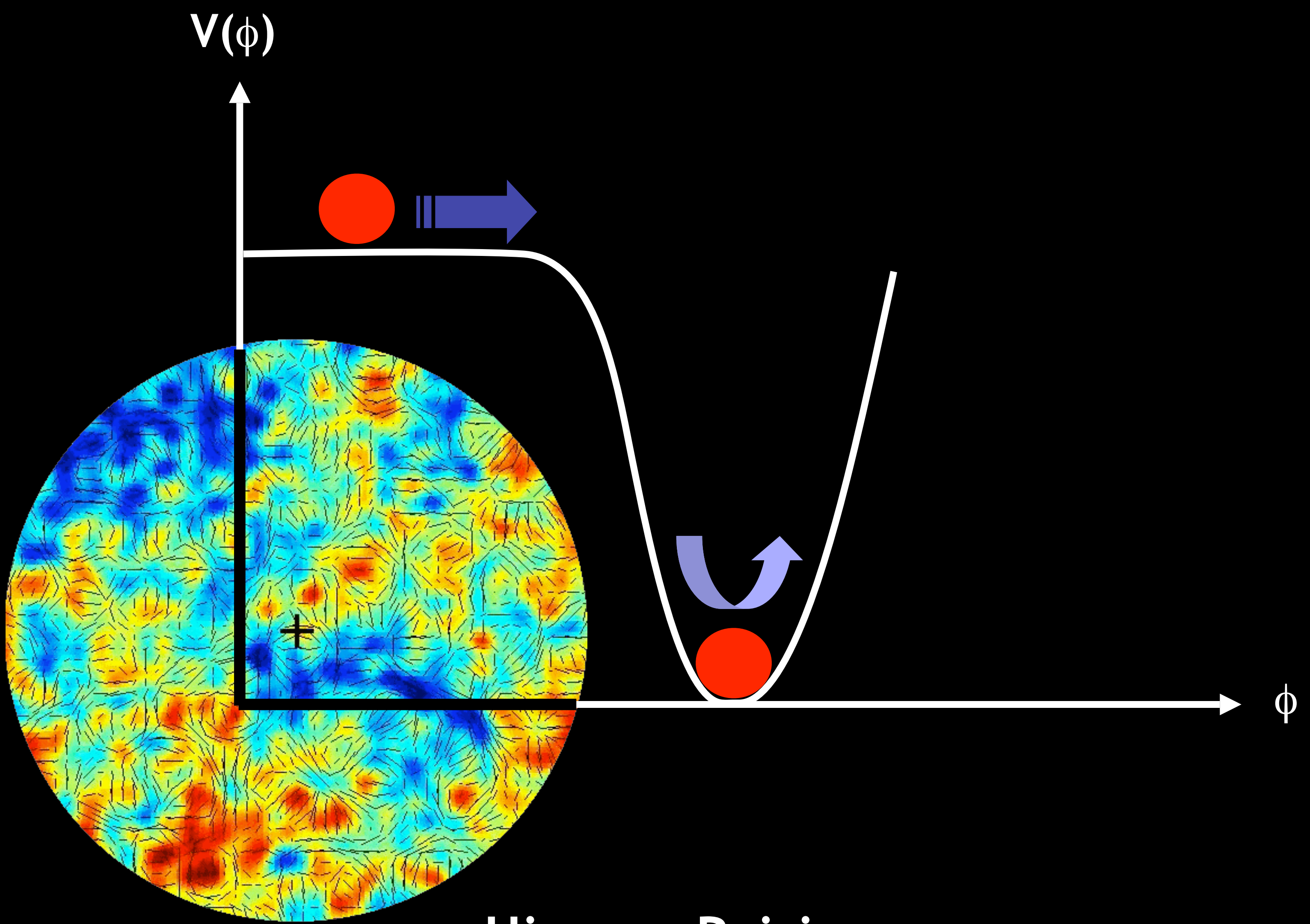
What have we learnt about the early universe?



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Roadmap

Lecture 1: The physics of the cosmic microwave background.

Lecture 2: What have we learnt about the early universe?

We are still testing the basic aspects of the inflationary mechanism rather than the specifics of its implementation.

Will concentrate here on “big picture” constraints on the paradigm rather than constraints on specific models.

$\Lambda\mathrm{CDM}$: The "Standard Model" of Cosmology

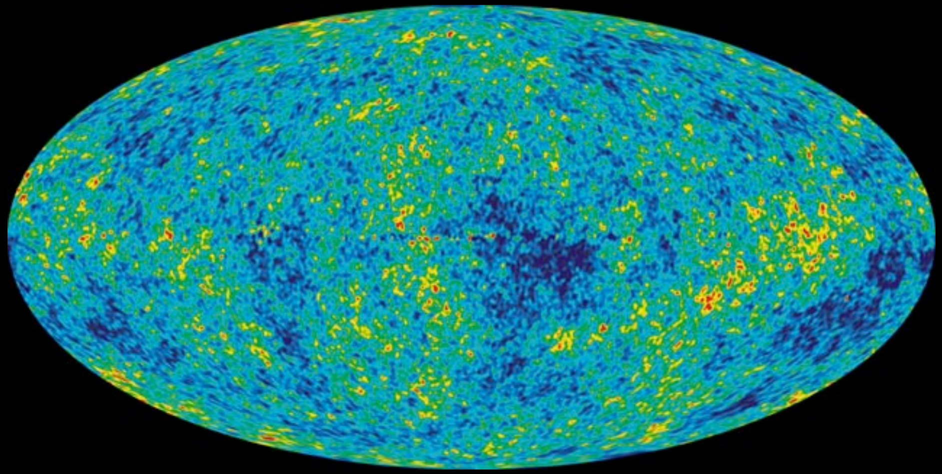
Homogeneous background

$$\Omega_b, \Omega_c, \Omega_\Lambda, H_0, \tau$$

- atoms 4%
- cold dark matter 23%
- dark energy 73%

Λ? CDM?

Perturbations



$$A_s, n_s, r$$

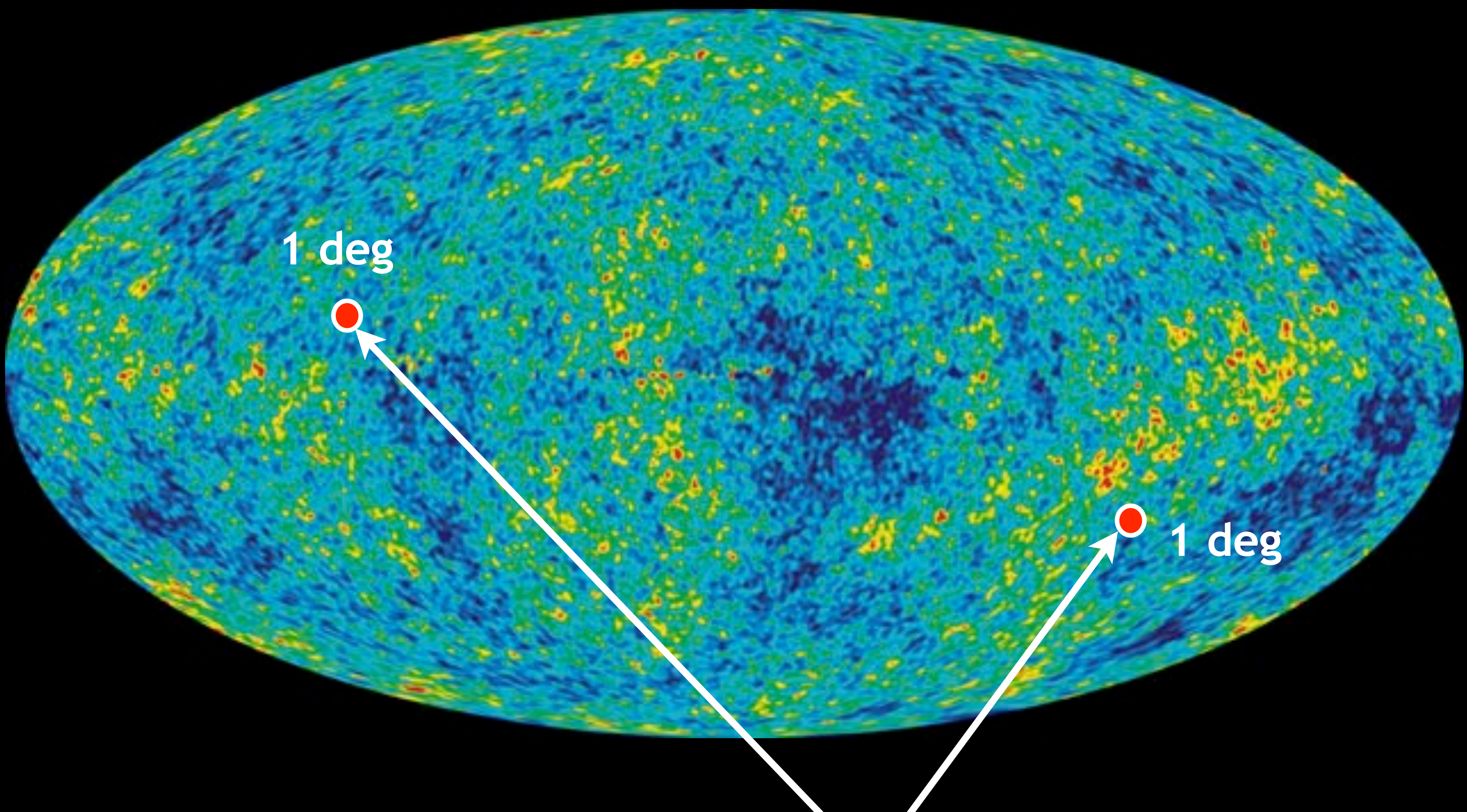
- nearly scale-invariant
- adiabatic
- Gaussian

ORIGIN??

The Horizon Problem

In Standard Big Bang Model, horizon scale at CMB release subtends ~ 1 deg

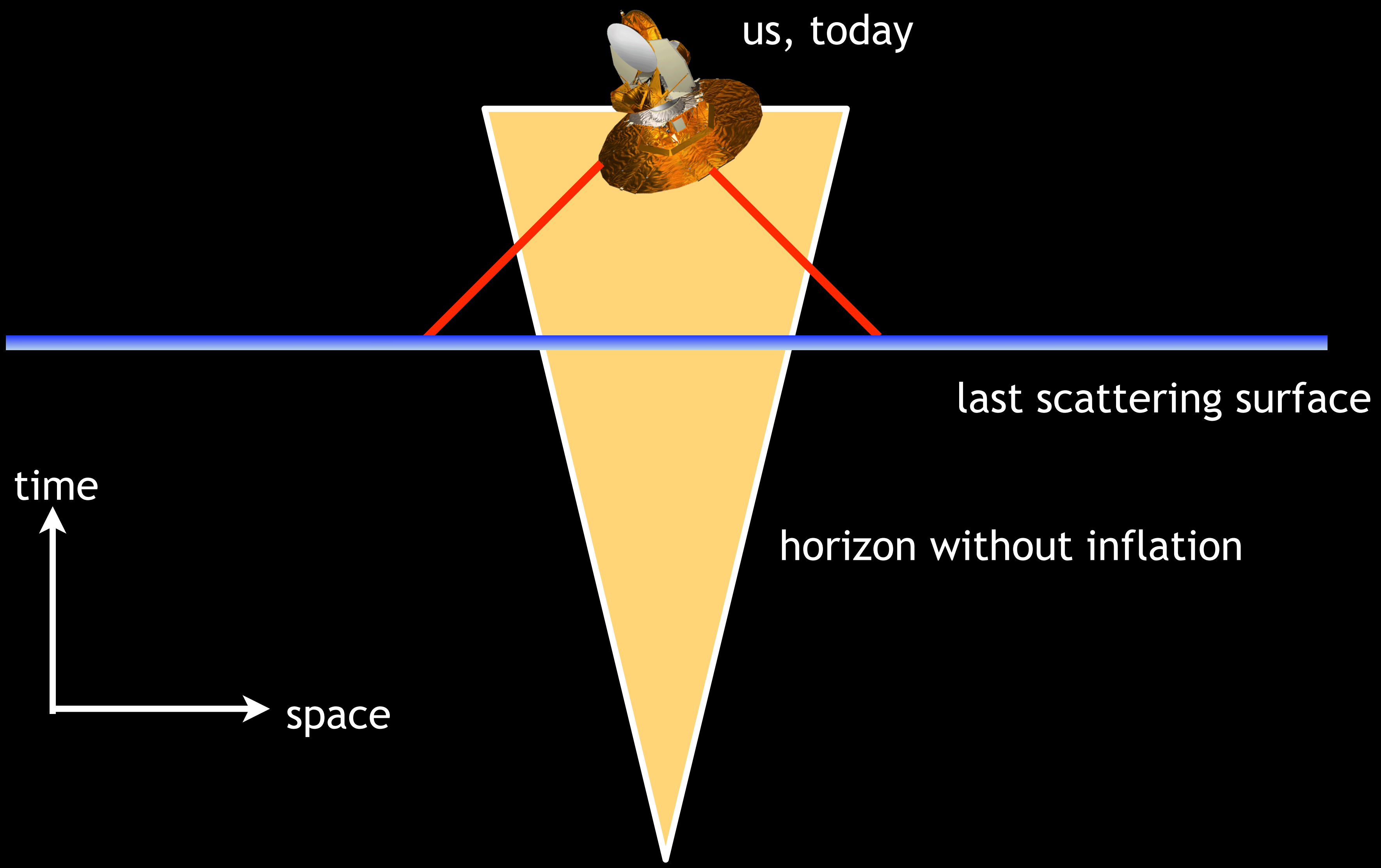
Regions separated by more than 1 deg could not have interacted previously



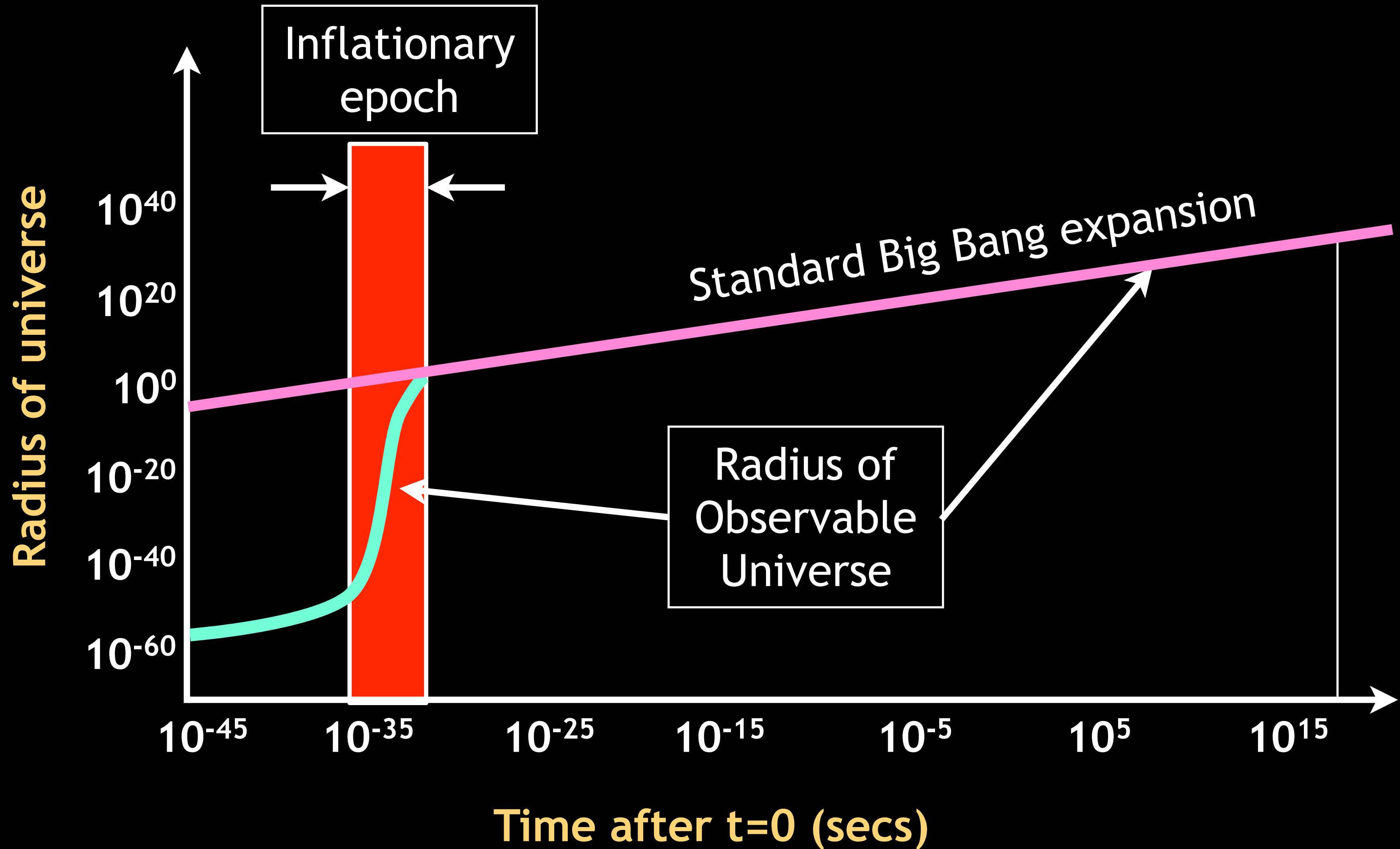
So why is the temperature of these patches the same to 1/100000?

Credit: NASA/WMAP Science Team

Horizon problem

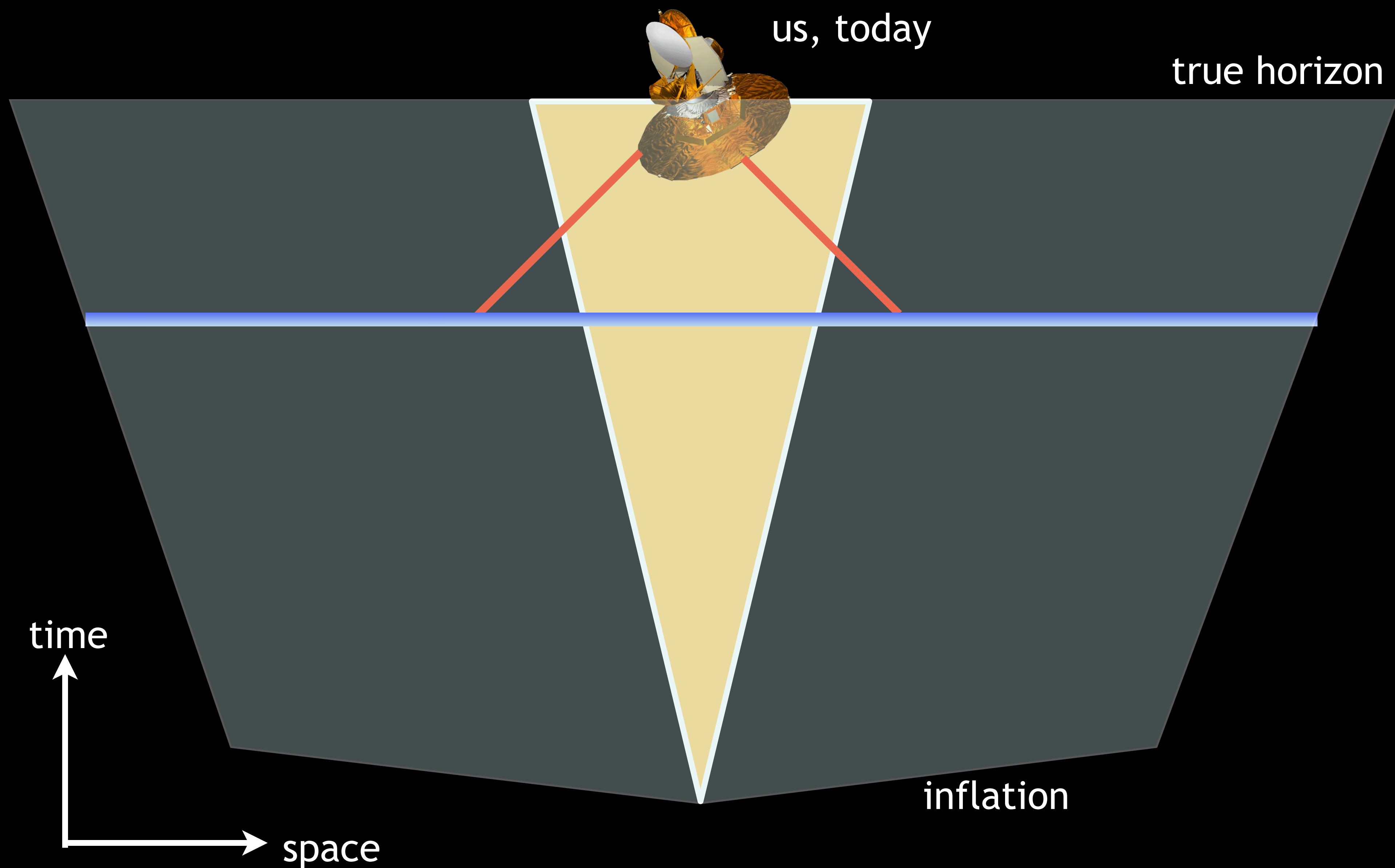


Inflation: accelerated super-expansion

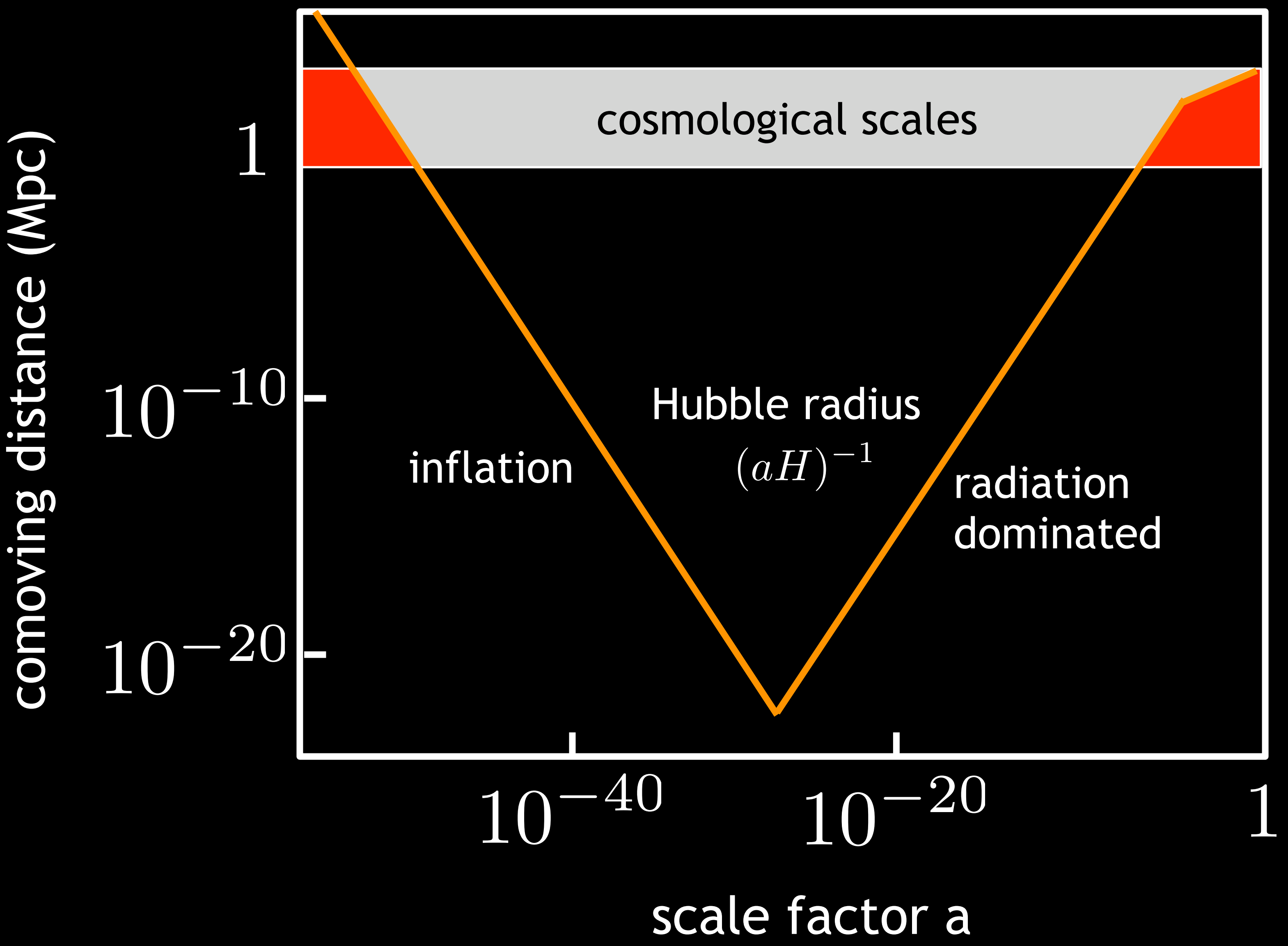


If inflation lasts long enough, CMB patches on opposite sides of the sky would have been close enough to communicate in the primordial times.

Inflationary resolution of horizon problem



Comoving Hubble radius during inflation



red: scales are smaller than horizon, and subject to microphysical processes

Inflation

A period of accelerated expansion

$$ds^2 = -dt^2 + e^{2Ht}dx^2 \qquad H \simeq \text{const}$$

- Solves:
  - horizon problem
  - flatness problem
  - monopole problem

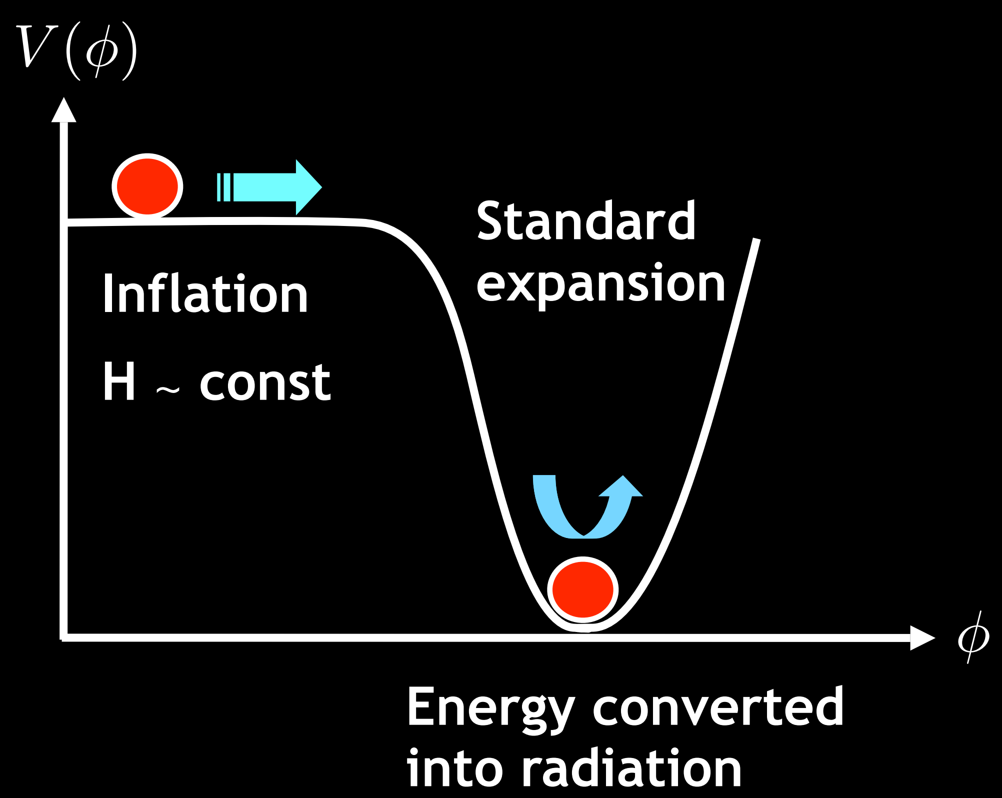
  i.e. explains why the Universe is so large, so flat, and so empty

- Predicts:
  - scalar fluctuations in the CMB temperature
    - ✓ nearly scale-invariant
    - ✓ approximately Gaussian (?)

  ? primordial tensor fluctuations (gravitational waves)

Inflation

Implemented as a slowly-rolling scalar field evolving in a potential:



$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left[\frac{1}{2}\dot{\phi}^2 + V(\phi)\right]$$

expansion rate

density

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

friction

overdot = d/dt

The inflationary background solution

Recall Einstein's Equation for the acceleration of the scale factor:

$$\frac{\ddot{a}}{a} = -\frac{4}{3}(\rho + 3P) \qquad \ddot{a} > 0 \Longrightarrow P < -\frac{\rho}{3}$$

For a canonical minimally coupled scalar field,

density: $$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$ pressure: $$P = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

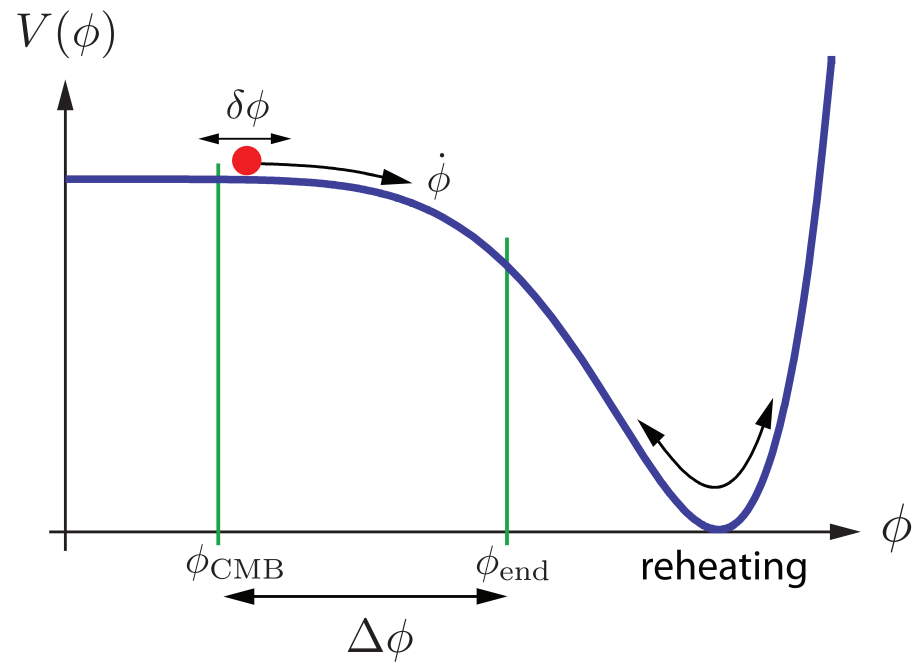
During slow roll, potential energy dominates kinetic energy: negative pressure:

$$P \simeq -V(\phi) \simeq -\rho$$

So expansion of the universe accelerates, scale factor grows exponentially:

$$a(t) \sim e^{Ht}, \quad H^2 \sim \frac{8\pi G}{3} V$$

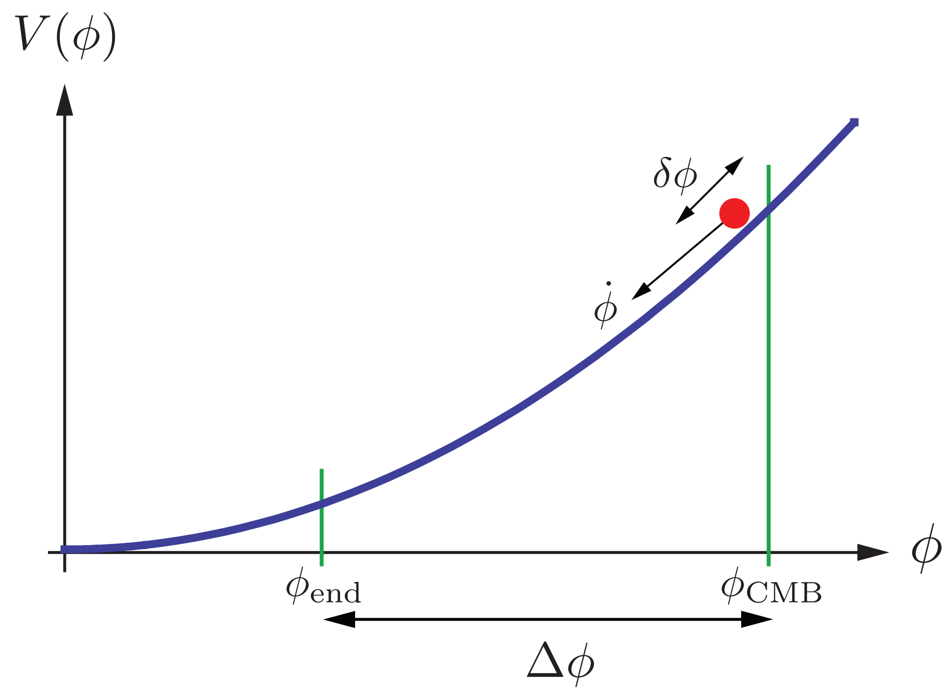
Example of an inflationary potential



- Acceleration occurs when PE dominates KE.
- Inflation ends when KE has grown comparable to PE: $\frac{1}{2}\dot{\phi}^2 \simeq V(\phi)$
- CMB fluctuations created by quantum fluctuations ~ 60 e-folds before the end of inflation.
- At end of inflation, energy density of the inflaton converted into radiation.

Image by D. Baumann

Large field inflation



- Important class of models where inflaton is driven by a monomial potential:

$$V(\phi) \sim \phi^p$$

- Field evolves over a super-Planckian distance during inflation: $\Delta\phi > M_{\rm Pl}$
- Large amplitude of gravitational waves produced by QM fluctuations.

Image by D. Baumann

Perturbations from inflation

Cosmological perturbations arise from quantum fluctuations, evolve classically.

$$P_\phi(k) \simeq \hbar \left(\frac{H}{2\pi}\right)^2$$

$$P_\mathcal{R} \simeq \frac{\hbar}{4\pi^2}\left(\frac{H^4}{\dot{\phi}^2}\right)_{k=aH}$$ scalar

$$P_h \simeq \frac{2\hbar}{\pi^2}\left(\frac{H}{m_{\rm Pl}}\right)^2_{k=aH}$$ tensor

Generation of perturbations: overview I

- QM fluctuations in inflaton produced when relevant scales causally connected.
- Perturbations driven out of the horizon by inflation.
- Perturbations re-enter much later to serve as initial conditions for structure formation.
- Inflation generates both scalar and tensor (metric) perturbations.

Generation of perturbations: overview II

- Perturbations best described in terms of Fourier modes.
- Individual modes are uncorrelated with each other.
- e.g. for the gravitational potential,

$$\langle \Phi(\vec{k}) \rangle = 0 \quad \text{zero mean}$$

$$\langle \Phi(\vec{k}) \Phi^*(\vec{k'}) \rangle = (2\pi)^3 k^{-3} P_\Phi(k) \delta^3(\vec{k} - \vec{k'}) \quad \text{non-zero variance}$$

- Goal: compute this variance in fields and see how it evolves during inflation.

Gravitational wave production

- Review tensor before scalar perturbations since not coupled to other perturbation variables; treat as fluctuations in a single field.

- Not coupled to density so not responsible for large scale structure, but induces CMB fluctuations.

- Unique signature of inflation, best window into inflationary physics.

- To compute QM fluctuations in metric, need to quantize field.

Conventions

From now, overdot will represent derivative w.r.t. conformal time:

$$\tau = \int \frac{dt}{a(t)} = \int \frac{da}{Ha^2}$$

don't confuse with optical depth!

Use natural units, $\hbar = c = k_B = 1$.

Reminder: Quantizing the SHO I

Simple harmonic oscillator with unit mass and frequency ω obeys:

$$\ddot{x} + \omega^2 x = 0$$

Upon quantization, x becomes quantum operator:

$$\hat{x} = v(\omega, t)\hat{a} + v^*(\omega, t)\hat{a}^\dagger$$

where $\hat{a}$ is a quantum operator and $v \propto \exp(i\omega t)$ is a solution to SHO eq.

Reminder: Quantizing the SHO II

$\hat{a}$ annihilates the vacuum state, $\hat{a}|0\rangle = 0$ (in which there are no particles) and satisfies commutation relation:

$$[\hat{a}, \hat{a}^\dagger] \equiv \hat{a}\hat{a}^\dagger - \hat{a}^\dagger\hat{a} = 1$$

giving variance: $\langle|\hat{x}|^2\rangle \equiv \langle 0|\hat{x}^\dagger\hat{x}|0\rangle = |v(\omega, t)|^2$

Tensor perturbations: metric

Tensor perturbations characterized by metric with: $g_{00} = -1, \; g_{0i} = 0$

$$g_{ij} = a^2 \begin{pmatrix} 1 + h_+ & h_\times & 0 \\ h_\times & 1 - h_+ & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

Perturbations described by two functions, $h_+, h_\times$ here assumed to be in *x*,*y* plane (*z* in dirn of wavevector) but more generally, cpts of a divergenceless, traceless, symmetric tensor.

Carry out usual operation with Einstein equation noting: $T_{\mu\nu} = 0$.

Tensor perturbations: quantization I

Each component individually obeys:

$$\ddot{h} + 2\frac{\dot{a}}{a}\dot{h} + k^2 h = 0$$

Want to massage into the form of a SHO.

Redefine: $\tilde{h} = \dfrac{ah}{\sqrt{16\pi G}}$ cunningly normalized!

SHO-like equation! No damping term!

$$\ddot{\tilde{h}} + \left(k^2 - \frac{\ddot{a}}{a}\right)\tilde{h} = 0 \qquad (\ddot{x} + \omega^2 x = 0)$$

Tensor perturbations: quantization II

Can just write down quantum operator:

$$\hat{\tilde{h}}(\vec{k},\tau) = v(\vec{k},\tau)\hat{a}_{\vec{k}} + v^*(\vec{k},\tau)\hat{a}^\dagger_{\vec{k}}$$

and the variance after transforming back to *h*:

$$\begin{aligned}\langle \hat{h}^\dagger(\vec{k},\tau)\hat{h}^\dagger(\vec{k},\tau)\rangle &= \frac{16\pi G}{a^2}|v(\vec{k},\tau)|^2(2\pi)^3\delta^3(\vec{k}-\vec{k'}) \\ &\equiv (2\pi)^3 k^{-3} P_h(k)\delta^3(\vec{k}-\vec{k'})\end{aligned}$$

power spectrum

Tensor perturbations: mode equation

Now have power spectrum: $$P_h(k) = 16\pi G \frac{k^3 |v(\vec{k},\tau)|^2}{a^2}$$

Have reduced problem to solving second order DE:

$$\ddot{v} + \left(k^2 - \frac{\ddot{a}}{a}\right) v = 0 \qquad \text{where} \qquad \frac{\ddot{a}}{a} \simeq \frac{2}{\tau^2}$$

Tensor perturbations: mode solution

Solution:

$$v = \frac{e^{-ik\tau}}{\sqrt{2k}} \left[1 - \frac{i}{k\tau} \right].$$

Modes leave horizon at $-k\tau < 1$.

Limits:

$$v \rightarrow \frac{e^{-ik\tau}}{\sqrt{2k}}$$ $k|\tau| >> 1$ well inside horizon $h \propto 1/a$ SHO soln.

$$v \rightarrow \frac{e^{-ik\tau}}{\sqrt{2k}} \frac{i}{k\tau}$$ $-k\tau \rightarrow 0$ well outside horizon $h \rightarrow \text{const}$

Tensor perturbations: power spectrum

Primordial power spectrum is thus constant after mode exits horizon. This constant determines the initial conditions for gravitational waves:

$$
\begin{aligned}
P_h(k) &= 16\pi G \frac{1}{2a^2\tau^2} \\
&\simeq 8\pi G H^2
\end{aligned}
$$

H is to be evaluated at horizon exit. $H \sim \mathrm{const} \rightarrow P_h$ nearly scale-invariant.

Gravitational wave detection measures Hubble rate during inflation!

Since Hubble rate dominated by potential energy during inflation, thus measure $V(\phi)$ at horizon exit!

Fluctuations are Gaussian, just like for an SHO.

Scalar perturbations in the inflaton

Decompose inflaton into zero-order homogeneous part and perturbation:

$$\phi(\vec{x},t) = \phi^{(0)}(t) + \delta\phi(\vec{x},t)$$

Assuming a smoothly expanding FRW metric, only first order pieces are perturbations to $T_{\mu\nu}$. After usual Einstein equation manipulations, find:

$$\ddot{\delta\phi} + 2\frac{\dot{a}}{a}\dot{\delta\phi} + k^2\delta\phi = 0$$

Same form as the tensor case; trivially copy solution, dropping normalization factor as we already have a scalar field:

$$P_{\delta\phi} = \frac{H^2}{2}$$

Perturbed FRW metric in CNG

The Conformal Newtonian Gauge describes the perturbed FRW metric.

$$ds^2 = a^2(\tau)[(1+2\Psi)d\tau^2 - \delta_{ij}(1-2\Phi)dx^i dx^j]$$

where τ = conformal time. Metric perturbations described by scalar potentials Ψ (Newtonian potential) and Φ (perturbation to spatial curvature).

Only describes scalar perturbations.

Gauge choice

Want to know how perturbations in ϕ get transferred to Ψ (or Φ, assumed identical in magnitude here). Just neglected metric perturbations so far.

Easiest way is to switch to a gauge where spatial part of the metric is unperturbed: a spatially flat slicing.

In such gauge, previous calculation is exact. Q: How to move back to CNG?

A: (i) Identify a gauge invariant variable $\propto \delta\phi$ in a spatially flat slicing (SFS). (ii) Find this variable in CNG, thus linking Ψ in CNG with $\delta\phi$ in SFS.

In this gauge, line element (with A, B characterizing perturbations) is:

$$ds^2 = -(1+2A)dt^2 - 2aB_{,i}dx^i dt + \delta_{ij}a^2 dx^i dx^j$$

Scalar perturbations in spatially flat slicing

Bardeen (1980) identified several gauge-invariant variables. In particular, in SFS, Bardeen's velocity is:

$$v = ikB - \frac{ik\dot{\phi}^{(0)}\delta\phi}{(\rho + P)a^2}$$

In SFS, Bardeen's Φ_H is $\Phi_H = aHB$ so find gauge-invariant combo:

$$\mathcal{R} \equiv -\Phi_H - \frac{iaH}{k}v = -\frac{aH}{\dot{\phi}^{(0)}}\delta\phi \quad \text{in SFS}$$

Immediately obtain power spectrum:

$$P_{\mathcal{R}} = \left(\frac{aH}{\dot{\phi}^{(0)}}\right)^2 P_{\delta\phi}$$

Spatial curvature at fixed time is $4k^2\Phi_H/a^2$ so in a comoving gauge, $\mathcal{R}$ can be called the curvature perturbation.

Slow roll parameters and power spectra

Useful to characterize inflationary dynamics by slow roll parameters which remain small during inflation.

$$\epsilon \equiv \frac{d}{dt}\left(\frac{1}{H}\right) = \frac{-\dot{H}}{aH^2} \qquad \eta \equiv \frac{1}{H}\frac{d^2\phi^{(0)}/dt^2}{d\phi^{(0)}/dt^2}$$

Prefactor in $P_{\mathcal{R}}$ is then $4\pi G/\epsilon$ so:

$$P_{\mathcal{R}} = 2\pi G \frac{H^2}{\epsilon}\bigg|_{k=aH}$$

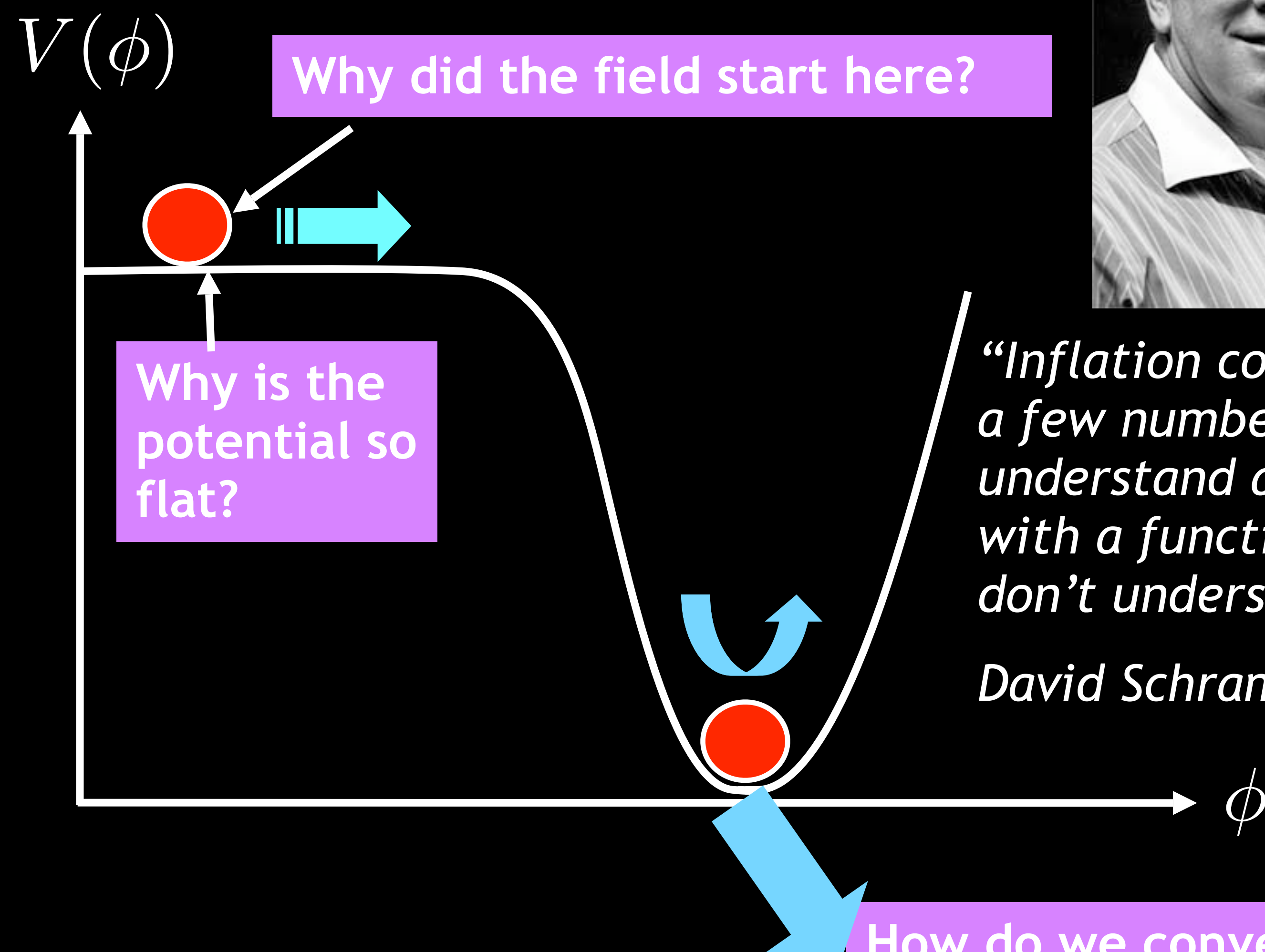
weakly scale dependent

In CNG, $\Phi_H = -\Phi$ and after inflation, $\mathcal{R} = -\frac{3}{2}\Psi = \frac{3}{2}\Phi$, so $P_{\mathcal{R}} = \frac{9}{4}P_{\Phi}$.

Often used empirical parameterizations:

$$P_{\mathcal{R}}(k) \simeq A_s\left(\frac{k}{k_0}\right)^{n_s-1} \qquad P_h(k) \simeq A_t\left(\frac{k}{k_0}\right)^{n_t} \qquad r = \frac{P_h(k_0)}{P_{\mathcal{R}}(k_0)}$$

What is the physics of inflation?



Where did this function come from?

Why did the field start here?

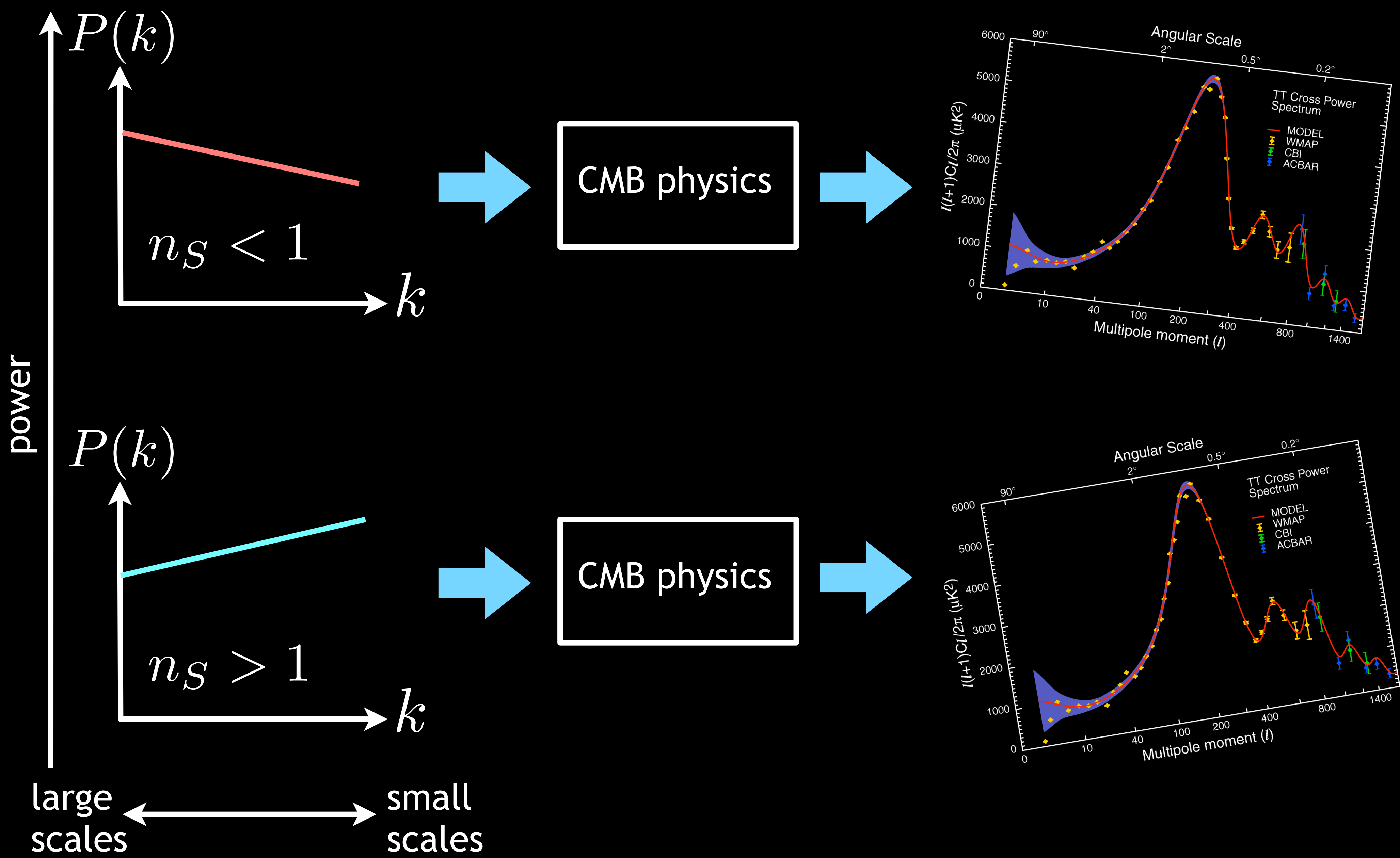
Why is the potential so flat?

How do we convert the field energy completely into radiation?

"Inflation consists of taking a few numbers that we don't understand and replacing it with a function that we don't understand"

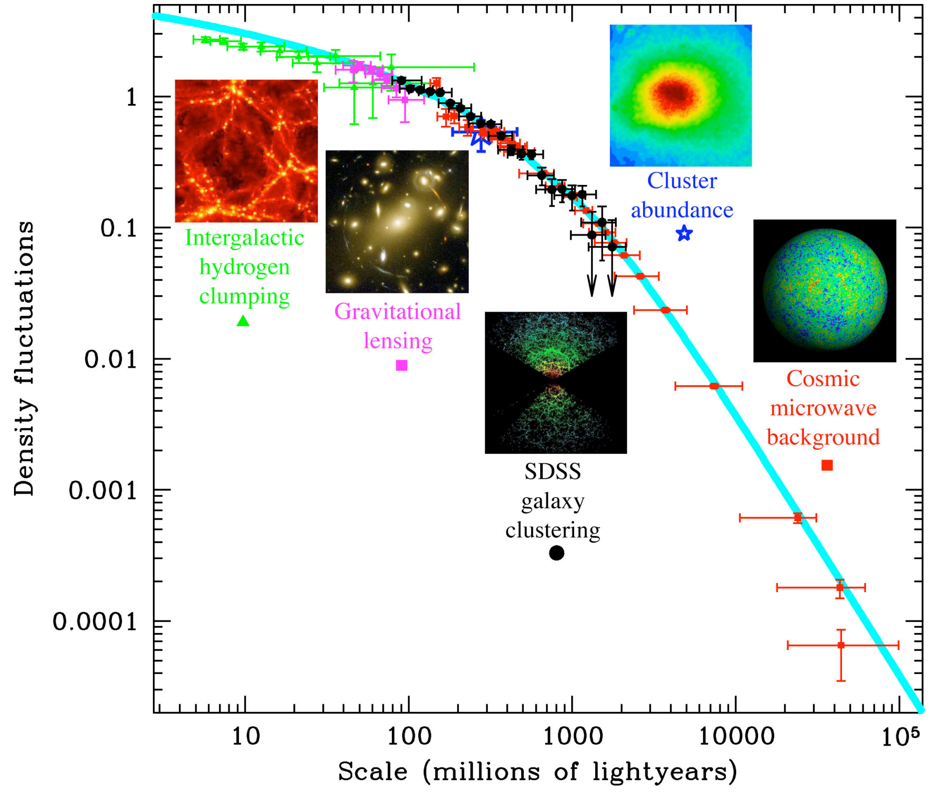
David Schramm 1945 -1997

Reminder: the primordial power spectrum & the CMB



Parameters from CMB: primordial power spectrum

- Scalar power spectrum C_l essentially $e^{-2\tau}\mathcal{P}_{\mathcal{R}}(k)$ at $k \approx l/d_A$ processed by acoustic physics
  - CMB probes scales $5\,\mathrm{Mpc} < k^{-1} < 5000\,\mathrm{Mpc}$
- Tensor power spectra sensitive to $e^{-2\tau}\mathcal{P}_h(k)$



Testing inflation

- Key predictions of *simple* inflation models:
  - Universe should be flat (cf. $\Omega_K = -0.005 \pm 0.006$)
  - Small curvature fluctuations and (possibly) gravitational waves with almost scale-invariant, power-law spectra:

$$\mathcal{P}_{\mathcal{R}}(k) \approx A_s (k/k_*)^{n_s - 1} \quad , \quad \mathcal{P}_h(k) \approx A_t (k/k_*)^{n_t}$$

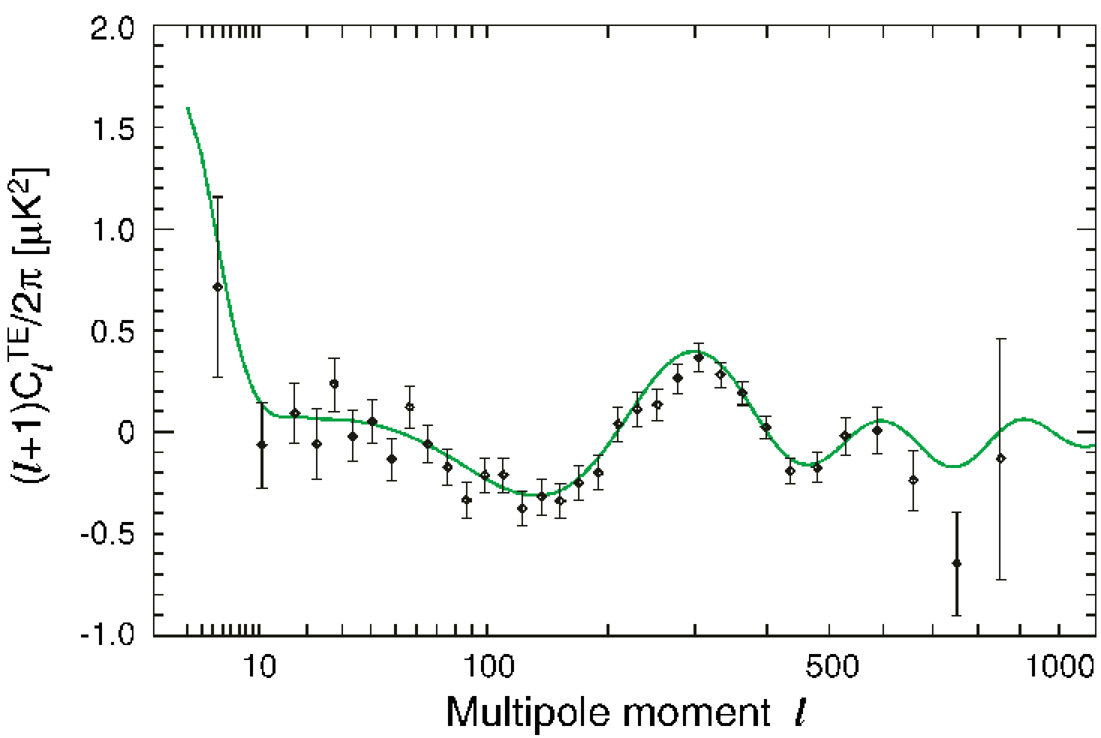
    with observables related to slow-roll parameters [≈ parameterise gradient and curvature of $V(\phi)$]

$$A_s = \frac{H^2}{\pi \epsilon m_{\mathrm{Pl}}^2}, \quad n_s - 1 = -4\epsilon + 2\eta, \quad A_t \equiv r A_s = \frac{16 H^2}{\pi m_{\mathrm{Pl}}^2}, \quad n_t = -2\epsilon$$

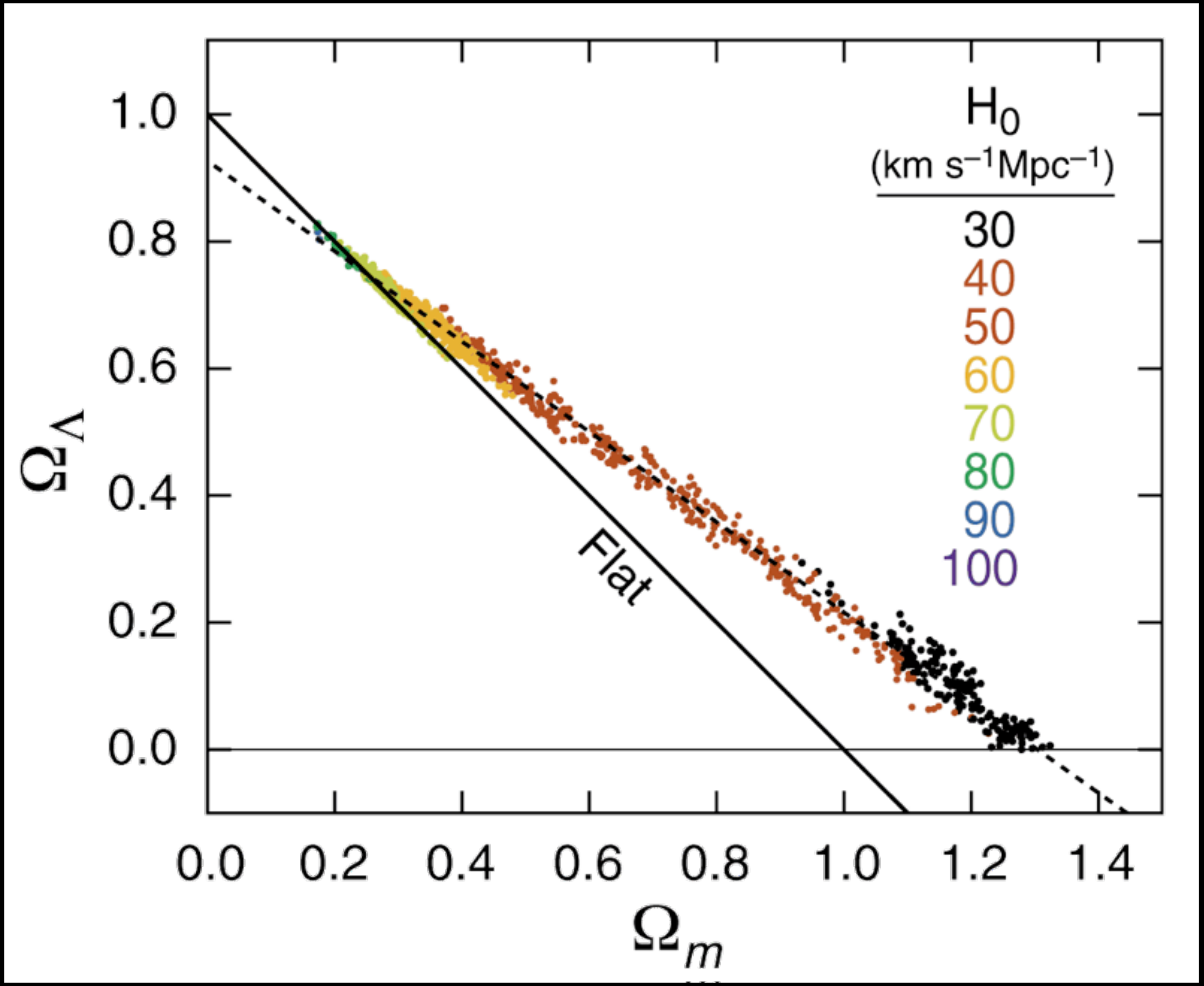
  - Adiabatic initial conditions
  - Fluctuations should be Gaussian (to observational accuracy; see later):

The character of fluctuations

- Well-defined peaks $\Rightarrow$ phase coherence (cf. defects)
- Super-horizon correlations at last scattering surface from TE correlation and sign $\Rightarrow$ adiabaticity
- Peak positions in TT, TE and EE consistent with adiabatic models
  - CMB still allows $\sim 10\%$ contribution from single, uncorrelated isocurvature modes and significantly more for more general cases (Bean et al. 2006), but not favoured over adiabatic



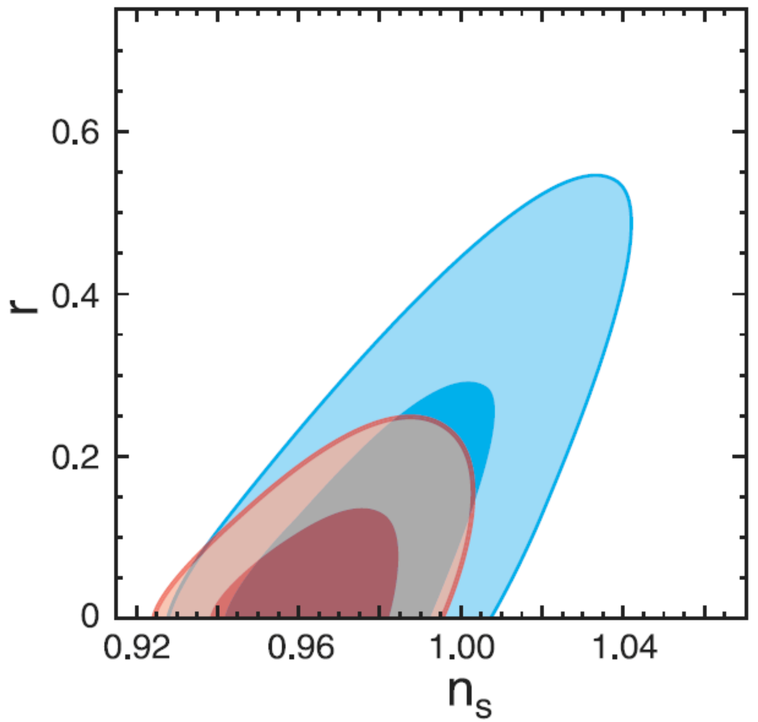
The flatness of the Universe?

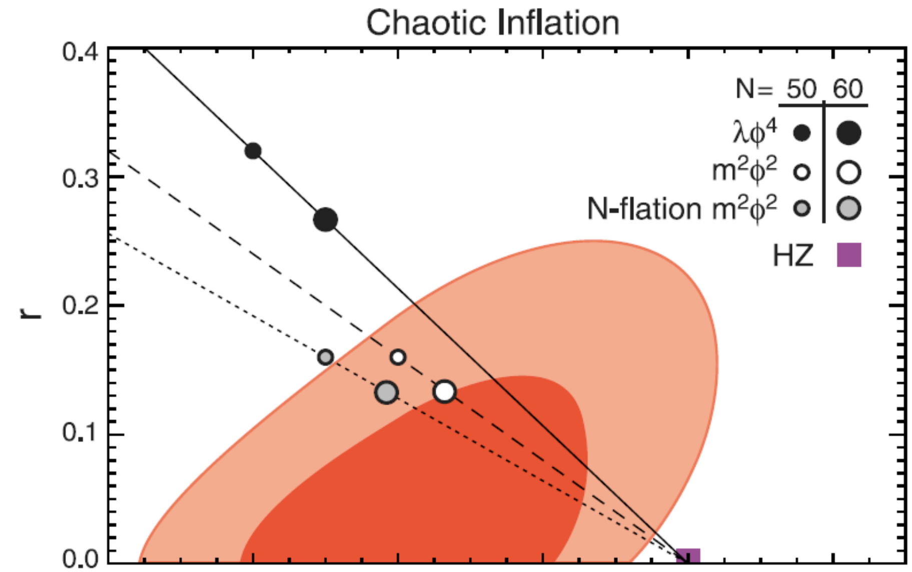


geometric degeneracy [powerlaw P(k)]: $\Omega_K \sim -0.304 + 0.407\Omega_\Lambda$

Spergel et al. (WMAP Collaboration, 2006)

Slow roll inflation

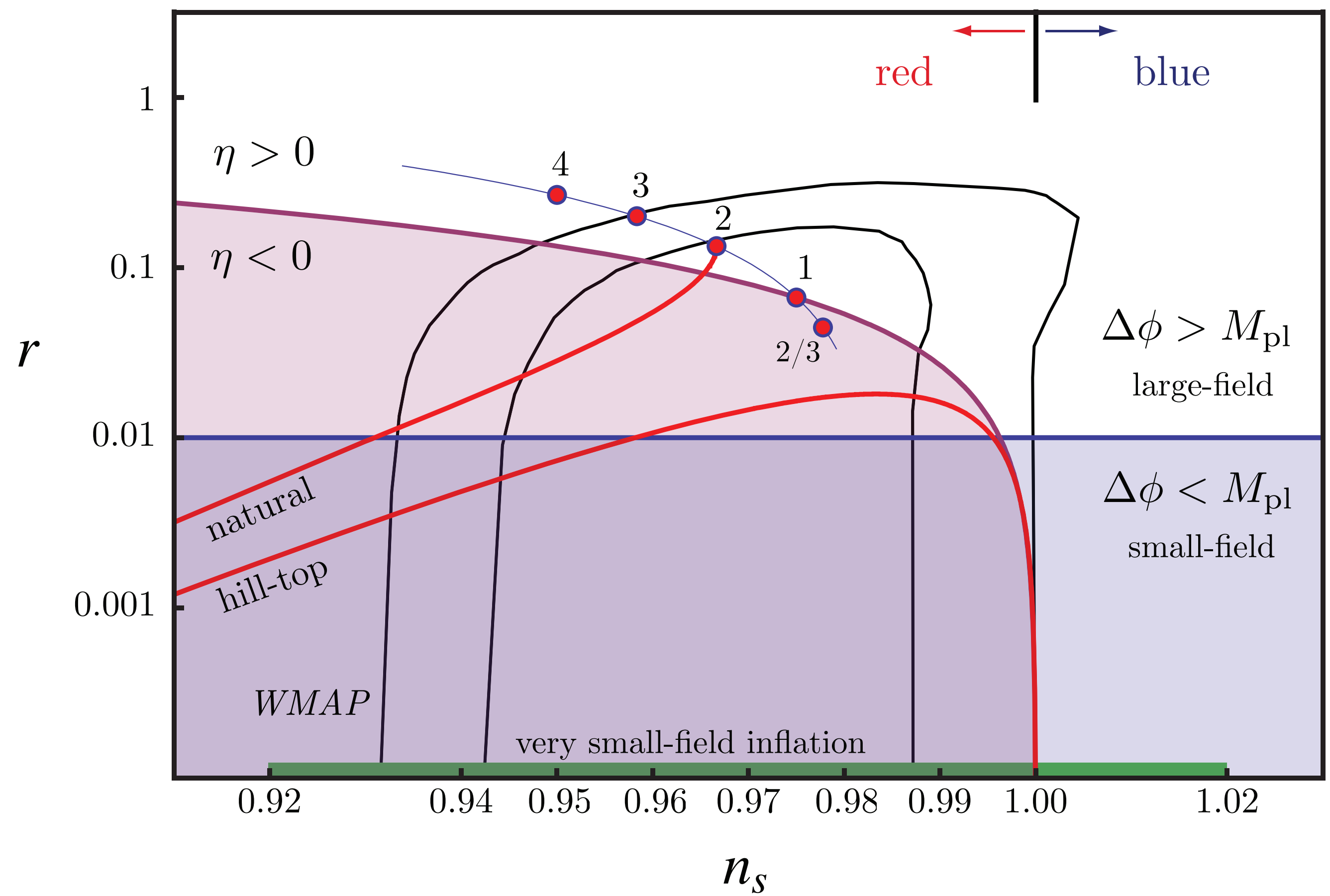




Komatsu et al. 2008

- Inflation energy scale unknown: $r < 0.2$ from low-l $\Delta T \Rightarrow E_{\text{inf}} < 2.2 \times 10^{16}$ GeV
- Dynamics not yet classified (e.g. small-field, large-field or hybrid phenomenology)
- $n_s < 1$ with CMB+BAO+SN and $n_s = 0.963 \pm 0.015$ from WMAP5, no running and $r = 0$
  - n_s-$\Omega_b h^2$ degeneracy main one now affecting n_s
- $dn_s/d\ln k = -0.037 \pm 0.028$ from WMAP5 with $r = 0$
  - Some shifts ($\sim -0.5\sigma$) if include small-scale CMB

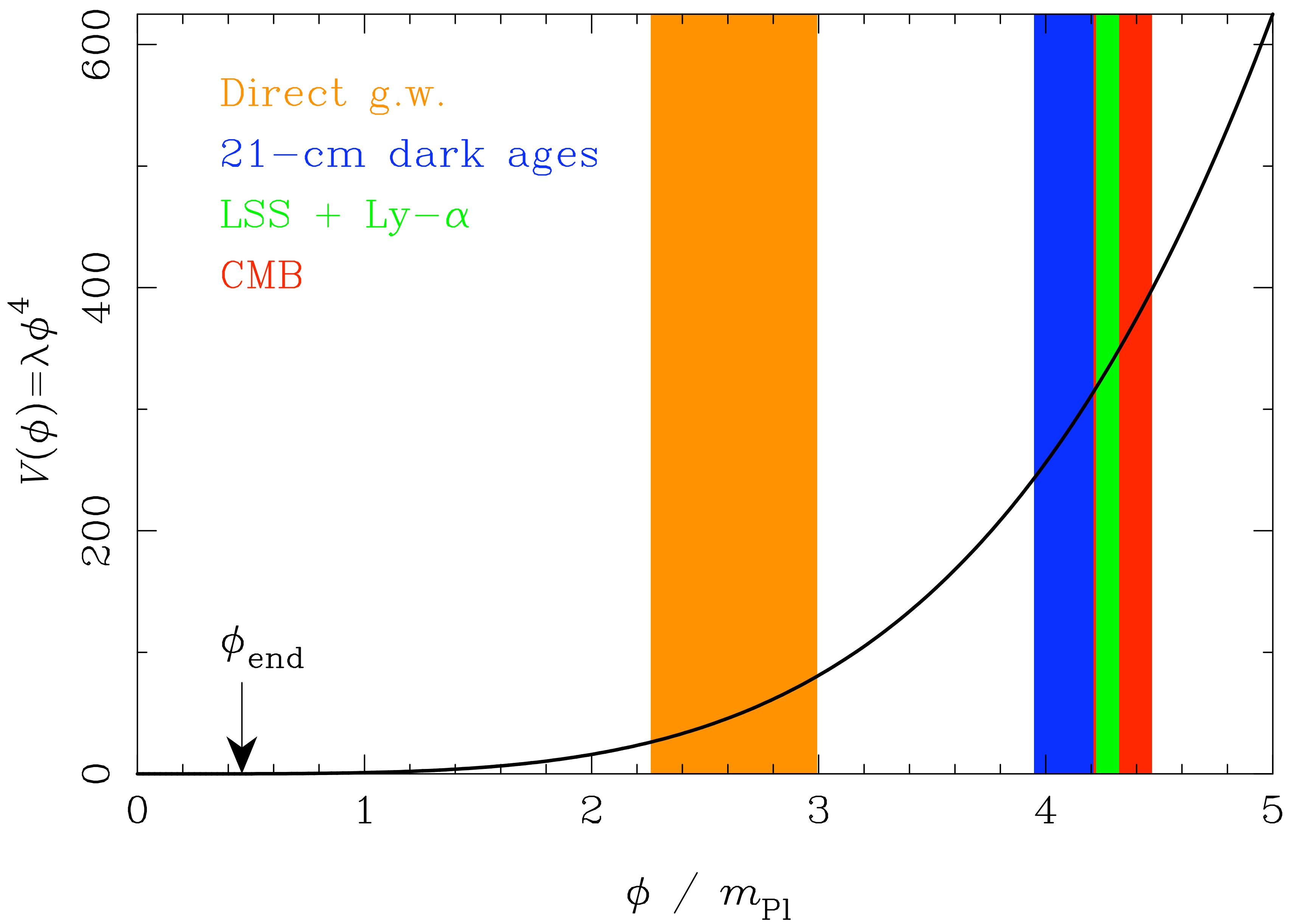
Constraints on specific models



- r determines whether model is large or small field.
- n_s determines whether spectrum is red or blue.
- a combination of n_s and r determines the curvature of the potential η.

Figure: D. Baumann & H.V. Peiris, invited review to be published in Advanced Science Letters

What range of potential does CMB sample?



Primordial non-Gaussianity

- Bispectrum of primordial curvature perturbation

momentum conservation

$$\langle \mathcal{R}(\boldsymbol{k}_1)\mathcal{R}(\boldsymbol{k}_2)\mathcal{R}(\boldsymbol{k}_3)\rangle \propto \delta(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3)F(k_1,k_2,k_3)$$

- Local form peaks on squeezed triangles

$$F(k_1,k_2,k_3) \propto f_{NL}\left(\frac{\mathcal{P}_{\mathcal{R}}(k_1)}{k_1^3}\frac{\mathcal{P}_{\mathcal{R}}(k_2)}{k_2^3} + 1 \leftrightarrow 3 + 2 \leftrightarrow 3\right)$$

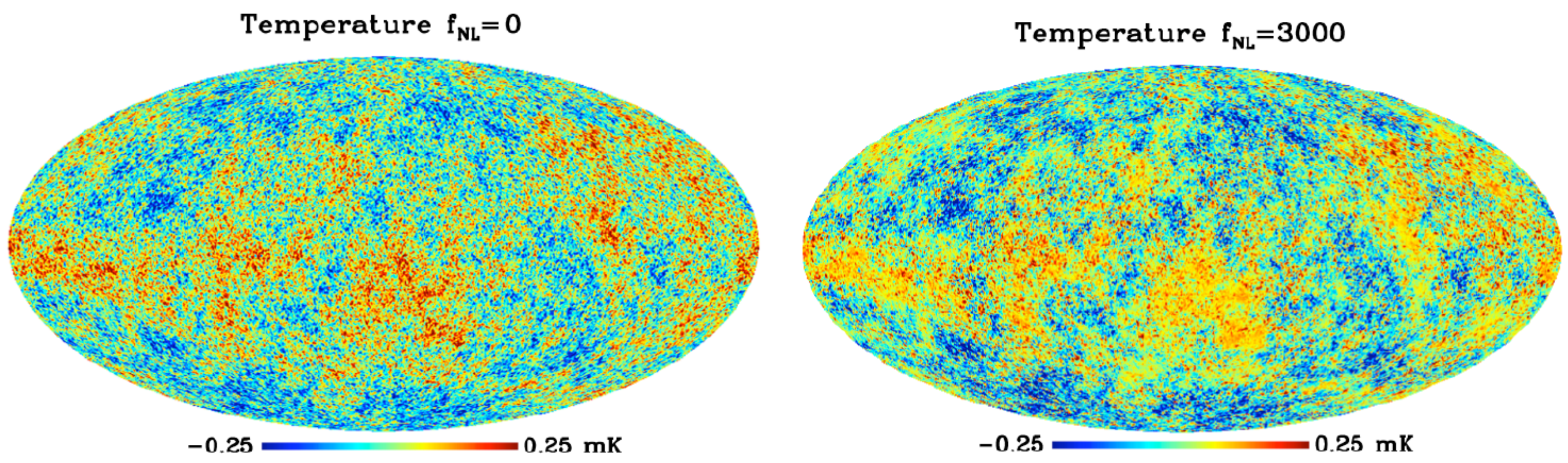
  - Arises when non-Gaussianity created outside horizon (e.g. multi-field inflation, curvaton, fluctuating reheating):

$$\mathcal{R}(\boldsymbol{x}) = \mathcal{R}_G(\boldsymbol{x}) - \frac{3}{5}f_{NL}\left(\mathcal{R}_G^2(\boldsymbol{x}) - \langle\mathcal{R}_G^2(\boldsymbol{x})\rangle\right)$$

  - Small in single-field inflation: $f_{NL} \sim n_s - 1$ in squeezed limit

- Non-local form peaks on equilateral triangles
  - E.g. $f[(\nabla\phi)^2]$ in DBI inflation

Testing the Gaussianity of the CMB



Liguori et al. (2007)

- Large-scale $\Delta T/T = \mathcal{R}/5$
  - Positive f_{NL} skews $\mathcal{R}$ and ΔT negative
- Fractional departure from Gaussianity very well measured: $\sim |f_{NL}|\sqrt{\mathcal{P}_{\mathcal{R}}} < 10^{-3}$
- Planck should achieve $\Delta f_{NL} = 5$

Constraints from WMAP5

- Komatsu et al. 2008) bispectrum analysis:

$$-9 < f_{NL}^{\text{local}} < 111 \quad \text{and} \quad -151 < f_{NL}^{\text{equilateral}} < 253 \quad (\text{V} + \text{W and } KQ75)$$

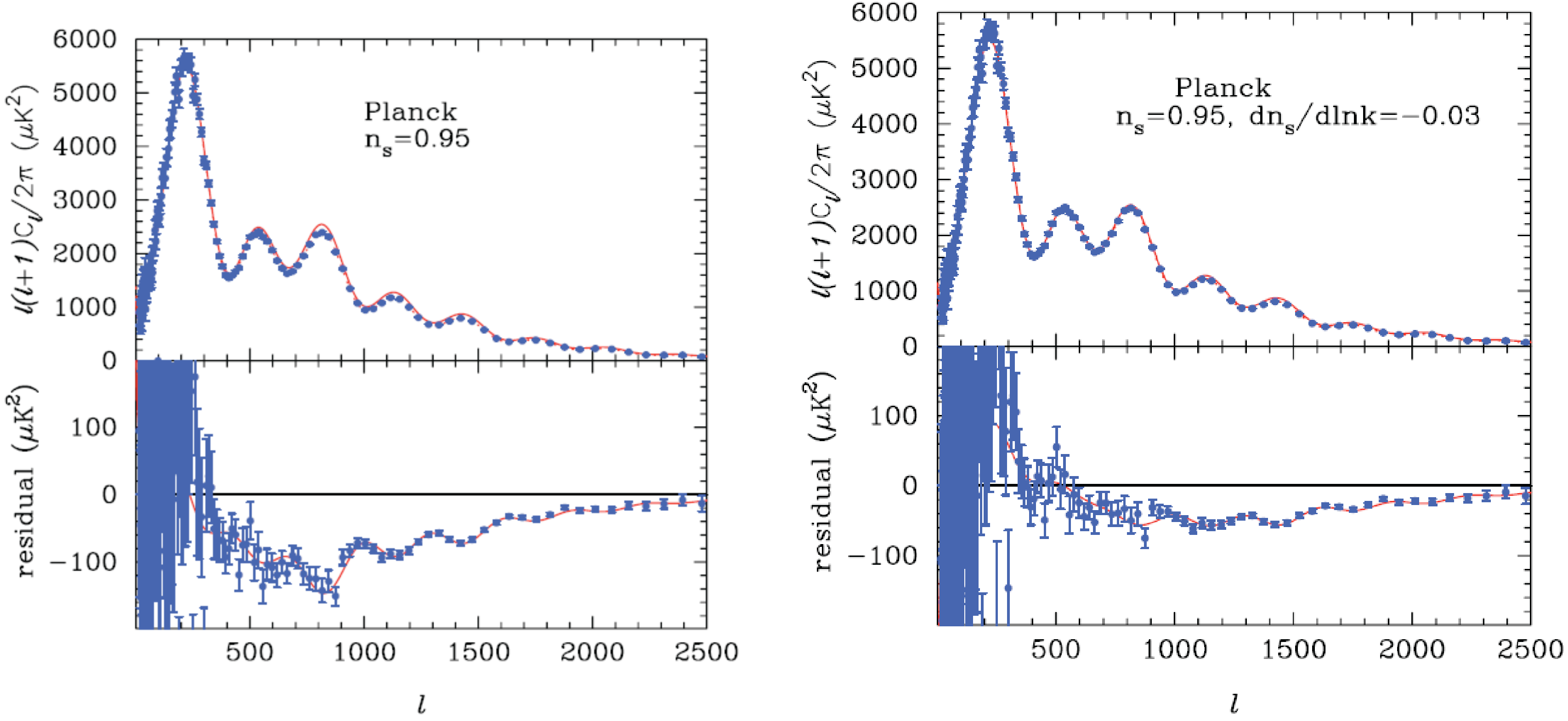
  – Map noise lower by 22%
  – New masks (e.g. $KQ75$ and $KQ75p$) that avoid potential upwards bias in f_{NL}
  – Null tests fine for $KQ75$ and foreground-cleaned $\text{V} - \text{W}$ maps
  – Corrections for point sources (small for local model)

- Analysis with Minkowski functionals: all consistent with Gaussianity

$$-178 < f_{NL}^{\text{local}} < 64 \quad (\text{V} + \text{W and } KQ75)$$

  – Mild tension with bispectrum results for f_{NL}^{local}

Improvements on scalar power spectrum



"Planck: the scientific programme" – Planck collaboration

- Marginalised error forecasts for
  $\ln \mathcal{P}_{\mathcal{R}}(k) = \ln A_s + (n_s - 1)\ln(k/k_0) + \frac{1}{2}(dn_s/d\ln k)\ln^2(k/k_0) + \cdots$:

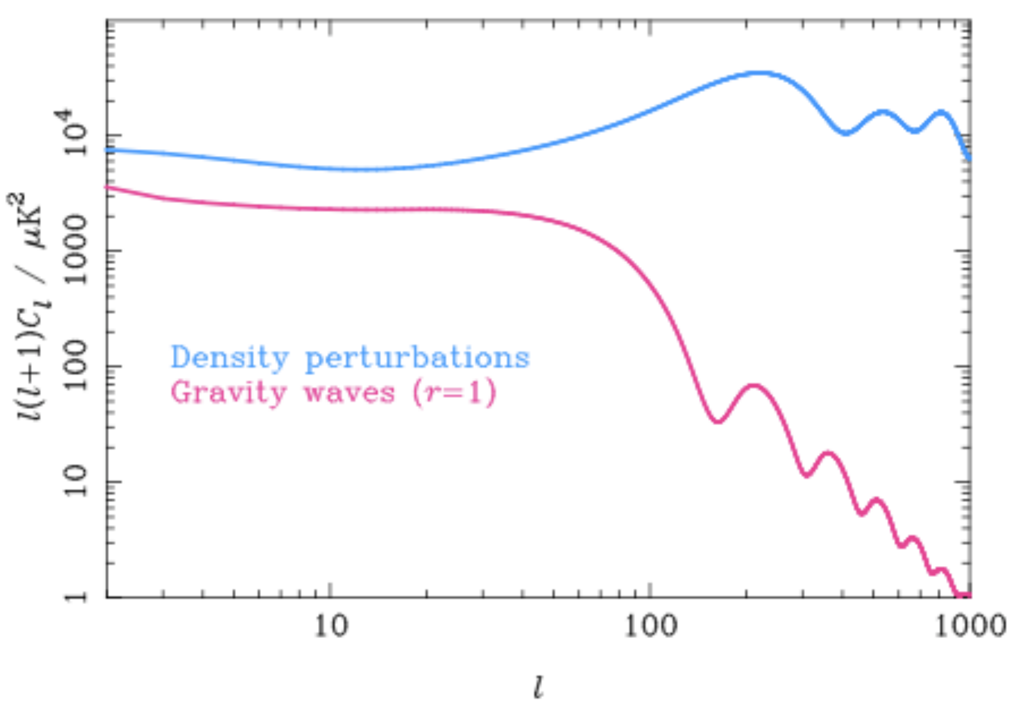
$$\Delta n_s = 0.0045 \quad \text{and} \quad \Delta(dn_s/d\ln k) = 0.005$$

Gravitational waves

- Tensor metric perturbations $ds^2 = a^2[d\eta^2 - (\delta_{ij} + h_{ij})dx^i dx^j]$ with $\delta^{ij}h_{ij} = 0$
  - Shear $\propto \dot{h}_{ij}$ gives anisotropic redshifting $\Rightarrow$

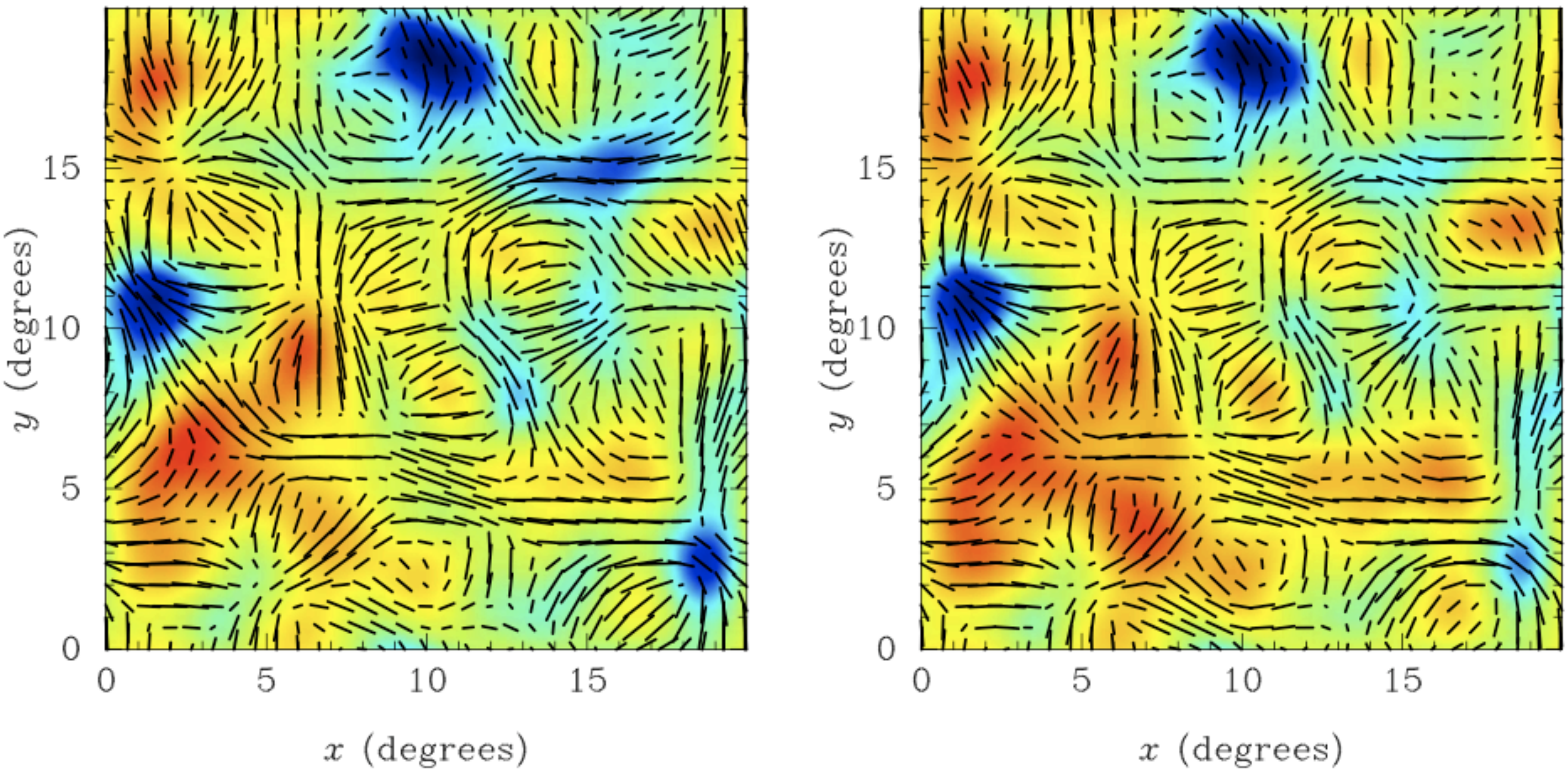
$$\Theta(\hat{\boldsymbol{n}}) \approx -\frac{1}{2}\int d\eta\, \dot{h}_{ij}\hat{n}^i\hat{n}^j$$

  - Only contributes on large scales since h_{ij} decays like a^{-1} after entering horizon



Tensors: B-mode contribution is small!

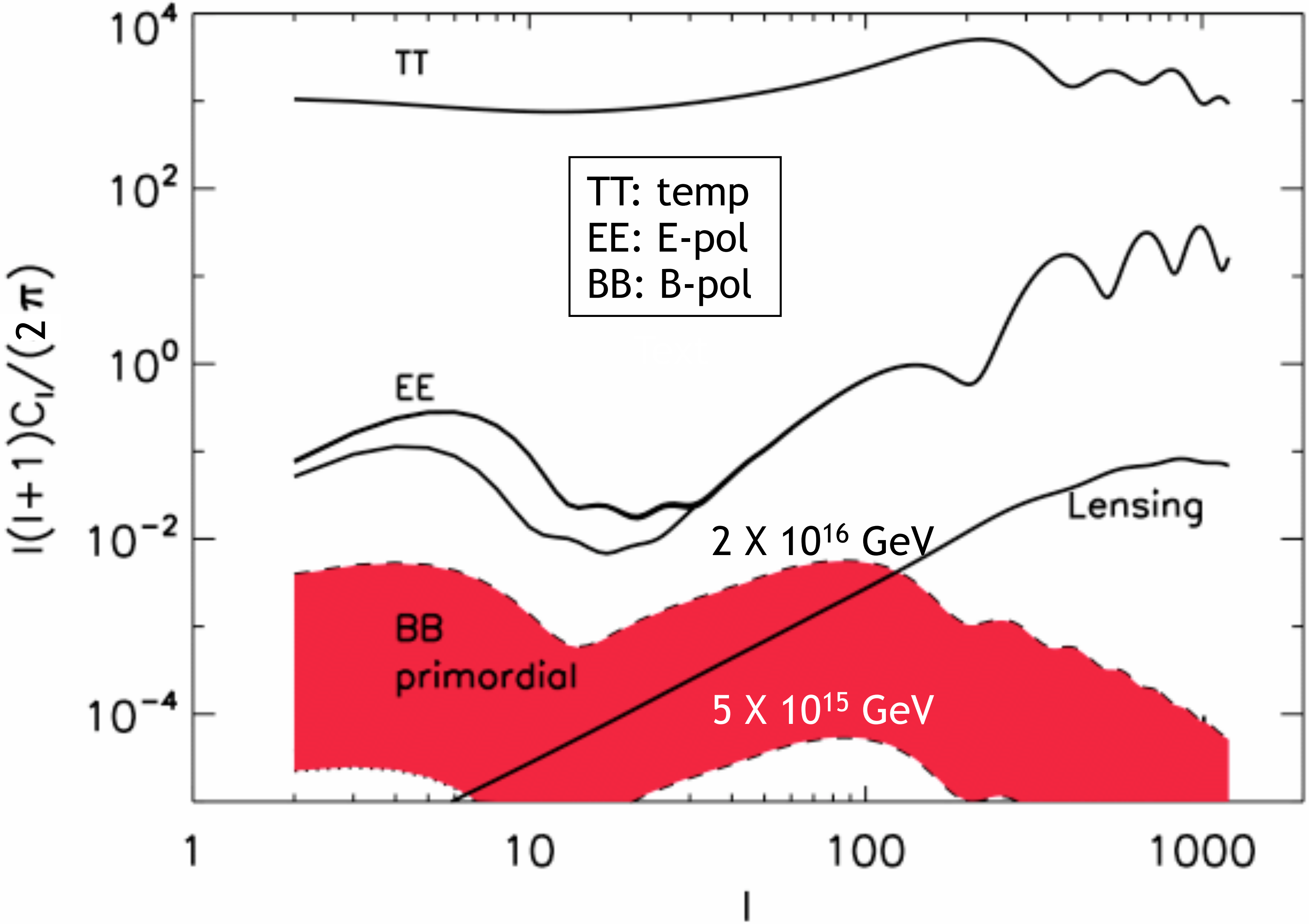
- R.m.s. B-mode signal from gravity waves $< 200\,\mathrm{nK}$



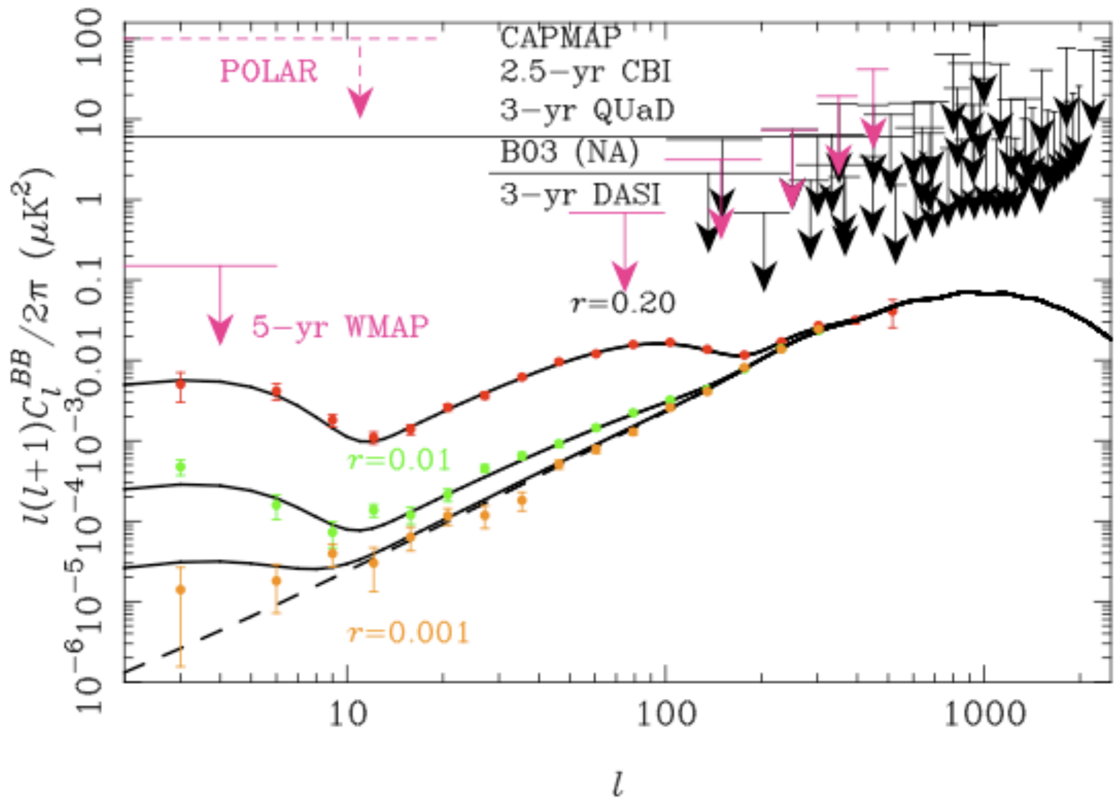
$r = 0.28$ $\qquad$ $r = 0.0$

Approximate range of primordial tensors accessible to upcoming experiments

$$V^{1/4} \simeq 3.3 \times 10^{16} r^{1/4} \text{ GeV}$$



Upcoming B-mode surveys



- B-mode polarization circumvents cosmic variance from (dominant) linear density perturbations but current upper limits not competitive with ΔT
- Next generation (Clover, QUIET, SPIDER, EBEX etc.) targeting $r > 0.01$
  - Futuristic full-sky(!) survey limited to $r > 10^{-4}$ *unless* implement lens cleaning
- Will require exquisite control of systematics and accurate removal of synchrotron and dust polarized foregrounds

Lyth Bound

In a de Sitter spacetime,

tensors: $P_h \propto \frac{H^2}{M_{\rm Pl}^2}$ scalars: $P_s \propto H^2 \left(\frac{H}{\dot{\phi}}\right)^2$

tensor to scalar ratio: $r \equiv \frac{P_h}{P_s} = 8\left(\frac{1}{M_{\rm Pl}}\frac{d\phi}{dN_e}\right)^2$

where $dN_e \equiv d\ln a = H\,dt = \left(\frac{H}{\dot{\phi}}\right) d\phi$

field variation relates to tensor signal: $\frac{\Delta\phi}{M_{\rm Pl}} = \int_{\phi_{\rm end}}^{\phi_{\rm CMB}} dN_e \sqrt{\frac{1}{8} r(N_e)}$

Useful if this can be computed from a microscopic theory!

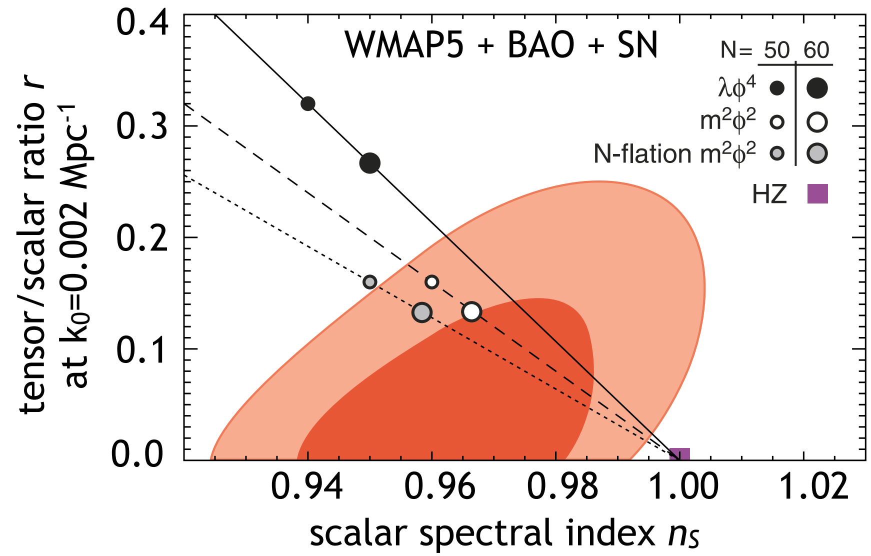
Useful if this can be constrained via observations!

Lyth (1996)

Measuring tensors

Current constraint: $r_{\rm CMB} \leq 0.2$

Realistically observable: $r_{\rm CMB} \geq 0.001$



A measurement of tensors
gives 2 pieces of information:

‣ **The energy scale of inflation.**

The measured scalar amplitude $P_s \sim \left(\frac{\delta\rho}{\rho}\right)^2 \sim 10^{-10}$ and $H^2 \simeq \frac{1}{3M_{\rm Pl}^2} V$ implies:

$$V^{1/4} \sim \left(\frac{r_{\rm CMB}}{0.001}\right)^{1/4} 10^{16}\ {\rm GeV}$$

‣ **Super-Planckian field variation.**

Observable gravitational waves require $\Delta\phi > M_{\rm Pl}$ during inflation:

$$\frac{\Delta\phi}{M_{\rm Pl}} > \mathcal{O}(1)\sqrt{\frac{r_{\rm CMB}}{0.001}}$$

e.g. $V(\phi) = \frac{1}{2}m^2\phi^2$ requires $\Delta\phi \sim 15 M_{\rm Pl}$.

WMAP Collaboration (2008), Knox & Song (2002), Verde, HVP & Jimenez (2005)

Beyond one number: tensor tilt

- If r is measured by CMBPOL, can we also detect the tensor tilt, n_t?
- Can we test the inflationary consistency condition, $r = -8n_t$?
- Can we detect a general sound speed? Define: $\mathcal{C} = -\frac{r}{8n_t}$

$\mathcal{C} = 1$ for canonical single-field slow roll

$\mathcal{C} = c_s^2 < 1$ for general sound speed

- Can we rule out $n_t > 0$?

Future observational prospects

- Go to small scales. Much better measurements of the primordial scalar power spectrum shape.
  - Planck l~3000 (k~0.2/Mpc)
  - ACT, SPT l~10000 (k~0.7/Mpc) [secondary effects]
  - Galaxies k~1/Mpc [non-linearity & bias]
  - Lyman alpha k~5/Mpc [gas phys. & radiation feedback]
  - Reionization k~50/Mpc [much is unknown]
- Detecting gravitational waves.
  - CMB: QUaD, BICEP, QUIET, CLOVER, PolarBeaR, EBEX, SPIDER, Planck, CMBPOL/B-Pol etc... [large scales]
  - GWO: direct detection of primordial gravitational waves (BBO) [solar system scales]
- Detecting primordial non-Gaussianity.
  - Can we detect f_{NL}~1 or f_{NL} >> 1?
  - Can we distinguish shape dependence? scale dependence?