



The Big Bang, Cosmic Inflation, and the Latest Observations

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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

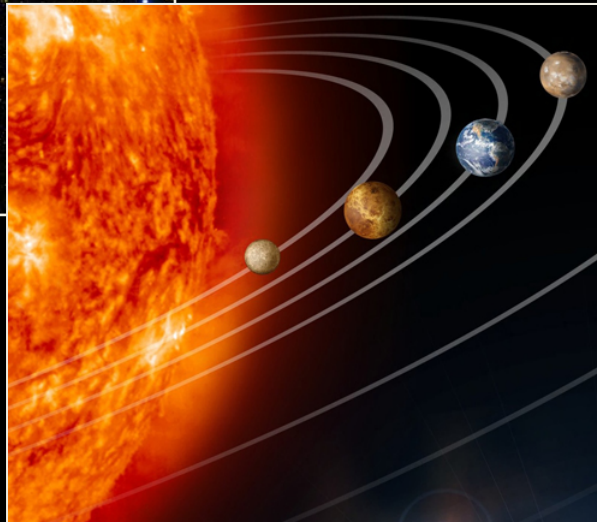
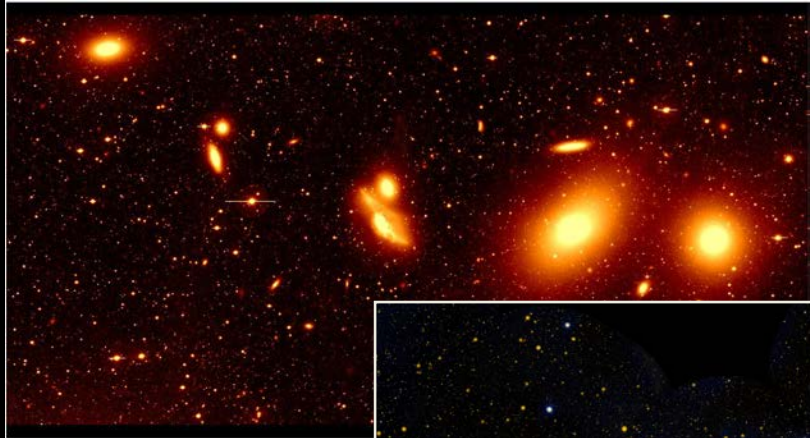
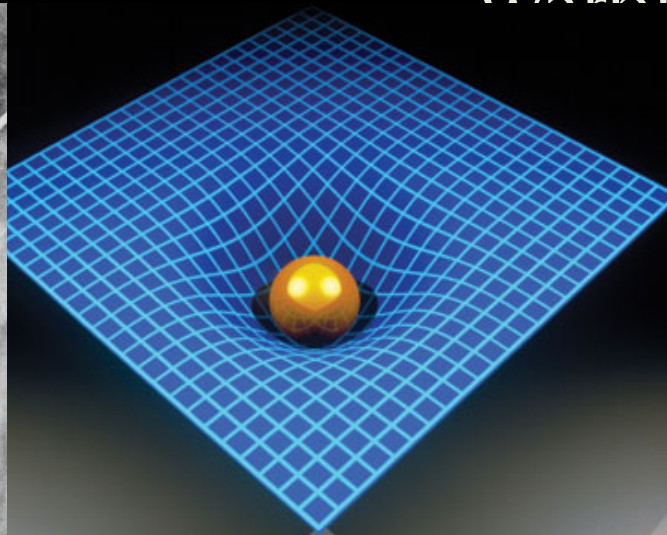
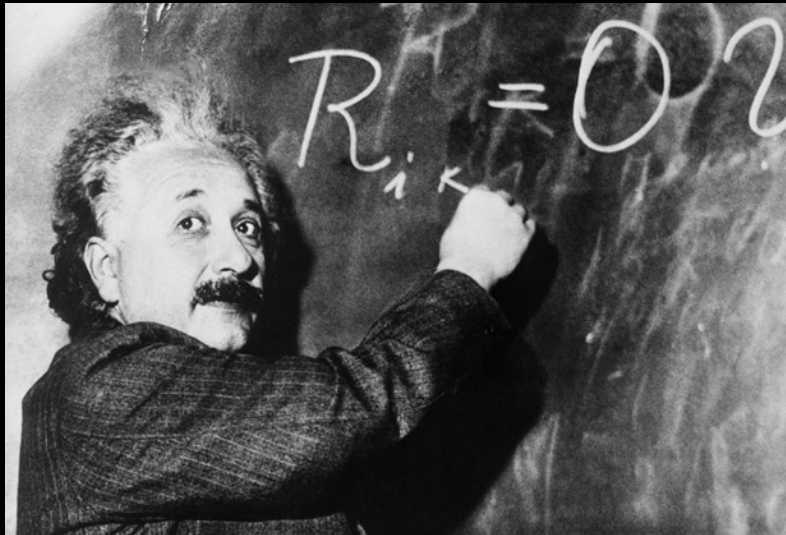


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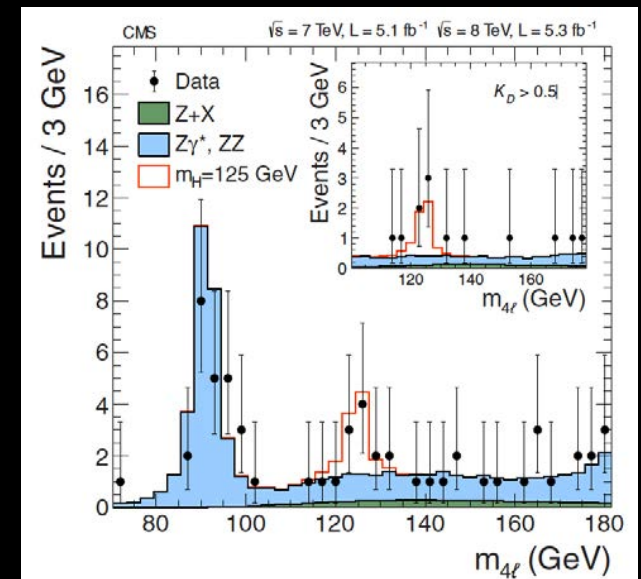
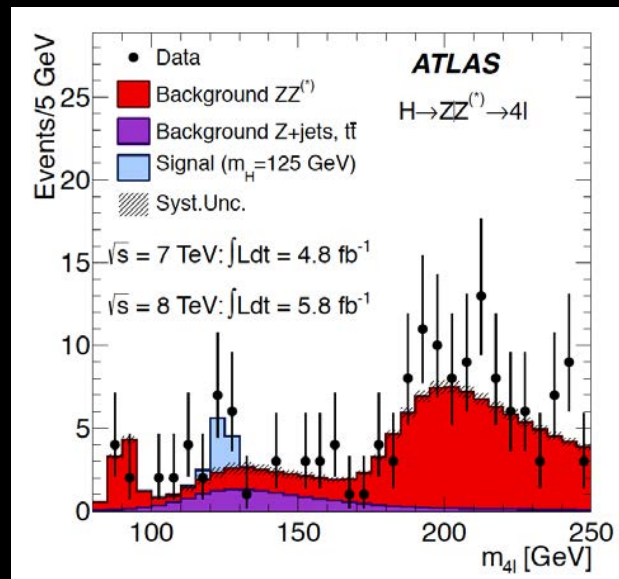
Ingredients



General Relativity:
warping spacetime

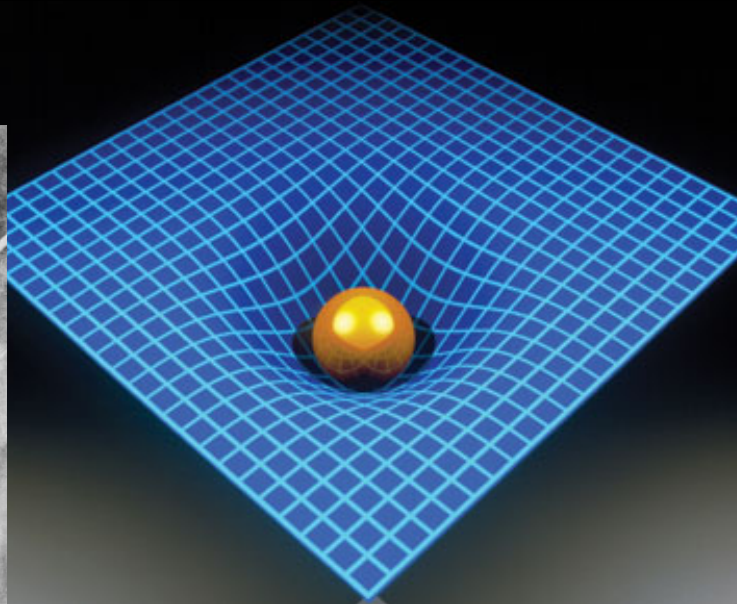
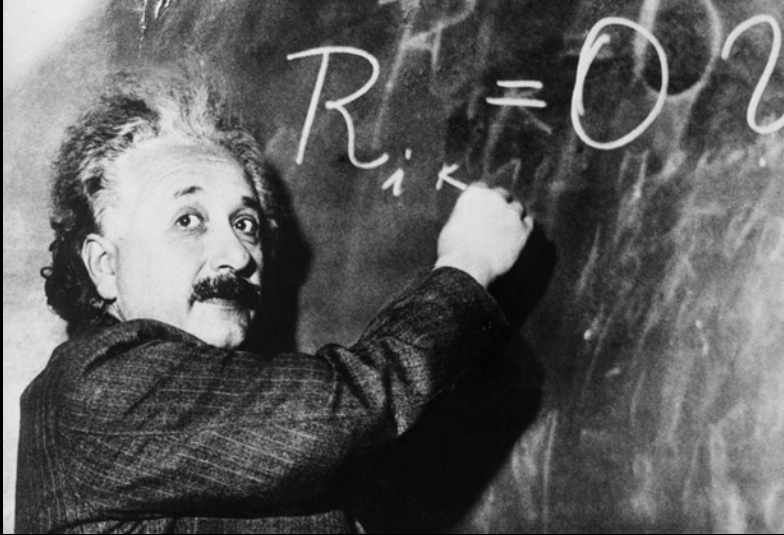
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Matter,
including —
hurray! — the
Higgs boson

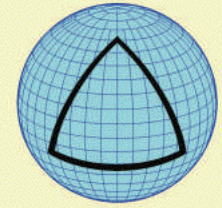


Images to right: Courtesy of CERN. Used under CC BY.

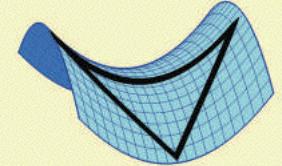
Warping Spacetime



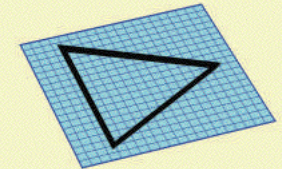
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Closed Geometry



Open Geometry



Flat Geometry

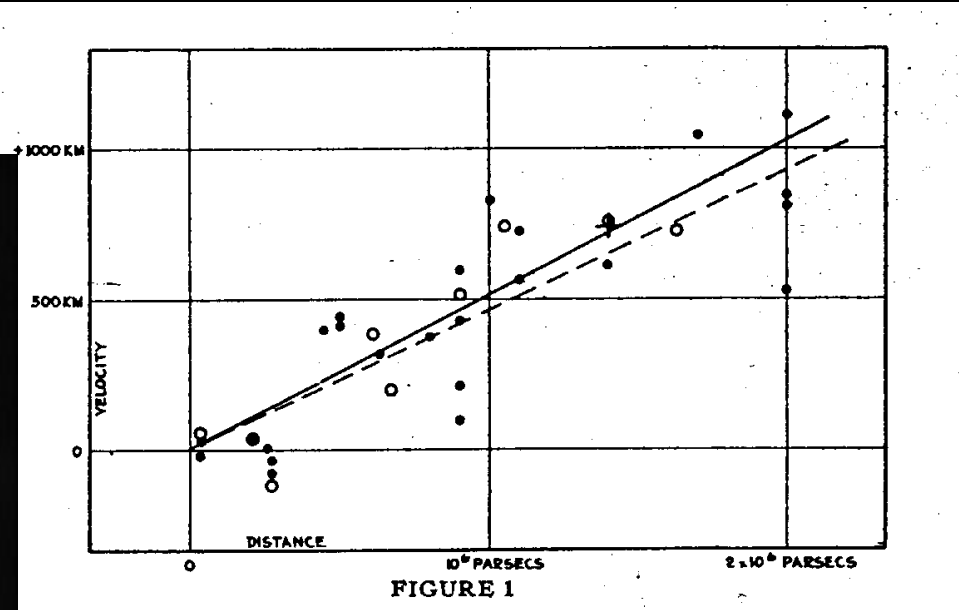
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

curvature of spacetime = distribution of matter and energy

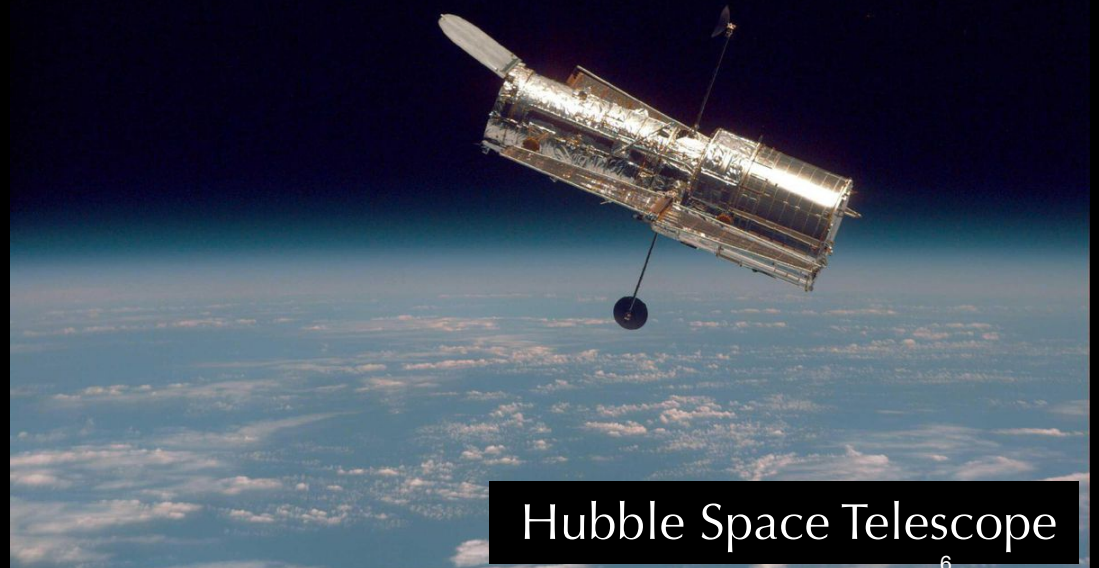
Expanding Universe



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age of the universe = 13.8 billion years

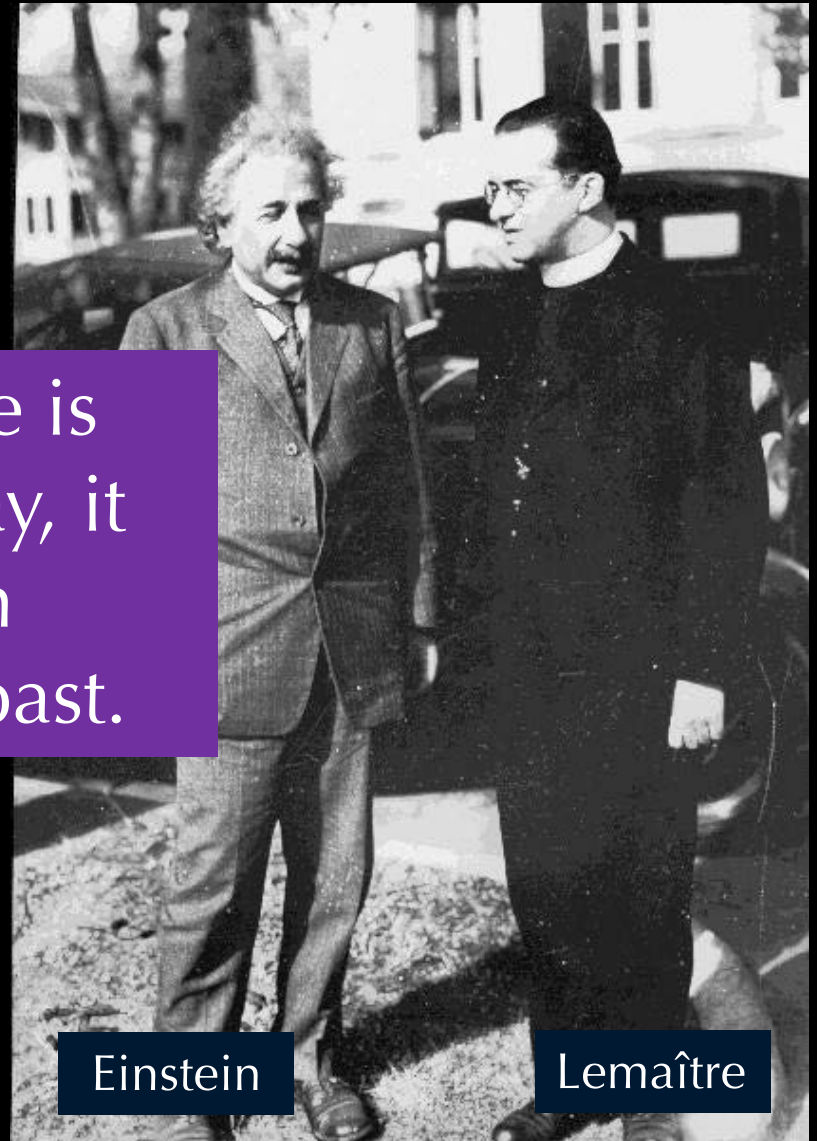


Hubble Space Telescope

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

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Einstein

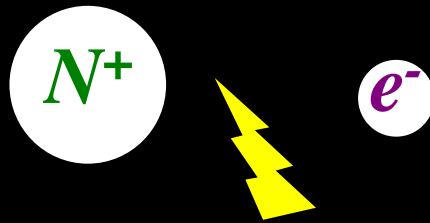
Lemaître

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.

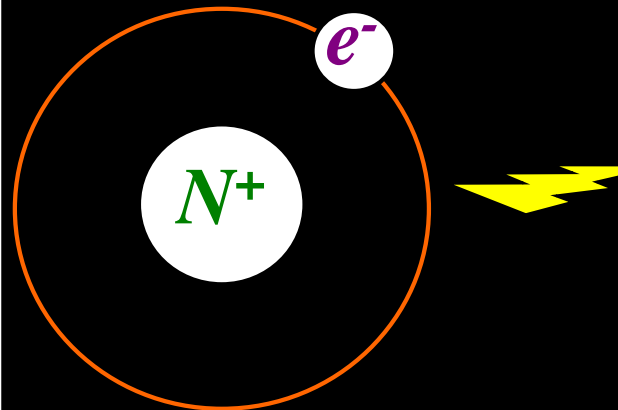


$$T > 10^4 \text{ K}$$

$$t < 380,000 \text{ years}$$

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:

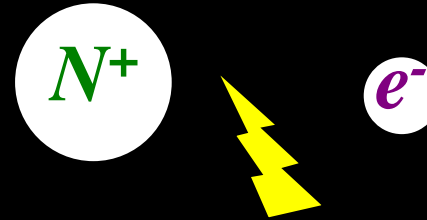
Cosmic Microwave Background Radiation

Like a Dance Party...



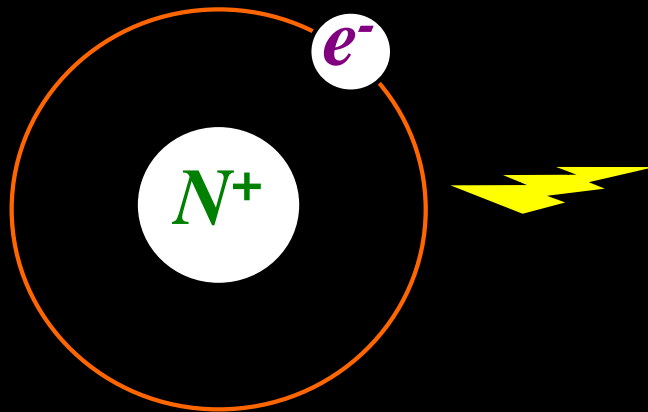
$$T > 10^4 \text{ K}$$

$$t < 380,000 \text{ years}$$



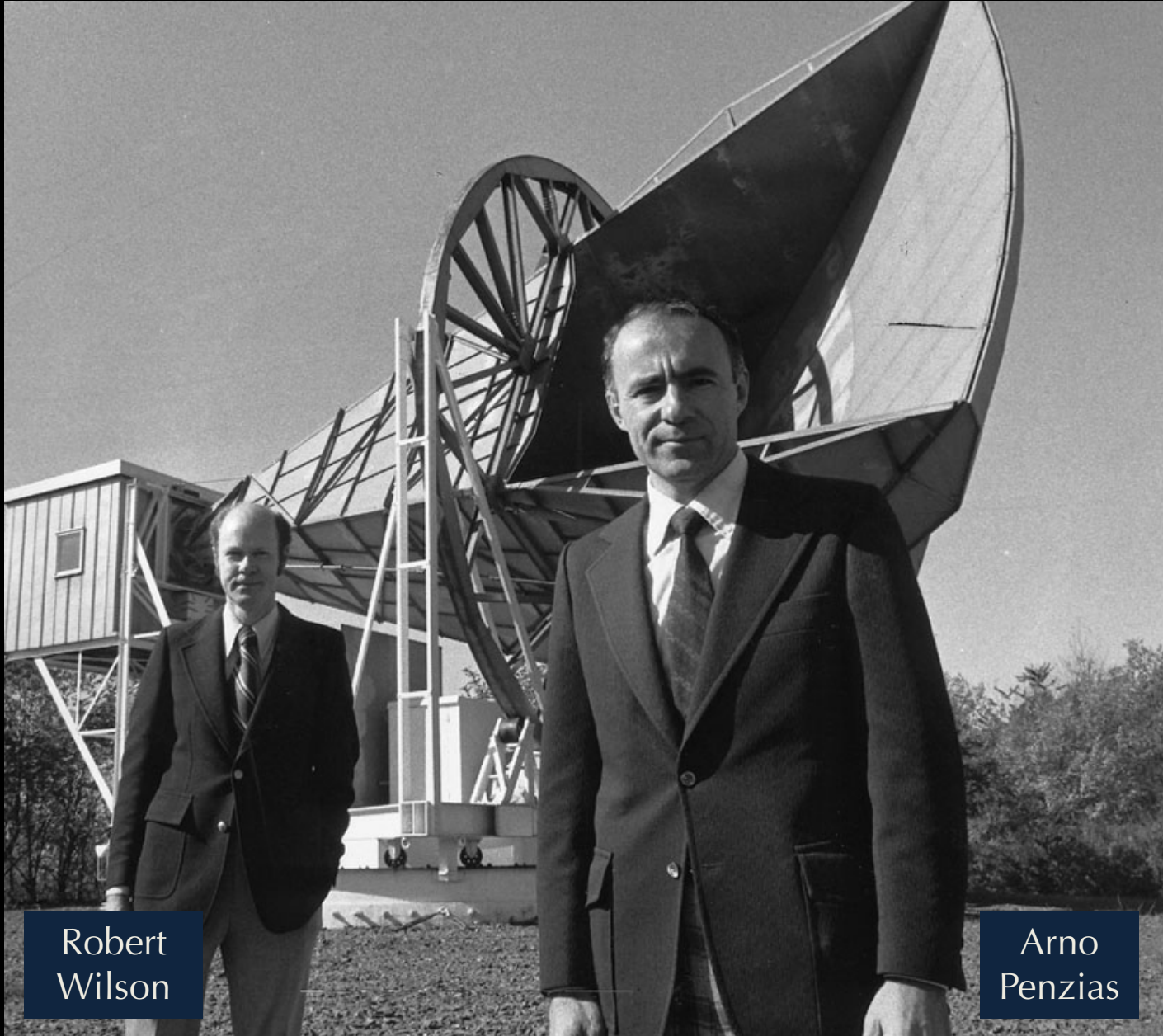
$$T < 10^4 \text{ K}$$

$$t > 380,000 \text{ years}$$



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

Accidental Discovery



Robert
Wilson

Arno
Penzias

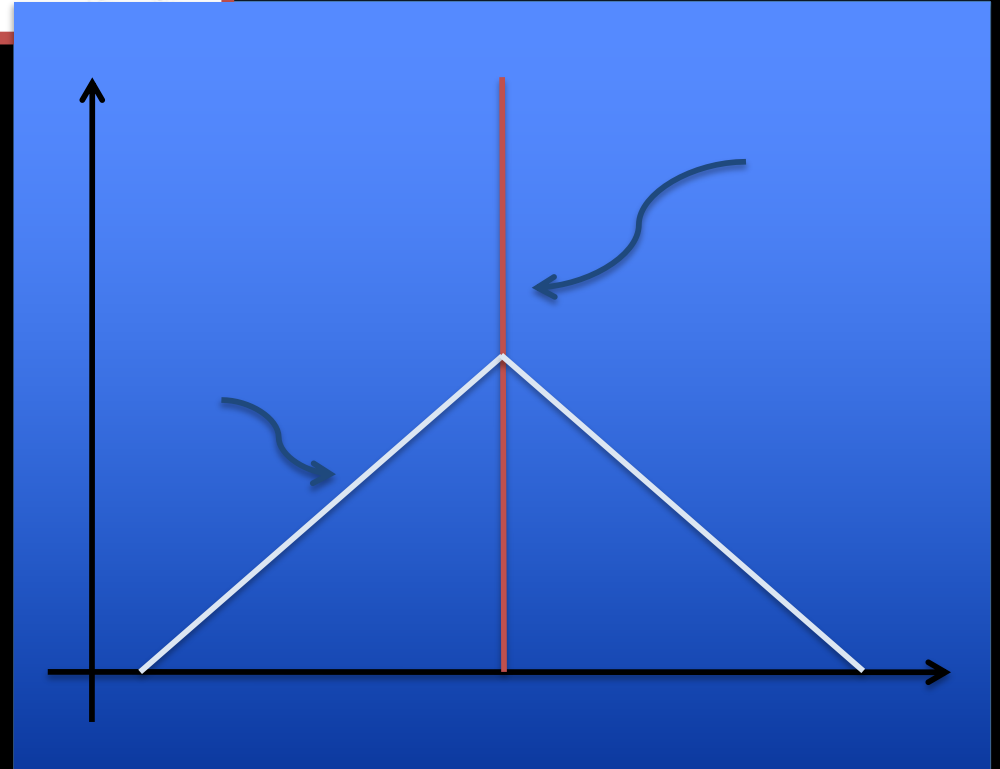
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Questions?

Clocks and Rulers

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

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



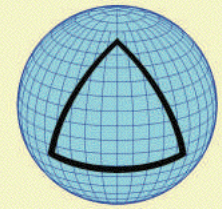
Flatness Problem

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

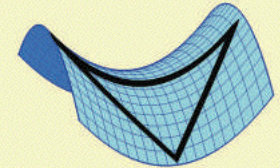
A *flat* universe has $\Omega = 1$

From Einstein's equations:

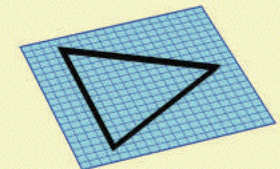
$$\frac{|\Omega - 1|}{\Omega} = \frac{1}{a^2 \rho} \sim a(t)$$



Closed Geometry



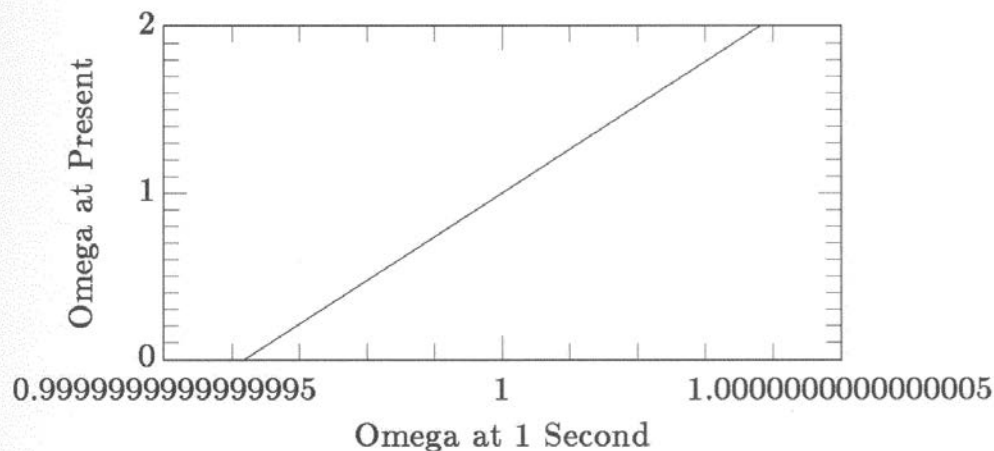
Open Geometry



Flat Geometry

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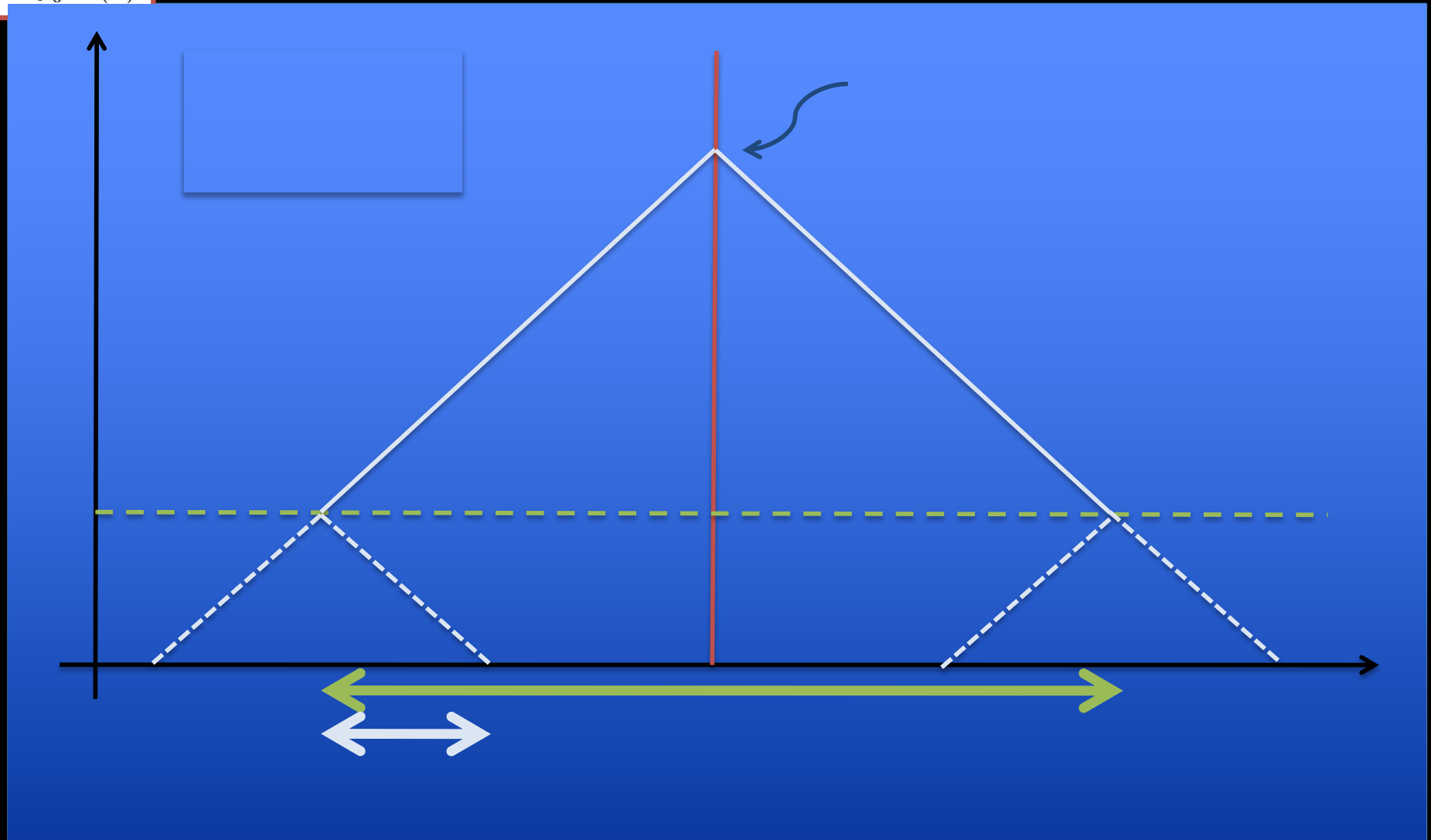
Over time, Ω should flow away from 1. After 14 billion years, why do we see anything even close to 1 today?



Horizon Problem

$$x = a(t)r$$

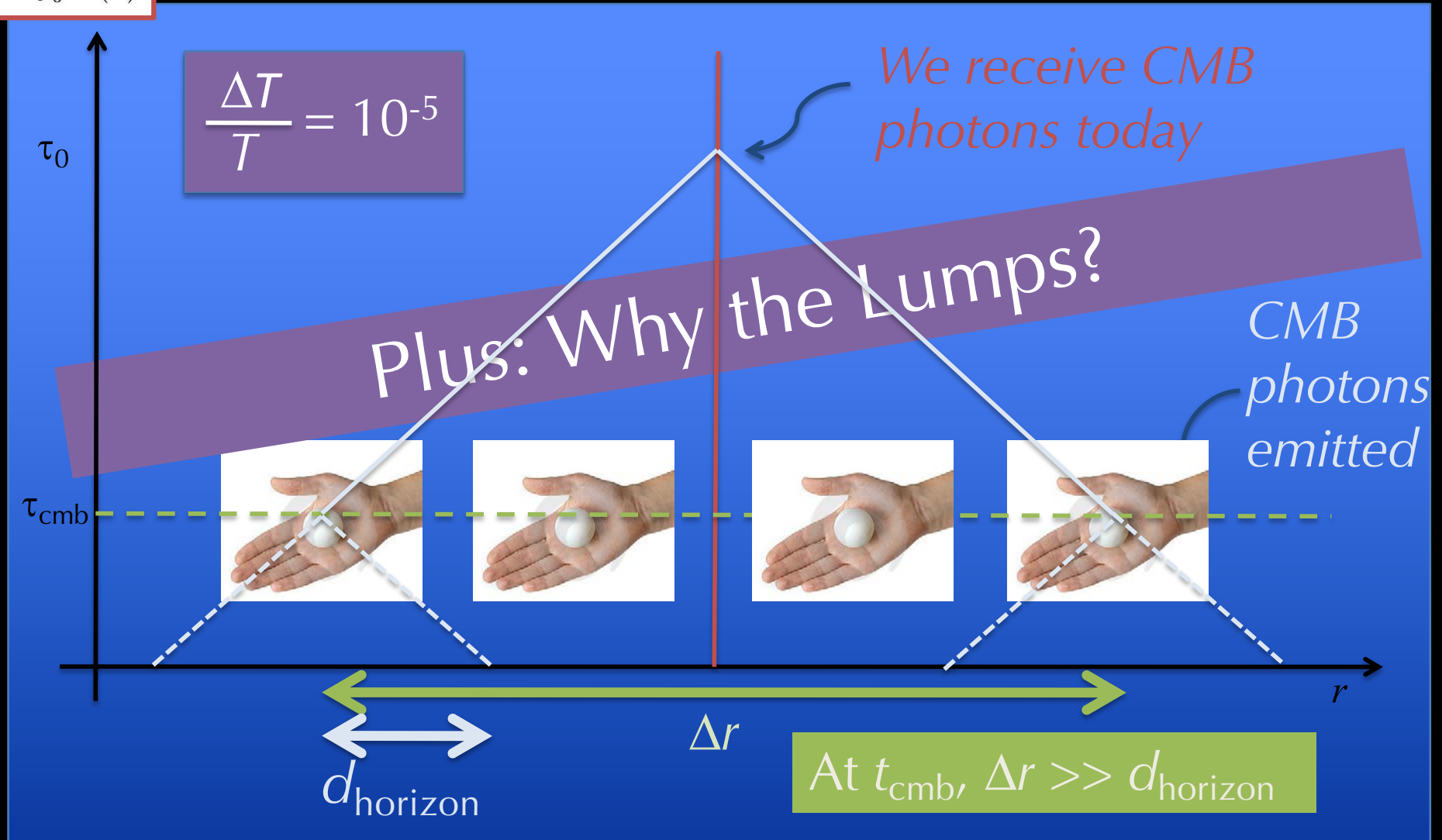
$$\tau = \int_0^t \frac{dt'}{a(t')}$$



Horizon Problem

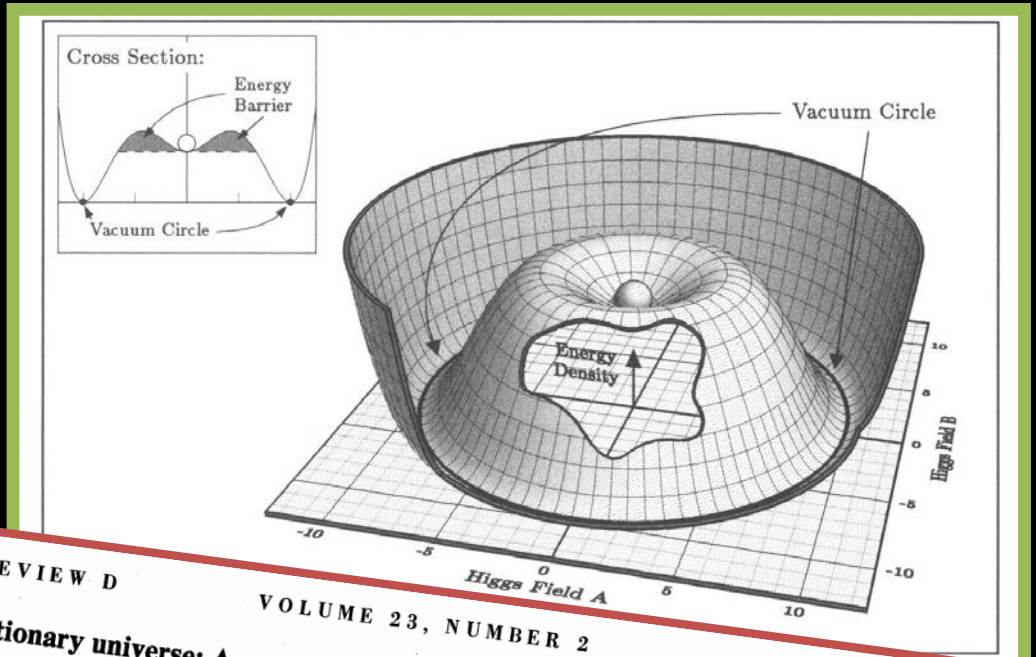
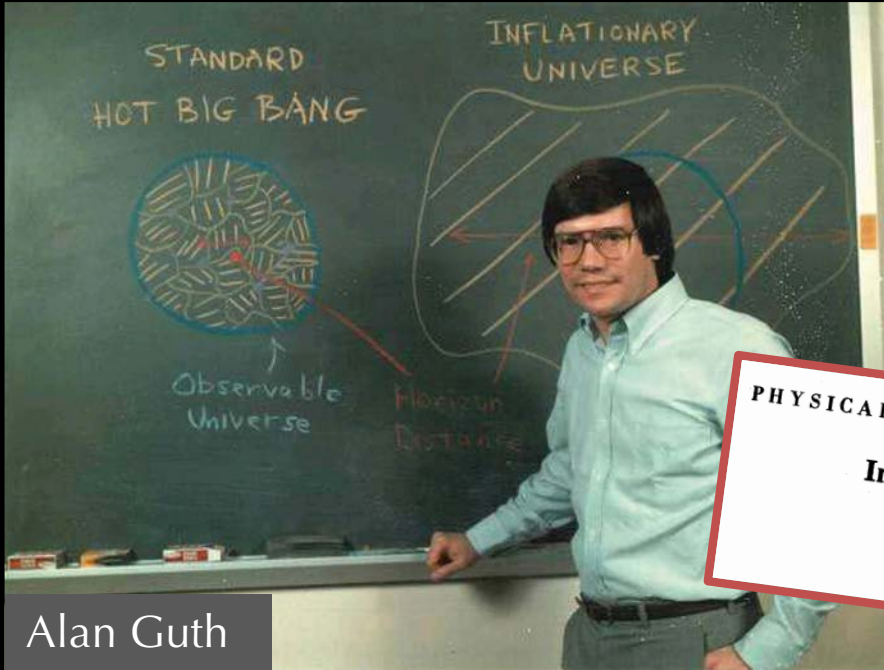
$$x = a(t)r$$

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



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)

Alan Guth

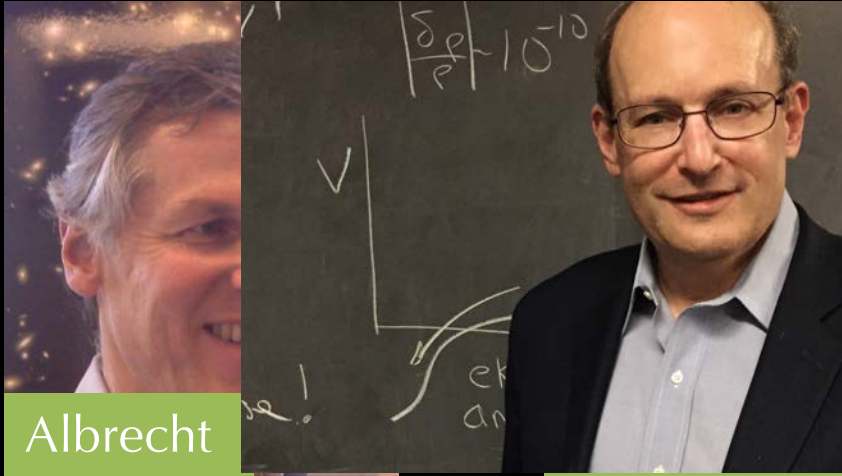
From general relativity, if $\rho \sim \text{constant}$, then $a(t) \sim e^{\sqrt{\rho} t}$.

SPECTACULAR REALIZATION:
 This kind of supercooling can explain why the universe today is so incredibly flat — and then...

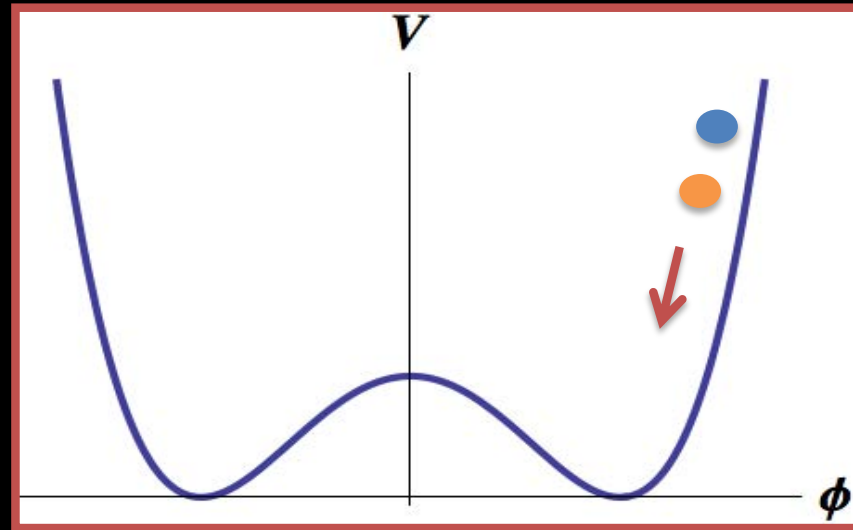
This happens naturally with Higgs-like matter; it doesn't occur for matter like protons and electrons.

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Inflation



Albrecht



Linde

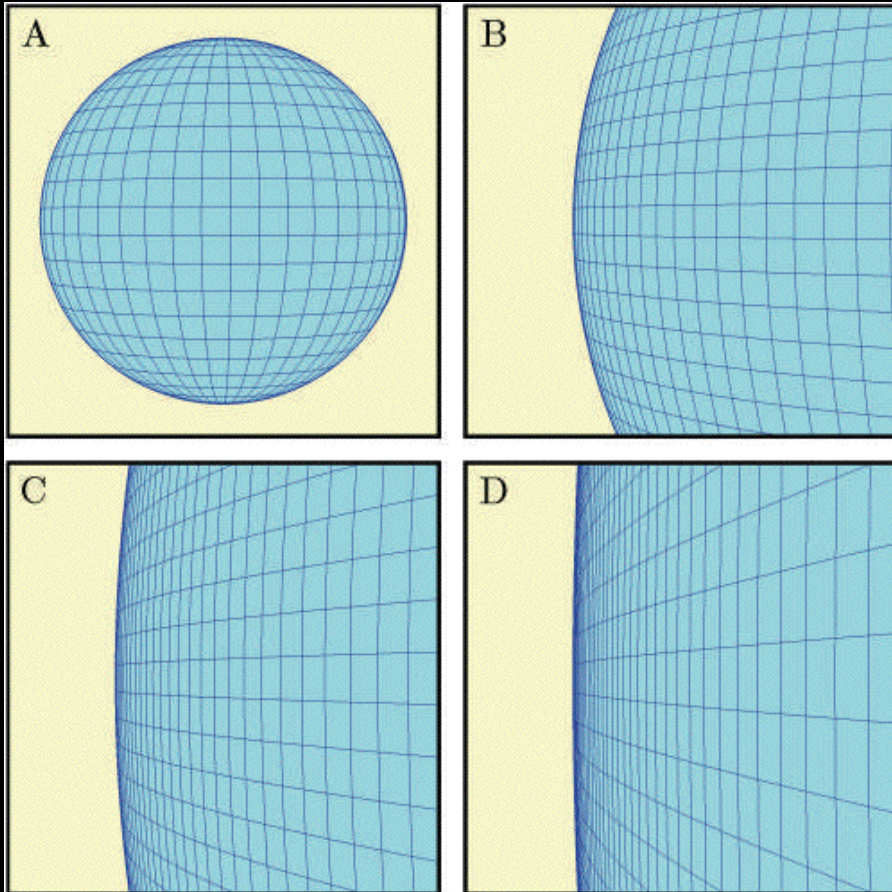
$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi}(\phi) = 0$$

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

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

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Inflation Solves the Flatness Problem



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

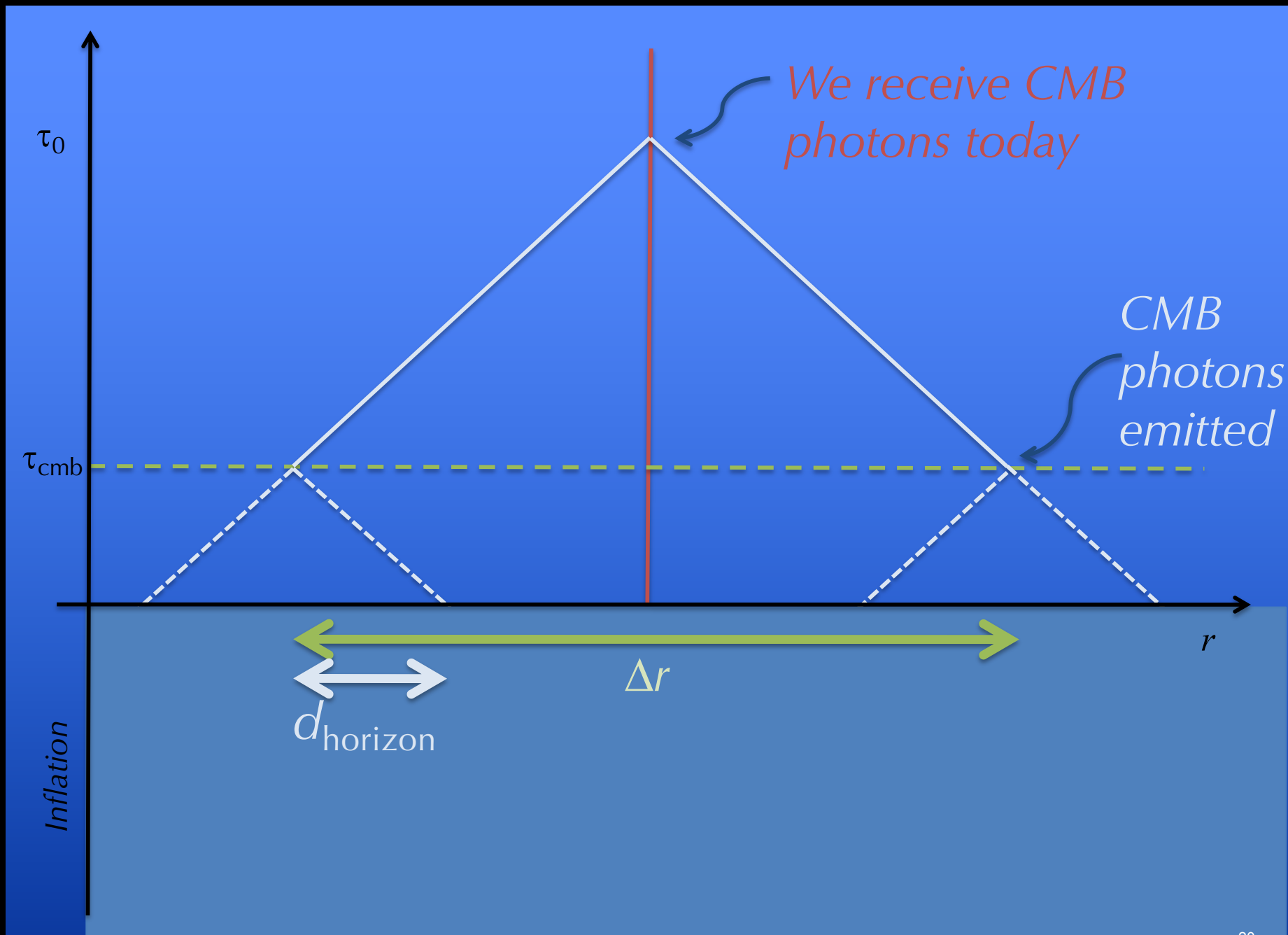
so as $a(t)$ gets big and ρ remains constant, $\Omega \rightarrow 1$.

Latest measurement:

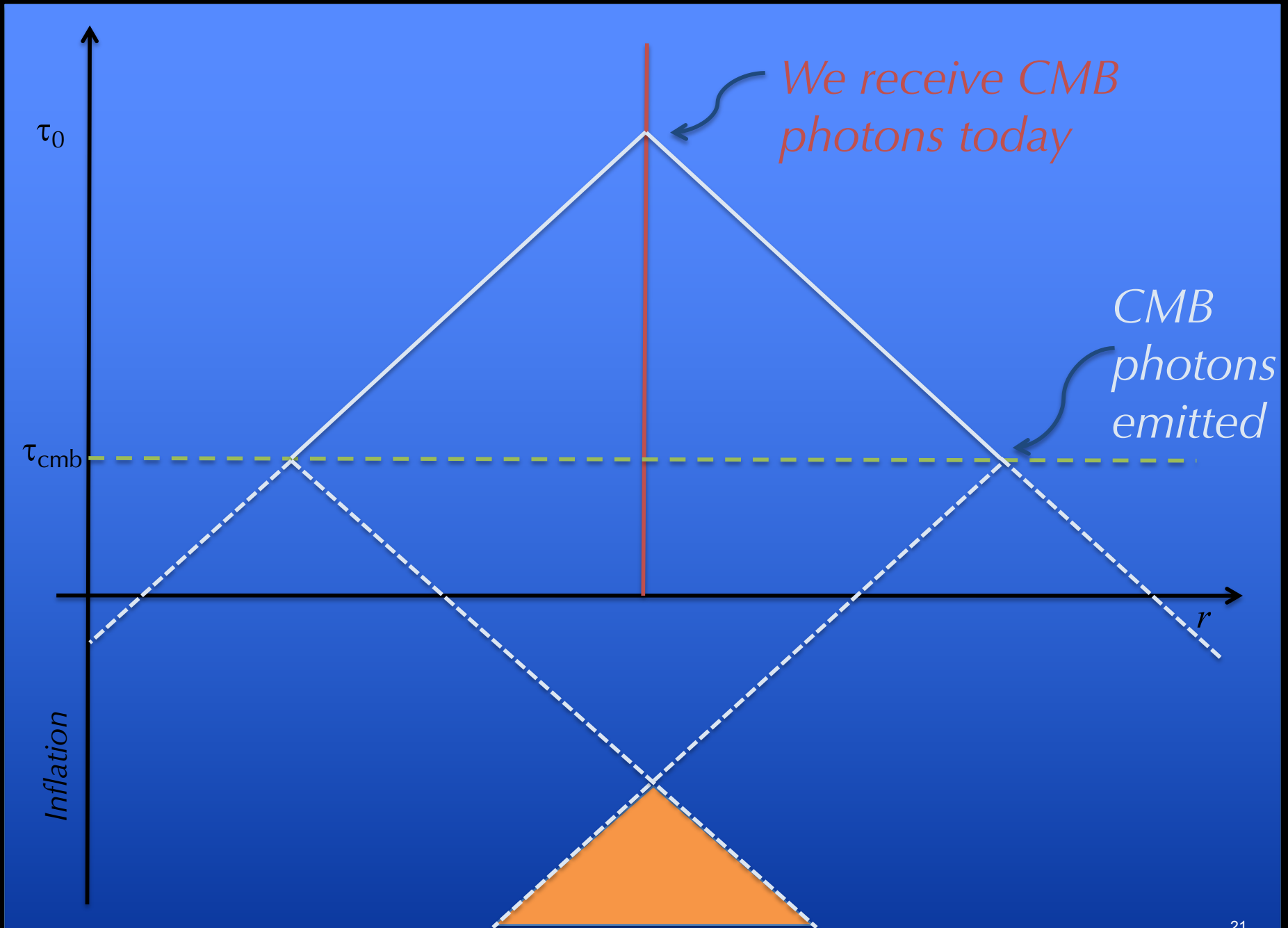
$$\Omega = 1.0007 \pm 0.0037$$

Planck collaboration,
arXiv:1807.06211

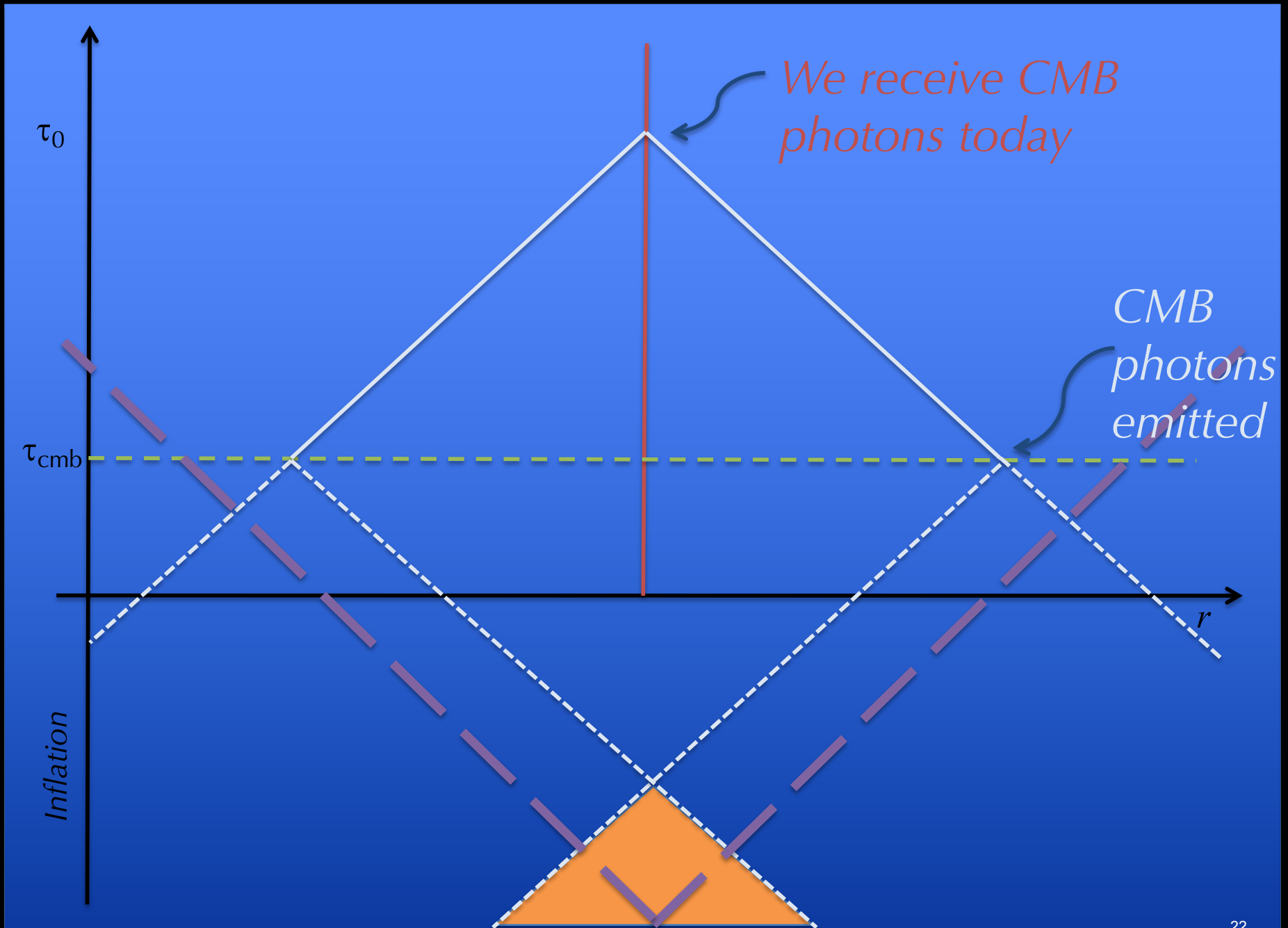
Inflation Solves the Horizon Problem



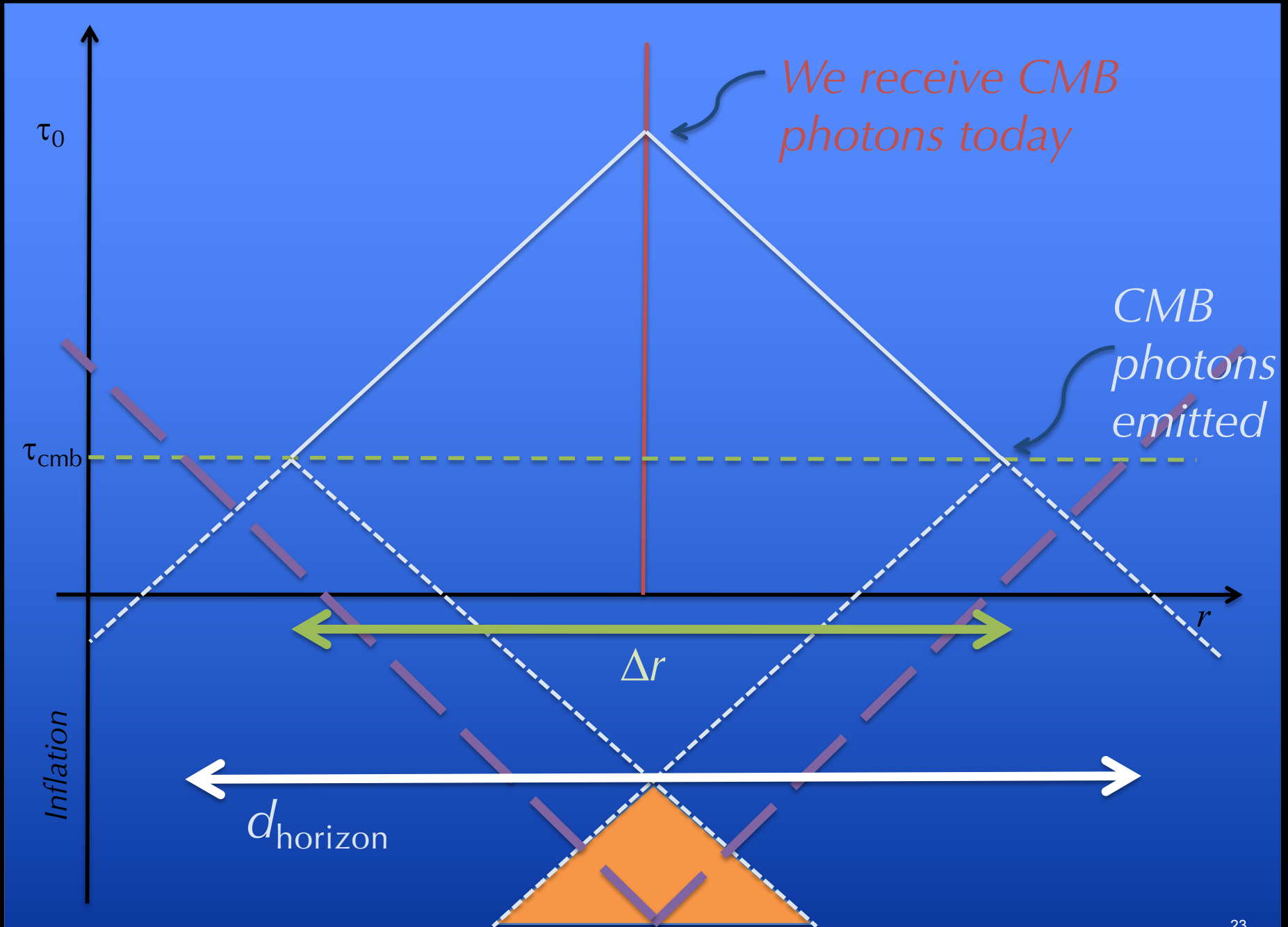
Inflation Solves the Horizon Problem



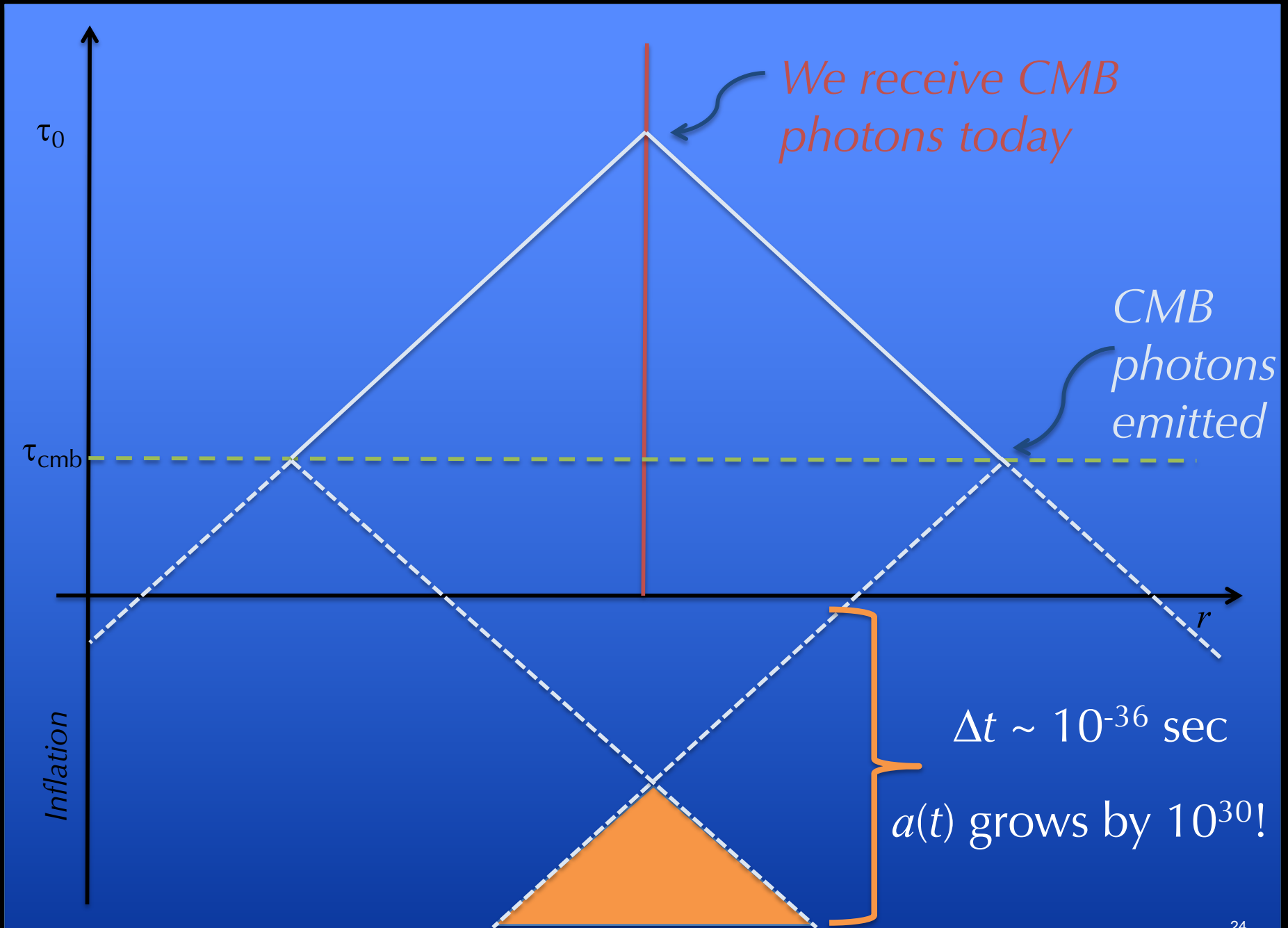
Inflation Solves the Horizon Problem



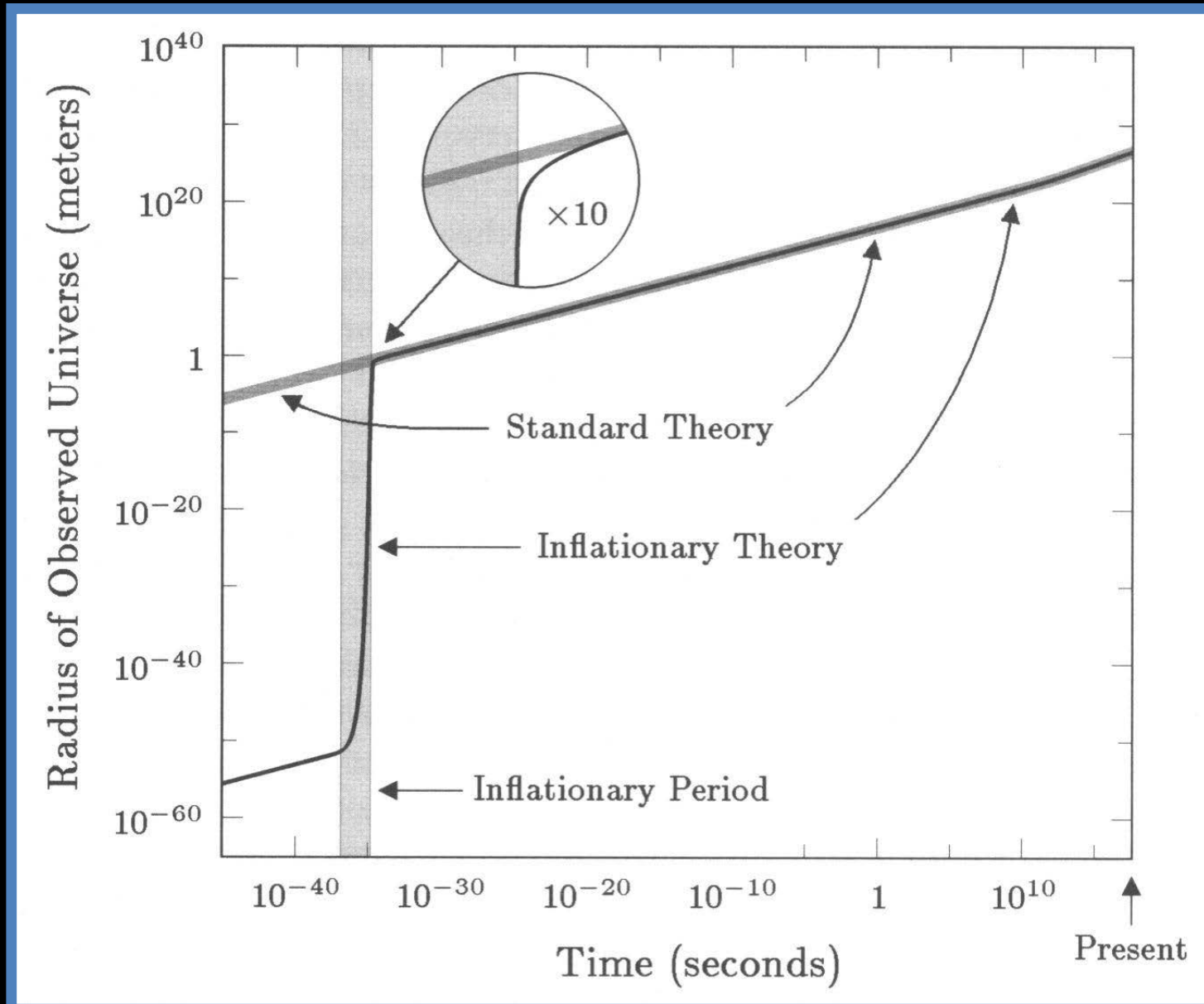
Inflation Solves the Horizon Problem



Inflation Solves the Horizon Problem

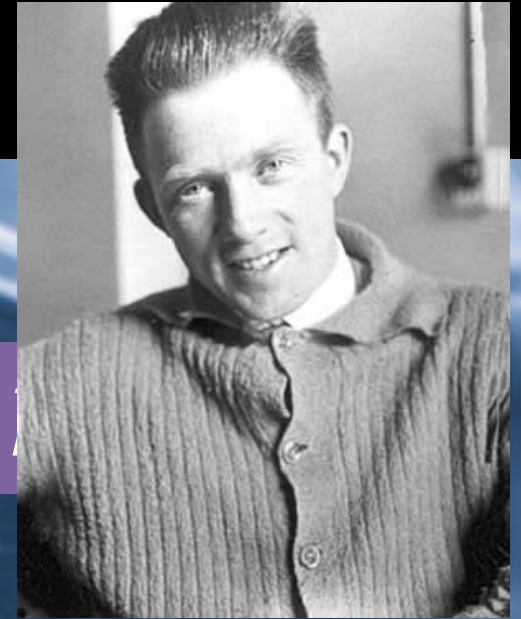


Inflation Solves the Horizon Problem

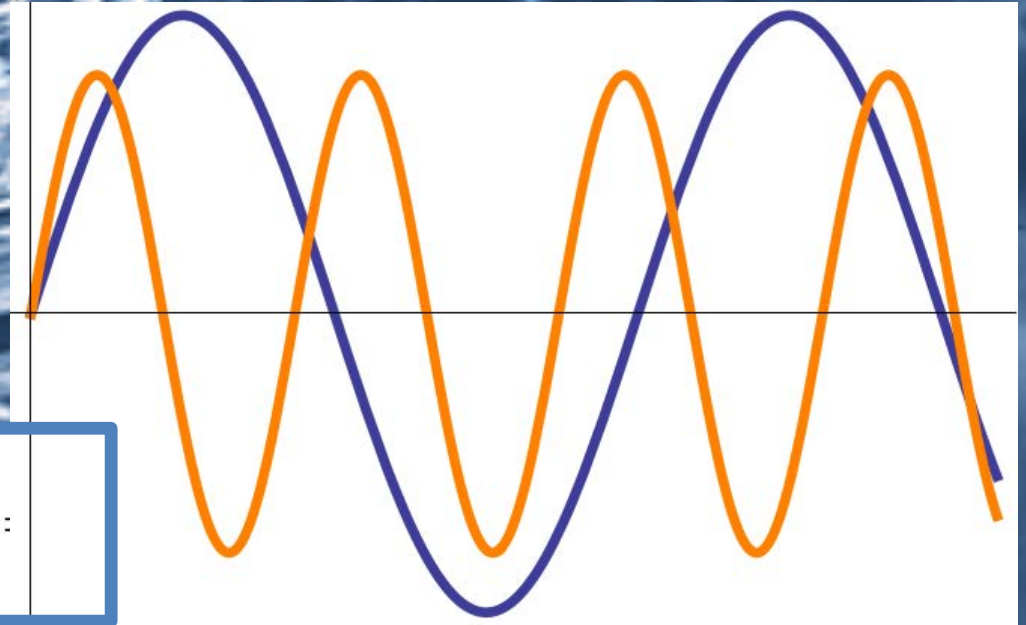
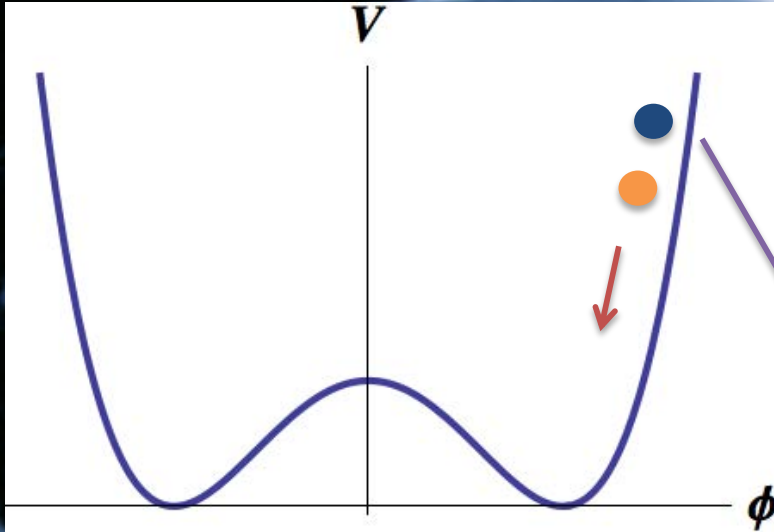


Primordial Wiggles

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$$\Delta x \Delta p \geq \hbar/2$$



$$\delta\ddot{\phi}_k + 3H\delta\dot{\phi}_k + \left[\frac{k^2}{a^2} + m_{\text{eff}}^2(t) \right] \delta\phi_k = 0$$

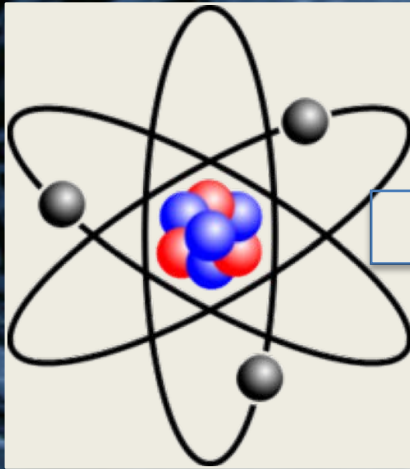
Gravity stretches and amplifies quantum fluctuations

Primordial Wiggles

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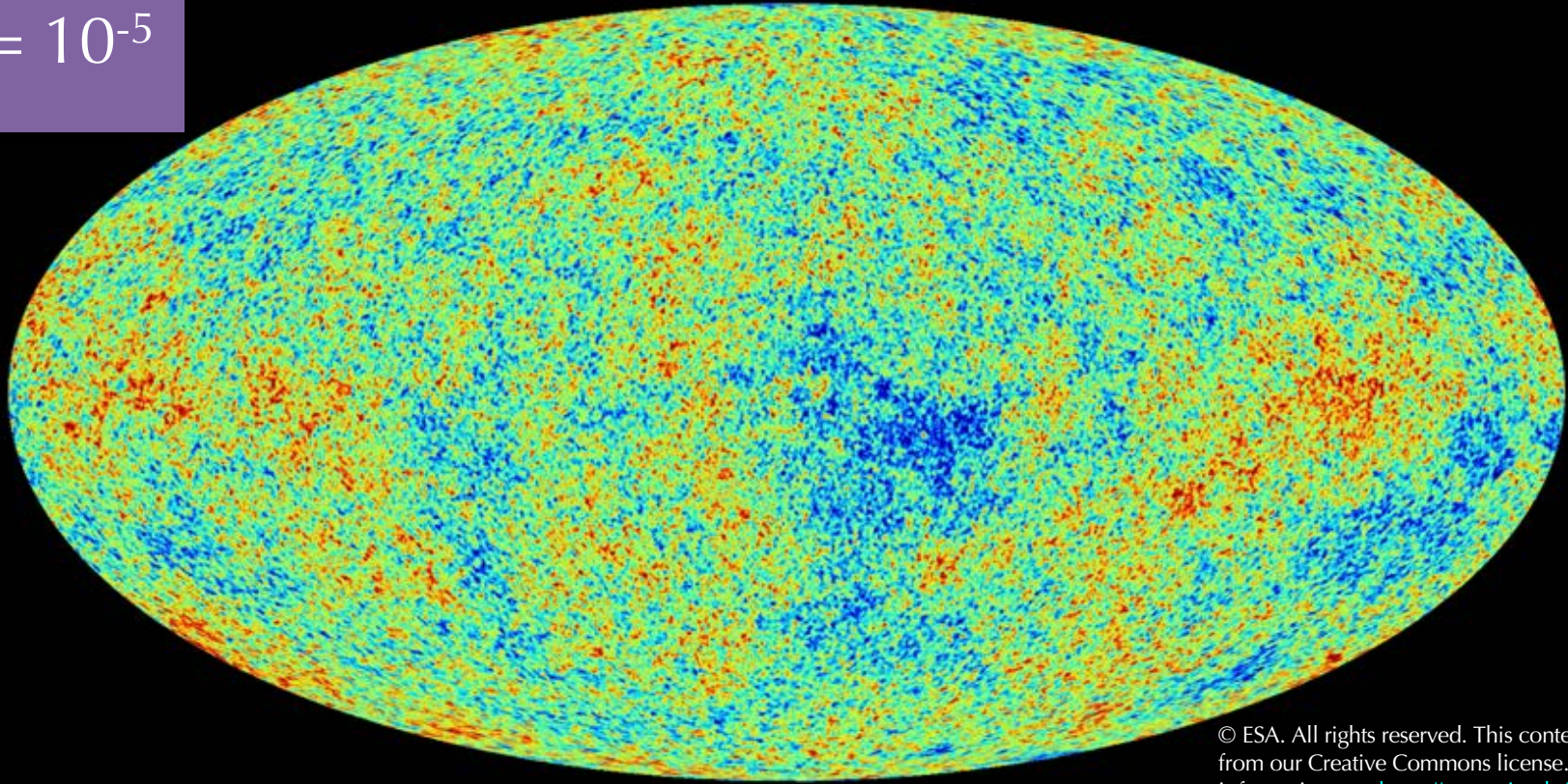
$a(t)$ grows by 10^{30} !



Gravity stretches and amplifies quantum fluctuations

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

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



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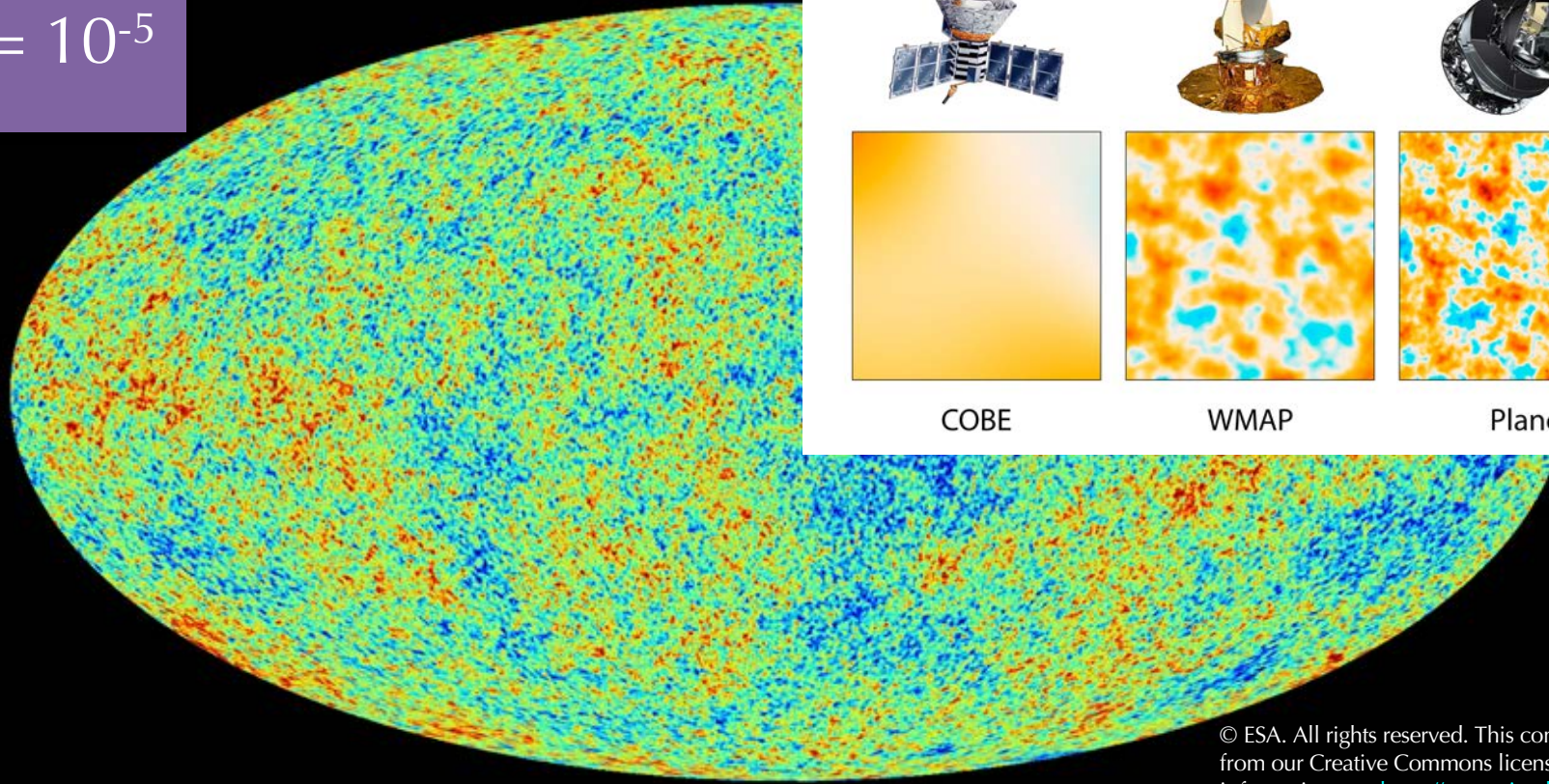
Photons released at t_{cmb} map the distribution of matter and energy at t_{cmb} .

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

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

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



COBE

WMAP

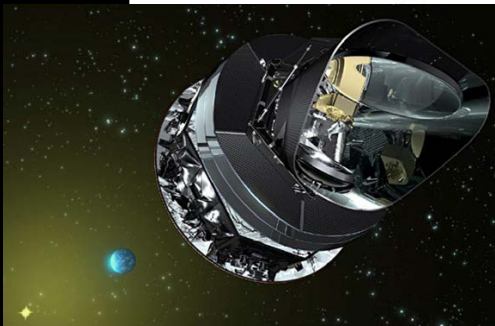
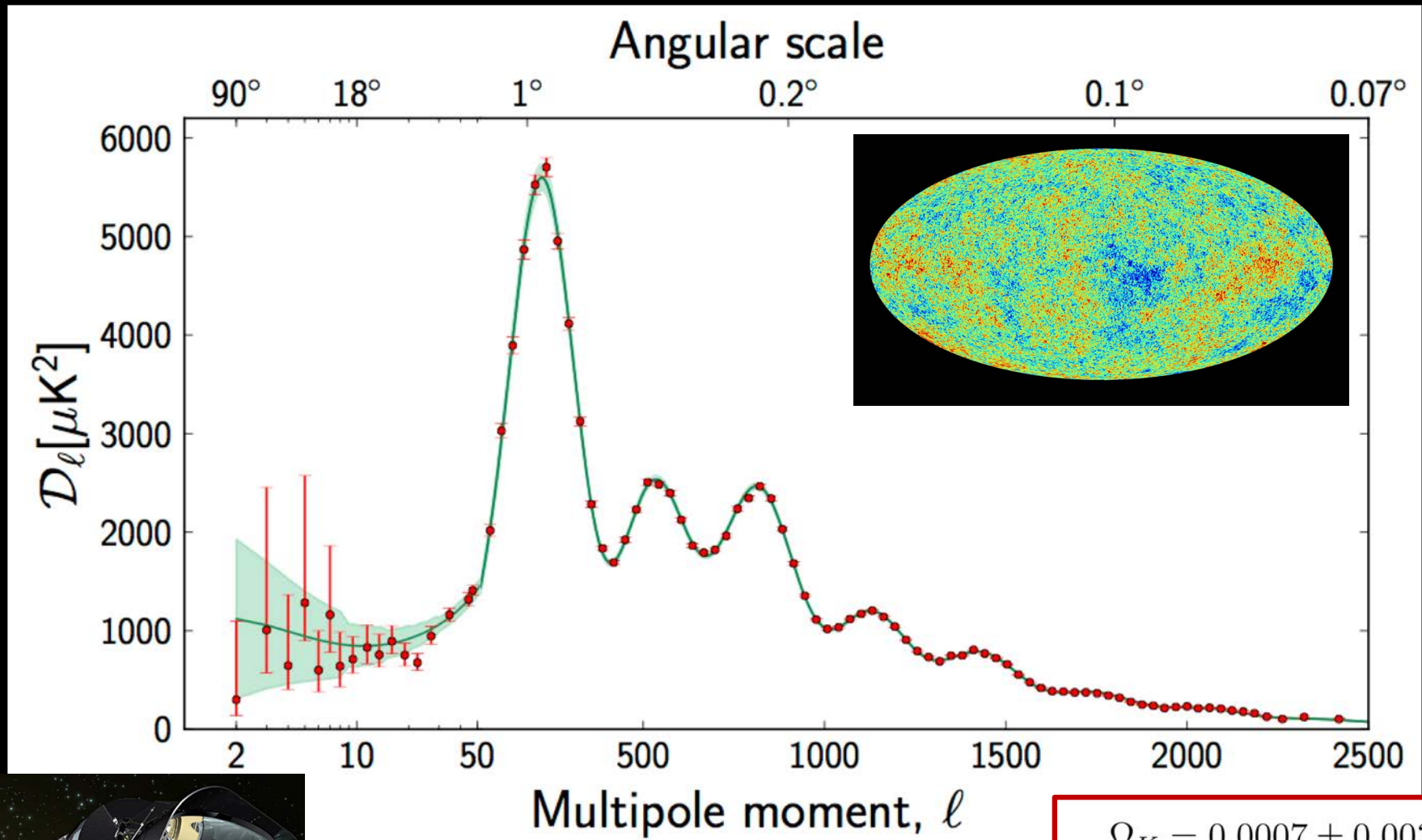
Planck

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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

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Planck collaboration,
arXiv:1807.06211

$$\Omega_K = 0.0007 \pm 0.0037$$

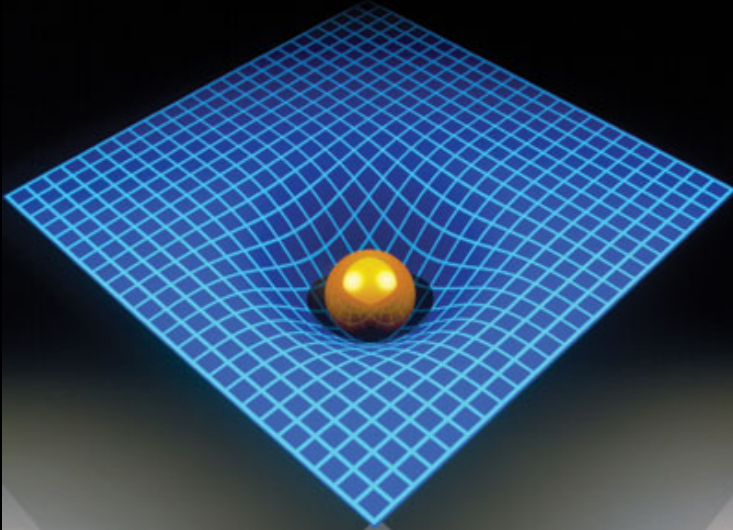
$$n_s = 0.965 \pm 0.004$$

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

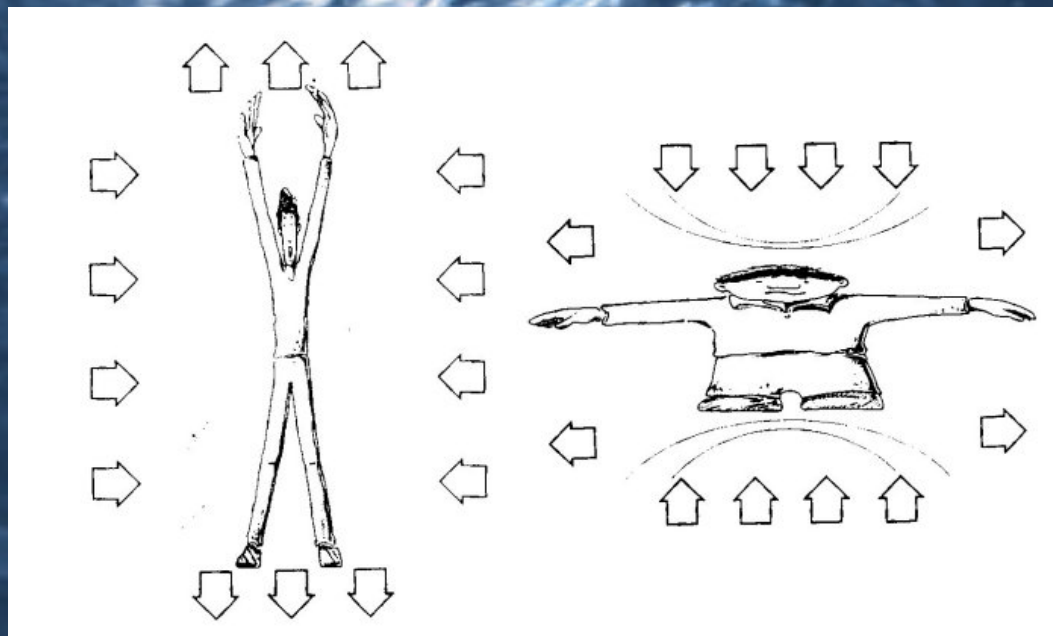
$$|f_{\text{NL}}^{\text{local}}| \leq 1.25$$

Primordial Gravity Waves

Space curve © LAGUNA DESIGN/SPL Water © source unknown. Stretched human © Augira group, INFN, Italy. All rights reserved. This content is excluded from our Creative Commons license. For more information, see <https://ocw.mit.edu/help/faq-fair-use/>.



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



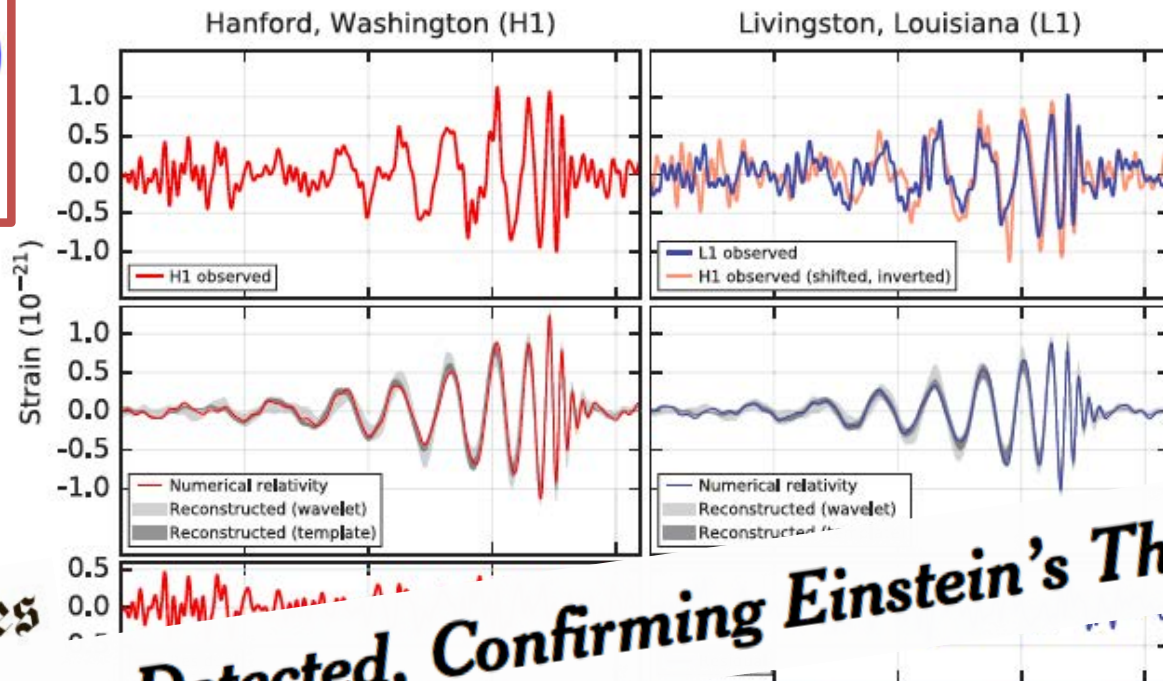
Auriga detector group, INFN, Italy

Primordial Gravity Waves

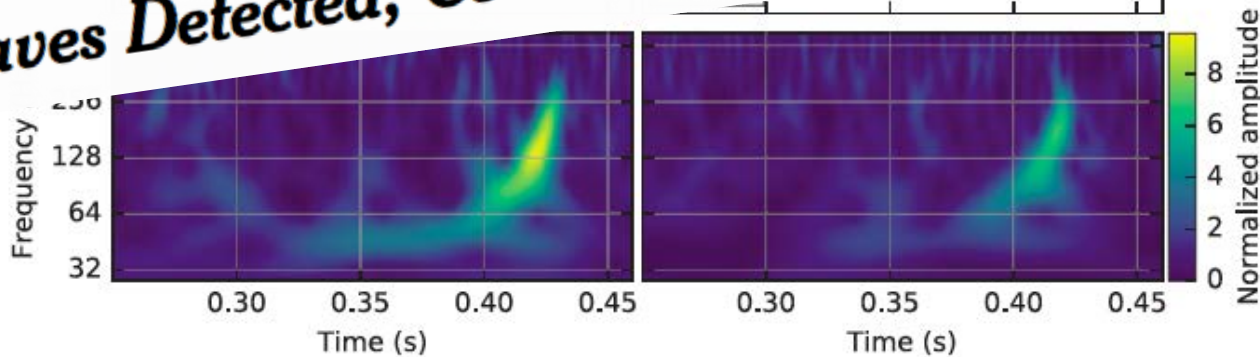
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Spacetime can wiggle in a

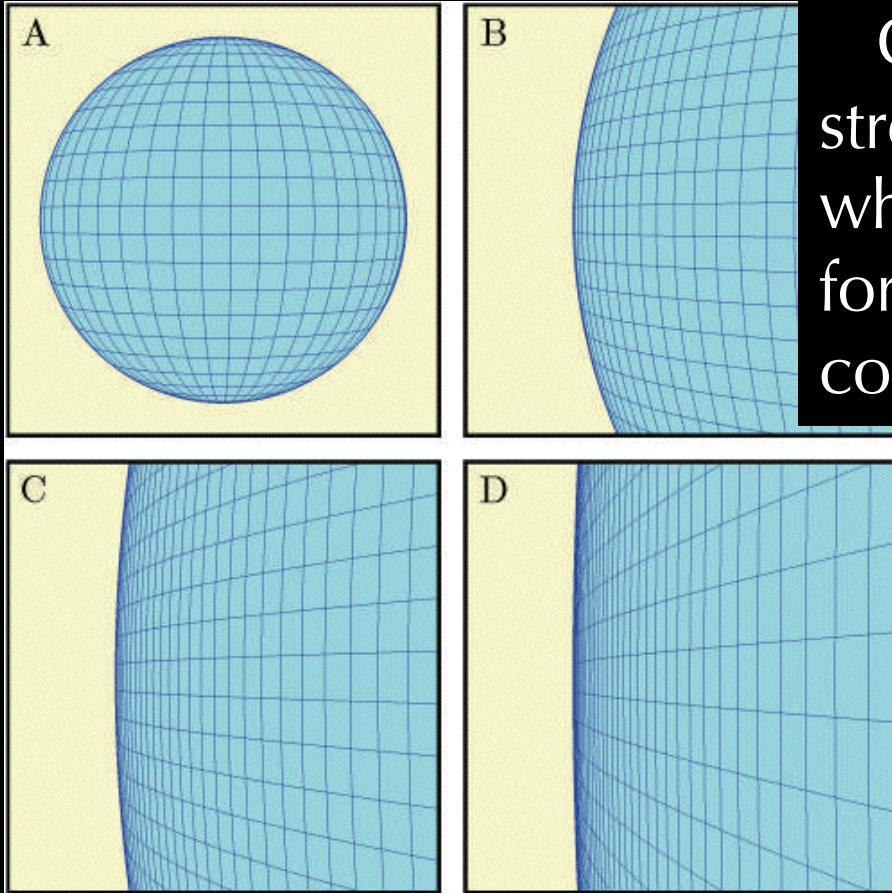


The New York Times
Gravitational Waves Detected, Confirming Einstein's Theory



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

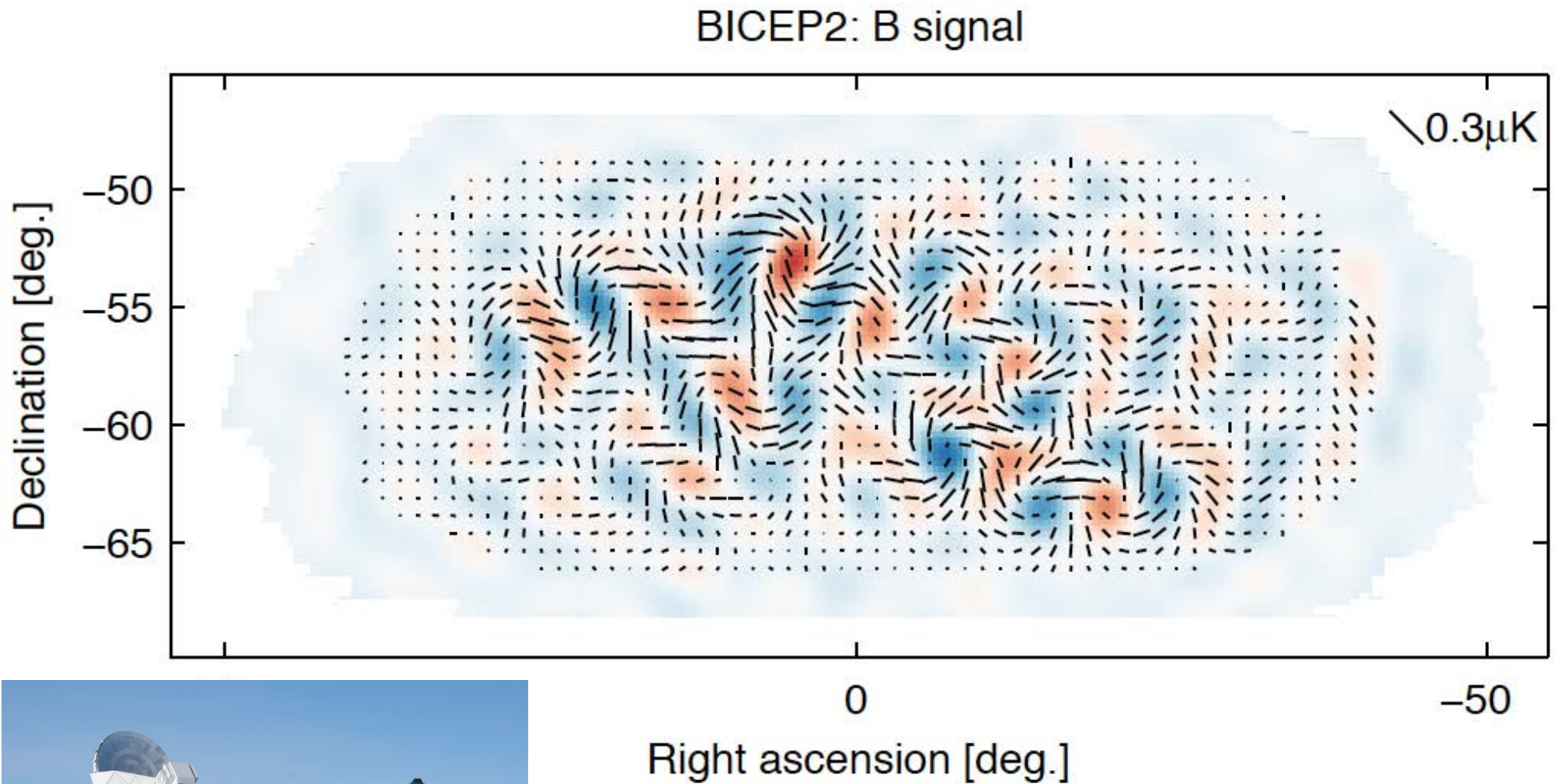
Primordial Gravity Waves



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.

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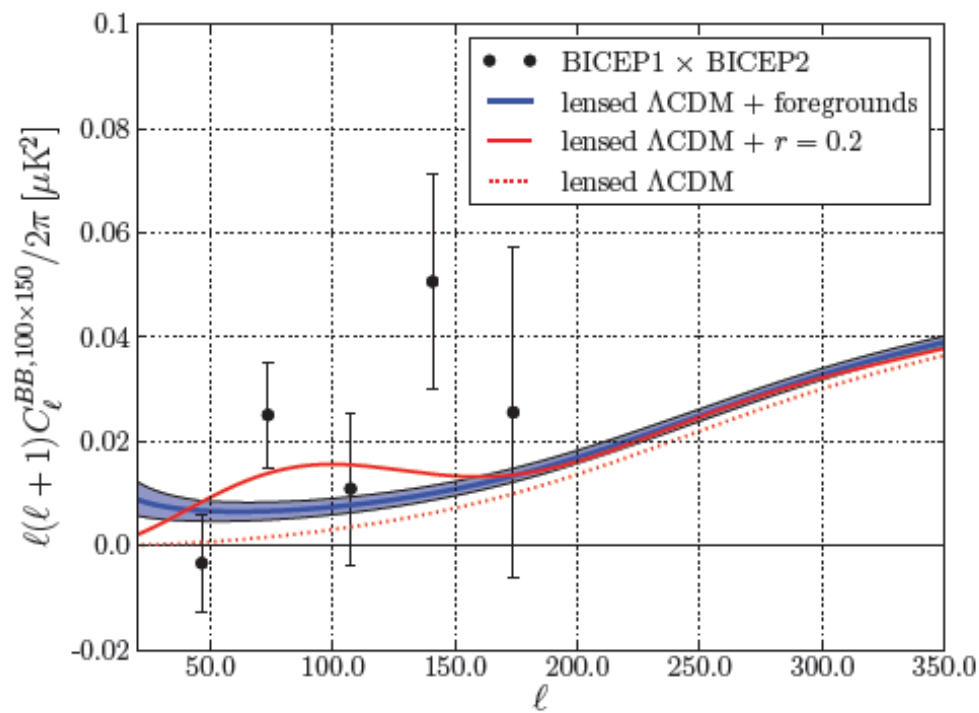
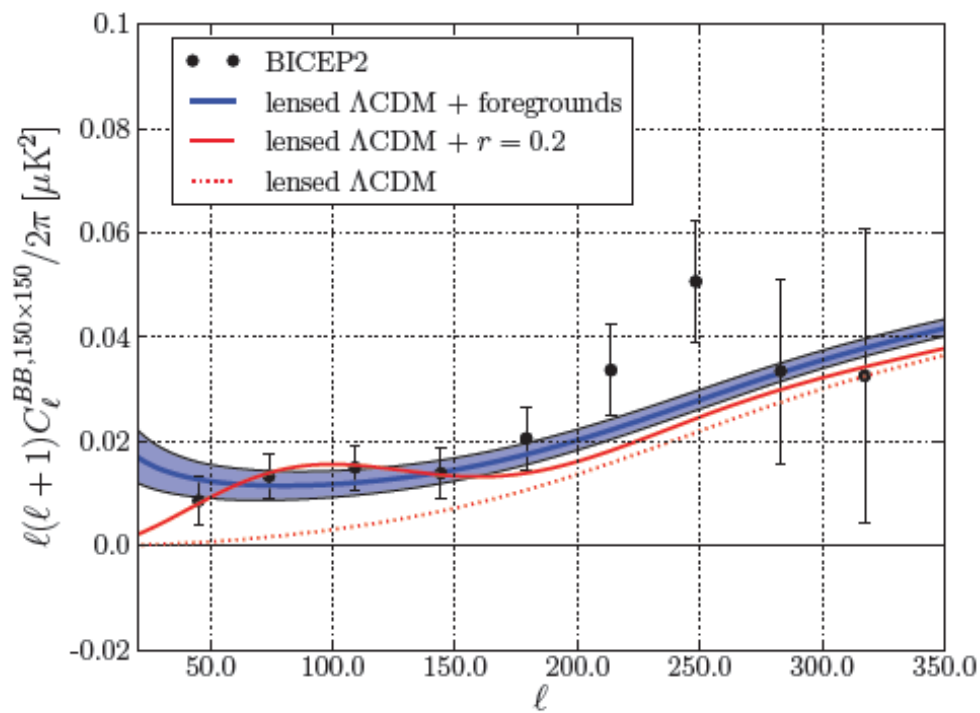
Gravity Waves Detected?



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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.

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Gravity Waves Detected?

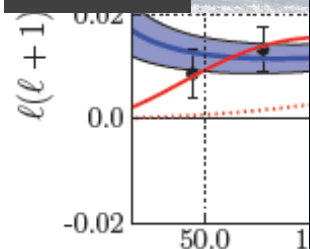
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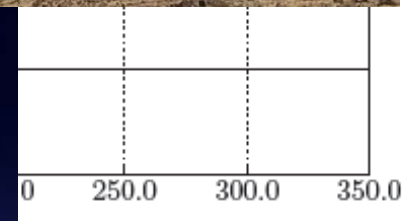
BICEP



Simons



South Pole Telescope



Planck-BICEP-Keck collaborations, arXiv:1606.01968

Simons Observatory collaboration, arXiv:1808.07445



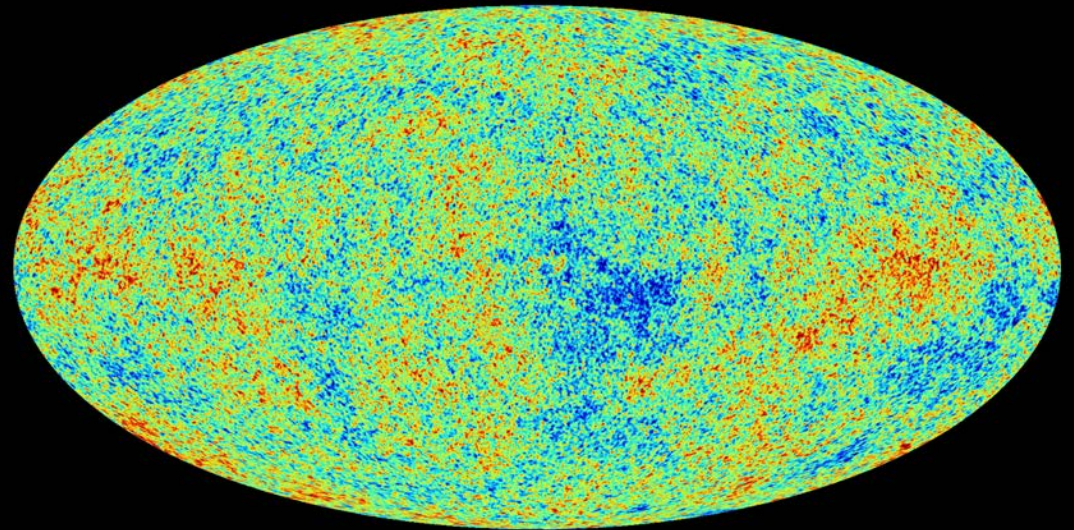
Planck

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.

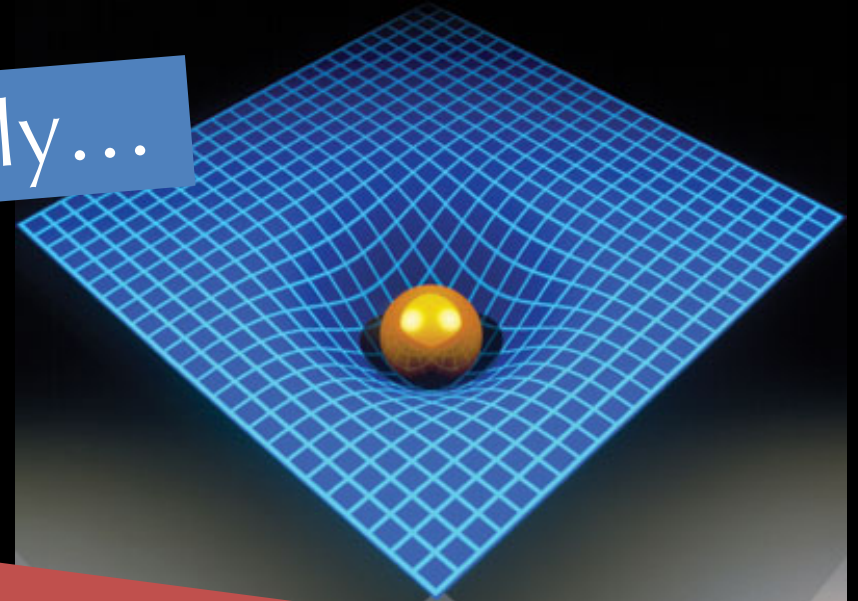
Simple models fit the latest observations to astonishing accuracy.



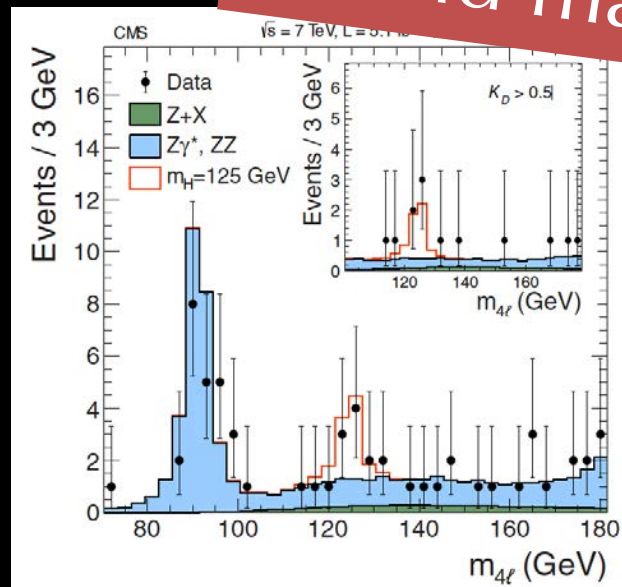
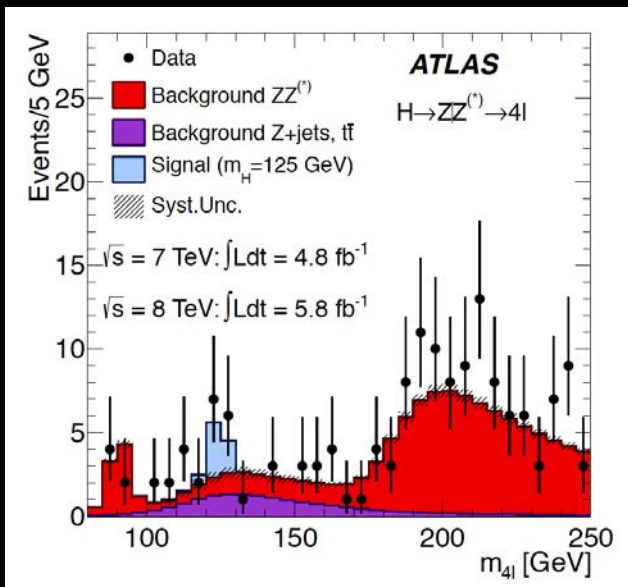
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So Why is the Universe Lumpy?

Because spacetime is wiggly...



... and matter is jiggly.



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STS.042J / 8.225J Einstein, Oppenheimer, Feynman: Physics in the 20th Century
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