Fossils from Inflation

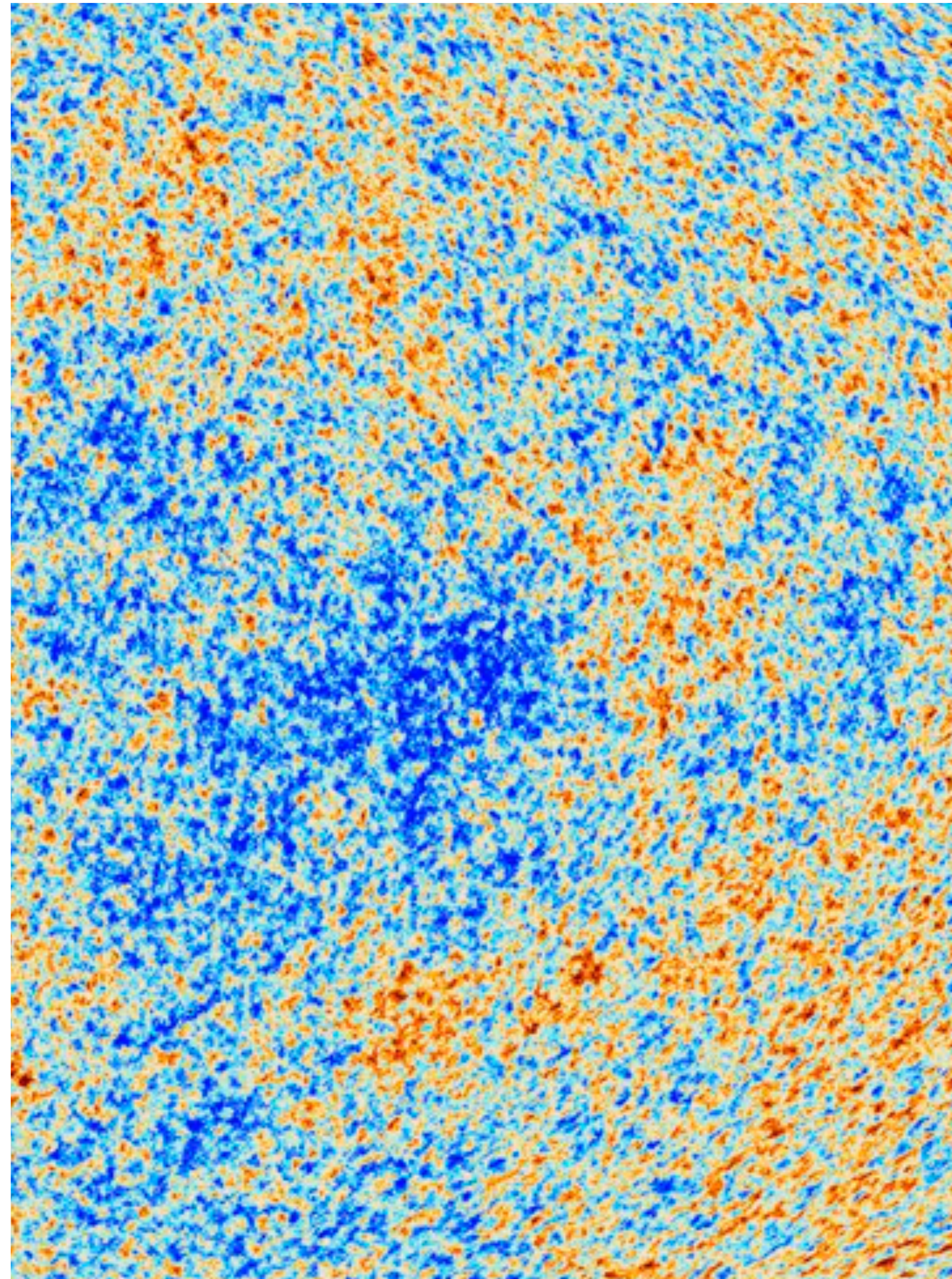
Daniel Baumann

University of Amsterdam

based on work with

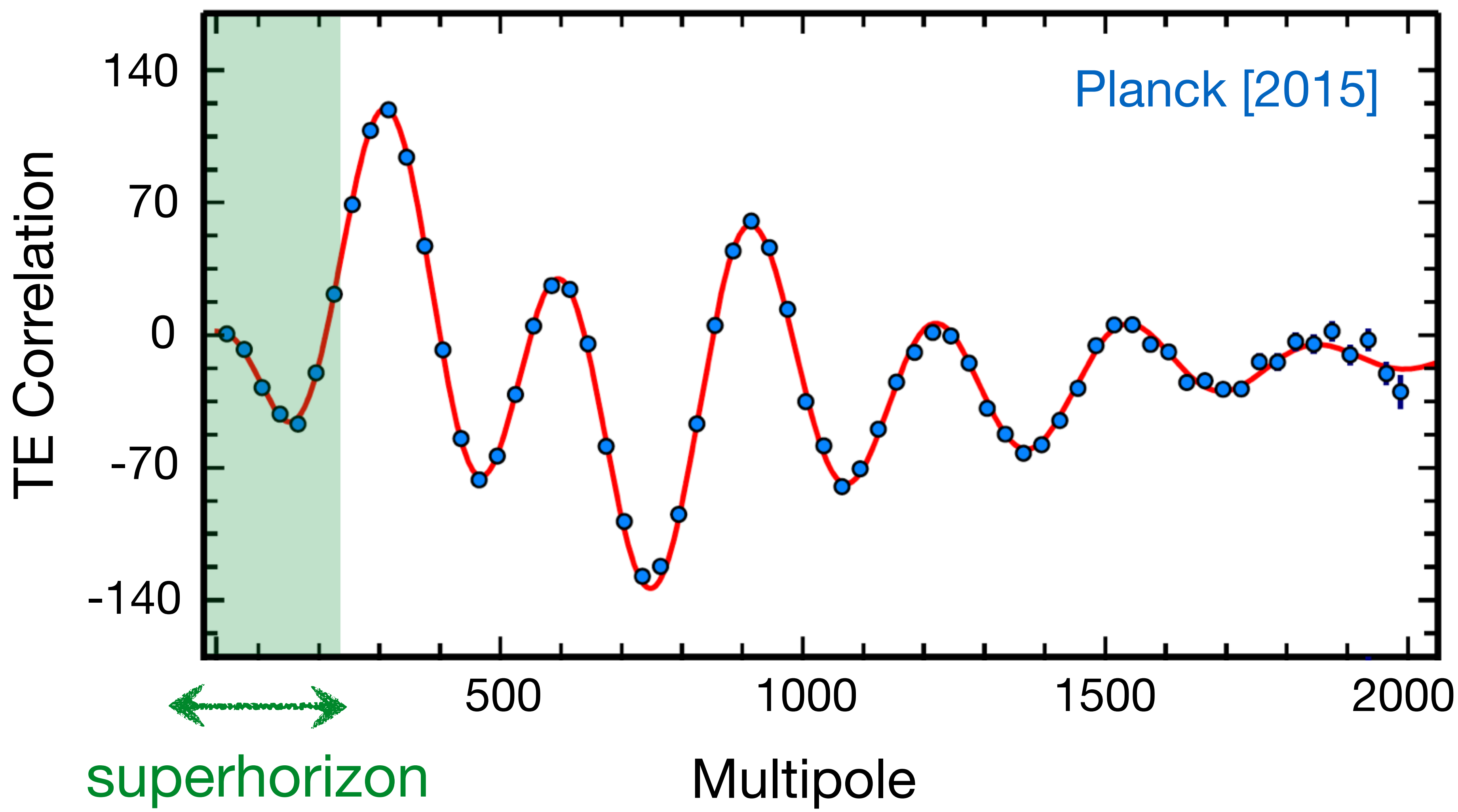
D. Green, G. Pimentel, H. Lee and R. Porto

The Cosmological Fossil Record

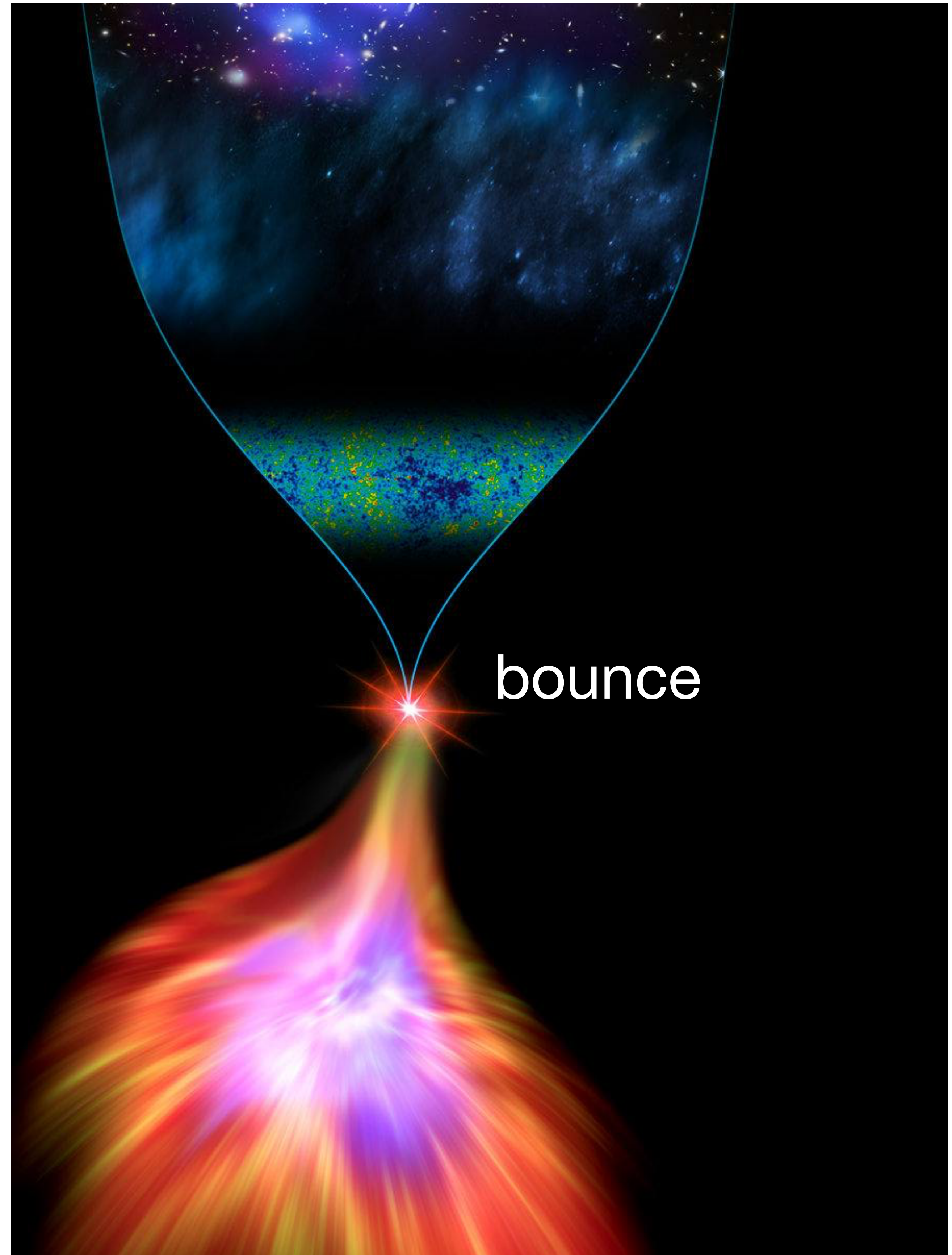


A Remarkable Fact

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



Rapid Expansion or Slow Contraction?



Open Questions

- Did inflation really occur?

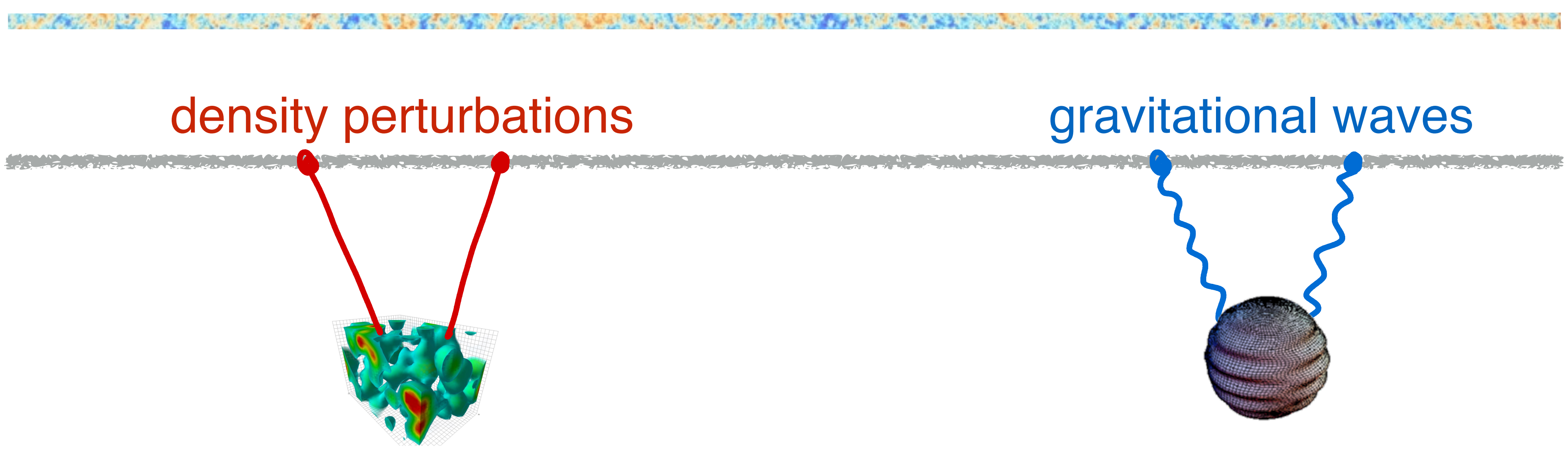
"Extraordinary claims require extraordinary evidence."

- 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.

Fossils from Inflation

Quantum fluctuations during inflation create frozen long-wavelength cosmological perturbations:



Fossils from Inflation

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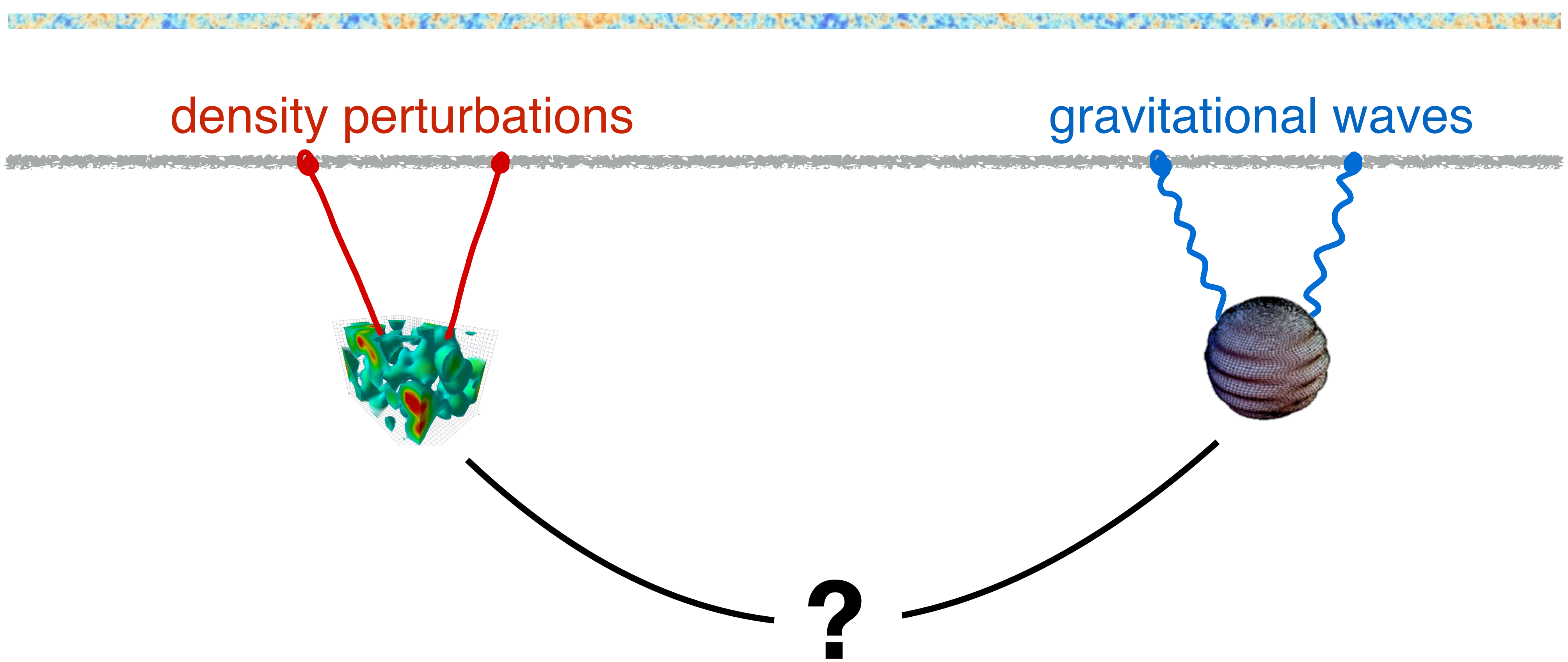


New massive particles may be created by the rapid expansion of the spacetime and produce distinct signals in the cosmological correlators.

Outline

1. **EFT of Inflation**
   - Massless modes
   - Unitarity bound
   - Causality constraints
   - Soft limits

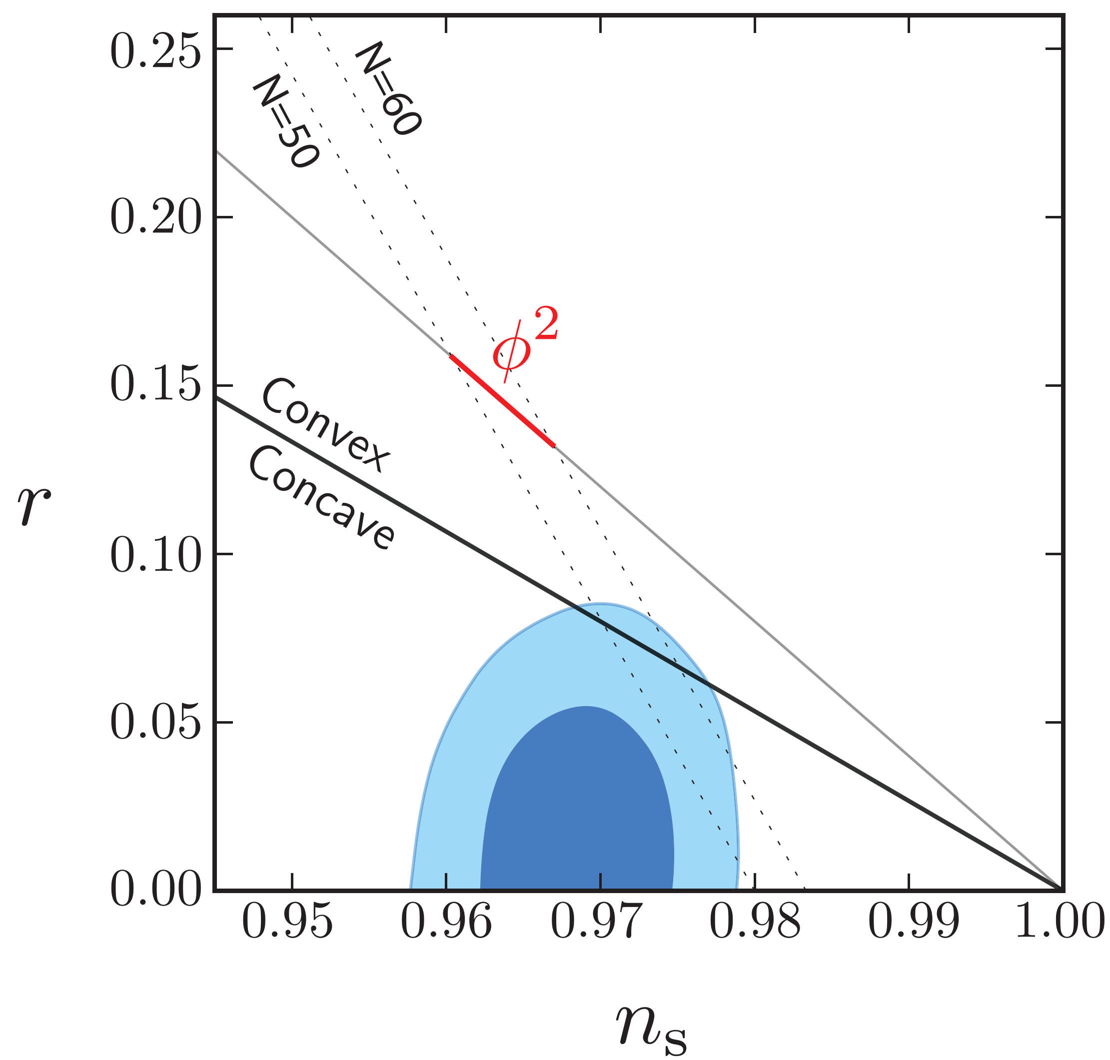
2. **New Particles**
   - Effects on scalars
   - Effects on tensors

Effective Theory of Inflation

Fossils from Inflation

CMB observations constrain the power spectra of primordial scalar and tensor perturbations:

tensor-to-scalar ratio



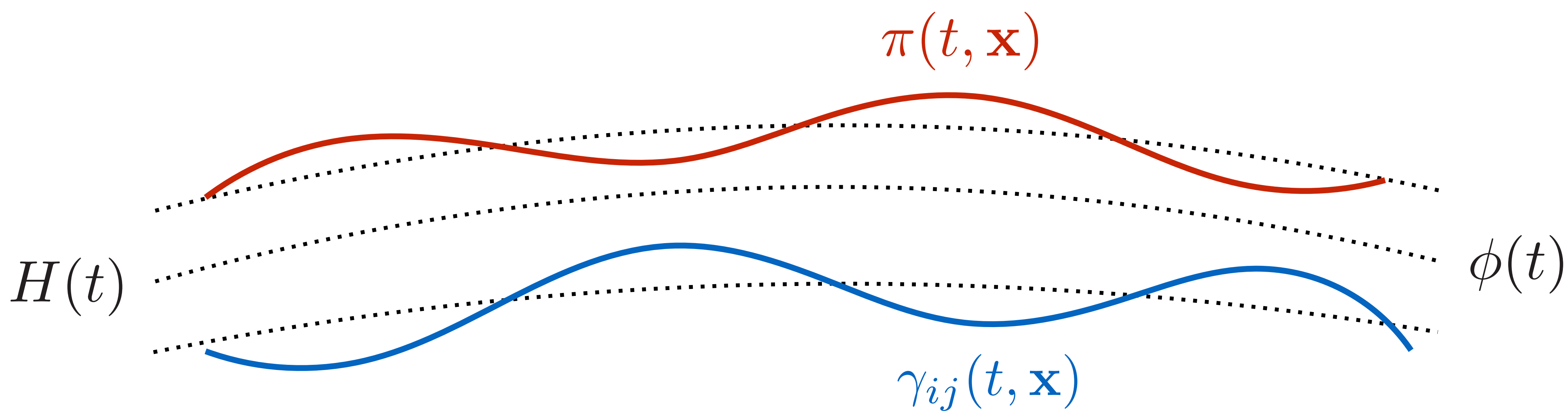
scalar spectral index

Keck Array + BICEP2 [2015]

This data can be described by a very simple EFT.

EFT of Inflation

Inflation is a symmetry breaking phenomenon:



The low-energy EFT is parameterized by two massless fields:

- **Goldstone boson**
  of broken time translations

$$\delta\phi = \phi(t + \pi) - \bar{\phi}(t)$$

- **Graviton**

EFT of Inflation

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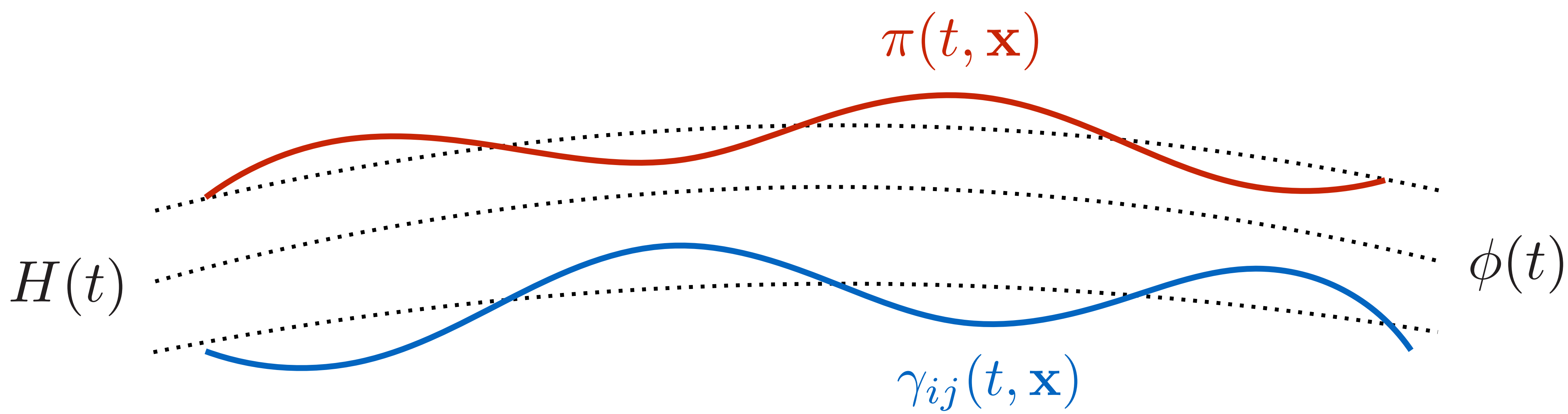

In comoving gauge, the Goldstone boson gets eaten by the metric:

$$g_{ij} = a^2 e^{2\zeta} [e^{\gamma}]_{ij}$$

curvature perturbation $\zeta = -H\pi$

Goldstone Lagrangian

The effective Goldstone Lagrangian is

Creminelli et al. [2006]
Cheung et al. [2008]

$$\mathcal{L}_\pi = M_{\rm pl}^2 \dot{H} (\partial\pi)^2 + \sum_{n=2}^{\infty} \frac{M_n^4}{n!} \left[-2\dot{\pi} + (\partial\pi)^2\right]^n + \cdots$$

$\dot{\phi}^2$ $(\partial\phi)^{2n}$

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$\dot{\phi}^2$ $\qquad\qquad\qquad\qquad$ $(\partial\phi)^{2n}$

There can be a nontrivial **sound speed** for the Goldstone boson:

$$\mathcal{L}_\pi = \frac{M_{\rm pl}^2 |\dot{H}|}{c_s^2} \left(\dot{\pi}^2 - c_s^2 \frac{(\partial_i \pi)^2}{a^2} \right) + \cdots$$

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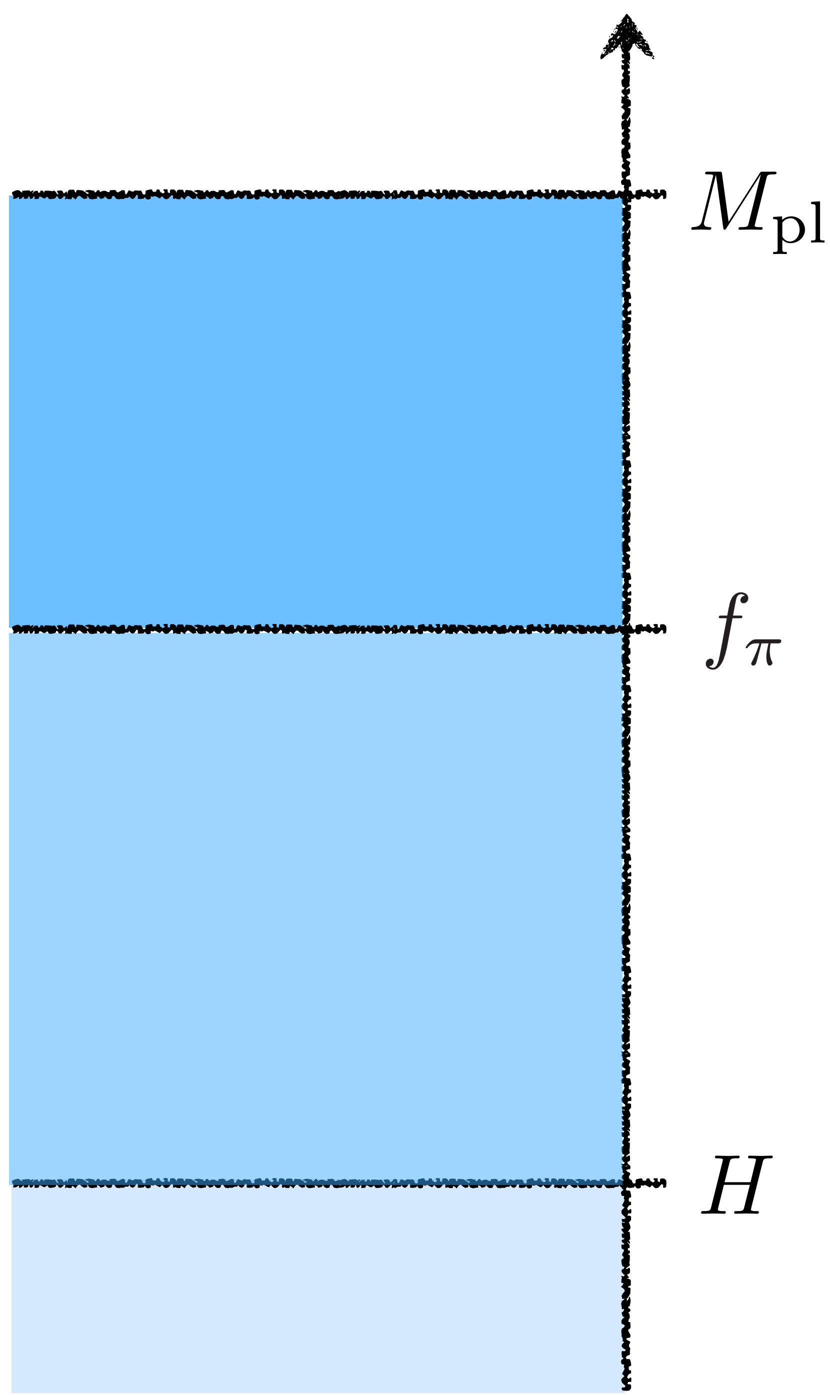
Energy Scales

The minimal model is characterised by three energy scales:



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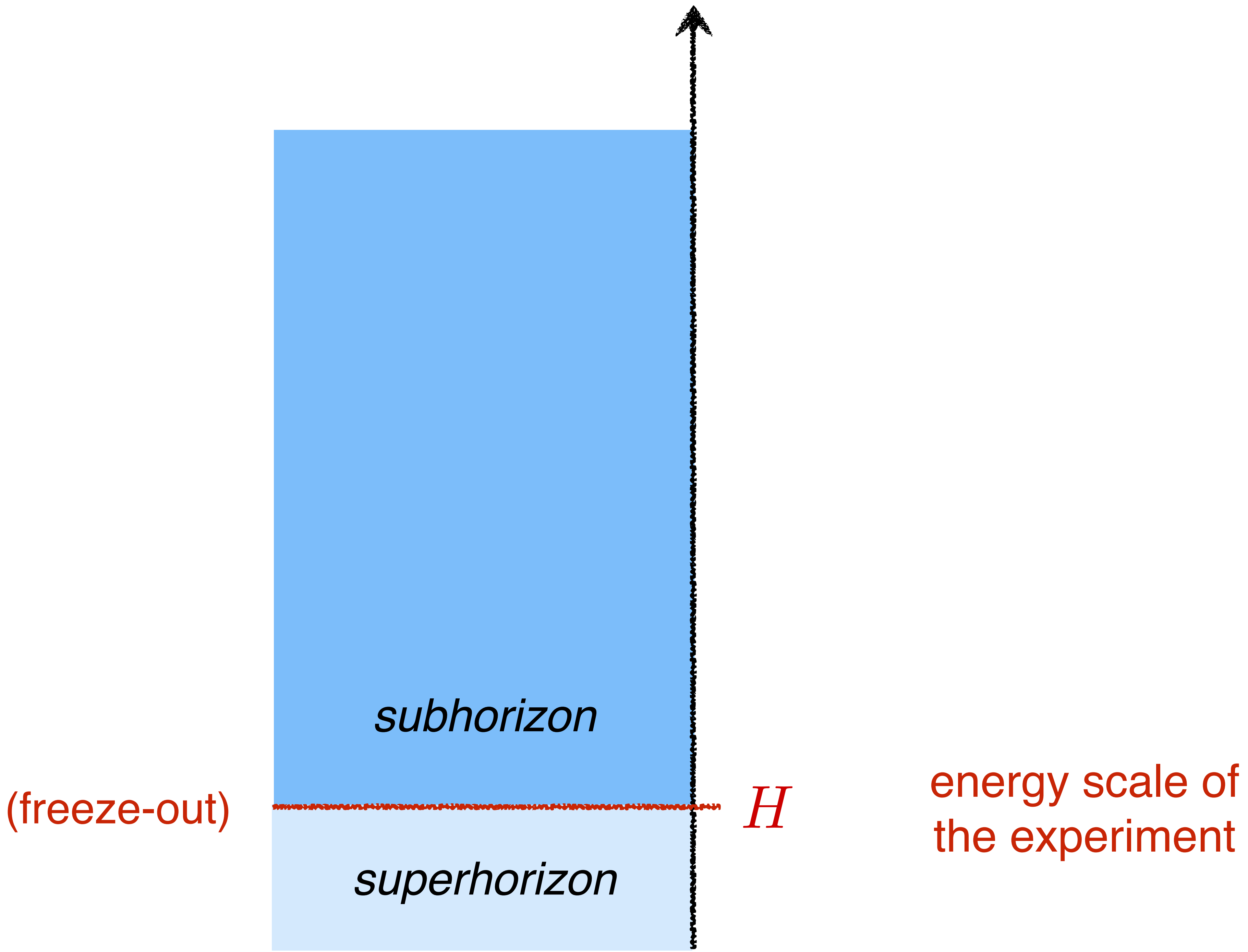

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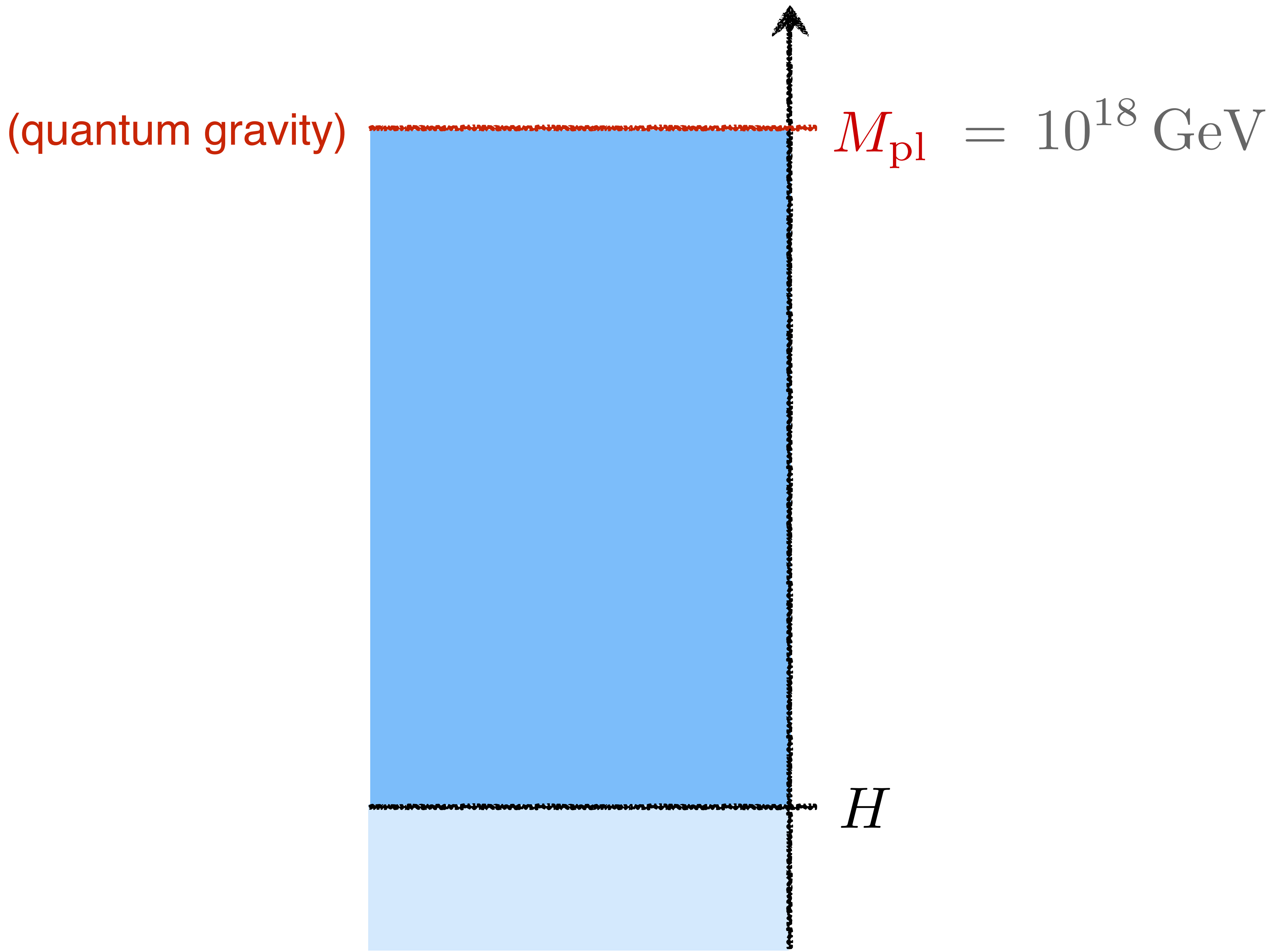

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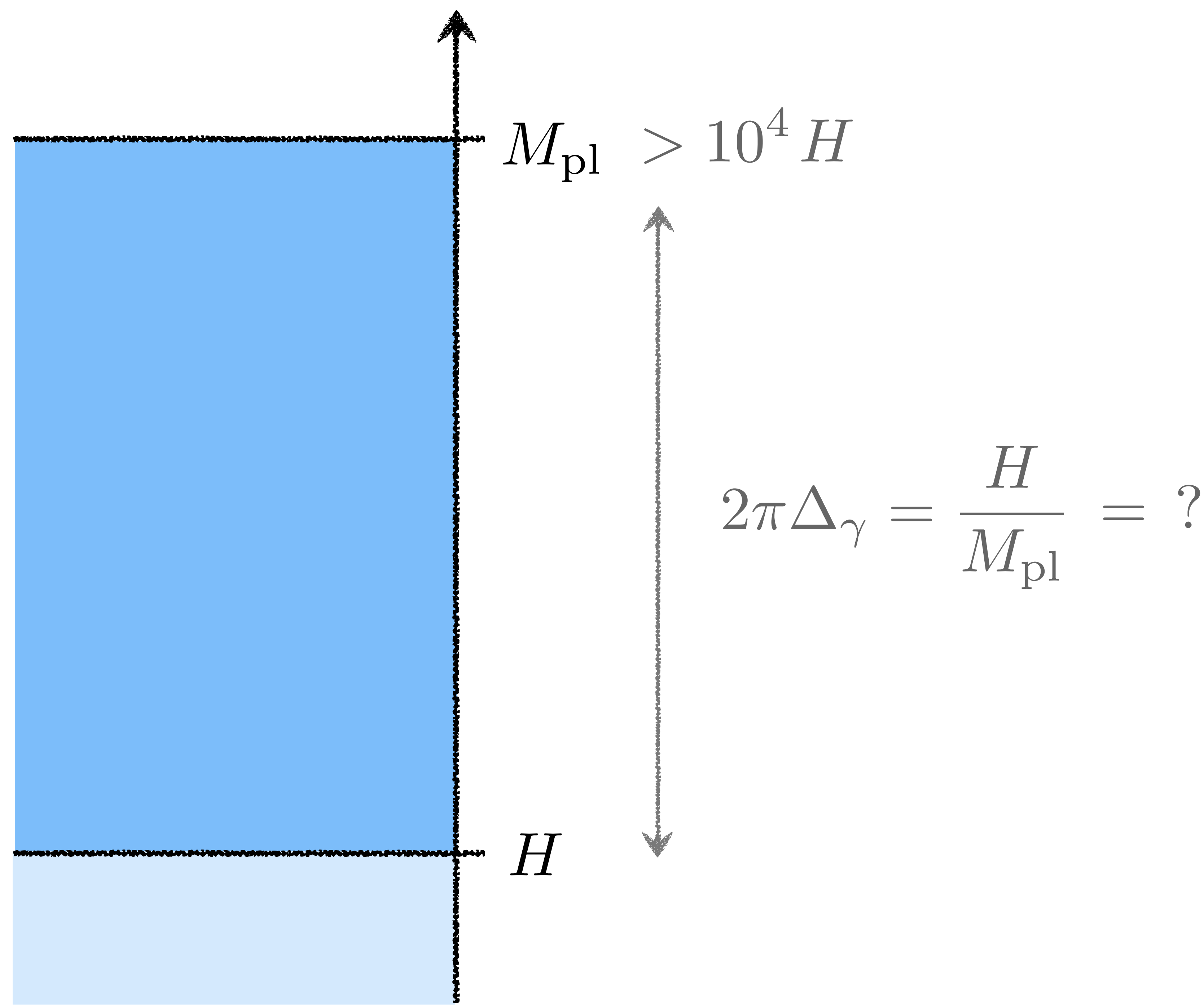

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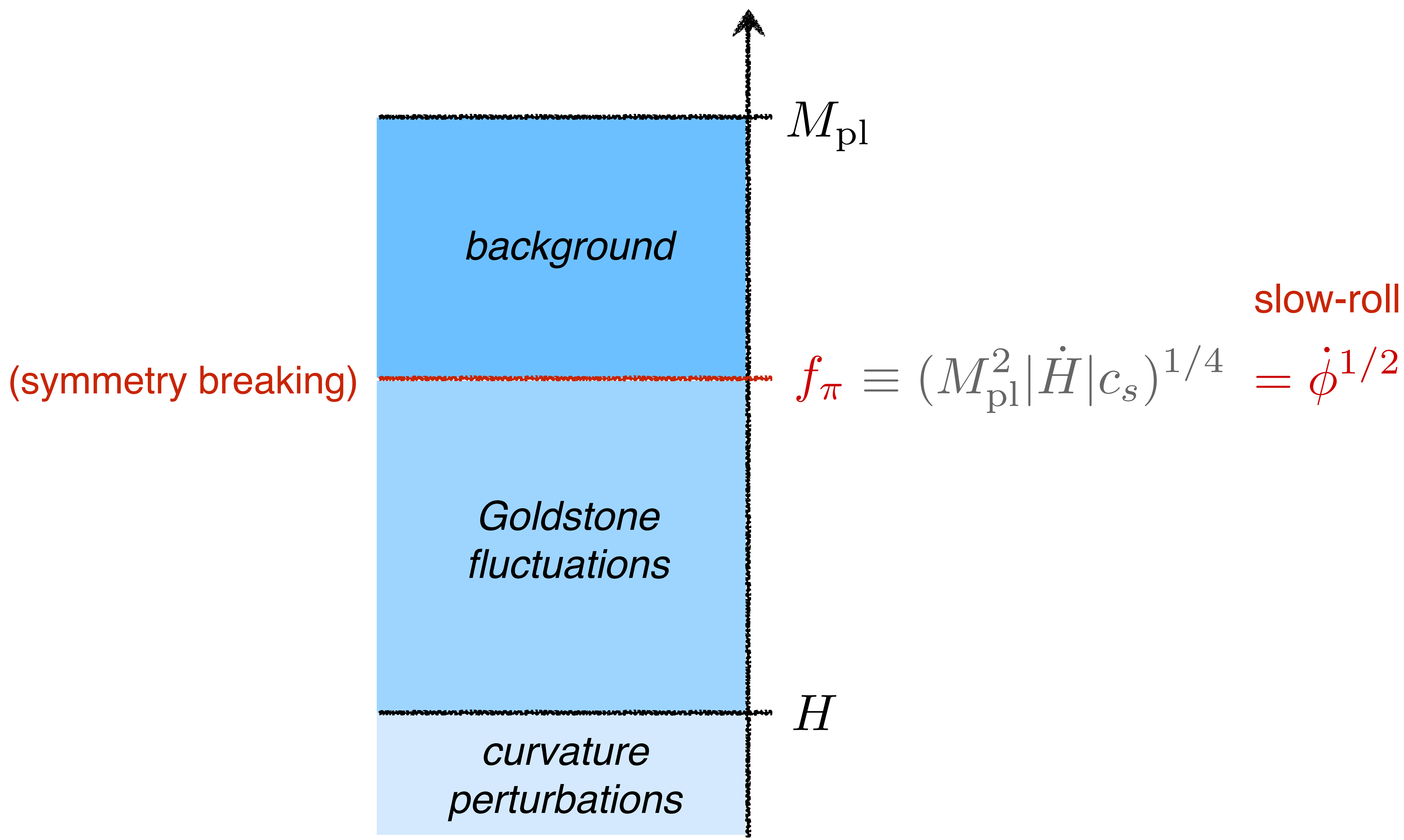

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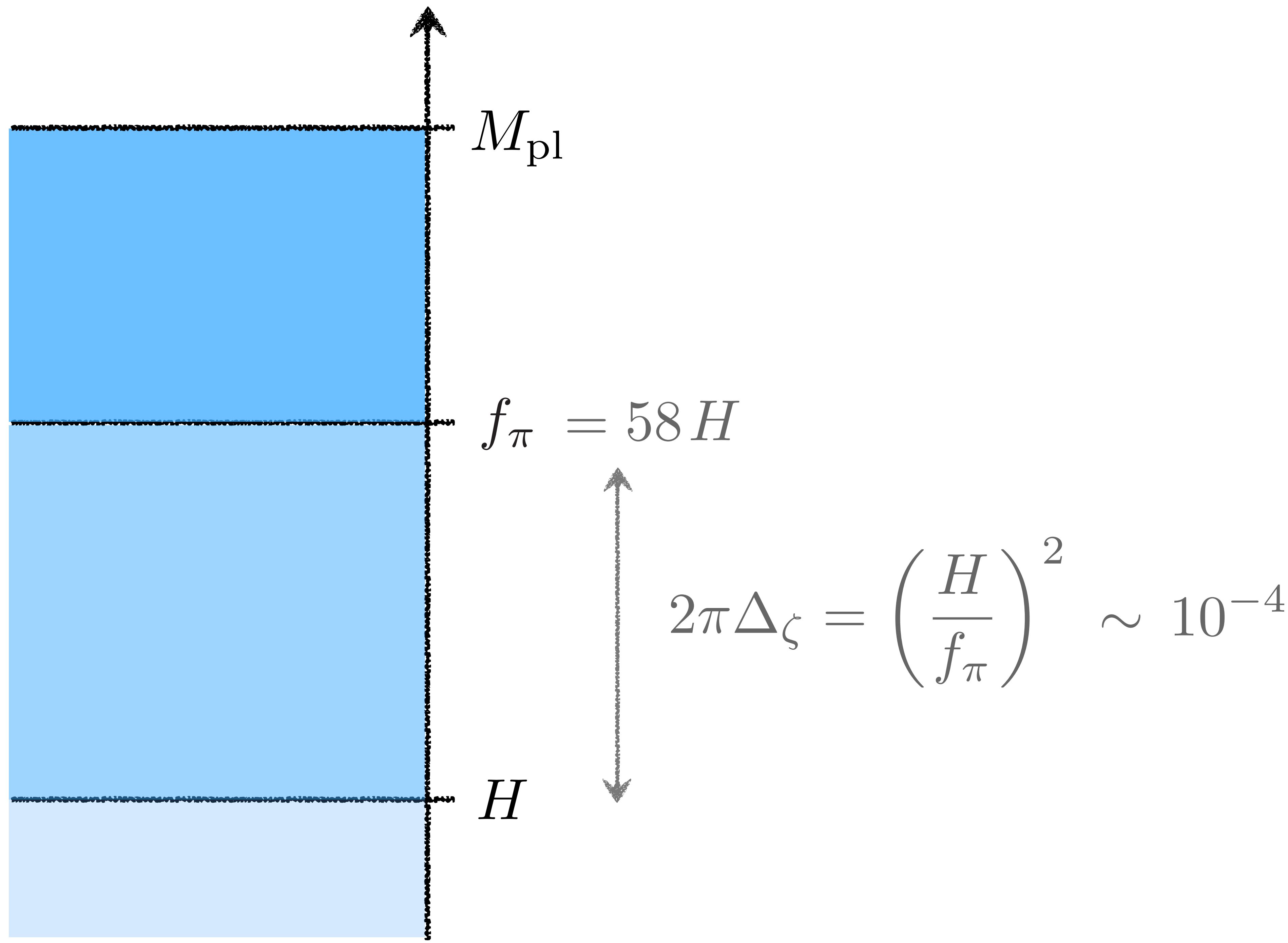
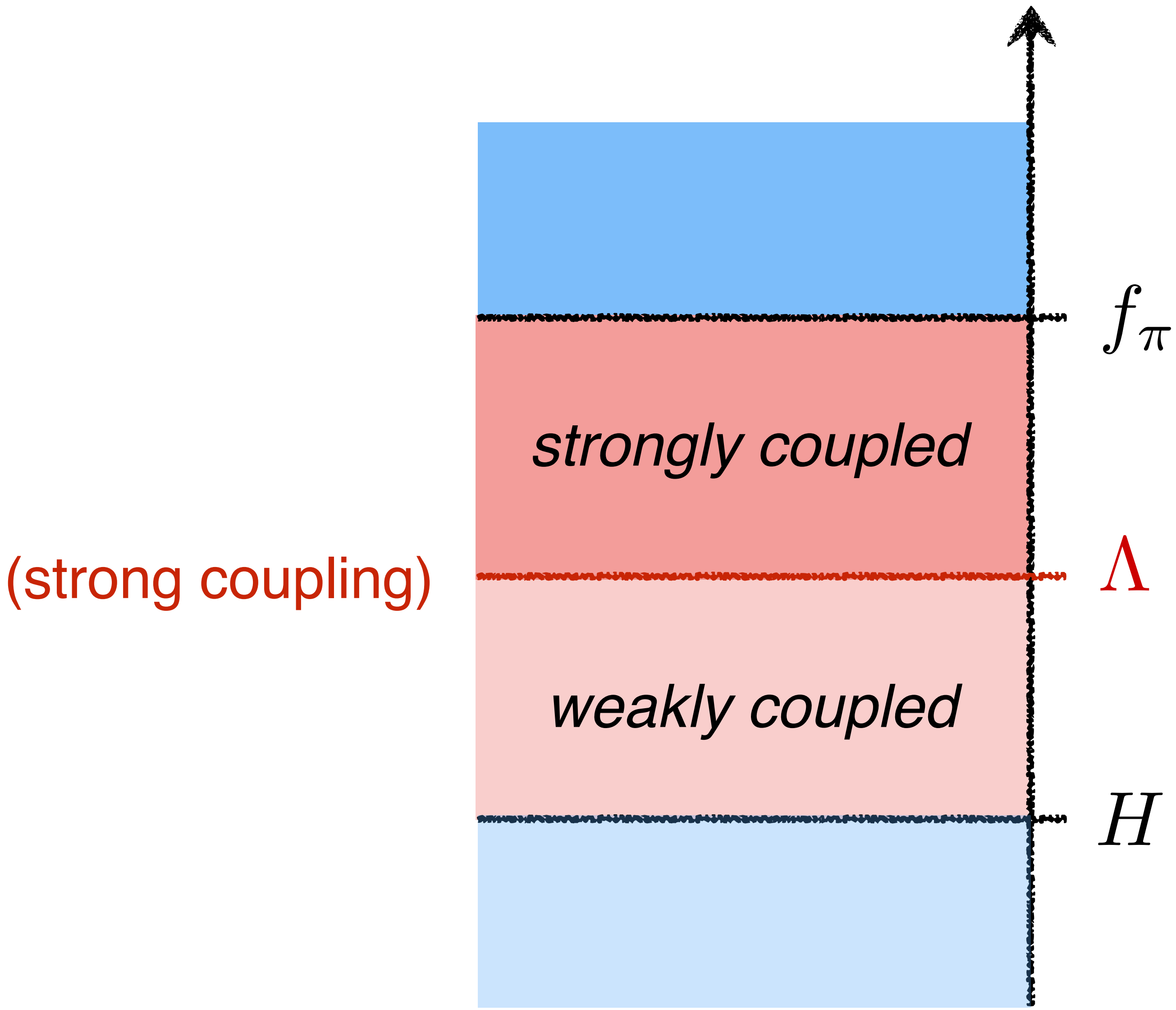


Energy Scales

Closer inspection may reveal additional scales associated with the interactions of the Goldstone boson:



These are constrained by the high degree of Gaussianity of the primordial perturbations.

Goldstone Interactions

The self-interactions of the Goldstone boson take the following form:

$$\mathcal{L}_\pi \subset \frac{1}{\Lambda^2}\left[\frac{\dot{\pi}_c(\partial_i \pi_c)^2}{c_s^2} + c_3\,\dot{\pi}_c^3\right] + \frac{1}{\Lambda^4}\left[c_4\,\dot{\pi}_c^4 + \cdots\right]$$

Cheung et al. [2008]

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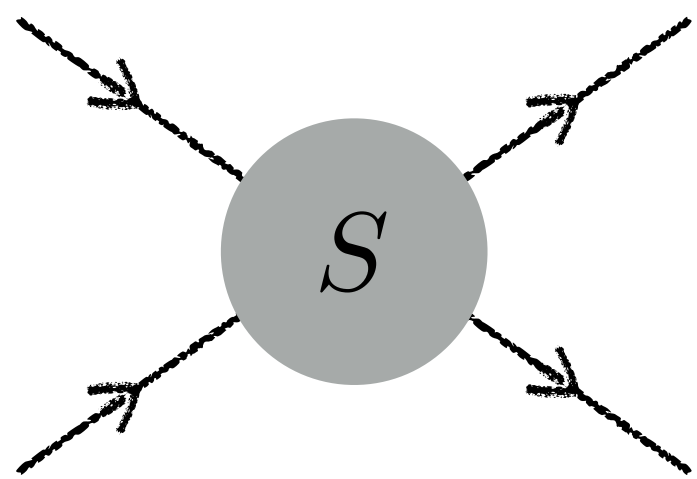
The parameters of the EFT are constrained by **unitarity** and **causality** of Goldstone scattering:



DB, Green, Lee and Porto [2015]

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Cheung et al. [2008]

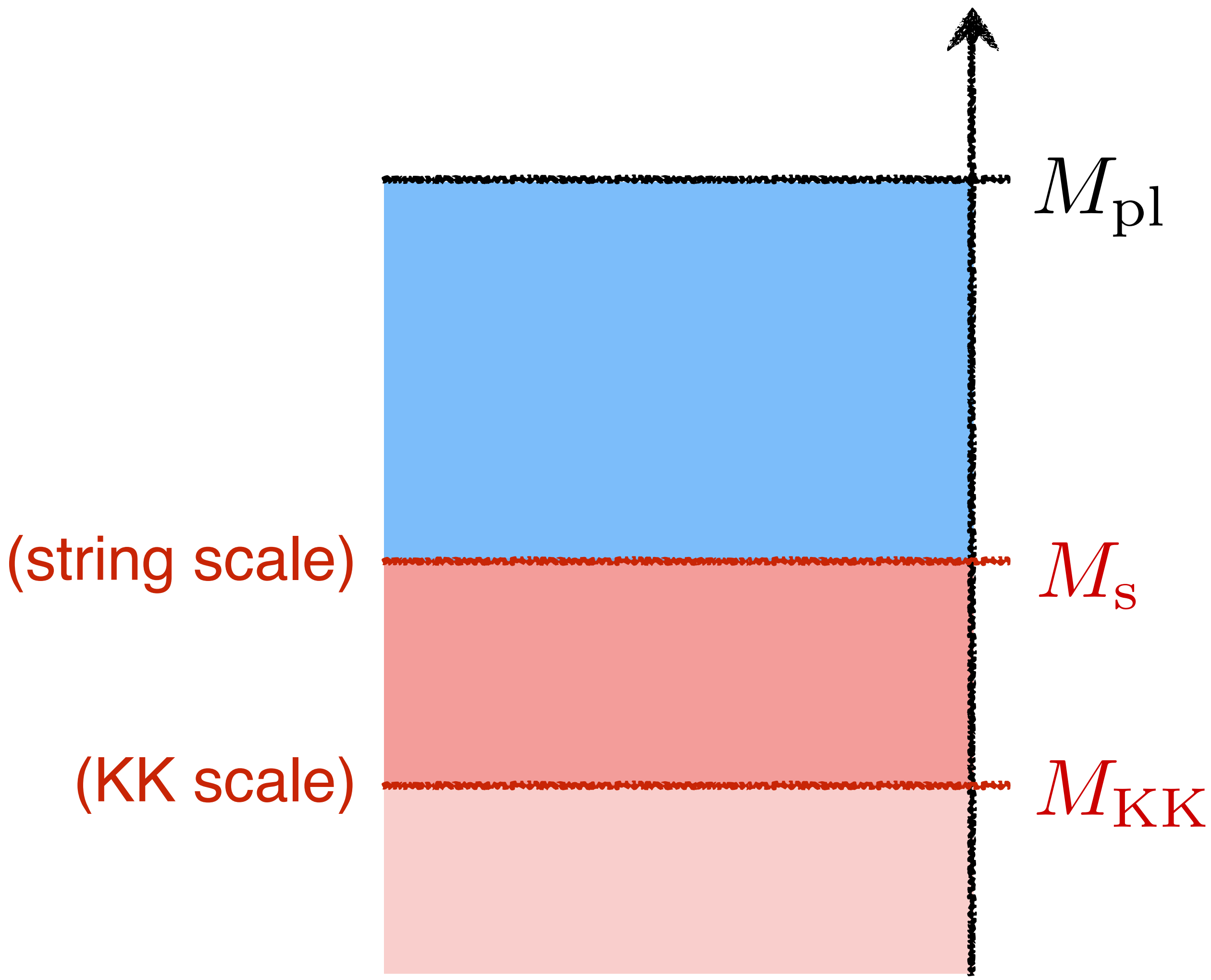
The parameters of the EFT are constrained by **unitarity** and **causality** of Goldstone scattering:

- The theory satisfies perturbative unitarity up to the symmetry breaking scale iff $c_s > 0.31$
- Causality implies a positivity constraint on the quartic coupling $c_4 > (2c_3)^2$

DB, Green, Lee and Porto [2015]

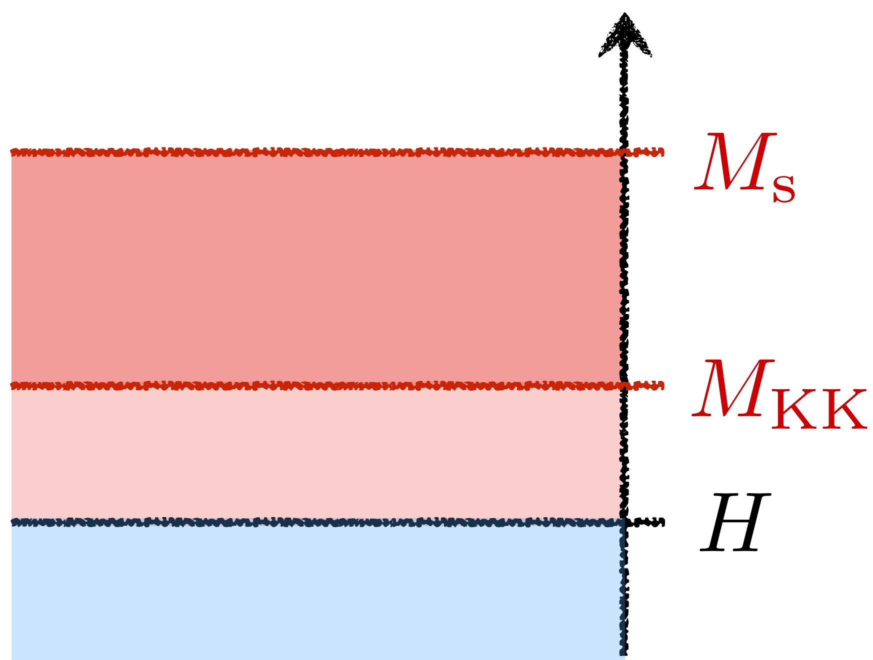
Ultraviolet Completion

The UV completion of inflation requires new scales below the Planck scale:



Ultraviolet Completion

For high-scale inflation these scales may not be far from the Hubble scale:



The inflationary perturbations can be affected by those scales:

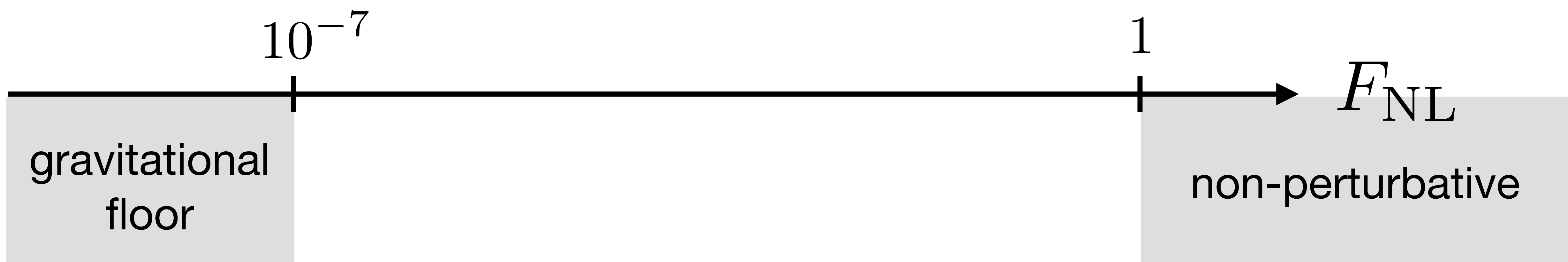
Non-Gaussianity

Modified Tensors

Non-Gaussianity

Non-Gaussianity

The theoretically interesting regime of non-Gaussianity spans about seven orders of magnitude:



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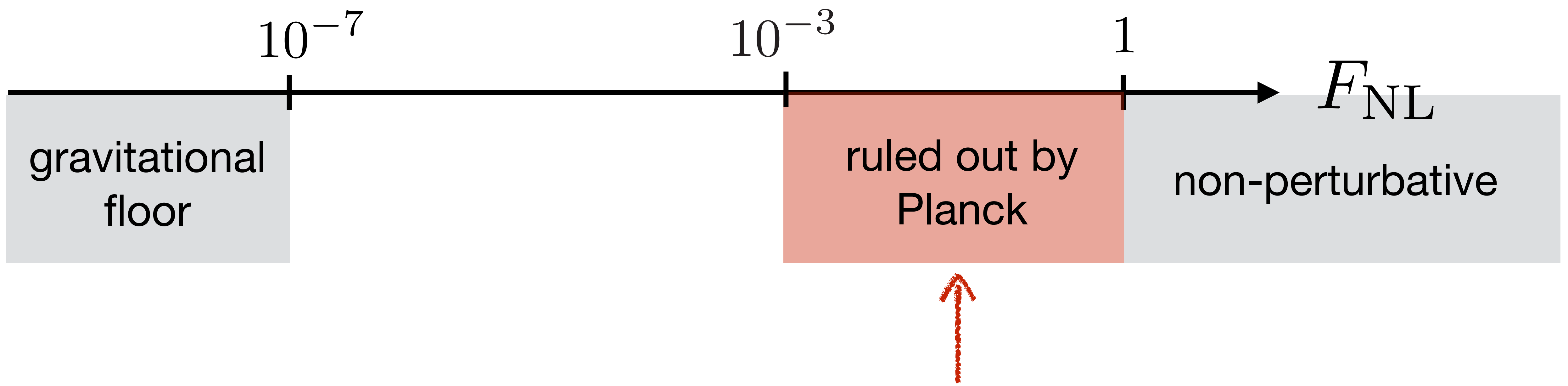

Planck has ruled out three orders of magnitude.

Non-Gaussianity

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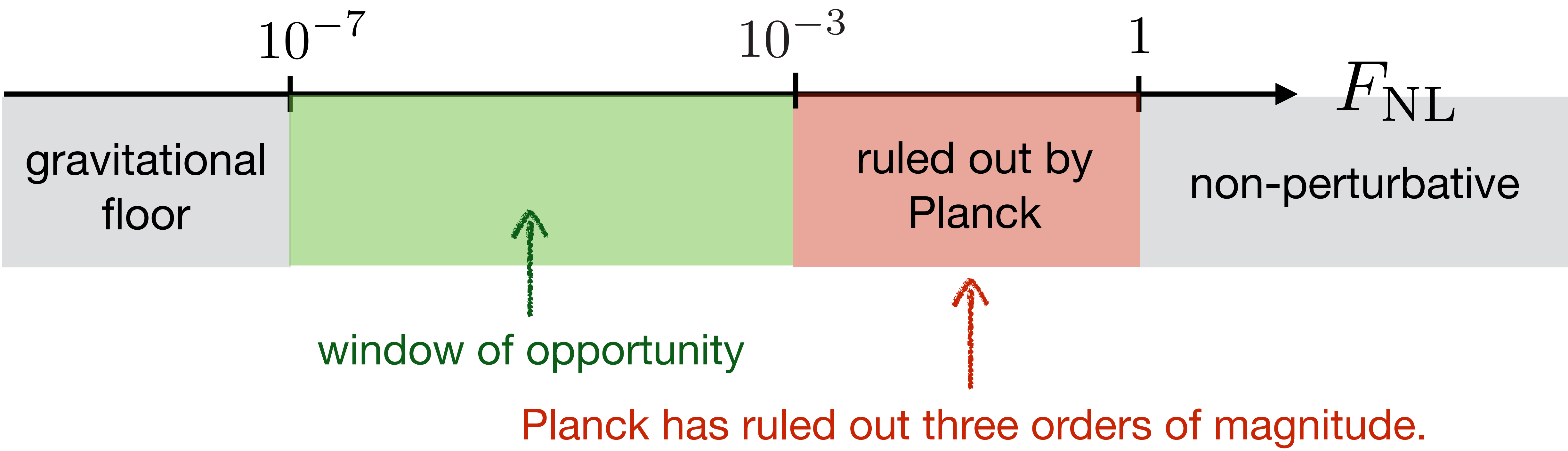
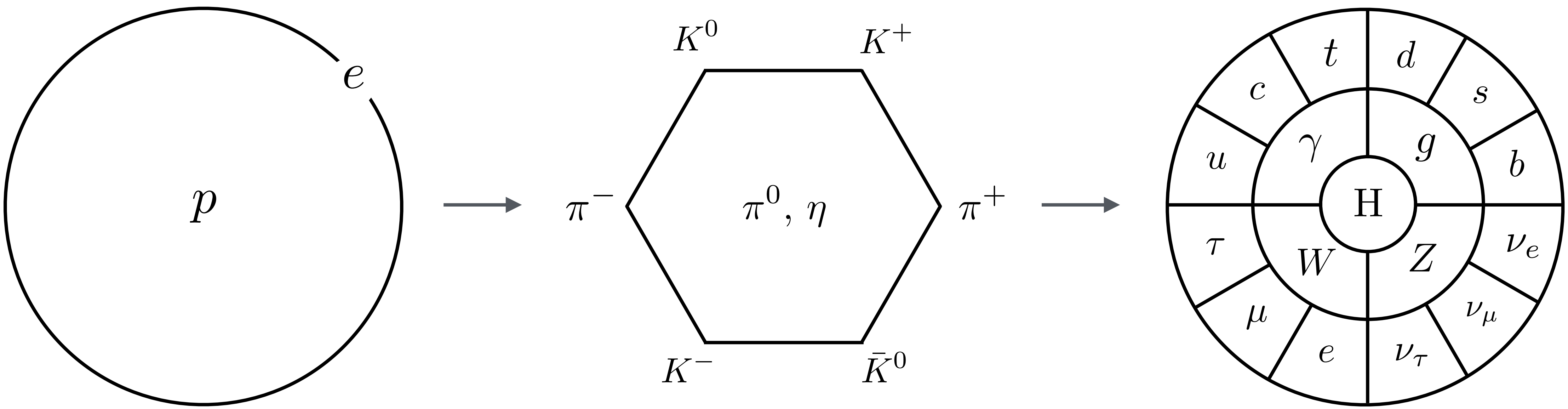


There is still room for new particles to leave their mark.

Particle Physics

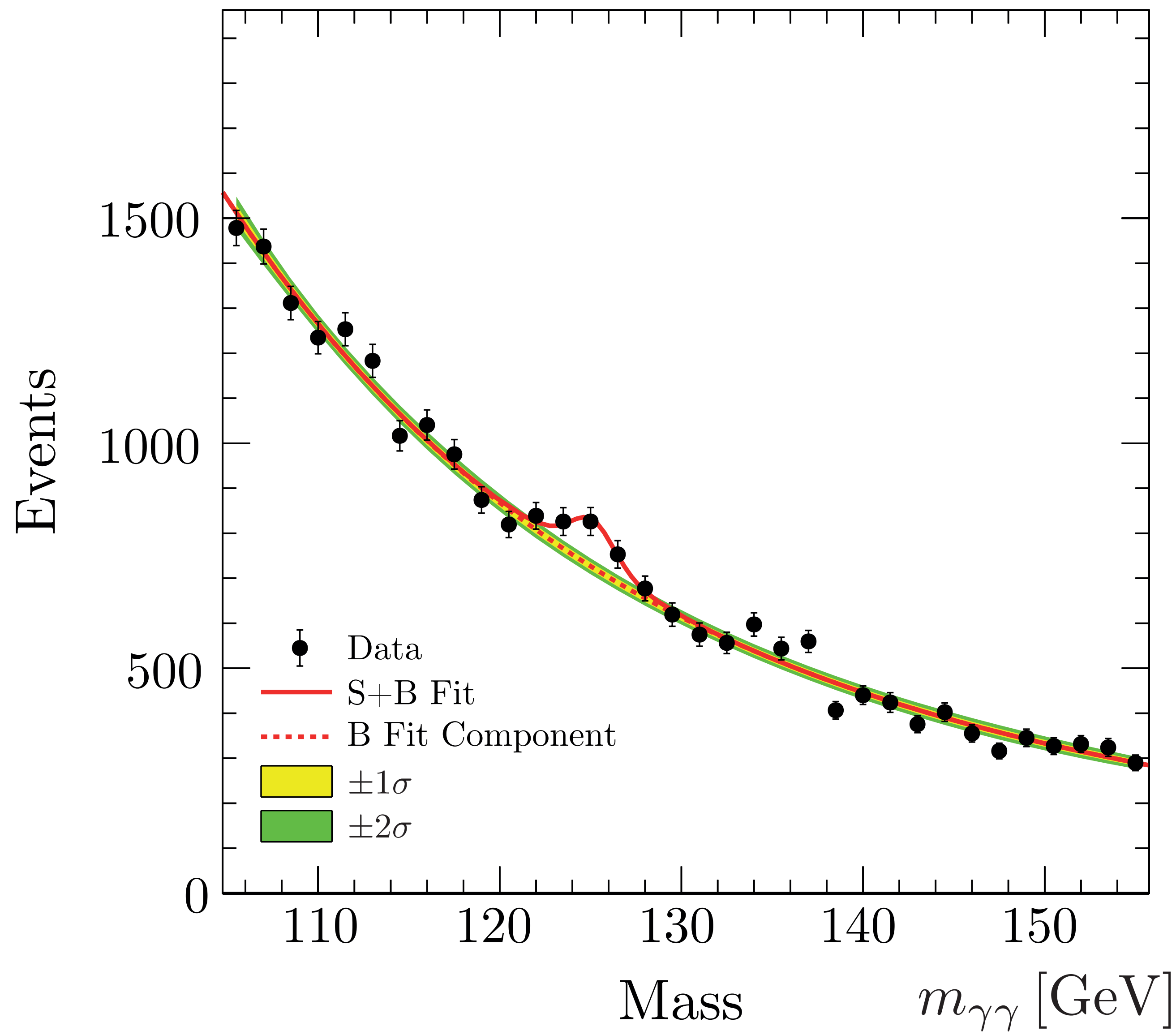
In particle physics, the discovery of new particles has helped to uncover the fundamental laws of physics.



In cosmology, the discovery of new particles during inflation could play a similar role and help to uncover the physics of inflation.

Particle Physics

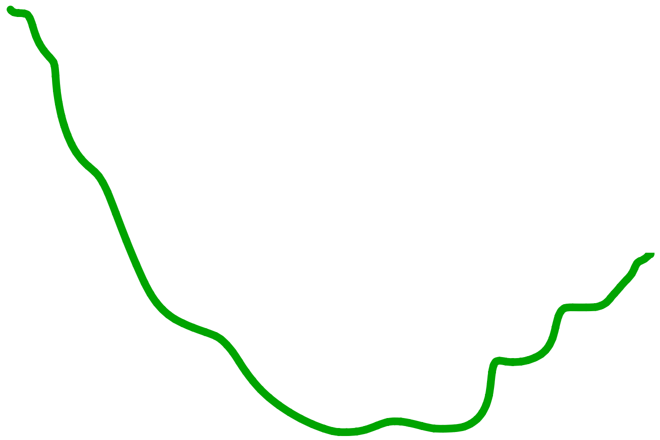
In particle physics, we identify new particles through resonances.



In cosmology, we do something very similar.

Cosmological Collider

Massive particles are spontaneously created in an expanding spacetime.

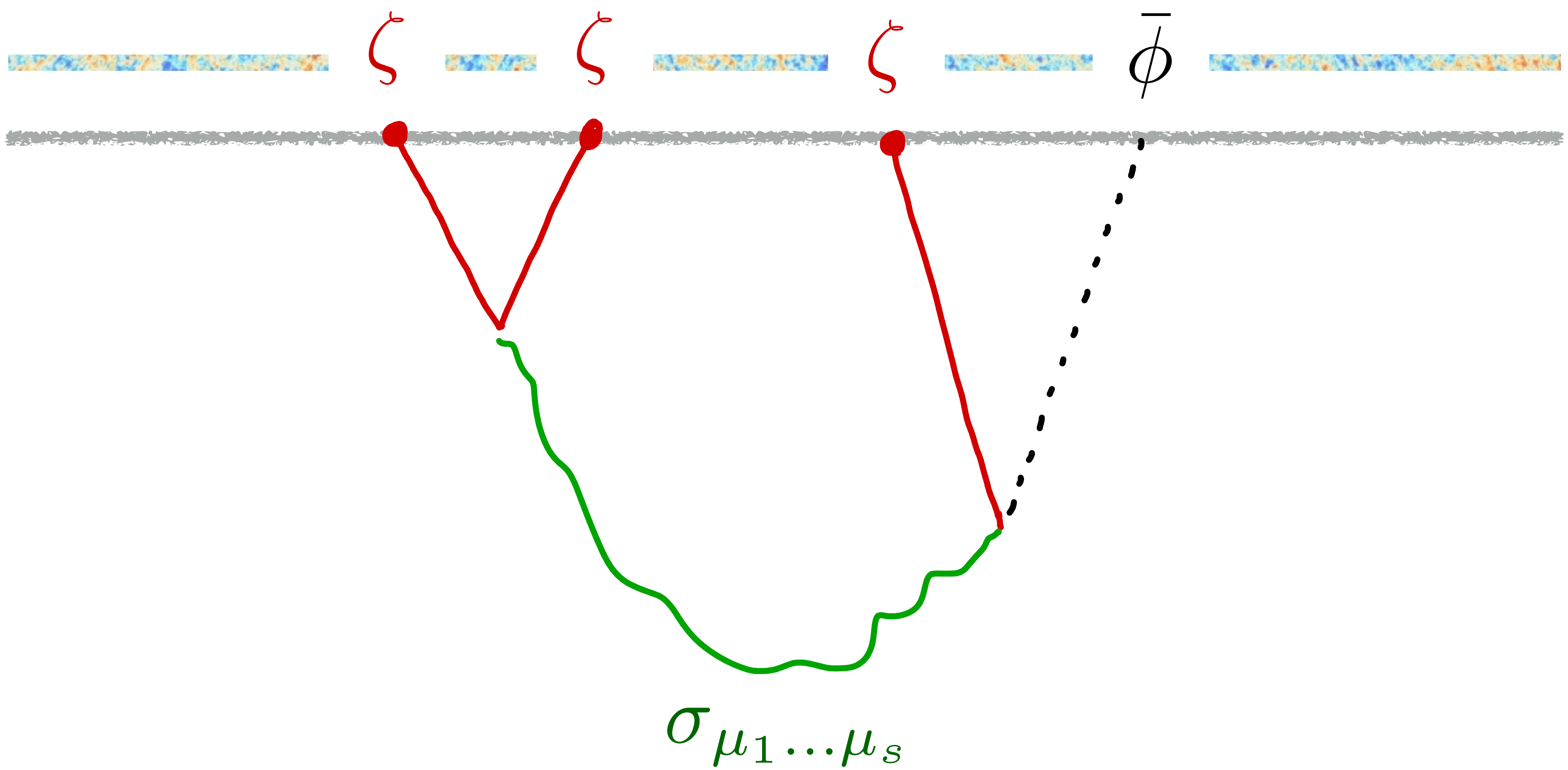


$\sigma_{\mu_1 \ldots \mu_s}$

However, they cannot be directly observed at late times.

Cosmological Collider

Instead, they decay into light fields.



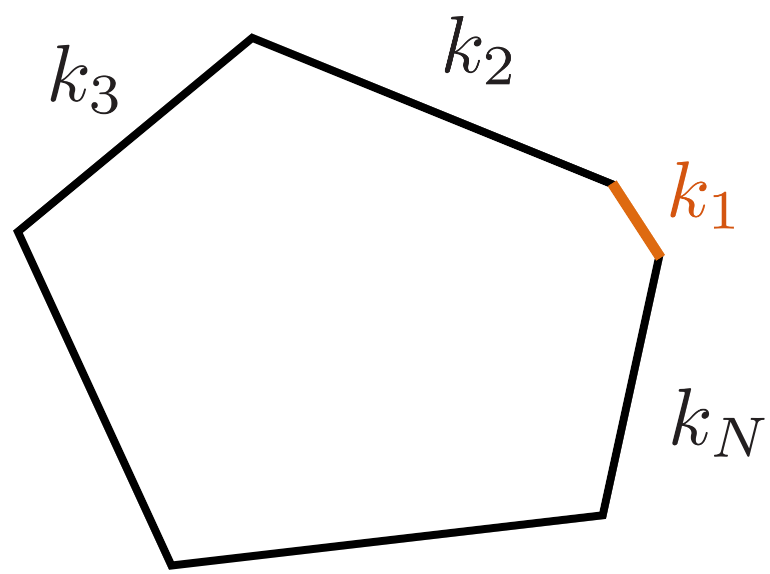
These correlated decays create distinct higher-order correlations in the inflationary perturbations.

Soft Limits

N-point functions in single-field 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**.

Scalar Consistency Relation

The squeezed limit of the bispectrum in single-field inflation satisfy the following consistency relation:

$$\boxed{\lim_{k_1\to 0} \frac{\langle \zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\rangle'}{P_\zeta(k_1)P_\zeta(k_2)} = -\frac{d\ln[k_2^3 P_\zeta(k_2)]}{d\ln k_2}} = \underbrace{(1-n_s)}_{\textit{unobservable}}$$

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]
Lee, DB and Pimentel [2016]

Tensor Consistency Relation

A similar consistency condition exists if the soft mode is a tensor mode:

$$\boxed{\lim_{k_1\to 0} \frac{\langle \gamma^{\lambda}_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle'}{P_\gamma(k_1) P_\zeta(k_2)} = \epsilon^{\lambda}_{ij} k_2^i k_2^j \, \frac{d \ln P_\zeta(k_2)}{d k_2^2}}$$

$$= \epsilon^{\lambda}_{ij} k_2^i k_2^j \, [3 - (1 - n_s)]$$

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

Bordin et al [2016]

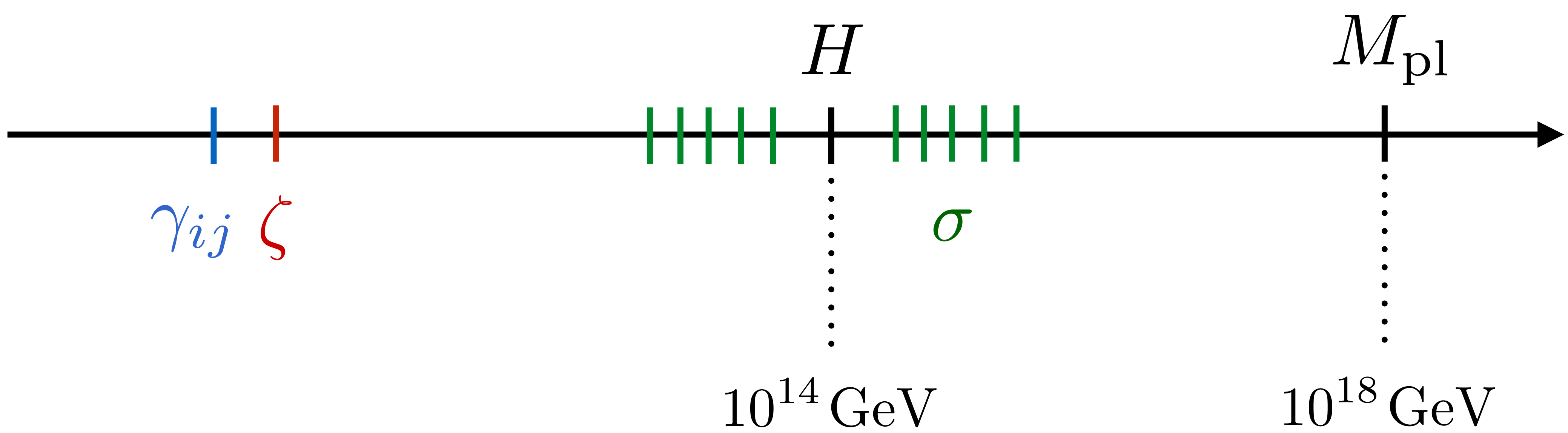
Lee, DB and Pimentel [2016]

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

Cosmological Collider

NG allows us to probe the particle spectrum at inflationary energies:



These particles could inform the UV completion of inflation.

We will treat these effects as additional particles in the EFT of inflation.

Wigner's Classification

Particles are classified by their masses and spin:

		degrees of freedom
• Particles in flat space can be	**massless**	2
	massive	$2s+1$
• Particles in de Sitter can be	**massless**	2
	massive	$2s+1$
	partially massless	$< 2s+1$

Particles in de Sitter

Particles in de Sitter space fall into three categories:

discrete	complementary	principal
$\dfrac{m^2}{H^2} = s(s-1) - t(t+1)$	$s(s-1) < \dfrac{m^2}{H^2} < \left(s - \dfrac{1}{2}\right)^2$	$\dfrac{m^2}{H^2} \geq \left(s - \dfrac{1}{2}\right)^2$
(partially) massless	**massive**	

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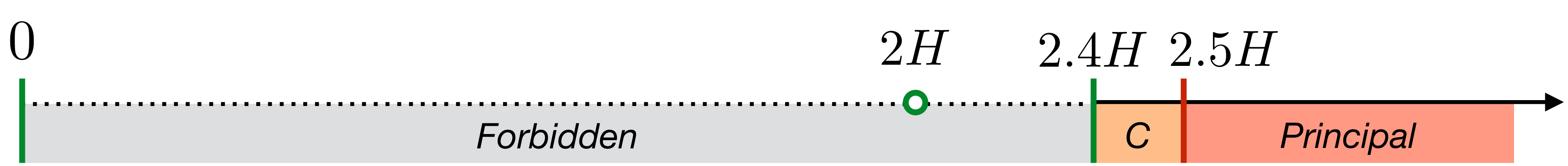
(partially) massless	**massive**	

E.g. the mass spectrum of a **spin-3 particle**:



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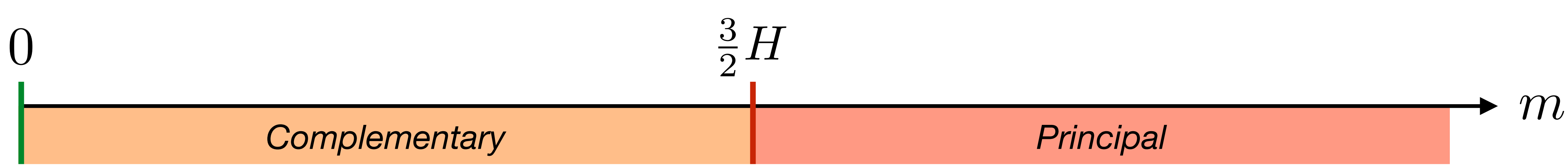
E.g. the mass spectrum of a **scalar field**:

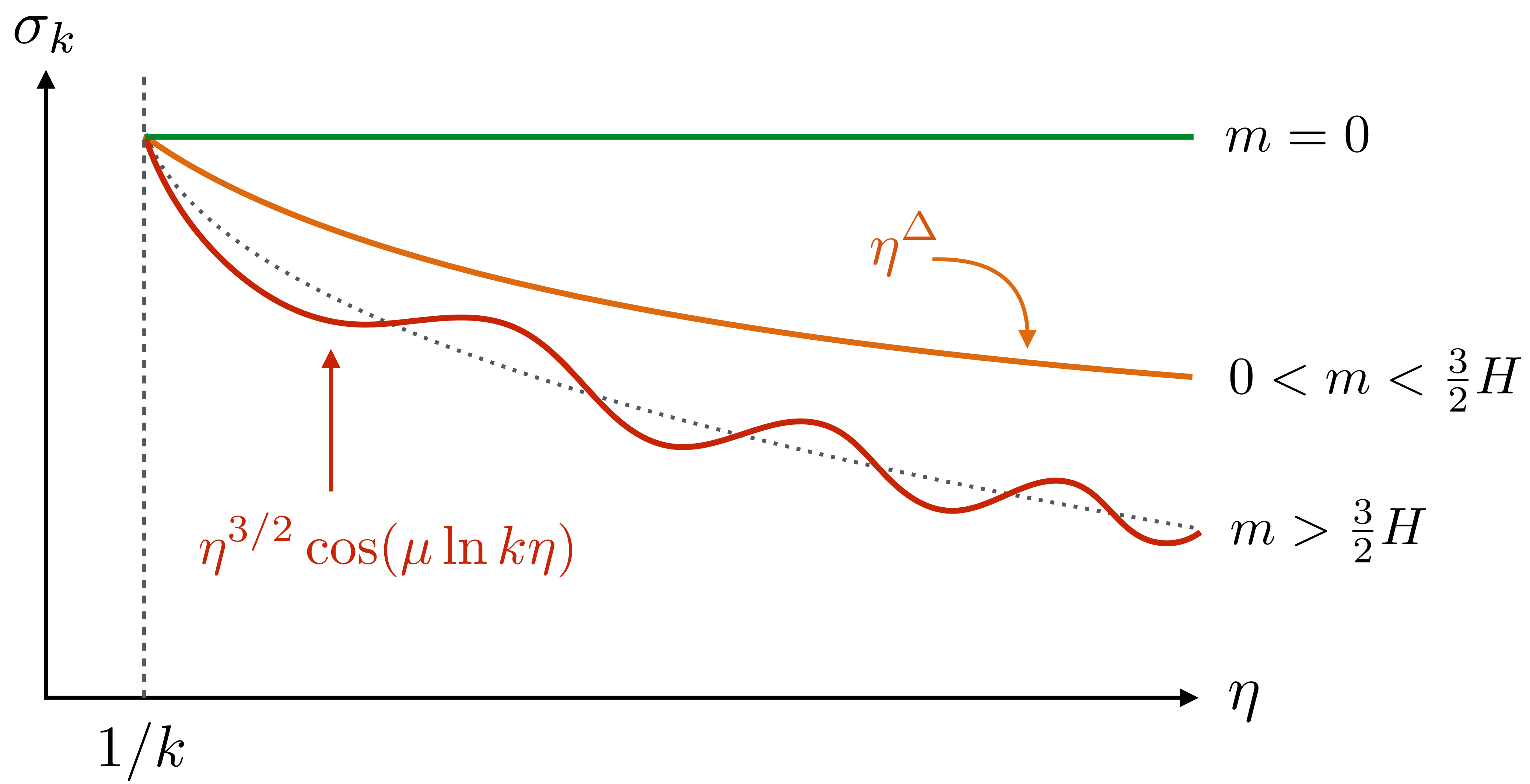


Chen, Wang [2009]
DB, Green [2011]
Noumi et al. [2012]

Arkani-Hamed, Maldacena [2015]
Lee, DB, Pimentel [2016]

Superhorizon Evolution

Massive particles evolve on superhorizon scales:

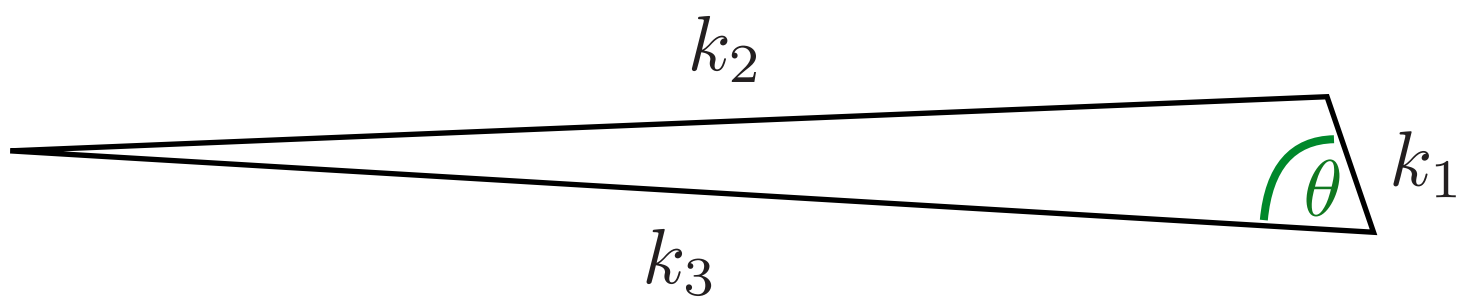


The time dependence is determined by the mass

$$\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

Squeezed Limit

This superhorizon evolution is reflected in the momentum dependence of the soft limit:



$$\lim_{k_1 \to 0} \langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle' \propto \begin{cases} \left(\dfrac{k_1}{k_3}\right)^{\Delta} & m < \frac{3}{2} H \\ \left(\dfrac{k_1}{k_3}\right)^{3/2} \cos\left[\mu \ln \dfrac{k_1}{k_3}\right] & m > \frac{3}{2} H \end{cases}$$

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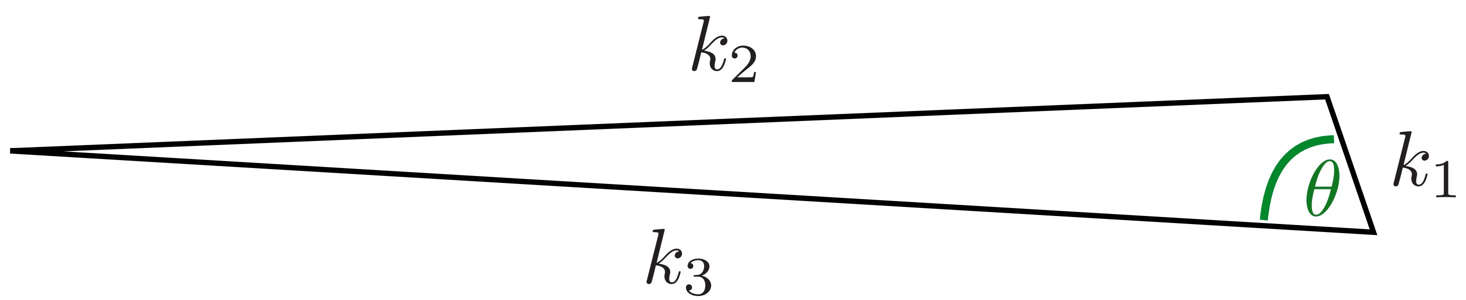

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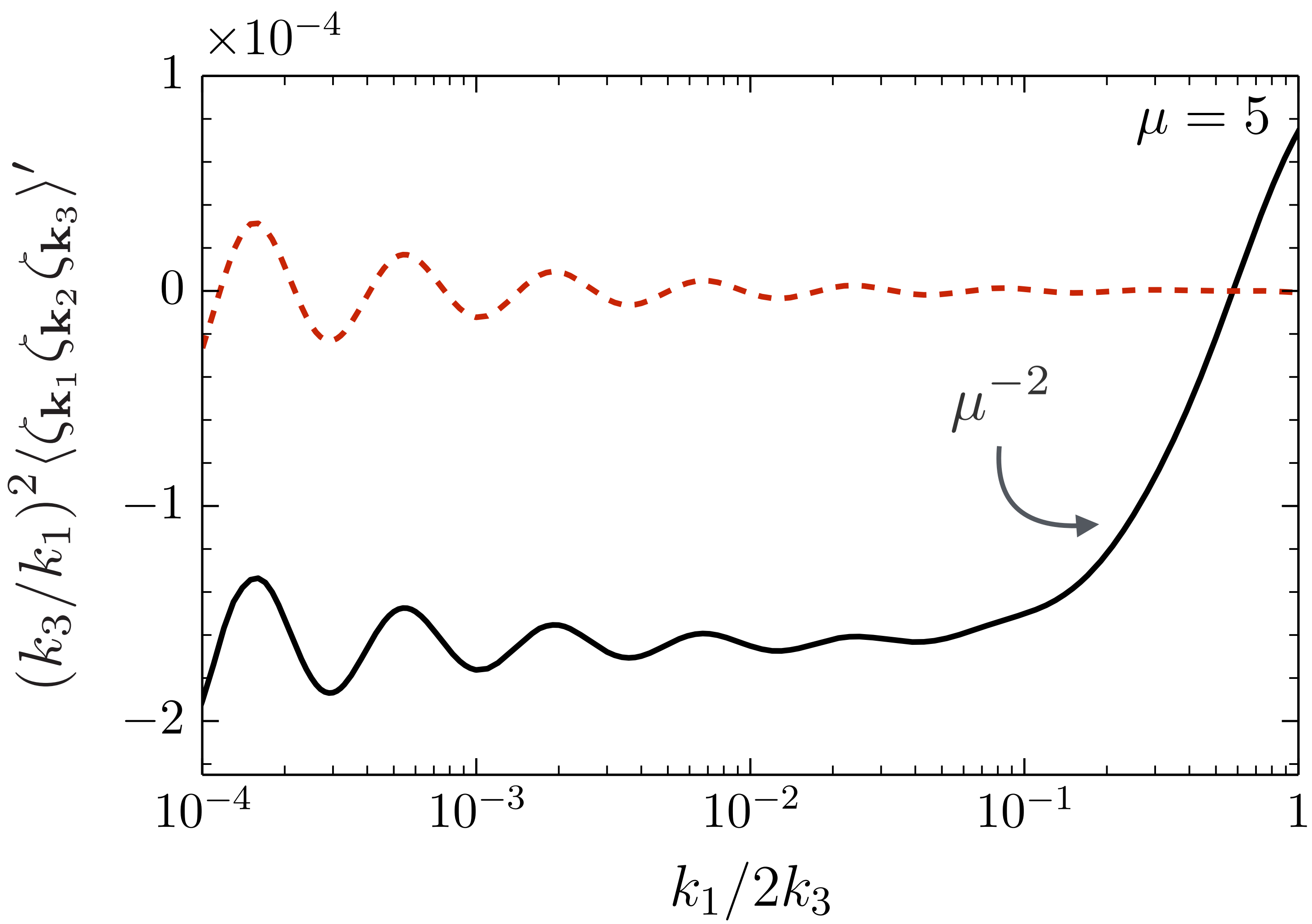
$$\propto P_s(\cos\theta)$$

spin

Mass Dependence

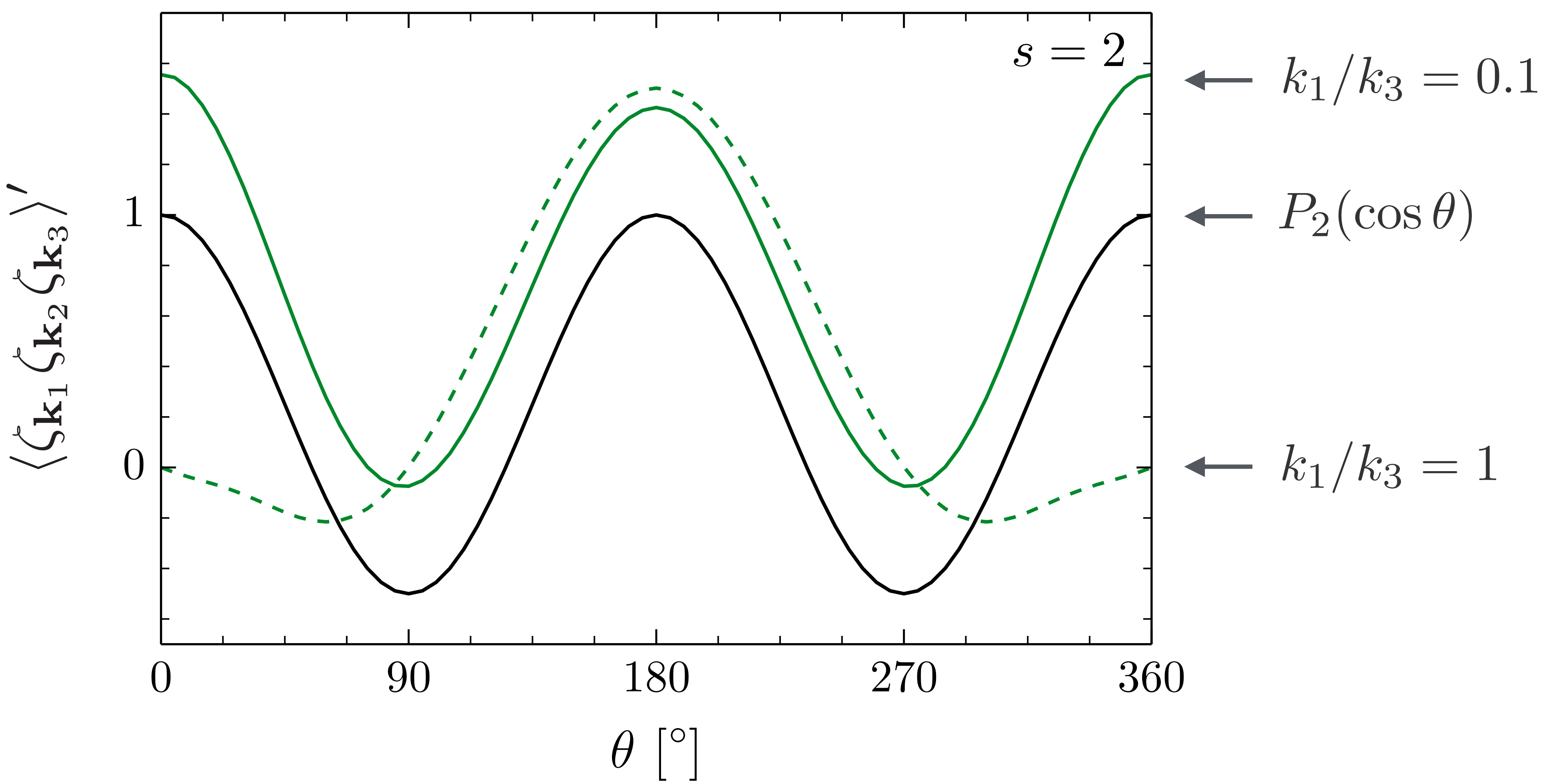
Oscillations in the squeezed limit determine the **mass** of the particle:



like resonances in particle colliders.

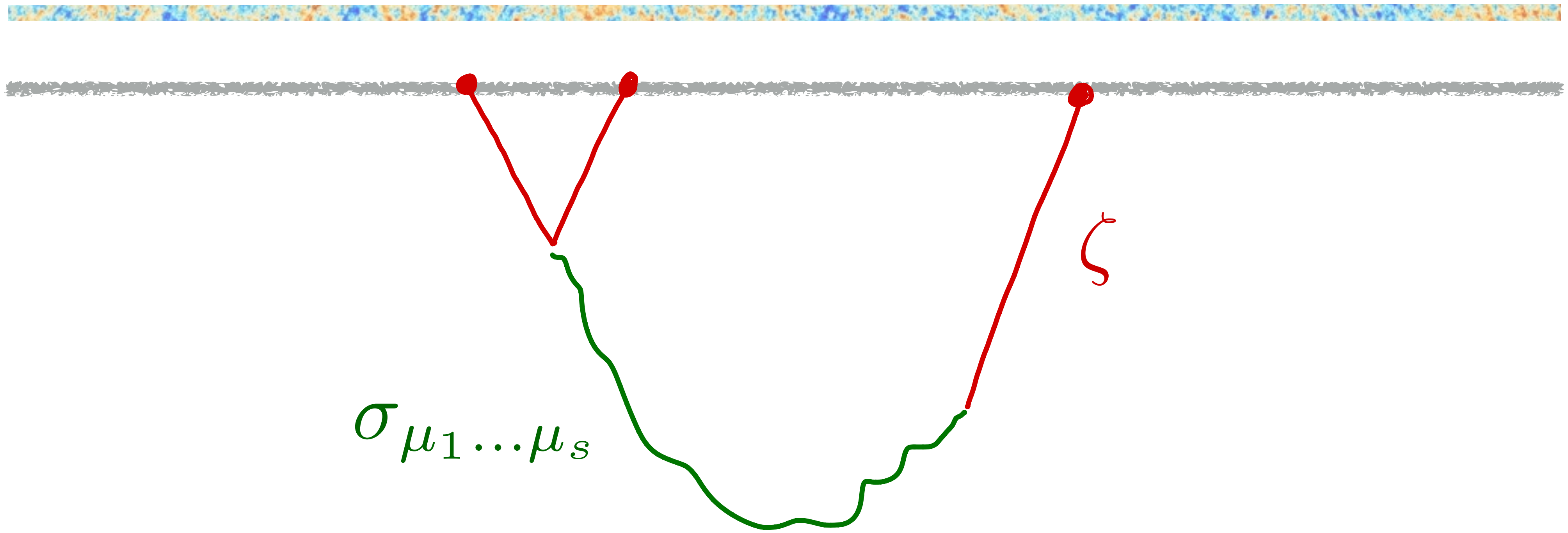
Spin Dependence

The angular dependence of the squeezed limit determines the **spin** of the particle:



like the angular dependence of the final states in particle colliders.

Scalar Squeezed Limit



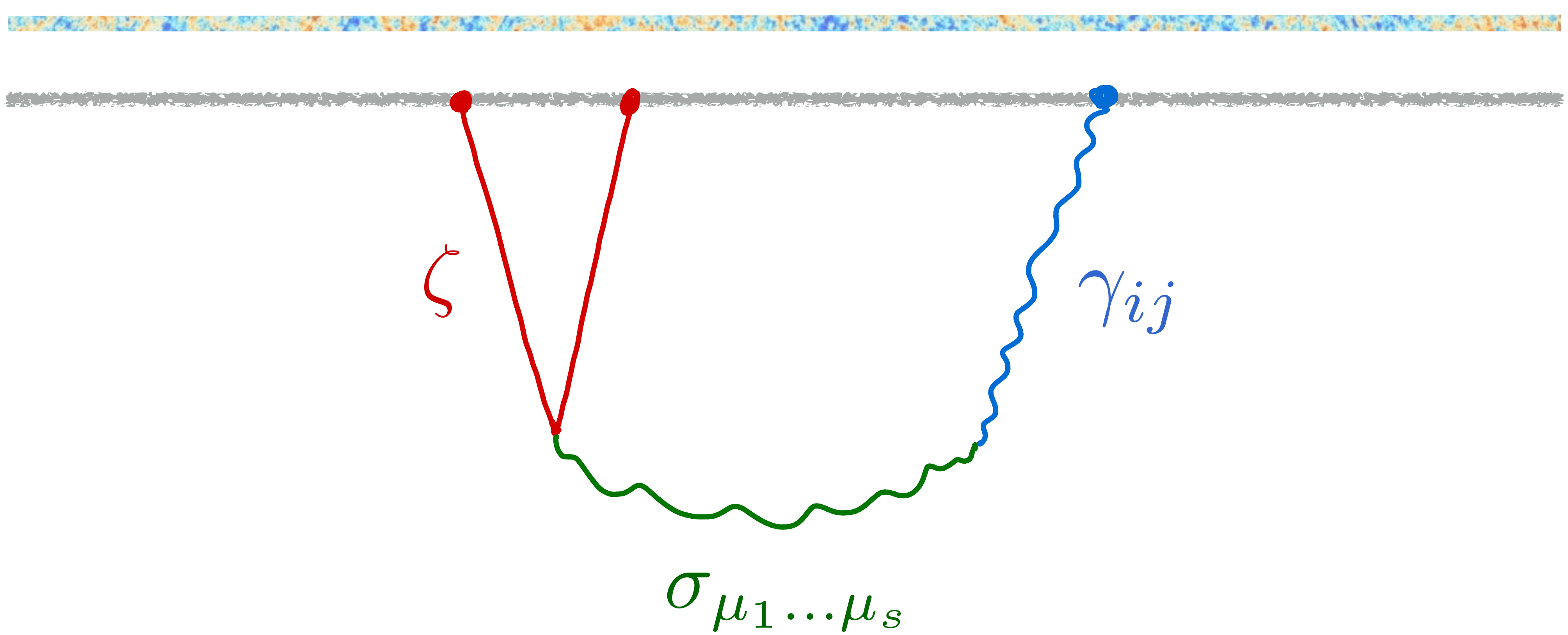
The signal may be observable in the <TTT> correlator, in the galaxy power spectrum (via scale-dependent bias) and in the galaxy bispectrum.

Moradinezhad Dizgah and Dvorkin [2017]
Chen, Dvorkin, Huang, Namjoo and Verde [2016]
Meerburg, Munchmeyer, Munoz and Cheng [2016]
Sefusatti, Fergusson, Chen and Shellard [2012]

Tensor Squeezed Limit

Partially massless fields may leave an imprint in the T-S-S bispectrum:

$$\lim_{k_1 \to 0} \langle \gamma^{\lambda}_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle' \propto \epsilon^{\lambda}_{ij}(k_1) k_2^i k_2^j \, P_s^{\lambda}(\cos\theta)$$



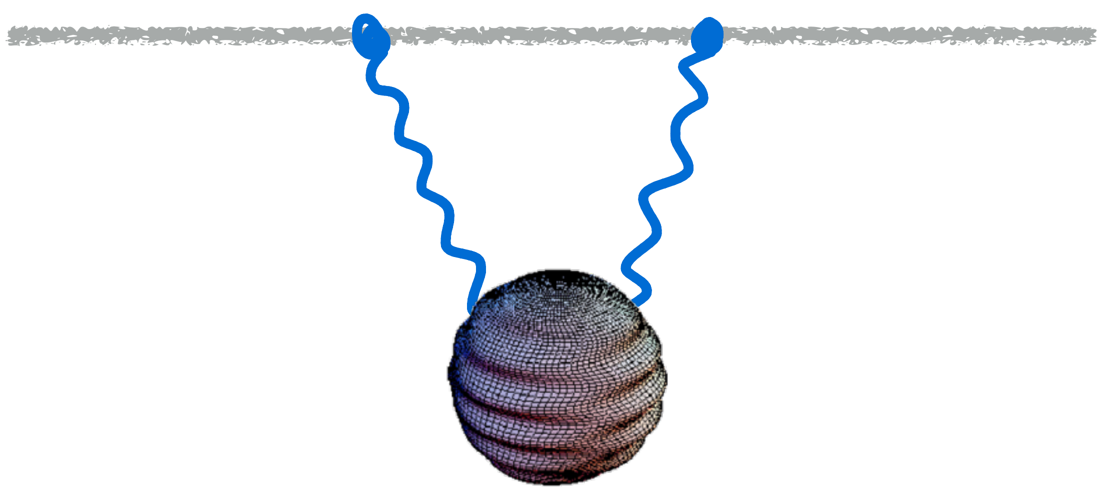
The signal may be observable in the <BTT> correlator.

Meerburg et al. [2016]
CMB Stage-IV [2016]

Tensor Modes

Minimal Tensors

The inflationary prediction for tensors is more robust than the prediction for scalars:



$$= \frac{2}{\pi^2}\frac{H^2}{M_{\rm pl}^2}$$

The spectrum is **scale invariant**, **Gaussian** and **parity symmetric**.

These properties may be broken by stringy effects.

Non-minimal Tensors

High-scale inflation is sensitive to gravitational corrections:

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

Non-minimal Tensors

High-scale inflation is sensitive to gravitational corrections:

Einstein

Weyl

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

anomalous tensor tilt
DB, Lee and Pimentel [2015]

parity violation
Lue, Wang and Kamionkowski [1998]

tensor non-Gaussianity
Maldacena and Pimentel [2011]

parity violation
Soda, Kodama and Mozawa [2011]

Non-minimal Tensors

High-scale inflation is sensitive to gravitational corrections:

Einstein

Weyl

$$\mathcal{L}_g = \frac{M_{\rm pl}^2}{2}\Big[R + f(\phi)\frac{W^2}{M_{\rm s}^2}$$

anomalous tensor tilt
DB, Lee and Pimentel [2015]

$$+ g(\phi)\frac{W\tilde{W}}{M_{\rm s}^2}$$

parity violation
Lue, Wang and Kamionkowski [1998]

$$+ \frac{W^3}{M_{\rm s}^4} + \frac{W^2\tilde{W}}{M_{\rm s}^4} + \cdots \Big]$$

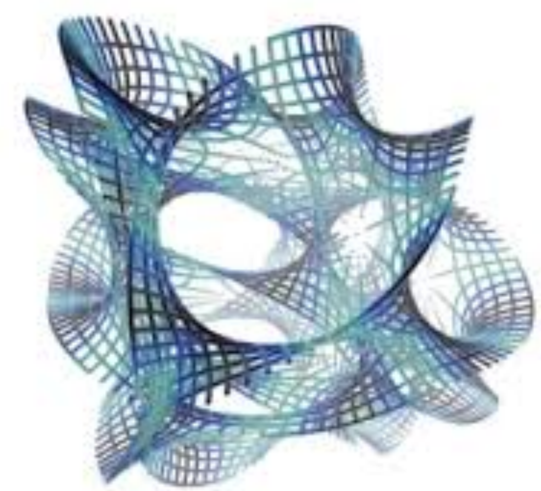
tensor non-Gaussianity
Maldacena and Pimentel [2011]

parity violation
Soda, Kodama and Mozawa [2011]

Stringy Inflation

The effects scale as $\left(\frac{H}{M_{\rm s}}\right)^2$ and are therefore only observable if the string scale is close to the Hubble scale.

Said more positively, non-minimal tensors are a diagnostic for a **stringy** origin of inflation.



The predictions in this regime can be controlled by the weakly broken **conformal symmetry** of the inflationary background.

Maldacena and Pimentel [2011]
McFadden and Skenderis [2010]
Mata, Raju and Trivedi [2012]
DB, Lee and Pimentel [2015]

Tensor Tilt

In the minimal model, the tensor tilt is determined by its amplitude:

$$\boxed{n_{\rm t} = -\frac{r}{8}}$$

Higher-derivative corrections may lead to:

$$\boxed{n_{\rm t} = -\frac{r}{8} + \beta\sqrt{r}\left(\frac{H}{M_{\rm s}}\right)^2}$$

DB, Lee and Pimentel [2015]

The spectrum can even be **blue**.

Tensor Non-Gaussianity

In the minimal model, the tensor bispectrum is unique and small:

$$\boxed{\langle \gamma_{\mathbf{k}_1}\gamma_{\mathbf{k}_2}\gamma_{\mathbf{k}_3}\rangle' = F(k_i)}$$

Higher-derivative corrections may lead to a new shape:

$$\boxed{\langle \gamma_{\mathbf{k}_1}\gamma_{\mathbf{k}_2}\gamma_{\mathbf{k}_3}\rangle' = F(k_i) + \left(\frac{H}{M_\mathrm{s}}\right)^4 G(k_i)}$$

Maldacena and Pimentel [2011]

A detection would be indirect evidence for **strings**:

Camanho et al. [2014]

W^3/M_s^4 $\longrightarrow$ *causality violation* $\longrightarrow$ *fixed by a tower of higher-spin particles*

Optimism of Pessimism?

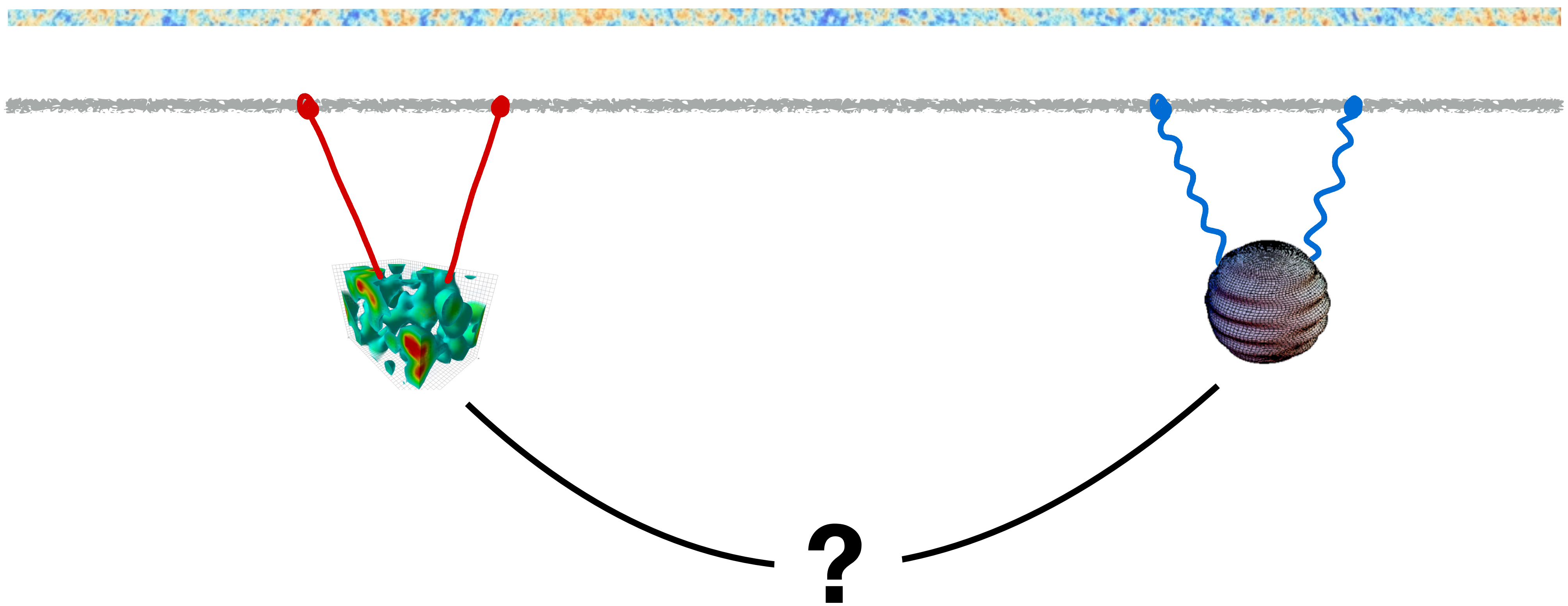
These effects will be hard to measure.

They are a direct probe of the UV completion of inflation.

Conclusions

Summary

- Current data is described by a simple EFT of two massless modes.

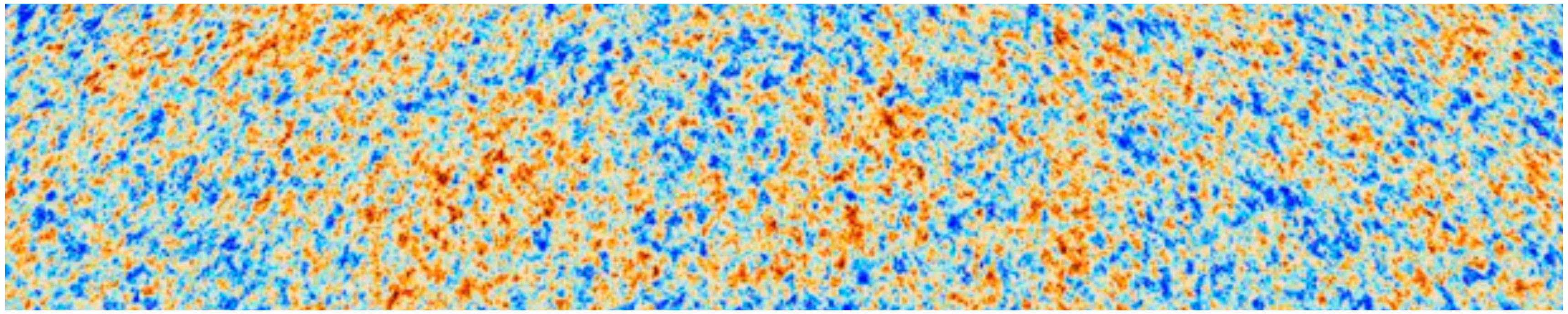


- Future data will sensitive to additional high-scale physics.
- CMB and LSS observations still have discovery potential.

Thanks for your attention

http://cosmology.amsterdam

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

$$n_s = 0.960 \pm 0.007$$

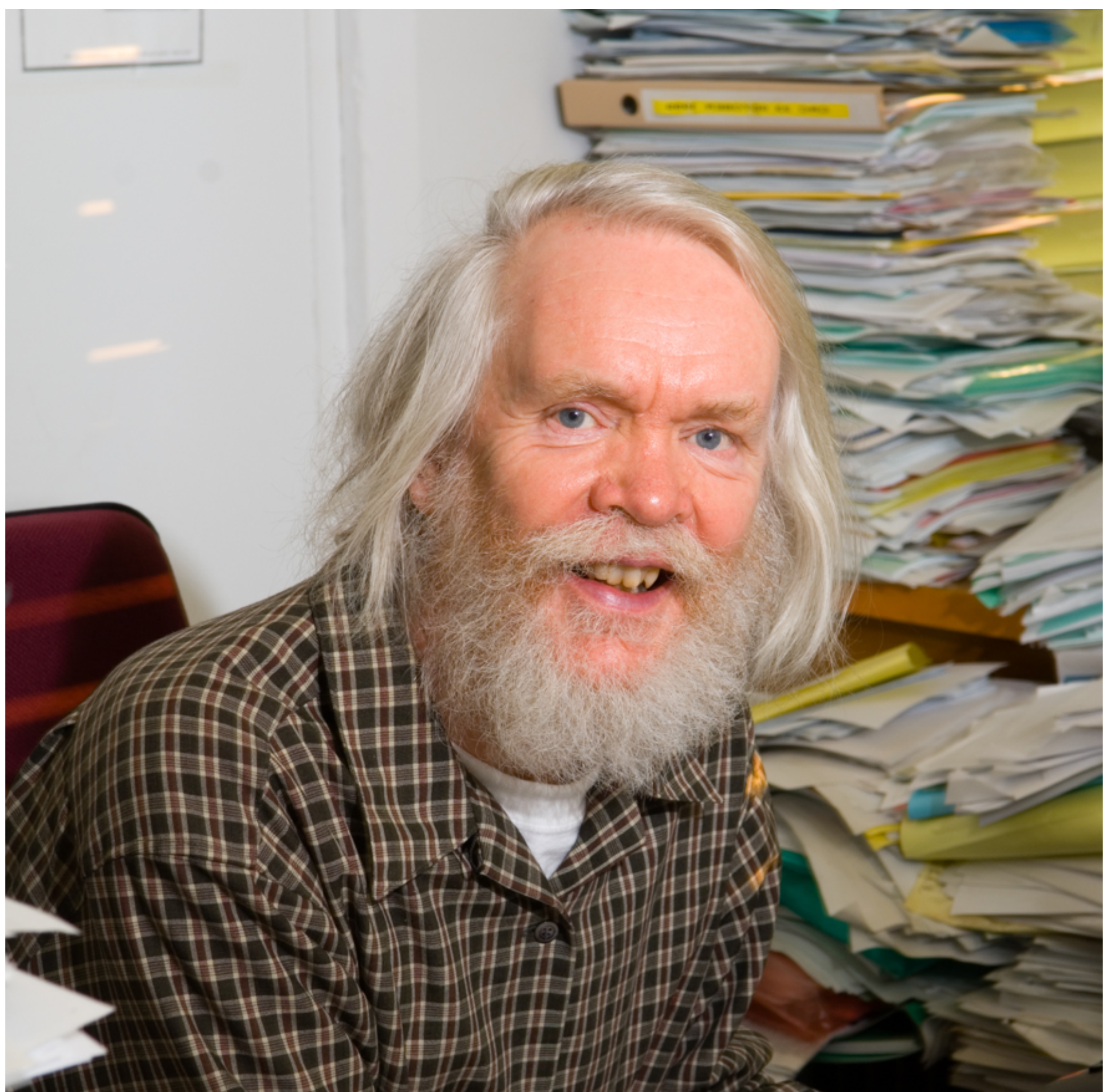
“I thought that it would take 1000 years to detect the logarithmic dependence of the power spectrum.”

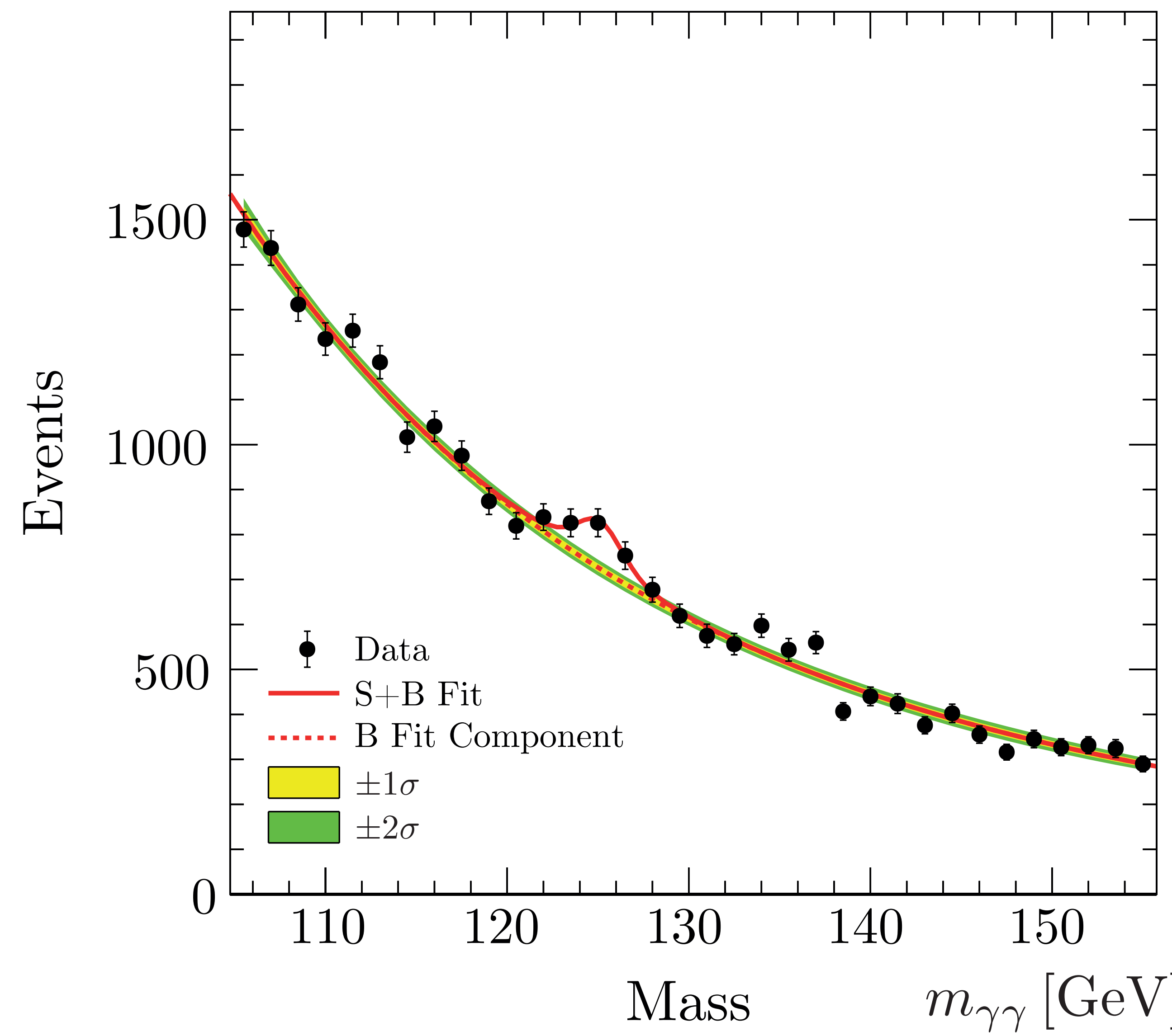
Slava Mukhanov

Lessons from the Past

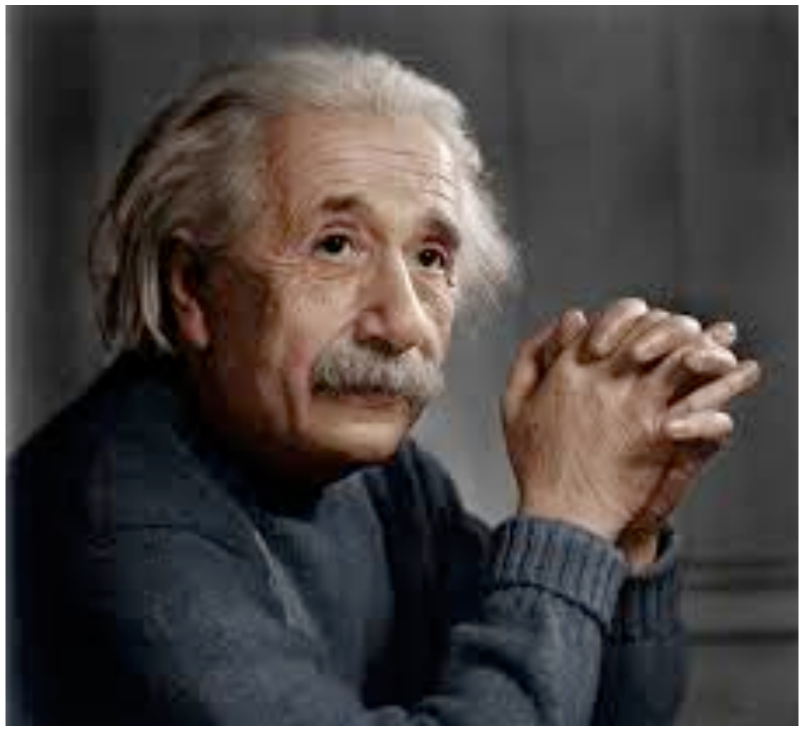
"We apologise to experimentalists for having no idea what is the mass of the Higgs boson and for not being sure of its couplings to other particles. For these reasons we do not want to encourage big experimental searches for the Higgs boson, …"

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