The story of a simpler universe

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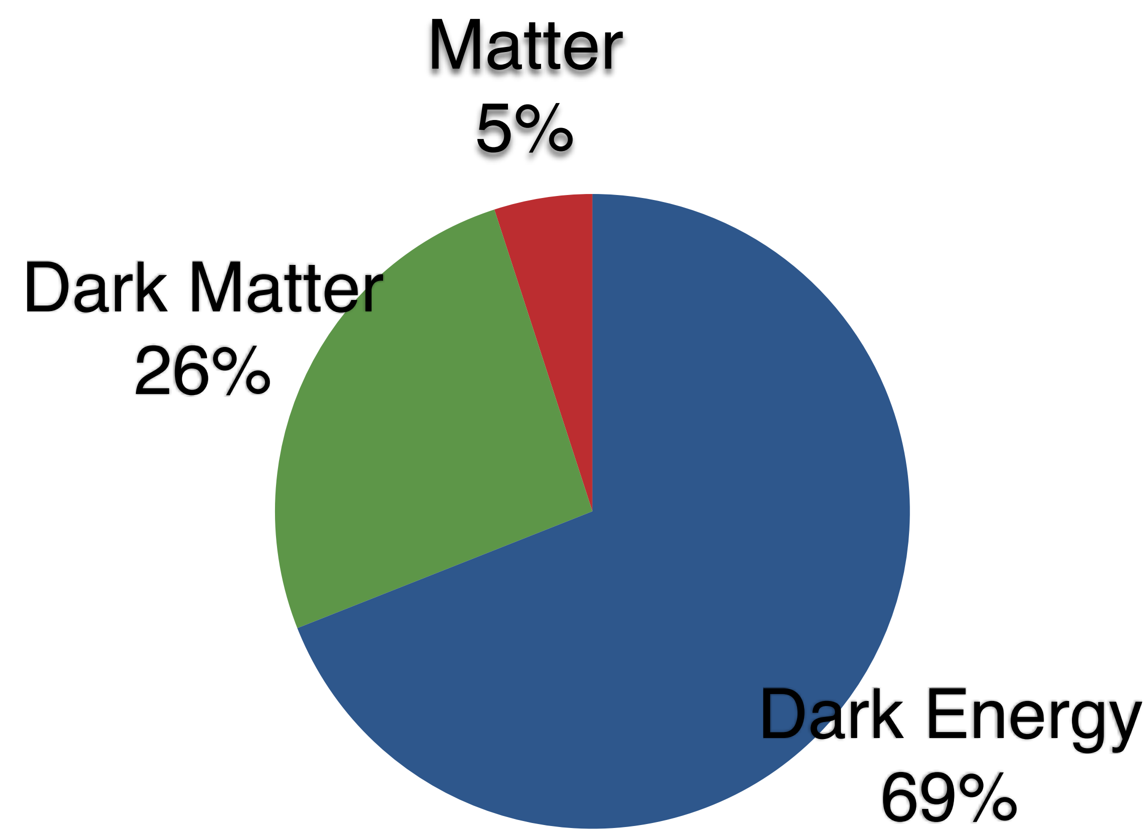
Outline

- Introduction: how the universe just got simpler
- The conformal limit of inflation
- The origin of the adiabatic mode
- Conclusion

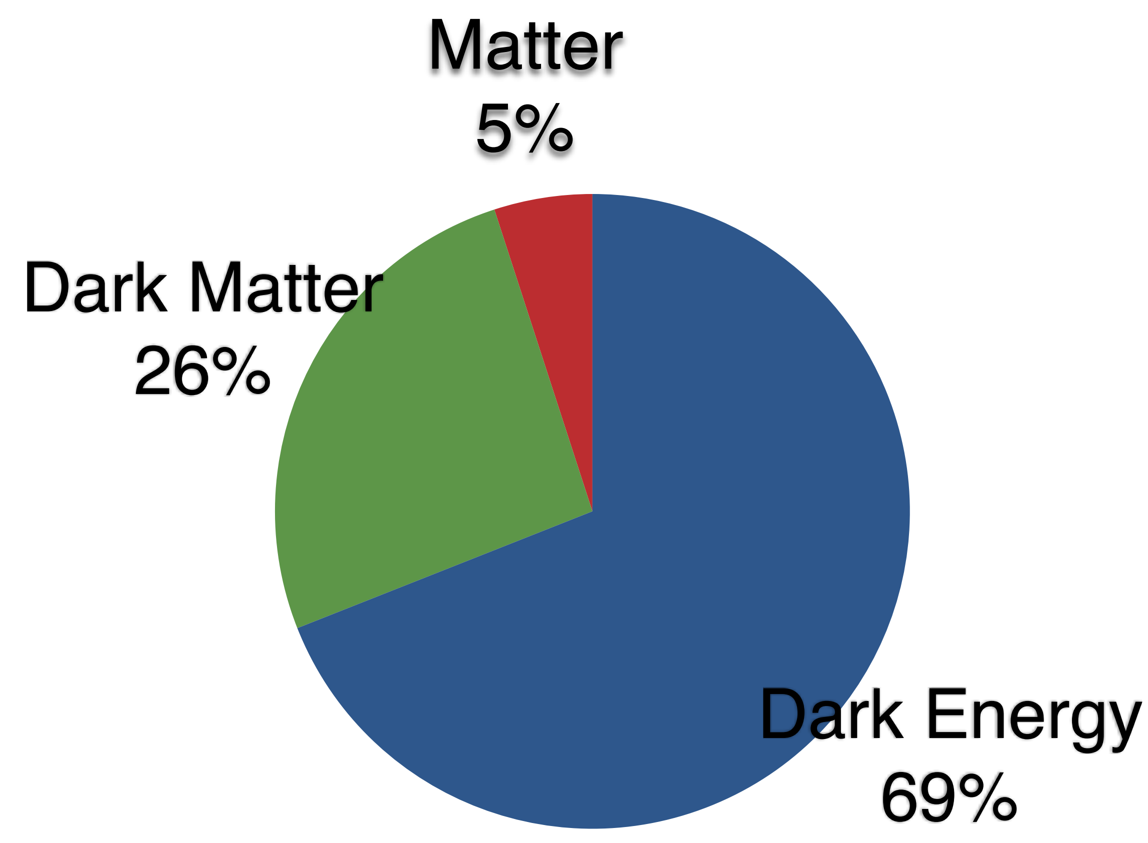
Introduction

- Cosmic pies
- Cosmic pies recipe book
- No news is interesting news

Cosmic pies



Cosmic pies


Matter
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Dark Matter
26%
Dark Energy
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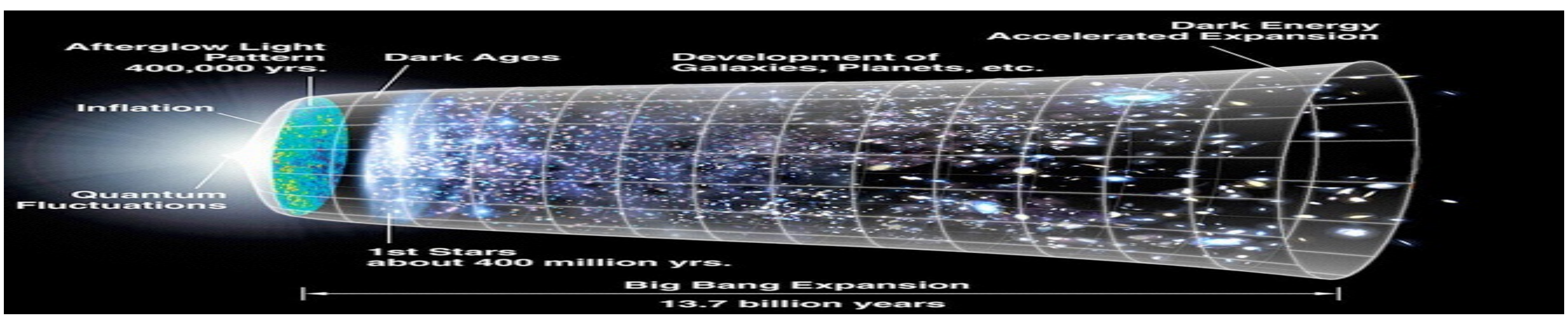
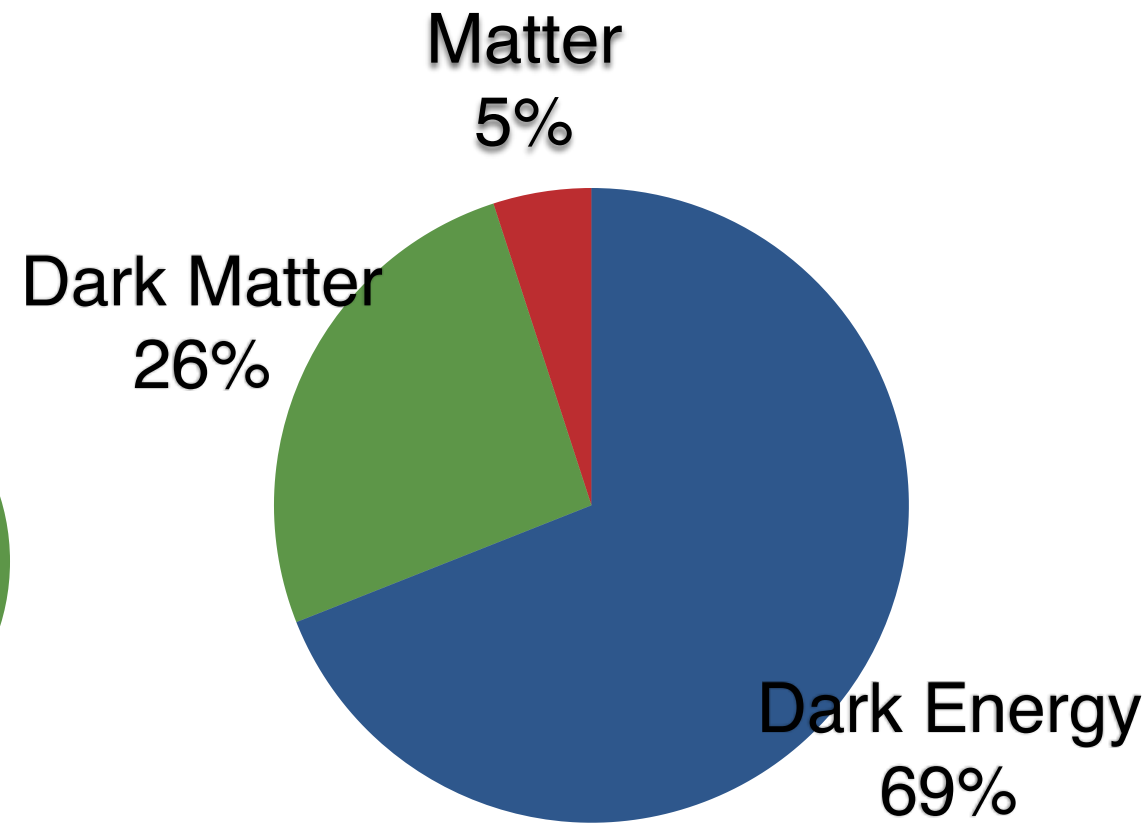

Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Dark Energy
Accelerated Expansion
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Cosmic pies


Matter
100%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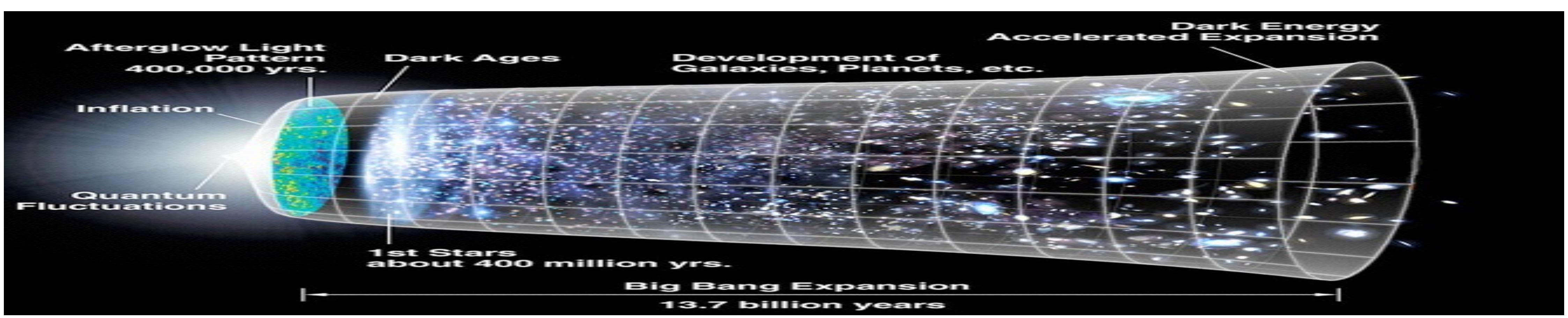
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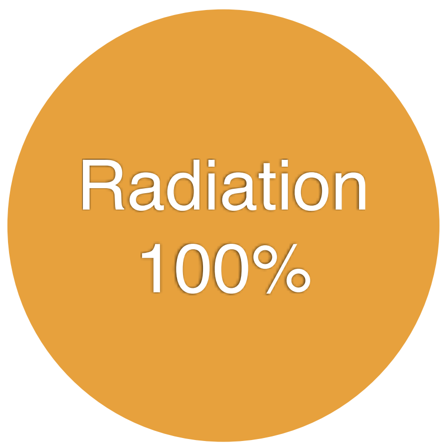
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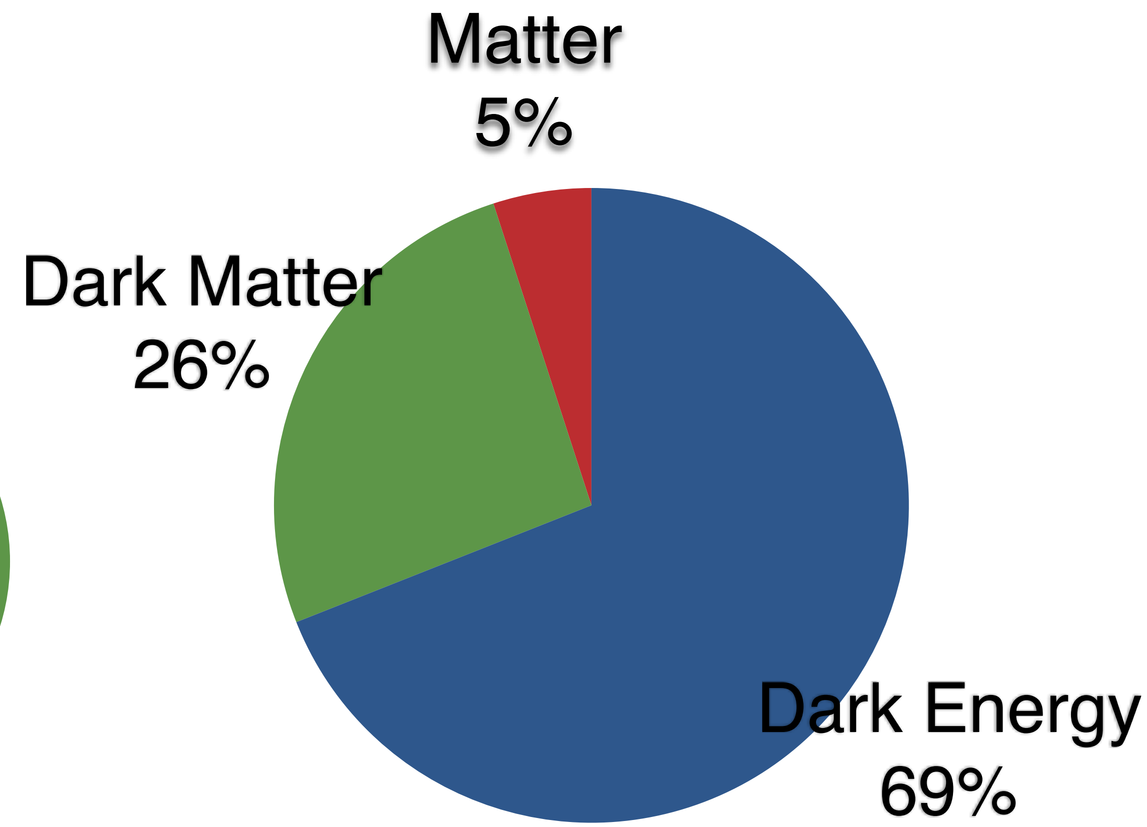
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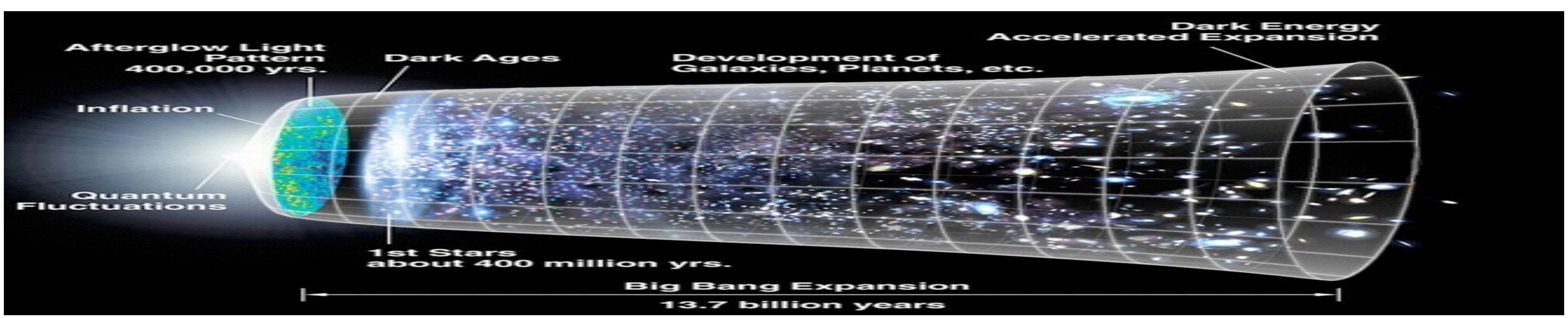
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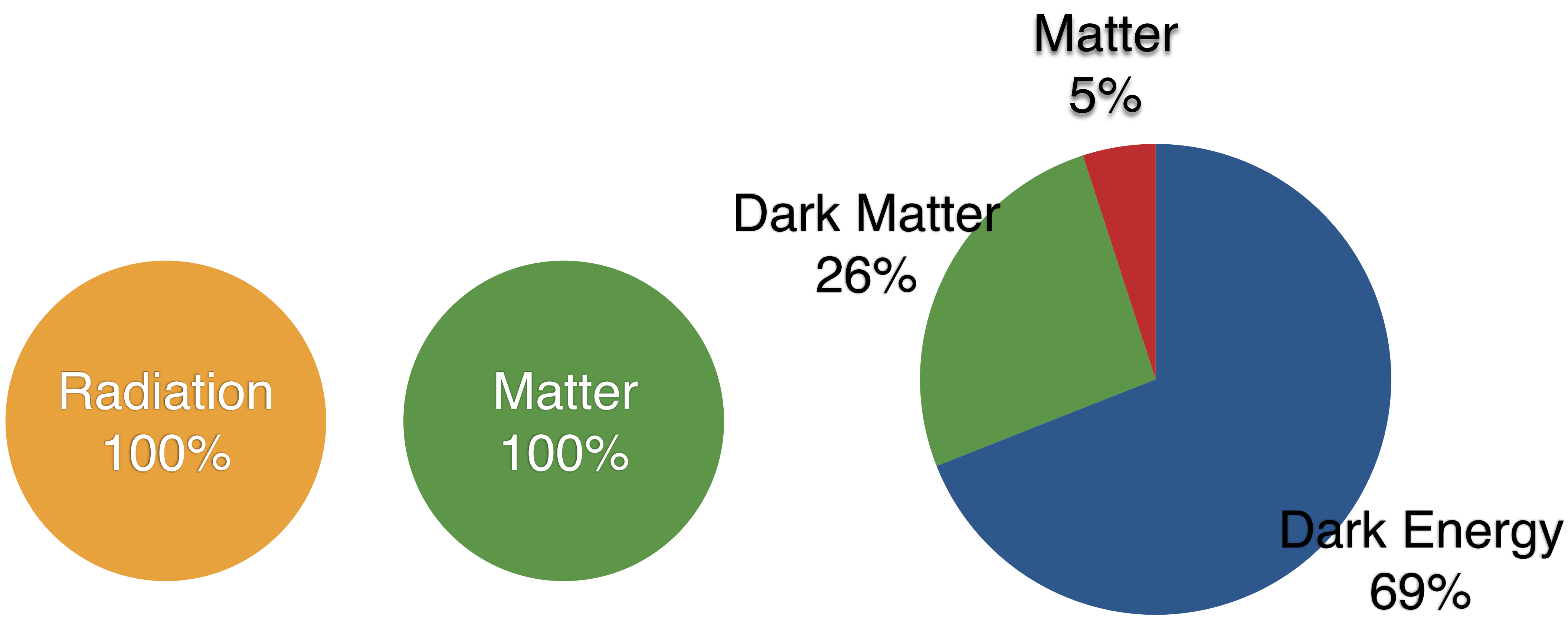
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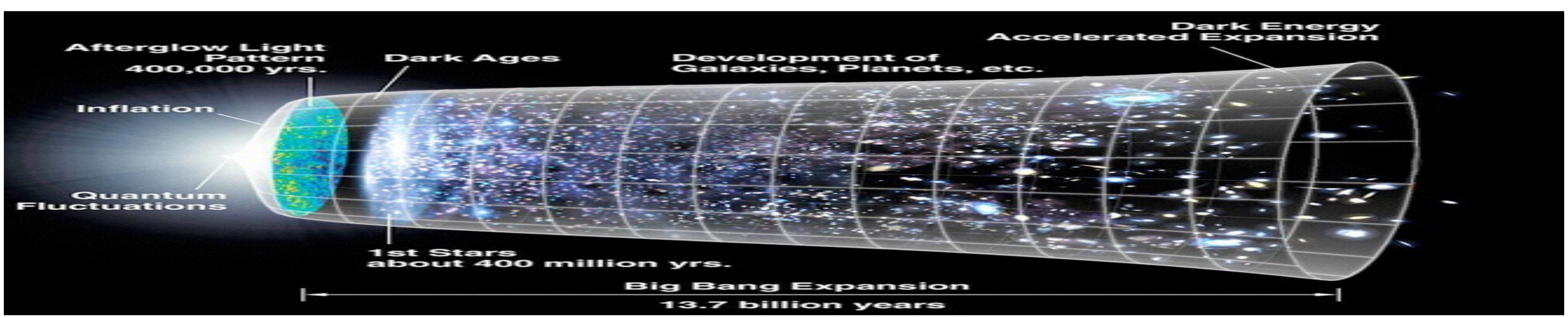
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Cosmic (pie) evolution

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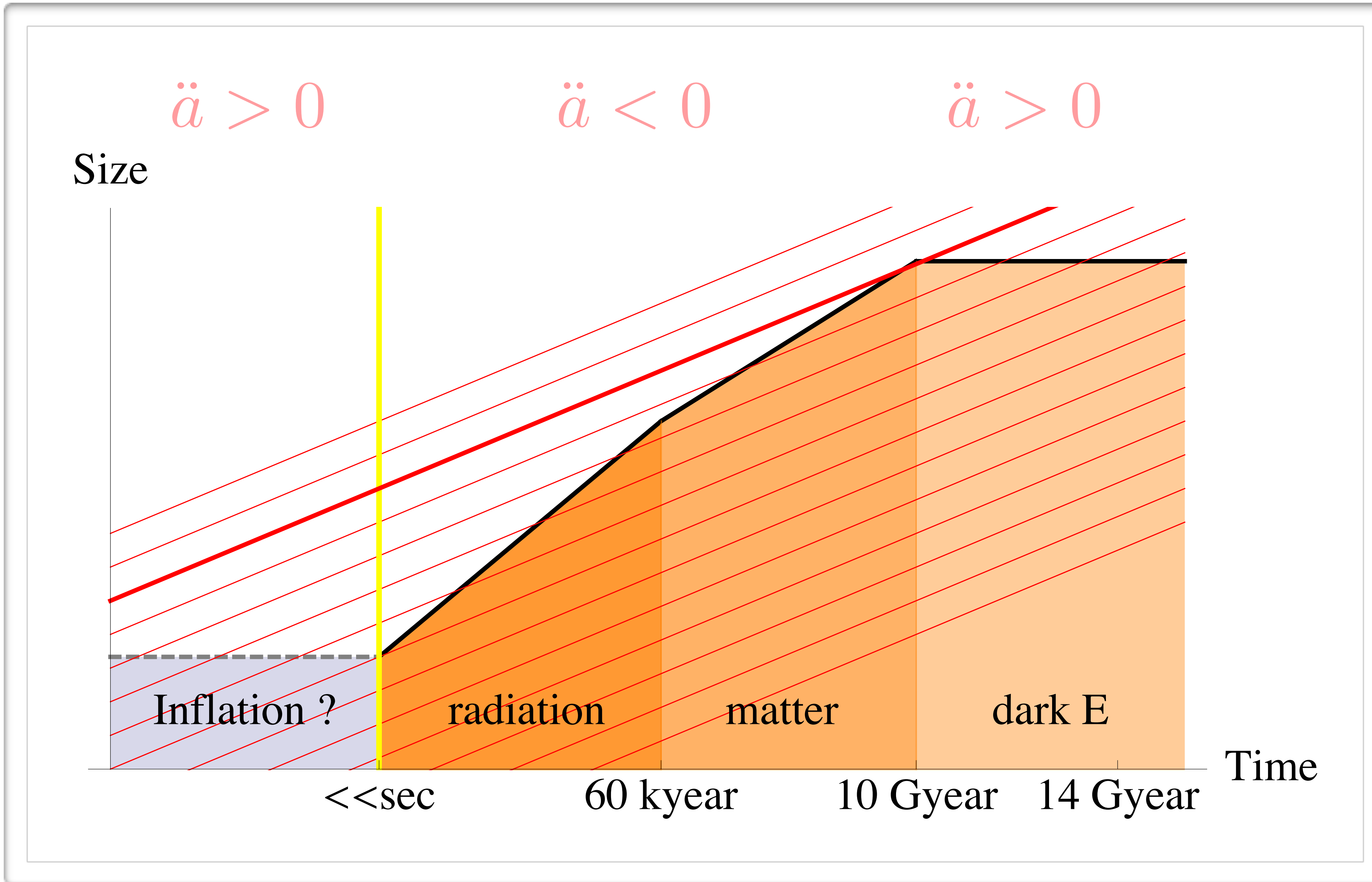

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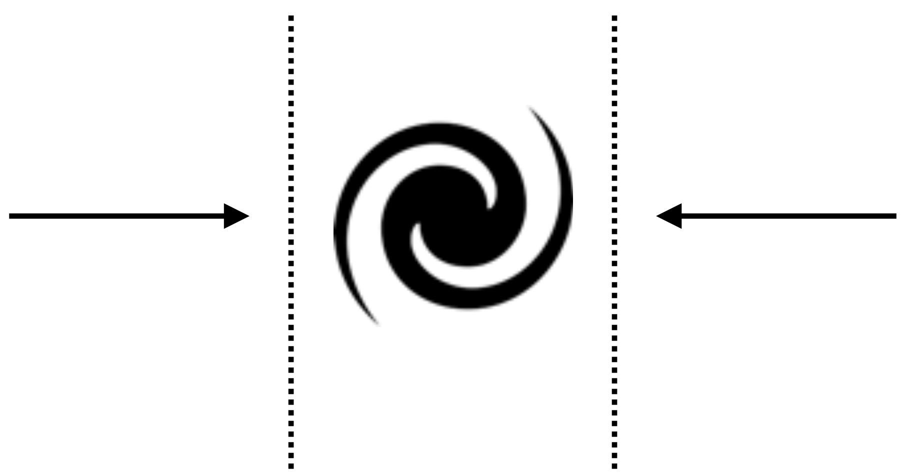
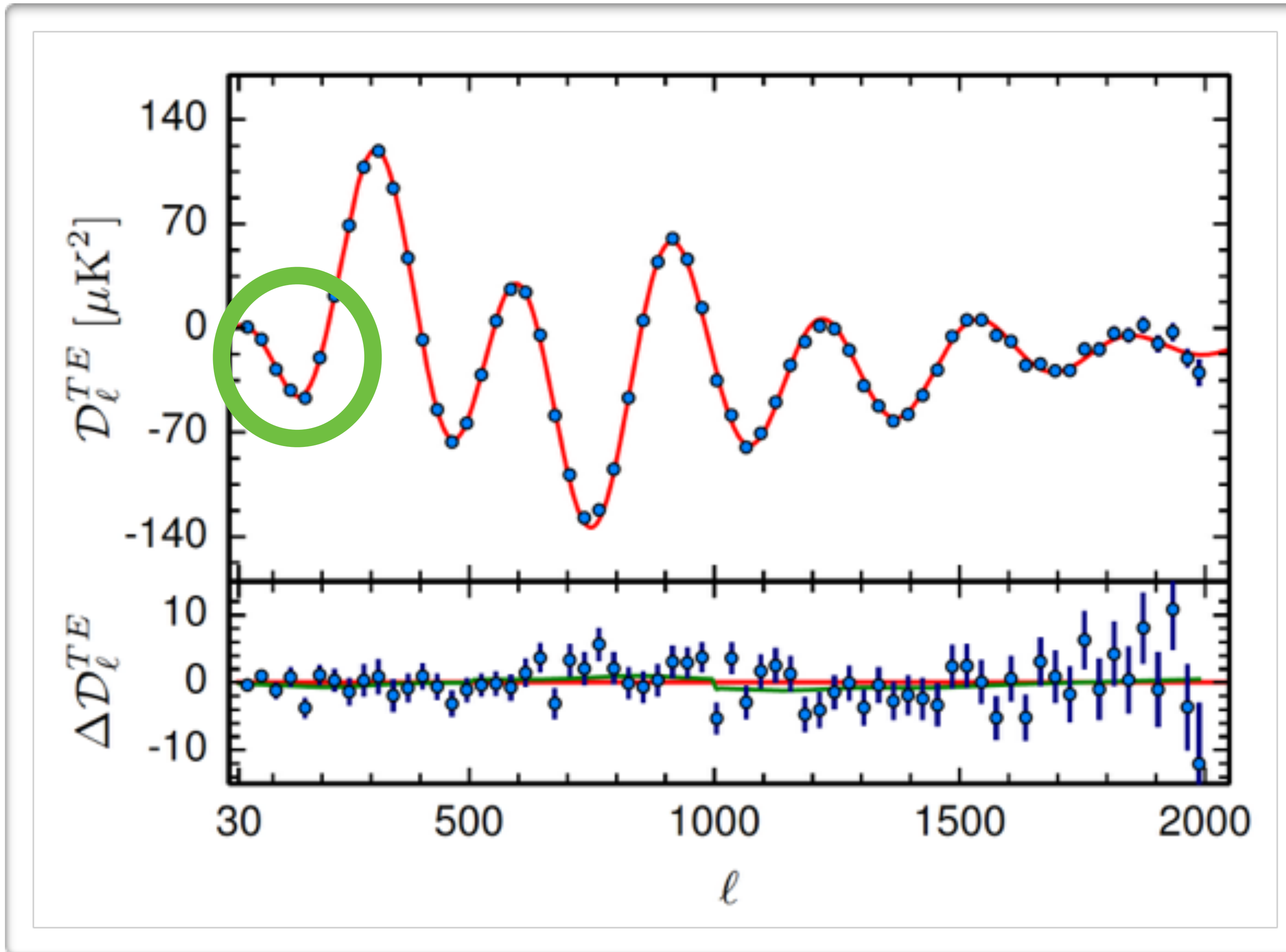
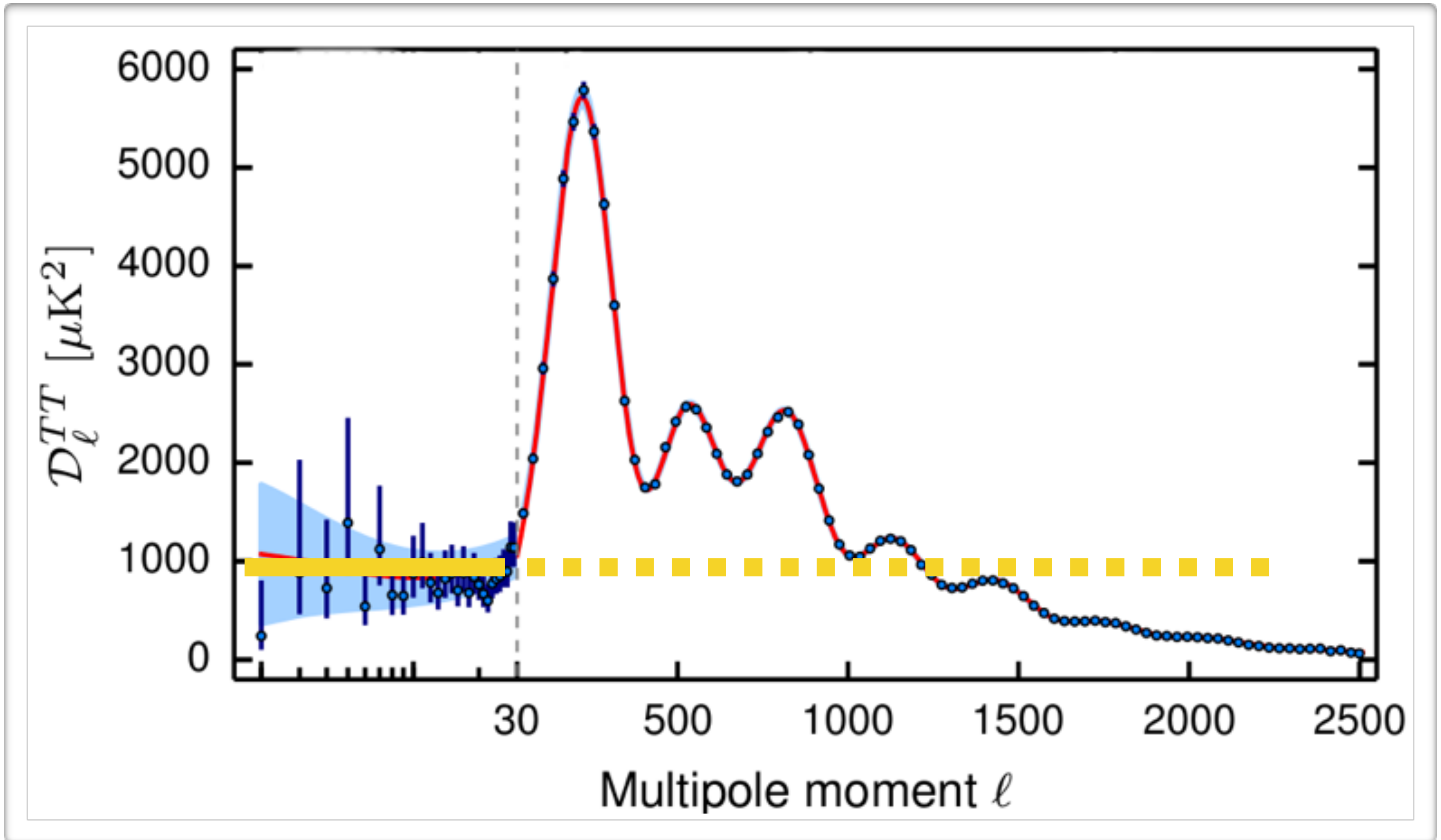
Cosmic recipe book, or how we learned to love inflation



Out-of-phase, coherent waves. Primordial explanation!

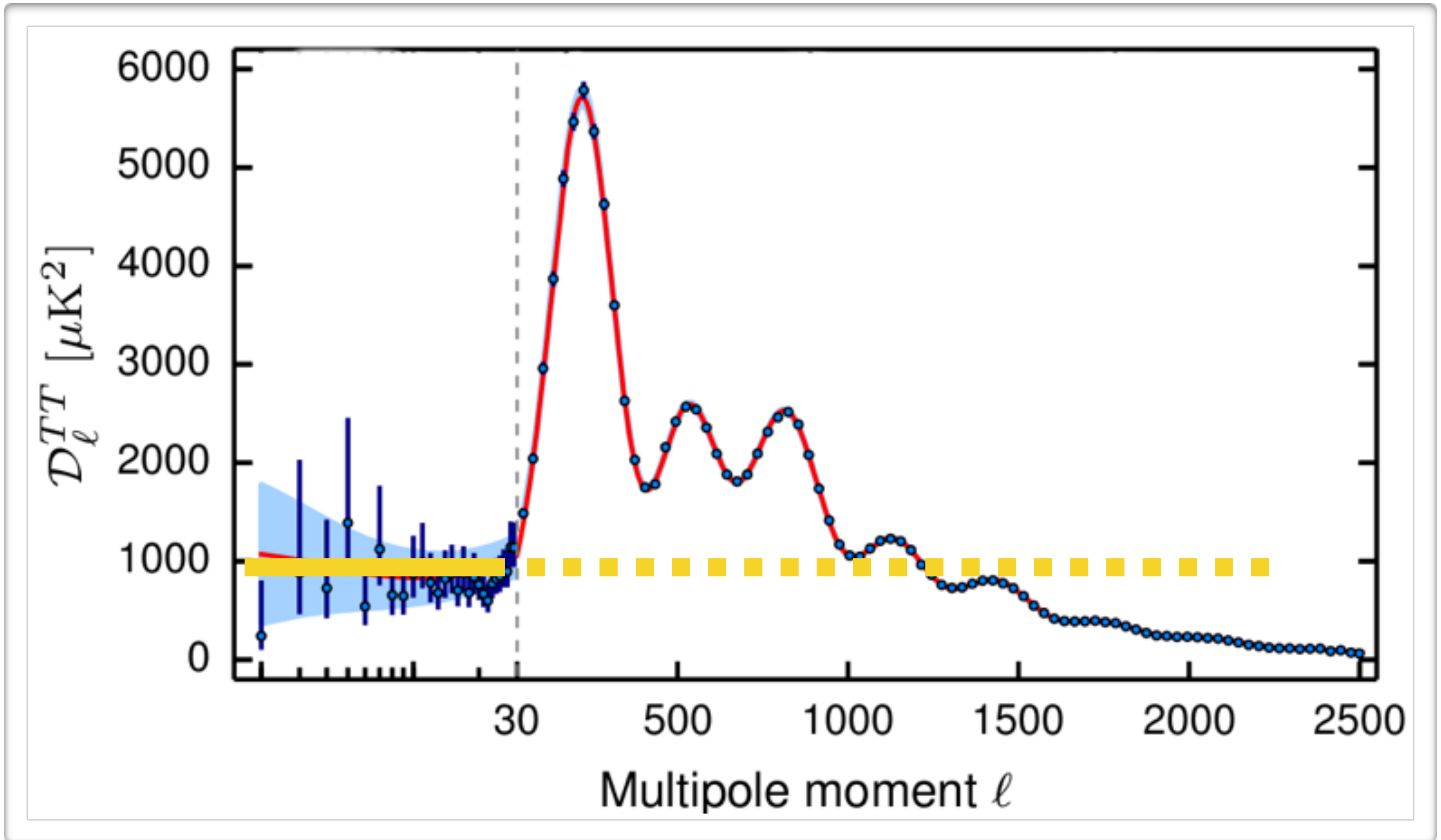


Scale invariance



Scale invariance emerges naturally from *de Sitter isometries*

Scale invariance



Scale invariance emerges naturally from *de Sitter isometries*

Inflation

- A phase of quasi-de Sitter (accelerated expansion) in the first fraction of a second
- At least one (new) field, the *inflaton*
- At least three *new* (independent?) scales
    - Hubble Rate of expansion: H
    - Rate of deceleration: $\epsilon \equiv \frac{\dot{H}}{H^2}$
    - Rate of deceleration or inflaton mass: $\eta \equiv \frac{\dot{\epsilon}}{\epsilon H}$

Primordial power spectra

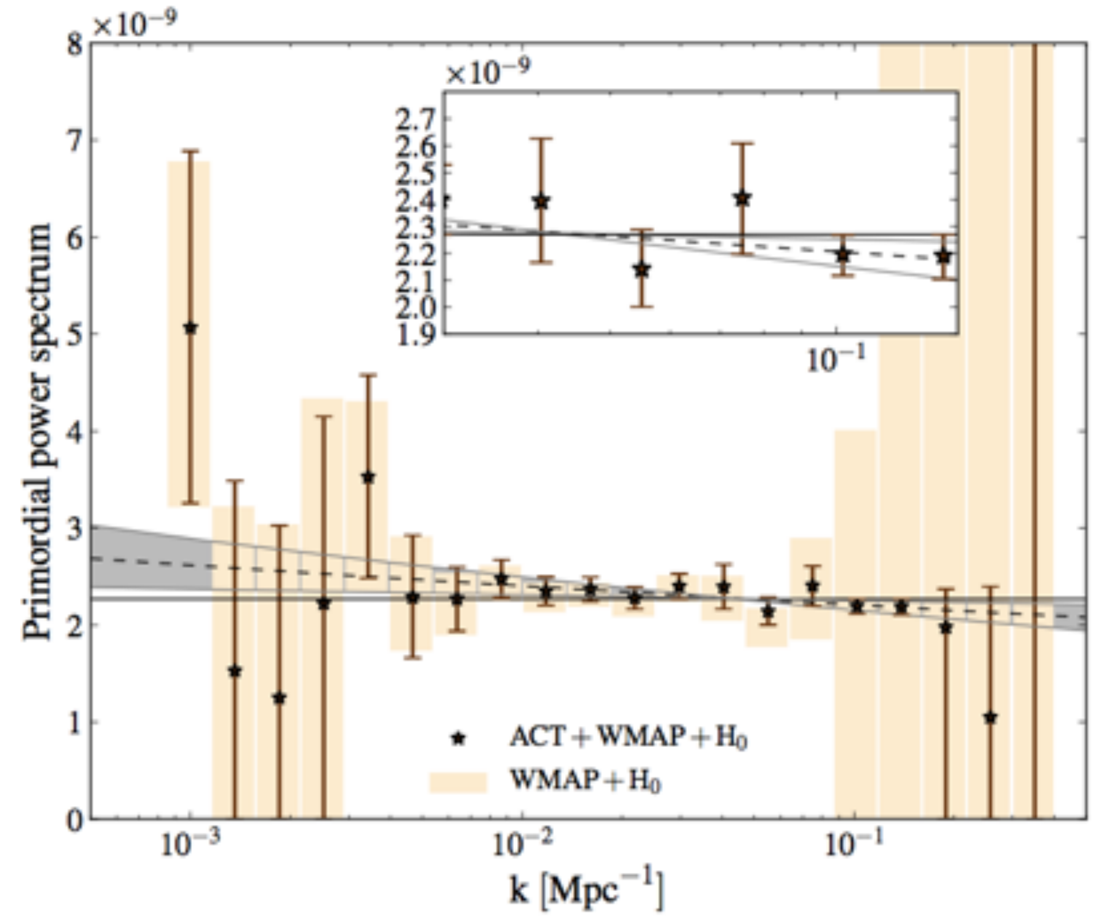
- Describe the free theory on time-dep background
- Scalars, a.k.a. *curvature* perturbation

$$\langle g_{ii}(k) g_{ii}(k) \rangle \sim \frac{H^2}{\epsilon M_{Pl}^2} \frac{1}{k^{3+(1-n_s)}}$$

- Tensors: aka *gravitational waves*

$$\langle \gamma_{ij}(k) \gamma_{ij}(k) \rangle \sim \frac{H^2}{M_{Pl}^2} \frac{1}{k^{3+8\epsilon}}$$

Observations

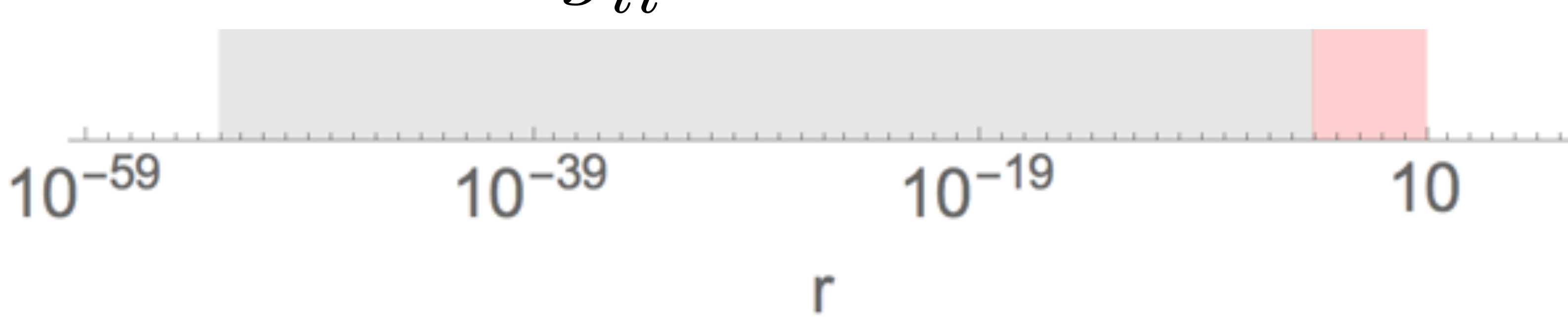


Observed:

- Scalar amplitude
- scalar tilt: $1 - n_s = 2\epsilon + \eta = 0.035$

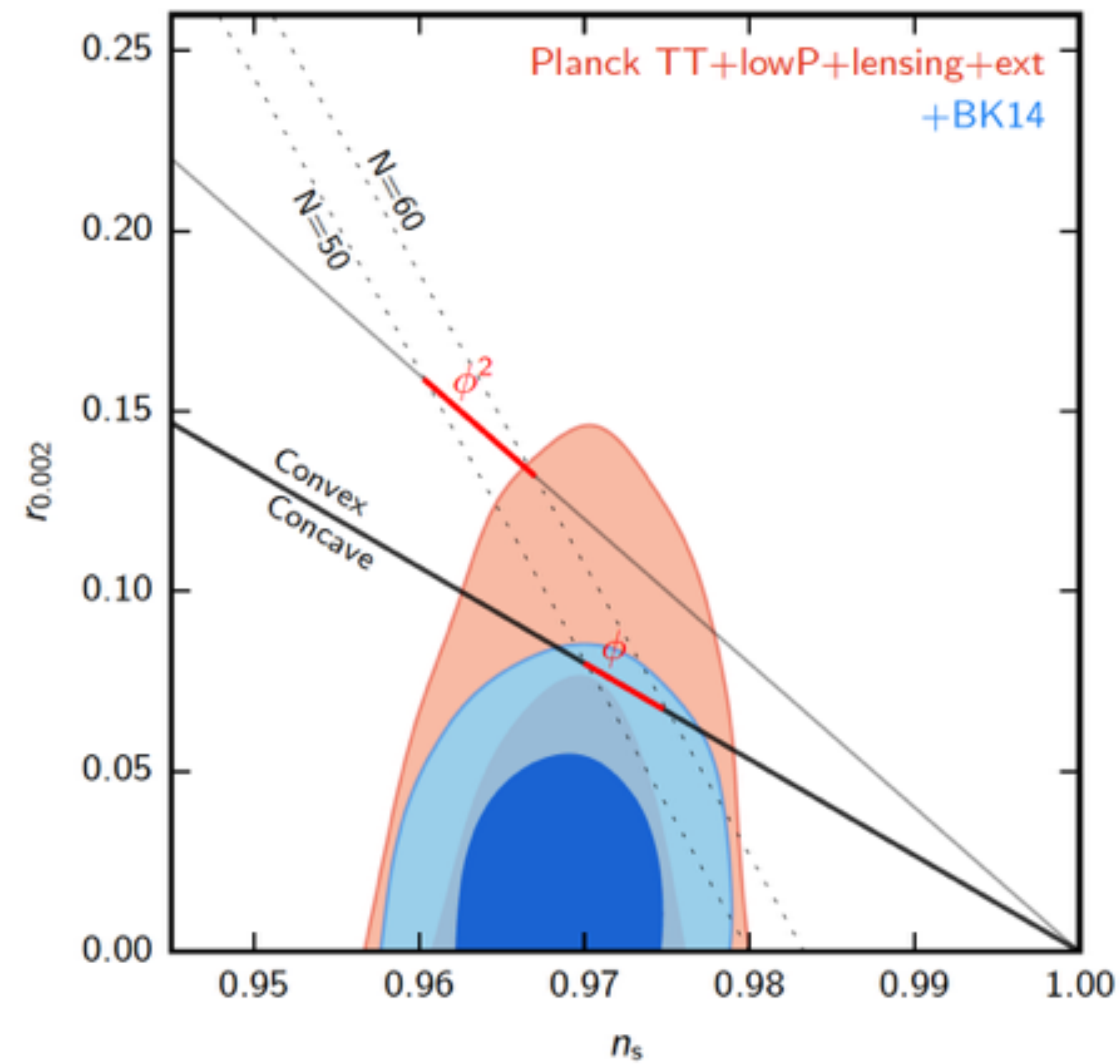
Might be observed in the future

- running of the scalar tilt: $\alpha_s \sim (1 - n_s)^2$
- tensor amplitude: $r \equiv \frac{\gamma^2}{g_{ii}^2} = 16\epsilon$ tensor tilt: $n_T = 8\epsilon$



No news is interesting news

- Improved constraints from CMB B-mode polarization lead to r<0.07 [Planck, Bicep2/Keck 15]
- The vanilla quadratic potential is out. Linear is next.
- A *new hierarchy* (of scales)



$$\left.\begin{aligned} 1 - n_s = 2\epsilon + \eta = 0.035 \\ r = 16\epsilon < 0.07 \end{aligned}\right\} \Rightarrow \epsilon \ll \eta$$

The conformal limit of inflation [with Mirbabayi, Pimentel, Simonovic, van Wijck to appear]

- New hierarchy of scales and slow-roll parameters
- de Sitter isometries and conformal symmetry
- All correlators are fixed by conformal sym.
- Consistency relations + Conformal symmetry
- Wave functional of the universe

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New slow-roll hierarchy

- To describe *our universe* the traditional slow-roll hierarchy needs to be updated for η>>ε
- *Decoupling limit* with fixed power spectrum

$$\epsilon \to 0 \quad \& \quad M_{\rm Pl} \to \infty \quad \text{with} \quad \frac{H^2}{\epsilon M_{\rm Pl}^2} = 10^{-7}$$

- *Gravitational interaction are turned off*. Gravity is only background
- *Conformal limit* = Decoupling + no breaking of dS isometries (e.g. no speed of sound cs)
- Simple class of models

$$\epsilon \sim \frac{1}{N^\beta} \quad \Rightarrow \quad \eta \sim \xi_n \sim \frac{1}{N} \gg \epsilon \qquad \left(\xi_{n+1} \equiv \frac{\dot{\xi}_n}{\xi_n H} \right)$$

dS & CFT

- Conformal limit: inflation is just a *scalar field in dS* (not true at O(ϵ))

$$ds^2 = \frac{-d\tau^2 + dx^2}{\tau^2 H^2}$$

- accelerated expansion: perturbations leave the horizon

- mass determines time dependence outside the horizon

$$\phi(x,\tau) \sim \sum_\Delta \tau^\Delta O_\Delta(x) \qquad \Delta = \frac{3}{2} \pm \sqrt{\frac{9}{4} - \frac{V''}{H^2}}$$

- *3+1 dS isometries, SO(4,1) Euclidean 3d conformal group*

- dS time translation = dilation, dS boost = special conformal transf

$$D: \; -\tau\partial_\tau - x\partial_x \quad \Rightarrow \quad -\Delta - x\partial_x$$

Two point function

- Dilations fix immediately the two point function

$$\langle \phi(k)\phi(k)\rangle' \stackrel{!}{=} \frac{C(\tau_*)}{k^{3-2\Delta}}$$

- Convert to zeta all modes at the same time

$$\zeta = \phi/\sqrt{2\epsilon(\tau_*)}$$

- this reproduces the right tilt for **ϵ**=0

$$1 - n_s = 2\epsilon + \eta \simeq \eta = -2\Delta$$

Interactions

- Higher n-point functions probe interactions (non-Gaussianities in the CMB and galaxies)
- Interactions in the scalar sector and from gravity
- Maldacena computed

$$\langle \zeta^3 \rangle' = (n_s - 1) \left[\frac{1}{k_1^3 k_2^3} + 2\,\mathrm{perms} \right] + \epsilon \times \mathrm{equi.} + (\eta^2, \epsilon^2)$$

$$\simeq -\eta \left[\frac{1}{k_1^3 k_2^3} + 2\,\mathrm{perms} \right]$$

- *The leading bispectrum follows from symmetry!*

Consistency relations

- In standard single field inflation, the squeezed limit of any n-point function is related to (n-1)-point functions

- This can be seen as a Ward identity for diffeomorphism invariance and is a manifestation of the equivalence principle

- A similar (simpler) argument holds without gravity

$$\begin{aligned}\langle \phi_L \phi_S \phi_S \rangle &= \langle \phi_L \langle \phi_S \phi_S \rangle_{\phi_L} \rangle \\ &= \langle \phi_L \phi_L \rangle \partial_{\phi_L} \langle \phi_S \phi_S \rangle\end{aligned}$$

Bispectrum

- Conformal invariance + the squeezed limit fully fixes the full bispectrum to leading order.

- We recover the bispectrum and deriver new terms that are higher order in slow-roll

$$\langle\zeta^3\rangle' = -(\eta+\eta\xi)\left[\frac{1}{k_1^3k_2^3}+2\,\mathrm{perms}\right]+\eta\xi\times\mathrm{equi.}+(\eta^3)$$

- non-Gaussianity is fixed by the *running of the spectral tilt* (observable) $\eta\xi$

- This an (observable) *consistency condition for single field* inflation in the scalar sector

- Gauge fixing the graviton breaks conformal invariance. Correlators with a graviton propagator are invariant only up to a gauge transformation (e.g. 4-point function). But gravity decouples…

Wave functional of the universe

- Quantum field theory in the Schroedinger picture (common in gauge-gravity duality)
- “The wave function of the Universe is like a diamond. From every angle it looks a different color. Yet it has no color.“ [M. Mirbabayi]

$$\langle O(\phi) \rangle = \int [d\phi(x)]\, |\psi|^2 O(\phi), \qquad \psi = \int [d\phi(x,\tau)]\, e^{iS[\phi]}$$

Weyl invariance

- The wave function of the universe in any FLRW is invariant under (3d) spatial diff's (Ward identities for squeezed limit consistency relations)

- In dS the wave function is also Weyl invariant

$$g_{ij} \to e^{2\lambda} g_{ij}, \quad \phi \to e^{\Delta\lambda}\phi, \quad \zeta \to \zeta + \lambda$$

- interactions are then constrained

$$\psi \sim \exp\left\{ \int_{x,y} P_\phi(x-y)^{-1} \phi(x)\phi(y) \left[1 - C\zeta(x)\right] \right\}$$

- reproduces the *local part of the bispectrum*

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- reproduces the *local part of the bispectrum*

Conformal limit

Hard to test experimentally, but interesting theoretically:

- All n-point correlators are *dS invariant* (leading order)
- new "scalar" consistency relation *away from the squeezed limit*
- new (physical!) relation: $f_{NL}^{eq} \sim \alpha_s$
- Bispectrum gives the 3-point function of a CFT in Fourier space (triple K-integral)

The origin of the adiabatic mode

- Adiabatic perturbations
- Two paradigms
- Slow-roll conditions in multifield
- Slow-descent inflation

Adiabatic perturbations

- primordial pert's are adiabatic to few % [Planck]

$$\left(\frac{\delta\rho}{\bar{\rho}+\bar{p}}\right)_{DM} = \left(\frac{\delta\rho}{\bar{\rho}+\bar{p}}\right)_{b} = \left(\frac{\delta\rho}{\bar{\rho}+\bar{p}}\right)_{\gamma} = \left(\frac{\delta\rho}{\bar{\rho}+\bar{p}}\right)_{\nu} = \dots$$

- Explaining it might be a legacy of our generation

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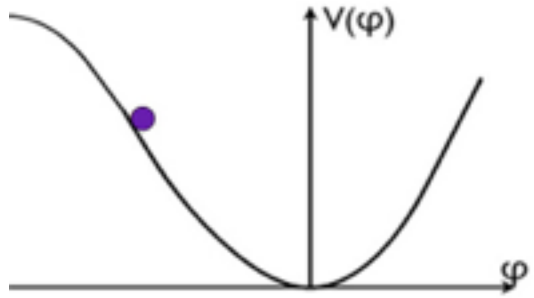


Two paradigms

Single field inflation

- Only one (light) field has superhorizon-scale pert's
- These freeze and re-enter at late times
- Pert's *are born* adiabatic
- Weinberg's adiabatic mode

Multi-field inflation

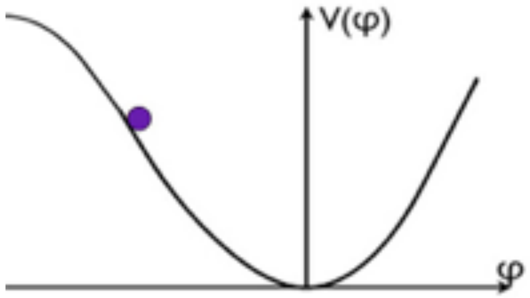
- Many fields are perturbed on super horizon scales
- Subhorizon *thermalization* (no conserved charges) erases isocurvature pert's

$$n_i \sim e^{-E_i/T} \rightarrow \delta n_i \sim \delta T$$

- Pert's *become* adiabatic

Adiabatic modes à la Weinberg

- Weinberg's argument mimics the proof of massless Goldstone bosons
- Consider classical GR perturbations around FLRW
- Fix the gauge *at finite momentum* (pert's vanish at infinity), e.g. Newton gauge (cosmological pert. theory)
- Apply a large diff. By diff-invariance it must generate a new solution that does not vanish at infinity (zero momentum)
- Two (non-decaying) solutions survive to finite momentum: the adiabatic mode and gravitational waves
- *If there is only one scalar mode, it is the adiabatic mode*



Two paradigms for (string) inflation

UV considerations suggest many fields:

- RG flow, explicit String Theory constructions,
- Hickam's dictum (cfr Occam's rasor): "Patients can have as many diseases as they damn well please"

How did a simple (adiabatic) universe emerged from the (complicated) UV theories of inflation?

- 99% of searched in the (ST) landscape are for single field
- Why not embrace the multi-field paradigms and its complexity?

Single-field slow roll

- Hubble slow-roll conditions are nice and clear

$$\epsilon \equiv -\frac{\dot{H}}{H^2} \ll 1 \quad \& \quad \eta \equiv \frac{\dot{\epsilon}}{\epsilon H} \ll 1 \quad \dots$$

- In single field they imply the potential slow-roll conditions

$$\epsilon_V \equiv \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2, \quad \eta \equiv M_{Pl}^2 \frac{V''}{V}$$

- Single field Inflation requires flat potentials and proceeds along the gradient (*gradient flow*)

$$3H\dot{\phi} \simeq -V'$$

Single field lamppost

- Hubble slow-roll conditions are again nice & clear

$$\epsilon \equiv -\frac{\dot{H}}{H^2} \ll 1 \quad \& \quad \eta \equiv \frac{\dot{\epsilon}}{\epsilon H} \ll 1 \quad \dots$$

- But "potential" slow-roll conditions are poorly understood and often misquoted

$$3H\dot{\phi}_i \simeq -V_{,\phi_i}$$

not necessary

$$\epsilon_V = \frac{M_P^2}{2}\frac{V_i V_i}{V^2} \ll 1$$

not necessary

$$\eta_V = M_P^2 \frac{\mathrm{minEvalue}(V_{,ij})}{V^2} \ll 1$$

neither necessary nor sufficient [see e.g. Yang 12]

Multi-field slow-roll conditions [with urzainqui & Cancer]

- Single field space geometry is always flat
- Multi-field space is curved (sigma models in String and Effective theories)

$$X \equiv G_{IJ}\dot{\phi}^I \dot{\phi}^J/2$$

- Slow-roll condition must be covariant under field space re-parameterization

$$3M_P^2 H^2 = V + X\,, \quad \dot{X} + 6HX + V_{,I}\dot{\phi}^I = 0$$

$$D_t\dot{\phi}^I + 3H\dot{\phi}^I + G^{IJ}V_{,J} = 0$$

Beyond gradient flow

$$\epsilon = \frac{3X}{V+X} \quad \Rightarrow \quad \eta = 2\epsilon + \frac{\dot{X}}{HX}$$

- Prolonged inflation requires

$$\dot{X} \ll 6HX \simeq -V_{,K}\dot{\phi}^K$$

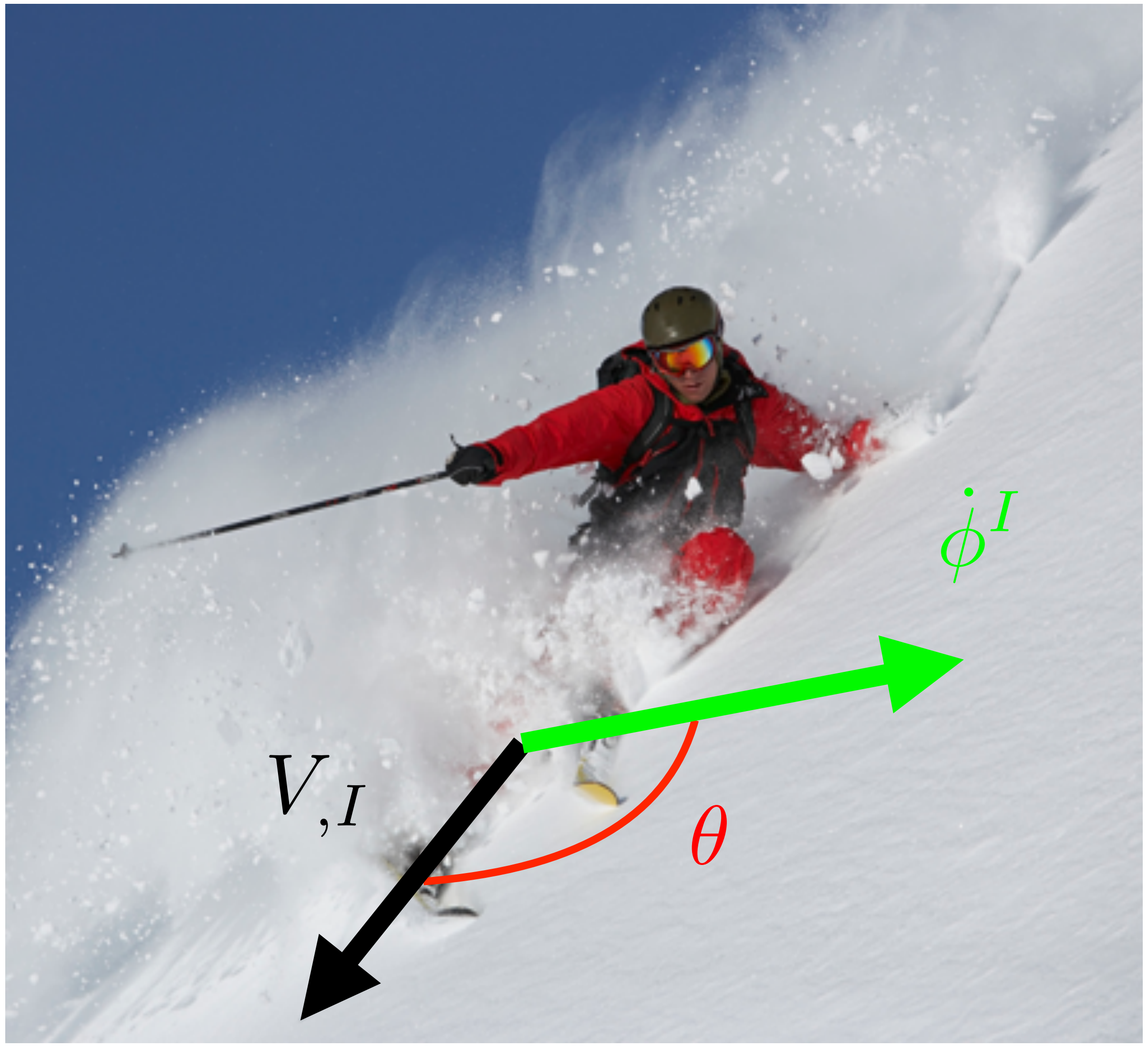
- instead of the common gradient flow assumption

$$D_t\dot{\phi}^I + 3H\dot{\phi}^I + G^{IJ}V_{,J} = 0$$

- for θ the angle between gradient and velocity

$$\epsilon_V = \frac{M_P^2}{2}\frac{V_{,K}V^{,K}}{V^2}\cos\theta^2$$

Slow-descent



If velocity is uncorrelated with gradient, then inflation is generic for sufficiently large N:

$$\langle \cos\theta^2 \rangle = \frac{1}{N}$$

This is a genuine multi-field behavior.

Does this happen in the landscape?

Existence proof

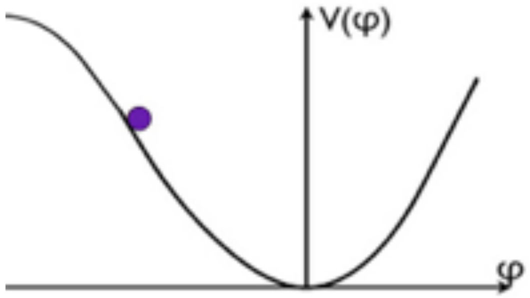
- Two (or more) fields. Steep gradient along y, canceled by “field-space gravity”

$$\ddot{y} + \Gamma^{y}_{yx}\dot{y}\dot{x} + 3H\dot{y} + \Gamma^{y}_{xx}\dot{x}\dot{x} + V_{,y} = 0$$

- evolution along x, where V is much flatter (⊥ to gradient)

- Formally analogous to Newtonian orbits [Yang ‘12]

- Robustness and generality?



Single vs multi-field

A few observables can rule out single field:

- isocurvature perturbations
- local non-Gaussianity

But can we rule out the multi-field paradigm?

- Computing multi-field predictions requires understanding: inflation, reheating, coupling to SM physics and thermalization

How to rule out multi-field

- Single field consistency relation:
  - Tensors: $r = 8 n_T$
  - Scalars (new): $f_{NL}^{equi.} = \alpha_s$
- Data suggest the simple relation [Mukhanov 13; Roest 13; Creminelli 14; Zavala 14; Gobbetti, EP, Roest 15]

$$1 - n_s = 2/N$$

- In single field this can easily happen (e.g. chaotic or Starobinski inflation). In multifield, it requires *tuning of the potential WITH of the initial conditions* [EP in progress]
- observation of running $-2/N^2$ would *rule out multifield*

Definition of multi-field

- Assume gradient flow, and at any point in field space compute efolds N(Φ) until the adiabatic attractor is reached

- On superhorizon scales, delta-N formalism gives

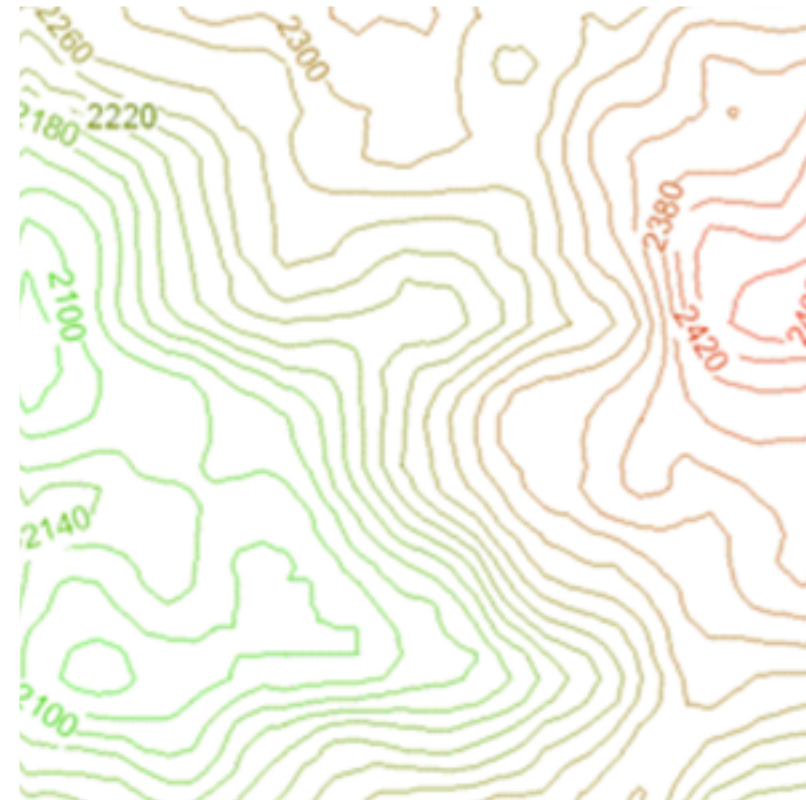
$$\zeta = \delta N = \frac{\partial N}{\partial \phi^I} \delta\phi^I + \dots$$

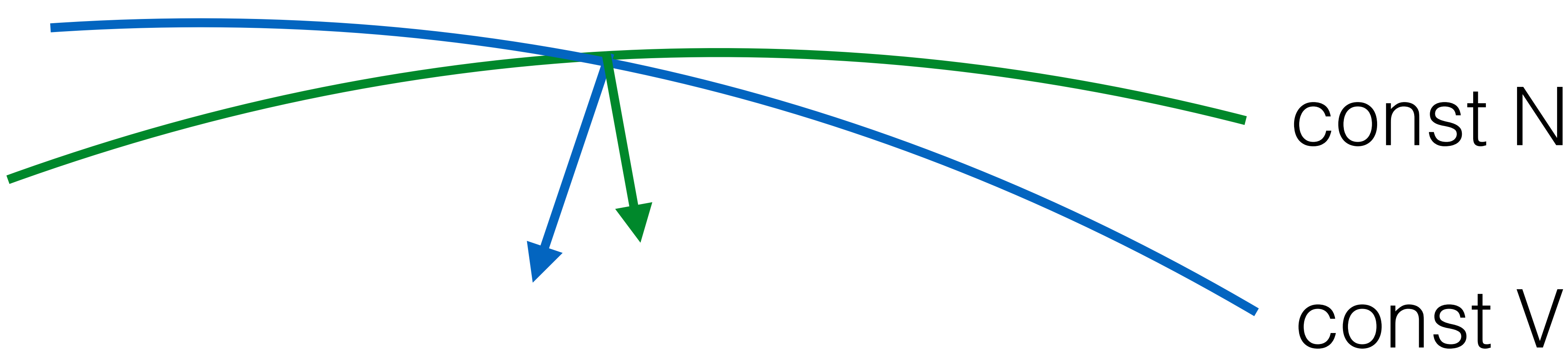
- The gradient of N(Φ) generated the observed pert's

Constant N lines

Definition of multi-field

- consider constant V surfaces normal to the gradient $V_{,\Phi}$
- In effective single field, the gradients of V and N are parallel





Simple scalings

- Data suggest the simple relation [Mukhanov 13; Roest 13; Creminelli 14; Zavala 14; Gobbetti, EP, Roest 15]

$$1 - n_s = \frac{2}{N}$$

- In single field this can easily happen (e.g. chaotic inflation or Starobinski)

- In multifield, even tuning the potential, the region of initial condition that satisfy 1/N has measure zero [EP in progress]

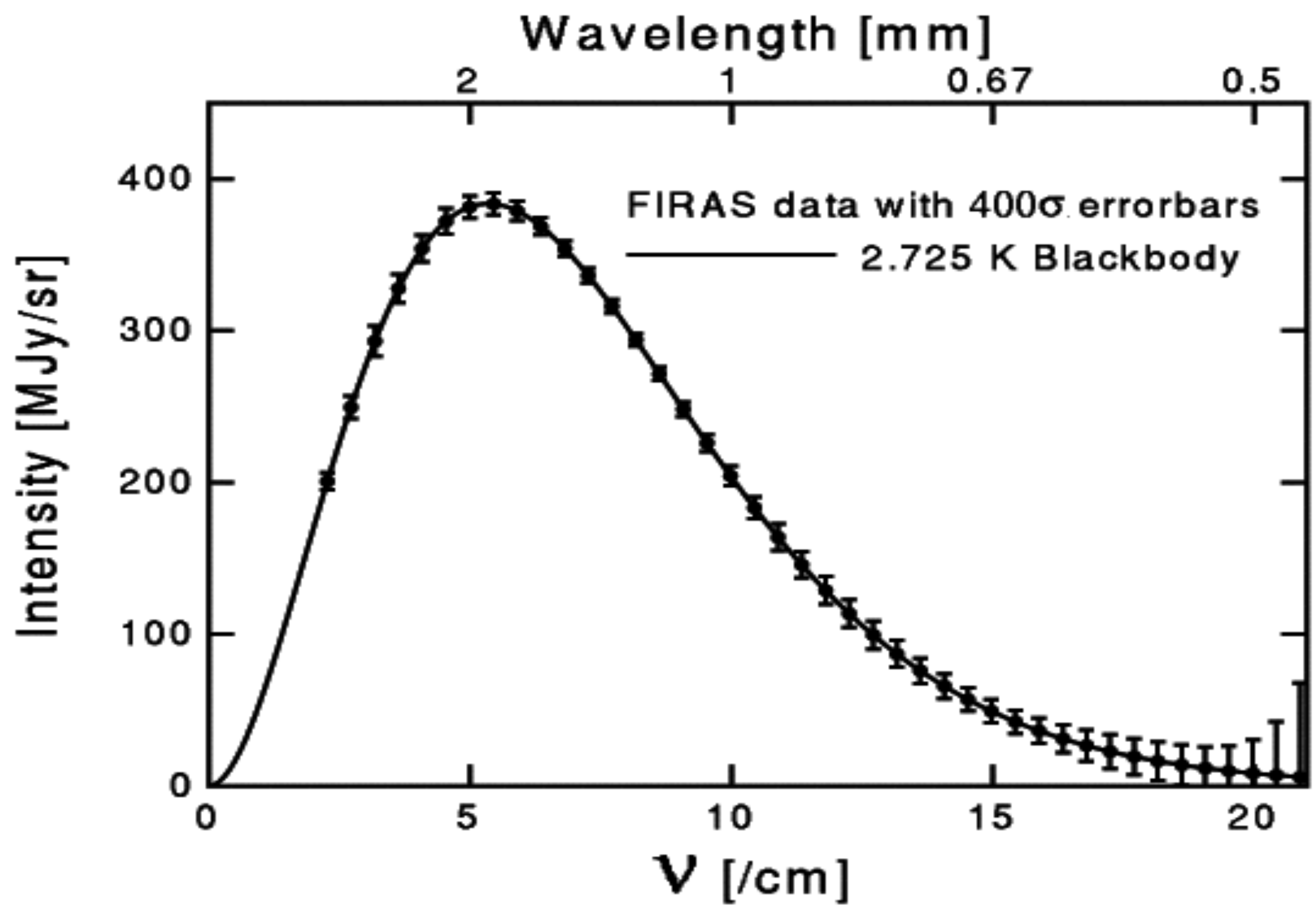
- In multifield, 1/N requires (more) *tuning of the potential AND of the initial conditions*

- observation of running $-2/N^2$ would *rule out multifield*

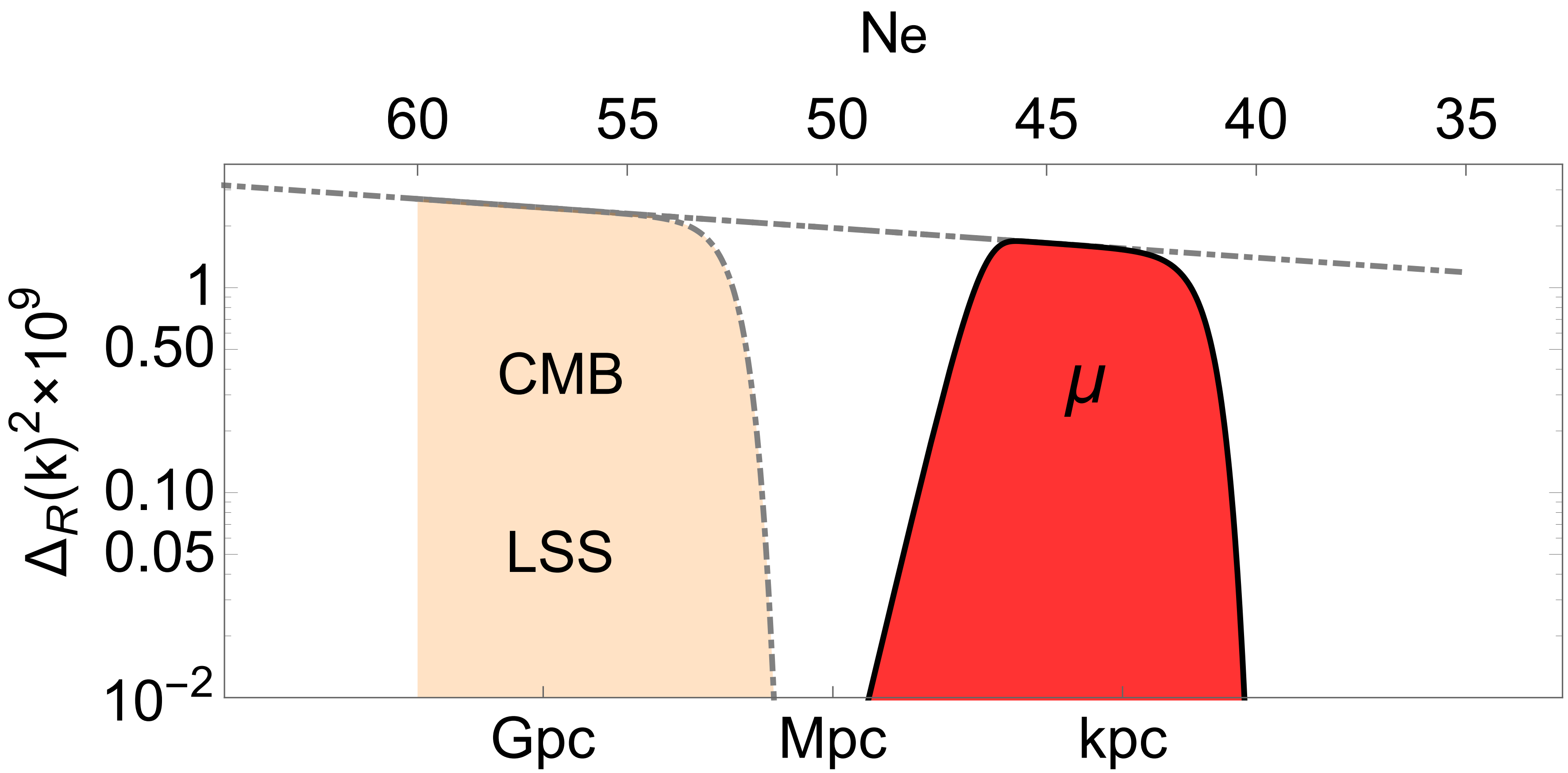
Conclusions

- Observations dictate a new hierarchy: $\varepsilon \ll \eta$
    - Primordial correlators are fixed by conformal symmetry
    - *New consistency condition:* $f_{NL}^{eq} \sim \alpha_s$ (physical)
    - Multi-field conformal limit?
- The origin of the adiabatic mode
    - Adiabaticity from complexity through thermalization
    - Embrace the complexity of multi-field dynamics
    - There's more to life than slow-roll gradient flow inflation
    - Does the landscape support slow-descent inflation?

CMB spectral distortions

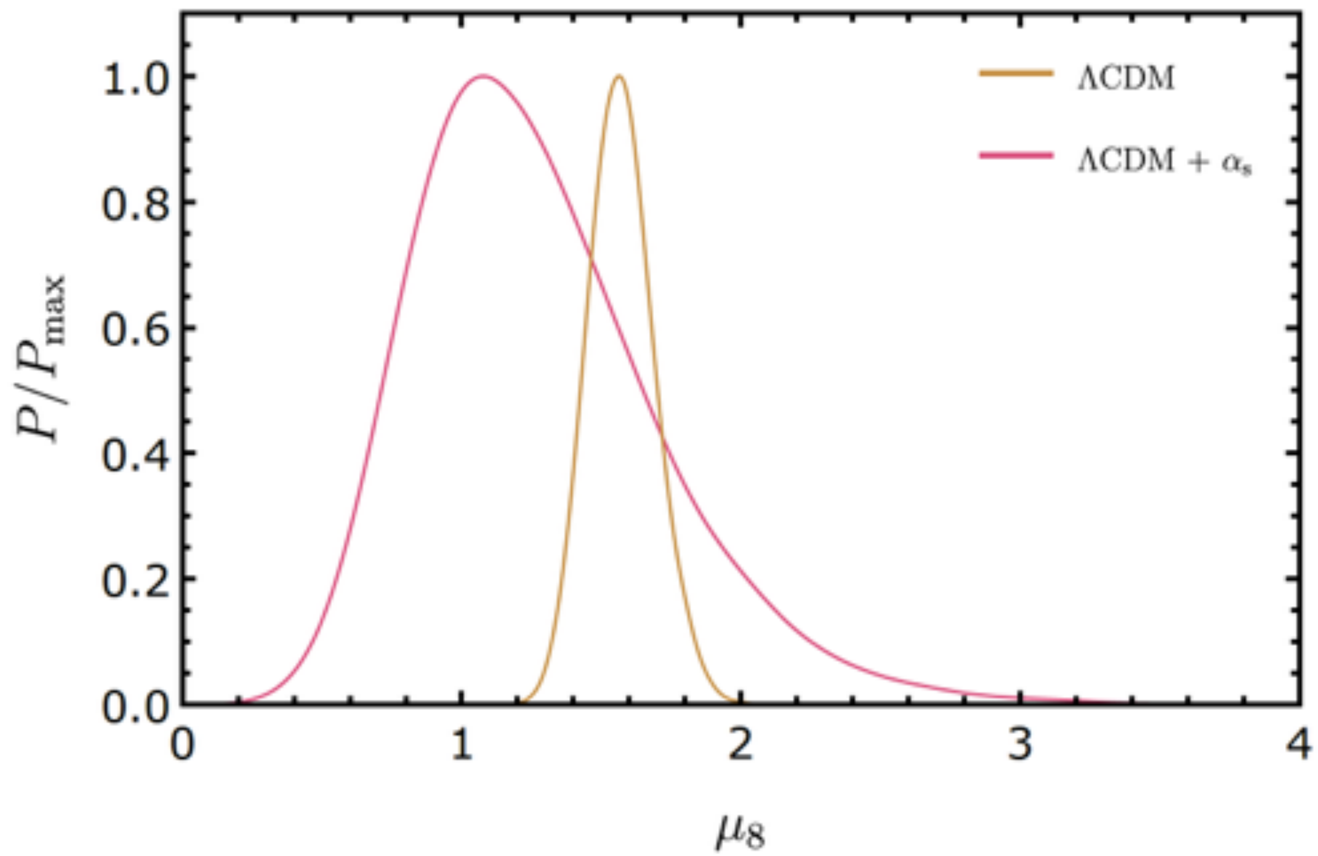


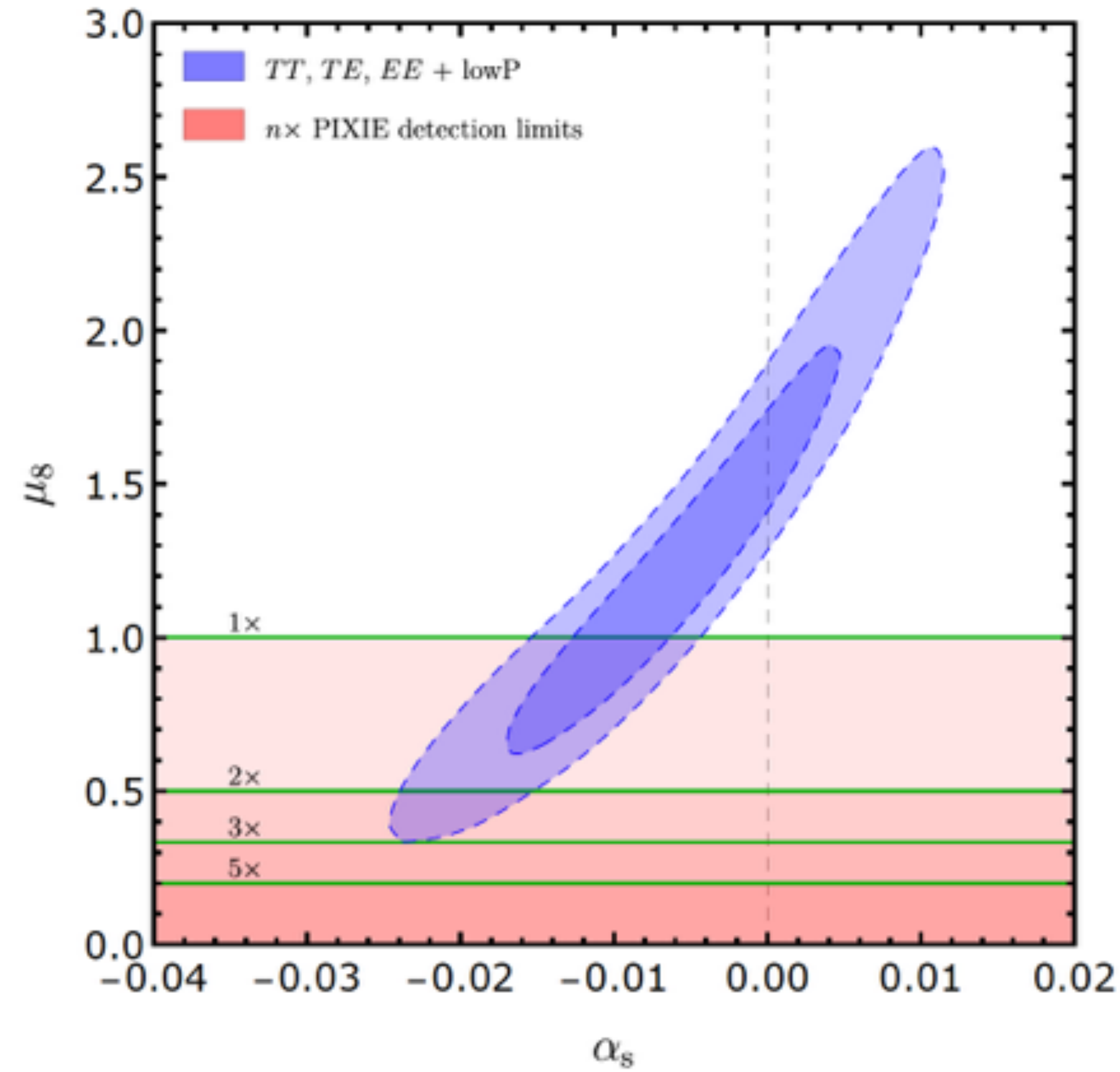
Another 10 efolds



- CMB/LSS probe only a narrow window of scales (~7 efolds)
- Dissipation at $2x10^6 > z > 4x10^4$ (frozen photon number) creates CMB spectral distortions
- Spectral distortion probes **another 5 efolds** $50<k$ Mpc$<10^4$ [Sunyaev, Zel'dovich, Silk, Peebles, Hu, Danese, de Zotti, Chluba, …]
- independent modes: CMB~10^6, LSS~$10^{9,}$ μ~10^{12}. Tiny cosmic variance!

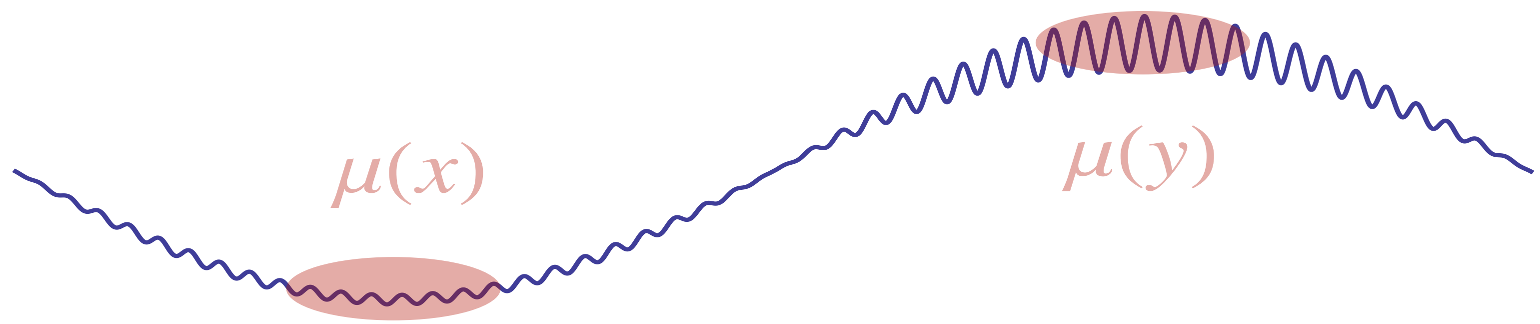
“If you build it, he will come” [Field of Dreams ‘89]





- Planck puts lower bound on μ, measurable by next CMB satellite (PIXIE, LightBIRD, PRISM)
- **Guaranteed discovery**: detection of μ, or of negative running [Cabass, Melchiorri, EP 16]

primordial non-Gaussianity



- *Anisotropies* in μ probe primordial non-Gaussianity
  [EP & Zaldarriaga '12]

- since $\mu \propto \delta^2$, correlation $C_l^{T\mu}$ gives local bispectrum

$$\langle a^{\mu}_{lm} a^{\Delta T}_{lm} \rangle \simeq 50\, f_{NL} \frac{\Delta^4_R}{l(l+1)}$$

- Cosmic Variance limit (futuristic) is $f_{NL} \sim 10^{-3}$