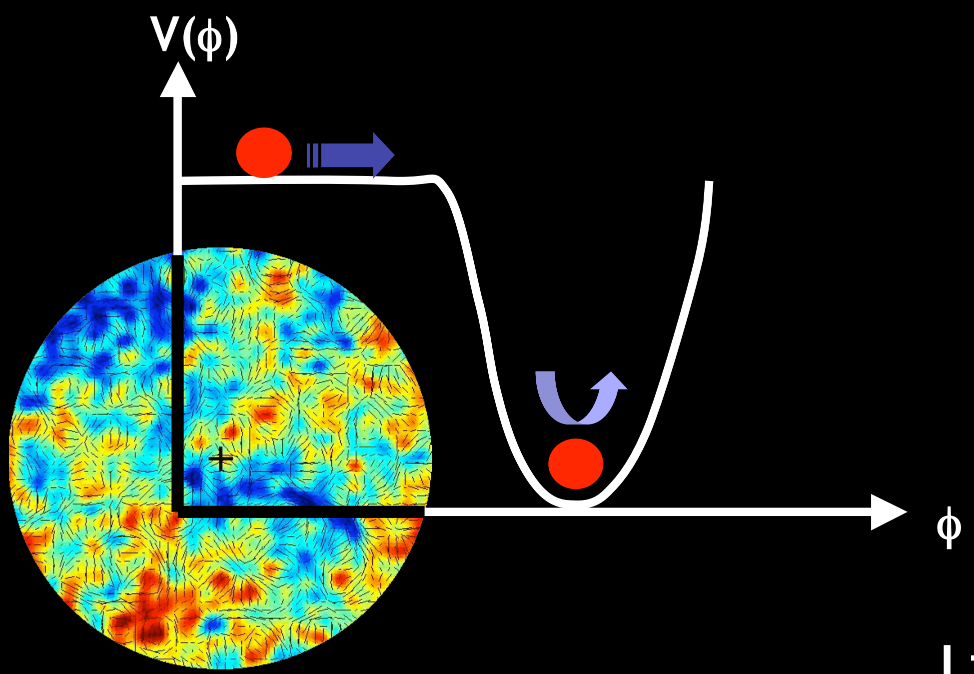
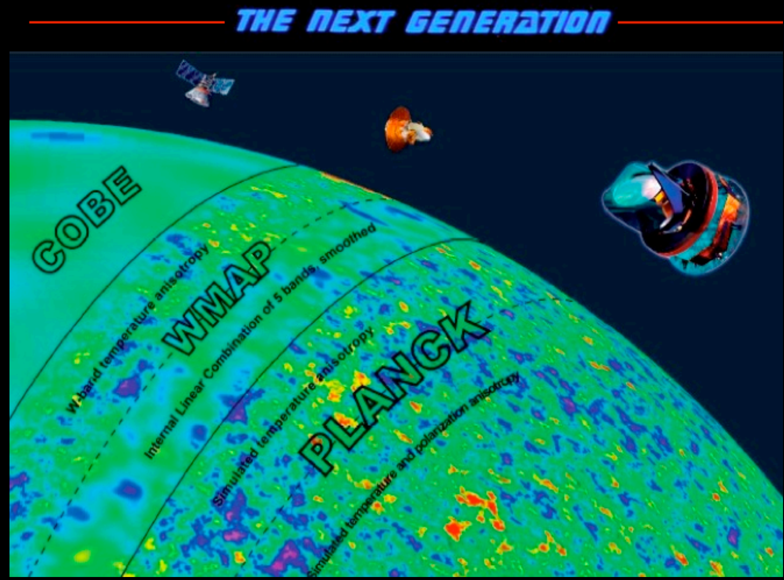
Cosmic Microwave Background
the next frontier?

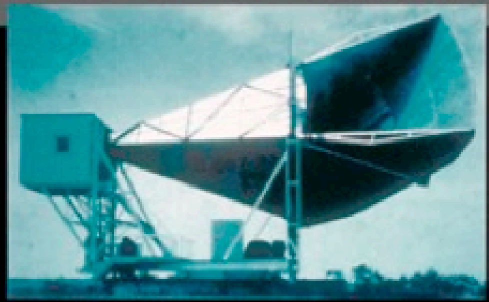




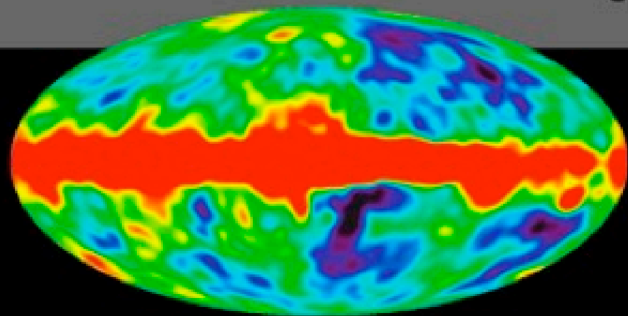
Licia Verde
ICREA & ICC
Barcelona
http://icc.ub.edu/~liciaverde

History of CMB temperature measurements

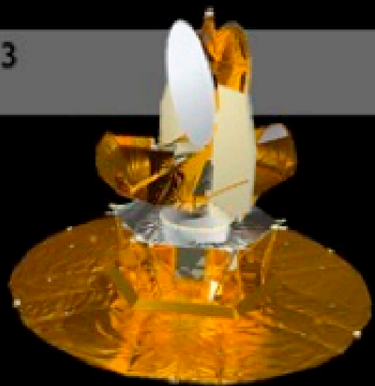
1965 — Penzias and Wilson

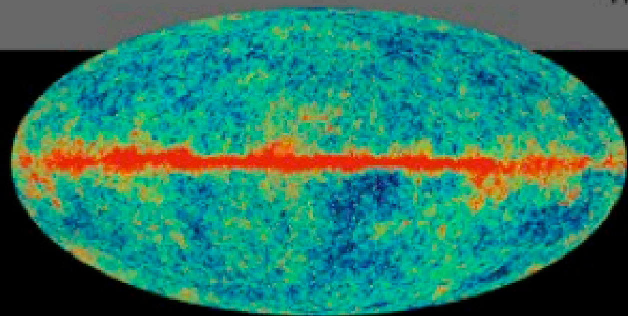


1992 — COBE



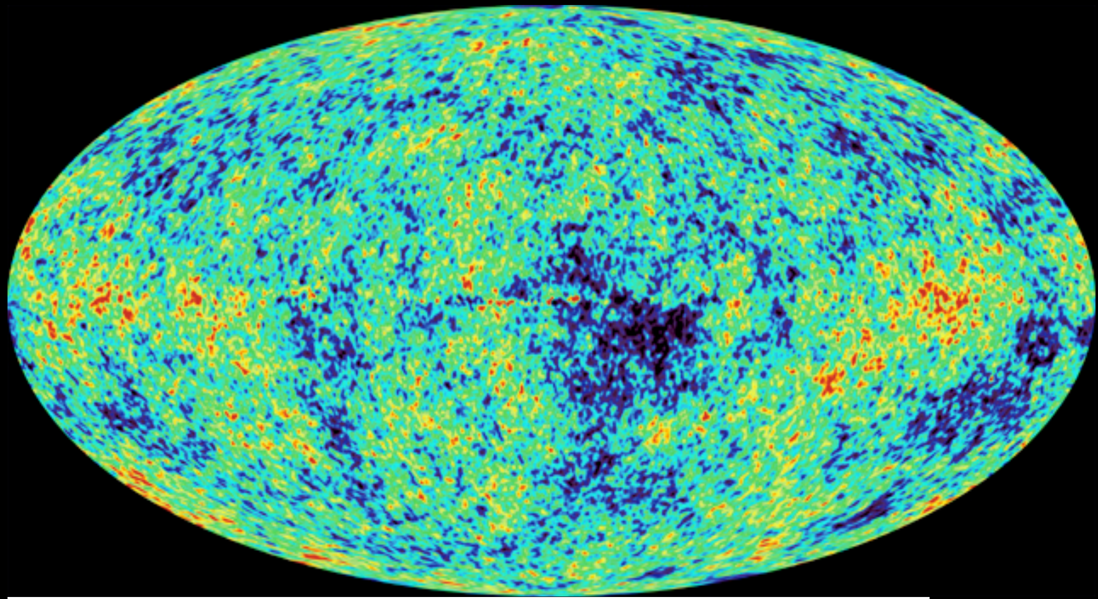
2003 — WMAP





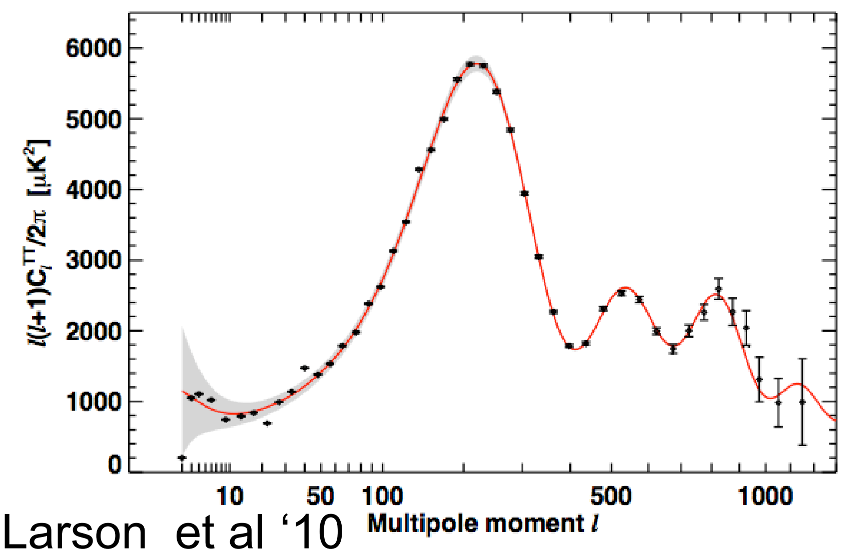
TOCO (1998) BOOMERANG (1998, 2003) MAXIMA (2000)
ARCHEOPS (2002) CBI (2002) ACBAR (2002) VSA (2002)

Importance to cosmology

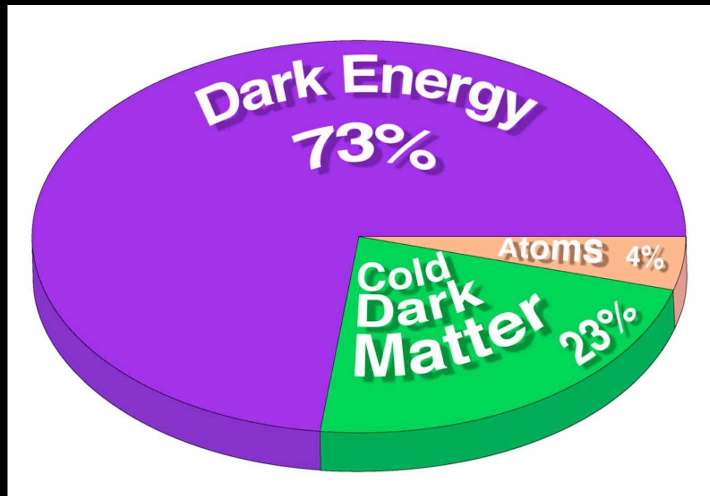


WMAP (2003)

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

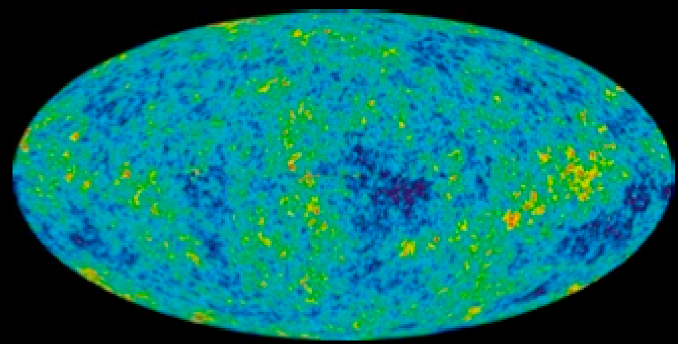
Homogenous background

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

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

Λ? CDM?

Perturbations

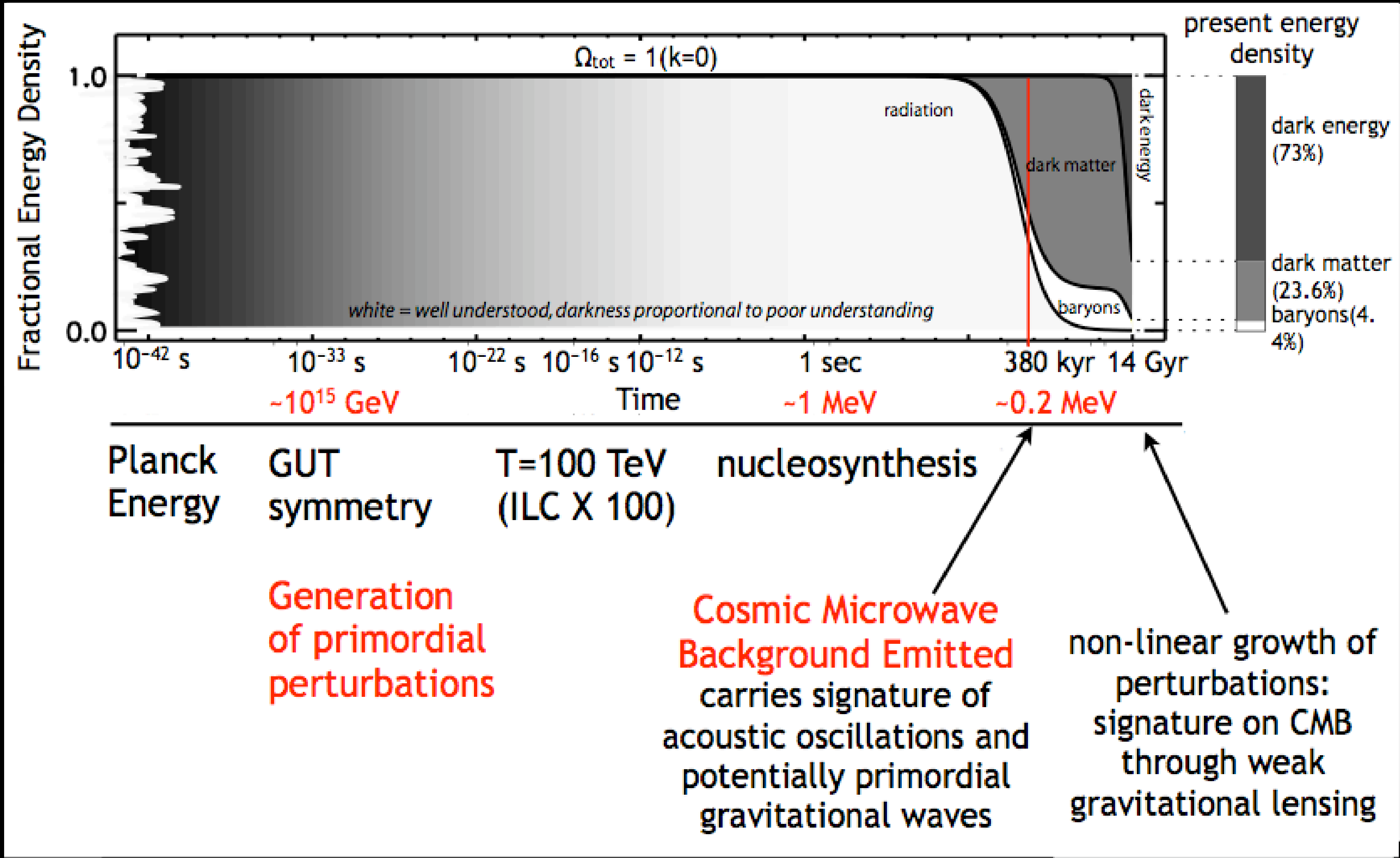


$$A_s, n_s, r$$

- nearly scale-invariant
- adiabatic
- Gaussian

ORIGIN??

Cosmic History / Cosmic Mystery

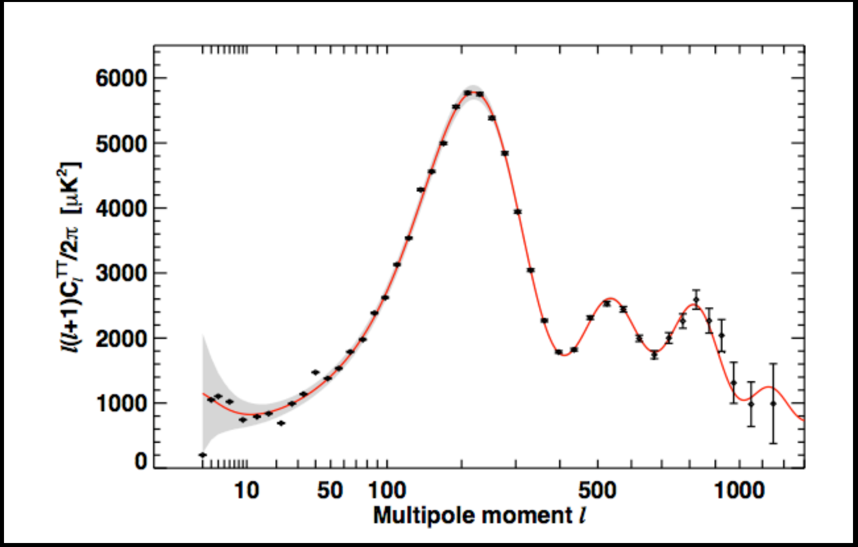


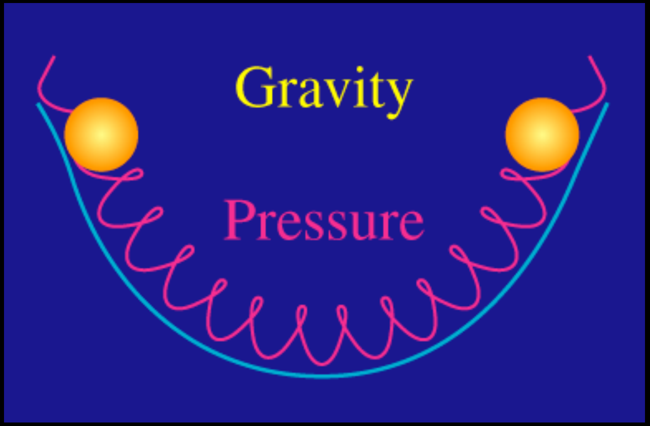
McMahon adapted by Peiris

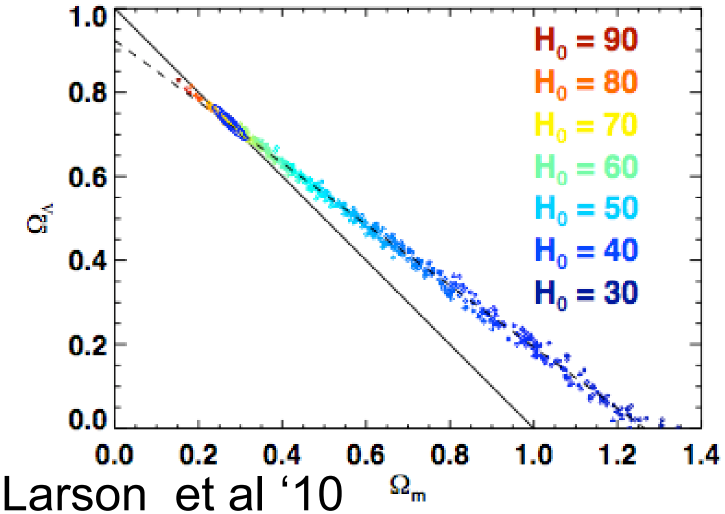
Deja vu

The era of precision cosmology:

Evidence for dark matter



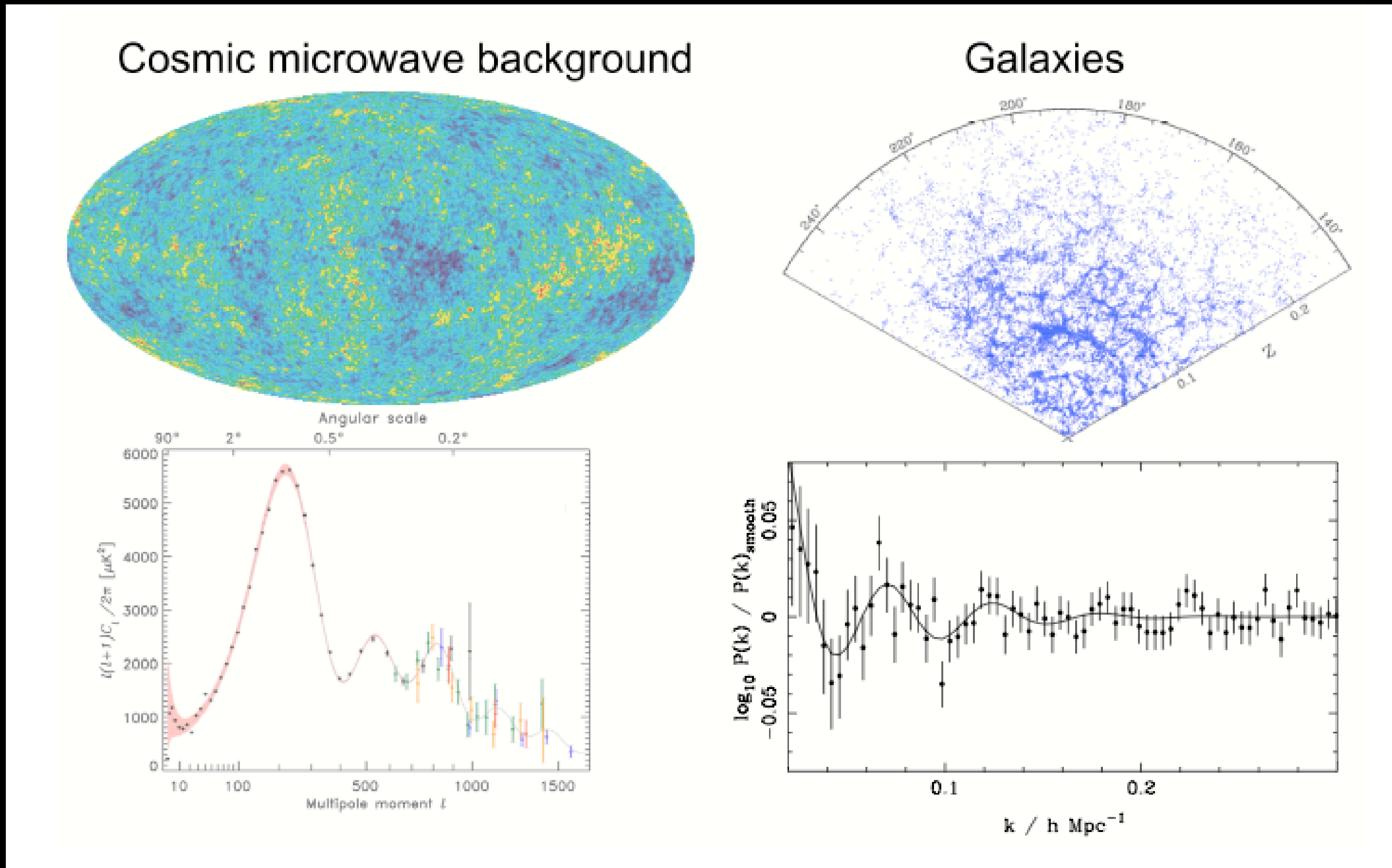




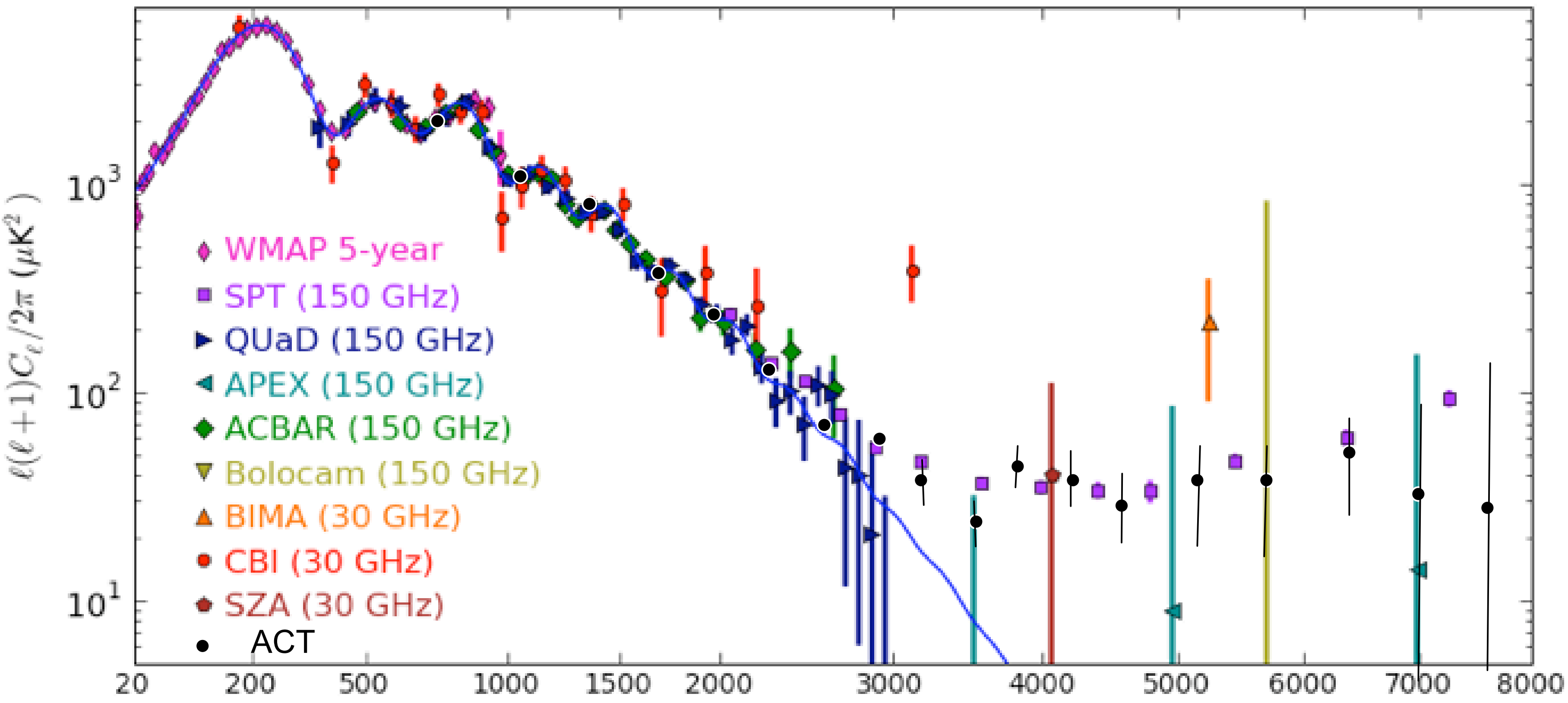
Larson et al '10

The era of precision cosmology:

Evidence for dark matter



State of the art: temperature



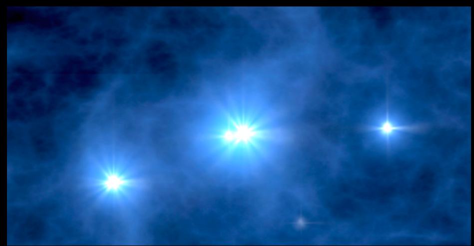
- Sachs-Wolfe plateau and the late time Integrated Sachs-Wolfe effect
- Acoustic peaks at "adiabatic" locations
- Damping tail and photon diffusion
- Weak gravitational lensing (detected in cross-correlation, Smith et al. 2007)

What next?

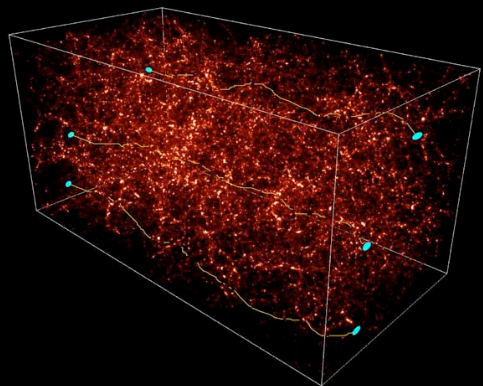
a) Beyond primary anisotropies

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

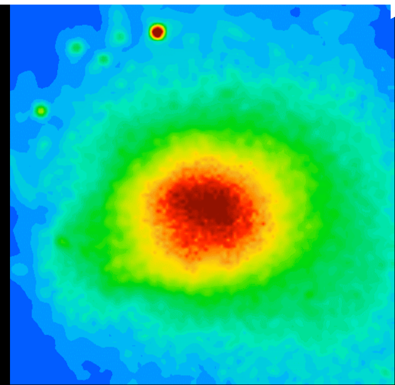
- First galaxies
- Universe is reionized
- Ostriker-Vishniac/KSZ



- weak lensing



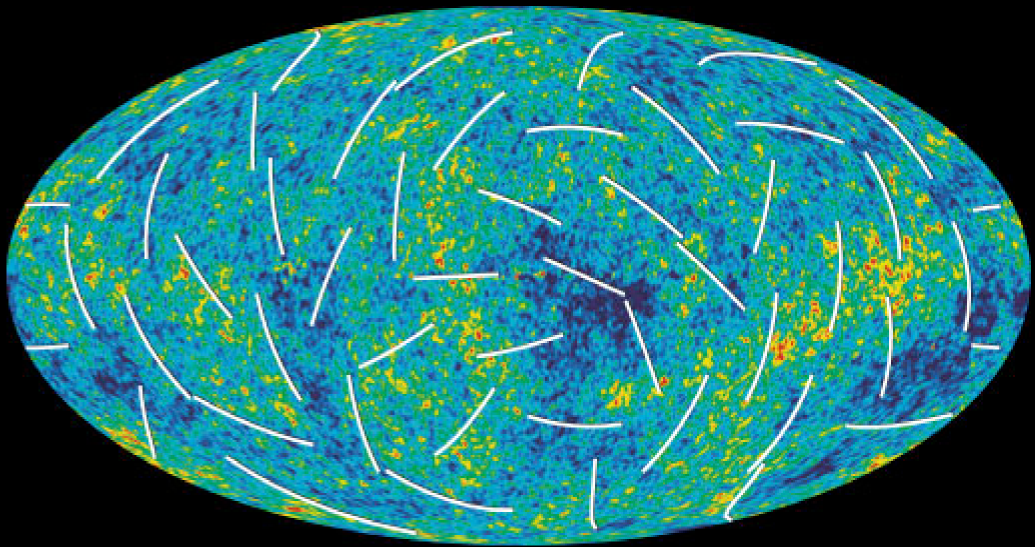
- Sunyaev-Zel'dovich (SZ) clusters
- Diffuse thermal SZ
- Kinetic SZ
- Rees-sciama/ISW



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

There's more!

Polarization

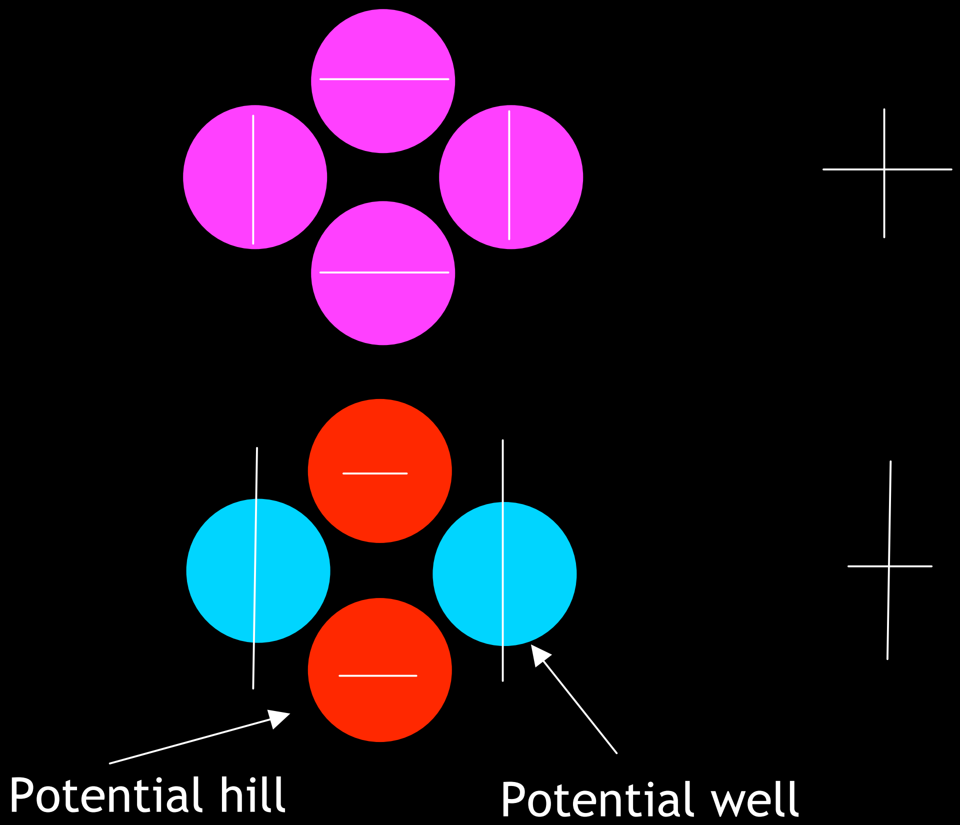


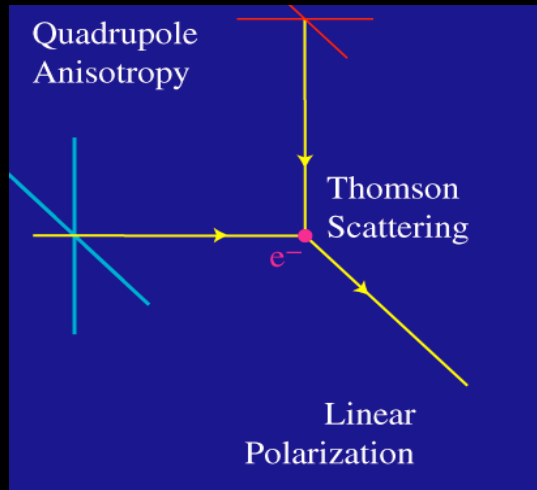
WMAP (2006)

First detected by DASI in 2002

Generation of CMB polarization

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

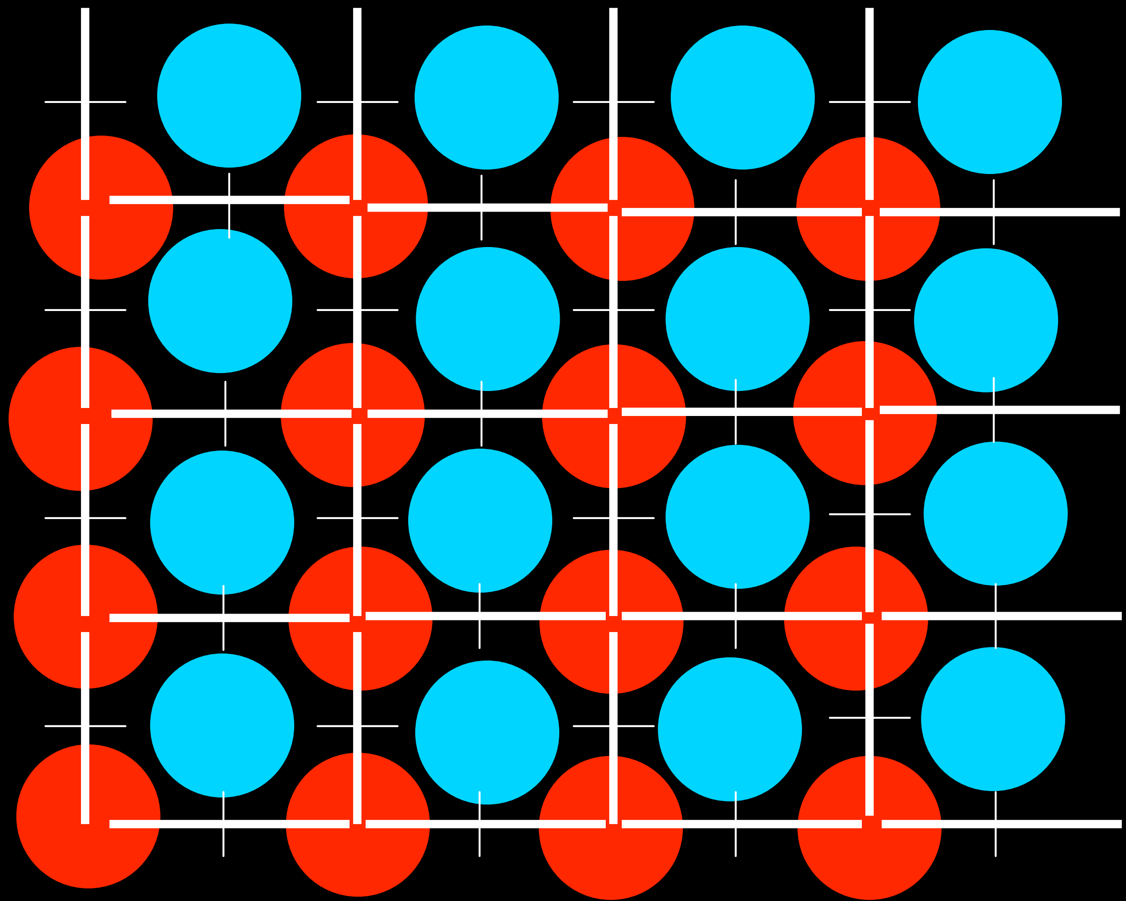




From Wayne Hu

Polarization for density perturbation

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

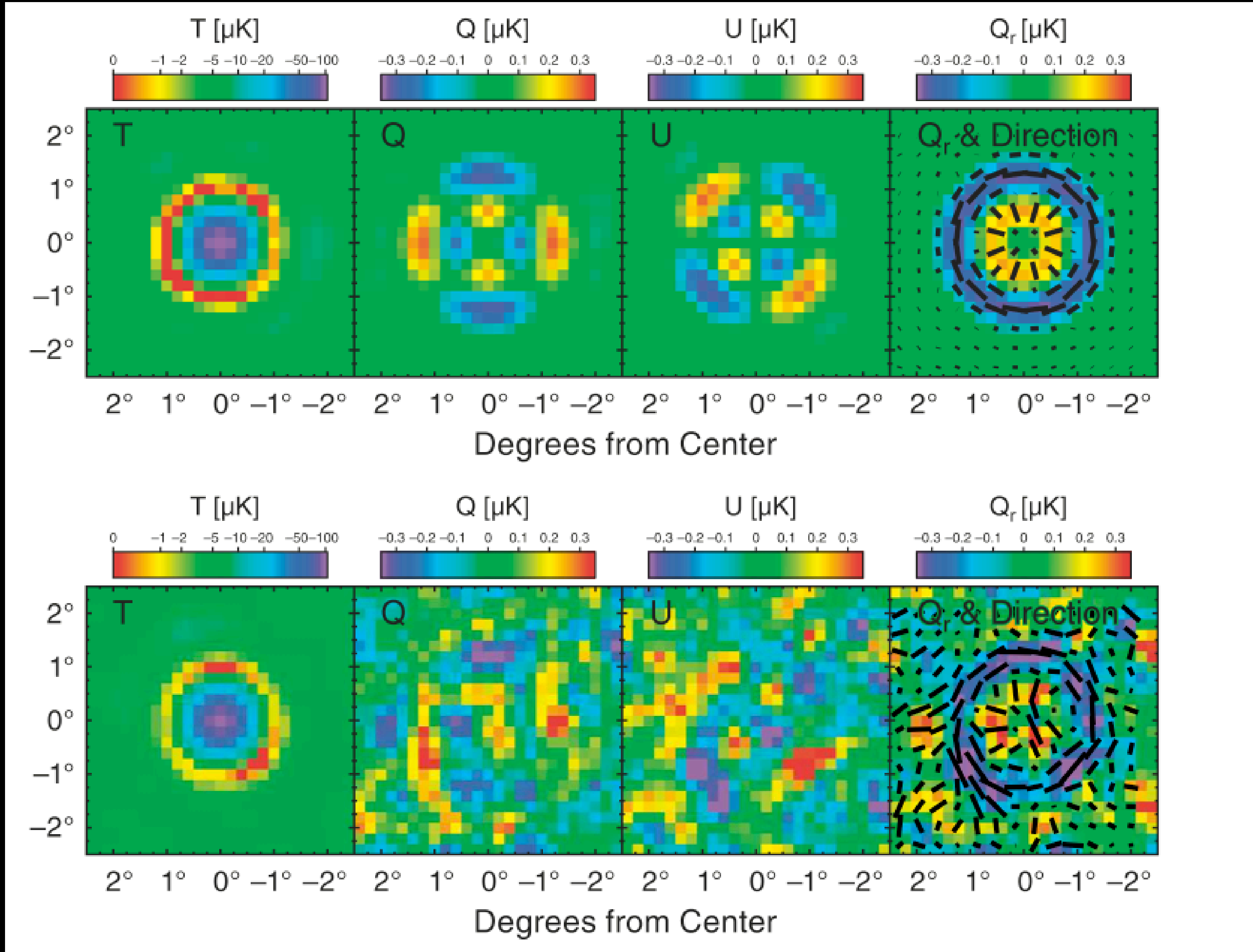


And it has been seen!

Komatsu, WMAP7yrs team (2010)

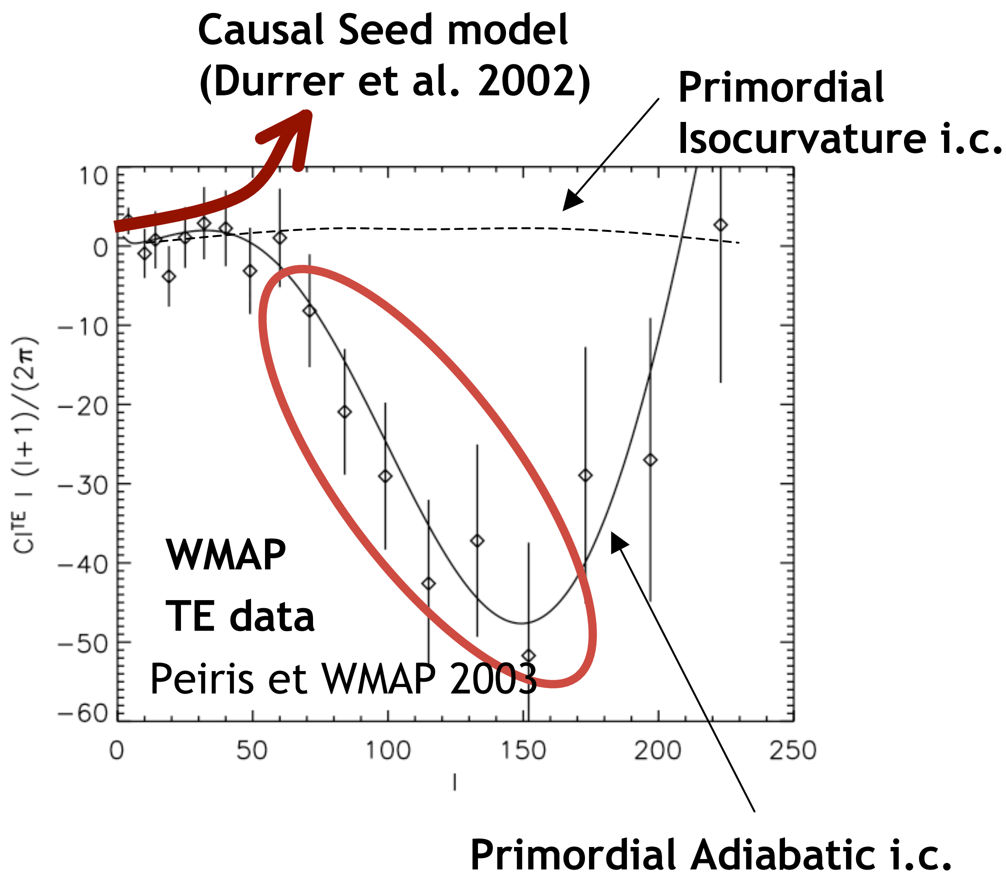
Theory prediction

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

Gravity waves stretch space…

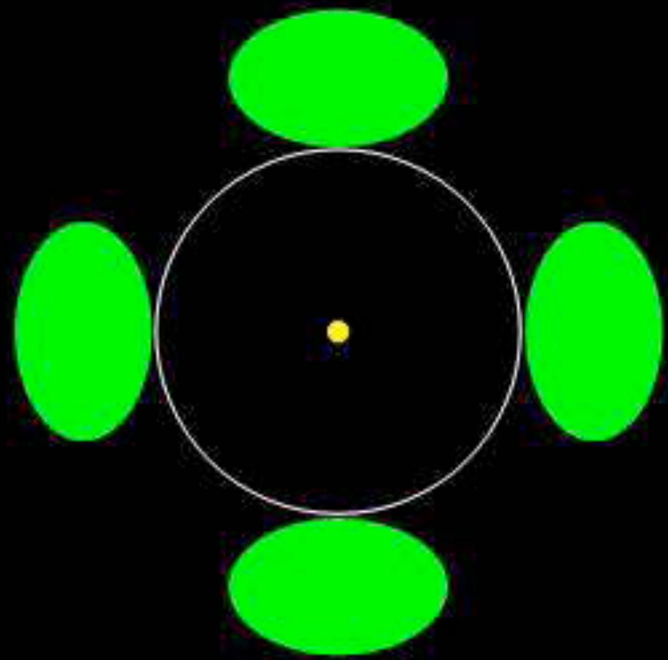


Image from J. Rhul.

… and create variations

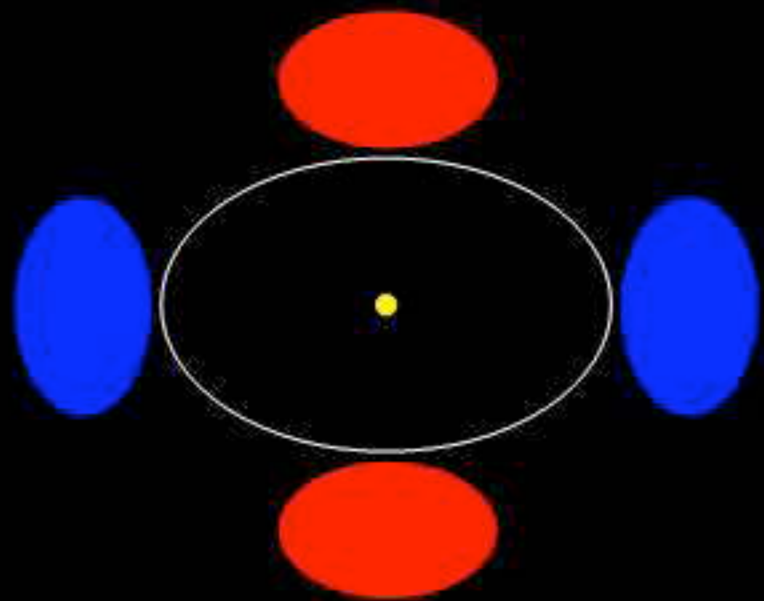
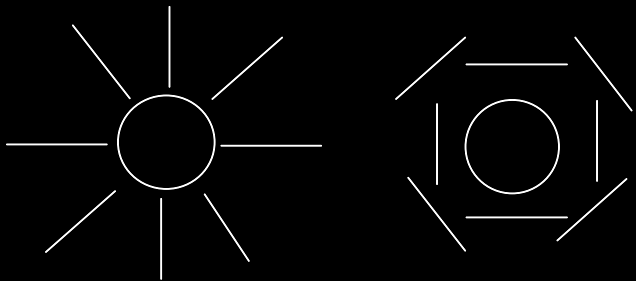


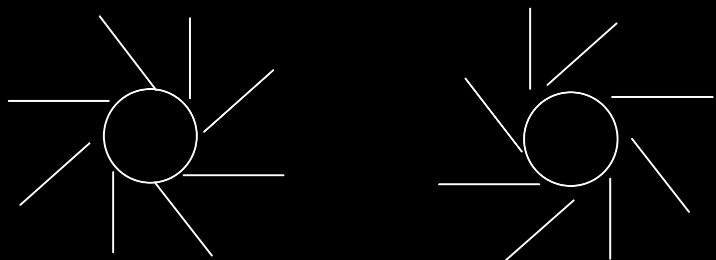
Image from J. Rhul.

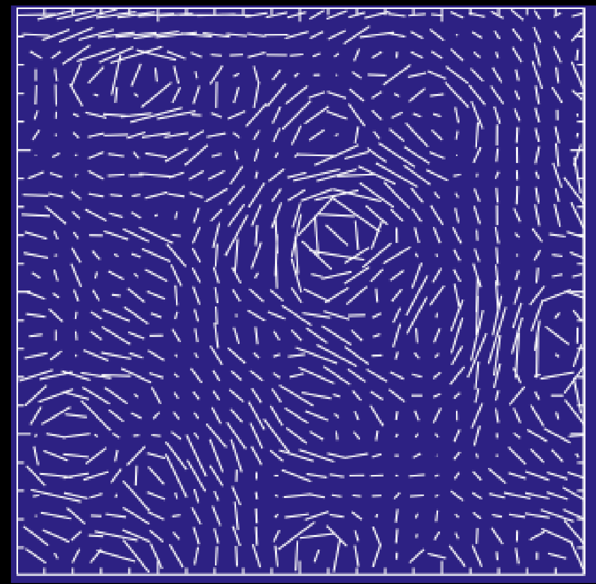
E and B modes polarization

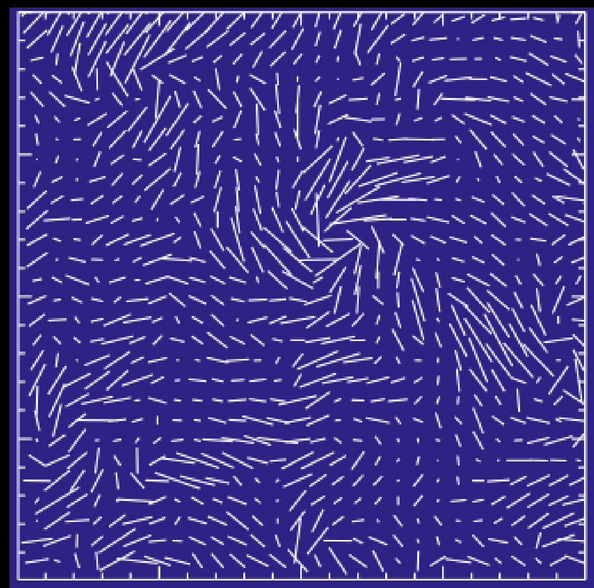
E polarization
from scalar and tensor modes



B polarization
only from tensor modes

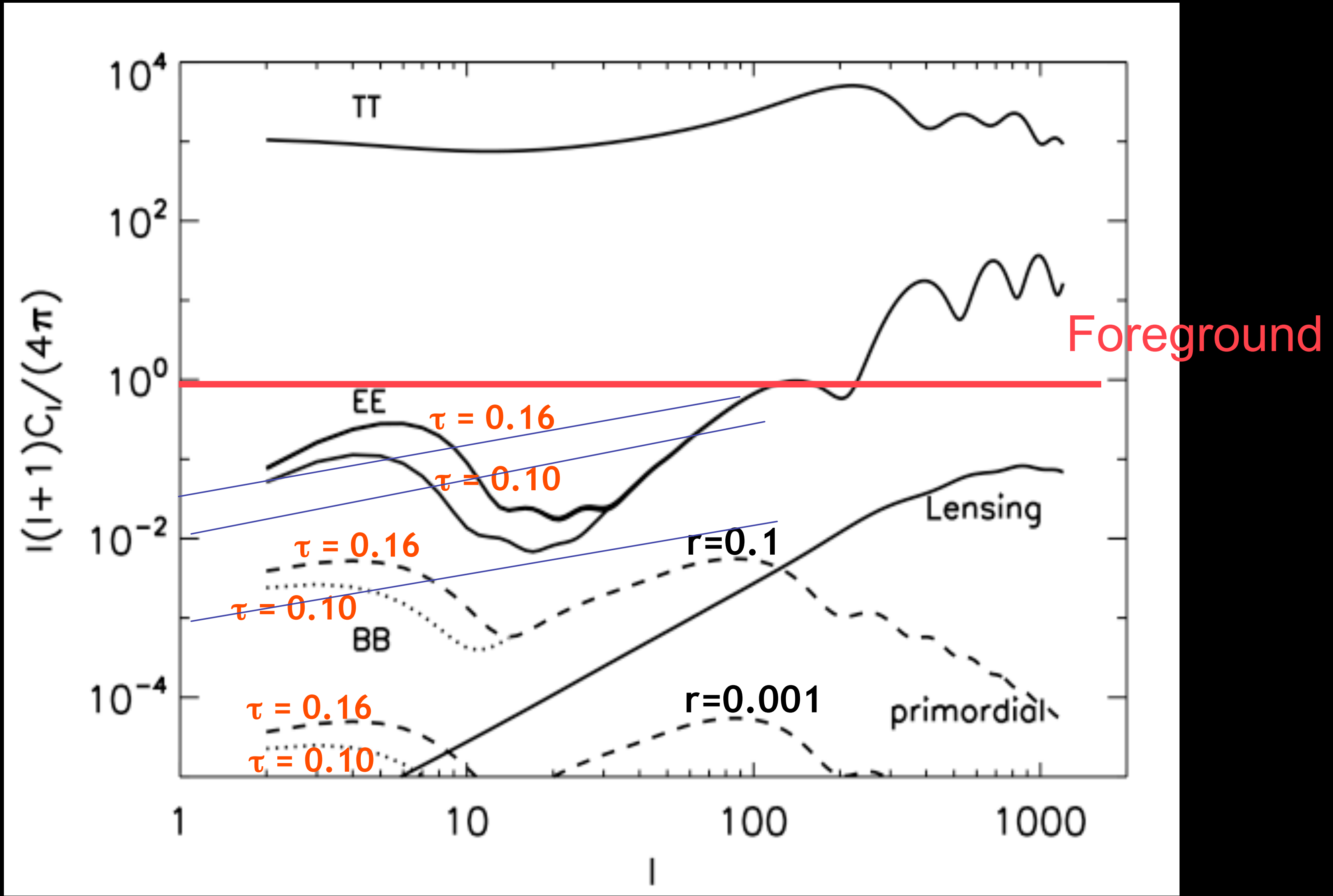




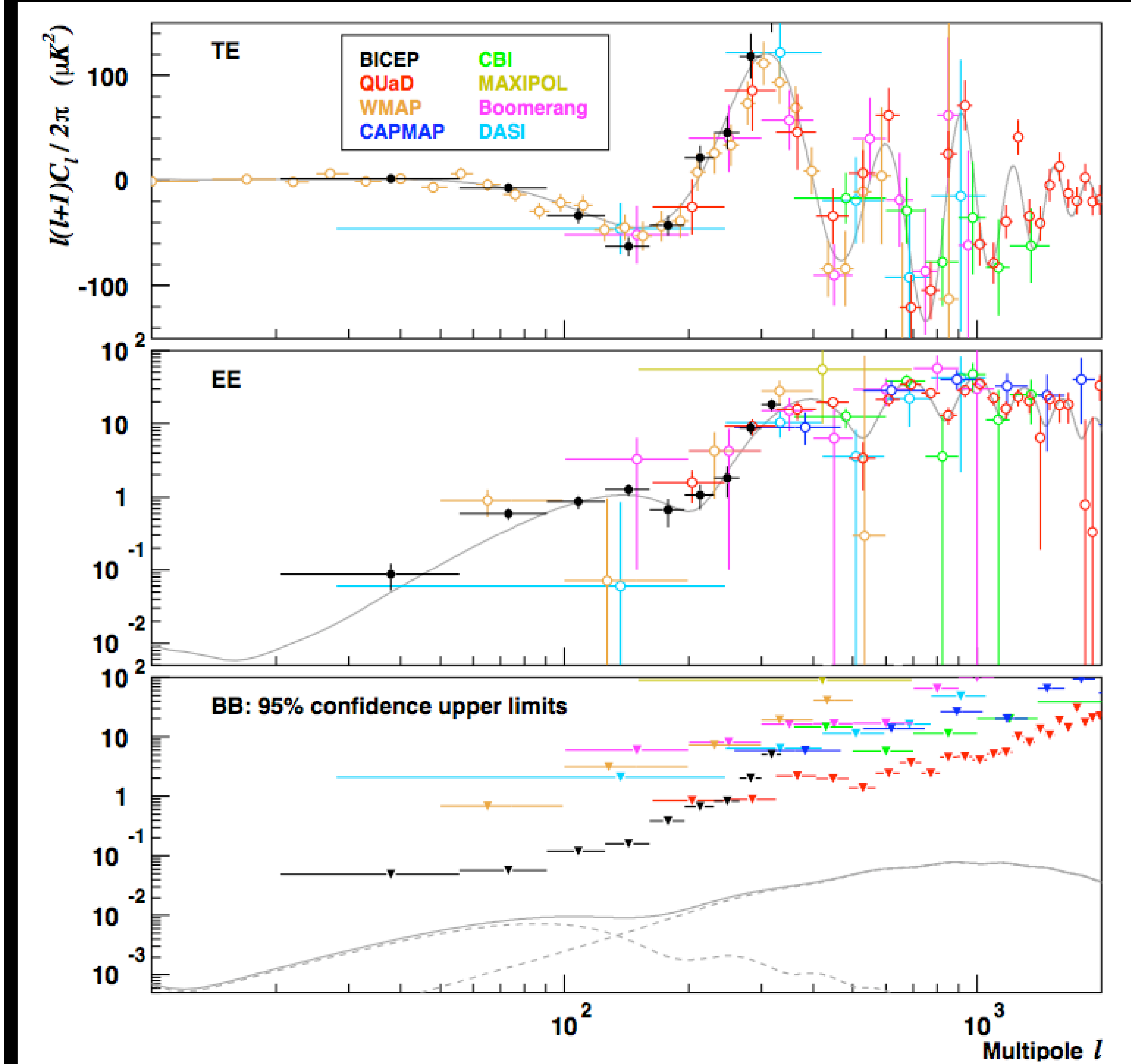


Kamionkowski, Kosowsky, Stebbings 1997, Zaldarriga & Seljak 1997

Relative Amplitudes of CMB power spectra



State of the art: polarization

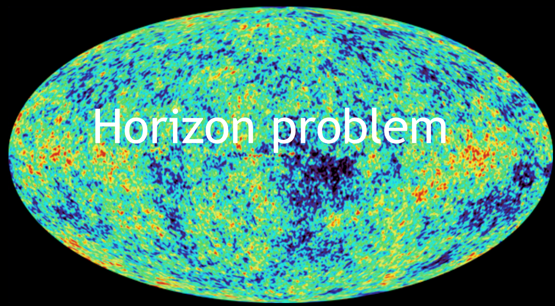


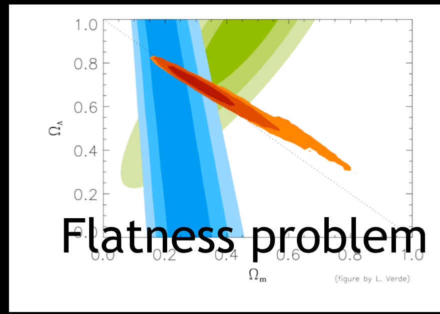
- Acoustic peaks at “adiabatic” locations
- E-mode polarization and cross-correlation with T
- Large angle polarization from reionization
- BICEP limit from BB-alone: T/S < 0.73 (95% CL)

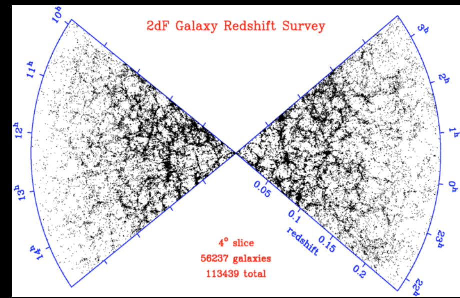
Figure: Chiang et al. (2009)

What mechanism generated the primordial perturbations?

Inflation:







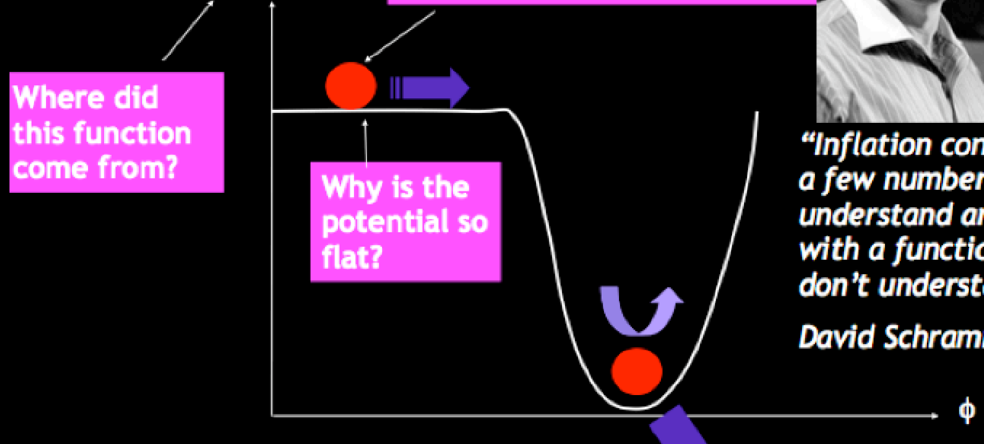
Structure Problem

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

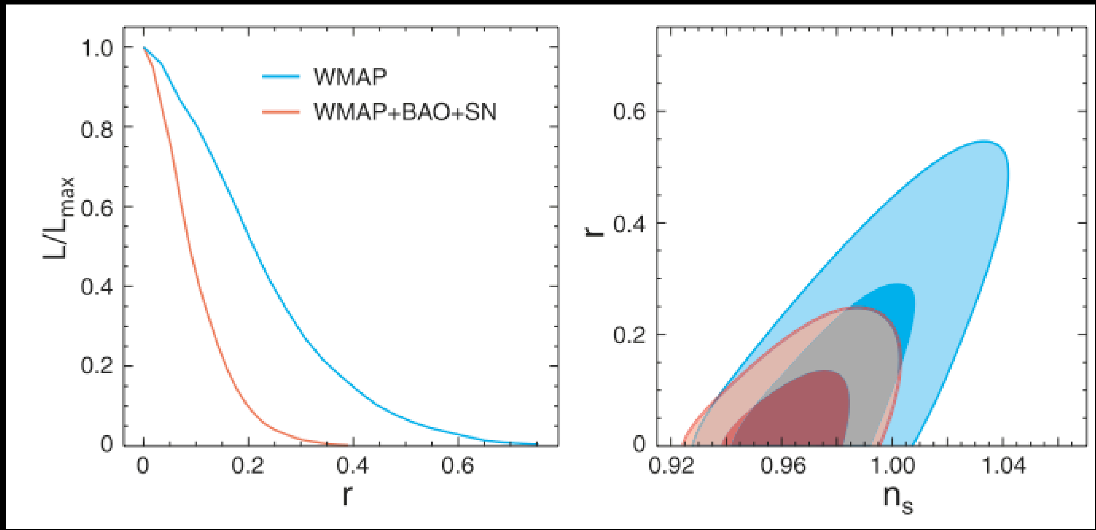
The energy scale of inflation is given by primordial tensor modes amplitude



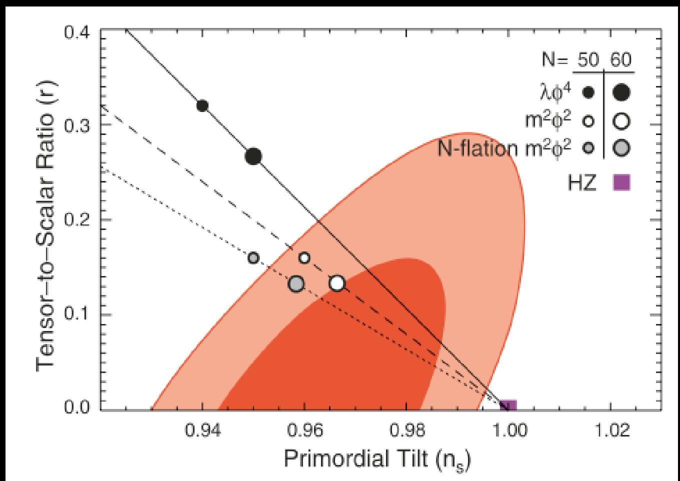
"Inflation consists of taking a few numbers that we don't understand and replacing it with a function that we don't understand"

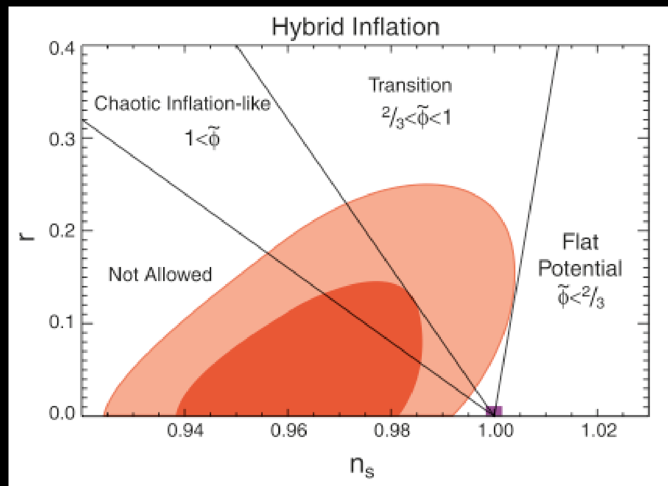
David Schramm 1945 -1997

Current constraints



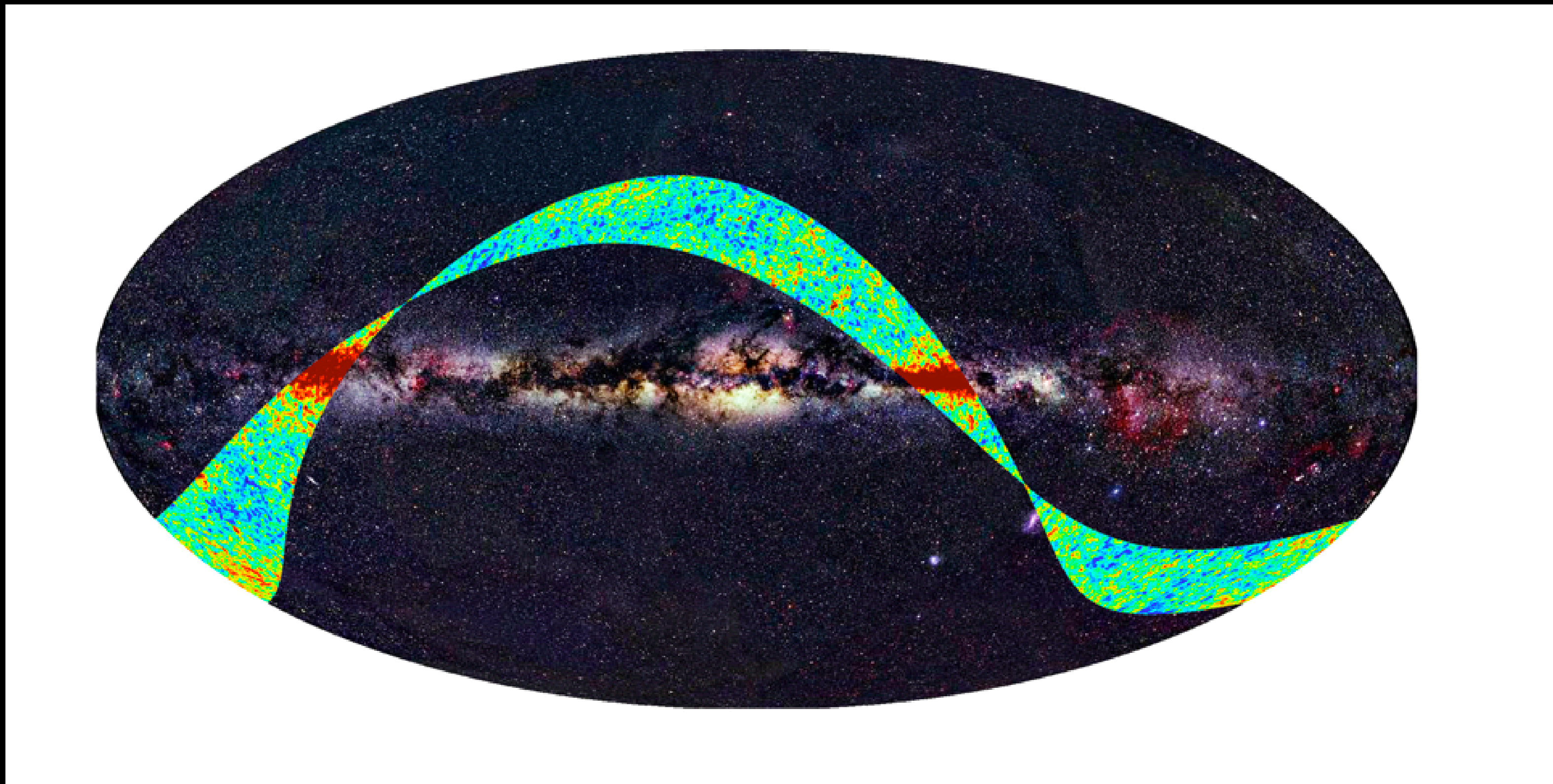
WMAP5
Komatsu et al 08
WMAP7
Komatsu et al 10





The future is here

Planck satellite successfully launched in May 2009!



“PR” image

The ultimate experiment for primary CMB temperature

What next?

b)Polarization, the next frontier

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?”
Improve cosmological constraints
Eventually, perhaps, test the theory of inflation.

Plans for the ultimate primary polarization CMB experiment
(CM)BPol (e.g., Bauman et al. arXiv:0811.3919)

Windows into the primordial Universe

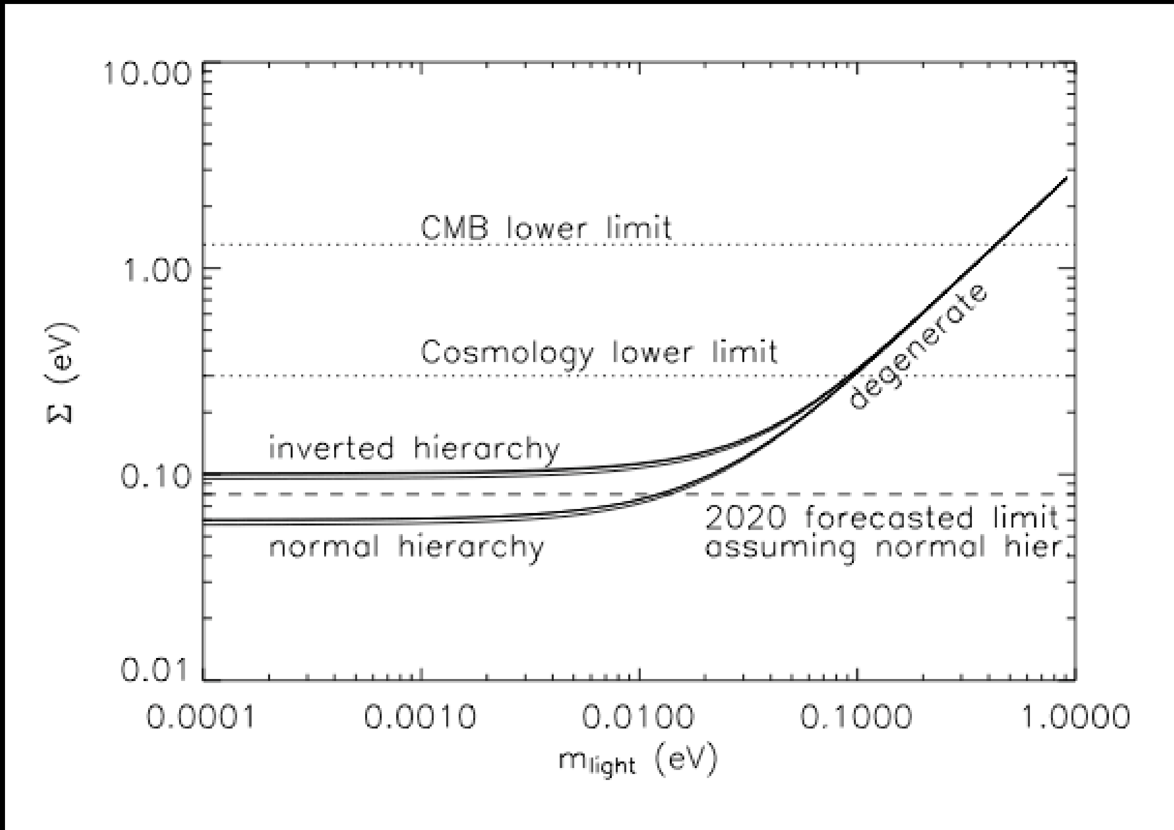
Recombination	380000 yrs	Atomic physics/GR
Nucleosynthesis	3 minutes	Nuclear phyiscs
LHC		TeV energies
inflation	10^{-30} s (?)	GUT?

Big BANG

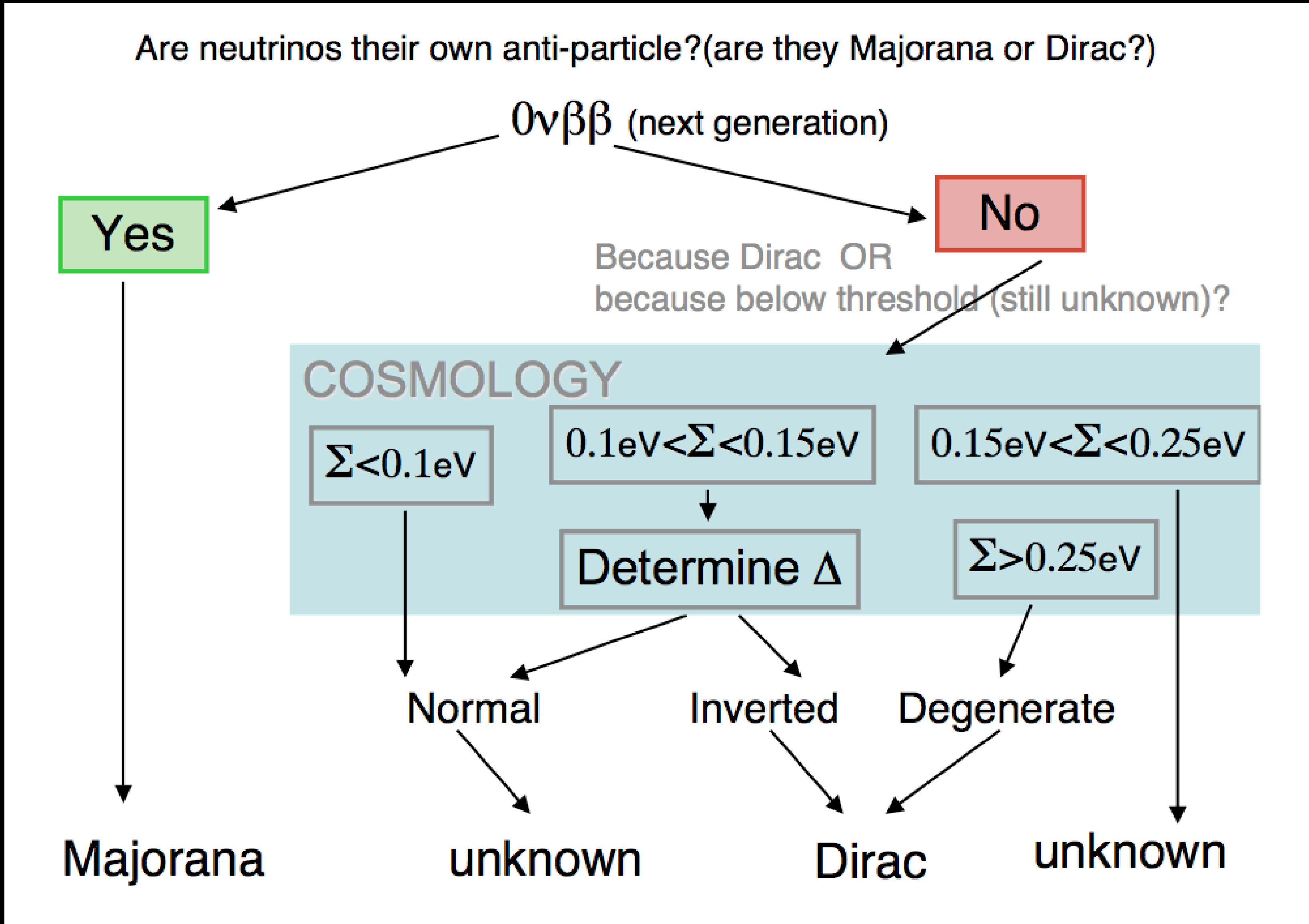
What about the lower -z Universe? Beyond the vanilla model

Example: neutrinos

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



Complementarity



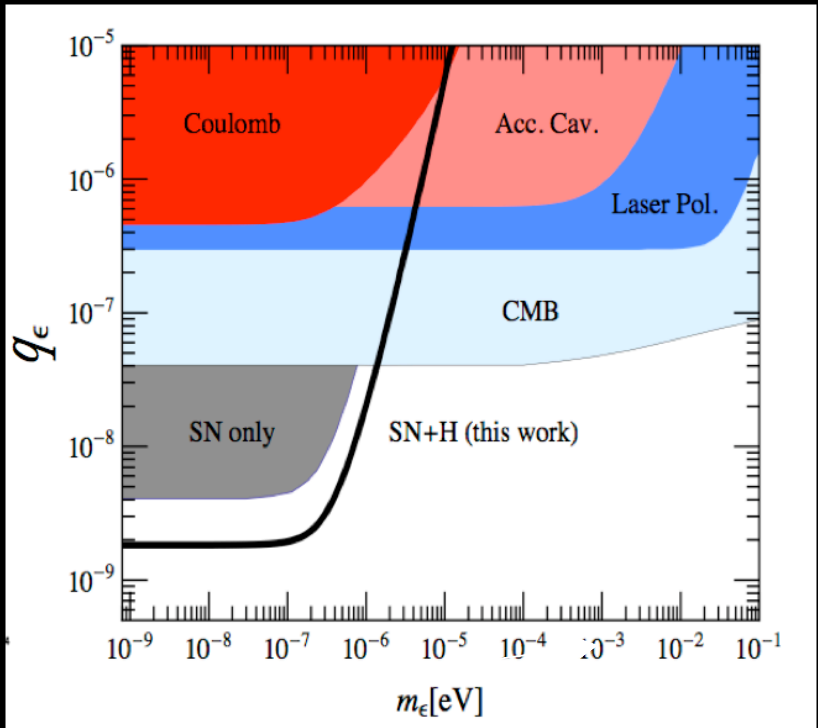
Jimenez, Garay, Kitching, LV, 2010

Insights into dark matter

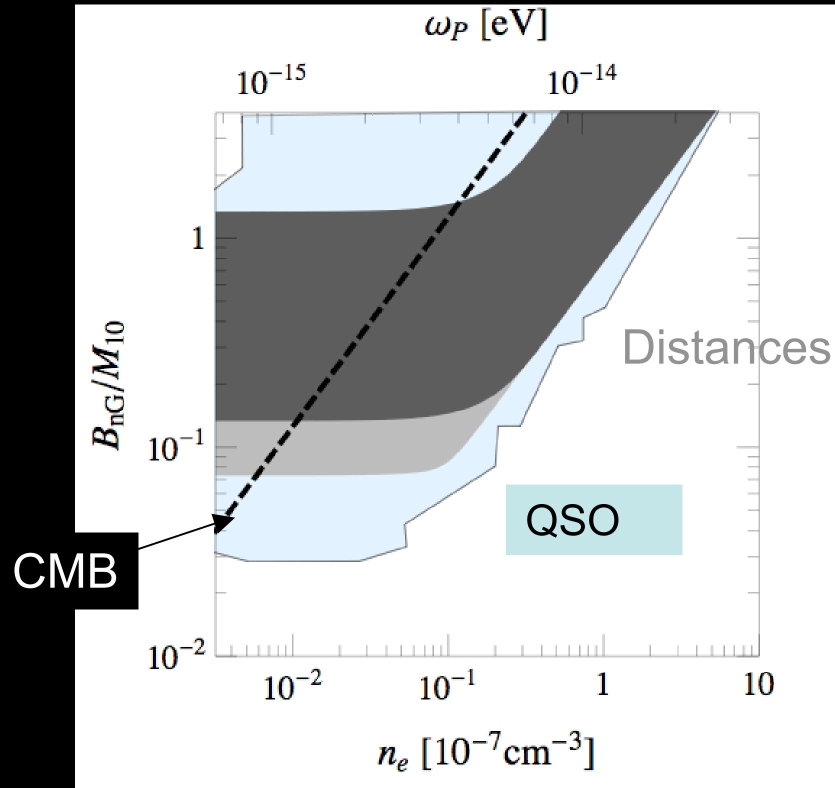
$$d_L(z) \stackrel{?}{=} (1+z)^2 d_A(z)$$

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

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 inflaton (self)interactions is primordial non-Gaussianity]

Complementarity: cosmology

Challenging!

END

Axion-like particles
Chameleons

SN only

SN +H(z)