Probing cosmological inflation

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33rd Rencontres de Blois
May 27th 2022

European Research Council
Established by the European Commission

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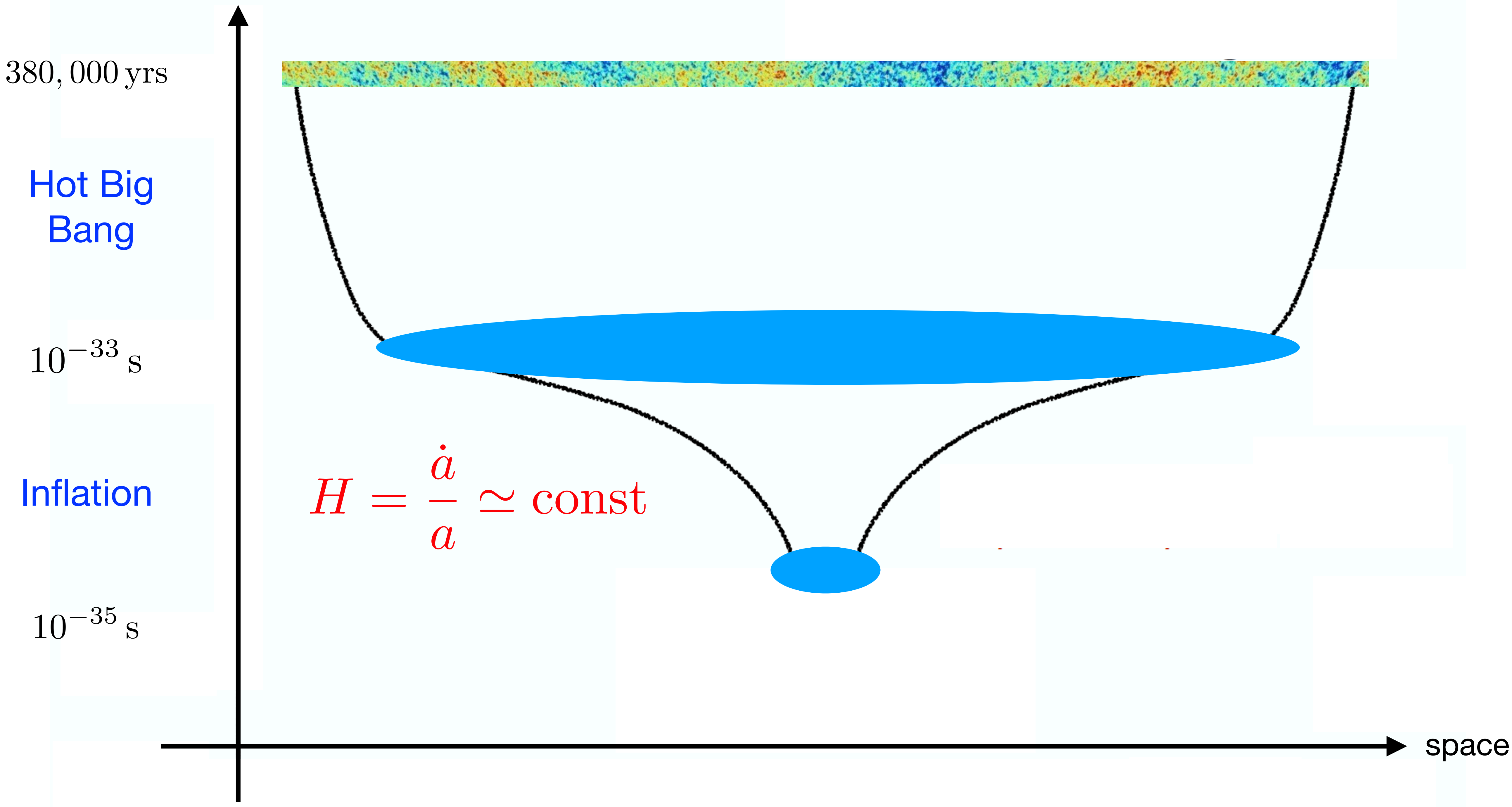
Inflation: a giant microscope

a tiny patch of space becomes the entire observable universe



Inflation: a giant microscope

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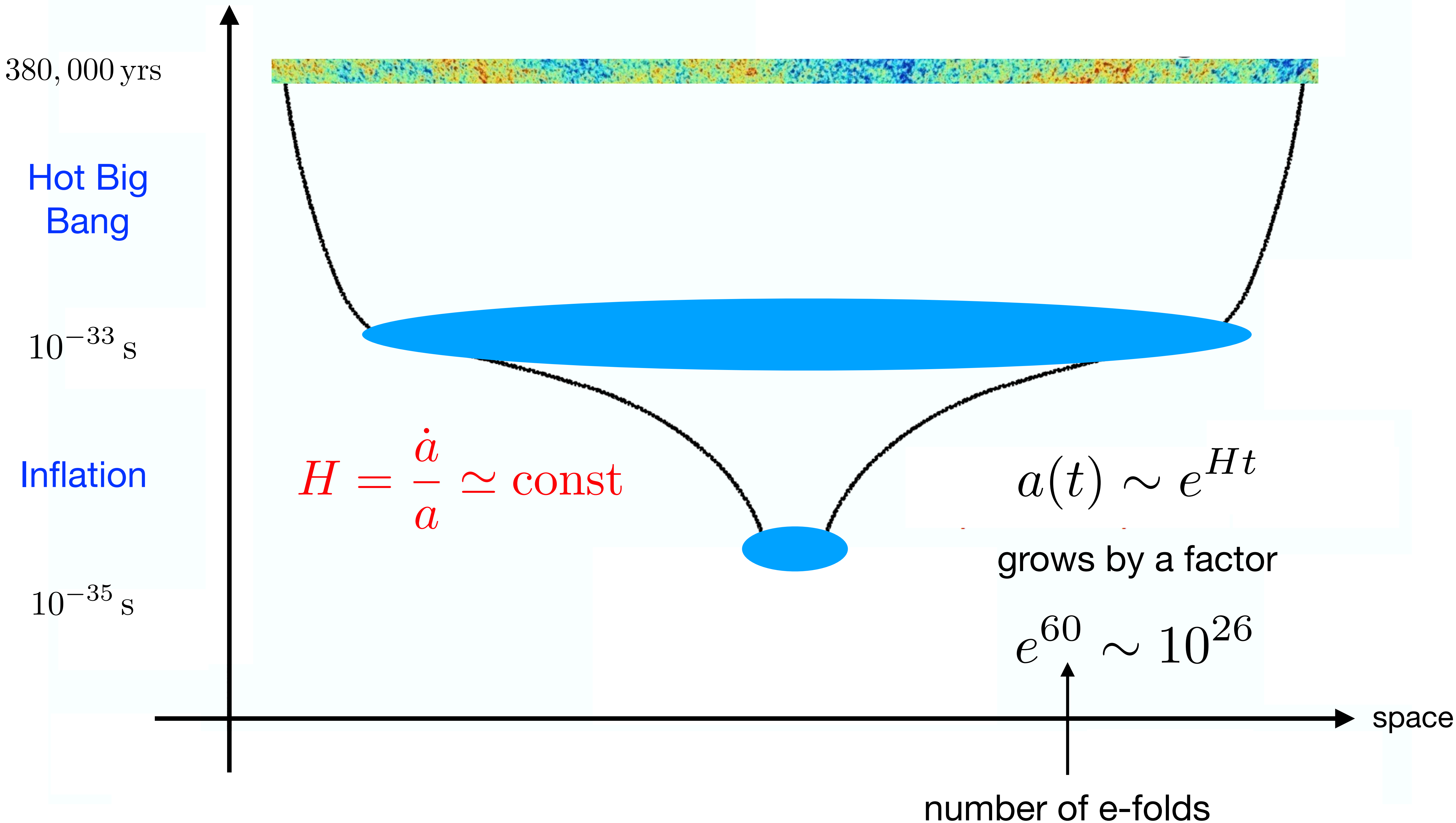
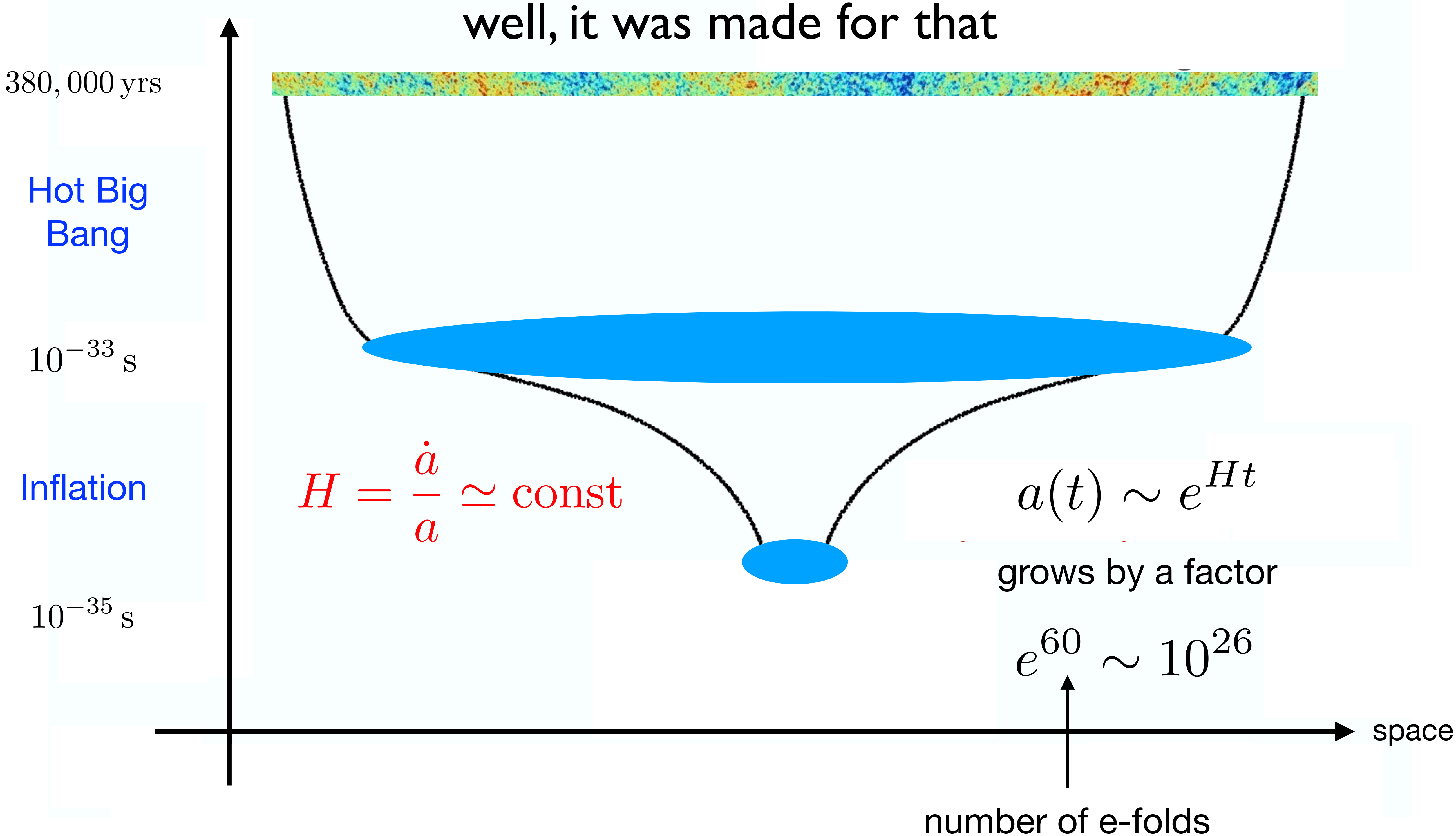


Inflation: a giant microscope

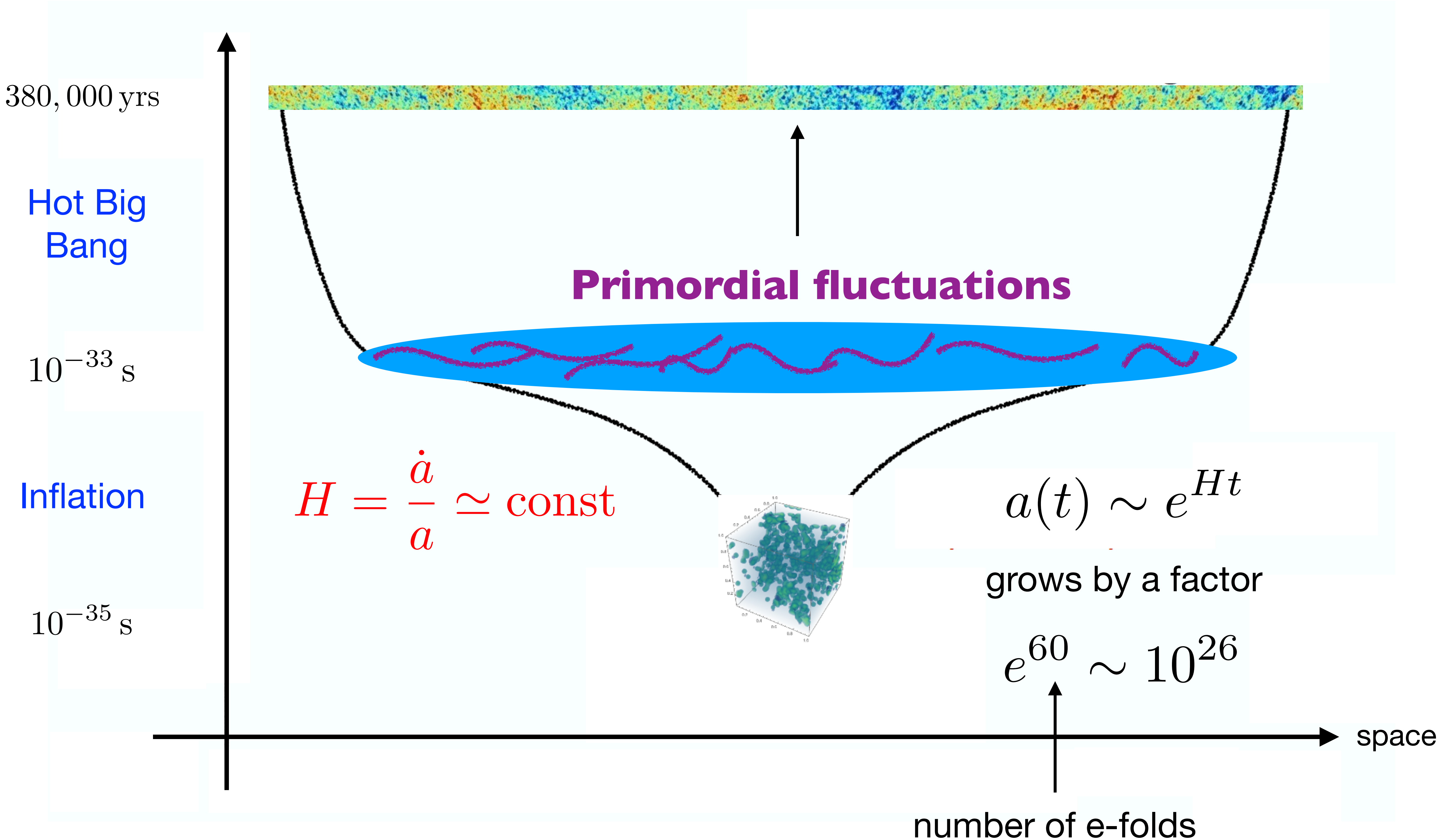
this explains why the universe is smooth (horizon, flatness problems)

well, it was made for that



Inflation: a giant microscope

vacuum quantum fluctuations stretched to cosmological scales



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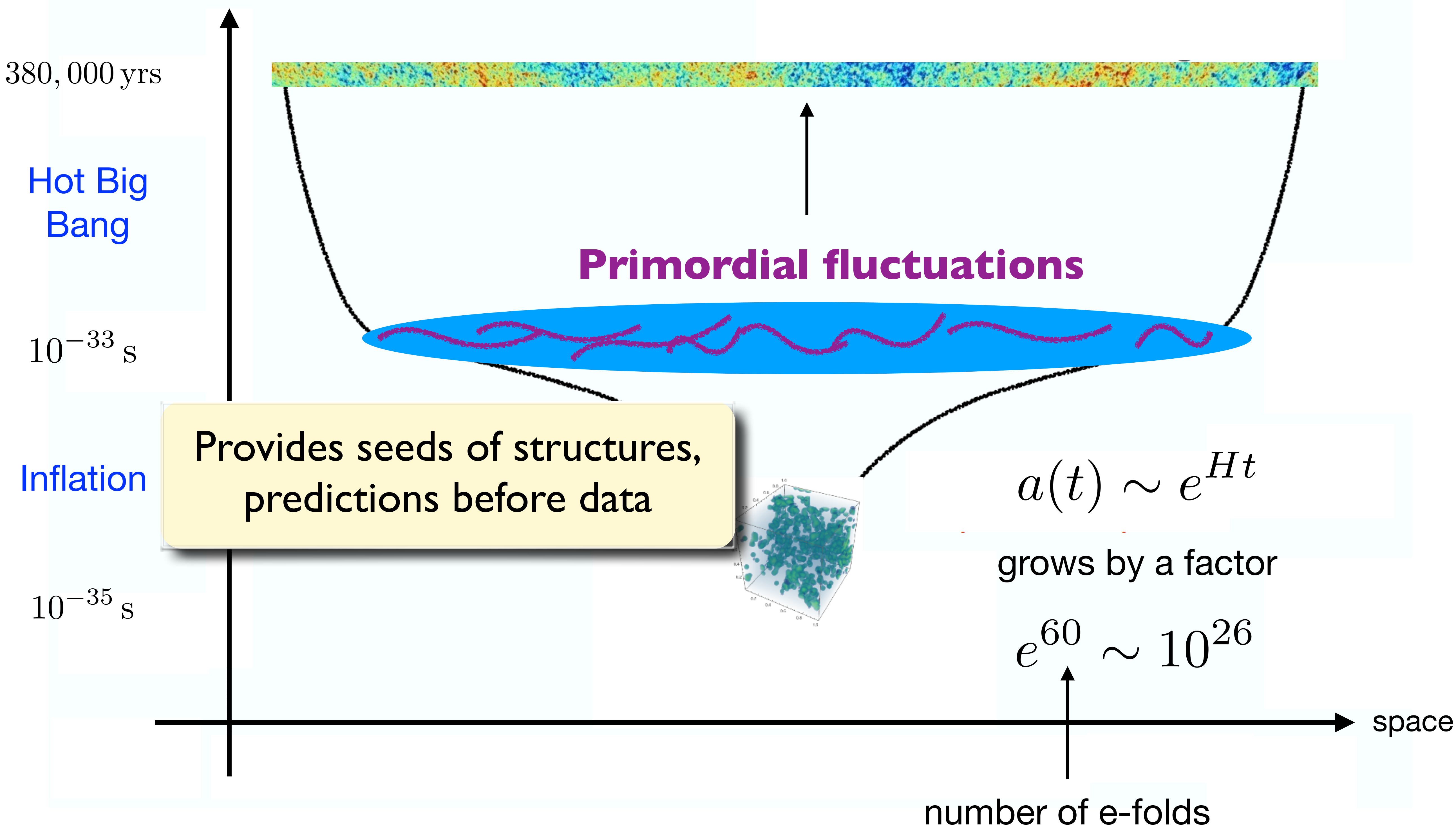
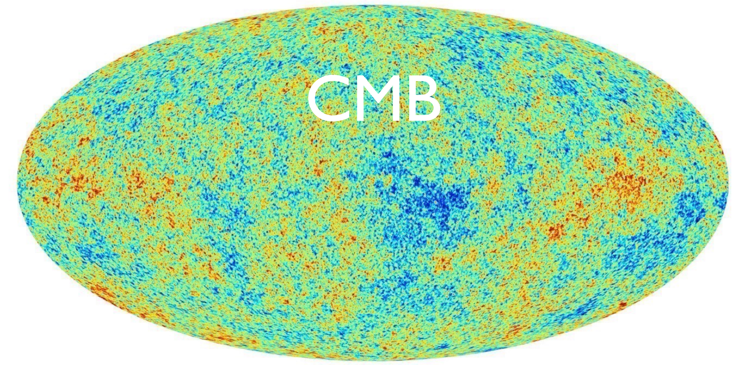
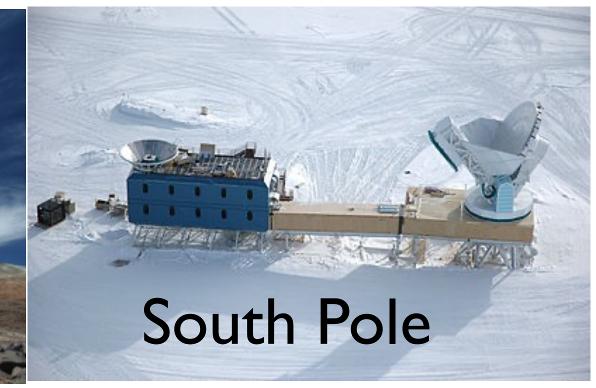
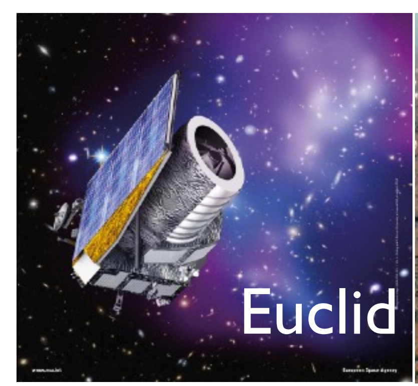


Quantum + gravitational physics, tested observationally!

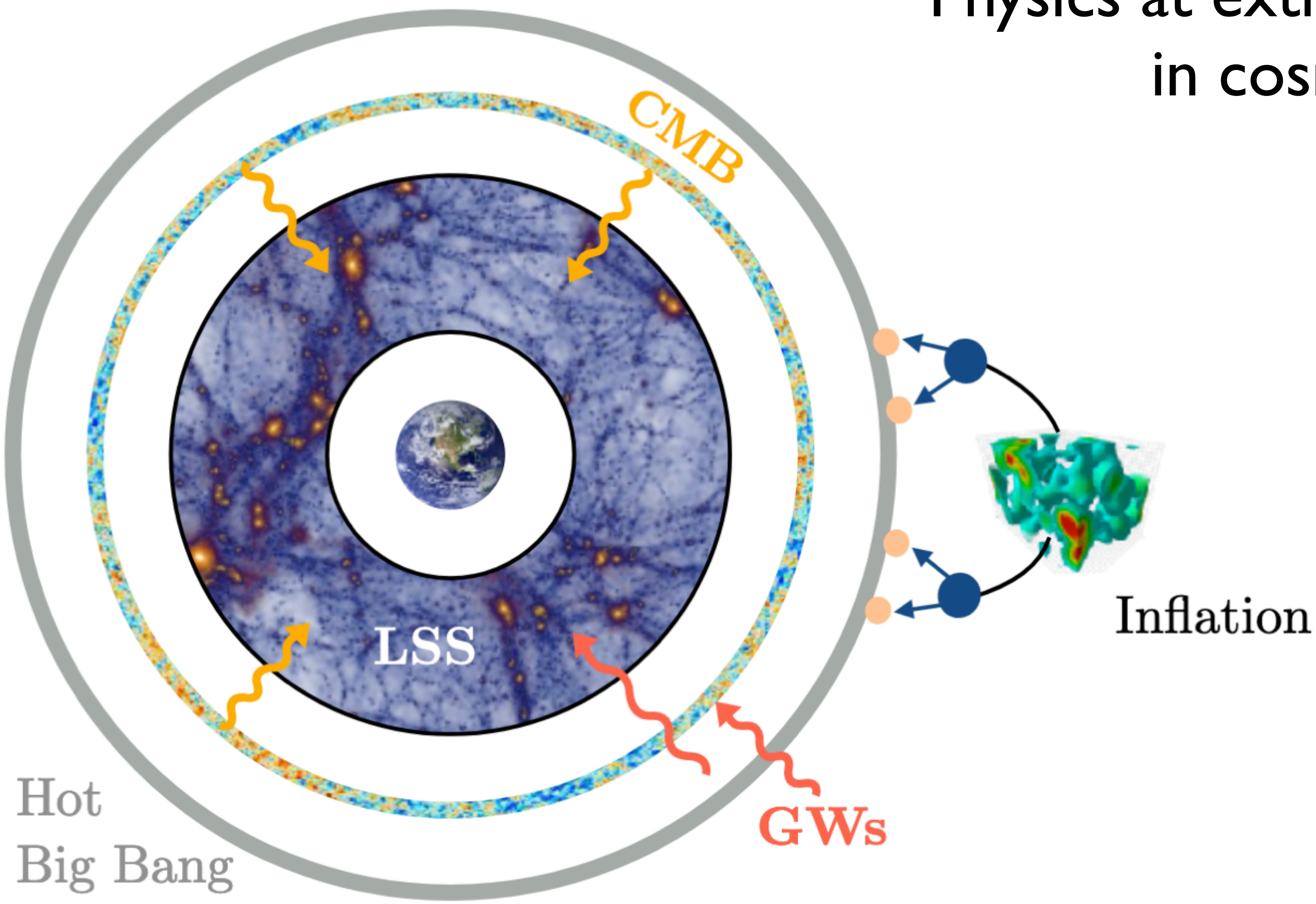
+







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)

I Why not just single-field slow roll?

II Inflation as a cosmological collider

III The dark era of inflation

I Why not just single-field slow roll?

Inflation is sensitive to physics at Planck scale

II Inflation as a cosmological collider

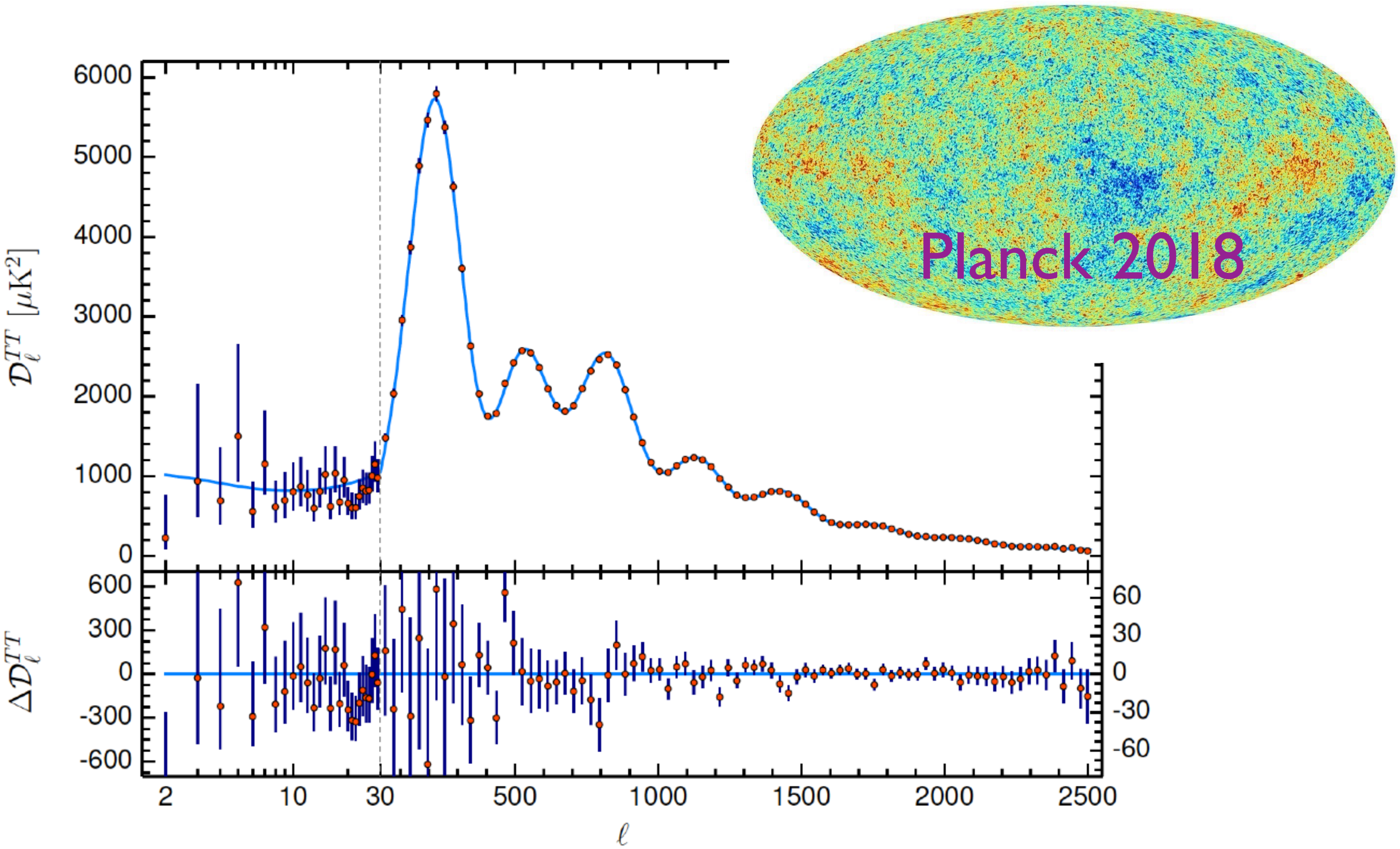
Detecting particles 1 billion times more
massive than with colliders on Earth!

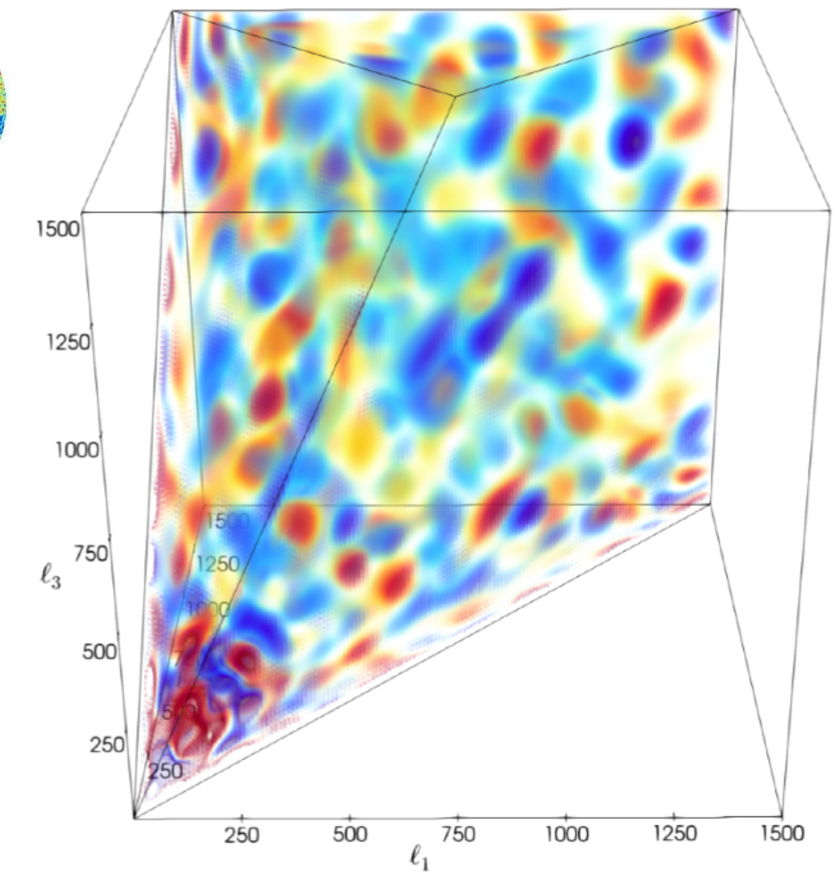
III The dark era of inflation

We only know 10 out of 60 e-folds of inflation

I Why not just single-field slow roll?

Primordial fluctuations





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

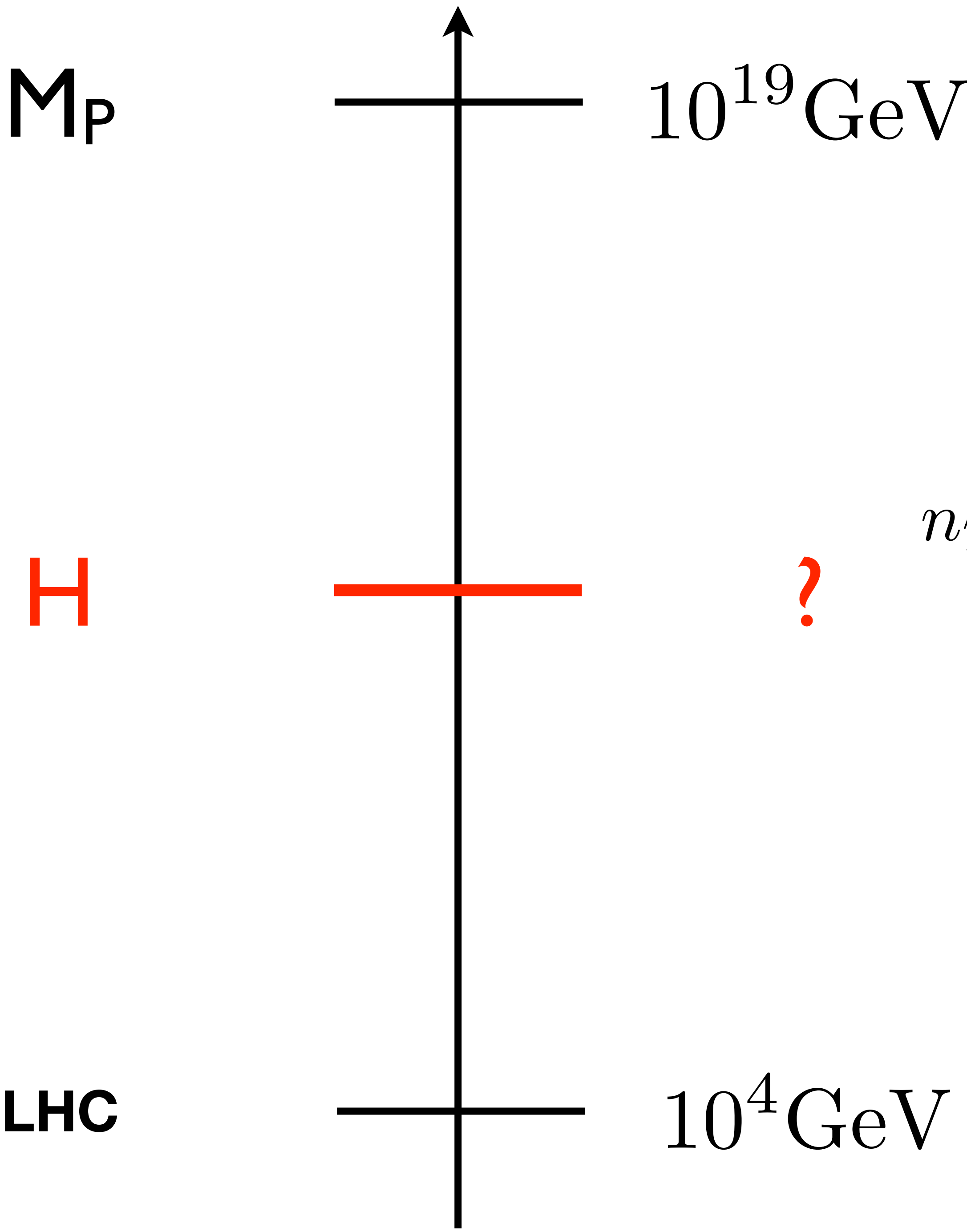
approximate time translation invariance during inflation

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

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

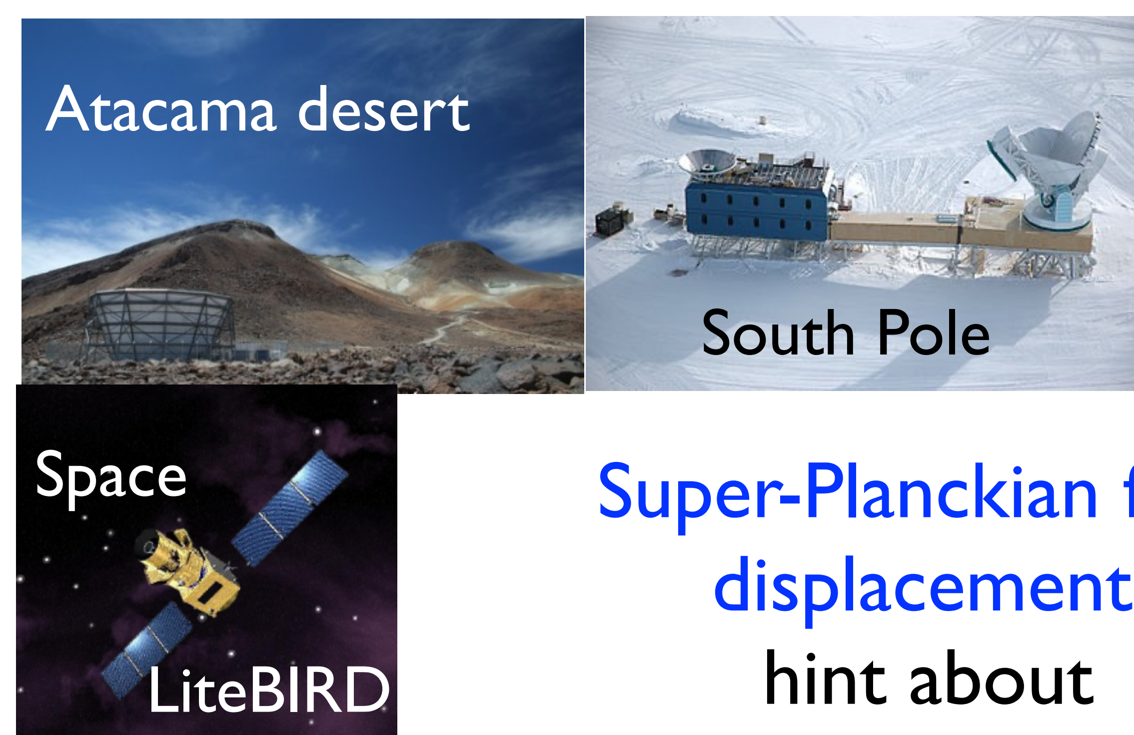
Gaussian to better than 0.1%

Energy scale of inflation?



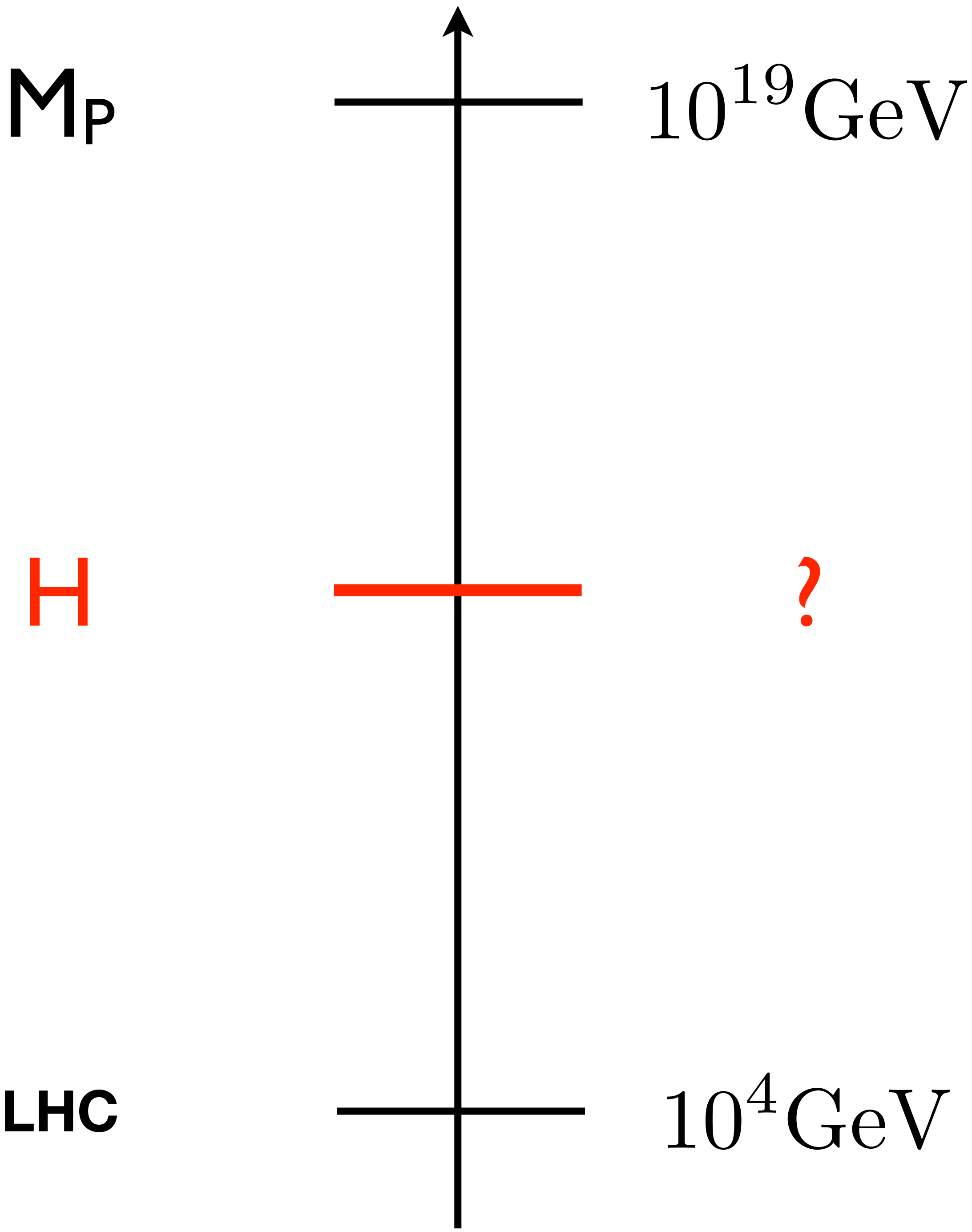
Primordial gravitational waves
from B-modes polarization of CMB

$$n_T = -r/8 \longrightarrow H \sim 10^{14}\mathrm{GeV}$$



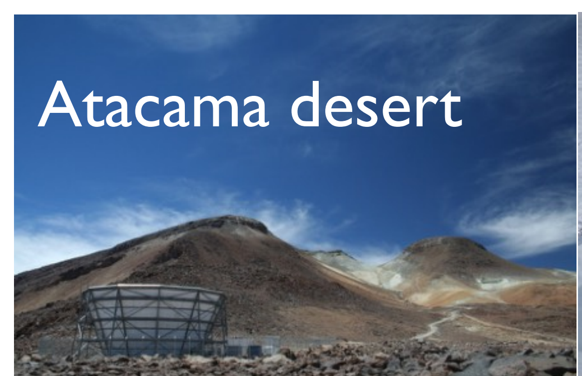
Super-Planckian field displacement:
hint about
gravity at Planck scale

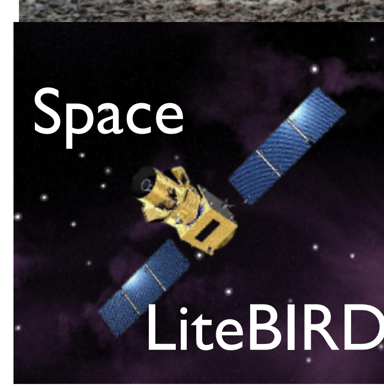
Energy scale of inflation?



No useful theoretical lower bound:
B-modes may be forever out of reach

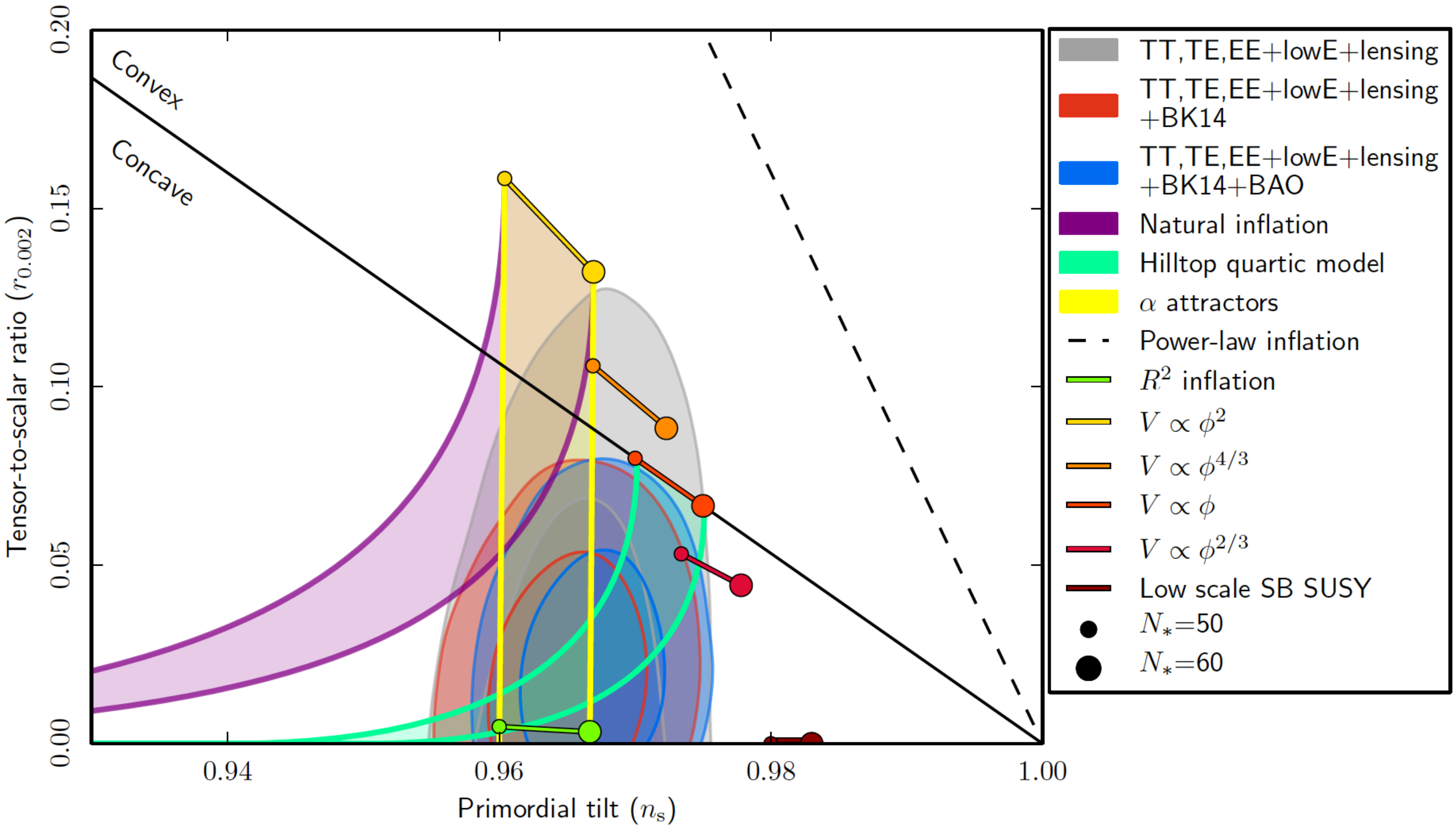
$$\longrightarrow \quad H \sim 10^{14}\mathrm{GeV}$$



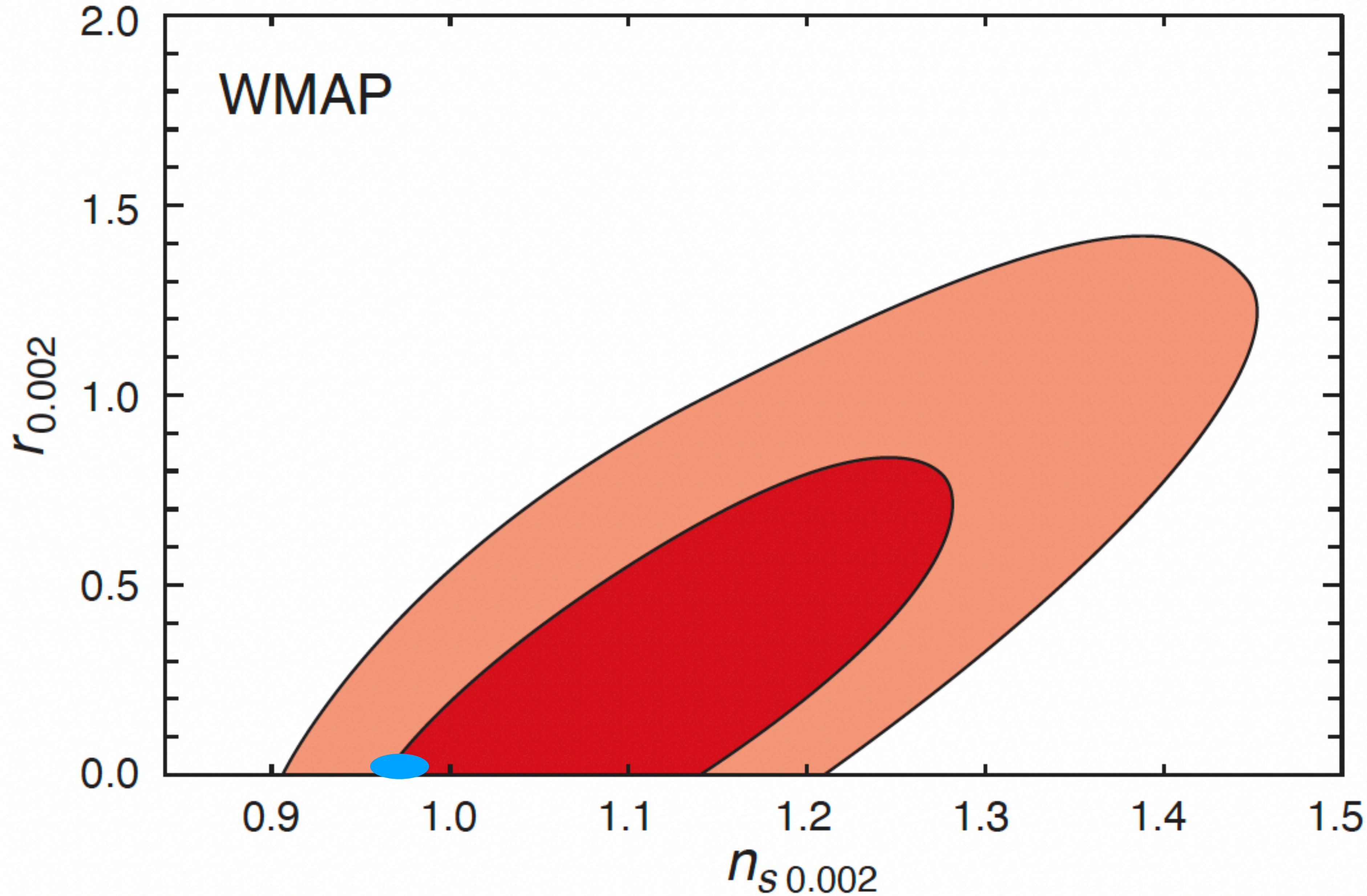


Super-Planckian field displacement:
hint about
gravity at Planck scale

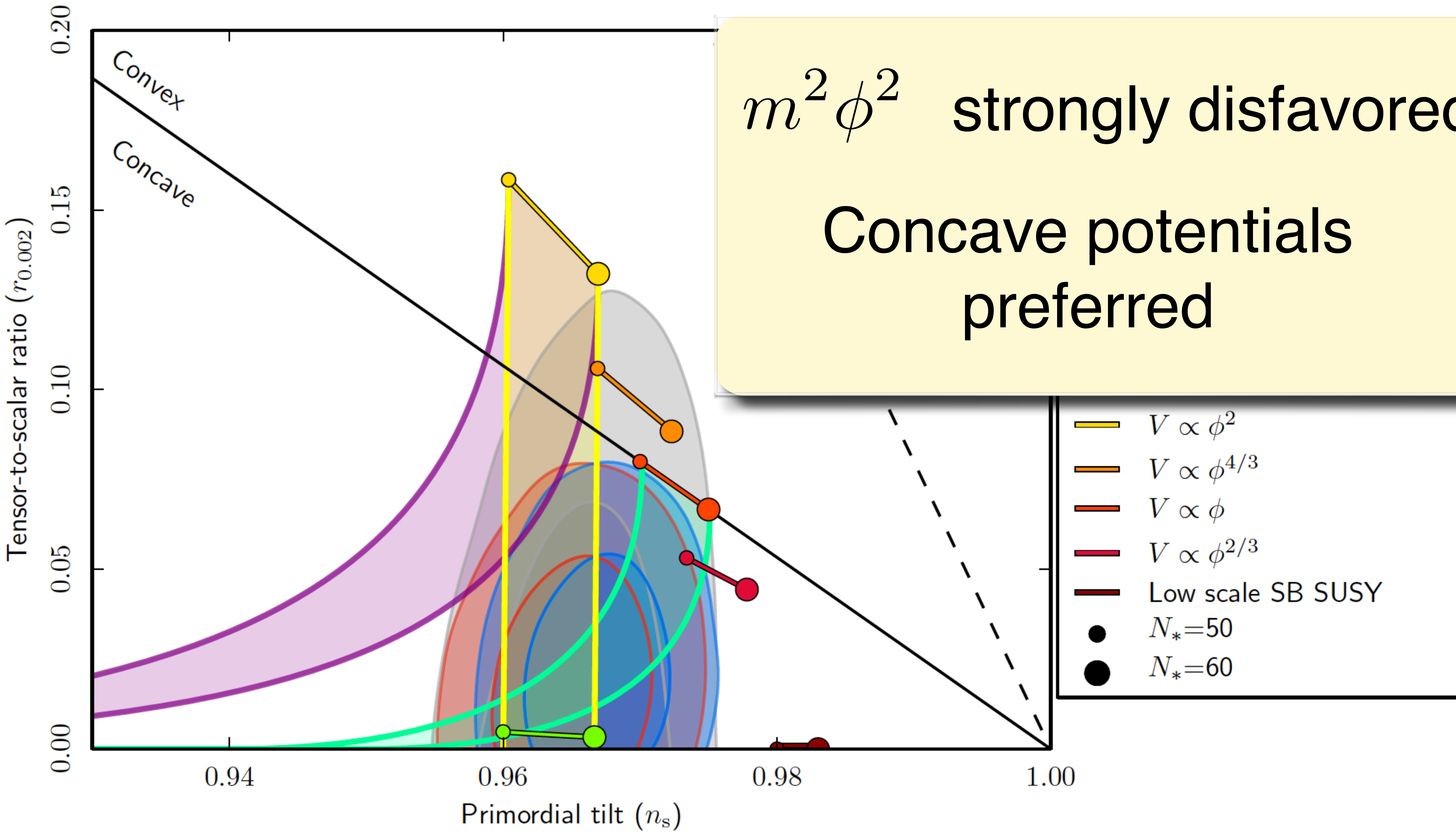
The Planck ns-r plane



The WMAP ns-r plane when I entered the field (2007)



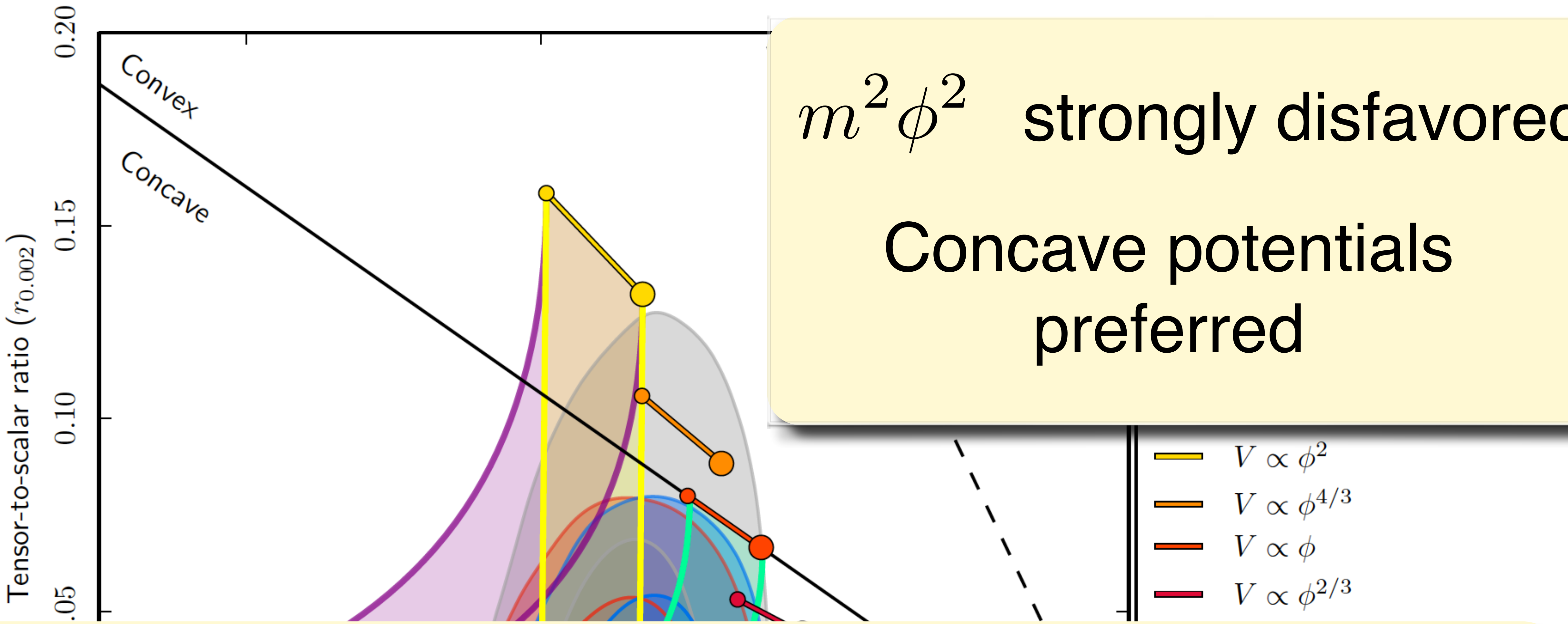
The Planck ns-r plane



$m^2\phi^2$ strongly disfavored

Concave potentials preferred

The Planck ns-r plane



$m^2\phi^2$ strongly disfavored

Concave potentials preferred

But truly: pinpointing the potential of the hypothetical inflaton is not the most interesting science

Physics of inflation?

What is the mechanism driving inflation?

Which extension of the Standard Model?

At which energy did inflation occur?

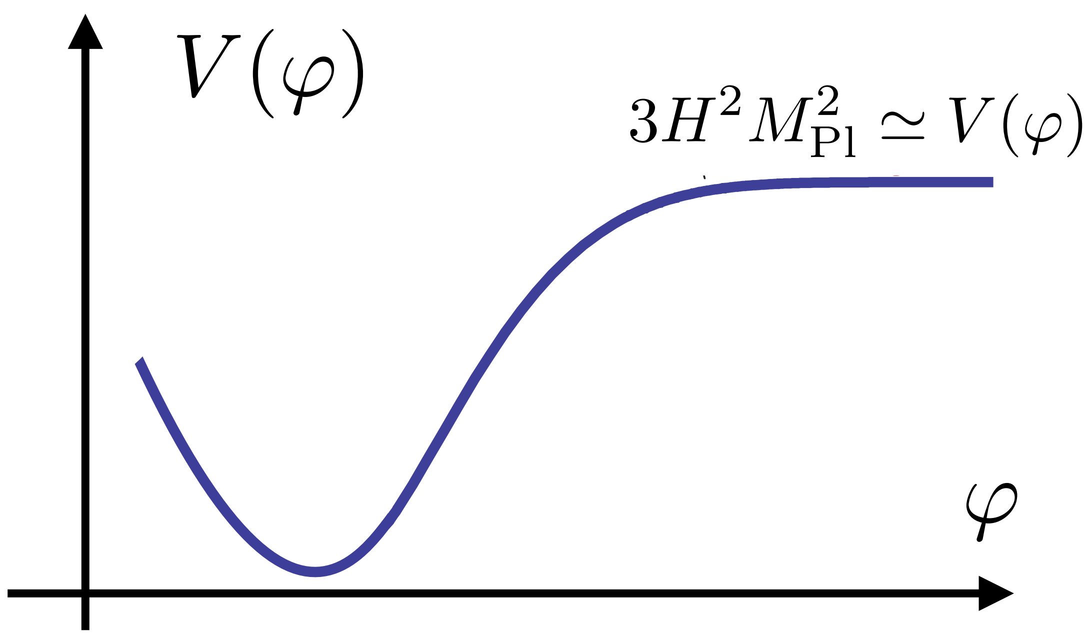
How is the inflationary energy transferred to Standard Model particles?

What is the particle content of inflation?

Alternatives to inflation?

Inflation: unique observational probe of high-energy physics

The Eta problem



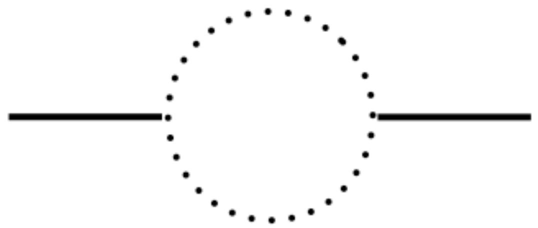
$$\eta \equiv M_{\rm pl}^2 \frac{V_{,\phi\phi}}{V} \ll 1$$

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

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

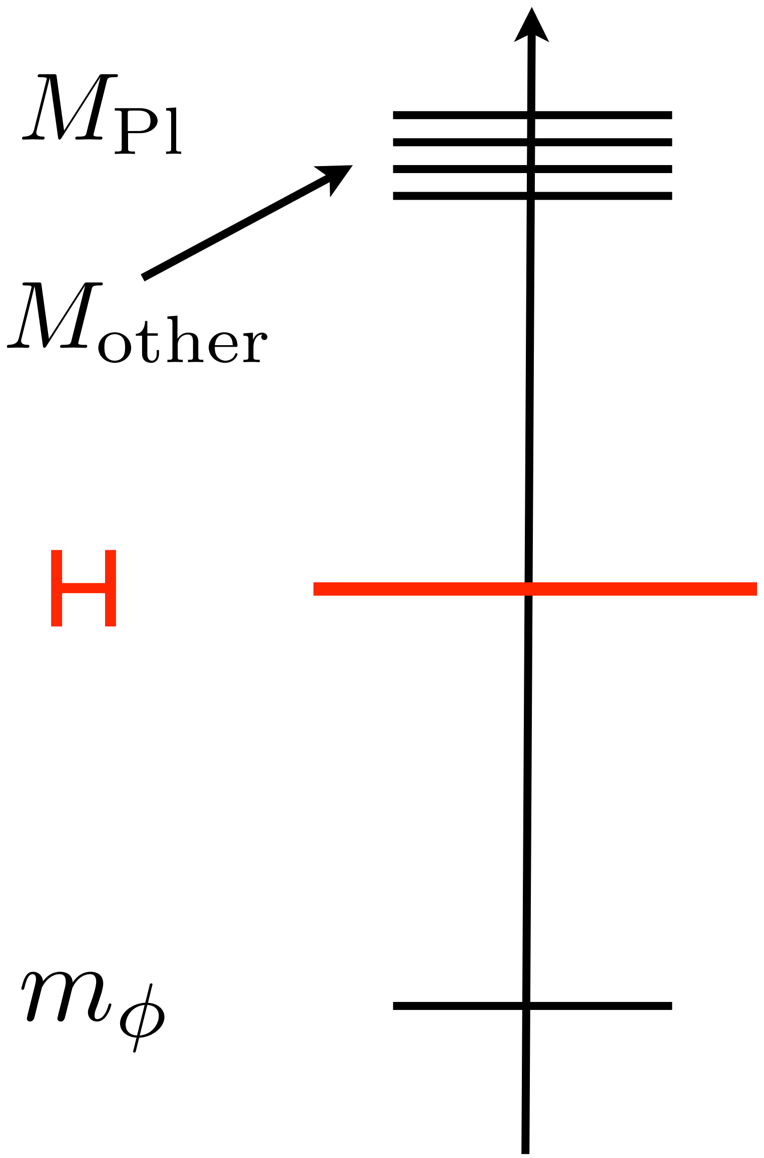
$$\Delta\eta \gtrsim 1$$

Planck-scale physics does not decouple

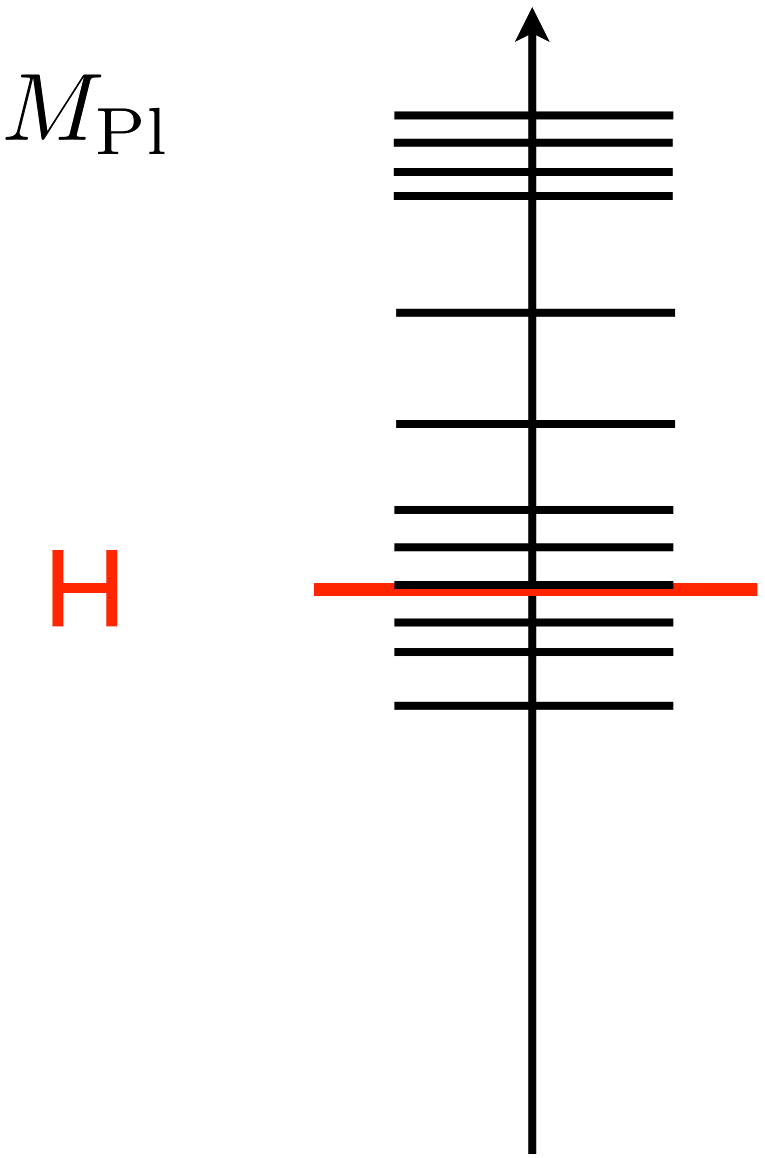
Symmetries do not help

Guidance from string theory?

Hope:



Find:



Guidance from string theory?

Top-down constructions:
difficult and rarely done consistently

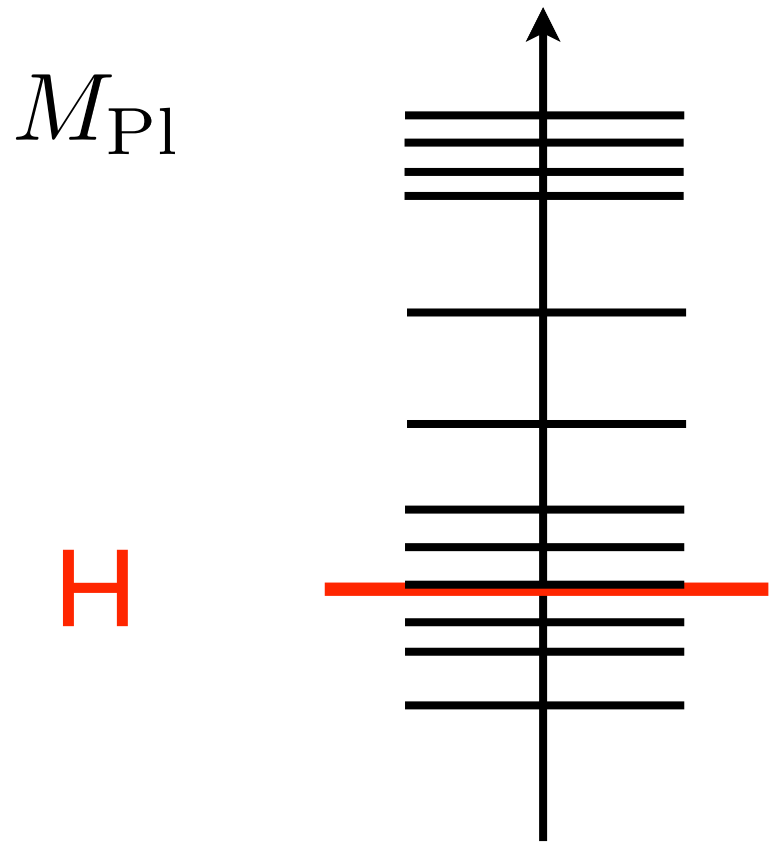
Find:

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

Bottom-up approach

UV perspective motivates looking for deviations to vanilla results (Gaussian fluctuations with power law spectrum)

Consider various field content and operators, and identify interesting signatures in cosmological correlators, to constrain in data.

- EFT of the background $\qquad S_{\text{inflation}}(\phi = \bar{\phi}(t) + \delta\phi)$
- EFT of fluctuations $\longrightarrow \qquad S_{\text{fluctuations}}(\delta\phi)$

Systematic, powerful and direct link with observations but gives up on realizing inflation

Bottom-up approach

UV perspective motivates looking for deviations to vanilla results (Gaussian fluctuations with power law spectrum)

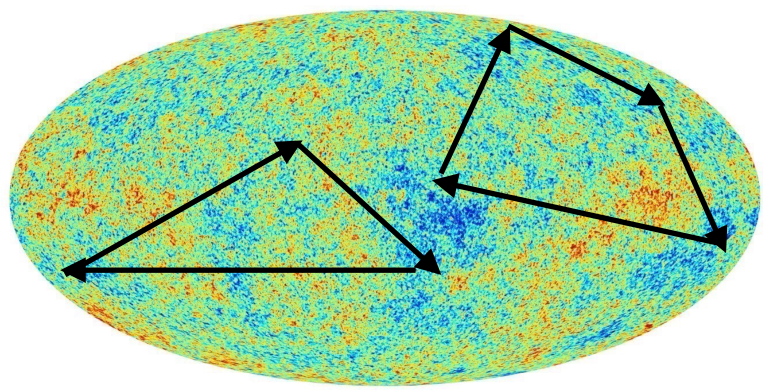
Consider various field content and operators, and identify interesting signatures in cosmological correlators, to constrain in data.

- EFT of the background $S_{\text{inflation}}(\phi = \bar{\phi}(t) + \delta\phi)$
- EFT of fluctuations $\longrightarrow$ $S_{\text{fluctuations}}(\zeta + \text{other fields})$

Systematic, powerful and direct link with observations
but gives up on realizing inflation

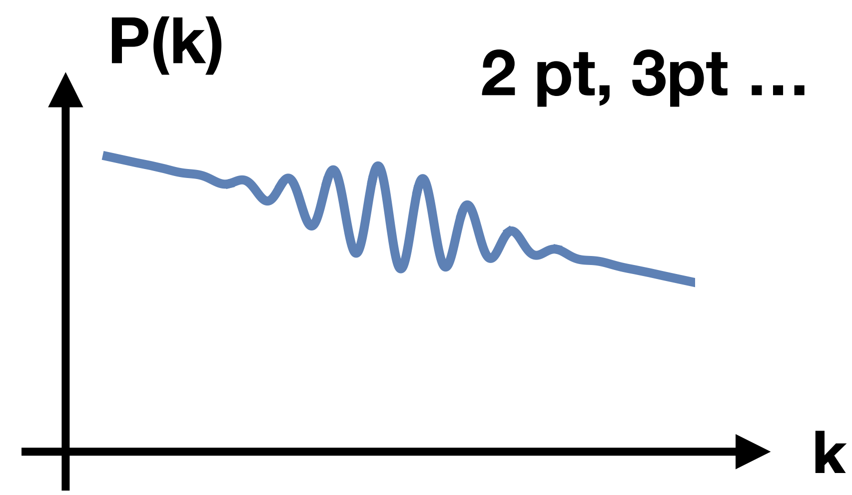
Looking for new physics
(signs of new dofs)

Primordial non-Gaussianities

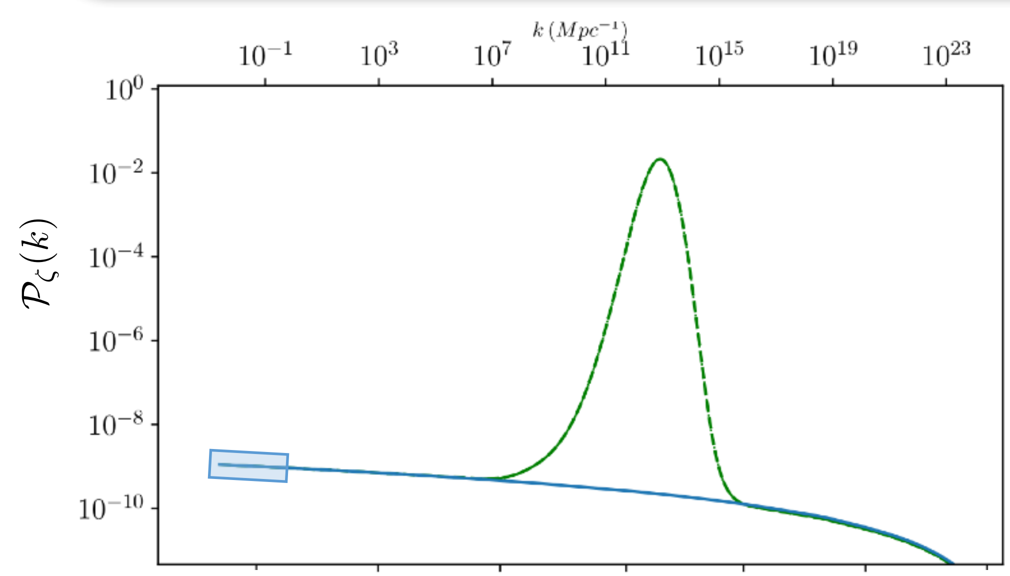


3pt, 4 pt …

Primordial features



Dark era of inflation



II Inflation as a cosmological collider

Primordial non-Gaussianities: Inflation as a collider

- Gaussian approximation: freely propagating particles

- Non-Gaussianities measure the ***interactions*** of the fields active during inflation

Introductory review: Renaux-Petel, 1508.06740

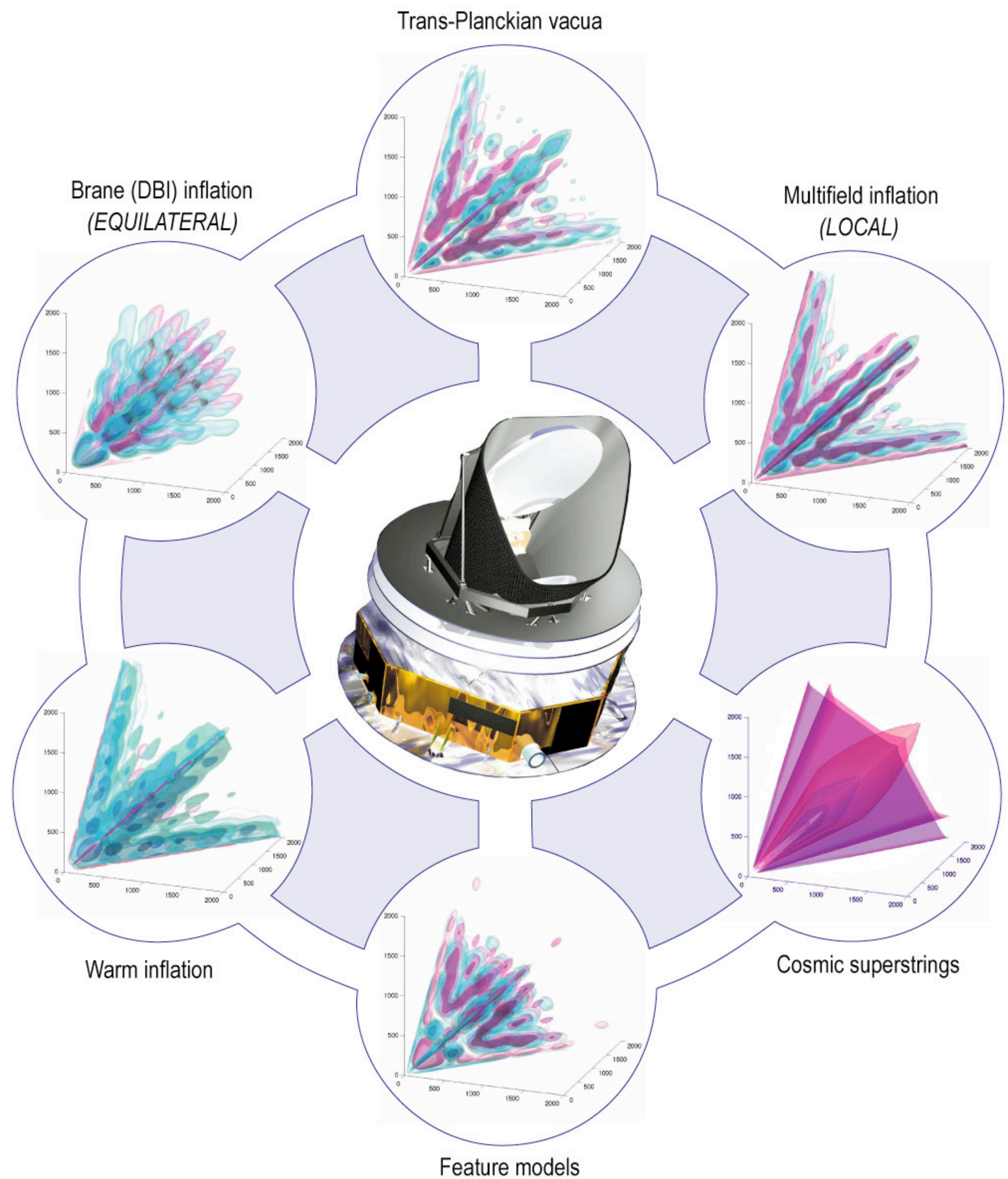
Particle physics

Cosmology

Primordial non-Gaussianities

'Happy families are all alike;
each unhappy family is
unhappy in its own way.'

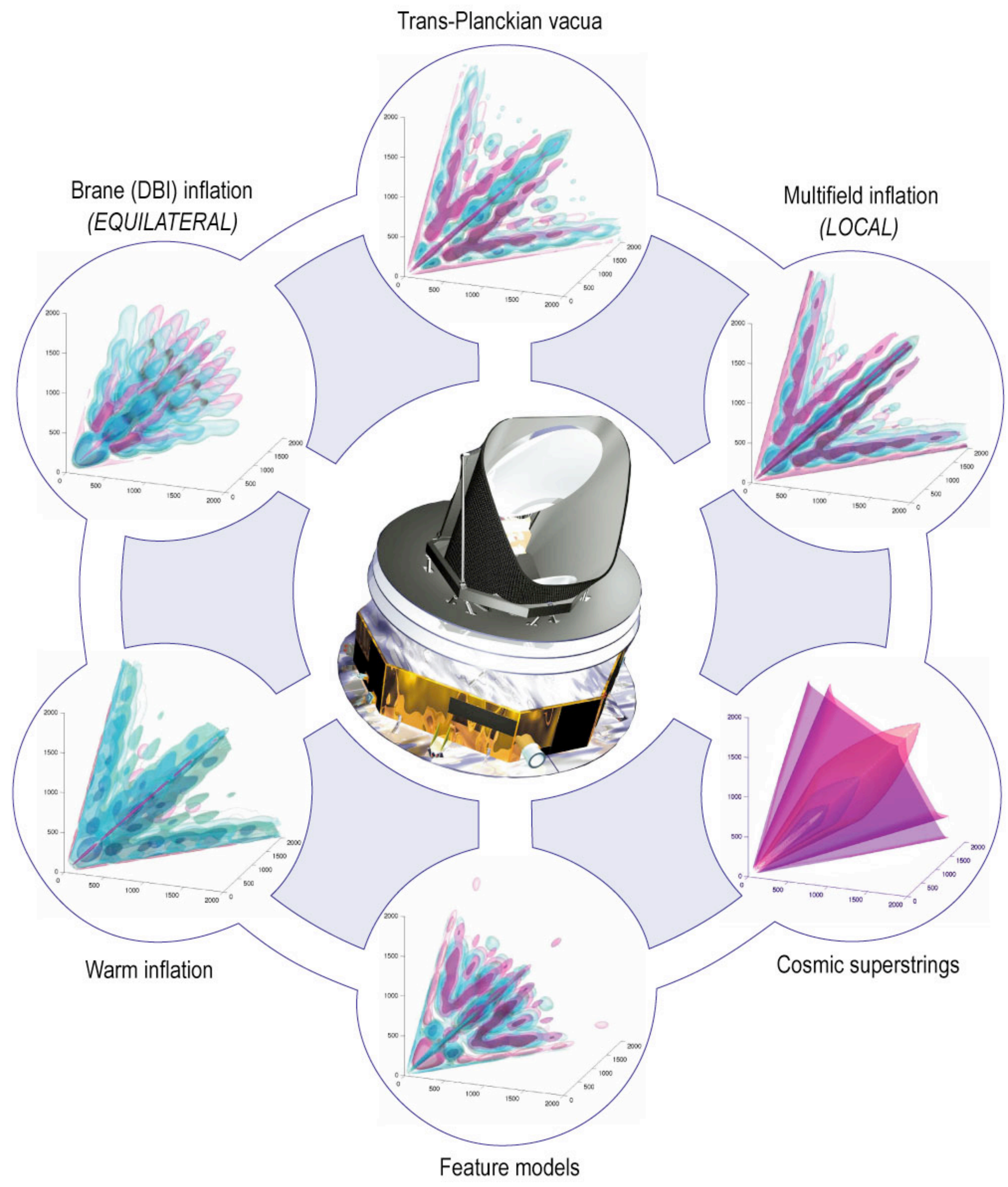
Anna Karénine, Tolstoï



Primordial non-Gaussianities

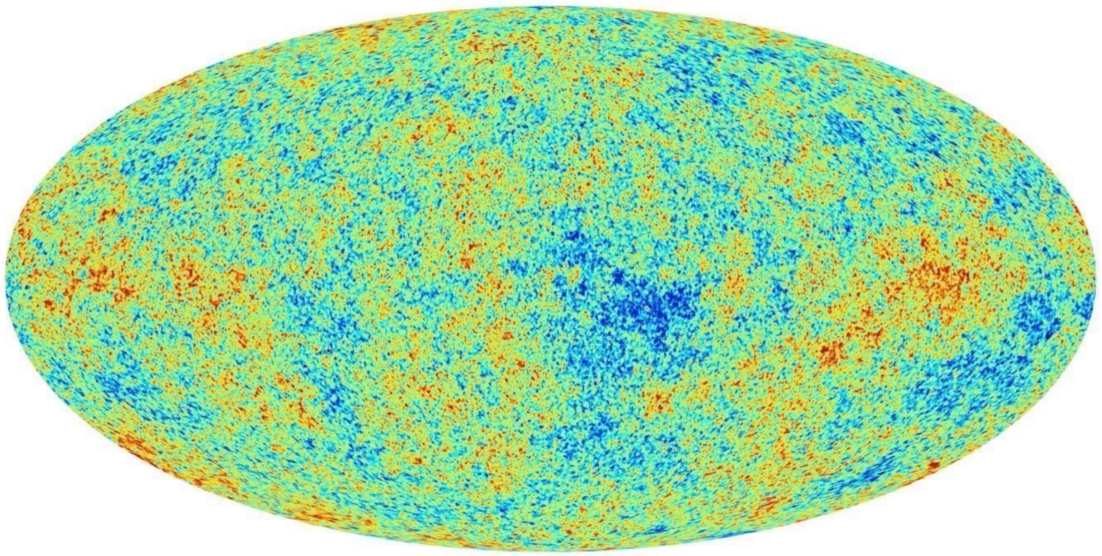
Gaussian distribution are all alike; each non-Gaussian distribution is non-Gaussian in its own way.

Cosmologist



Orders of magnitude

$$\frac{\delta T}{T} \sim \zeta \sim 10^{-5}$$



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

- Current Planck constraints: $|f_{\rm NL}| \lesssim \mathcal{O}(10)$

Gaussianity already tested to better than 0.1%

- Slow-roll single field prediction: Maldacena (03)

$$f_{\rm NL} \sim \mathcal{O}(\epsilon, \eta) \sim O(n_s - 1) \sim 10^{-2}$$

Guaranteed lower bound on NG
(GR is non linear)

Beyond vanilla models

$$f_{\rm NL} = \mathcal{O}(\epsilon, \eta) \sim 10^{-2}$$

UNDER HYPOTHESES

- Single field
- Standard kinetic term
- Slow-roll
- Initial vacuum state
- Einstein gravity

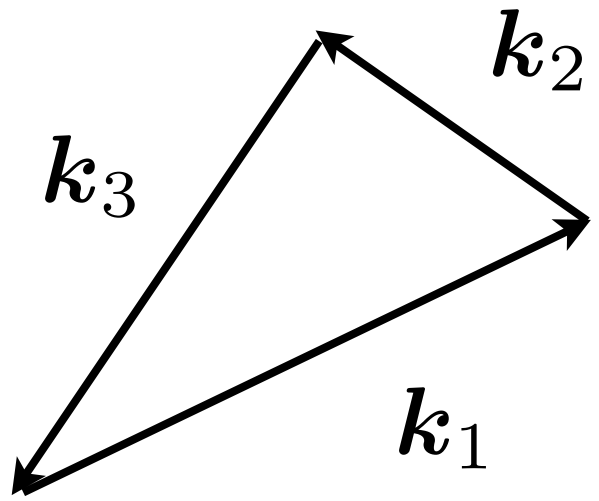
Violating any of these assumptions in general leads to observably `large' NGs.

$$f_{\rm NL} \gtrsim \mathcal{O}(1)$$

and we have a dictionary between physical effects and types of non-Gaussianities

The bispectrum

$$\langle\zeta(\boldsymbol{k}_1)\zeta(\boldsymbol{k}_2)\zeta(\boldsymbol{k}_3)\rangle = (2\pi)^7\delta(\sum_{i=1}^{3}\boldsymbol{k}_i)\mathcal{P}_\zeta^2\frac{S(k_1,k_2,k_3)}{(k_1k_2k_3)^2}$$



- $f_{NL} \sim S$ — dimensionless measure of the **amplitude** of the bispectrum

- **Scale-dependence** (growing or shrinking on small scales?)

- **Sign** (more or less cold spots?)

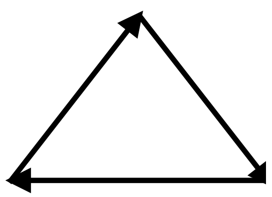
- **Shape** (dependence on the configuration of triangles)

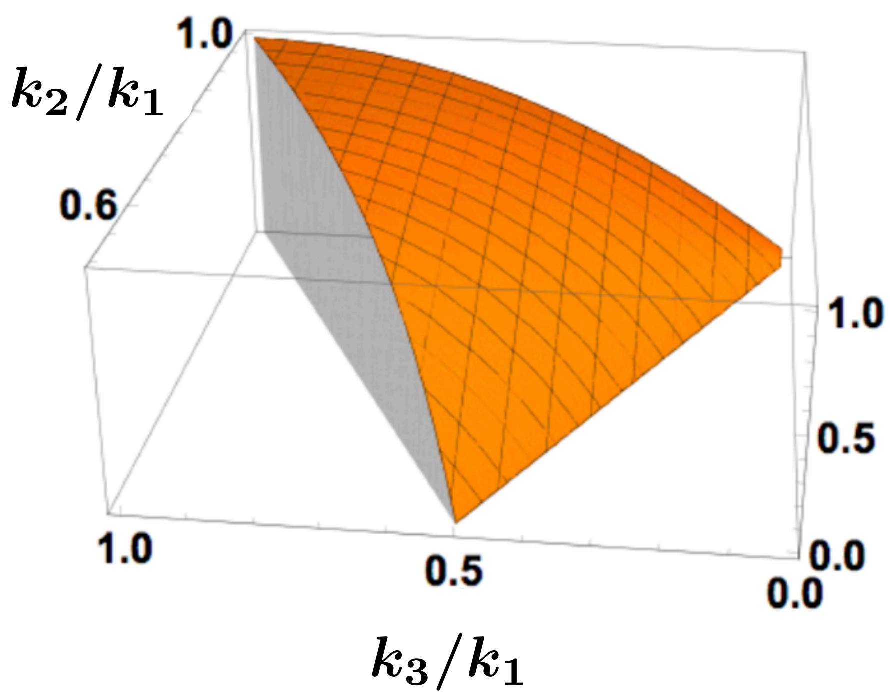
Each of these features can rule out large classes of models

Inflationary physics and non-Gaussian shapes

(tip of iceberg)

Equilateral





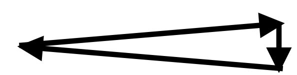
$$f_{\rm NL}^{\rm eq} = -26 \pm 47$$

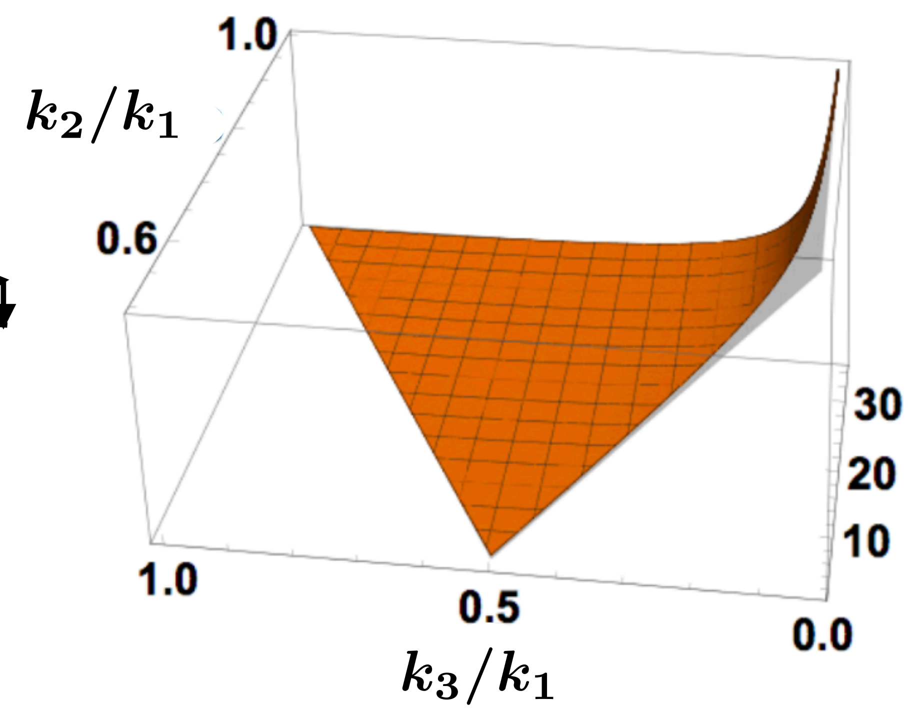
Heavy fields $(m \gg H)$

(or/and derivative self-interactions of zeta)

$$f_{\rm NL}^{\rm eq} \sim \frac{1}{c_s^2} - 1 \qquad c_s \geq 0.021$$

Local



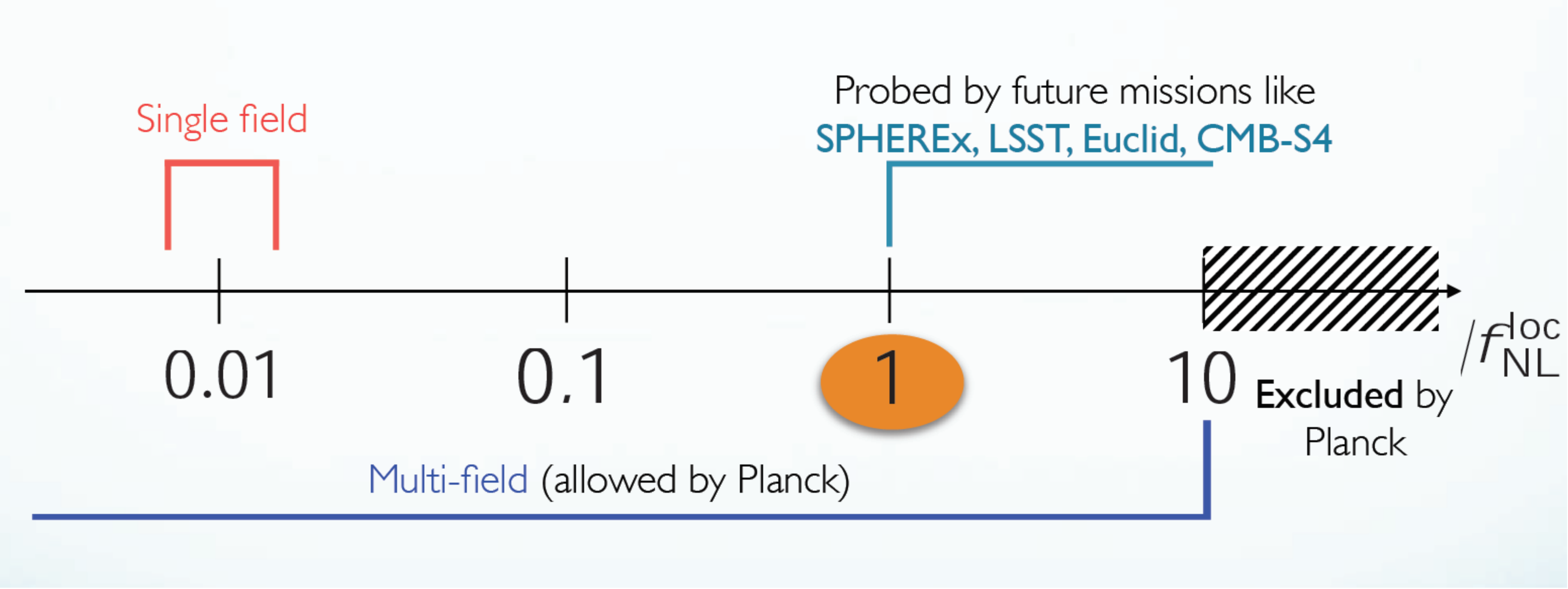


$$f_{\rm NL}^{\rm loc} = -0.9 \pm 5.1$$

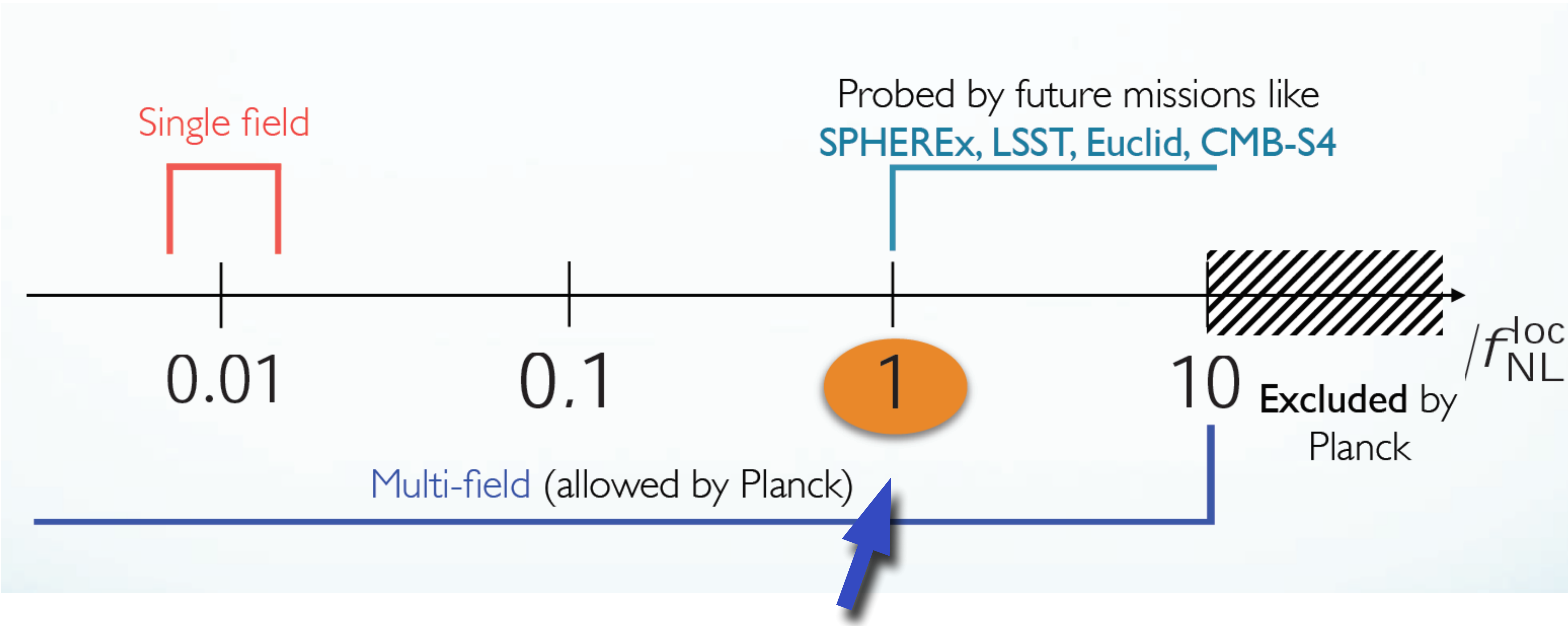
Additional light fields $(m \ll H)$

Not possible in single-clock inflation

Prospects

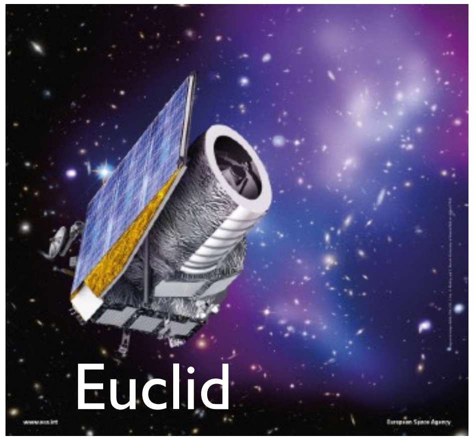

Single field
Probed by future missions like
SPHEREx, LSST, Euclid, CMB-S4
0.01
0.1
1
10
f_{NL}^{loc}
Excluded by
Planck
Multi-field (allowed by Planck)

Prospects

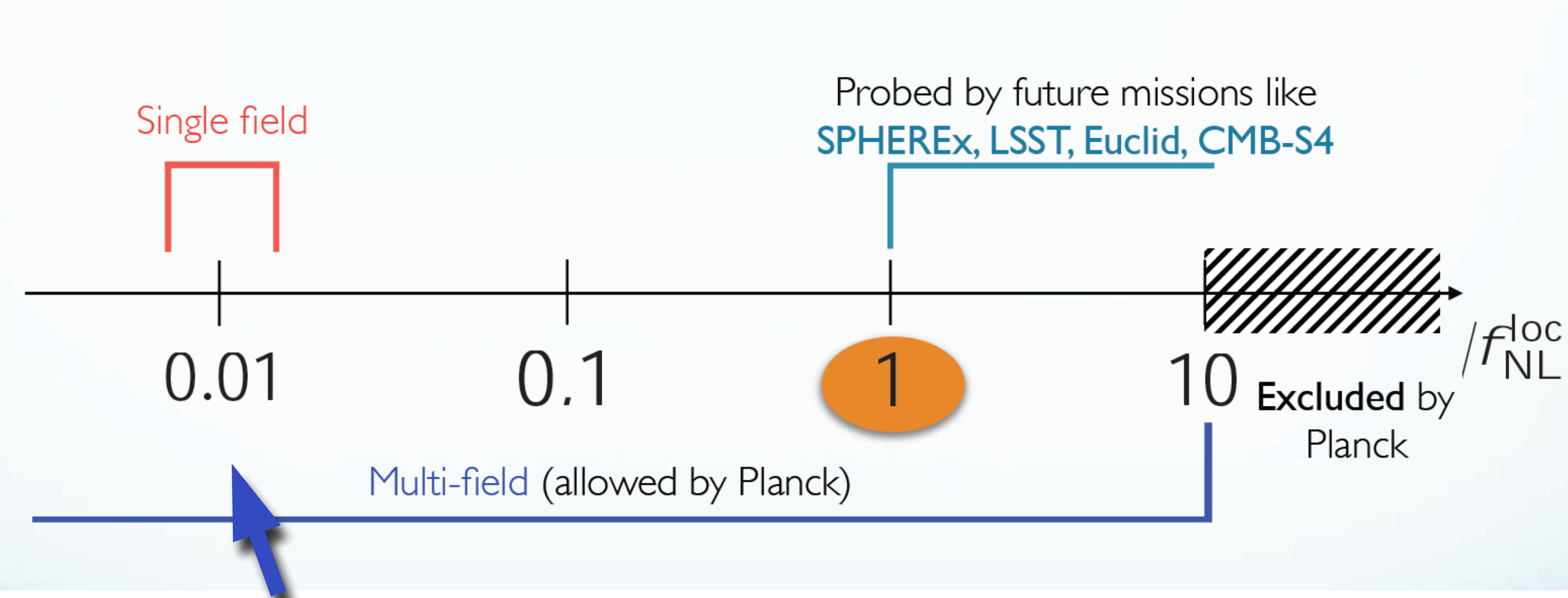


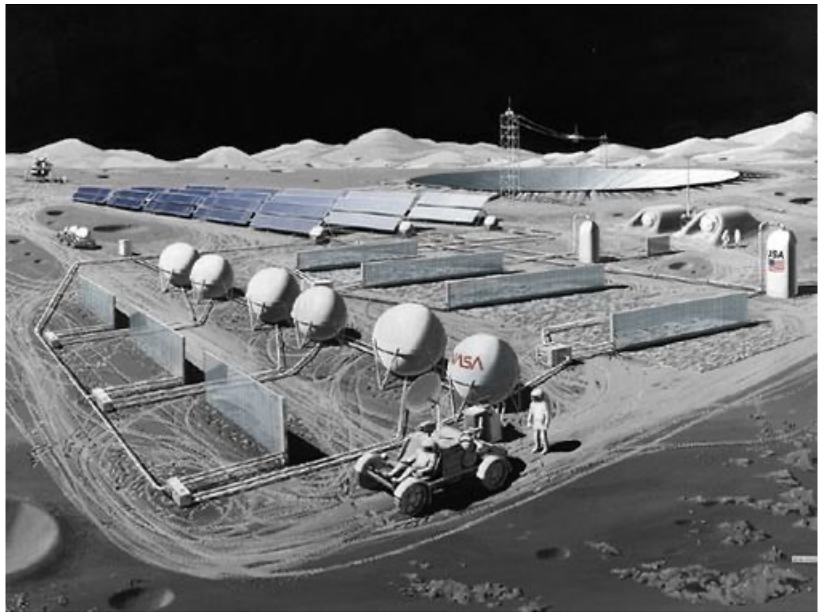
Huge efforts to reach this sensitivity with large-scale structure surveys

(scale-dependent bias, EFT of LSS, position space maps, simulation based inference etc)



Prospects



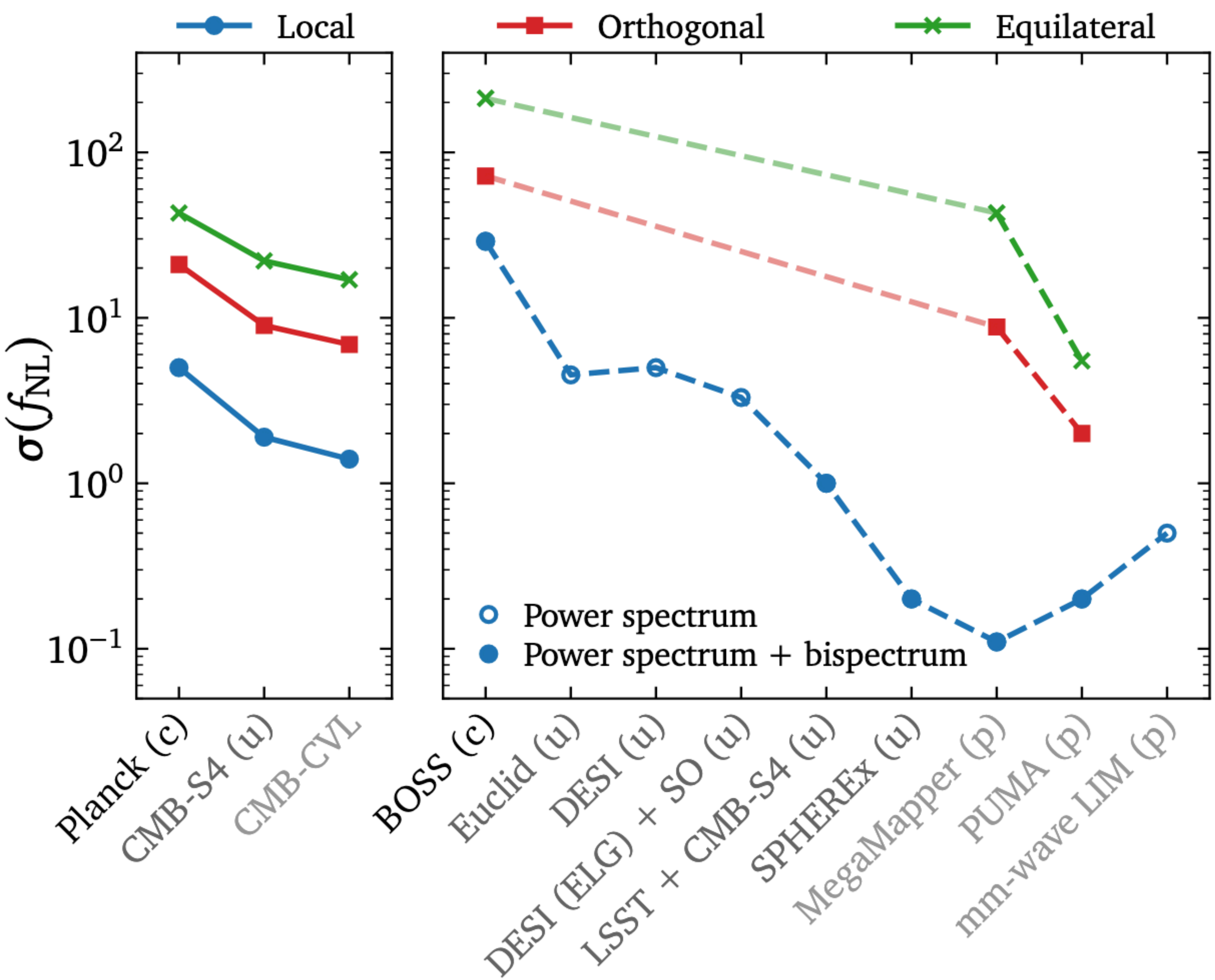


21cm emission from hydrogen clouds during dark ages

radio-astronomy

from the far side of the moon!

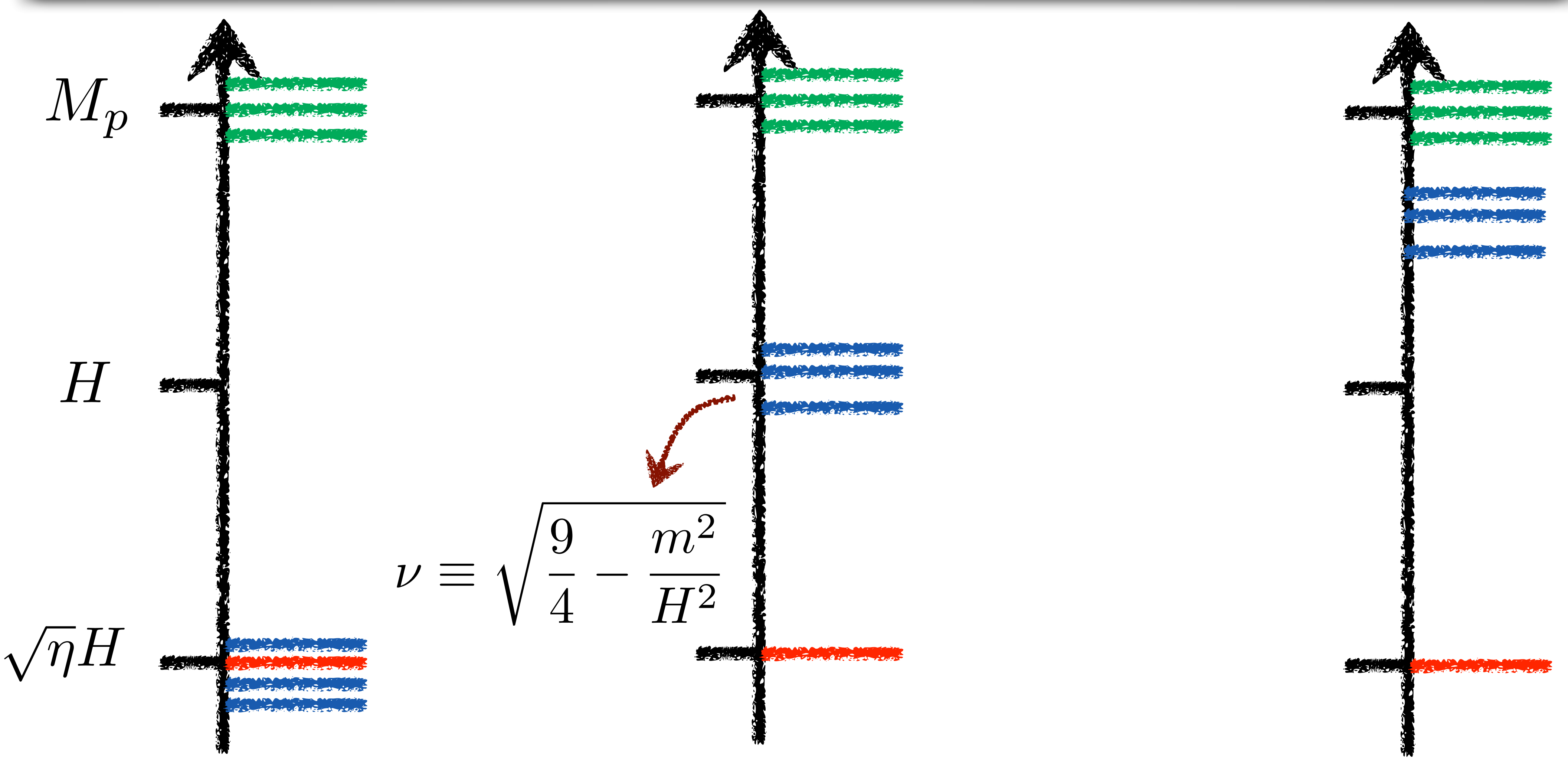
Prospects



Snowmass 2203.08128

Non-Gaussianity as a particle detector

Light dof	Quasi-single-field	Heavy dof

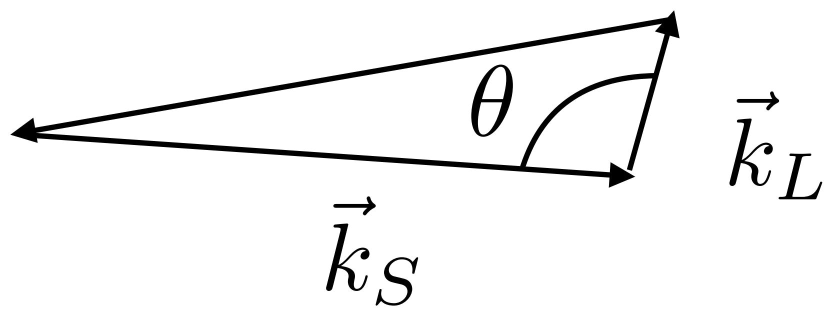


$$\nu \equiv \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}$$

$\lim_{k_L \to 0} k_L^3 \langle \zeta_{\vec{k}_L} \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \rangle$	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

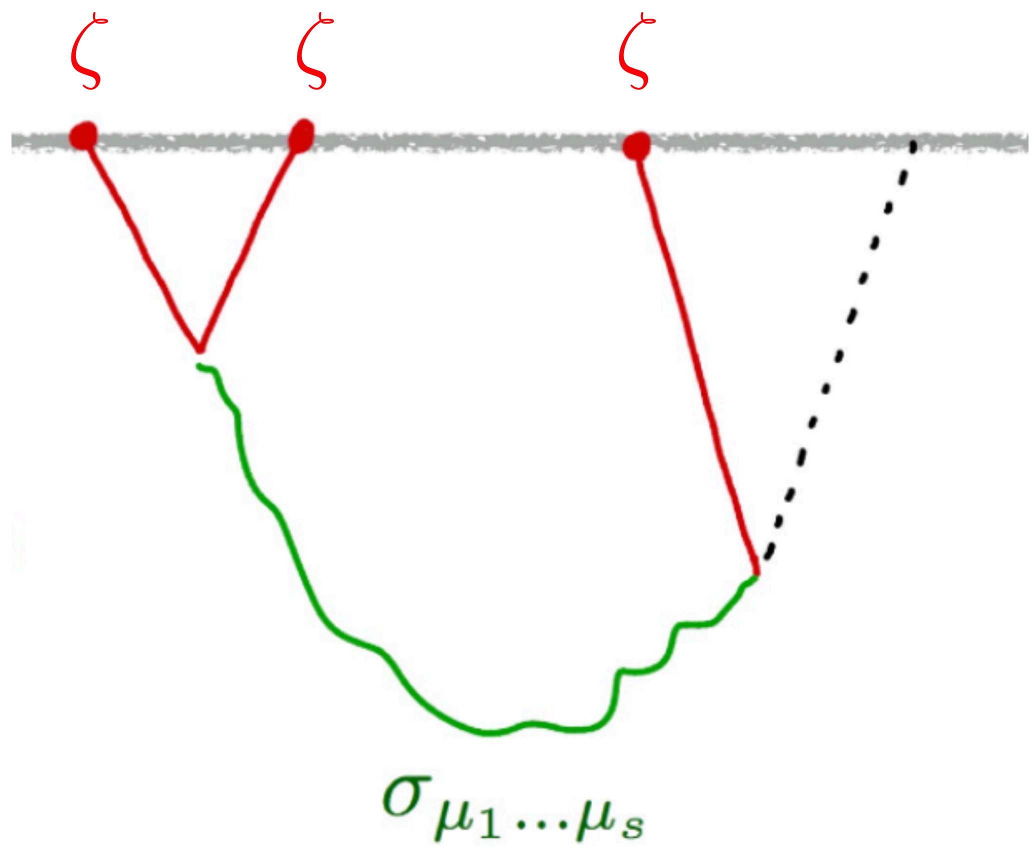
3pt



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

Mass & Spin

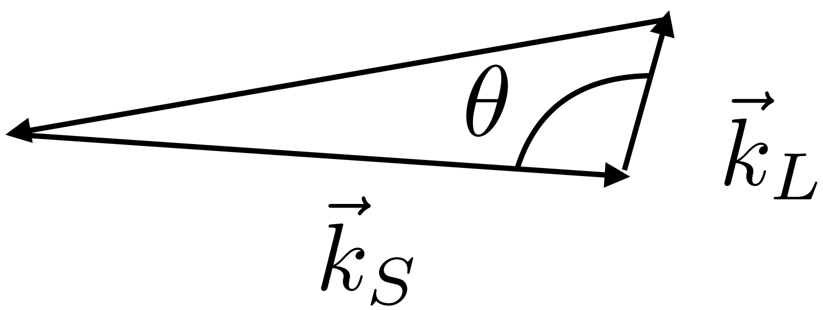
of heavy exchanged particle



Chen, Wang 2009
Baumann Green 2011
Noumi, Yamaguchi, Yokohama 2012
Arkani-Hamed, Maldacena 2015
Lee, Bauman, Pimentel 2016
Arkani-Hamed, Baumann, Lee, Pimentel 2018
Jazayeri, Renaux-Petel 2022

Cosmological collider physics

3pt

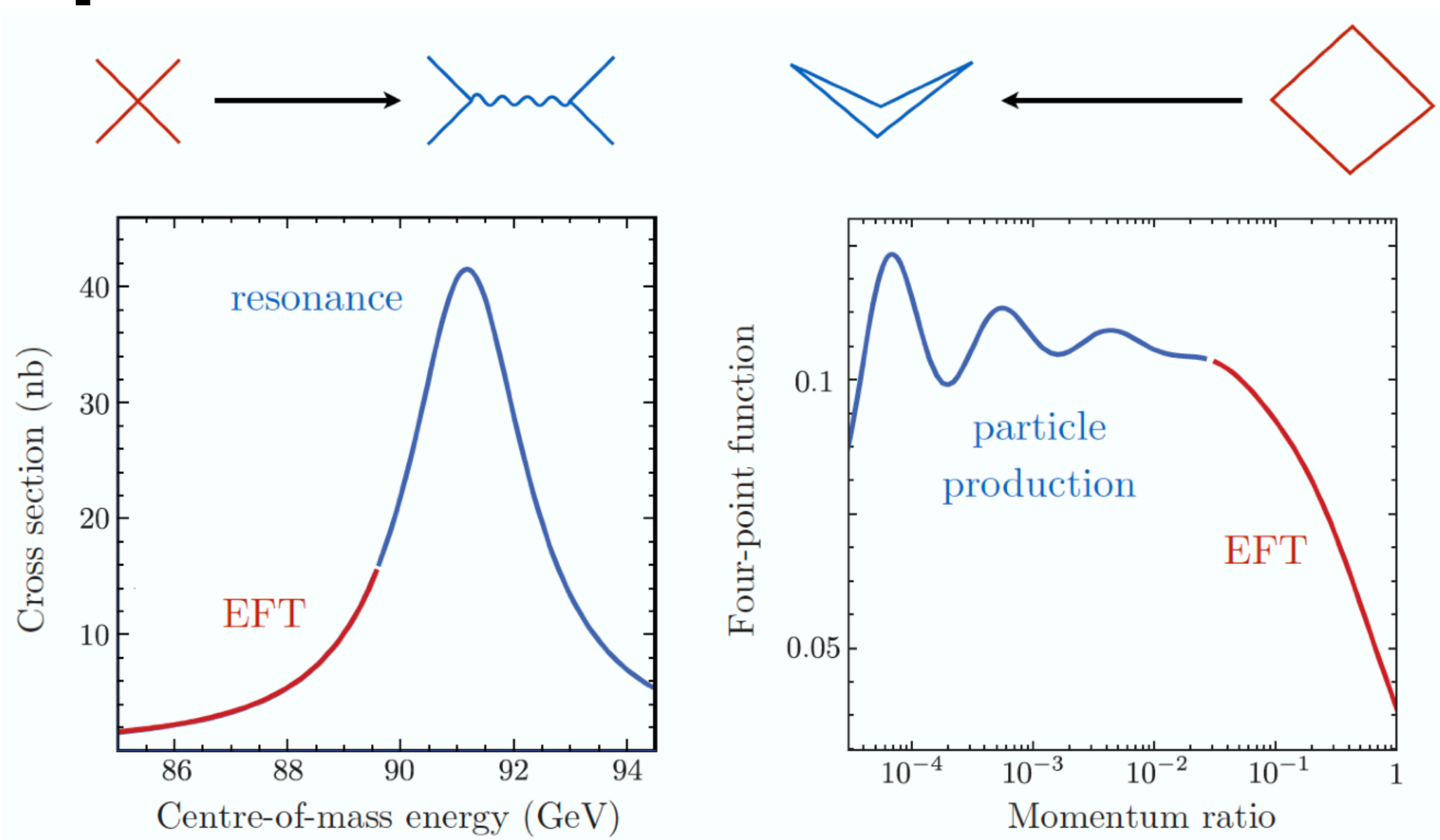


$$\lim_{k_L \to 0} \langle \zeta_{\vec{k}_L} \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \rangle \propto \left(\frac{k_L}{k_S} \right)^{3/2} \cos \left[\frac{M}{H} \ln \left(\frac{k_L}{k_S} \right) + \delta \right] P_S(\cos\theta)$$

Mass & Spin

of heavy exchanged particle

4pt



From 1811.00024

Chen, Wang 2009
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Arkani-Hamed, Maldacena 2015
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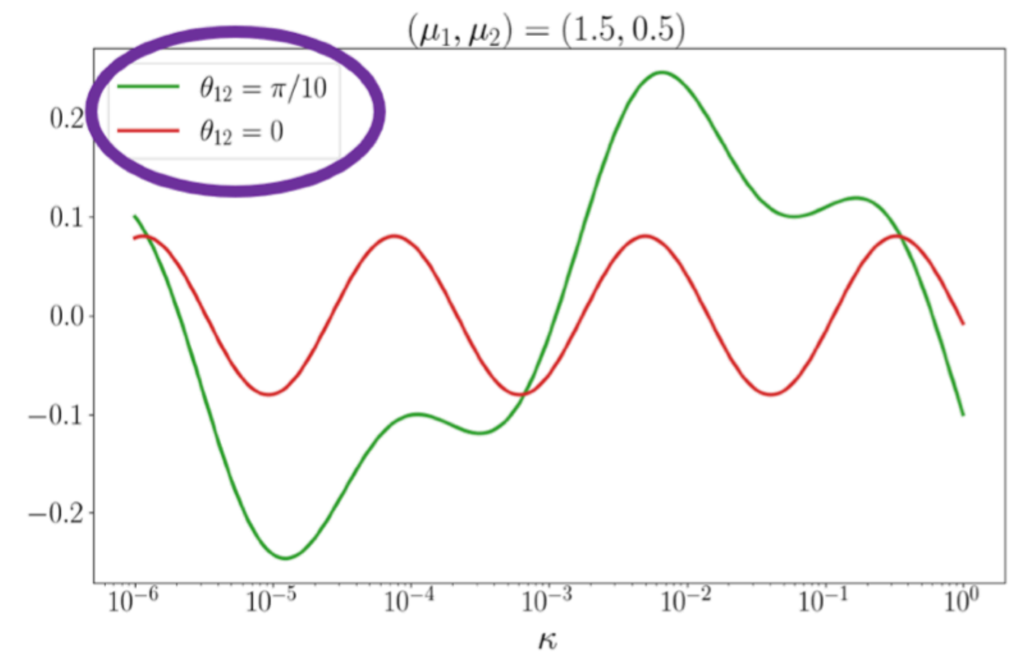
Arkani-Hamed, Baumann, Lee, Pimentel 2018
Jazayeri, Renaux-Petel 2022

Mass, spin, what else?

Which mass? Inflationary flavor oscillations and cosmic spectroscopy

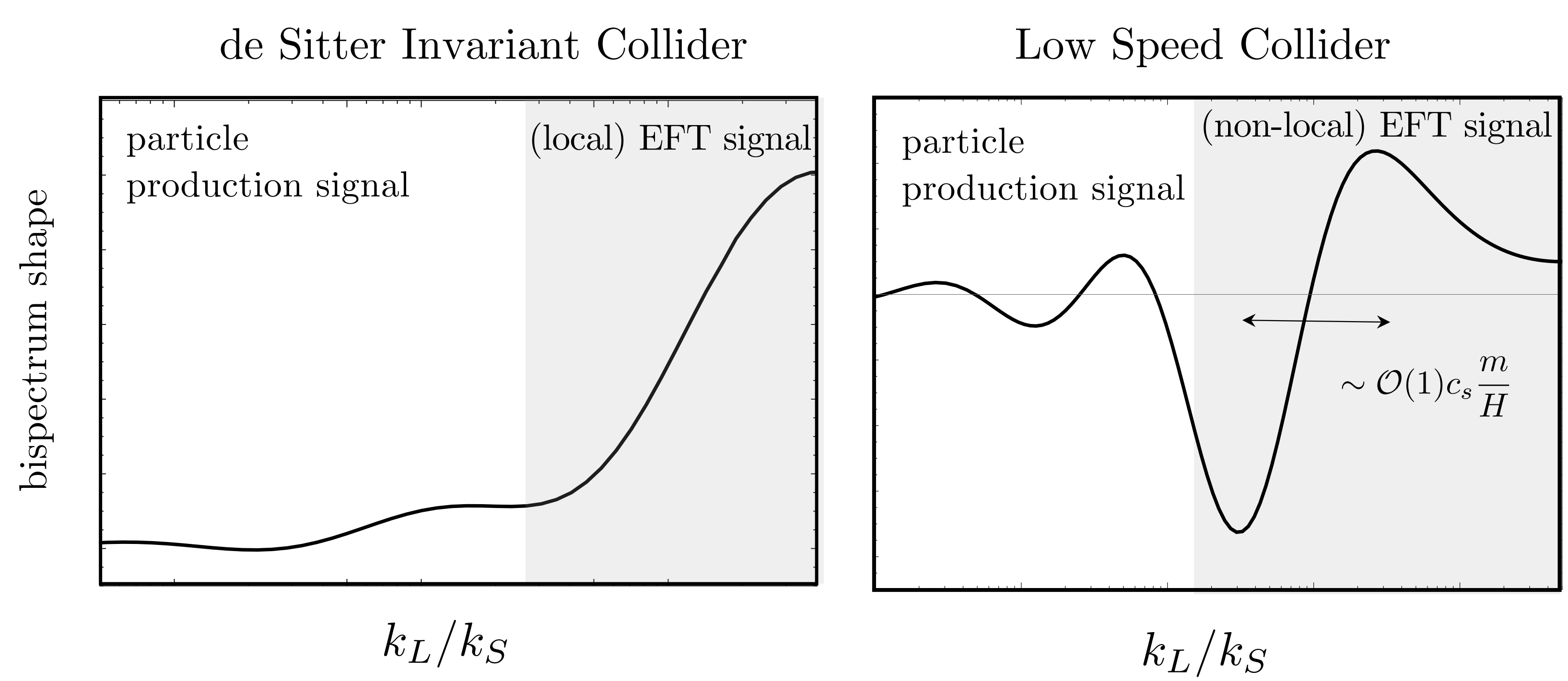
Pinol, Aoki, Renaux-Petel, Yamaguchi, 2112.05710



Squeezed limit of the bispectrum: $B_\zeta(k, k, \kappa \times k)$

Propagation speeds? Low speed collider

Jazayeri, Renaux-Petel, 2205.10340



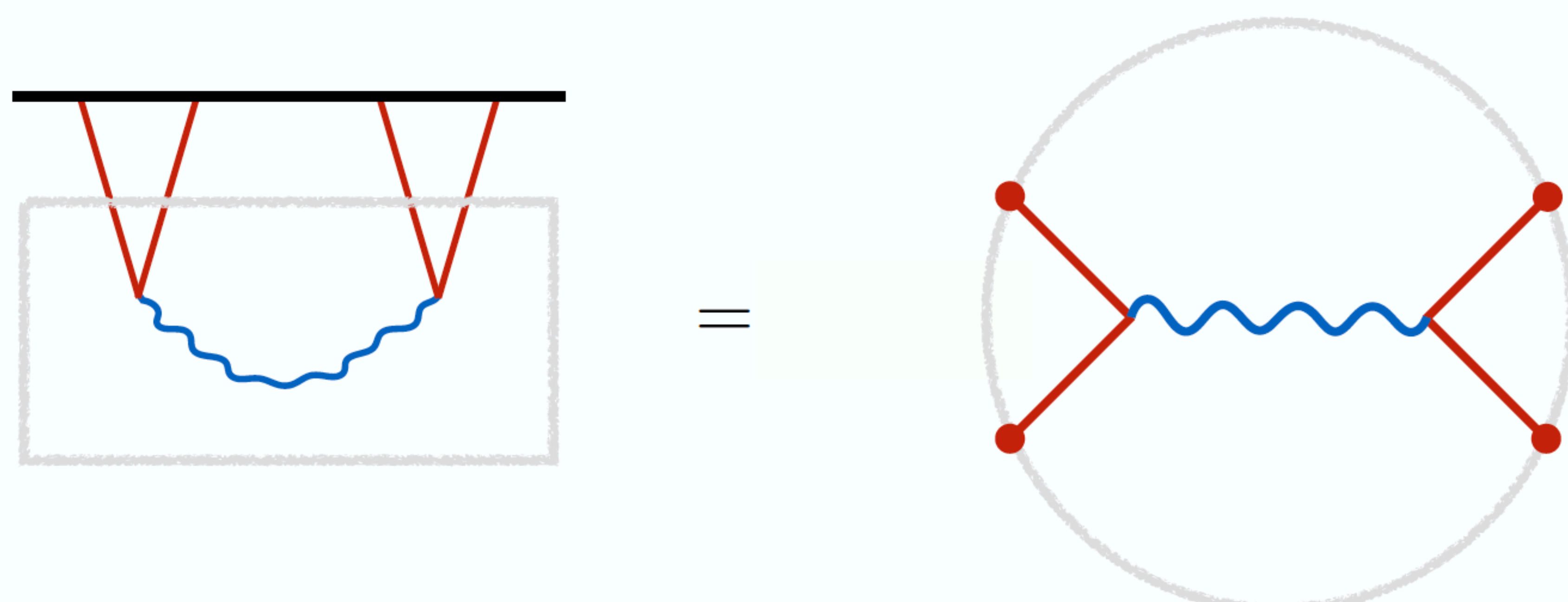
Cosmological bootstrap

Cosmological correlators constrained and computable from first principles (unitarity, locality, causality). Very active field.

Recent review, Baumann et al, 2203.08121

e.g.: scattering amplitudes contained in analytical structures of cosmological correlators

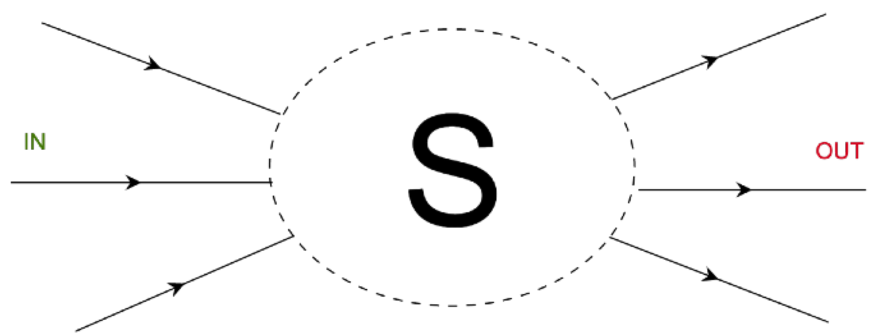
$$\lim_{k_1+k_2+k_3+k_4\to 0}$$



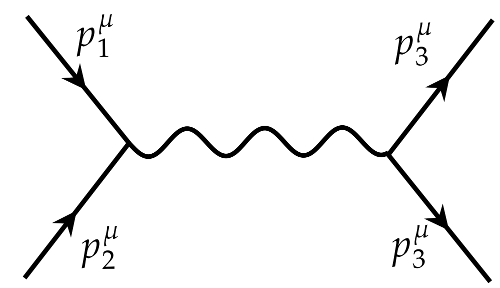
Cosmological bootstrap flavor

For our particle physics friends: time-dependent perturbation theory is hard

Flat space

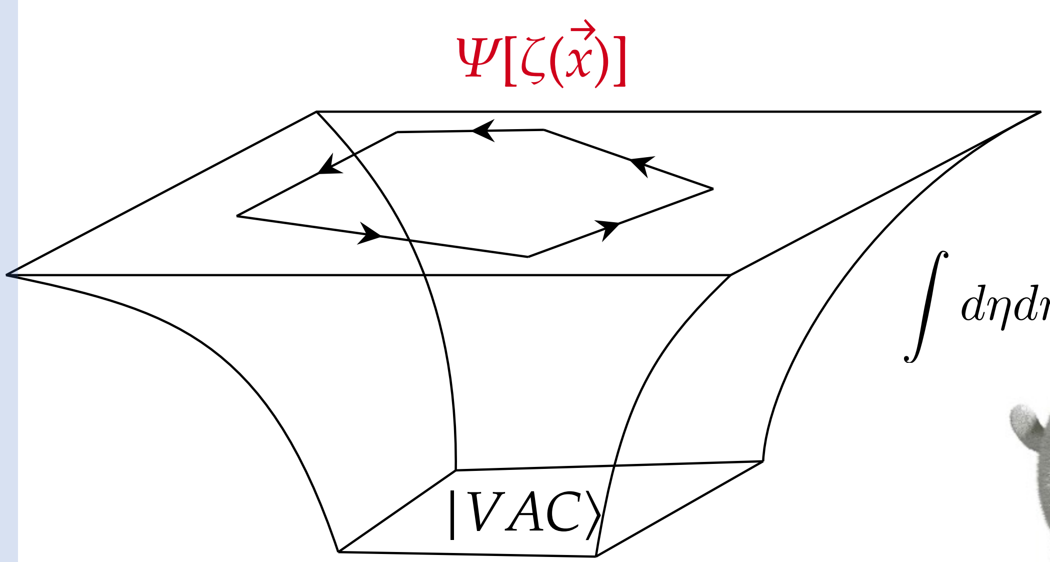


$$\int dt dt' \, e^{iE_1 t} e^{iE_2 t'} \subset$$



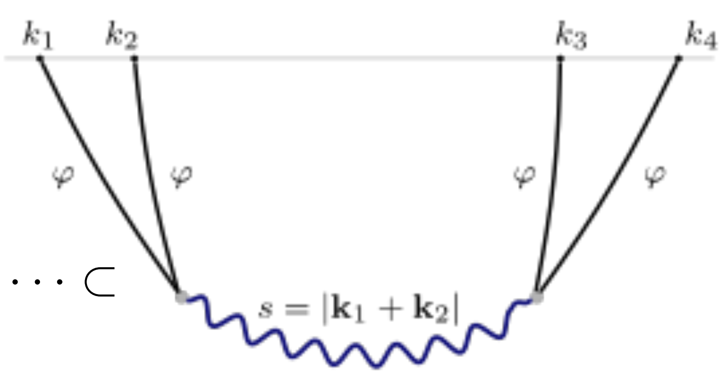
$$\mathcal{A}_{1,2\to3,4} = \frac{1}{(p_1+p_2)^2 - m^2} + t - u \text{ channels}$$

Cosmology



$$\Psi[\zeta(\mathbf{x}), t = -\infty] = \text{Gaussian}$$

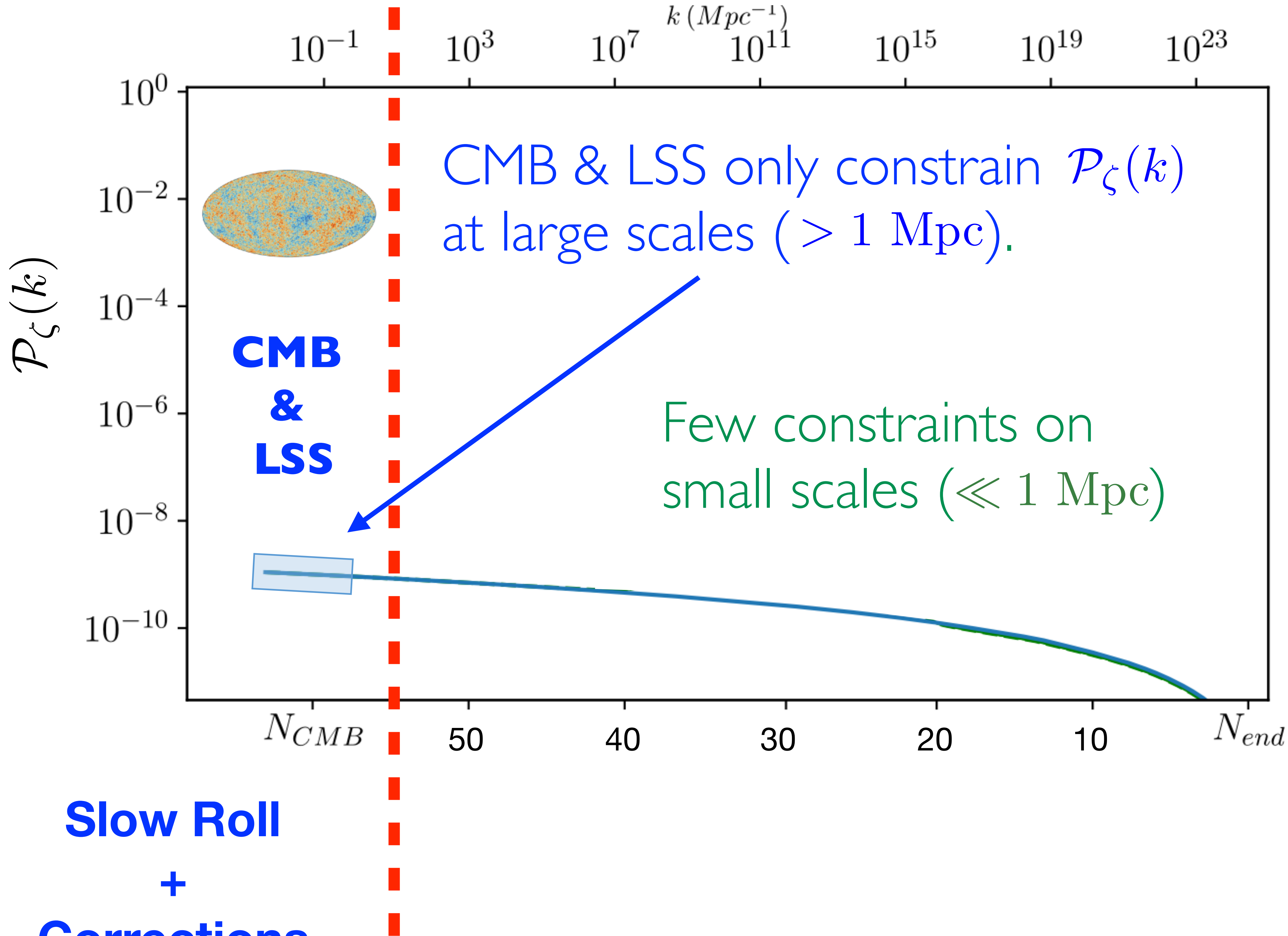
$$\int d\eta d\eta' a^p(\eta) \times e^{i|\mathbf{k}|\eta} \times H_{i\mu}(-|\mathbf{k}|\eta) \cdots \subset$$



Not until **2018** by Arkani-Hamed et al

III The dark era of inflation

Inflation on small scales?

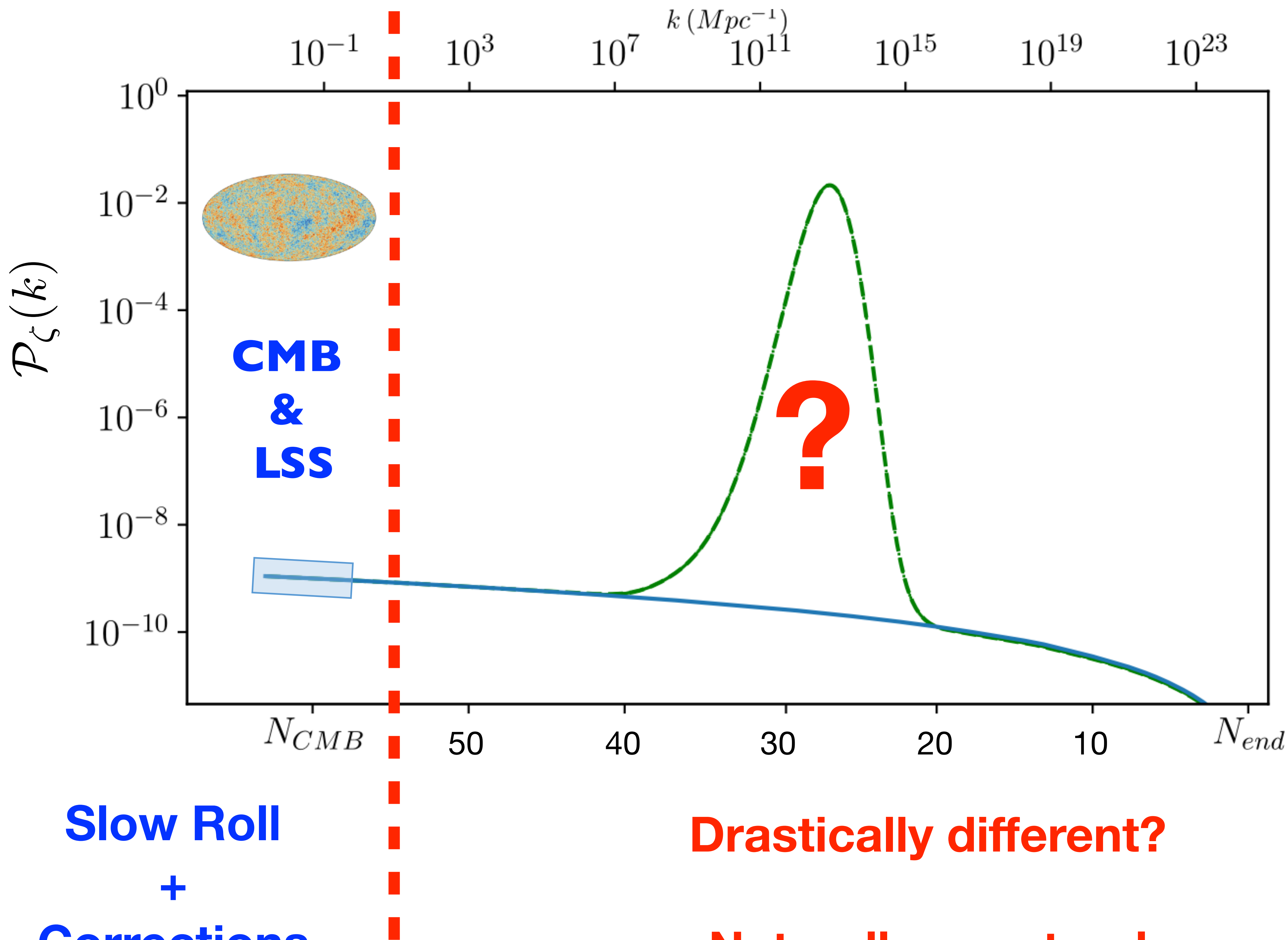


Slow Roll

+

Corrections

Inflation on small scales?



Slow Roll

+

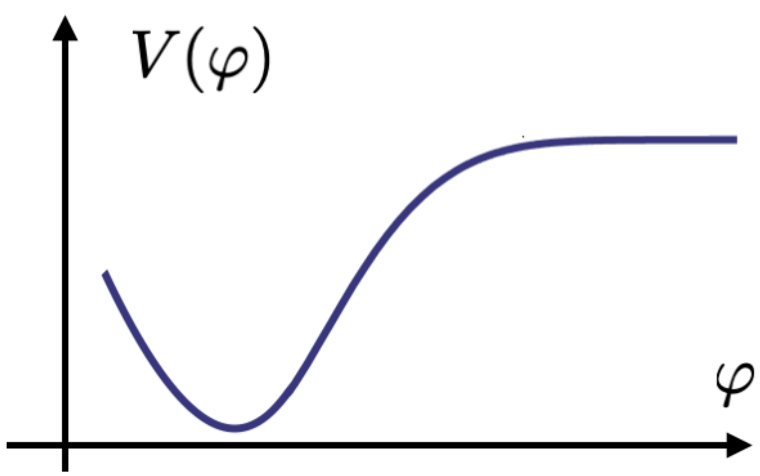
Corrections

Drastically different?

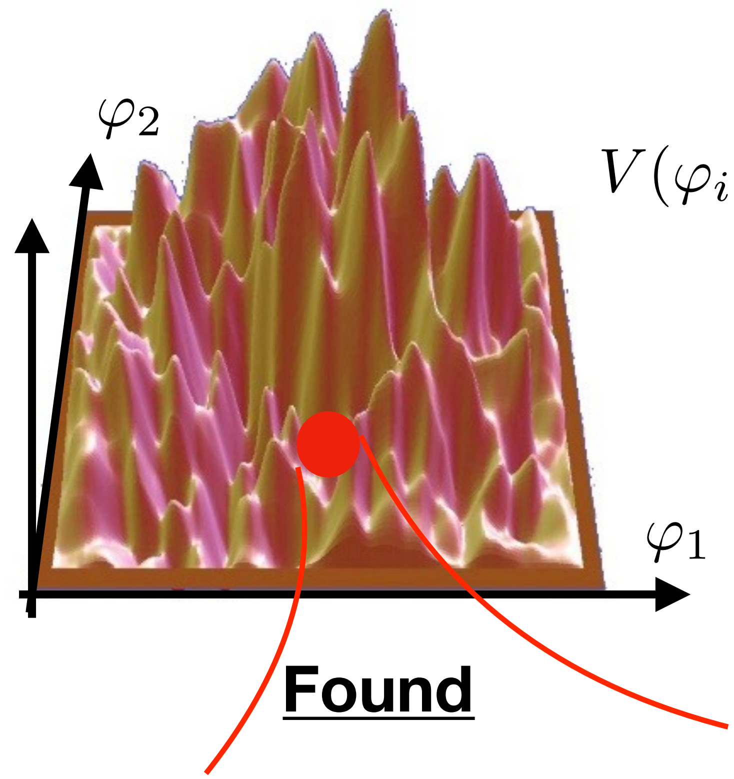
Naturally unnatural

Taking theory seriously

A prolonged phase of 60 e-folds of inflation is not natural (eta-problem)



Hoped

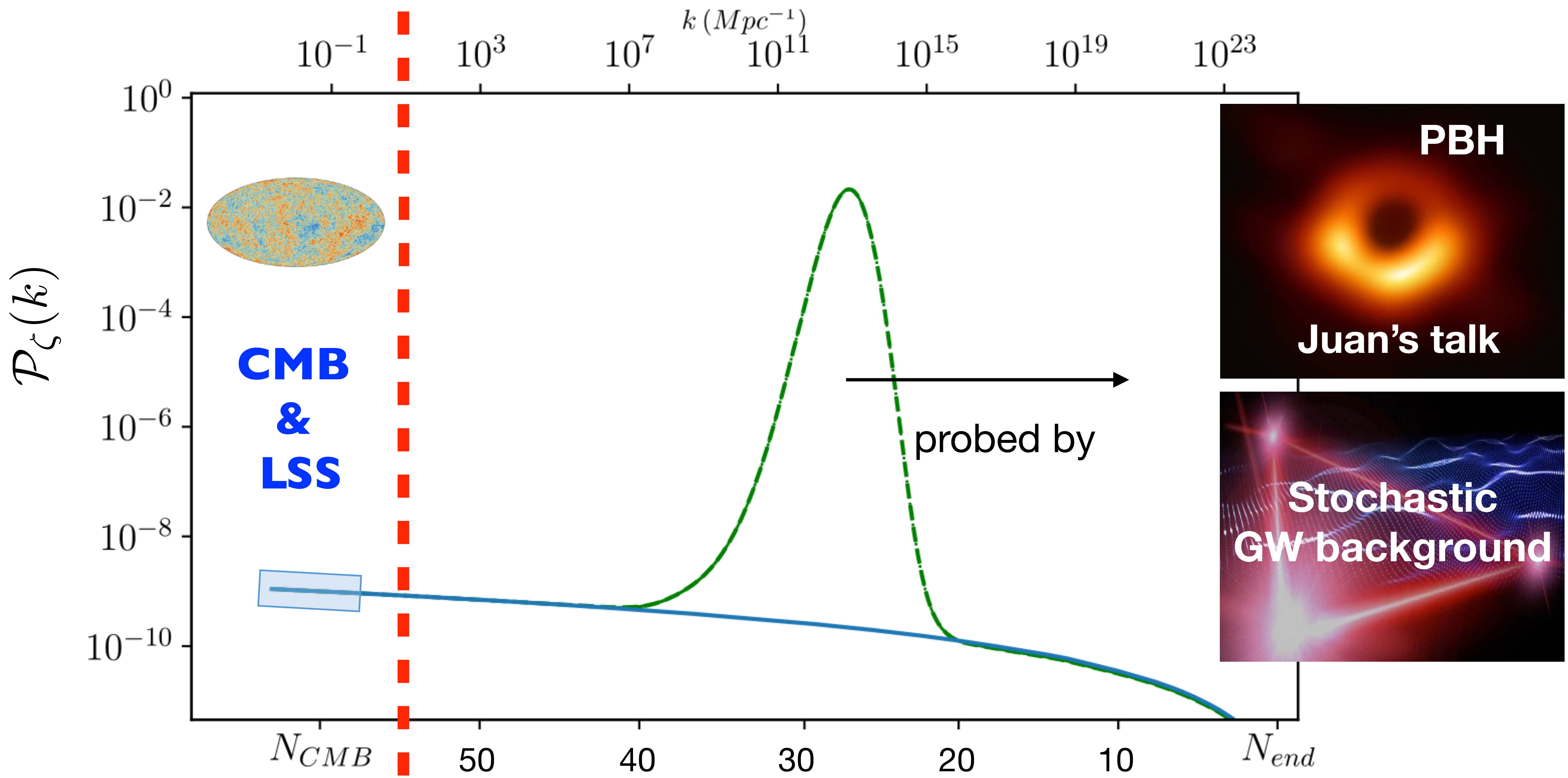


Found

More natural for inflation to have occurred in successive phases

Non-trivial physics at transitions: *features*

Inflation on small scales?



Slow Roll
+
Corrections

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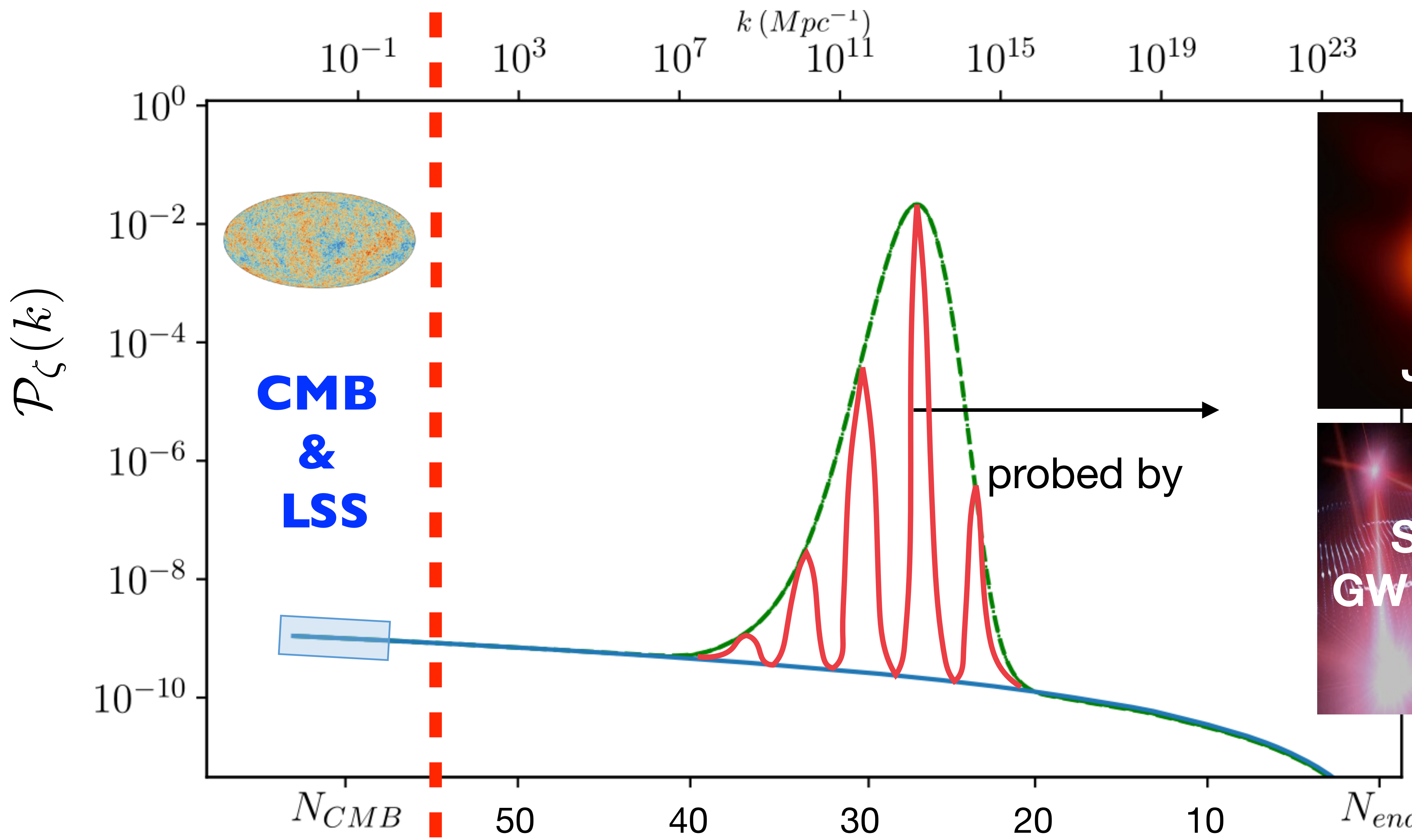
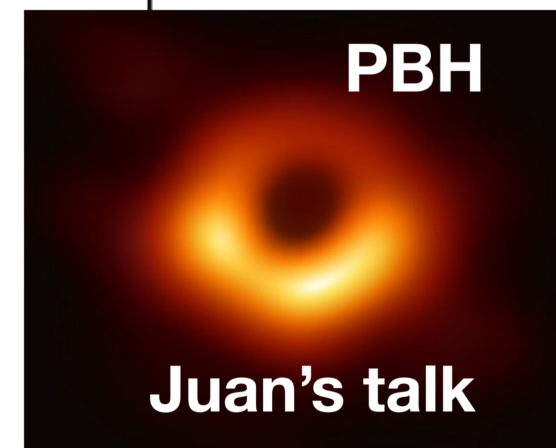
Inflation on small scales?





Slow Roll
+
Corrections

A sharp peak comes with large oscillations

Fumagalli, RP, Witkowski 2012.02761

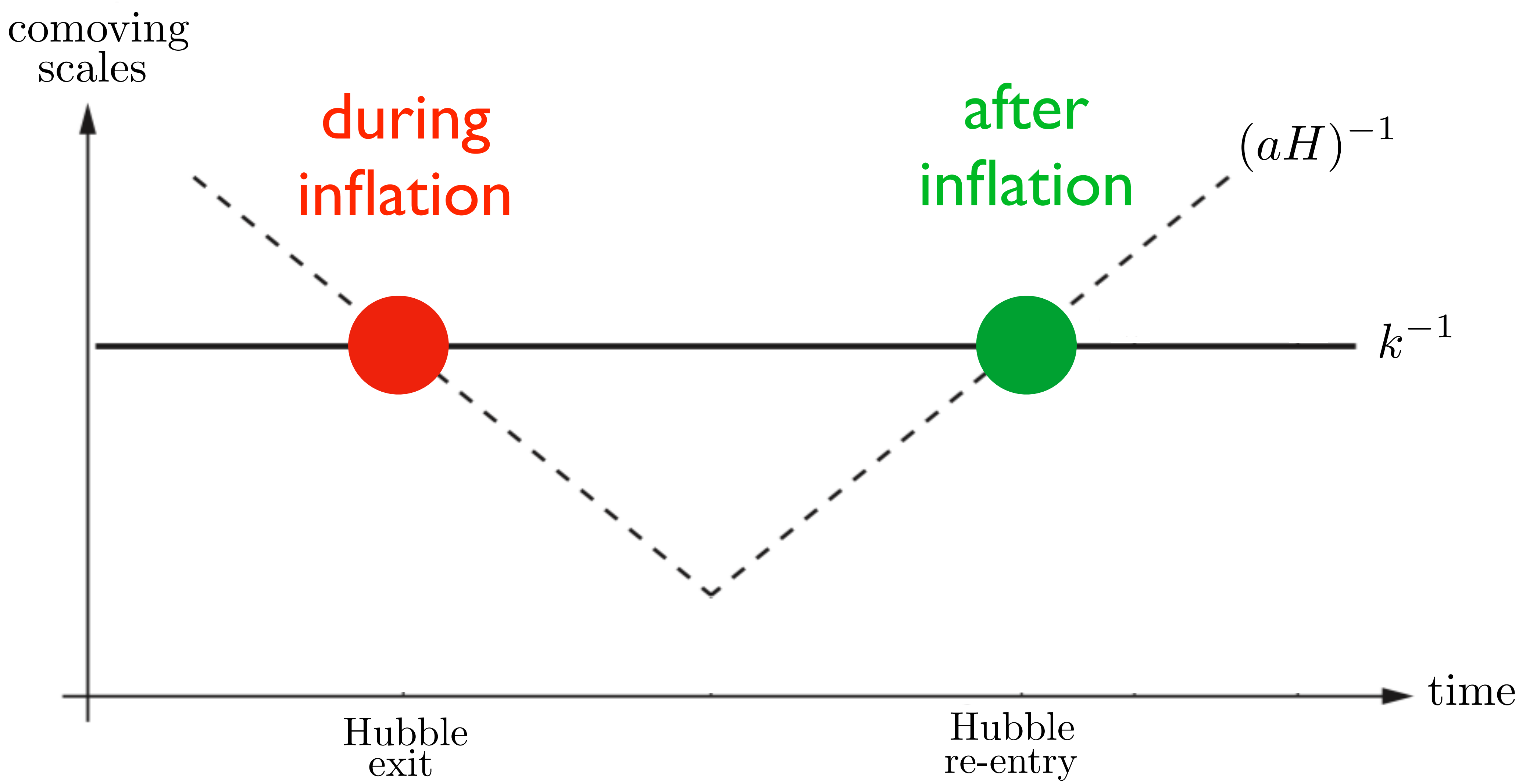
transferred

GW from inflation, which ones?

Vacuum quantum fluctuations $\Box h = 0$

well understood, looked for in CMB polarization, tiny for interferometers

Here: GW sourced by scalar fluctuations $\Box h \sim (\partial\zeta)^2$



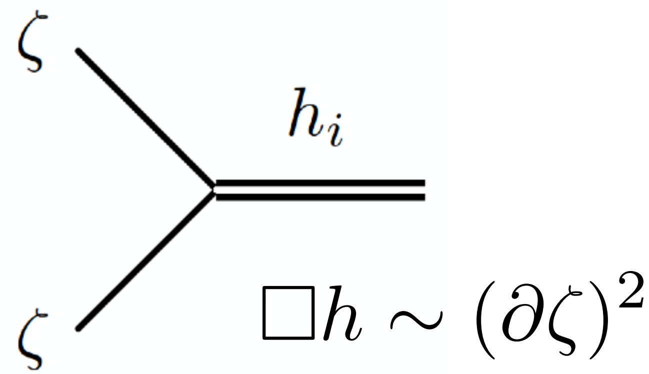
Probing inflation with the stochastic gravitational wave background

Frequency profile	$\Omega_{\rm GW}(f)$ $\quad \frac{f}{\rm Hz} = 1.5 \times 10^{-15} \frac{k}{\rm Mpc^{-1}}$
Chirality	$h_+ \neq h_\times$
Anisotropies	$\Omega_{\rm GW}(f, \hat{n})$
Correlations with other probes	$\rm GW \times (CMB, LSS, etc)$

Cosmology with the Laser Interferometer Space Antenna, 2204.05434

Post-inflationary scalar-induced GWs

Review Domenech 2021



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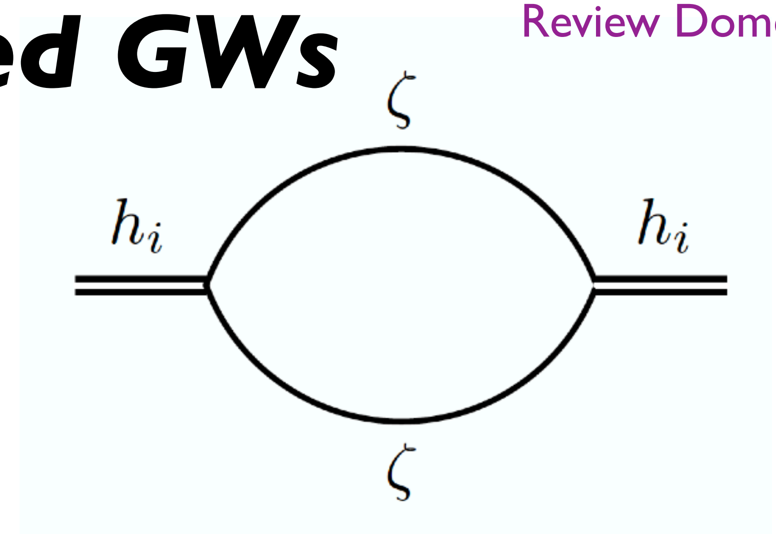


Enhanced $\delta\rho$ → Enhanced GWs at horizon re-entry after inflation

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

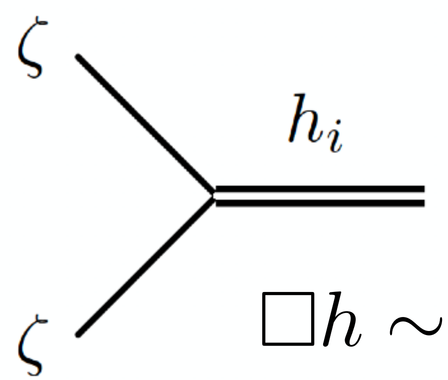
$$\Omega_{\rm GW}(k) = \int\int T(u,v)\mathcal{P}_\zeta(ku)\mathcal{P}_\zeta(kv) \quad \sim 10^{-5}\,\mathcal{P}_\zeta^2$$

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

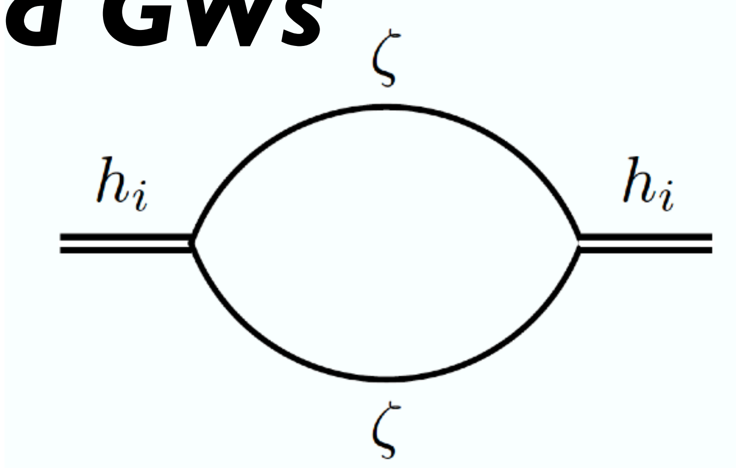
LISA

Post-inflationary scalar-induced GWs

Review Domenech 2021



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



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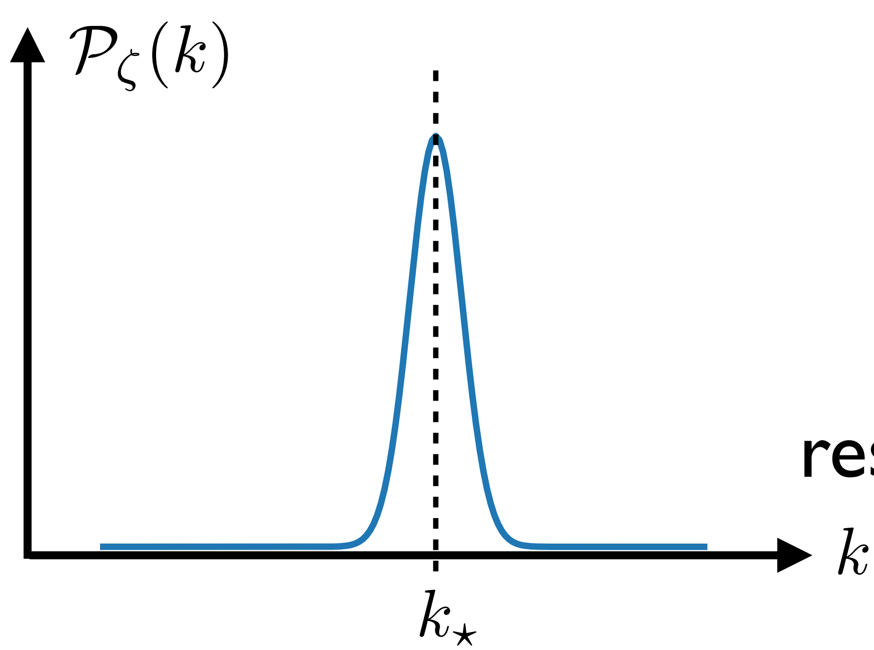
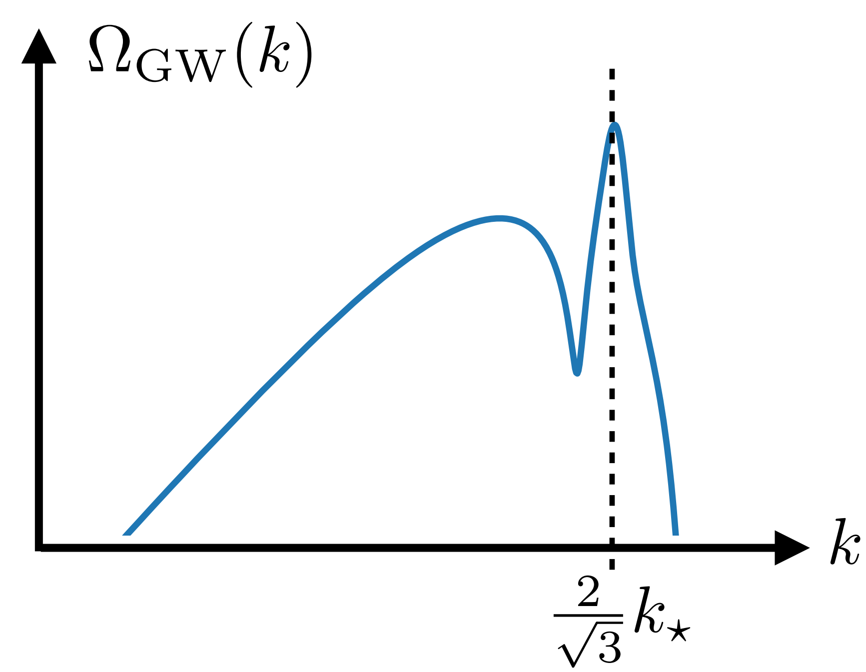
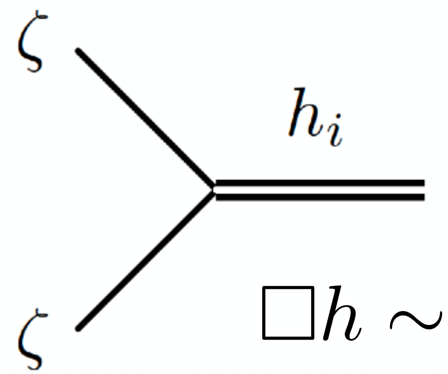


peak from resonant amplification



Post-inflationary scalar-induced GWs

Review Domenech 2021



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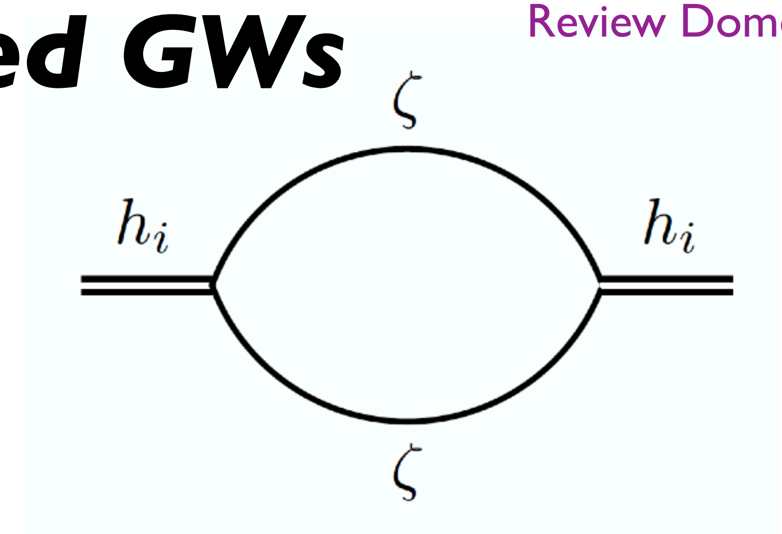
→



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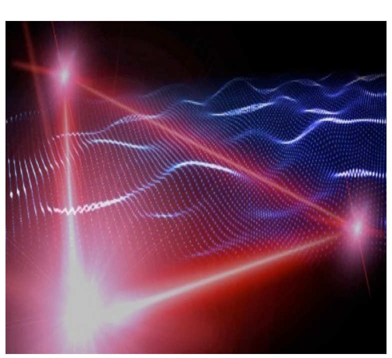
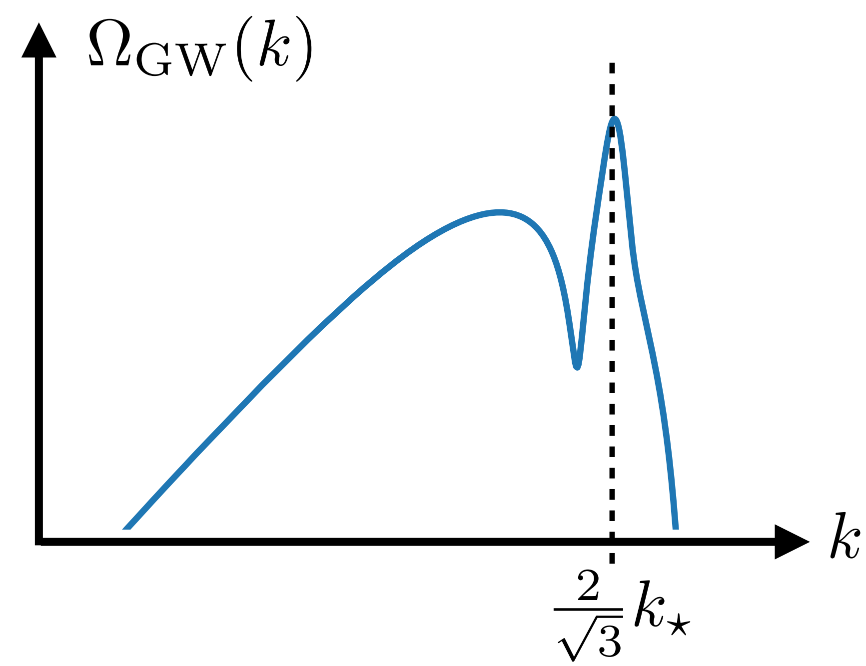
$$\Omega_{\rm GW}(k) = \int\int T(u,v)\mathcal{P}_\zeta(ku)\mathcal{P}_\zeta(kv) \quad \sim 10^{-5}\,\mathcal{P}_\zeta^2$$

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



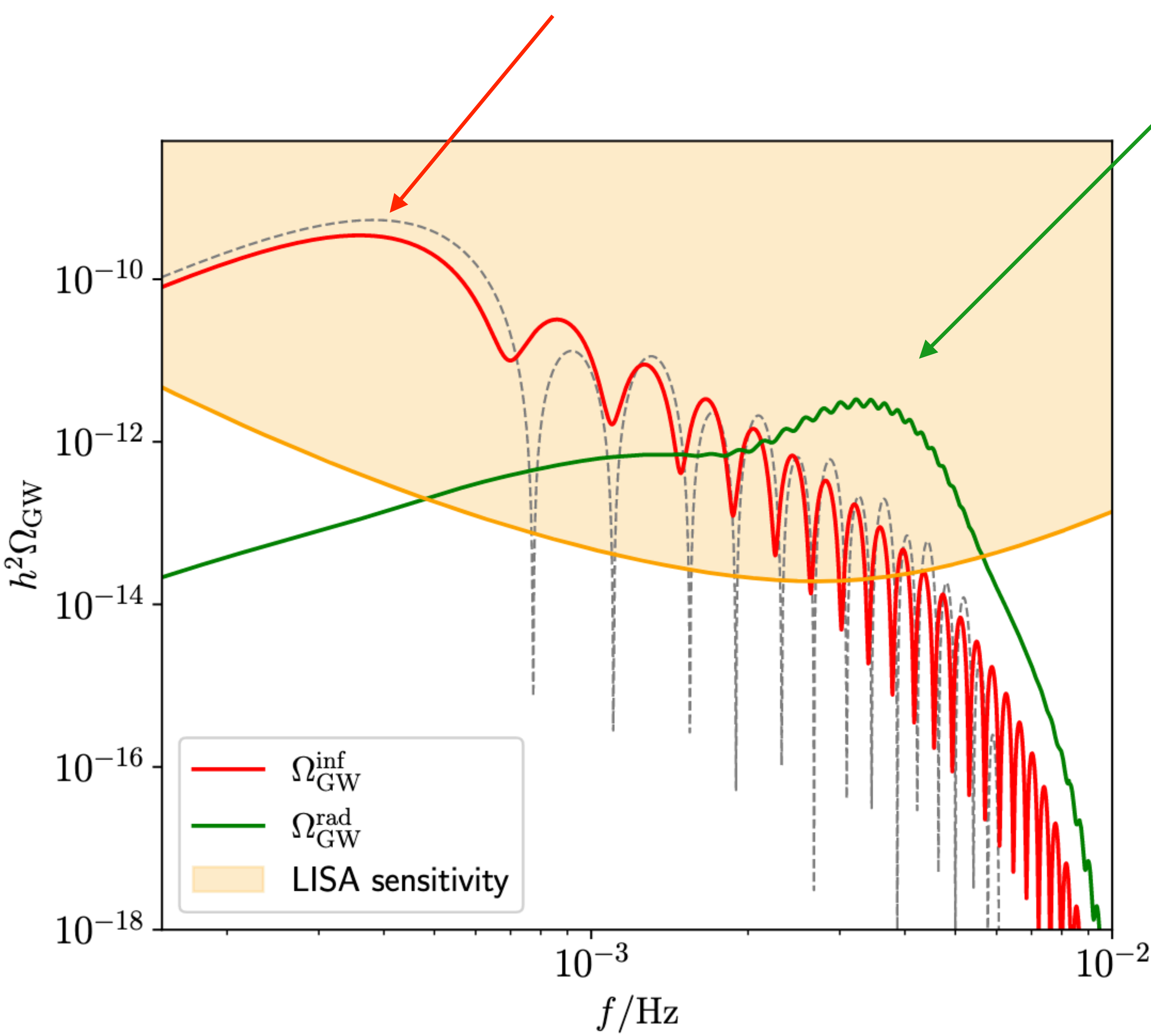
GW observatories probe inflation on small scales



Primordial GWs from sharp features

Scalar-induced GW during inflation

Scalar-induced GW after inflation



Oscillatory patterns in SGWB frequency profile

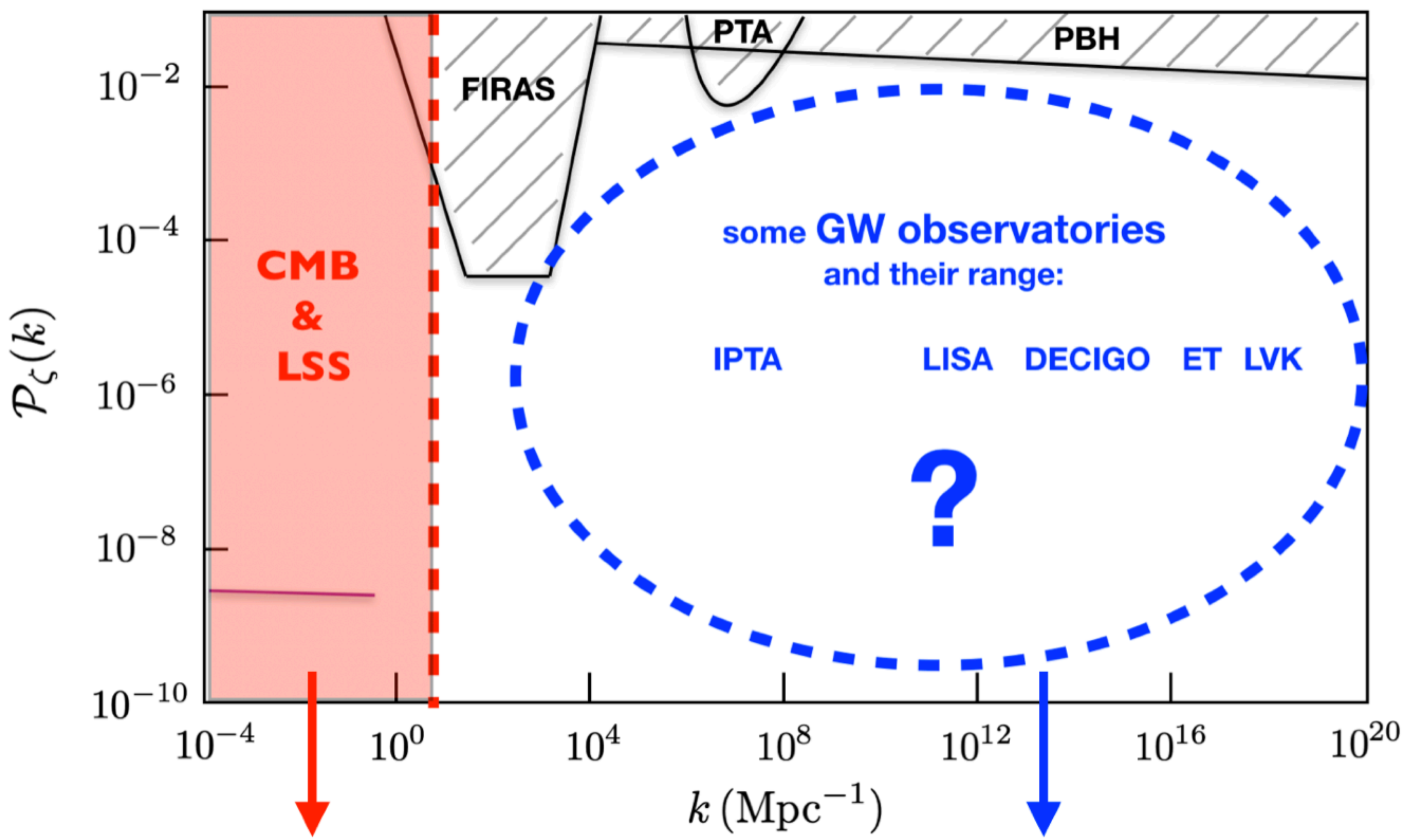
Model-independent information about physics of inflation on small scales

Motivated target of new physics

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

Conclusion:

Exciting time for inflationary cosmology!



Precision physics

Inflation as a cosmological collider

Exploratory physics

Probing dark inflationary era with gravitational waves

Conclusion:

Exciting time for inflationary cosmology!

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

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

- New mechanisms to inflate and new EFT of fluctuations

- Beyond standard perturbation theory (stochastic inflation, rare events, full pdf)