# Cosmic microwave background implications for particle physics

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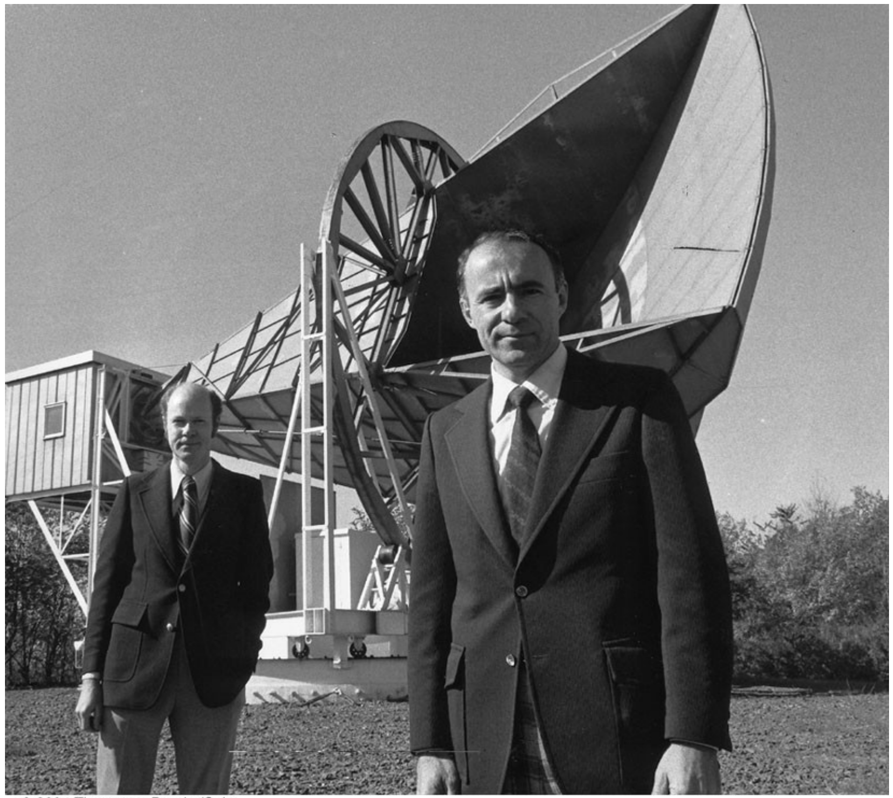
SUSY 2016, Melbourne, July 3 – 10, 2016

# 51 years of CMB measurements...

**CMB** = thermal relic radiation left over from ~400,000 years post big bang, first observed in 1965.

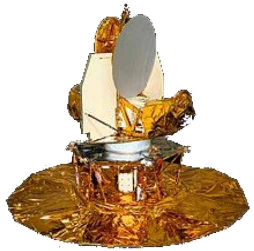




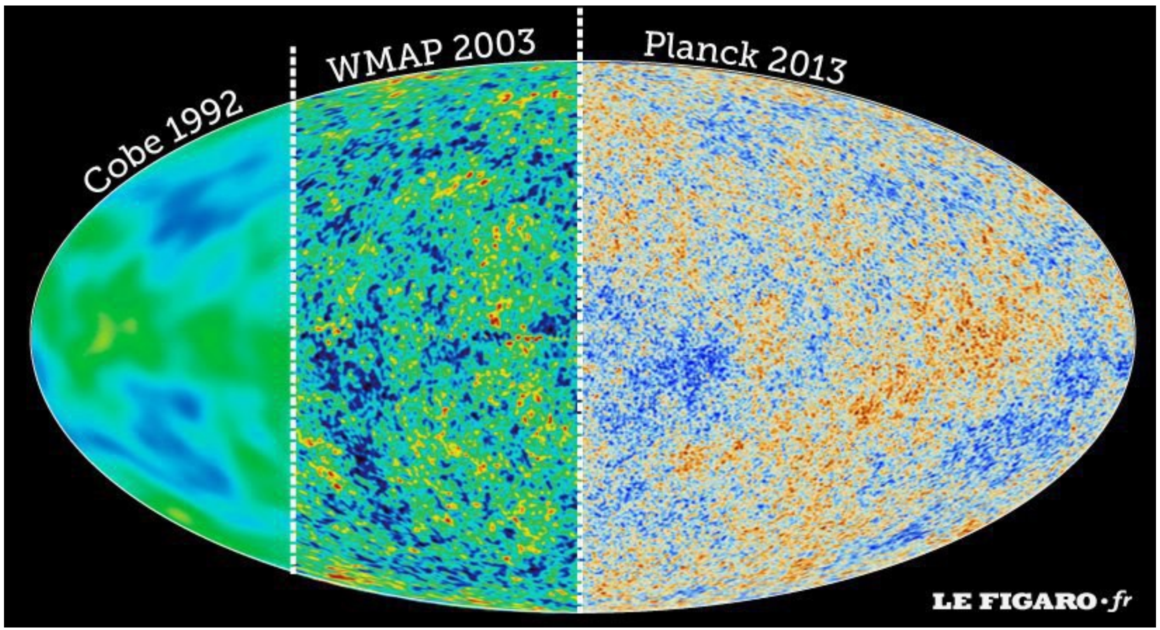
Arno Penzias &
Robert Woodrow Wilson
@ the Holmdel Horn Antenna

# Three generations of space-based CMB probes...


7°


0.3°


<0.1°




- Most perfect blackbody ever measured:

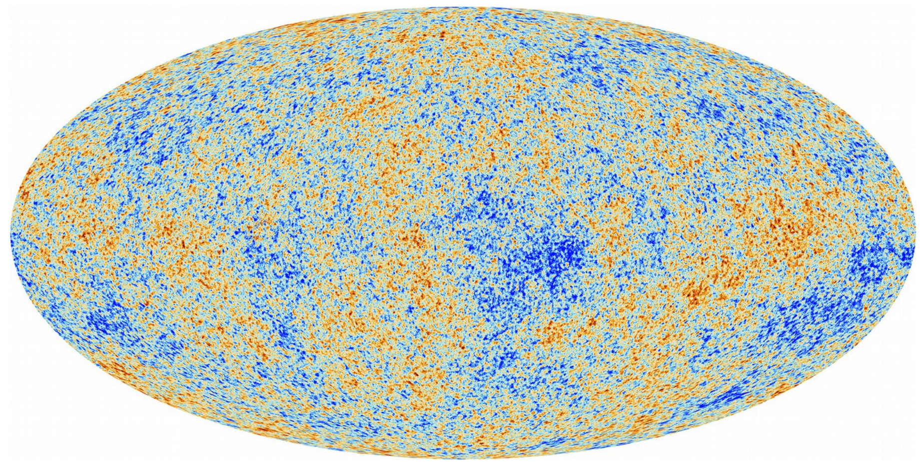
$$T_{\gamma} = 2.725 \pm 0.001\,\mathrm{K}$$

Mather et al., 1994

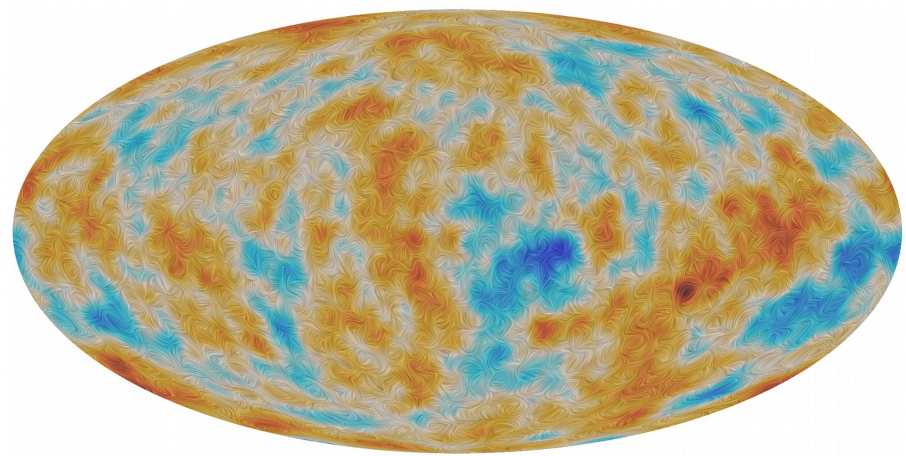
- Spatial temperature fluctuations of order $10^{-5}$; the “anisotropies”.

# CMB anisotropies as seen by Planck 2015...

**Temperature fluctuations**

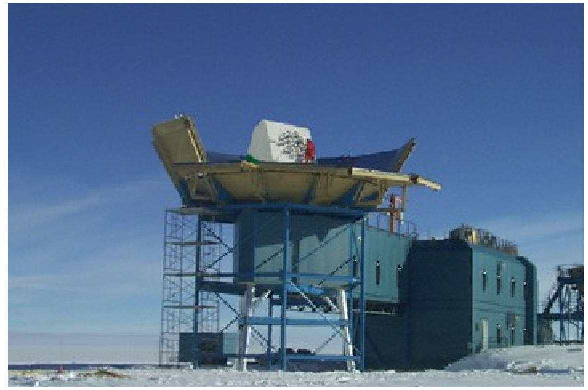


**Polarisation fluctuations**
(from Thomson scattering of
photons off electrons)

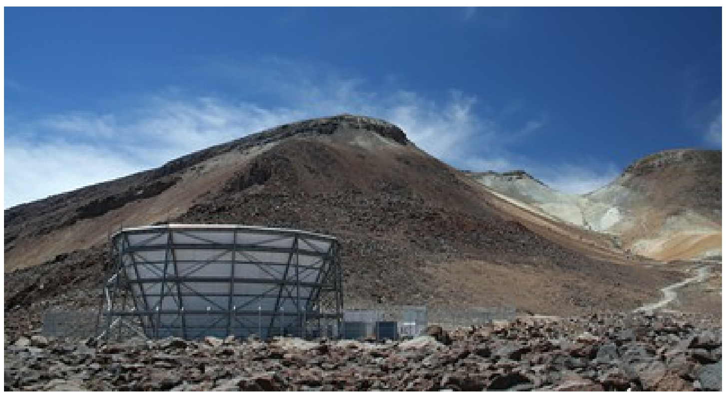


# Don't forget the ground-based/balloon experiments...

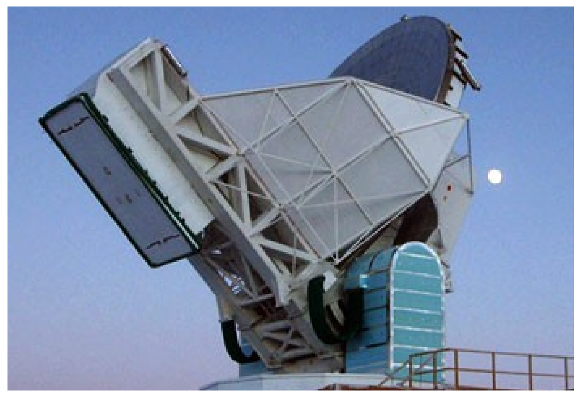
BOOMERanG  (flat spatial geometry 1999)



DASI (polarisation anisotropies 2002)



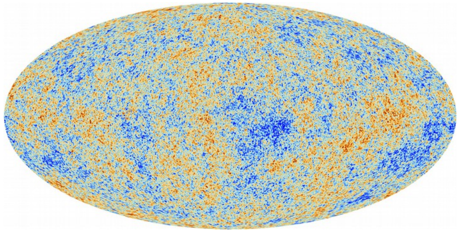
ACT...

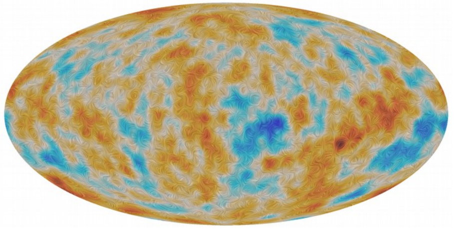


… and SPT (damping tail 2011)

Plus many others...

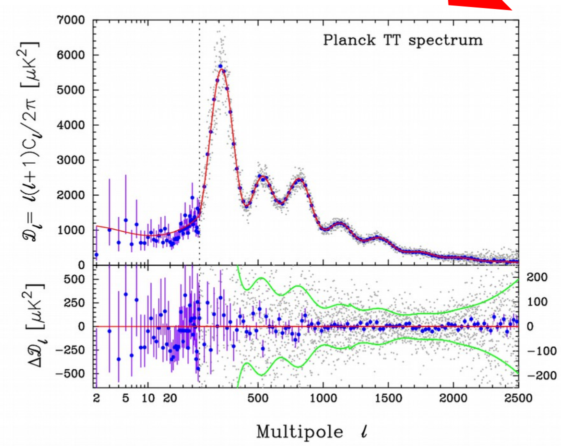
# CMB observables: what can be extracted from maps...



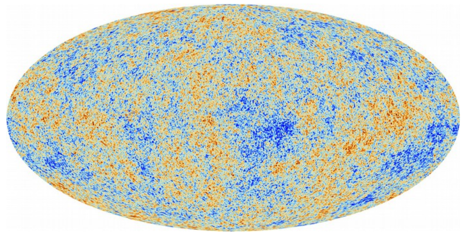


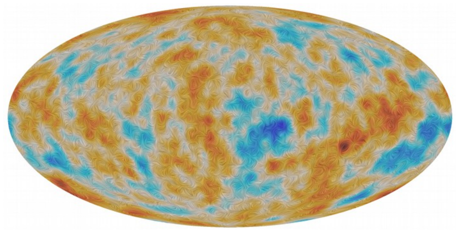
# CMB observables: what can be extracted from maps...

**2-point correlation**



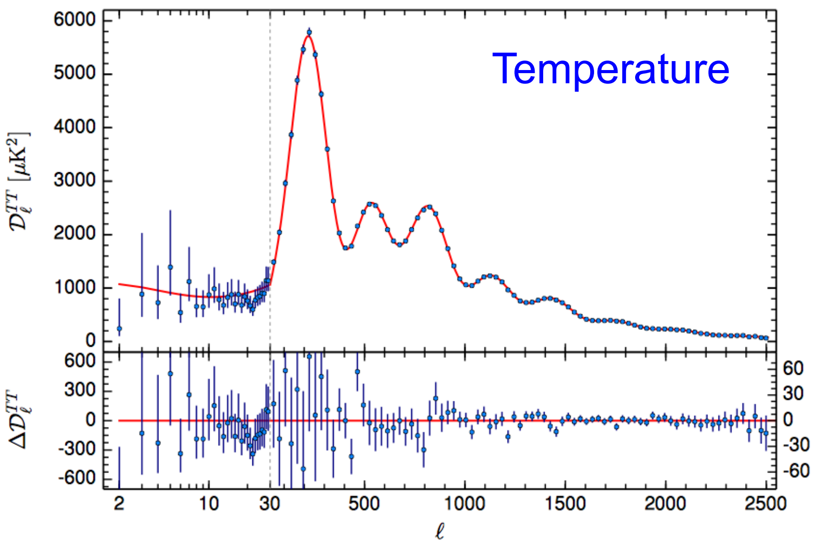

Angular power spectrum

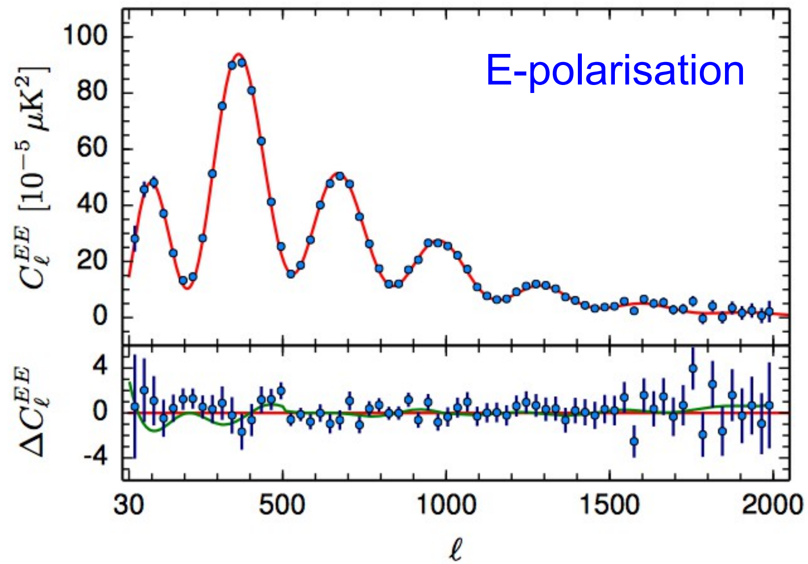


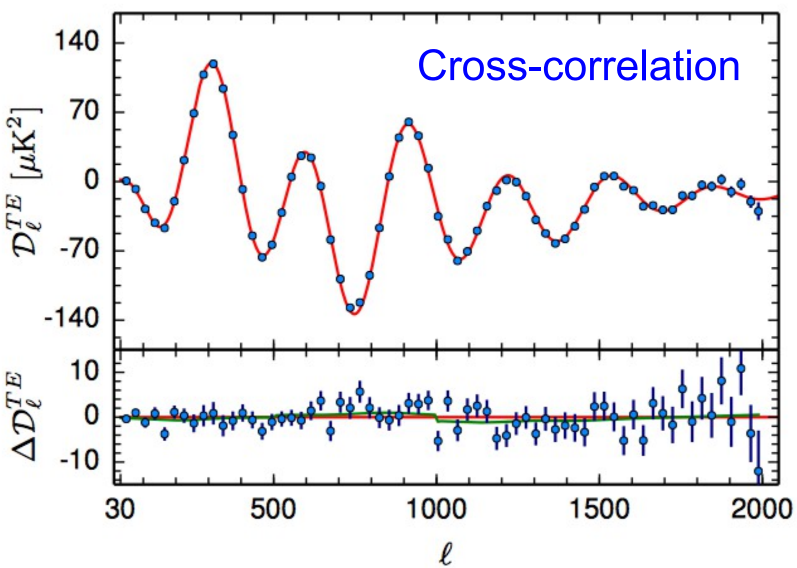


# 2-point correlation: angular power spectra...

Ade et al. [Planck] 2015




**A combination of**:

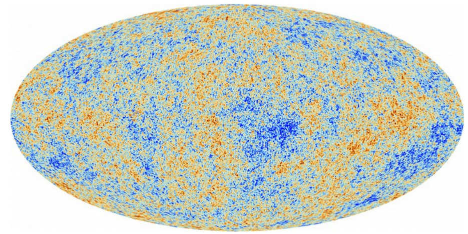
- Photon-baryon acoustic oscillations frozen on the LSS.
- Projection effects.
- Late-time secondaries, e.g., reionisation, ISW, lensing.

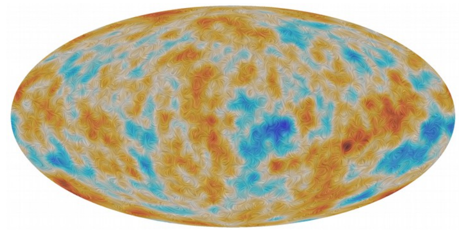
Initial conditions

Energy densities

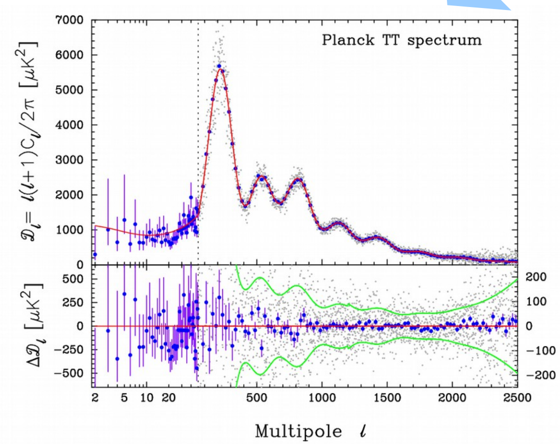
Spatial geometry

# CMB observables: what can be extracted from maps...



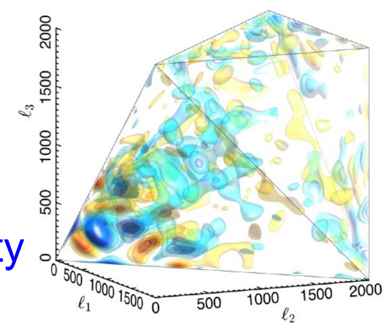


**2-point correlation**

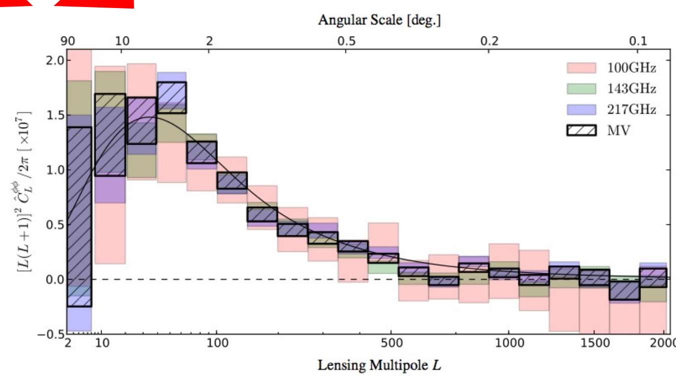



Angular power spectrum

**Higher-order correlations**

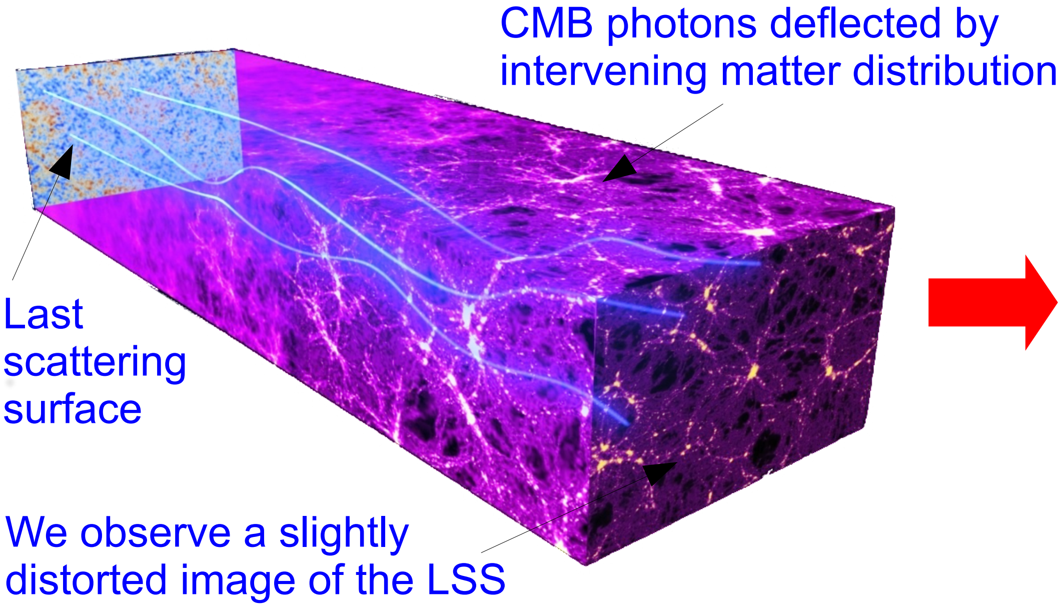



Primordial non-Gaussianity

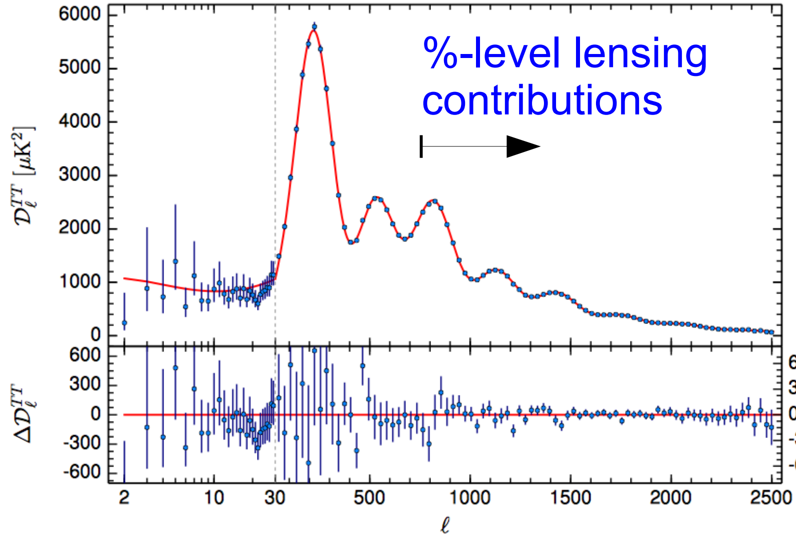



Lensing potential power spectrum

# Lensing...



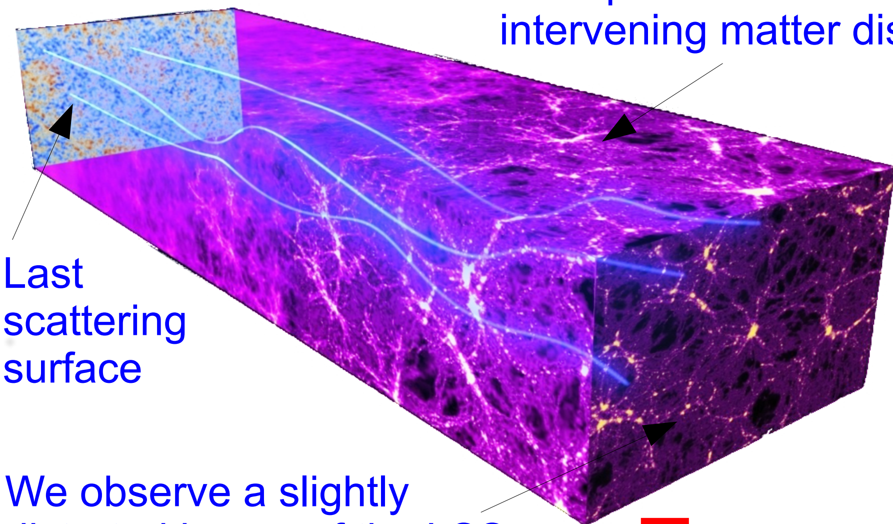
CMB photons deflected by
intervening matter distribution
Last
scattering
surface
We observe a slightly
distorted image of the LSS

%-level lensing
contributions
$\mathcal{D}_\ell^{TT}$ [$\mu$K$^2$]
$\Delta\mathcal{D}_\ell^{TT}$
$\ell$
6000
5000
4000
3000
2000
1000
0
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500

# Lensing potential power spectrum...

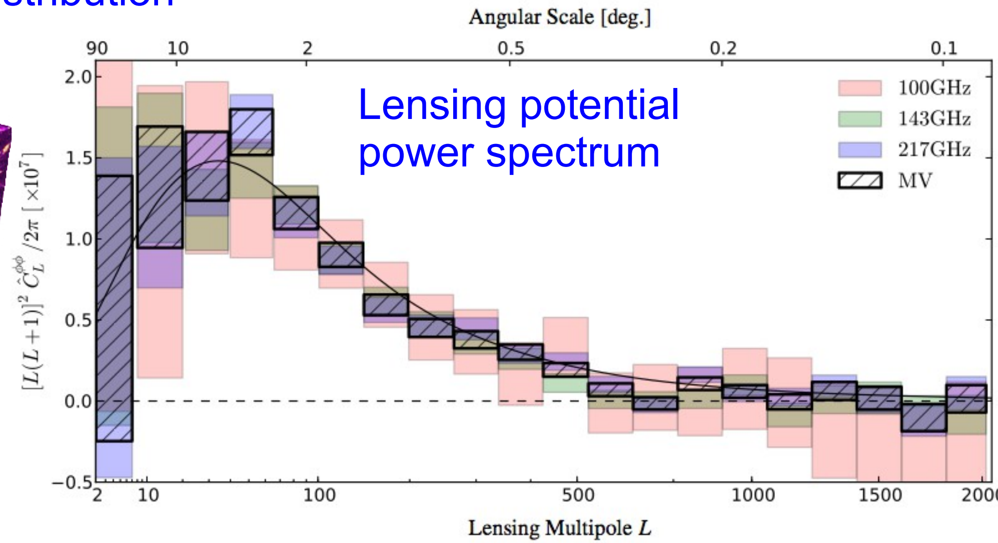
CMB photons deflected by intervening matter distribution



Last scattering surface

We observe a slightly distorted image of the LSS

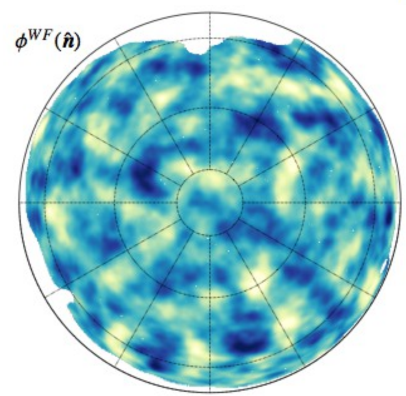
Ade et al. [Planck] 2013



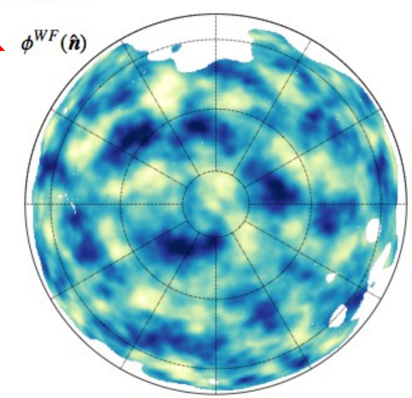

Use **4-point correlation** of observed map to infer the *unlensed* image.

→ Reconstruct deflection angle

→ Construct lensing potential map




Galactic North




Galactic South

# CMB observables: what can be extracted from maps...

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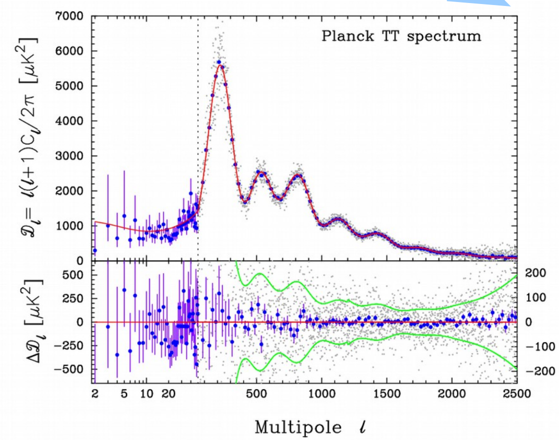
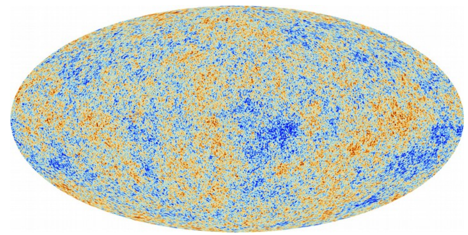
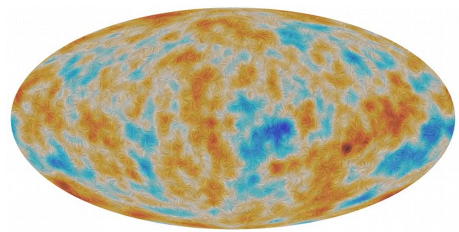
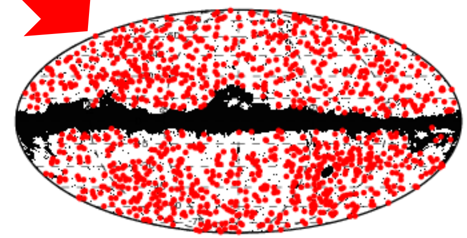



Angular power spectrum





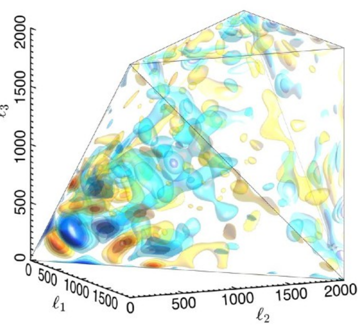
**Sunyaev-Zeldovich effect**

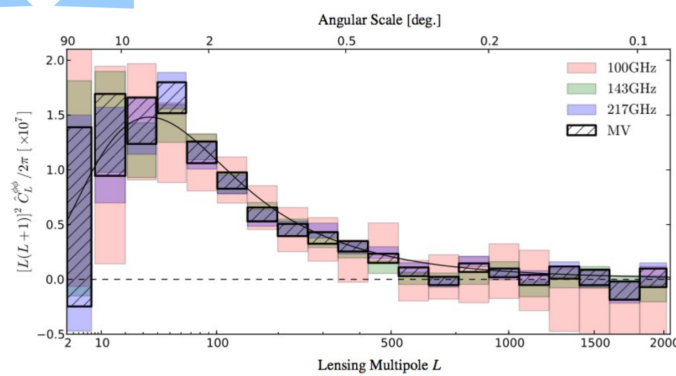


Cluster mass function (when combined with X-ray cluster mass measurements)

**Higher-order correlations**

Primordial non-Gaussianity

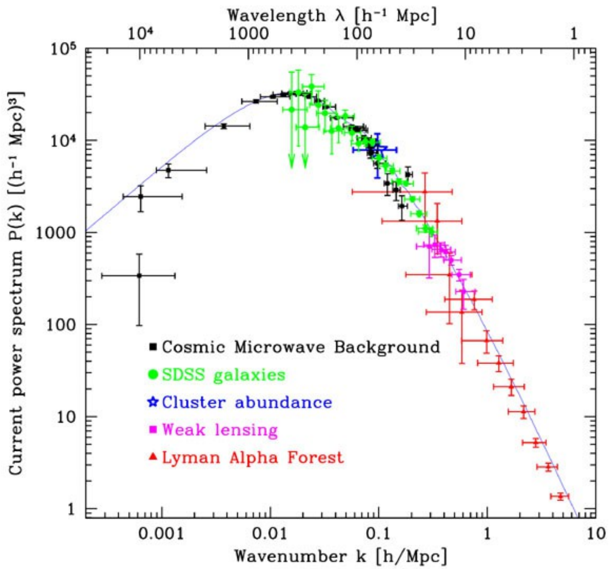


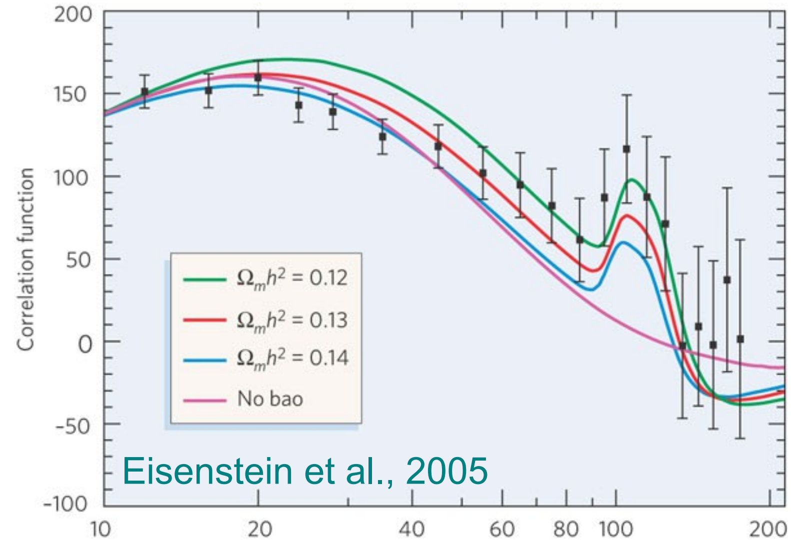




Lensing potential power spectrum

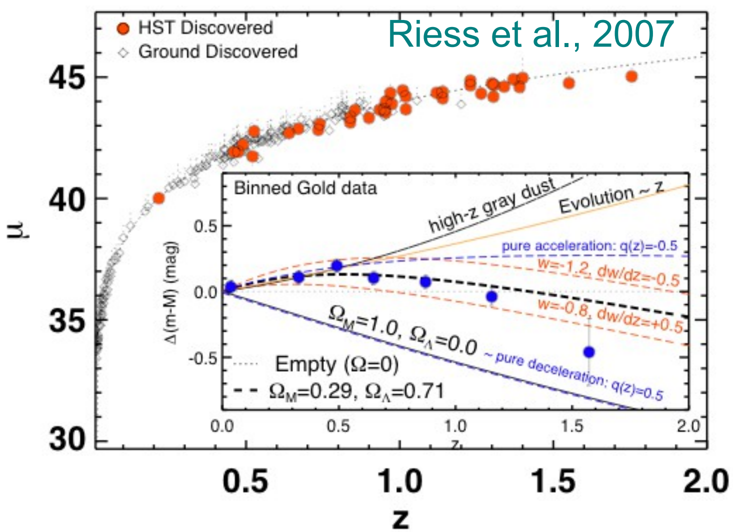
# Other non-CMB cosmological probes...

Baryon acoustic oscillations

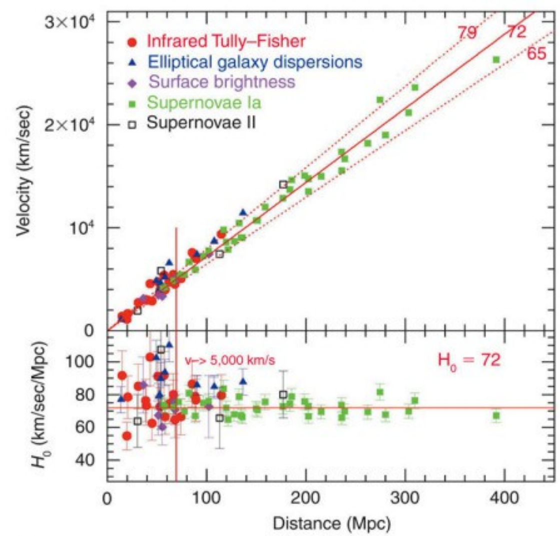



Large-scale matter power spectrum




Type Ia Supernovae




Local Hubble expansion rate

# What have we learnt from CMB measurements?

# The “standard” ΛCDM model...

**A 6-parameter model + flat spatial geometry**.

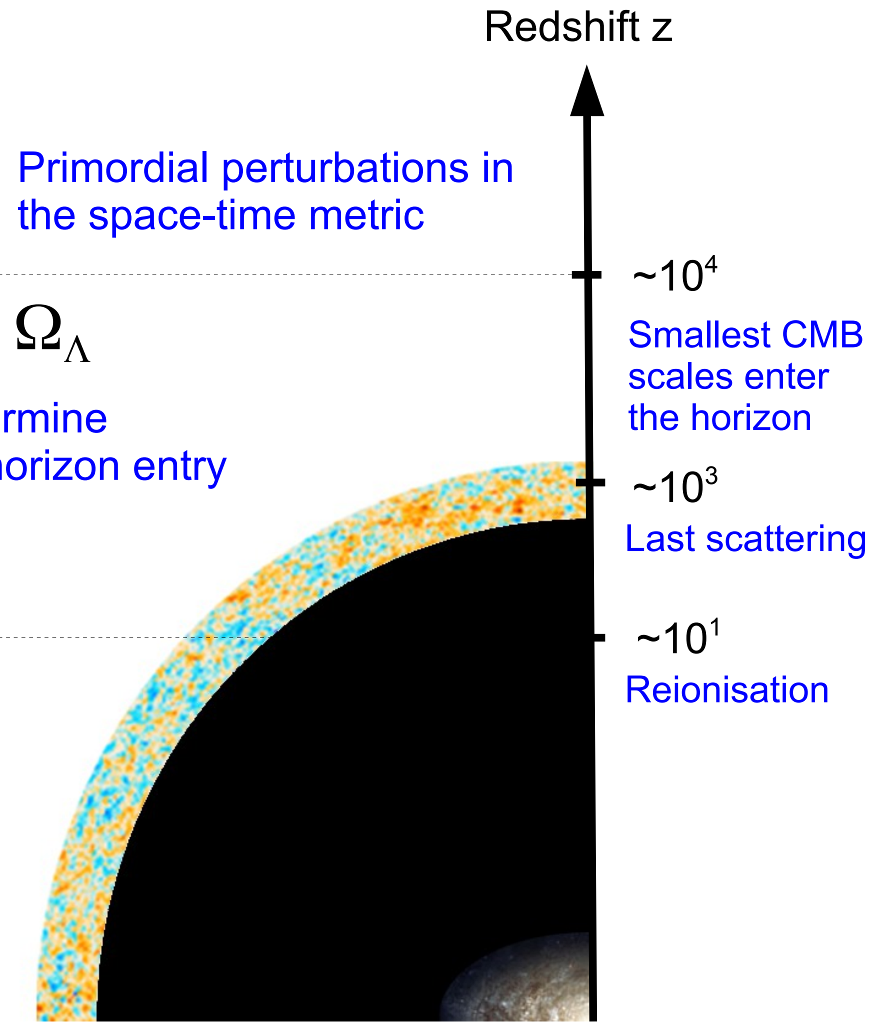
- Initial conditions (2): $P_{\mathrm{ini}}(k) = A_s k^{n_s - 1}$ Primordial perturbations in the space-time metric

- Energy densities (3): $\omega_{\mathrm{baryon}}, \omega_{\mathrm{dark\ matter}}, \Omega_\Lambda$

  Linearised GR+energy content determine how the perturbations evolve after horizon entry (the “transfer functions”).

- Optical depth to reionisation (1): $\tau$

  Degradation of anisotropies due to ionised medium at low redshifts



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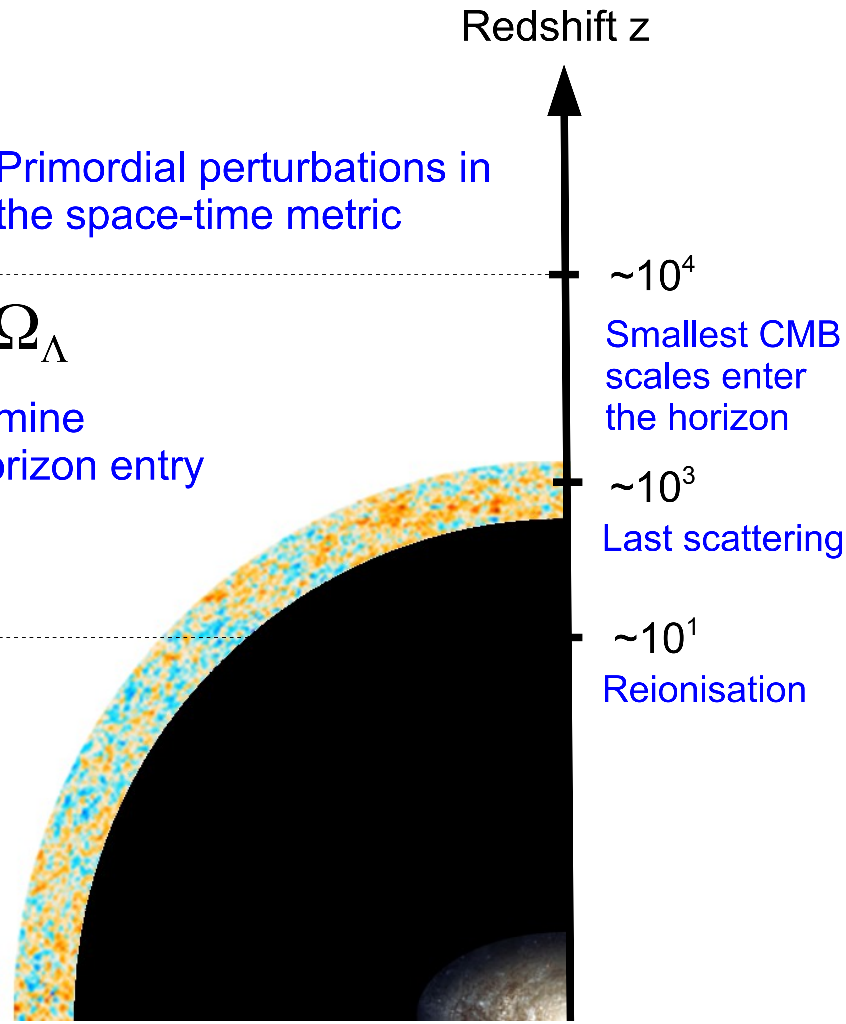
- Optical depth to reionisation (1): $\tau$

  Degradation of anisotropies due to ionised medium at low redshifts

- Plus nuisance parameters to model systematics:
  - 14 for Planck CMB data
  - Non-CMB data: e.g., tracer bias.



# Constraints on ΛCDM parameters...

Ade et al. [Planck] 2015

Planck temperature only

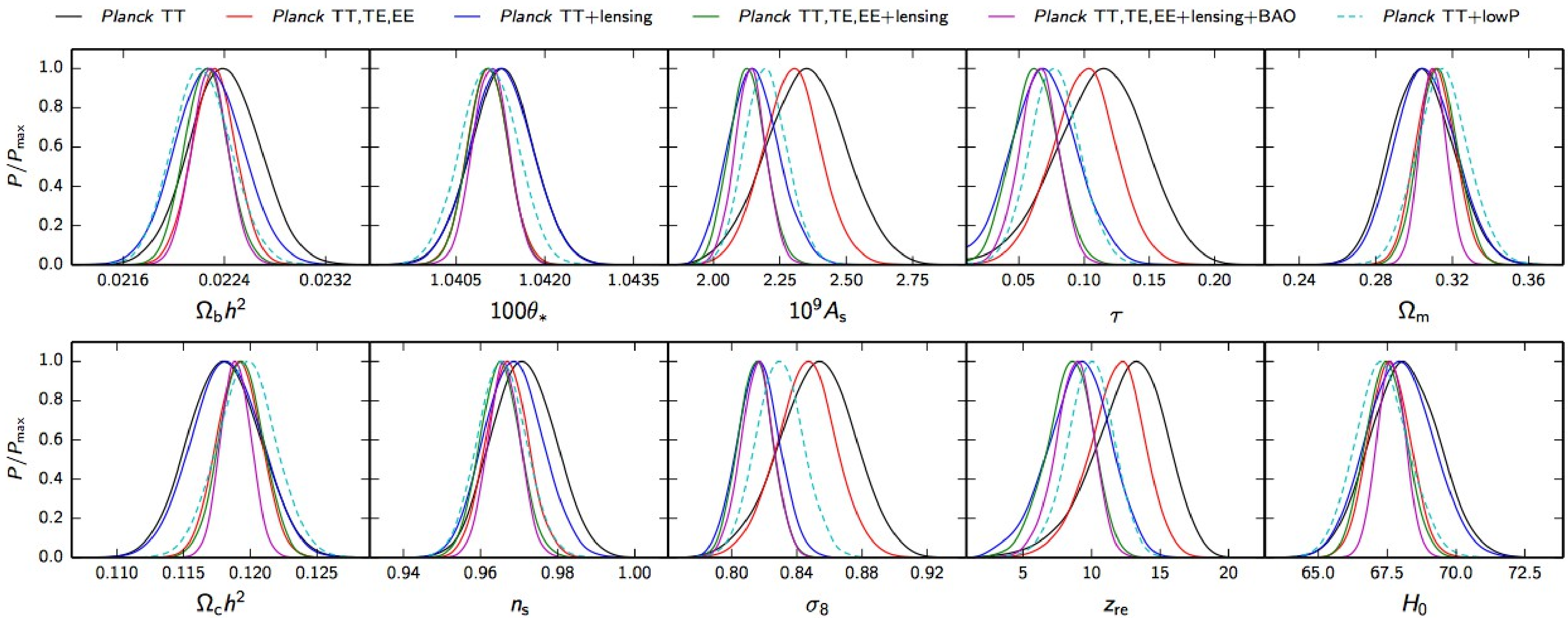
Temperature + polarisation

Temperature + lensing

Temperature + polarisation +lensing

Temperature + polarisation + lensing + **BAO**

Temperature + LowP



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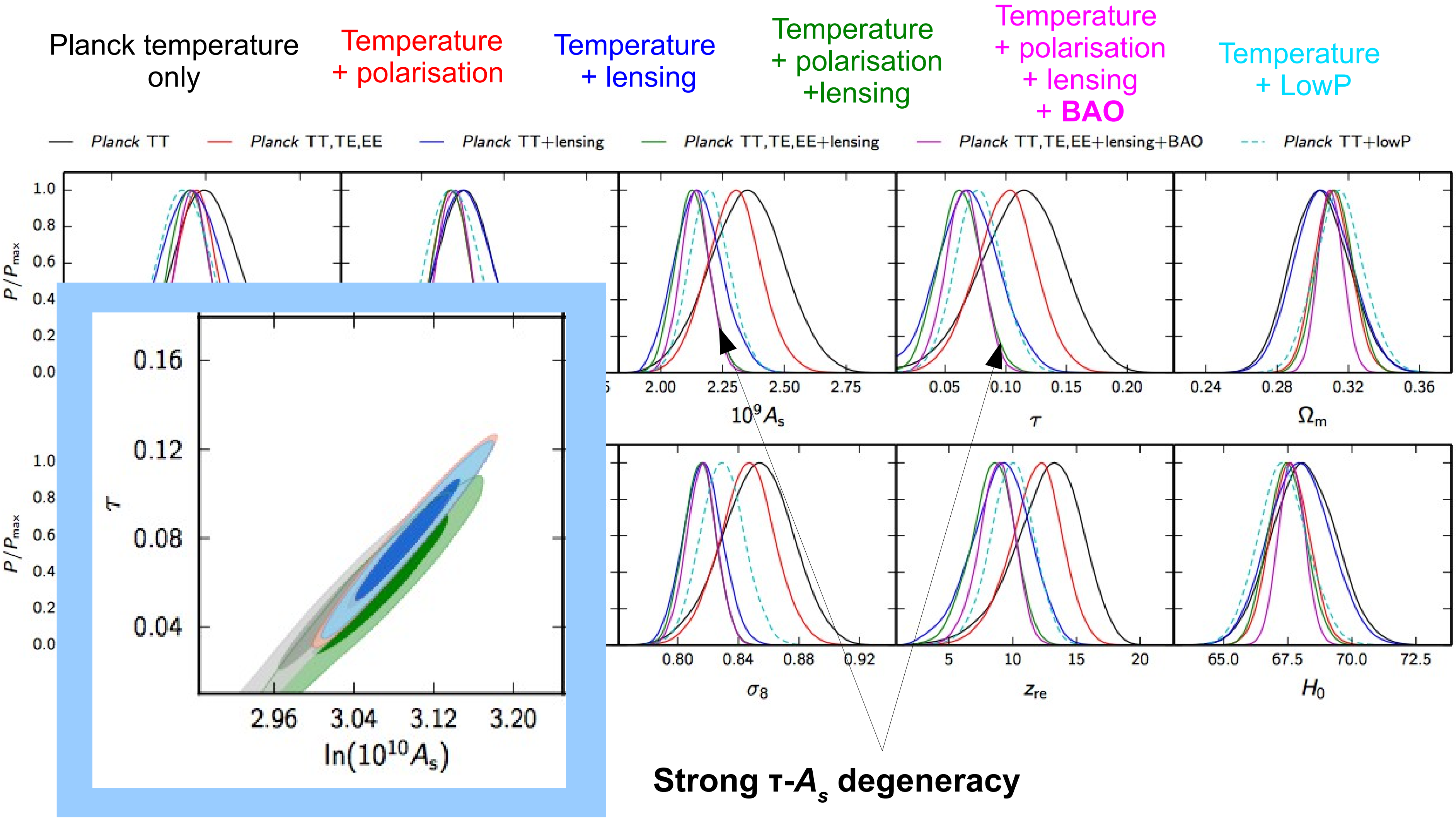


# $\Lambda$CDM+X...

There are many ways in which the $\Lambda$CDM parameter space can be extended:

- **Initial conditions**:
  - Primordial gravitational waves
  - Running of scalar spectral index
  - Primordial non-Gaussianity
  - …
- **Energy content**:
  - Nonzero neutrino mass
  - Extra relativistic particle species
  - Dynamical dark energy
  - ...
- Nonzero **spatial curvature**

Currently no evidence for any of these from CMB data alone...

**But...**

# Flies in the ointment...

- **Hubble parameter $H_0$**: Planck-inferred value lower than local HST measurement.
- **Small-scale RMS fluctuation $\sigma_8$**: Planck CMB prefers a higher value than galaxy cluster count and galaxy shear from CFHTLens.

Ade et al. [Planck] 2015

| Parameter | [1] *Planck* TT+lowP | [2] *Planck* TE+lowP | [3] *Planck* EE+lowP | [4] *Planck* TT,TE,EE+lowP | $([1]-[4])/\sigma_{[1]}$ |
|---|---|---|---|---|---|
| $\tau$ . . . . . . . . . . . . . . | $0.078 \pm 0.019$ | $0.053 \pm 0.019$ | $0.059^{+0.022}_{-0.019}$ | $0.079 \pm 0.017$ | $-0.1$ |
| $\ln(10^{10}A_s)$ . . . . . . | $3.089 \pm 0.036$ | $3.031 \pm 0.041$ | $3.066^{+0.046}_{-0.041}$ | $3.094 \pm 0.034$ | $-0.1$ |
| $n_s$ . . . . . . . . . . . . | $0.9655 \pm 0.0062$ | $0.965 \pm 0.012$ | $0.973 \pm 0.016$ | $0.9645 \pm 0.0049$ | $0.2$ |
| $H_0$ . . . . . . . . . . . . | $67.31 \pm 0.96$ | $67.73 \pm 0.92$ | $70.2 \pm 3.0$ | $67.27 \pm 0.66$ | $0.0$ |
| $\Omega_m$ . . . . . . . . . . . . | $0.315 \pm 0.013$ | $0.300 \pm 0.012$ | $0.286^{+0.027}_{-0.038}$ | $0.3156 \pm 0.0091$ | $0.0$ |
| $\sigma_8$ . . . . . . . . . . . . . | $0.829 \pm 0.014$ | $0.802 \pm 0.018$ | $0.796 \pm 0.024$ | $0.831 \pm 0.013$ | $0.0$ |
| $10^9 A_s e^{-2\tau}$ . . . . . . | $1.880 \pm 0.014$ | $1.865 \pm 0.019$ | $1.907 \pm 0.027$ | $1.882 \pm 0.012$ | $-0.1$ |

HST

$$H_0 = 73.24 \pm 1.74 \,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Riess et al. 2016

Planck SZ clusters $\sigma_8 (\Omega_m/0.27)^{0.3} = 0.782 \pm 0.01$

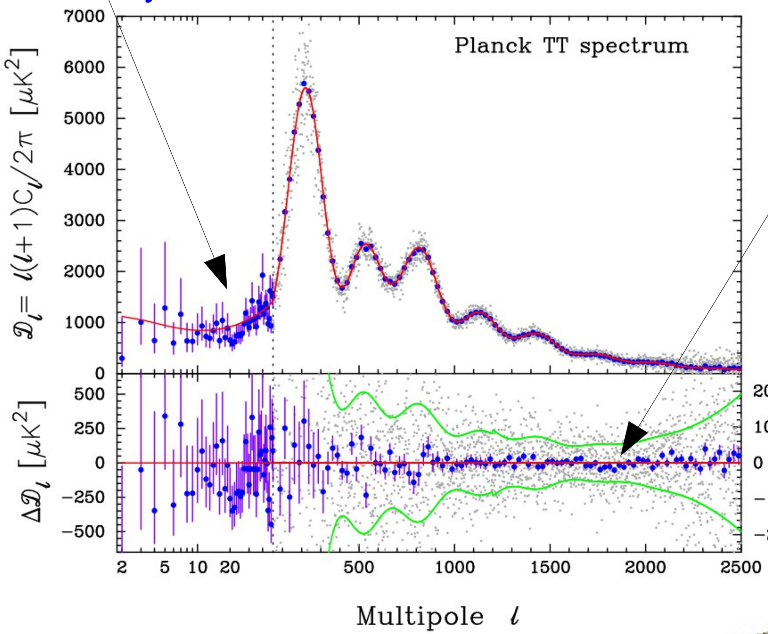
CFHTLens galaxy shear $\sigma_8 (\Omega_m/0.27)^{0.46} = 0.774 \pm 0.04$

Heymans et al. 2013

# … and other oddities...

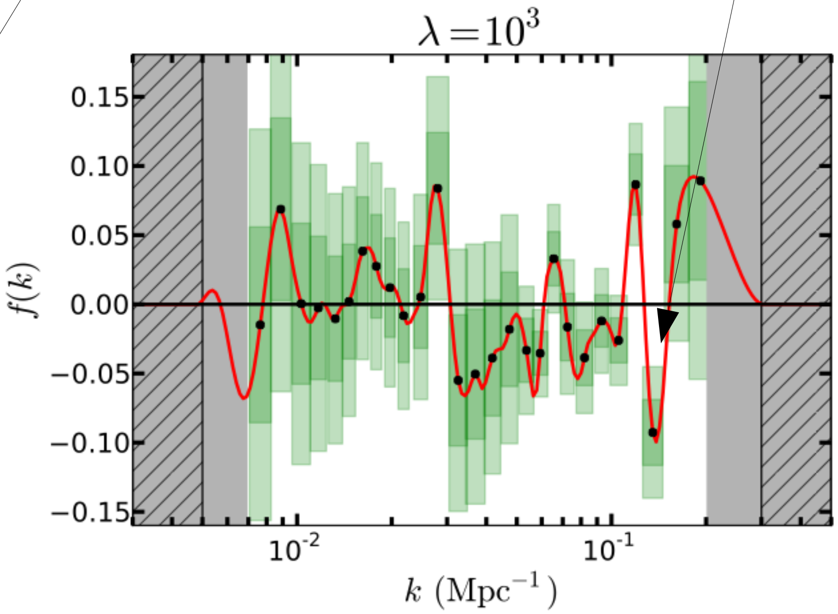
## Lack of power on large scales

Already present in WMAP; Now exacerbated by better small-scale data



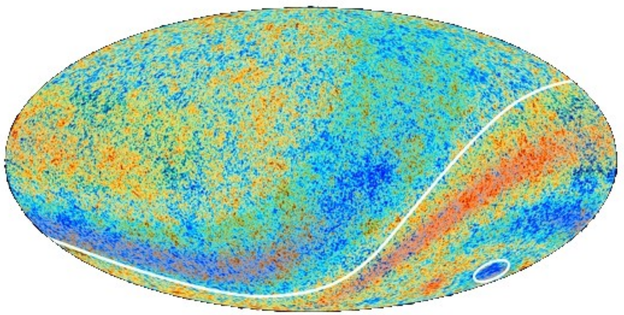

## A small feature on small scales

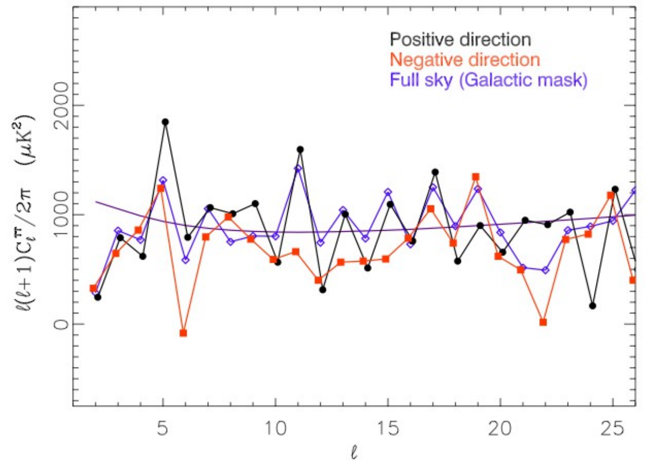
Nonparameteric reconstruction of the primordial power spectrum




## Hemispherical difference in power & the cold spot

Already present in WMAP;
Planck confirms that these are not due to data processing





What does this all mean for particle physics?

# Heaps of fun things to constrain...

- **Neutrinos**
- **Axions (QCD and axion-like particles)**
- **Dark matter models**
- Inflation models
- Models of dynamical dark energy
- ...

Complementary lab experiments, astrophysical observations, etc. available

# Implications for neutrino physics...

**Standard ΛCDM** has these fixed values:

Minimum mass sum established by neutrino oscillation experiments

$$\sum m_\nu = 0.06\ \mathrm{eV}$$
$$N_{\mathrm{eff}} = 3.046$$

Non-interacting radiation density equivalent to 1 thermalised species of massless standard model neutrinos with temperature $T_\nu = (4/11)^{1/3}\ T_\gamma$

**Not** the same number probed by LEP Z-width!

- Constraints:

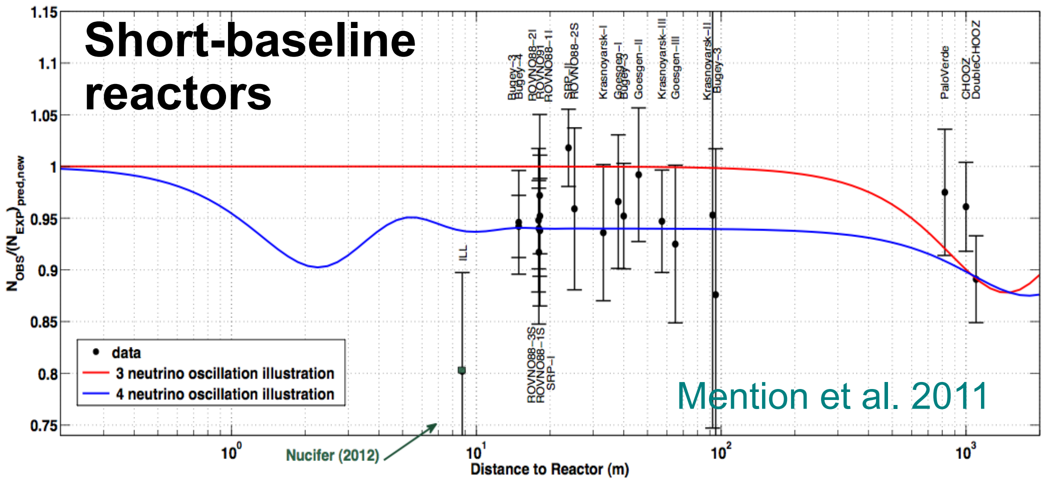
| 95% limits | Planck TT,TE,EE + lensing + lowP | Planck + Baryon acoustic oscillations | Planck + Lyman-alpha |
|---|---|---|---|
| $\sum m_\nu$ | $<0.59$ eV | $<0.23$ eV | $<0.12$ eV<br>Palanque-Delabrouille et al. 2015 |
| $N_{\mathrm{eff}}$ | $2.99 \pm 0.40$ | $3.04 \pm 0.18$ | |

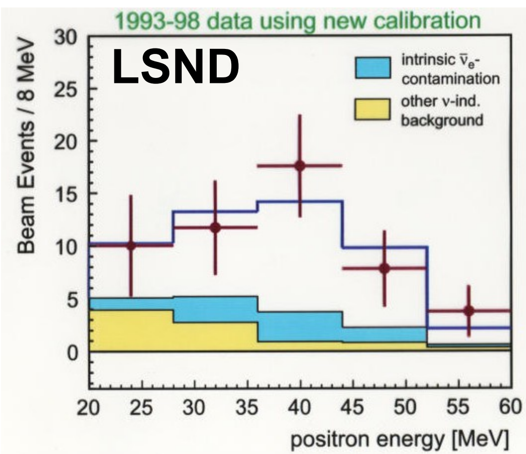
→ **No evidence** for light neutrino masses or “additional neutrino species”...

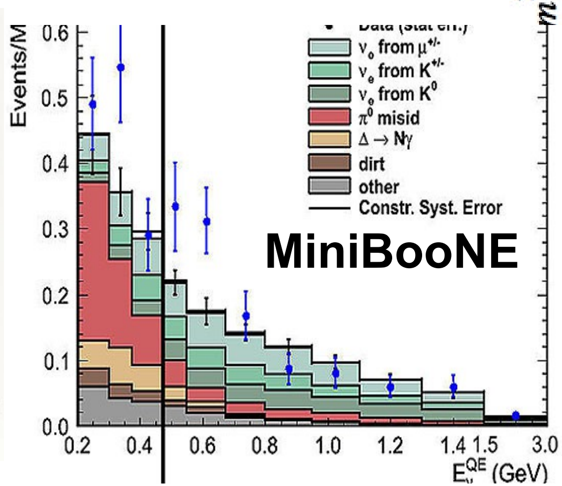
Doesn't bode well for the **~eV-mass "short baseline" sterile neutrino**...

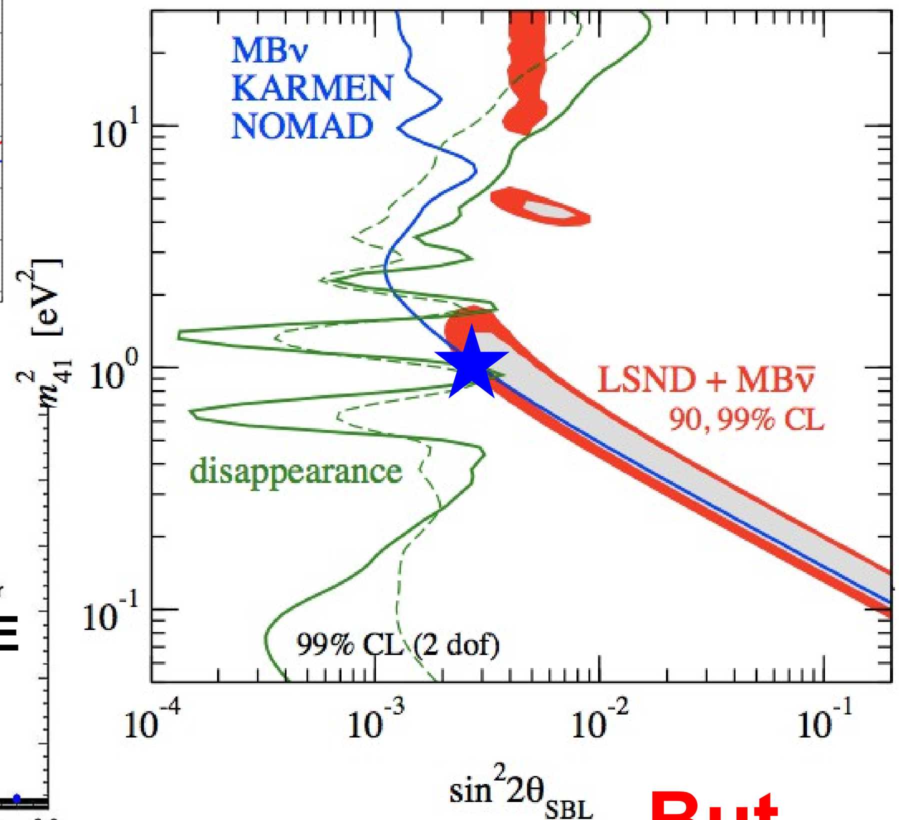
$$\Delta m^2_{SBL} \sim 1 \ \ \mathrm{eV}^2$$
$$\sin^2 2\theta_{SBL} \sim 3\times 10^{-3}$$

Kopp, Maltoni & Schwetz 2011



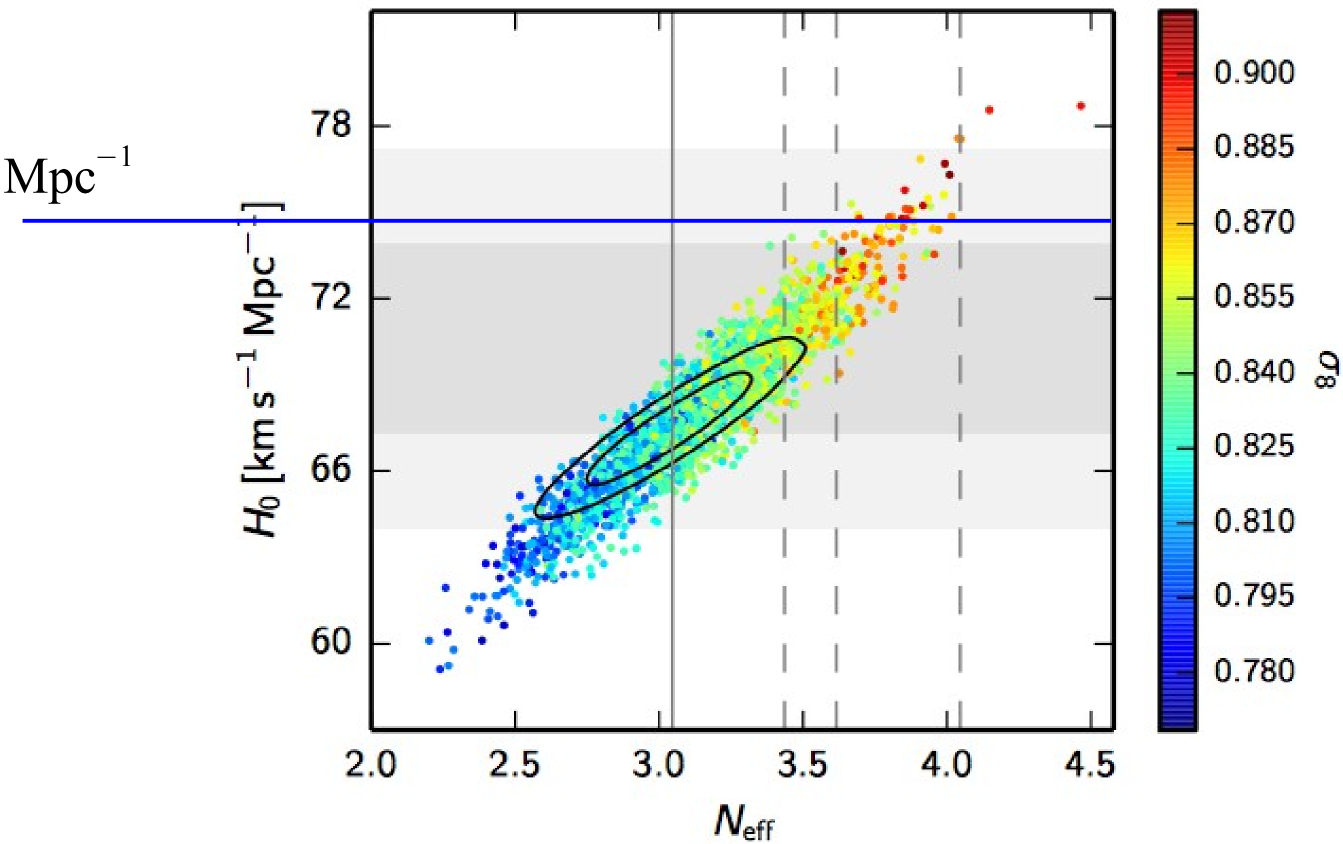

**But...**

# Neutrinos > The $N_{eff}$-$H_0$ degeneracy...

A larger $N_{\rm eff}$ does bring the Planck-inferred $H_0$ into better agreement with the HST measurement of the local expansion rate .

$$H_0 = 73.24 \pm 1.74\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Riess et al. 2016



# Implications for the QCD axion...

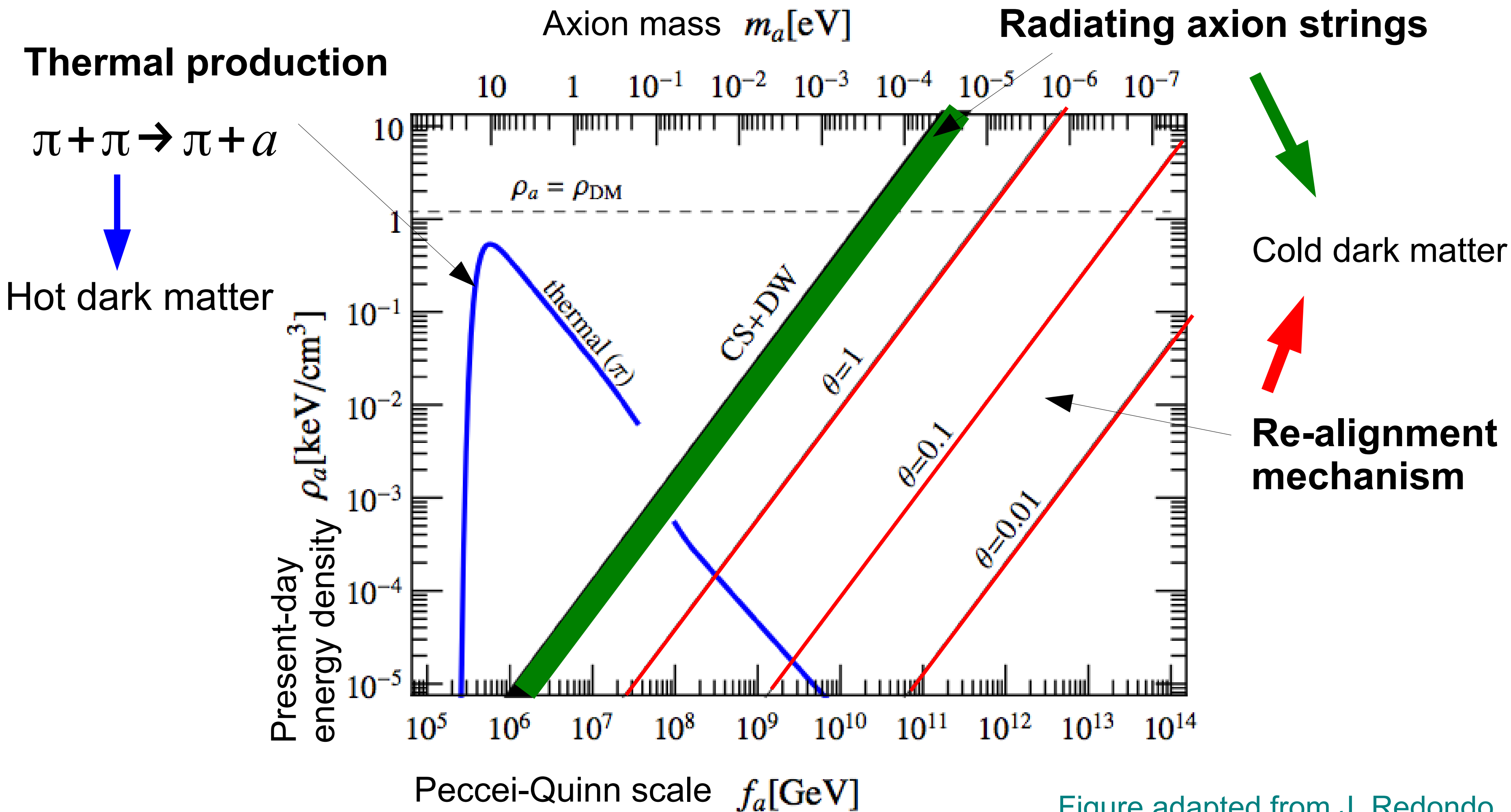
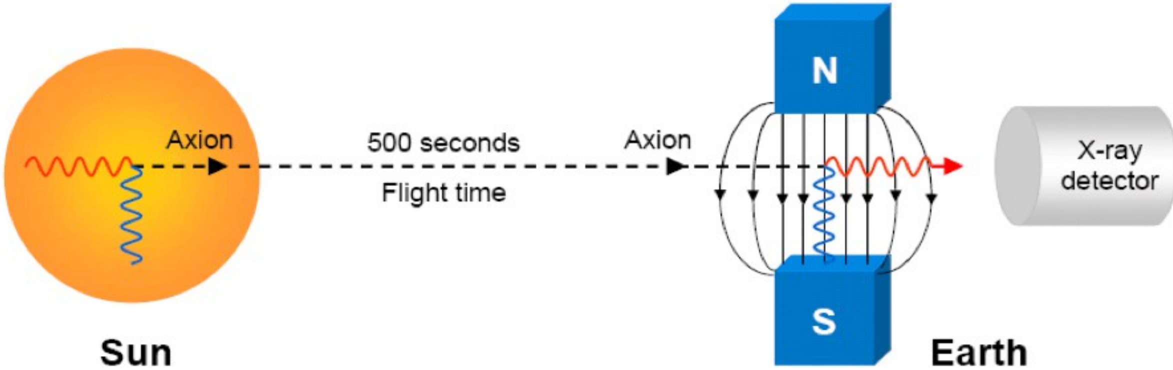



Figure adapted from J. Redondo

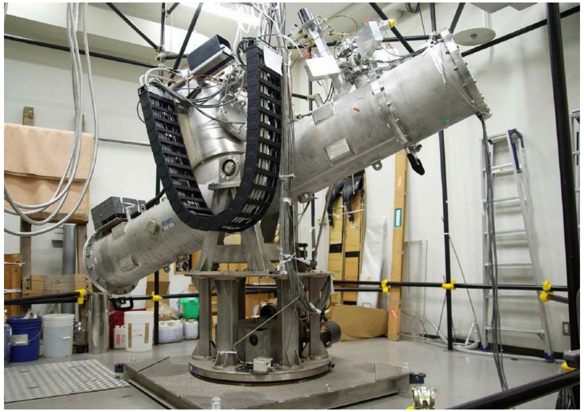
# QCD axion > CMB vs solar axion searches...

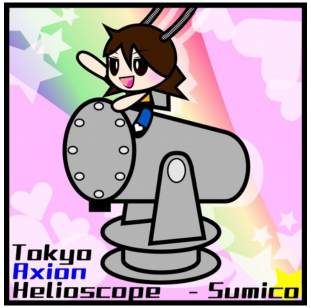
The hot dark matter axion parameter space overlaps with the search range for **solar axions**.



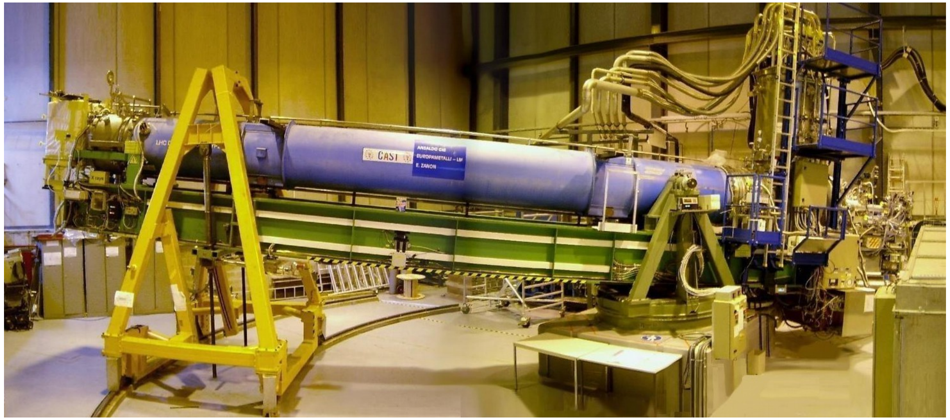


**Tokyo Axion Helioscope "Sumico"**





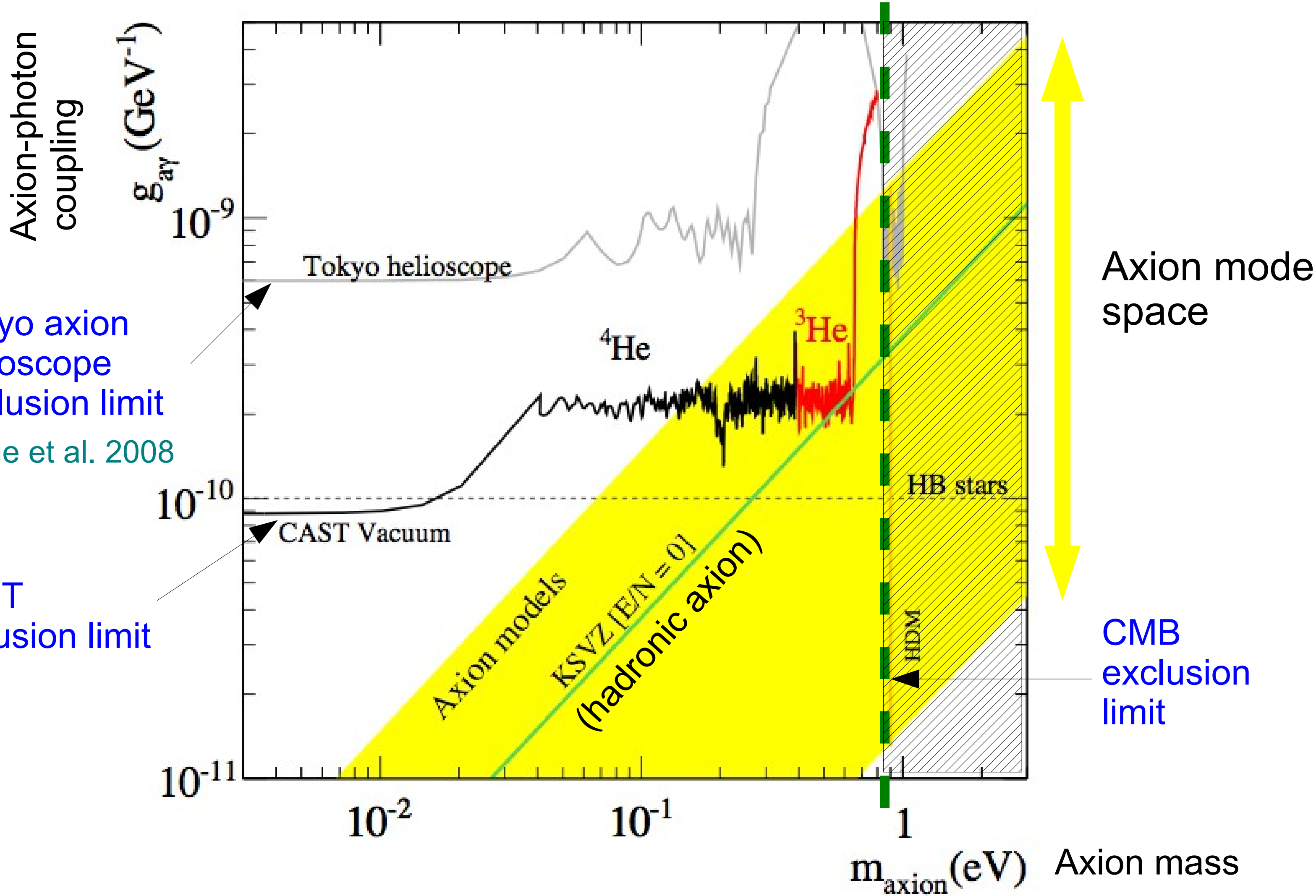

**CERN Axion Solar Telescope**




Tokyo axion helioscope exclusion limit

Inoue et al. 2008


CAST exclusion limit



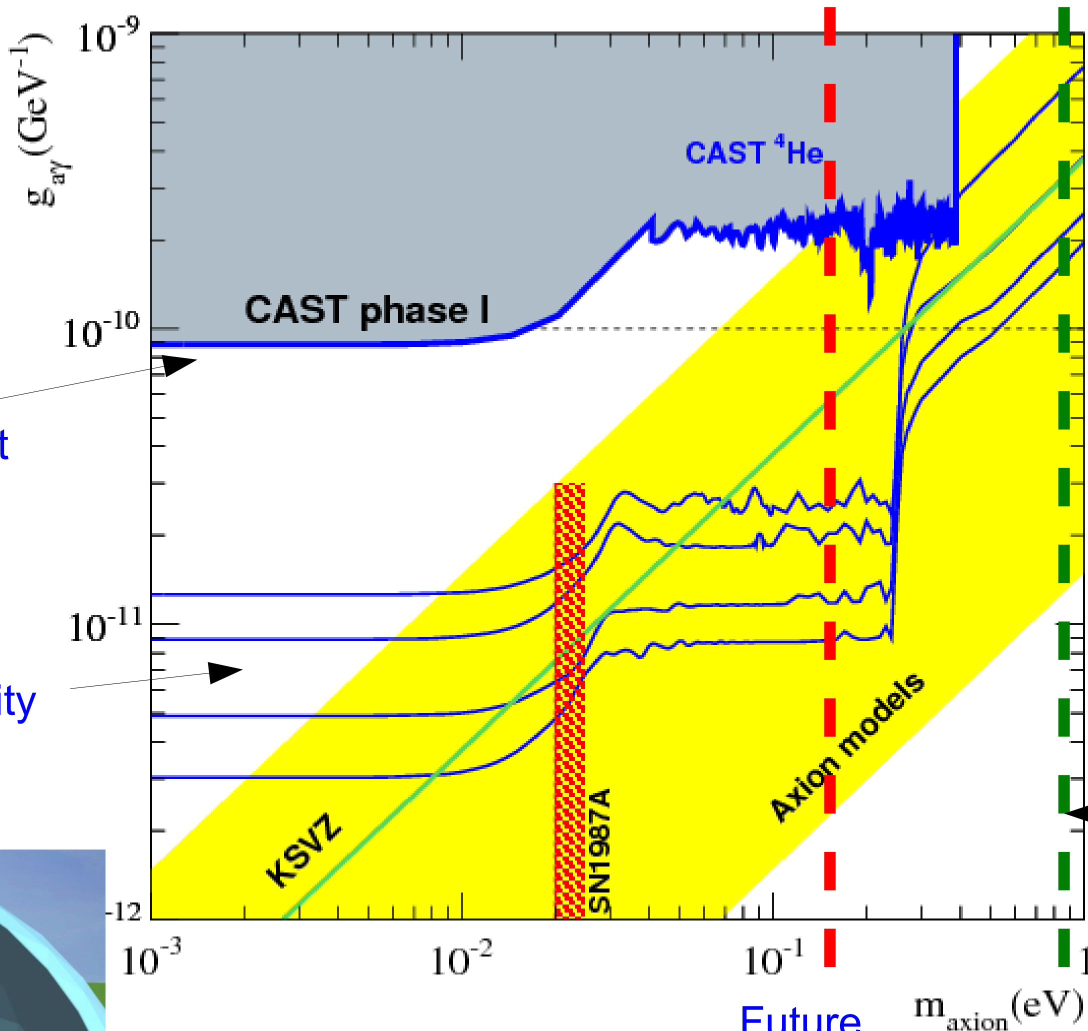

CMB exclusion limit

Aune et al. [CAST] arXiv:1106.3919

arXiv:1401.3233

Axion-photon coupling

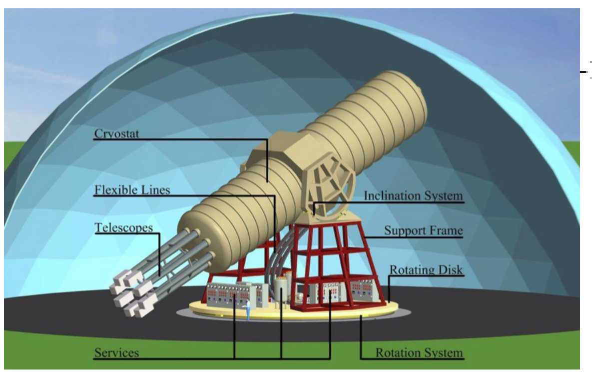

CAST exclusion limit




Axion model space

IAXO expected sensitivity

CMB exclusion limit




**Next generation**:
The **I**nternational **AX**ion **O**bservatory (IAXO)

Future cosmological sensitivity
Archidiacono et al. 2015

Axion mass

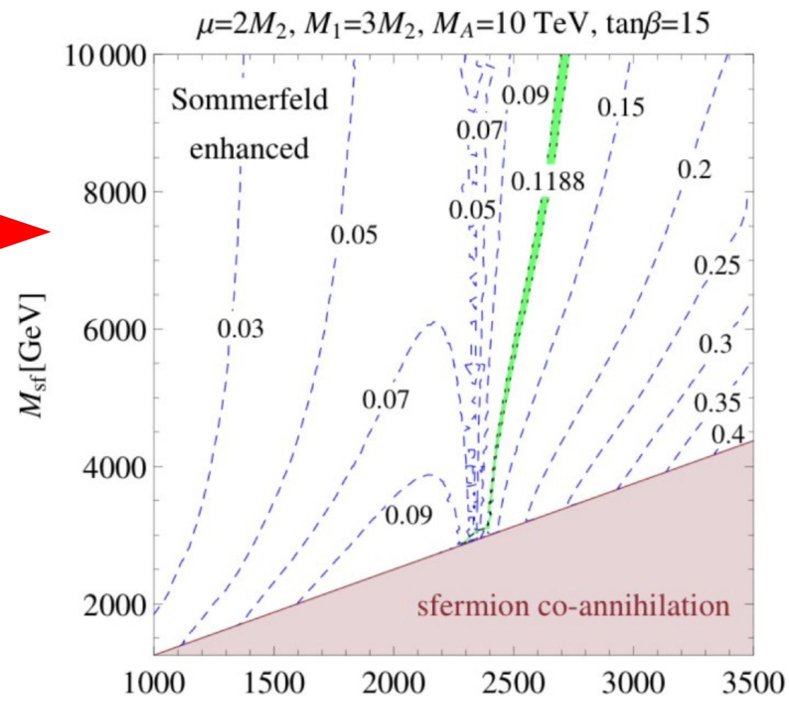
# Implications for dark matter models...

Constraint on the dark matter relic density:

$$\Omega_{\mathrm{DM}} h^2 = 0.1198 \pm 0.0015$$

Planck TT,TE,EE+lowP
6-parameter ΛCDM fit

- Translated into constraints in DM model parameter space, e.g.,

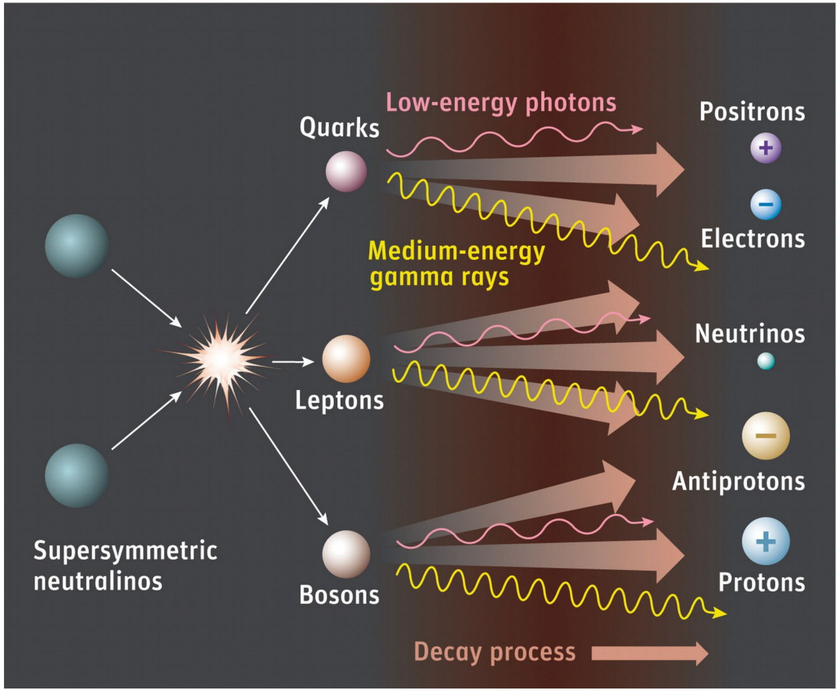



Many talks in the “Dark Matter & Particle Astrophysics session”

Wino-like DM in the MSSM $M_2$ [GeV] Beneke et al. 2016

# Dark matter > WIMP annihilation...

Chen & Kamionkowski 2004
Padmanabhan & Finknbeiner 2005




Annihilation injects energy into the plasma.

- Rate of energy release per unit volume:

Annihilation cross-section

$$\frac{dE}{dt\,dV} = \rho_{\mathrm{crit}}^2 \Omega_{\mathrm{DM}}^2 (1+z)^6 f(z) \frac{\langle \sigma v \rangle}{m_\chi}$$

Fraction of energy absorbed by the medium (model-dependent)

WIMP mass

- Heats up the medium.
- Ionisation and excitation of H → increases free electron fraction.

→ Delay photon decoupling

# Dark matter > WIMP annihilation...

Ade et al. [Planck] 2015

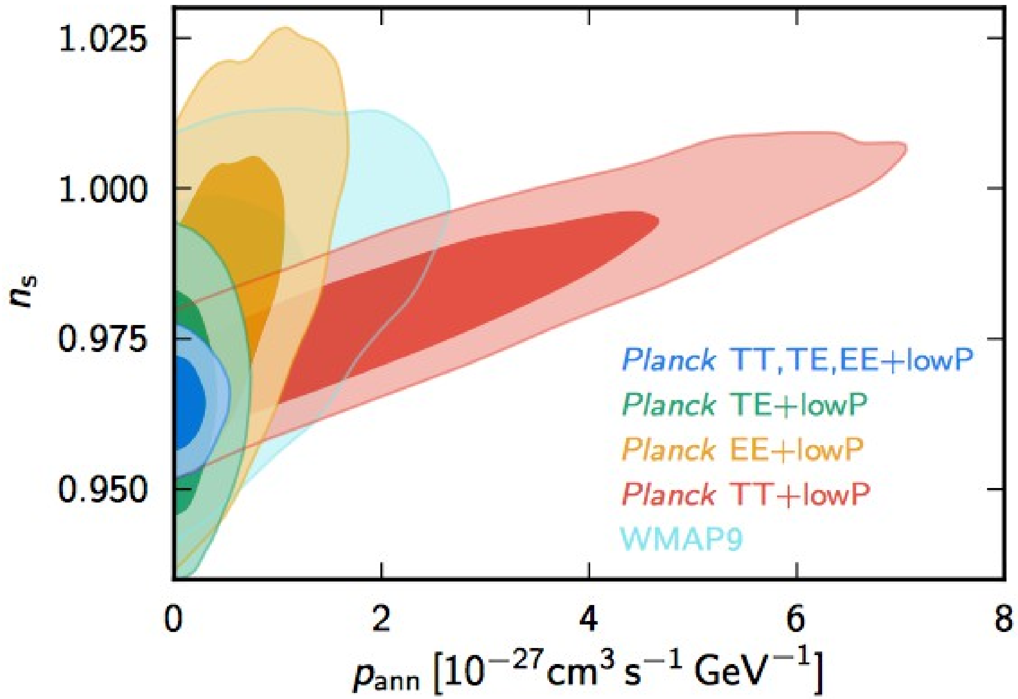



**Fig. 40.** 2-dimensional marginal distributions in the $p_{\rm ann}$–$n_s$ plane for *Planck* TT+lowP (red), EE+lowP (yellow), TE+lowP (green), and *Planck* TT,TE,EE+lowP (blue) data combinations. We also show the constraints obtained using WMAP9 data (light blue).

Parameter constrained by CMB data:

Annihilation cross-section

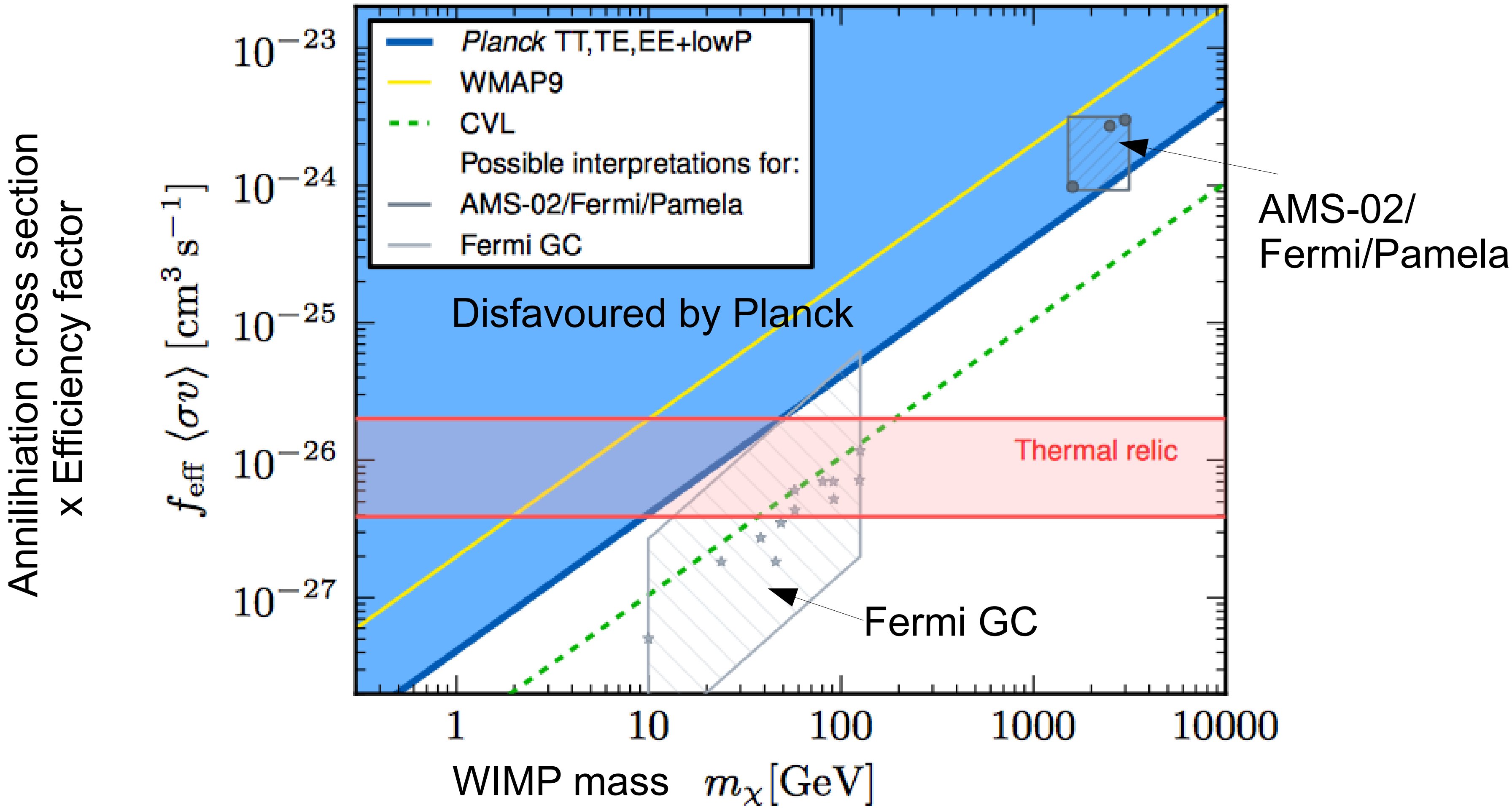
$$p_{\rm ann} \equiv f_{\rm eff} \frac{\langle \sigma v \rangle}{m_\chi}$$

Fraction of energy absorbed by the medium (model-dependent)

WIMP mass

# Dark matter > WIMP annihilation...

Ade et al. [Planck] 2015



# Dark matter > elastic scattering, invisible decay, etc.

Other DM scenarios constrainable by the CMB:

- DM elastic scattering
  - DM-photons
  - DM-neutrinos
  - DM-baryons (electrons or protons)
- Invisible decay

Wilkinson, Boehm & Lesgourgues 2013, 2014
Mangano, Melchiorri, Serra, et al. 2006
Dvorkin, Blum & Kamionkowski 2013
Gong & Chen 2008
Dutta & Scherrer 2010
Audren, Lesgourgues, Mangano & Tram 2014
etc.

# 13th International Symposium on Cosmology and Particle Astrophysics (CosPA 2016), Sydney, Nov 28 – Dec 2, 2016

LOC: Jan Hamann (USyd), Gary Hill (Adelaide), Archil Kobakhidze (USyd), Geraint Lewis (USyd), Michael Schmidt (USyd), Kevin Varvell (USyd), Yvonne Wong (UNSW)

# Summary...

- There are many ways in which the "standard" ΛCDM model may be extended, some of which follow from particle physics motivations.

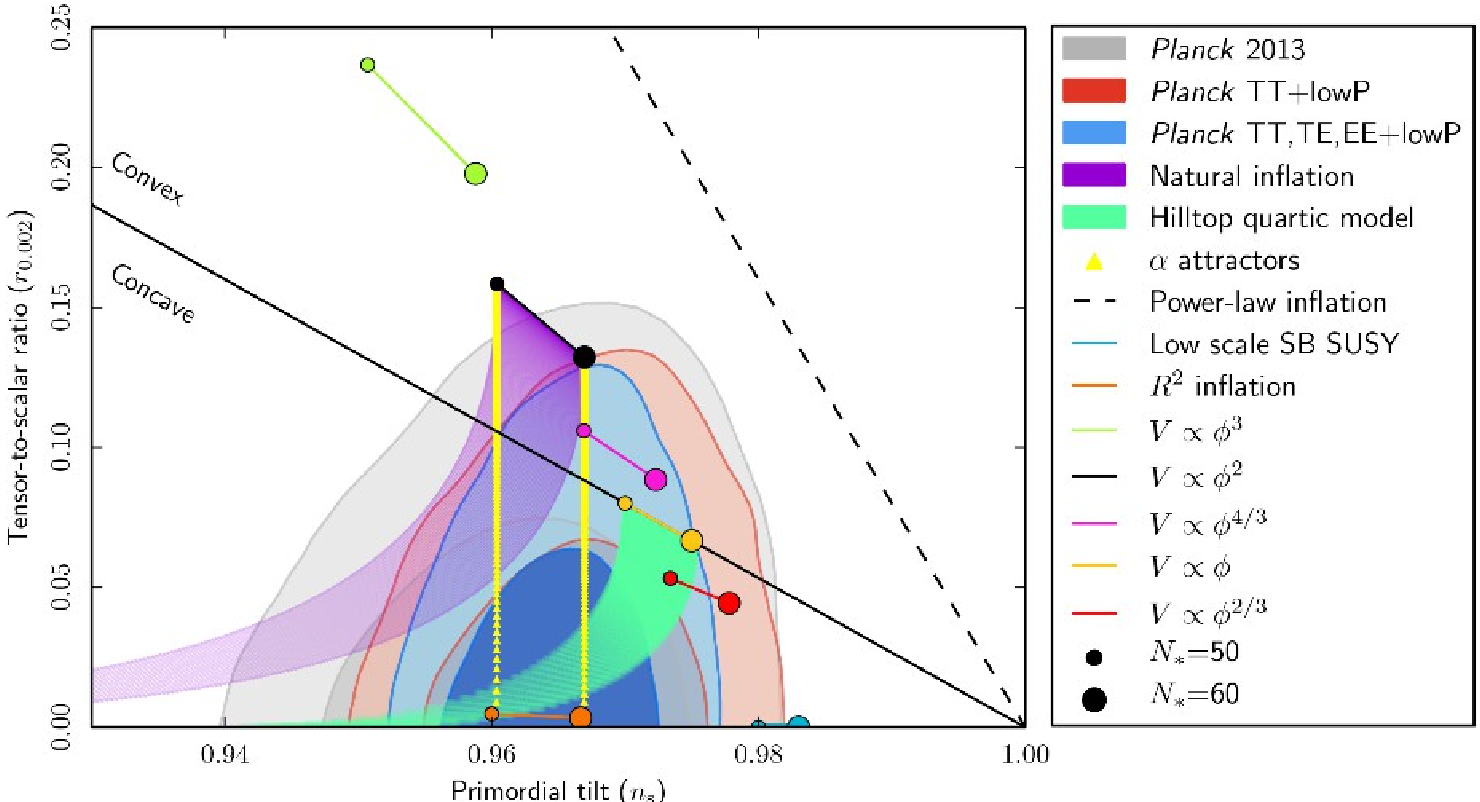
- Precision cosmological observations of the CMB and other non-CMB probes allow us

  - to explore the robustness of the assumptions underpinning ΛCDM, and hence

  - to set constraints on these extensions (or maybe even find them one day...). Many of these constraints, especially those on neutrino and dark matter properties, are even competitive with and/or complementary to other available measurements (laboratory, astrophysical observations, etc.).

# Implications for inflation models...

**Tensor-to-scalar amplitude ratio, *r*, vs scalar spectral index, $n_s$,** for various inflation models:




Ade et al. [Planck] 2015

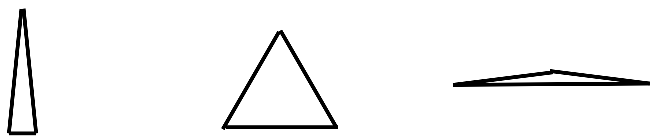
# Inflation > Primordial non-Gaussianity...

**Non-Gaussianity** = nonzero connected N-point function, N>2.

- 3-point function:

$$\langle \Phi(\vec{k}_1)\Phi(\vec{k}_2)\Phi(\vec{k}_3)\rangle = (2\pi)^3\,\delta^{(3)}\overbrace{(\vec{k}_1+\vec{k}_2+\vec{k}_3)}^{\text{Enforces triangular configuration}}\,\overbrace{f_{\rm NL}\;F(k_1,k_2,k_3)}^{\text{Bispectrum}}$$

- Planck constraints on 3 limiting cases:



| $f_{\rm NL}$ | | |
|---|---|---|
| Local | Equilateral | Orthogonal |
| $2.7 \pm 5.8$ | $-42 \pm 75$ | $-25 \pm 39$ |

→ **No evidence** for primordial non-Gaussianity

→ Constraints consistent with $f_{\rm NL} < 1$ for single-field canonical slow-roll inflation

# Implications for dynamical dark energy...

**No evidence** for an equation of state deviating from $w = P/\rho = -1$.

- Constraints:

| 95% limits | Planck TT + lowP | Planck TT,TE,EE + lowP + Baryon acoustic oscillations + H0 + SNIa |
|---|---|---|
| $w$ | $-1.54^{+0.62}_{-0.50}$ | $-1.019^{+0.075}_{-0.080}$ |

→ A **cosmological constant** $(w = -1)$ still works very well.

- Quintessence: $w > -1$
- Phantom energy: $w < -1$
- etc.