Introduction to Inflation: Non-gaussianity

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Outline : Lecture 2

Non-gaussanity in Single-field

Single-Field Consistency Conditions

Multifield inflation

Cosmology after Planck

References : Lecture 1

The Effective Field Theory of Inflation

Cheung, Creminelli, Fitzpatrick, Kaplan, & Senatore

arXiv : 0709.0293

Equilateral Non-Gaussanity and
New Physics on the Horizon

Baumann & DG

arXiv: 1102.5343

See Baumann's TASI lectures for more background

References : Lecture 2

Consistency Conditions:

Non-gaussian features of primordial fluctuations

Maldacena

astro-ph/0210603

Single-Field Consistency Condition for the 3pt func.

Creminelli & Zaldarriaga

astro-ph/0407059

References : Lecture 2

Conventional Multifield:

The Effective Field Theory of Multifield Inflation

Senatore & Zaldarriaga

arXiv : 1009.2093

NG in models with a varying inflaton decay rate

Zaldarriaga

astro-ph/0306006

References : Lecture 2

Quasi-Single Field Inflation

Quasi-Single Field Inflation & NG

Chen & Wang

arXiv : 0911:3380

Signatures of Supersymmetry of the Early Universe

Baumann & DG

arXiv : 1109.0292

References : Lecture 2

Fun Applications

Planck Suppressed Operators

Assassi, Baumann, DG & McAllister

arXiv : 1304.5226

Cosmological Collider Physics

Arkani-Hamed & Maldacena

arXiv : 1503.08043

Lightning Review of Lecture 1

Inflation is a period of quasi-de Sitter expansion

$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$$

$$H = \frac{\dot{a}}{a} \simeq \text{Const.} \qquad a \simeq a_0 e^{Ht}$$

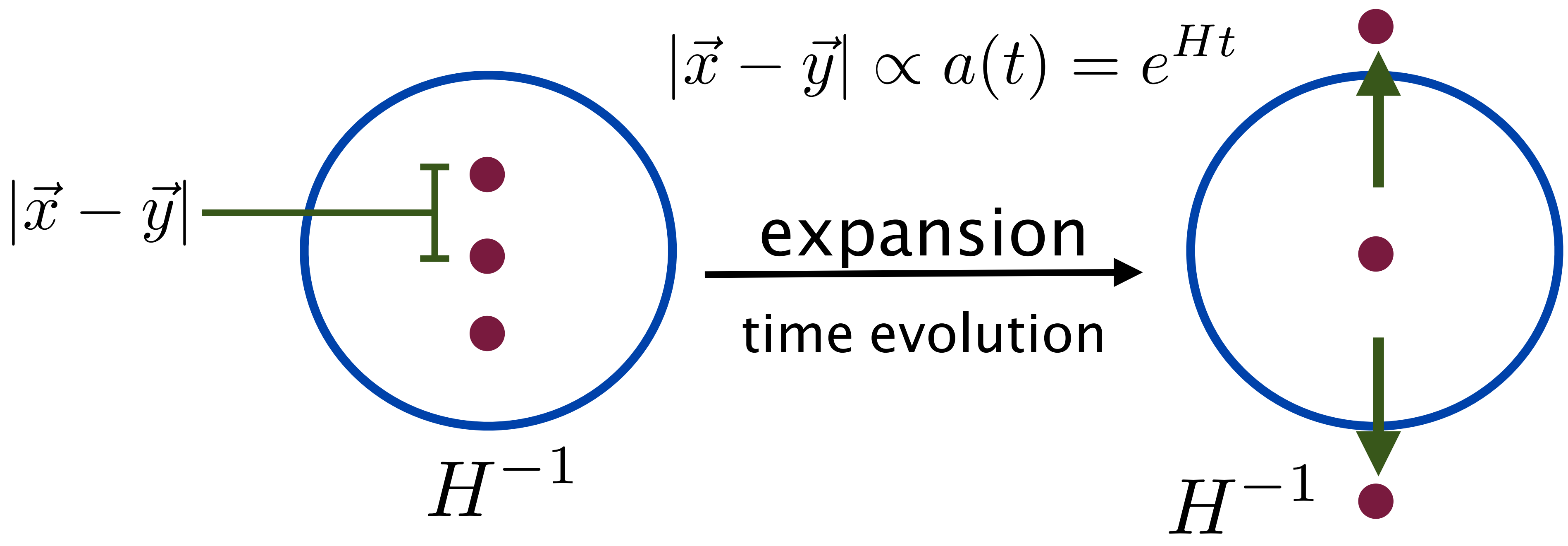
We can pick some general $H(t)$ as long as

$$H(t)^2 \gg |\dot{H}(t)|$$

We also needed a clock to end this period

Lightning Review of Lecture 1

During inflation, quantum fluctuations produced



Flat space intuition applies when $k_p \equiv \frac{k}{a} \gg H$

Modes free outside the horizon $k_p \equiv \frac{k}{a} \ll H$

Lightning Review of Lecture 1

Variations in length of inflation = density fluctuations

$$ds^2 = -dt^2 + a^2(t)e^{2\zeta}d\vec{x}^2$$

$$\zeta(\vec{x}) = \frac{d\log a}{dt}\delta t(\vec{x}) = H\delta t(\vec{x})$$

EFT of Inflation = EFT of clock the controls length

Single-field = no spectators, just a clock

Lightning Review of Lecture 1

EFT described by $U = t + \pi$

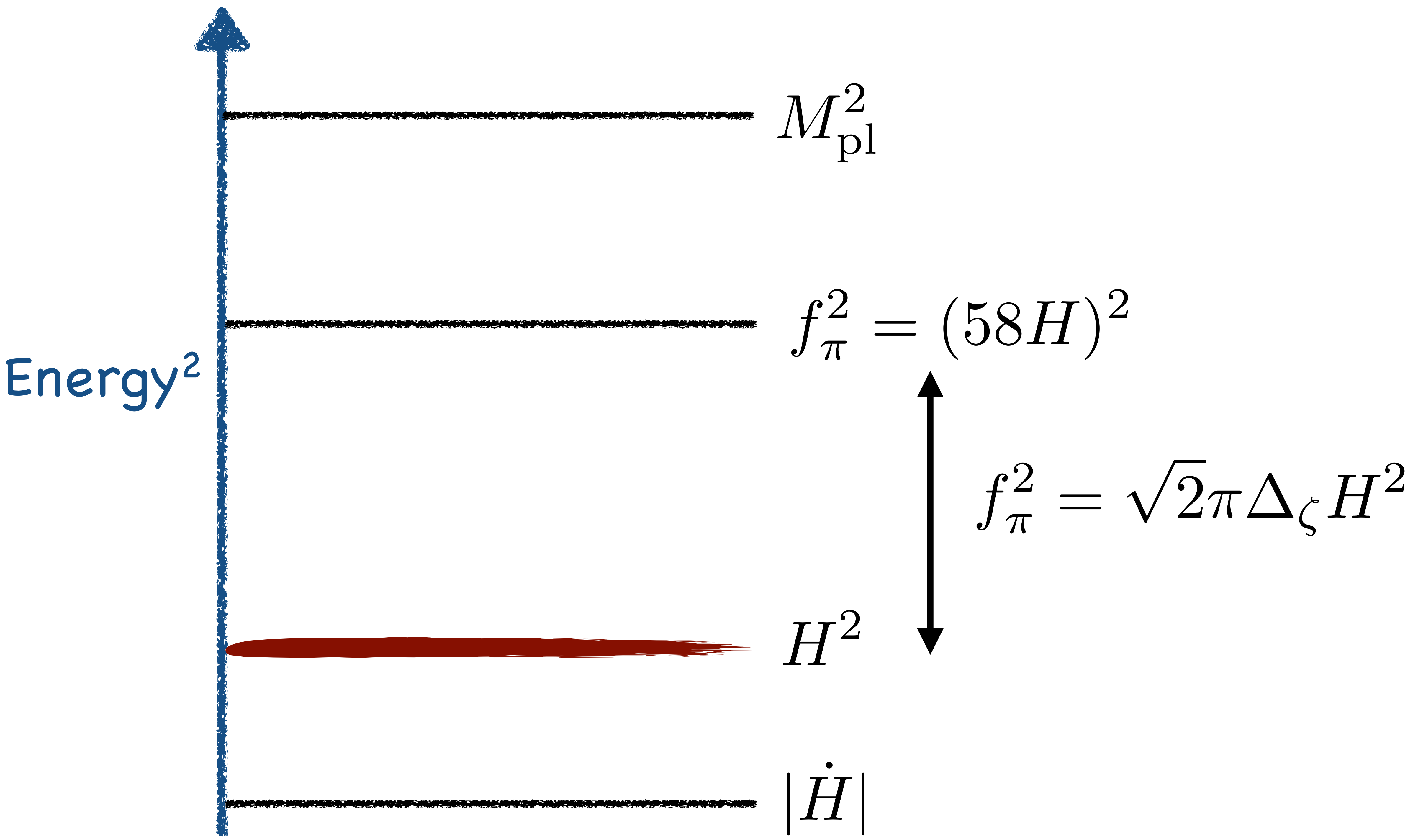
$$\mathcal{L} = M_{\rm pl}^2 \dot{H} \partial_\mu U \partial^\mu U - M_{\rm pl}^2 (H^2 + \dot{H}) + \sum_{n \geq 2} M_n^4(U)(\partial_\mu U \partial^\mu U + 1)^n + \mathcal{O}(\nabla_\mu \nabla_\nu U)$$

Keeping up to $n = 2$

$$\mathcal{L}_\pi = \frac{M_{\rm pl}^2 |\dot{H}|}{c_s^2} \left[(\dot{\pi}^2 - c_s^2 \partial_i \pi \partial^i \pi) - (1 - c_s^2)(\dot{\pi} \partial_i \pi \partial^i \pi - \dot{\pi}^3) \right]$$

Define breaking scale $f_\pi^4 = 2 M_{\rm pl}^2 |\dot{H}| c_s$

Energy Scales



Non-Gaussanity in Single-Field Inflation

Strong Coupling Scale

EFTs include operators of all dimensions

The irrelevant operators show where theory breaks

$$\mathcal{L} = \mathcal{L}_{\text{rel.}} + \sum_{\Delta > 4} \frac{c}{\Lambda^{\Delta - 4}} \mathcal{O}_{\Delta}$$

Scale Λ hints at the UV origin of our EFT

Constraints on Λ from precision measurements

Strong Coupling Scale

Action contains irrelevant operators

$$\mathcal{L}_3 = \frac{M_{\rm pl}^2 |\dot{H}| (1 - c_s^2)}{c_s^2} [\dot{\pi}\partial_i\pi\partial^i\pi - \dot{\pi}^3]$$

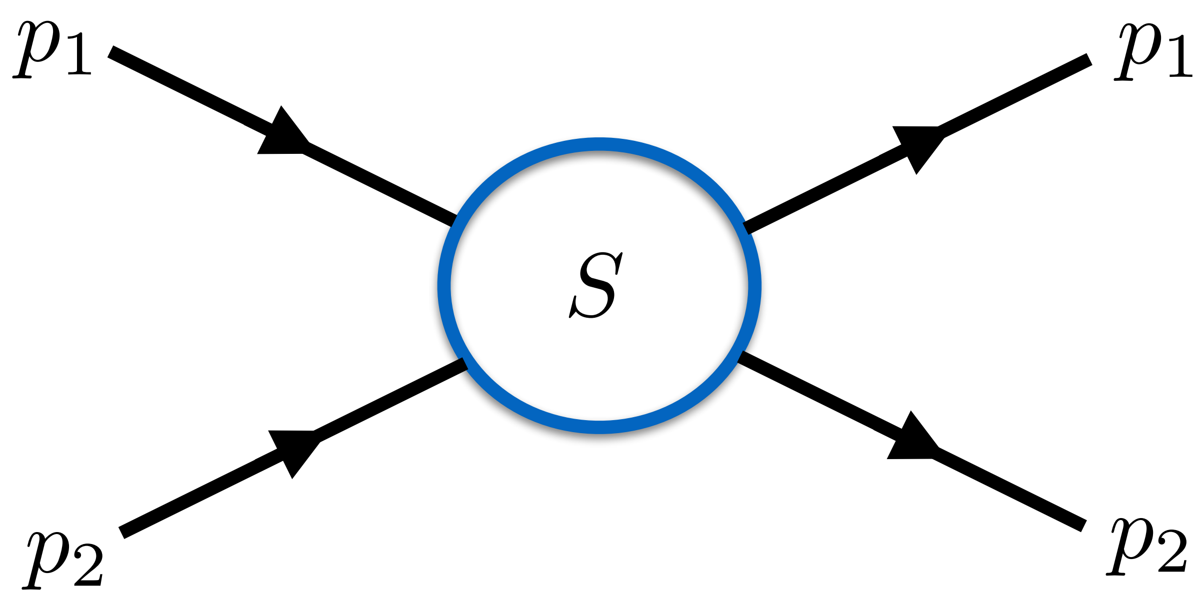
Canonically normalize and rescale $x = c_s \tilde{x}$

$$\tilde{\mathcal{L}}_3 = \frac{1}{\Lambda^2}\left[\dot{\pi}\tilde{\partial}_i\pi\tilde{\partial}^i\pi - c_s^2\dot{\pi}^2\right] \qquad \Lambda^4 = 2M_{\rm pl}^2|\dot{H}|\frac{c_s^5}{(1-c_s^2)^2}$$

Guess that strong coupling at $\omega > \Lambda$

Strong Coupling Scale

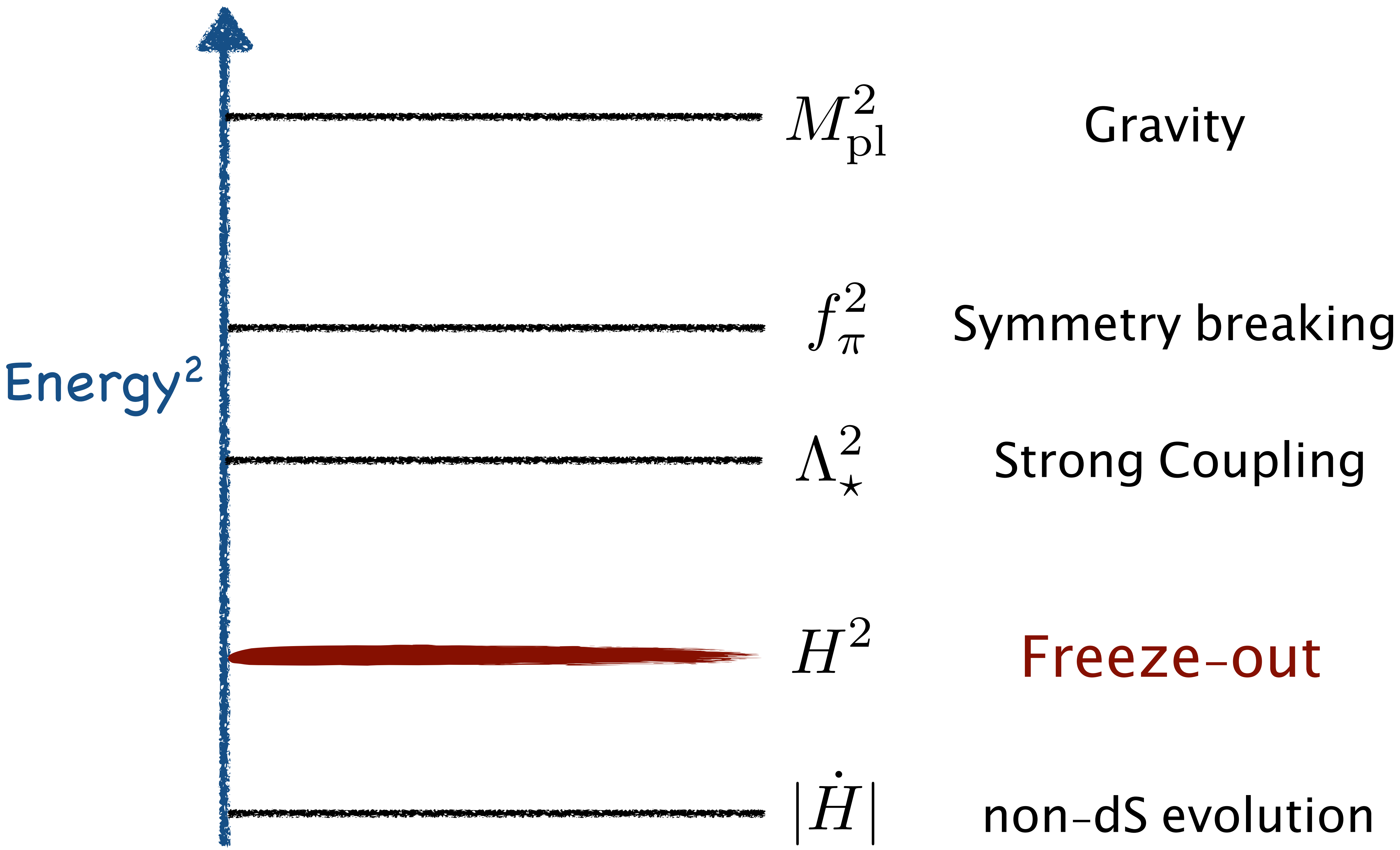
A more precise measure is perturbative unitarity



Unitarity requires partial wave amplitude $|a_\ell| \leq \dfrac{1}{2}$

Violated for $\omega^4 \geq 30\pi \dfrac{f_\pi^4 c_s^4}{1-c_s^2} = 30\pi(1-c_s^2)\Lambda^4 \equiv \Lambda_\star^4$

Energy Scales



Non-Gaussanity

Quadratic action leads to gaussian statistics

(i.e. 2-pt function determines everything)

We saw that interactions are allowed

$$\tilde{\mathcal{L}}_3 = \frac{1}{\Lambda^2}\left[\dot{\pi}\tilde{\partial}_i\pi\tilde{\partial}^i\pi - c_s^2\dot{\pi}^2\right]$$

At horizon crossing, size of interaction $\frac{\omega^2 \sim H^2}{\Lambda^2}$

This effect is naturally small (irrelevant)

Non-Gaussanity

Using perturbation theory, we compute bispectrum

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

The precise function is called the “shape”

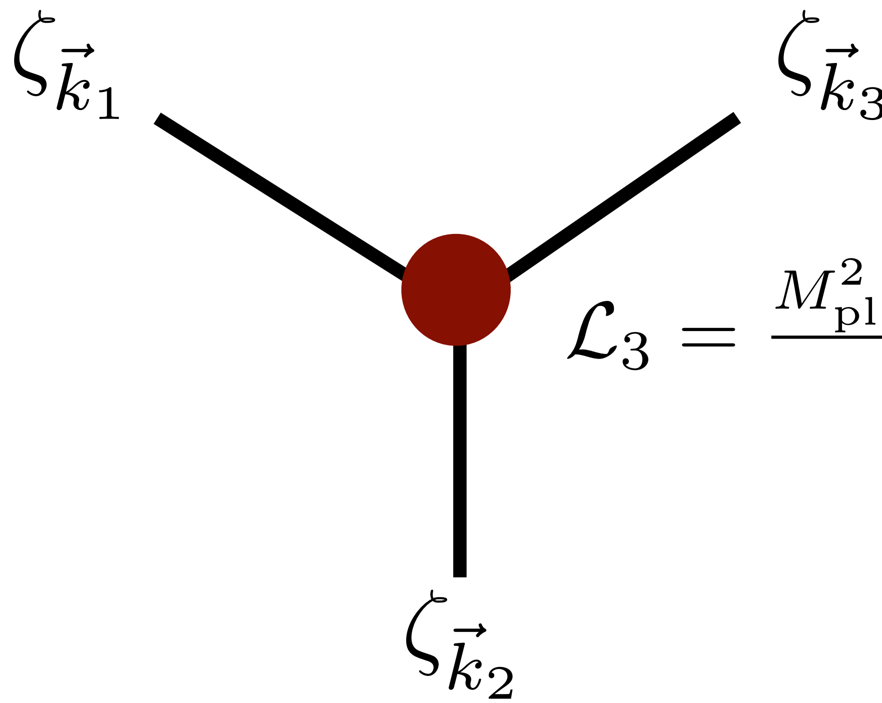
The amplitude is typically given in terms of

$$f_{\rm NL} = \frac{5}{18} \frac{B(k,k,k)}{P_\zeta^2(k)}$$

Order one non-gaussian means $f_{\rm NL} \sim 10^5$

Non-Gaussanity

Intuitively, we should expect $f_{\rm NL}\Delta_\zeta \sim \dfrac{H^2}{\Lambda^2}$



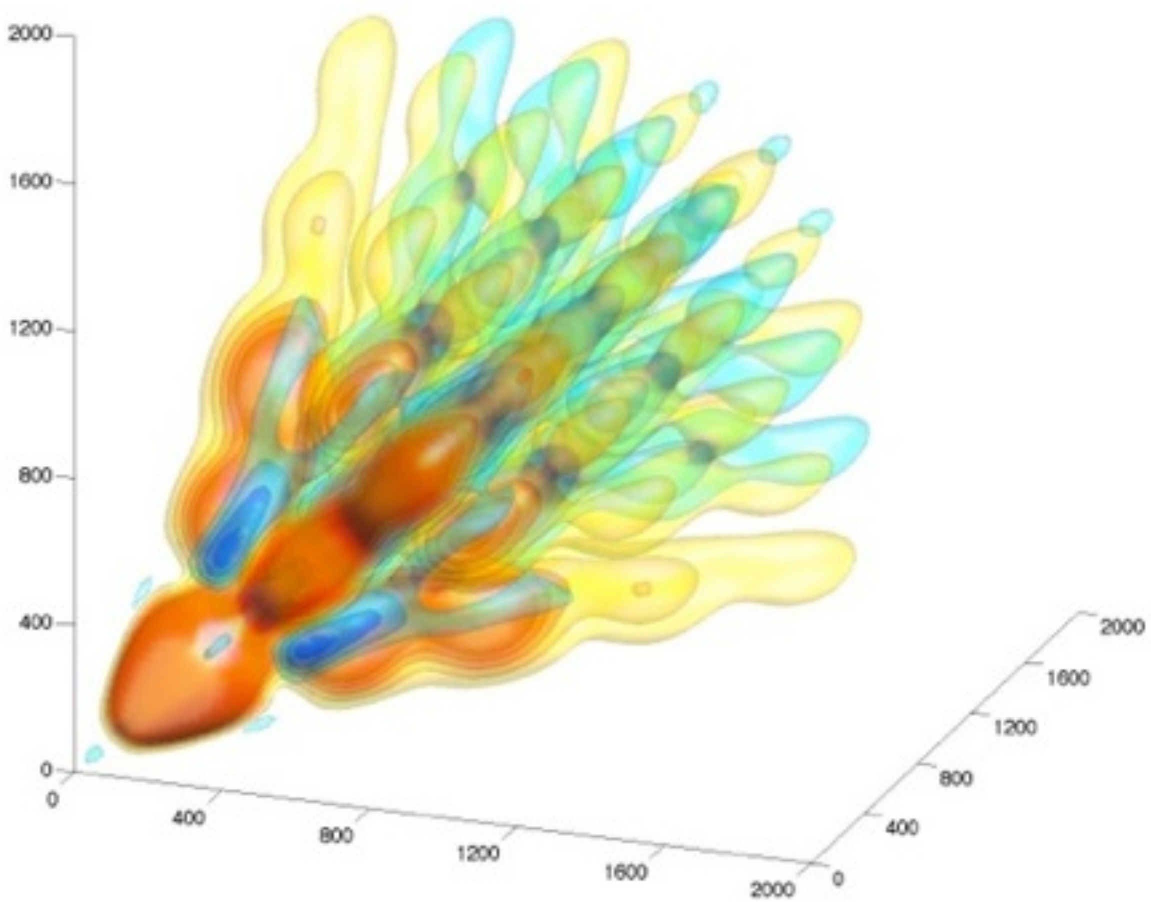
$$\mathcal{L}_3 = \frac{M_{\rm pl}^2 H(1-c_s^2)}{c_s^2}\dot{\pi}(\partial\pi)^2$$

For the speed of sound term, we get

$$f_{\rm NL}^{\rm equilateral} = -\frac{85}{325}\frac{H^2}{\Lambda^2}(2\pi\Delta_\zeta)^{-1} = -\frac{85}{325}\frac{f_\pi^2}{\Lambda^2}$$

Non-Gaussanity

Planck looks for this shape in the data



Equilateral

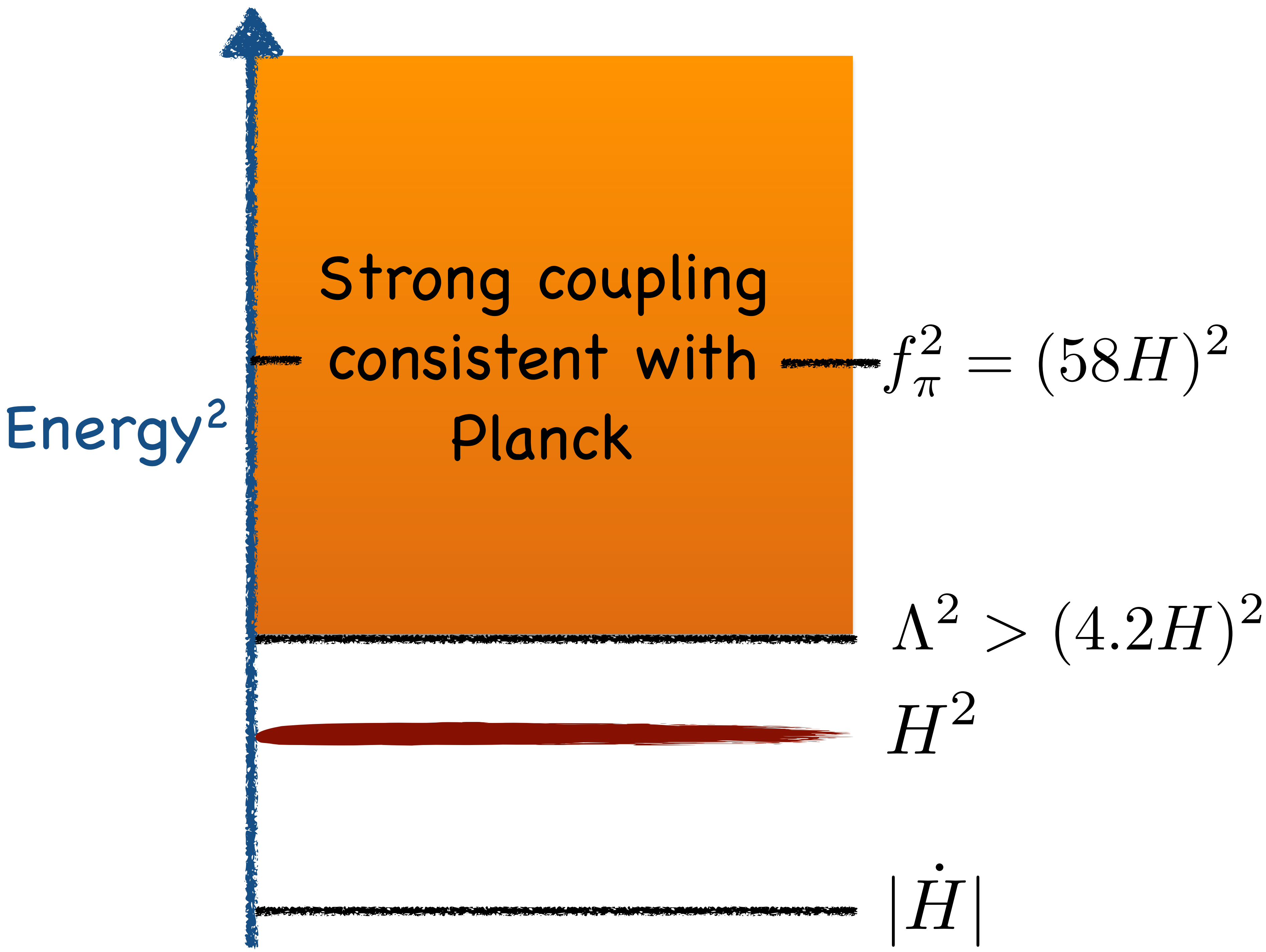
Peaked at:

$$k_1 = k_2 = k_3$$

$$f_{\rm NL}^{\rm equil.} = -4 \pm 43$$ (68% C.I.)

Courtesy of Fergusson & Shellard

Non-Gaussanity



Non-Gaussanity

What would we expect from slow-roll?

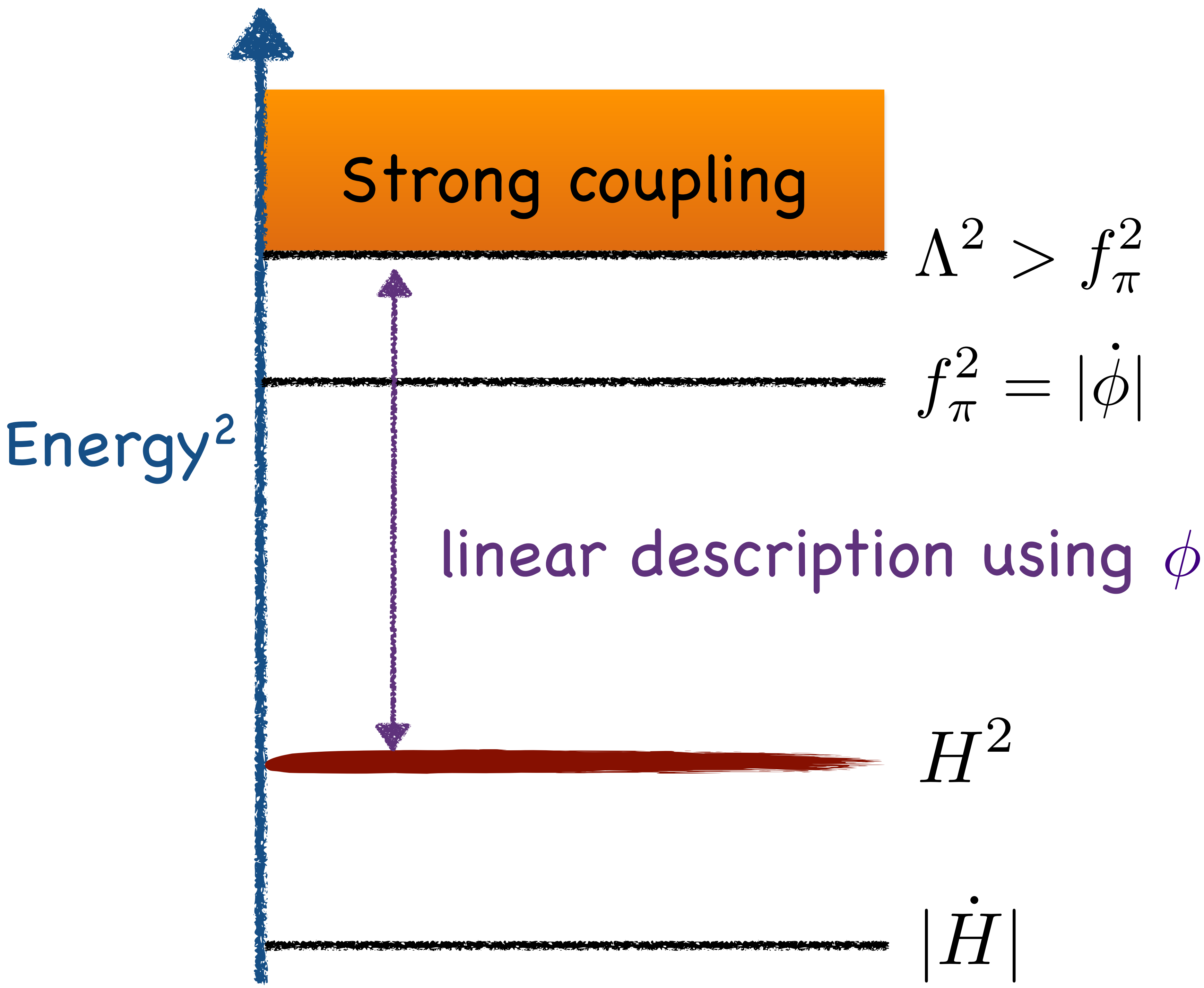
$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{1}{\tilde{\Lambda}^4}(\partial_\mu\phi\partial^\mu\phi)^2$$

Control of background requires $\tilde{\Lambda}^2 > \dot{\phi}$

Expand in fluctuations to find bispectrum

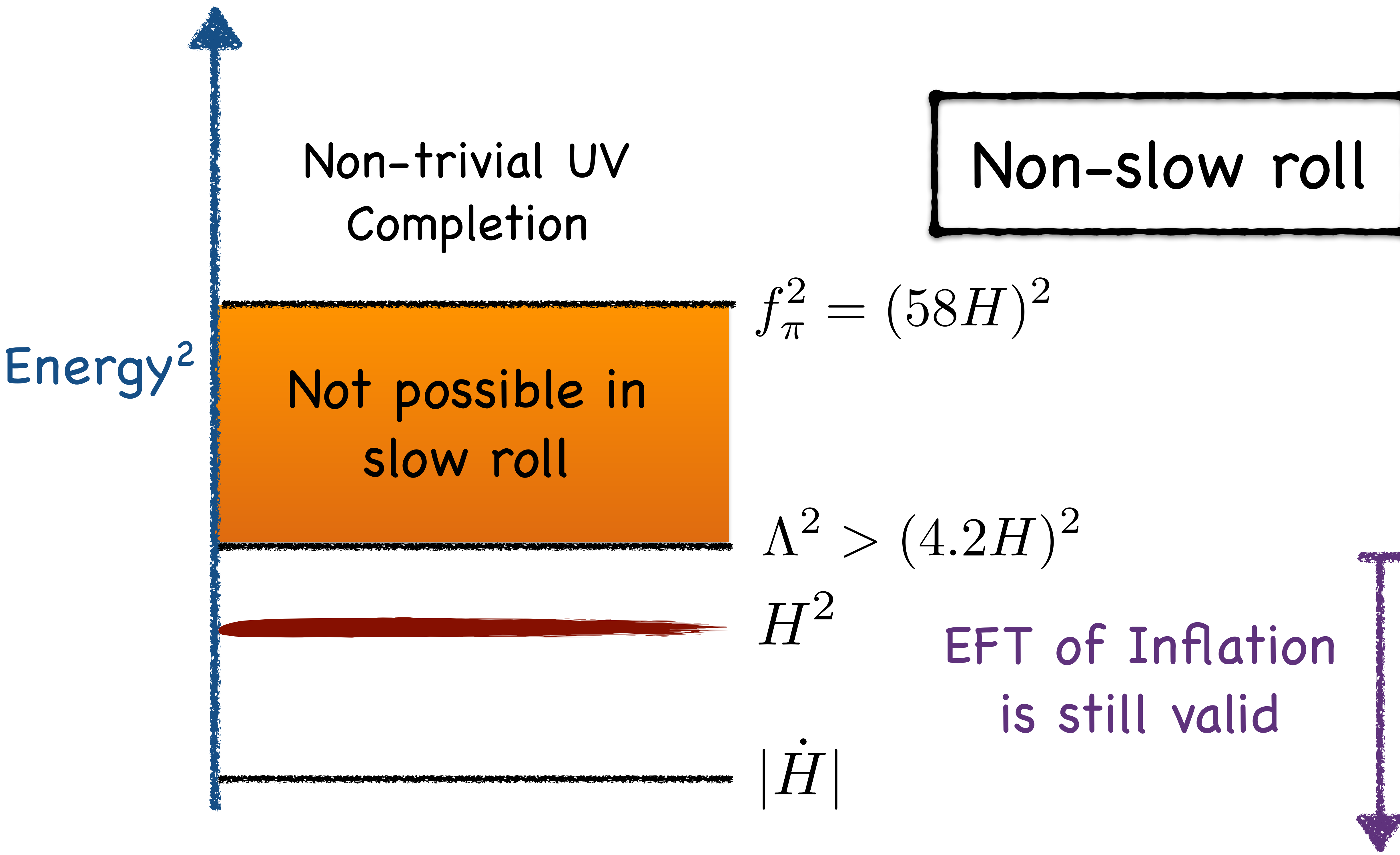
$$\mathcal{L}_3 \sim \frac{\dot{\phi}}{\tilde{\Lambda}^4}\delta\dot{\phi}(\partial\delta\phi)^2 \qquad f_{\rm NL} \sim \frac{f_\pi^2\dot{\phi}}{\tilde{\Lambda}^4} = \frac{\dot{\phi}^2}{\tilde{\Lambda}^4} \ll 1$$

Non-Gaussanity



Slow-roll

Non-Gaussanity



Non-Gaussanity

General take-aways:

NG is like precision EW tests of the Standard model

NG is an IR probe of higher dim. effective operators

Current constraints are $\Lambda > \mathcal{O}(5)H$

Current tests are not sensitive enough to suggest inflation is weakly coupled (i.e. slow-roll)

Summary

These few assumptions explain:

- Gaussianity of fluctuations (irrelevant interactions)
- Small amplitude of fluctuations (hierarchy of scales)
- Near scale invariance (near de Sitter background)
- Small tensor amplitude (scale of inflation)

These features are generic (but can be violated with work)

Single-Field Consistency Conditions

Adiabatic modes

For scalar fluctuations, the metric we use is

$$ds^2 = -dt^2 + a^2(t)e^{2\zeta}d\vec{x}^2$$

Last time, we used our gauge freedom to write

$$\zeta = -H\pi + \mathcal{O}(\pi^2)$$

This is a good idea inside the horizon

Outside the horizon, need ζ to make predictions

Adiabatic modes

For scalar fluctuations, the metric we use is

$$ds^2 = -dt^2 + a^2(t)e^{2\zeta}d\vec{x}^2$$

Now lets focus on ζ directly

Outside the horizon, ζ has important properties:

- Conserved outside the horizon
- Relations between N and N+1 correlation functions

Adiabatic modes

It all boils down to a simple observation

$$ds^2 = -dt^2 + a^2(t)e^{2\zeta}d\vec{x}^2$$

This metric has a symmetry

$$x \to e^\lambda x \qquad \zeta \to \zeta - \lambda$$

This is a diffemorphism (it is not physical)

But we have already “fixed the gauge”

This is a “large” diffeomorphism

Adiabatic modes

But these are connected to physical solutions

$$\lim_{k\to 0} \zeta_{\mathrm{k}} = -\lambda + \mathcal{O}(k^2)$$

But we can't tell them apart until we take derivatives

These solutions must exist: is THE solution when:

- There is only 1 degree of freedom (single-field)
- Thermal equilibrium (controlled by 1 parameter T)

Conservation of ζ

Why is this true physically?

Time evolution is determined locally

Since metric is only degree of freedom, must be

$$\mathcal{R} \simeq a^{-2}\partial^2\zeta \to 0$$

We can't measure ζ locally because it is pure gauge

Adiabatic modes

Big picture:

In FRW, $SO(4,1)$ is non-linearly realized
(isometries of dS, 3d conformal group)

The "goldstone" is ζ

E.g. it acts like a dilaton $x \to e^{\lambda} x \quad \zeta \to \zeta - \lambda$

Just like any goldstone - it has interesting

(1) Soft limits

(2) Ward identities relating N and N+1 correlations

Adiabatic modes

Big picture:

Extra degrees of freedom much less constrained

E.g. Conservation no longer required

$$\dot{\zeta} = \cancel{c_1 \zeta} + c_2 \sigma$$

Forbidden by symmetry

Sensible possibility

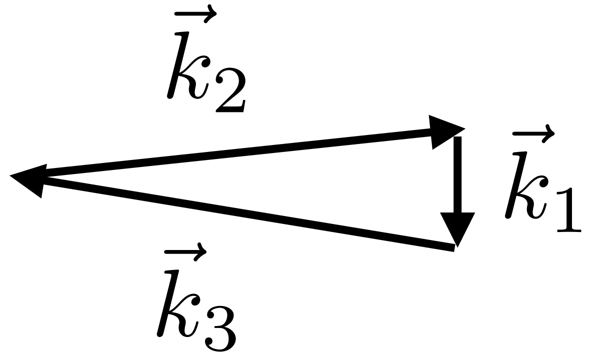
Robust to astrophysics / Easiest to detect

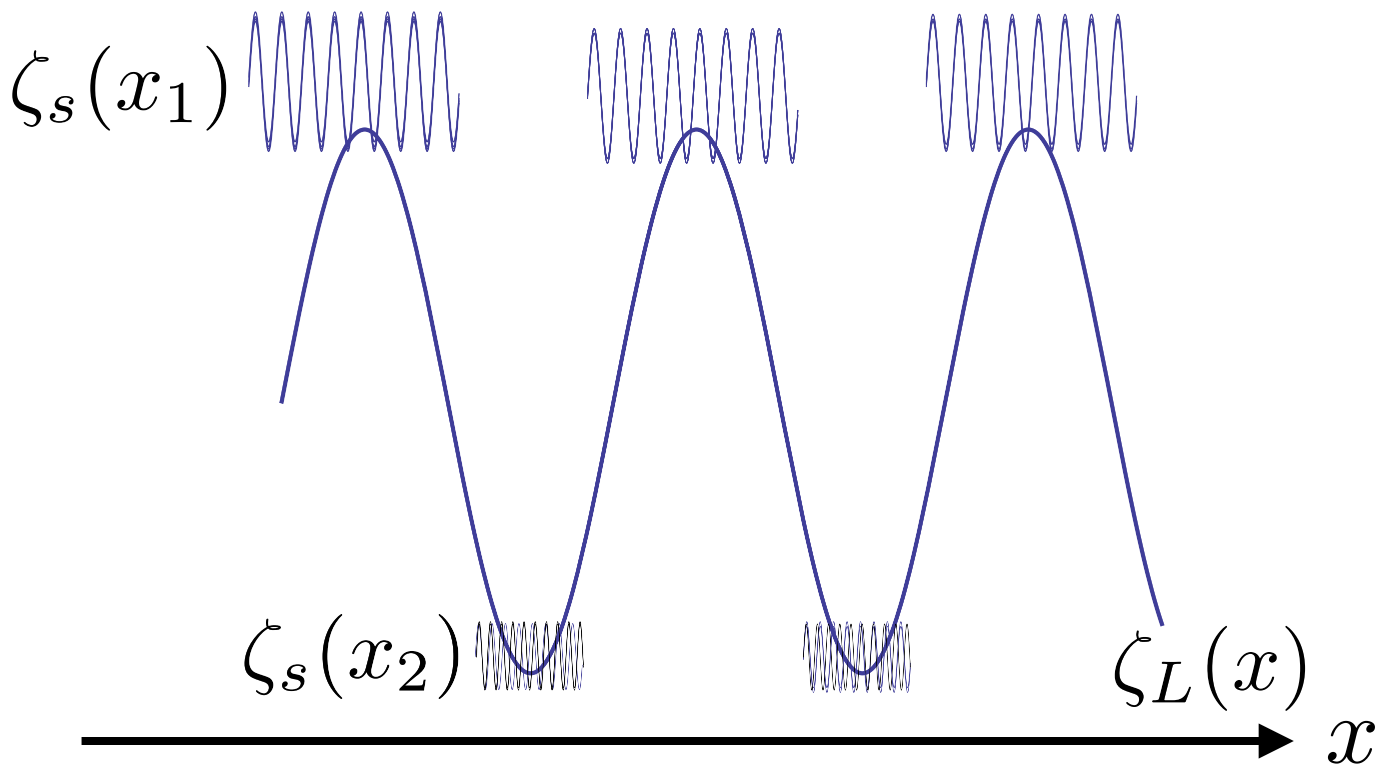
Squeezed-limit

Squeezed limit :

$$\lim_{k_1 \to 0} \langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle$$

Momentum conservation





Squeezed-limit

The canonical example is local NG

$$\zeta = \sigma(x) + \frac{3}{5} f_{\rm NL}^{\rm local} \sigma(x)^2$$

Long-short coupling from $\sigma = \sigma_L + \sigma_S$

$$\zeta_S = \sigma_S(x) + \frac{6}{5} f_{\rm NL}^{\rm local} \sigma_L \sigma_S(x)$$

which gives the squeezed bispectrum

$$\lim_{k_1 \to 0} \langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle = \tfrac{12}{5} f_{\rm NL}^{\rm local} P(k_1) P(k_2)$$

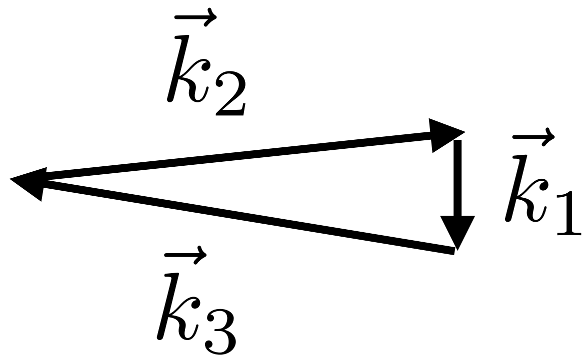
Generally arise from local mode coupling

Squeezed-limit

Squeezed limit :

$$\lim_{k_1 \to 0} \langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle$$

→ Momentum conservation



Bispectrum determined at horizon crossing

Means we have to wait for $k_2 \simeq k_3 = aH \gg k_1$

Long mode has long since crossed the horizon

Squeezed-limit

Measures small-scale power coupling to $\zeta_{k_1 \to 0}$

$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle \simeq \frac{\partial}{\partial \zeta_{k_1}} \langle \zeta_{k_2} \zeta_{k_3} \rangle_{\zeta_{k_1}} \times \langle \zeta_{k_1}^2 \rangle$$

Measures short power in the presence of long mode

But long mode is just a diffeomorphism

$$\zeta_L \equiv x \to e^{-\zeta_L} x \qquad \frac{\partial}{\partial \zeta_L} \langle \zeta_{k_2}^2 \rangle = -2 \partial_{\vec{k}} \cdot (\vec{k} \langle \zeta_{k_2}^2 \rangle)$$

$$f_{\rm NL}^{\rm local} = -\frac{5}{12}(n_s - 1) \ll 1$$

Squeezed-limit

In fact, even the $f_{\rm NL}^{\rm local} \neq 0$ is just a coordinate artifact

The long mode cannot be measured locally

But, physical units are different

$$k_{2,\rm physical} \simeq \frac{k_2}{a e^{\zeta_L}}$$

In a physical measurement

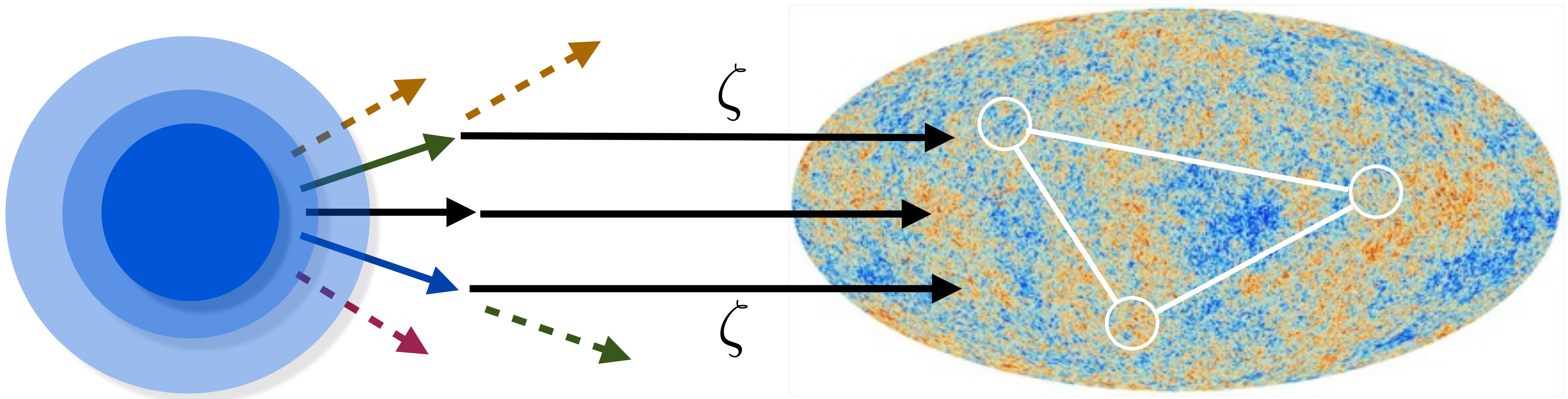
$$\lim_{k_{1,p}\to 0} \langle \zeta_{k_{1,p}} \zeta_{k_{2,p}} \zeta_{k_{3,p}} \rangle = \mathcal{O}(k_{1,p}^2) P(k_{1,p}) P(k_{2,p})$$

I.e. there is no “local” non-gaussanity

Multi-field Inflation

Why Multifield?

All particles with $m^2 \lesssim H^2$ are produced

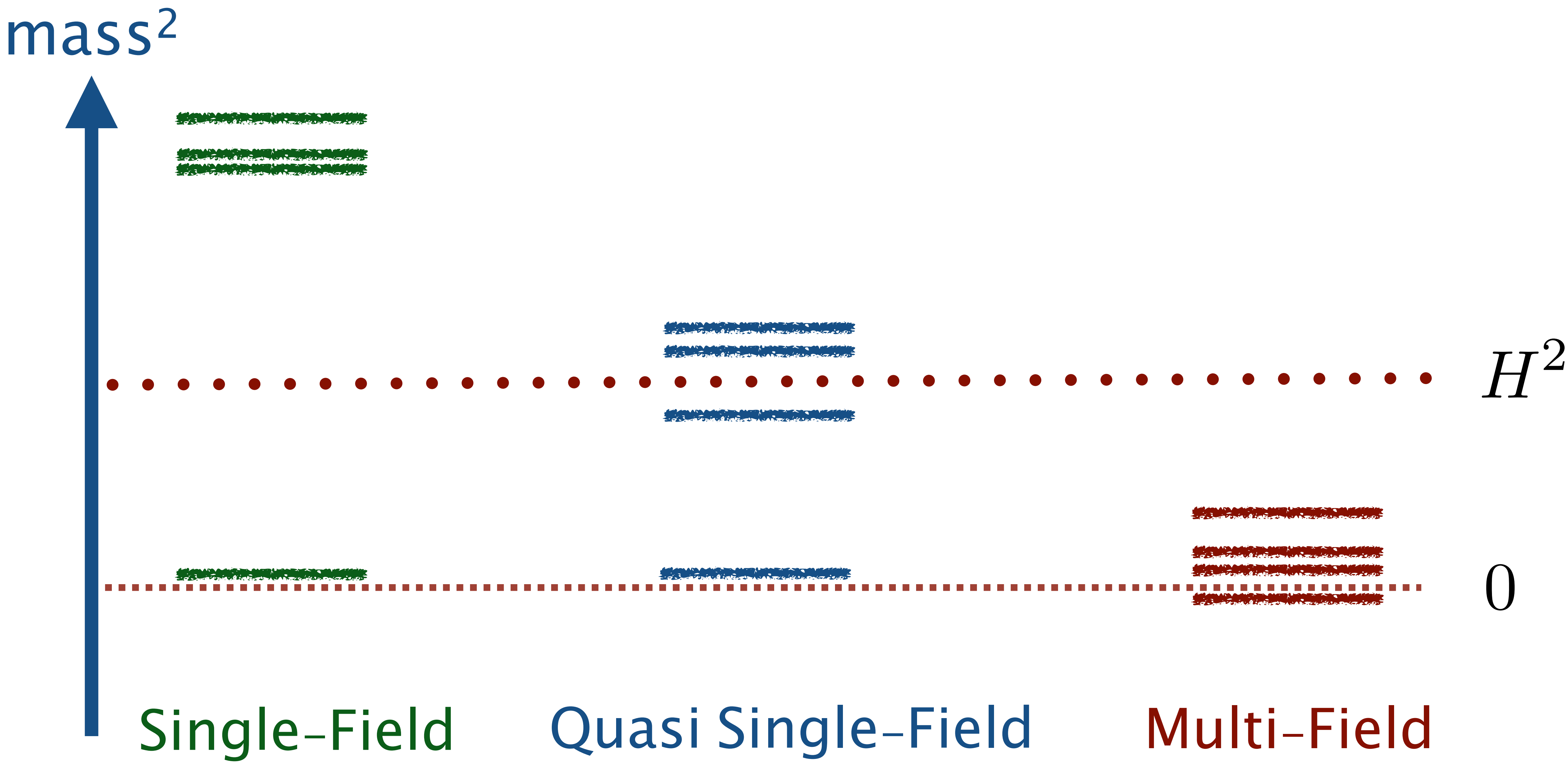


Energy could be as high as $H \simeq 5 \times 10^{13}\mathrm{GeV}$

We observe the “decays” to ζ

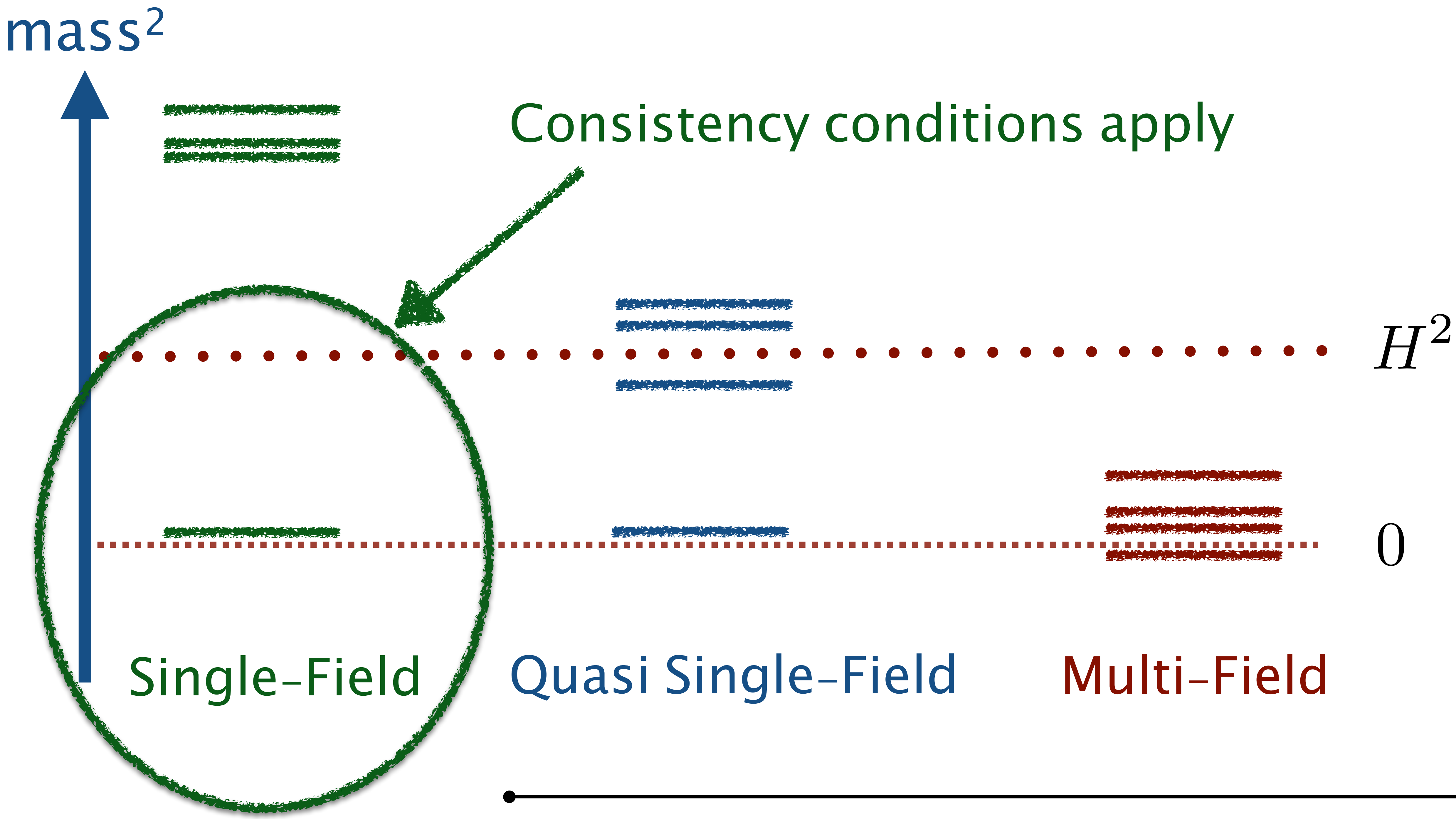
Types of Multi-field models

Particle spectra during inflation



Types of Multi-field models

Particle spectra during inflation



Types of Multi-field models

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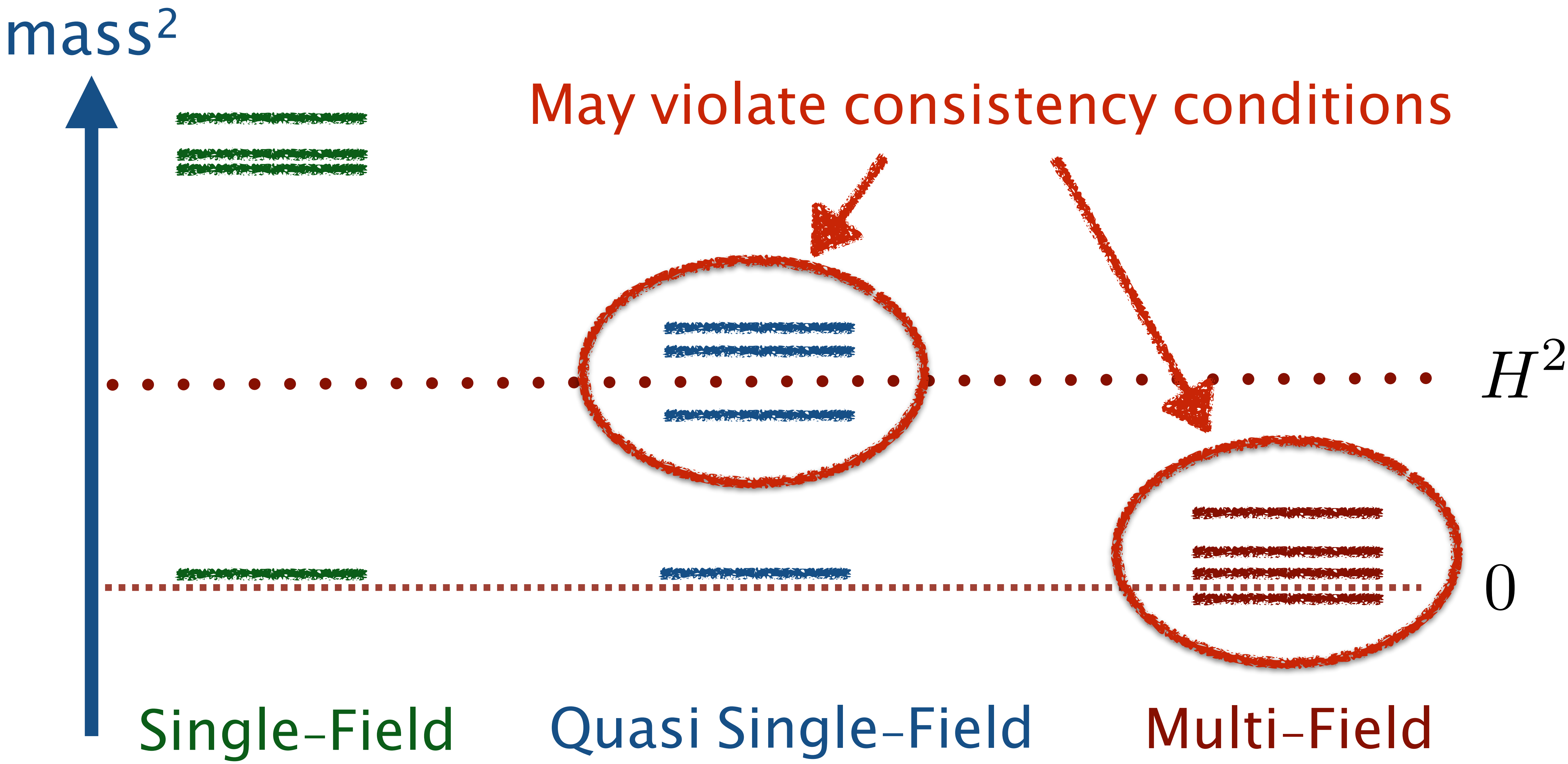
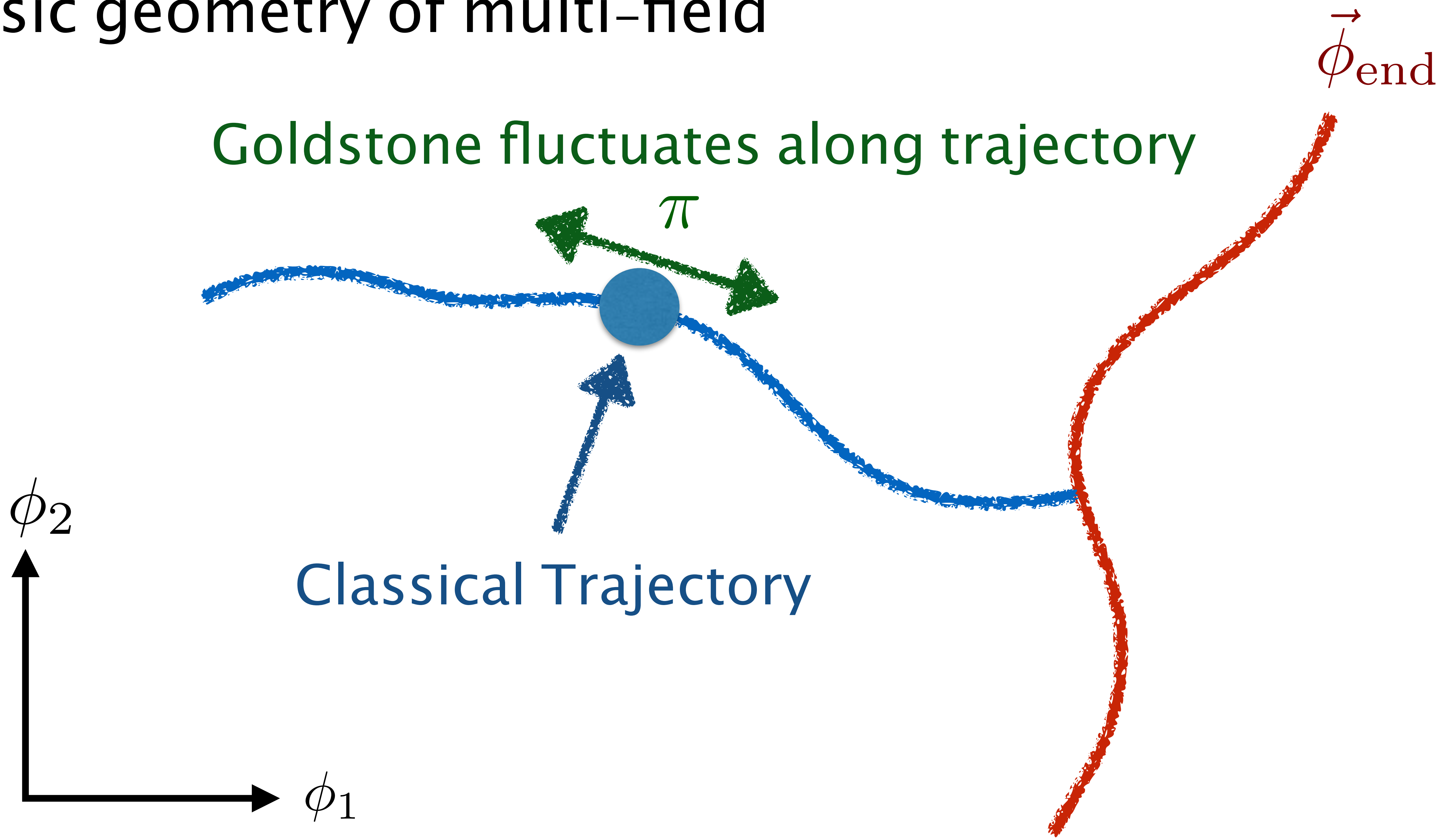


Conventional Multi-field

Basic geometry of multi-field



Conventional Multi-field

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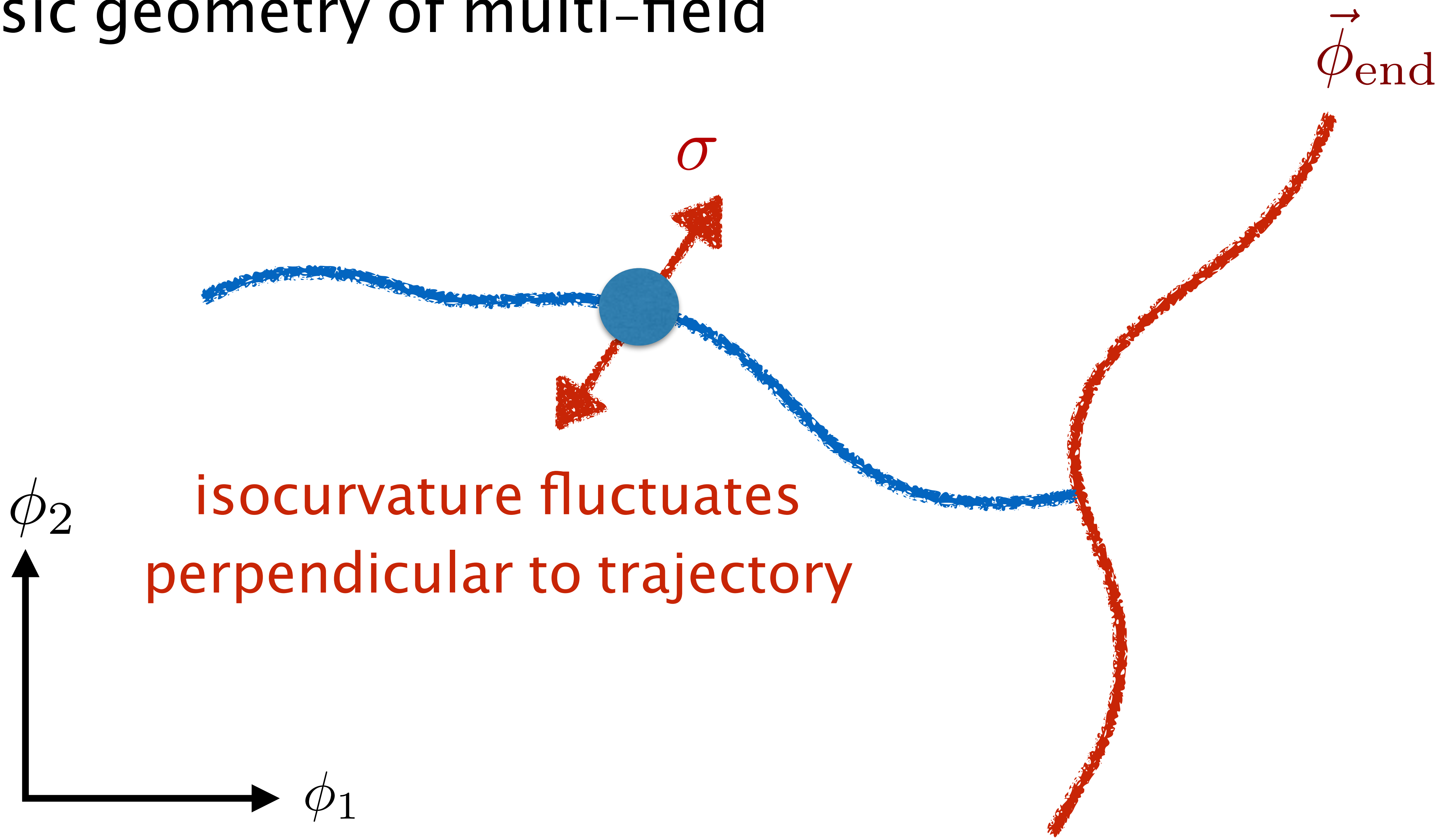


Conventional Multi-field

Curvature perturbation is still length of inflation

$$\zeta(x,t) \simeq \log a(x,t) - \log a_0$$

Reheating / ending inflation is a local process

$$\zeta(x,t) = \frac{\partial \log a}{\partial \pi}\pi(x,t) + \frac{\partial \log a}{\partial \sigma}\sigma(x,t) + \ldots$$

If we force $\sigma = 0$ then it must reproduce single-field

$$\zeta = -H\pi + H\pi\dot{\pi} + \frac{1}{2}\dot{H}\pi^2 + \mathcal{O}(\pi^3)$$

Conventional Multi-field

Orthogonal directions are not constrained

$$\zeta = \tilde{\sigma} + \tfrac{3}{5} f_{\rm NL}^{\rm local} \tilde{\sigma}^2 + \ldots$$

where $\frac{3}{5} f_{\rm NL}^{\rm local} = \frac{1}{2} \frac{\partial^2 \log a}{\partial^2 \sigma}$

Small scale power is modulated

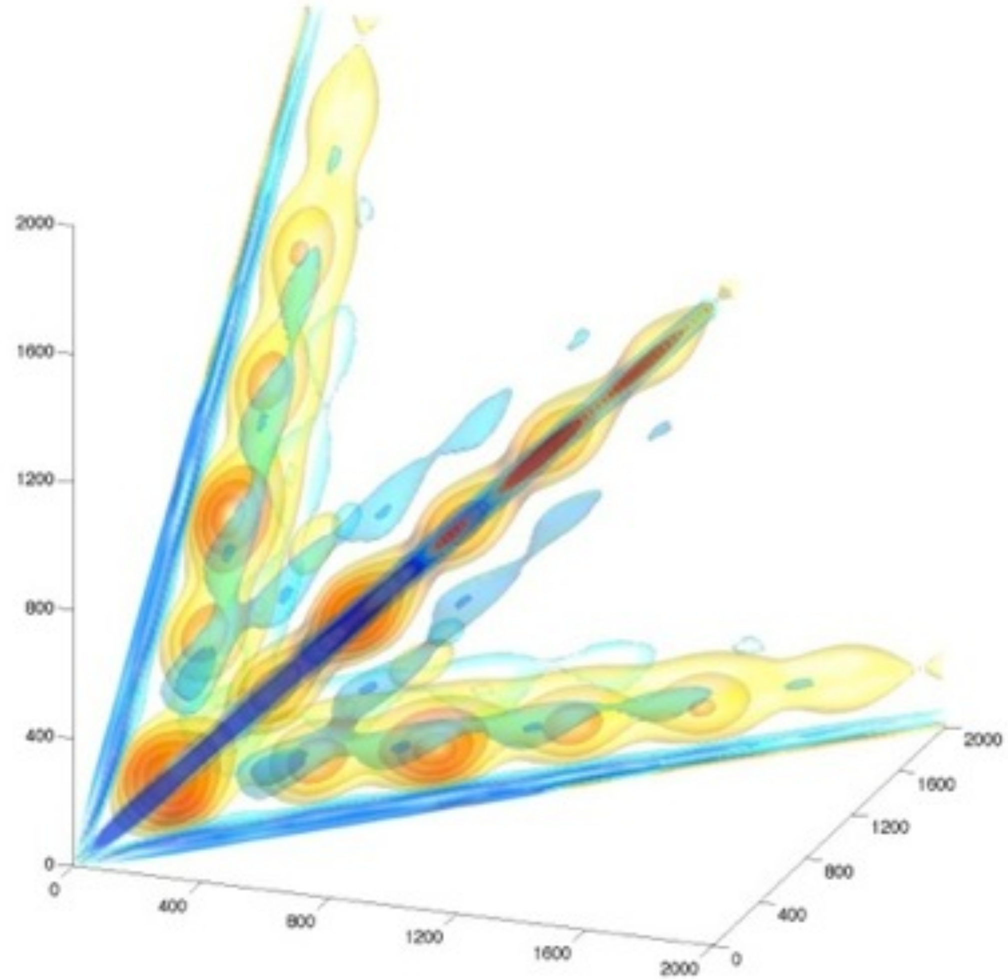
$$\langle \zeta_S^2 \rangle = (1 + \tfrac{12}{5} f_{\rm NL}^{\rm local} \zeta_L) P(k_S) + \ldots$$

Leads to conventional local non-gaussianity

$$\lim_{k_1 \to 0} \langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle = \tfrac{12}{5} f_{\rm NL}^{\rm local} P(k_1) P(k_2)$$

Conventional Multi-field

This is the “local model” of non-gaussianity



Local

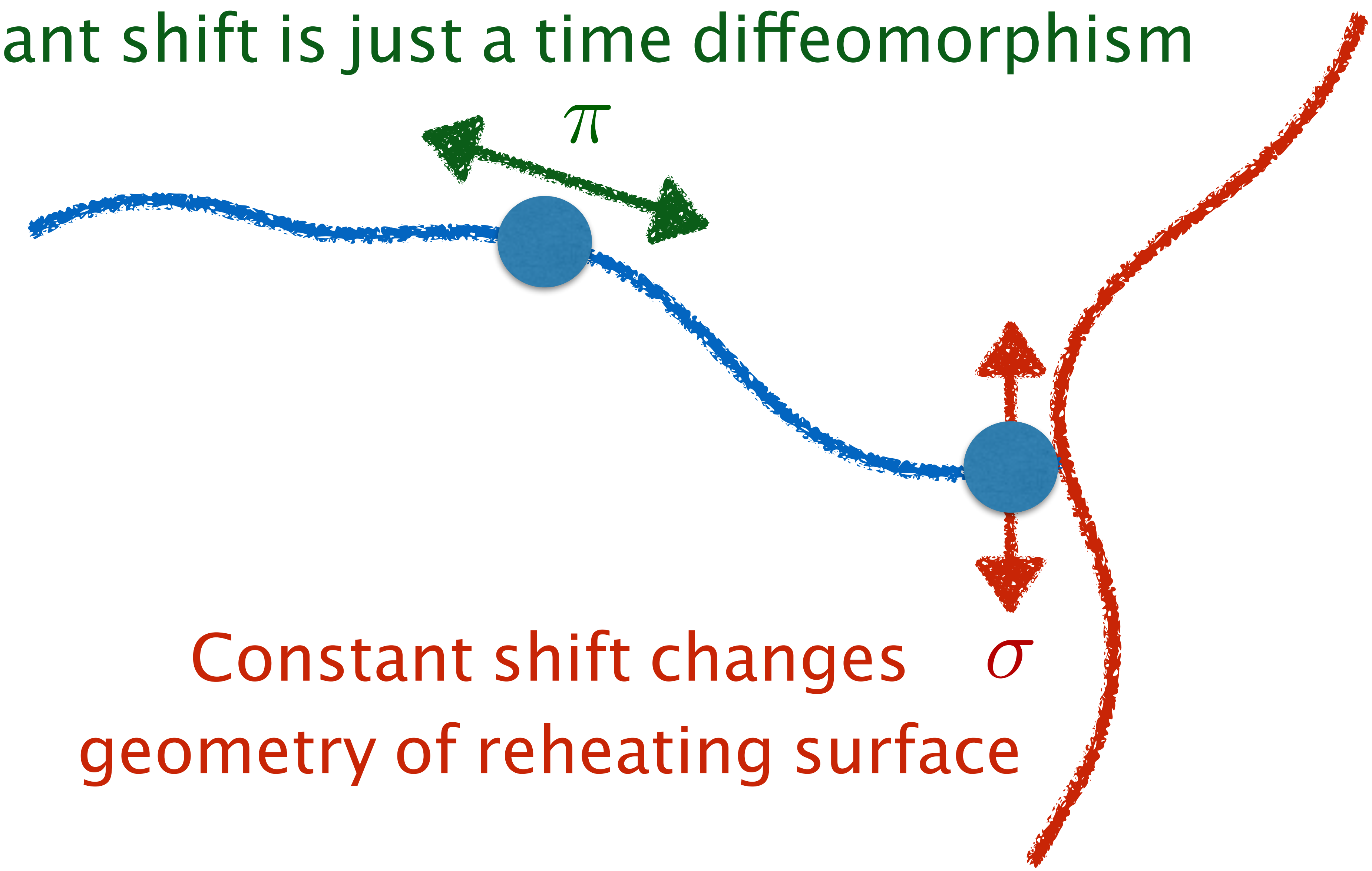
Peaked at:

$$k_1 \ll k_2 \sim k_3$$

$$f_{\rm NL}^{\rm local} = 0.8 \pm 5.0 \quad \text{(68\% C.I.)}$$

Conventional Multi-field

What makes these orthogonal directions different?



Conventional Multi-field

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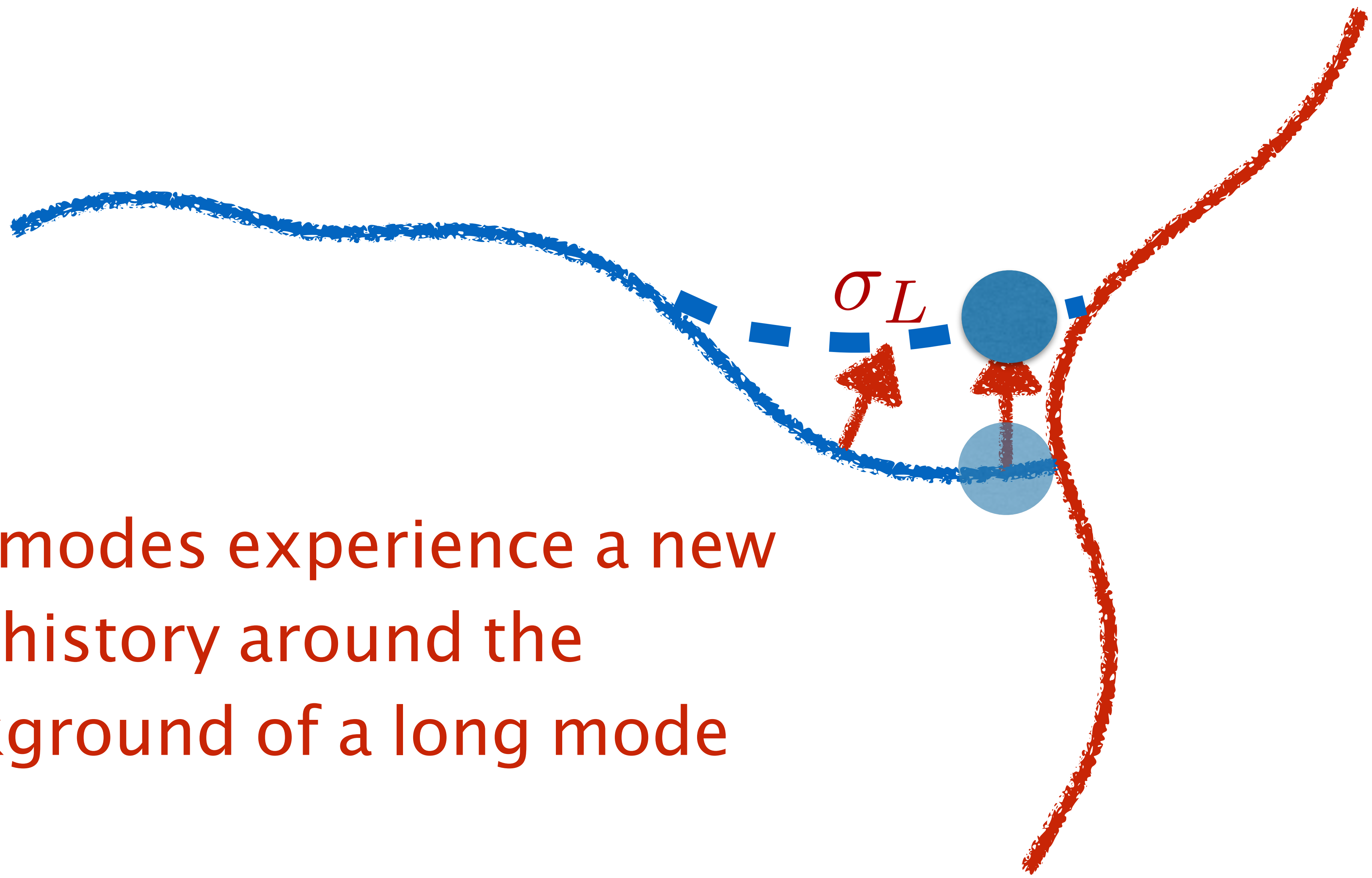


Short modes experience a new history around the background of a long mode

Complications

The picture as drawn is simple:

Assumed instantaneous conversation to adiabatic

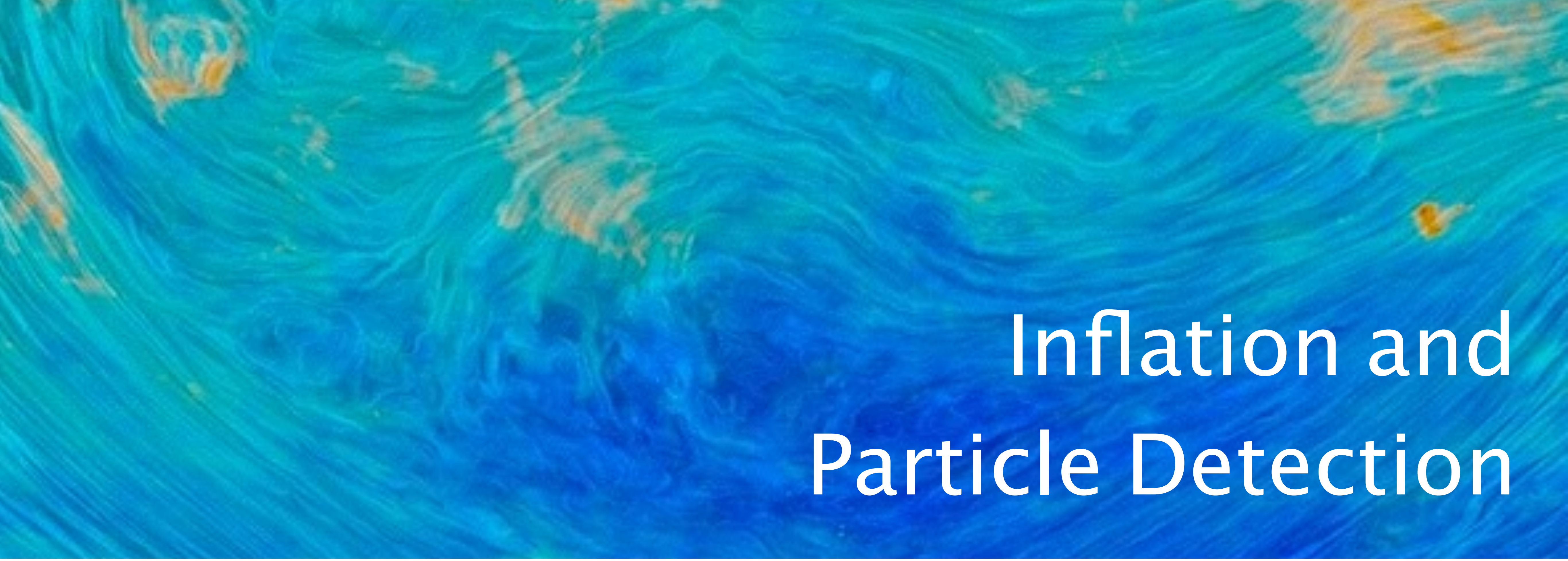
Instead, isocurvature modes can exist after inflation

E.g. extra light scalar field with independent fluctuations

Isocurvature may slowly evolve into adiabatic

But, essential physics is always local

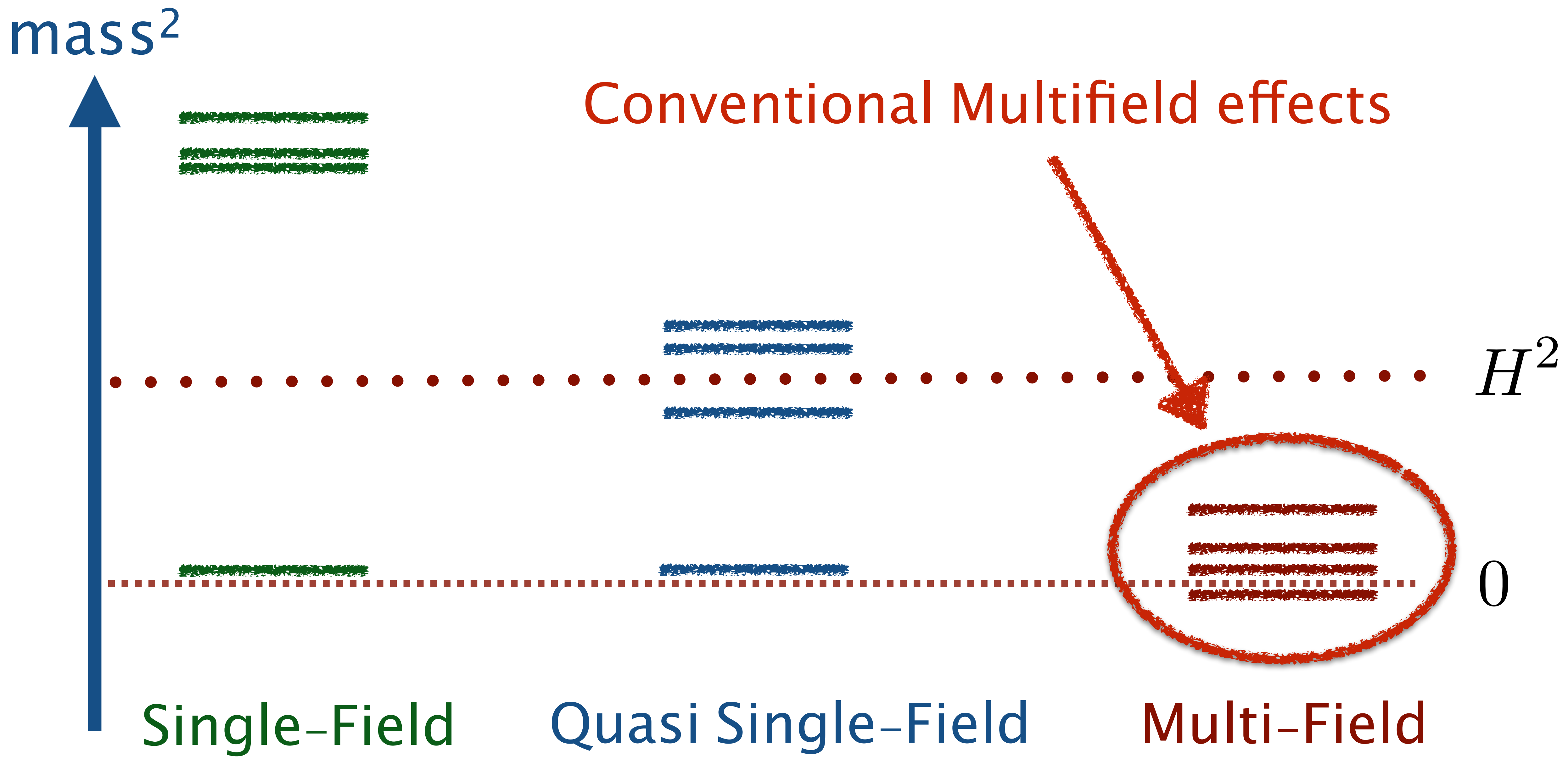
$$\zeta(\vec{x}) = f(\sigma(\vec{x}), t) + \mathcal{O}(\partial^2 \sigma)$$



Inflation and Particle Detection

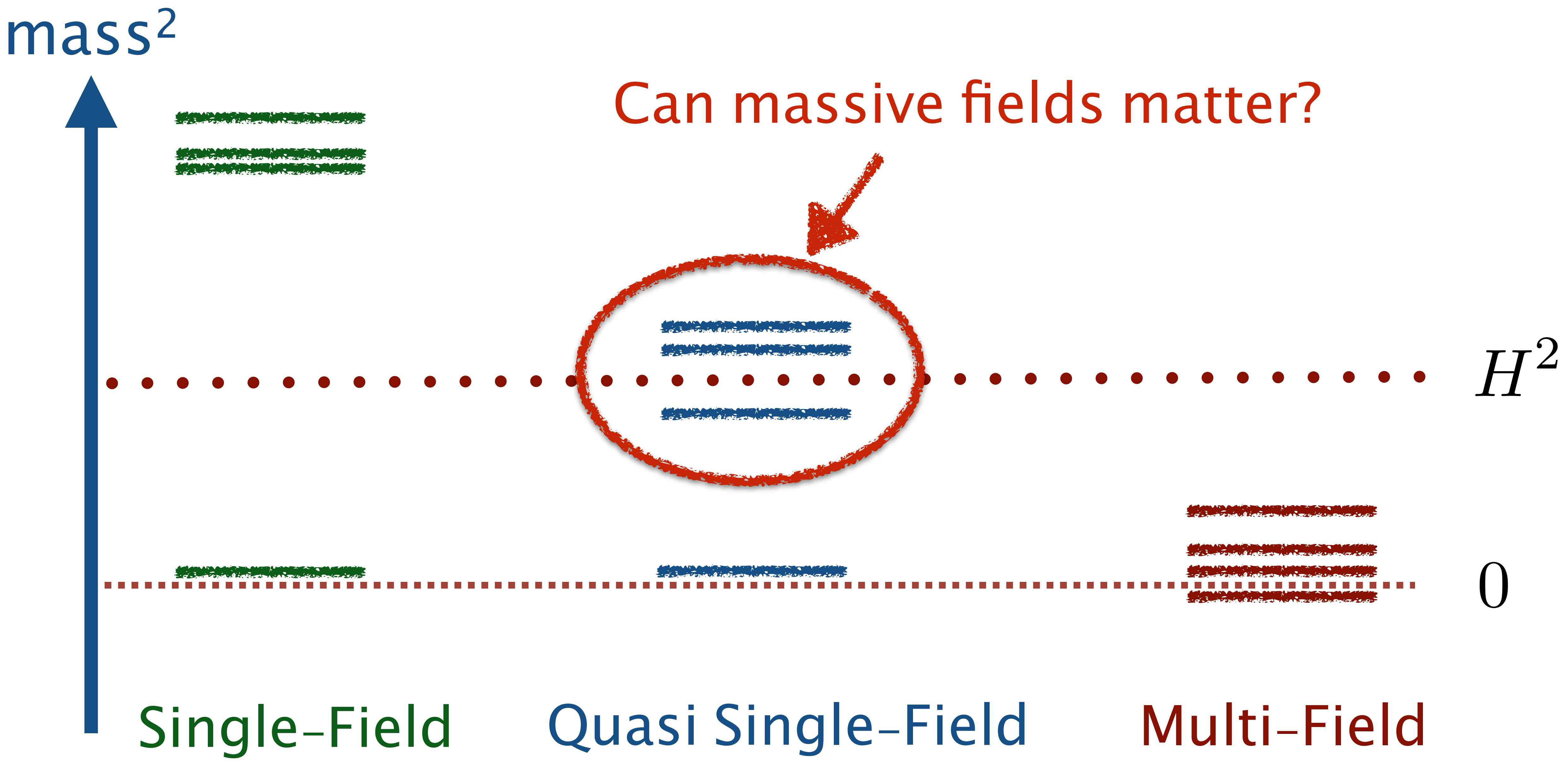
Quasi-Single Field Inflation

Particle spectra during inflation



Quasi-Single Field Inflation

Particle spectra during inflation



Massive fields in de Sitter

It is easy to solve for free massive field

$$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \tfrac{1}{2}m^2\sigma^2 \qquad \hat{\sigma}_k = \sigma_k \hat{a}_k + \text{h.c.}$$

$$\sigma_k = \frac{\sqrt{\pi}}{2} H(-\tau)^{3/2} H_\nu^{(1)}(-k\tau) \qquad \nu = \sqrt{\tfrac{9}{4} - \tfrac{m^2}{H^2}}$$

Mode decays outside the horizon

$$\lim_{\tau\to 0} \sigma_k \to H \frac{\Gamma[\nu]}{\sqrt{\pi}2^{1-\nu}} \frac{\tau^{3/2}}{(k\tau)^\nu} \to 0$$

Has no “conventional” effect at the end of inflation

Massive fields in de Sitter

Does this make sense intuitively?

$$\ddot{\sigma} + 3H\dot{\sigma} + (\frac{k^2}{a^2} + m^2)\sigma = 0$$

At late times $\frac{k^2}{a^2} \to 0$

$$\sigma = c_1 e^{\frac{t}{2}(-3H+\sqrt{9H^2-4m^2})} + c_2 e^{\frac{t}{2}(-3H-\sqrt{9H^2-4m^2})}$$

Using $\tau = -(Ha)^{-1} = -He^{-Ht}$

$$\sigma \simeq C(He^{-Ht})^{\frac{3}{2}-\sqrt{\frac{9}{4}-\frac{m^2}{H^2}}} = C(-\tau)^{3/2-\nu} \to 0$$

Has no "conventional" effect at the end of inflation

Quasi-Single Field Inflation

Just like single-field inflation

$$\zeta = -H\pi + H\pi\dot{\pi} + \frac{1}{2}\dot{H}\pi^2 + \mathcal{O}(\pi^3)$$

This alone isn't equivalent to consistency conditions

$$\pi(t_{\rm end}) = \pi_{\rm single-field} + \int_0^{t_{\rm end}} dt\, G_\pi(t_{\rm end}, t) J(\sigma(t), t) + \ldots$$

Goldstone evolution is influenced by isocurvature

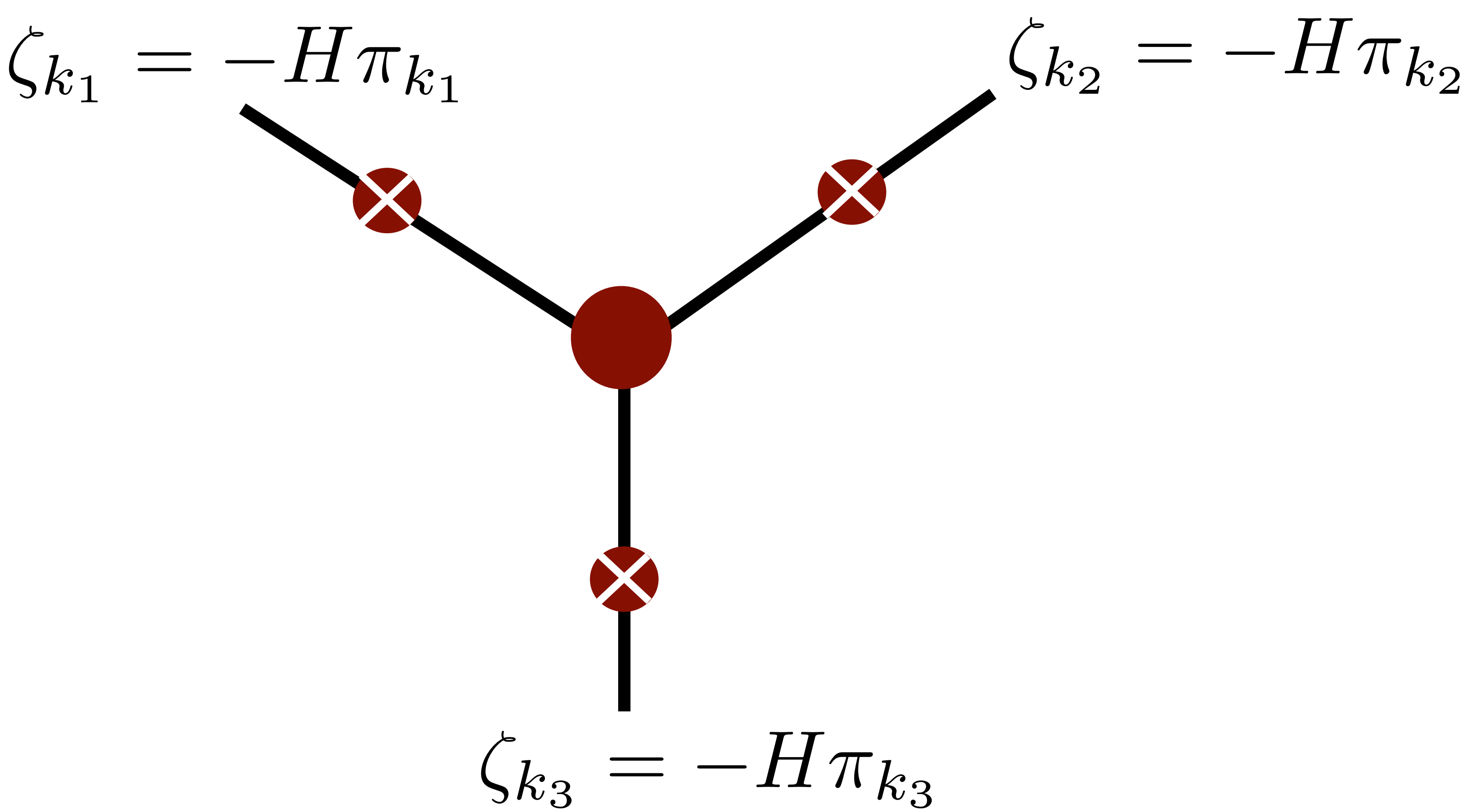
System has memory of the past (after horizon crossing)

Quasi-Single Field Inflation

Consider a simple model

$$\mathcal{L}_\pi = M_{\rm pl}^2 \dot{H} \partial_\mu \pi \partial^\mu \pi \qquad \mathcal{L}_{\rm mix} = -\rho M_{\rm pl} |\dot{H}|^{1/2} \dot{\pi} \sigma + \dots$$

$$\mathcal{L}_\sigma = -\frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma - \frac{1}{2} m^2 \sigma^2 - \frac{\mu}{3!}\sigma^3$$

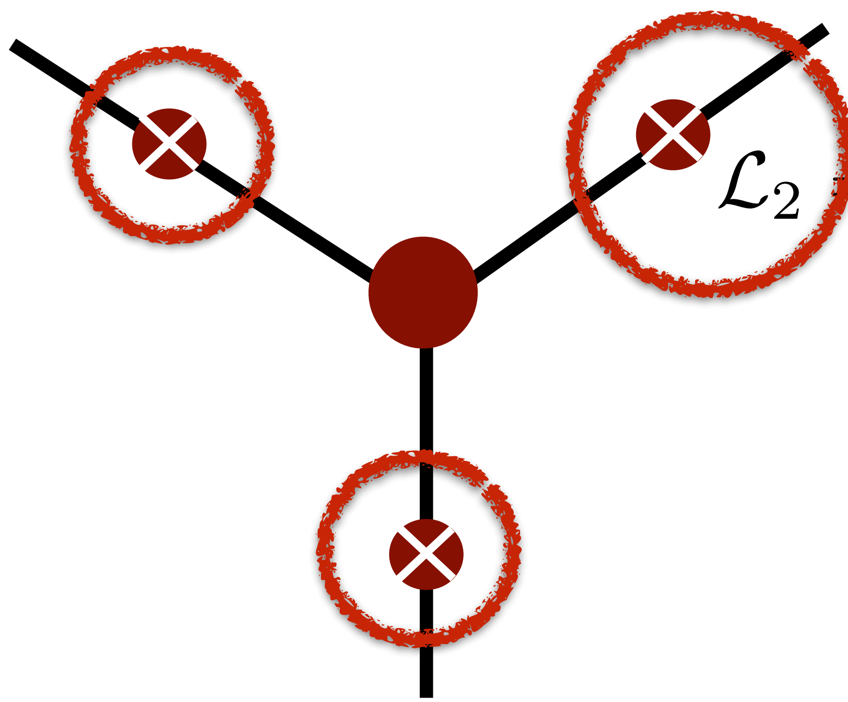


Quasi-Single Field Inflation

Consider a simple model

$$\mathcal{L}_\pi = M_{\rm pl}^2 \dot{H} \partial_\mu \pi \partial^\mu \pi \qquad \mathcal{L}_{\rm mix} = -\rho M_{\rm pl} |\dot{H}|^{1/2} \dot{\pi} \sigma + \dots$$

$$\mathcal{L}_\sigma = -\tfrac{1}{2} \partial_\mu \sigma \partial^\mu \sigma - \tfrac{1}{2} m^2 \sigma^2 - \tfrac{\mu}{3!} \sigma^3$$



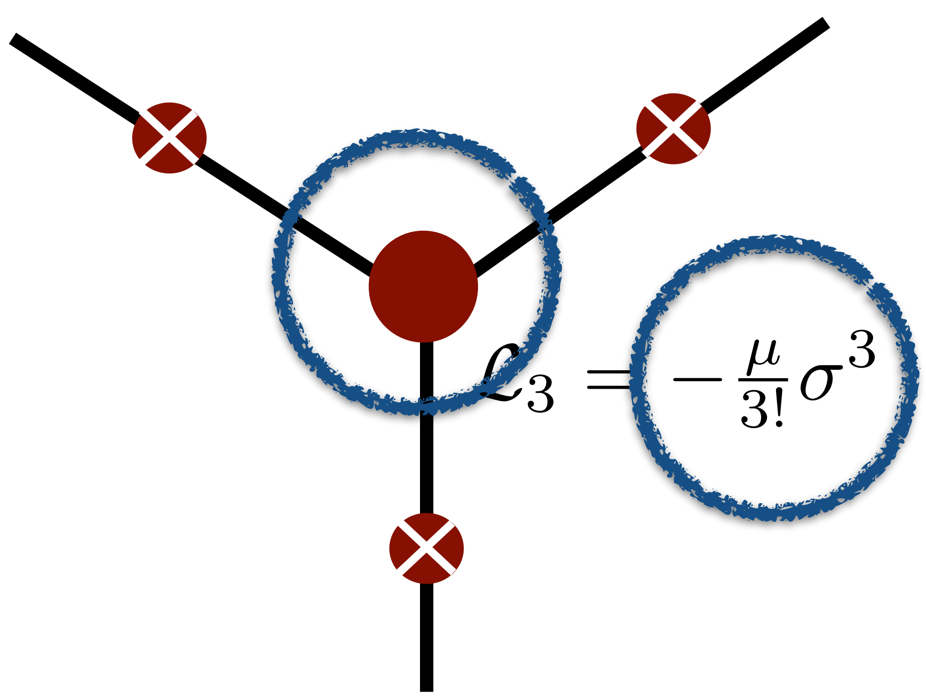
$$\mathcal{L}_2 = -\rho M_{\rm pl} |\dot{H}|^{1/2} \dot{\pi} \sigma$$

Quasi-Single Field Inflation

Consider a simple model

$$\mathcal{L}_\pi = M_{\rm pl}^2 \dot{H} \partial_\mu \pi \partial^\mu \pi \qquad \mathcal{L}_{\rm mix} = -\rho M_{\rm pl} |\dot{H}|^{1/2} \dot{\pi} \sigma + \ldots$$

$$\mathcal{L}_\sigma = -\frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma - \frac{1}{2} m^2 \sigma^2 - \frac{\mu}{3!}\sigma^3$$



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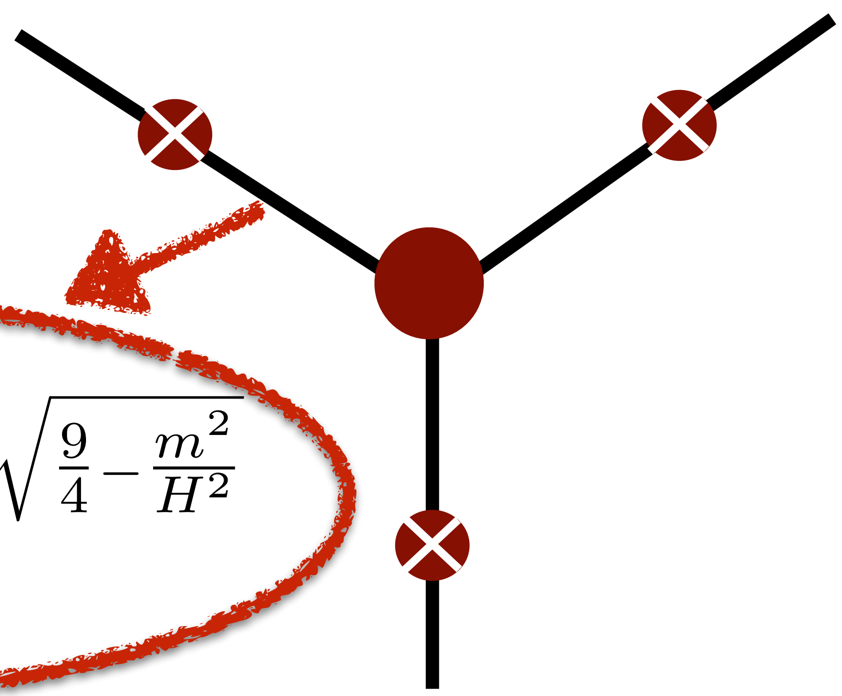


$$\lim_{\tau,\tau' \to 0} \langle \sigma \sigma \rangle \propto (\tau \tau')^{3/2 - \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}}$$

Quasi-Single Field Inflation

Consider a simple model

$$\lim_{k_1 \to 0} \langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle \sim \frac{12}{5} f_{\rm NL} \left(\frac{k_1}{k_2} \right)^{\frac{3}{2}-\nu} P(k_1) P(k_2)$$

$$f_{\rm NL} \simeq \frac{1}{2\pi \Delta_\zeta} \frac{\mu}{H} \left(\frac{\rho}{H} \right)^3$$

Intermediate shape - local : $f_{\rm NL} P(k_1)$

- equil. : $f_{\rm NL} k_1^2 P(k_1)$

Amplitude can be large : $f_{\rm NL} \sim 10^5 \times \lambda_\mu \lambda_\rho^3$

Squeezed limit

Locality + mode coupling would suggest

$$\langle \pi_S^2 \rangle \simeq (1 + \tfrac{6}{5} f_{\rm NL} \sigma_L) P(k_1) \xrightarrow{?} \langle \zeta_S \zeta_S \zeta_L \rangle \sim \tfrac{12}{5} f_{\rm NL}^{\rm local} P(k_1) P(k_2)$$

It matters when the mode coupling happens

Freeze-in means short modes cross-horizon

But remember long mode decays $\sigma \propto (-\tau)^{\frac{3}{2}-\nu}$

Squeezed limit

Keeping track of time

$$\langle \pi^2_{k_2}(\tau = k_2^{-1}) \rangle = \left(1 + \tfrac{6}{5} f_{\rm NL} \sigma_{k_1}(k_2^{-1})\right) P(k_2)$$

but because of the decay outside the horizon

$$\sigma_{k_1}(\tau = k_2^{-1}) \simeq \left(\frac{k_1}{k_2}\right)^{\frac{3}{2}-\nu} \sigma(\tau = k_1^{-1})$$

Time dependence that suppressed local shape

$$\langle \zeta^3 \rangle_{k_1 \to 0} \simeq P(k_1) P(k_2) \left(\frac{k_1}{k_2}\right)^{\frac{3}{2}-\nu}$$

Amplitude

Amplitude can naturally be quite large

$$f_{\rm NL} \simeq \frac{1}{2\pi\Delta_\zeta}\frac{\mu}{H}\left(\frac{\rho}{H}\right)^3$$

Weak coupling means $\mu, \rho \lesssim H$ → $f_{\rm NL} \ll 10^5$

Perturbative suppression is intuitive

Scalar is $\mathcal{O}(1)$ non-gaussian when $\mu \sim H$

Non-gaussianity of ζ only suppressed by mixing

Amplitude

But what do we know about these parameters

SUSY makes natural $m^2, \mu^2 \sim H^2$

Mixing in the UV should be irrelevant

$$\mathcal{L}_{\rm mix} = \frac{\sigma}{\Lambda}\partial_\mu\phi\partial^\mu\phi \to \frac{M_{\rm pl}^2\dot{H}}{\Lambda}\dot{\pi}\sigma + \ldots \qquad \rho = \frac{M_{\rm pl}|\dot{H}|^{1/2}}{\Lambda}$$

$$\rho \lesssim H \to \Lambda \gtrsim 3.3\times 10^3 H$$

Amplitude

Squeezed limit important in case of detection

Current bounds from equilateral shape $|f_{\rm NL}| > 47$

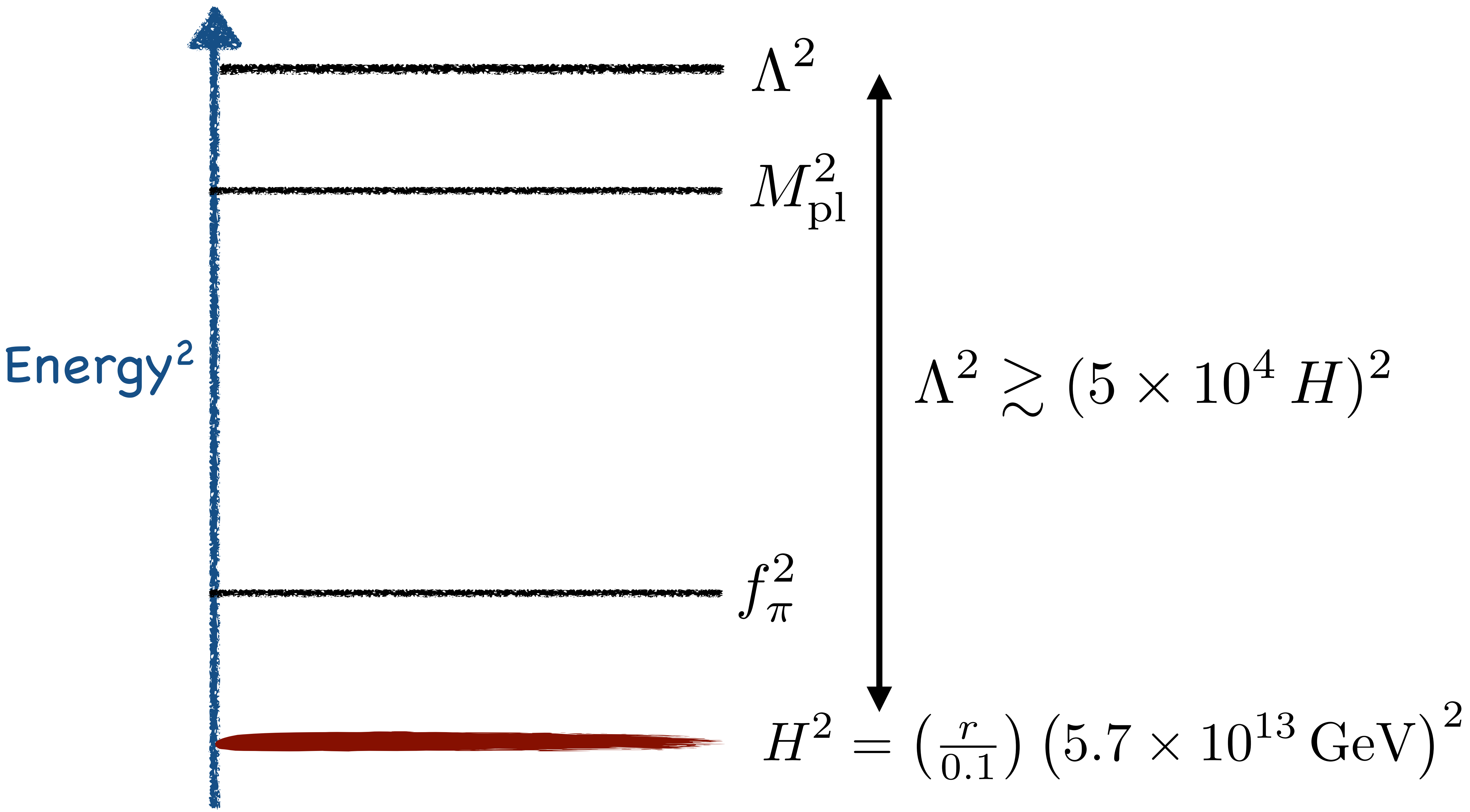
$$\Lambda > 4 \times 10^4 \left(\frac{|\mu|}{H}\right)^{1/3} H$$

Hubble scale is determine by tensors

$$\Lambda > 1.6\, M_{\rm pl} \left(\frac{|\mu|}{H}\right)^{1/3} \left(\frac{r}{0.1}\right)^{1/2}$$

Sensitive to Planck supposed couplings

Amplitude



Energy^2
Λ^2
$M_{\rm pl}^2$
f_π^2
$\Lambda^2 \gtrsim (5 \times 10^4\, H)^2$
$H^2 = \left(\frac{r}{0.1}\right) \left(5.7 \times 10^{13}\,\mathrm{GeV}\right)^2$

QSFI Summary

Massive fields can impact inflationary observables

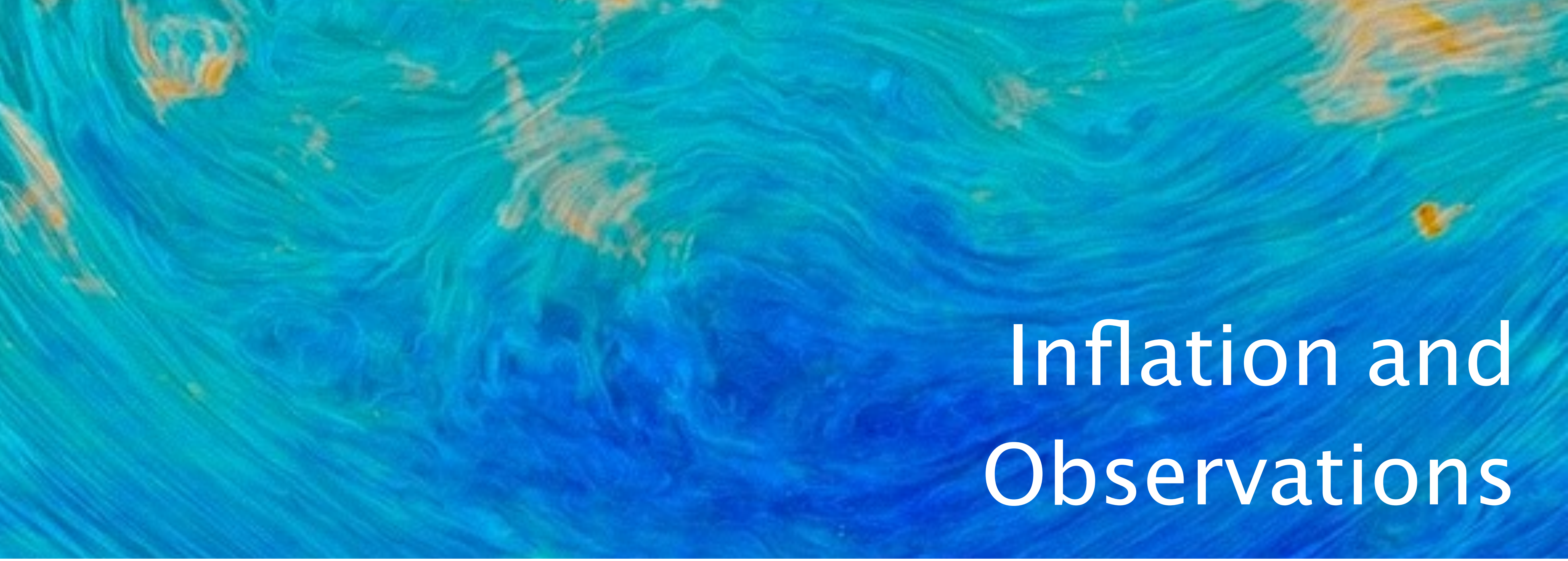
Can produce significant non-gaussian signal

Squeezed limit depends on mass

$$\langle \zeta^3 \rangle_{k_1 \to 0} \propto \left(\frac{k_1}{k_2}\right)^{\frac{3}{2}-\sqrt{\frac{9}{4}-\frac{m^2}{H^2}}} P(k_1)P(k_2)$$

Effect is measurable (we can determine the mass)

Not degenerate with other effects



Inflation and Observations

Future Directions

We probe initial conditions (inflation) through

1. The cosmic microwave background (CMB)

2. The large scale structure of the universe

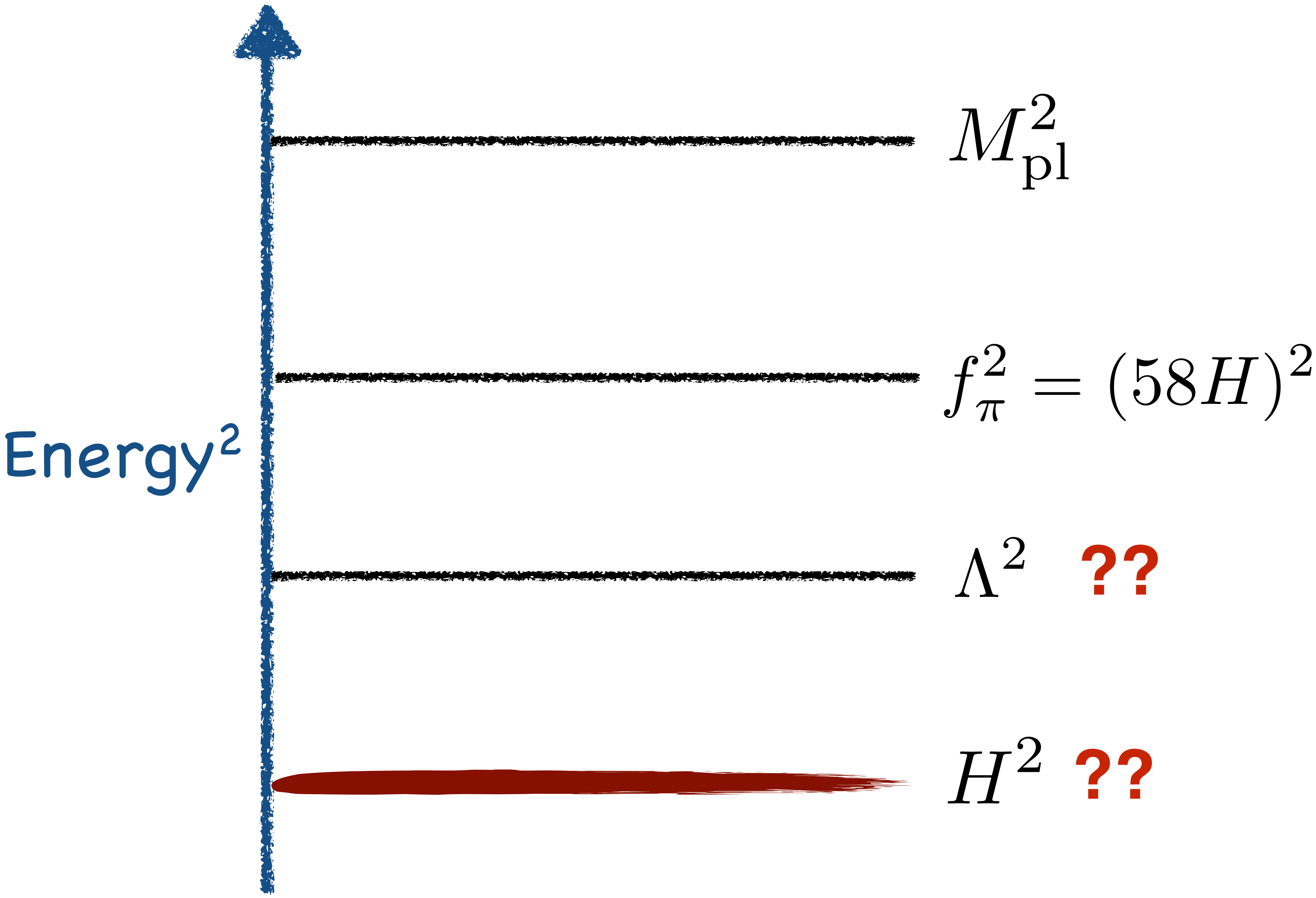
Measure density fluctuations + GR after inflation

$$d_{k,\mathrm{observable}} = T_{\mathrm{obs.}}(k,a)\zeta_{\mathrm{k}}$$

Pros / Cons are then just about the details

Future Directions

We are still trying to figure out the basic picture



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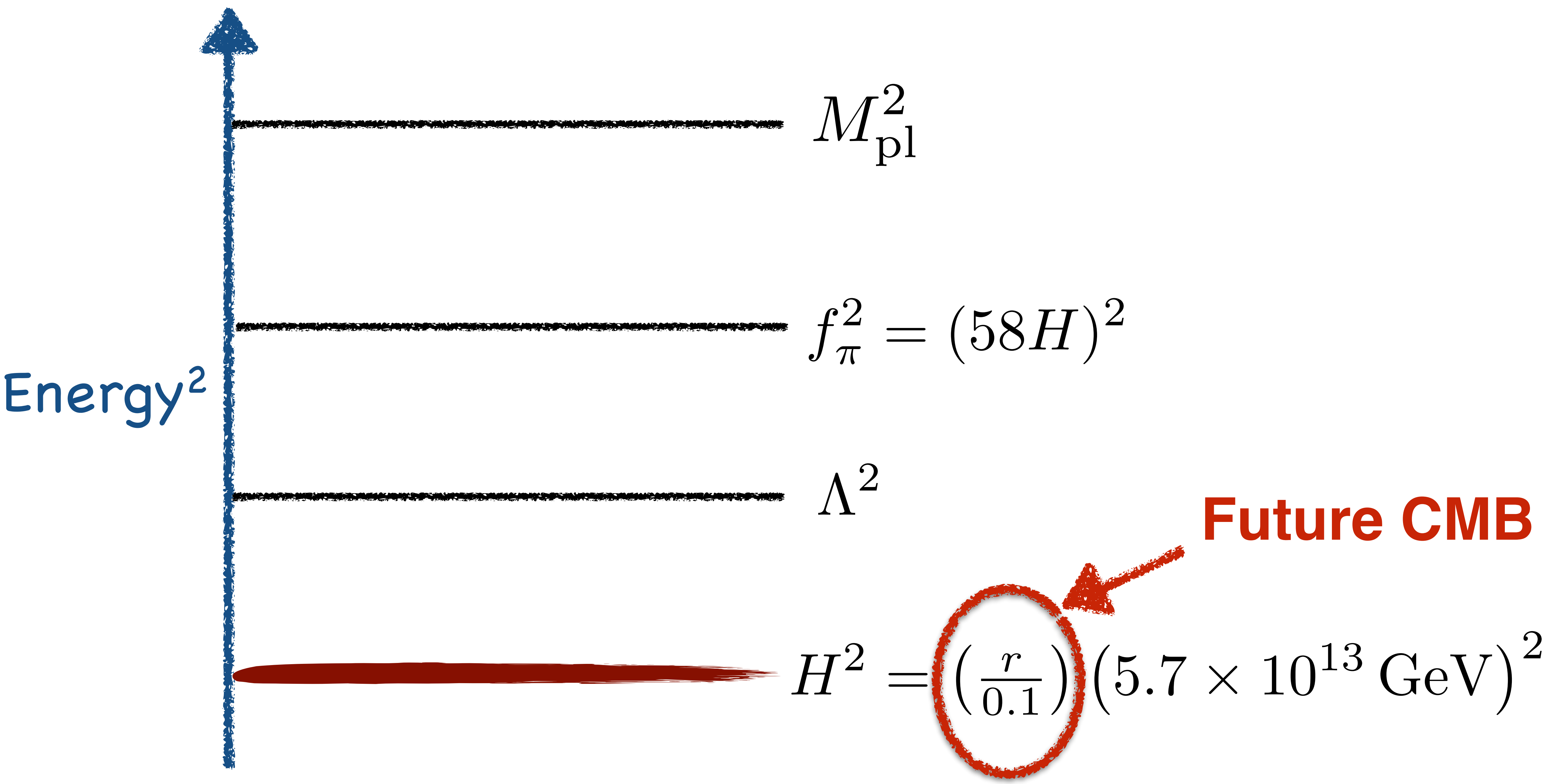

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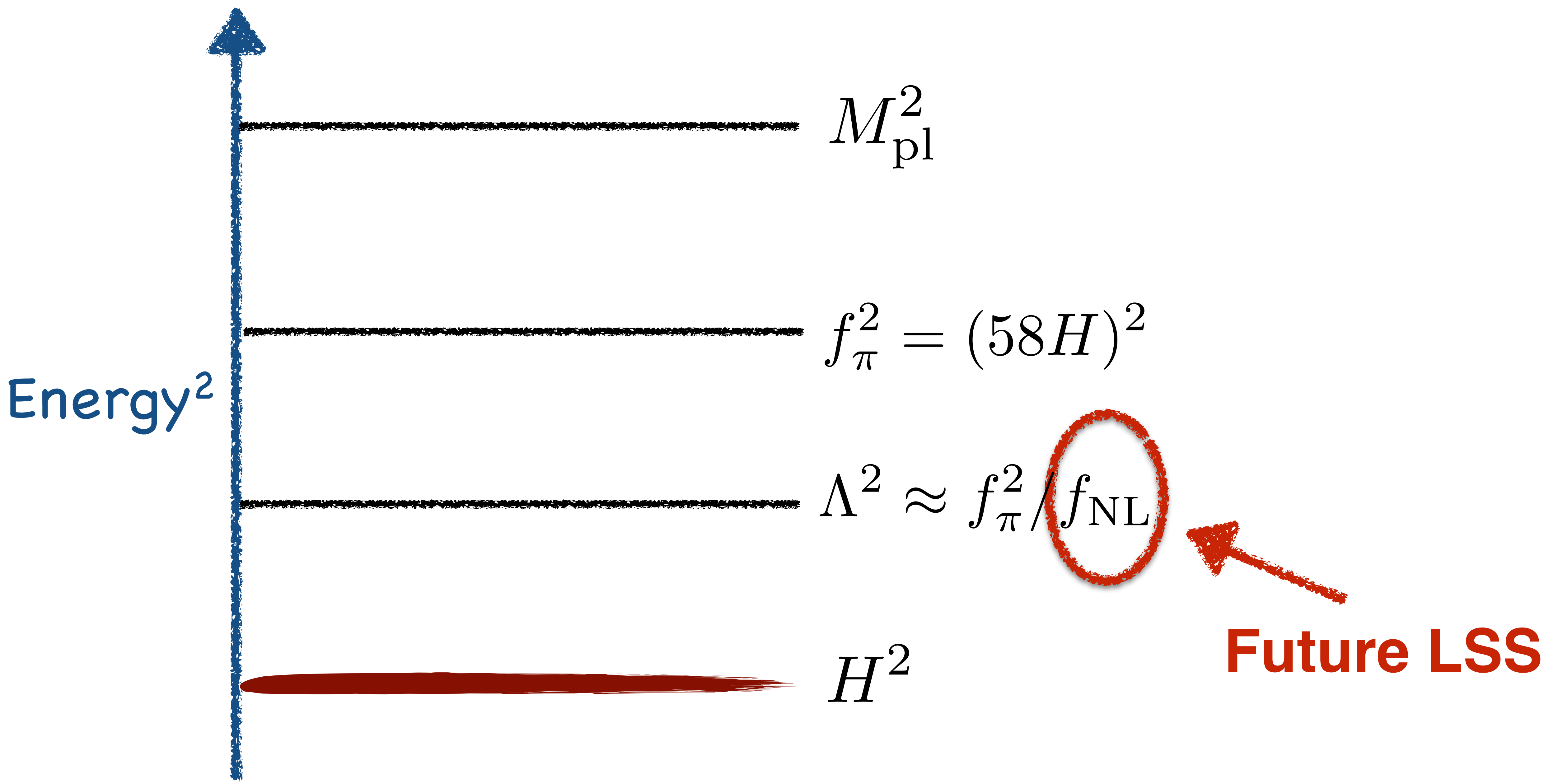
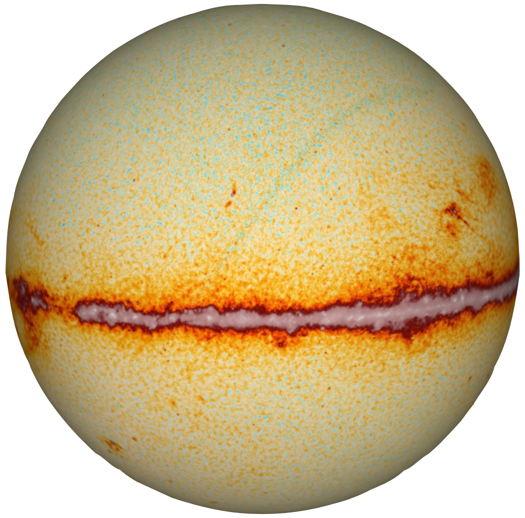
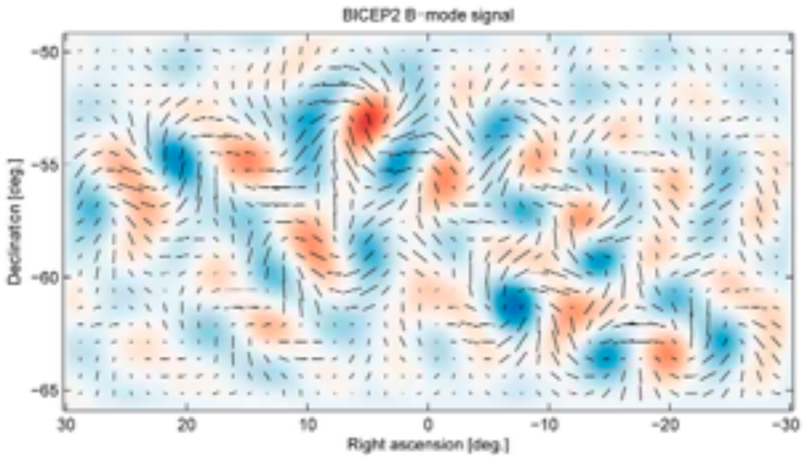
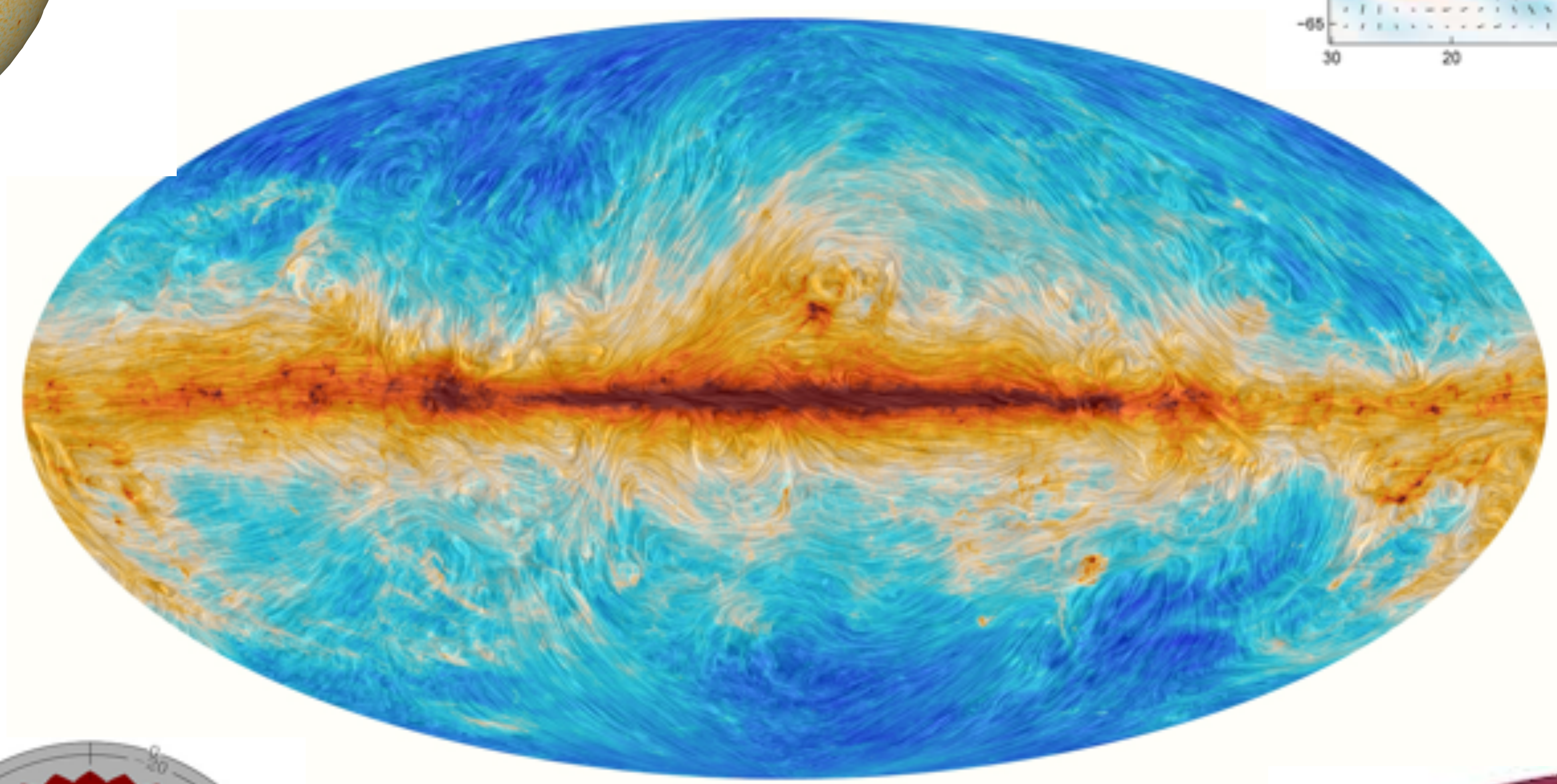
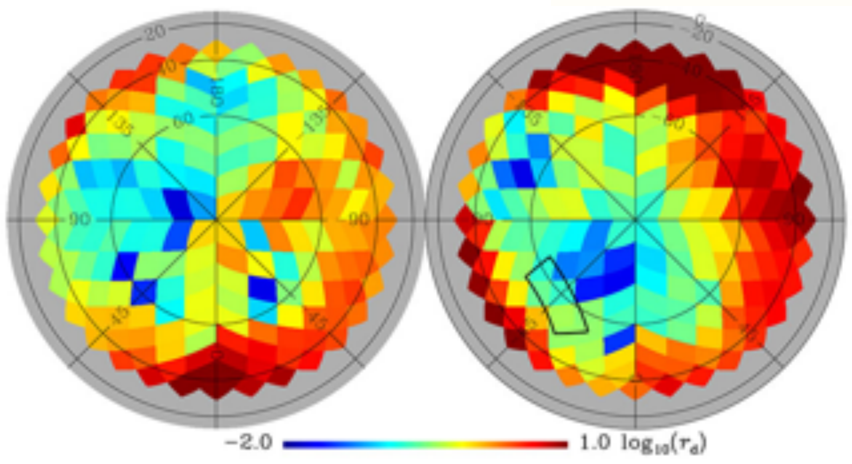


The CMB



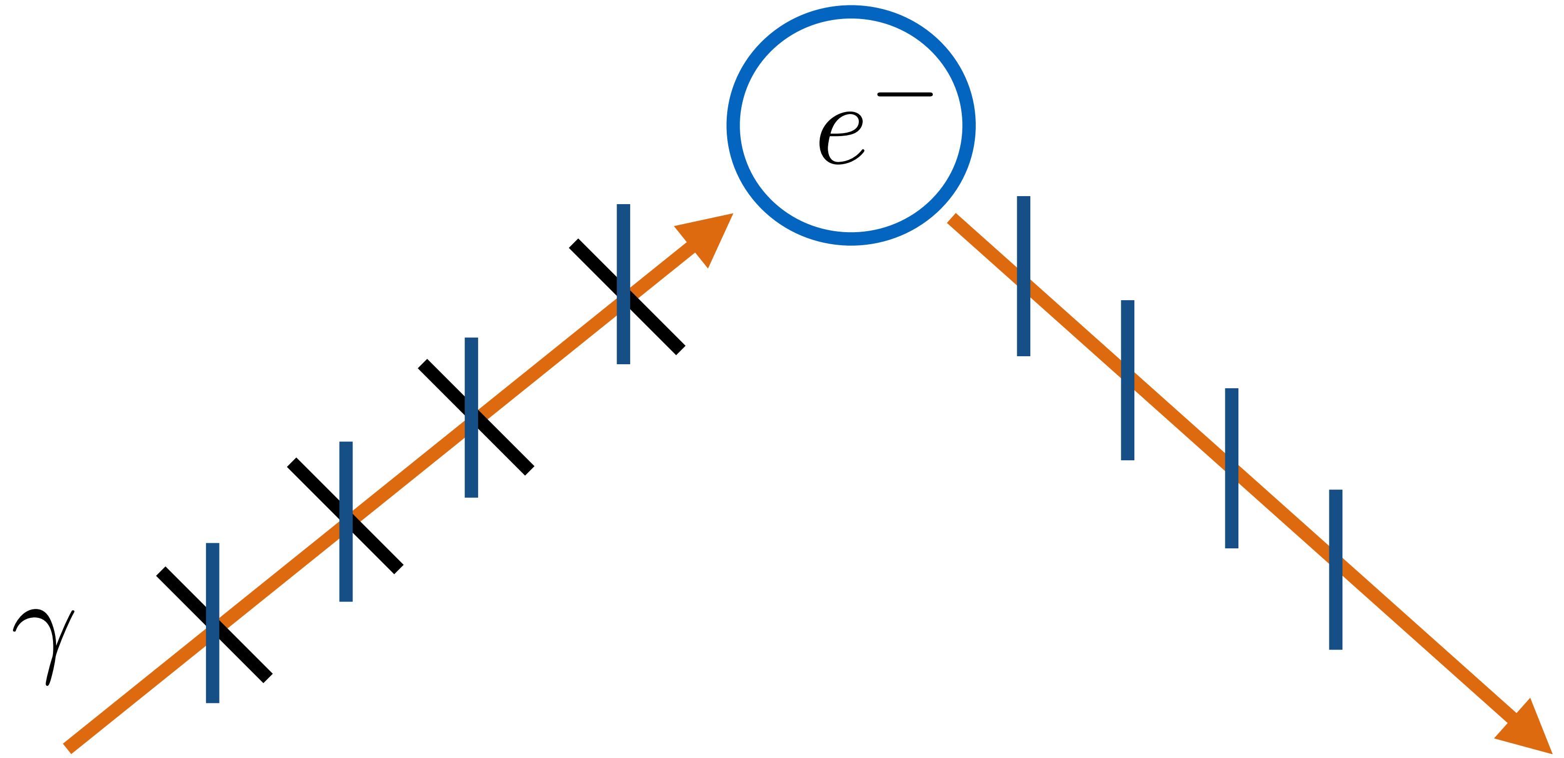

BICEP2 B-mode signal
Declination [deg.]
Right ascension [deg.]




−2.0
1.0 log$_{10}$(r_d)

CMB Polarization

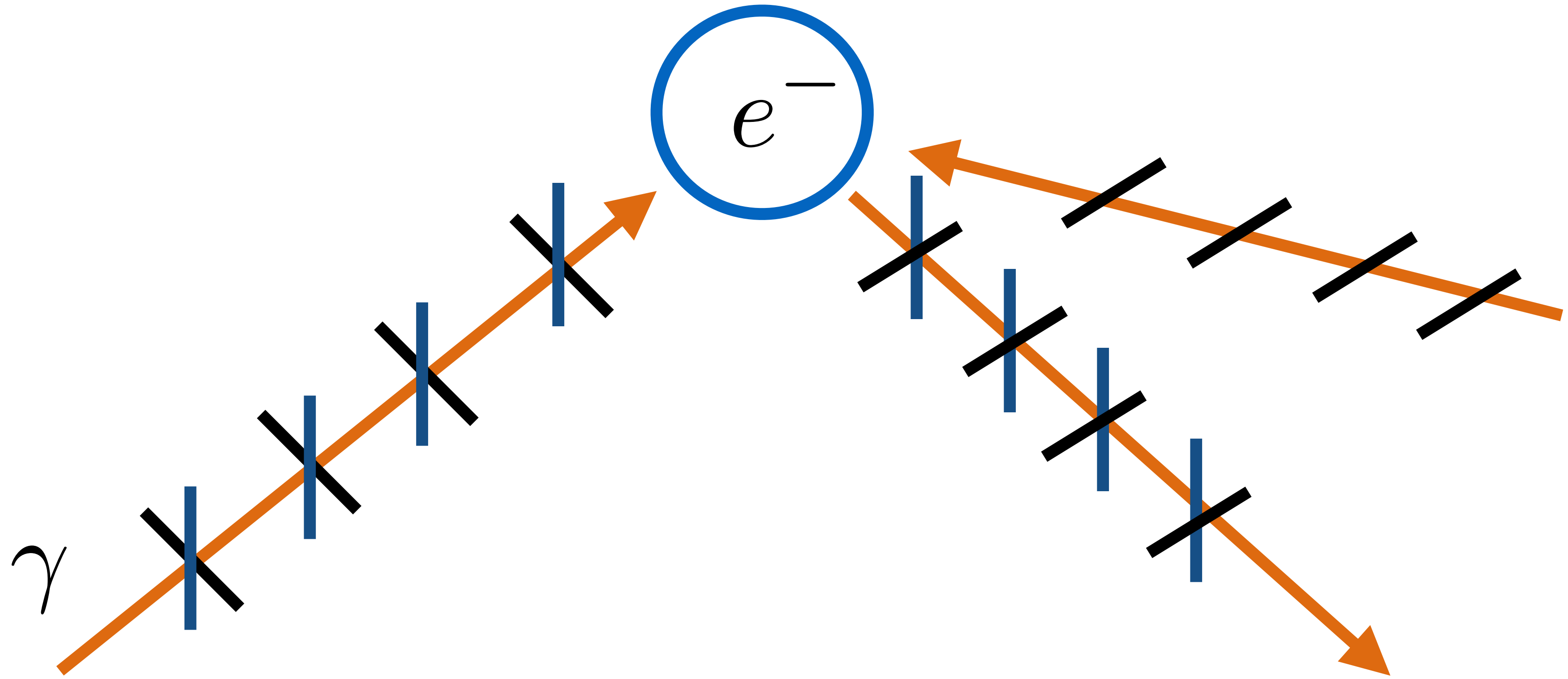
Compton scattering polarizes light



Polarization vector must be transverse to motion

CMB Polarization

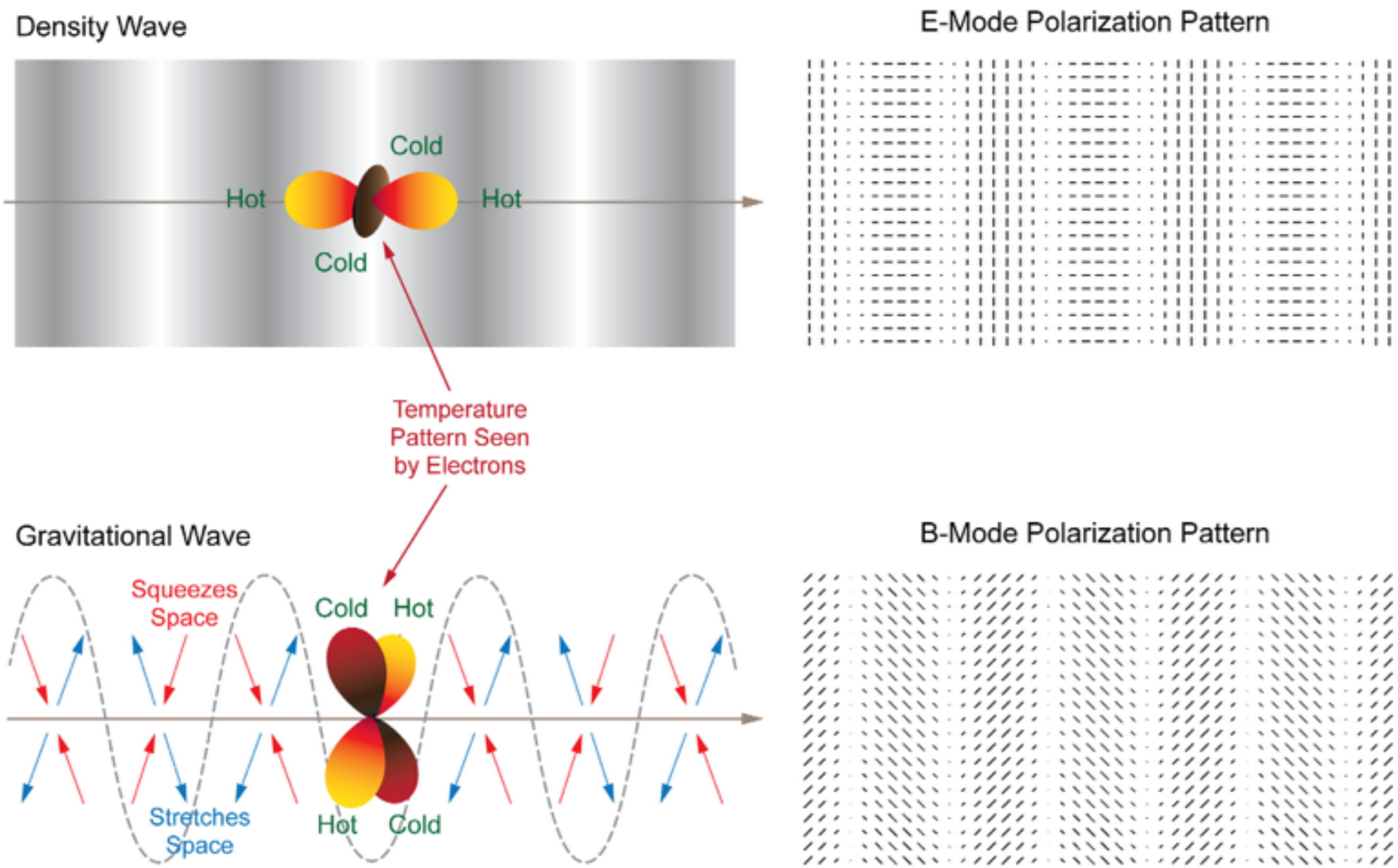
No polarization if incoming light is uniform



Polarized light requires a non-zero quadrupole

CMB Polarization

The polarization pattern depends on the source

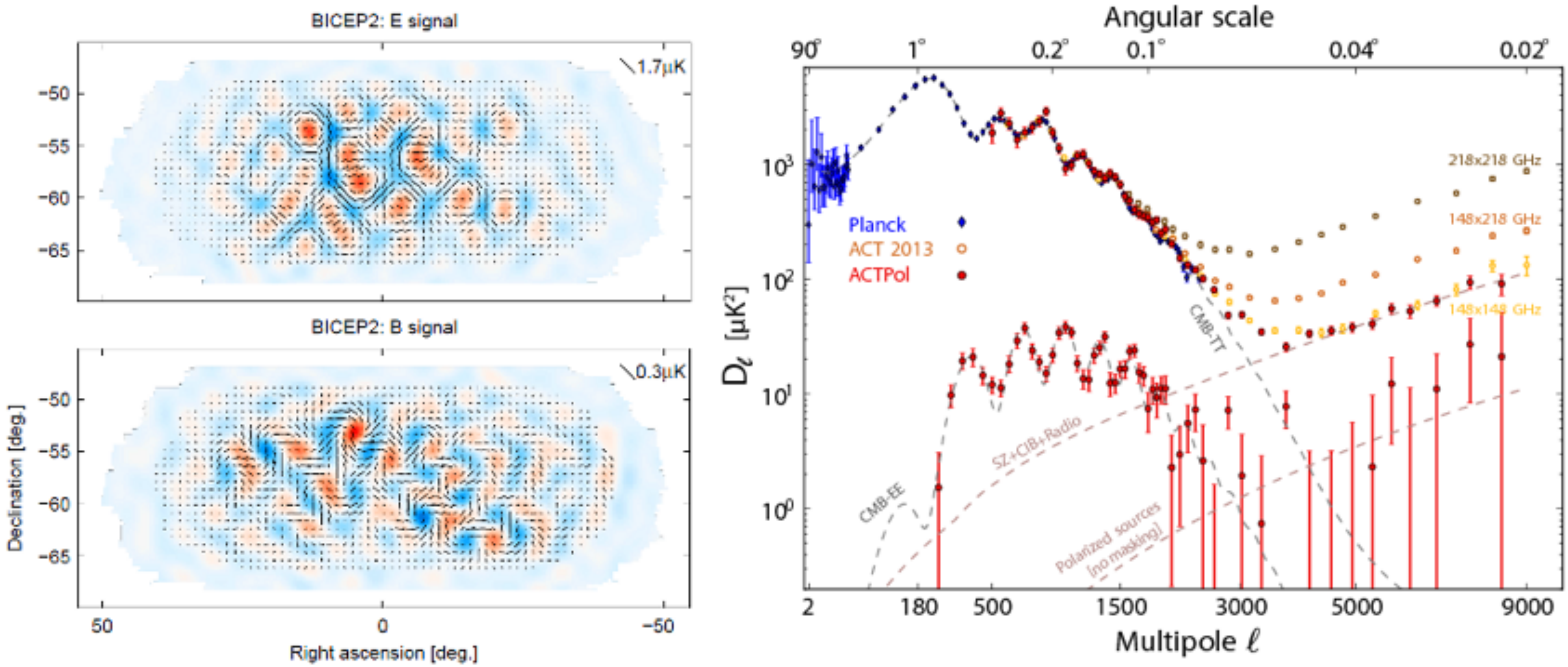


Courtesy of Bicep

CMB Polarization

Polarization is split into E and B modes

E-modes : measure the scalar density fluctuations

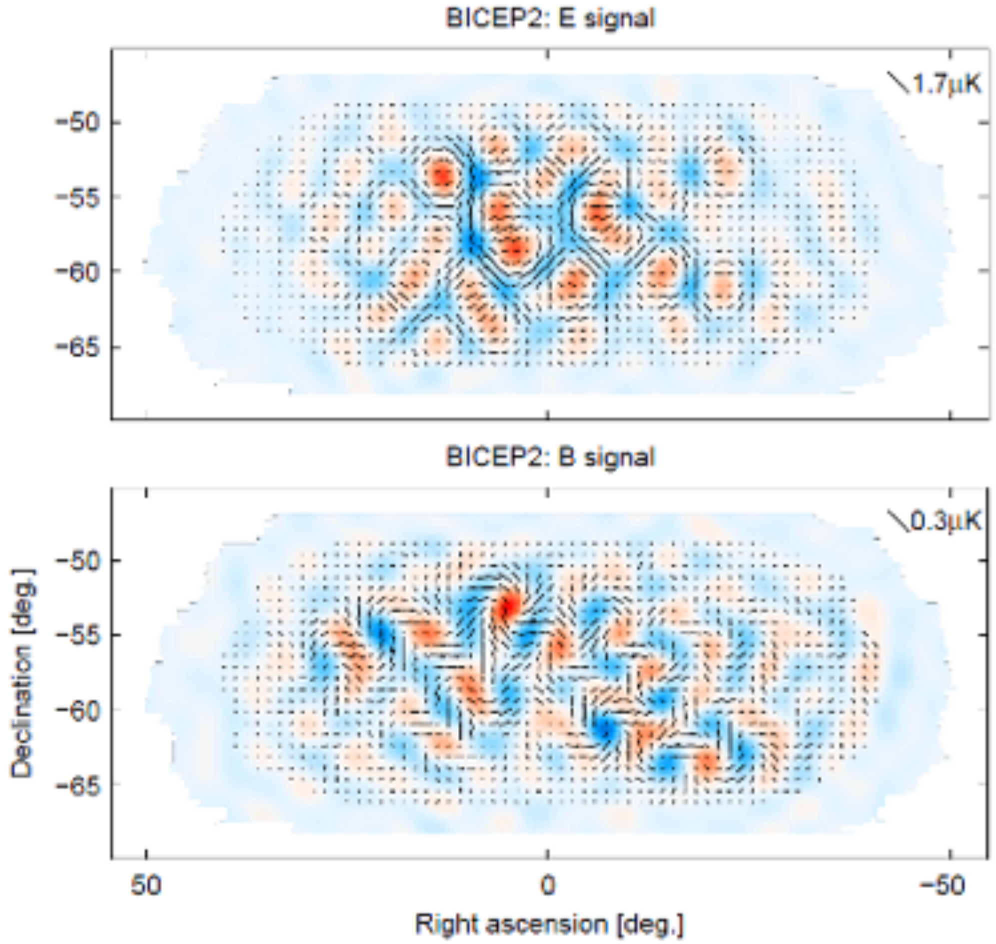


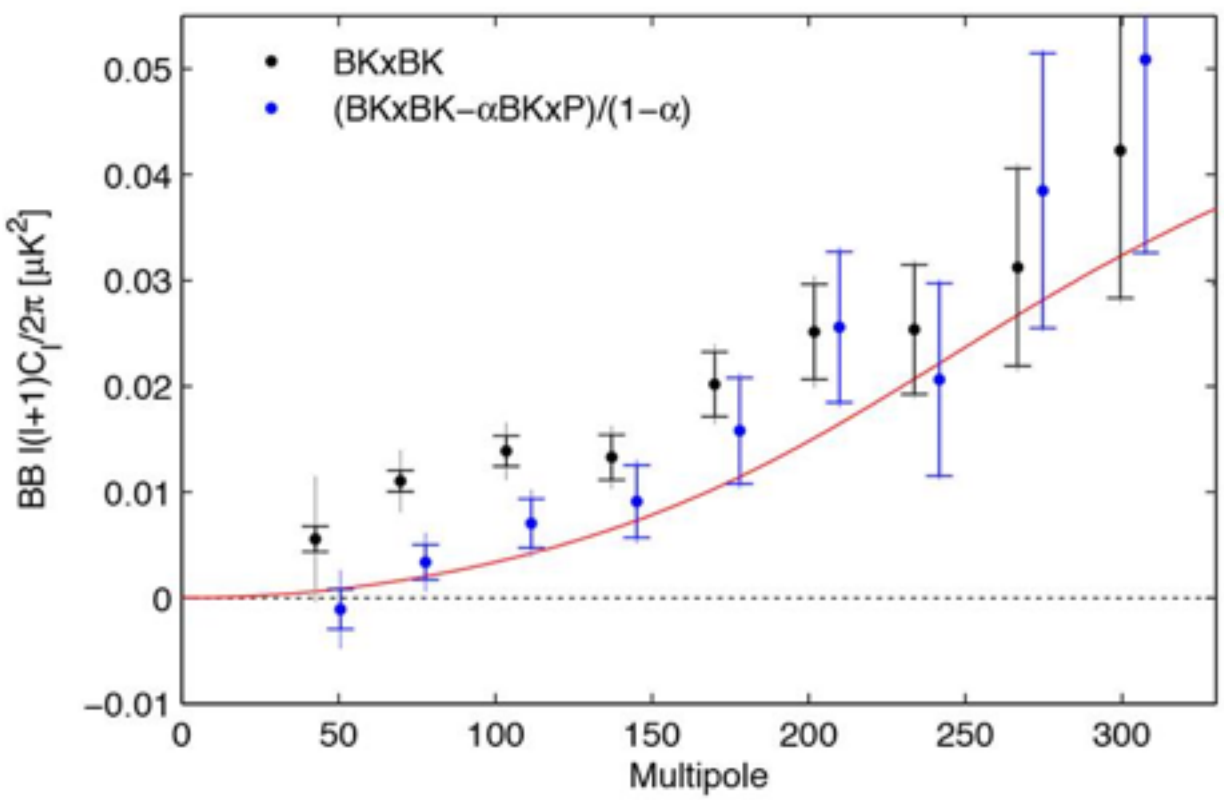
More sensitive to cosmological parameters than T

CMB Polarization

Polarization is split into E and B modes

B-modes : directs of gravitational waves

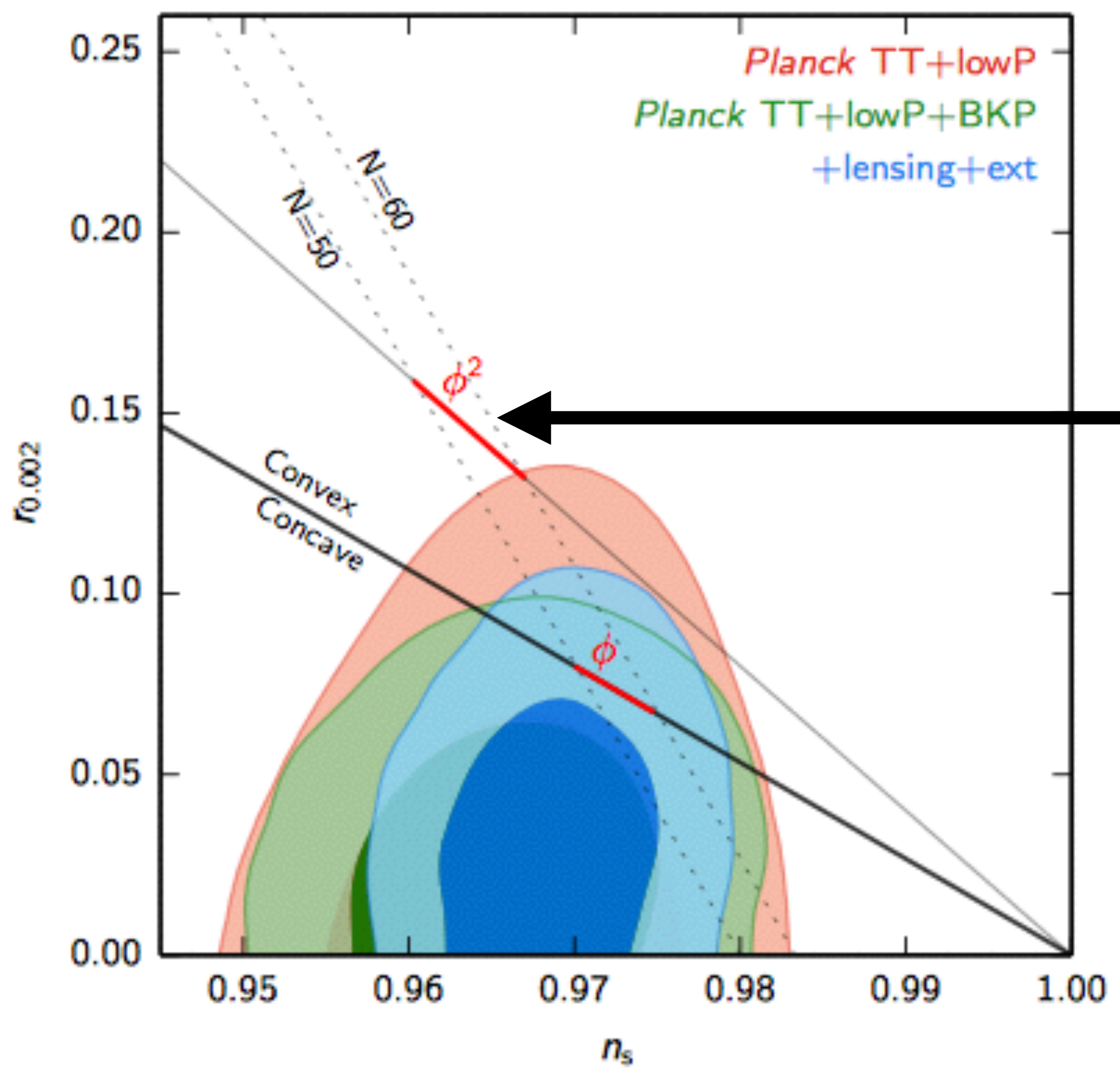




Constrains the Hubble parameter during inflation

CMB Polarization

Tensor amplitude fixes all the scales in inflation



$$V(\phi) = \frac{1}{2}m^2\phi^2$$

Already a strong constraint on many popular ideas

Status of CMB

Name of the game is number of detectors

Today (Stage 2): 1000 detectors $\Delta r \sim 0.02$

ACTpol, BICEP, Keck, Spider, SPT, ...

Next few years (Stage 3): 10000 detectors $\Delta r \lesssim 0.01$

Advanced ACT, SPT3G, Keck-array,...

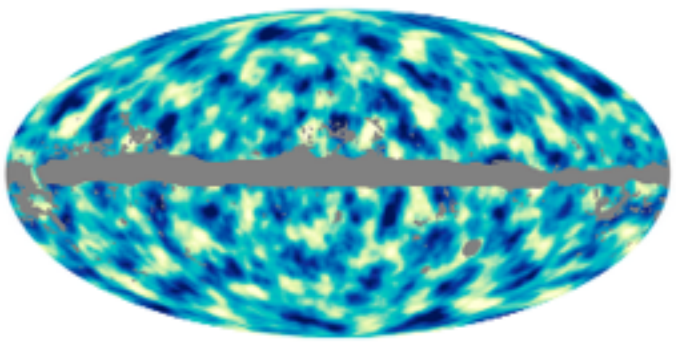
Stage 4: 100 000 - 1 000 000 detectors $\Delta r \sim 0.001$

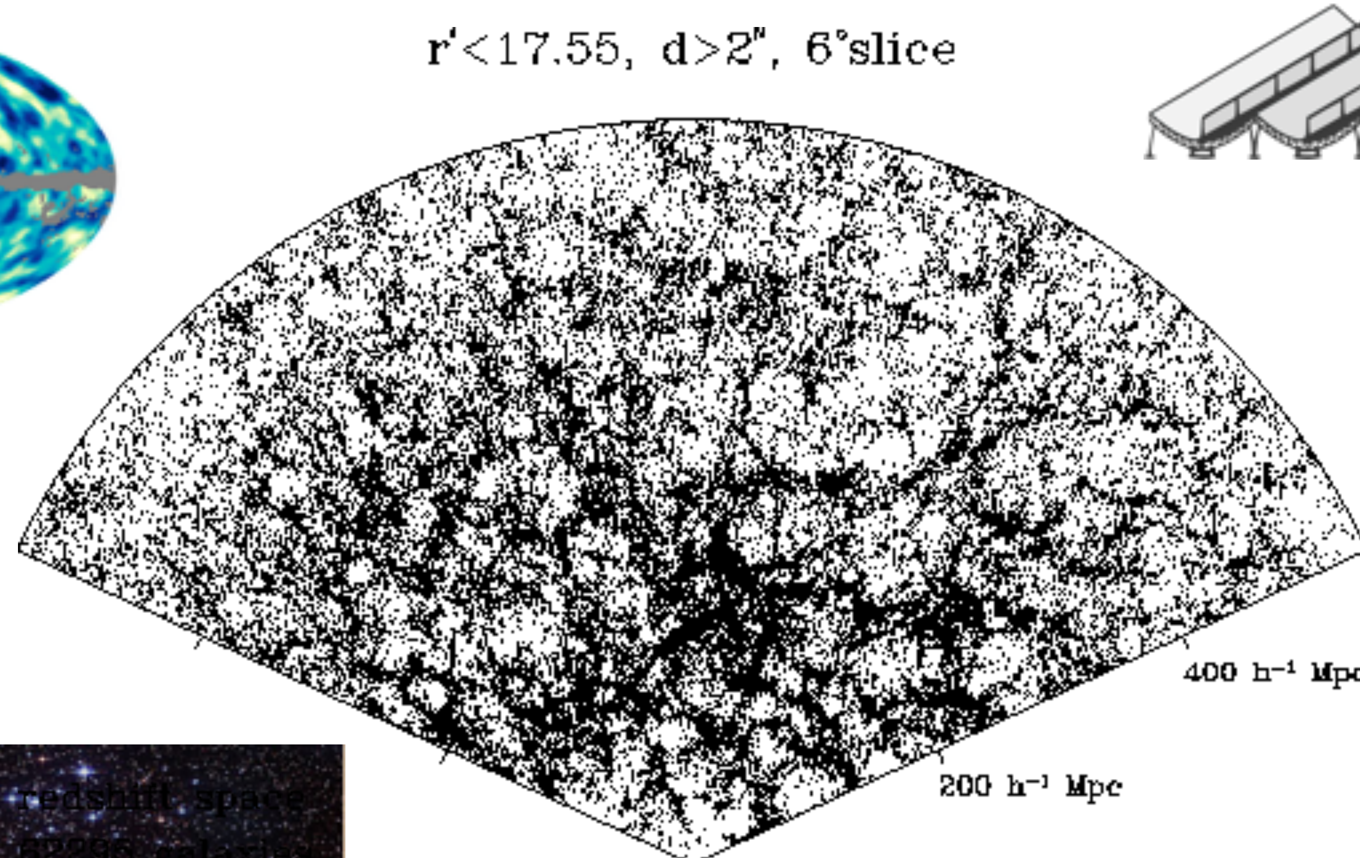
Strongly endorsed by DOE/NSF

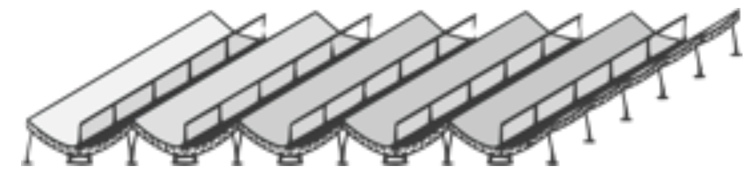
Currently in planning stage

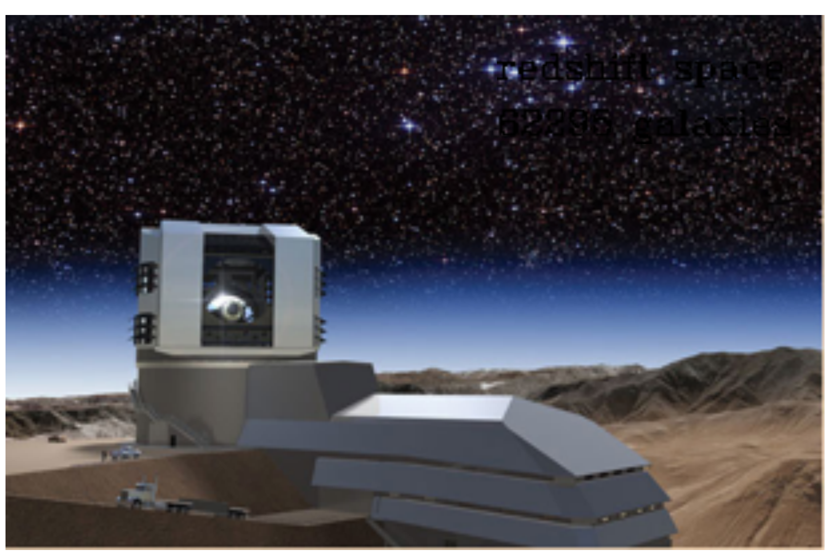
Large Scale Structure

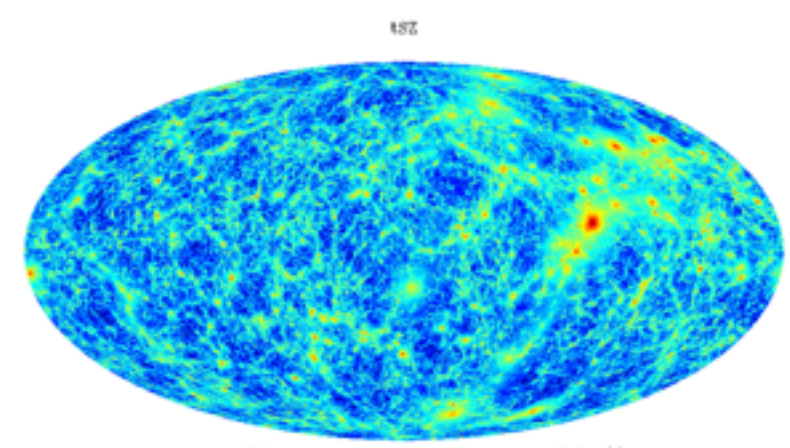
For raw statistical power we need LSS





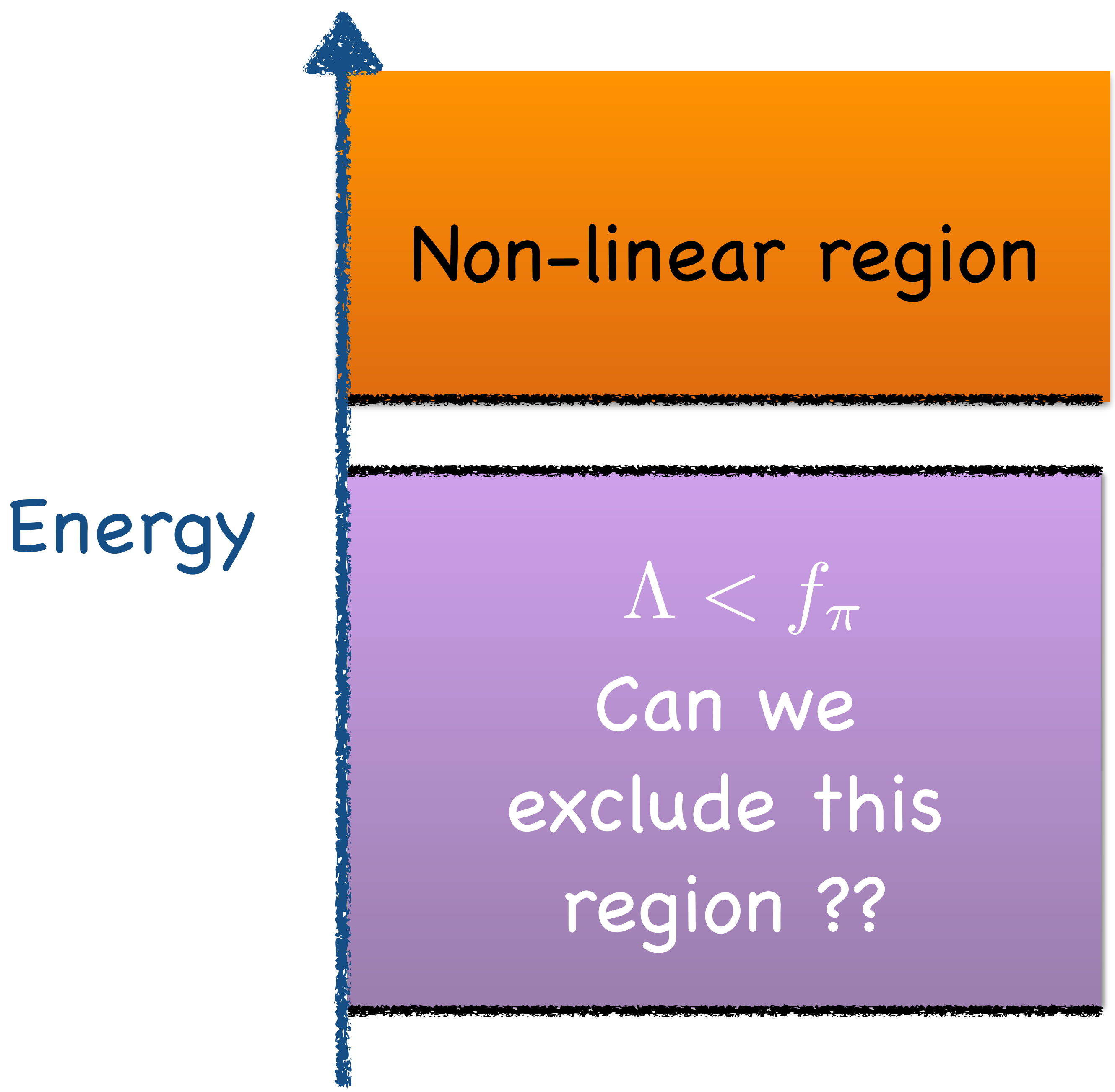






Large Scale Structure

One goal is to test the full non-slow-roll region



$\Lambda > f_\pi$

$f_\pi = 58\ H$

H Hubble scale

Large Scale Structure

One goal is to test the full non-slow-roll region

In terms of measurable parameters we need

$$f_{\rm NL}^{\rm equilateral} < 1 \;\; (2\sigma)$$

Best limit today is $\Delta f_{\rm NL}^{\rm equilateral} = 84 \;\; (2\sigma)$

WMAP to Planck(2015) was a factor of 4 improvement

Large Scale Structure

The brute force approach is to find more "modes"

When each bin is cosmic variance limited

$$\Delta f_{\rm NL} \sim \frac{10^5}{\sqrt{N_{\rm modes}}}$$

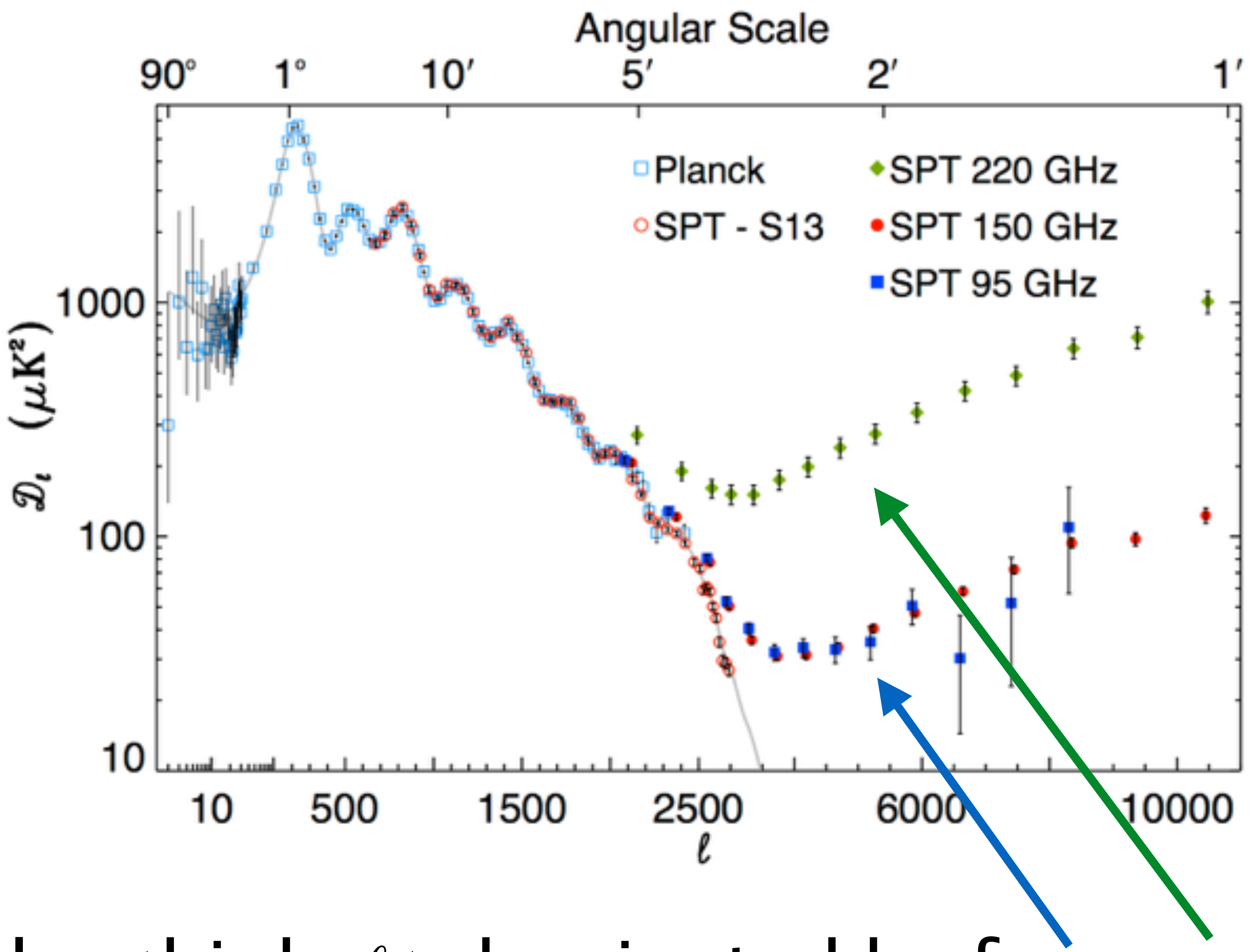
E.g. From Planck we get roughly

$$N_{\rm modes,Planck} \sim \ell^2_{\rm max} \sim 2 \times 10^6$$

To improve by 10^2 we will need 10^{10} modes!

Large Scale Structure

There aren't many more modes in the CMB



Small scales (high ℓ) dominated by foregrounds

Large Scale Structure

For raw statistical power we need LSS

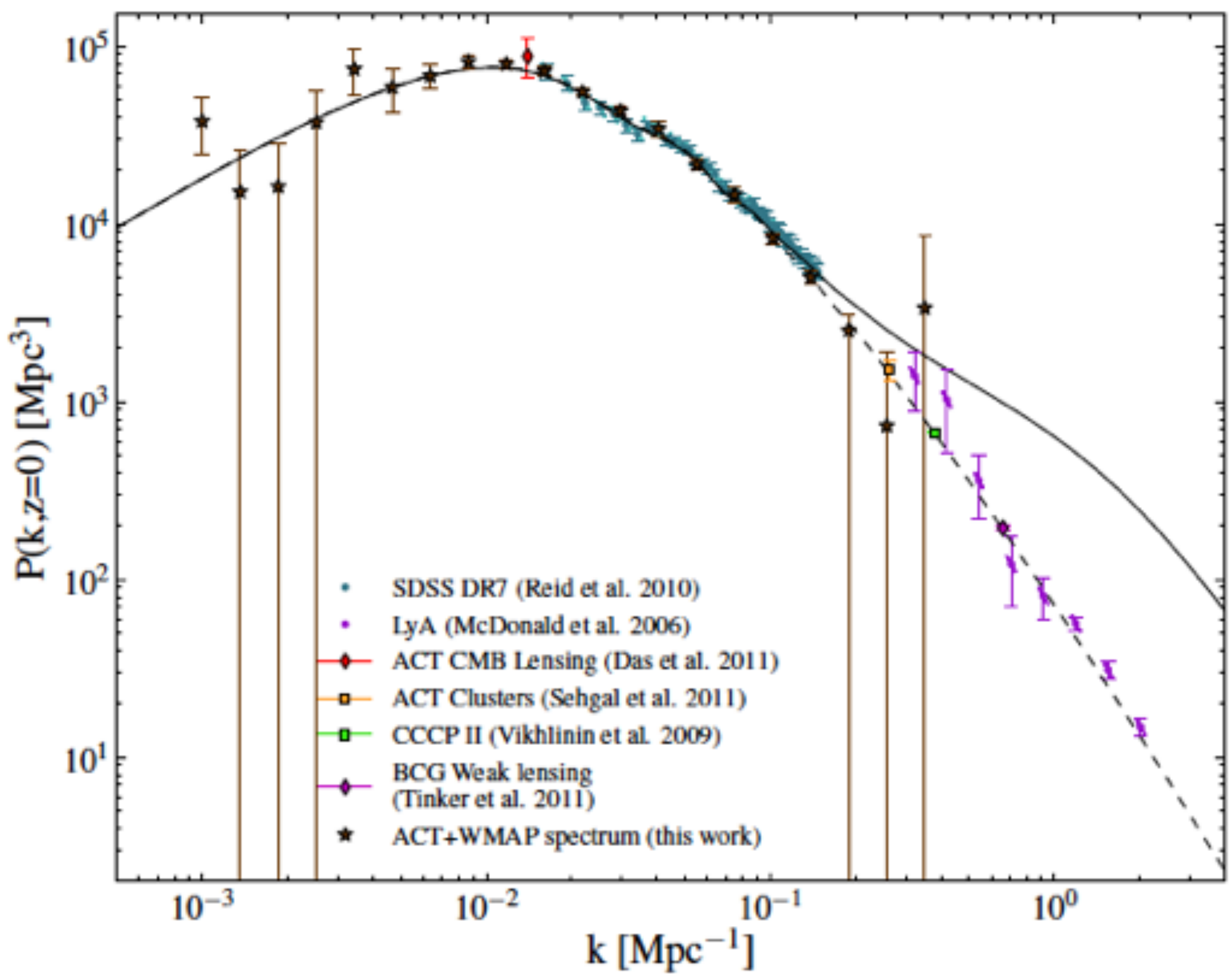
Basic advantage: a lot more linear fourier modes

Reason 1 : LSS is 3d versus 2d CMB

Reason 2 : Larger range of scales

Large Scale Structure

CMB



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

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

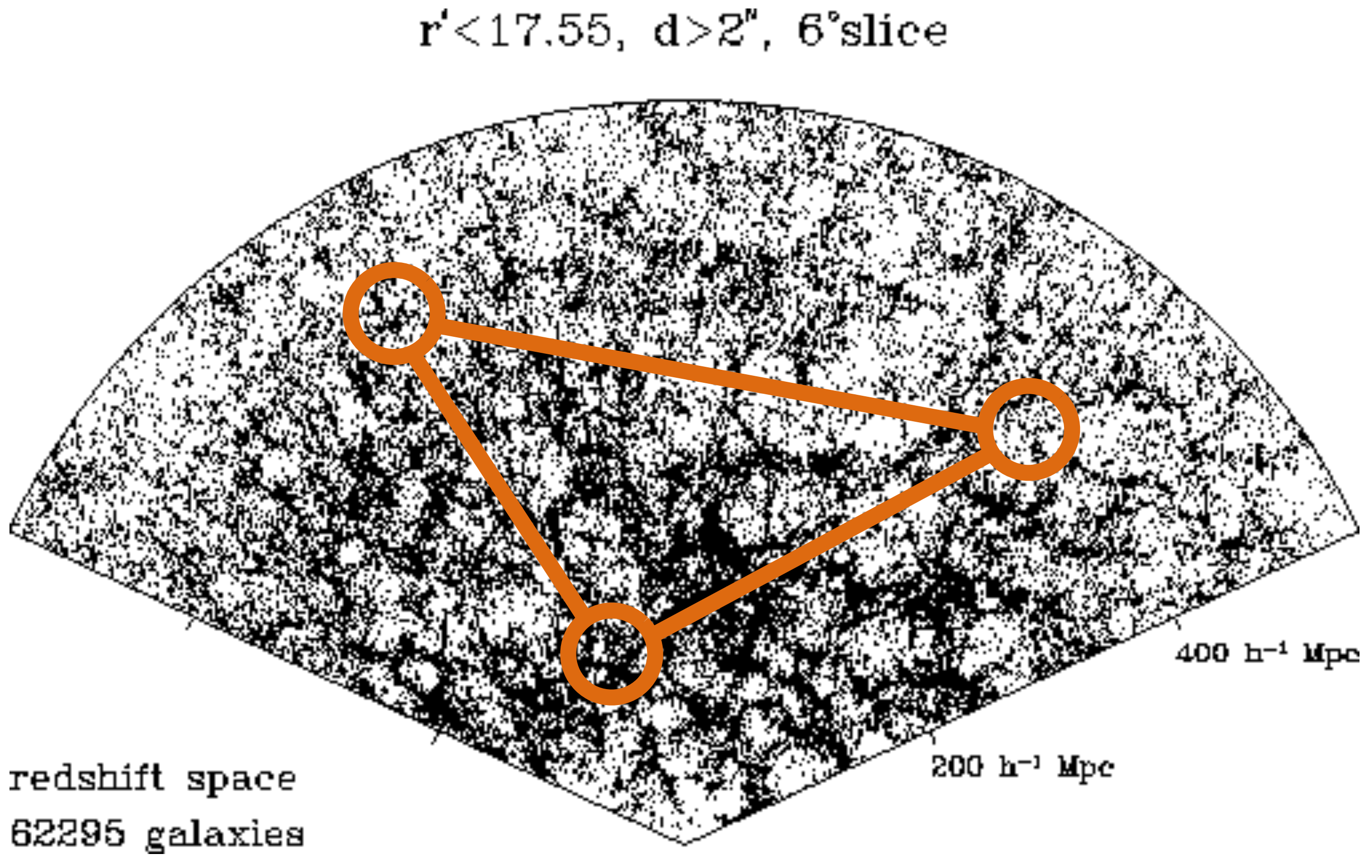
Linear regime of LSS

Figure from Hlozek et al.

Large Scale Structure

Capable of improving tests of gaussianity

Idea: Constraint higher point statistics of galaxies



This is the only way to beat current limits from CMB

Large Scale Structure

Non-gaussanity measurements will be difficult

To take advantage of 3d modes we need:

- Very accurate redshifts
- Good model for galaxy formation
- Control of many many new systematics

For these (and other) reasons, no one has actually performed the analysis that will be needed

Local NG and LSS

Some problems can be avoided for local NG

E.g. galaxy formation depends on $\Phi_{\rm Newtonian}$

Not possible from astrophysics / Newtonian gravity

Systematics are still a big problem

SPHEREx is best designed approach: $\Delta f_{\rm NL}^{\rm local} \sim 0.3$

Status of LSS

	LSST	DESI	Euclid	SPHEREx	CHIME
Survey type	photo	spectro	photo+spectro	low-res spectro	21-cm
Ground or space	ground	ground	space	space	ground
Previous surveys	CFHTLS, DES, HSC	BOSS, eBOSS, PFS	no direct precursor	PRIMUS, COMBO-17, COSMOS	GBT HIM
Survey start	2020	2020	2018	2020	2016
Redshift-range	$z < 3$ (1% sources above 3)	$z < 1.4$, $2 < z < 3.5$ (Lya)	$z < 3$	$z < 1.5$	$0.75 < z < 2.5$
Survey area [deg^2]	20k	14k	15k	40k	20k
Approximate number of objects	2×10^9 (WL sources)	22×10^6 gal., $\sim 2.4 \times 10^5$ QSOs	40×10^6 redshifts, 1.5×10^9 photo-zs	15×10^9 pixels	10^7 pixels
Galaxy clustering	✓✓°	✓	✓	✓	✓
Weak lensing	✓		✓		✓
RSD		✓	✓	✓✓	✓✓
Multi-tracer	✓✓	✓✓	✓✓	✓	

Taken from Alvarez et al.

Status of LSS

Funded

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RSD		✓	✓	✓✓	✓✓
Multi-tracer	✓✓	✓✓	✓✓	✓	

Taken from Alvarez et al.

Summary

Summary

Inflation is more than a scalar field on a flat potential

In single-field, strongly coupled models still allowed
(i.e. analogue of technicolor still possible)

We are also sensitive to full spectrum of particles
(interesting possibilities in weakly coupled models)

Probes of physics at (possibly) very high energies

Significant experimental progress expected