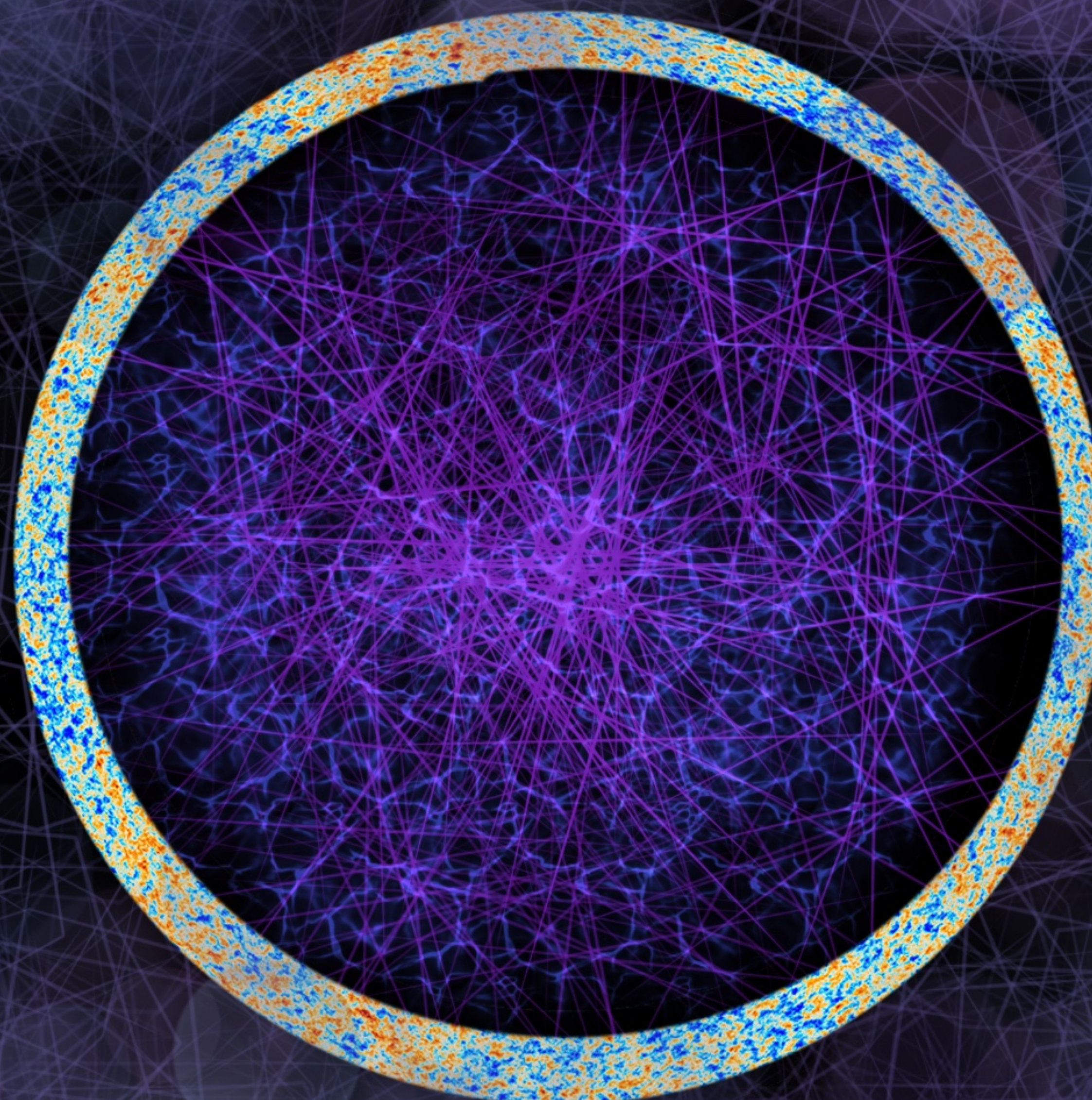
Status of Inflation



Daniel Green
UC San Diego

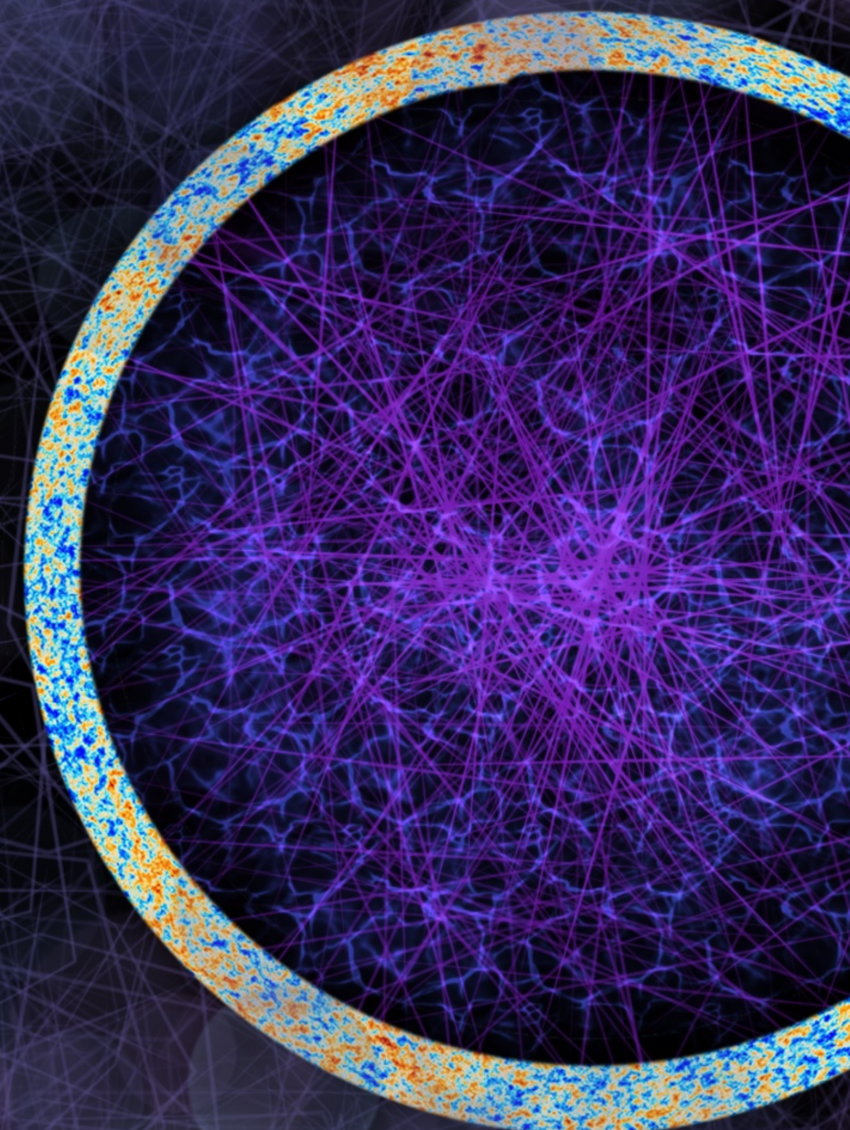
Motivation

Single Field Inflation

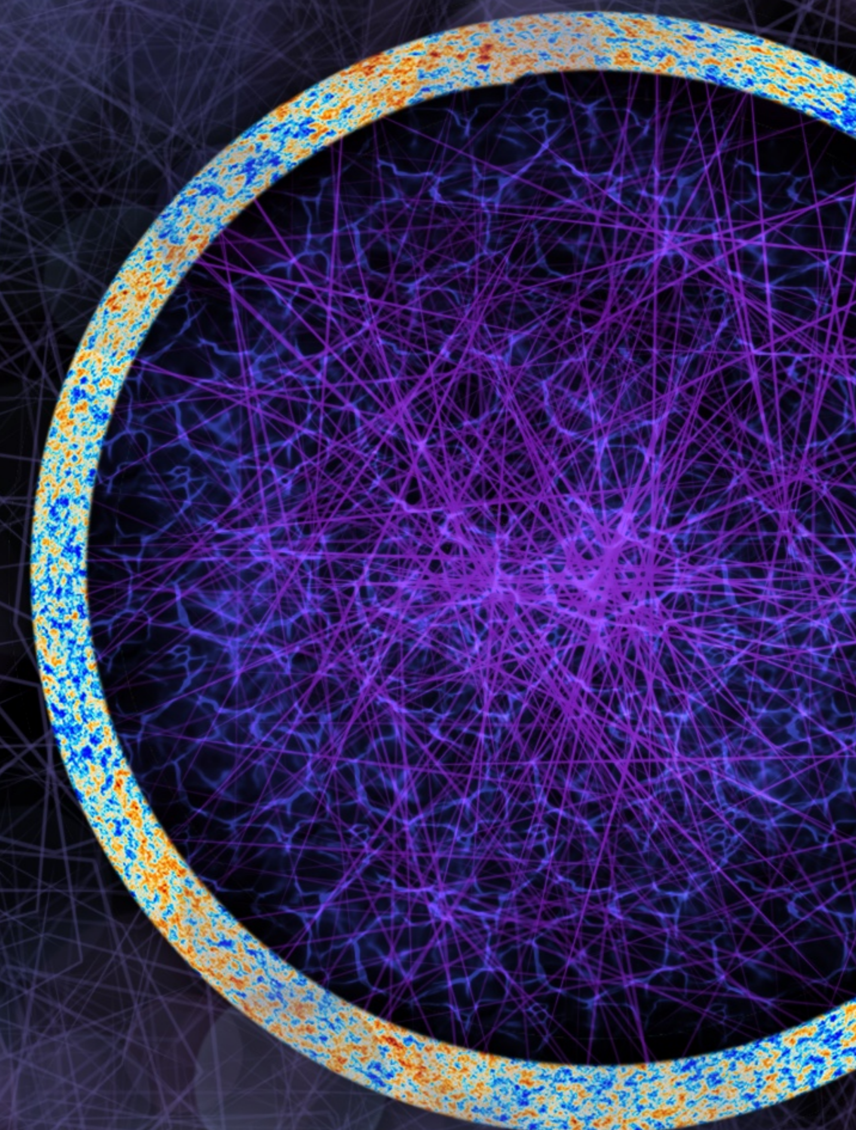
Multi-field Inflation

Recent Theory Developments

Future Observations

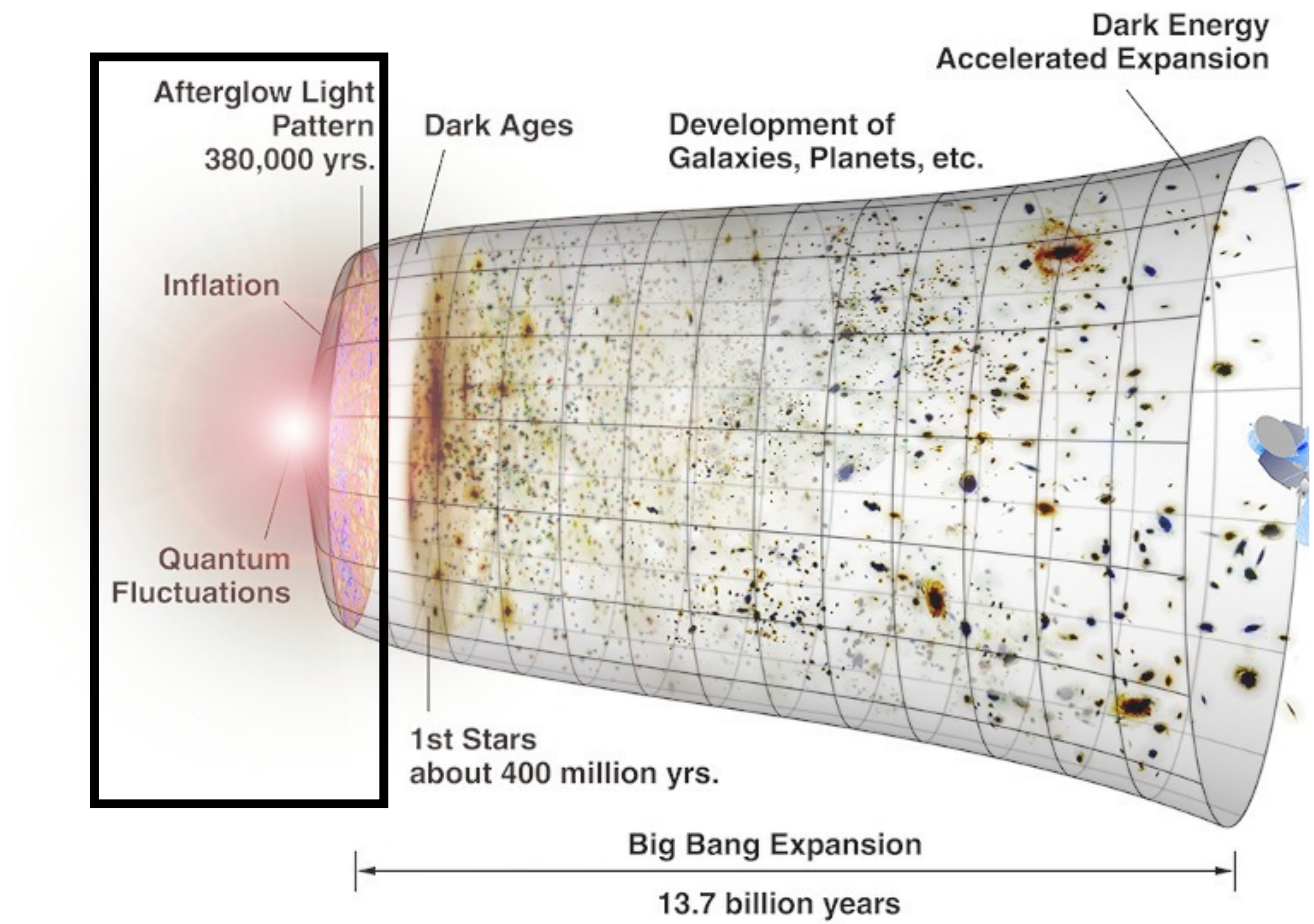


Motivation



The Nature of Inflation

The story of inflation is often told in one way

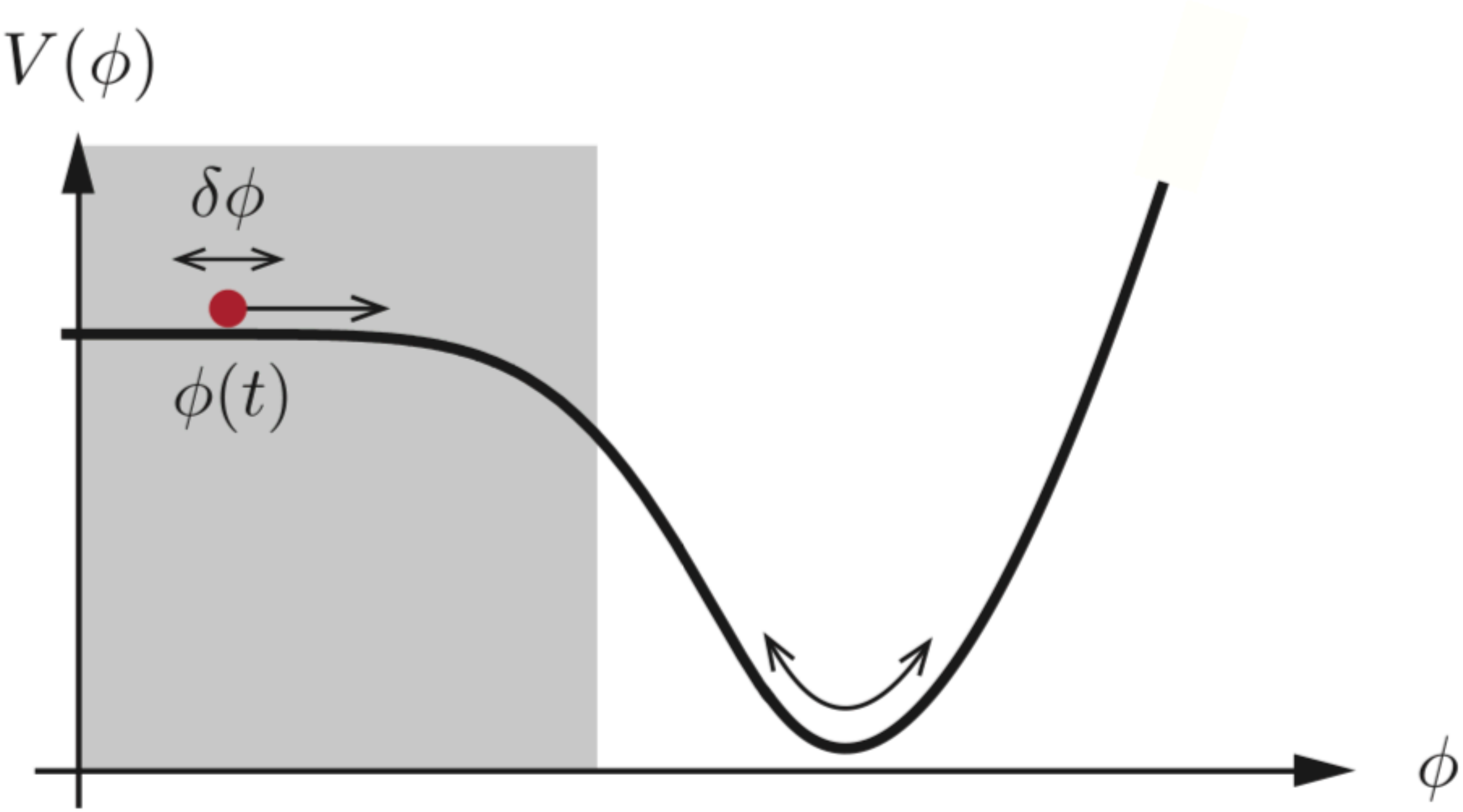


Period of exponential expansion

From WMAP

The Nature of Inflation

The story of inflation is often told in one way

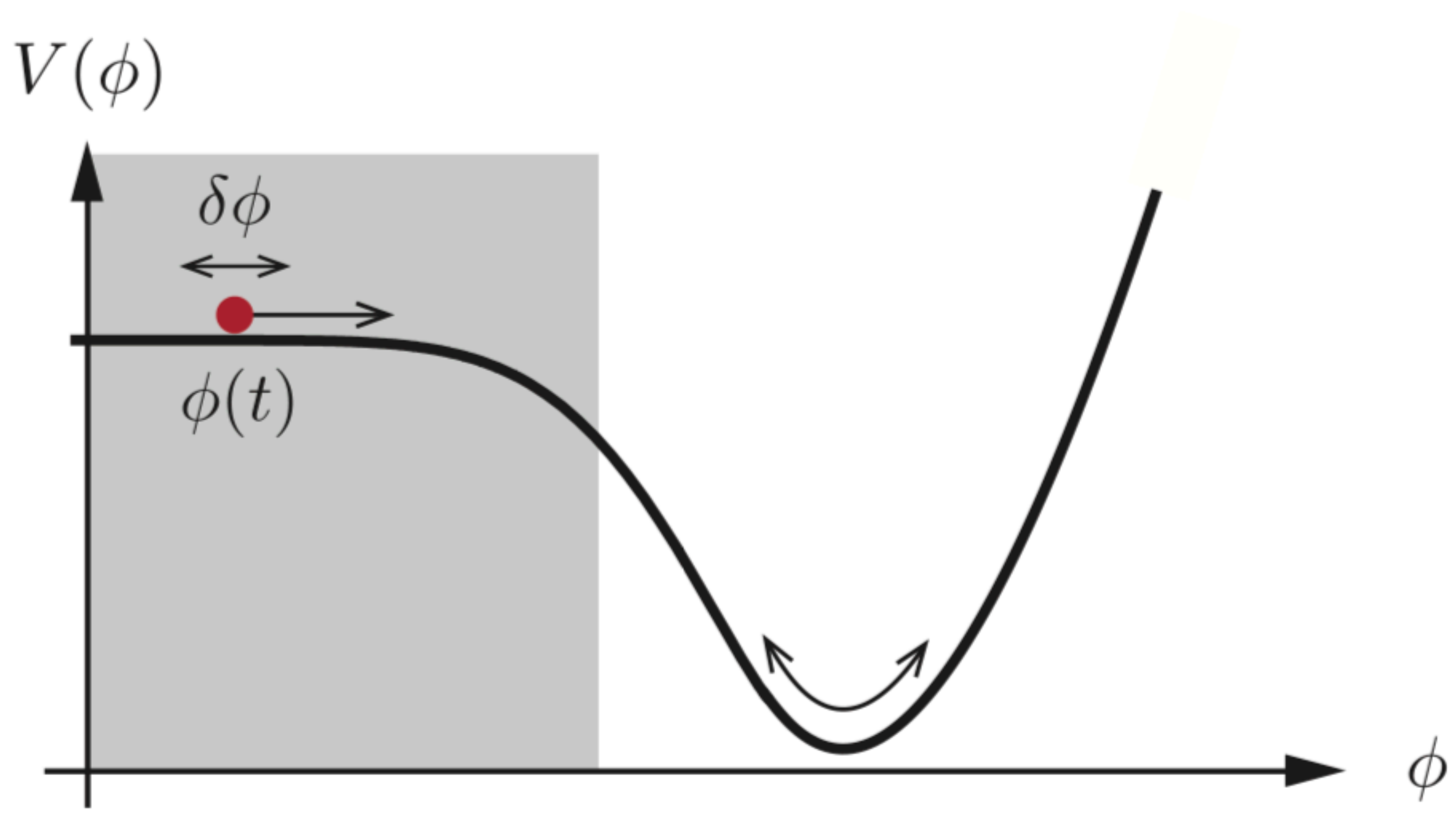


Driven by a slowly rolling scalar field

From Baumann & McAllister

The Nature of Inflation

The story of inflation is often told in one way

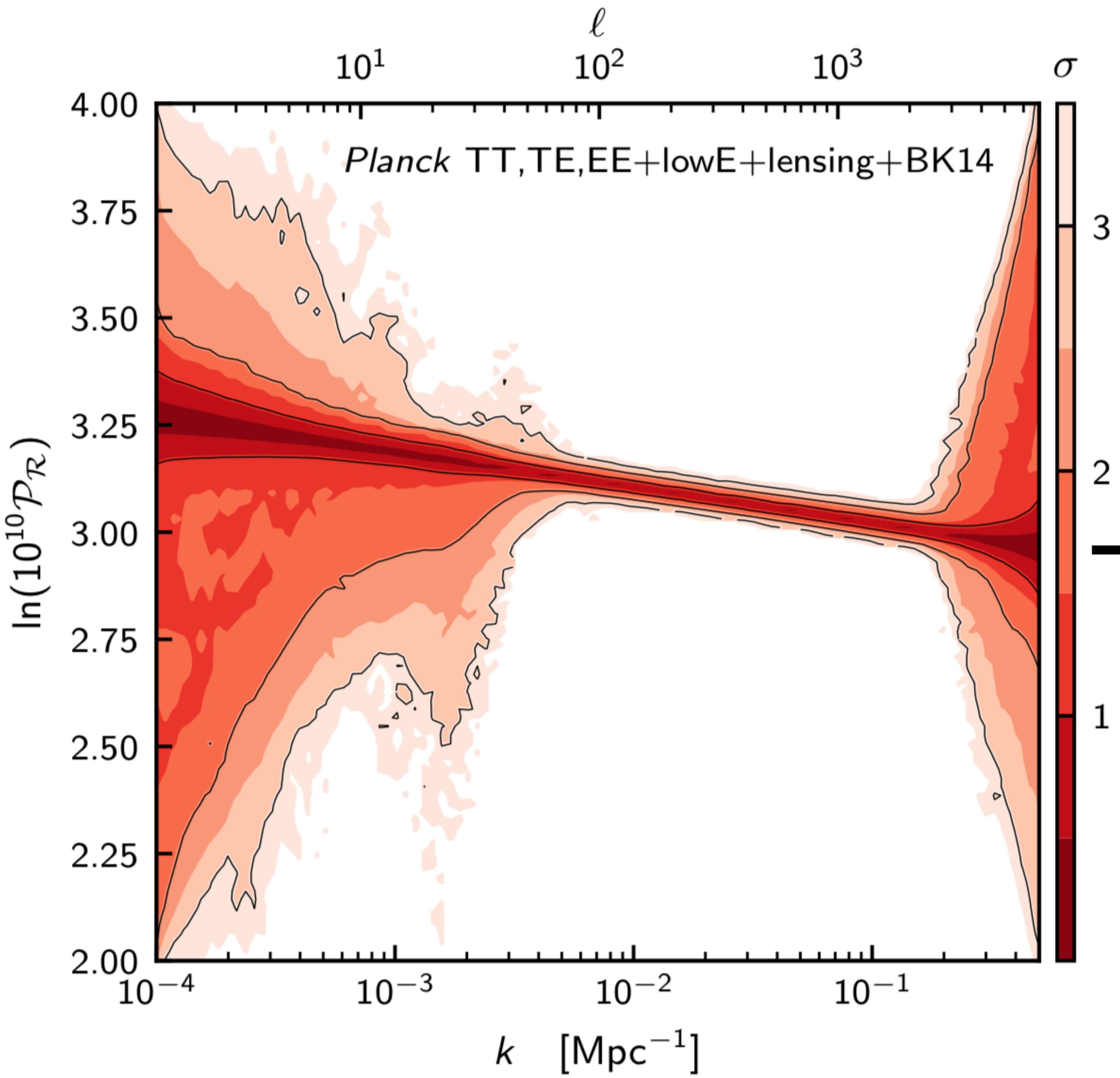


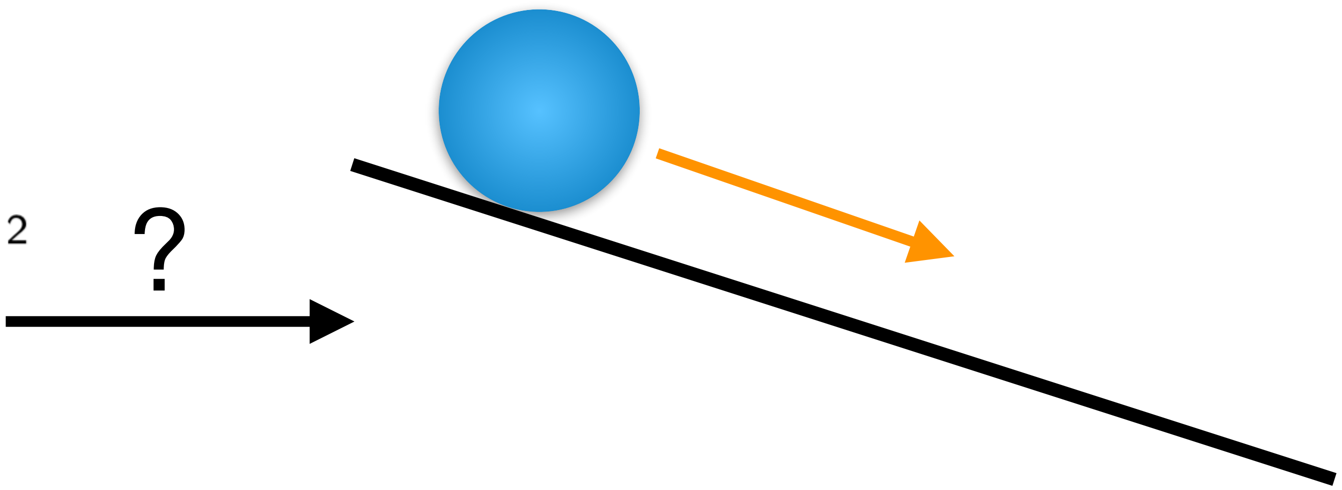
Quantum fluctuations of this field = initial conditions

From Baumann & McAllister

The Nature of Inflation

This pictures is consistent with observations





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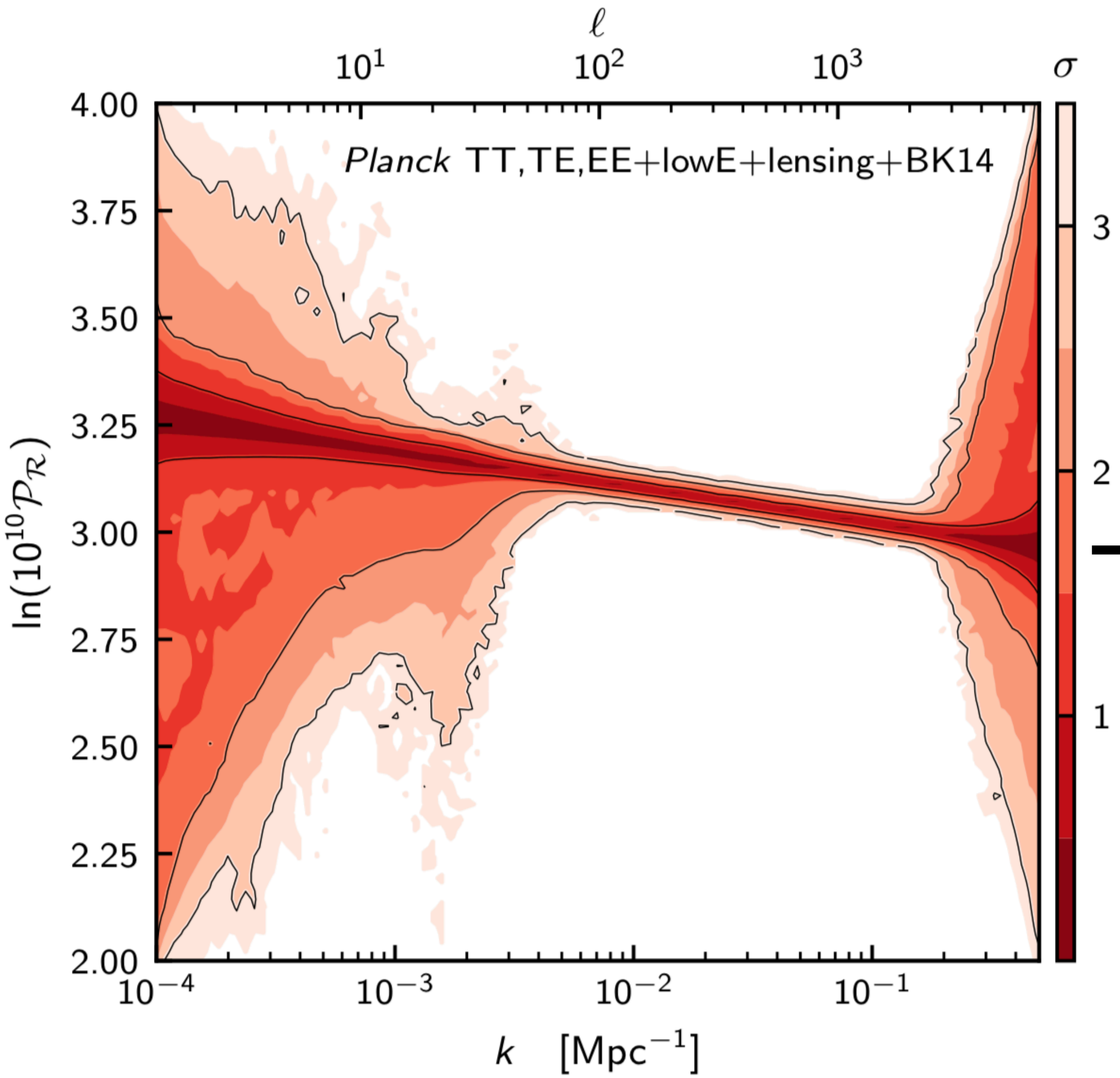
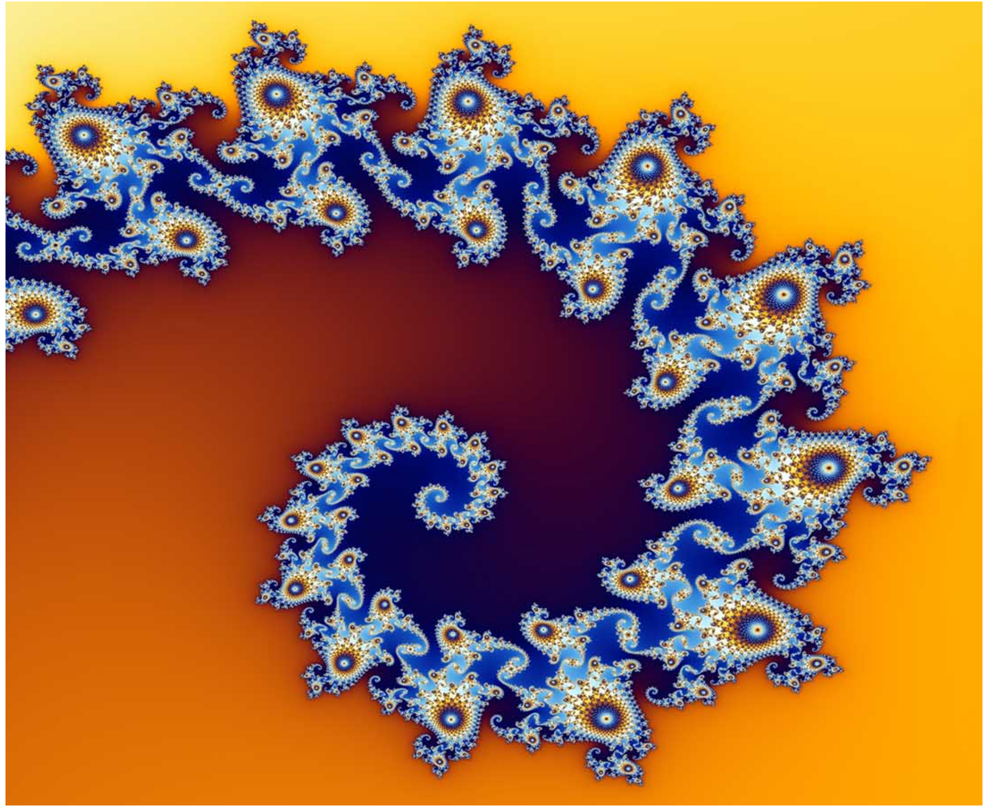
The Nature of Inflation

But is it necessary ?



?



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The Nature of Inflation

Inflation：A definition

（1）A period of quasi-de Sitter expansion

$$H \equiv \frac{\dot{a}}{a} \qquad \dot{H}(t) \ll H^2 \qquad a(t) \approx e^{Ht}$$

（2）Inflation ends：requires a physical clock

In slow roll inflation – we set our clocks to $\phi(t) \approx \dot{\phi}\, t$

The Nature of Inflation

Raises the question: what is the clock?

Real world clocks are not fundamental scalars

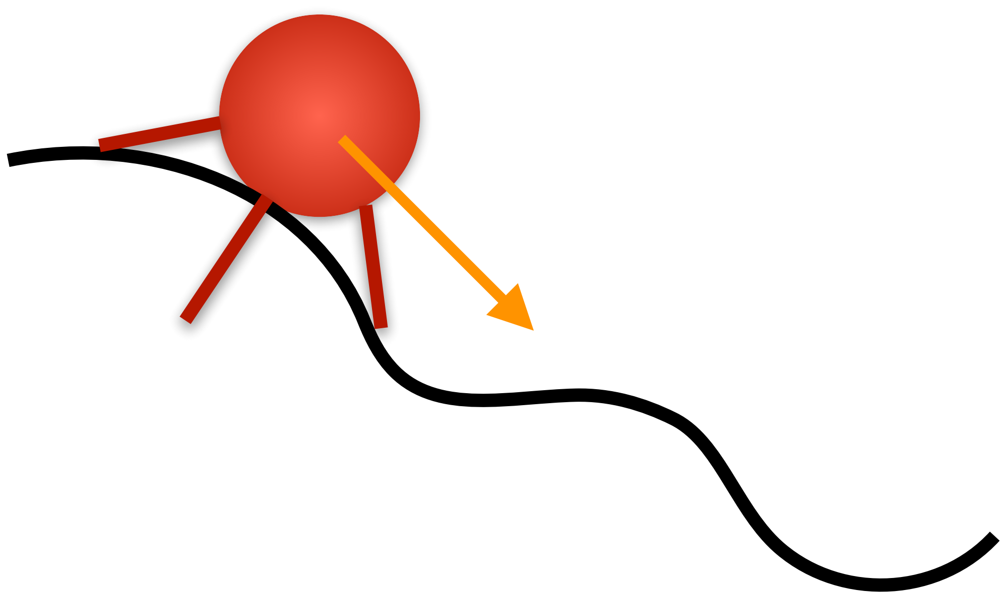
Many seemingly different mechanisms give the same or similar predictions

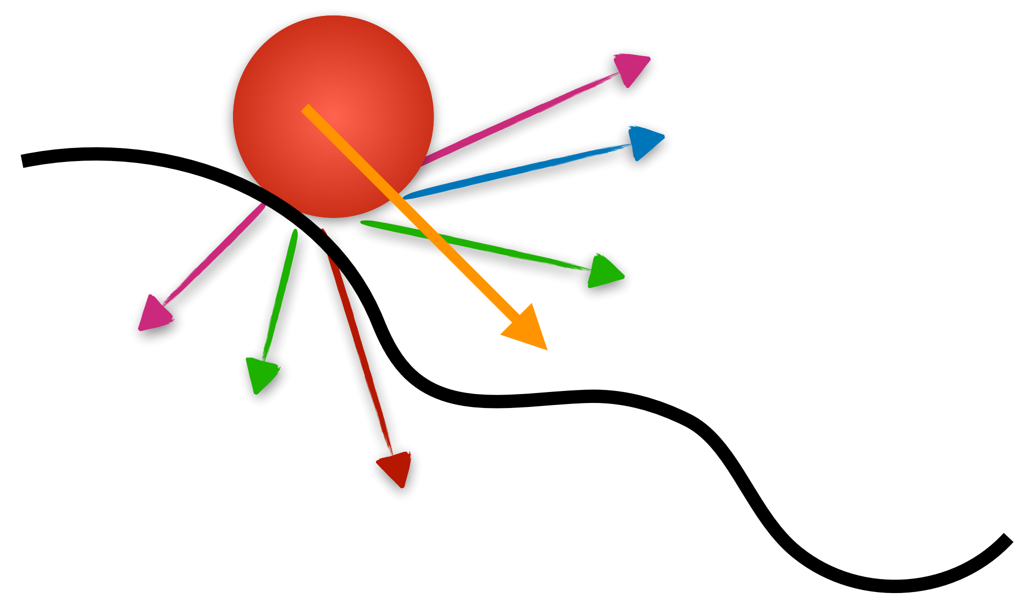
What is inflation and how do we test the framework?

The Nature of Inflation

Might expect dynamics = non-Gaussian

Seen in specific examples



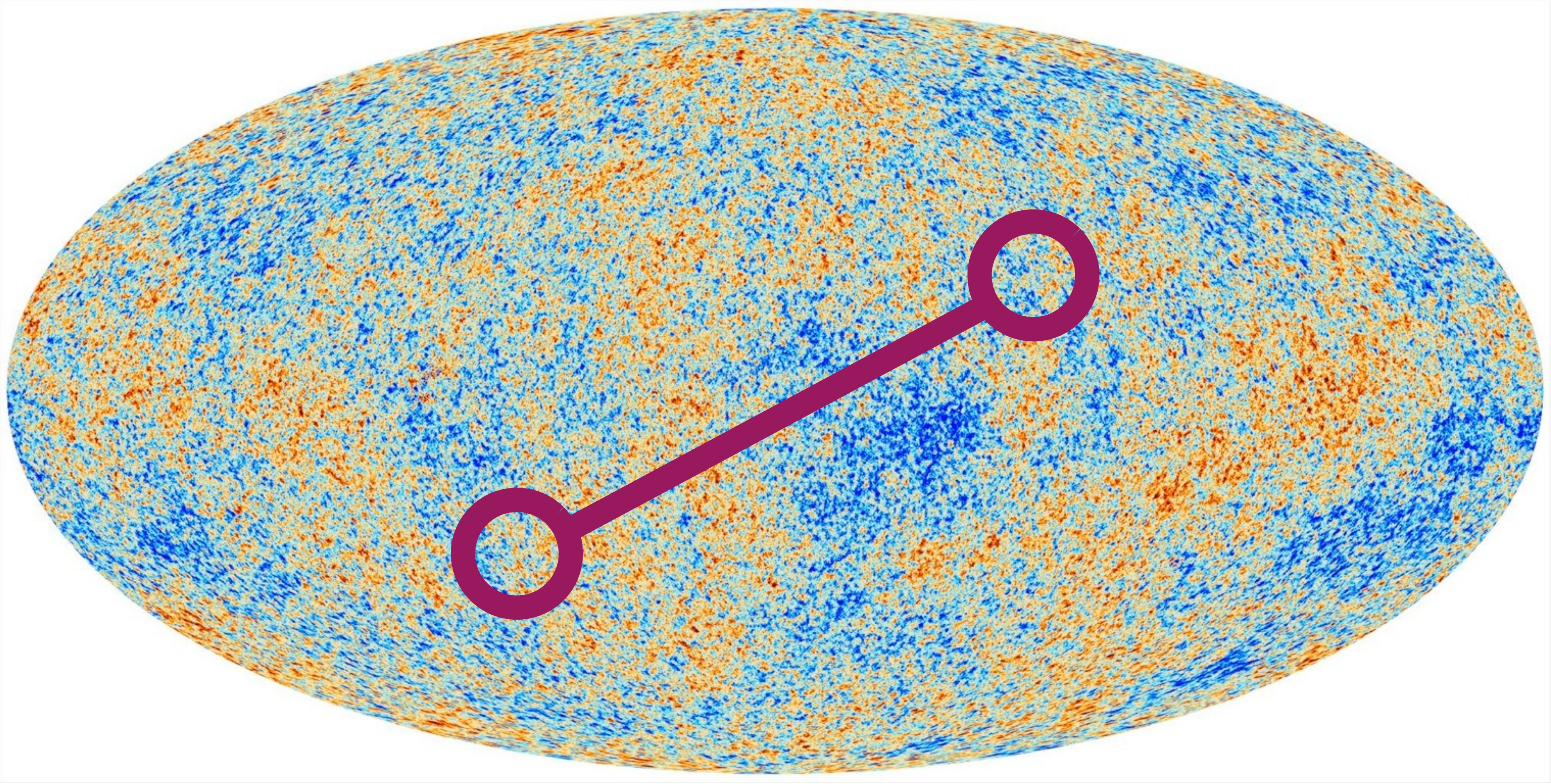


e.g. self-interactions or particle-production

Both lead to large non-Gaussian correlations

Gaussian Fluctuations

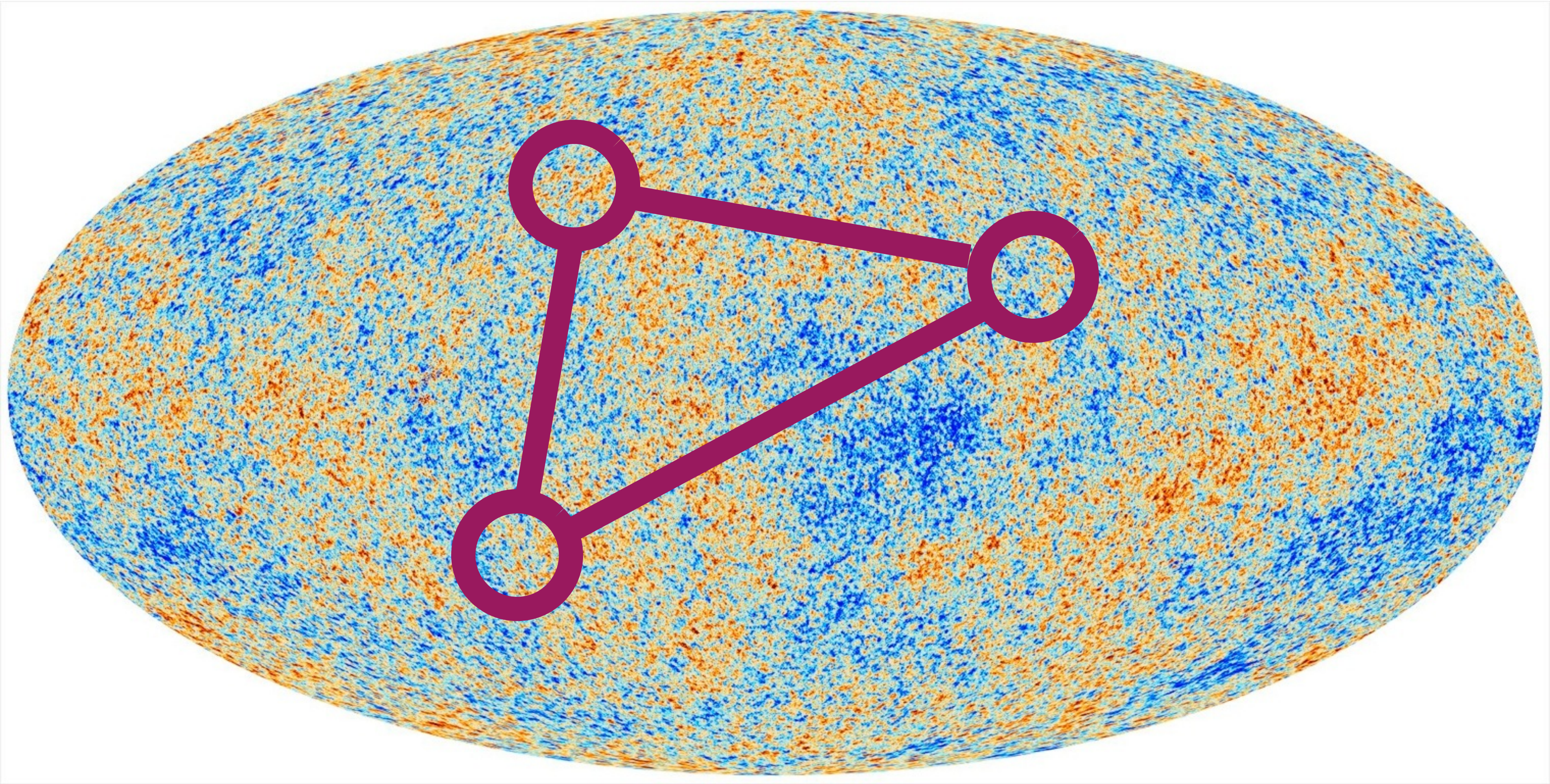
Fixed by two-point statistics



$$\langle \delta T(\vec{x}) \delta T(\vec{x}') \rangle = f(|\vec{x} - \vec{x}'|) \leftrightarrow \langle \zeta_{\vec{k}} \zeta_{\vec{k}'} \rangle = \tilde{f}(k)(2\pi)^3 \delta(\vec{k} + \vec{k}')$$

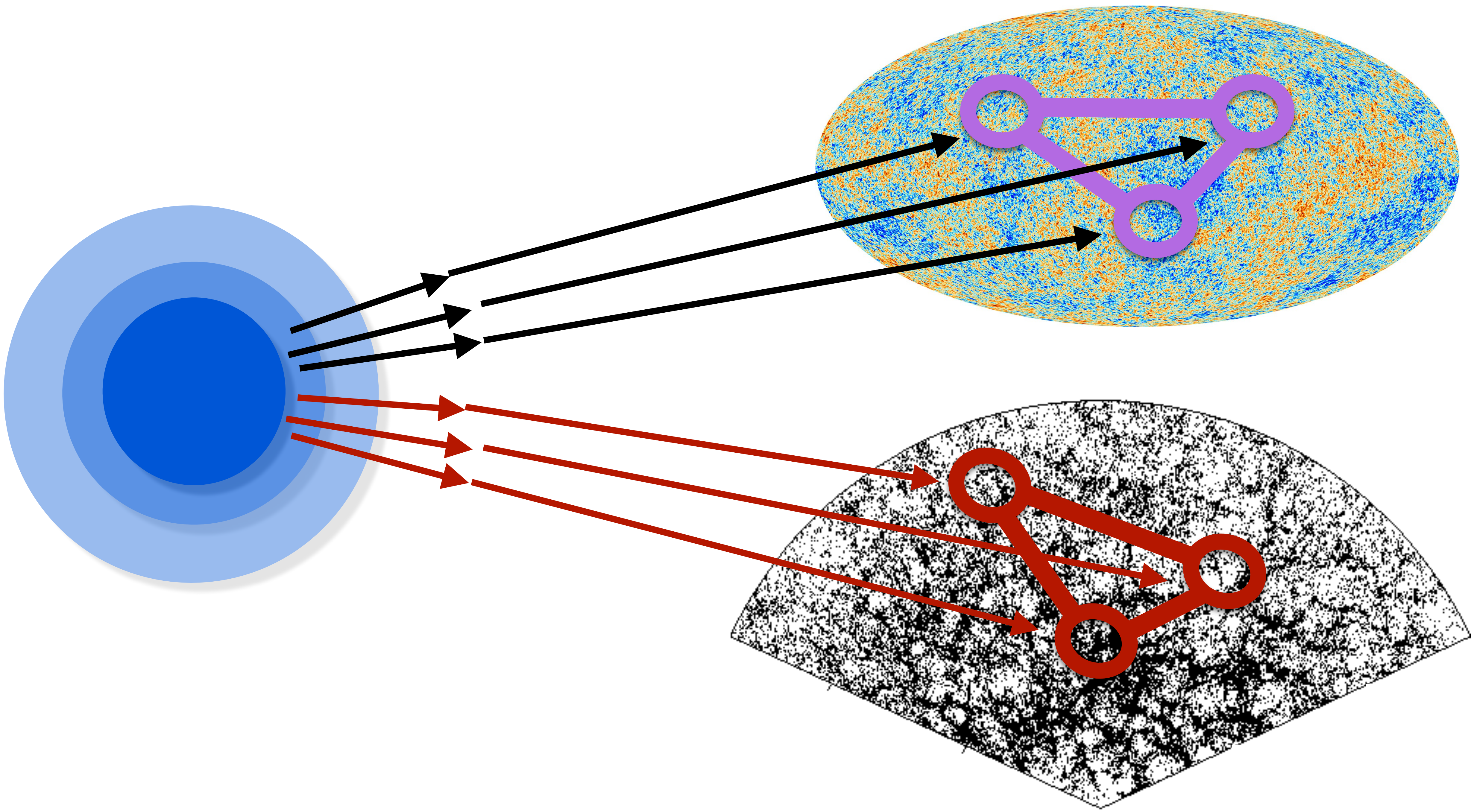
Non-Gaussian Fluctuations

What about non-Gaussian correlators? E.g. 3-point



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

Primordial Non-Gaussianity

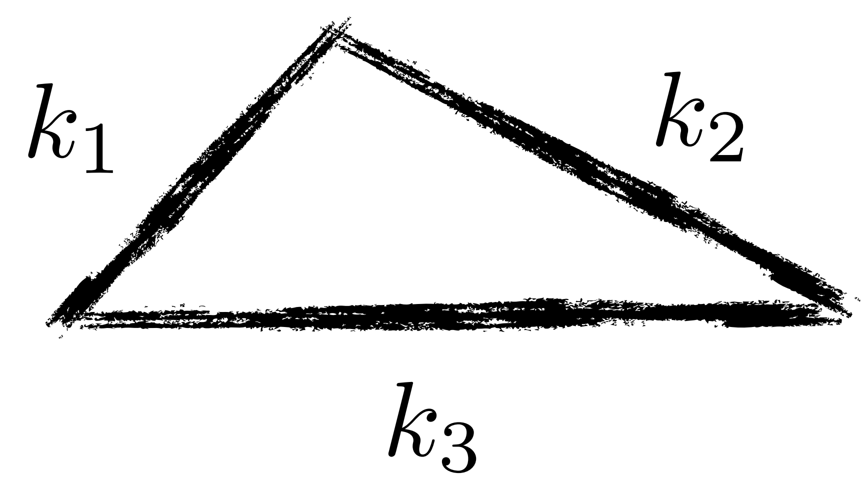


Primordial Non-Gaussianity

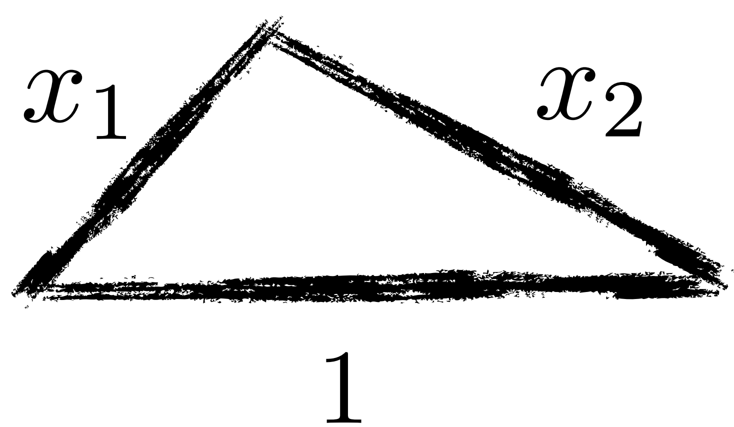
On general grounds, bispectra take the form

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

Momentum conservation:



Scale invariance:



$$\times \frac{1}{k_3^6}$$

Primordial Non-Gaussianity

Defined by amplitude and "shape"

$$B(k_1, k_2, k_3) = f_{\rm NL} \frac{18}{5} \frac{\Delta_\zeta^4}{k_3^6 x_1^2 x_2^2} S(x_1, x_2)$$

The shapes live in a basis of orthogonal functions

$$\int dx_1 dx_2 S_1(x_1, x_2) S_2(x_1, x_2) = S_1 \cdot S_2 = \cos_{12}$$

Cosine is how easily they are distinguish (in 3pt)

Primordial Non-Gaussianity

Amplitude defined so that statistics are Gaussian if

$$\Delta_\zeta f_{\rm NL} \approx \frac{\langle \zeta^3 \rangle'}{\left(\langle \zeta^2 \rangle'\right)^{\frac{3}{2}}} \qquad\qquad f_{\rm NL} \ll \Delta_\zeta^{-1} \approx 10^4$$

E.g. for a derivative interaction $\mathcal{L}_{\rm int} \supset \frac{1}{\Lambda^2} \dot{\pi}_c \nabla_\mu \pi \nabla^\mu \pi$

Weak coupling at horizon crossing means

$$\frac{H^2}{\Lambda^2} \approx f_{\rm NL} \Delta_\zeta \ll 1$$

Current Limits

The "Local Shape"

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

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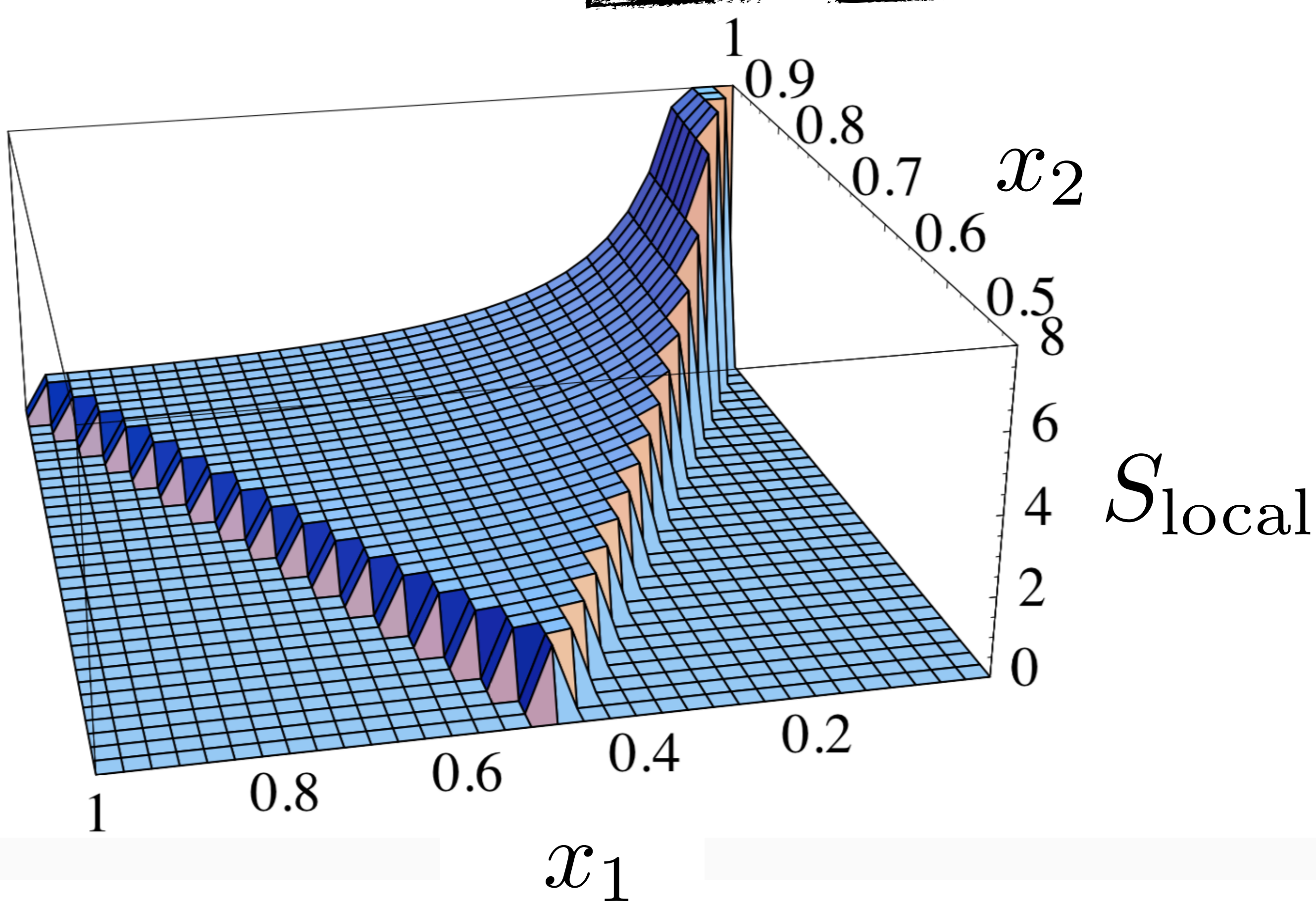

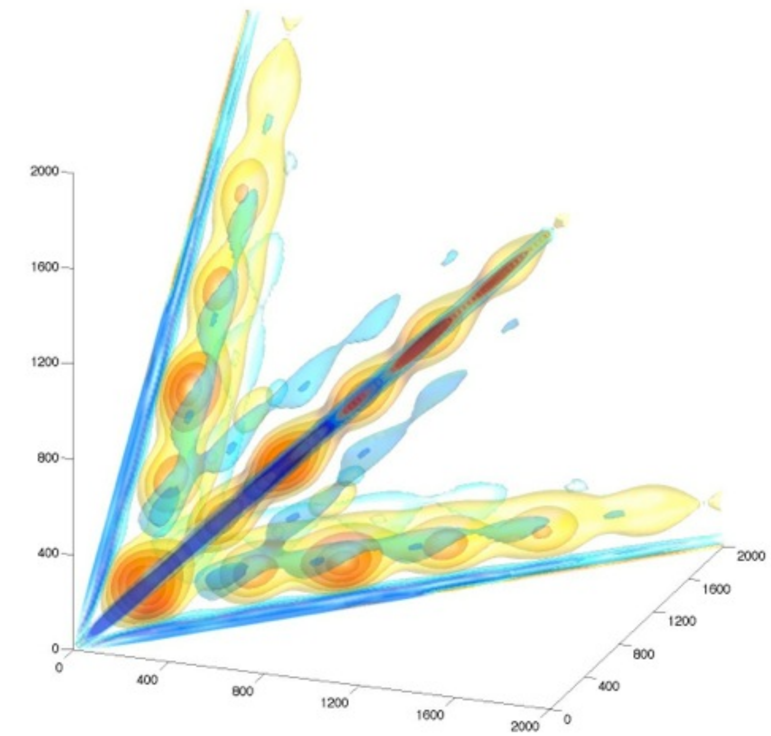

Courtesy of Fergusson & Shellard

Babich et al. (2004)

Current Limits

The “Equilateral Shape”

$$f_{\mathrm{NL}}^{\mathrm{equil}} = -26 \pm 47$$

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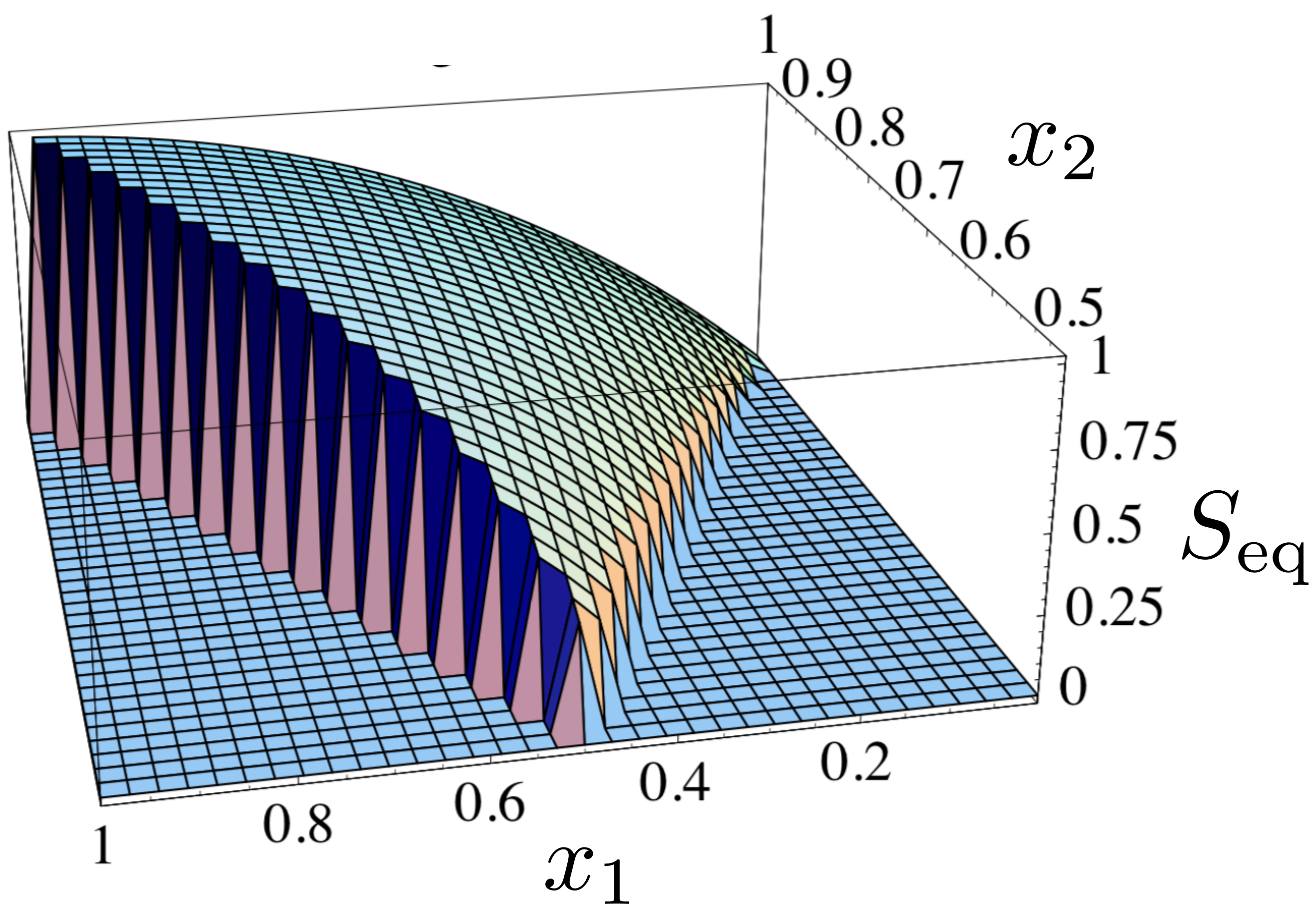

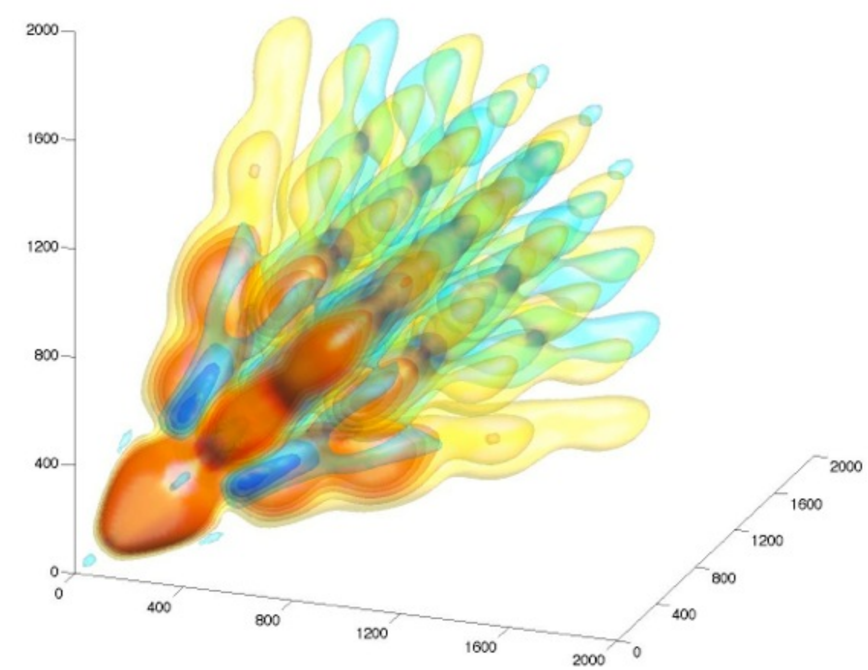

Courtesy of Fergusson & Shellard

Babich et al. (2004)

Current Limits

The "Orthogonal Shape"

$$f_{\rm NL}^{\rm ortho} = -38 \pm 24$$

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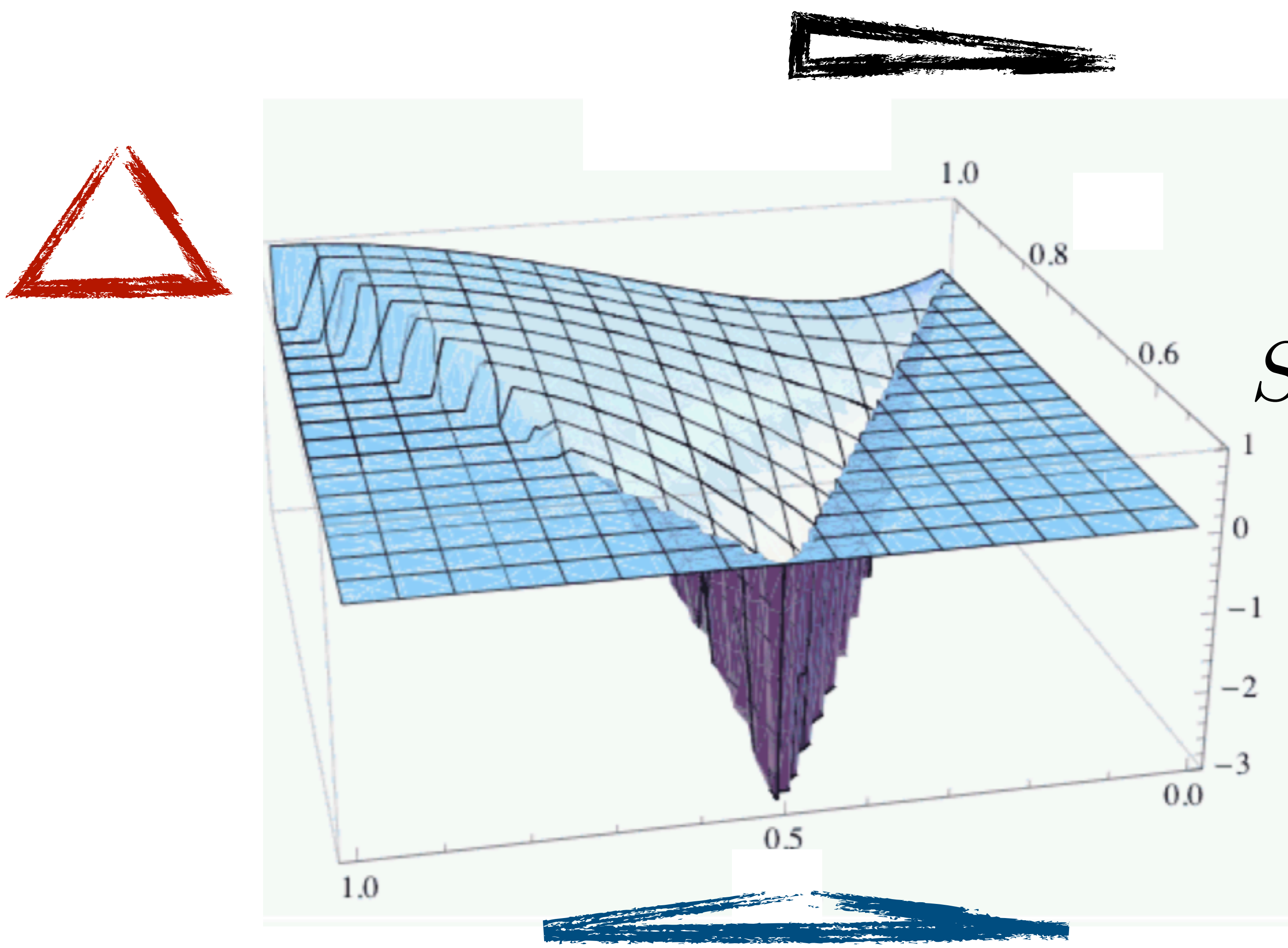
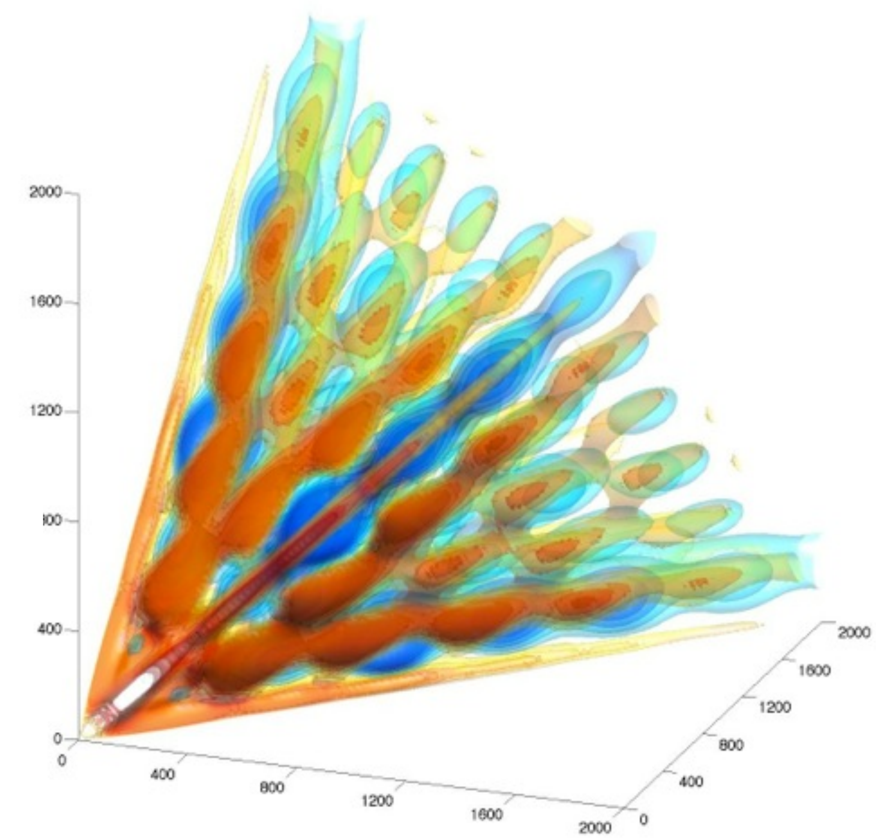


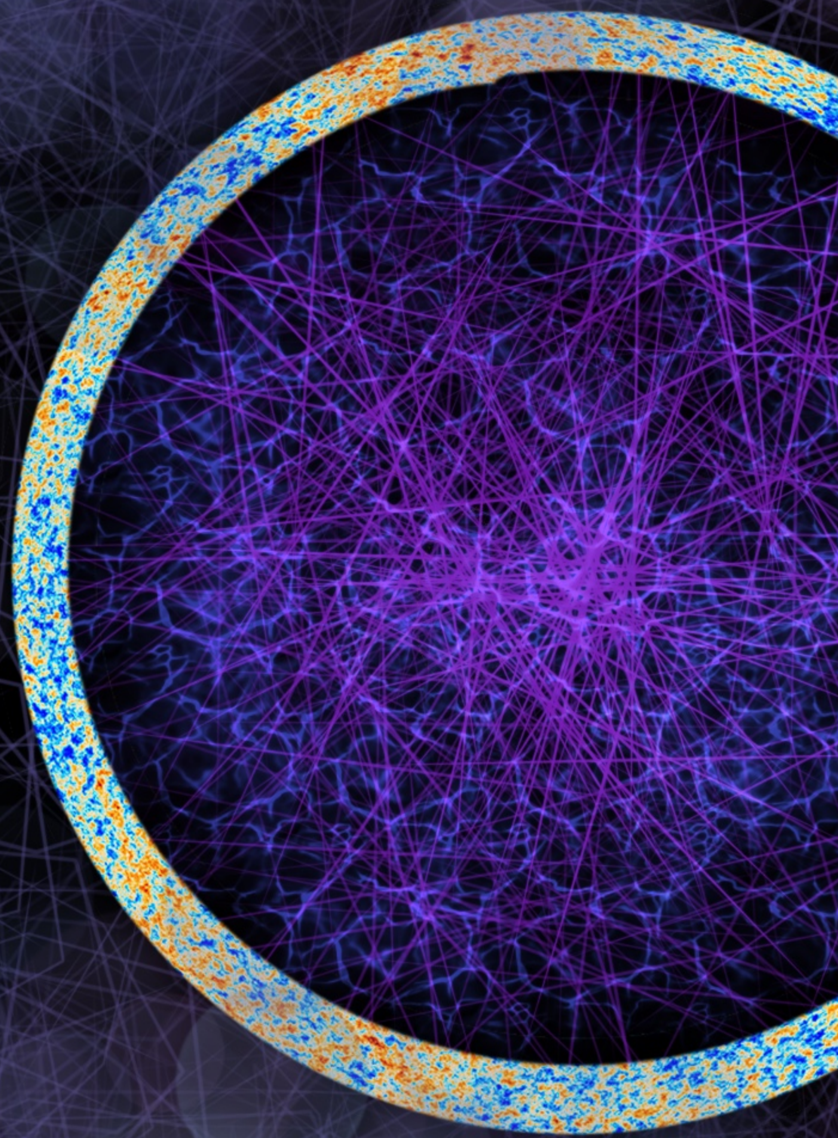
$S_{\rm ortho}$



Courtesy of Fergusson & Shellard

Smith et al. (2009)

Single Field Inflation



EFT of Inflation

Definition is formalized by the EFT of Inflation

Cheung et al. (2007)

Clock breaks time-translations

$$\langle \mathcal{O} \rangle \propto t \qquad\qquad U \equiv t + \pi$$

The field $\pi(\vec{x}, t)$ are the fluctuations of the clock

We can write the most general possible action

$$S \supset \int d^4x \sqrt{-g}\, F(U, \nabla_\mu)$$

Nothing about this requires a fundamental scalar

EFT of Inflation

Gravity gauges the time-translation symmetry

The goldstone is generally eaten by the metric:

$$ds^2 = -dt^2 + a^2 e^{2\zeta} dx^2 \qquad \zeta = -H\pi + \mathcal{O}(\pi^2)$$

Equivalence theorem applies in decoupling limit:

$$M_{\rm pl} \to \infty \quad \dot{H} \to 0 \qquad M_{\rm pl}^2 \dot{H} = \text{constant}$$

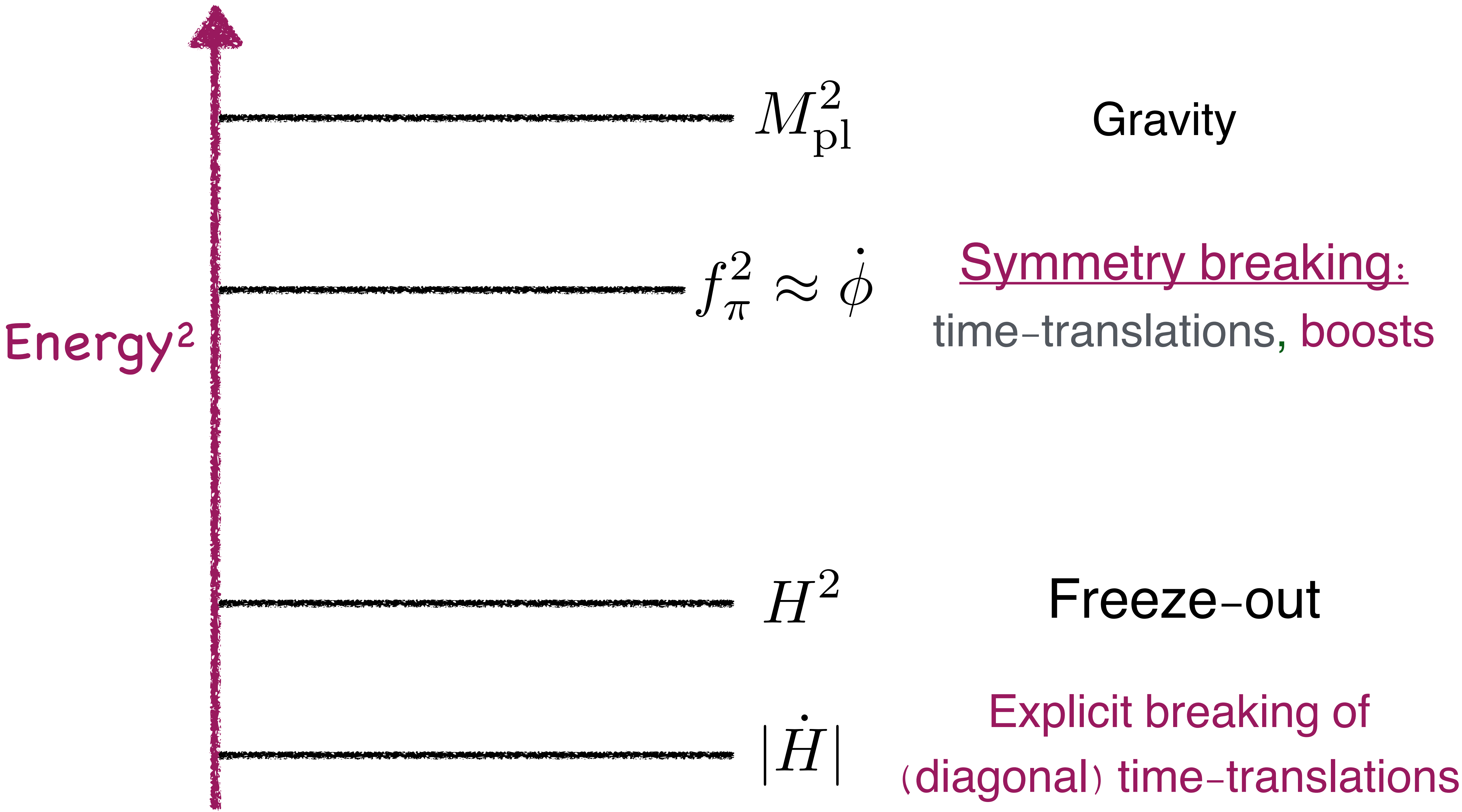
Dynamical gravity decouples / metric pure dS

Goldstone action will be accurate up to small corrections

Baumann & DG (2011)

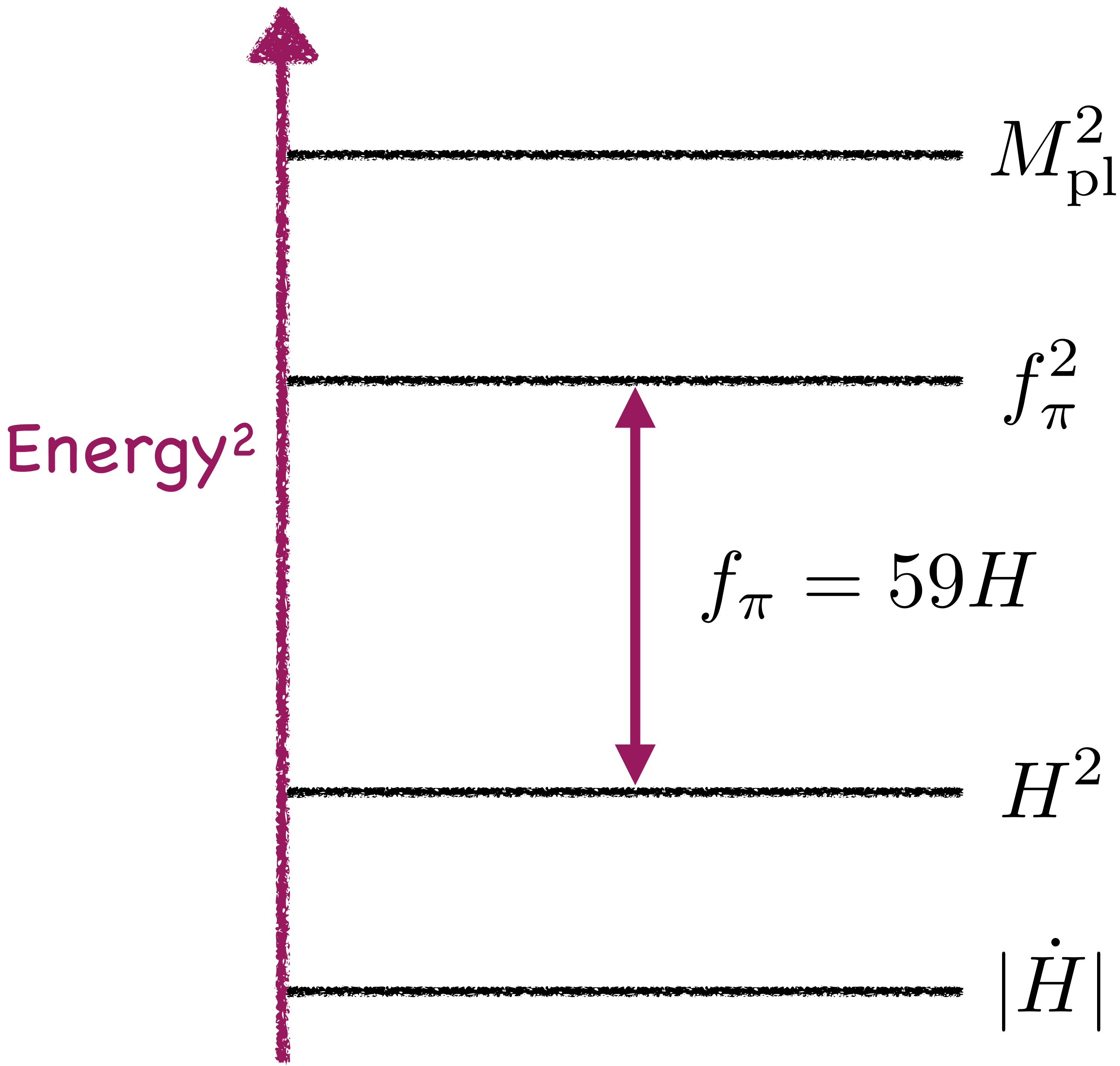
EFT of Inflation

In a generic model, space-time symmetries are badly broken



Single Field Inflation

In a generic model, space-time symmetries are badly broken



Symmetry breaking

$$2\pi\Delta_\zeta \sim \left(\frac{H}{f_\pi}\right)^2$$

Scale of observations

Single Field Inflation

Expanding the action imposing symmetries nonlinearly

$$S \supset \int d^4x \sqrt{-g}\, F(U, \nabla_\mu) \qquad U \equiv t + \pi$$

It is useful to work with $\quad \partial_\mu U \partial^\mu U + 1 = 2\dot{\pi} + \partial_\mu \pi \partial^\mu \pi$

To leading order in derivatives

$$S \supset \sum_{n=0}^{\infty} M_n^4(U)(\partial_\mu U \partial^\mu U + 1)^n$$

Scale invariance: $M_n^4(U) \to M_n^4$

$\mathcal{O}(\pi^n)$

Single Field Inflation

We find the quadratic action

$$\mathcal{L}_0 = -M_{\rm pl}^2 \dot{H} \left[c_s^{-2}\dot{\pi}^2 - a^{-2}(\partial\pi)^2\right] \qquad c_s^2 \equiv \frac{M_{\rm pl}^2 \dot{H}}{M_{\rm pl}^2 \dot{H} - 2M_2^4}$$

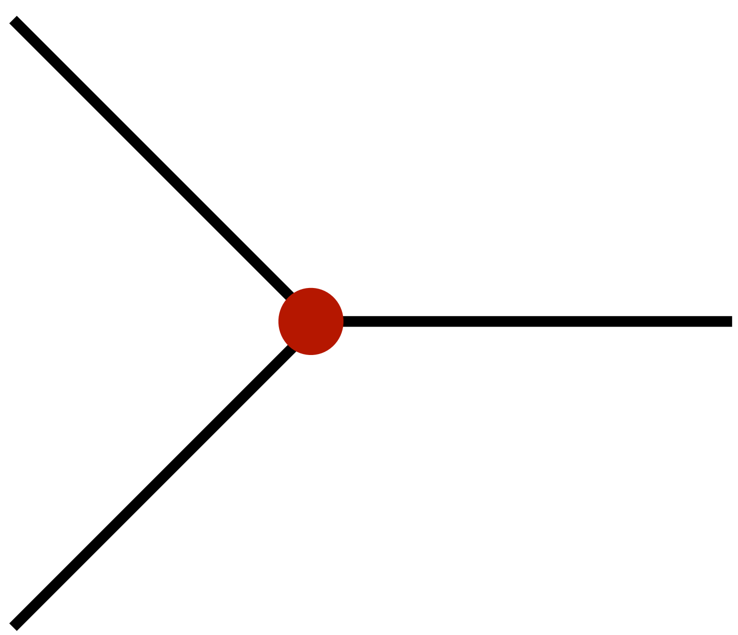
The speed of propagation is related to interactions

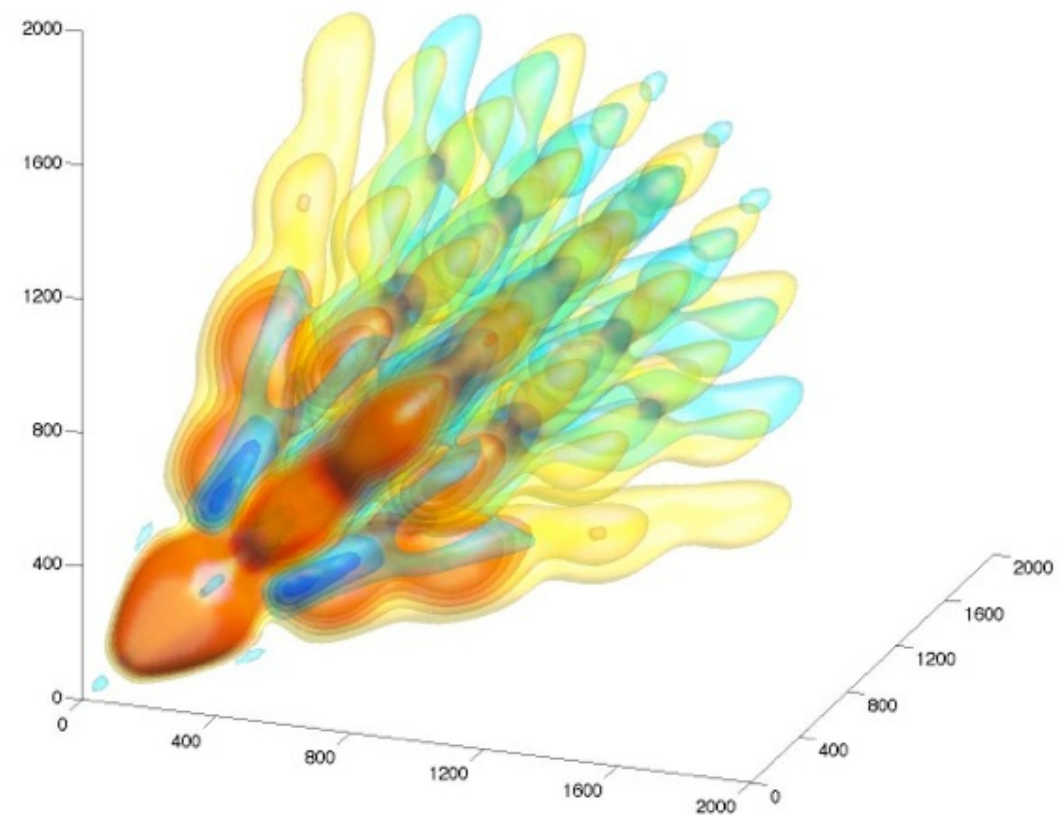
$$\mathcal{L}_{\rm int} = \boxed{\left(1 - c_s^{-2}\right)} M_{\rm pl}^2 \dot{H} \left[-\dot{\pi}(\nabla\pi)^2 + \frac{1}{4}(\nabla\pi)^4\right] - 2M_3 \left[\frac{2}{3}\dot{\pi}^3 - \dot{\pi}^2(\nabla\pi)^2\right] + \frac{2}{3}M_4\dot{\pi}^4$$

Small sound speed = large interactions

Single Field Inflation

What do we know from data?



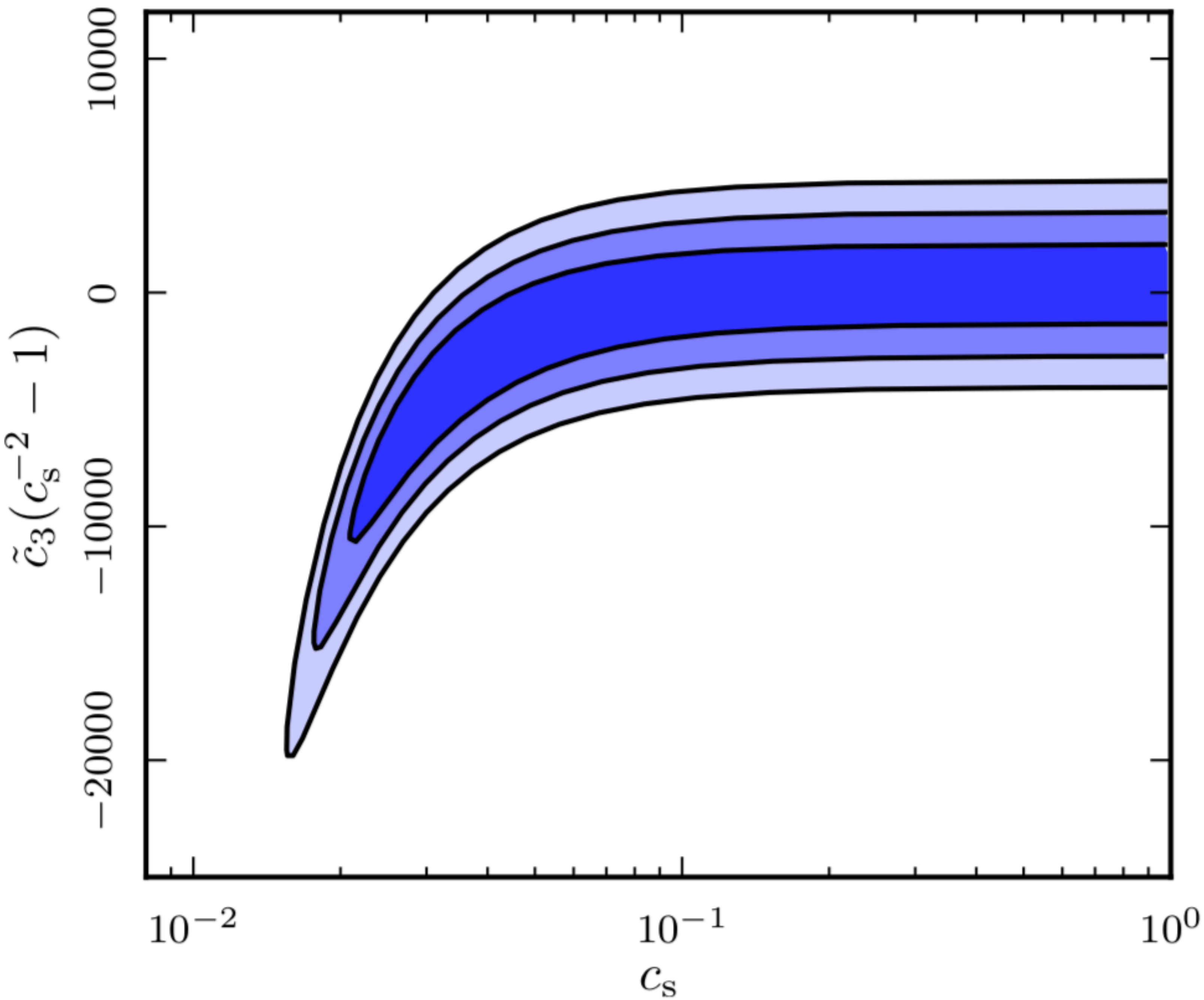


$$\mathcal{L}_{\rm int} \supset \frac{1}{\Lambda^2}\dot{\pi}_c \nabla_\mu \pi_c \nabla^\mu \pi_c$$

$$\Delta_\zeta^{-1}\frac{H^2}{\Lambda^2} \approx f_{\rm NL}^{\rm eq} = -26 \pm 94\,(95\%)$$

EFT of Inflation

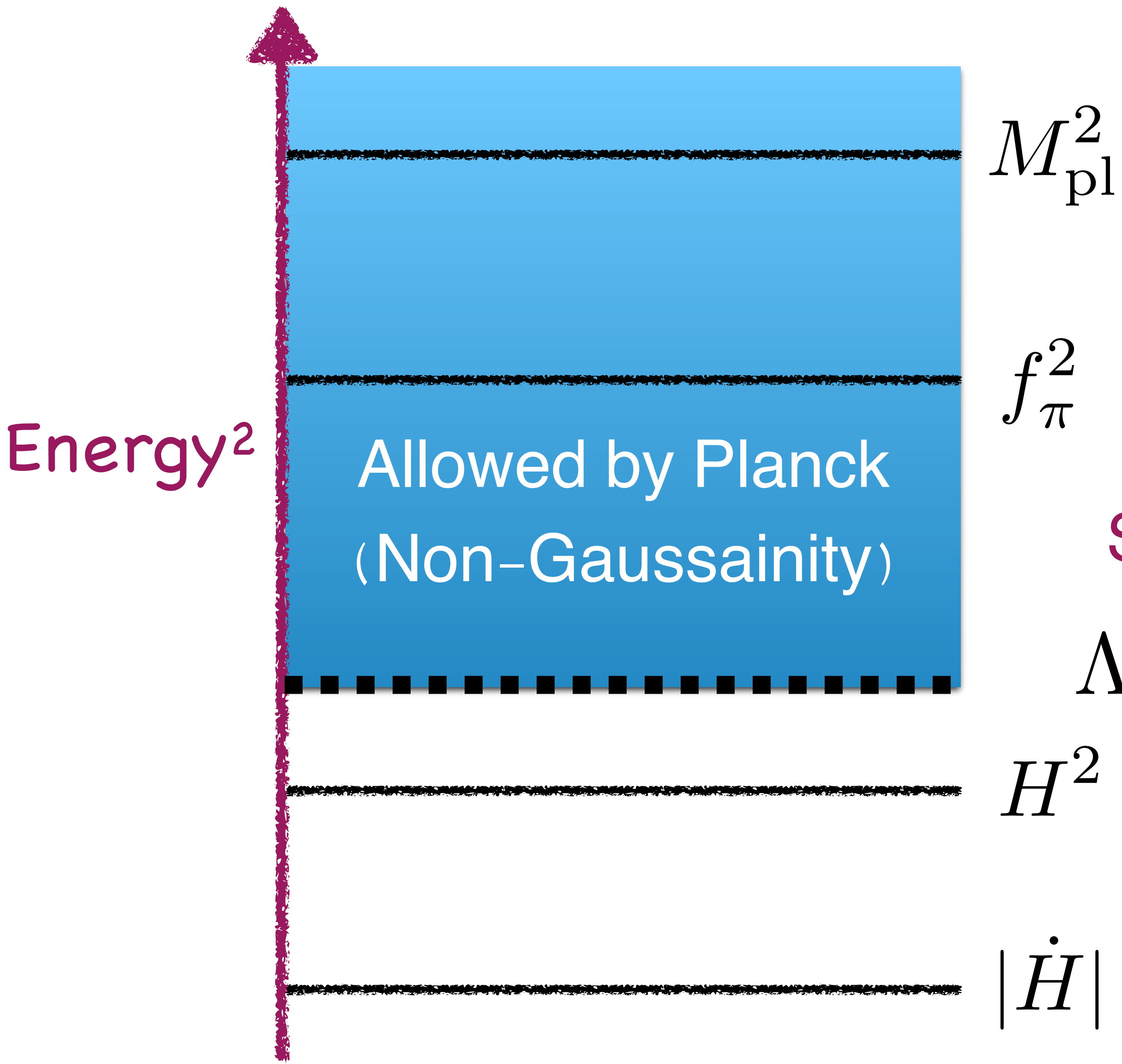
M_3^4



$$c_s > 0.021 \, (95\%)$$

Single Field Inflation

What do we know from data?

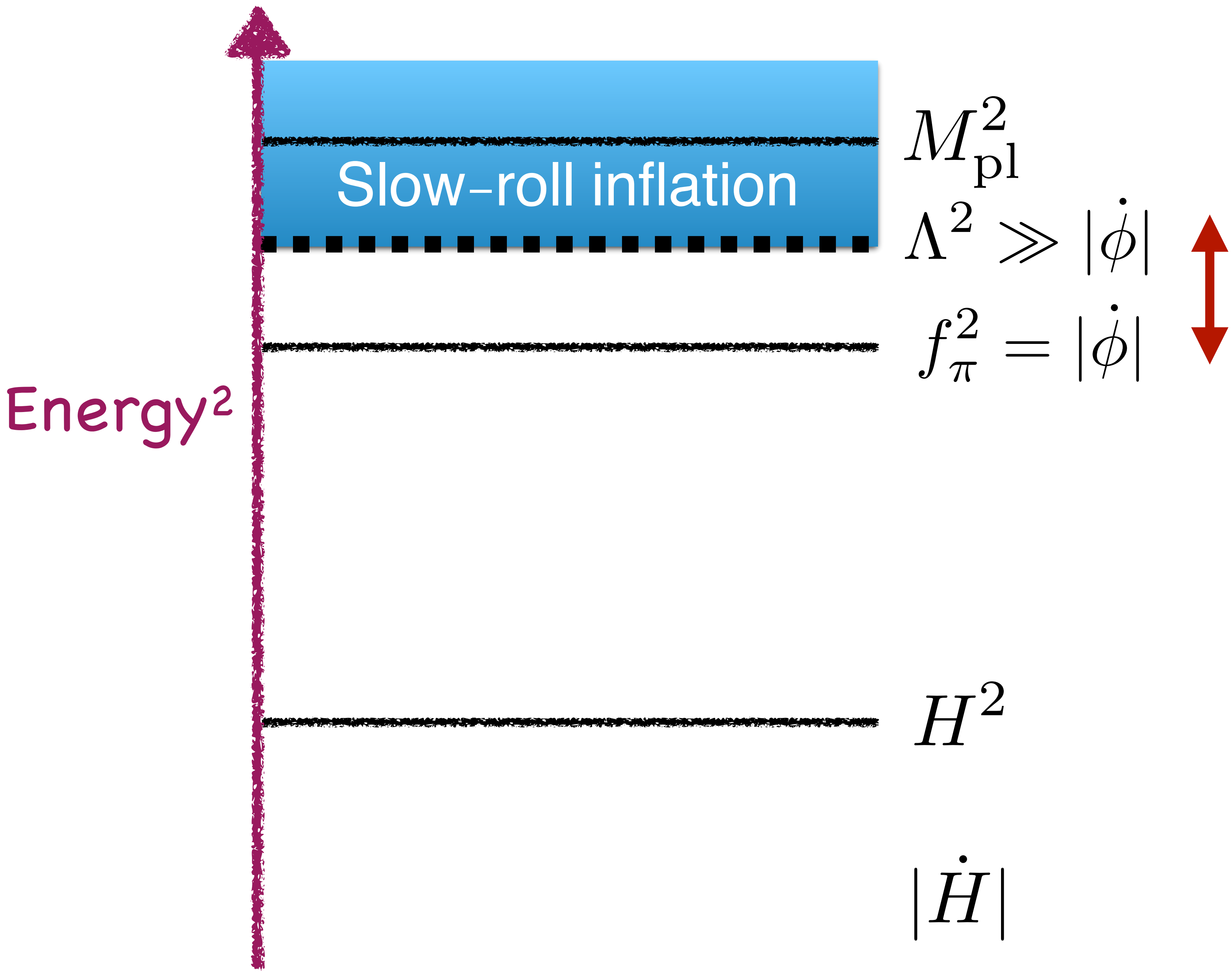


Scale of Cubic-Interactions

$$\Lambda \geq (5-10)\, H \quad (95\%)$$

Slow-roll inflation predicts:

Creminelli (2003)

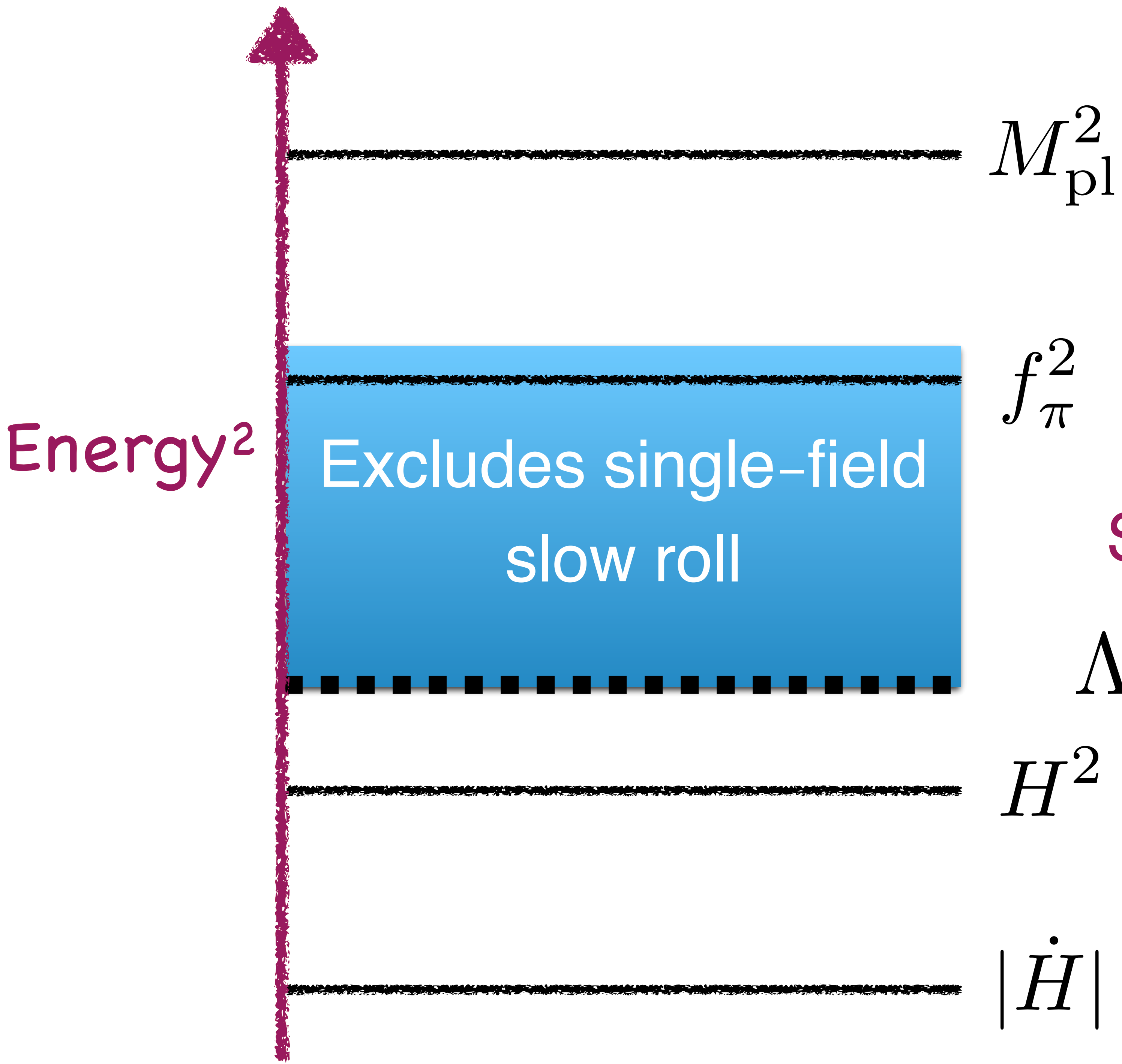


Weakly coupled scalar

$$f_{\rm NL}^{\rm eq} \ll 1$$

Single Field Inflation

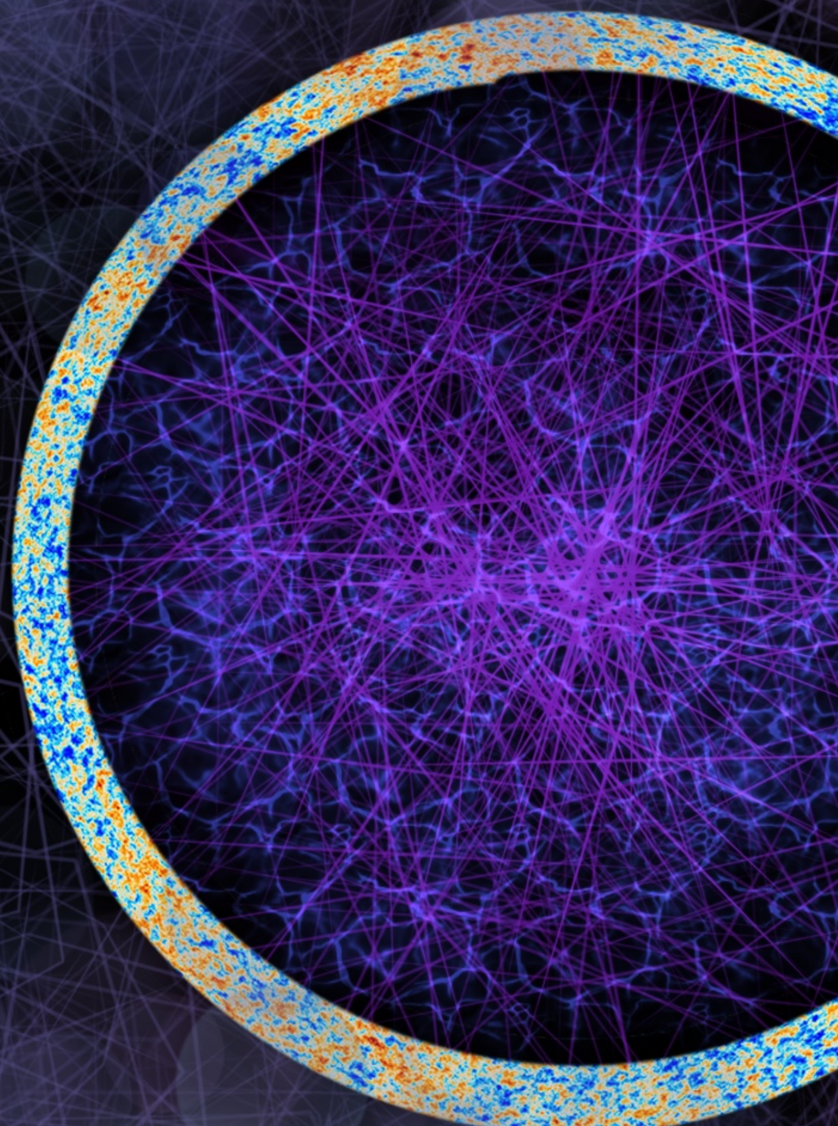
What do we know from data?



Scale of Cubic-Interactions

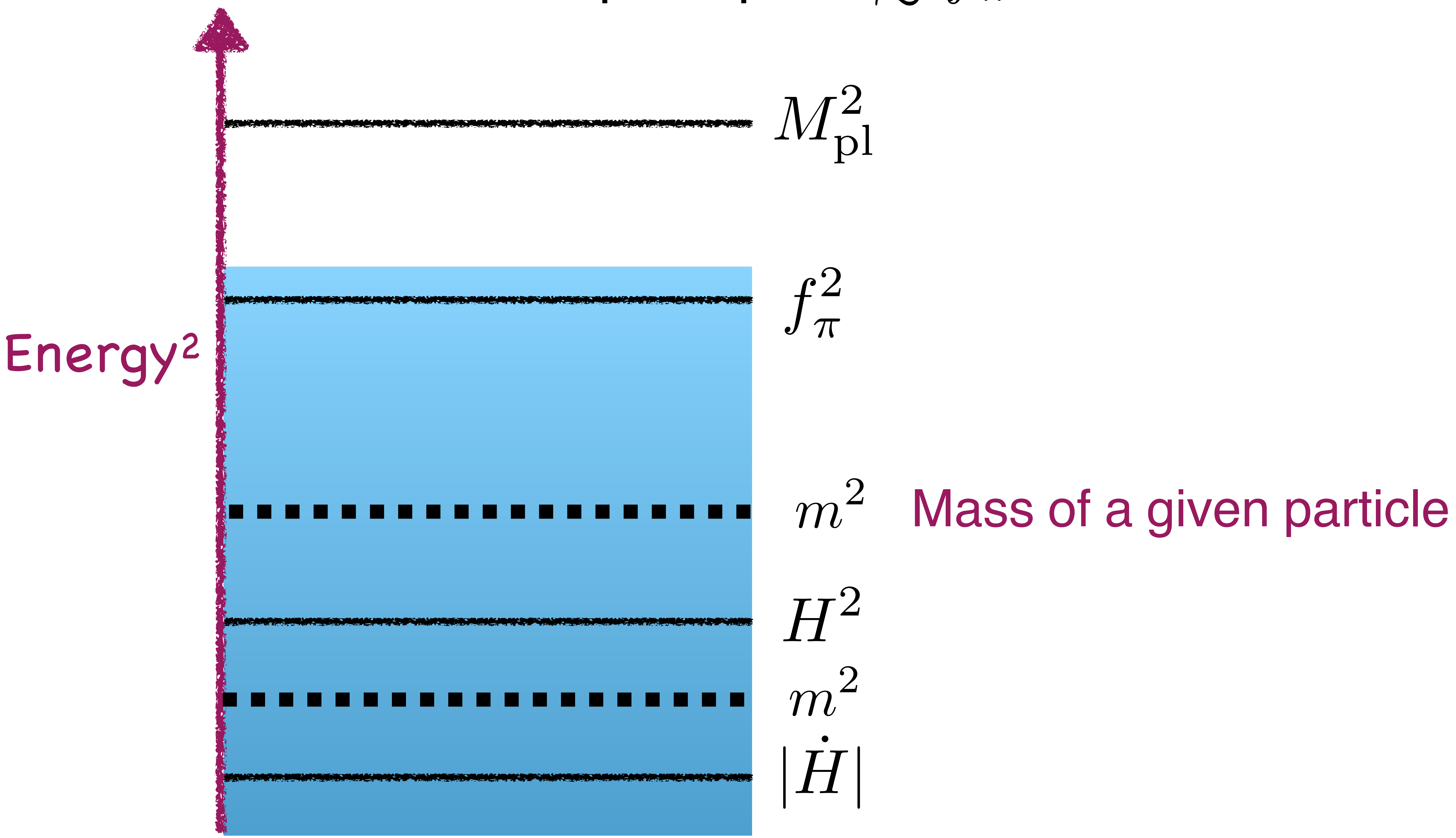
$$\Lambda \geq (5-10)\, H \quad (95\%)$$

Multi-Field Inflation



Quasi-Single Field Inflation

New states can created up to up $E \gtrsim f_\pi$



Quasi-Single Field Inflation

We can couple the inflation to other fields

$$\mathcal{L} \supset F_1(t+\pi)\mathcal{O}_1 + F_2(t+\pi)\dot{\pi}\mathcal{O}_2 + \ldots$$

Extra fields not constrained by (nonlinear) symmetries

E.g. quasi-single field $\mathcal{L} \supset \dot{\pi}\sigma + \mu\sigma^3$ Chen & Wang (2009)

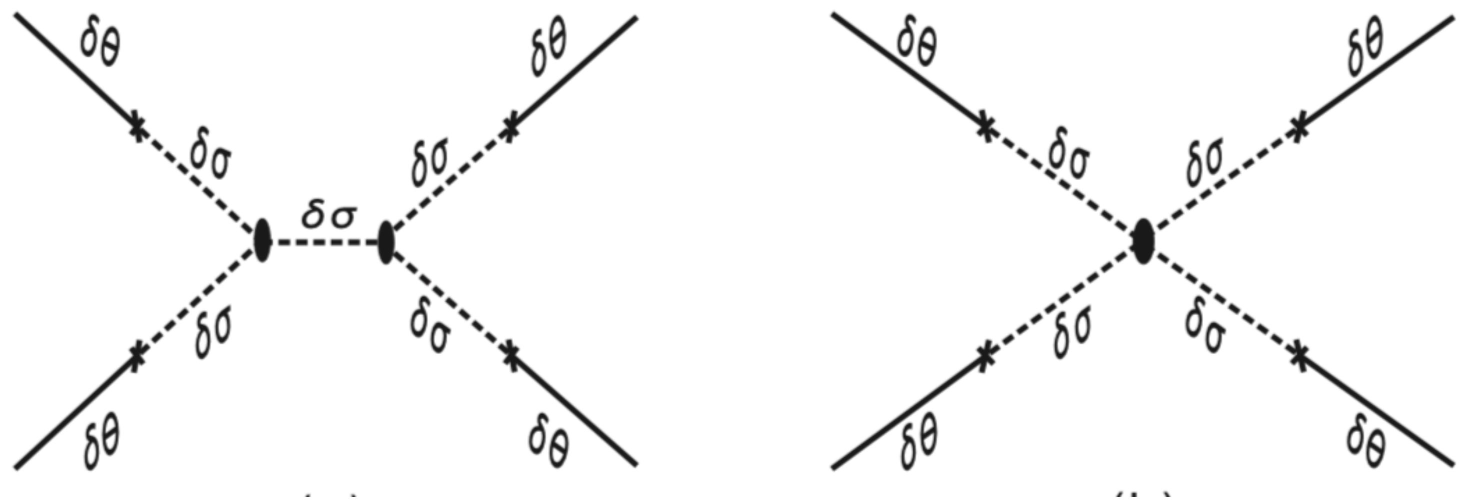
Extra field is very non-Gaussian when $\mu \sim H$

Same operator is not allowed for goldstone

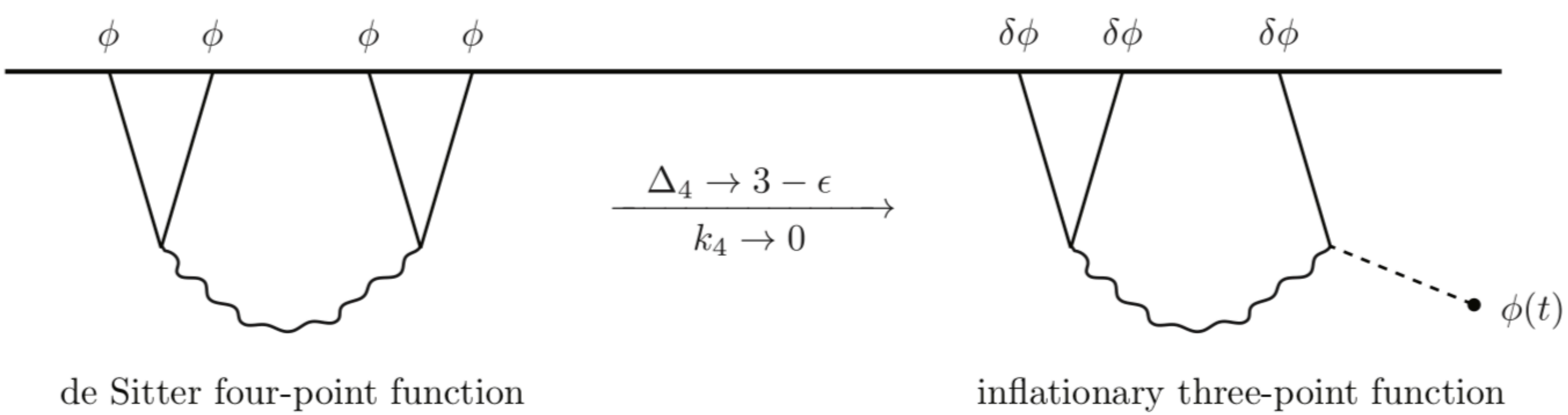
Quasi-Single Field Inflation

Additional (massive) fields and interact during inflation

E.g.



Chen & Wang (2009)



Arkani-Hamed et al. (2018)

Multi -Field Inflation

Additional light fields can be important after inflation

Conservation is local but nonlinear

$$\zeta(\vec{x}) = \zeta_{\rm inflation}(\vec{x}) + \sum_n \sigma^n(\vec{x})$$

non-Gaussianity may also be generated during inflation

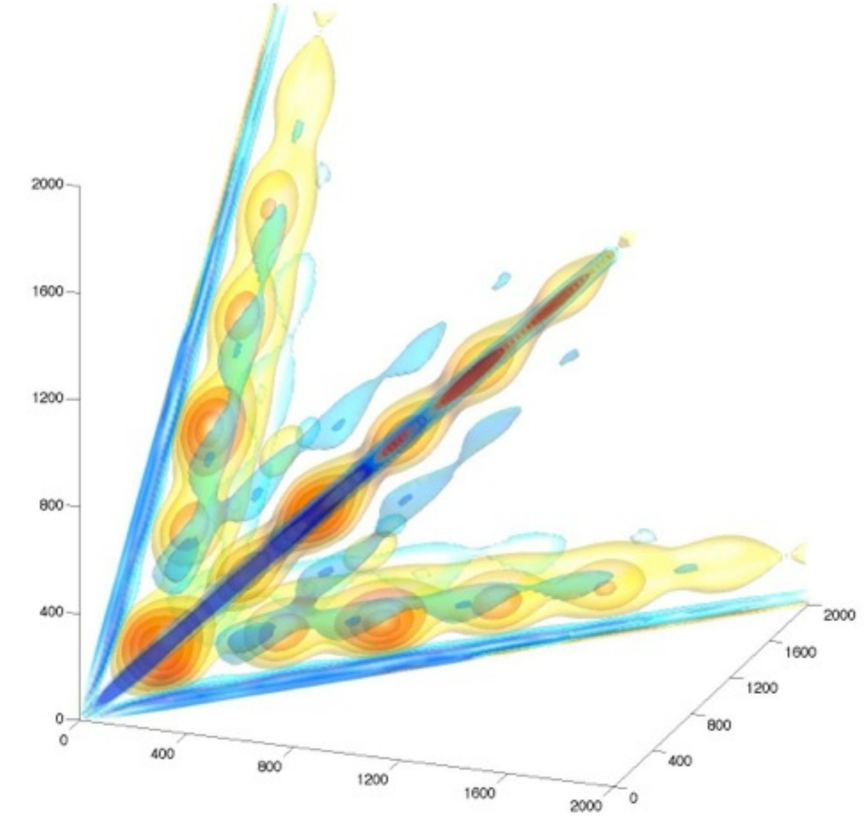
$$\langle \sigma(\vec{k}_1)..\sigma(\vec{k}_n)\rangle \neq 0$$

Will be nearly dS invariance unless coupled to inflation

Multi –Field Inflation

Multiple massless fields usually give local NG

$$\zeta = \sigma(\vec{x}) + f_{\rm NL}^{\rm local}\sigma^2(\vec{x})$$



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

Without fine tuning, multi–field usually gives $f_{\rm NL}^{\rm local} \gtrsim 1$

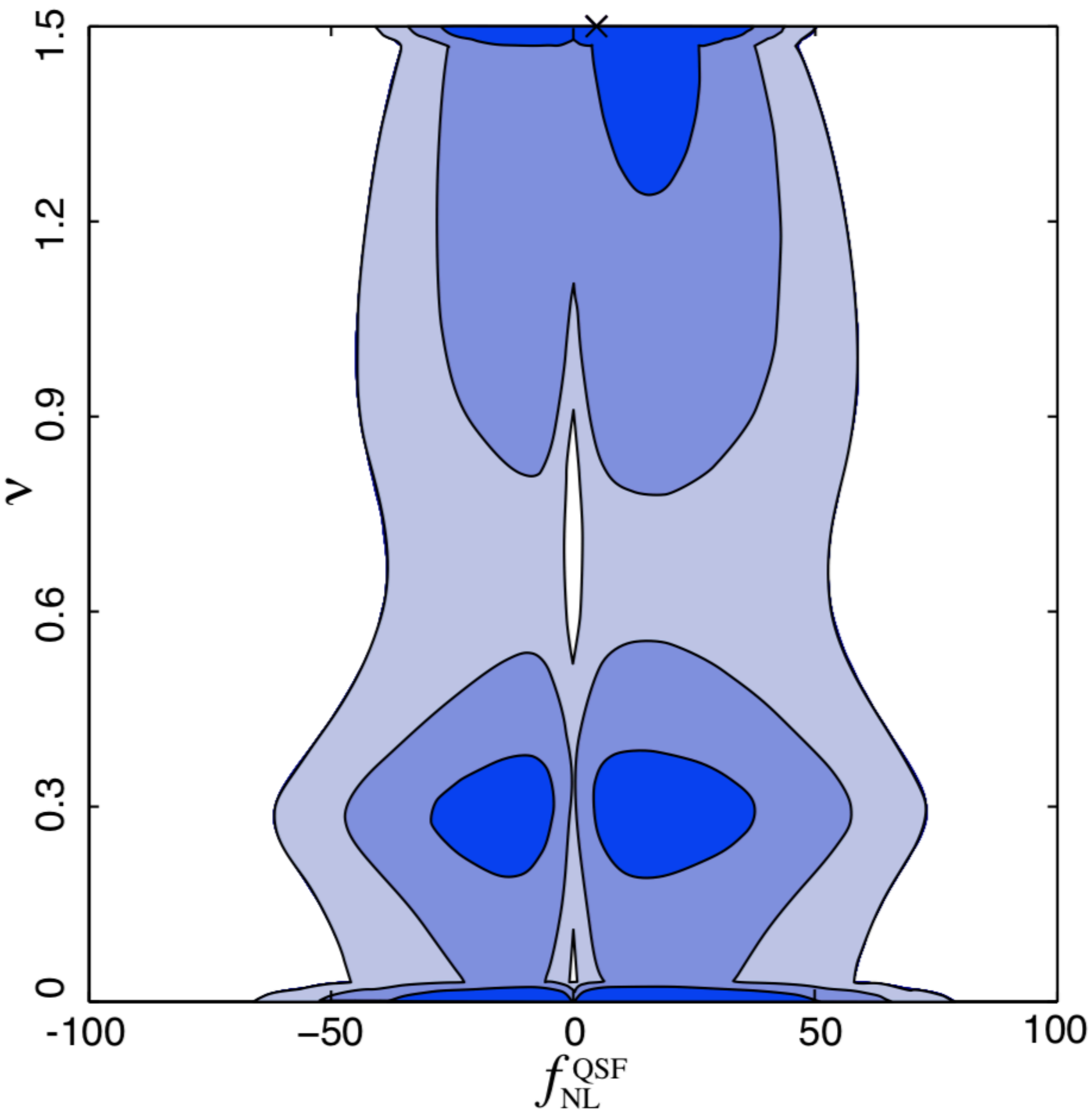
Multi –Field Inflation

New states can created up to up $E \gtrsim f_\pi$

$$m^2 = 0$$

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

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

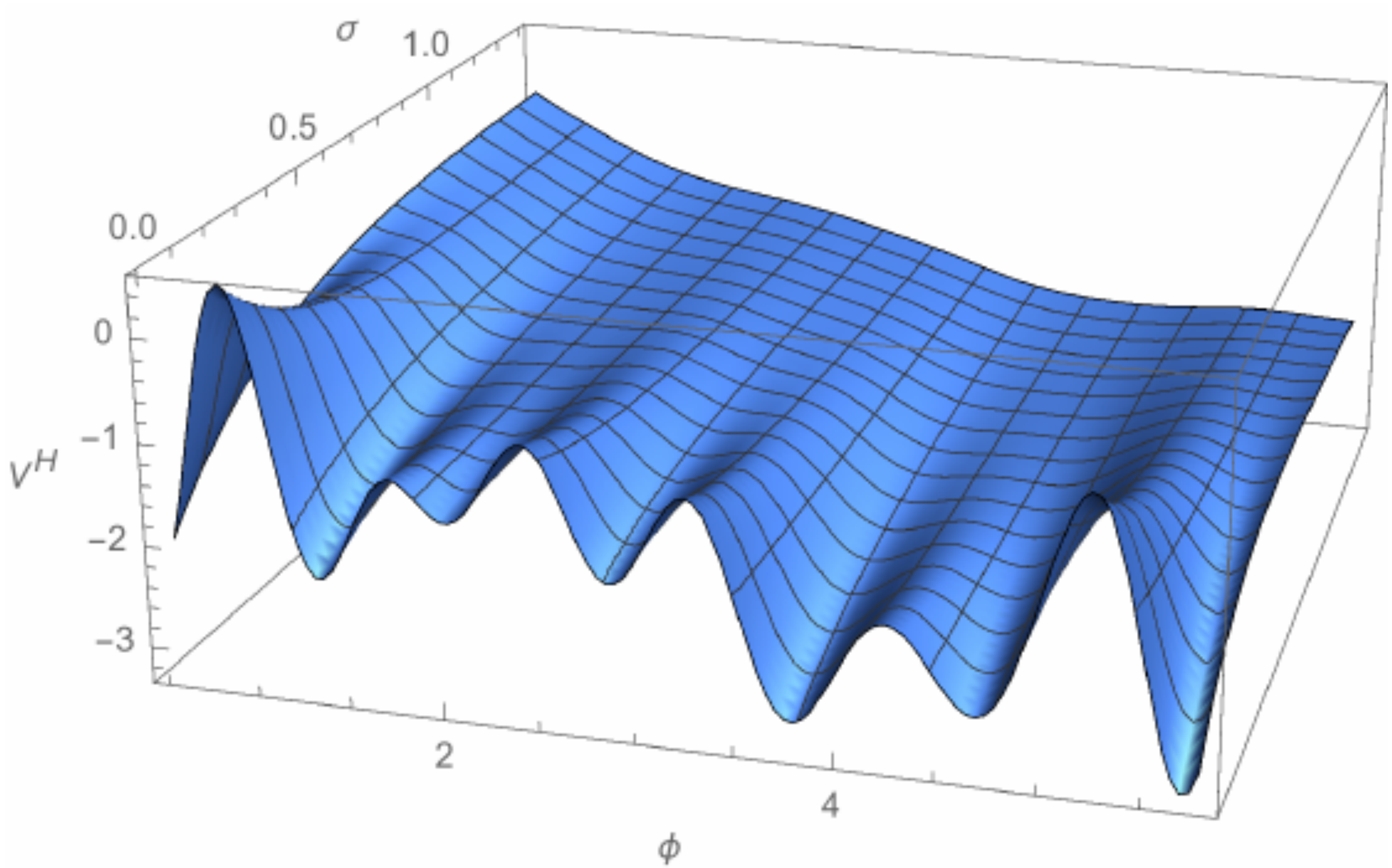


Local NG

Equil. NG

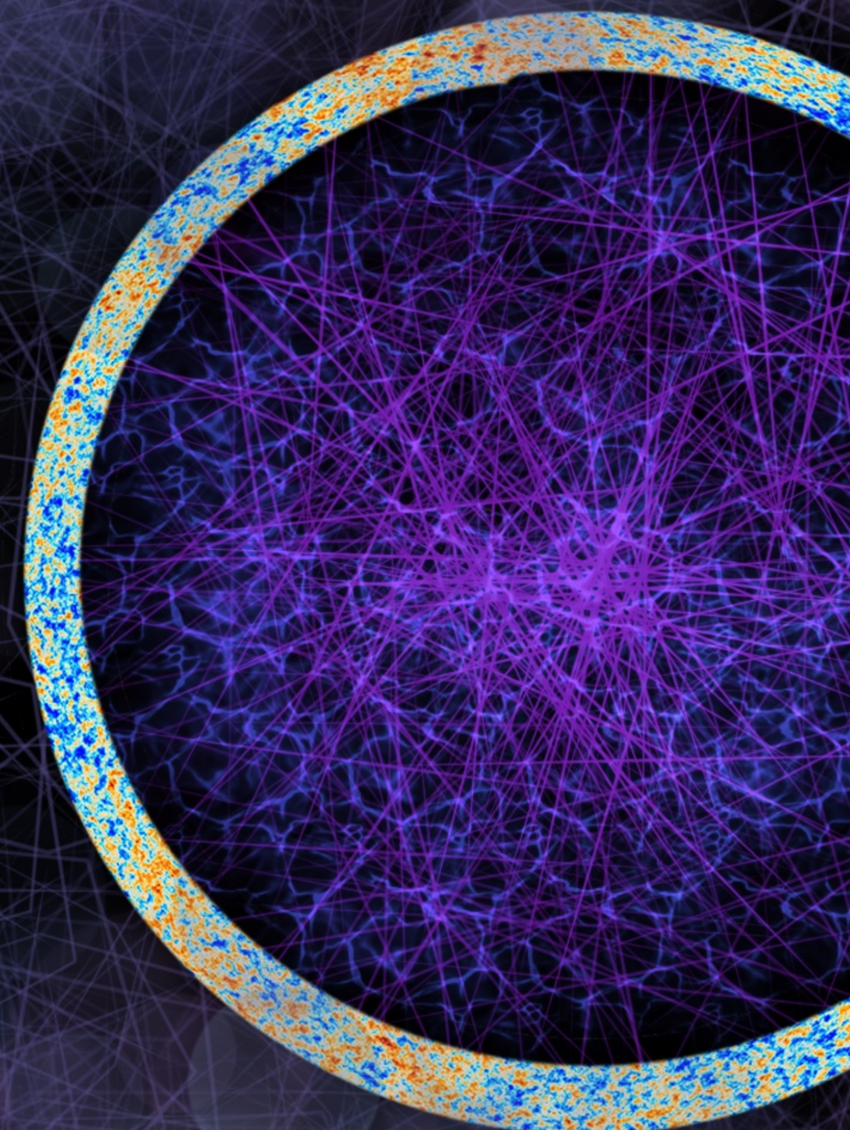
Multi –Field Inflation

More generally, possibilities are vast



We are still exploring the landscape of possibilities

Recent Developments



Cosmological Bootstrap

Define cosmological correlators directly from principles

A Key Idea: correlators contains the scattering amplitude.

E.g.

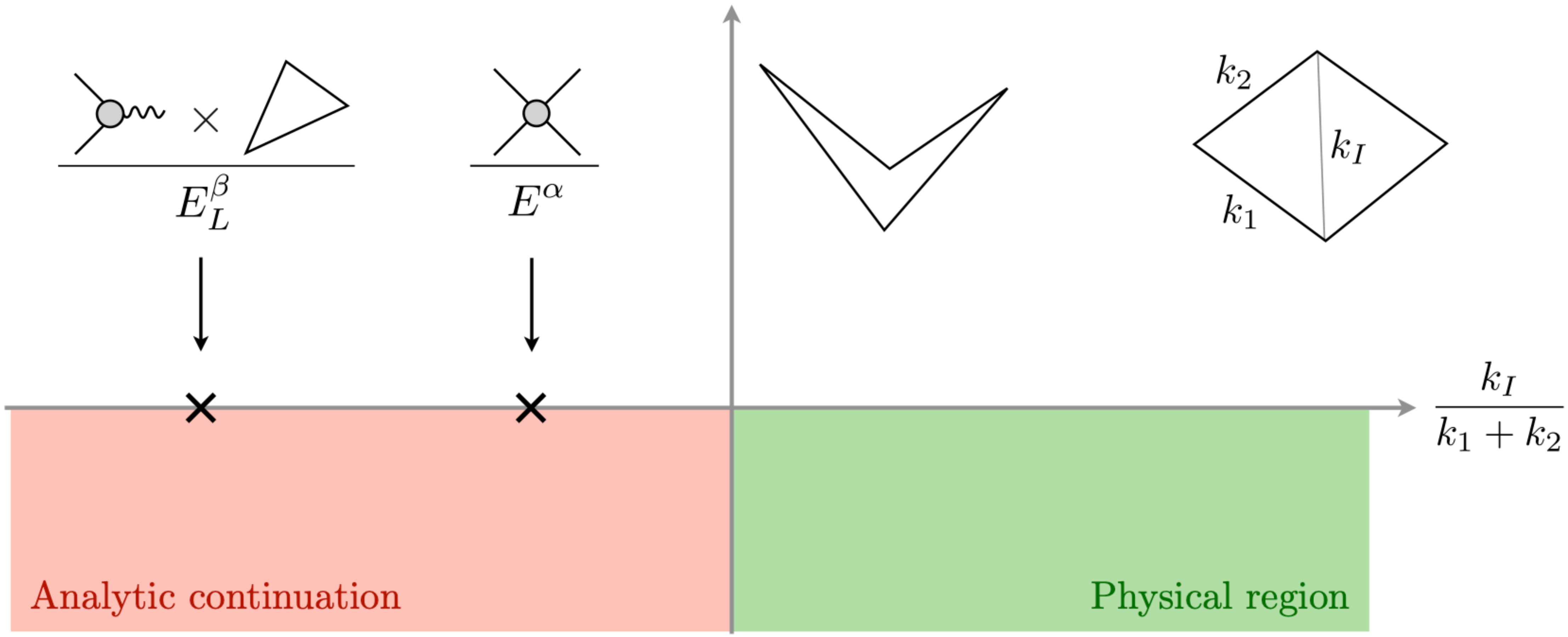
$$\lim_{E\to 0}\langle\phi(\vec{k}_1)..\phi(\vec{k}_n)\rangle = \frac{iA_n}{E^\alpha}$$

Residue in “total energy” $E = \sum_{i=1}^{n} k_i$

Analytic structure in “energy” constrains correlators

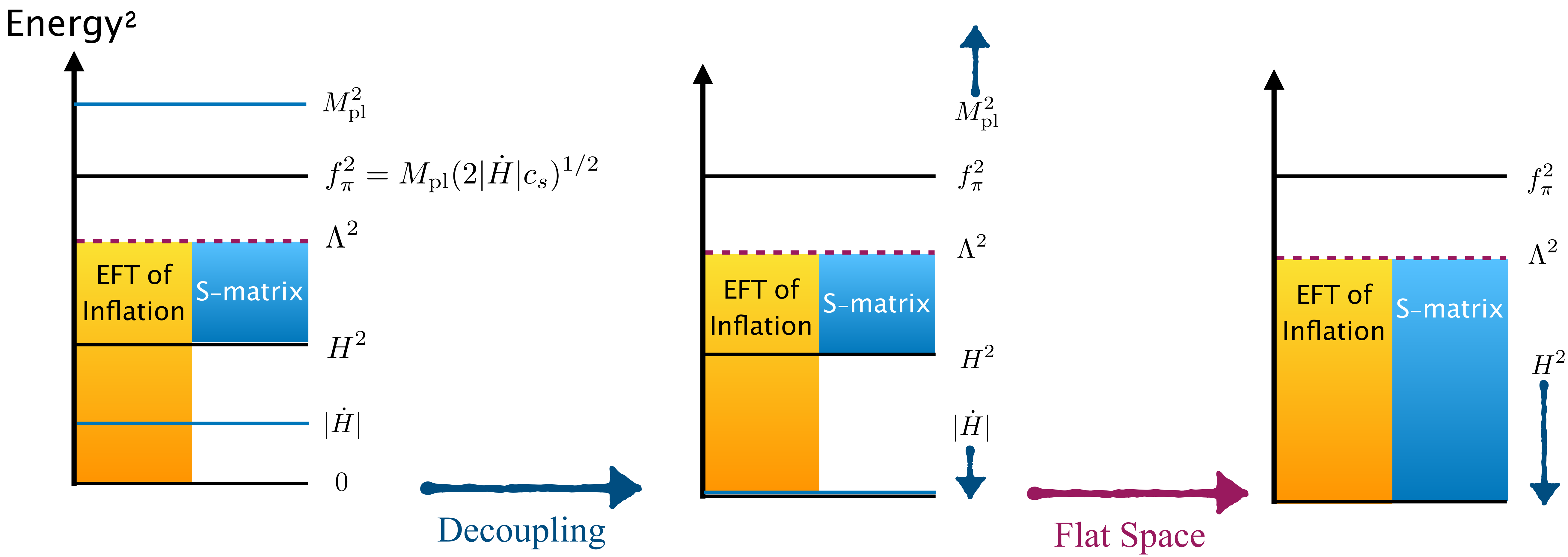
arXiv:2203.08121（review）

Physical input dictates the behavior of the poles



arXiv:2203.08121 (review)

This motivates studying scattering in the EFT of Inflation



arXiv:2203.08121 (review)

Cosmological Bootstrap

Amplitudes can be bootstrapped to correlators

Pajer, + et al.

EFT of inflation can be understood in terms of soft-theorems

DG, Huang, Shen; Hui et al.

Investigations of positivity constraints

E.g. Baumann et al., Creminelli et al.

Current limitation: most work is still perturbative (tree level)

Some progress in non-perturbative bootstrap

Hogervorst et al.; Di Pietro et al.

Loops in dS / Inflation

"IR Issues" have long been a source of confusion

Even without gravity we have:

- Confusing divergences in loop diagrams
- Surprising "secular growth" (growth with time)

Problems:

- Dim reg fails in cosmological backgrounds
- Power counting is unclear

arXiv:2210.05820 (review)

Loops in dS / Inflation

Most IR issues are just due to poor regulators

For massless scalars, IR signals RG flow

Callan-Symanzik equation is "stochastic inflation"

$$\frac{\partial}{\partial t} P(\phi, t) = \frac{H^3}{8\pi^2} \frac{\partial^2}{\partial \phi^2} P(\phi, t) + \frac{1}{3H} \frac{\partial}{\partial \phi} \left[V'(\phi) P(\phi, t) \right]$$

Quantum noise Classical drift

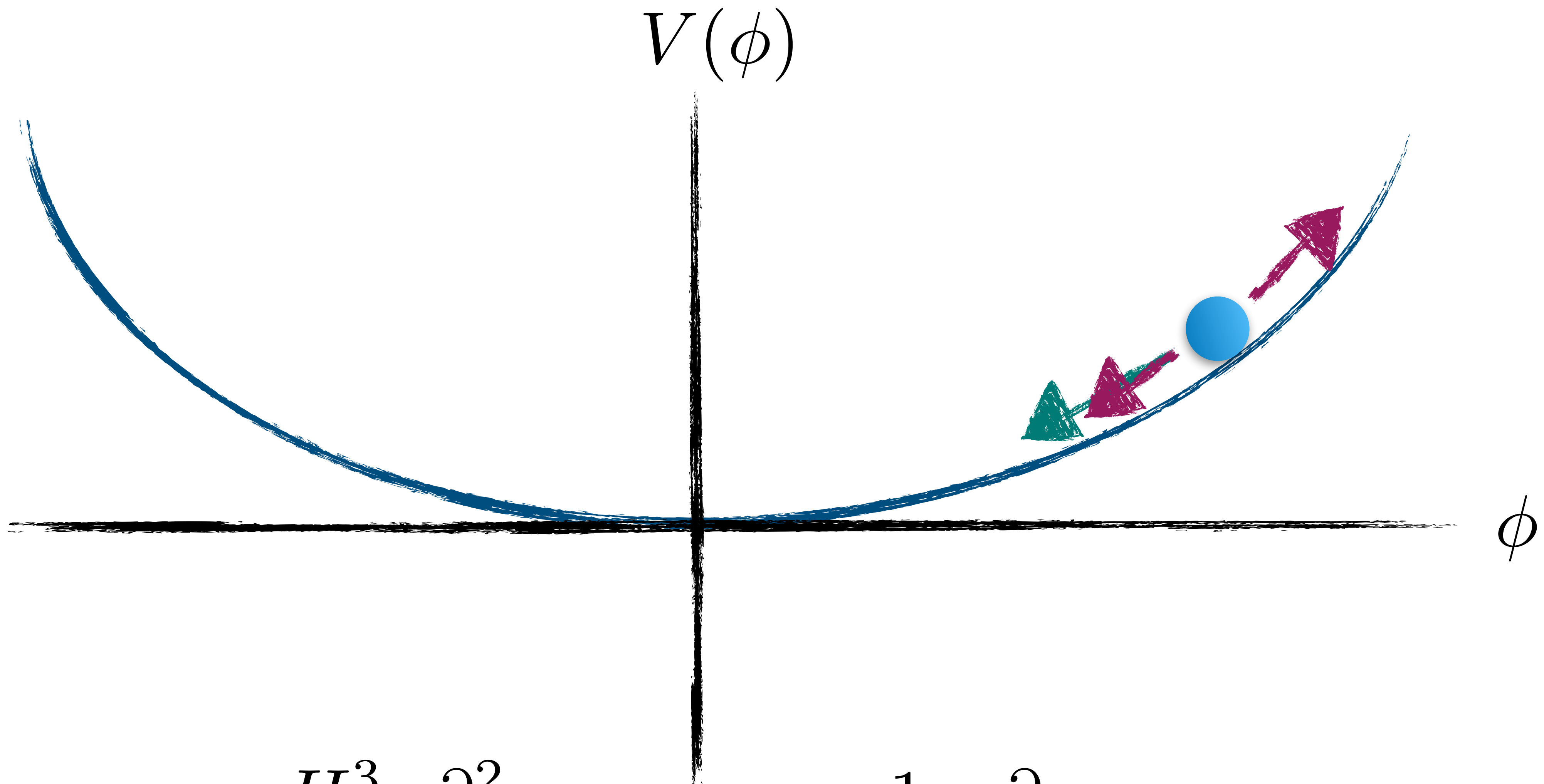
1-to-1 correspondence with operator mixing

arXiv:2210.05820 (review)

Stochastic Inflation

dS Physics well described by a random walk

Starobinsky



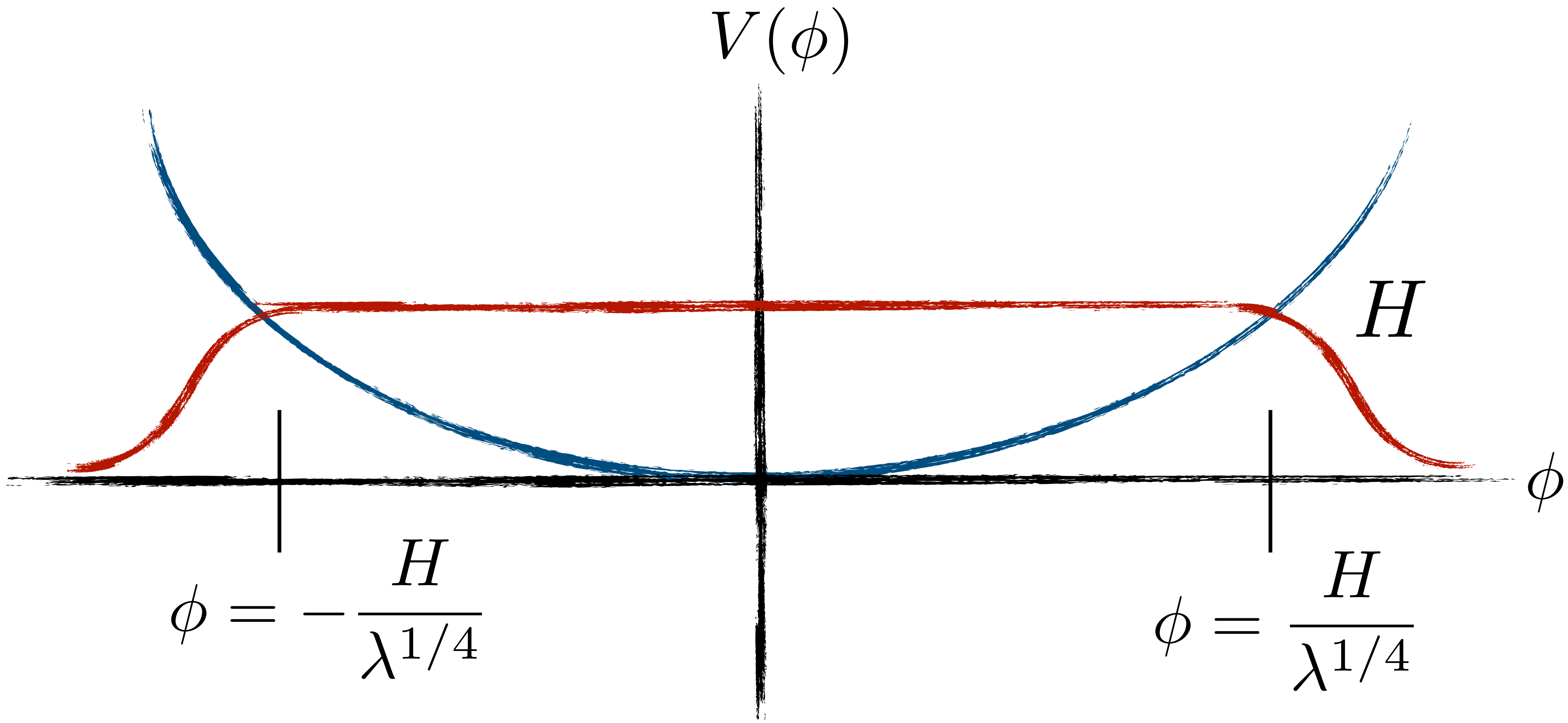
$$\frac{\partial}{\partial t}P(\phi,t) = \frac{H^3}{8\pi^2}\frac{\partial^2}{\partial\phi^2}P(\phi,t) + \frac{1}{3H}\frac{\partial}{\partial\phi}\left[V'(\phi)P(\phi,t)\right]$$

Quantum noise

Classical drift

Power Counting in SI

Equilibrium Probability covers large field range



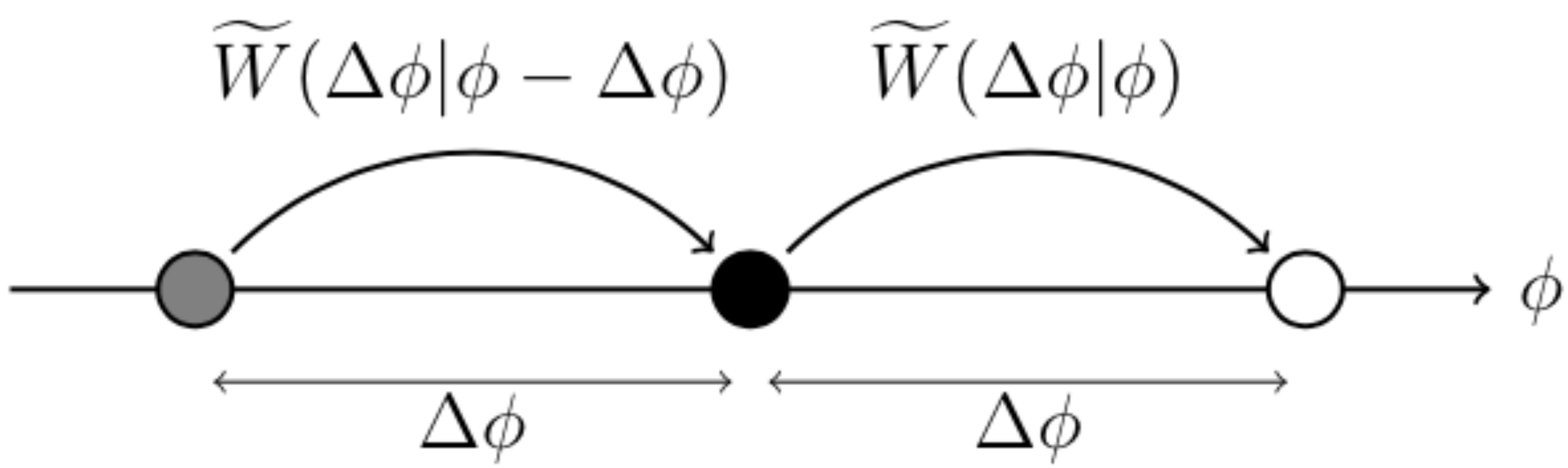
$$P_{\rm eq}(\phi) = C e^{-8\pi V(\phi)/3H^4}$$

Power Counting in SI

Is Stochastic Inflation consistent for large fields?

What are the possible corrections?

$$\frac{\partial}{\partial t}P(\phi,t)=\int d\Delta\phi\Big[P(\phi-\Delta\phi,t)\widetilde{W}(\Delta\phi,\phi-\Delta\phi)-P(\phi,t)\widetilde{W}(\Delta\phi,\phi)\Big]$$



Power Counting in SI

If jumps are bounded, we (Kramers-Moyal) expand

$$\frac{\partial}{\partial t}P(\phi,t) = \sum_{n=1}^{\infty}\frac{1}{n!}\frac{\partial^n}{\partial\phi^n}\,\Omega_n(\phi)P(\phi,t)$$

$$\Omega_n(\phi) \equiv \int d\Delta\phi\,\left(-\Delta\phi\right)^n \widetilde{W}(\Delta\phi|\phi)$$

Derivative expansion is controlled by the moments

Non-gaussianity encoded in higher derivatives

Power Counting in SI

Expanding moments in power of field locations

$$\frac{\partial}{\partial t}P(\phi,t) = \sum_{n=2}^{\infty}\frac{1}{n!}\frac{\partial^n}{\partial\phi^n}\left[\sum_{m=0}^{\infty}\frac{1}{m!}\Omega_n^{(m)}\phi^m\, P(\phi,t)\right] + \frac{1}{3H}\frac{\partial}{\partial\phi}\left[V'(\phi)P(\phi,t)\right]$$

We will take $V(\phi) = \frac{\lambda}{4!}\phi^4$

Educated guess: power count according to scaling

$$[\phi] \approx \frac{H}{\lambda^{1/4}} \qquad \Omega_n^{(m)} = \mathcal{O}\left(\lambda^{n+m}\right)$$

Power Counting in SI

Large field value still allows a consistent expansion

LO: $$\frac{\partial}{\partial t}P(\phi,t)=\frac{H^3}{8\pi^2}\frac{\partial^2}{\partial\phi^2}P(\phi,t)+\frac{1}{3H}\frac{\partial}{\partial\phi}\left[\frac{1}{3!}\lambda\phi^3P(\phi,t)\right]$$

NLO: $$\frac{\partial}{\partial t}P(\phi,t)=O\left(\lambda^{1/2}\right)+\frac{\partial^2}{\partial\phi^2}\left[\Omega_2^{(2)}\phi^2P(\phi,t)\right]+\frac{1}{3H}\frac{\partial}{\partial\phi}\left[\frac{1}{5!}c_6\phi^5P(\phi,t)\right]$$

NNLO: $$\frac{\partial}{\partial t}P(\phi,t)=O\left(\lambda^{1/2}\right)+O\left(\lambda\right)+\frac{H^3}{8\pi^2}\frac{\partial^2}{\partial\phi^2}\left(\Omega_2^{(4)}\phi^4P(\phi,t)\right)$$
$$+\frac{1}{3H}\frac{\partial}{\partial\phi}\left[\frac{1}{7!}c_8\phi^7P(\phi,t)\right]+\frac{\partial^3}{\partial\phi^3}\left(\Omega_3^{(1)}\phi P(\phi,t)\right)$$

Power Counting in SI

Large field value still allows a consistent expansion

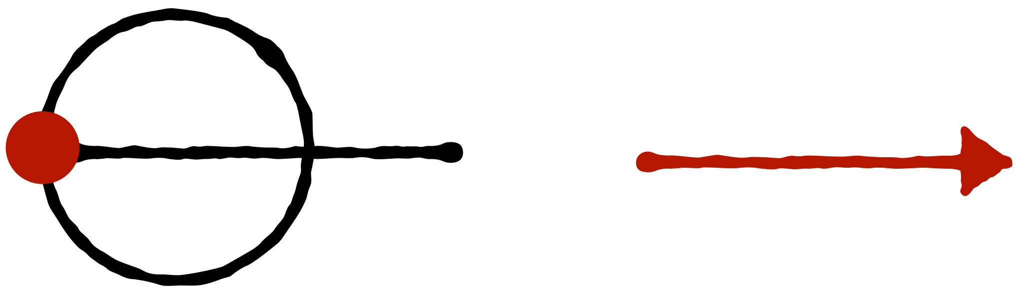
LO: $$\frac{\partial}{\partial t}P(\phi,t) = \frac{H^3}{8\pi^2}\frac{\partial^2}{\partial\phi^2}P(\phi,t) + \frac{1}{3H}\frac{\partial}{\partial\phi}\left[\frac{1}{3!}\lambda\phi^3 P(\phi,t)\right]$$

NLO: $$\frac{\partial}{\partial t}P(\phi,t) = O\left(\lambda^{1/2}\right) + \frac{\partial^2}{\partial\phi^2}\left[\Omega_2^{(2)}\phi^2 P(\phi,t)\right] + \frac{1}{3H}\frac{\partial}{\partial\phi}\left[\frac{1}{5!}c_6\phi^5 P(\phi,t)\right]$$

NNLO: $$\frac{\partial}{\partial t}P(\phi,t) = O\left(\lambda^{1/2}\right) + O\left(\lambda\right) + \frac{H^3}{8\pi^2}\frac{\partial^2}{\partial\phi^2}\left(\Omega_2^{(4)}\phi^4 P(\phi,t)\right) + \frac{1}{3H}\frac{\partial}{\partial\phi}\left[\frac{1}{7!}c_8\phi^7 P(\phi,t)\right] + \frac{\partial^3}{\partial\phi^3}\left(\Omega_3^{(1)}\phi P(\phi,t)\right)$$

NNLO Corrections

One universal term at NNLO



$$\Omega_3^{(1)} = H^{-2}\frac{\lambda}{192\pi^2}$$

Physical interpretation as non-Gaussian noise

Also find an effective potential

$$V'_{\rm eff} = \frac{\lambda_{\rm eff}}{3!}\left(\phi^3 + \frac{\lambda_{\rm eff}}{18}H^{-2}\phi^5 + \frac{\lambda_{\rm eff}^2}{162}H^{-4}\phi^7\right)$$

Implications

Equilibrium wave-function at NNLO

$$P_{\rm eq}(\phi) = C\exp\left[-8\pi^2 V_{\rm eff}(\phi)/3\right]\exp\left[\frac{\lambda_{\rm eff}^2\phi^4}{192H^4}\left(1-\frac{2}{81}\pi^2\lambda_{\rm eff}H^{-4}\phi^4\right)\right]$$

Relaxation Eigenvalues at NNLO:

$$\frac{d}{dt}P_n = -\Lambda_n P_n$$

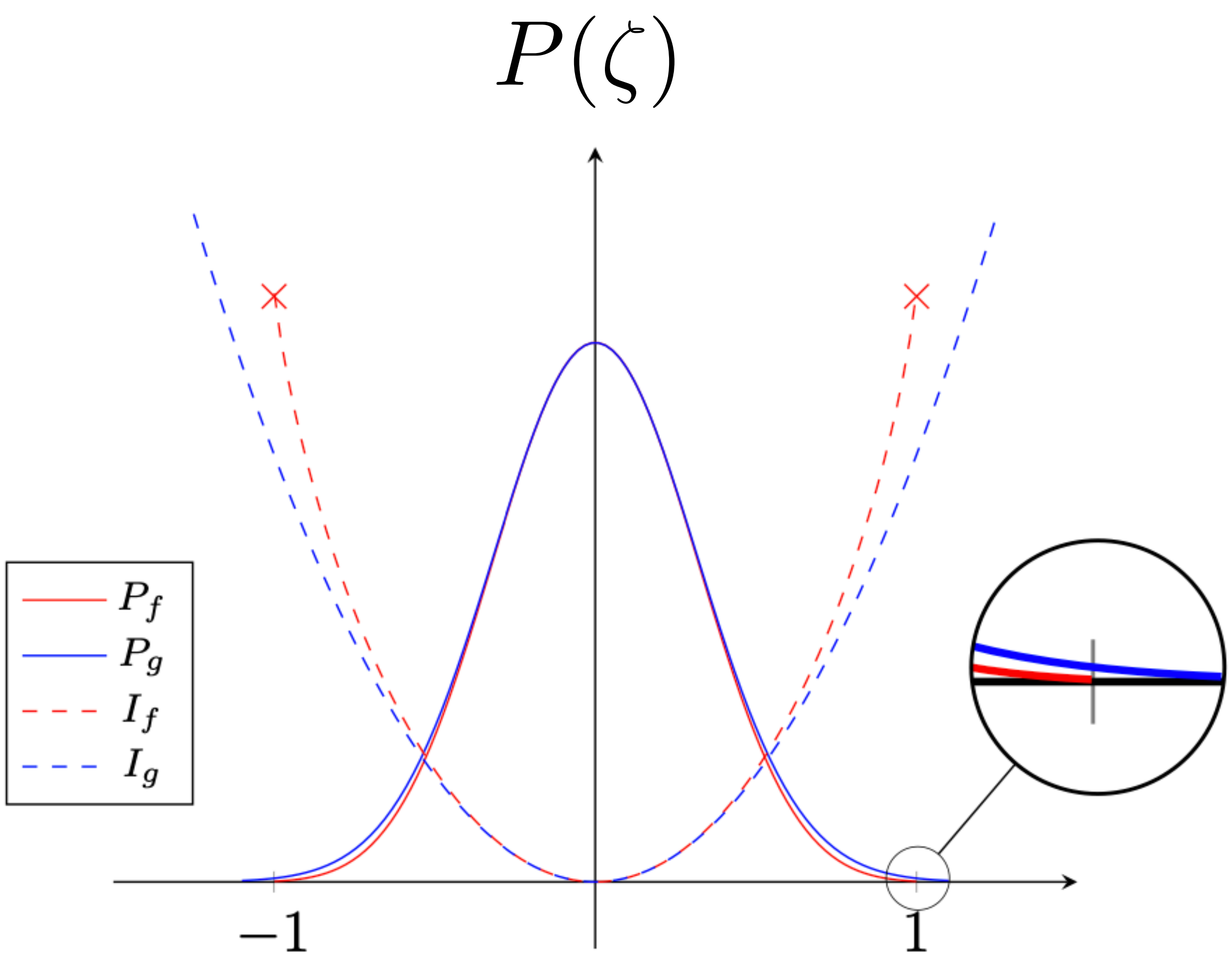
n	Λ_n
1	$0.03630\,\lambda^{1/2} + 0.00076\,\lambda + 0.00049\,\lambda^{3/2}$
2	$0.11814\,\lambda^{1/2} + 0.00338\,\lambda + 0.00138\,\lambda^{3/2}$
3	$0.21910\,\lambda^{1/2} + 0.00795\,\lambda + 0.00316\,\lambda^{3/2}$

LO NLO NNLO

Non-Perturbative Non-Gaussianity

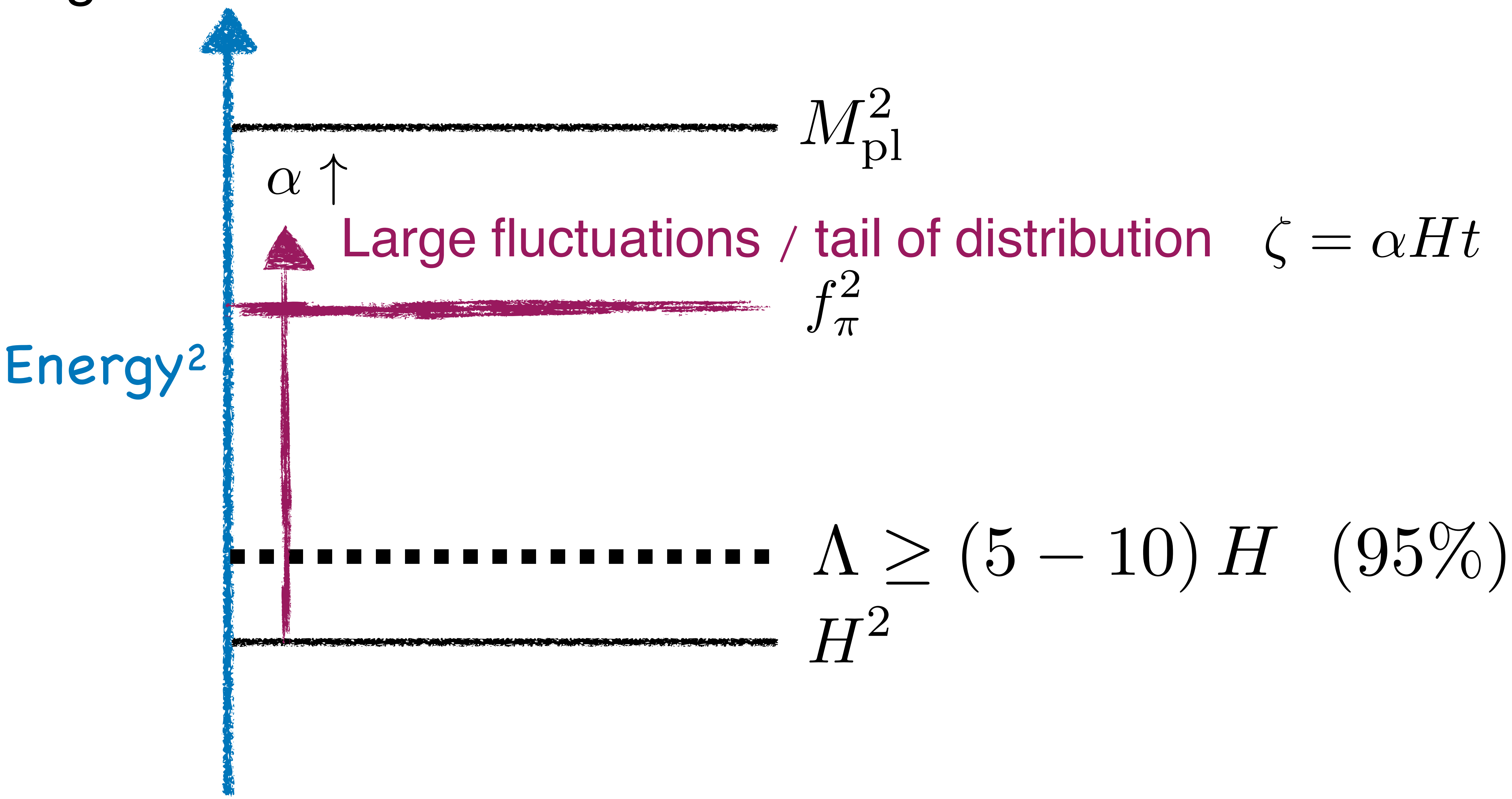
In some models, information lives at high N-point correlators

Related to calculating the tail of the probability distribution



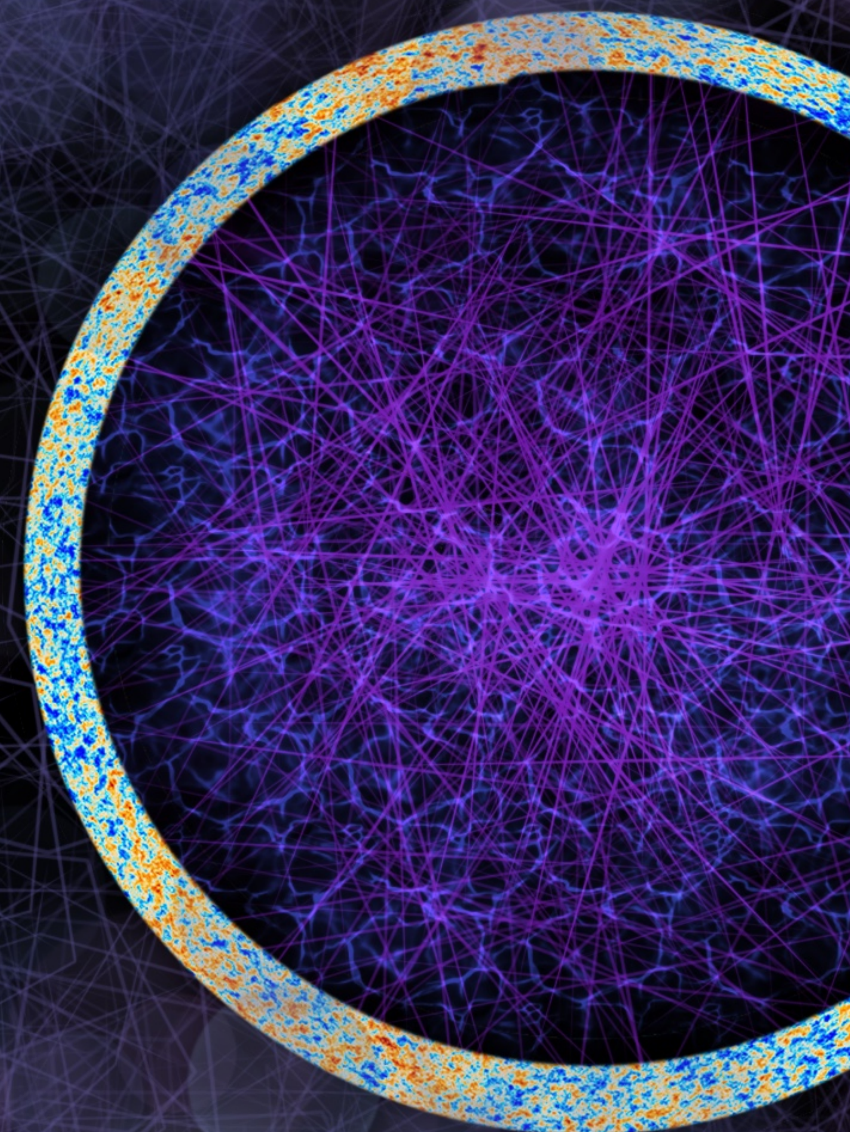
Non-Perturbative Non-Gaussianity

Large fluctuations cannot be calculated in EFT

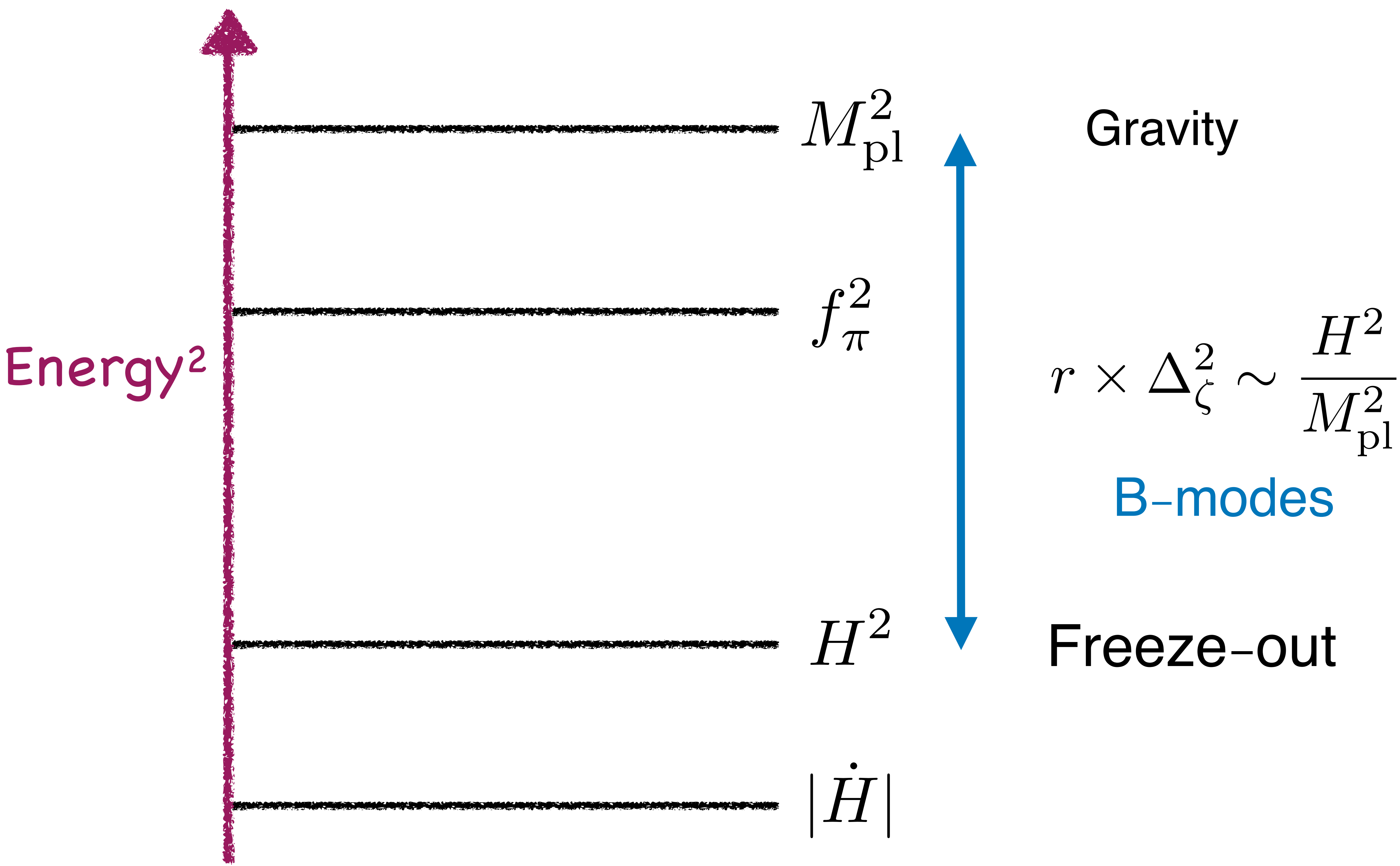


Can be understood as example of Large Deviation Principle

Future Observations



Gravitational Waves



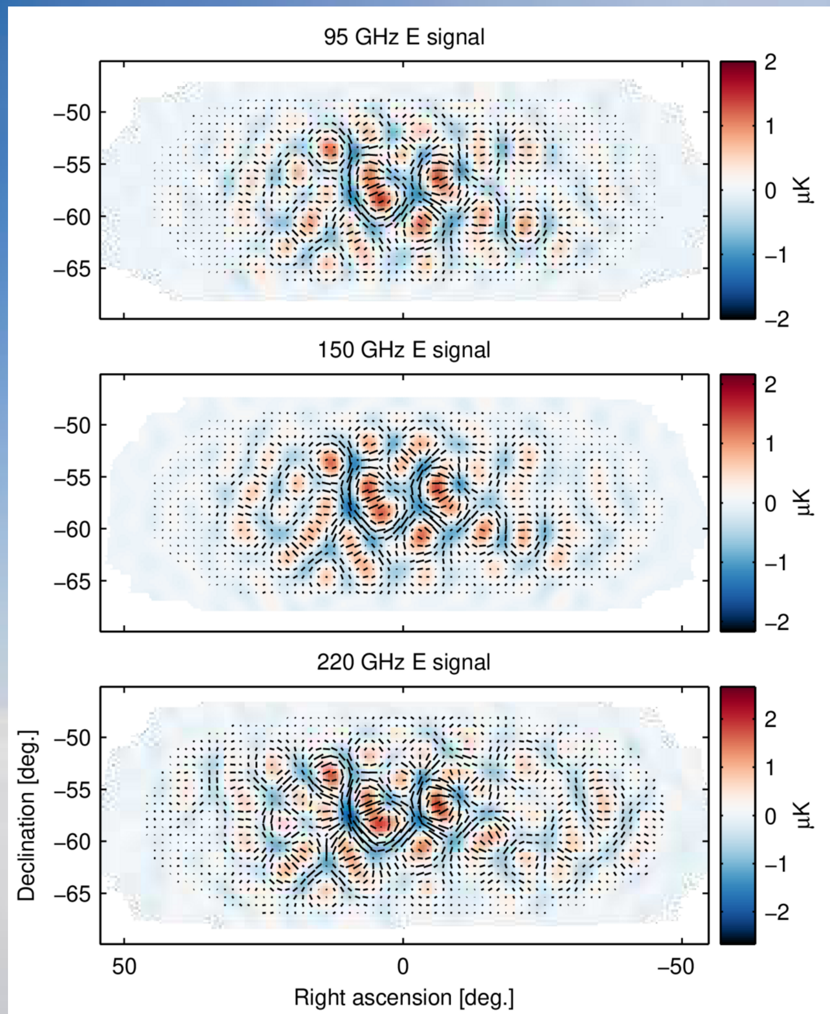


Image from BICEP/Keck

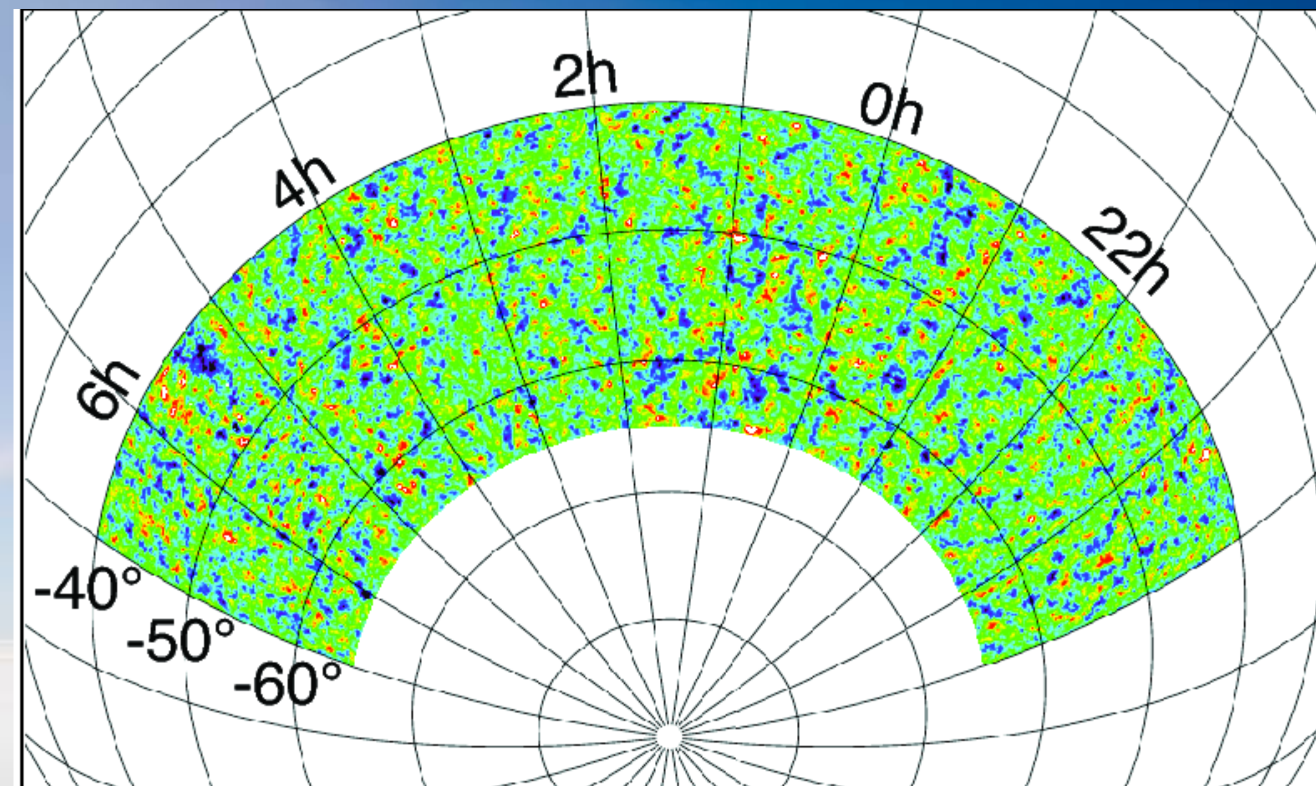
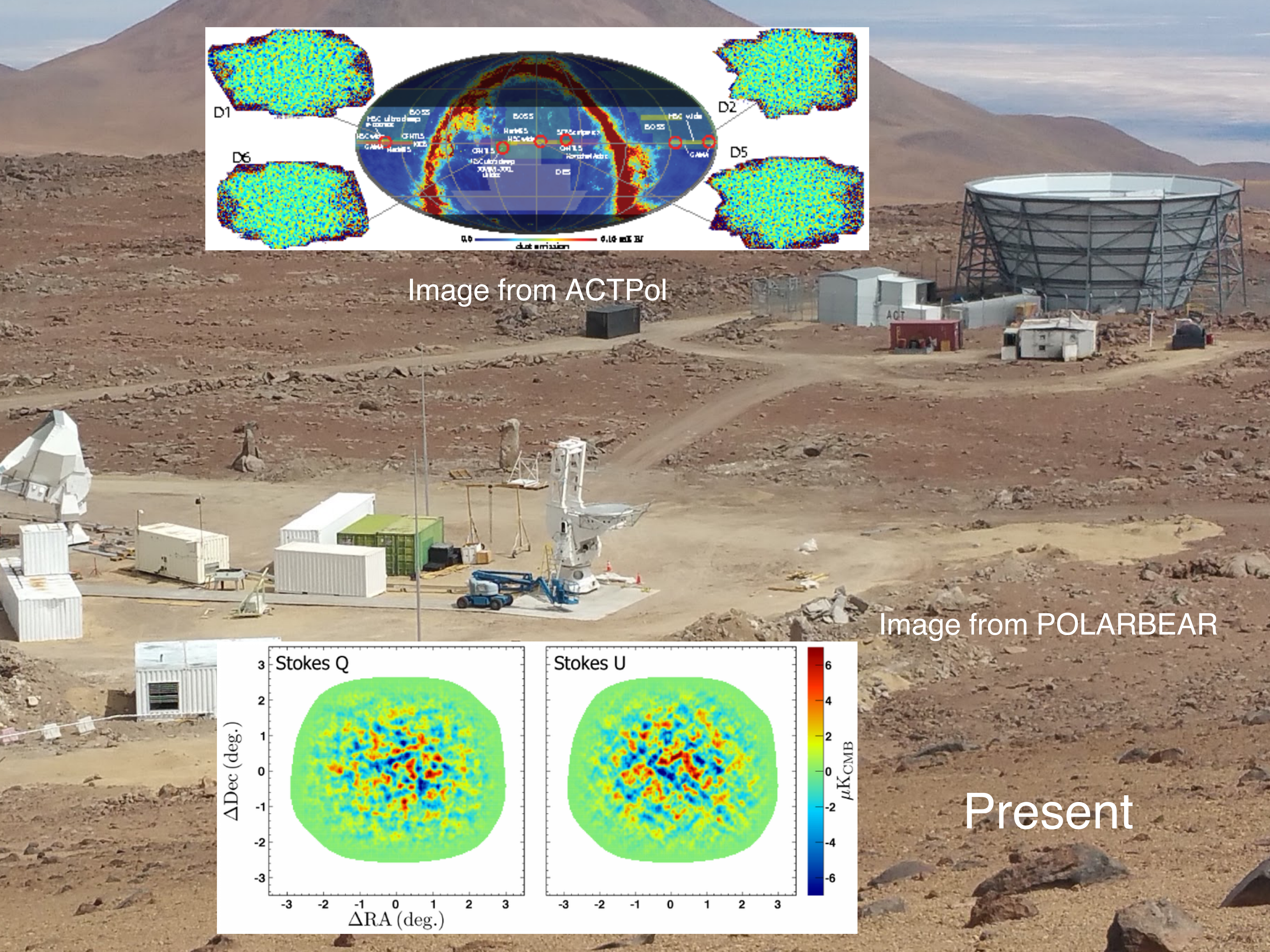


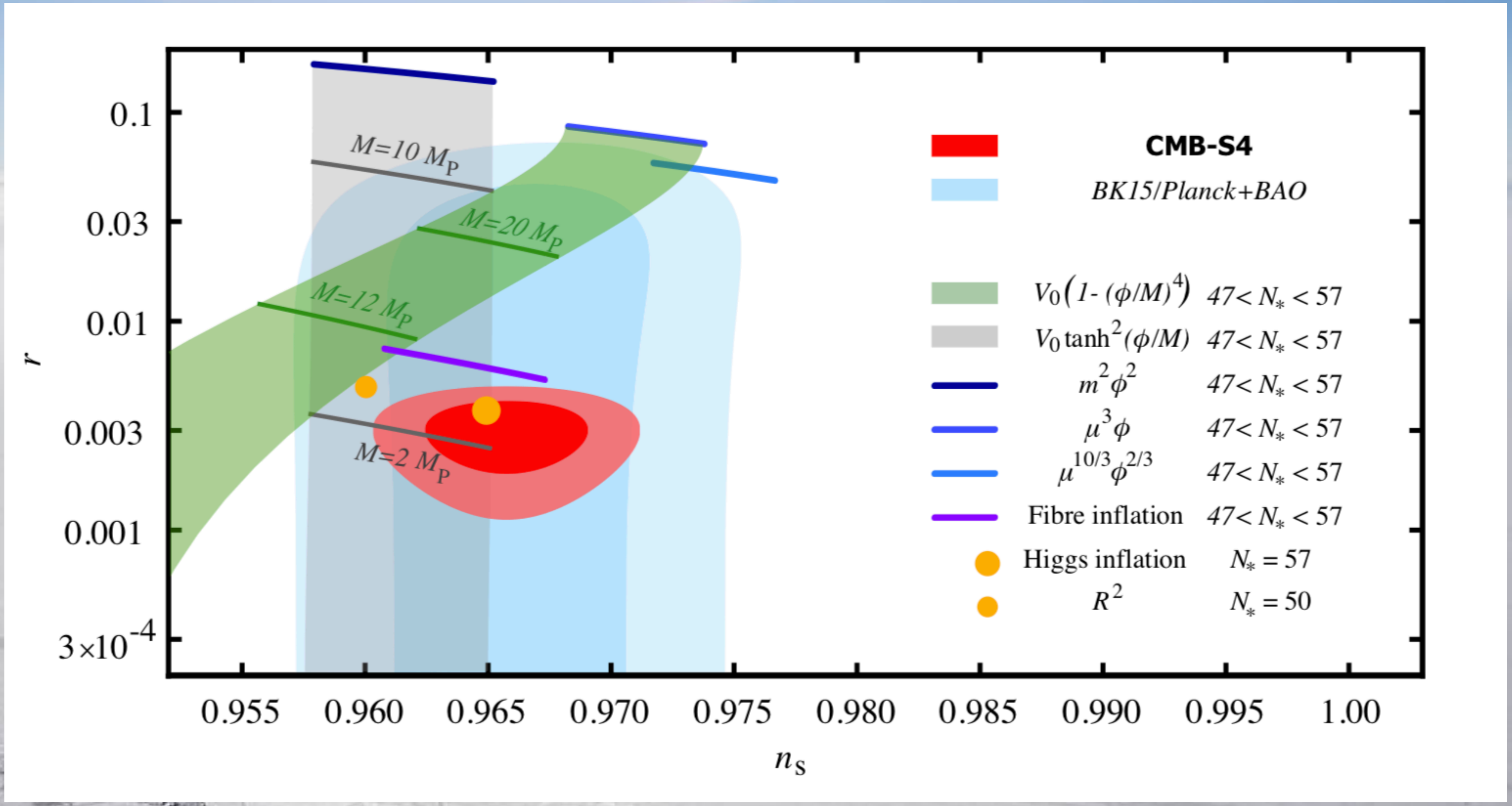
Image from SPT

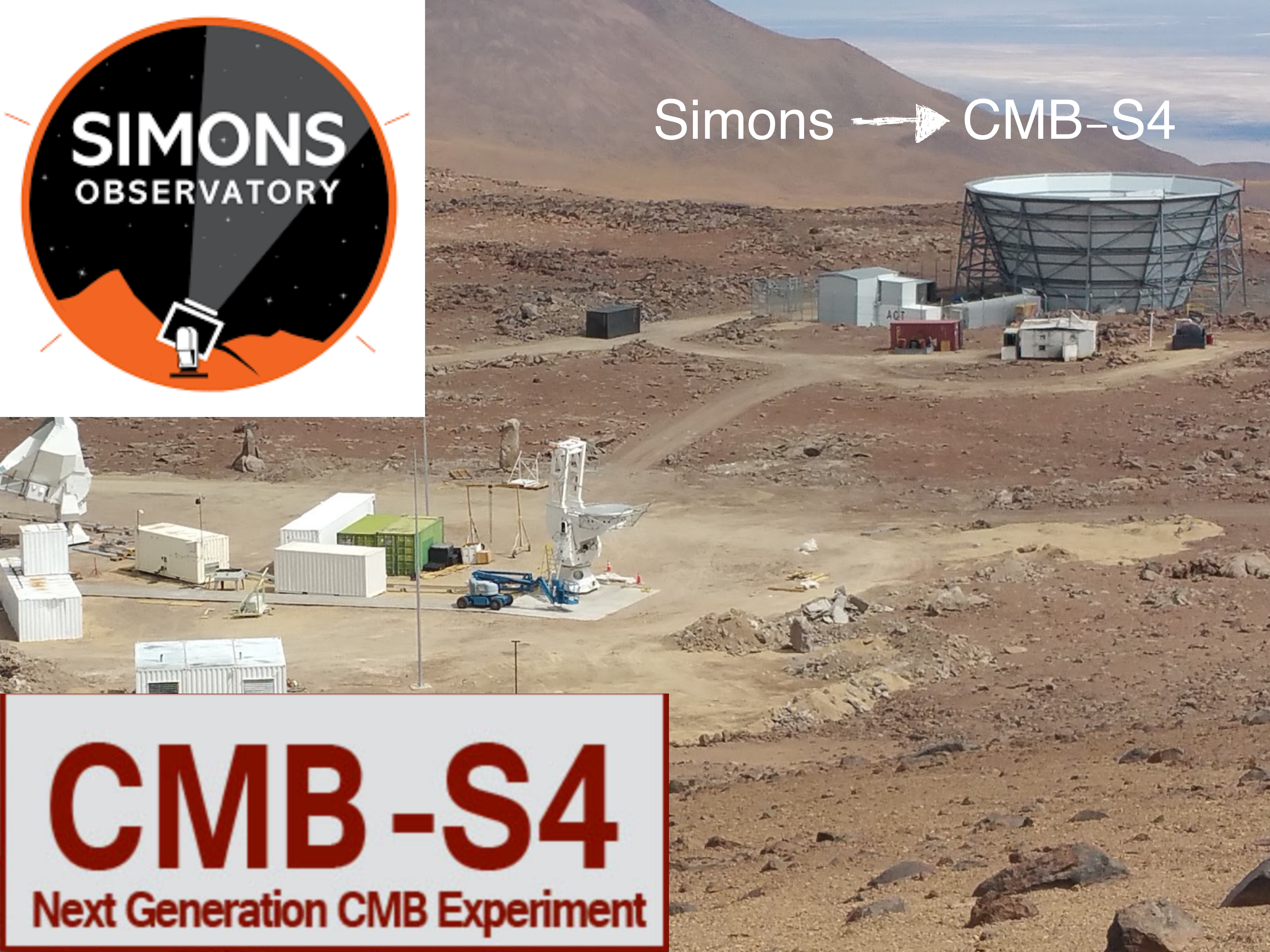


D1
D2
D6
D5
Image from ACTPol
Image from POLARBEAR
Stokes Q
Stokes U
ΔDec (deg.)
ΔRA (deg.)
μK_CMB
Present

SPT + Keck → CMB-S4(?)

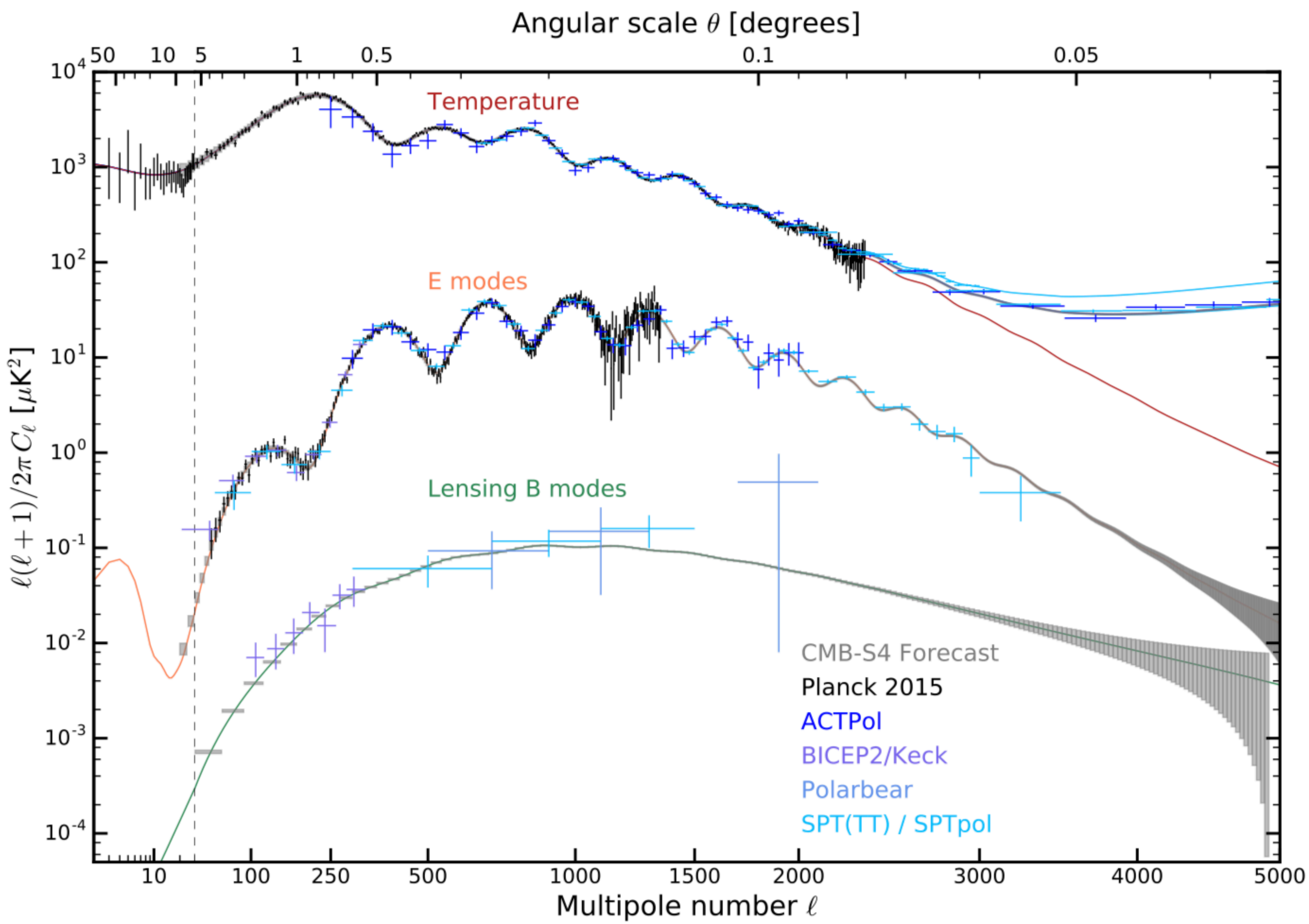
CMB-S4
Next Generation CMB Experiment




SIMONS
OBSERVATORY
Simons → CMB-S4
ACT
CMB-S4
Next Generation CMB Experiment

CMB has limits

Not enough modes left in the CMB



CMB has limits

Not enough modes left in the CMB

Type	*Planck* actual (forecast)	CMB-S4	CMB-S4 + low-ℓ *Planck*
Local	$\sigma(f_{\rm NL}) = 5\,(4.5)$	$\sigma(f_{\rm NL}) = 2.6$	$\sigma(f_{\rm NL}) = 1.8$
Equilateral	$\sigma(f_{\rm NL}) = 43\,(45.2)$	$\sigma(f_{\rm NL}) = 21.2$	$\sigma(f_{\rm NL}) = 21.2$
Orthogonal	$\sigma(f_{\rm NL}) = 21\,(21.9)$	$\sigma(f_{\rm NL}) = 9.2$	$\sigma(f_{\rm NL}) = 9.1$

Naive mode counting tells us that $\sigma(f_{\rm NL}^{\rm eq}) \propto \ell_{\rm max}^{-1}$

In detail, we only get the scaling $\sigma(f_{\rm NL}^{\rm eq}) \propto \ell_{\rm max}^{-0.55}$

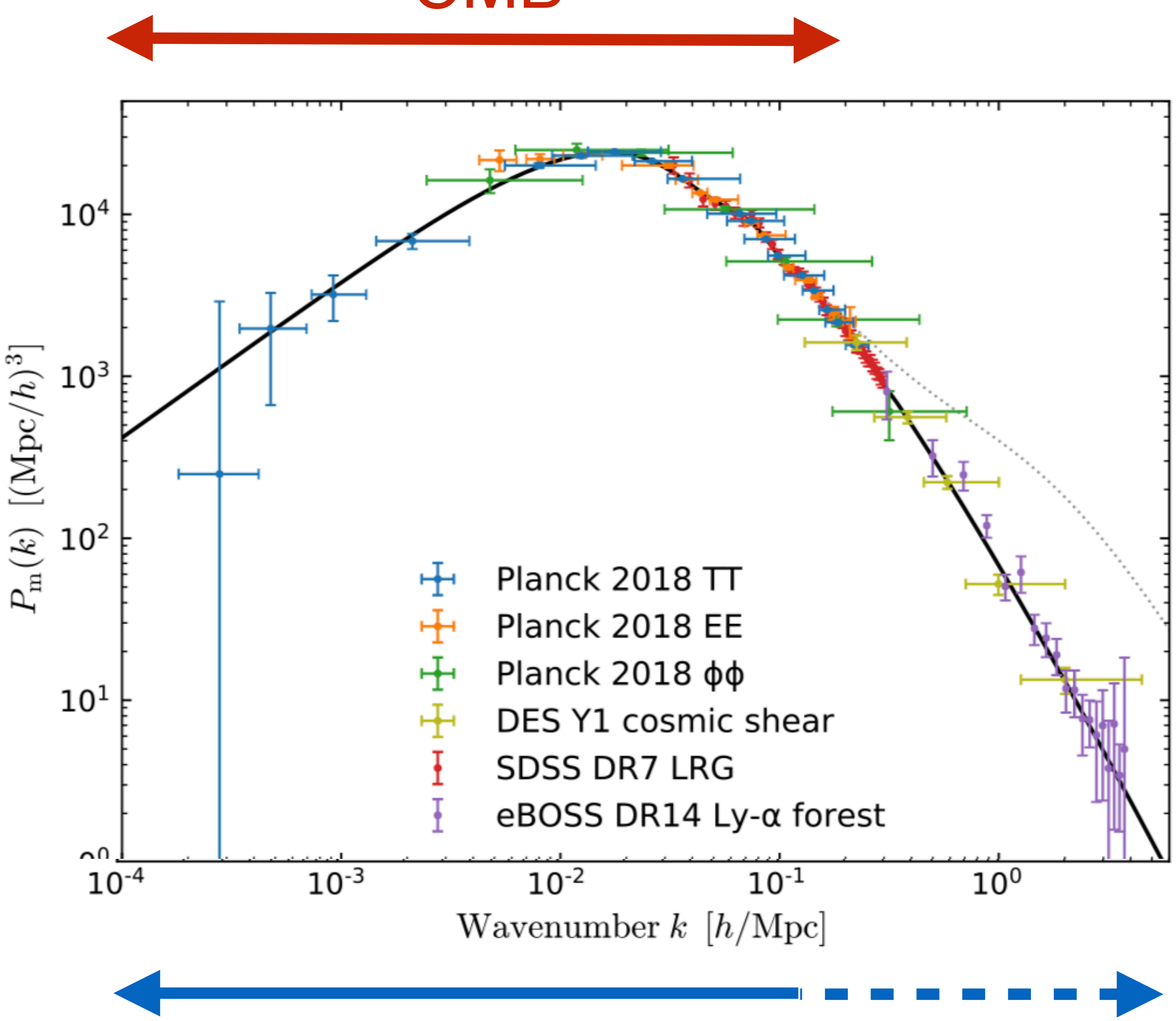
Kalaja et al. (2020)

Lose information from projection from 3d to 2d

LSS is the future

LSS is a key to our to understanding inflation

CMB



Linear regime of LSS

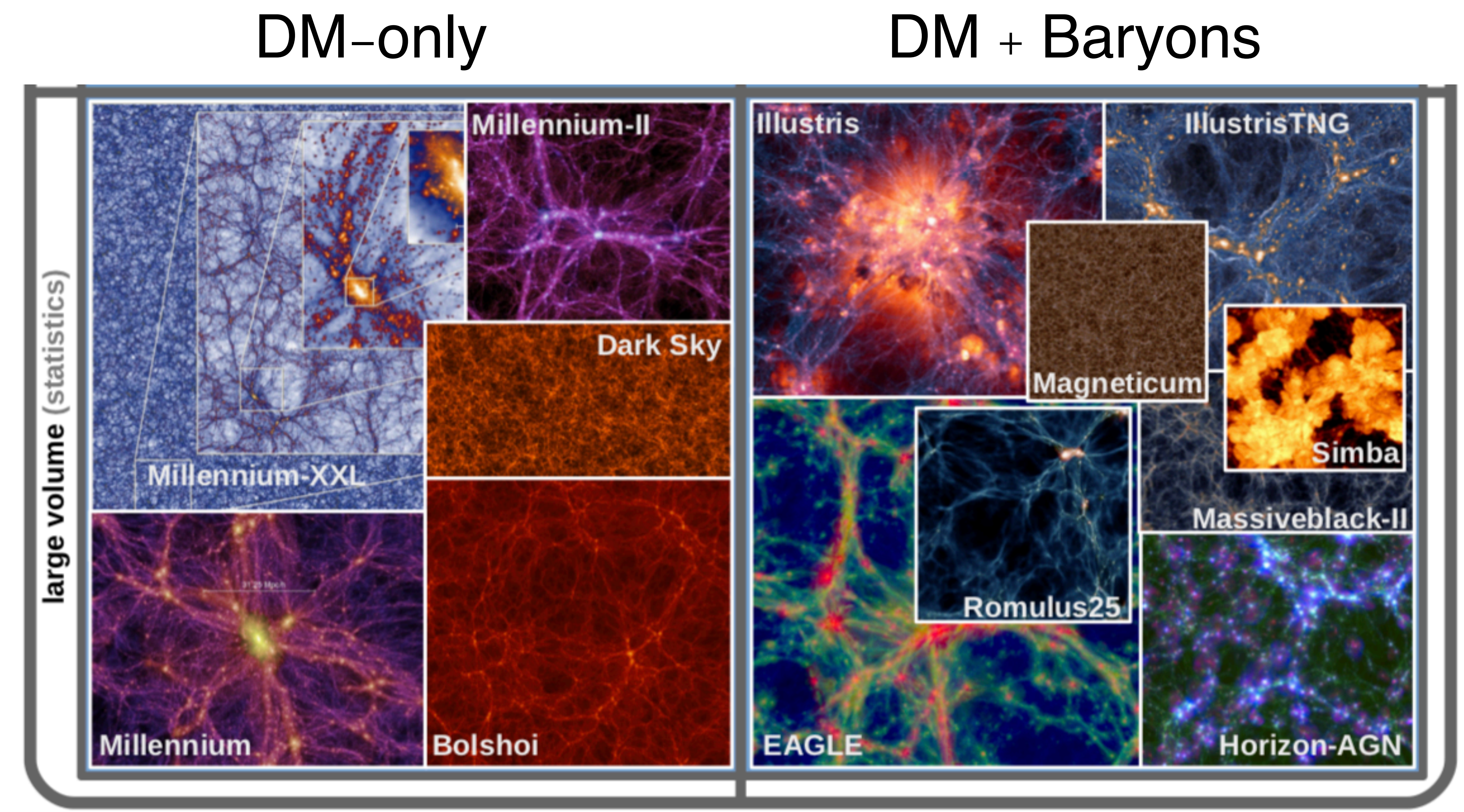
$$N_{\rm modes}^{\rm CMB} \sim \left(\frac{k_{\rm max}}{k_{\rm min}}\right)^2$$

$$N_{\rm modes}^{\rm LSS} \sim \left(\frac{k_{\rm max}}{k_{\rm min}}\right)^3$$

Figure from Chabanier et al.

LSS is the future

Problem: low redshift universe is hard to model



Vogelsberger et al. (2019)

Strategies

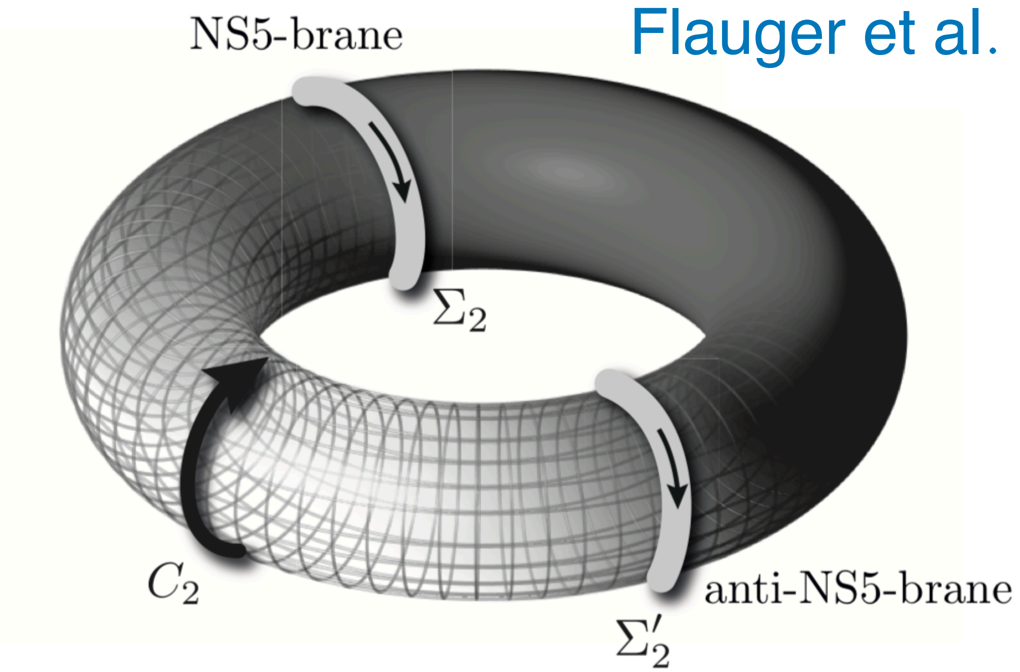
Inflation	LSS Modeling	Principles
Look for novel signals:	Improve accuracy:	Protected quantities
Top down (QG)	N-body	Locality
EFT/symmetries	Sims with baryons	Causality
New fields	Machine learning	Symmetries
New mechanisms	EFT / perturbative	Bootstrap

Top Down Model Building

E.g. axion monodromy inspires features searches

$$V(\phi) = \mu^3\phi + \Lambda^4 \cos\left(\frac{\phi}{f}\right) = \mu^3\left[\phi + bf\cos\left(\frac{\phi}{f}\right)\right]$$

Flauger et al. (2009)



Originated from string models

Silverstein & Westphal (2008)

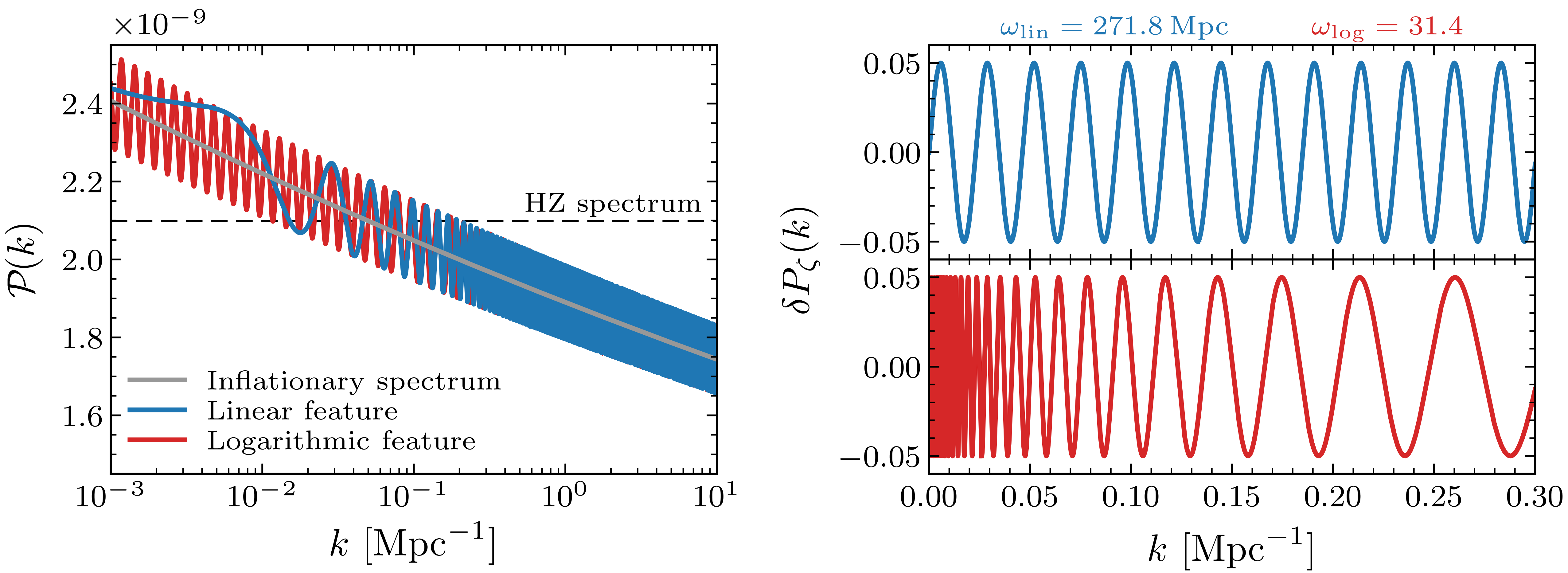
McAllister, Silverstein, & Westphal (2008)

Logarithmic oscillations tied to non-perturbative effects

Figure from Baumann & McAllister

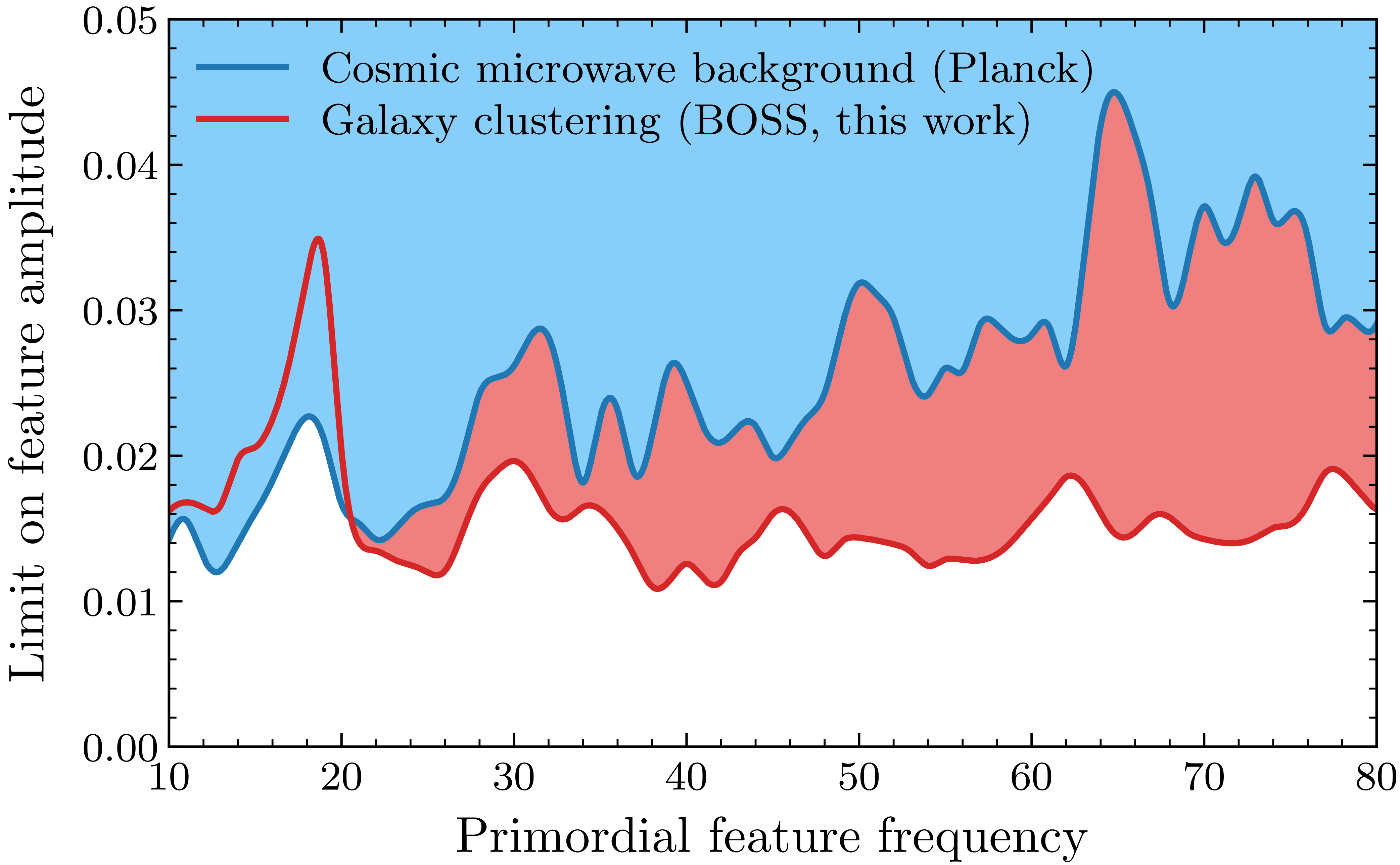
Top Down Model Building

Oscillatory features in correlators



Top Down Model Building

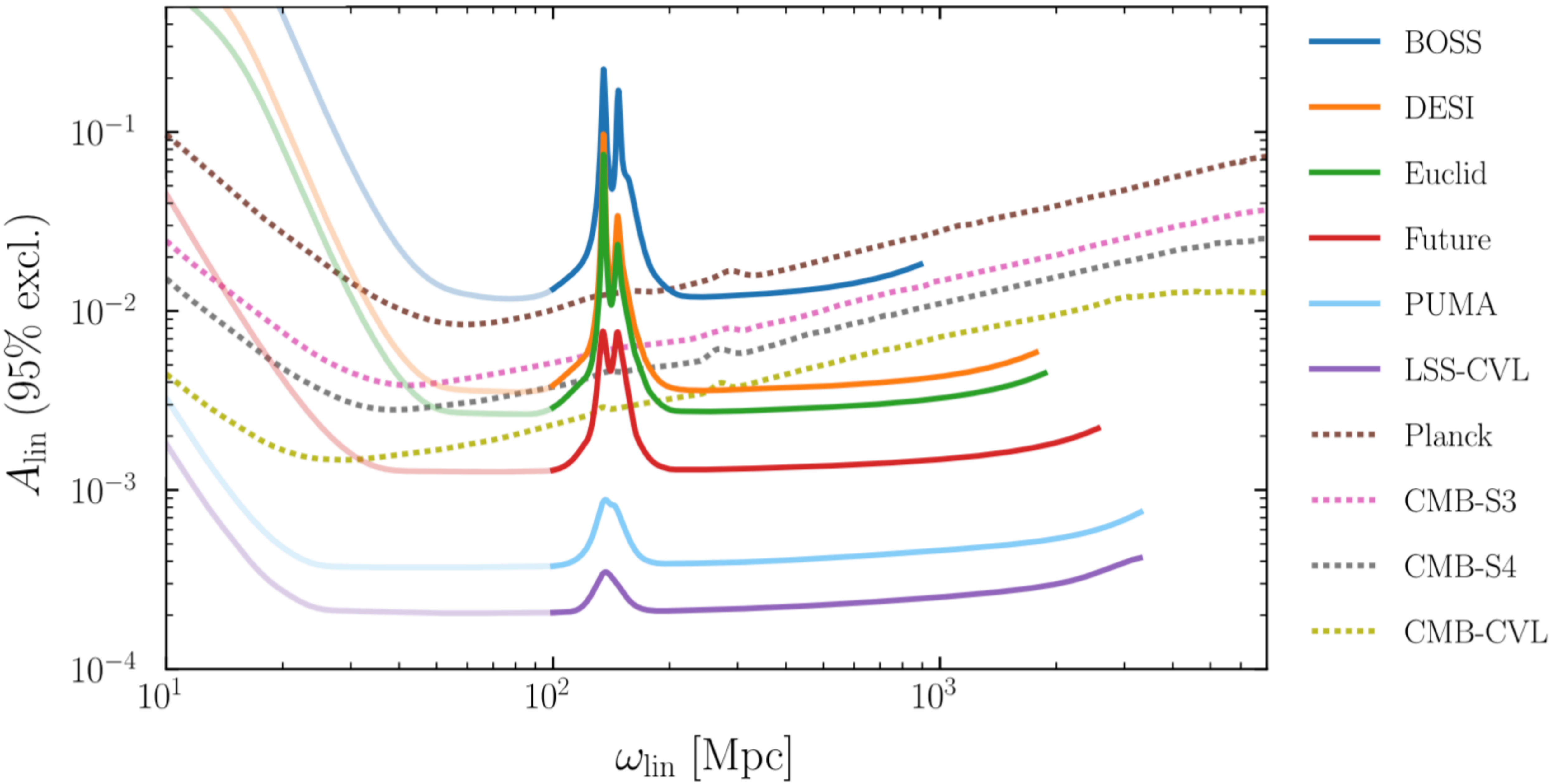
Oscillatory signals in LSS are distinct from nonlinearity



Beutler, Biagetti, DG, Slosar, & Wallisch (2019)

Top Down Model Building

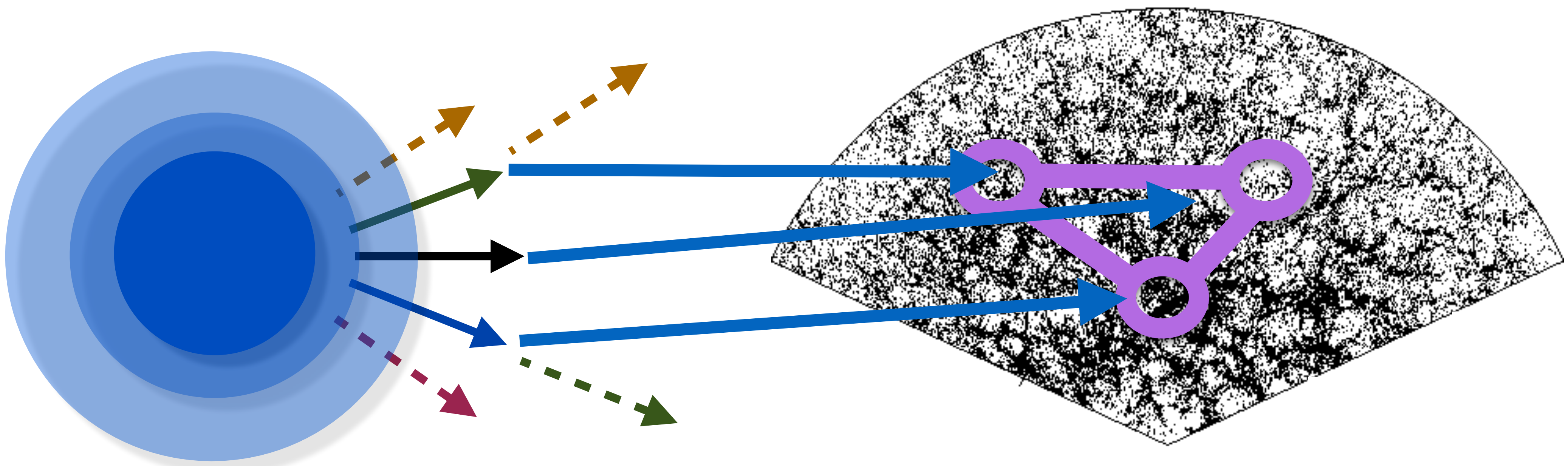
Oscillatory signals in LSS are distinct from nonlinearity



Beutler, Biagetti, DG, Slosar, & Wallisch (2019)

Cosmological Collider

Light(ish) particles are detectable via non-Gaussianity



Leaves unique signatures in the soft limits

Chen & Wang (2009); DG & Baumann (2011); Chen & Wang (2012); Noumi et al. (2012); Arkani-Hamed & Maldacena (2015); Lee et al. (2016); + many many more

Violates the single-field consistency conditions

Maldacena (2002); Creminelli & Zaldarriaga (2004)

Cosmological Collider

Single field consistency can be applied directly to LSS

Creminelli et al. (2013 x 3)

Breaking of consistency–scale dependent bias, e.g.

Dalal et al. (2007)

Galaxies Matter

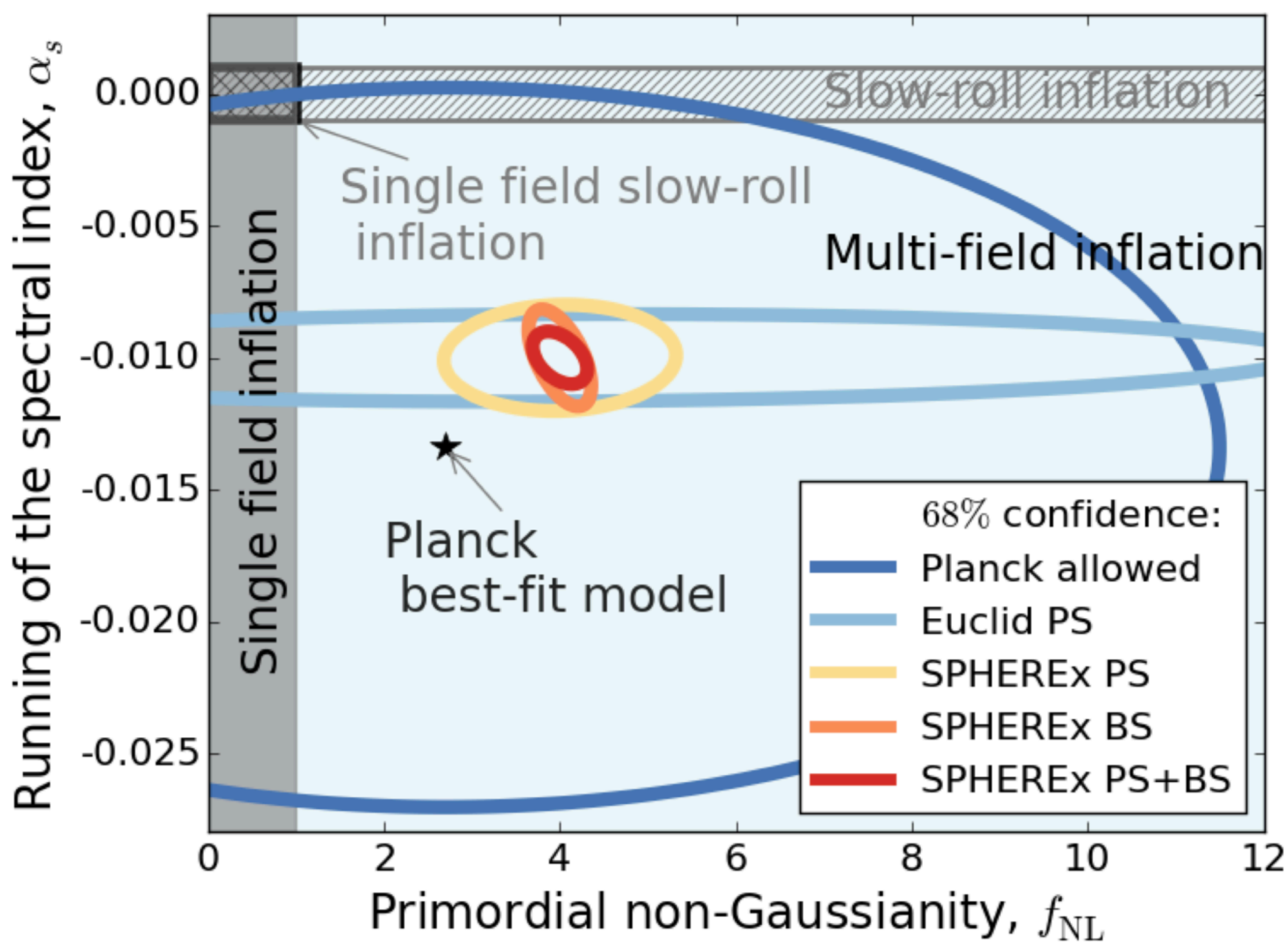
$$\delta_g(\vec{k}) \approx \frac{1}{k^{1/2+\nu}}\delta_m(\vec{k}) \qquad \nu \equiv \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}$$

Looks like a violation of equivalence principle

Does not arise from nonlinear dynamics

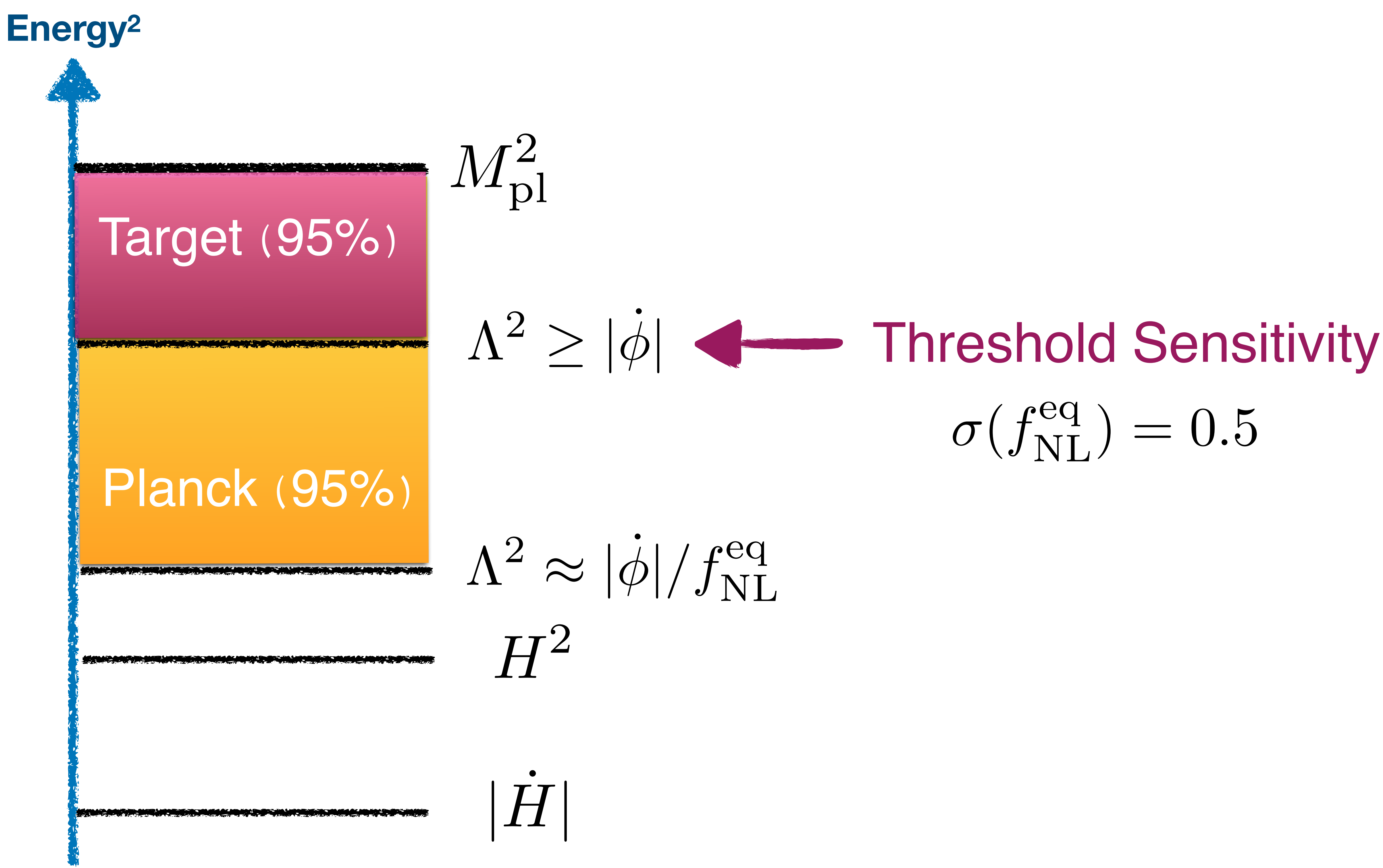
Cosmological Collider

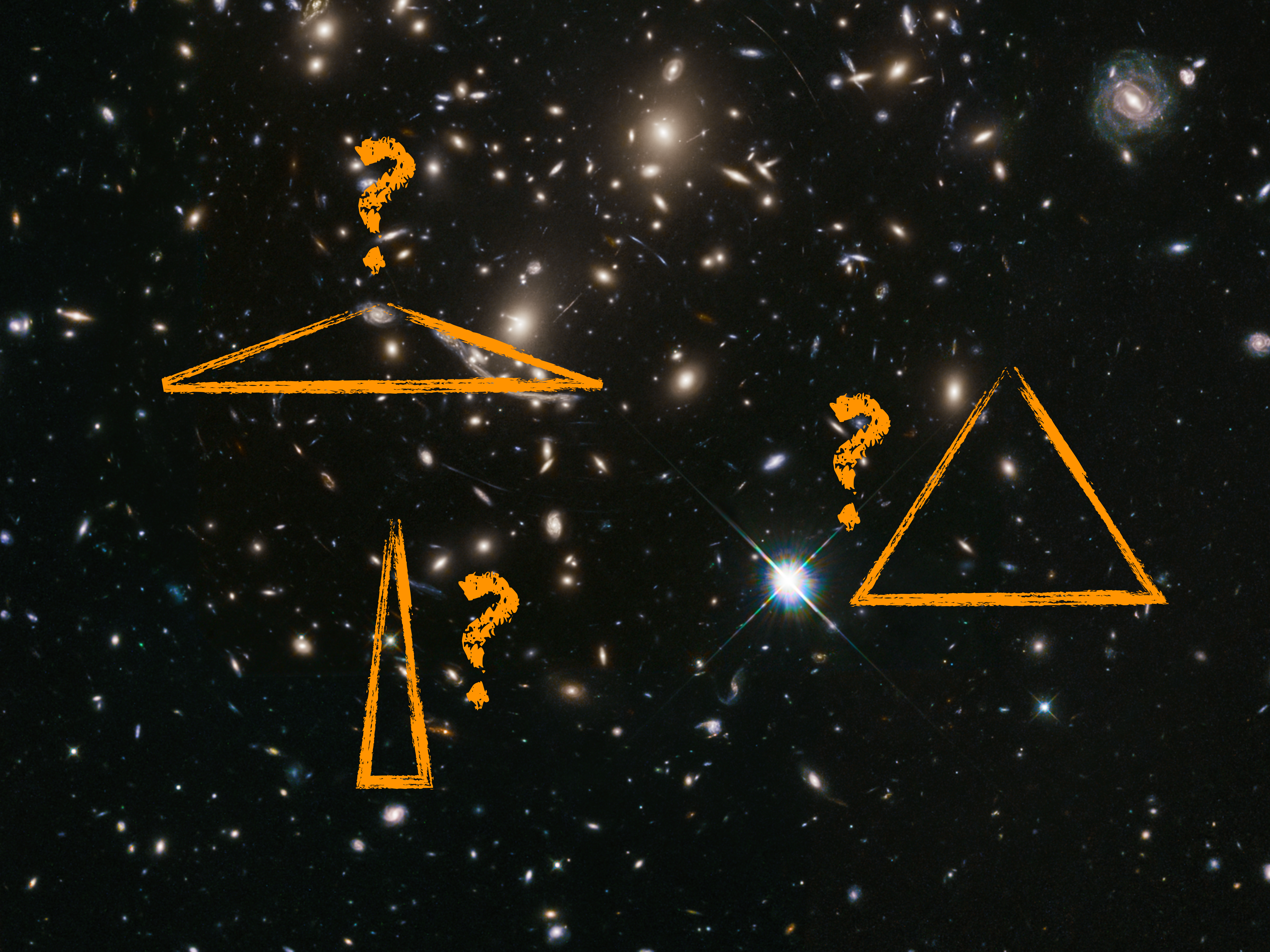
For extra light fields, LSS will make large improvement



Doré et al. (2014) [SPHEREx]

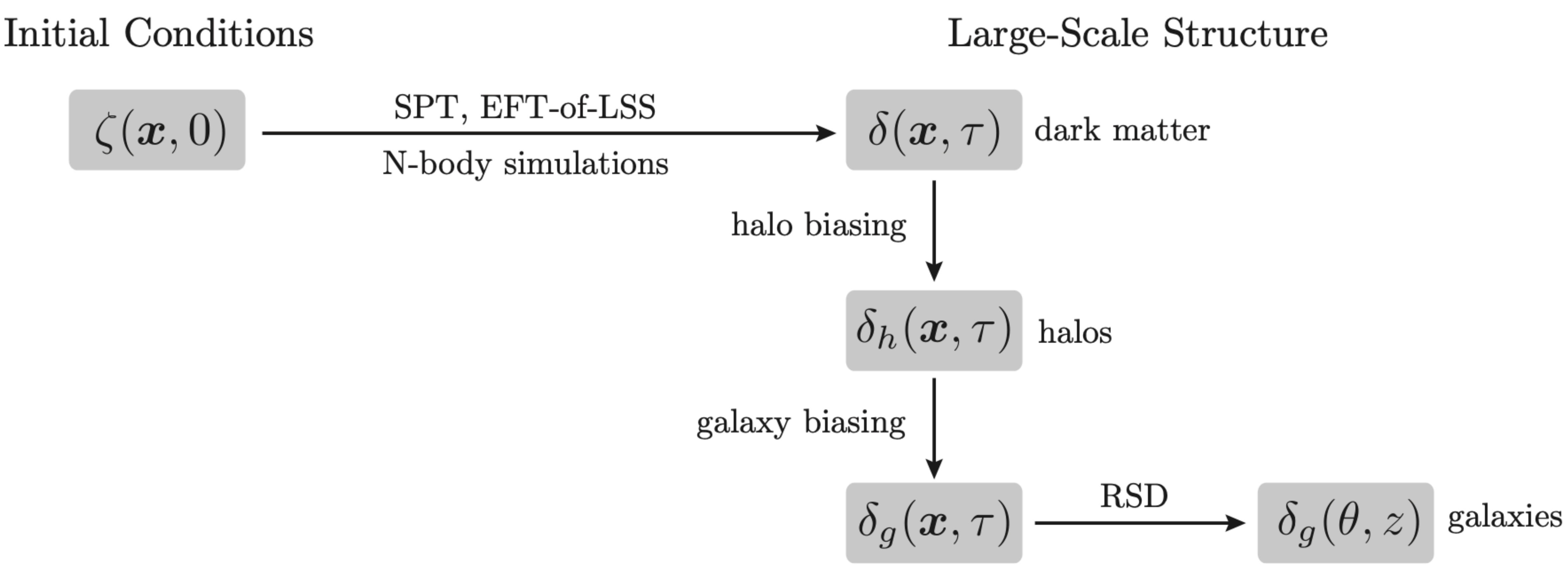
The Nature of Inflation





Strategy

Brute force modeling with perturbation theory

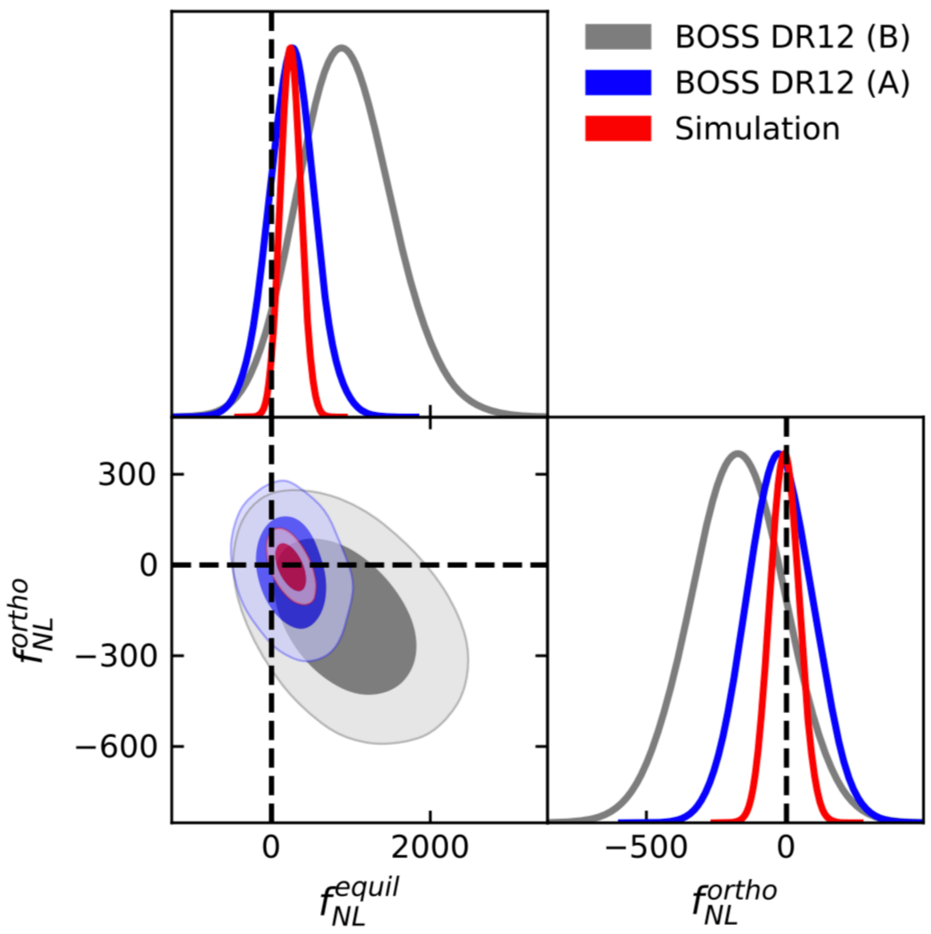


Cut data to $k < k_{\rm max}$ to minimize variance and bias

Status

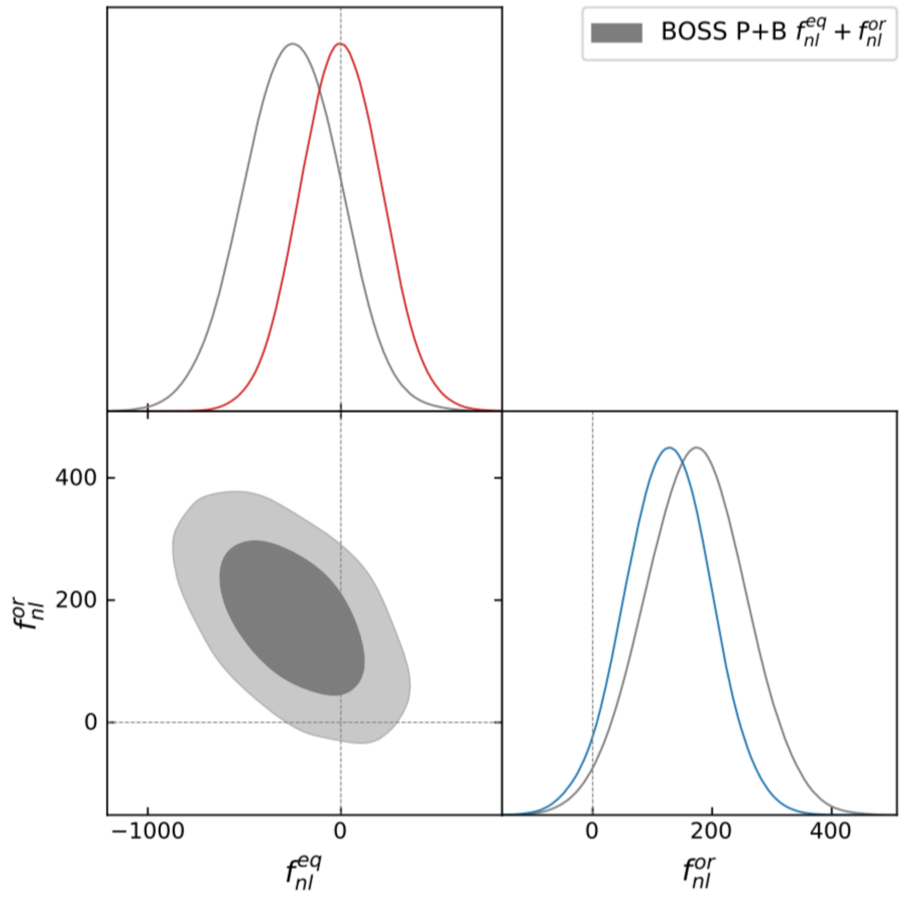
First constraints from BOSS

$$f_{\rm NL}^{\rm eq} = 260 \pm 300$$



Cabass et al. (2022)

$$f_{\rm NL}^{\rm eq} = 2 \pm 212$$



D'Amico et al. (2022)

Status

Published Forecasts for future surveys

Euclid Spec: $\sigma(f_{\rm NL}^{\rm eq}) = 35$ $k_{\rm max} = 0.24 \,\text{at}\, z = 2$

Euclid (w. WL) $\sigma(f_{\rm NL}^{\rm eq}) = 7.5$

PUMA $\sigma(f_{\rm NL}^{\rm eq}) = 4.5$ $k_{\rm max} = 0.1\, h\,{\rm Mpc}^{-1}/D(z)$

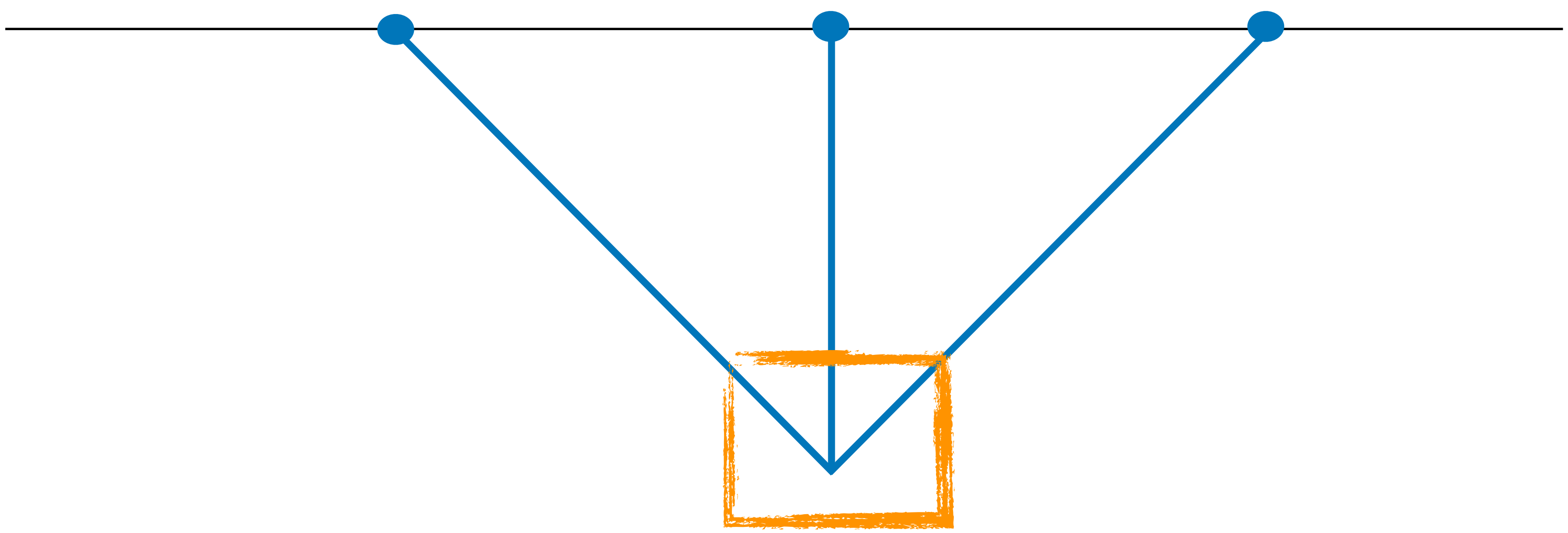
MegaMapper: $\sigma(f_{\rm NL}^{\rm eq}) = 14$ $k_{\rm max} = 0.2 \,\text{at}\, z = 3$

Locality

The inflationary signal is nonlocal in space

Created at the past intersection of the light cones

DG & Porto (2020)

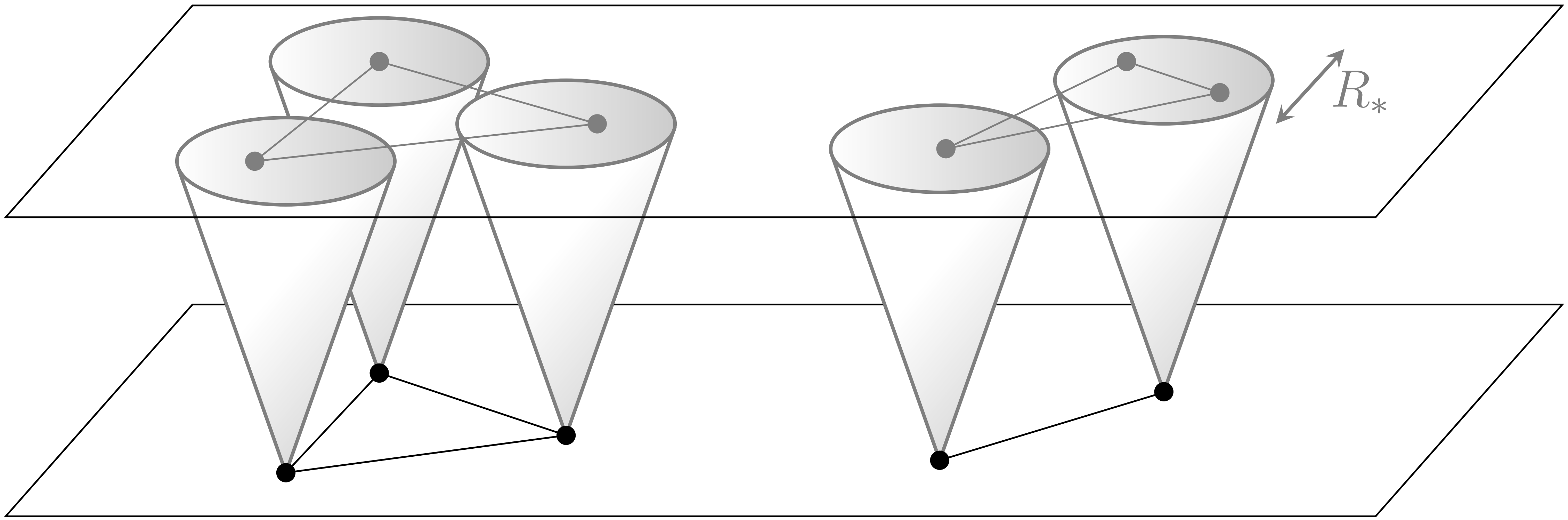


$$B_{\rm eq} = 162\, f_{\rm NL}^{\rm eq}\, \frac{\mathcal{T}(k_1)\mathcal{T}(k_2)\mathcal{T}(k_3)\Delta_\Phi^2}{k_1 k_2 k_3 (k_1+k_2+k_3)^3}$$

Proportional to 3 commutators: uniquely quantum!

Locality

Dark matter is slow: late-time evolution is ultra-local*



Primordial NG

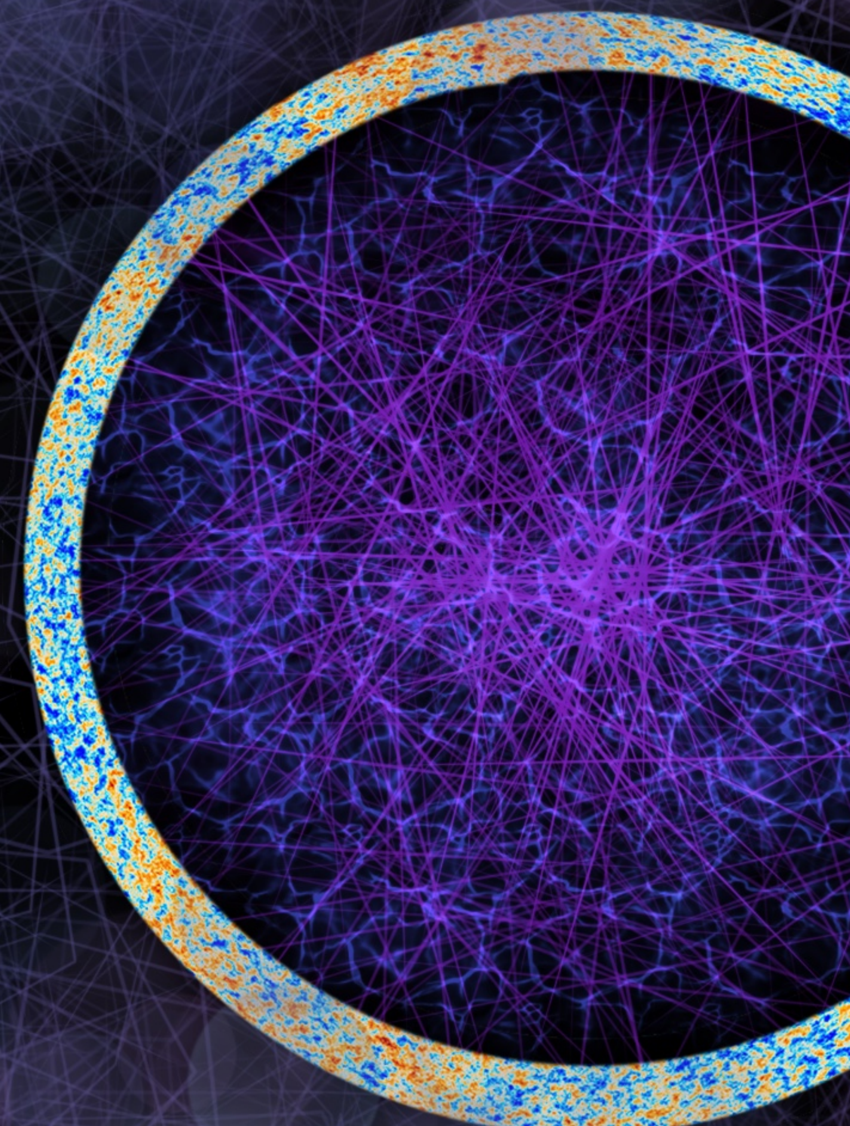
Late-time NG

Nonlinearity can never completely mimic the signal

Differences seen at map-level

DG & Baumann (2021)

Summary



Summary

Core theoretical progress has been around correlators

- EFT has been powerful in framing questions
- Bootstrap is proving to be an important tool
- Loops/IR issues are mostly understood in dS
- Calculating loops remains limited by technology
- Non-perturbative problems are the next frontier

Summary

Key observational progress in both CMB and LSS

- CMB remains essential for gravitational waves
- CMB+LSS cross-correlation useful for local NG
- LSS has exceed CMB for primordial features
- Progress in NG from LSS but a long way to go

Thank you