Inflationary cosmology

Sébastien Renaux-Petel

CNRS - Institut d'Astrophysique de Paris

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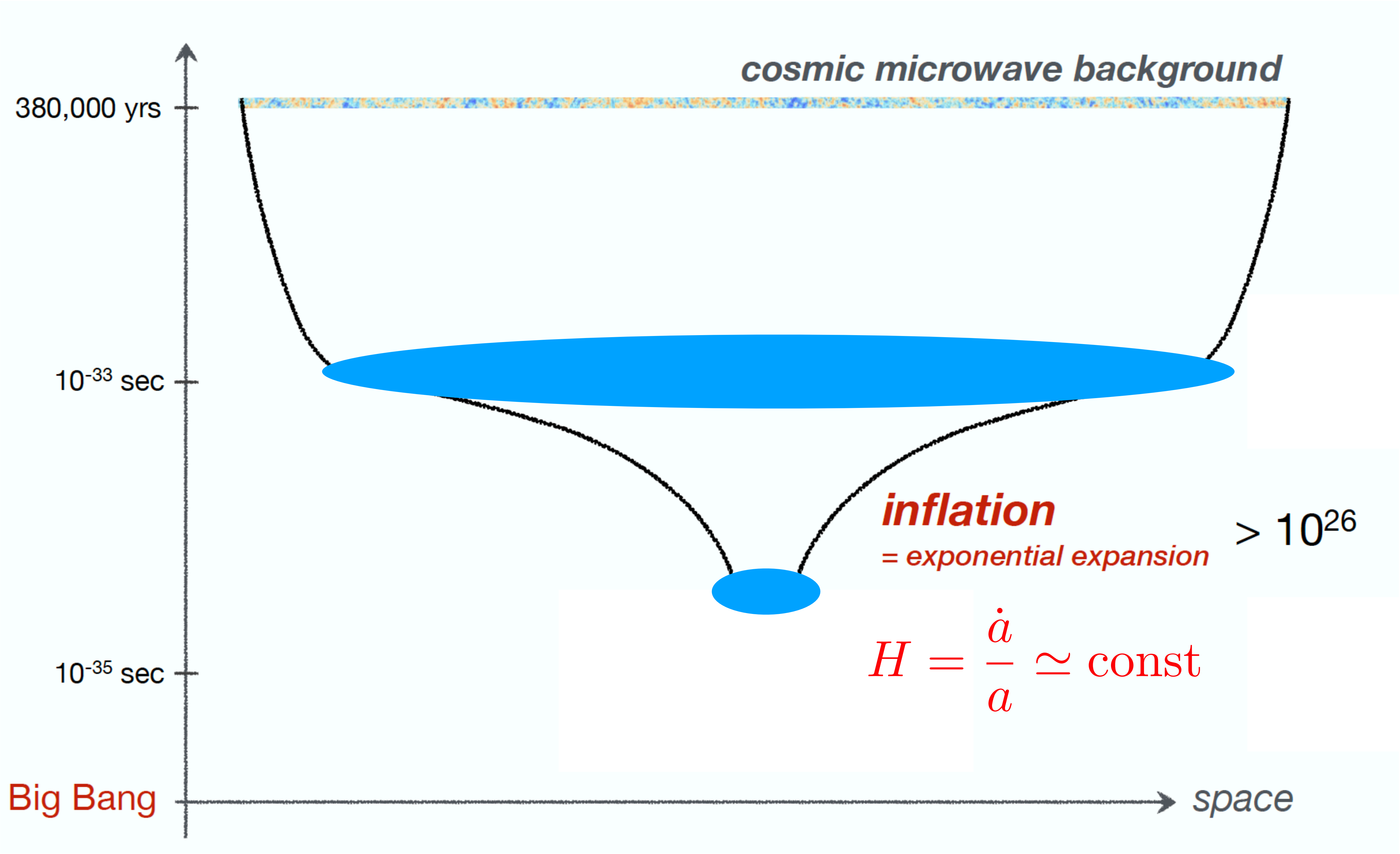
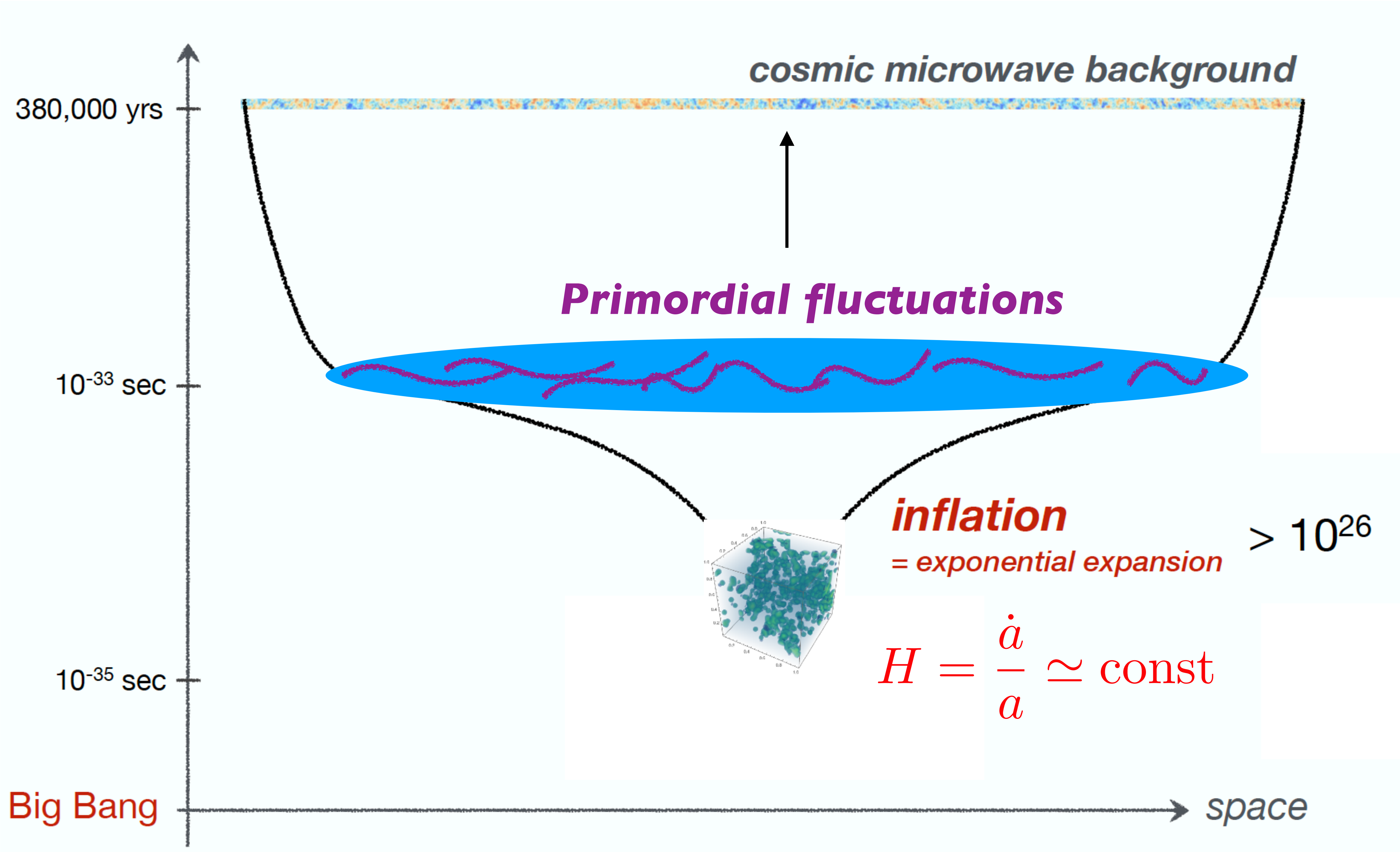
Inflation: a giant microscope

a tiny patch of space becomes the entire observable universe

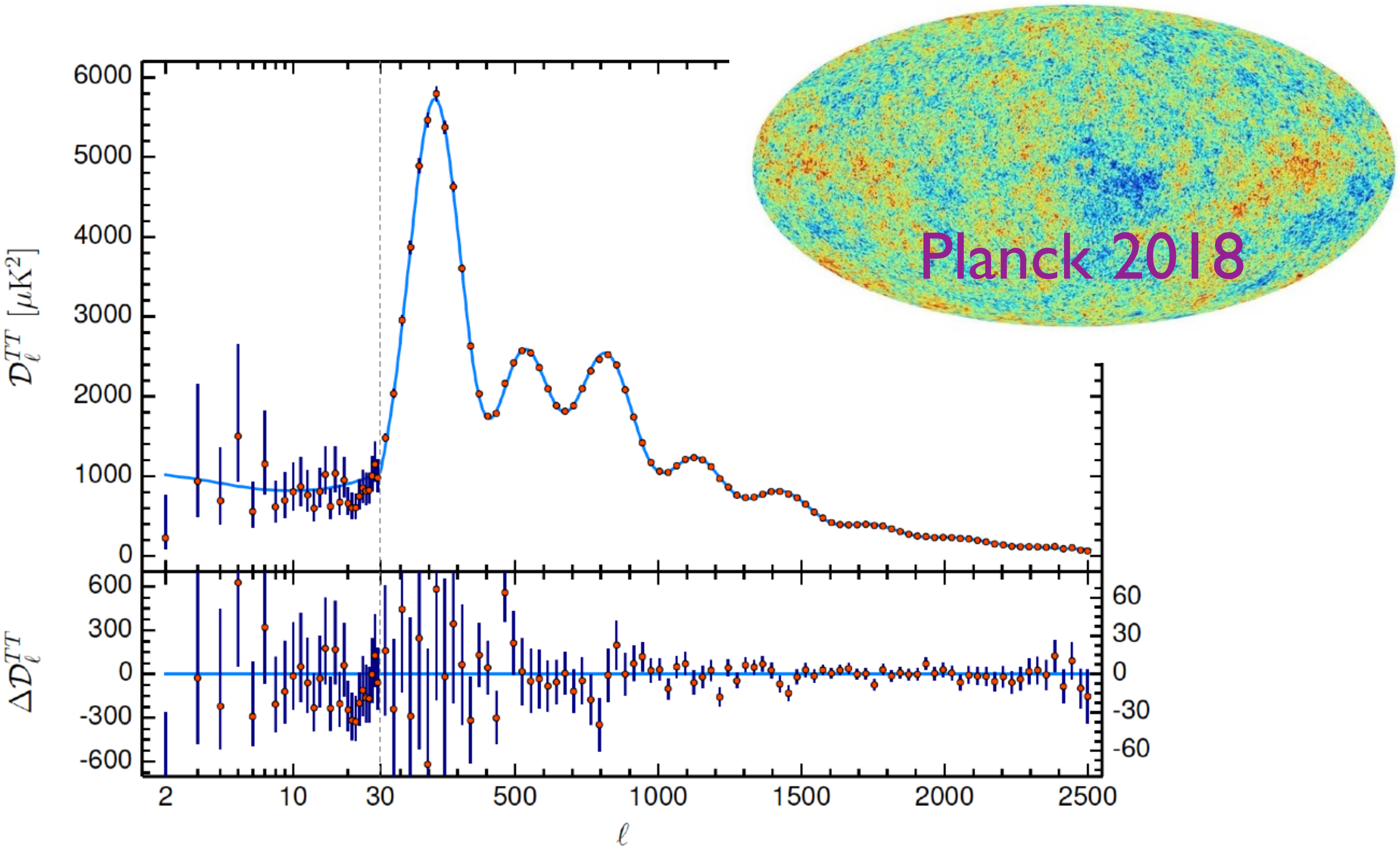


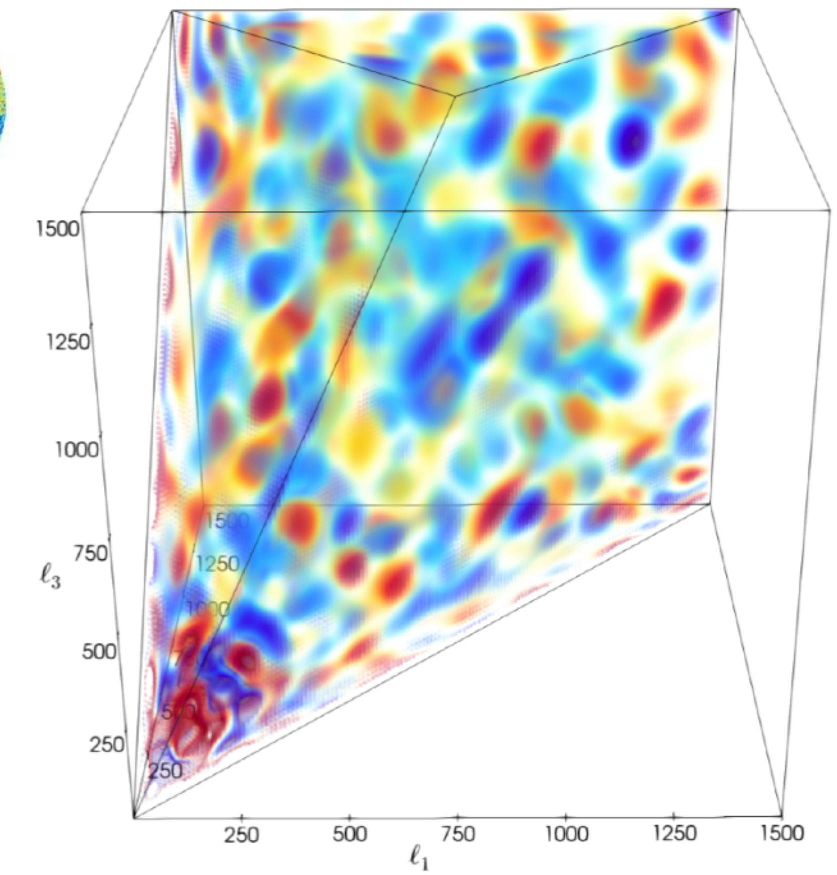
Inflation: a giant microscope

vacuum quantum fluctuations stretched to cosmological scales



Primordial fluctuations





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

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

Primordial fluctuations

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

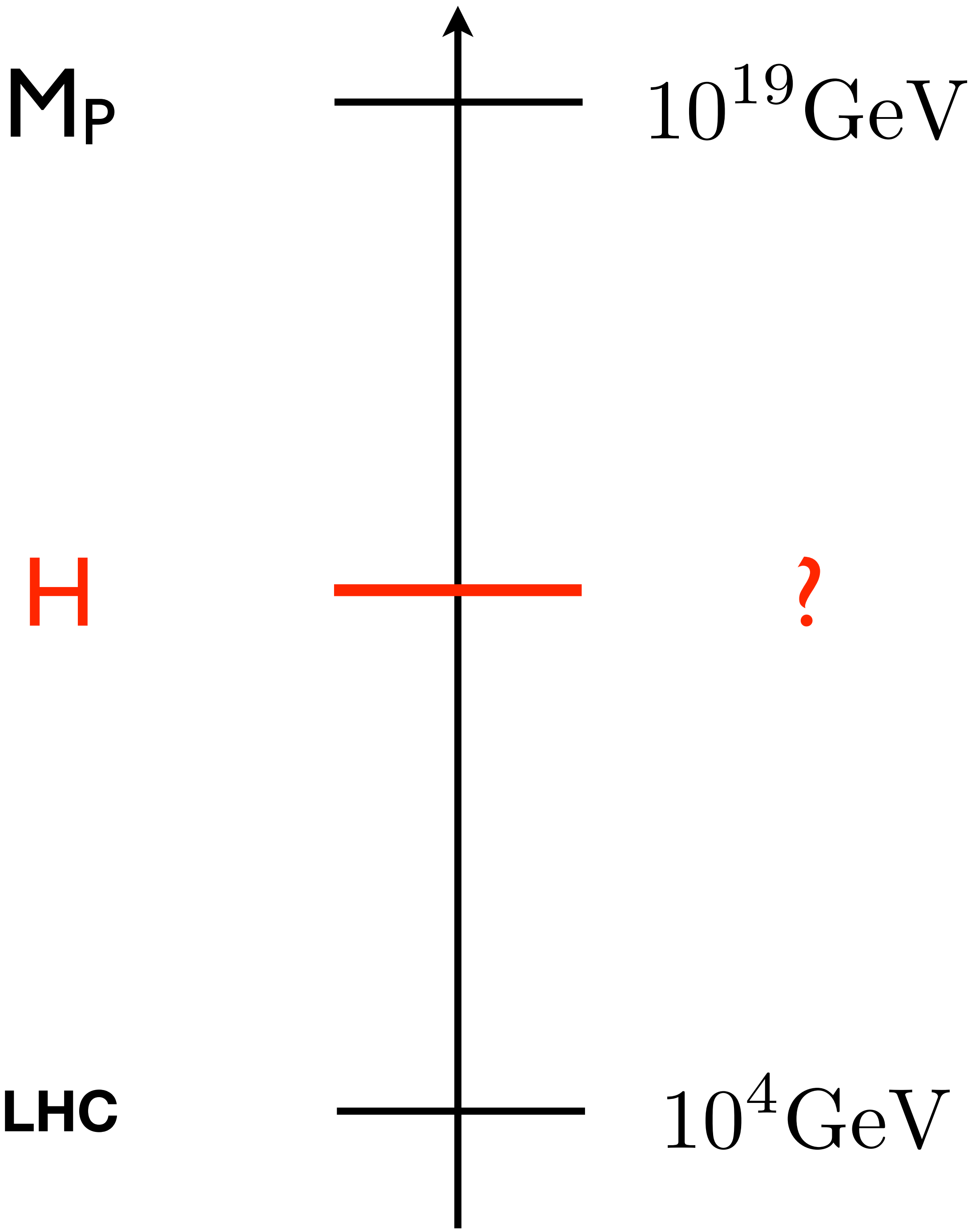
almost scale-invariance $\mathcal{P}_\zeta(k)\sim(10^{-5})^2\left(\frac{k}{k_\star}\right)^{n_s(k_\star)-1}$ $n_s=0.9649\pm0.0042\ (68\%\mathrm{CL})$

approximate time translation invariance during inflation

Gaussian $\zeta\sim\zeta_G\left(1+f_{\rm NL}\zeta_G\right)$ $|f_{\rm NL}|\lesssim\mathcal{O}(10)$

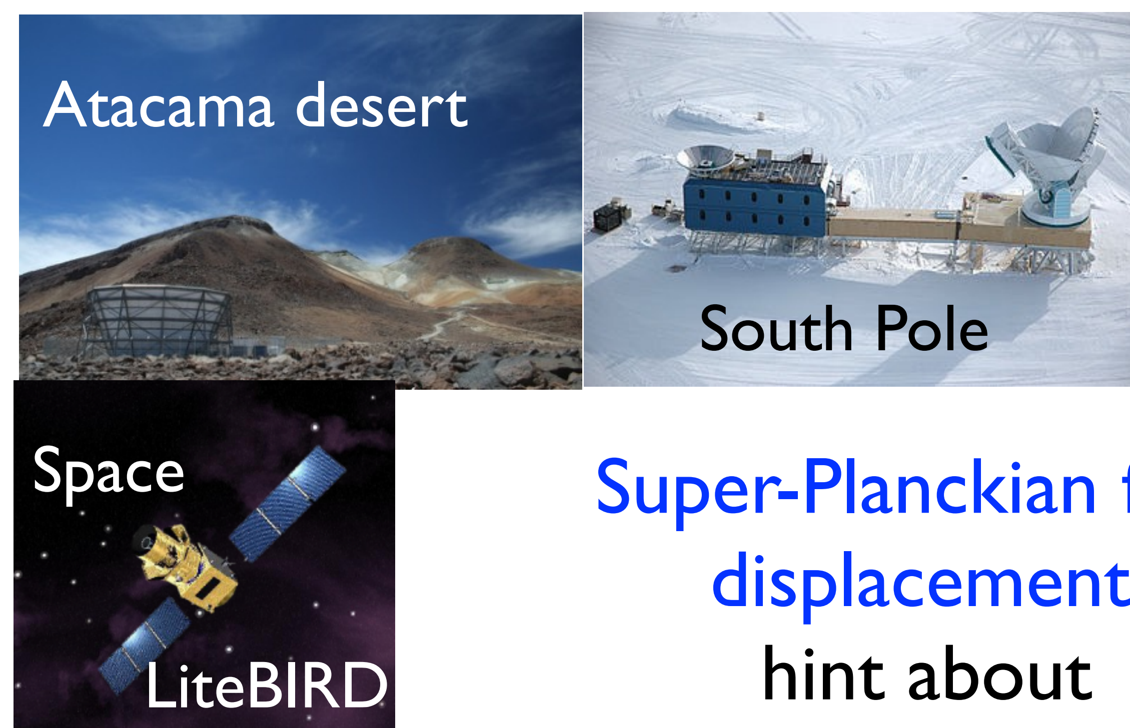
Gaussian to better than 0.01%

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?

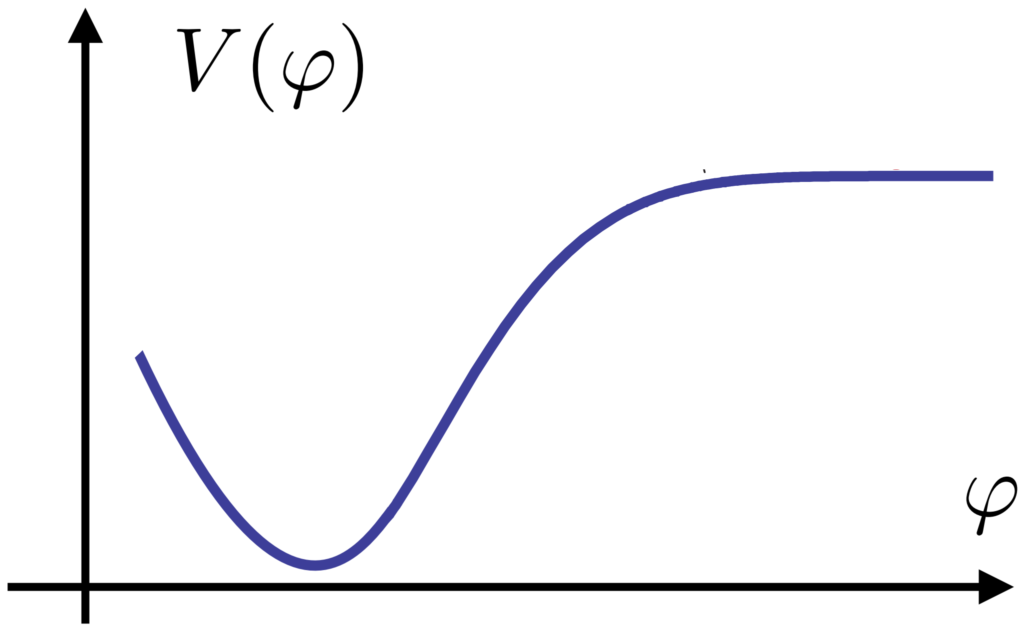
How did it transfert its energy to Standard Model particles?

The only degree of freedom?

Coupling to other fields?

…

The Eta problem



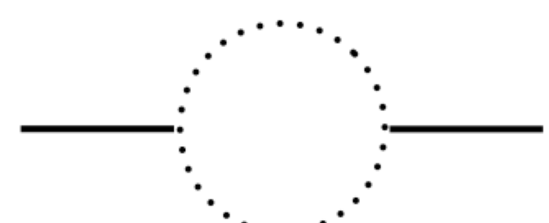
$$\eta \equiv M_{\rm pl}^2 \frac{V_{,\phi\phi}}{V} \ll 1$$

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

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

→ $$\Delta\eta \gtrsim 1$$

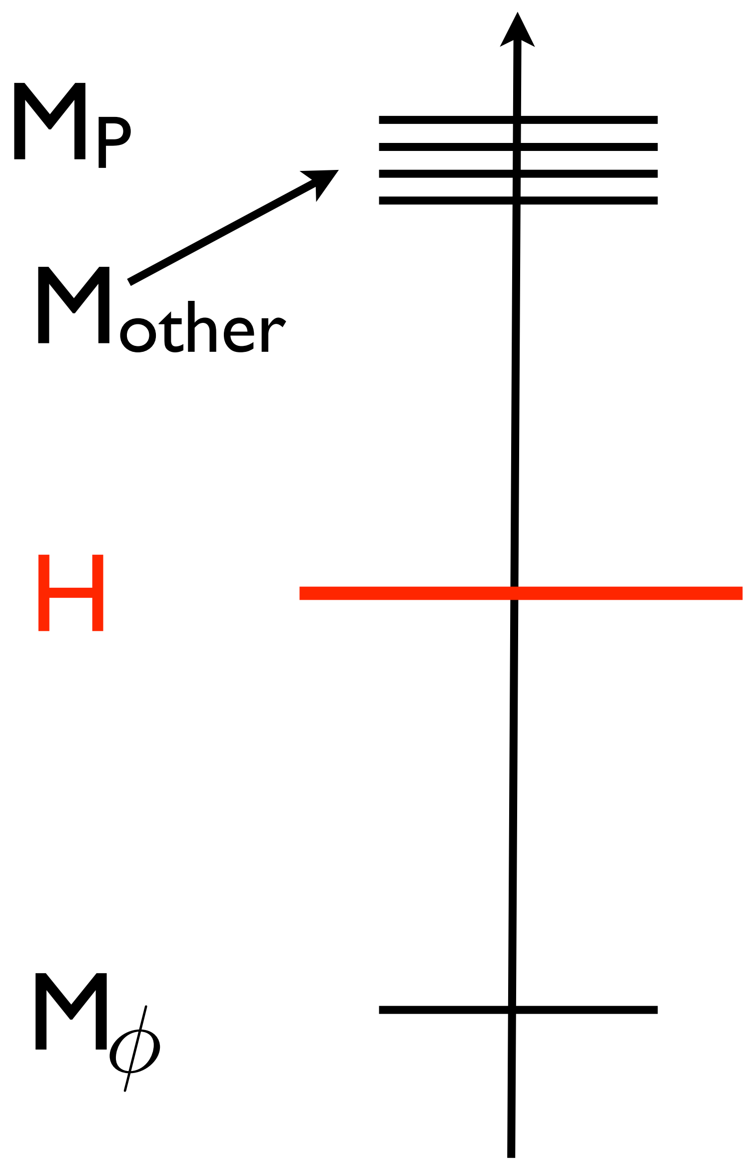
Planck-scale physics does not decouple

Symmetries do not help

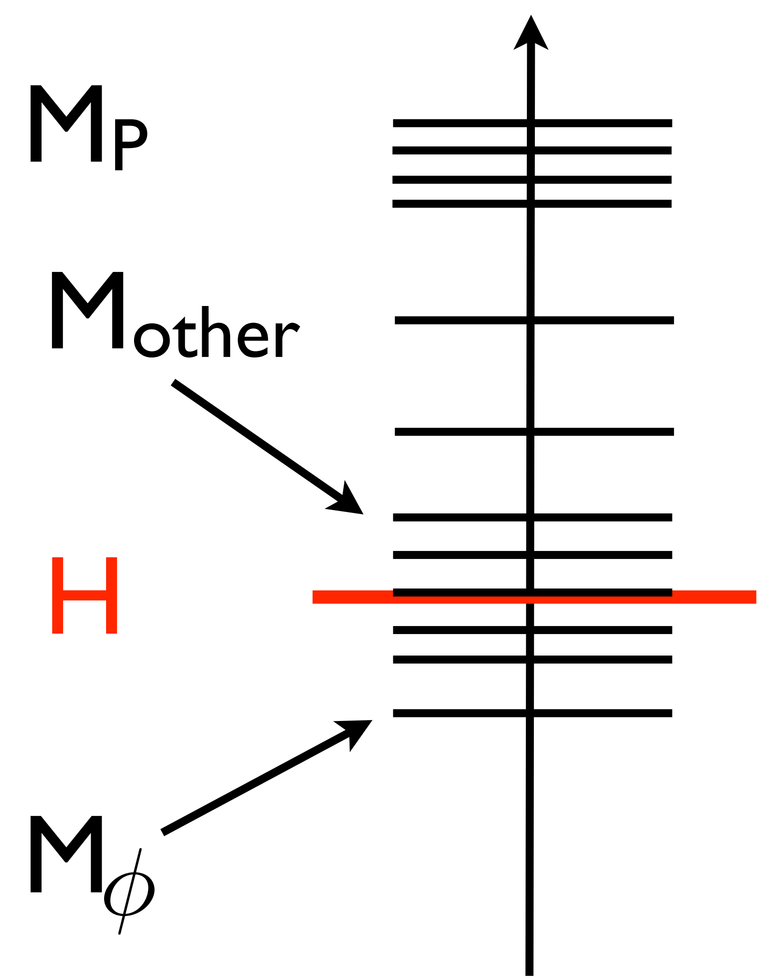
Guidance from UV complete theories

Supergravity, string theory: many degrees of freedom

Hope: light inflaton, Planck-mass dofs



Find: masses of all kinds



Guidance from UV complete theories

Supergravity, string theory: many degrees of freedom

<u>Hope</u>: light inflaton, Planck-mass dofs

<u>Find</u>: masses of all kinds

M_P

M_m

H

M_ϕ

Multiple degrees of freedom

Steep potentials

Large couplings

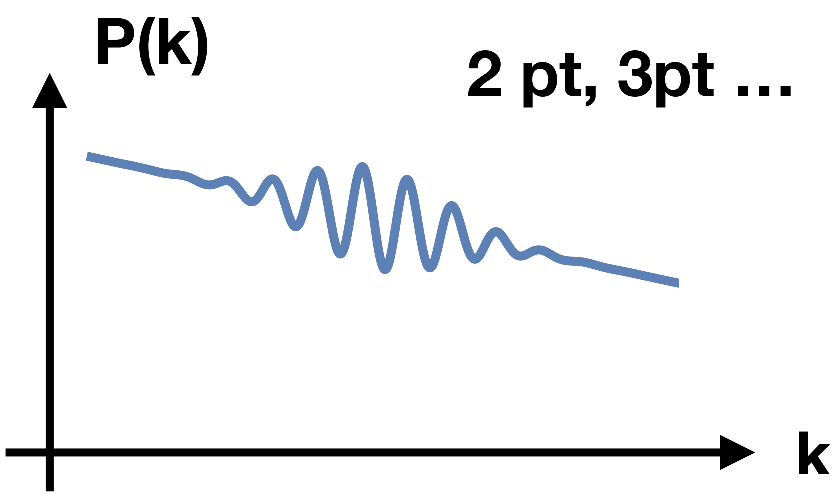
How does simplicity of data emerge from complicated UV theories?

Looking for new physics

- Single-field slow-roll: at best emergent approximate description
- Cosmologists seek deviations to it in motivated manner

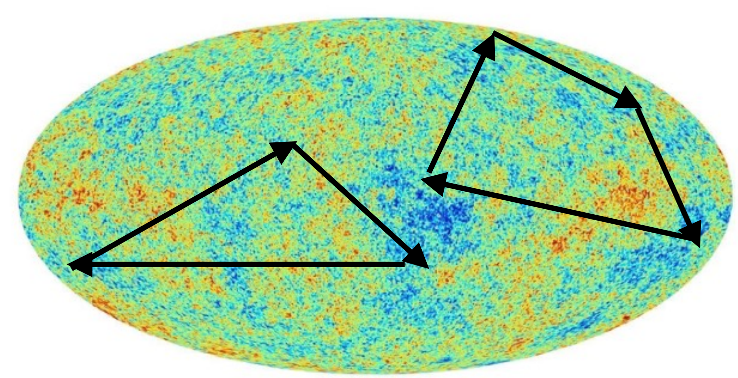
Primordial features

Primordial non-Gaussianities



Crucial insight into physics of inflation

Extensively studied for CMB, LSS, with interesting constraints



3pt, 4 pt …

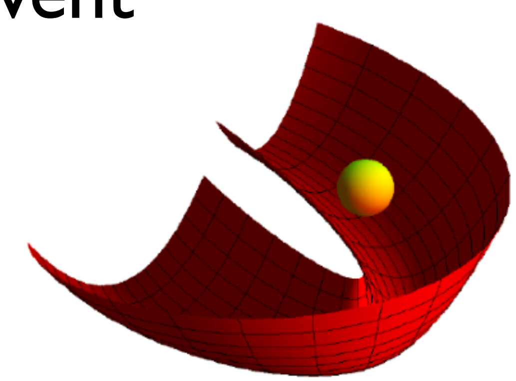
Primordial features

Sharp feature

$$\frac{\mathcal{P}_\zeta(k)}{\mathcal{P}_{\rm env}(k)} = \left[1 + A_{\rm lin}\cos\left(\omega_{\rm lin}k + \varphi_{\rm lin}\right)\right]$$

Localized event

step in potential
turn in field space ...

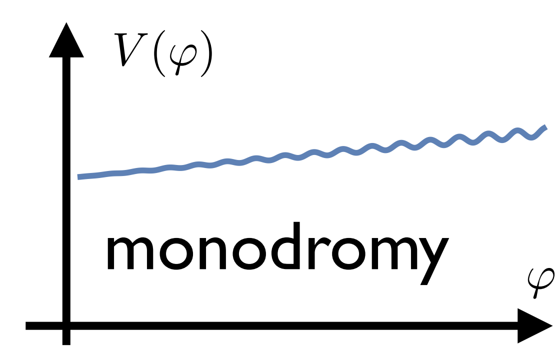


Breaking of
time translation invariance

Resonant feature

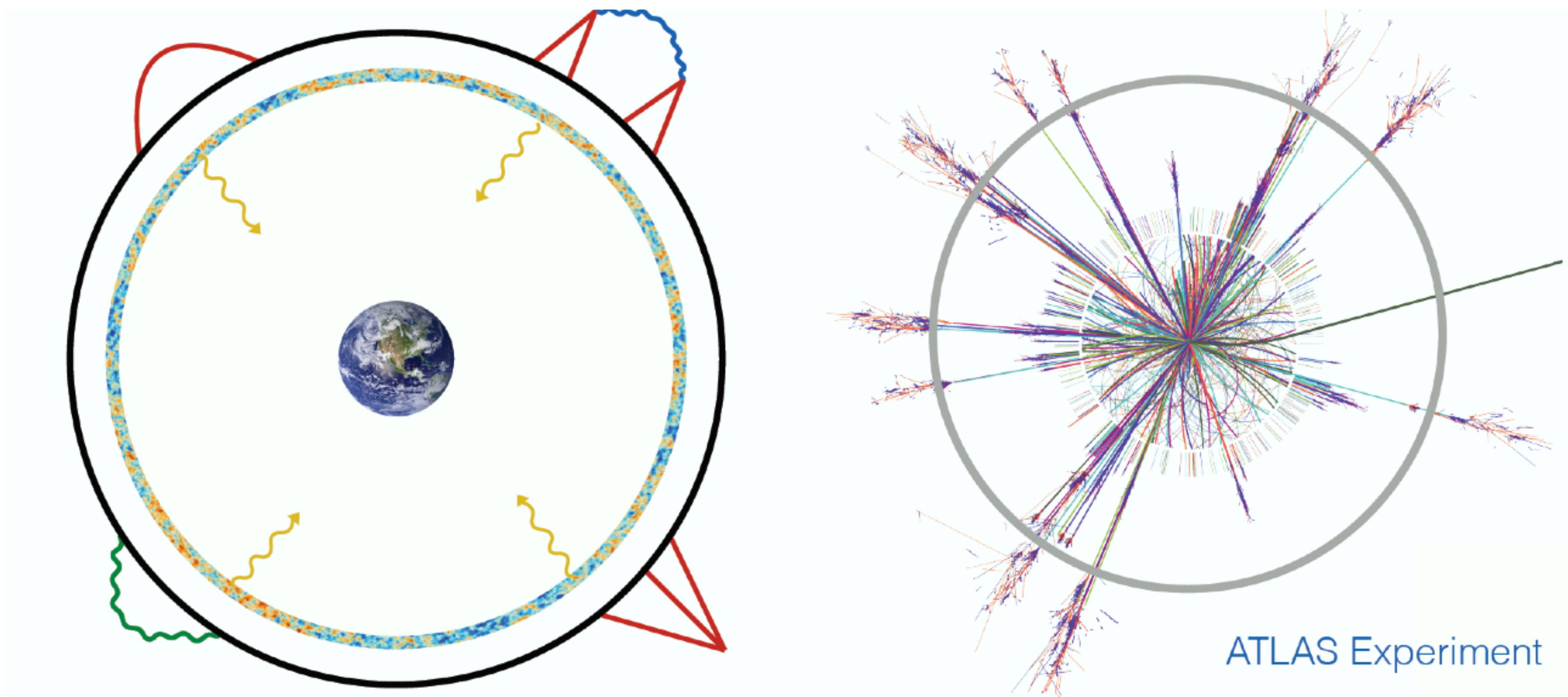
$$\left[1 + A_{\rm log}\cos\left(\omega_{\rm log}\log(k/k_\star) + \varphi_{\rm log}\right)\right]$$

Resonance btw
background
oscillations and
quantum modes
oscillations

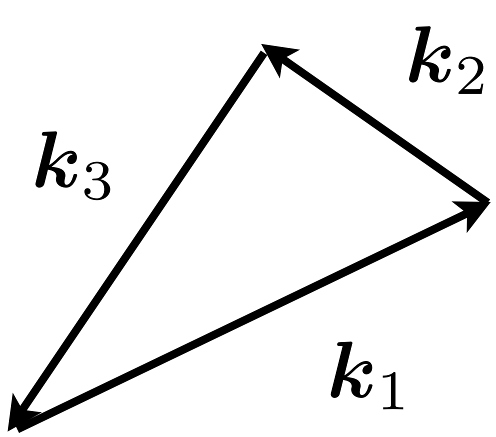


Primordial non-Gaussianities: Inflation as a collider

Higher-order correlators: beyond free fields



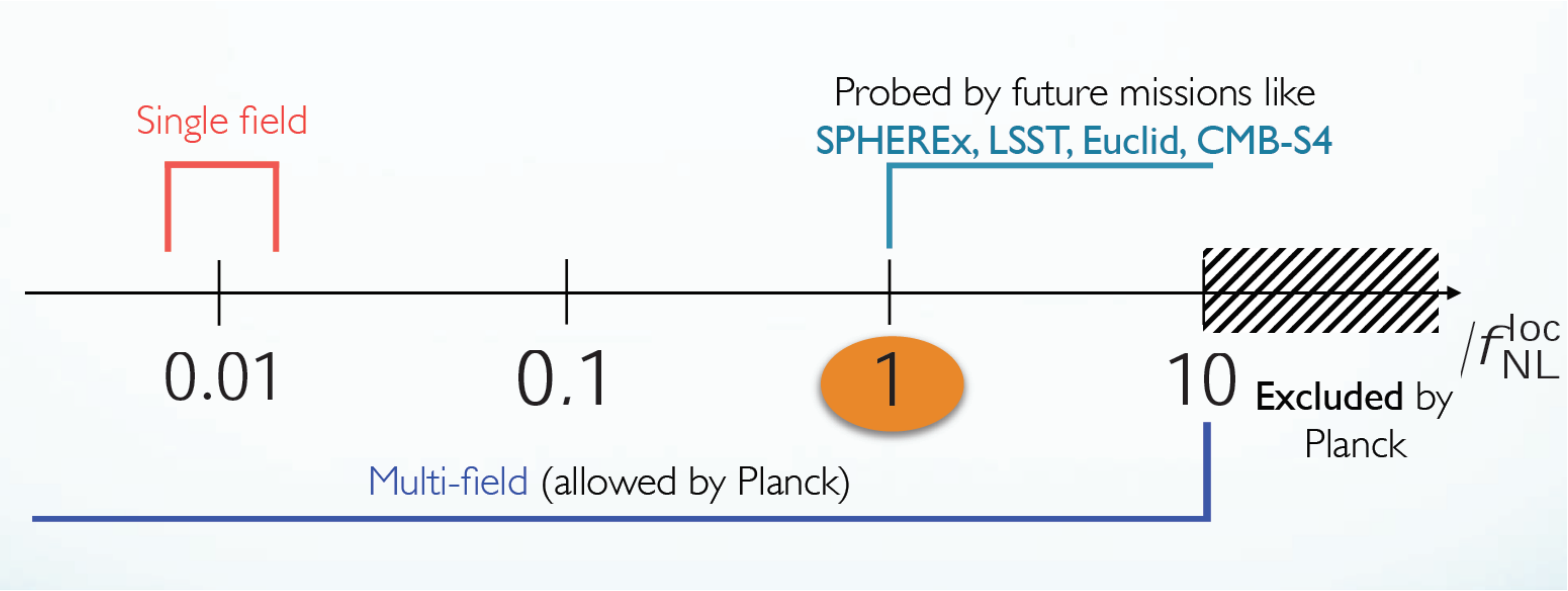
bispectrum (3 pt function)



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

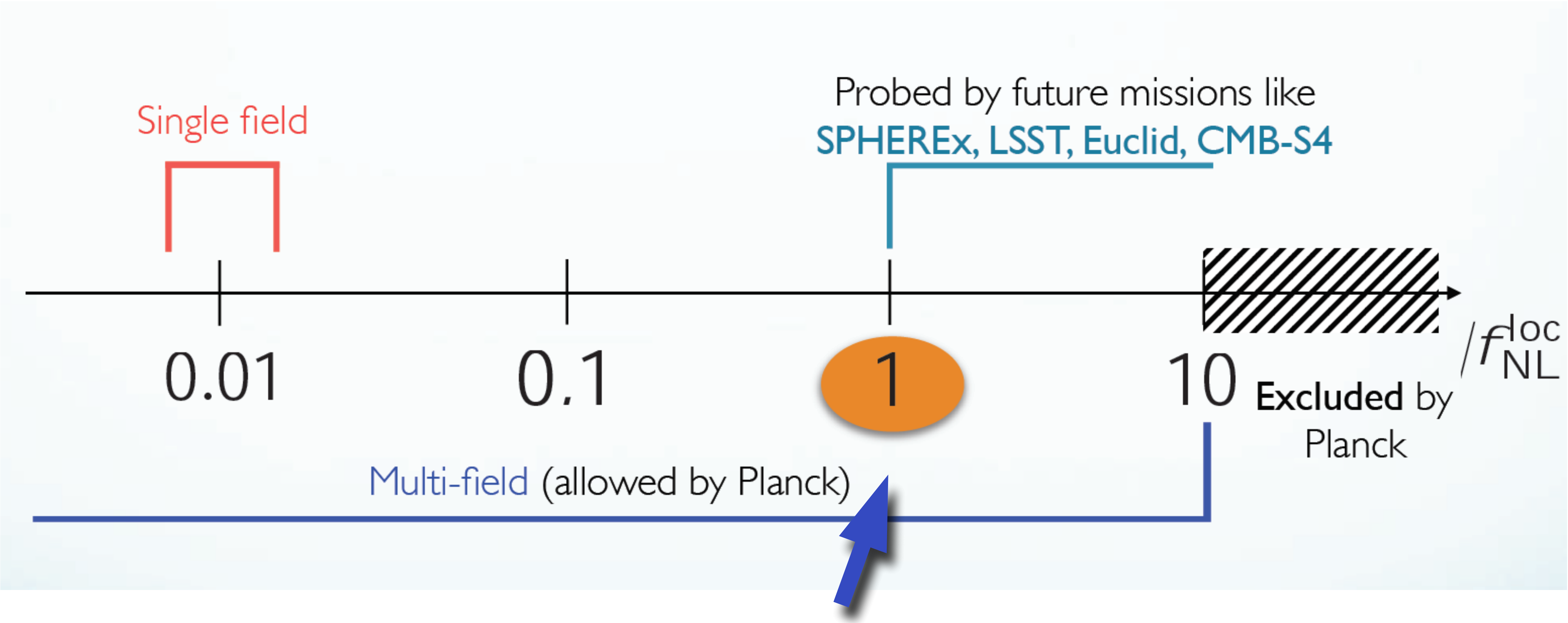
Significance of local shape:
not possible in single-clock inflation

Prospects

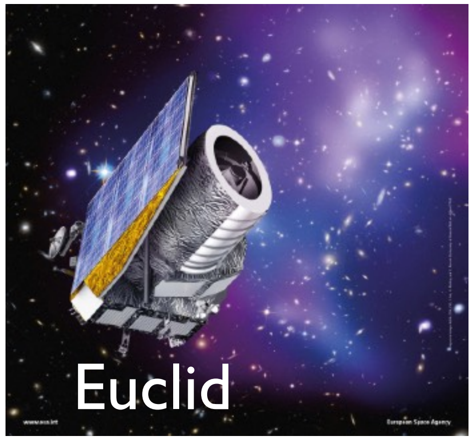


Probed by future missions like
SPHEREx, LSST, Euclid, CMB-S4
Single field
0.01
0.1
1
10
f_{NL}^{loc}
Excluded by Planck
Multi-field (allowed by Planck)

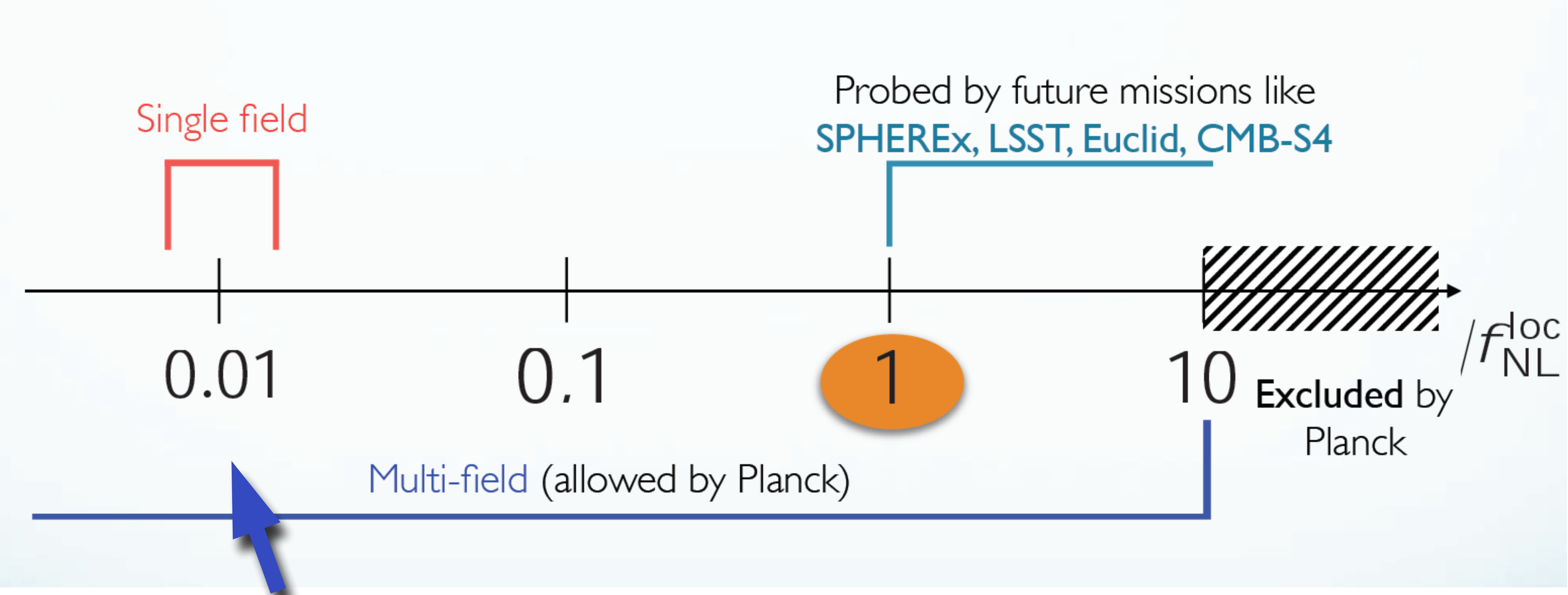
Prospects

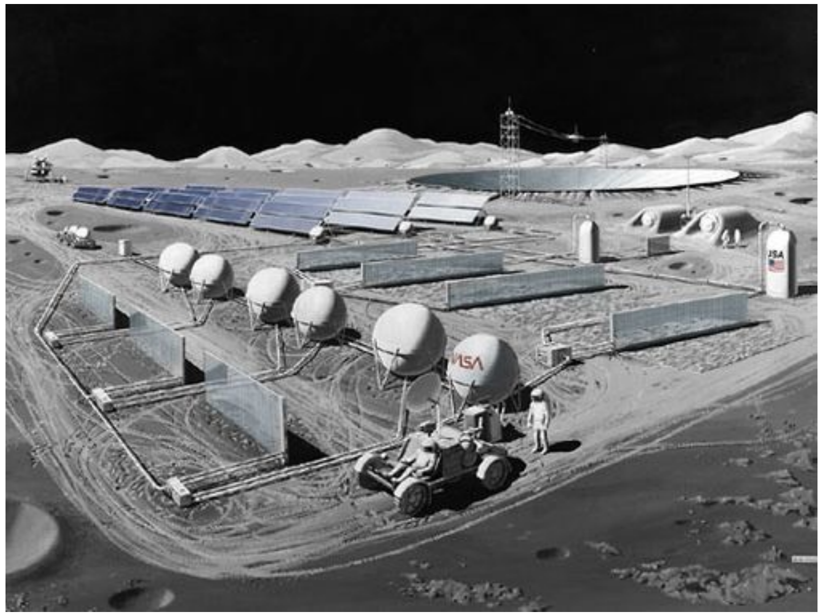


Huge efforts to reach this sensitivity
with large-scale structure surveys
and scale-dependent bias



Prospects





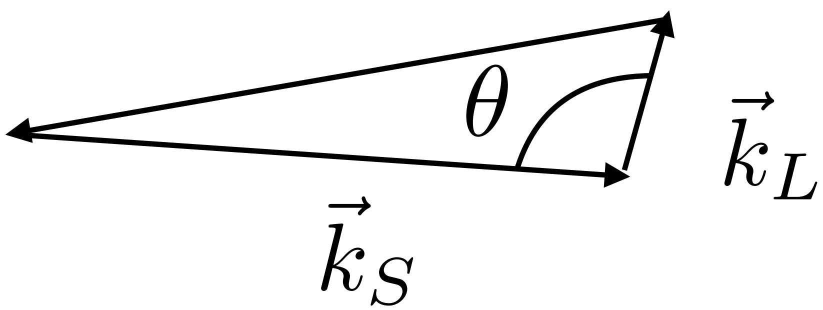
21cm emission from hydrogen clouds during dark ages

radio-astronomy

from the far side of the moon!

Cosmological collider physics, aka NGs in soft limits

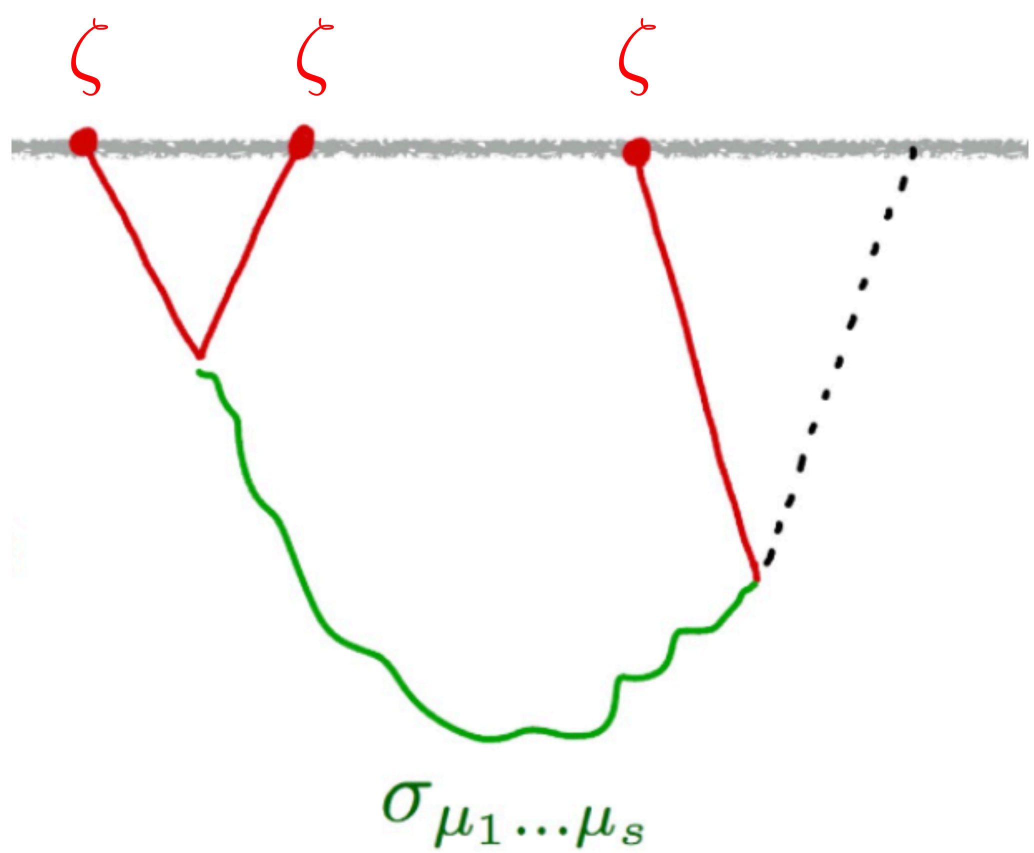
3pt



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

Mass & Spin

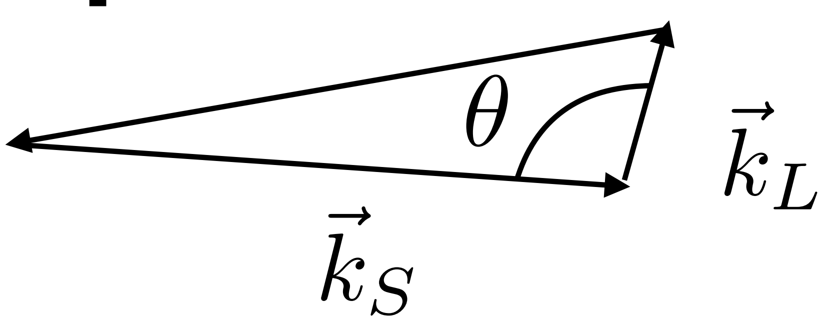
of heavy exchanged particle



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

Cosmological collider physics, aka NGs in soft limits

3pt

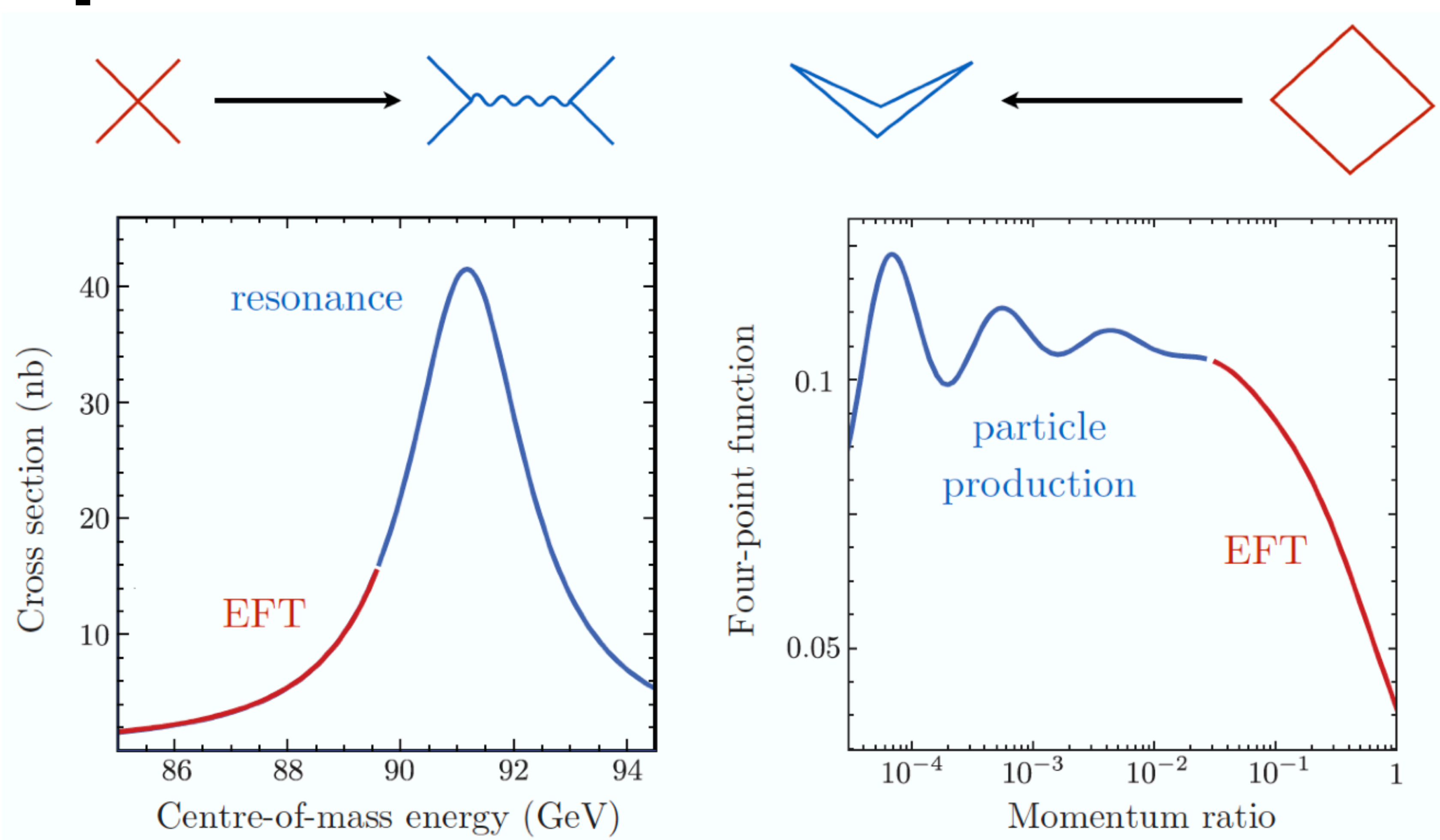


$$\lim_{k_L \to 0} \langle \zeta_{\vec{k}_L} \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \rangle \propto \left(\frac{k_L}{k_S} \right)^{3/2} \cos \left[\frac{M}{H} \ln \left(\frac{k_L}{k_S} \right) + \delta \right] P_S(\cos\theta)$$

Mass & Spin

of heavy exchanged particle

4pt



From 1811.00024

Chen, Wang 2009
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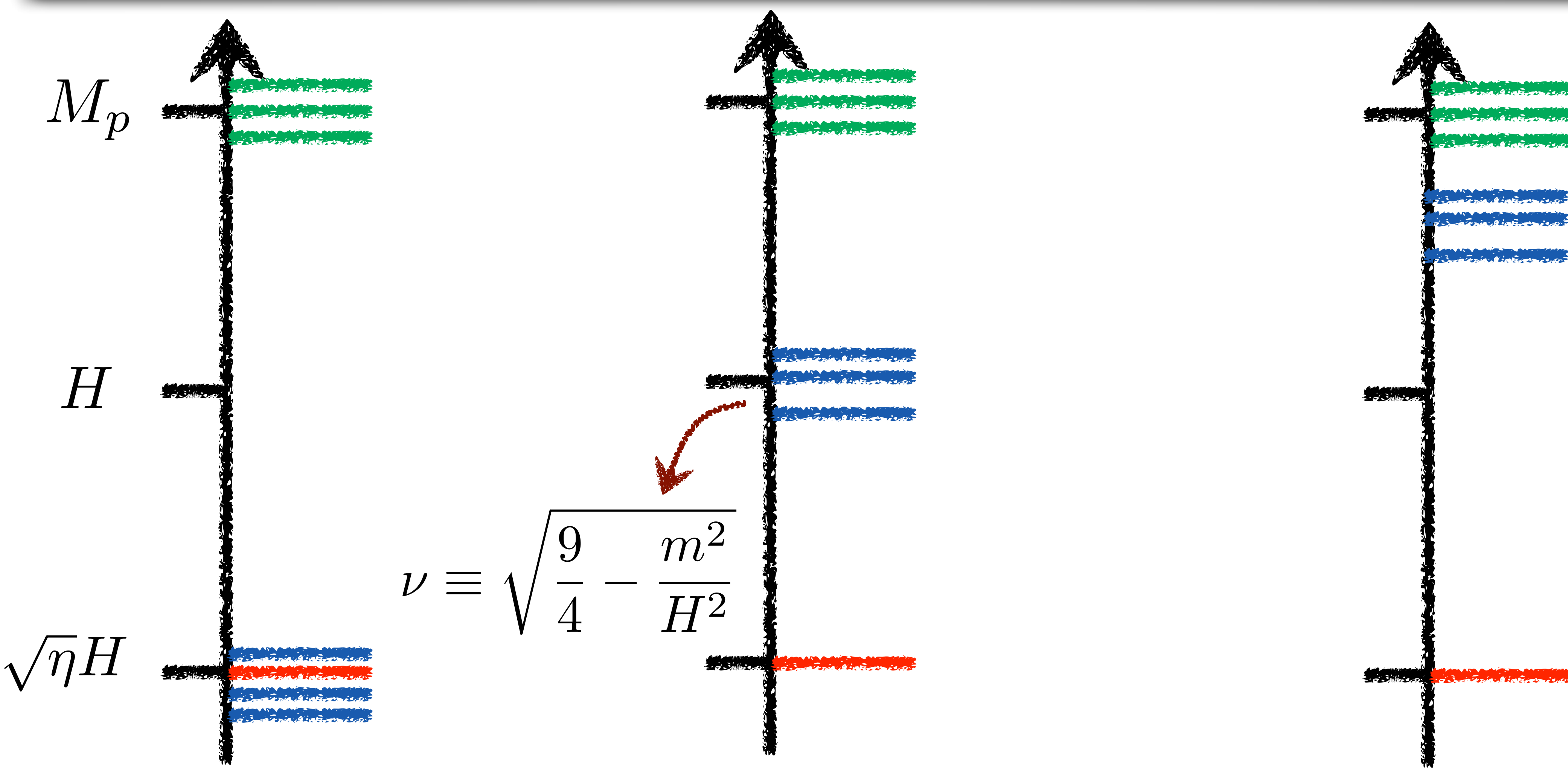
…

Non-Gaussianity as a particle detector

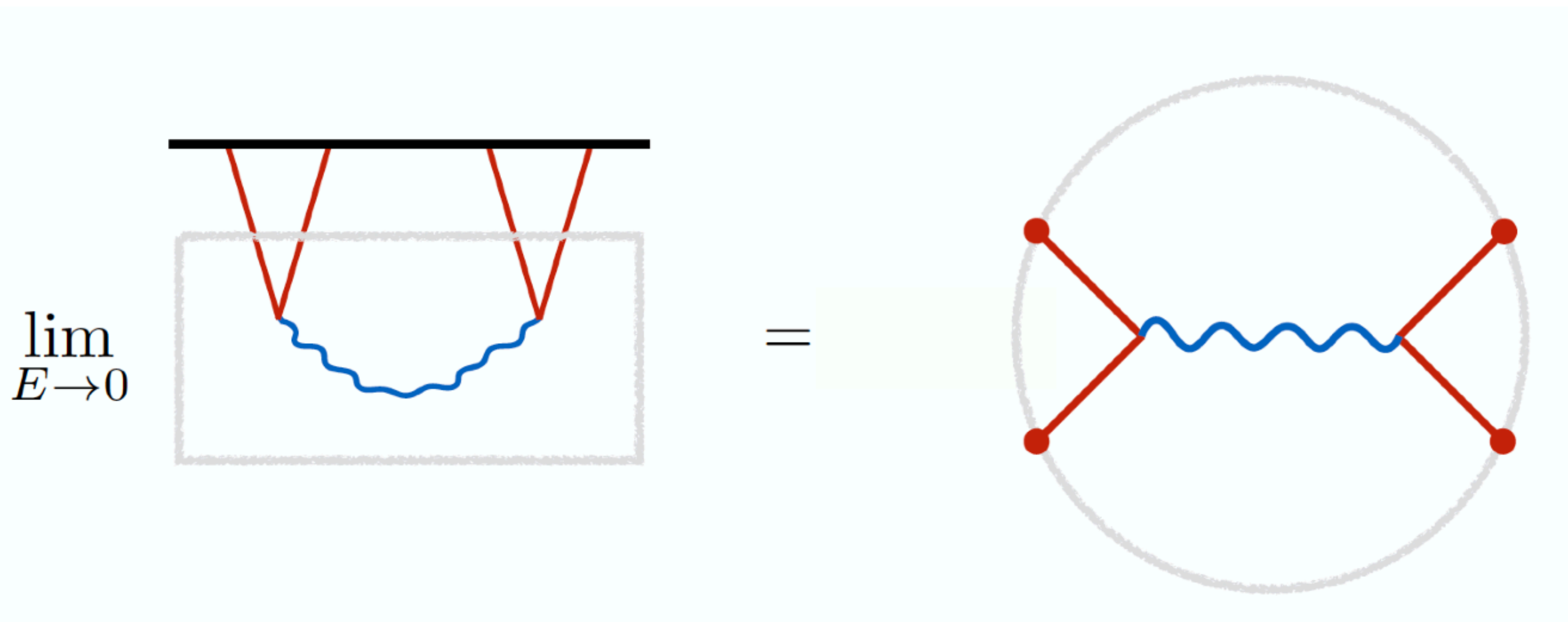
	Light dof	Quasi-single-field	Heavy dof



	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 bootstrap

Scattering amplitudes contained in analytical structures of cosmological correlators

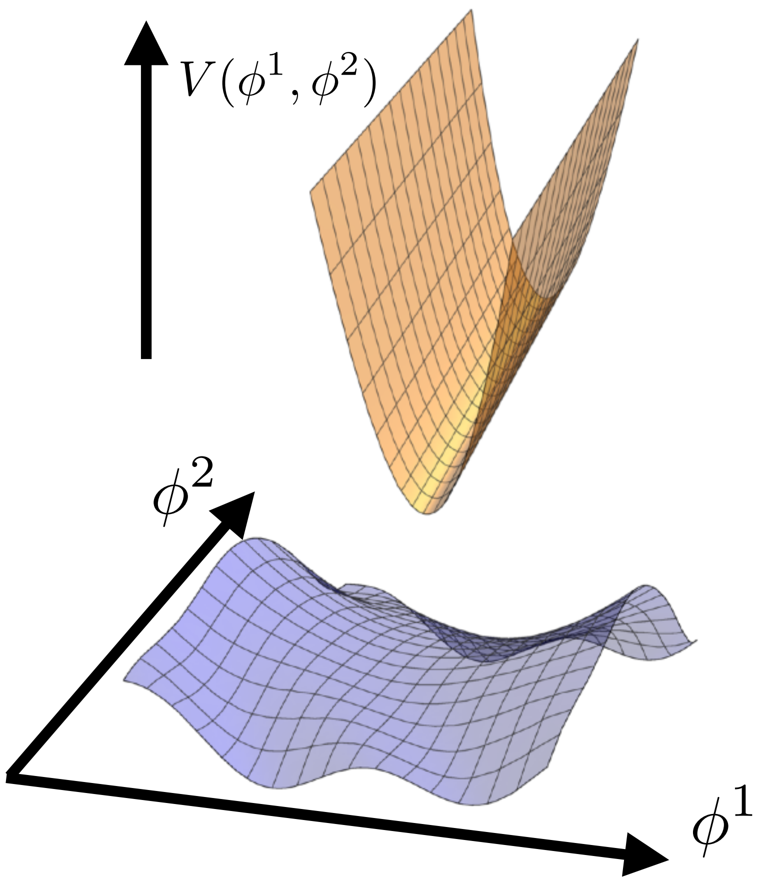


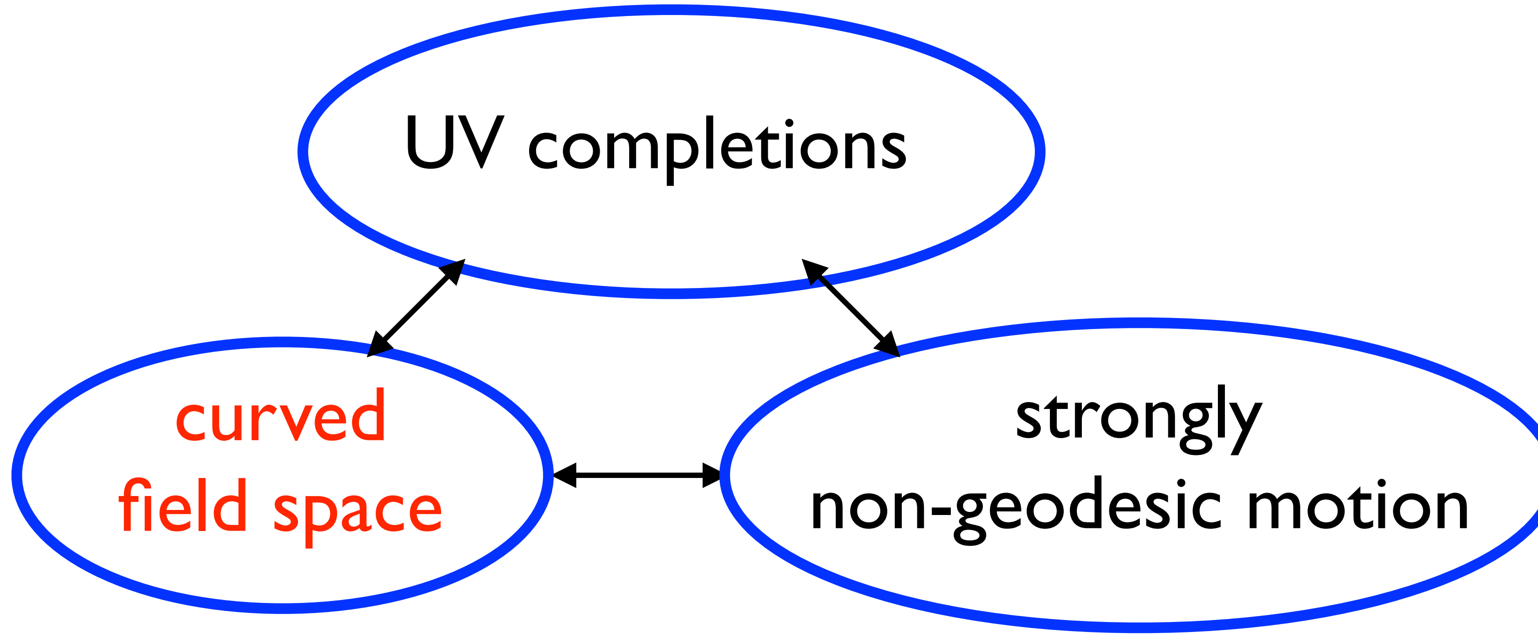
Cosmological correlators constrained and computable from first principles (unitarity, locality, causality)

Cosmological Correlators
7 Sep 2020, 10:00 → 9 Sep 2020, 21:15 Europe/Zurich
CERN

Positivity and the Bootstrap
31 May 2021 to 2 June 2021
CERN
Europe/Zurich timezone

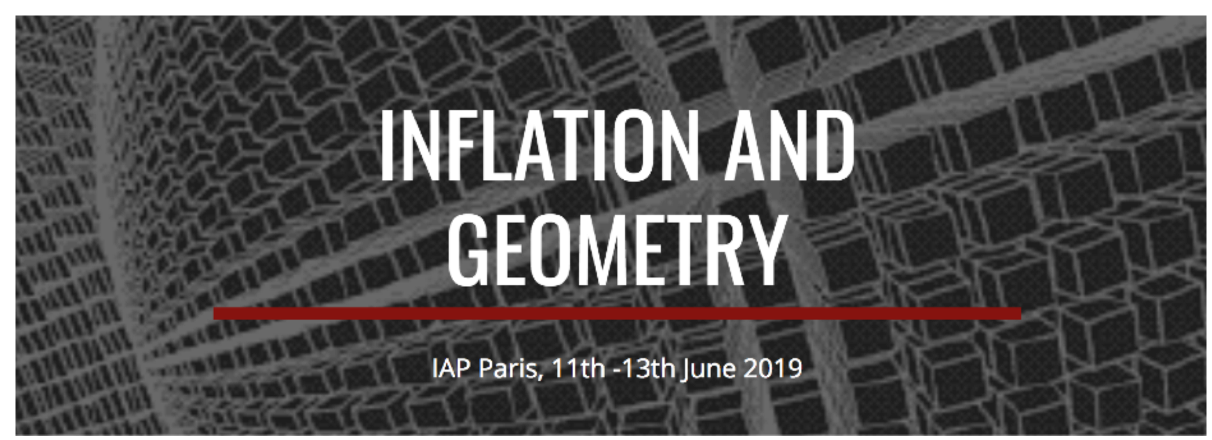
Beyond the potential



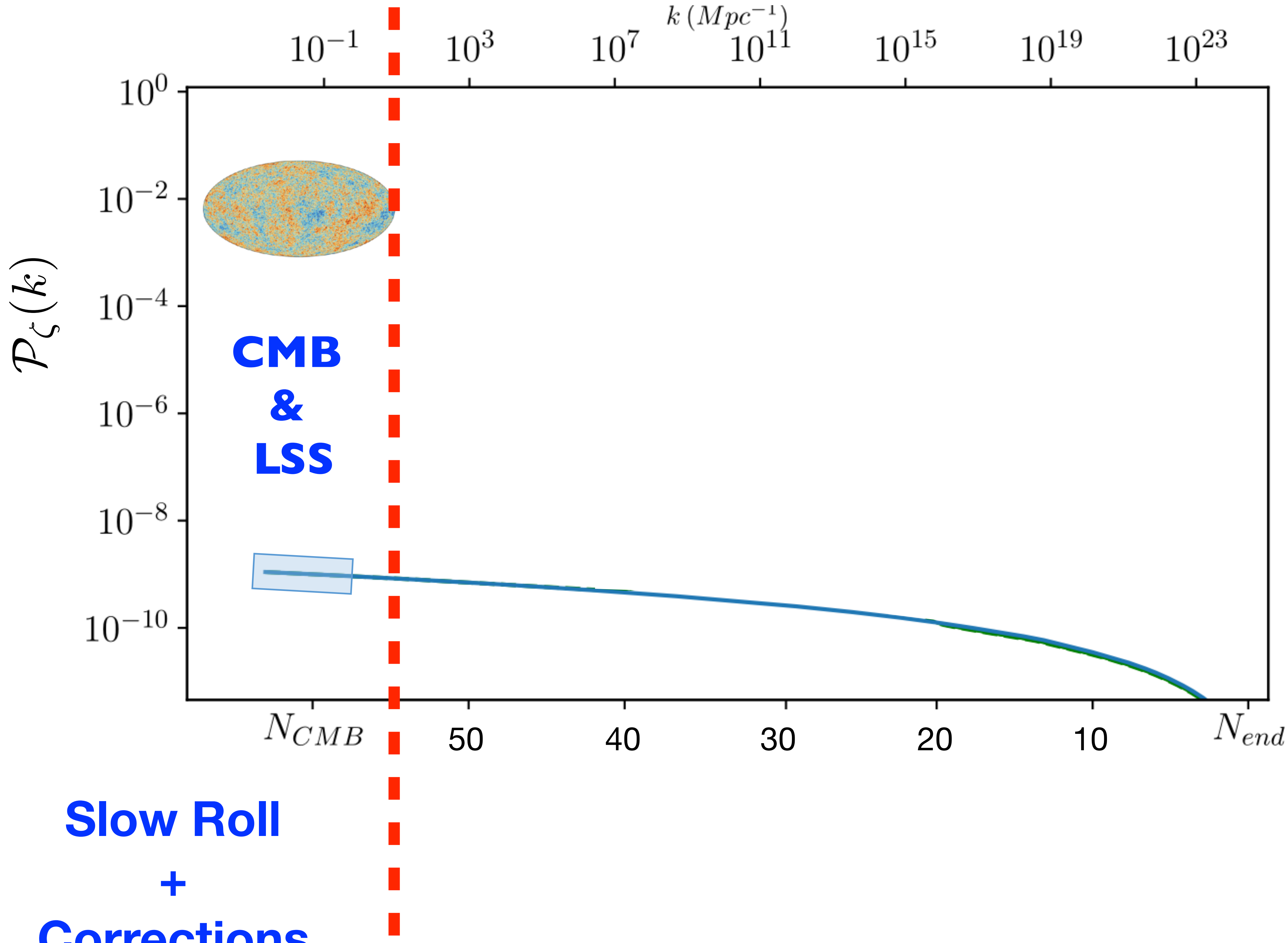


Geometrical destabilization of inflation

Renaux-Petel, Turzynski 2015



Inflation on small scales?



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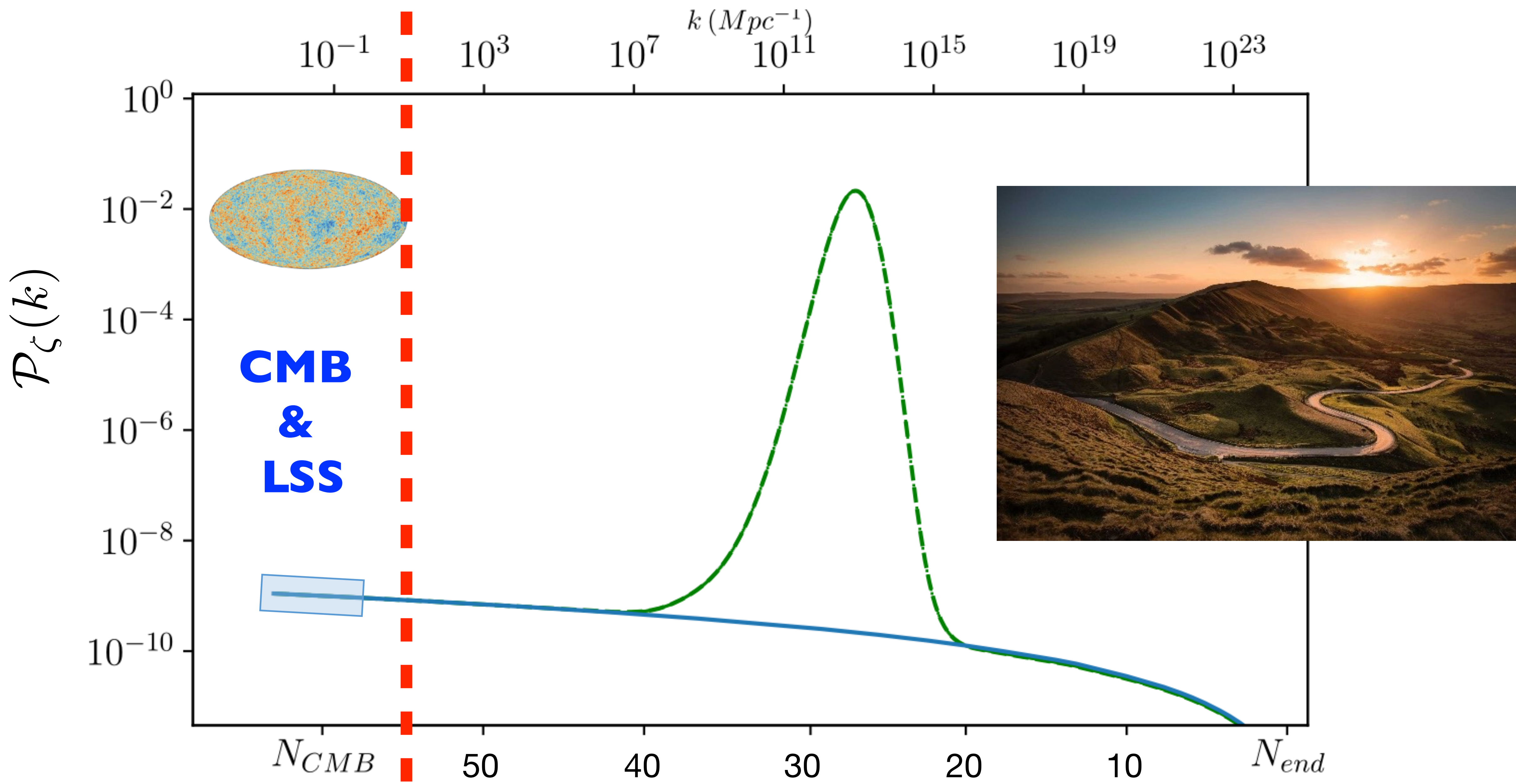


Slow Roll

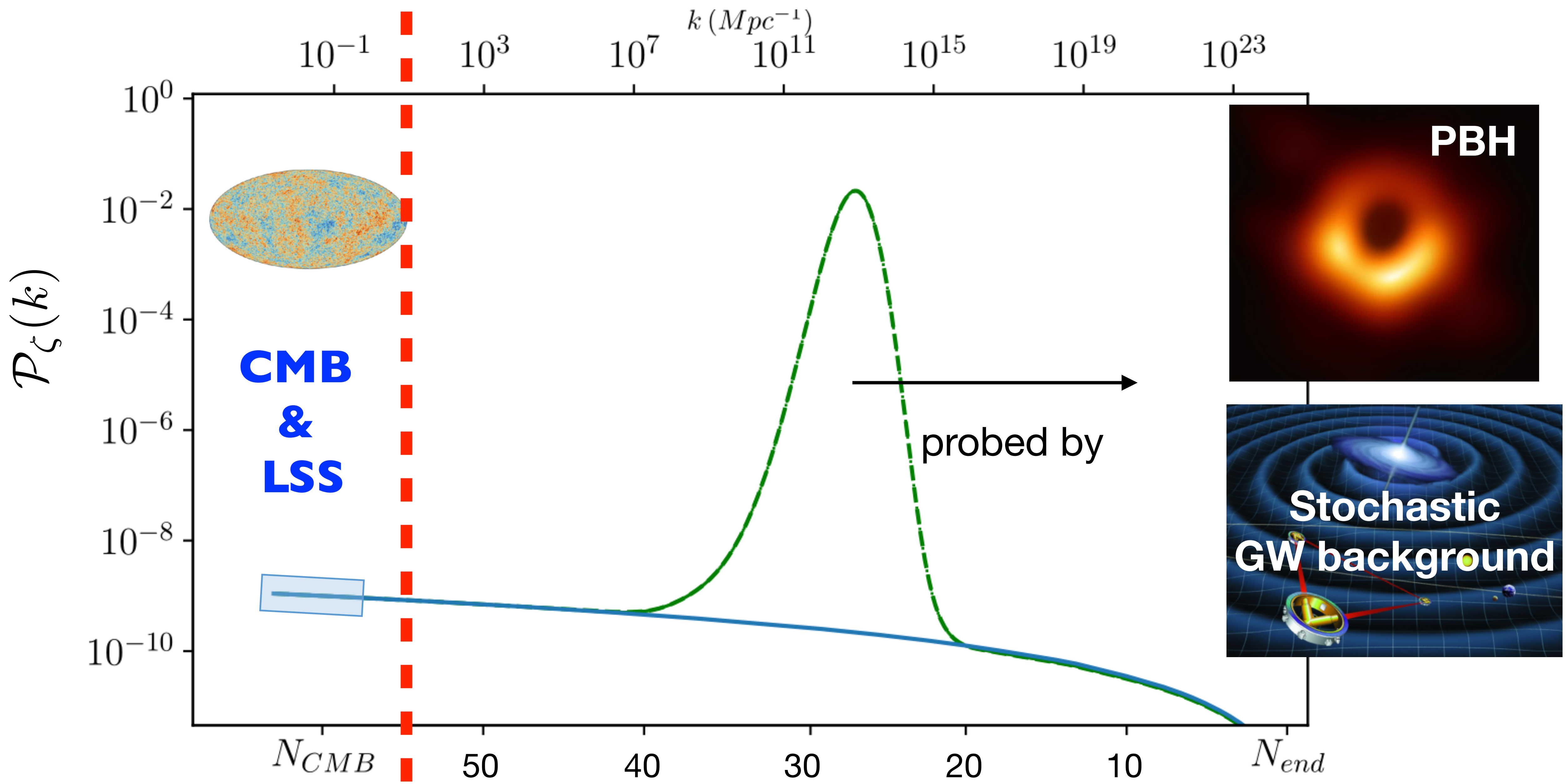
+

Corrections

Drastically different?

Motivated by high-energy embeddings

Inflation on small scales?



Slow Roll
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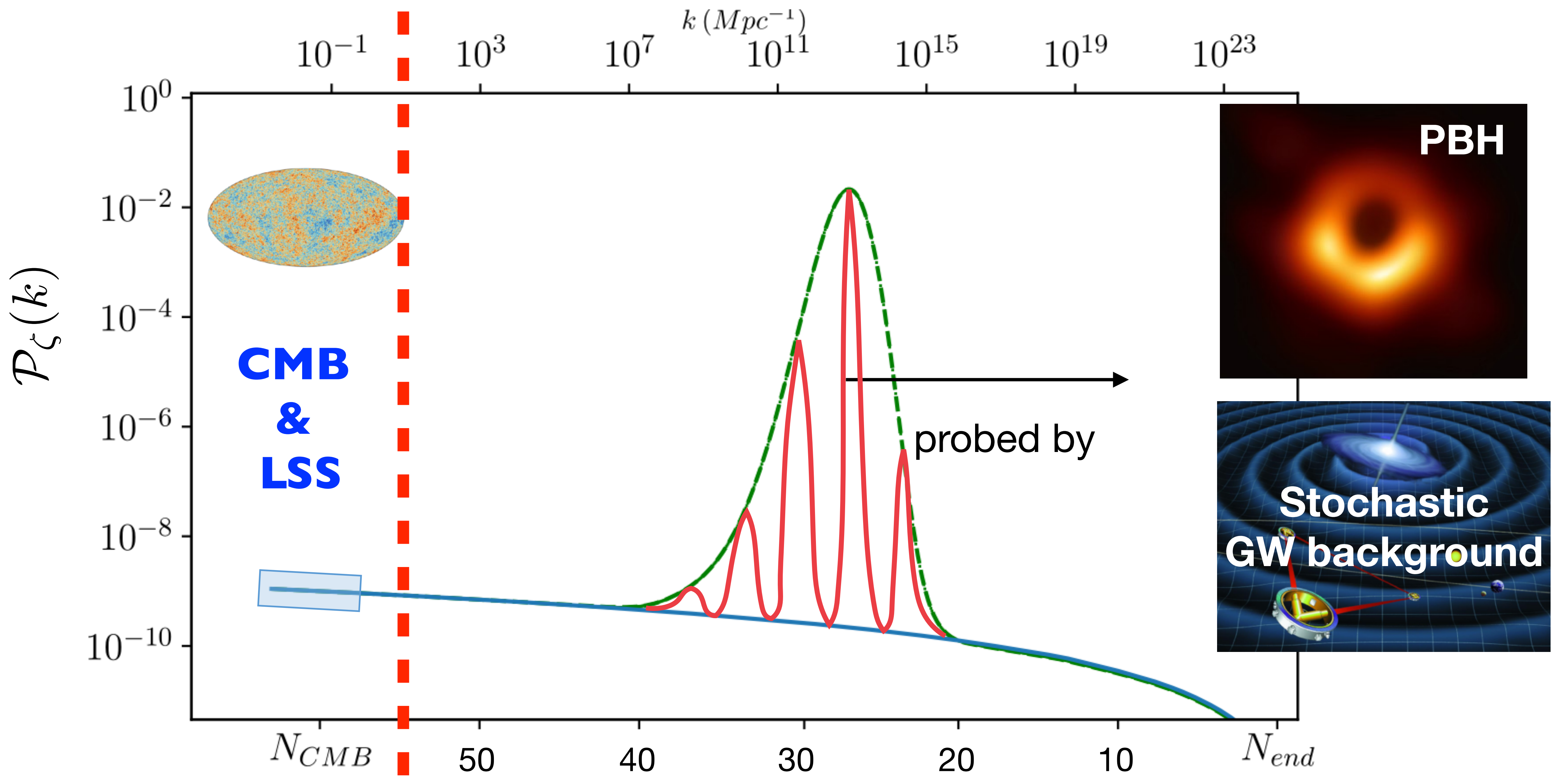
Inflation on small scales?

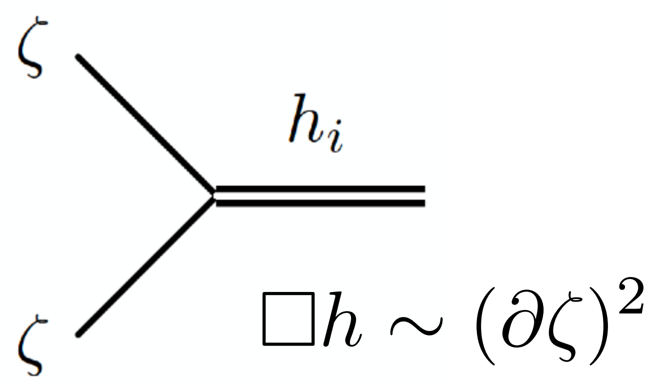


Slow Roll
+
Corrections

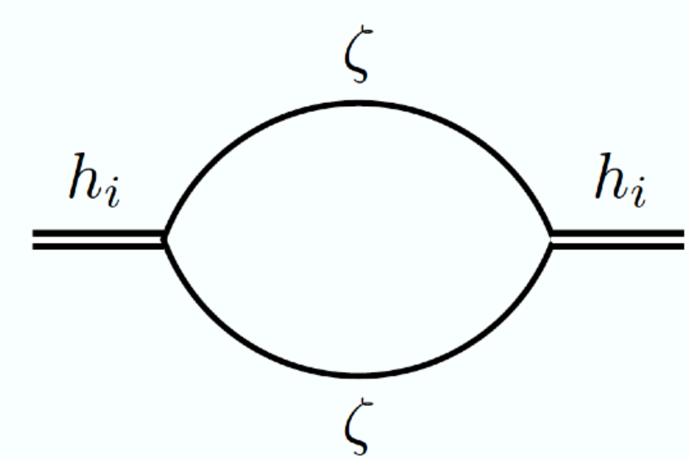
A peak is often associated with oscillations.

Features can be large

Scalar-induced GWs



$\longrightarrow$

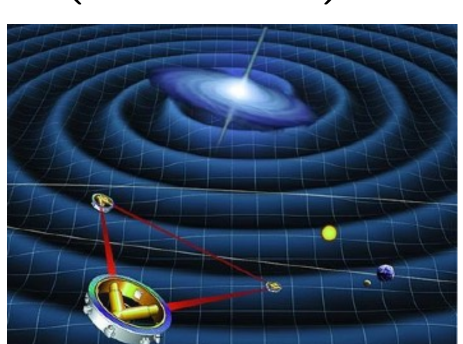


Enhanced $\delta\rho$ $\longrightarrow$ Enhanced GWs at horizon re-entry after inflation

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

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

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



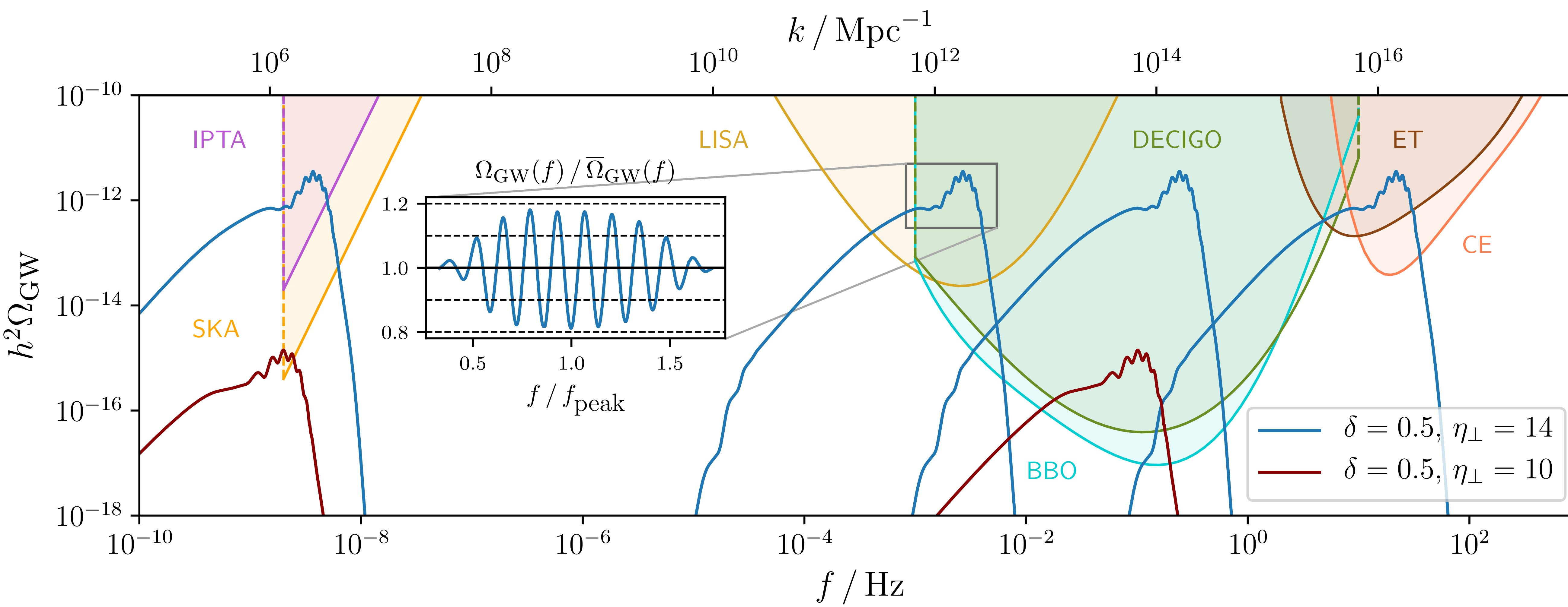
GW observatories probe inflation on small scales

Probing small-scale primordial features

Oscillations in primordial scalar power spectrum → Oscillations in frequency profile of $\Omega_{\rm GW}(f)$

Precious probe of inflation on small scales

Fumagalli, Renaux-Petel, Witkowski (2020,2021)
Braglia, Chen, Hazra (2020)



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

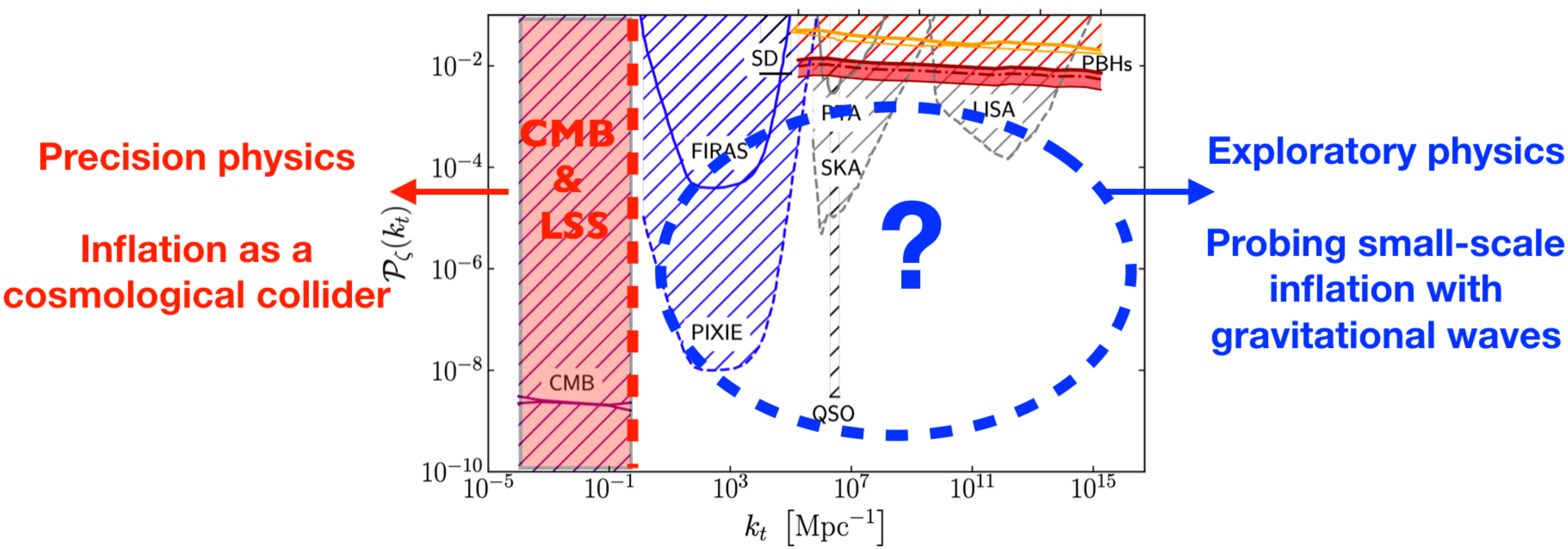
Frequency profile

Chirality

Non-Gaussianity/correlation with other probes

SGWB anisotropies

Many reasons for IN2P3 to support early-universe theorists



From precision experiments and
formal developments close to particle physics
to new observational windows