Beyond the Standard Model of cosmology

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- Standard Model of cosmology:
  - ΛCDM
  - Inflation

  Consistent with all data.

- Can one think of alternatives?

  Emphasis of this talk: inflation

We are confident that the hot epoch was not the beginning

- Key: cosmological perturbations

Our Universe is not exactly homogeneous.

Inhomogeneities: ⊙ density perturbations and associated gravitational potentials (3d scalar), observed;

⊙ gravitational waves (3d tensor), not observed (yet?).

Today: inhomogeneities strong and non-linear

In the past: amplitudes small,

$$\frac{\delta\rho}{\rho} = 10^{-4} - 10^{-5}$$

Linear analysis appropriate.

Fairly well measured (CMB, galaxy surveys, grav. lensing, ...)

- Properties of perturbations in conventional ("hot") Universe.

Friedmann–Lemaître–Robertson–Walker metric:

$$ds^2 = dt^2 - a^2(t) d\vec{x}^{\,2}$$

Expanding Universe:

- $a(t) \propto t^{1/2}$ at radiation domination stage (before $T \simeq 1$ eV, $t \simeq 60$ thousand years)
  $a(t) \propto t^{2/3}$ at matter domination stage (until recently).

- Cosmological horizon (assuming that nothing preceeded hot epoch): length that light travels from Big Bang moment,

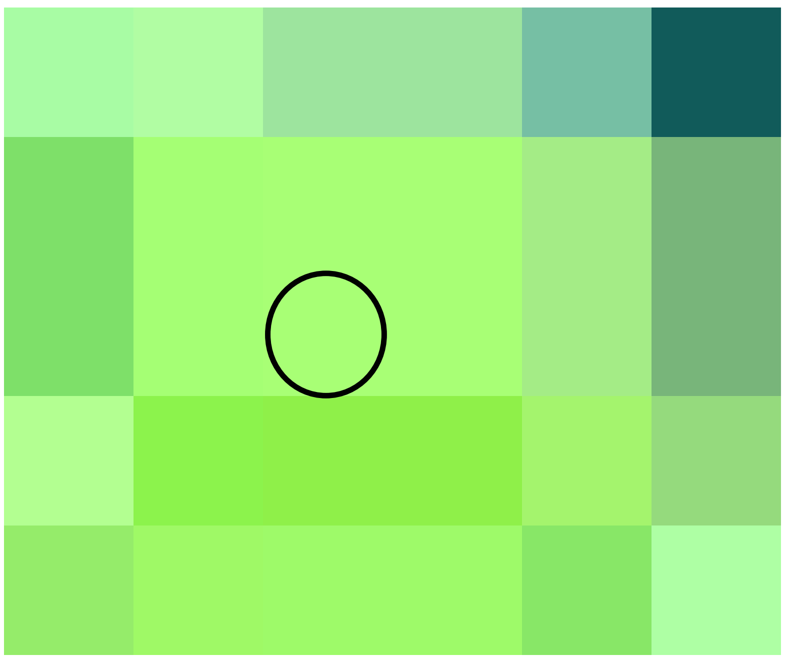
$$l_H(t) = (2-3)t$$

- Wavelength of perturbation grows as $a(t)$.
  E.g., at radiation domination

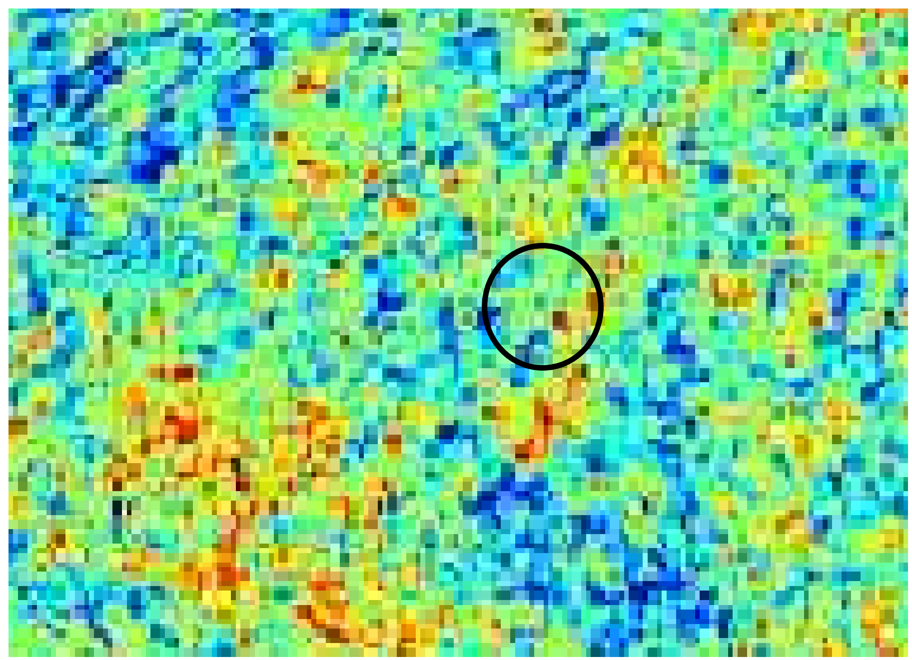
$$\lambda(t) \propto t^{1/2} \quad \text{while} \quad l_H \propto t$$

Today $\lambda < l_H$, subhorizon regime

Early on $\lambda(t) > l_H$, superhorizon regime.



superhorizon mode



subhorizon mode

- In other words, physical wavenumber (momentum) gets redshifted,

$$q(t) = \frac{2\pi}{\lambda(t)} = \frac{k}{a(t)}\,, \qquad k = \text{const} = \text{coordinate momentum}$$

Today

$$q > H \equiv \frac{\dot{a}}{a}$$

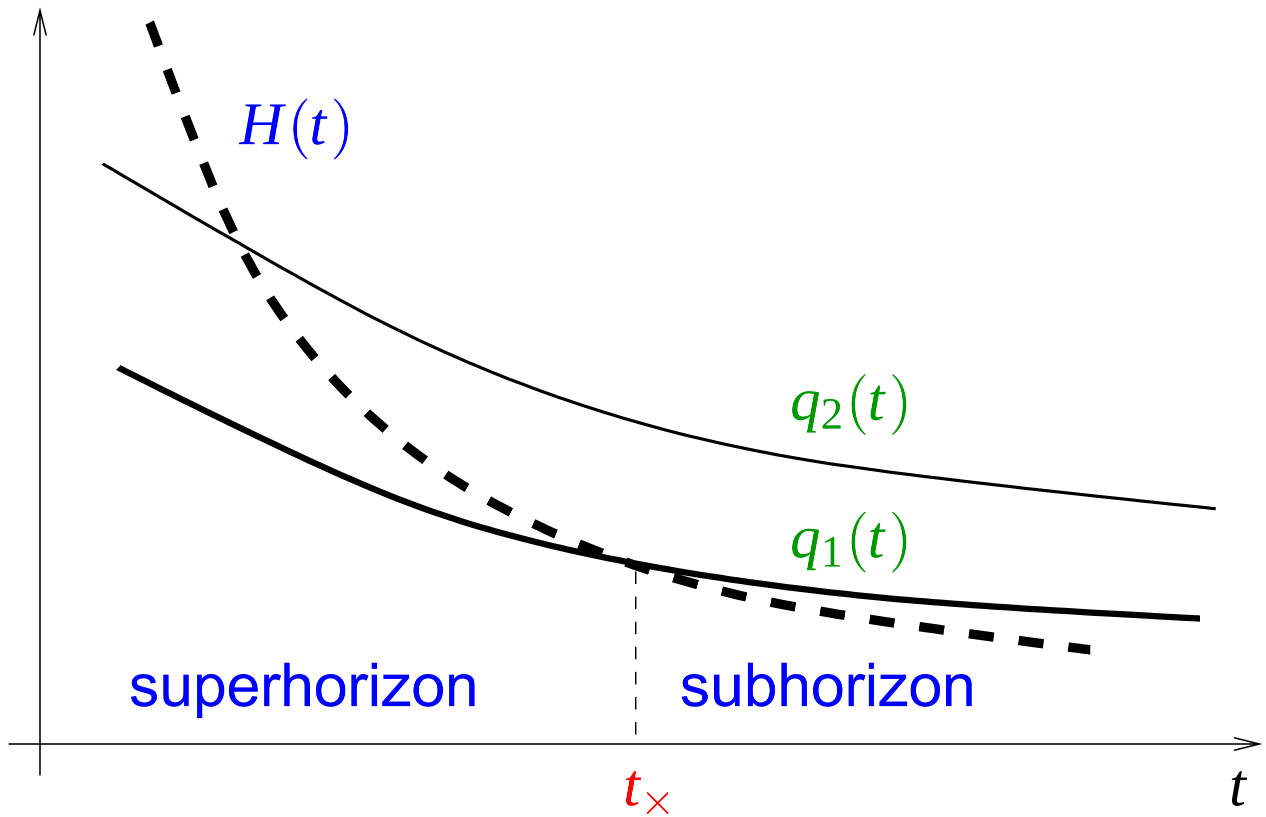
Early on

$$q(t) < H(t)$$

Very different regimes of evolution.

NB: Horizon entry occured after Big Bang Nucleosynthesis epoch for modes of all relevant wavelengths $\Longleftrightarrow$ no guesswork at this point.

Regimes at radiation (and matter) domination



$q_2 > q_1$

- Causality $\Longrightarrow$ perturbations can be generated only when they are subhorizon.

Off-hand possibilities:

- Perturbations were never superhorizon, they were generated at the hot cosmological epoch by some causal mechanism.

  E.g., seeded by topological defects (cosmic strings, etc.)

  N. Turok et.al.' 90s

  The only possibility, if expansion started from hot Big Bang.

  No longer an option!

- Hot epoch was preceeded by some other epoch. Perturbations were generated then.

- Perturbations in baryon-photon plasma = sound waves.

  If they were superhorizon, they started off with one and the same phase.

  Reason: solutions to wave equation in superhorizon regime in expanding Universe

$$\zeta = \text{const} \qquad \text{and} \qquad \zeta = \frac{\text{const}}{t^{3/2}}$$

$$[(\delta\rho/\rho, \Phi) \Longrightarrow \zeta]$$

  Assume that modes were superhorizon. If the Universe was not very inhomogeneous at early times, the initial condition is unique (up to amplitude),

$$\zeta = \text{const} \Longrightarrow \frac{d}{dt}\zeta = 0$$

  Acoustic oscillations start after entering the horizon at zero velocity $\Longrightarrow$ phase of oscillations uniquely defined.

- Perturbations develop different phases by the time of photon last scattering (= recombination), depending on wave vector:

$$\zeta(t_r) \propto \cos\left(\int_0^{t_r} dt\ v_s\ q(t)\right)$$

(v_s = sound speed in baryon-photon plasma) $\Longrightarrow$

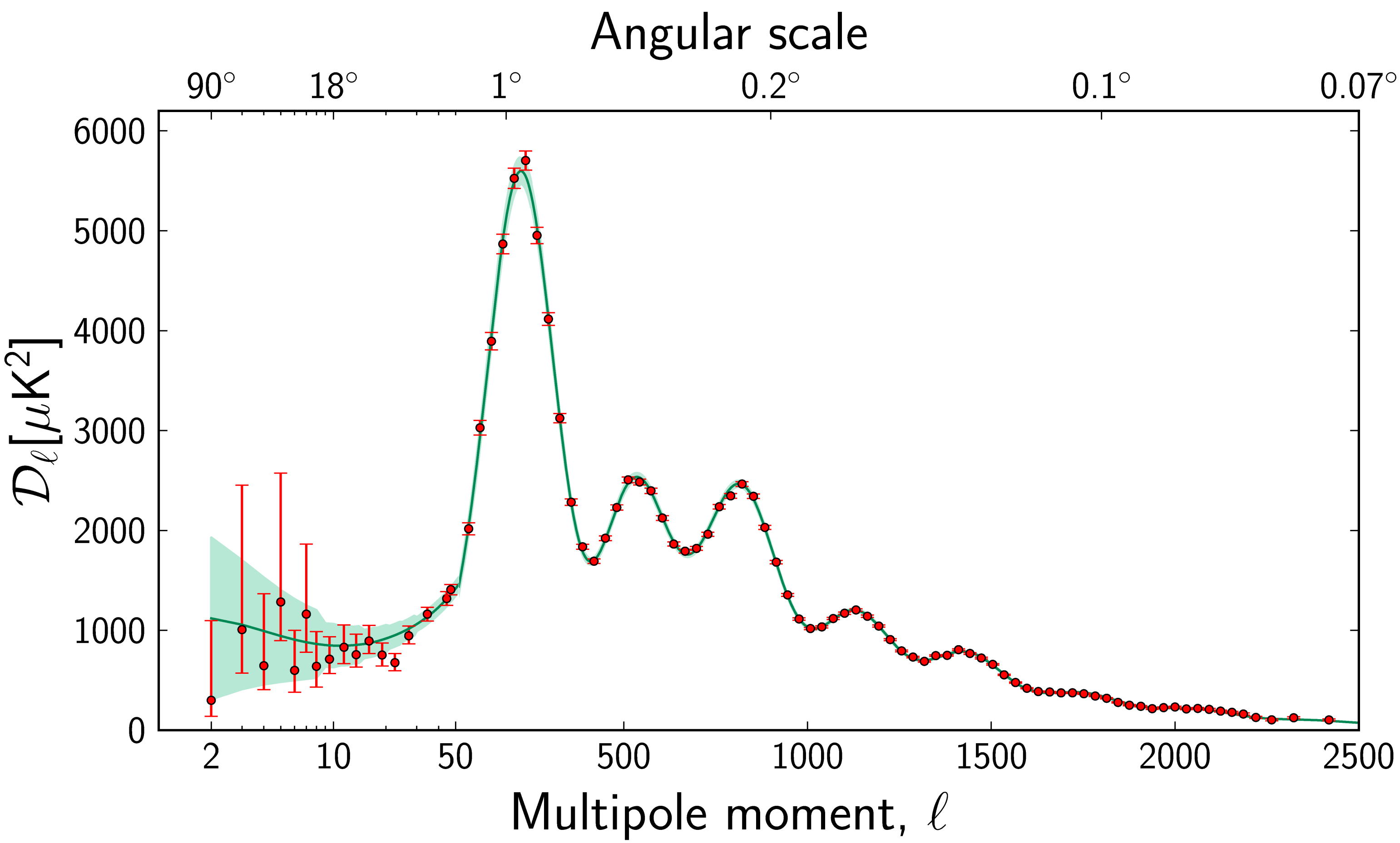
- Oscillations in CMB temperature angular spectrum

  Fourier decomposition of temperatue fluctuations:

$$\delta T(\theta,\varphi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\varphi)$$

$\langle a_{lm}^* a_{lm} \rangle = C_l$, temperature angular spectrum;

larger $l \Longleftrightarrow$ smaller angular scales, shorter wavelengths

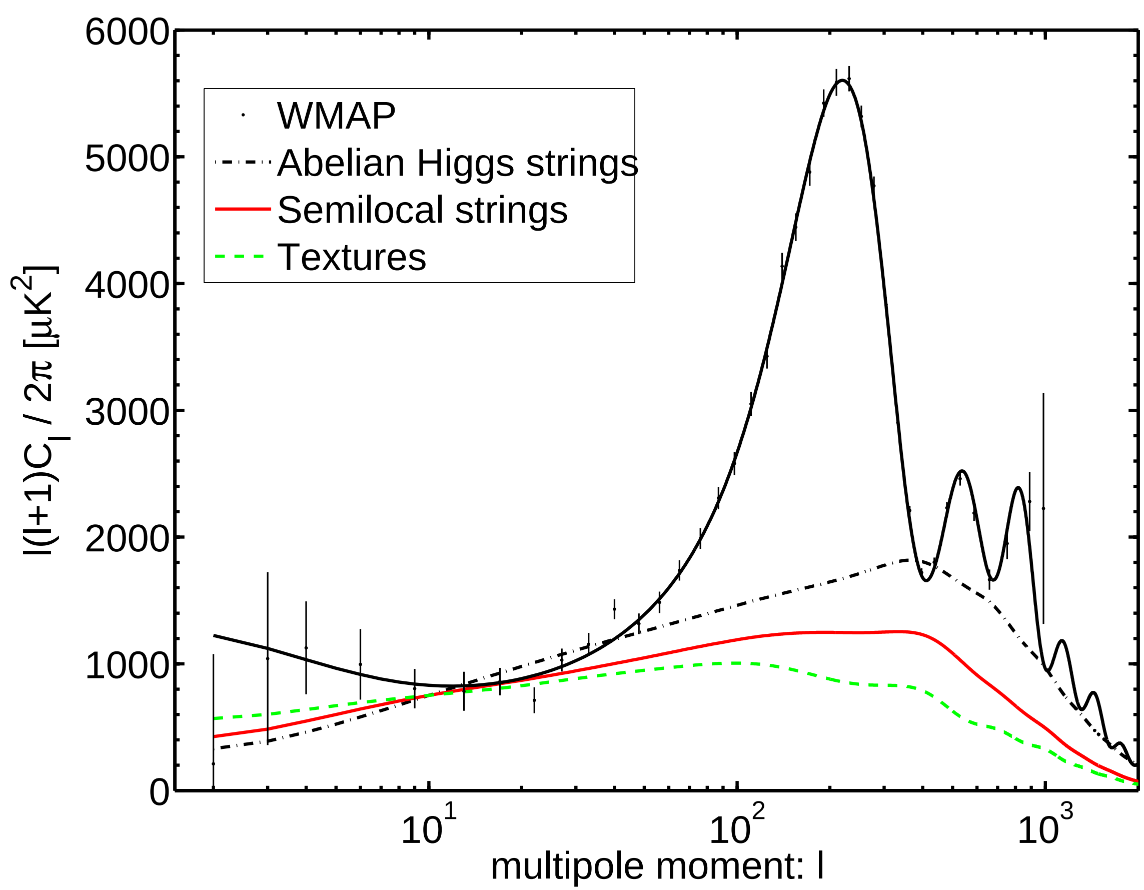


Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

Planck' 2013

- Furthermore, there are perturbations which were superhorizon at the time of photon last scattering

These properties would not be present if perturbations were generated at hot epoch in causal manner.



Primordial perturbations were generated at some yet unknown epoch before the hot expansion stage.

That epoch must have been long and unusual: perturbations were subhorizon early at that epoch, our visible part of the Universe was in a causally connected region.

- Excellent guess: inflation

Starobinsky'79; Guth'81; Linde'82; Albrecht and Steinhardt'82

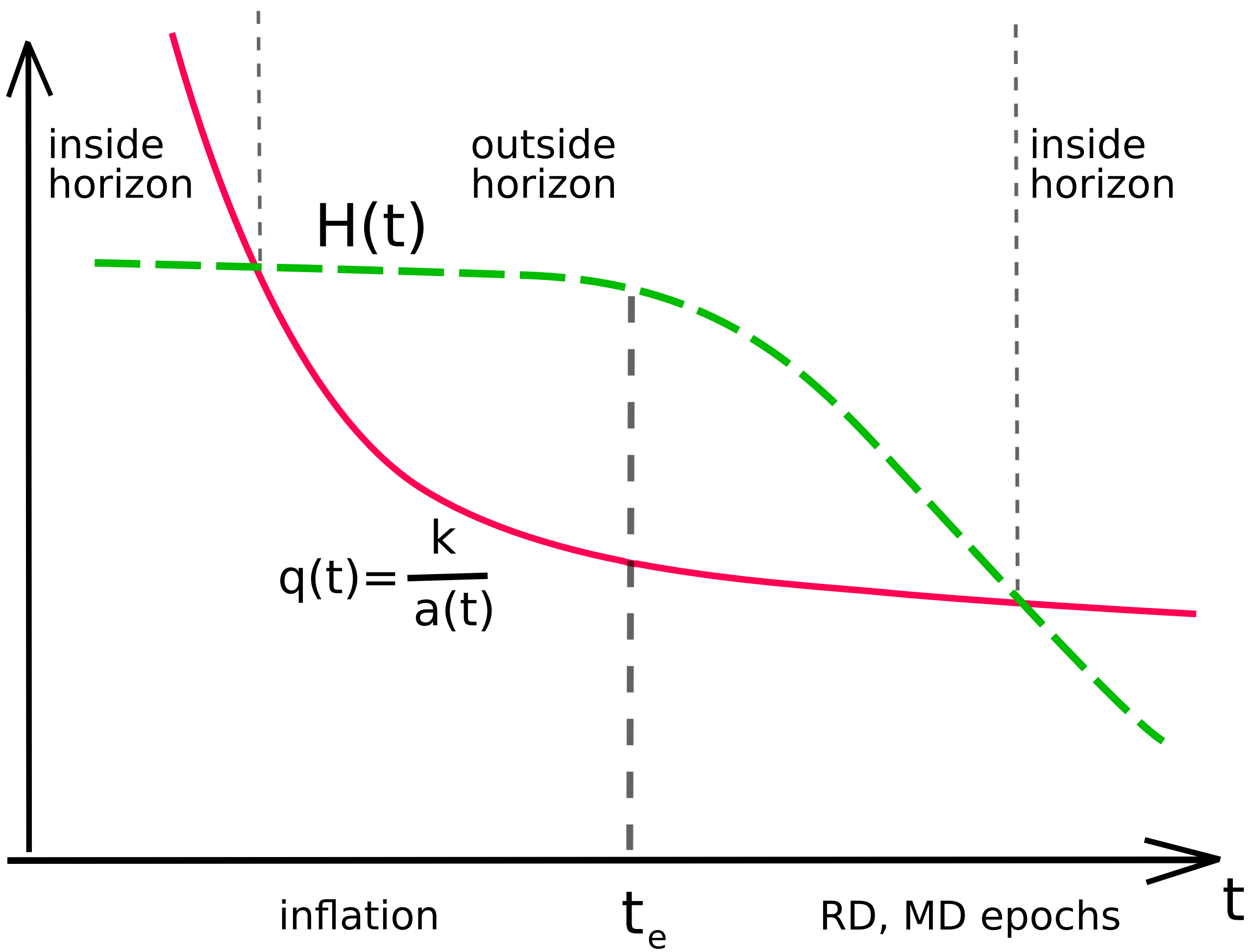
Exponential expansion with almost constant Hubble rate,

$$a(t) = \mathrm{e}^{\int H dt}, \qquad H \approx \text{const}$$

Perturbations subhorizon early at inflation:

$$q(t) = \frac{k}{a(t)} \gg H$$

Physical wave number and Hubble parameter at inflation and later:



Alternatives to inflation:

- Contraction — Bounce — Expansion
- Start up from static state $\Longleftrightarrow$ Genesis

Creminelli et.al.'06; '10

Difficult.
Einstein equations (neglecting spatial curvature)

$$H^2 = \frac{8\pi}{3} G\rho$$

$$\frac{dH}{dt} = -4\pi(\rho + p)$$

$\rho =$ energy density, $p =$ pressure, $H = \dot{a}/a$.

Bounce, start up scenarios $\Longrightarrow \frac{dH}{dt} > 0 \Longrightarrow \rho > 0$ and $p < -\rho$

Very exotic matter.
(or, possibly, gravity beyond General Relativity).

$$p < -\rho \ , \quad \rho > 0$$

Violation of the Null Energy Condition, NEC

NEC: $T_{\mu\nu} n^\mu n^\nu \geq 0$

for any null vector n^μ, such that $n_\mu n^\mu = 0$.

$$n^\mu = (1,1,0,0) \Longrightarrow \rho + p > 0$$

- NEC has many faces:
  - Covariant energy-momentum conservation:

$$\frac{d\rho}{dt} = -3H(\rho + p)$$

NEC: energy density decreases during expansion,

except for $p = -\rho$, cosmological constant.

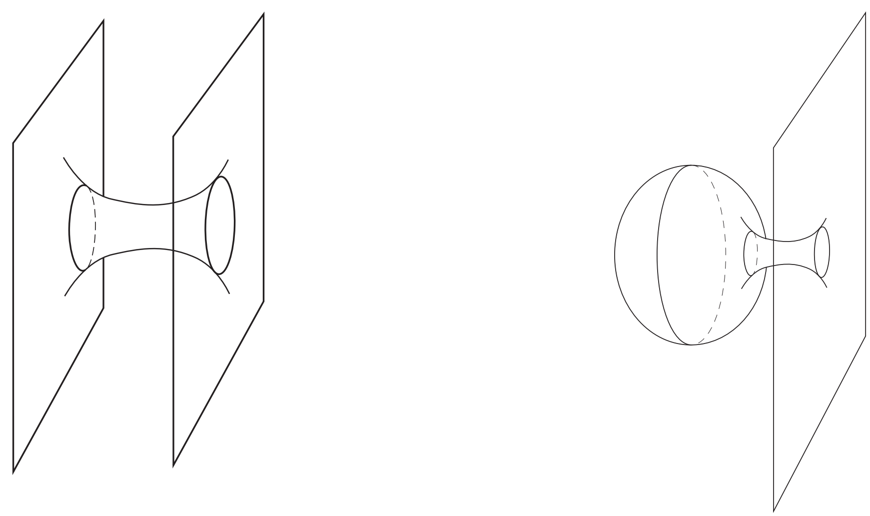
- Penrose theorem:

Penrose' 1965

Once there is (anti)trapped surface (Hubble sphere, black hole horizon), there must be singularity (in the past)

  - Cosmological and black hole singularities
  - No way of creating a Universe in the laboratory

- No way of creating throats in space (Lorentzian wormholes, semiclosed worlds)



- And more...

Can Null Energy Condition be violated?

- Folklore until recently: NO!

  Pathologies:

  - Ghosts:

$$E = -\sqrt{p^2 + m^2}$$

Example: theory with wrong sign of kinetic term,

$$\mathscr{L} = -(\partial\phi)^2 \quad \Longrightarrow \quad \rho = -\dot{\phi}^2 - (\nabla\phi)^2 \,, \qquad p = -\dot{\phi}^2 + (\nabla\phi)^2$$

$$\rho + p = -2\dot{\phi}^2 < 0$$

Catastrophic vacuum instability

NB: Can be cured by Lorentz-violation

(but hard! – even though Lorentz-violation is inherent in cosmology)

Other pathologies

- Gradient instabilities:

$$E^2 = -(p^2 + m^2) \implies \varphi \propto \mathrm{e}^{|E|t}$$

- Superluminal propagation of excitations

No-go theorem for theories with Lagrangians involving first derivatives of fields only

Dubovsky, Gregoire, Nicolis, Rattazzi' 2006

NEC violation today: YES,

Null Energy Condition can be violated in a healthy way

Senatore' 2004;
V.R.' 2006;
Creminelli, Luty, Nicolis, Senatore' 2006

- General properties of non-pathological NEC-violating field theories:
  - Non-standard kinetic terms
  - Non-trivial background, instability of Minkowski space-time

Example: scalar field – Galileon $\pi(x^\mu)$,

$$L = F(Y) \cdot \mathrm{e}^{4\pi} + K(Y) \cdot \Box\pi \cdot \mathrm{e}^{2\pi}$$

$$\Box\pi \equiv \partial_\mu \partial^\mu \pi \, , \qquad Y = \mathrm{e}^{-2\pi} \cdot (\partial_\mu \pi)^2$$

Horndeski' 1974; Fairlie et. al.' 1992;
A. Nicolis, R. Rattazzi and E. Trincherini' 2009
Deffayet, Pujolas, Sawicki, Vikman' 2010; Kobayashi, Yamaguchi, Yokoyama' 2010

- Second order equations of motion
- Scale invariance: $\pi(x) \to \pi'(x) = \pi(\lambda x) + \ln\lambda$.

(technically convenient)

Homogeneous solution in Minkowski space (attractor)

$$e^{\pi_c} = \frac{1}{\sqrt{Y_*}(t_* - t)}$$

- $Y \equiv e^{-2\pi_c} \cdot (\partial_\mu \pi_c)^2 = Y_* =$ const, a solution to

$$Z(Y_*) \equiv -F + 2Y_* F' - 2Y_* K + 2Y_*^2 K' = 0$$

$$' = d/dY \; .$$

Energy density

$$\rho = e^{4\pi_c} Z = 0$$

Effective pressure T_{11}:

$$p = e^{4\pi_c} \left(F - 2Y_* K\right)$$

Can be made negative by suitable choice of $F(Y)$ and $K(Y)$
$\Longrightarrow \rho + p < 0$, violation of Null Energy Condition.

Switching on gravity

$$p = \mathrm{e}^{4\pi_c}(F - 2Y_* K) = -\frac{M^4}{Y_*^2 (t_* - t)^4}, \qquad \rho = 0$$

- M: mass scale characteristic of π
- Use $\dot{H} = -4\pi G(p + \rho) \Longrightarrow$ Genesis

$$H = \frac{4\pi}{3} \frac{M^4}{M_{Pl}^2 Y_*^2 (t_* - t)^3}, \quad \text{grows in time starting from zero}$$

NB:

$$\rho \sim M_{Pl}^2 H^2 \sim \frac{1}{M_{Pl}^2 (t_* - t)^6}$$

Early times $\Longrightarrow$ weak gravity, $\rho \ll p$

- Add other matter $\Longrightarrow$ bouncing Universe

Qui' 2011; Osipov, VR' 2013

Perturbations about homogeneous solution in Minkowski

$$\pi(x^\mu) = \pi_c(t) + \delta\pi(x^\mu)$$

- Quadratic Lagrangian for perturbations:

$$L^{(2)} = \mathrm{e}^{2\pi_c} Z' (\partial_t \delta\pi)^2 - V(\vec{\nabla}\delta\pi)^2 + W(\delta\pi)^2$$

$V = V[Y; F, K, F', K', K'']$. Absence of ghosts, gradient instabilities and superluminal propagation:

$$Z' \equiv dZ/dY > 0\,, \qquad V > 0\,; \qquad V < \mathrm{e}^{2\pi_c} Z'$$

Can be arranged.

VIABLE FRAMEWORK

FOR BOUNCING UNIVERSE AND GENESIS

Other suggestive observational facts about density perturbations

(valid within certain error bars!)

- Primordial perturbations are Gaussian.

  Gaussianity = Wick theorem for correlation functions

  This suggests the origin: enhanced vacuum fluctuations of weakly coupled quatum field(s)

  NB: Linear evolution does not spoil Gaussianity.

  - Inflation does the job very well: fluctuations of all light fields get enhanced greatly due to fast expansion of the Universe.

    Including the field that dominates energy density (inflaton)
    $\Longrightarrow$ perturbations in energy density.

    Mukhanov, Chibisov'81; Hawking'82; Starobinsky'82;
    Guth, Pi'82; Bardeen et.al.'83

  - Enhancement of vacuum fluctuations is less automatic in alternative scenarios

Nearly flat power spectrum

$$\langle \zeta(\vec{k})\zeta(\vec{k}')\rangle = \frac{1}{4\pi k^3}\mathscr{P}(k)\delta(\vec{k}+\vec{k}')$$

$\mathscr{P}(k) =$ power spectrum, gives fluctuation in logarithmic interval of momenta,

$$\langle (\zeta(\vec{x}))^2\rangle = \int_0^\infty \frac{dk}{k}\,\mathscr{P}(k)$$

$$\mathscr{P} \propto k^{n_s-1}$$

Flat spectrum, $n_s = 1$

Harrison' 70; Zeldovich' 72

Small red tilt favored by observations, $n_s - 1 \approx -0.04$.

There must be some symmetry behind flatness of spectrum

- Inflation: symmetry of de Sitter space-time, $SO(4,1)$

$$ds^2 = dt^2 - \mathrm{e}^{2Ht} d\vec{x}^{\,2}$$

Symmetry: spatial dilatations supplemented by time translations

$$\vec{x} \to \lambda \vec{x}\,, \quad t \to t - \frac{1}{2H} \log \lambda$$

Inflation automatically generates nearly flat spectrum.

- Alternative: conformal symmetry $SO(4,2)$

Conformal group includes dilatations, $x^\mu \to \lambda x^\mu$.

$\Longrightarrow$ No scale, good chance for flatness of spectrum

First mentioned by Antoniadis, Mazur, Mottola' 97

Concrete models: V.R.' 09;

Creminelli, Nicolis, Trincherini' 10

What if our Universe started off from or passed through

an unstable conformal state

and then evolved to much less symmetric state we see today?

- Exploratory stage: toy models + general arguments so far.

General setting:

Hinterbichler, Khouri' 11

- Effectively Minkowski space-time
- Conformally invariant theory
- Field ρ of conformal weight $\Delta \neq 0$
- Instability
  of conformally invariant background $\rho = 0$

  Homogeneous classical solution

$$\rho_c(t) = \frac{\text{const}}{(t_* - t)^{\Delta}}$$

by conformal invariance.

NB: Spontaneous breaking of conformal symmetry:
$O(4,2) \to O(4,1)$

- Another scalar field θ of conformal weight 0.
- Kinetic term dictated by conformal invariance (modulo field rescaling)

$$L_\theta = \rho^{2/\Delta}(\partial_\mu\theta)^2$$

- Assume potential terms negligible $\Longrightarrow$ Lagrangian in rolling background

$$L_\theta = \frac{1}{(t_* - t)^2} \cdot (\partial_\mu\theta)^2$$

Exactly like scalar field minimally coupled to gravity in de Sitter space, with $t =$ conformal time, $a(t) = \text{const}/(t_* - t)$.

θ develops perturbations with flat power spectrum.

There are various ways to reprocess perturbations of field θ into density perturbations, e.g., at hot epoch. Density perturbations inherit shape of power spectrum and correlation properties from $\delta\theta$, plus possible additional non-Gaussianity.

Peculiarity: perturbations in rolling field.

V.R.' 09;
Libanov, V.R.' 10

- In long wavelength regime, $k \ll 1/(t_* - t)$, late times

  Red spectrum:

$$\langle \delta\rho^2 \rangle \propto \int \frac{d^3k}{k^5}$$

- Dictated by symmetry breaking pattern $SO(4,2) \to SO(4,1)$

- Interaction between modes $\delta\theta$ (precursors of density perturbations) and $\delta\rho$ yields potentially observable effects:
  - Non-Gaussianity
  - Statistical anisotropy

Can one tell?

More intricate properties of cosmological perturbations

Not detected yet.

- Primordial gravitational waves

Sizeable amplitude, (almost) flat power spectrum predicted by simplest (and hence most plausible) inflationary models

Starobinsky' 1979

but not alternatives to inflation

May make detectable imprint on CMB temperature anisotropy

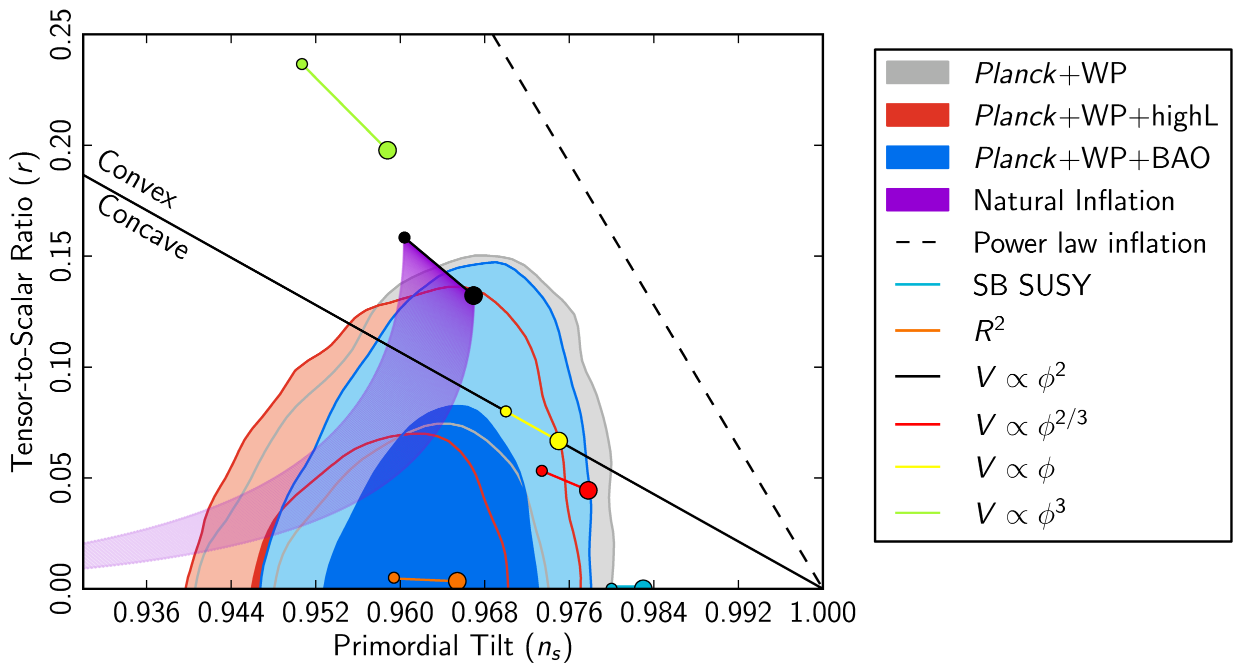
V.R., Sazhin, Veryaskin' 82;
Fabbri, Pollock' 83; ...

and especially on CMB polarization

Kamionkowski, Kosowsky, Stebbins' 96;
Seljak, Zaldarriaga' 96; ...

Smoking gun for inflation

Scalar tilt vs tensor power



Planck

NB:

$$r = \left(\frac{\text{amplitude of gravity waves}}{\text{amplitude of density perturbations}} \right)^2$$

Non-Gaussianity

- Very small in the simplest inflationary theories
- Sizeable in more contrived inflationary models and in alternatives to inflation. Often begins with bispectrum

$$\langle \frac{\delta\rho}{\rho}(\mathbf{k_1})\frac{\delta\rho}{\rho}(\mathbf{k_2})\frac{\delta\rho}{\rho}(\mathbf{k_3})\rangle = \delta(\mathbf{k_1}+\mathbf{k_2}+\mathbf{k_3})G(k_i^2,\mathbf{k_1k_2},\mathbf{k_1k_3})$$

  Shape of $G(k_i^2,\mathbf{k_1k_2},\mathbf{k_1k_3})$ different in different models $\Longrightarrow$ potential discriminator.

- Sometimes bispectrum vanishes, e.g., due to some symmetries: $\theta \to -\theta$ in conformal scenario. But trispectrum (connected 4-point function) may be measurable.
- Very specific shape of trispectrum in conformal models

Libanov, Mironov, V.R.' 10, 11

Statistical anisotropy

$$\mathscr{P}(\mathbf{k}) = \mathscr{P}_0(k)\left(1 + w_{ij}(k)\frac{k_i k_j}{k^2} + \dots\right)$$

- Anisotropy of the Universe at pre-hot stage
- Possible in inflation with strong vector fields (rather contrived)

Ackerman, Carroll, Wise' 07; Pullen, Kamionkowski' 07; Watanabe, Kanno, Soda' 09

- Natural in conformal models

Libanov, V.R.' 10; Libanov, Ramazanov, V.R.' 11

- Would show up in correlators

$$\langle a_{lm} a_{l'm'} \rangle \quad \text{with} \quad l' \neq l \quad \text{and/or} \quad m' \neq m$$

WMAP, Planck: bounds on anisotropy parameters at 1% level

Ramazanov, Rubtsov' 2013 and in progress

To summarize:

- Available data on cosmological perturbations (notably, CMB anisotropies) give confidence that the hot stage of the cosmological evolution was preceeded by some other epoch, at which these perturbations were generated.

- Inflation is consistent with all data. But there are competitors: the data may rather point towards (super)conformal beginning of the cosmological evolution.

More options:

Matter bounce, Finelli, Brandenberger' 01.

Negative exponential potential, Lehners et. al.' 07;
Buchbinder, Khouri, Ovrut' 07; Creminelli, Senatore' 07.

Lifshitz scalar, Mukohyama' 09

- Only very basic things are known for the time being.

Good chance for future

- Detection of B-mode (partity odd) of CMB polarization $\Longrightarrow$ effect of primordial gravity waves $\Longrightarrow$ simple inflation
  - Together with scalar and tensor tilts $\Longrightarrow$ properties of inflaton
- Non-trivial correlation properties of density perturbations (non-Gaussianity) $\Longrightarrow$ contrived inflation, or something entirely different.
  - Shape of non-Gaussianity $\Longrightarrow$ choice between various alternatives
- Statistical anisotropy $\Longrightarrow$ anisotropic pre-hot epoch.
  - Shape of statistical anisotropy $\Longrightarrow$ specific anisotropic model

At the eve of new physics

LHC $\Longleftrightarrow$ Planck,
dedicated CMB polarization experiments,
data and theoretical understanding
of structure formation ...

Good chance to learn
what preceeded the hot Big Bang epoch

Barring the possibility that Nature is dull

NB: Conformal symmetry has long been discussed in the context of Quantum Field Theory and particle physics.

Particularly important in the context of supersymmetry: many interesting superconformal theories.

Large and powerful symmetry behind, e.g., adS/CFT correspondence and a number of other QFT phenomena

Maldacena' 97

It may well be that ultimate theory of Nature is (super)conformal

What if our Universe started off from a conformal state
and then evolved to much less symmetric state we see today?

Exploratory stage: toy models so far.

A toy model:

V.R.' 09;
Libanov, V.R.' 10

Conformal complex scalar field ϕ with negative quartic potential (to mimic instability of conformally invariant state)

$$S = \int \sqrt{-g} \left[g^{\mu\nu} \partial_\mu \phi^* \partial_\nu \phi + \frac{R}{6}|\phi|^2 - (-h^2|\phi|^4) \right]$$

Conformal symmetry in 4 dimensions. Global symmetry $U(1)$ (to mimic other symmetries of conformally invariant theory).

Homogeneous and isotropic cosmological background

$$ds^2 = a^2(\eta)[d\eta^2 - d\vec{x}^2]$$

Evolution of the scalar field is basically independent of $a(\eta)$, because of conformal symmetry.
NB: behaviour of scale factor may be arbitrary.
E.g., contraction or start-up.

Homogeneous isotropic evolution:

$$\phi_c(\eta) = \frac{1}{ha(\eta)(\eta_* - \eta)}$$

(in conformal time). Dictated by conformal invariance.
$\eta_* =$ integration constant, end of roll time.

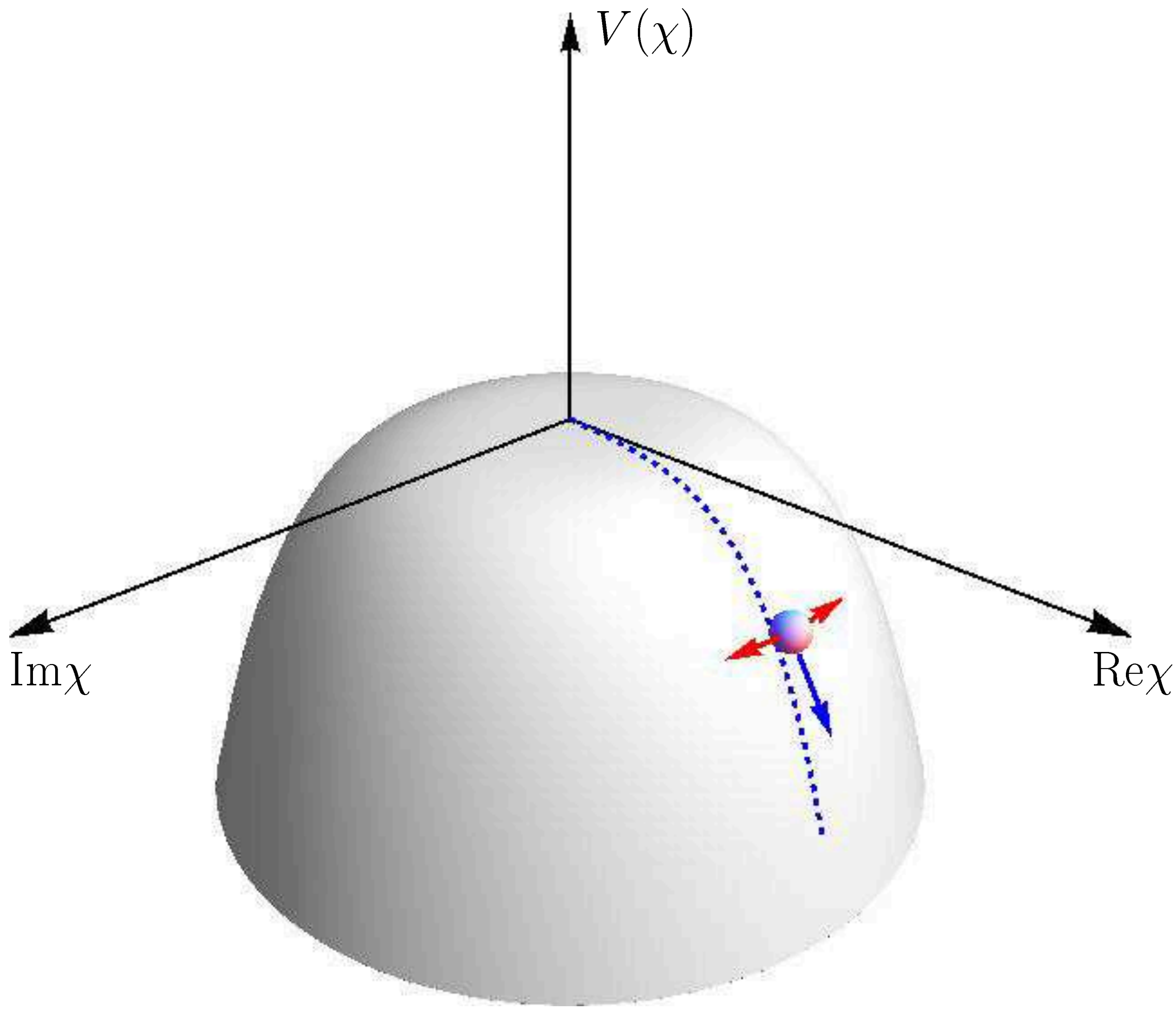
Vacuum fluctuations of the phase Arg ϕ get enhanced, and freeze out at late times.

They become Gaussian random field with flat spectrum,

$$\langle \delta\theta^2 \rangle = \frac{h^2}{2(2\pi)^3} \int \frac{d^3k}{k^3}$$

This is automatic consequence of global $U(1)$ and conformal symmetry

Conformal evolution

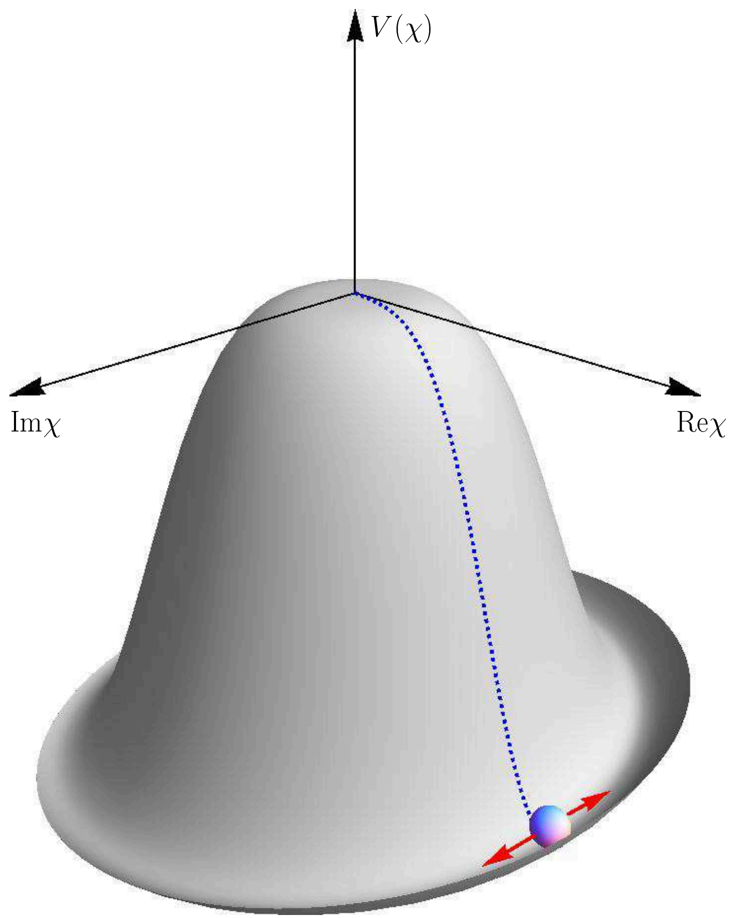


Later on, conformal invariance is broken, and perturbations of the phase get reprocessed into density perturbations.

This can happen in a number of ways

Reprocessing in inflationary context: Linde, Mukhanov' 97;
Enqvist, Sloth' 01; Moroi, Takahasi' 01; Lyth, Wands' 01;
Dvali, Gruzinov, Zaldarriaga' 03; Kofman' 03

One way: θ = pseudo-Nambu-Goldstone field. Generically, it ends up at a slope of its potential



Anisotropy in conformal model

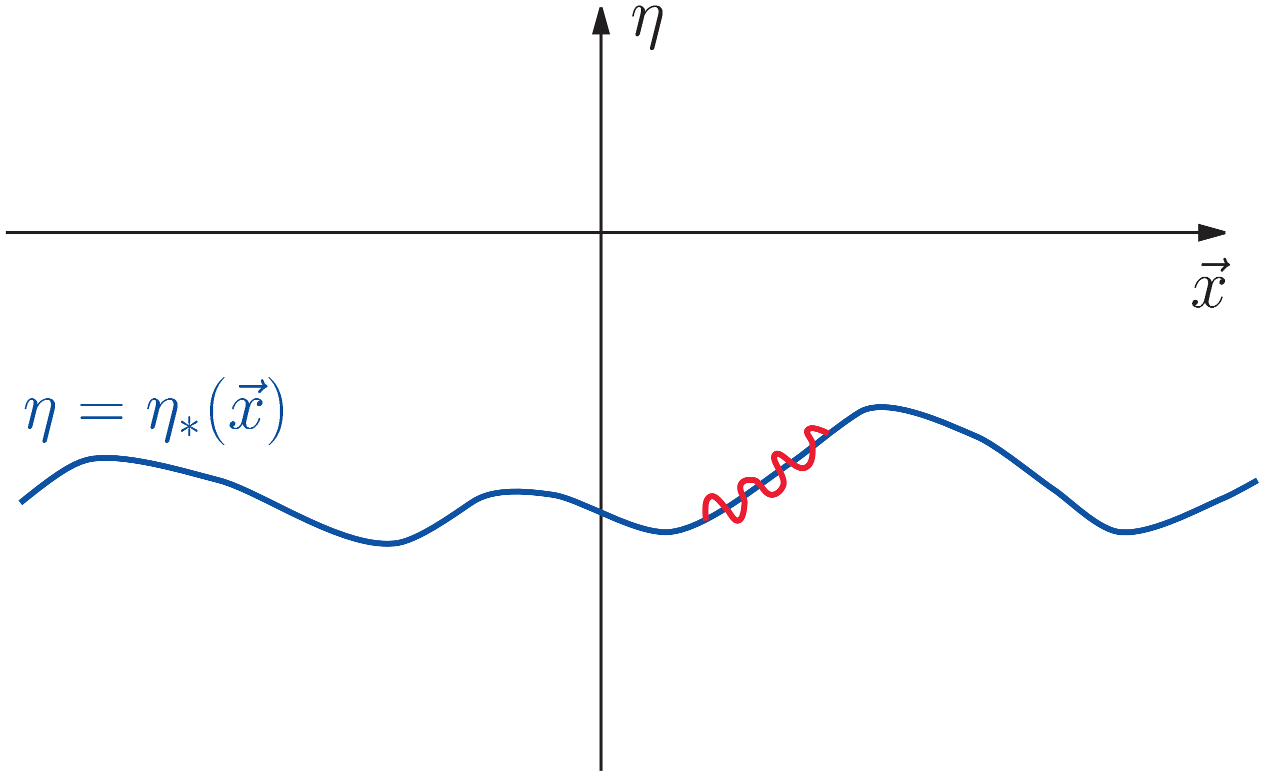
Perturbations of radial field $|\phi| \Longrightarrow$ inhomogeneous background ϕ_c $\Longrightarrow$ inhomogeneous end-of-roll time:

$$\phi_c(\eta, \mathbf{x}) = \frac{1}{ha(\eta)(\eta_*(\mathbf{x}) - \eta)}$$

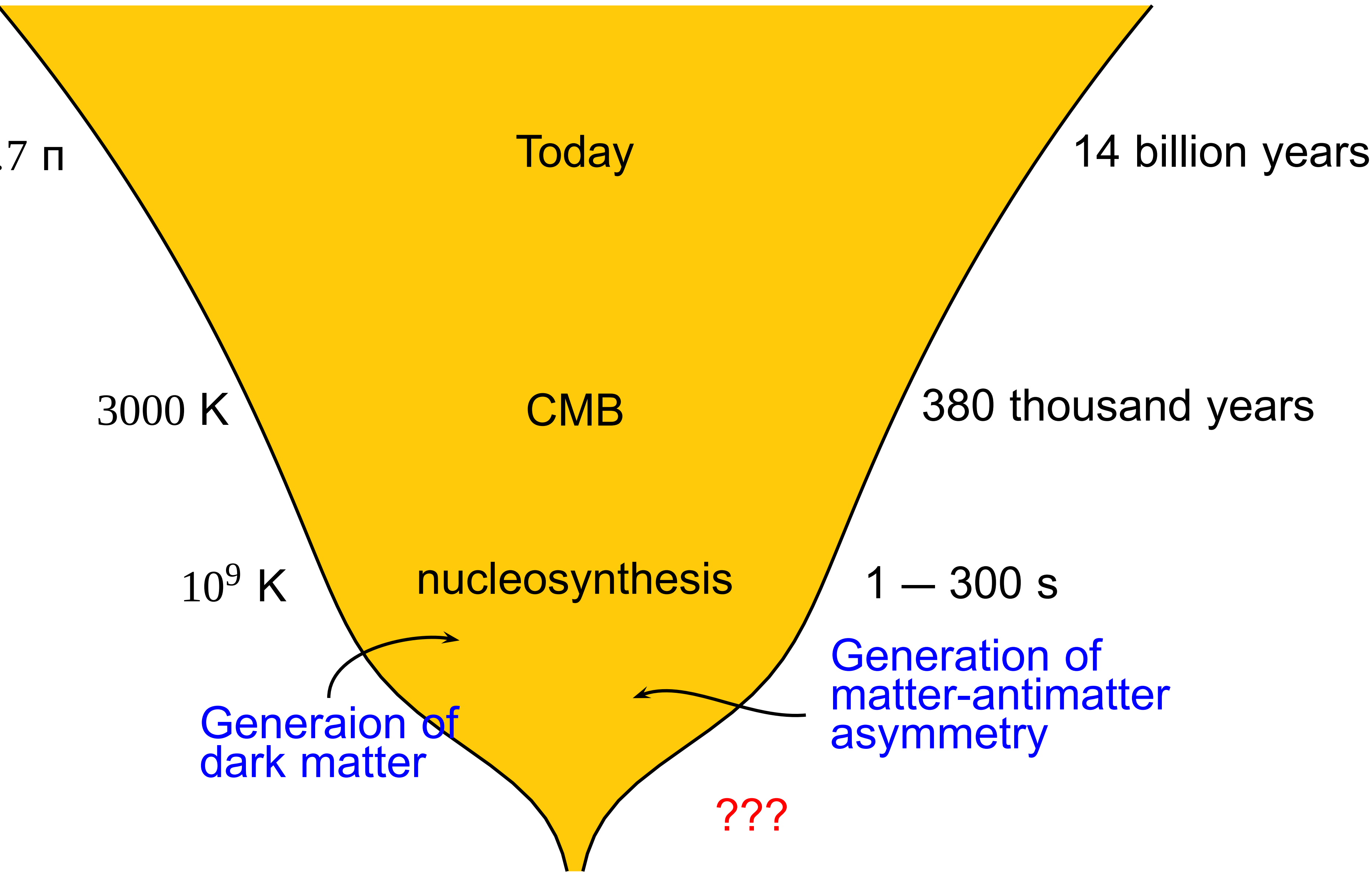
Large wavelength perturbations of $\eta_*(\mathbf{x}) \Longrightarrow$ keep gradient only,

$$\eta_*(\mathbf{x}) = \text{const} + \mathbf{v}\mathbf{x}$$

$\Longrightarrow$ frame of homogeneous $\phi_c \neq$ cosmic frame $\Longrightarrow$ anisotropy.



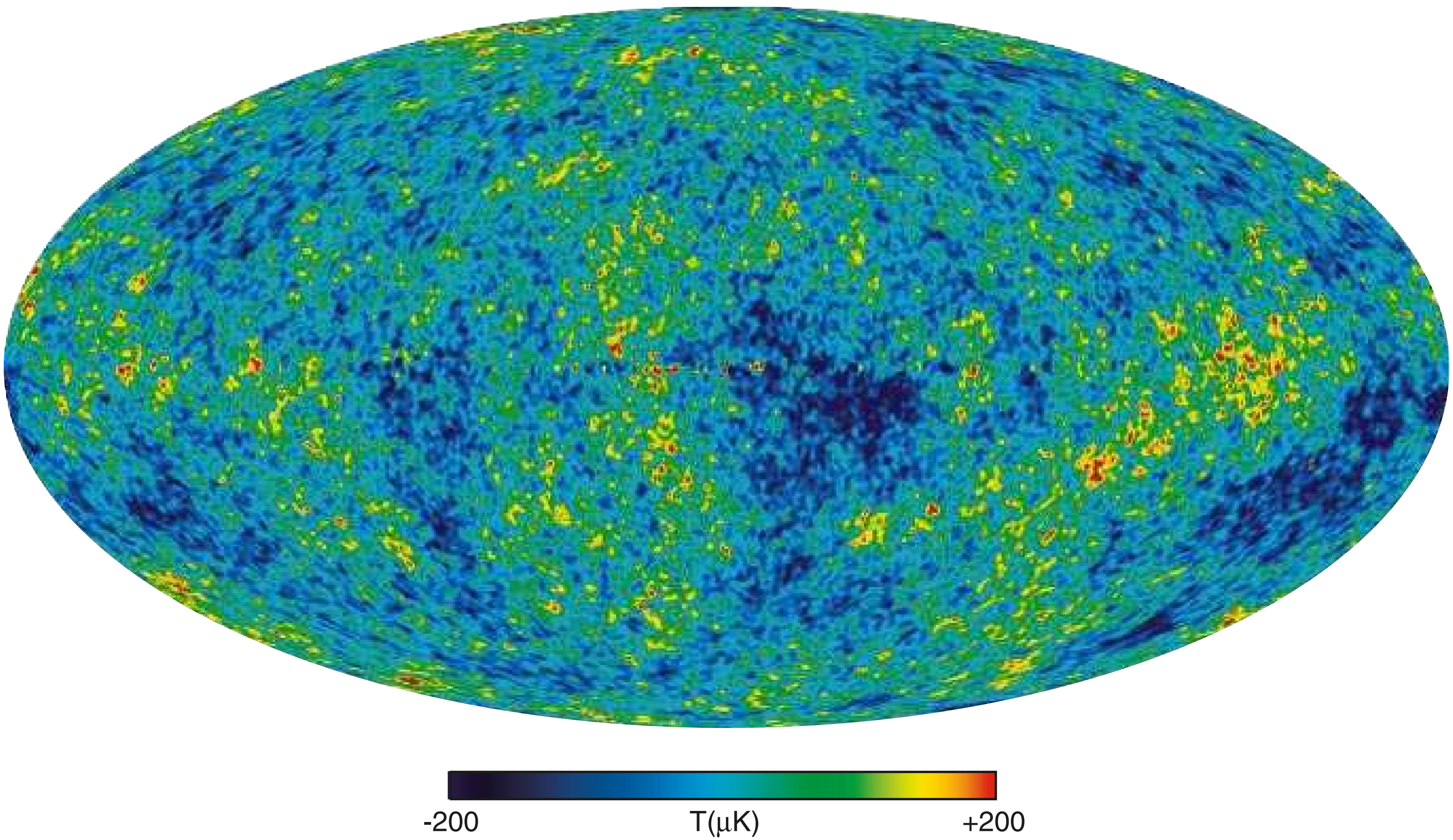
Reference frame of conformal rolling is boosted with respect to cosmic frame $\Longrightarrow$ anisotropy due to relative velocity of the two frames



.7 п
Today
14 billion years
3000 K
CMB
380 thousand years
10^9 K
nucleosynthesis
1 — 300 s
Generation of
matter-antimatter
asymmetry
Generaion of
dark matter
???

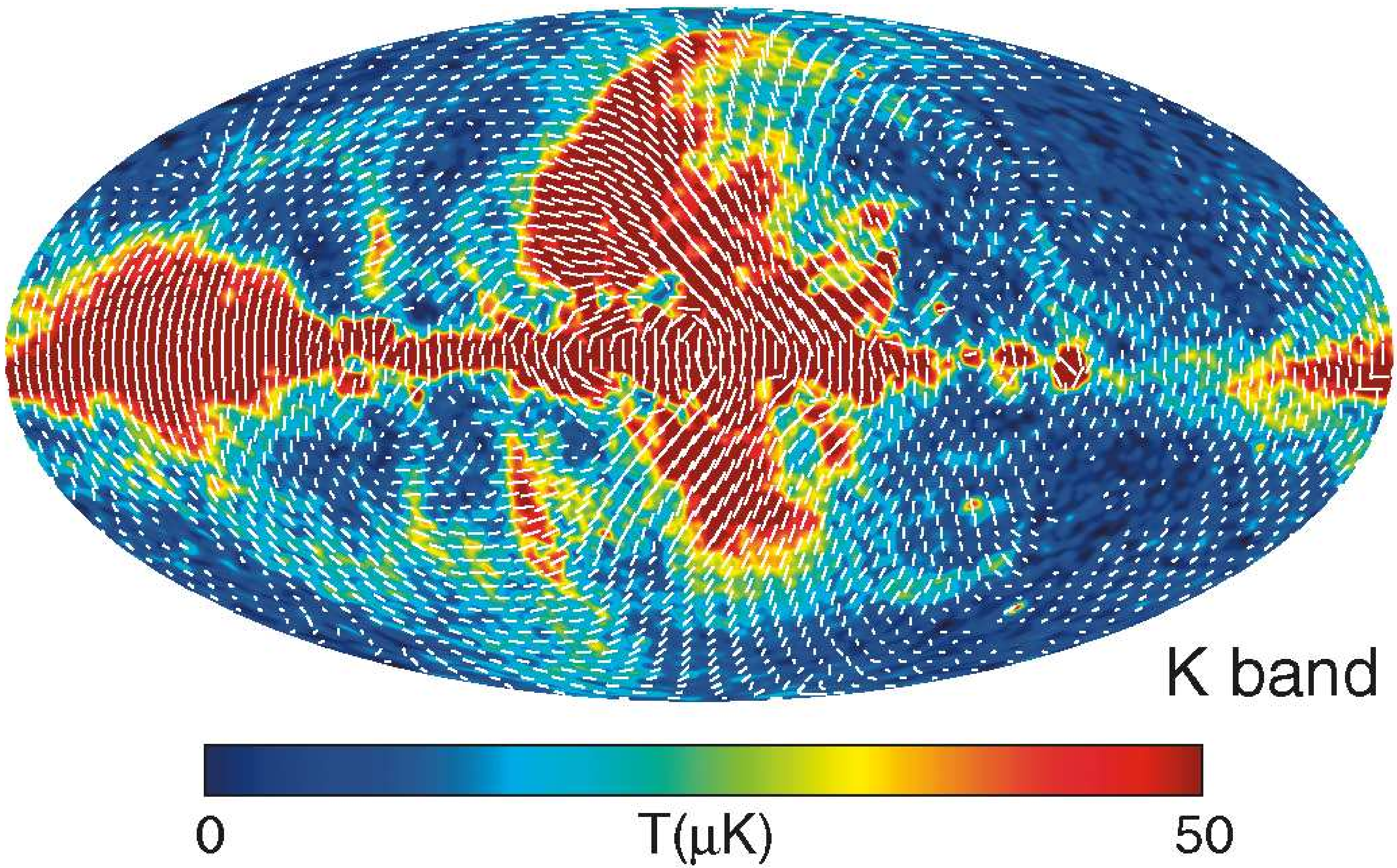
CMB temperature anisotropy

$$T = 2.725^{\circ}K, \quad \frac{\delta T}{T} \sim 10^{-4} - 10^{-5}$$

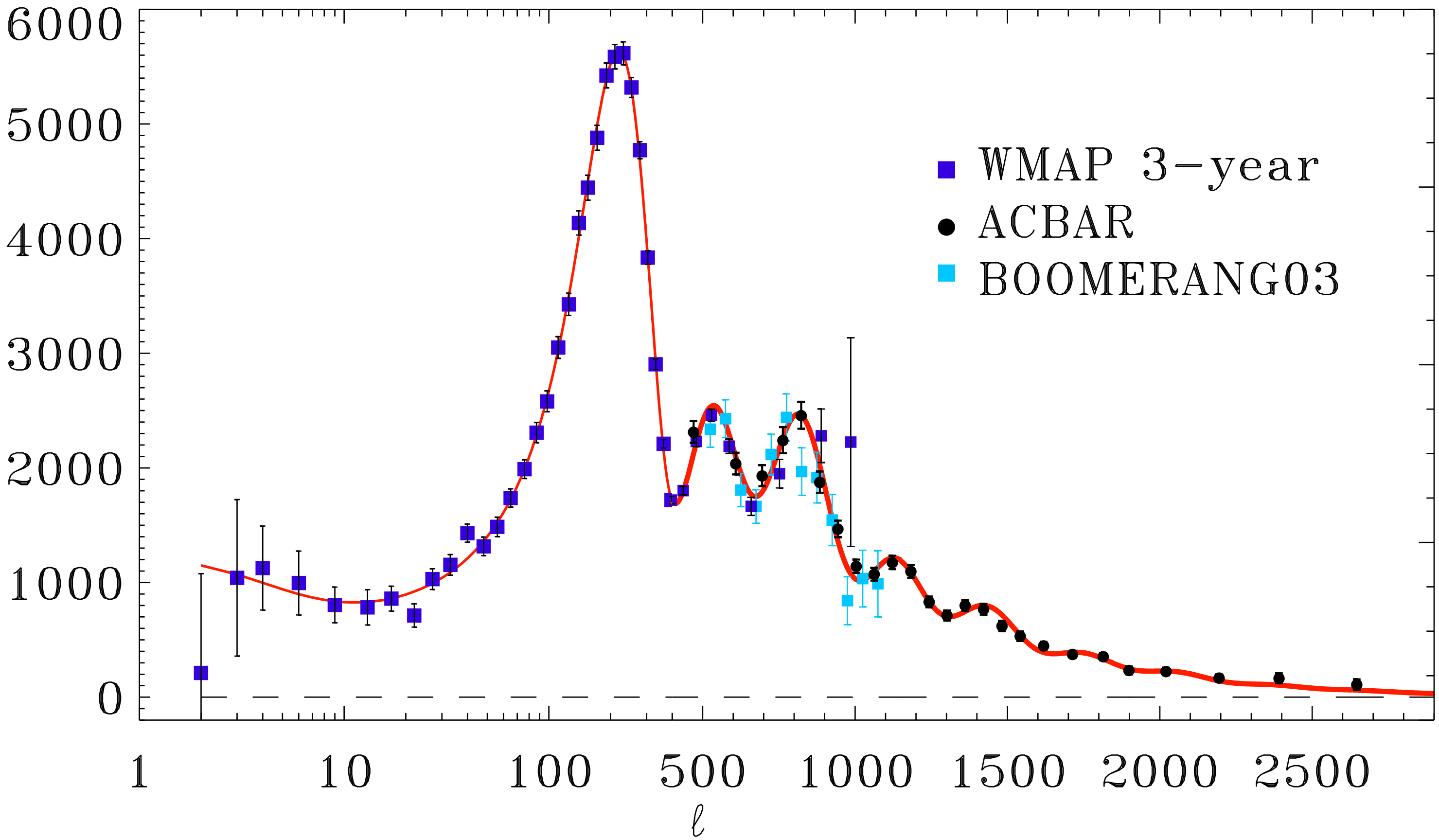


WMAP

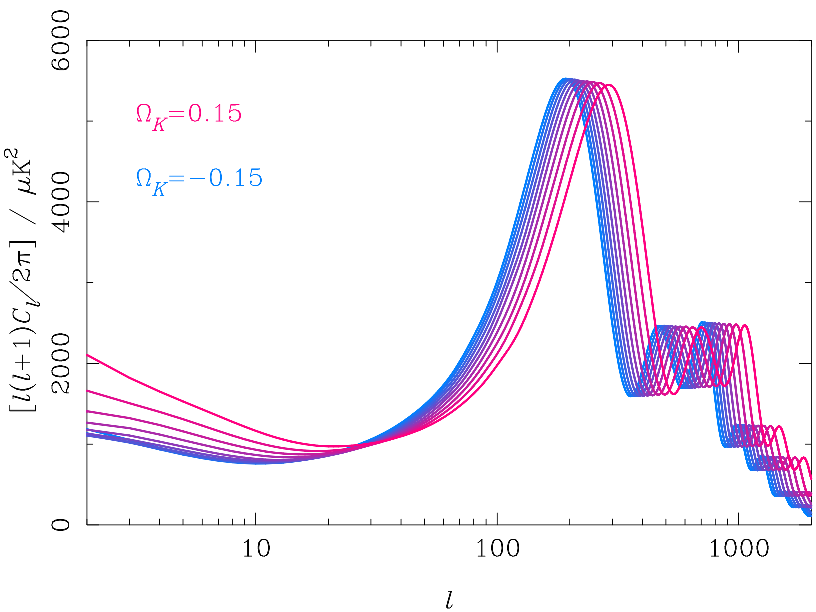
CMB polarization map

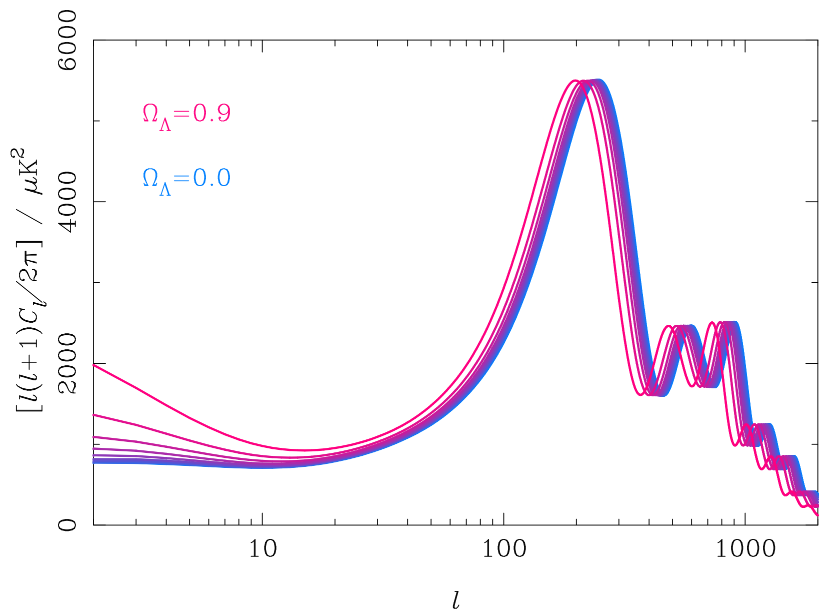


CMB anisotropy spectrum

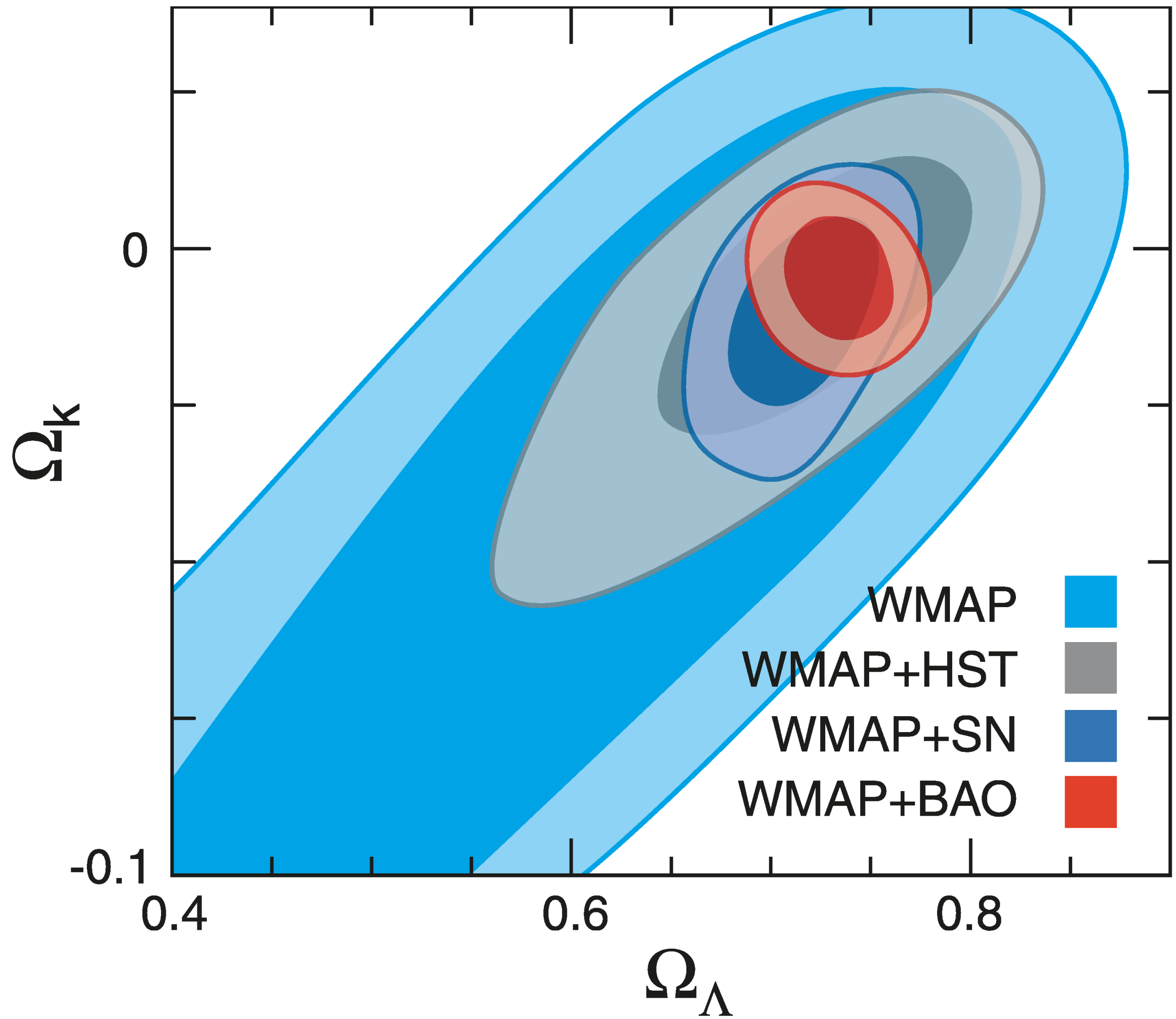


Effect of curvature (left) and Λ

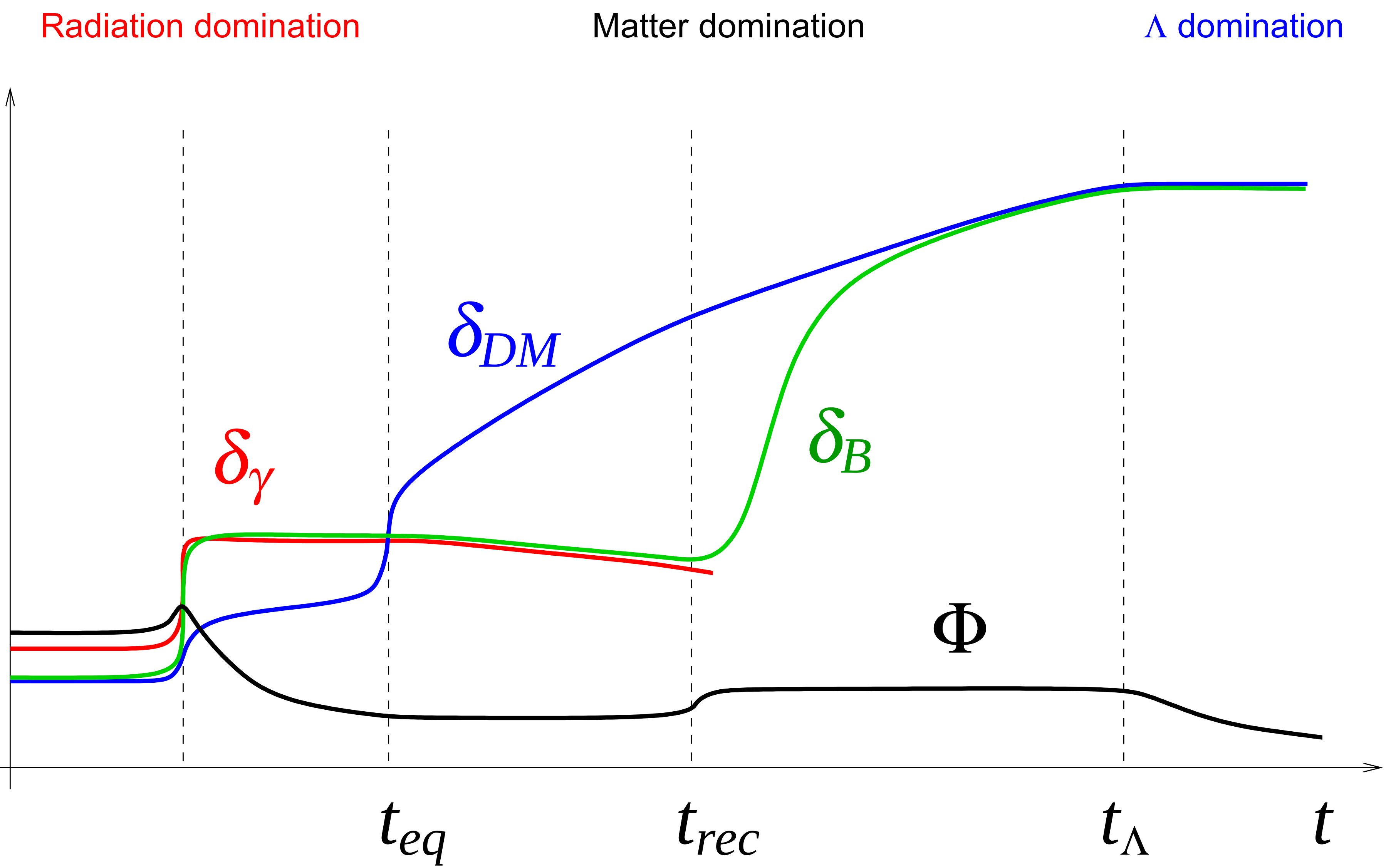




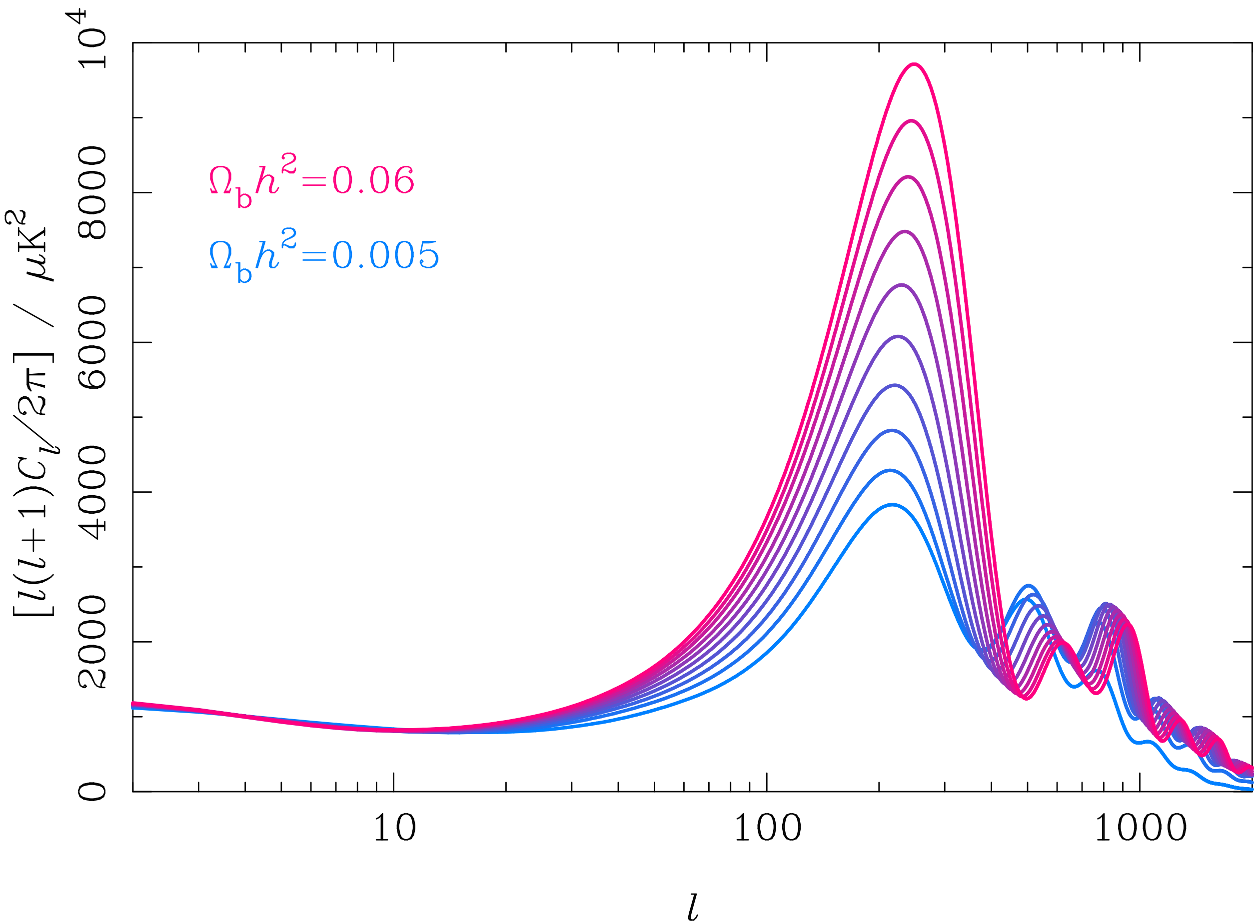
Allowed curvature and Λ



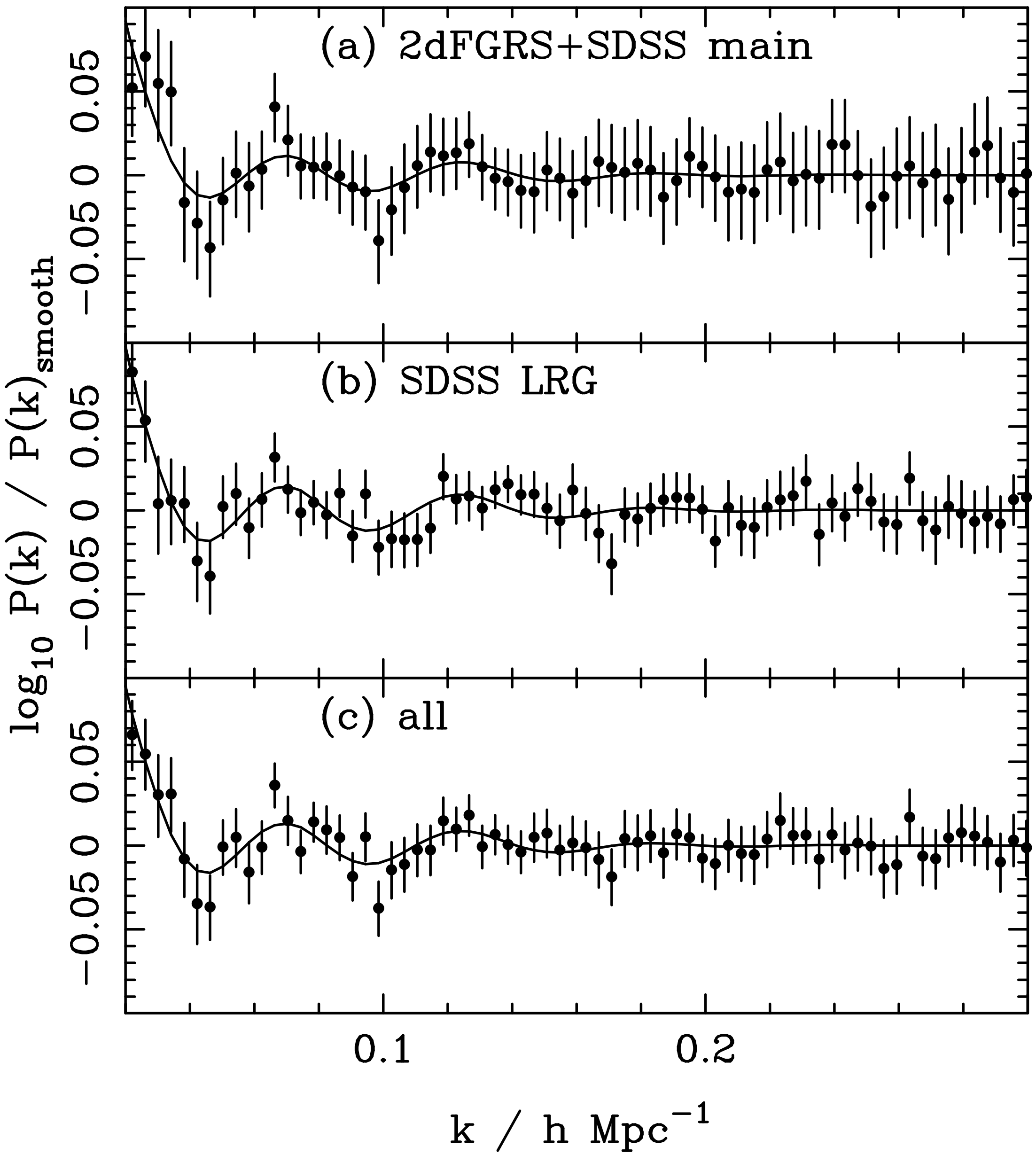
Growth of perturbations (linear regime)



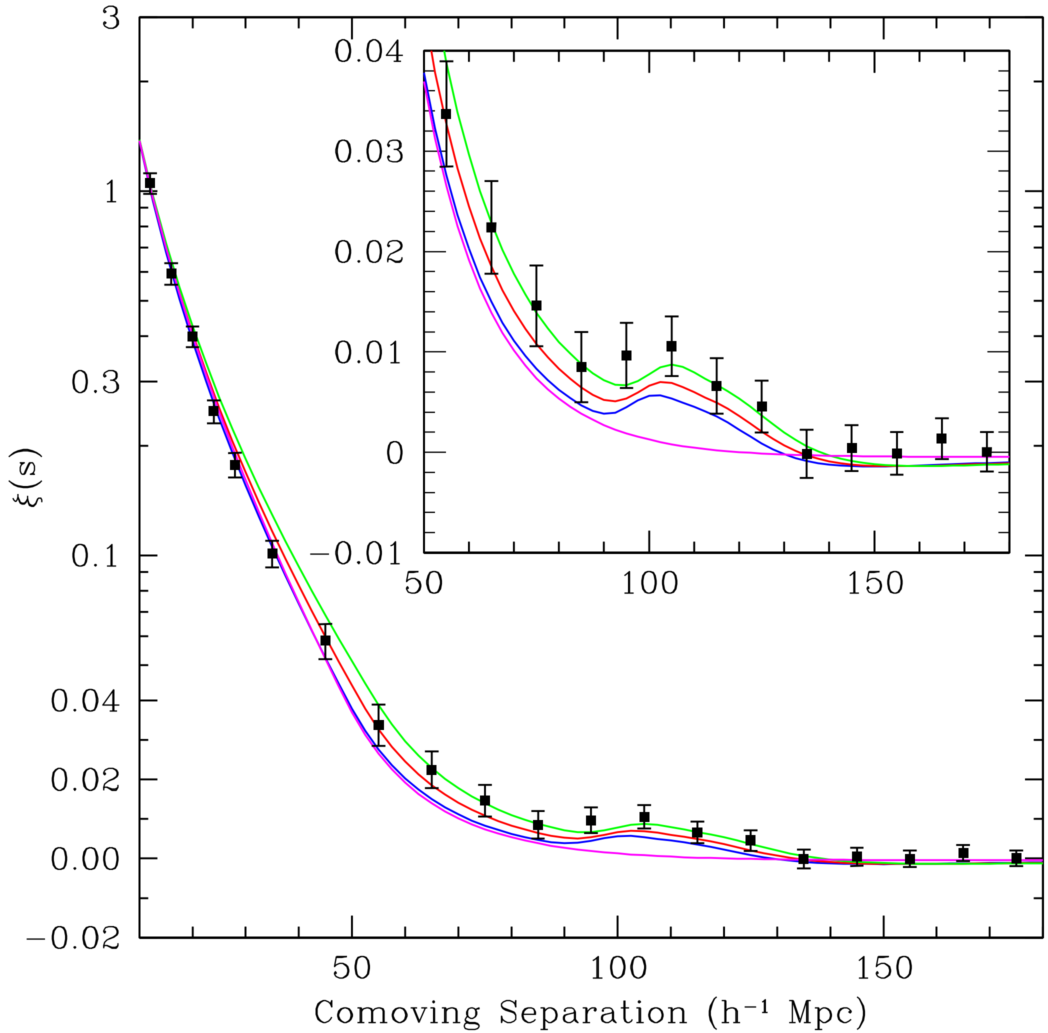
Effect of baryons



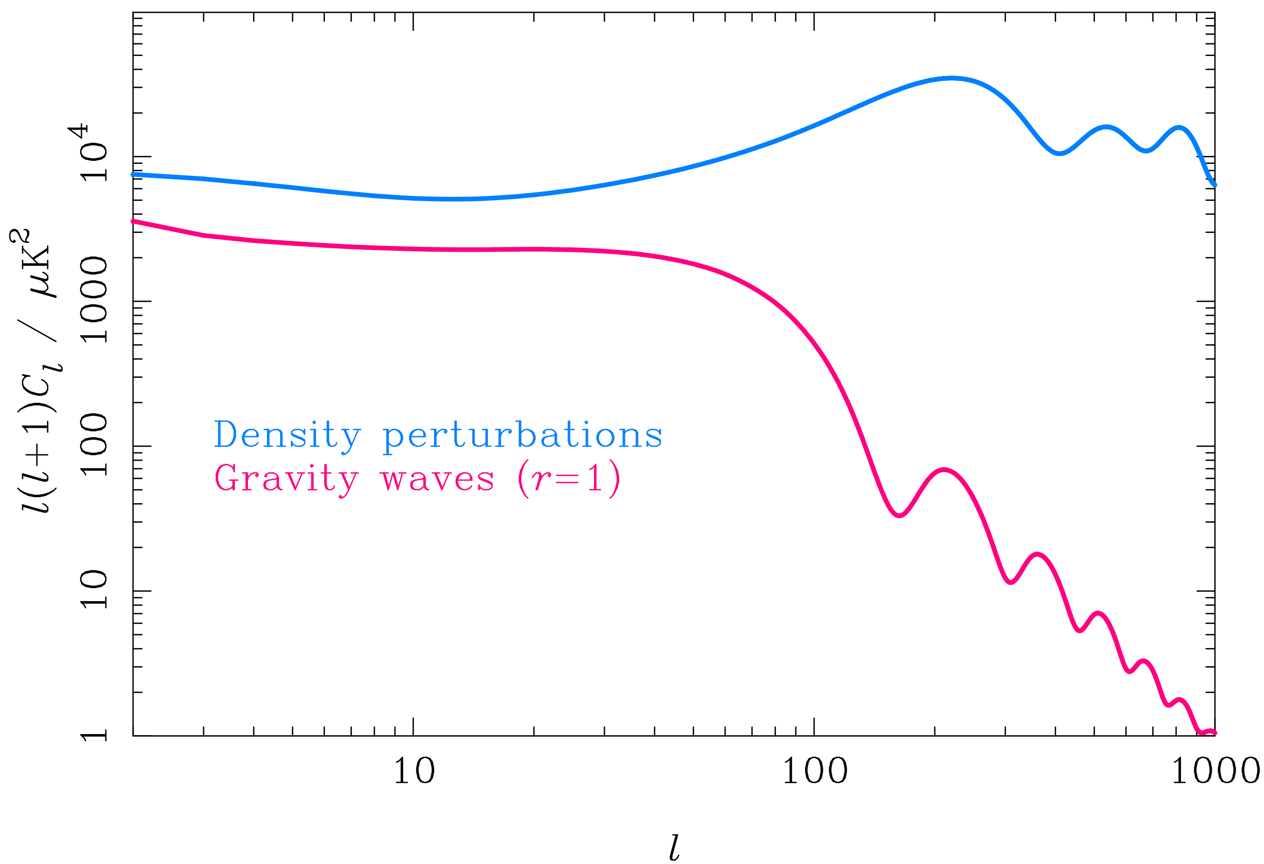
BAO in power spectrum



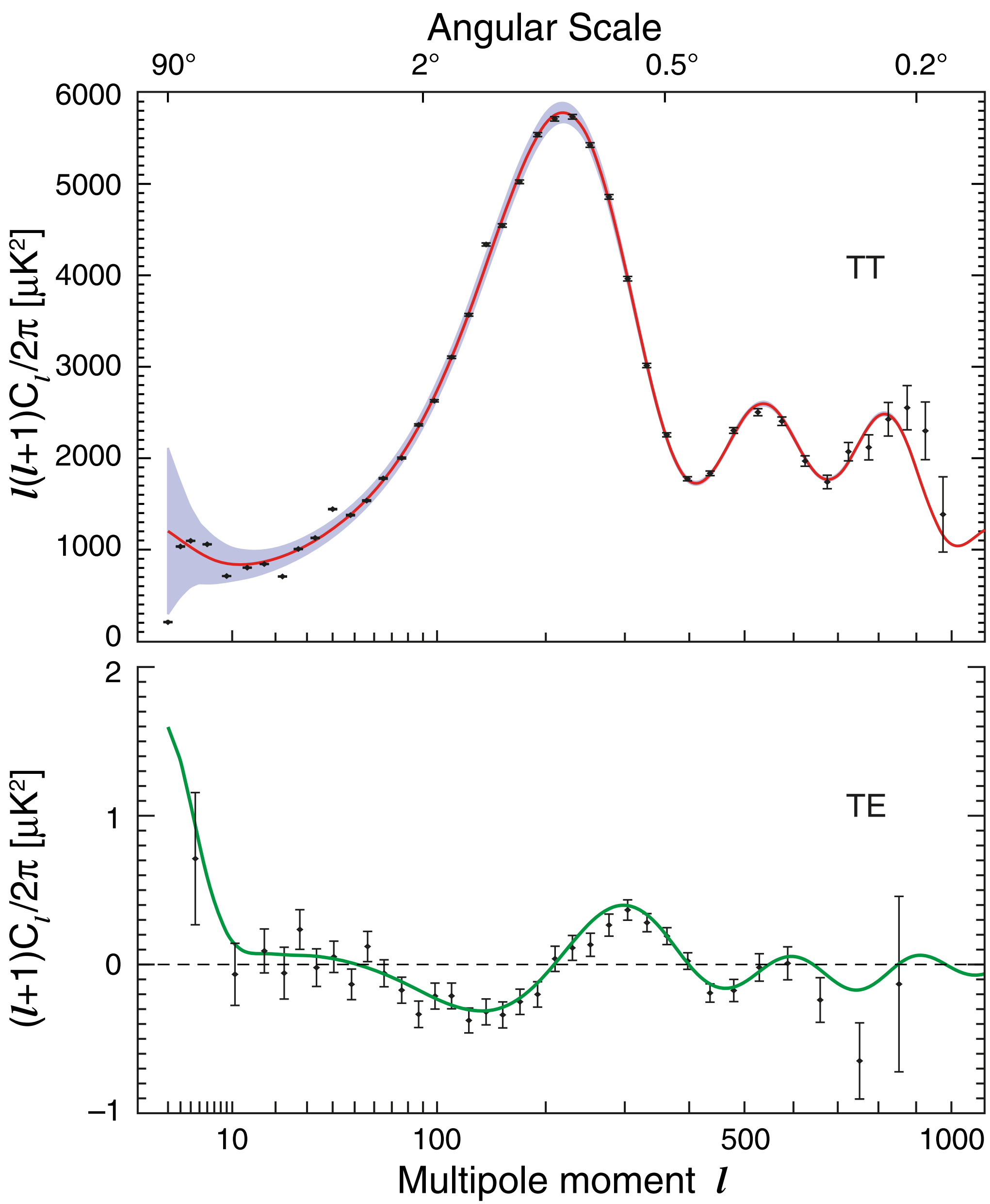
BAO in correlation function



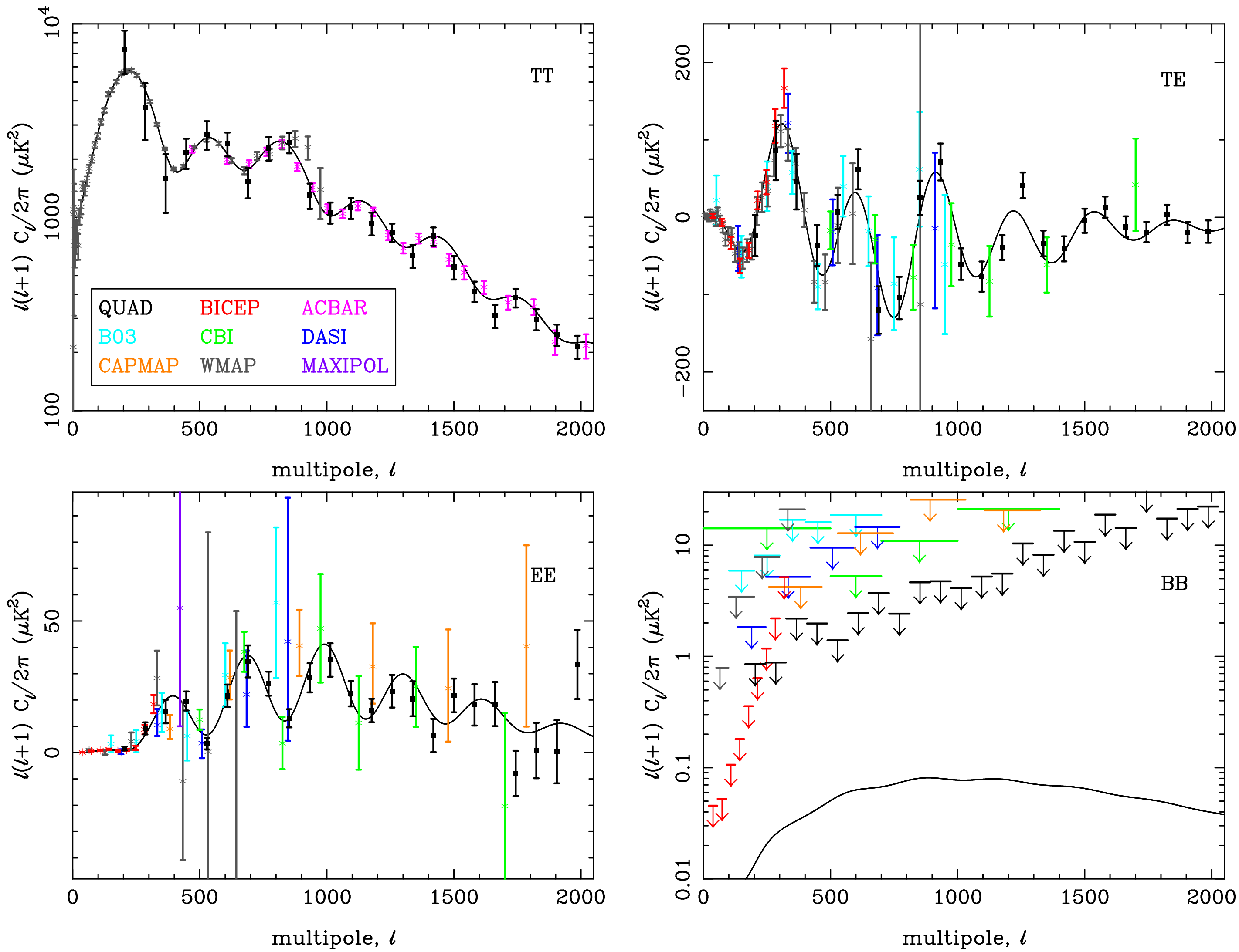
Effect of gravity waves



CMB temperature and polarization



CMB temperature and polarization



Effect of gravity waves on polarization (right)