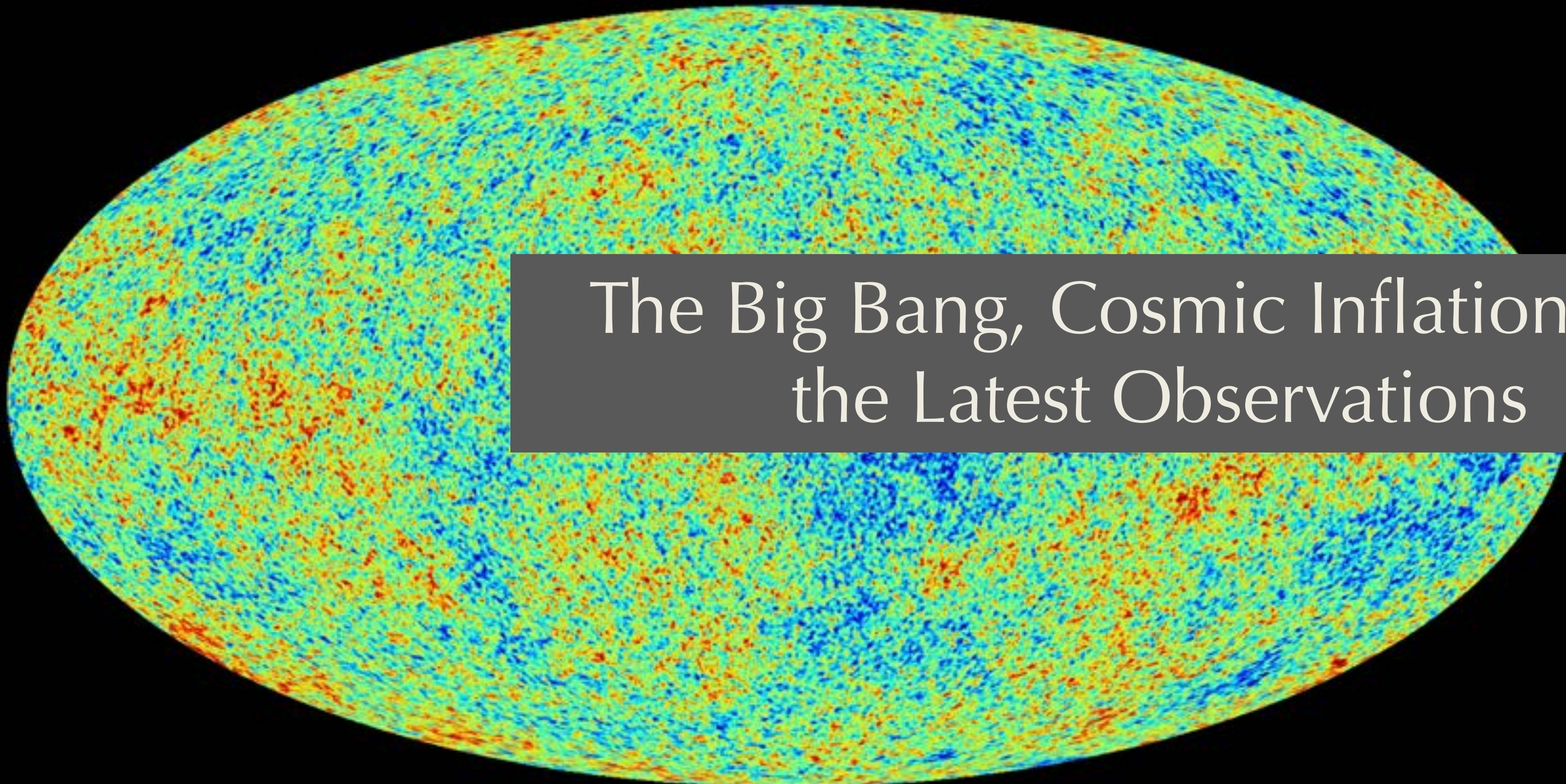


The Big Bang, Cosmic Inflation, and the Latest Observations

8.225 / STS.042, Physics in the 20th Century

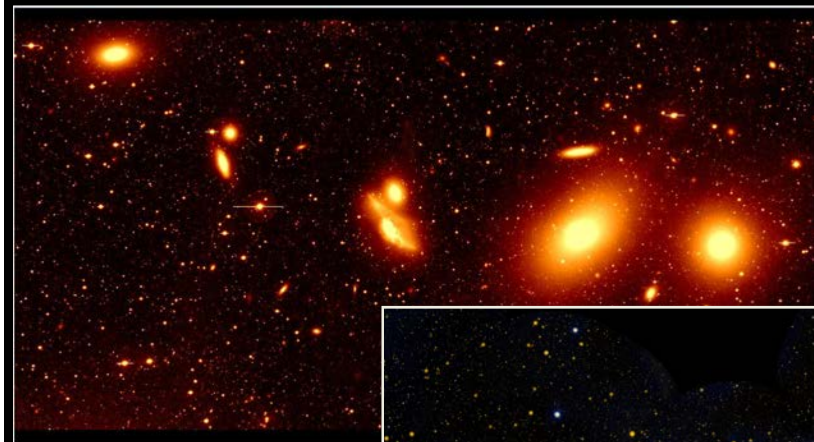
Professor David Kaiser, 7 December 2020

1. Successes of the Big Bang Model

2. Shortcomings of the Big Bang Model

3. Cosmic Inflation and
Large-Scale Structure

Large-Scale Structure



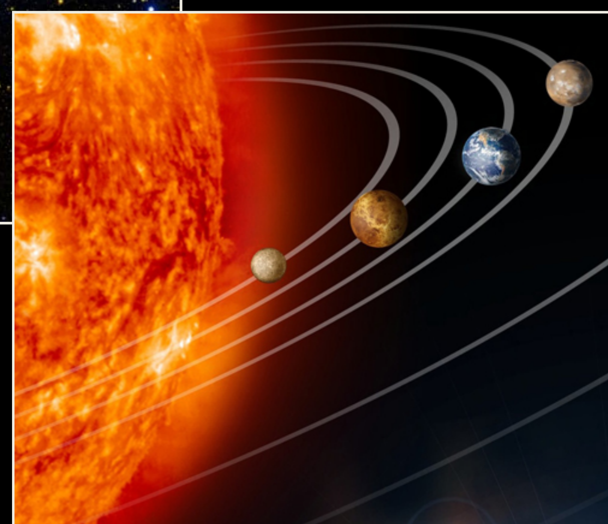
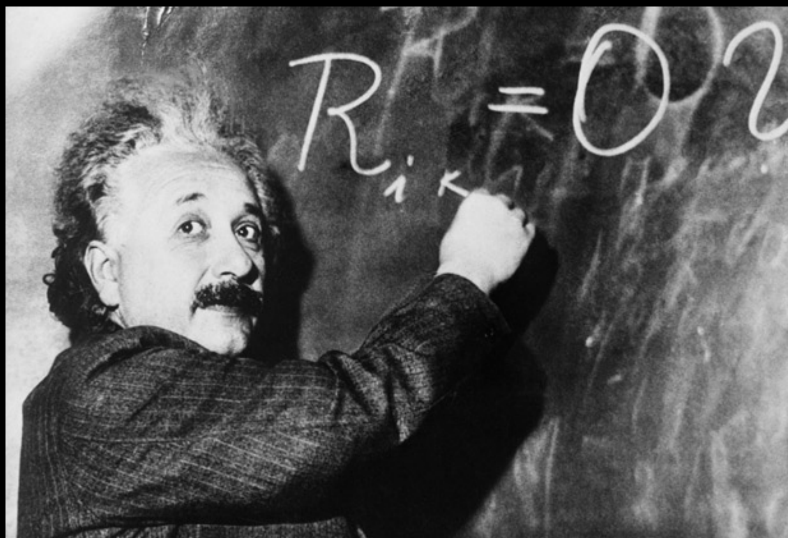
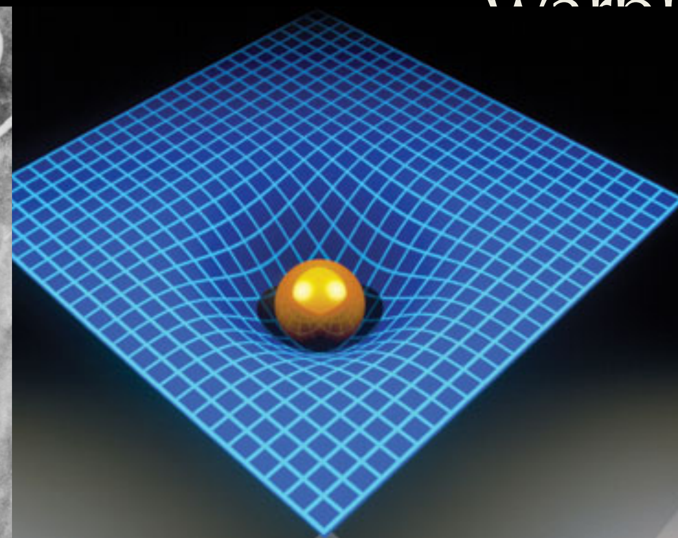


Image is in the public domain.

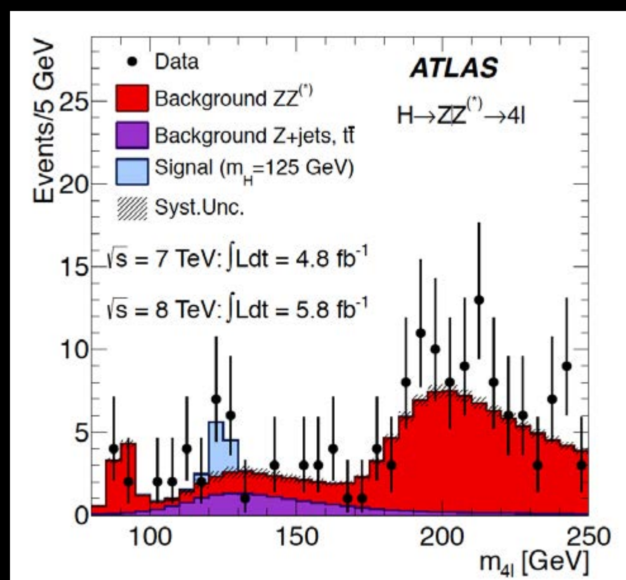
Ingredients

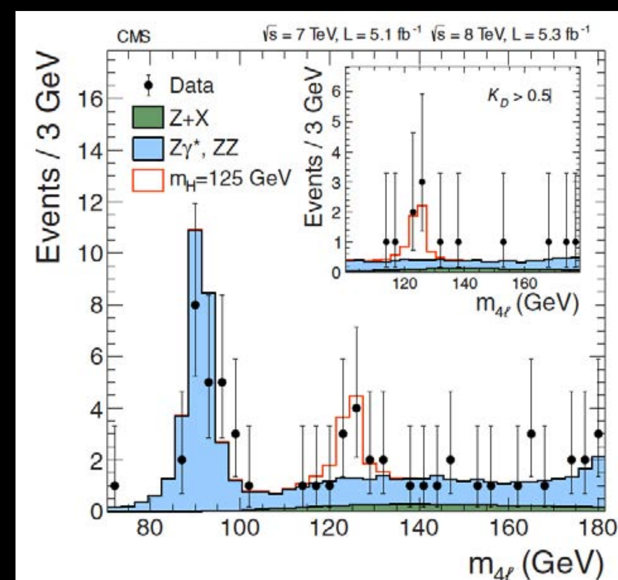
General Relativity: warping spacetime



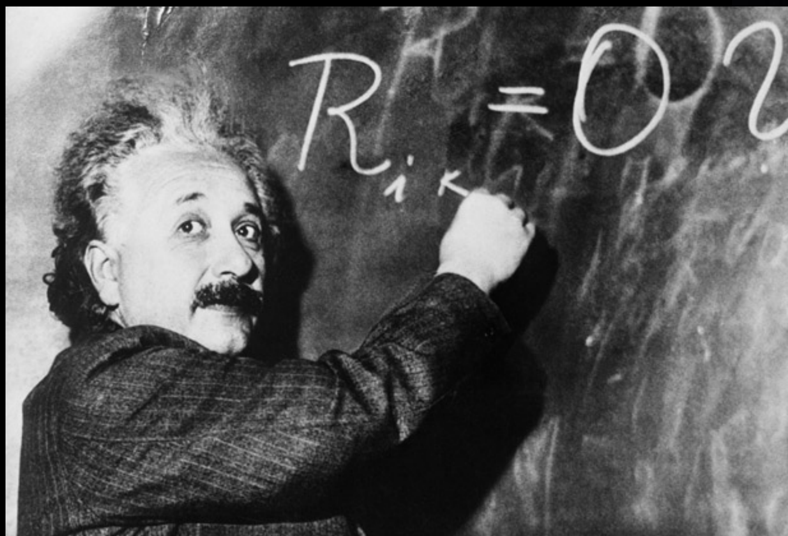


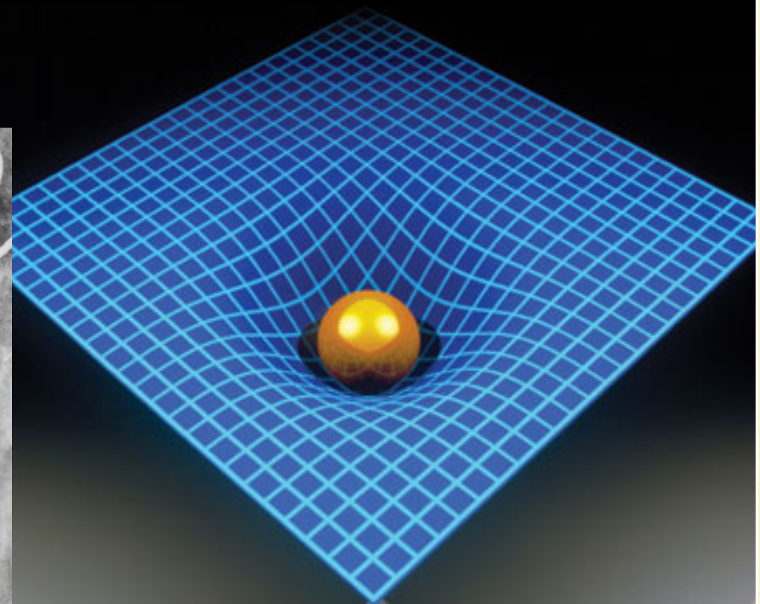
Matter, including — hurray! — the Higgs boson

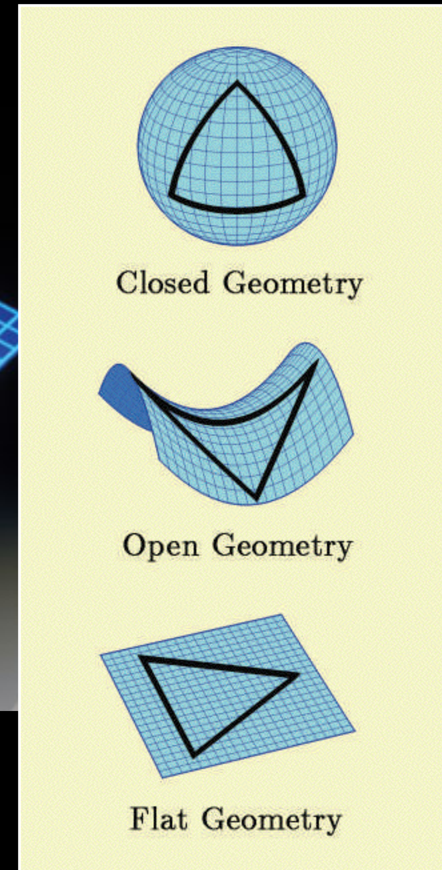




Warping Spacetime



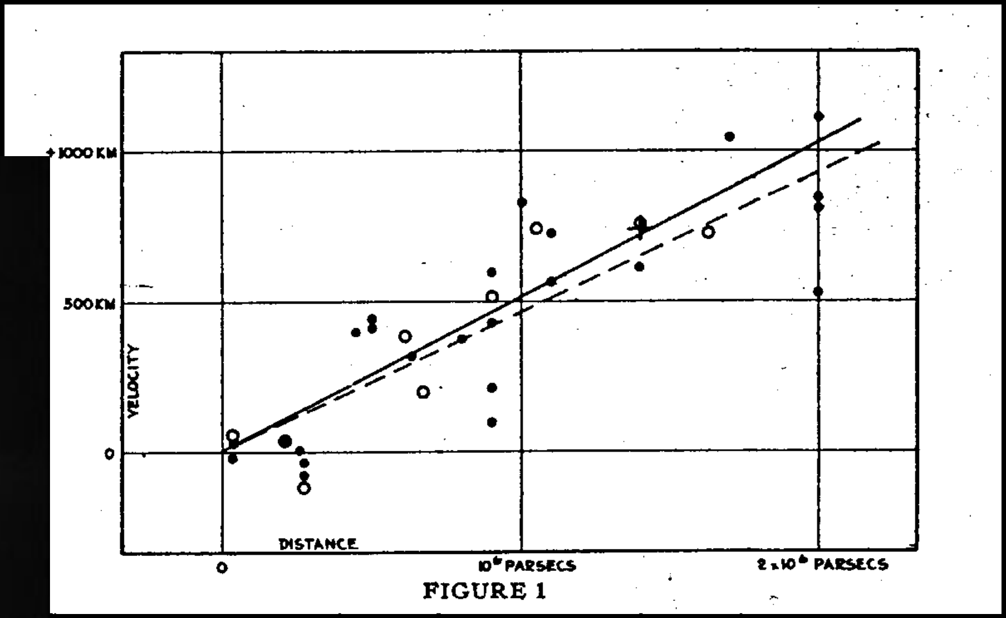




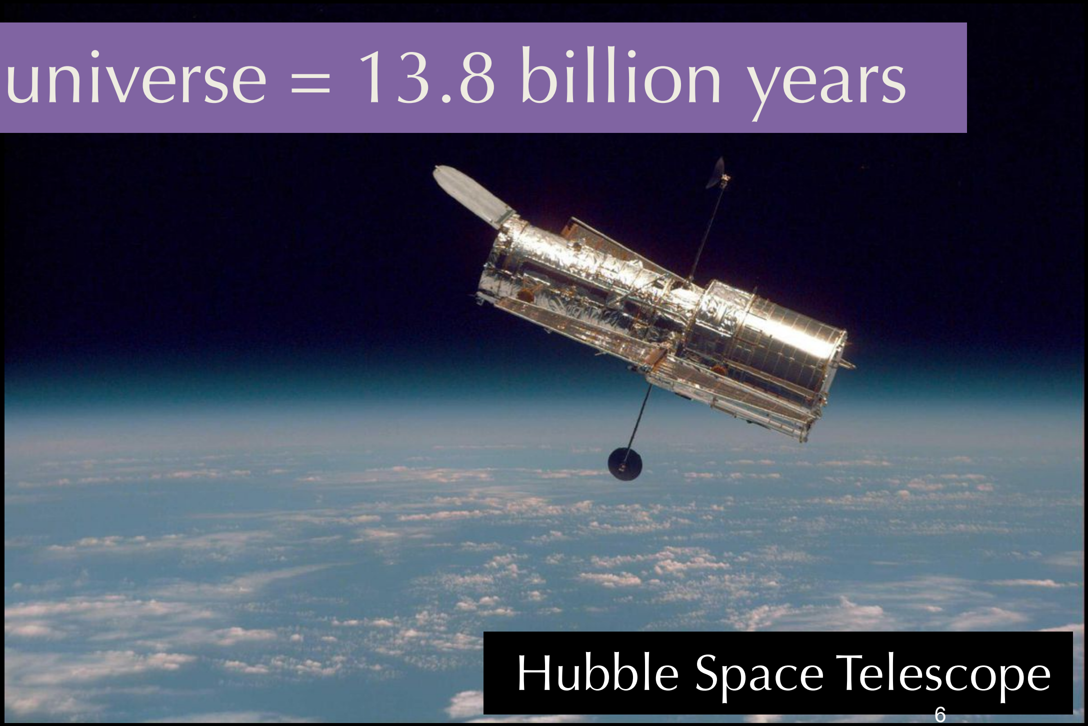
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

curvature of spacetime = distribution of matter and energy

Expanding Universe

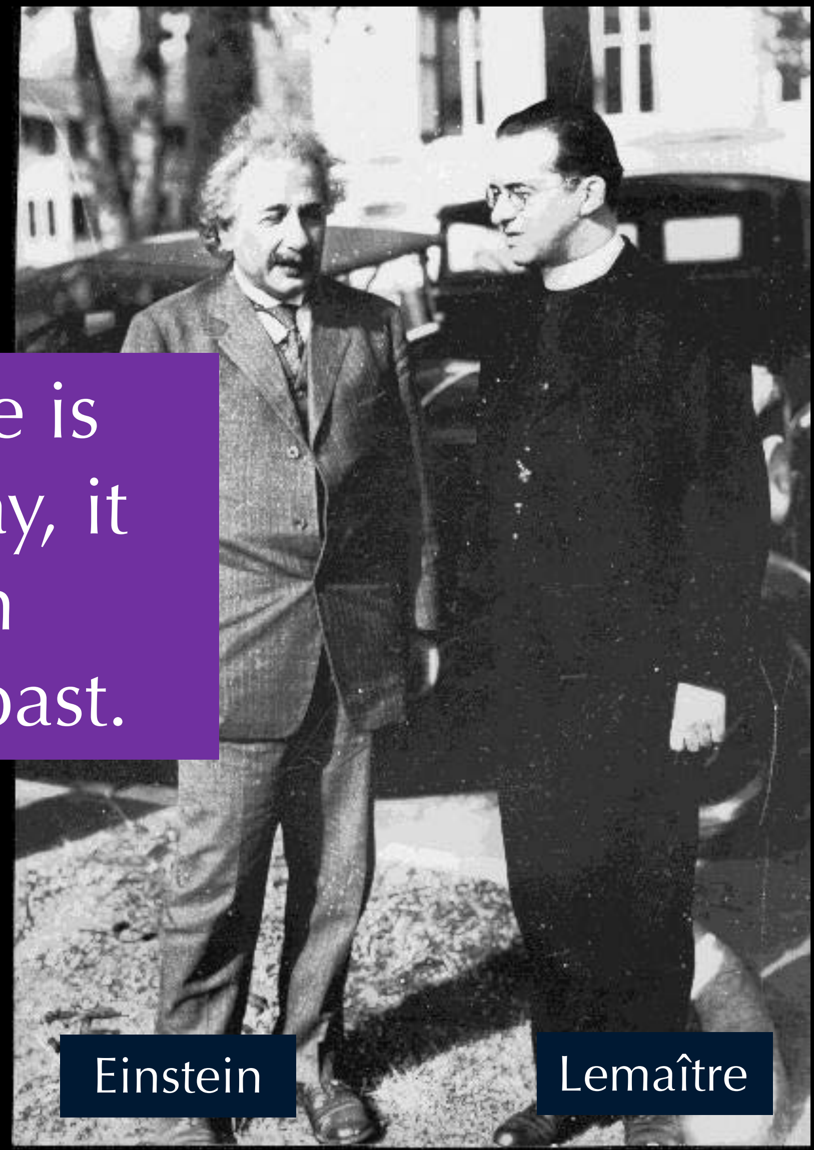


age of the universe = 13.8 billion years



Hubble Space Telescope

If the universe is ***expanding*** today, it must have been ***smaller*** in the past.

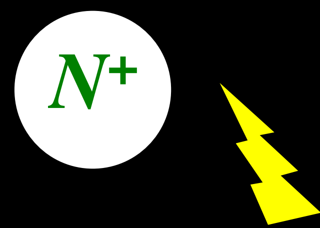


The universe began in a very ***hot, dense state*** and has been expanding ever since.

Remnant Glow

At early times, the universe was so hot that individual photons carried more energy (on average) than the binding energy of a hydrogen atom.

Photons are ***trapped*** between charged particles.

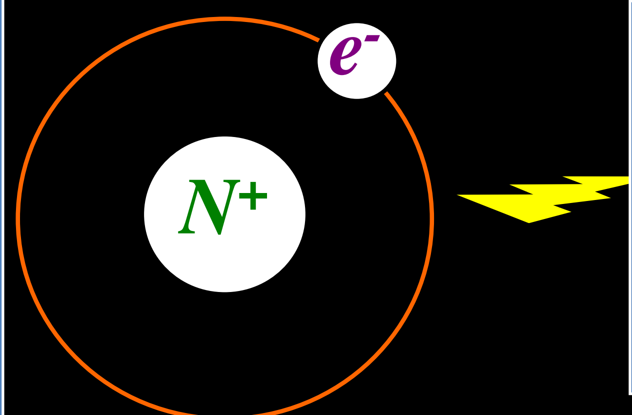


$T > 10^4$ K

$t < 380{,}000$ years

Only around $t = 380{,}000$ years could neutral atoms form:

Photons are ***free***. As the universe expands, their wavelengths get ***stretched***.



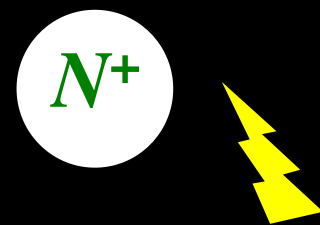
Today the universe is filled with this radiation:

Cosmic Microwave Background Radiation

Like a Dance Party…

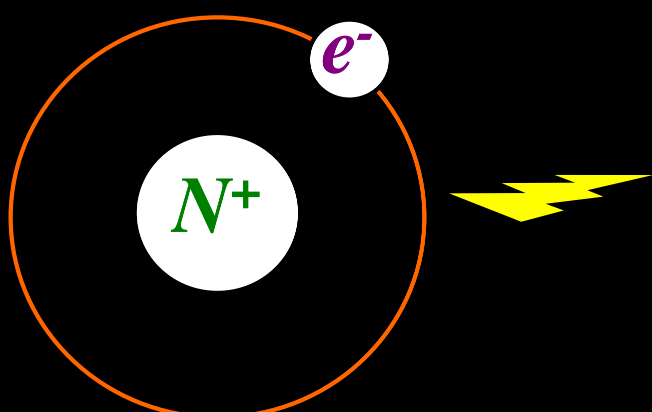
$T > 10^4$ K

$t < 380{,}000$ years



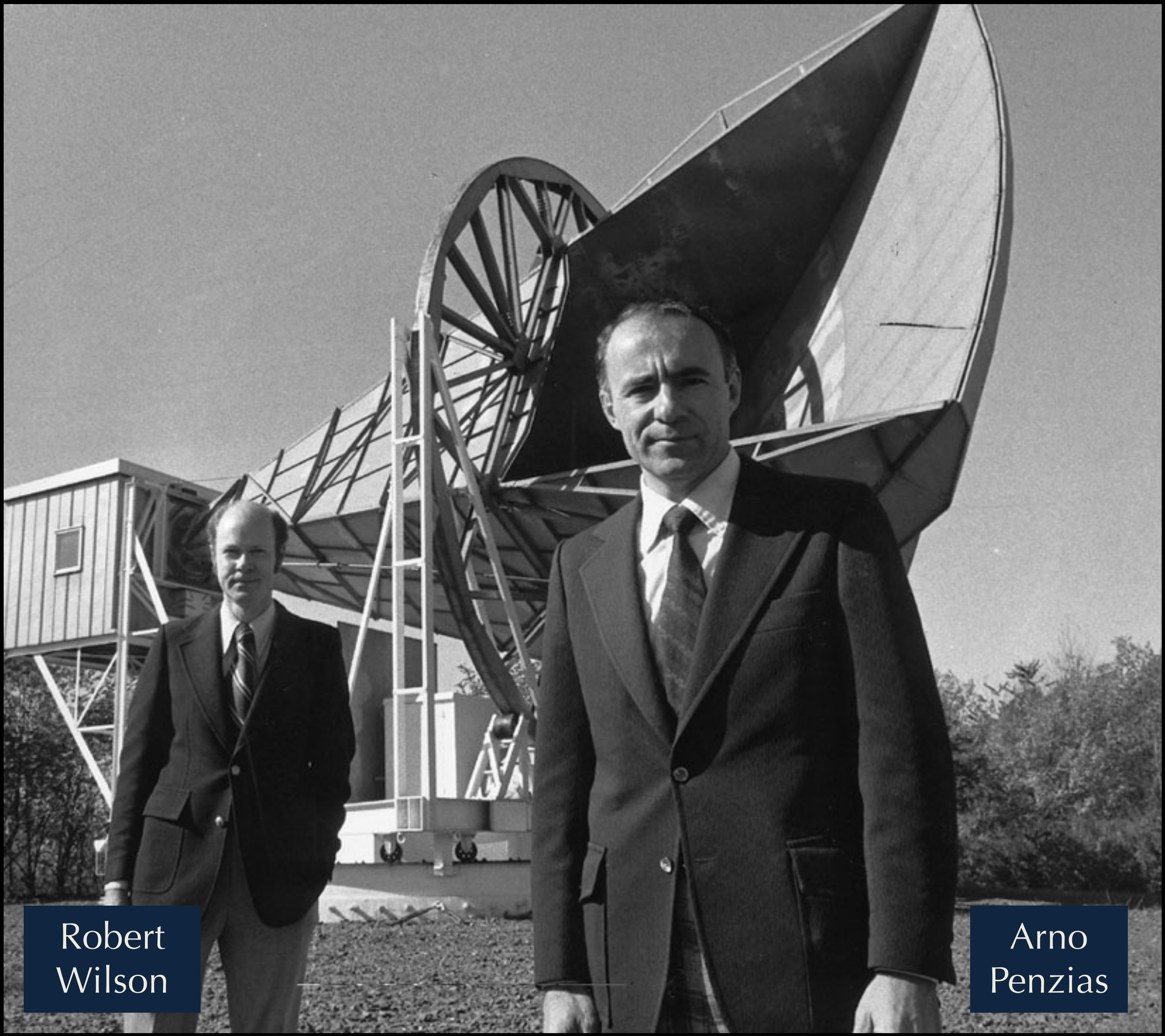
$T < 10^4$ K

$t > 380{,}000$ years



[Still image from Harry Potter removed due to copyright restrictions.]

Accidental Discovery



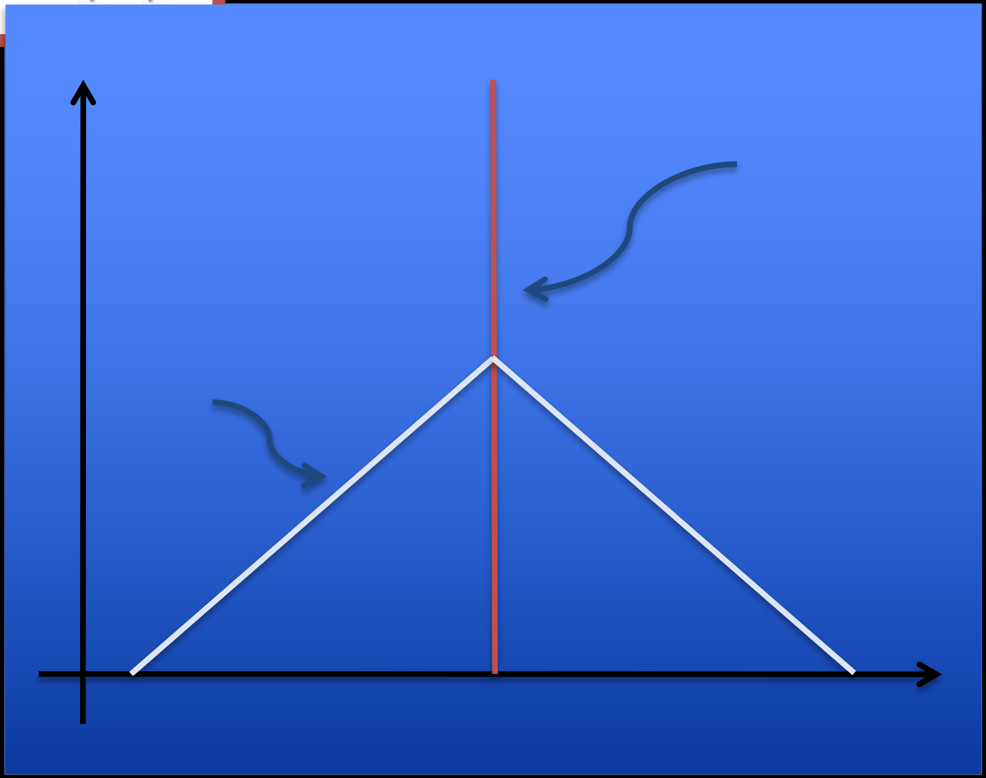
Questions?

Clocks and Rulers

It is convenient to use coordinates that take into account the stretching of space:

$$x = a(t)r$$

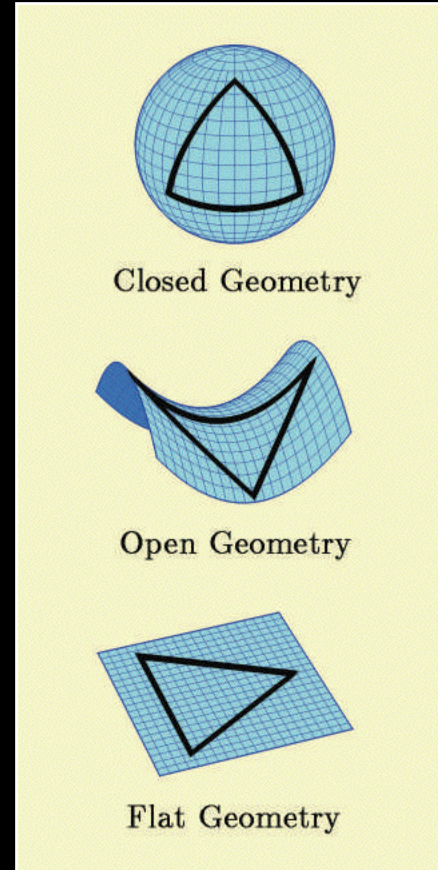
$$\tau = \int_0^t \frac{dt'}{a(t')}$$



Flatness Problem

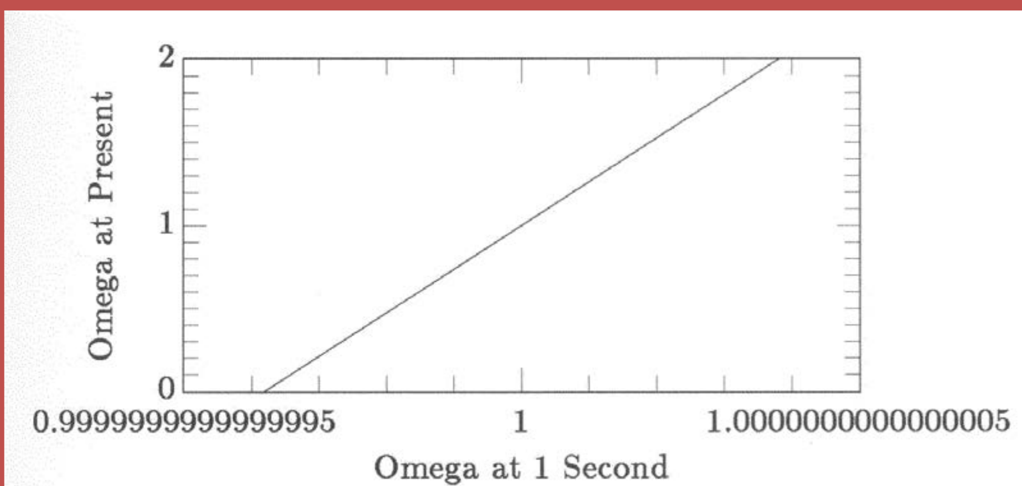
$$\Omega \equiv \frac{\rho}{\rho_{\rm crit}}$$

A *flat* universe has $\Omega = 1$



From Einstein's equations:

$$\frac{|\Omega - 1|}{\Omega} = \frac{1}{a^2\rho} \sim a(t)$$

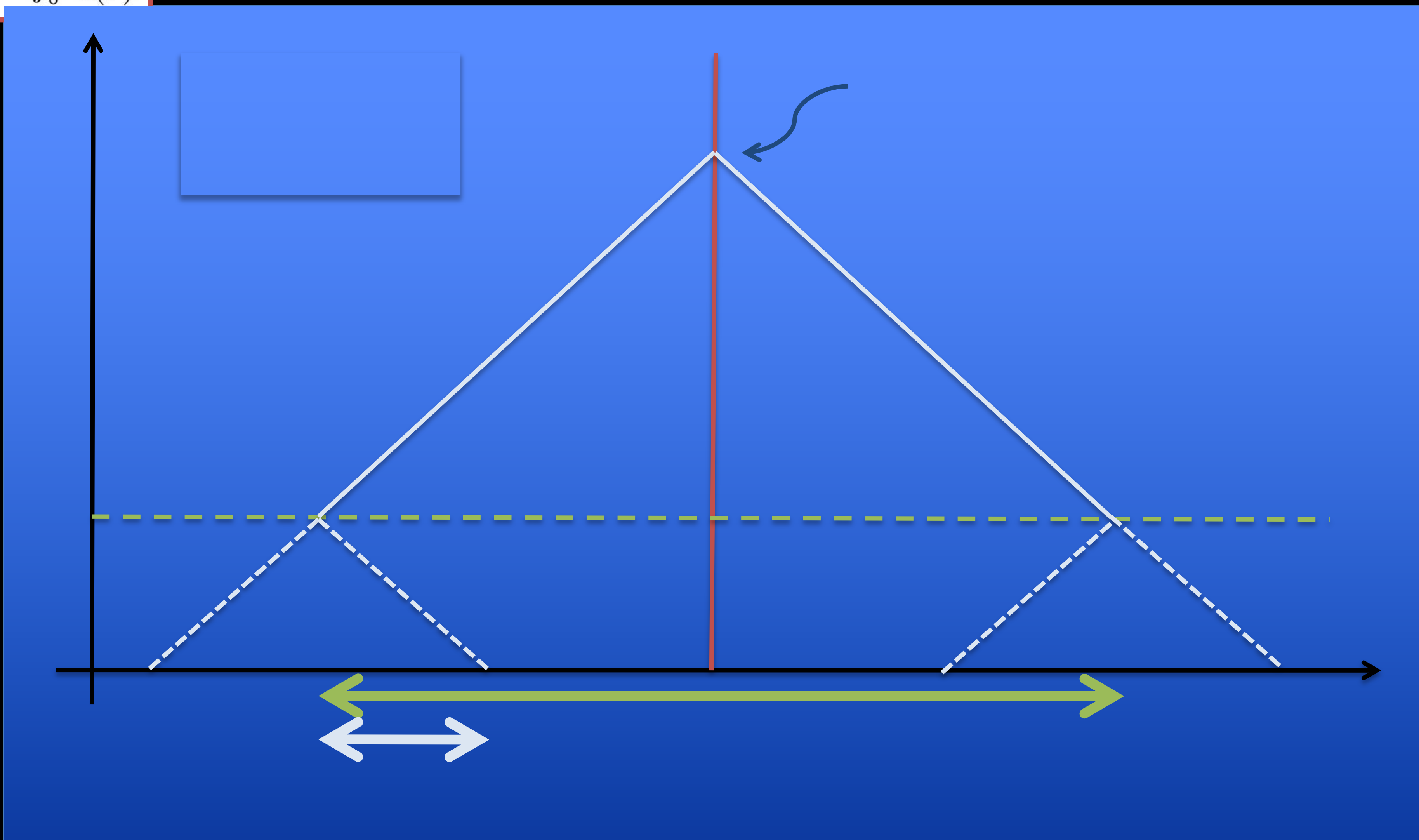


Over time, Ω should flow *away* from 1. After 14 billion years, why do we see anything even close to 1 today?

Horizon Problem

$$x = a(t)r$$

$$\tau = \int_0^t \frac{dt'}{a(t')}$$



Robert Dicke and James Peebles, 1979

Horizon Problem

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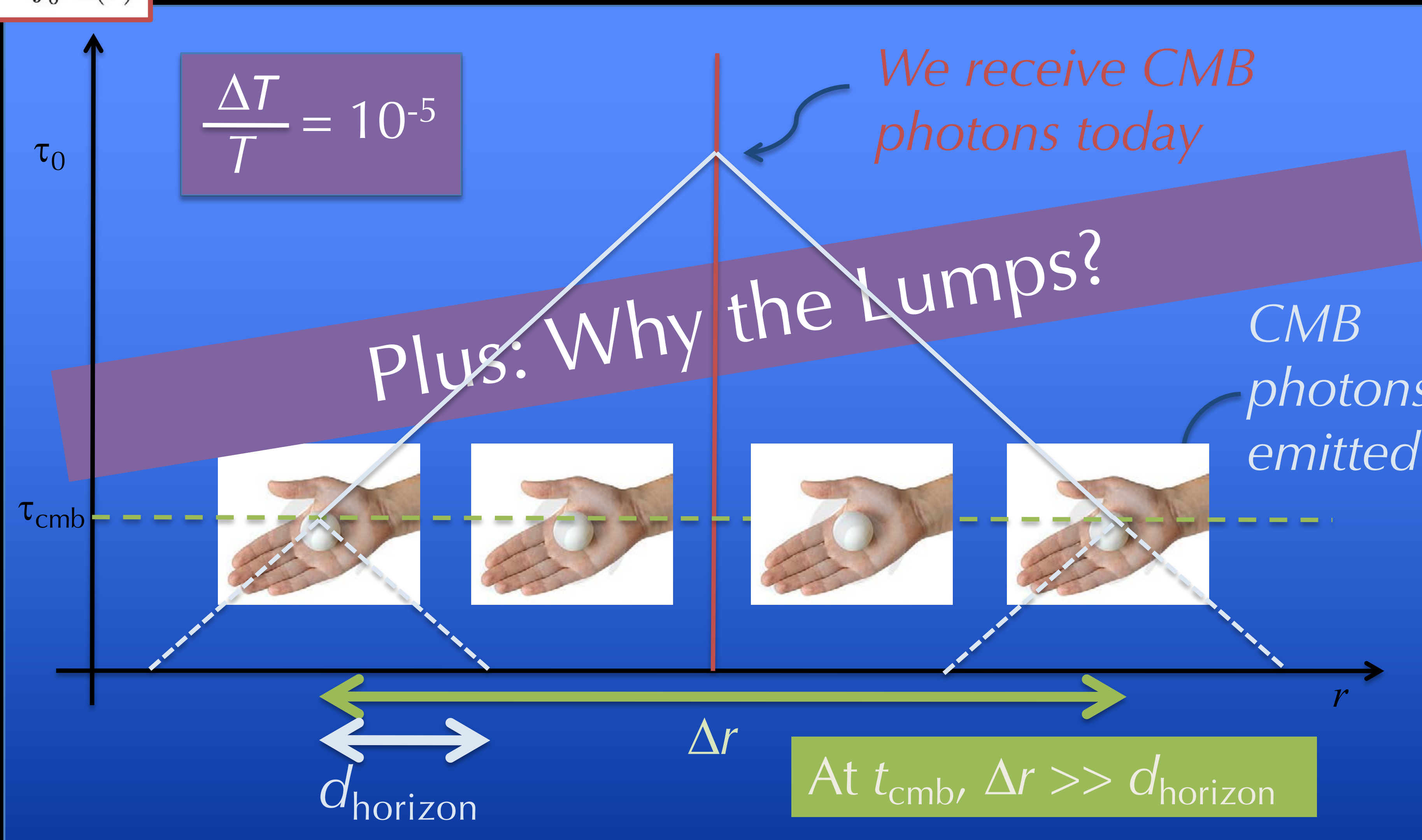
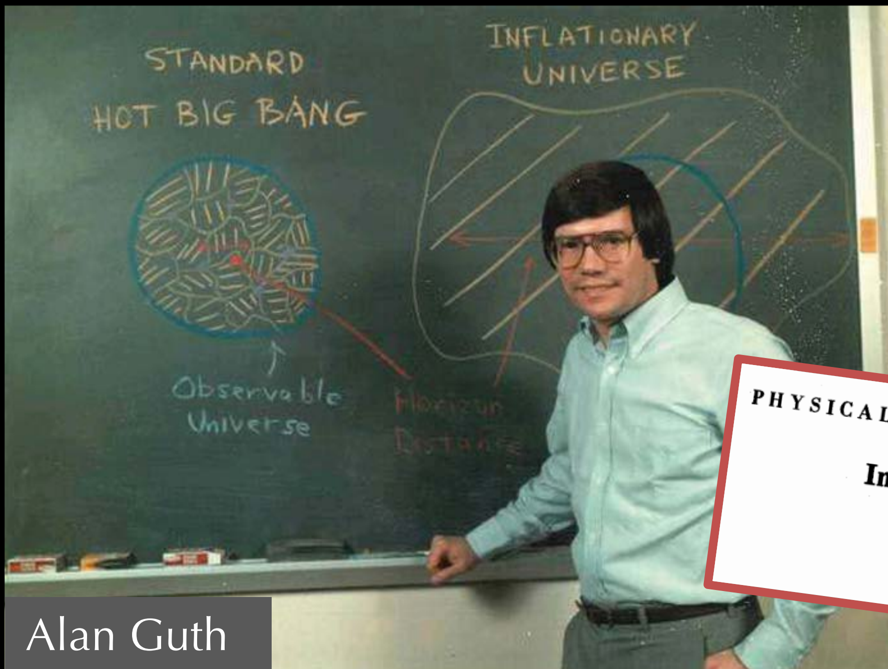
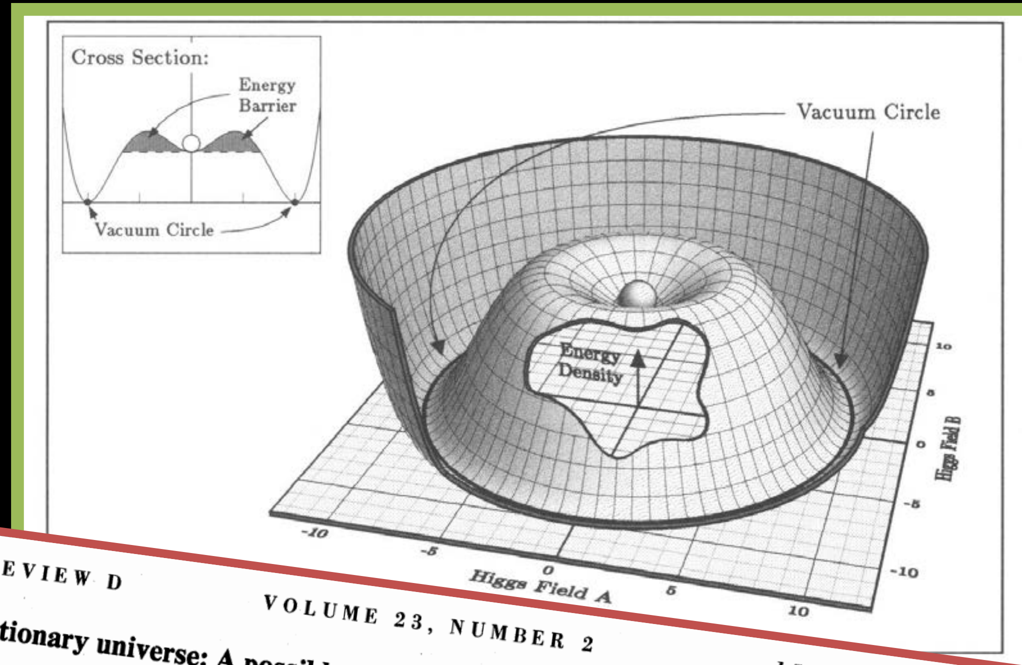


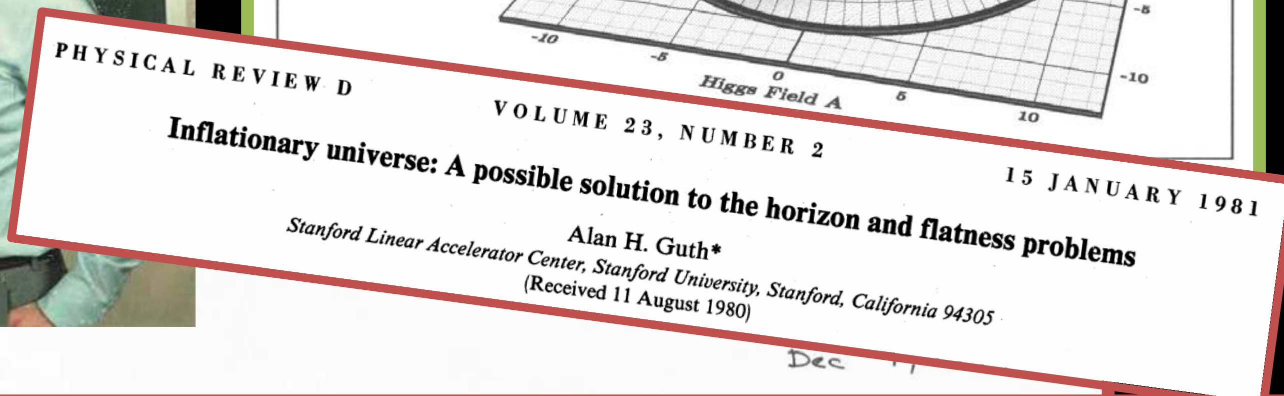
Robert Dicke and James Peebles, 1979

Questions?

Inflation





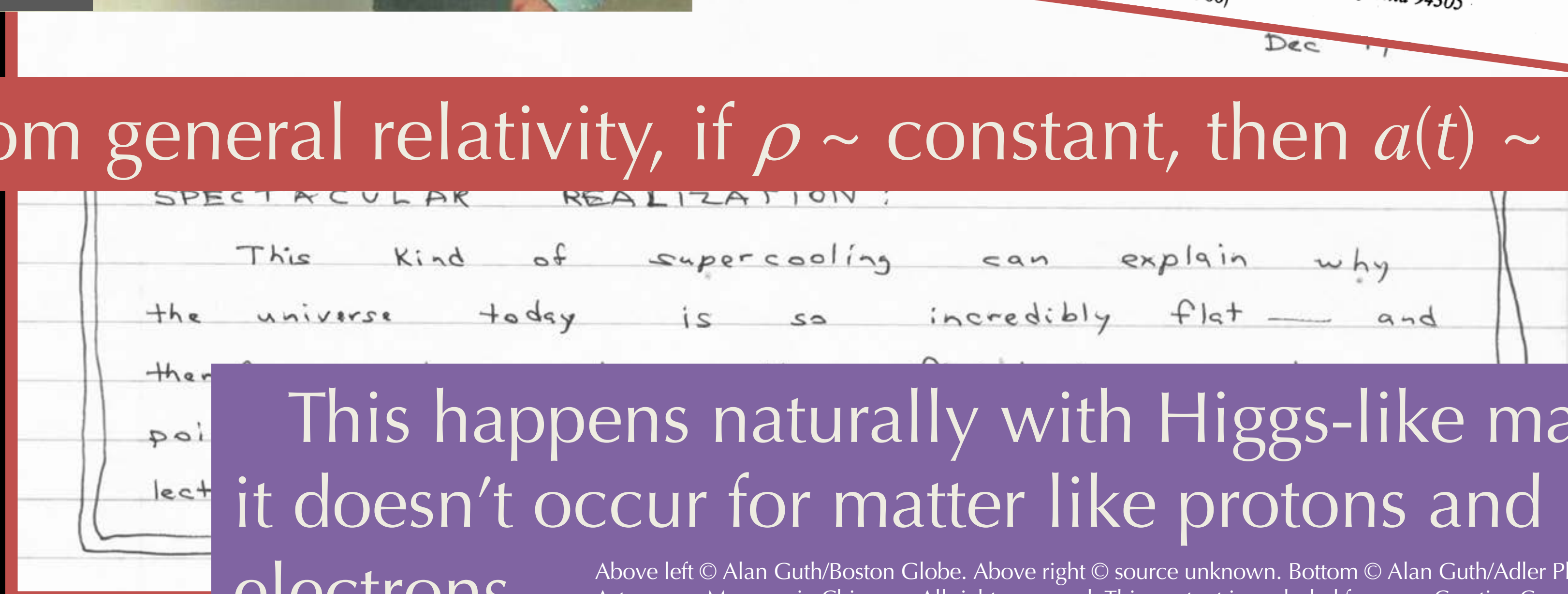

PHYSICAL REVIEW D VOLUME 23, NUMBER 2 15 JANUARY 1981

Inflationary universe: A possible solution to the horizon and flatness problems

Alan H. Guth*

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

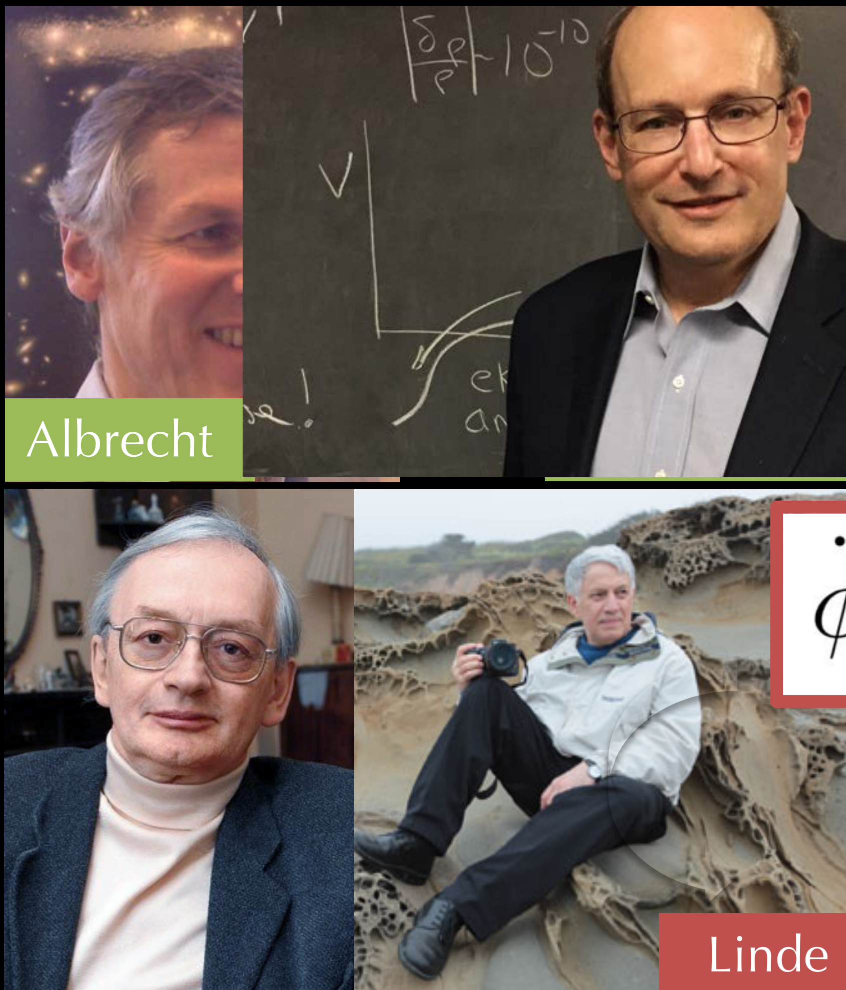
(Received 11 August 1980)

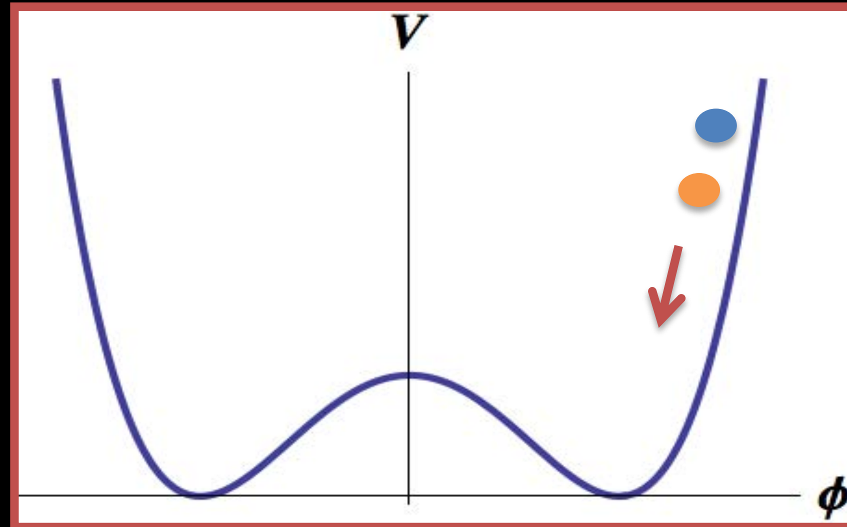


From general relativity, if ρ ~ constant, then $a(t) \sim e^{\sqrt{\rho}\, t}$.

This happens naturally with Higgs-like matter; it doesn't occur for matter like protons and electrons.

Inflation



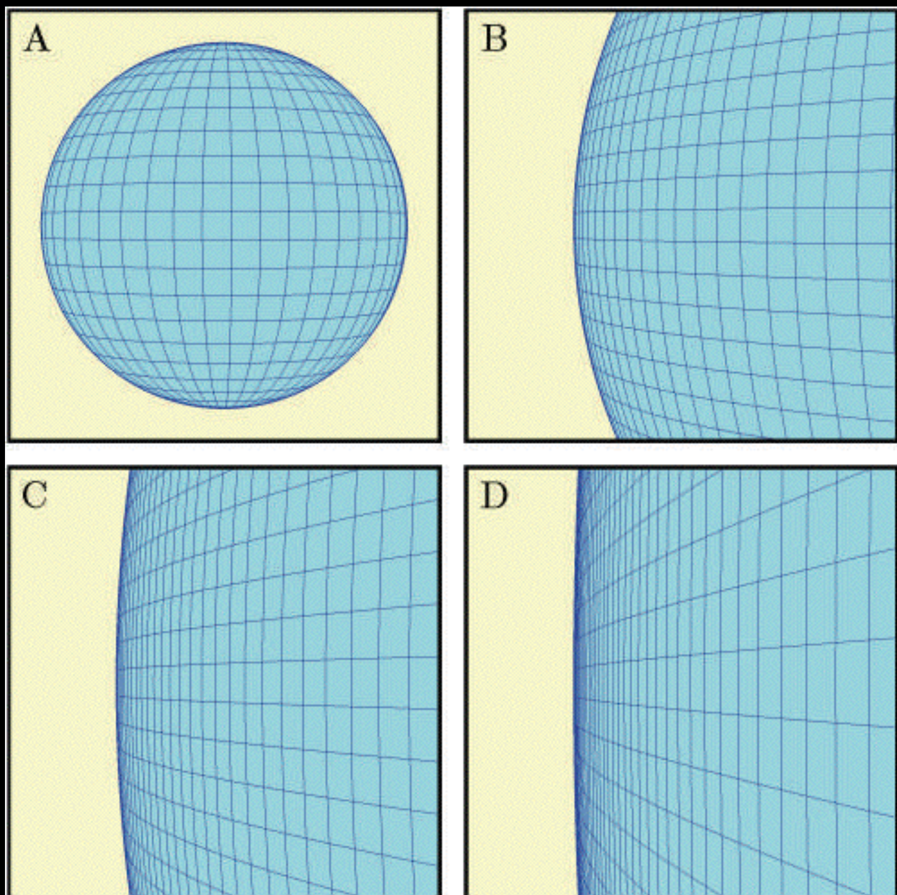


$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi}(\phi) = 0$$

$$a(t) \simeq a_0 e^{Ht}$$

This happens naturally with Higgs-like matter; it doesn't occur for matter like protons and electrons.

Inflation Solves the Flatness Problem



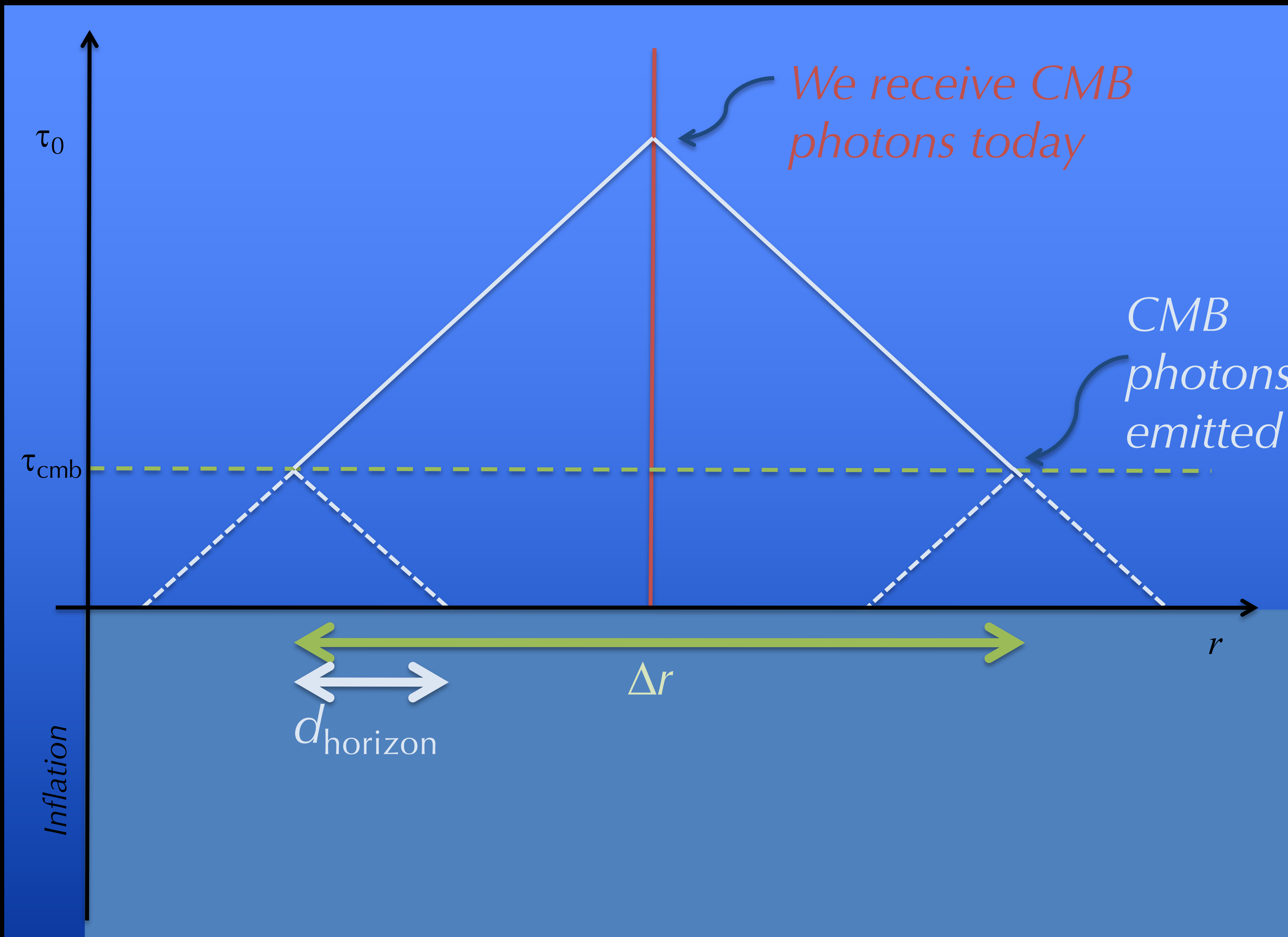
$$\frac{|\Omega - 1|}{\Omega} = \frac{1}{a^2 \rho}$$

so as $a(t)$ gets big and ρ remains constant, $\Omega \rightarrow 1$.

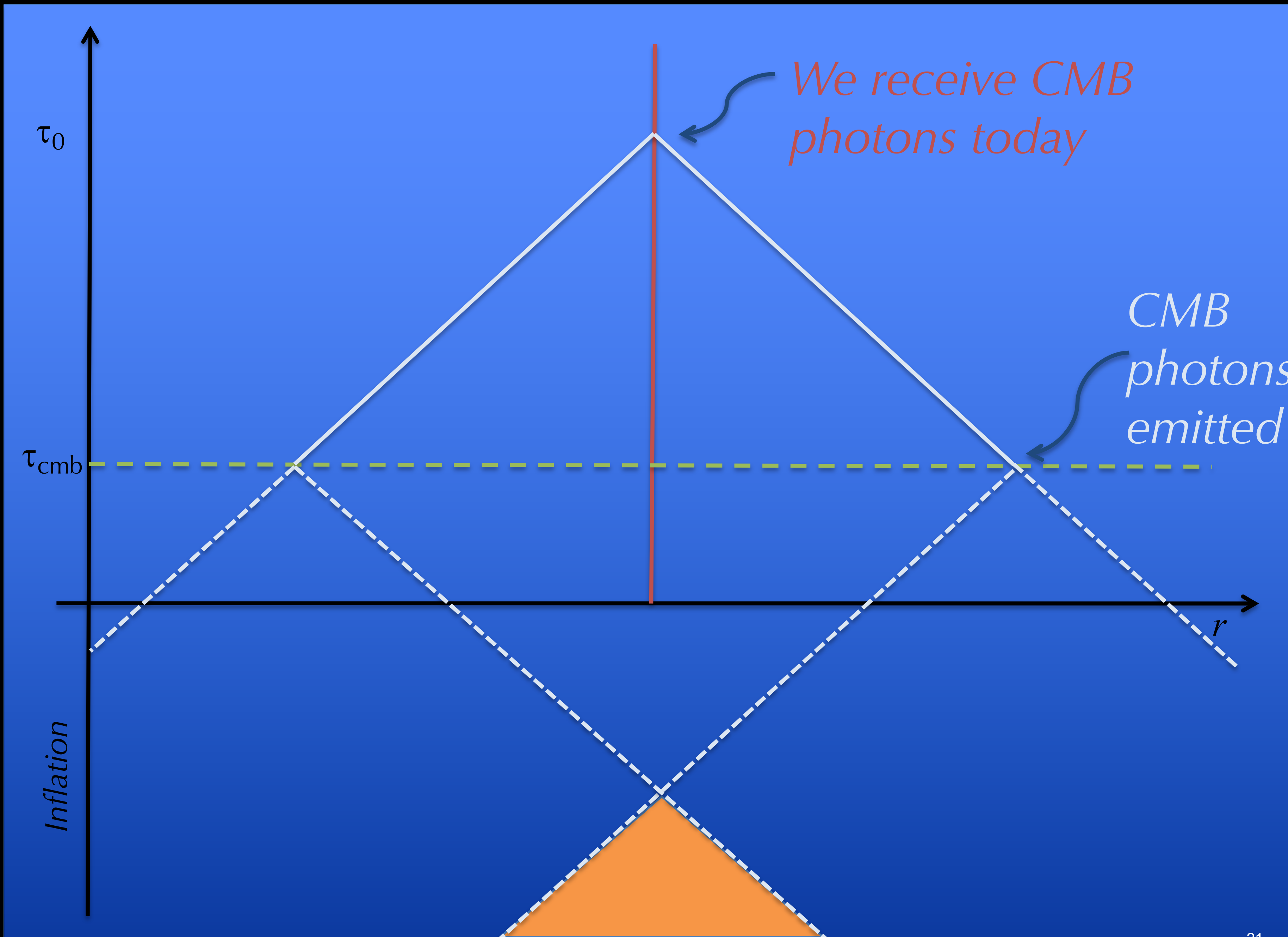
Latest measurement: $\boldsymbol{\Omega = 1.0007 \pm 0.0037}$

Planck collaboration, arXiv:1807.06211

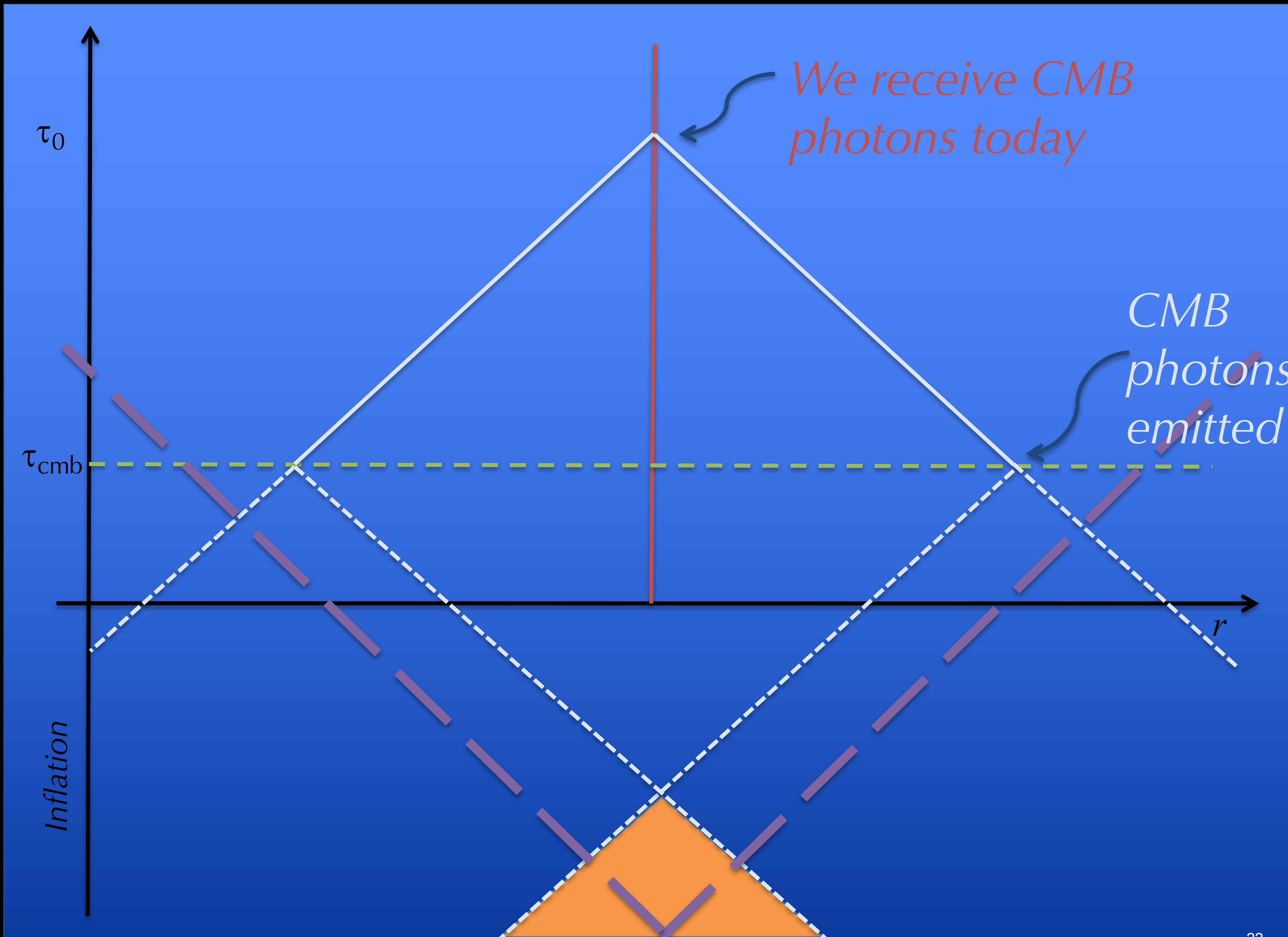
Inflation Solves the Horizon Problem



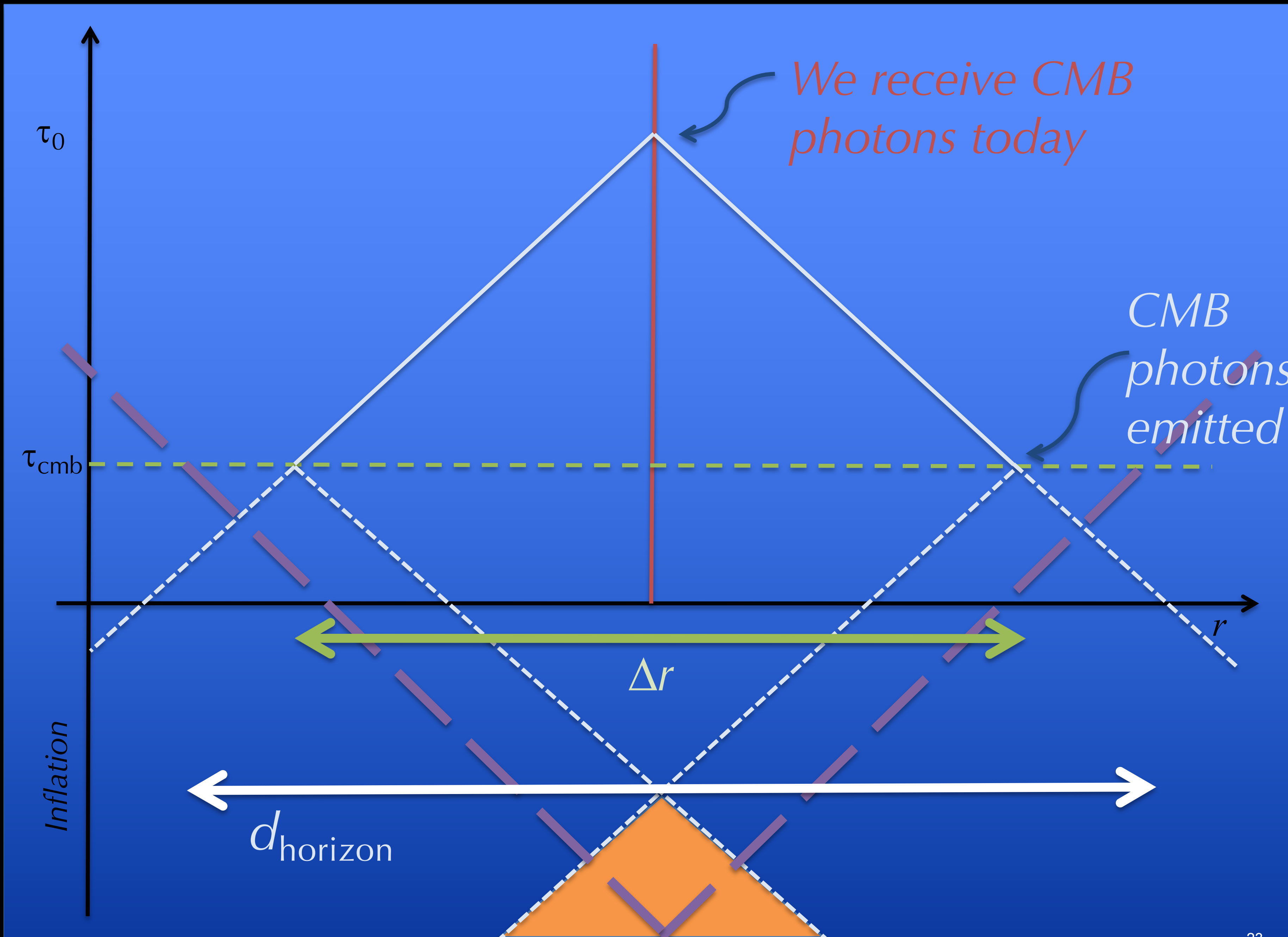
Inflation Solves the Horizon Problem



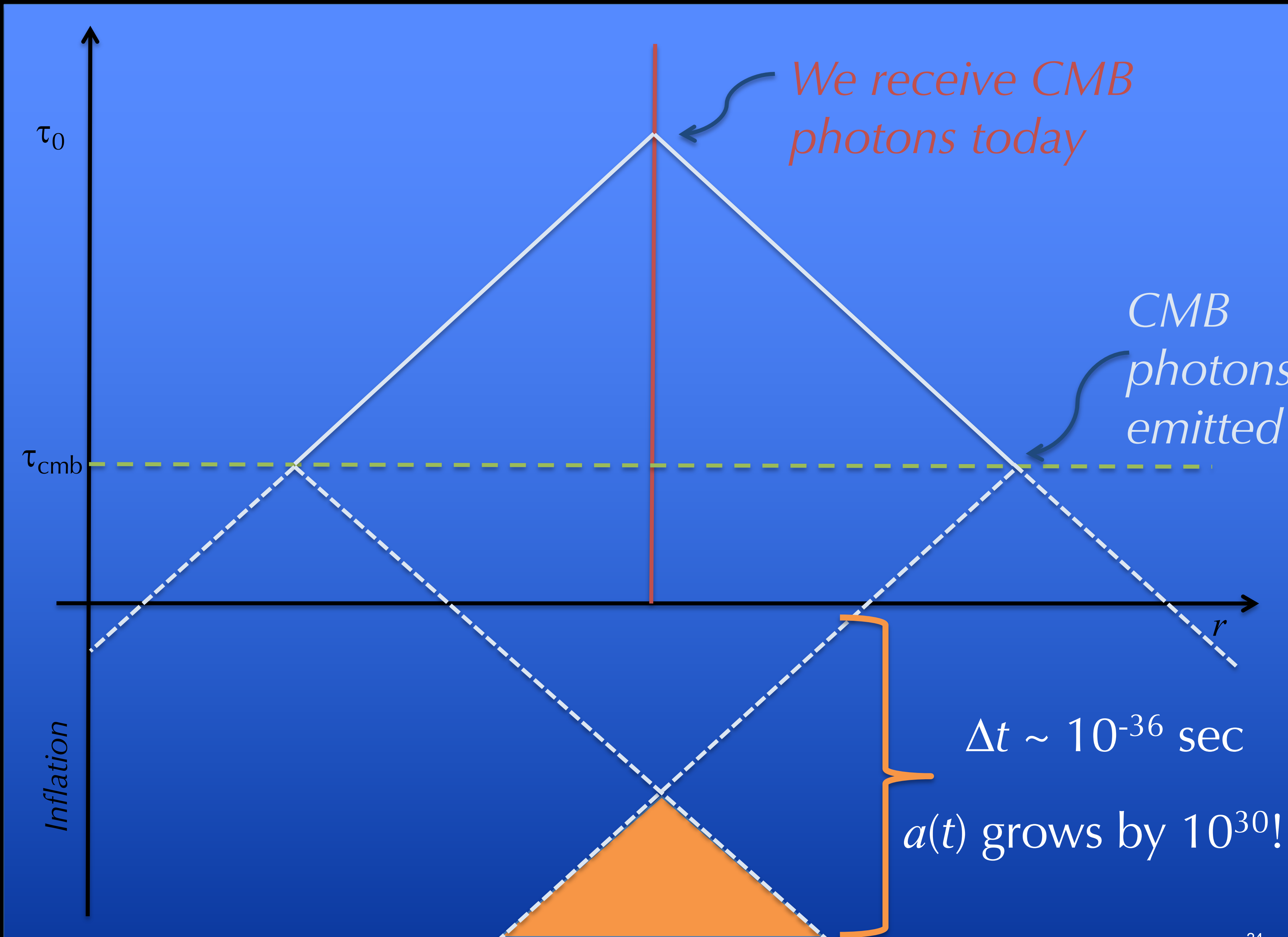
Inflation Solves the Horizon Problem



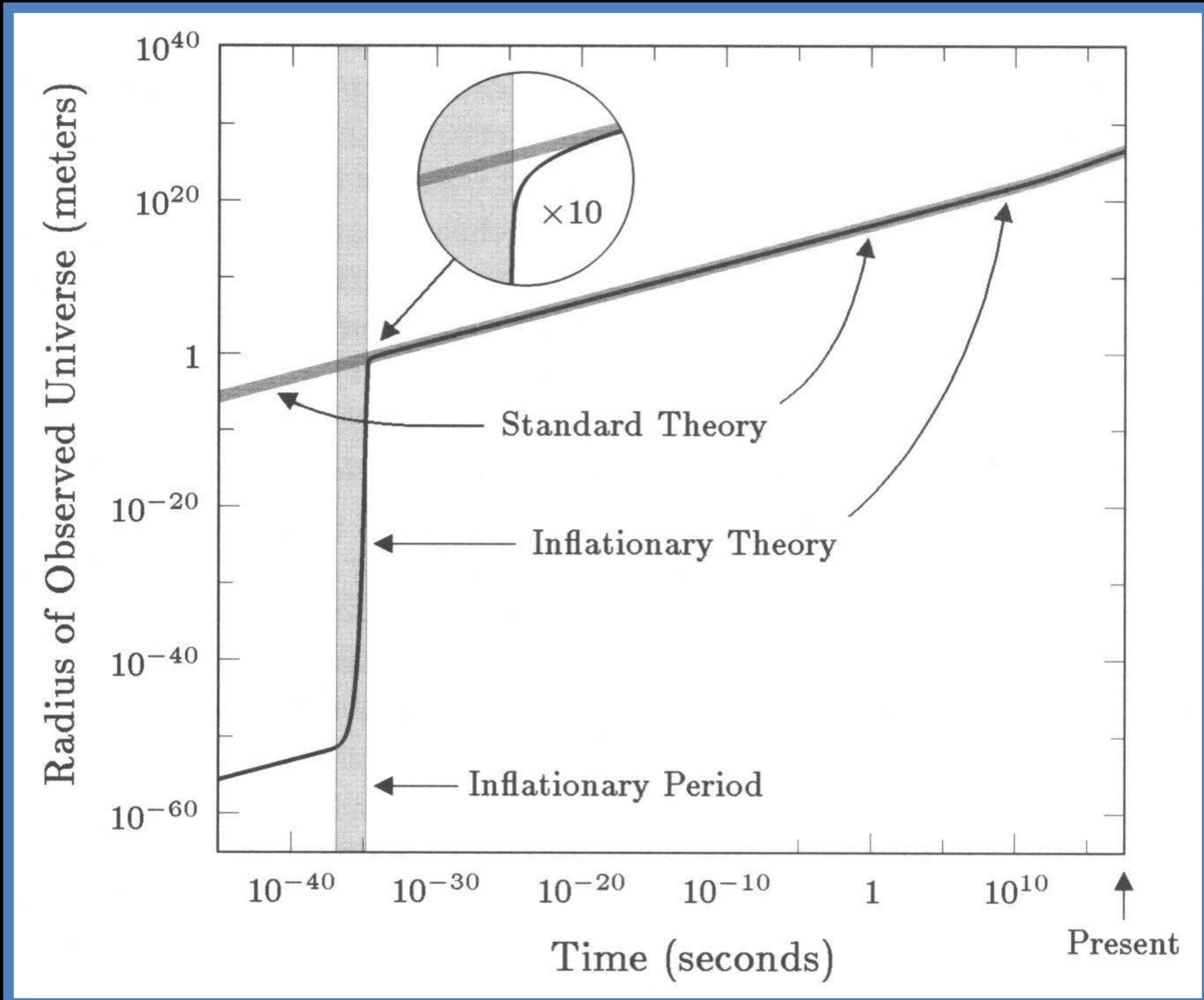
Inflation Solves the Horizon Problem



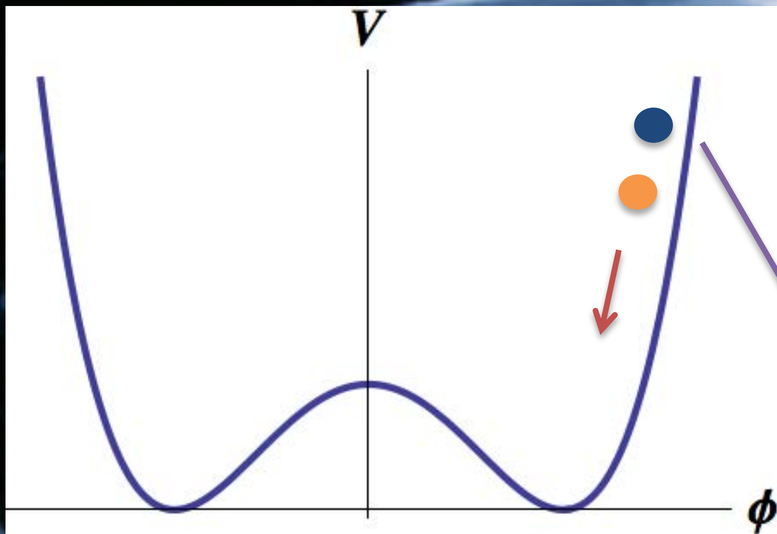
Inflation Solves the Horizon Problem



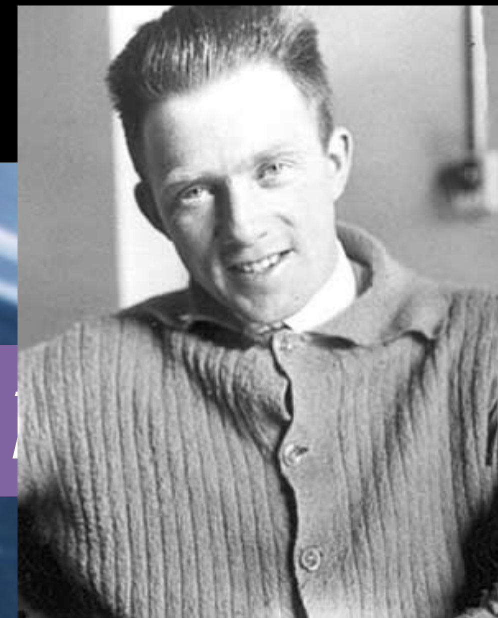
Inflation Solves the Horizon Problem

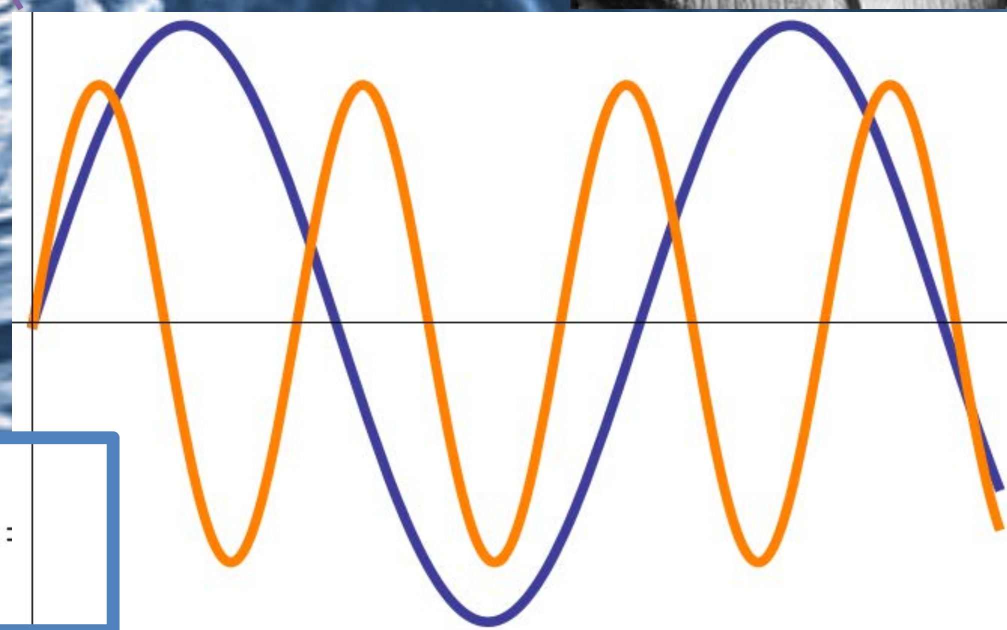


Primordial Wiggles



$\Delta x \, \Delta p \geq$



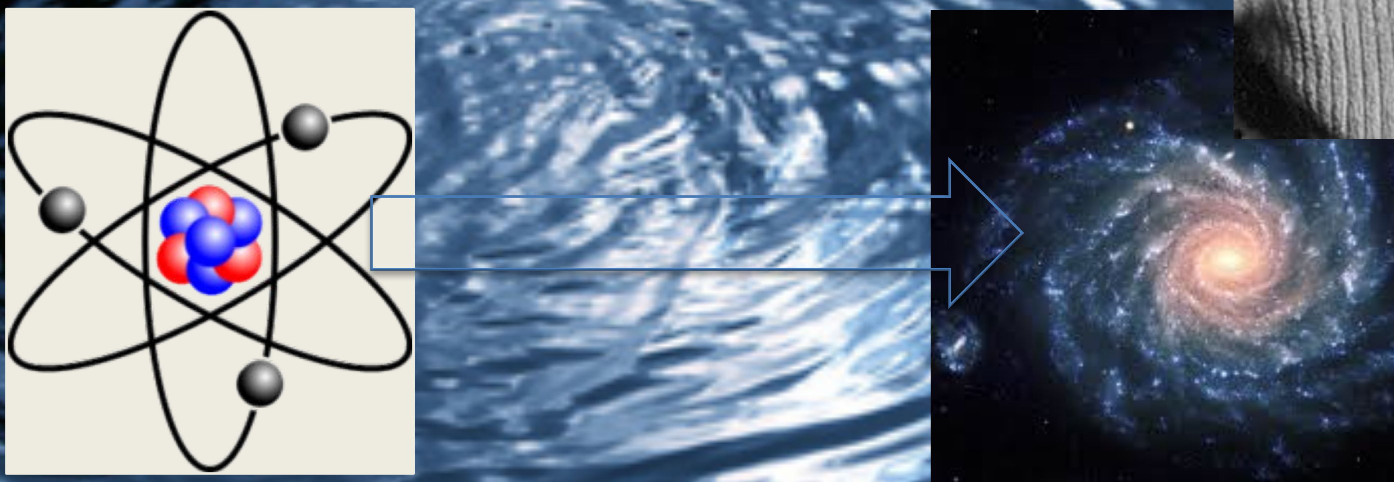


$$\delta\ddot{\phi}_k + 3H\delta\dot{\phi}_k + \left[\frac{k^2}{a^2} + m_{\rm eff}^2(t)\right]\delta\phi_k$$

Gravity stretches and amplifies quantum fluctuations

Primordial Wiggles

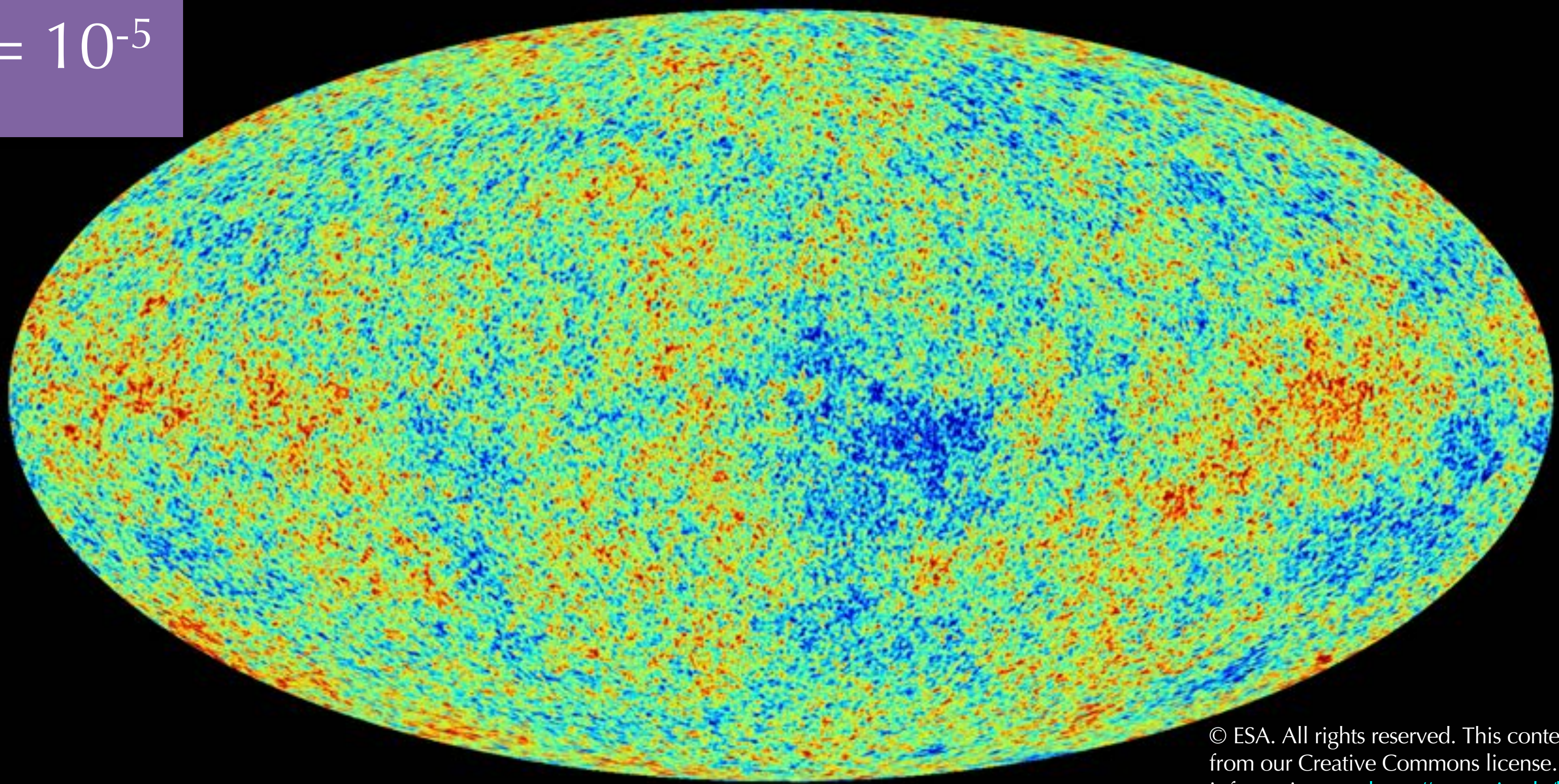
$a(t)$ grows by 10^{30}!



Gravity stretches and amplifies quantum fluctuations

From $\delta\phi$ to Bumps on the Sky

$$\frac{\Delta T}{T} = 10^{-5}$$

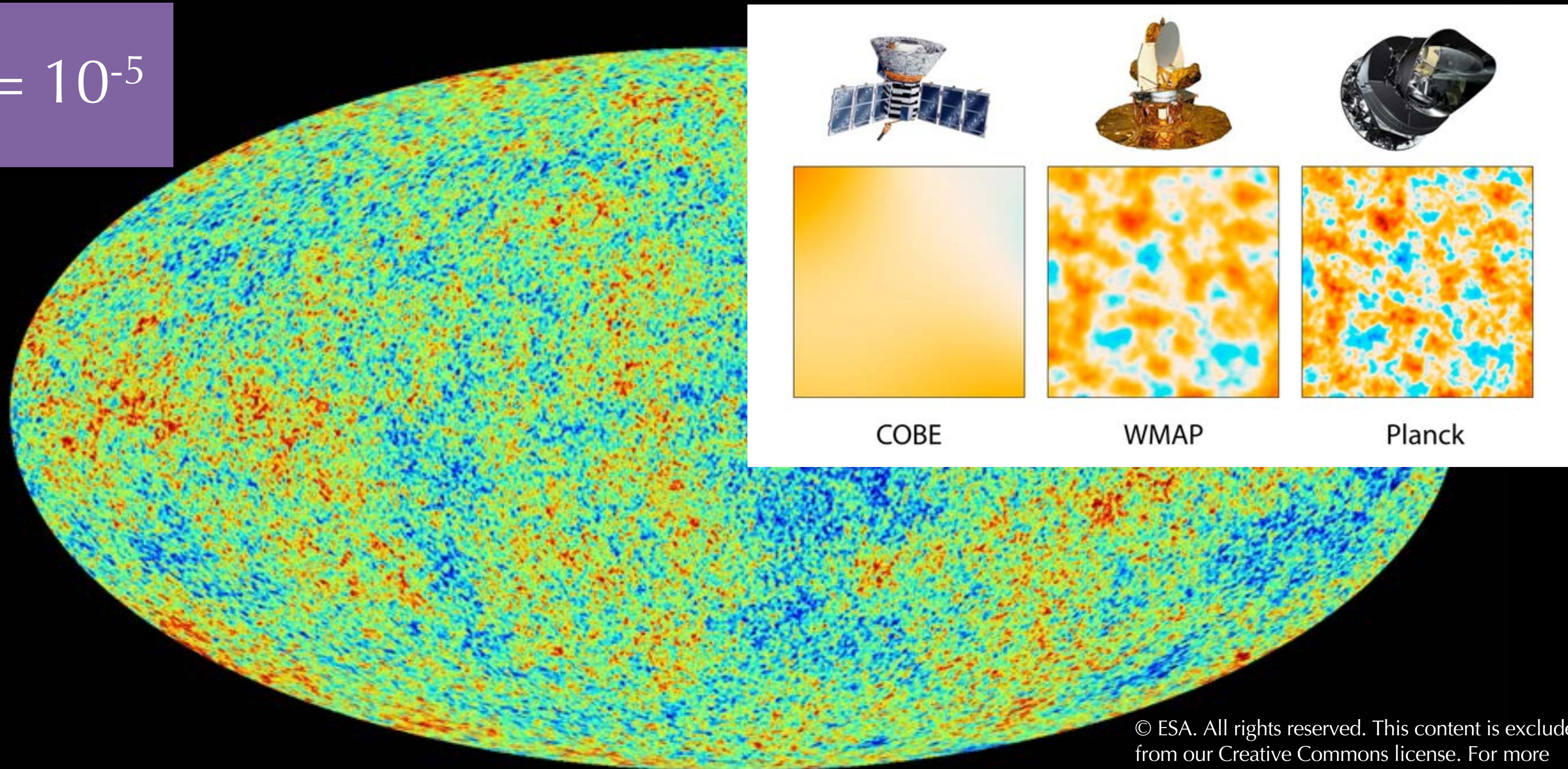


Photons released at t_{cmb} map the distribution of matter and energy at t_{cmb}.

$$\delta\phi \longrightarrow \Phi \longrightarrow \Delta T$$

From $\delta\phi$ to Bumps on the Sky

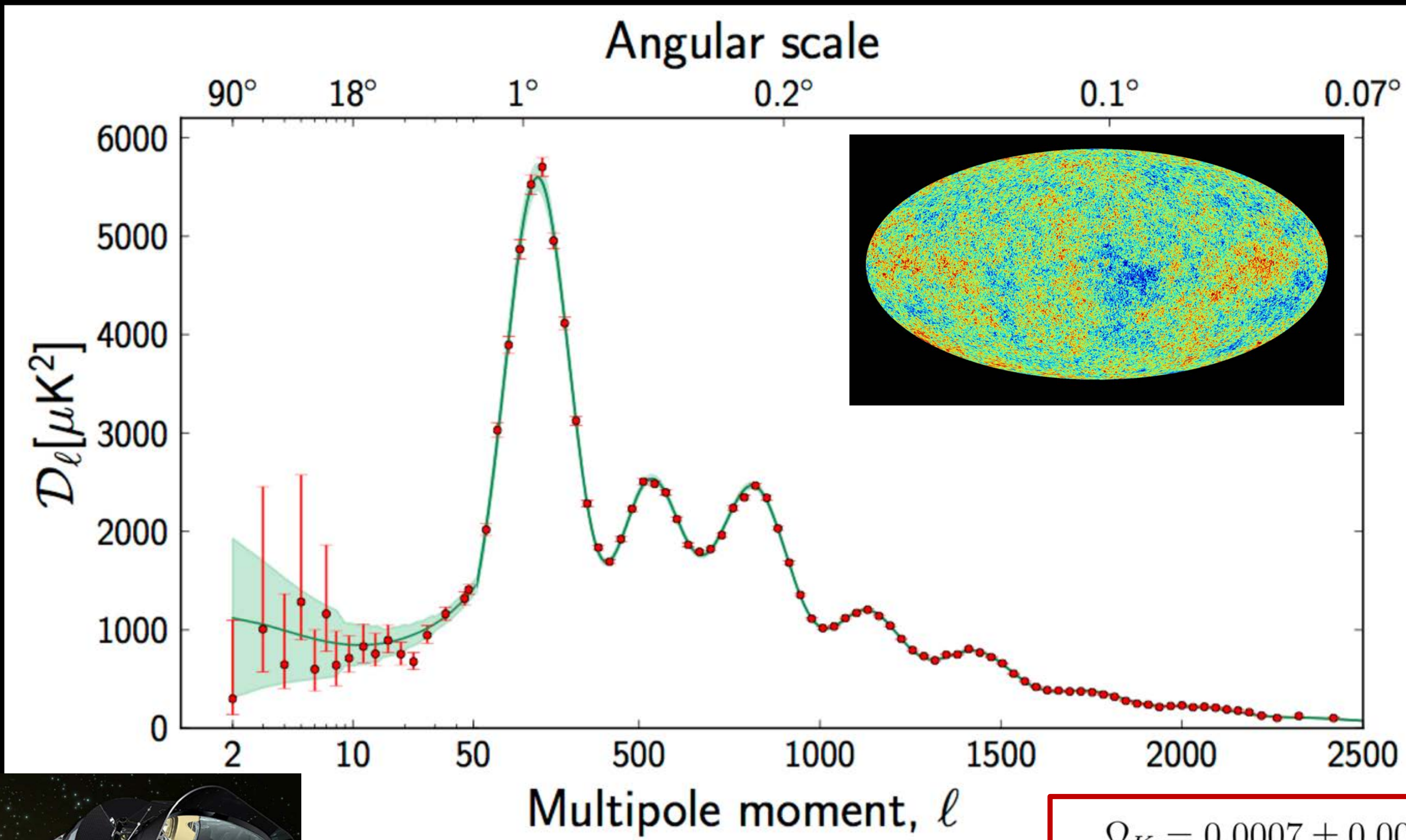
$$\frac{\Delta T}{T} = 10^{-5}$$



Photons released at t_{cmb} map the distribution of matter and energy at t_{cmb}.

$$\delta\phi \longrightarrow \Phi \longrightarrow \Delta T$$

Primordial Spectrum



Planck satellite

Planck collaboration,
arXiv:1807.06211

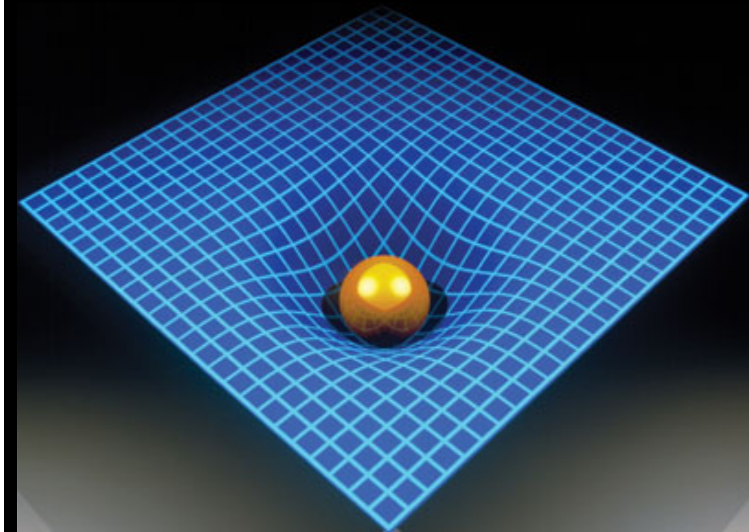
$$\Omega_K = 0.0007 \pm 0.0037$$

$$n_s = 0.965 \pm 0.004$$

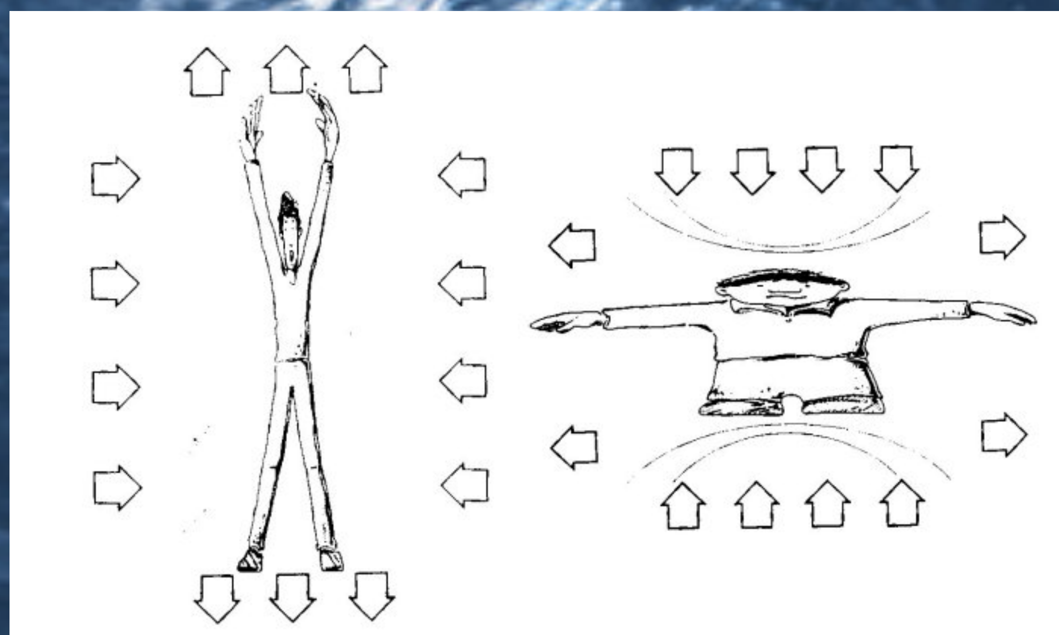
$$\beta_{\rm iso} \lesssim \mathcal{O}(0.1)$$

$$|f_{\rm NL}^{\rm local}| \leq 1.25$$

Primordial Gravity Waves

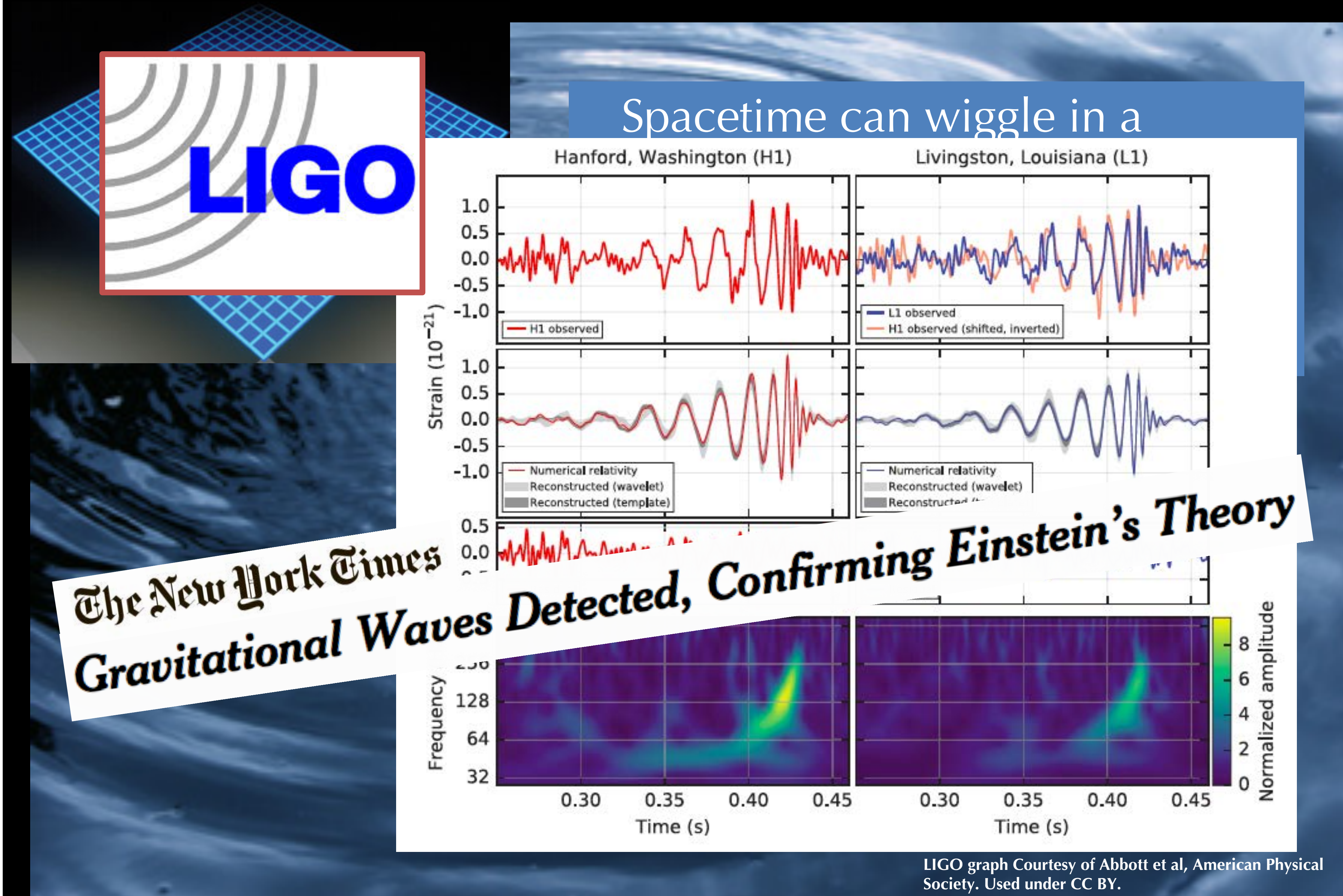


Spacetime can wiggle in a different way, too: *gravity waves* periodically stretch and squeeze objects as they pass through a region.



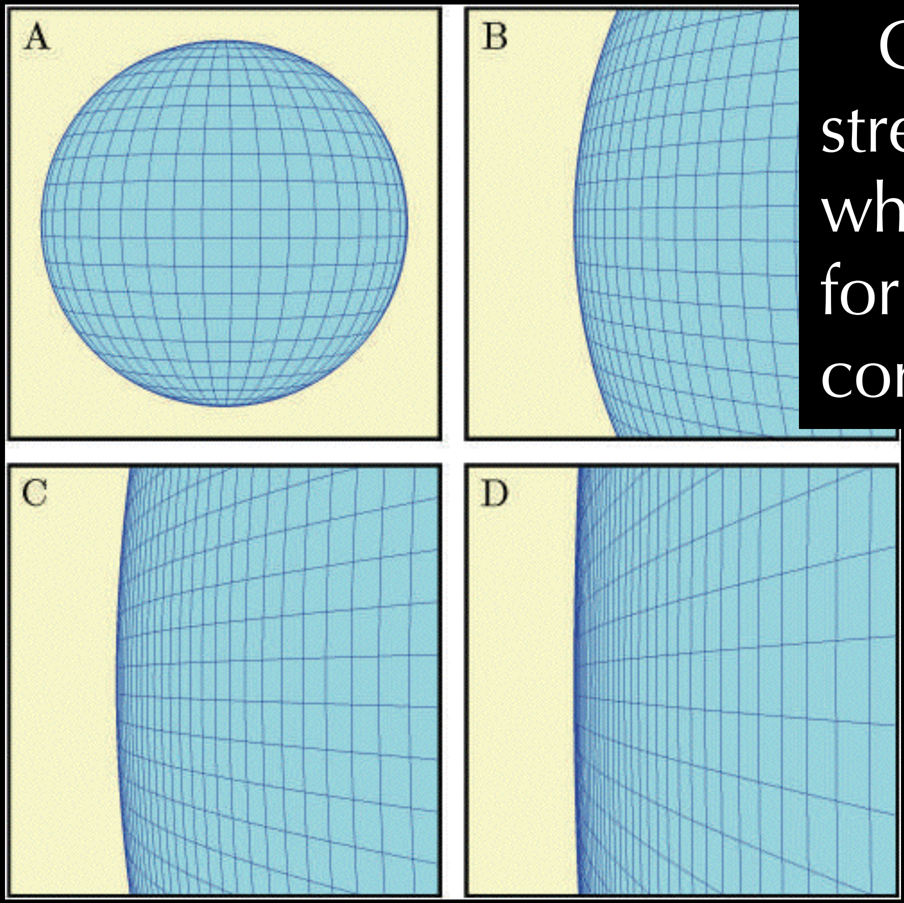
Auriga detector group, INFN, Italy

Primordial Gravity Waves



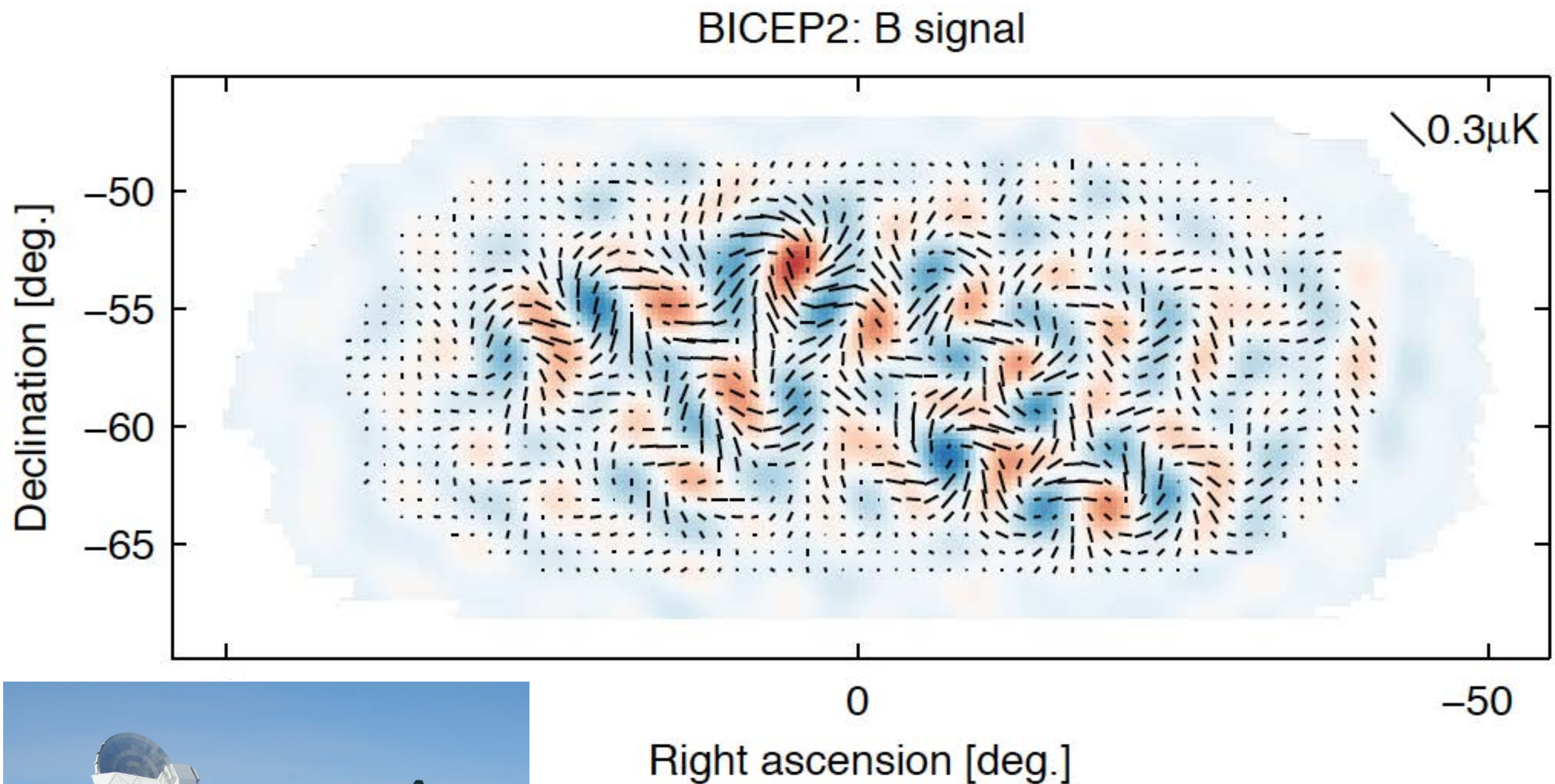
LIGO graph Courtesy of Abbott et al, American Physical Society. Used under CC BY.

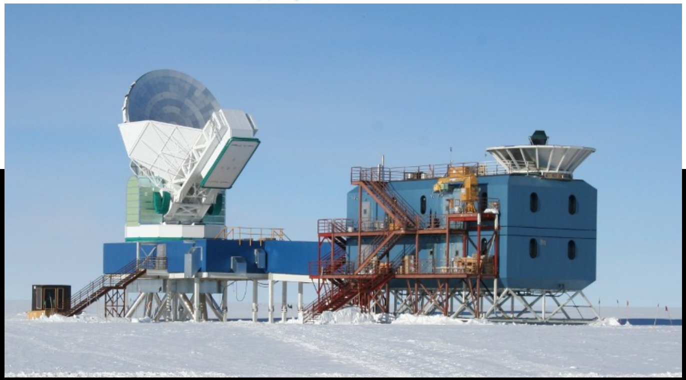
Primordial Gravity Waves



Gravity waves from inflation would stretch and squeeze the spacetime in which hydrogen atoms were first forming, adding a *polarization* or corkscrew pattern to the emitted light.

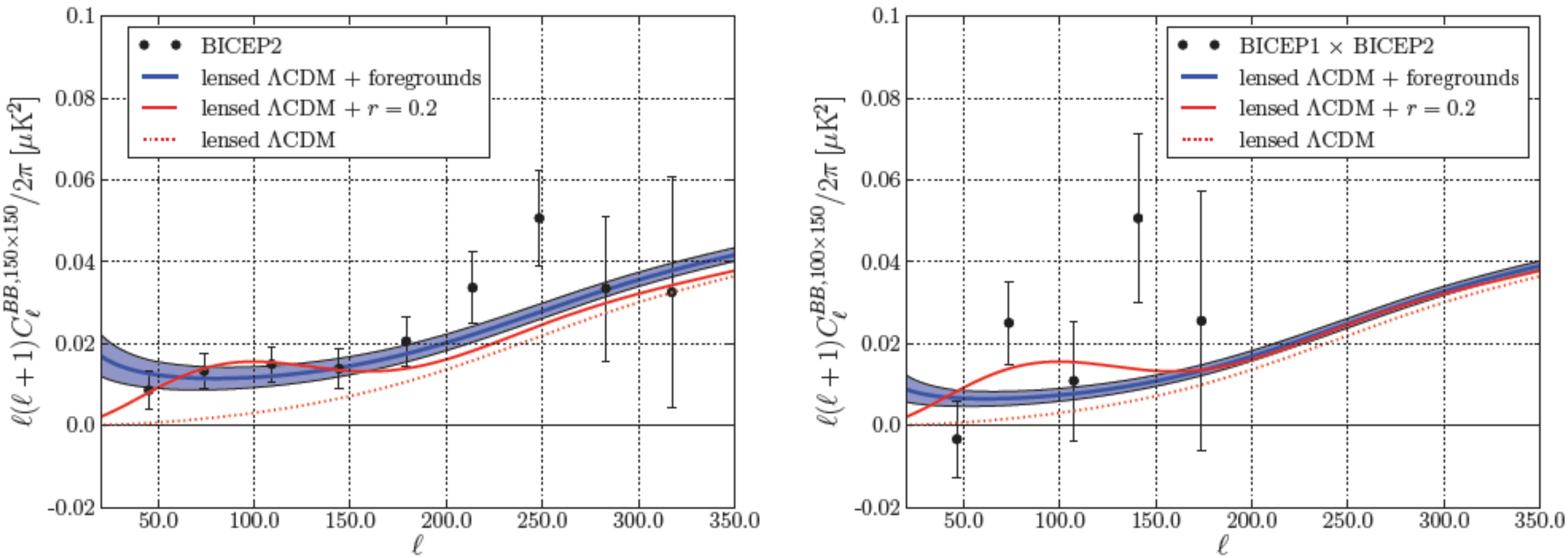
Gravity Waves Detected?





BICEP collab., *Phys. Rev. Lett.* (2014), arXiv:1403.3985

Gravity Waves Detected?



The B-mode signal detected by BICEP is consistent with *late-universe* dust ("foregrounds"), rather than *primordial* gravitational waves.

Flauger, Hill, Spergel, 1405.7351

Gravity Waves Detected?

Planck-BICEP-Keck collaborations, arXiv:1606.01968

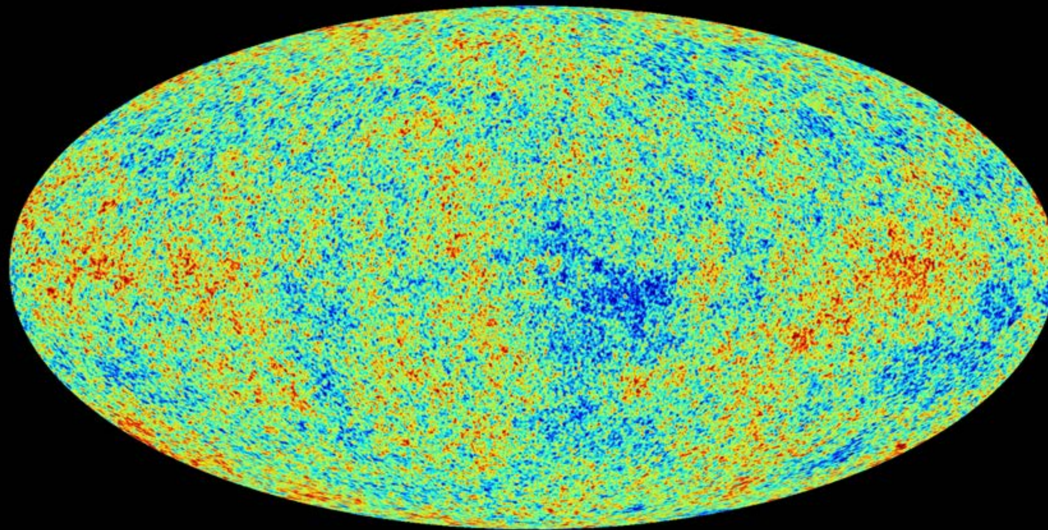
Simons Observatory collaboration, arXiv:1808.07445

Conclusions

Cosmic inflation arises from types of matter and interactions that we now know to exist — hurray, Higgs boson! — and it addresses several long-standing cosmic puzzles.

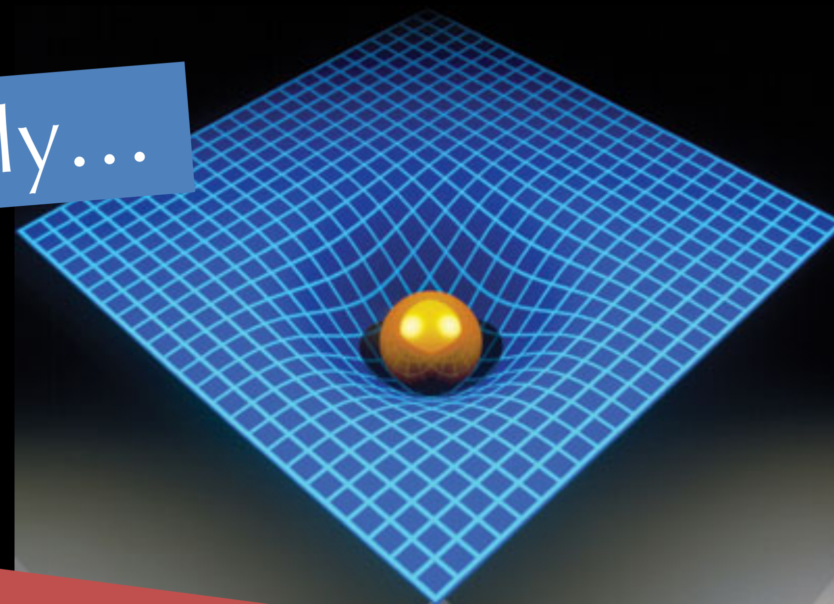
Inflation makes several specific predictions for what the universe should look like today.

Simple models fit the latest observations to astonishing accuracy.

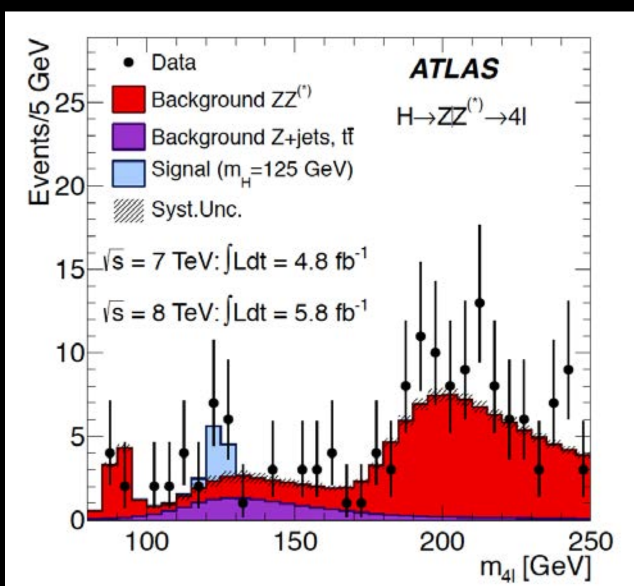


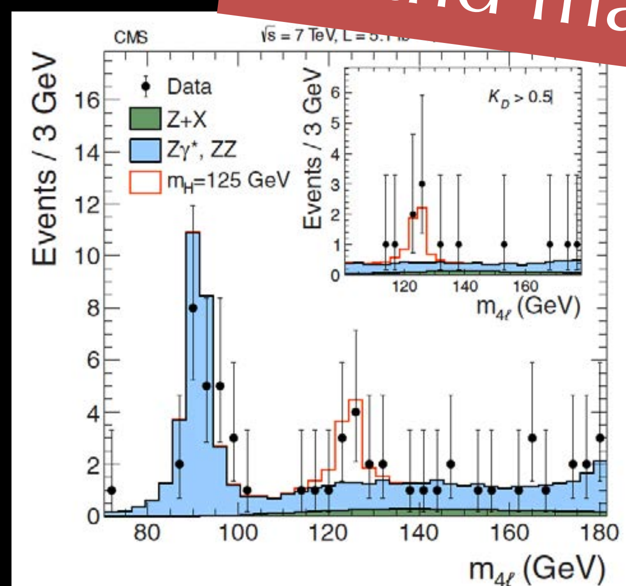
So Why is the Universe Lumpy?

Because spacetime is wiggly…



… and matter is jiggly.






031
Prof. Alan Guth
Center for Theoretical Physics-MIT