A Review Of

# Primordial Cosmology

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Strings 2016

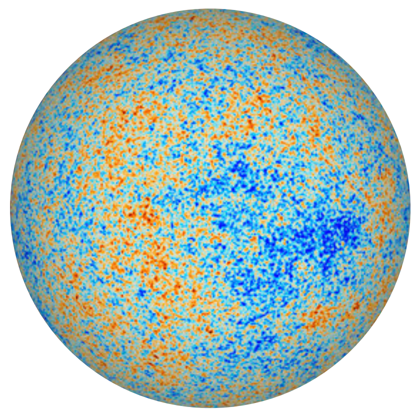
# Plan of the Talk

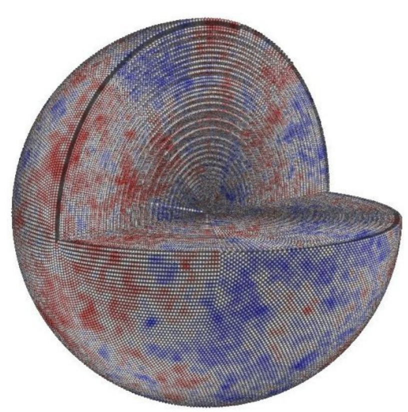
| | | |
|---|---|---|
| **1.** | Cosmological Inverse Problem | *Extracting UV information from IR observables.* |
| **2.** | Non-Gaussianity | *Probing the particle spectrum at $10^{14}$ GeV.* |
| **3.** | Tensor Modes | *Probing high-scale physics with tensors.* |
| **4.** | Outlook and Open Questions | *Prospects of future observations.* |

# The Cosmological Inverse Problem

# The Inverse Problem

late-time observables

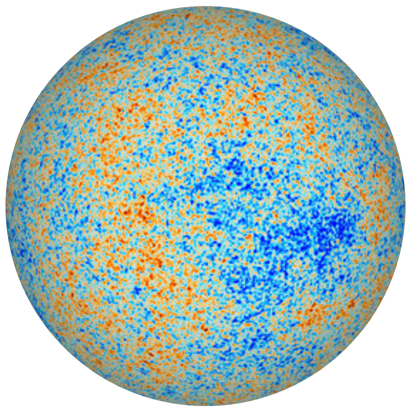


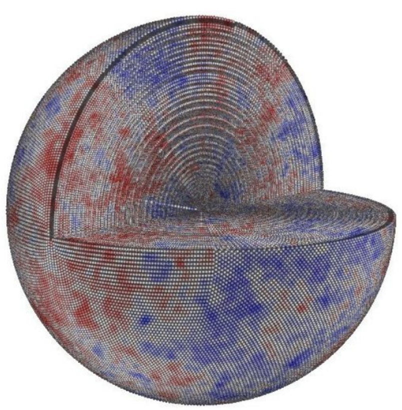


primordial perturbations

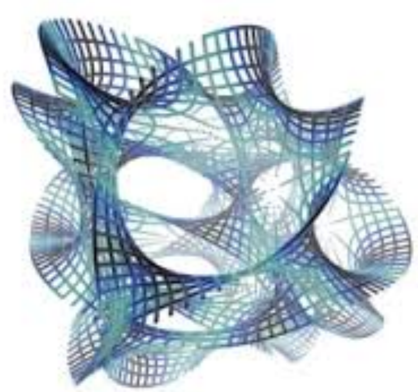
# The Inverse Problem

late-time observables





primordial perturbations

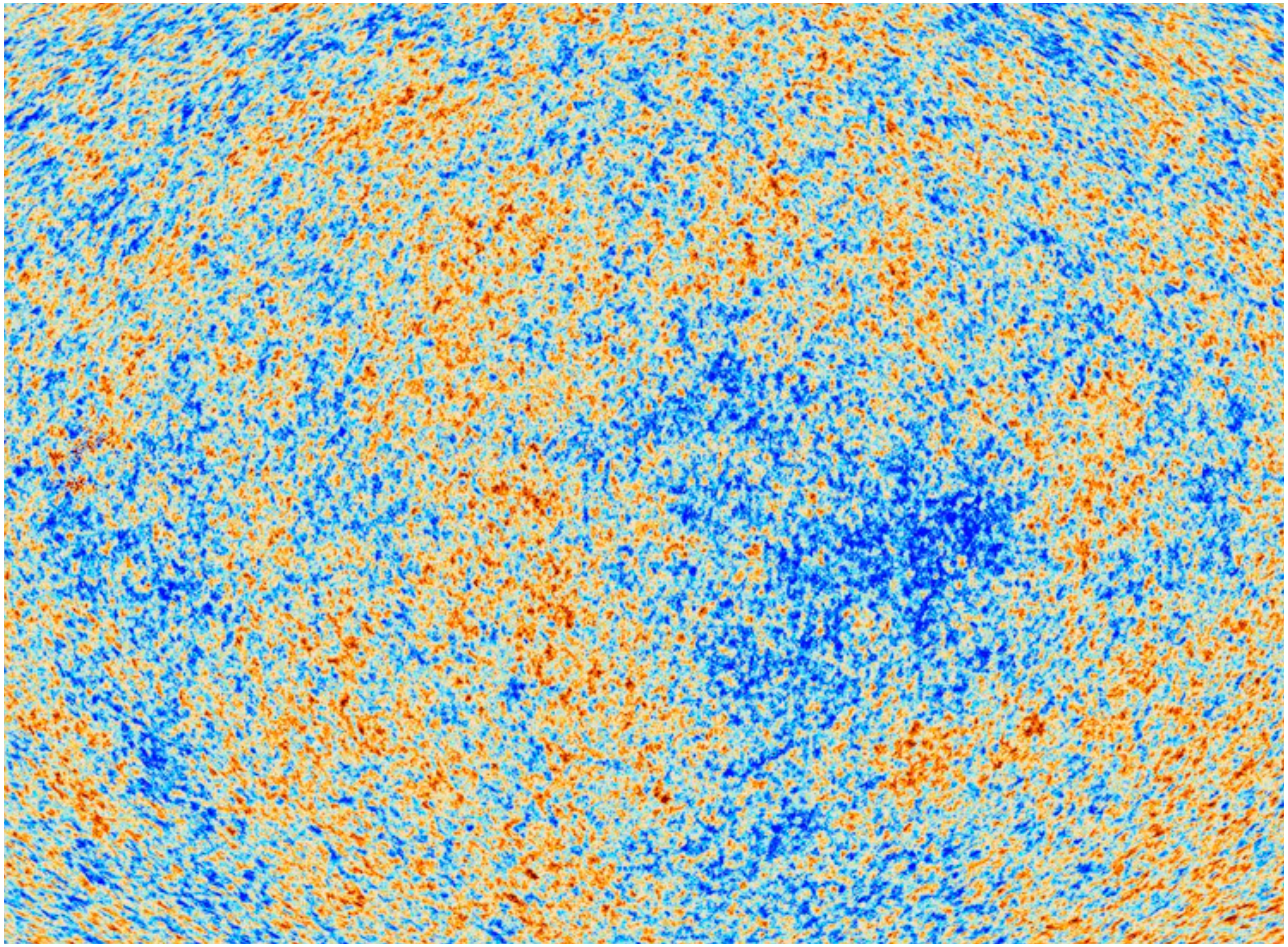


UV origin?

# CMB Anisotropies

The key cosmological observable is the cosmic microwave background:

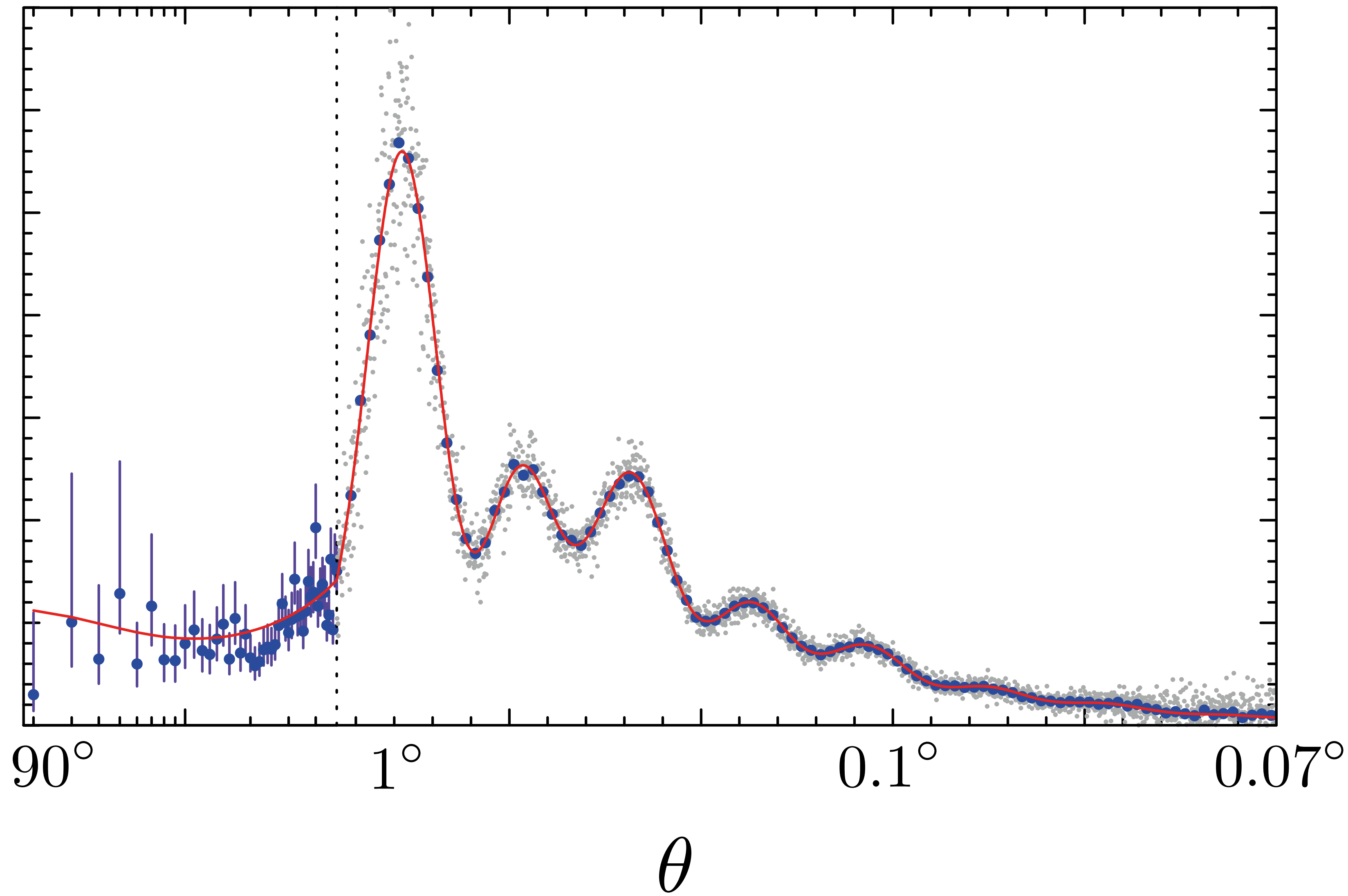
$$\delta T(\vec{\theta}) =$$



# CMB Anisotropies

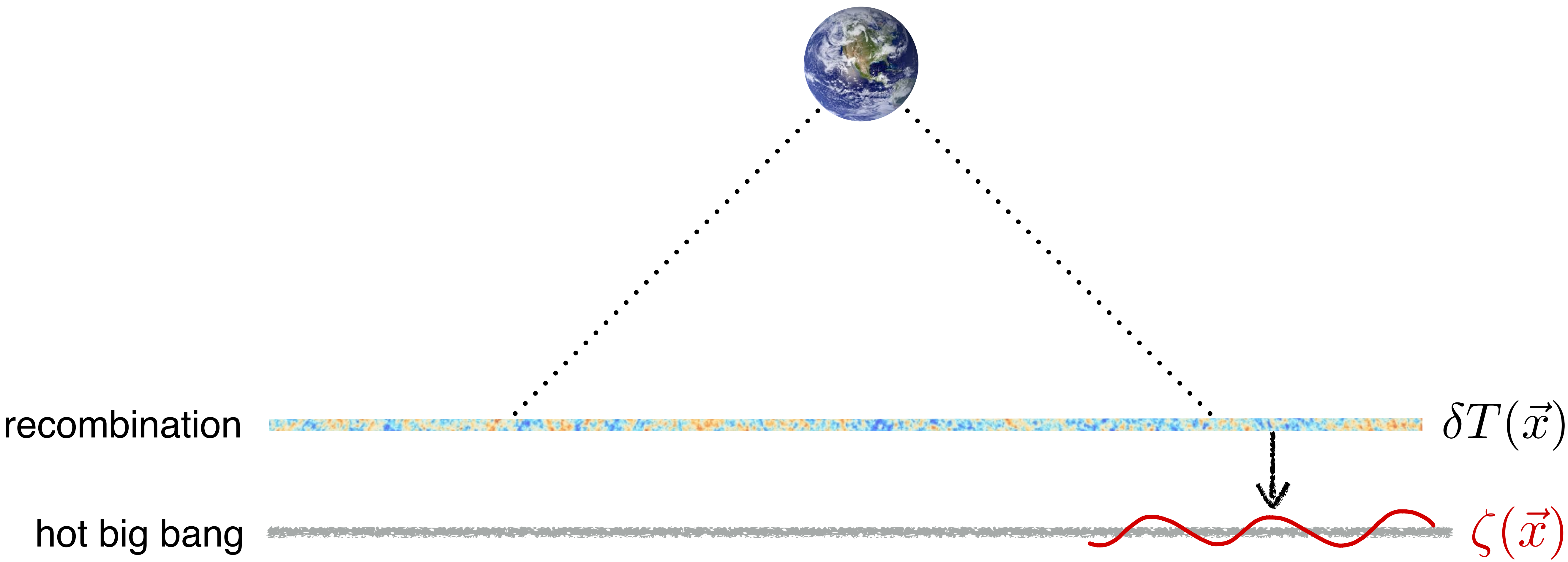
A simple six parameter model fits the $10^6$ data points of the two-point correlation function:

$$\langle \delta T(\vec{\theta}) \delta T(\vec{0}) \rangle =$$



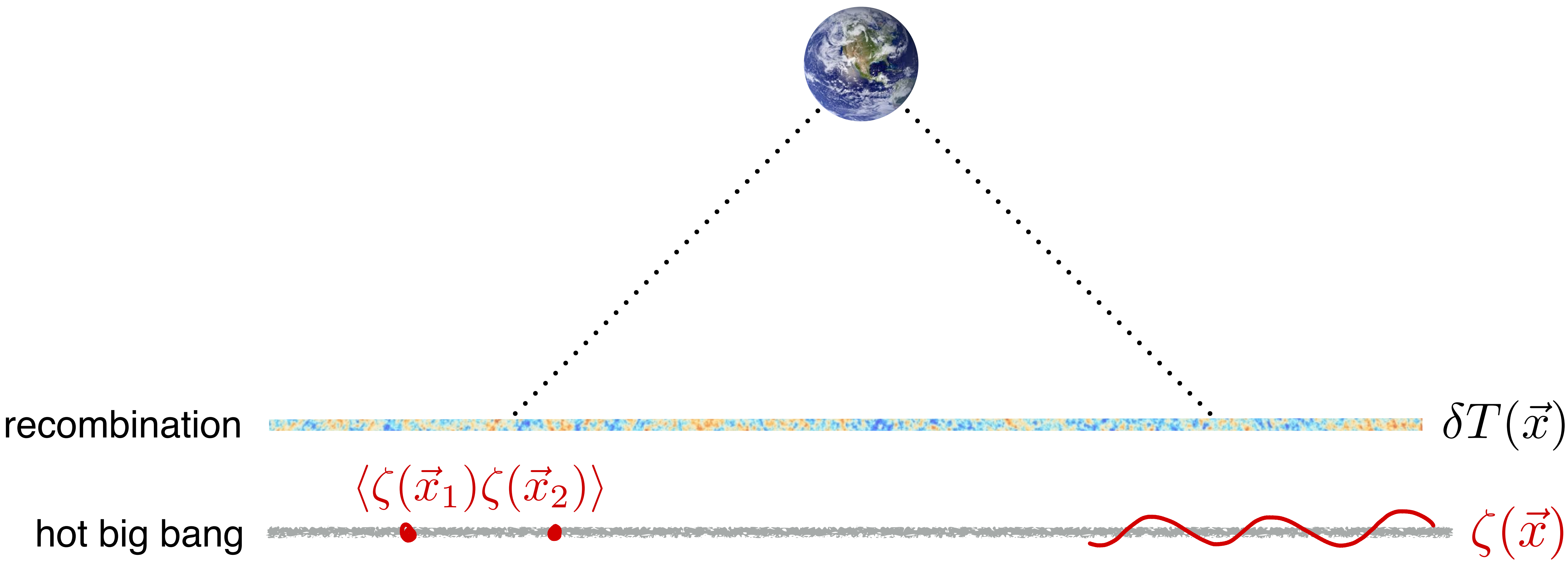

Planck [2015]

# Initial Conditions




The observed CMB fluctuations can be traced back to a spectrum of **curvature perturbations** at the beginning of the hot big bang.

# Initial Conditions




- The **power spectrum** is nearly **scale-invariant**:

$$n_\mathrm{s} = 0.968 \pm 0.006$$

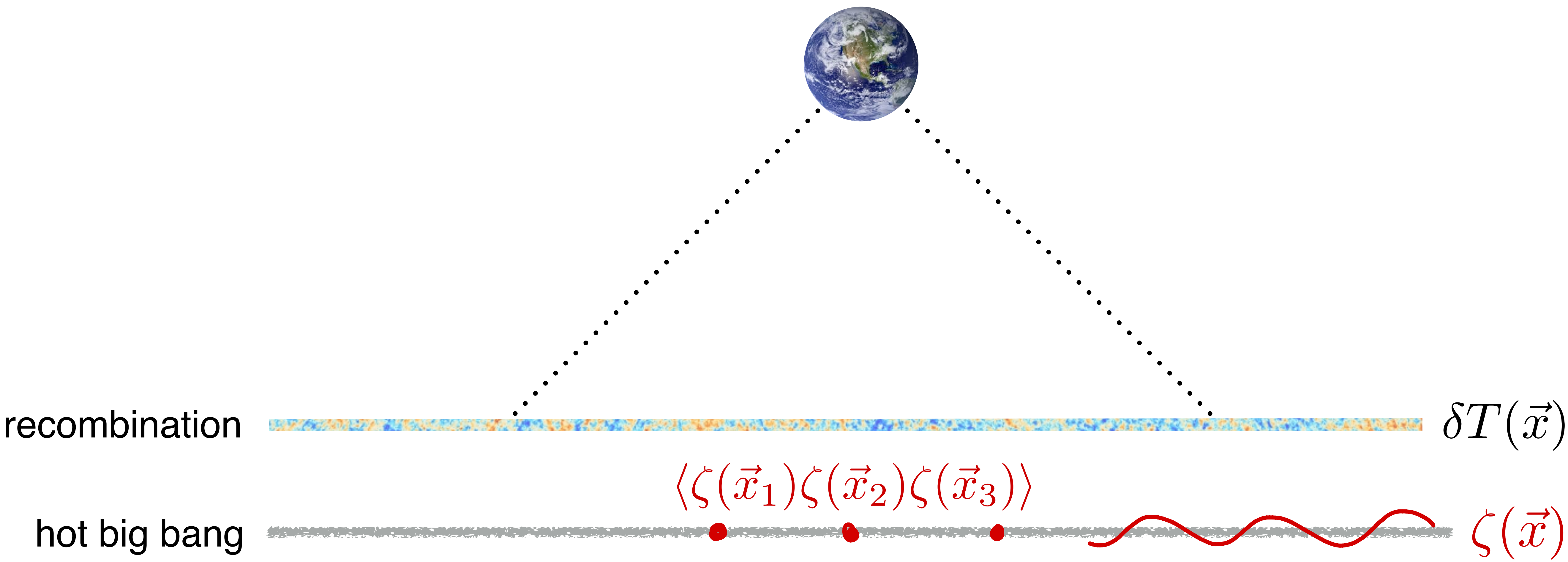
Planck [2015]

$$\Delta^2_\zeta(k) \equiv \frac{k^3}{2\pi^2}\langle \zeta(\vec{k})\zeta^*(\vec{k})\rangle \;=\; A_\mathrm{s}\left(\frac{k}{k_\star}\right)^{n_\mathrm{s}-1}$$

$$A_\mathrm{s} = 2.2 \times 10^{-9}$$

COBE [1992]

# Initial Conditions

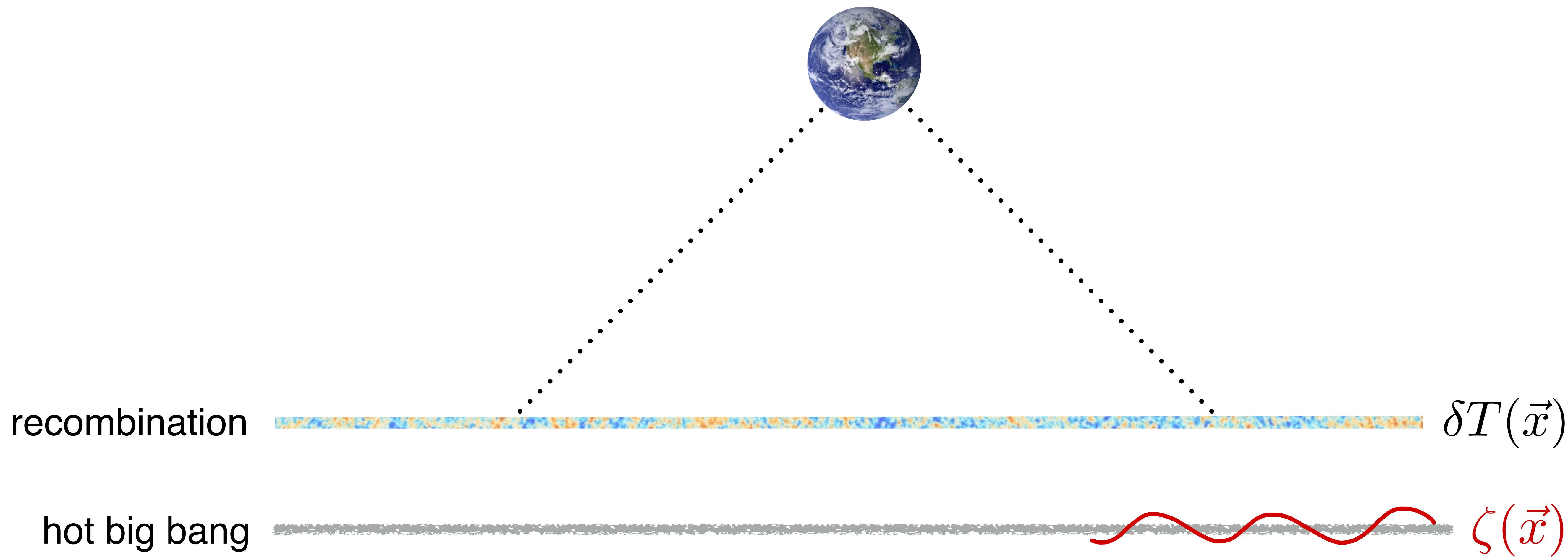



- The perturbations are very **Gaussian**:

$$F_{\rm NL} \equiv \frac{\langle \zeta\zeta\zeta \rangle}{\langle \zeta\zeta \rangle^{3/2}} \lesssim 10^{-3}$$

Planck [2015]

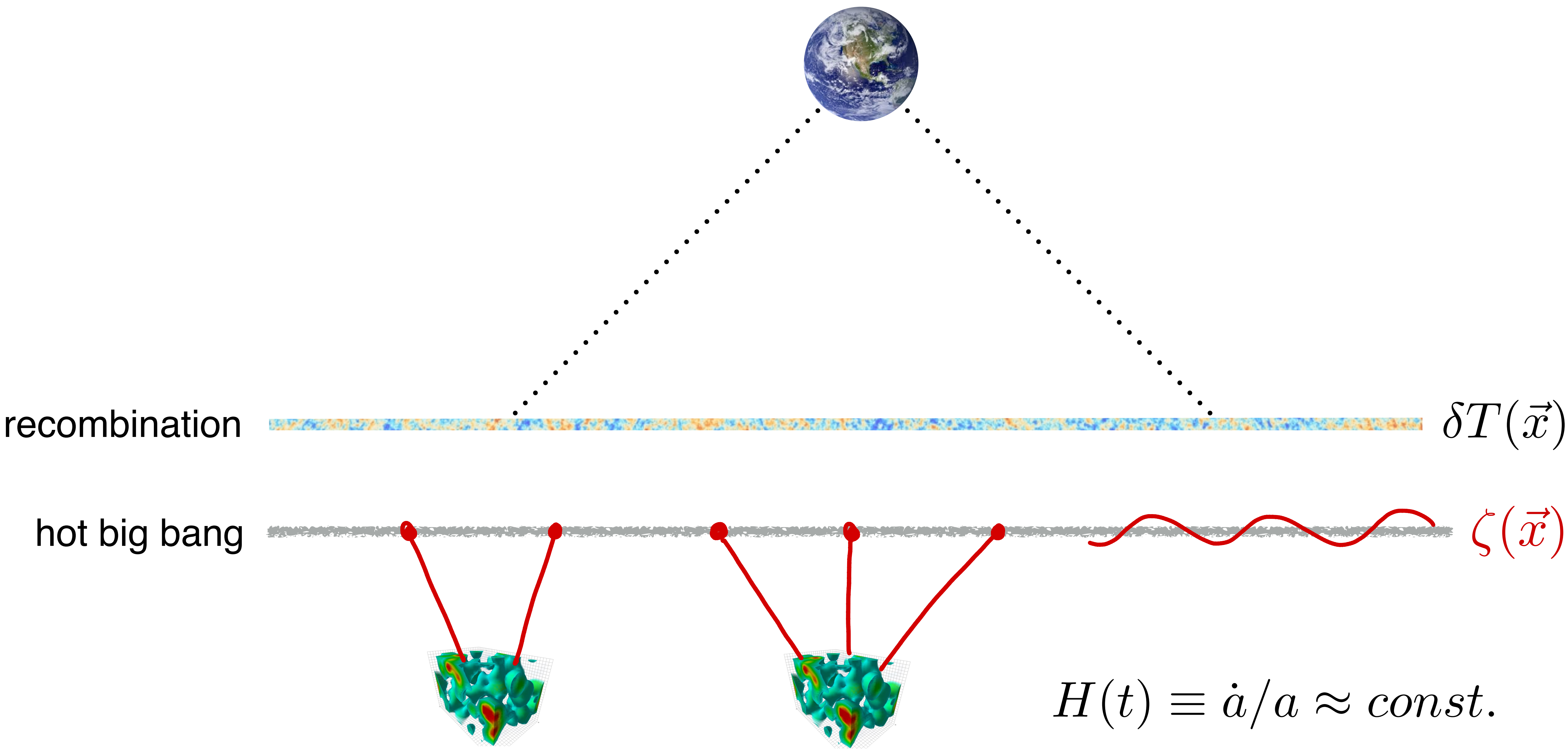
# Initial Conditions




- The perturbations are correlated on **superhorizon scales**, suggesting that they were generated before the hot big bang.

WMAP [2003]

# Initial Conditions




Inflation provides an elegant mechanism to produce
the observed correlations from quantum fluctuations.

# EFT of Inflation

Consider the massless mode corresponding to a **local time shift** of the inflationary history:

$$H(t + \pi(\vec{x}, t))$$

- adiabatic mode
- Goldstone boson
  of broken time translations
- clock

In the simplest scenarios, quantum fluctuations in this mode are the seeds of structure:

$$\zeta = -H\pi \qquad\qquad g_{ij} = a^2 e^{2\zeta} \delta_{ij}$$

This model-insensitive description of inflationary perturbations is called the **EFT of Inflation**.

# EFT of Inflation

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

The EFT of the adiabatic mode during inflation is

$$\mathcal{L}_\pi \;=\; M_{\rm pl}^2 \dot{H} (\partial\pi)^2$$

$\uparrow$

slow-roll inflation

- Compare this to

$$\mathcal{L}_\phi \;=\; \frac{1}{2}(\partial\phi)^2 - V(\phi)\,,$$

with

$$\phi(t + \pi(\vec{x}, t))$$

$$M_{\rm pl}^2 \dot{H} = \dot{\phi}^2$$

# EFT of Inflation

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

The EFT of the adiabatic mode during inflation is

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

- Compare this to

$$\mathcal{L}_\phi \;=\; \frac{1}{2}(\partial\phi)^2 + \frac{(\partial\phi)^4}{\Lambda^4} + \cdots$$

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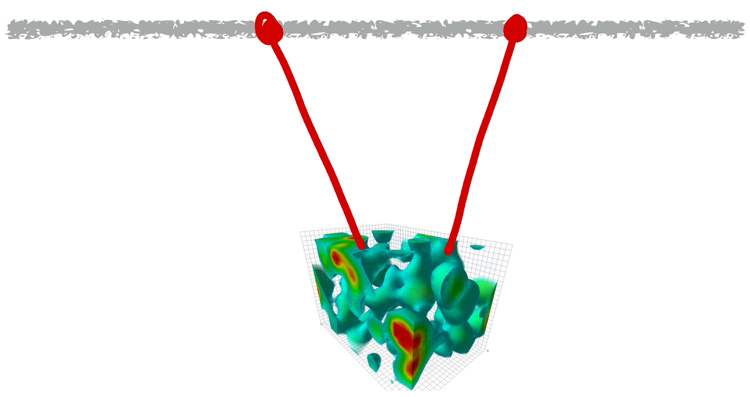
- Broken Lorentz allows for a nontrivial **sound speed**: $c_s^2 \equiv \frac{M_{\rm pl}^2 \dot{H}}{M_{\rm pl}^2 \dot{H} - 2M_2^4}$

- The **power spectrum** of curvature perturbations is $\Delta_\zeta^2 = \frac{1}{8\pi^2} \frac{H^4}{M_{\rm pl}^2 |\dot{H}| c_s}$



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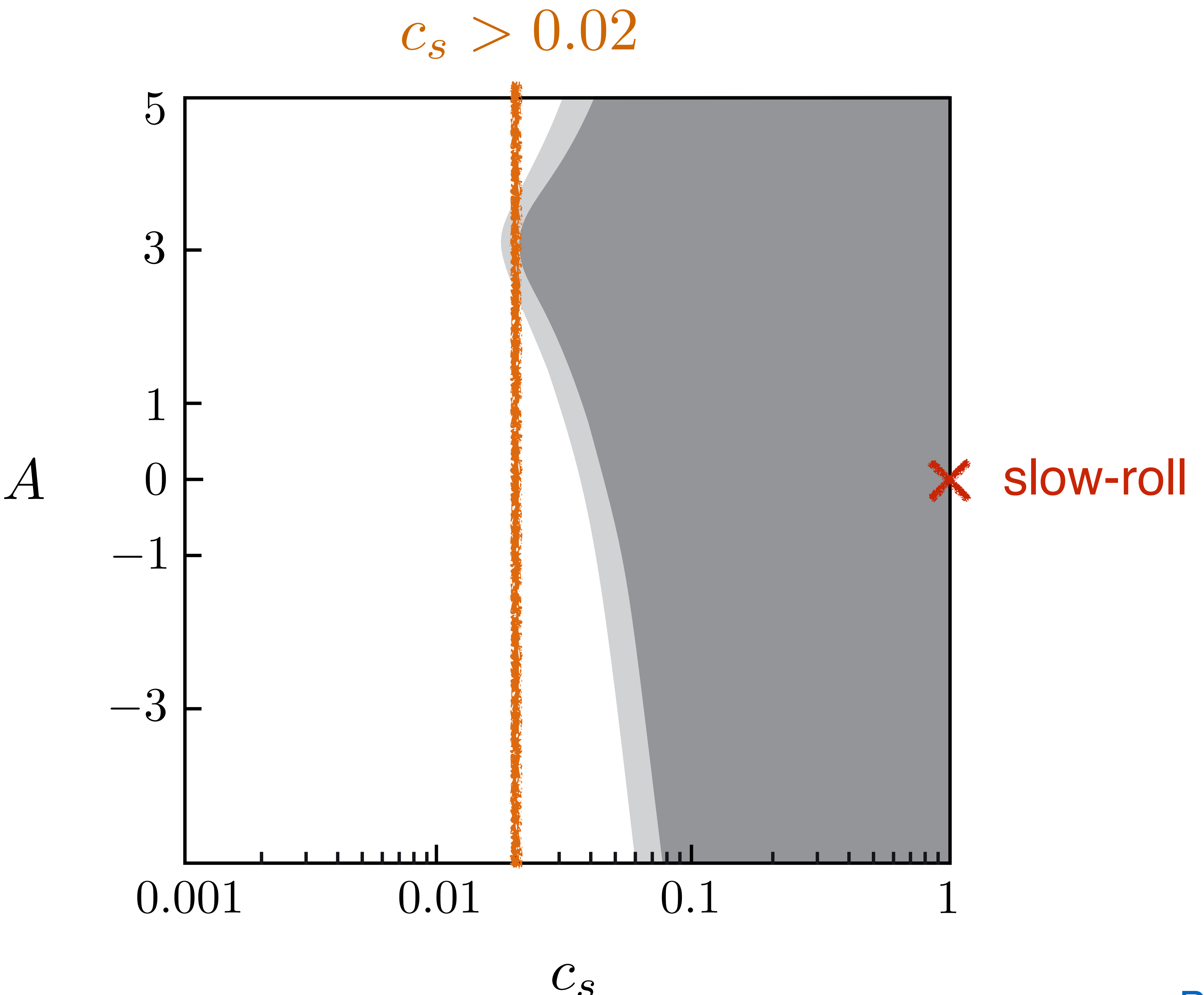
nonlinearly realized symmetry

- **Symmetry** relates a small sound speed to **large interactions**:

$$\mathcal{L}_\pi \subset \frac{M_{\rm pl}^2 \dot{H}}{c_s^2}(1-c_s^2)\left(\dot{\pi}(\partial_i\pi)^2 + \frac{A}{c_s^2}\dot{\pi}^3\right) + \cdots \longrightarrow \boxed{F_{\rm NL} \propto c_s^{-2}}$$

$M_3 \neq 0$

# Current Constraints




Planck [2015]

# EFT of Inflation

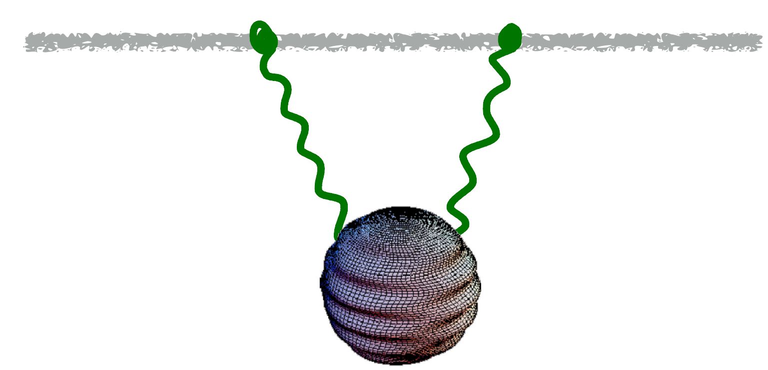
A second massless field during inflation is the **graviton**

$$\mathcal{L}_h = \frac{M_{\rm pl}^2}{8}(\partial h_{ij})^2 + \cdots$$

$$g_{ij} = a^2(\delta_{ij} + h_{ij})$$

- The **power spectrum** of tensor perturbations is

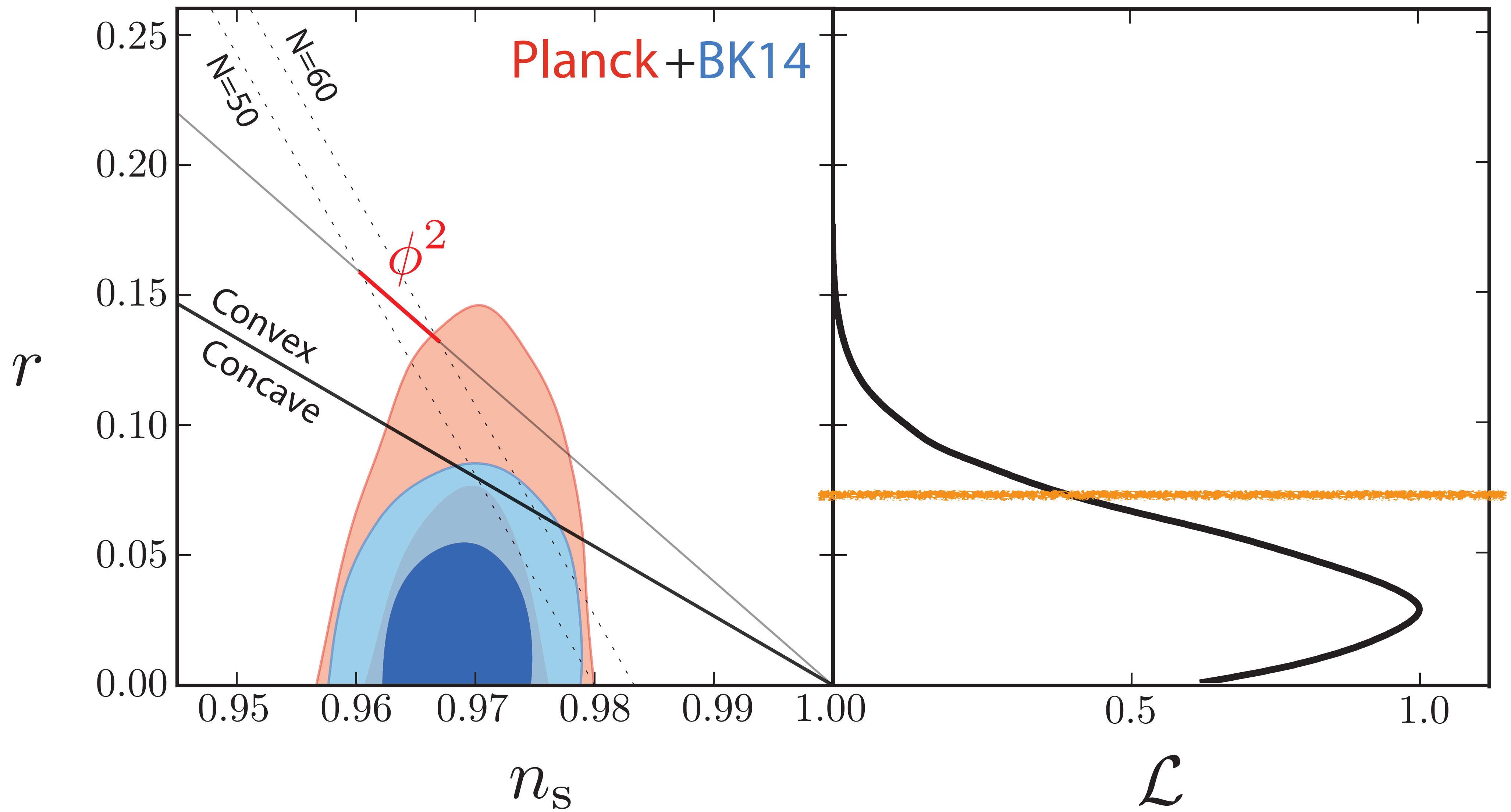
$$\Delta_h^2 = \frac{2}{\pi^2}\frac{H^2}{M_{\rm pl}^2}$$



- Observational constraints are often expressed in terms of the **tensor-to-scalar ratio**

$$r \equiv \frac{\Delta_h^2}{\Delta_\zeta^2}$$

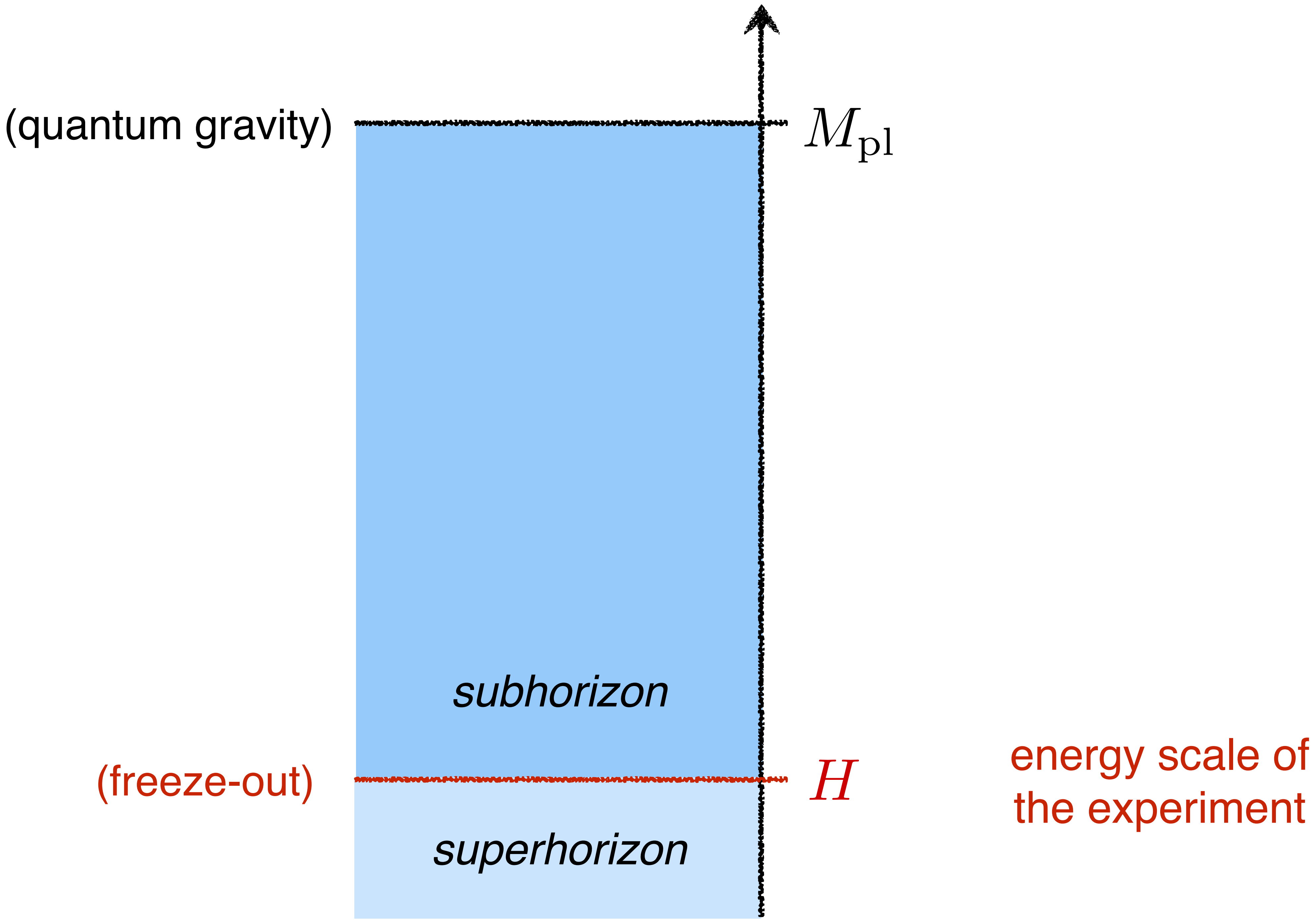
# Current Constraints




$r < 0.07$

Keck Array + BICEP2 [2015]

# Energy Scales



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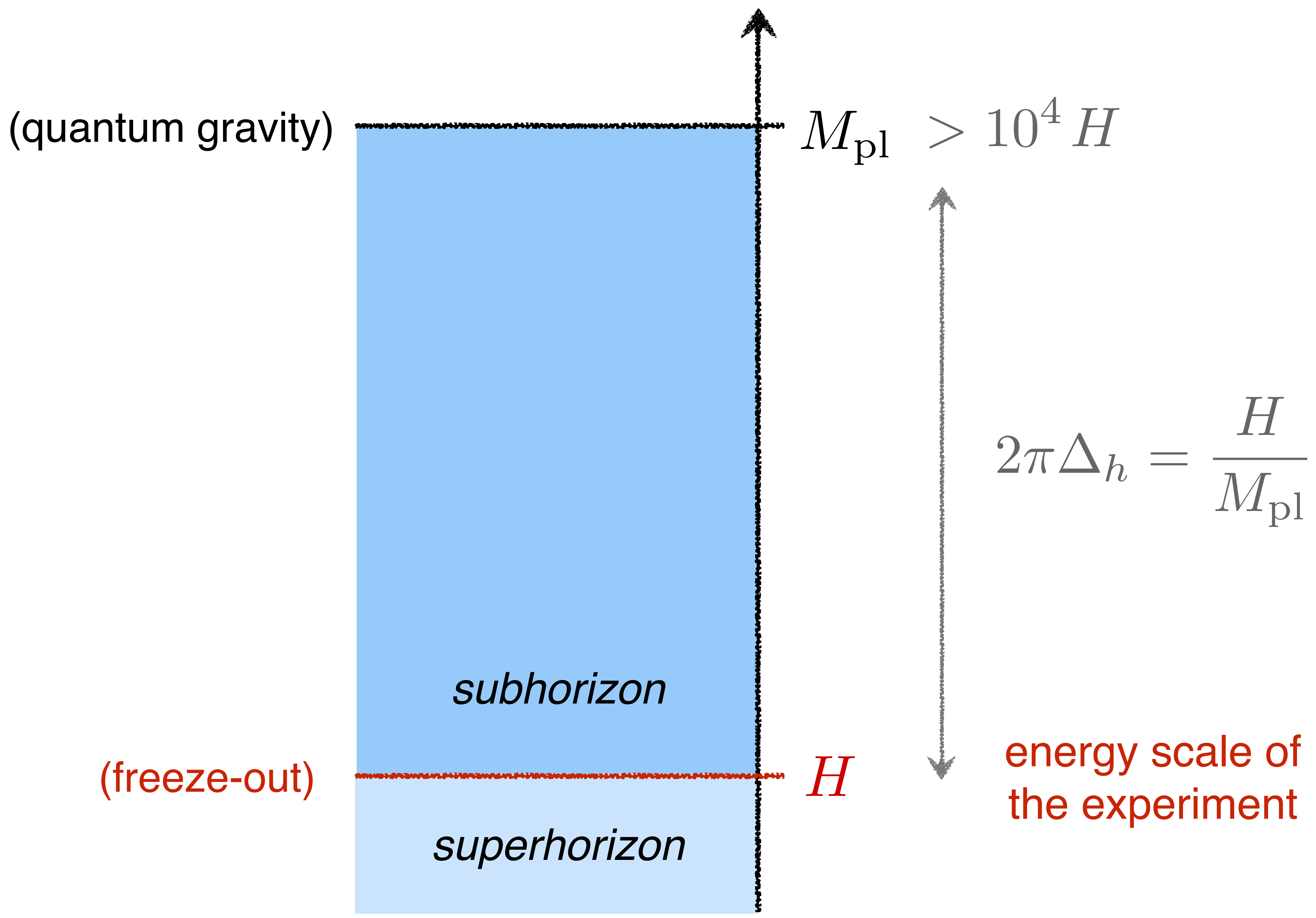

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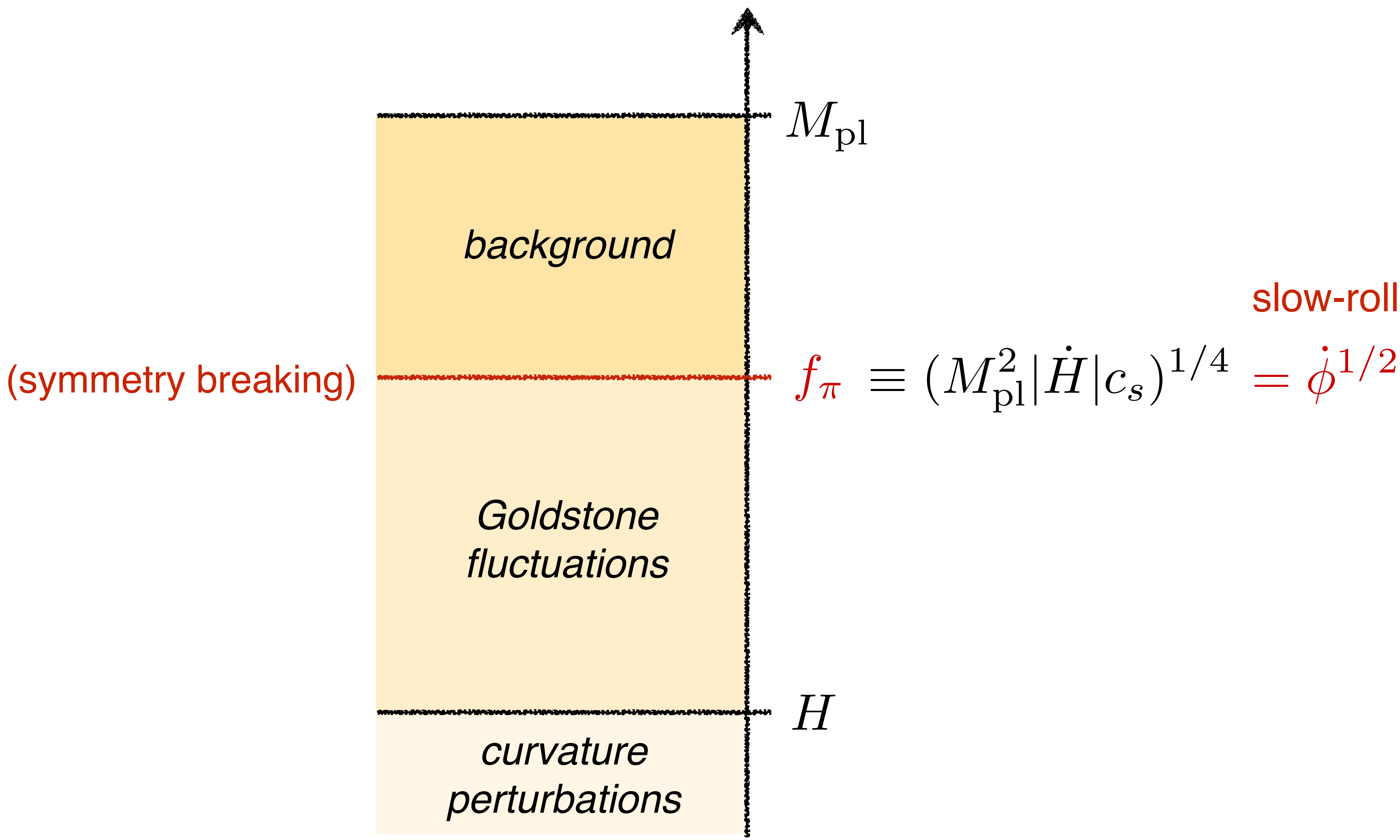


DB and Green [2011]

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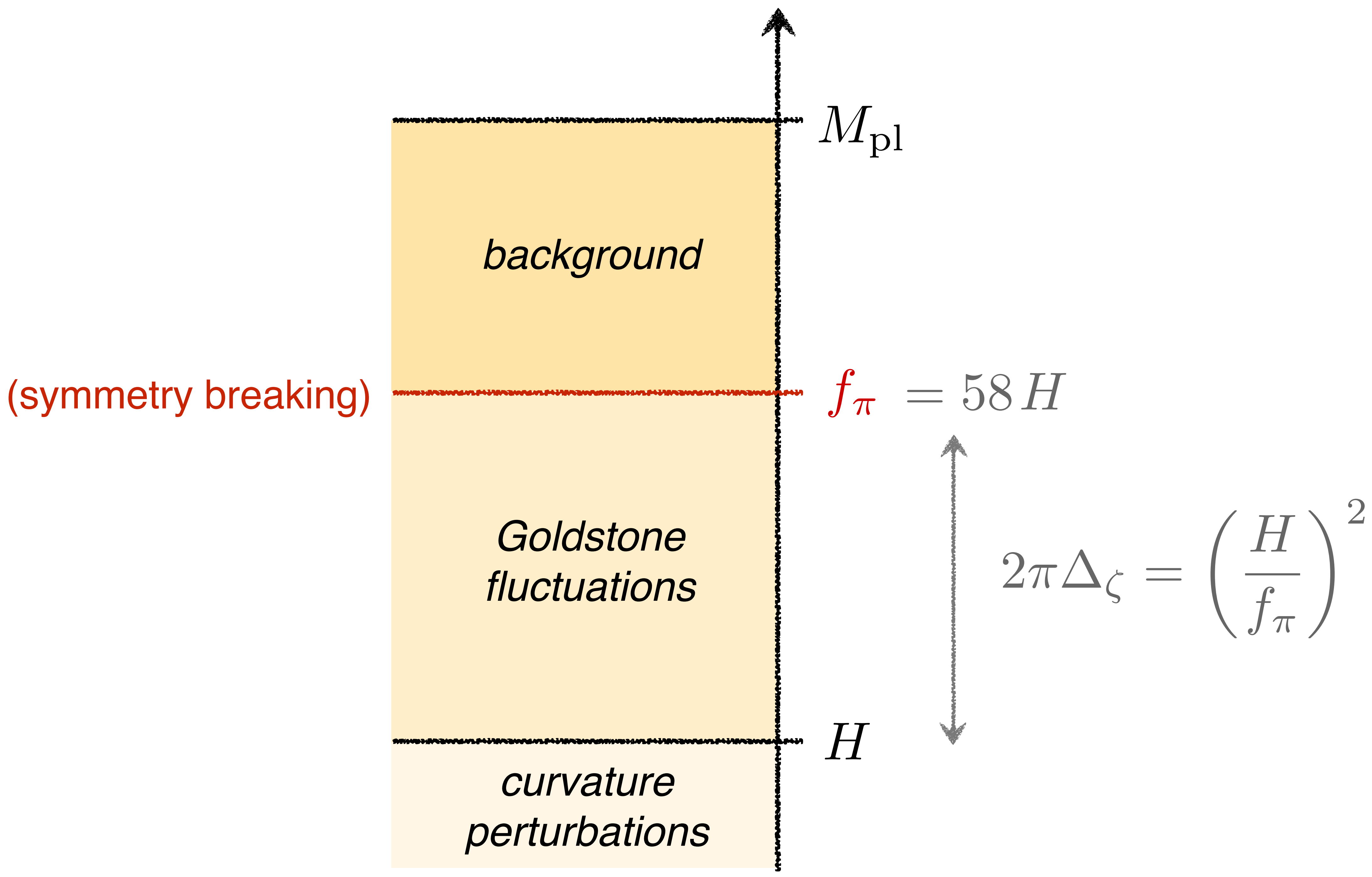


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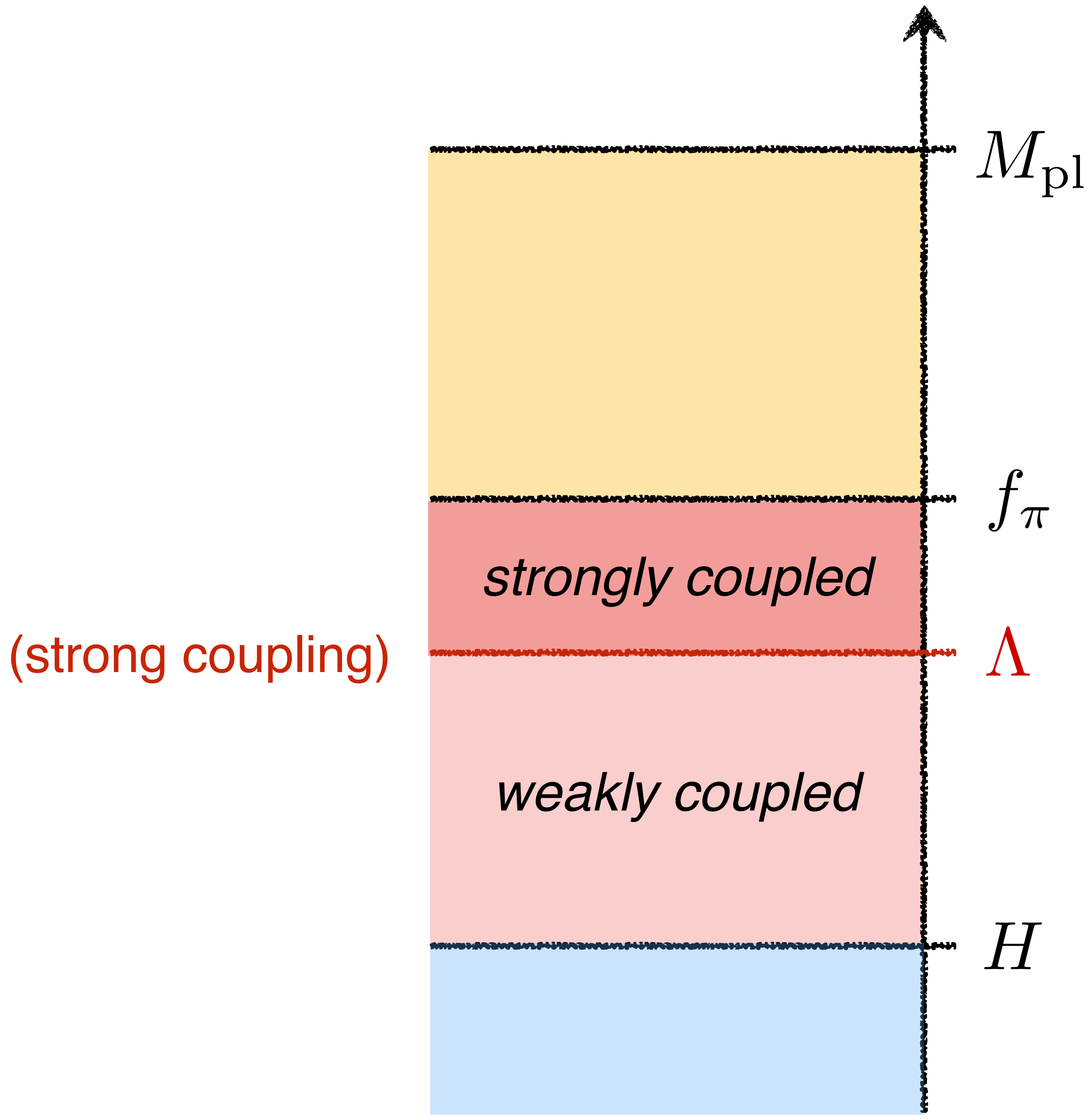


Cheung et al. [2008]
DB, Green, Lee and Porto [2015]

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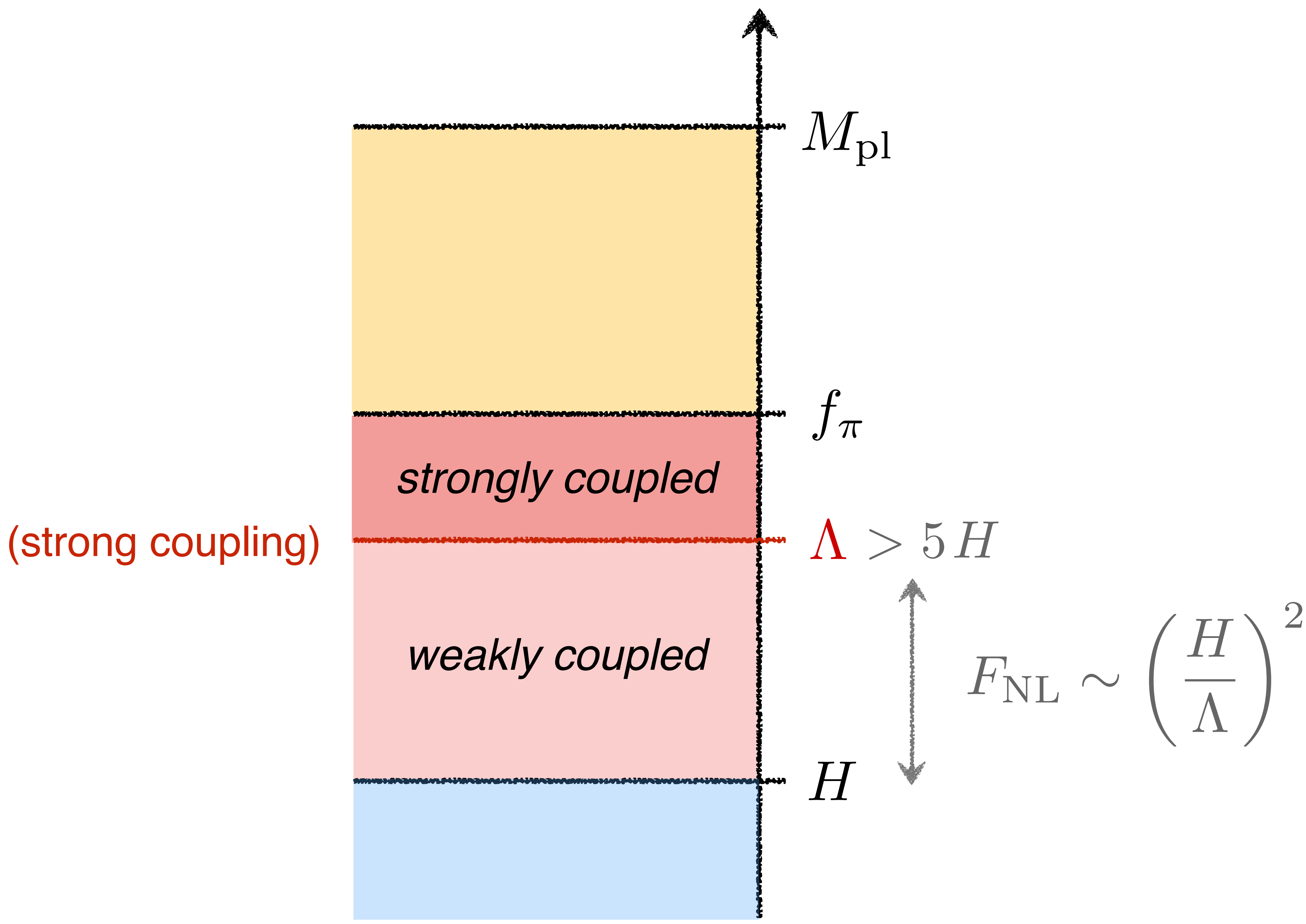


Cheung et al. [2008]
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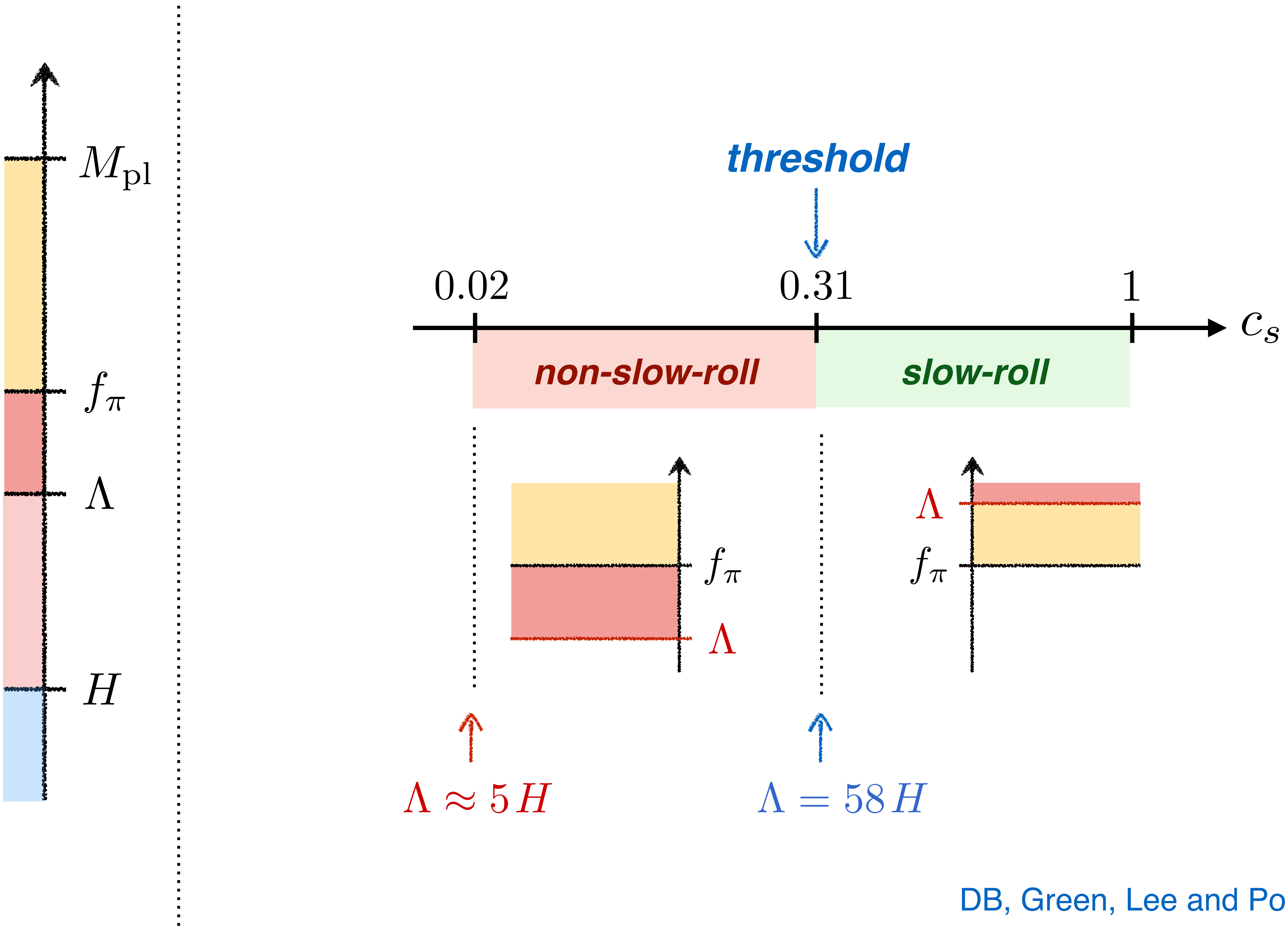
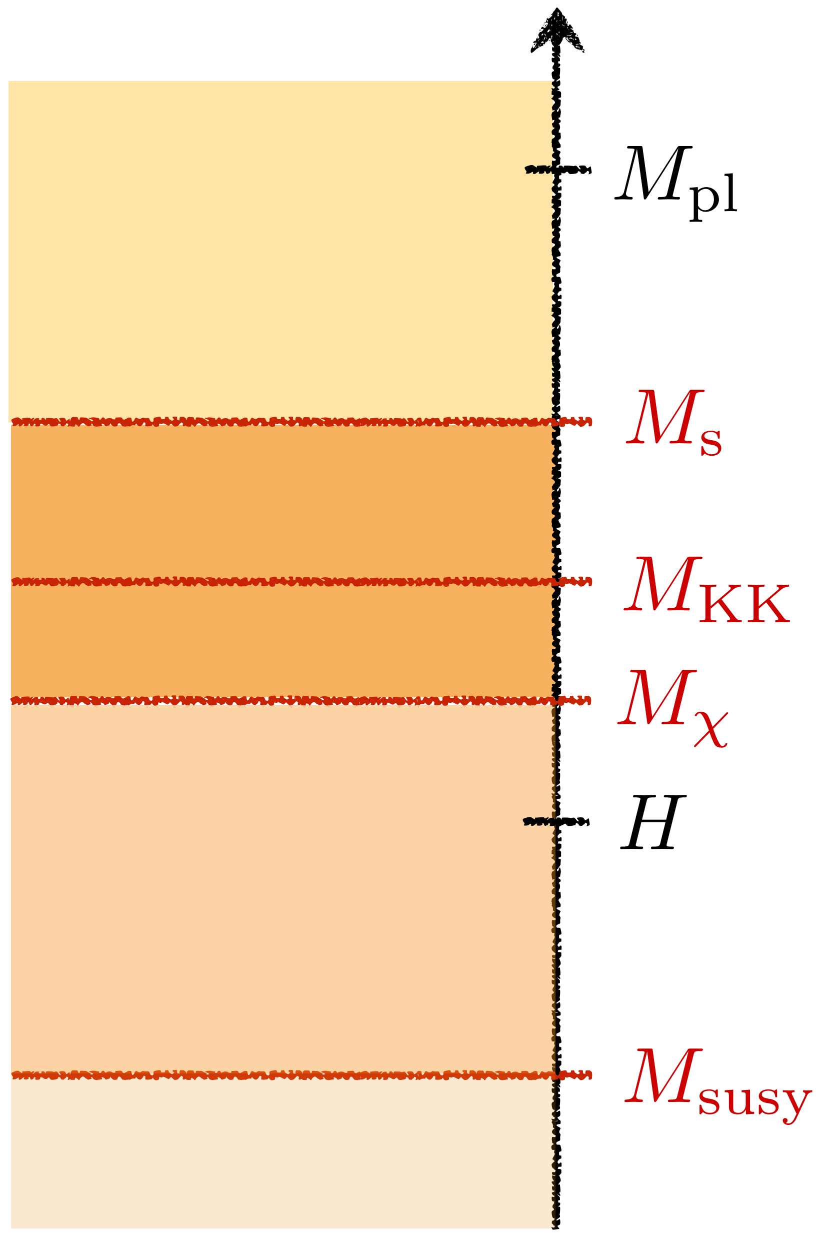
# Unitarity Bound




DB, Green, Lee and Porto [2015]

# 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.

# Ultraviolet Sensitivity

There are two ways in which inflation is sensitive to high-scale physics:

**I.** Inflationary **background** is sensitive to **Planck-suppressed corrections**:

$$\Delta V = \frac{V(\phi)}{M_{\rm pl}^2}\phi^2$$

see talks by Silverstein [Strings 2014]
McAllister [Strings 2011]

**II.** Inflationary **perturbations** are sensitive to **massive particles**.

**Chen and Wang [2009]**
DB and Green [2011]
Noumi et al. [2013]
Green et al. [2013]
Assassi, DB, Green and McAllister [2013]
…
Arkani-Hamed and Maldacena [2015]

see talks by Maldacena [Strings 2015]
Arkani-Hamed [TASI 2016]

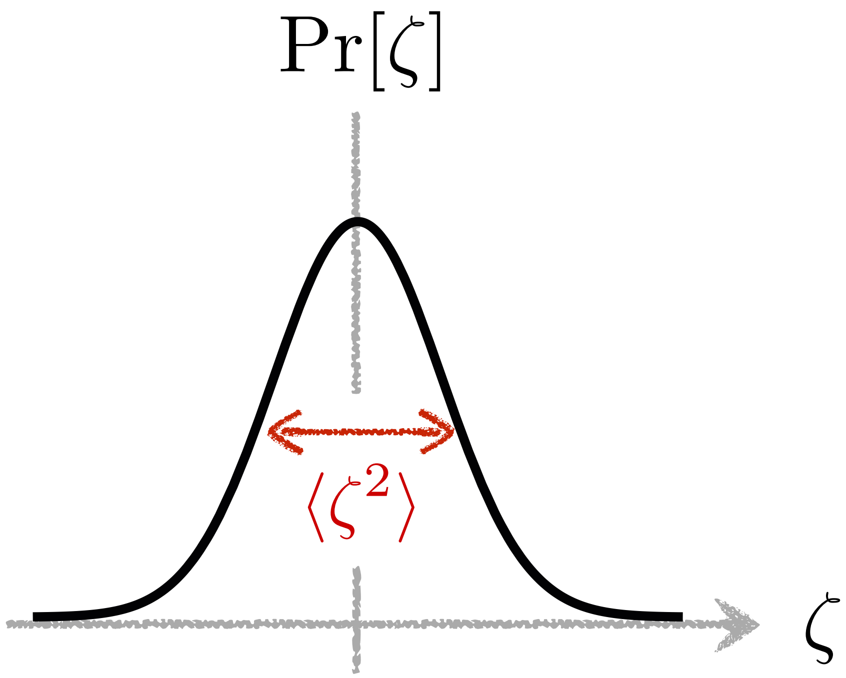
*I will describe the imprints of massive fields on two types of cosmological observables:*

- ***Non-Gaussianity*** $\langle\zeta\zeta\zeta\rangle$
- ***Tensor Modes*** $\langle hh\rangle\,,\,\langle hhh\rangle$

# Non-Gaussianity

# Non-Gaussian Statistics

There is only one way to be Gaussian,




*power spectrum determines everything*

$$\langle\zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\rangle = (2\pi)^3\delta_D(\vec{k}_1+\vec{k}_2)P_\zeta(k_1)$$

but many ways to be non-Gaussian.

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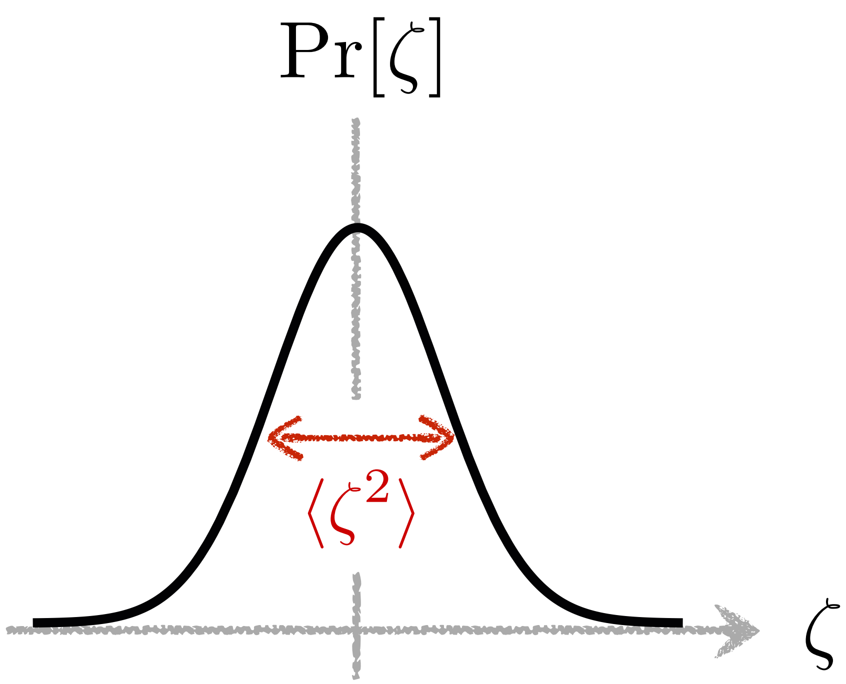


*power spectrum determines everything*

$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \rangle = (2\pi)^3 \delta_D(\vec{k}_1 + \vec{k}_2) P_\zeta(k_1)$$

but many ways to be non-Gaussian. The data suggests a perturbative treatment. The first diagnostic of non-Gaussianity is the **bispectrum**:

$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle = (2\pi)^3 \delta_D(\vec{k}_1 + \vec{k}_2 + \vec{k}_3) B_\zeta(k_1, k_2, k_3)$$

# Current Constraints

The **amplitude** of the bispectrum is conventionally defined as

$$F_{\mathrm{NL}} \equiv \frac{B_\zeta(k,k,k)}{P_\zeta(k)^{3/2}}$$

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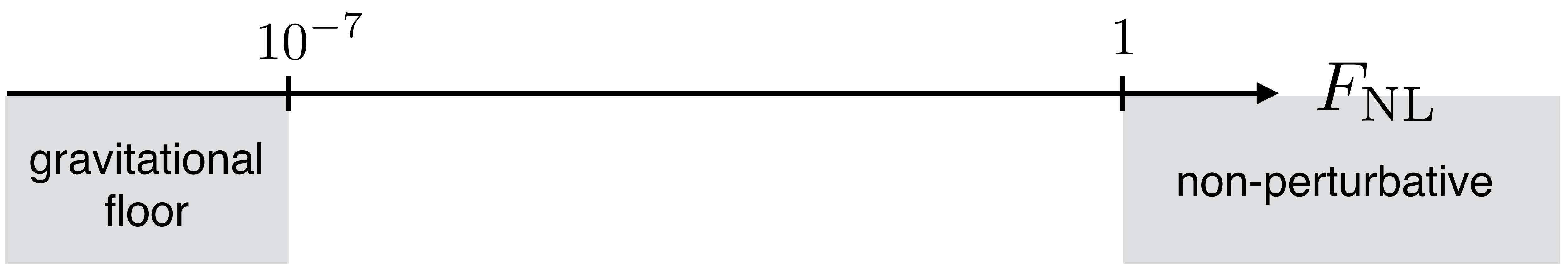
The theoretically interesting regime of non-Gaussianity spans about seven orders of magnitude:



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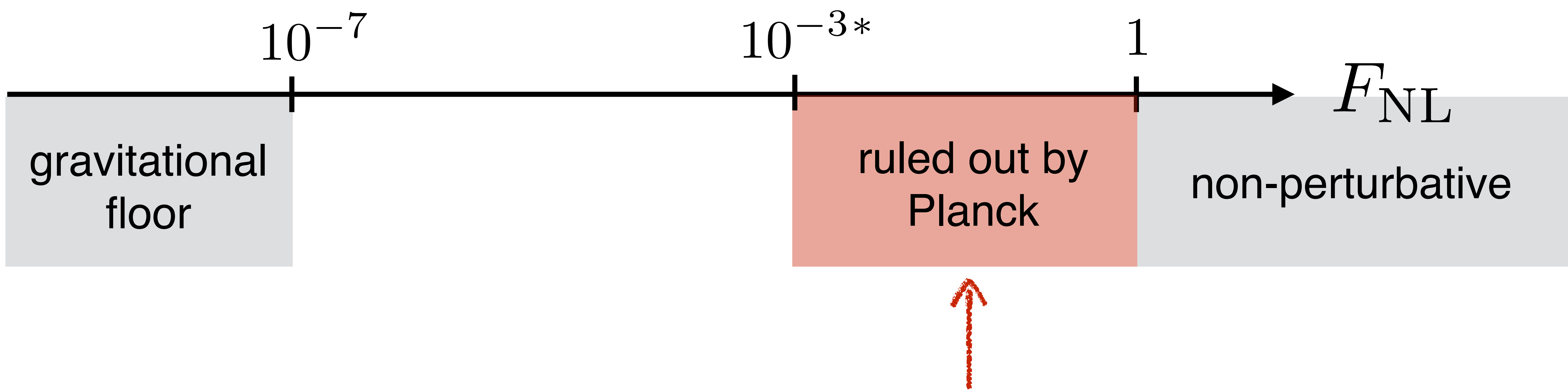


Planck has ruled out three orders of magnitude.

$^*$ Precise limit depends on the shape of the non-Gaussianity!!!

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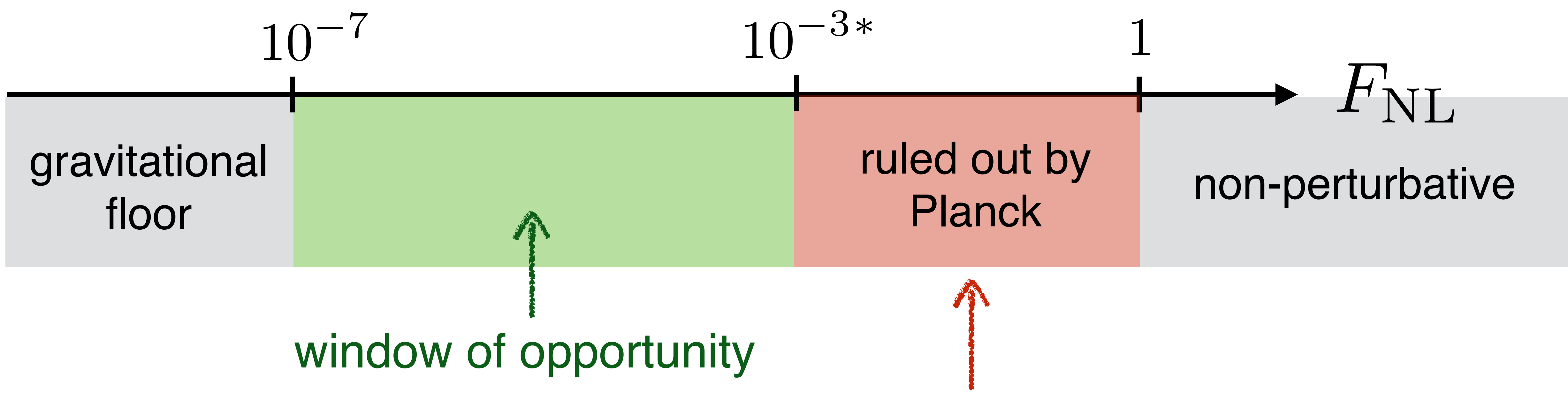


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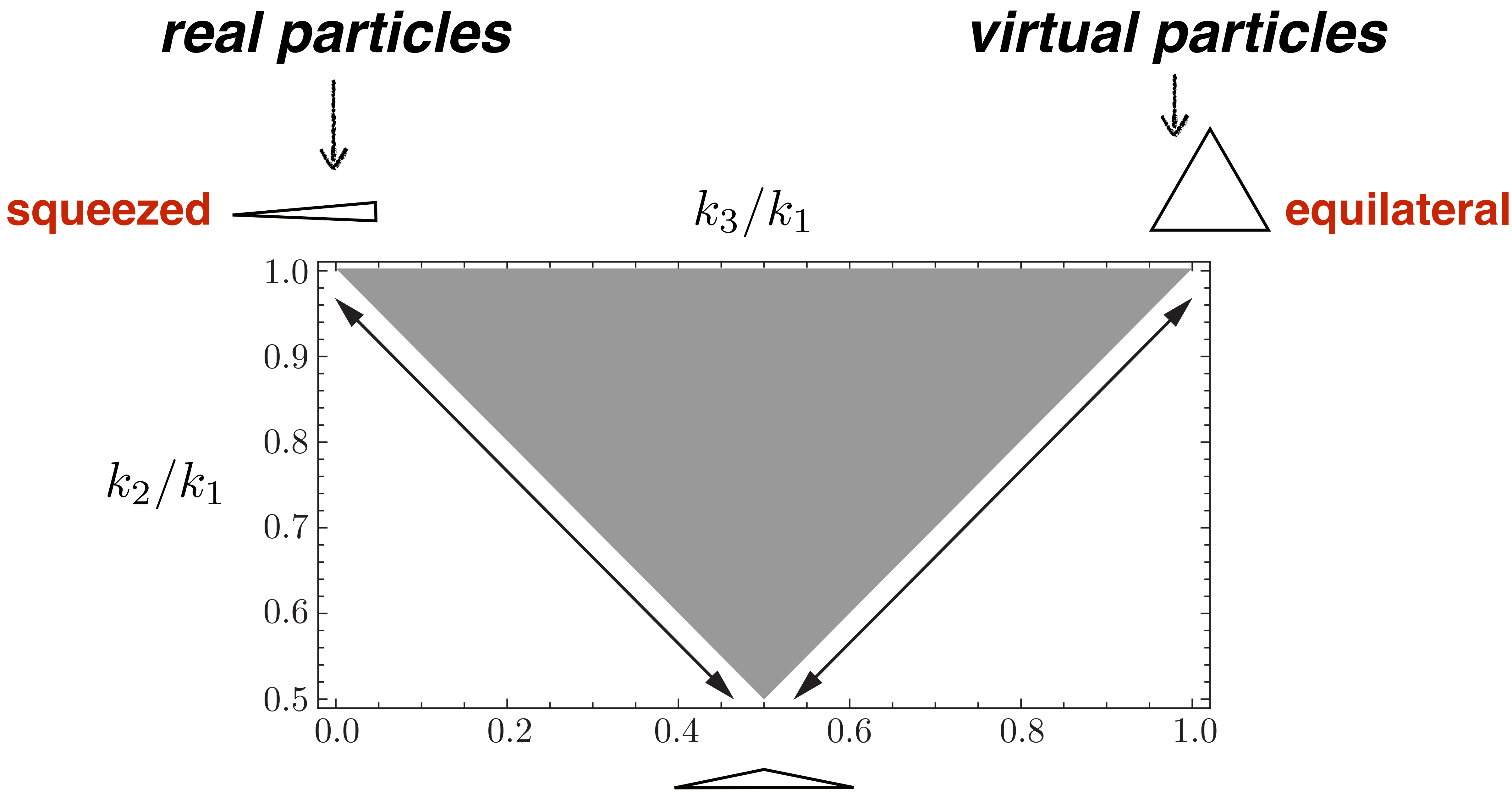
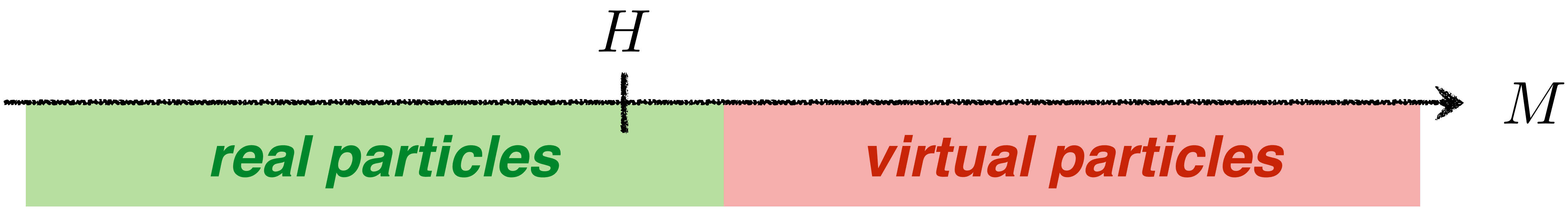
# Triangles in the Sky

Information about **extra particles** is encoded in the **shape** of the bispectrum:



# Real vs. Virtual




can be **produced** during inflation

lead to **non-local** interactions

lead to **non-analytic** soft limits

can be **integrated out** during inflation

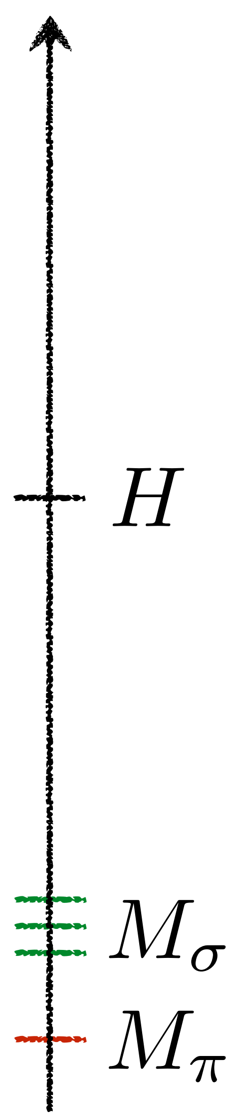
lead to **local** interactions

lead to **analytic** soft limits

# Real Particles

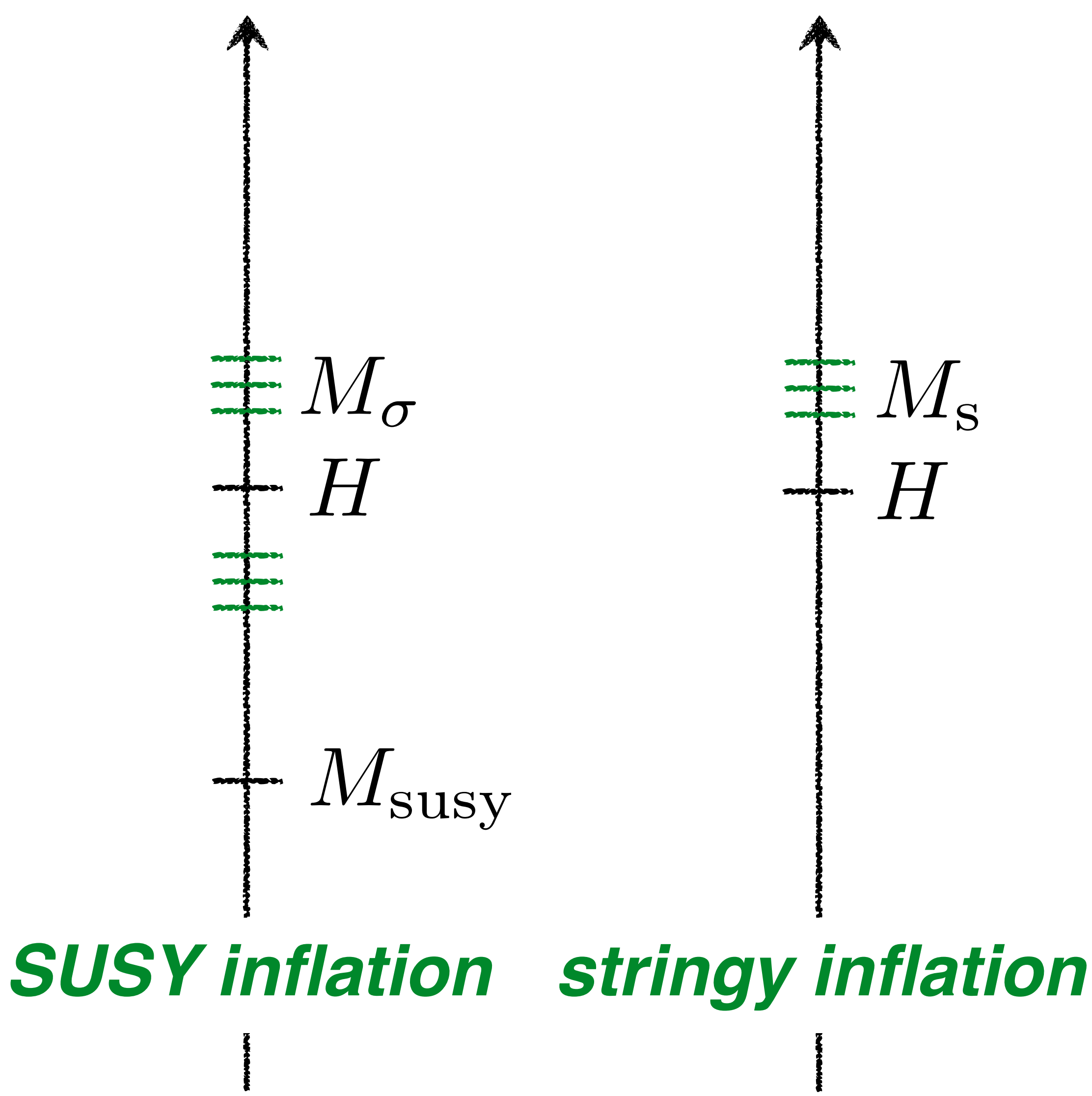
Particles with masses $M \lesssim \text{few} \times H$ cannot be integrated out:

$M \ll H$



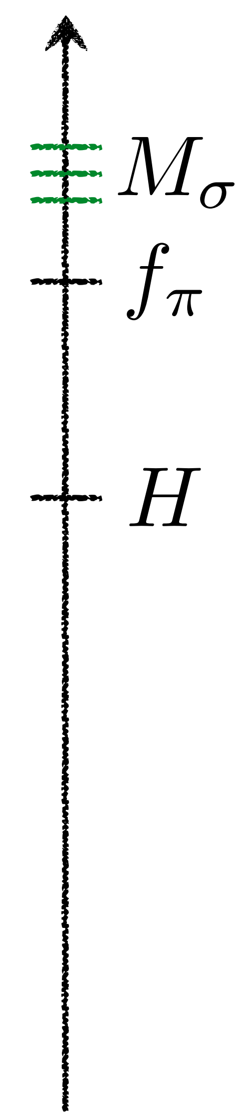

Enqvist and Sloth [2001],
Lyth and Wands [2002],
Moroi and Takahashi [2001]

$M \sim H$




**Chen and Wang [2009]**
DB and Green [2011], Noumi et al. [2013]
… , Arkani-Hamed and Maldacena [2015]

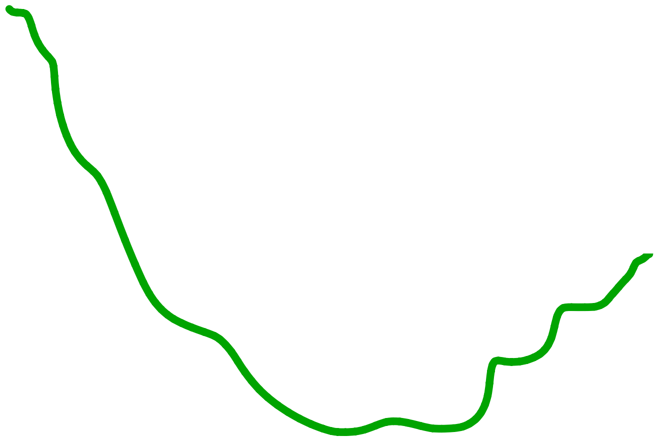
$M \sim f_\pi$




Flauger et al. [2016]
Silverstein [Strings 2016]

# Real Particles

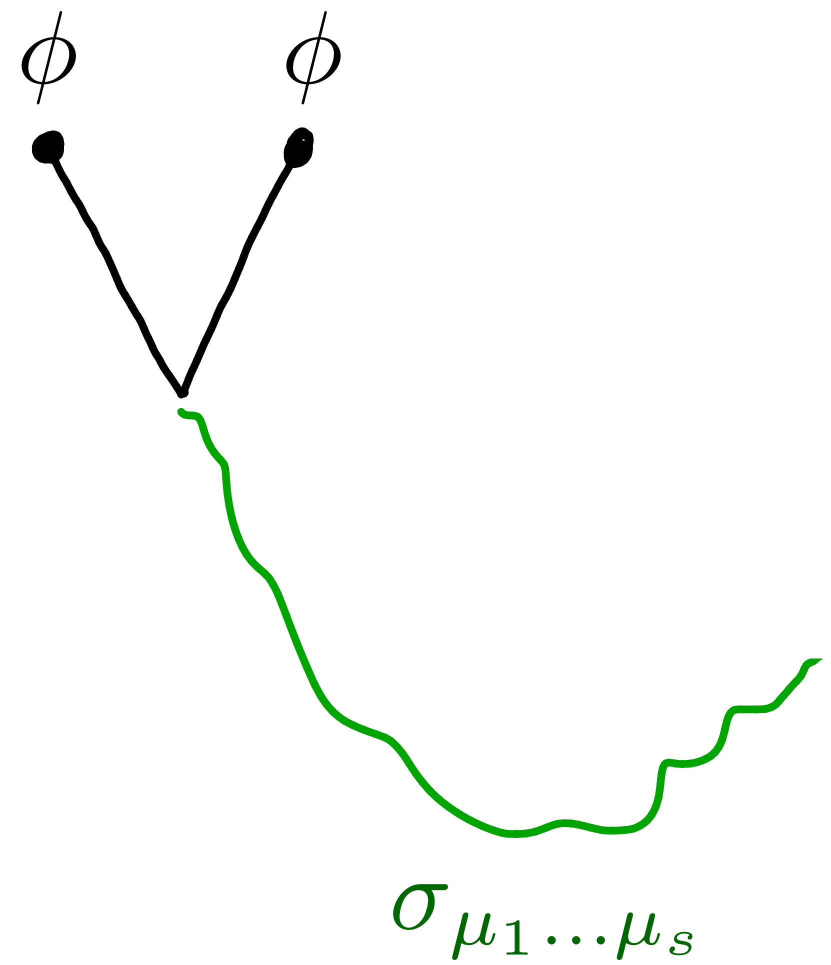
These particles are produced by the expanding spacetime:



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

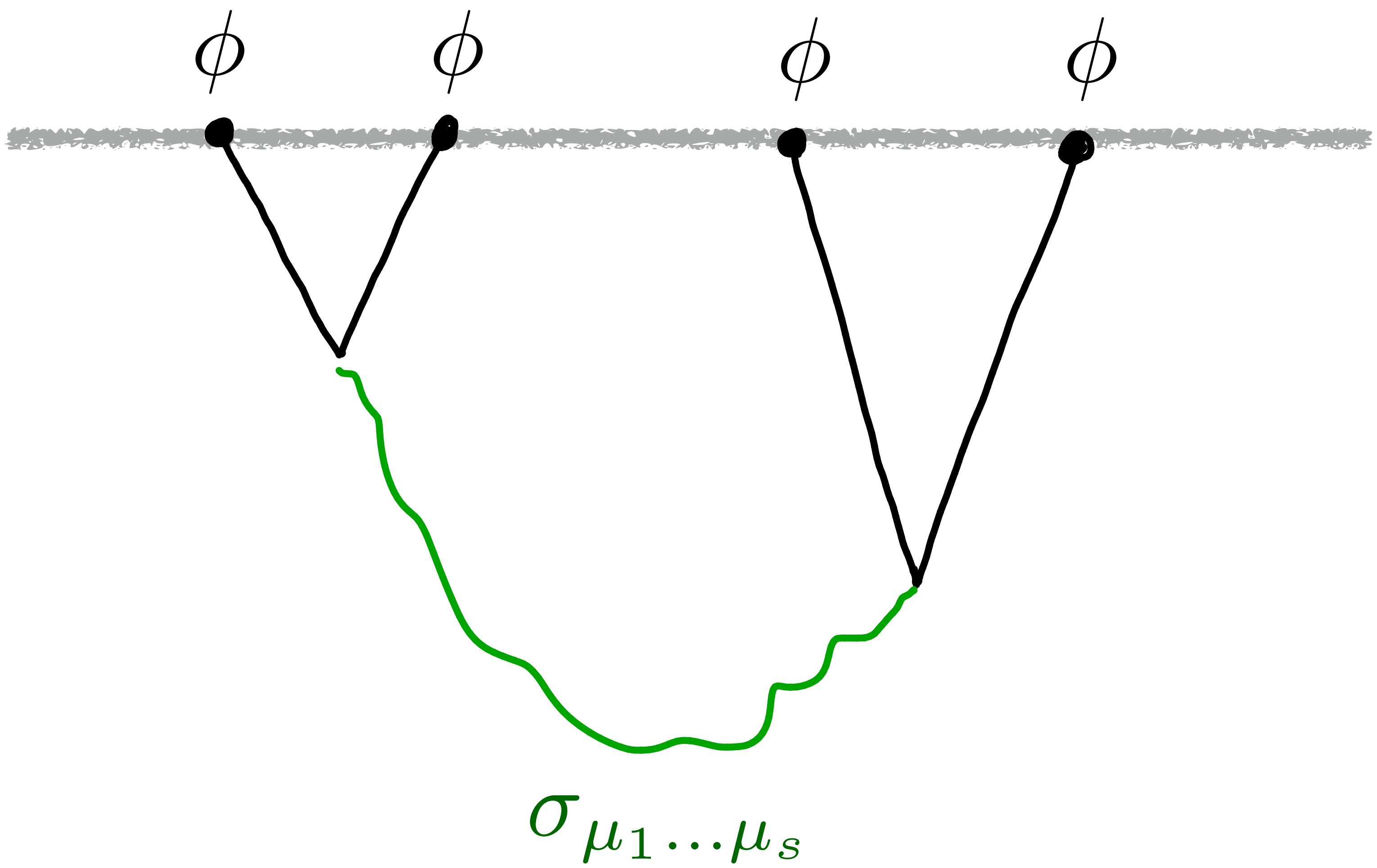
# Real Particles

These massive particles decay into the inflaton:



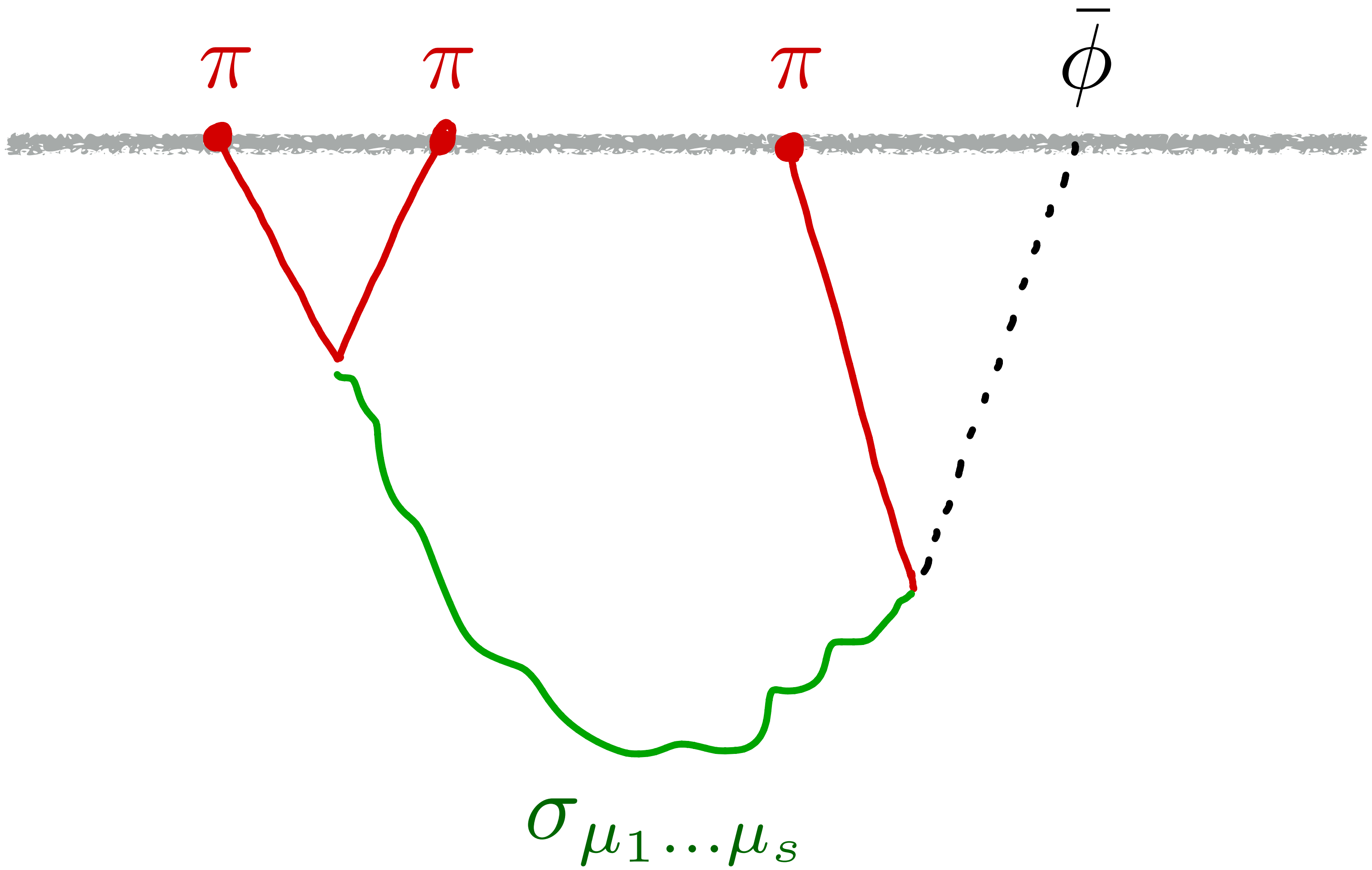
# Real Particles

The correlated decays create higher-order correlations in the inflaton:



# Real Particles

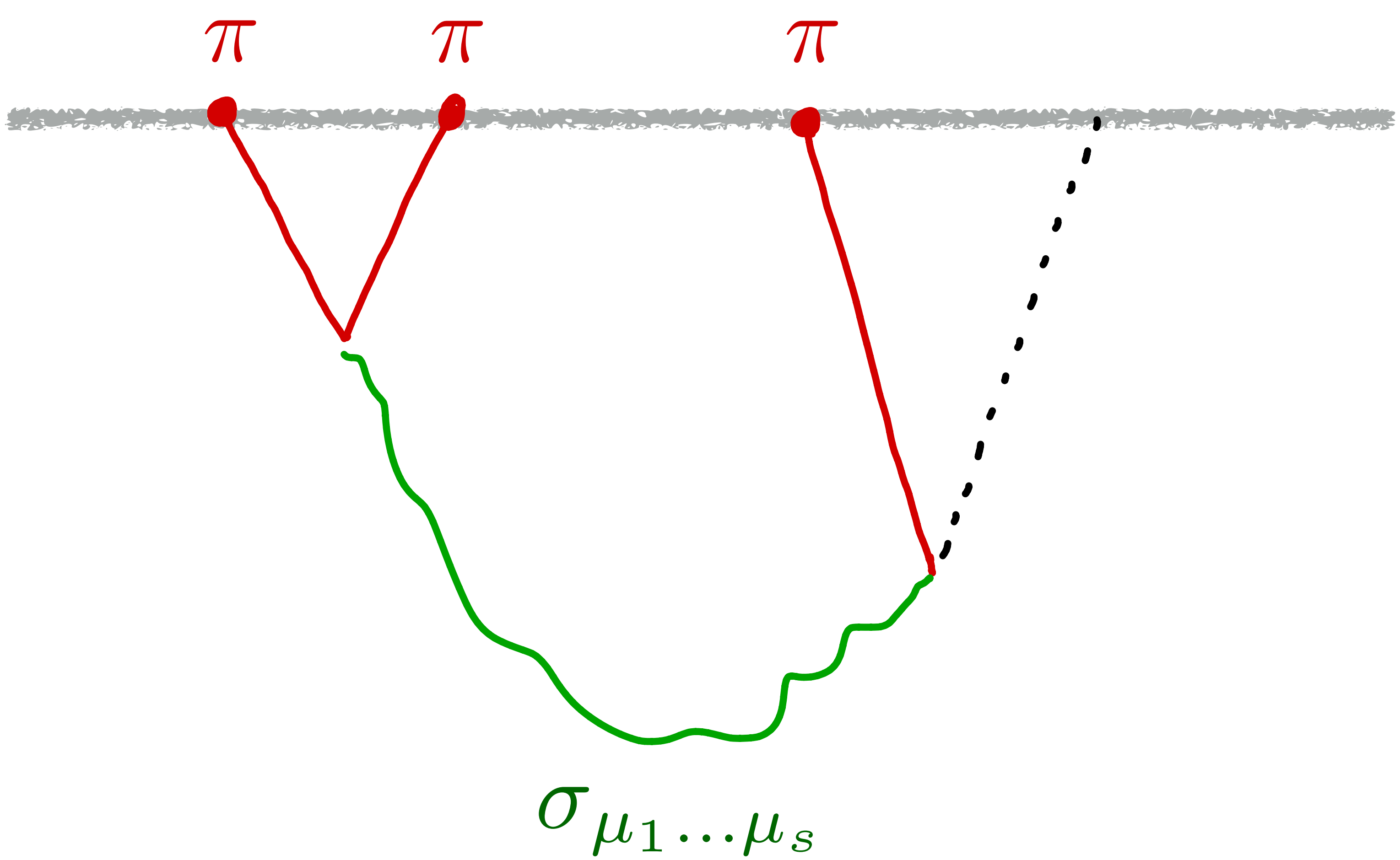
Evaluating one leg on the background. $\bar{\phi}(t)$. leads to a three-point correlation for the perturbation, $\phi(t + \pi(\vec{x}, t))$ :



# Real Particles

This effect leads to a characteristic **non-locality** in cosmological correlators.

Arkani-Hamed and Maldacena [2015]



# Real Particles

Consider the following example:

$$\mathcal{L} = (\partial\phi)^2 + (\partial\sigma)^2 - M^2\sigma^2 + \frac{\sigma(\partial\phi)^2}{\Lambda} \,, \quad \text{with } M = \text{few} \times H \,.$$

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- Integrating out the massive field gives

$$\mathcal{L}_{\text{eff}} = (\partial\phi)^2 + \frac{1}{\Lambda^2}(\partial\phi)^2\frac{1}{\Box + M^2}(\partial\phi)^2 + \cdots$$

$$\approx (\partial\phi)^2 + \frac{1}{\Lambda^2 M^2}\left(\underset{\uparrow\ \text{local}}{(\partial\phi)^4} + \underset{\uparrow\ \text{local}}{(\partial\phi)^2\frac{\Box}{M^2}(\partial\phi)^2} + \underset{\uparrow\ \text{local}}{\cdots}\right)$$

$\sim$ expansion in $(H/M)^2$

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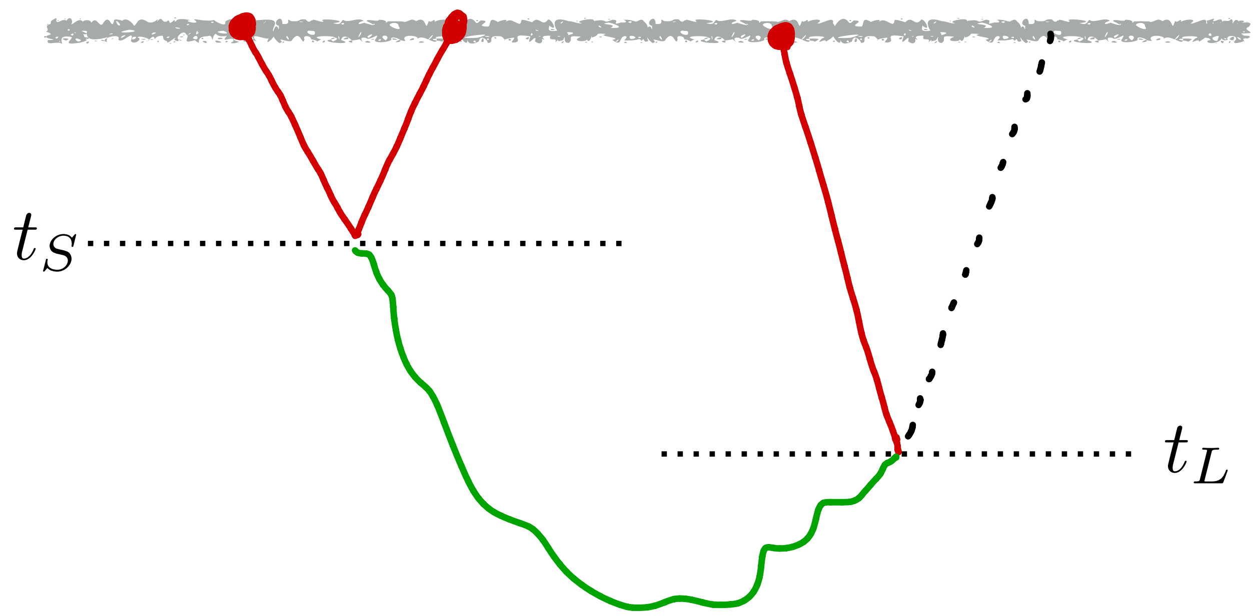
$\sim$ expansion in $(H/M)^2$

- Particle production leads to **non-local** terms proportional to $e^{-M/H}$.

# Real Particles

- The **non-locality** shows up as **non-analyticity** in the **squeezed limit**:




$$\sim \; e^{iM(t_L - t_S)}$$

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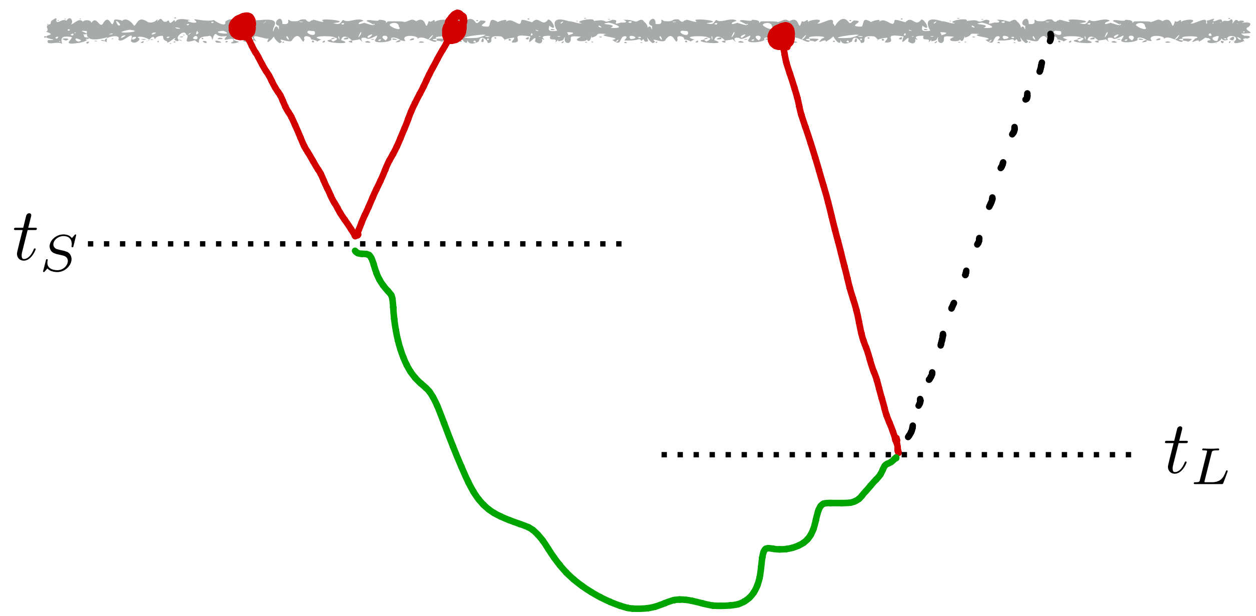


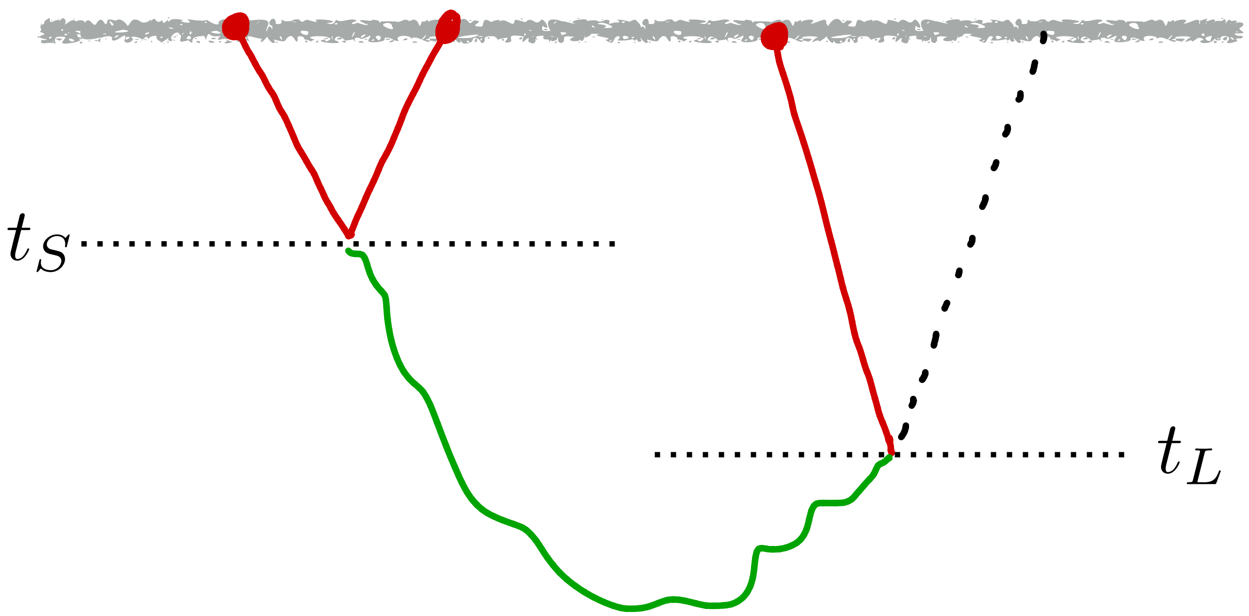

$$\sim \; e^{iM(t_L - t_S)}$$

- The **mass** of the particles leads to distinct **oscillations**:

$$\boxed{\lim_{k_L \to 0} \langle \zeta_{\vec{k}_S} \zeta_{\vec{k}_S} \zeta_{\vec{k}_L} \rangle \;\propto\; \cos\left[\frac{M}{H} \ln\left(\frac{k_L}{k_S}\right) + \delta\right]}$$

# Real Particles

- The **non-locality** shows up as **non-analyticity** in the **squeezed limit**:

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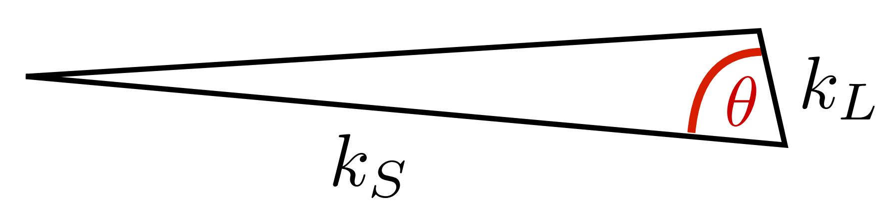
- Particles with **spin** lead to a unique **angular dependence**:

$$\boxed{\lim_{k_L \to 0} \langle \zeta_{\vec{k}_S} \zeta_{\vec{k}_S} \zeta_{\vec{k}_L} \rangle \;\propto\; P_S(\cos\theta)}$$



# Real Particles

- For gravitational mixing, $\Lambda = M_{\rm pl}$, the **amplitude** is small:

Boltzmann

$$\boxed{F_{\rm NL} \ \propto \ \varepsilon \ e^{-M/H}}$$

gravity

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$$\varepsilon \sim 10^{-2} \quad \Rightarrow \quad \Delta_\zeta^{-1} \sim 10^5$$

Chen and Wang [2009]
Lee, DB and Pimentel [2016]

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Chen and Wang [2009]
Lee, DB and Pimentel [2016]

- For time-dependent masses, the Boltzmann suppression can be reduced:

$$e^{-M/H} \quad \Rightarrow \quad e^{-M^2/\dot\phi}$$

extending the reach to heavier particles.

Flauger et al. [2016]
Silverstein [Strings 2016]

# Real Particles

- For gravitational mixing, $\Lambda = M_{\rm pl}$, the **amplitude** is small:

Boltzmann

$$\boxed{F_{\rm NL} \;\propto\; \varepsilon \; e^{-M/H}}$$

gravity

- For $M < H$, there is no Boltzmann suppression.* Chen and Wang [2009]

  The momentum scaling becomes

$$\left(\frac{k_L}{k_S}\right)^{3/2} \cos\left[\frac{M}{H} \ln\left(\frac{k_L}{k_S}\right)\right] \;\Rightarrow\; \left(\frac{k_L}{k_S}\right)^{\Delta} \qquad \Delta \equiv \frac{3}{2} - \sqrt{\frac{9}{4} - \frac{M^2}{H^2}}$$

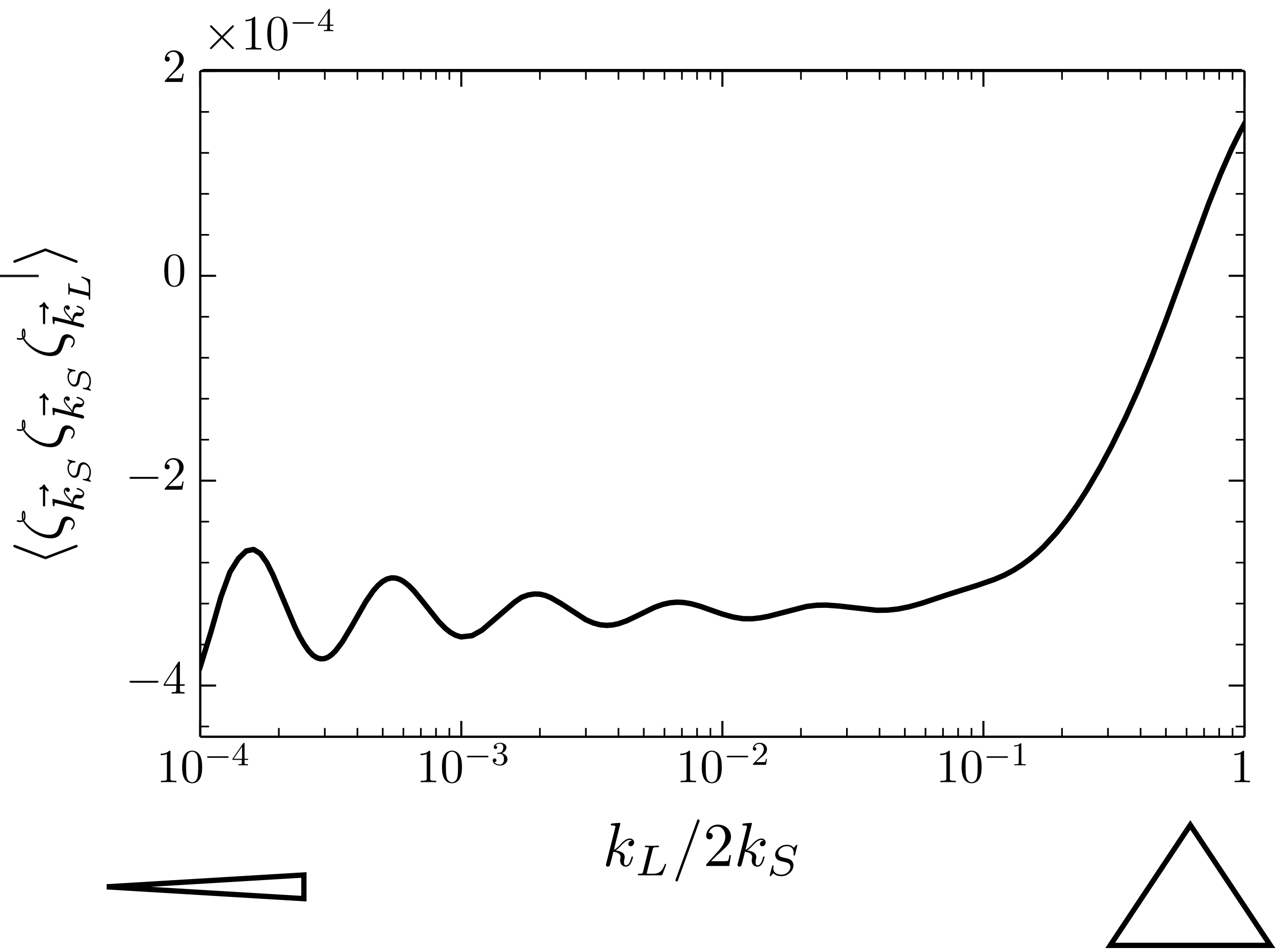
* For higher-spin particles, this limit is restricted by the Higuchi bound:

$$m^2 > s(s-1)H^2$$

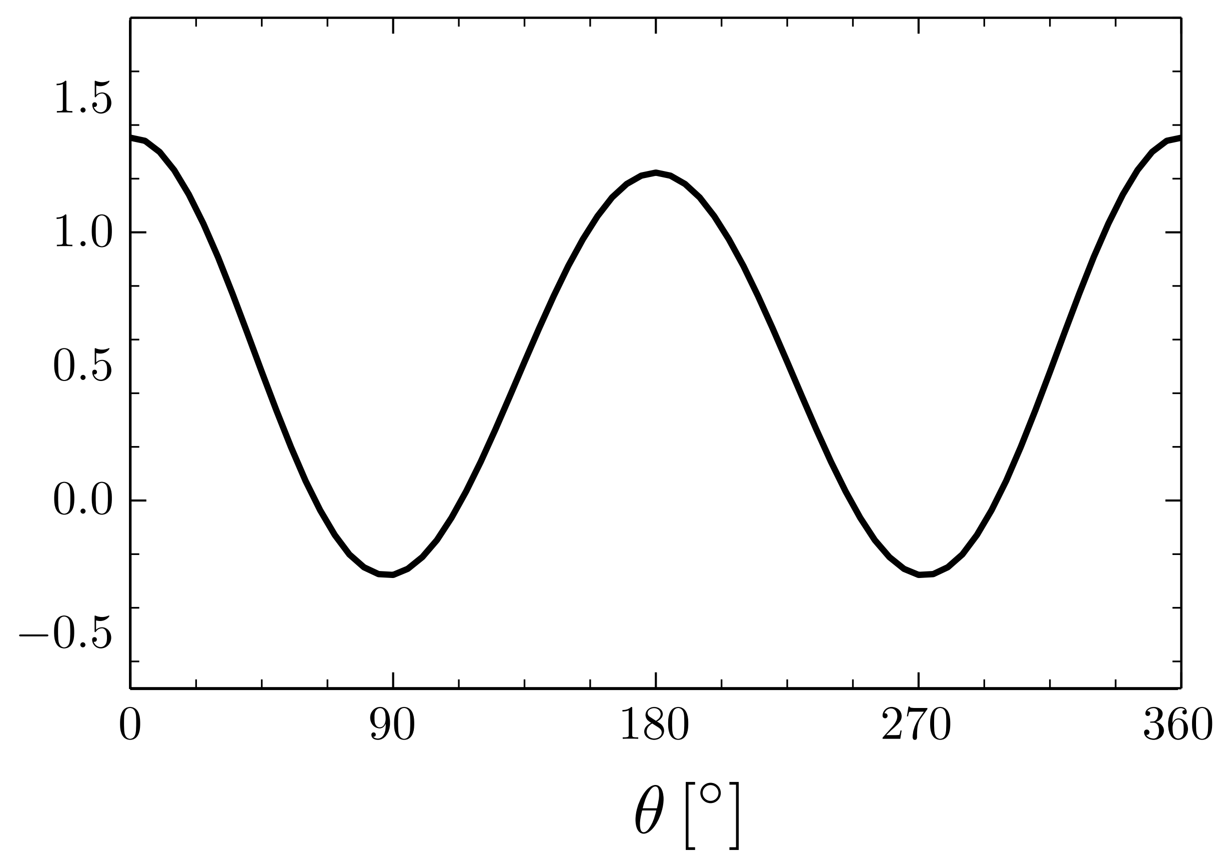
# Particle Spectroscopy

$$\lim_{k_L \to 0} \langle \zeta_{\vec{k}_S} \zeta_{\vec{k}_S} \zeta_{\vec{k}_L} \rangle \propto \left( \frac{k_L}{k_S} \right)^{3/2} \cos \left[ \frac{M}{H} \ln \left( \frac{k_L}{k_S} \right) + \delta \right] P_S(\cos\theta)$$

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



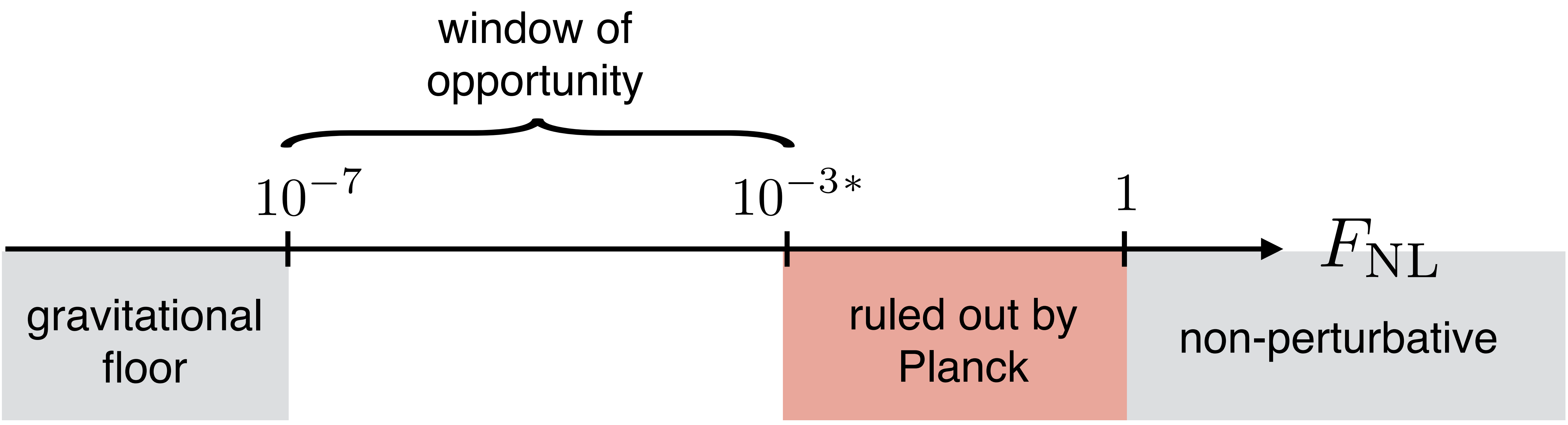

*Angular dependence in the squeezed limit measures the* ***spin*** *of the particle:*




Lee, DB and Pimentel [2016]

# Future Observations

Future observations of CMB and LSS still have discovery potential:




$^*$ Precise limit depends on the shape of the non-Gaussianity.

Note: $F_{\rm NL} = f_{\rm NL}\Delta_\zeta$

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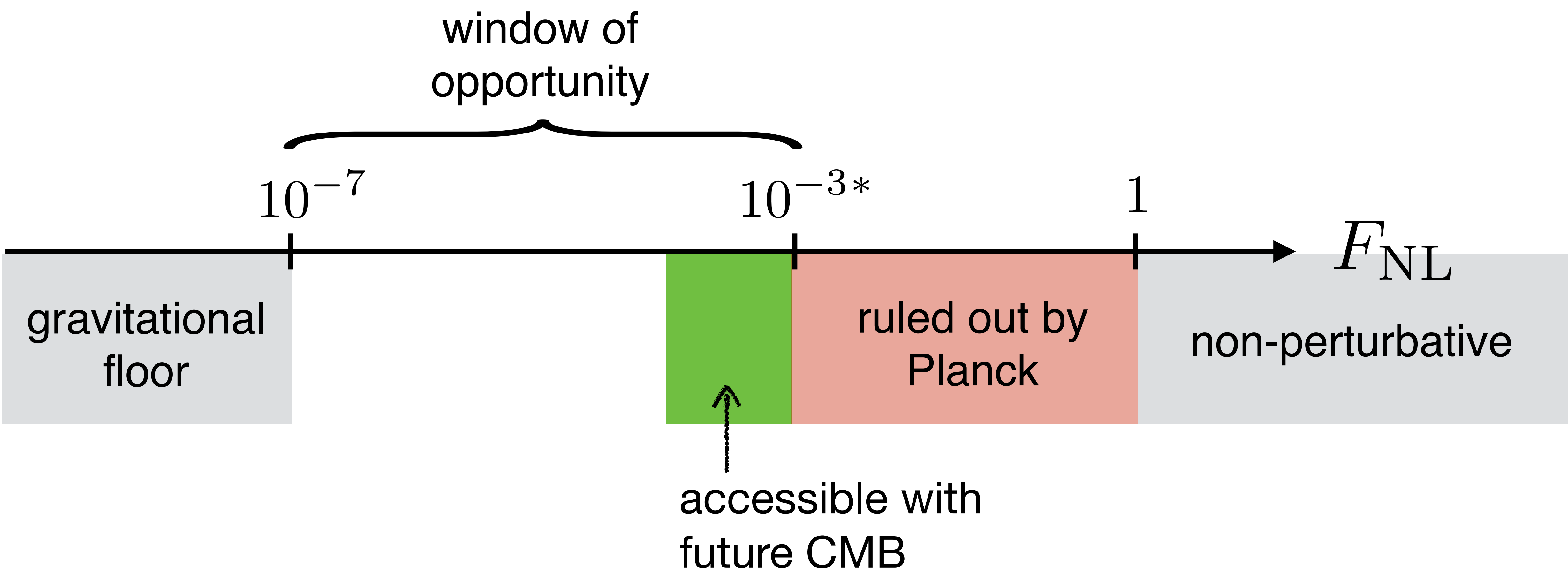


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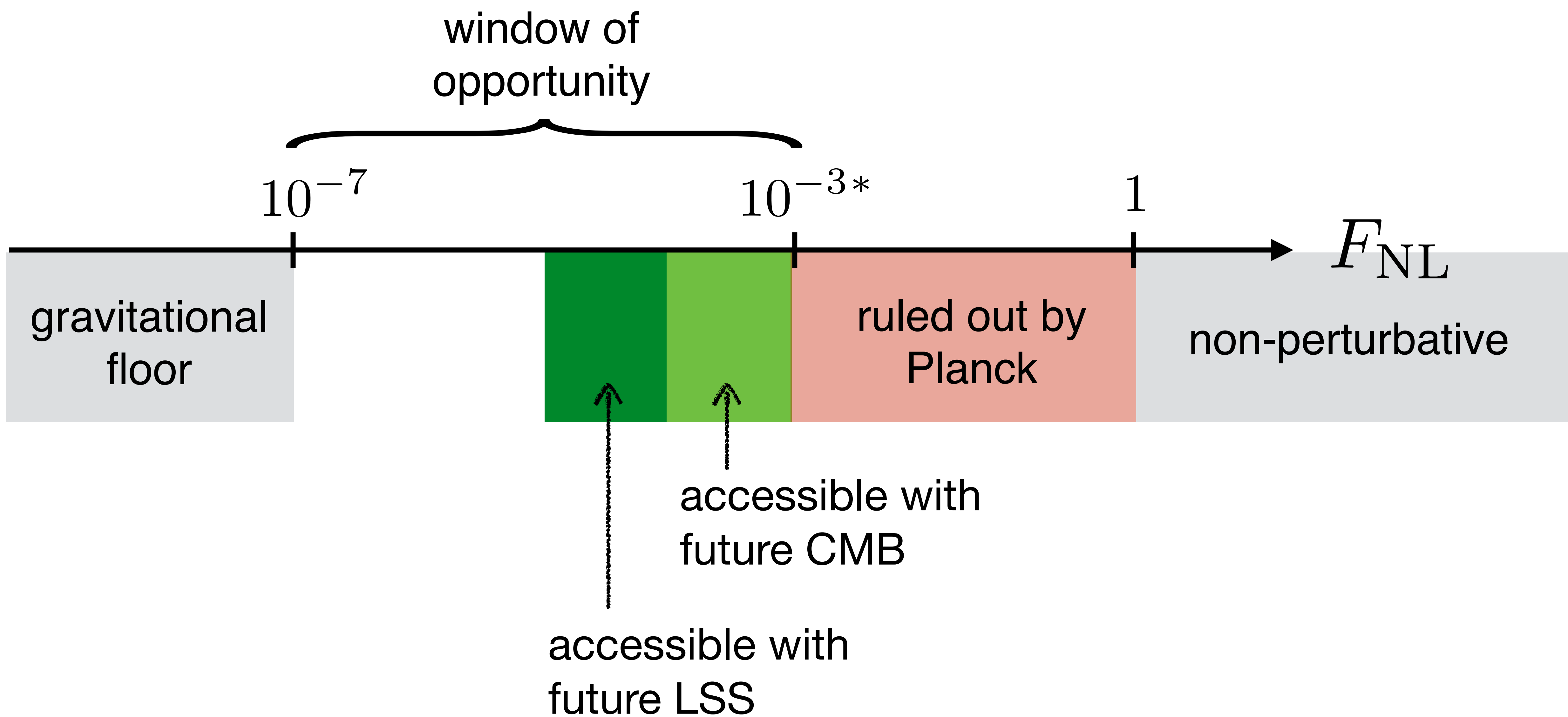


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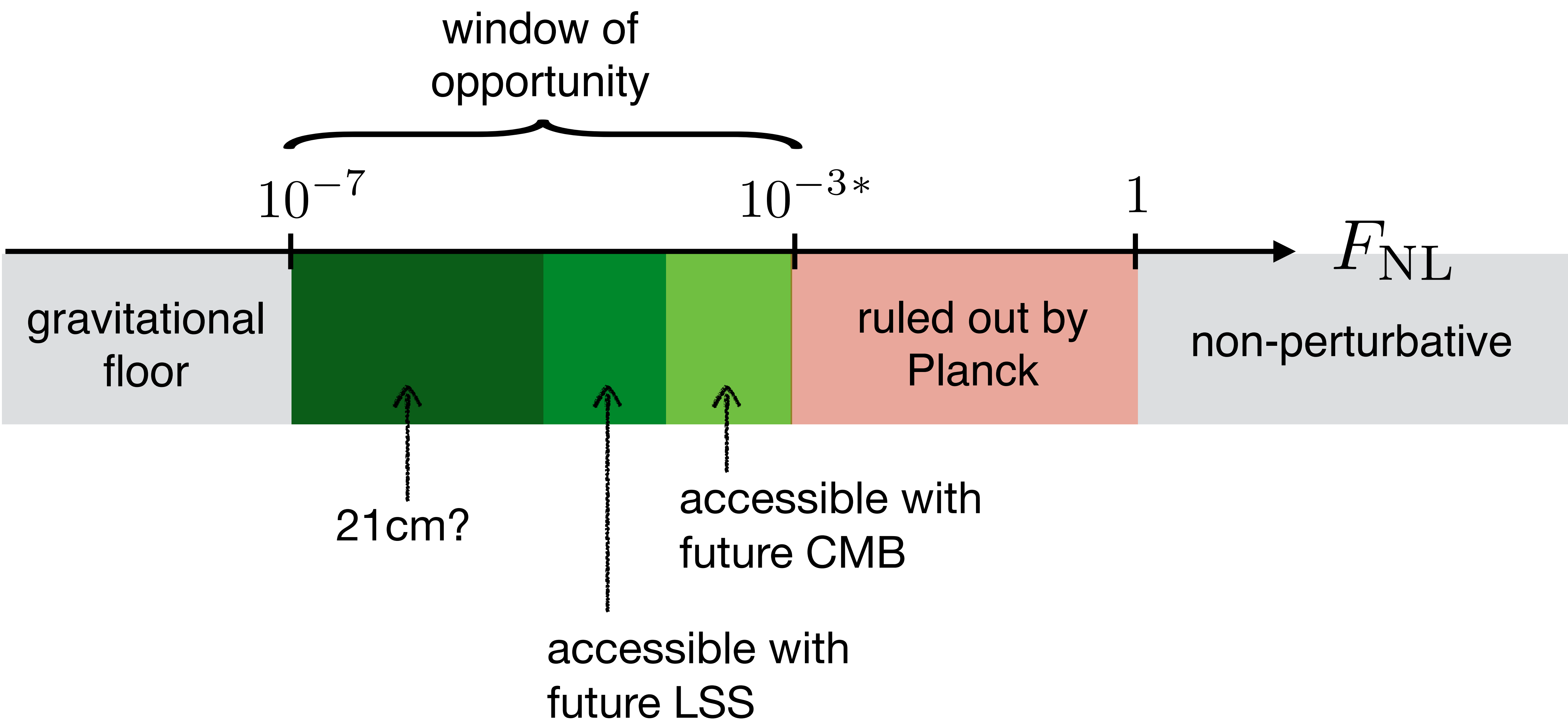


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# Tensor Modes

# Theoretical Targets

- **Tensor amplitude**

    *probes the UV sensitivity of the inflationary **background***

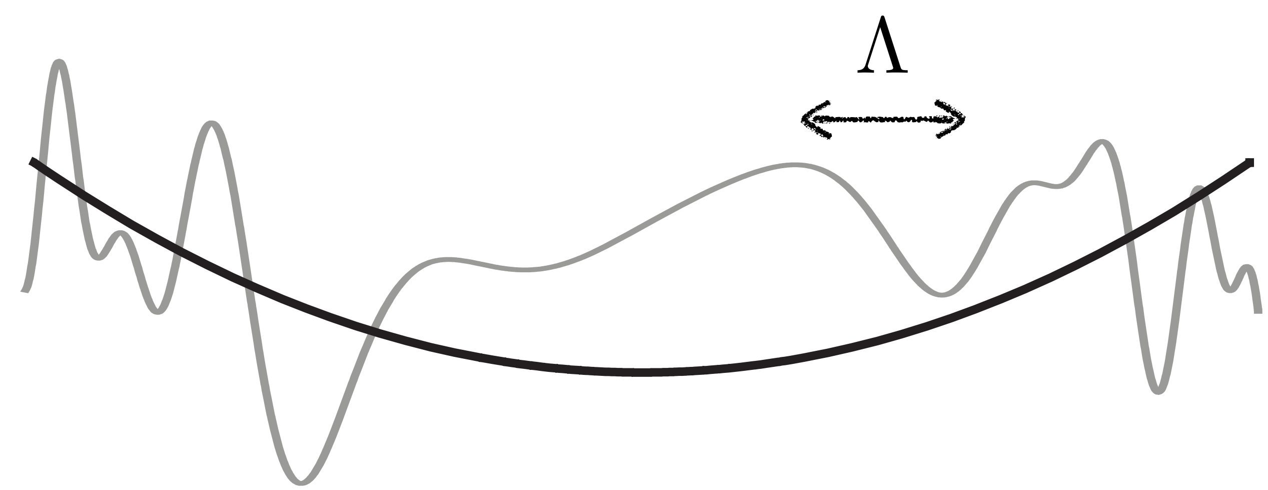
- **Tensor tilt**
- **Tensor non-Gaussianity**

    *probe the UV sensitivity of the inflationary **perturbations***

# Tensor Amplitude

Famously, observable tensors (**r > 0.01**) require a **super-Planckian field excursion**. This implies a maximal UV sensitivity of inflation: Lyth [1997]

$$\frac{\Delta V}{V} = \sum_n c_n \left(\frac{\phi}{\Lambda}\right)^n \qquad \sim$$




EFTs of large-field inflation rely on **symmetries** to forbid these corrections.

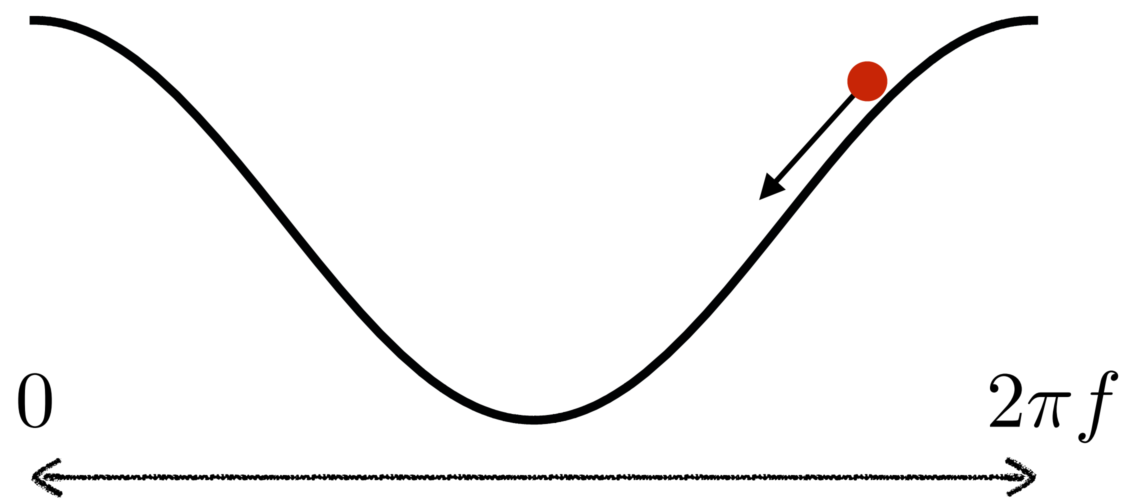
Whether these symmetries survive the coupling to gravity is a question for **string theory**:

*"no global symmetries in quantum gravity"*

# Axions

Axions are promising candidates for large-field inflation:

Their perturbative shift symmetry is broken by instanton effects, leading to a periodic inflaton potential $V(\phi)$




- Successful **natural inflation** requires a super-Planckian axion decay constant:

$$f > M_{\rm pl}$$

Freese, Frieman and Olinto [1990]

- This does not seem possible in controlled string compactifications.

Banks, Dine, Fox and Gorbatov [2003]

Svrcek and Witten [2006]

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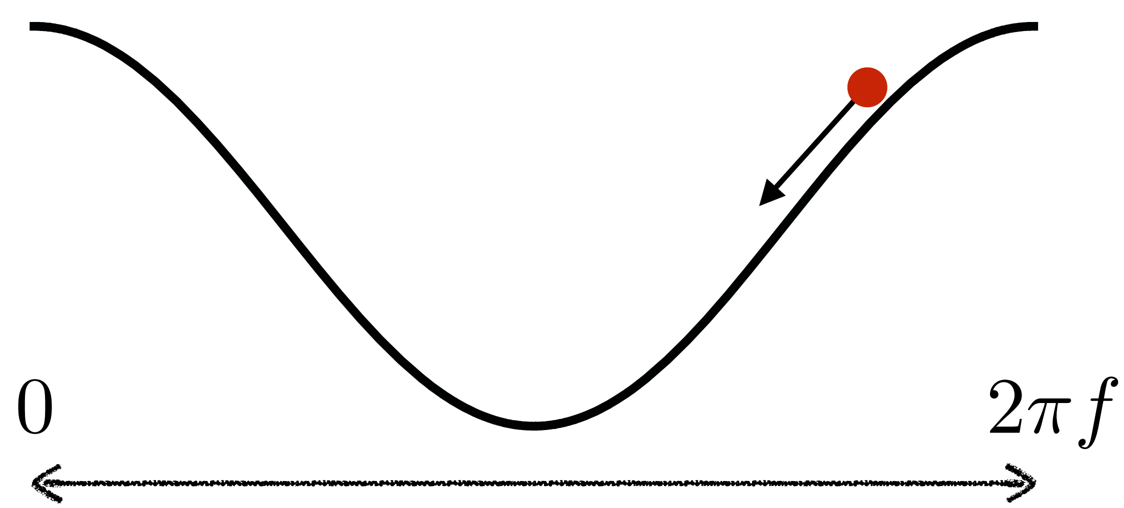


- Mechanism to avoid the no-go:

*N-flation*

Dimopoulos et al. [2008]

*Alignment*

Kim, Nilles and Peloso [2005]

*Axion Monodromy*

Silverstein and Westphal [2008]

McAllister, Silverstein and Westphal [2010]

Marchesano, Shiu and Uranga [2014]

see talks by Silverstein [Strings 2014]
McAllister [Strings 2011]

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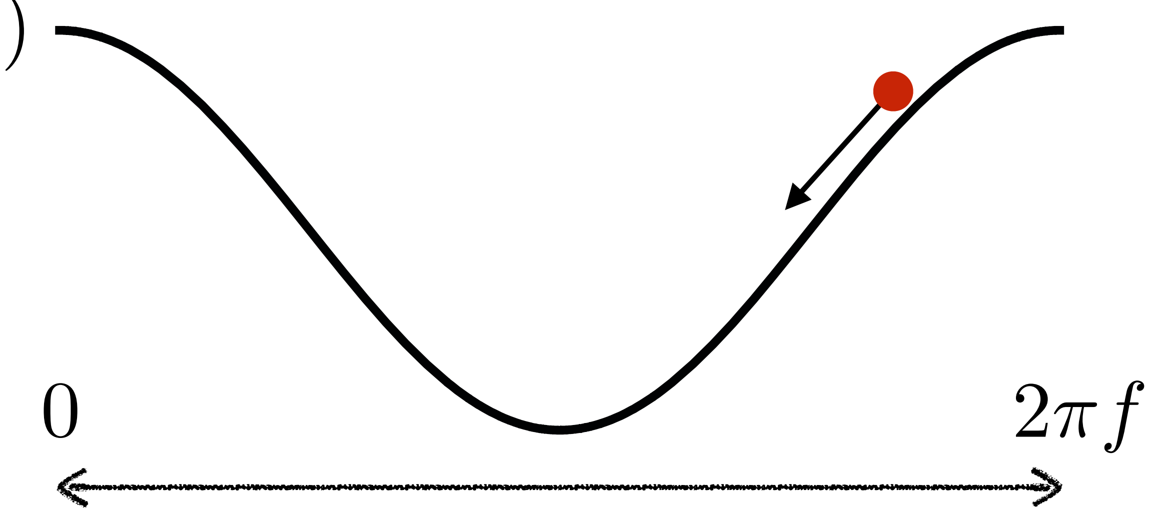


- Recently, it was shown that the **W**eak **G**ravity **C**onjecture is inconsistent with N-flation and alignment (modulo loopholes).

Arkani-Hamed et al. [2007]

Cheung and Remmen [2014]

Rudelius [2015]

Montero et al. [2015]

Brown et a. [2015]

*See extra slides and talks by Uranga and Shiu.*

*If we were to observe tensors, what else can we look for?*

*I will briefly discuss a few futuristic examples.*

# Curvature Corrections

String theory predicts **higher-curvature corrections** to Einstein gravity.

If the **string scale** is not too far above the Hubble scale, then these corrections can show up in the spectrum of tensor fluctuations:


Kaloper et al. [2002]

The corrections 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]

# Tensor Tilt

The leading correction to the **quadratic action** for tensors is

*Weyl tensor*

$$\mathcal{L}_g = \sqrt{-g}\,\frac{M_{\rm pl}^2}{2}\left[R + f(\phi)\frac{W^2}{M_{\rm s}^2}\right]$$

Weinberg [2008]

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Weinberg [2008]

- The main effect is a nontrivial tensor **sound speed**: $\frac{1}{c_{\rm t}^2} - 1 = 8f(\phi)\frac{H^2}{M_{\rm s}^2}$
- The coupling to the inflaton induces a correction to the **tensor tilt**:

$$n_{\rm t} = \underbrace{-2\varepsilon}_{\text{Einstein gravity}} \pm \underbrace{\sqrt{\varepsilon}\left(\frac{H}{M_{\rm s}}\right)^2}_{\text{stringy correction}}$$

violation of the consistency relation $n_{\rm t} \neq -r/8$

tilt can be blue: $n_{\rm t} > 0$

DB, Lee and Pimentel [2015]

# Tensor Non-Gaussianity

The leading correction to the **cubic action** for tensors is

*related to $R^3$ by field redefinition*

$$\mathcal{L}_g = \sqrt{-g}\,\frac{M_{\rm pl}^2}{2}\left[R + \frac{W^3}{M_{\rm s}^4}\right]$$

Maldacena and Pimentel [2011]

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Maldacena and Pimentel [2011]

- The main effect is a new shape of the graviton three-point function:

$$\langle hhh \rangle = \underbrace{F(k_i)}_{\text{Einstein gravity}} + \underbrace{\left(\frac{H}{M_{\rm s}}\right)^4 G(k_i)}_{\text{stringy correction}}$$

- A detection would be indirect evidence for strings:

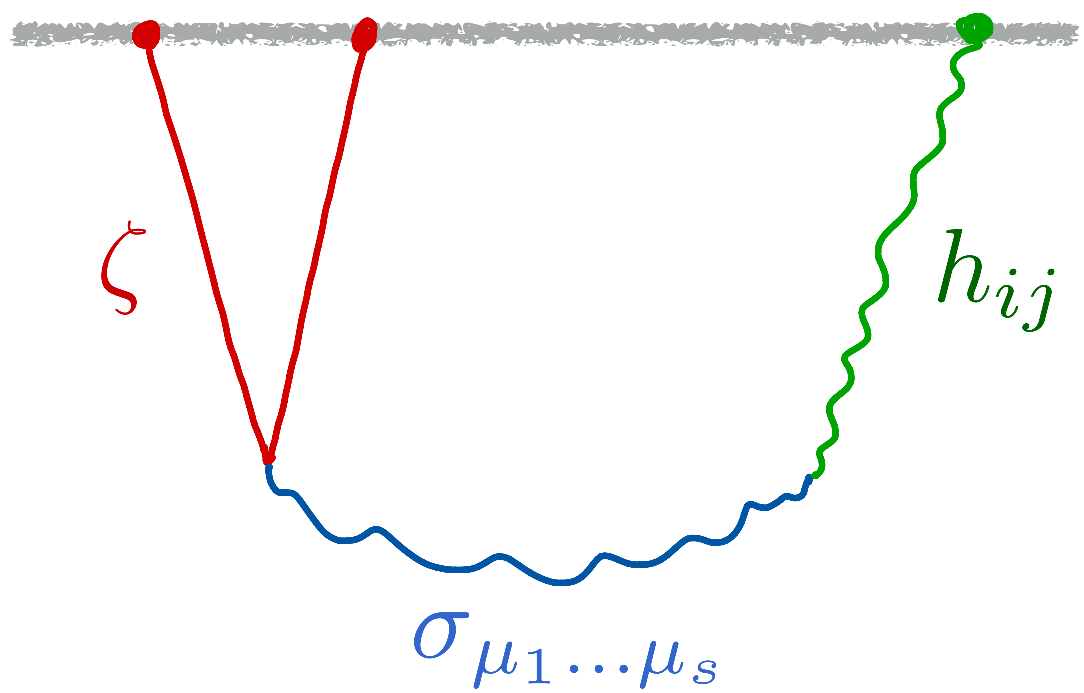
$W^3/M_{\rm s}^4 \longrightarrow$ causality violation $\longrightarrow$ fixed by a tower of higher-spin particles

Camanho et al. [2014]

# Tensor Non-Gaussianity

$\langle hhh \rangle$ will be very hard to measure.

A larger signal may be found in $\langle h\zeta\zeta \rangle$ :

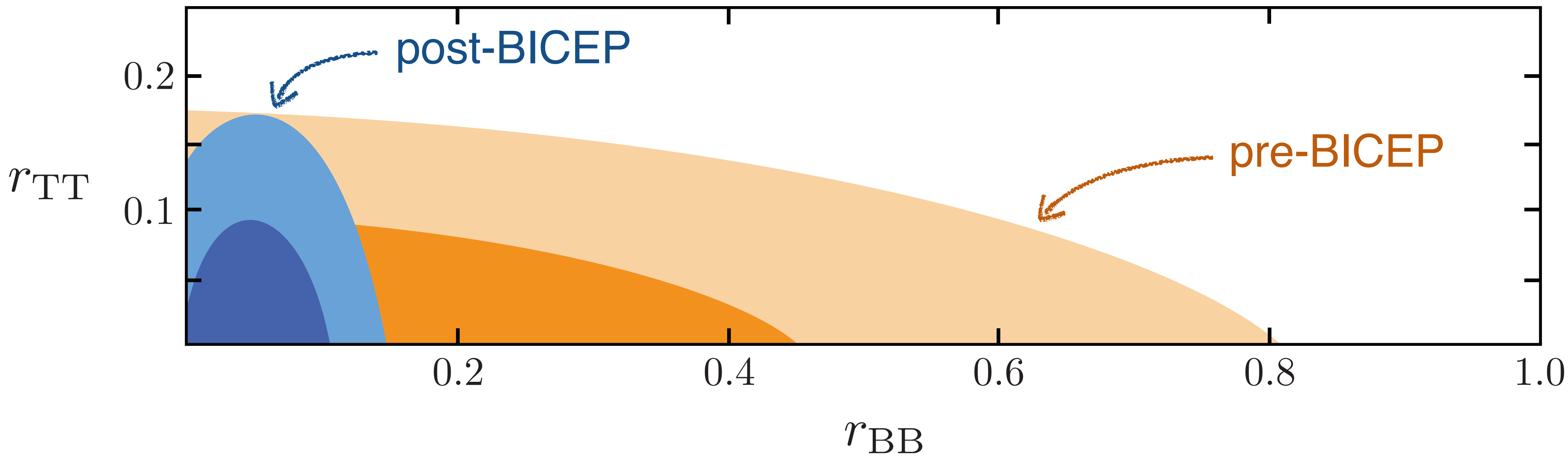



This can receive contributions from **massive higher-spin particles**, but not from scalars. Detection channel for stringy effects?

The effect can be looked for in $\langle BTT \rangle$ . Meerburg et al. [2016]

# Future Observations

There has been great experimental progress in recent years:

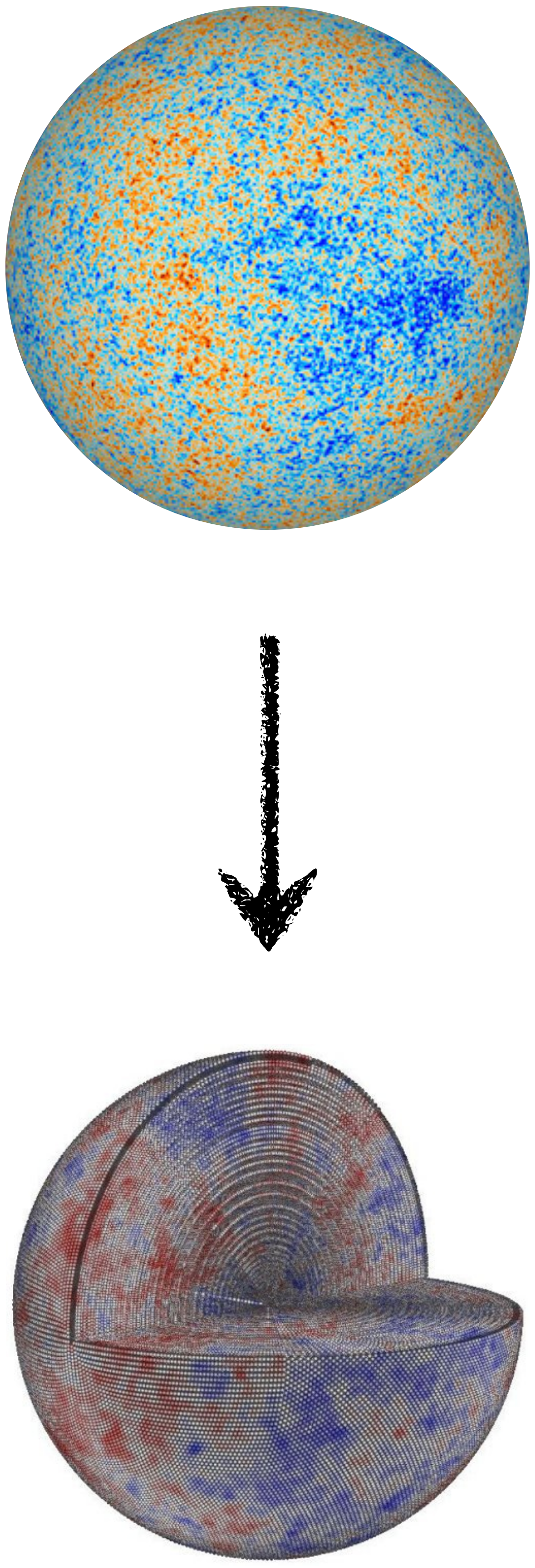



But, the era of B-mode cosmology is only beginning:

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

# Outlook

# The Inverse Problem

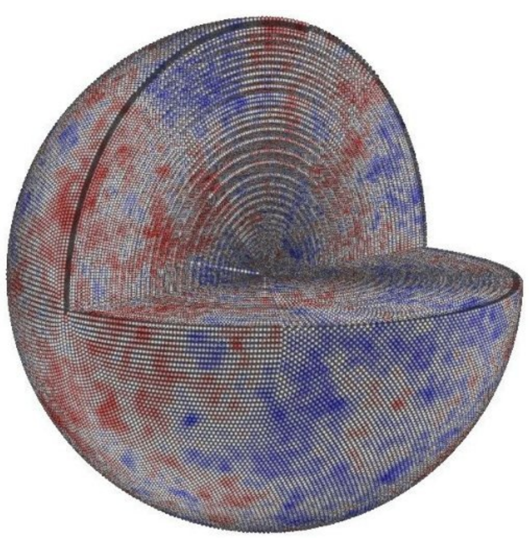


*Measurements of the CMB anisotropies provide very precise constraints on the spectrum of primordial perturbations.*

# The Inverse Problem

*At present, the initial conditions are described by just two numbers* $(A_\mathrm{s}, n_\mathrm{s})$*.*

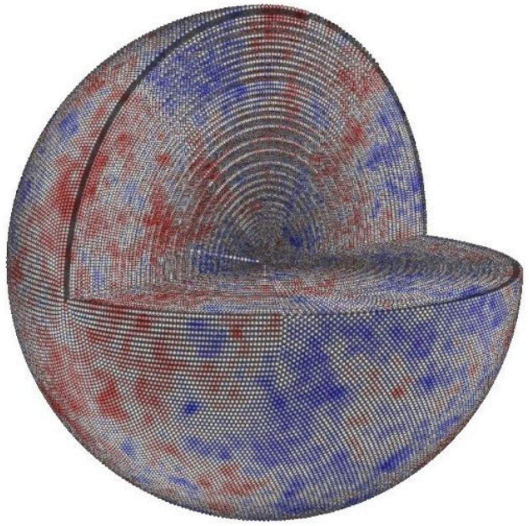
*It is hard to extract details on the physics of inflation from that information alone.*

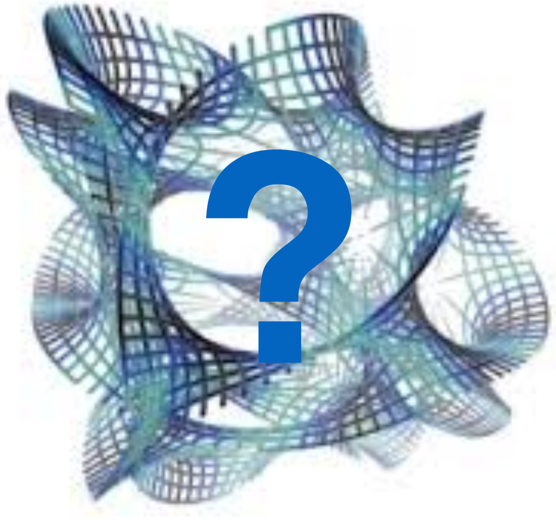


# The Inverse Problem

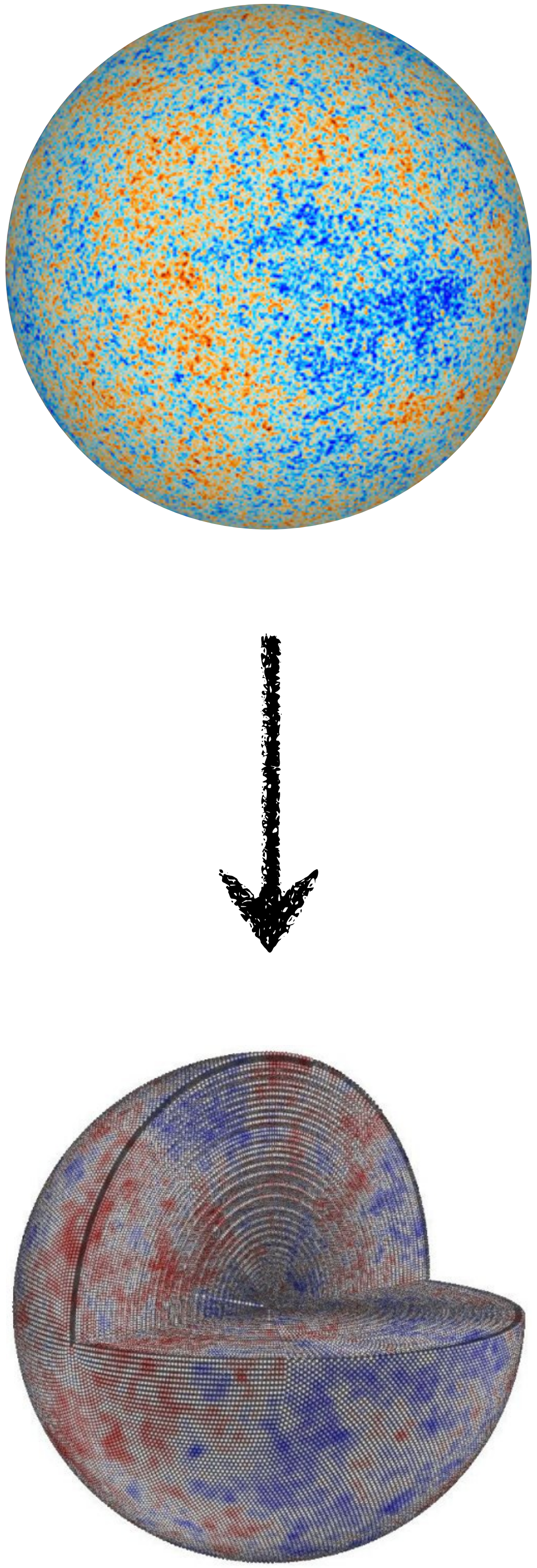
*To make progress on the inverse problem, we need theoretical predictions for deviations from these simple initial conditions:*

*e.g.*
- ***Non-Gaussianity***
- ***Tensor Modes***

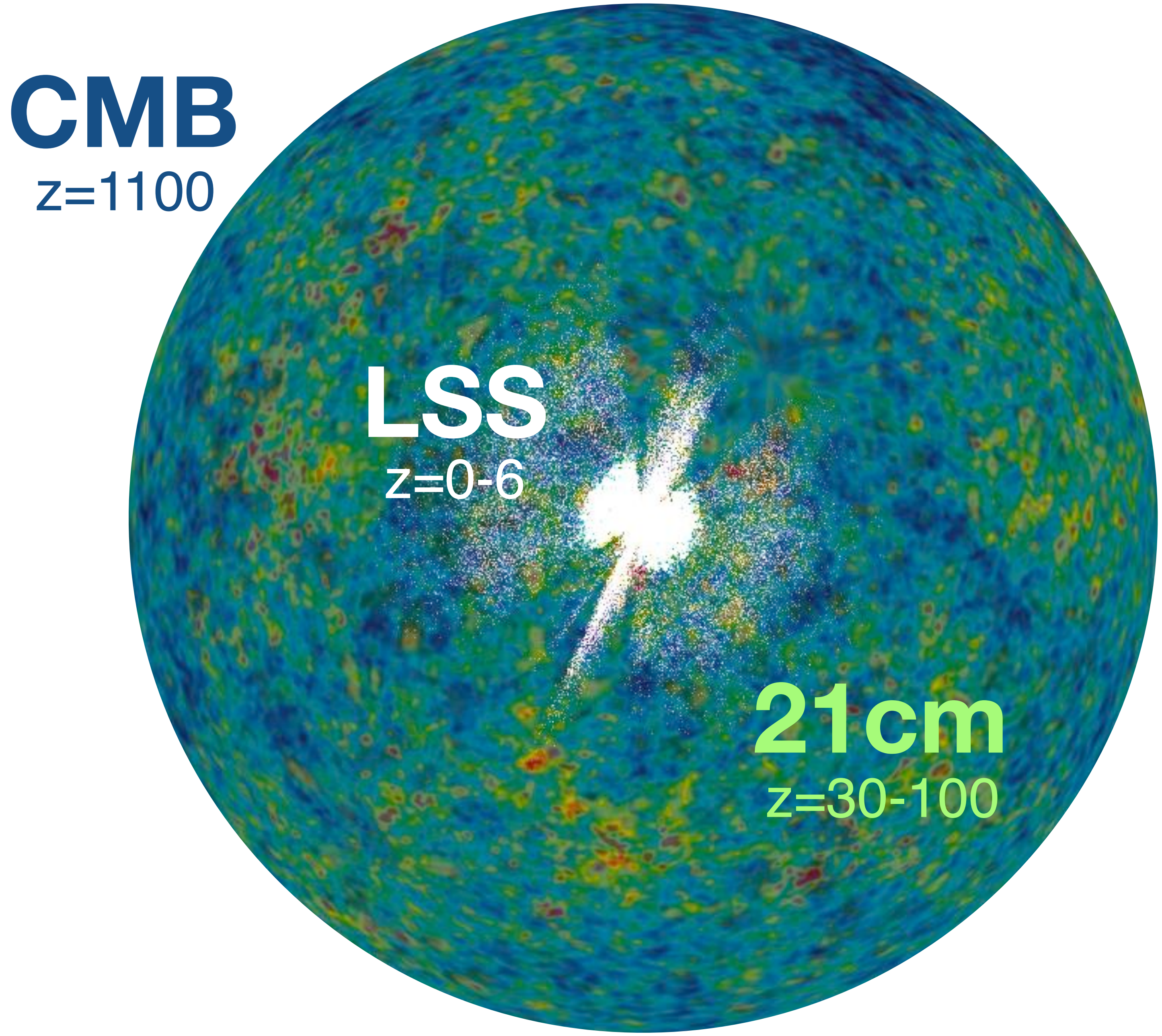




# The Inverse Problem



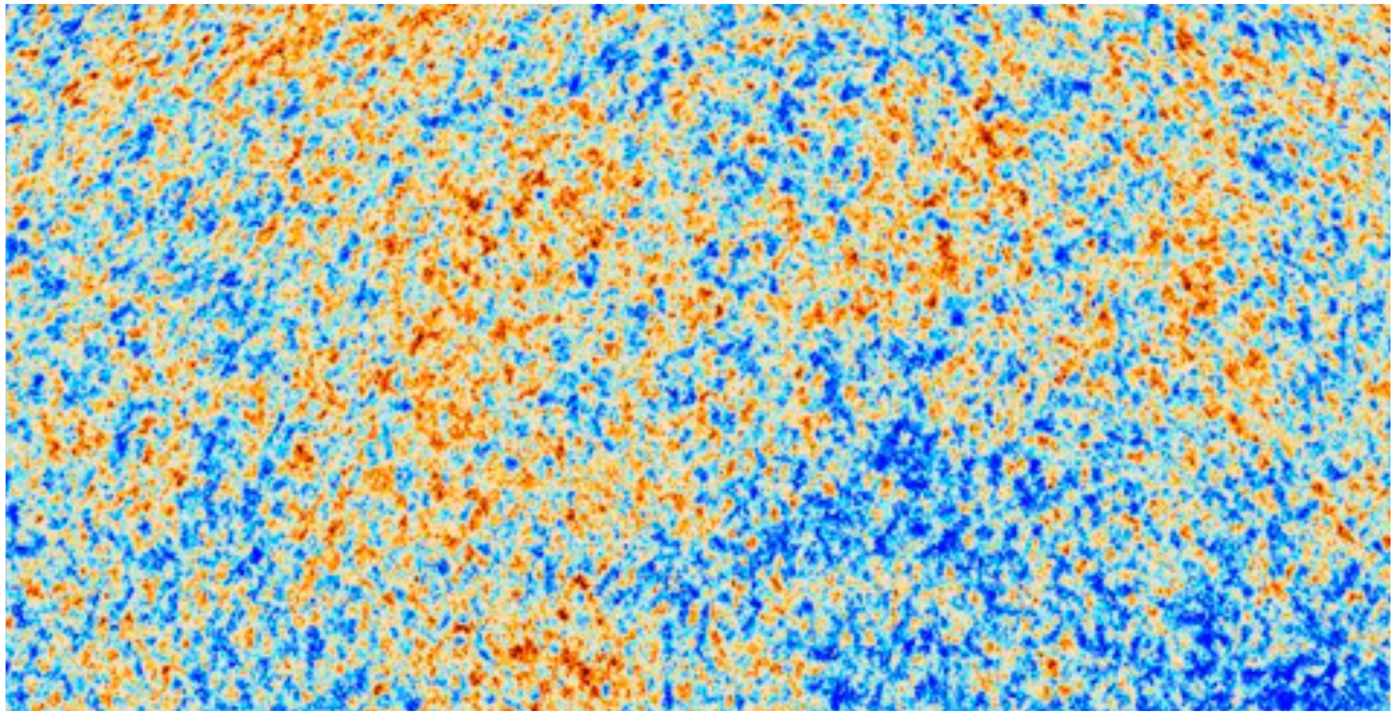
*Future data will provide stringent tests of these ideas:*



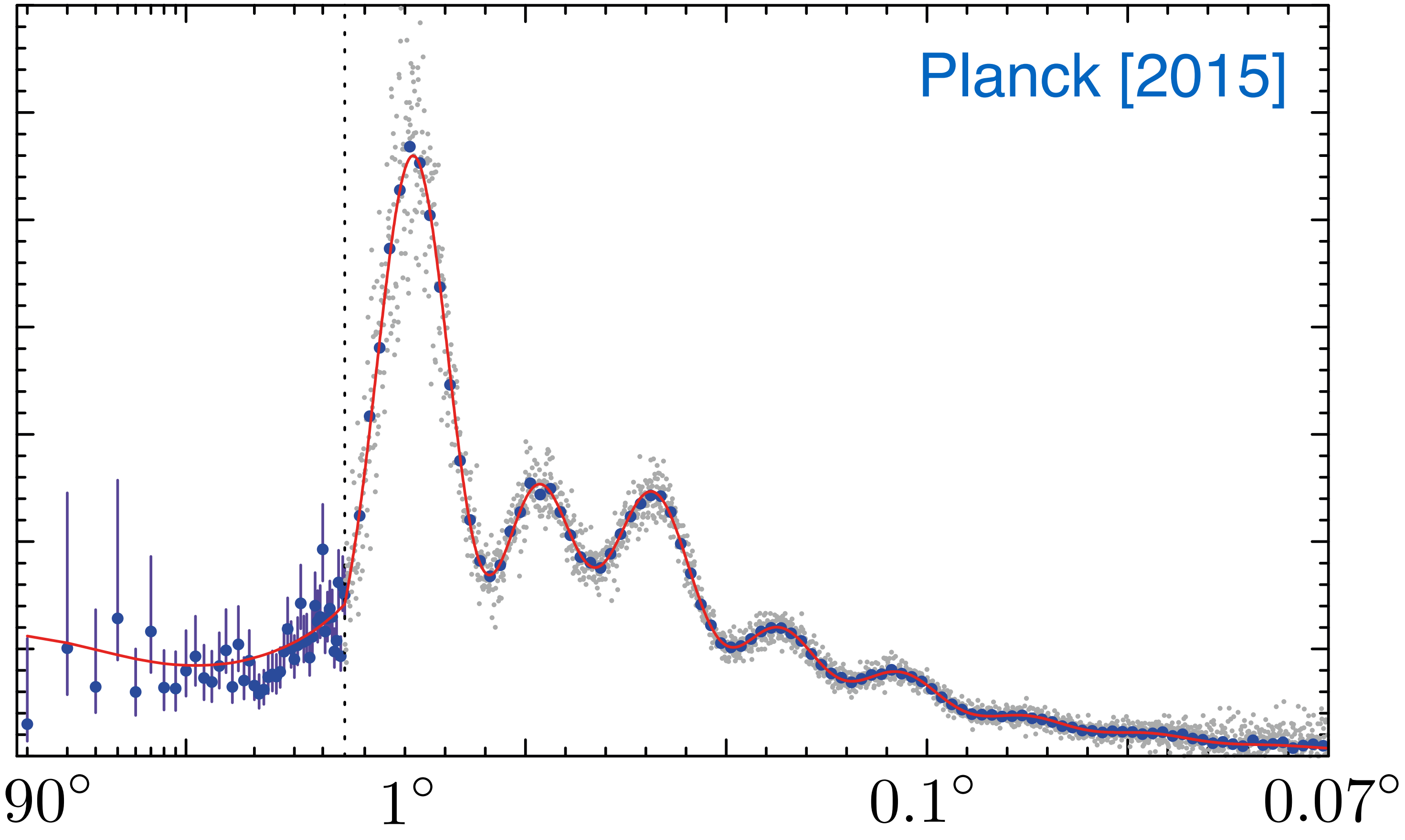
# *Thanks for your attention*

# Cosmological Observables

$$\delta T(\vec{\theta}) =$$

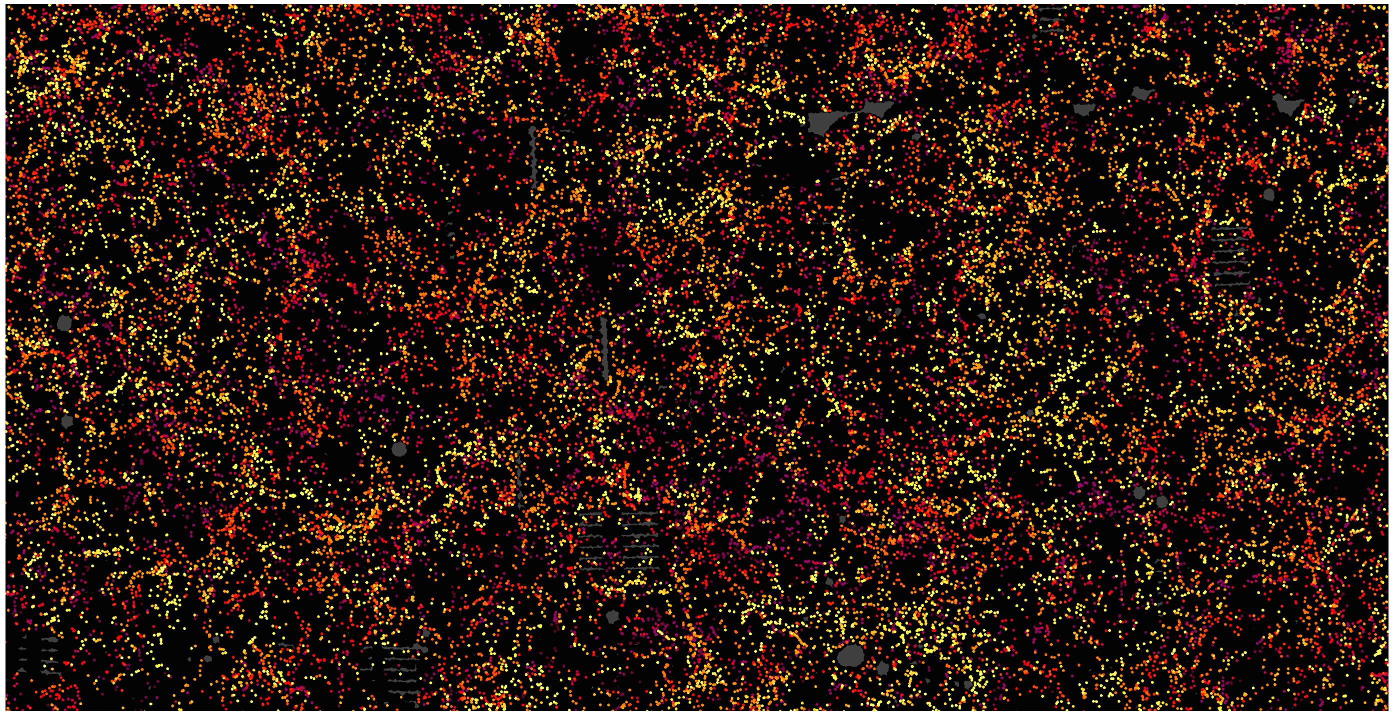


$$\langle \delta T(\vec{\theta}) \delta T(\vec{0}) \rangle =$$

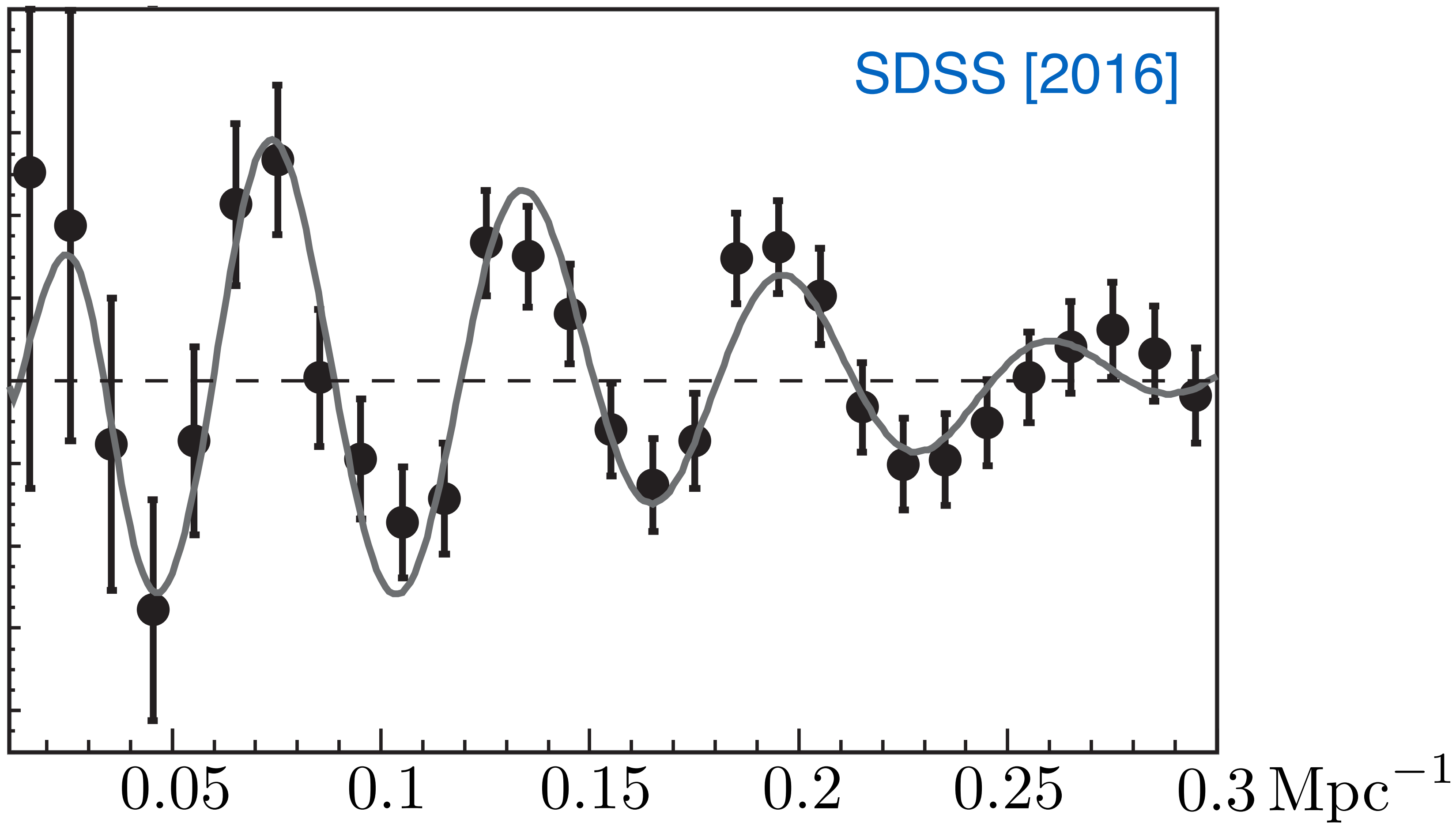


# Cosmological Observables

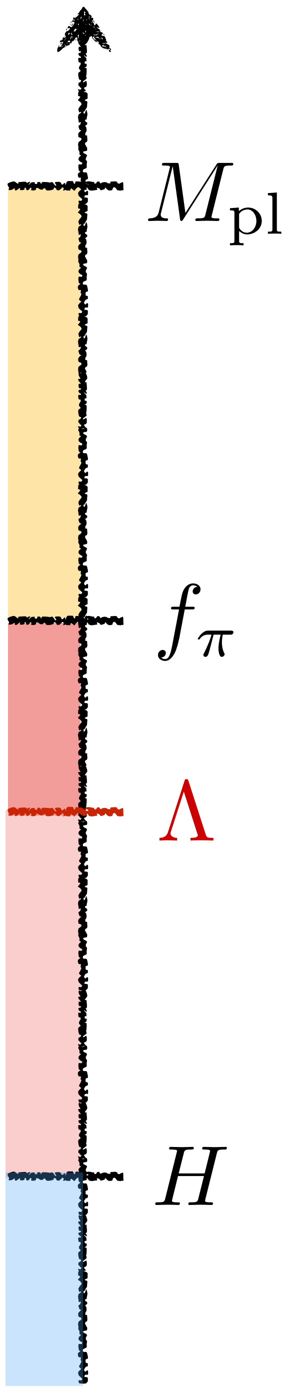
$$\delta\rho_g(\vec{x}) \; =$$



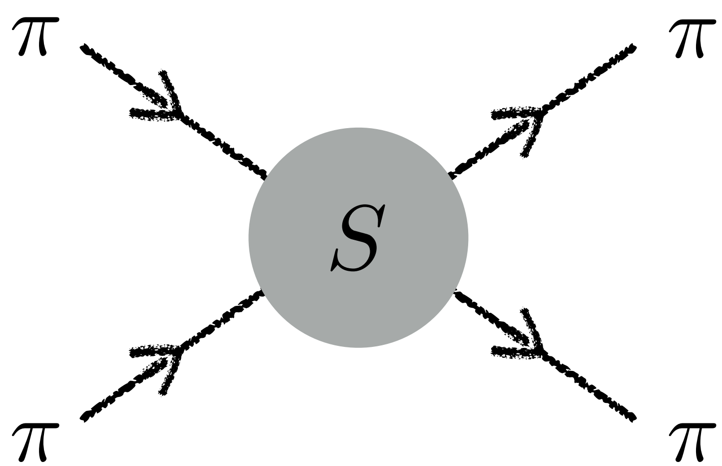
$$\langle \delta\rho_g(\vec{k})\delta\rho_g^*(\vec{k})\rangle \; =$$



# Unitarity Bound




Consider 2-to-2 scattering of the Goldstone:



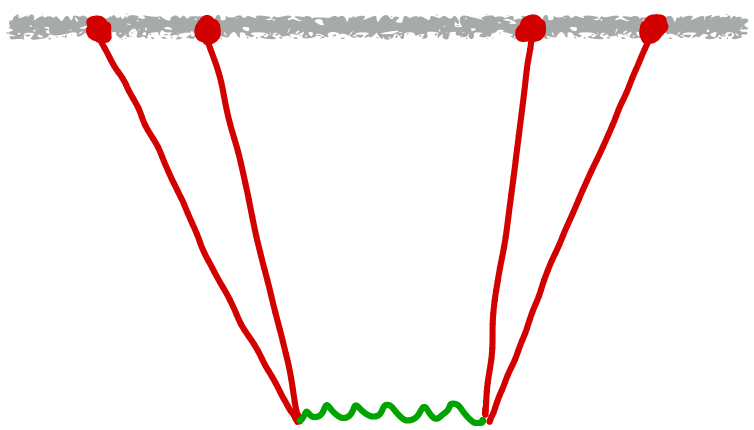

$$= \; 16\pi \sum_\ell (2\ell+1) a_\ell(E) P_\ell(\cos\theta)$$

- The **d-wave amplitude** depends only on the **sound speed**.
- The EFT violates **unitary** below $f_\pi$ if $c_s < 0.31$ .

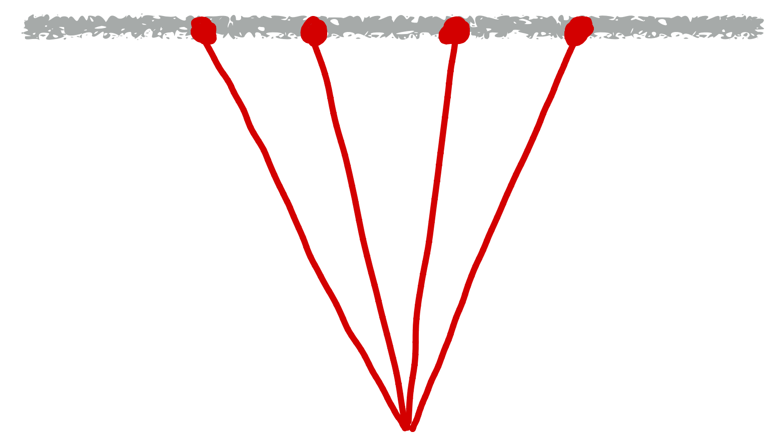
DB, Green, Lee and Porto [2015]

# Virtual Particles

Particles with masses $M \gg H$ can be integrated out during inflation:



$\sim$



local interaction

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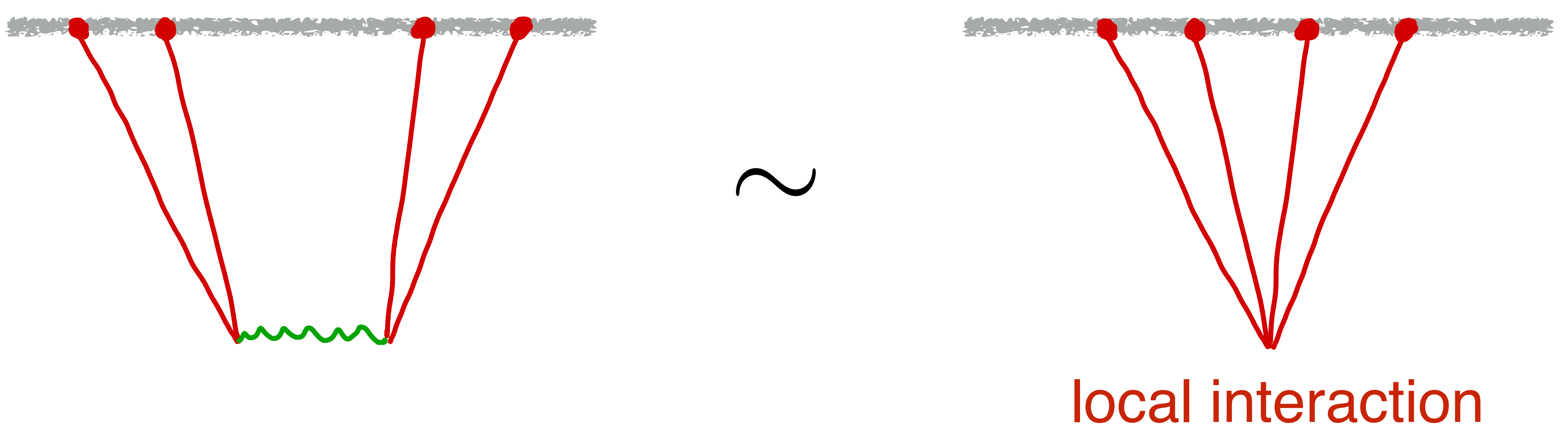


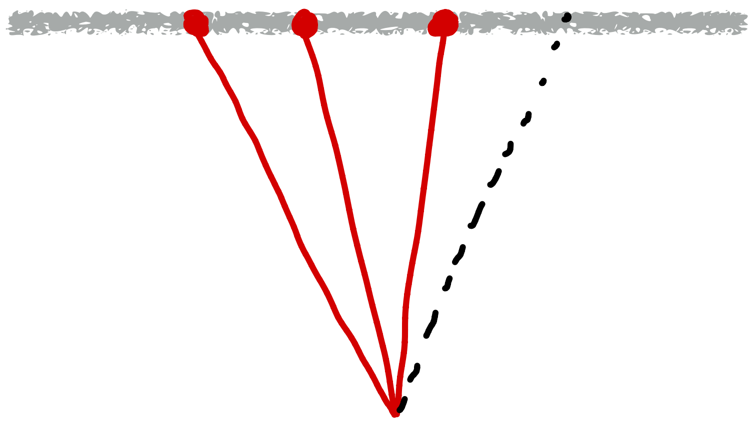

For example, integrating out the Higgs in the linear sigma model leads to higher-derivative corrections to the Goldstone kinetic term:

$$\mathcal{L}_\phi = \frac{1}{2}(\partial\phi)^2 + \frac{(\partial\phi)^4}{\Lambda^4} + \cdots \qquad \Lambda^2 \equiv Mv$$

Let us take this to be the inflaton Lagrangian. Creminelli [2003]

# Virtual Particles

Evaluating one leg on the background, $\bar{\phi}(t)$, leads to a three-point vertex for the perturbation, $\phi(t + \pi(\vec{x}, t))$ :



$$\mathcal{L}_\pi = \frac{1}{2}(\partial\pi_c)^2 + \frac{\dot{\phi}}{\Lambda^4}\,\dot{\pi}_c(\partial\pi_c)^2 + \cdots$$

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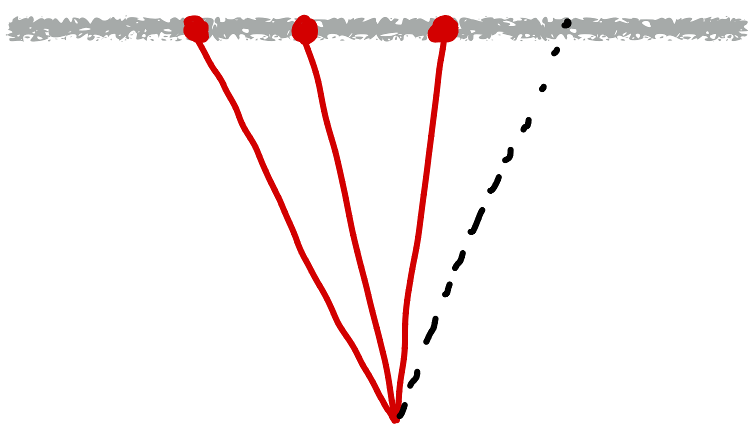


$$\mathcal{L}_\pi = \frac{1}{2}(\partial\pi_c)^2 + \frac{\dot{\phi}}{\Lambda^4}\,\dot{\pi}_c(\partial\pi_c)^2 + \cdots$$

This is a special case of the **EFT of inflation**:

$$\mathcal{L}_\pi = \frac{1}{2}(\partial\pi_c)^2 - \frac{1}{\Lambda^2}\left[\dot{\pi}_c(\partial_i\pi_c)^2 + A\dot{\pi}_c^3\right] \qquad \Lambda^2 \equiv \frac{f_\pi^2 c_s^2}{1-c_s^2}$$

# Strings from Massive Higher Spins

Detecting massive particles with **S > 2** would be interesting.

$\downarrow$

A weakly coupled UV completion requires an **infinite tower of massive higher-spin particles**.

$\downarrow$

**string theory?** (cf. detecting SUSY)

Veneziano [1968]

Camanho, Edelstein, Maldacena and Zhiboedov [2014]

Caron-Huot, Komargodski, Sever, and Zhiboedov [2016]

Arkani-Hamed, Y.T. Huang, and T.C.Huang [to appear]

see talks by Komargodski [Strings 2016]

Arkani-Hamed [Strings 2016]

# Weak Gravity Conjecture(s)

The WGC quantifies the belief that there are no global symmetries in QG*:*

*"gravity is the weakest force"* Arkani-Hamed et al. [2007]

or:

| A consistent theory of gravity coupled to a $U(1)$ gauge field must contain a charged particle with $q \geq m/M_{\rm pl}$. | (mild form) |
|---|---|
| Above statement holds for the lightest charged particle. | (strong form) |

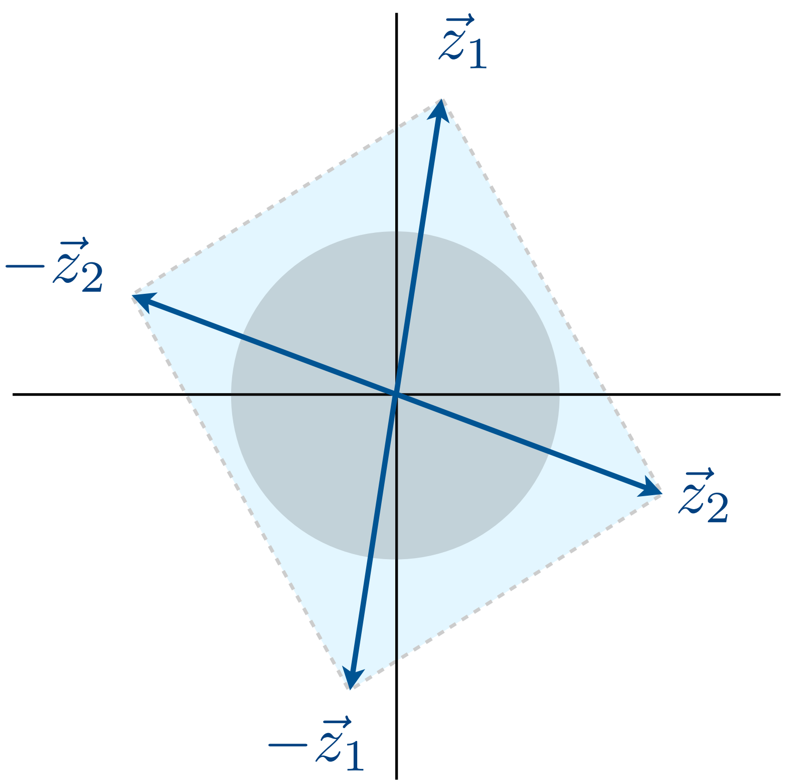
Generalized to the coupling to axions (0-forms) the WGC states that there should be an instanton with

$$1 < \boxed{S \leq \frac{M_{\rm pl}}{f}} \quad \Rightarrow \quad f < M_{\rm pl}$$

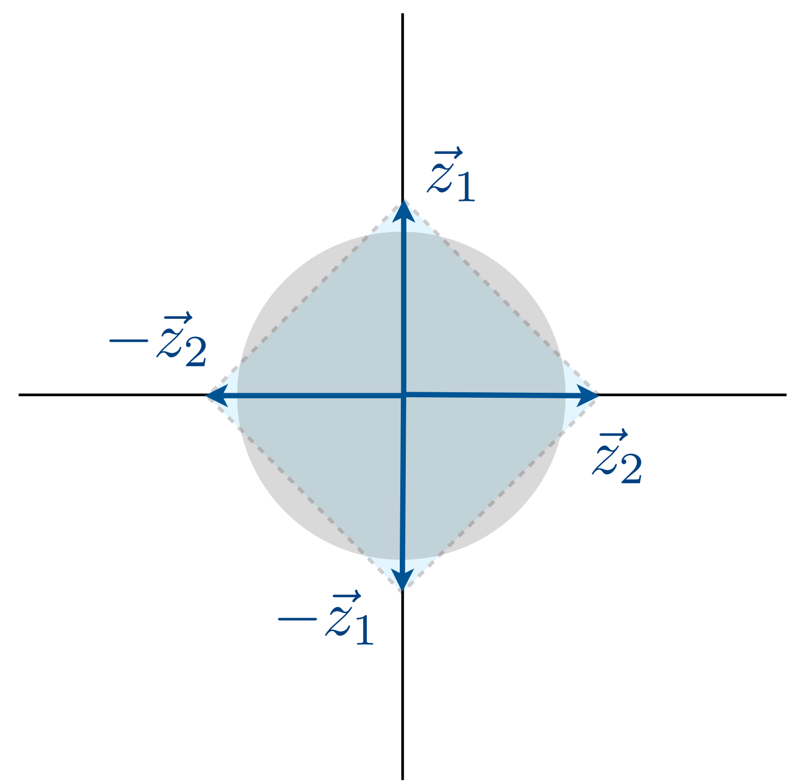
If this is the same instanton that generates the inflaton potential, then the WGC excludes successful natural inflation.

# Weak Gravity Conjecture(s)

Activity was revived, when the WGC was generalized to multiple axions:




consistent with WGC




inconsistent with WGC

$$\vec{z}_i \equiv \vec{q}_i \frac{M_{\rm pl}}{m_i}$$

Cheung and Remmen [2014]

It was found that this form of the WGC rules out N-flation and alignment,

Rudelius [2015]

Montero, Uranga and Valenzuela [2015]

Brown, Cottrell, Shiu and Soler [2015]

but leaves axion monodromy unconstrained.

Hebecker, Rompineve and Westphal [2015]

# Weak Gravity Conjecture(s)

A lot of recent work was inspired by **loopholes** in the above no-go results:

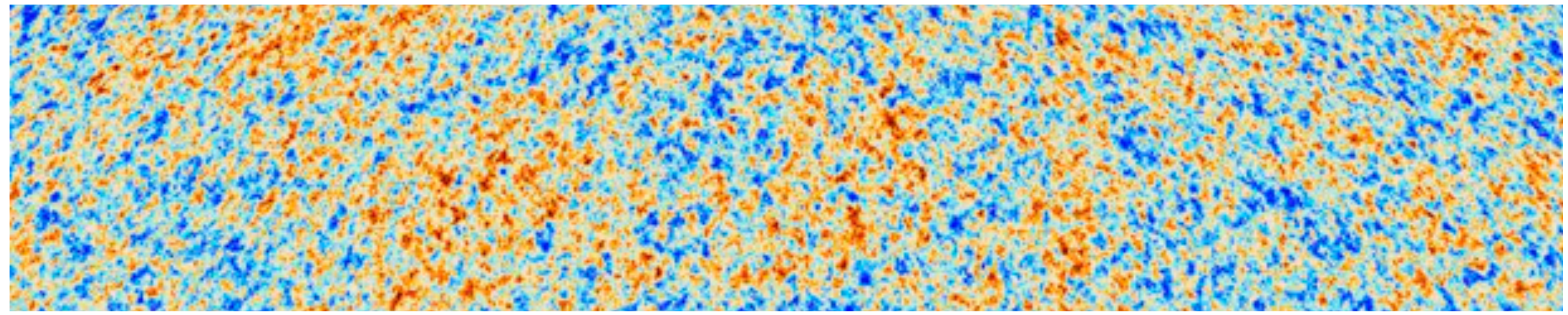
Instantons satisfying WGC give dominant contributions to the inflationary potential

de la Fuente, Saraswat and Sundrum [2014]
Brown, Cottrell, Shiu and Soler [2015]
Rudelius [2015]
Montero, Uranga and Valenzuela [2015]
Bachlechner, Long and McAllister [2015]
Hebecker, Mangat, Rompineve and Witkowski [2015]
Heidenreich, Reece and Rudelius [2015]
Junghans [2015]
Harlow [2015]
Kappl, Nilles and Winkler [2015]
Hebecker, Rompineve and Westphal [2015]
Conlon and Krippendorf [2016]
Heidenreich, Reece and Rudelius [2016], …

Stronger versions of the WGC that avoid these loopholes are work in progress.

see talk by Shiu [Strings 2016]

# 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

$$n_s = 0.960 \pm 0.007$$

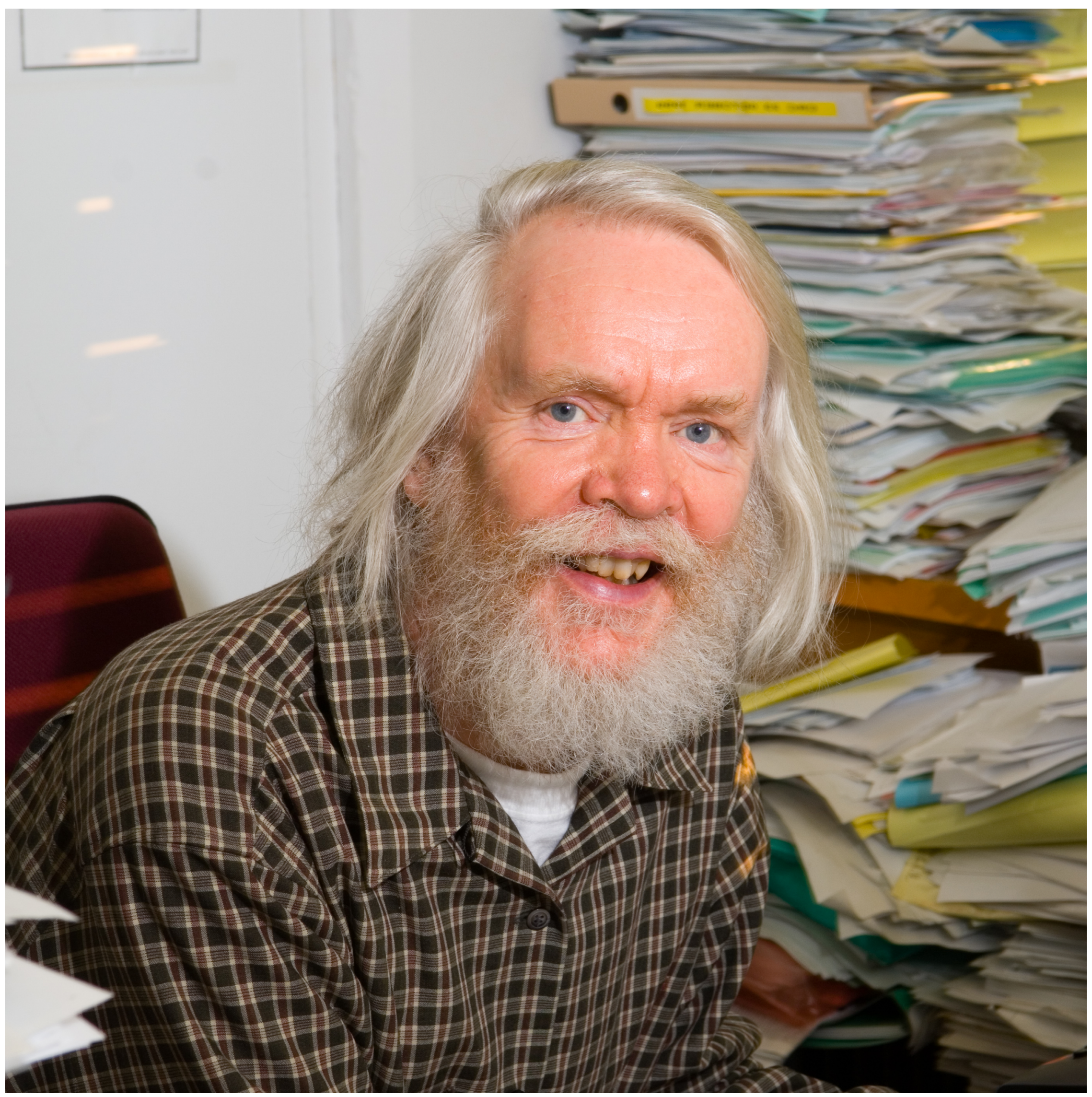
“I thought that it would take 1000 years to detect the logarithmic dependence of the power spectrum.”

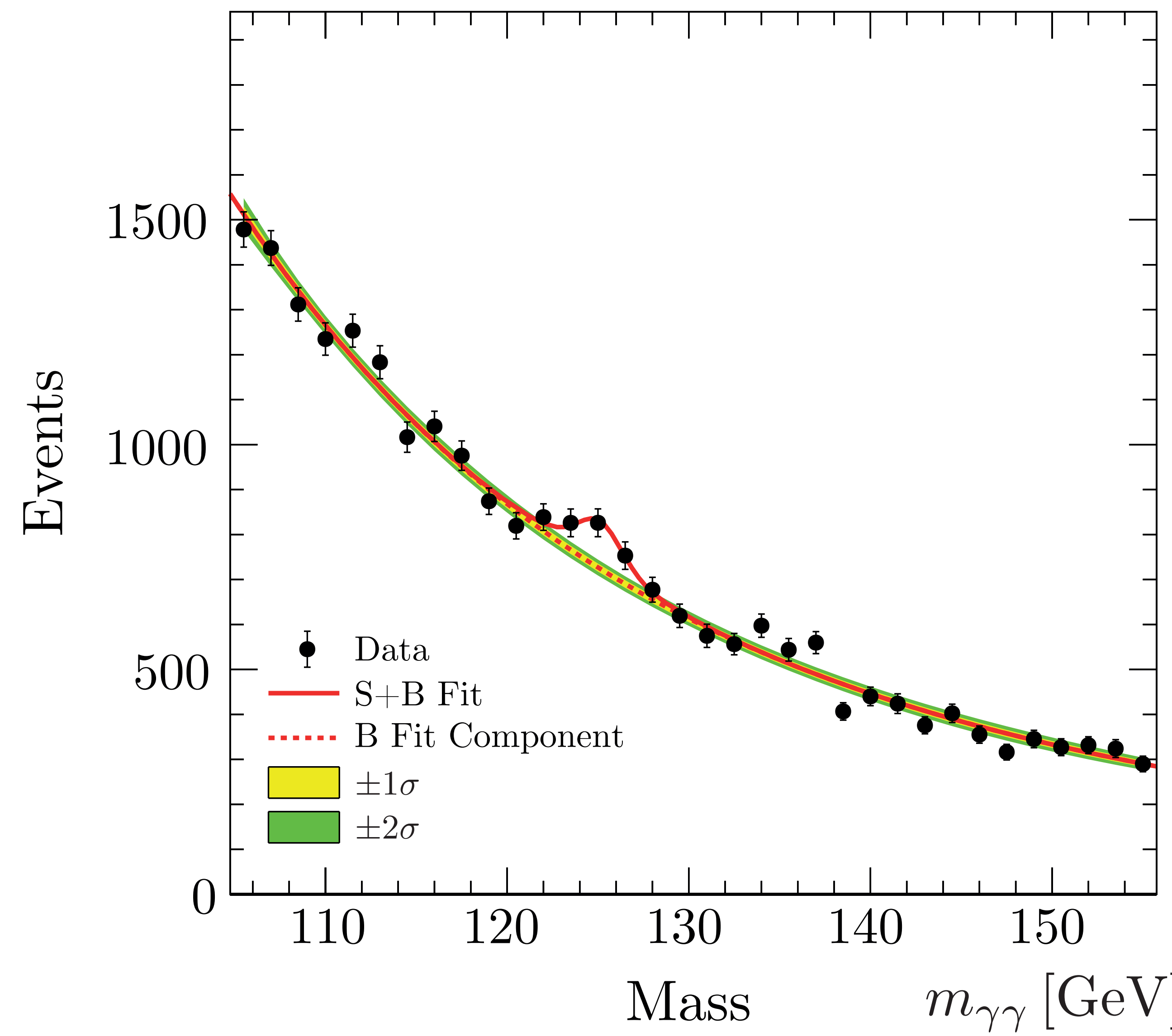
Slava Mukhanov

# Lessons from the Past

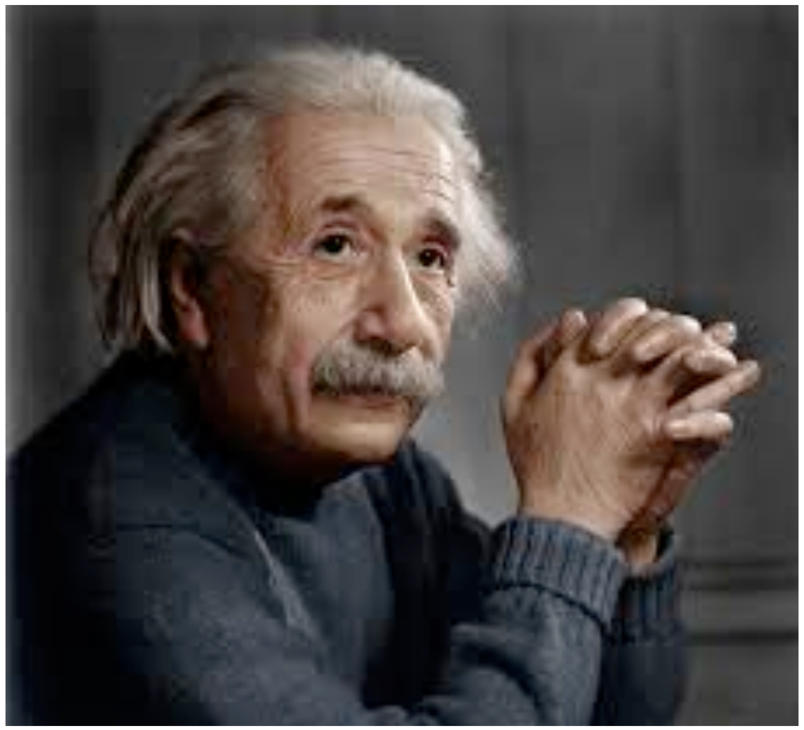
"We apologise to experimentalists for having no idea what is the mass of the Higgs boson and for not being sure of its couplings to other particles. For these reasons we do not want to encourage big experimental searches for the Higgs boson, …"

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