Status of Cosmological Observations

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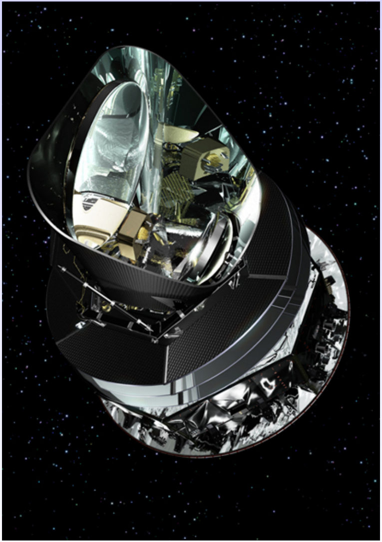
Aspen Skiing, 1/25/14

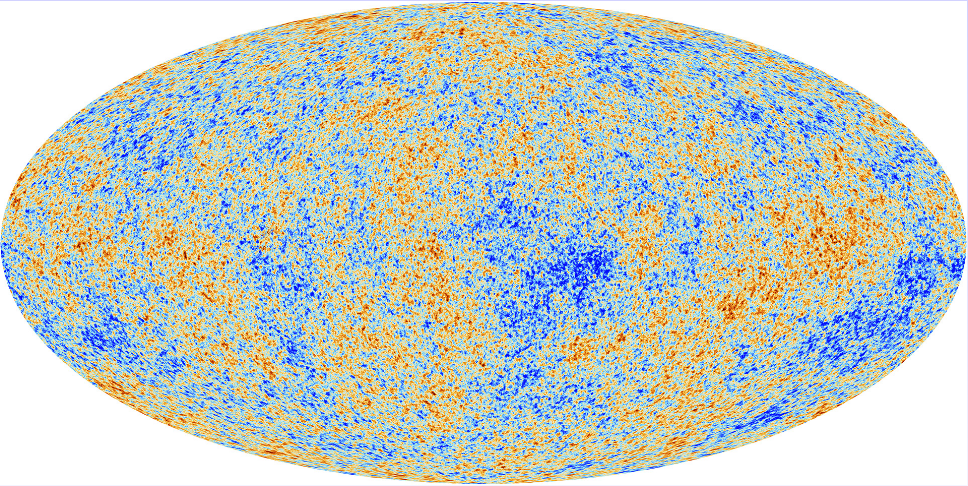
Plan for the talk

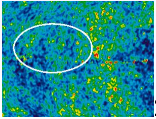
- Big News in 2013: Planck and the new normal:
  - Experiment working pretty well, but in small tension with low-redshift probes
  - Naïve model fittings indicate either neutrino mass (with $N_{\rm eff}$) or phantom dark energy ($w < -1$) at moderate significances
- BOSS: percent level distance measurements through BAO
- What to watch out in the next decade:
  - CMB
    - After Planck, temperature CMB essentially done
    - A number of B-mode experiments
    - Stage 4 CMB going after neutrino mass through lensing
  - Galaxy clustering:
    - DESI - spectroscopy
    - LSST - photometry
    - CHIME - 21cm

The Planck Satellite



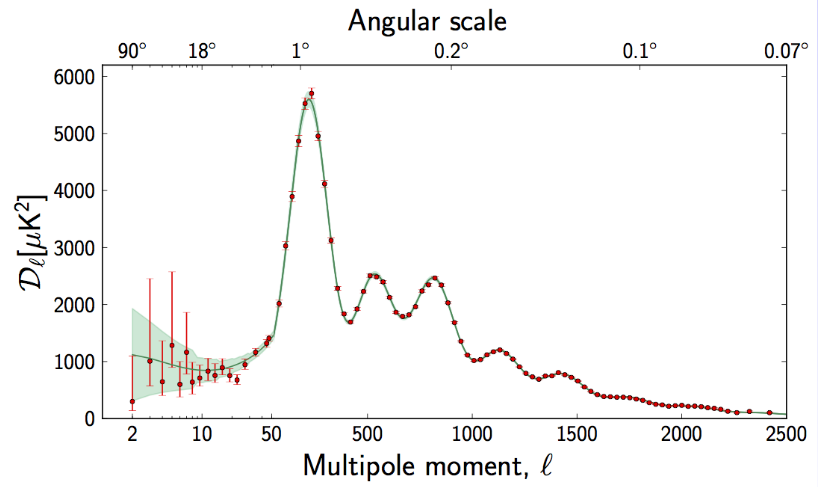
- Flown 2009-2014
- Relies on coolant therefore impossible to keep extending it
- Big improvements over WMAP:
  - Cosmic variance limited to $\ell < 2000$ rather than $\ell < 600$
  - 3+6 bands from 30GHz-857GHz rather than 5 from 23GHz-94GHz
- Not much left to do in temperature
- Can improve significantly in polarization, especially B-modes and lensing reconstruction, but not clear if space is optimal for that at this stage



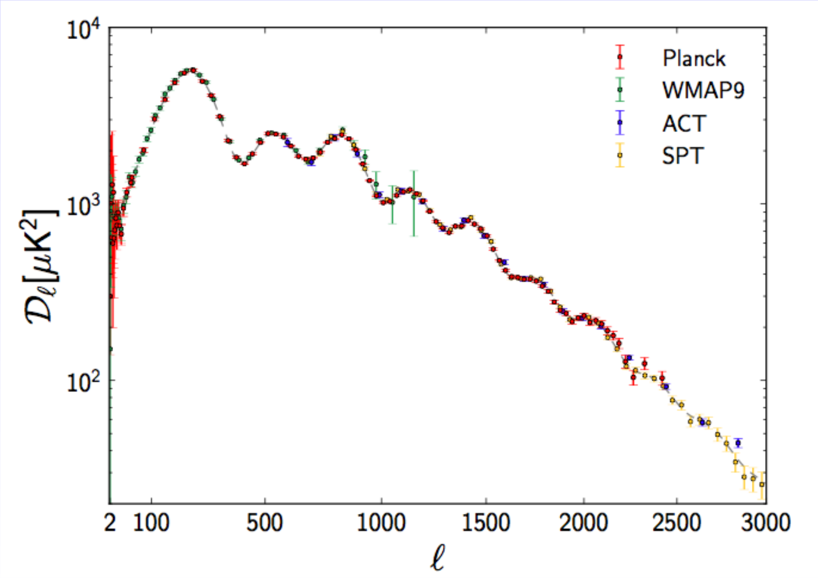


Stephen still around, but noisier...

Planck results



Planck results



Consistency

January 2014:

April 2013:

Title	Authors	Publication
Planck 2013 results. I. Overview of products and results	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. II. Low Frequency Instrument data processing	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. III. LFI systematic uncertainties	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. IV. LFI beams	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. V. LFI calibration	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. VI. High Frequency Instrument data processing	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. VII. HFI time response and beams	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. VIII. HFI calibration and mapmaking	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. IX. HFI spectral response	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. X. HFI energetic particle effects	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. XI. Consistency of the data	Planck Collaboration	2013 In preparation
Planck 2013 results. XII. Component separation	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. XIII. Galactic CO emission	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. XIV. Zodiacal emission	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. XV. CMB power spectra and likelihood	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. XVI. Cosmological parameters	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. XVII. Gravitational lensing by large-scale structure	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. XVIII. The gravitational lensing-infrared background correlation	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. XIX. The integrated Sachs-Wolfe effect	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. XX. Cosmology from Sunyaev-Zeldovich cluster counts	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. XXI. All-sky Compton-parameter map and characterization	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. XXII. Constraints on inflation	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. XXIII. Isotropy and statistics of the CMB	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. XXIV. Constraints on primordial non-Gaussianity	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. XXV. Searches for cosmic strings and other topological defects	Planck Collaboration	2013 Submitted to A&A
Planck 2013 results. XXVI. Background geometry and topology of the Universe	Planck Collaboration	2013 Submitted to A&A

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Planck 2013 results. X. HFI energetic particle effects	Planck Collaboration
Planck 2013 results. XI. All-sky model of thermal dust emission	Planck Collaboration
Planck 2013 results. XII. Component separation	Planck Collaboration
Planck 2013 results. XIII. Galactic CO emission	Planck Collaboration
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Planck 2013 results. XXVIII. The Planck Catalogue of Compact Sources	Planck Collaboration
Planck 2013 results. XXIX. The Planck catalogue of Sunyaev-Zeldovich sources	Planck Collaboration
Planck 2013 results. XXX. Cosmic infrared background measurements and implications for star formation	Planck Collaboration
Planck 2013 results. XXXI. Consistency of the data	Planck Collaboration
Planck 2013 results. Explanatory supplement	Planck Collaboration
Planck 2013 results. Web-based explanatory supplement	Planck Collaboration

Ok, not getting much love from the Planck team!

Parameter Shifts in Planck

The Planck data *is* somewhat different for ΛCDM:

- Higher $\Omega_m = 0.315 \pm 0.017$ rather than $\Omega_m \sim 0.28$
- Lower $H_0 = 67.3 \pm 1.2$ rather than $H_0 \sim 72$
- Higher $\sigma_8 = 0.829 \pm 0.012$ rather than $\sigma_8 \sim 0.80$

This is a 2-3 σ odds with local Universe in particular

- Hubble parameter using distance ladders
- matter density using supernova Ia
- σ_8 using weak lensing, SZ, cluster counts

Are we dealing with confirmation bias in old measurements or systematics?
If taken at a face value, these results indicate new physics!

Detour: Neutrinos in Cosmology

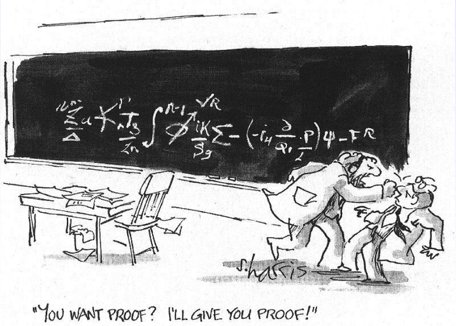
particle physicist's view on neutrinos from cosmology

From André de Gouvêa's talk at Brookhaven Forum 2011:

> Bounds can be evaded with non-standard cosmology. Will we learn about neutrinos from cosmology or about cosmology from neutrinos?
>
> **Recent ν Results**

Common misconceptions:

- It all depends on the "assumed model"
- More than one numerical result means that we "don't understand systematics"
- Systematics will never get better



neutrinos in cosmology

- Universe homogeneous when neutrino background is formed, we understand the physics
- It can be shown:

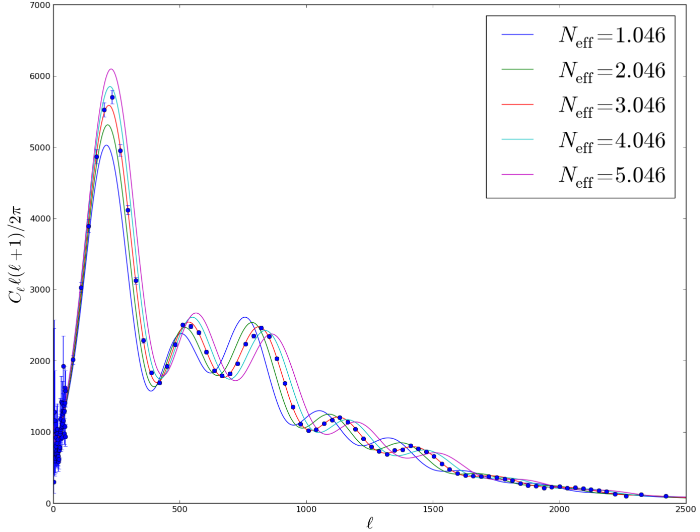
$$\rho_\nu c^2 = 3 \times \frac{7}{8} \times \left(\frac{4}{11}\right)^{4/3} \rho_\gamma c^2$$

- **In terms of energy density, neutrinos as important as radiation!**
- Can parametrize the effective number of neutrinos

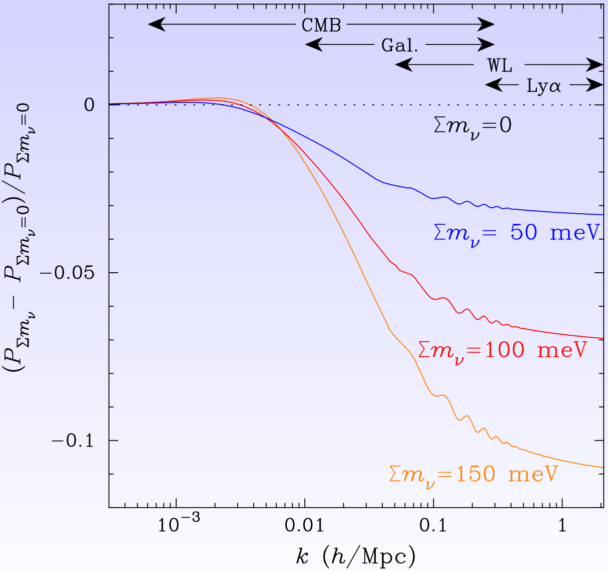
$$\rho_\nu c^2 = N_{\mathrm{eff}} \times \frac{7}{8} \times \left(\frac{4}{11}\right)^{4/3} \rho_\gamma c^2$$

  and fit.
- Planck measures $N_{\mathrm{eff}} = 3.36 \pm 0.34$ - a **nearly** 10σ **detection**

$N_{\rm eff}$ and Planck



effect of the finite neutrino mass



- Relatively large effects: O(5%)
- Different probes sensitive on different scales
- Measure the unique suppression using one probe
- Combine two probes at two different scales
- **Note characteristic scale and shape of neutrino mass supression.**

End of Detour

Sexy explanation #1: neutrinos

A number of papers claims neutrino mass and/or $N_{\rm eff}$ by combining Planck with low-redshift probes, e.g.:

- Battye & Moss 2013: $\sum m_\nu = (0.320 \pm 0.081)$eV or $m_{s\nu} = (0.450 \pm 0.124)$eV with $N_{\rm eff} = 3.49 \pm 0.23$
- Jan Hamann & Hasenkamp: $m_{s\nu} = (0.44 \pm 0.13)$eV with $N_{\rm eff} = 3.65 \pm 0.30$
- Wyman et al: $\sum m_\nu = (0.39 \pm 0.11)$eV with $N_{\rm eff} = 3.51 \pm 0.26$

These explanations rely on the fact that the amplitude predicted by Planck is high compared to what local probes measure.

Sexy explanation #2: w

Some papers also claim $w < -1$:

- Pan-STARRS1 SN gives $w = -1.186^{+0.076}_{-0.065}$
- Suyu et al strong lensing: $w = -1.55^{+0.19}_{-0.21}$

Here

$$p = w\rho_{\mathrm{DE}} \tag{1}$$

with $w = -1$ for cosmological constant.

These explanations rely on the fact that the Hubble's parameter is low compared to what local probes measure.
It would take an entire talk to go through all these possibilities, but. . .

Sexy explanations

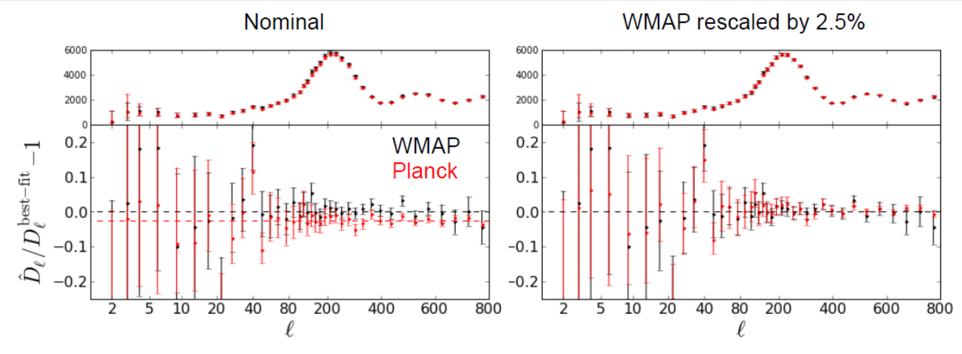
- All these analyses to some extend present an inevitable a-posteriori statistics: a kosher statistician decides which datasets to combine in advance
- Extensions of the minimal model alleviate tensions, *but do not eliminate it*. For example, in Battye et al, there is still a remaining 2.8σ tension *after fitting for neutrinos*.
- WMAP1-3-5 floated wildly and stabilised only after WMAP5

Two differences wrt to WMAP

There seem to be two separate effects driving the difference:

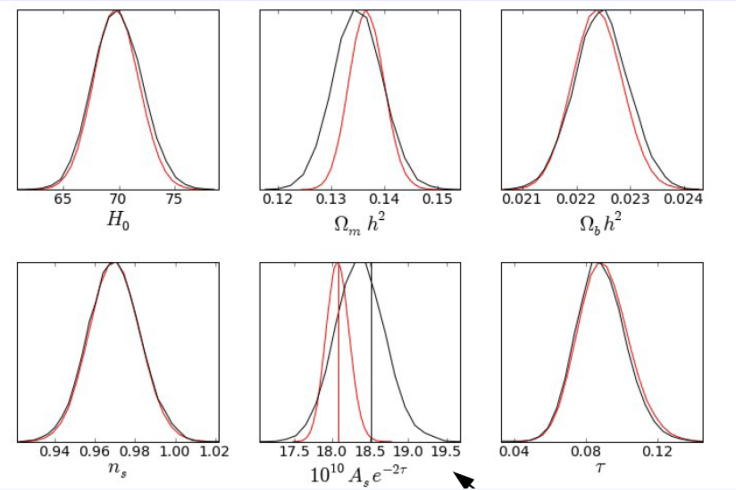
- Power in Planck approximately 2.5% low in Planck compared to WMAP.
- Fishy things going on in 217×217 GHz channels (Spergel et al)

Power difference



From Marius Millea's talk.

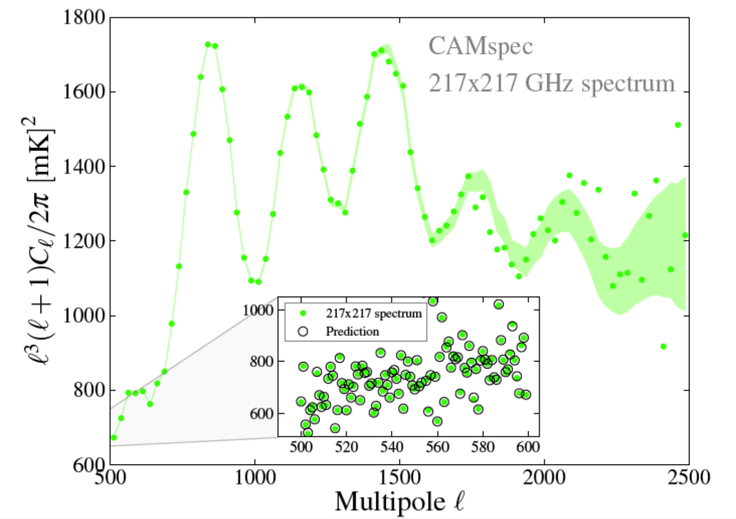
$Fitting\ \ell < 800$



From Marius Millea's talk.

- Planck is low, pushing local σ_8 even higher if "corrected" to WMAP
- 2% is *a lot*!

$217 \times 217GHz$ Channel

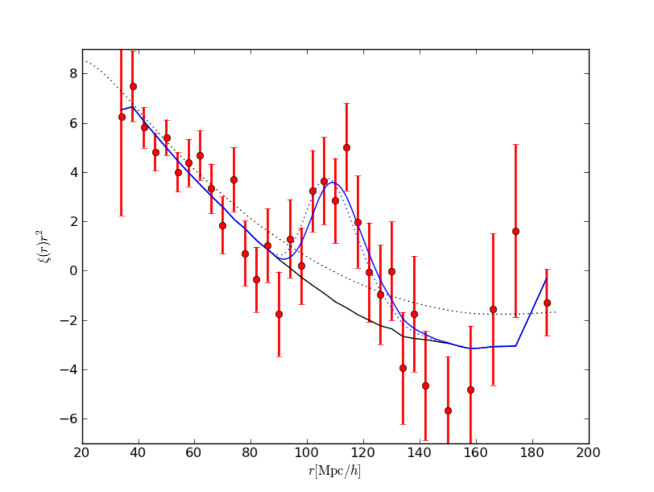


From Spergel et al.

Recap

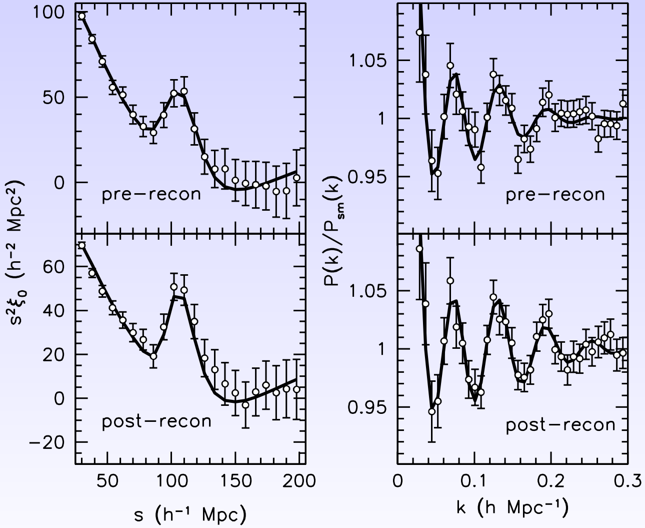
- Planck at tension with many local measurements
- Maybe, they all conspired to get what WMAP wanted?
- Adding new parameters relieves, but does not removes tension
- Some evidence for systematic effects in either Planck or WMAP or both
- Need to wait for v2 on Planck!

BOSS results: DR9 Lyman-α BAO



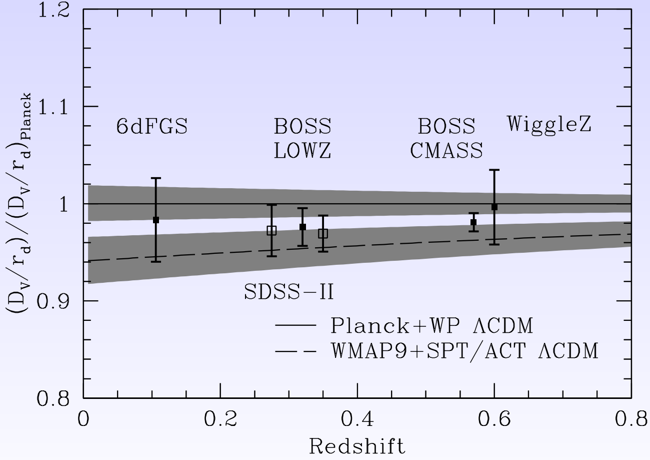
- First measurements of Hubble's parameter at redshift $z > 2$ – come talk to me if you are interested

BOSS results: DR11 galaxy BAO



- Percent level distance to $z = 0.57$

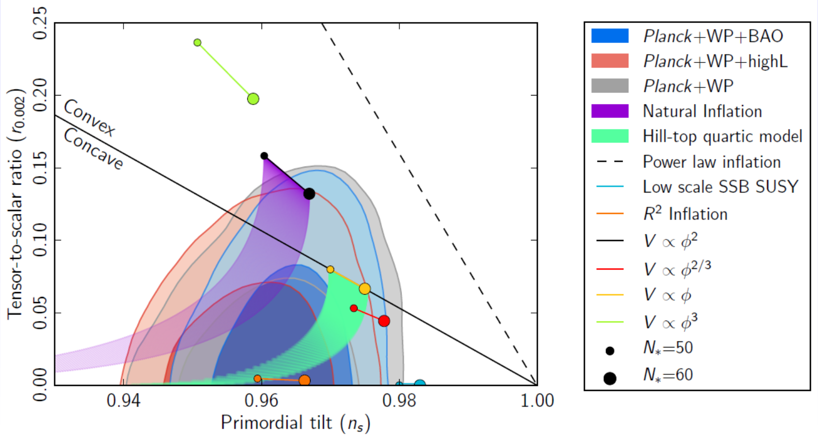
BAO vs Planck and WMAP+highL



Future prospects

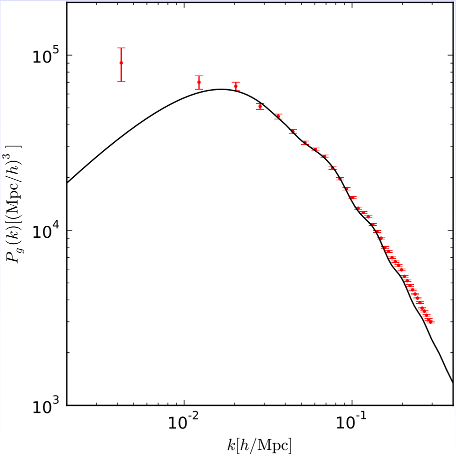
B-modes in CMB

- *B*-mode polarization is the analogue of divergence-free field and is uniquely sensitive to tensor modes of primordial fluctuations
- Important number is tensor-to-scalar ratio r
- Strongest limits from Planck, but these are cosmic variance limited
- $r \sim 0.001 - 0.01$ is a watershed value: small or large field inflation
- CMB-S4 with O(500,000) detectors by 2020 could do it

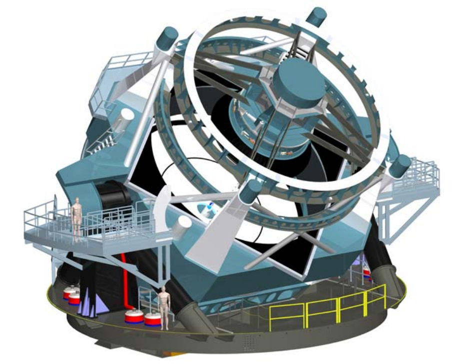


Counting galaxies

- Galaxies are tracer of the underlying structure – EFT-like approaches will allow us to robustly use them into mildly non-linear regime
- Fundamentally more information: 3D rather than 2D

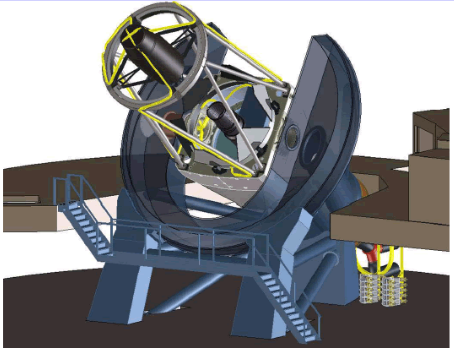


- Monopole power spectrum used in Anderson et al
- Note large scale junk
- Note the idiotic precision of the measurement
- Note small deviation from linear biasing kicking in as we go to smaller scales



LSST:

- Photometric experiment: takes pictures of the sky
- 5 bands can give an estimate of a redshift

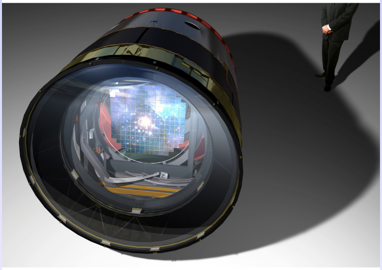


DESI:

- Spectroscopic experiment: takes spectra
- Spectra give redshifts - real 3D experiment

Large Synoptic Survey Telescope

- Wide, fast, deep
- 3.2 Gpix camera on effectively 6.7m telescope
- 9.6 square degrees FOV – massive etendue
- Passed CD0, CD1; DOE flagship DE experiment
- First light ∼2019

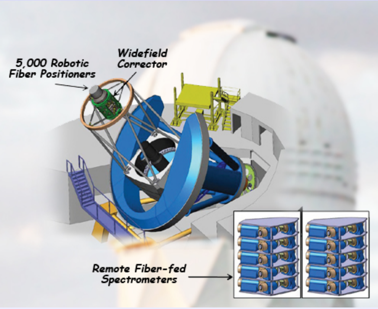


Science:

- Will measure positions of ∼ 10 billion galaxies
- Missing third dimension, so essentially a few thick slices in radial direction
- Designed to be measure weak lensing
- Non-gaussianity of photo-*z*s will be a problem

Dark Energy Spectroscopic Instrument

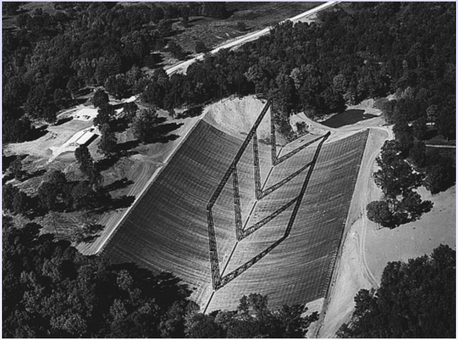
- BigBOSS+DESpec = DESI
- 4000 fiber robotically actuated spectrograph on 4m Mayal telescope
- Order of magnitude more powerful than BOSS with 20-30 millions measured spectra.
- Excellent complimentarity with photometric surveys such as LSST
- A DOE experiment run in the tradition of particle physics



Science:

- Will measure 3D power spectrum of galaxies with unprecedented precision
- Main project is measuring expansion history through BAO
- Statistically, the anisotropic power spectrum is the most promising

CHIME



(400 ft Illinois telescope)

- Idea is to measure integrated emission from many galaxies shining in 21cm spin-flip transition
- Telescope is dish in one direction, interferometer in the other
- Super cheap - the entire project is O($20 million)
- If it works it would be amazing

What do we expect to see in 2020

Prognosis for neutrino masses really good:

- Natural goal: $\sum m_\nu = 0.06$eV.
- At least three different techniques should get us to $\Delta m_\nu = 0.02$eV independently

Properties of DE:

- No natural goal, but knowledge of w and related params will reach percent level accuracy

Extra radiation:

- Natural goal: $\Delta N_{\rm eff} = 0.04$
- Forecasts around $\Delta N_{\rm eff} = 0.06 - 0.1$
- This will still strongly rule out lots of thermalized something-something

What do we expect to see in 2020

Running of spectral index:

- Third number on inflation

$$\alpha_s = d\frac{d \log n_s}{d \log k} \tag{2}$$

- Natural goal $O((n_s - 1)^2) \sim 10^{-3}$
- Forecasts around $\Delta\alpha_s = 3 - 8 \times 10^{-3}$

Non-Gaussianity:

- Planck measured $f_{\mathrm{NL}} = 2 \pm 8$
- This will prove very hard to improve on using techniques we trust
- Bispectrum should help a lot, but it is a very difficult measurement

Conclusions

By now, I'm likely to be over-time, so you need to read this by yourselves:

- Planck produced amazing results, which taken at face value imply new physics when combined with low-z probes
- Most likely this will turn out to be a combination of systematics and a-posteriori data selection – wait for v2
- In the future, watch out for
  - B-mode polarization experiments
  - Emergence of galaxies as a comprehensive probe beyond BAO
  - New ideas like CHIME
- Guaranteed neutrino mass detection in next 10 years
- Very interesting limits on $N_{\rm eff}$, α_s
- **Come to dark side!**