Status of inflation

Marco Peloso, University of Minnesota

- Basics
- Models $\leftrightarrow$ Observations

Homogeneous / isotropic / flat universe is a very unnatural state for the universe. Problem of initial conditions Guth '80

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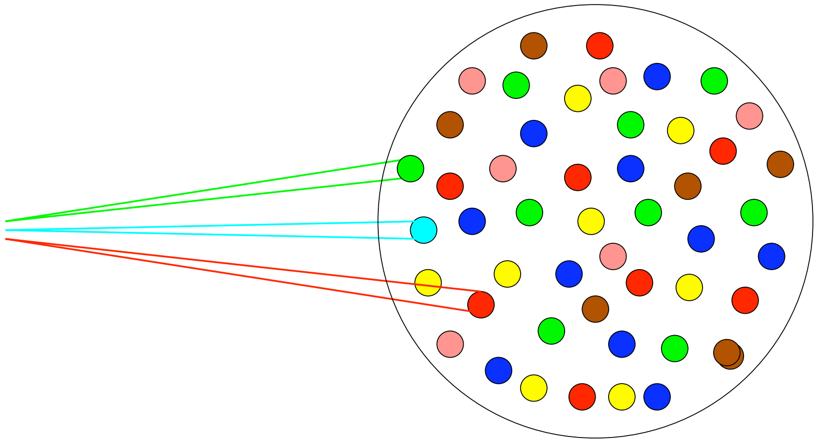
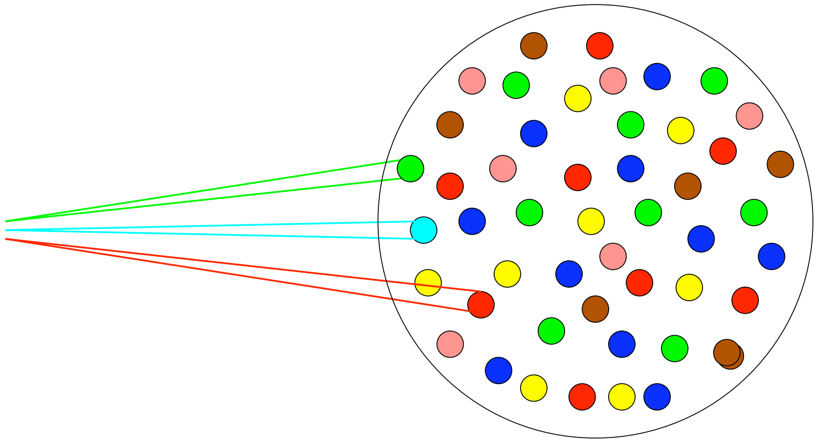


Matter / radiation universe

Homogeneous / isotropic / flat universe is a very unnatural state for the universe. Problem of initial conditions Guth '80



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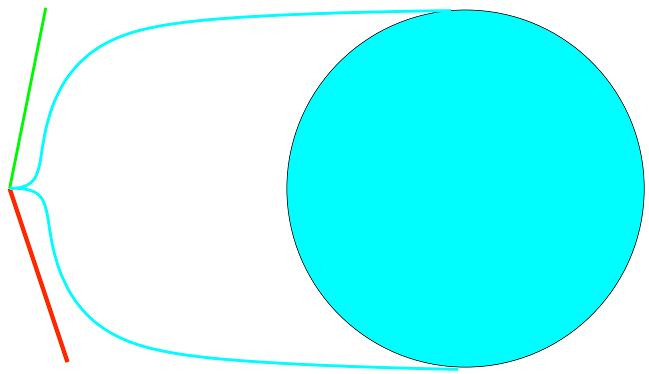

Faster (accelerated) expansion at $t \ll 1\,\mathrm{s}$

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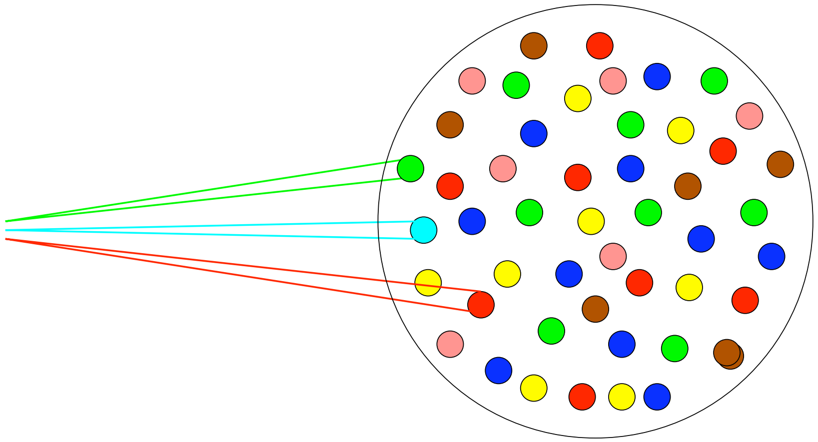

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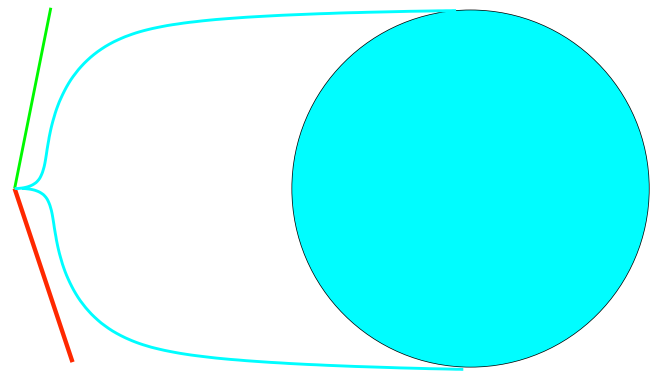


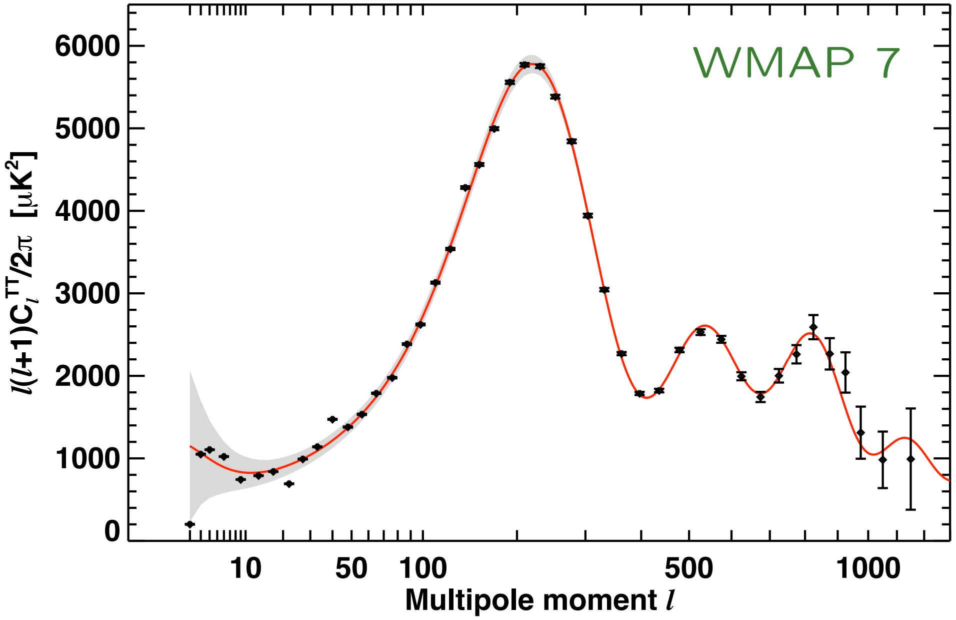
Faster (accelerated) expansion at $t \ll 1\,\mathrm{s}$

An accelerated expansion also

Flattens the universe (explaining why $\Omega_{k,0} < 1\%$)

Dilutes away unwanted relics (gravitinos, monopoles,...)

Allows for large entropy (generated at reheating)

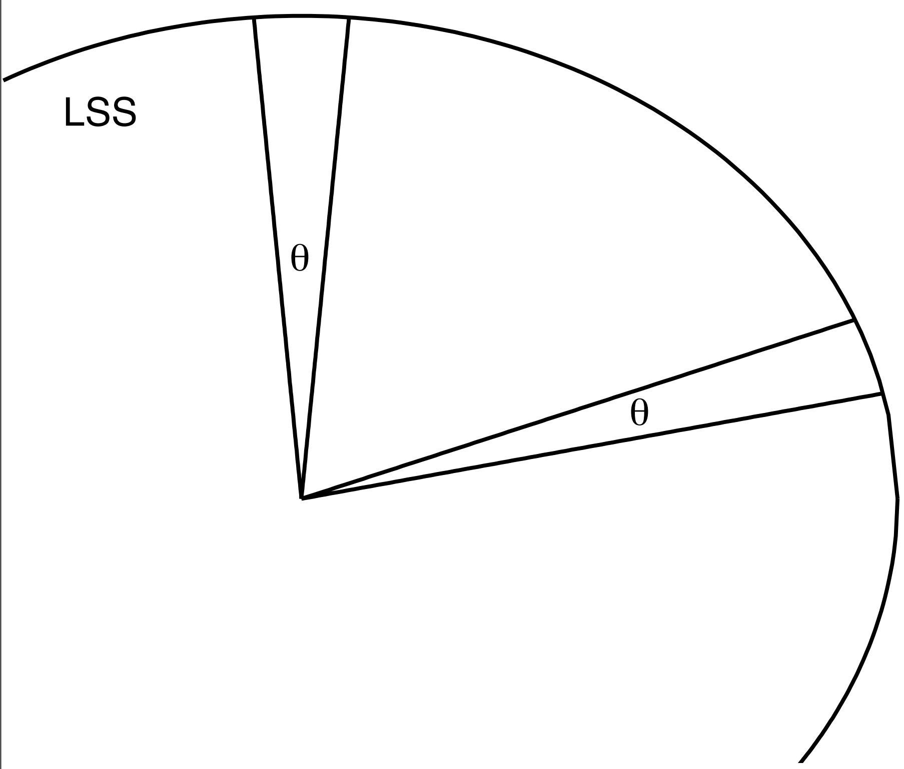


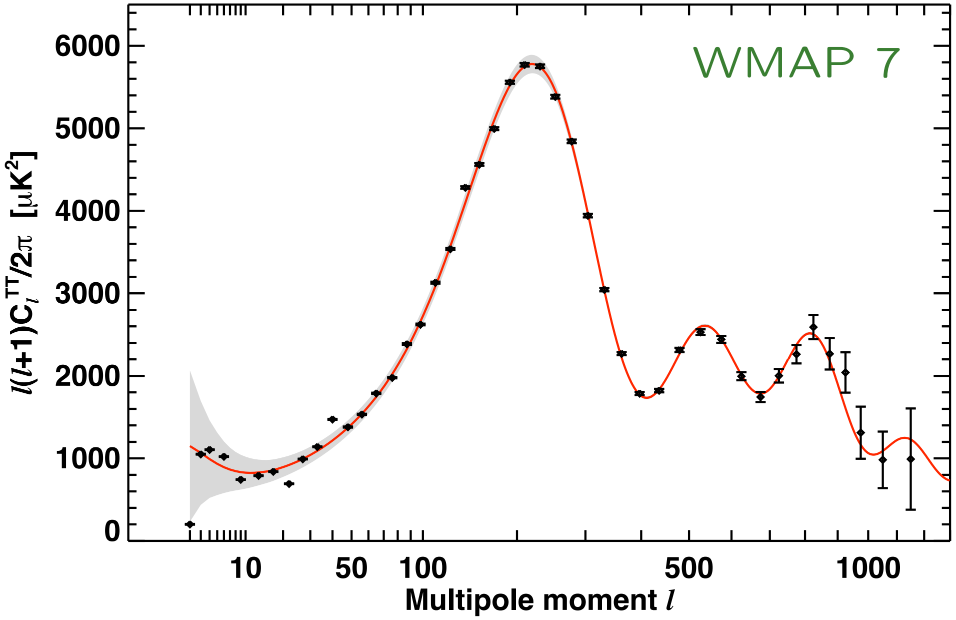
$$T = \sum_{\ell m} a_{\ell m} Y_{\ell m}$$

$$\ell \sim \frac{180^0}{\theta} \quad , \quad m \equiv \text{orientation}$$

$$C_\ell \propto \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

Acoustic peaks





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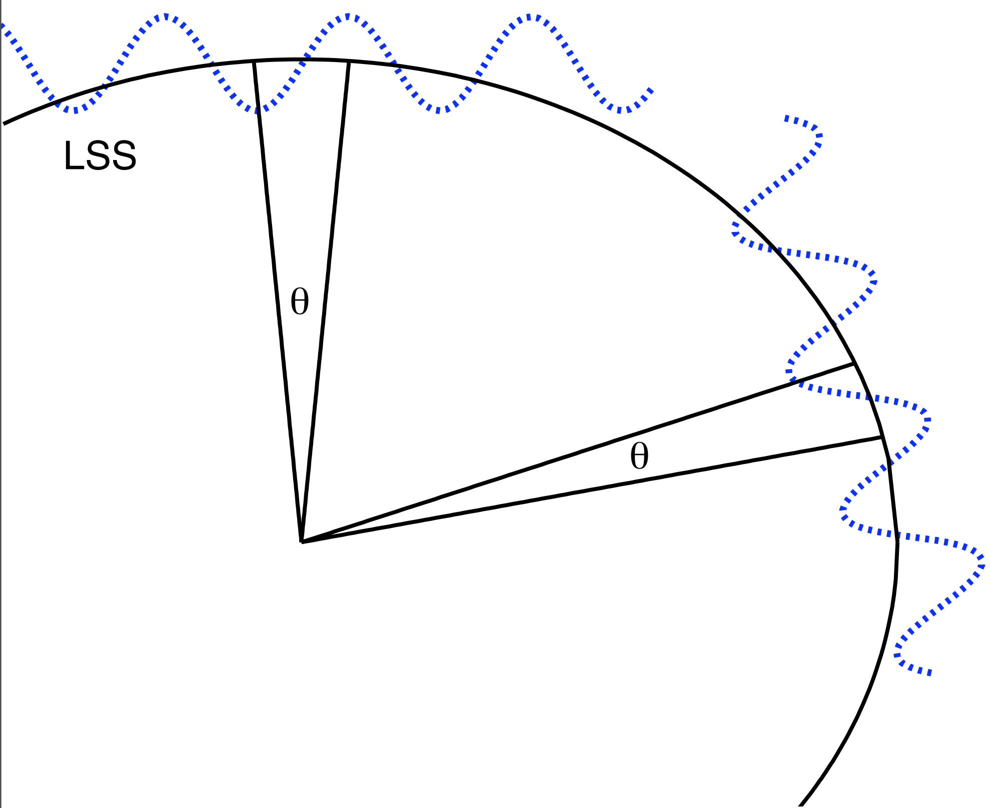
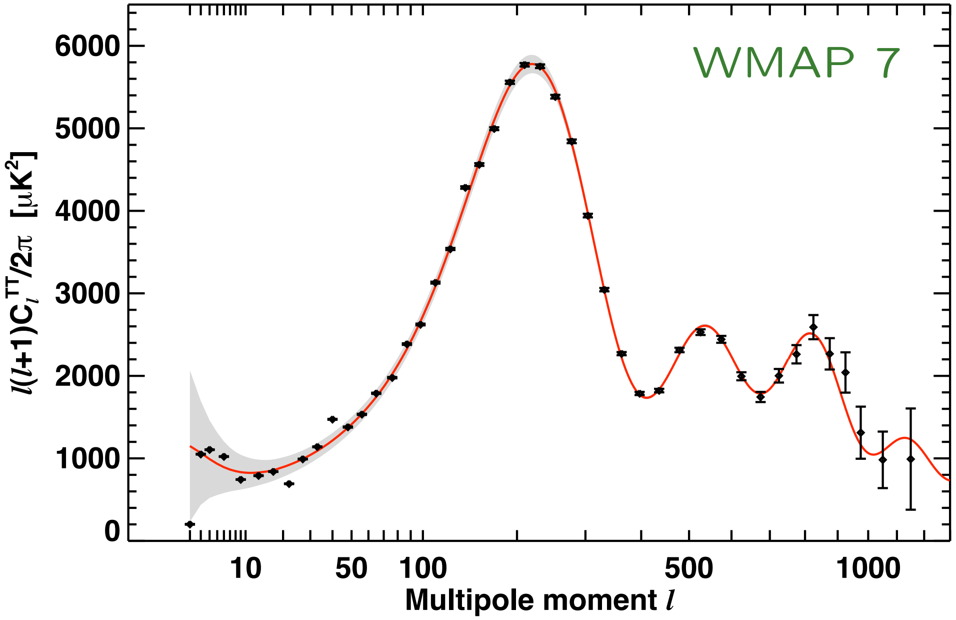


Coherence: All $\delta_{\vec{k}}$ with the same k but $\neq$ orientations must oscillate in phase



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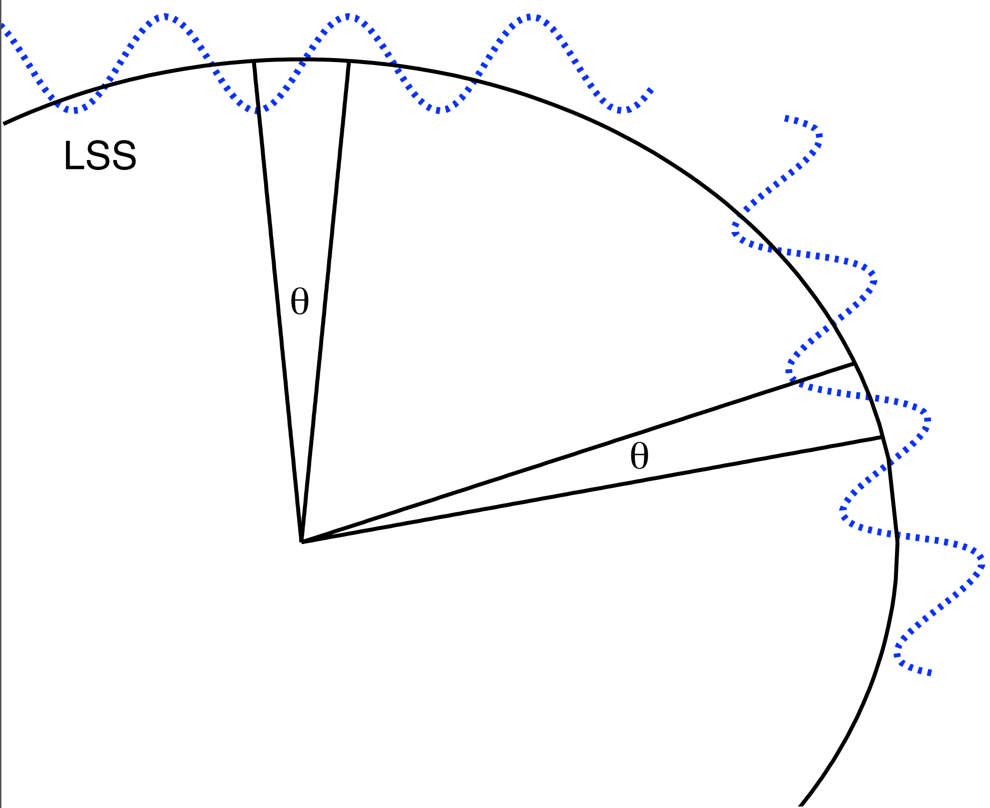

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No acoustic peaks if perturbations actively sourced by defects

CMB gets polarized during scatterings; direct probe of what present on the LSS (ignore reionization)

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No appreciable perturbations expected at $\theta > 1^0$ (the size of the horizon on the LSS) in active models. If present, signal that "something" has caused super-horizon perturbations

Coulson, Crittenden, Turok '94

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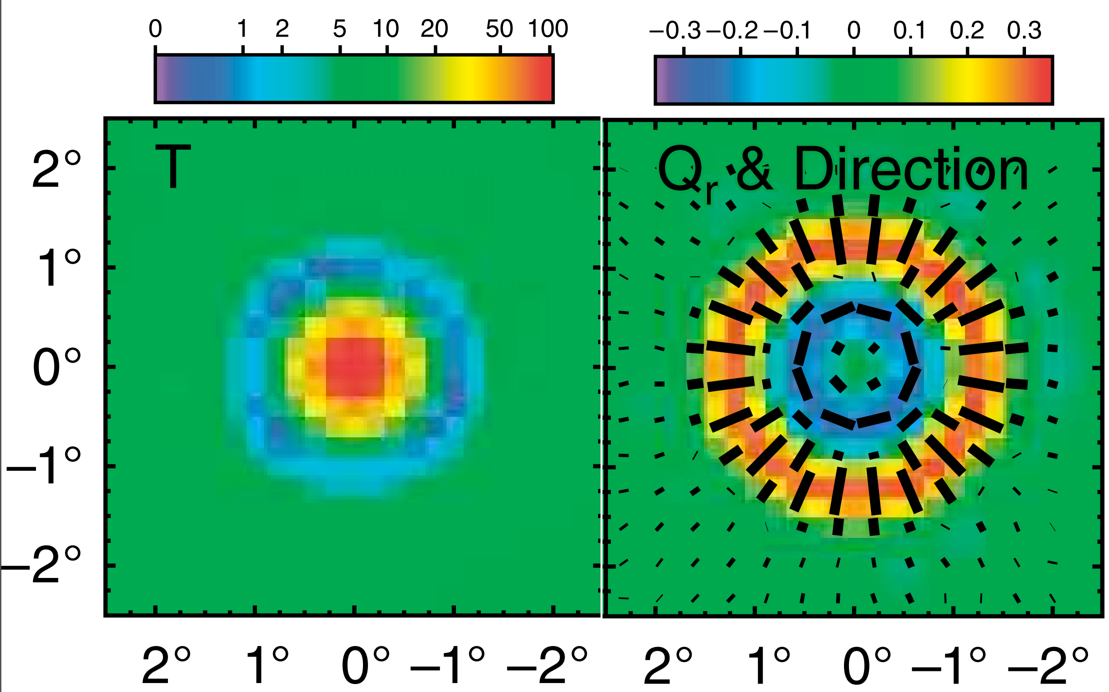
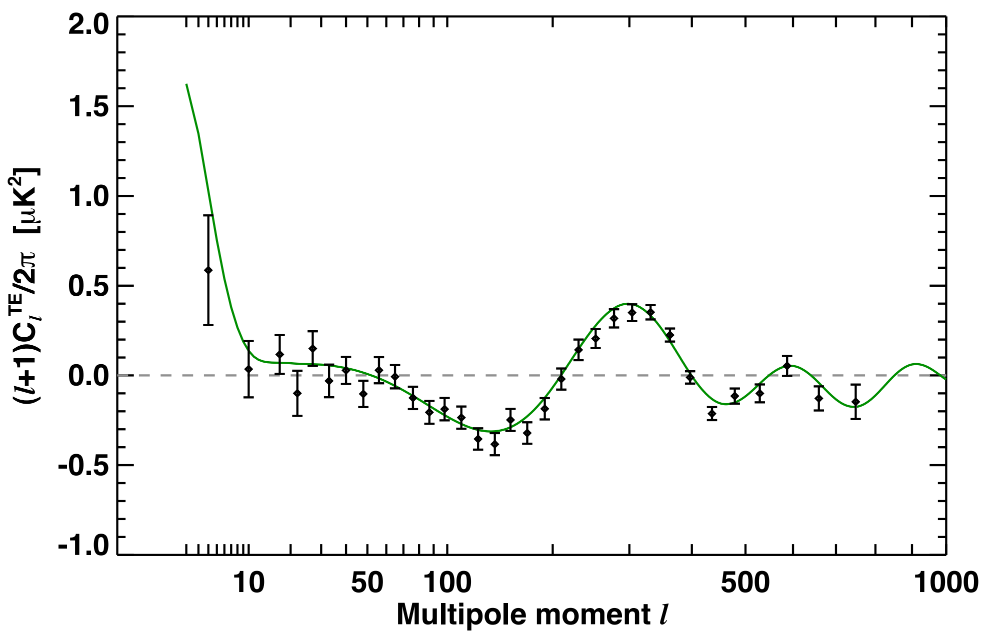
WMAP 7, stacked images of hot spots





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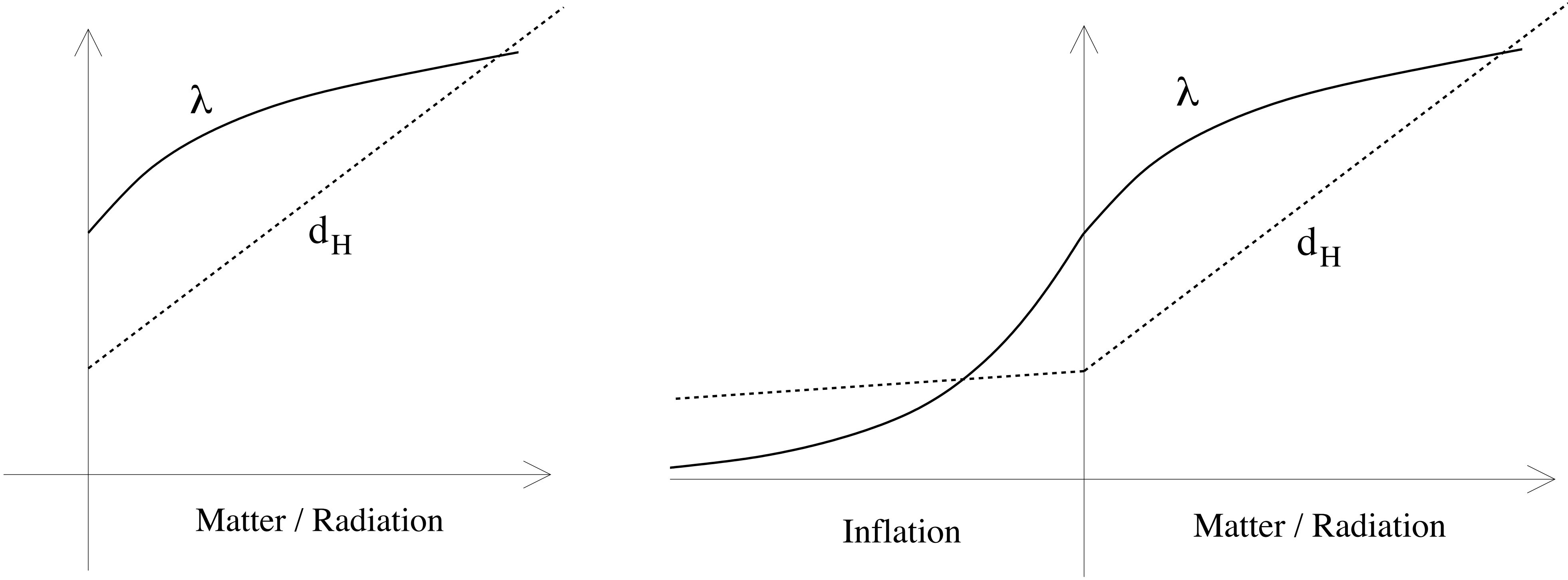

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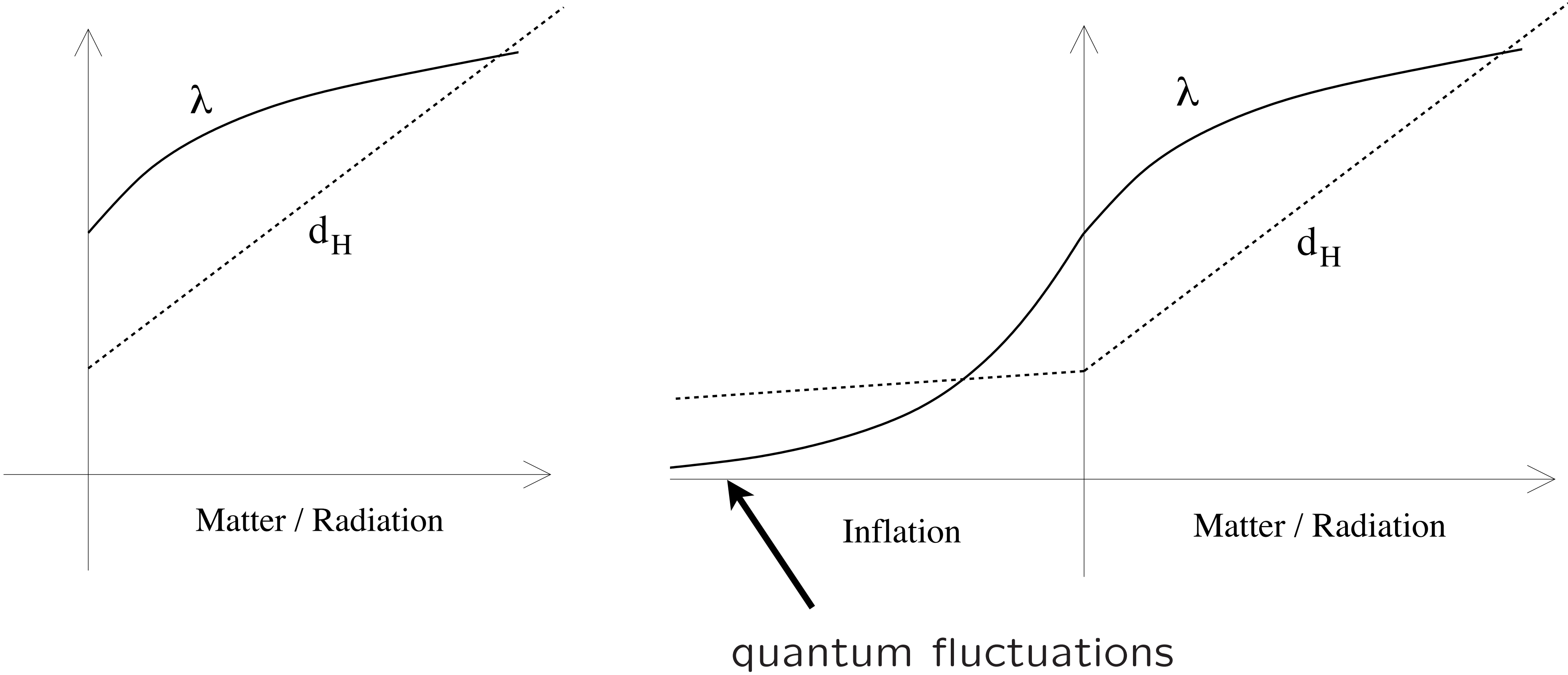

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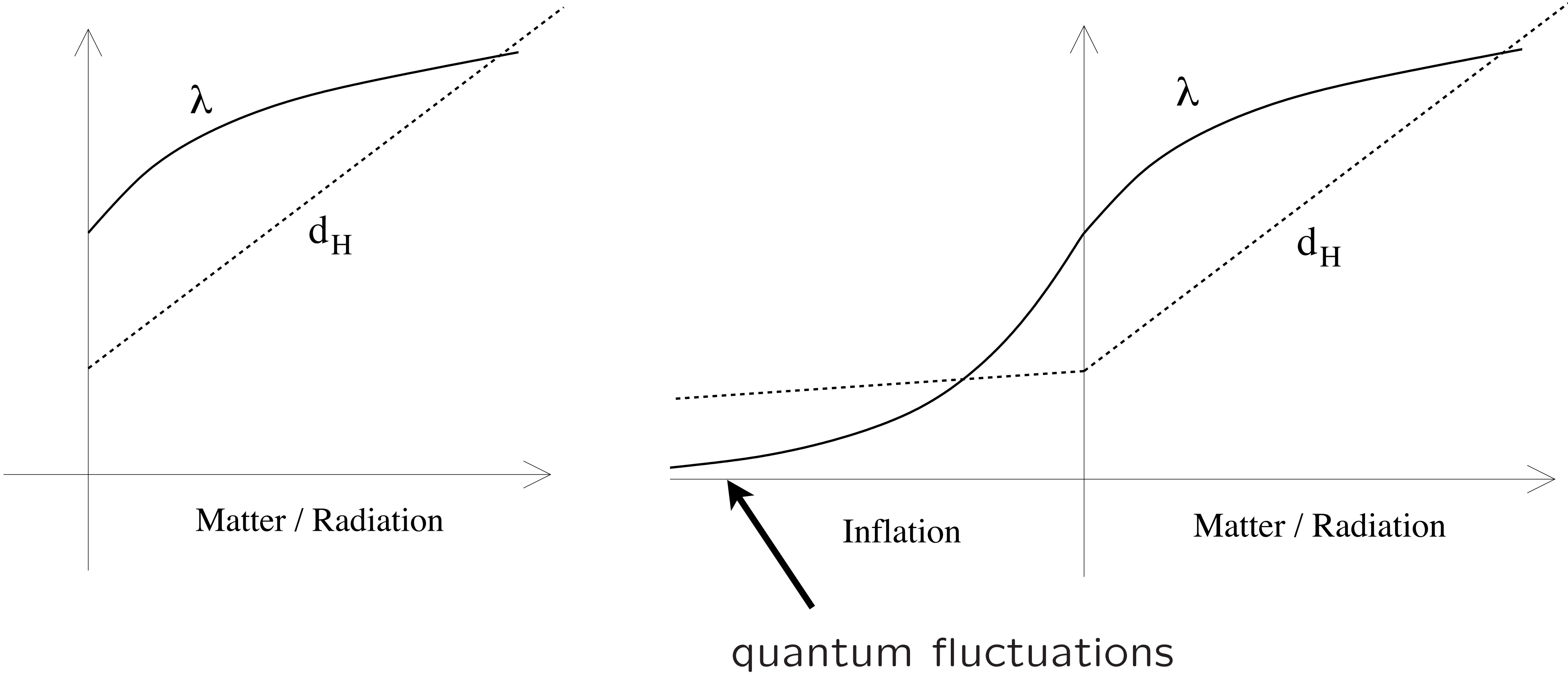


- Alternative to inflation exist, but less complete

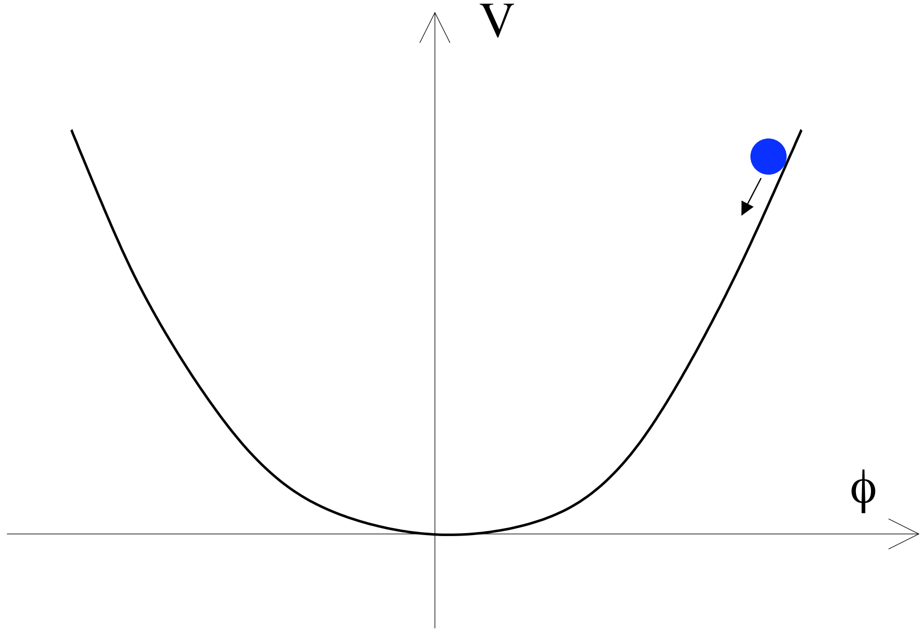
Slow roll inflation

Linde '82

Albrecht and Steinhradt '82

Scalar field slowly rolling due to Hubble friction

Potential energy slowly changes $\longrightarrow\ a \approx \mathrm{e}^{H\,t}$



$$\ddot{\phi} + 3\,H\,\dot{\phi} + \frac{dV}{d\phi} = 0 \quad , \quad H \propto V^{1/2}$$

Requires $\quad \epsilon \equiv \dfrac{M_p^2}{2}\left(\dfrac{V'}{V}\right)^2 \ll 1 \quad , \quad \eta \equiv M_p^2\,\dfrac{V''}{V} \ll 1$

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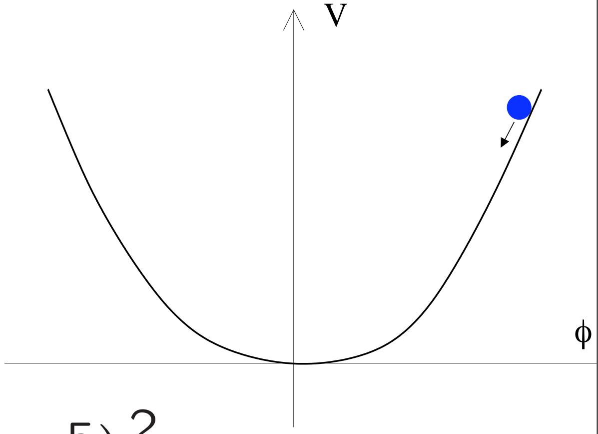

$$P_{\text{scalar}} = \frac{1}{24\,\pi^2\,M_p^4}\,\frac{V}{\epsilon}\Big|_{\text{hor. cross.}} \sim \left(5\cdot 10^{-5}\right)^2$$

- Small
- Nearly scale invariant

$$P_s \propto k^{n_s - 1} \quad , \quad n_s - 1 \simeq 2\eta - 6\epsilon$$

- Unknown scale of inflation ! (the smaller the scale, the flatter V)

$$P_{\text{scalar}} = \frac{1}{24\,\pi^2\,M_p^4}\,\frac{V}{\epsilon}\Big|_{\text{hor. cross.}} \sim \left(5\cdot 10^{-5}\right)^2 \qquad \epsilon \propto \left(\frac{V'}{V}\right)^2 \ll 1$$

$$P_{\text{tensor}} = \frac{2}{3\,\pi^2}\,\frac{V}{M_p^4}\Big|_{\text{hor. cross.}} \qquad \text{unmeasured} \qquad r \equiv P_t/P_s$$

- Scale of inflation from tensors (GW). Scalar > Tensor

$$V^{1/4} = 10^{16}\,\text{GeV}\left(\frac{r}{0.01}\right)^{1/4}$$

- Larger $r \longrightarrow$ larger $\epsilon \longrightarrow$ Inflaton moves more

Lyth '96

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Large field models

Measure GW, know V

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Lyth '96

Large field models

Measure GW, know V

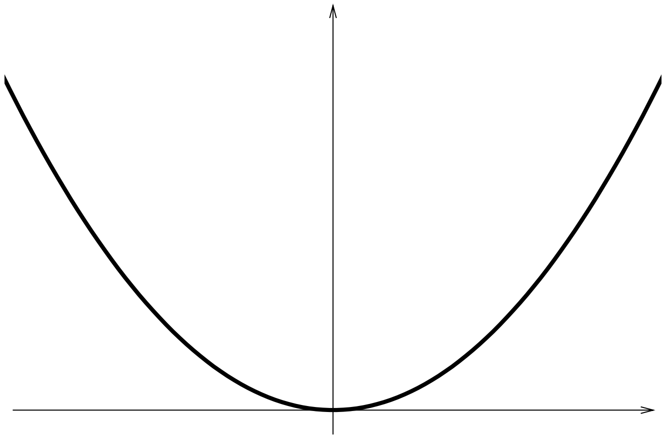
Small field models

Bad luck !

Examples of large field models

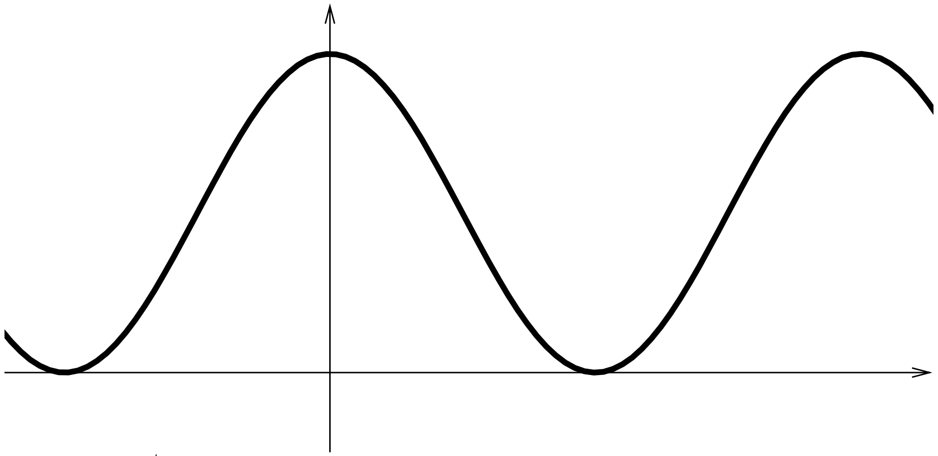
Chaotic inflation:

$$V = \frac{1}{2} m^2 \phi^2 \ , \ \ \frac{\lambda}{4} \phi^4 \ \ , \ldots$$



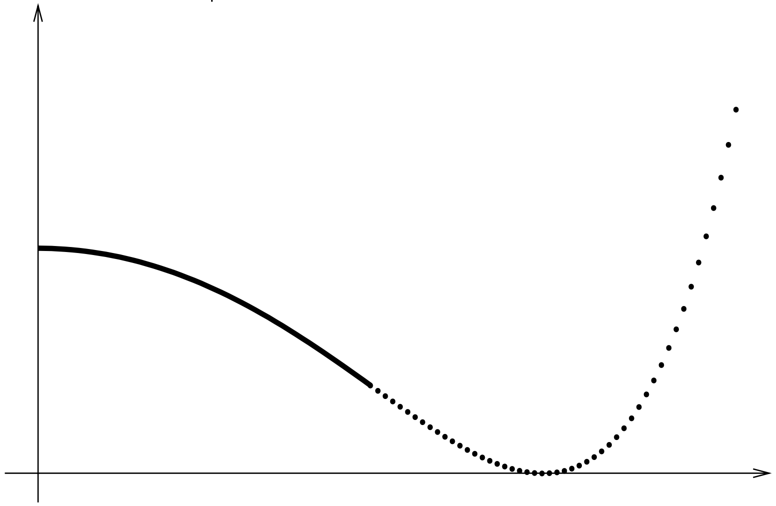
Natural inflation:

$$V = V_0 \left[1 - \cos \frac{\phi}{f} \right]$$

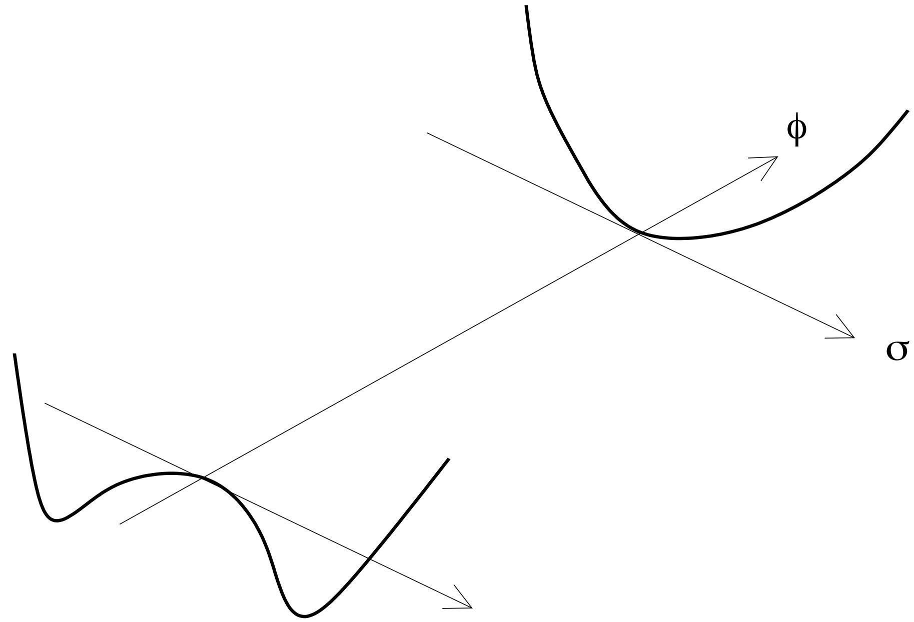


Hill-top (symm. breaking):

$$V = V_0 \left[1 - \left(\frac{\phi}{f} \right)^p \right] + \ldots$$



Examples of small field models



Hybrid inflation:

$$V = \frac{\lambda}{4}\left(\sigma^2 - v^2\right)^2 + \frac{g^2}{2}\phi^2\sigma^2$$

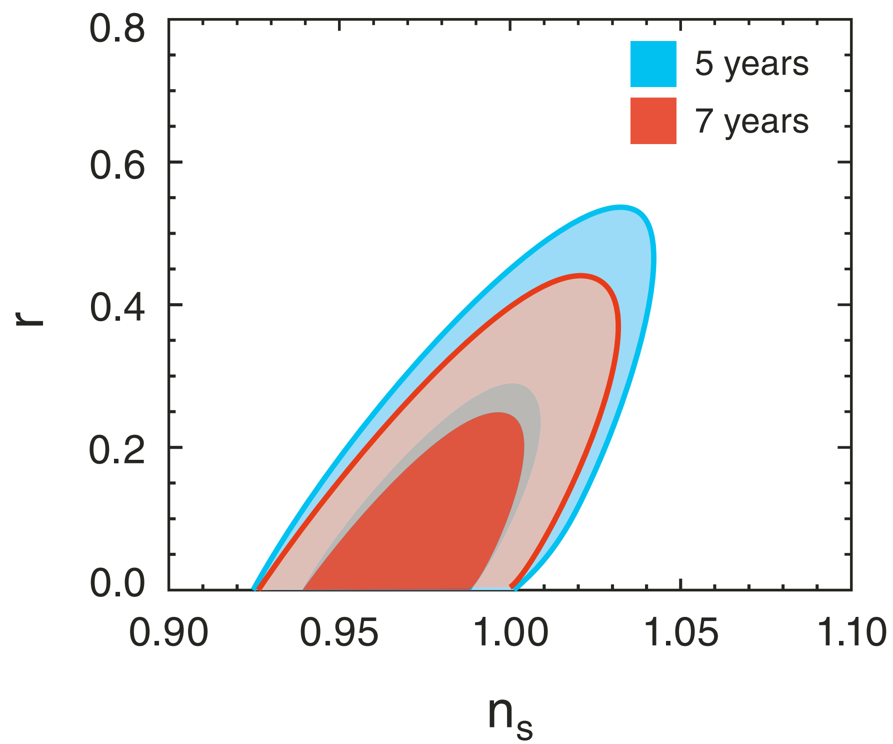
Realized in supergravity (no large $\exp K = \exp \frac{\phi^2}{M_p^2}$ terms)

and in $D-$brane inflation (string theory)

Hill-top (symm. breaking):

$$V = V_0\left[1 - \left(\frac{\phi}{f}\right)^p\right] + \ldots \qquad f \ll M_p$$

Where we stand



WMAP only

WMAP7 + ACBAR + QUaD: $n_s = 0.979 \pm 0.018$, $r < 0.33$ (95% CL)

WMAP7 + BAO + H_0 : $n_s = 0.973 \pm 0.014$, $r < 0.24$ (95% CL)

Quest for r

$$\vec{v} = \vec{\nabla}\phi + \vec{\nabla} \times \vec{A} = \text{electric} + \text{magnetic}$$

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Scalar perturbations $\longrightarrow$ $E-$mode polarization

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$$\begin{tikzcd}
\text{Scalar perturbations} \arrow[r] & E\text{−mode polarization} \\
\text{Tensor perturbations} \arrow[r] \arrow[ur] & B\text{−mode polarization}
\end{tikzcd}$$

Quest for r

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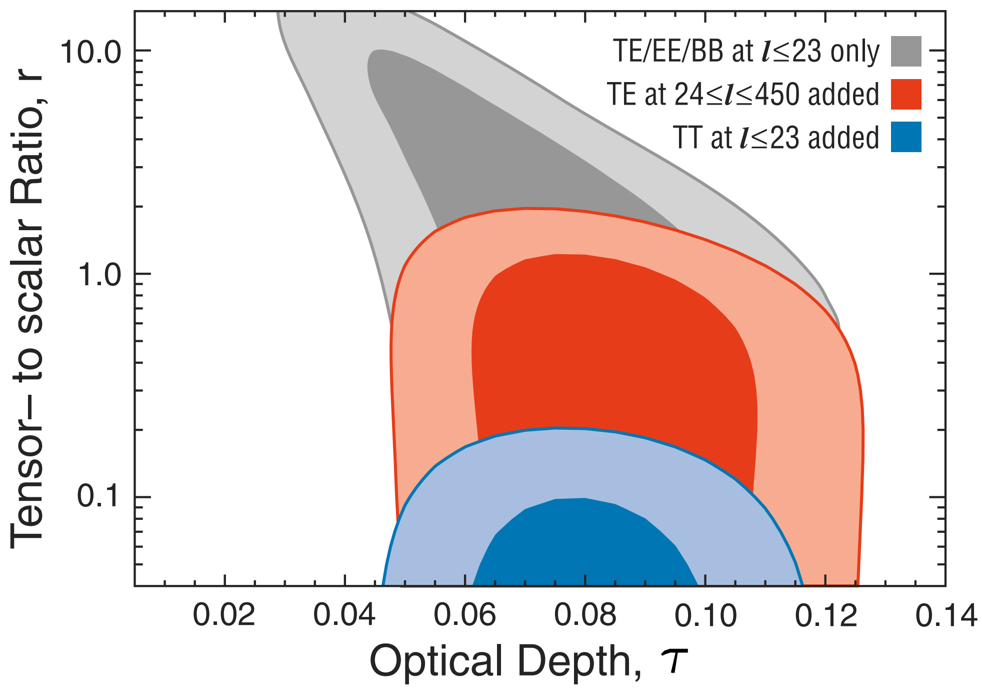
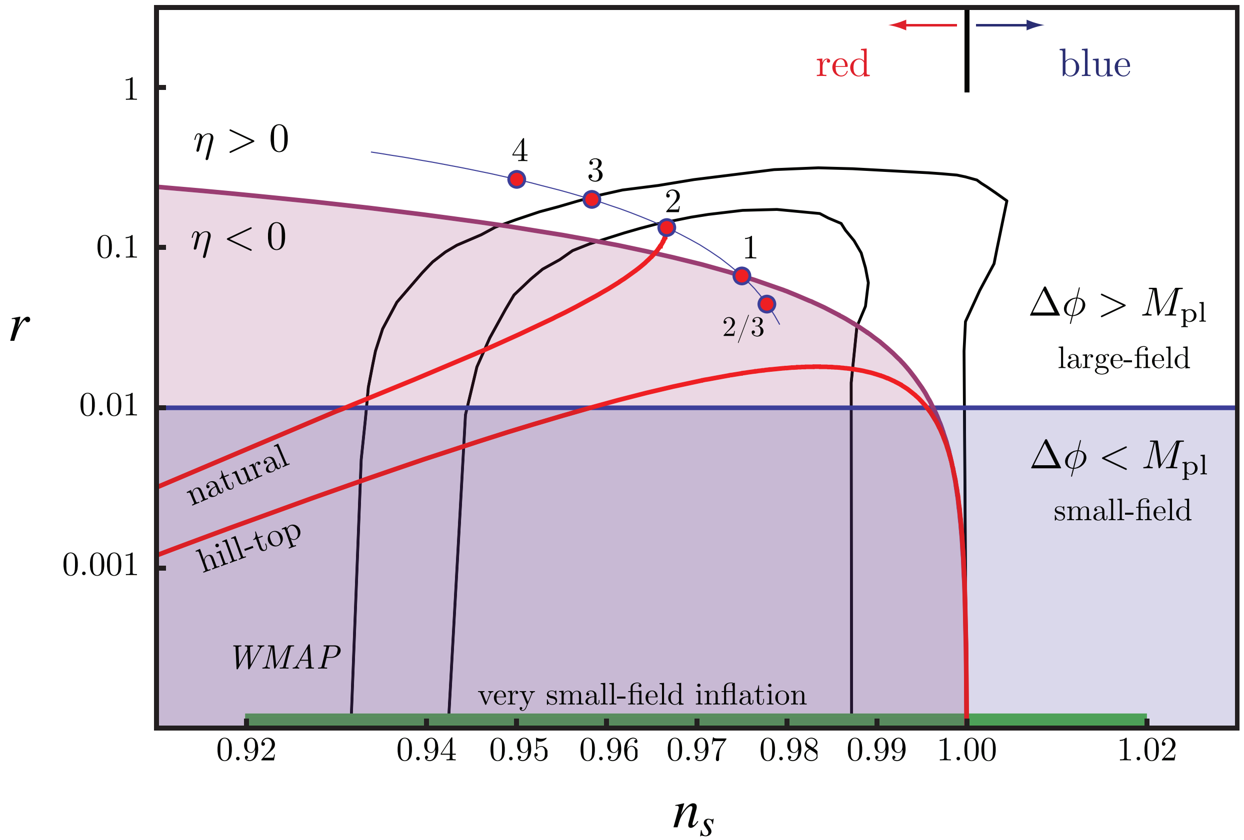
Scalar perturbations $\longrightarrow$ $E-$mode polarization

Tensor perturbations $\longrightarrow$ $E-$mode polarization, $B-$mode polarization



WMAP 5



WMAP 5 contours

Current / upcoming experiments with $r \lesssim 0.05$ target

Satellite: Planck

Balloon: EBEX, PIPER, SPIDER

Ground: ABS, ACTpol, BICEP2, BRAIN, CLASS, Keck Array, MBI, Poincare, POLAR, PolarBeaR, QUIJOTE, SPTpol

Planck (bluebook)

- Launched 5/2009
- First sky survey 1/2010
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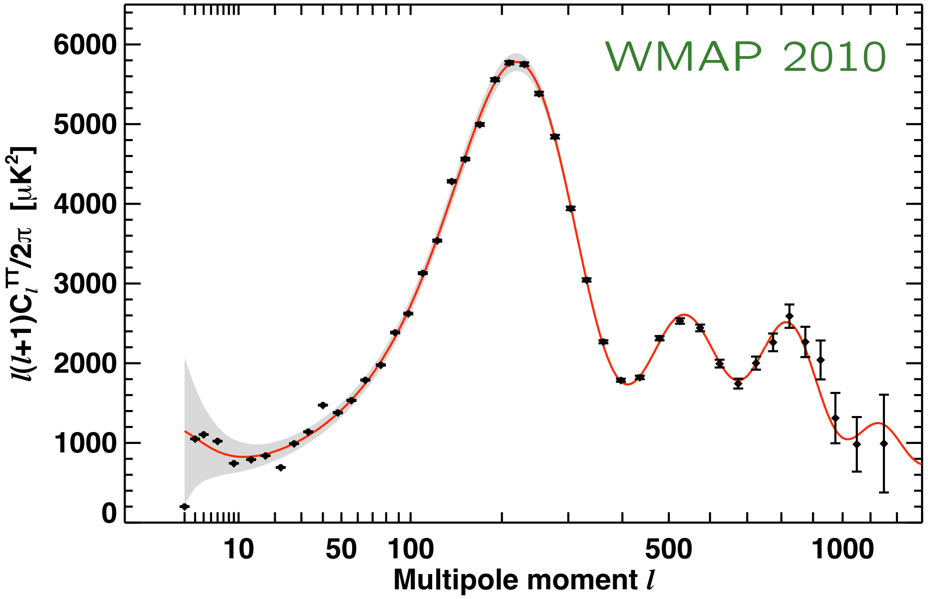

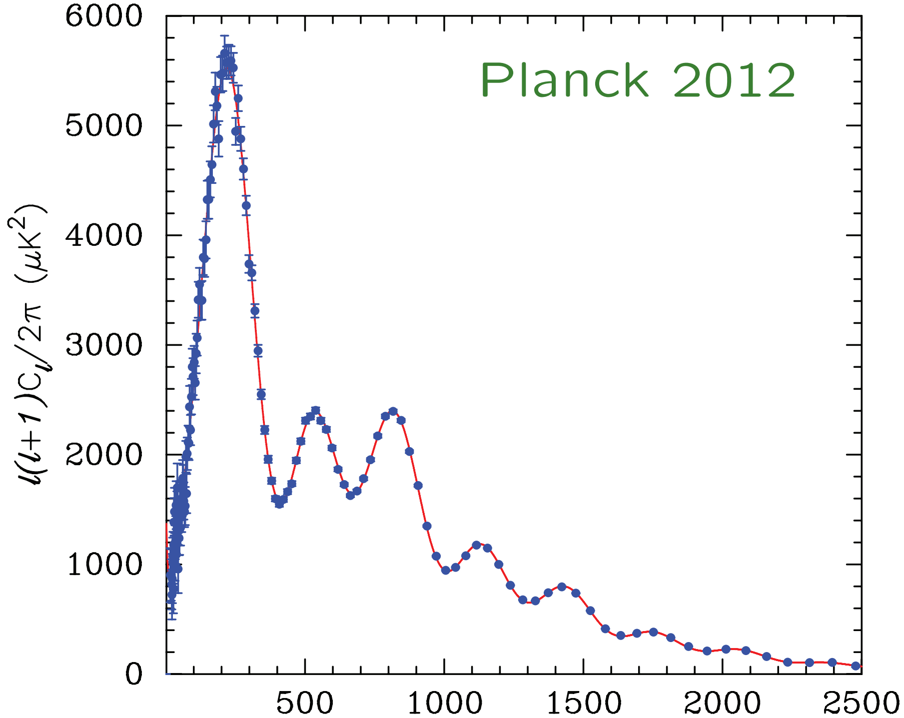

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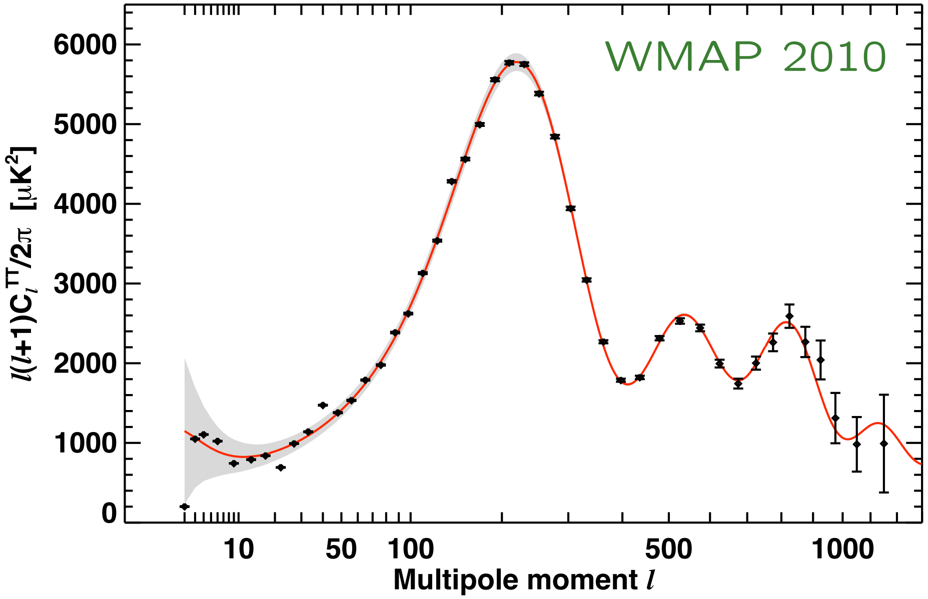

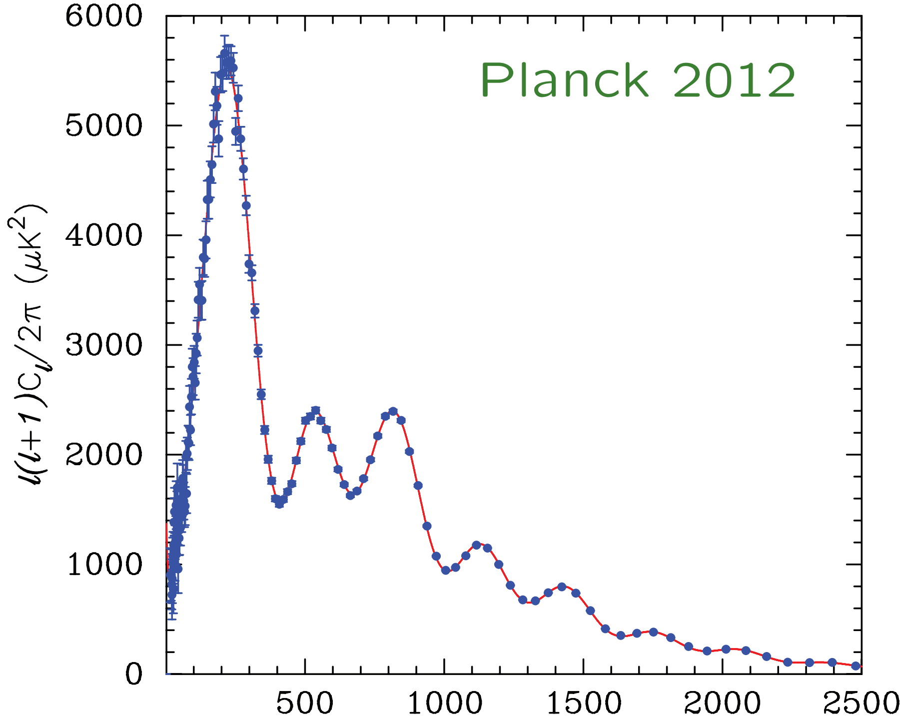

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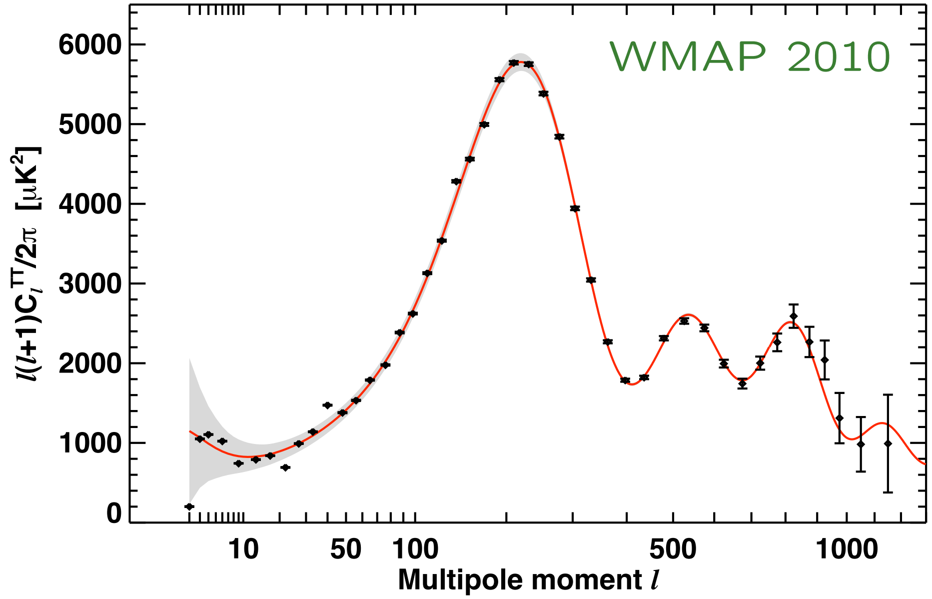

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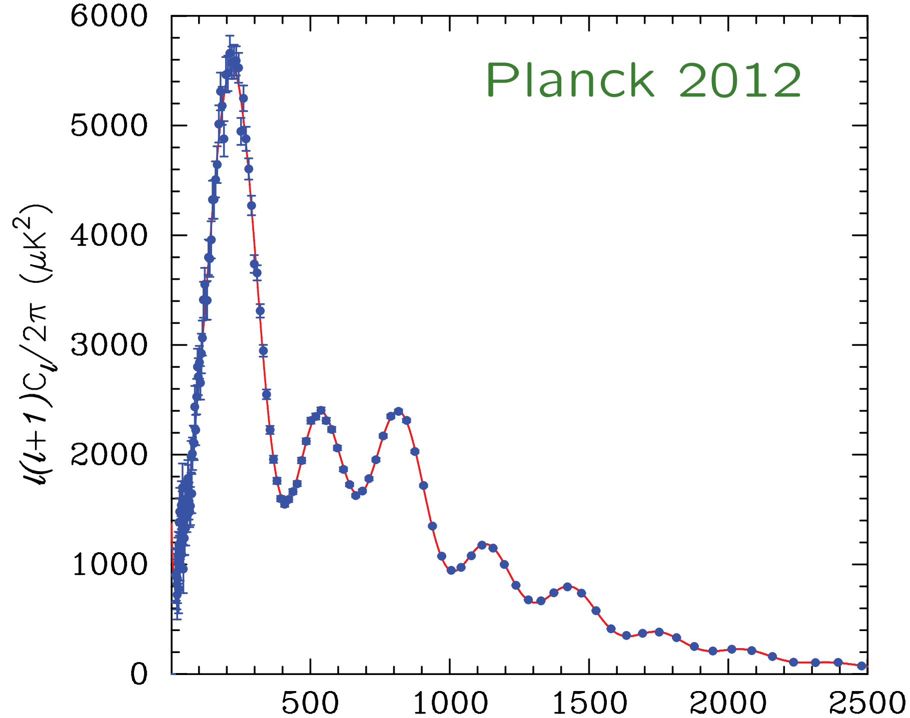
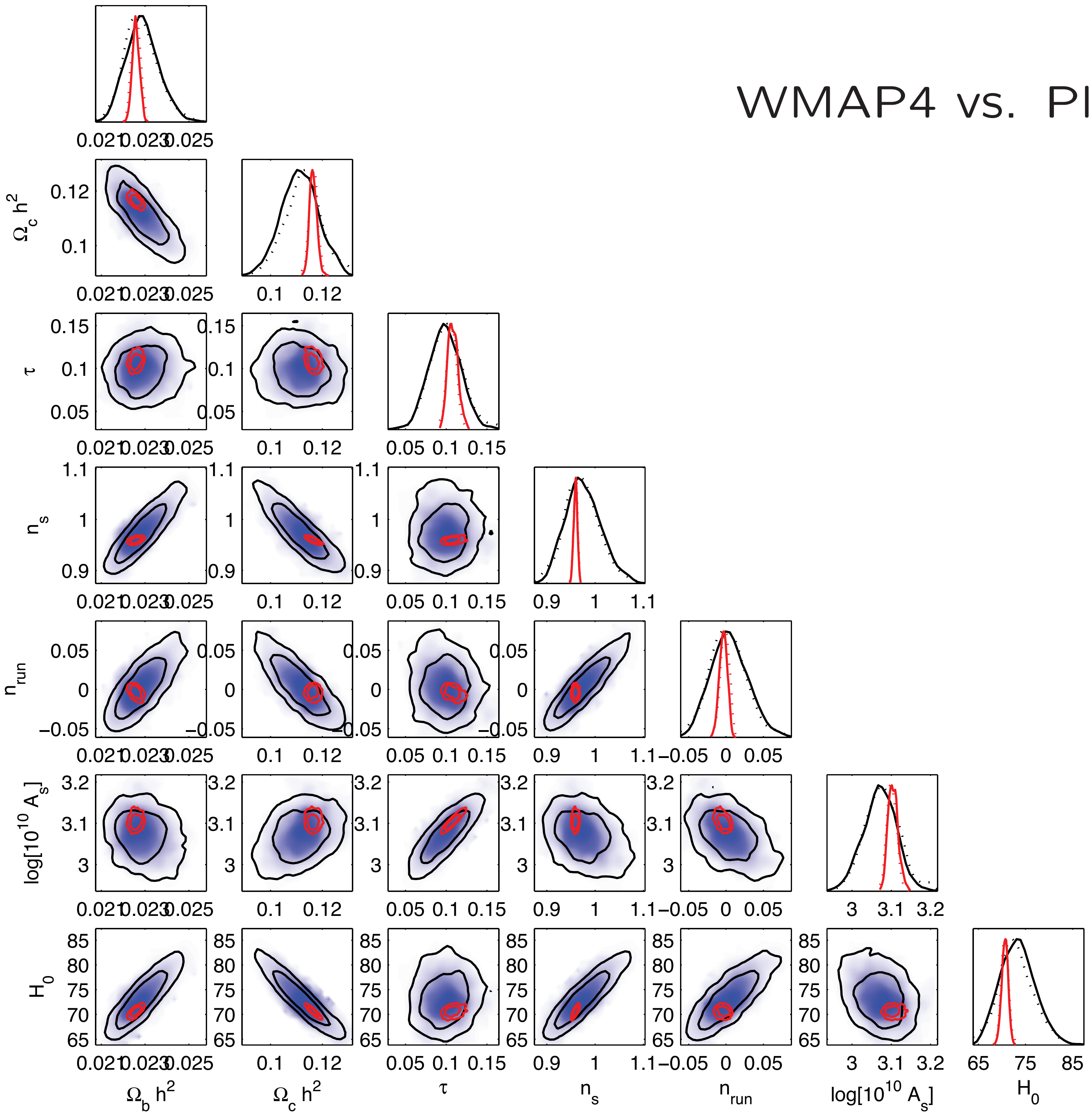


$r \gtrsim 0.1$ in 14 months

0.05 28

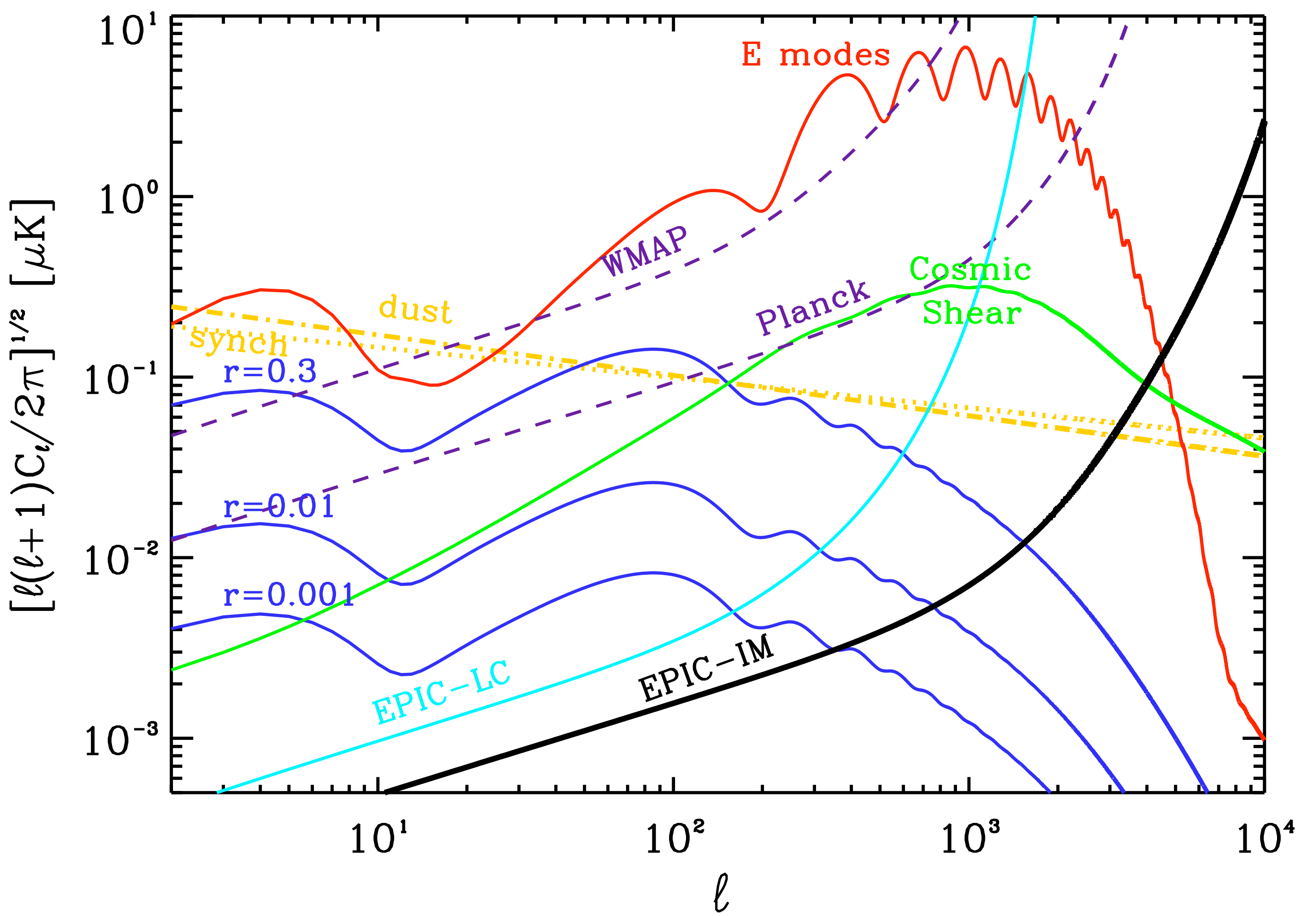
Efstathiou, Gratton 09

WMAP4 vs. Planck1



EPIC: dedicated polarization satellite mission

Reject $r = 0.01$ at high CL



Raw accuracy

Non-gaussianity

Noninteracting inflaton $\rightarrow$ gaussianity. At least gravity. Tiny ($\sim 10^{-6}$) non-gaussianity for single field slow roll inflation (flat potential)

Salopek, Bond '90   Maldacena '02

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Phenomenological parametrization

$$\mathcal{R}(\mathbf{x}) = \mathcal{R}_g(\mathbf{x}) + \frac{3}{5} f_{\mathrm{NL}}^{\mathrm{local}} \left[\mathcal{R}_g(\mathbf{x})^2 - \langle \mathcal{R}_g(\mathbf{x})^2 \rangle \right]$$

Komatsu, Spergel '00

Since local in space, called local non-gaussianity

(since $\mathcal{R} \sim 10^{-5}, \Rightarrow f_{NL} \sim 10$ means nongaussianity at 0.01% level)

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From *, and from scale invariance $\quad B_{\mathcal{R}} \propto \dfrac{1}{(k_1 k_2)^3} + \dfrac{1}{(k_1 k_2)^3} + \dfrac{1}{(k_1 k_2)^3}$

Non-gaussianity

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non-gaussianity for single field slow roll inflation (flat potential)

Salopek, Bond '90 Maldacena '02

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Enhanced for $k_1 \ll k_2 \simeq k_3$

squeezed

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Creminelli, Zaldarriaga '04

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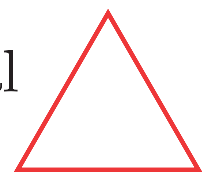
Creminelli, Zaldarriaga '04

Nonstandard kinetic term ($k-$, ghost, DBI inflation), or potential with some specific features, maximal non-gaussianity when $k_1 \sim k_2 \sim k_3$

equilateral



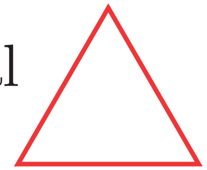
Models with multiple fields (multiple fields inflation, curvaton) have isocurvature → curvature perturbations conversion outside horizon, where gradients are irrelevant → local nongaussianity

Detection of $f_{NL}^{\text{local}} > 1$ in the squeeze limit would rule out all single field models of inflation

Creminelli, Zaldarriaga '04

Nonstandard kinetic term ($k-$, ghost, DBI inflation), or potential with some specific features, maximal non-gaussianity when $k_1 \sim k_2 \sim k_3$

equilateral

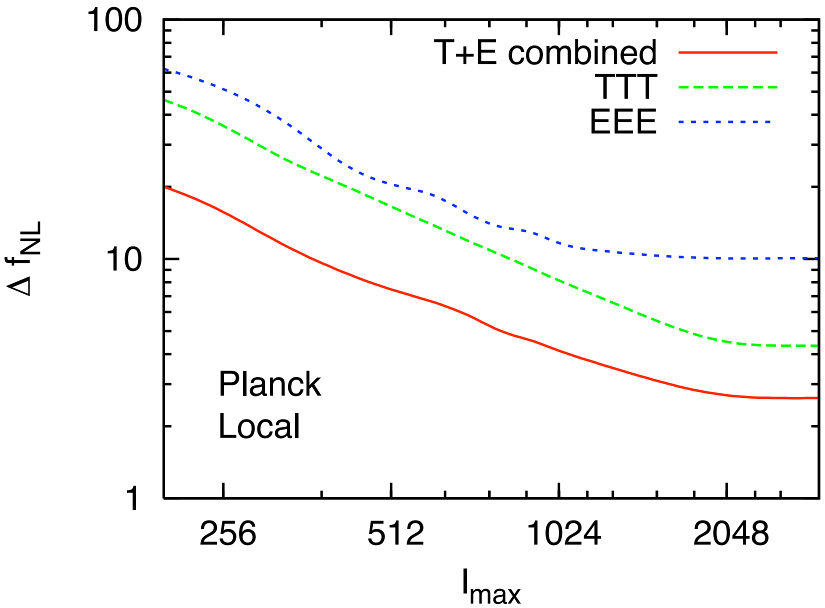


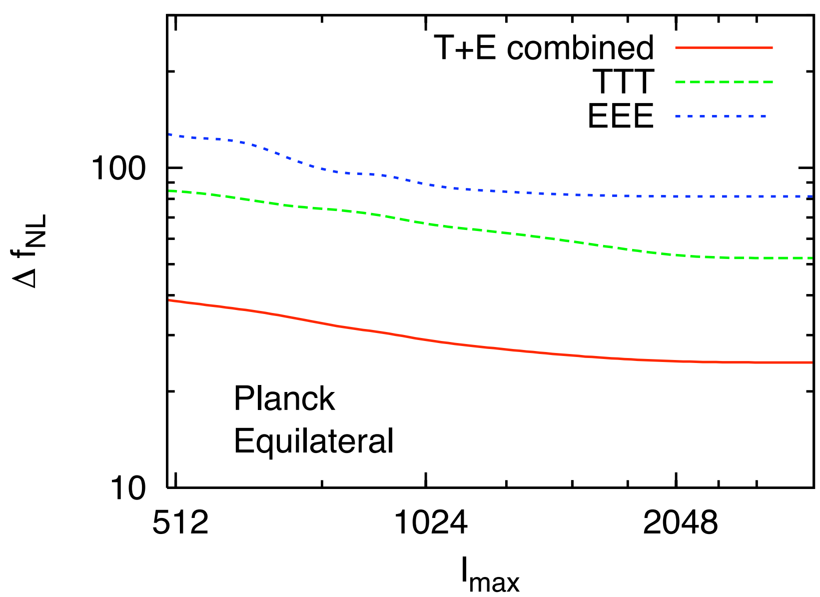
Moral: Non-gaussianty allows to discriminate between different models (→ different level, and shape), and to rule out models that have an acceptable 2 point function

WMAP7 : $-10 < f_{NL}^{\text{local}} < 74 \qquad -254 < f_{NL}^{\text{equil}} < 306 \qquad$ at 95% C.L.

$LSS - SDSS$: $-29 < f_{NL}^{\text{local}} < 70 \qquad$ at 95% C.L.

Yadav, Wandelt '10





Secondary astrophysical non-gaussianity: $\Delta\, f_{NL}^{\text{local}} \sim 10$

Second order Boltzmann $\Delta\, f_{NL}^{\text{local}} \sim 5$

Conclusions

- Inflation most complete paradigm for the very early universe
- Makes falsifiable predictions beyond its original motivations: acoustic peaks, large scale TE, EE
- Most likely, very high energy scale, at which we do not have other tests of physics. Hard to find what the right model of inflation is, and not unlimited number of observations

Horizon problem   Guth '80

- Light travels finite distance in finite time

  Scales $> d_H(t)$ cannot be causally connected

$$d_H(t) \sim t$$

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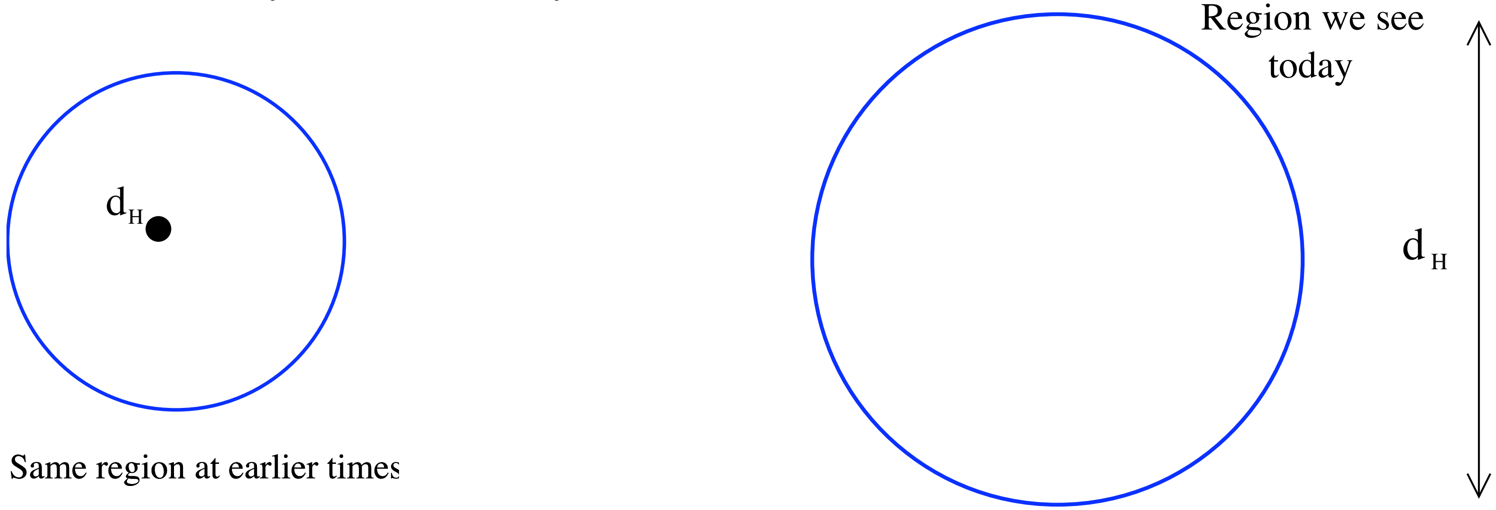

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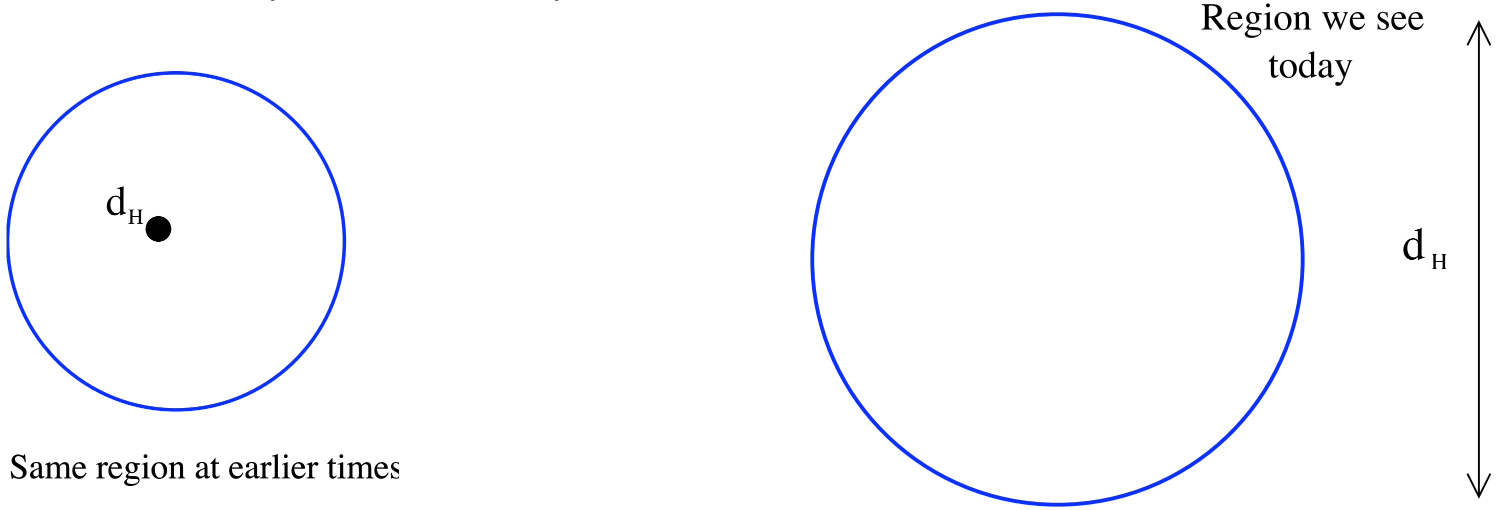
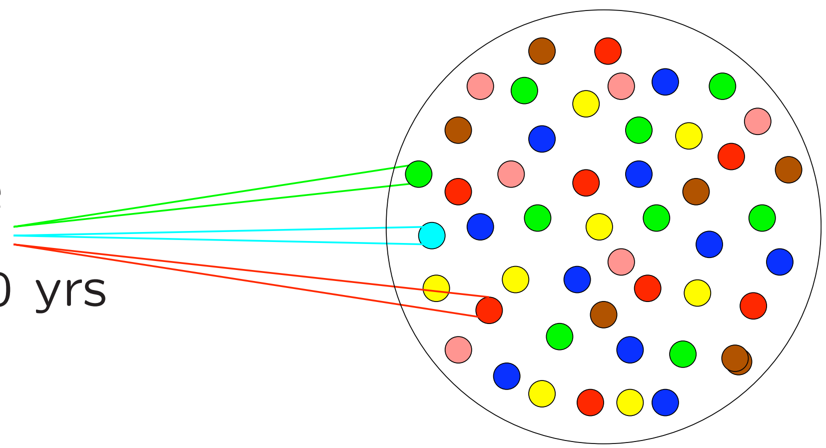


Earlier time

$t_{\text{CMB}} \simeq 380,000$ yrs



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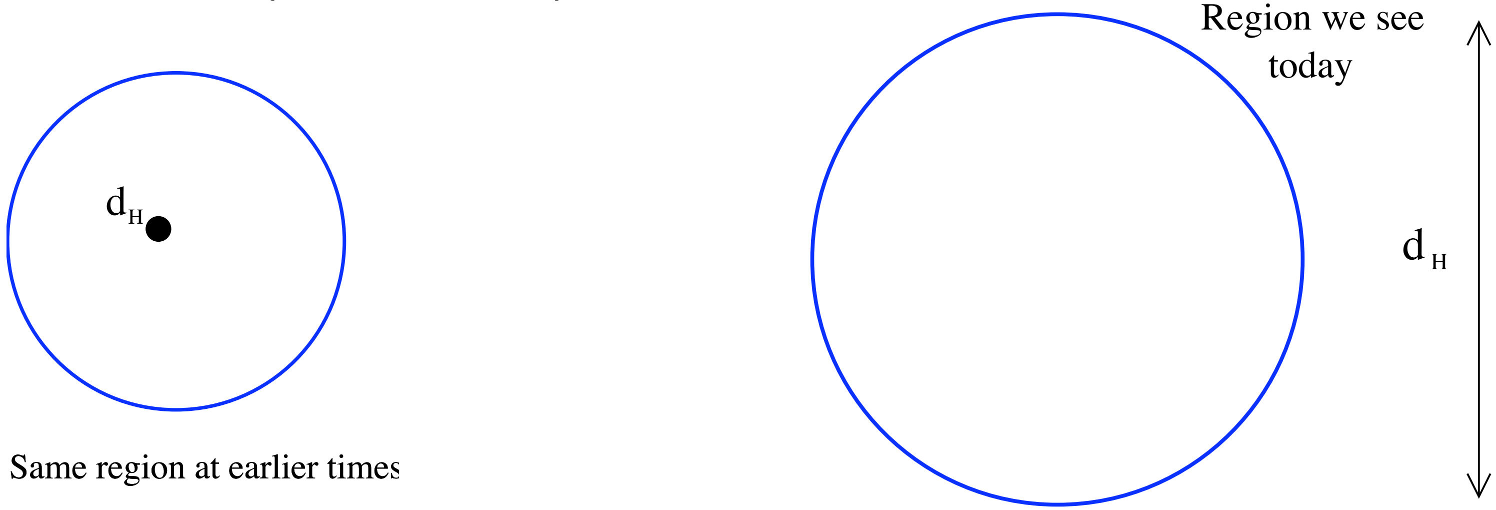

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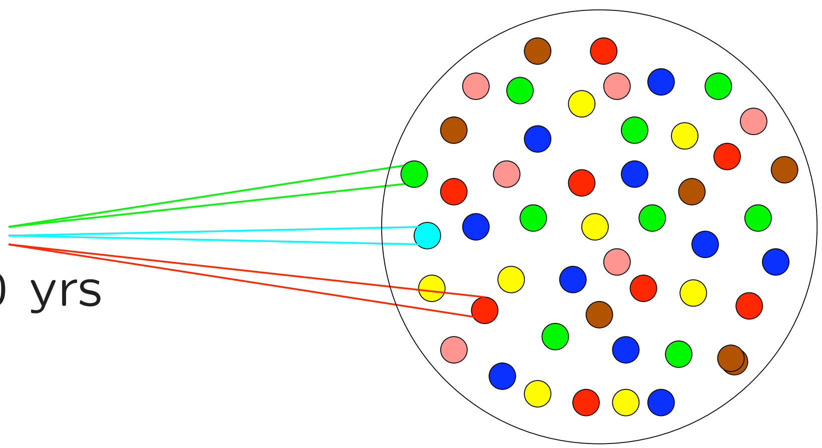
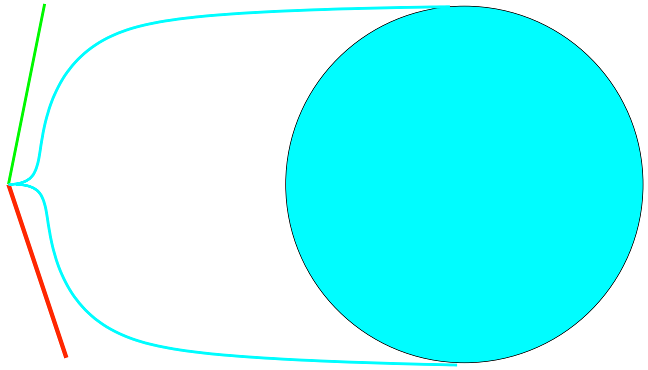


Sharp contrast with the observed $T_0 \simeq 2.73$K everywhere

Solved if physical scales (a) grew faster than horizon (t)

Need $\ddot{a} > 0$, acceleration $\equiv$ inflation



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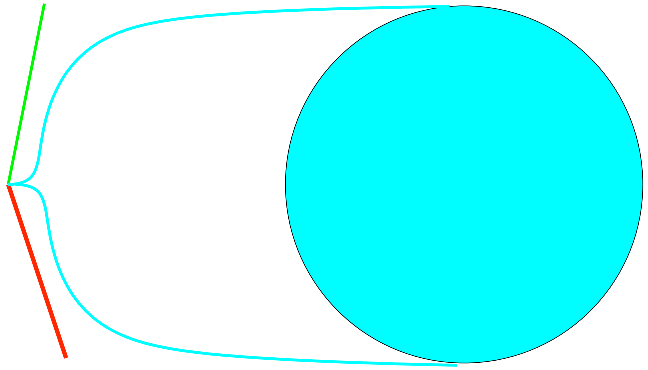

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Flatness problem

$$\frac{\dot{a}^2}{a^2} = \frac{8\pi}{3M_p^2}\left[\frac{\rho_M}{a^3} + \frac{\rho_R}{a^4}\right] - \frac{k}{a^2}$$

Curvature $\leq 1\%$ today. Must have been $\leq 10^{-18}$ at BBN.

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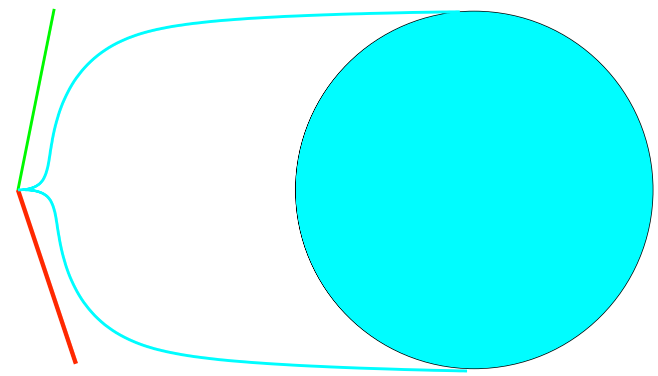

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Idea: what if, in the past, $$\frac{\dot{a}^2}{a^2} = \frac{8\pi}{3M_p^2}\rho_X - \frac{k}{a^2}$$

with ρ_X decreasing slower than a^{-2}, and then $X \to M, R$

Universe "flattens out" while X dominates

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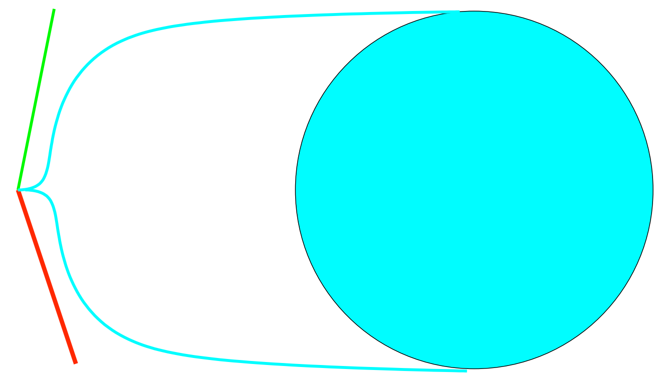

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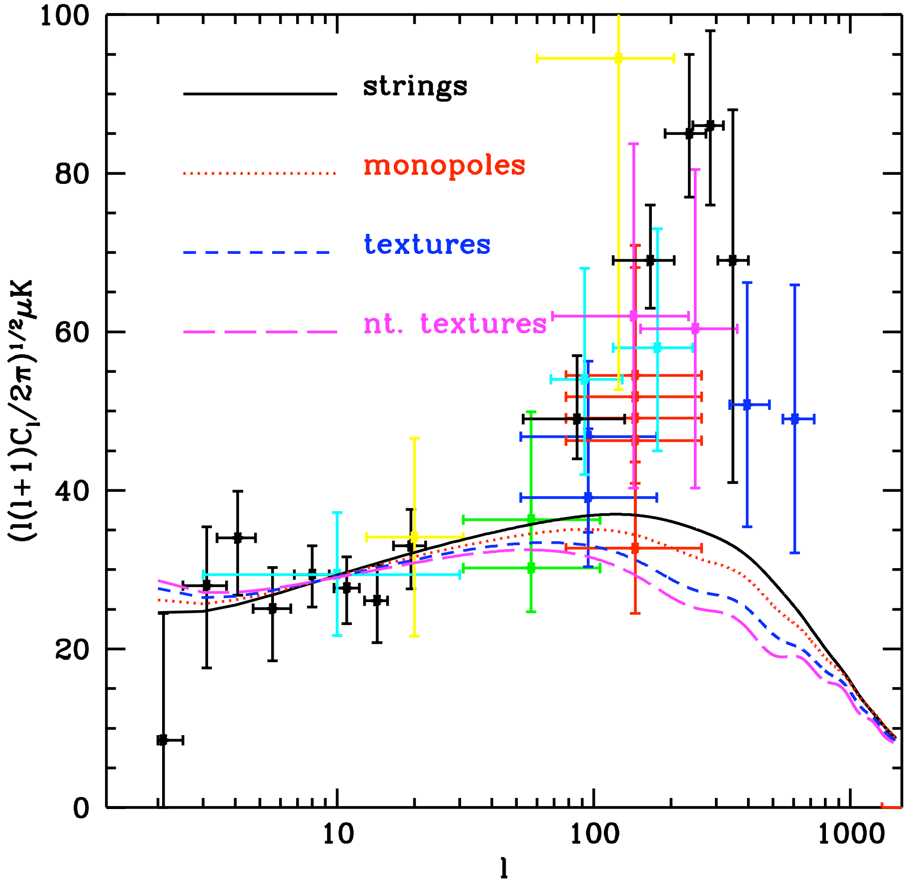
Universe "flattens out" while X dominates

This $\Rightarrow$ $a^2 \rho_X$ is growing $\Rightarrow$ $\ddot{a} > 0$, inflation

Most immediate idea is that perturbations are actively sourced, e.g. by topological defects. Some uncertainty in the evolution (numerical simulations), but most likely incoherent



No acoustic peaks

Pen, Seljak, Turok '97

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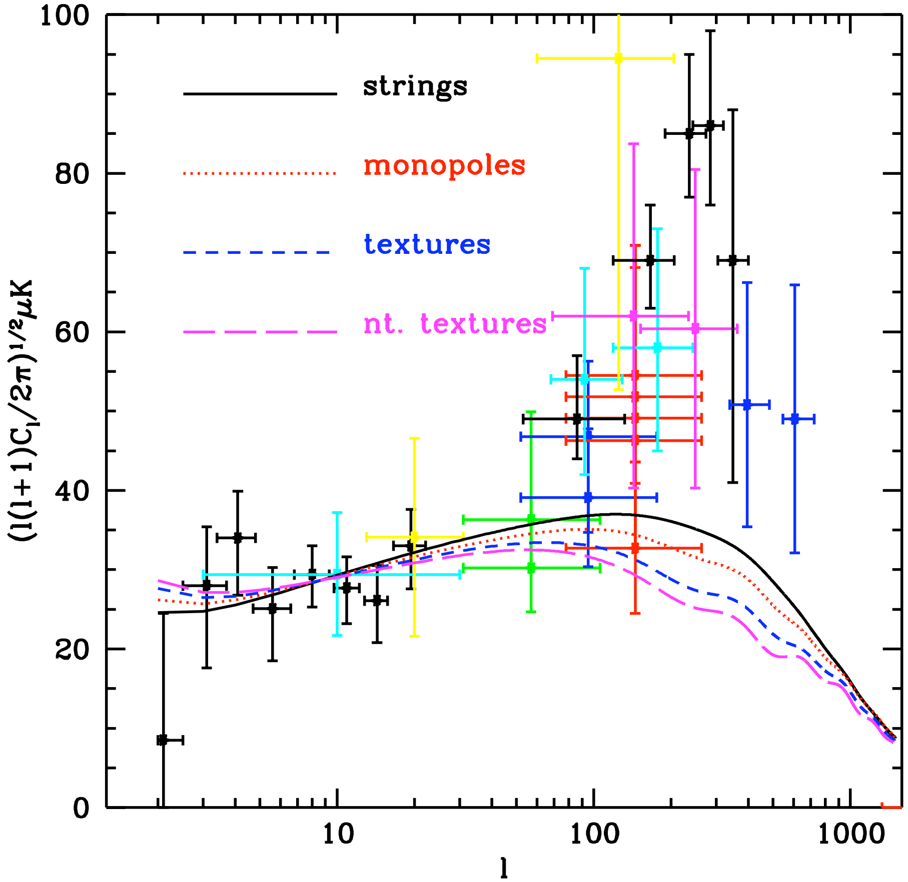


No acoustic peaks

Pen, Seljak, Turok '97

Counter-example: One can mathematically construct a coherent active source that reproduces acoustic peaks, Turok '97

Cosmic strings

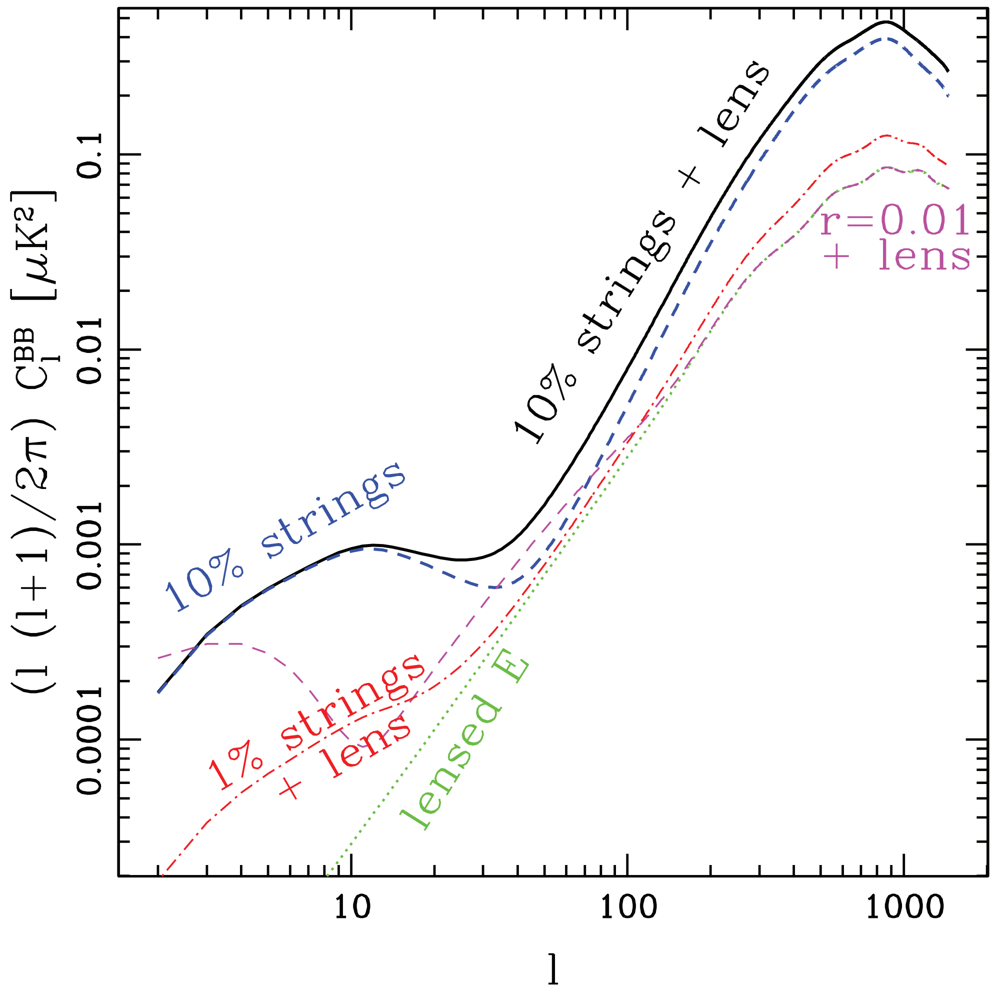
May form at the end of hybrid, and $D-$brane inflation

Can give $\lesssim$ 10% contribution to anisotropies: $G\mu \lesssim \text{few} \times 10^{-7}$

Wyman, Pogosian, Wasserman '06

Seljak, Slosar, McDonald '06

Bevis, Hindmarsh, Kunz, Urrestilla '07

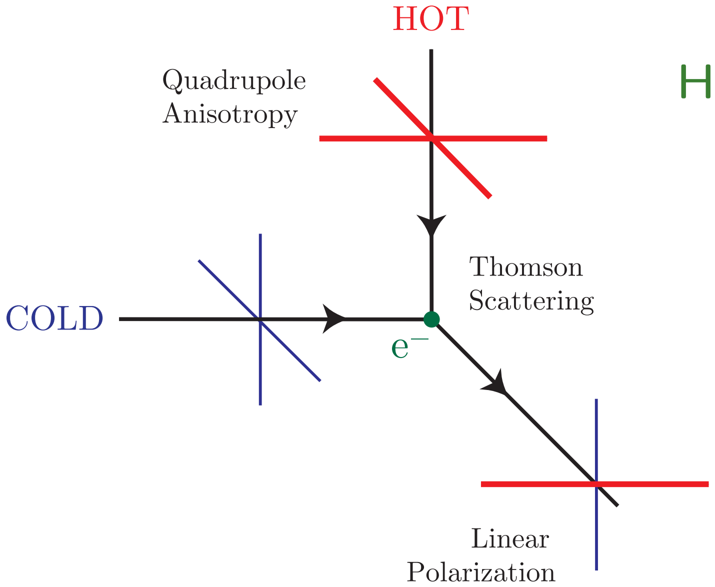


Characteristic and efficient

B-mode polarization

from vector perturbations

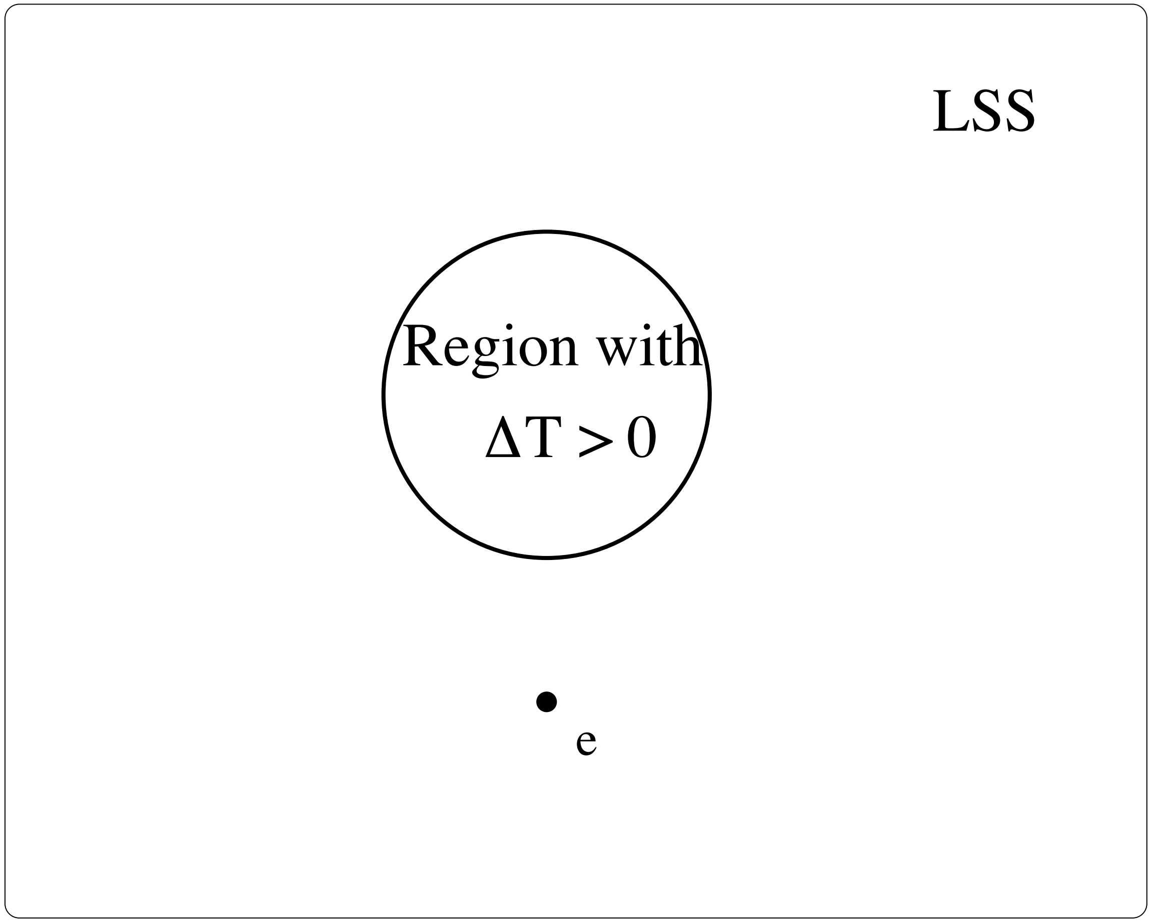
(1% contribution detectable by CMBPol)

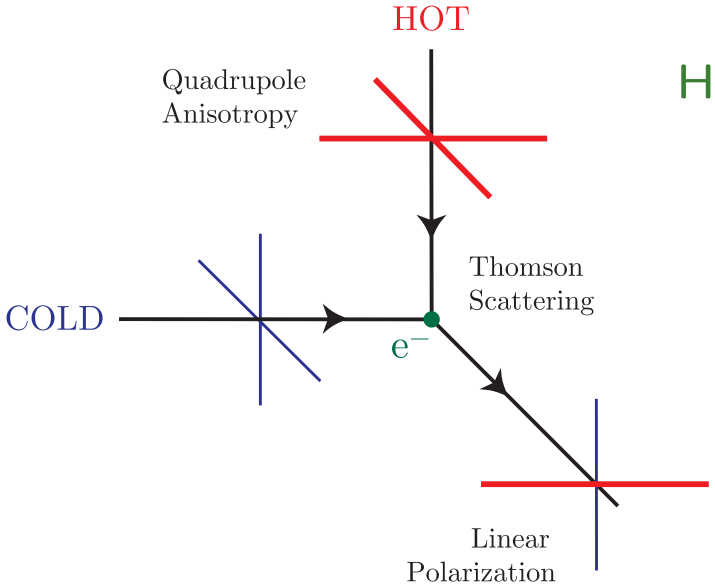


Hu and White '97

Net polarization in the direction

from which fewer photons arrived





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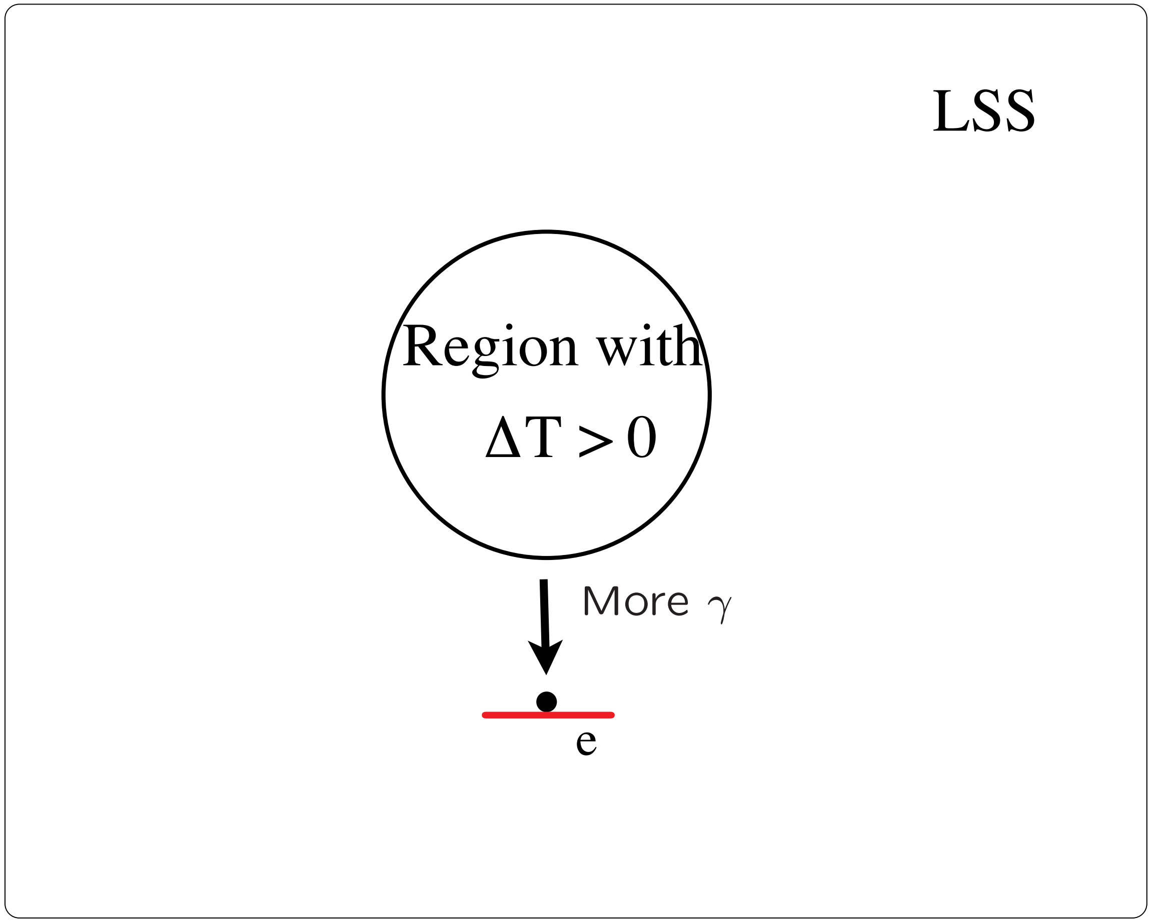

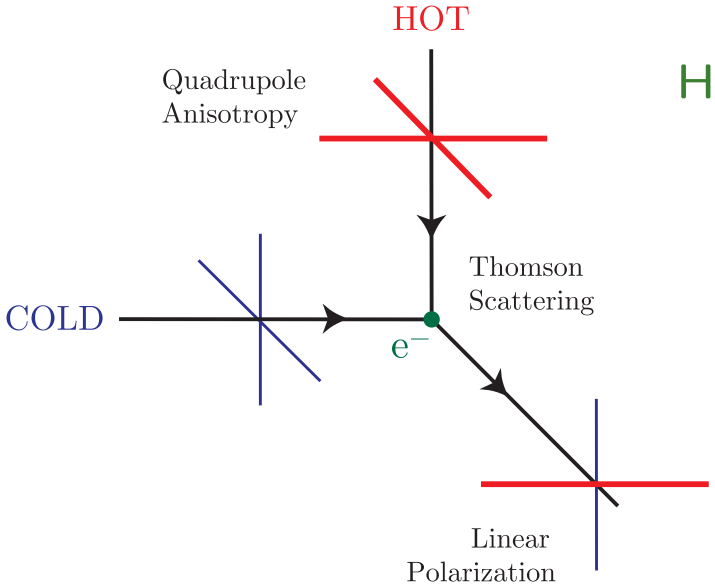

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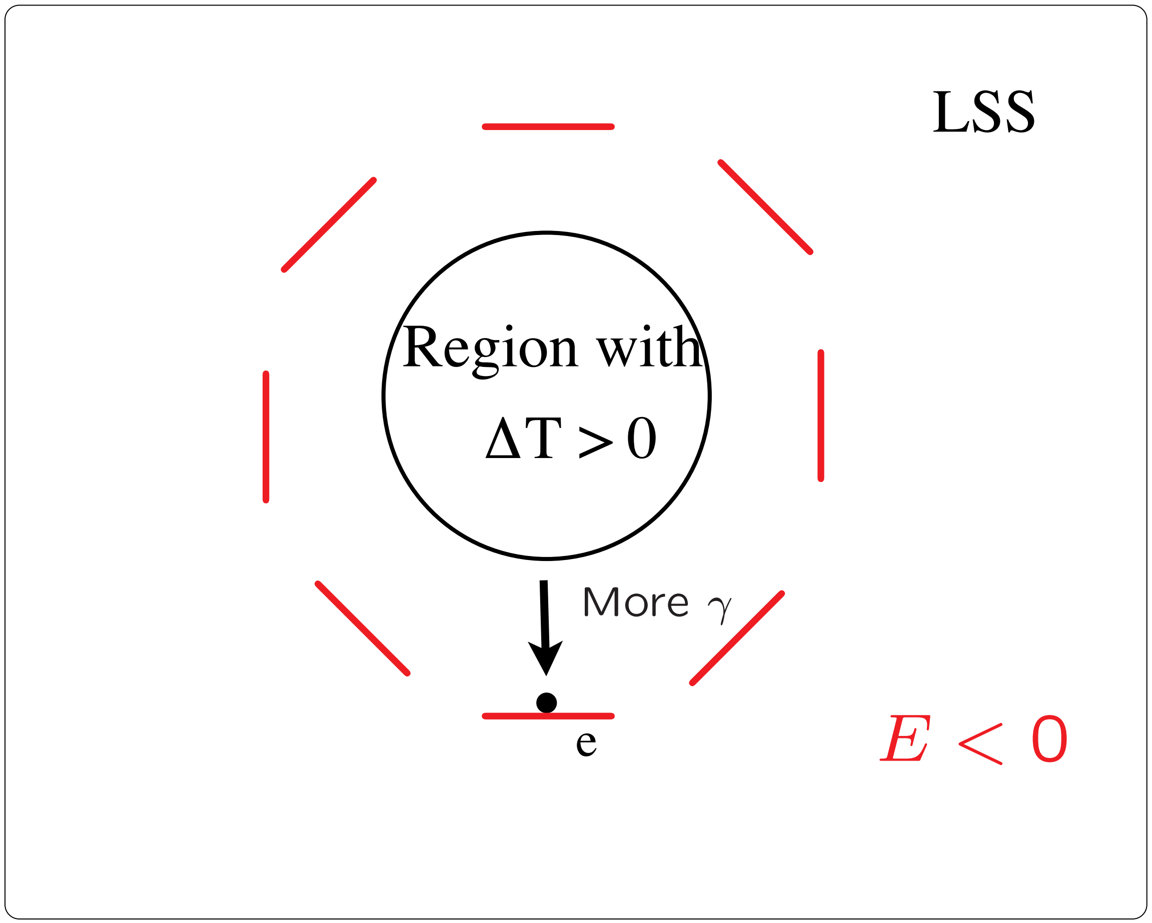

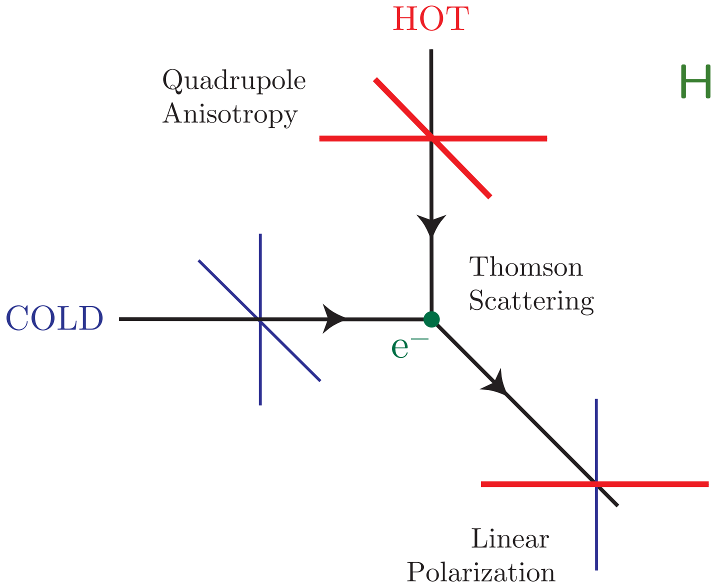

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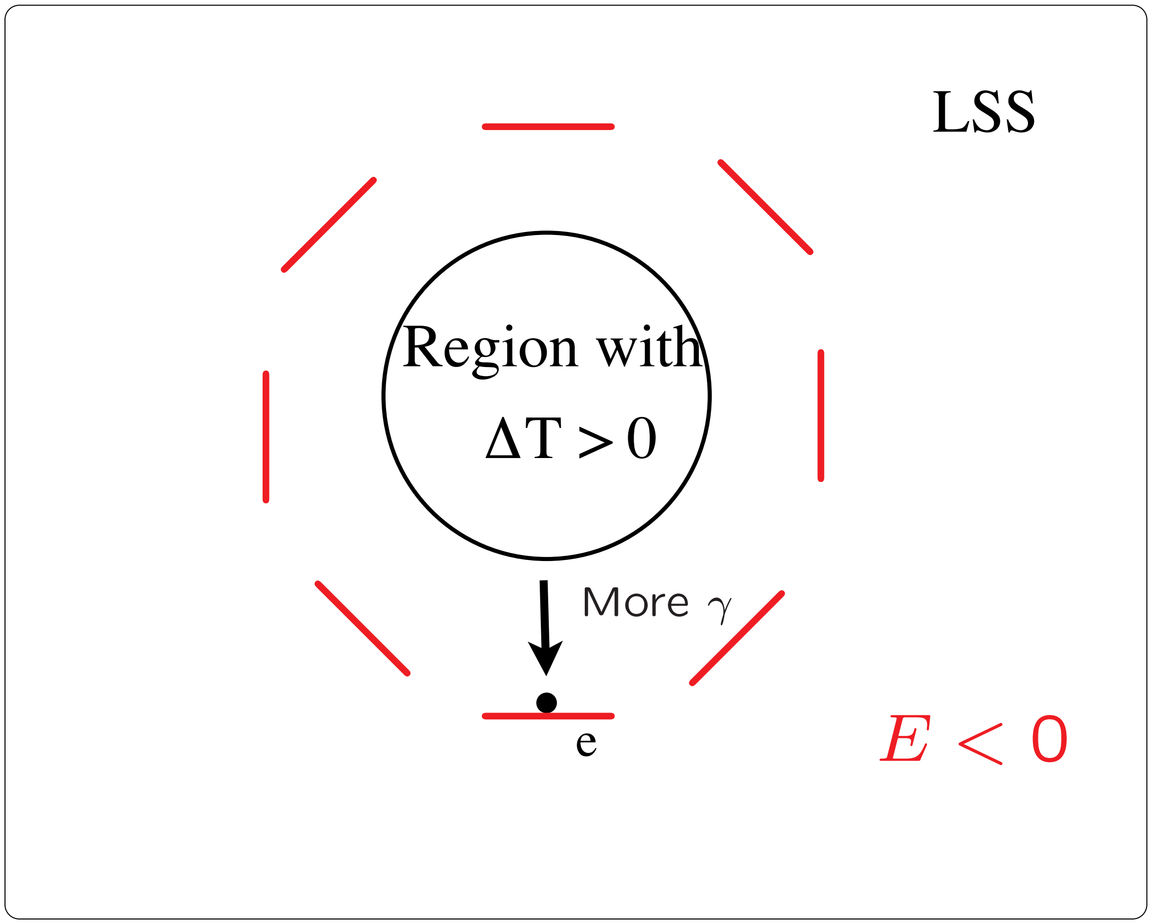
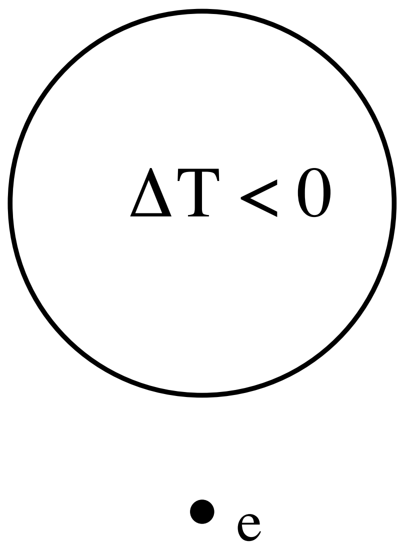
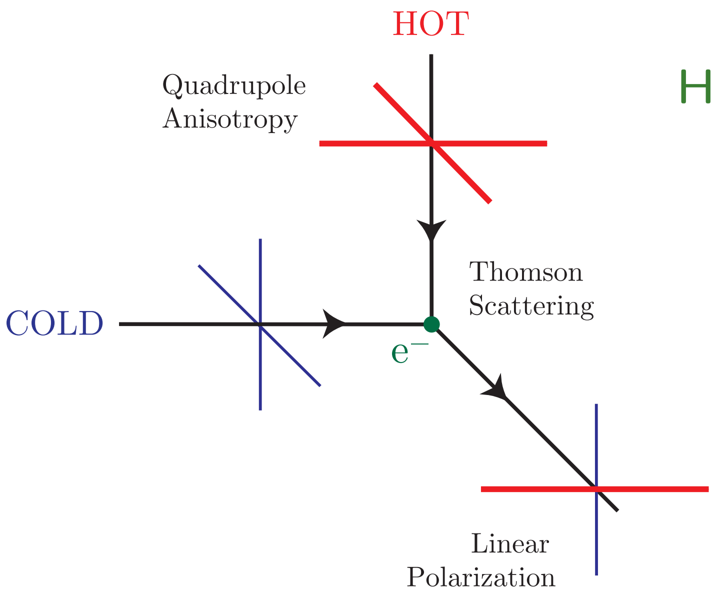




Monday, June 21, 2010



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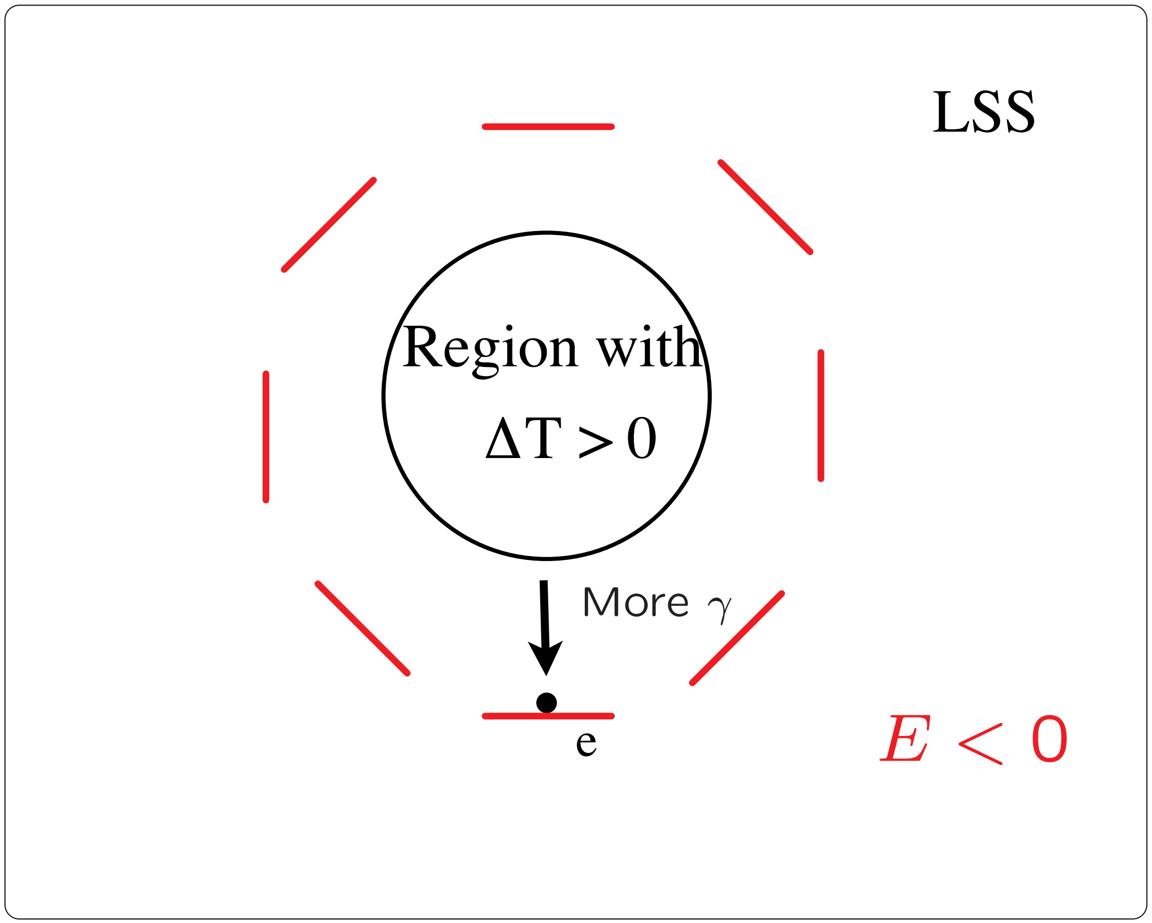
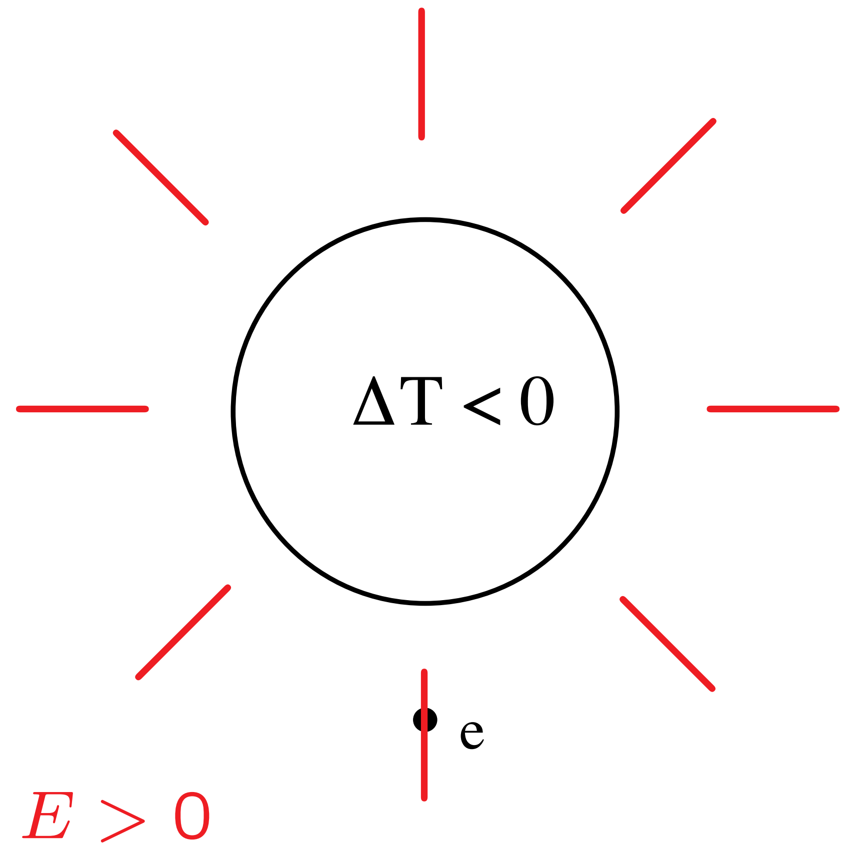
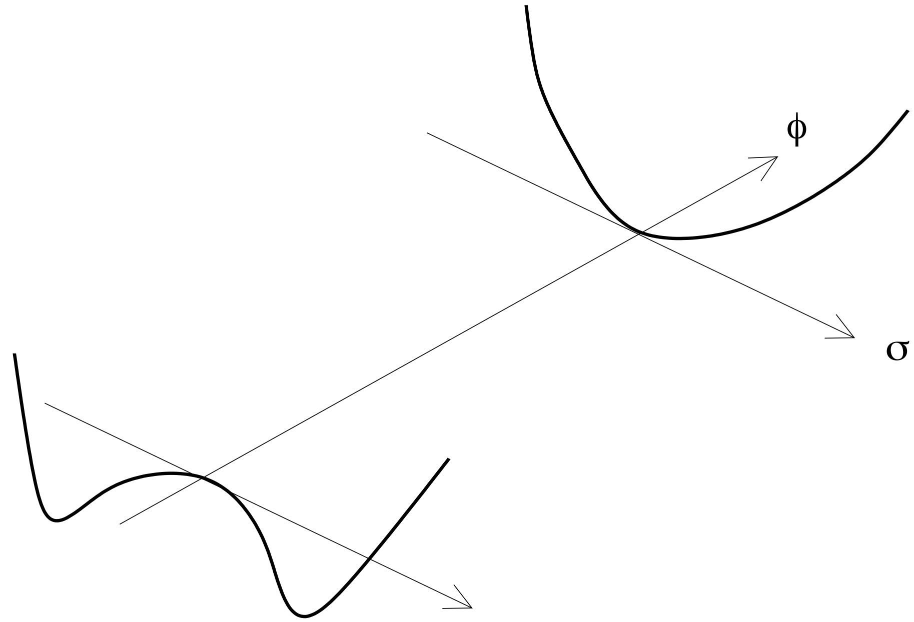




Examples of small field models

Hybrid inflation:

$$V = \frac{\lambda}{4}\left(\sigma^2 - v^2\right)^2 + \frac{g^2}{2}\,\phi^2\,\sigma^2$$



Supergravity:

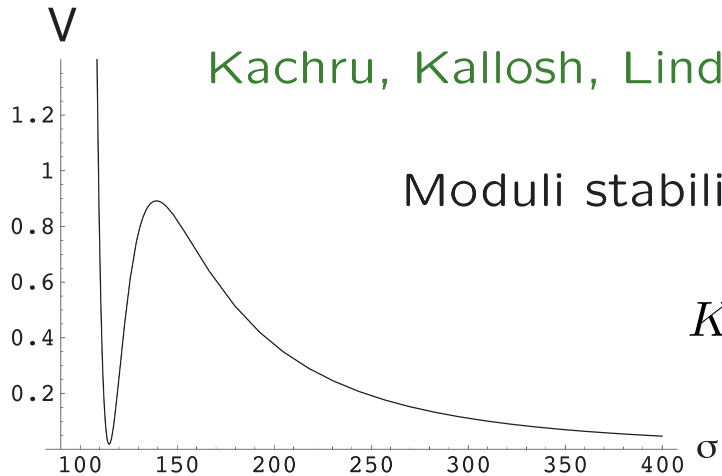
$$K = \phi_i\,\phi_i^* \;\Rightarrow\; V = V_D + V_F\ ,$$

$$e^{\frac{K}{M_p^2}} \simeq 1 \;\text{ for }\; \phi \ll M_p$$

$$V_F = e^{\frac{K}{M_p^2}}\left[\left|\frac{\partial W}{\partial \phi_i} + \phi_i^*\,W\right|^2 - \frac{3|W|^2}{M_p^2}\right]$$

V_{hybrid} typical $V_D + V_F$

Inflation in string theory



Kachru, Kallosh, Linde, Trivedi '03

Moduli stabilization from fluxes (W_0) $\rightarrow$ AdS vacuum

$$K = -3\ln(T+\bar{T})\ , \qquad W = W_0 + Ae^{-aT}$$

uplift from gaugino condensation
or wrapped brane instantons

($\sigma = T + \bar{T}$ volume modulus)

Models tuned: explicitly deal with QFT assumption UV is under control

(1) Brane-(anti)brane inflation   (2) Modular inflation Blanco-Pillado et al '04

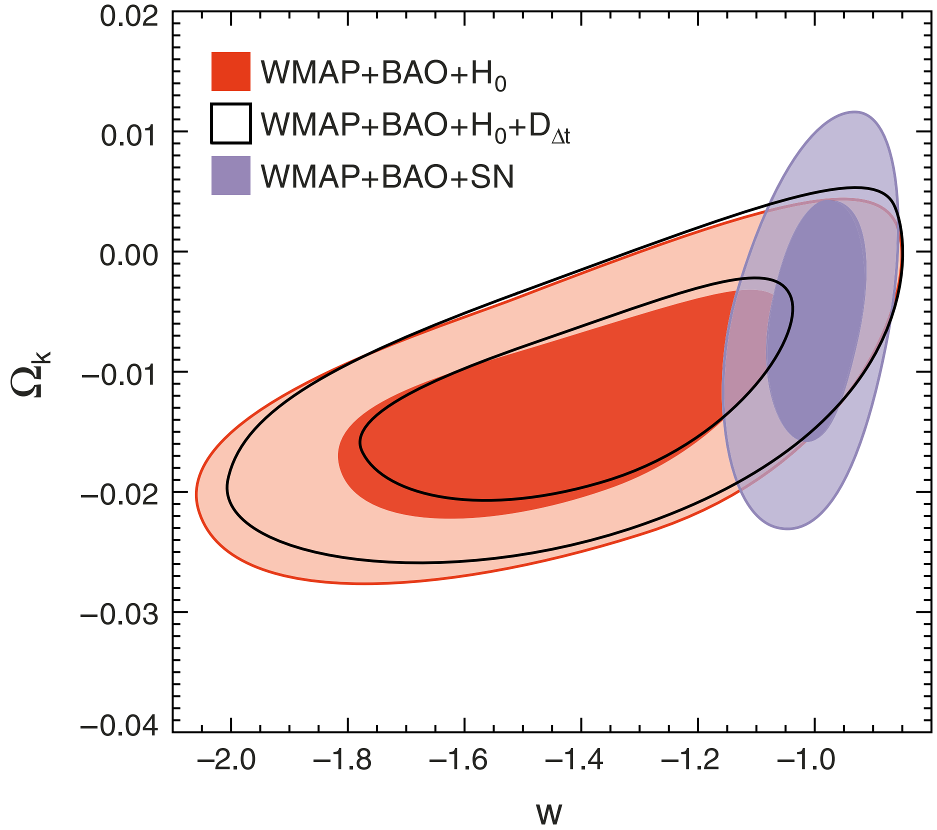
(1) Kachru, Kallosh, Linde, Maldacena, McAllister, Trivedi '03

DBI (relativistic motion) Alishahiha, Silverstein, Tong '04

Volume of internal space limits $\phi \ll M_p$ (small r)

Monodromy ($\neq$ potential after a closed circular motion) Silverstein, Westphal '08

Spatial curvature vs. equation of state dark energy



Flat:

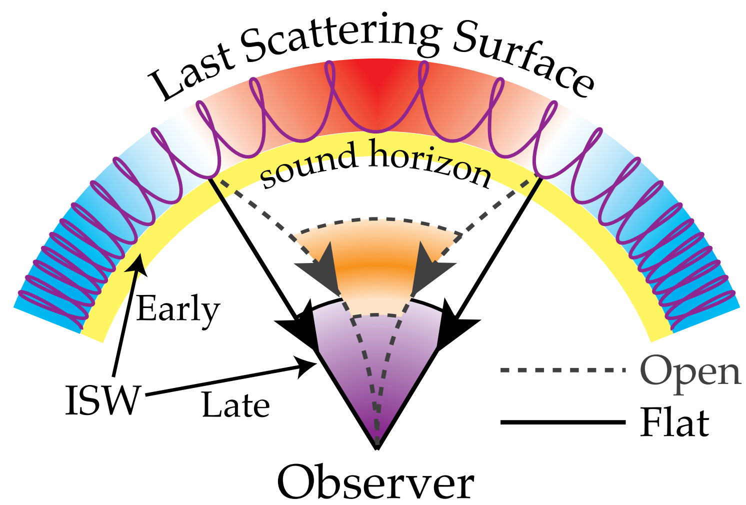
WMAP + BAO + H_0 $\quad w = -1.10 \pm 0.14$

WMAP + BAO + SN $\quad w = -0.980 \pm 0.053$

c.c.:

WMAP + BAO + H_0

$$-0.0133 < \Omega_k < 0.0084 \ (95\% \text{ CL})$$



Wayne Hu

Isocurvature perturbations

Linear combinations of fluctuations of $\neq$ species that do not create $\delta\mathcal{R}$

Multi fields during inflation

For CDM and photons, $$\mathcal{S}_{c,\gamma} \equiv \frac{\delta\rho_c}{\rho_c} - \frac{3\delta\rho_\gamma}{4\rho_\gamma} \qquad \frac{\alpha}{1-\alpha} \equiv \frac{P_{\mathcal{S}}(k_0)}{P_{\mathcal{R}}(k_0)},$$

$$k_0 = 0.002 \text{ Mpc}^{-1}.$$

Parameter	ΛCDM[b]	ΛCDM+anti-correlated[c]	ΛCDM+uncorrelated[d]
Fit parameters			
$\Omega_b h^2$	$0.02258^{+0.00057}_{-0.00056}$	$0.02293^{+0.00060}_{-0.00061}$	$0.02315^{+0.00071}_{-0.00072}$
$\Omega_c h^2$	0.1109 ± 0.0056	$0.1058^{+0.0057}_{-0.0058}$	$0.1069^{+0.0059}_{-0.0060}$
Ω_Λ	0.734 ± 0.029	0.766 ± 0.028	0.758 ± 0.030
$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.24 \pm 0.13) \times 10^{-9}$	$(2.38 \pm 0.11) \times 10^{-9}$
n_s	0.963 ± 0.014	0.984 ± 0.017	0.982 ± 0.020
τ	0.088 ± 0.015	0.088 ± 0.015	0.089 ± 0.015
α_{-1}	$\cdots$	< 0.011 (95% CL)	$\cdots$
α_0	$\cdots$	$\cdots$	< 0.13 (95% CL)
Derived parameters			
t_0	13.75 ± 0.13 Gyr	13.58 ± 0.15 Gyr	13.62 ± 0.16 Gyr
H_0	71.0 ± 2.5 km/s/Mpc	$74.5^{+3.1}_{-3.0}$ km/s/Mpc	73.6 ± 3.2 km/s/Mpc
σ_8	0.801 ± 0.030	$0.784^{+0.033}_{-0.032}$	0.785 ± 0.032