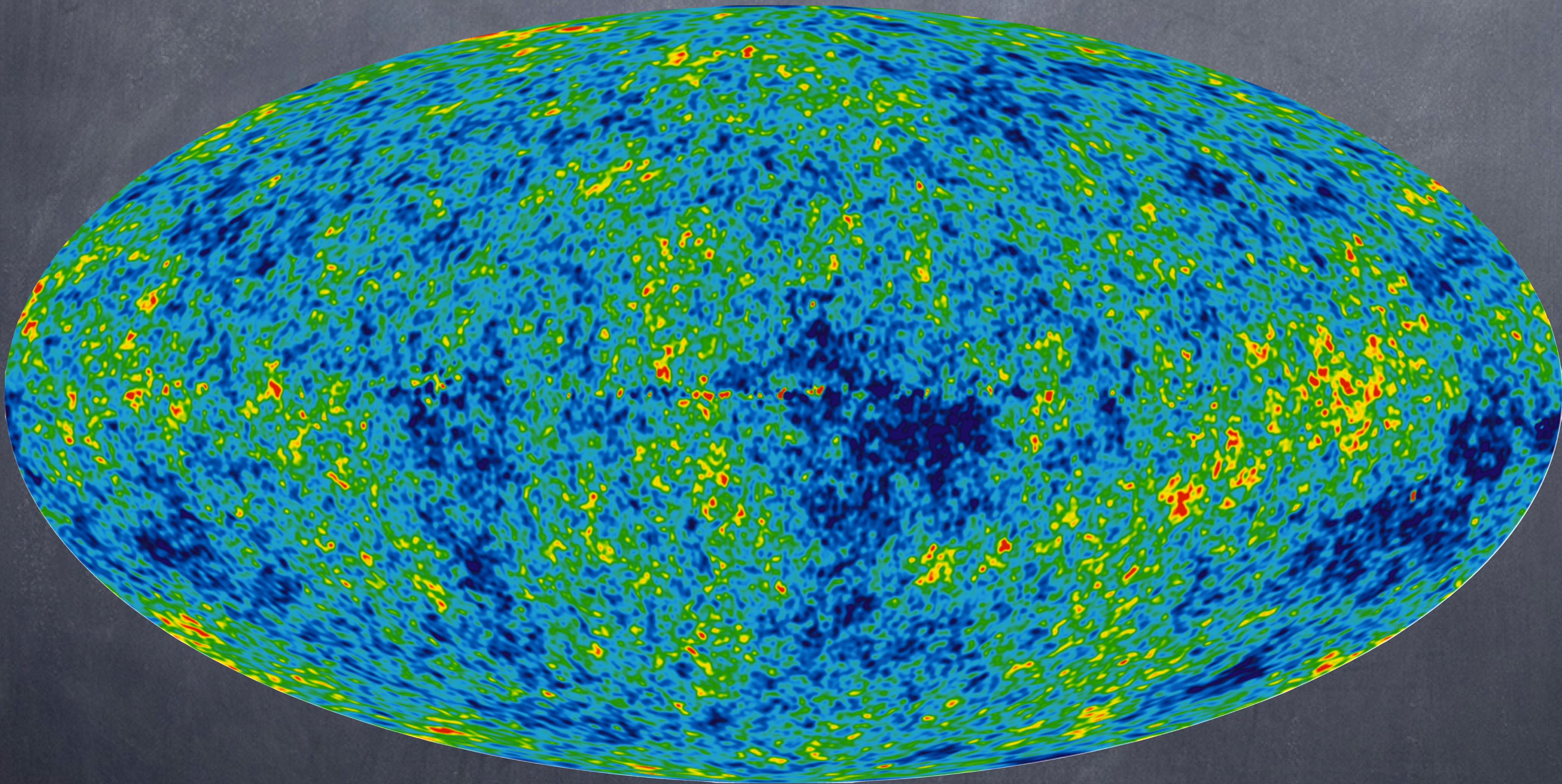
Searching for new physics in the inflationary density perturbation

Higgs colloquium, 1 March 2013

David Seery
University of Sussex

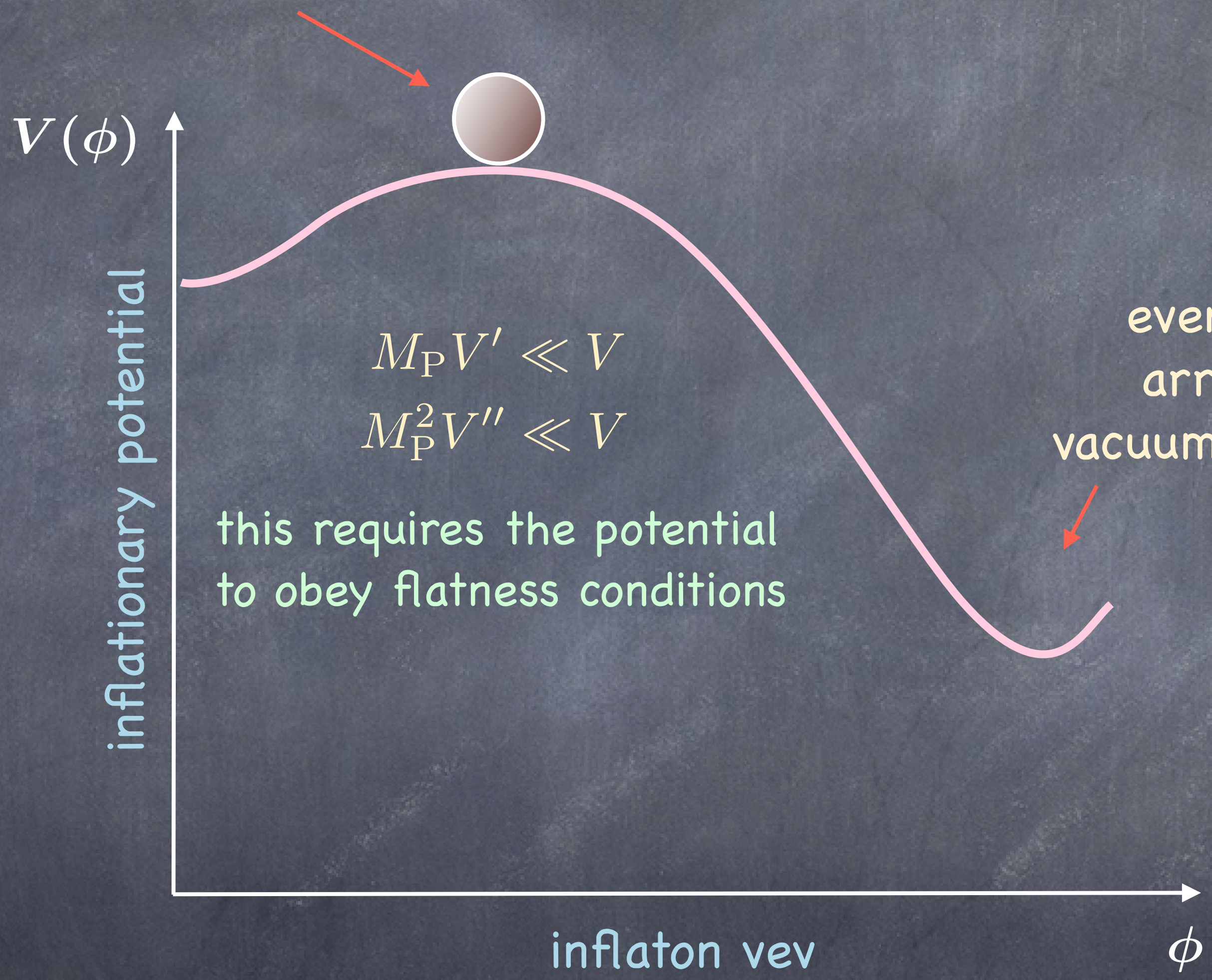
University of Sussex

Many cosmological observations lead us to challenging conclusions

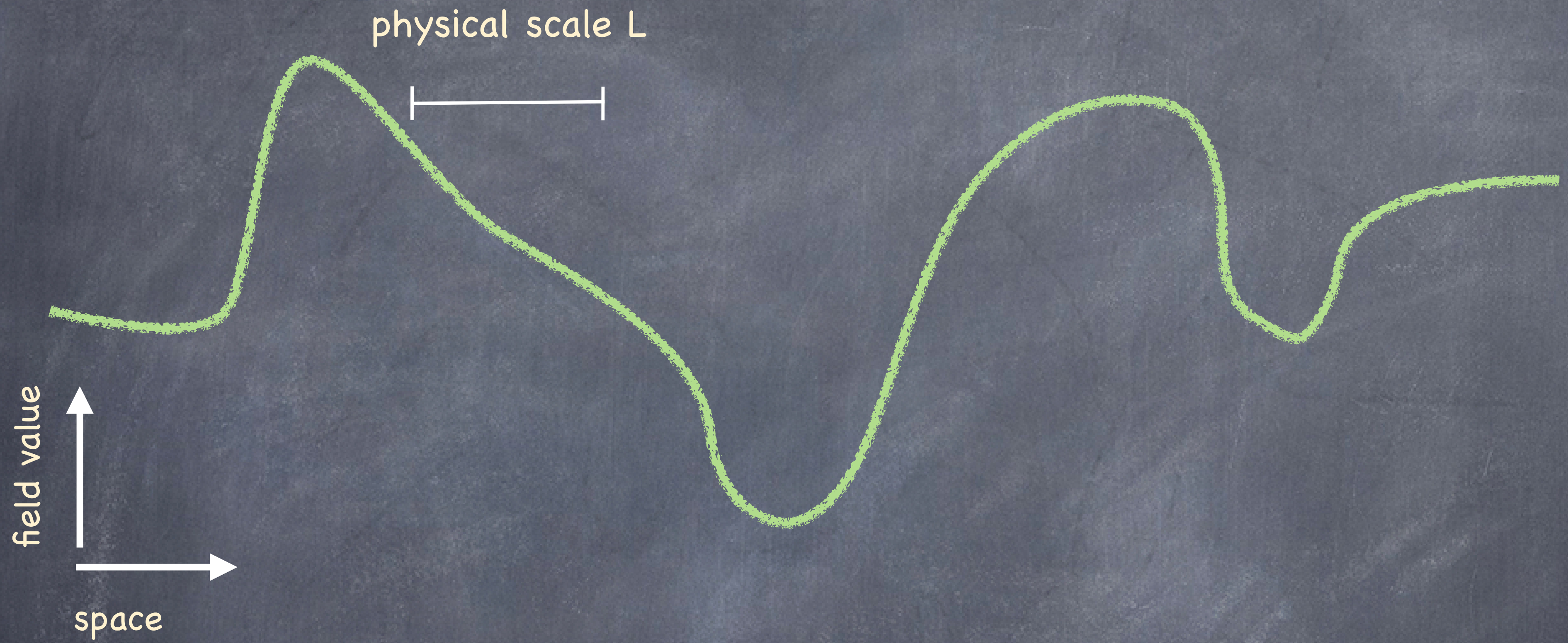


The explanation favoured by most cosmologists is “inflation”

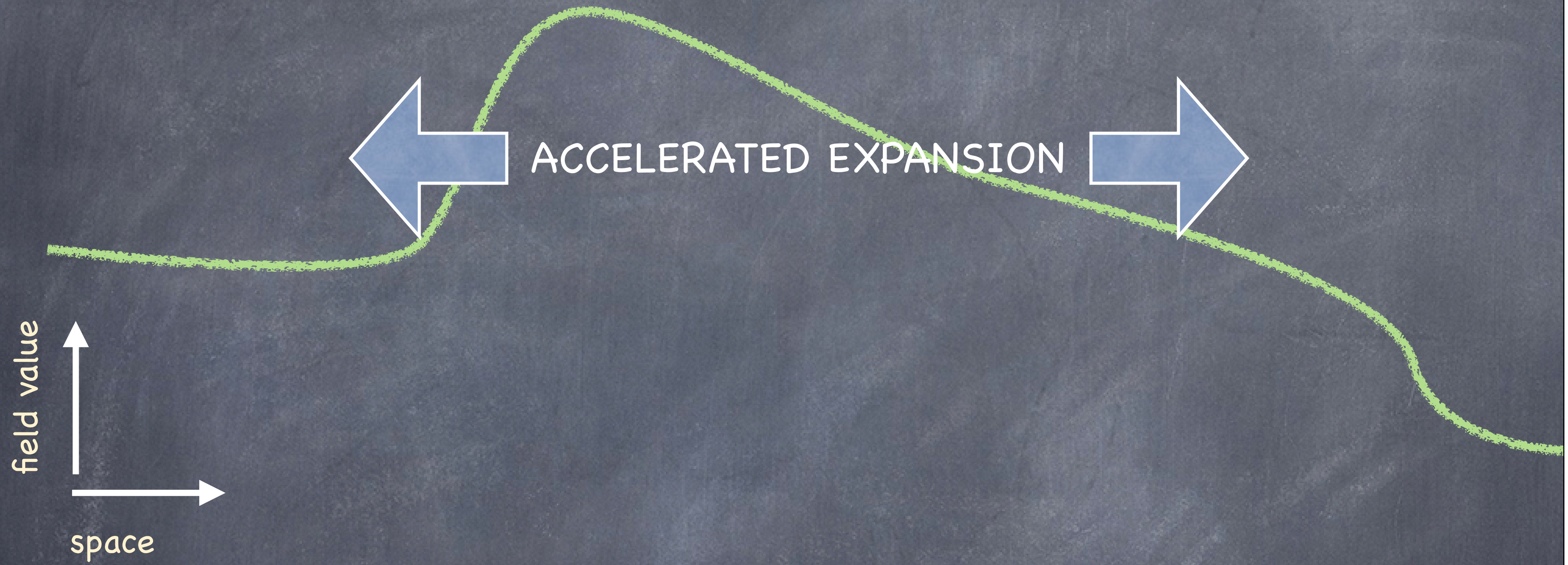
in most scenarios, inflation
happens because the universe
is dominated by potential energy



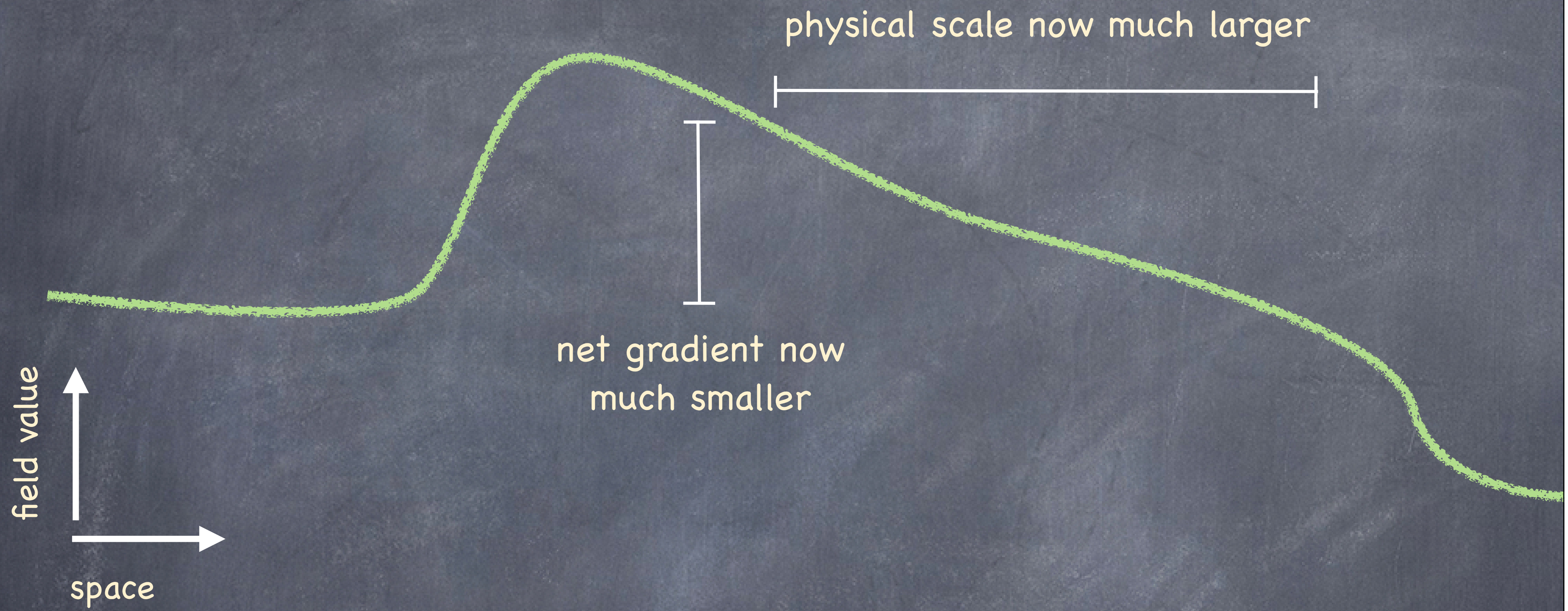
eventually the field
arrives in a stable
vacuum and inflation ends



In principle, the field configuration in the very early universe could have been highly disordered.

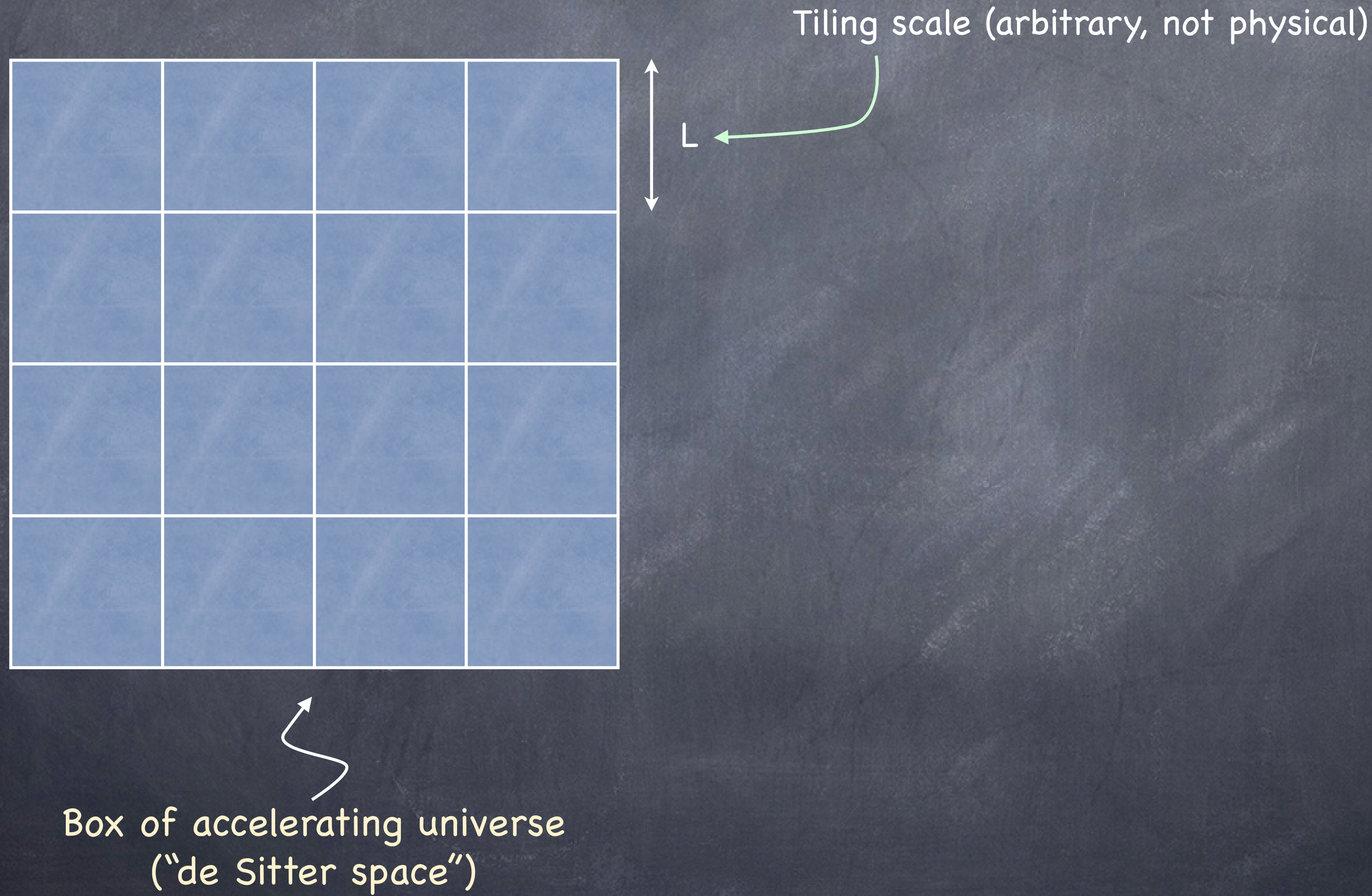


In principle, the field configuration in the very early universe could have been highly disordered.

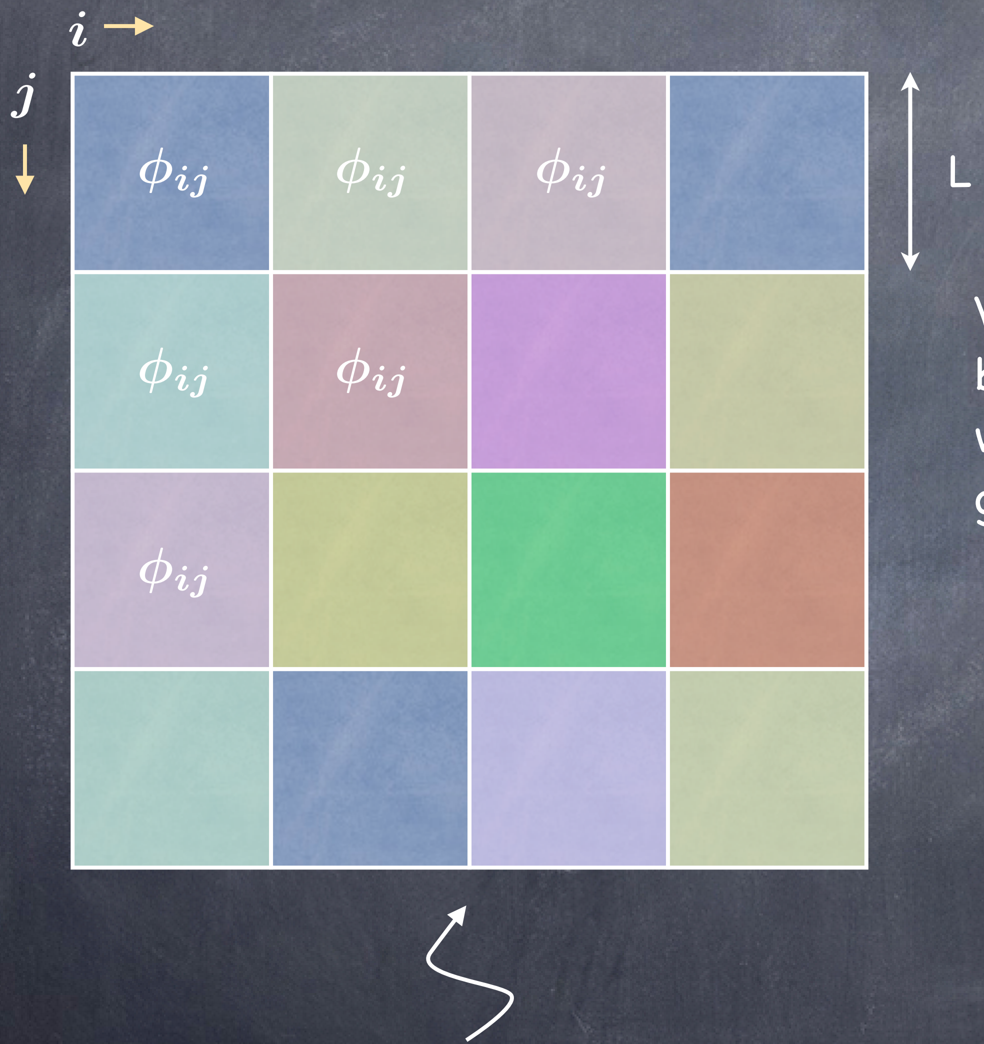


In principle, the field configuration in the very early universe
could have been highly disordered.

Fluctuations from inflation



Fluctuations from inflation



Tiling scale (arbitrary, not physical)

We need a nearly smooth background field ϕ_{ij} in each “tile” or “box,” which evolves coherently up to small gradient corrections

Box of accelerating universe
(“de Sitter space”)

energy

TeV scale – energy scale of electroweak symmetry breaking

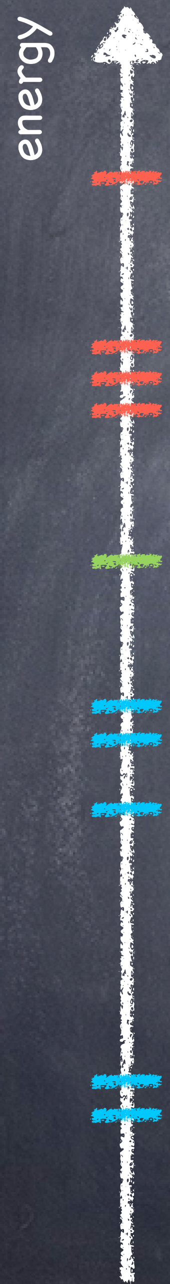
Top quark, mass ≈ 170 GeV

~~Perhaps many heavy modes in a model like technicolour?~~ NO

probable Higgs, mass ≈ 125 GeV

S, T, U parameters

Electroweak vector bosons, mass ≈ 90 GeV



Planck scale - quantum gravity effects

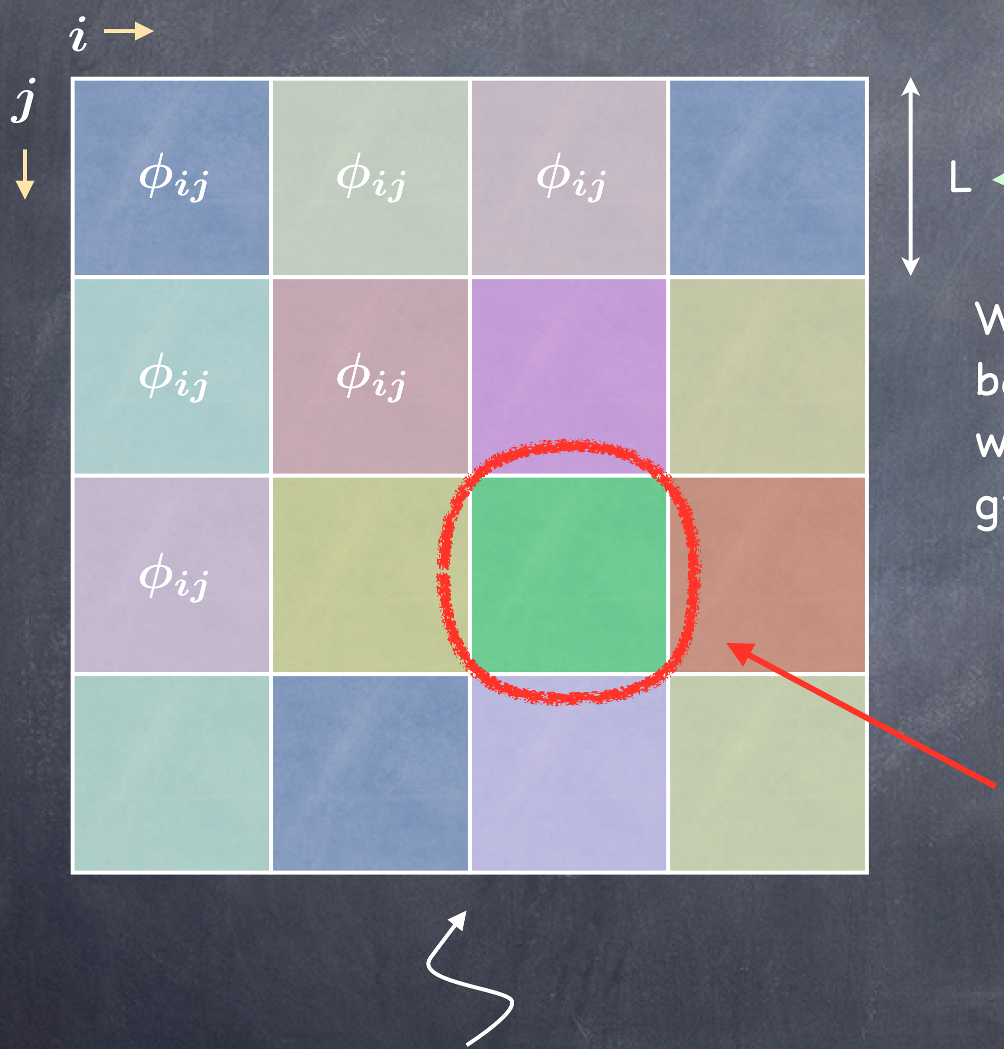
Presumably some fluctuations which are heavy compared to the Hubble scale

Hubble scale - energy density of the background

At least one fluctuation which is light compared to the Hubble scale

Possibly more light fluctuations

Fluctuations from inflation



Tiling scale (arbitrary, not physical)

We need a nearly smooth background field ϕ_{ij} in each "tile" or "box," which evolves coherently up to small gradient corrections

Focus on a single tile

Box of accelerating universe
("de Sitter space")

time

e-folds N (measures time)

active scalars Φ

horizon crossing for mode k

time N_k

"observation"

time N_{obs}

→ unobserved inflation → → observable inflation →

a fluctuation is generated

here, the fluctuations can be quite different

at horizon-crossing, we have two clear, separated scales which help control the calculation

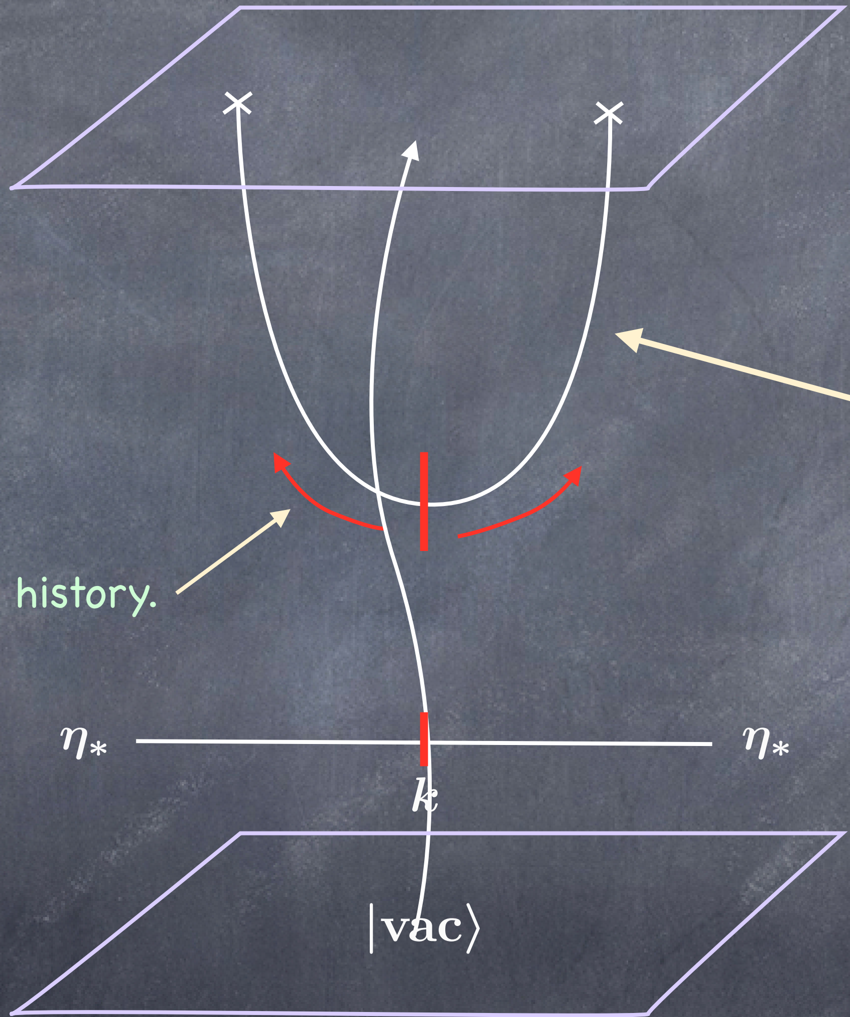
time scales (slow roll scales) $\quad \epsilon \sim \frac{V'^2}{V^2} \quad \eta \sim \frac{V''}{V} \quad \xi \sim \frac{V'''V'}{V^2} \quad \mathbf{10^{-2}}$

quantum scale $\quad \frac{H^2}{M_{\mathrm{P}}^2} \quad \mathbf{10^{-10}}$ ish

The calculation we need is "in-in" quantum field theory

~~late time, fixed state~~
~~time η_*~~

~~"Feynman" formulation~~
"Schwinger" formulation



both external legs at late time, so no quanta enter the diagram.

Instead, they are nucleated like an instanton

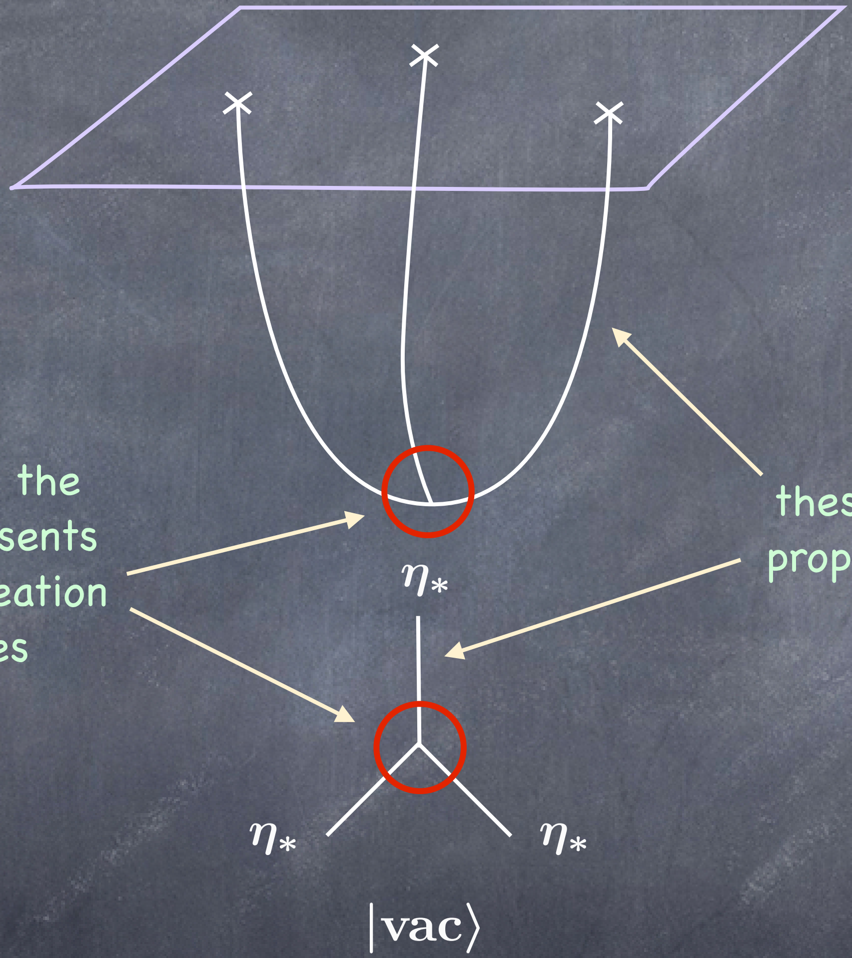
two quanta appear and then separate, sharing a history. So they are correlated.

early time, fixed state
time η_{init}

The situation is similar for higher-order diagrams

late time, ~~fixed~~ state
~~time η_*~~

"Schwinger" formulation



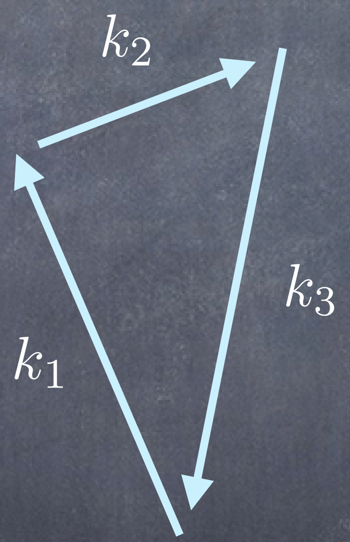
cut the diagram at the vertex, which represents the (expensive) nucleation of three particles

these three particles propagate to the final surface

early time, fixed state
time η_{init}

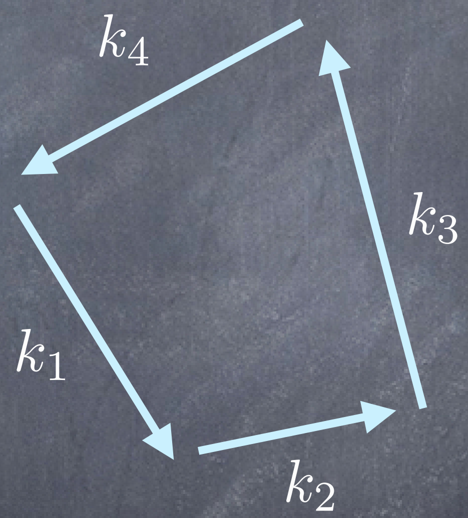
For the last decade, we have mostly been looking at the two-point function.
But the higher n-pfs are more sensitive to detailed microphysics.

The three- and four-point functions are complicated.
They depend on time and the momentum configuration



3pf triangle

$$\boldsymbol{k}_1 + \boldsymbol{k}_2 + \boldsymbol{k}_3 = 0$$



4pf quadrilateral

$$\boldsymbol{k}_1 + \boldsymbol{k}_2 + \boldsymbol{k}_3 + \boldsymbol{k}_4 = 0$$

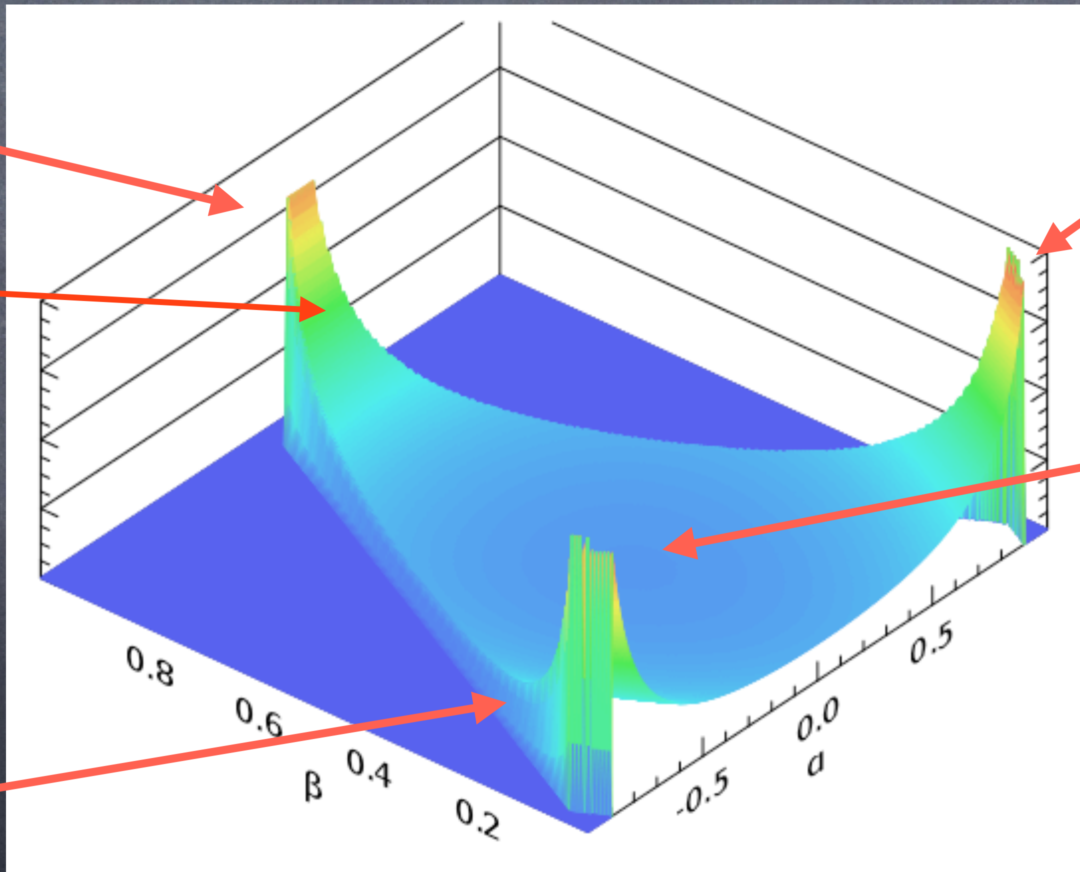
In principle, these functions can be arbitrarily complicated. But in many models they turn out to be fairly simple.

$$k_1 = \frac{k_t}{4}(1+\alpha+\beta) \qquad k_2 = \frac{k_t}{4}(1-\alpha+\beta) \qquad k_3 = \frac{k_t}{2}(1-\beta)$$

$$k_t = \text{perimeter} = k_1 + k_2 + k_3 \qquad 0 \le \beta \le 1 \qquad \beta - 1 \le \alpha \le 1 - \beta$$

$k_3 \to 0$

Lots of long/short correlation



$k_2 \to 0$

Very little like-like correlation

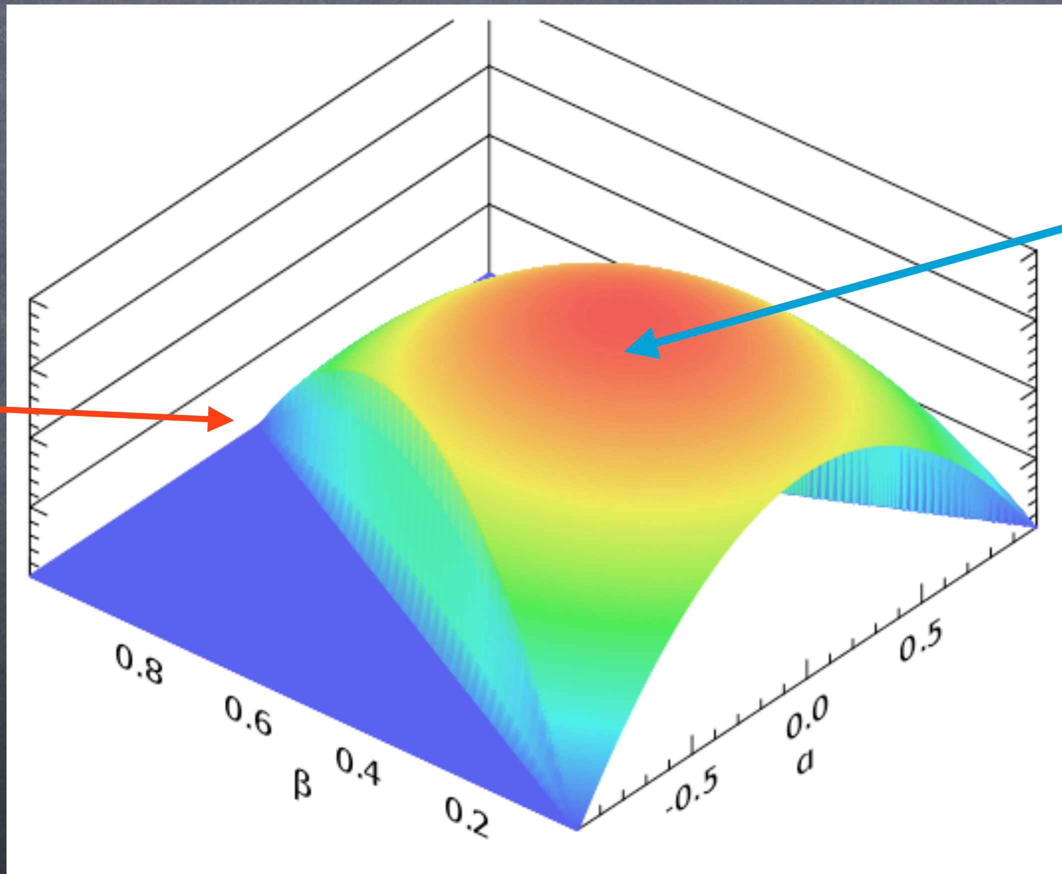
$k_1 \to 0$

In principle, these functions can be arbitrarily complicated.
But in many models they turn out to be fairly simple.

$$k_1 = \frac{k_t}{4}(1+\alpha+\beta) \qquad k_2 = \frac{k_t}{4}(1-\alpha+\beta) \qquad k_3 = \frac{k_t}{2}(1-\beta)$$

$$k_t = \text{perimeter} = k_1 + k_2 + k_3 \qquad 0 \le \beta \le 1 \qquad \beta - 1 \le \alpha \le 1 - \beta$$

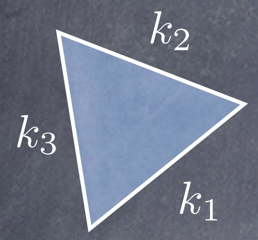
Negligible long/short correlation



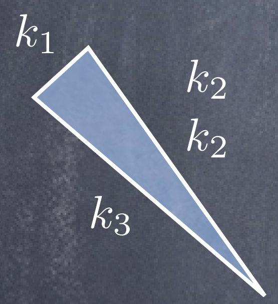
$k_1 \approx k_2 \approx k_3$

Lots of like-like correlation

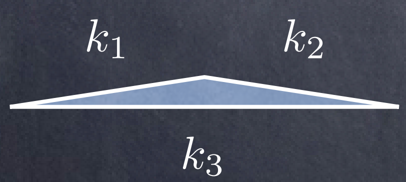
Where the bispectrum peaks is a signal of the microphysics underlying the fluctuations



Equilateral. Indicates that the fluctuations have strong, nontrivial self-interactions.
Favours stringy or supergravity scenarios.
Dominantly like-like correlations.



Squeezed. Indicates that there are long-range forces which set up large-scale correlations, so implies multiple light modes.
Dominantly long-short correlations.

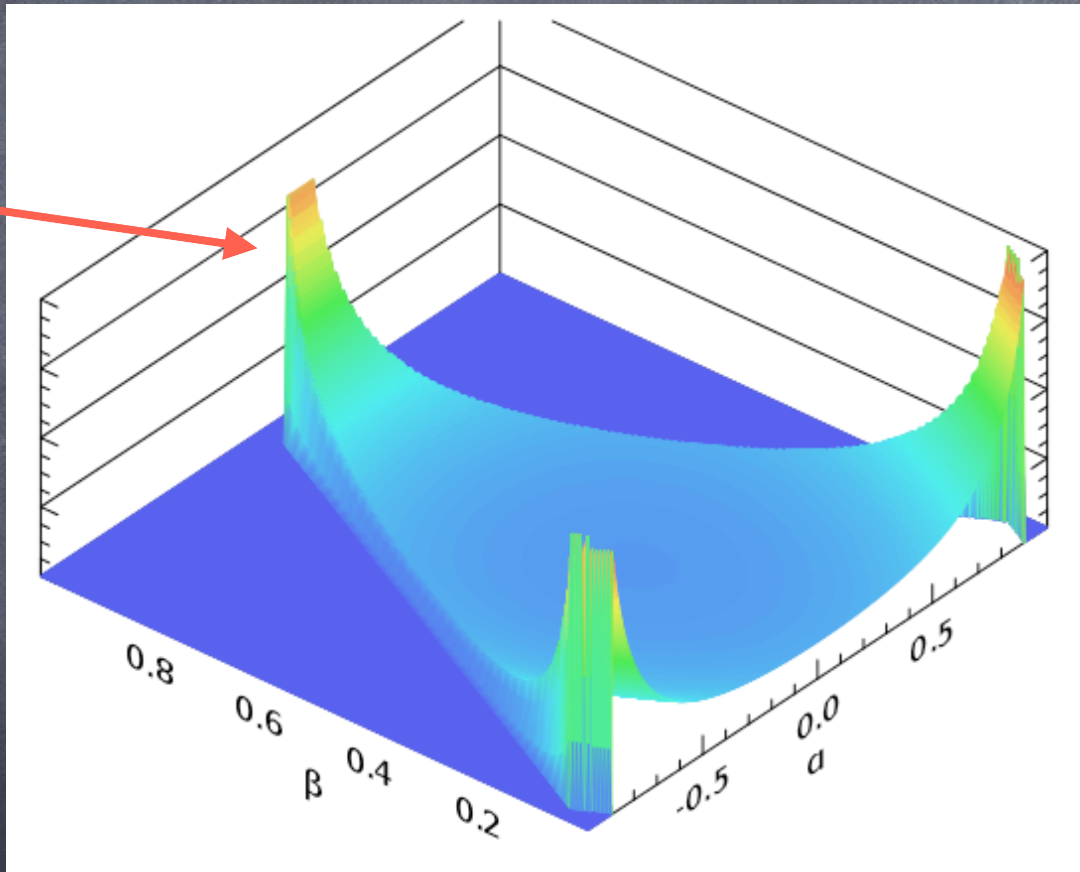


Folded. Indicates a near zero-energy "resonance" between positive and negative energy modes.
Favours non-vacuum initial conditions.
Special case of like-like correlations.

One case of special interest is the bispectrum produced by long-range forces, which peaks in the limit $k_i \to 0$

[This bispectrum is often called the "local shape".]

In this limit, the bispectrum is growing like $1/k^3$

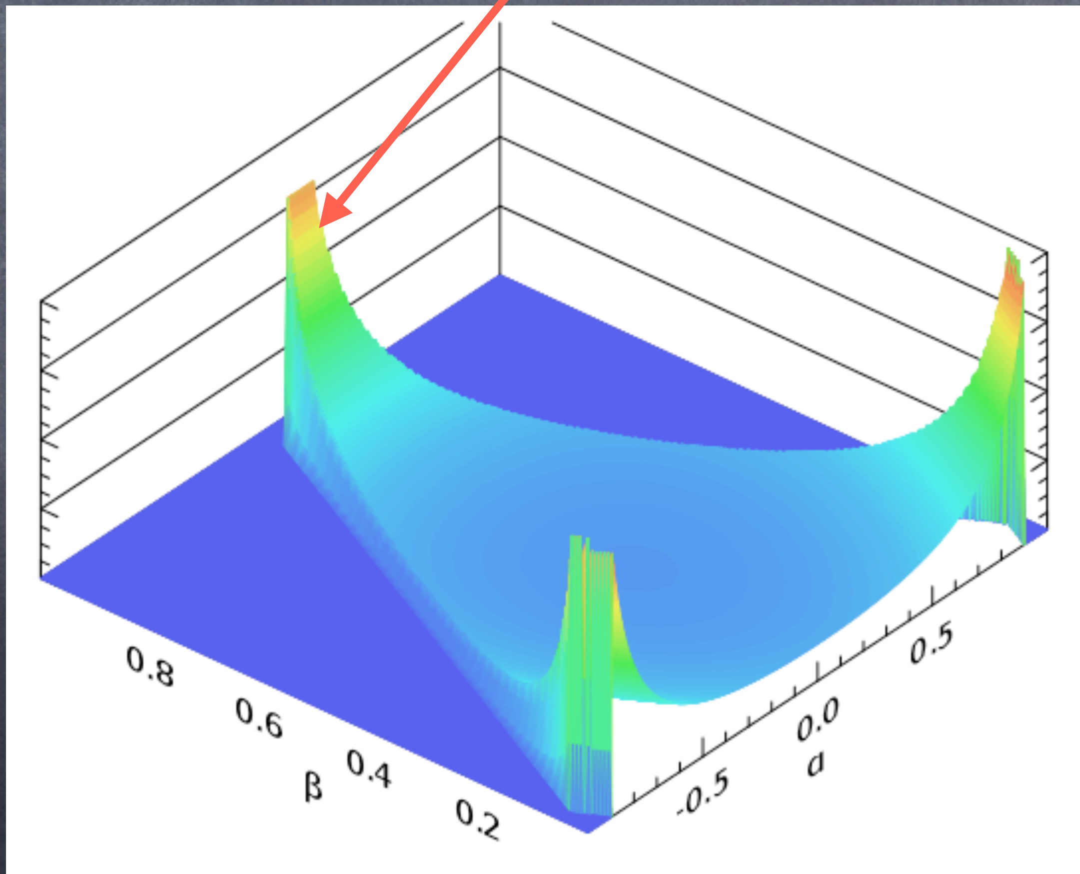


This is diagnostic of multiple modes which are lighter than the Hubble scale.

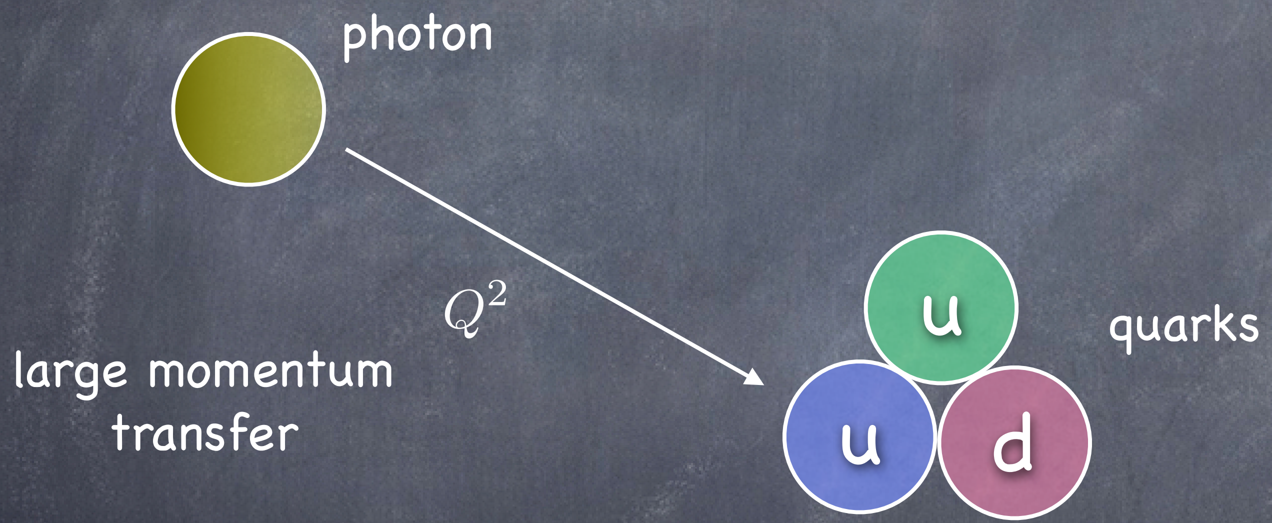
More generally, if there are also massive modes, the scaling of the spikes in the squeezed limit can be different from $1/k^3$

$$\langle \zeta(\boldsymbol{k}_1)\zeta(\boldsymbol{k}_2)\zeta(\boldsymbol{k}_3)\rangle \sim \frac{1}{k^{-3/2-\nu}}$$

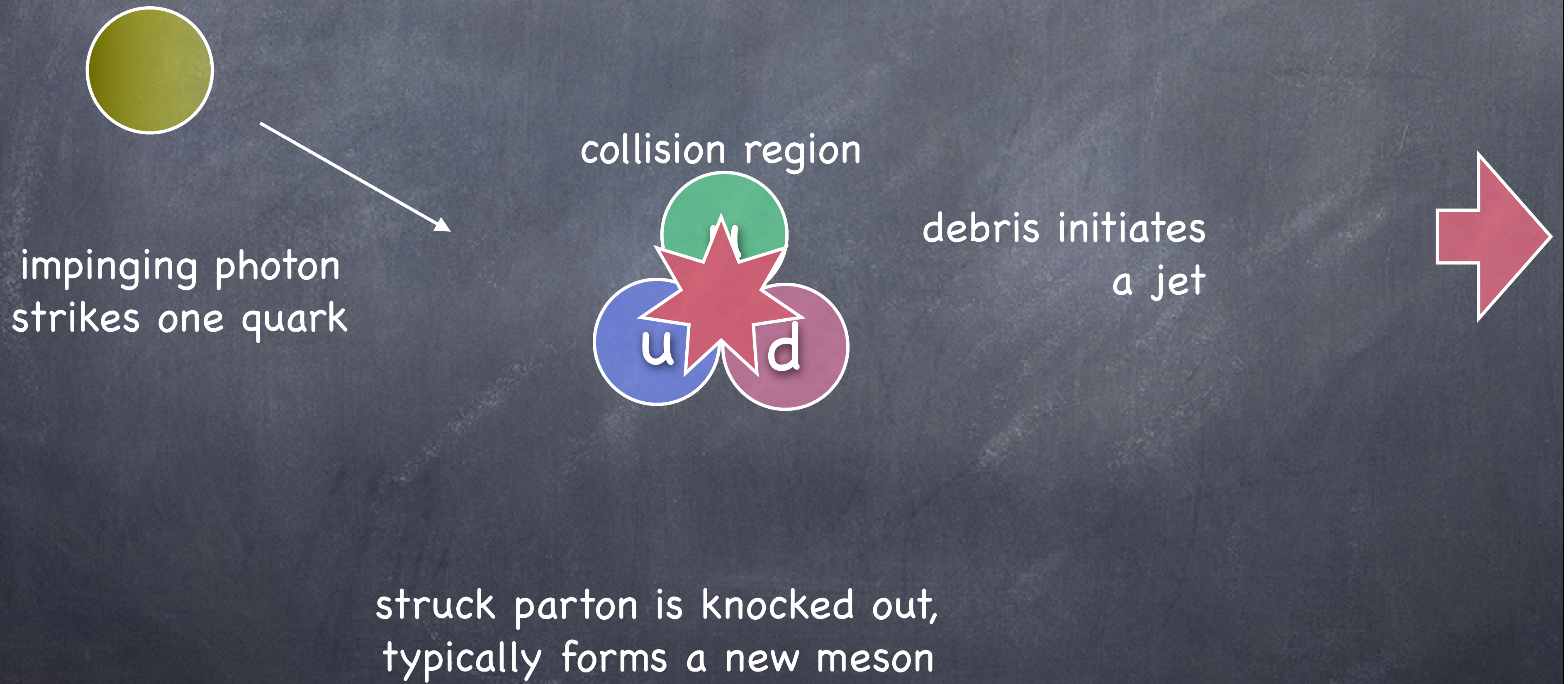
One way to think of the change in scaling is a suppression of long-range forces, and therefore correlations



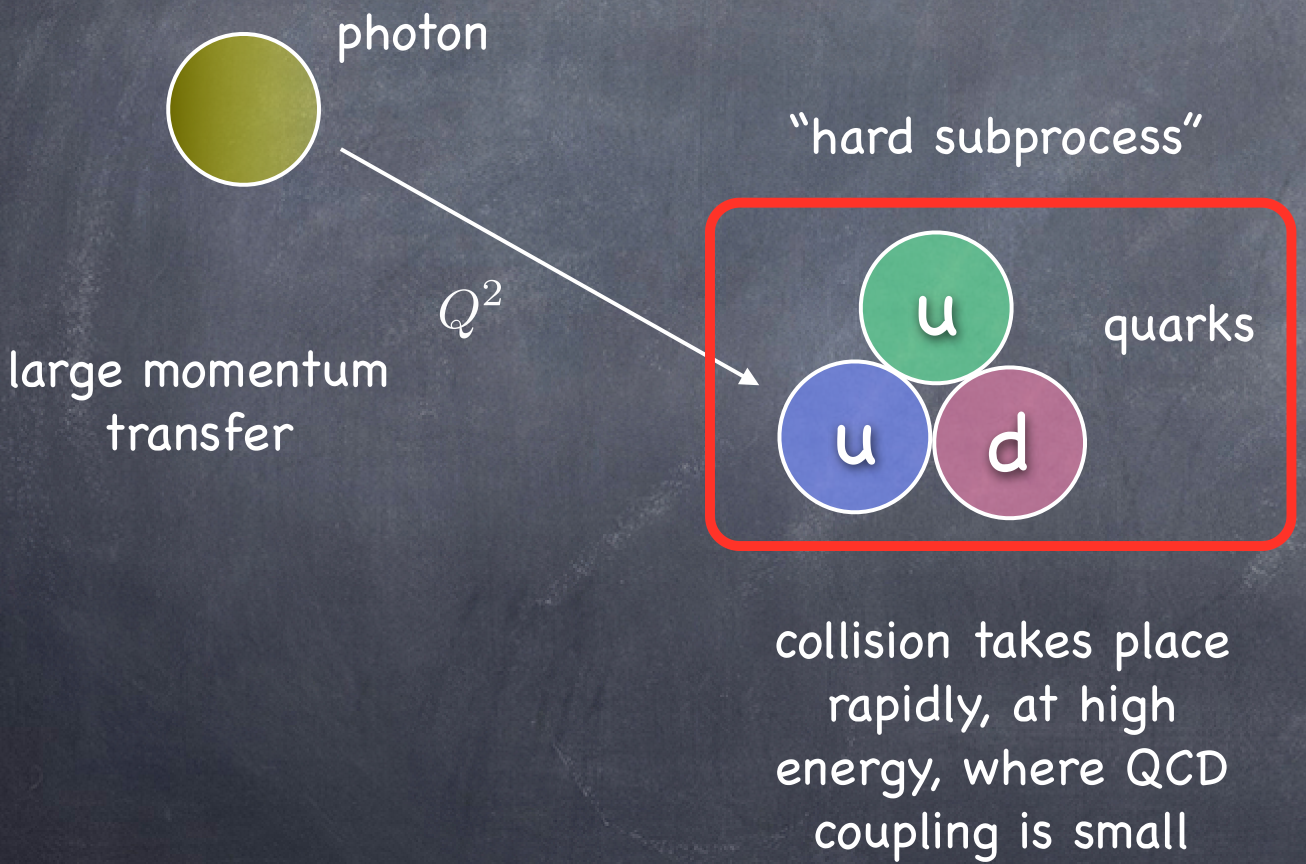
Searching for scaling effects as a signature of the particle spectrum brings us very close to QCD, where we would like to observe the presence of quarks



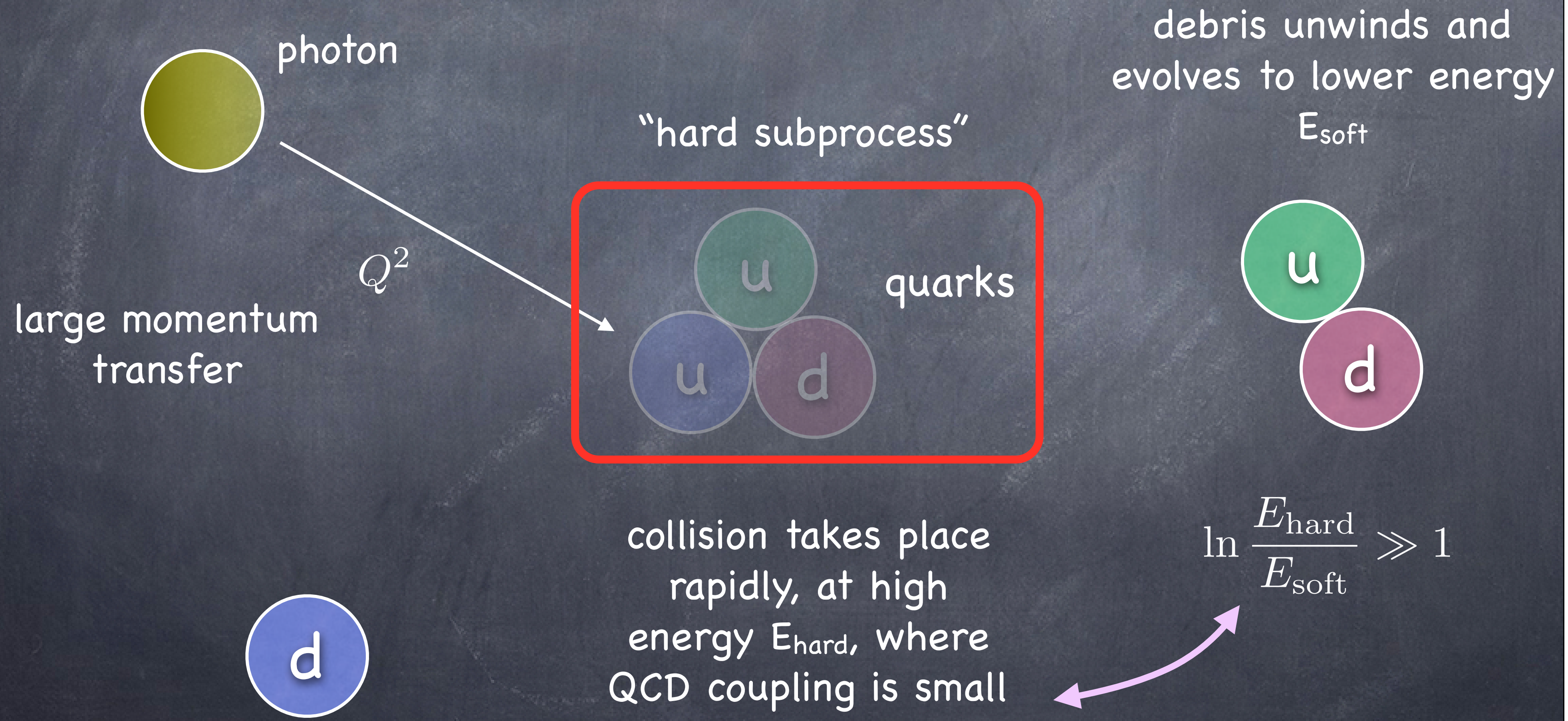
Searching for scaling effects as a signature of the particle spectrum brings us very close to QCD, where we would like to observe the presence of quarks



Searching for scaling effects as a signature of the particle spectrum brings us very close to QCD, where we would like to observe the presence of quarks



Searching for scaling effects as a signature of the particle spectrum brings us very close to QCD, where we would like to observe the presence of quarks

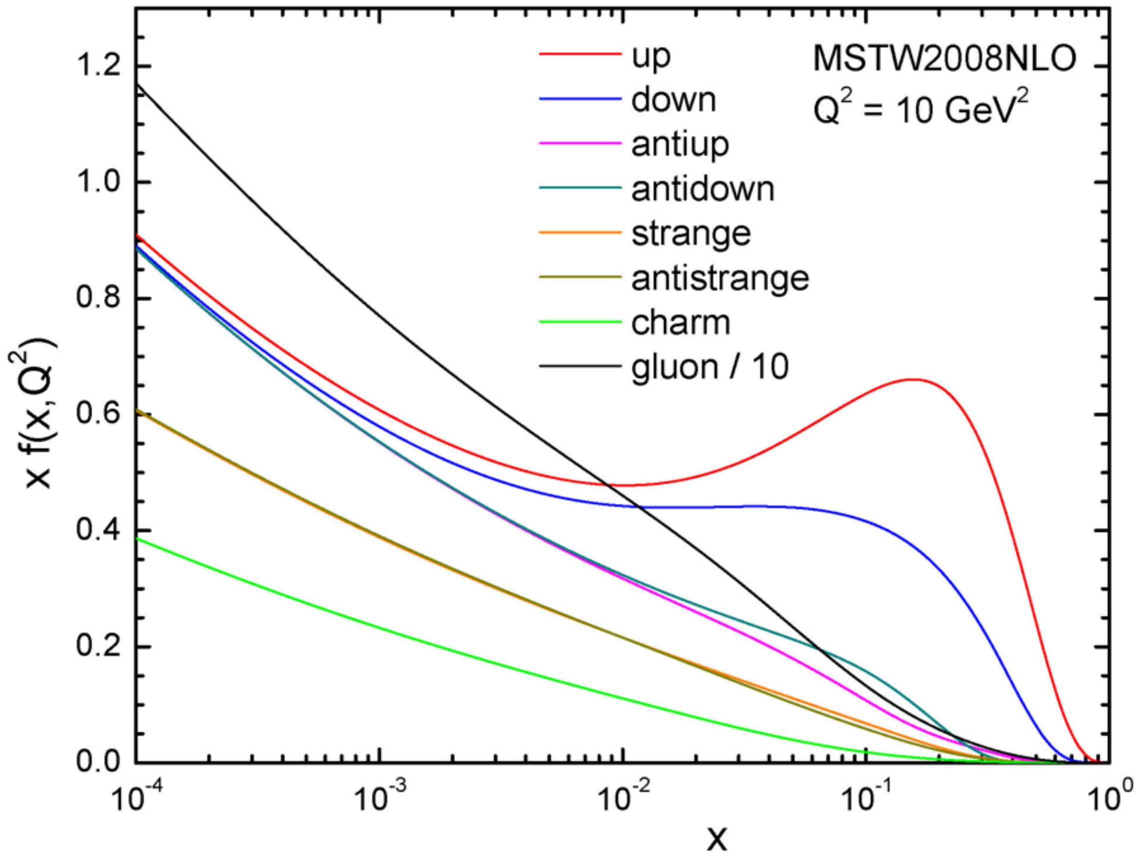


$$\ln \frac{E_{\mathrm{hard}}}{E_{\mathrm{soft}}} \gg 1$$

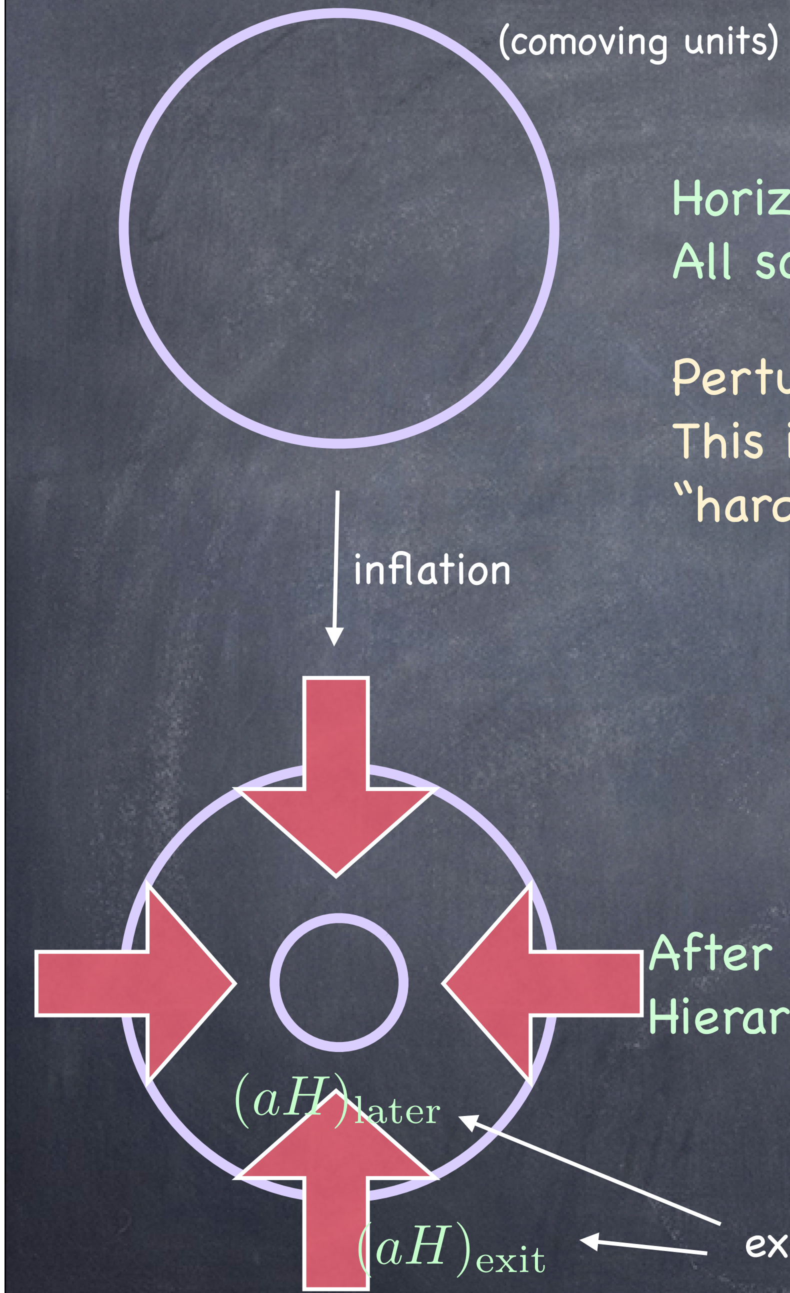
The hard subprocess is not necessarily the best diagnostic.

$$\ln \frac{E_{\rm hard}}{E_{\rm soft}} \gg 1$$

Instead, details of the theory show up in these large logs.
But it's no good just calculating to a few more orders in PT.



Credit: James Stirling



Horizon exit:
All scales comparable $\quad \boldsymbol{aH \sim k_i \sim k_*}$

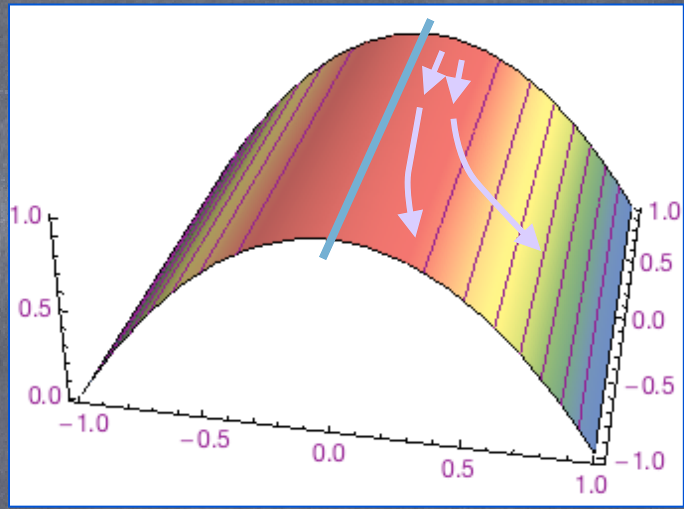
Perturbation theory is acceptable.
This is a very close analogue of the "hard subprocess" in pQCD

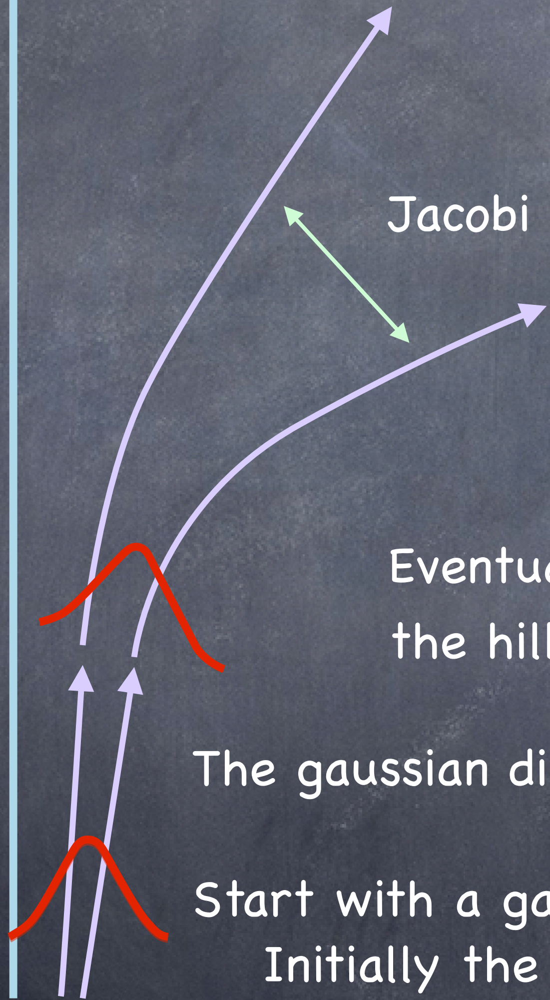
After horizon exit:
Hierarchy of scales

$$\ln \frac{(aH)_{\text{exit}}}{(aH)_{\text{later}}} = \ln |k_{\text{exit}}\eta| \gg 1$$

exponential hierarchy of scales

Eventually they disperse nonlinearly away from the ridge





Eventually a few trajectories slide away down the hillside, generating a **heavy tail**

The gaussian distribution is preserved in the early phases

Start with a gaussian distribution

Initially the trajectories keep close to each other

Ridge

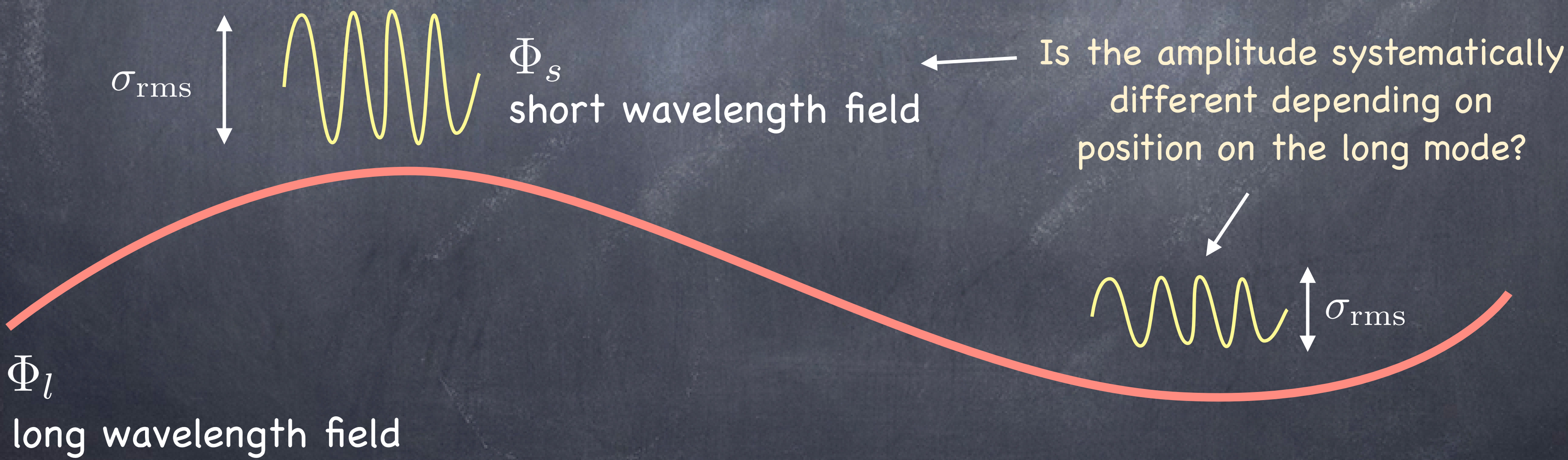
Scale-dependent effects: nonlinear bias, μ-distortions

$$\Phi = \Phi_g + f_{\rm NL}\Phi_g^2 + \cdots$$

Local in real space,
hence "local" model

Beginning of a power-series.
This says that Φ is a biased tracer of the Gaussian field

split long and short wavelengths $\quad \Phi_g = \Phi_l + \Phi_s$



$$\Phi = \Phi_g + f_{\rm NL}\Phi_g^2 + \cdots$$

long/short split

$$\Phi_l + \boxed{\Phi_s} = \boxed{\Phi_s^g} + \Phi_l^g + f_{\rm NL}\left[(\Phi_s^g)^2 + \boxed{2\Phi_s^g\Phi_l^g} + (\Phi_l^g)^2\right] + \cdots$$

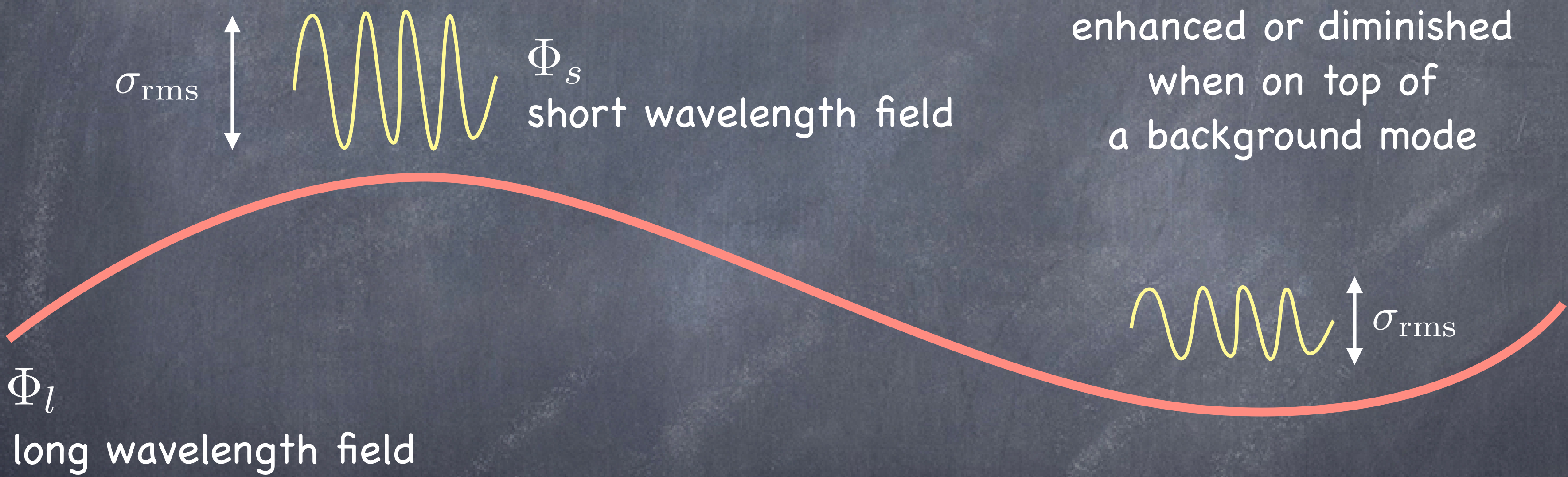
$$\Phi_s \approx \Phi_s^g + 2f_{\rm NL}\Phi_s^g\Phi_l^g + \cdots$$

$$\Phi_s \approx \Phi_s^g\underbrace{(1 + 2f_{\rm NL}\Phi_l^g)}_{\text{bias b}} + \cdots$$

To get the density, we need to take the Laplacian of Φ

$$\delta\rho_s \approx \delta\rho_s^g \left(1 + A f_{\mathrm{NL}} \frac{\delta_l^g}{k^2}\right)$$

short-wavelength amplitude
enhanced or diminished
when on top of
a background mode



The effect gets stronger when you look at modulation on longer and longer scales, where k $\to$ 0

To see how this works in general, use

$$\nu = \frac{\delta_c}{\sigma_M}$$

Press-Schechter critical density

$$\xi_{h,M}(\boldsymbol{x}_1, \boldsymbol{x}_2) = \frac{\nu^2}{\sigma_M^2}\xi_R^2(\boldsymbol{x}_1, \boldsymbol{x}_2) + \frac{\nu^3}{\sigma_M^3}\left[\xi_R^3(\boldsymbol{x}_1, \boldsymbol{x}_1, \boldsymbol{x}_2) + \xi_R^3(\boldsymbol{x}_1, \boldsymbol{x}_2, \boldsymbol{x}_2)\right] + \cdots$$

halo correlation function, mass M

density correlation functions, smoothed on scale R

The nonlinear relationship between haloes and the underlying matter field means that information about higher n-pfs of the density fluctuation gets communicated to lower n-pfs of the tracer population

After going to Fourier space, this will give us the power spectrum

$$P_{hh}(k) = b^2 P_{\delta\delta}(k)$$

$$b = b_0 + \Delta b$$

$$Q^2 = k^2 + q^2 + 2kq\mu$$

$$\Delta_b \approx \frac{\delta_c^2}{4\pi^2} \frac{M_R^{-1}(k,z)}{\sigma_M^4} \int_0^\infty q^2 \, \mathrm{d}q \, M_R(q,z) \int_{-1}^{+1} \mathrm{d}\mu \, M_R(Q,z) \frac{B_\Phi(k,Q,z)}{P_\Phi(k)}$$

$$\delta(\boldsymbol{k}, z) = M(k,z)\Phi(\boldsymbol{k})$$ (smoothed on the scale R)

On large scales, M ≈ k^{-2}. But there can be other contributions if the bispectrum doesn't scale like the power spectrum in regions where the integral gets a significant contribution

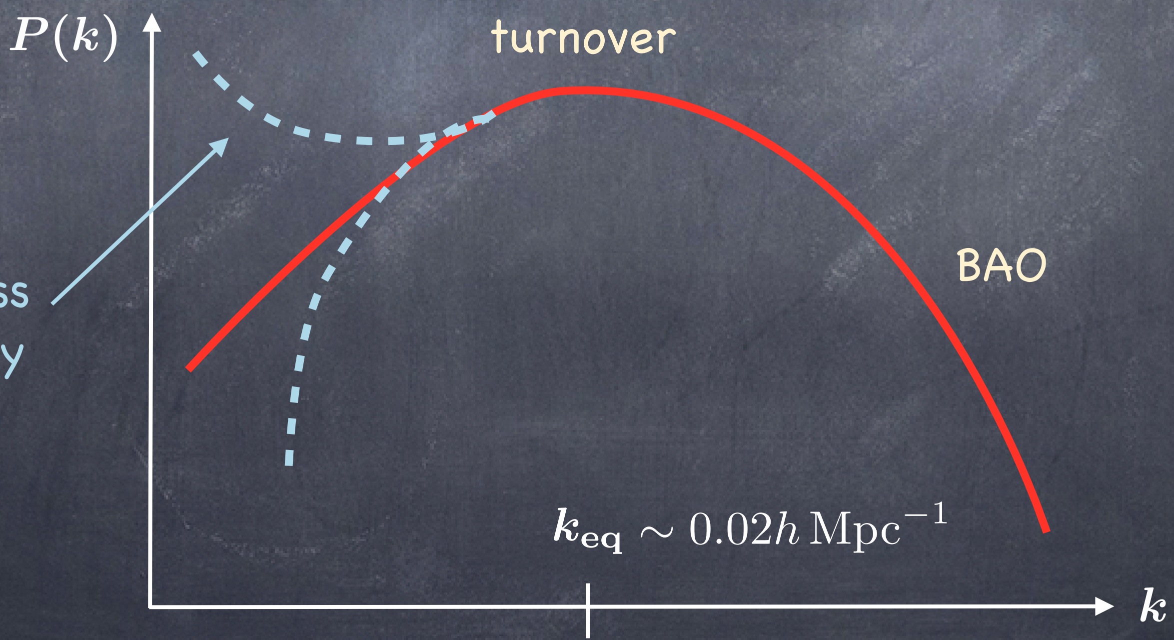
In many inflationary models, the result is approximately

$$\Delta b \sim k^{-2+n_{\rm sq}-(n_s-1)}$$

scaling of the bispectrum in the squeezed limit.
Needs detailed calculations to predict

Conventional spectral index

Search for excess or deficit on very small scales



TAKE-HOME MESSAGES

- Most cosmologists accept inflation as an explanation for the origin of the primordial density perturbation.
  But a convincing test requires a detection of microphysics.

- Planck data arrive on 21 March.
  Over the next decade, a new suite of observables from galaxy surveys will come on-line. These will probe higher-order correlations which are hard to detect in the CMB.

- We are importing a lot of machinery from particle physics and condensed matter physics in order to do these calculations. Sometimes we re-invent the wheel, but there is a lot of opportunity for crossover.