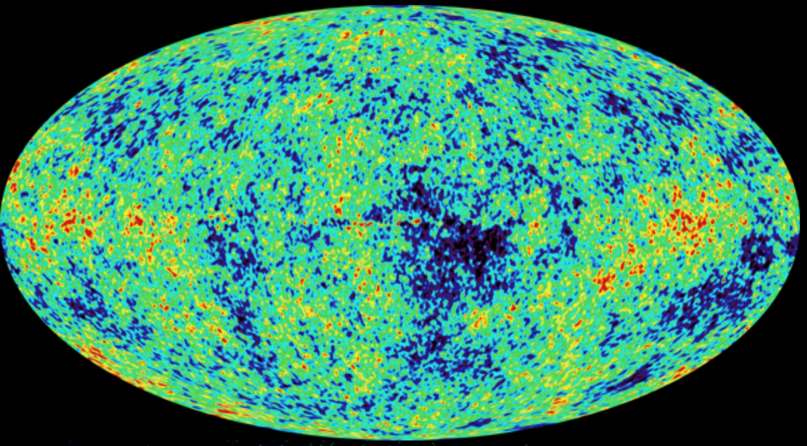
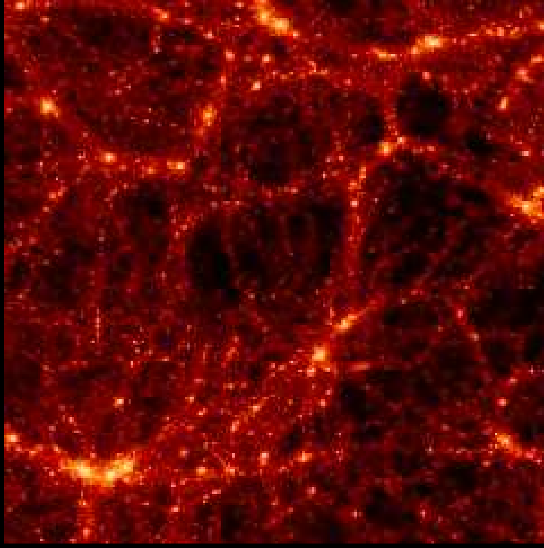
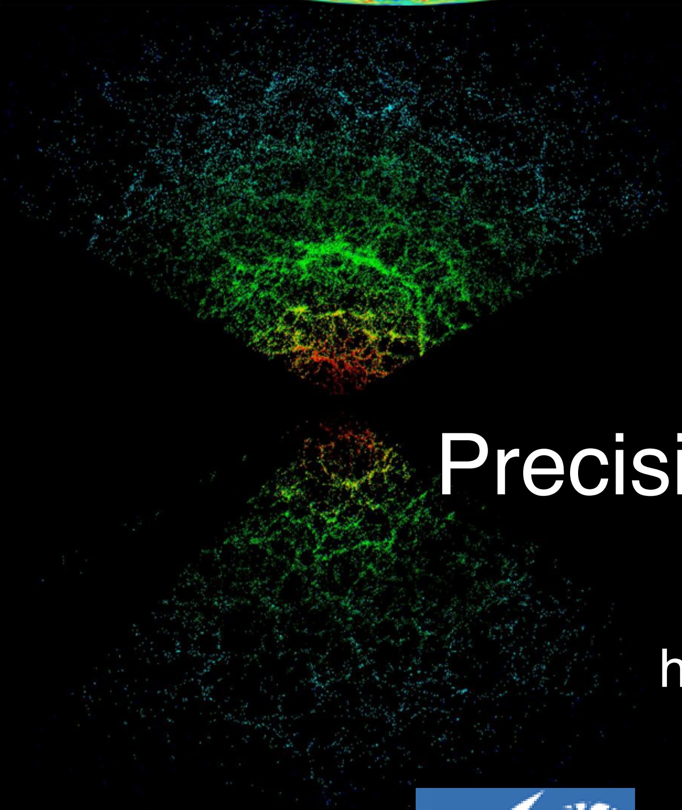






Raul Jimenez

ICREA & ICCUB
Barcelona

Precision cosmology turns 20

http://icc.ub.edu

Institut de Ciències del Cosmos

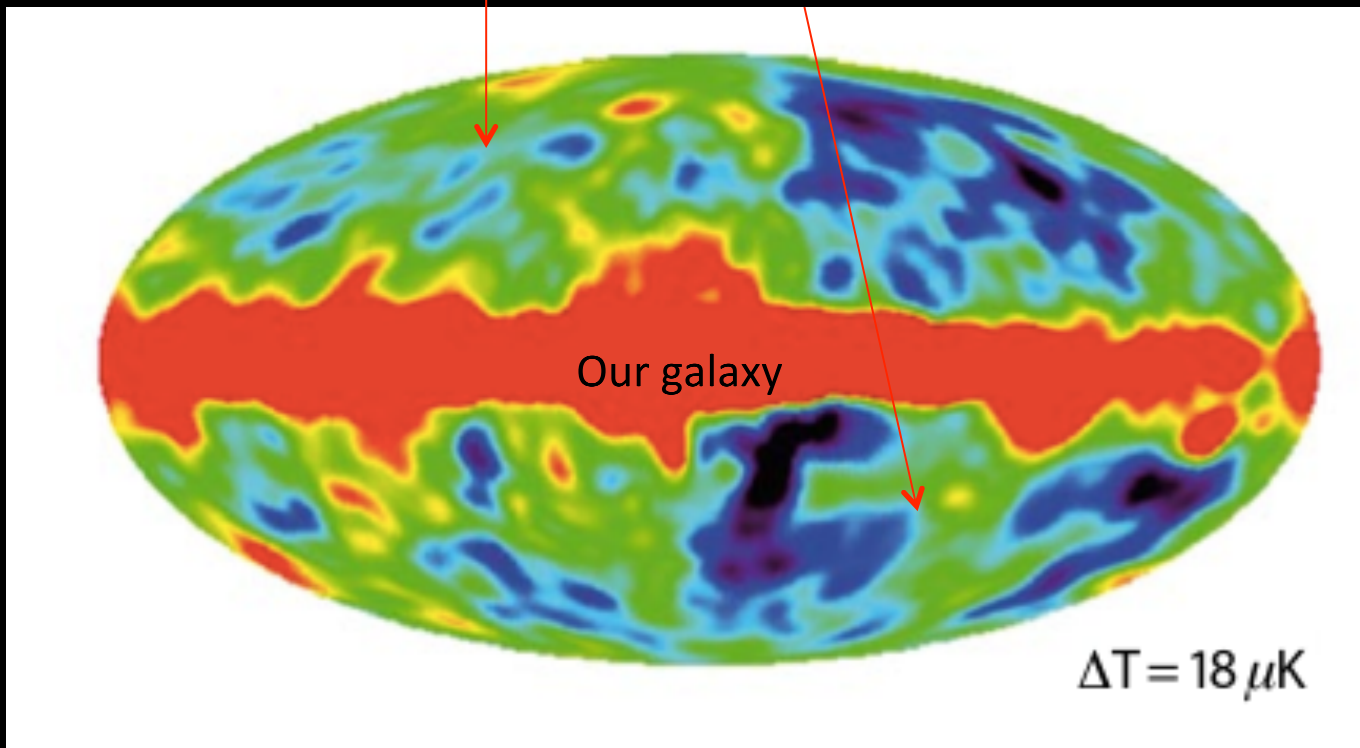
Context and overview

- Cosmology over the past 20 years has made the transition to *precision cosmology*
- Cosmology has moved from a *data-starved science* to a *data-driven science*
- Cosmology has now a *standard model.* The *standard cosmological model* only needs few parameters to describe origin composition and evolution of the Universe
- Big difference between modeling and understanding

The Nobel Prize in Physics 2006

John C. Mather, George F. Smoot

The primordial fireball, CMB



1992-1994

The COBE results provided increased support for the Big Bang scenario for the origin of the Universe, as this is the only scenario that predicts the kind of cosmic microwave background radiation measured by COBE.

These measurements also marked the inception of cosmology as a precise science.

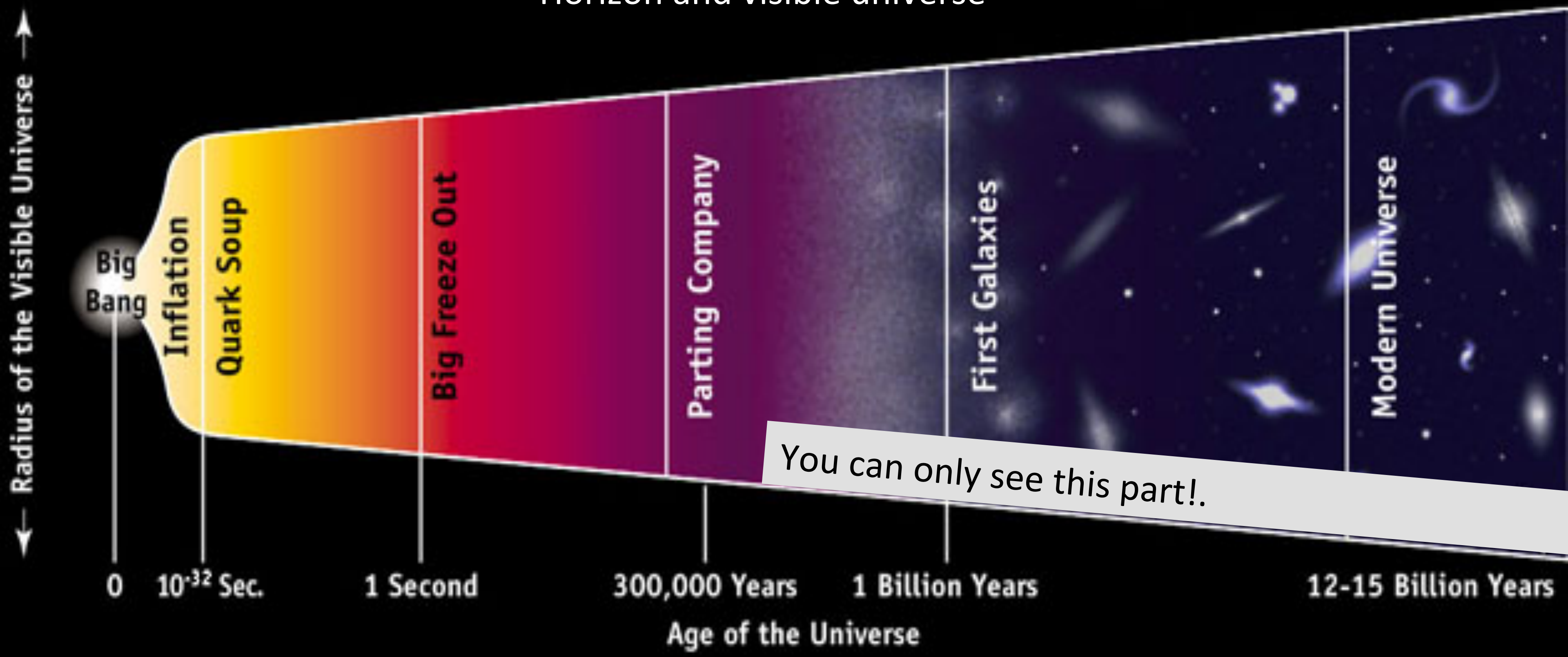
The expanding universe

Thanks to the work of many: Slipher, Hubble, Alpher, Gamov, Herman….

Hot big bang

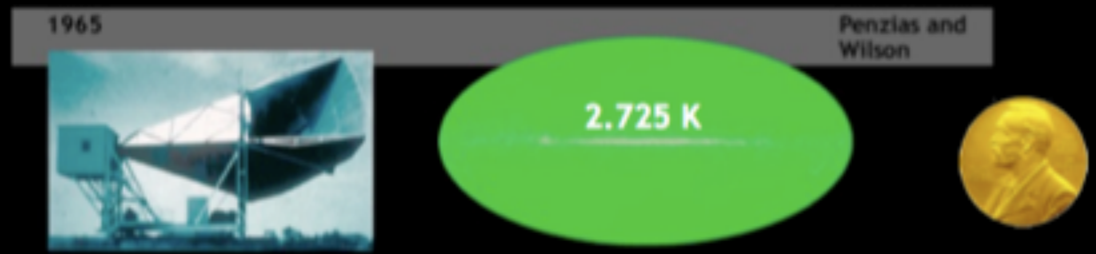
Looking far away is looking back in time and looking at high z

Horizon and visible universe



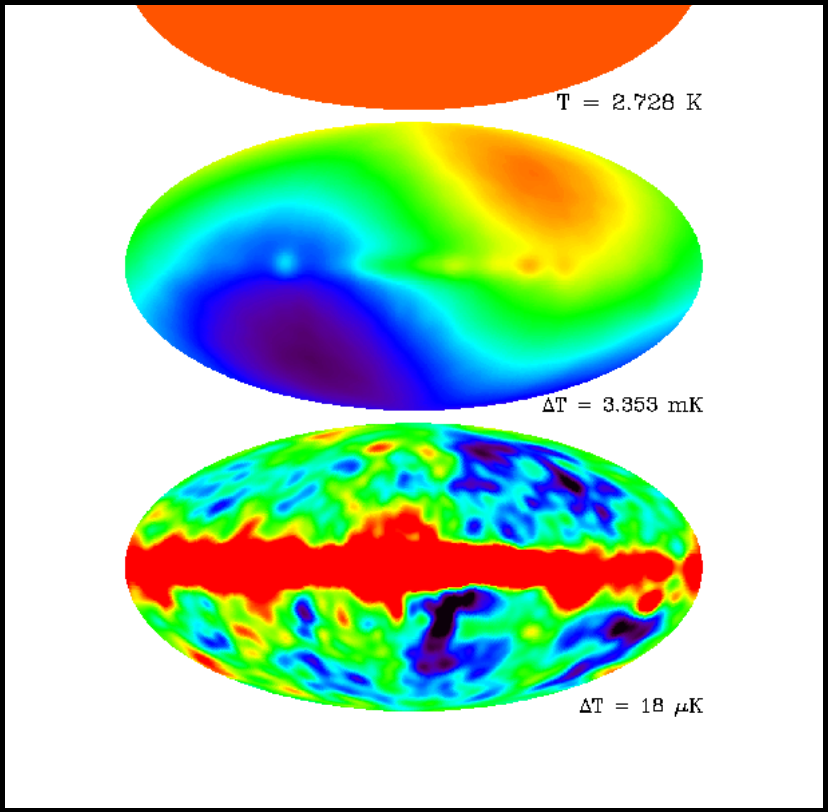
History of CMB temperature measurements

- Penzias & Wilson saw only a uniform glow…



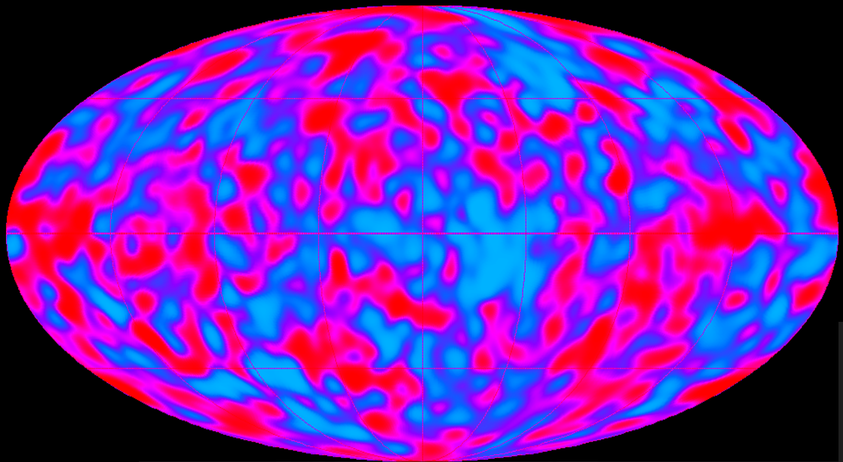
- Later, Doppler shift from Milky Way's motion seen; the Galaxy is moving towards Hydra/Centaurus at 620 km/s…

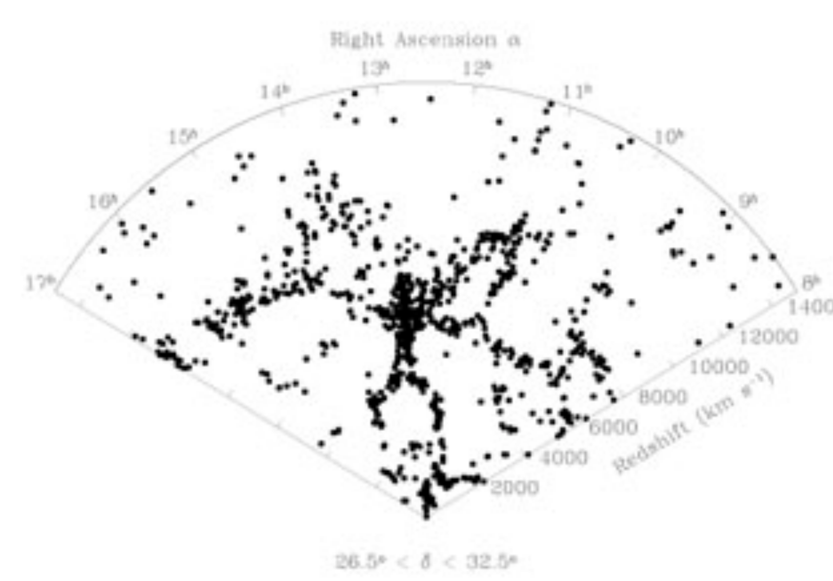
- Only in 1992 was any nonuniformity in the CMB observed—and then only about 10^{-5} K worth.

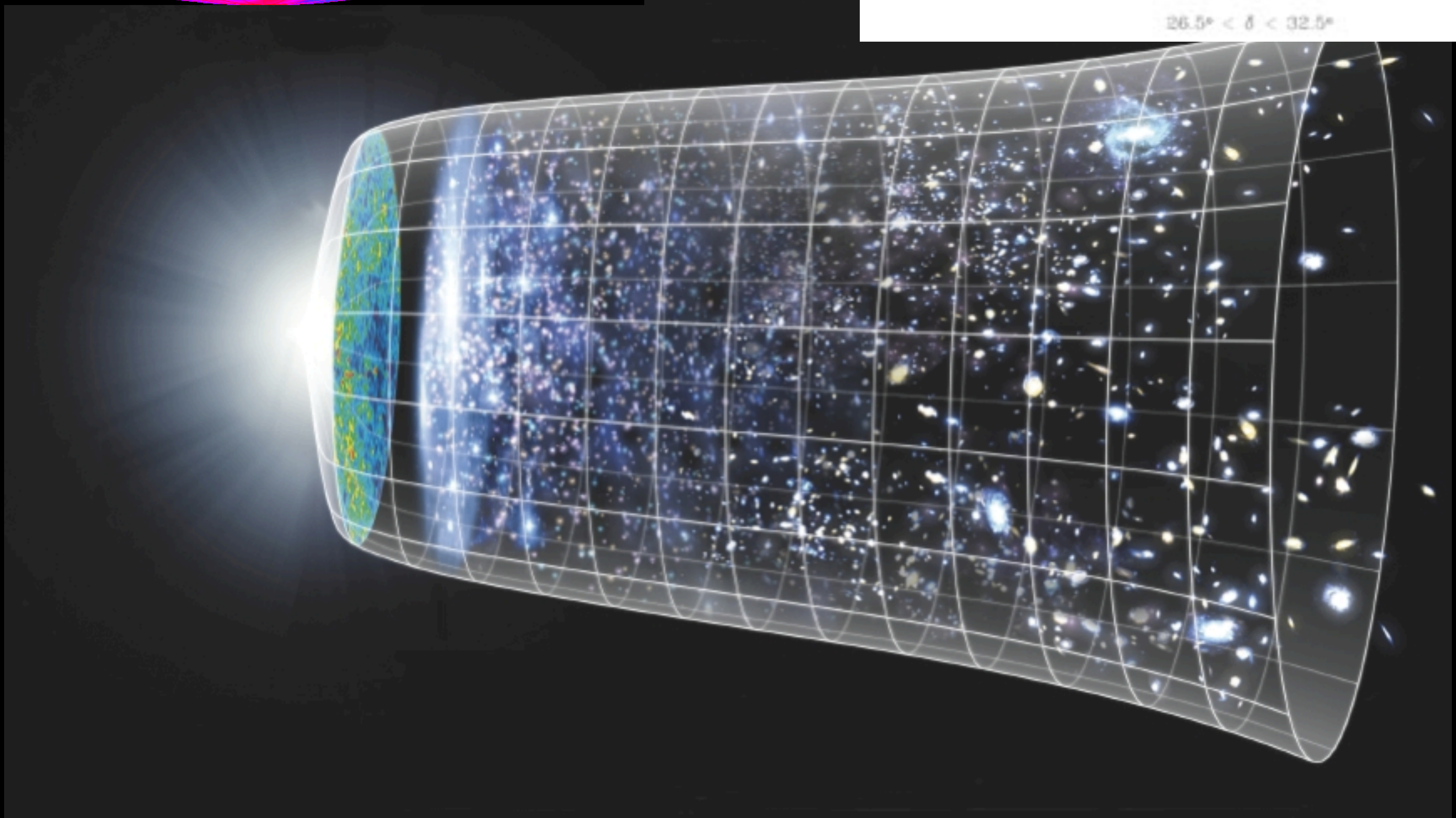


The seeds of galaxies (planets,...us)

In other words….. In the early 1990…



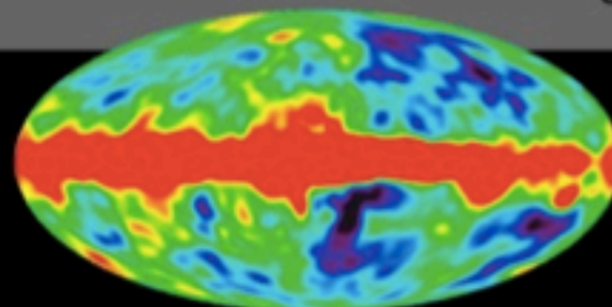




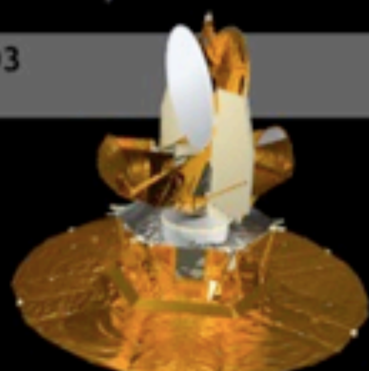
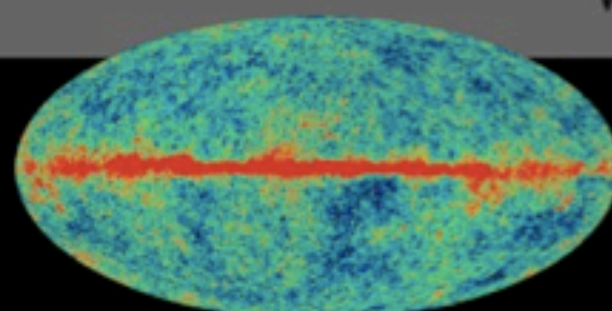
History of CMB temperature measurements

1965 Penzias and Wilson


1992 COBE


2003 WMAP

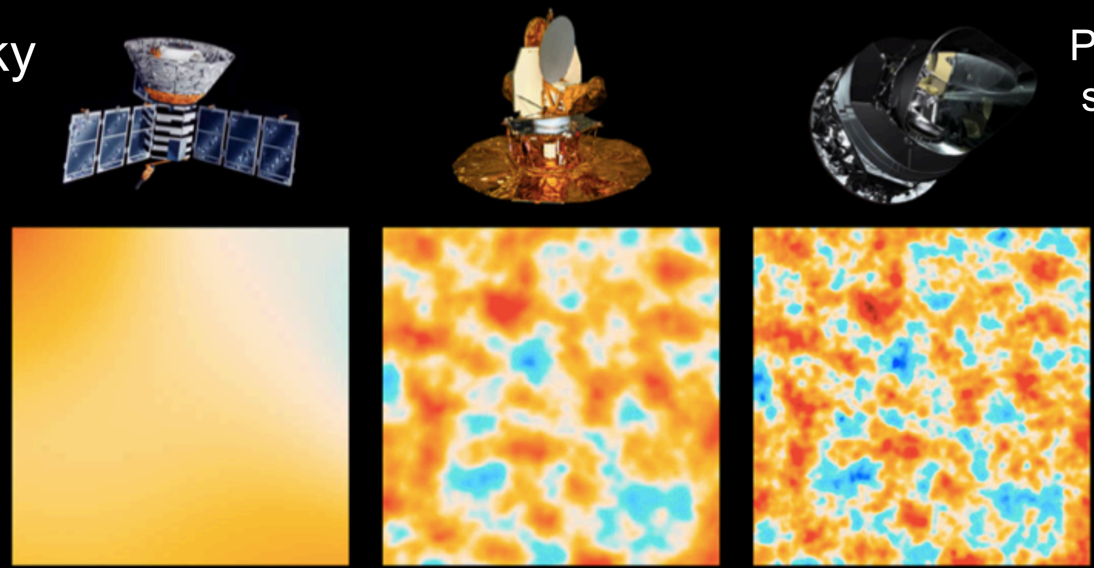



TOCO (1998) BOOMERANG (1998, 2003) MAXIMA (2000)
ARCHEOPS (2002) CBI (2002) ACBAR (2002) VSA (2002)

History of CMB temperature measurements:milestones

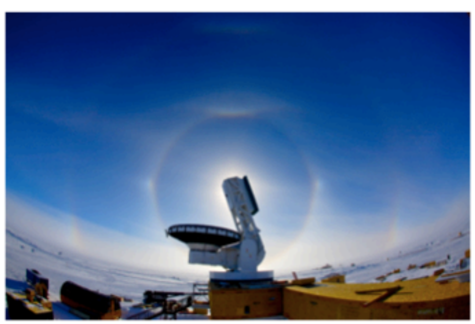
Satellites: full sky

Planck a NASA/ ESA satellite mission

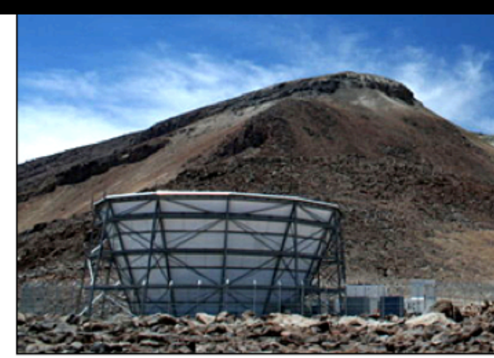


COBE WMAP Planck

Ground-based experiments (not full sky but better resolution)

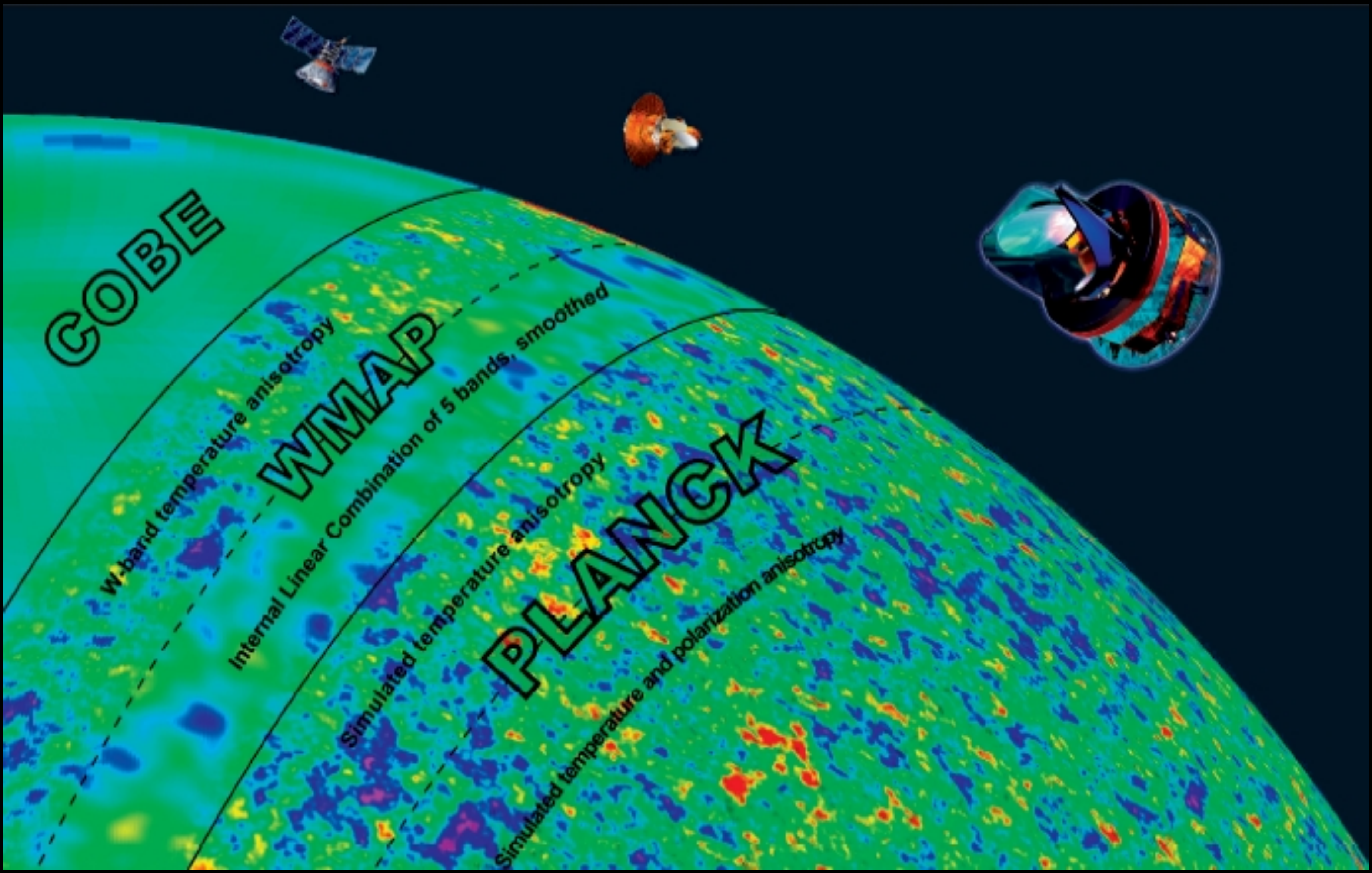


South Pole Telescope (SPT)



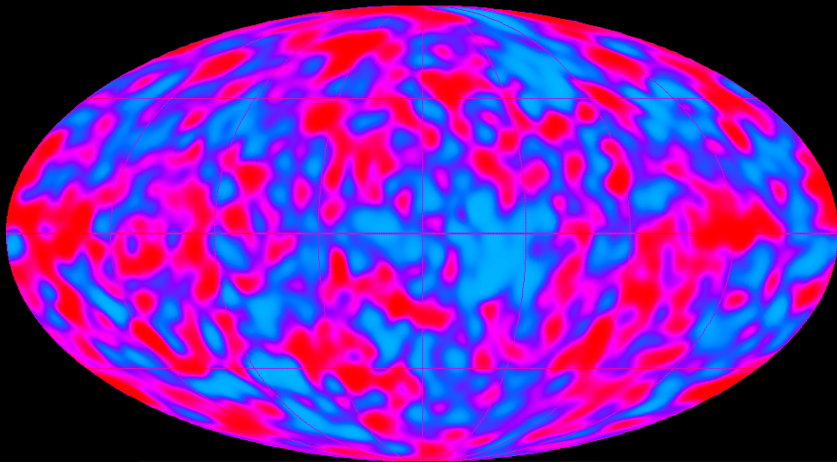
Atacama Cosmology Telescope (ACT)

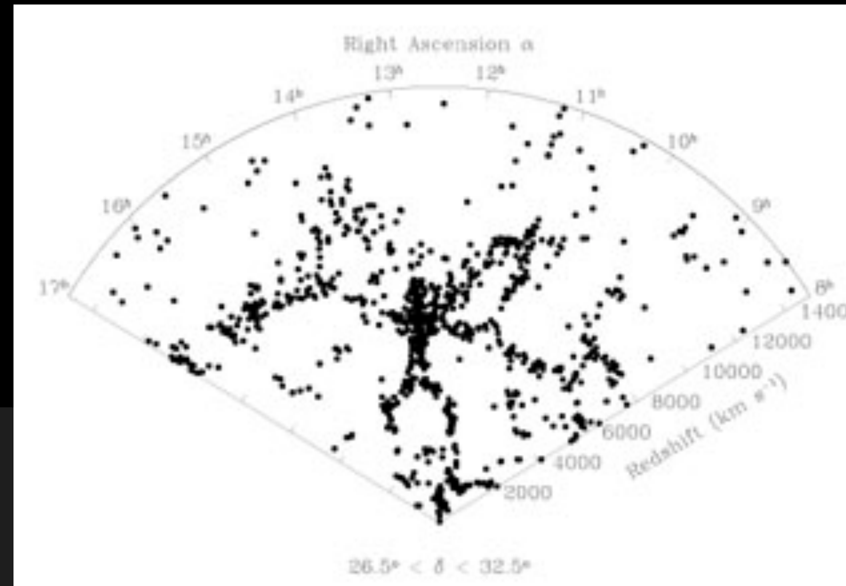
History of CMB temperature measurements

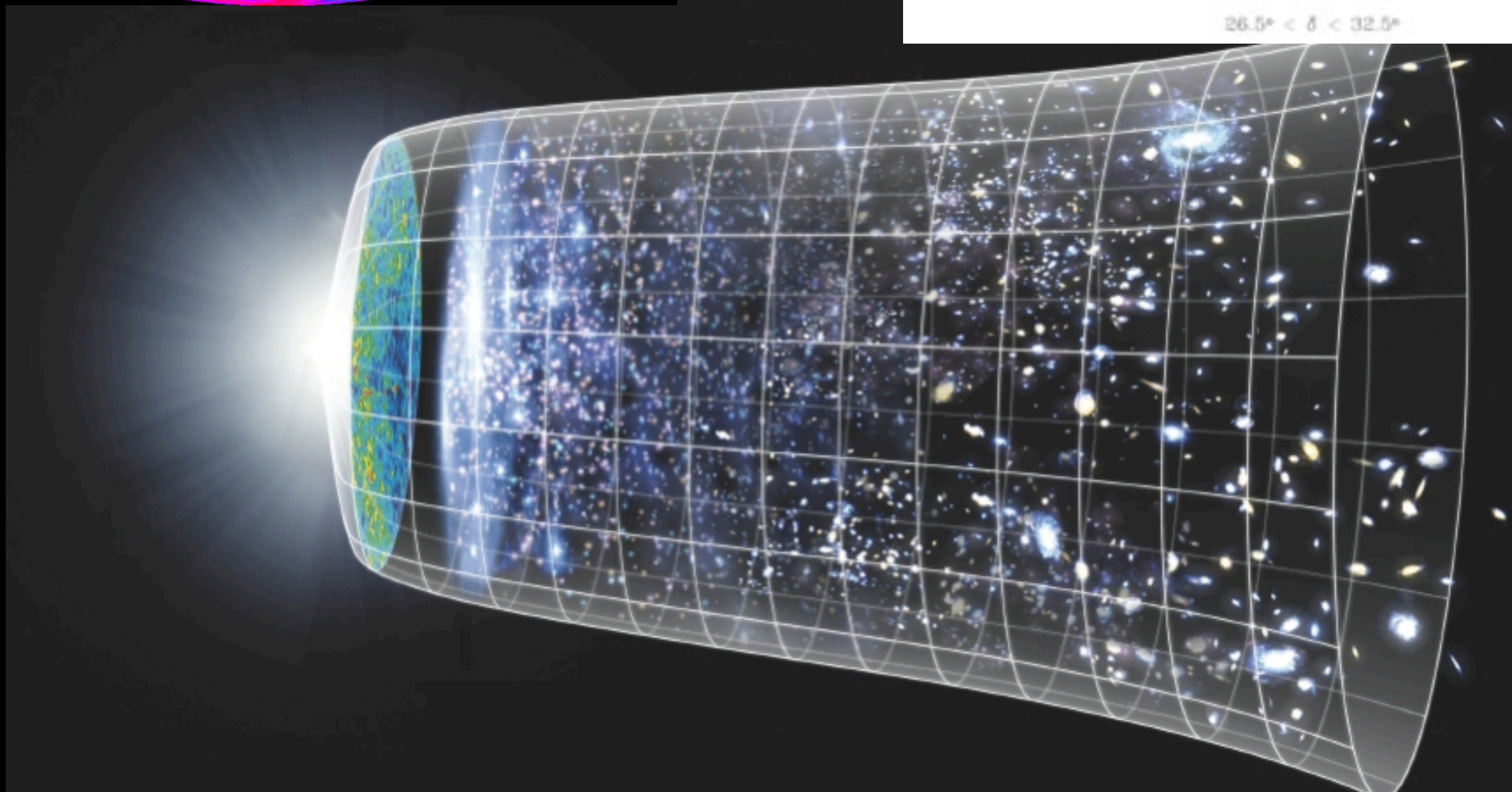


In other words…..

In the early 1990…



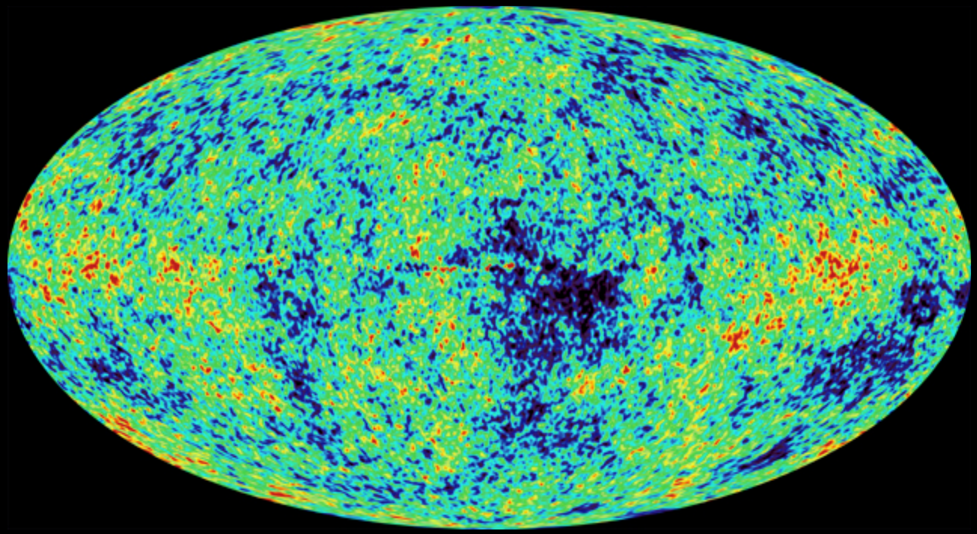


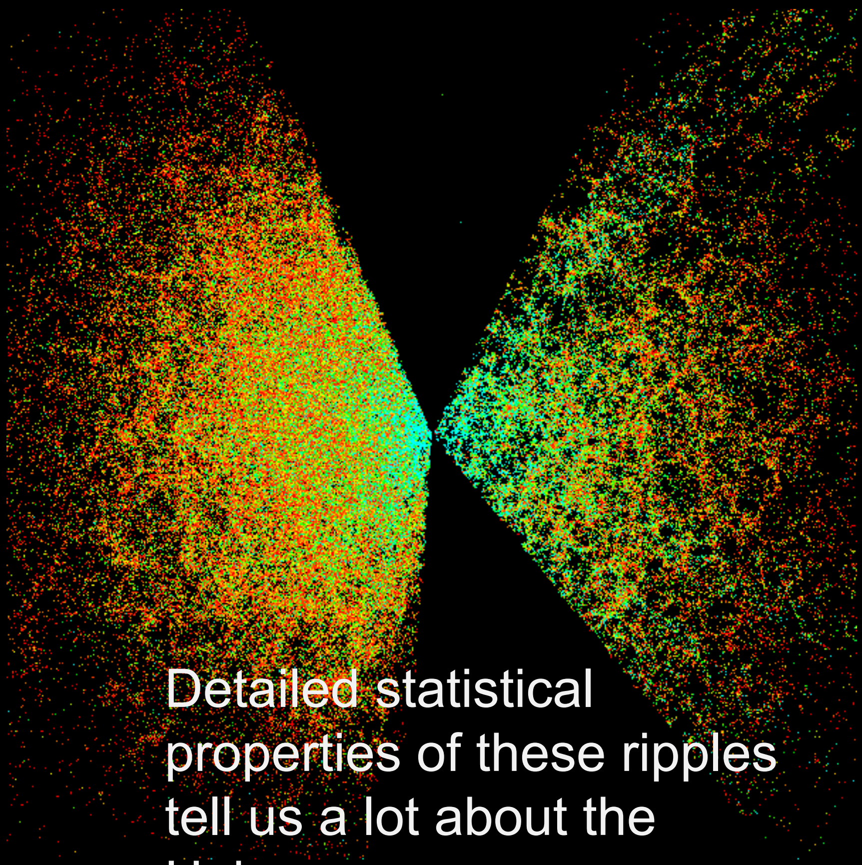


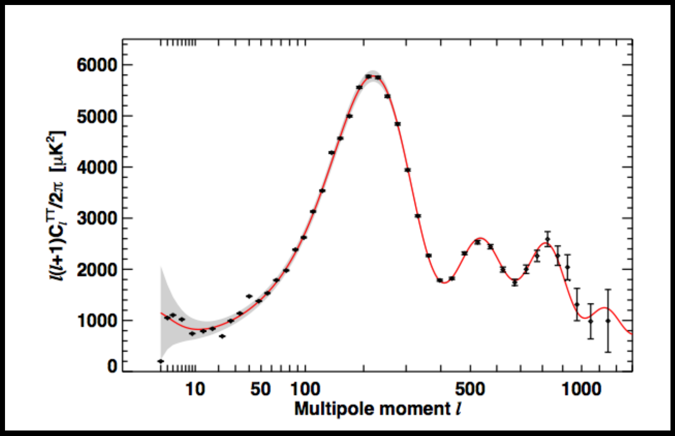
Let us not forget the accelerating universe 1998 (Noble prize in physics 2011)

Avalanche of data

Into the first decade of the new century

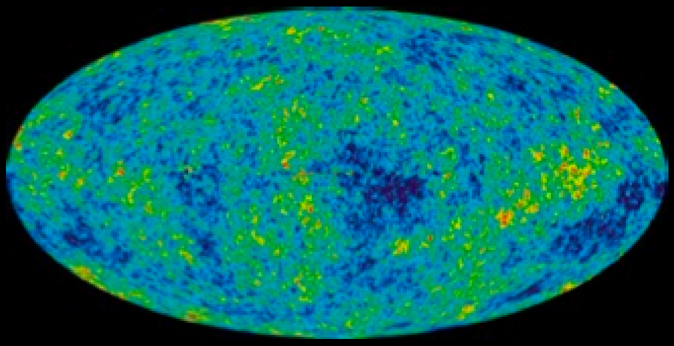






Detailed statistical properties of these ripples tell us a lot about the Universe

Precision cosmology



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

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

$$A_s, n_s, r$$

- nearly scale-invariant
- adiabatic
- Gaussian

Extremely successful standard model for cosmology: LCDM or ΛCDM

ASIDE: We only have one observable universe

The curse of cosmology

We can only make observations (and only of the observable Universe) not experiments: we fit models (i.e. constrain numerical values of parameters) to the observations: <u>Any statement is model dependent</u>

Gastrophysics and non-linearities get in the way :
Different observations are more or less “trustable”, it is however somewhat a question of personal taste (think about Standard & Poor’s credit rating for countries)

Results will depend on the data you (are willing to) consider.
I try to use > A rating ;)

….And the Blessing

We can observe all there is to see

The era of precision cosmology:

ΛCDM or LCDM: the "standard" model for cosmology

Few parameters describe the Universe composition and evolution

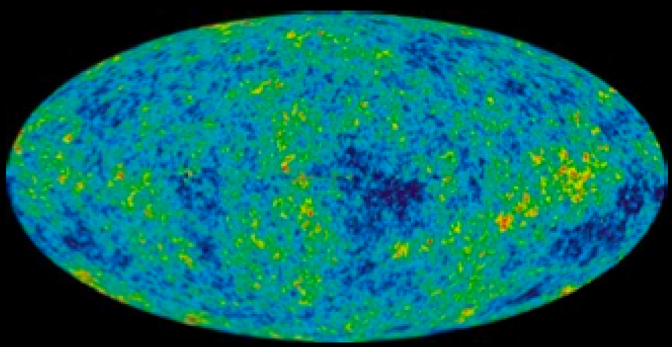
Homogenous background

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

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

Λ? CDM?

Perturbations

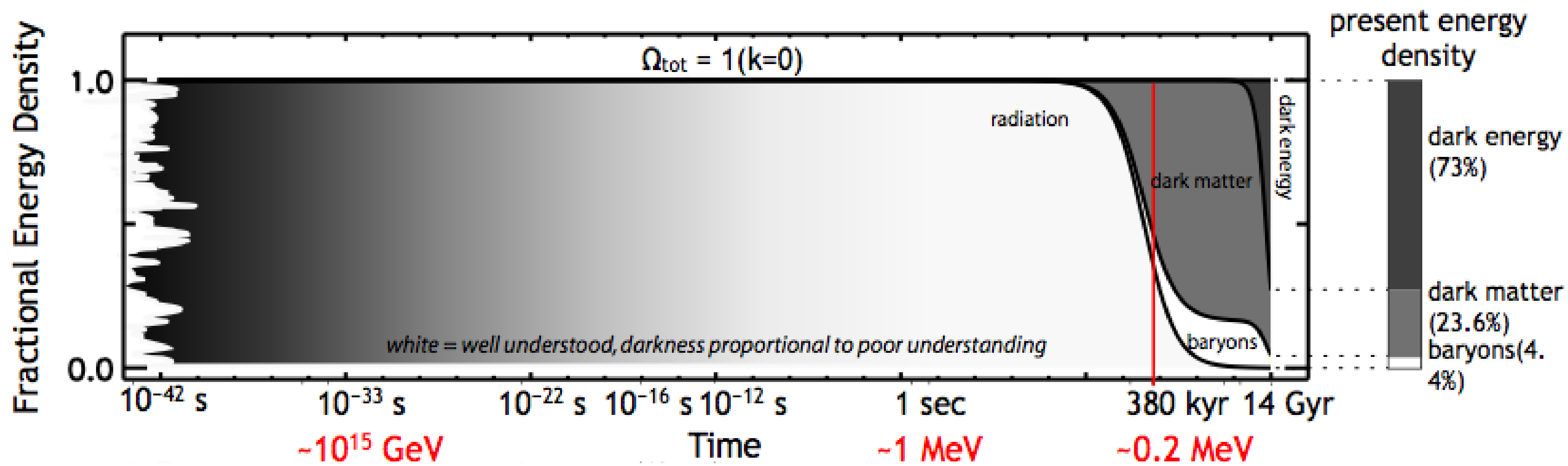


$$A_s, n_s, r$$

- nearly scale-invariant
- adiabatic
- Gaussian

ORIGIN??

Cosmic History / Cosmic Mystery



Planck Energy

GUT symmetry

T=100 TeV (ILC X 100)

nucleosynthesis

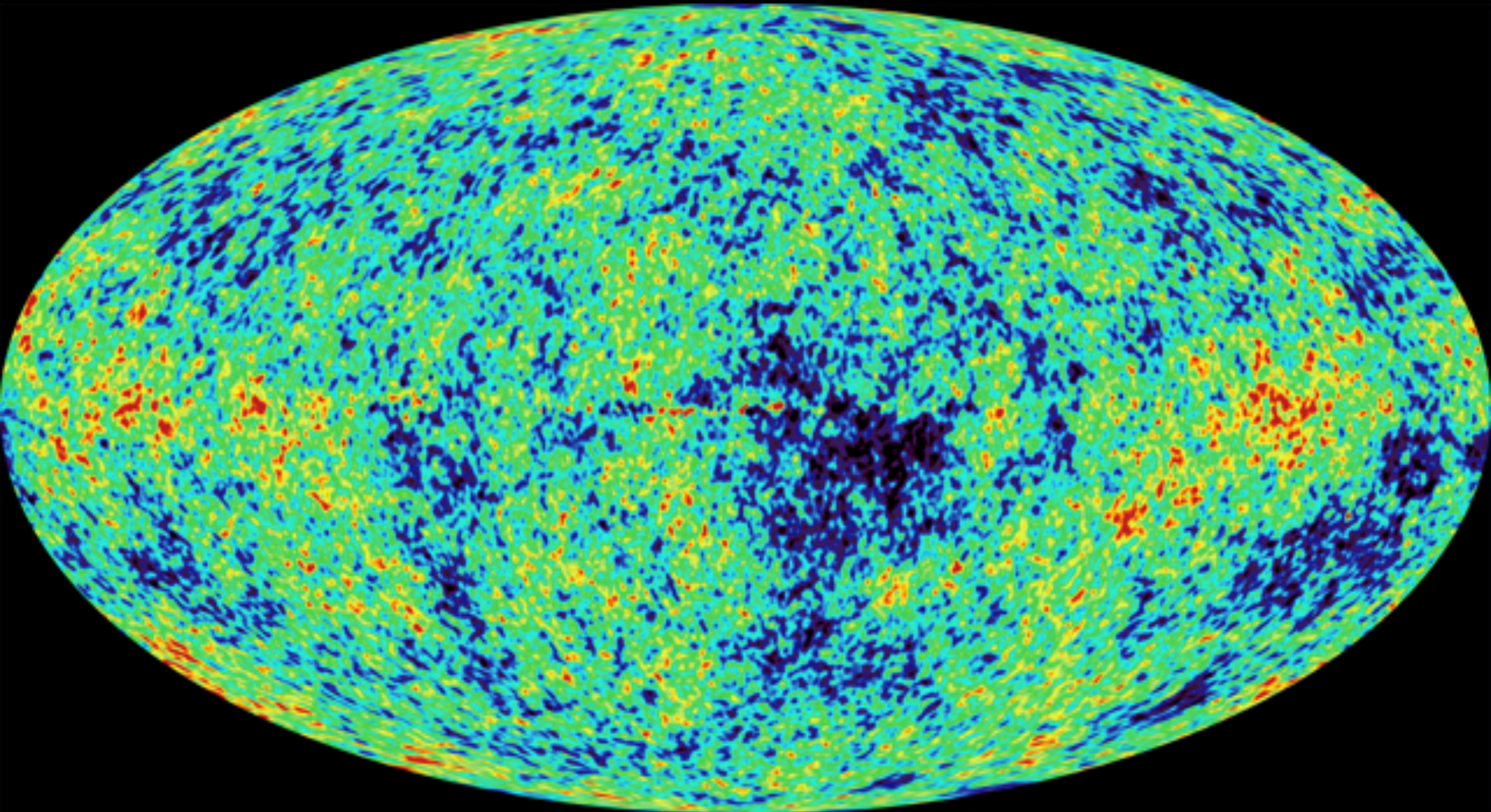
Generation of primordial perturbations

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

Hot and cold spots → Tiny ripples in density → seeeds of galaxies



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

How's that?

The Universe back then was made of a very hot and dense "gas", so it was emitting radiation

This is the radiation we see when we look at the CMB

Uniform , but with tiny (contrast x 100000) density (and temperature) ripples

Ripples in a gas? SOUND WAVES!

Truly a cosmic symphony… We are seeing sound!

These tiny fluctuations, quantitatively, give rise galaxies

We try to listen to the sound and figure out how the instrument is made

Fundamental scale→ Fundamental mode and overtones

like blowing on a pipe….

HOW? *WHY?* CMB THEORY

"Seeing sound" (W. Hu)

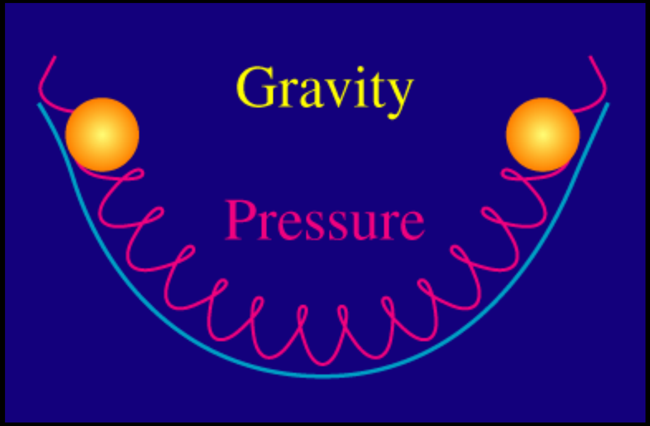
Last scattering surface:
snapshot of the photon-baryon fluid (plasma)

On large scales : primordial ripples

What put them there?

On smaller scales: { Photons radiation pressure / Gravity compression } Sound waves

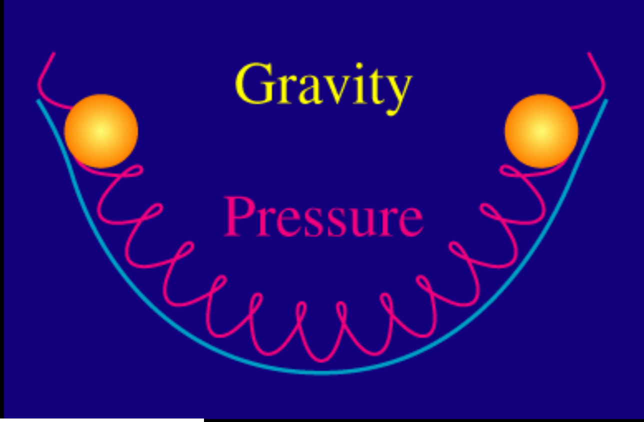
Stop oscillating at recombination

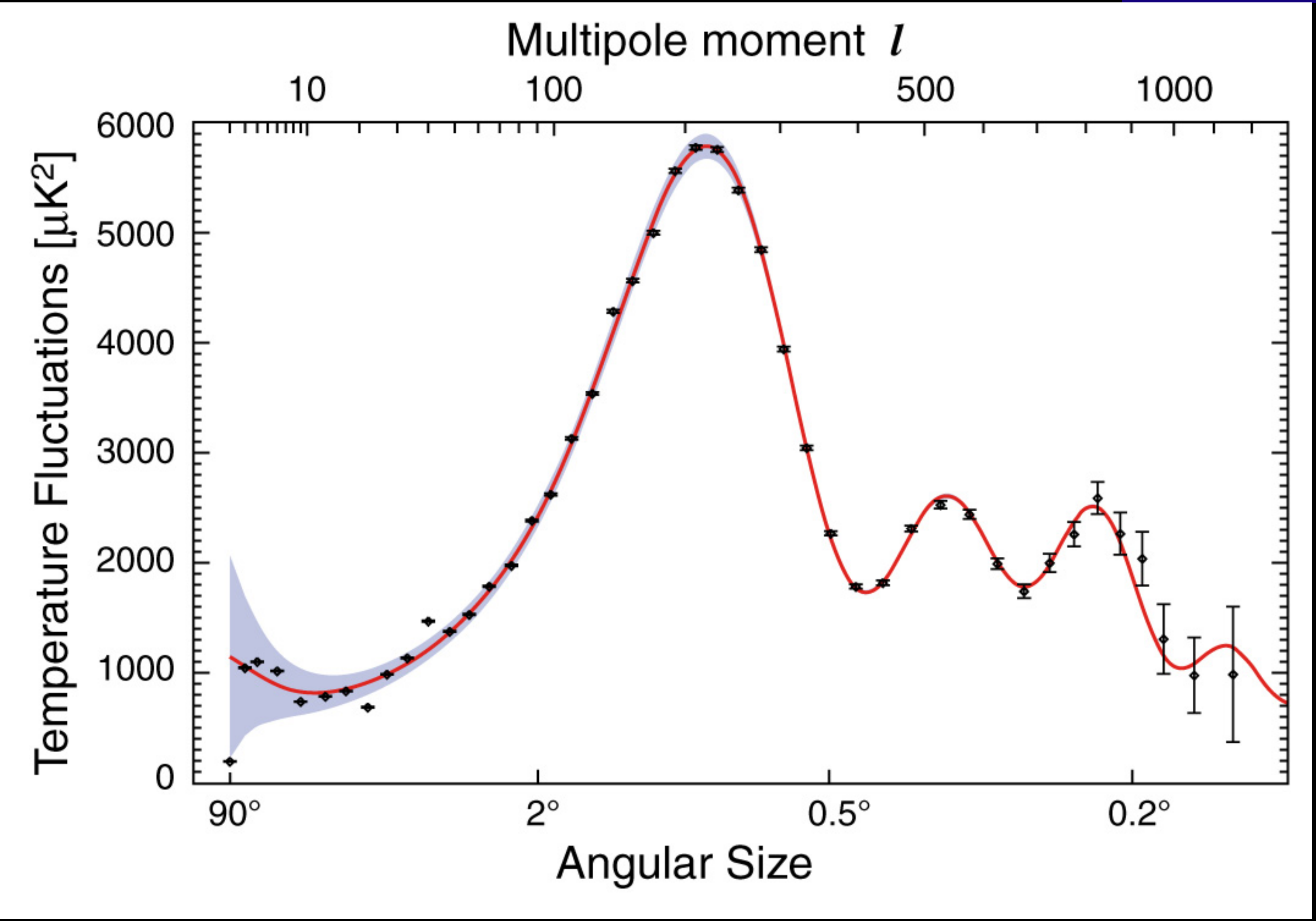


Horizon size at last scattering → Fundamental mode (over tones)

SEEING SOUND

Compressing information





WMAP
9yr results

ΛCDM: The standard cosmological model

"Cosmology now has a standard model: a flat universe composed of matter, baryons and vacuum energy with a nearly scale-invariant spectrum of primordial fluctuations.[…] Cosmology is now in a similar stage in its intellectual development to particle physics three decades ago when particle physicists converged on the current standard model. The standard model of particle physics fits a wide range of data, but does not answer many fundamental questions: "what is the origin of mass? why is there more than one family?, etc." Similarly, the standard cosmological model has many deep open questions: "what is the dark energy? what is the dark matter? what is the physical model behind inflation (or something like inflation)?" Over the past three decades, precision tests have confirmed the standard model of particle physics and searched for distinctive signatures of the natural extension of the standard model: supersymmetry. Over the coming years, improving CMB, large scale structure, lensing, and supernova data will provide ever more rigorous tests of the cosmological standard model and search for new physics beyond the standard model."

WMAP team, parameters paper 2003

2012 not supersymmetry but Higgs, at least

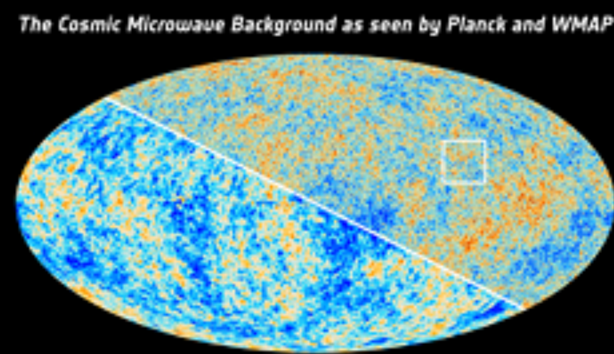
Look for deviations from the standard model

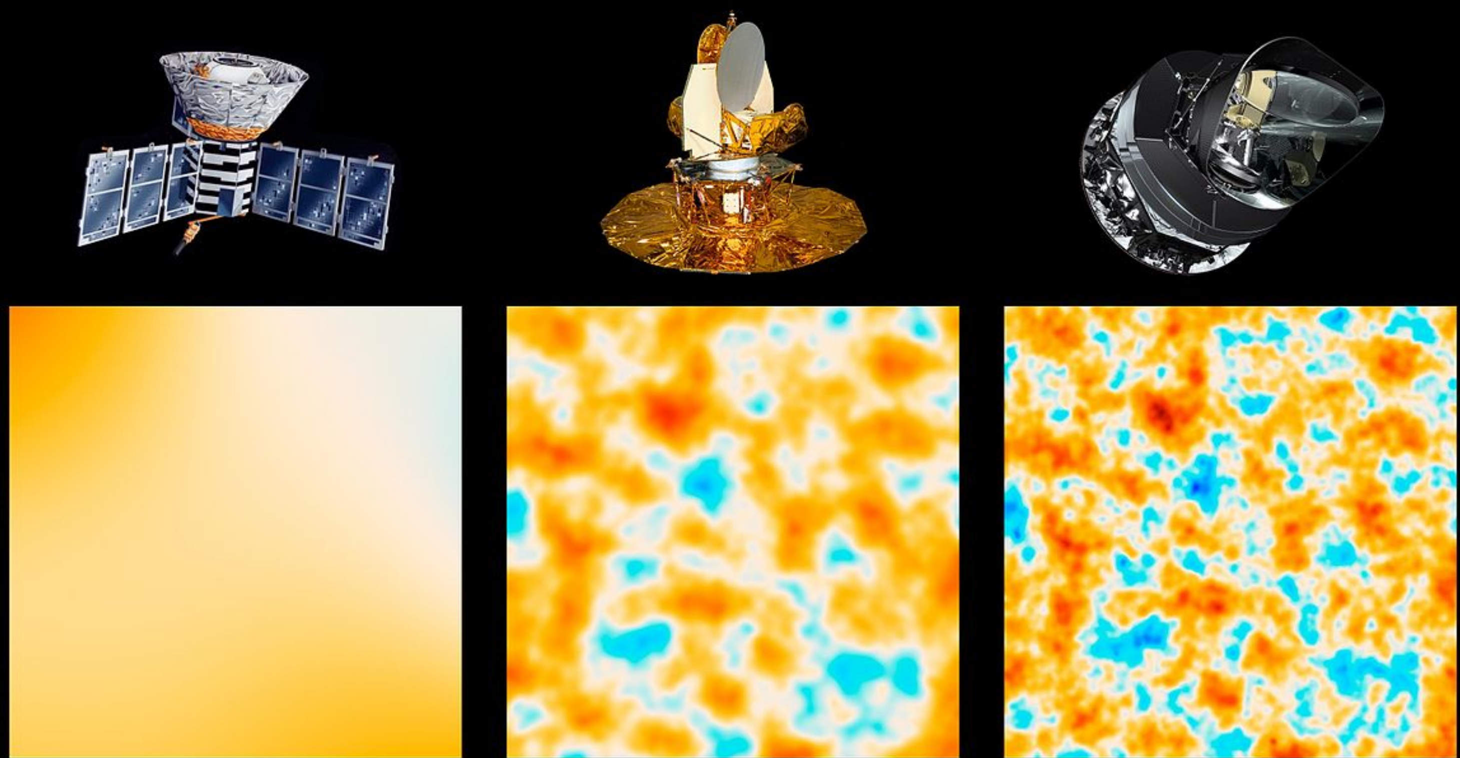
Test physics on which it is based and beyond it

- Dark energy
- Nature of initial conditions: Adiabaticity, Gaussianity
- Neutrino properties
- Inflation properties
- Beyond the standard model physics…

Note that there is no mention to dark matter here

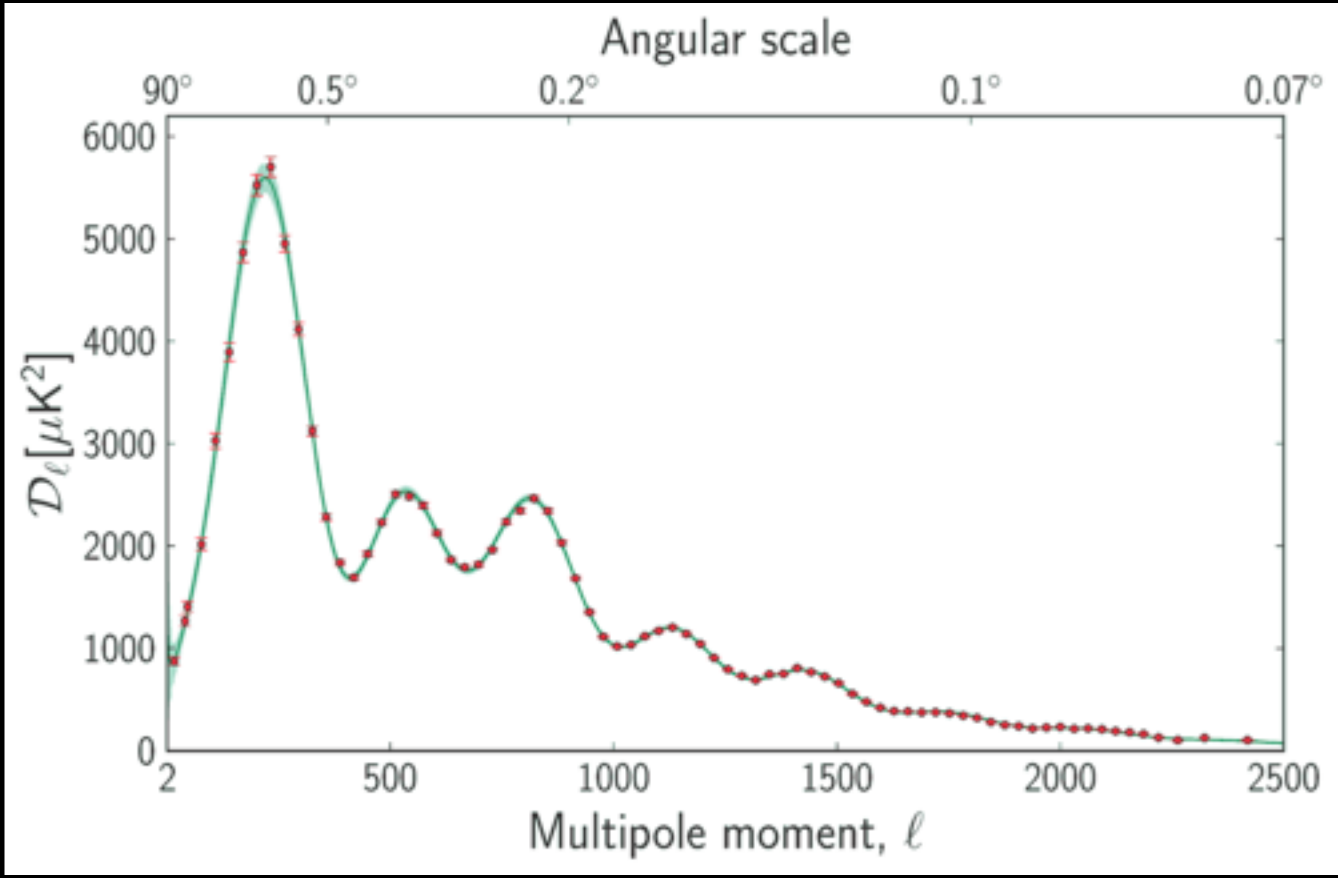
Planck ESA satellite map the Cosmic Microwave Background





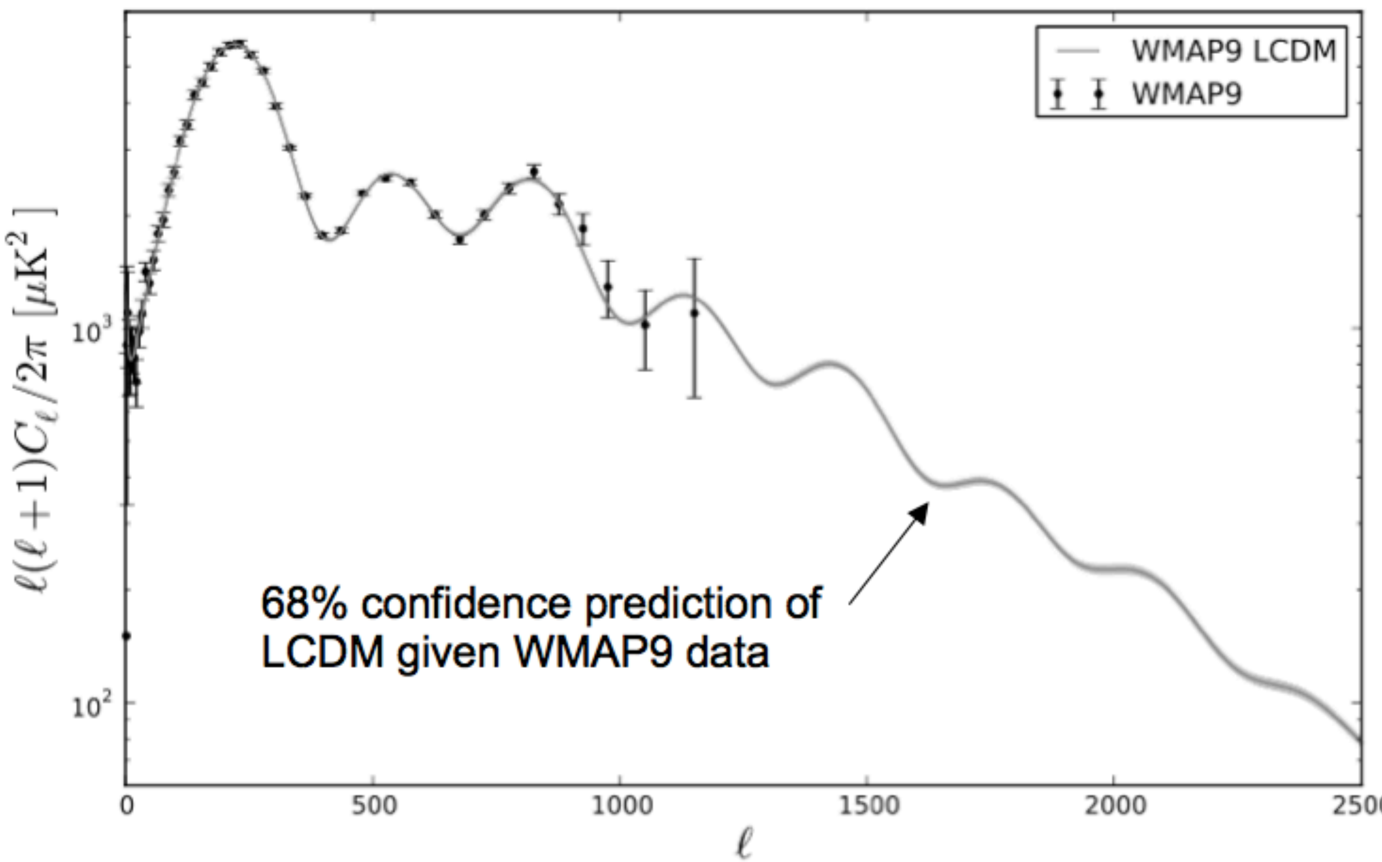
COBE WMAP Planck

Compressing information

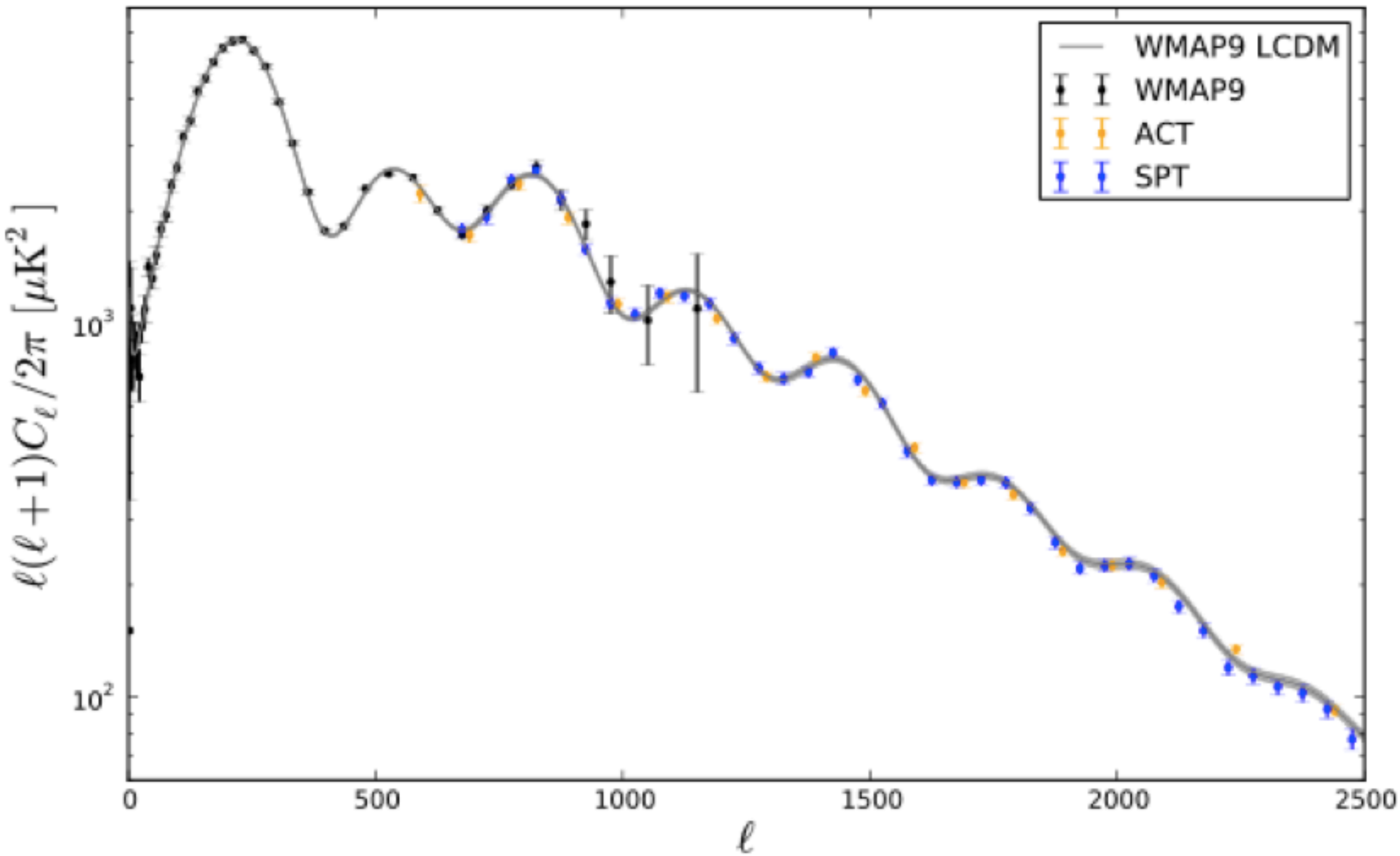


Planck collaboration , 2013, paper XVI

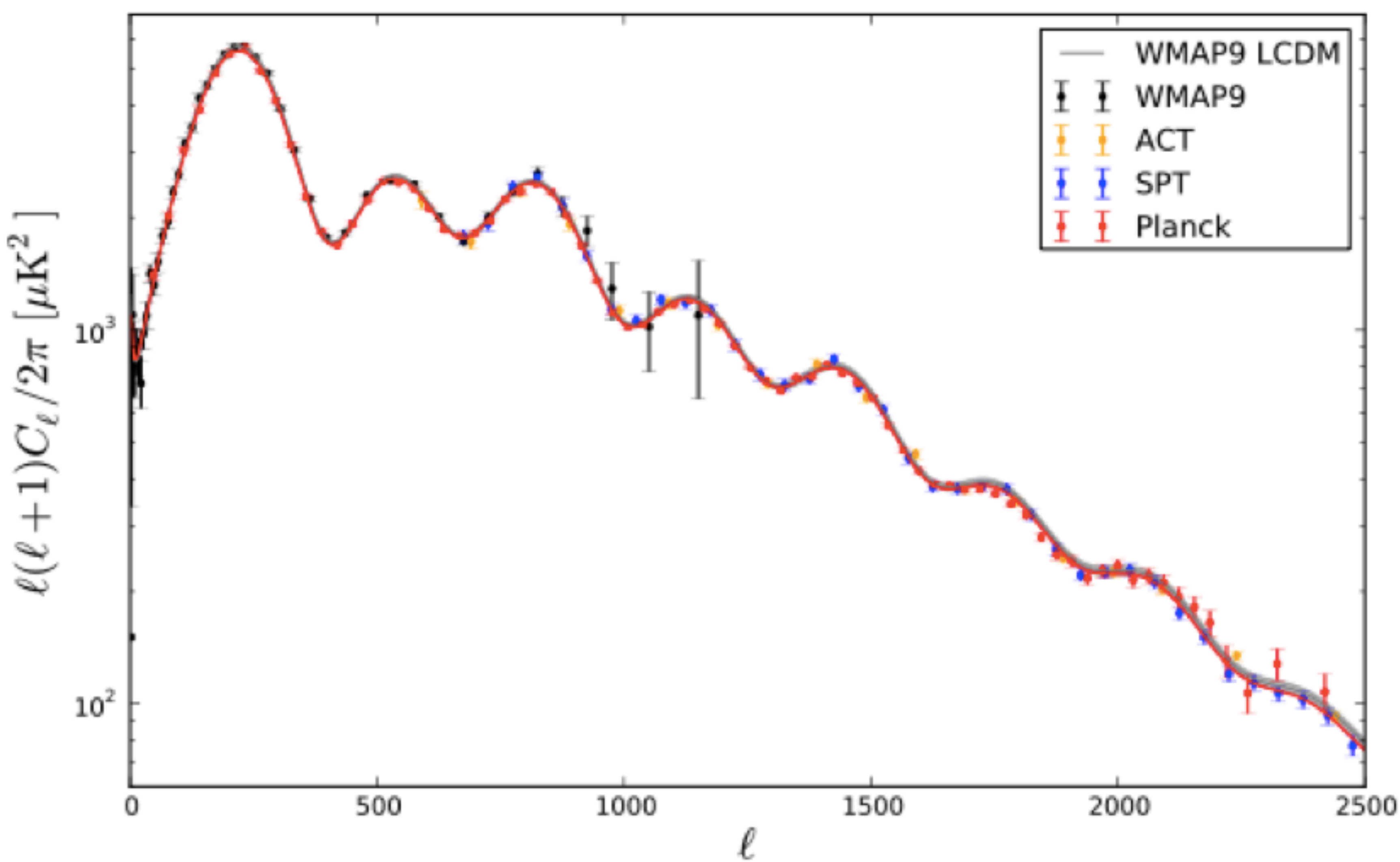
LCDM makes a very precise prediction



Slide credit: M. Millea

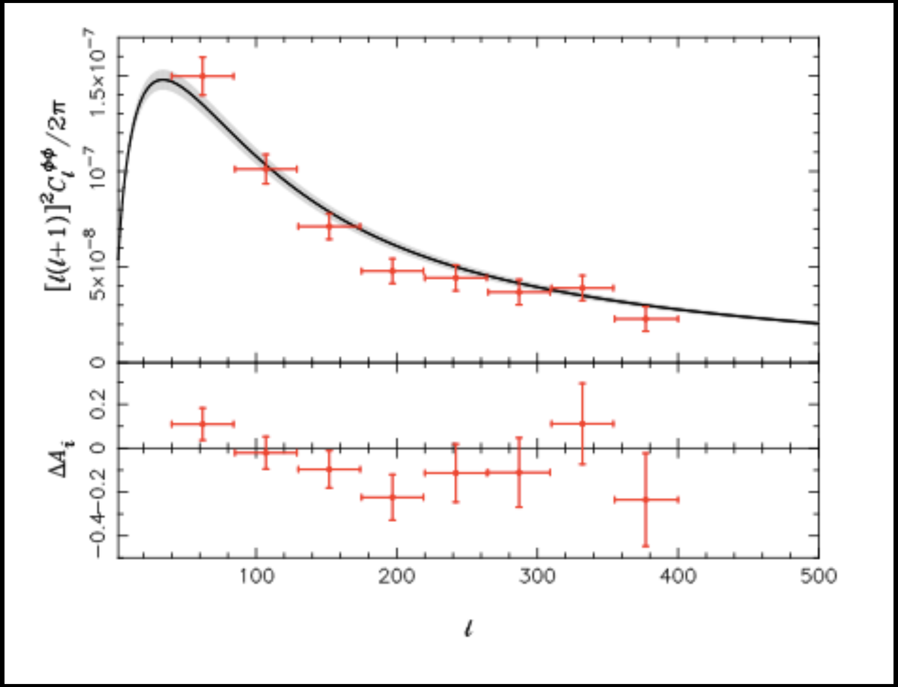


Slide credit: M. Millea

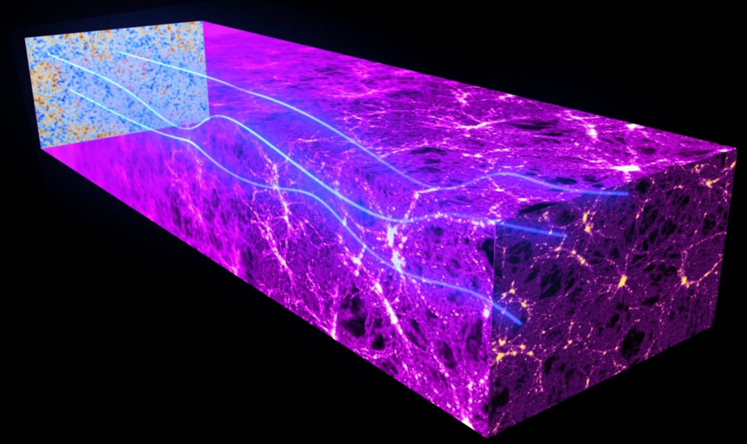


Slide credit: M. Millea

NEW measurement

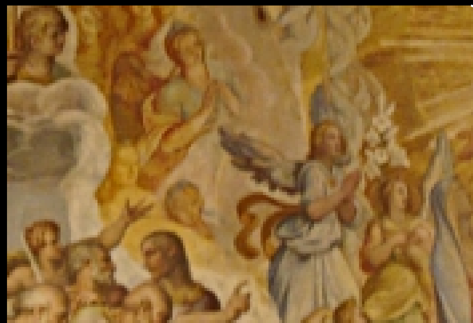


Planck collaboration , 2013, paper XVI



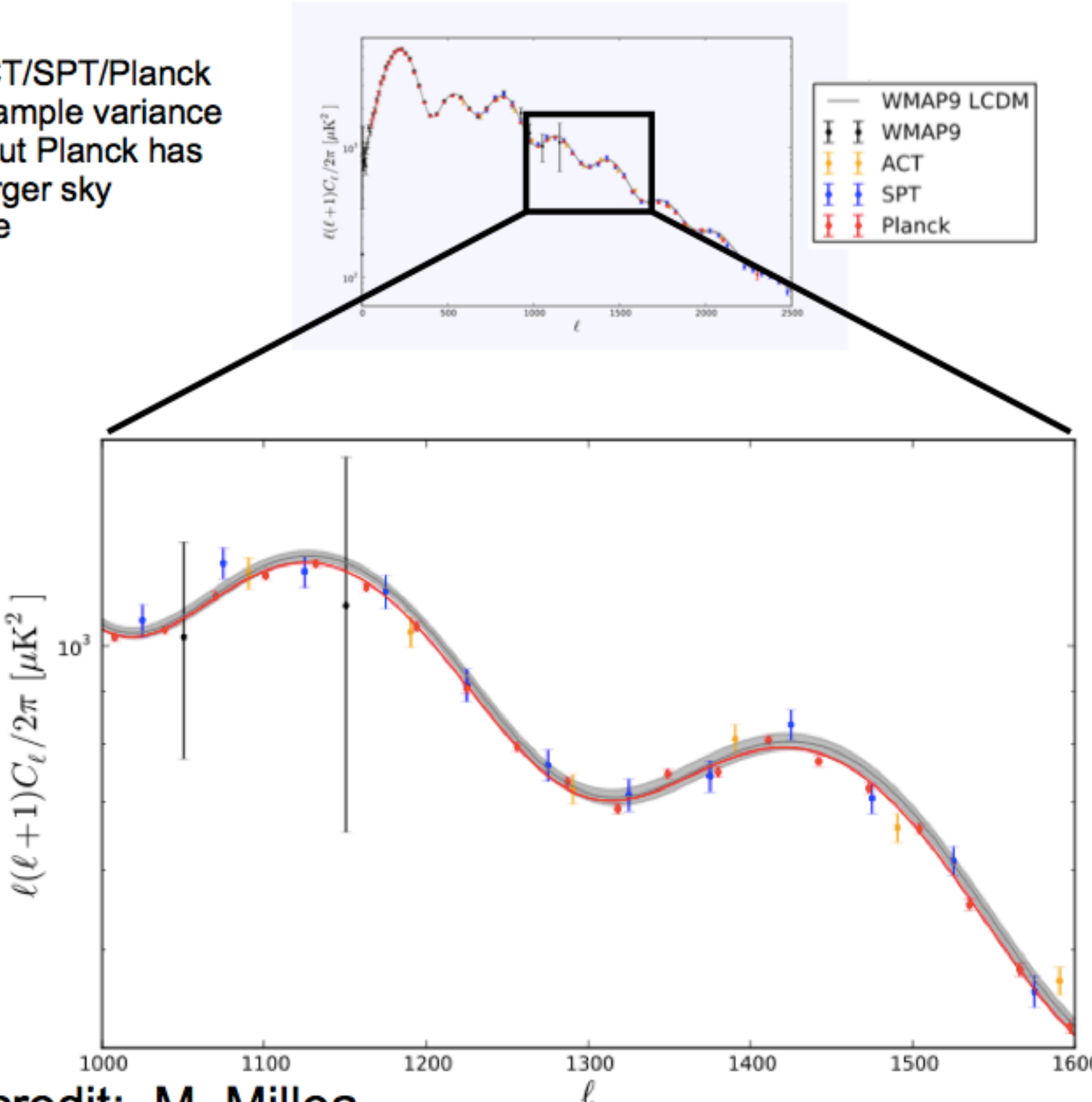
Wonderful agreement of new data with the ΛCDM model

what everybody is talking about



Last Judgment, Vasari, Florence Duomo

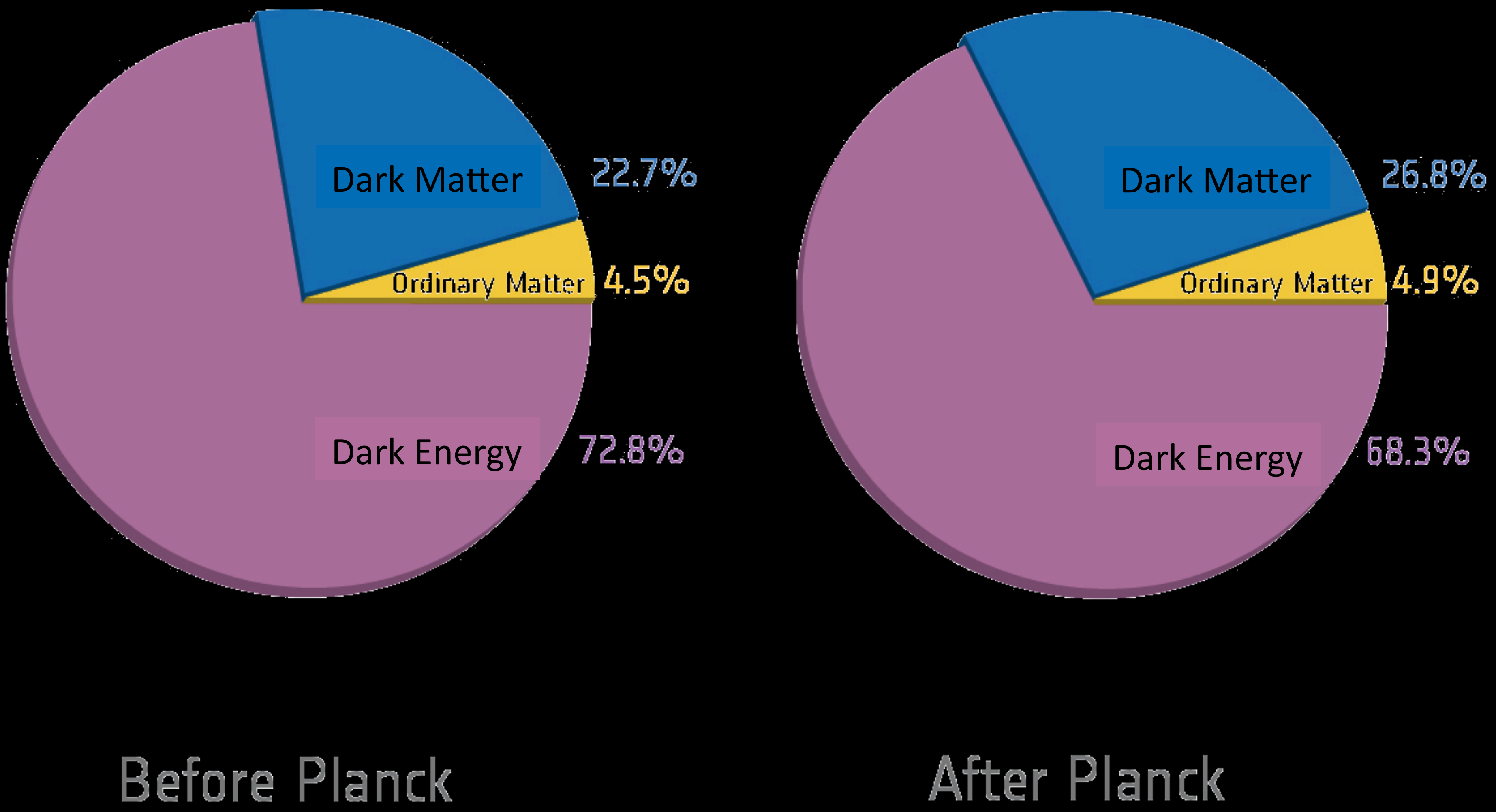
- Here ACT/SPT/Planck are all sample variance limited but Planck has much larger sky coverage



Slide credit: M. Millea

what everybody is talking about

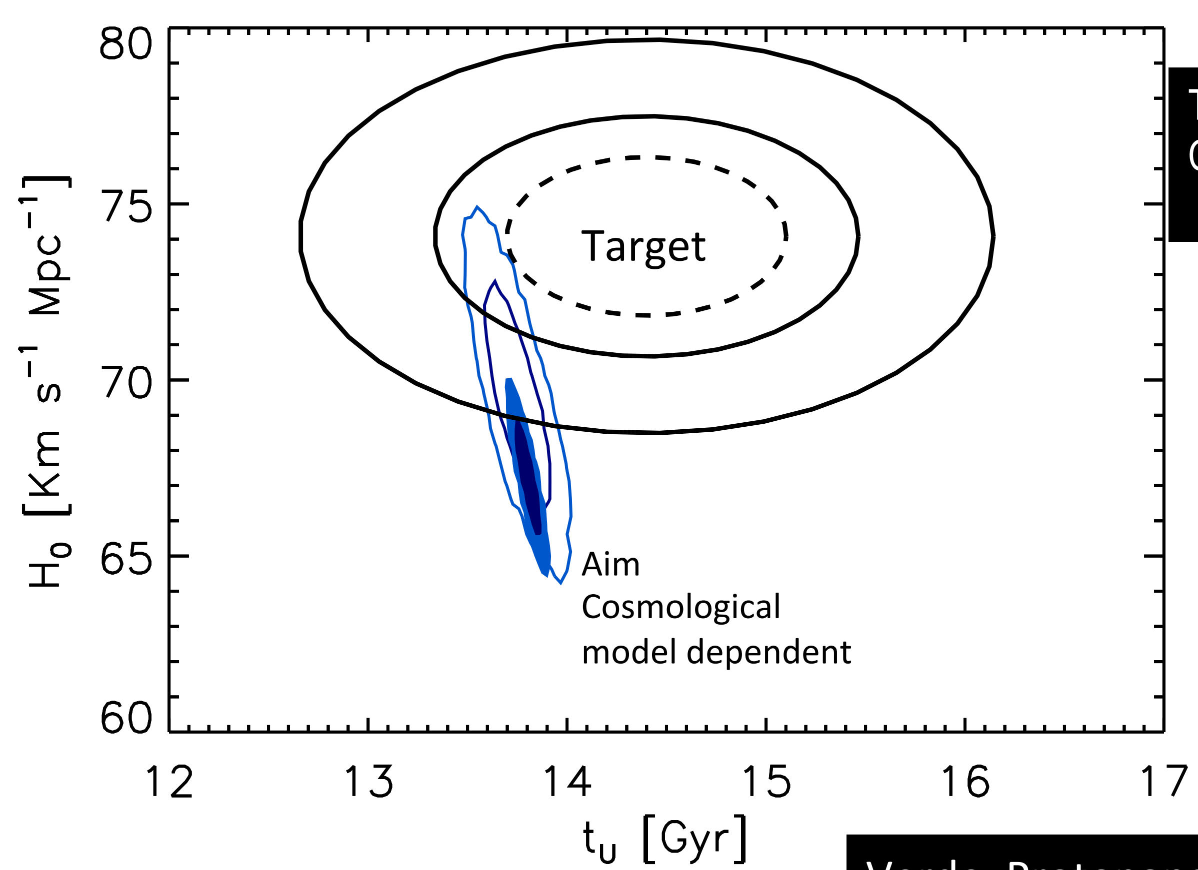
Cosmic recipe adjustments



what everybody is talking about

The importance of local measurements:

"Shooting at a "target" from the other side of the Universe"

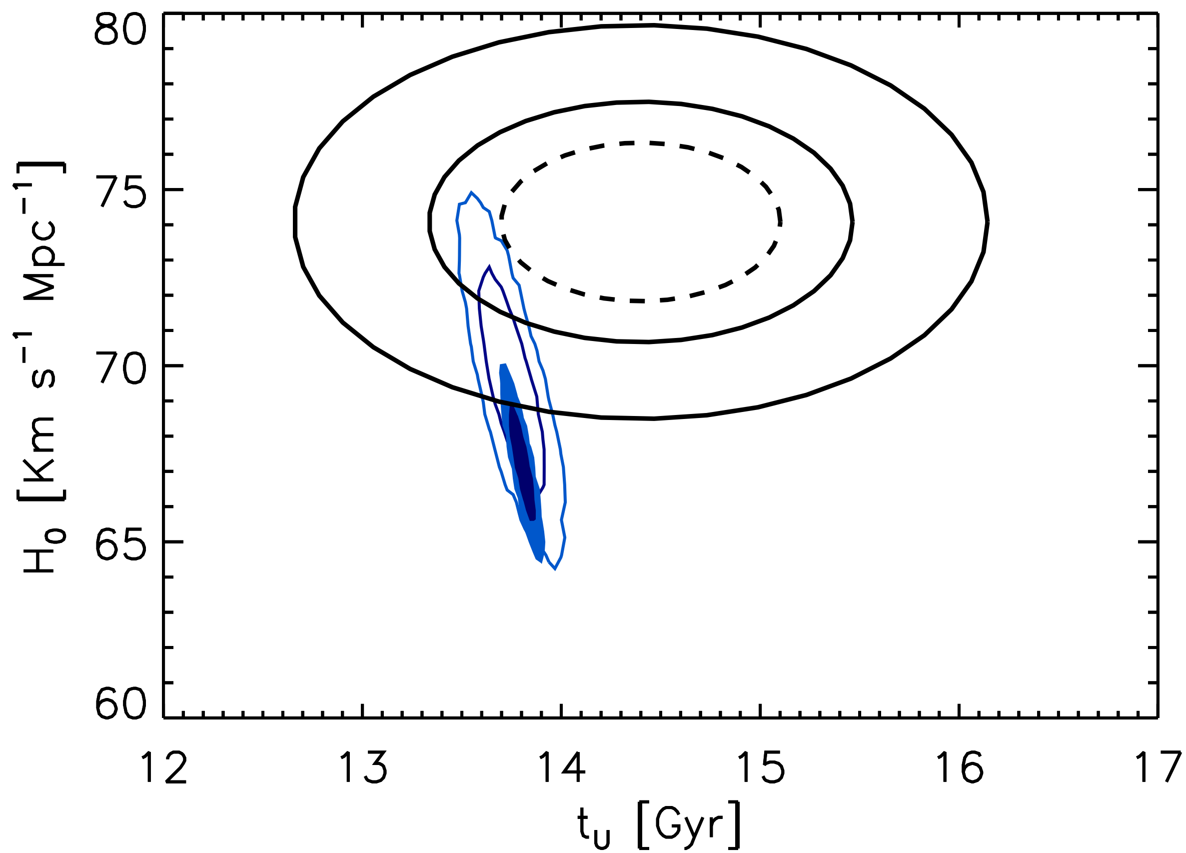


Target:
Cosmological model
independent

Verde, Protopapas, Jimenez, 2013
Verde, Jimenez, Feeney 2013

what everybody is talking about

Precision cosmology! (accuracy cosmology?)



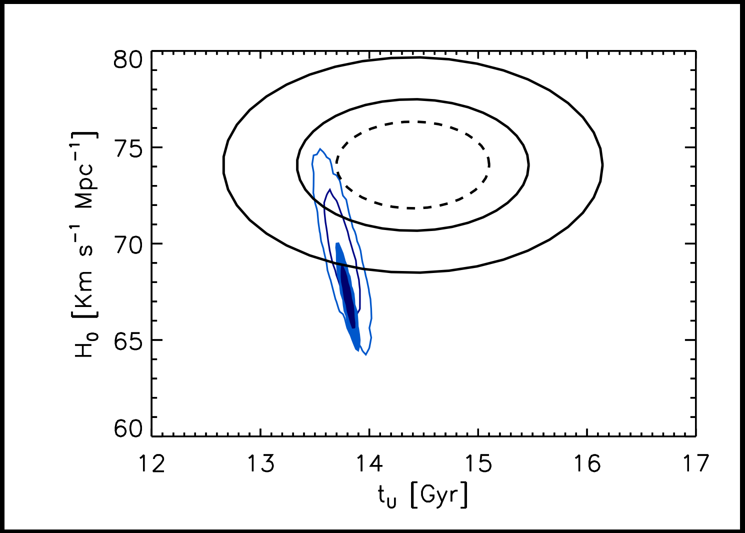
TENSION!!!

Odds: 1:53

Verde, Protopapas, Jimenez, 2013
Verde, Jimenez, Feeney 2013

TENSION!!!

You can “Blame the data”
(illustrous people have gone this way)



Is there any model
extension that fixes this???

Neutrino mass <0.15 eV for tension not to be highly significant (1:150)

3.4<Neff<4.1 reduce tension to substantial (better than 1:12)
(NO value makes it not significant)

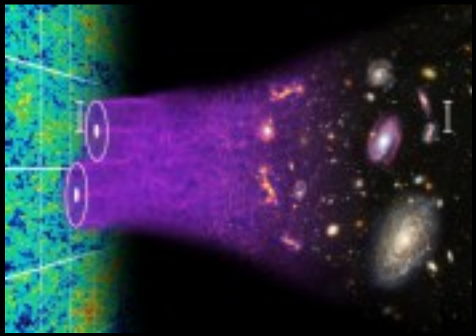
However there are other data out there which do not support this interpretation

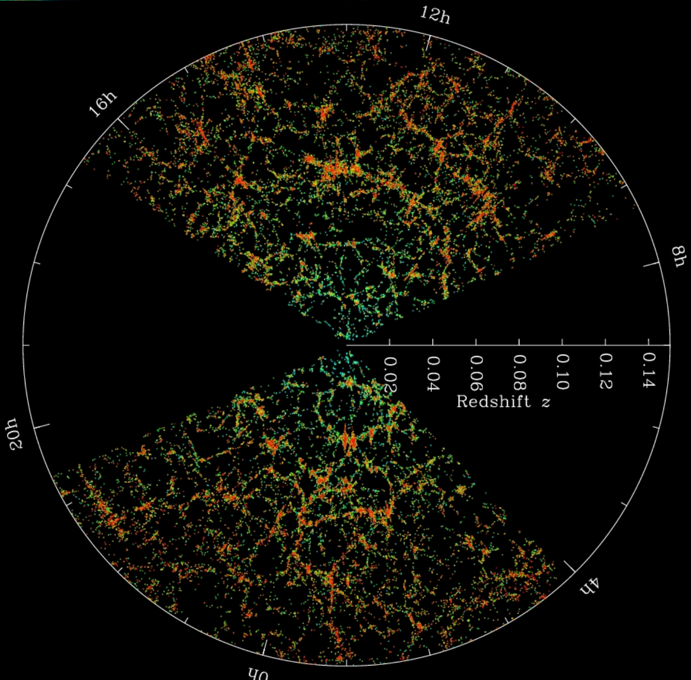
Neff>4.6 makes tension highly significant

w ~ -1.2 makes tension not significant!

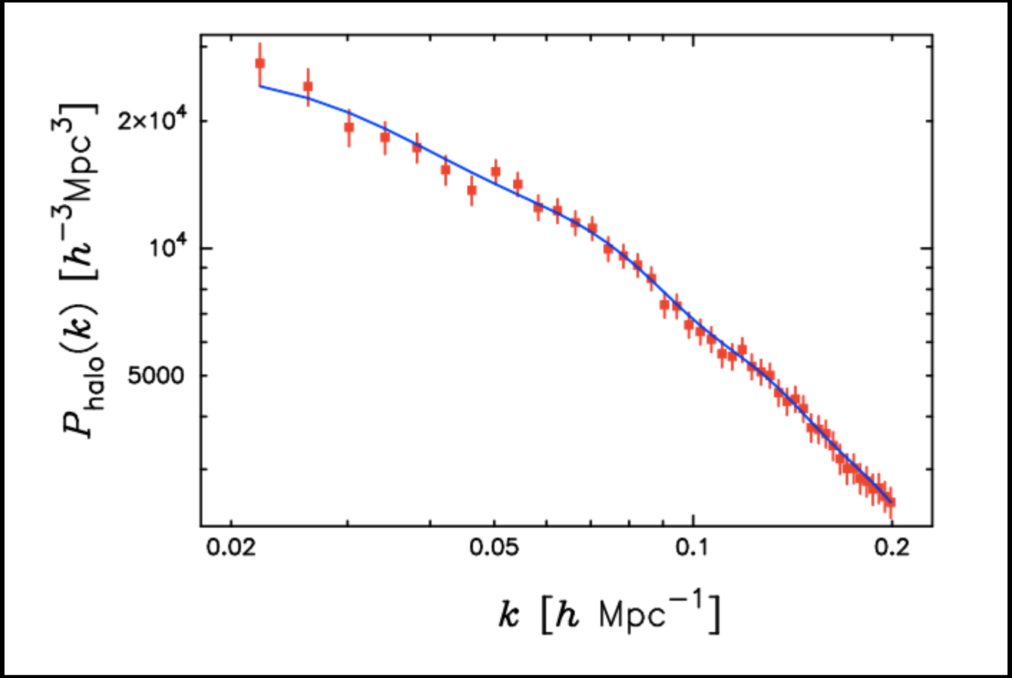
Verde, Protopapas, Jimenez, 20

ΛCDM remains a very good fit to the Universe



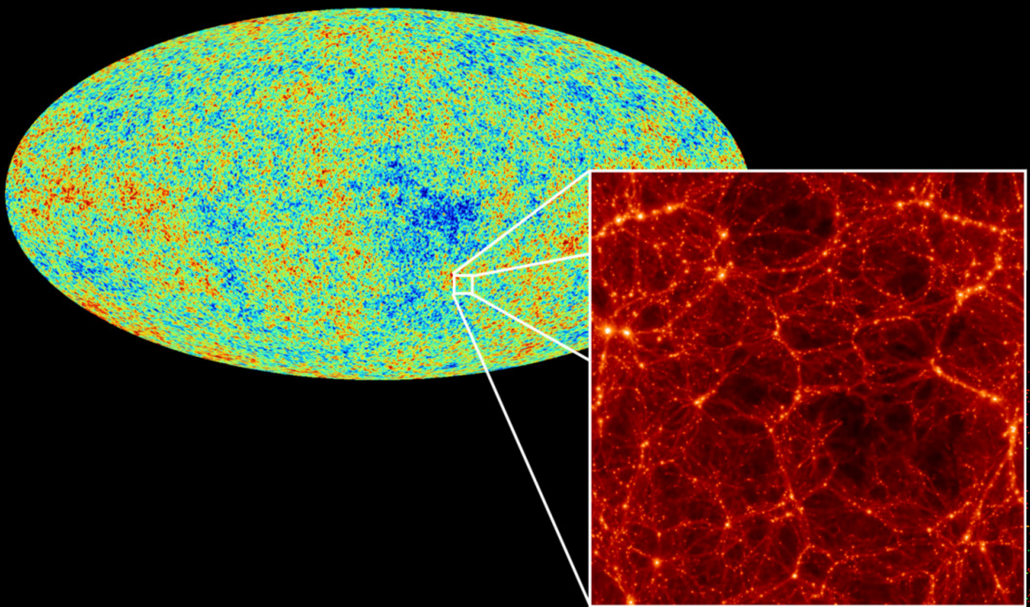


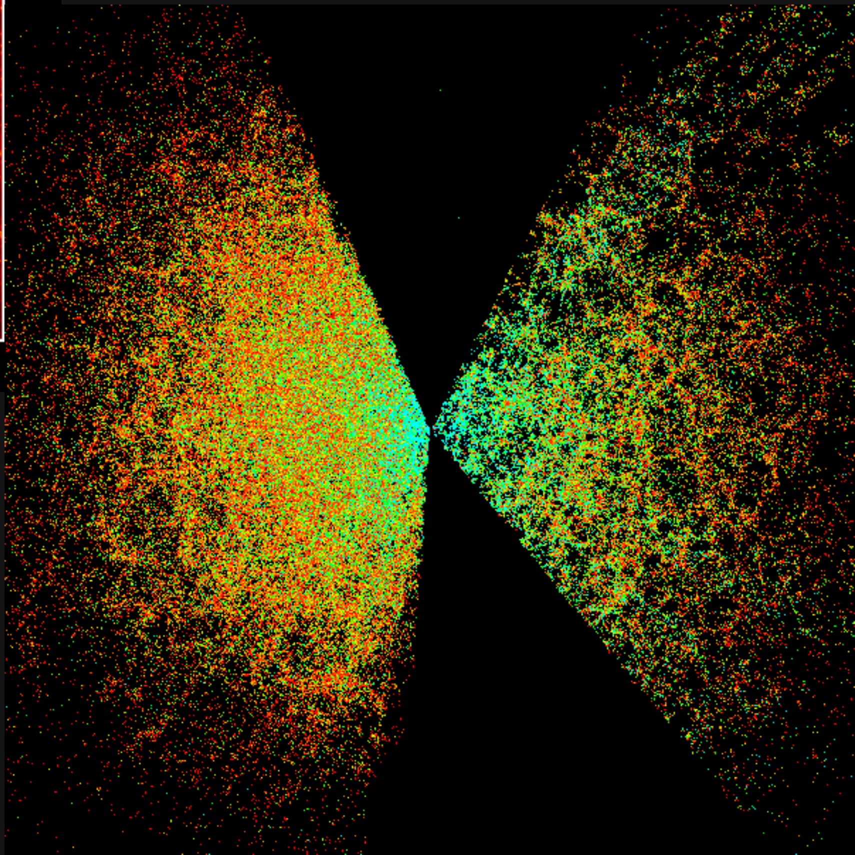
SDSS LRG galaxies power spectrum (Reid et al.)



13 billion years of gravitational evolution

Exploring the low-er-redshift Universe





MOTIVATIONS

- CMB primary temperature “all done”
- Three main open issues: dark matter, cosmic acceleration (dark energy) and origin of perturbations (inflation)
- a lot of info in the lower-redshift Universe where we have the technical capability to perform an ultimate experiment
- (more on CMB polarization later)

MOTIVATIONS

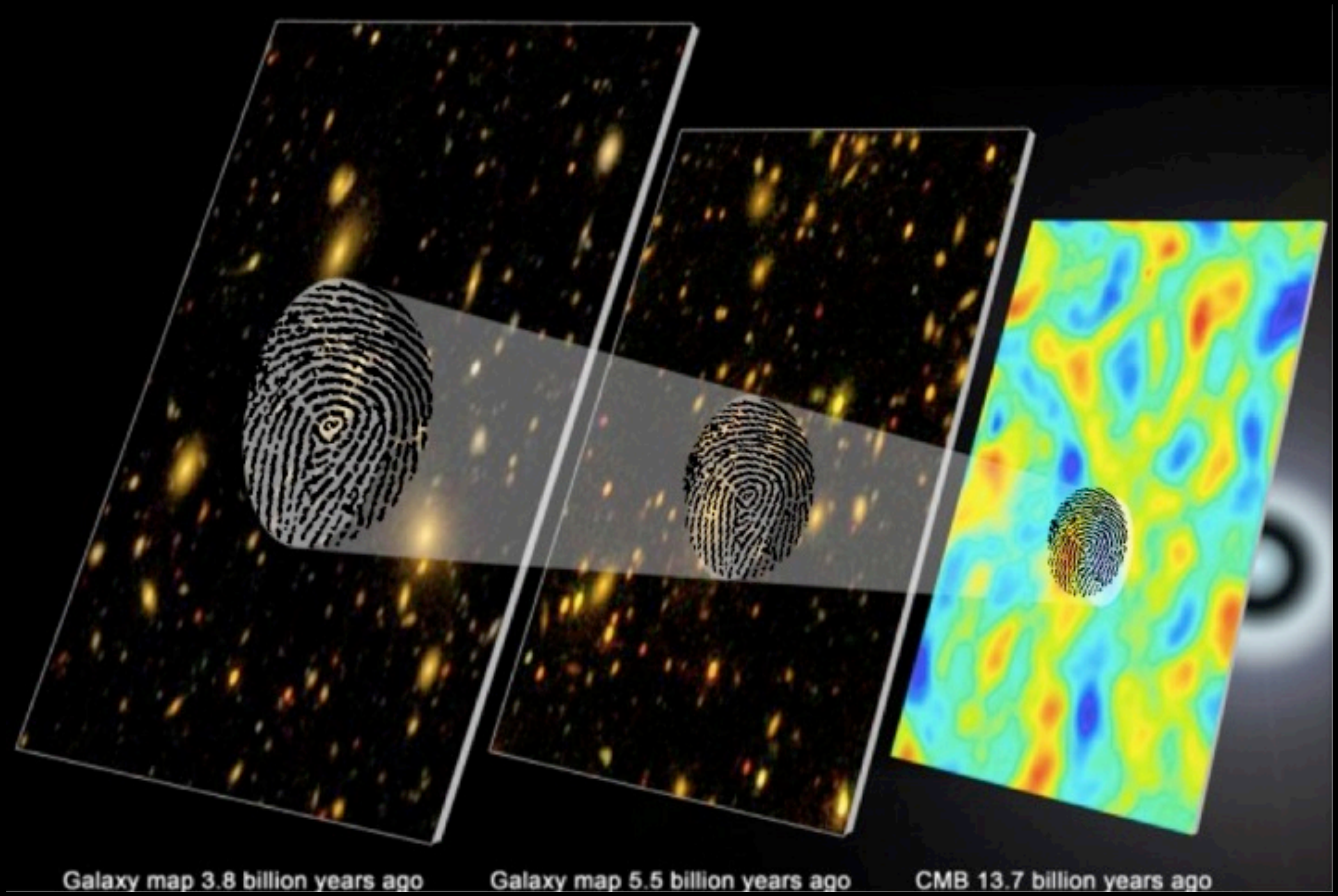
- Two BIG open questions in cosmology:

what is dark energy?

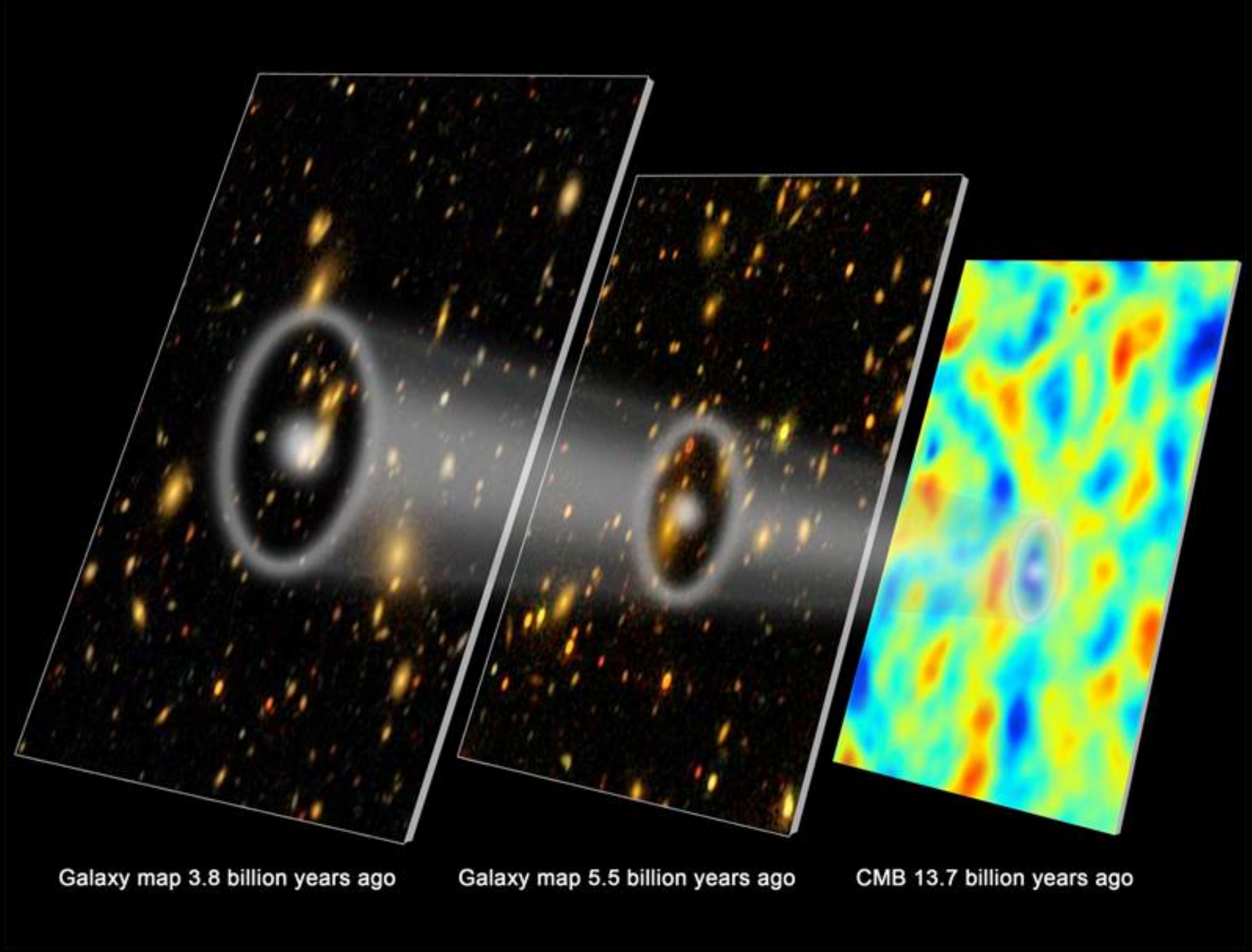
What is the physics behind inflation?

- Common aspects:
  - They both involve a period of accelerated expansion
  - The both an ultimately be solved only looking up at the sky

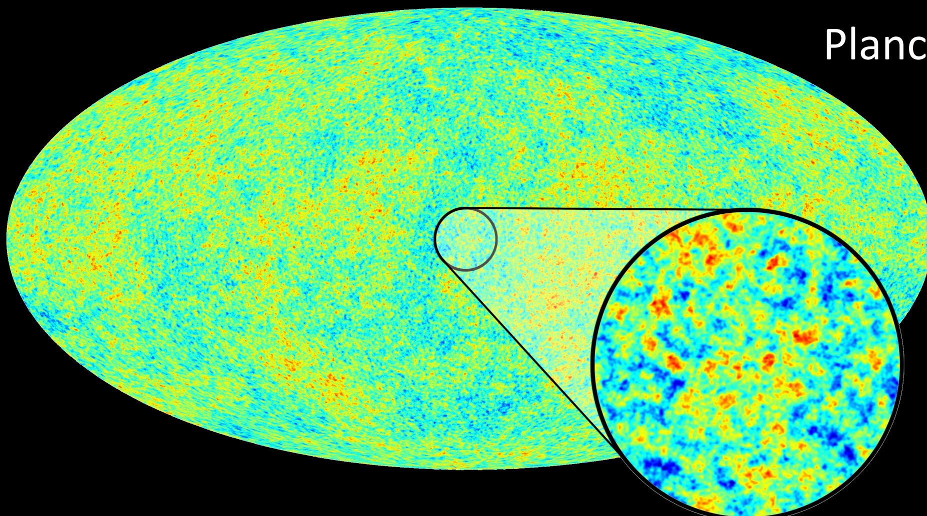
Baryon acoustic oscillations (BAO)



Baryon acoustic oscillations (BAO)



Baryon acoustic oscillations

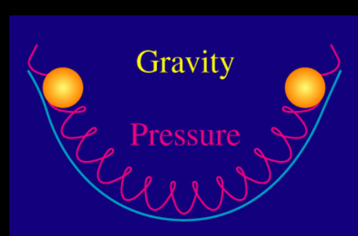


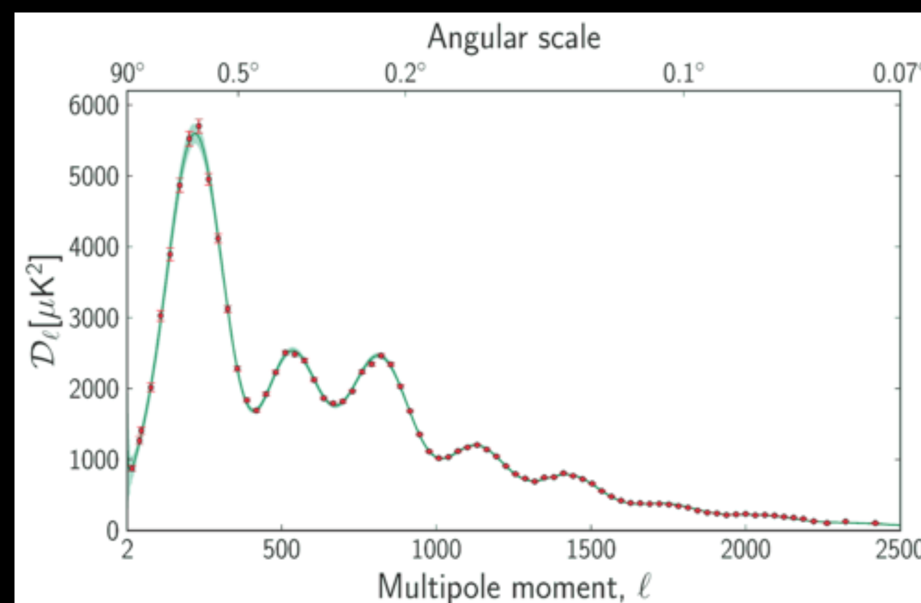
Planck

Sound horizon at decoupling

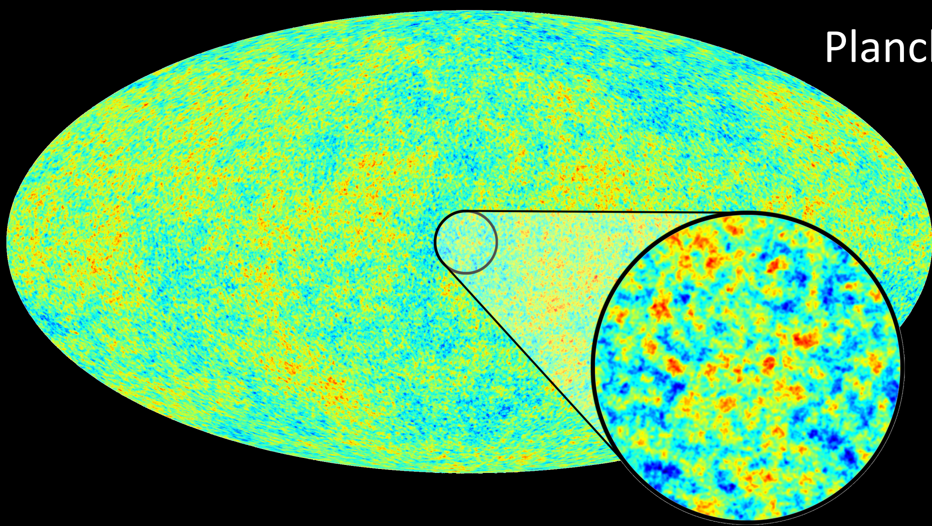
$$k_{\rm bao} = 2\pi/s$$

$$s = \frac{1}{H_0\Omega_m^{1/2}}\int_0^{a_*} da\,\frac{c_s}{(a+a_{\rm eq})^{1/2}}$$





Baryon acoustic oscillations

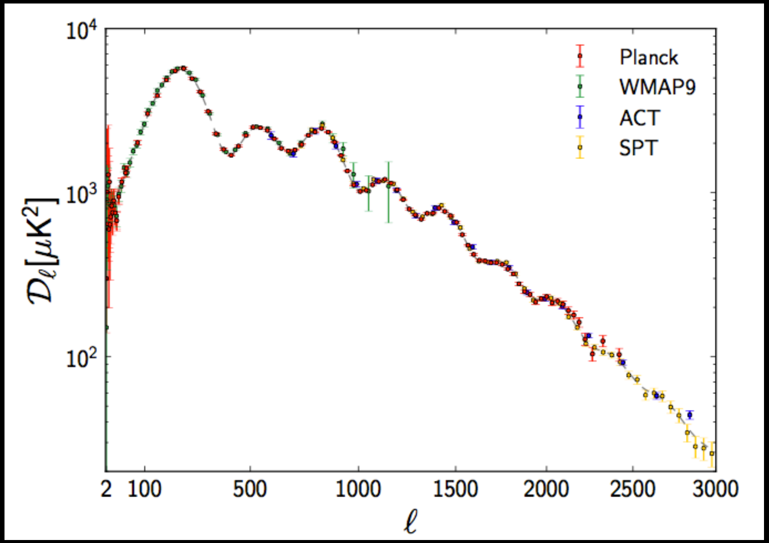


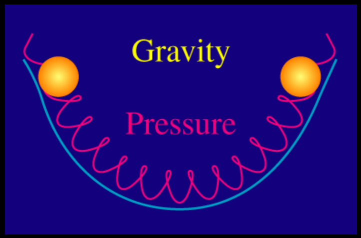
Planck

Sound horizon at decoupling

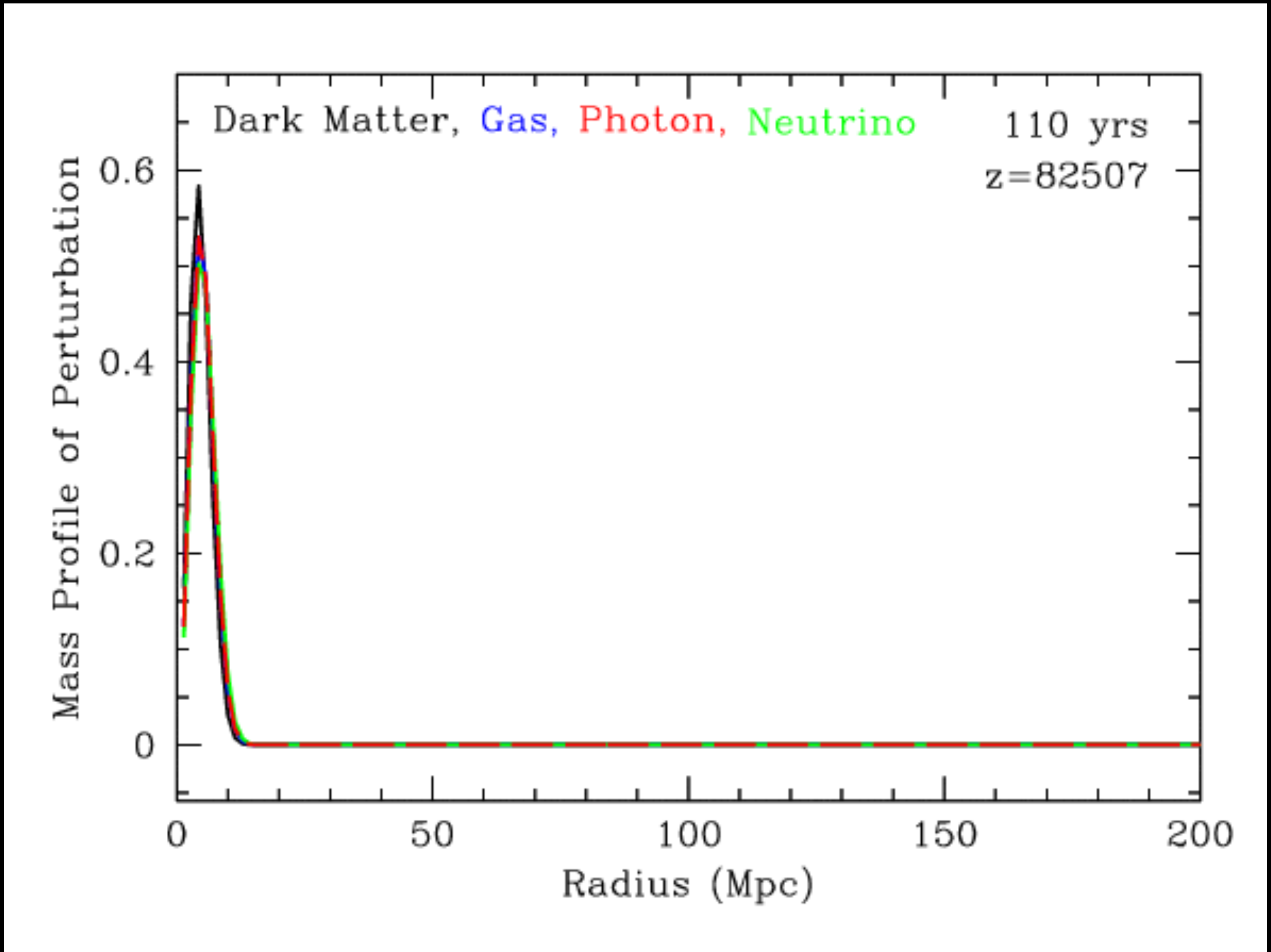
$$k_{\rm bao} = 2\pi/s$$

$$s = \frac{1}{H_0 \Omega_m^{1/2}} \int_0^{a_*} da \frac{c_s}{(a + a_{\rm eq})^{1/2}}$$





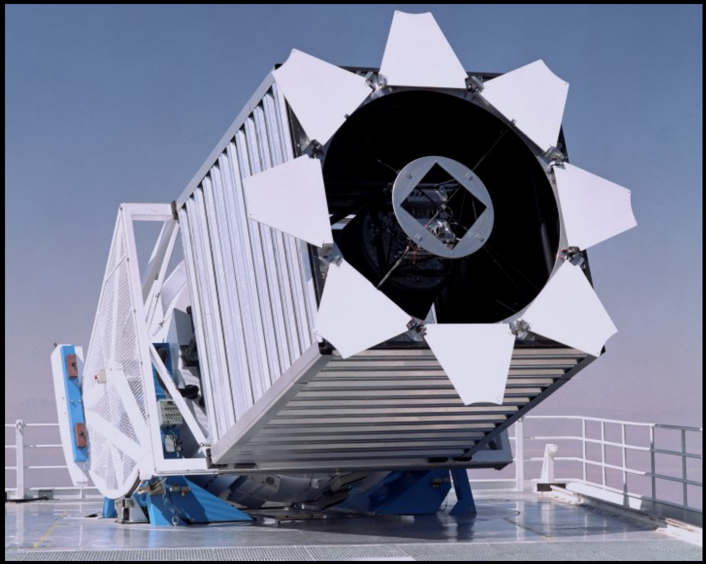
Baryon acoustic oscillations (BAO)



Animation courtesy of D. Eisenstein

SDSSIII (BOSS)

Sloan Digital Sky Survey Telescope



2.5 meters in New Mexico

Photometry + spectroscopy

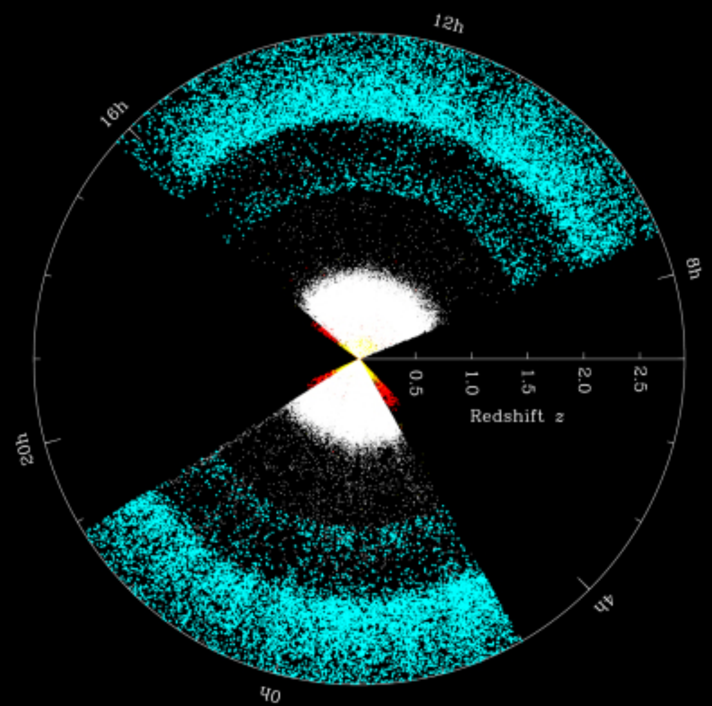
SDSS used by over 5000 refereed papers

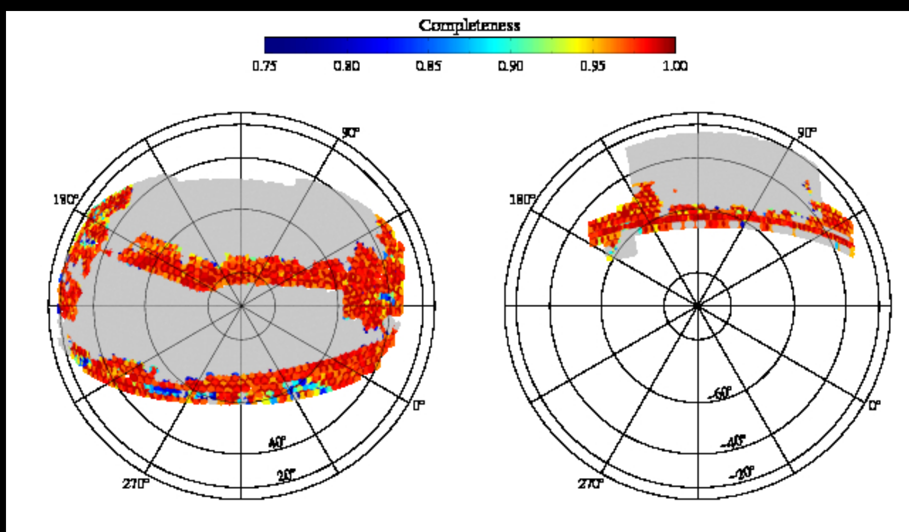
SDSSIII BOSS

Baryon Oscillation Spectroscopic Survey

1000 fibers spectrograph   2 M spectra!

Luminous red galaxies (LRG)   Quasars



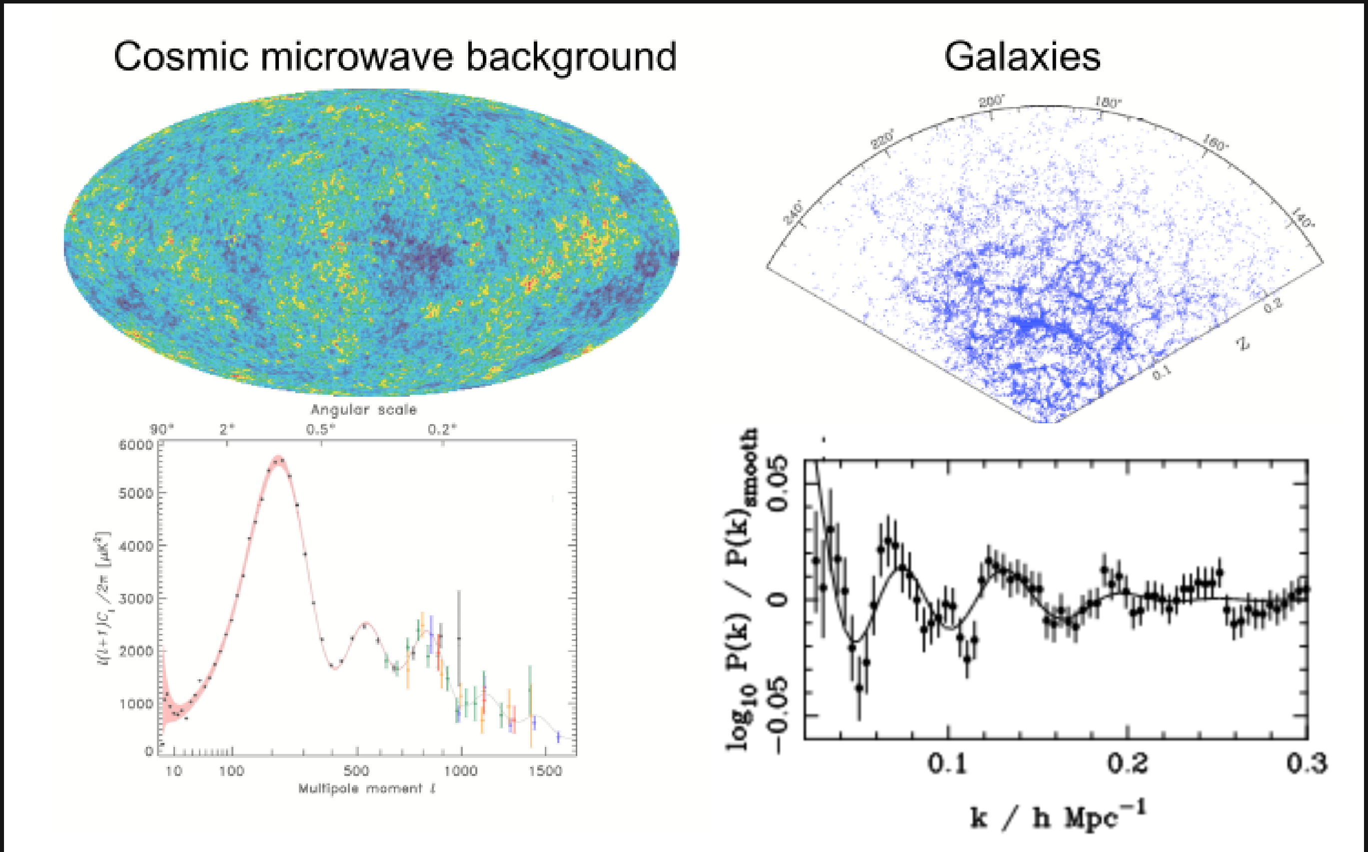


DR9 survey footprint galactic coordinates (Sanchez et al. 2012)

400K galaxy spectra

WHY LRG?   Luminous and highly biased

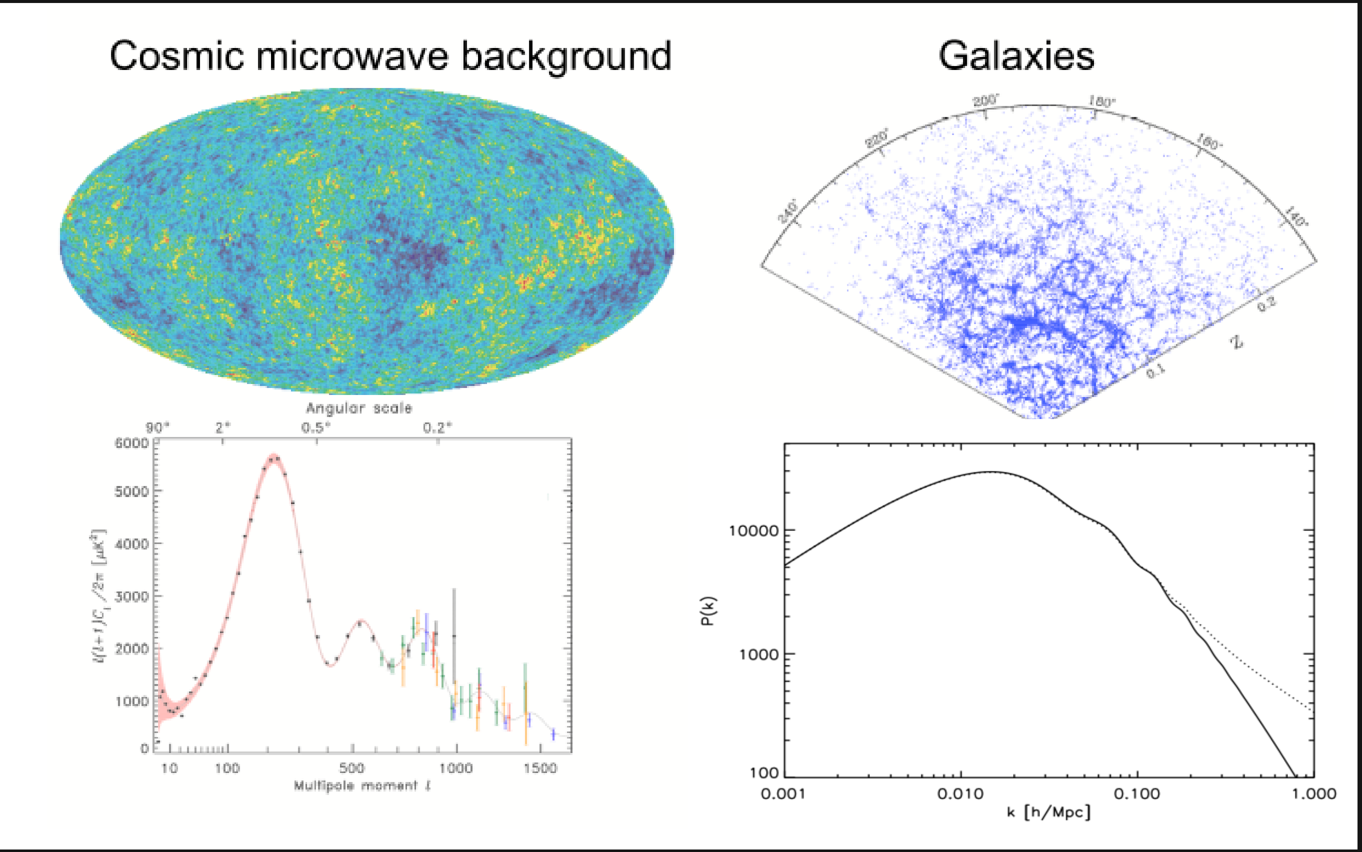
What surveys aim to measure



Anderson et al 2012

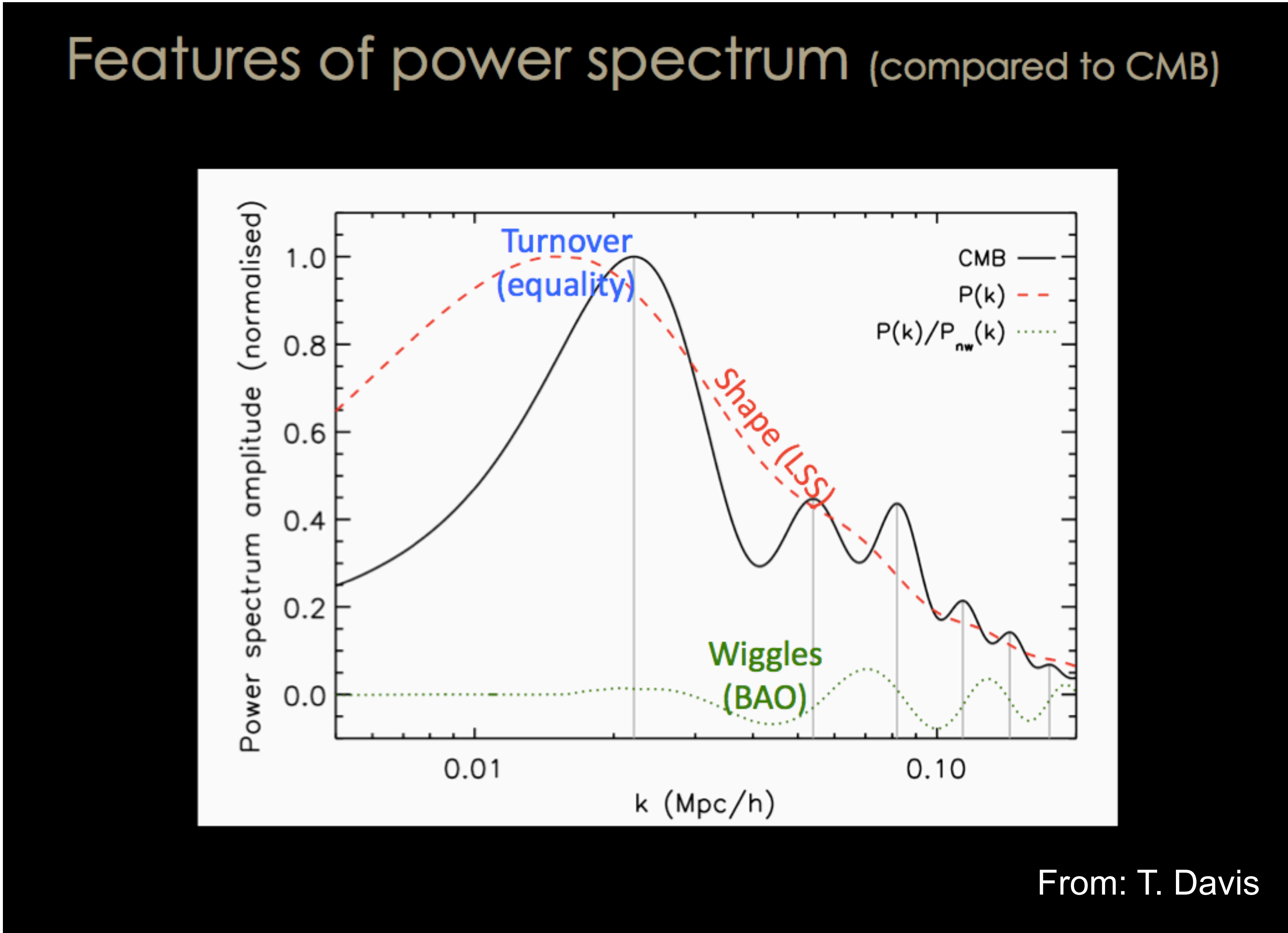
But there is <u>much more</u> cosmological information

What surveys aim to measure



But there is much more cosmological information

Another way to see this:



BAO

Standard rulers at different redshifts

In principle: two measurements in one

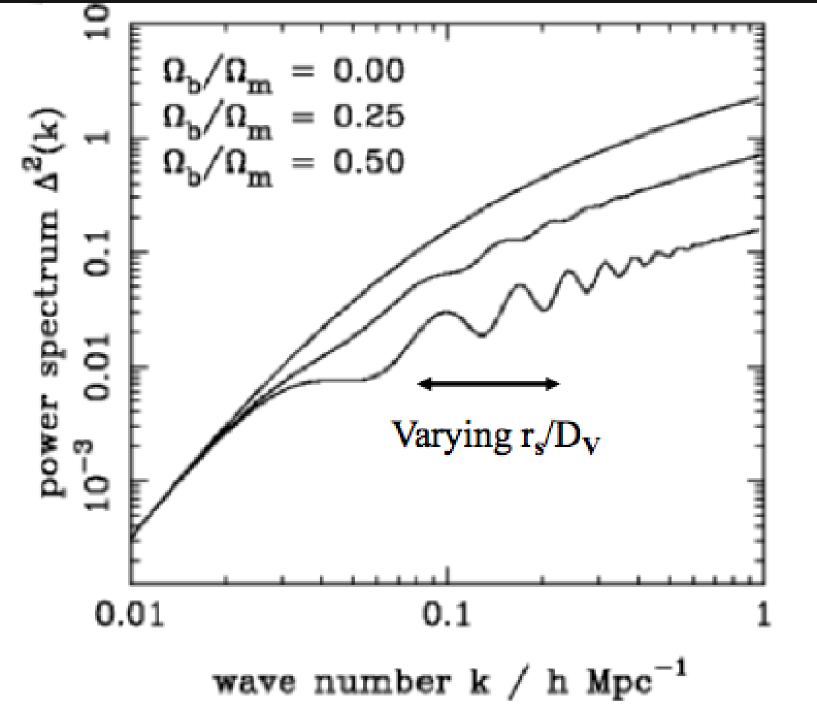
BAO measurements linked to physical BAO scale through:

Radial direction

$$\frac{c}{H(z)}\Delta z$$

Angular direction

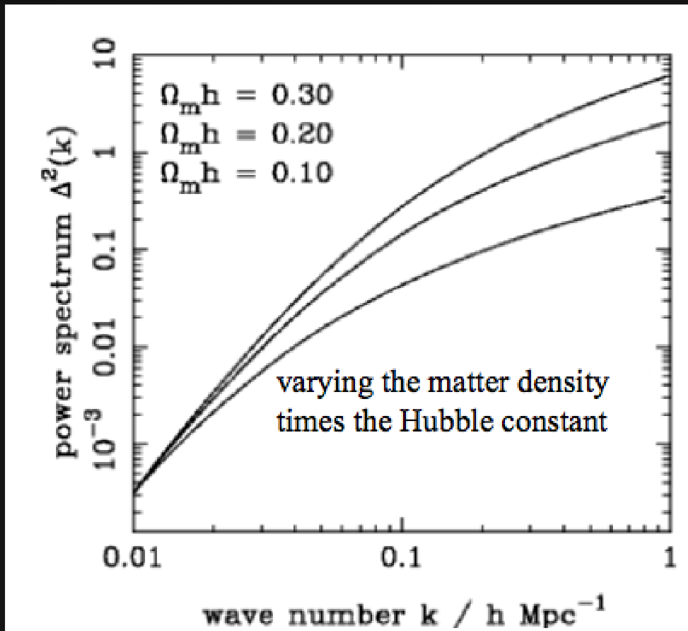
$$(1+z)D_A\Delta\theta$$

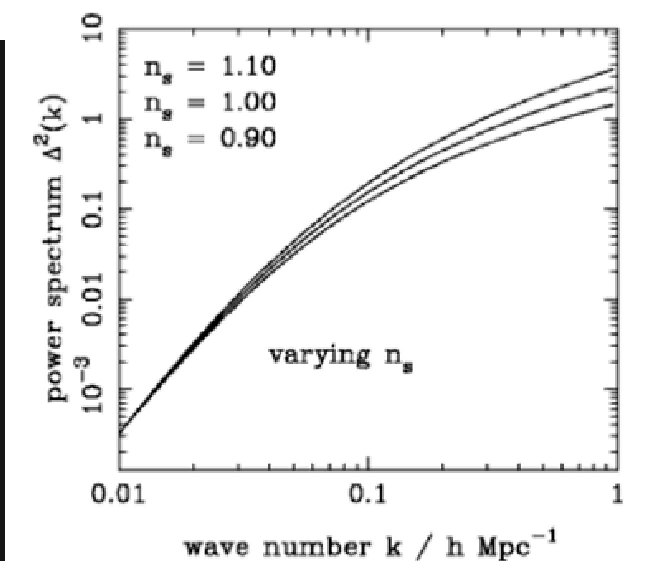


On Average:

$$D_V(z) = \left[(1+z)^2 D_A^2(z)\frac{cz}{H(z)}\right]^{1/3}$$

Large scale structure P(k) shape





Turn over:
Matter-radiation equality

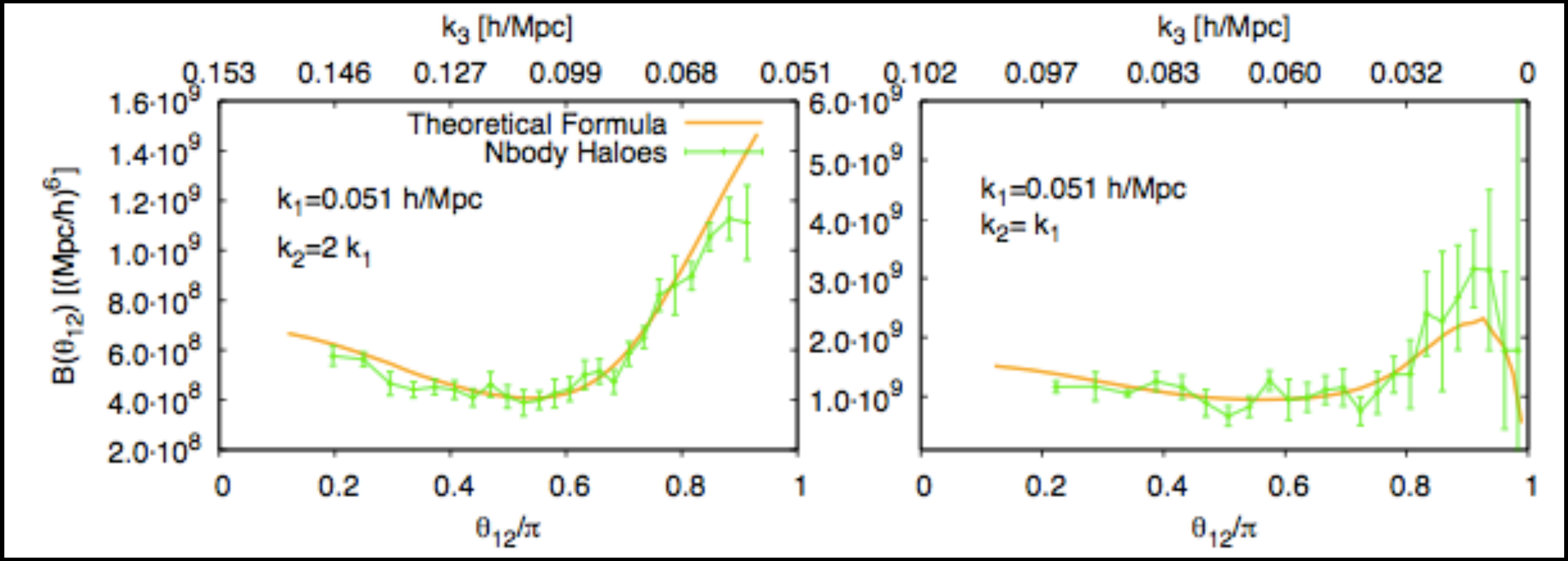
During radiaton domination
Pressure support means
large jeans length so sub-horizon
perturbations cannot grow

Slope: inflation seeding
primordial perturbations
Inflaton shape

Plus other subtle effects…

Using the broadband shape

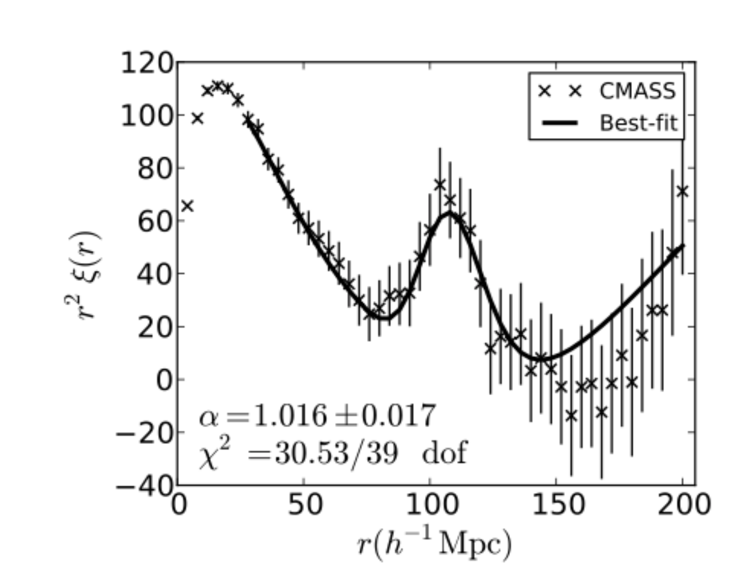
Beware of :
non –linearities
We see galaxies, who inhabit dark matter halos
Bias
We observe the third dimension along the line of sight distorted

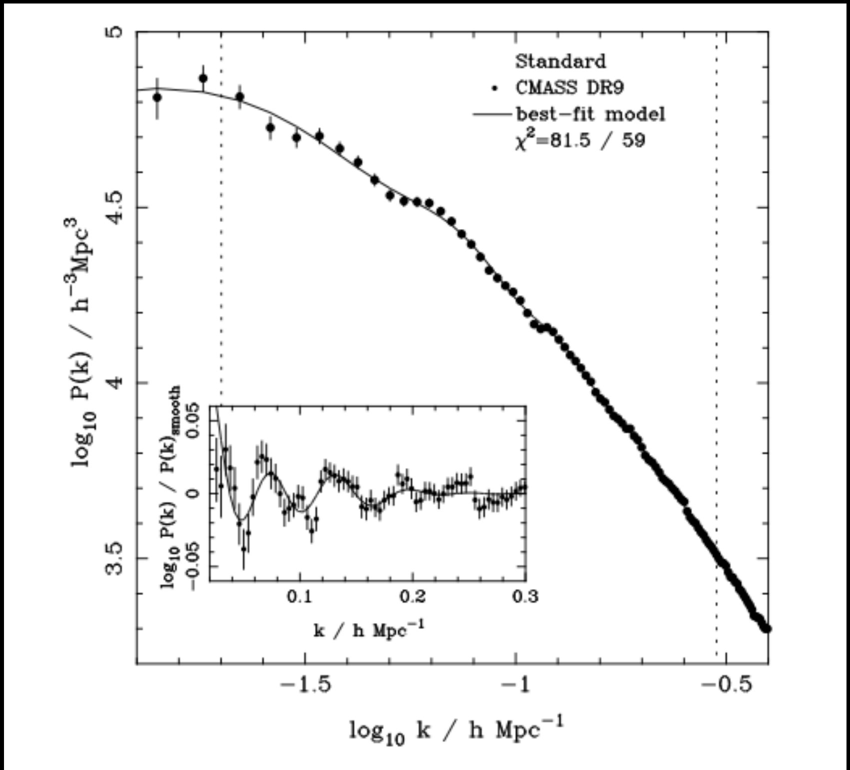


Gil Marin et al in prep.

Baryon acoustic oscillations (BAO)

Here it is!





Anderson et al 2012, 2013 (BOSS)

Not new

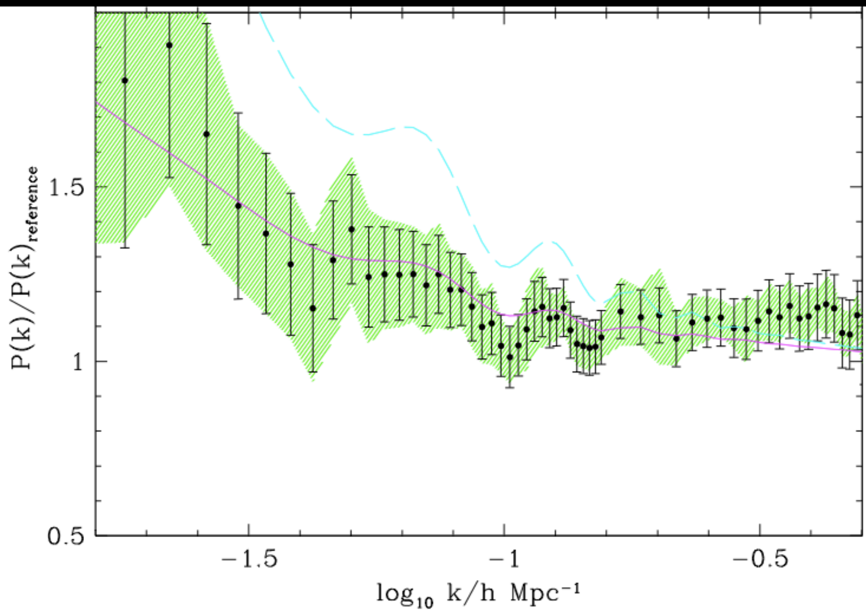
- Predicted in the 1990ies, but realization one could do cosmology with is a 1997 paper by Eisenstein & Hu
- First detected in 2005:

2dF Cole et al 2005; SDSS Eisenstein et al 2005

- But extremely, excruciatingly low signal-to-noise

Not new

2dF



SDSS

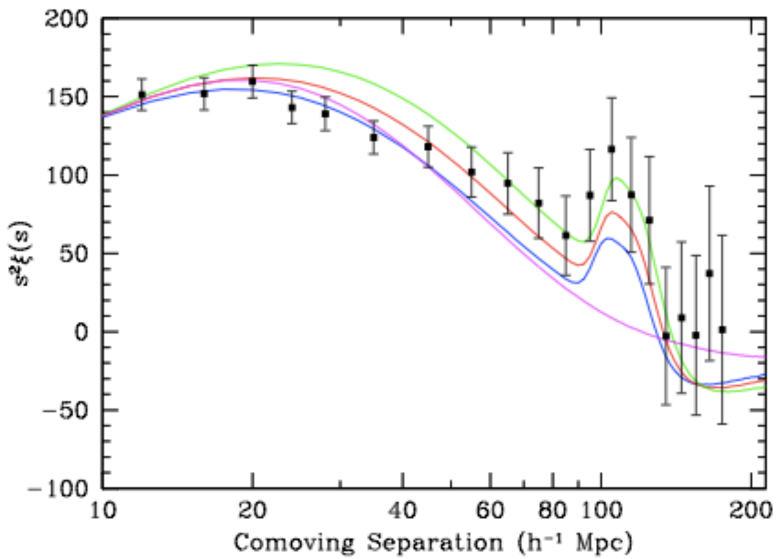
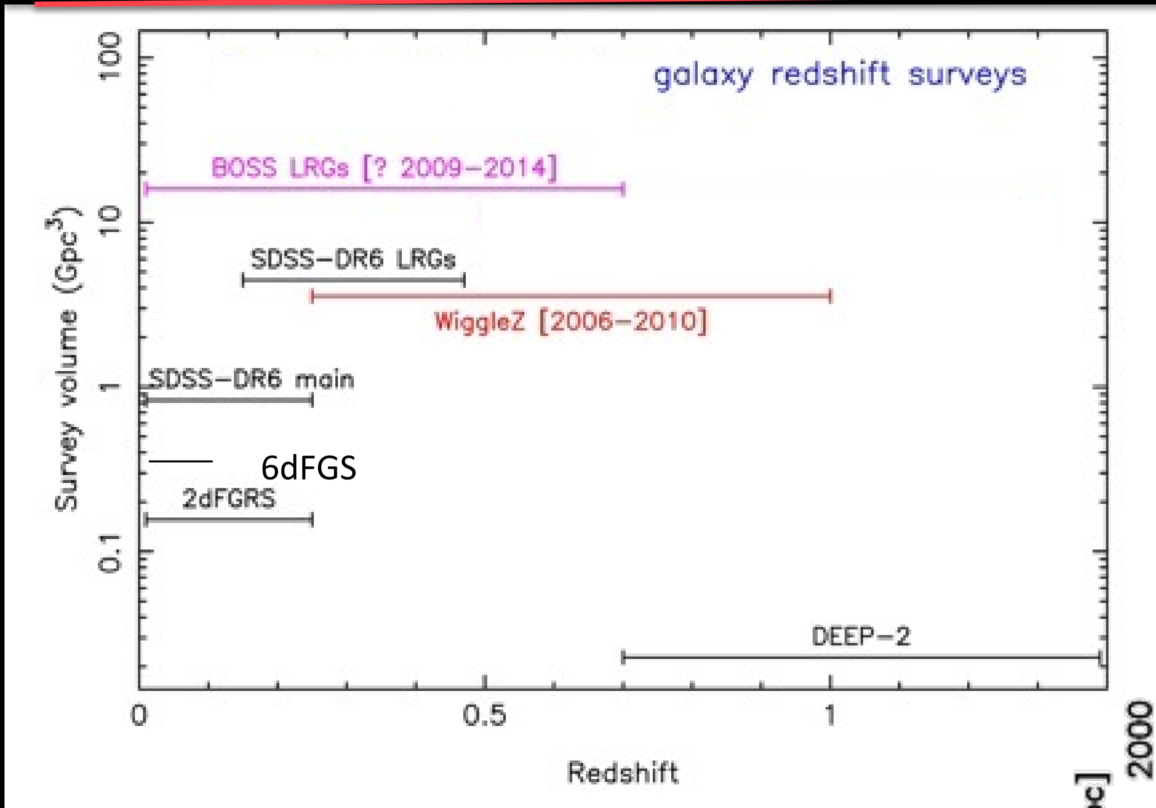


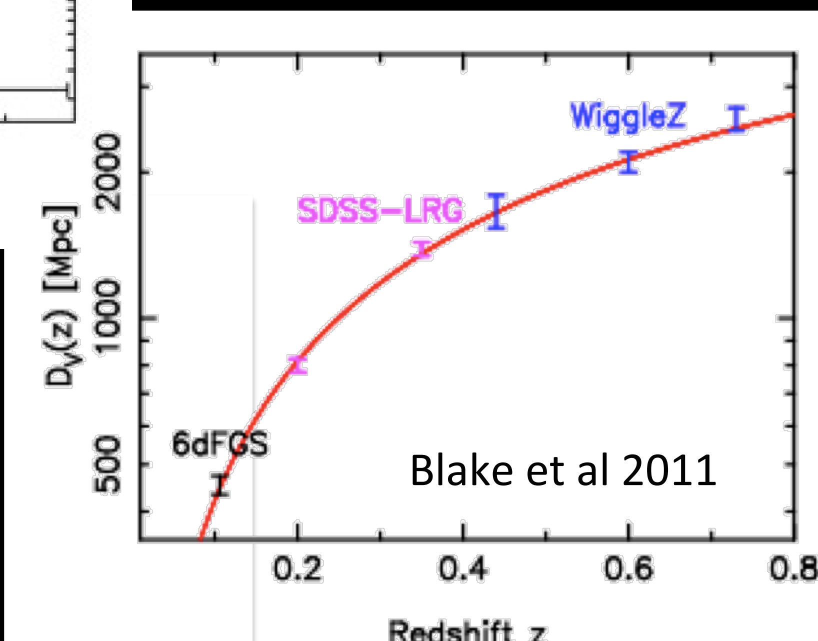
FIG. 3.— As Figure 2, but plotting the correlation function times s^2. This shows the variation of the peak at $20h^{-1}$ Mpc scales that is controlled by the redshift of equality (and hence by $\Omega_m h^2$). Varying $\Omega_m h^2$ alters the amount of large-to-small scale correlation, but boosting the large-scale correlations too much causes an inconsistency at $30h^{-1}$ Mpc. The pure CDM model (magenta) is actually close to the best-fit due to the data points on intermediate scales.

But extremely, excruciatingly low signal-to-noise

Some surveys

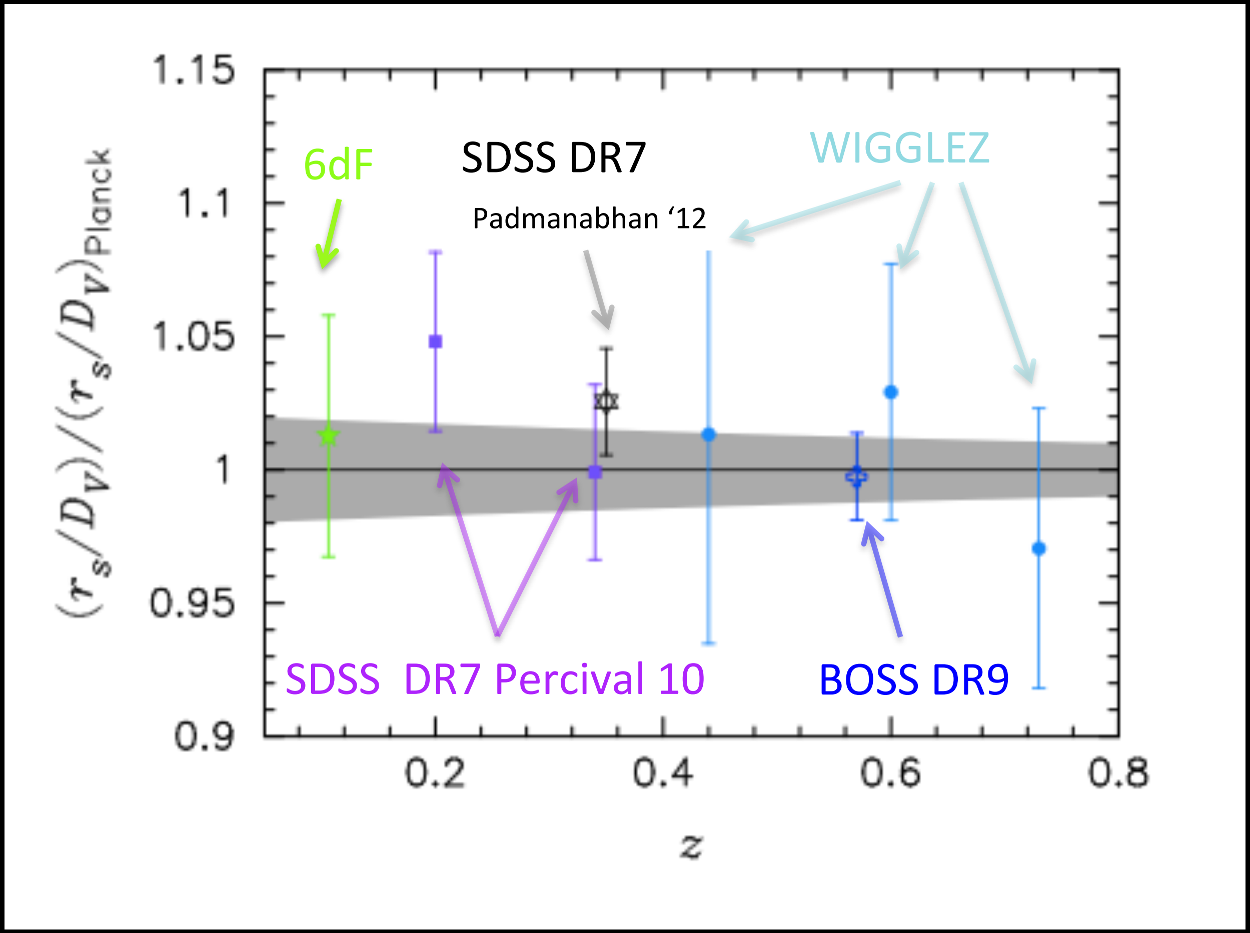


Adapted from WiggleZ web page



The power of BAO

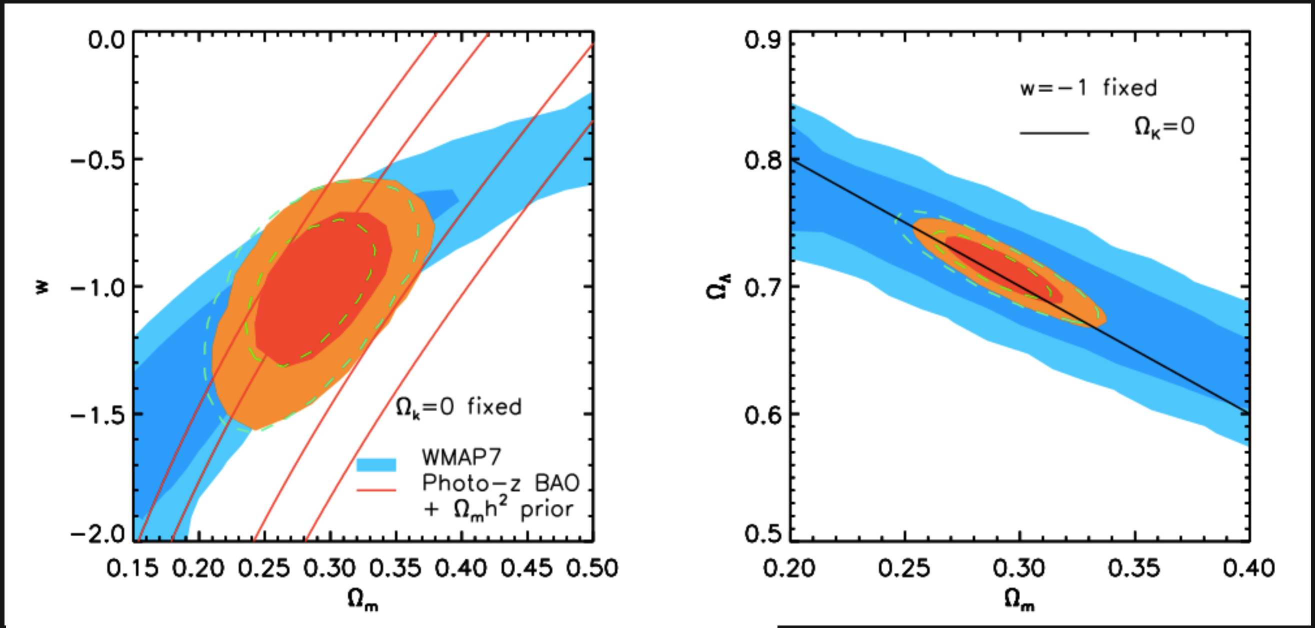
From the Planck cosmological parameters paper: almost the state of the art

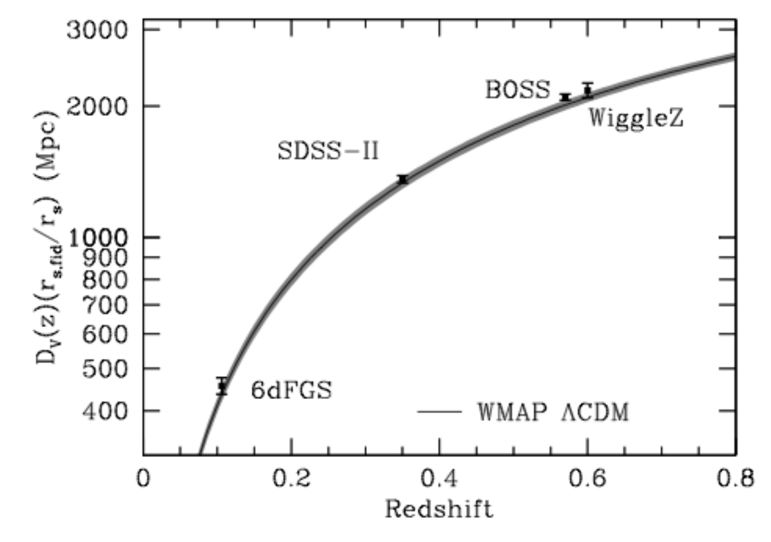


Yes, broadly consistent with a LCDM model

Adapted from Planck collaboration, 2013, paper XVI

SDSS III: BOSS





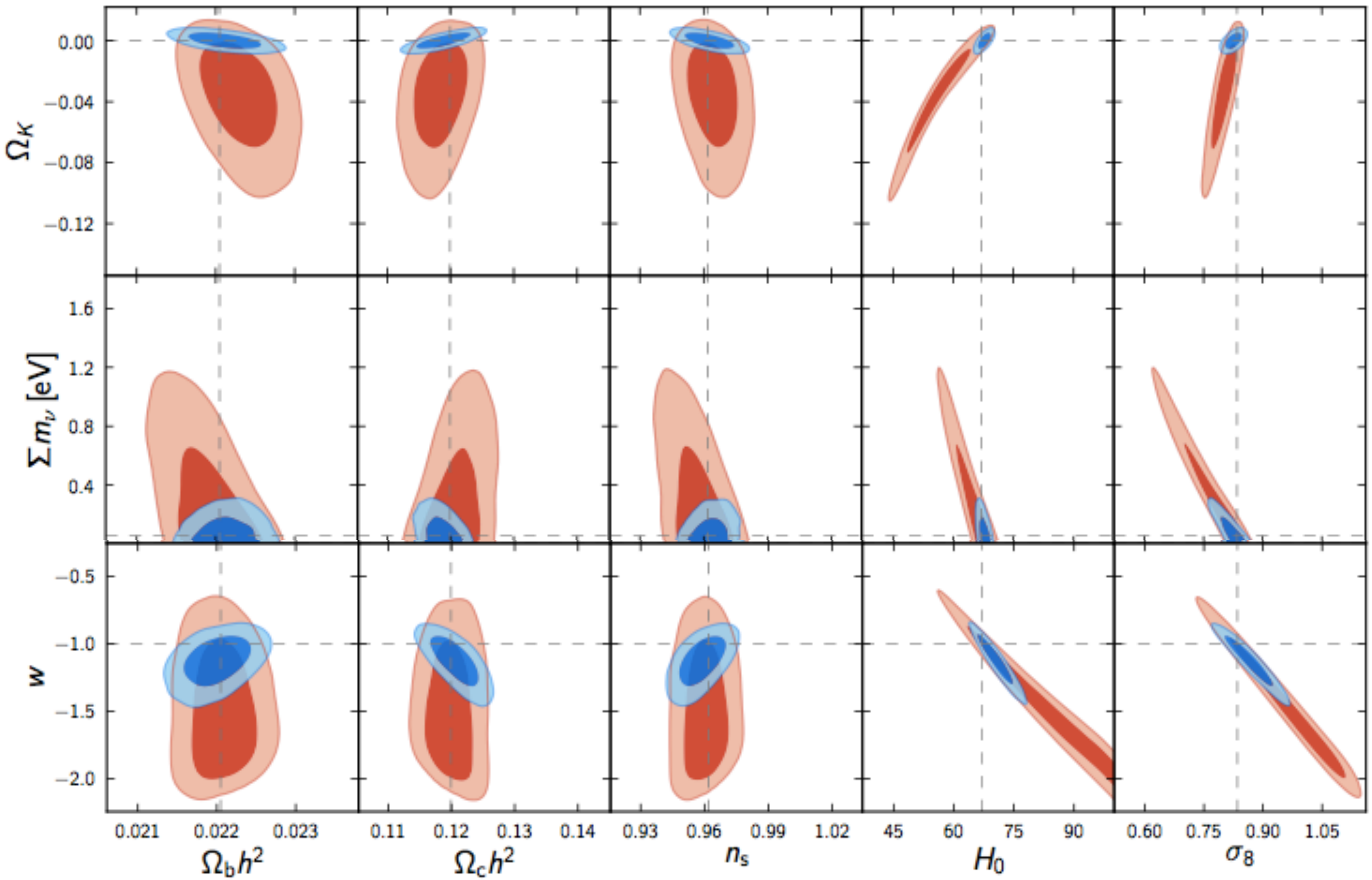
Yes, consistent with a LCDM

Seo et al. , Anderson et al., 2012, 2013

The power of BAO

Planck collaboration paper XVI

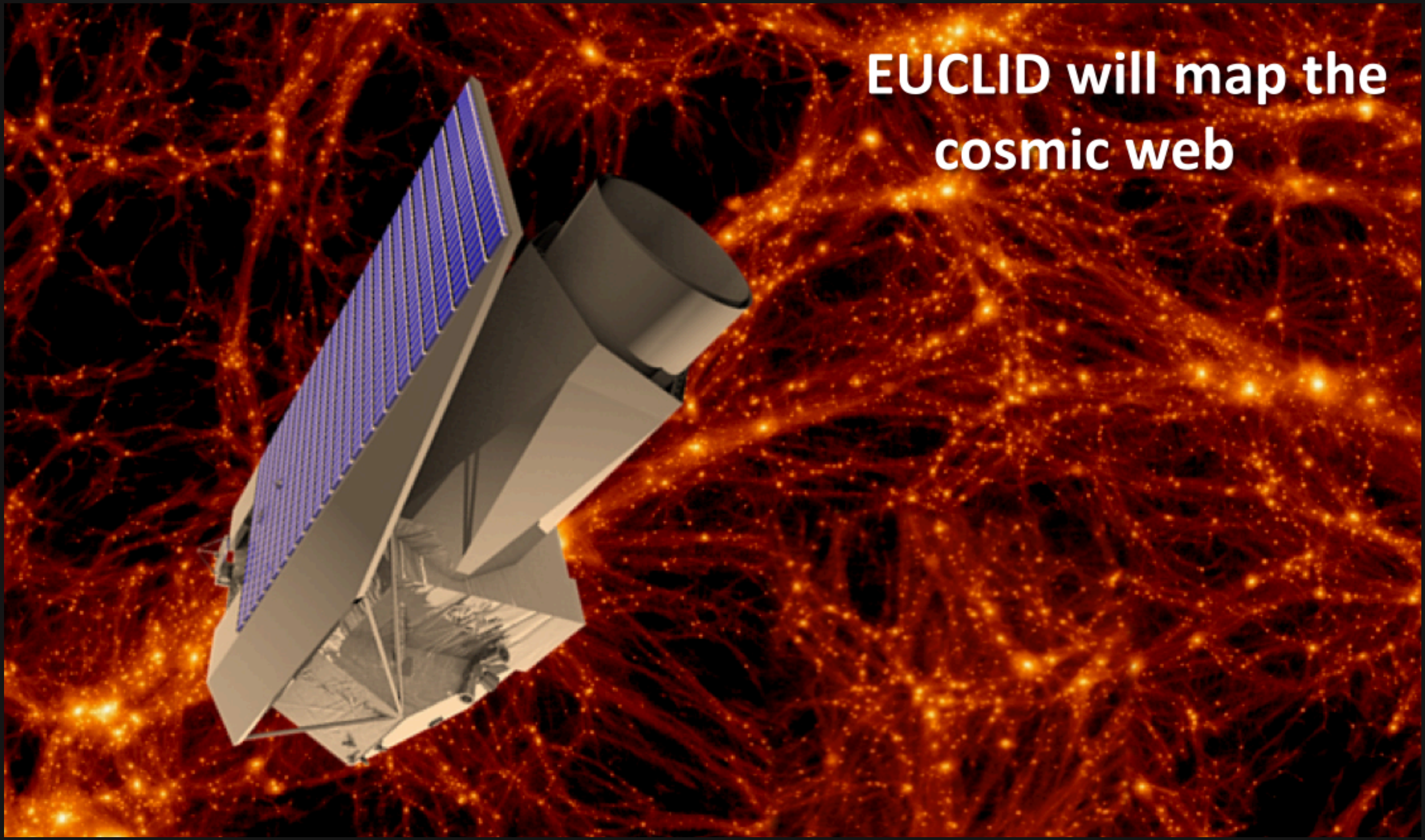
Planck+WP +BAO



Planck collaboration , 2013, paper XVI

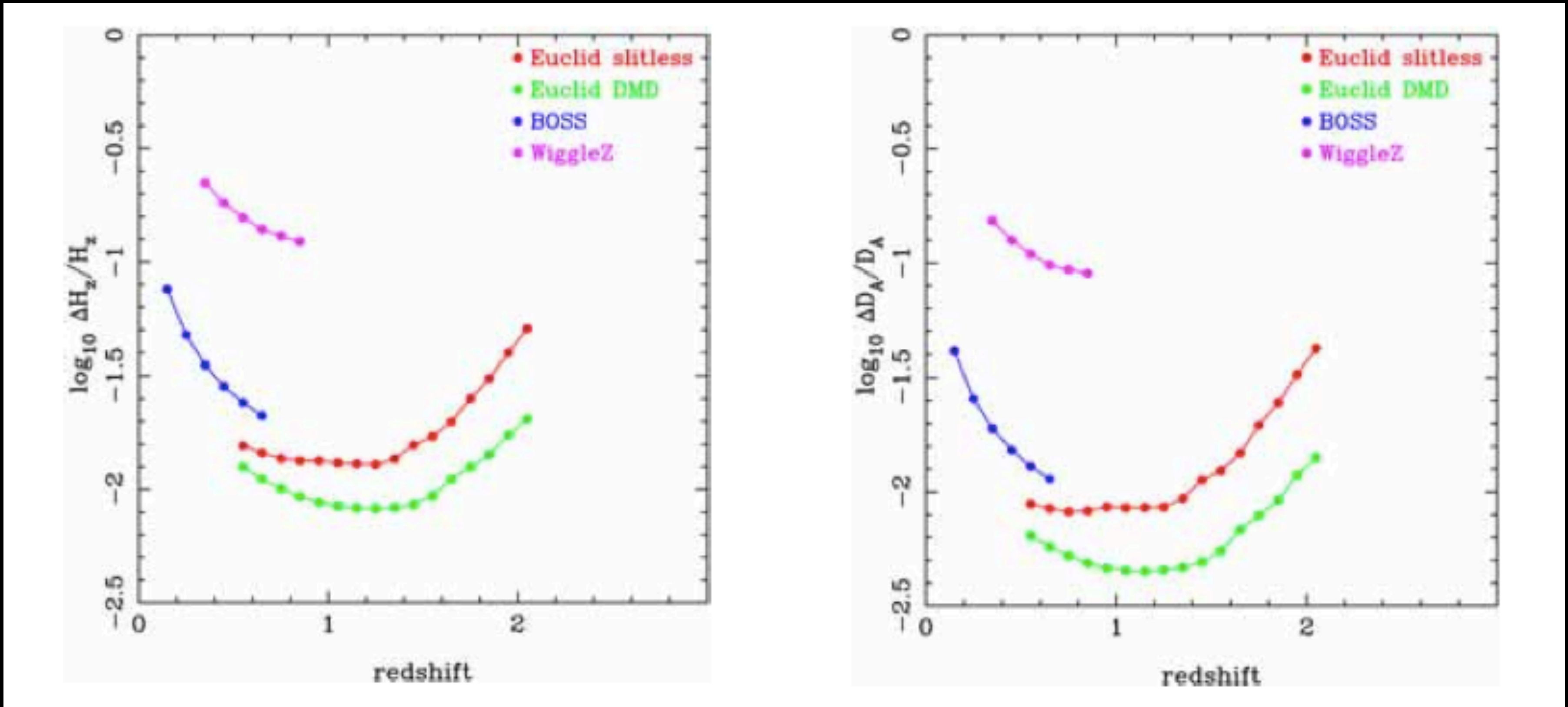
Discuss if there are reasons to go beyond LCDM

In the future



All the way back to when the Universe was 1/3 of current size and less than ¼ of current age

What's coming...

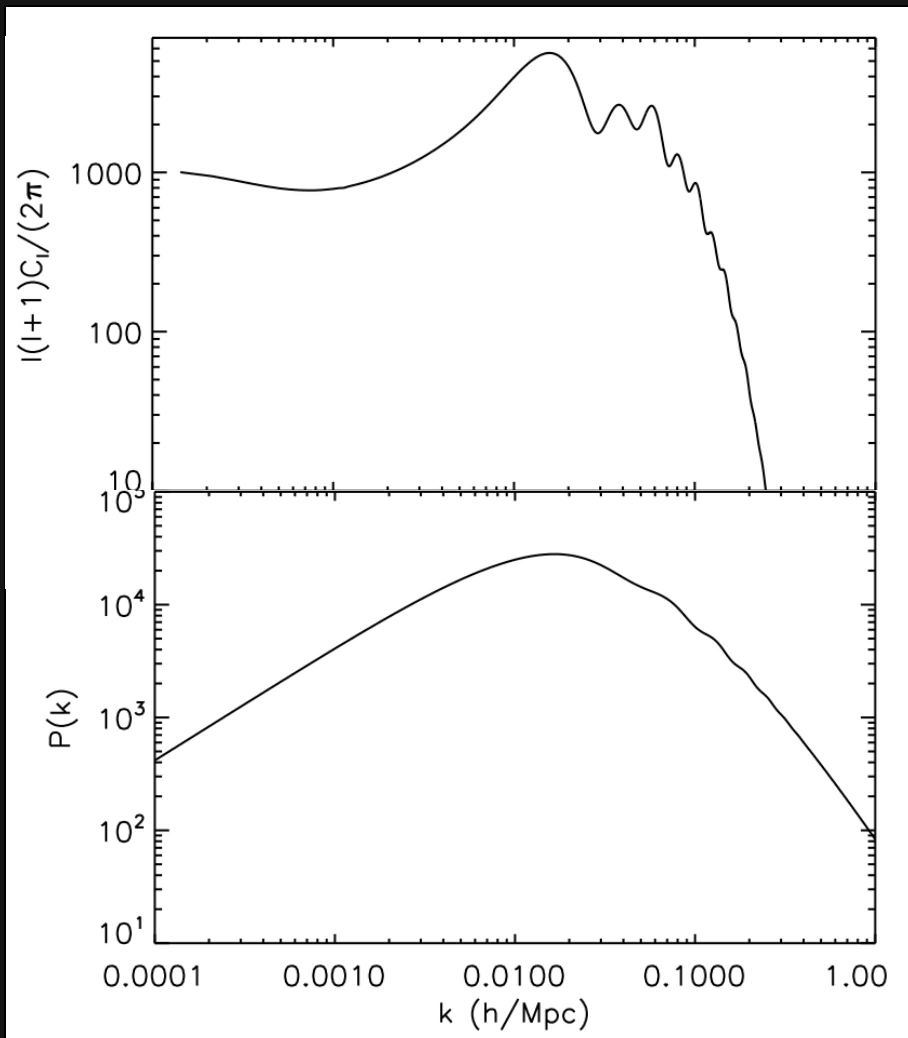


Laurejis et al 09

ULTIMATE EXPERIMENT, what I call "legacy"

Information about inflation

Huang, Verde, Vernizzi 2012



Cosmological information in P(k)

Error on P(k) ~N_{mod}

~l (2D) ~k^2 (3D)

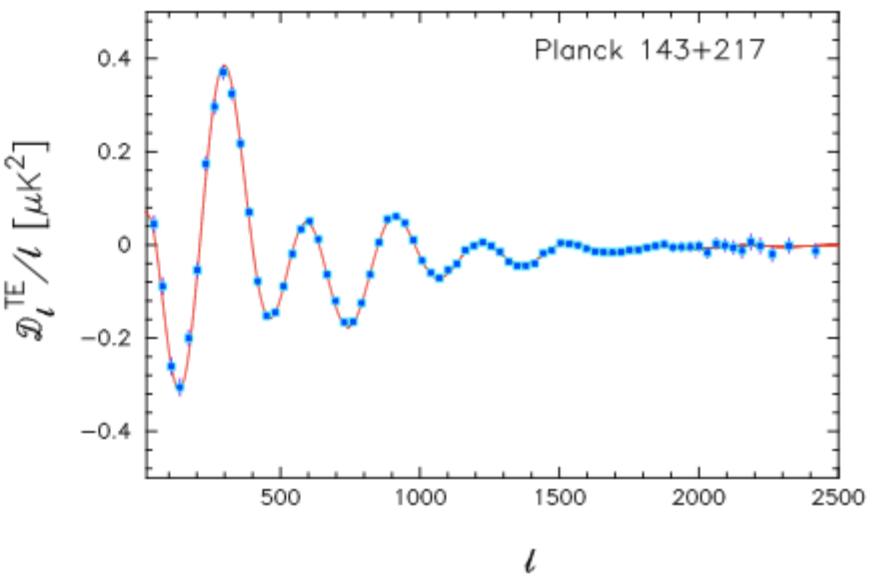
Slow-roll models or single field potential reconstruction: error bars halved

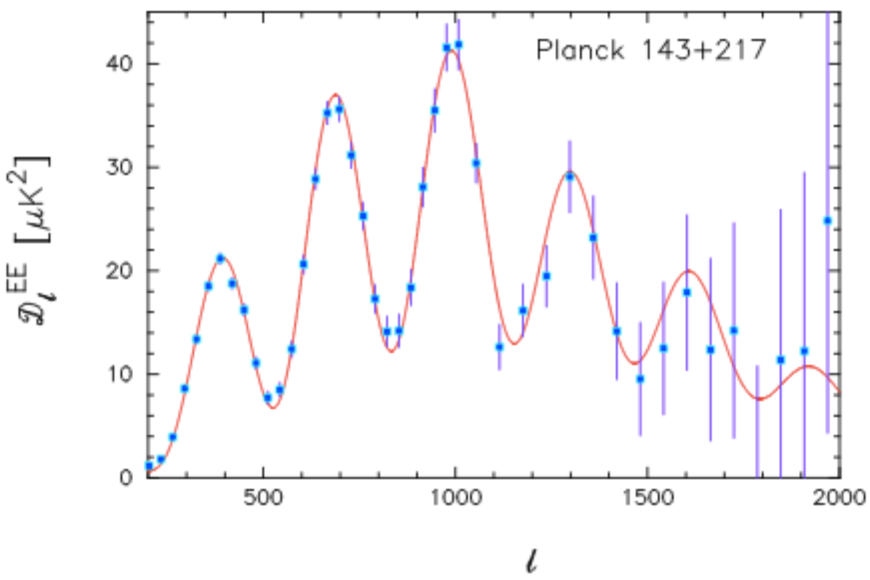
Qualitative improvement for models w/ features or oscillations

MORE TO COME:

POLARIZATION

Teaser plots



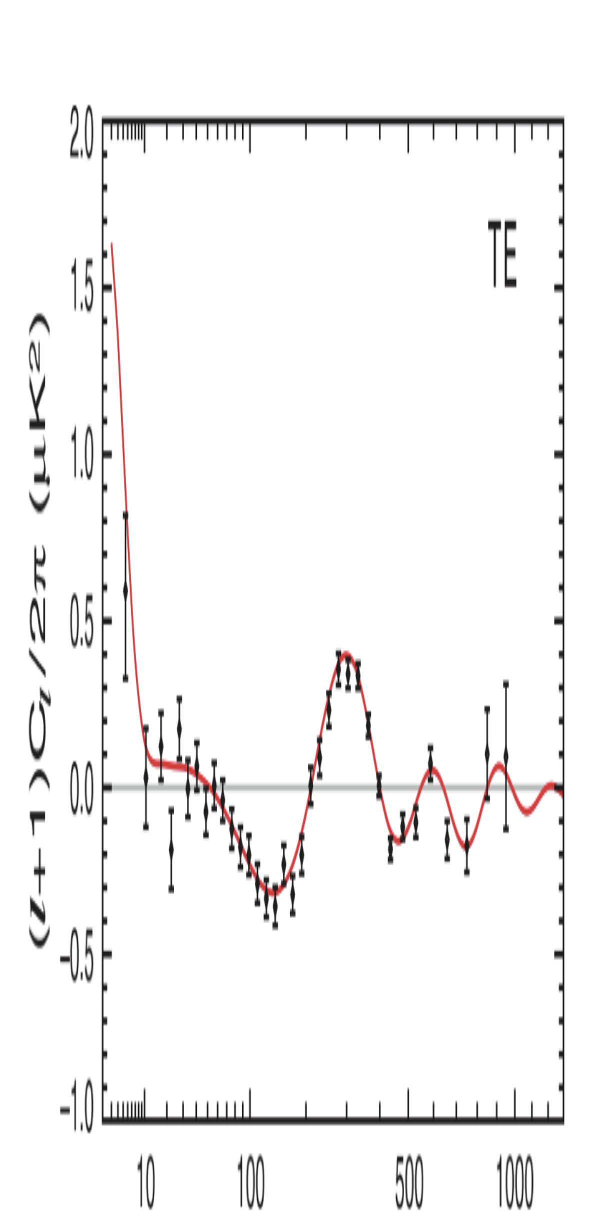


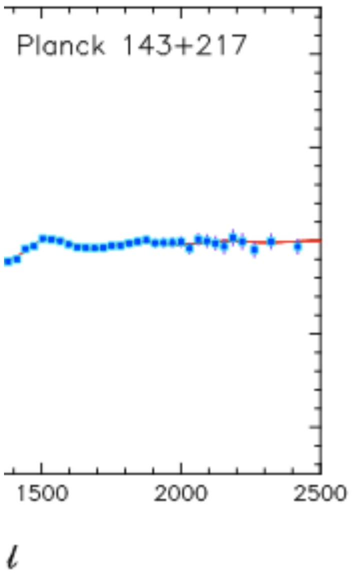
Planck collaboration , 2013, paper XVI

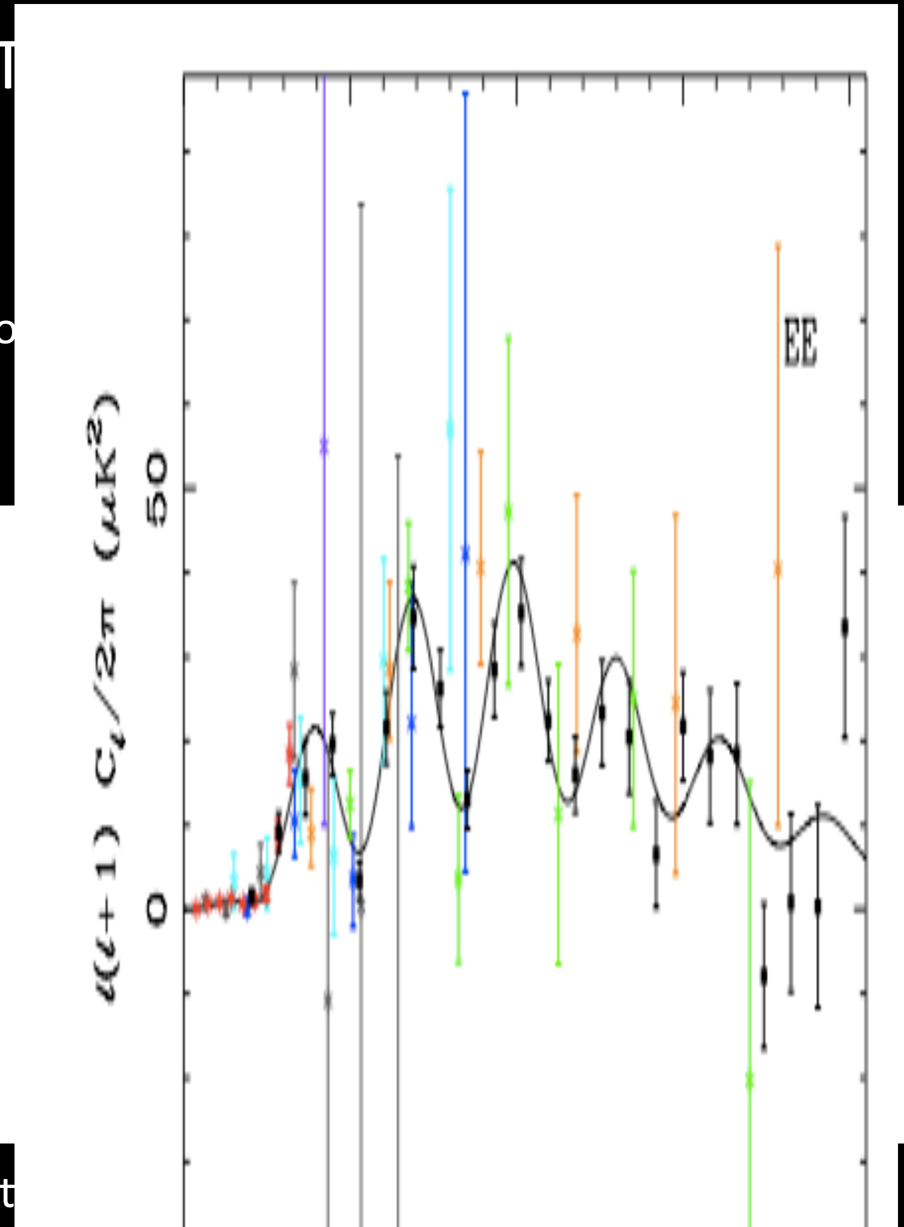
MORE TO COME:

POLARIZAT

Teaser plo



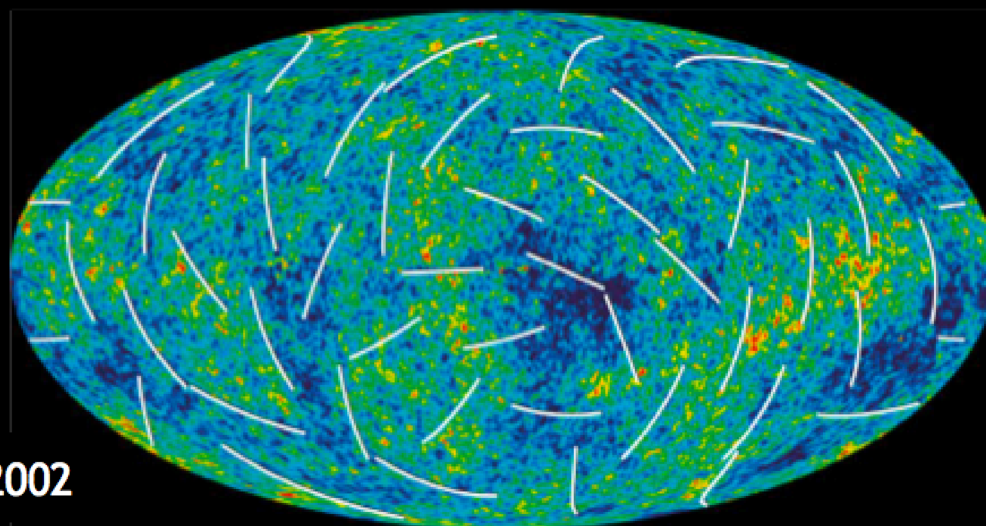




Planck collaborat

What next?

Polarization, the next frontier



First detected by DASI in 2002

WMAP science team 2006

Why measure CMB Polarization?

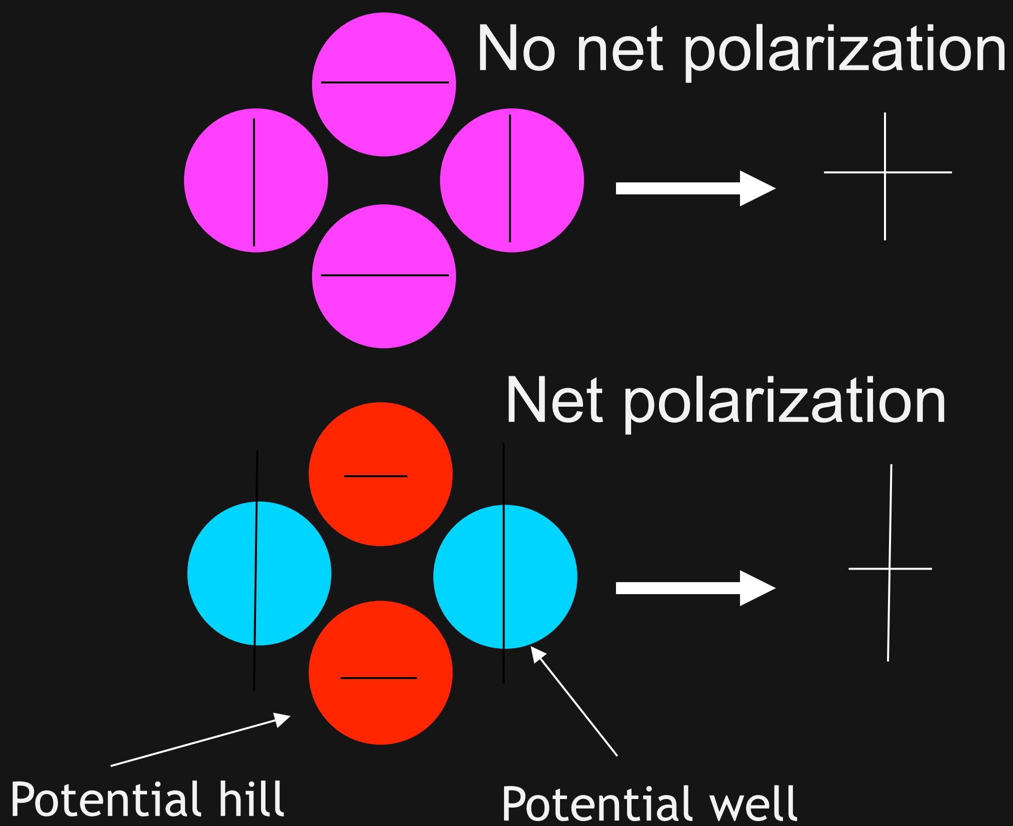
Directly measures dynamics in early universe

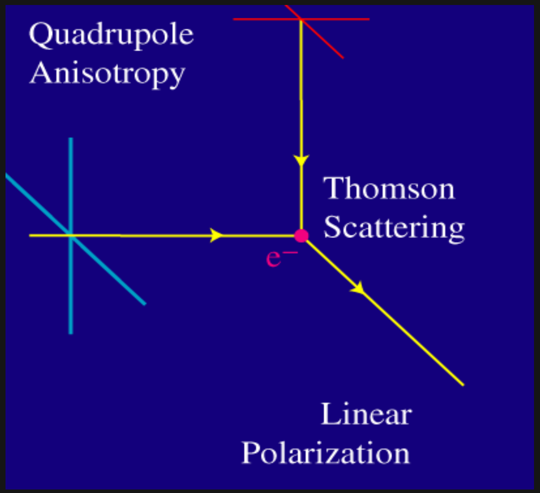
So far: Critical test of the underlying theoretical framework for cosmology

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

Generation of CMB polarization

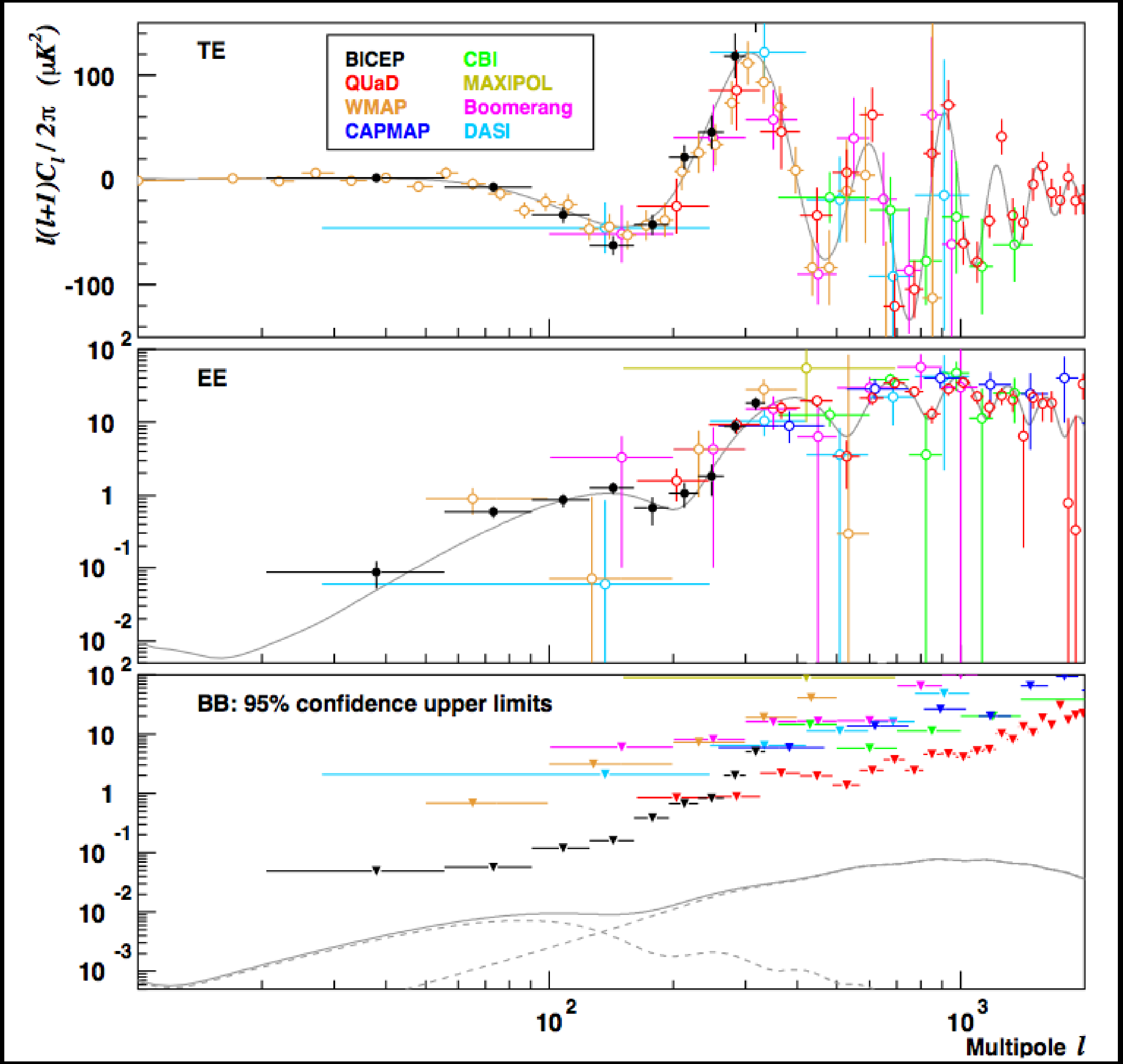
- Temperature quadrupole at the surface of last scatter generates polarization.





From Wayne Hu

State of the art: polarization

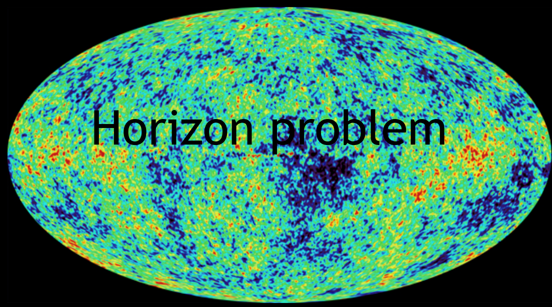


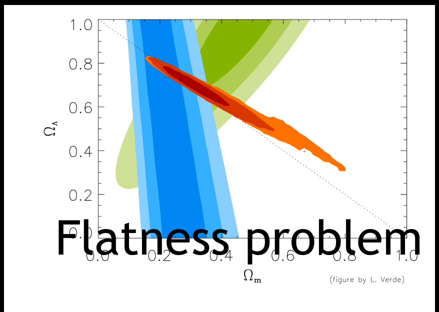
- Acoustic peaks at "adiabatic" locations
- E-mode polarization and cross-correlation with T
- Large angle polarization from reionization
- BICEP limit from BB-alone: T/S < 0.73 (95% CL)

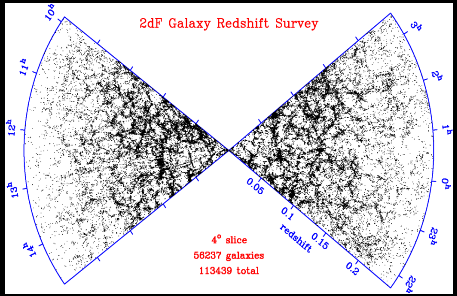
Figure: Chiang et al. (2009)

What mechanism generated the primordial perturbations?

Inflation:







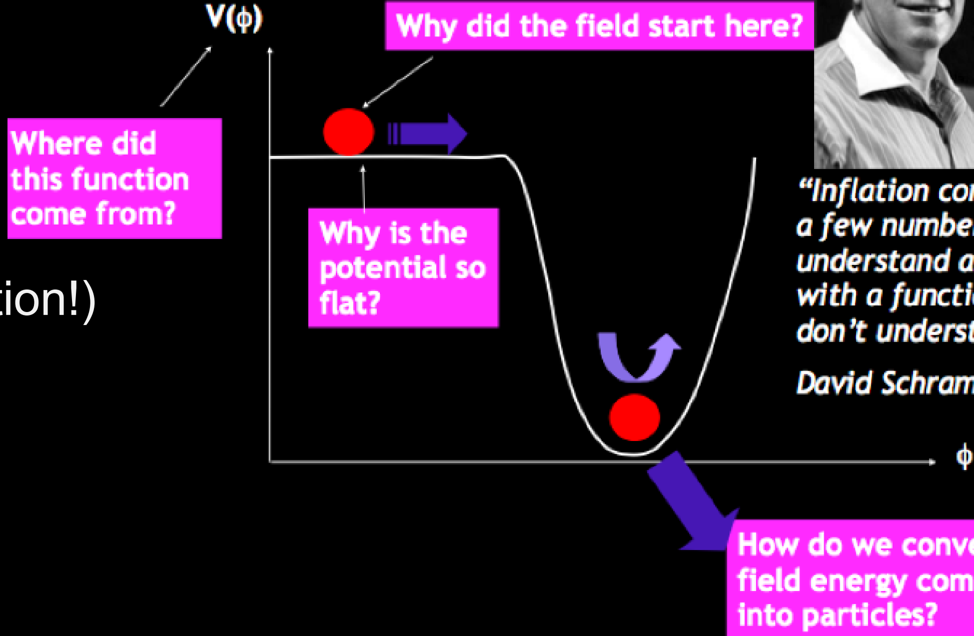
Structure Problem

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 (CMB+Large scale structure)

The energy scale of inflation is given by primordial tensor modes amplitude (CMB polarization!)



“Inflation consists of taking a few numbers that we don’t understand and replacing it with a function that we don’t understand”

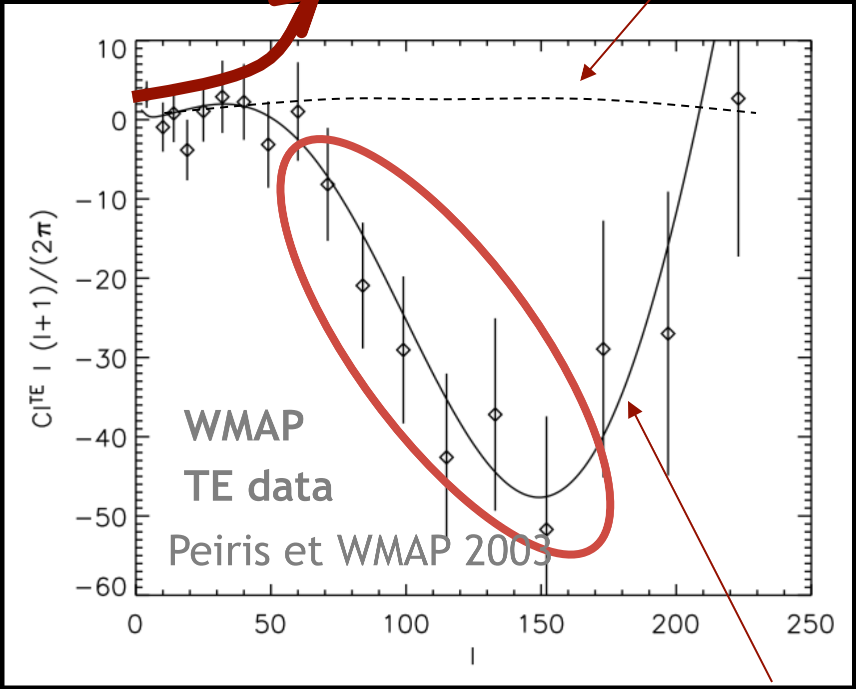
David Schramm 1945 -1997

CMB Consistent with Simplest Inflationary Models

- Superhorizon, adiabatic fluctuations
  - T and E anticorrelated at superhorizon scales
- Flatness tested to 1%.
- Gaussianity tested to 0.005%
- nearly scale-invariant fluctuations
  - red tilt indicated at ~ 5 σ

Causal Seed model (Durrer et al. 2002)

Primordial Isocurvature i.c.



Primordial Adiabatic i.c.

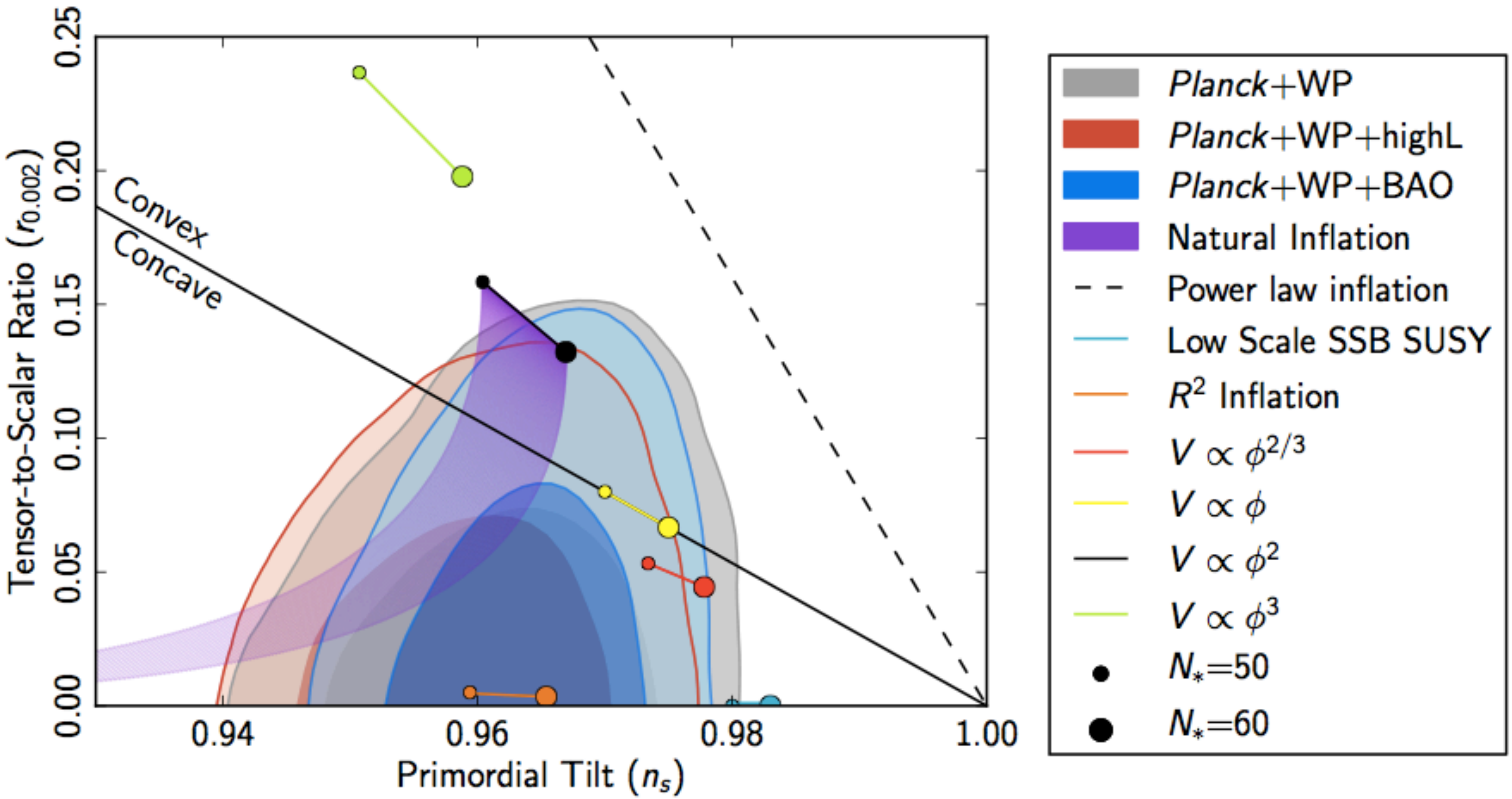
Hu & Sujiyama 1995
Zaldarriaga & Harari 1995
Spergel & Zaldarriaga 1997

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

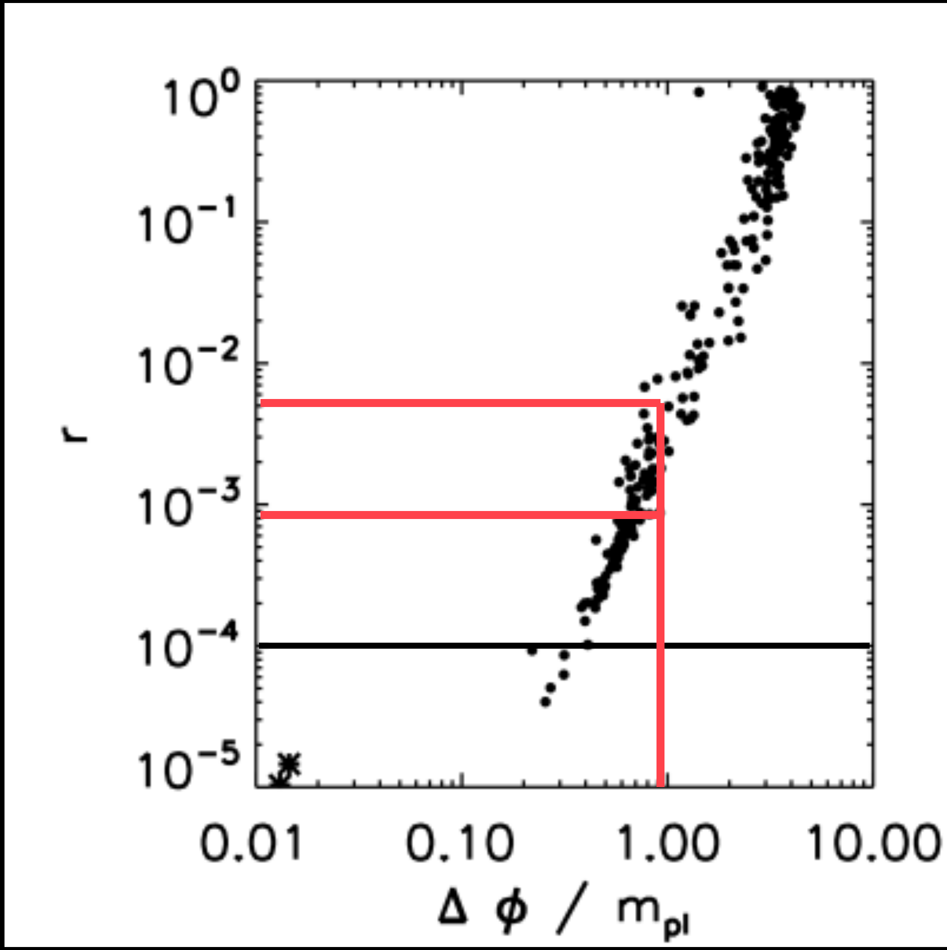
Current constraints



Planck collaboration (2013), inflation paper

Clues about high-energy physics with the CMB polarization

Monte Carlo simulation of the inflationary flow equations.



3.2×10^{13}

1.7×10^{13}

9.7×10^{12}

5.5×10^{12}

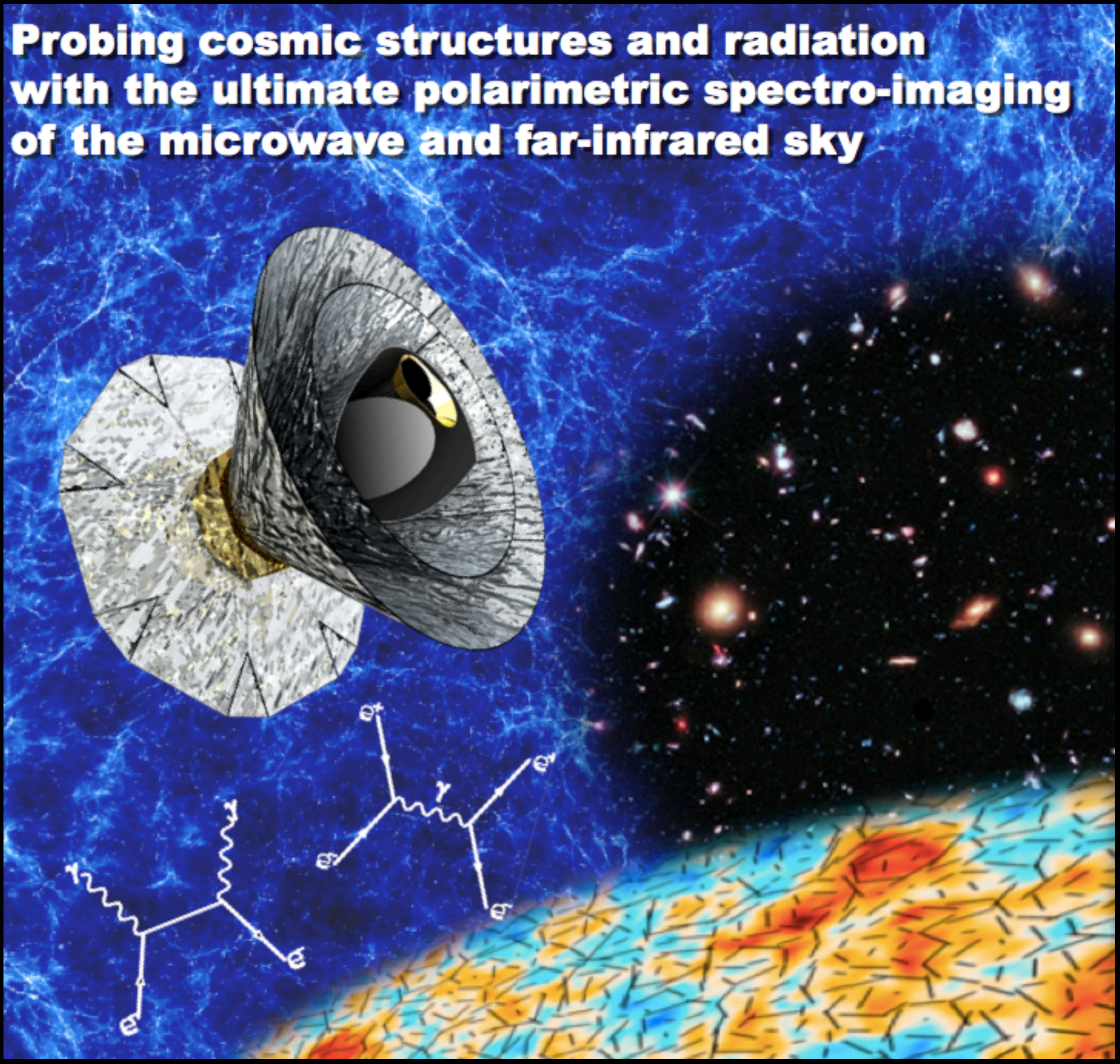
3×10^{12}

TeV

LV, Peris, Jimenez 2005

A "critical value" … the dream of PRISM…

More in the future

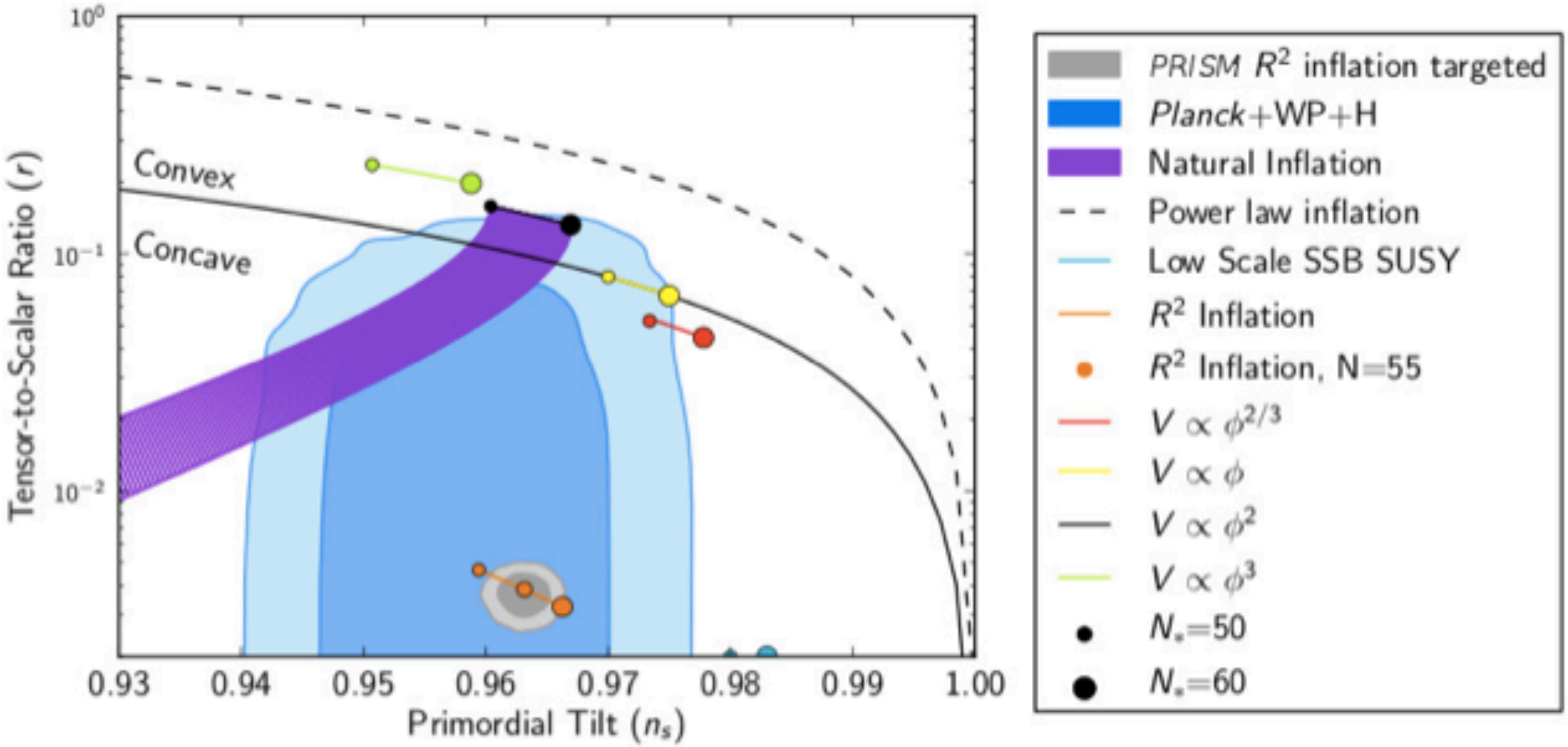


PRISM

No, not THAT PRISM

Find out more and offer your support at

http://www.prism-mission.org



10^0
10^{-1}
10^{-2}
Tensor-to-Scalar Ratio (r)
Convex
Concave
0.93
0.94
0.95
0.96
0.97
0.98
0.99
1.00
Primordial Tilt (n_s)
PRISM R^2 inflation targeted
Planck+WP+H
Natural Inflation
Power law inflation
Low Scale SSB SUSY
R^2 Inflation
R^2 Inflation, N=55
$V \propto \phi^{2/3}$
$V \propto \phi$
$V \propto \phi^2$
$V \propto \phi^3$
N_*=50
N_*=60

… the maximally boring universe…

The standard cosmological model has survived ever more stringent tests

Deviations from it are even more constrained

Eventually something will have to give, the model IS incomplete

The point is how much smaller would the observational error bars have to be

Neutrino mass is within the reach of the next generation experiments (large scale structure)

Conclusions

Precision cosmology: "from what to why"

Precision cosmology -> address fundamental physics questions (examples: neutrinos, initial conditions, dark energy)

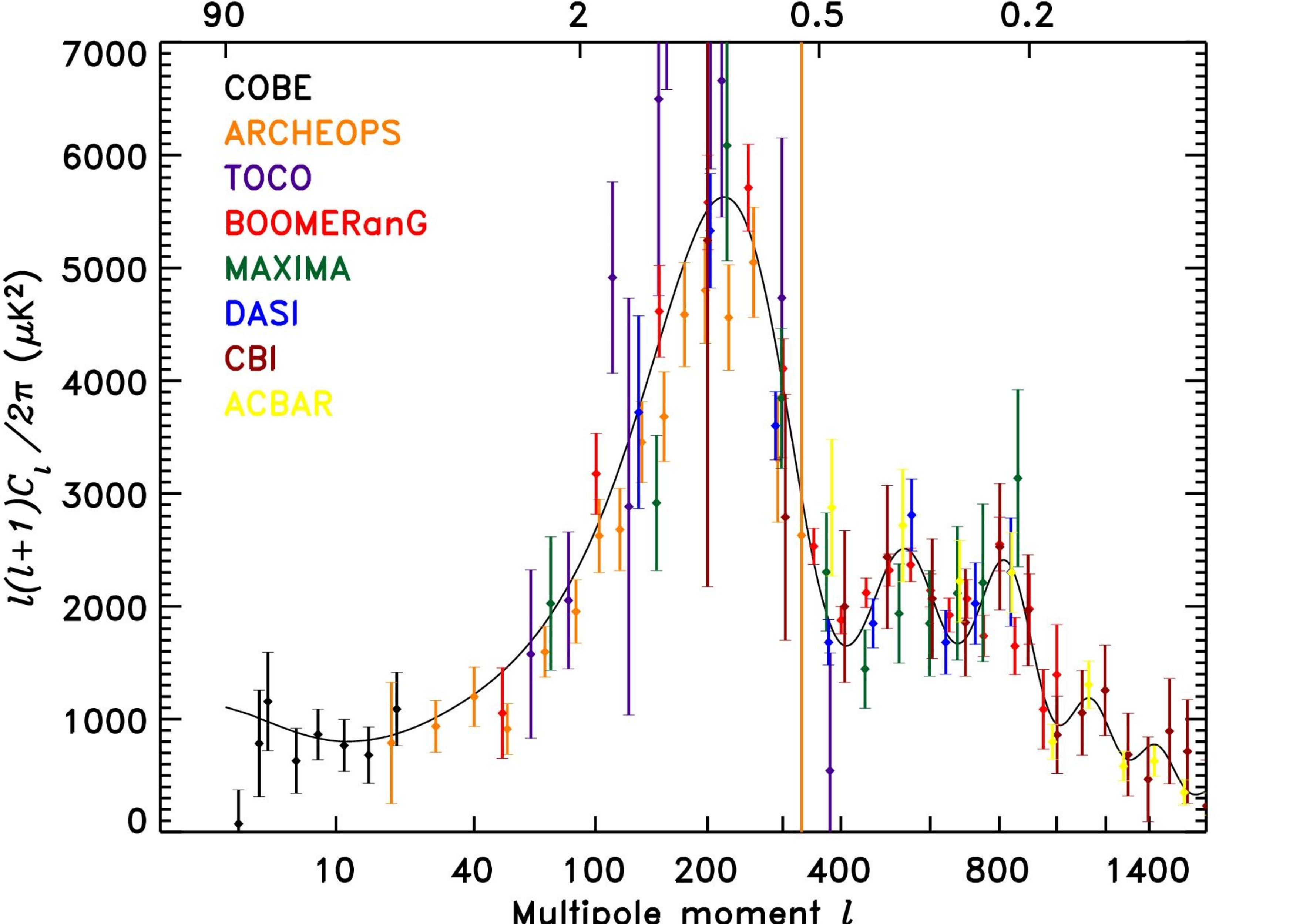
Challenging!

From the precision era to the accuracy era!

Large on-going and future galaxy surveys cover large fraction of observable Universe, driven by dark energy study, but there's much more

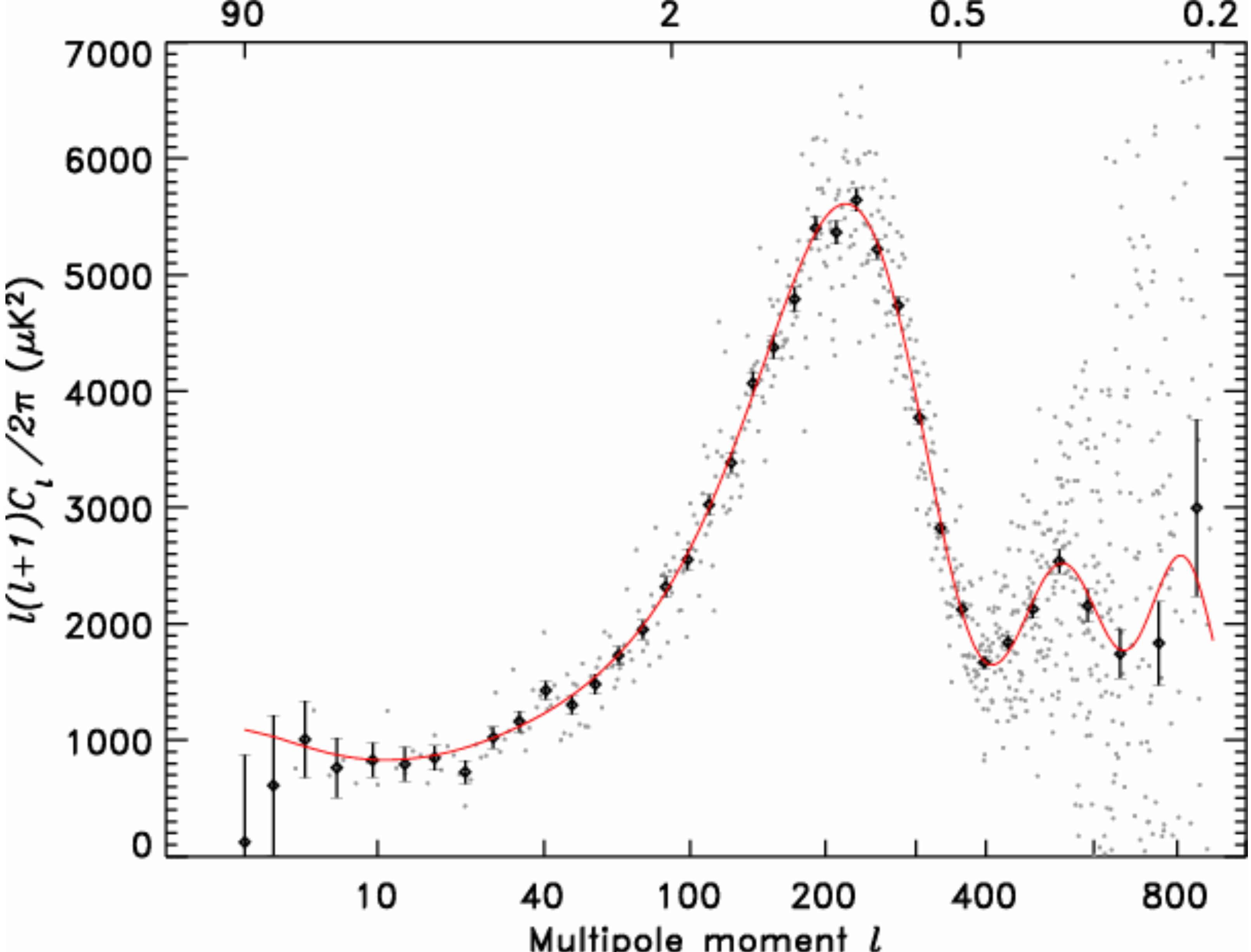
CMB polarization is a window in the early universe and into new physics at high energies

END



Before 11 Feb. 2003

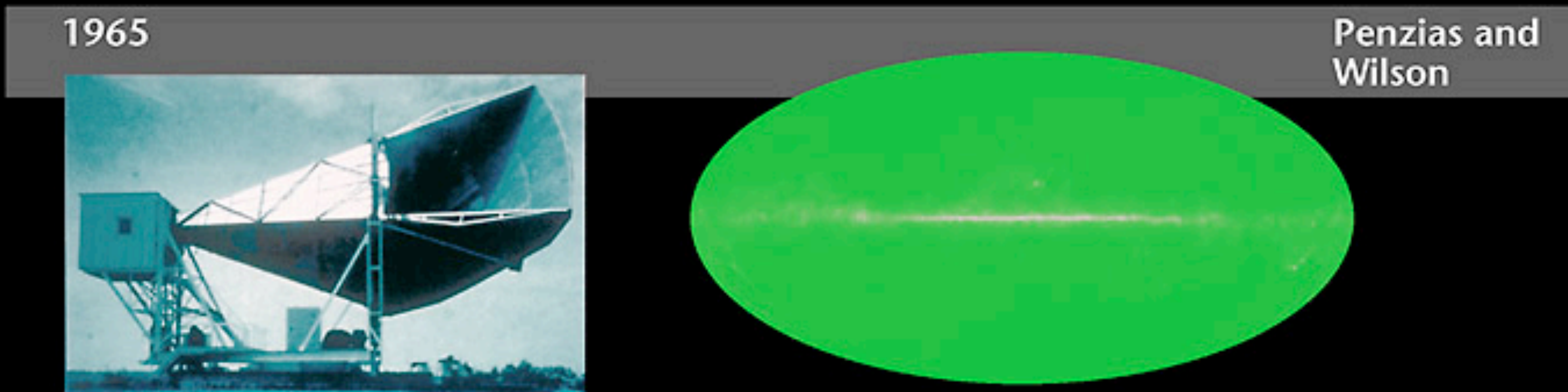
(From Hinshaw et al 2003)



90
2
0.5
0.2
7000
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ (μK^2)
10
40
100
200
400
800
Multipole moment l

After

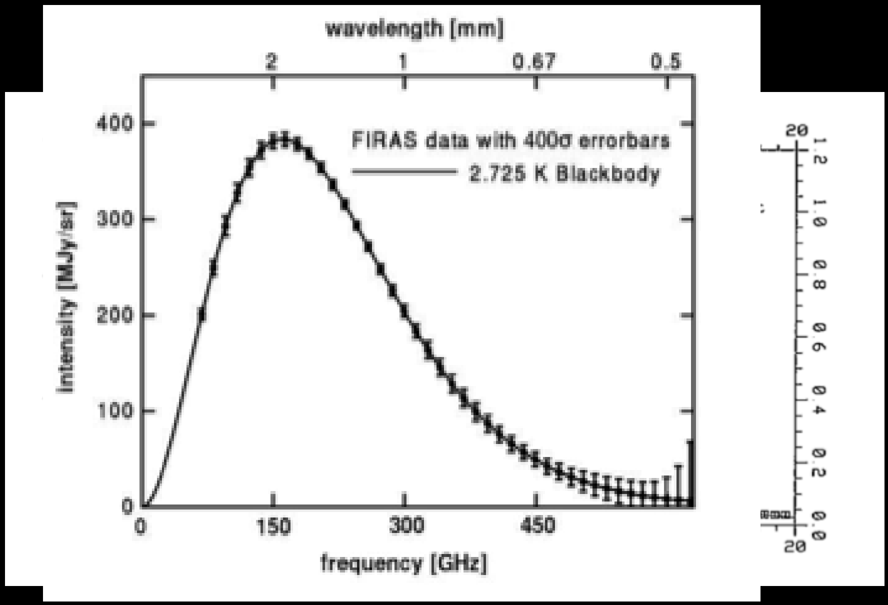
Discovery of the CMB



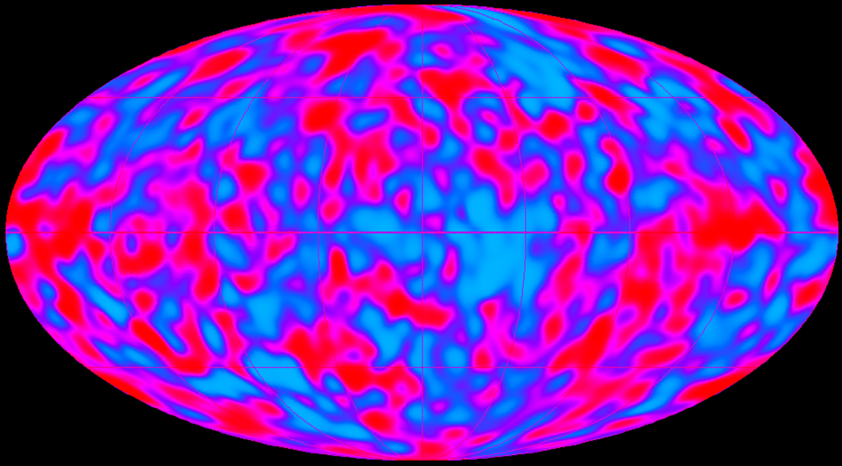
A hot big bang!

It should be a blackbody

T_{CMB}= 2.725 +/- 0.002 K



Should carry the seeds of galaxies



COBE

History…

SMALL-SCALE FLUCTUATIONS OF RELIC RADIATION*

R. A. SUNYAEV and YA. B. ZELDOVICH
Institute of Applied Mathematics, Academy of Sciences of the U.S.S.R., Moscow, U.S.S.R.

(Received 11 September, 1969)

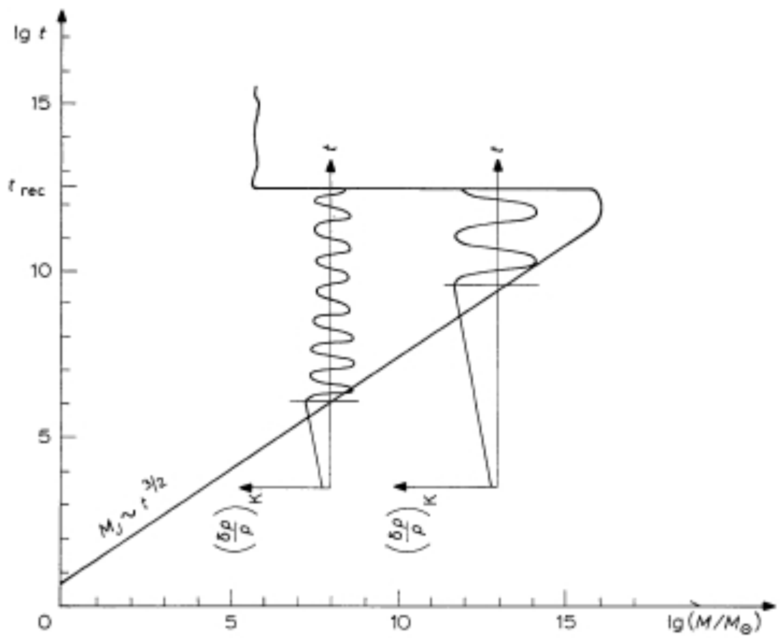


Fig. 1a. Diagram of gravitational instability in the 'big-bang' model. The region of instability is located to the right of the line $M_J(t)$; the region of stability to the left. The two additional lines of the graph demonstrate the temporal evolution of density perturbations of matter: growth until the moment when the considered mass is smaller than the Jeans mass and oscillations thereafter. It is apparent that at the moment of recombination perturbations corresponding to different masses correspond to different phases.

SMALL-SCALE FLUCTUATIONS OF RELIC RADIATION*

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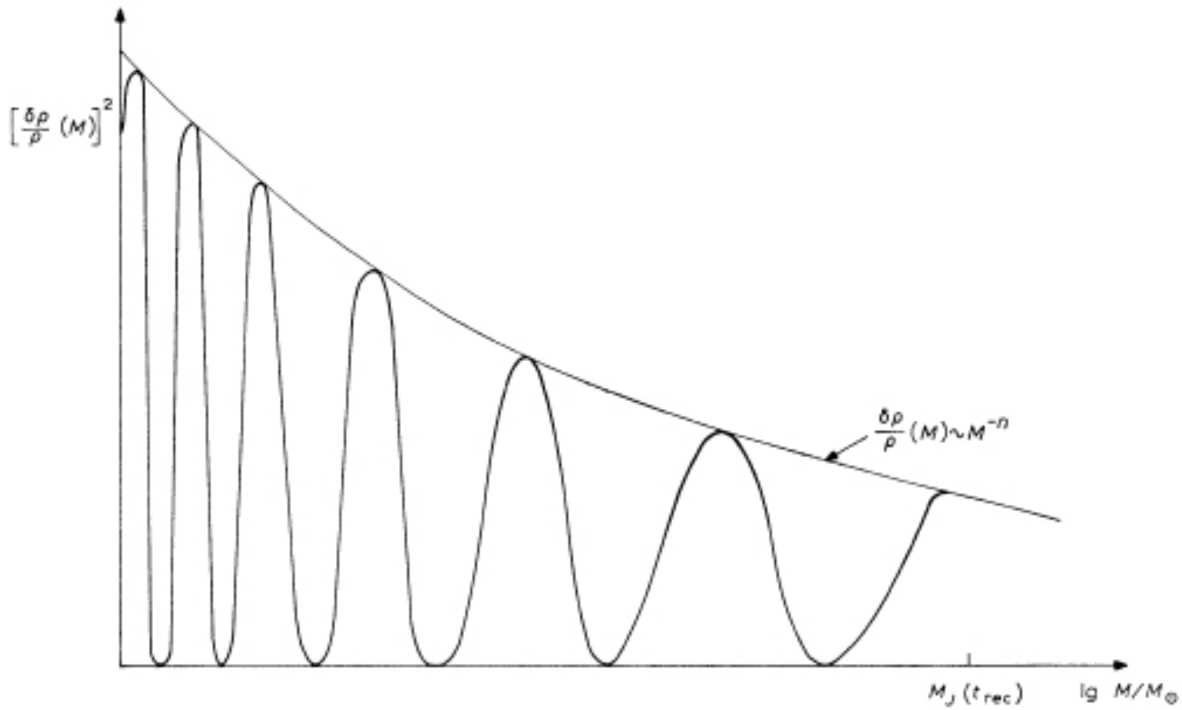


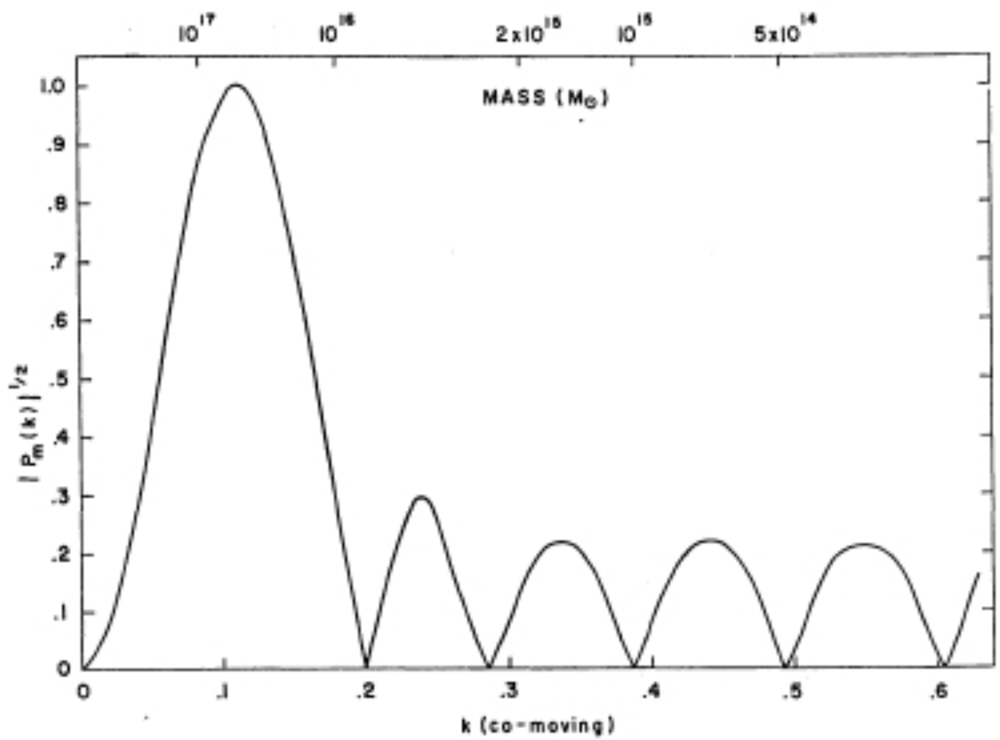
Fig. 1b. The dependence of the square of the amplitude of density perturbations of matter on scale. The fine line designates the usually assumed dependence $(\delta\varrho/\varrho)_M \sim M^{-n}$. It is apparent that fluctuations of relic radiation should depend on scale in a similar manner.

THE ASTROPHYSICAL JOURNAL, 162:815–836, December 1970

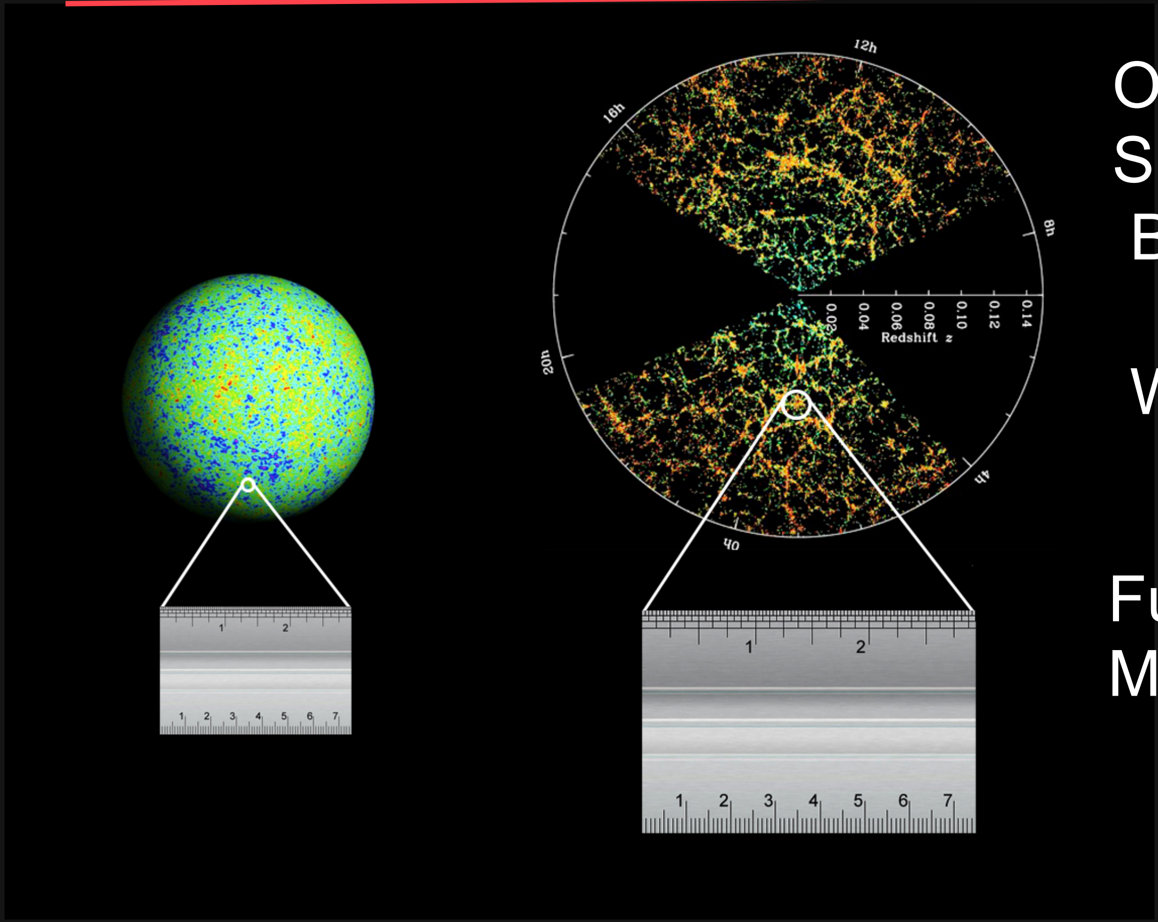
Meanwhile, on the other side of the iron curtain…

PRIMEVAL ADIABATIC PERTURBATION IN AN EXPANDING UNIVERSE*

P. J. E. PEEBLES†
Joseph Henry Laboratories, Princeton University
AND
J. T. YU‡
Goddard Institute for Space Studies, NASA, New York
Received 1970 January 5; revised 1970 April 1



What's next?
Explore low-redshift Universe



On going:
Sloan Digital Sky Survey III
BOSS

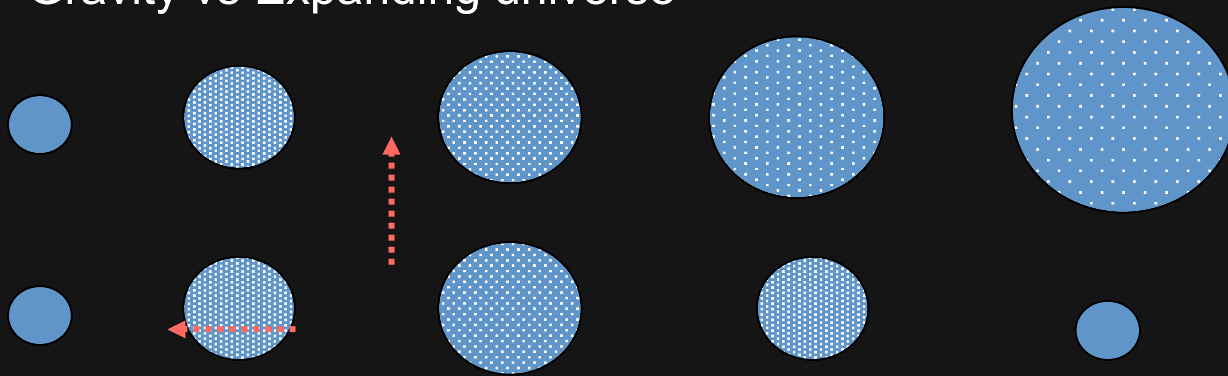
Wigglez

Future :e.g., DES, EUCLID, MS DASI etc.

BOSS: results coming out

Growth of perturbations

Gravity vs Expanding universe



Typical region

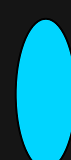
overdense region

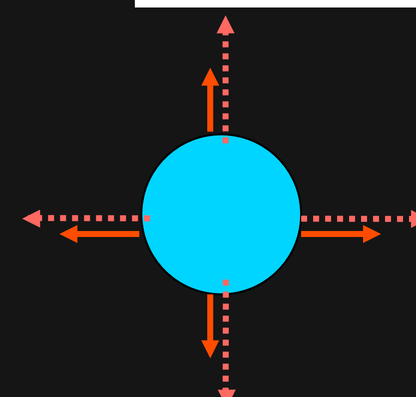
Deviates from the Hubble flow; But we assume uniform Hubble flow to convert recession velocity in distances! This is a problem … or maybe not….

$z_{obs} = z_{true} + \delta v / c$

δv prop. to $f\, \delta\rho/\rho = f\, b^{-1} \delta n/n$

$$f = \frac{d \ln \delta}{d \ln a}$$





Growth of perturbations

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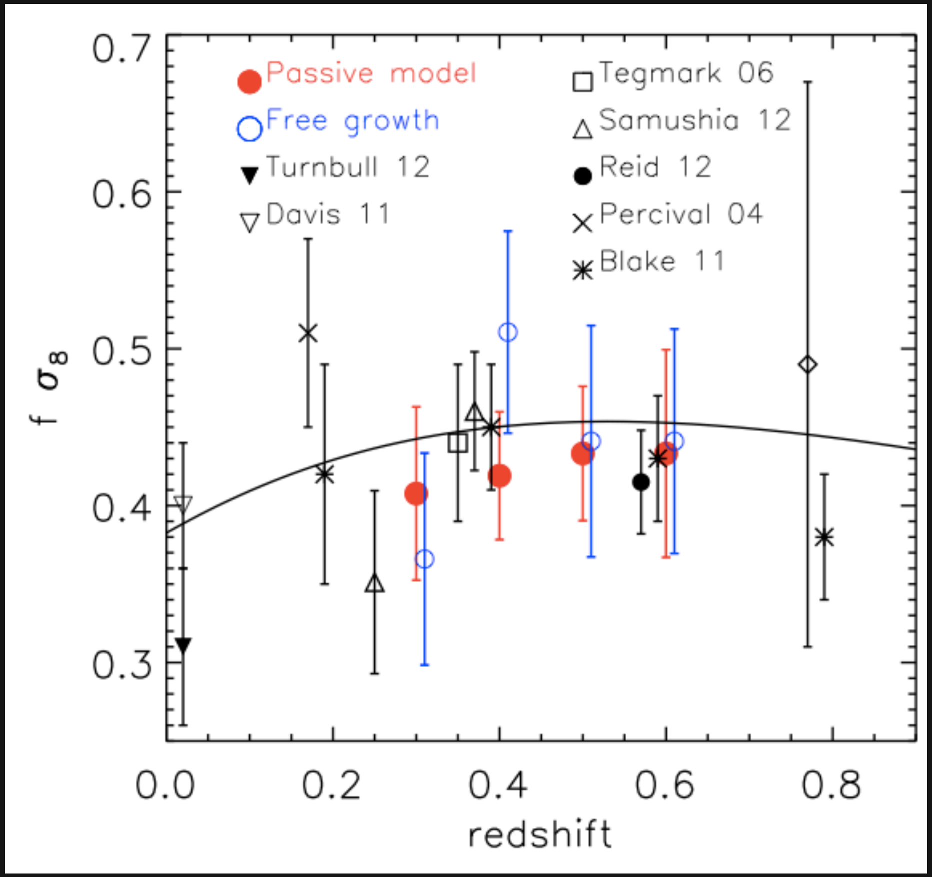


Compilation of measurements

Reid et al., Tojiero et al, 2012

What next?

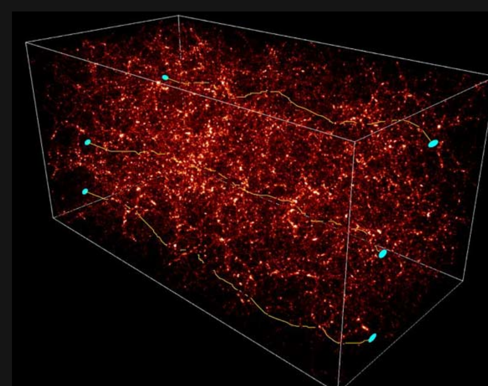
a) Beyond primary anisotropies

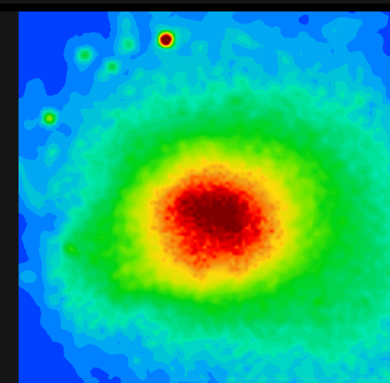
Use the CMB as a backlight to illuminate the growth of cosmological structure.

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

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

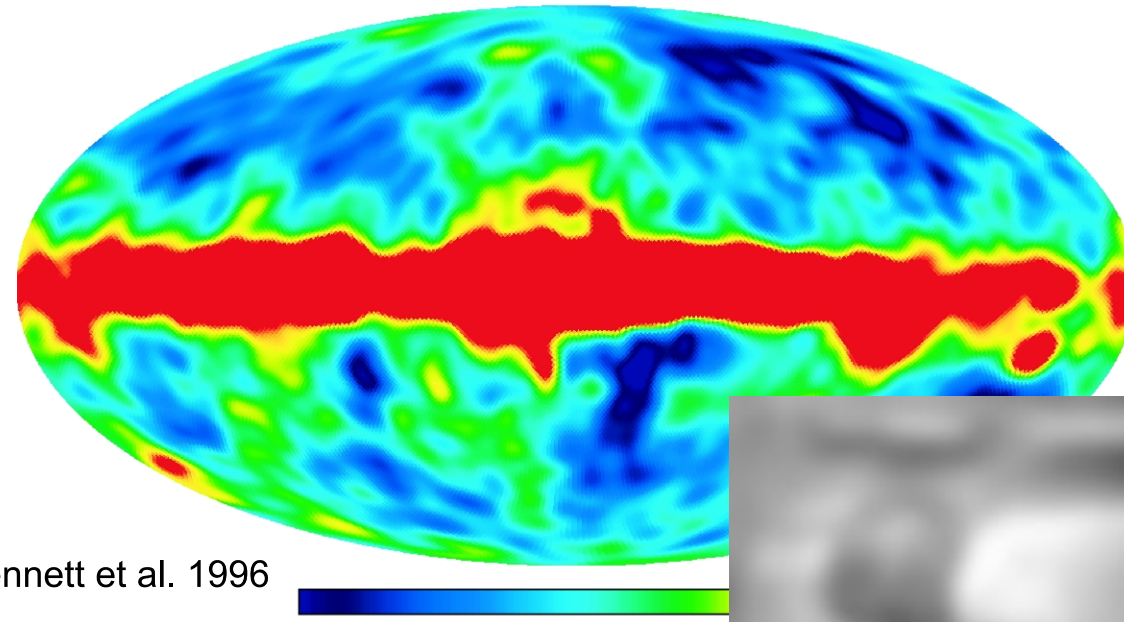
- weak lensing



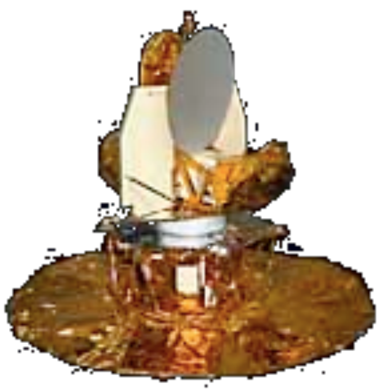


Ground based experiments like e.g.,
South Pole Telescope or Atacama Cosmology Telescope
Planck's higher resolution maps

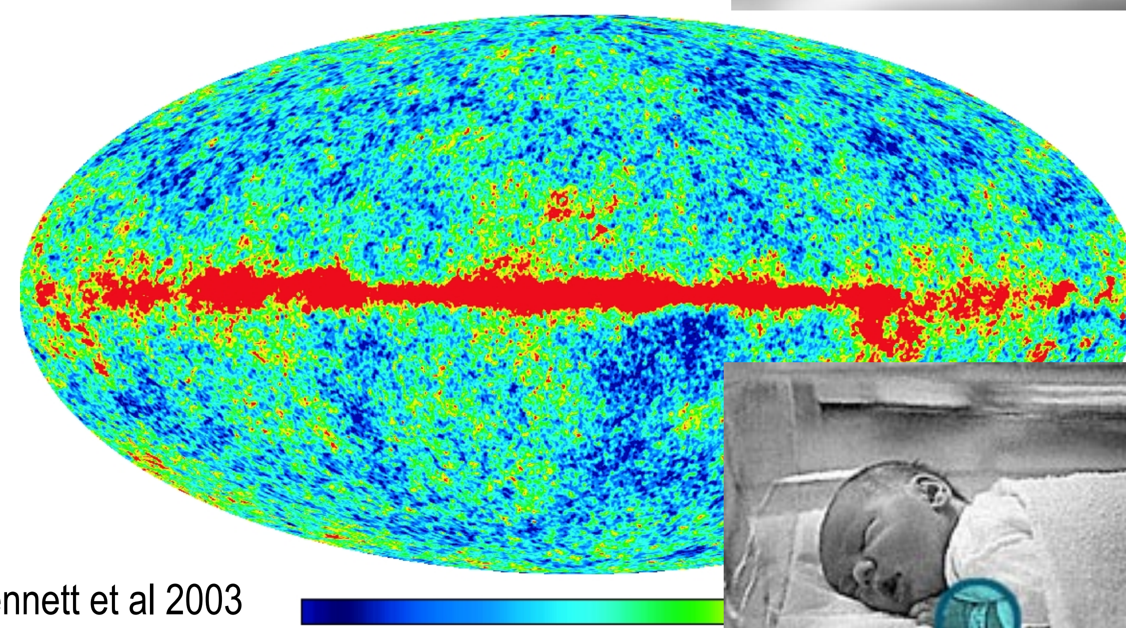
COBE 1992



Bennett et al. 1996



WMAP 2003



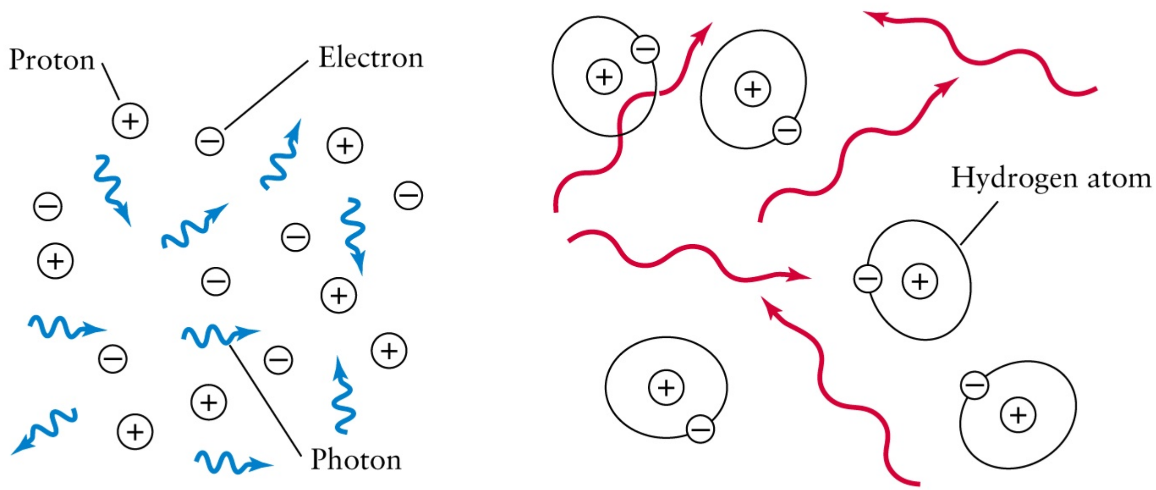
Bennett et al 2003

The cosmic microwave background (CMB) radiation

Regular hydrogen gas lets light pass through more or less unimpeded. This is the case today, where the hydrogen gas is either cold and atomic, or very thin, hot, and ionized.

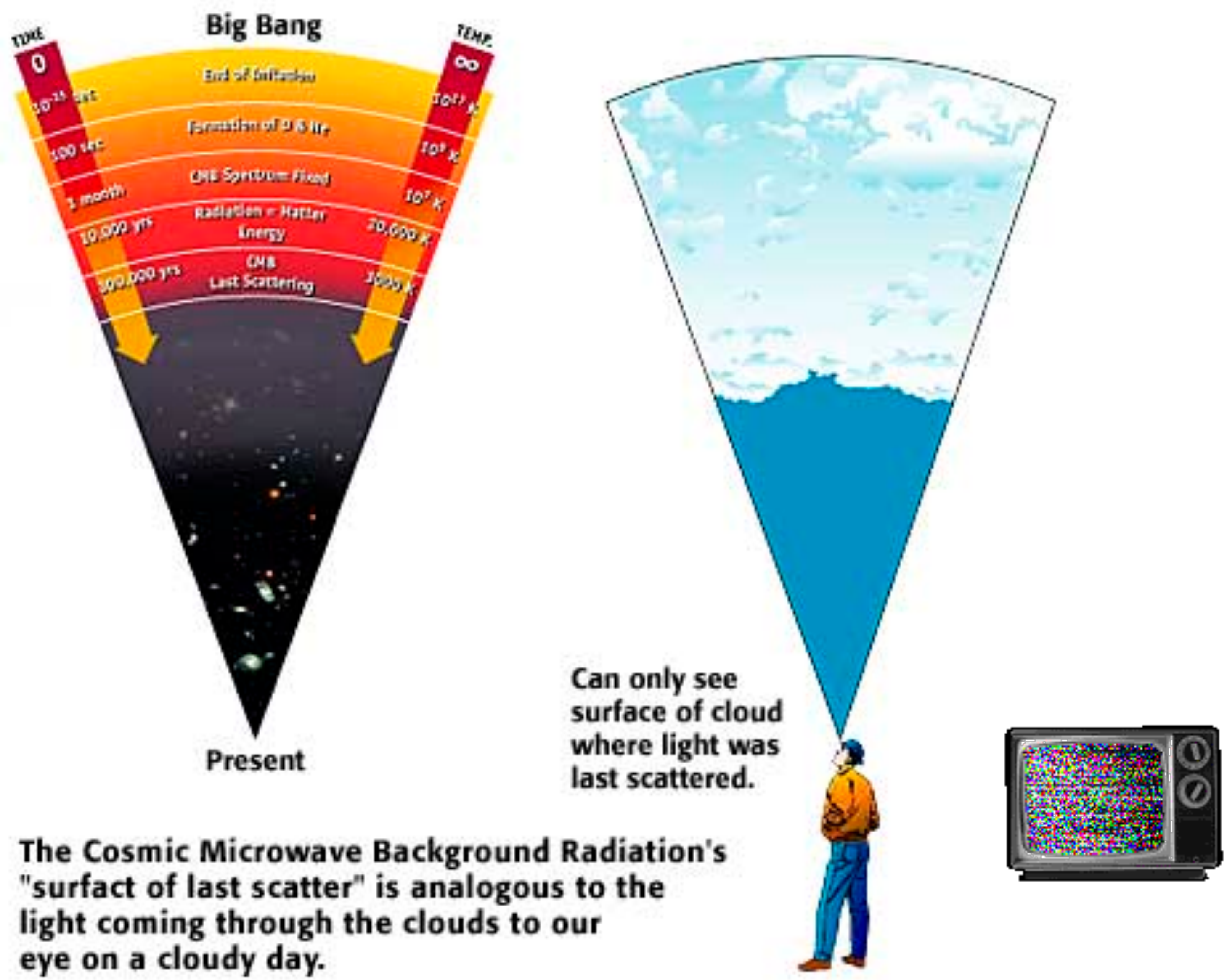
But in the early universe, when it was much warmer, the gas would have been ionized, and the universe opaque to light—as if you were in a dense fog.

As the universe cooled, the electrons and protons "recombined" into normal hydrogen, and the universe suddenly became transparent.

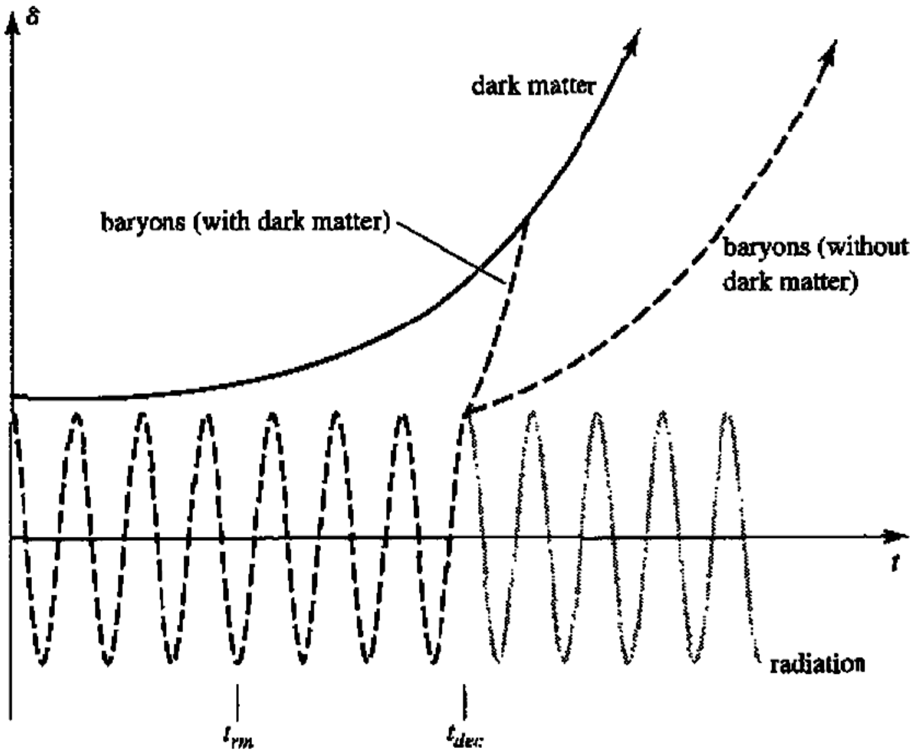


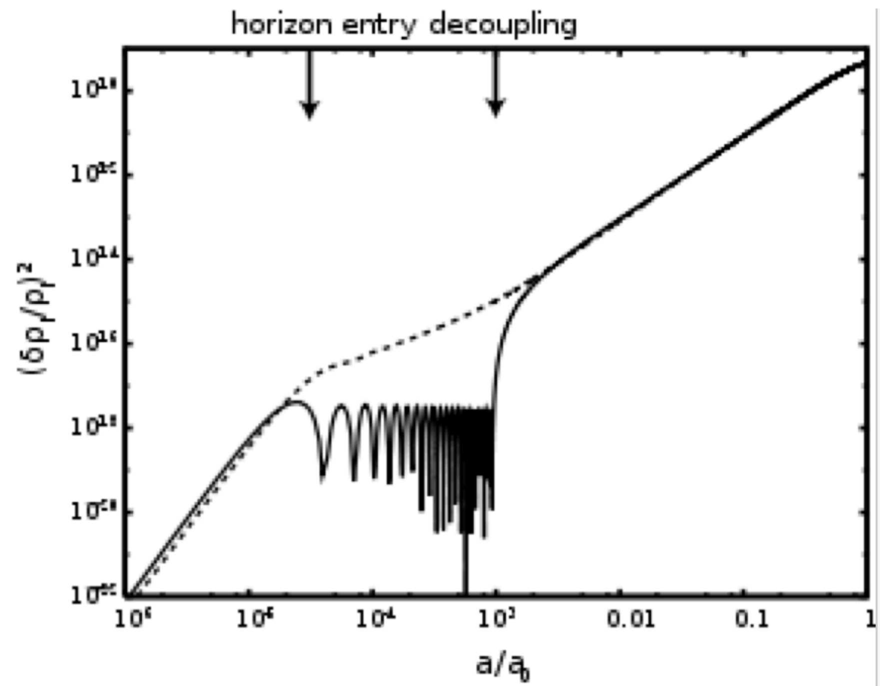
a Before recombination   b After recombination

The last scattering surface: a snapshot of the early universe



Schematic of perturbation growth

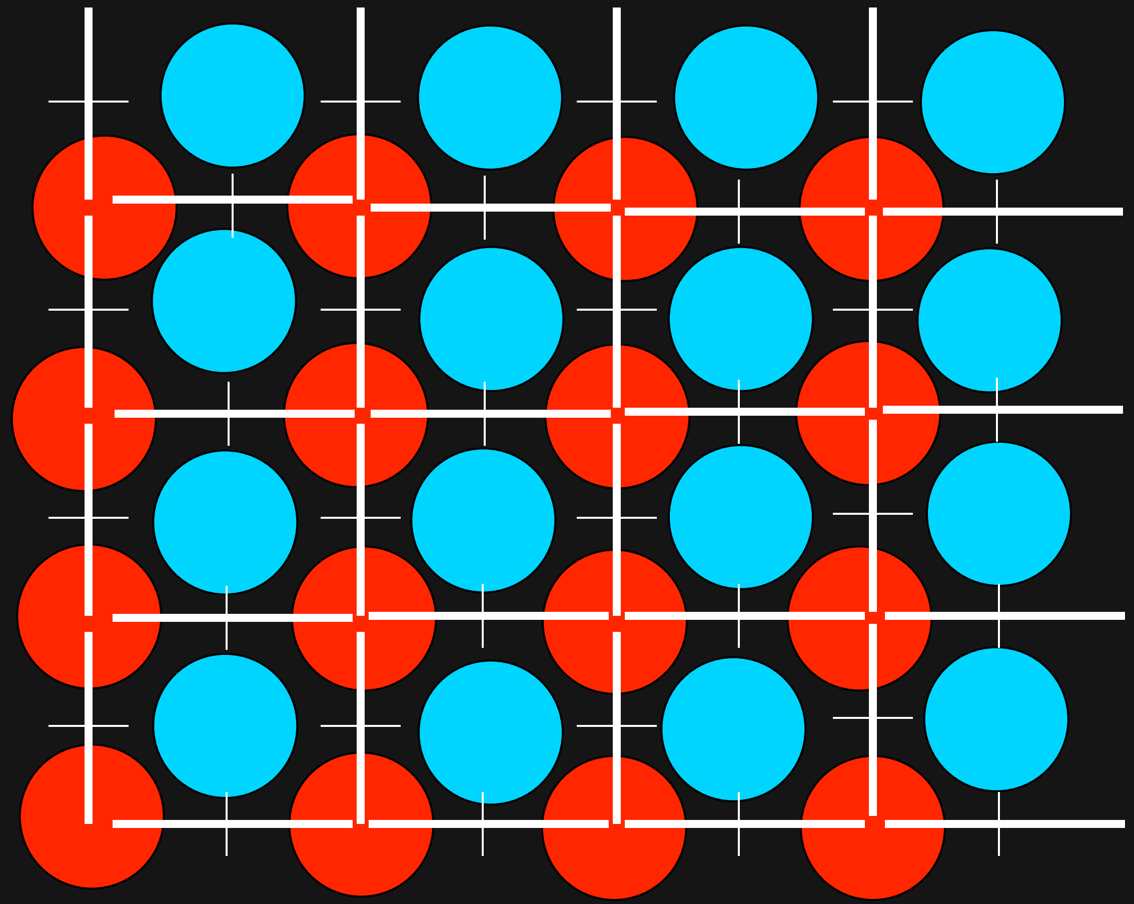




Baryons coupled to photons till decoupling

Polarization for density perturbation

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

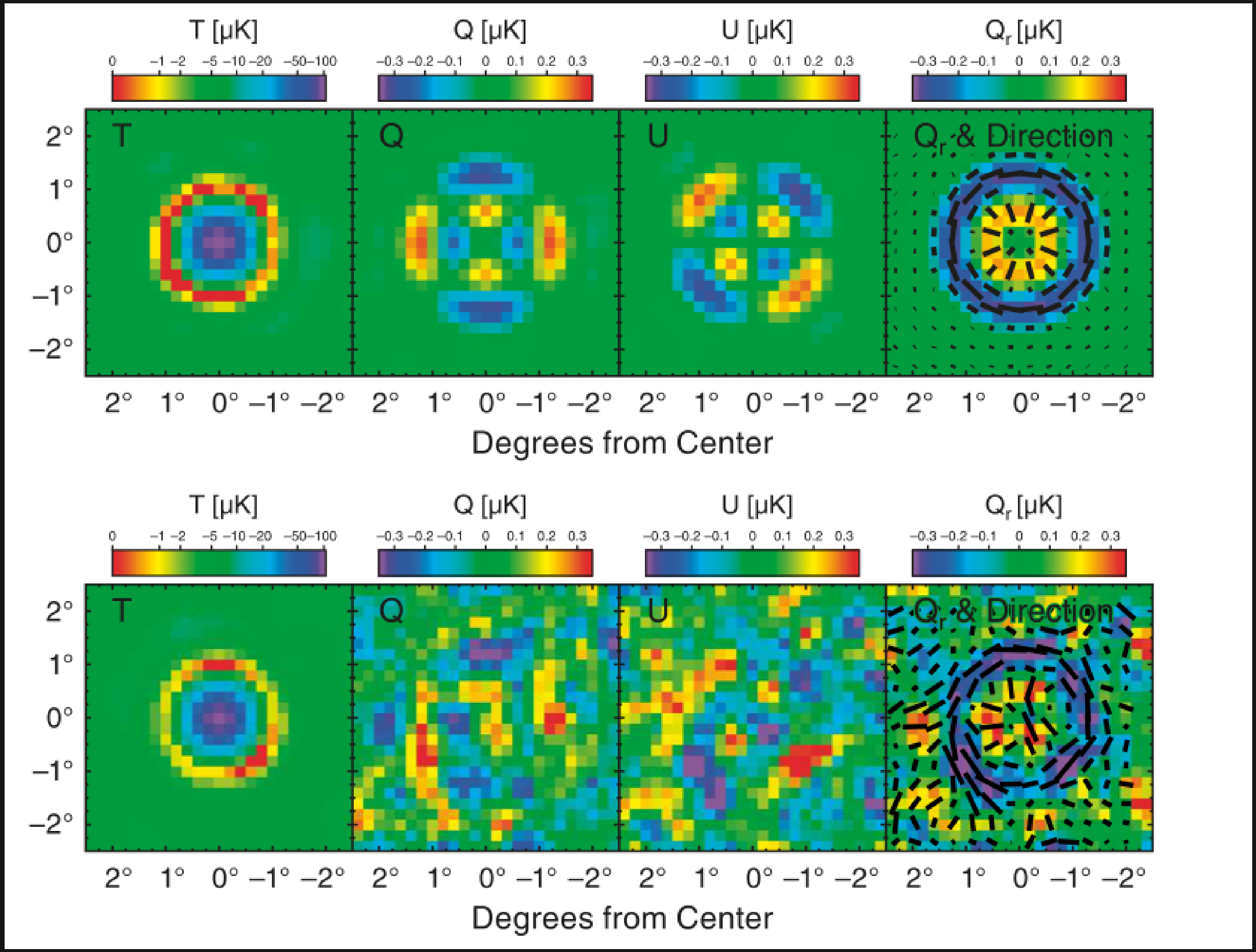


And it has been seen!

Komatsu, WMAP7yrs team (2010)

Theory prediction

Observed



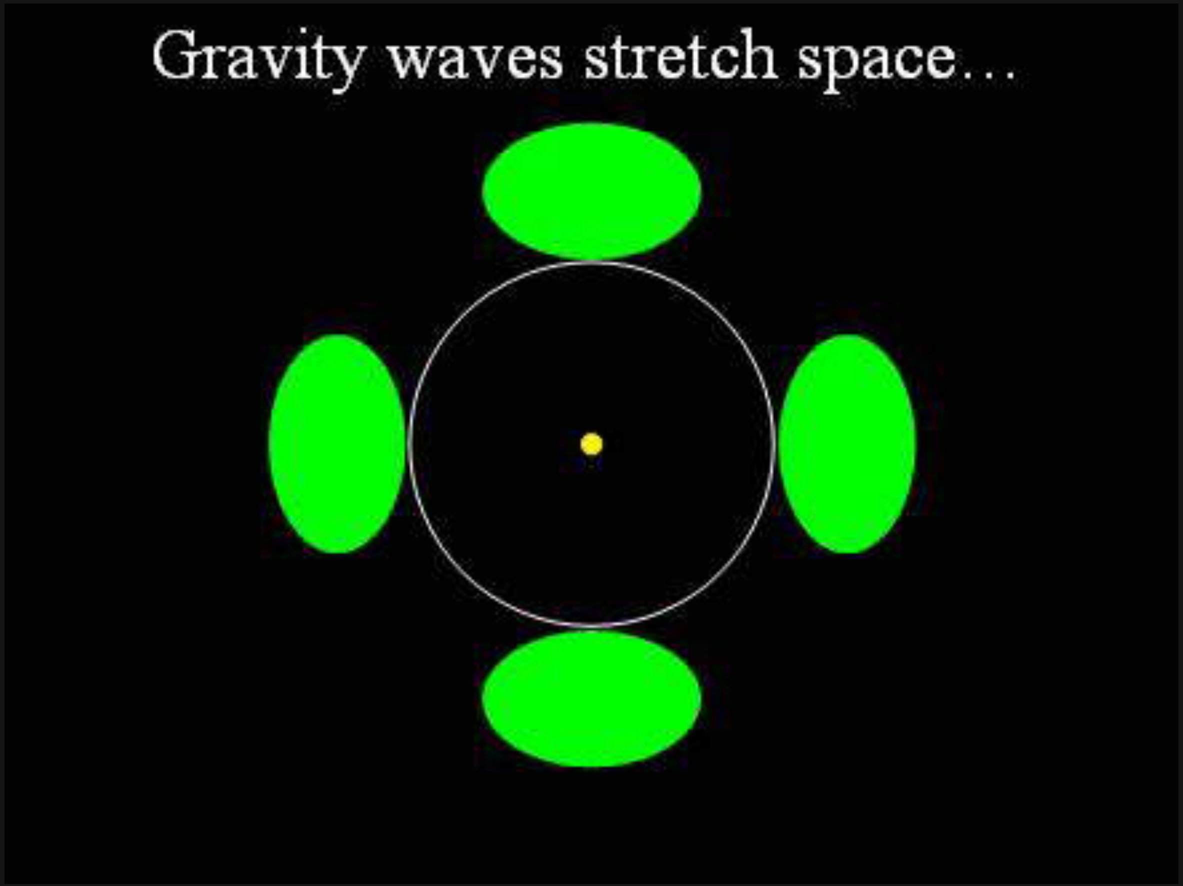


Image from J. Rhul.

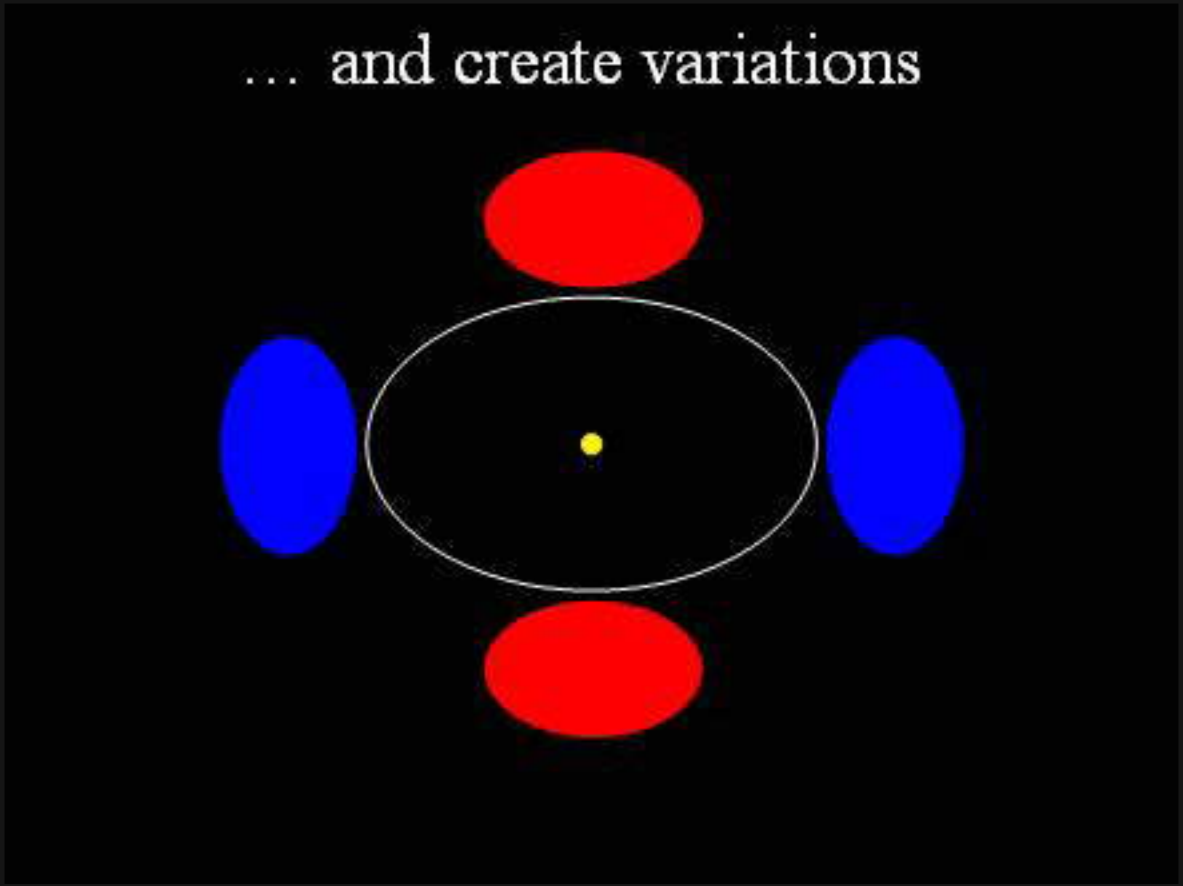
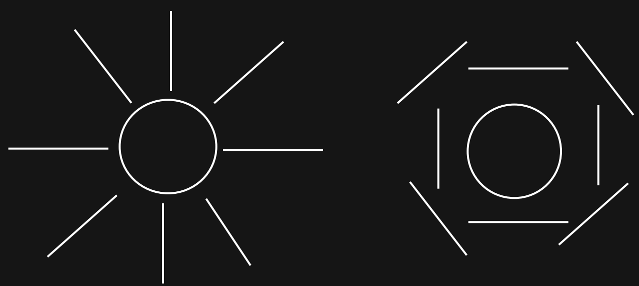
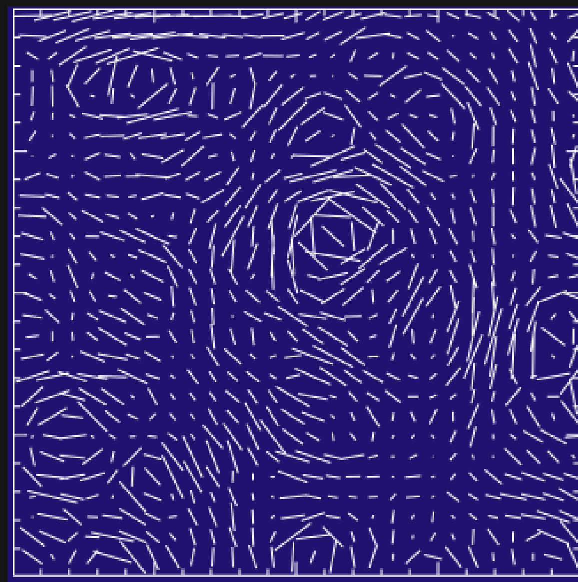


Image from J. Rhul.

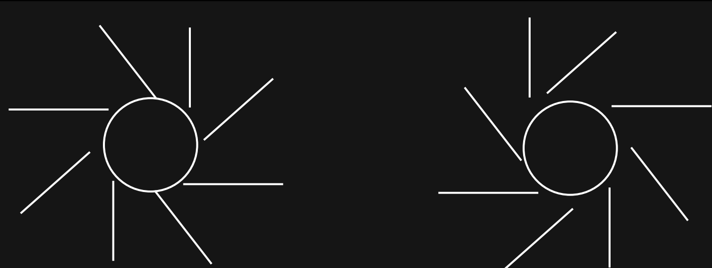
E and B modes polarization

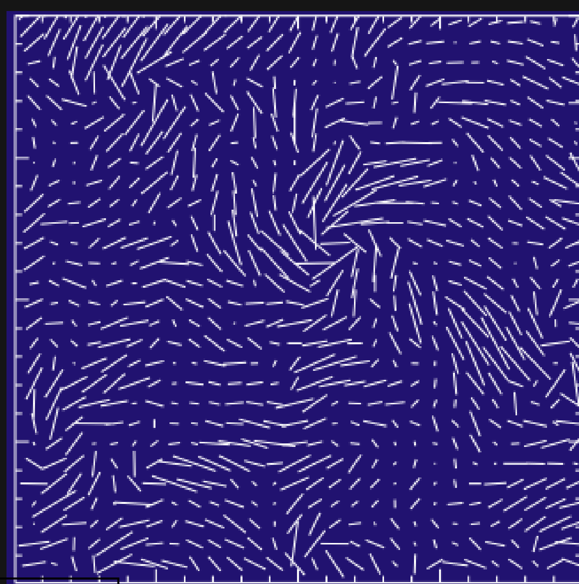
E polarization
from scalar and tensor modes





B polarization
only from tensor modes





Kamionkowski, Kosowsky, Stebbings 1997, Zaldarriga & Seljak 1997

Relative Amplitudes of CMB power spectra