Inflation in the post-Planck era

What is new?

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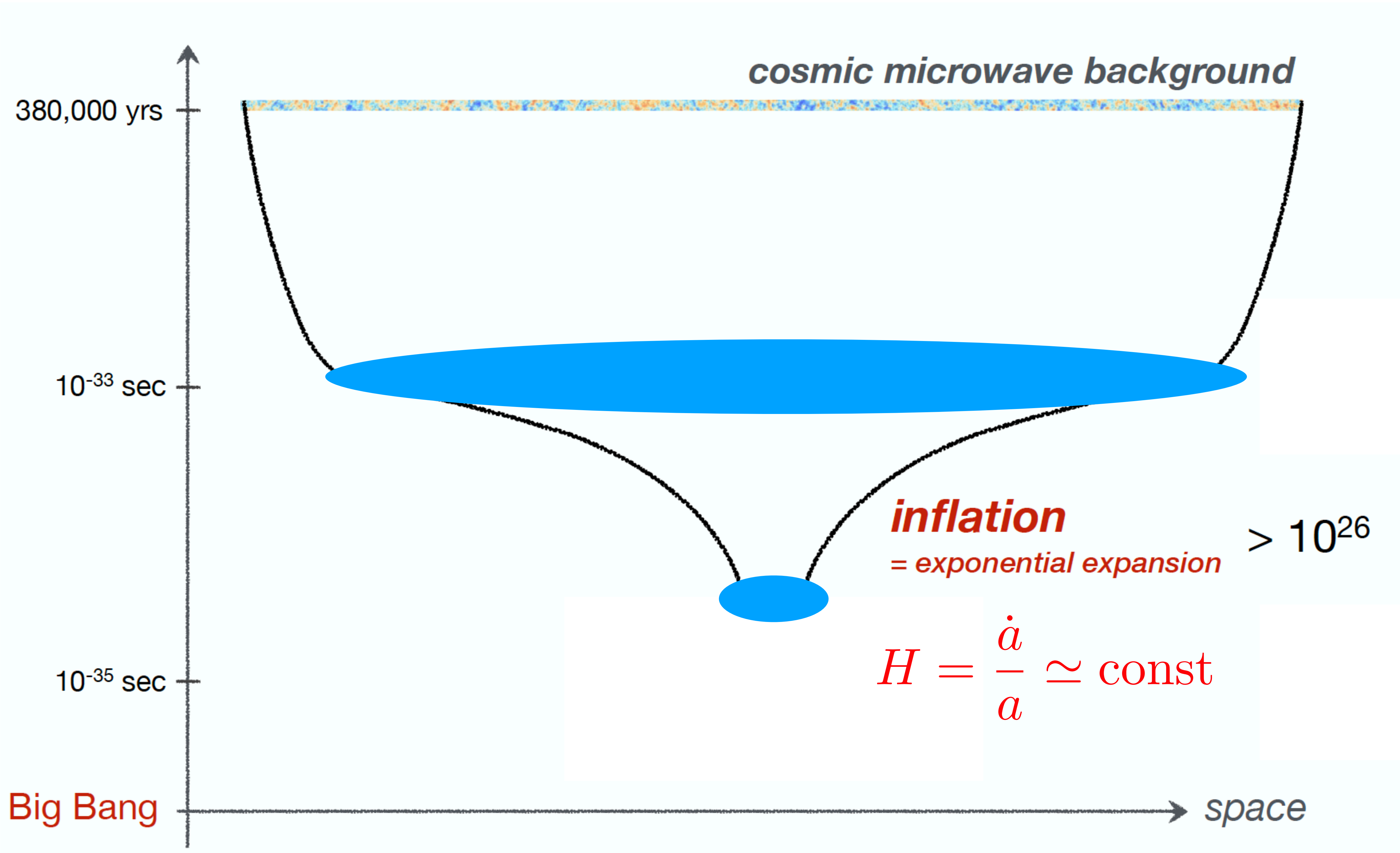
TUG meeting, IHP
December 13th 2021

European Research Council
Established by the European Commission

GEODESI

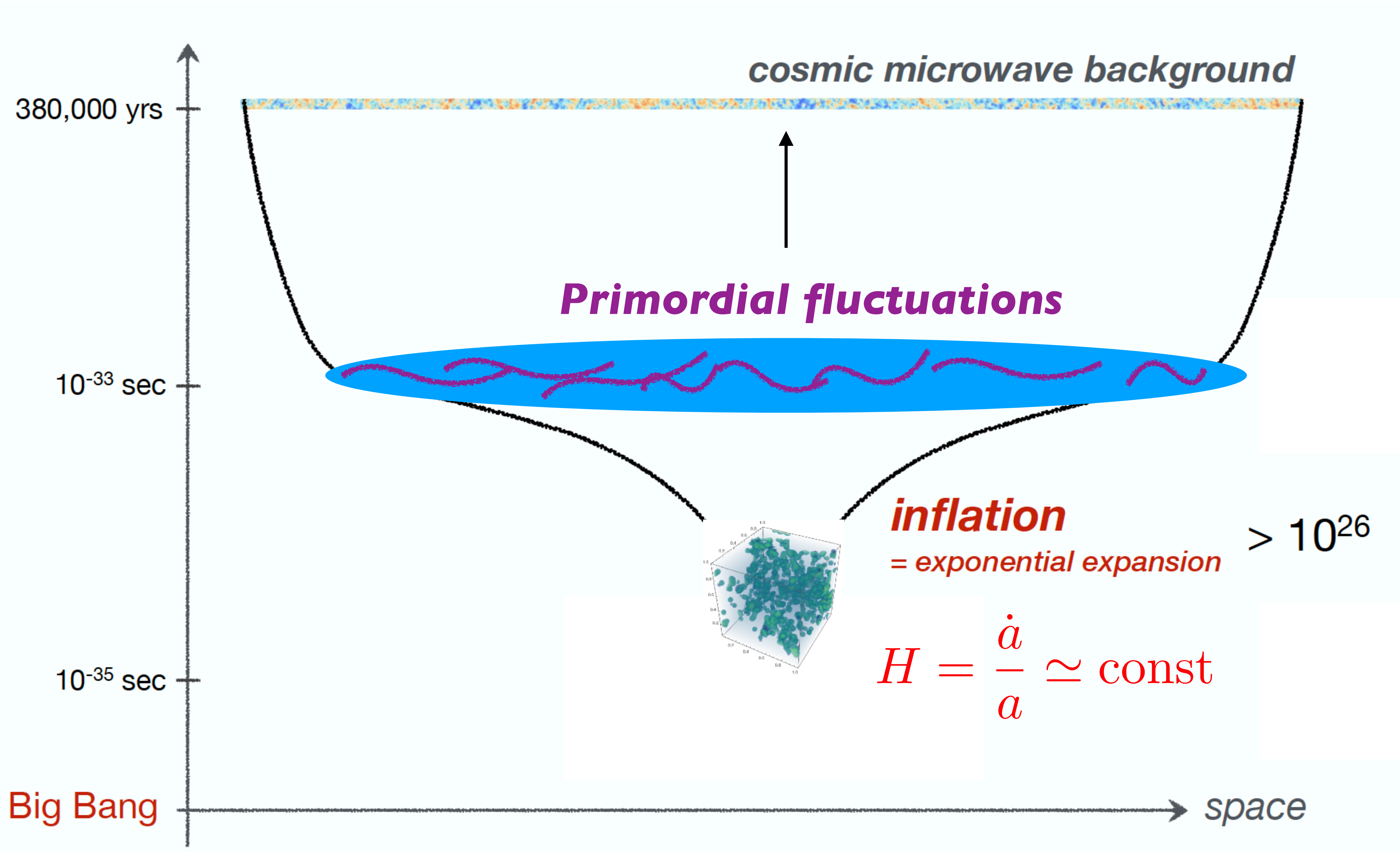
Inflation: a giant microscope

a tiny patch of space becomes the entire observable universe



Inflation: a giant microscope

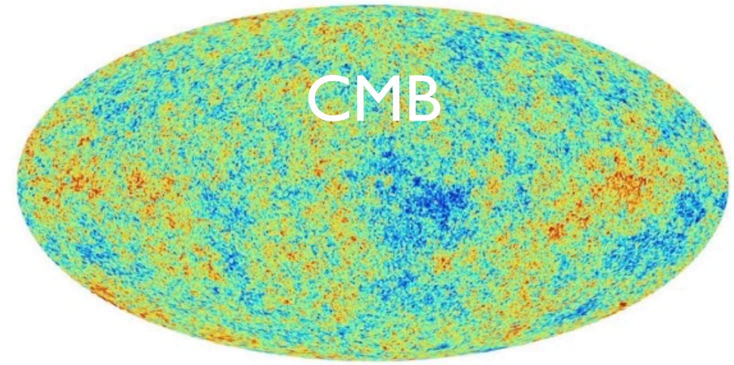
vacuum quantum fluctuations stretched to cosmological scales

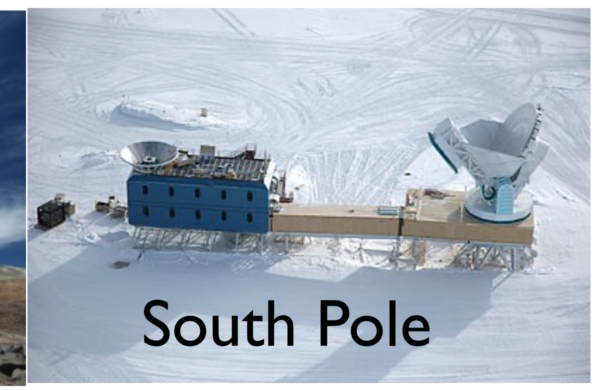


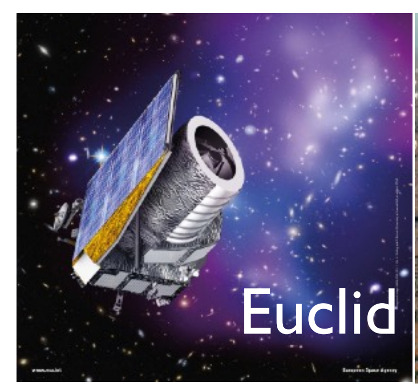
Quantum + gravitational physics, tested observationally!

cf Amaury Micheli's talk, with
Martin & Vennin

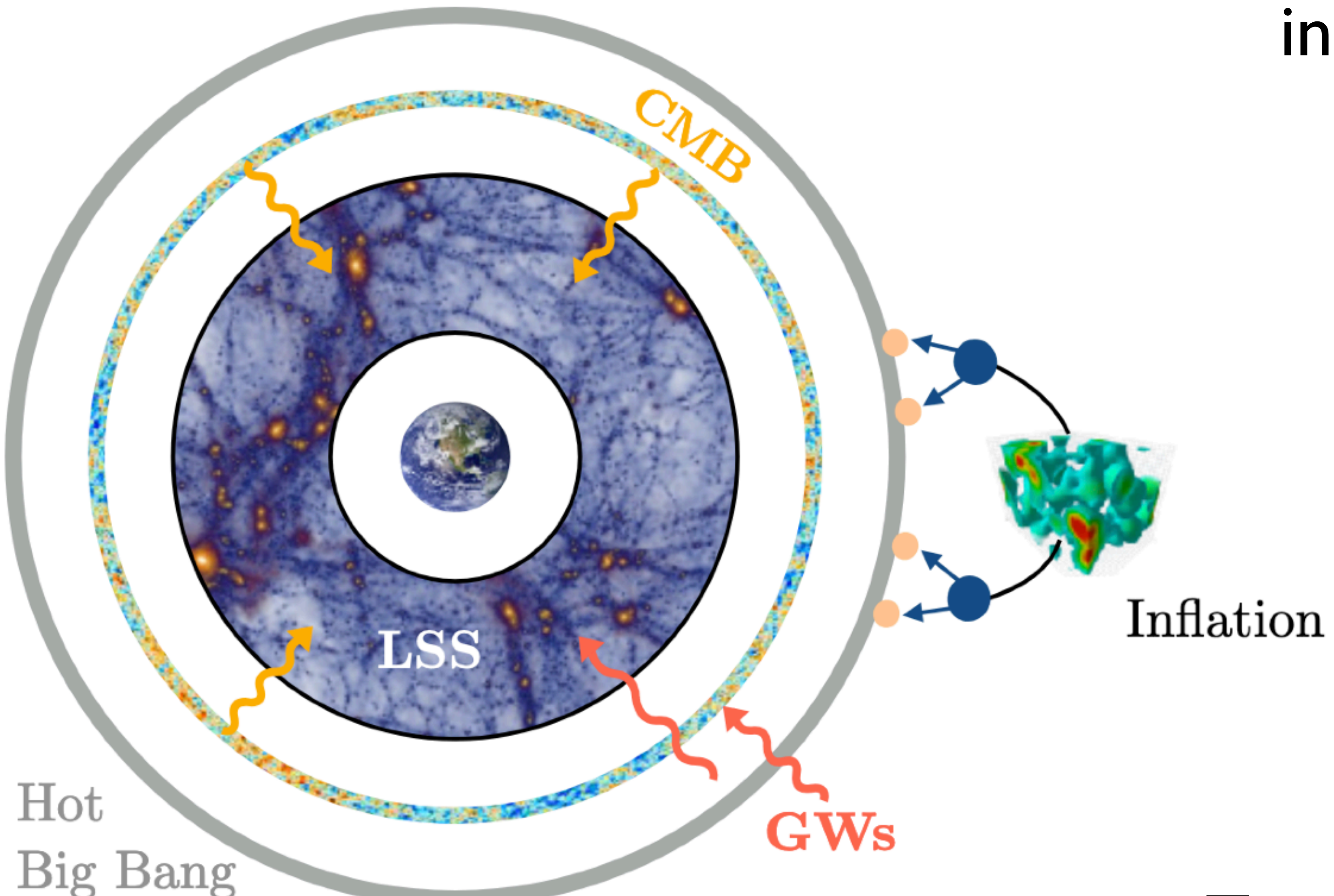
+







How?



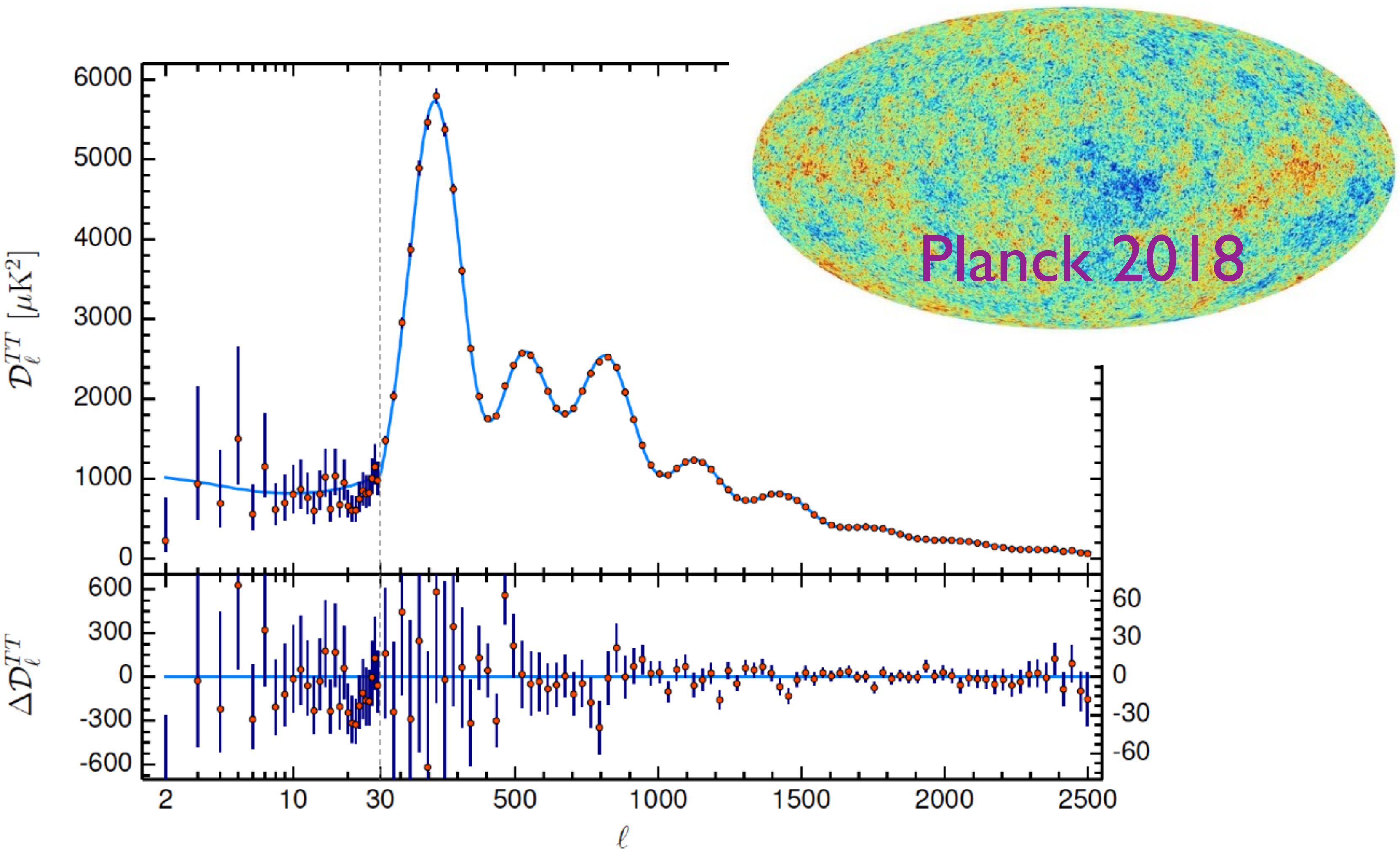
Physics at extremely high-energies encoded in cosmological correlators

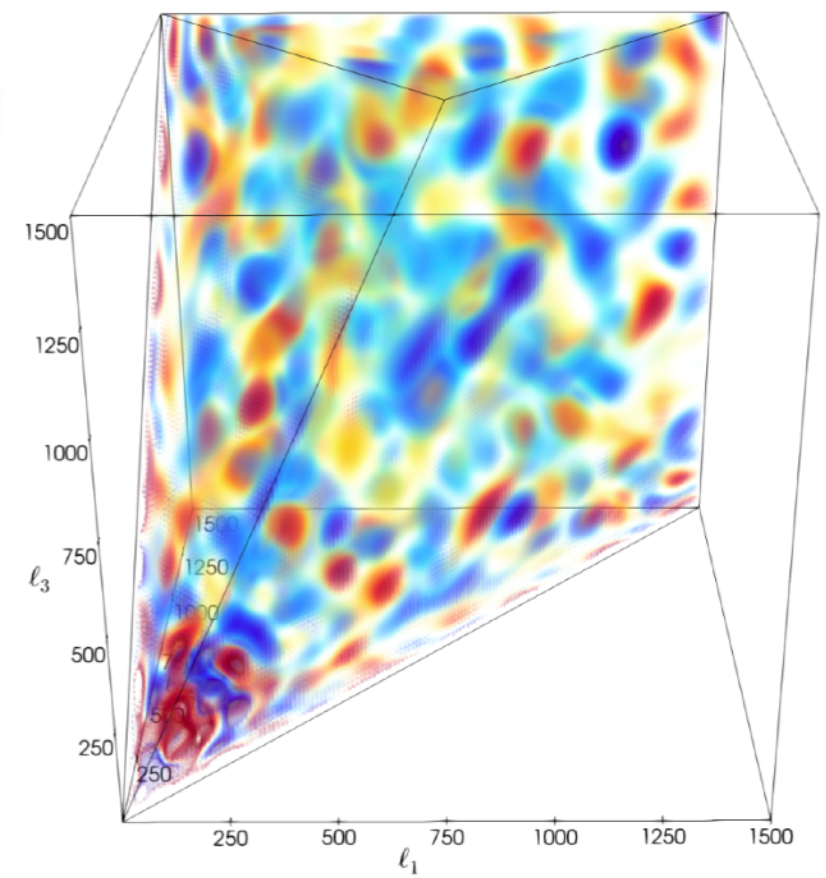
density fluctuations & gravitational waves

2pt, 3pt, n-pt
Even full pdf?

Treasure of information to extract (e.g. cosmological collider physics)

What we know





Primordial density fluctuations: Superhorizon - adiabatic almost scale-invariant - Gaussian

Simplest fit: single-field slow-roll inflation… … but not more than toy models

What we know

adiabatic $\delta\left(\frac{n_X(\boldsymbol{x})}{n_Y(\boldsymbol{x})}\right)=0 \longrightarrow$ ζ curvature perturbation

almost scale-invariance $\mathcal{P}_\zeta(k)\sim(10^{-5})^2\left(\frac{k}{k_\star}\right)^{n_s(k_\star)-1}$ $n_s=0.9649\pm0.0042\ (68\%\mathrm{CL})$

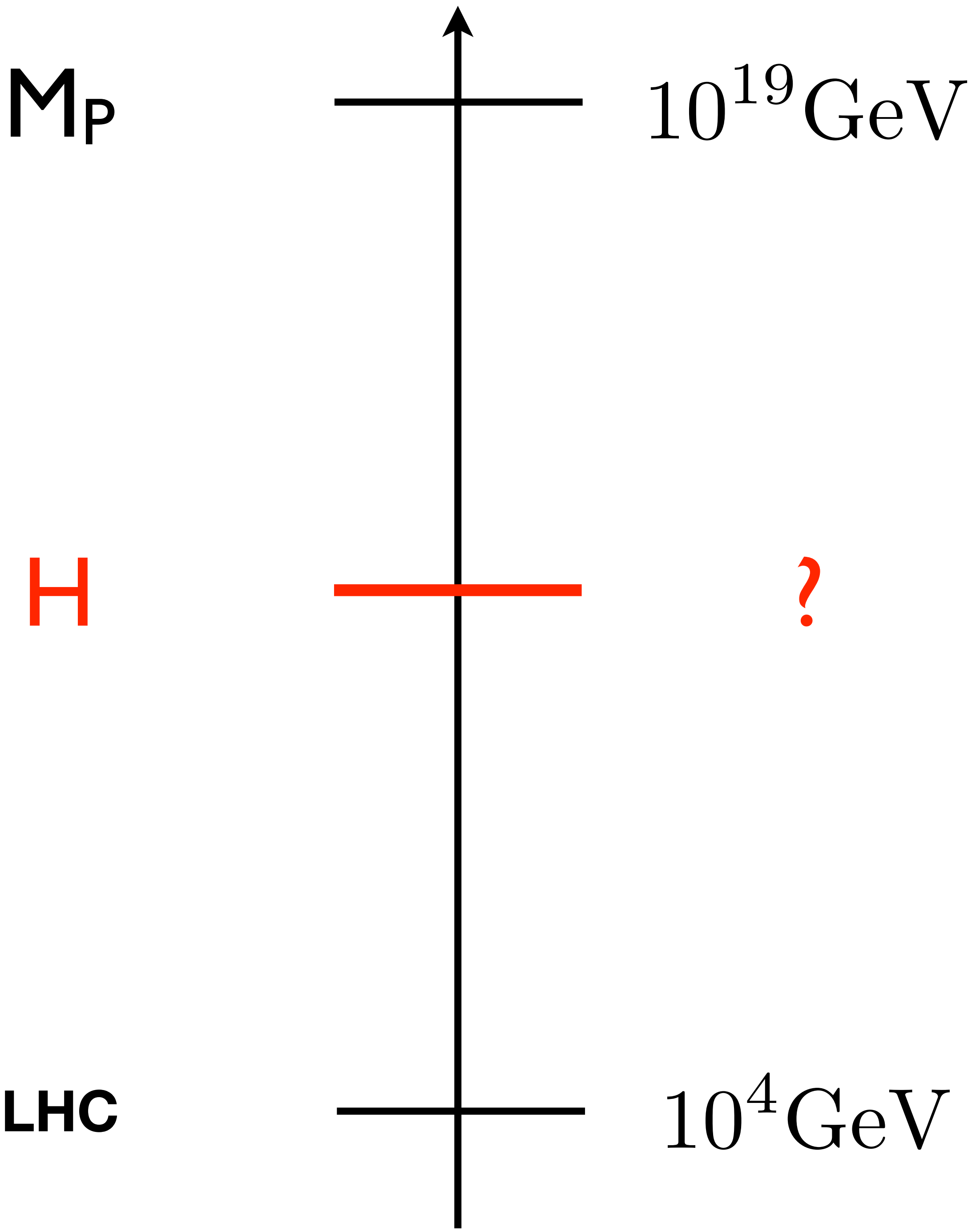
approximate time translation invariance during inflation

Gaussian $\zeta\sim\zeta_G\left(1+f_{\mathrm{NL}}\zeta_G\right)$

$$\begin{pmatrix} f_{\mathrm{NL}}^{\mathrm{loc}} = -0{,}9 \pm 5{,}1 \\ f_{\mathrm{NL}}^{\mathrm{eq}} = -26 \pm 47 \\ f_{\mathrm{NL}}^{\mathrm{orth}} = -38 \pm 24 \end{pmatrix} (68\,\%\ \mathrm{CL})$$

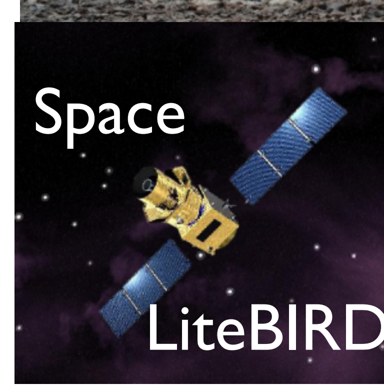
Gaussian to better than 0.01%

Energy scale of inflation?



Primordial gravitational waves
from B-modes polarization of CMB

$\longrightarrow \quad H \sim 10^{14}\mathrm{GeV}$



Super-Planckian field
displacement:
hint about
gravity at Planck scale

Physics of inflation?

Primordial universe: invaluable observational probe of high-energy physics

What is the inflaton?

Origin of its potential?

Which extension of the Standard Model?

At which energy inflation occured?

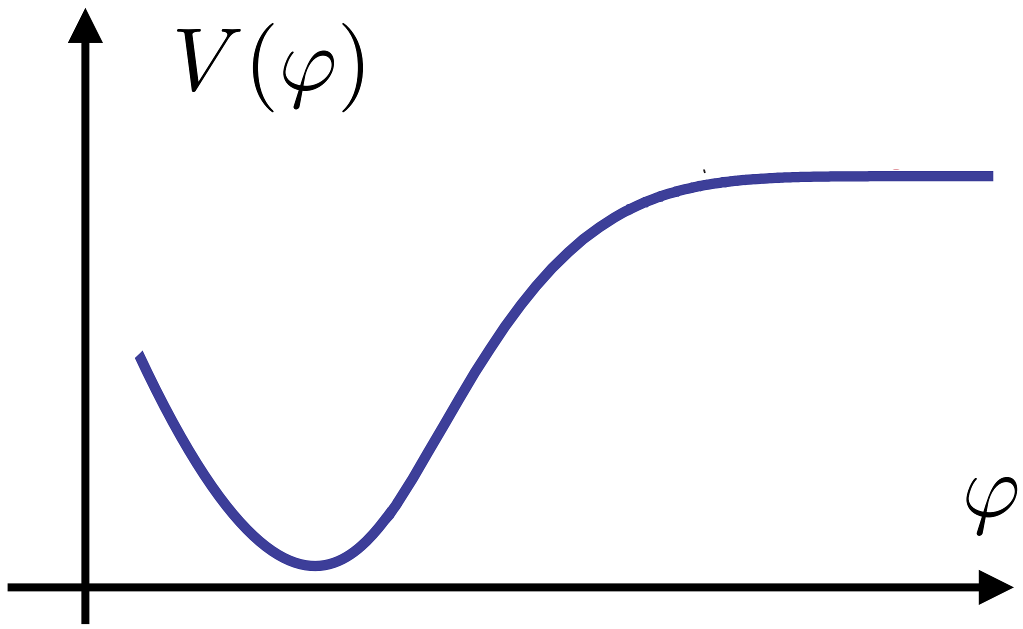
How did it transfert its energy to Standard Model particles?

The only degree of freedom?

Coupling to other fields?

…

The Eta problem

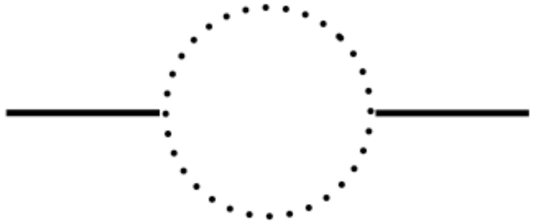


$$\eta \equiv M_{\rm pl}^2 \frac{V_{,\phi\phi}}{V} \ll 1$$

Prolonged phase of inflation

Why is the inflaton so light? $\eta \approx \frac{m_\phi^2}{H^2} \ll 1$

like the Higgs
hierarchy problem



$m_\phi^2 \sim \Lambda_{\rm uv}^2 \gg H^2$

UV-sensitivity of inflation

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V_0(\phi) + \sum_\delta \frac{\mathcal{O}_\delta(\phi)}{M^{\delta-4}}$$

Slow-roll action

Corrections to the low-energy effective potential

$$\frac{\Delta m_\phi^2}{H^2} \sim \left(\frac{M_{\rm Pl}}{M}\right)^2$$

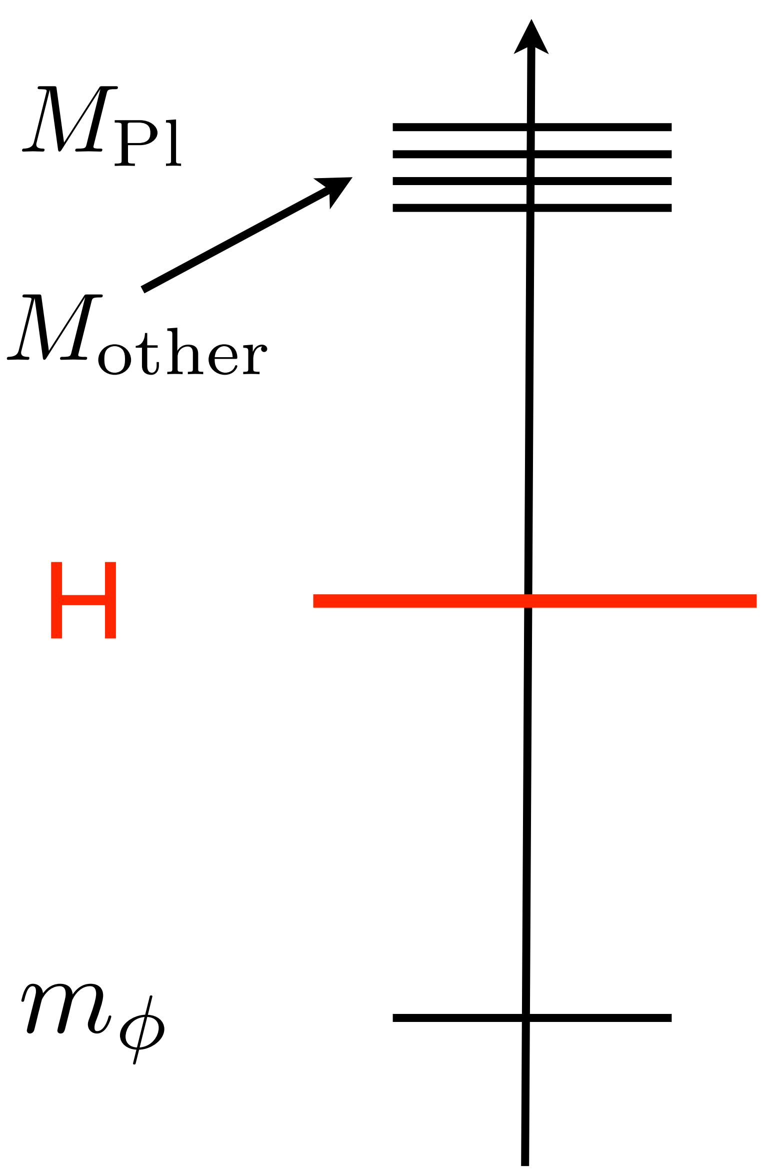
$$\Delta\eta \gtrsim 1$$

Planck-scale physics does not decouple

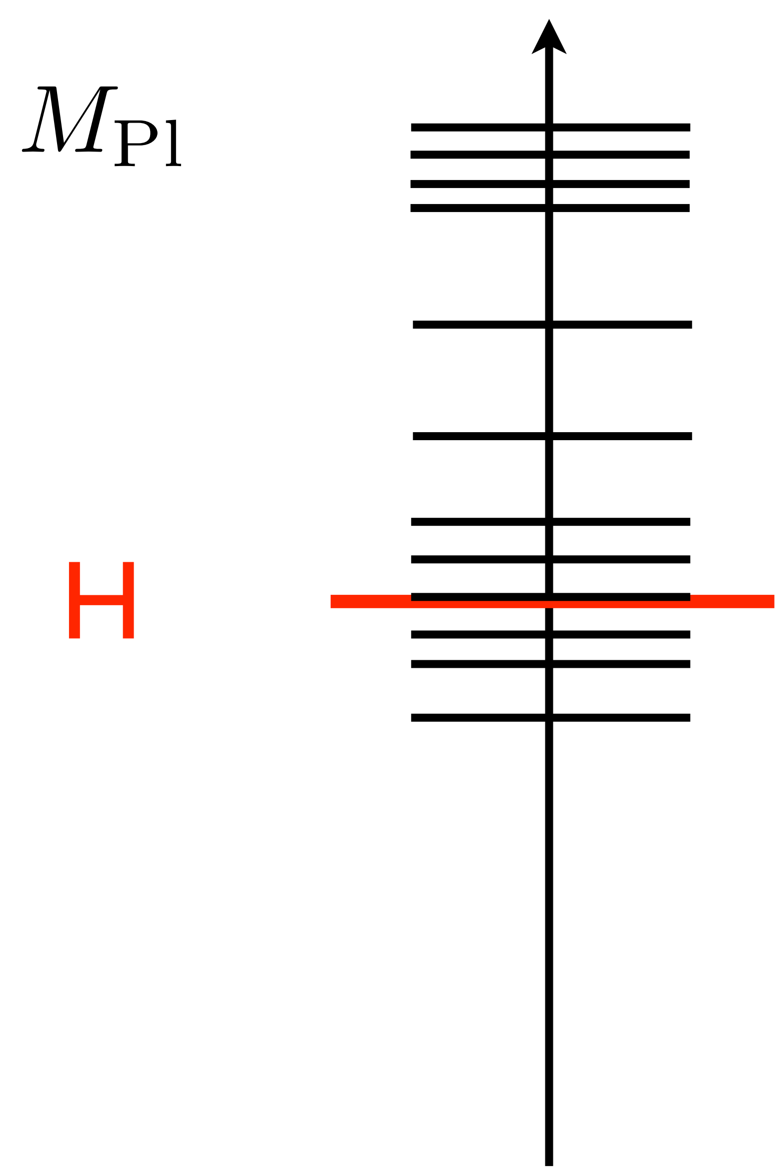
Symmetries do not help

Guidance from string theory?

Hope:



Find:



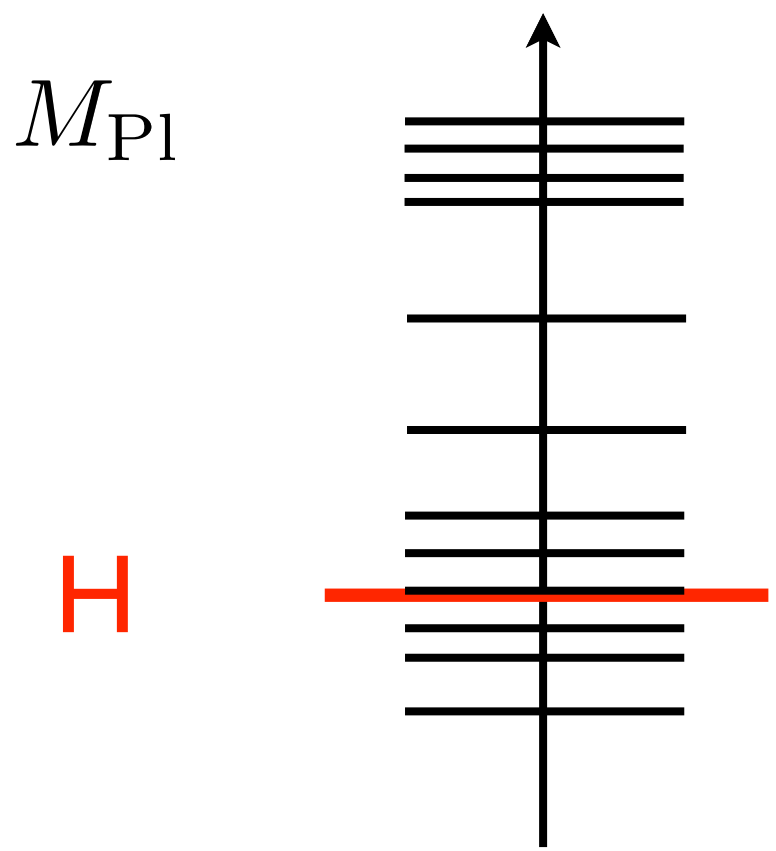
Guidance from string theory?

Top-down constructions:
difficult and rarely done consistently

Find:

But general picture: Baumann McAllister, 2014

- Multiple degrees of freedom
- Steep potentials
- Large couplings

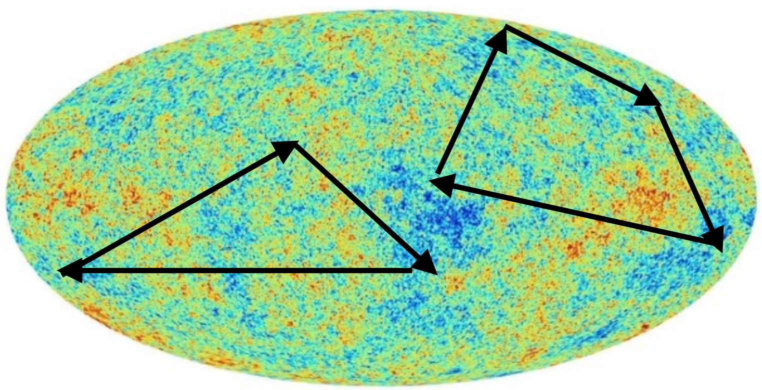


→ How can data be so simple?

Single-field slow-roll: at best emergent approximate description

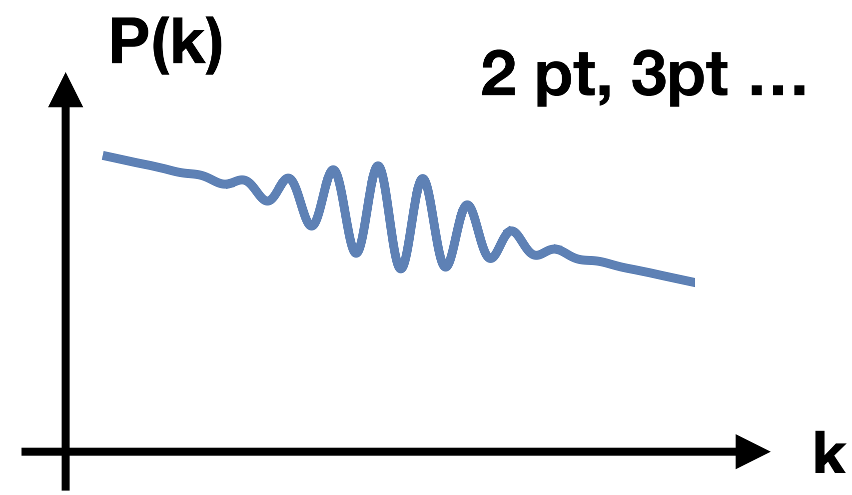
Looking for new physics
(signs of new dofs)

Primordial non-Gaussianities

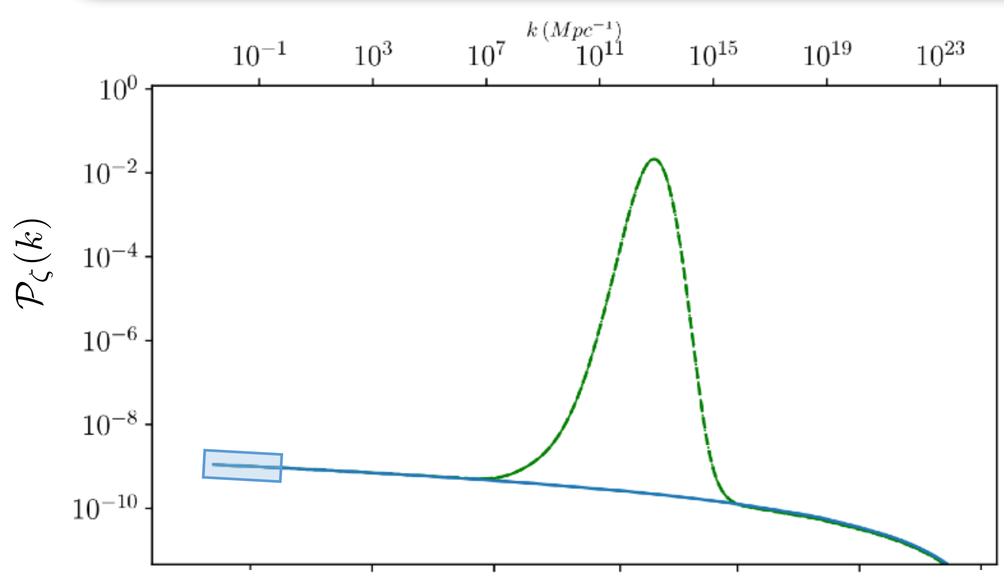


3pt, 4 pt …

Primordial features



Dark ages of inflation



I Inflation in curved field space

II Cosmological collider and bootstrap

III Stochastic inflation

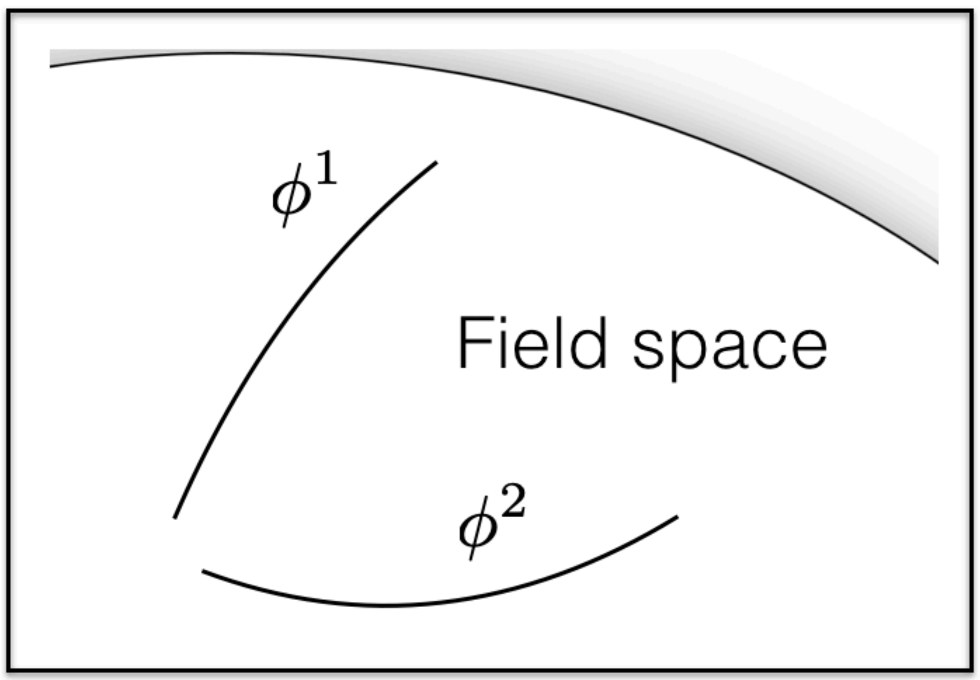
IV Inflation on small scales

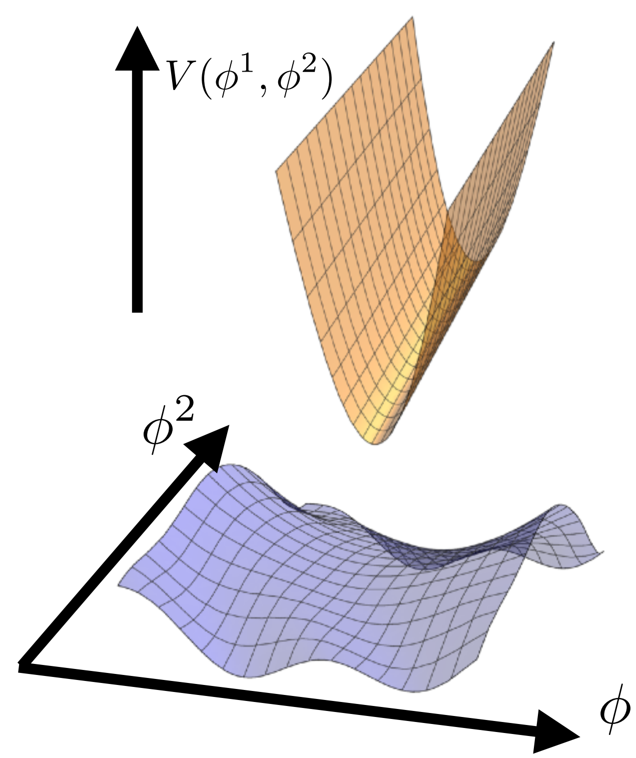
I Inflation in curved field space

Inflation in curved field space

$$S = \int d^4x\sqrt{-g}\left(-\frac{1}{2}G_{IJ}(\phi^K)\partial_\mu\phi^I\partial^\mu\phi^J - V(\phi^I)\right)$$

Curved field space is generic





Invariance under field redefinitions:
fields are coordinates on a `field space',

Inflation in curved field space

$$S = \int \mathrm{d}^4x \sqrt{-g} \left(-\frac{1}{2} G_{IJ}(\phi^K) \partial_\mu \phi^I \partial^\mu \phi^J - V(\phi^I) \right)$$

Curved field space is generic

- Encompass large class of top-down constructions
- Useful test-bed to sharpen our understanding
- Reveals new mechanisms to inflate and new EFT of fluctuations

Inflation in curved field space

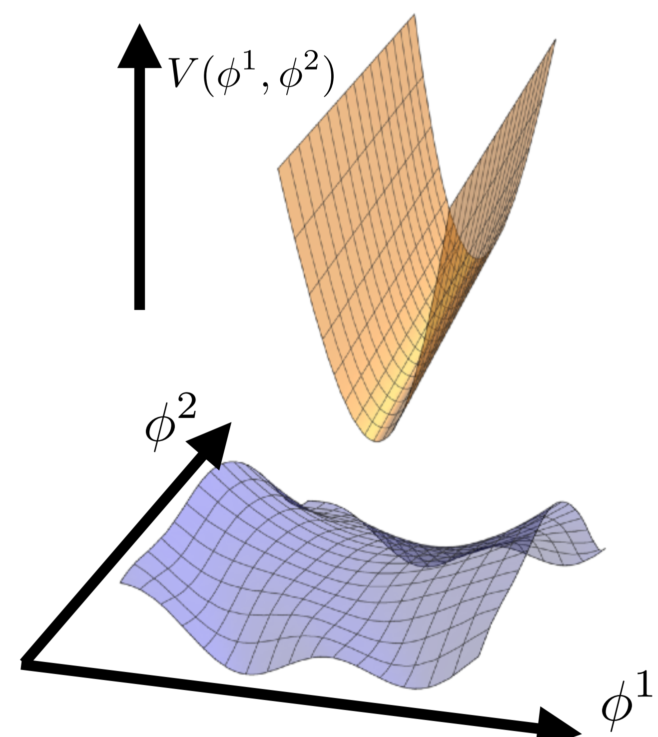
$$S = \int \mathrm{d}^4x \sqrt{-g} \left(-\frac{1}{2} G_{IJ}(\phi^K) \partial_\mu \phi^I \partial^\mu \phi^J - V(\phi^I) \right)$$

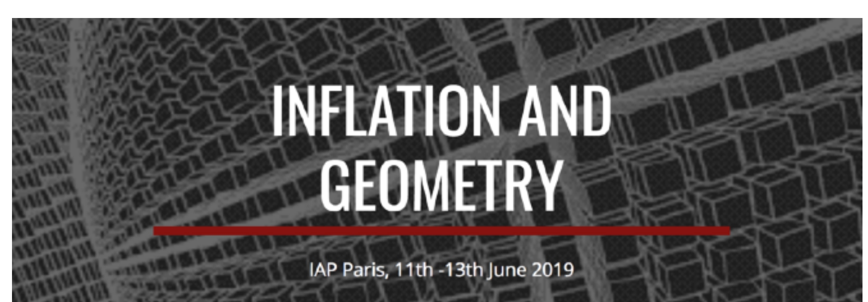
Curved field space is generic

Impacts:

- background (stability)
- linear fluctuations
- non-Gaussianities

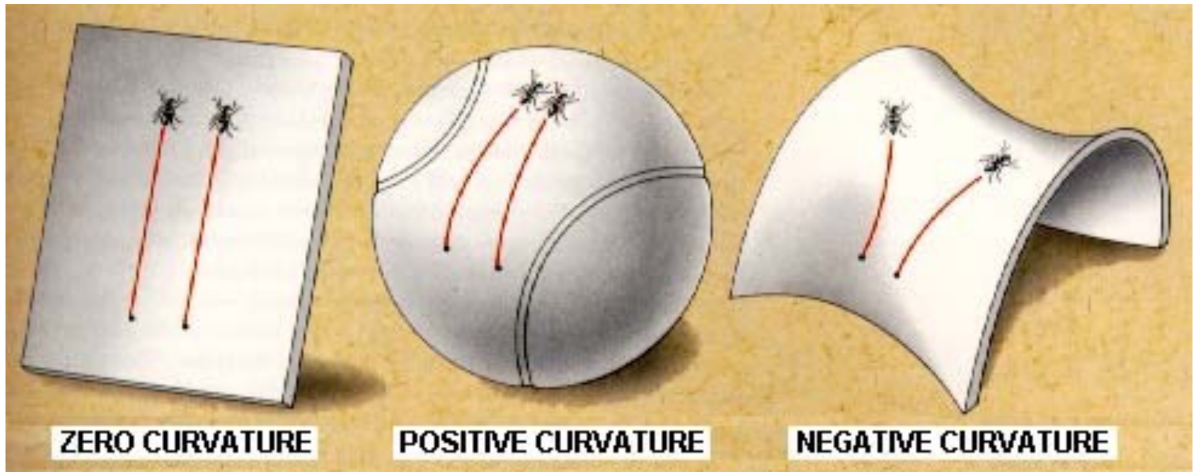
...





Geometrical destabilization of inflation

Initially neighboring geodesics tend to fall away from each other in the presence of negative curvature.



This effect applies during inflation,
it can overcome the effect of the potential,
and can destabilize inflationary trajectories.

Renaux-Petel, Turzynski, 16
PRL Editors' Highlight

Similarity with the eta-problem

$$\mathcal{L}_{\rm eff}[\phi^I] = \mathcal{L}_l[\phi^I] + \sum_i c_i \frac{\mathcal{O}_i[\phi^I, \partial\phi^I, \ldots]}{M^{\delta_i - 4}}$$

Slow-roll action

Corrections to the low-energy effective action

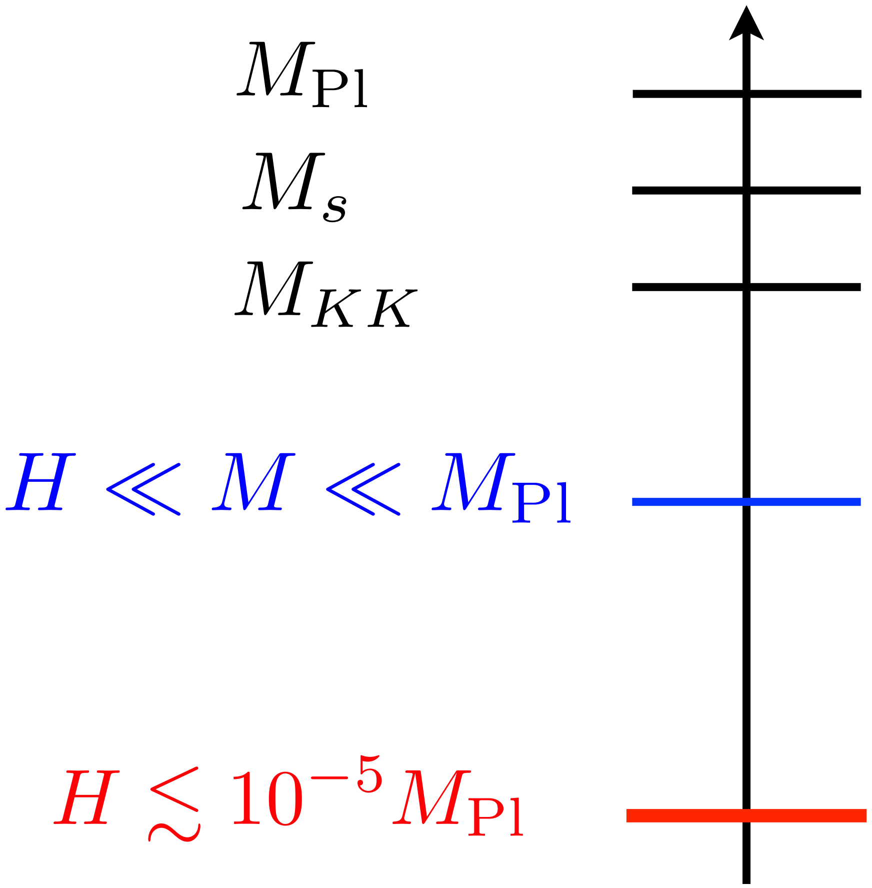
Correction to kinetic terms

$$\Delta\mathcal{L} = c(\partial\phi)^2 \frac{\chi^2}{M^2}$$

$$\longrightarrow \quad \frac{\Delta m_\chi^2}{H^2} \sim c\frac{(\partial\phi)^2}{H^2 M^2} \sim c\,\epsilon\left(\frac{M_P}{M}\right)^2$$

Geometrical destabilization of inflation

Rolling of the inflation in a negatively curved field space tends to induces an instability



A **large hierarchy** is generic in string theory constructions

$$R^{\text{field space}} M_{\rm Pl}^2 \sim (M_{\rm Pl}/M)^2 \sim 10^5$$

Can easily compensate ϵ suppression

Destabilize would-be stable trajectories

Similarity with the eta-problem

$$\mathcal{L}_{\rm eff}[\phi^I] = \mathcal{L}_l[\phi^I] + \sum_i c_i \frac{\mathcal{O}_i[\phi^I, \partial\phi^I, \ldots]}{M^{\delta_i - 4}}$$

Slow-roll action

Corrections to the low-energy effective action

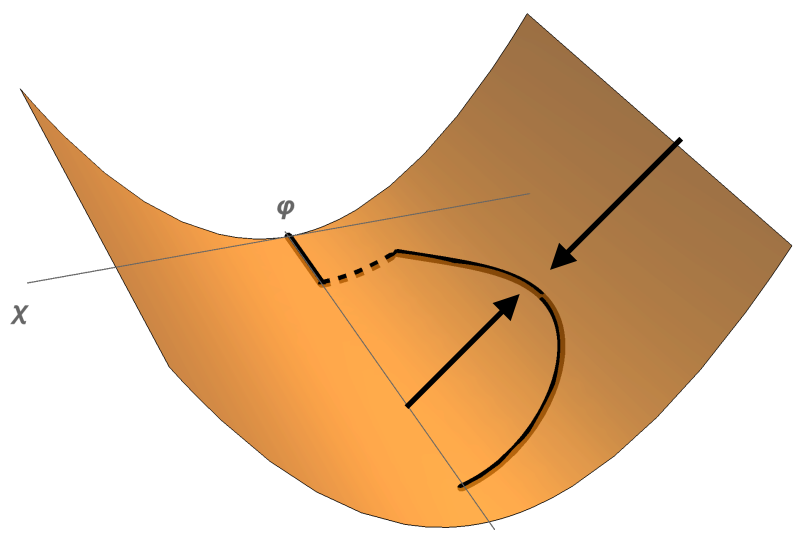
Geometry as important as potential,
characterization of the whole action

Often (used to be) ignored in explicit constructions

'Trivial field space metric for simplicity' is not possible

Inflation with strongly non-geodesic motion

In negatively curved field space, new inflationary attractors, very different from slow-roll



Competition potential vs geometry:

Strongly non-geodesic motion

Requirement:
flat potentials wrt curvature scale

$$M\frac{V_{,\varphi}}{V} \ll 1\,, \qquad M\frac{V_{,\varphi\varphi}}{V_{,\varphi}} \ll 1$$

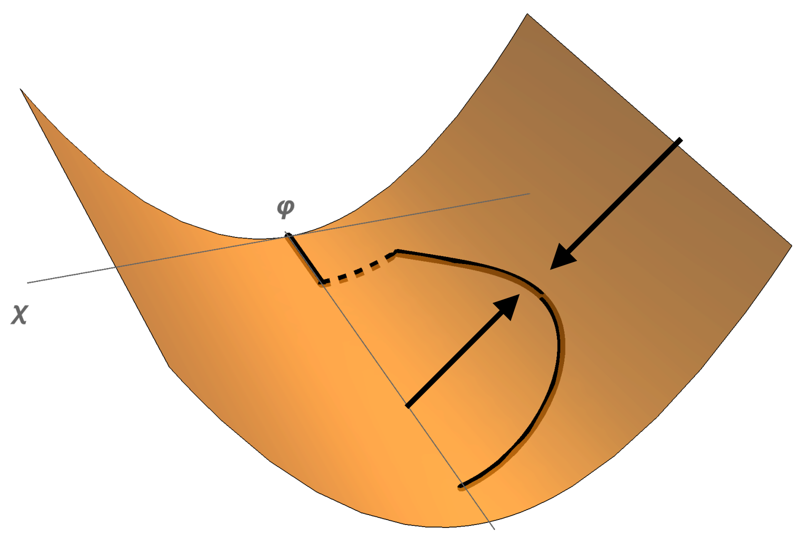
Under scrutiny in recent years

sidetracked inflation
hyperinflation
angular inflation
rapid-turn
fat inflaton
...

different names
but overall
similar
mechanism

Inflation with strongly non-geodesic motion

In negatively curved field space, new inflationary attractors, very different from slow-roll



Competition potential vs geometry:

Strongly non-geodesic motion

Requirement:
flat potentials wrt curvature scale

$$M\frac{V_{,\varphi}}{V} \ll 1\,, \qquad M\frac{V_{,\varphi\varphi}}{V_{,\varphi}} \ll 1$$

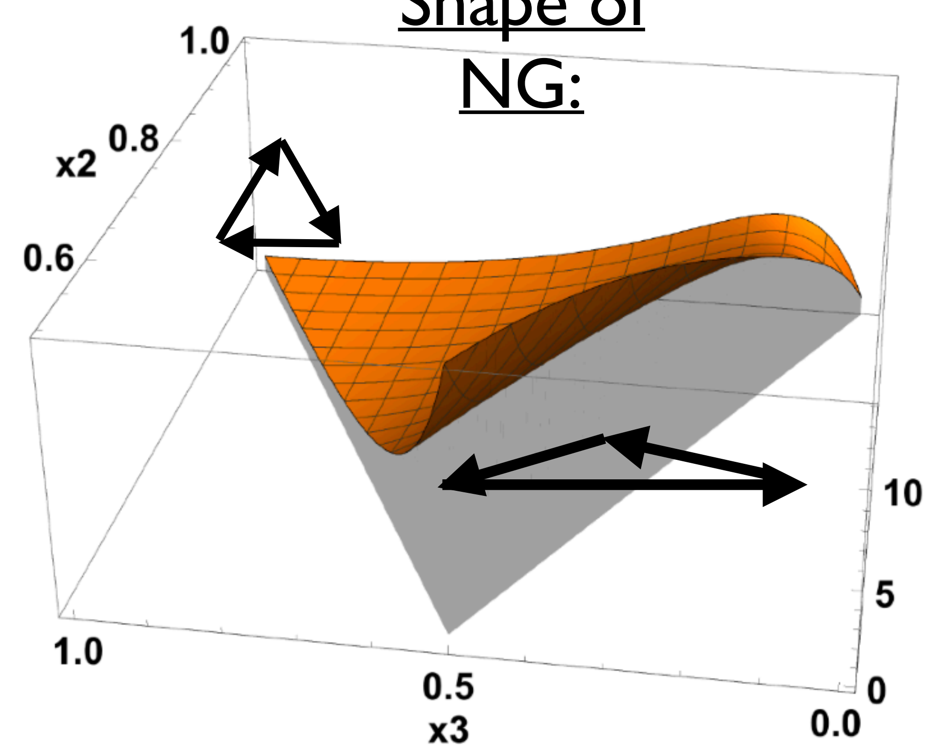
But with cutoff $M \ll M_{\rm Pl}$

Natural expectation to have structures over distance M

As tuned as slow-roll

Observational signatures

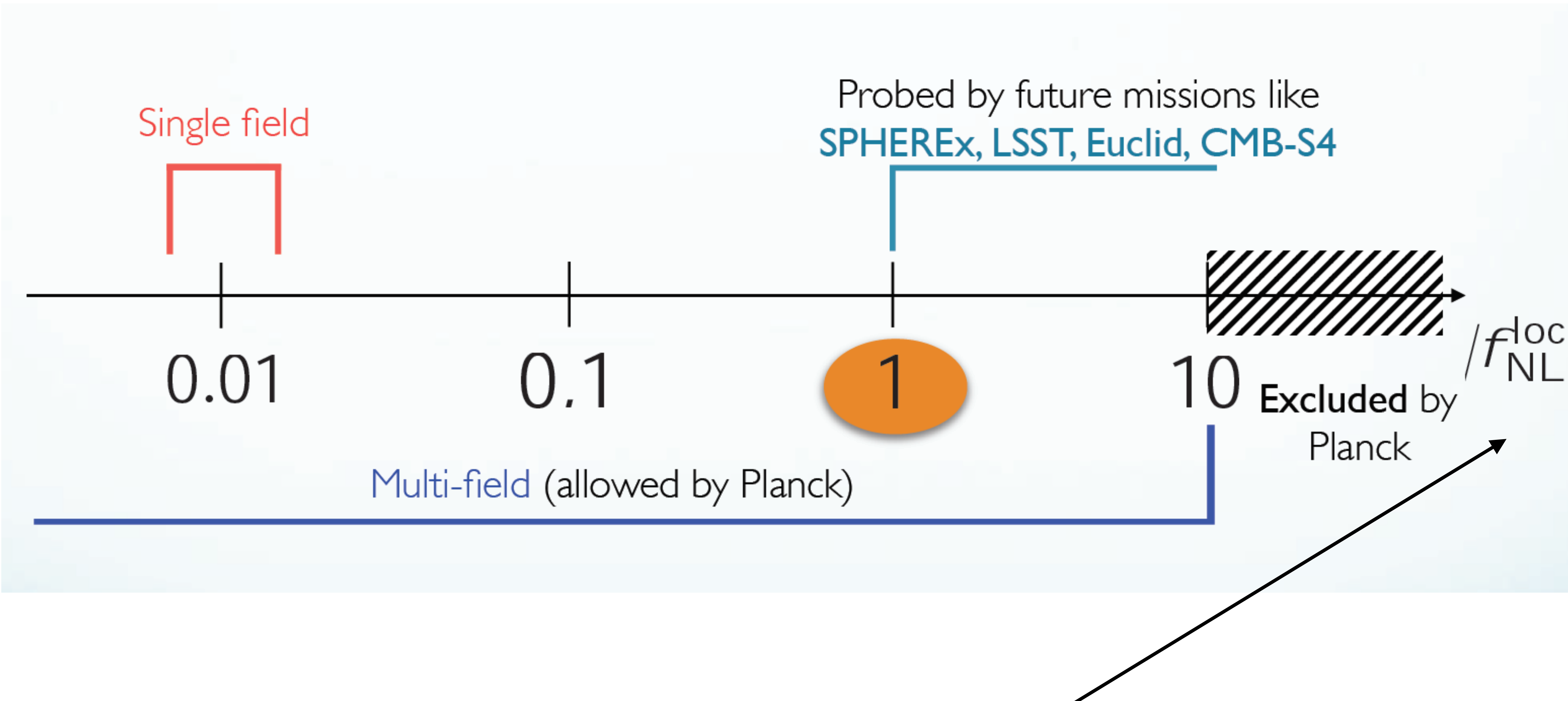
- Transient tachyonic instability around Hubble crossing (like axion gauge-field)
- Can be described by single-clock EFT of inflation with imaginary sound speed
- Unobservable exponential enhancement of power spectrum
- But bispectrum and all n-point functions enhancement in flattened configurations (similarities with non-Bunch-Davies vacuum)



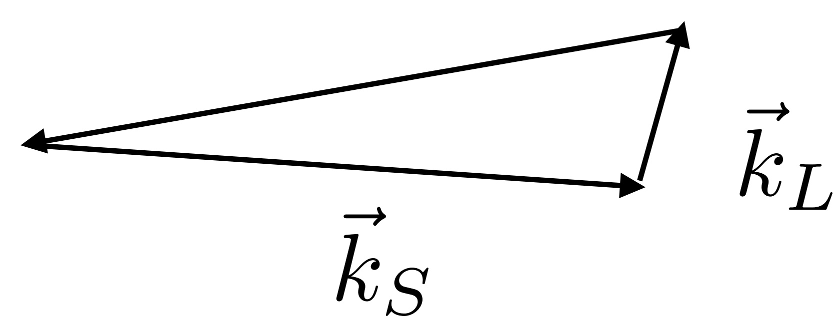
Garcia-Saenz, Pinol, RP, Ronayne, Fumagalli 18,19

II Cosmological collider and bootstrap

Non-Gaussianities: observational prospects

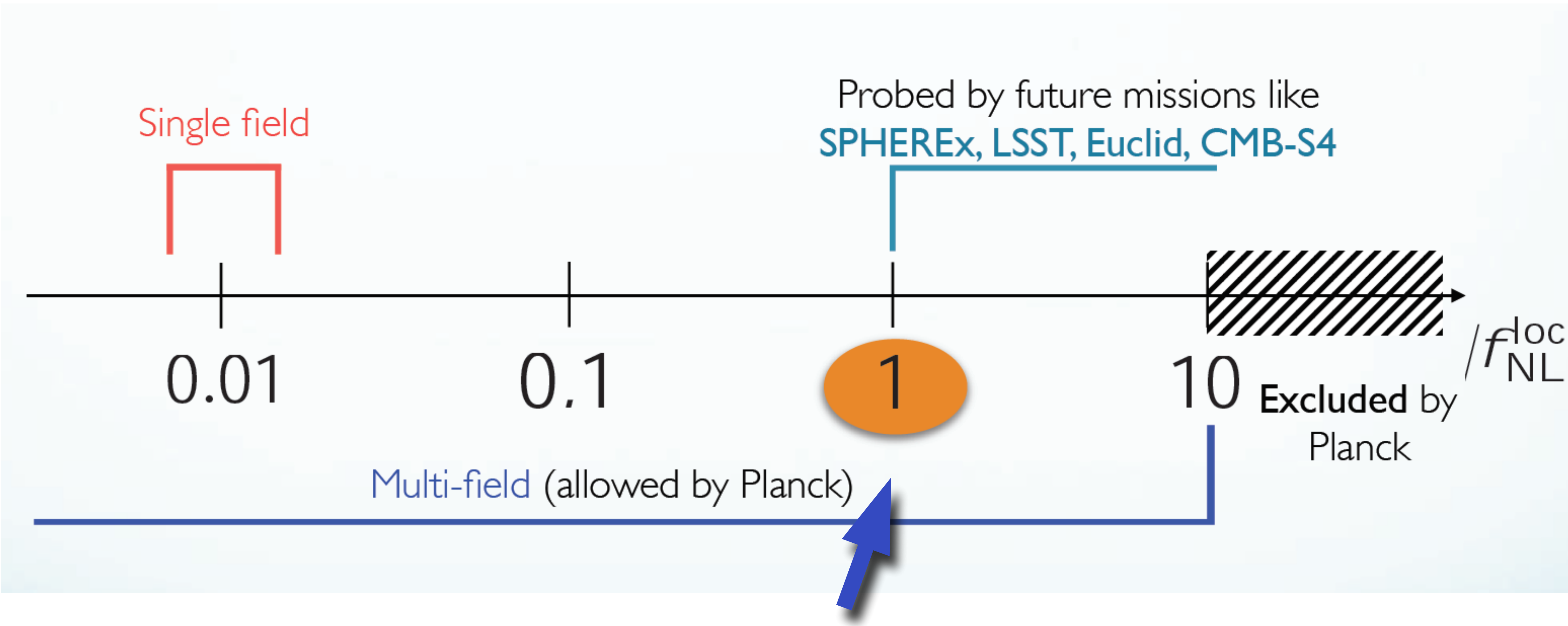


Significance of local shape:
not possible in single-clock inflation



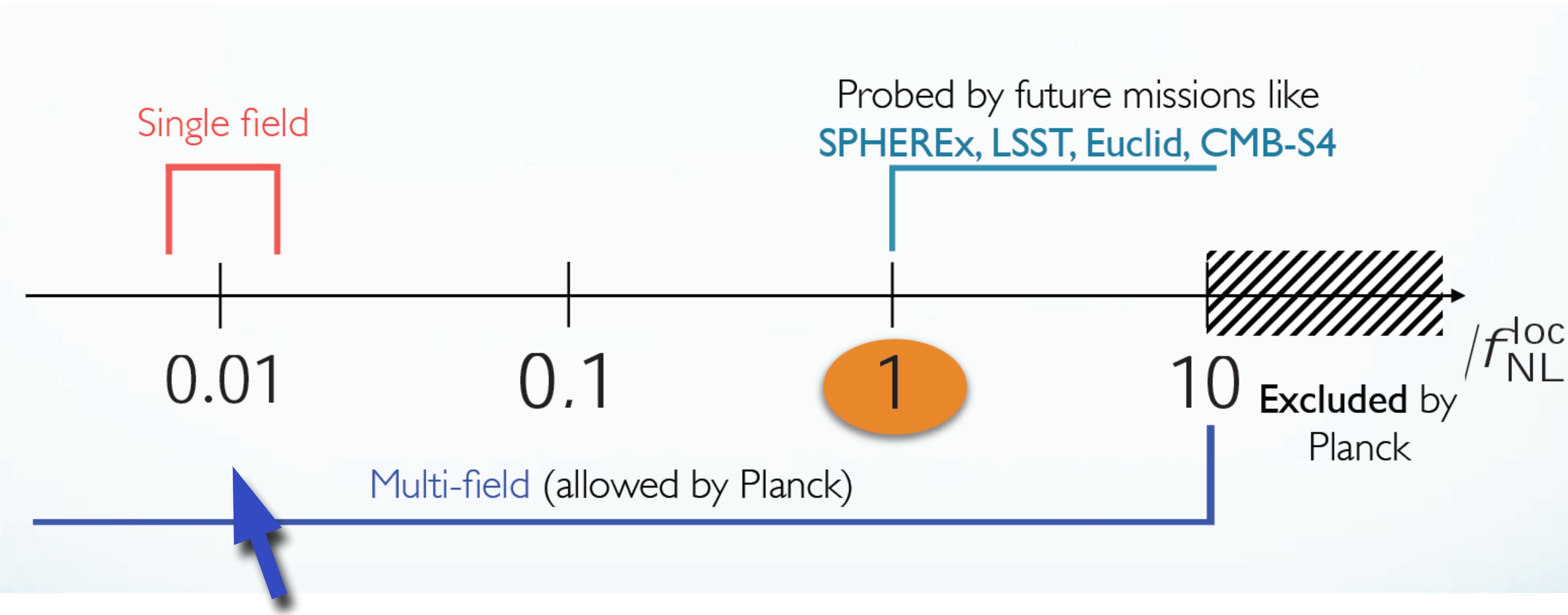
Peak for squeezed triangles

Non-Gaussianities: observational prospects



Huge efforts to reach this sensitivity
with large-scale structure surveys
and scale-dependent bias

Non-Gaussianities: observational prospects

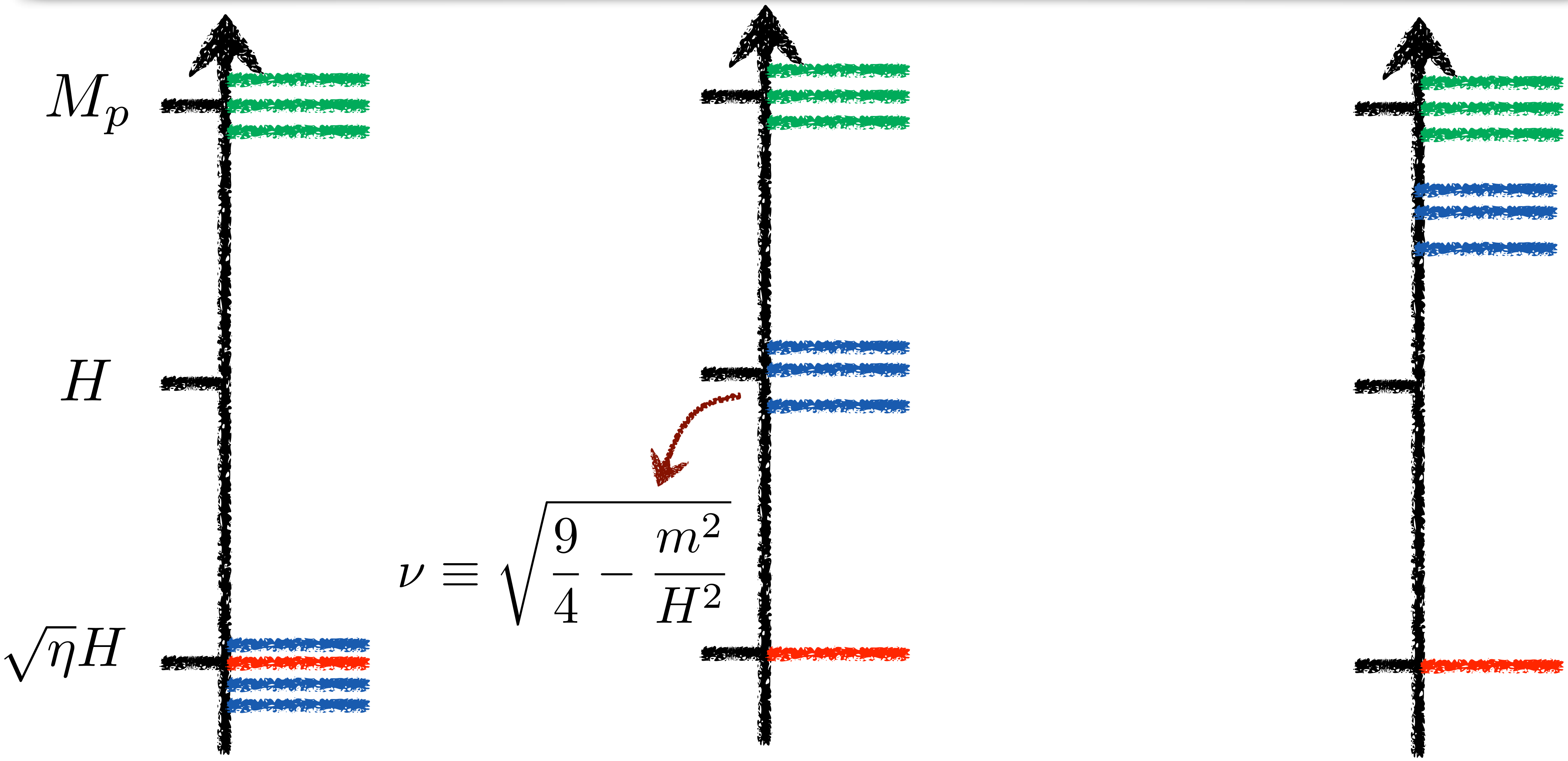


21cm emission from hydrogen clouds during dark ages

radio-astronomy from the far side of the moon!

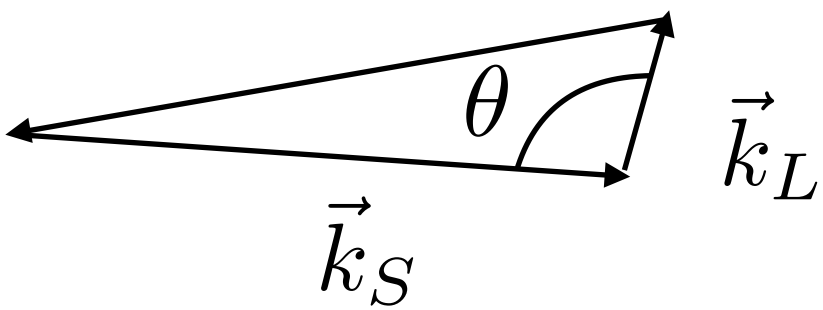
Non-Gaussianity as a particle detector

	Light dof	Quasi-single-field	Heavy dof
$\lim_{k_L \to 0} k_L^3 \langle \zeta_{\vec{k}_L} \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \rangle$	1	$\left(\frac{k_L}{k_S}\right)^{\frac{3}{2}-\nu}$	$\left(\frac{k_L}{k_S}\right)^{\frac{3}{2}} \cos\left[\lvert\nu\rvert \ln\left(\frac{k_L}{k_S}\right) + \delta \right]$



Cosmological collider physics

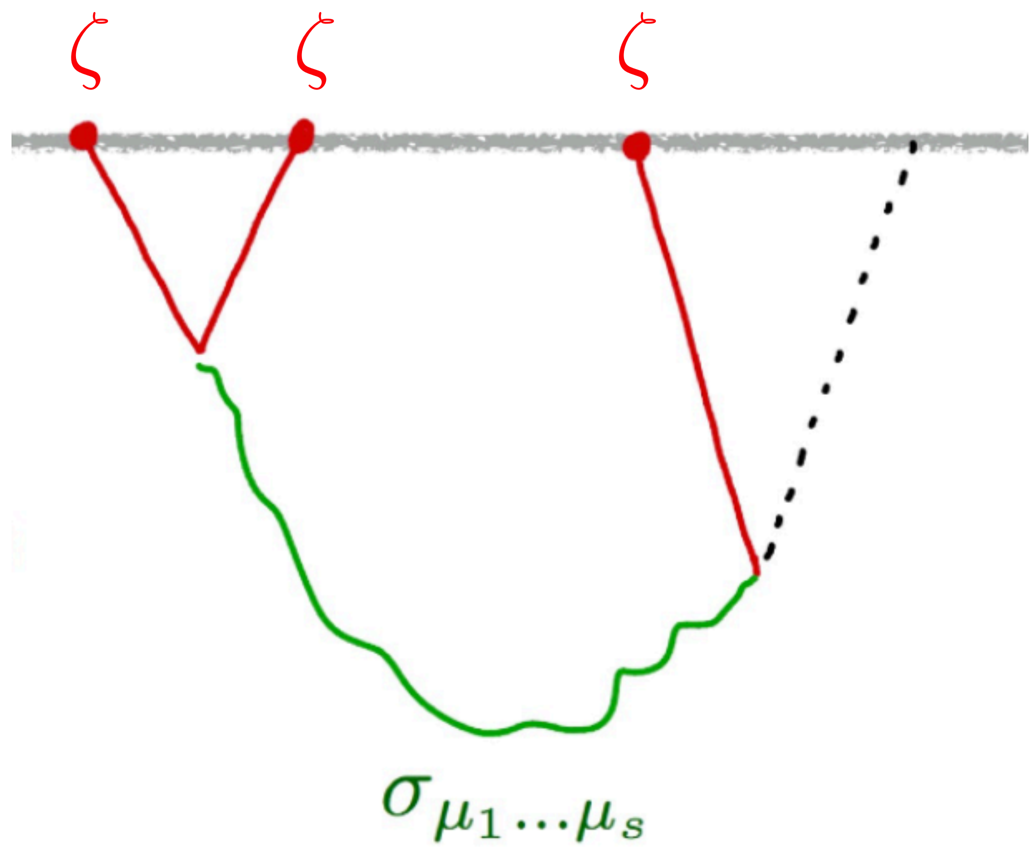
3pt



$$\lim_{k_L \to 0} \langle \zeta_{\vec{k}_L} \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \rangle \propto \left(\frac{k_L}{k_S} \right)^{3/2} \cos \left[\frac{M}{H} \ln \left(\frac{k_L}{k_S} \right) + \delta \right] P_S(\cos\theta)$$

Mass & Spin

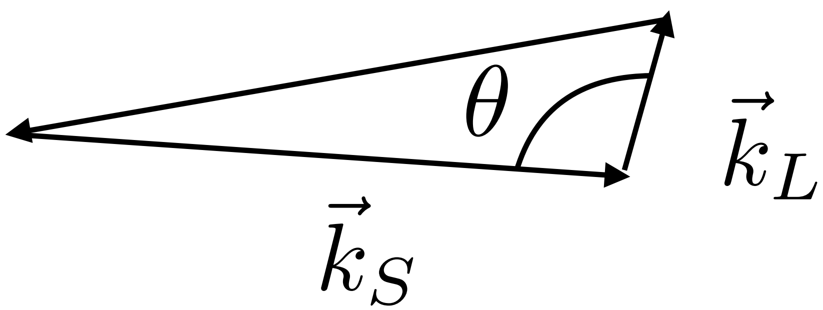
of heavy exchanged particle



Chen, Wang 2009
Baumann Green 2011
Noumi, Yamaguchi, Yokohama 2012
Arkani-Hamed, Maldacena 2015
Lee, Bauman, Pimentel 2016
Arkani-Hamed, Baumann, Lee, Pimentel 2018
Pinol, Aoki, RP, Yamaguchi 2021
…

Cosmological collider physics

3pt

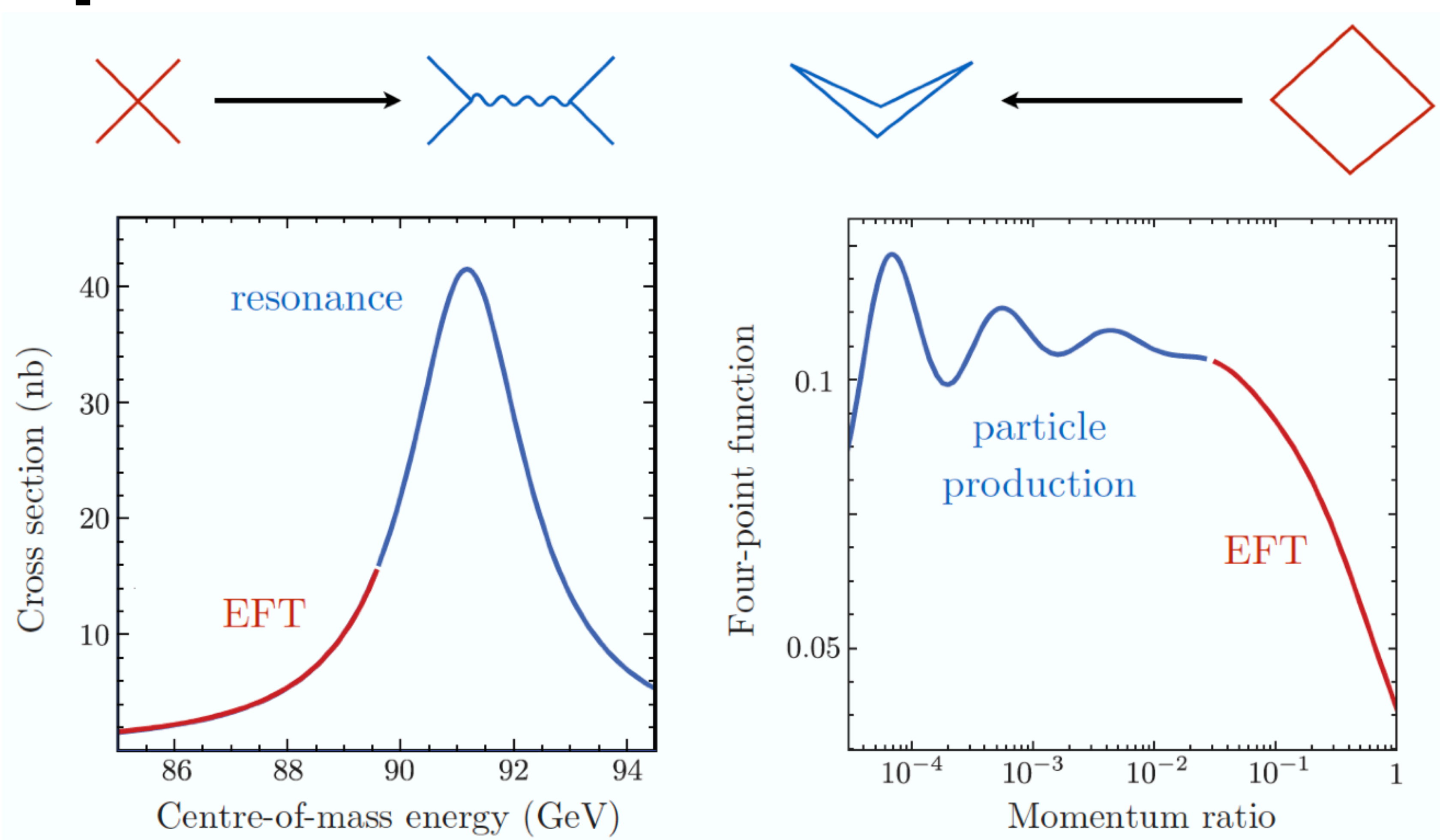


$$\lim_{k_L\to 0}\langle \zeta_{\vec{k}_L}\zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\rangle \propto \left(\frac{k_L}{k_S}\right)^{3/2}\cos\left[\frac{M}{H}\ln\left(\frac{k_L}{k_S}\right)+\delta\right]P_S(\cos\theta)$$

Mass & Spin

of heavy exchanged particle

4pt



From 1811.00024

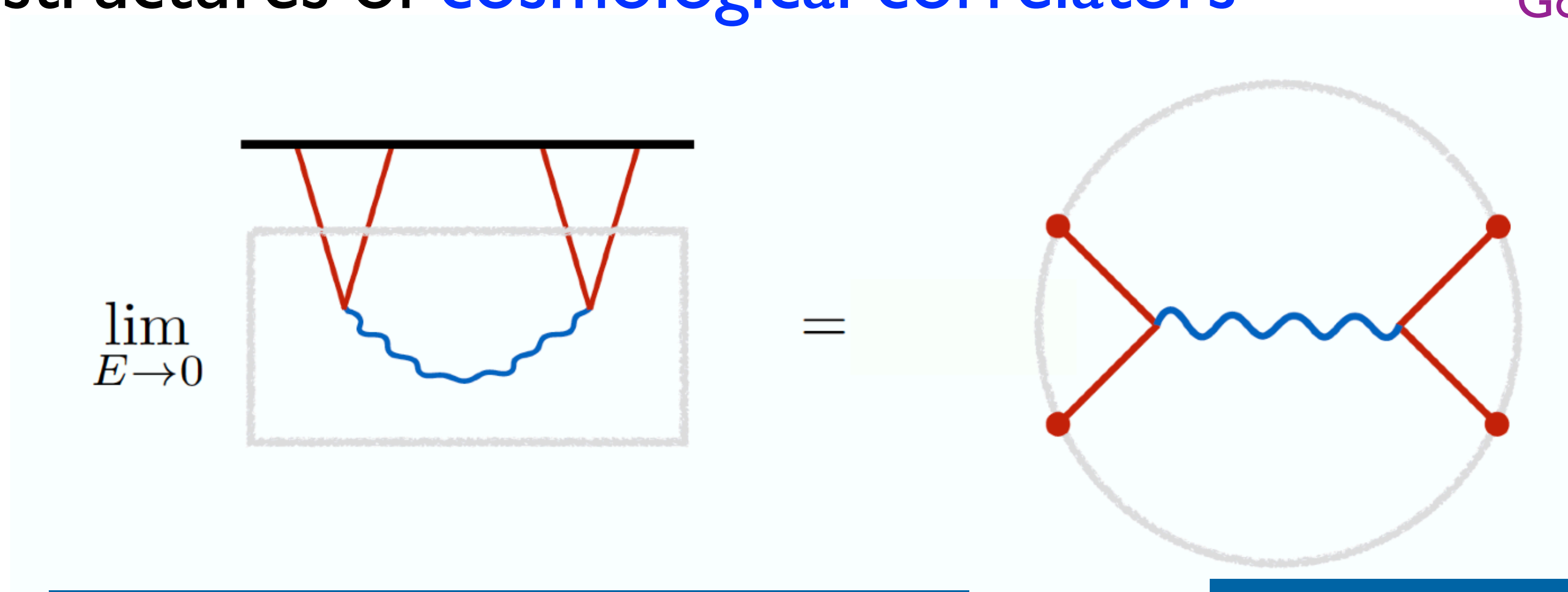
Chen, Wang 2009
Baumann Green 2011
Noumi, Yamaguchi, Yokohama 2012
Arkani-Hamed, Maldacena 2015
Lee, Bauman, Pimentel 2016
Arkani-Hamed, Baumann, Lee, Pimentel 2018
Pinol, Aoki, RP, Yamaguchi 2021
…

Cosmological bootstrap

Different methods in past years. Aim: carve out space of inflationary correlators consistent with basic physical principles (unitarity, locality, causality)

Example of interesting developments: scattering amplitudes contained in analytical structures of cosmological correlators

Arkani-Hamed, Benincasa 2017
Arkani-Hamed, Baumann, Lee, Pimentel 2018
Sleight, Taronna 2019
Goodhew, Jazayeri, Pajer, 2020 …



III Stochastic inflation

Why stochastic inflation?

- Standard approach: classical background + quantum fluctuations:

  - conceptually not satisfactory

  - breaks down for very light scalar fields

- Late time IR structure of correlators in (near) de Sitter, eternal inflation

many people!

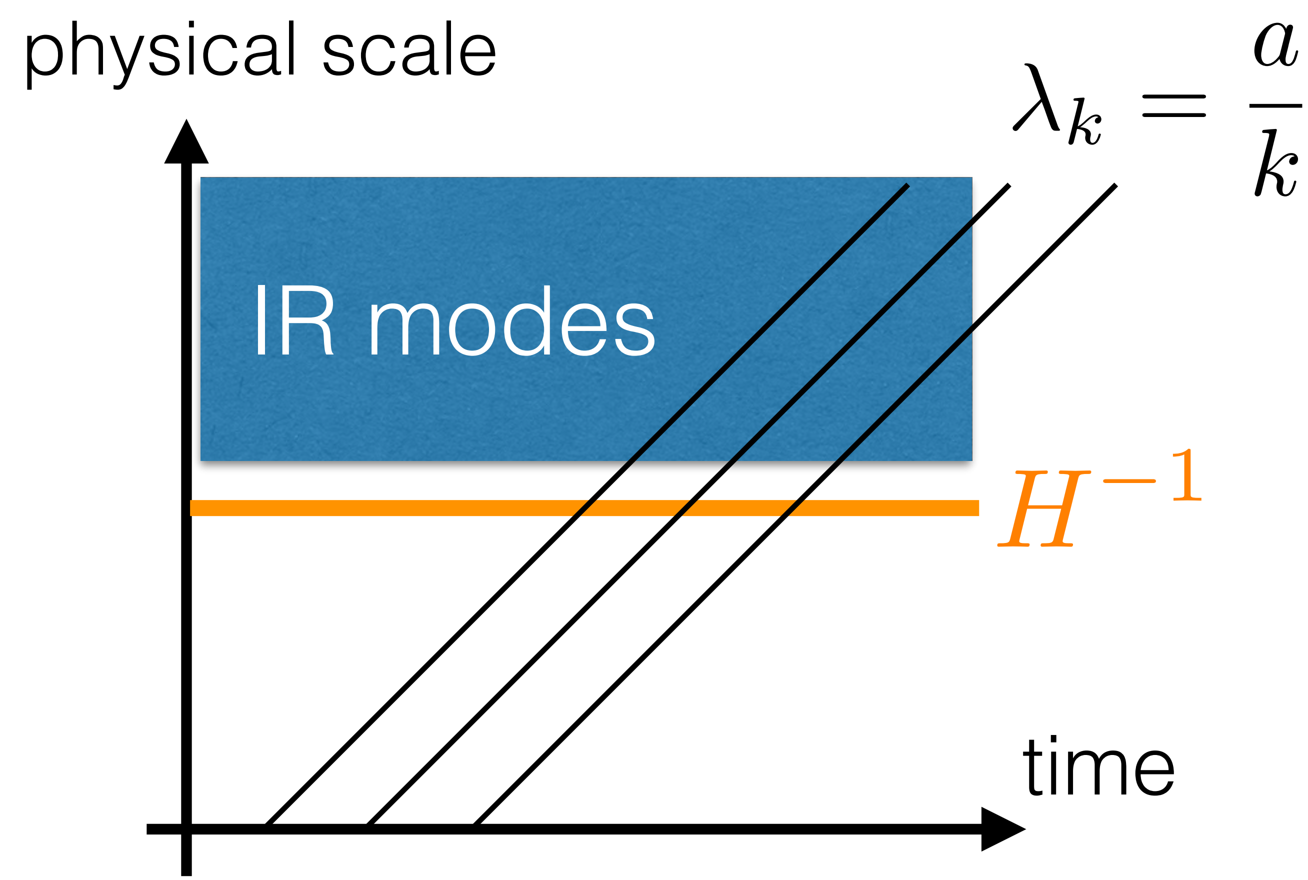
- Can be used to compute full pdf of ζ (e.g. for PBH), with stochastic $\delta\mathcal{N}$ formalism

Fujita, Kawasaki, Tada, Takesako 2013, 2014
Vennin, Starobinsky 2015

Stochastic formalism

Classical stochastic effective theory for coarse-grained fields

Background → super-Hubble modes



Continuous flow of initially sub-Hubble (UV) modes joining the super-Hubble (IR) sector

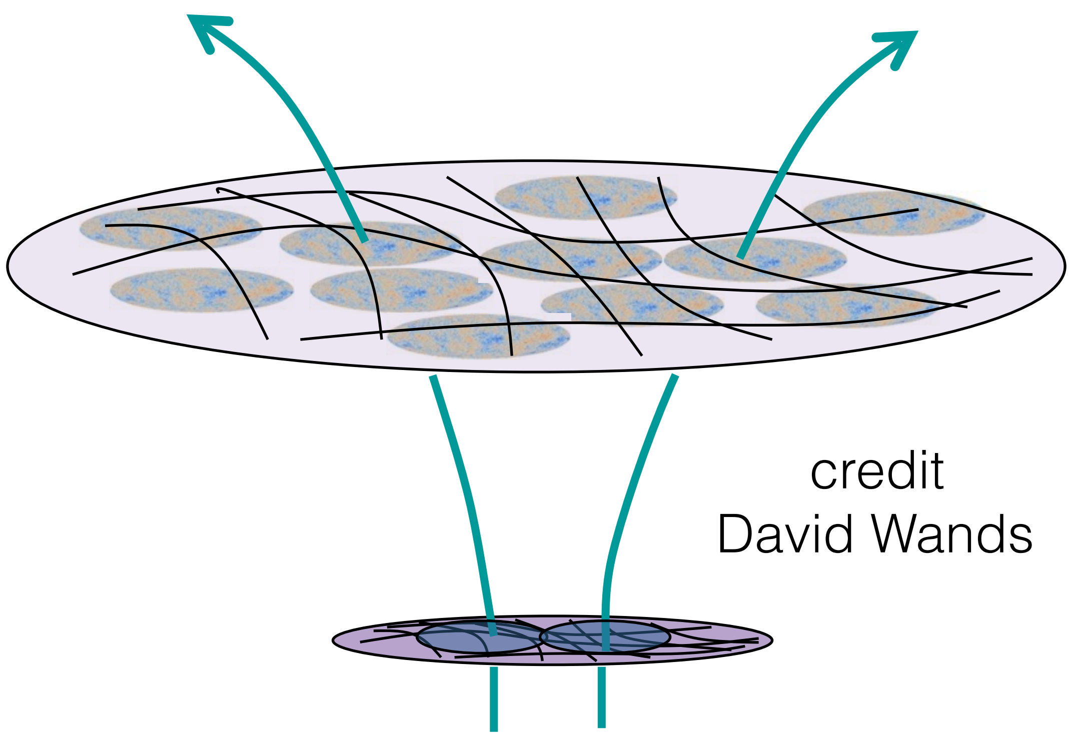
$$\frac{\mathrm{d}\varphi}{\mathrm{d}N} = -\frac{V'(\varphi)}{3H^2} + \frac{H}{2\pi}\xi$$

↖ Gaussian white noise

Starobinsky, 86

Stochastic formalism

Many (super)-Hubble regions evolving like locally separate universes, emerging from same initial conditions



credit
David Wands

classical drift
(slow-roll)

Langevin equation

$$\frac{\mathrm{d}\varphi}{\mathrm{d}N} = -\frac{V'(\varphi)}{3H^2} + \frac{H}{2\pi}\xi$$

quantum diffusion

$$\langle \xi(N)\xi(N') \rangle = \delta(N - N')$$

stochastic dynamics of a representative Hubble region

φ coarse-grained long-wavelength scalar field

Fokker-Planck equation

$$\frac{\partial P(\varphi, N)}{\partial N} = \mathcal{L}_{\mathrm{F}P} \cdot P(\varphi, N)$$

probability density function of field's values at time N

IR resummation

- Agreement with QFT computations (but much simpler)

Woodard, Starobinsky, Rigopoulos …

- Enables one to resum late time divergences of perturbative QFT

e.g. in $\lambda\varphi^4$ theory in de Sitter, secular effects for $\lambda N^2 > 1$

and derive non-perturbative results, e.g. $P_{\mathrm{eq}}(\varphi) \propto e^{-8\pi^2 V(\varphi)/(3H_0^4)}$

- Outstanding questions: limitations, rigorous derivation, corrections

Gorbenko, Senatore 19, Mirbabayi 19,
Baumgart, Sundrum 19, Cohen, Green 20, 21

Cosmological correlators

Stochastic $\delta\mathcal{N}$ formalism:

$P(\varphi_{\rm stoc}, N)$

pact-dependent fields with deterministic clock

invert FP equation $\mathcal{L}_{\rm FP}^{\dagger}$

$P(\mathcal{N}_{\rm stoc}(\varphi))$

patch-dependent durations of inflation, starting from progenitor patch

$\mathcal{N}(\varphi)$ number of e-folds of inflation realized starting from field value φ

stochastic quantity, directly related to observable curvature perturbation

$$\zeta = \delta\mathcal{N} = \mathcal{N} - \langle\mathcal{N}\rangle$$

→ Full pdf of curvature perturbation

Fujita, Kawasaki, Tada, Vennin, Starobinsky, Pattison, Assadullahi, Firouzjahi, Noorbala, Wands, Pinol, RP …

Some developments

- Quantum diffusion leads to exponential tail of the pdf, enhances abundance of PBH

Vennin et al, 19, 20

- Formulation in a manifestly covariant manner under field redefinitions (resolution of stochastic anomalies)

Pinol, RP, Tada 19, 20

- Derivation and corrections in EFT language

Cohen, Green, Premkumar 20, 21

IV Inflation on small scales

Context

• LIGO/Virgo observations: one may have already detected Primordial Black Holes (PBH)

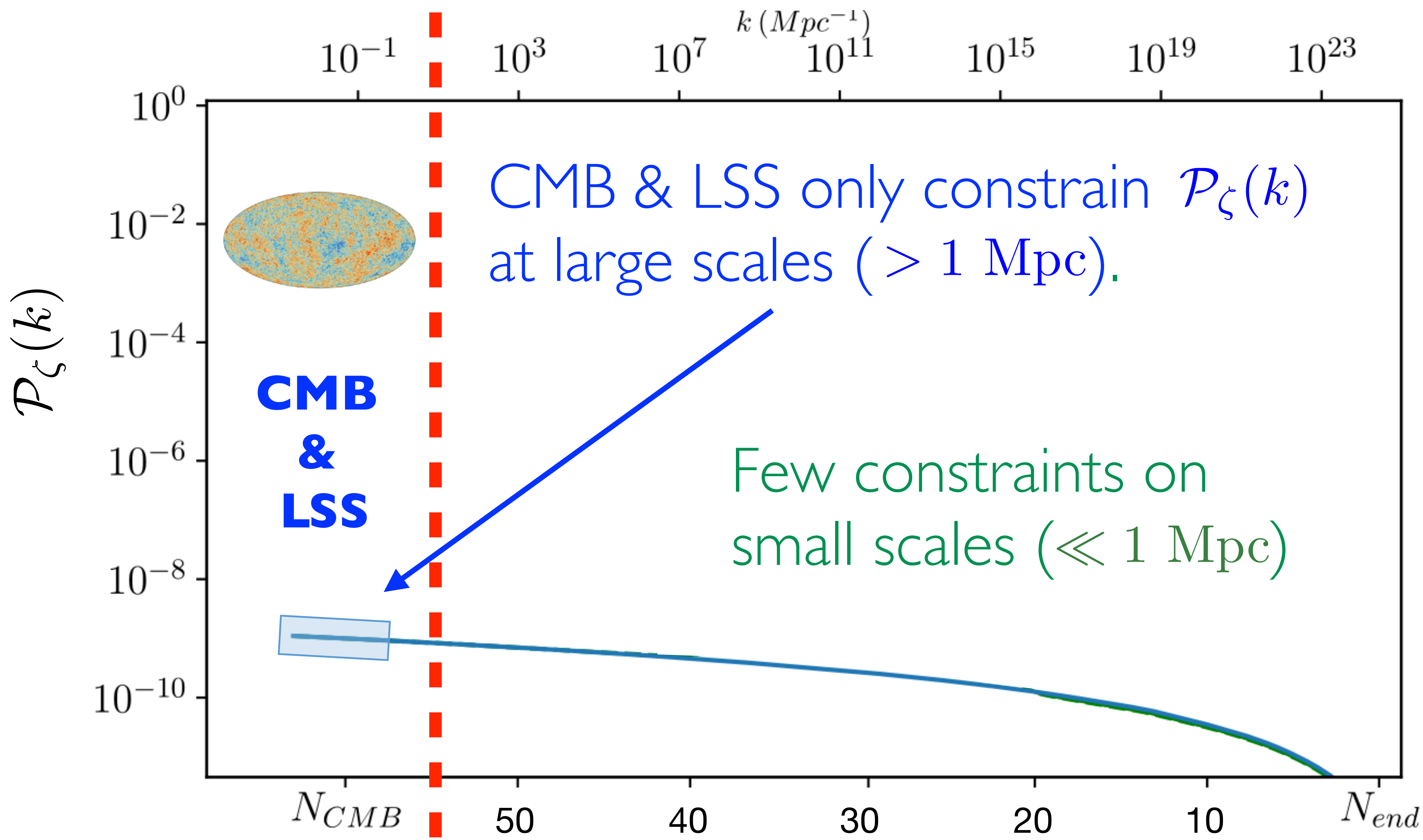
Clesse, Bellido, Riotto et al, Jedamzik …

• PBH generating mechanisms can be tested with stochastic gravitational wave background (SGWB) counterpart signatures

PBHs with $10^{-12} M_{\odot} \longrightarrow$ SGWB in mHz range of LISA Bartolo et al 18

• PBHs and GWs (combined or independently): new window on dark ages of inflation

Inflation on small scales?

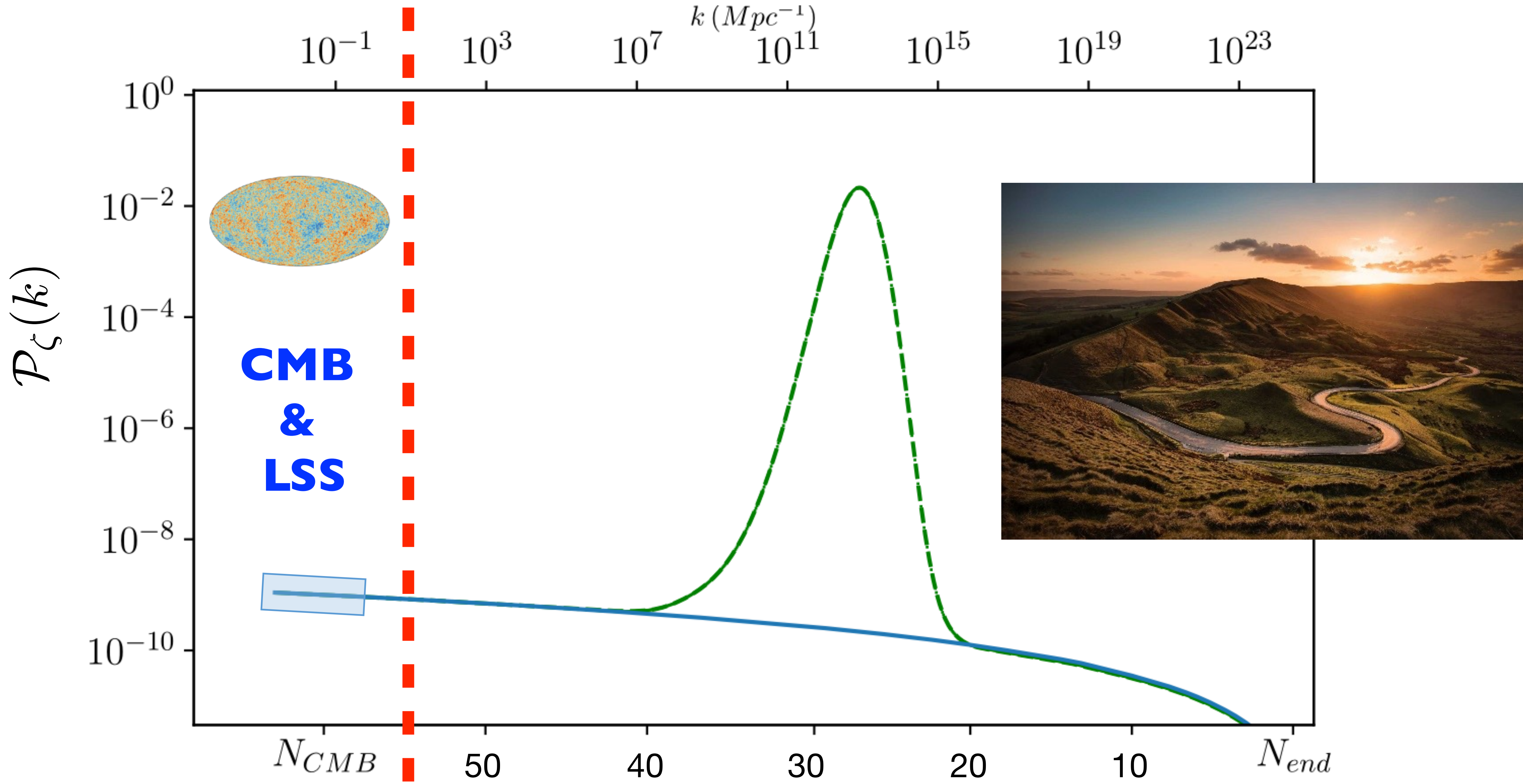


Slow Roll

+

Corrections

Inflation on small scales?



Slow Roll

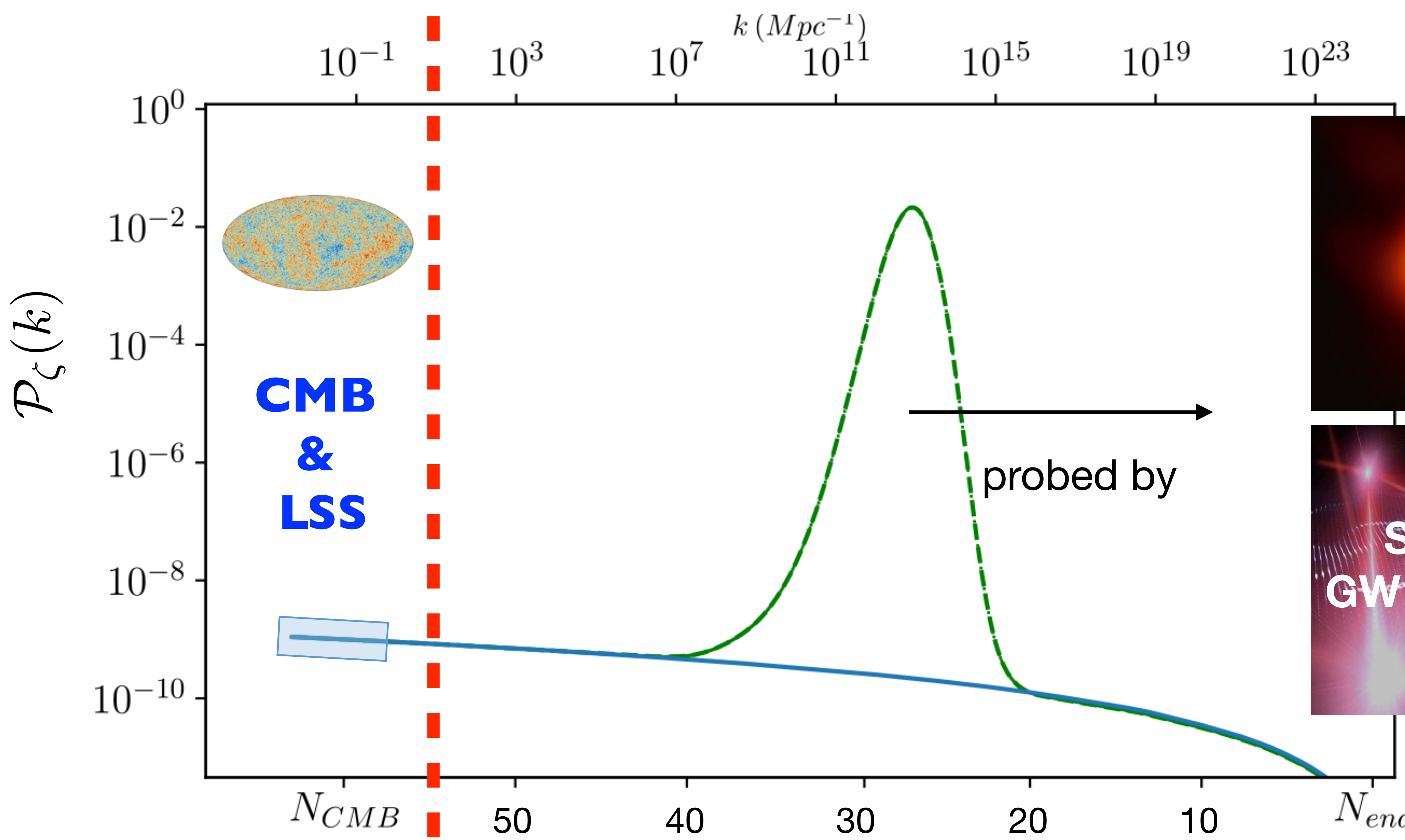
+

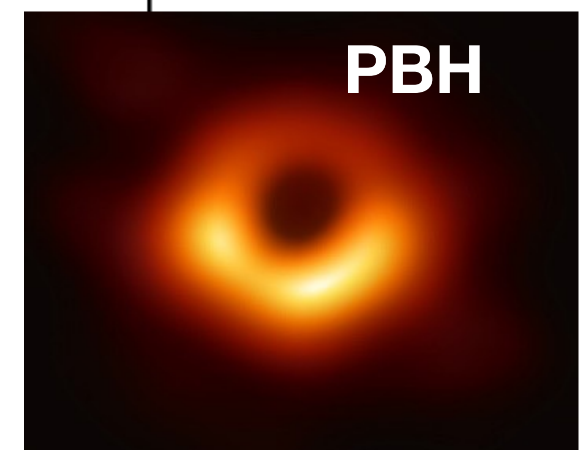
Corrections

Drastically different?

Naturally unnatural

Inflation on small scales?





Slow Roll

+

Corrections

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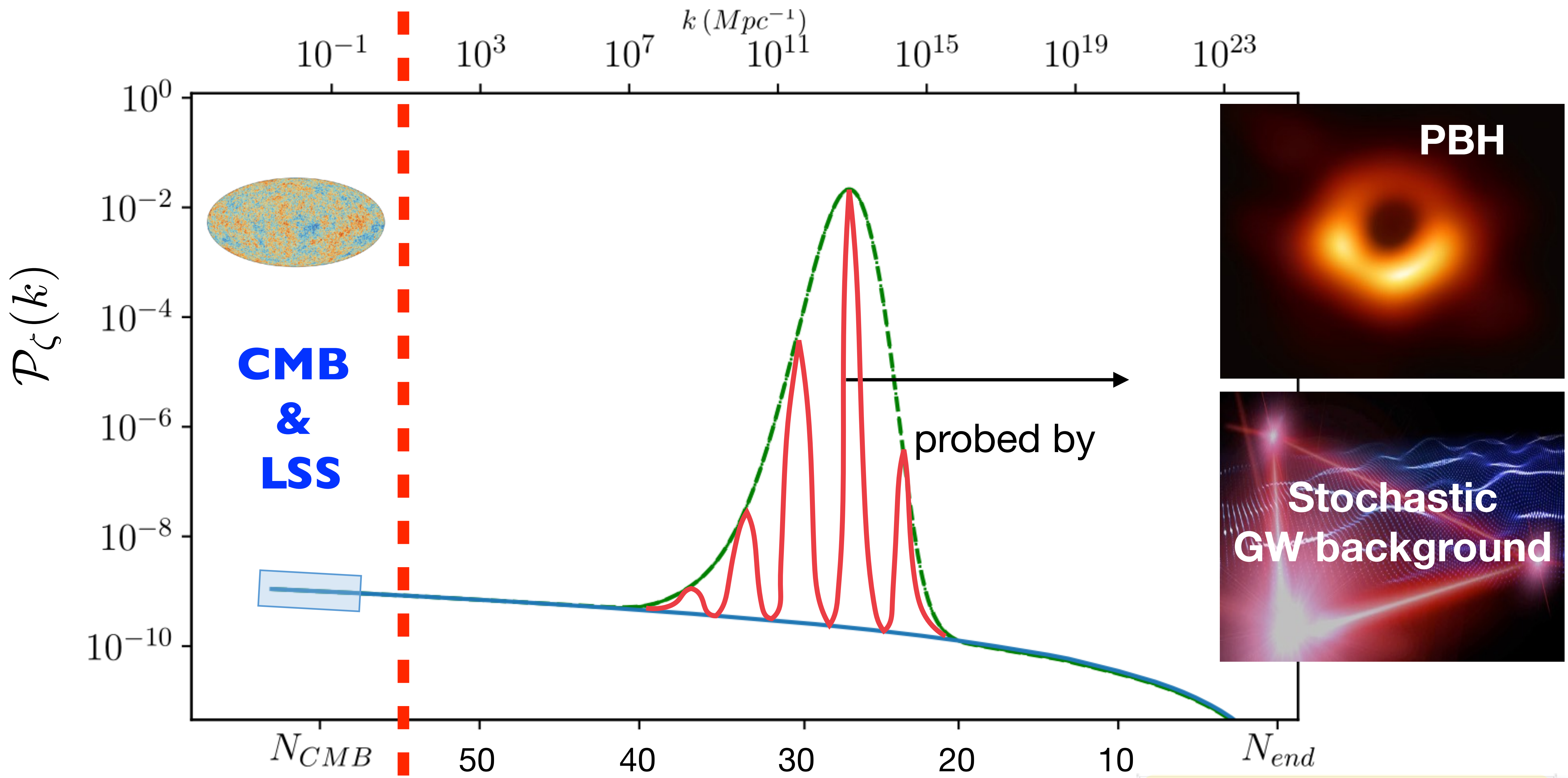
Inflation on small scales?



Slow Roll
+
Corrections

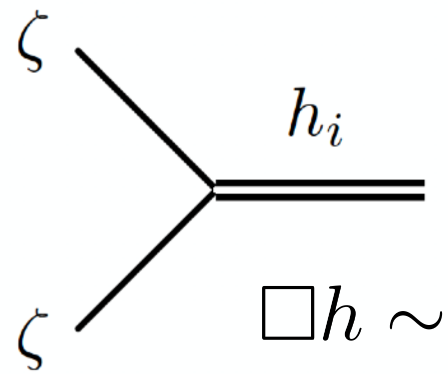
A peak is often associated with oscillations →

Features can be large

Transferred to
frequency profile
of induced SGWB

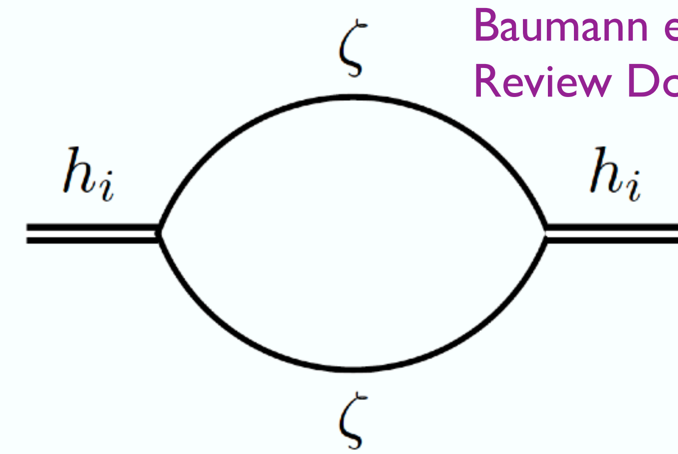
Scalar-induced GWs

Acquaviva et al. 02
Mollerach, Harari, Matarrese 03
Ananda, Clarkson, Wands 06
Baumann et al. 07
Review Domenech 2021



$\Box h \sim (\partial\zeta)^2$

→



Enhanced $\delta\rho$ → Enhanced GWs at horizon re-entry after inflation

energy density per $\log(k)$ -interval:

$$\Omega_{\rm GW}(k) = \int\int T(u,v)\mathcal{P}_\zeta(ku)\mathcal{P}_\zeta(kv) \quad \sim 10^{-5}\,\mathcal{P}_\zeta^2$$

$$\mathcal{P}_\zeta \sim 10^{-4} \longrightarrow \Omega_{\rm GW} \gtrsim 10^{-13}$$

LISA

Scalar-induced GWs

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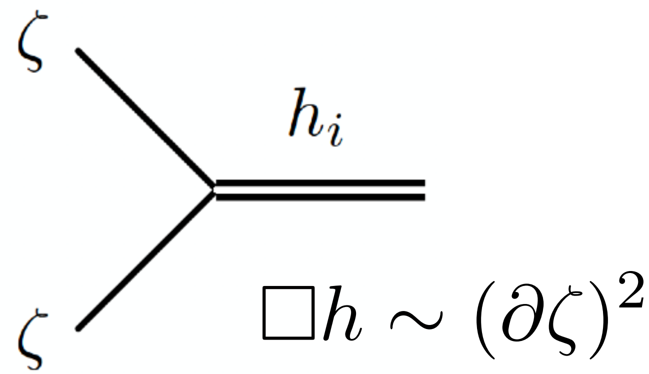

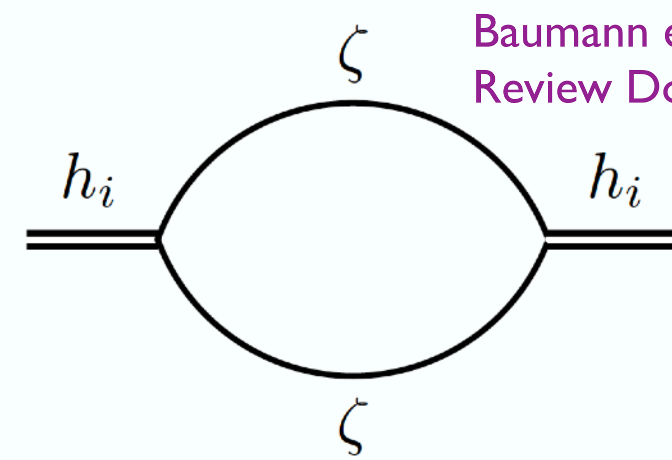

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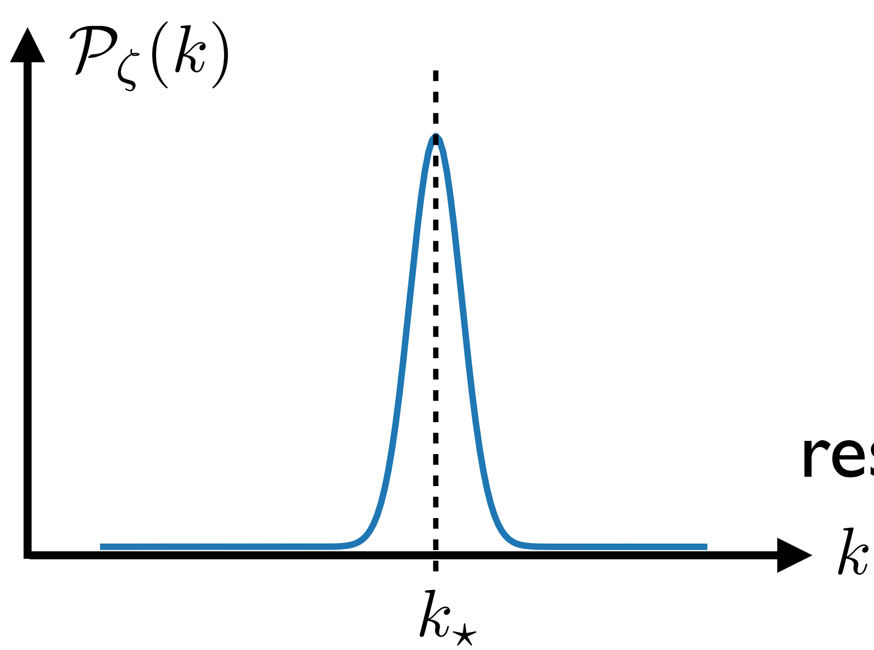
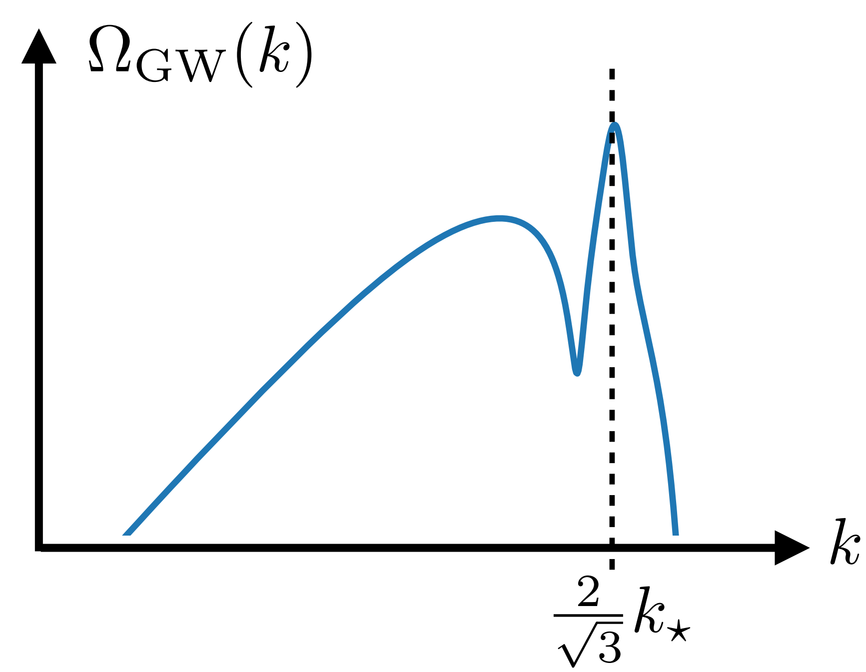


peak from resonant amplification



Scalar-induced GWs

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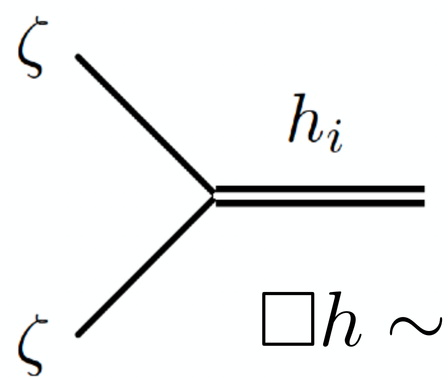
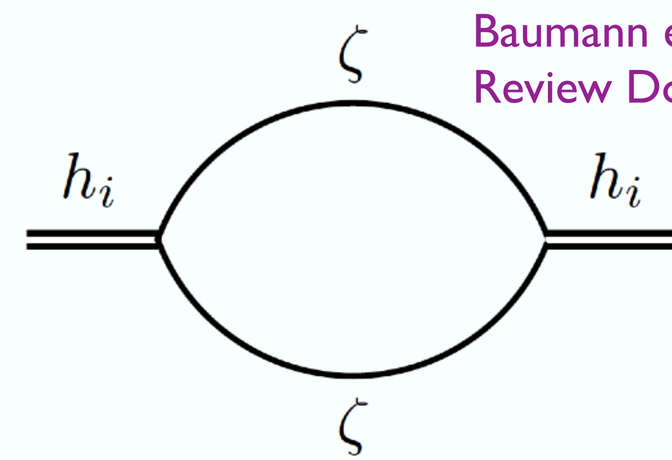


$\Box h \sim (\partial\zeta)^2$

$\longrightarrow$



Enhanced $\delta\rho$ $\longrightarrow$ Enhanced GWs at horizon re-entry after inflation

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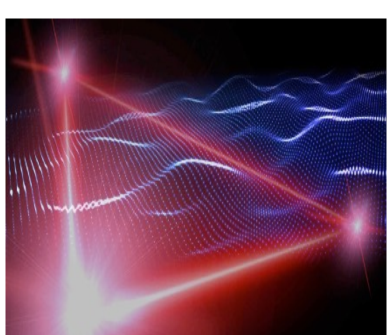
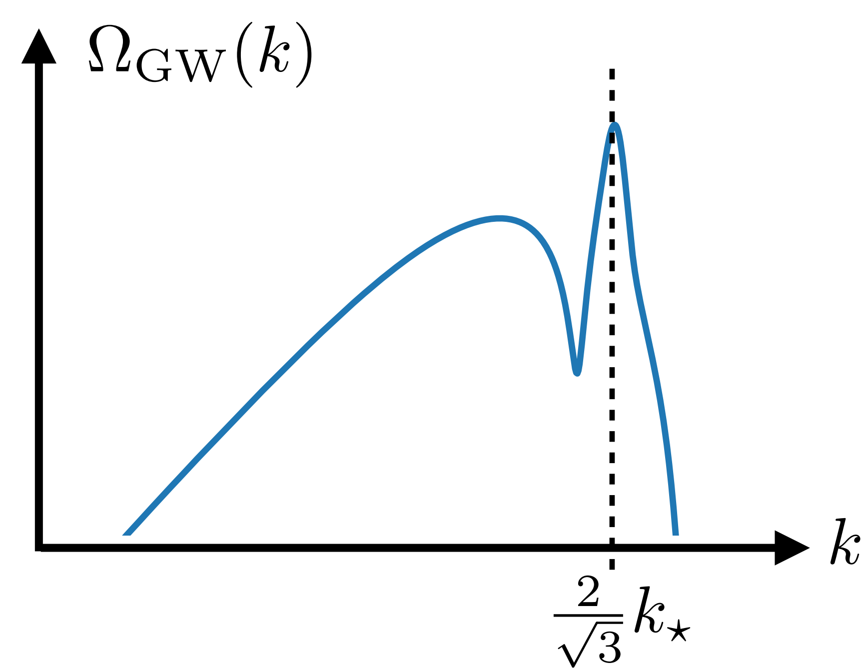
$$\Omega_{\rm GW}(k) = \int\int T(u,v)\mathcal{P}_\zeta(ku)\mathcal{P}_\zeta(kv) \quad \sim 10^{-5}\,\mathcal{P}_\zeta^2$$

$$\log\left(\frac{f}{10^{-3}\rm Hz}\right) \simeq \log\left(\frac{k}{10^{12}\rm Mpc^{-1}}\right) \simeq N_{\rm after\ CMB} - 30$$



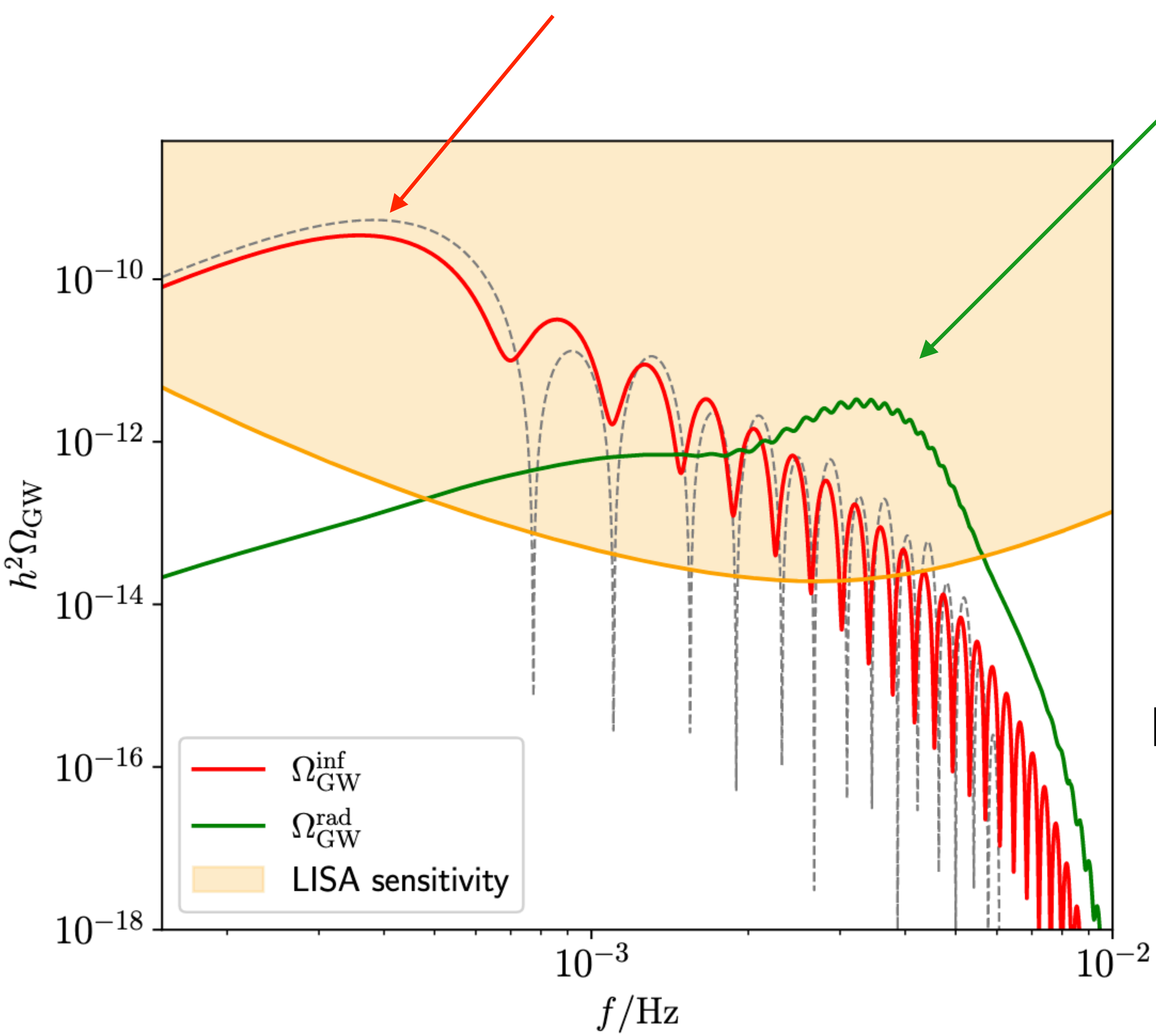
GW observatories probe inflation on small scales



Primordial GWs from sharp features

Scalar-induced GW during inflation

Scalar-induced GW after inflation



Oscillatory patterns in SGWB frequency profile

Model-independent information about physics of inflation on small scales

Motivated target of new physics

Fumagalli, RP, Witkowski et al (2020,2021)
several more aspects

Gravitational-Wave Primordial Cosmology

17-19 May 2021

Europe/Paris timezone

https://indico.in2p3.fr/event/23850/overview

Work to prepare for observations:

identify observables →

figure out best use of data

Frequency profile

Chirality

Non-Gaussianity/correlation with other probes

SGWB anisotropies

Conclusion

- Exciting time for inflationary cosmology and theorists

- No immediate motivation from observations leads to burst of new ideas and concepts

- New mechanisms to inflate and new EFT of fluctuations

- Inflation as a particle detector and formal developments close to particle physics

- Beyond standard perturbation theory with stochastic inflation

- New window on dark ages of inflation with GWs and PBHs