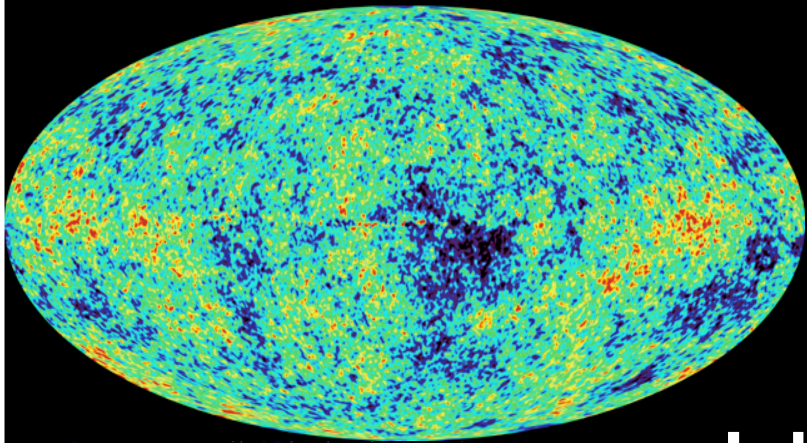
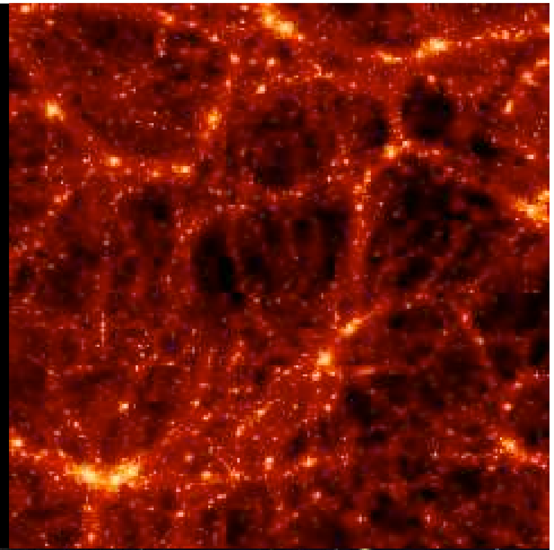
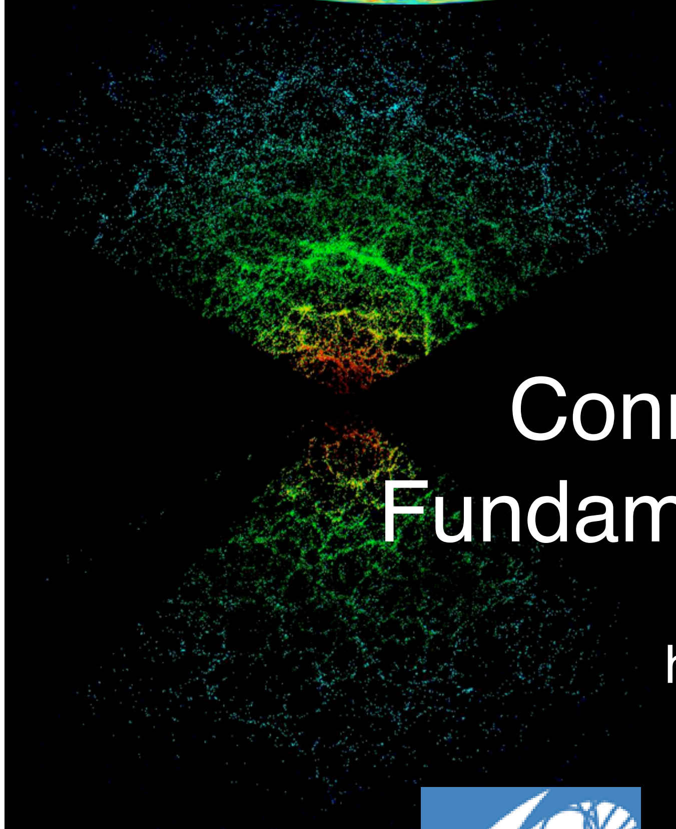
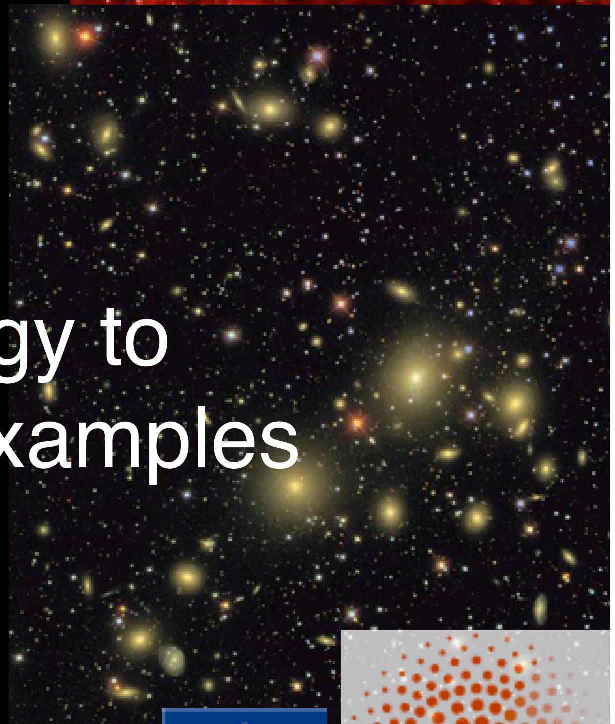








Licia Verde

ICREA & ICC-UB

Connecting Cosmology to Fundamental Physics: Examples

http://icc.ub.edu/~liciaverde

icrea Institució Catalana de Recerca i Estudis Avançats

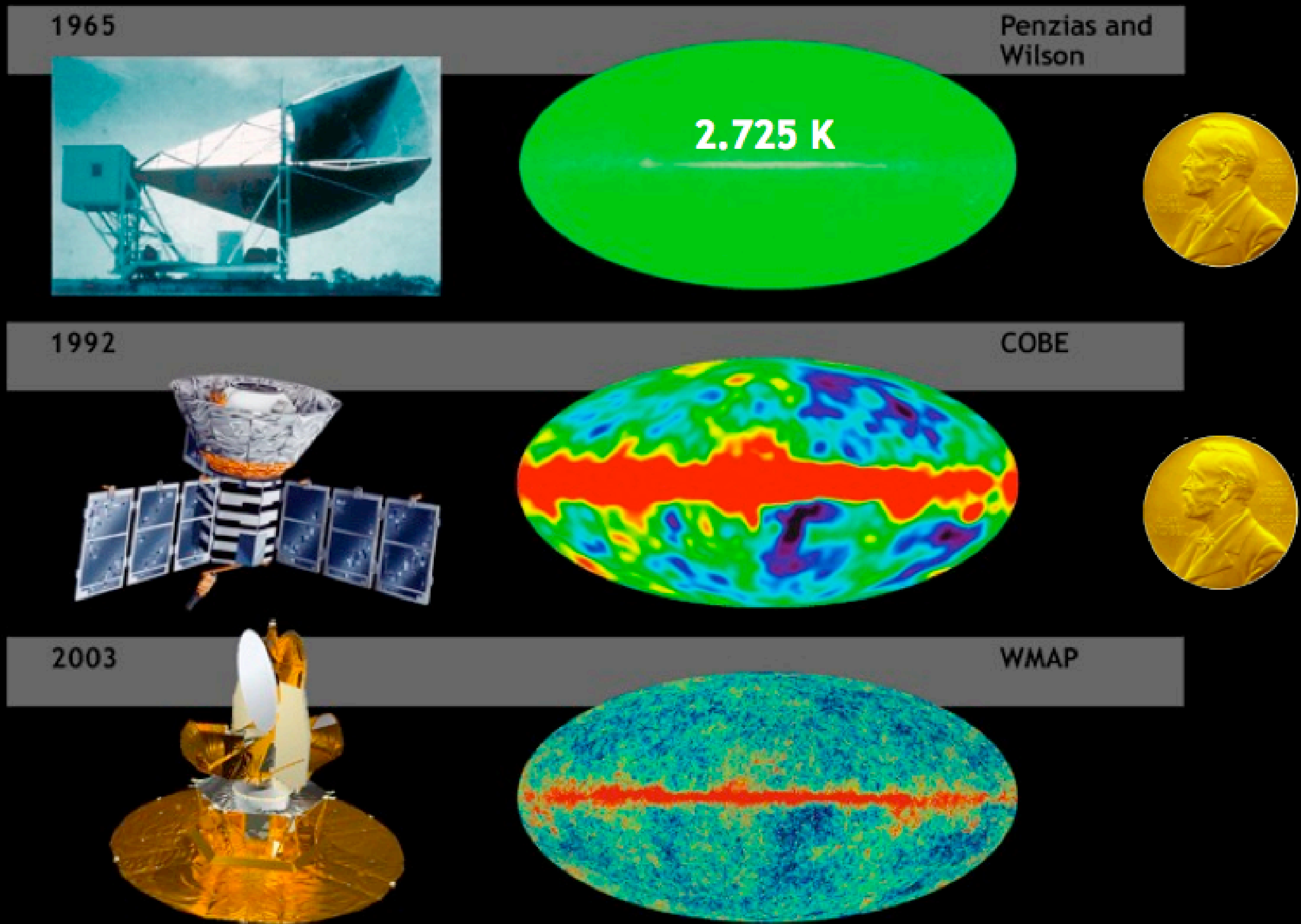
ICCUB Institut de Ciències del Cosmos

UNIVERSITAT DE BARCELONA

IEEC

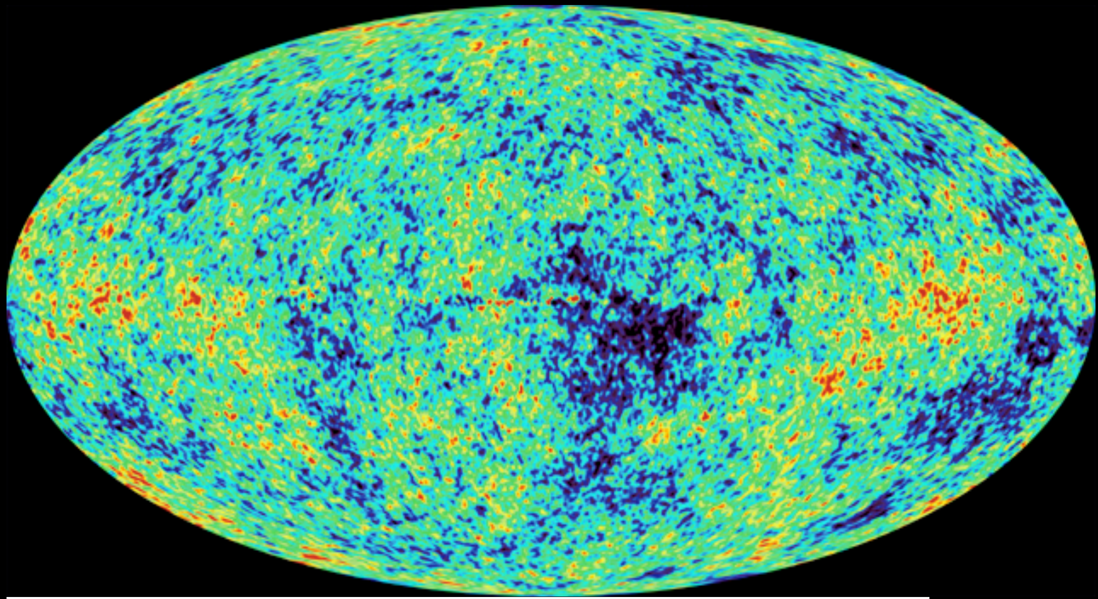
erc

History of CMB temperature measurements



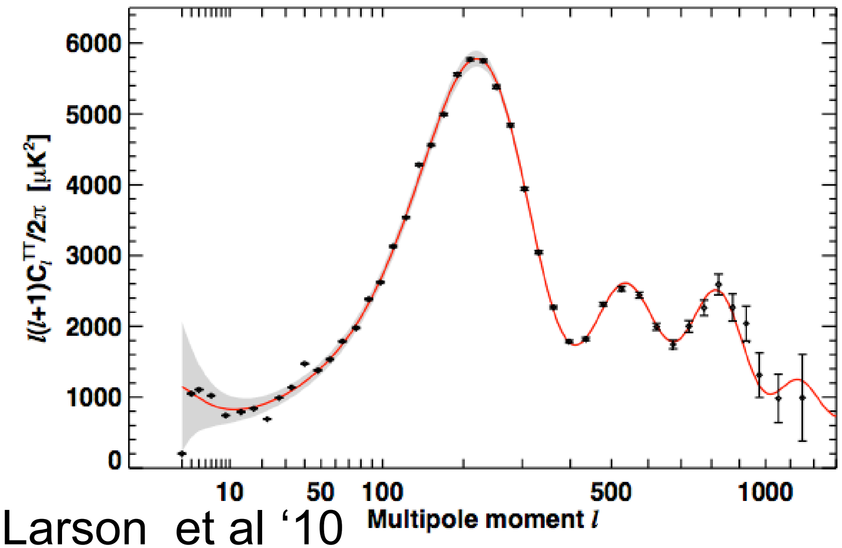
TOCO (1998) BOOMERANG (1998, 2003) MAXIMA (2000)
ARCHEOPS (2002) CBI (2002) ACBAR (2002) VSA (2002)

Importance to cosmology

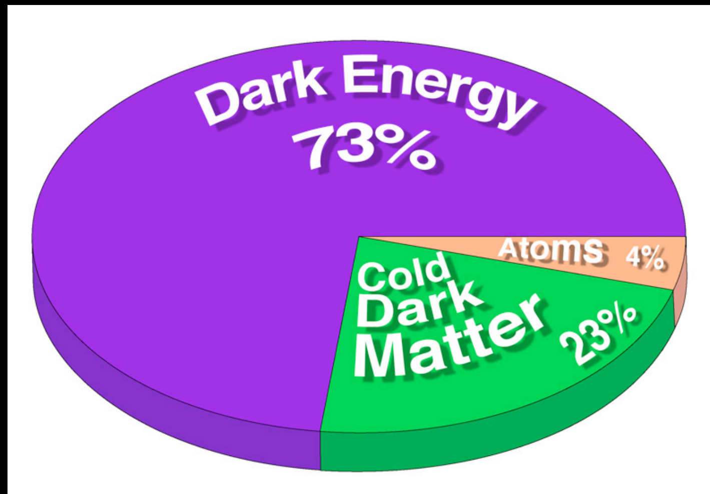


WMAP (2003)

Detailed statistical properties of these ripples tell us a lot about the Universe



Larson et al ‘10



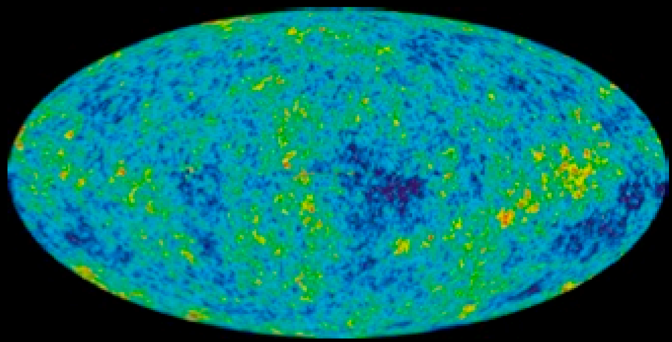
The era of precision cosmology:

LCDM: the "standard" model for cosmology

Few parameters describe the Universe composition and evolution

Homogenous background

Perturbations



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

A_s, n_s, r

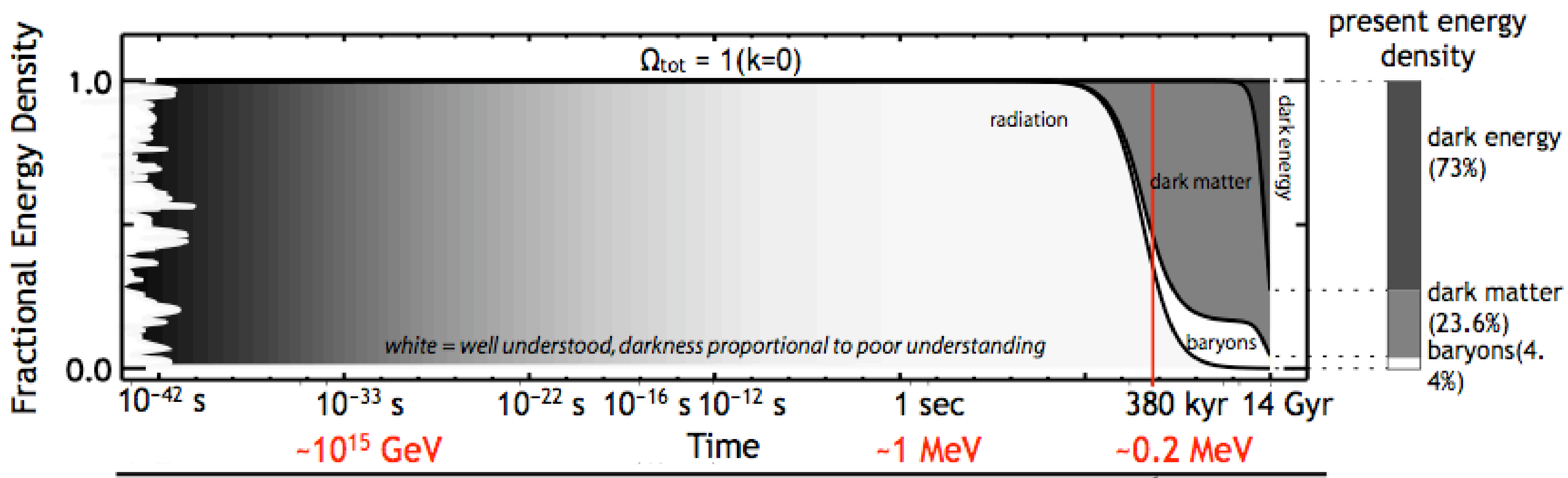
- atoms 4%
- cold dark matter 23%
- dark energy 73%

- nearly scale-invariant
- adiabatic
- Gaussian

Λ? CDM?

ORIGIN??

Cosmic History / Cosmic Mystery



Planck Energy

GUT symmetry

T=100 TeV (ILC X 100)

nucleosynthesis

Generation of primordial perturbations

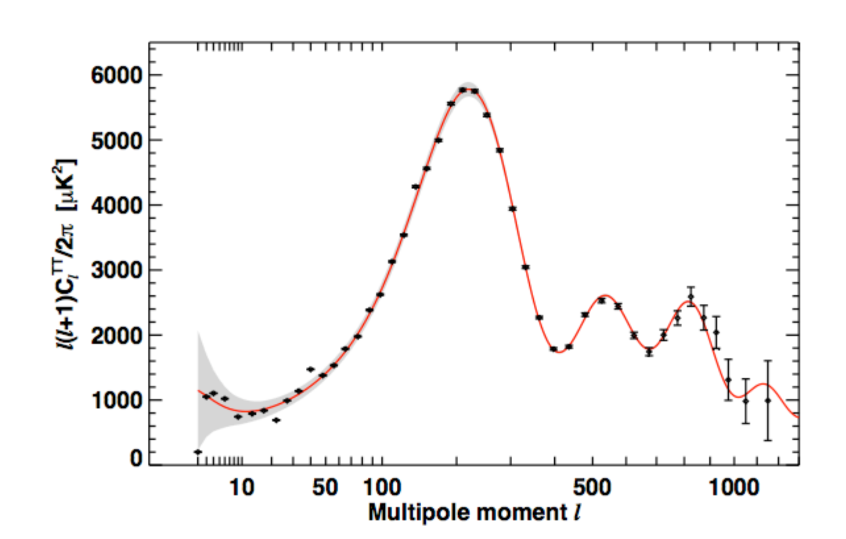
Cosmic Microwave Background Emitted carries signature of acoustic oscillations and potentially primordial gravitational waves

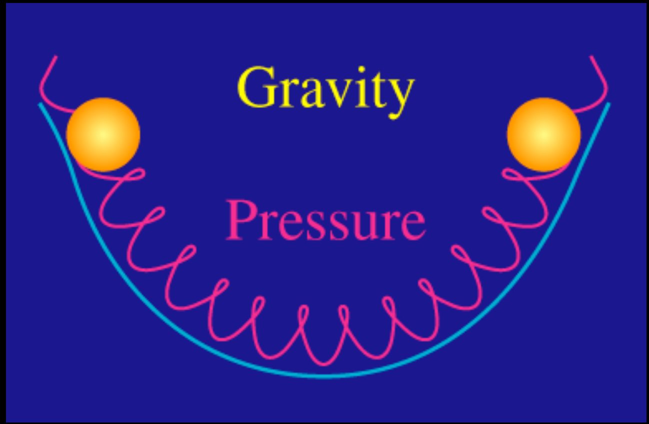
non-linear growth of perturbations: signature on CMB through weak gravitational lensing

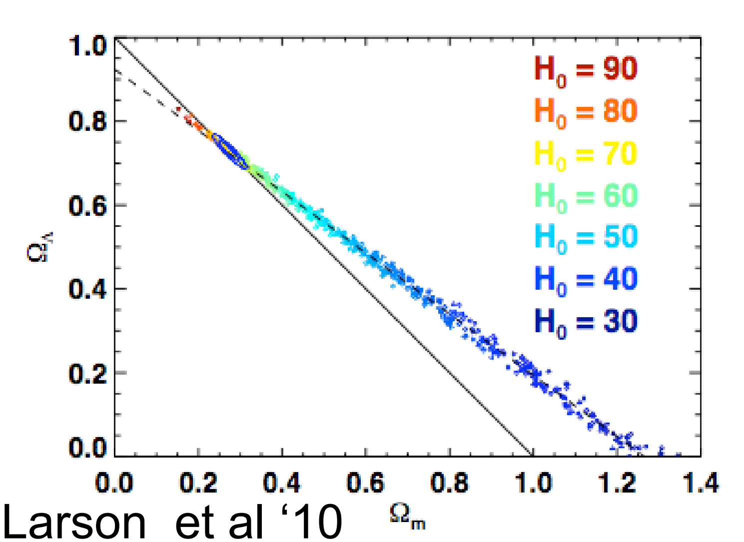
McMahon adapted by Peiris

The era of precision cosmology:

Evidence for dark matter





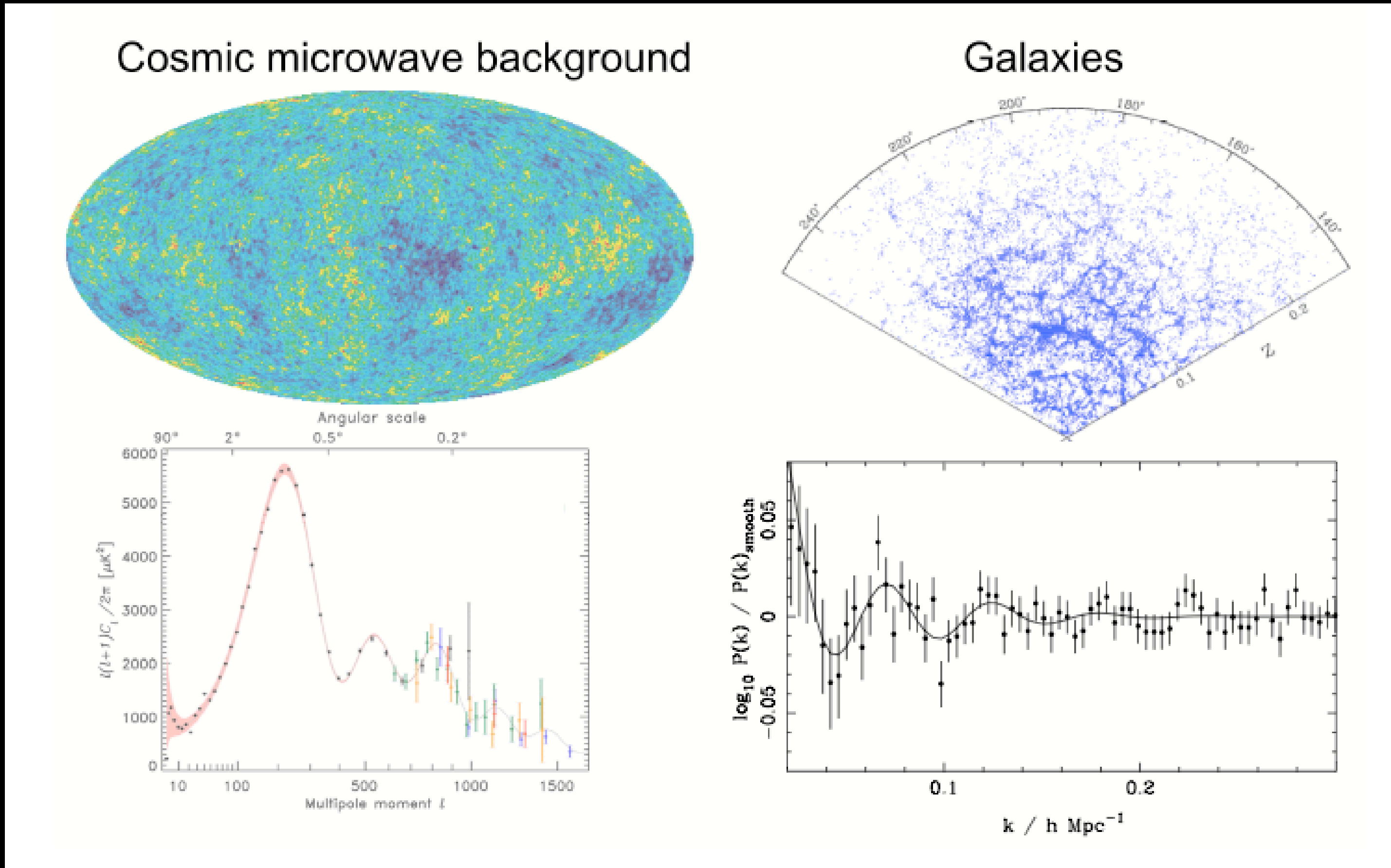


Larson et al '10

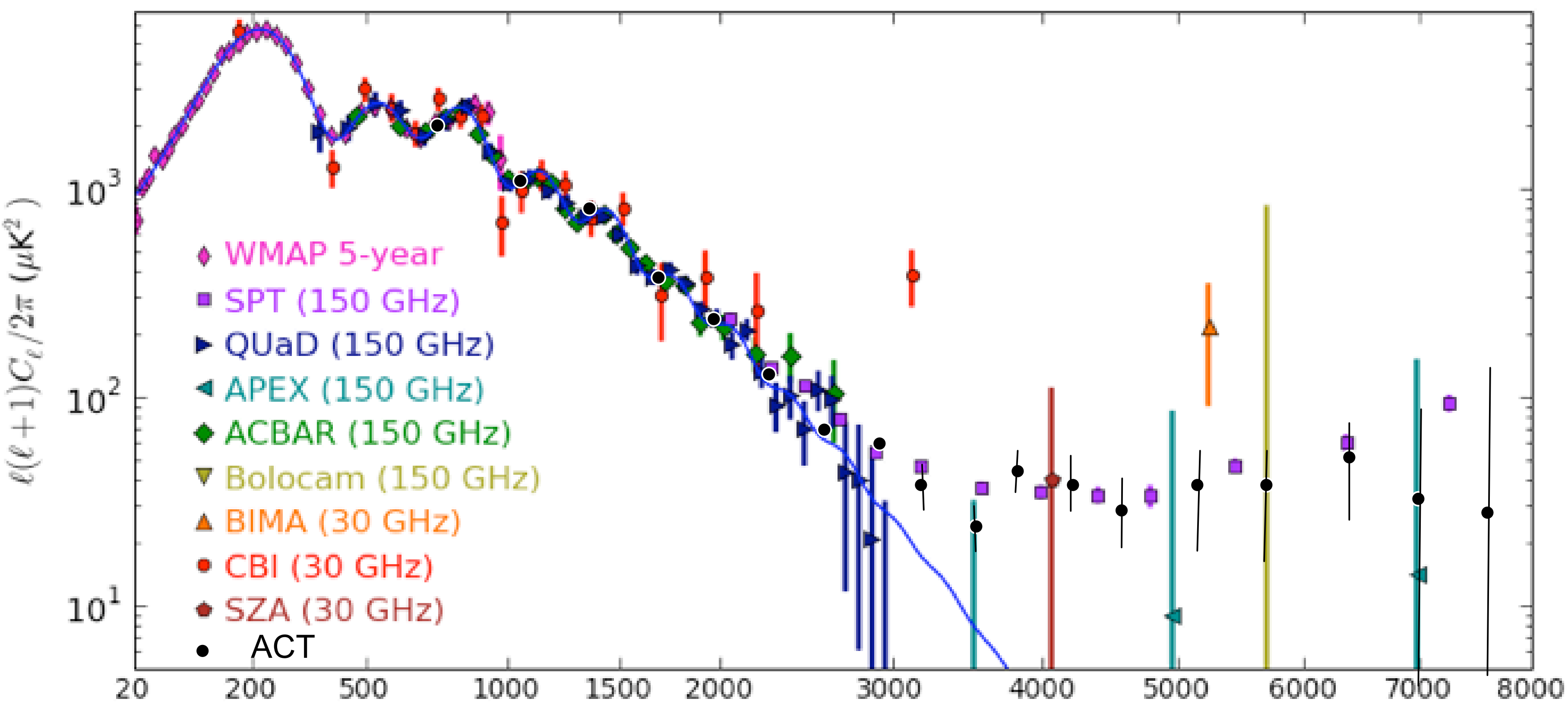
And dark energy when combined with other data

The era of precision cosmology:

Evidence for dark matter



State of the art: temperature



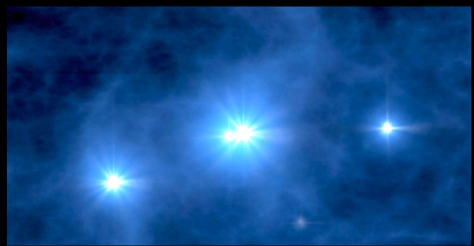
- Sachs-Wolfe plateau and the late time Integrated Sachs-Wolfe effect
- Acoustic peaks at "adiabatic" locations
- Damping tail and photon diffusion
- Weak gravitational lensing (detected in cross-correlation, Smith et al. 2007)

What next?

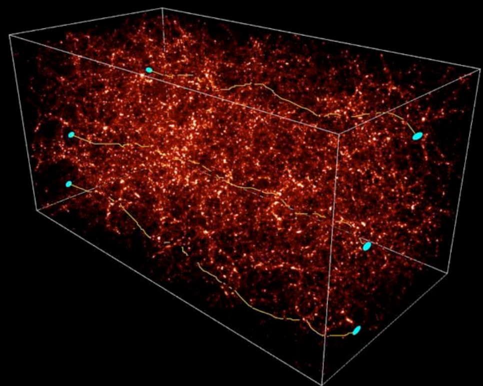
a) Beyond primary anisotropies

Use the CMB as a backlight to illuminate the growth of cosmological structure.

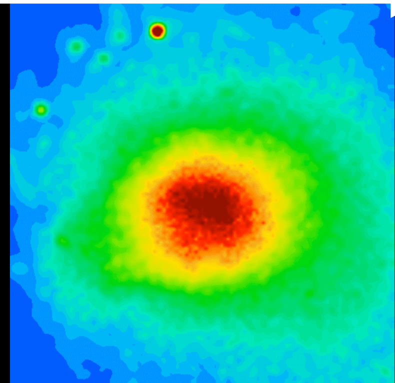
- First galaxies
- Universe is reionized
- Ostriker-Vishniac/KSZ



- weak lensing



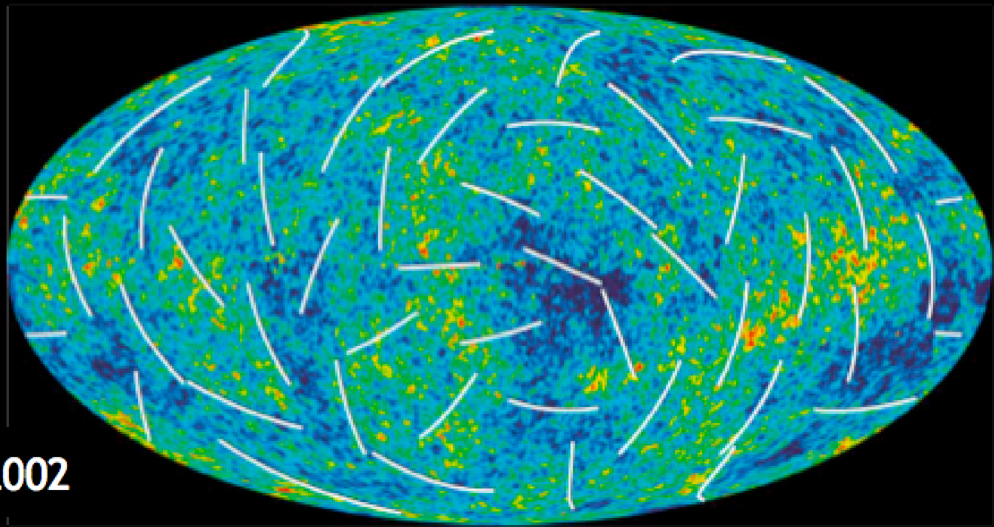
- Sunyaev-Zel'dovich (SZ) clusters
- Diffuse thermal SZ
- Kinetic SZ
- Rees-sciama/ISW



Watch this space because experiments like e.g., South Pole Telescope or Atacama Cosmology Telescope are releasing data these days

What next?

b)Polarization, the next frontier



First detected by DASI in 2002

WMAP science team 2006

Why measure CMB Polarization?

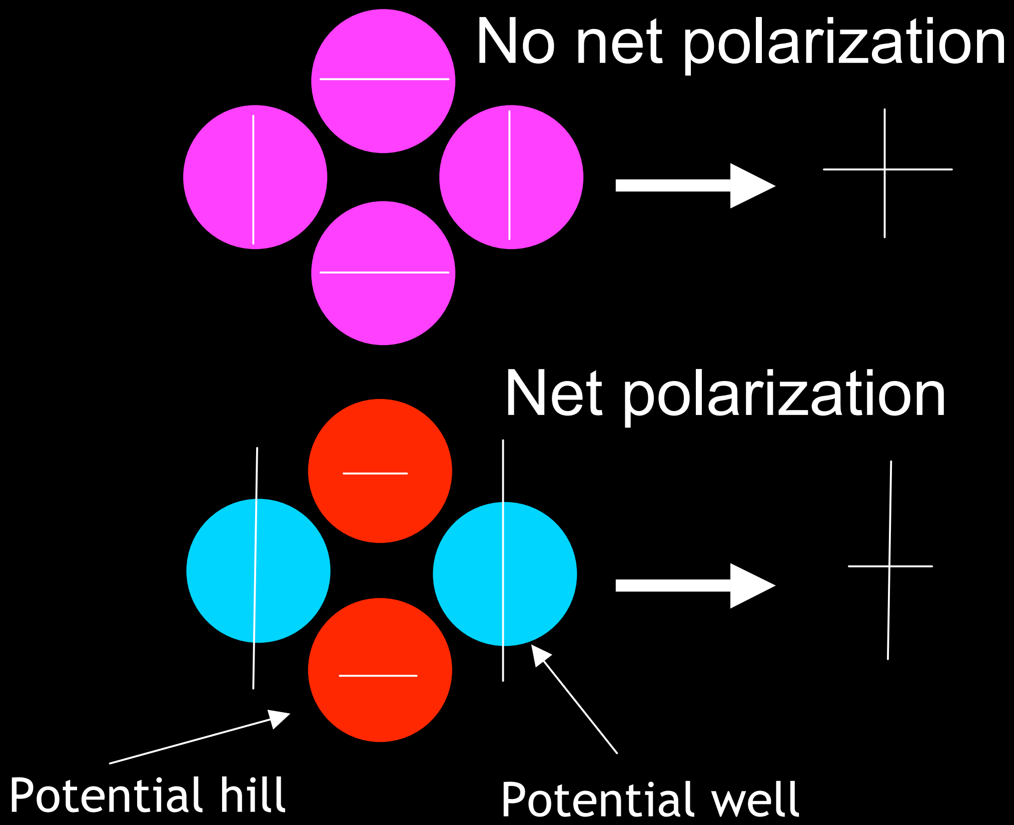
Directly measures dynamics in early universe

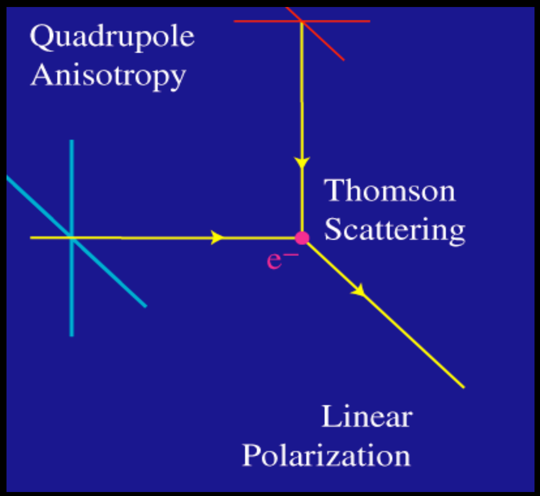
So far: Critical test of the underlying theoretical framework for cosmology

Future: “How did the Universe begin?” Eventually, perhaps, test the theory of inflation.

Generation of CMB polarization

- Temperature quadrupole at the surface of last scatter generates polarization.

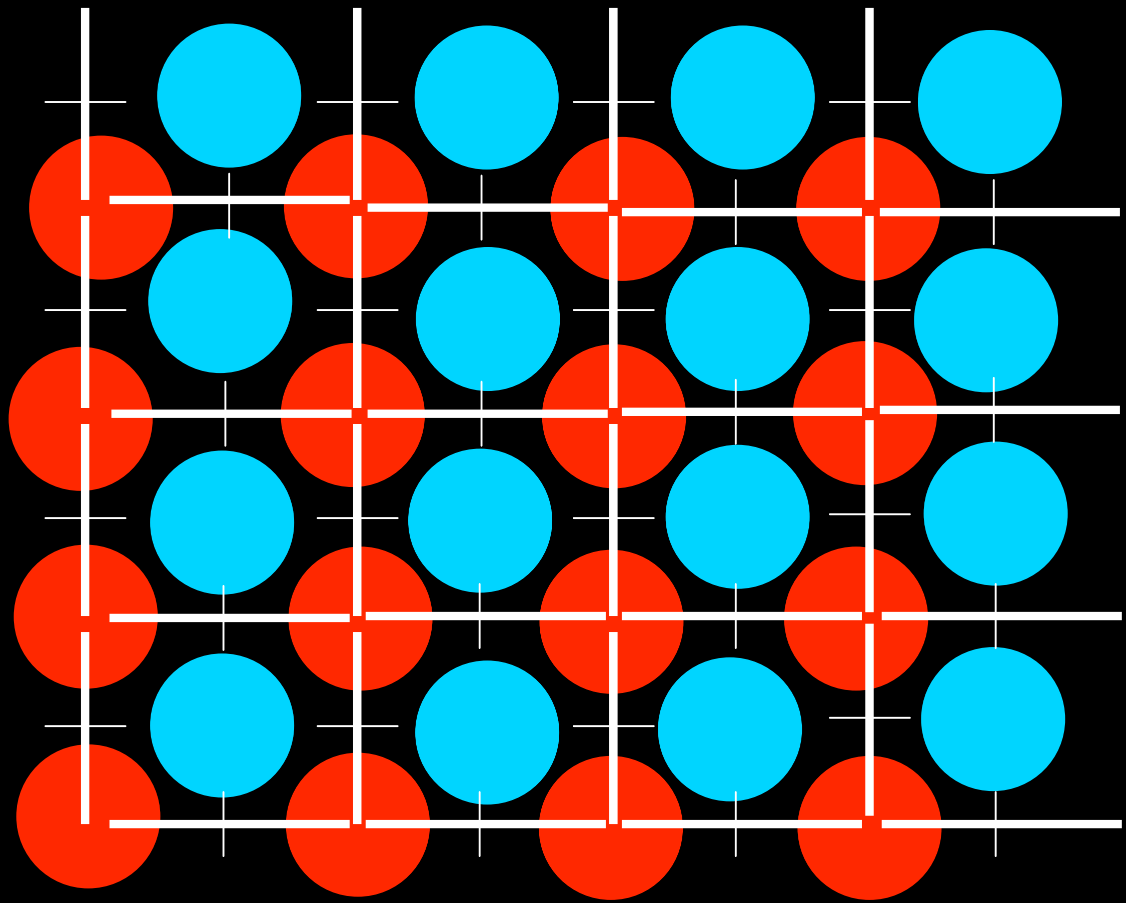




From Wayne Hu

Polarization for density perturbation

- Radial (tangential) pattern around hot (cold) spots.

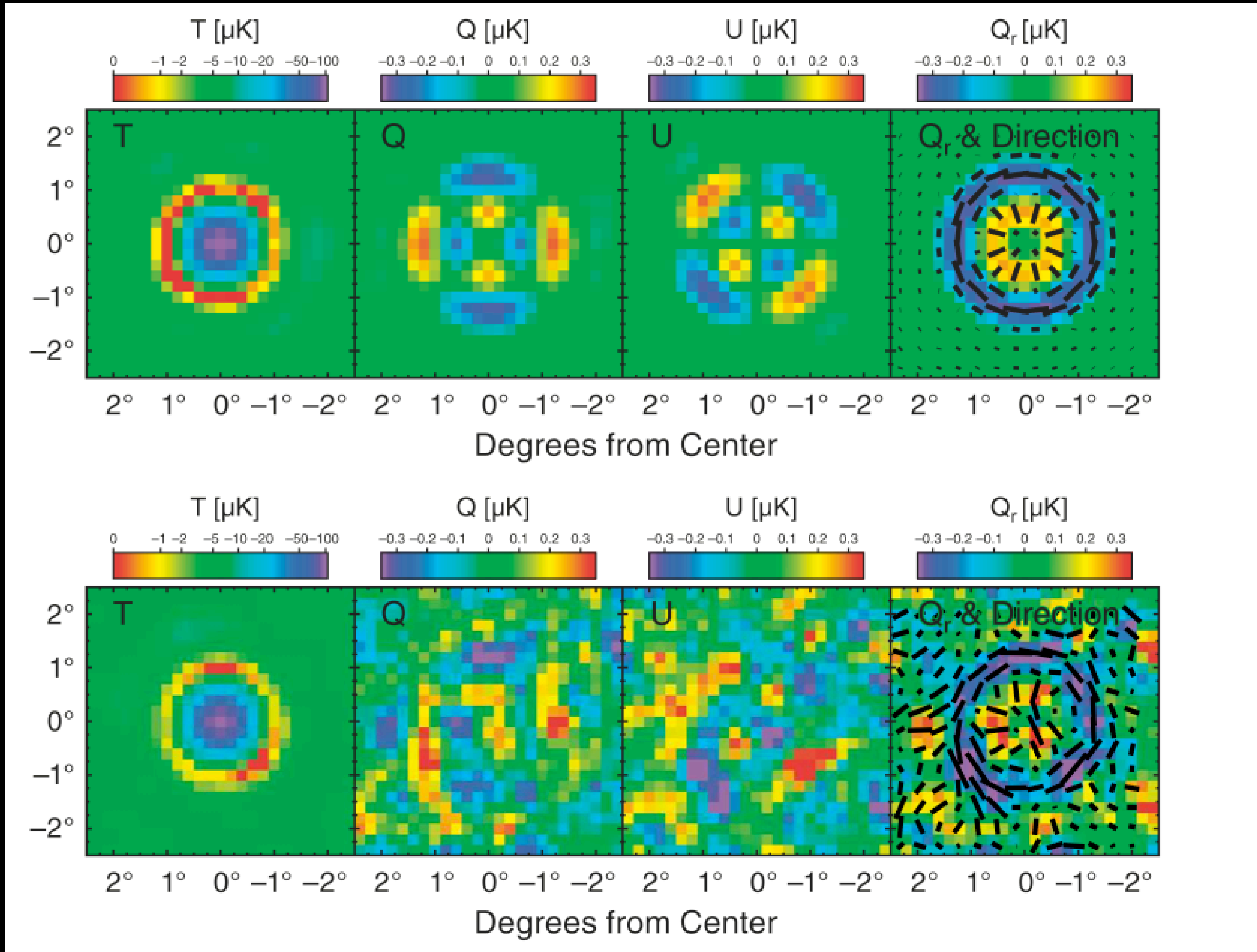


And it has been seen!

Komatsu, WMAP7yrs team (2010)

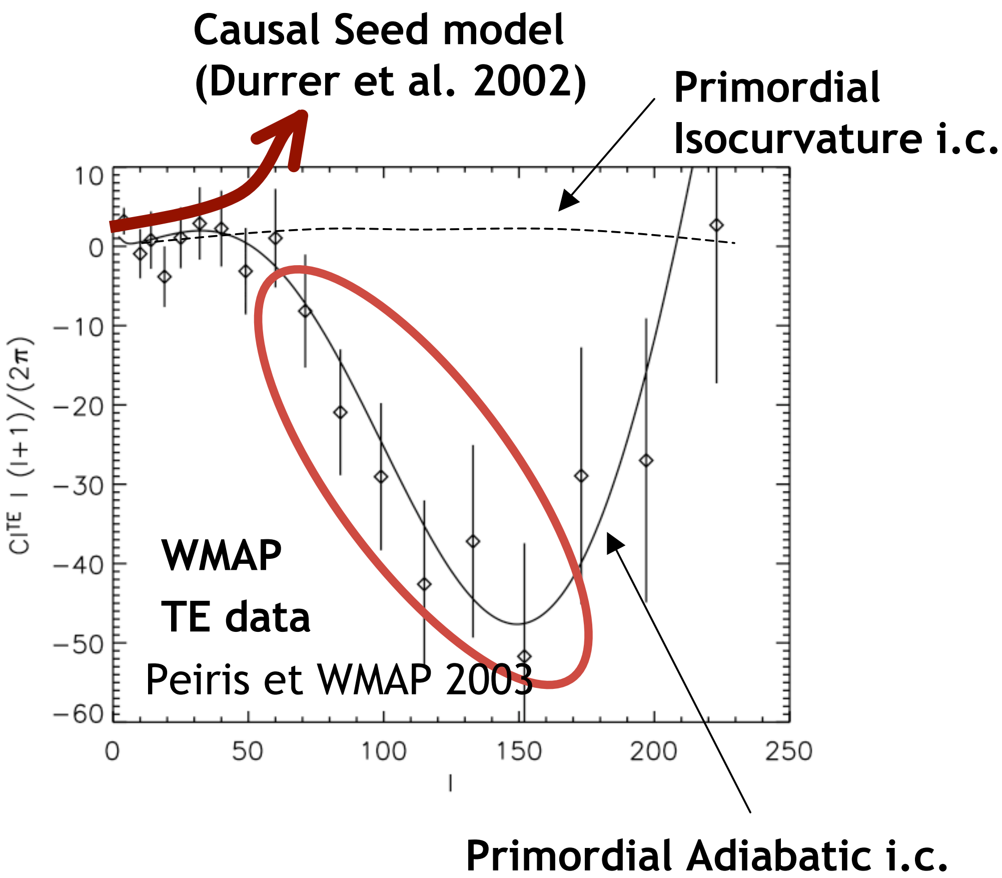
Theory prediction

Observed



CMB Consistent with Simplest Inflationary Models

- Superhorizon, adiabatic fluctuations
  - T and E anticorrelated at superhorizon scales
- Flatness tested to 1%.
- Gaussianity tested to 0.1%.
- nearly scale-invariant fluctuations
  - red tilt indicated at ~2.5 σ



Hu & Sujiyama 1995
Zaldarriaga & Harari 1995
Spergel & Zaldarriaga 1997

Still testing basic aspects of inflationary mechanism rather than specific implementations

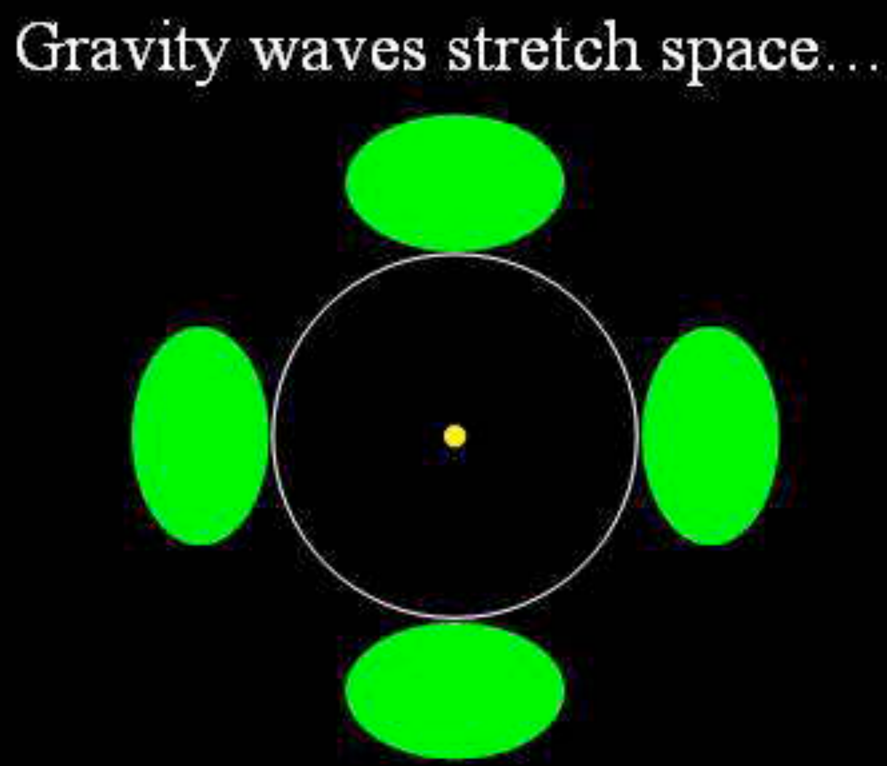


Image from J. Rhul.

… and create variations

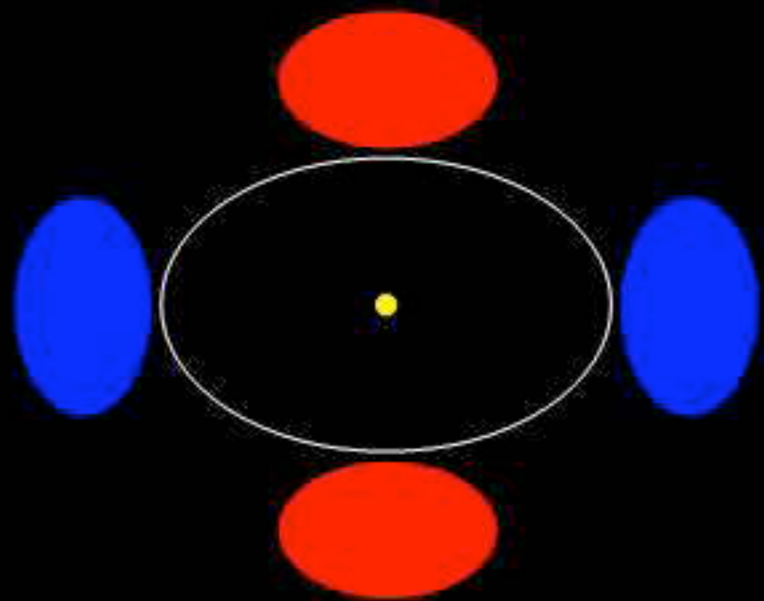
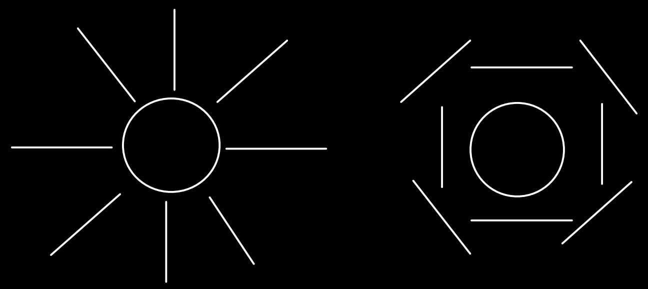
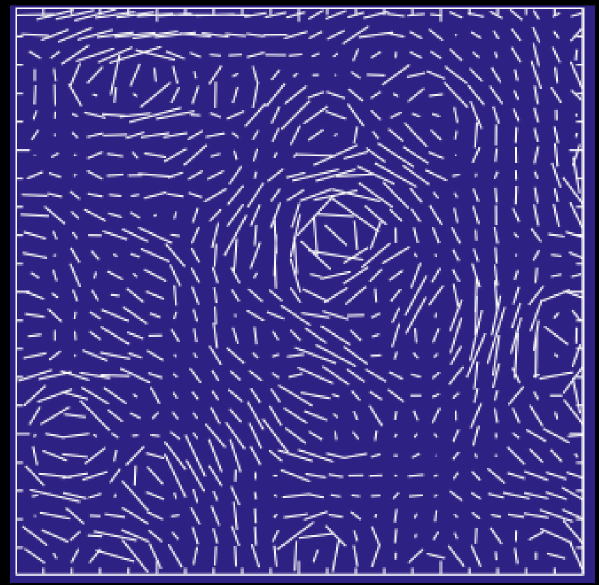


Image from J. Rhul.

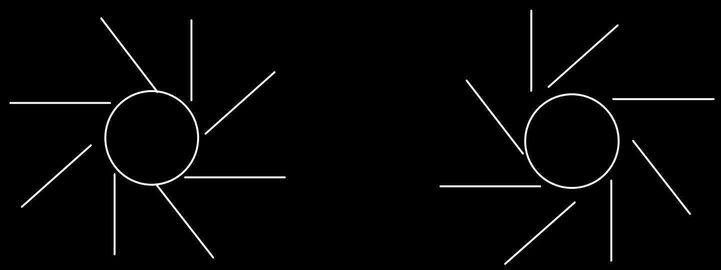
E and B modes polarization

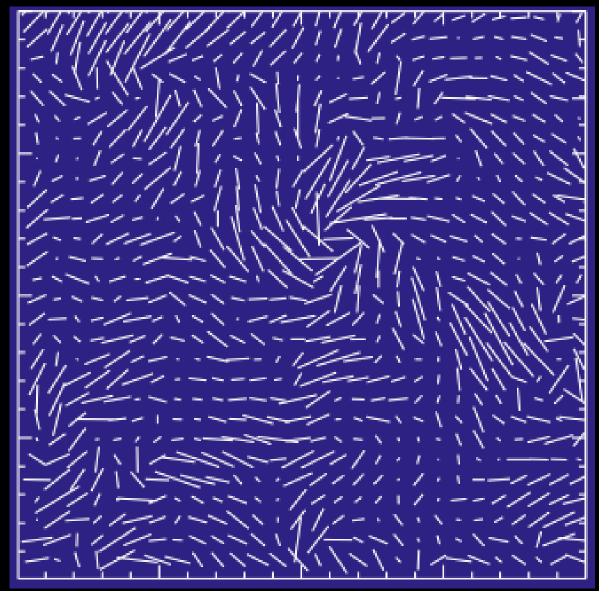
E polarization
from scalar and tensor modes





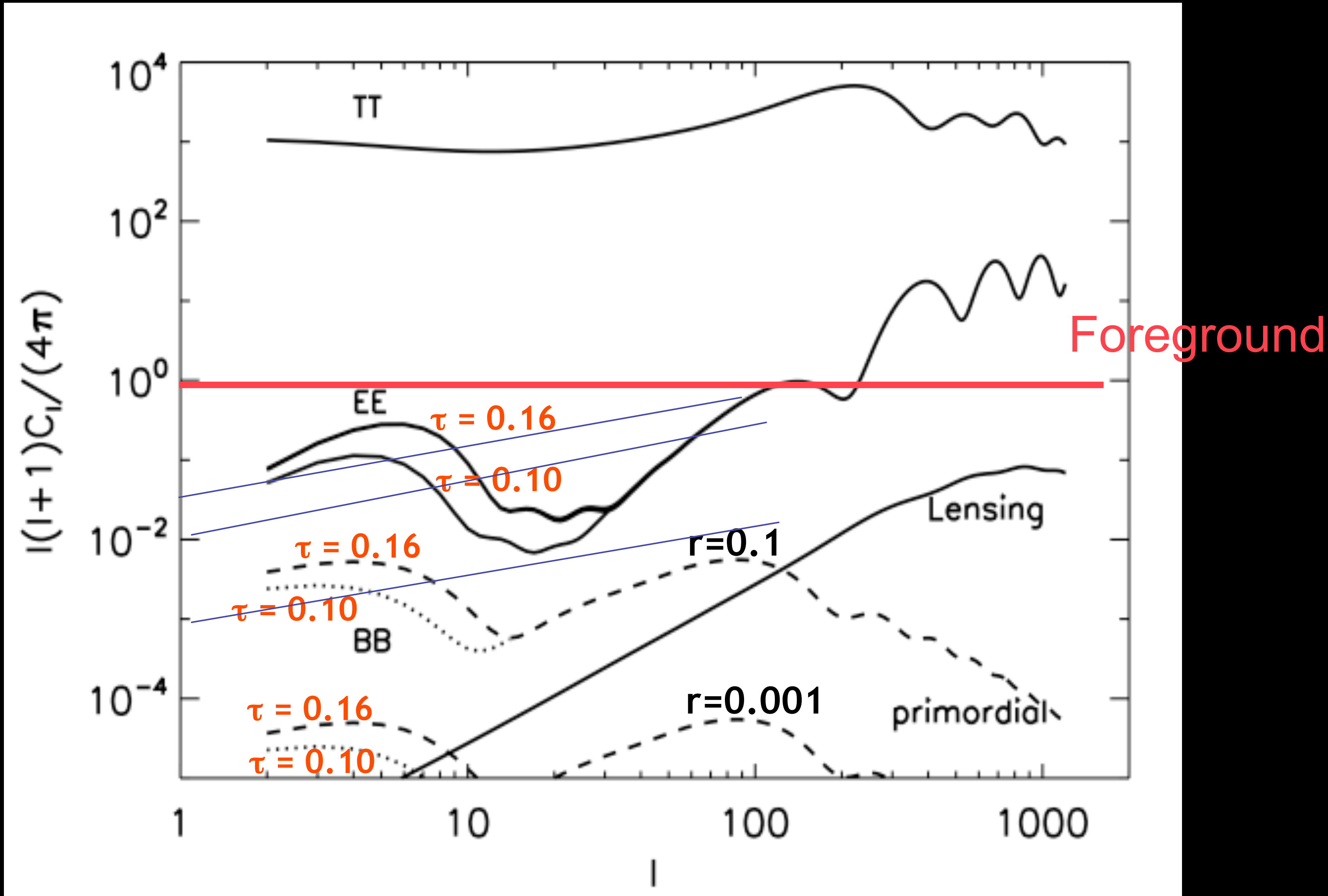
B polarization
only from tensor modes



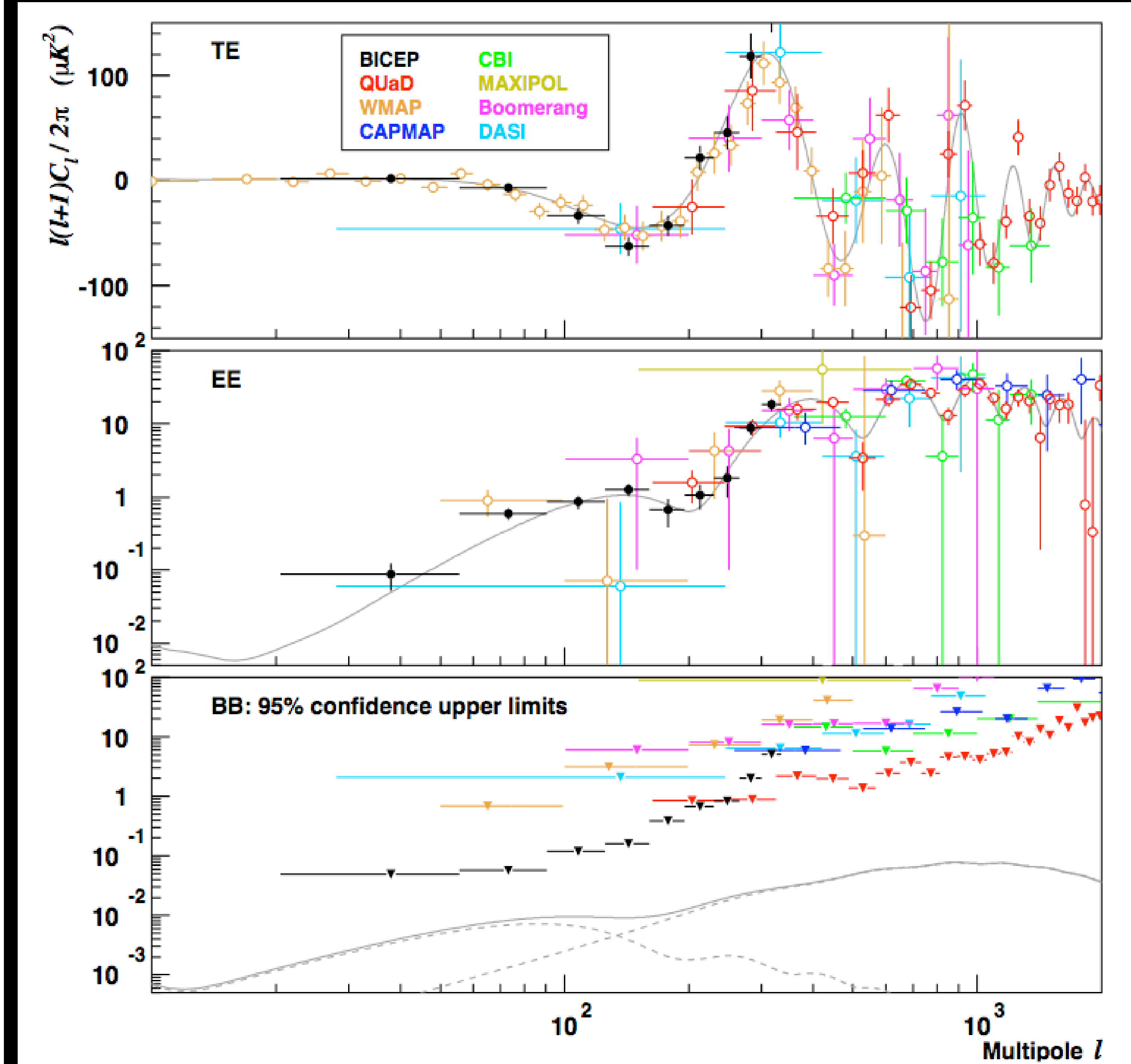


Kamionkowski, Kosowsky, Stebbings 1997, Zaldarriga & Seljak 1997

Relative Amplitudes of CMB power spectra



State of the art: polarization

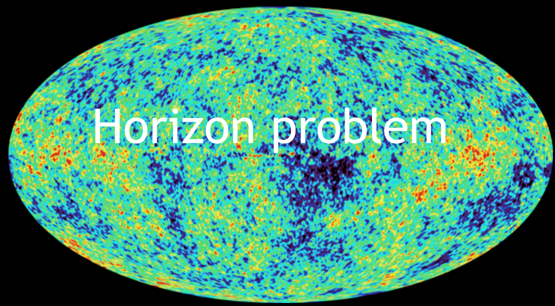


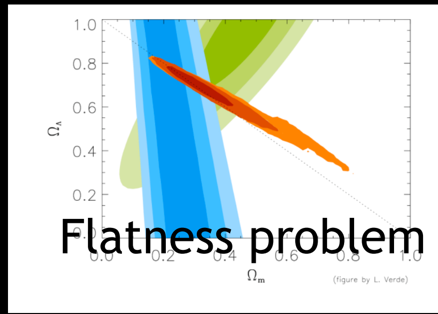
- Acoustic peaks at "adiabatic" locations
- E-mode polarization and cross-correlation with T
- Large angle polarization from reionization
- BICEP limit from BB-alone: T/S < 0.73 (95% CL)

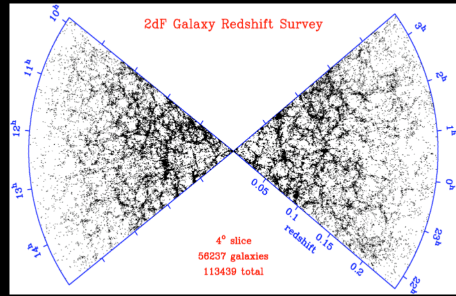
Figure: Chiang et al. (2009)

What mechanism generated the primordial perturbations?

Inflation:







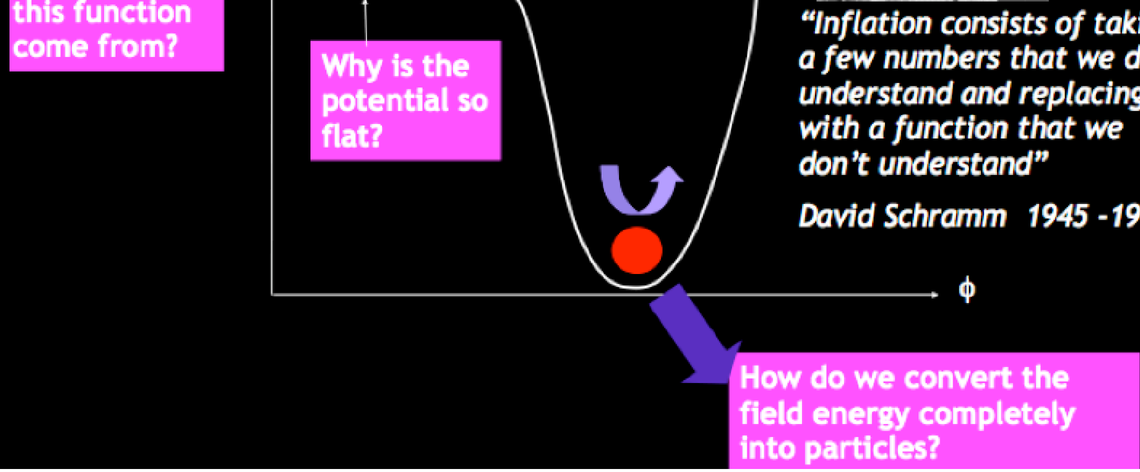
Structure Problem

Accelerated expansion:

Quantum fluctuations get stretched to become classical and "super-horizon"

The shape of the primordial power spectrum encloses information on the shape of the inflaton potential

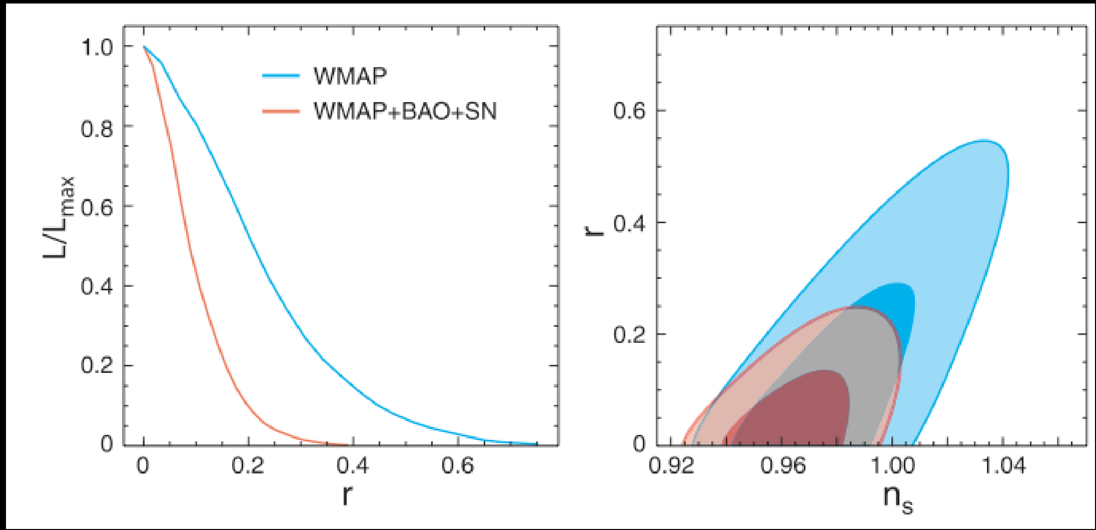
The energy scale of inflation is given by primordial tensor modes amplitude



"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

Current constraints

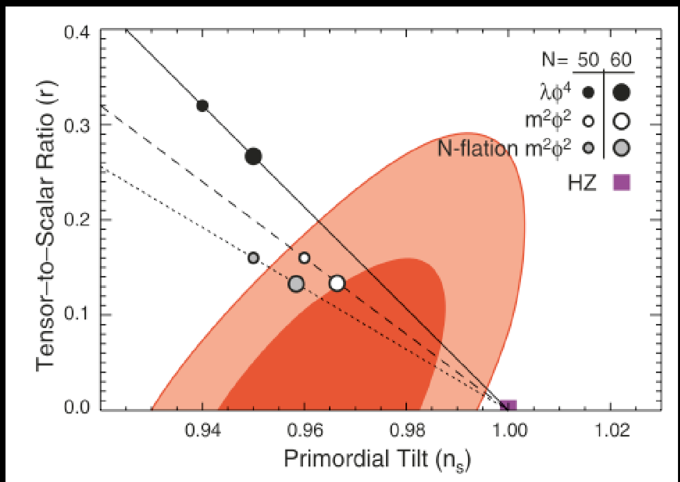


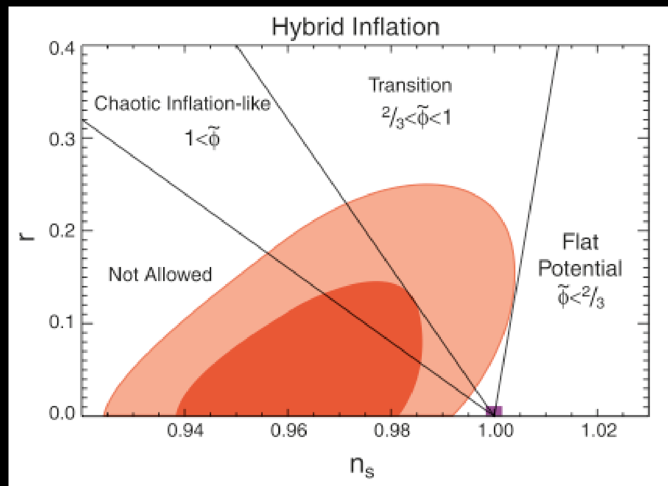
WMAP5

Komatsu et al 08

WMAP7

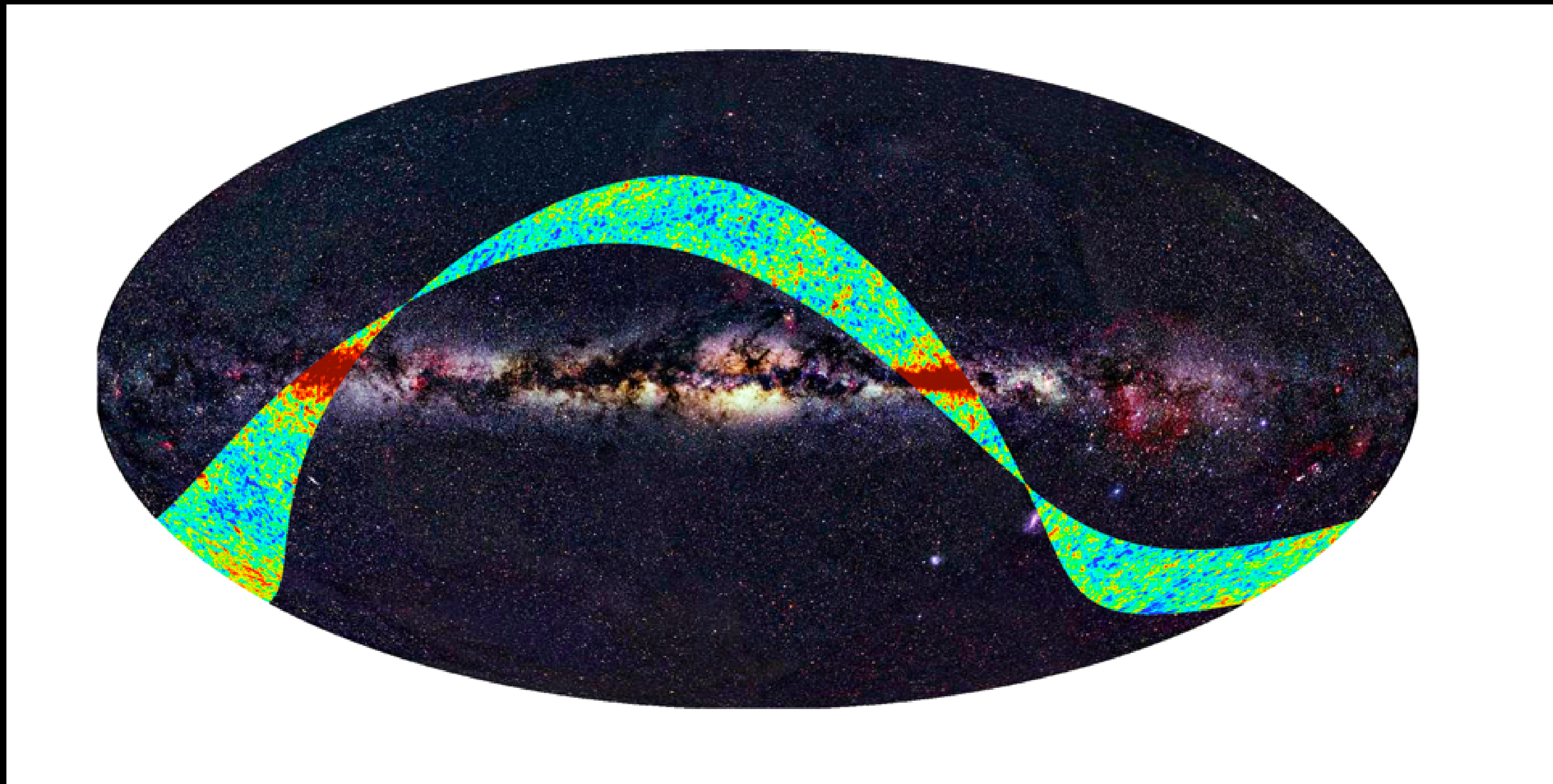
Komatsu et al 10





The future is here

Planck satellite successfully launched in May 2009!



“PR” image

The ultimate experiment for primary CMB temperature

Windows into the primordial Universe

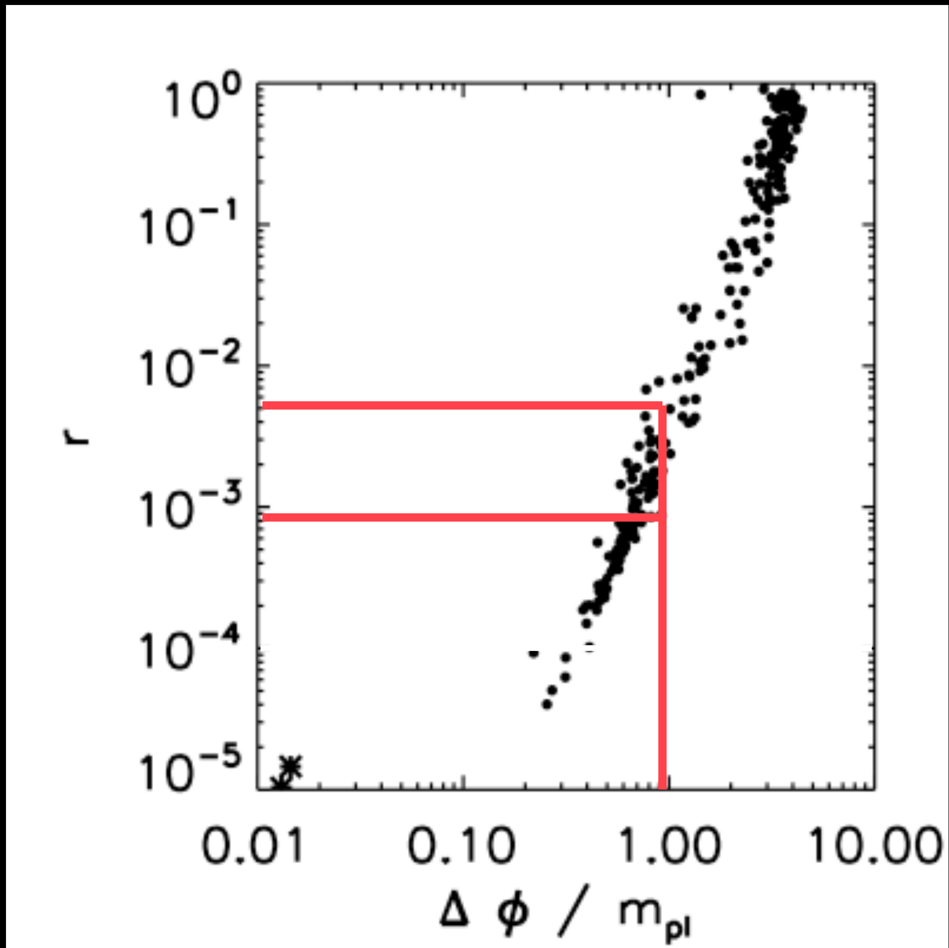
Recombination	380000 yrs	Atomic physics/GR
Nucleosynthesis	3 minutes	Nuclear phyiscs
LHC		TeV energies
inflation	10^{-30} s (?)	GUT?

Big BANG

Clues about high-energy physics with the CMB polarization

Monte Carlo simulation of the inflationary flow equations.

$$\frac{\Delta\phi}{m_{Pl}} \approx 6\, r^{1/4}$$



3.2×10^{13}

1.7×10^{13}

9.7×10^{12}

5.5×10^{12}

3×10^{12}

TeV

LV, Peris, Jimenez 2005

A “critical value” … the dream of (CM)BPol

LCDM: the "standard" model for cosmology

Test physics on which it is based and beyond it

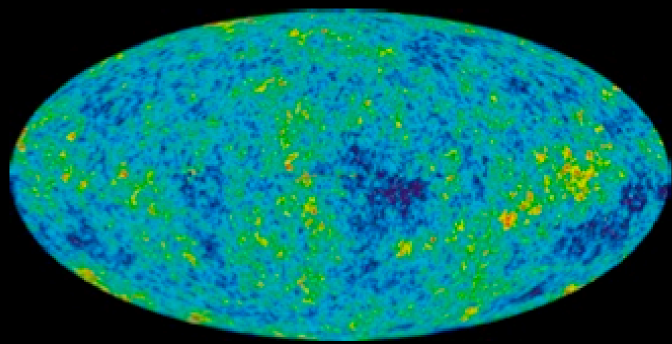
Neutrinos, initial conditions, etc.

Homogenous background

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

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

Perturbations



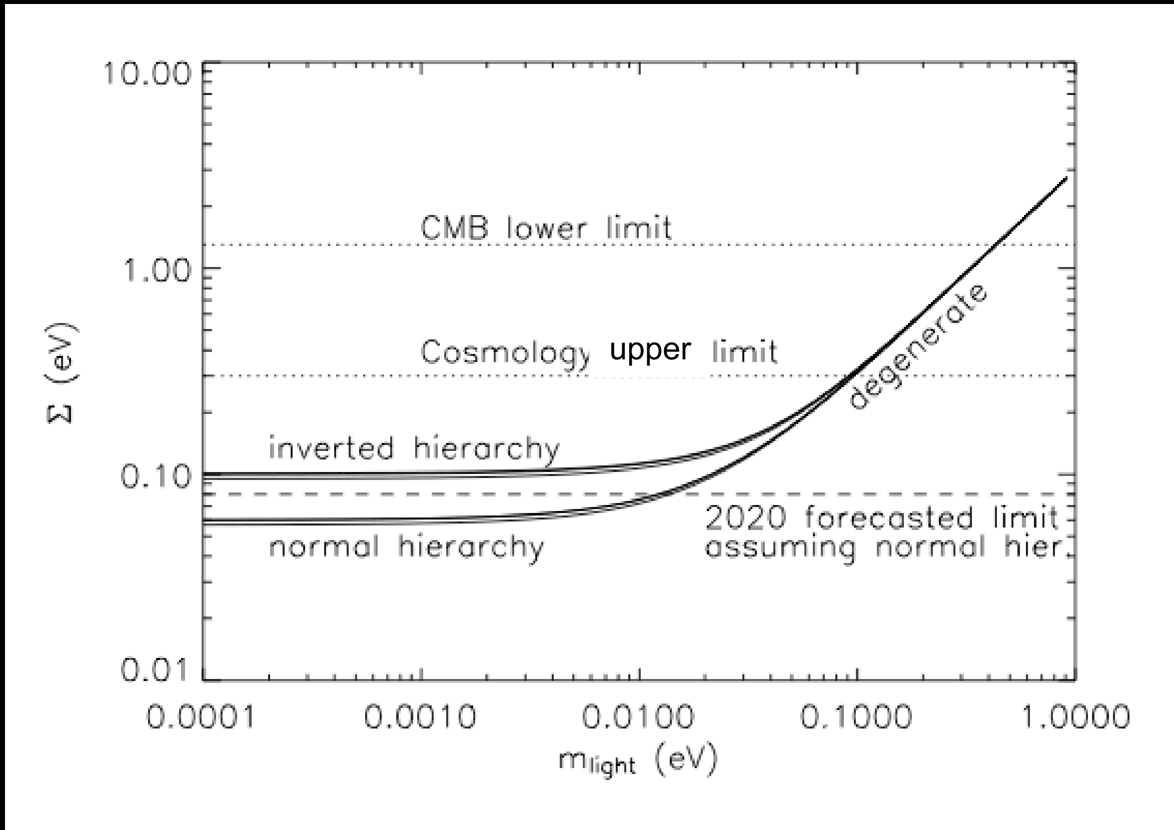
$$A_s, n_s, r$$

- nearly scale-invariant
- adiabatic
- Gaussian

What about the lower -z Universe? Beyond the vanilla model

Example: neutrinos

Cosmology is the key to determine the absolute mass scale



See Percival talk

(Robust) Neutrino mass constraints (Reid et al 2010, JCAP)

Physical effects

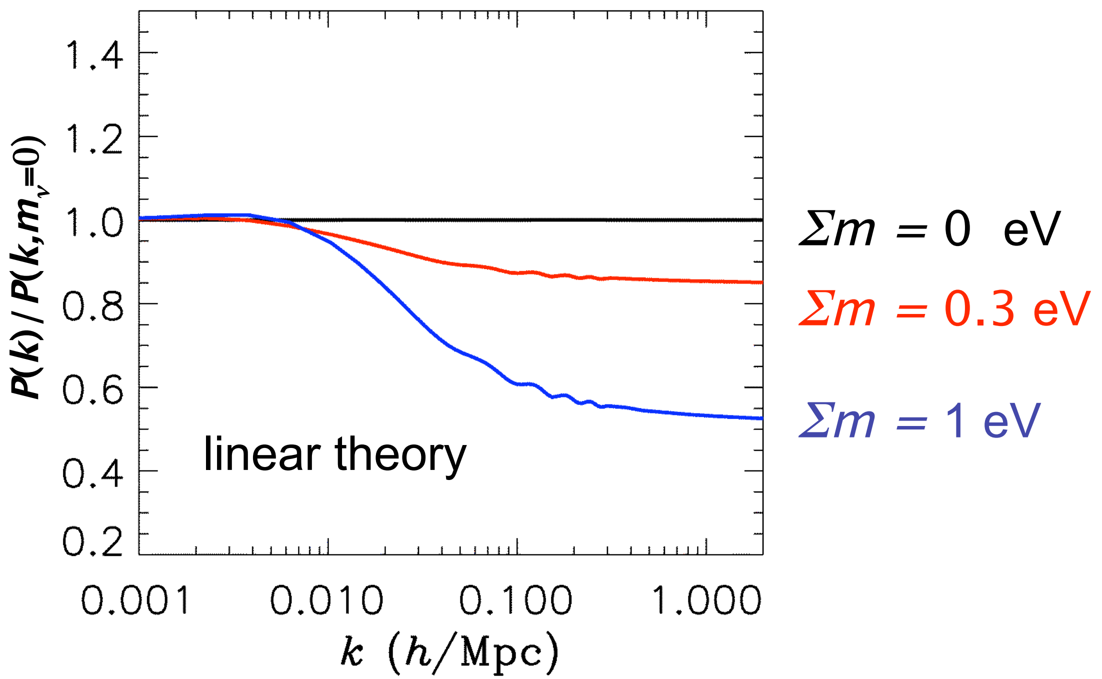
Total mass >~1 eV become non relativistic before recombination CMB

Total mass <~1 eV become non relativistic after recombination:
alters matter-radn equality but effect can be "cancelled"
by other parameters

Degeneracy

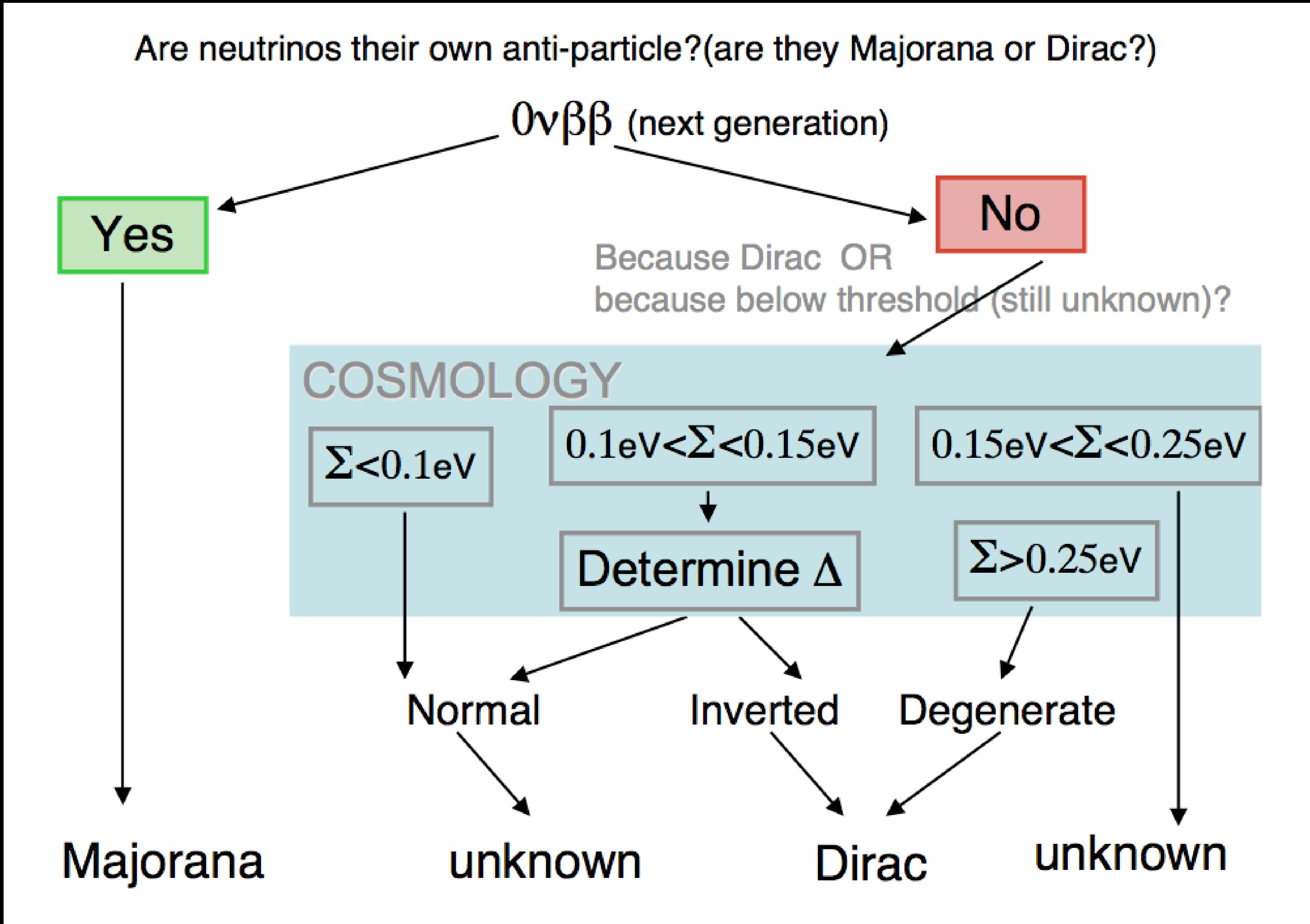
After recombination

FINITE NEUTRINO MASSES SUPPRESS THE MATTER POWER SPECTRUM ON SCALES SMALLER THAN THE FREE-STREAMING LENGTH



Different masses become non-relativistic a slightly different times

Complementarity



Jimenez, Garay, Kitching, LV, 2010

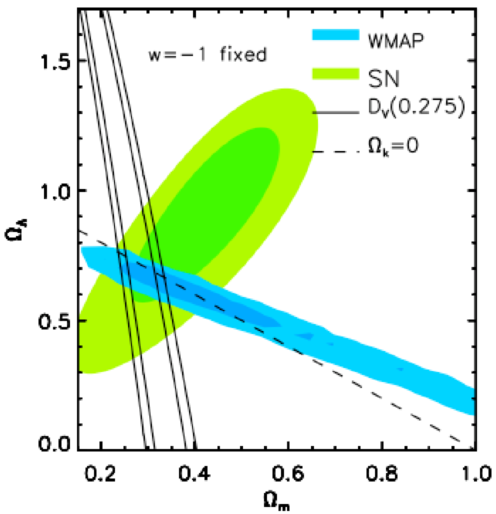
Insights into exotic physics from distance measures

Distance measures: $d_A(z)$, $d_L(z)$, $H(z)$

Both d_A and d_L are $\propto \int_0^z \frac{1}{H(z)} dz$

SN

$$d_L(z) = (1+z)^2 d_A(z)$$



Percival et al 09

Cosmology!

$$d_L(z) \stackrel{?}{=} (1+z)^2 d_A(z)$$

Photon conservation!

$$d_L = \sqrt{\frac{L}{4\pi F}}$$

Transparency
Axions, Chameleons
Mini-charged particles

Avgoustidis, Verde, Jimenez, 2009,JCAP 0906:012
Avgoustidis, Burrage, Redondo, Verde, Jimenez, arxiv:1004.2053

THE IDEA

$$d_L(z) \overset{?}{=} (1+z)^2 d_A(z)$$ Etherington relation

$$d_L = \sqrt{\frac{L}{4\pi F}}$$ Violate photon conservation

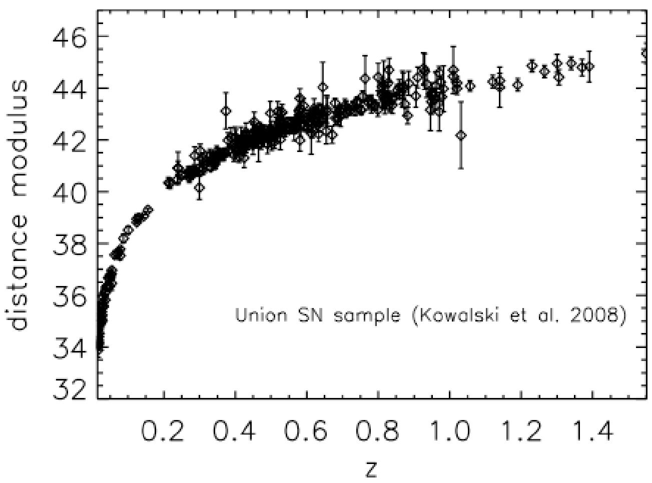
$$d^2_{L,obs} = d^2_{L,true} e^{\tau(z)}$$ "opacity"

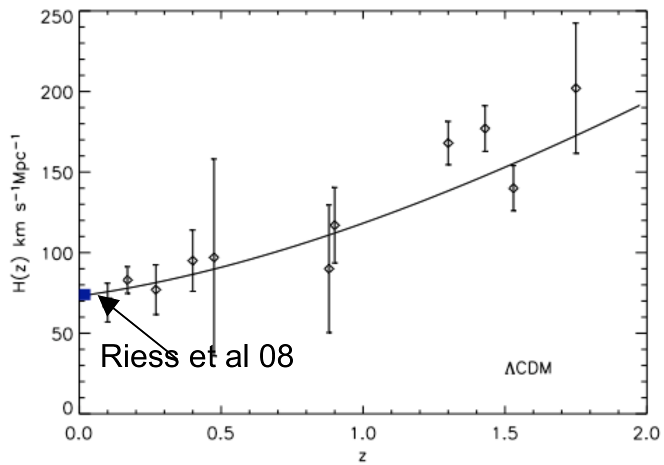
Measure from SN observations

Predict from H(z) data

Constrain!

& interpret



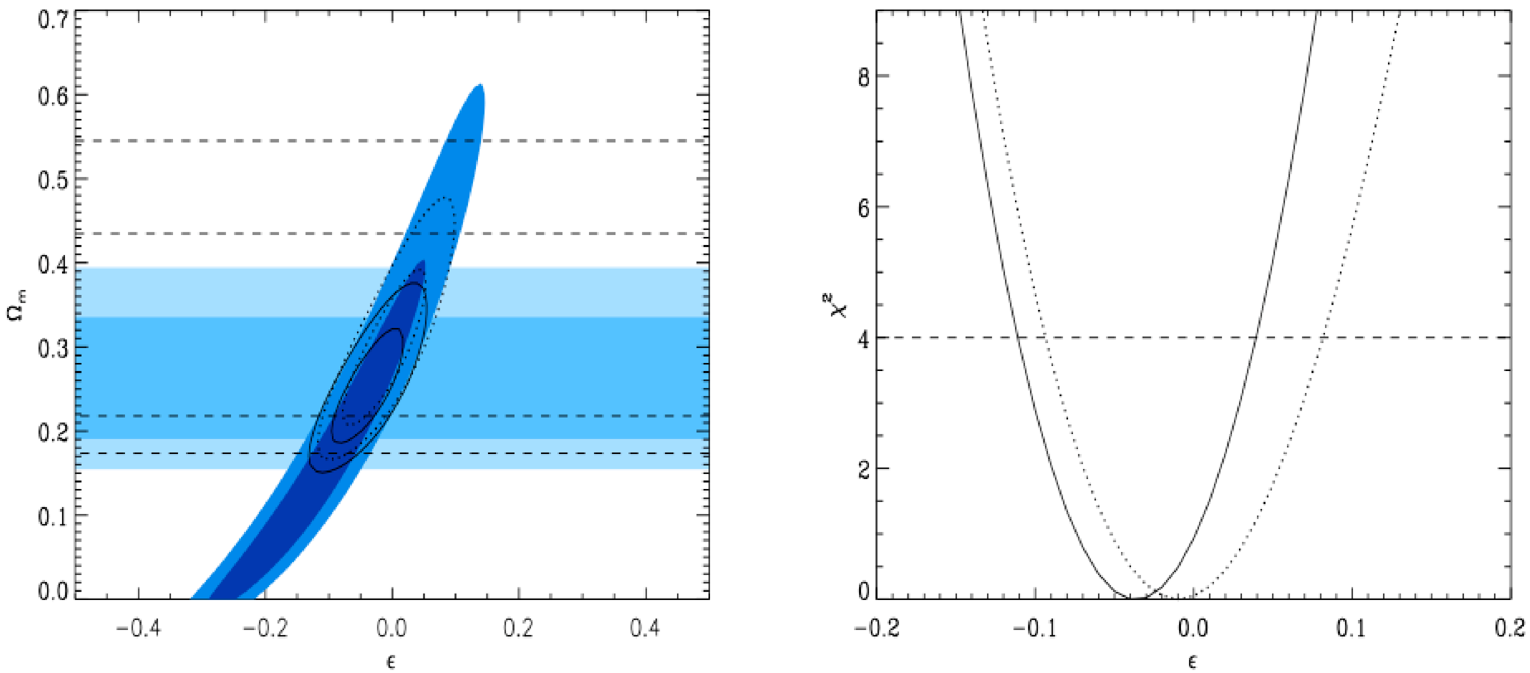


Stern, Jimenez, Verde, Kamionkowski, Stamford, 2009

Transparency (parametric)

Bovy et al. 2008, BAO+SNe non-parametric

$$d_L(z) = d_A(z)(1+z)^{2+\epsilon}$$



$$\epsilon = -0.04^{+0.08}_{-0.07} \text{ at } 95\%$$

τ (z) ~ 2ε¸z

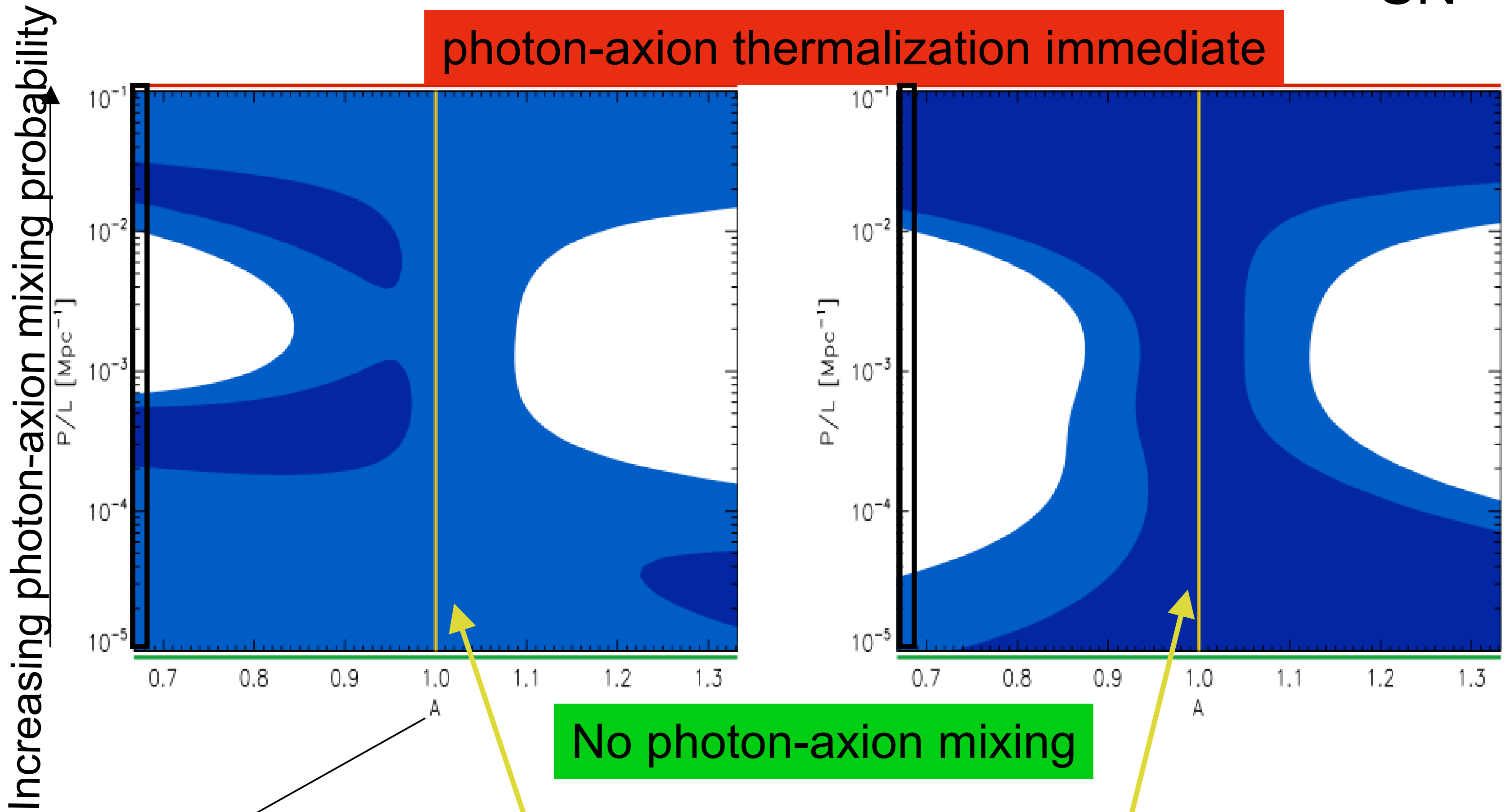
$$\tau = (1+z)^{\alpha} - 1 \longrightarrow \alpha = 2\epsilon$$

Axion-like particles
Chameleons

SN only

SN +H(z)

photon-axion thermalization immediate



No photon-axion mixing

Defines initial flux mix

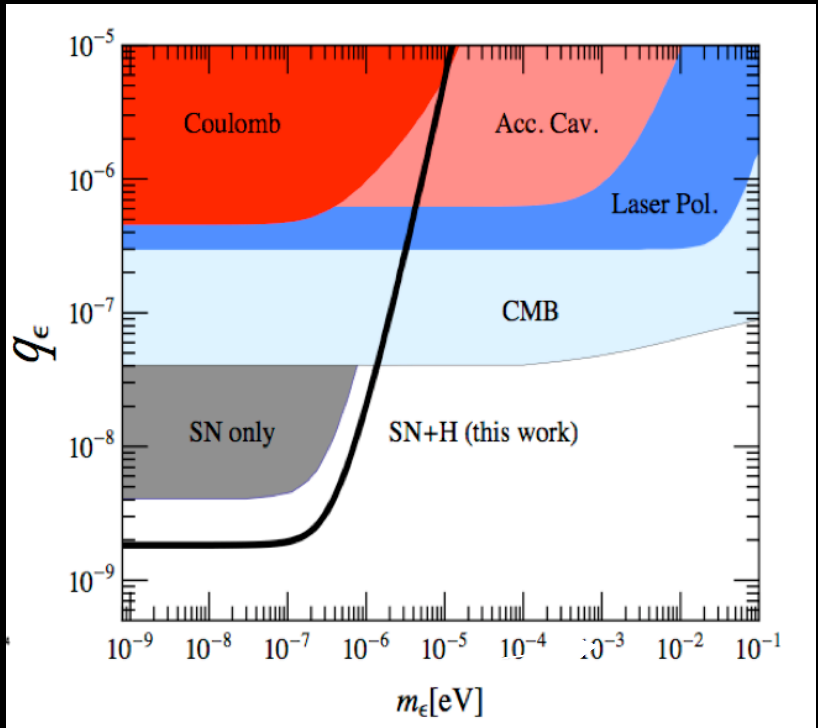
Equilibrated Photon-axion flux from SNe:
no propagation effect

Insights into dark matter from distance measures

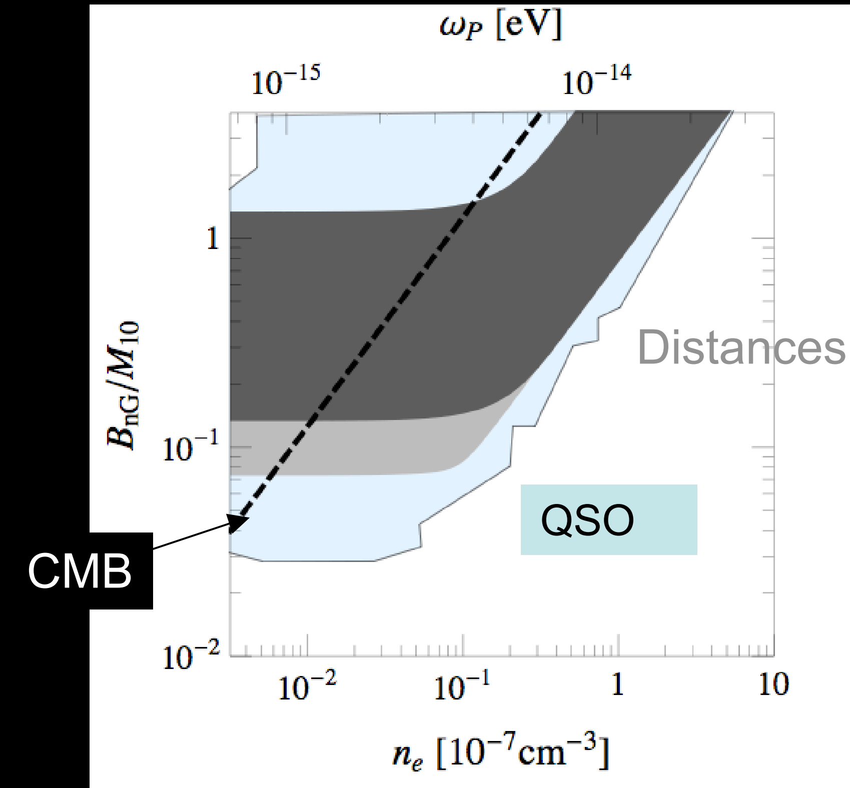
$$d_L(z) \stackrel{?}{=} (1+z)^2 d_A(z)$$

Photon conservation!

Transparency
Axions, Chameleons
Mini-charged particles



Mini charged particles

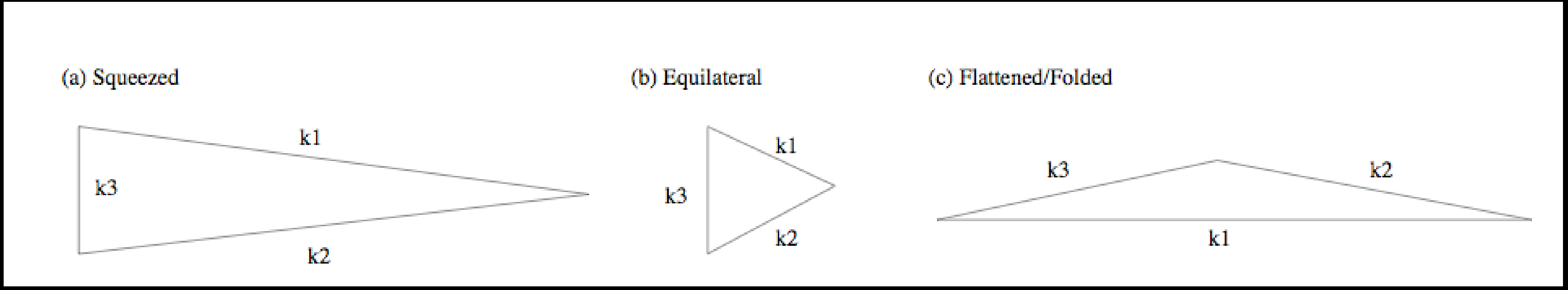


Axions

Avgoustidis, Verde, Jimenez, 2009,JCAP 0906:012
Avgoustidis, Burrage, Redondo, Verde, Jimenez, _arxiv:1004.2053

Non-Gaussinaity

Probes the interaction of the field(s) during inflation



Non-gaussianity is <u>unobservable in many single field, slow roll models</u> IF

Single field only one quantum filed driving inflation and generating perturbations

Canonical kinetic energy speed propagation of fluctuations is speed of light

Slow roll field evolution slow compared to Hubble time during inflation

Initial bunch-Davies vacuum the quantum field was in the preferred adiabatic vacuum state just before fluctuations generation

A detectable amount is created when <u>any</u> of these conditions is violated

"Non-dog is my co-pilot"

What about other shapes?

It is crucial to test on N-body simulations, both the bias and the mass function. Non trivial problem.

Christian Wagner, LV, L. Boubekeur, 2010, JCAP, arXiv:1006.5793

Solution (CMB-inspired)

$$\Phi_{\mathbf{k}} = \Phi_{\mathbf{k}}^{G} + \Phi_{\mathbf{k}}^{NG}$$

$$\Phi_{\mathbf{k}}^{NG} = \frac{1}{6(2\pi)^3}\int d^3k_2 d^3k_3 B(k,k_2,k_3)\delta^D(\mathbf{k}+\mathbf{k}_2+\mathbf{k}_3)\frac{\Phi_{\mathbf{k}_2}^{*G}\Phi_{\mathbf{k}_3}^{*G}}{P(k_2)P(k_3)}$$

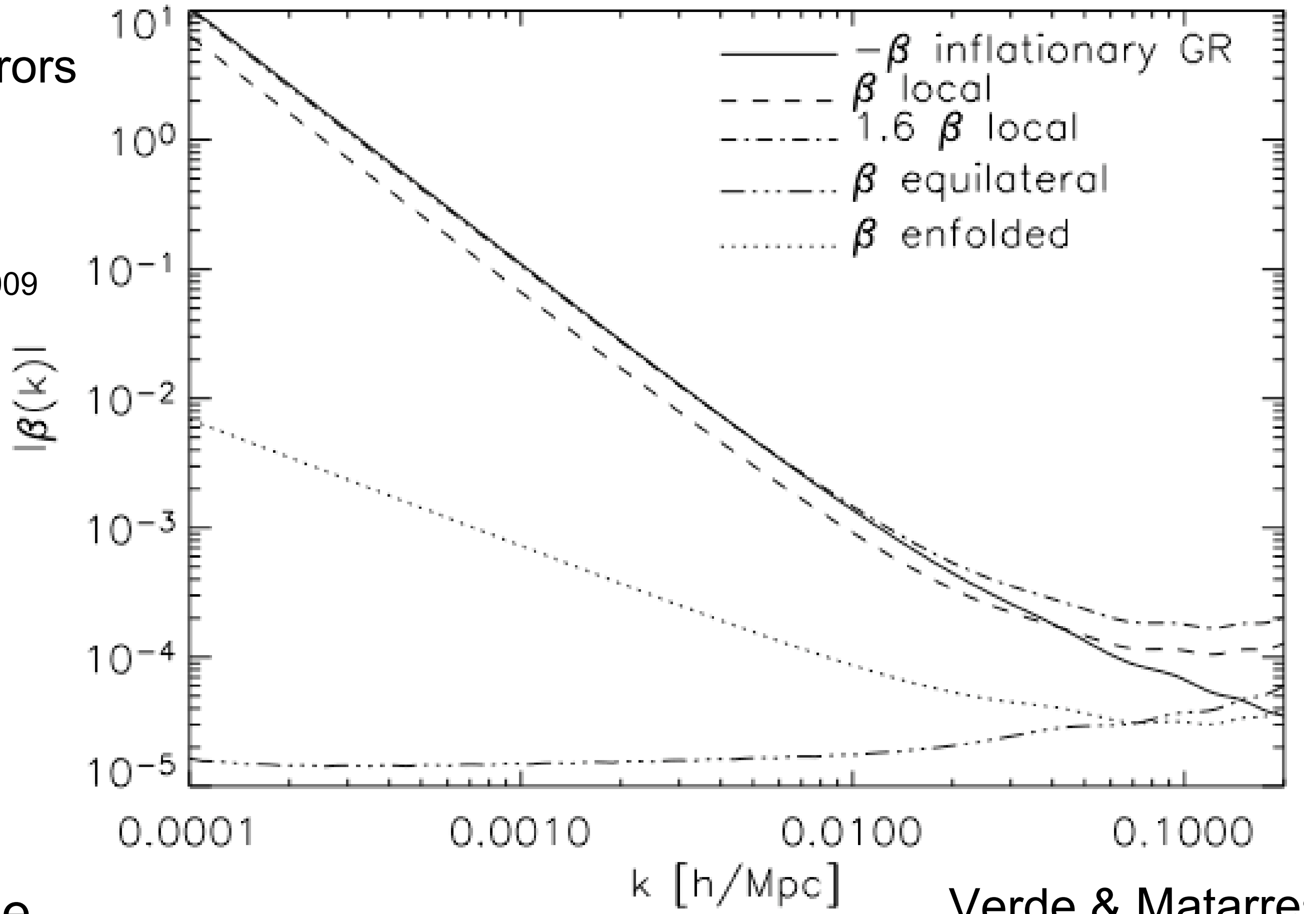
$$= \frac{1}{6(2\pi)^3}\int d^3k_2 B(k,k_2,|\mathbf{k}+\mathbf{k}_2|)\frac{\Phi_{\mathbf{k}_2}^{*G}}{P(k_2)}\frac{\Phi_{\mathbf{k}+\mathbf{k}_2}^{G}}{P(|\mathbf{k}+\mathbf{k}_2|)}$$

$$\Phi_{\mathbf{k}}^{NG} = \frac{1}{6}\sum_{\mathbf{k}'} B(k,k',|\mathbf{k}+\mathbf{k}'|)\frac{\Phi_{\mathbf{k}'}^{*G}}{P(k')}\frac{\Phi_{\mathbf{k}+\mathbf{k}'}^{G}}{P(|\mathbf{k}+\mathbf{k}'|)}$$

Non-Gaussian halo bias

Forecasted errors of ~ unity

e.g., Carbone, LV, Matarrese 2008, Carbone, Mena, LV, 2009



1. shape

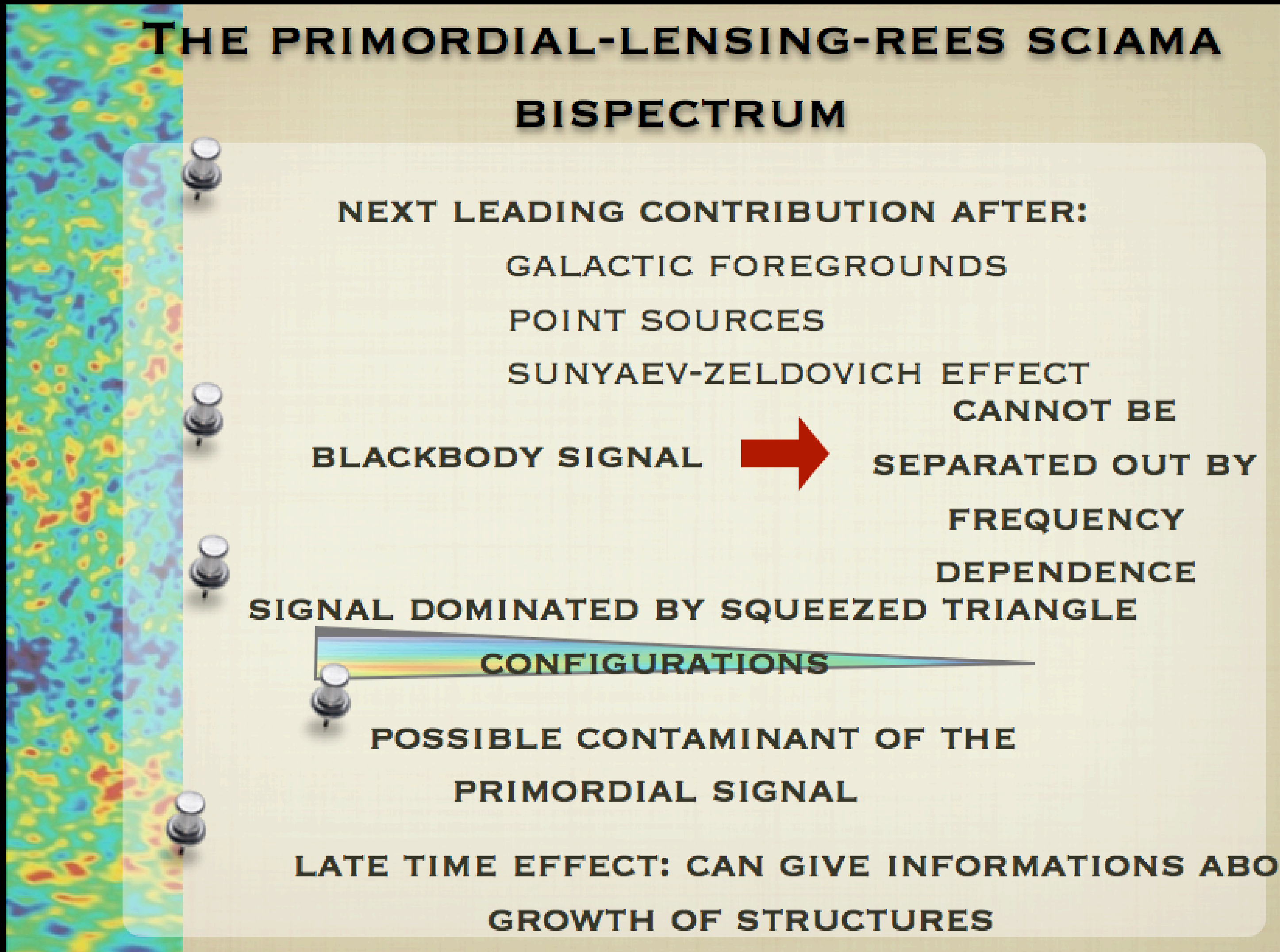
Verde & Matarrese 2009

2. On horizon-scales Poisson equation gets quadratic corrections: Needs IC set up of inflation, parallels the TE anti-correlation.

At a potentially detectable level!

CMB non-gaussianity

Planck $\Delta f_{NL}=3$ CMB-Pol $\Delta f_{NL}=2$



Mangilli, LV, Phys. Rev. D 80, 123007 (2009)

One man’s trash is another man’s treasure…

PRIMORDIAL LOCAL

L-RS vs PRIMORDIAL BISPECTRUM

f_{NL} ESTIMATOR

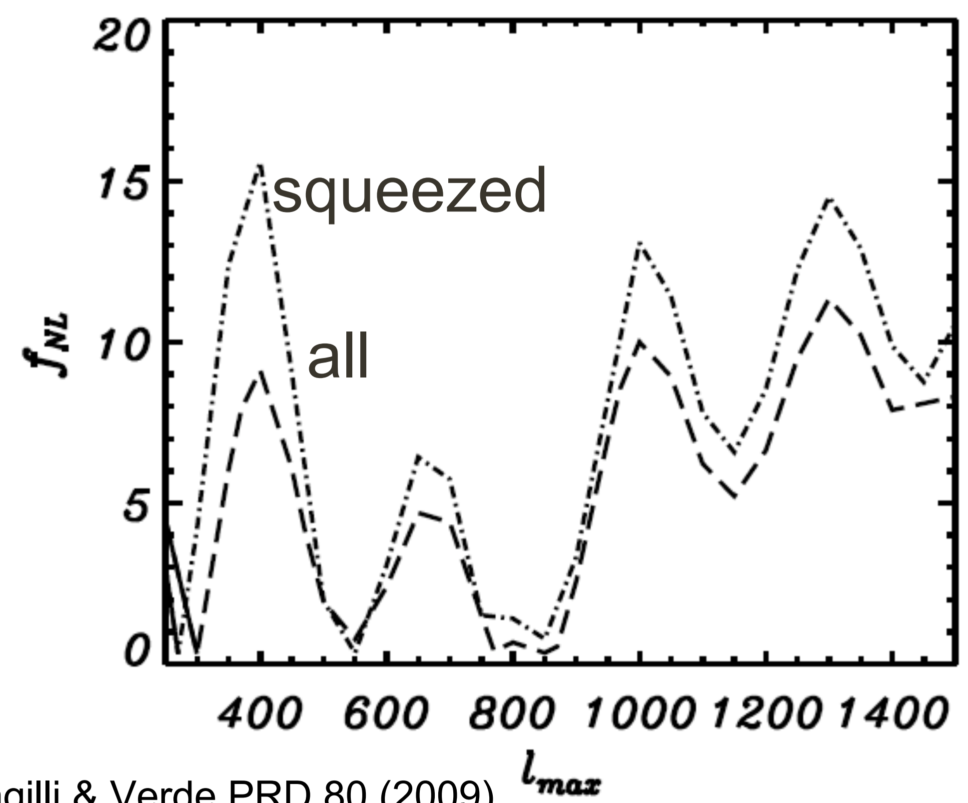
Weights the bispectrum of every triplet by the signal-to-noise of the primary bispectrum

Contamination due to the L-RS signal

$$\hat{f}_{NL} = \frac{\hat{S}}{N}$$

$$\hat{S} = \sum_{2\leqslant\ell_1\ell_2\ell_3} \frac{B^{L-RS}_{\ell_1\ell_2\ell_3}\, B^{P}_{\ell_1\ell_2\ell_3}}{C_{\ell_1}C_{\ell_2}C_{\ell_3}}$$

$$N = \sum_{2\leqslant\ell_1\ell_2\ell_3} \frac{(B^{P}_{\ell_1\ell_2\ell_3})^2}{C_{\ell_1}C_{\ell_2}C_{\ell_3}}.$$



Mangilli & Verde,PRD 80 (2009)

See also: Hansen & al, arXiv:0905.4732

Guaranteed no null result!!!

Putting it all together

Complementarity!

	CMB Bispectrum		Halo bias	
type NG	Planck	(CM)BPol	Euclid	LSST
		$1-\sigma$ errors		
Local	$3^{A)}$	$2^{A)}$	$1.5^{B)}$	$0.7^{B)}$
Equilateral	$25^{C)}$	$14^{C)}$	–	–
Enfolded	$\mathcal{O}10$	$\mathcal{O}10$	$39^{E)}$	$18^{E)}$
		$\#\sigma$ Detection		
GR	N/A	N/A	$1^{E)}$	$2^{E)}$
Secondaries	$3^{F)}$	$5^{F)}$	N/A	N/A

A) Yadav, Komatsu & Wandelt (2007) B) Carbone et al. (2008) C) Baumann et al. (2009); Sefusatti et al. (2009) E)Verde & Matarrese 2009
F) Mangilli & Verde 2009, Hanson et al. 2009

About initial conditions….

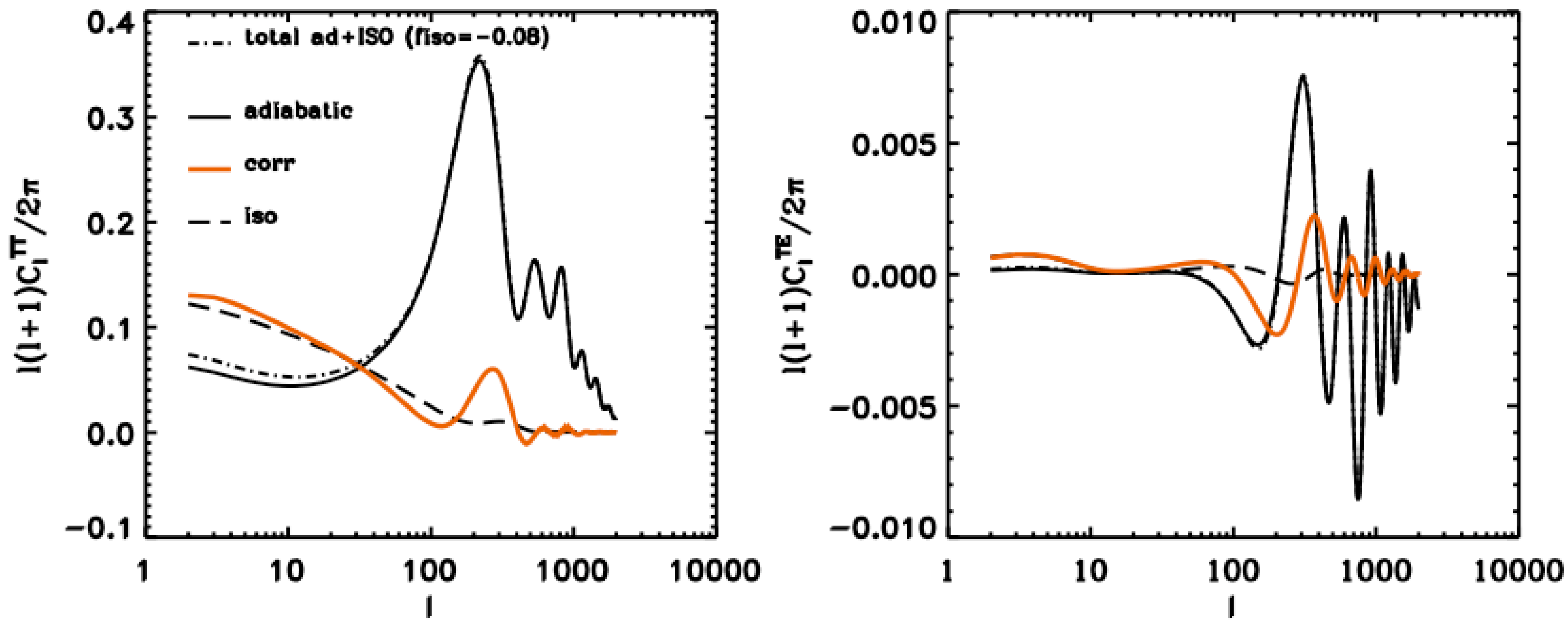
Anna Mangilli, LV, M. Beltran JCAP 2010 in press, arXiv:1006.3806

Isocurvature modes and Baryon Acoustic Oscillations

What's dark energy got to do
with the nature of the initial perturbations?

Current data allow for a mix of adiabatic+isocurvature contributions to the initial conditions; BAO science relies on the measurement of the sound horizon at radiation drag $r_s(z_d)$ from CMB.

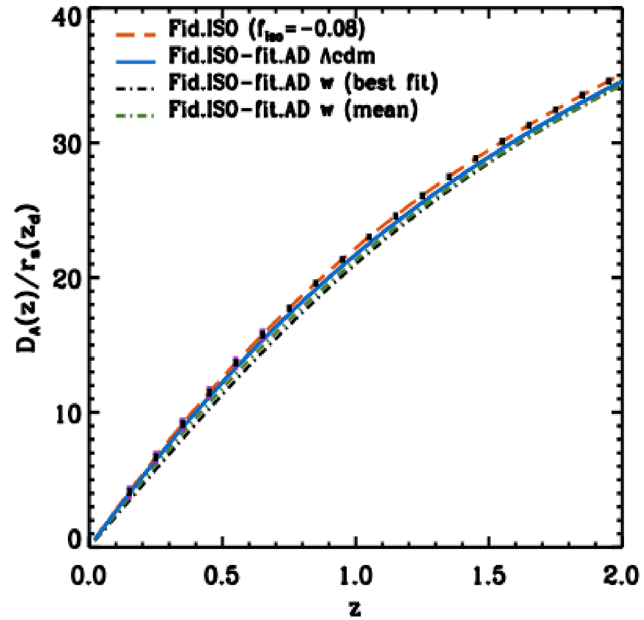
Effect of isocurvature

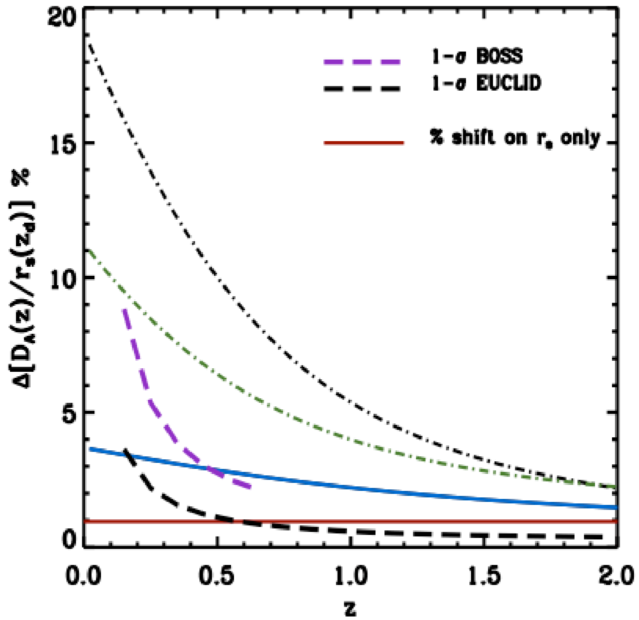


$$C_\ell = \langle \mathcal{R}^2_{rad} \rangle [C_\ell^{ad} + f_{iso}^2 C_\ell^{iso} + 2 f_{iso} \cos \Delta_{k_0} C_\ell^{cor}].$$

Neglecting isocurvatures in parameter fit, can introduce systematic shifts in estimated parameters, including $r_s(z_d)$

Effects on BAO quantities Da(z)





In order to recover an *unbiased determination for the sound horizon* and dark energy parameters, a component of isocurvature perturbations must be included in the model when analyzing CMB data. Fortunately, doing so does not increase parameter errors significantly.

On the other hand this is saying that by doing a joint fit CMB+BAO the constraints on primordial isocurvature modes can be improved (compared to CMB-only constraints)

ISOCURVATURE

Conclusions

CMB: there will be life after Planck

Precision cosmology: “from what to why”

CMB polarization is a window in the early universe
and into new physics at high energies

[other window into inflation (self)interactions is primordial non-Gaussianity]

Precision cosmology --> addressing fundamental physics questions
(examples: neutrinos, transparency, initial conditions)

Challenging!