Brookhaven forum 2025: Launching the second Century of Quantum Physics

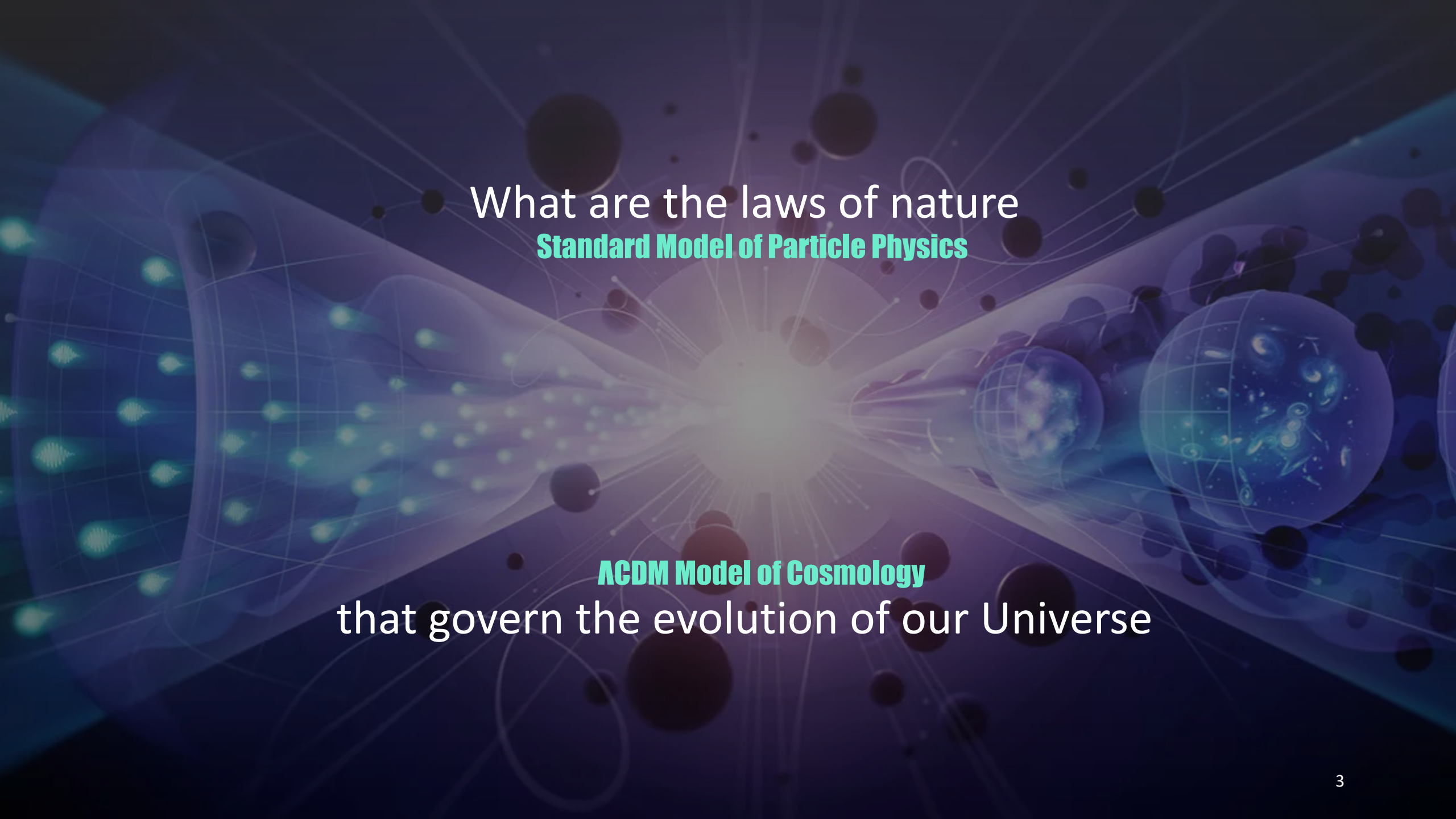
The strong force could have heated the Universe's first moment

Kim V. Berghaus

California Institute of Technology

Brookhaven National Laboratory

What are the laws of nature
that govern the evolution of our Universe


What are the laws of nature
Standard Model of Particle Physics
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Fundamental Physics in the Era of Precision Cosmology

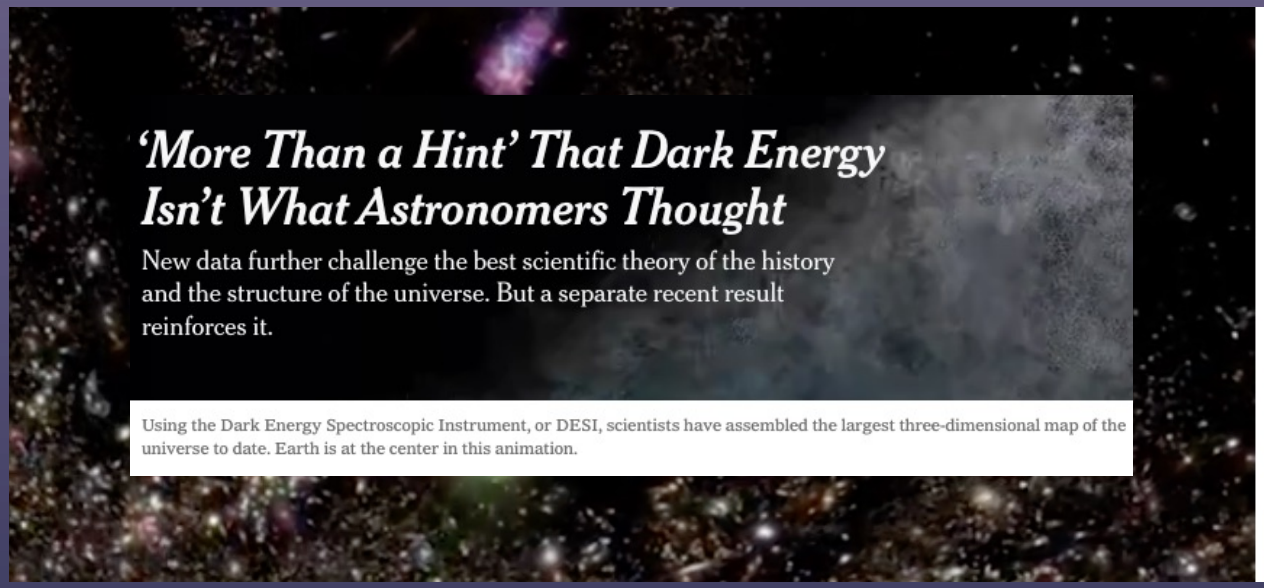
Evolving dark energy

A Tantalizing 'Hint' That Astronomers Got Dark Energy All Wrong

Scientists may have discovered a major flaw in their understanding of that mysterious cosmic force. That could be good news for the fate of the universe.

New York Times,
April 4th , 2024

Evolving dark energy



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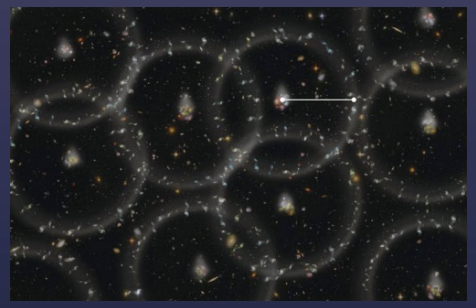
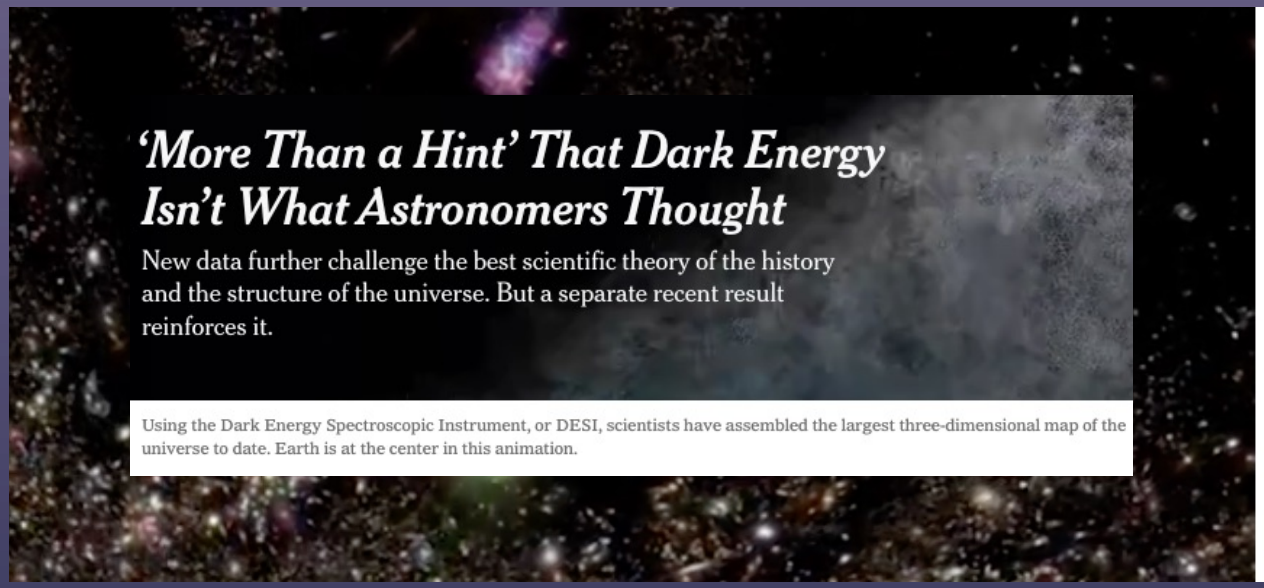


DESI measures baryon acoustic oscillations and combined with other datasets sees hints of evolving dark energy

Evolving dark energy



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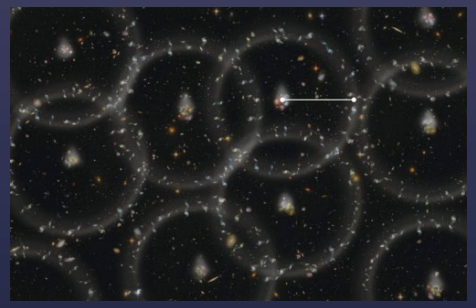

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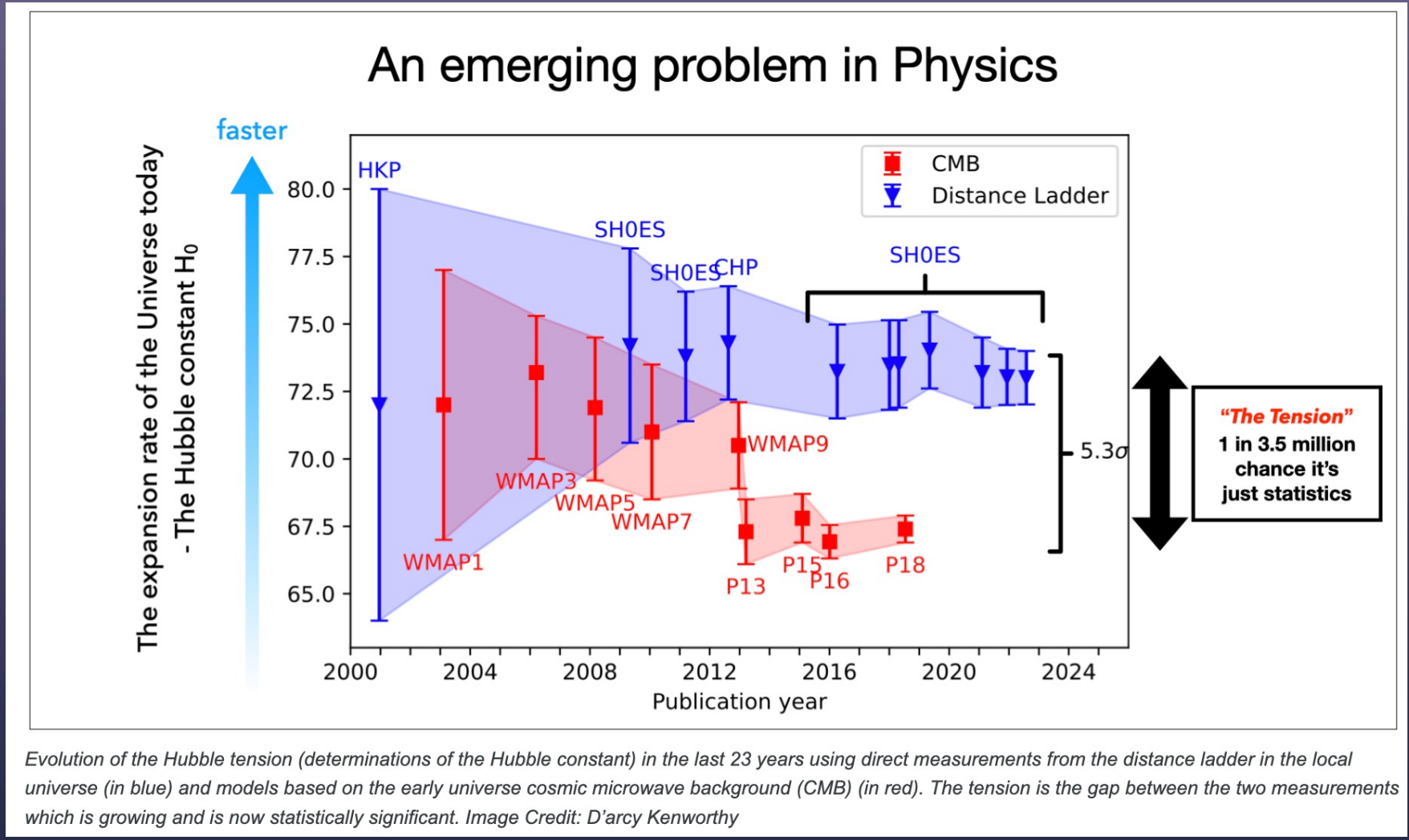
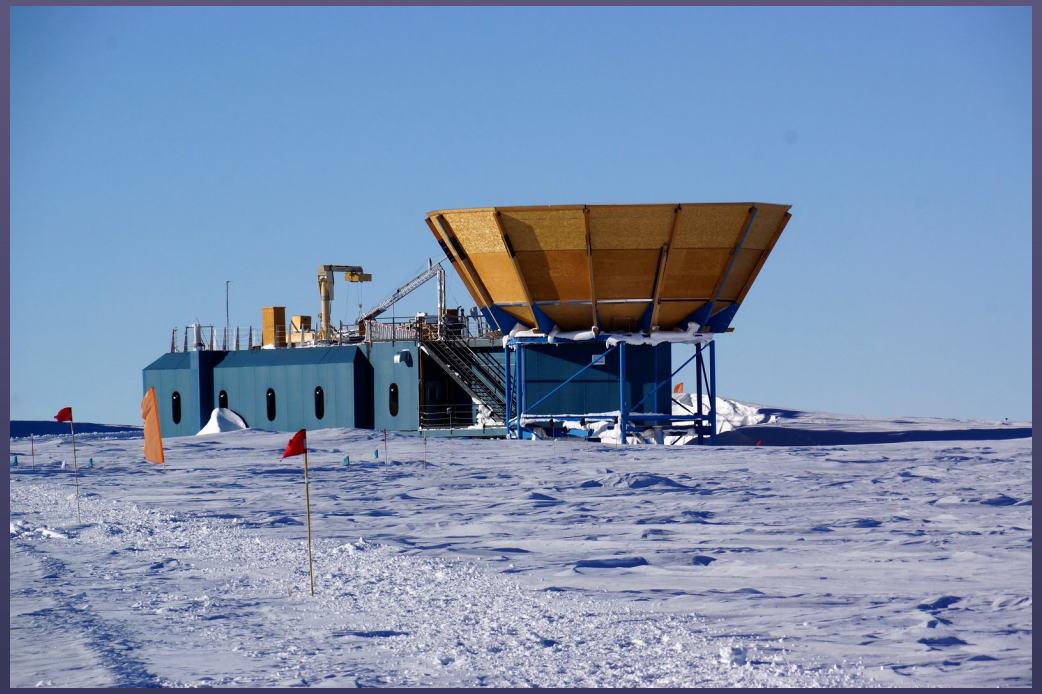
The Hubble Tension

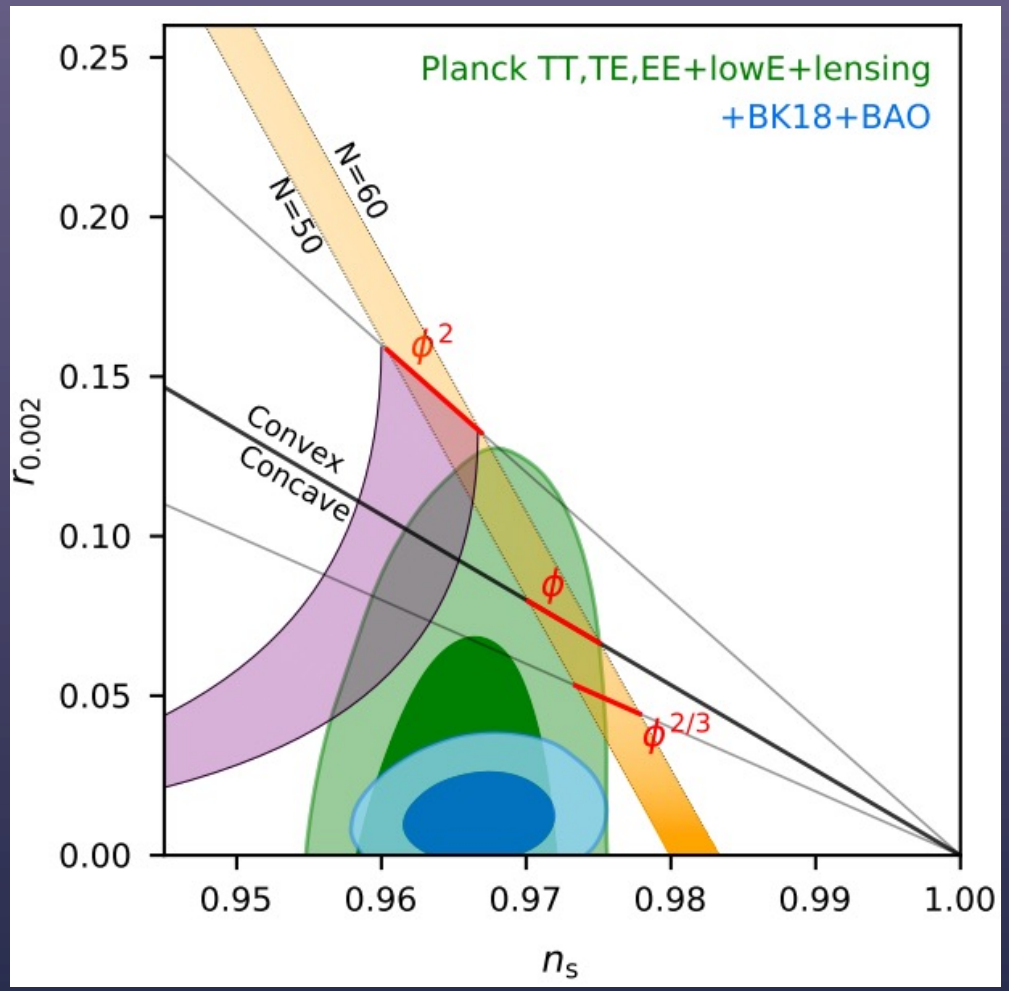


Evolution of the Hubble tension (determinations of the Hubble constant) in the last 23 years using direct measurements from the distance ladder in the local universe (in blue) and models based on the early universe cosmic microwave background (CMB) (in red). The tension is the gap between the two measurements which is growing and is now statistically significant. Image Credit: D'arcy Kenworthy

(Lack of) primordial gravitational waves



BICEP Array



Bicep/Keck XIII, 2021

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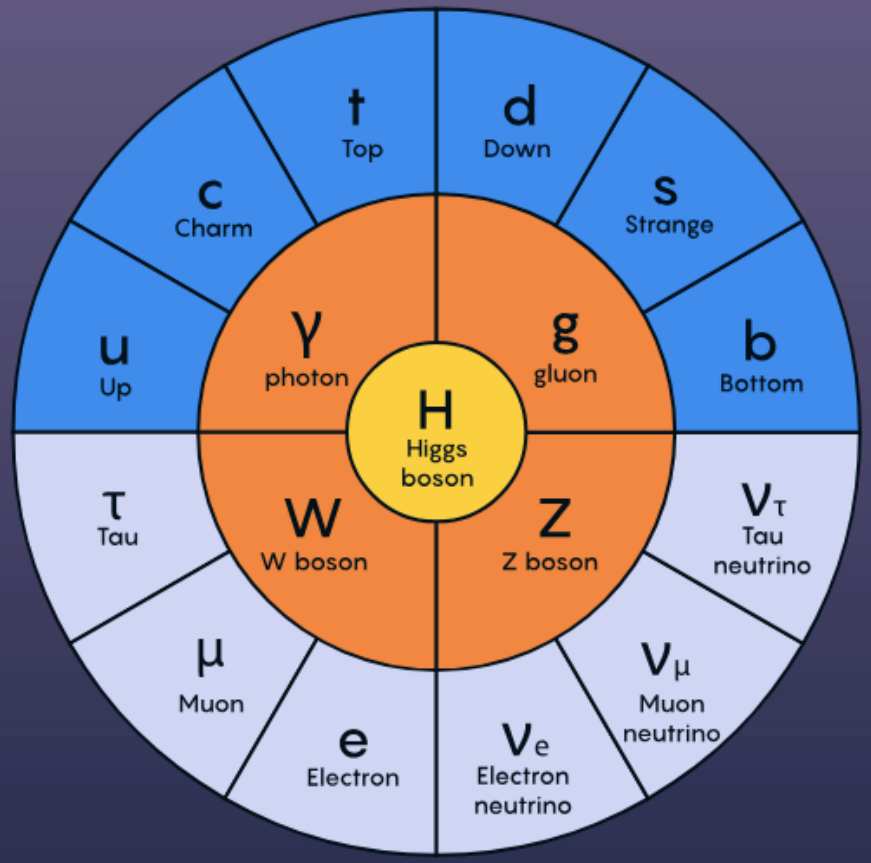
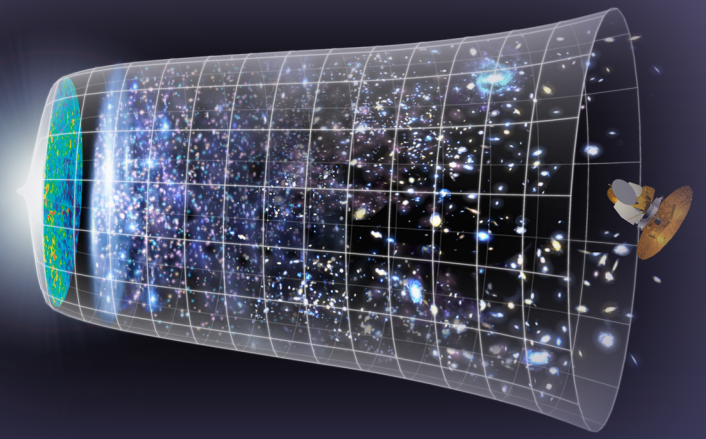
The Standard Model



ΛCDM Model of Cosmology

six parameters



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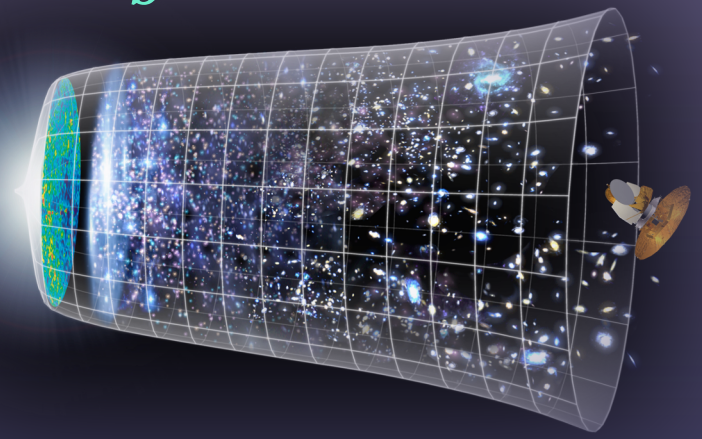
Ω_b



ΛCDM Model of Cosmology

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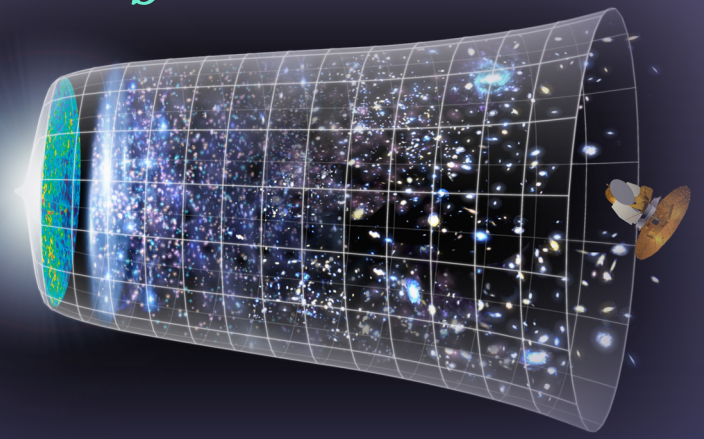
Ω_b Ω_{cdm}



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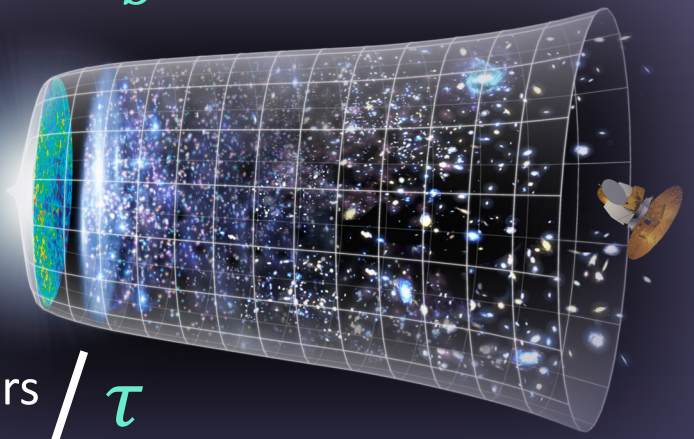


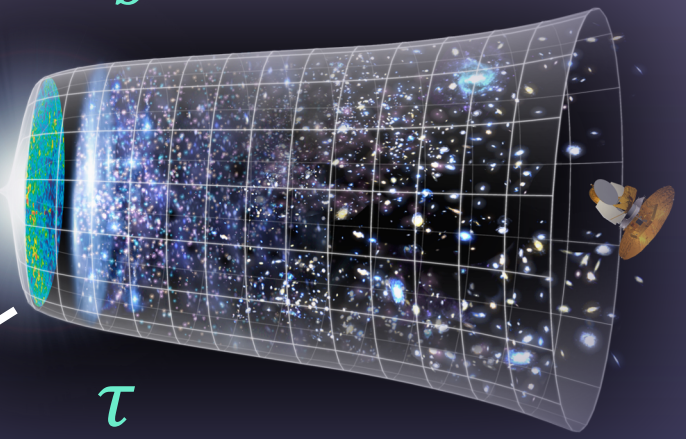
1 billion years / τ

star formation

ΛCDM Model of Cosmology

six parameters

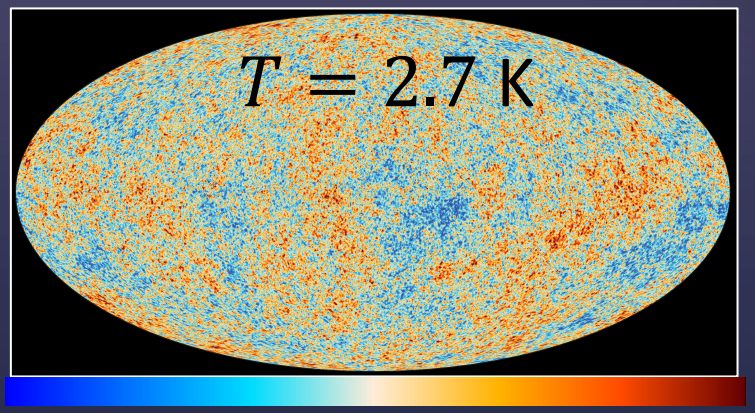
Ω_b Ω_{cdm}



400.000 years

τ

cosmic microwave background (CMB)



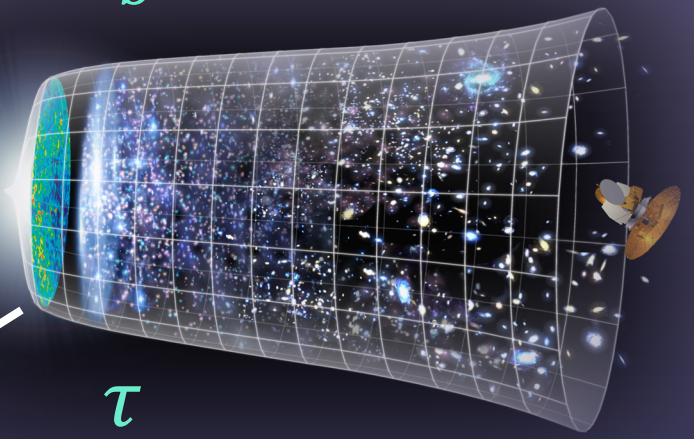
30 μK 70 μK

ΛCDM Model of Cosmology

six parameters

Ω_b

Ω_{cdm}



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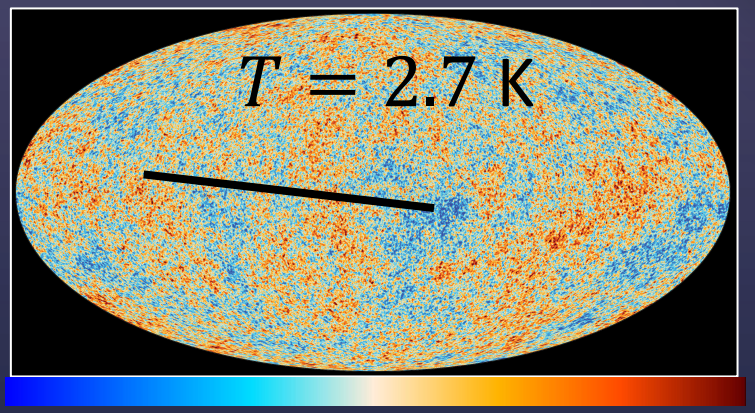


A_s

30 μK

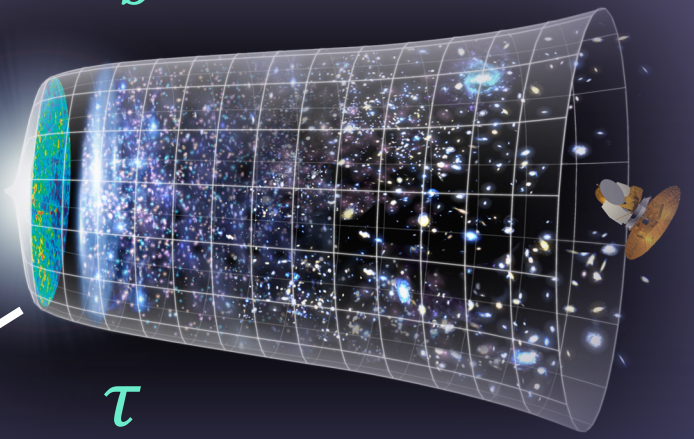
70 μK

ΛCDM Model of Cosmology

six parameters

Ω_b

Ω_{cdm}



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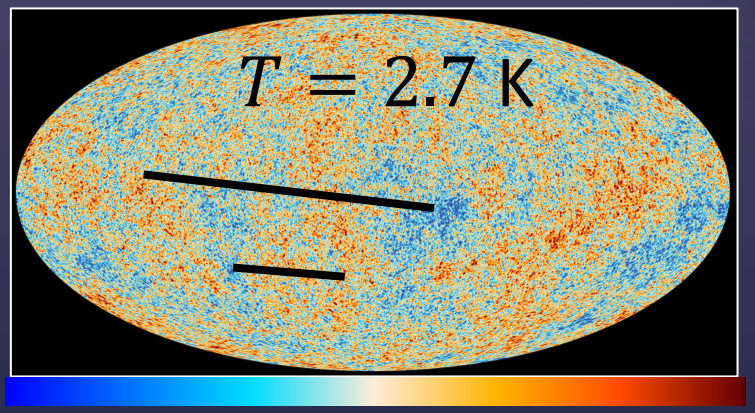


A_s, n_s

30 μK

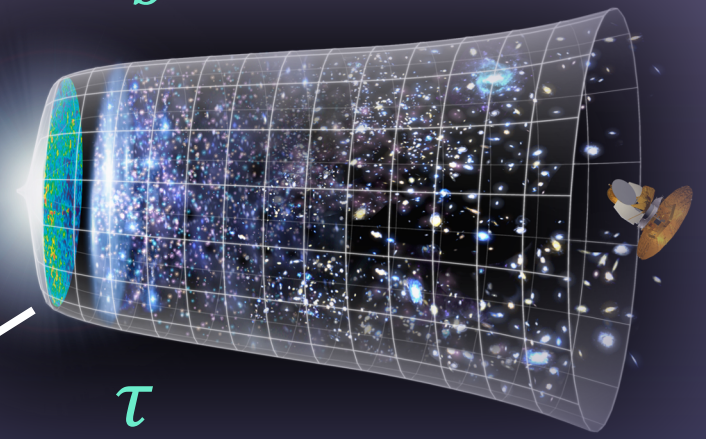
70 μK

ΛCDM Model of Cosmology

six parameters

Ω_b

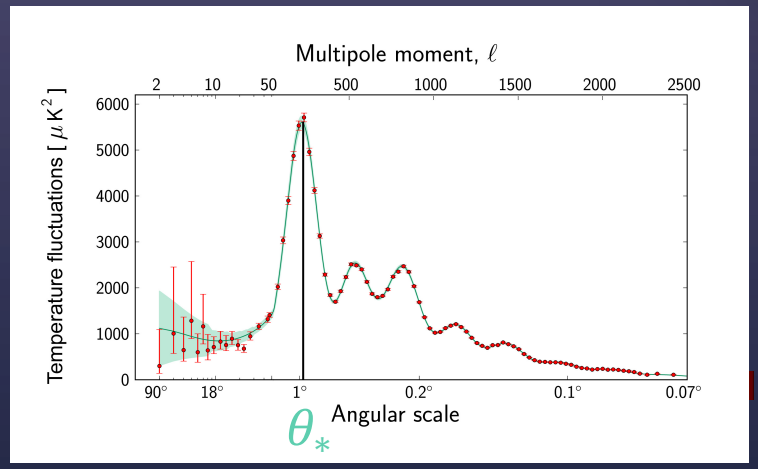
Ω_{cdm}



400.000 years

cosmic microwave background (CMB)

τ

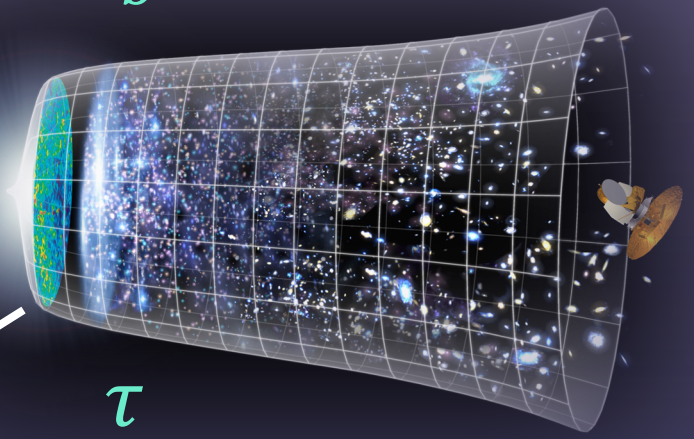


A_s, n_s, θ_*

ΛCDM Model of Cosmology

six parameters

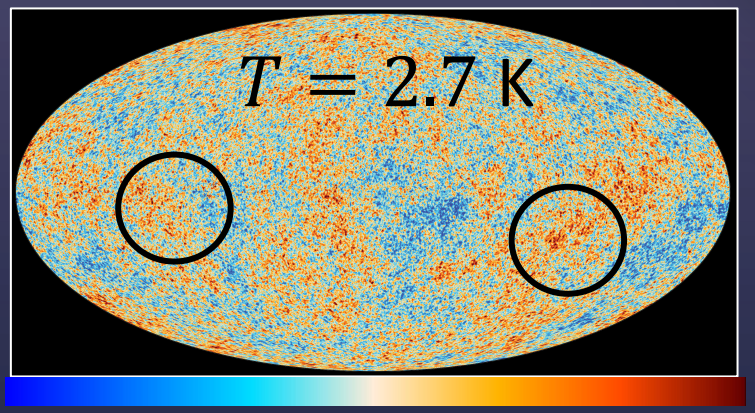
Ω_b Ω_{cdm}



400.000 years

τ

cosmic microwave background (CMB)



A_s, n_s, θ_*

30 μK 70 μK

ΛCDM Model of Cosmology

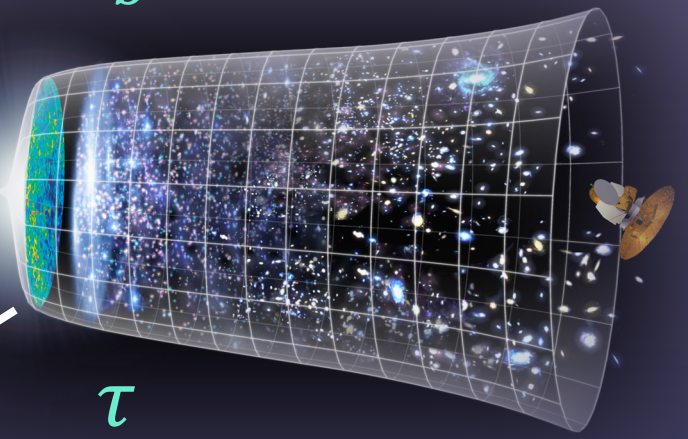
cosmic inflation

six parameters

Ω_b

Ω_{cdm}

$\ll s$



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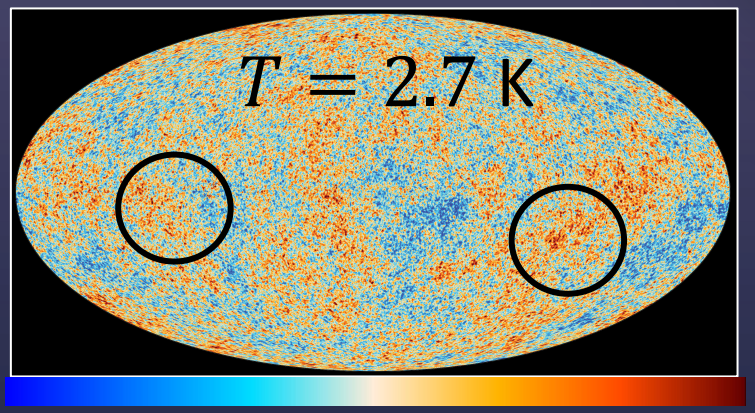


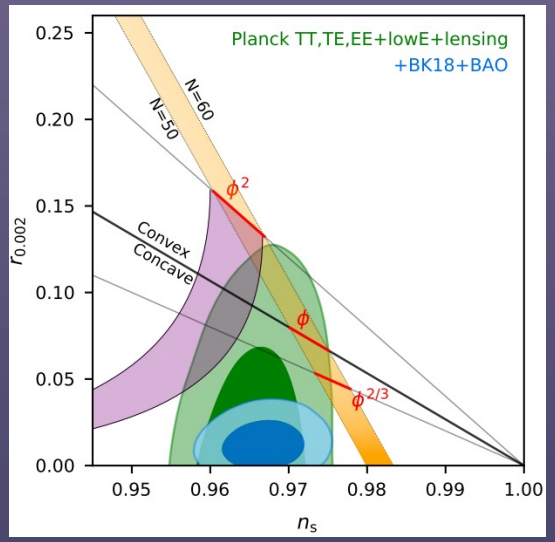
A_s, n_s, θ_*

30 μK

70 μK

lack of inflationary gravitational waves

cosmic inflation



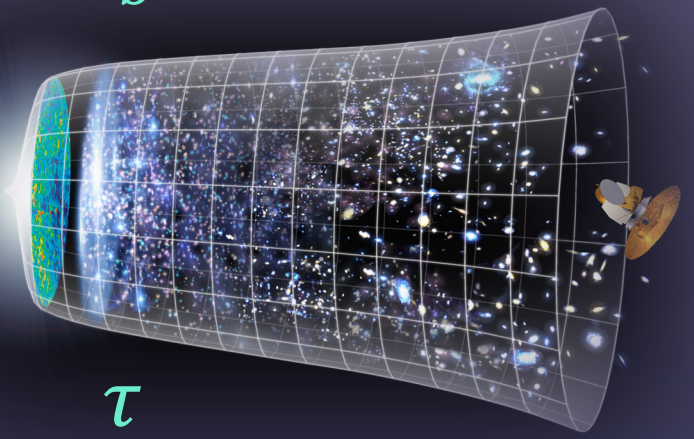
Bicep/Keck XIII, 2021

ΛCDM Model of Cosmology

six parameters

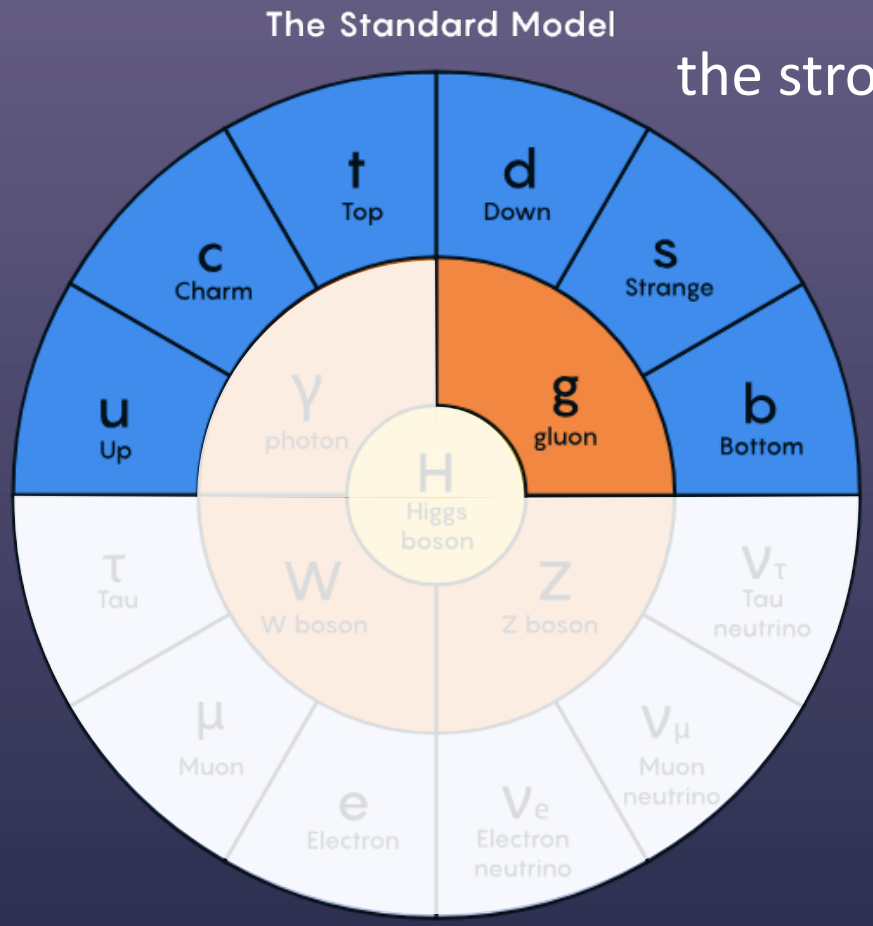
Ω_b Ω_{cdm}

$\ll s$

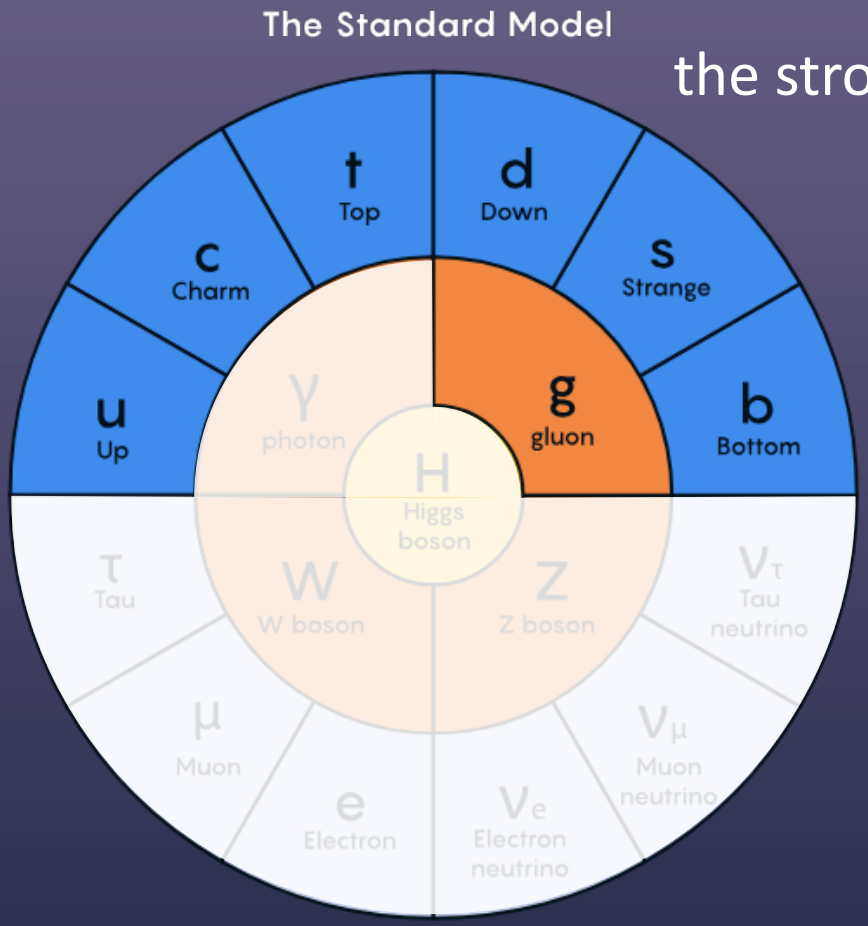


τ

A_s, n_s, θ_*

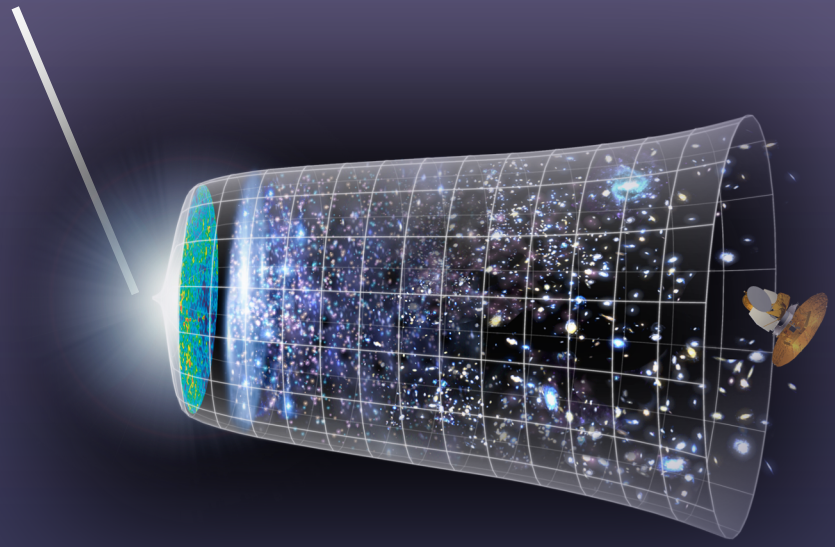


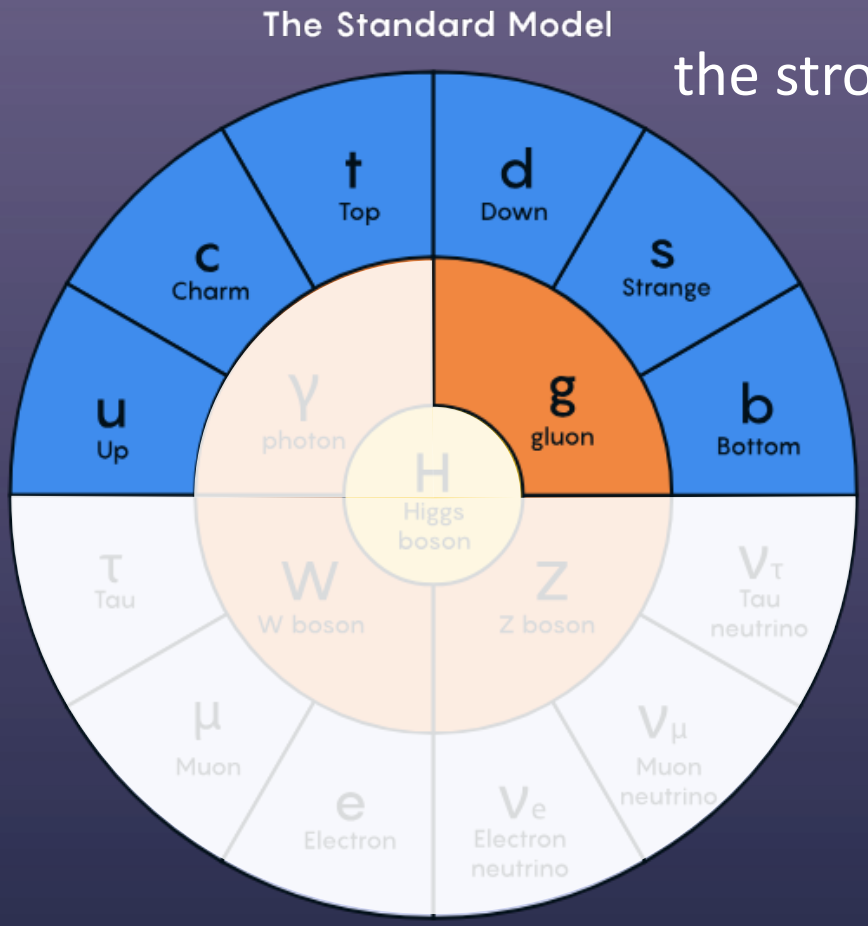
the strong force



the strong force

cosmic inflation





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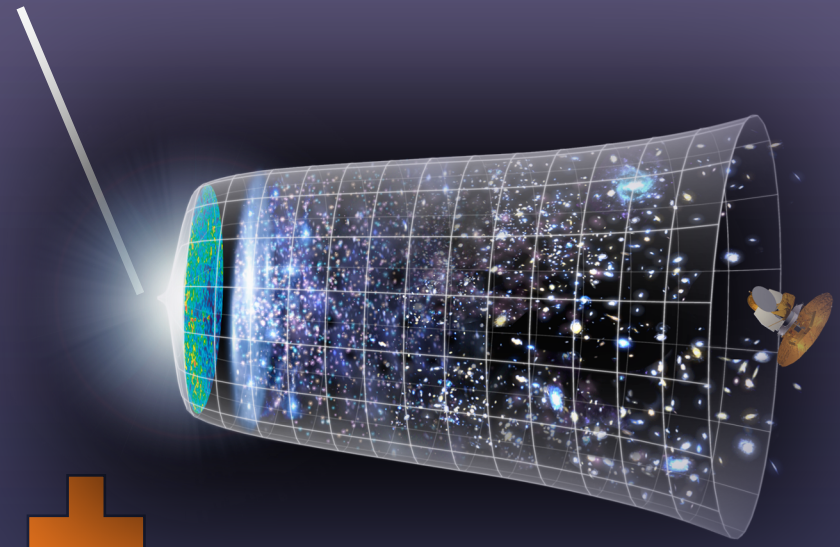
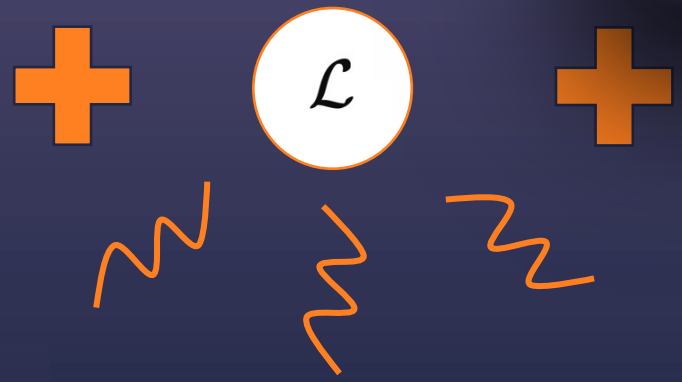
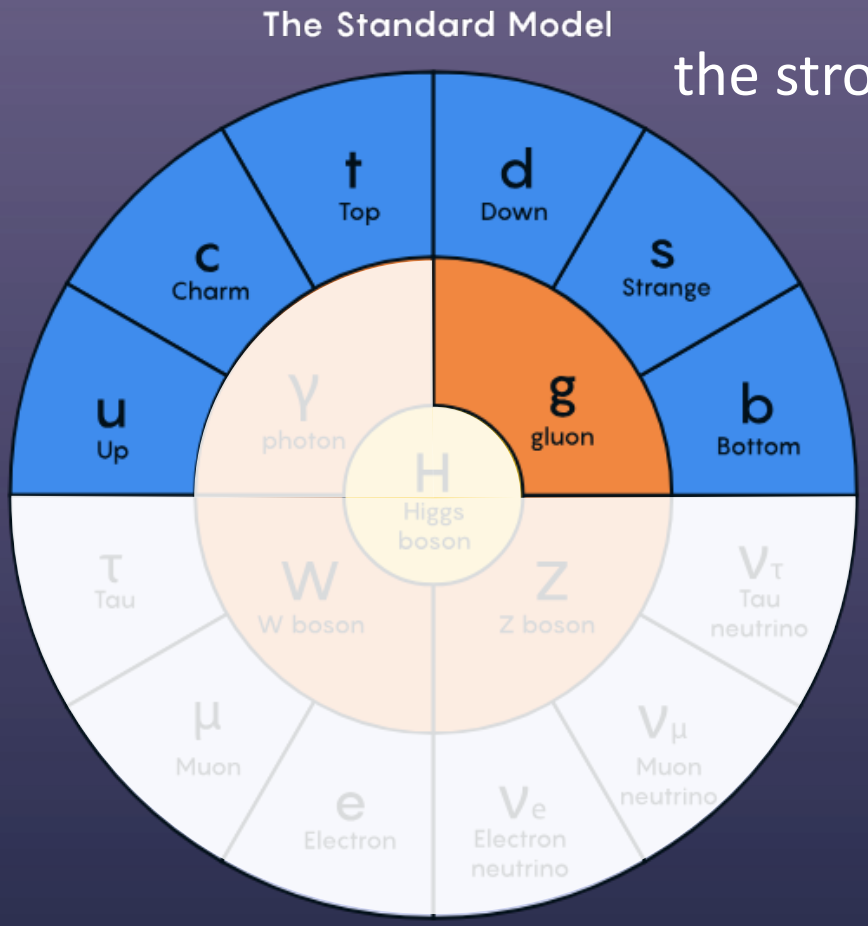


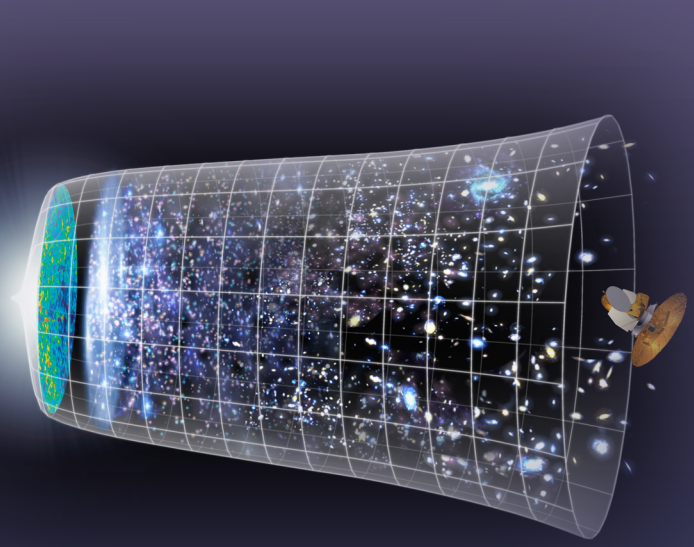


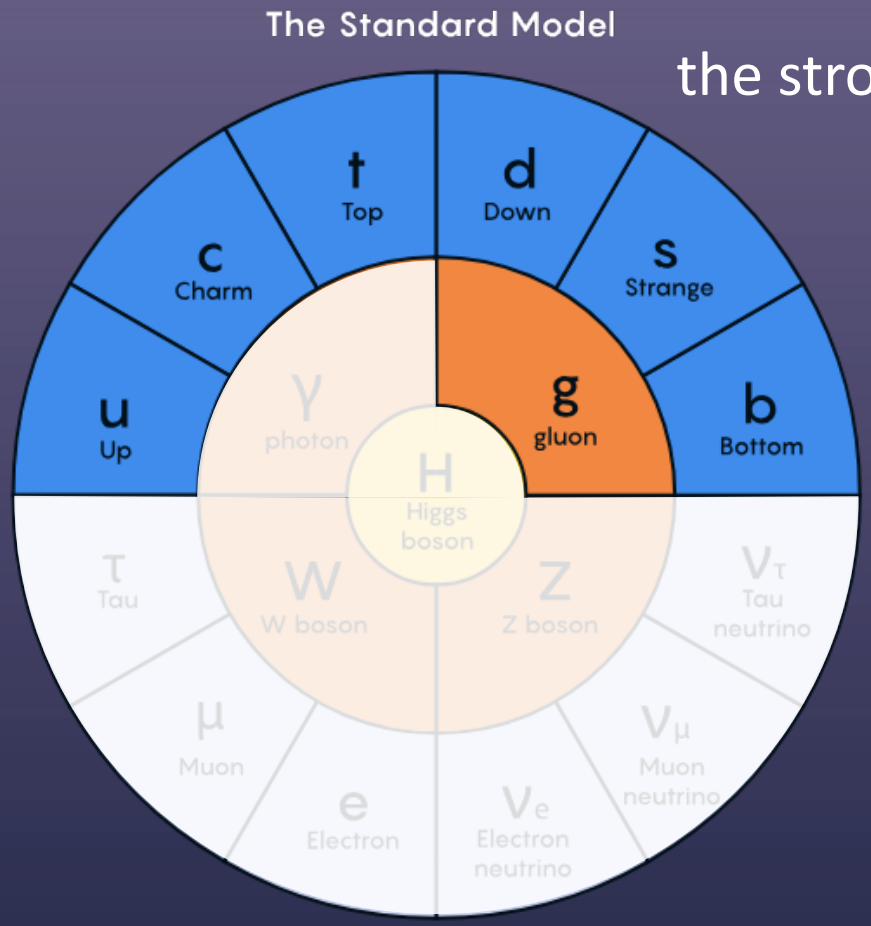


the strong force

cosmic inflation

$$\mathcal{L}_{\text{int}} = -\phi \frac{\alpha_s}{16\pi f} \tilde{G} G$$





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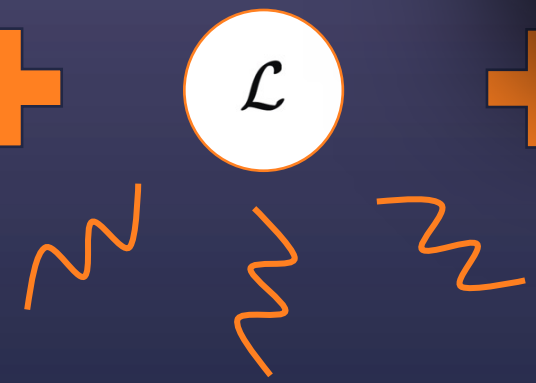
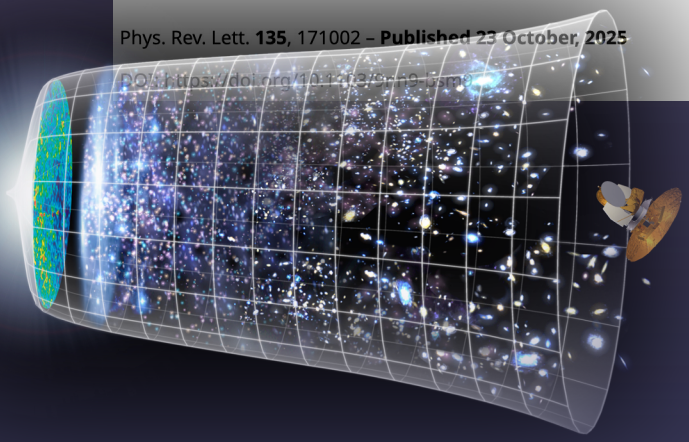
$+ \quad \mathcal{L} \quad +$





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Warm Inflation with the Standard Model

Kim V. Berghaus [1], Marco Drewes [2,3], and Sebastian Zell [4,5,2]

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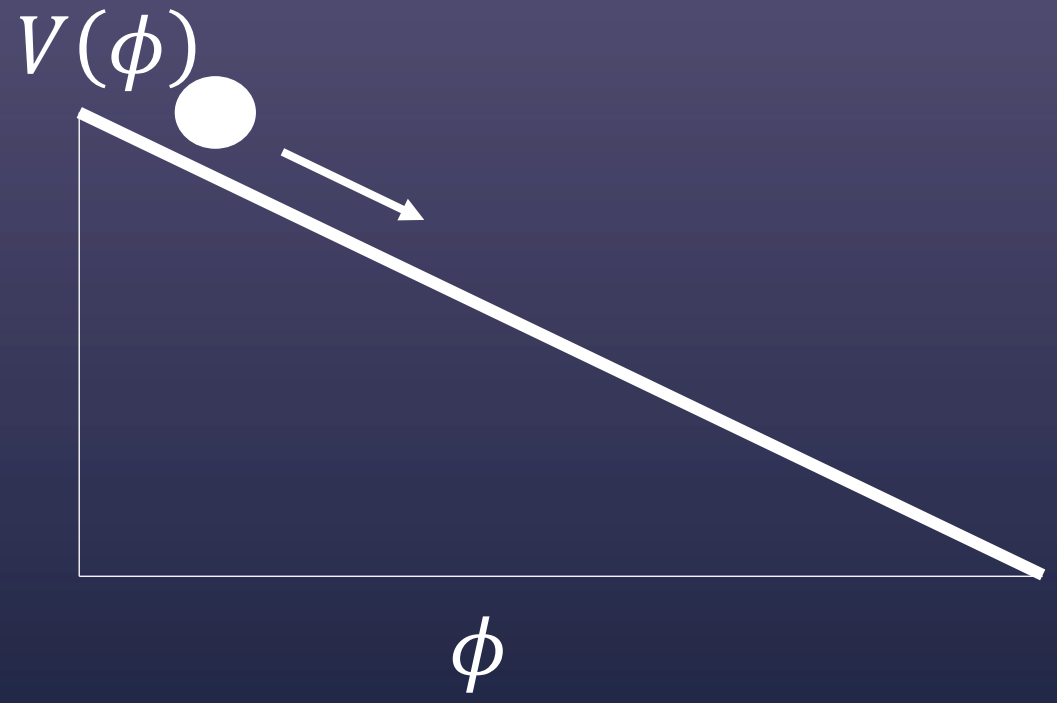
Phys. Rev. Lett. **135**, 171002 – **Published** 23 October, 2025

Inflation

General relativity: content of our Universe dictates its expansion

Condition for accelerated expansion: $\frac{P}{\rho} < -\frac{1}{3}$ (negative pressure, quite exotic)



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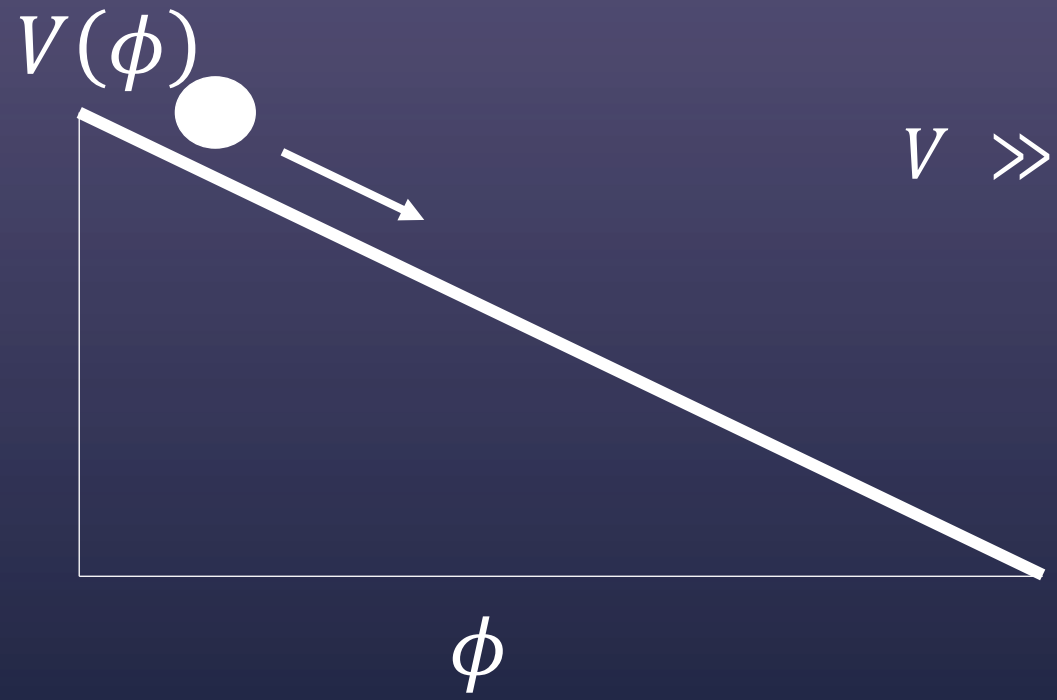

$$V \gg \frac{1}{2}\dot{\phi}^2$$

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

Hubble friction from expansion

Inflation

$$\varepsilon_V = \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

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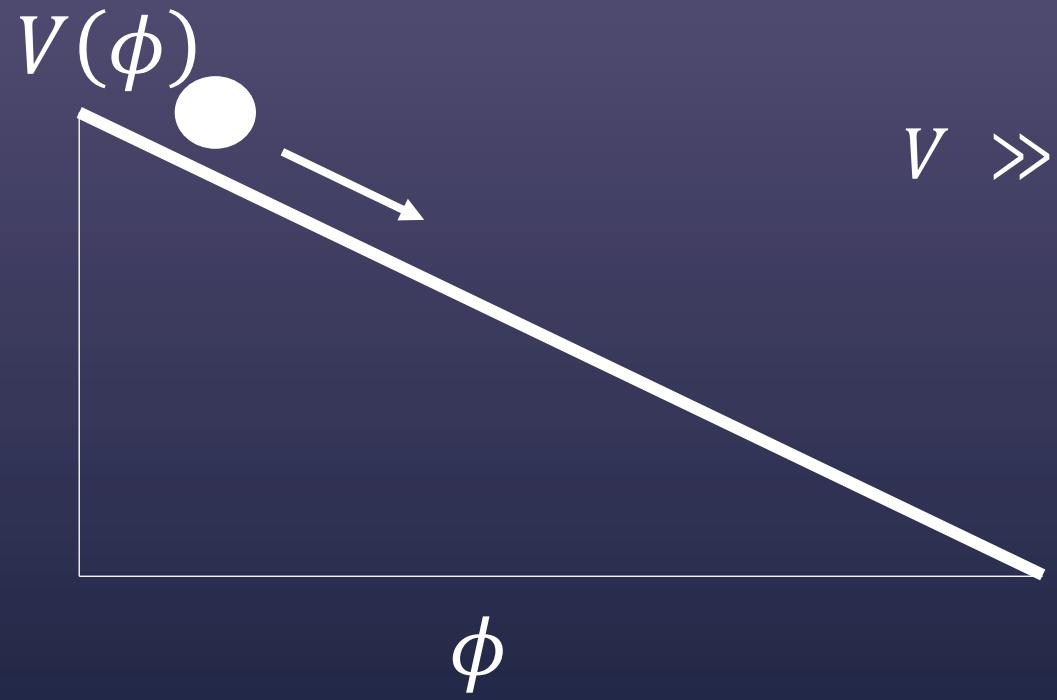

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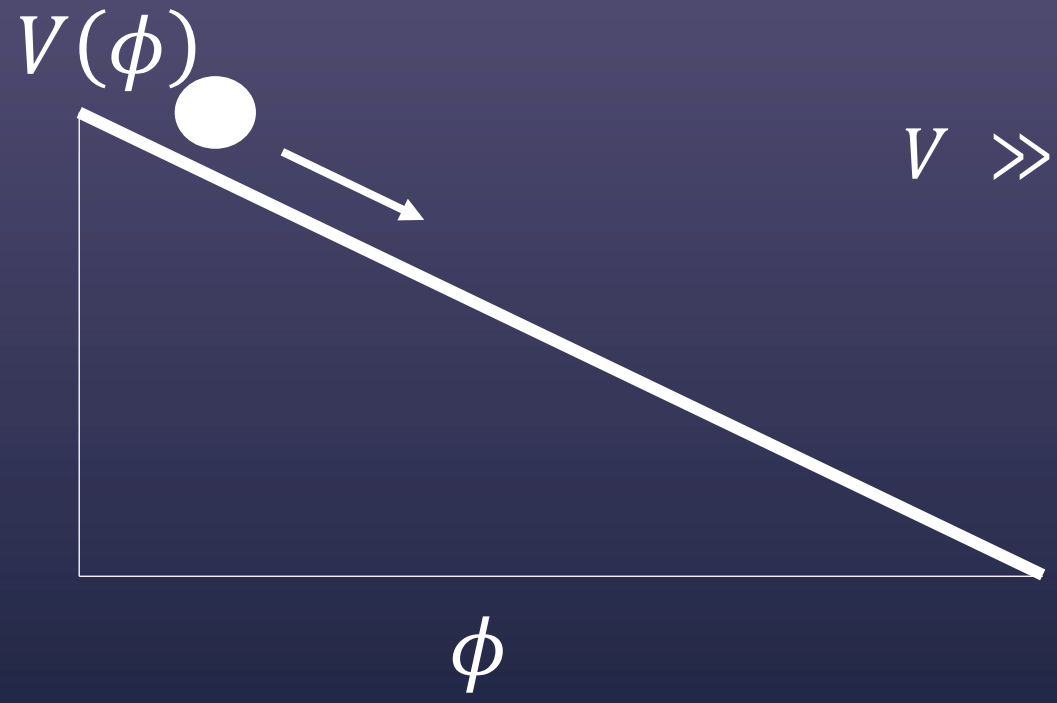

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Hubble friction from expansion

$$\langle \delta\phi\delta\phi \rangle \propto A_s$$

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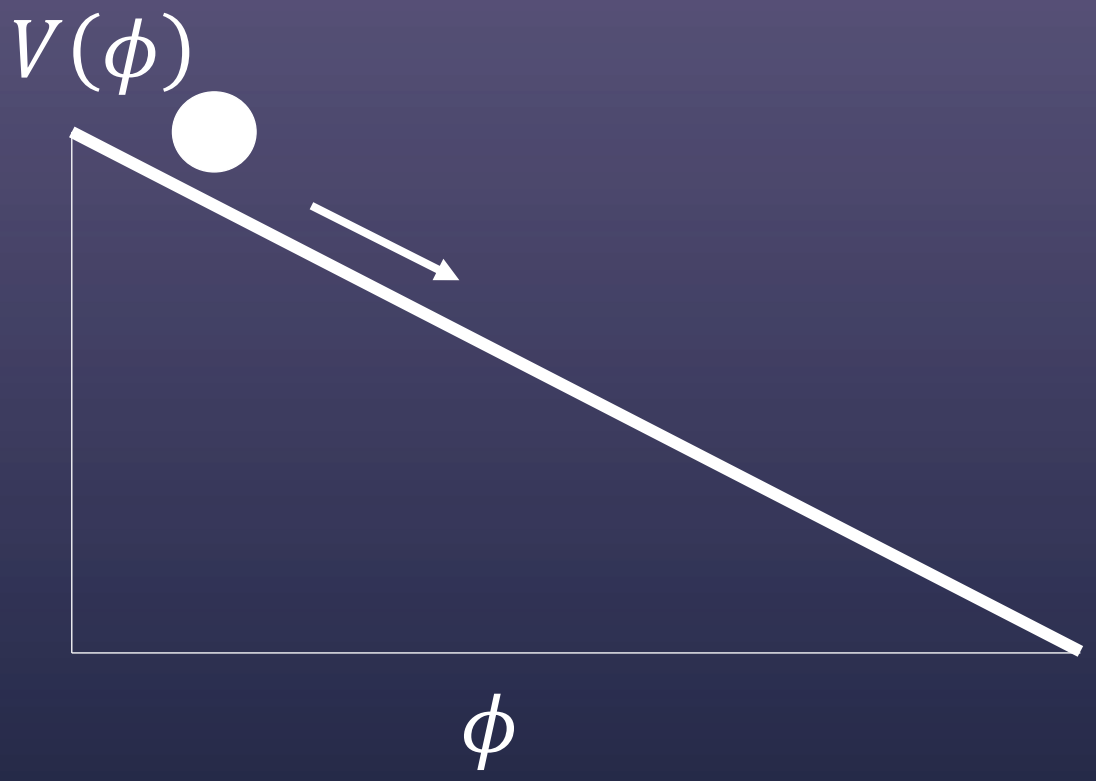

$\delta\phi \sim H$ quantum fluctuations seed structure

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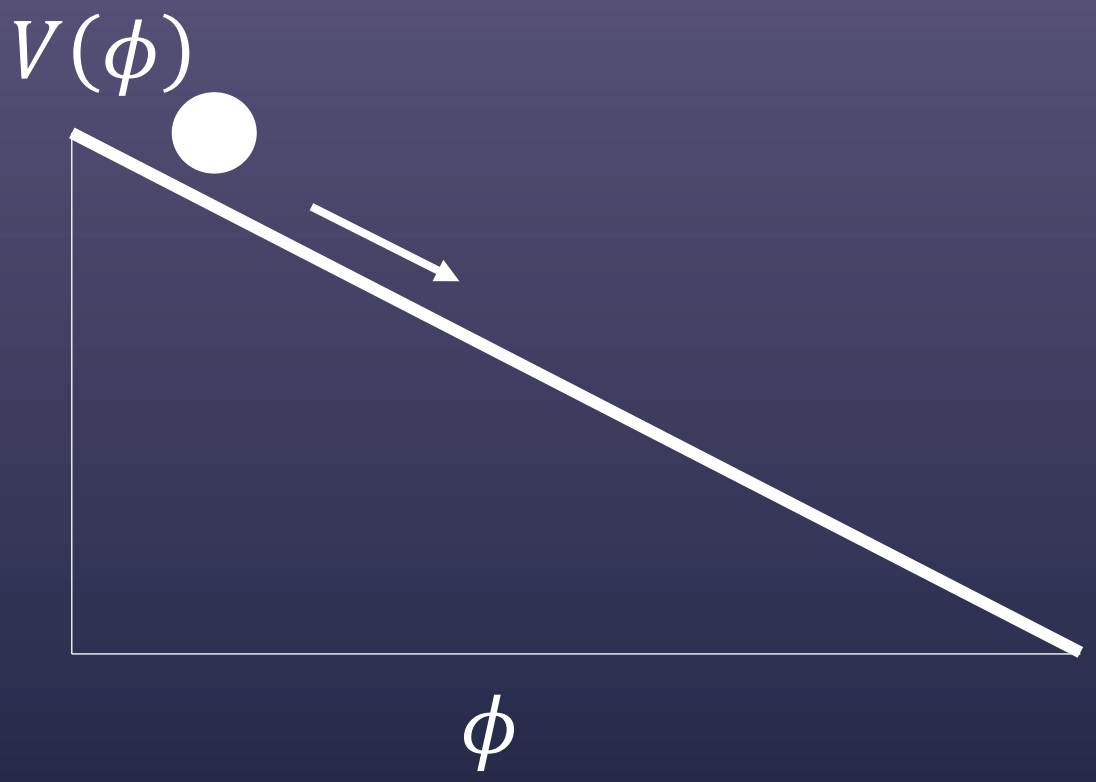
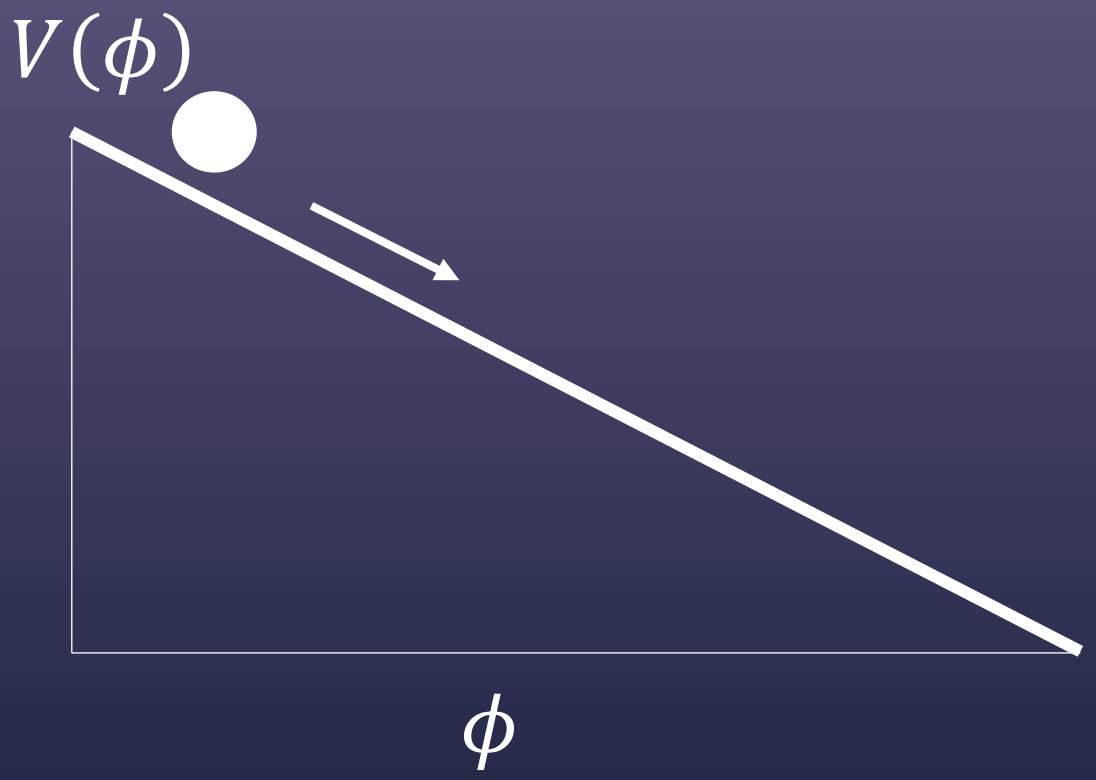


$\delta\phi \sim H$ quantum fluctuations seed structure

$h \sim H$ quantum fluctuations seed gravitational waves

Inflation

$$\varepsilon_V = \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$



$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

$\delta\phi \sim H$ quantum fluctuations seed structure

$h \sim H$ quantum fluctuations seed gravitational waves

$$r \propto \frac{\langle hh \rangle}{\langle \delta\phi\delta\phi \rangle} \approx 16\varepsilon_V$$

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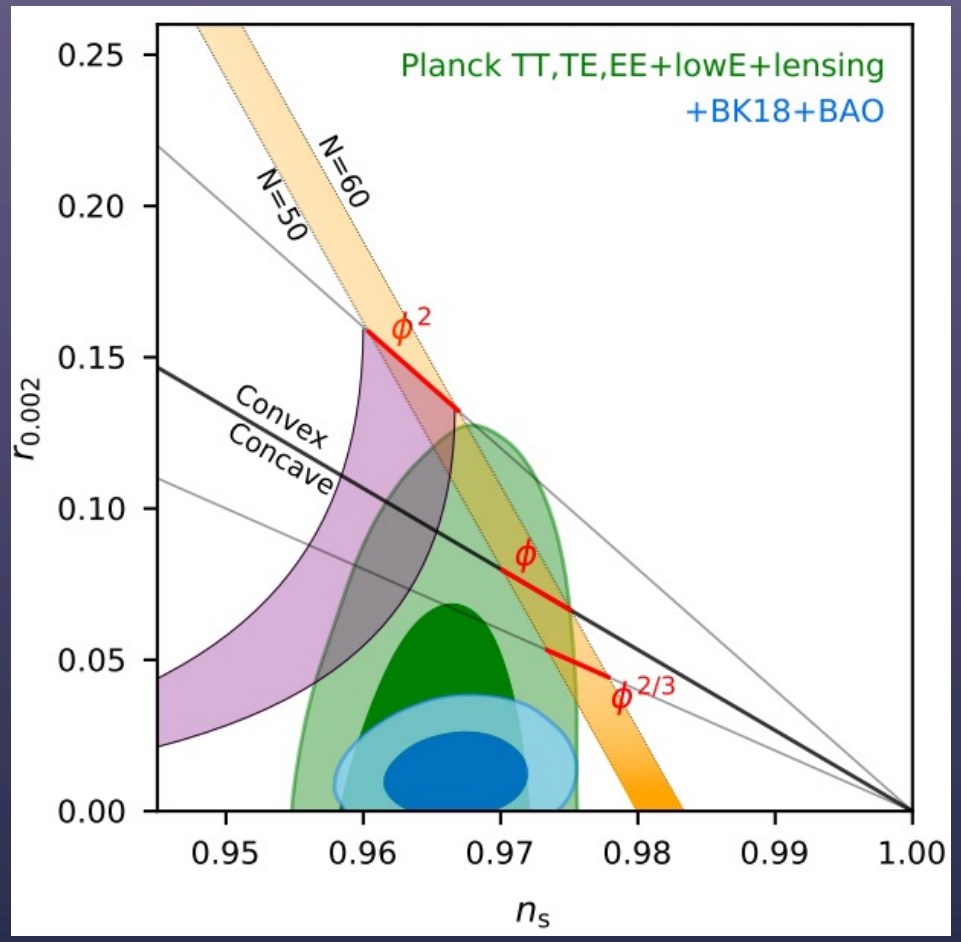

Bicep/Keck XIII, 2021

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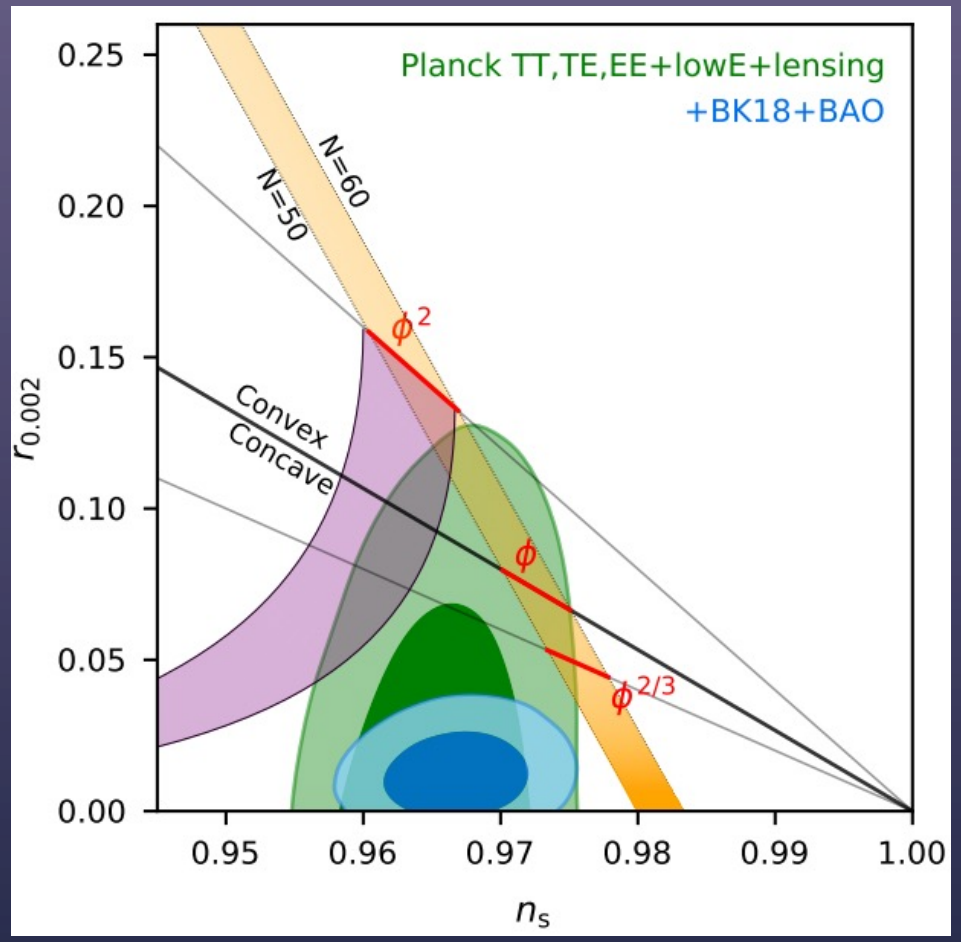

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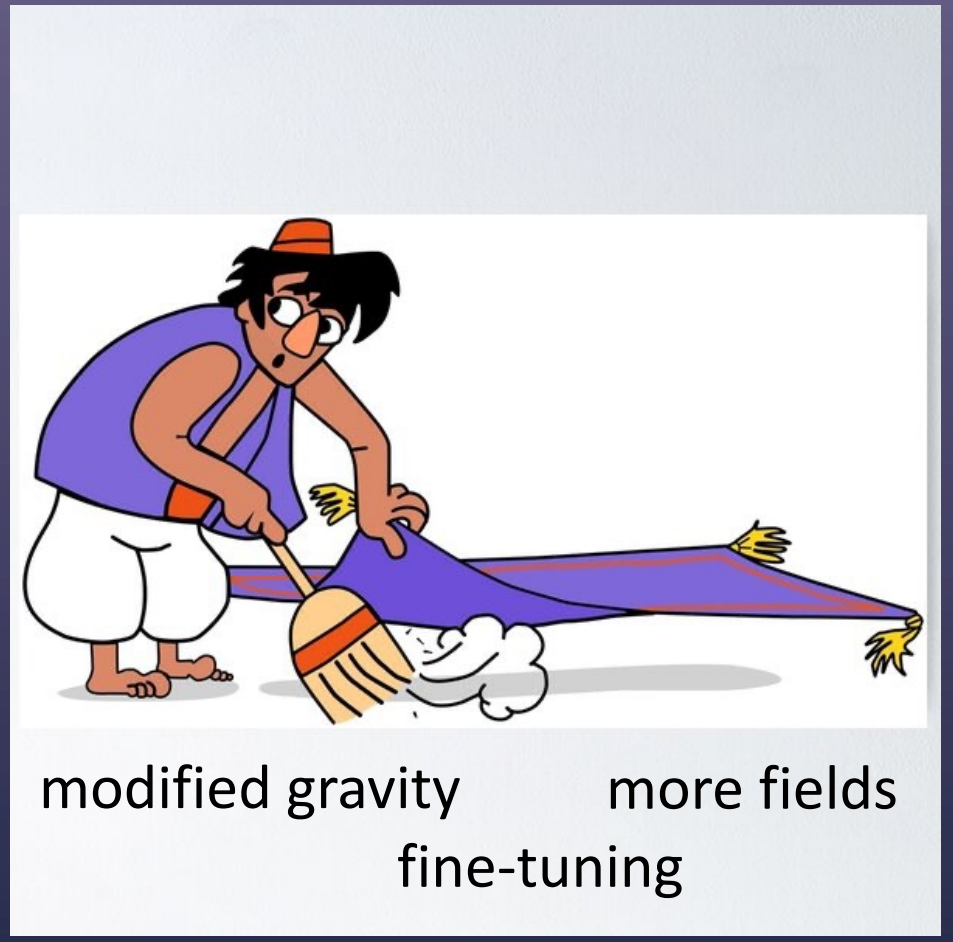
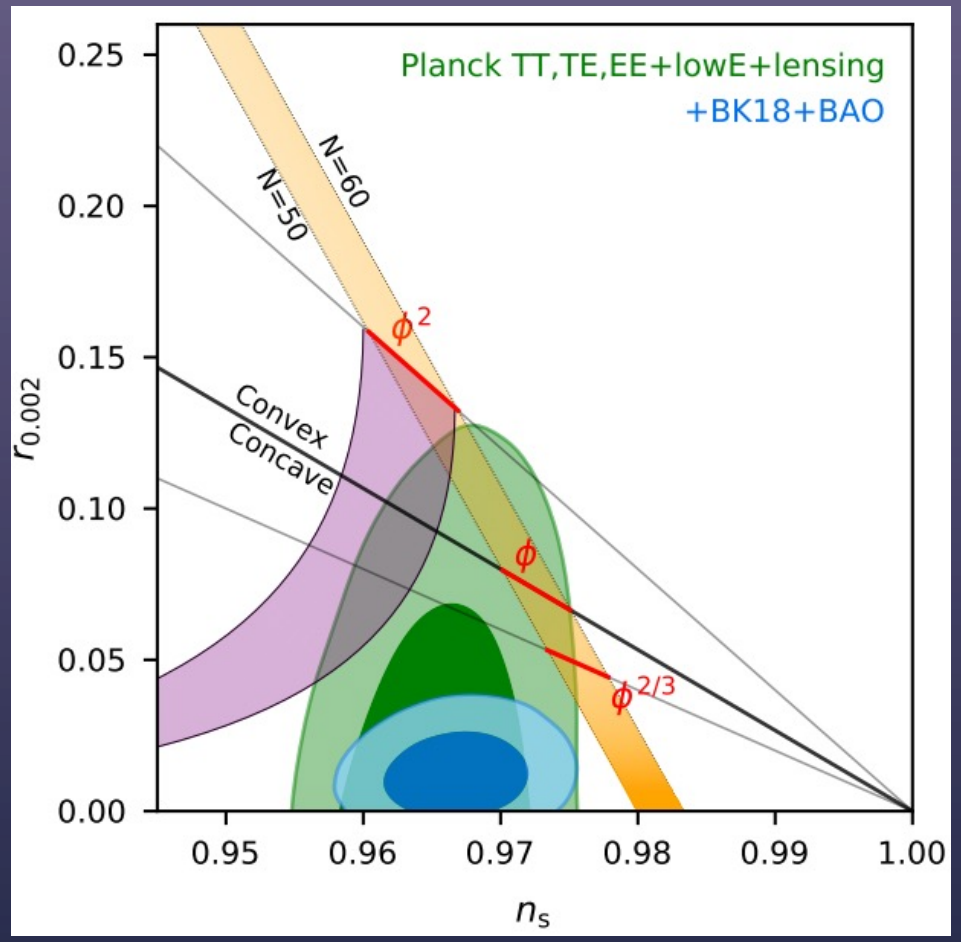


Let’s include interactions

Inflation



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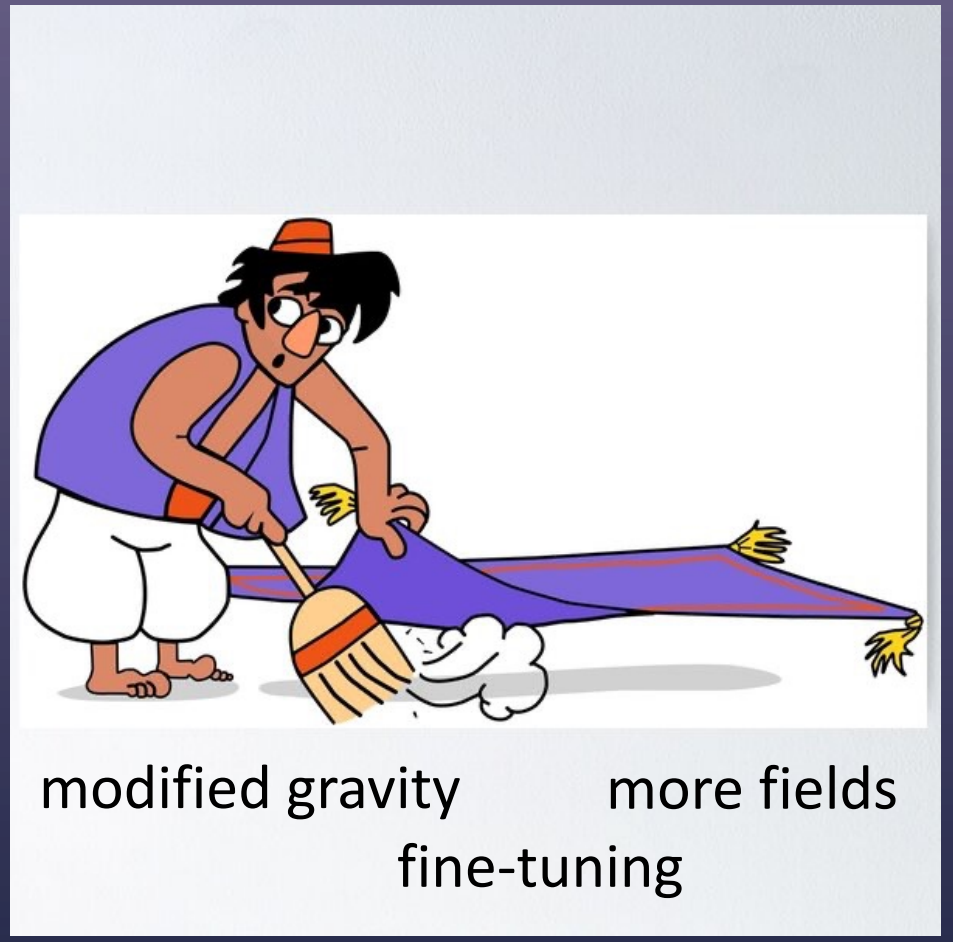


modified gravity more fields

fine-tuning

Let’s include interactions

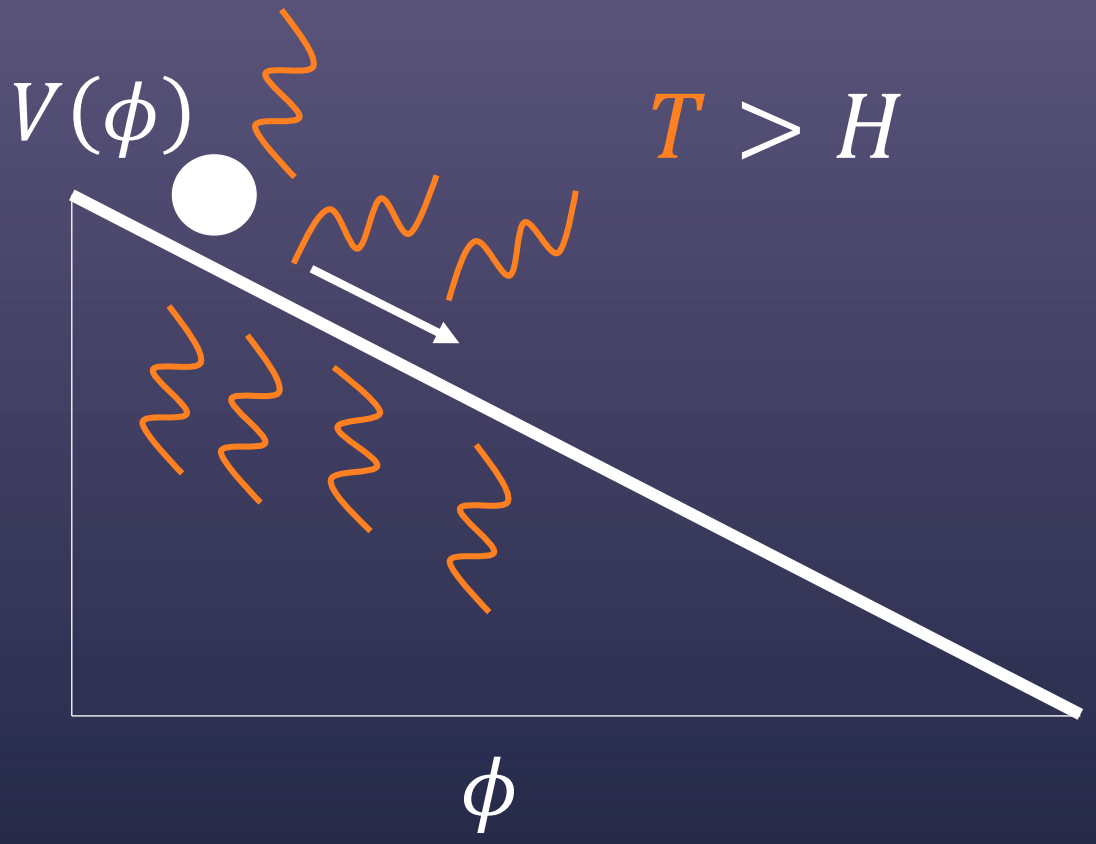
Warm Inflation

Warm Inflation

$$\varepsilon_V = \frac{M_{Pl}^2}{2(1+\Upsilon/3H)}\left(\frac{V'}{V}\right)^2 \ll 1$$

consider particle interactions

$$\ddot{\phi} + 3(H+\Upsilon)\dot{\phi} + V' = 0$$



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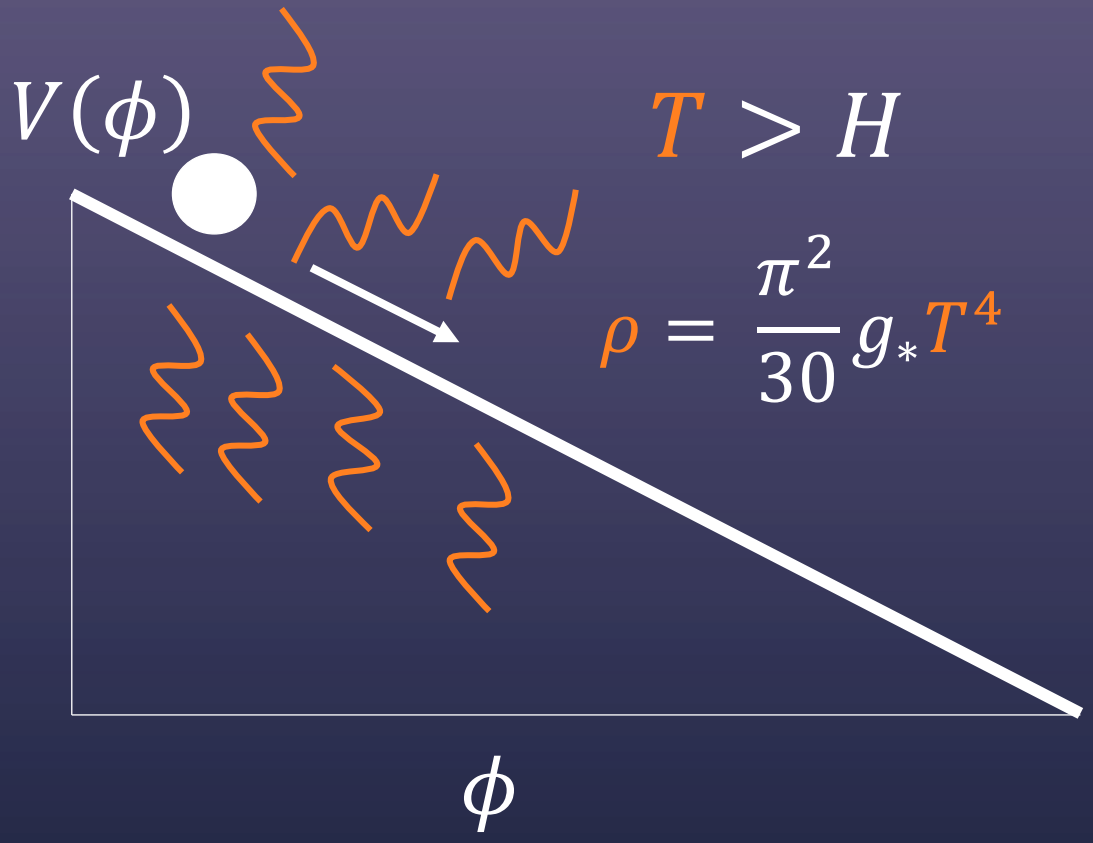

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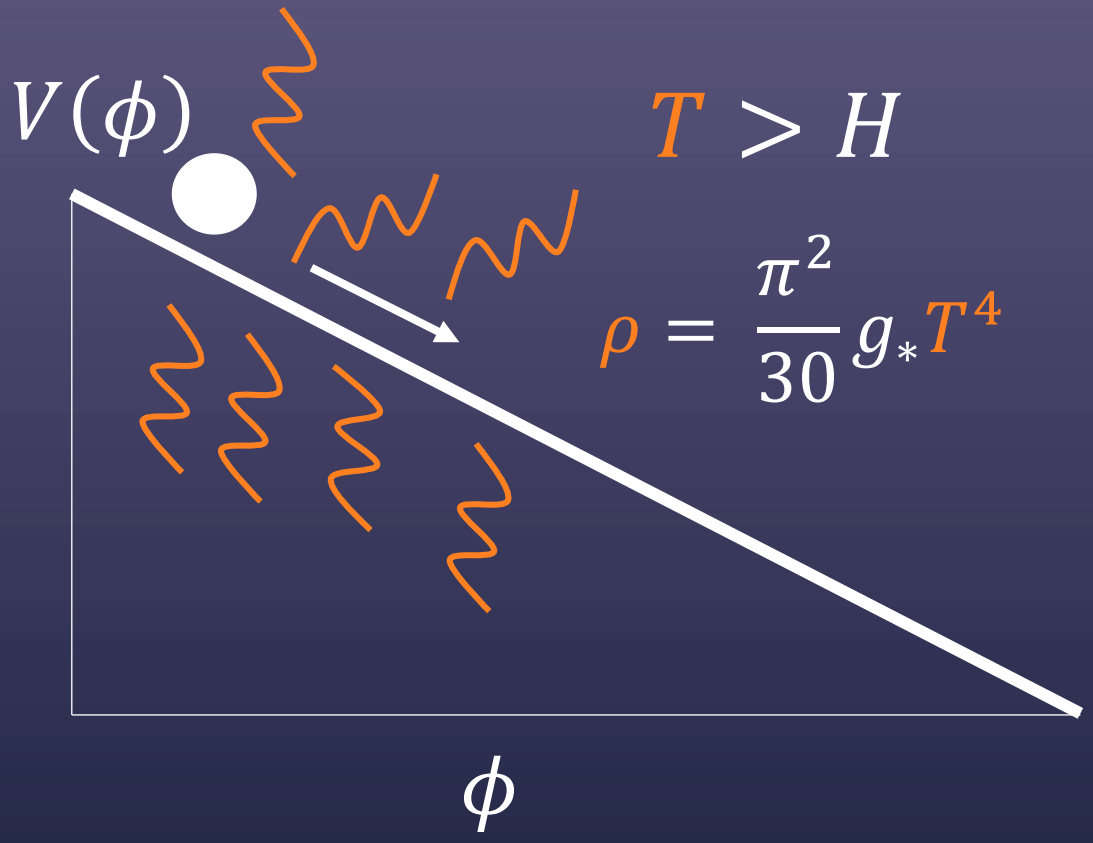

$$T > H$$

$$\rho = \frac{\pi^2}{30} g_* T^4$$

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$$\dot{\rho} + 4H\rho = \Upsilon\dot{\phi}^2$$

sink term $\approx$ source term

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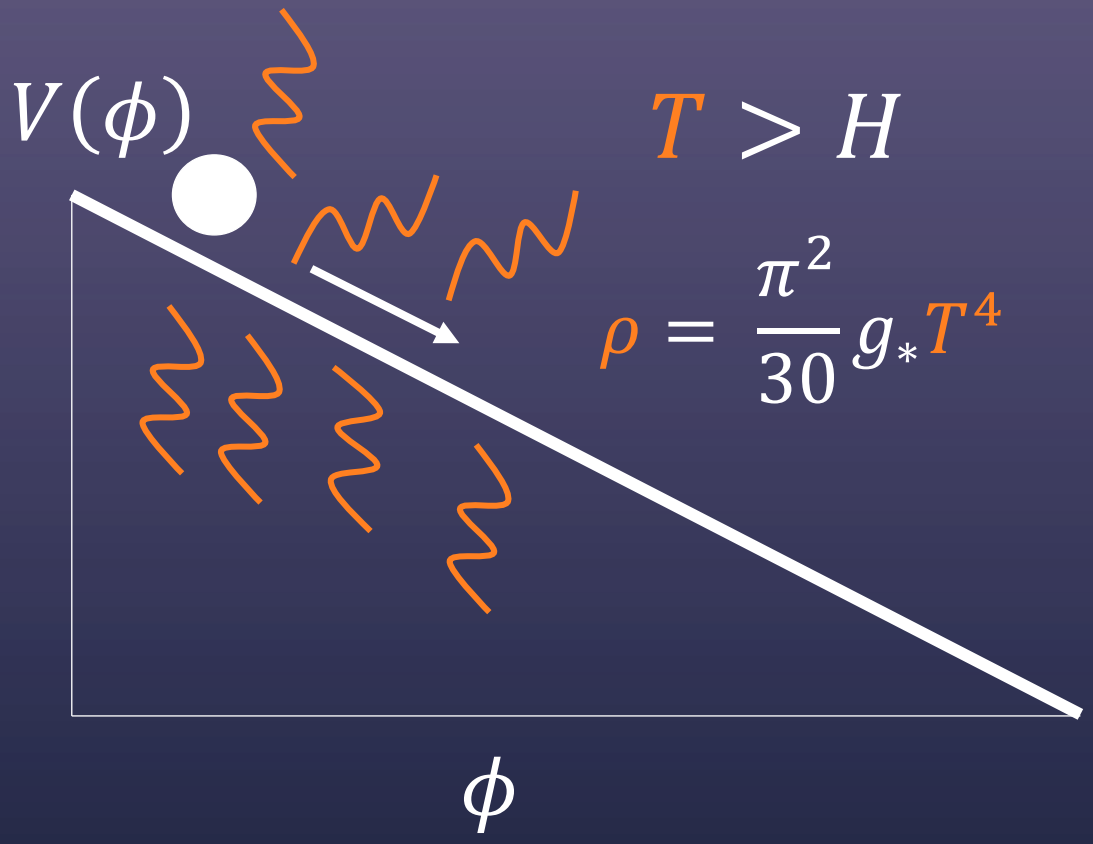

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$\approx$

$$\delta\phi \sim \sqrt{H\,T}$$

classical fluctuations seed structure

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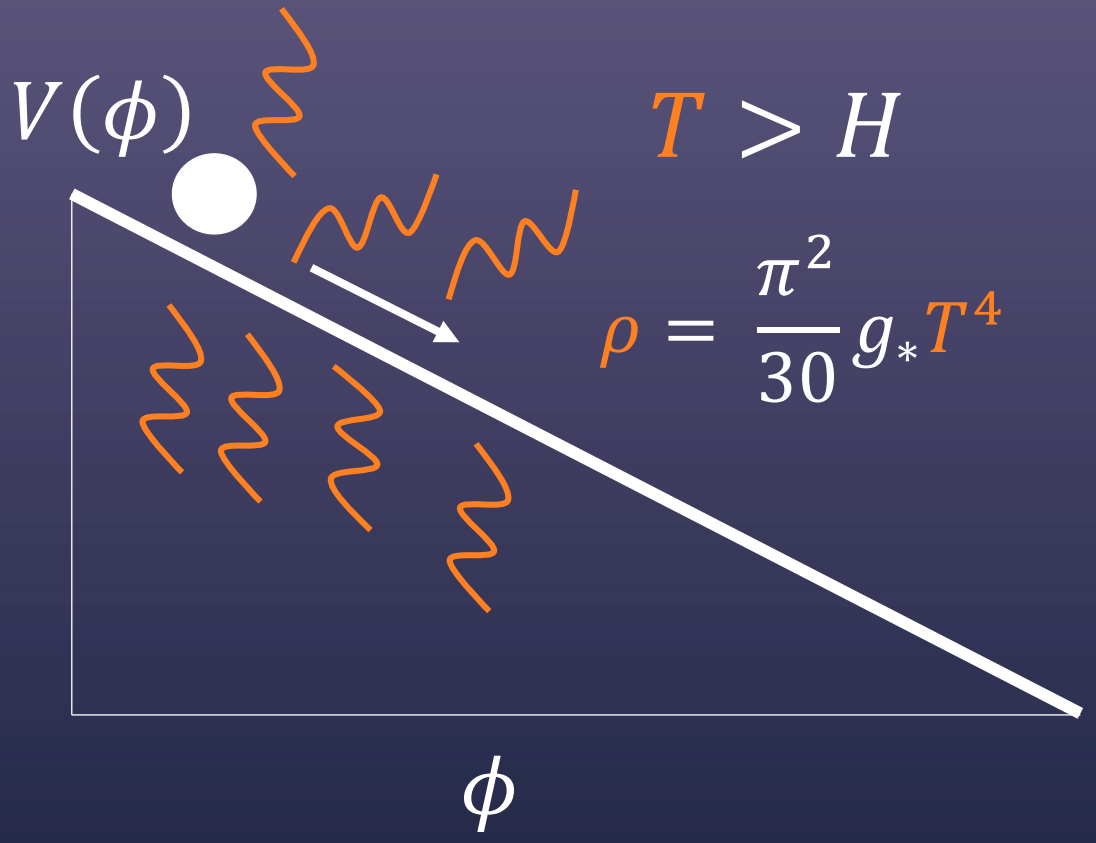

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Warm Inflation from first principles

- couple inflaton to light degrees of freedom $\mathcal{L}_{\rm int} = -\phi\, J_{\rm int}$

$$\ddot{\phi} + 3H\dot{\phi} + V' = -\langle J_{int} \rangle$$

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back-reacts

$$\langle J_{int} \rangle \approx m_{th}^2 \phi + \Upsilon \dot{\phi} + O(\ddot{\phi})$$

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back-reacts

$$\langle J_{int} \rangle \approx m_{th}^2 \phi + \Upsilon \dot{\phi} + O(\ddot{\phi})$$

Usually $m_{th}^2 \phi \gg \Upsilon \dot{\phi}$

Is warm inflation possible?

Minimal Warm Inflation

- couple inflaton to light degrees of freedom $\mathcal{L}_{\rm int} = -\phi \frac{\alpha}{16\pi f} \tilde{G} G$

$$\ddot{\phi} + 3H\dot{\phi} + V' = -\left\langle \frac{\alpha}{16\pi f} \tilde{G} G \right\rangle$$

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not allowed
by symmetry

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enhanced by sphalerons

$$\left\langle \frac{\alpha}{16\pi f} \tilde{G} G \right\rangle \approx \cancel{m_{th}^2 \phi} + \Upsilon \dot{\phi} + O(\ddot{\phi})$$

not allowed
by symmetry

Sphalerons

July 17, 1984

The Editor
Physical Review D
1 Research Road
Box 1000
Ridge, NY 11961

Dear Sir:

Please find enclosed our manuscript "A Saddle-Point Solution in the Weinberg-Salam Theory", which we have revised in response to some of the referee's criticisms. In particular, we have substantially rewritten the Introduction, and added few sentences at the end of Sec. III, in order to clarify that our solution is a saddle-point.

We have continued to use the word "sphaleron" in our paper, for which we think there is a real need. It describes a static unstable solution, localized in space, in any field theory, and not just the solution in the Weinberg-Salam theory which we discuss in this paper. Such solutions are very common in a variety of field theories, and they usually reflect the topological complexity of the theory. We think "sphaleron" is quite a nice word, and we spent some time seriously looking for alternatives, but were less happy with those. Sphaleron has the same root (sphaleros) as sphalerite, which is the name of a fairly common mineral. We noted that the referee had to refer to "this thing" when he didn't use the work sphaleron, which indicates that there is no obvious alternative word.

We would have liked to be more specific about the physical significance of our solution, as the referee requested, but this is a subject of ongoing research by us, and we have nothing more to say in the present paper.

We hope that the paper can be published in its present form.

Yours sincerely,

Frans Klinkhamer

Nicholas Manton

Sphalerons

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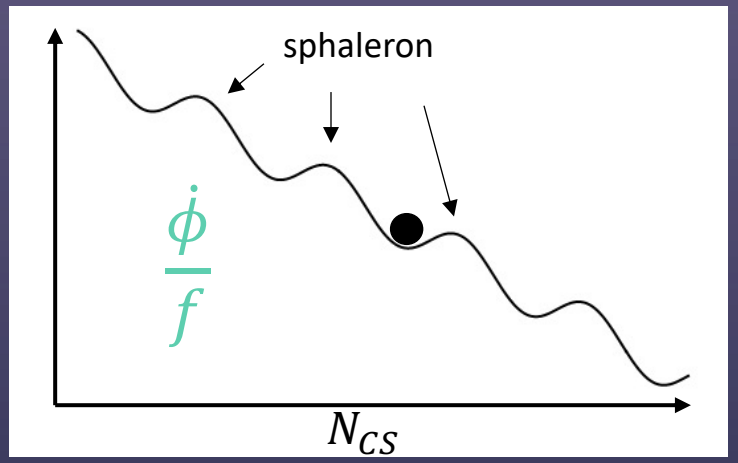
Frans Klinkhamer

Nicholas Manton

Sphaleron friction

$$\mathcal{L}_{\rm int} = -\phi \frac{\alpha}{8\pi f} \tilde{G} G \approx \dot{\phi}/f \, N_{CS}$$

Inflaton acts as "chemical potential" for N_{CS}



Not drawn to scale

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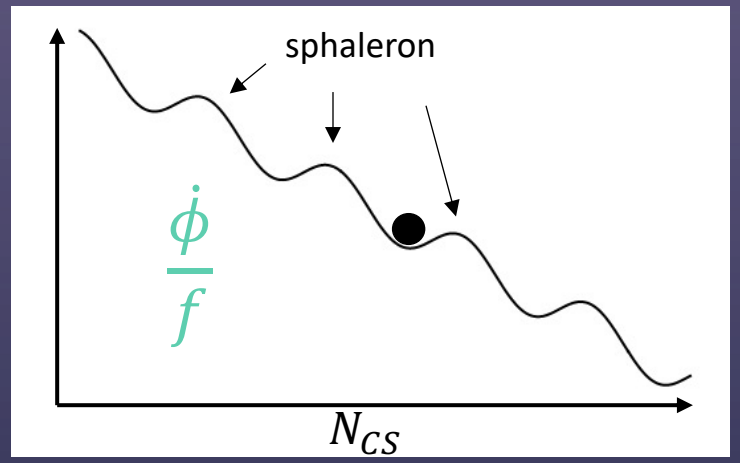

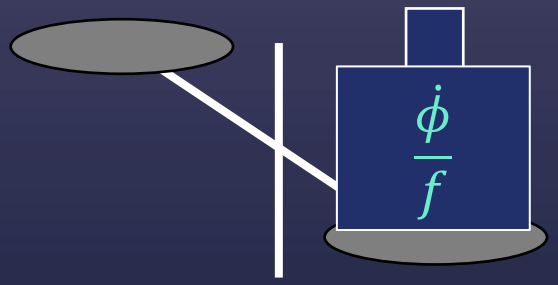

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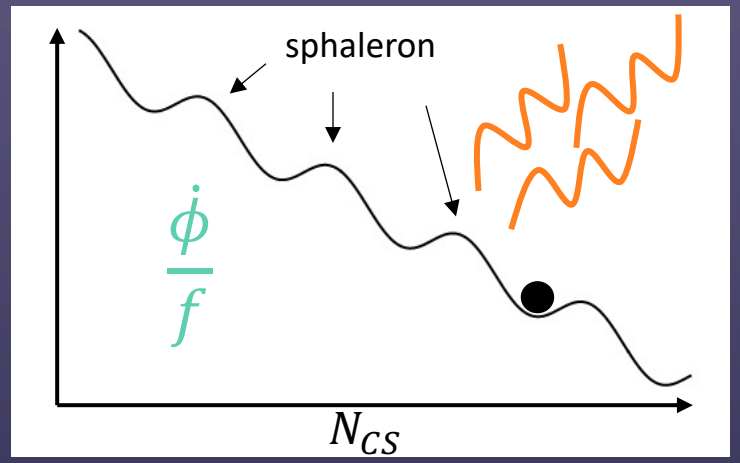
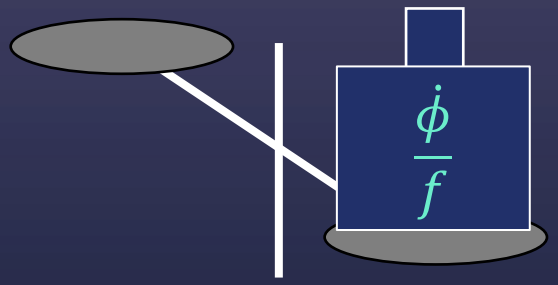




Inflaton acts as "chemical potential" for N_{CS}

induces CS-friction

$$\Upsilon \approx N_c^5 \alpha^5 \frac{T^3}{f^2}$$

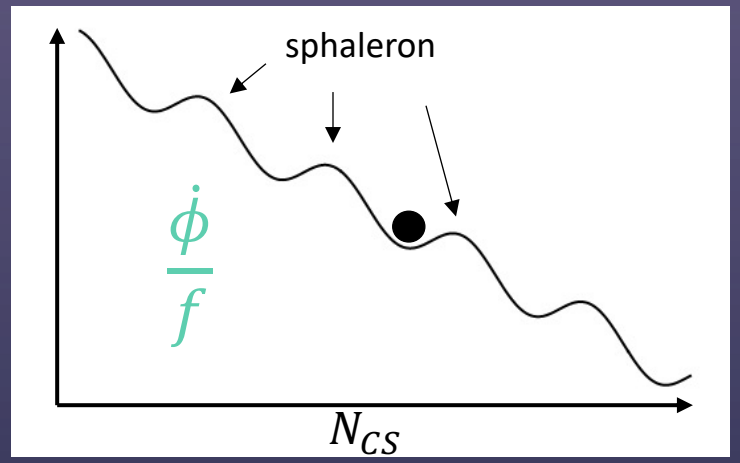
$$\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + V' = 0$$

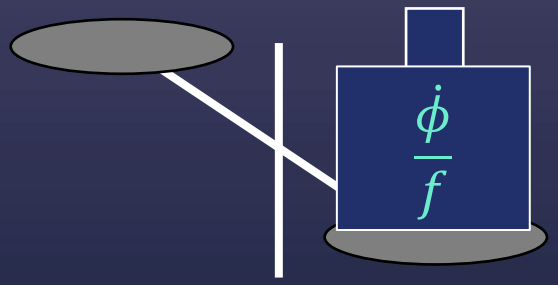
$$\rho + 4H\rho = \Upsilon \dot{\phi}^2$$

Sphaleron friction with the SM

$$\mathcal{L}_{\rm int} = -\phi \frac{\alpha}{8\pi f} \tilde{G} G \approx \dot{\phi}/f \, N_{CS}$$

QCD $\sim g, q$





Inflaton acts as "chemical potential" for N_{CS}

Transitions violate chiral quark charge

Induces an opposite chemical potential to inflaton

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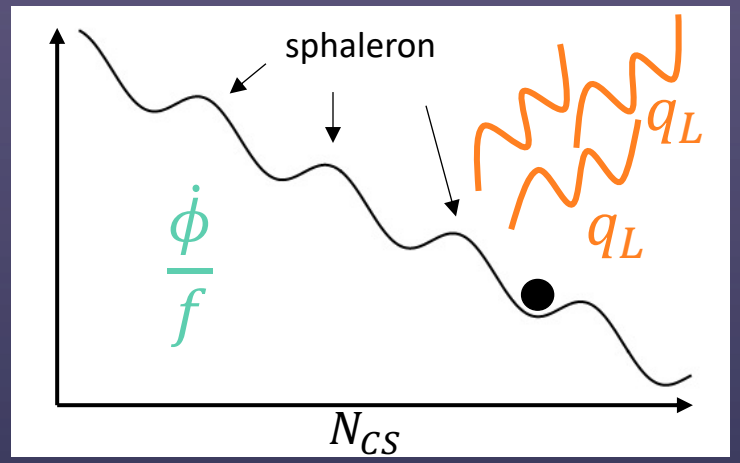

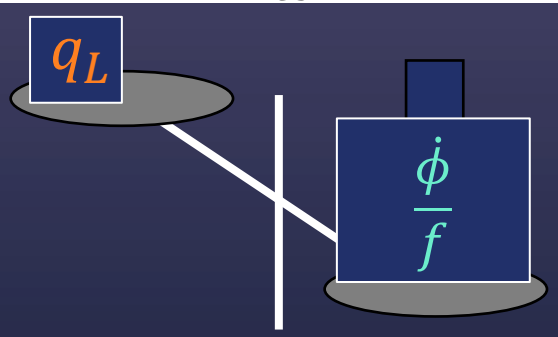

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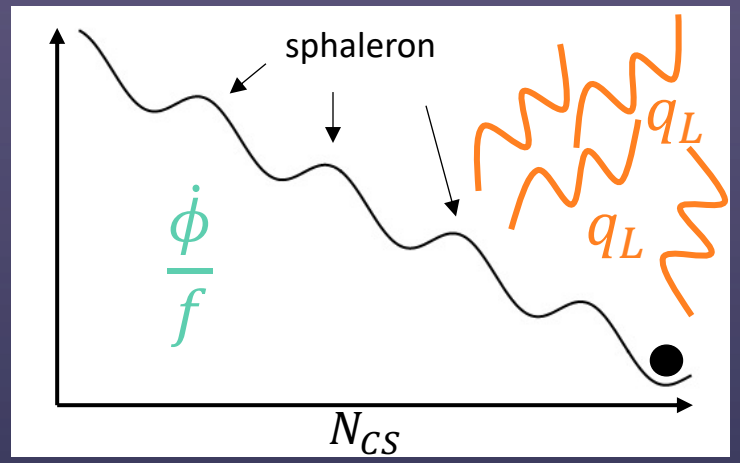

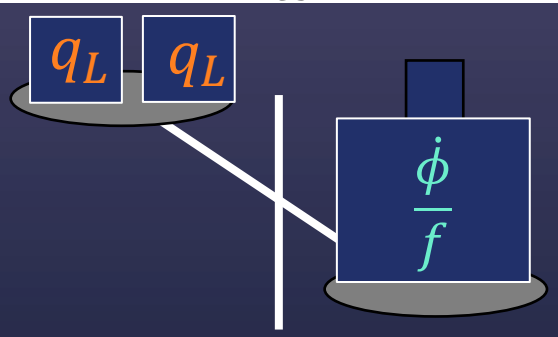

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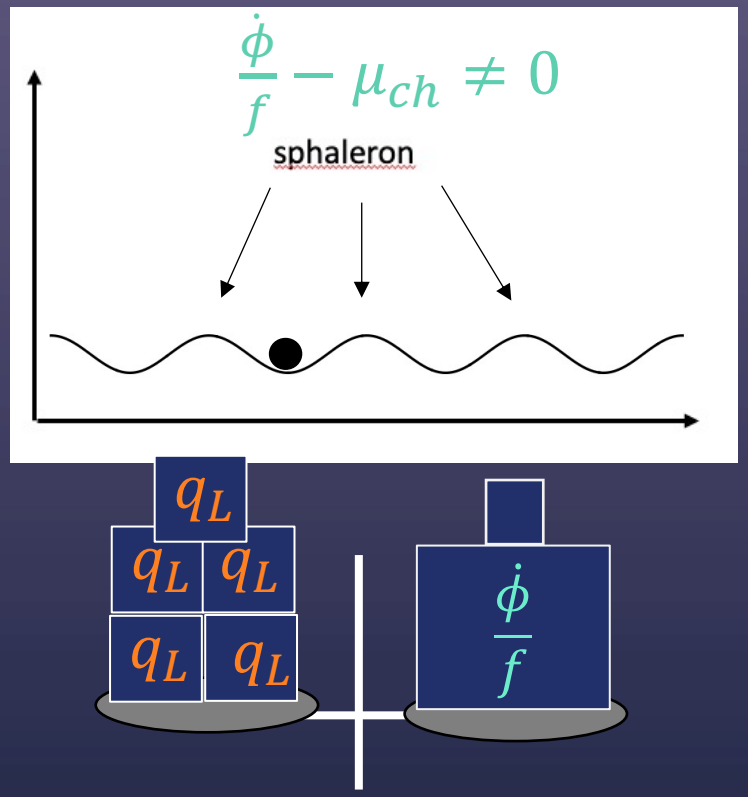

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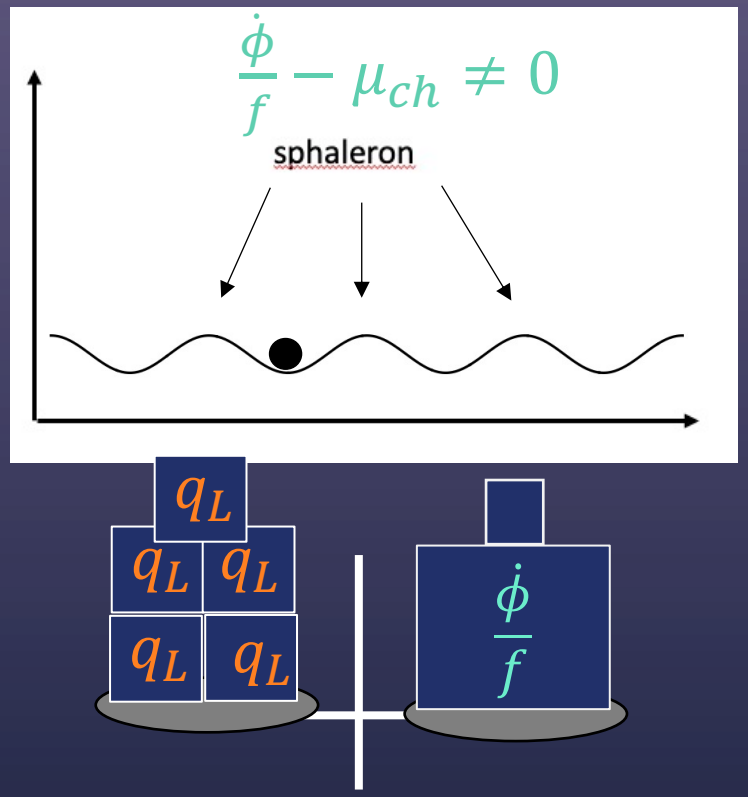

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Berghaus, Drewes, Zell, 2025

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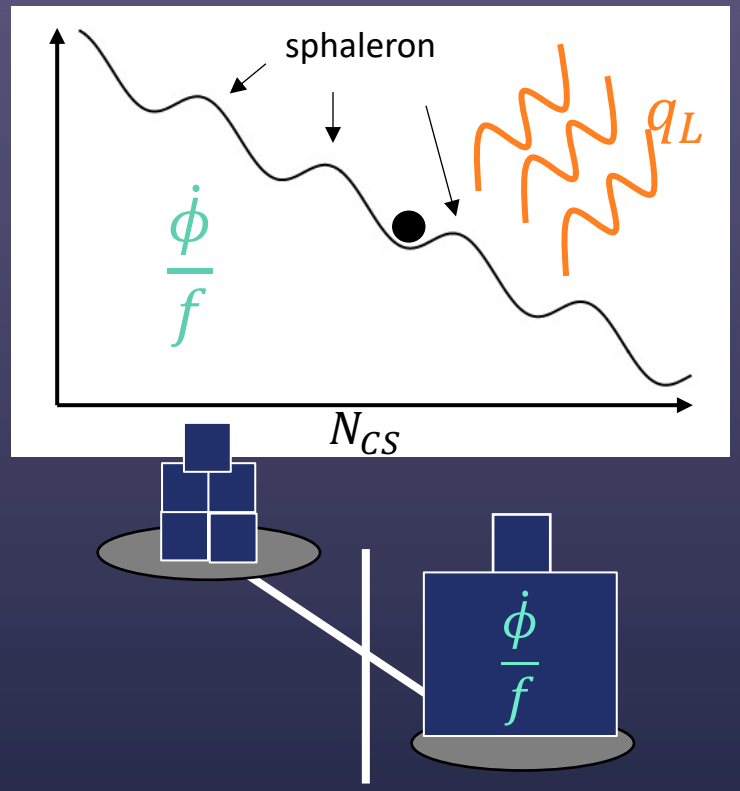

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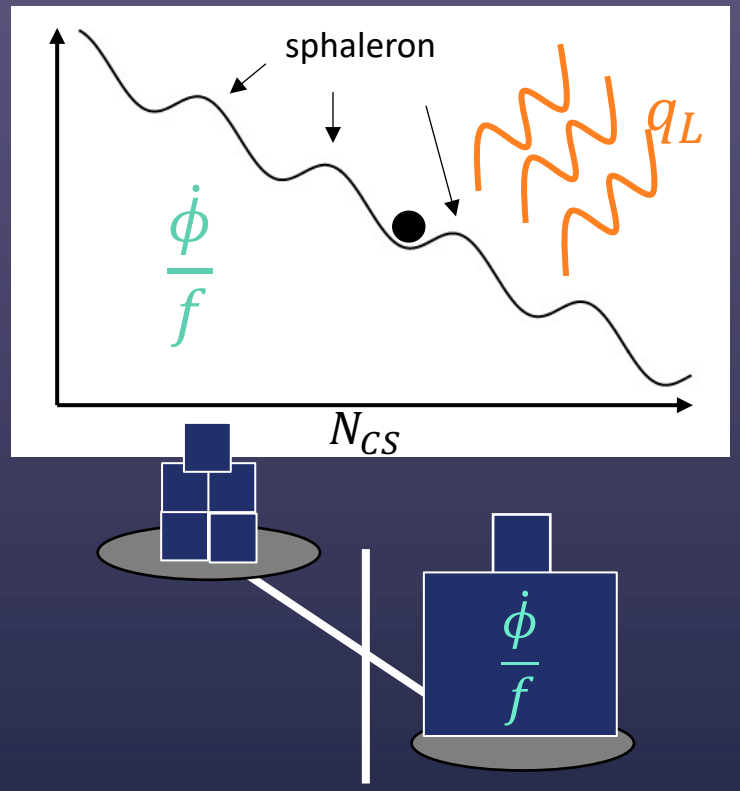

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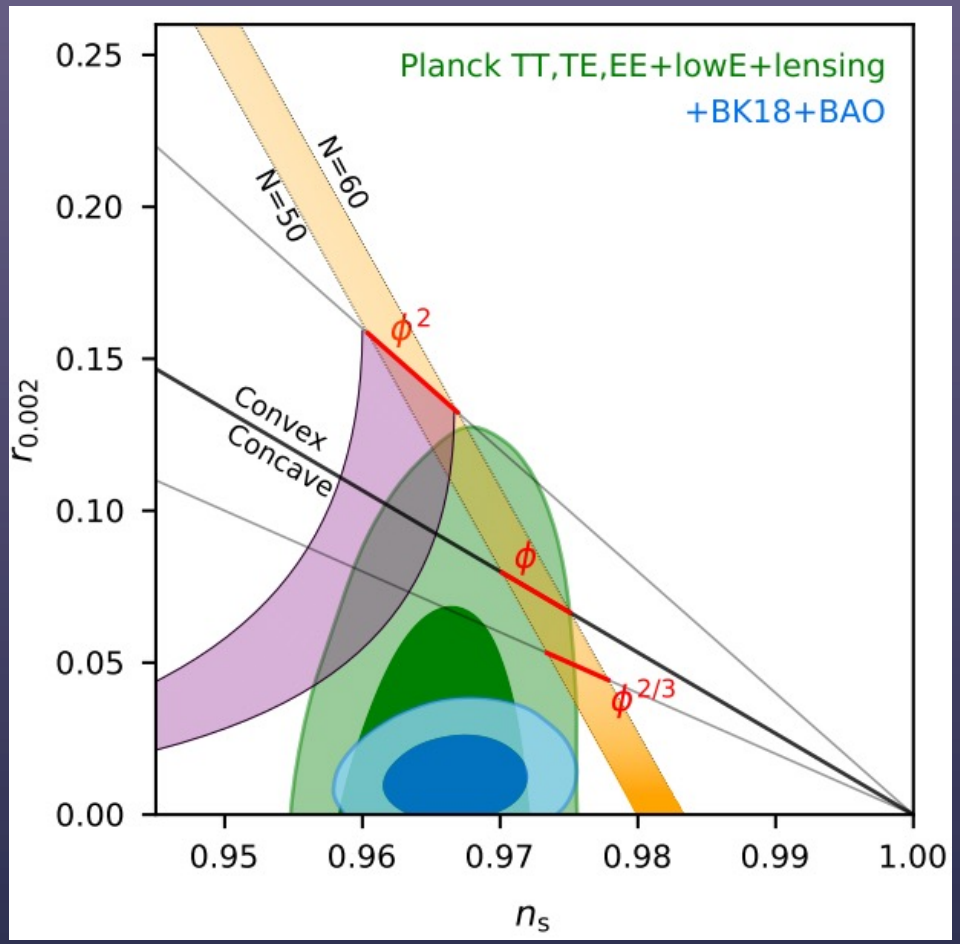
Berghaus, Drewes, Zell, 2025

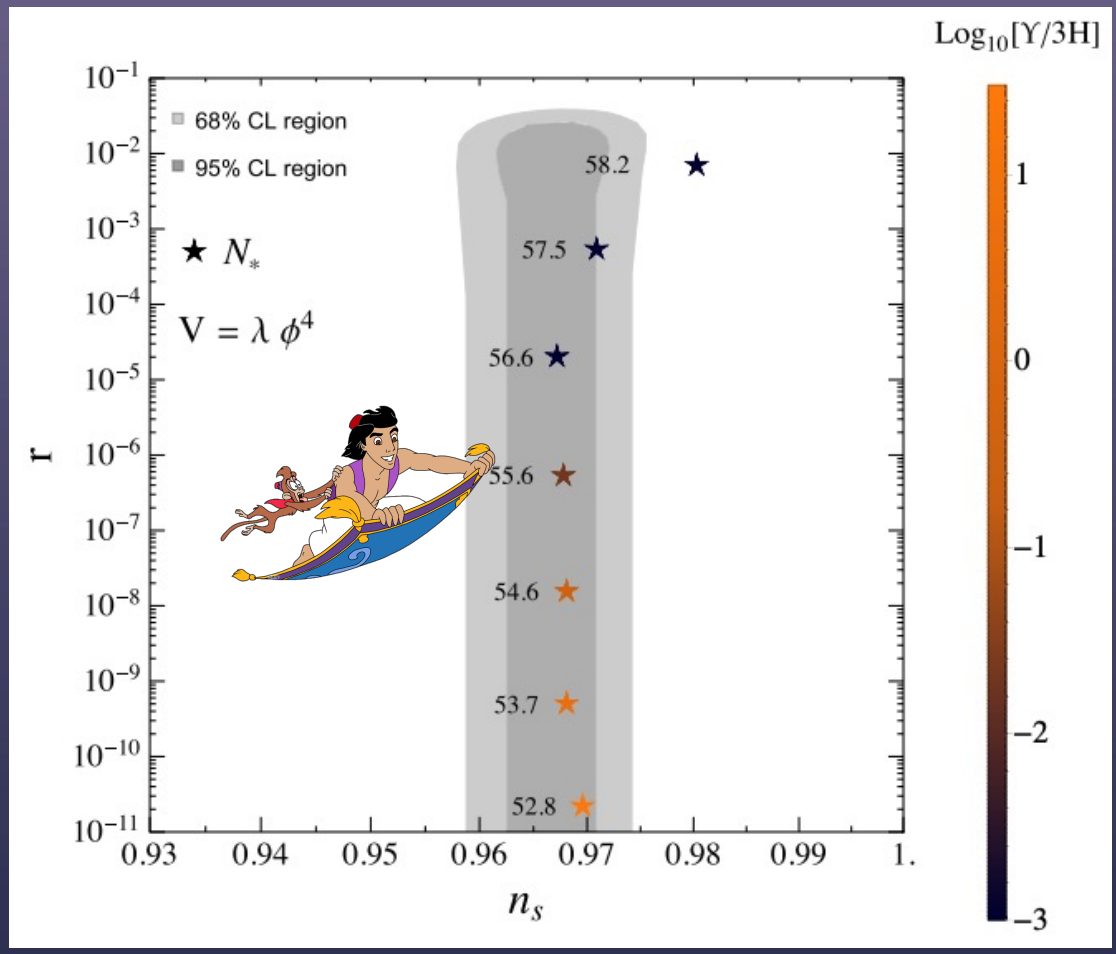
$$\Upsilon_{eff} = \Upsilon / \left(1 + \frac{N_f}{N_c} \frac{12 f^2}{T^2} \frac{\Upsilon}{3H}\right)$$

Berghaus, Drewes, Zell, 2025

Warm Inflation with the Standard Model



Bicep/Keck XIII, 2021



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$$V = \lambda\phi^4$$

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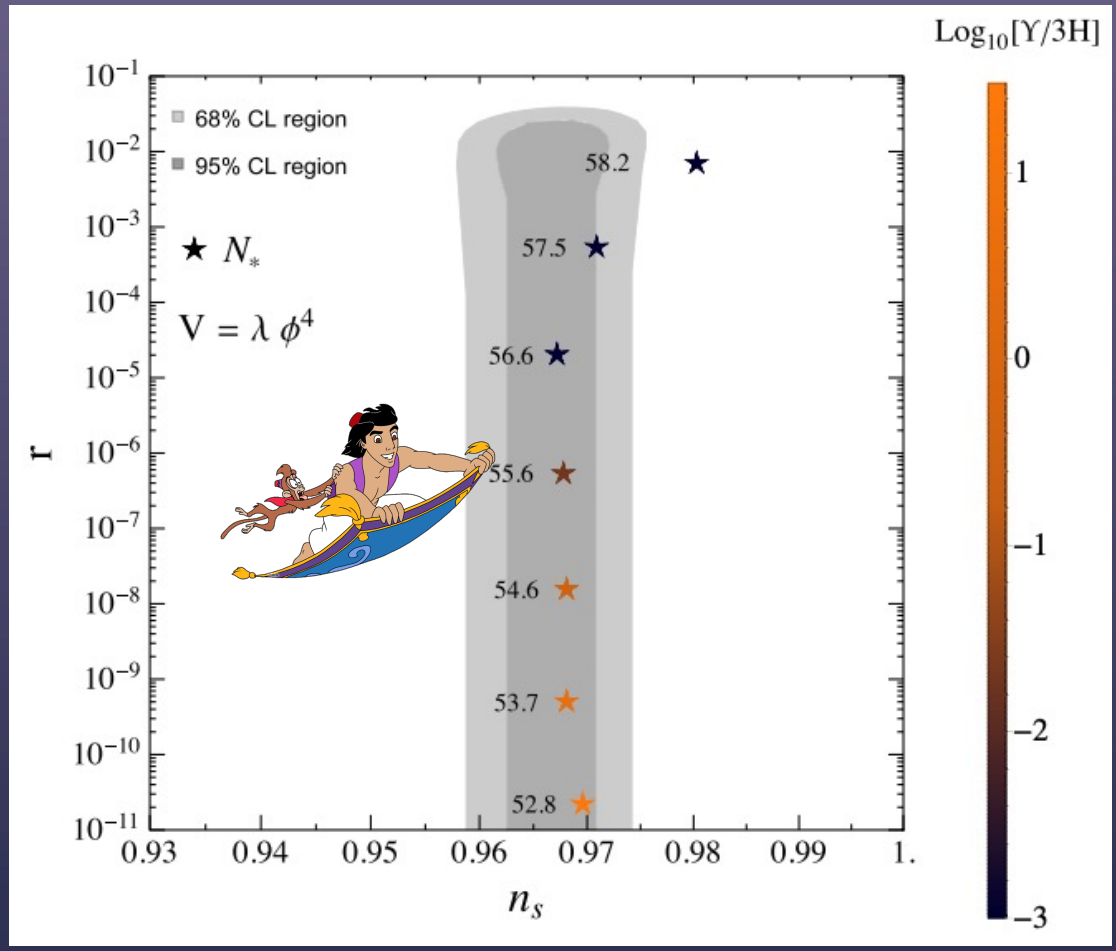

Berghaus, Drewes, Zell, 2025

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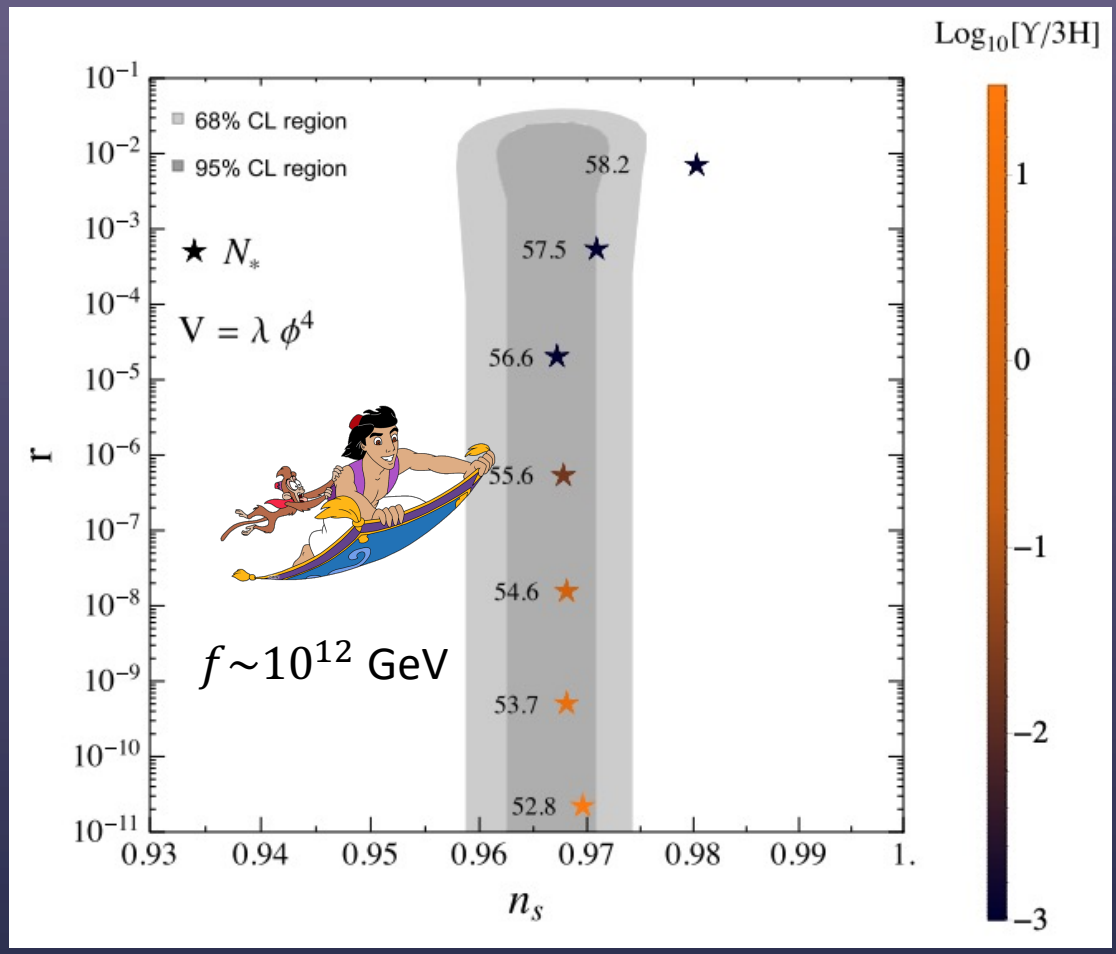

Berghaus, Drewes, Zell, 2025

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Predicts direct transition into quark gluon plasma filled universe

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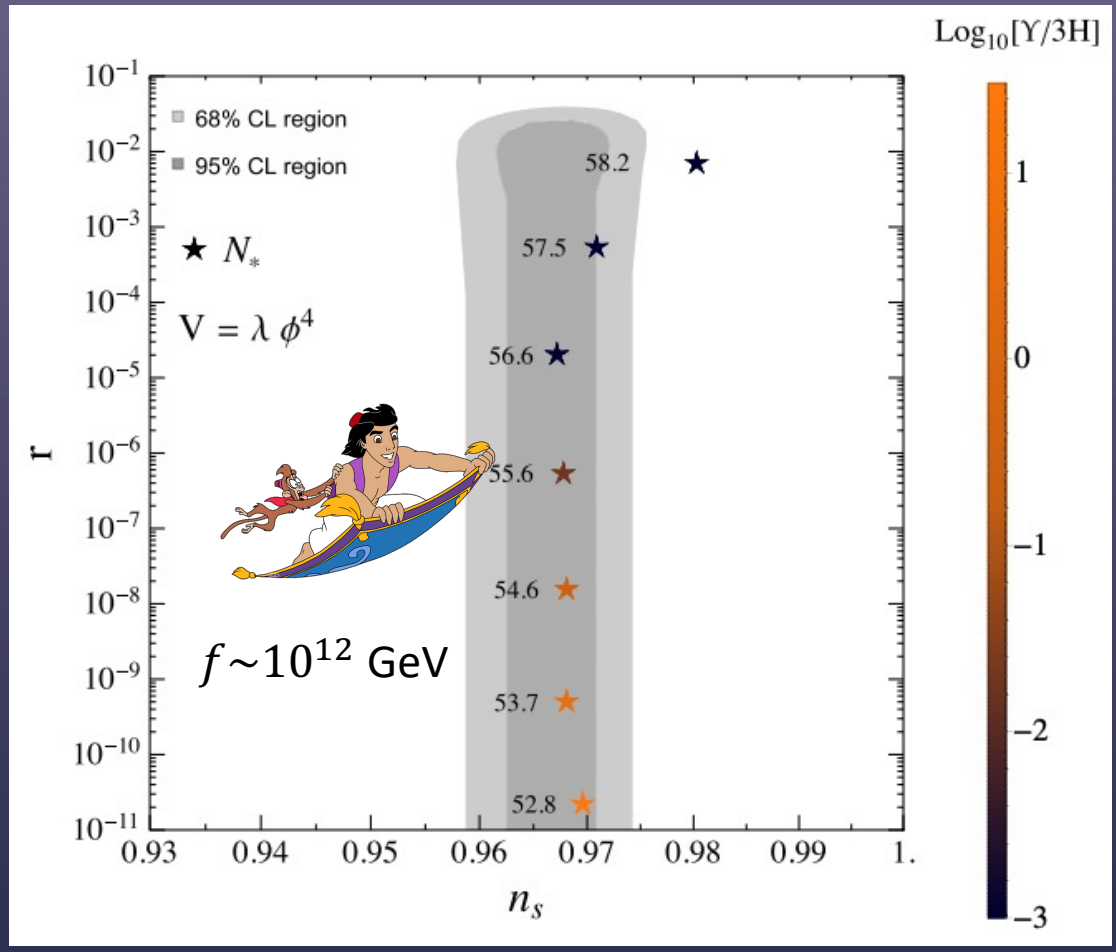

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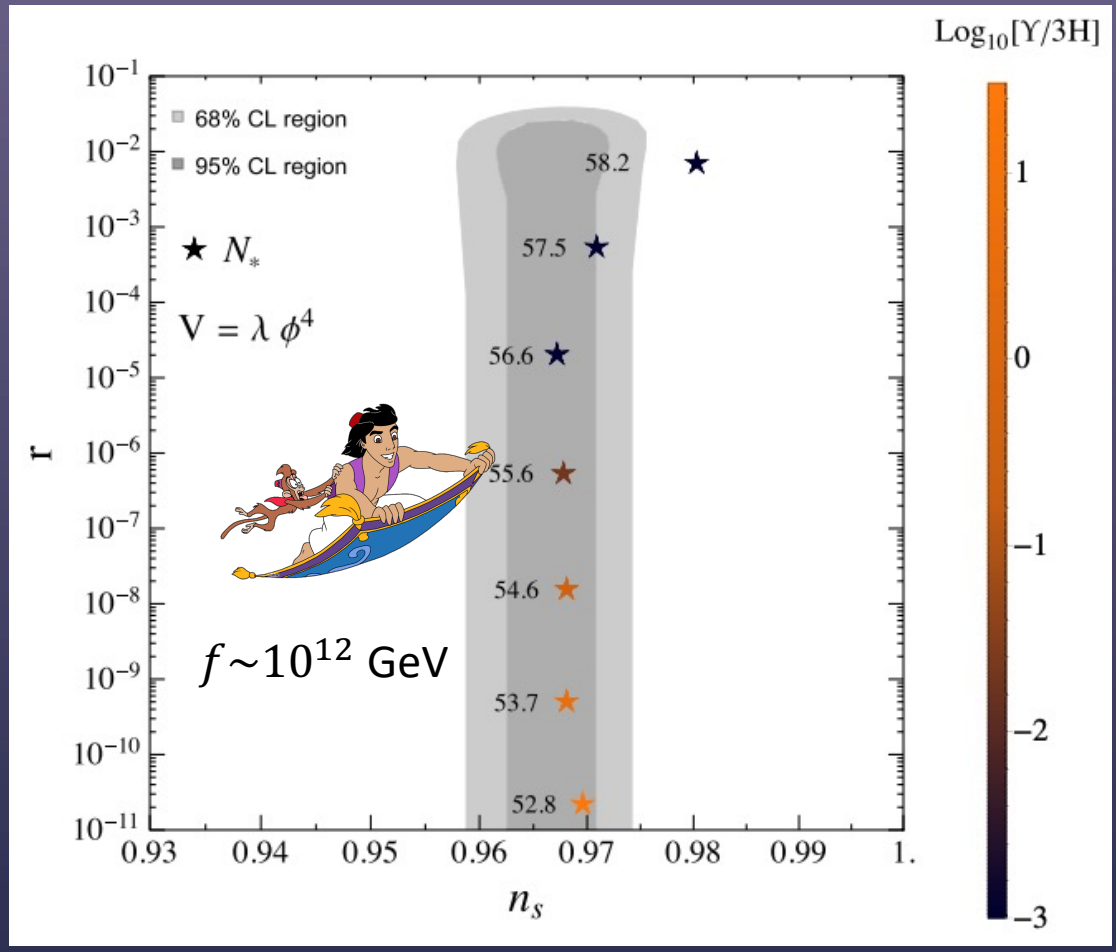
Can explain no inflationary gravitational waves for simple quartic potential

accessible by axion probes



Berghaus, Drewes, Zell, 2025

Warm Inflation with the Standard Model

$$V = \lambda\phi^4$$

$$\mathcal{L}_{\rm int} = -\phi\frac{\alpha_s}{8\pi f}\tilde{G}G$$

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Predicts direct transition into quark gluon plasma filled universe

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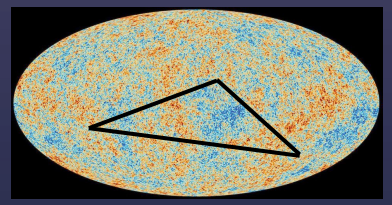
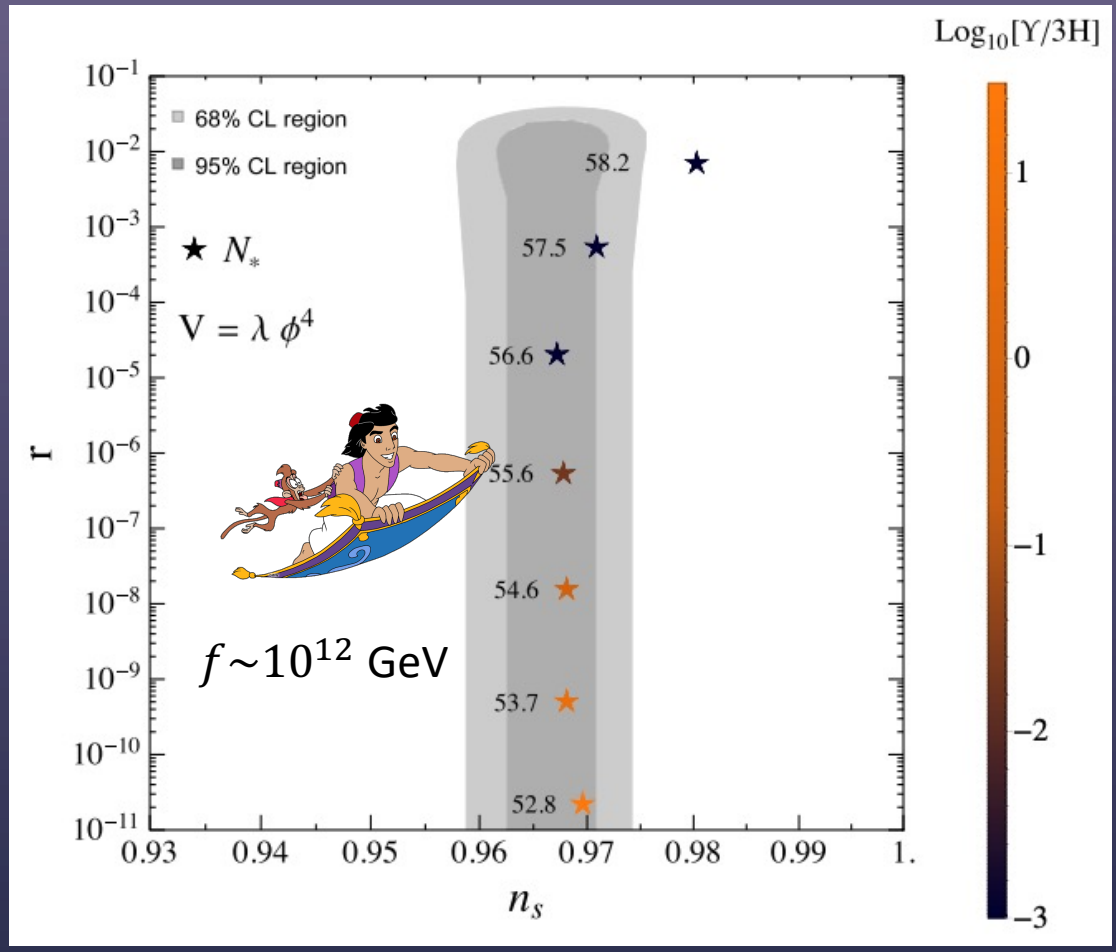
Smoking gun signature in non-gaussianity imprints





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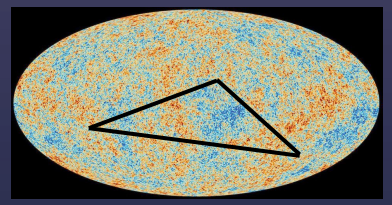

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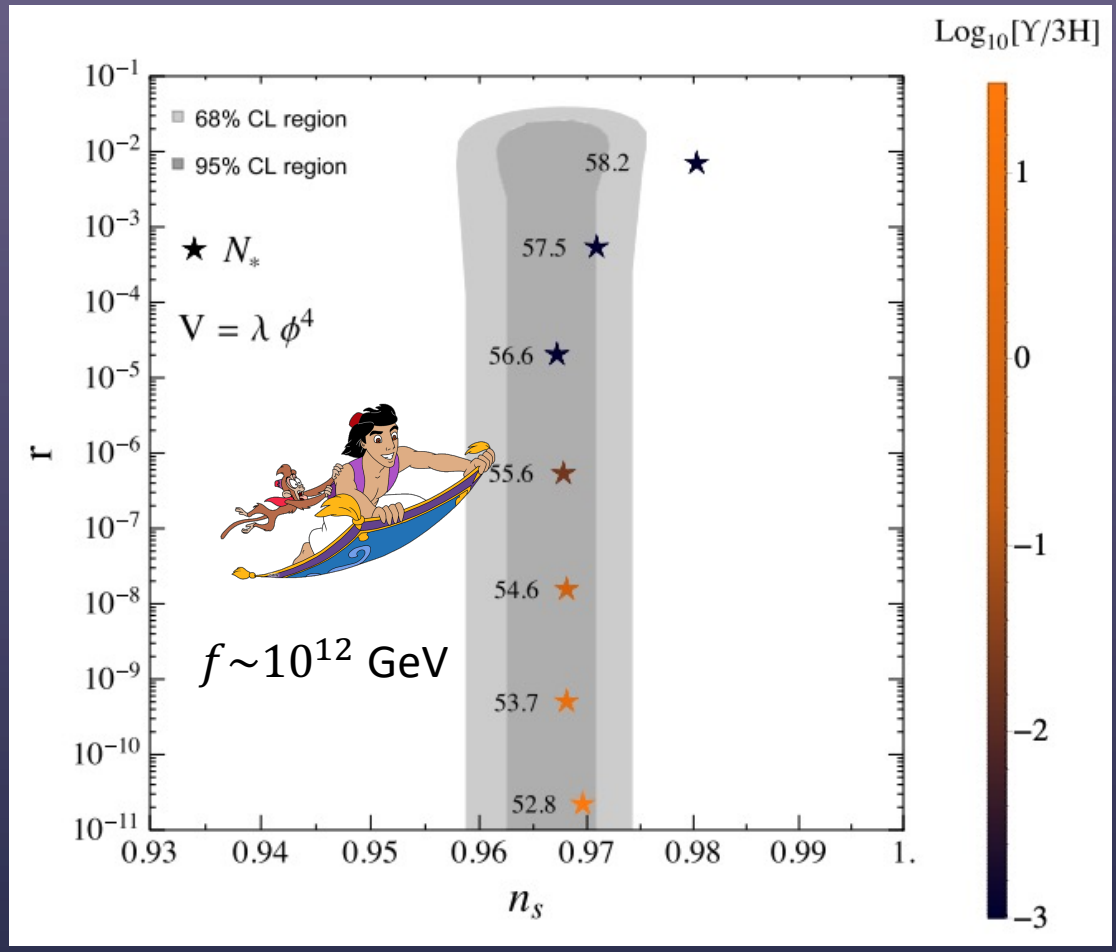

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What are the laws of nature

heating the early Universe

the strong CP problem

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Thank you!