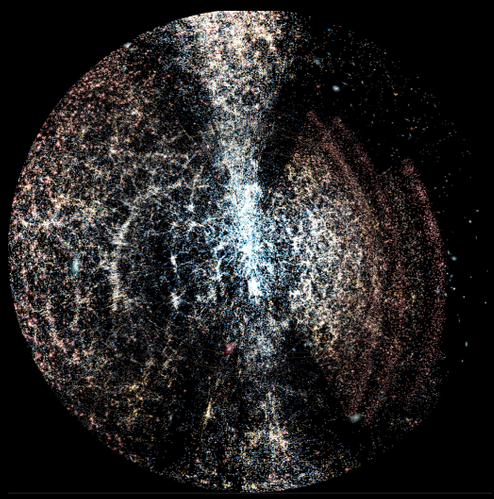
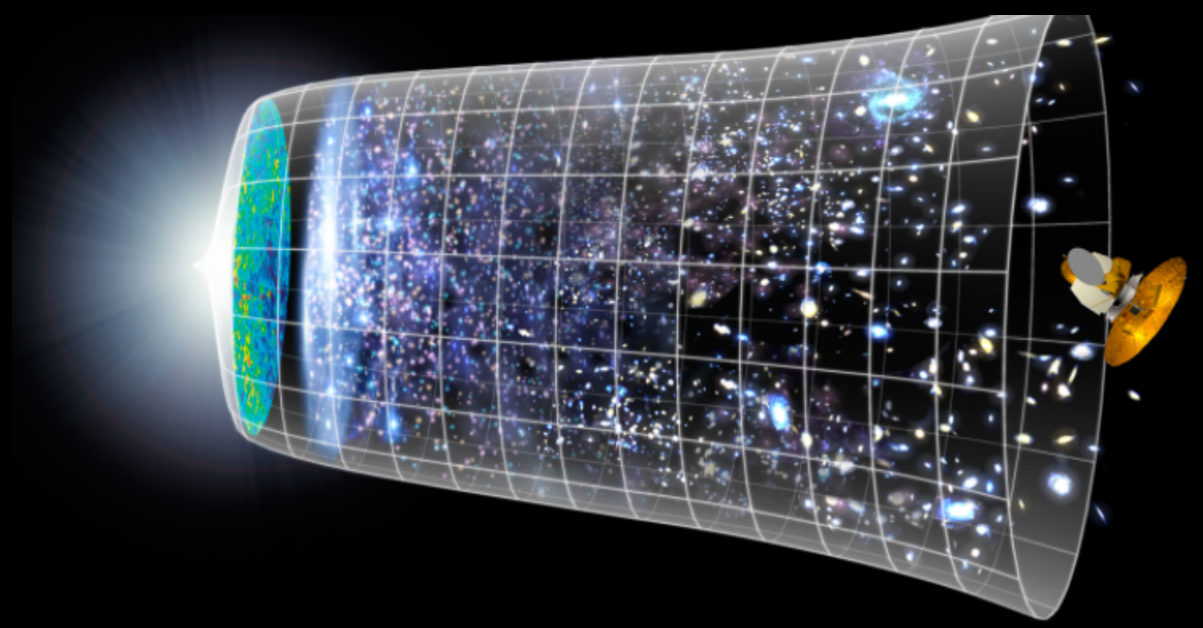
Signals of a Quantum Universe

Rafael A. Porto



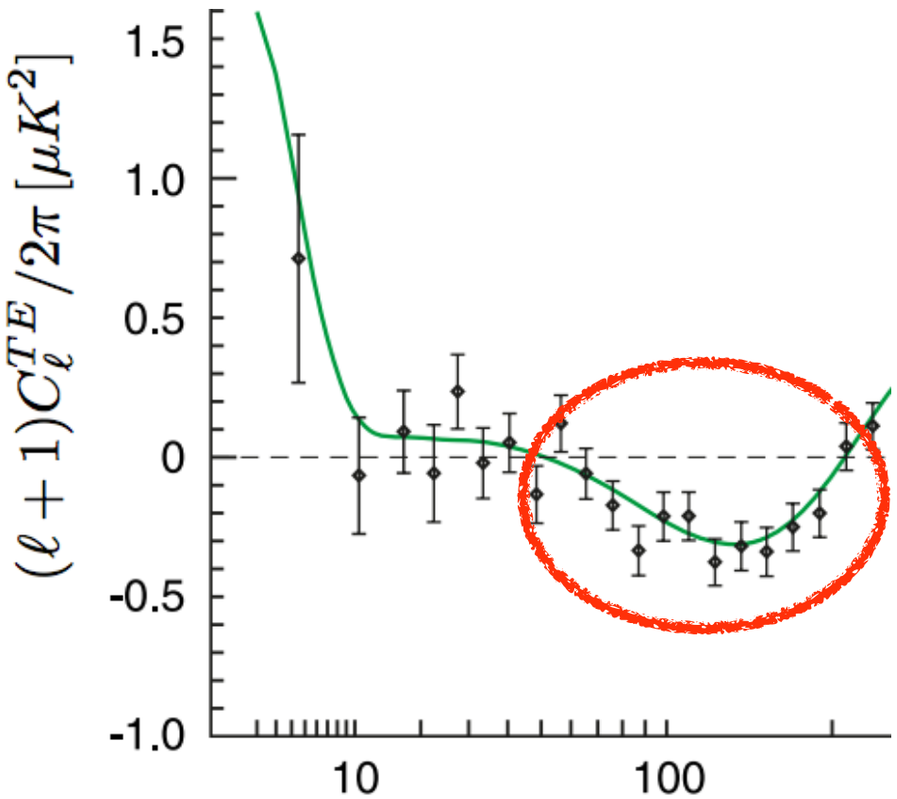
Where the %$@42& did it all come from?*

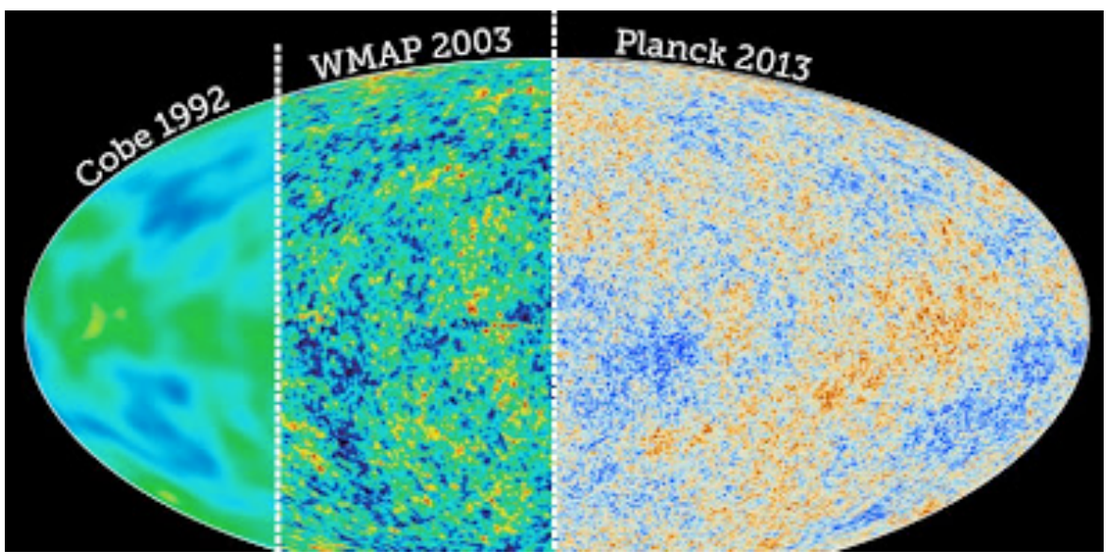
"The quantum jumps replace the initial conditions of the old mechanistic view"



Main actor (so far): The CMB
Fossil from an epoch when the the cosmos was young and hot (unlike today)

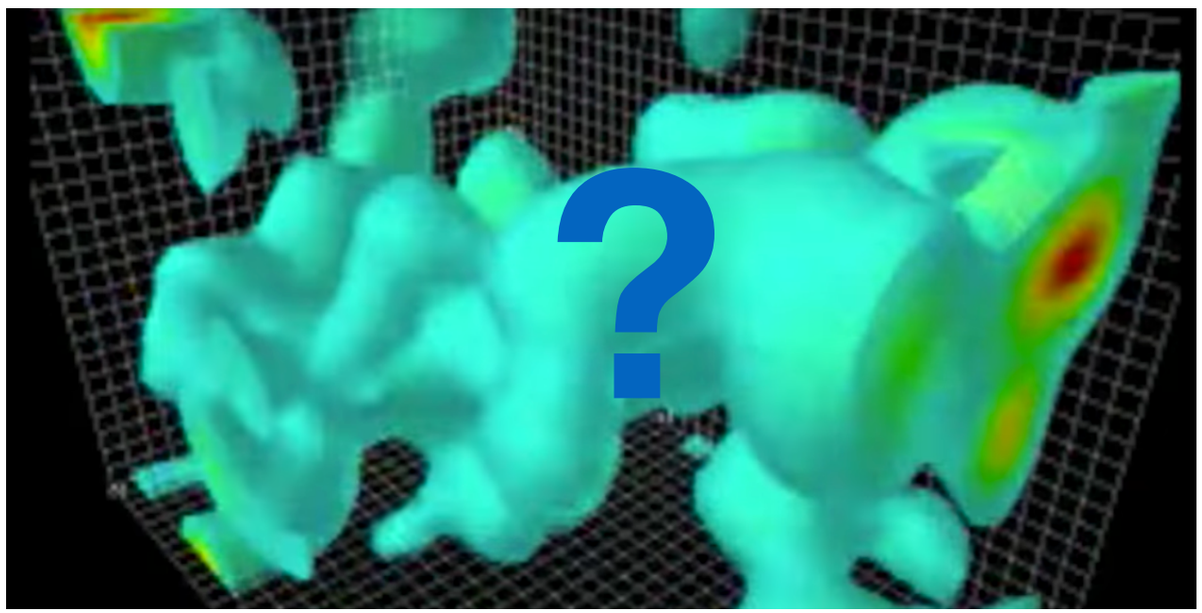
Coherent phases and (large-angle) cross-correlations suggest a primordial nature

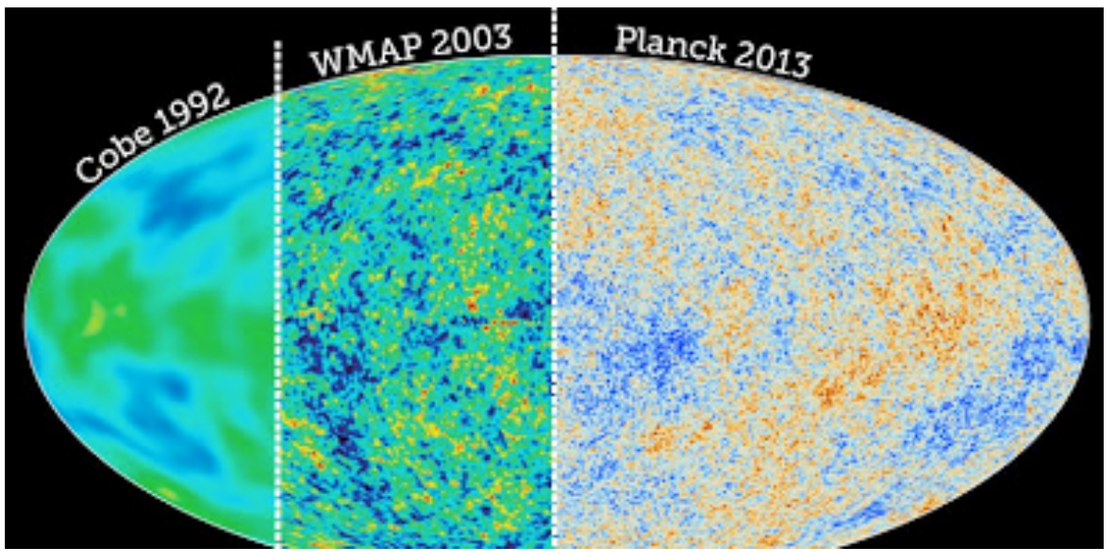




Main actor (so far): The CMB
Fossil from an epoch when the
the cosmos was young and hot
(unlike today)

Origin: Quantum
vacuum fluctuations
during an earlier
('dark-energy') phase?





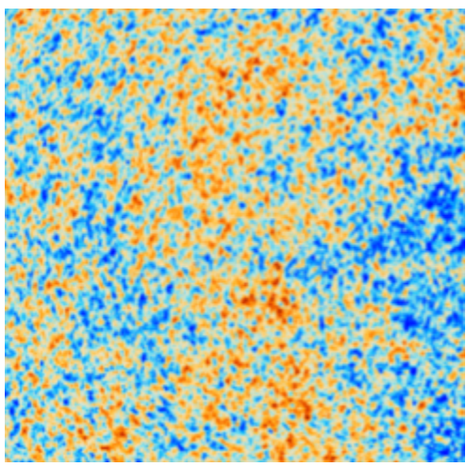
IR clues to a UV puzzle

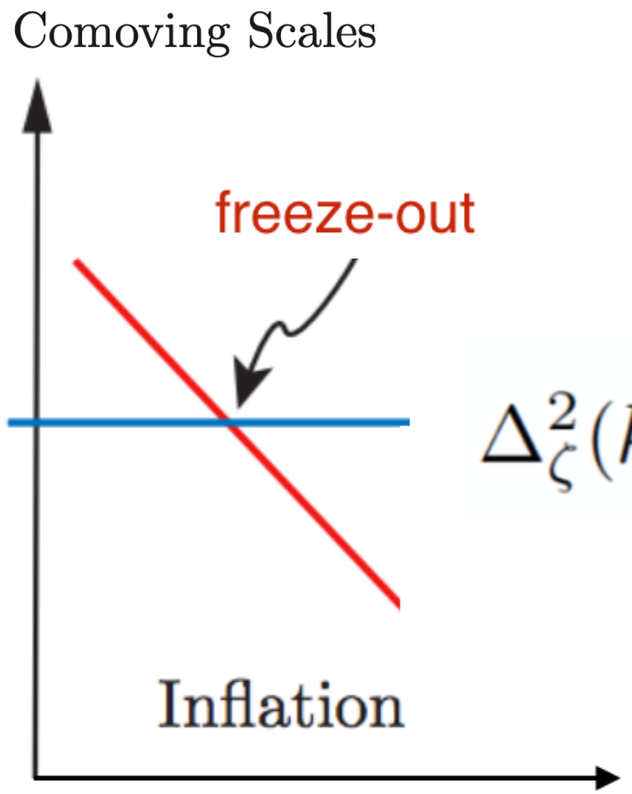
The very-early universe resembles a ‘fixed-energy’ experiment

UV origin

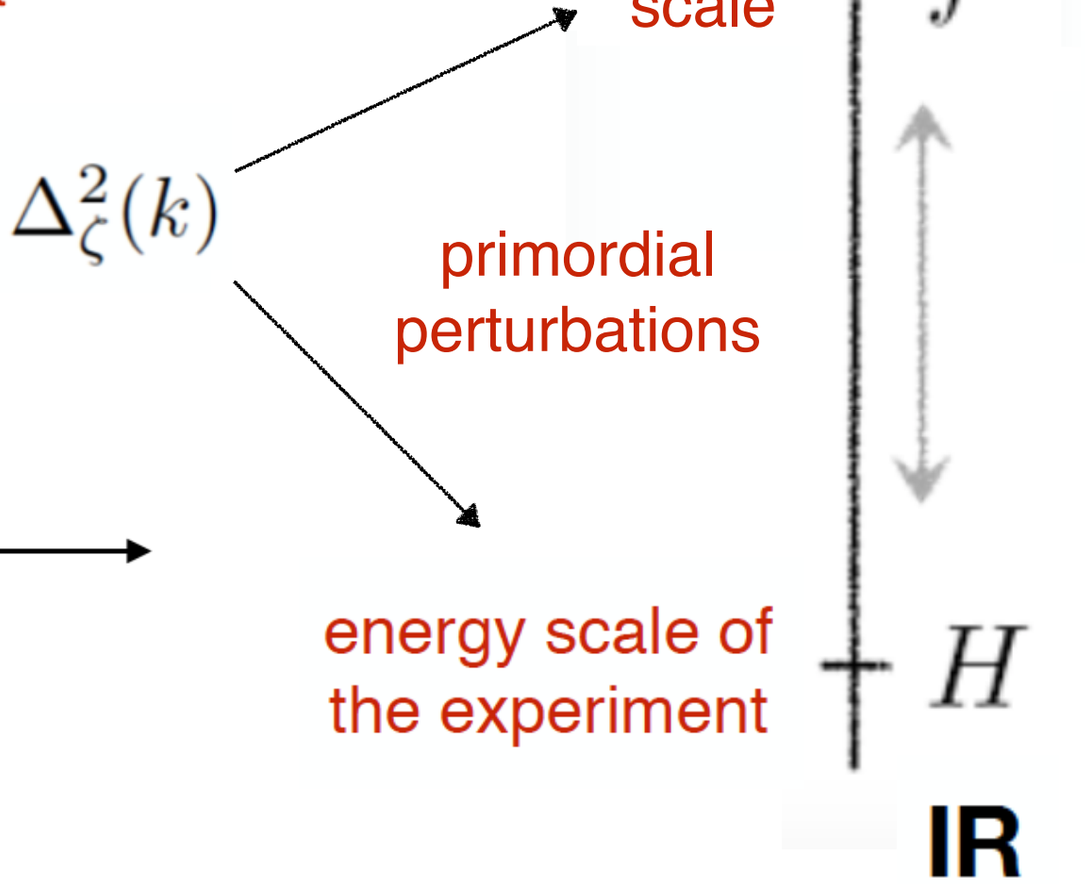
?

Observations



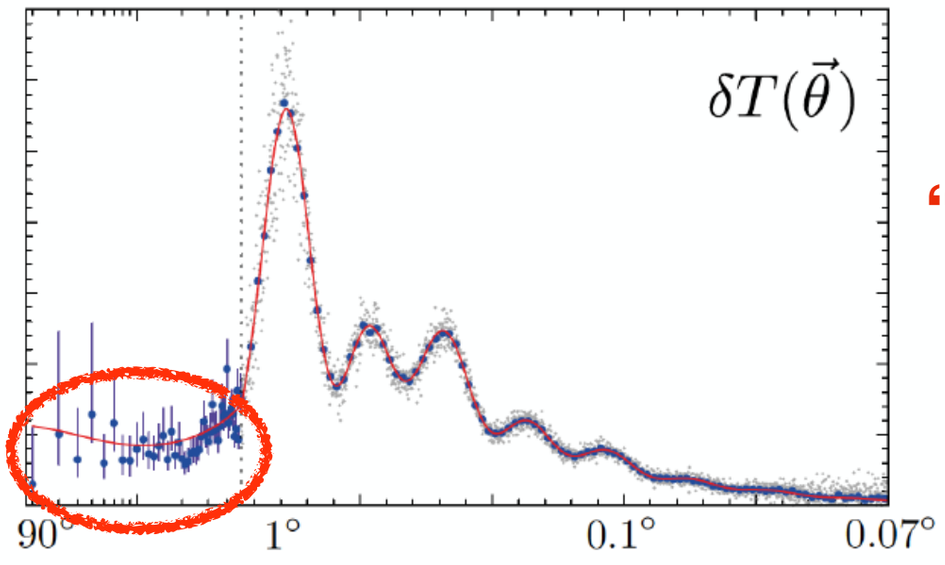


$\Delta^2_\zeta(k)$

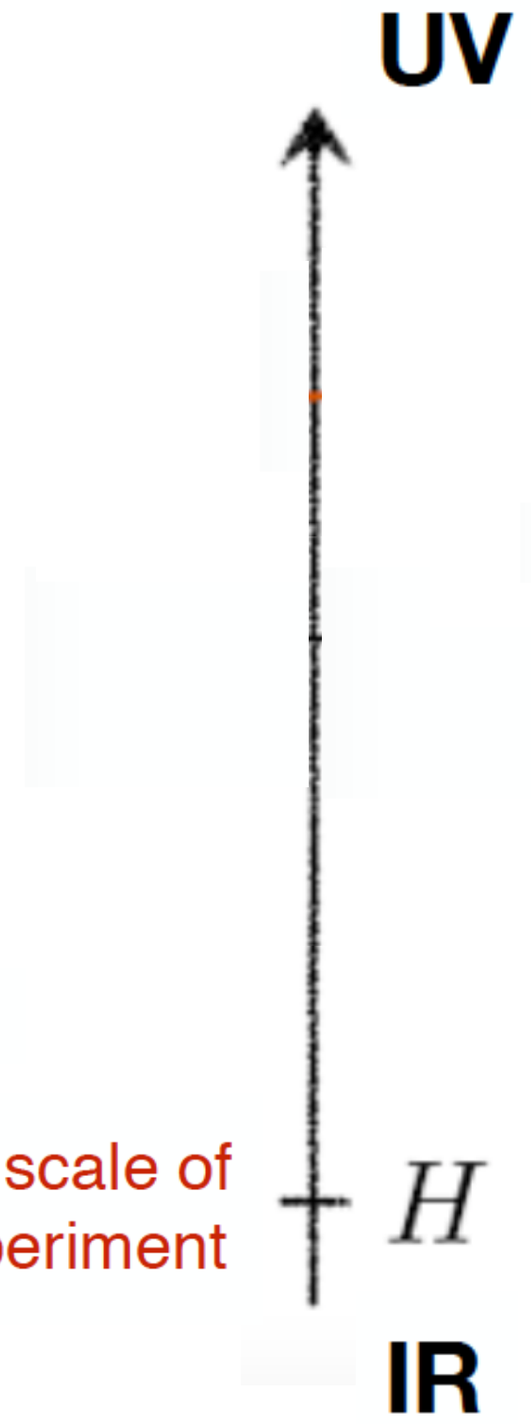


What have we learned about the relevant scales from the CMB

$$\Delta^2_\zeta(k) \;=\; A_{\rm s}\left(\frac{k}{k_\star}\right)^{n_{\rm s}-1}$$



“De Sitter like”



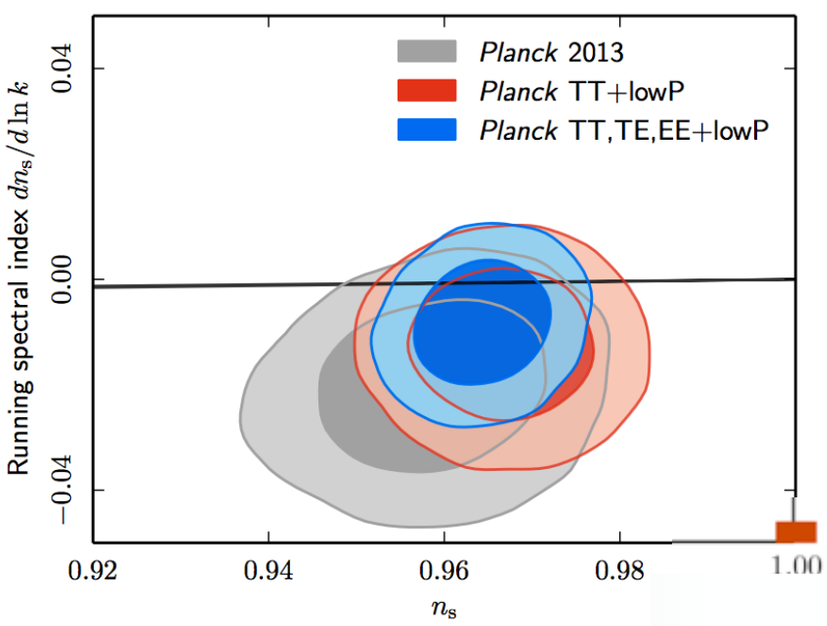
What have we learned about the relevant scales from the CMB

$$\Delta^2_\zeta(k) = A_{\rm s}\left(\frac{k}{k_\star}\right)^{n_{\rm s}-1}$$

$n_{\rm s} = 0.968 \pm 0.006$

Planck [2015]

Energy scale not fixed



“De Sitter like”

scale invariant

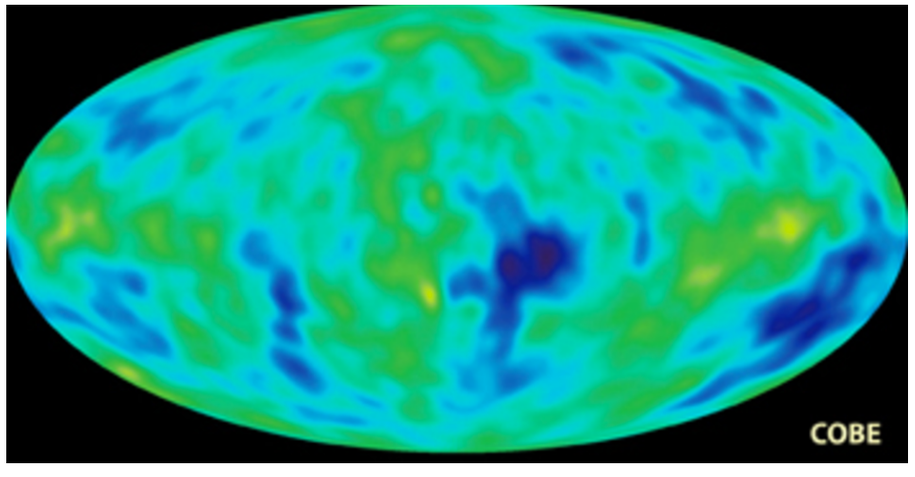
Inflation must end dynamically!

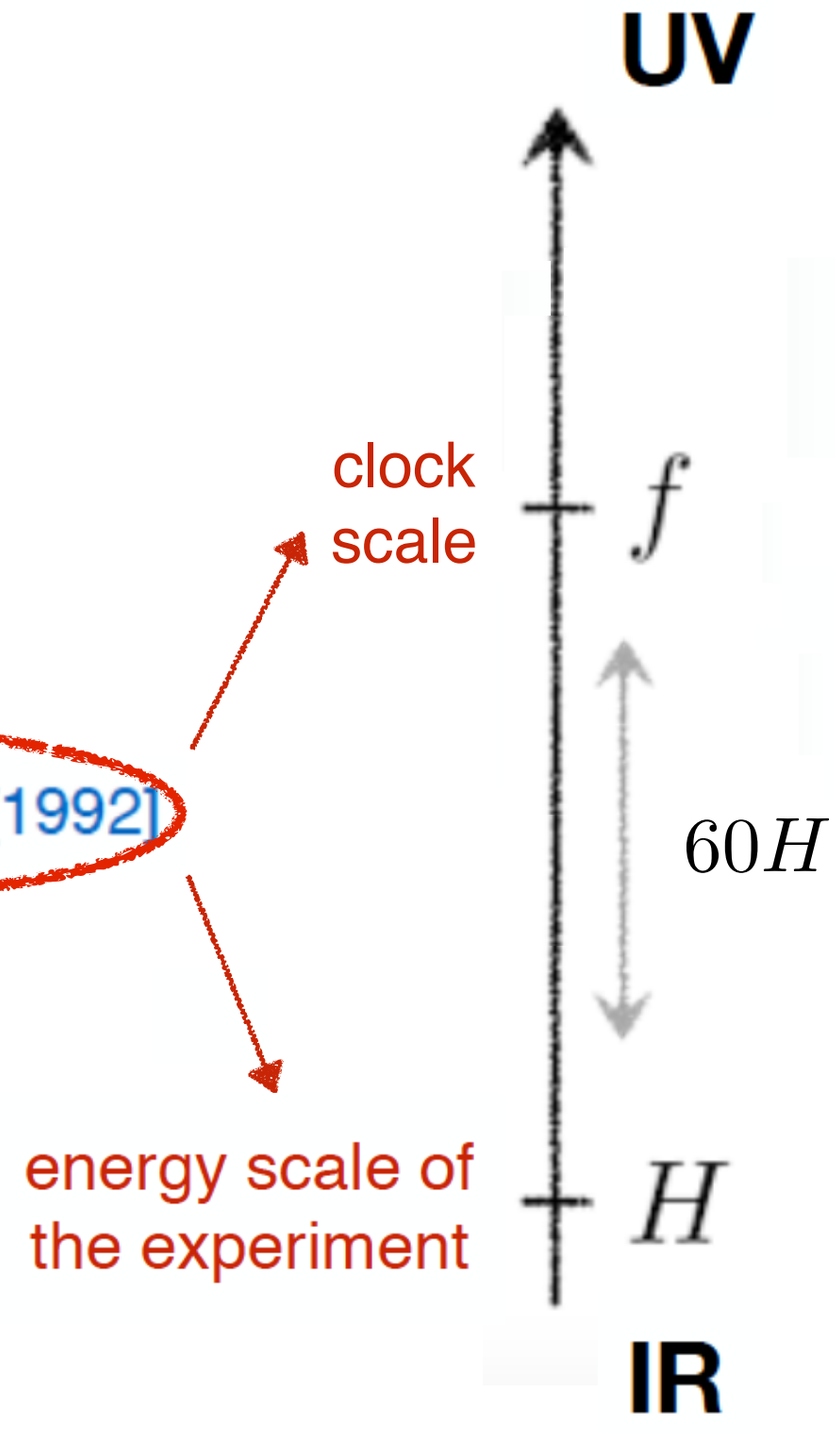
$$|\dot{H}/H^2| \ll 1$$

What have we learned about the relevant scales from the CMB

$$\Delta^2_\zeta(k) \;=\; A_{\rm s}\left(\frac{k}{k_\star}\right)^{n_{\rm s}-1}$$

$A_{\rm s} = 2.2\times 10^{-9}$ COBE [1992]

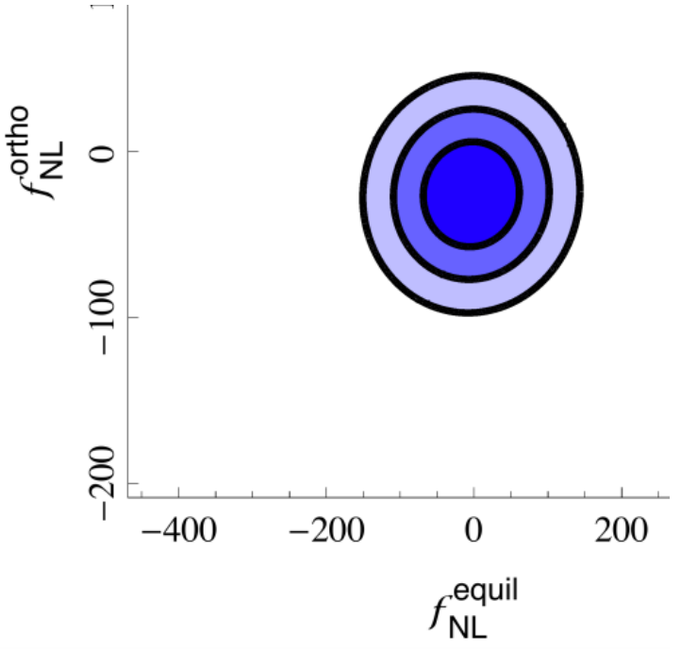


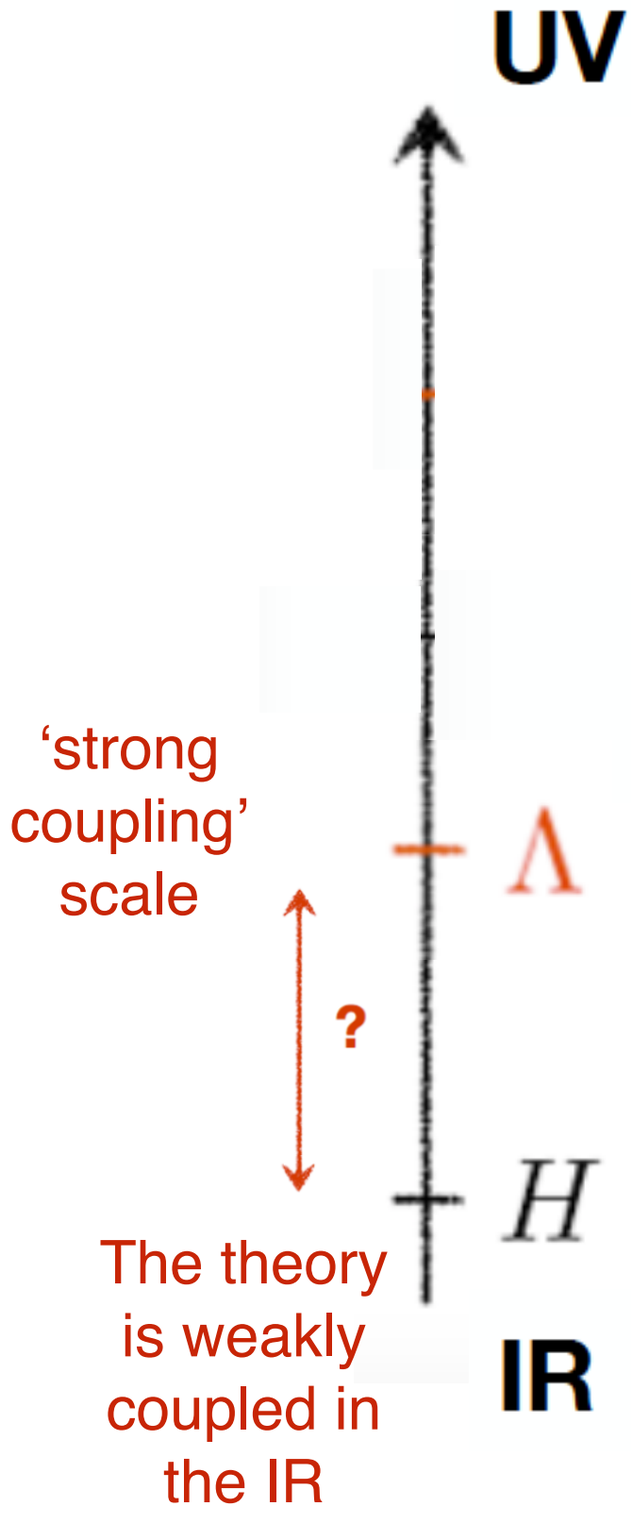


We have not yet ‘detected’ any other scale(s) related to interactions

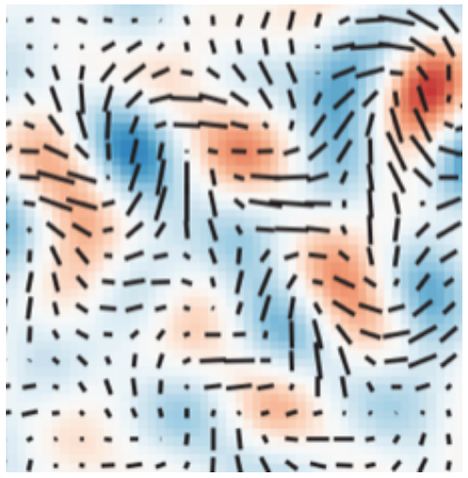
$$\frac{\langle\zeta\zeta\zeta\rangle}{\langle\zeta\zeta\rangle^{3/2}} \lesssim 10^{-3}$$

Planck [2015]



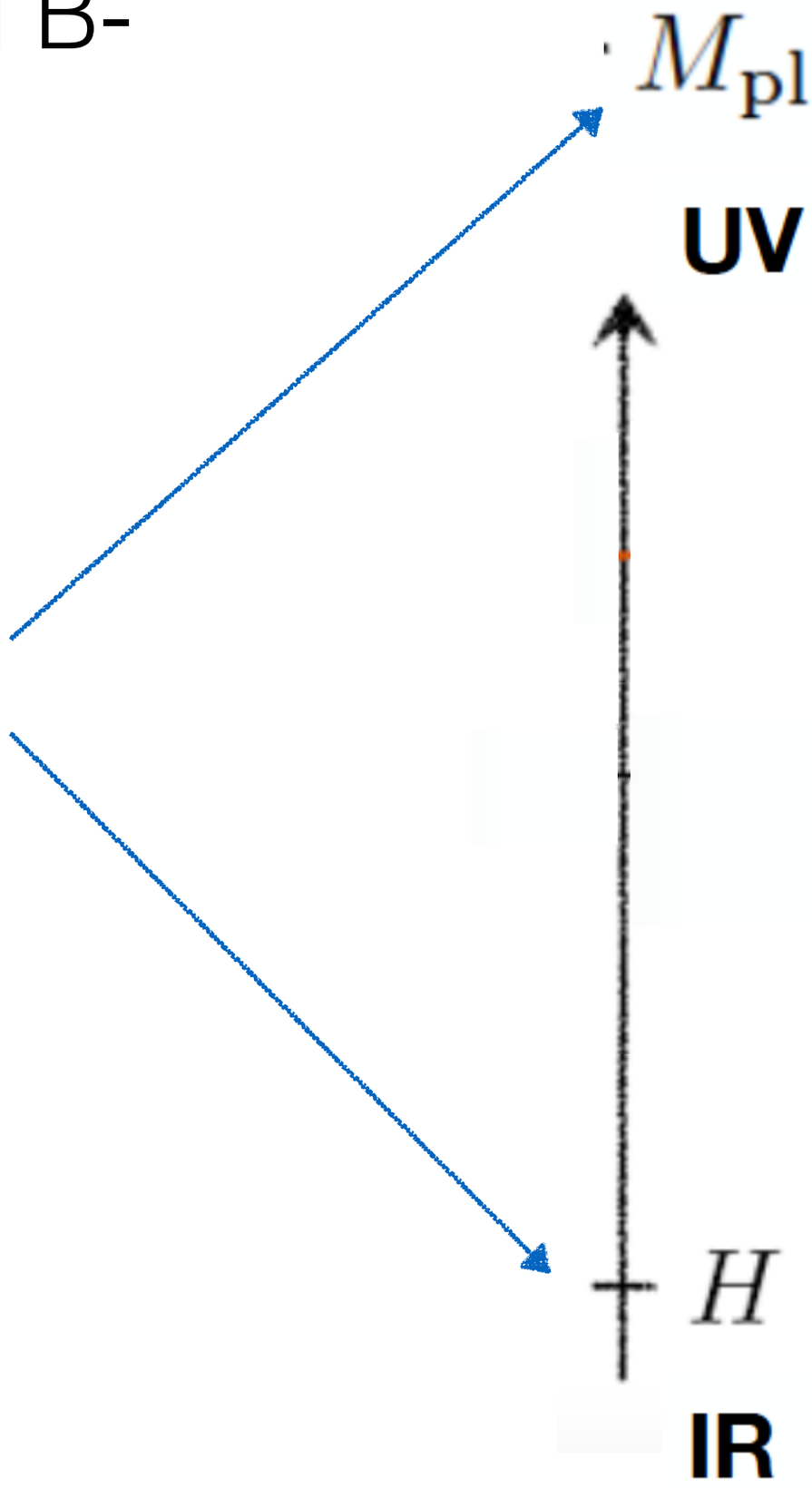


We have not yet detected B-modes either

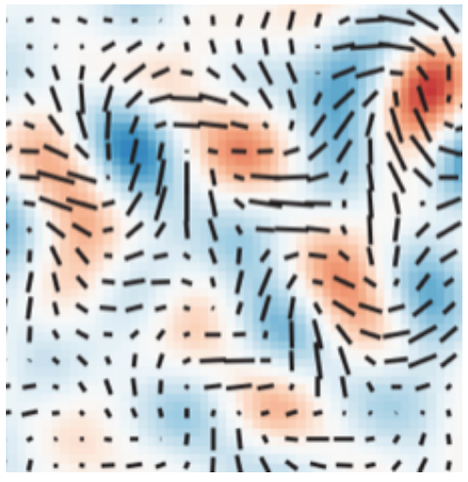


$r < 0.1$

r=T/S



We have not yet detected B-modes either

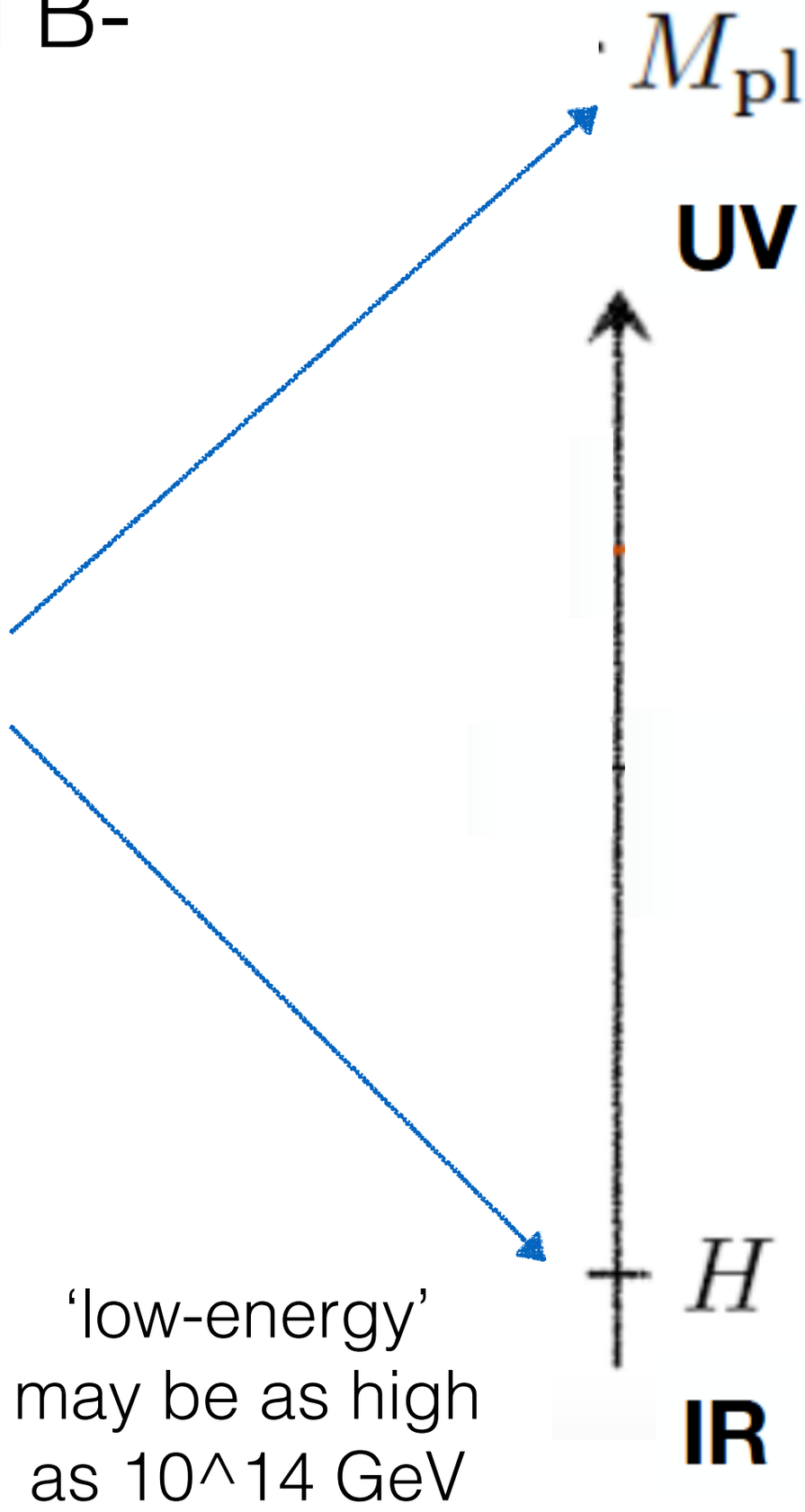


r ≈ 0.01?

r < 0.01?

CMB-S4

Tensor Modes



‘low-energy’ may be as high as 10^14 GeV

Baumann
Green
RAP

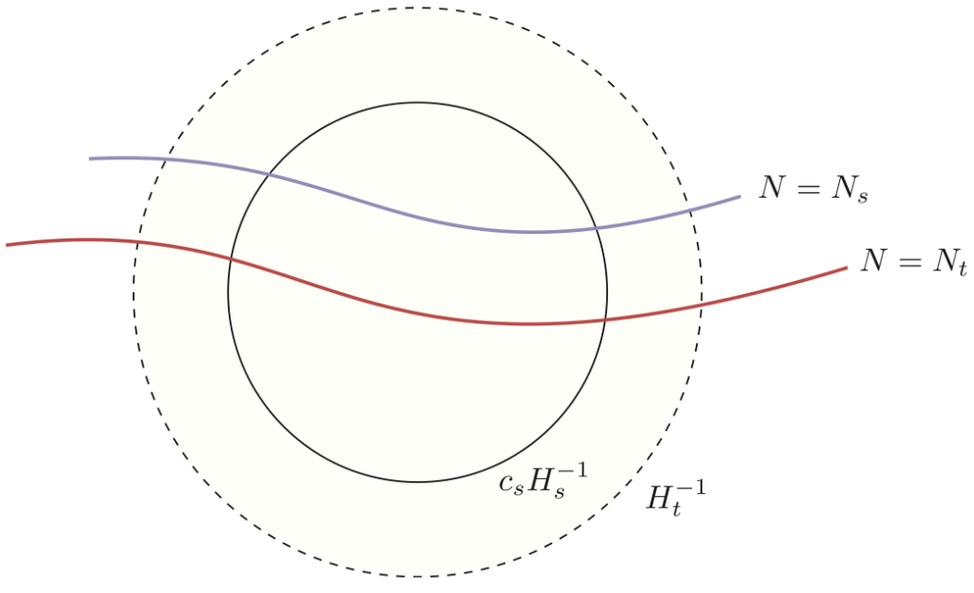
B-modes and the Nature of Inflation

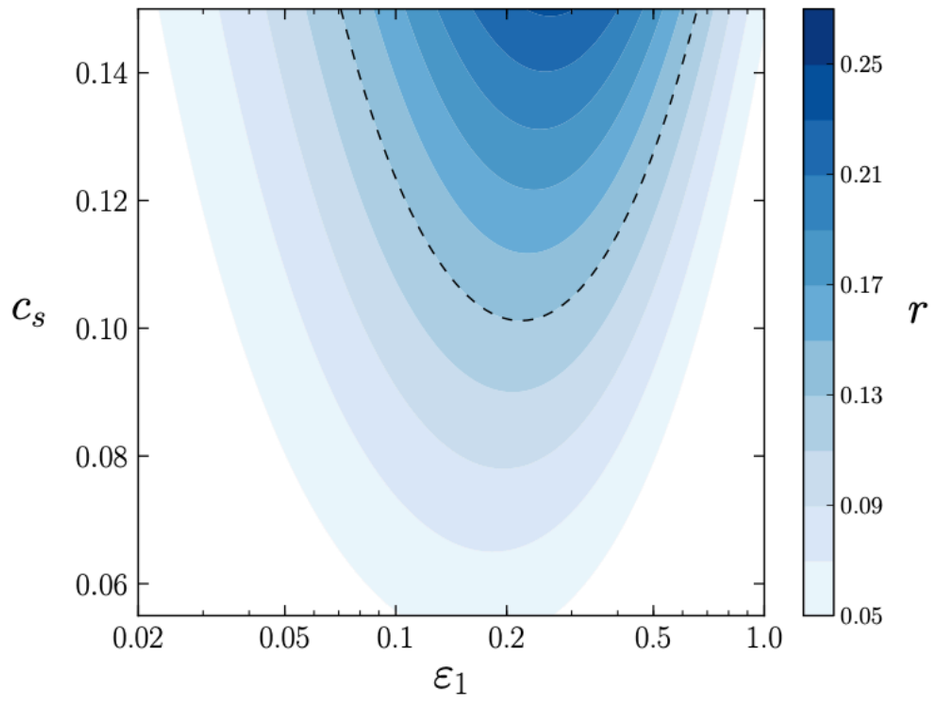
It may also constraint the
UV scales (indirectly) through the
'sound speed'

$$r = 16\varepsilon_1 c_s \left(\frac{H_t}{H_s}\right)^2$$

$$r \simeq 16\varepsilon_1 c_s^{1+2\varepsilon_1}$$

$$r = 16\varepsilon_1 c_s^{1+2\varepsilon_1\cdot(1-c_s^{-\varepsilon_2})/(\varepsilon_2 \ln c_s)}$$



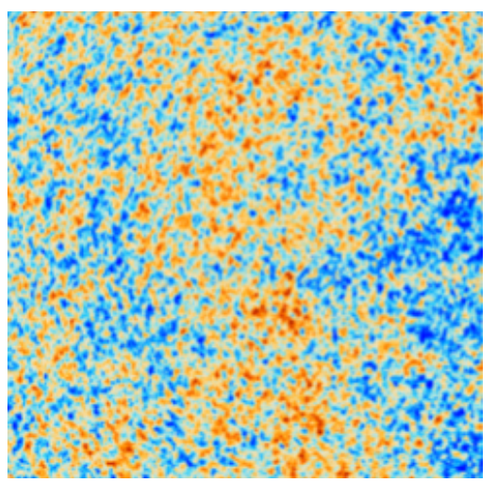


cutoff-scale
depends on
speed of sound!

UV completion

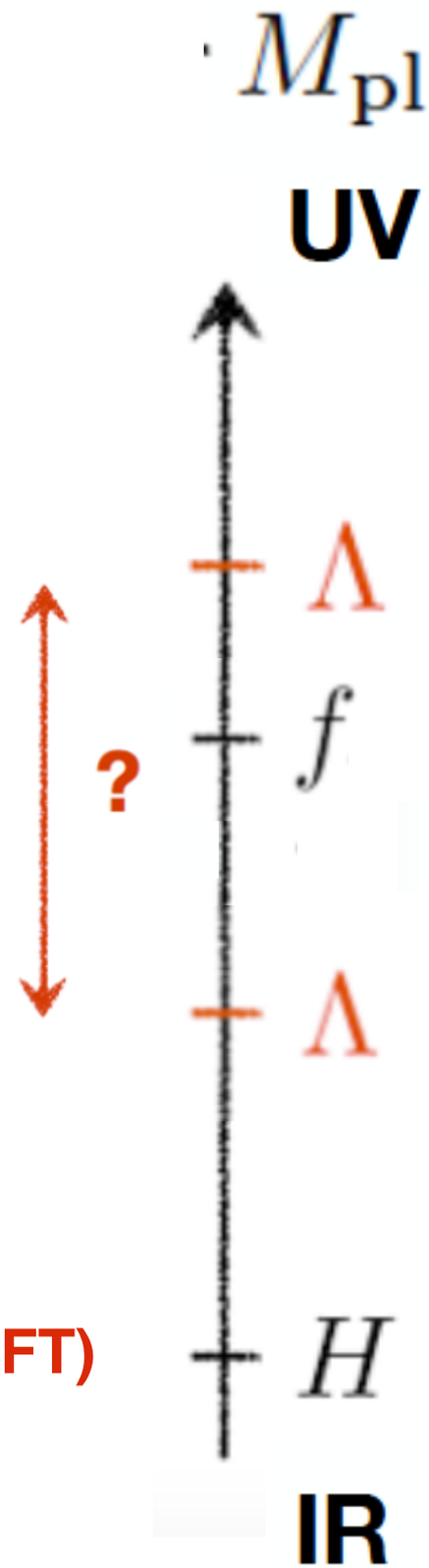
?

scale of observations



This picture invites us
to construct a
bottom-up approach
to explore where the
'new physics' is hiding!

Effective Field Theory (EFT)

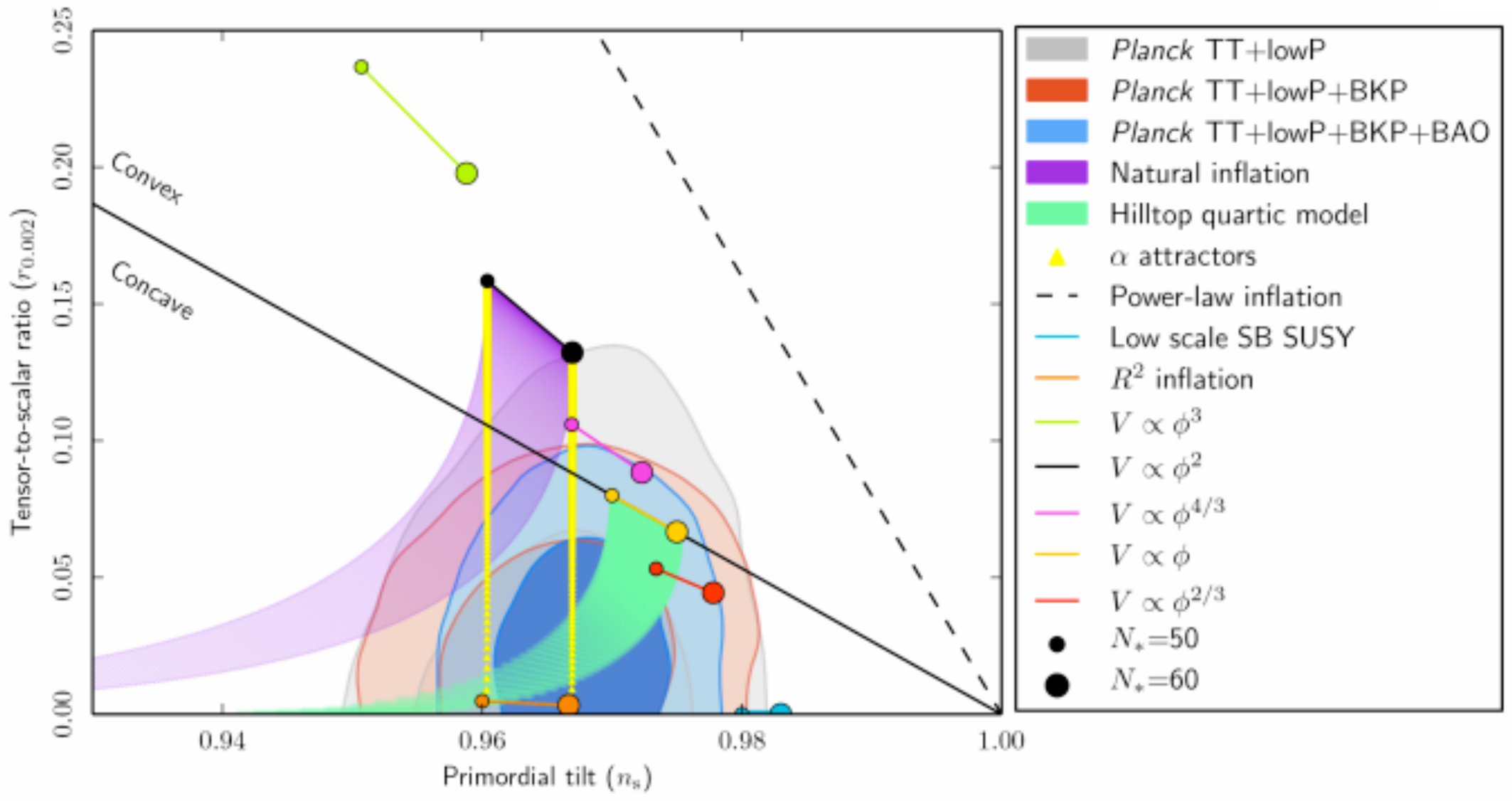


Encyclopædia Inflationaris

Comments: 368 pages, 192 figures

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi)$$

Planck Collaboration: Constraints on inflation

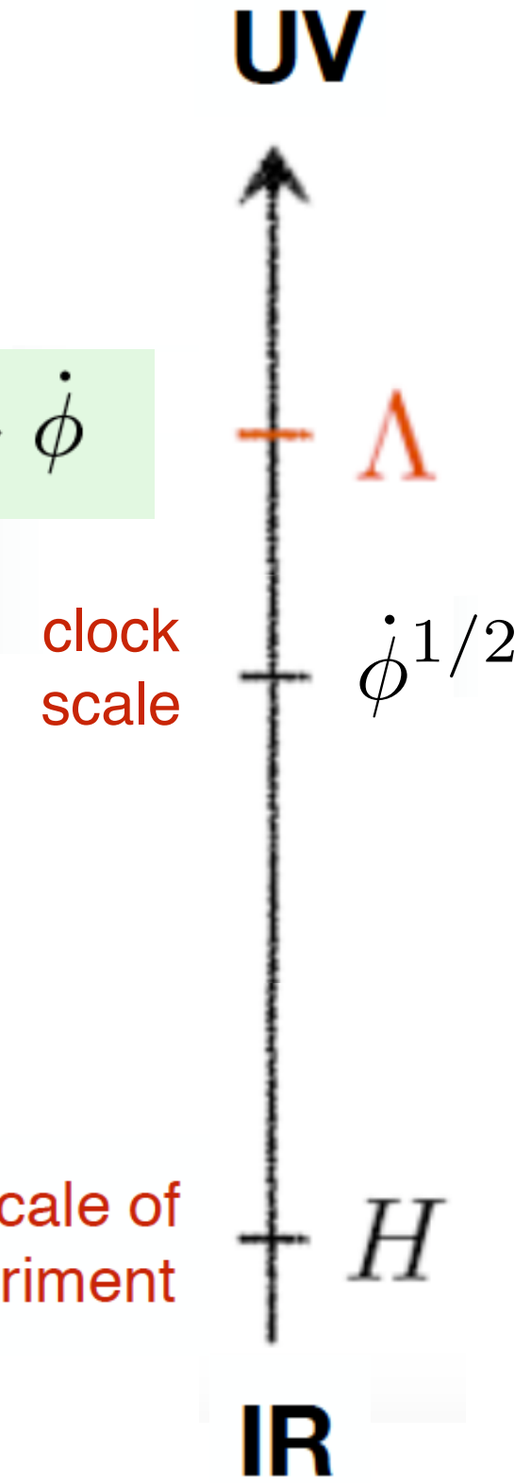


Class I: ‘Slow-roll’ Inflation

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) \; - \frac{(\partial\phi)^4}{\Lambda^4} + \; ..$$

$\Lambda^2 \gg \dot{\phi}$

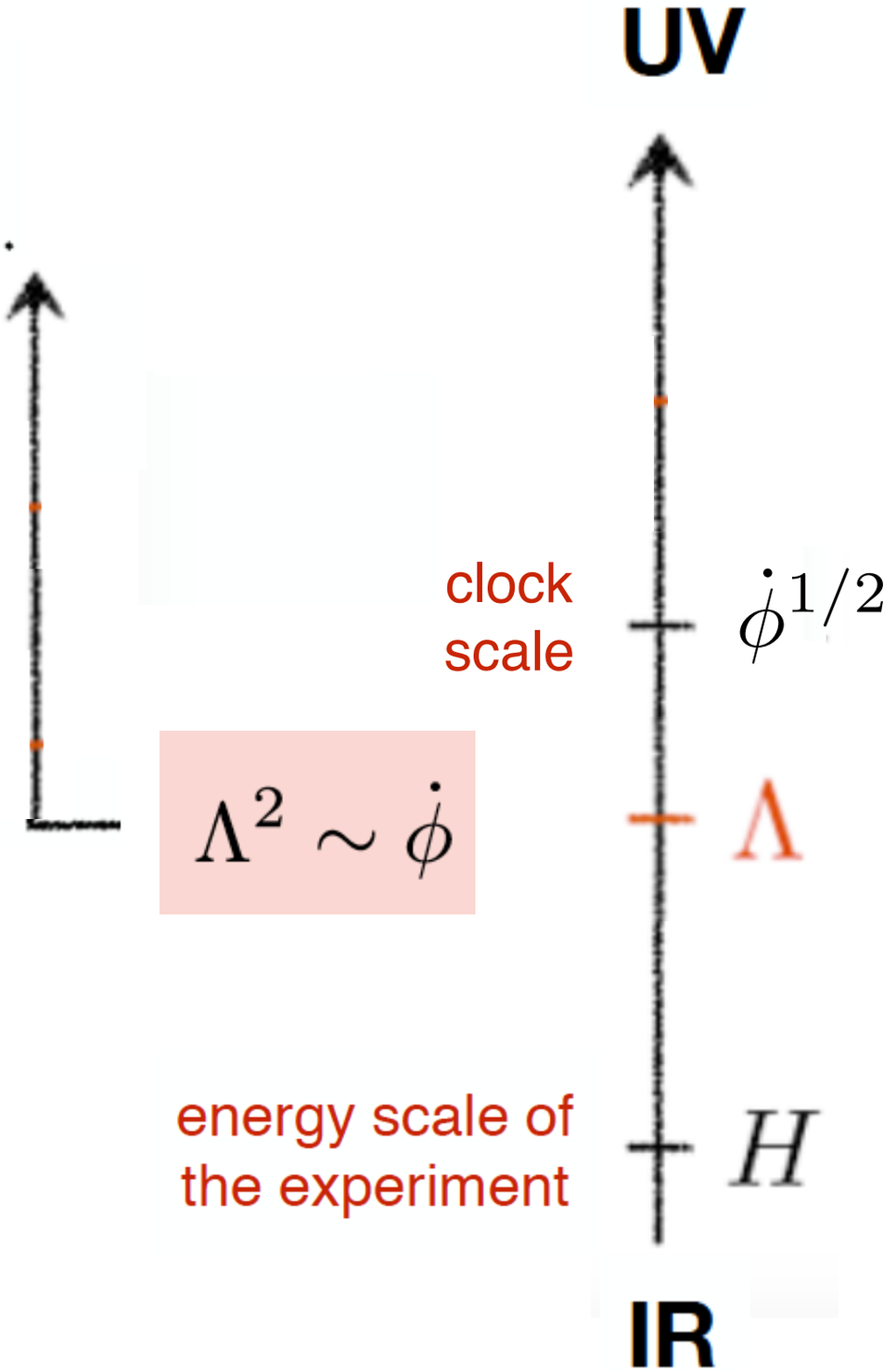
Weakly coupled scalar
well-defined
perturbative expansion



Class II: 'Non-slow-roll' Inflation

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) \; - \frac{(\partial\phi)^4}{\Lambda^4} + \; ..$$

New states to restore weak coupling!
or control over UV theory (e.g. DBI)



Cheung et al.

The EFT approach

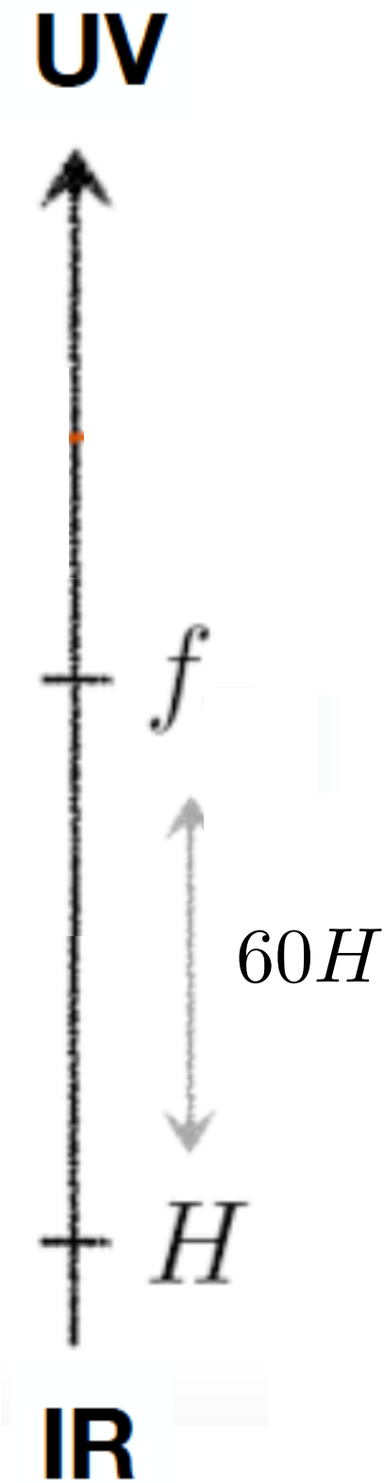
$$\mathcal{L}_2 \propto \dot{\pi}^2 - c_s^2 (\partial_i \pi)^2$$

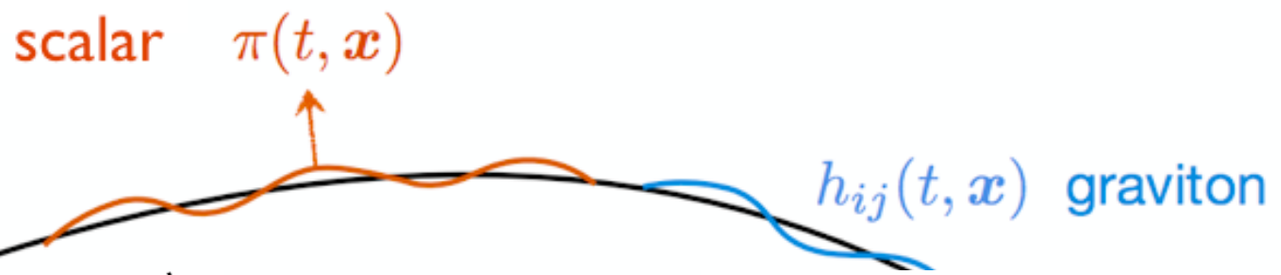
speed of sound

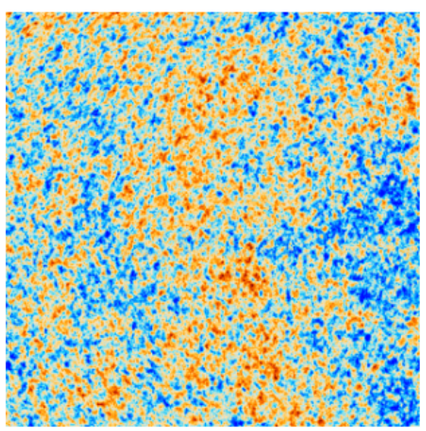
$$\mathcal{L}_3 \propto \frac{1}{c_s^2} \dot{\pi} (\partial_i \pi)^2 + \frac{\mathcal{O}(1)}{c_s^2} \dot{\pi}^3$$

clock scale as a sym. scale

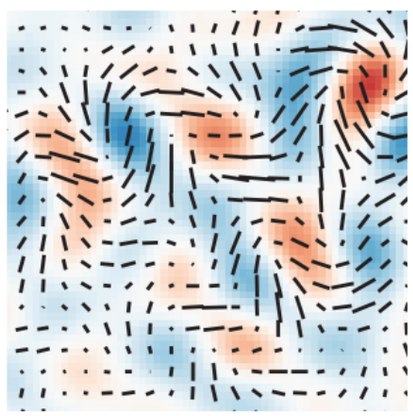
$M_{\rm pl}^2 |\dot{H}| c_s$







- Goldstone boson
  of broken time translations
- clock



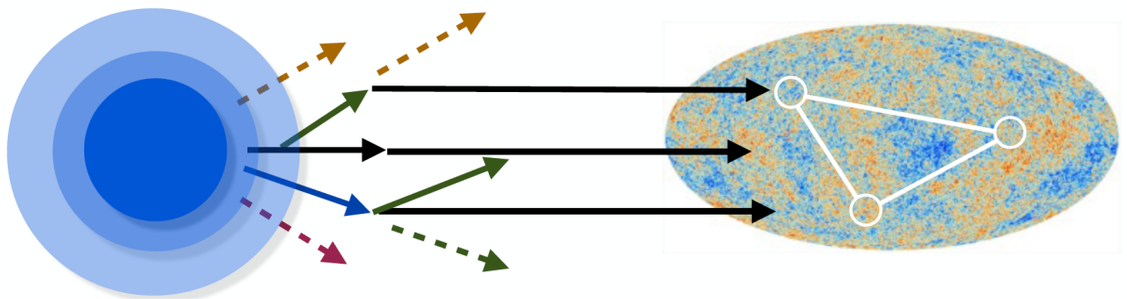
The EFT approach

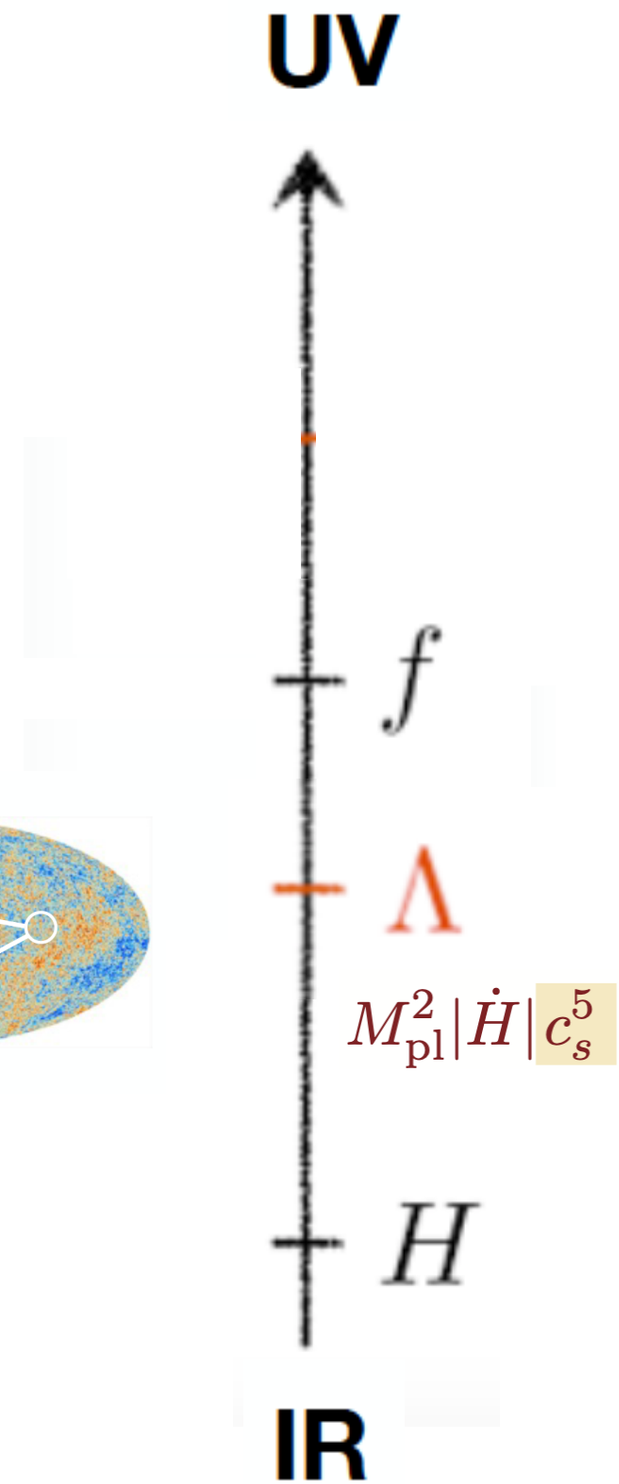
$$\mathcal{L}_2 \propto \dot{\pi}^2 - c_s^2 (\partial_i \pi)^2$$

speed of sound

$$\mathcal{L}_3 \propto \frac{1}{c_s^2} \dot{\pi} (\partial_i \pi)^2 + \frac{\mathcal{O}(1)}{c_s^2} \dot{\pi}^3$$

Is there a natural threshold between the two classes?



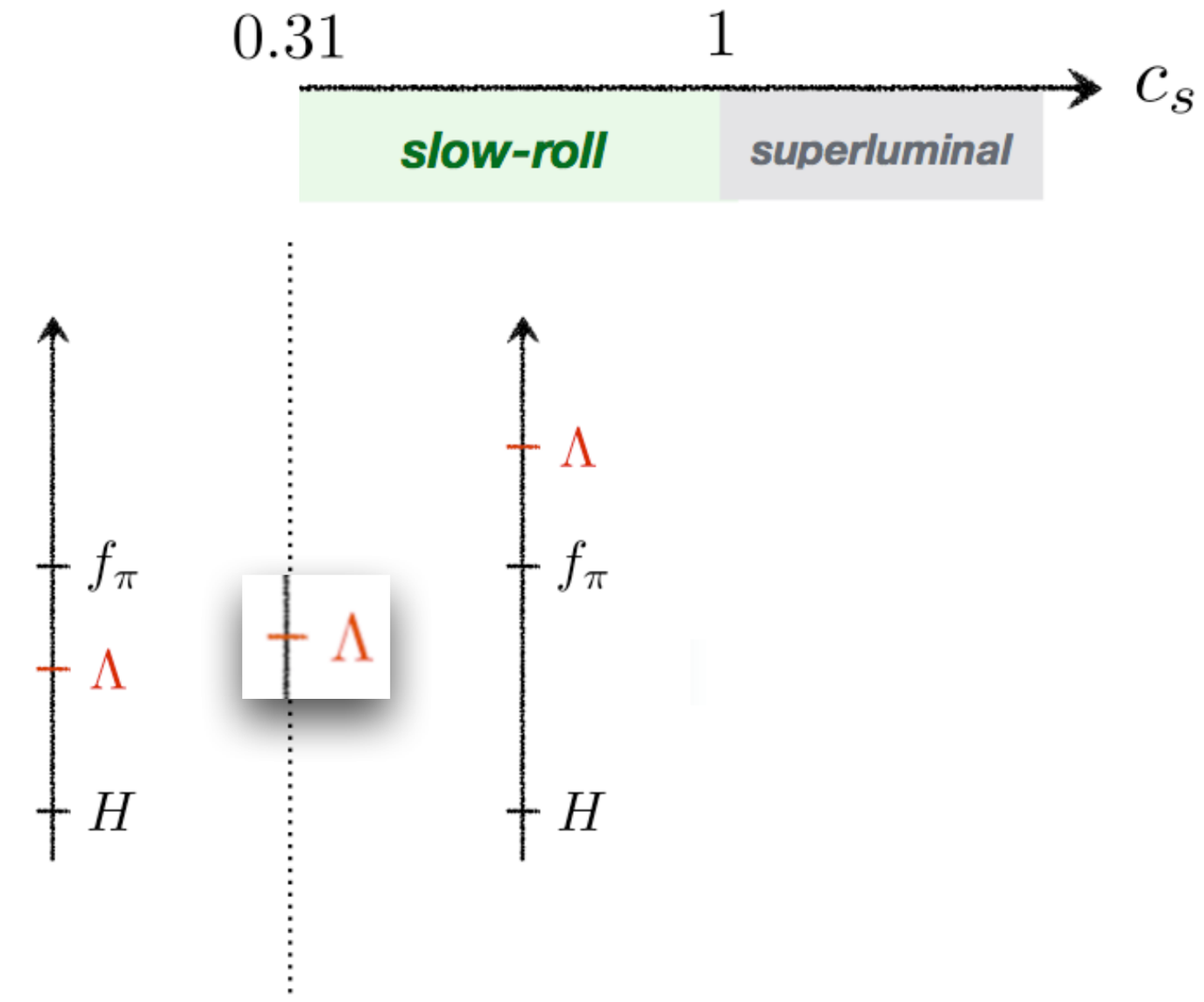


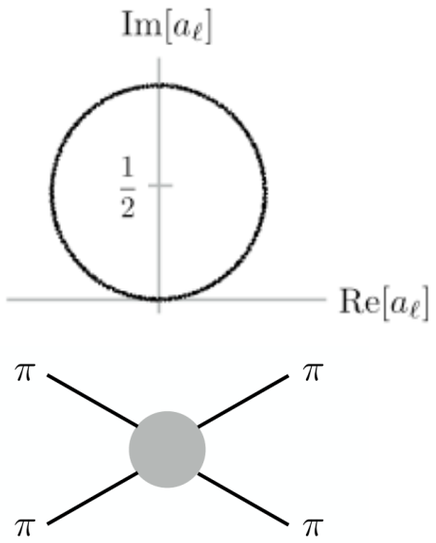
Baumann
Green
RAP

The ‘cross-over’ scale

$$\frac{\langle\zeta\zeta\zeta\rangle}{\langle\zeta\zeta\rangle^{3/2}} \lesssim 10^{-5}$$

threshold





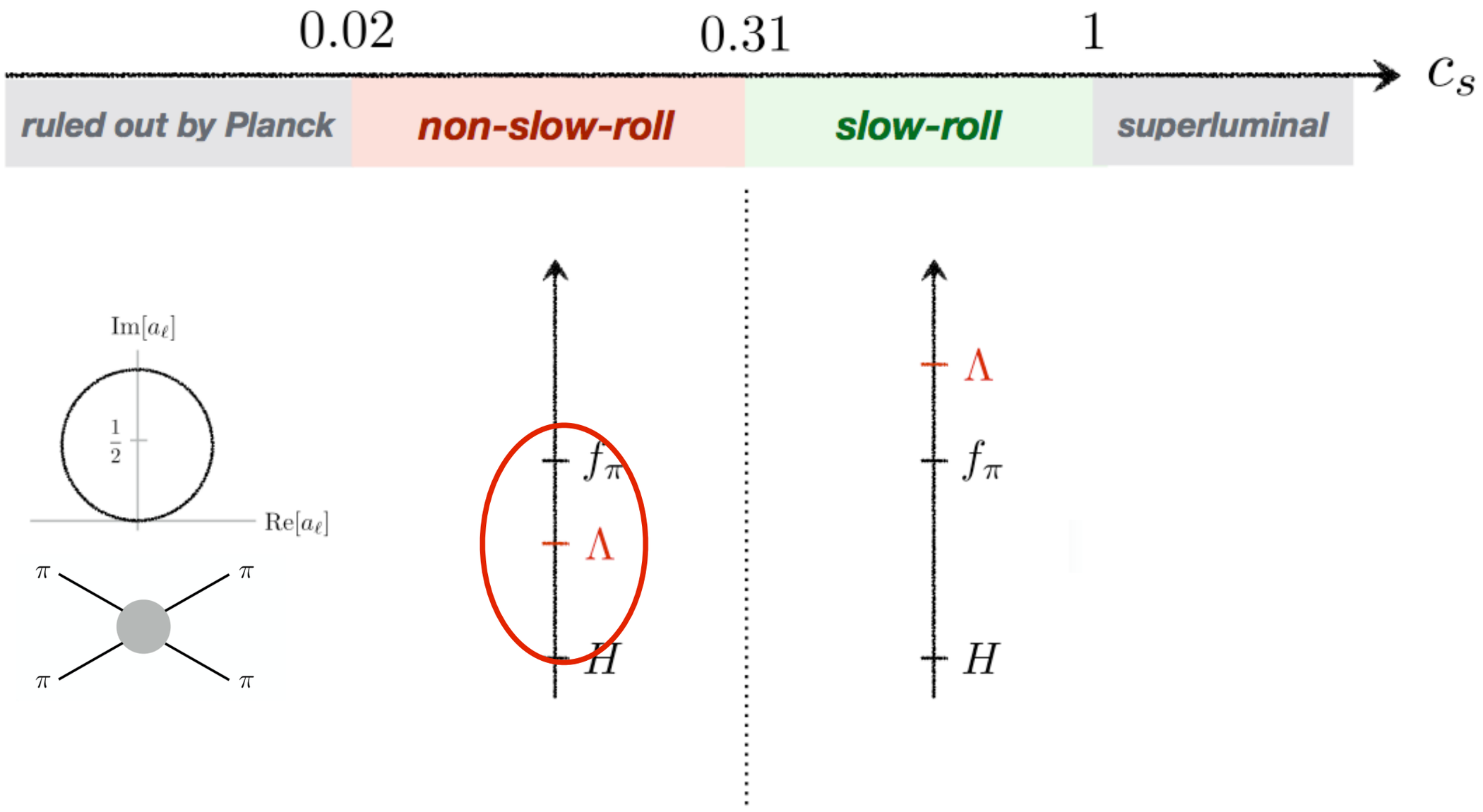
$$f_{\rm NL}^{\rm equil} \sim 1$$

Baumann
Green
RAP

Where are we now?

$$\frac{\langle\zeta\zeta\zeta\rangle}{\langle\zeta\zeta\rangle^{3/2}} \lesssim 10^{-3}$$

Planck [2015]



$$f_{\rm NL}^{\rm equil} \sim 1$$

Baumann
Green
RAP

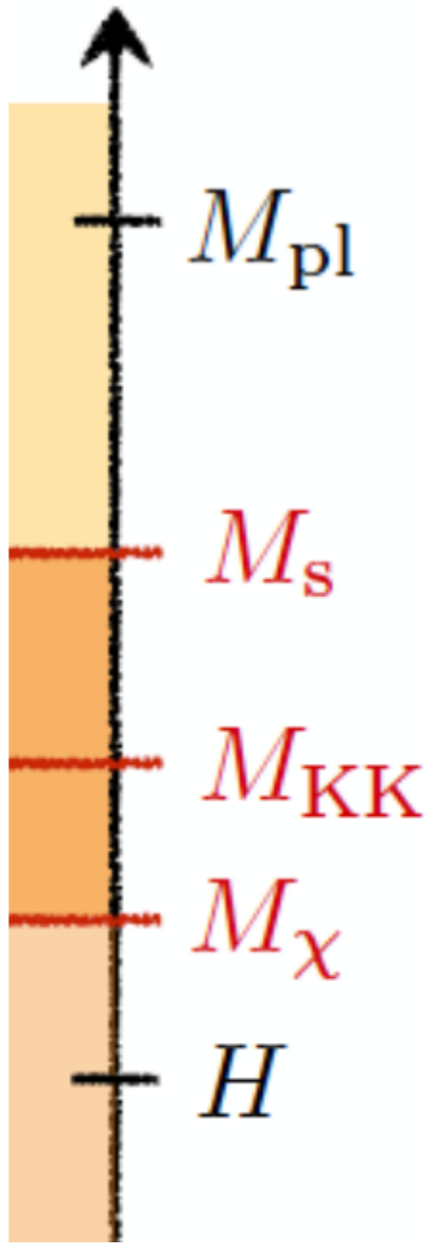
$$\frac{\langle\zeta\zeta\zeta\rangle}{\langle\zeta\zeta\rangle^{3/2}} \lesssim 10^{-5}$$

threshold

window
opportunity

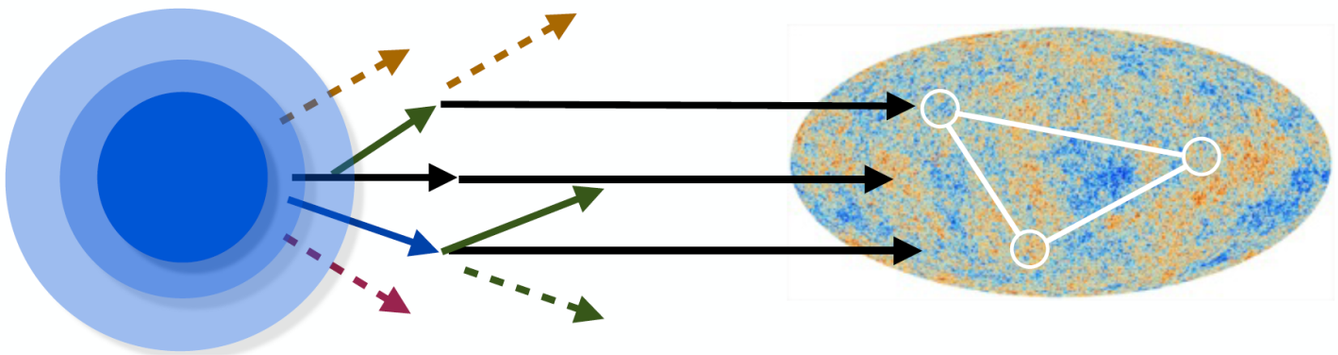
0.02 0.31

ruled out by Planck ***non-slow-roll*** ***slow-***



The physics
of inflation may involve a
plethora of new scales
around the corner

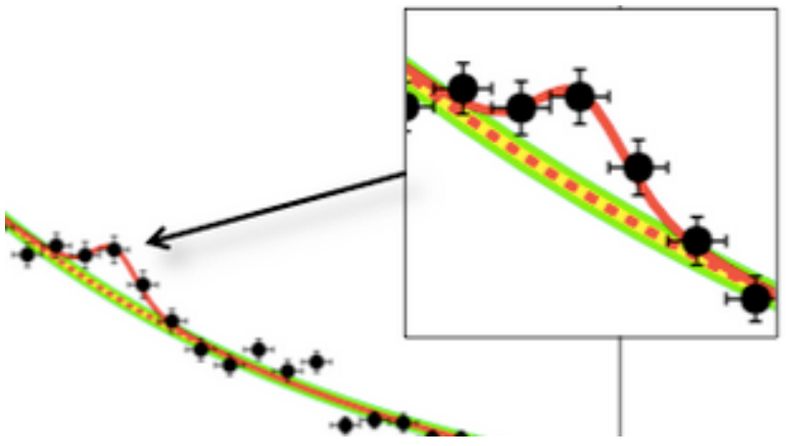
The nature of the primordial seed

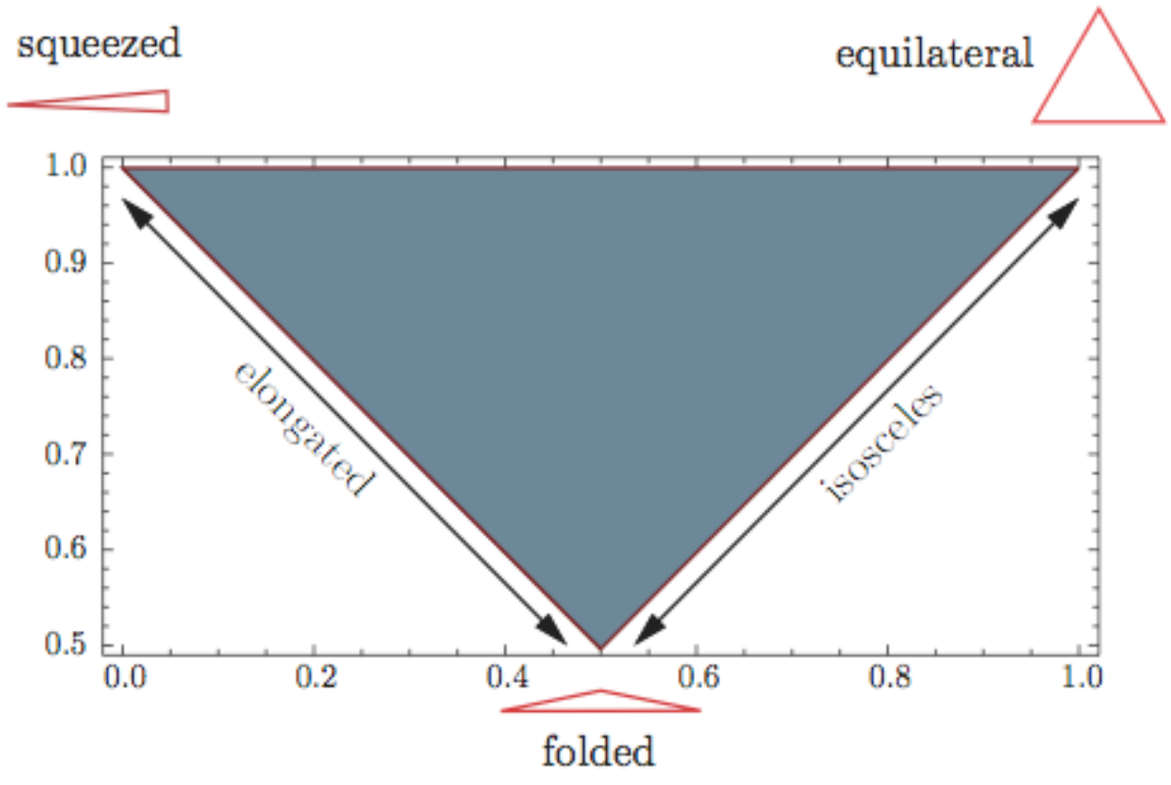


$$\frac{\langle\zeta\zeta\zeta\rangle}{\langle\zeta\zeta\rangle^{3/2}} \lesssim 10^{-5}$$

threshold

The shape of Non-Gaussianity as a ‘particle detector’

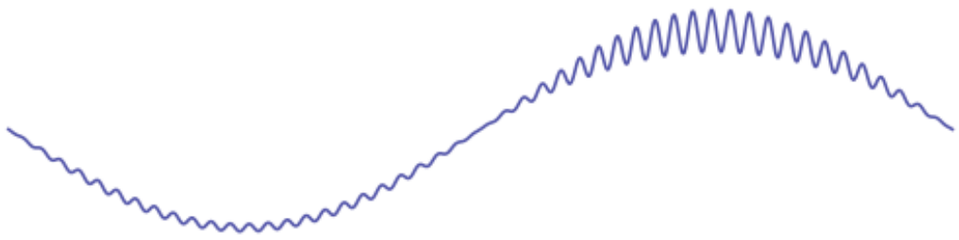




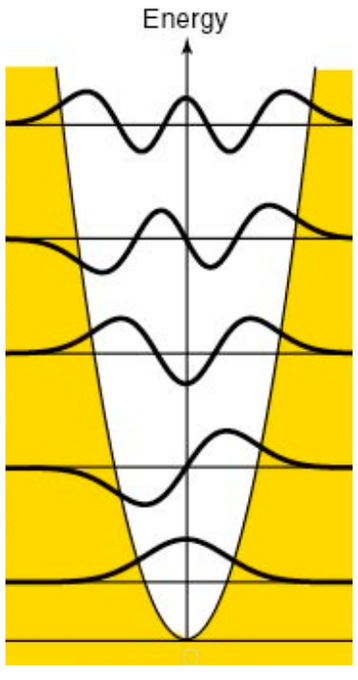
Flauger
Green
RAP

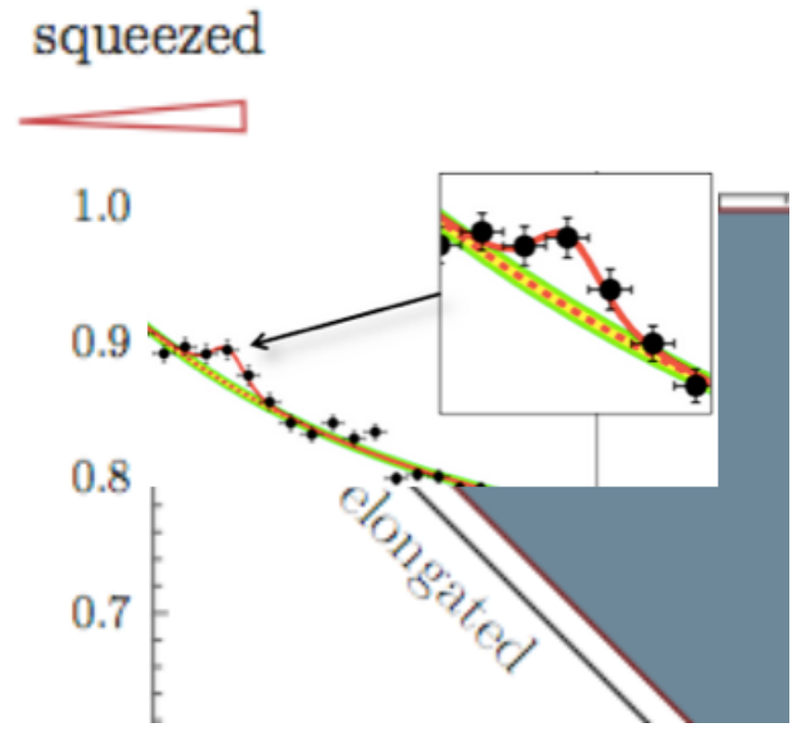
Excited states

Physics near threshold:
The Cosmological Collider



excited?
resonances?

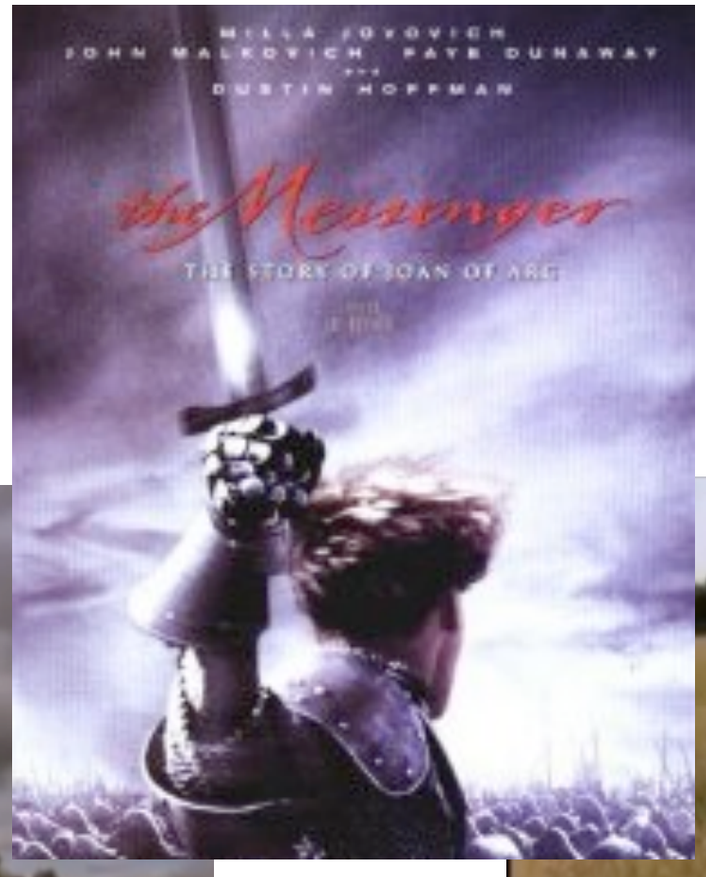


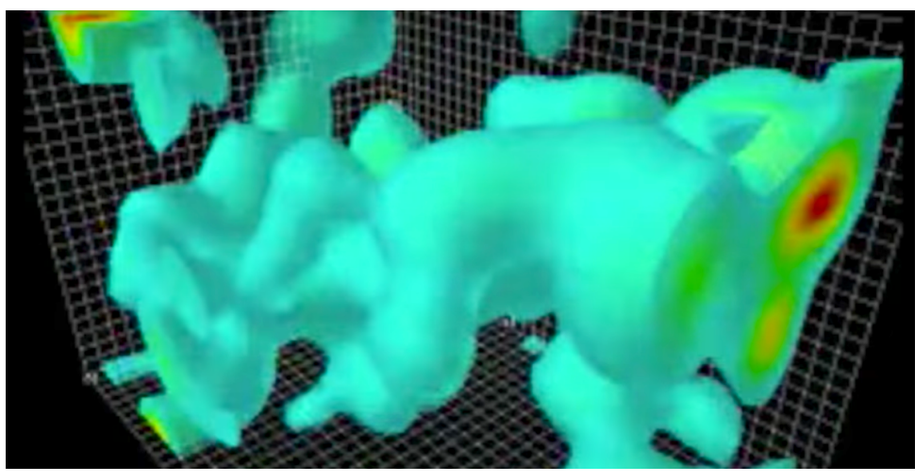


$$\frac{k_L}{k_S} \gtrsim \frac{H}{\dot{\phi}^{\frac{1}{2}}} \simeq \Delta_\zeta^{1/2} \simeq 10^{-2}.$$

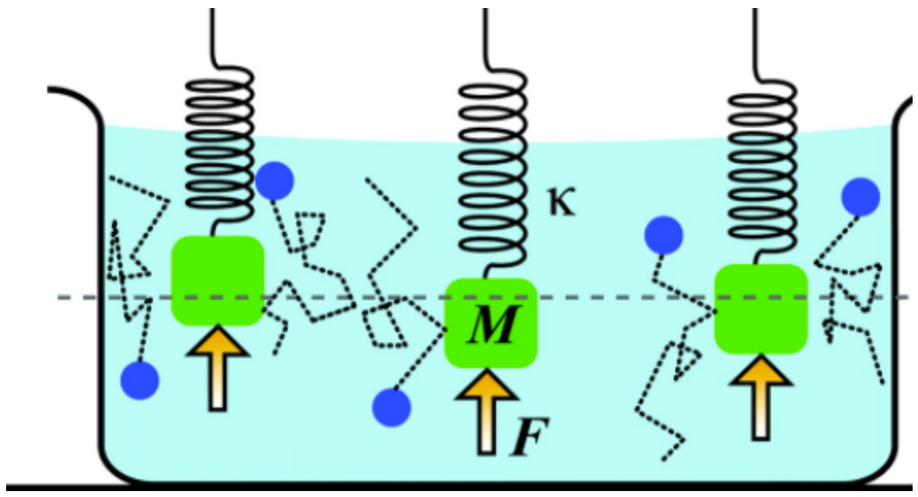
Green

RAP





VS

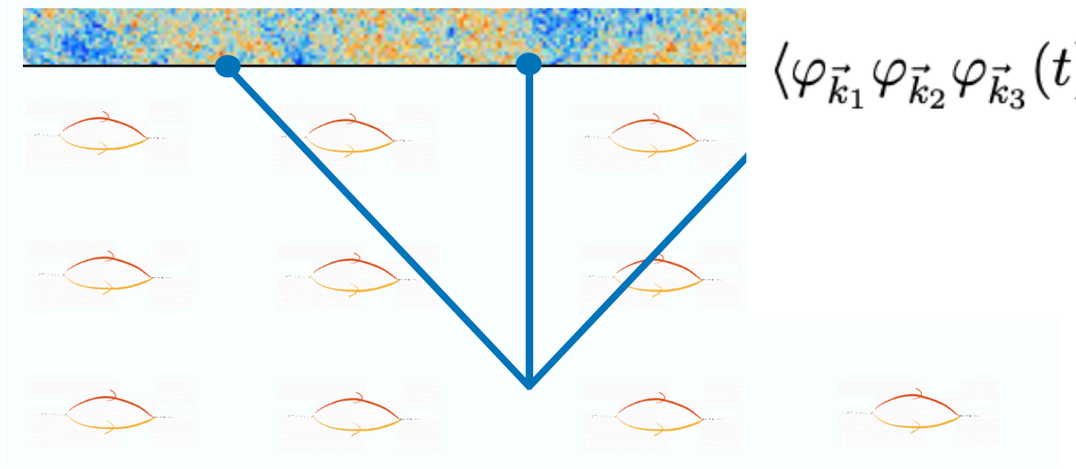


CAN WE TELL THEM APART?

Flauger
Green
RAP

Signals of a Quantum Universe

$$H_{\rm int} = \tfrac{1}{6}\mu\varphi^3,$$



$$\langle\varphi_{\vec{k}_1}\varphi_{\vec{k}_2}\varphi_{\vec{k}_3}(t)\rangle' = -i\tfrac{1}{8k_1k_2k_3}\int_{-\infty(1-i\epsilon)}^{t} dt'\,\mu e^{i(k_1+k_2+k_3)(t'-t)} - \text{c.c.}$$

$$= -\mu\frac{1}{4k_1k_2k_3(k_1+k_2+k_3)},$$

interaction “energy pole”

Quantum (Vaccum)

Uncertainty principle

$$\Delta t \sim 1/\Delta E \leftarrow 1/k_t.$$

Earlier times are
exponentially suppressed!

$$\delta(k_1+k_2+k_3) \to \frac{1}{k_1+k_2+k_3}$$

Scattering in-in correlator

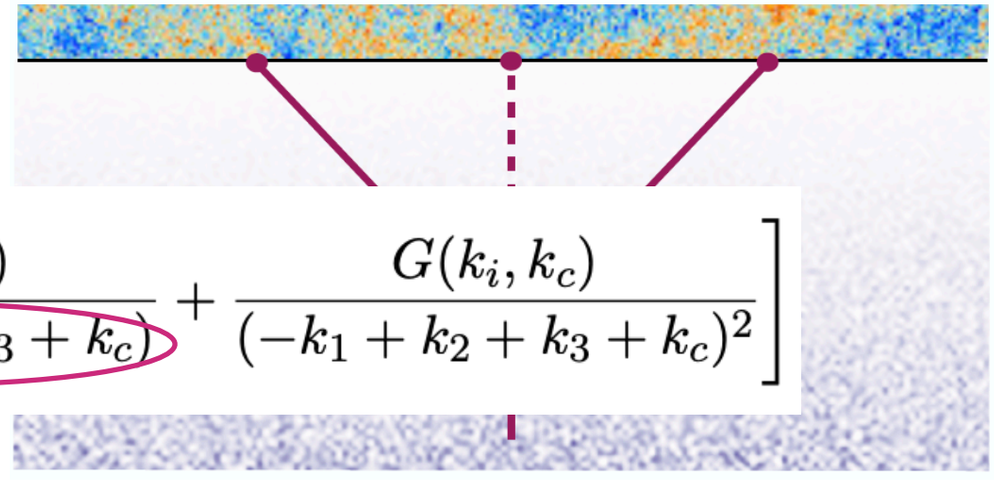
There is a manifestation of a more direct connection between pology (‘residues’) in flat space and correlators in cosmology!

The 1/kt pole can change if 1) we have particles in the initial state (classical), or 2) break of time translations (resonant NG)

Dissipative effects in Inflation

Nacir
RAP
Zaldarriaga

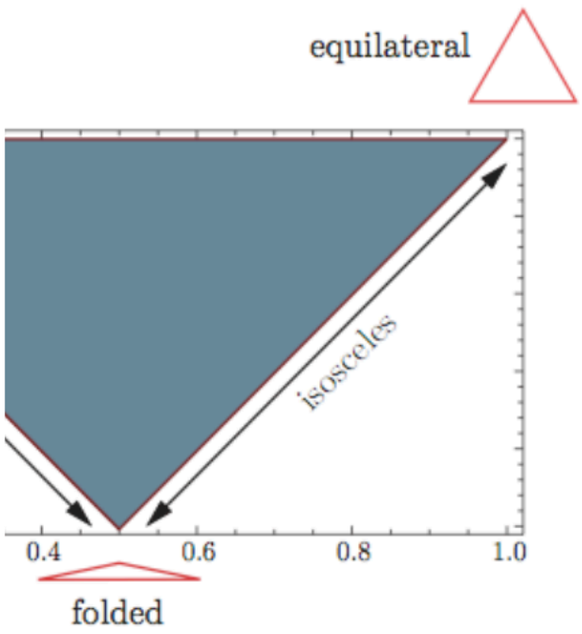
$$k_\star \sim \sqrt{\gamma H}$$



$$B(k_i,k_c) \simeq \frac{\Delta_\zeta^4 f_{\rm NL}^{\rm eq}}{k_1^3 k_2^3 k_3^3}\left[-k_1^3+k_2^3+k_3^3+\frac{F(k_i,k_c)}{(-k_1+k_2+k_3+k_c)}+\frac{G(k_i,k_c)}{(-k_1+k_2+k_3+k_c)^2}\right]$$

energy pole becomes “real”
(also gets a width as expected!)

(Semi-)Classical



$$|f_{\rm NL}^{\rm fold}| \simeq \frac{1}{2}|f_{\rm NL}^{\rm equil}|$$

$$|f_{\rm NL}| \sim \frac{\gamma}{c_s^2 H}.$$

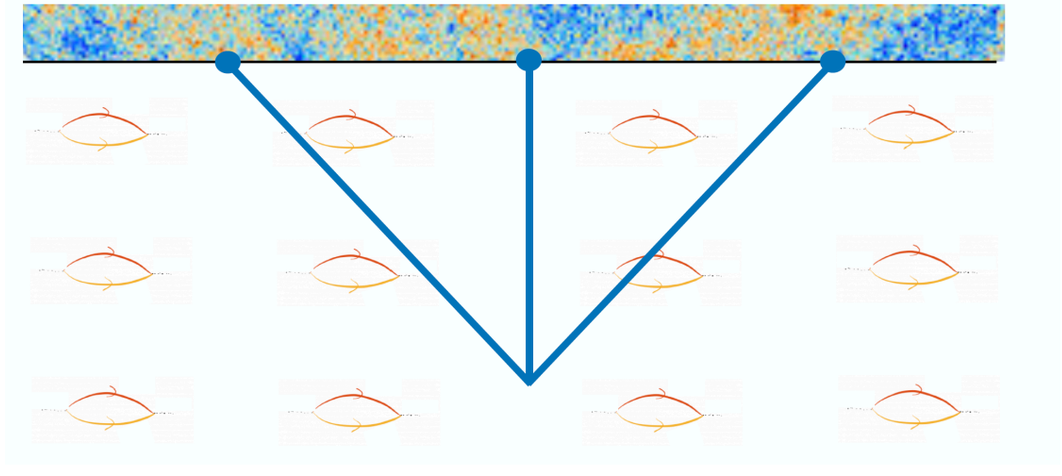
‘Friction and Noise’

$$\ddot{\zeta}+\gamma\dot{\zeta}+\omega_0^2\zeta=\mathcal{O}(t)\,,$$

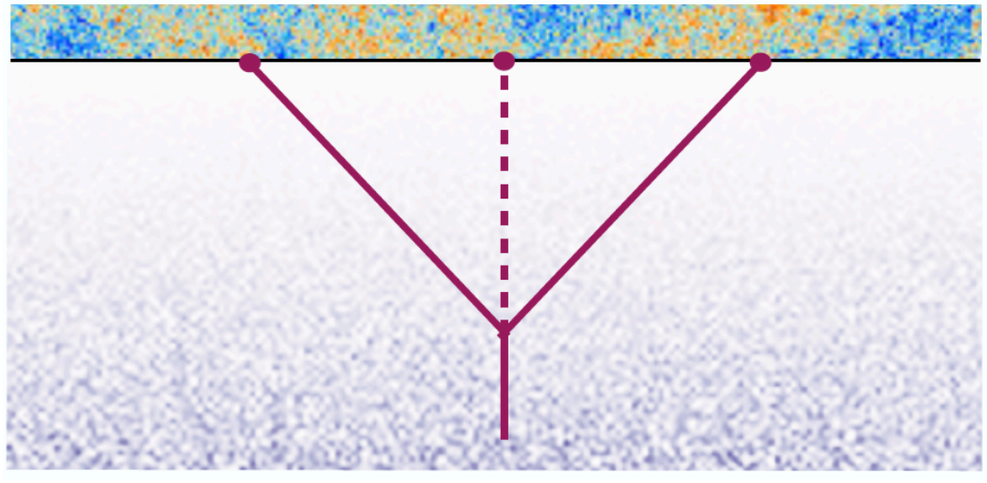
The n-point functions are
dominated by the noise
(loss of memory of initial conditions)

Signals of a Quantum Universe

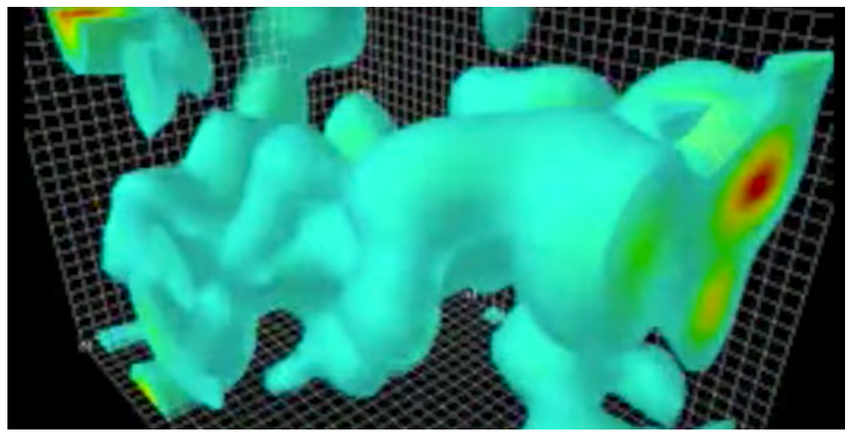
Green
RAP



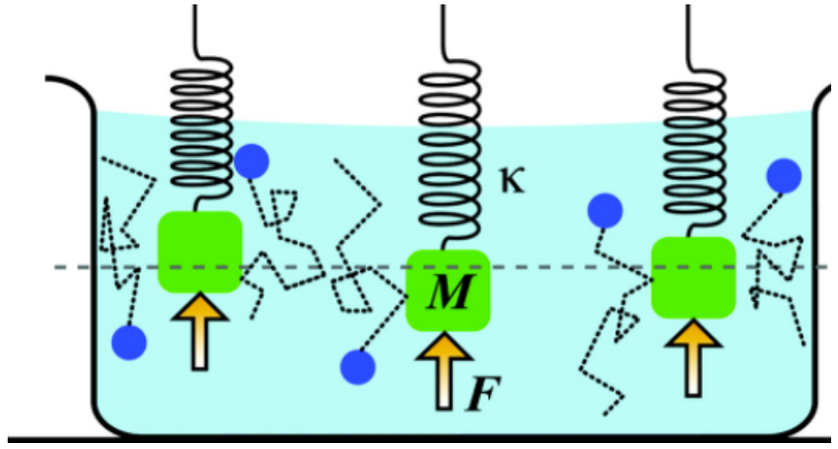
Quantum (Vaccum)



(Semi-)Classical



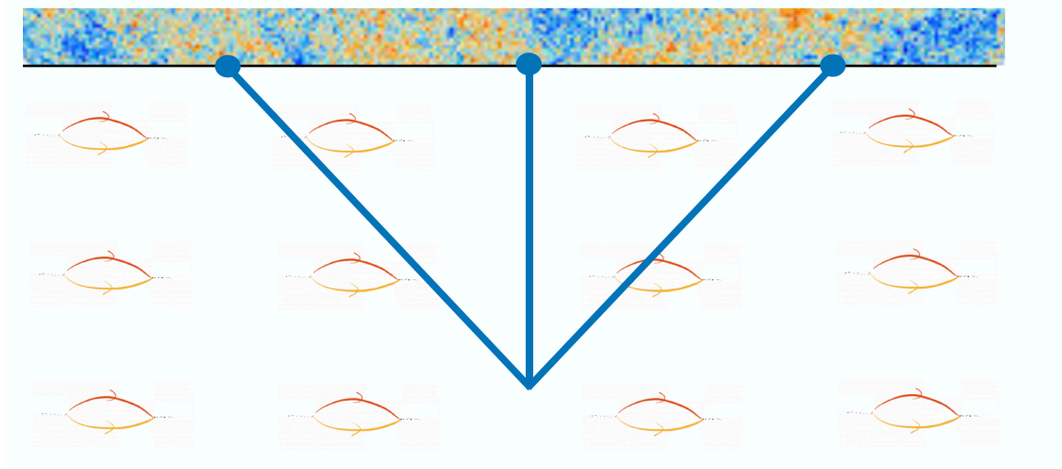
VS

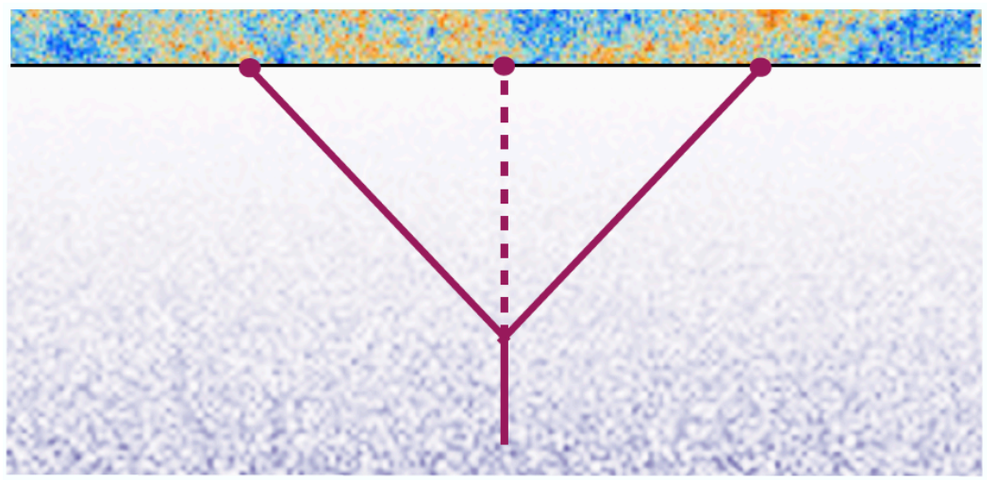


ARE THESE GENERIC FEATURES?

Signals of a Quantum Universe

Green
RAP





Quantum (Vaccum)

(Semi-)Classical

$$\langle 0|a_{\mathbf{k}'}a^\dagger_{\mathbf{k}}|0\rangle = \delta(\mathbf{k}-\mathbf{k}')\,, \qquad \langle 0|a^\dagger_{\mathbf{k}}a_{\mathbf{k}'}|0\rangle = 0\,, \qquad \langle a^\dagger_{\mathbf{k}}a_{\mathbf{k}'}\rangle_c = \frac{1}{2}\delta(\mathbf{k}-\mathbf{k}') = \langle a_{\mathbf{k}'}a^\dagger_{\mathbf{k}}\rangle_c\,,$$

Vacuum fluctuations
are observed ‘later’
(energy injected through expansion)

Quantum modes
carry positive/negative
energy

Classical fluctuations
are ‘real’

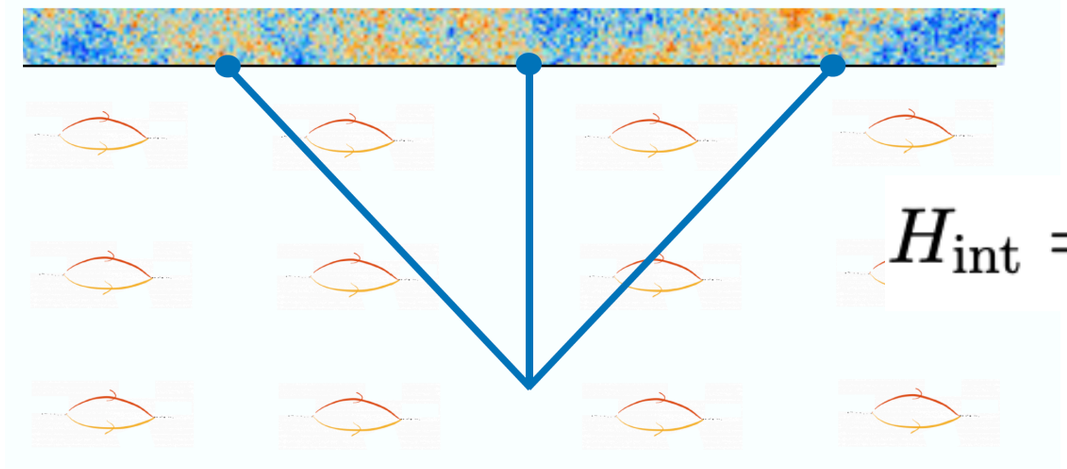
Classical modes are sines/cosines
with ‘unknown’ amplitude from
a prob. distribution.
We can easily reproduce 2pt.

$$\zeta(\mathbf{x},\tau) = \int \frac{d^3k}{(2\pi)^3}\frac{\Delta_\zeta}{\sqrt{k^3}}e^{i\mathbf{k}\cdot\mathbf{x}}[a^\dagger_{\mathbf{k}}(1-ik\tau)e^{ik\tau} + a_{-\mathbf{k}}(1+ik\tau)e^{-ik\tau}]$$

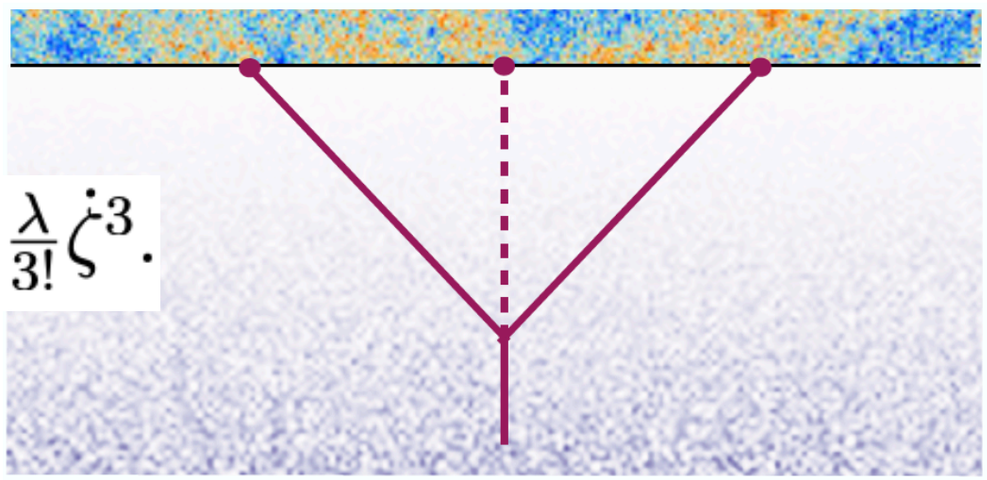
Green

RAP

Signals of a Quantum Universe Dynamically



$$H_{\rm int} = -\frac{\lambda}{3!}\dot{\zeta}^3 .$$



Quantum (Vaccum) **(Semi-)Classical**

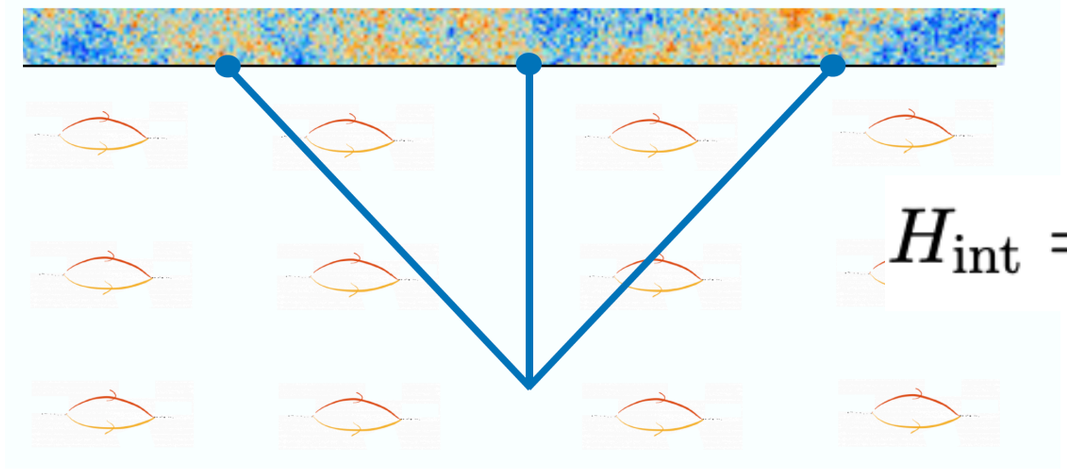
$$\langle 0|a_{\mathbf{k}'}a^\dagger_{\mathbf{k}}|0\rangle = \delta(\mathbf{k}-\mathbf{k}')\,, \qquad \langle 0|a^\dagger_{\mathbf{k}}a_{\mathbf{k}'}|0\rangle = 0\,, \qquad \langle a^\dagger_{\mathbf{k}}a_{\mathbf{k}'}\rangle_c = \frac{1}{2}\delta(\mathbf{k}-\mathbf{k}') = \langle a_{\mathbf{k}'}a^\dagger_{\mathbf{k}}\rangle_c\,,$$

$$\begin{aligned}
\langle\zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\rangle'_q &= i\int d\tau'\langle[H_{\rm int}(\tau'),\zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}(0)]\rangle \\
&= 2\frac{\lambda}{H}\frac{\Delta^6_\zeta}{k_1k_2k_3}\,{\rm Im}\int_{-\infty}^0 d\tau'\tau'^2 e^{i(k_1+k_2+k_3)\tau'} \\
&= \frac{4\lambda H^{-1}\Delta^6_\zeta}{(k_1+k_2+k_3)^3k_1k_2k_3}\,,
\end{aligned}$$

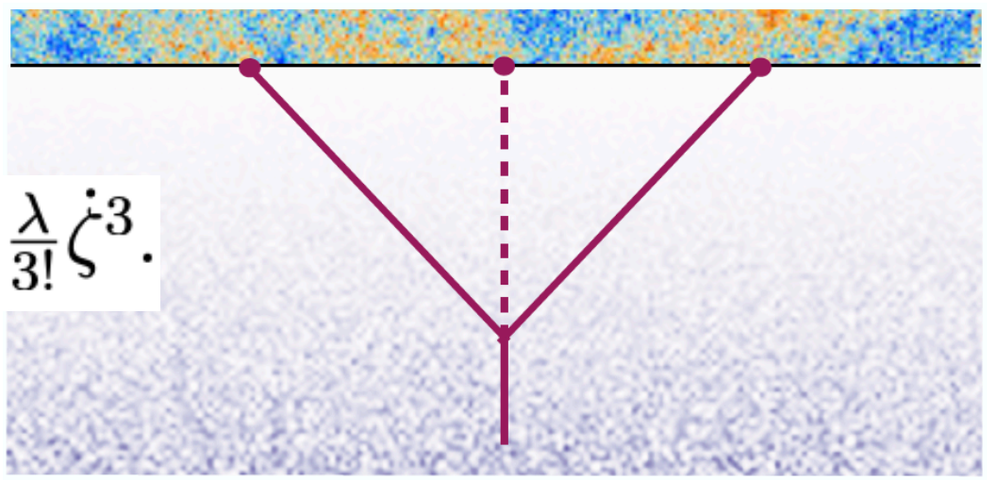
These are all allowed by the S-matrix!
The only difference
is the overlap with the state

Green
RAP

Signals of a Quantum Universe



$$H_{\rm int} = -\frac{\lambda}{3!}\dot{\zeta}^3 .$$



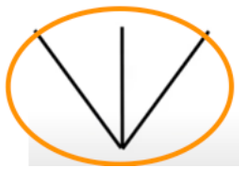
Quantum (Vaccum) **(Semi-)Classical**

$$\langle 0|a_{\mathbf{k}'}a^\dagger_{\mathbf{k}}|0\rangle = \delta(\mathbf{k}-\mathbf{k}')\,, \qquad \langle 0|a^\dagger_{\mathbf{k}}a_{\mathbf{k}'}|0\rangle = 0\,, \qquad \langle a^\dagger_{\mathbf{k}}a_{\mathbf{k}'}\rangle_c = \frac{1}{2}\delta(\mathbf{k}-\mathbf{k}') = \langle a_{\mathbf{k}'}a^\dagger_{\mathbf{k}}\rangle_c\,,$$

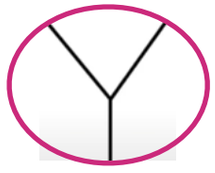
$$\begin{aligned}\langle\zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\rangle'_q &= i\int d\tau'\langle[H_{\rm int}(\tau'),\zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}(0)]\rangle \\ &= 2\frac{\lambda}{H}\frac{\Delta^6_\zeta}{k_1k_2k_3}\,{\rm Im}\int_{-\infty}^0 d\tau'\tau'^2 e^{i(k_1+k_2+k_3)\tau'} \\ &= \frac{4\lambda H^{-1}\Delta^6_\zeta}{(k_1+k_2+k_3)^3k_1k_2k_3}\,,\end{aligned}$$

$$\langle\zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\rangle'_c = \frac{\lambda H^{-1}\Delta^6_\zeta}{6k_1k_2k_3}\left[\frac{1}{k_t^3} + \frac{1}{(k_1+k_2-k_3)^3} + \frac{1}{(k_1-k_2+k_3)^3} + \frac{1}{(k_1-k_2-k_3)^3} + \text{permutations}\right]$$

The would-be delta-function is now real!



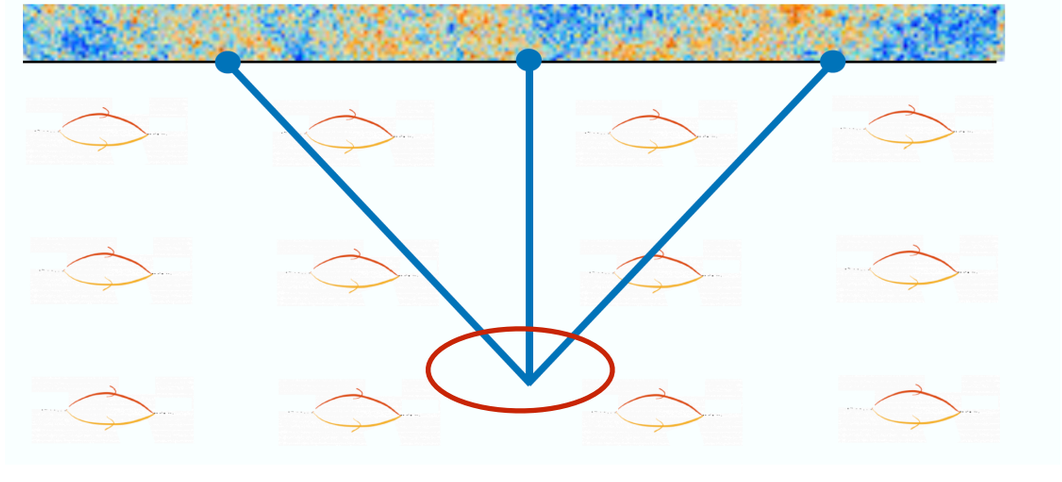
There are no particles in the vacuum!



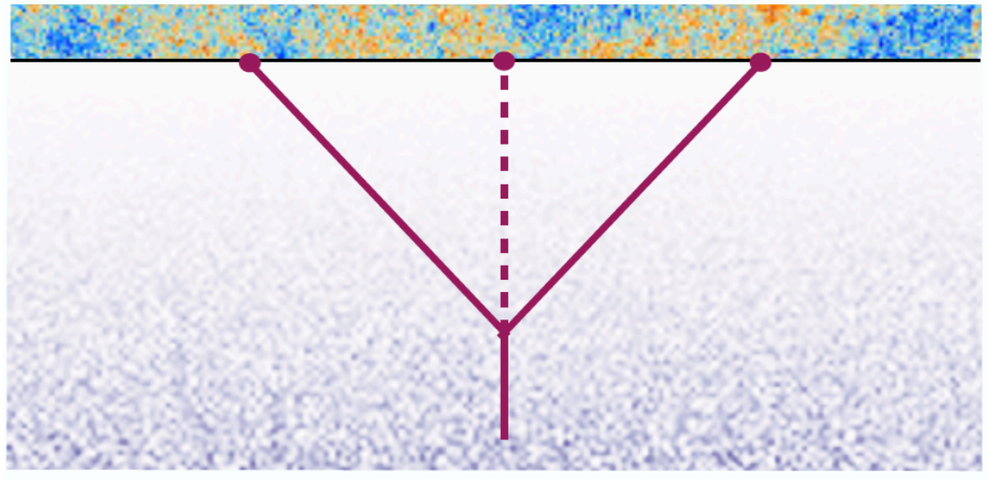
The state has a **very large number** of particles that can be ***'annihilated'***

Signals of a Quantum Universe

Green
RAP



Quantum (Vaccum)



(Semi-)Classical

$$\langle\zeta(\mathbf{x}_1,\tau)\zeta(\mathbf{x}_2,\tau)\zeta(\mathbf{x}_3,\tau)\rangle_q - \langle\zeta(\mathbf{x}_1,\tau)\zeta(\mathbf{x}_2,\tau)\zeta(\mathbf{x}_3,\tau)\rangle_c =$$

$$+\frac{i\lambda}{4}\int_{-\infty}^{\tau} d\tau' d^3x' a^4(\tau')\underbrace{[\zeta(\mathbf{x}_1,\tau),\dot{\zeta}(\mathbf{x}',\tau')]}[\zeta(\mathbf{x}_2,\tau),\dot{\zeta}(\mathbf{x}',\tau')]\underbrace{[\zeta(\mathbf{x}_3,\tau),\dot{\zeta}(\mathbf{x}',\tau')]},$$

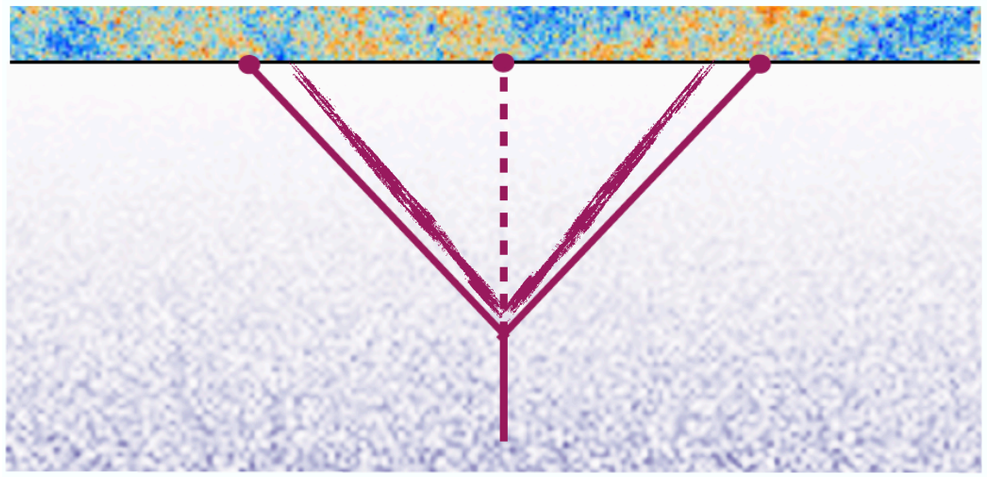
vanishes outside of the light cone

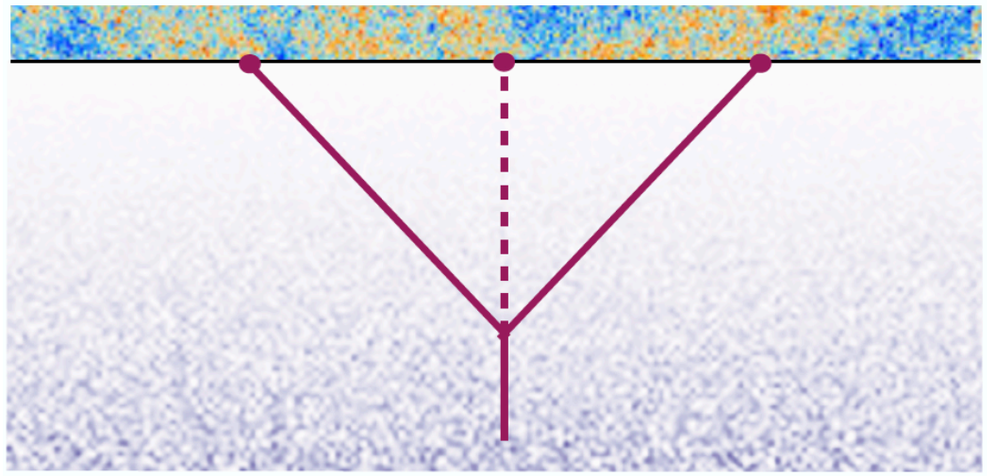
non-zero in QM!

The correlations are created **inside the horizon**
in the intersection of the past light-cones — **can't be changed later!**

Signals of a Quantum Universe

Green
RAP





Non-Local **(Semi-)Classical**

(Semi-)Classical

Hidden variables?

$$G^{\rm eff}_{\mathbf{k}}(\tau \to 0, \tau') = \frac{1}{k} e^{-ik\tau'} \,,$$

Flips the the signs by decaying to ‘anti-particles’ leading to kt pole (only positive modes)

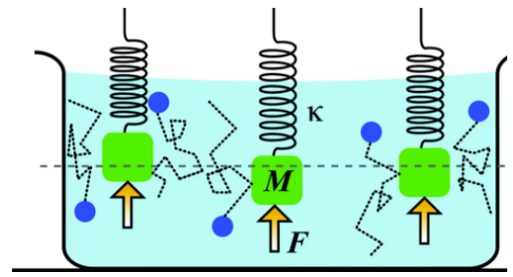
This theory is non-local!

$$G^{\rm eff}_{\mathbf{k}}(\tau' \to 0) \simeq k^{-1}$$

Causal Green’s function

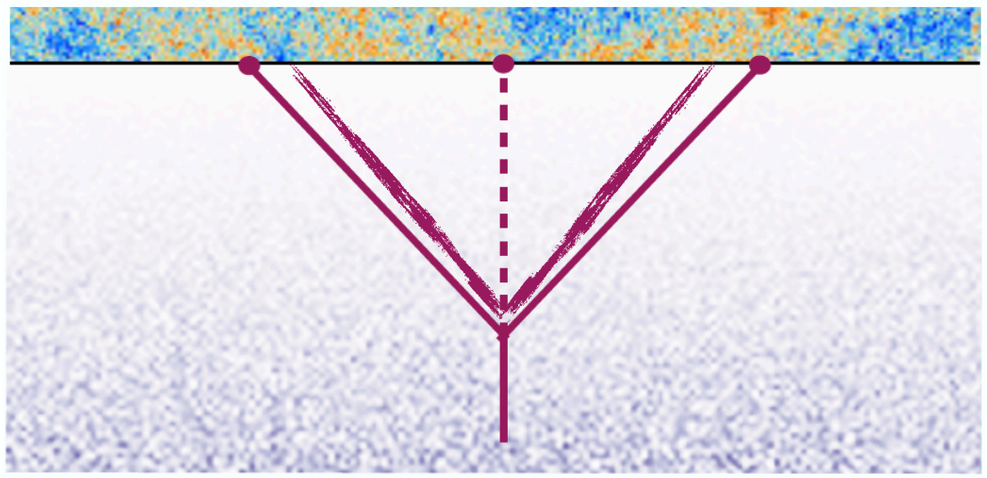
$$G^{\rm eff,causal}_{\mathbf{k}}(\tau \to 0, \tau') \propto \frac{1}{k} \sin(k\tau') \,,$$

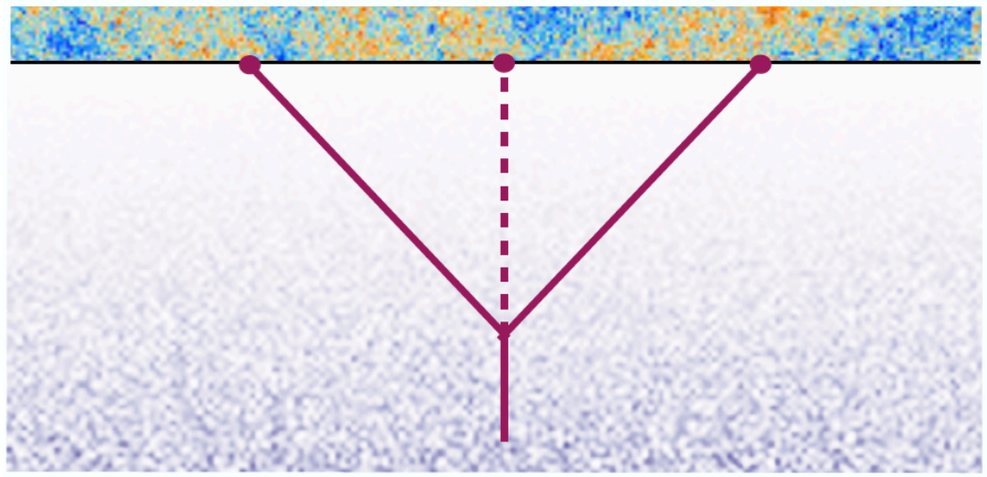
both positive/negative modes



Signals of a Quantum Universe

Green
RAP





Non-Local **(Semi-)Classical**

(Semi-)Classical

Hidden variables?

$$G_{\mathbf{k}}^{\rm eff}(\tau \to 0, \tau') = \frac{1}{k} e^{-ik\tau'} \,,$$

Flips the the signs by decaying to ‘anti-particles’ leading to same kt pole (only positive modes)

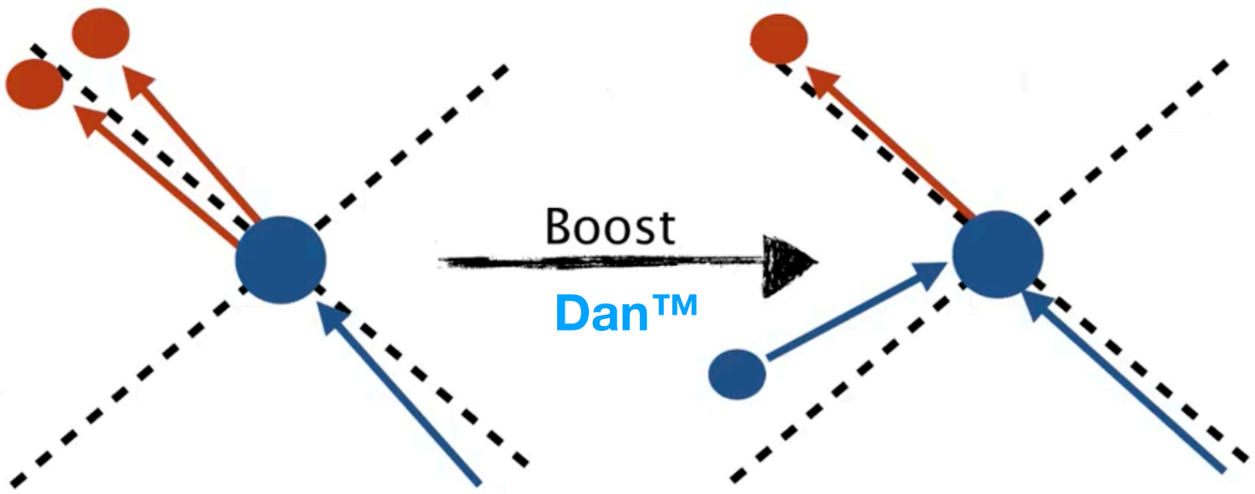
This theory is non-local!

$$G_{\mathbf{k}}^{\rm eff}(\tau' \to 0) \simeq k^{-1}$$

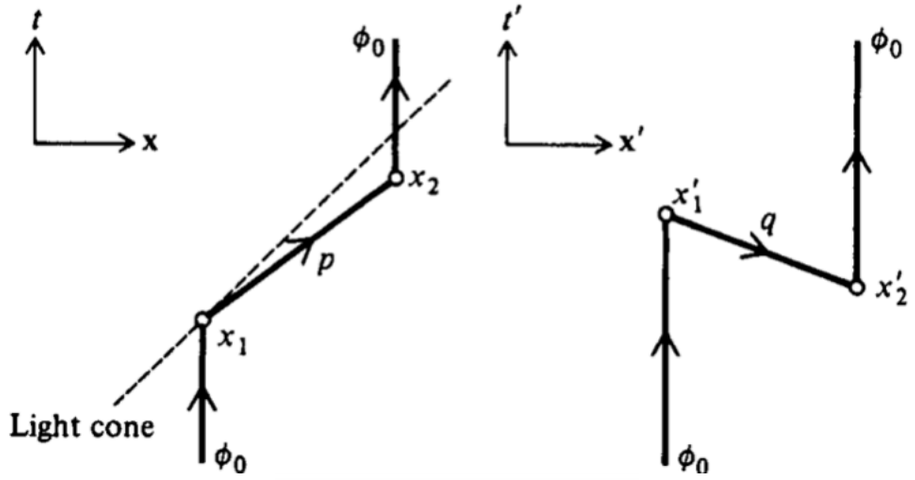
Can make causal with no anti-particles but lack long-range!

$$G_{\mathbf{k}}^{\rm eff,causal}(\tau \to 0, \tau') = \tau'^{\alpha} k^{2\beta} \,,$$

This needs a UV completion!
(“slowly moving”)



Lorentz invariance requires they come together



THE REASON
FOR ANTIPARTICLES

Richard P. Feynman

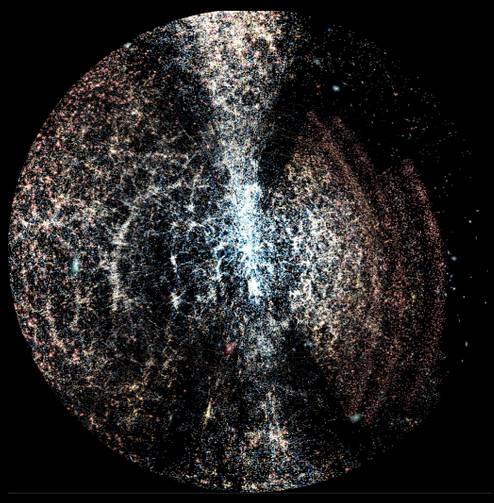
If a function $f(t)$ can be Fourier decomposed into positive frequencies only, i.e. if it can be written

$$f(t) = \int_0^\infty e^{-i\omega t} F(\omega)\, d\omega, \qquad (4)$$

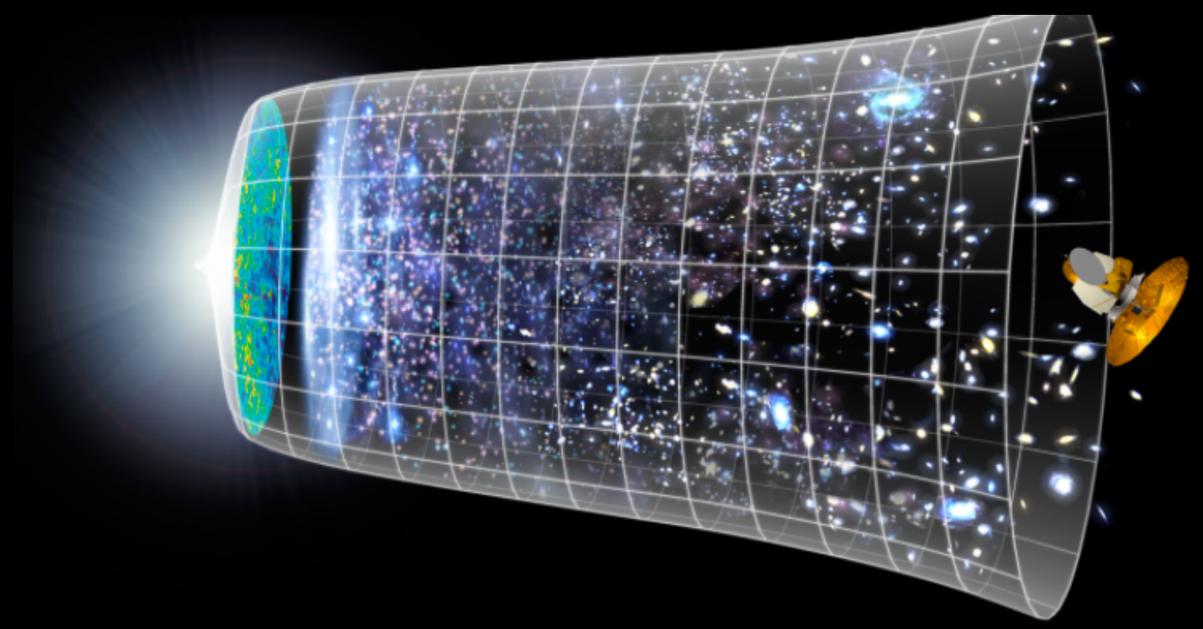
then f cannot be zero for any finite range of t, unless trivially it is zero everywhere. The validity of this theorem depends on $F(\omega)$ satisfying certain properties, the details of which I would prefer to avoid.

You may be a bit surprised at this theorem because you know you can take a function which is zero over a finite range and Fourier analyze it, but then you get positive *and* negative frequencies. I am insisting that the frequencies be positive only.

Relativistic dynamics must allow for all processes (crossing!)



- Outlook
  (Take home message)



Green
RAP

Signals of a Quantum Universe

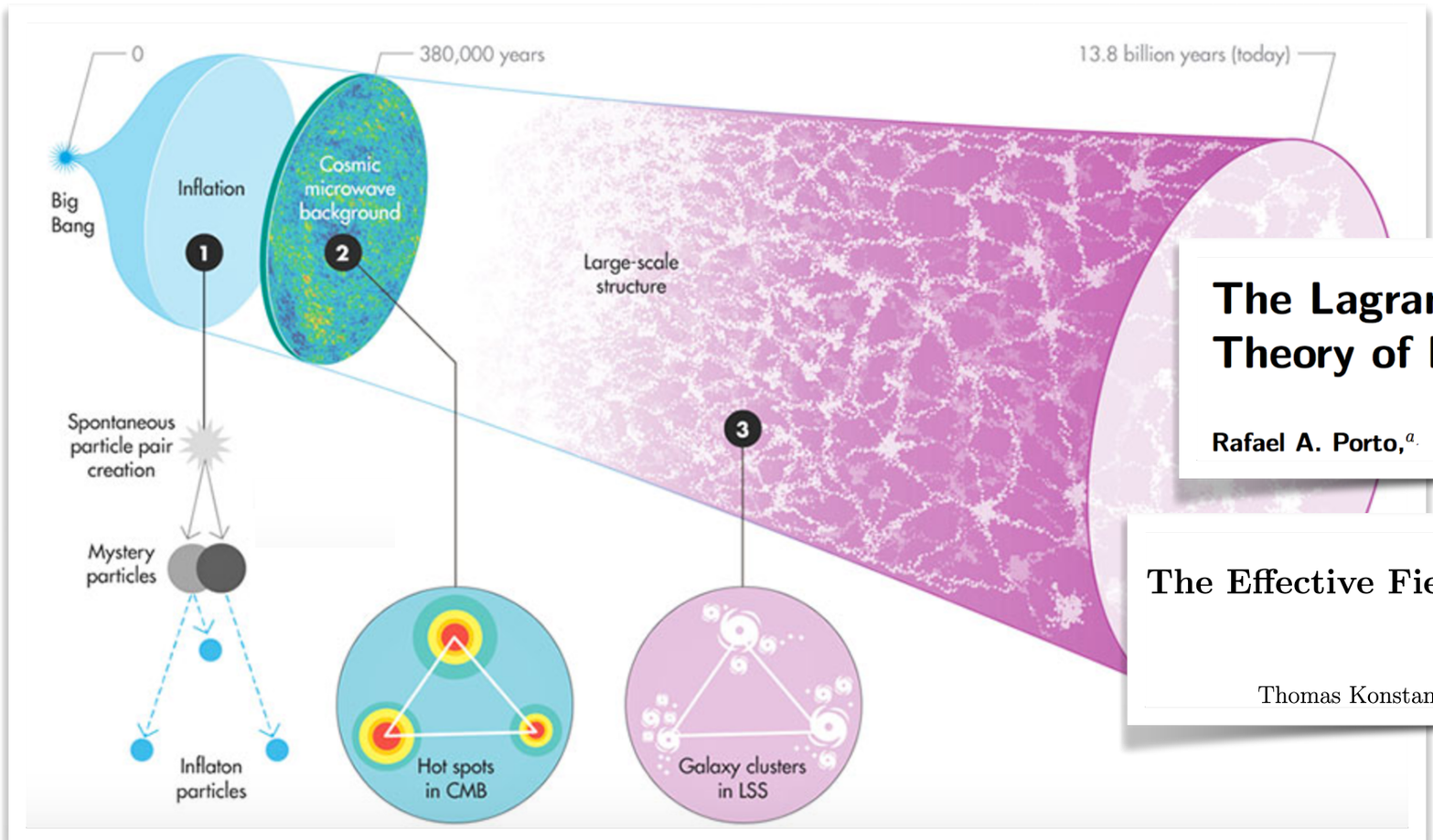
Structure in the Universe is widely believed to have originated from *quantum* fluctuations during an early epoch of accelerated expansion. Yet, the patterns we observe today do not distinguish between quantum or classical primordial fluctuations; current cosmological data is consistent with either possibility. We argue here that a detection of primordial non-Gaussianity can resolve the present situation, and provide a litmus-test for the quantum origin of cosmic structure. Unlike in quantum mechanics, vacuum fluctuations cannot arise in classical theories and therefore long-range classical correlations must result from (real) particles in the initial state. Similarly to flat-space scattering processes, we show how basic principles require these particles to manifest themselves as poles in the n-point functions, in the so-called folded configurations. Following this observation, and assuming fluctuations are *(i)* correlated over large scales, and *(ii)* generated by local evolution during an inflationary phase, we demonstrate that: *the absence of a pole in the folded limit of non-Gaussian correlators uniquely identifies the quantum vacuum as the initial state*. In the same spirit as Bell's inequalities, we discuss how this can be circumvented if locality is abandoned. We also briefly discuss the implications for simulations of a non-Gaussian universe.

A theoretical threshold must be an observational target!!

$$\frac{\langle\zeta\zeta\zeta\rangle}{\langle\zeta\zeta\rangle^{3/2}} \lesssim 10^{-5}$$

threshold

The primordial seed is in the distribution of galaxies!

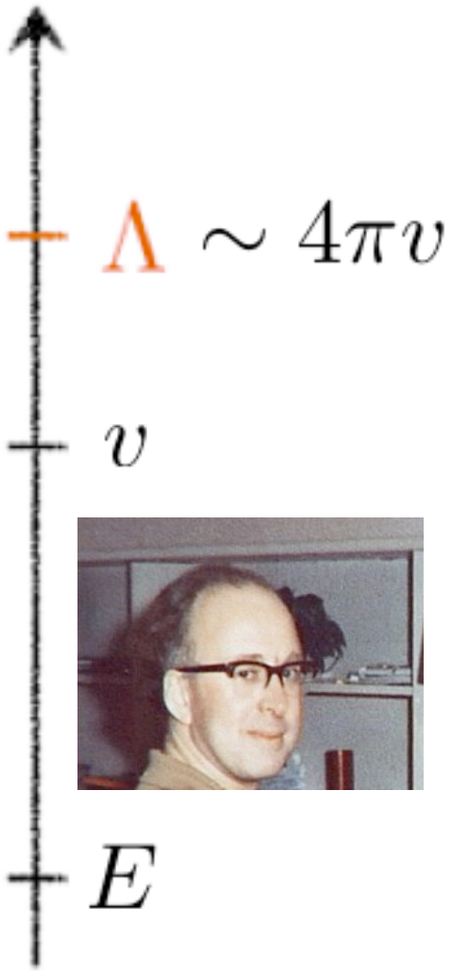


The Lagrangian-space Effective Field Theory of large scale structures

Rafael A. Porto,[a] Leonardo Senatore[c,d,e] and Matias Zaldarriaga[a]

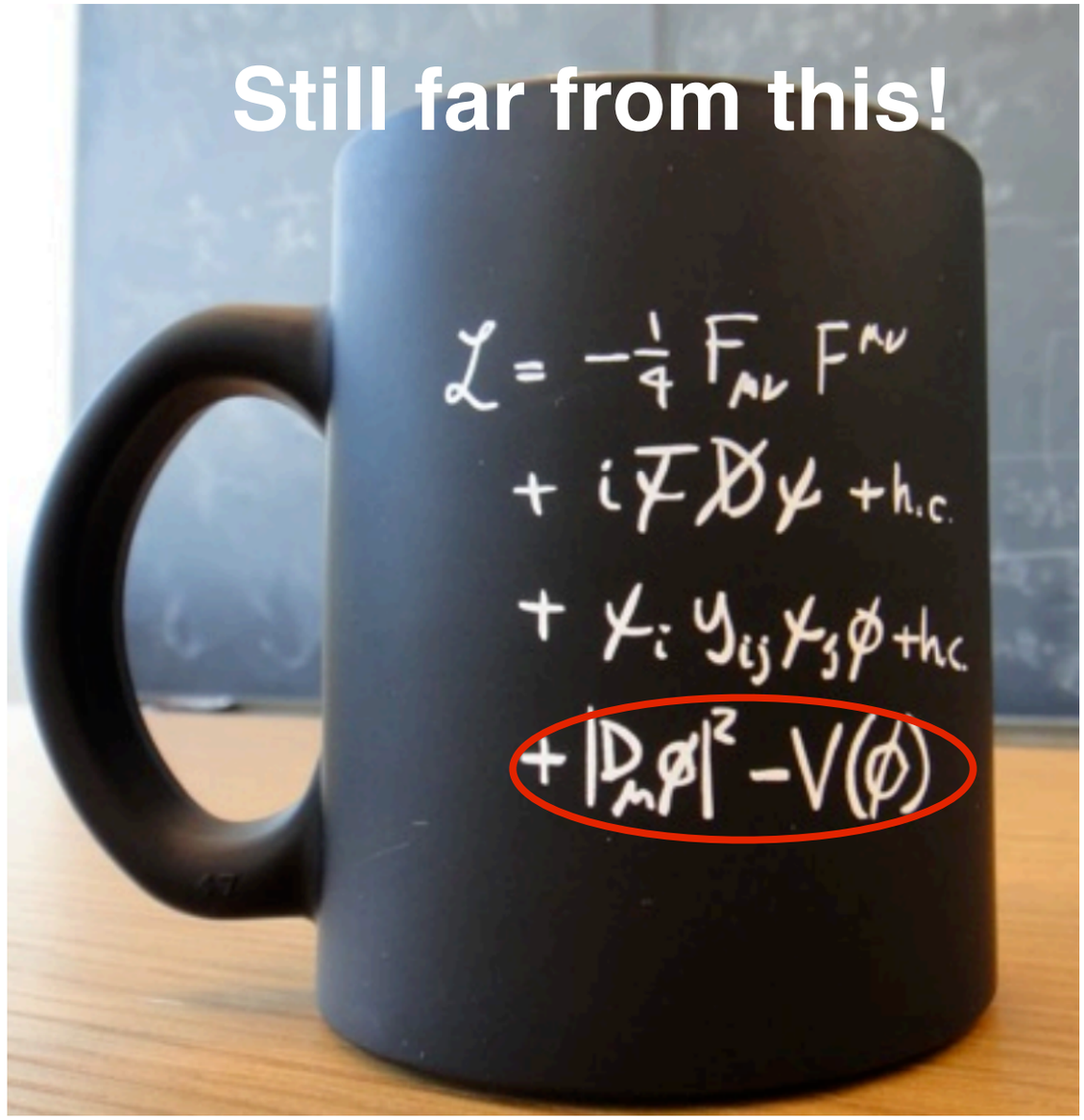
The Effective Field Theory of Large Scale Structure at Three Loops

Thomas Konstandin,[1] Rafael A. Porto[1,2] and Henrique Rubira[1,3]

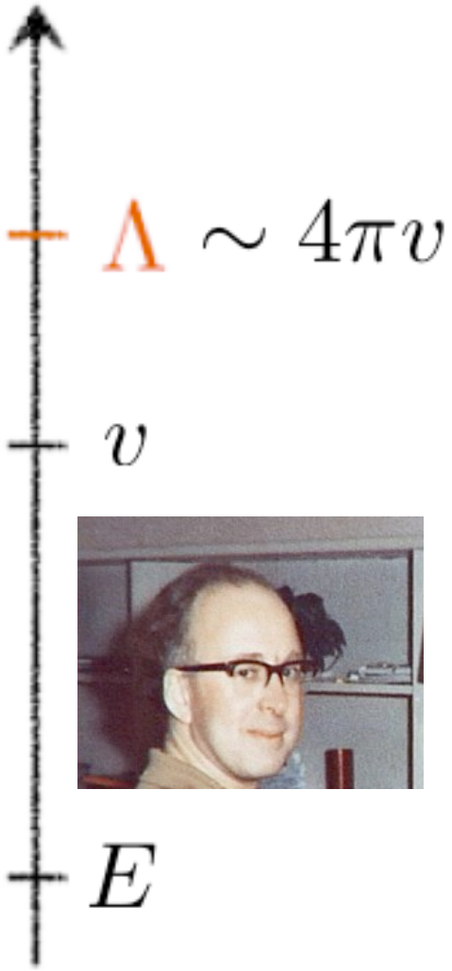


KEEP
CALM
AND
PROCEED
WITH CAUTION

Particle Physics Analogy

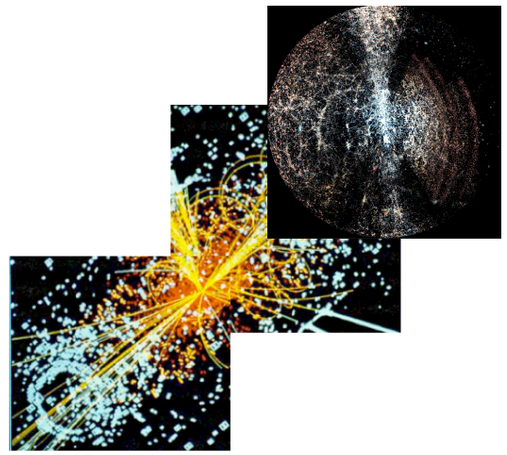


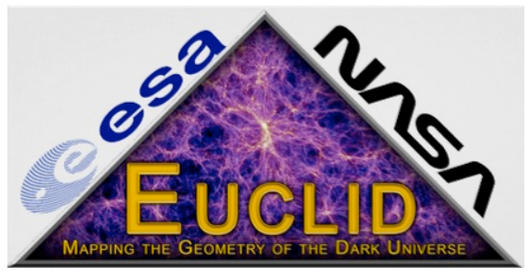
The situation ‘resembles’
pre-Large Hadron Collider
(many possible UV completions
for cold and/or warm inflation?)



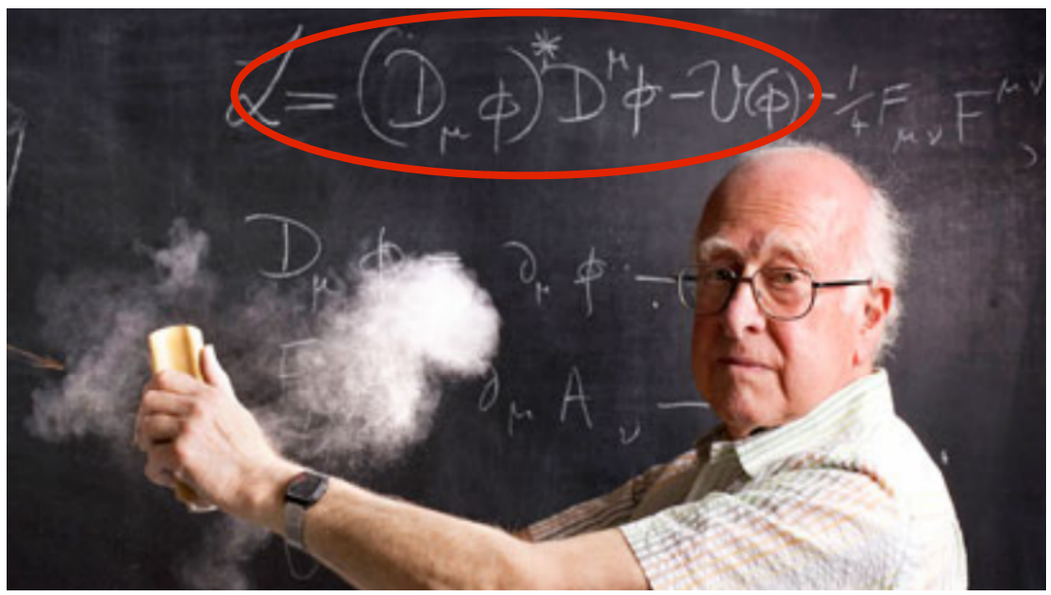
KEEP
CALM
AND
PROCEED
WITH CAUTION

Particle Physics Analogy

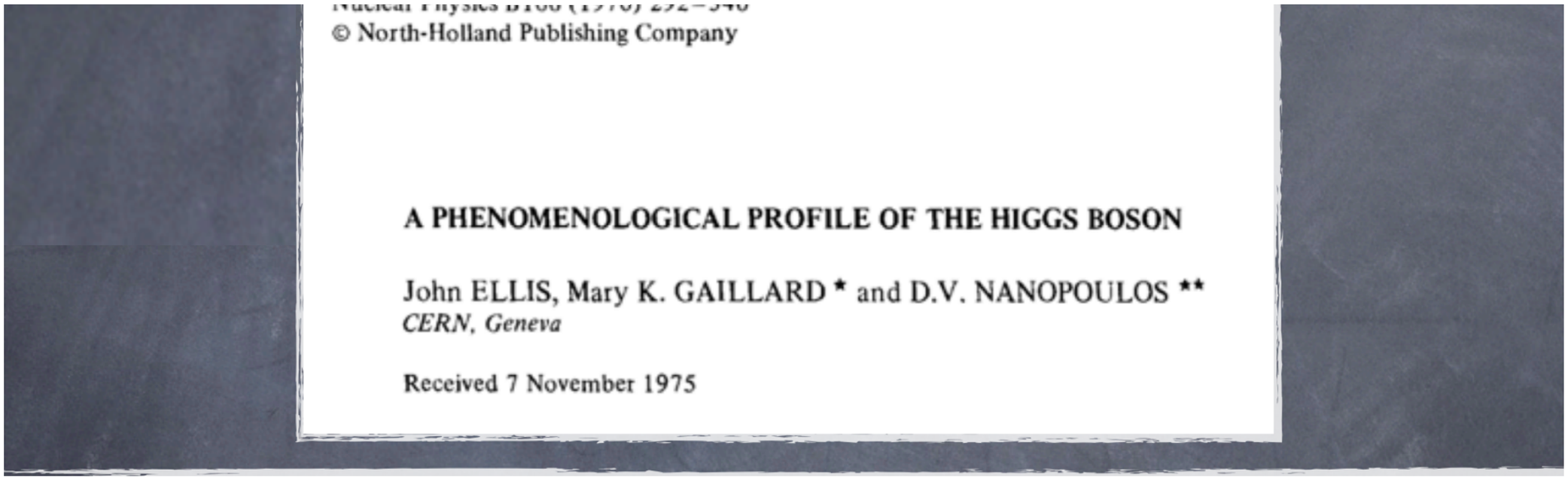




(hopefully sooner!)



Historical lesson



Nuclear Physics B150 (1979) 292–340

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

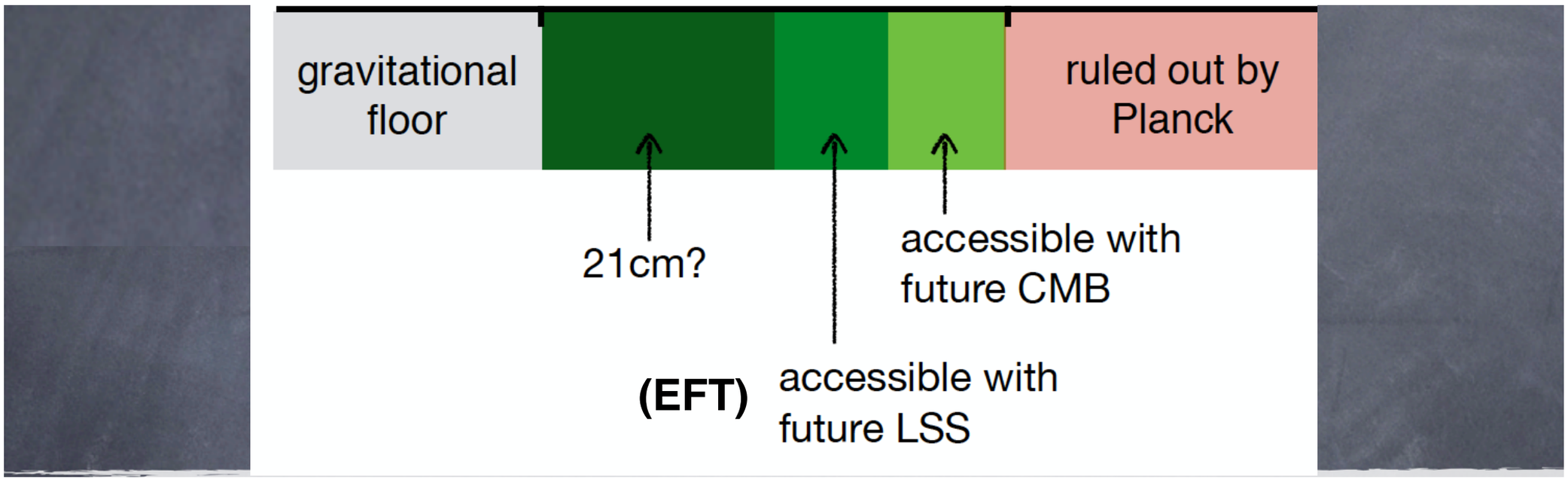
$$\frac{\langle\zeta\zeta\zeta\rangle}{\langle\zeta\zeta\rangle^{3/2}} \lesssim 10^{-5}$$

threshold

4 orders of magnitude

$$\frac{\langle\zeta\zeta\zeta\rangle}{\langle\zeta\zeta\rangle^{3/2}} \lesssim 10^{-3}$$

Planck [2015]



We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Replace ‘the Higgs boson’ by ‘NG initial conditions’

Thank you for listening!