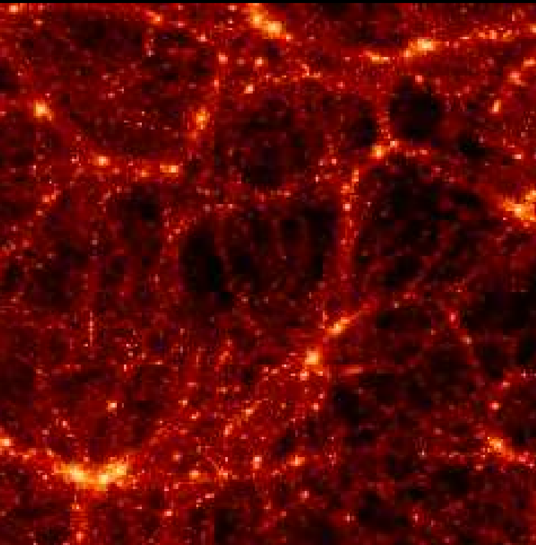
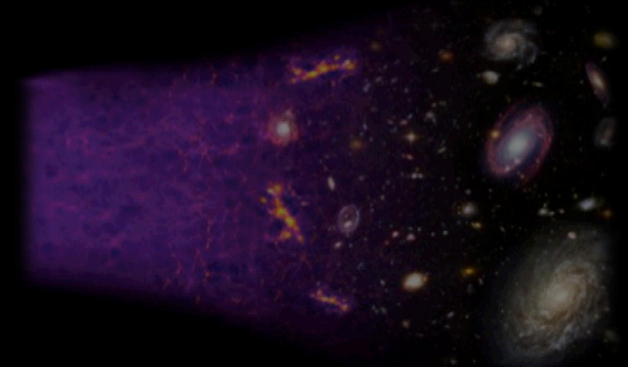
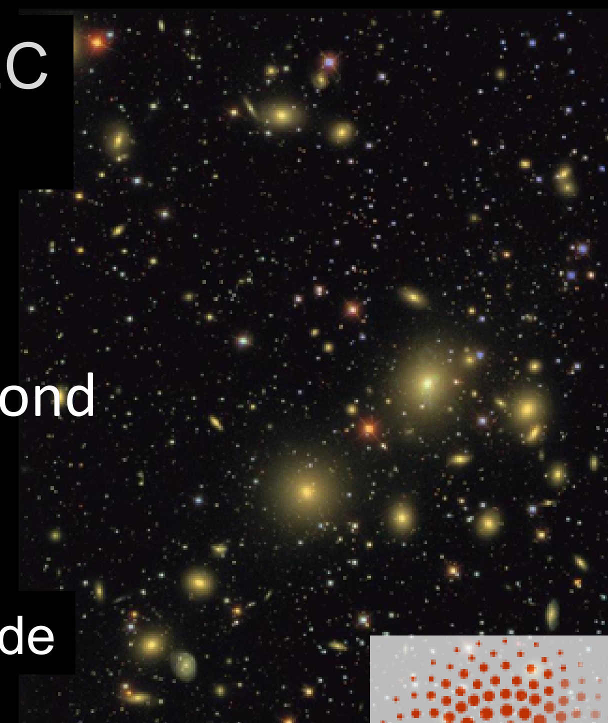




Licia Verde

ICREA & ICC-UB-IEEC
BARCELONA



Precision cosmology and beyond

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

Precision cosmology

ΛCDM: The standard cosmological **model**

Just 6 numbers…..

describe the Universe composition and evolution

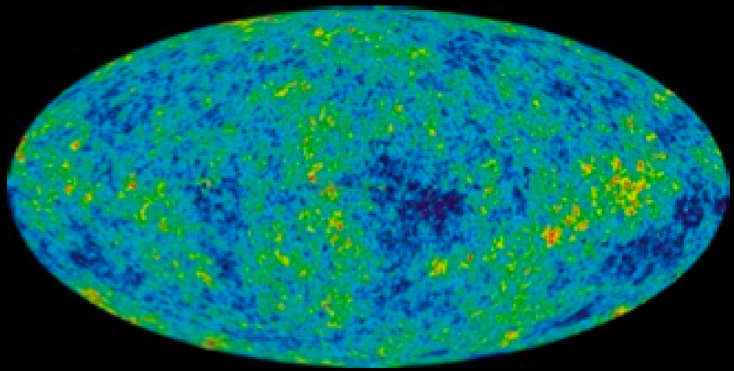
Homogenous background

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

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

Λ? CDM?

Perturbations



$$A_s, n_s$$

- nearly scale-invariant
- adiabatic
- Gaussian

ORIGIN??

Cosmology is special

We can't make experiments, only observations

We have to use the entire Universe as a detector:
the detector is given, we can't tinker with it.

This has driven a massive experimental effort

- Observe as much as possible of the Universe.

A mixed blessing

The curse of cosmology

We only have one observable universe

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: (Almost) <u>any statement is model dependent</u>

*"Gastrophysics"** and non-linearities get in the way

….And the Blessing

We can observe all there is to see

** Not a typo, means complex astrophysics that is poorly understood/hard to model*

….And the Blessing

We can observe all there is to see

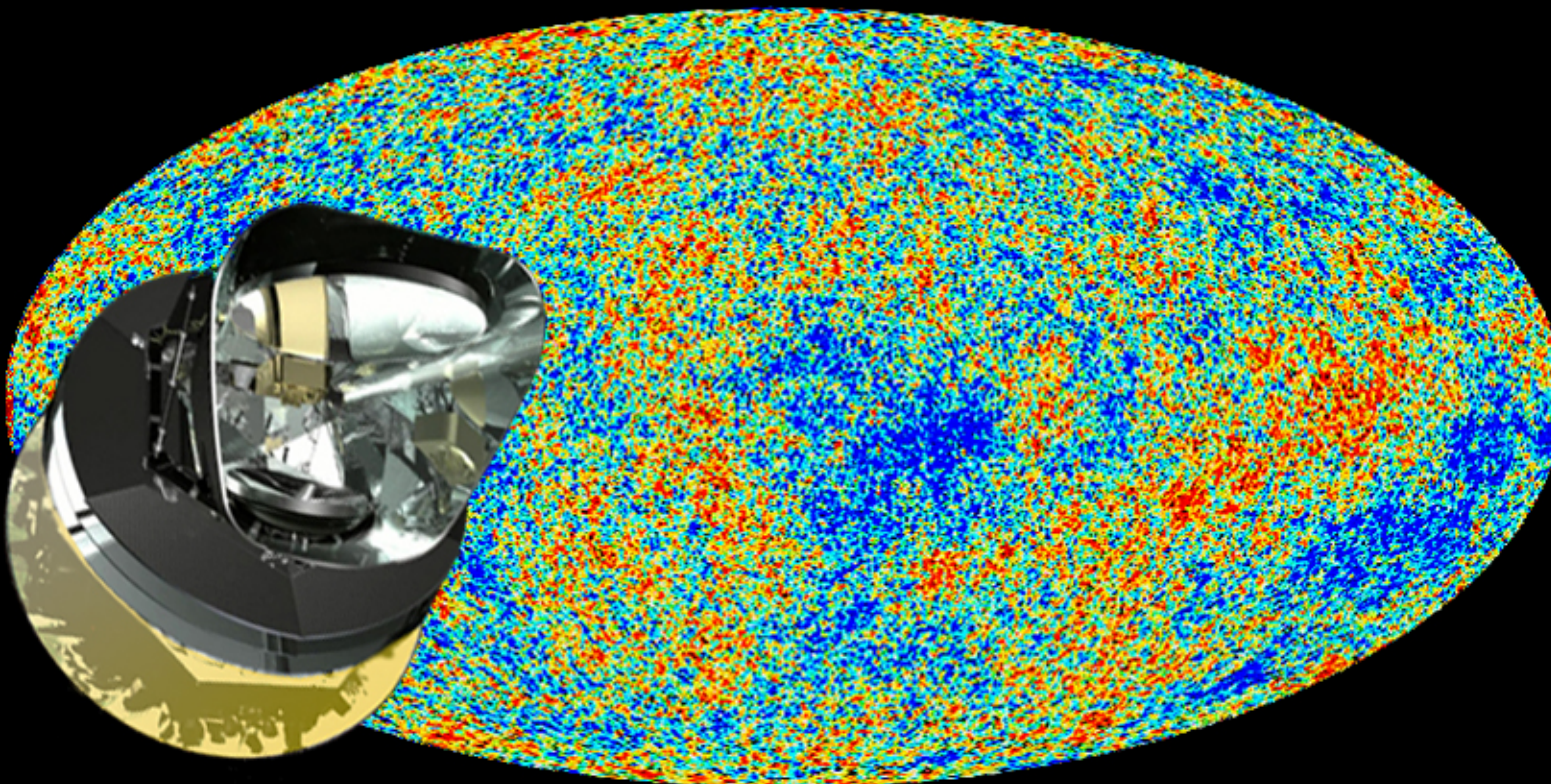
And almost do

Ultimate survey

The future is bright!

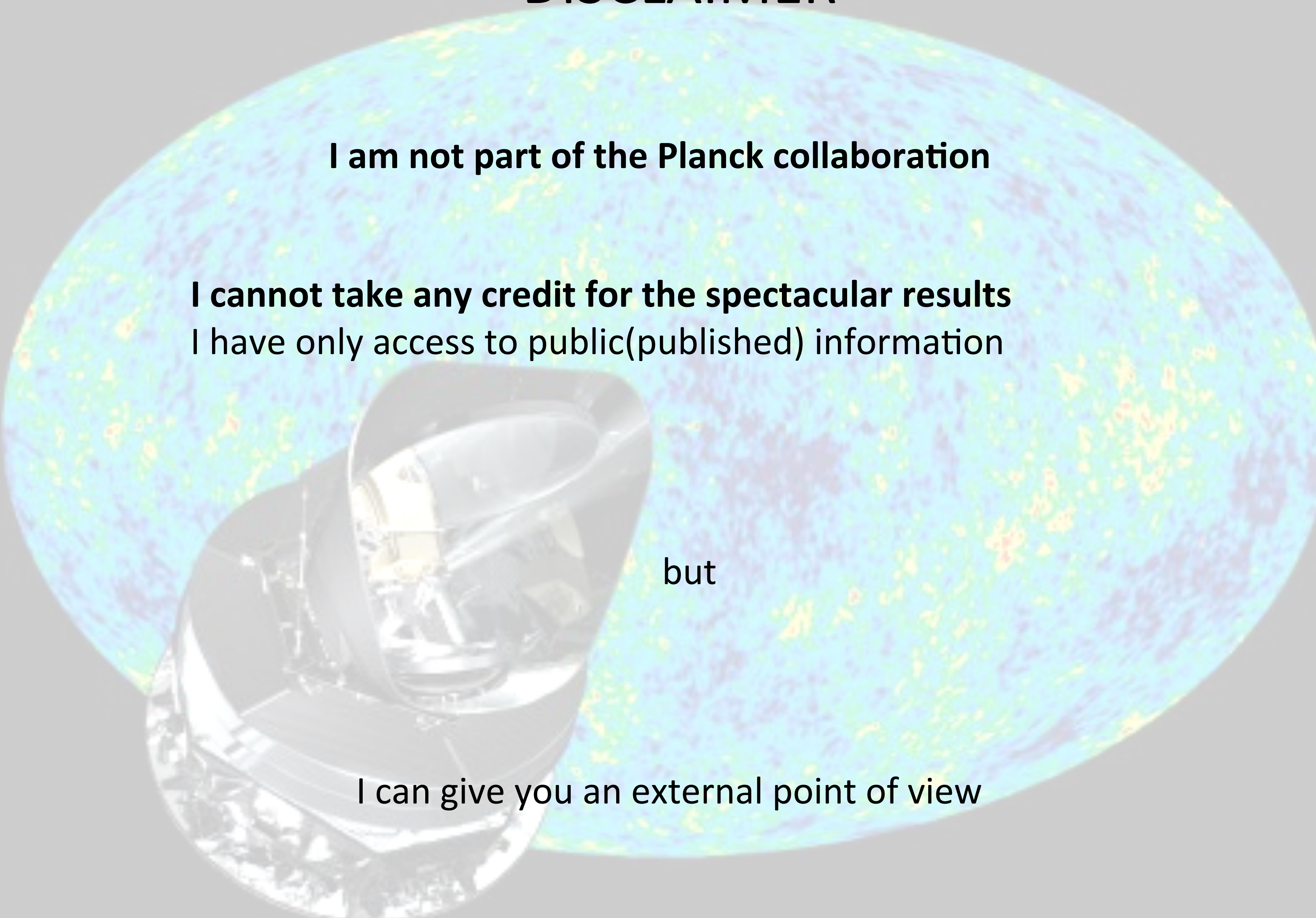
Ultimate surveys!

The future is here!



Planck 2015

DISCLAIMER



I am not part of the Planck collaboration

I cannot take any credit for the spectacular results
I have only access to public(published) information

but

I can give you an external point of view

Planck

ESA-NASA mission to map temperature and polarization of the CMB on the full sky
First major release in 2013
Second major release in 2015 in total >> 100 papers

I will do a massive compression of information

CMB: “The primordial fireball”, “the last scattering surface”

Dependence on cosmological parameters

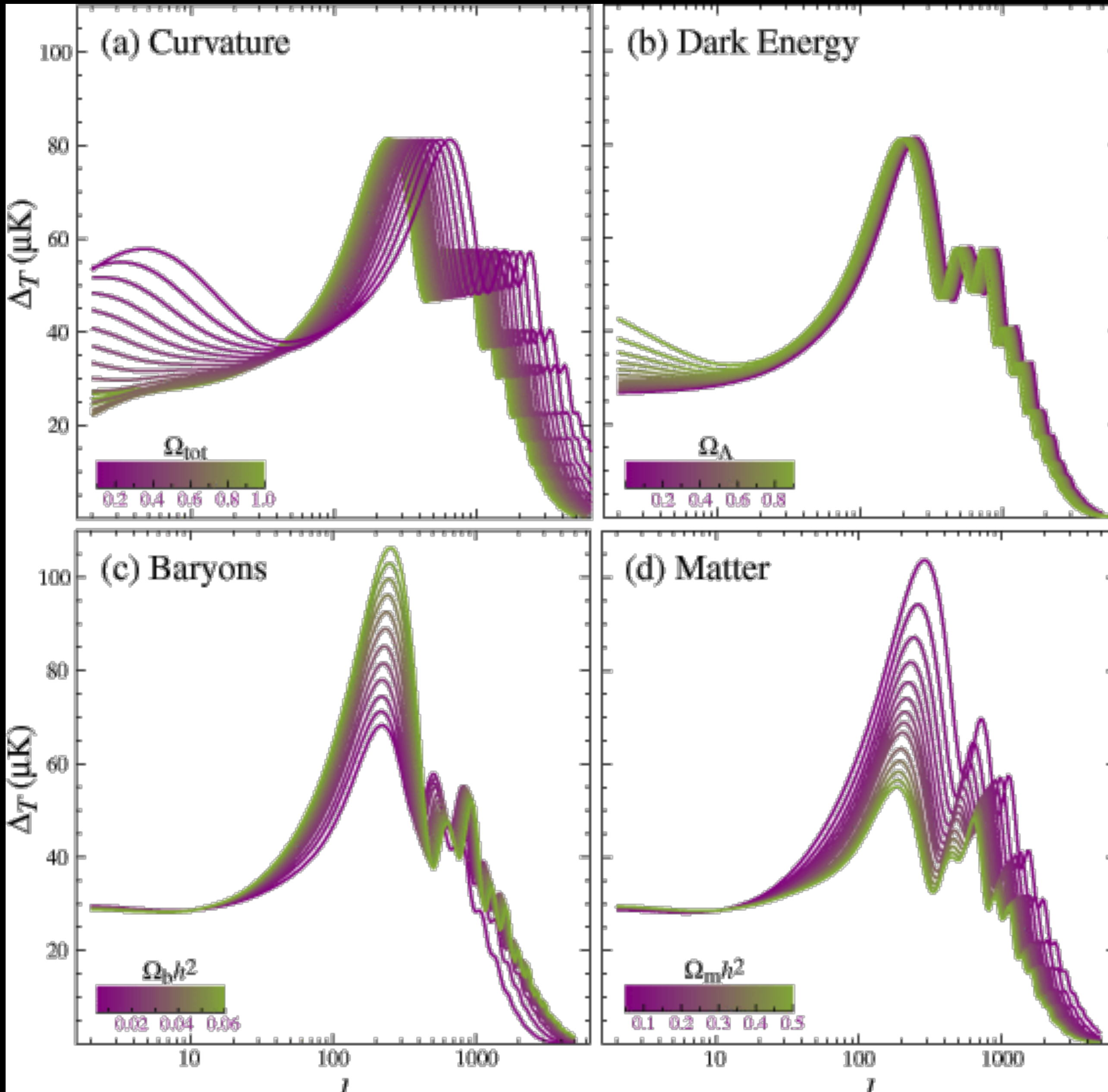
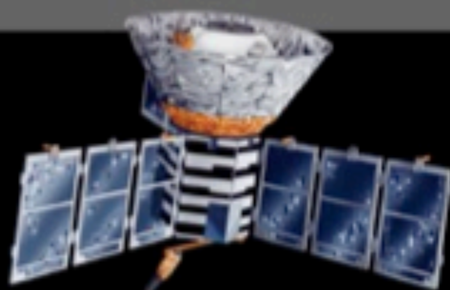


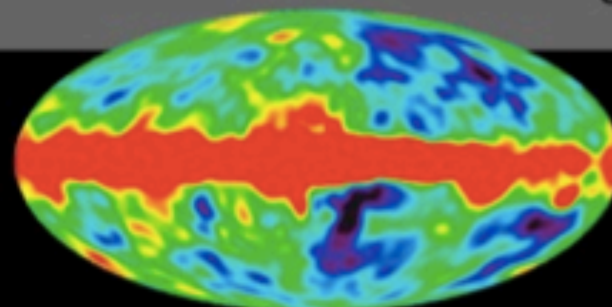
Fig. courtesy of W. Hu

History of CMB temperature measurements

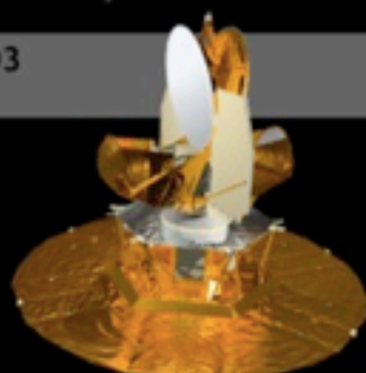
1965 — Penzias and Wilson

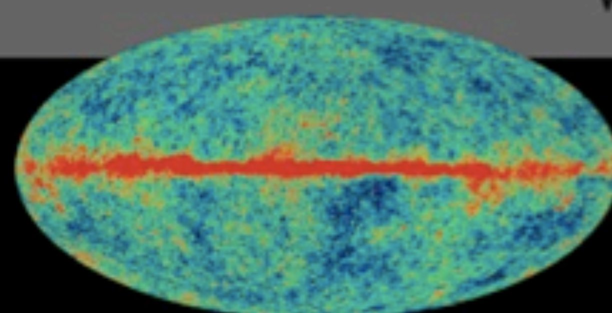
1992 — COBE





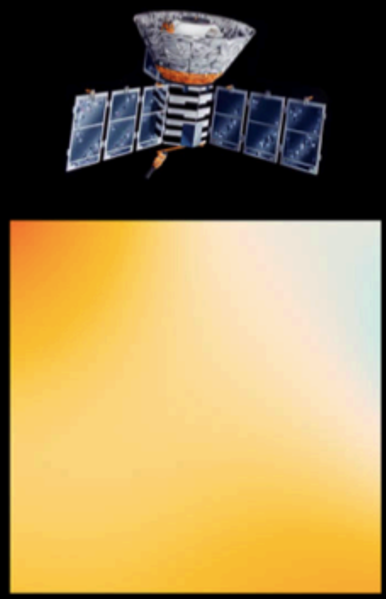
2003 — WMAP



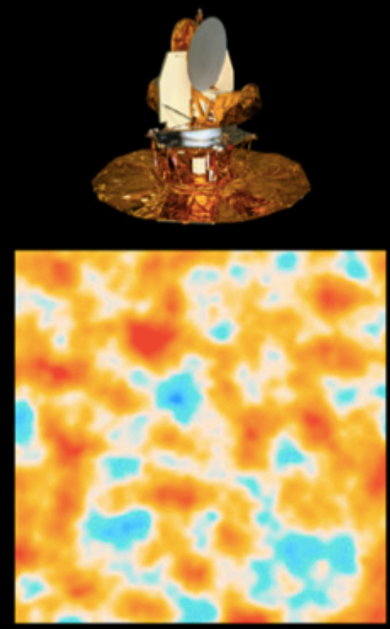


TOCO (1998) BOOMERANG (1998, 2003) MAXIMA (2000)
ARCHEOPS (2002) CBI (2002) ACBAR (2002) VSA (2002)

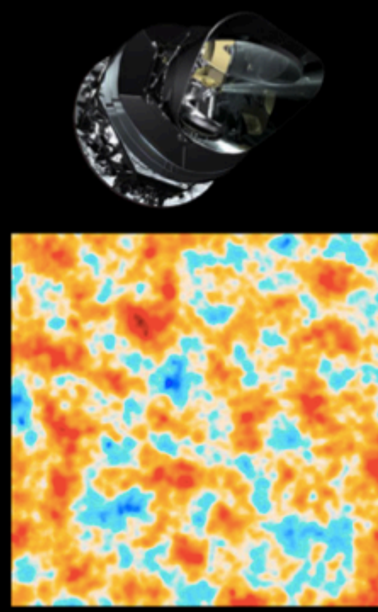
In context….



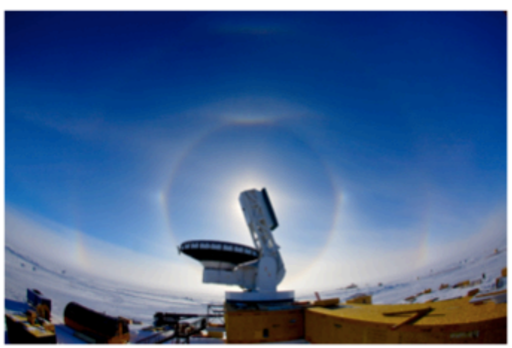
COBE



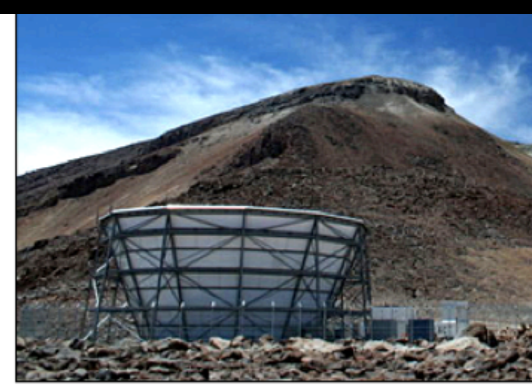
WMAP



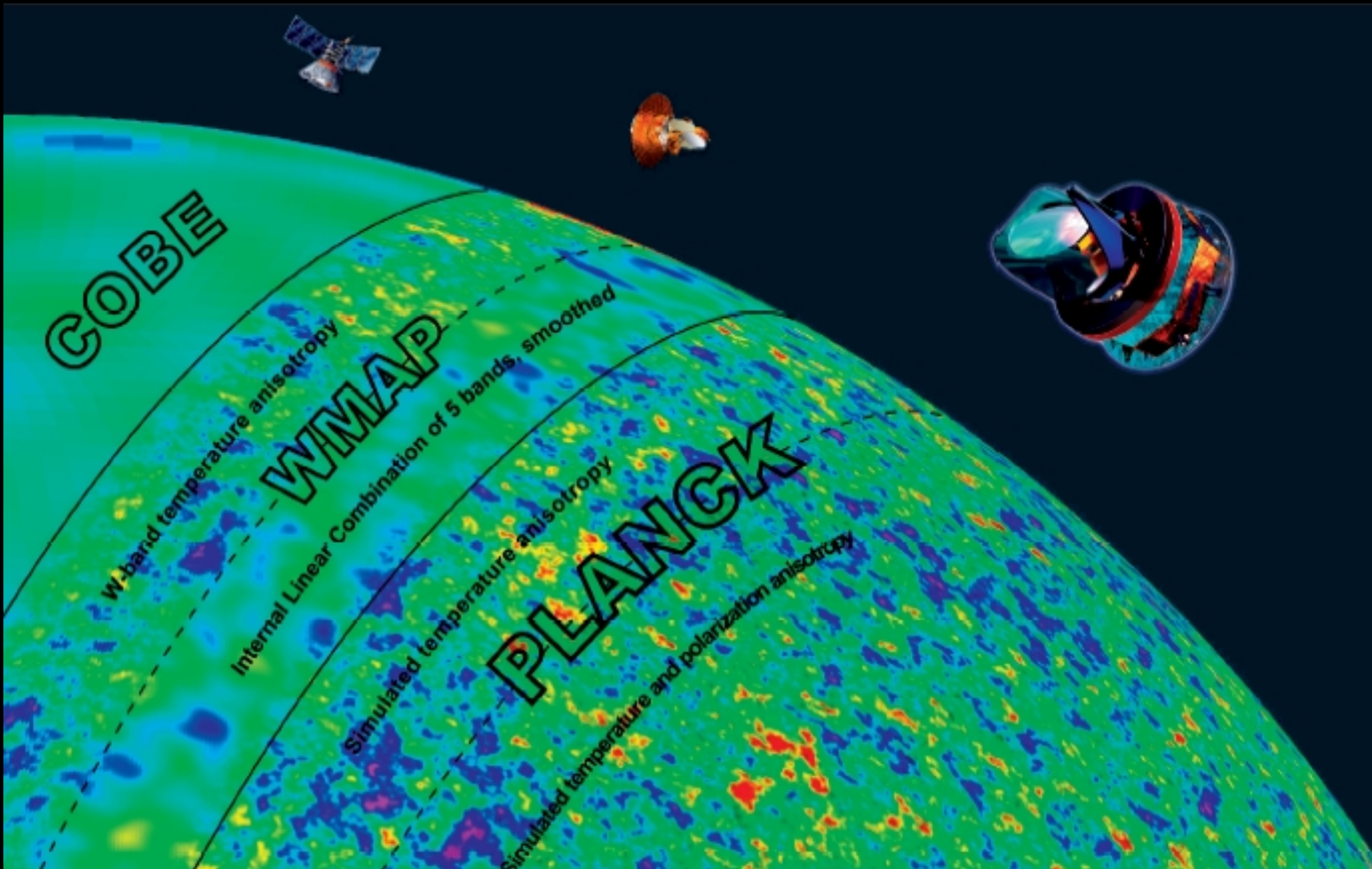
Planck



South Pole Telescope (SPT)

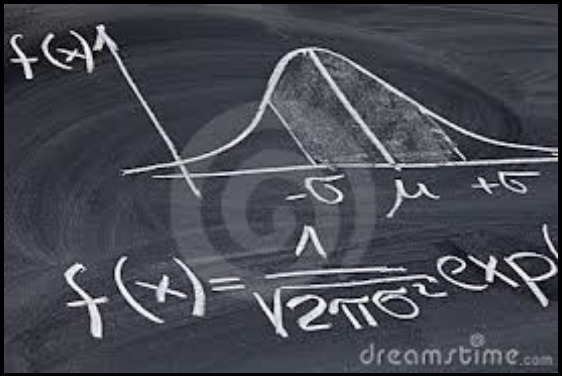


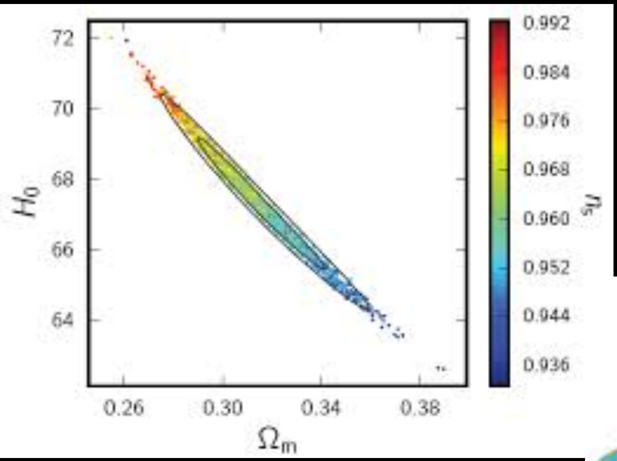
Atacama Cosmology Telescope (ACT)

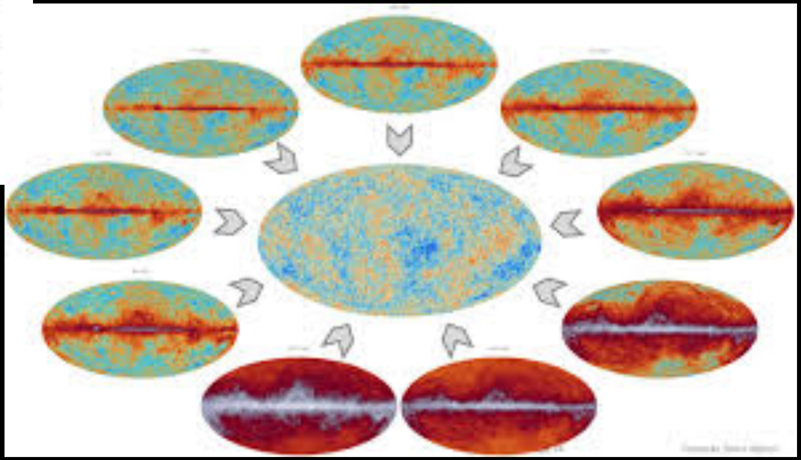

COBE
W-band temperature anisotropy
WMAP
Internal Linear Combination of 5 bands, smoothed
Simulated temperature anisotropy
PLANCK
Simulated temperature and polarization anisotropy

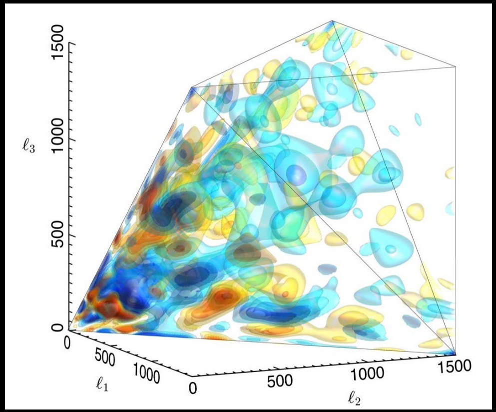
Statistical techniques to make precision cosmology possible

Heroic effort to refine statistical and data analysis techniques to exquisite level

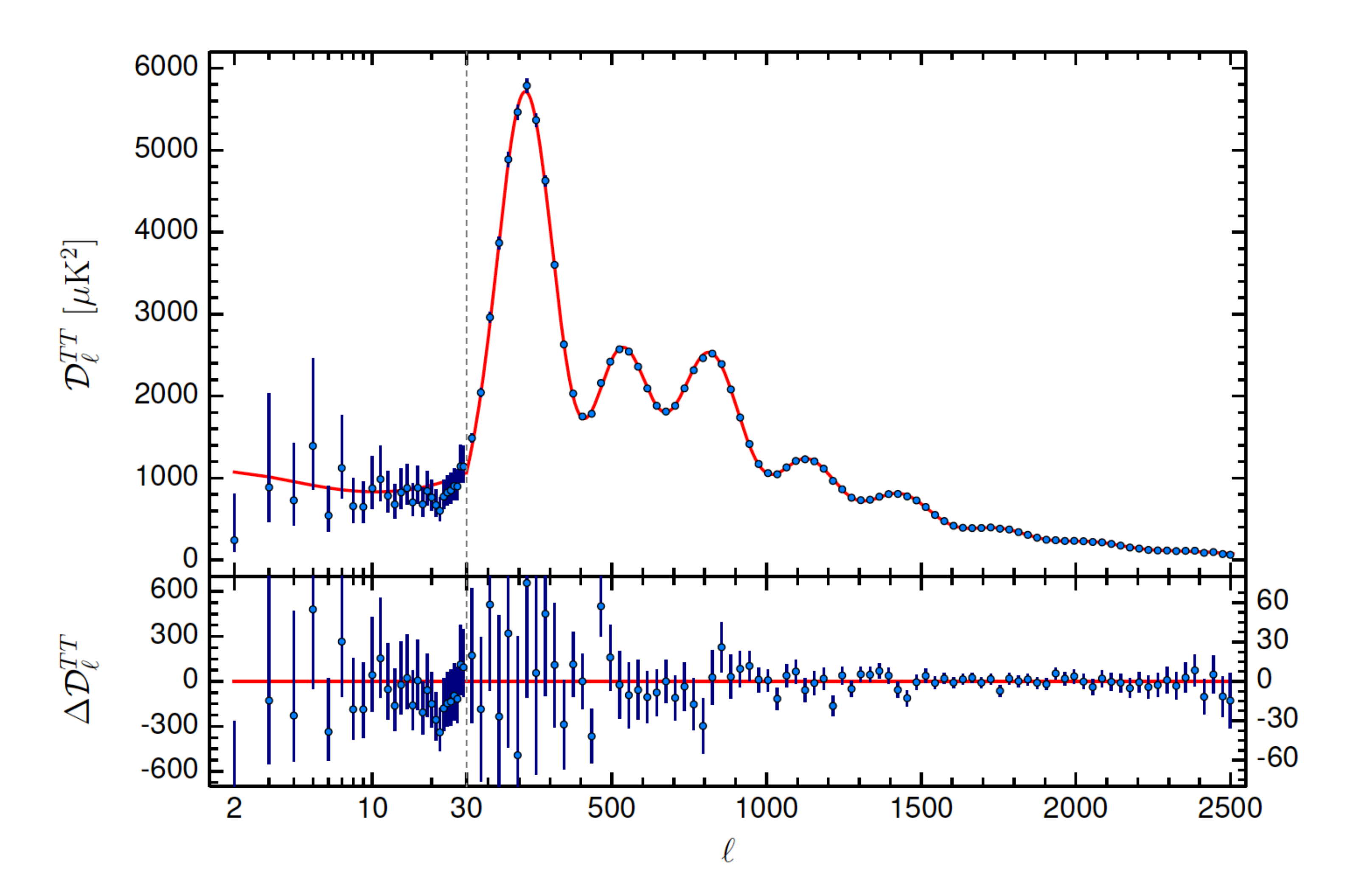








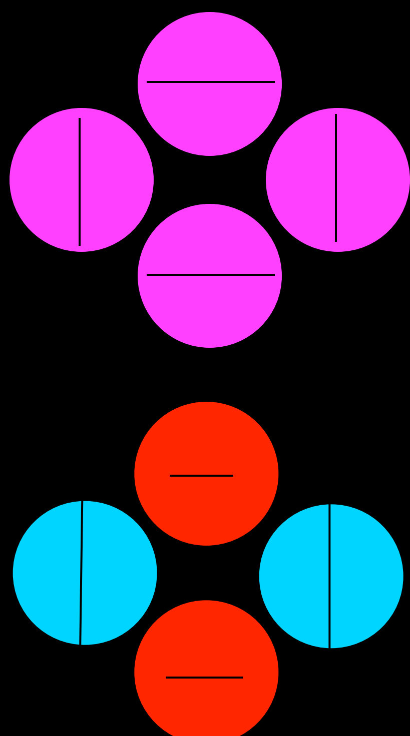
Temperature anisotropy power spectrum



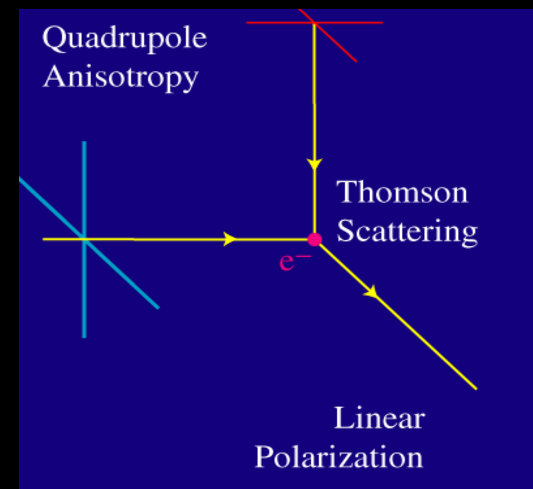
Planck 2015

Generation of CMB polarization

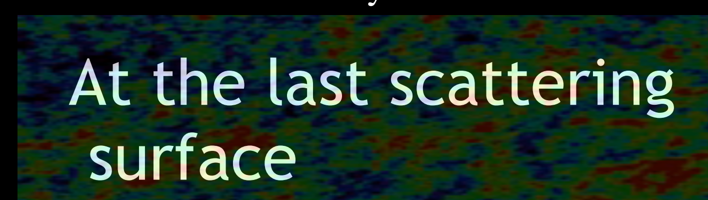
- Temperature quadrupole at the surface of last scatter generates polarization.

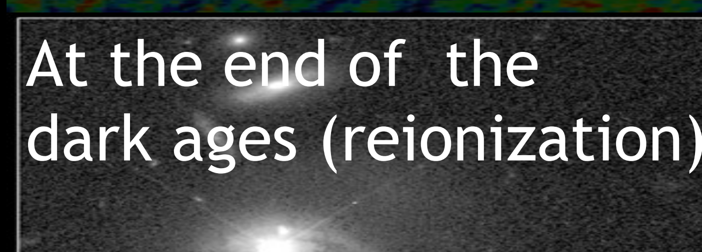


Potential hill Potential well

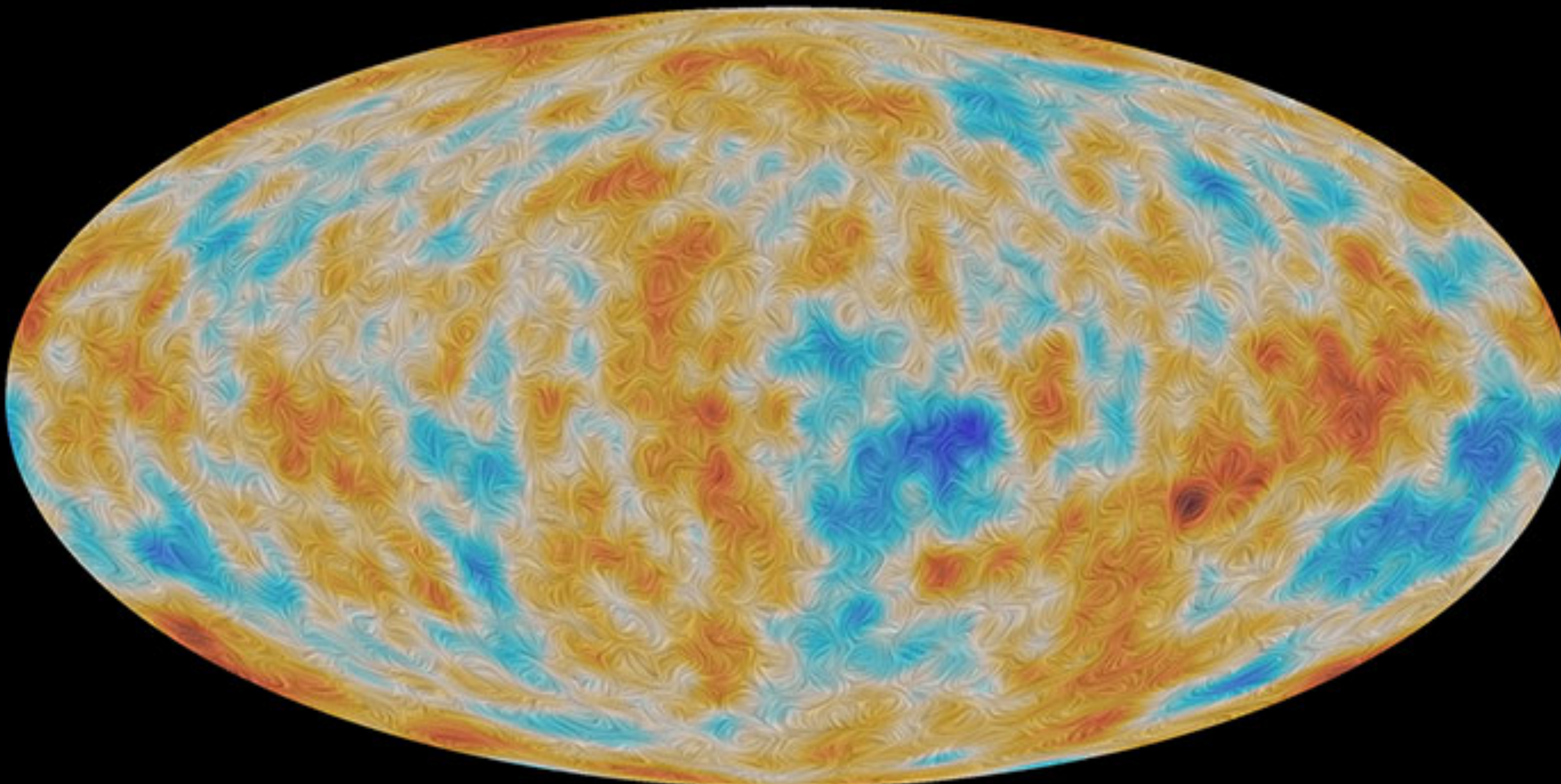


From Wayne Hu



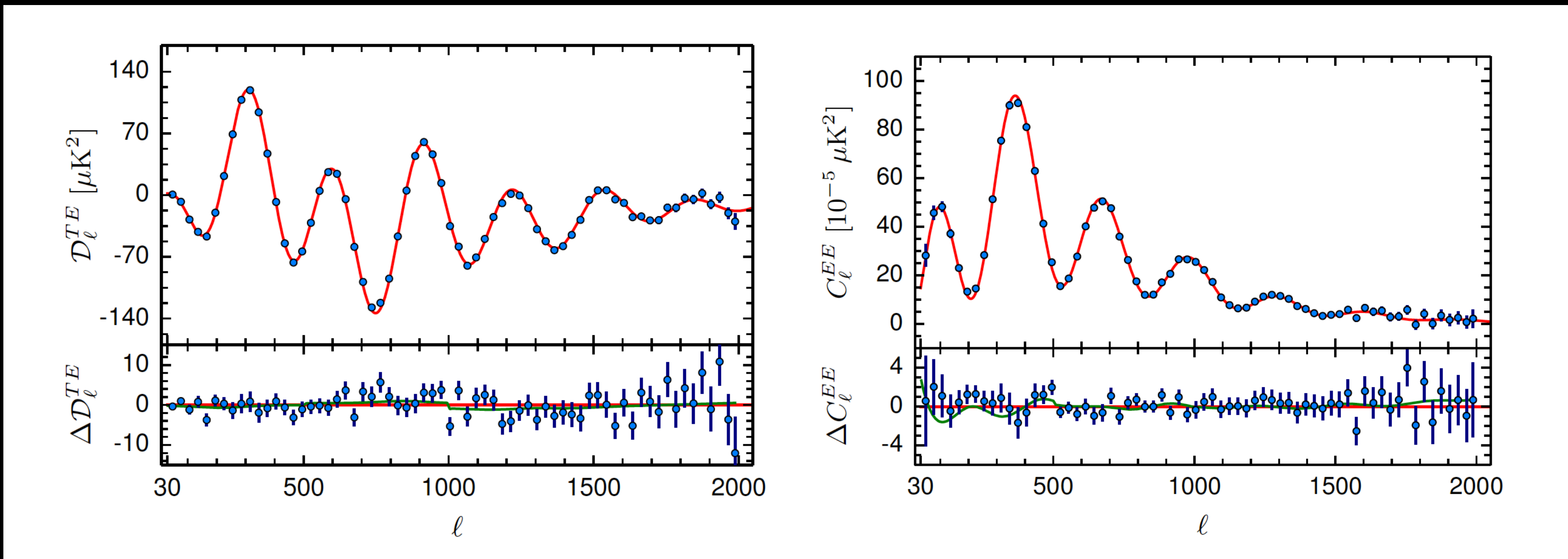


Polarization



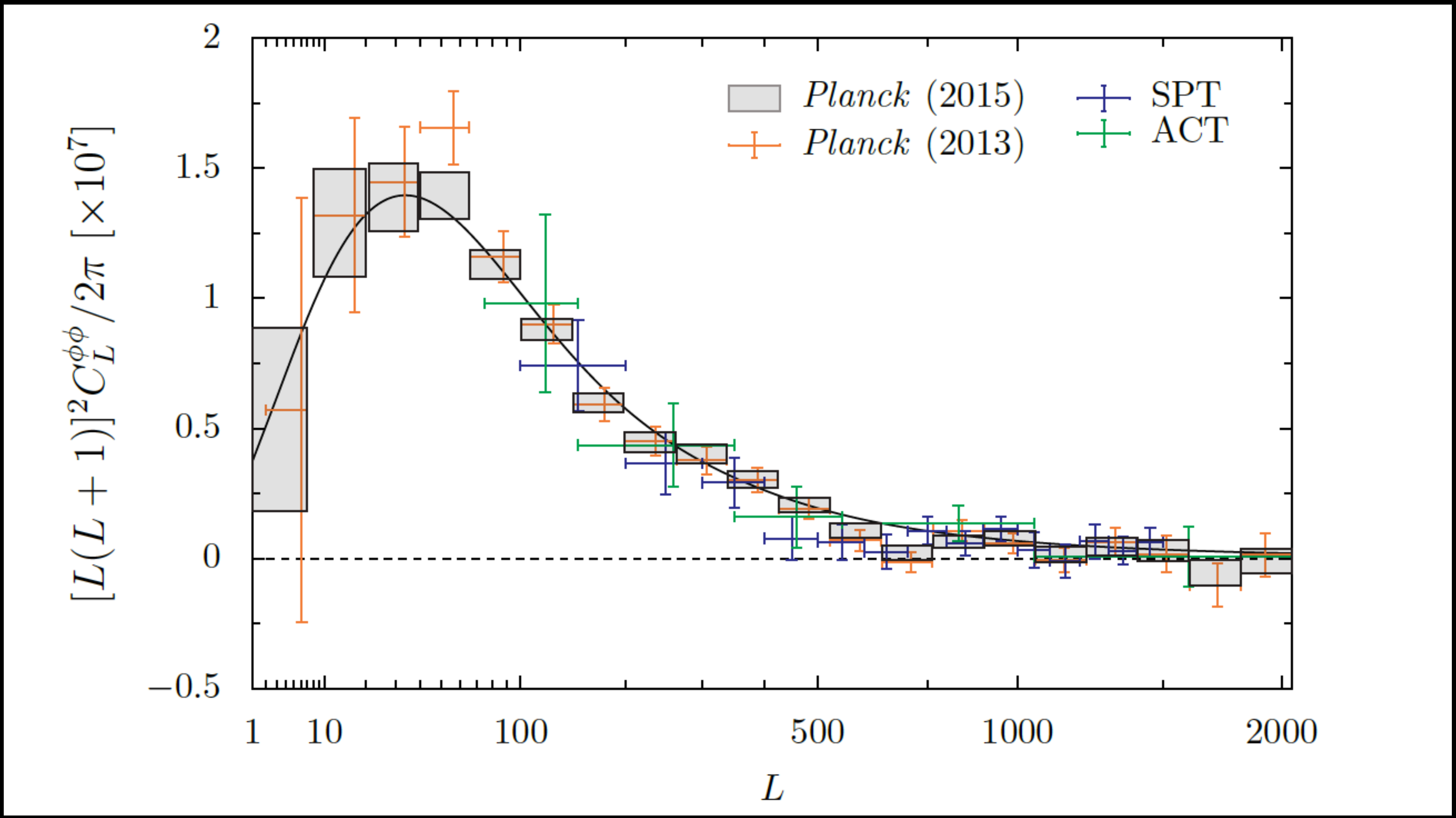
Planck 2015

Polarization power spectra



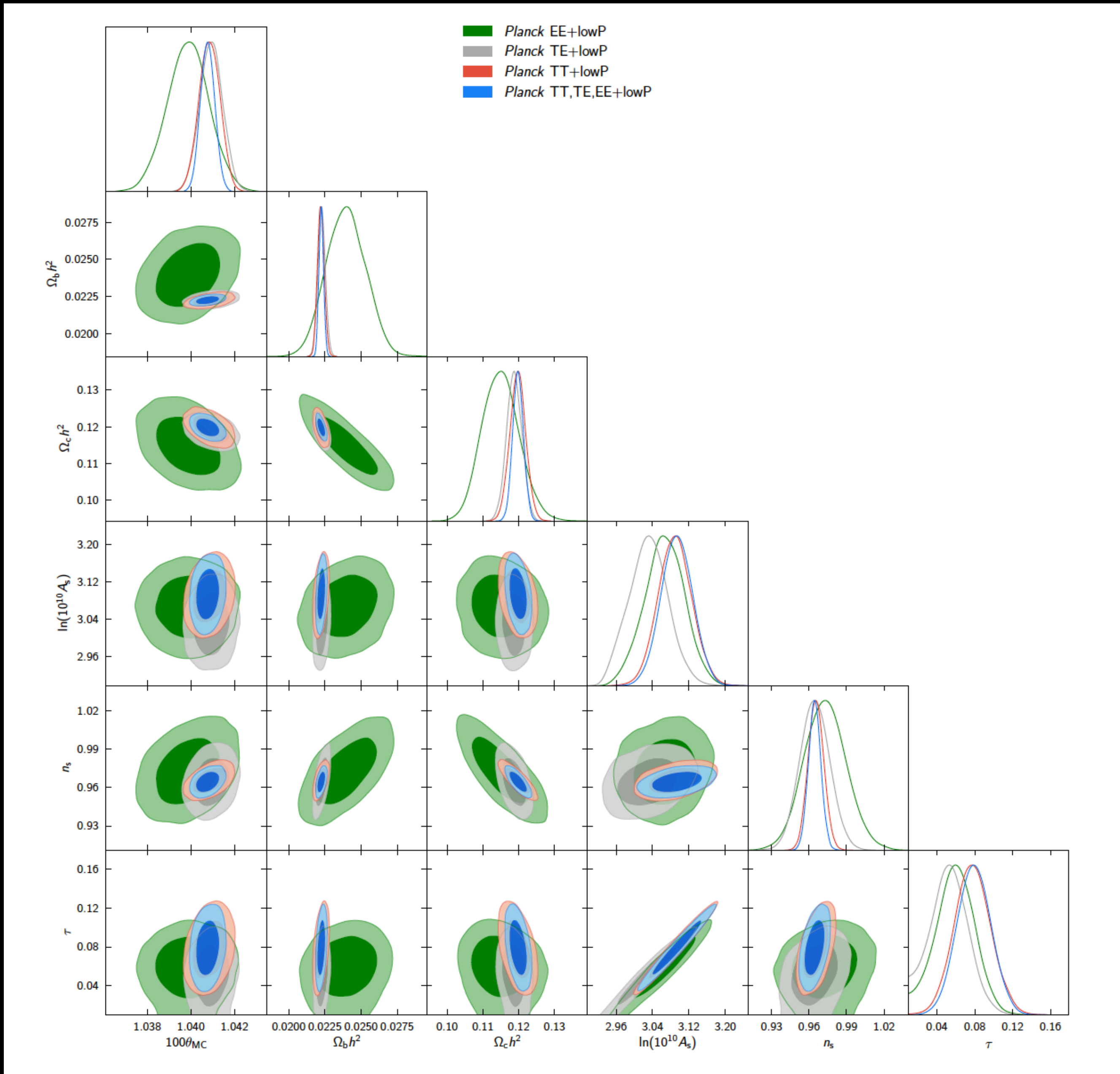
Planck 2015

CMB lensing



40 σ detection of lensing ; amplitude constrained to 2.5%

The power of polarization



Planck 2015

Wonderful agreement of new data with the ΛCDM model*

"the maximally boring Universe"

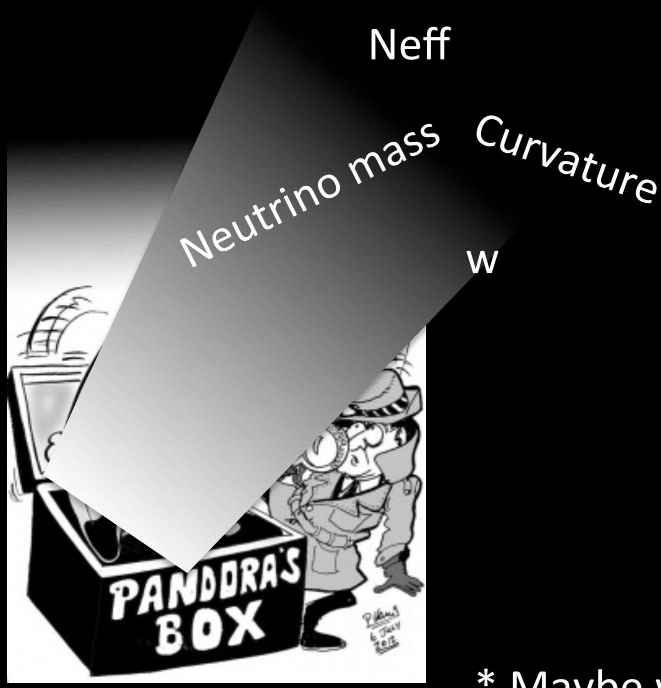
* With some notable exceptions which are still up for discussion.

STILL….

The model IS incomplete… Neutrinos have mass

The model is unsatisfactory

The cosmological constant problem*
Inflation is more than n_s

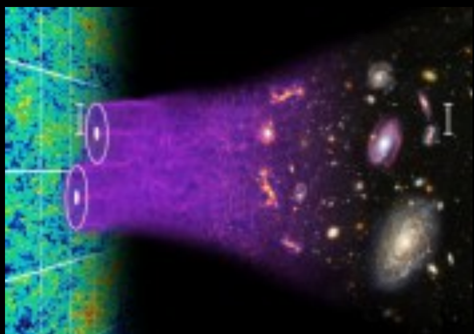


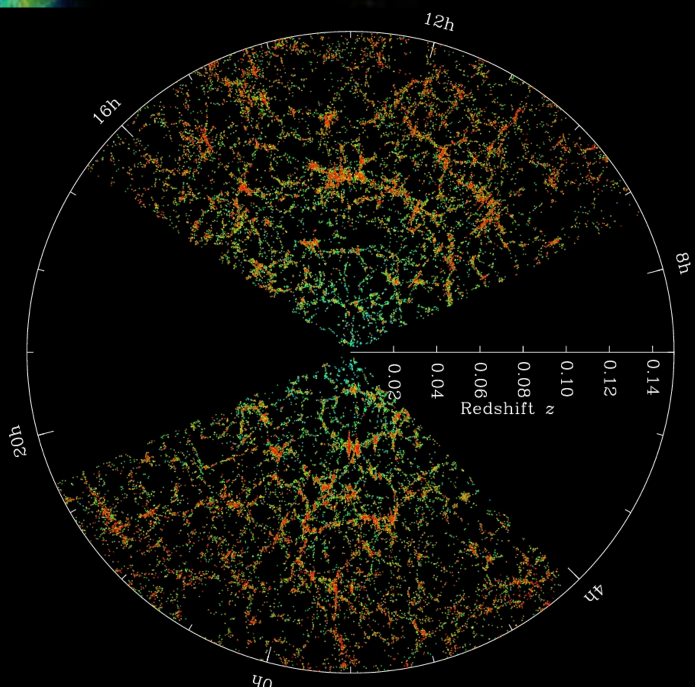
This drives a massive experimental effort

* Maybe we need to "think out of the box"… talk to F. Simpson!

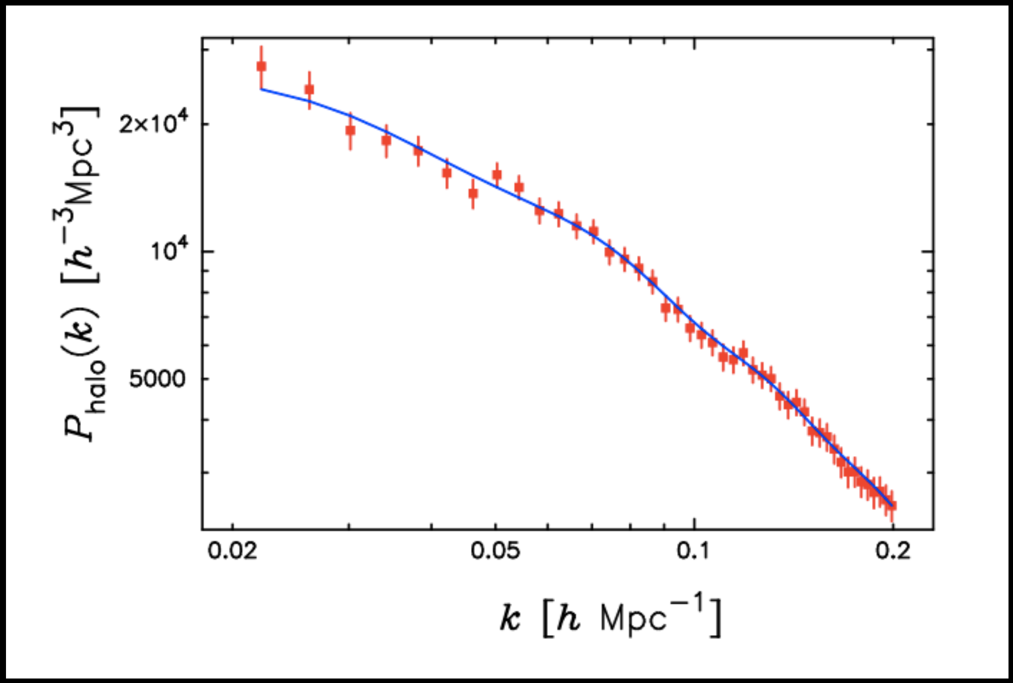
Can now do (precision) tests of fundamental physics with cosmological data

CMB temperature information content has been saturated
The near future is large-scale structure





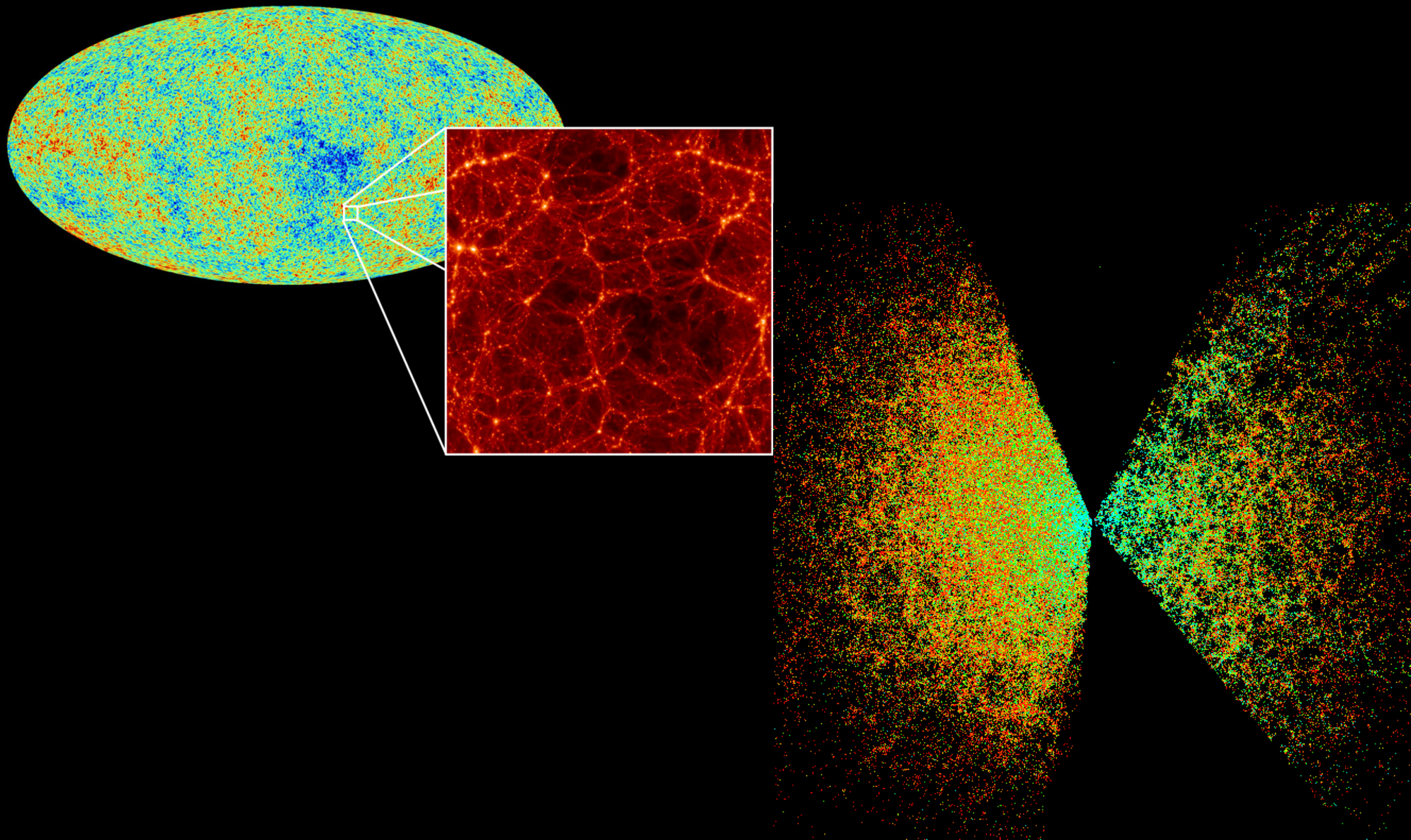
SDSS LRG galaxies power spectrum (Reid et al. 2010)



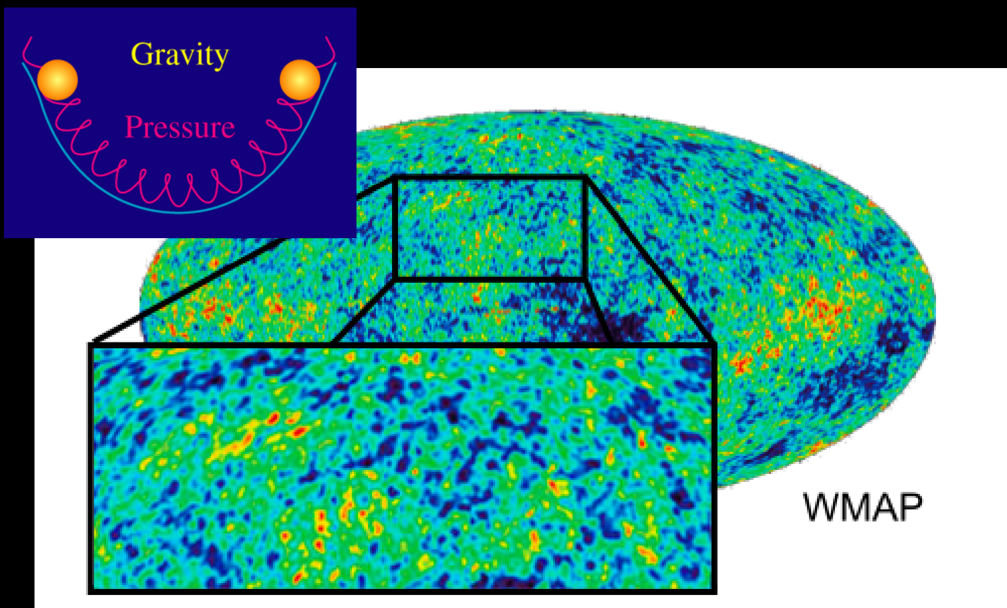
13 billion years of gravitational evolution

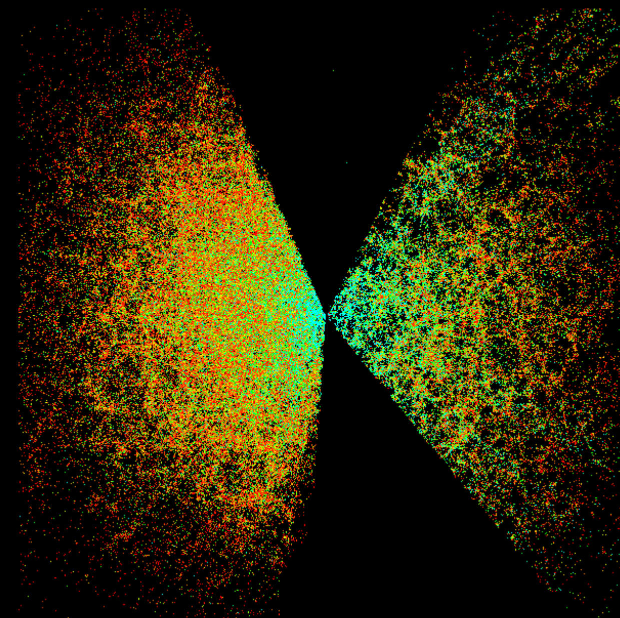
Longer-term timescale: CMB polarization

NEXT: Explore low(er)-redshift Universe



BAOs
Baryon acoustic oscillations





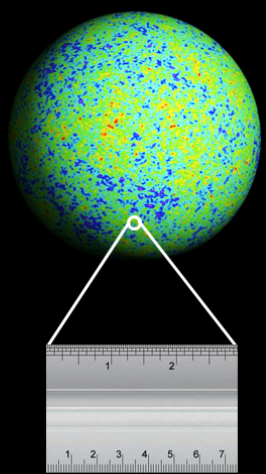
Observe photons

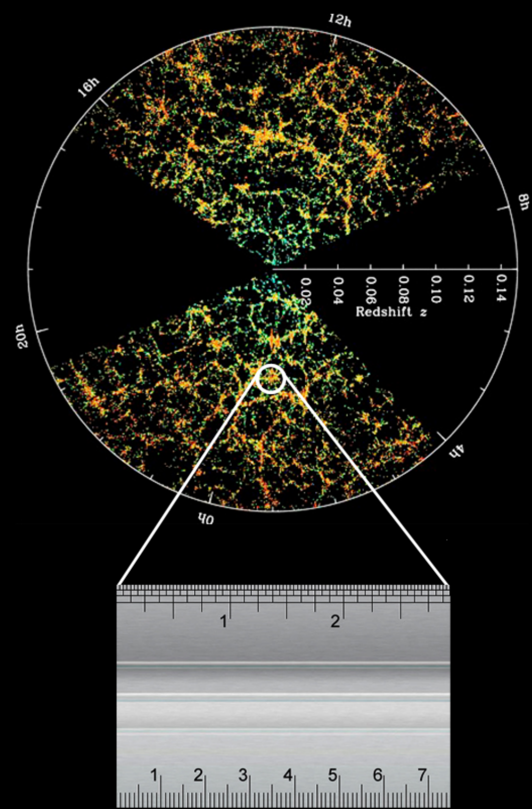
Photons coupled to baryons

“See” dark matter

AS baryons are ~1/6 of the dark matter these baryonic oscillations leave some imprint in the dark matter distribution (gravity is the coupling)

Explore low-redshift Universe: BAO





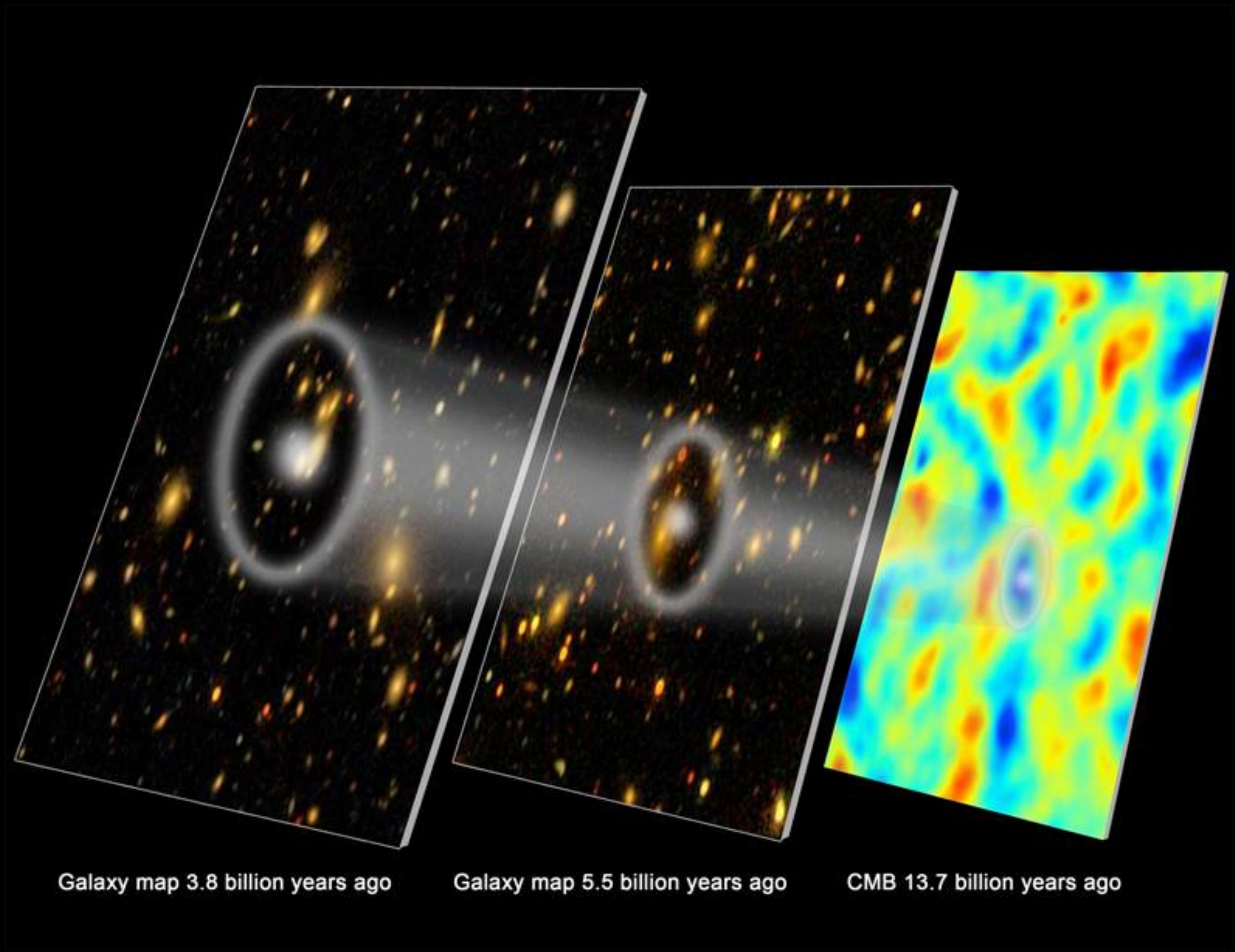
available:
Sloan Digital Sky Survey III
BOSS

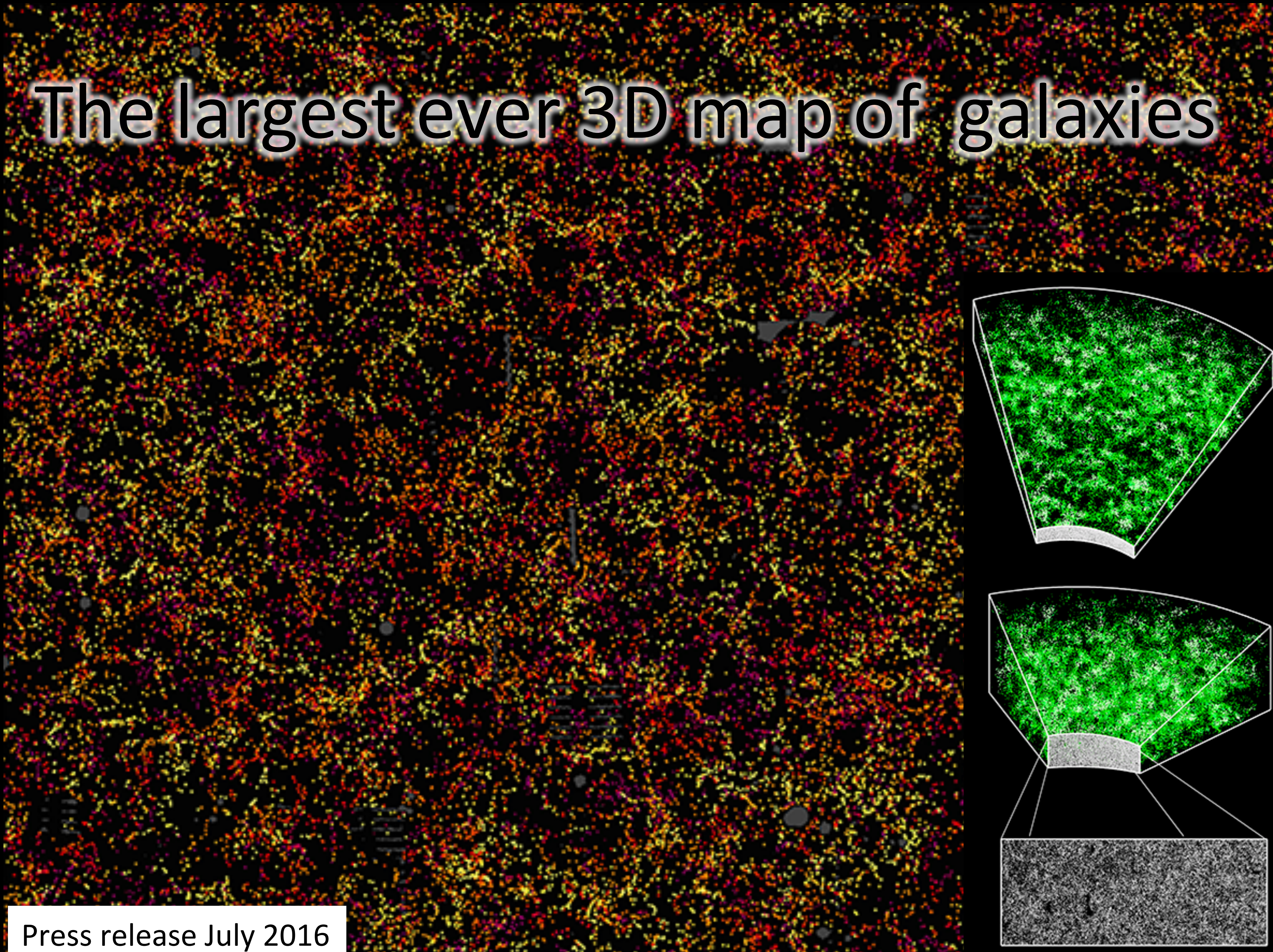
Wigglez

Future :e.g., DES, EUCLID, DESI etc.

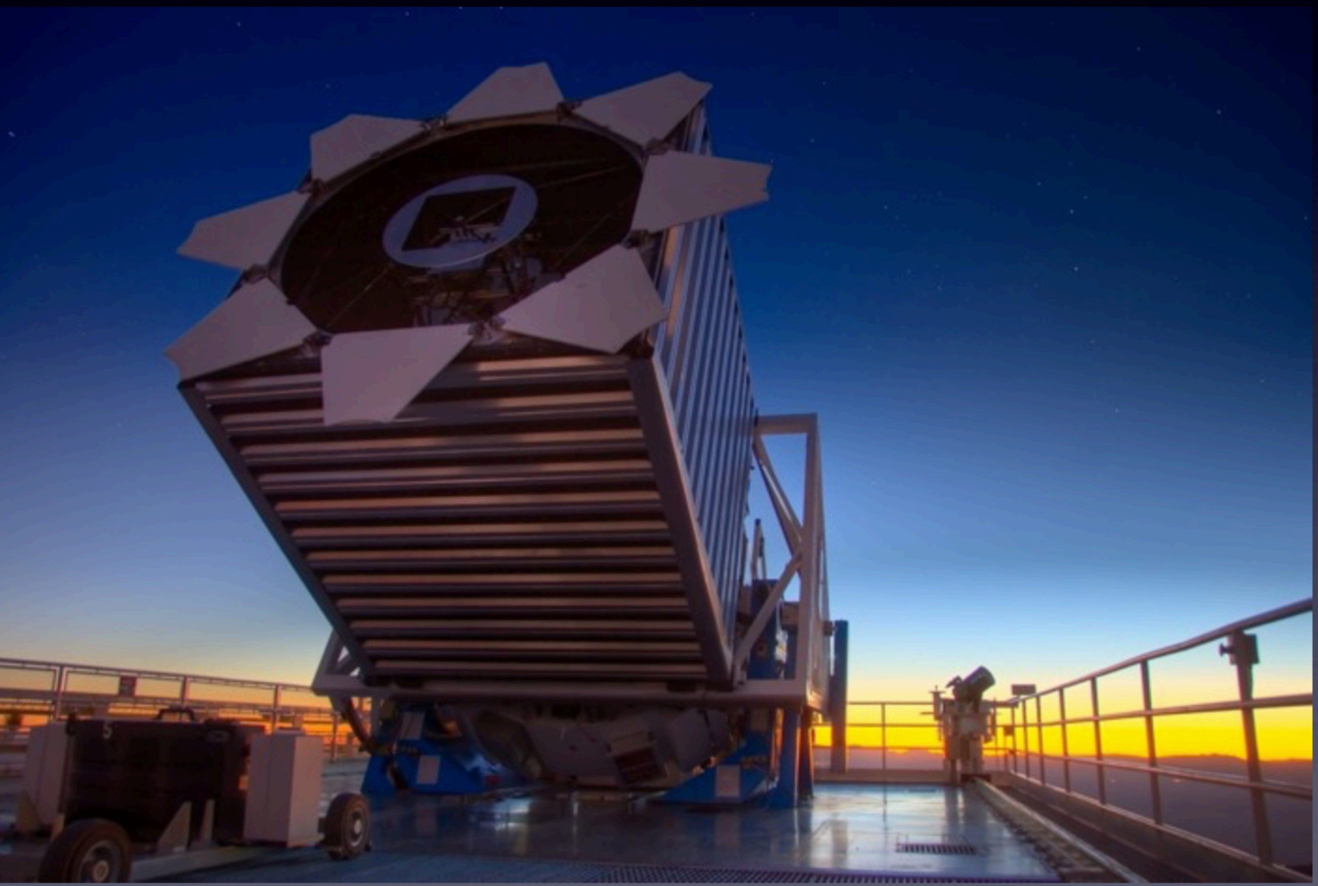
BOSS: final results …..

Baryon acoustic oscillations (BAO)




The largest ever 3D map of galaxies
Press release July 2016

SDSSIII BOSS survey (2009-2016)

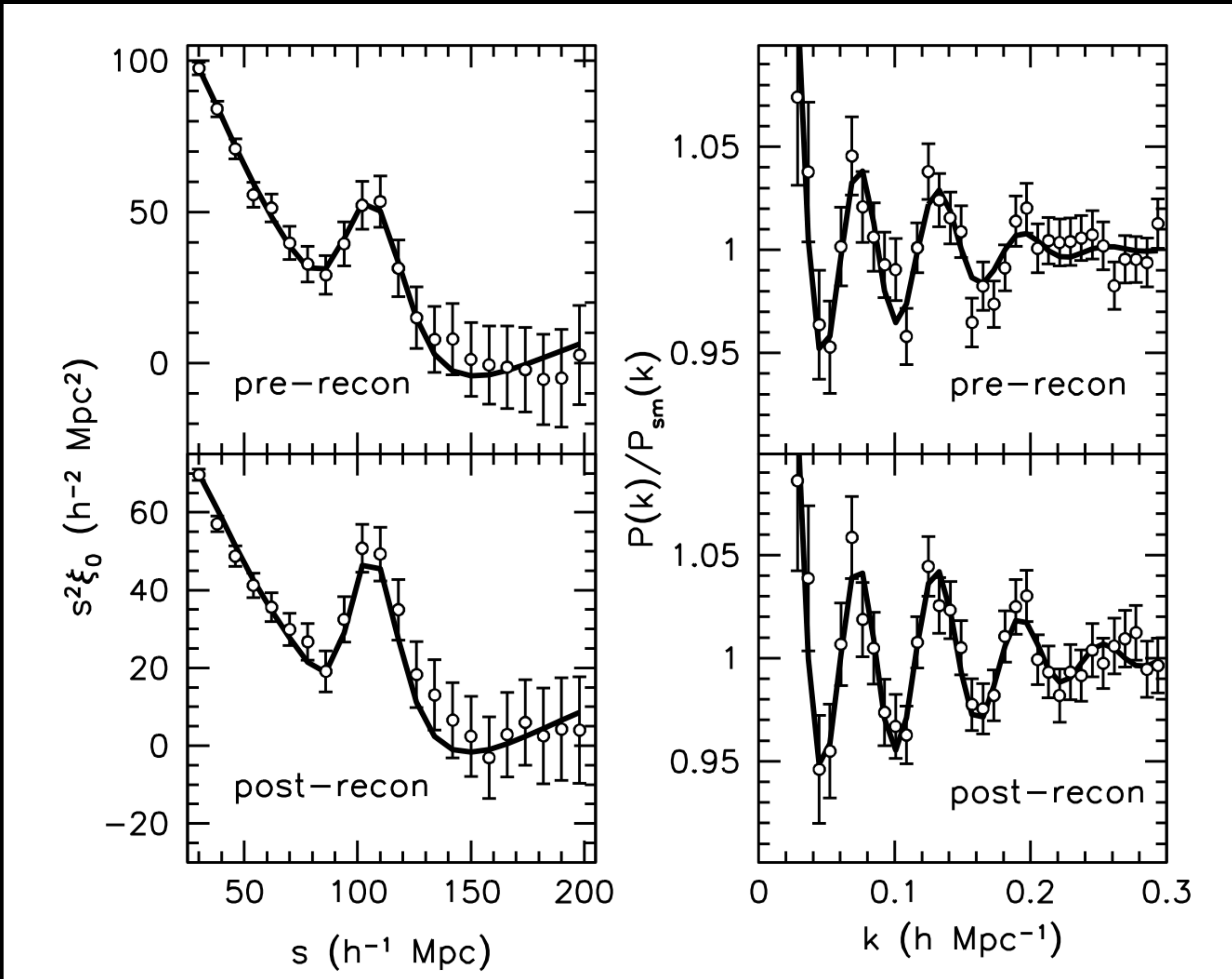


July 2008 - June 2014
51 participating institutions
> 1,000 scientists

SDSS Telescope
2.5m dedicated
Apache Point, NM
(operating since 1998)

https://www.sdss3.org/surveys/boss.php

Baryon acoustic oscillations (BAO) “today”

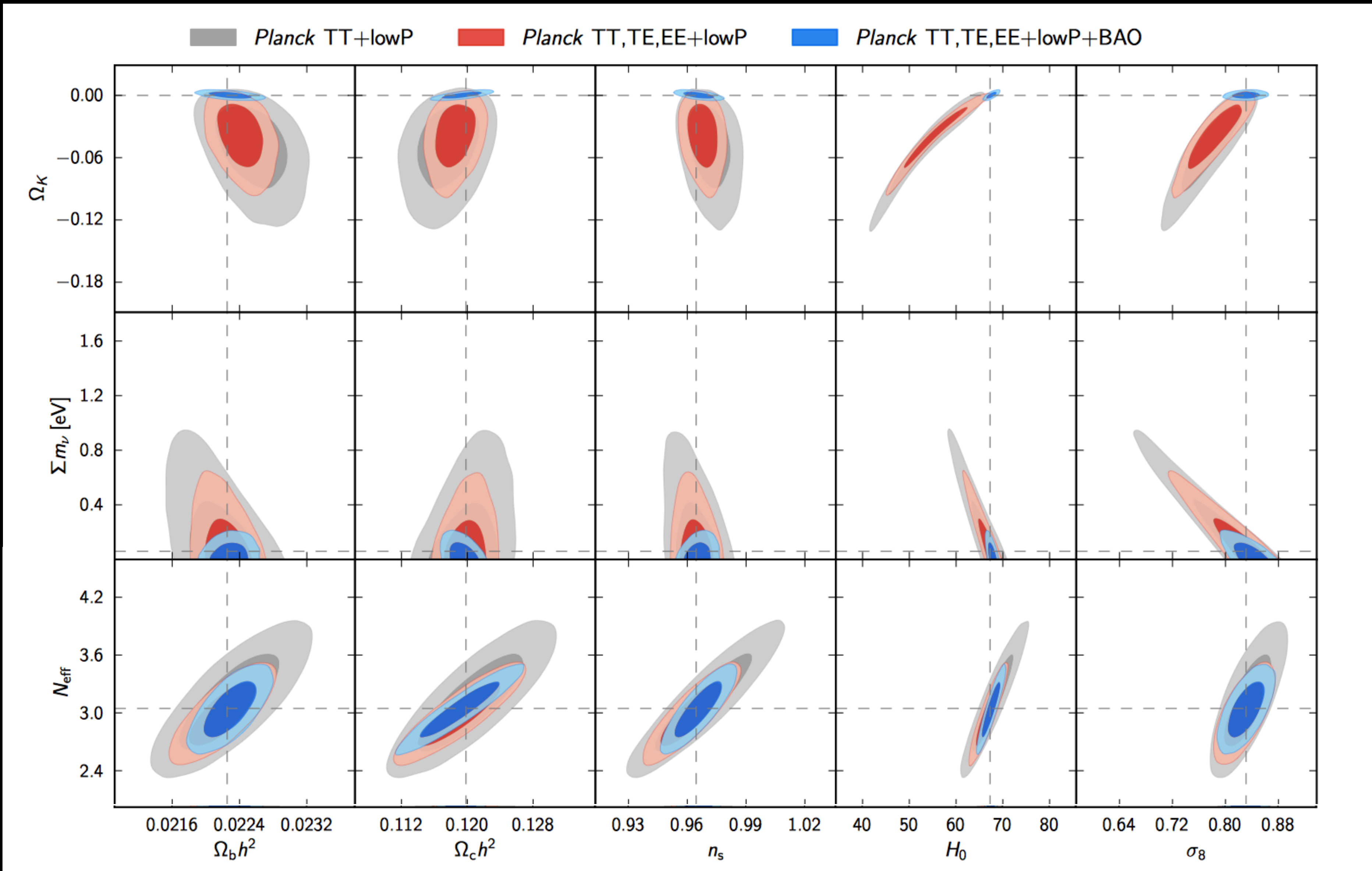


Here it is!

Anderson et al 2015 (BOSS)

The power of BAO

Planck collaboration 2016



Physical information from large-scale structure

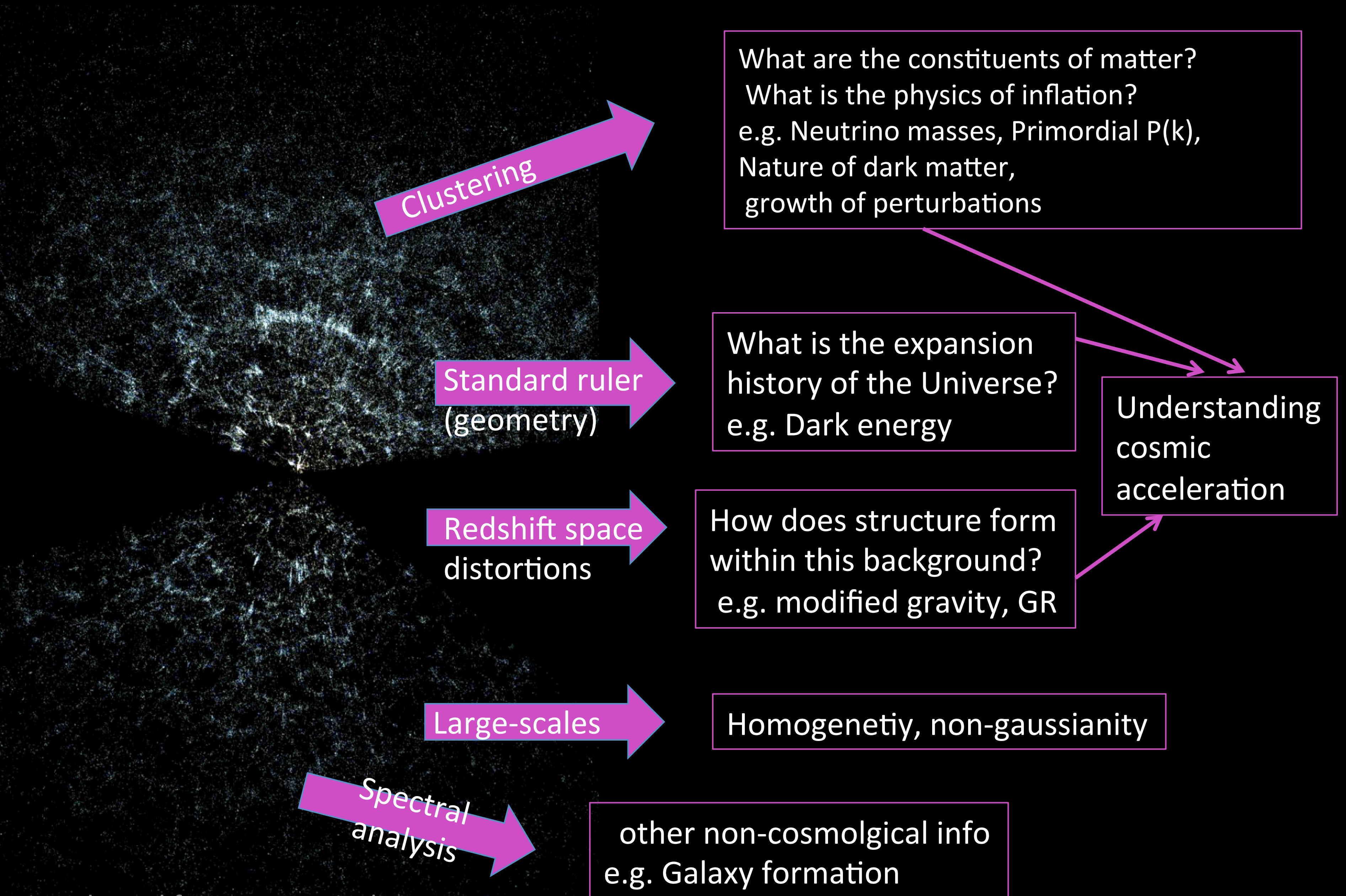
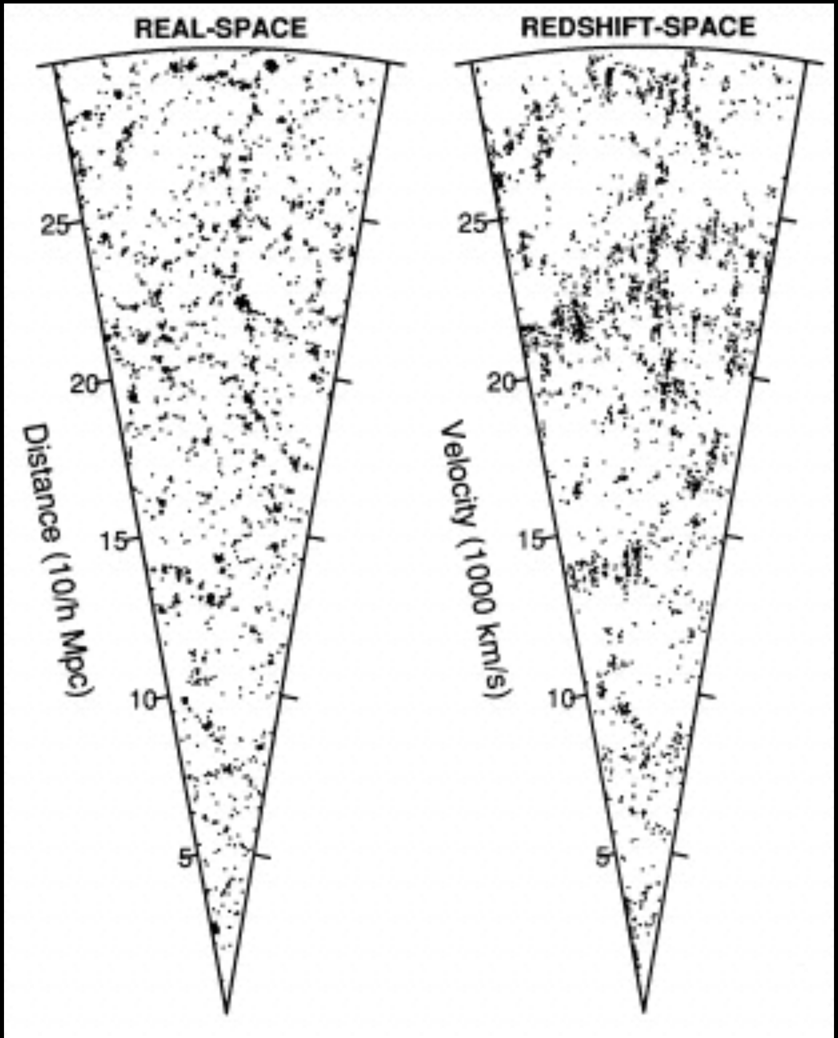
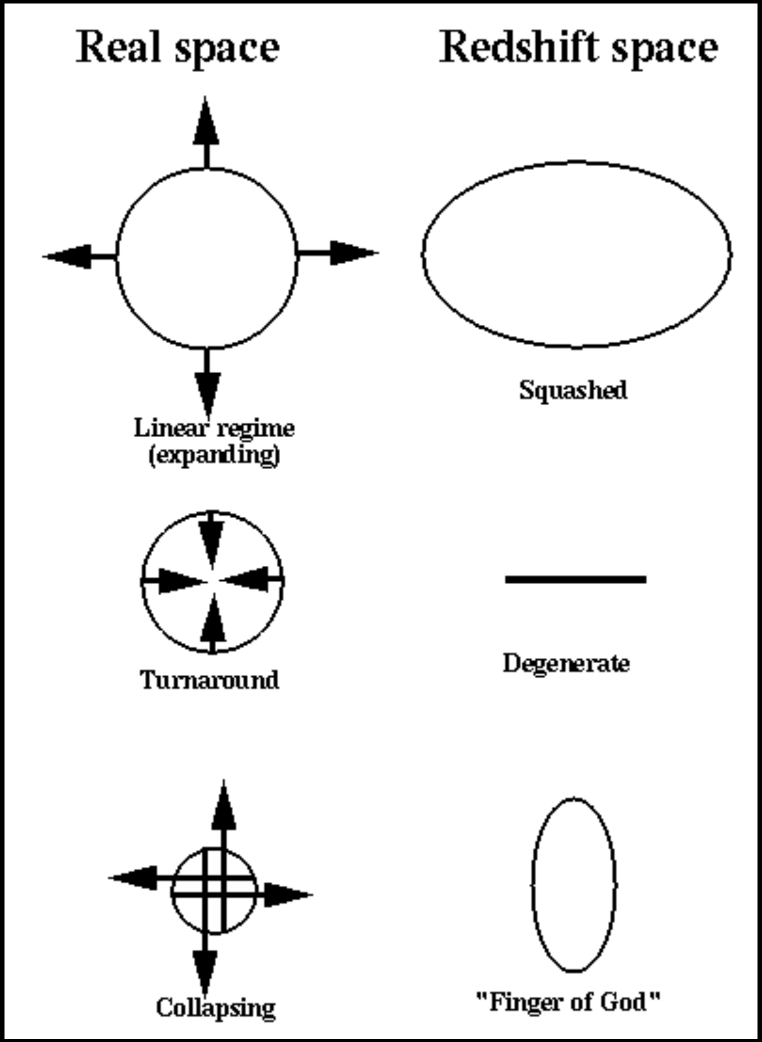


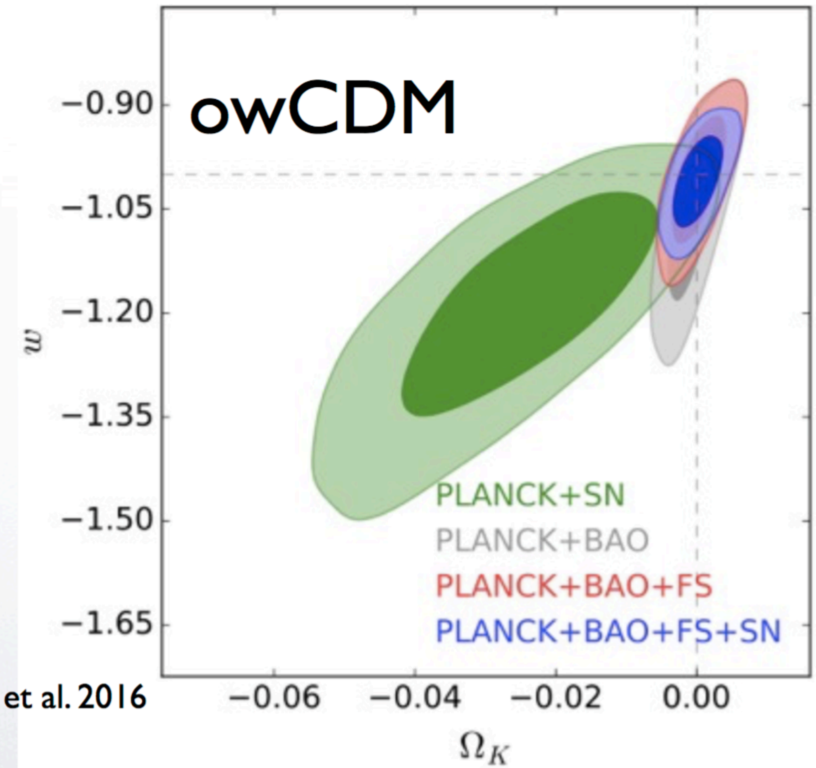
Fig. adapted from W. Percival

Redshift space distortions

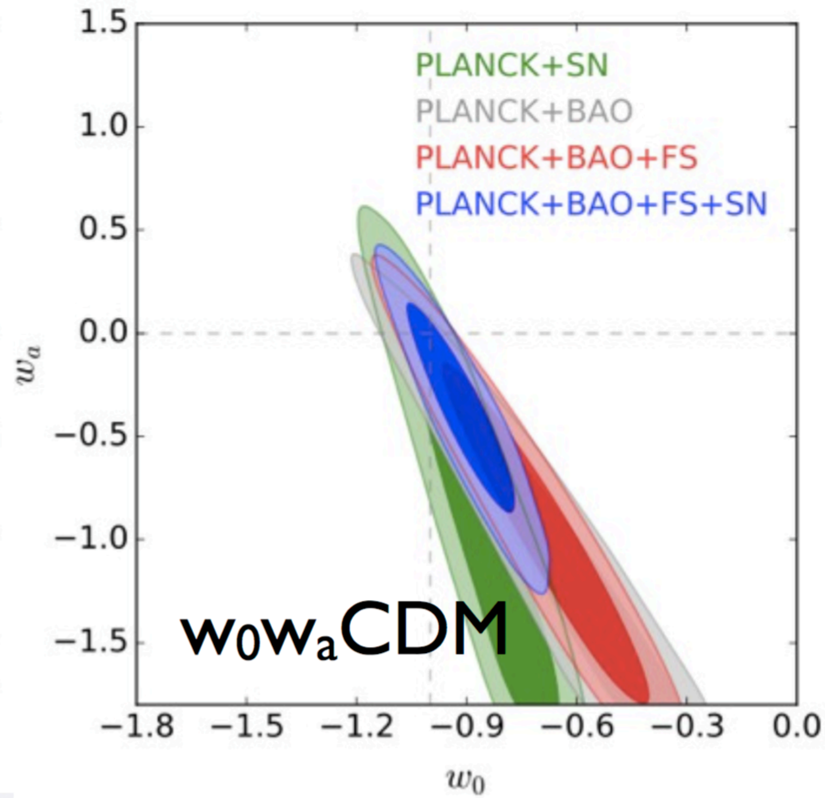




Curvature and Dark Energy



Alam et al. 2016



Ω_k is 0 with an error of 0.0026 (0.0023 with SN)

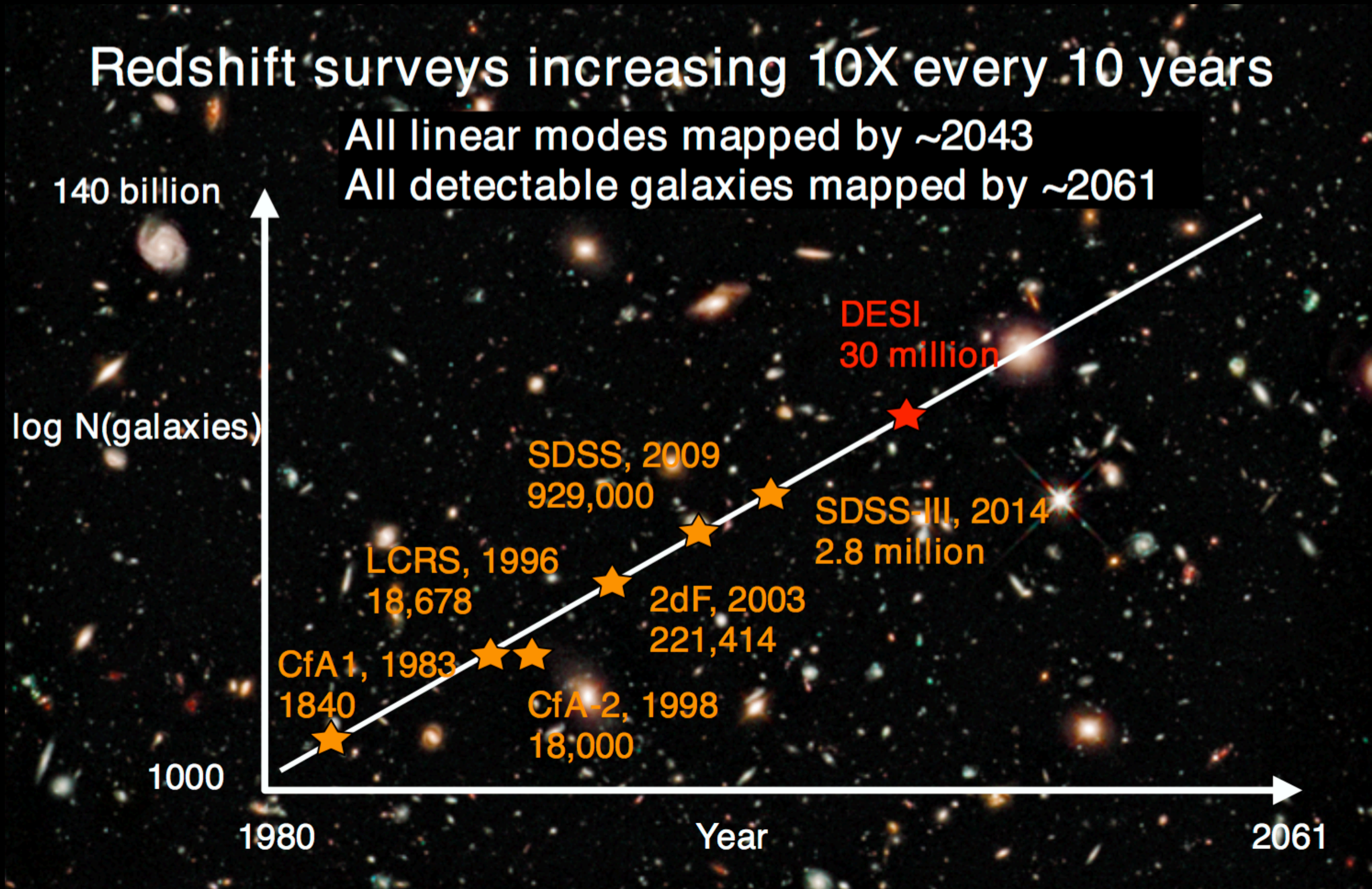
w is -1 with an error of 0.06 (0.04 with SN)

w_0 is -1 with an error of 0.10 with SN

w_a is 0 with an error of 0.34 with SN

Alam et al 2016

Golden age or Gold rush?



Courtesy of D. Schlegel

Challenges and opportunities

The CMB was simple, well understood physics,
galaxies in the late-time universe are not simple nor well understood

Big data

Planck 5×10^7 pixels DESI 5×10^7 spectra! DES 3×10^8 galaxies to measure shapes

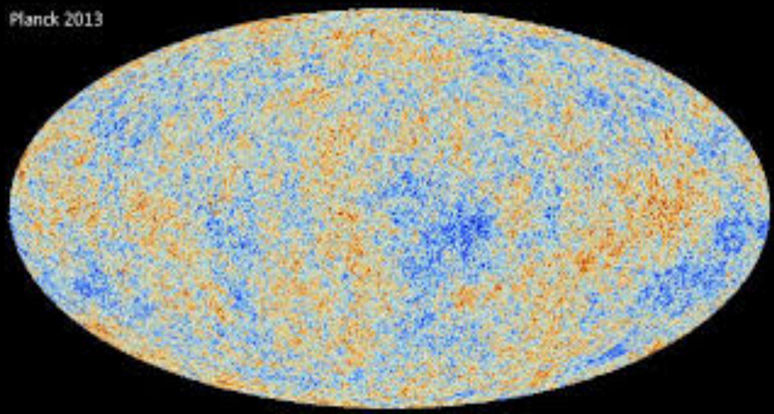
Astrophysics, non-linearities (non-gaussianity)

Precision vs accuracy

Systematic errors will be the limiting factor

Analysis techniques must evolve and adapt

WHY SHOULD YOU CARE?



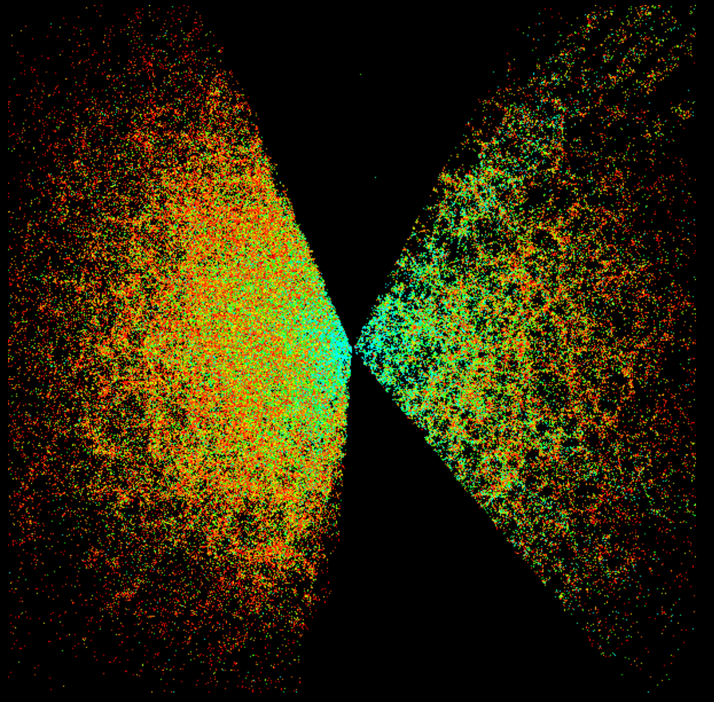
Forthcoming new avalanche of data enables

PRECISION tests beyond the standard model

Two examples

1) Neutrinos contribute at least to ~0.5% of the total matter density

Use the entire Universe as "detector"!



2) Model-independent tests

Planck++ Constraints on Neutrinos

$$\sum m_\nu < 0.72 \text{ eV} \quad \textit{Planck} \text{ TT+lowP};$$
$$\sum m_\nu < 0.21 \text{ eV} \quad \textit{Planck} \text{ TT+lowP+BAO};$$
$$\sum m_\nu < 0.49 \text{ eV} \quad \textit{Planck} \text{ TT,TE,EE+lowP};$$
$$\sum m_\nu < 0.17 \text{ eV} \quad \textit{Planck} \text{ TT,TE,EE+lowP+BAO}.$$

95% CL

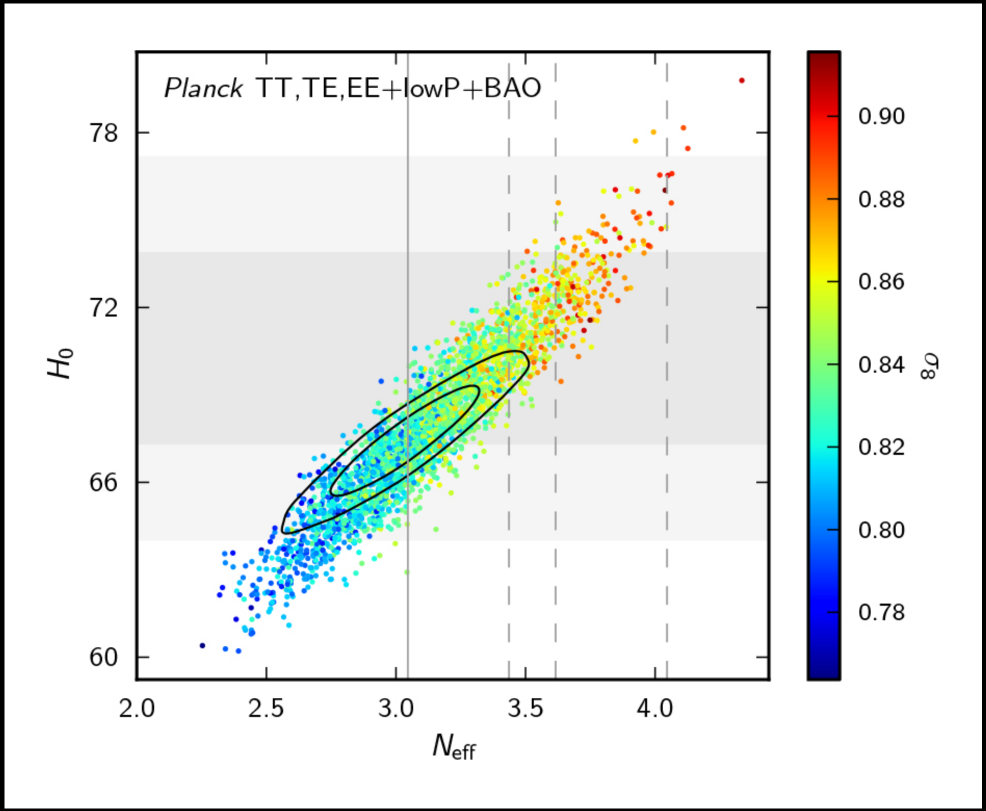
$$N_{\text{eff}} = 3.13 \pm 0.32 \quad \textit{Planck} \text{ TT+lowP};$$
$$N_{\text{eff}} = 3.15 \pm 0.23 \quad \textit{Planck} \text{ TT+lowP+BAO};$$
$$N_{\text{eff}} = 2.99 \pm 0.20 \quad \textit{Planck} \text{ TT,TE,EE+lowP};$$
$$N_{\text{eff}} = 3.04 \pm 0.18 \quad \textit{Planck} \text{ TT,TE,EE+lowP+BAO}.$$

68% CL

Planck collaboration 2015

The CνB has been detected to extremely high statistical significance

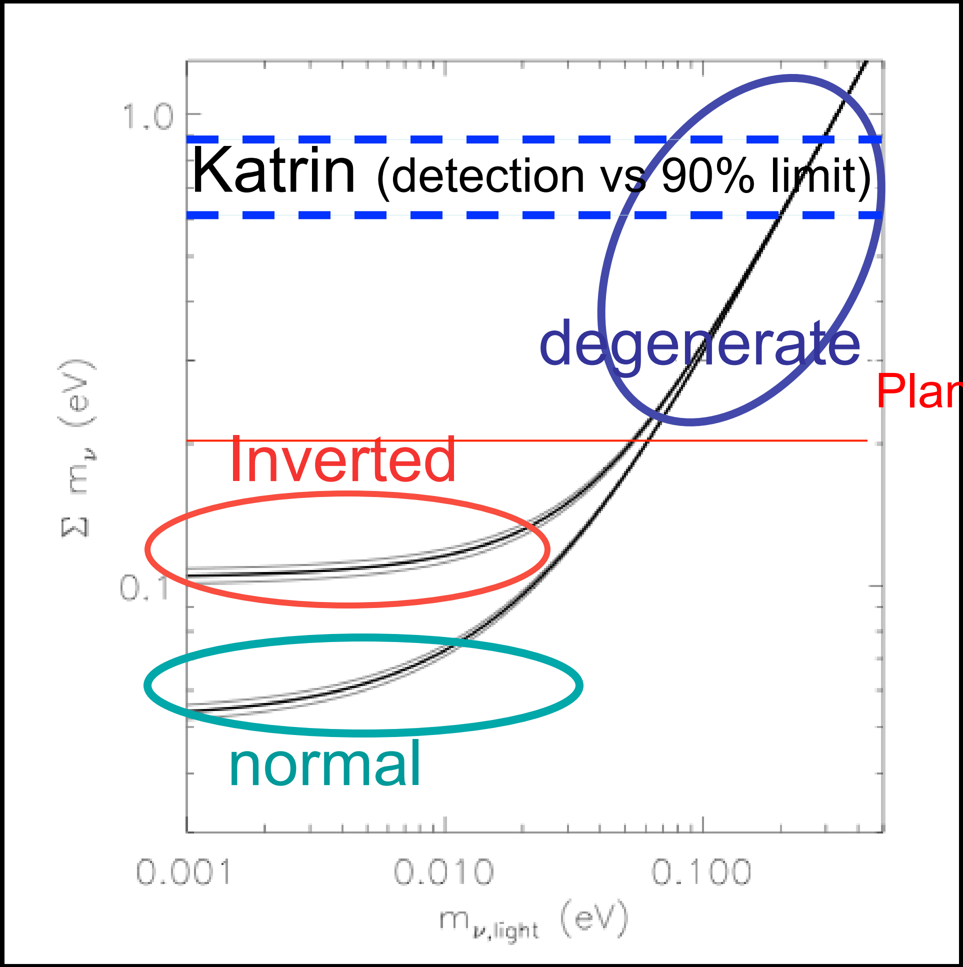
Results from Planck 2015



N_{eff}=0 excluded at "17sigma"

Also, the possibility of a 4th neutrino is fading away (dashed lines)

Cosmology is key in determining the absolute mass scale



Planck +BAO (95% limit)

The problem is systematic errors

This means that neutrinos contribute at least to ~0.5% of the total matter density

Including large-scale structure clustering

Pros: see the “signature” scale-dependent clustering suppression

Cons: astrophysics, bias

Possible approach:
Useful exercise   : use completely different tracers and see if there is agreement

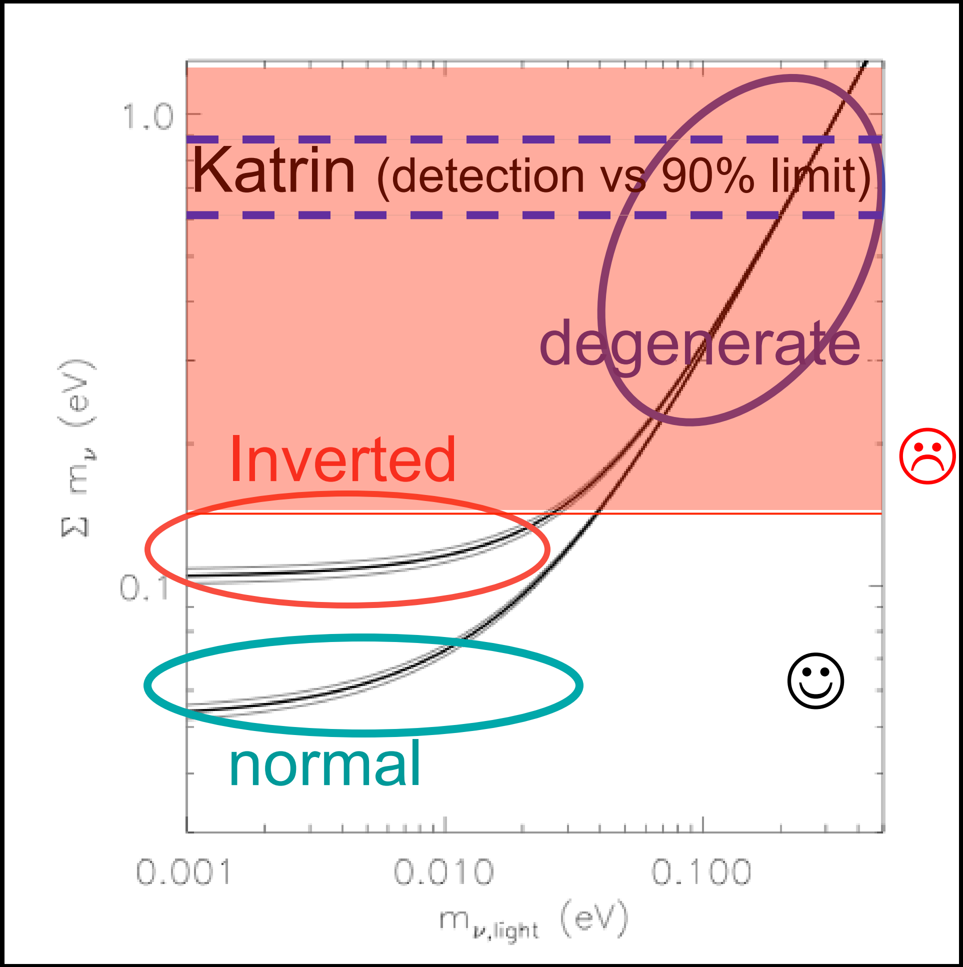
Cuesta, Niro, LV, 2016

Neutrino mass limits:
robust information from the power spectrum of galaxy surveys

(Wiggle Z, blue EL galaxies; SDSS LRG; and compare with IGM Lyalpha)

Mv<0.13 eV @95%

The pessimist: The inverted hierarchy is under pressure
The optimist: If IH then a measurement of Mv is just around the corner!



With Lya < 0.12 eV

Note the bracket!

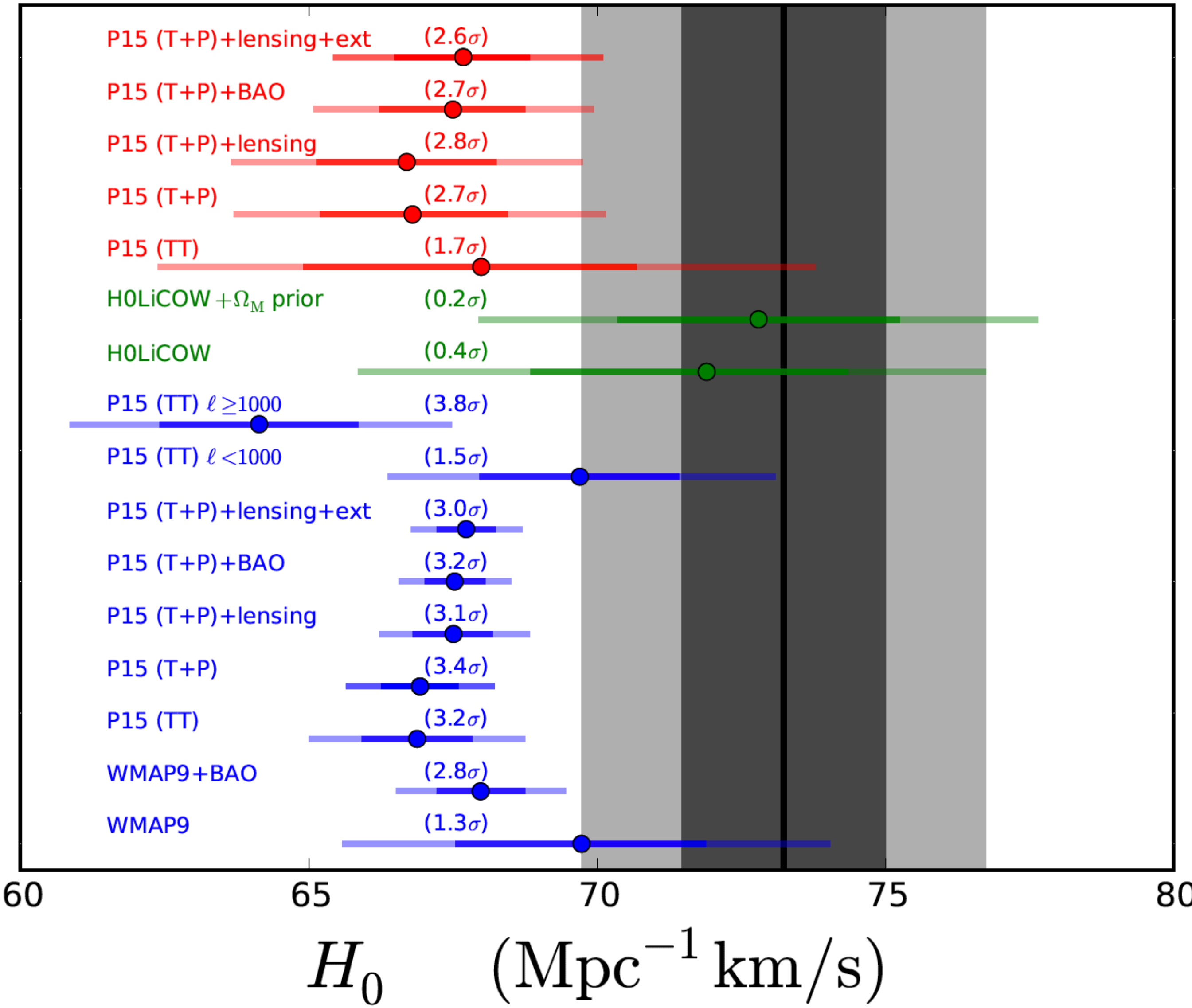
This means that neutrinos contribute at least to ~0.5% of the total matter density

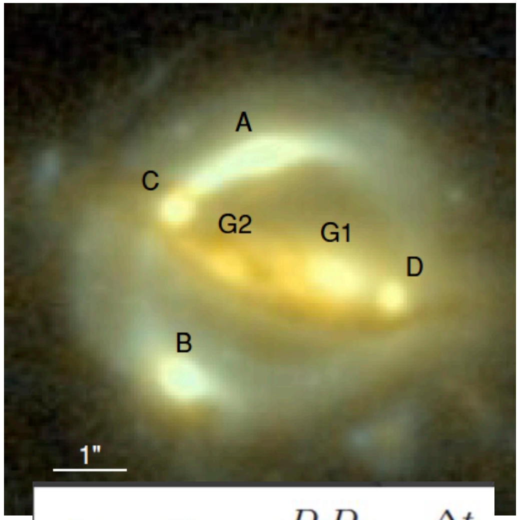
The trouble with H_0

JL Bernal, LV,.A Riess, JACP 2016

- Direct measurement: 73.24 ± 1.74 km/s/Mpc (Riess et al 2016; verified with GAIA parallaxes)
- Planck (ΛCDM): 67.8± 0.9(66.9±0.6) km/s/Mpc
- Formally 3.4 σ, maybe we should pay attention
- Possibly worst with Planck low l polarization re-analysis

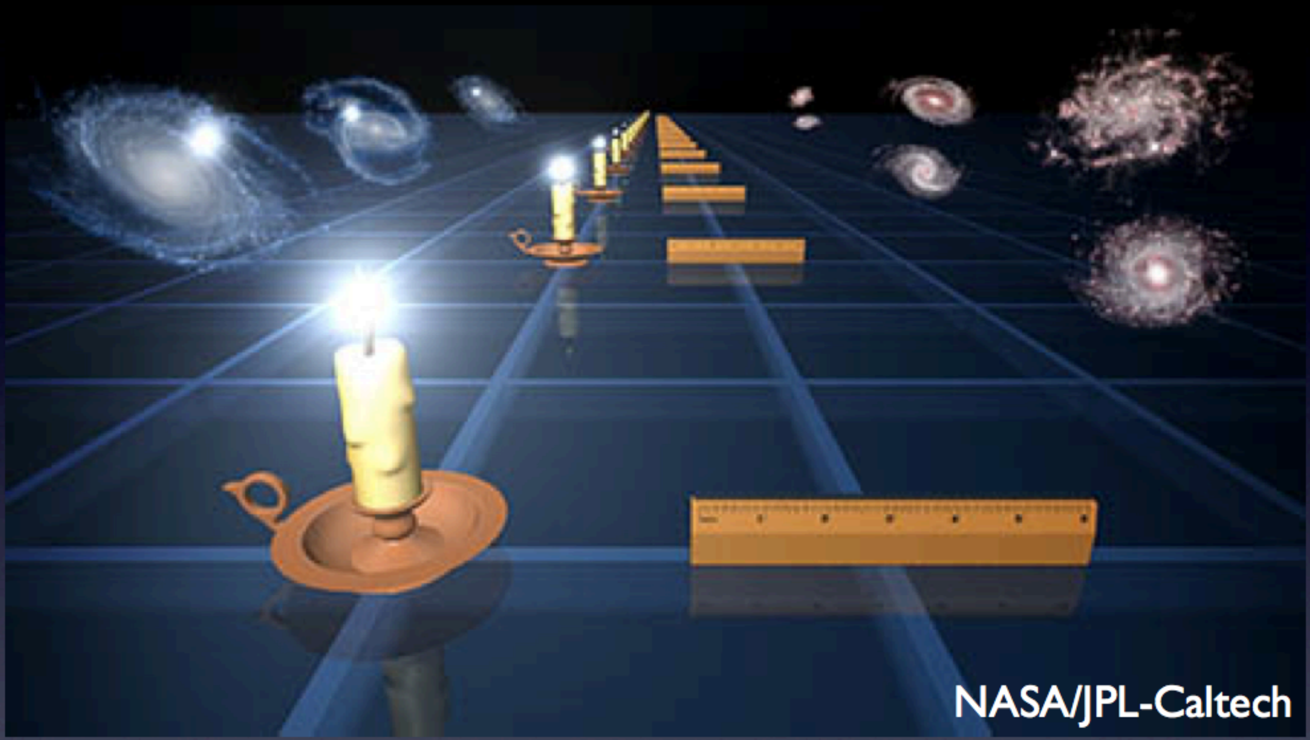
The landscape





$$D_{\Delta t} \equiv (1+z_l)\frac{D_l D_s}{D_{ls}} = \frac{\Delta t}{\Delta \phi}$$

Standard candles & Standard rulers

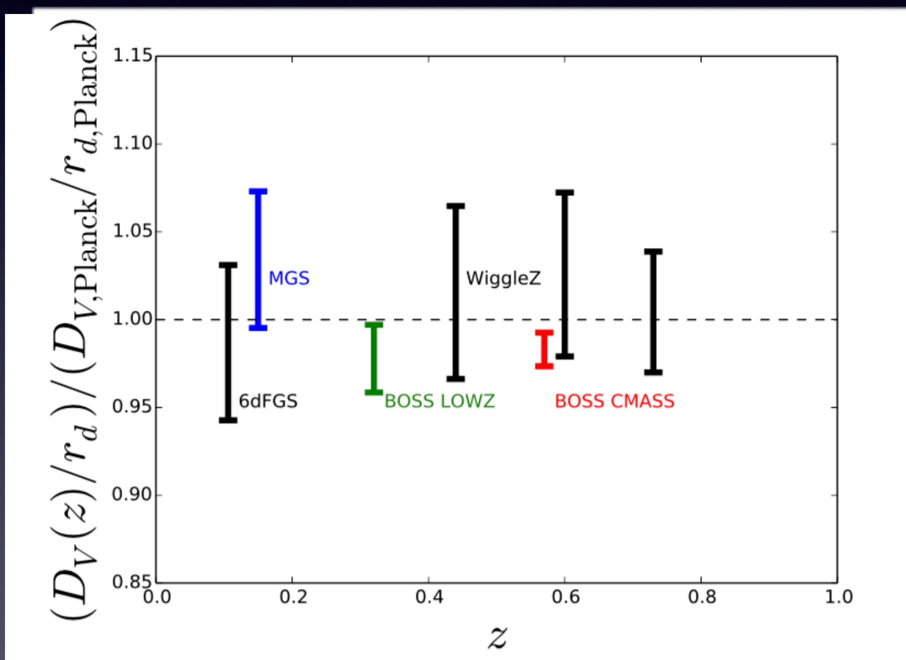


Type-Ia SNe measure
relative distances,
since there is large uncertainty
on the absolute magnitude M
of a fiducial SN

BAOs measure
absolute distances,
but depend on the value of
sound horizon r_{drag}

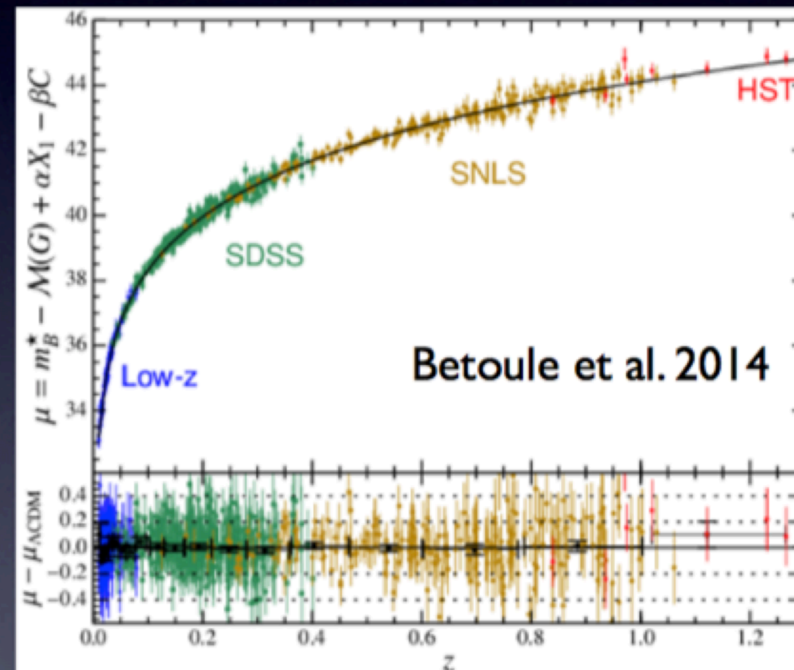
Visually

BAO + r_d



$$D_V(z) = \{D_A(z)^2\, c\, z\, /H(z)\}^{1/3}$$

SN



$$\mu(z) = 25 + 5\log_{10} D_L(z)$$

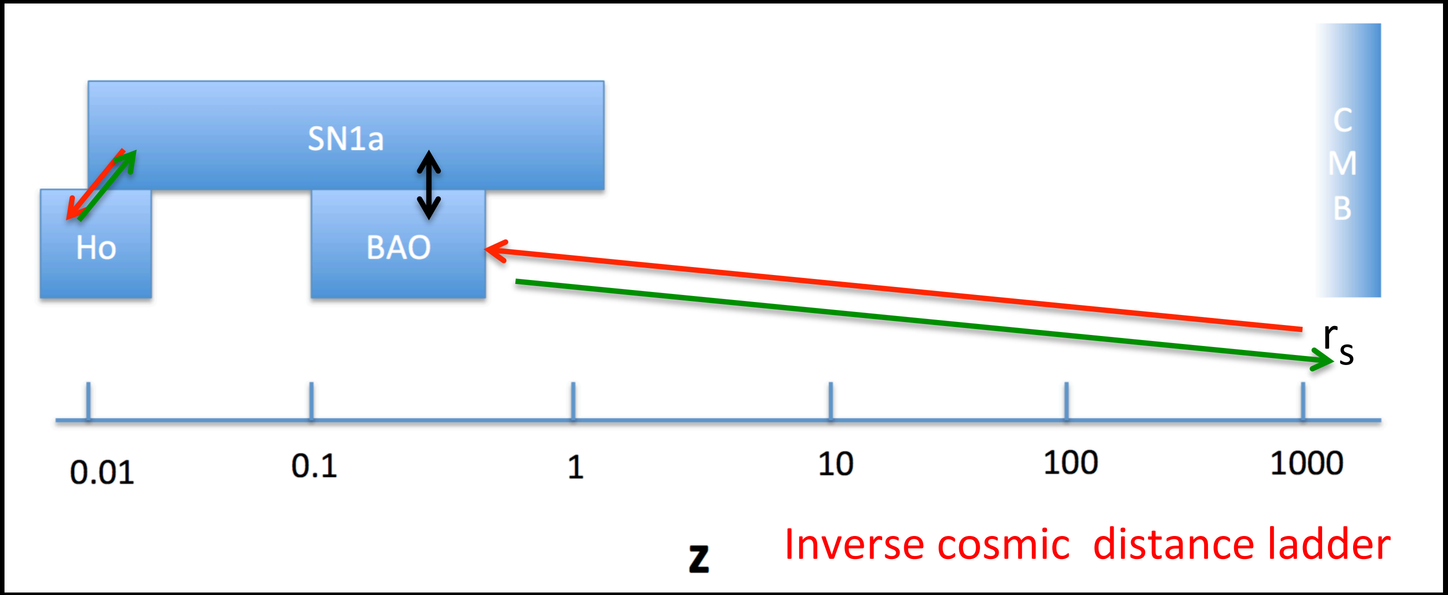
Direct and inverse distance ladder

- Spline reconstruction of the expansion history

H(z) with 4 (5 with SNe) knots.

Direct and inverse cosmic distance ladder (Cuesta et al 2015)

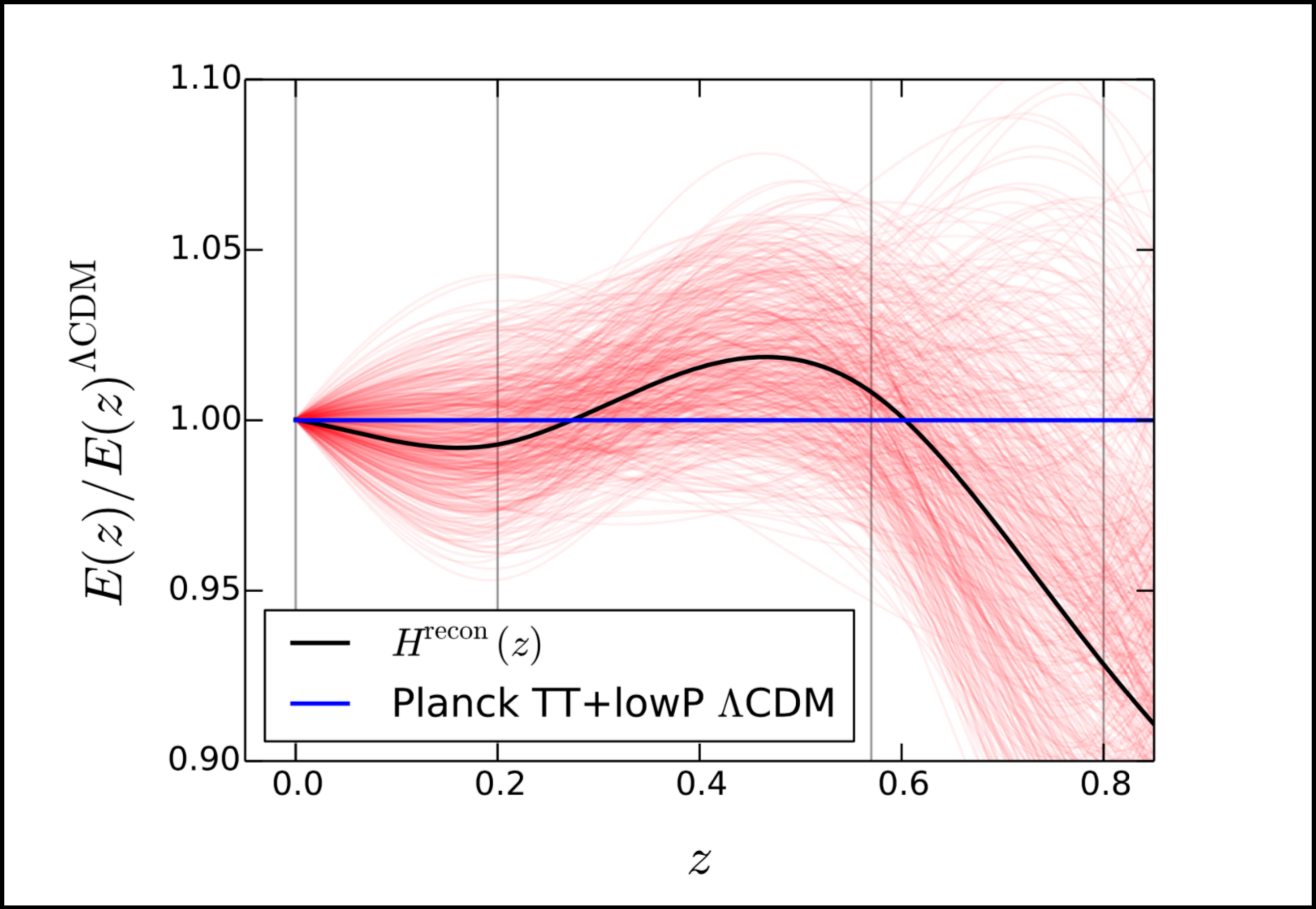
Direct cosmic distance ladder



Inverse cosmic distance ladder

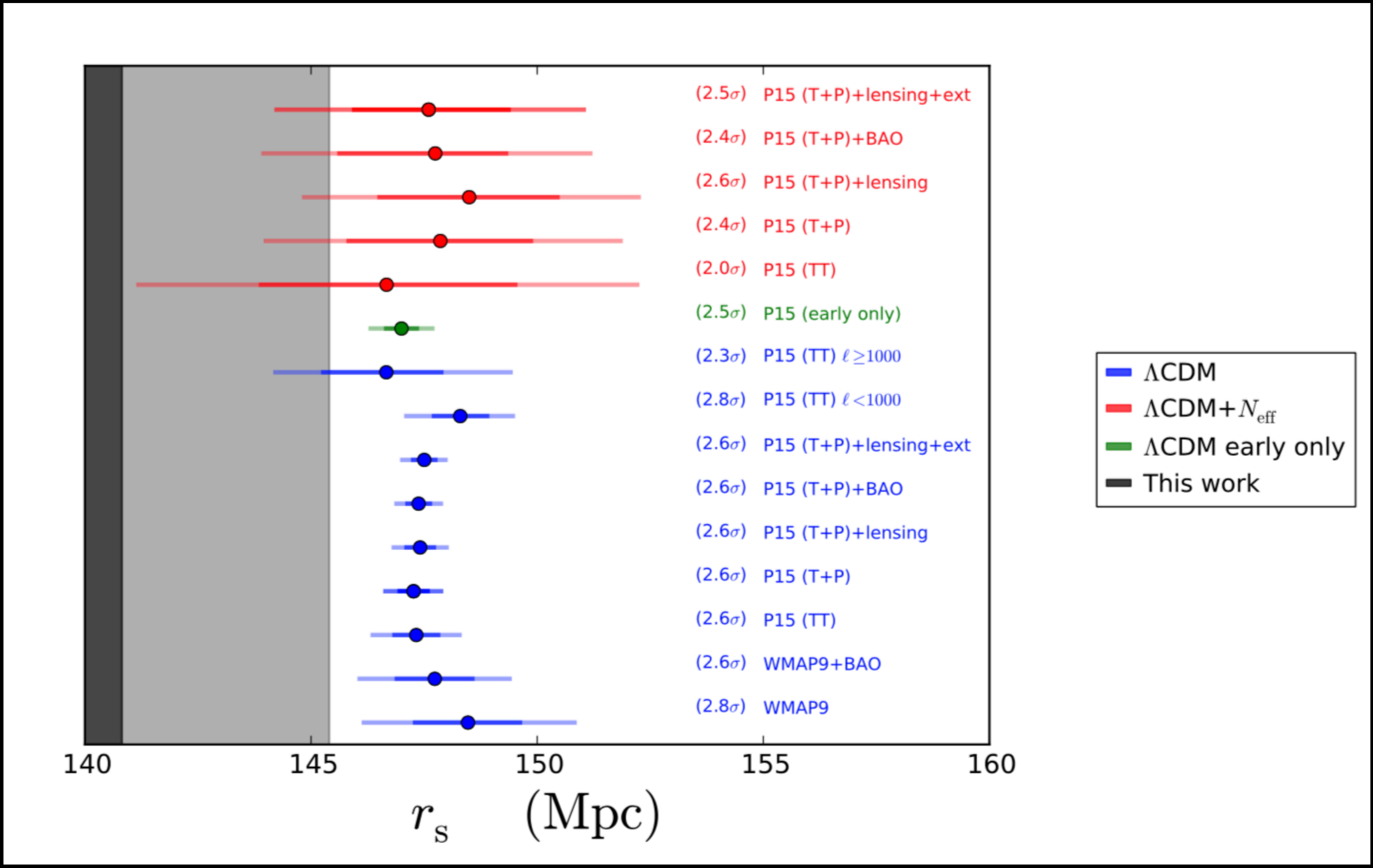
Here is where in LCDM or its simple variations the two ladders do not match

The SHAPE of expansion history is well constrained



The issue is with the normalization

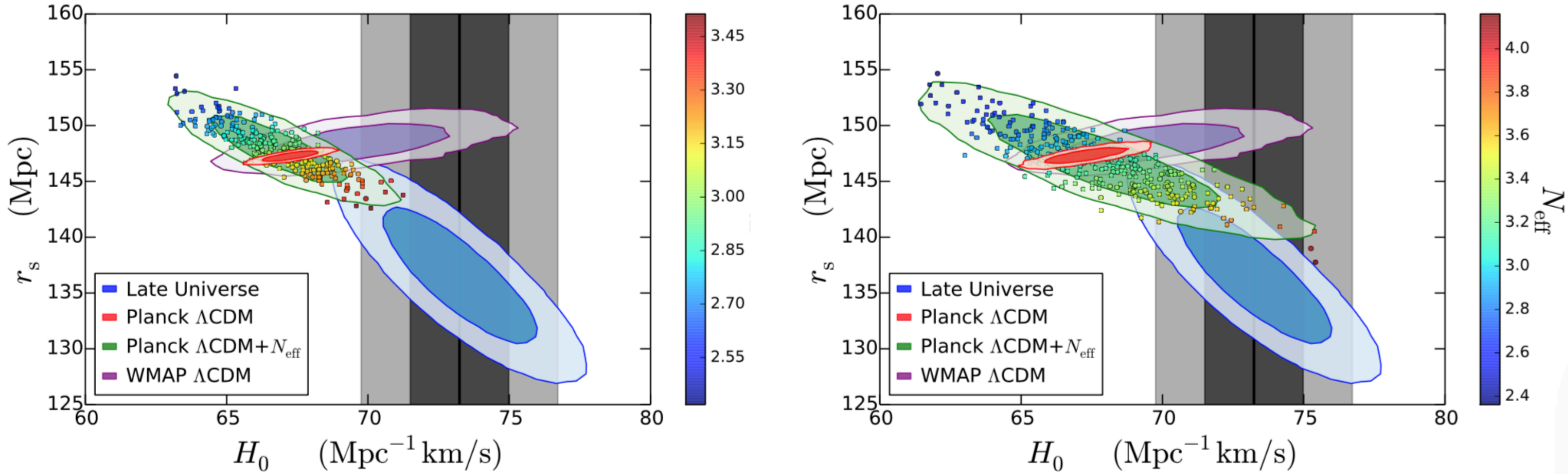
The H_0 problem as a r_s problem



It is a problem of anchors (problem appears to be at z=0 or z=1000 not in between)

Why so much interest in Neff…

With high l polarization | w/o high l polarization



ΔNeff ~0.4 fixes "everything" but is disfavored by high l Planck polarization

Other issues

- Amplitude of perturbations (SZ Clusters)
- Amplitude of perturbations (gravitational lensing)
- Reionization (not of interest for this audience)

From precison cosmology to accurate cosmology

J. Peebles 2002

“We can’t live in a state of perpetual doubt, so we make up the best story possible and we live as if the story were true.”

Daniel Kahneman about theories

GR, big bang, choice of metric, nucleosynthesis, etc etc…

Cosmology tends to rely heavily on models (both for “signal” and “noise”)

Essentially, all models are wrong , but some are useful
(Box and Draper 1987)

With ~1% precision, systematics become the name of the game

Systematics in the data
Systematics in the model (analysis)

Beyond precision cosmology my view

It is possible to be less model dependent? At what price?

The error bars will grow, but that may be a GOOD THING!

Can we separate late-lime from early-time physics in the CMB? *Verde, Bellini et al 2016*
Can we combine data suitably so that the systematics cancel out? *Norena et al 2012*
Can we reconstruct the primordial power spectrum non-parametrically? *Ravenni et al 2016, Bird et al in prep*
Can we "marginalize" safely over baryonic effects? *Kitching et al 2016*
If we see neutrino mass, how can we be sure it is really that? *Jimenez, Garay, LV 2016*

Conclusions (glass half empty)

… the maximally boring universe…

The standard cosmological model has survived ever more stringent tests

Deviations from it are even more constrained

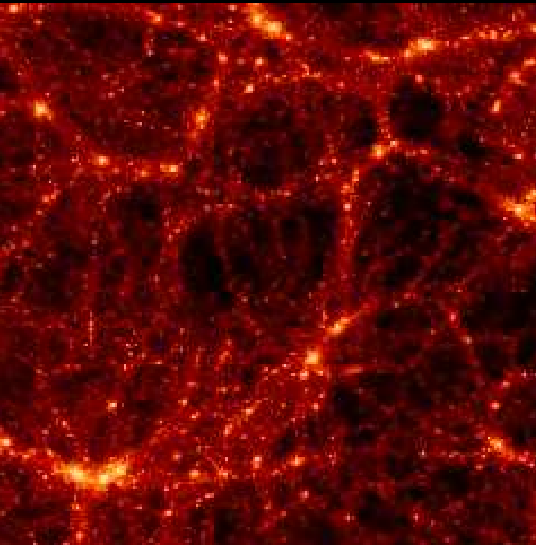
Eventually something will have to give, the model IS incomplete
(and the cosmological constant IS ugly..
And we have extrapolated the law of gravity some 13 orders of magnitude!!)

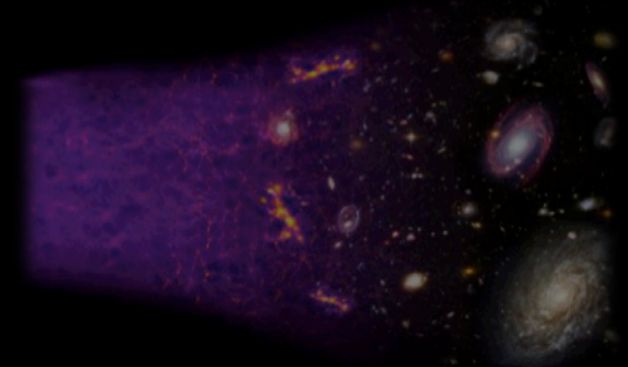
The point is how much smaller would the observational error bars have to be

Conclusions (glass half full)

- Precision cosmology means that we can start (or prepare for) constraining interesting physical quantities, and make model-independent tests.
- Neutrino properties: absolute mass scale, number of families, possibly hierarchy The (indirect) detection of neutrino masses is within the reach of forthcoming experiments (even for the minimum mass allowed by oscillations)
- Large future surveys means that sub % effects become detectable, which brings in a whole new set of challenges and opportunities
- Systematic and real-world effects are the challenge, need for in-build consistency checks!
- **Beyond model fitting, towards model-independent tests; Model independent measurements**

END





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Precision cosmology and beyond

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

icrea Institució Catalana de Recerca i Estudis Avançats

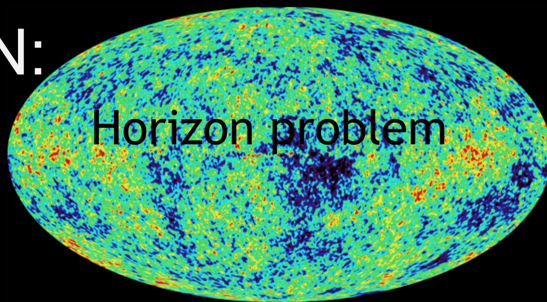
ICCUB Institut de Ciències del Cosmos

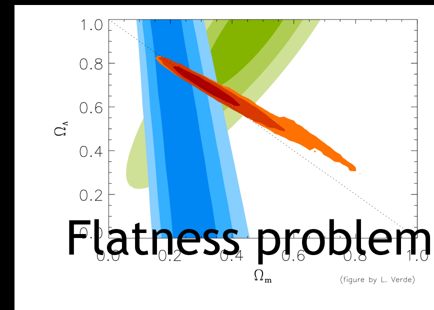
UNIVERSITAT DE BARCELONA

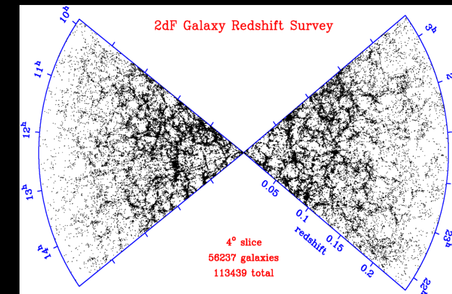
erc

What mechanism generated the primordial perturbations?

INFLATION:







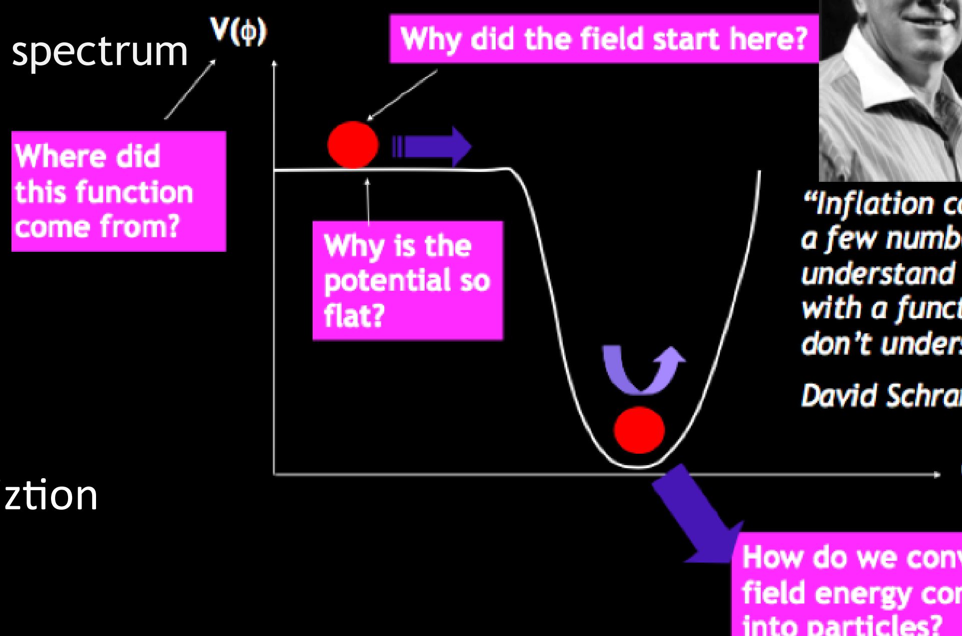
Structure Problem

Old standing problems and the inflationary solution

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



"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

Extra key information from polariztion

Inflationary predictions

Simplest Inflationary Models

- Spatially flat universe

- Nearly Gaussian initial perturbations

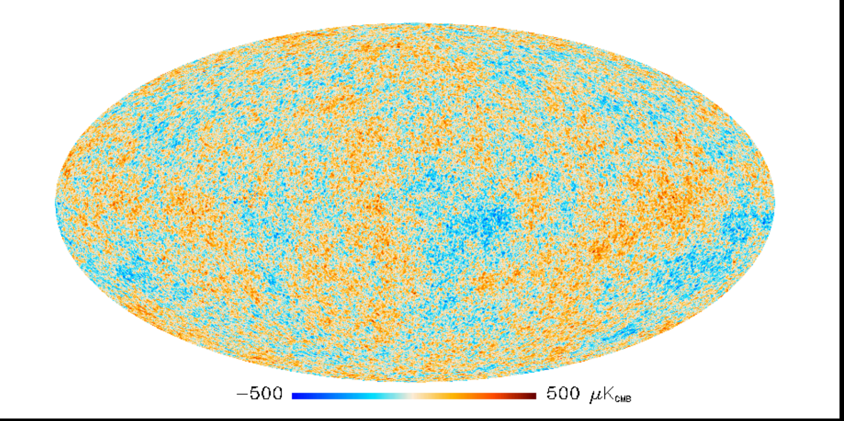
- Adiabatic initial conditions

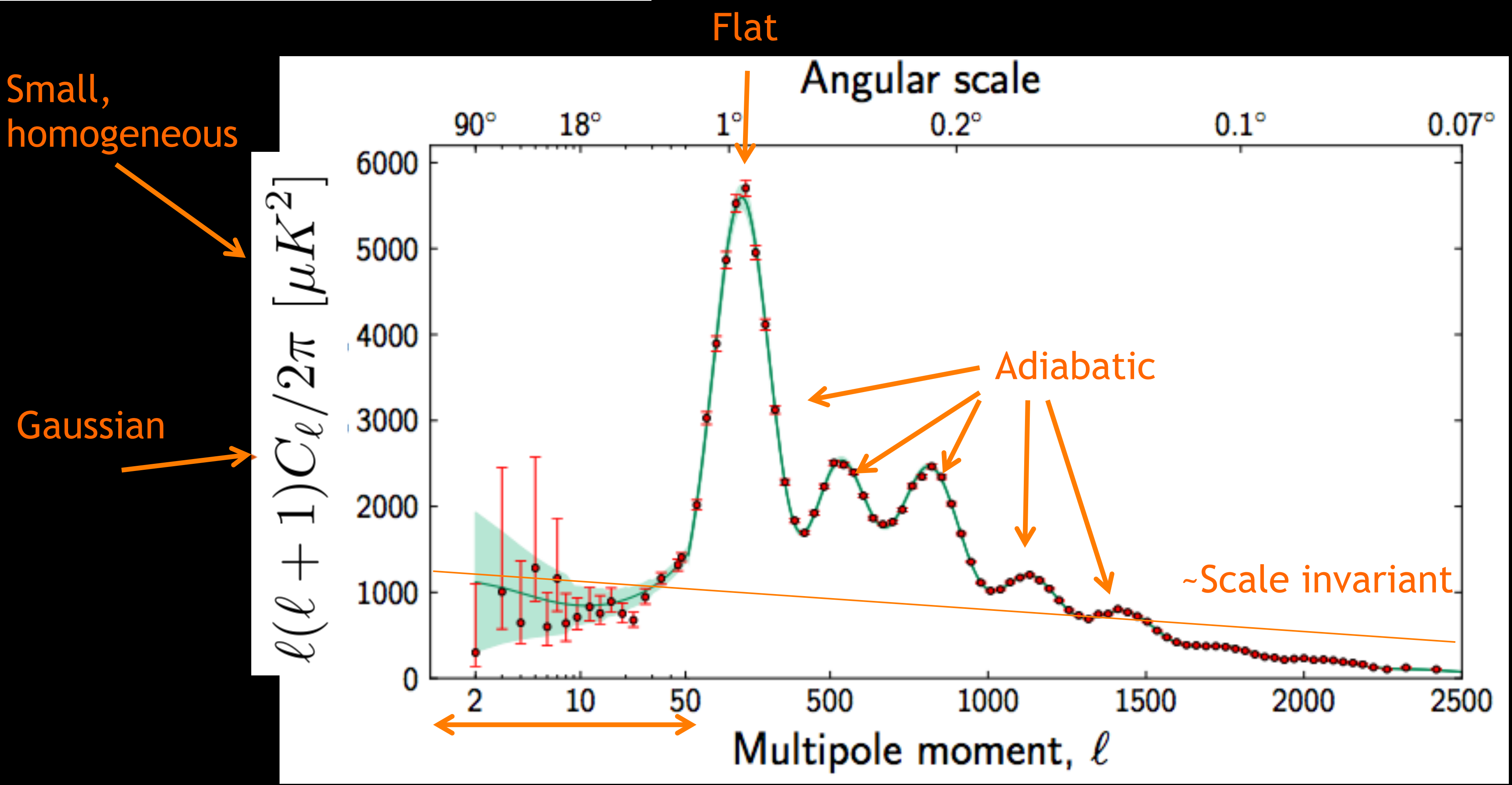
- Power spectrum spectral index nearly scale invariant
(small red tilt in many implementations)

- Super-horizon perturbations

- A stochastic background of gravity waves

Spectacular success

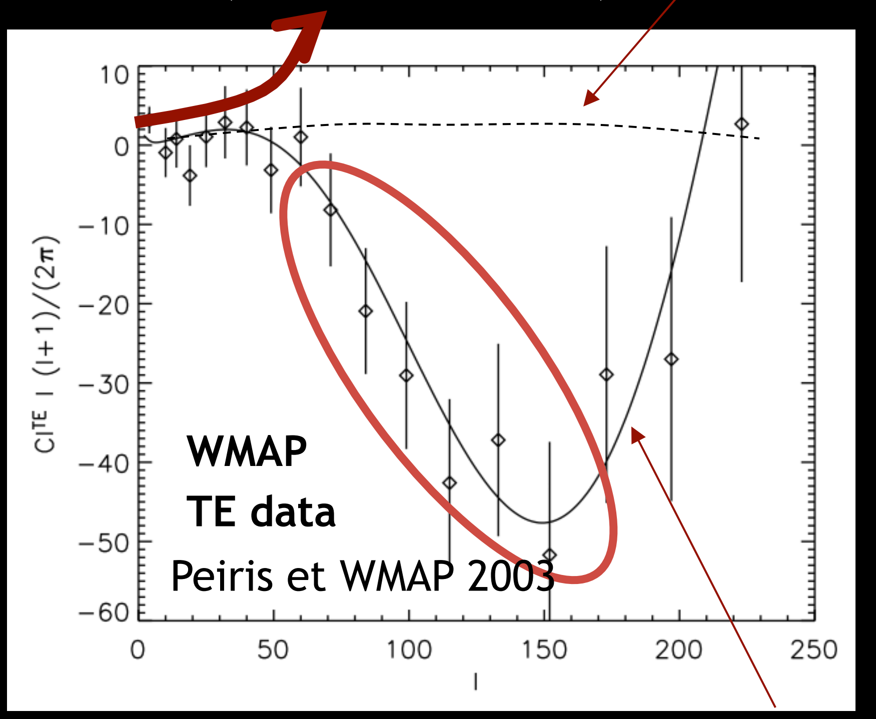




Super-horizon perturbations

On super-horizon scales the quadrupole anisotropy that generates polarization is given by velocities: off-phase to density

ANTI CORRELATION T-E



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

inflation:
(5 out of 6 predictions of inflation confirmed)

- Spatially flat universe ✓
- (Nearly) Gaussian initial perturbations ✓
- Adiabatic initial conditions ✓
- Power spectrum spectral index nearly scale invariant (small red tilt in many implementations) ✓
- Super-horizon perturbations ✓
- A stochastic background of gravity waves