Non-Gaussianity as a Probe of New Physics

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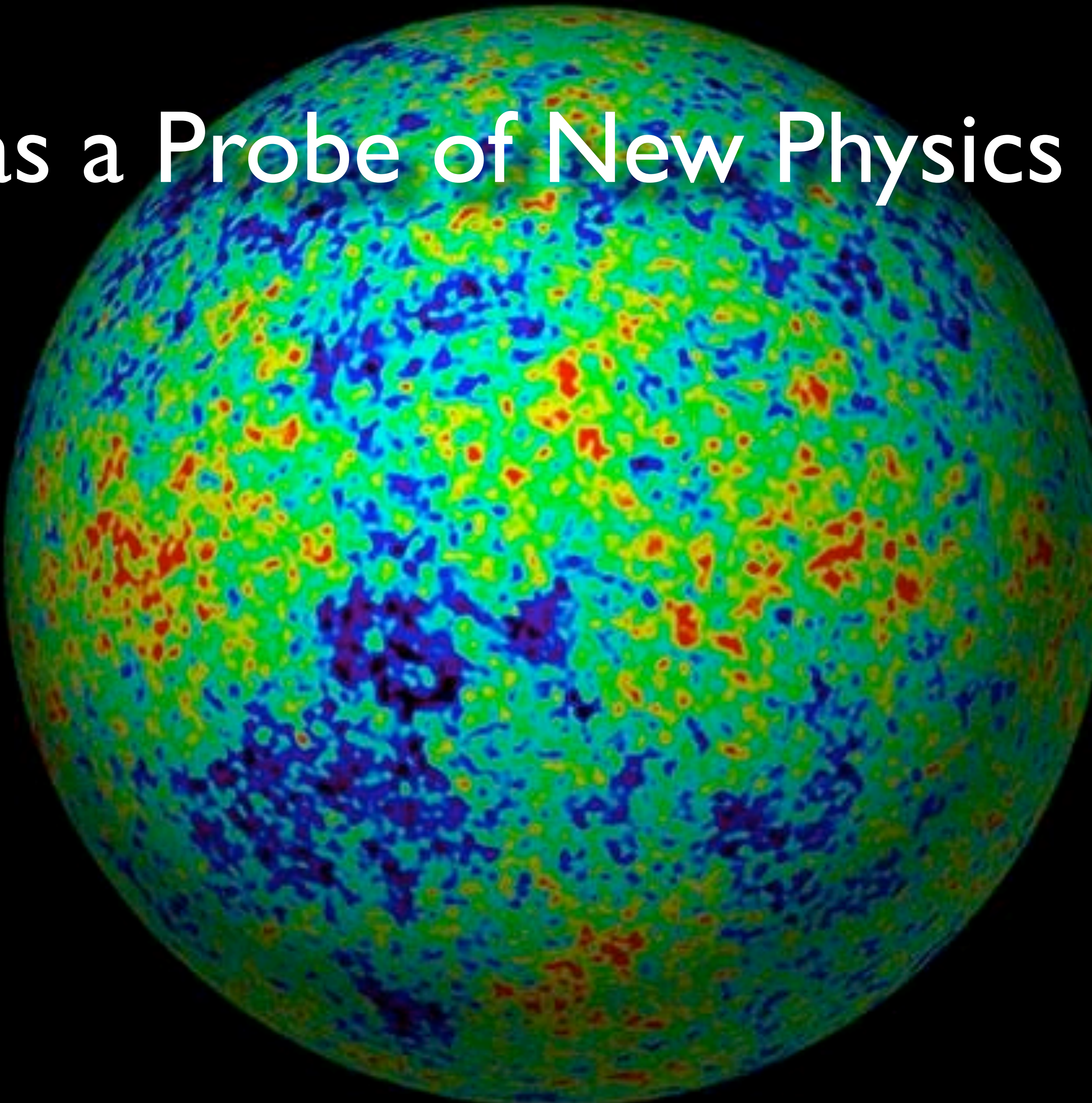
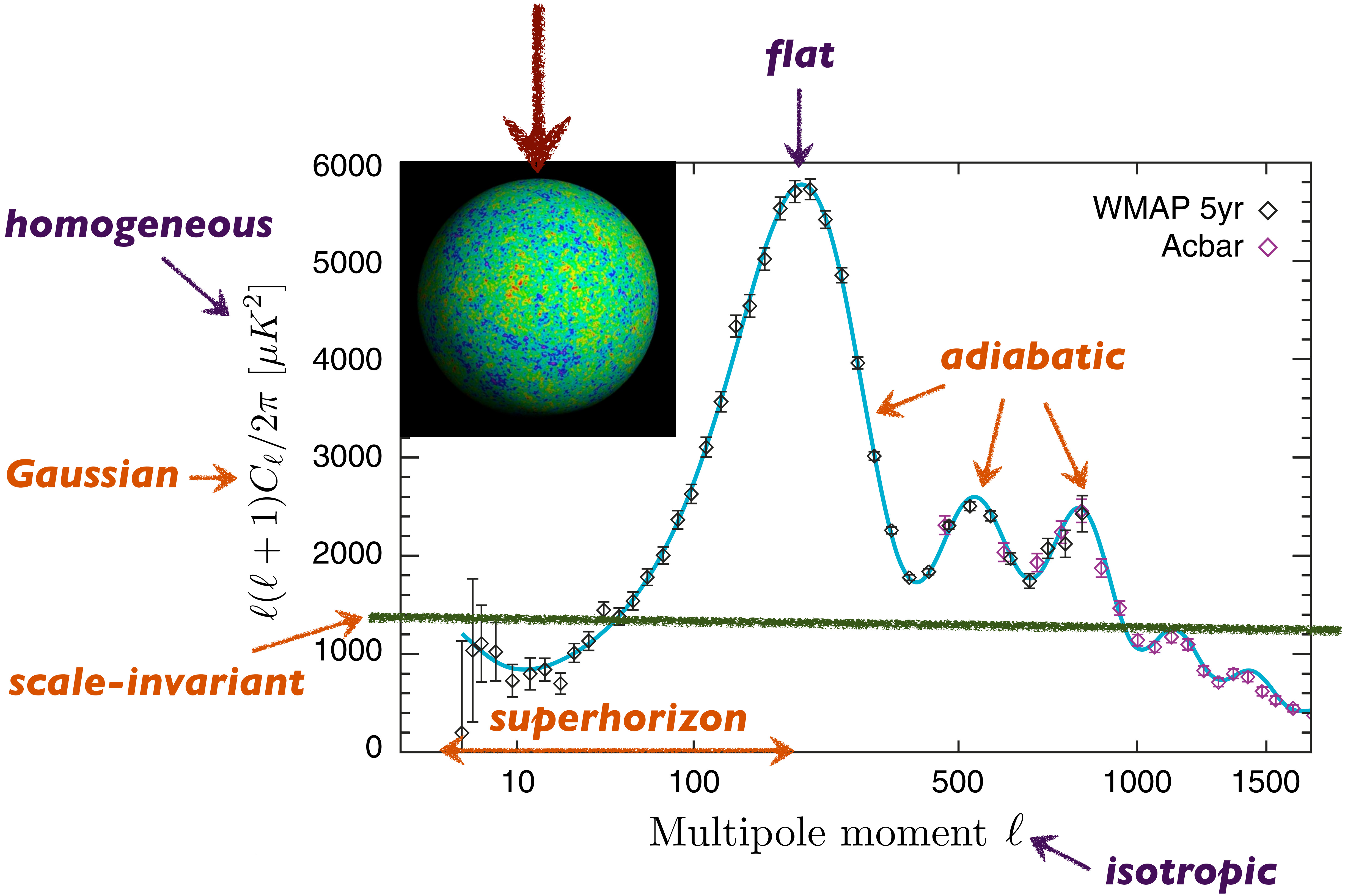


based on work with Daniel Green

Cornell, July 2011

Inflation



flat
homogeneous
Gaussian
scale-invariant
superhorizon
adiabatic
isotropic
WMAP 5yr
Acbar
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
Multipole moment ℓ

The current data can be explained completely by

FREE FIELDS in quasi-de Sitter

$$|\dot{H}| \ll H^2$$

Future data may distinguish models by:

- deviation from scale-invariance (**n_s-1**) - probes $\dot{H}$ $\ddot{H}$
- B-mode polarization (**r**) - measures energy scale H
- non-Gaussianity (**f_{NL}**) - probes physics beyond $H(t)$

INTERACTIONS

↕

EFFECTIVE THEORY?

Effective Theory of Inflation

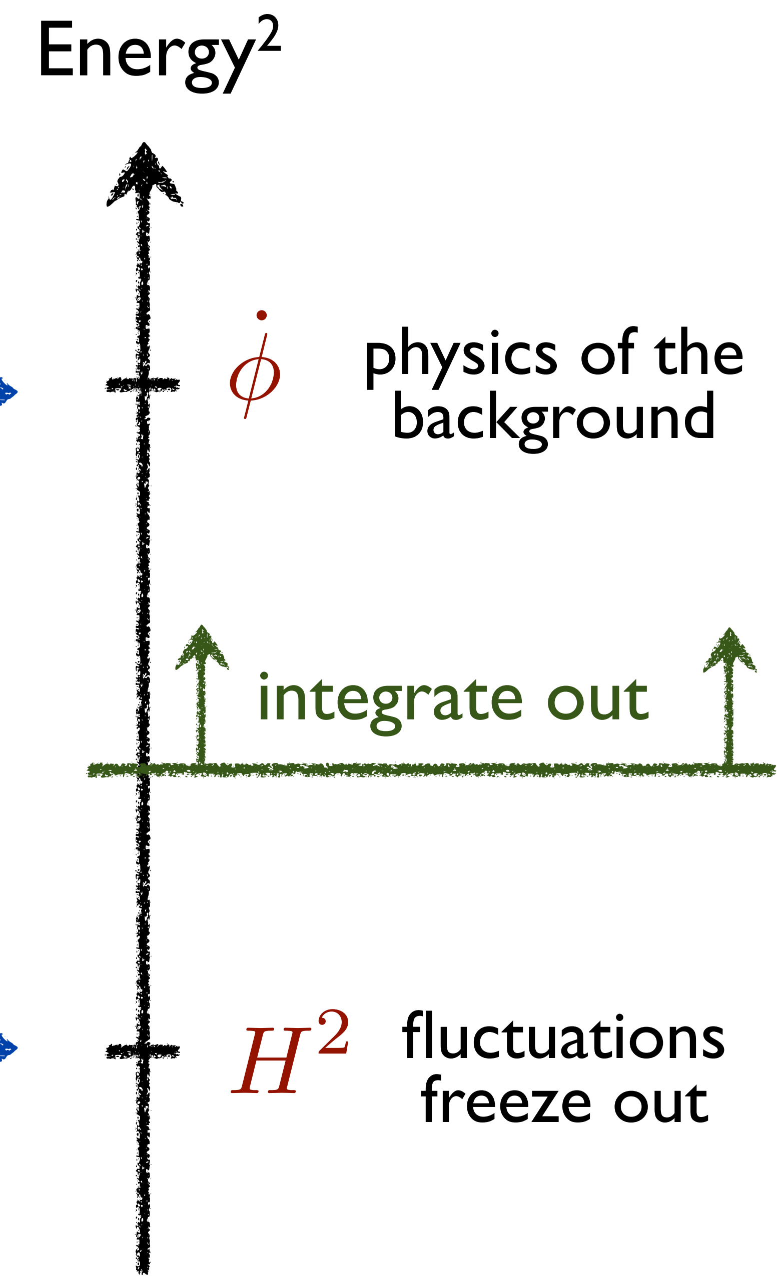
Cheung et al.

de Sitter is ***time translation invariant***

Inflation has to end, so ***symmetry is broken***

Goldstone bosons
describe fluctuations

CMB + LSS observations probe frozen modes



Effective Theory of Inflation

Cheung et al.

Given an EFT describing the data, we still want to know:

(1) What type of (UV) physics gives rise to the EFT?

(2) When does new physics become important?

Cosmology as a Probe of New Physics

Top Down

String Theory

$E \sim M_s$

- moduli stabilization
- metastable de Sitter
- inflationary instabilities

Low-E Predictions

$E \sim H$

Bottom Up

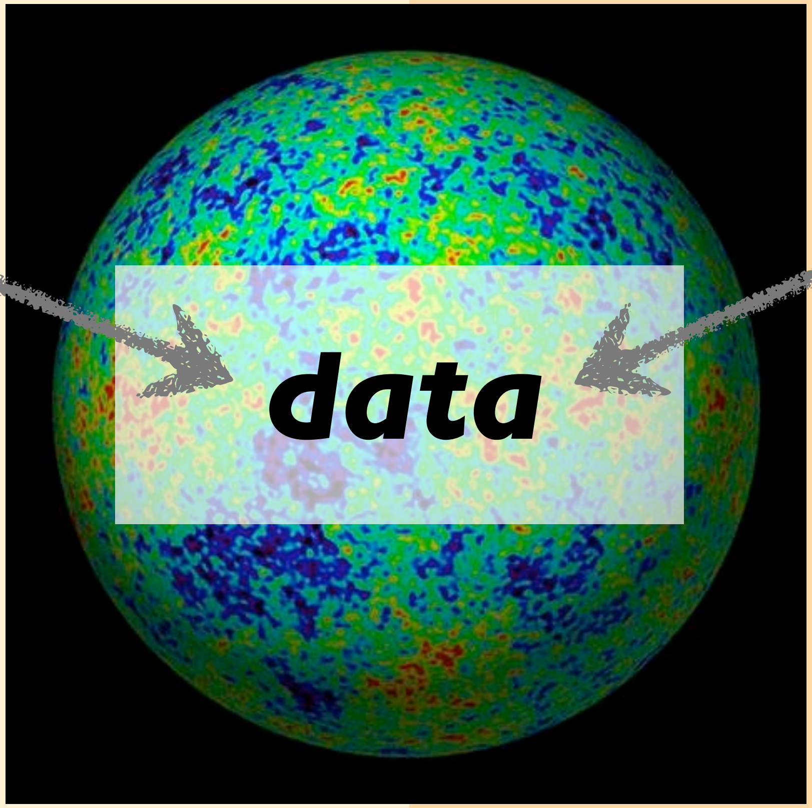
New Physics

$E > H$

- UV sensitivity
- strong coupling
- naturalness

Effective Theory

$E \sim H$



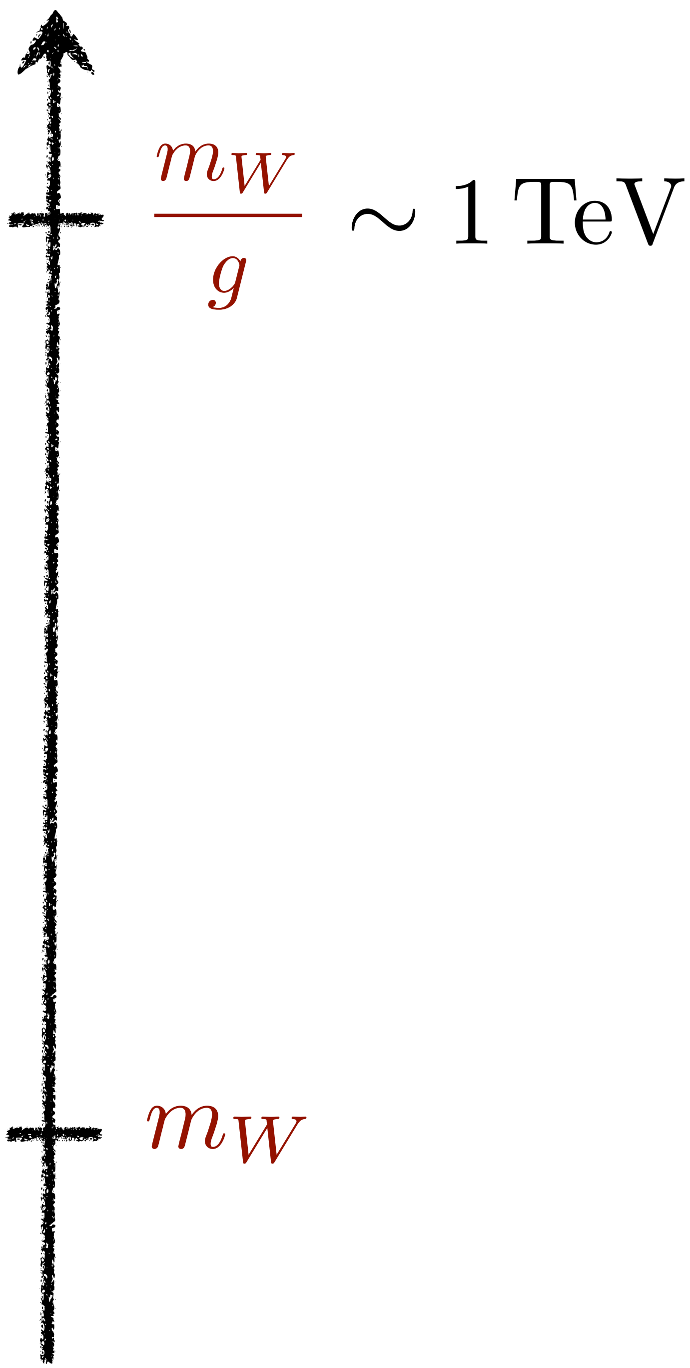
New Physics

- UV sensitivity
- ***strong coupling***
- ***naturalness***

Effective Theory

The Standard Model

without the Higgs

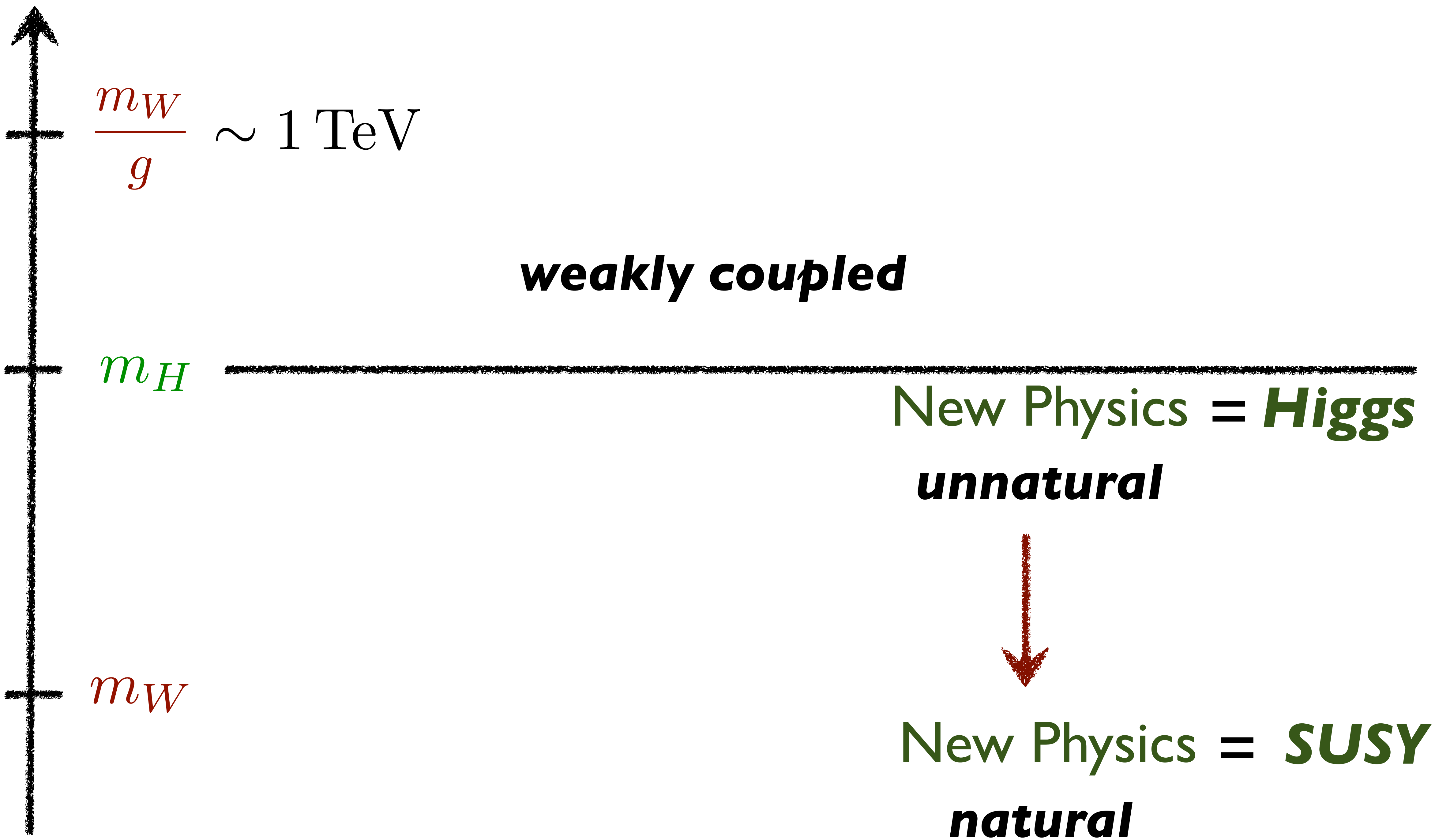


strong coupling

WW scattering violates perturbative unitarity

The Standard Model

with the Higgs



Inflation

with small sound speed

$M_{\rm pl}^2 \dot{H} c_s$ symmetry breaking

$M_{\rm pl}^2 \dot{H} c_s^5$ strong coupling

weakly coupled

New Physics = ***modified dispersion***

H^4 ***unnatural***

↓

New Physics = ***SUSY***

Outline

I. Effective Theory of Inflation

(inflationary perturbations as ***Goldstone bosons***)

Creminelli et al.
Cheung et al.

II. Energy Scales

III. Weakly-Coupled UV-Completion

DB and Daniel Green

IV. Natural SUSY Realization

(work in progress)

The Effective Theory of Inflation

Cheung, Creminelli, Fitzpatrick, Kaplan and Senatore

Creminelli, Luty, Nicolis and Senatore

Adiabatic Perturbations as Goldstone Bosons

cosmology

$a(t)$

time-dependent FRW backgrounds
break time translation invariance

↓

introduce Goldstone boson

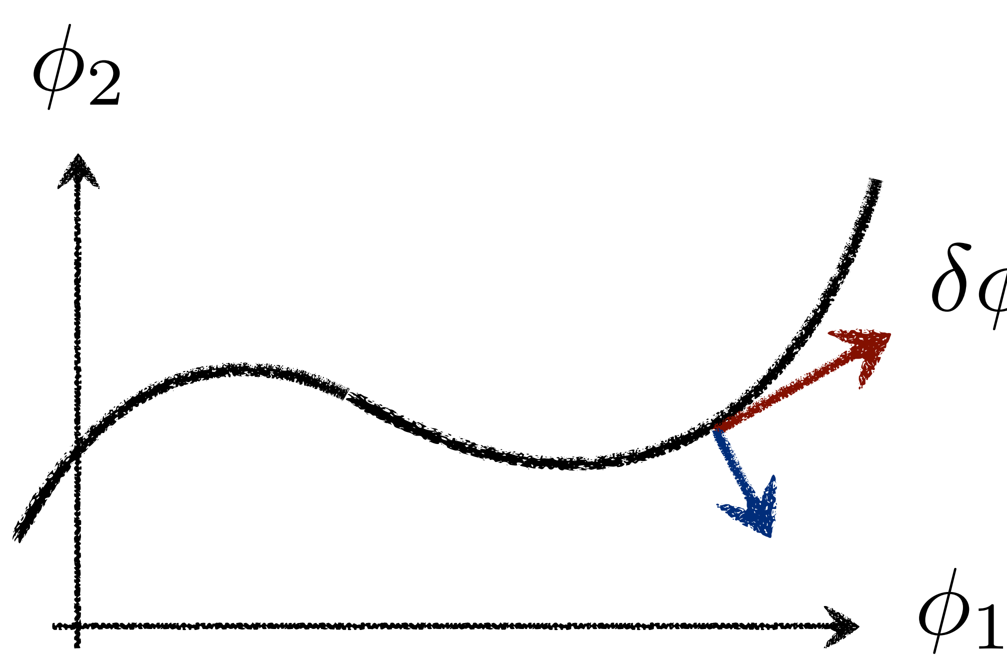
$$U \equiv t + \pi(x)$$

adiabatic perturbations

$$\delta\phi_a(x) \equiv \phi_a(t + \pi(x)) - \bar{\phi}_a(t)$$

curvature perturbations

$$\zeta = H\pi$$



gauge theory

spontaneous breaking of a non-Abelian symmetry

$$G \longrightarrow H$$

Goldstone bosons

$$U = e^{i\,\pi(x)/f_\pi}$$

generators of G/H

The low-energy expansion of

$$U \equiv t + \pi(x)$$

$$t \to t + \xi_0(x)$$
$$\pi \to \pi - \xi_0(x)$$

is the *effective theory of inflation*:

$$\mathcal{L}_{\rm eff} \; = \; f(U, (\partial U)^2, \Box U, \cdots)$$

Slow-Roll Inflation

$$\mathcal{L} = M_{\rm pl}^2 \dot{H} (\partial_\mu U)^2 - M_{\rm pl}^2 (3H^2 + \dot{H})$$

coefficients fixed uniquely by the background

$$H(U)$$

no tadpoles!

Slow-Roll Inflation

$$\mathcal{L} = M_{\rm pl}^2 \dot{H} (\partial_\mu U)^2 - M_{\rm pl}^2 (3H^2 + \dot{H})$$

$$\uparrow \qquad\qquad\qquad\qquad \uparrow$$

$$-\frac{1}{2}(\partial_\mu \phi)^2 \qquad\qquad\qquad\qquad V(\phi)$$

just slow-roll inflation in disguise!

Slow-Roll Inflation

$$\mathcal{L} = M_{\rm pl}^2 \dot{H} (\partial_\mu U)^2 - M_{\rm pl}^2 (3H^2 + \dot{H})$$

↑

$$g^{\mu\nu} \partial_\mu (t+\pi) \partial_\nu (t+\pi)$$

decoupling

$g^{\mu\nu} \rightarrow \bar{g}^{\mu\nu}$

↓

$$(\partial_\mu U)^2 = -1 - 2\dot{\pi} + (\partial_\mu \pi)^2$$

$$\mathcal{L}_{\rm s.r.} = M_{\rm pl}^2 \dot{H} (\partial_\mu \pi)^2$$

massless

Gaussian

Small Sound Speed

$$M_{\rm pl}^2 \dot{H} (\partial_\mu \pi)^2 \quad + \quad \frac{1}{2} M_2^4 \left[(\partial_\mu U)^2 + 1 \right]^2$$

no tadpoles!

decoupling

$$(\partial_\mu U)^2 = -1 - 2\dot{\pi} + (\partial_\mu \pi)^2$$

$$2M_2^4 \left(\dot{\pi}^2 - \dot{\pi}(\partial_\mu \pi)^2 + \cdots \right)$$

modifies kinetic term but ***not*** gradient term:

$$-(M_{\rm pl}^2 \dot{H} - 2M_2^4)\dot{\pi}^2 + M_{\rm pl}^2 \dot{H} (\partial_i \pi)^2$$

i.e. induces a ***sound speed***

$$\frac{1}{c_s^2} \equiv 1 - \frac{2M_2^4}{M_{\rm pl}^2 \dot{H}}$$

Small Sound Speed

$$M_{\rm pl}^2 \dot{H} (\partial_\mu \pi)^2 \quad + \quad \frac{1}{2} M_2^4 \left[(\partial_\mu U)^2 + 1 \right]^2$$

no tadpoles!

decoupling

$$(\partial_\mu U)^2 = -1 - 2\dot{\pi} + (\partial_\mu \pi)^2$$

$$2 M_2^4 \left(\dot{\pi}^2 - \dot{\pi} (\partial_\mu \pi)^2 + \cdots \right)$$

non-linearly realized symmetry

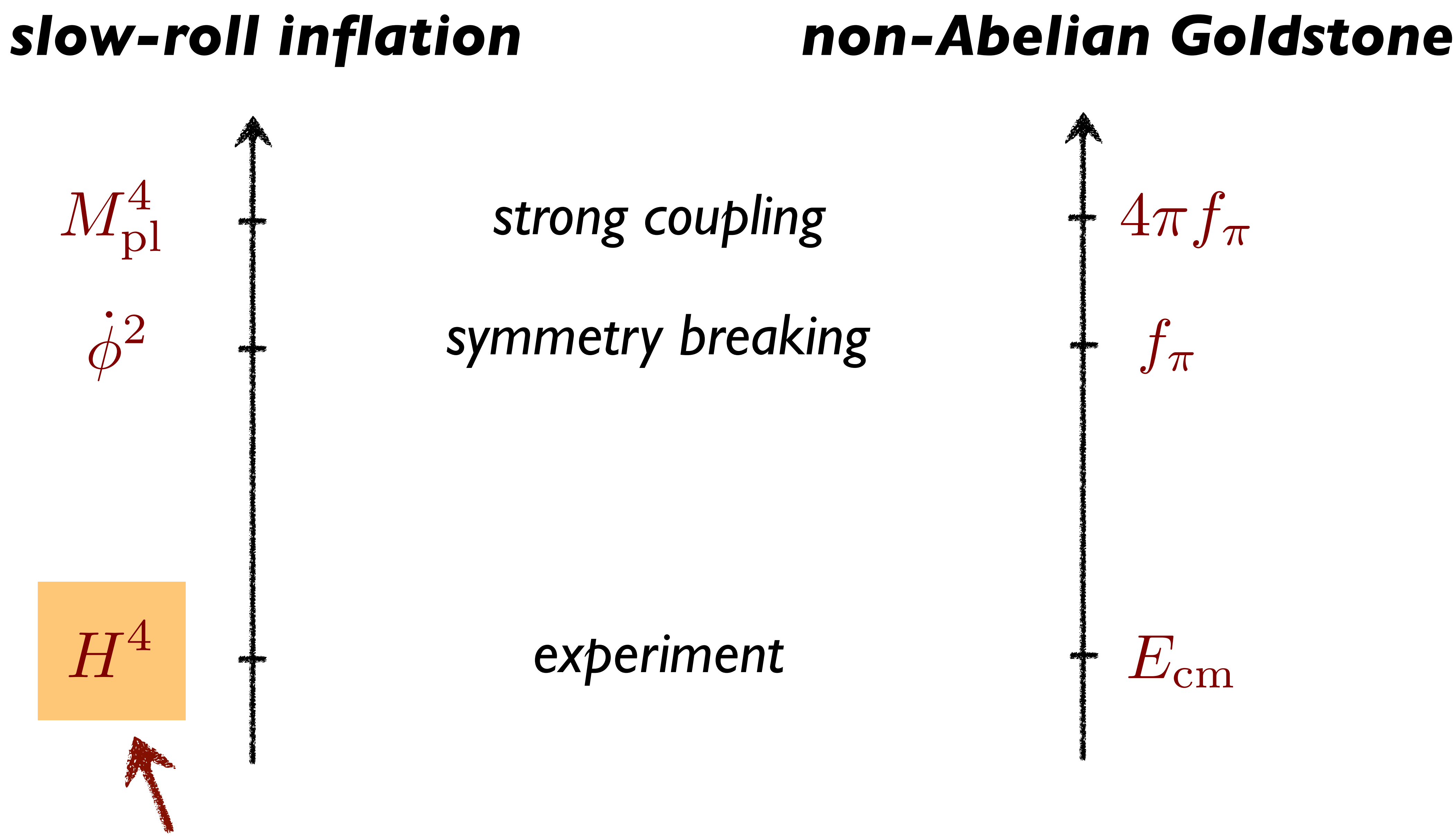
relates ***small sound speed*** to ***large interactions***

Cheung et al.

Energy Scales

with Daniel Green

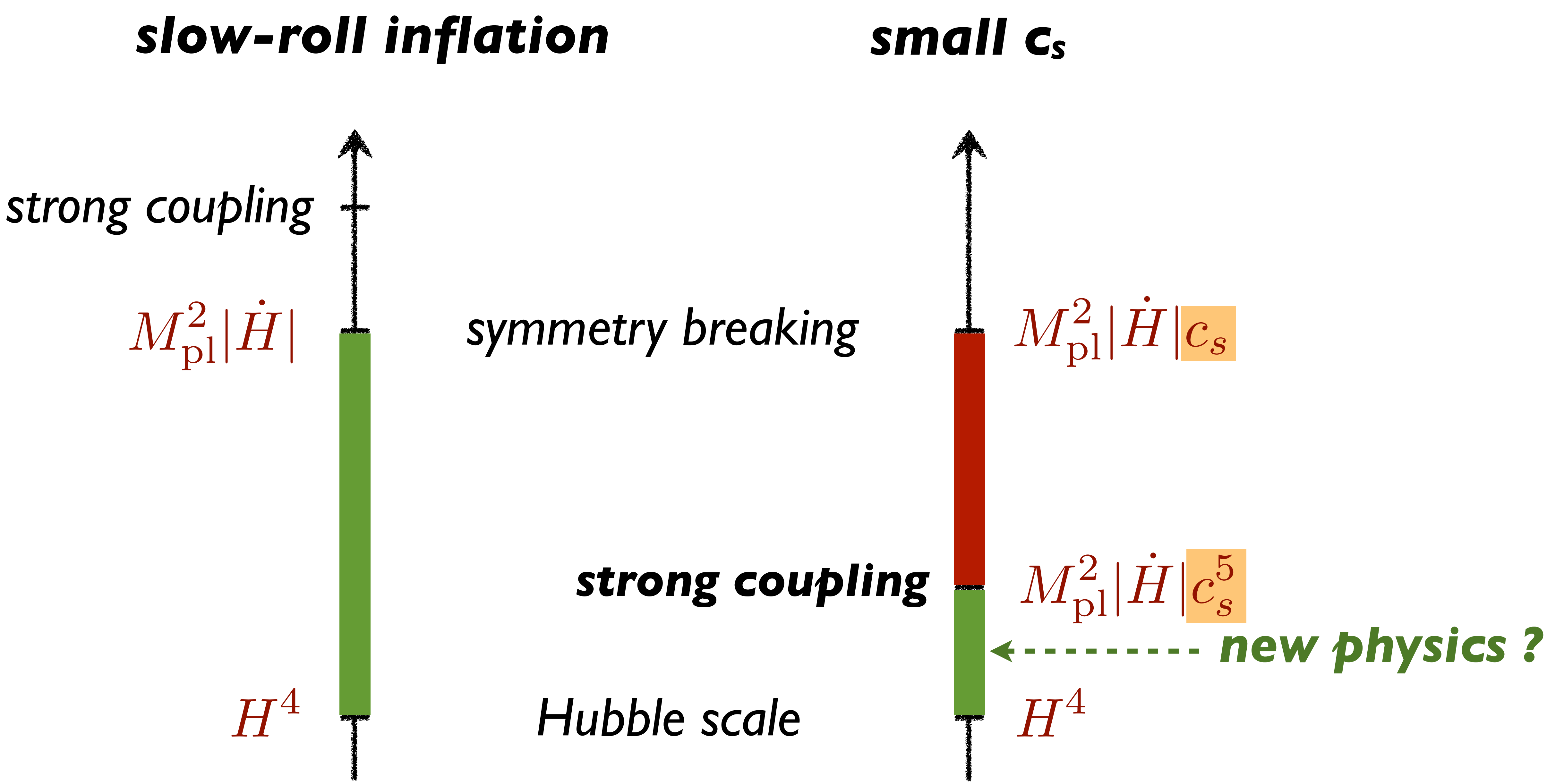
Energy Scales



freeze-out at Hubble is universal

other scales are model-dependent

Energy Scales



Symmetry Breaking Scale

Spontaneously broken global symmetry: $\cancel{Q} = \int d^3x\, j^0$ *does not exist at low-E*

$$j^\mu = \underbrace{f_\pi \partial^\mu \pi}_{\text{low-E}} + \overbrace{\cdots}^{\text{high-E}} \xrightarrow{x \to \infty} j^0 = f_\pi x^{-2} + \cdots$$

Natural definition of the ***symmetry breaking scale***:

$$\Lambda_b = f_\pi$$

Symmetry Breaking Scale

Current of time translations:

$$j^\mu = T^{0\mu}$$

Symmetry breaking:

~~Q~~ $= \int d^3x\, T^{00}$ doesn't exist.

EFT of Inflation:

$$T^{00} = \frac{M_{\rm pl}^2 \dot{H}}{c_s^2}\dot{\pi} + \cdots$$

$M_{\rm pl}^2 \dot{H} c_s^{-2}$ controls breaking.

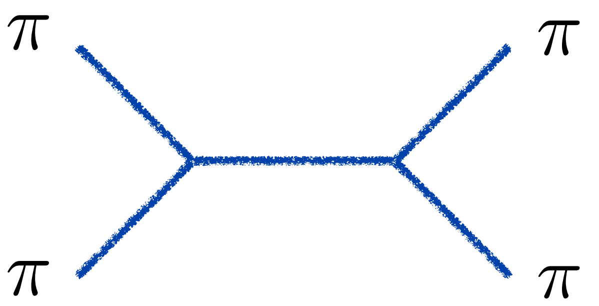
But this is an energy *density* not an energy^4.

Use dispersion relation: $\omega = c_s k$

$$\Lambda_b^4 = M_{\rm pl}^2 |\dot{H}| c_s$$

Strong Coupling Scale

$$\mathcal{L} = \dot{\pi}_c^2 - c_s^2(\partial_i \pi_c)^2 + \frac{1}{M_\star^2}\dot{\pi}_c(\partial_i \pi_c)^2$$



$M_\star^4 = M_{\rm pl}^2 |\dot{H}| c_s^{-2}$ determines strong coupling.

This is *not* an energy^4.

Use dispersion relation:

$$\omega = c_s k$$

$$\Lambda_\star^4 = M_\star^4 \times c_s^7$$

$$\Lambda_\star^4 = M_{\rm pl}^2 |\dot{H}| c_s^5$$

Small Sound Speed

Hierarchies are (or will be) fixed by observations:

Energy^4

$$\Lambda_b^4 = M_{\rm pl}^2 |\dot H| c_s$$

background

$$f_{\rm NL}^2 \sim \frac{1}{c_s^4}$$

$$P_\zeta^{-1}$$

$$\Lambda_\star^4 = M_{\rm pl}^2 |\dot H| c_s^5$$

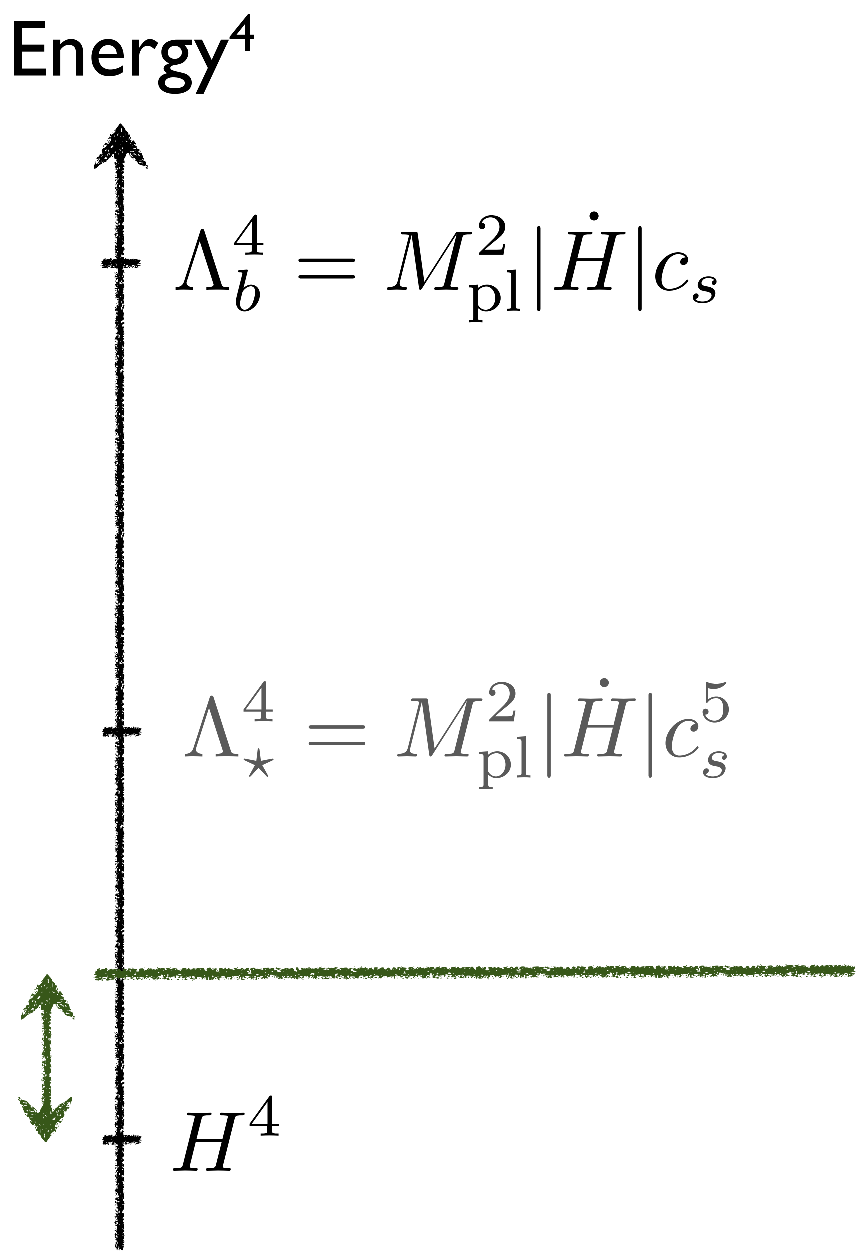
strong coupling

$$\frac{\Lambda_\star}{H} \sim 5 \quad \textit{for} \quad f_{\rm NL} \sim 100$$

$$H^4$$

Small Sound Speed

New Physics near Hubble ?



background

strong coupling

New Physics ??

- should enter ***below*** $\Lambda_\star$
- ***not decoupled*** from experiments at H ?

$E \sim H$

New Physics on the Horizon

Planck

with Daniel Green

Weakly Coupled UV-Completion

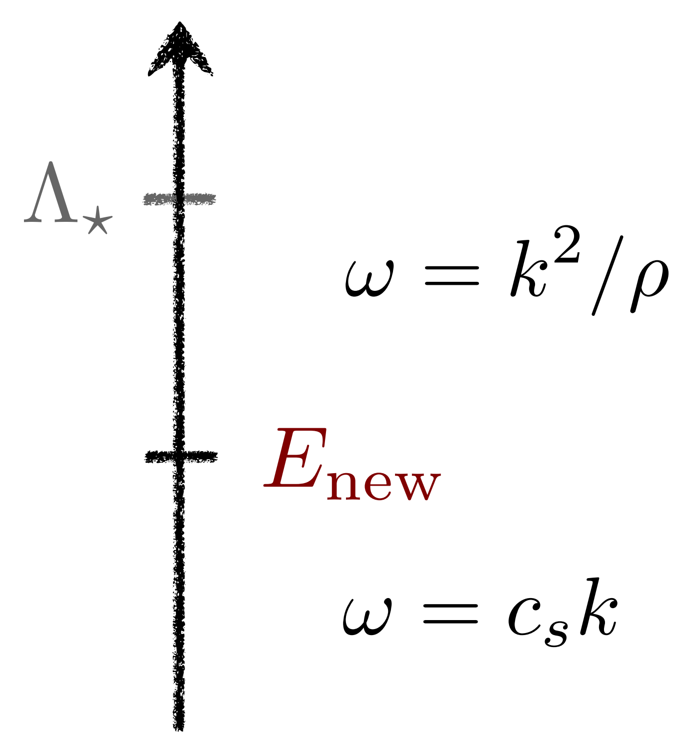
Recall:

$$\Lambda_\star^4 = M_{\rm pl}^2 |\dot{H}| c_s^{-2} \times c_s^7$$

dispersion relation

What 'new physics' can keep the theory weakly coupled ?

Change the dispersion relation!



Weakly Coupled UV-Completion

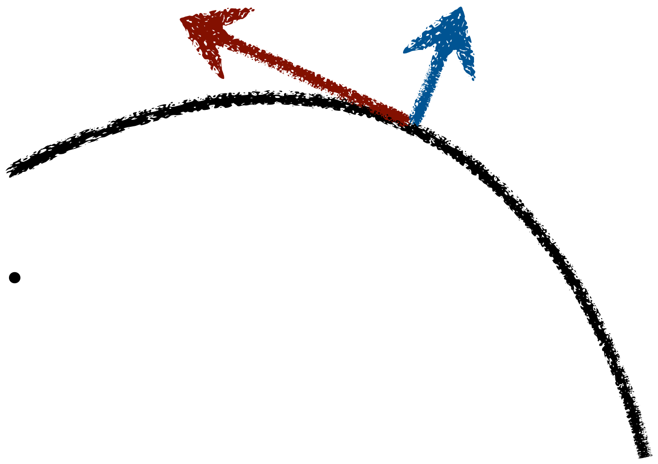
1. *Consider two decoupled free fields.*

$$-(\partial_\mu \pi_c)^2 - (\partial_\mu \sigma)^2$$

Weakly Coupled UV-Completion

1. *Consider two decoupled free fields.*
2. *Perturb by a relevant "mixing operator".*

$$-(\partial_\mu \pi_c)^2 - (\partial_\mu \sigma)^2 \; + \rho \, \dot{\pi}_c \, \sigma$$



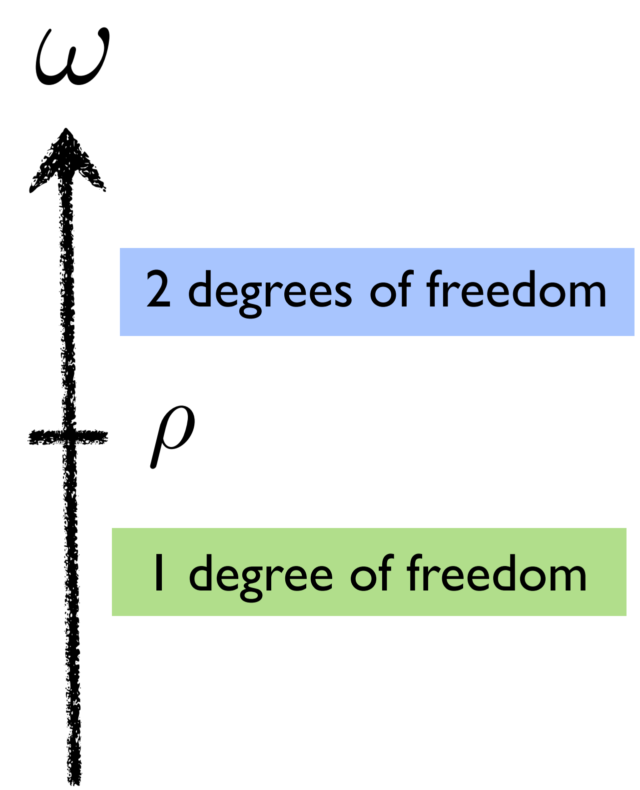
e.g. gelaton, curved trajectories, ...

Tolley and Wyman, Cremonini et al.,
Achucarro et al., Chen and Wang, ...

Weakly Coupled UV-Completion

1. *Consider two decoupled free fields.*
2. *Perturb by a relevant "mixing operator".*

$$-(\partial_\mu \pi_c)^2 - (\partial_\mu \sigma)^2 \ + \rho\, \dot{\pi}_c\, \sigma$$



for $\omega > \rho$: the mixing is a small perturbation

for $\omega < \rho$: the mixing dominates the dynamics

↓

non-relativistic theory
with non-linear dispersion: $\omega = \dfrac{k^2}{\rho}$

Weakly Coupled UV-Completion

1. *Consider two decoupled free fields.*
2. *Perturb by a relevant "mixing operator".*
3. *Add a small mass term:* $\mu \ll \rho$

$$-(\partial_\mu \pi_c)^2 - (\partial_\mu \sigma)^2 + \rho \, \dot{\pi}_c \, \sigma - \mu^2 \sigma^2$$

for $\omega < E_{\rm new} \equiv \dfrac{\mu^2}{\rho}$: the mass term dominates over gradients

$$\rightarrow \quad \sigma \sim \frac{\rho}{\mu^2} \dot{\pi}_c \quad \rightarrow \quad \mathcal{L}_{\rm eff} \sim \left(1 + \frac{\rho^2}{\mu^2}\right) \dot{\pi}_c^2 - (\partial_i \pi_c)^2$$

$$\nwarrow \frac{1}{c_s^2}$$

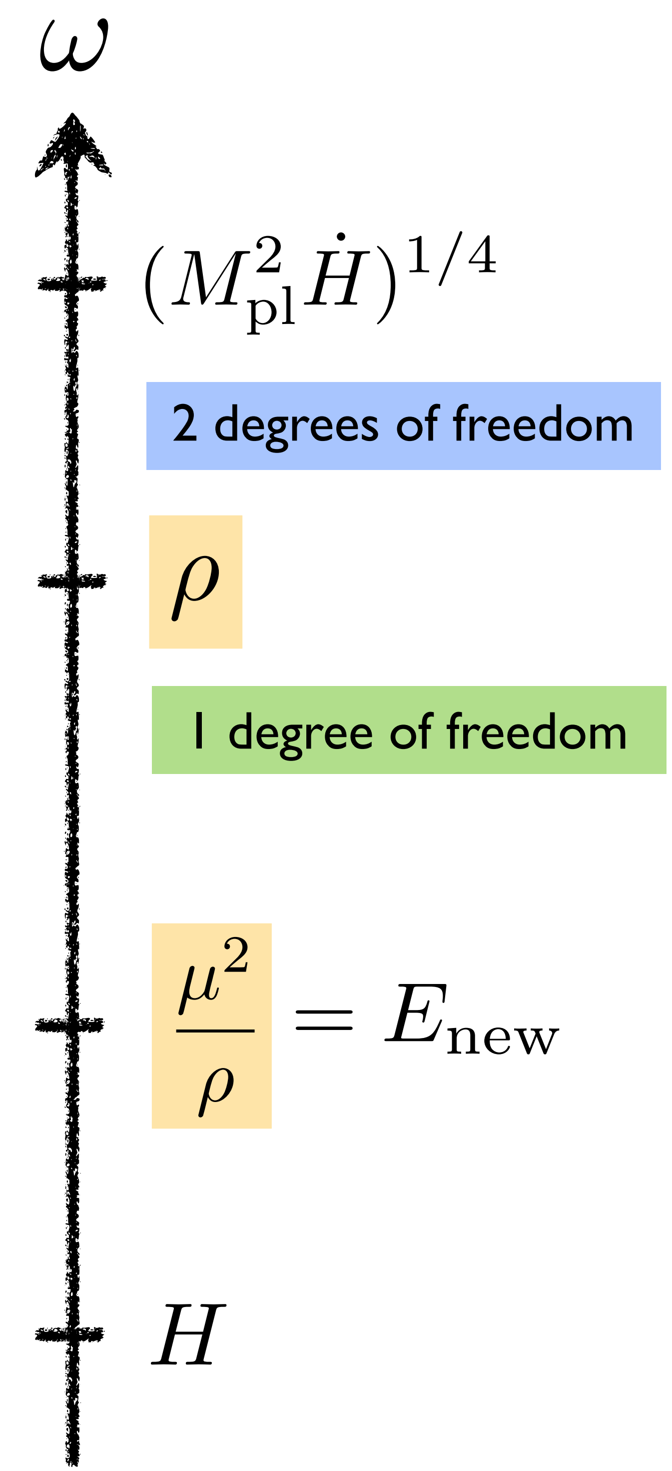
Weakly Coupled UV-Completion

$$\mathcal{L}_2 = \dot{\pi}_c^2 - (\partial_i \pi_c)^2 + \dot{\sigma}^2 - (\partial_i \sigma)^2 + \rho\, \dot{\pi}_c \sigma - \mu^2 \sigma^2$$

modified dispersion $\longleftrightarrow$ $\omega \propto k^2$

small sound speed $\longleftrightarrow$ $\omega = c_s k$

$$c_s \simeq \frac{\mu}{\rho} \ll 1$$



Weakly Coupled Effective Theory

mixing operator

$$\rho\,\dot{\pi}_c\sigma \quad \longleftrightarrow \quad m^3\left[(\partial_\mu U)^2+1\right]\sigma$$

$$= -2m^3\left[\dot{\pi}-\tfrac{1}{2}(\partial_\mu\pi)^2\right]\sigma$$

"integrating out" σ

↘

non-local action for π

$$\mathcal{L}_{\rm eff} \,=\, M_{\rm pl}^2\dot{H}(\partial_\mu\pi)^2+\left[\dot{\pi}-\frac{1}{2}(\partial_\mu\pi)^2\right]\frac{m^6}{\Box+\mu^2}\left[\dot{\pi}-\frac{1}{2}(\partial_\mu\pi)^2\right]$$

Use this action to compute observables at freeze-out $\omega = H$

Distinguishing Models

Two types of models:

Strongly Coupled e.g. DBI inflation / P(X) models

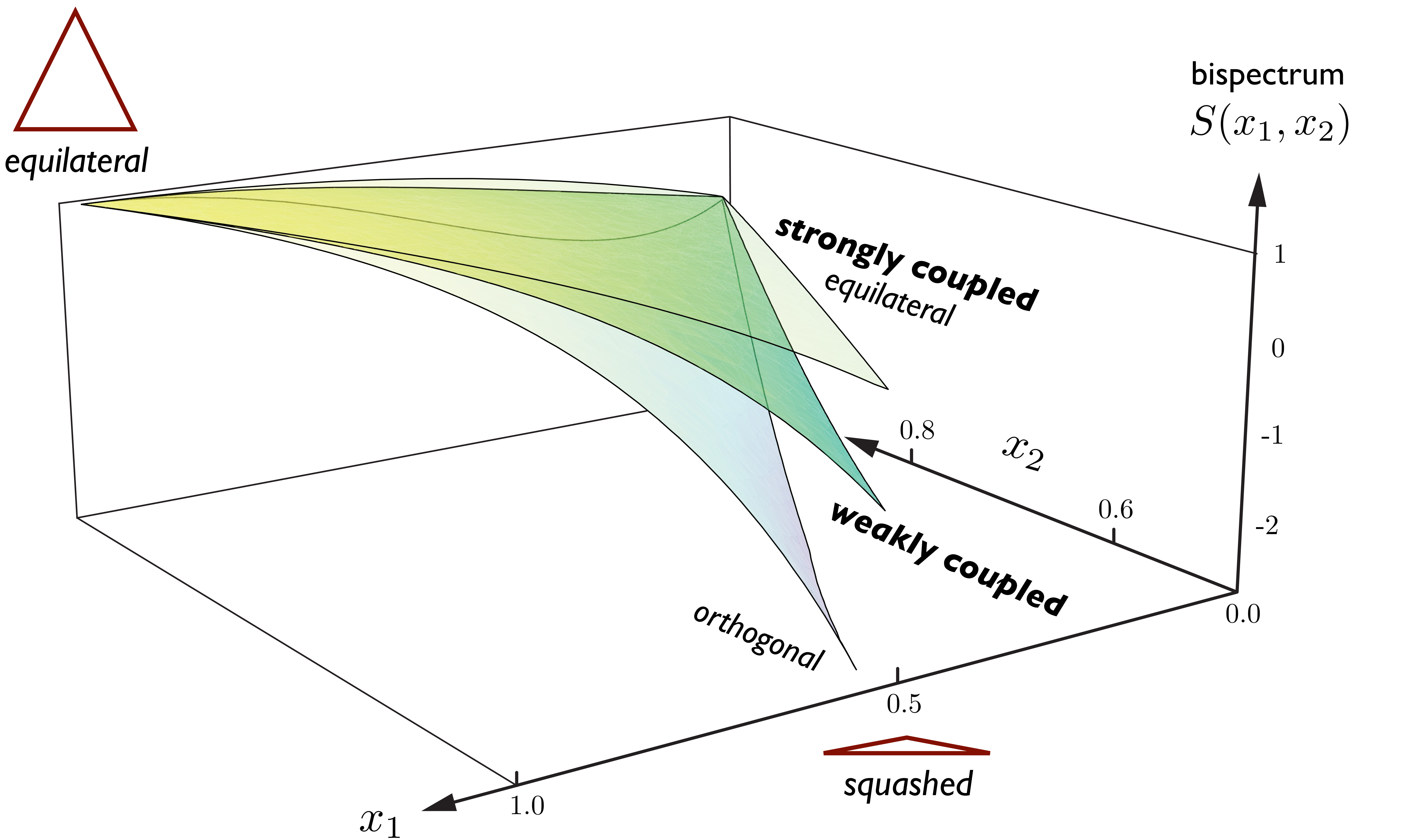
- weakly coupled at freeze-out
- background requires UV-completion

Weakly Coupled e.g. change in dispersion

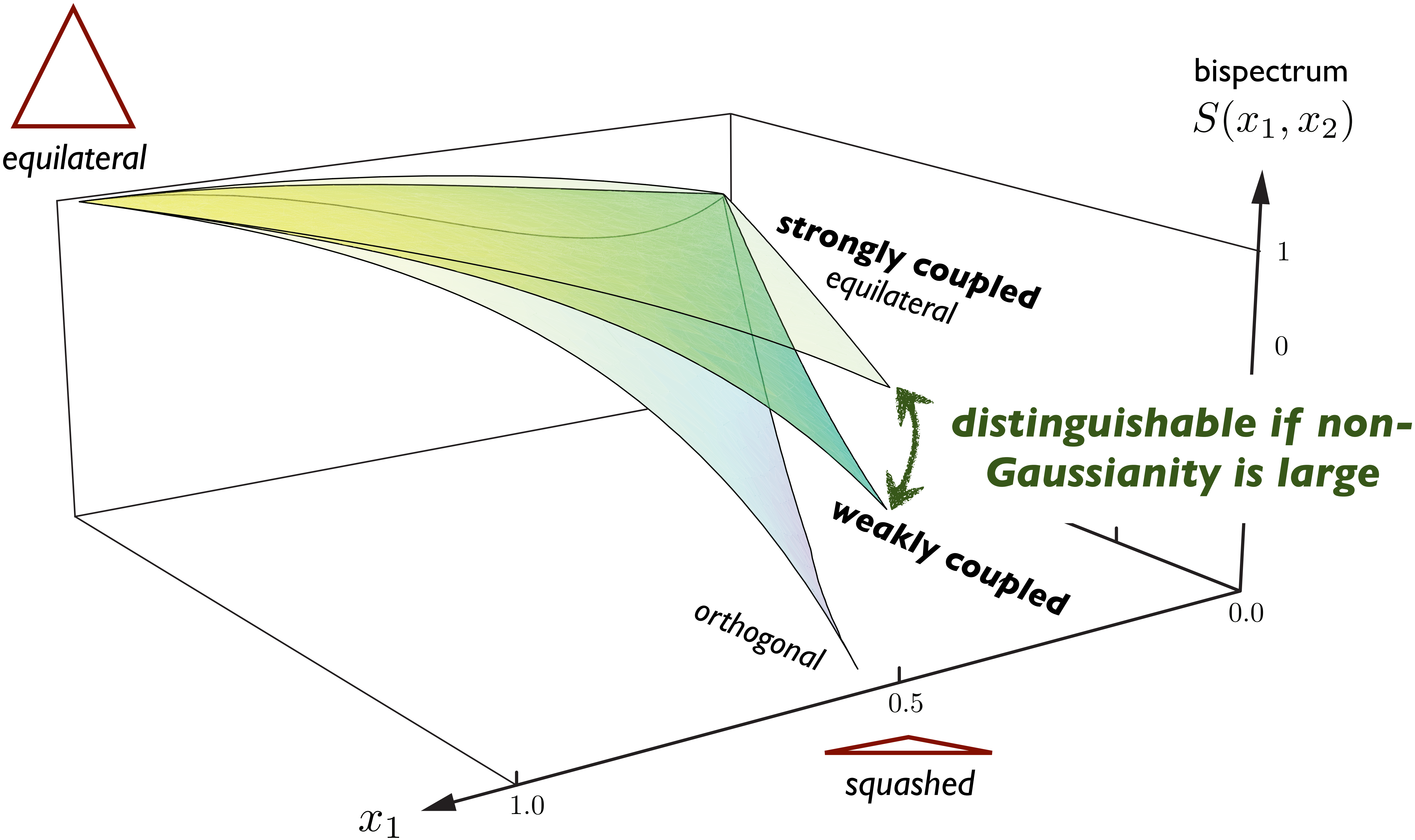
- can arise in controlled effective theory
- requires full model to compute 3-point function

Try to distinguish by correction to 3-point function

Observational Signatures



Observational Signatures



Naturalness

with Daniel Green

(work in progress)

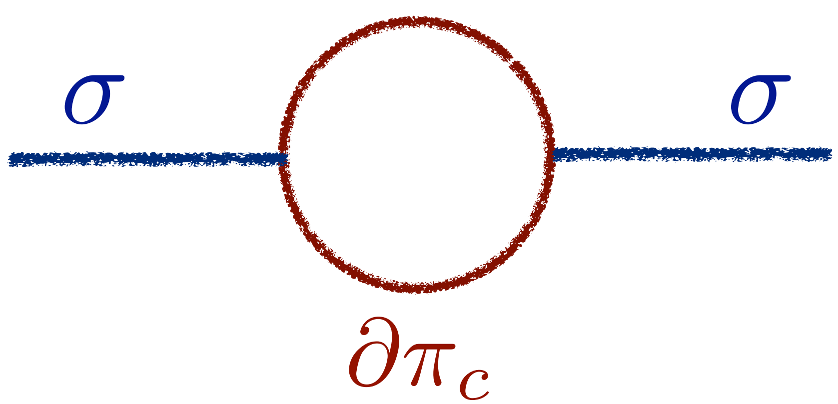
Is $c_s \simeq \dfrac{\mu}{\rho} \ll 1$ natural ?

No!

$$\mathcal{L} \subset \rho \left(\dot{\pi}_c + \frac{(\partial_\mu \pi_c)^2}{(M_{\rm pl}^2 \dot{H})^{1/2}} \right) \sigma - \mu^2 \sigma^2$$

loop correction

$$\delta\mu^2 =$$



$$= \frac{\rho^2}{M_{\rm pl}^2 \dot{H}} \Lambda_{\rm uv}^4 = \rho^2$$

$$\Lambda_{\rm uv}^4 = M_{\rm pl}^2 \dot{H}$$

natural sound speed

$$\delta c_s \sim 1$$

Supersymmetry

see Daniel Green's talk

Consider a chiral superfield

$$\Phi \;=\; \sigma + i(M_{\rm pl}^2 \dot{H})^{1/2}(t+\pi) + \cdots$$

with Lagrangian

$$\mathcal{L} \;=\; \int d^4\theta \left[(\Phi + \Phi^\dagger)^2 + \frac{1}{\Lambda}(\Phi+\Phi^\dagger)^3 + \cdots\right]$$

$$\rho \left[(\partial_t t)\dot{\pi}_c + \frac{(\partial_\mu \pi_c)^2}{(M_{\rm pl}^2 \dot{H})^{1/2}}\right]\sigma \quad + \quad \textit{fermions}$$

$$\rho = \frac{(M_{\rm pl}^2 \dot{H})^{1/2}}{\Lambda}$$

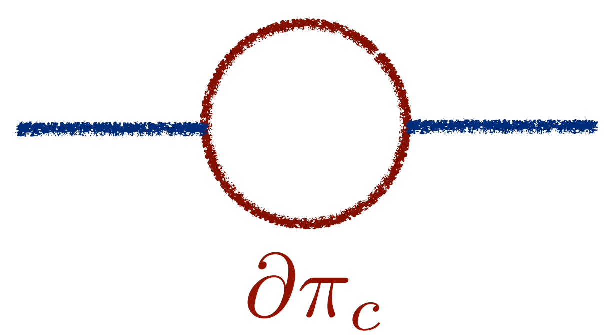
Supersymmetry

see Daniel Green's talk

$$\rho \left[(\partial_t t)\dot{\pi}_c + \frac{(\partial_\mu \pi_c)^2}{(M_{\rm pl}^2 \dot{H})^{1/2}} \right] \sigma \quad + \quad \textit{fermions}$$

breaks SUSY @ ρ

doesn't break SUSY



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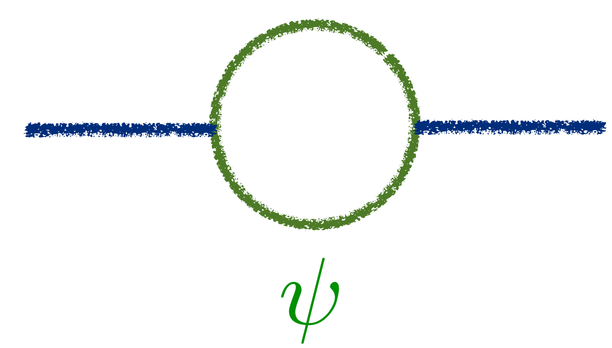
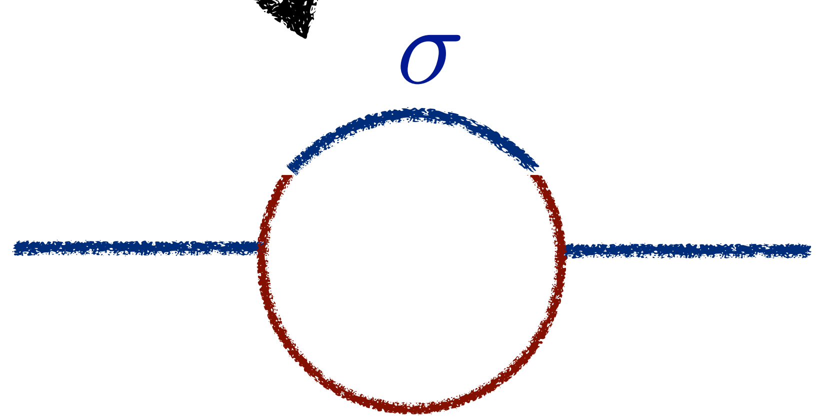


$= \; 0$

$$\delta\mu^2 \; =$$



$$= \; \frac{\rho^4}{M_{\rm pl}^2 \dot{H}} \Lambda_{\rm uv}^2 \; = \; \frac{\rho^2}{(M_{\rm pl}^2 \dot{H})^{1/2}} \rho^2$$

Supersymmetry

see Daniel Green's talk

without SUSY

$$\delta\mu^2 = \rho^2$$

$$c_s^2 \sim 1$$

with SUSY

$$\delta\mu^2 = \frac{\rho^2}{(M_{\rm pl}^2 \dot{H})^{1/2}}\, \rho^2 \ll \rho^2$$

$$c_s^2 = \frac{\rho^2}{(M_{\rm pl}^2 \dot{H})^{1/2}} \ll 1$$

Small sound speed is unnatural without SUSY, but becomes natural with SUSY !

Even if SUSY isn't discovered at the TeV scale, naturalness motivates SUSY in inflation.

for a systematic treatment
see Daniel Green's talk :

Signatures of Supersymmetry from the Early Universe


THANK YOU !