The Reionized Inflationary Universe

Observational status and prospects after WMAP

Olivier Doré
Princeton University

Outline

Observational Cosmology:

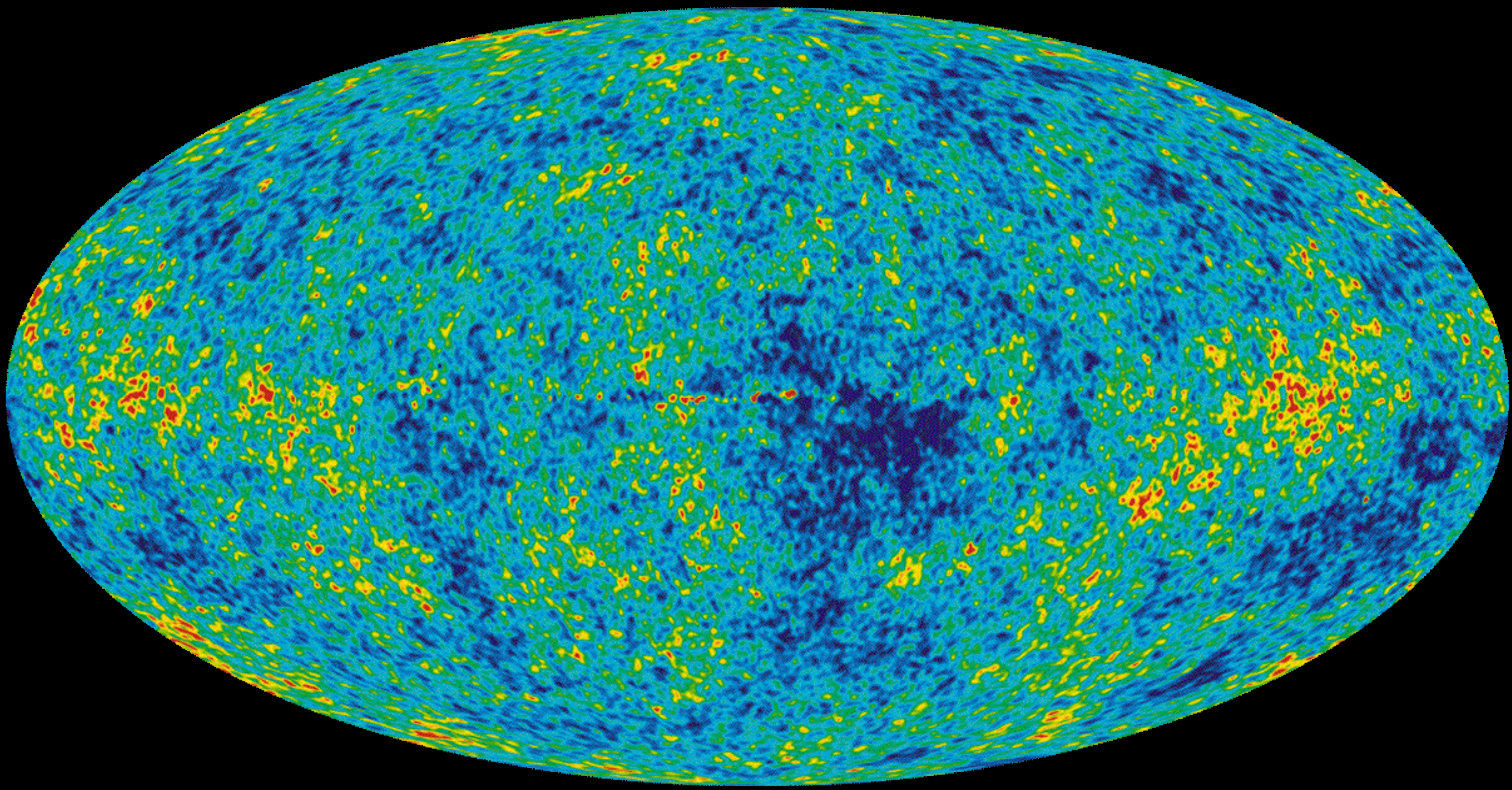
Concordance and successes of the ΛCDM model after WMAP

The Inflationary observables and evidences of an inflationary phase in the early Universe

How can we challenge the Inflation paradigm ?

Why do we need to figure out reionization ?

What has WMAP done for us ?



- WMAP improved over COBE by a factor of 45 in sensitivity and 33 in angular resolution
- Color codes temperature (intensity) : here fluctuations ± 100 μK
- Temperature traces the gravitational potential then
- The statistical analysis of this map yields detailed cosmological information

Confronting those sky maps with theoretical expectations

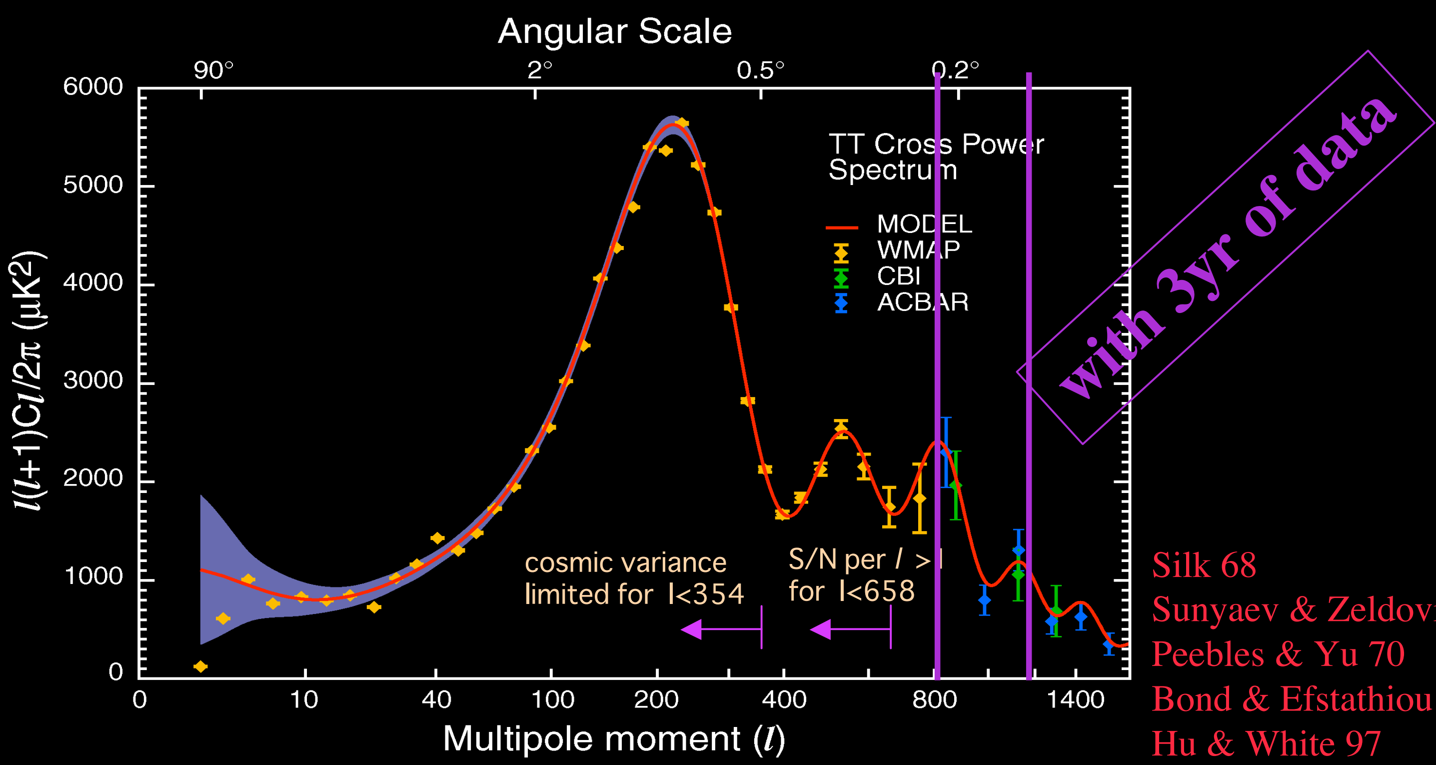
- It is both observationally and theoretically sound to consider the CMB temperature fluctuations as a Gaussian random field, so that a_{lm}'s are Gaussian random variables

$$T(\hat{n}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{n})$$

- Thus sufficient to consider the Angular Power Spectrum

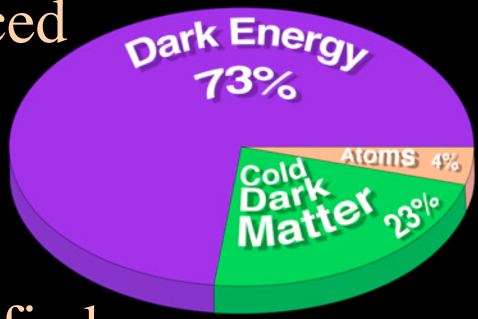
$$C_\ell = \frac{1}{2\ell+1} \sum_m a_{\ell m} a^*_{\ell m}$$

- Physics in the linear regime, well described by a 3000K photon-baryon fluid adiabatically oscillating in the pre-existing dark matter potential well



Silk 68
Sunyaev & Zeldovich 70
Peebles & Yu 70
Bond & Efstathiou 87
Hu & White 97

Cosmology now have a standard model



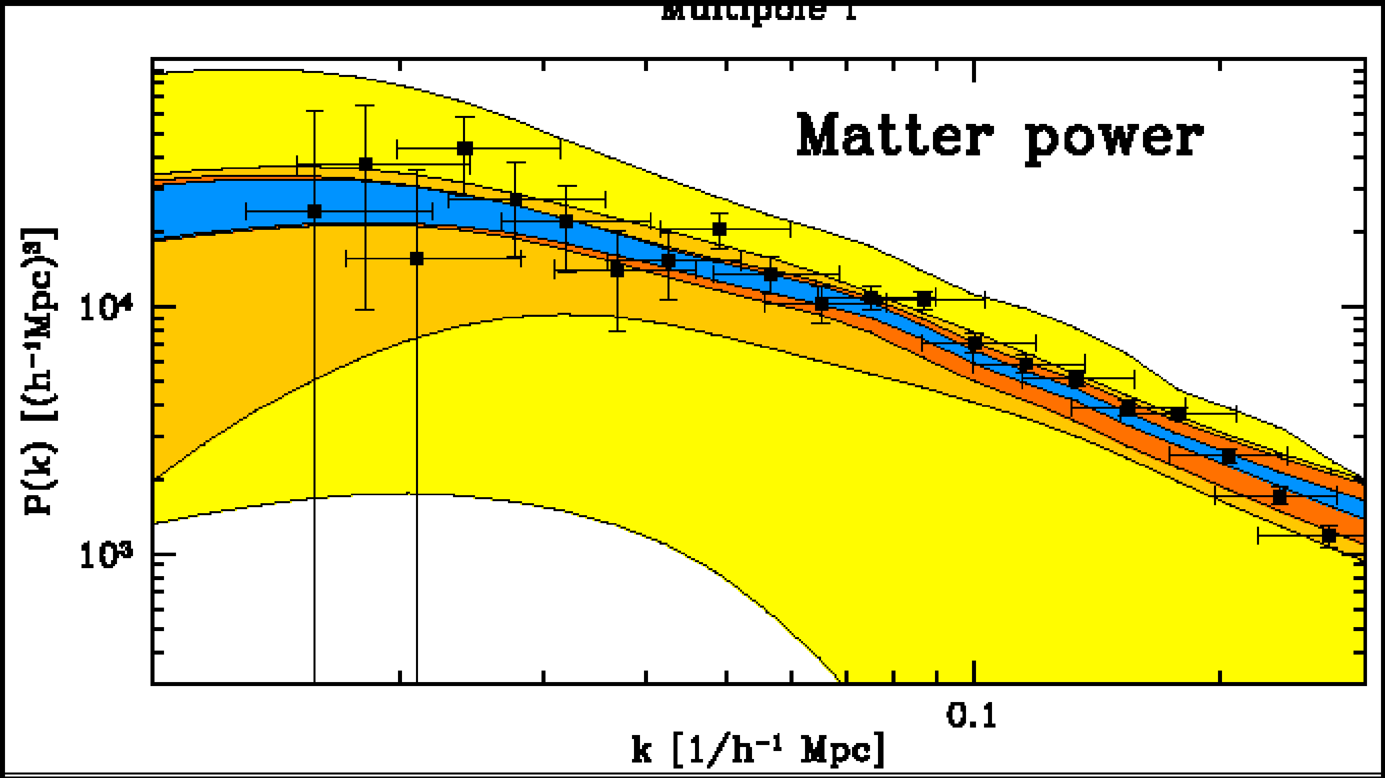
- Only 6 parameters fit 1342 data points (reduced χ^2/dof~1.066):

Flat ΛCDM model with Ω_b, Ω_Λ, h, n_s, τ, A_s

- Simplest inflation model predictions are satisfied
  - Flat universe
  - Gaussianity
  - Power Spectrum spectral index nearly scale-invariant
  - Initial Adiabatic perturbations
- Neutrino mass < 0.23 eV
- In agreement with a wealth of other astrophysical observations involving different physics at different time
- Joint use help breaking some important parameter degeneracies

CMB observations allow to predict Universe Today

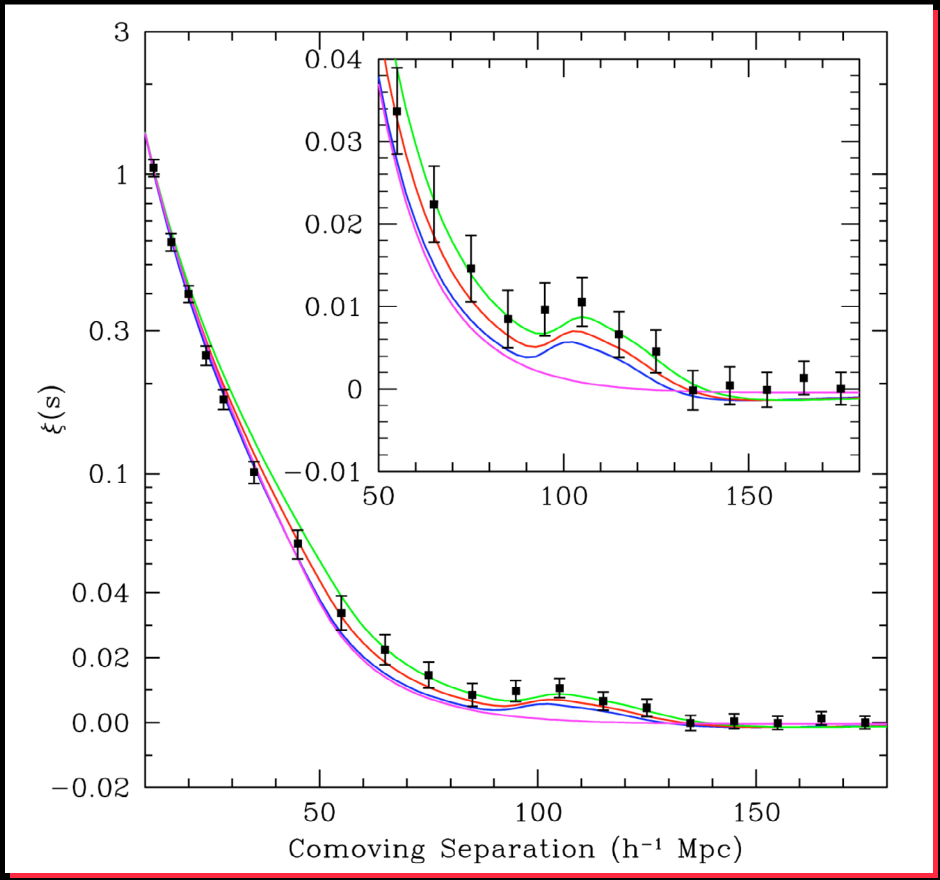
SDSS 3D power spectra as measured with ~200 000 galaxies
Tegmark et al. 03



From outside in
- WMAP only
- + w=-1
- + Ω_k=r=α=0
- + SDSS

Concordance…
- Different physics
- Different scales
- Different times (*z* =1000 *vs* 1)

Following the baryonic oscillations through time



SDSS
~46 000 gal. over 4000 sq. deg
Eisenstein et al. 05

- Baryon are important enough so that their imprint on the P(k) is measurable at low z
- Median populations here at z~0.25 ($0.16 < z < 0.47$)
- Detection at 3.4σ
- This is a smoking gun for CDM and subdominant baryons
- Geometrical test of Dark energy

Where are we now ?

Solid phenomenological success

The current phenomenological success means :

1. *The initial primordial spectrum of inhomogeneities is scale invariant and predominantly adiabatic*
2. *We have a successful GR based theory of cosmological linear perturbations to evolve them*
3. *We have a correct effective description of the main components even if we do not know what they are*

This success also rise new questions:

- *Physics that we don't know* (String theory, quantum cosmology, physics beyond the standard model…)
  - How did the universe begin? Are we really leaving in a inflationary universe ?
  - What is the dark energy?
  - What is the dark matter?
- *Physics that we don't know how to calculate* (Non-linear hydro, star formation…)
  - First stars and how did the Universe get reionized ?
  - Galaxy formation

Inflationary Observables

- Scalar modes
  - Initial power spectrum
  - Power spectrum features?
  - Higher Moments, *i.e.* "non-gaussianity"

$$k^3 \langle \Phi\Phi \rangle \propto k^{n_s - 1}$$

$$n_s(k) - 1 = n_s(k_0) - 1 + \frac{dn_s}{d\ln k}\ln(k_0)$$

↑ "*running*"

→ CMB (Temperature + Polarization) + LSS

- Tensor modes

→ CMB (B mode Polarization) only

- Vector modes
  - Strings from hybrid models?

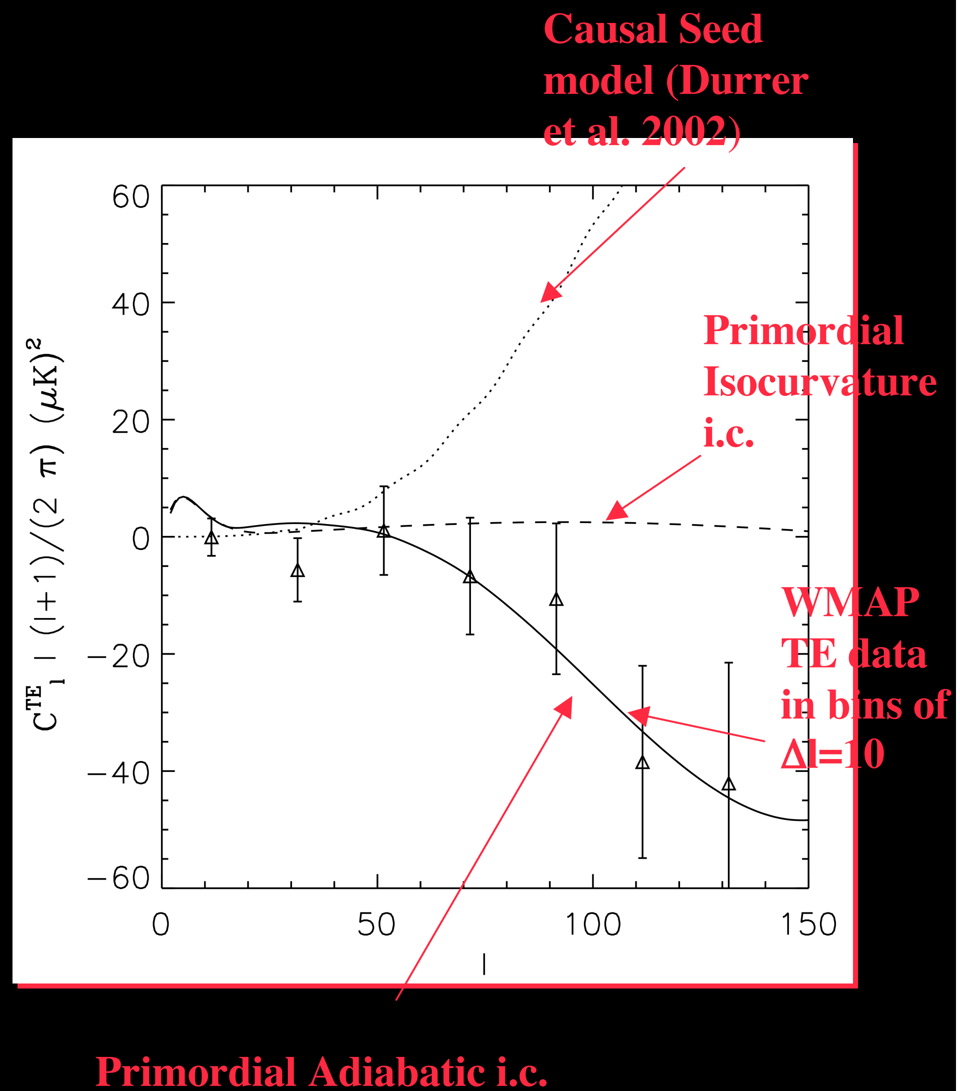
→ CMB (Temperature + Polarization)

WMAP Supports Single Field Inflationary Models

- Flat universe: $\Omega_{tot} = 1.02 \pm 0.02$
- Gaussianity: $-58 < f_{NL} < 134$
- Power Spectrum spectral index nearly scale-invariant:

  $n_s = 0.99 \pm 0.04$ (*WMAP* only)
- Adiabatic initial conditions
- Super-horizon fluctuations

  (TE anticorrelations)
- No evidence for entropy perturbations between CDM and photons (no evidence for multi-field inflation)



Spergel et al. 03

Relating the observables to the Inflaton potential

- The shape of the scalar field potential, $V(\phi)$, determines the observables.
- We use three parameters to characterize the shape:
  - ε : "slope" of potential, $(V'/V)^2$
  - η : "curvature" of potential, V''/V
  - ξ : "jerk" of potential, $(V'/V)(V'''/V)$
- These allows to define the relevant **observables** and their **consistency relations**

$$n_S = 1 - 6\varepsilon + 2\eta$$

$$r = 16\varepsilon$$

$$\frac{dn_s}{d\ln k} = -2\xi + 16\varepsilon\eta - 24\varepsilon^2$$

"running"

$$r = \frac{8}{3}(1 - n_s) + \frac{16}{3}\eta$$

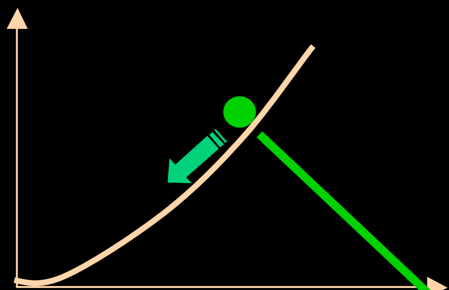
$$\frac{dn_s}{d\ln k} + 2\xi = -\frac{2}{3}\left[(1 - n_s)^2 - 4\eta^2\right]$$

r fixes the amplitude of the gravitational wave production at the end of inflation

Testing inflation mostly consists in exploring these consistency relations

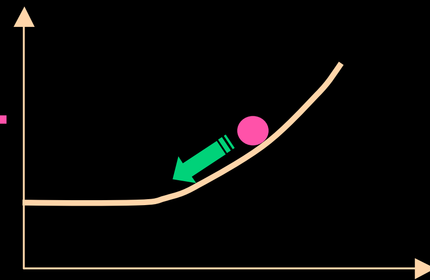
Starting to test single field inflation various potentials

Kinney et al. 02, Peiris et al. 03

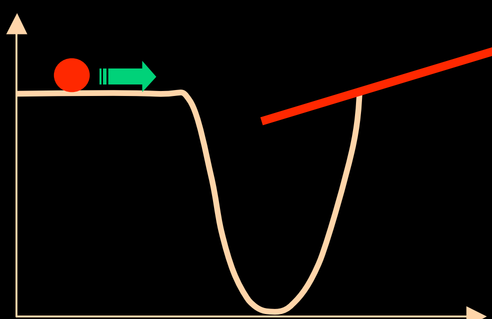


- Small positive curvature
- Chaotic inflation or Extended Inflation, (Linde 83 and Lu & Steinhardt 89)

Red tilt (n_s<1, largel r and tinyrunning)

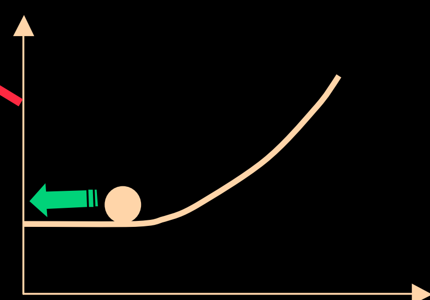


- Intermediate positive curvature
- BLue tilt (n_s>)1, largel r and small running



- Negative curvature
- Spontaneous symmetry breaking potential (e.g. new inflation, Albrecht & Steinhardt 81)

Red tilt (n_s<1, small r and running)



- Large positive curvature
- Hybrid inflation (Linde 83)
- Blue tilt (n_s>1), tiny r and running)

- r<0.9 (no priors)

=> Energy scale of inflation

$V^{1/4} < 3.3 \text{ X } 10^{16}$ GeV (95% CL)

- Exclude simple $\lambda\phi^4$ model at 3σ

Inflation and Non-Gaussianity

- Level of gaussianity is quite well constrained by inflation theory with a non linear coupling parameter $$\Phi = \Phi_L + f_{NL}(\Phi_L^2 - \bar{\Phi}_L^2)$$ where Φ is gravitational potential

- We expect f_{NL}~10^{-2}-10^{-1} (Maldacena 03) (for single field inflation) (0<f(k)<5/6) $$f_{NL} = \frac{5}{12}(1 - n_s + f(k)(1 - n_t))$$

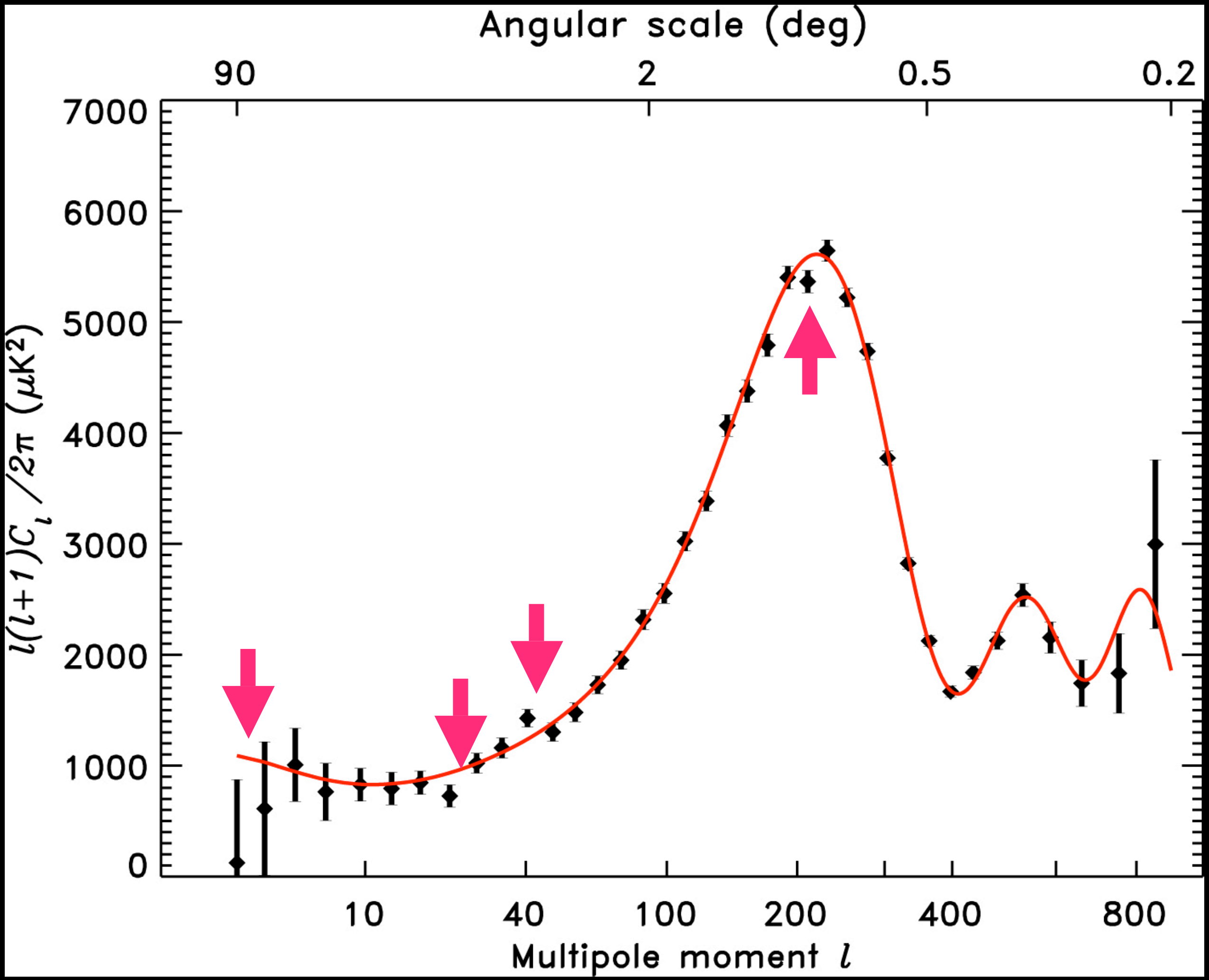
- Current best limit from WMAP alone using bispectrum or Minkowski functionals are $-58 < f_{NL} < 134$ (95%)

- Worth noting that is by nature a delicate measurements since the maps ARE non-gaussian because of point sources, foregrounds and inhomogeneous noise

- Although the inflation theory predictions are somewhat clear, going beyond that is a theoretical no-man's land (except for topology type studies)

- Note that some "hybrid model" predict also the production of cosmic strings that should imprint a NG signature

Are some WMAP outliers another signatures of Inflation?



Reduced χ^2 for TT only 1.09

Some questions to ask first

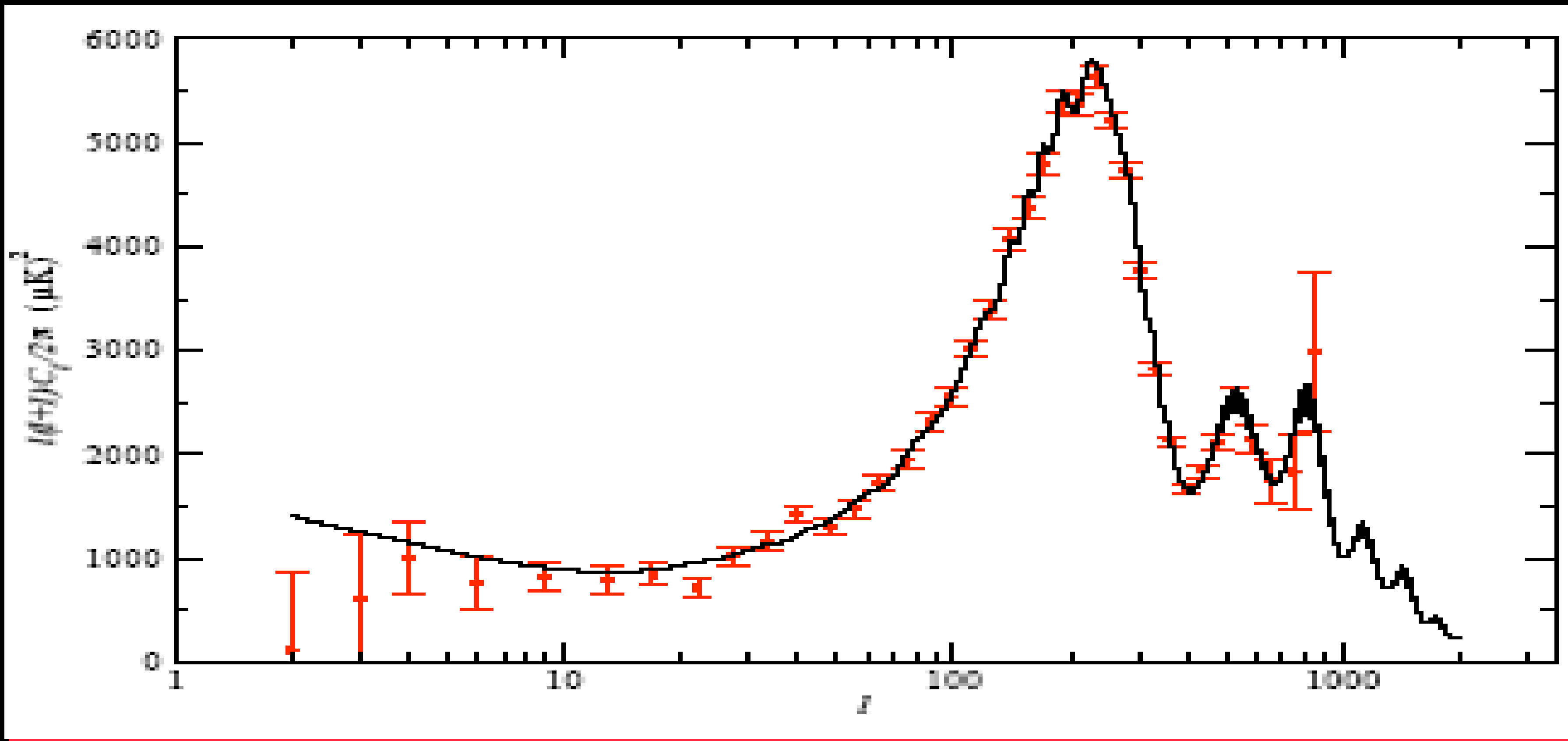
- Is the signal real ?
  - Various systematic effects: beams, foregrounds, etc.
- Are the statistics right ?
  - An underestimation of the Fisher matrix, which is a particular form of the 4pt function could account for this χ^2
  - Underestimated known terms (lensing, pt sources)
  - Could also be some particular form of non due to some new physics that creates some 4pt contribution without violating the 3pt limits, *e.g.* with a potential like

$$\Phi(\vec{x}) = \phi(\vec{x})\left(1 + g_{NL}\psi(\vec{x})\right)$$

(analogous to the Komatsu et al. 03, f_{nl})

  - It is thus also worth to probe this kind of NG

A specific signature of Trans-Planckians ?



Martin & Ringeval 03 and Okamoto and Lim 03 fit toy trans-Planckian model to spectrum $\Delta\chi^2 = 16$ for 3(?) parameters and $H/M_c < 6.6\times10^{-3}$

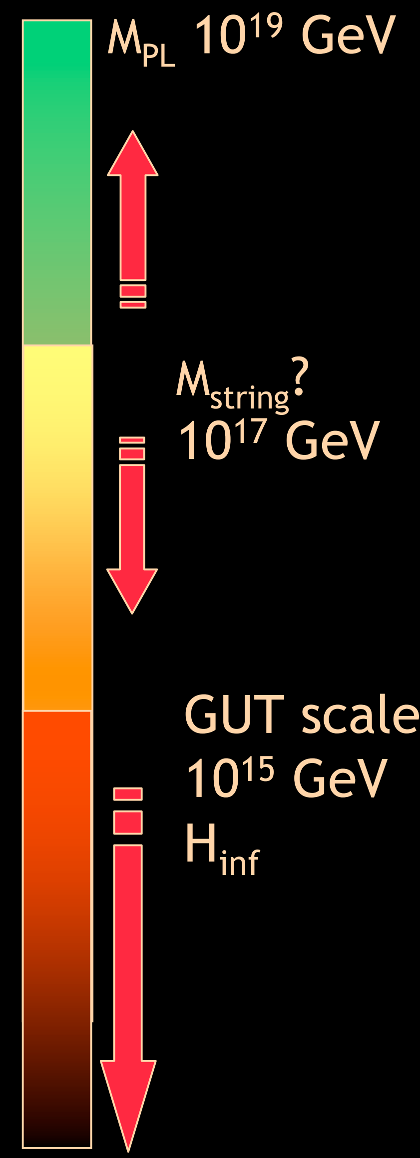
Hardly significant

(see also *e.g.* Easther et al. 03, Greene et al. 05 for more theoretical arguments)

Are TP effects observable even in principle?

Dimensional Analysis

- Assume a fundamental mass scale M
- Quantum Gravity/Planck scale - 10^{19} GeV
- String Scale up to two orders of magnitude lower? ~ 10^{17} GeV
- Inflationary scale ~ 10^{15} GeV
- Dimensionless combination: (H/M)
- Impact of fundamental scale ~ $(H/M)^p$
- Key question: is p=1 or p=2?
- Effects on the power spectrum are proportional to $(H/M)^p$, so at most a 1% effect
- Note that Martin & Ringeval have an upper limit of H/M $<10^{-3}$ in their model



How well can we measure Power Spectra?

The accuracy achievable can simply be written as

$$\frac{\delta P}{P} = \frac{1}{\sqrt{N_{modes}}}$$

Measuring the power spectrum with the CMB

$$N_\ell = \sum_l \frac{(2\ell+1)C_\ell}{C_\ell + n_\ell}$$

WMAP (1 yr): $l_{max} = 300$

WMAP (6 yr): $l_{max} = 600$

PLANCK : $l_{max} = 1500$

IDEAL : $l_{max} = 2000$

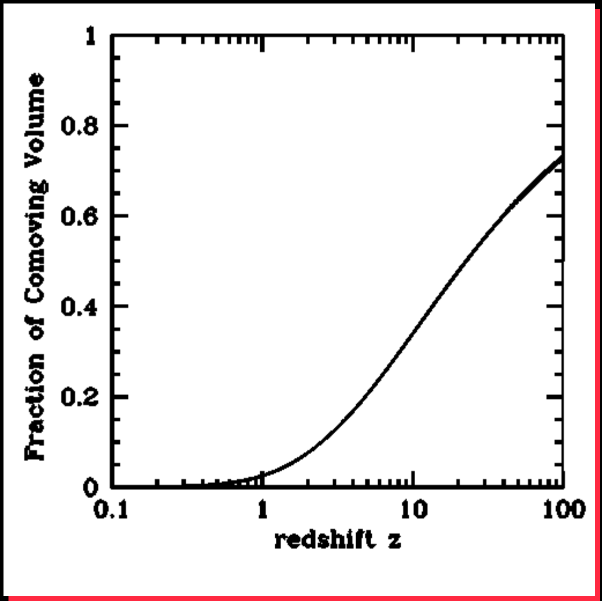
Gives about 10^{-2} for WMAP today and about $\sim 10^{-3}$ for WMAP/Planck in the future. Limited by the 2D nature of the signal

Measuring the power spectrum with the LSS

$$N_k = \int_0^{k_{max}} \frac{k^2 dk\, P(k)}{P(k) + \frac{V}{N_{gal}}}$$

- k_{max} chosen to be at the non-linear scale
- 3D mode counting
- V = $(13000)^3$ Mpc^3 v(z) ~ 10^{13} v(z) Mpc^3

$$v(z < z_0) = \frac{4\pi}{3}(\Delta\eta)^3 \propto \left(1 - \frac{1}{\sqrt{1+z}}\right)^3$$



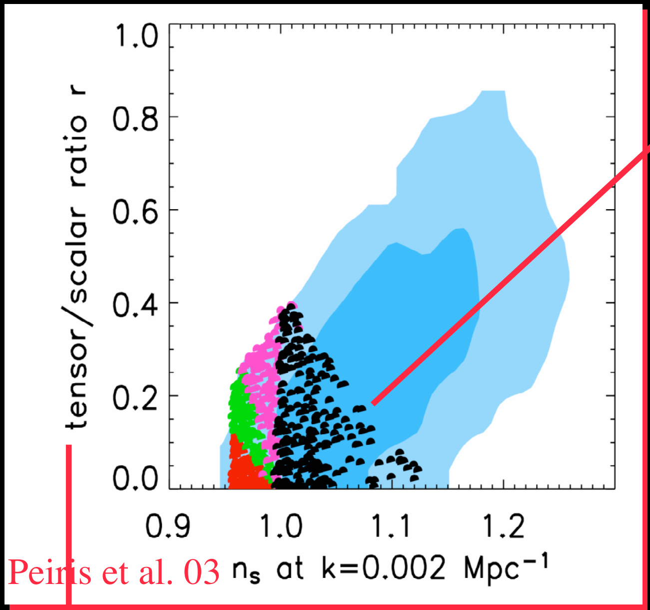
e.g. SDSS volume (z=0.2, 10% of the sky)

~ 10^8 $(\mathrm{Mpc})^3$

Power Spectrum prospect summary

- Today: 10^{-2}
- Soon (WMAP/Planck) : 10^{-3}
- Planned Galaxy Surveys (KAOS, LSST, Pan-Starr): 10^{-4}
- Future Galaxy Surveys (21 cm survey up to z~30) : 10^{-5}
- Theoretical Bound: 10^{-6}
- So in principle TP effects as we “understand” them now might be probed in a not so far future, ignoring all the galaxy evolution related complications...
- We need to know what to look for !

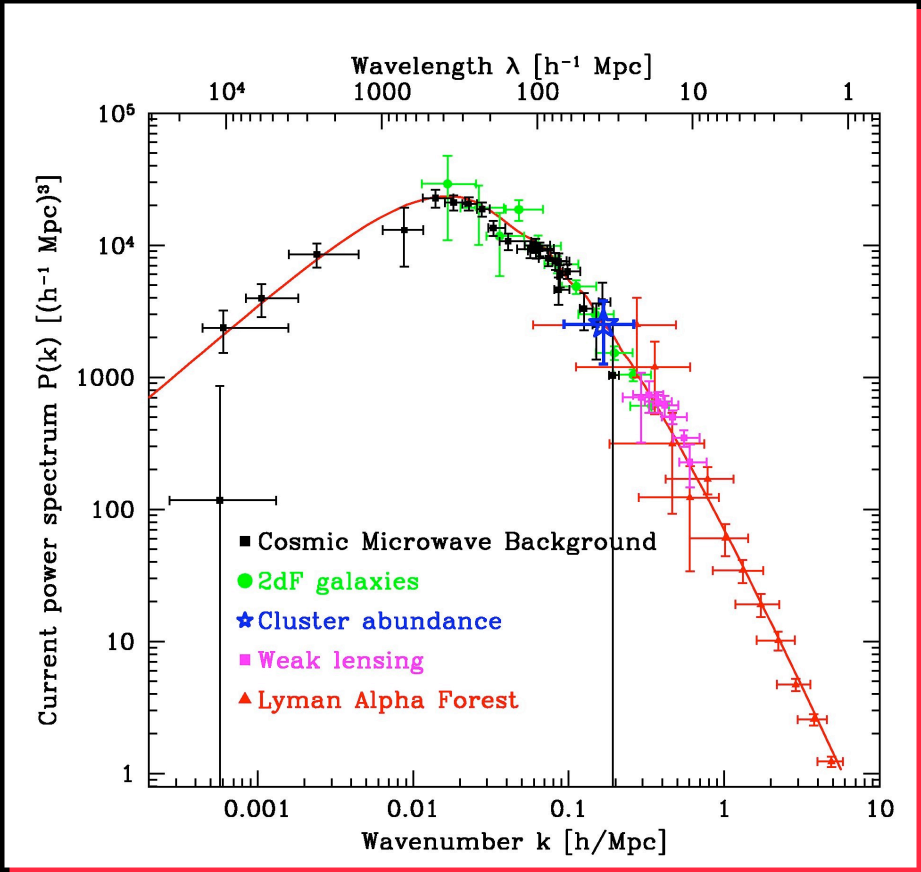
How can we challenge further Inflation?



Peiris et al. 03

Improved constraints on n_s and running, *i.e.* better P(k) measurements

Improved constraints on r:
The only way seems to be CMB large angular scale polarization and eventually the measured of the B modes
This very fact makes the detection of B modes the holy grail of the CMB community



Tegmark and Zaldarriaga 02

The cleaner probes might be the CMB at higher *l* and weak-lensing

Future observational prospects

- Much better measurements of the primordial power spectrum shape.
  - Planck l~3000 (k~0.2/Mpc)
  - ACT l~10000 (k~0.7/Mpc)

    secondary effects
  - Galaxies and/or lensing k~1/Mpc

    non-linearity (except at high z) & bias
  - Lyman alpha k~5/Mpc

    gas phys. & radiation feedback
  - Reionization k~50/Mpc

    much is still unknown but potentially the way to go

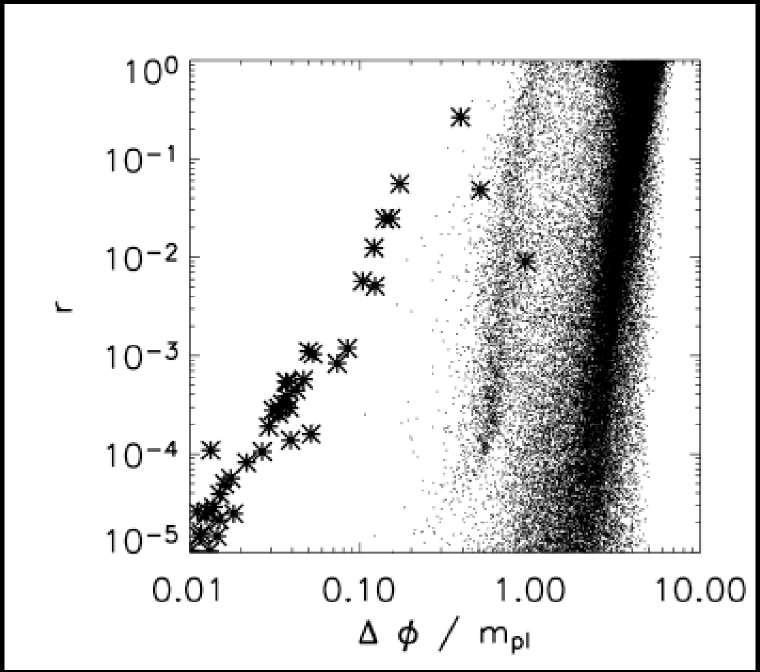
- Detecting non-Gaussianity from 2nd order gravity
  - Can we detect $f_{NL} < 1$?

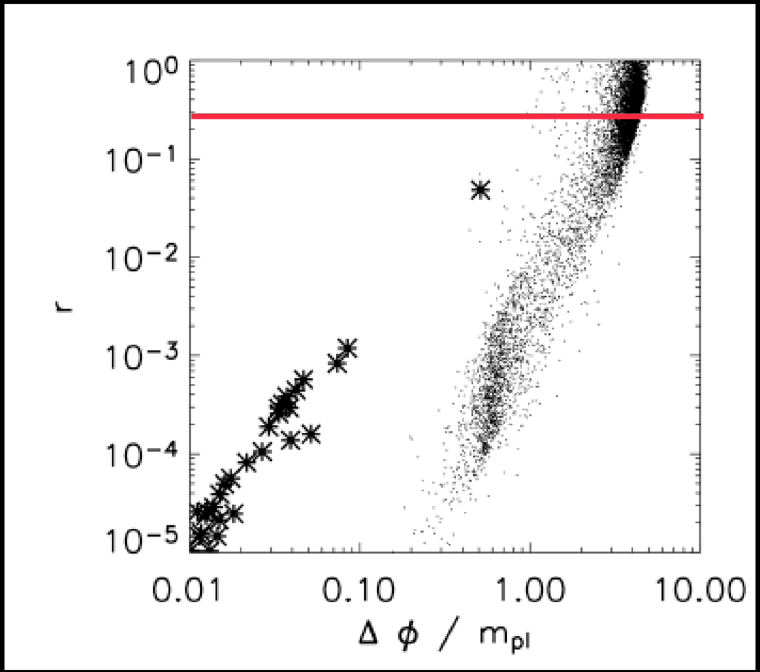
Gravity Wave Detection and r limit

$$V^{1/4} \sim 3.3.\ 10^{16}\ r^{1/4}\ \text{GeV}$$

- Current limits (r < 0.3 - 1): Indirect
  - $V^{1/4} < 2.6\ 10^{16}$ GeV or $V < 2.2 \times 10^{-11} m_{Pl}^4$
- Upcoming Experimental Tests with CMB polarization and B-mode measurement
  - WMAP (soon !) (r < 0.2) (sensitivity)
  - Planck, Clover & Upcoming Balloons (EBEX) (r < 0.01 *ie* $V^{1/4} < 10^{16}$ GeV)
  - CMBPOL (r < 0.001, *ie* $V^{1/4} < 10^{15}$ GeV)
- Polarization will be very challenging
  - Control of instrumental systematics
  - Polarization foregrounds so far unknown
- Note that a detection of GW would rule out Ekpyrotic (Khoury et al. 03) or pre-big bang models (Gasperini & Veneziano 93)

Some remarks on the detection of primordial GW background





Apply constraints from CMB+LSS (Seljak et al. 2004)

$0.32<n_s<1.06$ / $-0.04<dn_s/d\ln k<0.03$

- Self-consistency of effective field theory approach to describe inflation requires $\Delta\phi \ll m_{Pl}$. But r is a very steep function of $\Delta\phi$ (Efstathiou & Mack 2005):

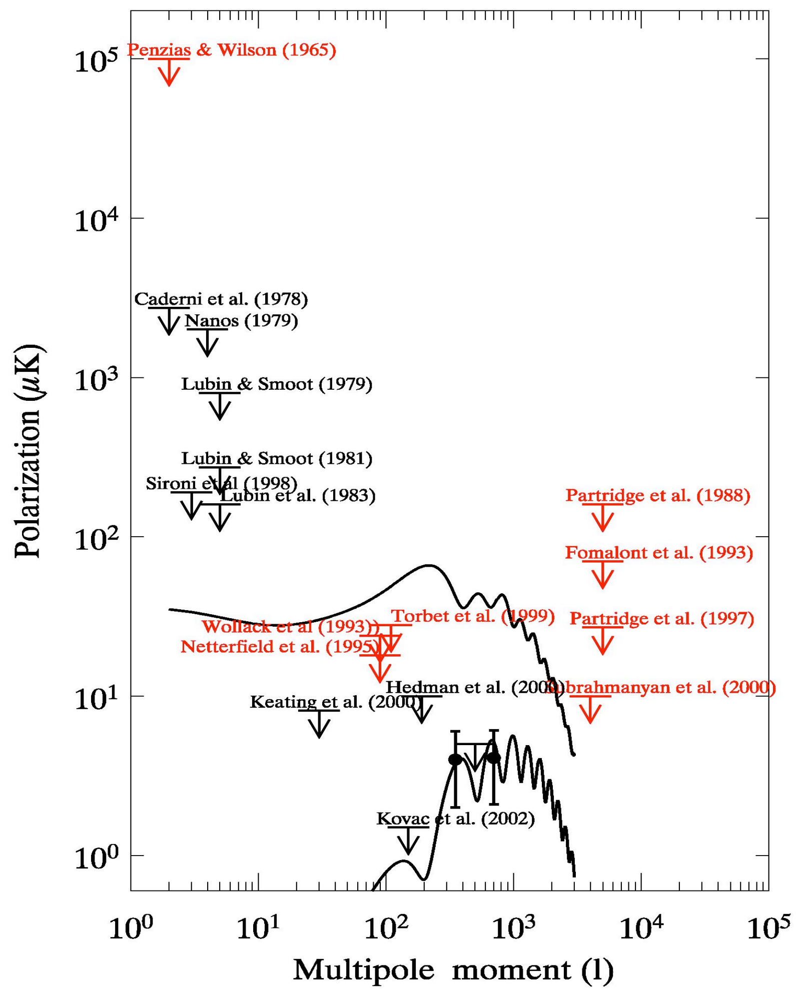
$$\frac{\Delta\Phi}{m_{Pl}} \simeq 6r^{1/4}$$

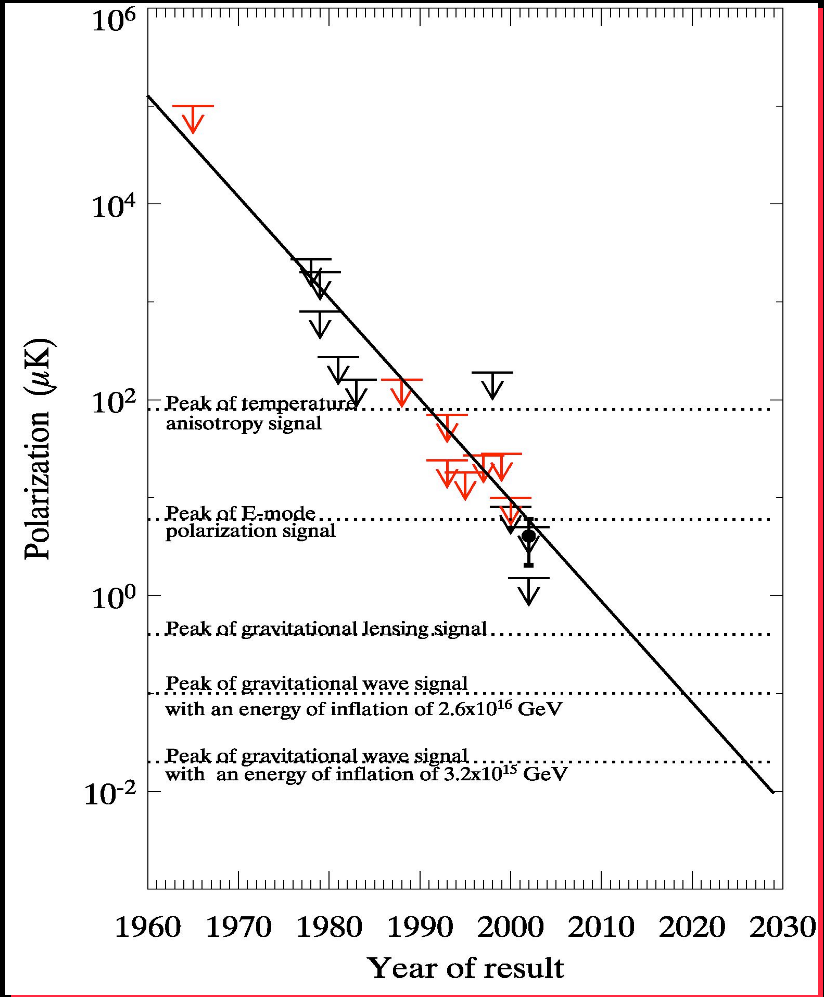
Revisited Lyth (96) bound

- Unless we can detect $r < 10^{-4}$, we can only test the large field models. Any foreseeable CMB experiments will only be testing models which are driven by some physics not captured by an EFT description (might be an issue or not)

- It still appears to be a challenge to construct a particle physics motivated inflation model with large $\Delta\phi$

Detecting B modes within 5/10 years ?





- Already long history
- Primordial gravitational detection around 2015?

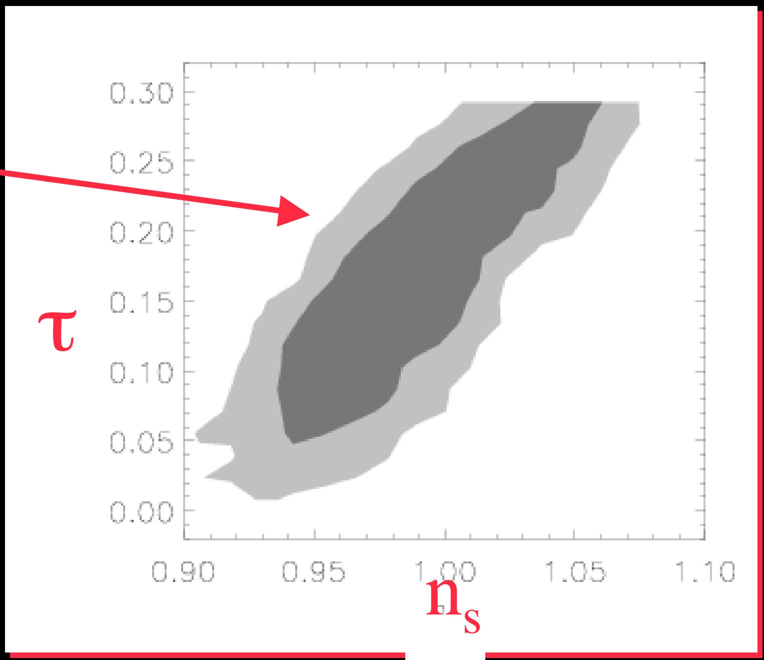
D. Barkats & S. Staggs

We also need to figure out reionization

Reionization signal is required to break some key degeneracies

- Temperature alone suffers from severe degeneracies, e.g. only the product $A_s e^{-2\tau}$ is accurately measured (30% scattered)
- The inclusion of TE allows the measurement of τ and thus A_s , but also n_s

1 and 2 σ joint confidence contours



Main degeneracy using TT and TE After WMAP 1

Spergel *et al.* 03

Driven by tension between low l TT power and high τ coming from TE

- Key for measuring n_s and *running* and so to probe Inflation
- Key to measure absolute normalization, i.e. σ_8 and so Dark Energy
- WMAP 2-3 will improve a lot with regards to this degeneracy

We need a precise and accurate τ to nail down n_s

Effect on Temperature anisotropies I

1- Damping: blending of photons from different lines of sight

$$\bar{T} + \Delta T \longrightarrow (\bar{T} + \Delta T) - (\bar{T} + \Delta T)(1 - e^{-\tau}) + \bar{T}(1 - e^{-\tau})$$
$$\longrightarrow \bar{T} + \Delta T e^{-\tau}$$

$$\boxed{C_\ell = C_\ell e^{-2\tau}}$$

(Ignore scale dependence here)

Current numbers tell us we have a suppression by ~30% for *l* greater than 40

Makes it hard to measure absolute initial conditions normalization

2-Doppler effects

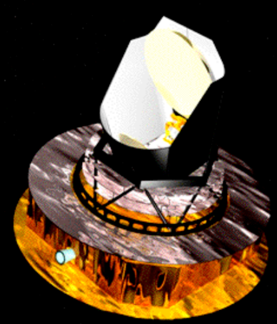
$$\frac{\Delta T}{T}(\hat{n}) = \sigma_T \int_{\eta_{ion}}^{\eta_0} d\eta \, x_e(\hat{x}) n_p(\hat{x}) \hat{n} \cdot v_e(\hat{x})$$

Cancellations along the line of sight due to variation in v_e :

- Except at larger scale : *l*~100
- Reduced if modulations in n_p : *Ostriker-Vishniac effect, kinetic SZ*
- Reduced if modulations in x_e : *Patchy reionization*

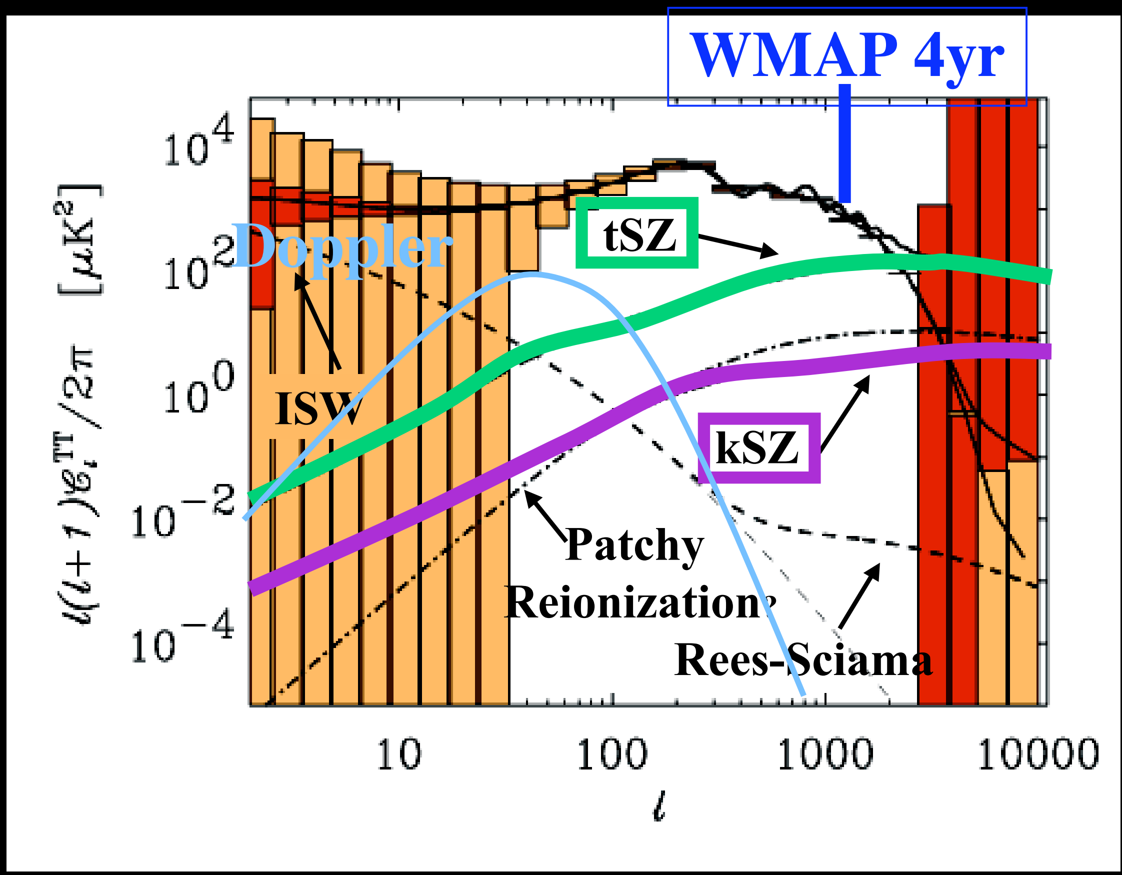
e.g. Knox and Haiman astro-ph/9902311 for a review

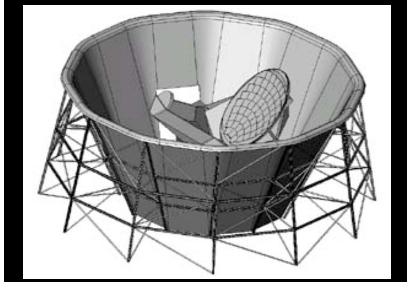
Effect on Temperature anisotropies II



Planck mission

PI: Jean-Loup Puget
Joint ESA + NASA
Launch end 2007





Atacama Cosmology Telescope

PI: Lyman Page, Princeton First light 2006

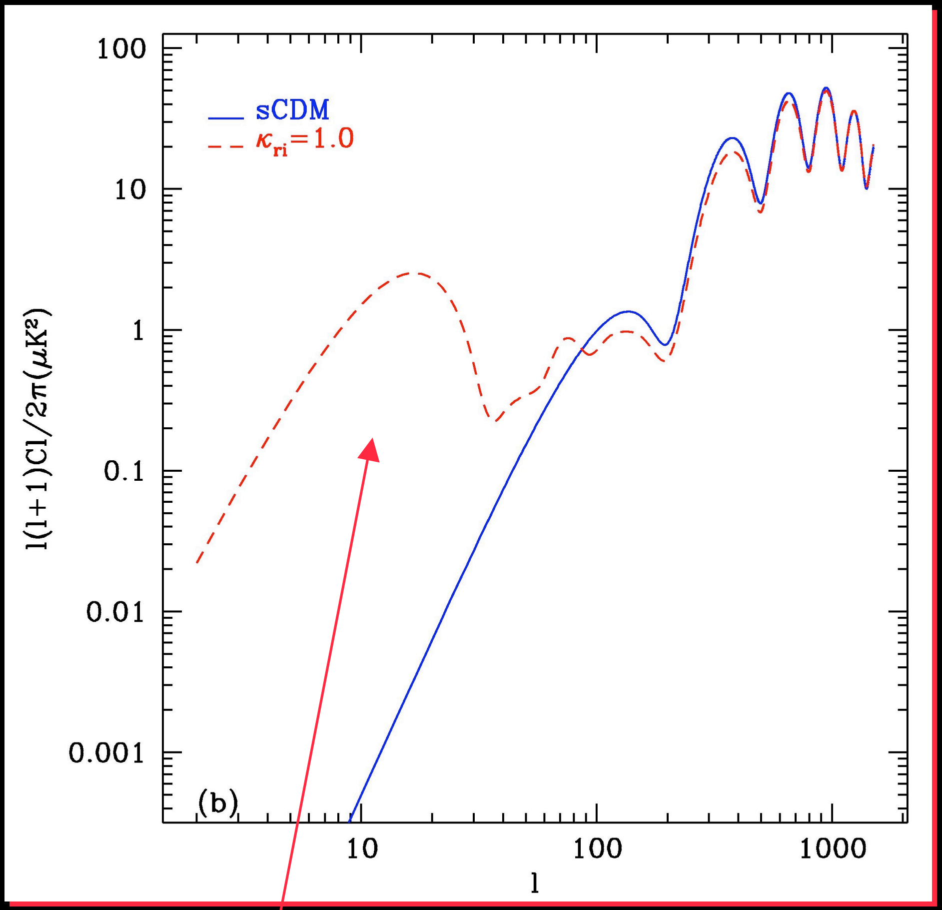
PLANCK
5 μK and θ_{fwhm}= 5'

ACT
2μK and θ_{fwhm}= 1.7'

Doré, Hennawi & Spergel et al. 04

Effect on Polarization

EE
Angular Power
Spectrum



Zaldarriaga 97

Angular Scale of Horizon at the time of reionization

Unambiguous signature (unlike for T), amplitude proportional to τ^2

Observational Prospects

- Very few experience can improve the reionization relevant polarization measurement since
  - Hard to measure large angular scales from ground
  - Require good handling of systematic effects
  - Multi-frequency instruments are required since the polarized foregrounds are important but unknown so far
- But we can hope to learn more from
  - WMAP now extended to 6 (8) years
  - Planck (first results ~2009)
  - CMBPOL (Part of the NASA beyond Einstein Program)
- But as well from some high sensitivity arcminute scale telescope under construction, first light in 2006, e.g. ACT or SPT

Prospects: 1σ errors

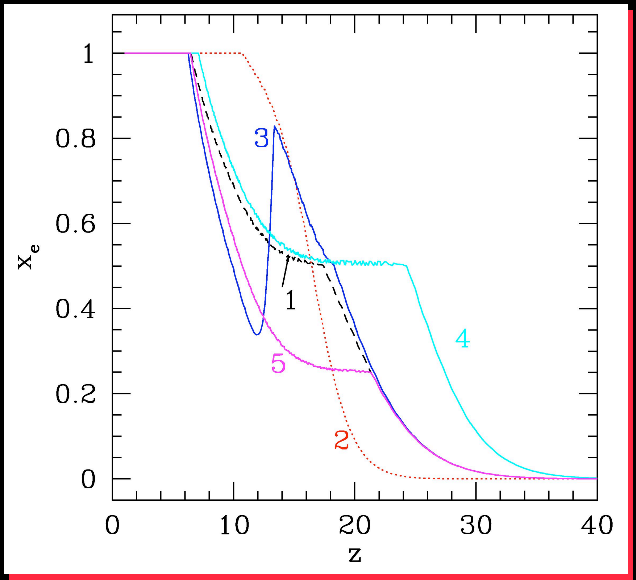
9 parameters (including running and (*w*,*w'*)), flat universe
Consider T, E, B and 2 point shear for lensing
Ignore foregrounds and systematics
Somewhat optimistic thus

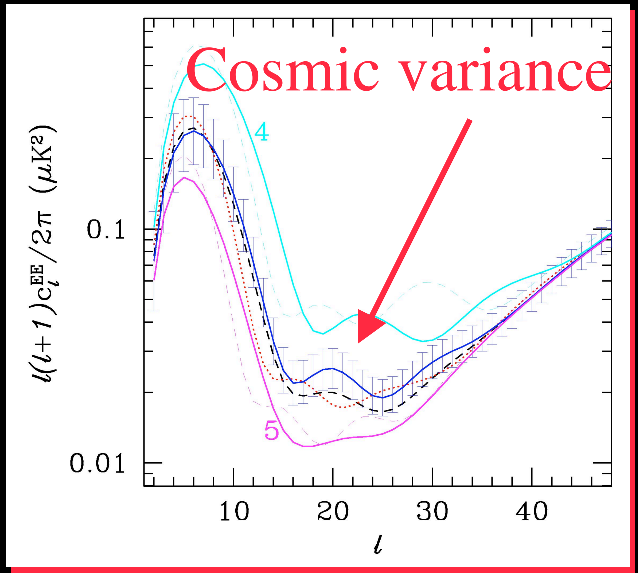
	τ (=0.1)	n_s (=1 fid.)
Planck	0.010	0.0078
Planck + lensing (2π)	0.0083	0.0046
CMBPol	0.0097	0.0031
CMBPol + lensing (2π)	0.0060	0.0026

Song & Knox astro-ph/0312175

Could we be sensitive to the details of the reionization history ?

- Can we learn about the detailed reionization history ?
- If not, can our ignorance bias the cosmological interpretation?





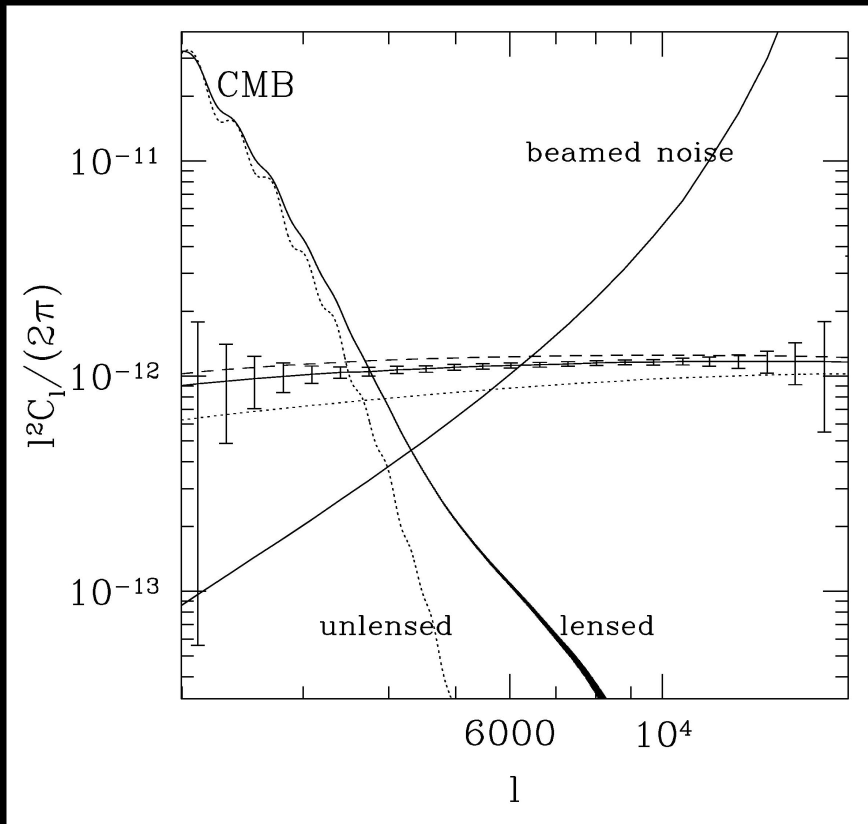
Difficult since integrated effect

- 5 different physically motivated models
- Models 1-3 have the same τ
- All consistent with WMAP latest measurements
- A single step reionization history is enough for WMAP but not for Planck
- Assuming a double step reionization scenario avoid any significant bias in measuring τ

Holder *et al*. astro-ph/0302404

Prospects through the kSZ and ACT/SPT

ACT error bars

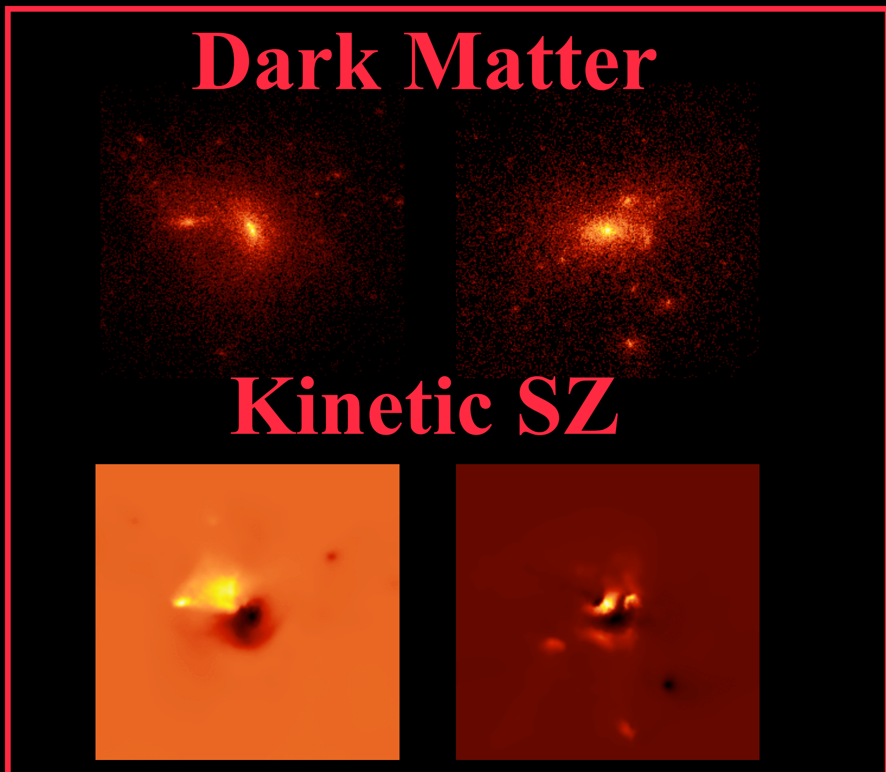


- $z_r = 7$
- $z_r = 16.5$
- $z_r = 21$ & 7

Zhang *et al.* astro-ph/0304534

- In principle allows1% measurement of kSZ allow a 3% determination of z_r if all the other parameters are known
- But degeneracy with σ_8 that goes as $z_r \propto (\Omega_b h)^6 \sigma_8^{15}$
- Plus extra-uncertainties in extracting the kSZ (lensing, patchy reionization, point sources)
- Might benefit from lensing, ie correlating $T^2\kappa$ where we expect a very strong correlation: SNR > 40 (Doré *et al.* 03)
- The conclusion is that it will be difficult but new and exciting and it is coming soon !

Can weak-lensing help probing the kSZ ?



Martin White website

- High resolution CMB experiments and weak lensing surveys will both achieve high SNR at 2'
- Simplest 3-point function: "Collapsed" statistic"

$$C_l^{\mathrm{kSZ}^2-\kappa} = \langle \left(\frac{\Delta T}{T}\right)^2 (\ell_1)\kappa(\ell_2)\rangle$$

- Booming signal! Total signal to noise ratio >1300

- Strong probe of σ_8: scales as $C_l \propto \sigma_8^7$

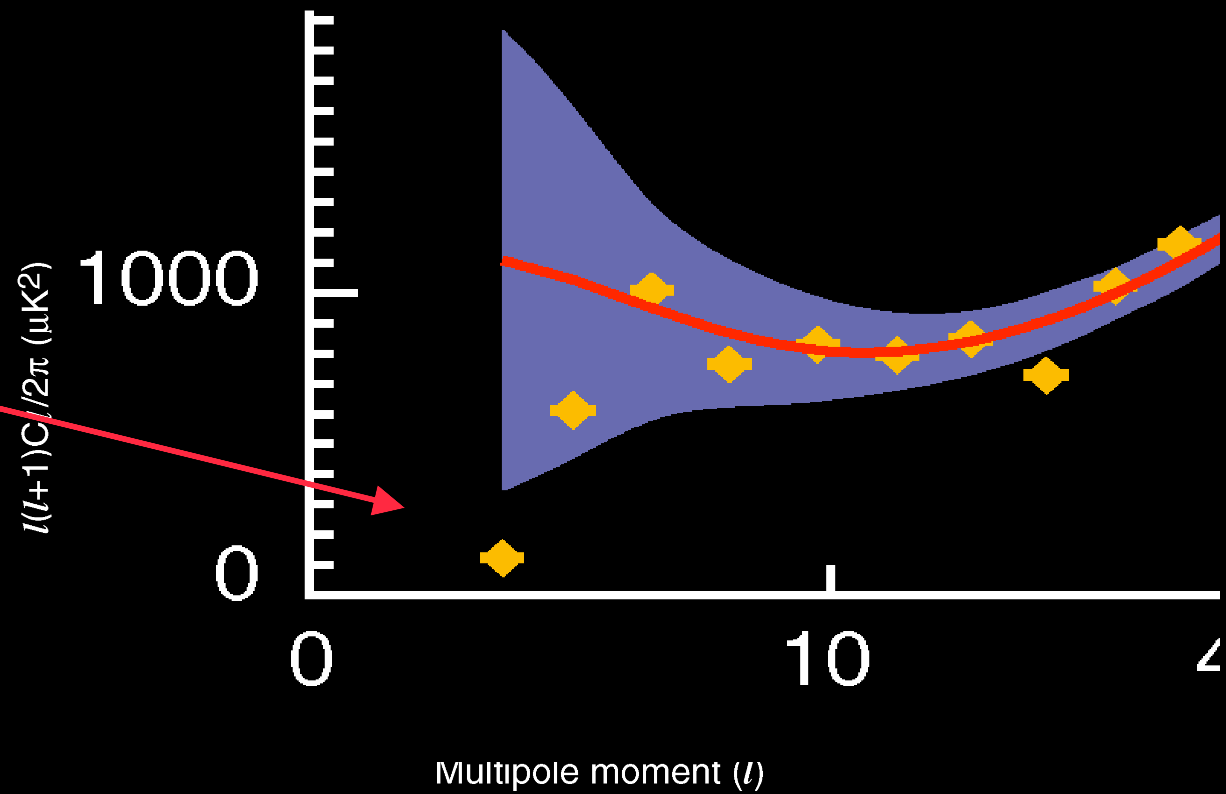
- Probe 3-point coupling between dark matter and *baryon momentum*

- Isolates kSZ: Will help cleaning the signal

Doré, Hennawi & Spergel et al. 04

Angular Power Spectrum at low l

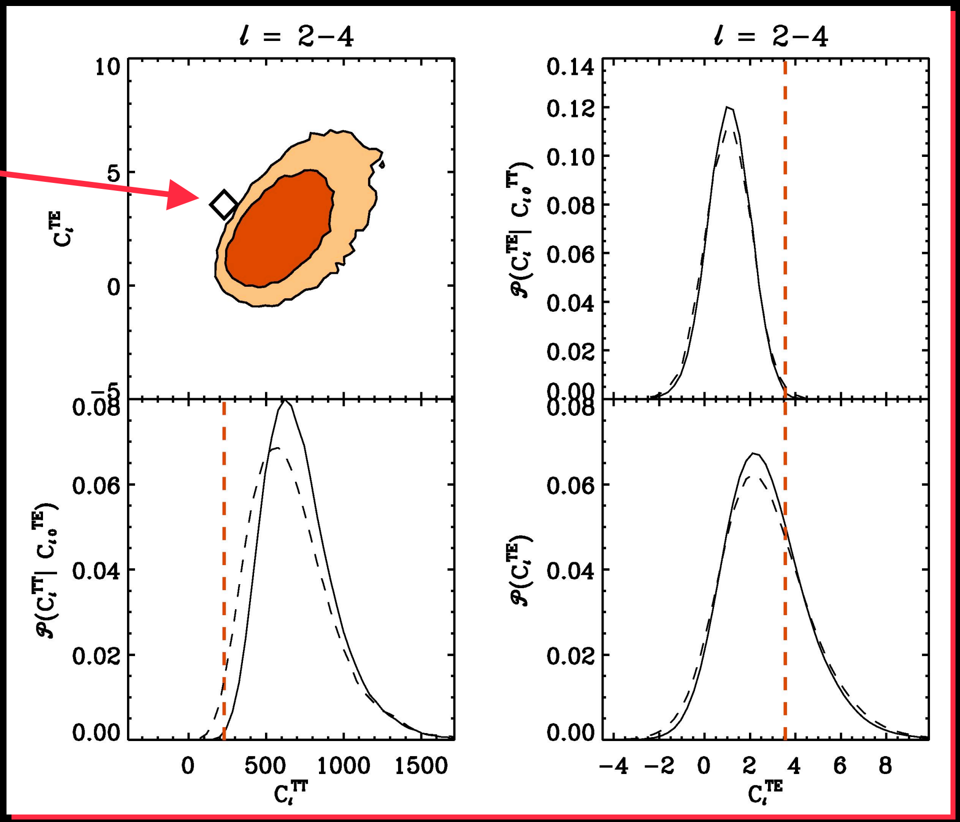
Likelihood of about 2-10% for a ΛCDM model



- Already seen in COBE
- Several theoretical arguments have been put forward, *e.g.*
  - Various means of truncating the primordial power spectrum (Closed Universe (Eftshatiou 03) or appropriate inflation model (Contaldi *et al.* 03) , etc.)
  - Somewhat related to a characteristic Dark Energy scale ?
  - DE clustering (Hu 99, Bean & Doré 03)
- Delicate situation since it is difficult to probe these scales by other means

The low quadrupole on a polarized light

Year 1 WMAP



- Test the consistency of *l=2* TT and *l=2* TE using the theoretically well known correlation between both
- Given the low C_2^{TT} you would expect a high C_2^{TE}
- This consistency test gives another handle on the low *l* quadrupole

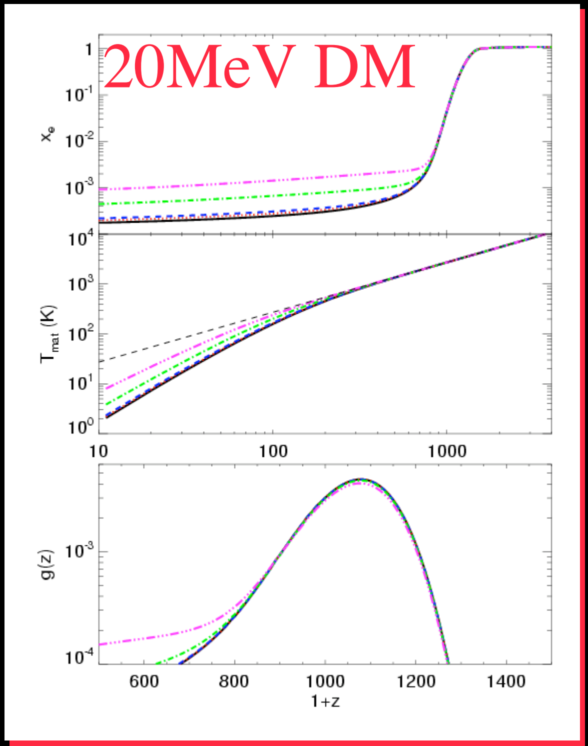
Doré, Holder & Loeb 03

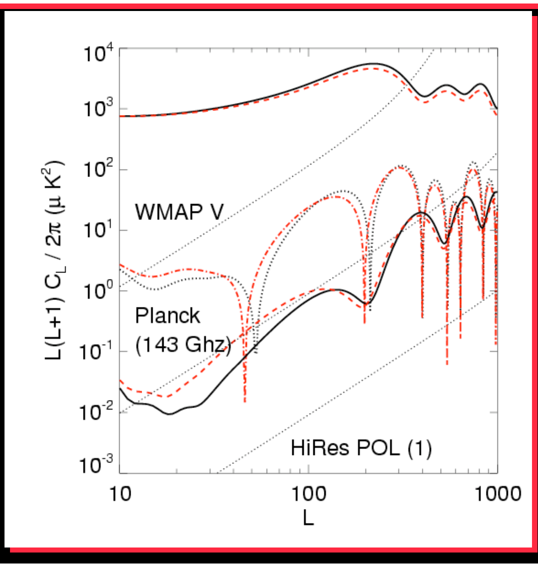
This would be all too easy if they were no other exciting new scenario to consider…

Reionization by annihilating Dark Matter

Padmanabhan & Finkbeiner 2005

- There is a chance that DM is made of light WIMPs, and their annihilation has a profound effect on the reionization of the Universe.
- Annihilating DM Produce γ's and e^+e^- near M_{DM}
- If dark matter annihilates, the annihilation, products can partially ionize H, He at *z*=1000 (the time of "re-combination") and cause a higher residual ionization than otherwise expected.
- 3 -yr WMAP data can rule out (or find!) 20 MeV DM, even if power is inefficiently converted to ionizations
- 100 GeV DM cannot be ruled out even by *Planck*





Conclusions

- Cosmology now has a standard model
- Cosmology provides lots of evidence for physics beyond the standard model.
- Upcoming observations will test (and keep requiring) new ideas in physics
  - Gravity Waves
  - Inflation Physics
  - Physics close to the Planck scale…
  - …and to the MeV scale
- A detailed understanding of reionization might be required to probe inflation if non-standard scenario are seen
- All this will happen in the coming 5-10 years


http://cosmocoffee.info
MAP990163