A later “mini Inflation”?

What’s inflation?

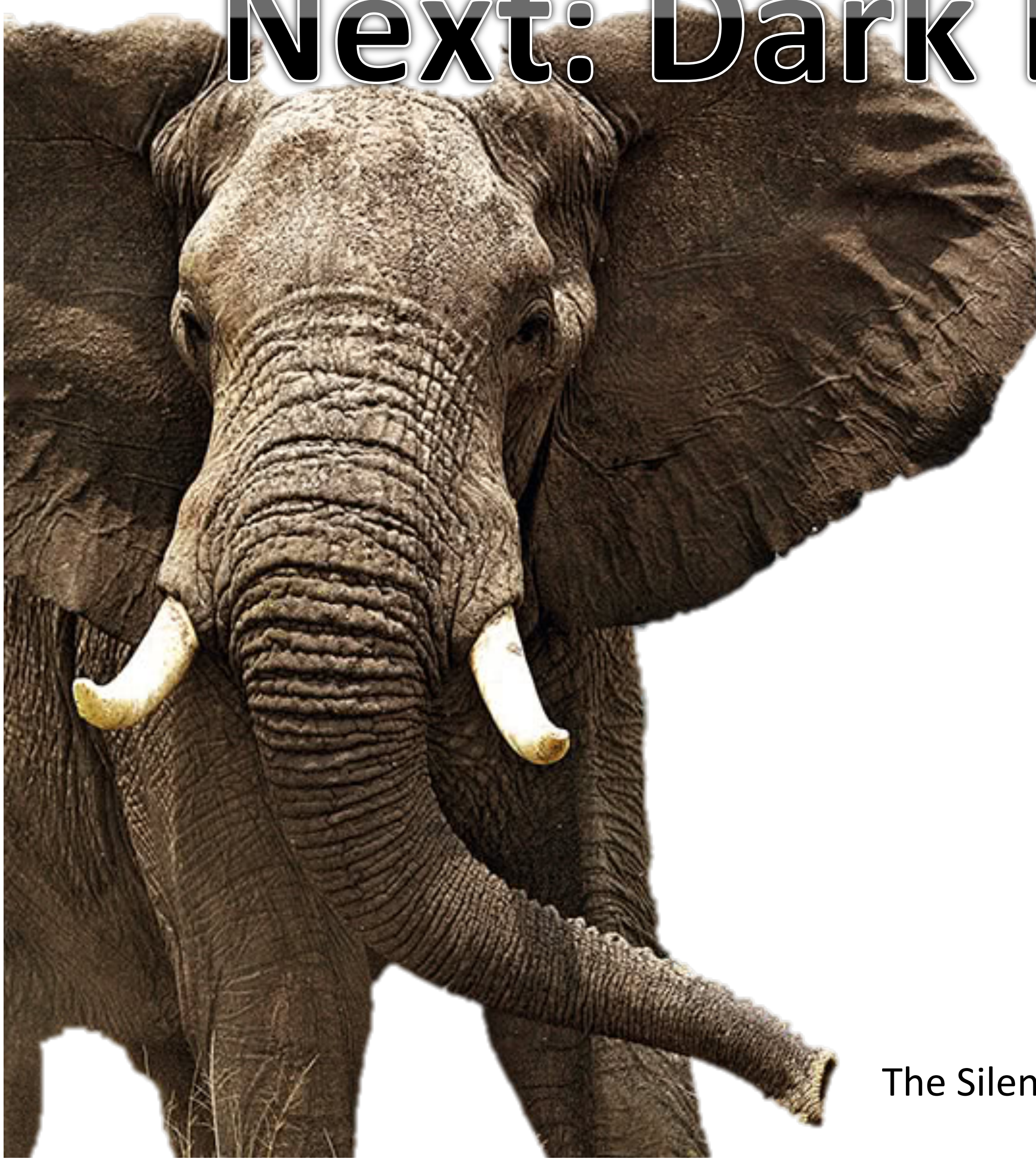
“Long, long ago, when the universe was only about 100,000 years old — a buzzing, expanding mass of particles and radiation — a strange new energy field switched on. That energy suffused space with a kind of cosmic antigravity, delivering a not-so-gentle boost to the expansion of the universe.

Then, after another 100,000 years or so, the new field simply winked off, leaving no trace other than a speeded-up universe.”

Dennis Overbye, NY Times, 25 Feb 2019

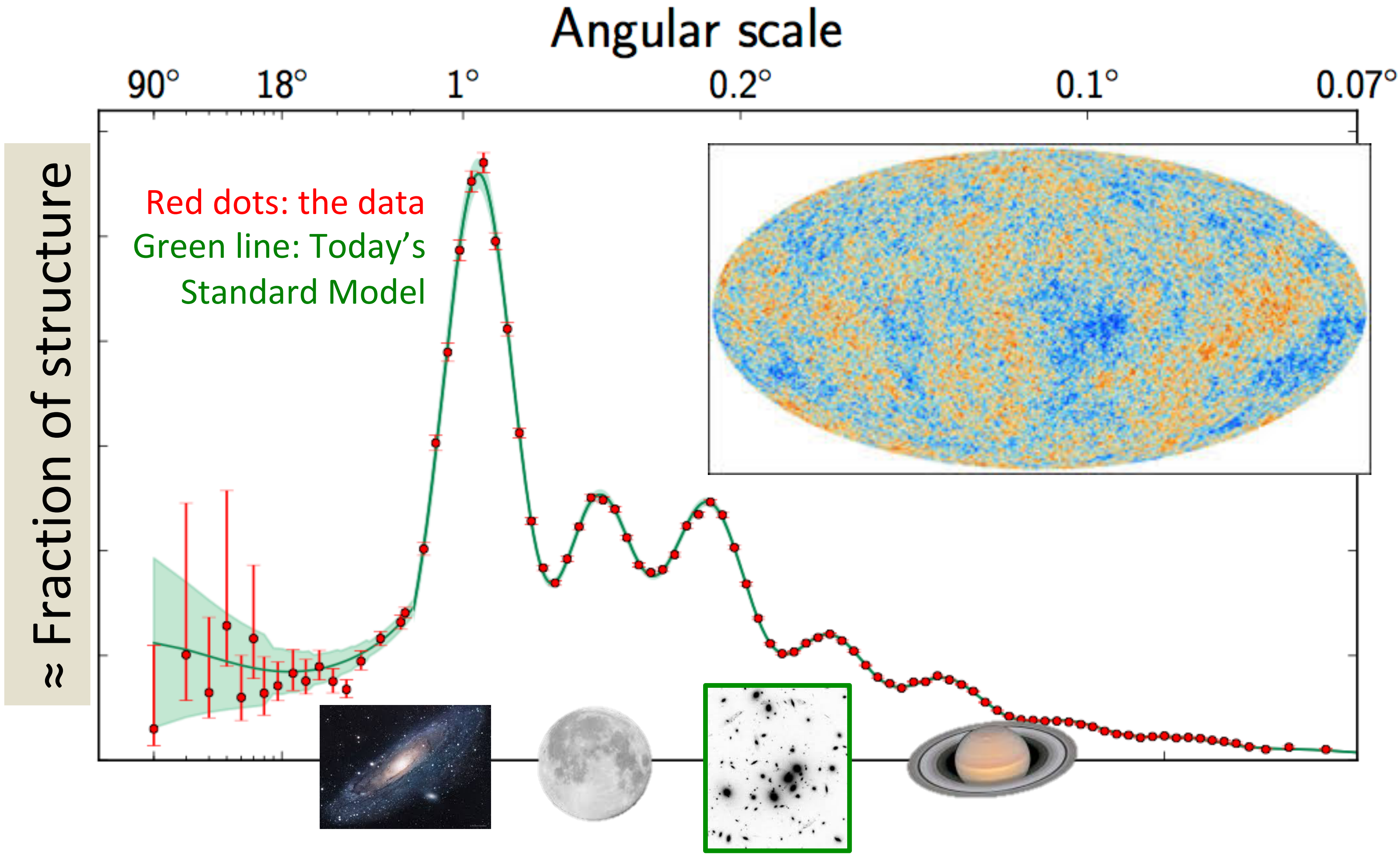
How can the expansion of a Universe mass (and light) possibly accelerate??

Next: Dark Energy



The Silent Elephant in the Room

Dark Energy sets the cosmic scale

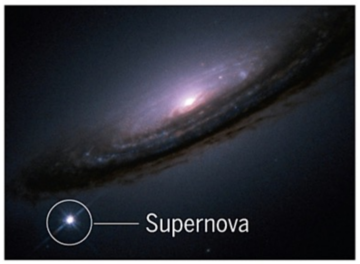


Evidence for Dark Energy

Shining a light on dark energy

Science
11 Aug2017
p. 538

Astronomical surveys are using four techniques to pin down dark energy, the mysterious force accelerating the expansion of the universe.



Supernovae

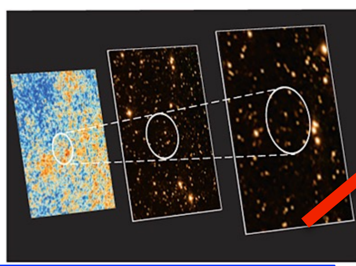
Distant supernovae are dimmer and hence farther away than they should be for a steadily expanding universe. Measuring both their distance and the speed at which they're receding reveals the effect of dark energy.

Weak gravitational lensing

The shape of a distant galaxy is distorted by the gravity of all intervening matter. By imaging millions of galaxy distortions, astronomers map the distribution of matter over time and see how dark energy is pushing it apart.

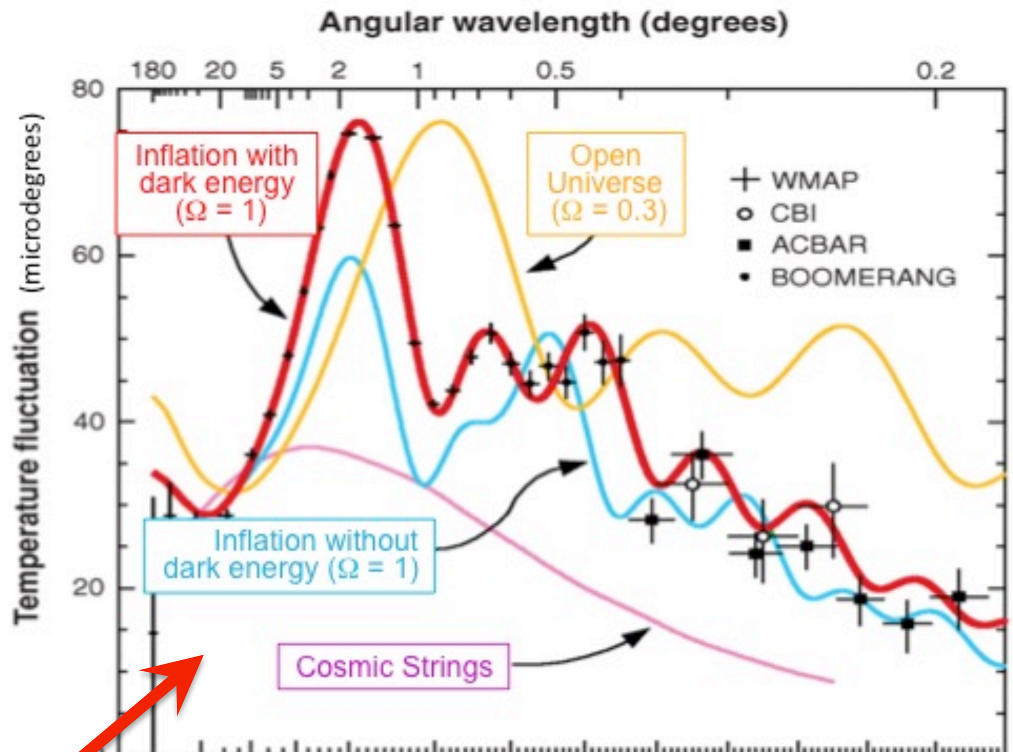
Galaxy cluster counts

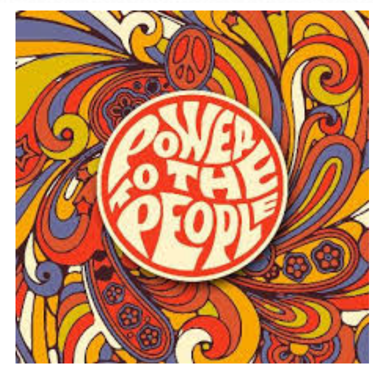
Over time, blobs of dark matter pull galaxies into a cosmic web. Counting galaxy clusters, astronomers can look for deviations in the growth of the web that point to dark energy.



Baryon acoustic oscillations

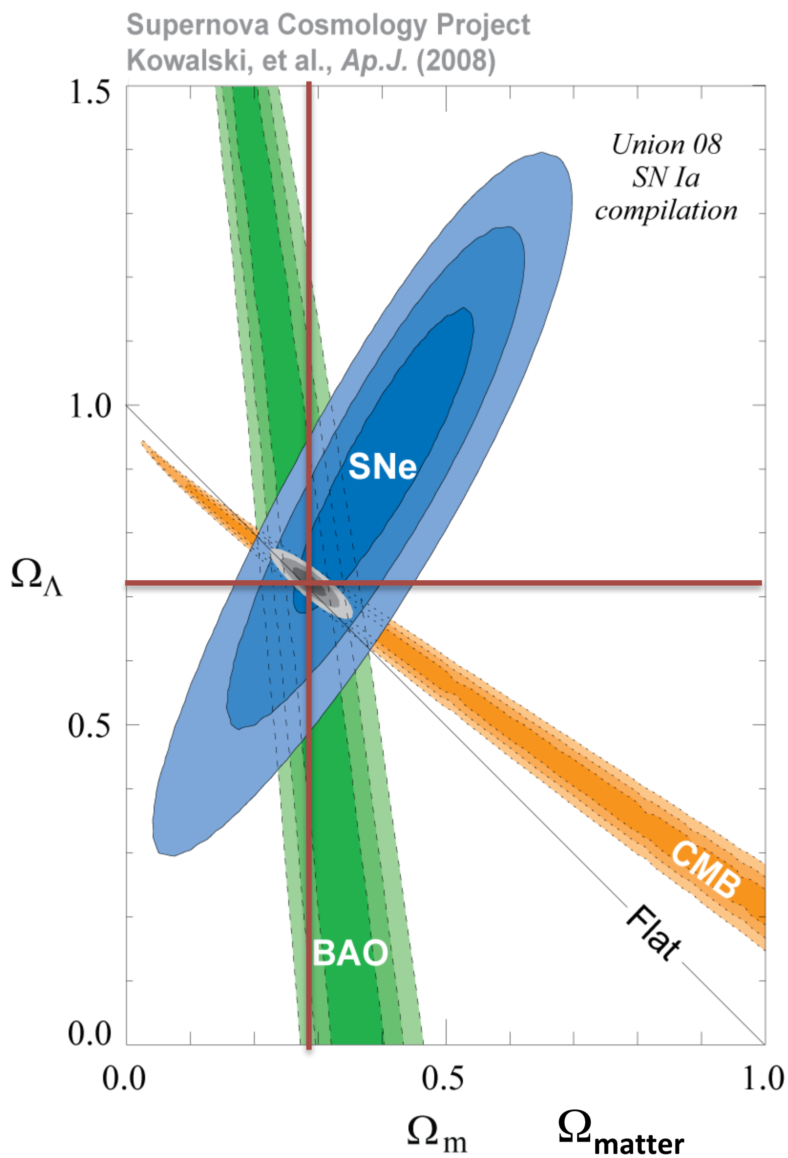
Sound waves in the roiling gas of the early universe left an imprint in the matter left behind. The growth of that imprint over time shows how dark energy is altering the universe's expansion rate.





Power to the ripples!

Various independent best results



"Error ellipses".
Best estimate of Ω_m & Ω_Λ

Supernovae
CMB ripples
Web-like structure of nearby clusters of galaxies

$$\Omega_{tot} = \Omega_m + \Omega_\Lambda$$

Ω_m = matter (grav)

Ω_Λ = dark energy

= 1.0023 ± 0.0055

Goldilocks

Forcing Flatness:
Fudge a repulsive term in Einstein's equation for space!

If Einstein could do it in 1927 then why can't we?

Einstein's Field Equation including his Λ fudge

Property of mass-energy

Property of space-time

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = -8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu} = 0$$

geometry and curvature of space

T describes the distribution of mass-energy. G is Newton's constant of gravitation (attractive)

insert this with $\Lambda > 0$ (repulsive). Fine-tuning Λ gives zero curvature

Dark Energy in an Empty Universe

($\Omega_{mass\text{-}energy} = 0$)

Perfectly empty space will accelerate if $\Lambda > 0$

~~Attraction~~ Repulsion

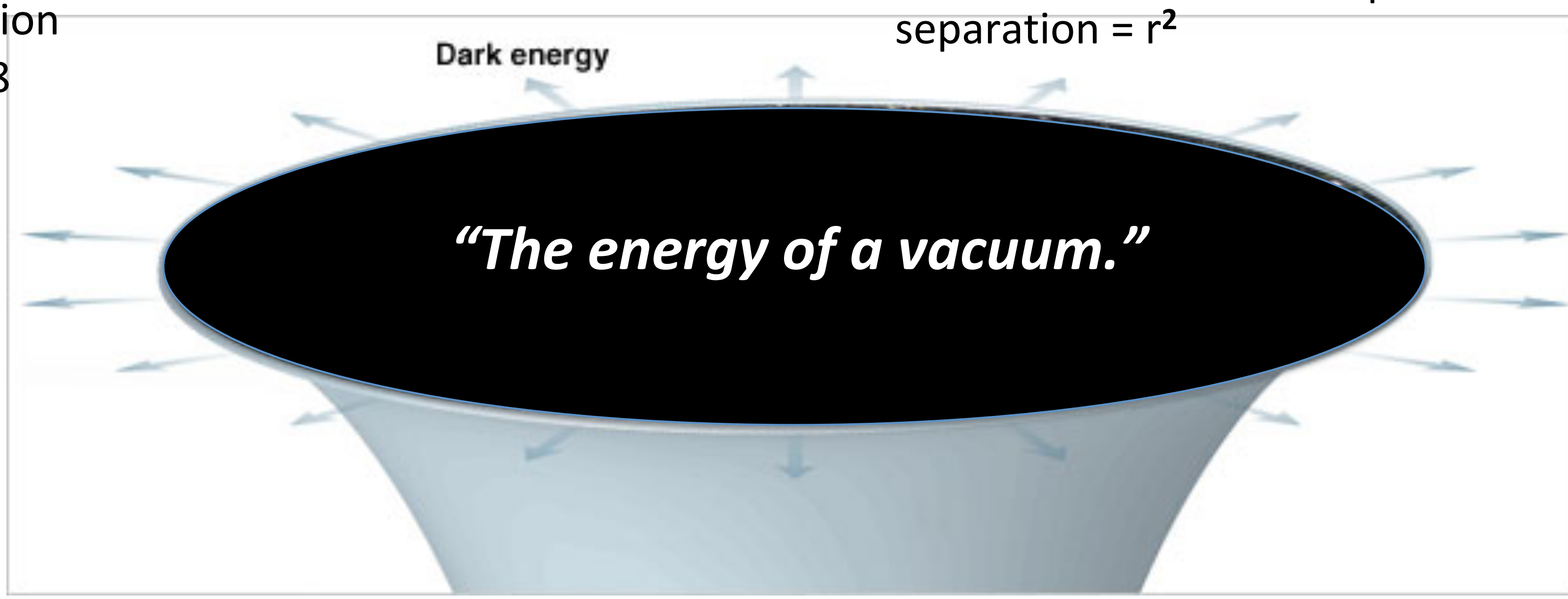
~~**contraction**~~ **expansion**

$$acceleration = \cancel{-GM/r^2} + \Lambda \cdot r/3$$

Newton's Law: decreases as separation = r^2

increases with separation = r

Based on Equation A18



Dark Energy in Our Universe?

We can rewrite the field equation Of GR in a local environment.

In this case the ugly tensor math in Einstein's field equation becomes manageable (p274).

Net acceleration of two nearby isolated bodies separated by distance r

Attraction **contraction**

Repulsion **expansion**

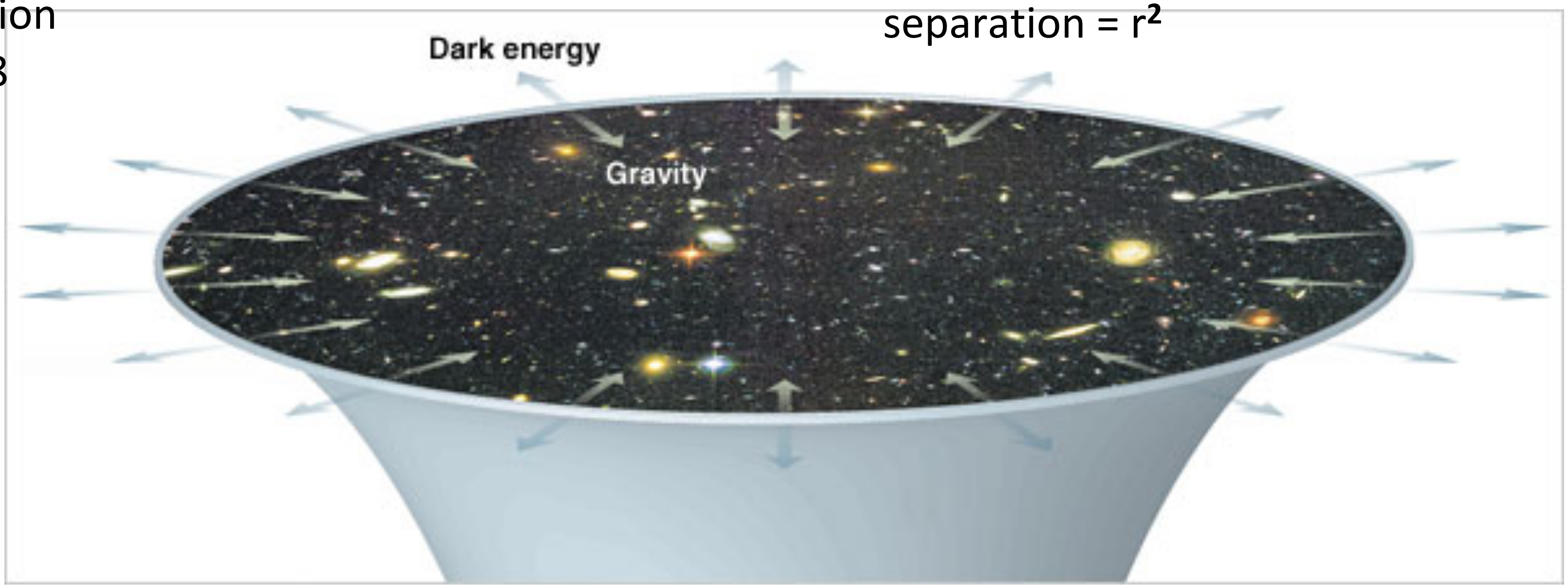
$$acceleration = -GM/r^2 + \boxed{\Lambda} \cdot r/3$$

Your favorite number here

Newton's Law: decreases as separation = r^2

increases with separation = r

Based on Equation A18



Dark Energy and motions: the local approximation of the field equation

Over small distances the field equation with Dark Energy is readily simplified:

Attraction
(Closes Space)

Repulsion
(opens space)

$$accel = -GM / r^2 \; + \; \Lambda \cdot r / 3$$

$\boxed{\Lambda \approx 10^{-122}\,!}$

Add the precisely required value of Λ to the list of nagging cosmic “problems”!

These terms act in opposition.

• If $\boldsymbol{r}$ is increased the force of gravity decreases and the repulsive “force” increases in strength. So once the Universe expands it can’t stop.
• Similarly, if the Universe shrinks a little then the opposite occurs. The contraction is not stoppable.

In summary, cosmic space is unstable (page 214).

Note: Einstein originally added the Λ term before 1920 as a patch to force a static Universe. This was capricious: Physics doesn’t require the Λ term. Later, Hubble et al. showed that the Universe isn’t static; it expands. So Einstein yanked the Λ term from his field equation. Dark Energy revived the term as a *possible* description of its observed cosmic consequences.

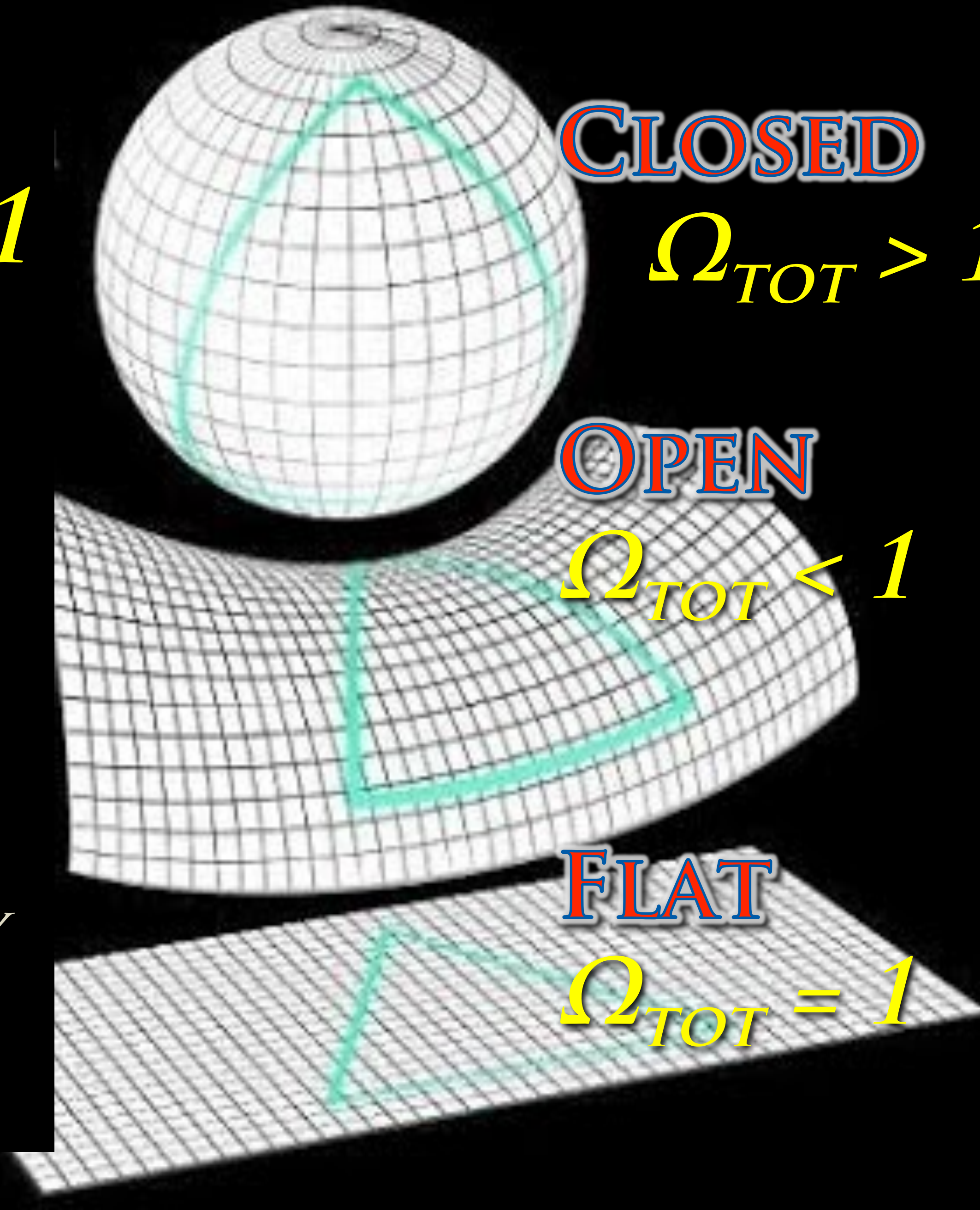
$$\Omega = \Omega_{TOT}$$

FLAT: $\Omega_{TOT} = 1$

$$\Omega_{TOT} = \Omega_M + \Omega_\Lambda$$

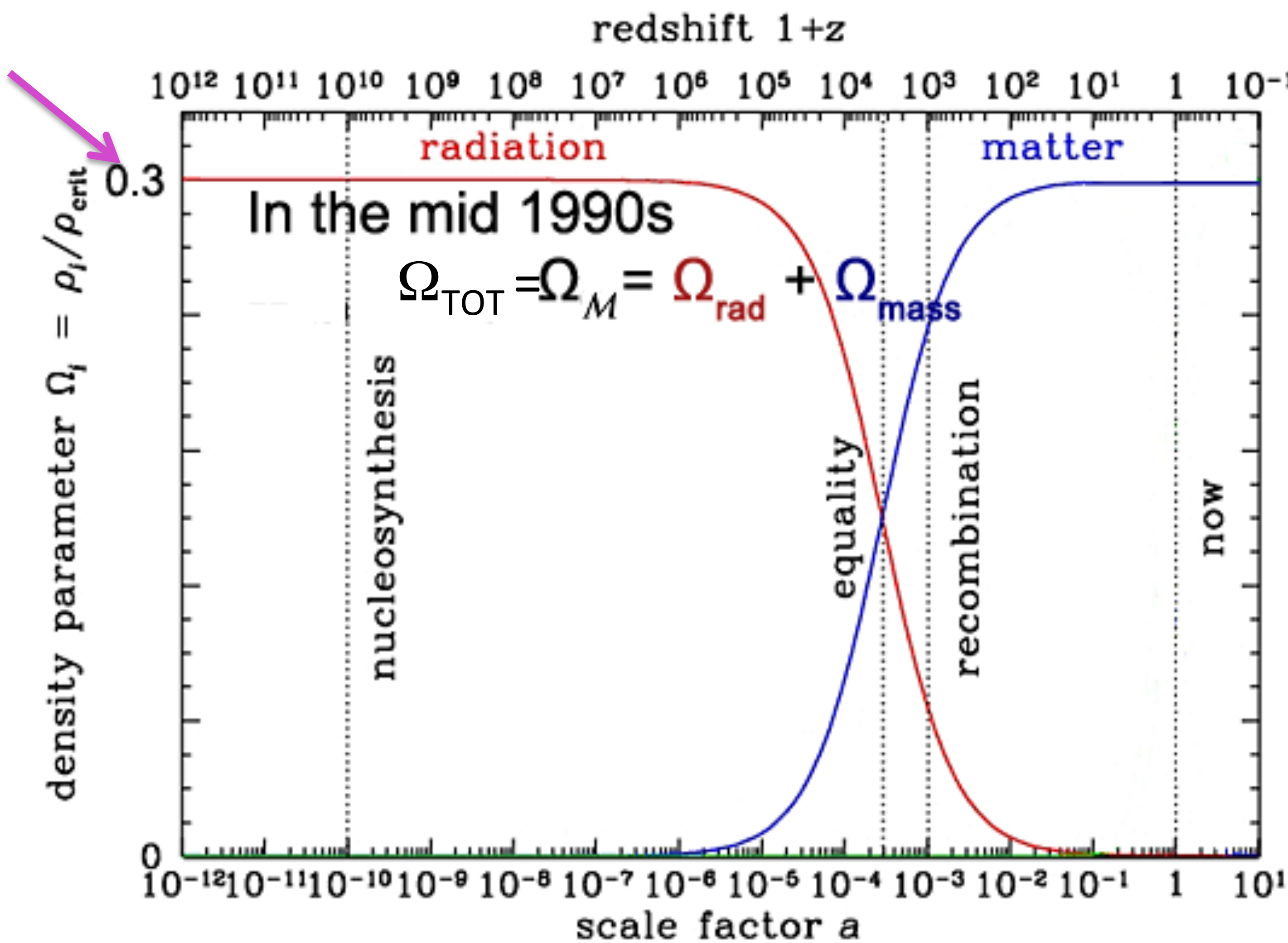
$$\Omega_M = \Omega_{MATTER} + \Omega_{RADIATION} \approx 0.3$$

$$\Omega_\Lambda = \Omega_{DARK\ ENERGY} \approx 0.7$$



The Outlook of Observers, 1990s

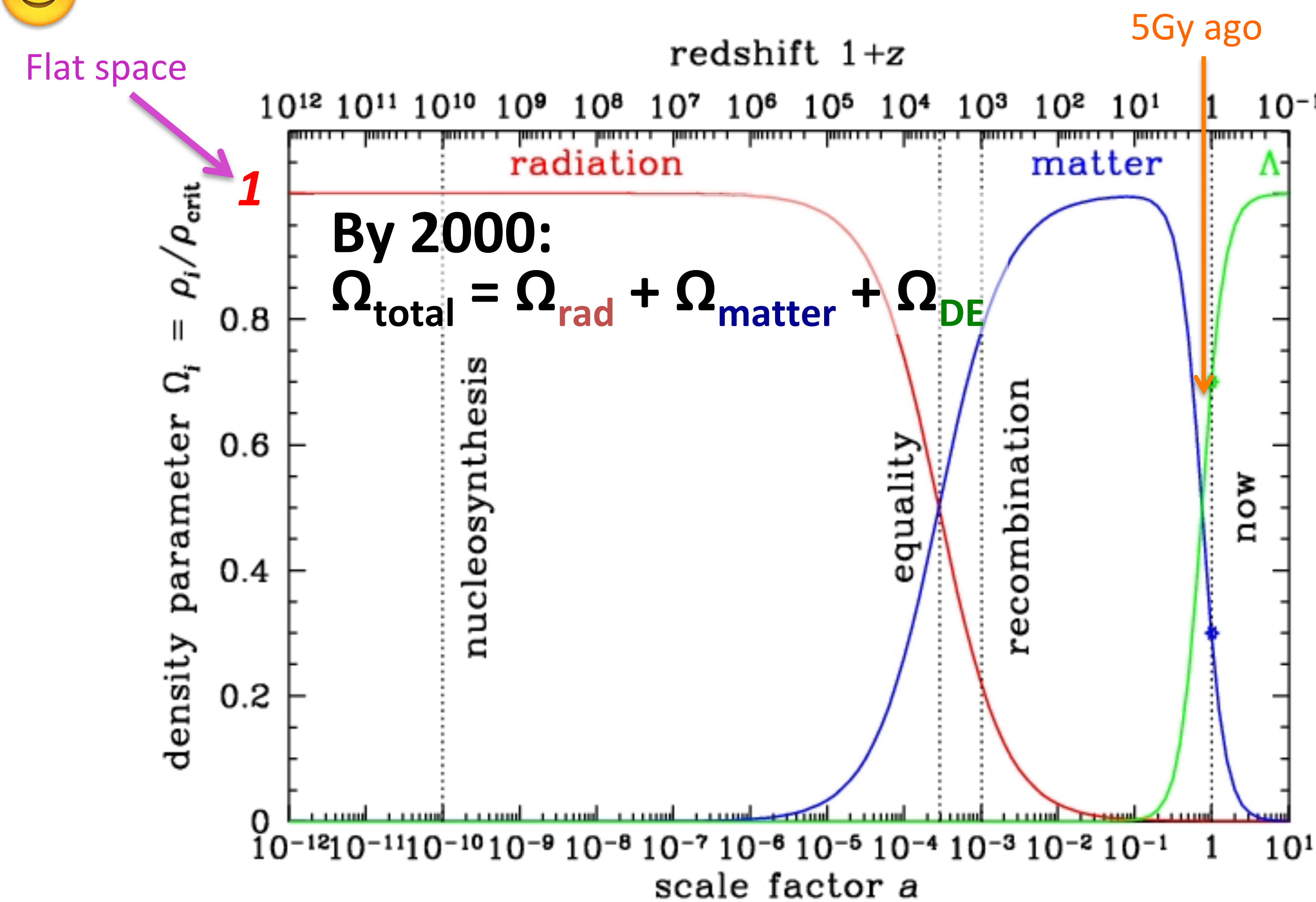
Best observations implied $\rho/\rho_c = \Omega_{\mathcal{M}} = 0.3$ with ≈ 10% uncertainties



Important note:
Photons of energy E have an "effective mass" E/c^2 and contribute to Ω_{total} just like mass

Goldilocks

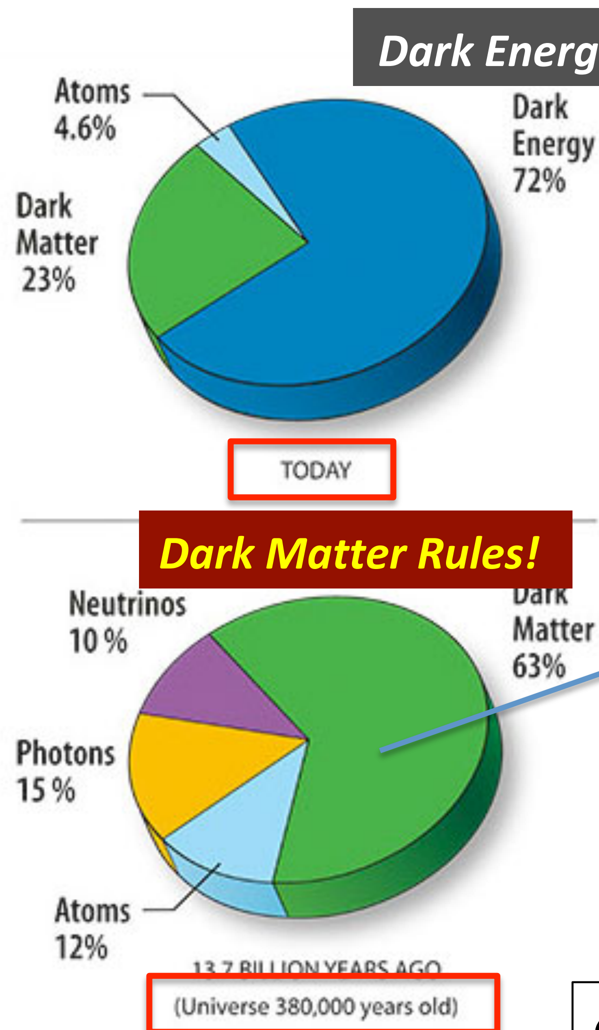
The Outlook of Observers, 2000s

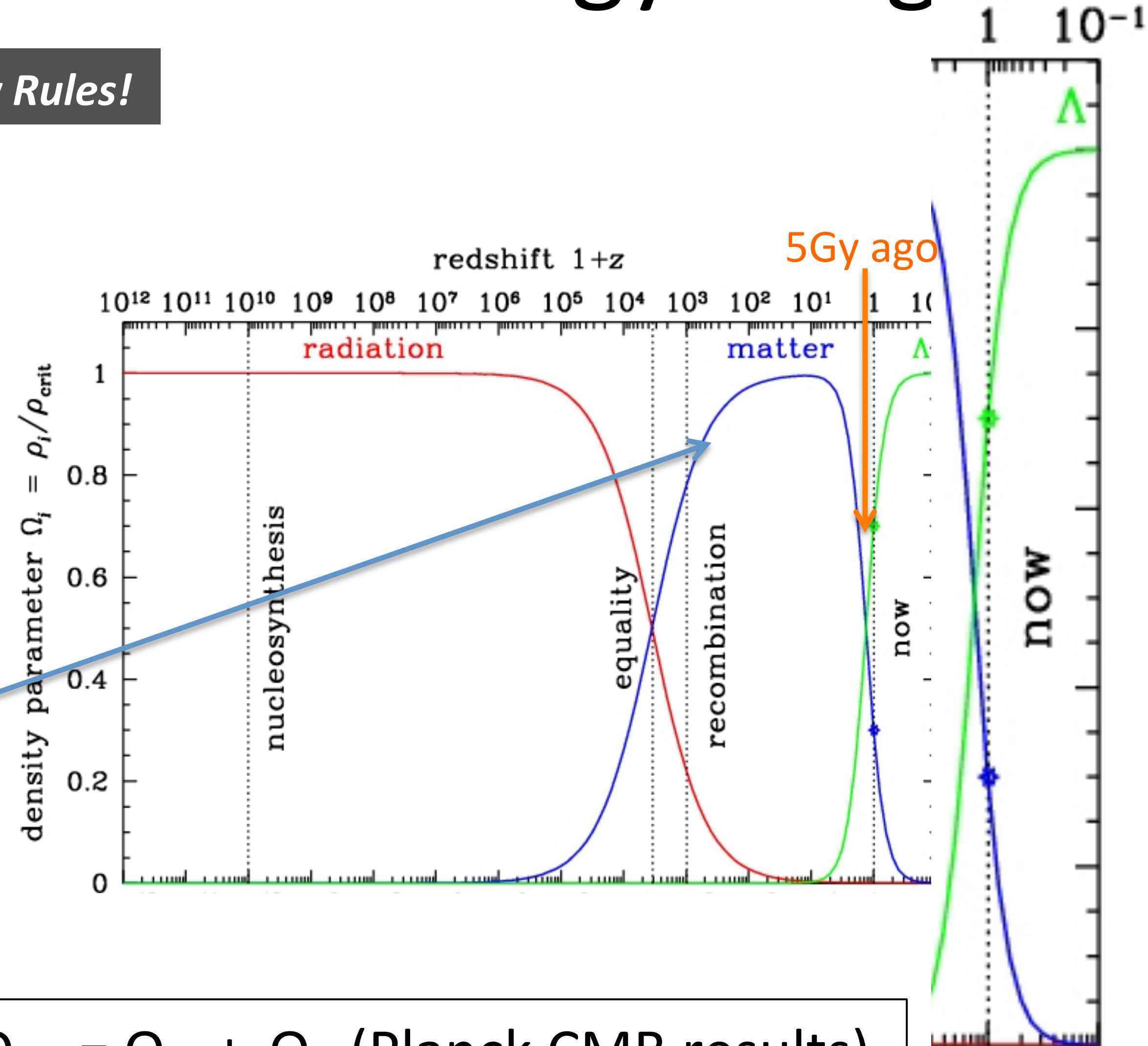


Important note:

Photons of energy E have an "effective mass" E/c^2 and contribute to Ω_{total} just like mass

The Evolving Cosmic Energy Budget





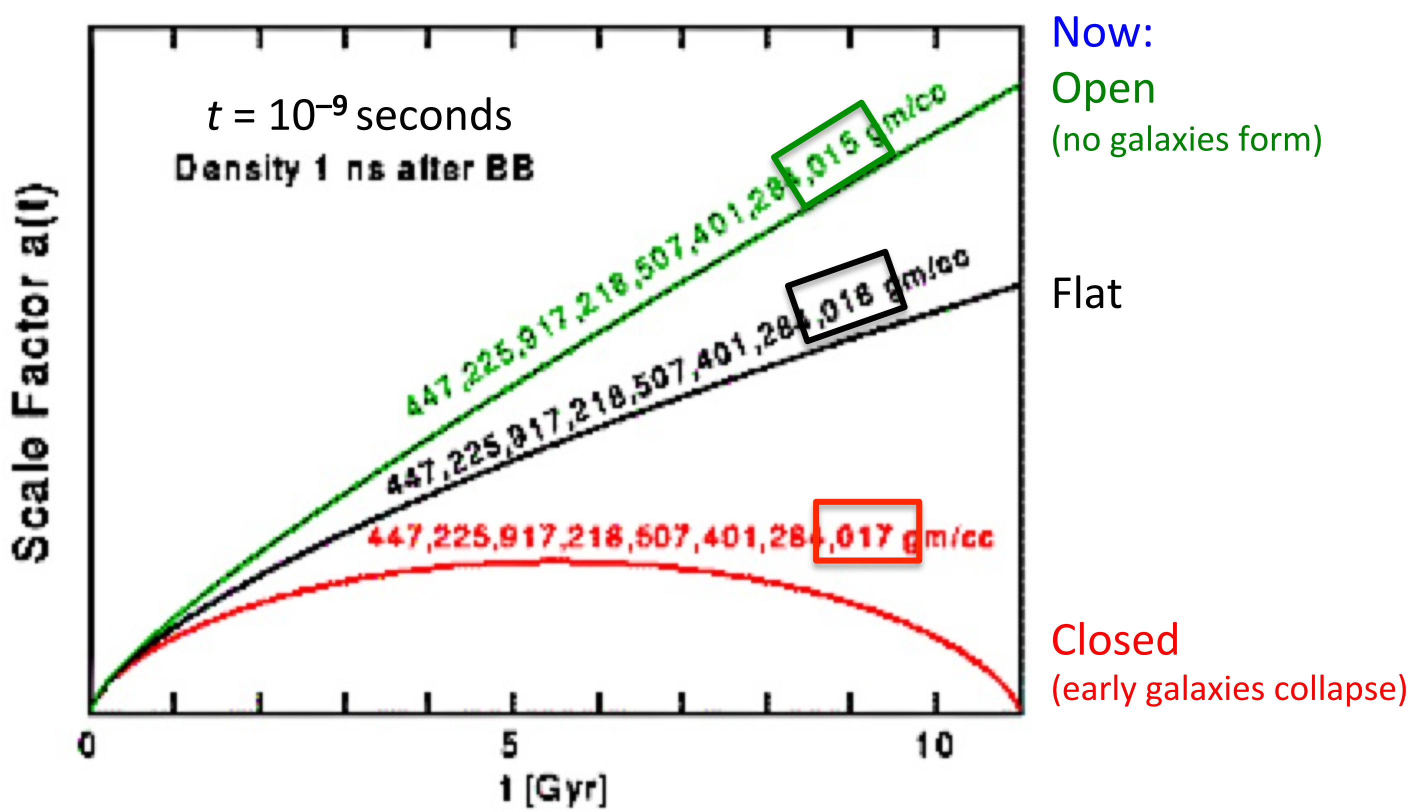
380,000 y ABB, when Universe became transparent.

$\Omega_{tot} = \Omega_M + \Omega_\Lambda$ (Planck CMB results)

Ω_M = rad+matter = 0.6911±0.0062 (today)

Ω_Λ = dark energy = 0.3089 ± 0.0062 "

Extreme fine tuning!

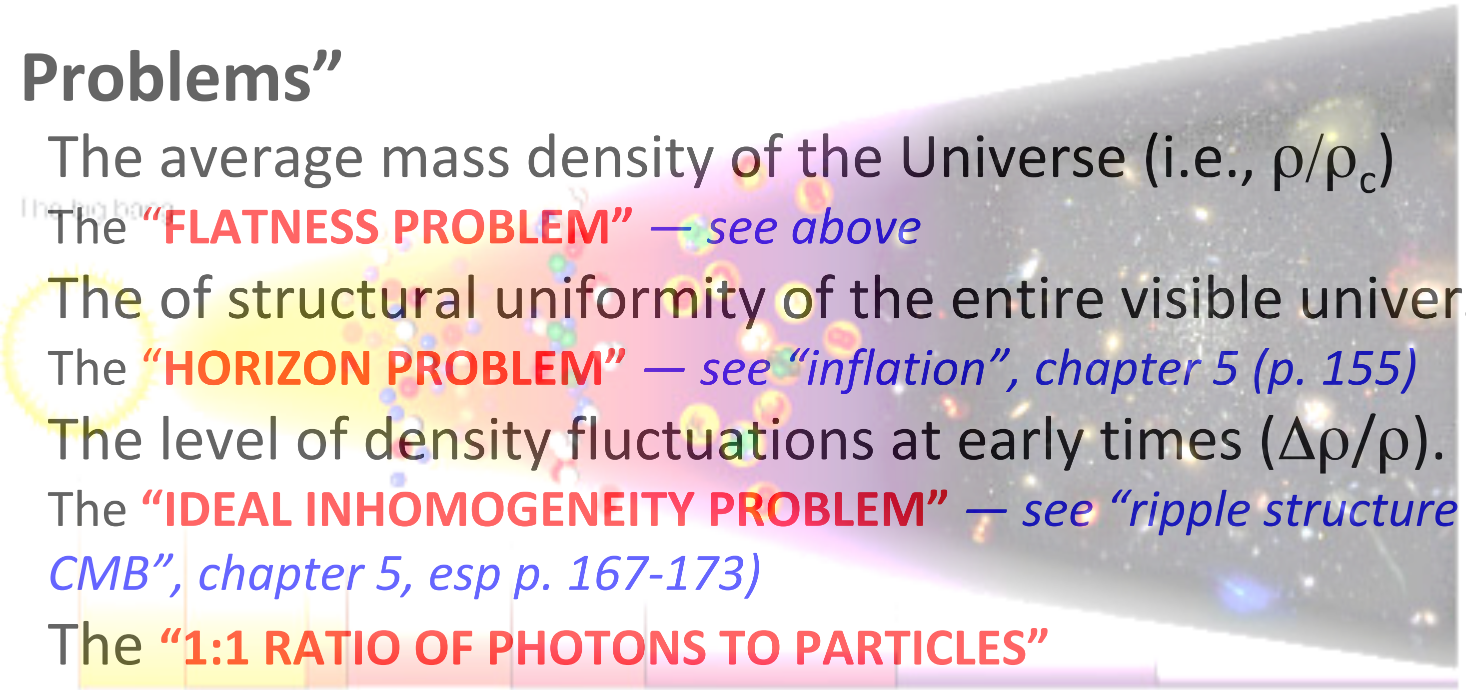


The differences in density amount to just 4 ounces in every region as massive as the moon!

No present theory predicts flatness, so the outcome is by chance!

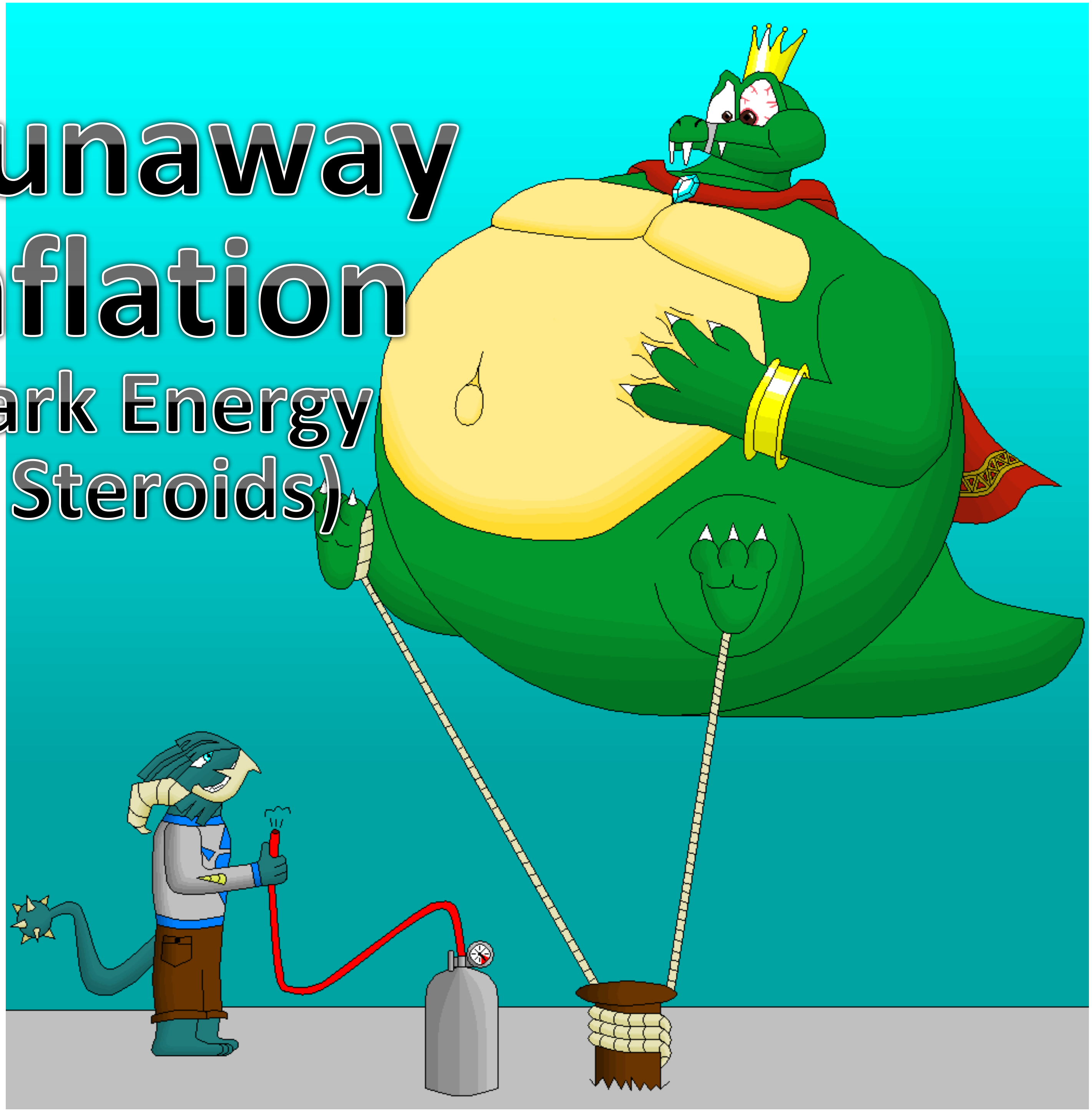
Unresolved Consequences

"The Problems"



1. The average mass density of the Universe (i.e., ρ/ρ_c)
   The **"FLATNESS PROBLEM"** — *see above*
2. The of structural uniformity of the entire visible universe
   The **"HORIZON PROBLEM"** — *see "inflation", chapter 5 (p. 155)*
3. The level of density fluctuations at early times ($\Delta\rho/\rho$).
   The **"IDEAL INHOMOGENEITY PROBLEM"** — *see "ripple structure of the CMB", chapter 5, esp p. 167-173)*
4. The **"1:1 RATIO OF PHOTONS TO PARTICLES"**
5. The **"MATTER-ANTIMATTER IMBALANCE"** tiny but perplexing
6. The **"PERFECT CHARGE BALANCE"** net ZERO cosmic charge
7. The **"ABSENCE OF MAGNETIC MONOPOLES"** & other exotica
   - *Items 4, 5, 6, 7 are esoteric; we will largely ignore them*

Runaway Inflation (Dark Energy on Steroids)



Cosmic Inflation!

Connected space abruptly expands by $\approx 10^{50}$!!!

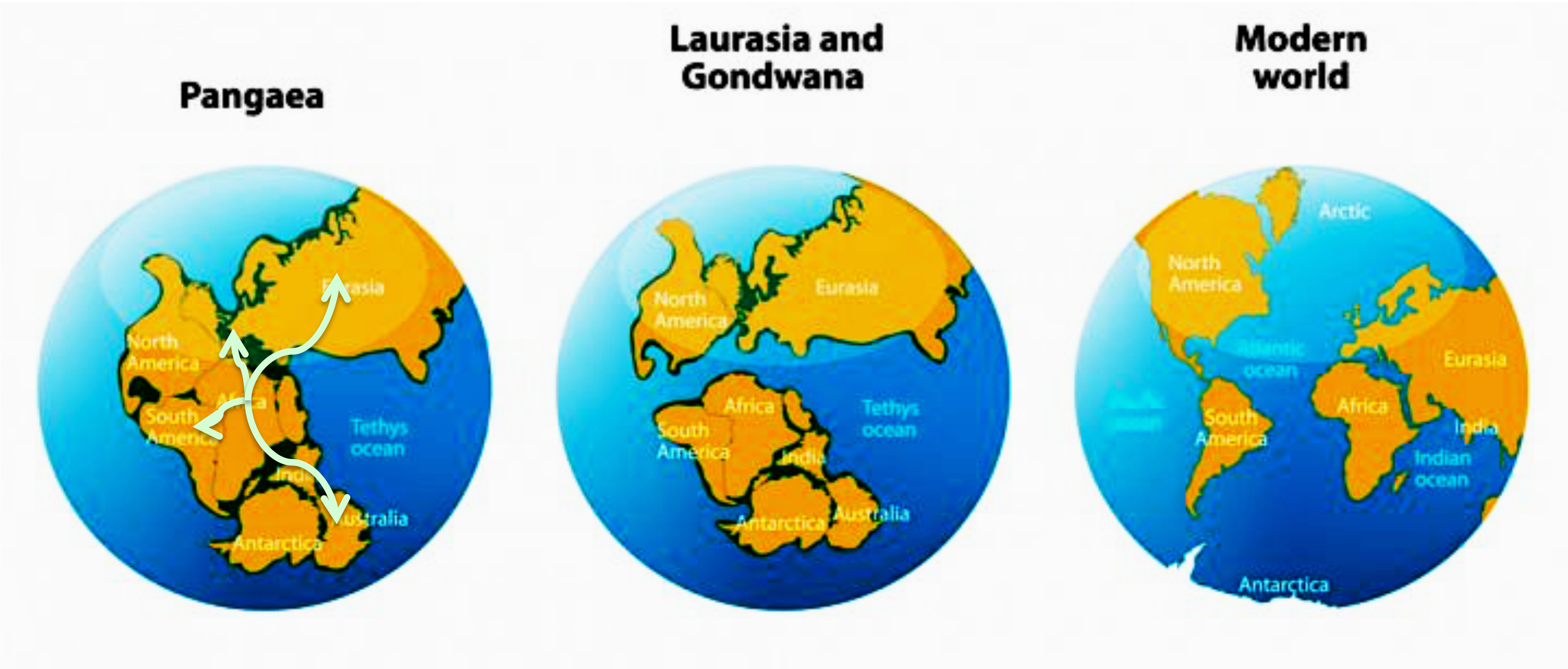
Nearby objects separate v > c; soar beyond their mutual observable horizons and lose all contact

Cosmic Homogeneity: Inflation

Every puddle grows <u>many</u> times over: far larger than 14 billion light years (our visible universe today).

- ***The universe now appears very homogeneous.***
- ***None of the other puddles is visible anymore.***

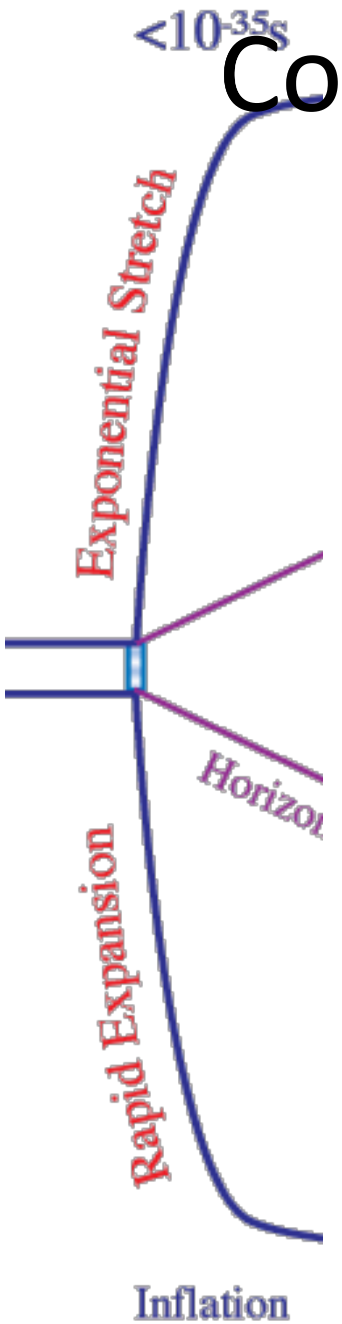
An Analogy: Continental Drift Leads to "Global Cultural Uniformity"



As plates drift, portions of the first African tribes begin to fall outside each other's "spheres of influence", taking their languages, songs, religions, jokes, and diseases with them.

Very remote cultures are surprisingly homogeneous.

Cosmic Homogeneity: Inflation



***WHAT**: Sudden growth of the cosmic horizon*

***WHEN**:* 10^{-35} s ABB

***WHERE**:* everywhere

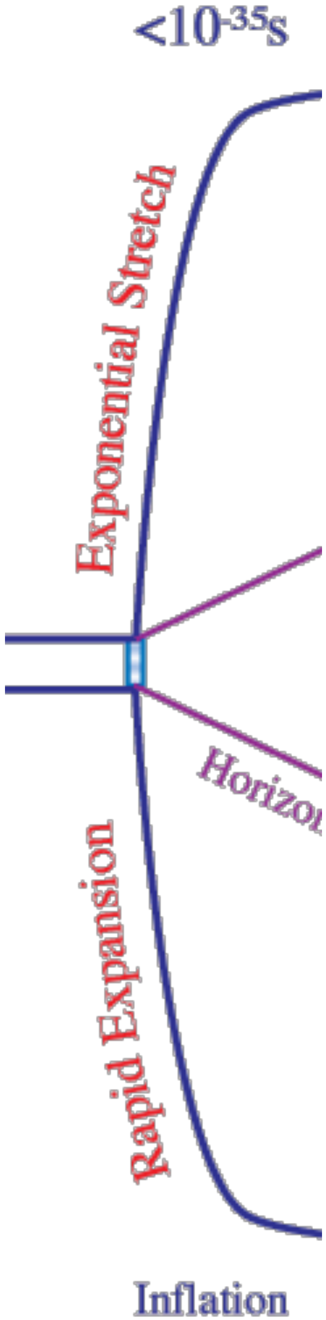
✪ Space inflated (multiplied) in scale by a factor of ***10^{50}*** between I = 10^{-35} and 10^{-33}**s** ABB.

✪ the horizon (radius of spheres of influence) ballooned from $10^{-28.5}$ km to $10^{+23.5}$ km ≈100 x the radius or today's visible universe l.y.

✪Size of proton grew from 10^{-13} cm to 10^{32} km = 10^{19} l.y. !

✪ Regions once in close touch suddenly lost touch and no longer influence each other's evolution (and never will)

✪ However, these regions shard (still share) their "inherited <u>genes</u>"- physical properties, forces, & processes



Inflation resolves problems

WHAT: *Expansion by 10^{50} in 10^{-33} sec*

WHEN: 10^{-35} s to 10^{-35} s ABB

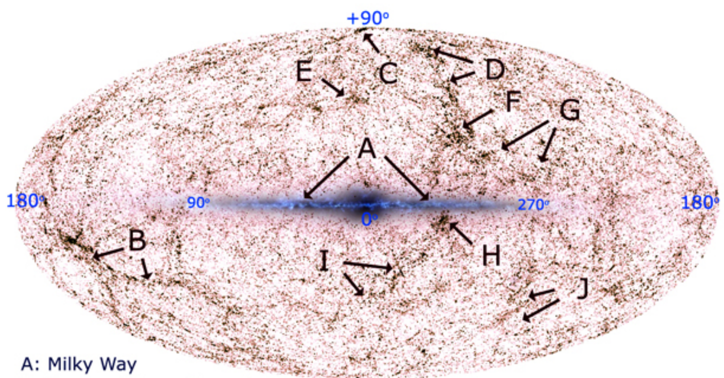
WHERE: everywhere

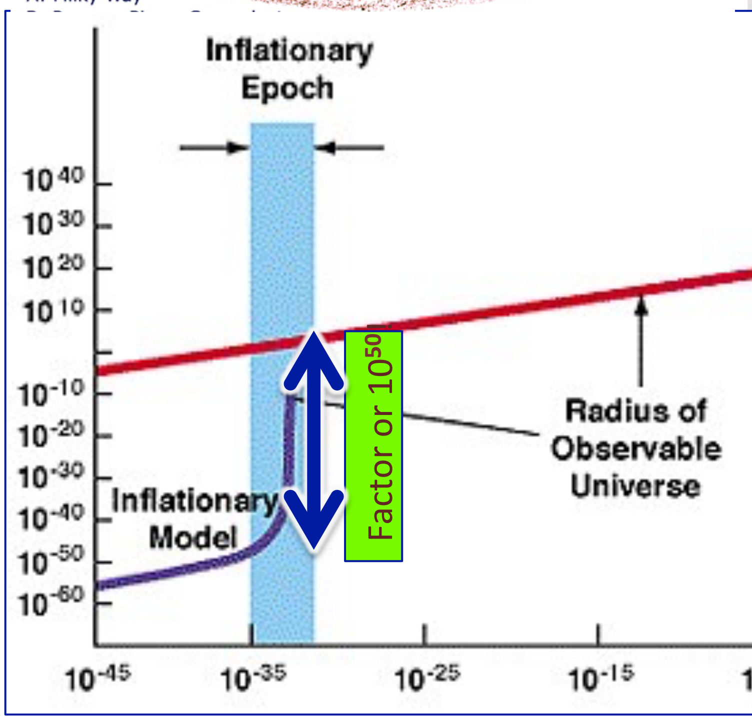
✪ Horizon Problem: Inflation insured that every part of the visible universe, even 180 degrees apart, were once in thermal contact, and would have the same temperature.

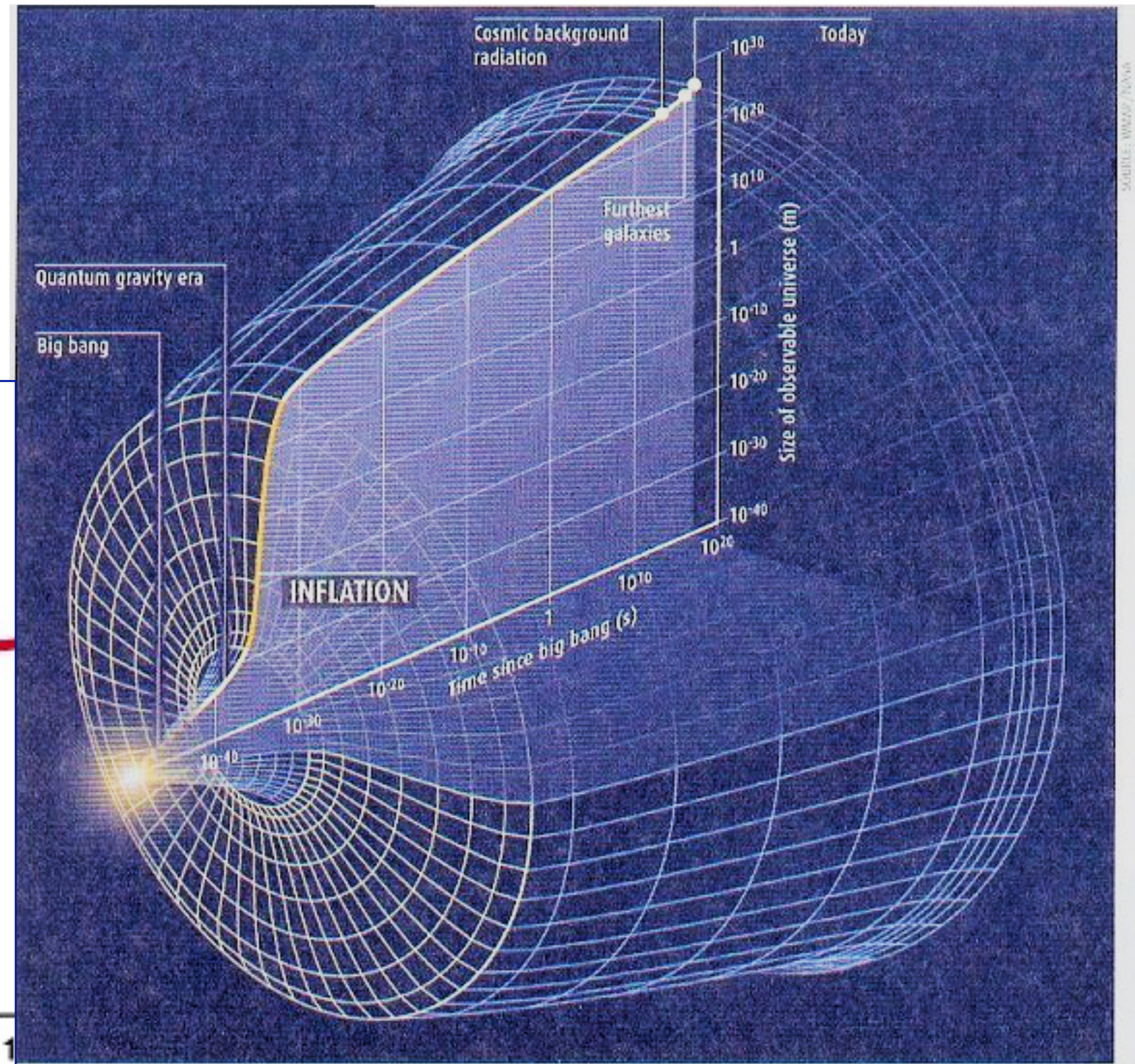
✪ Smoothness Problem: The number of particles in the initial unit that became our visible universe after inflation was much smaller. So Inflation prevents clumping from being larger than observed (rather than being too smooth).

✪ Flatness Problem: The inflation decreased the curvature of space-time by a factor of 10^{50}. That made it flat to all practical purposes.

Cosmic Homogeneity: Inflation





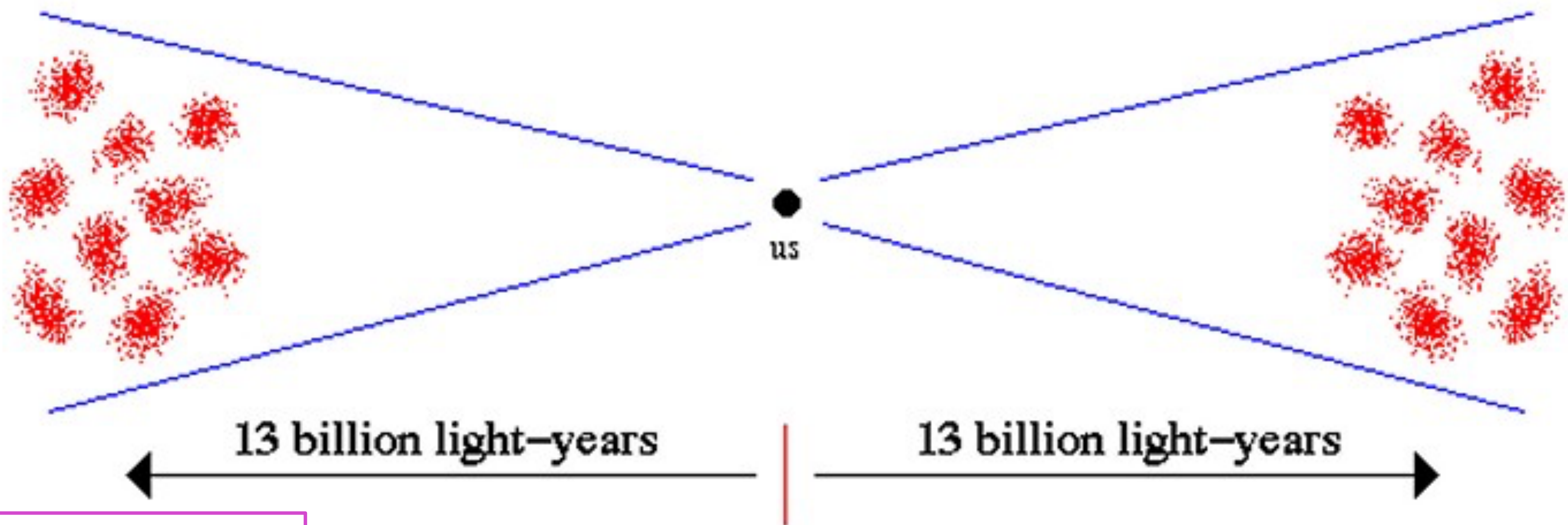


Who Needs Inflation?

Why does each part of the sky look much the same?

Horizon Problem

the number and size of density fluctuations on both sides of the sky are similar, yet they are separated by a distance that is greater than the speed of light times the age of the Universe, i.e. they should have no knowledge of each other by special relativity



Horizon Solution

at some time in the early Universe, all parts of spacetime were causally connected, this must have happened after the spactime foam era, and before the time where thermalization of matter occurred.

Pages 155-56