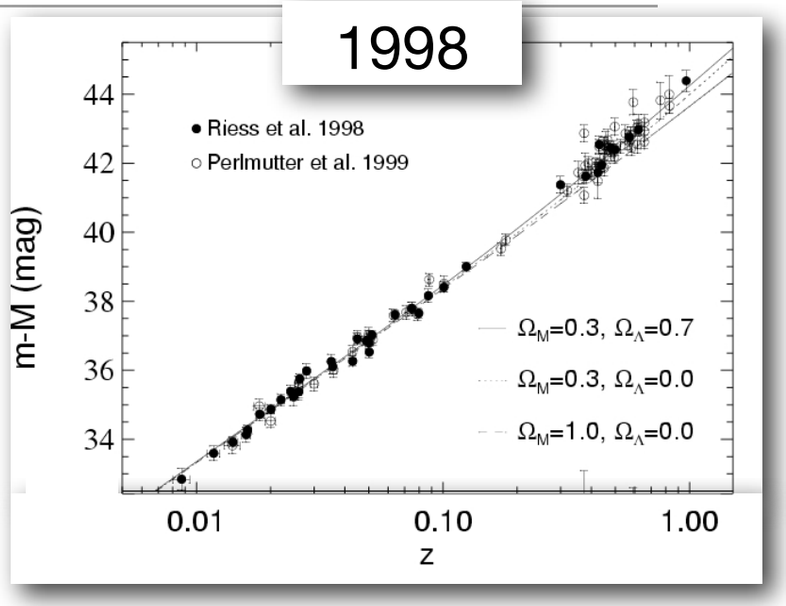


1998



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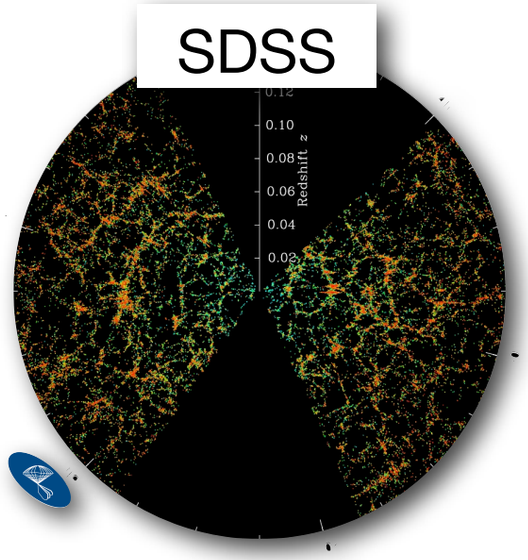

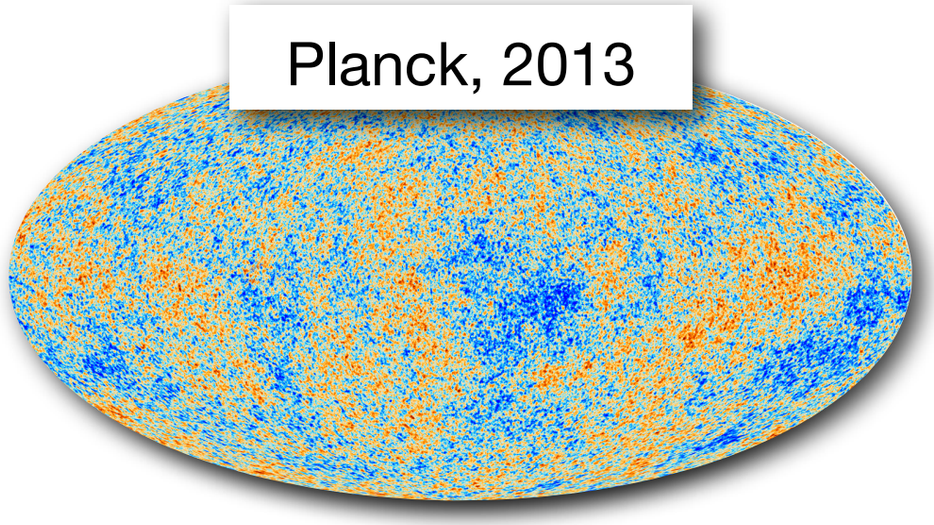

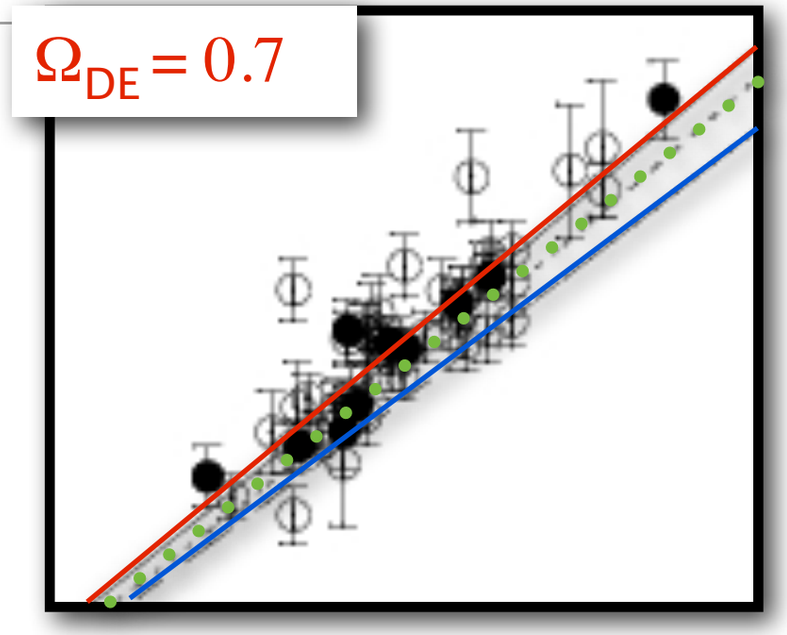

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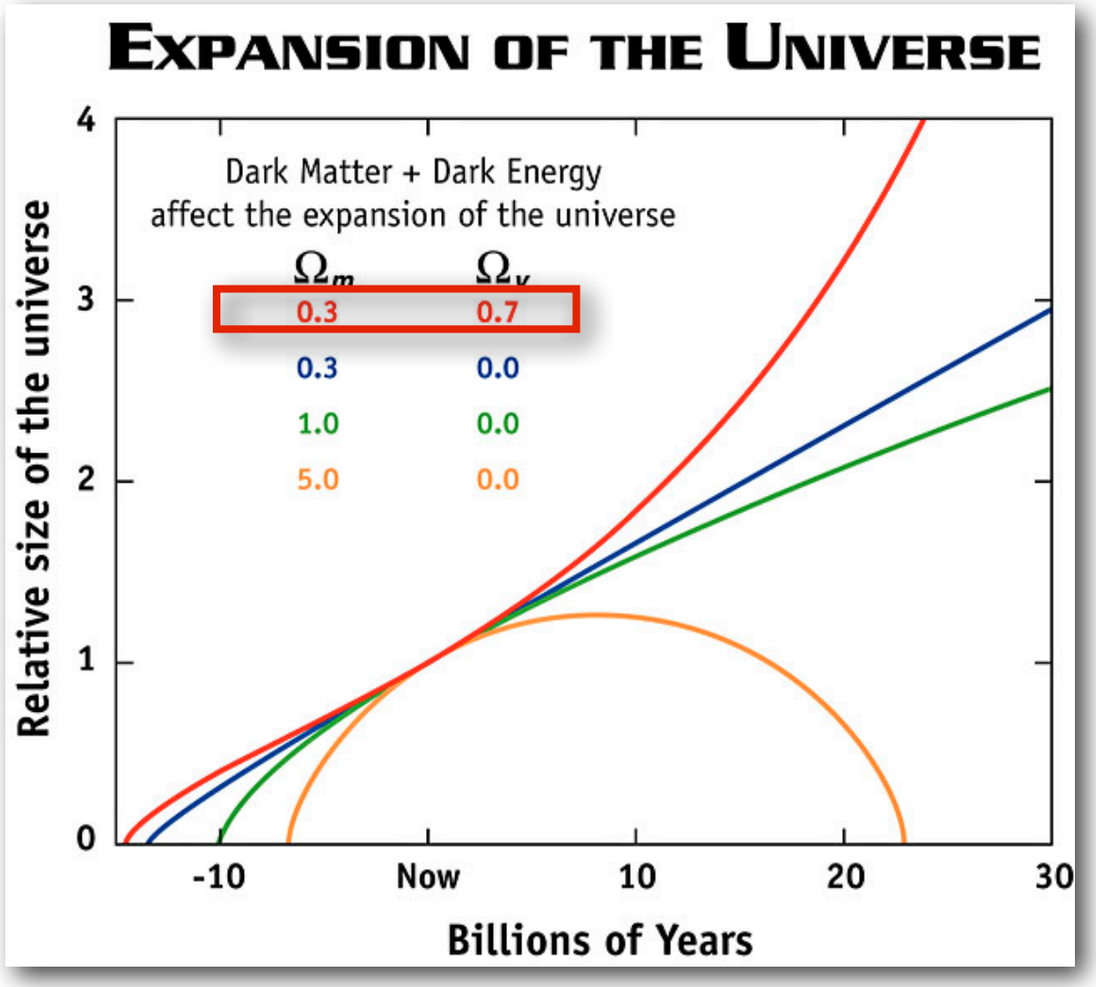
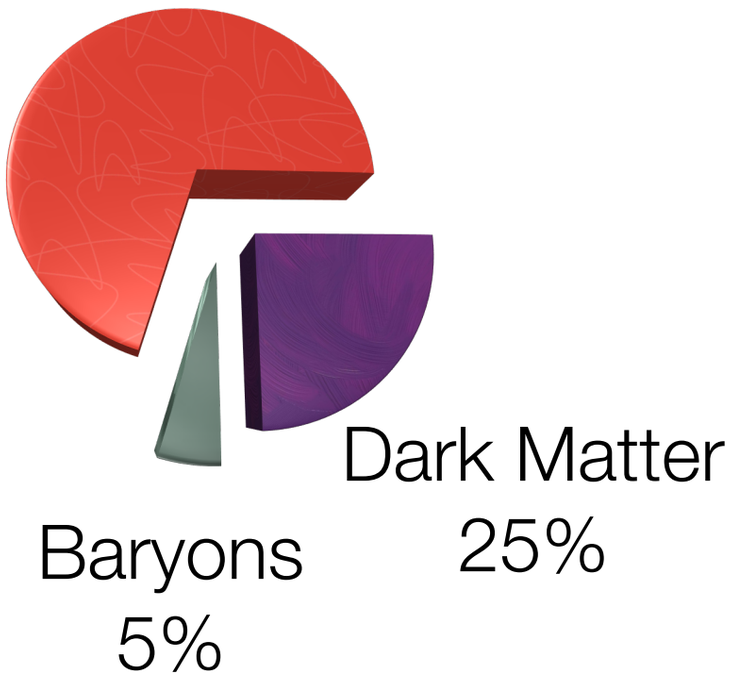
A Tug of War:
The ΛCDM Paradigm



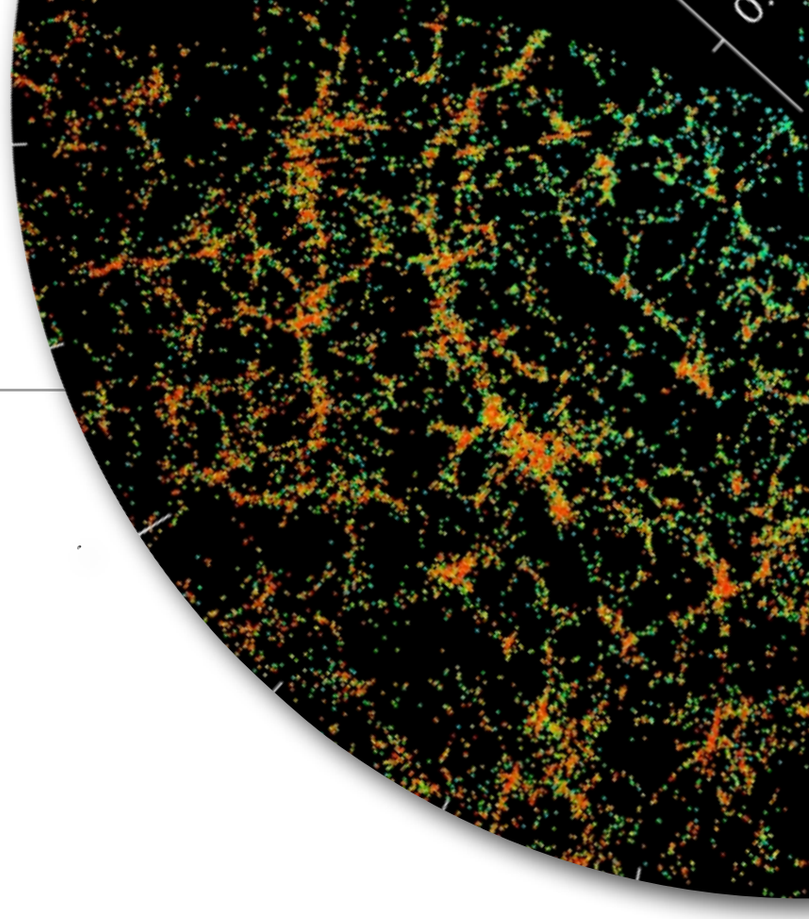


Hubble Parameter

$H^2(a) \sim [\ \Omega_M a^{-3} + \Omega_{DE}\ ]$

What is causing Cosmic Acceleration?

Pushing the Envelope:
Three Paths to Cosmic Acceleration



- <u>Violations of Homogeneity and Isotropy</u>
  - Do we live in a matter under-dense region, a void?

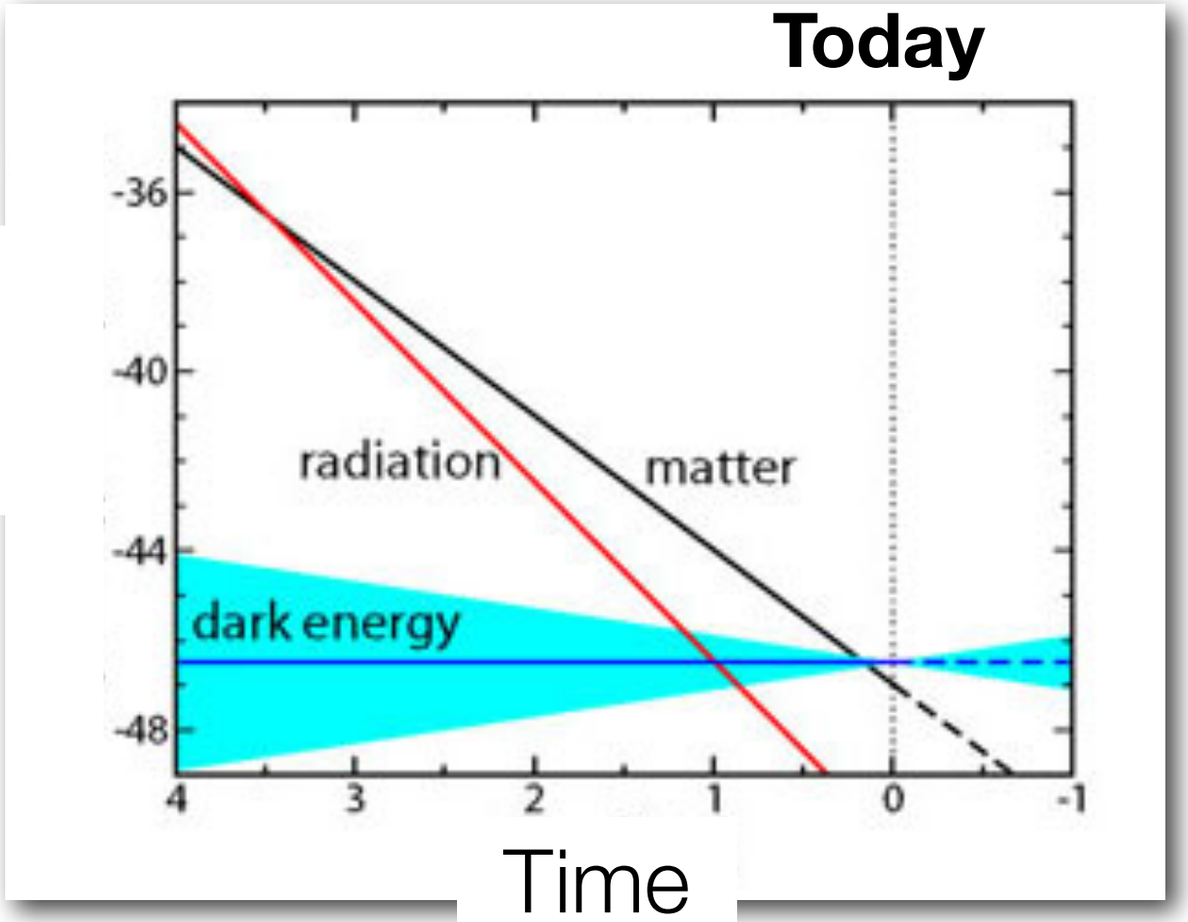
- <u>Modification of General Relativity</u>
  - Does gravity act differently at scales larger than the Solar System?

- <u>A New, Dark Energy?</u>
  - constant vacuum energy (i.e., cosmological constant)?
  - variable scalar energy field (i.e., quintessence)?

Dark energy as Vacuum Energy

A Cosmological Constant

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu}$$



Dark energy density is constant: the vacuum replenishes itself as space grows.

We live now and forever in a dark energy-dominated era.

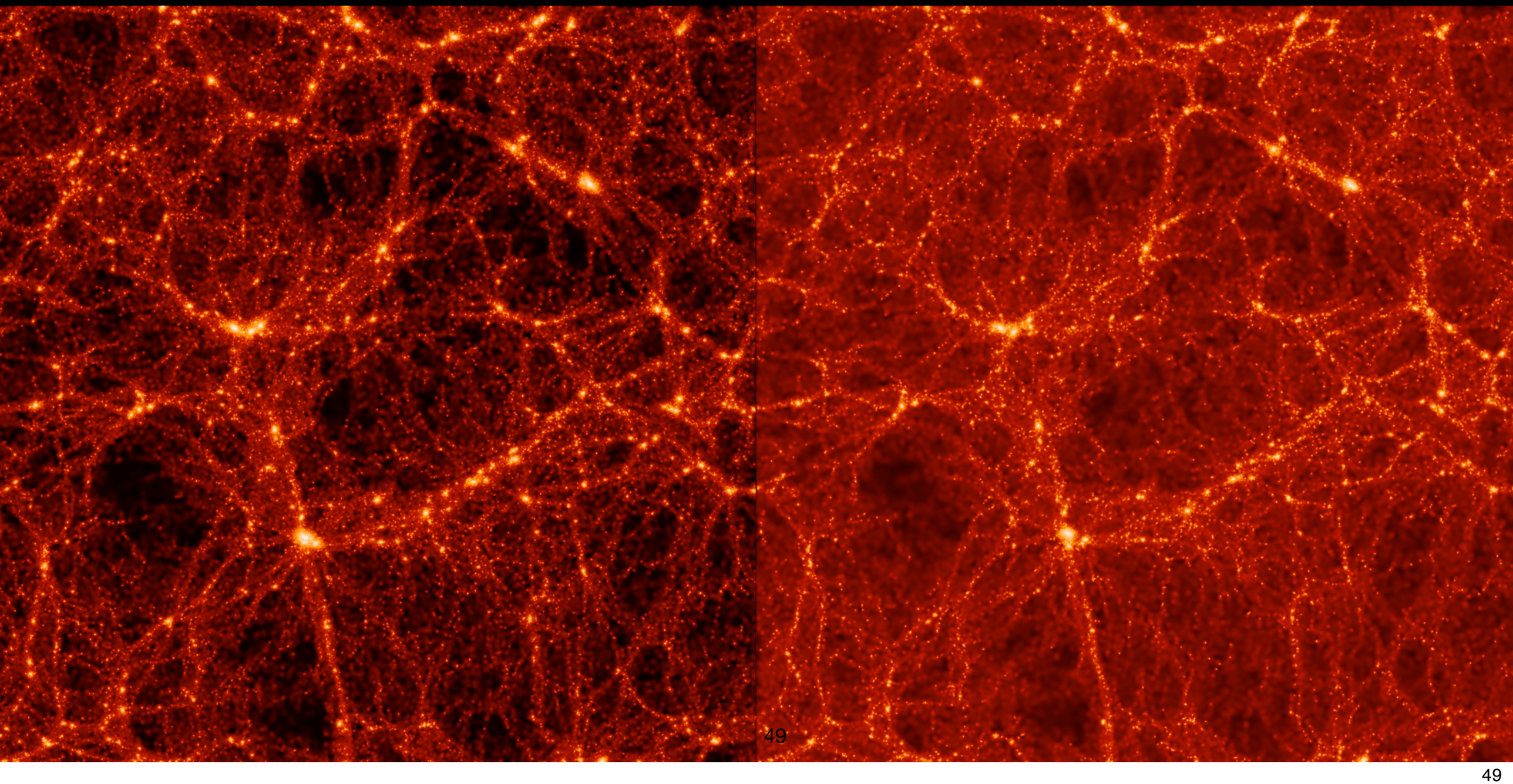
Hubble Parameter

$H^2(a) \sim [\ \Omega_M a^{-3} + \Omega_{DE}\ ]$ ($w_{DE} = -1$)

Structure Growth

Reveals the battle

Which is DE-dominated?



Pushing the Envelope:
Dark Energy Evolution

- Evolving DE Equation of state:
  - Taylor series expansion of **w** around a = 1 (today)

$$w(a) = w_0 + (1 - a)w_a + \ldots$$

- DE Equation of state measurement today:

w_0 = -0.957 ± 0.124
w_a = -0.336 ± 0.552

Hubble Parameter

$$H^2(a) \sim \Omega_M a^{-3} + \Omega_{DE} \exp\left[3 \int (1+w(a)\, d \ln(a^{-1}) \right]$$

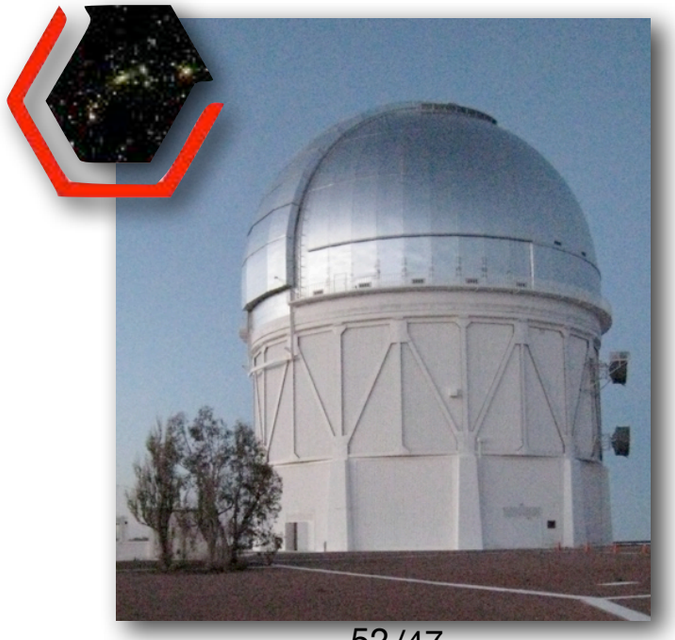
($w_{DE} \neq$ constant)

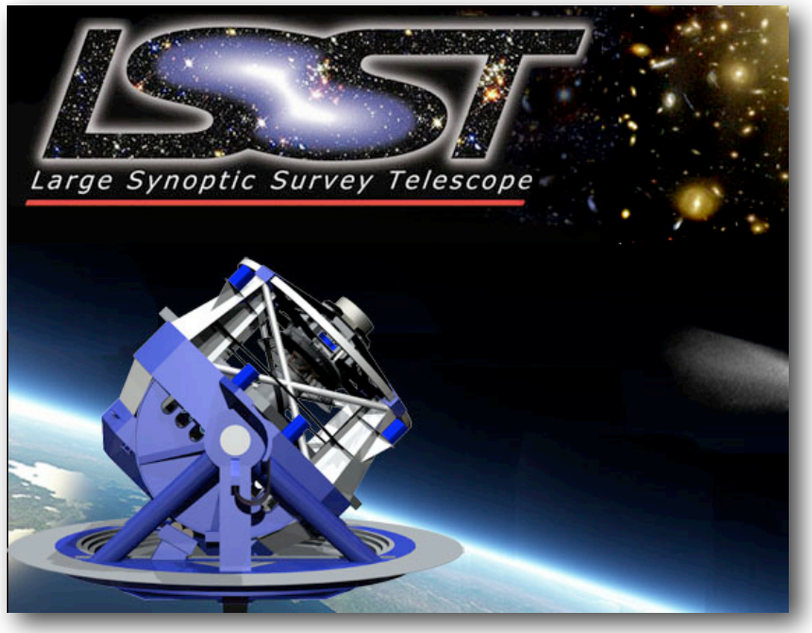
How do we measure dark energy?

Large Optical Surveys:

Past, Current and Future

SDSS I-II	DES	LSST
[Stage I/II]	[Stage III]	[Stage IV]
2000-08	2013-18	2022-32
2.5-meter mirror	4-meter	8.4 -meter
O(10^8) Galaxies	O(10^8) Galaxies	O(10^9) Galaxies
10k sq. deg.	5k sq. deg.	20k sq. deg.
200 Gb/Night	500 Gb/Night	1,500 Gb/Night





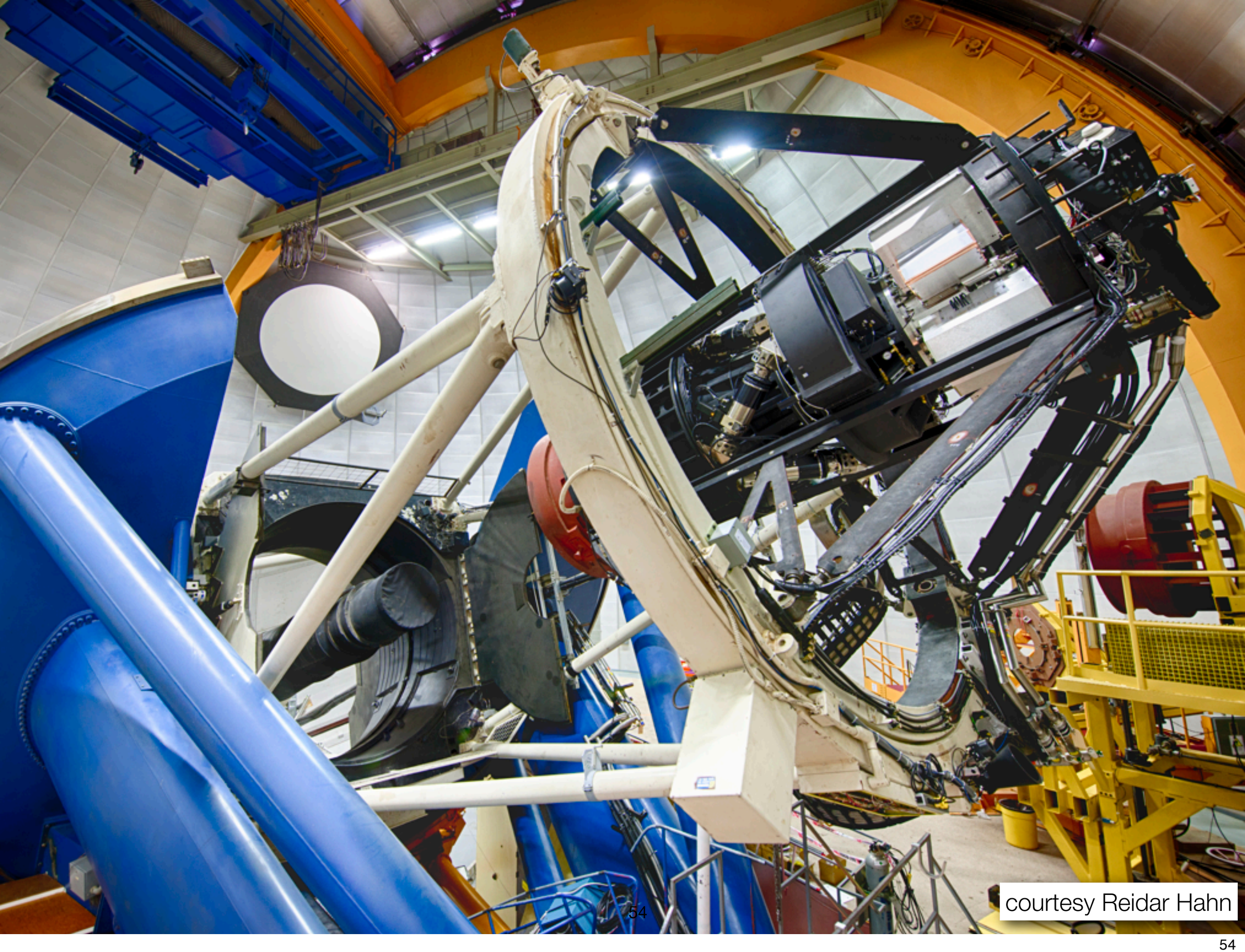
Blanco 4-meter Telescope:

Home of the Dark Energy Camera

Human-sized door

Blanco 4-meter Telescope:

Home of the Dark Energy Camera



courtesy Reidar Hahn

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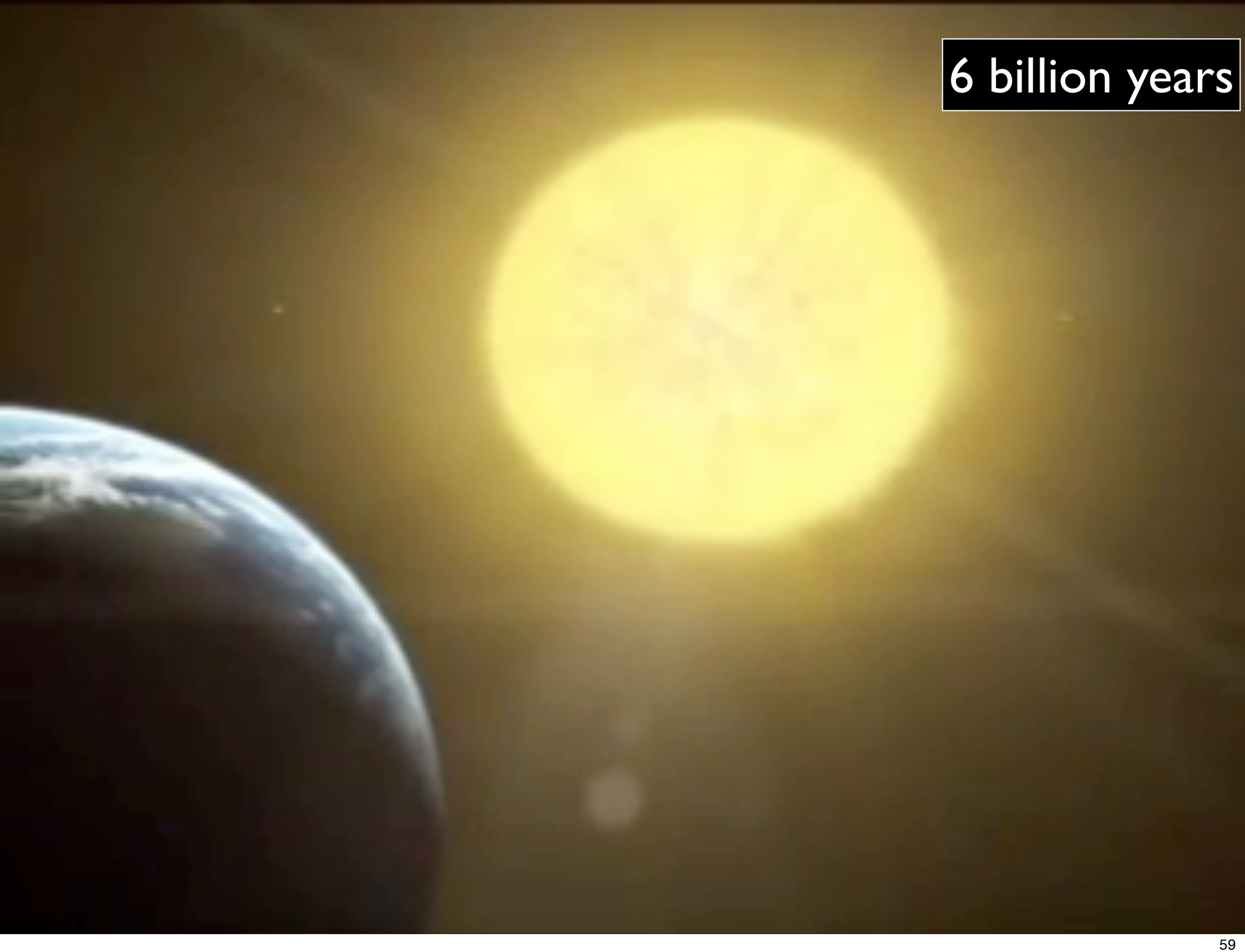
Our Future:
A Series of Unfortunate Events


6 billion years


2.657 billion ye


4 billion years
2.657 billion ye


a = 0.244


50 billion years
a = 0.244


a = 0.244

Questions Asked During Talked

- Q: What do you mean by "open universe"? If I go very fast, why can't I reach the edge?

- A: An "open" universe defines the geometry always, regardless of whether there is dark energy or not. If there is *no* dark energy, then it also means that the universe must grow ever faster, as the universe's temperature approaches absolute zero asymptotically.

- A: There is no known edge to the universe. The Universe is all there is (as far as we know). We attempt to measure some patterns in cosmic radiation (e.g., CMB) that might reveal some repetitions in cosmic structure (which would signal a closed universe.)

- A: Even in a closed universe, there are no edges. This is similar to being on a planet surface.

Questions Asked During Talked

- Q: What happens during the Big Rip? Is there a scenario (e.g., is there a strength of dark energy) that would eventually lead to ripping the fabric of spacetime itself?

- A: The Big Rip is the scenario in which dark energy is strong enough (its equation of state parameter, w<-1) to eventually allow the accelerating spacetime to pull apart structures in the universe---from galaxy clusters down to atoms and smaller. This does *not* rip the space time fabric itself.

- A: As space expands, it fills into itself; it makes room and then more space is put in between points of space. There is then more space than previous. Dark energy accelerates this process ... accelerates the adding of spacetime. I don't think this can simultaneously add spacetime and cause a rip in it. These are caused by different mechanisms. (see next answer)

- The Big Bang occurs at a singularity, a point of infinite density. The solution to GR equations for the Big Bang is then similar to the equations for a black hole. This (a singularity) is the closest thing we have to a rip in spacetime.

  If the universe were to be massive enough to re-collapse, it would return to a singularity, the thing we know of that is closest to a 'rip' in spacetime.