Inflation

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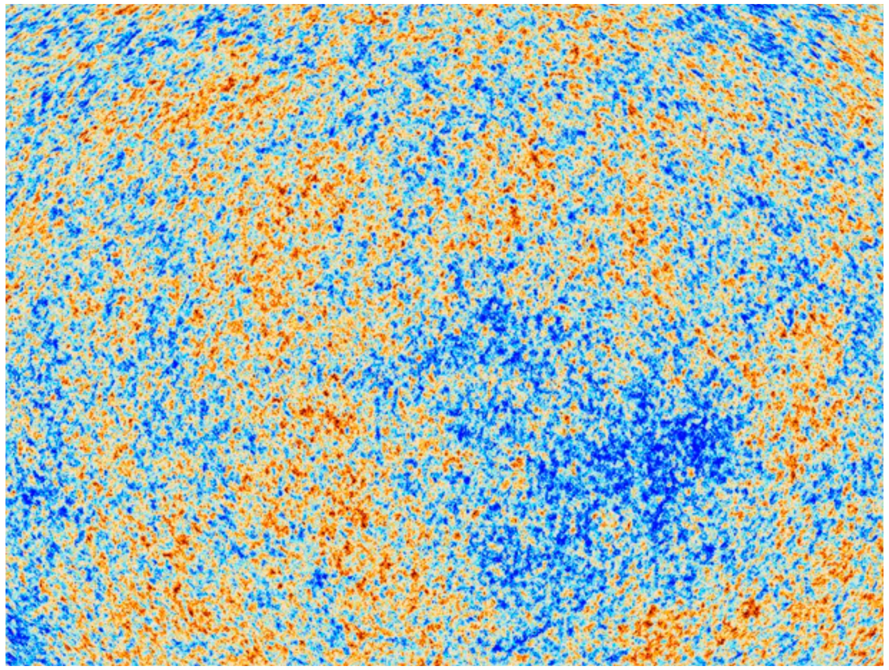
Florence, Sept 2017

Cosmological structures formed by the gravitational collapse of primordial density perturbations.



gravity

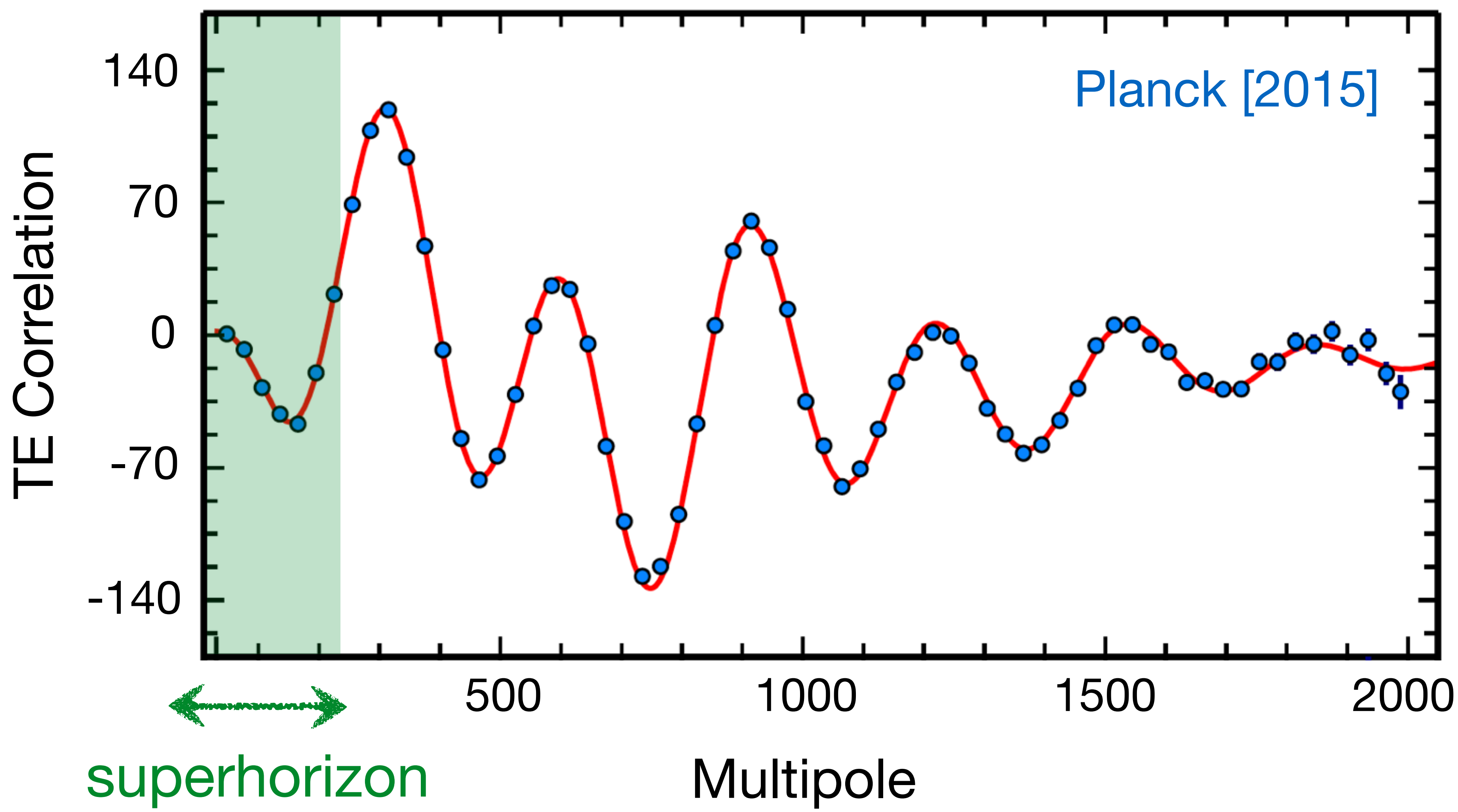
380,000 yrs

13.8 billion yrs

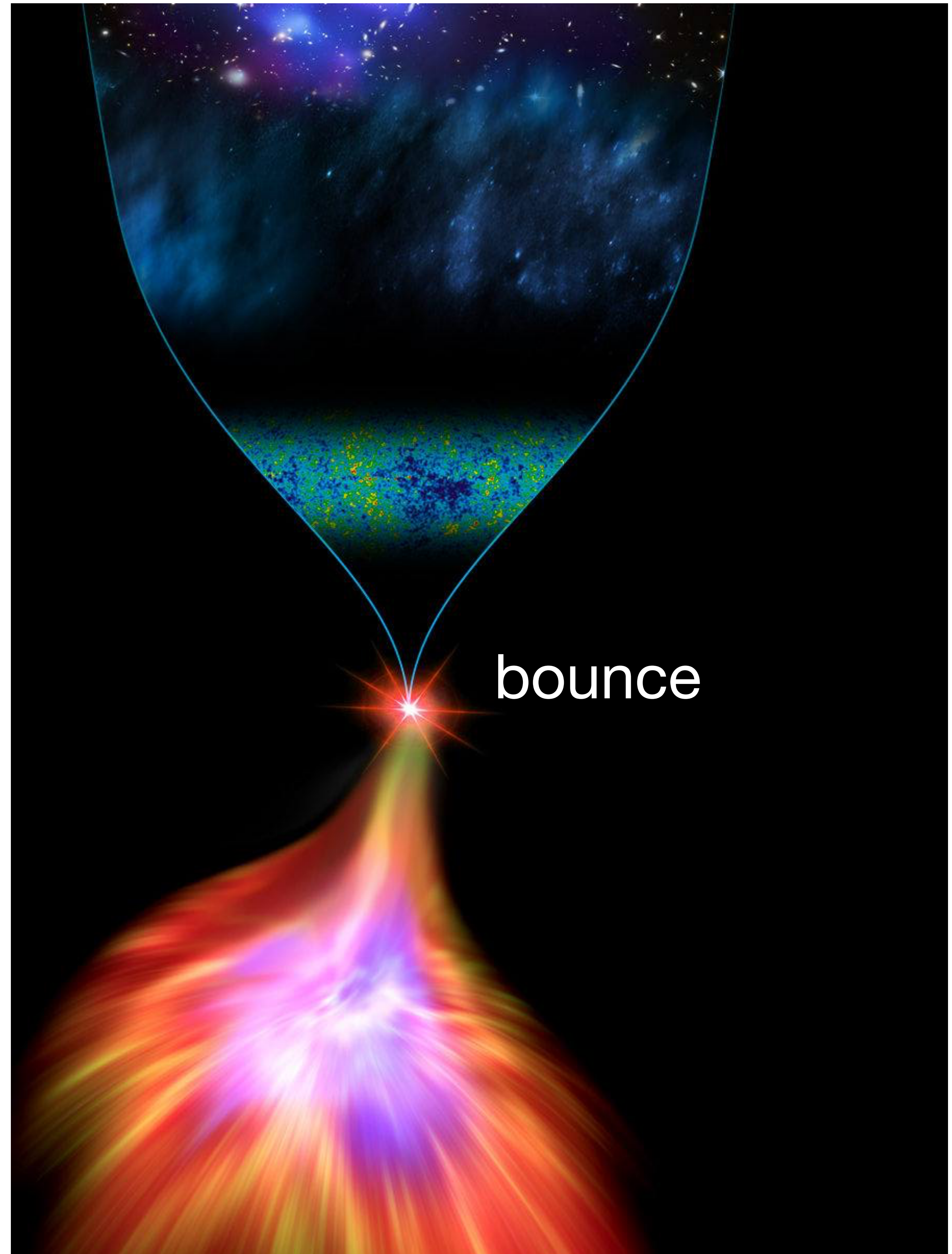
What generated the initial fluctuations?

A Remarkable Fact

The fluctuations were created **before the hot Big Bang**:

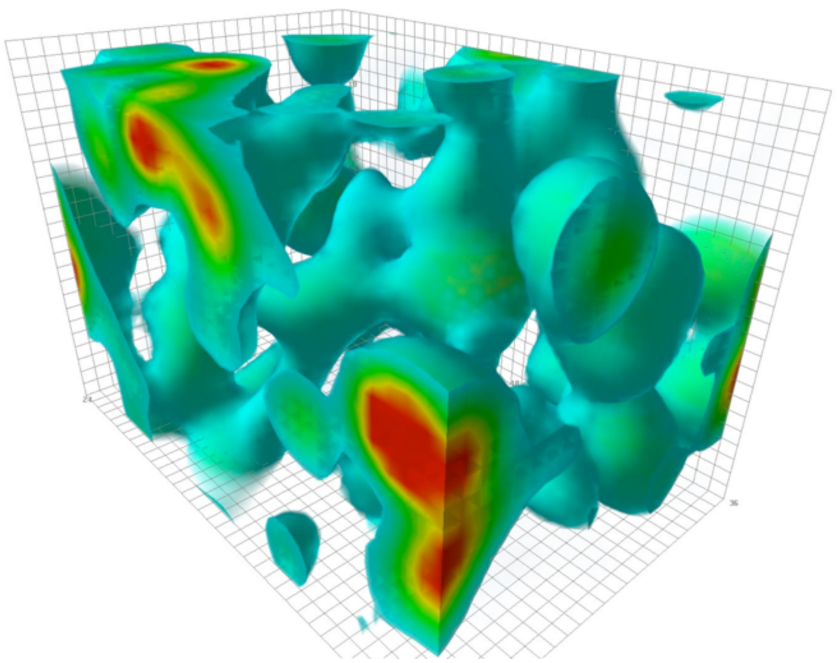


Rapid Expansion or Slow Contraction?



Quantum Fluctuations during Inflation

Any massless field experiences quantum fluctuations during inflation:



Inflation stretches these to macroscopic scales.

Two massless fields are guaranteed to exist during inflation:

$$\mathrm{d}\ell^2 = e^{2Ht}\left[(1+\zeta)\delta_{ij} + h_{ij}\right]\mathrm{d}x^i \mathrm{d}x^j$$

expansion — $H(t) \approx const$

scalar — *isotropic stretching*

tensor — *anisotropic stretching*

Primordial Spectra

recombination

hot big bang

inflation predicts

$$\langle \zeta^2 \rangle = \frac{1}{8\pi^2} \frac{H^4}{M_{\rm pl}^2 |\dot{H}|}$$

$$\langle h_{ij}^2 \rangle = \frac{2}{\pi^2} \frac{H^2}{M_{\rm pl}^2}$$

↑

observed
- adiabatic
- Gaussian
- superhorizon
- scale-invariant

↑

required to show that

$$|\dot{H}| \ll H^2$$

Open Questions

- Did inflation really occur?

"Extraordinary claims require extraordinary evidence."

- What was the physical mechanism of inflation?
- What is the energy scale of inflation?
- How did inflation begin?
- How did it end? How did the universe reheat?
- Was the origin of perturbations quantum or classical?
- …

Opportunity to learn deep facts about the early universe from future observations.

In this talk, I will review the ***theoretical foundations*** *of inflation and discuss future* ***observational tests****.*

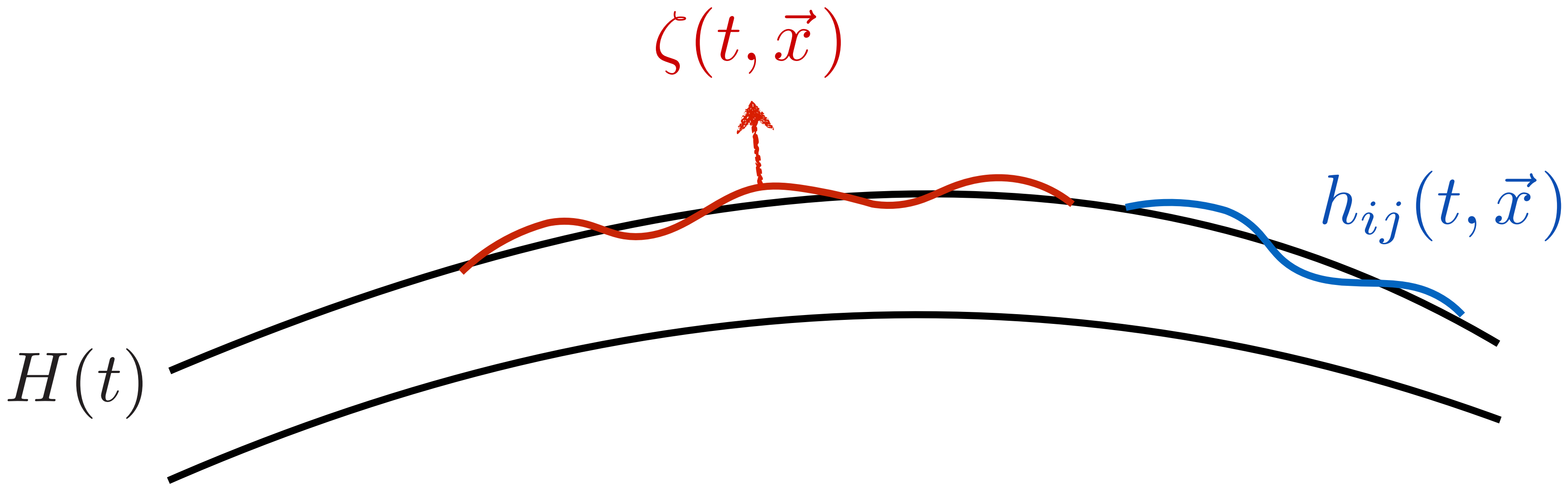
Theoretical Foundations

A Benchmark

It is useful to define a **standard model** …

Single-clock inflation

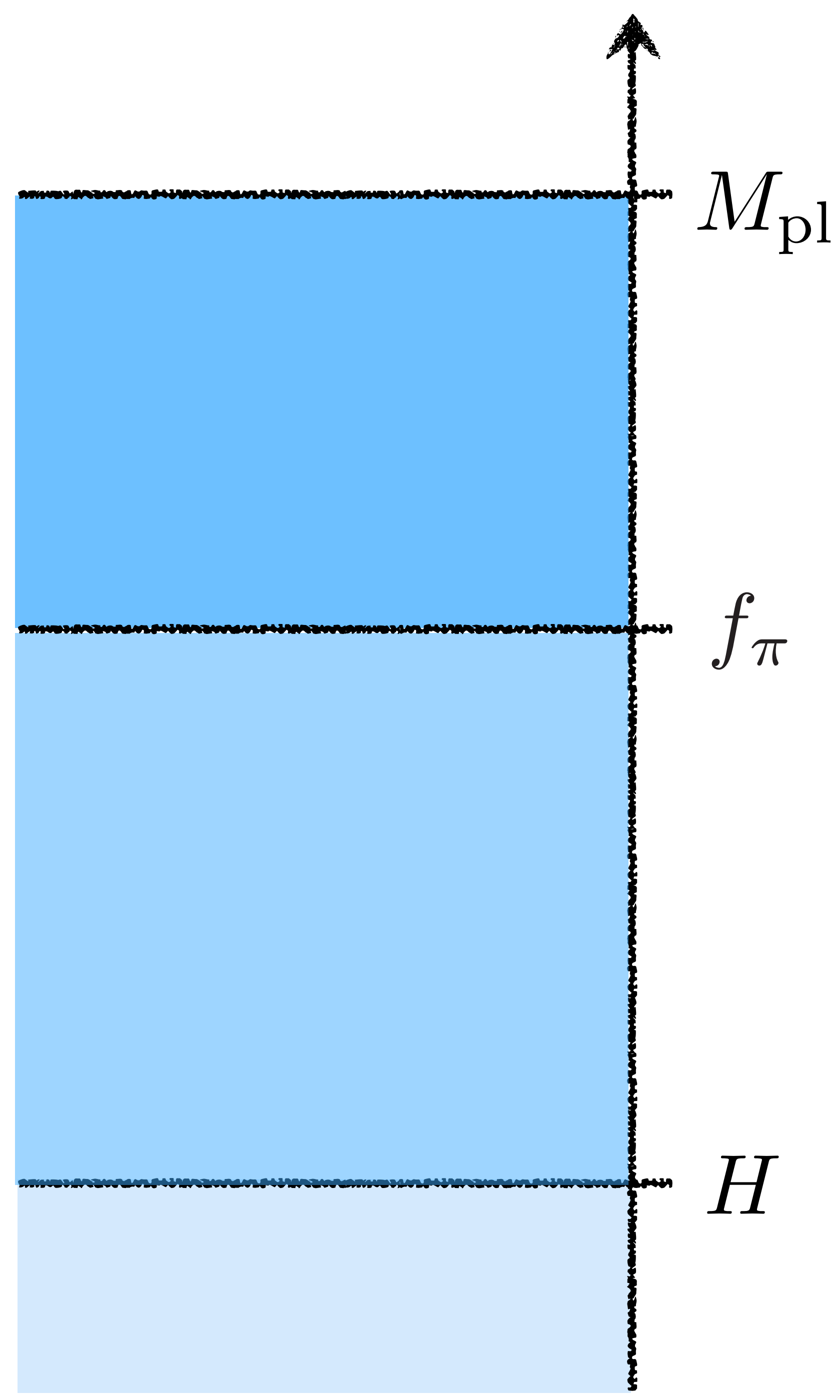
⊂ single-field slow-roll inflation



… and then try to **kill it.**

Energy Scales

The model is characterized by three energy scales:



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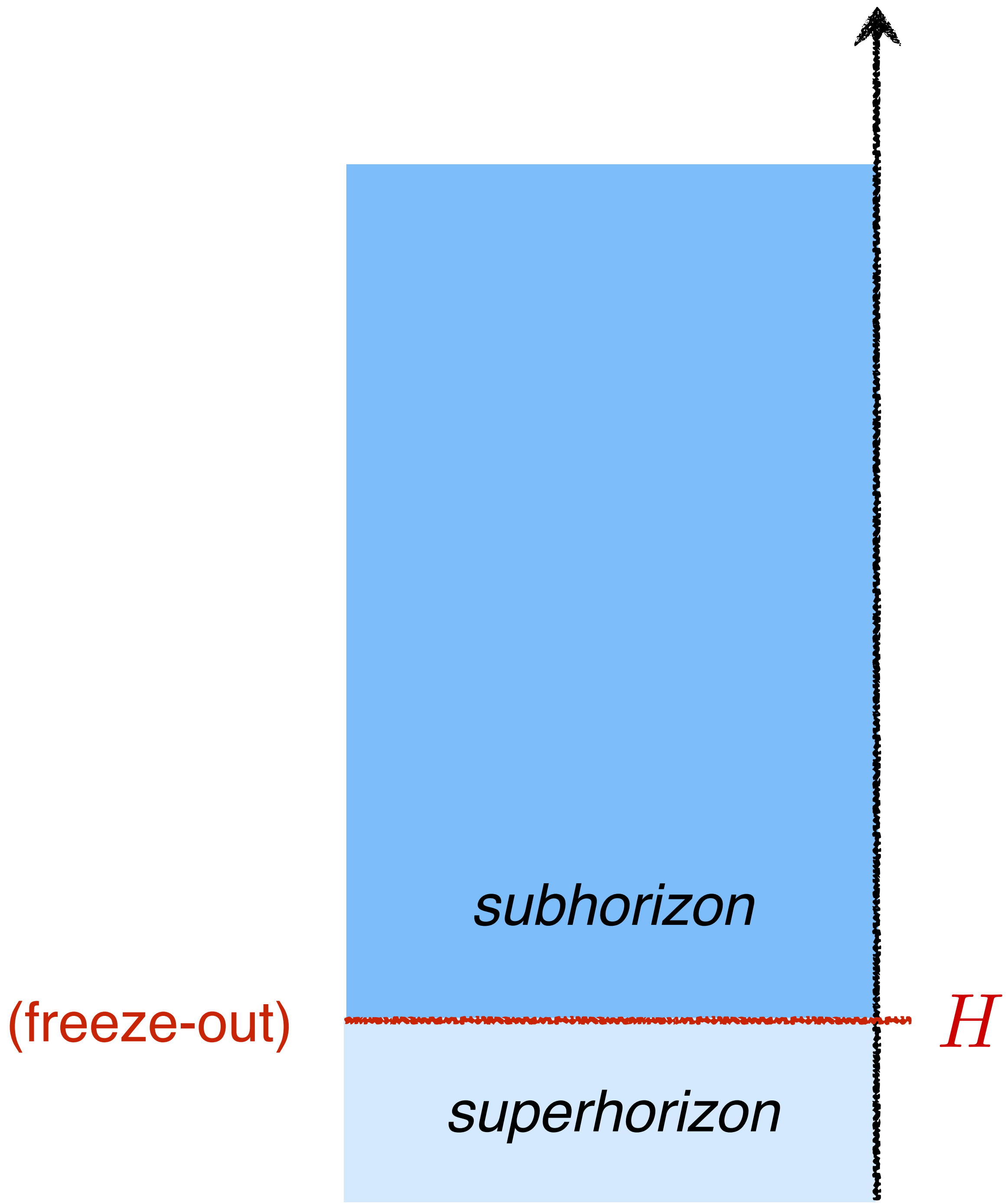

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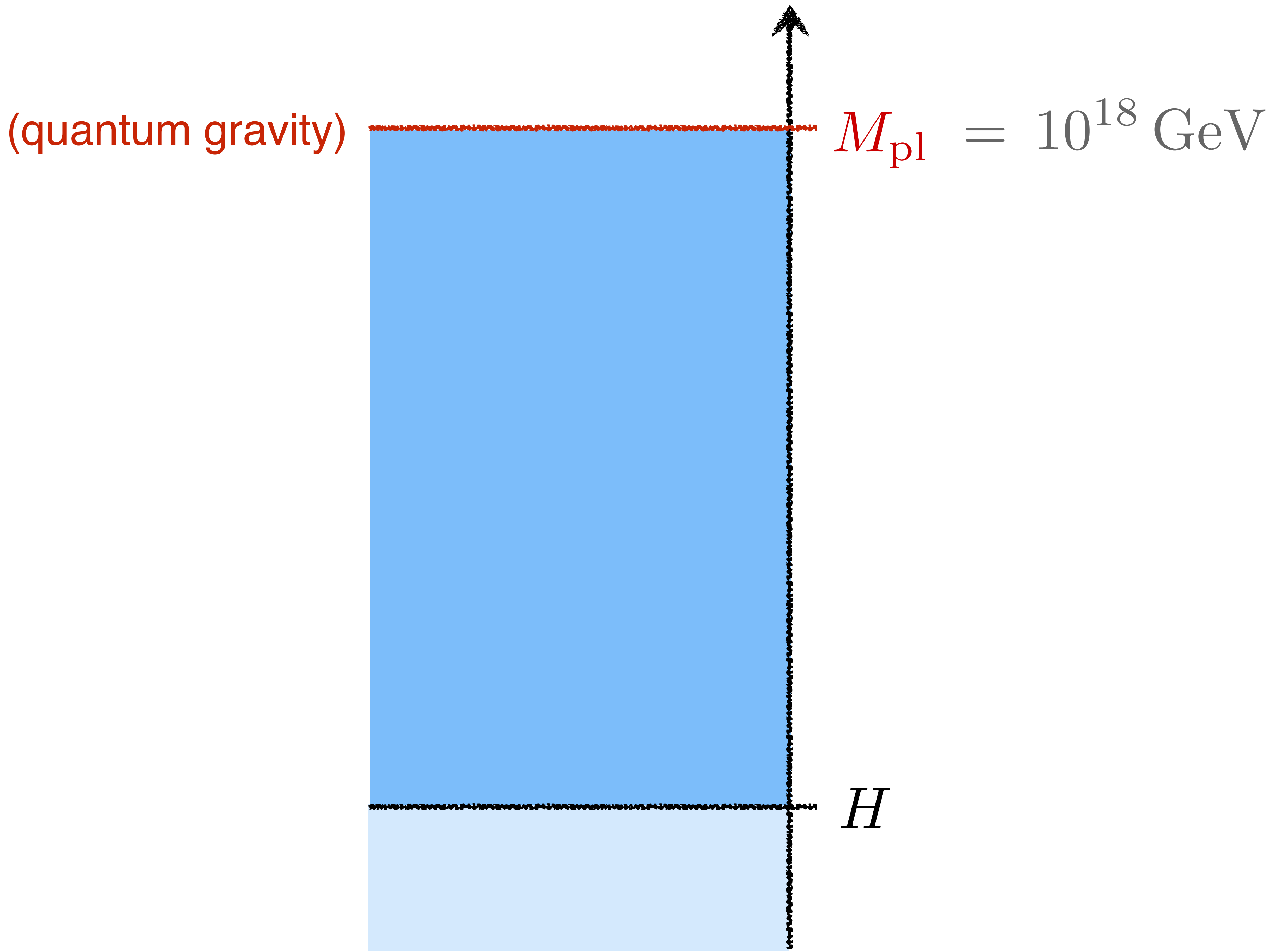

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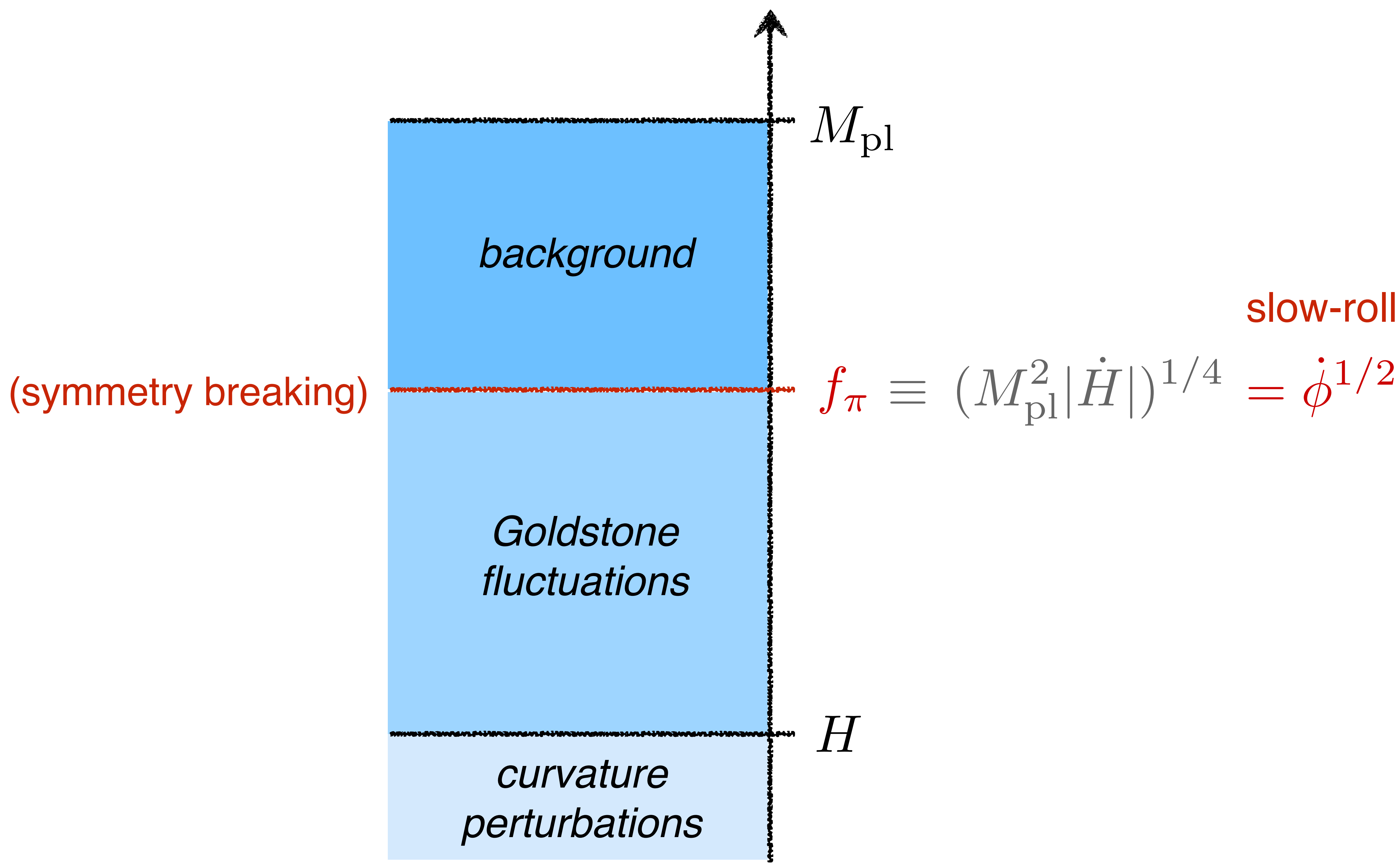

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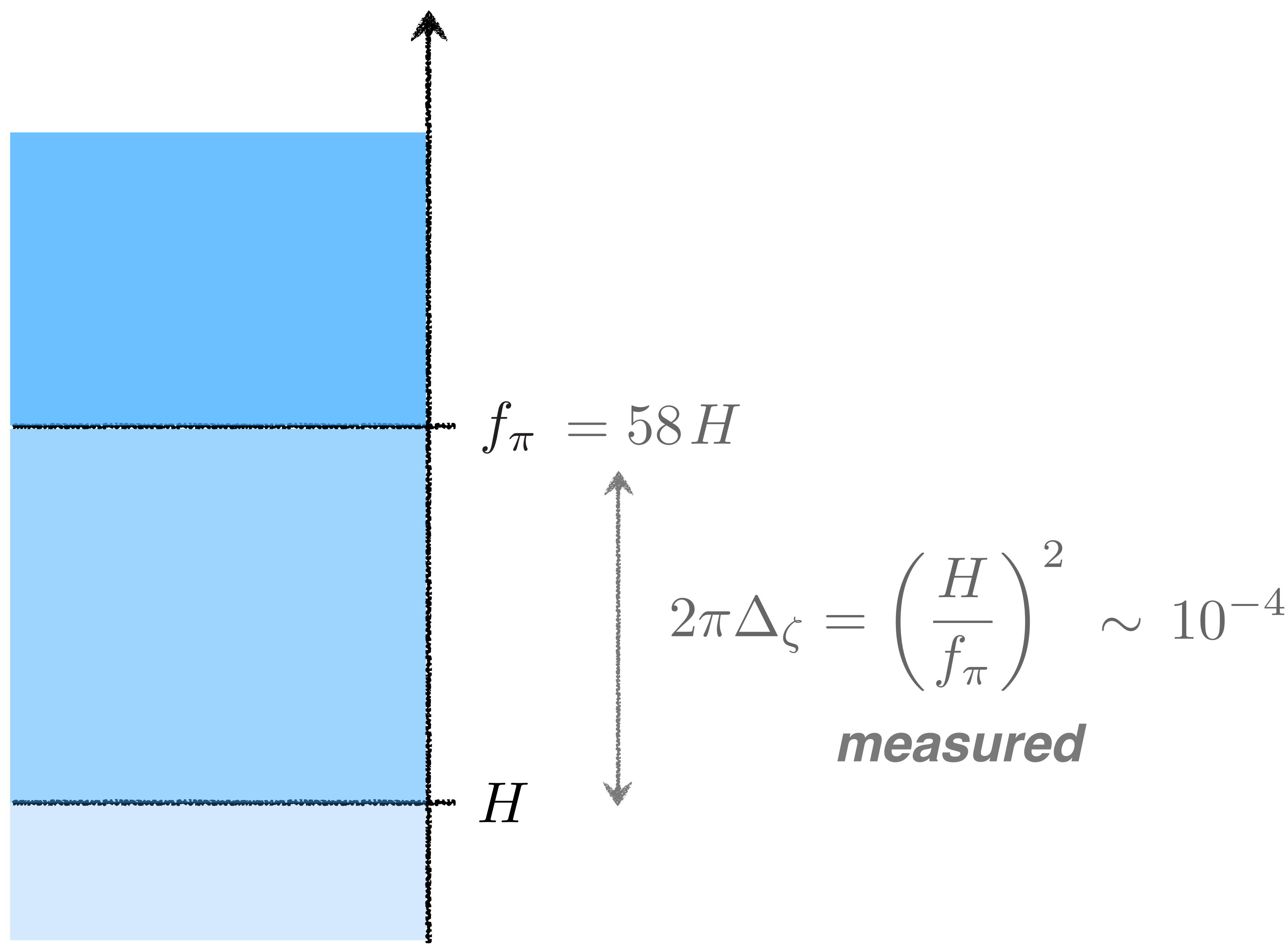

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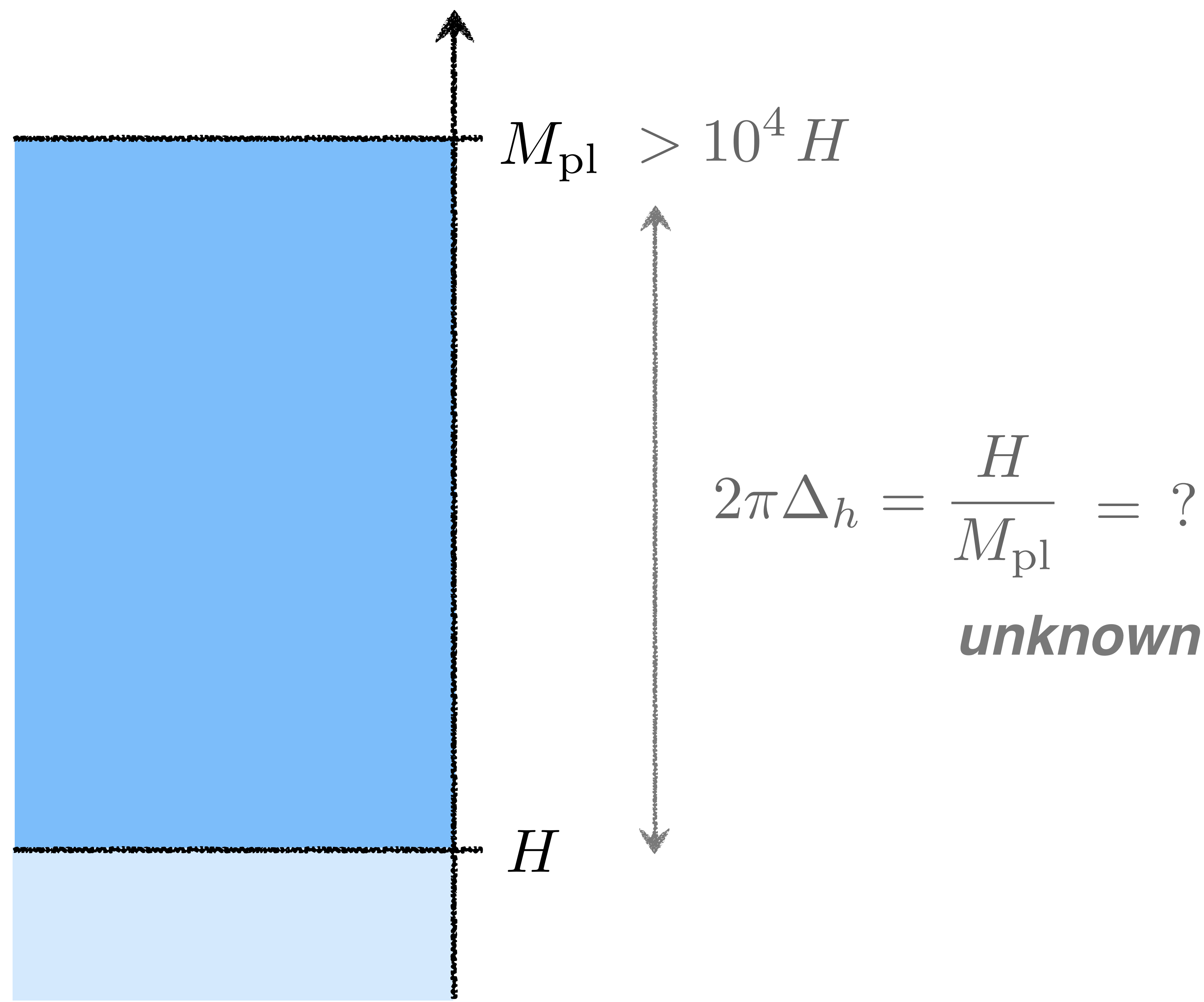
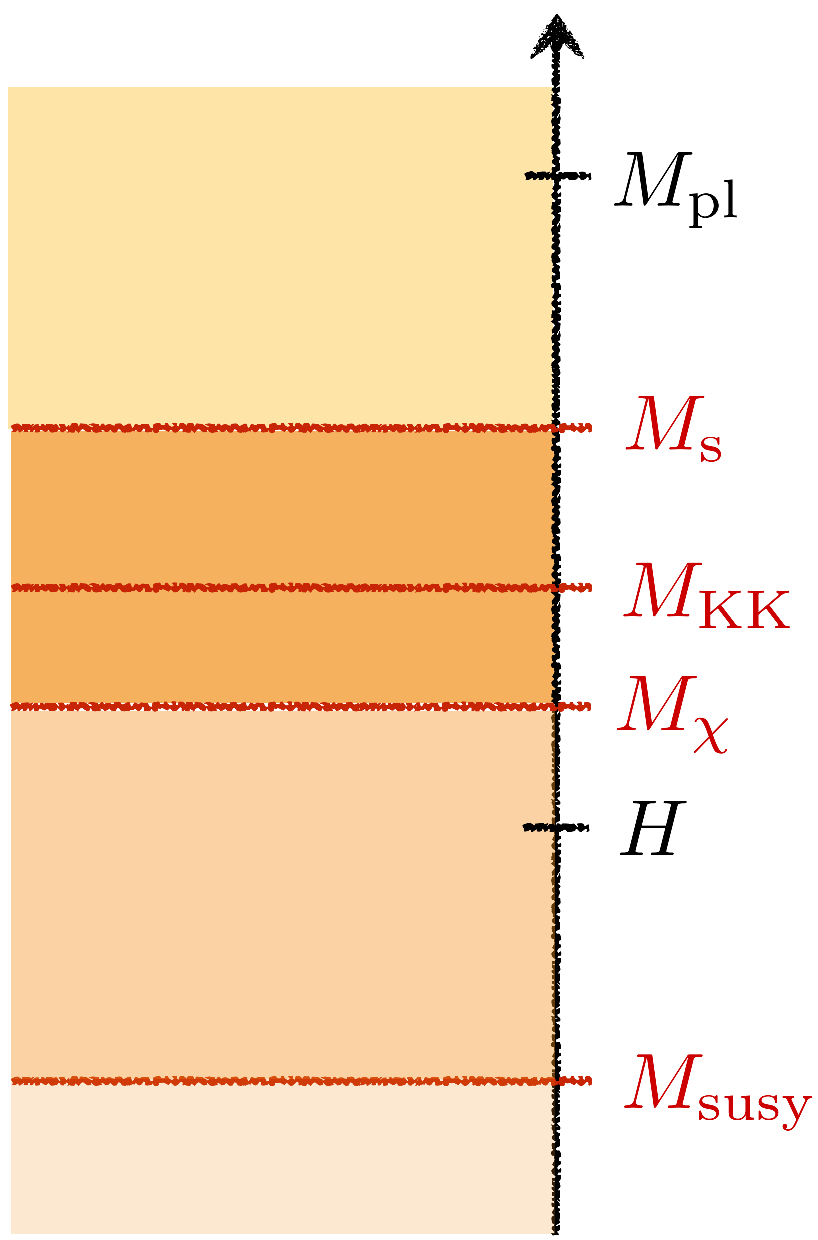


Ultraviolet Completion

The UV completion of inflation requires new scales between the Planck scale and the Hubble scale:



The inflationary dynamics is sensitive to those scales.

Cosmological Collider

A detection of B-modes would suggest a large inflation scale

$$H \sim 10^{14}\,\mathrm{GeV}$$

This is both a **challenge** and an **opportunity**.

↗ The inflationary **background** is sensitive to high scales. Lyth [1996]

↘ The inflationary **perturbations** can be affected by high scales.

Chen and Wang [2009]

DB and Green [2011]

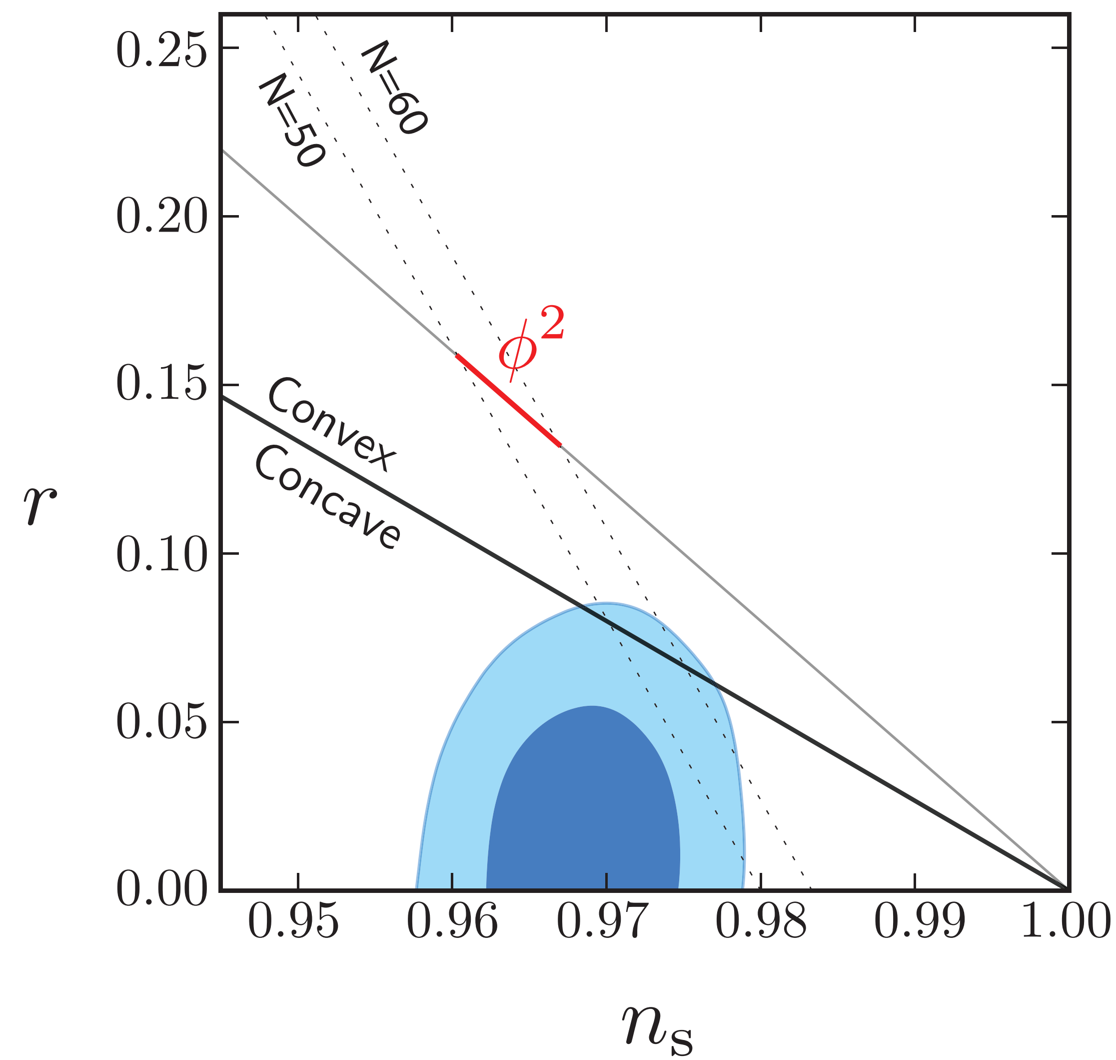
Arkani-Hamed and Maldacena [2015]

Observational Tests

Current Constraints

The data is starting to become really interesting

tensor-to-scalar ratio

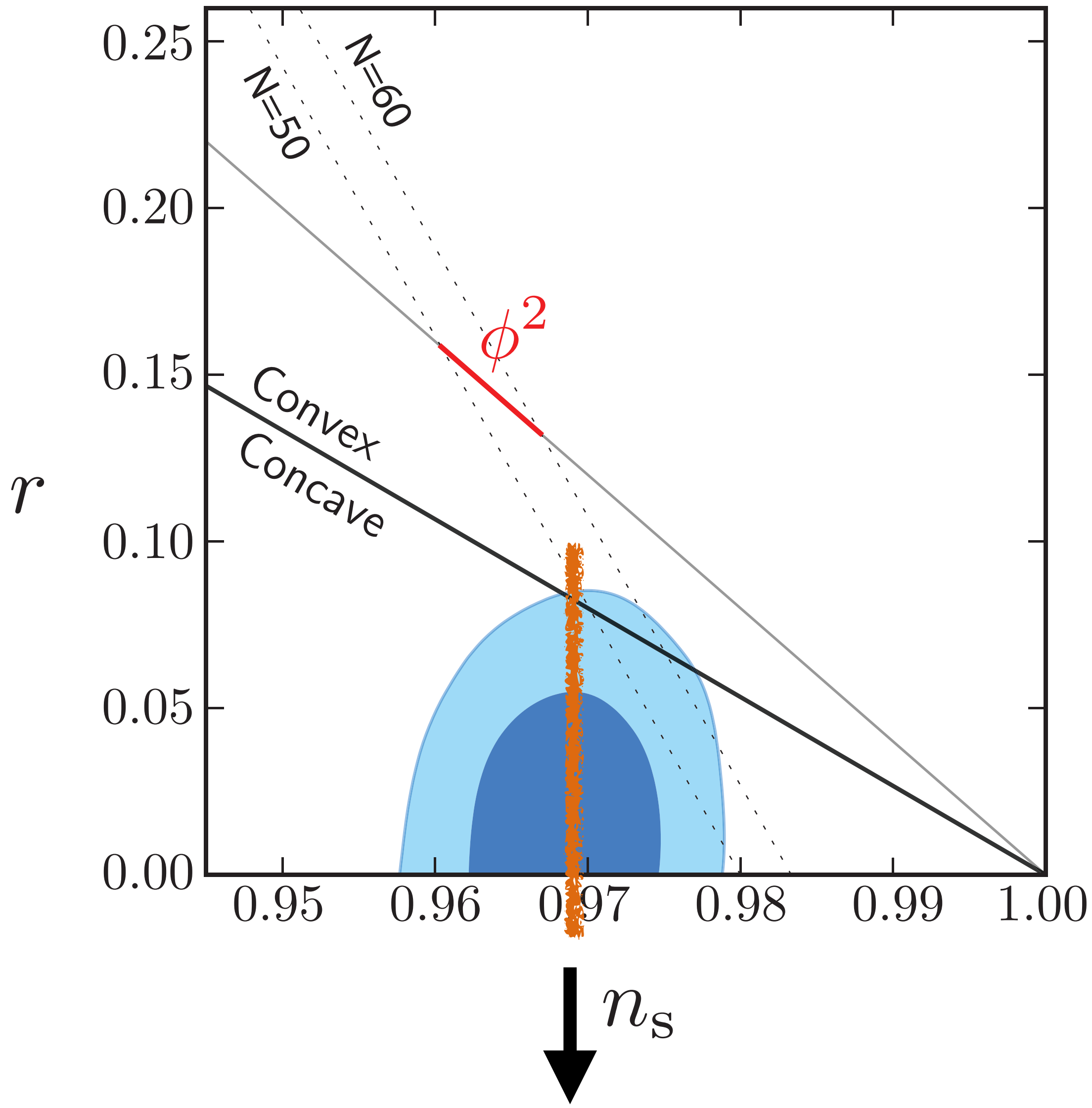


scalar spectral index

Keck Array + BICEP2 [2015]

Current Constraints

The data is starting to become really interesting



Keck Array + BICEP2 [2015]

broken scale invariance

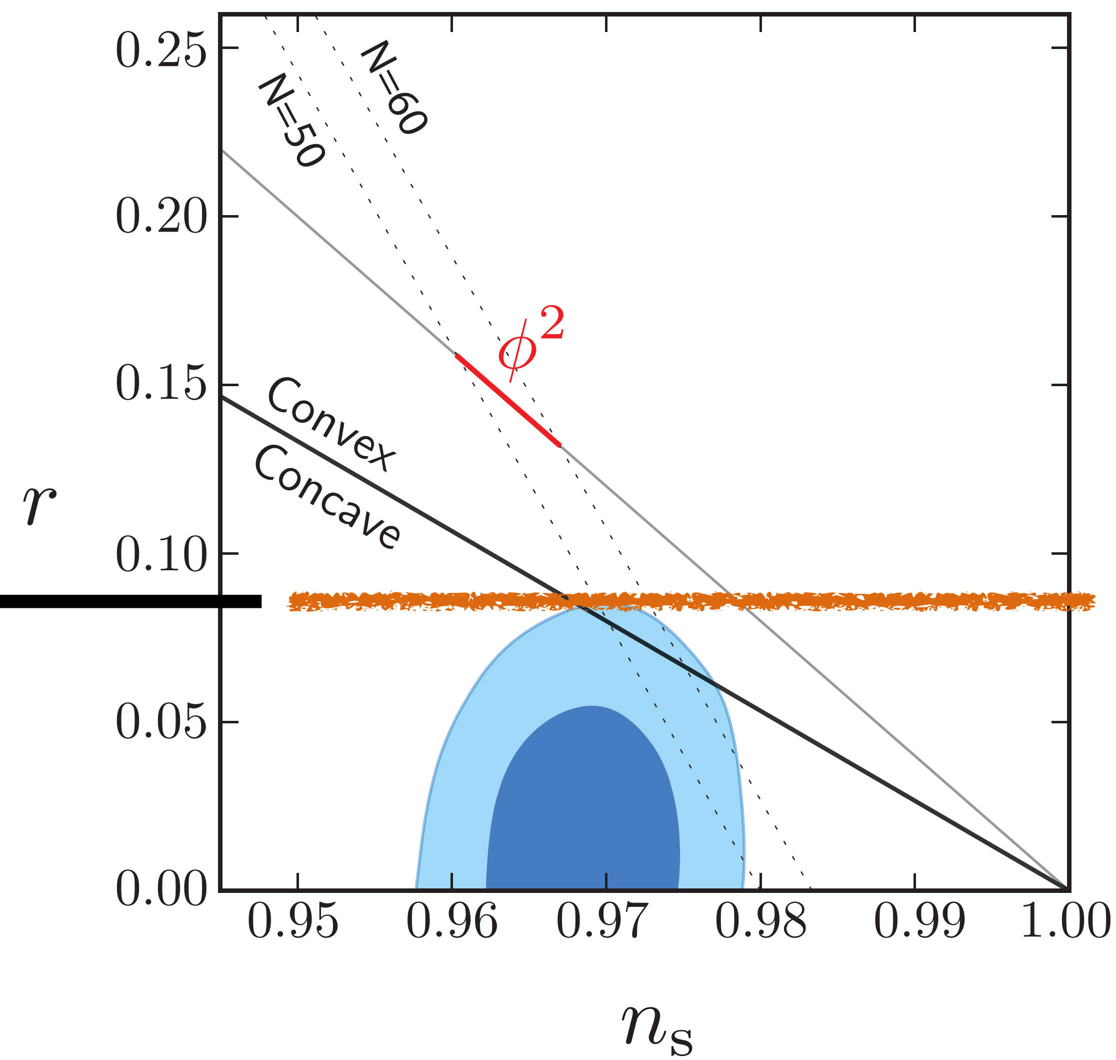
$$n_s = 0.960 \pm 0.007$$

Current Constraints

The data is starting to become really interesting

bound on tensors

$r < 0.07$



Keck Array +
BICEP2 [2015]

Current Constraints

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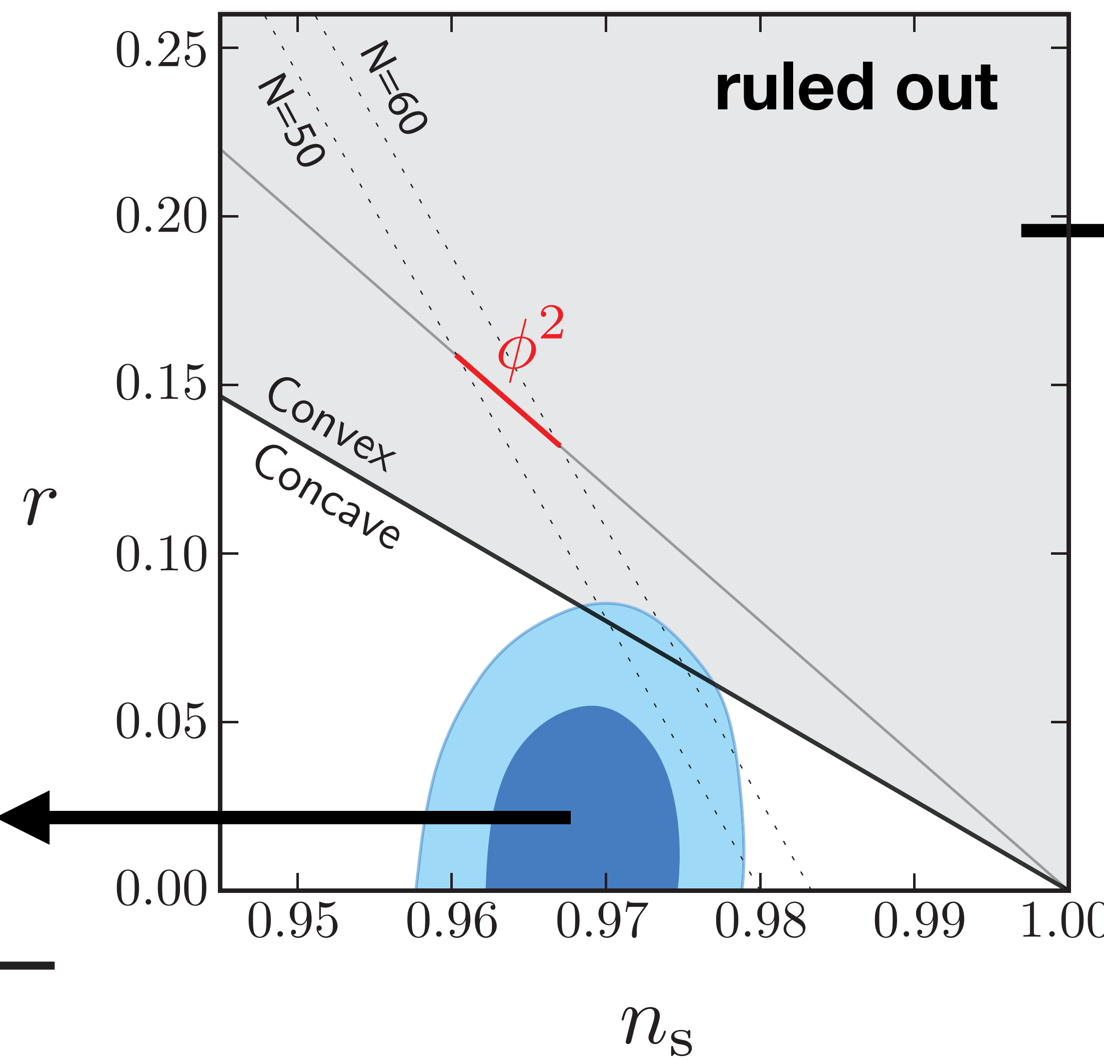
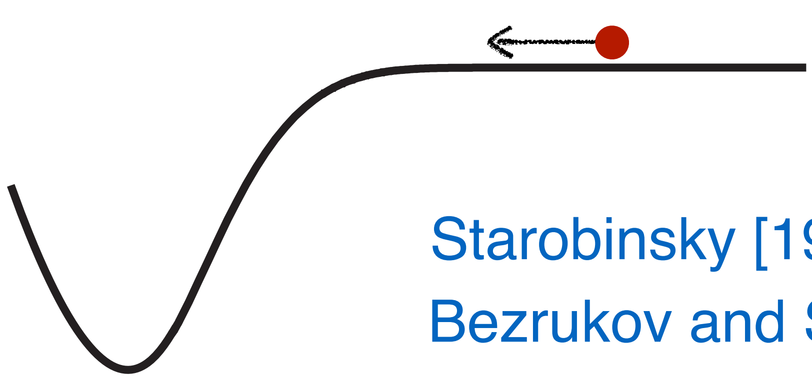


favoured



Keck Array +
BICEP2 [2015]

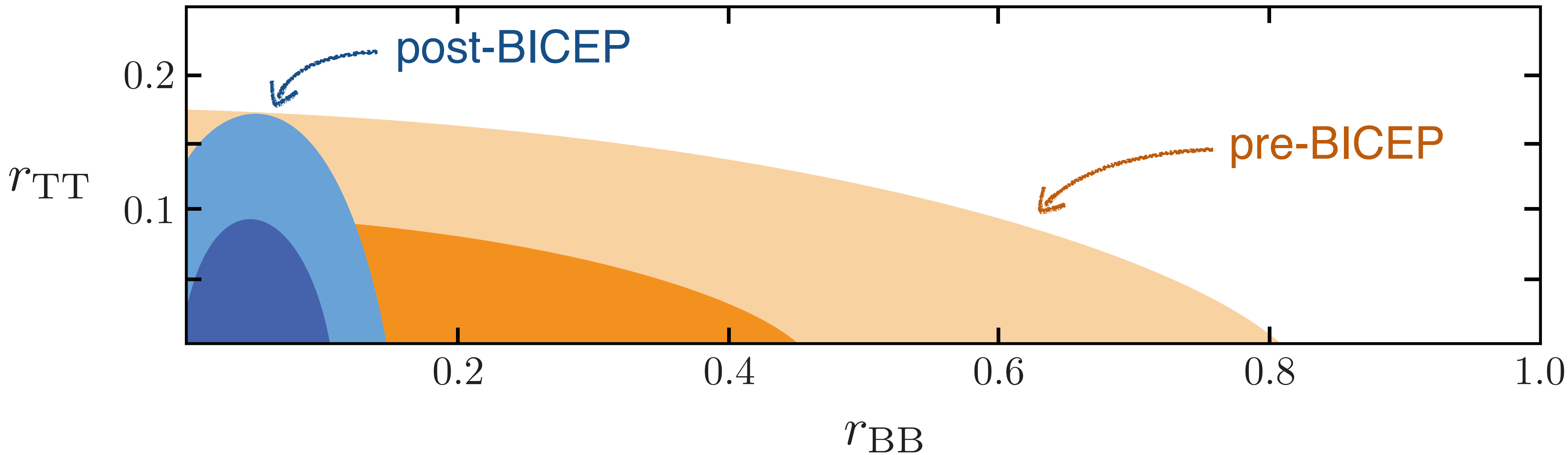
Starobinsky [1980]

Bezrukov and Shaposhnikov [2007]

Kallosh, Linde and Roest [2013]

Future Optimism

There has been great experimental progress in recent years:



But, the era of B-mode cosmology is only beginning:

ground		balloon	future
BICEP2	PolarBear	EBEX	LiteBird
Keck Array	Simons Array	Spider	CMB Stage IV
BICEP3	C-BASS	Piper	COrE
SPTpol	QUIJOTE		
ACTpol	B-Machine		
ABS	CLASS		

Future Optimism

What should we do ***after*** a B-mode detection?

- Check for consistency:
  - Gaussian
  - scale-invariant
  - superhorizon
  - parity-invariant

- Look for additional signatures of high-scale physics:

Non-Gaussianity

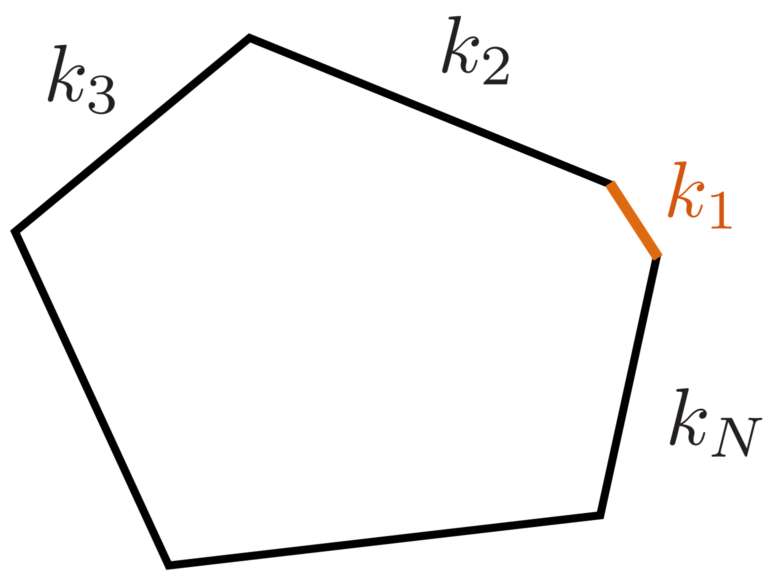
Non-minimal Tensors

Non-Gaussianity

N-point functions in single-clock inflation are strongly constrained by symmetries.

Their **soft limits** “vanish”

$$\lim_{k_1 \to 0}$$

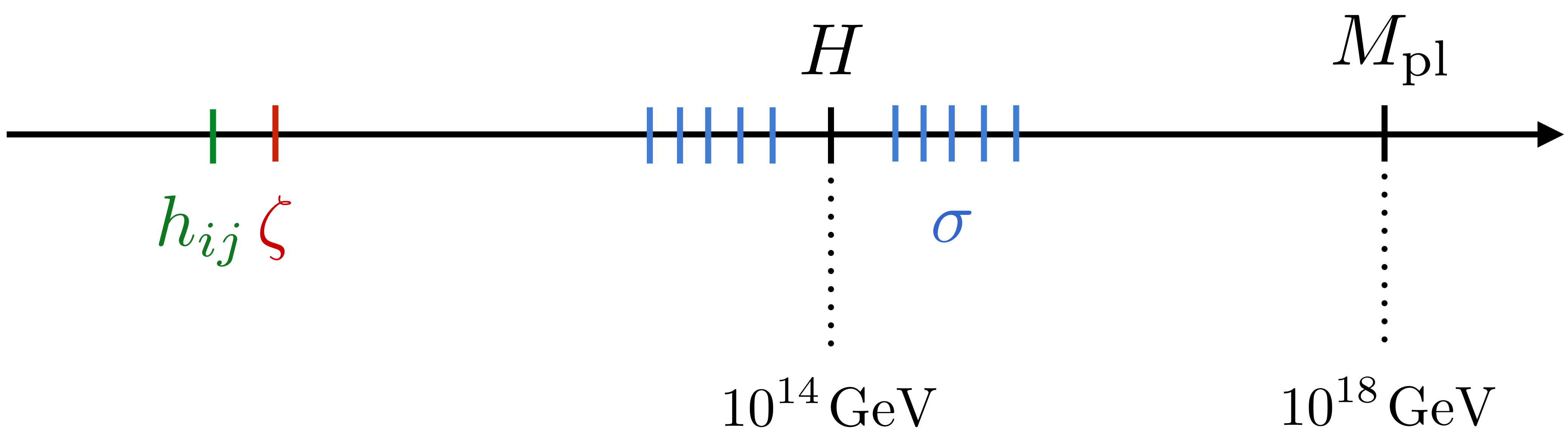


$$\sim \quad 0$$

The signal in the soft limit acts as a **particle detector**.

Non-Gaussianity

If inflation occurred at a high scale (maybe as high as **10^{14} GeV**), we have the opportunity to probe the particle spectrum at those energies:

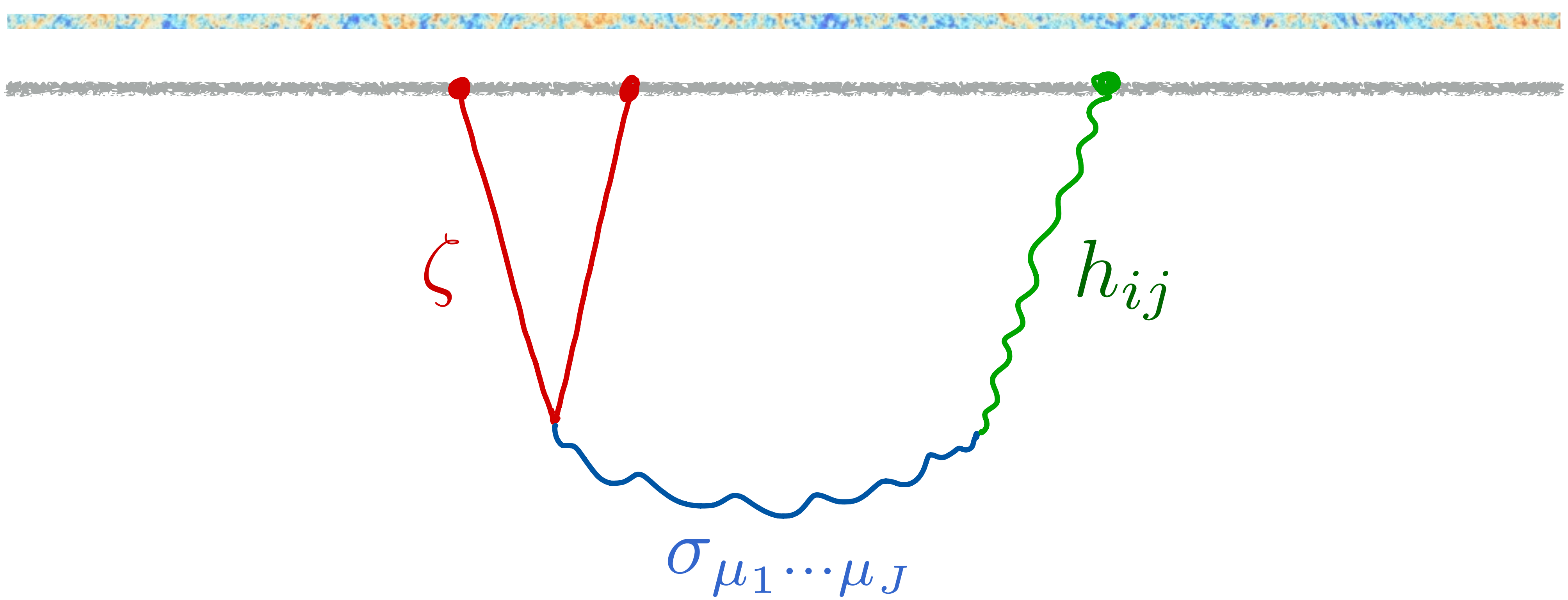


These fields could tell us something about the **microphysics of inflation.**

Chen and Wang [2009]
DB and Green [2011]
Arkani-Hamed and Maldacena [2015]

Non-Gaussianity

The rapid expansion of the spacetime creates these **massive particles**:



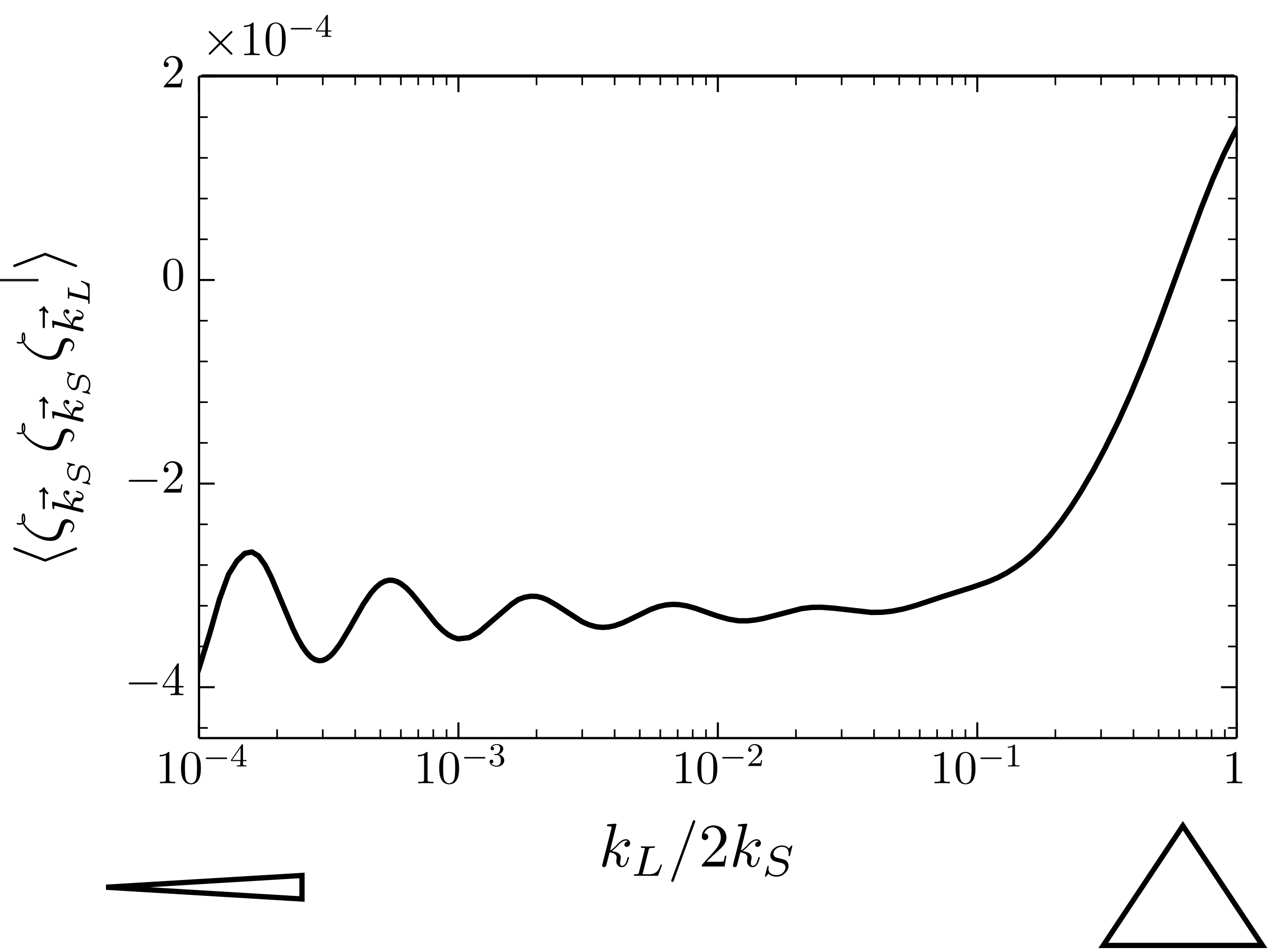
The decay of the particles produces distinct correlations.

The signal depends on **mass** and **spin** on the particles.

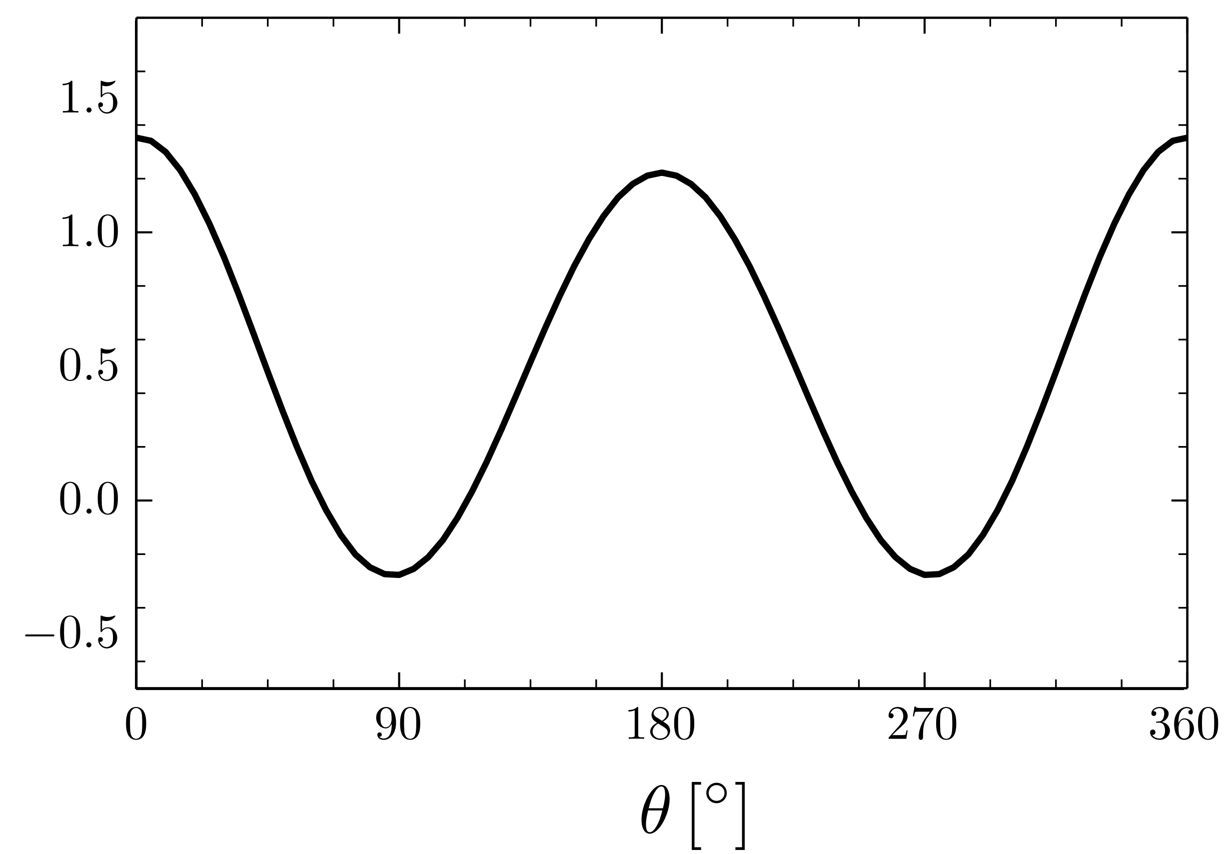
Non-Gaussianity

$$\lim_{k_\mathrm{L}\to 0} \langle \zeta_{\vec{k}_\mathrm{L}} \zeta_{\vec{k}_\mathrm{S}} \zeta_{-\vec{k}_\mathrm{S}} \rangle \;\propto\; \cos\left[\frac{M}{H}\ln\left(\frac{k_\mathrm{L}}{k_\mathrm{S}}\right)\right] P_J(\cos\theta)$$

Oscillations in the squeezed limit measure the ***mass*** *of the particle:*



Angular dependence in the squeezed limit measures the ***spin*** *of the particle:*



Lee, DB and Pimentel [2016]

Non-minimal Tensors

High-scale inflation is sensitive to gravitational corrections:

$$\mathcal{L}_g = \frac{M_{\rm pl}^2}{2}\left[R + f(\phi)\frac{W^2}{M_{\rm s}^2} + g(\phi)\frac{W\tilde{W}}{M_{\rm s}^2} + \frac{W^3}{M_{\rm s}^4} + \frac{W^2\tilde{W}}{M_{\rm s}^4} + \cdots \right]$$

anomalous tensor tilt (the $f(\phi)\frac{W^2}{M_{\rm s}^2}$ term)
DB, Lee and Pimentel [2015]

parity violation (the $g(\phi)\frac{W\tilde{W}}{M_{\rm s}^2}$ term)
Lue, Wang and Kamionkowski [1998]

tensor non-Gaussianity (the $\frac{W^3}{M_{\rm s}^4}$ term)
Maldacena and Pimentel [2011]

parity violation (the $\frac{W^2\tilde{W}}{M_{\rm s}^4}$ term)
Soda, Kodama and Mozawa [2011]

After a detection of B-modes it would be worth looking for non-minimal features in the tensor sector.

Quantum or Classical?

- Gaussian
- scale-invariant
- parity-invariant
- super-Planckian fields

Quantum fluctuations

↓

$$\Box h_{ij} = 16\pi G \, \tau_{ij}$$

↑

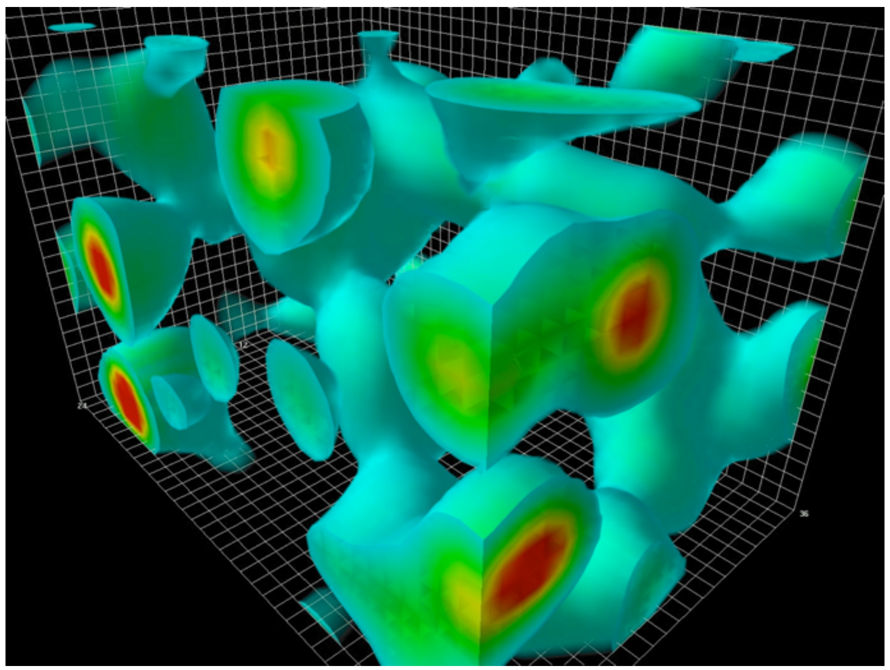
Classical source e.g. SU(2) gauge fields

- non-Gaussian
- non-scale-invariant
- parity violating
- sub-Planckian fields

Agrawal, Fujita and Komatsu [2017]

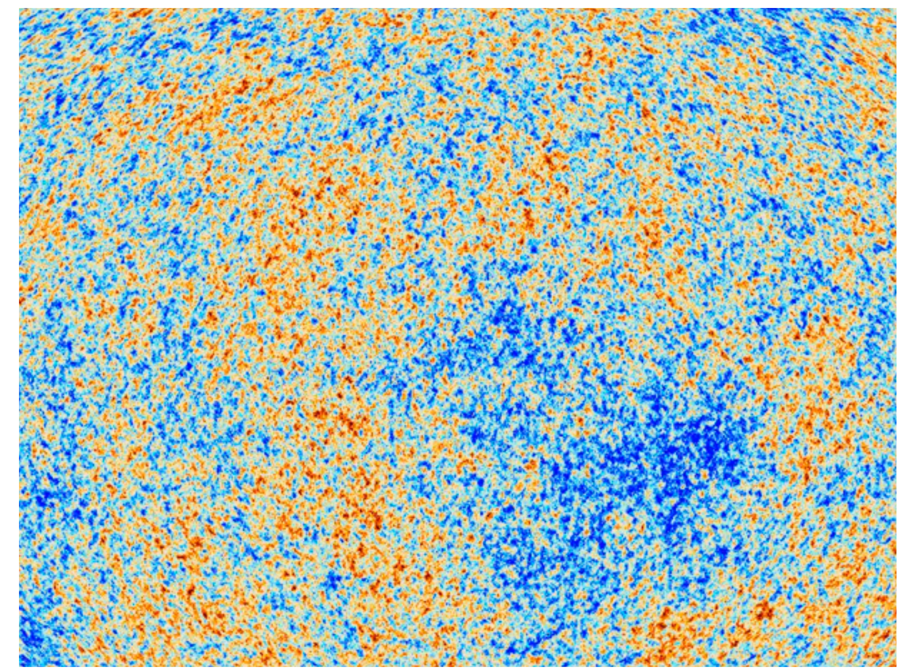
Conclusion

A B-mode detection would be a milestone towards a complete understanding of the origin of all structure in the universe



10^{-33} sec

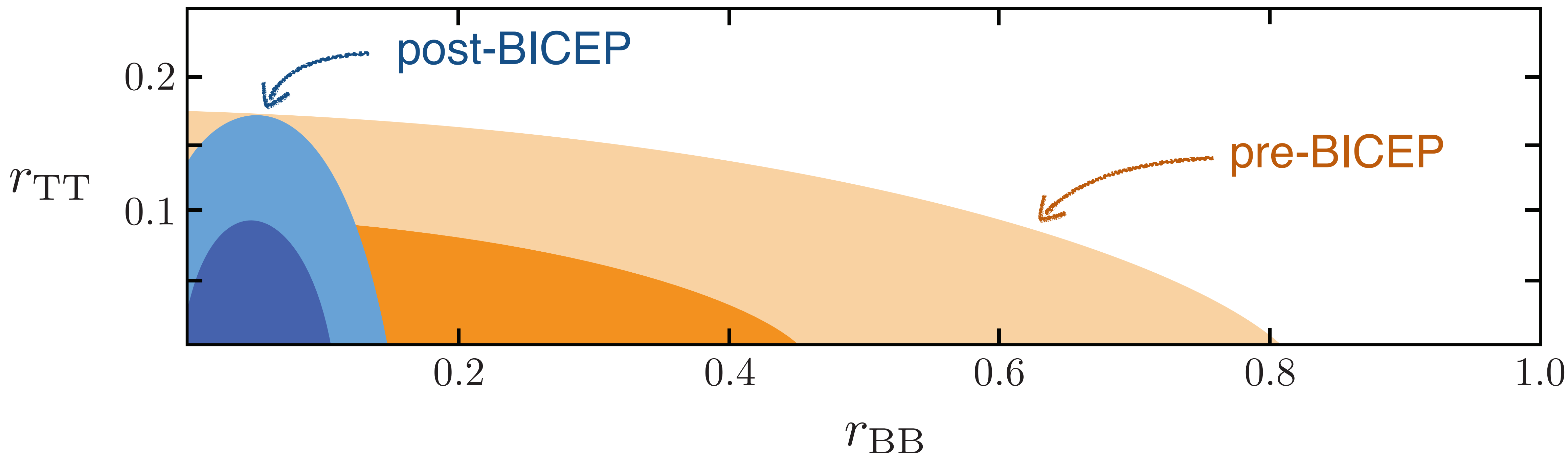
inflation



380,000 yrs

It would also give us the opportunity to probe physics at the highest energy scales.

There has been great experimental progress in recent years:



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ABS			
CLASS			


Thanks for your attention
http://cosmology.amsterdam

Scalar Consistency Relation

Consider the squeezed limit of the scalar bispectrum.

At the freeze-out of the short modes, the long mode is classical and acts as a rescaling of the coordinates:

$$\lim_{k_\mathrm{L}\to 0} \frac{\langle \zeta_{\vec{k}_\mathrm{L}} \zeta_{\vec{k}_\mathrm{S}} \zeta_{-\vec{k}_\mathrm{S}} \rangle}{P_\zeta(k_\mathrm{L}) P_\zeta(k_\mathrm{S})} = -\frac{d \ln [k^3 P_\zeta(k_\mathrm{S})]}{d \ln k_\mathrm{S}} = (1 - n_s)$$

Maldacena [2003]
Creminelli and Zaldarriaga [2004]

unobservable

Pajer, Schmidt and Zaldarriaga [2015]

A violation of this consistency relation signals:

- new particles
- non-inflationary perturbations

Chen and Wang [2009]
DB and Green [2011]
Arkani-Hamed and Maldacena [2015]

Tensor Consistency Relation

A similar argument applies if the long mode is a tensor mode:

$$\lim_{k_{\rm L}\to 0} \frac{\langle h^\lambda_{\vec{k}_{\rm L}} \zeta_{\vec{k}_{\rm S}} \zeta_{-\vec{k}_{\rm S}} \rangle}{P_\zeta(k_{\rm L}) P_\zeta(k_{\rm S})} = \epsilon^\lambda_{ij} k^i_{\rm S} k^j_{\rm S} \frac{d \ln P_h(k_{\rm S})}{d k^2_{\rm S}}$$

$$= \epsilon^\lambda_{ij} \hat{k}^i_{\rm S} \hat{k}^j_{\rm S} \left[3 - (1 - n_s)\right]$$

This is even more robust than the scalar consistency relation, since it is hard to violate even with extra particles.

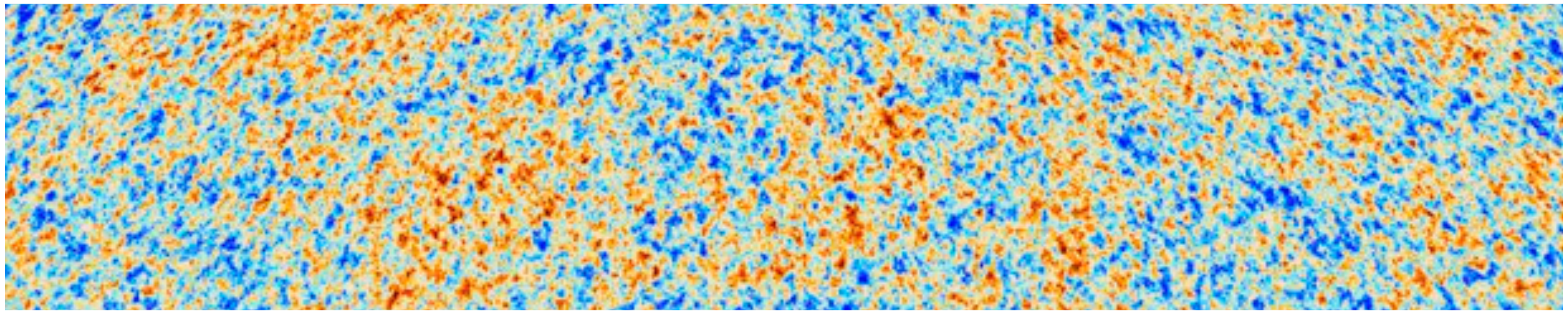
Bordin et al [2016]

Lee, DB and Pimentel [2016]

A violation of this consistency relation signals:

- broken spatial symmetries — Endlich, Nicolis and Wang [2012]
- exotic new particles — Lee, DB and Pimentel [2016]
- non-inflationary perturbations

Lessons from the Past



"I did not continue with studying the CMB, because I had trouble imagining that such tiny disturbances to the CMB could be detected ..."

Jim Peebles

$$n_s = 0.960 \pm 0.007$$

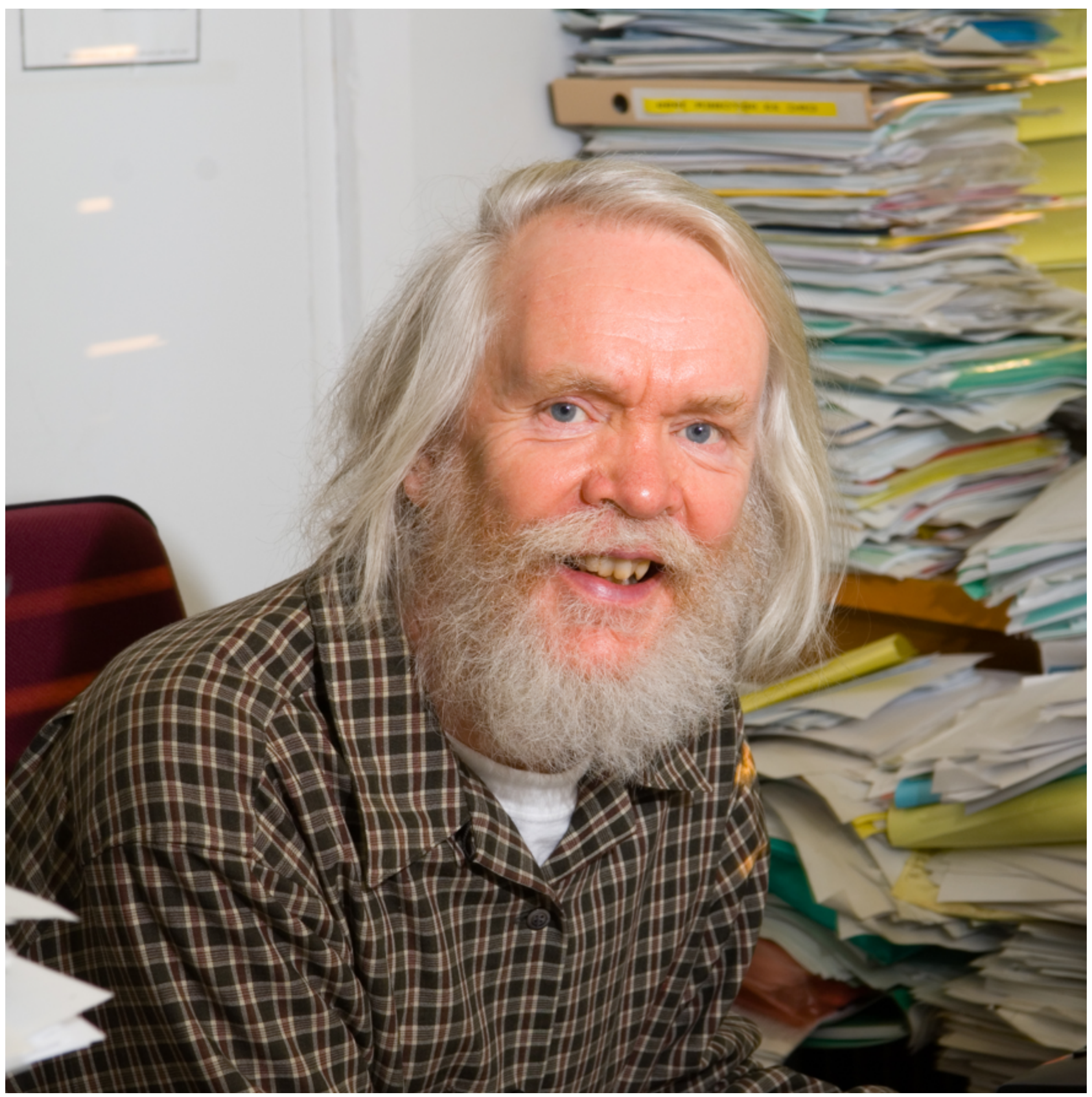
"I thought that it would take 1000 years to detect the logarithmic dependence of the power spectrum."

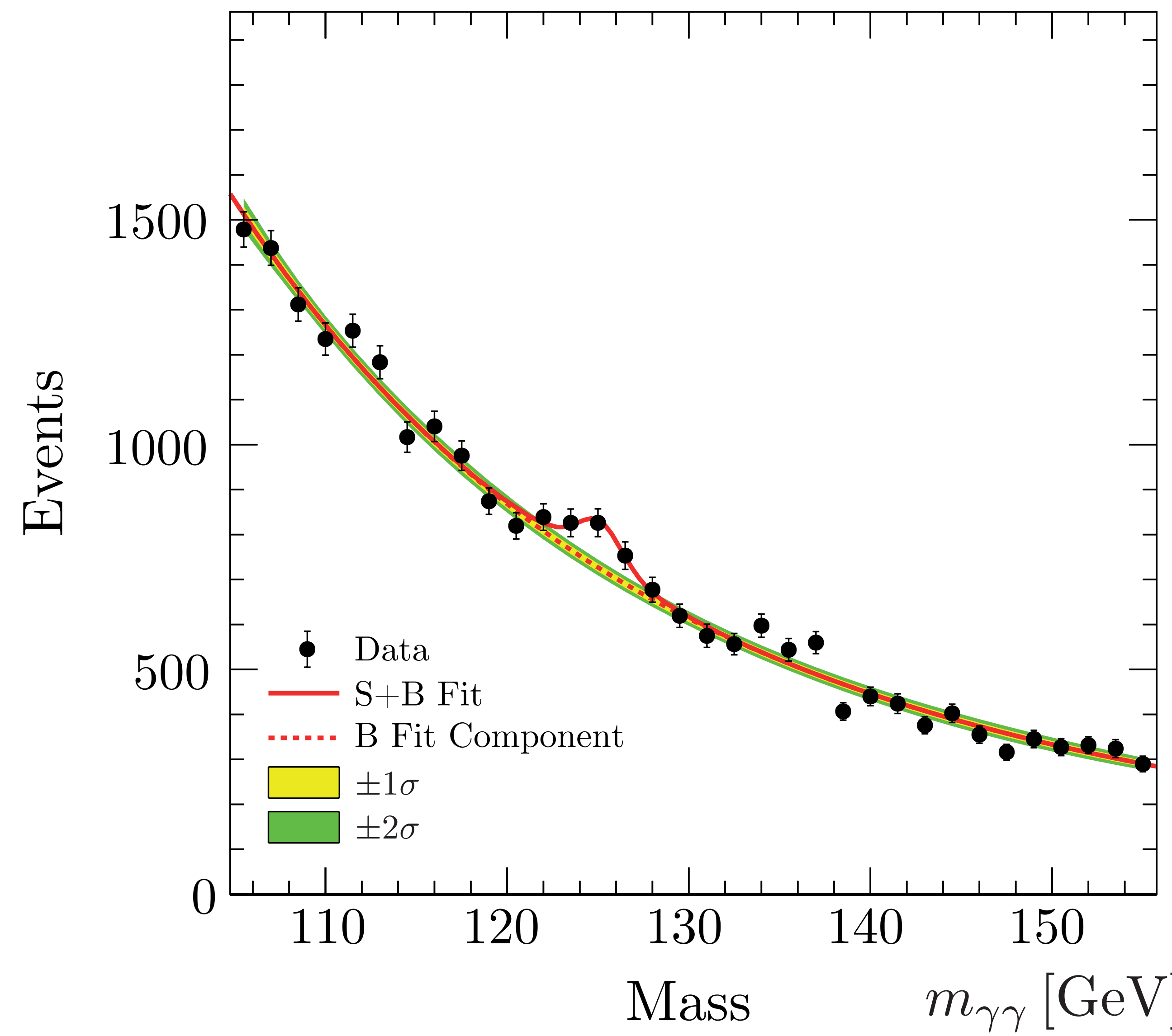
Slava Mukhanov

Lessons from the Past

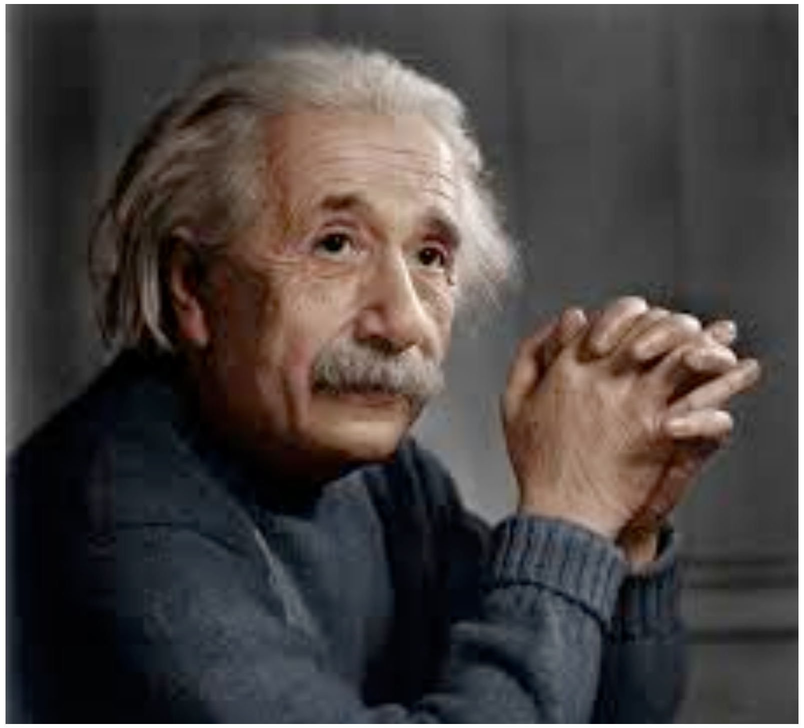
"We apologise to experimentalists for having no idea what is the mass of the Higgs boson and for not being sure of its couplings to other particles. For these reasons we do not want to encourage big experimental searches for the Higgs boson, …"

Ellis, Gaillard and Nanopoulos





Lessons from the Past



"I arrived at the interesting result that gravitational waves do not exist, …"

Einstein, in a letter to Born