COSMOLOGICAL CONSTRAINTS ON LIGHT STERILE NEUTRINOS

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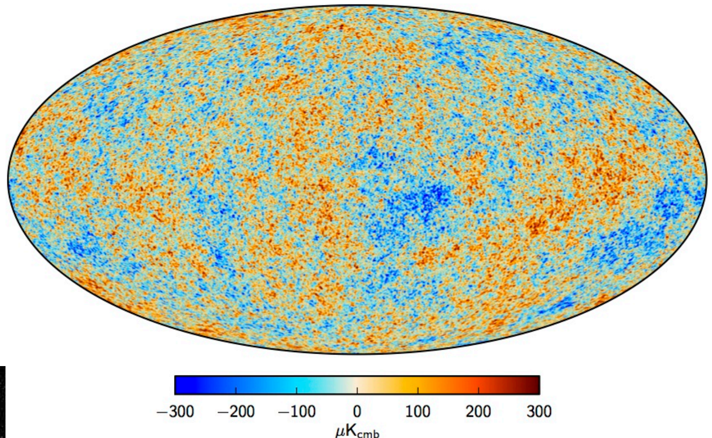
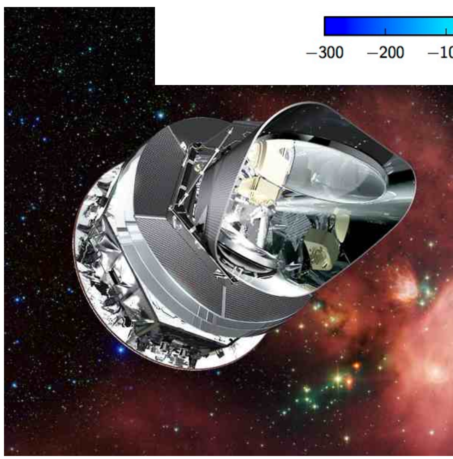
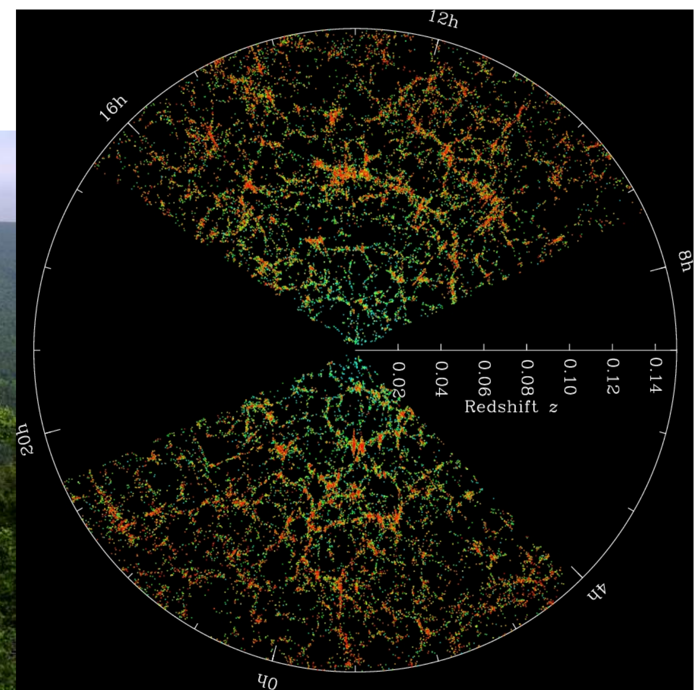
WORKSHOP ON SHORT BASELINE NEUTRINO OSCILLATION PHYSICS
UNIVERSITY OF PITTSBURGH, 26 JANUARY 2016

The Standard Cosmological Model





The six-parameter, vacuum-dominated cold dark matter (ΛCDM) cosmological model is the simplest model that can explain present cosmological observations

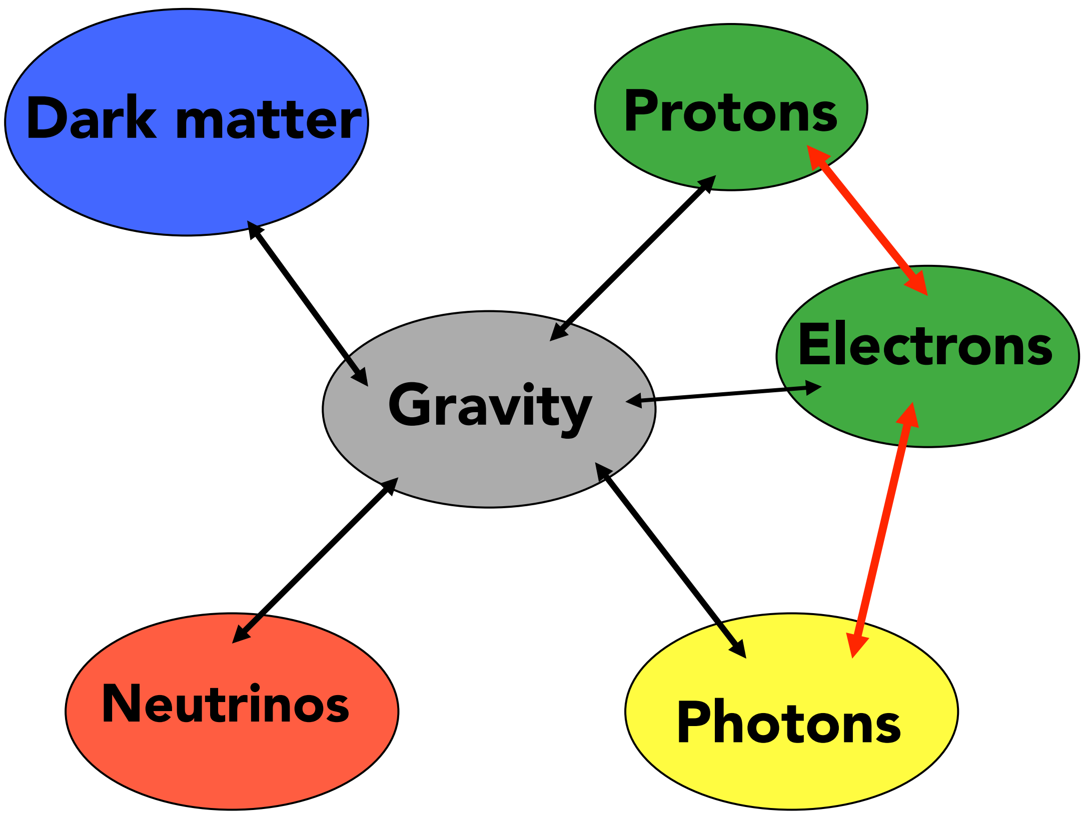


THE STANDARD COSMOLOGICAL MODEL

- The Universe is spatially homogeneous and isotropic (cosmological principle)
- The Universe is **flat**, and its energy density is provided by
  - **non-relativistic matter** (baryons and dark matter) (~25% today)
  - "**radiation**" (photons and neutrinos) (~10^{-5} today)
  - a **cosmological constant**-like component (~75% today)
- The initial fluctuations were **gaussian**, **adiabatic** and with a **nearly scale-invariant** spectrum – generated from single-field inflation.
- **Six parameters**: three for the **matter-energy content and background geometry** (usually baryon density, DM density, distance to last scattering surface), two for **initial conditions** (amplitude and slope of the primordial spectrum), one for **reionization**.

THE STANDARD COSMOLOGICAL MODEL

Should be cold or warm



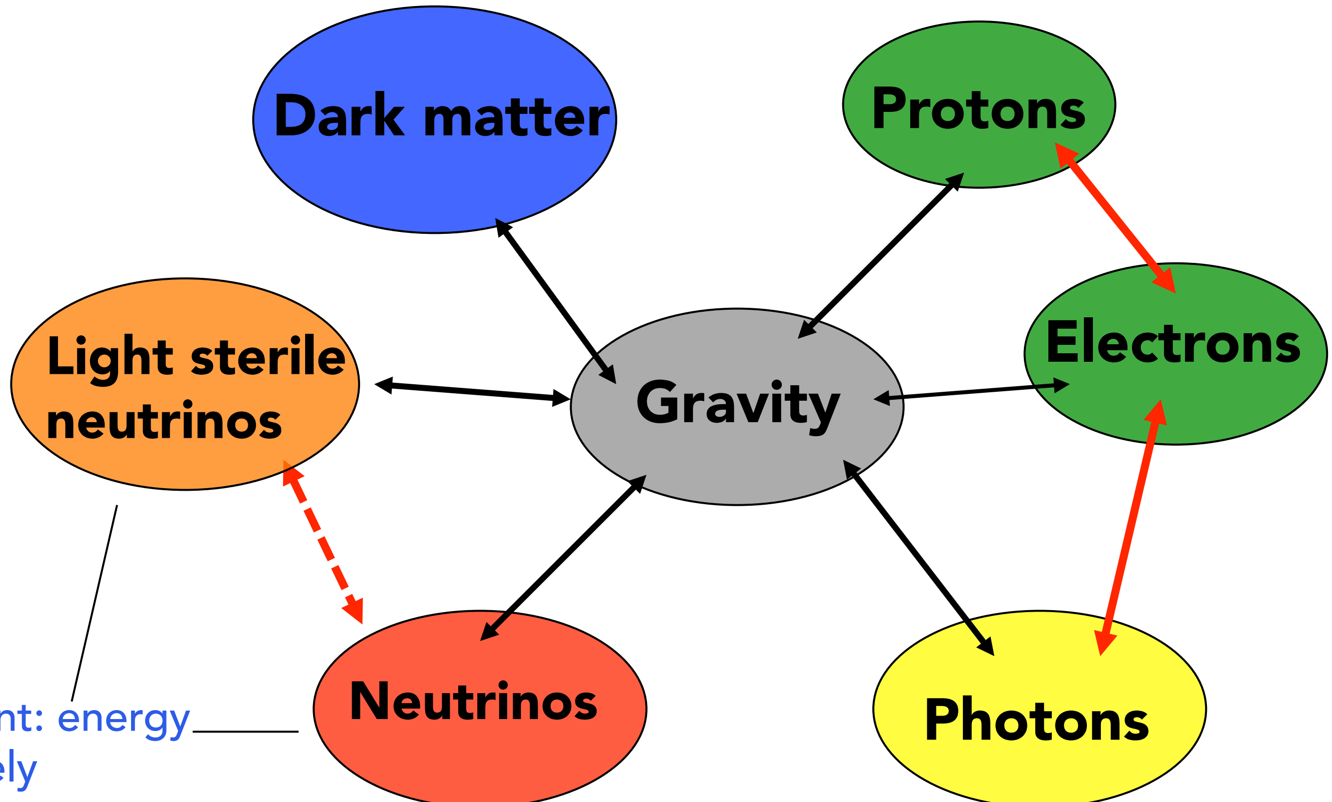
Hot component: energy density severely constrained by structure formation

Number density fixed by SM physics.
One unknown: total mass (in LCDM fixed to the minimum value from oscillations)

Energy density fixed by observations

Cosmology and sterile neutrinos

Should be cold or warm



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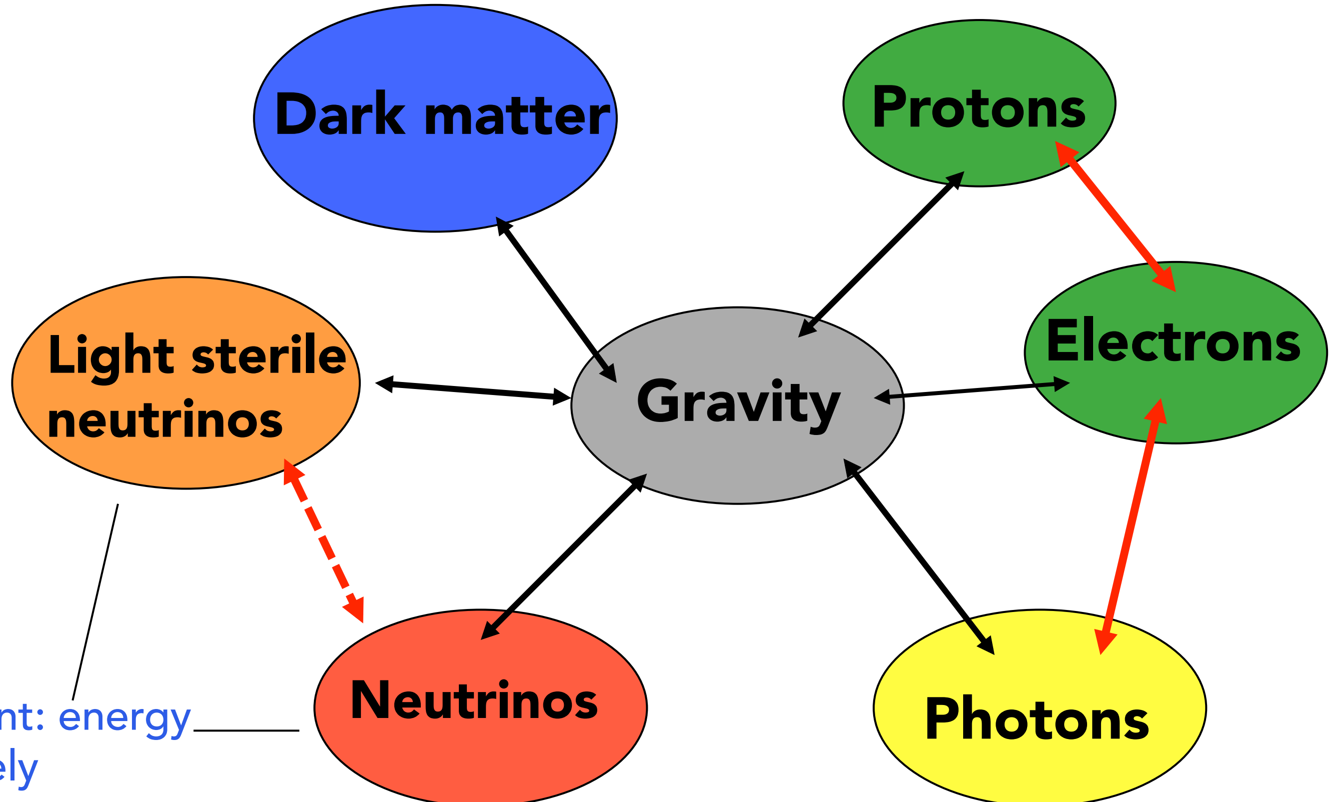
COSMOLOGY AND STERILE NEUTRINOS

Should be cold or warm

Larger density of relativistic species (faster expansion)
+
Suppression of small-scale perturbations



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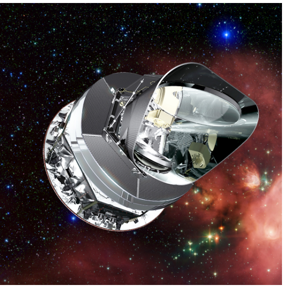
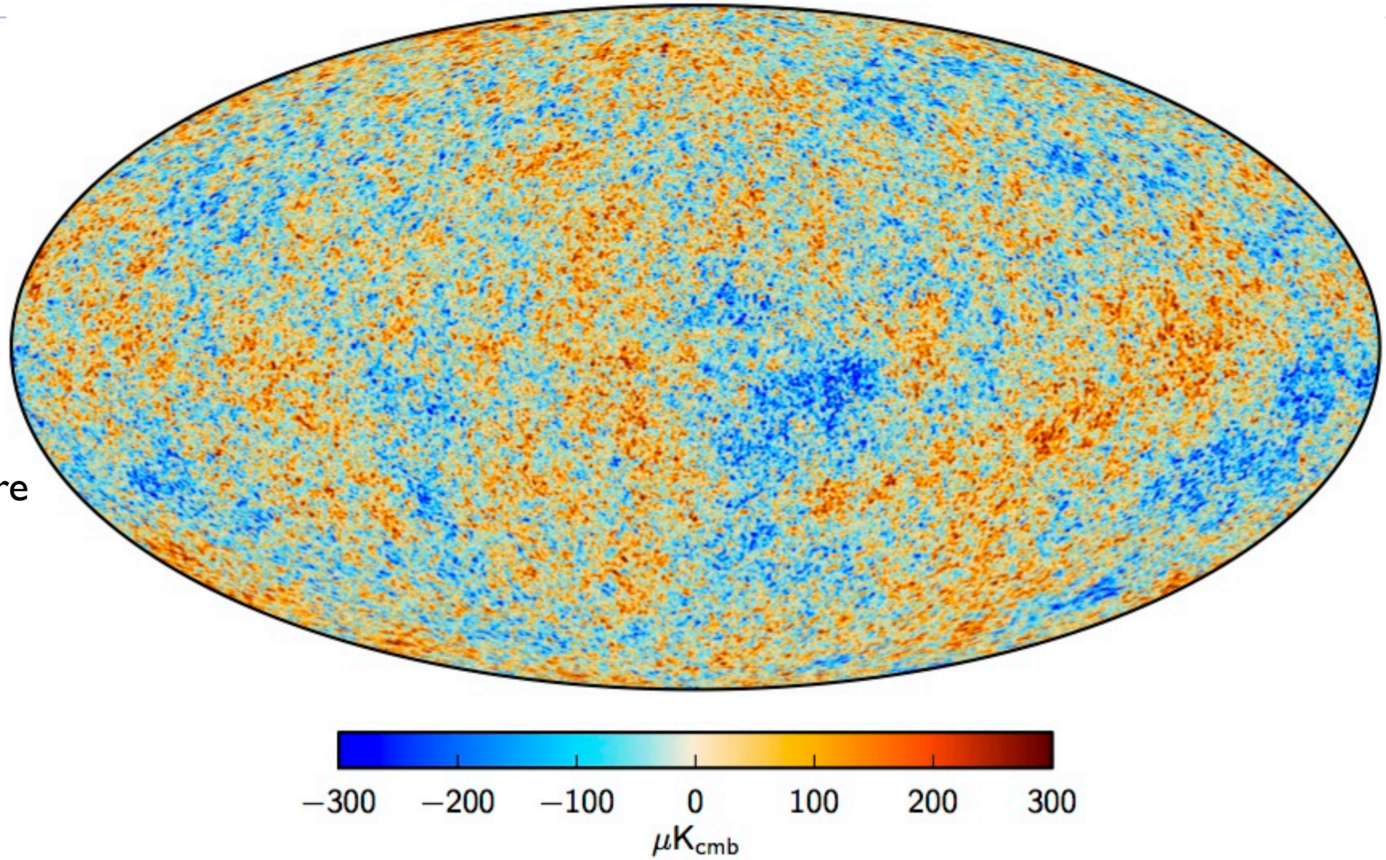
The Cosmic Microwave Background



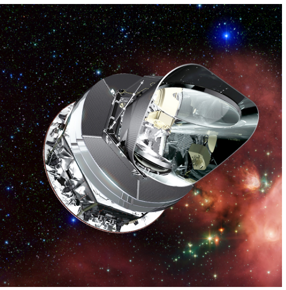


Full sky temperature map from Planck (2015)

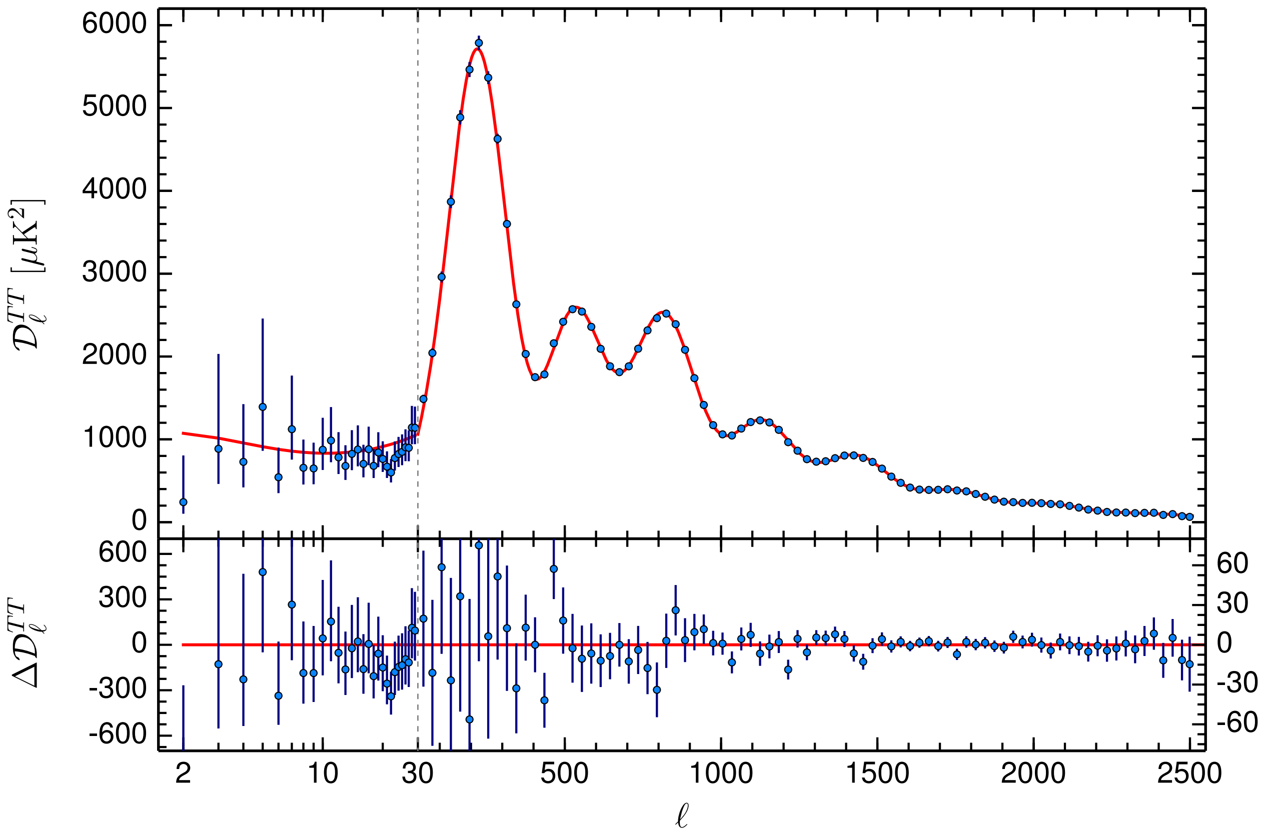
The CMB is a blackbody radiation with T=2.7 K extremely uniform across the whole sky; it is the relic radiation emitted at the time the nuclei and electrons recombined to form neutral hydrogen, when the Universe was ~ 400,000 years old (the so-called last scattering surface, LSS).

Its tiny (~ 10^{-5}) temperature and polarization anisotropies encode a wealth of cosmological information.

THE COSMIC MICROWAVE BACKGROUND



Power spectrum of temperature fluctuations from Planck (2015)



If the fluctuations are gaussian, all the statistical information in the map is encoded in the two point correlation function or in its harmonic transform, the angular power spectrum:

$$\Theta(\hat{n}) = \sum_{\ell=0}^{\ell=\infty} \sum_{m=-\ell}^{+\ell} a_{\ell m} Y_{\ell m}(\hat{n})$$

$$\langle a_{\ell m} a^*_{\ell' m'} \rangle = \delta_{\ell\ell'} \delta_{mm'} C_\ell$$

COSMOLOGY AND STERILE NEUTRINOS

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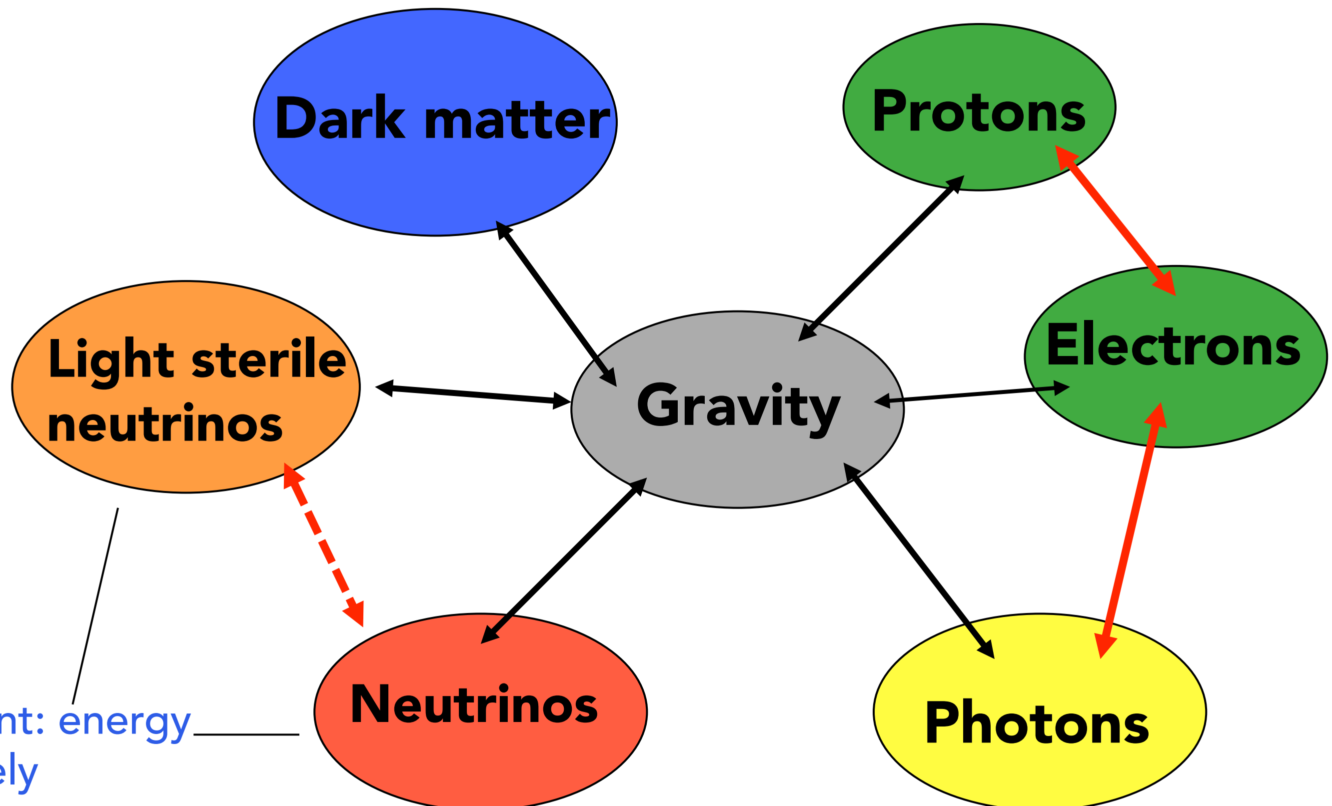

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Energy density fixed by observations

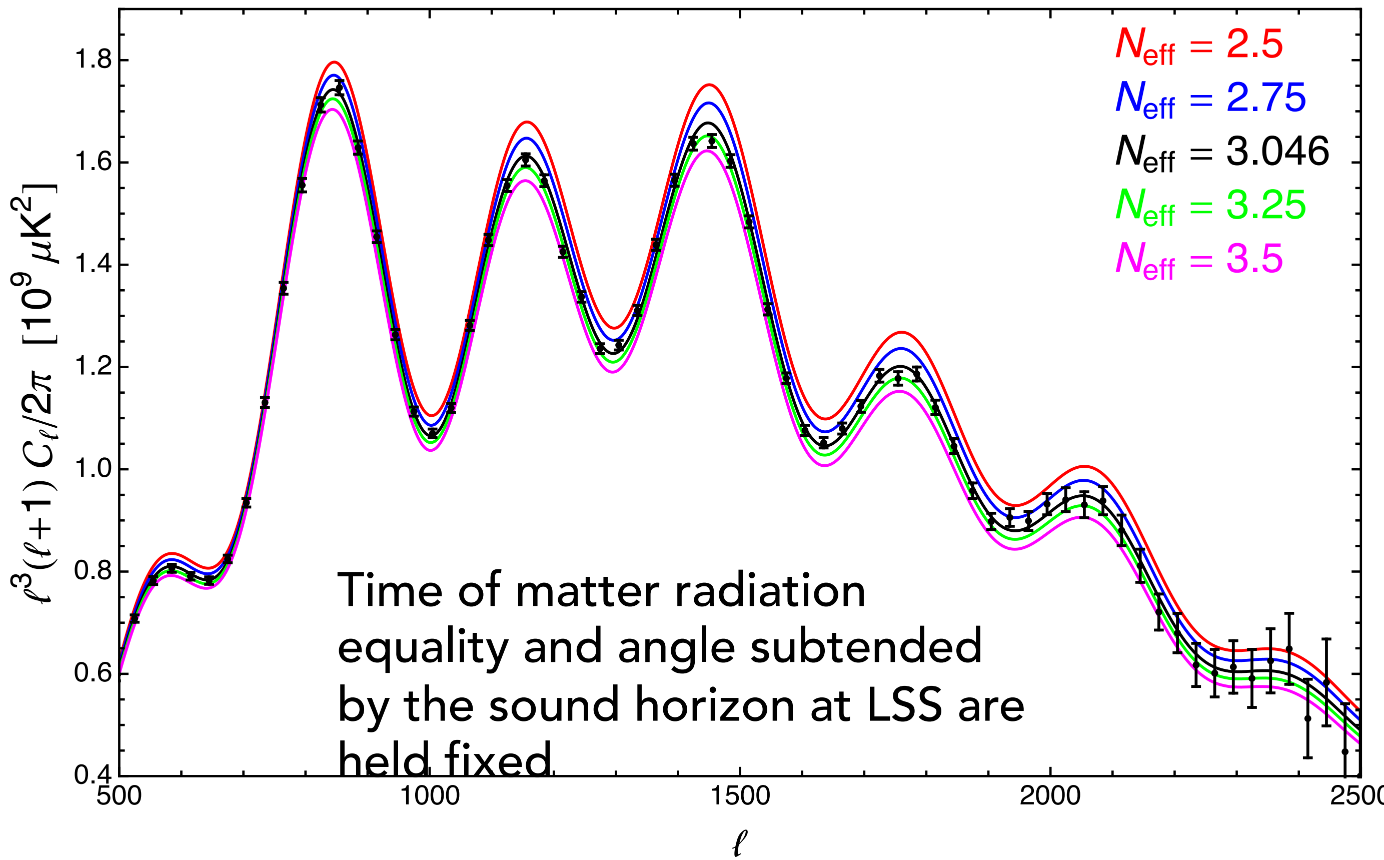
The Cosmic Neutrino Background

$$\rho_{\rm rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

Energy density in units of "standard" neutrino density (thermally distributed with T=1.9 K)

Increasing $N_{\rm eff}$ makes the Universe younger at recombination and increases the angular scale of the photon diffusion length

increased Silk damping and reduced power in the damping tail.



(note I am showing ~ $l^4 C_l$, not $l^2 C_l$)

COSMOLOGY AND STERILE NEUTRINOS

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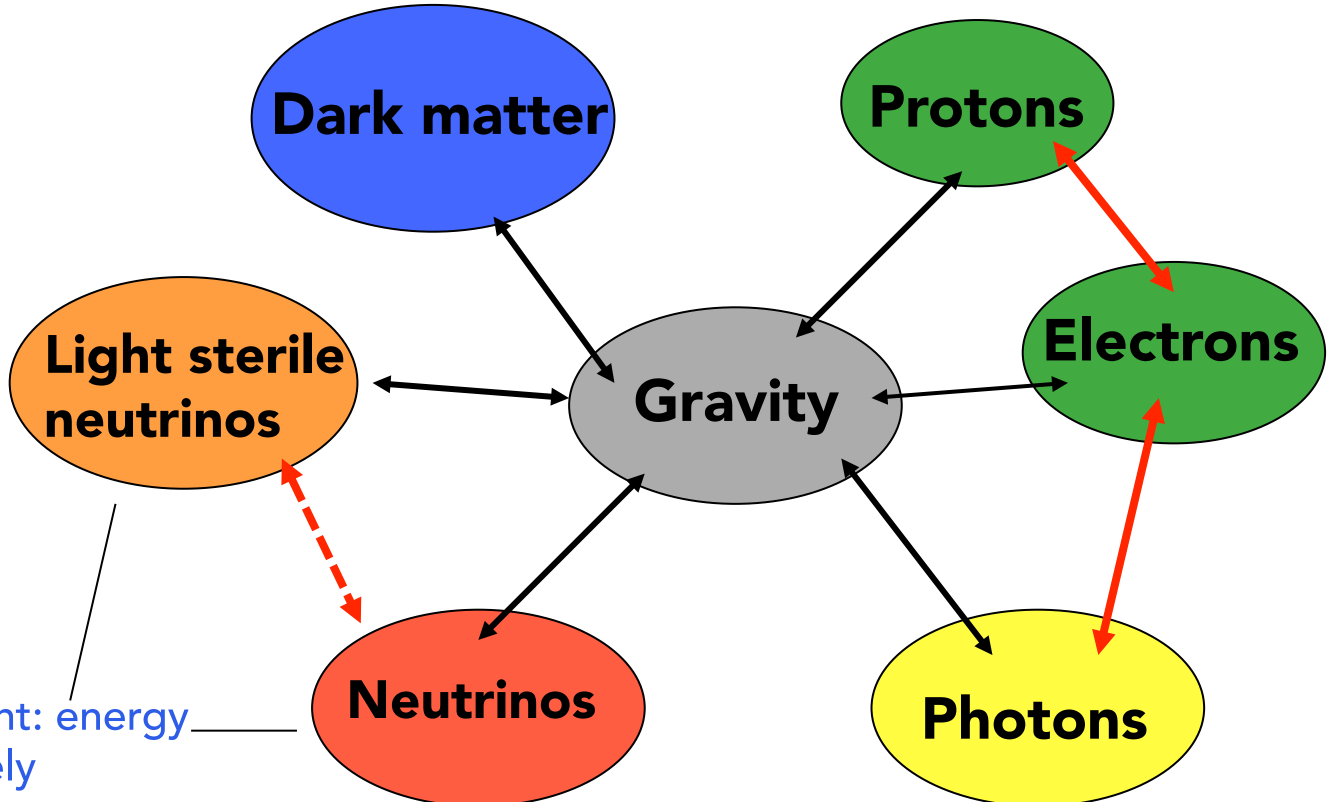

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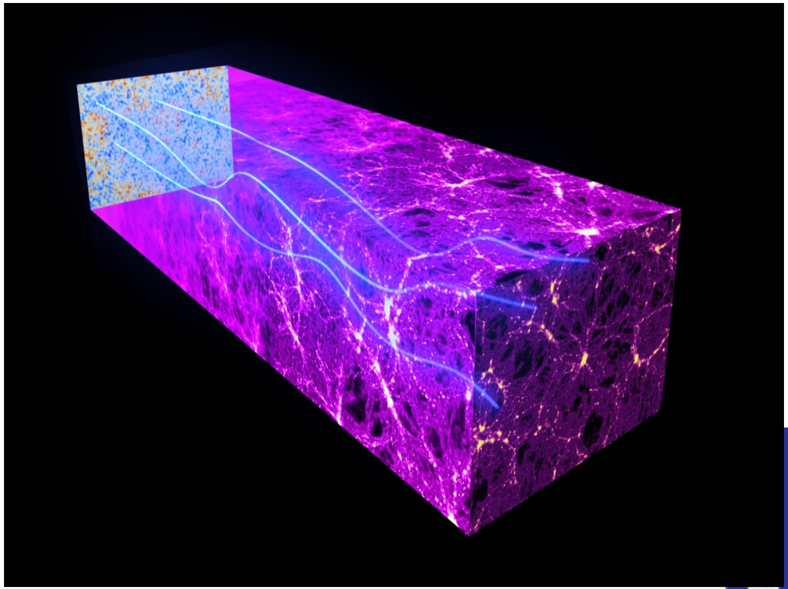
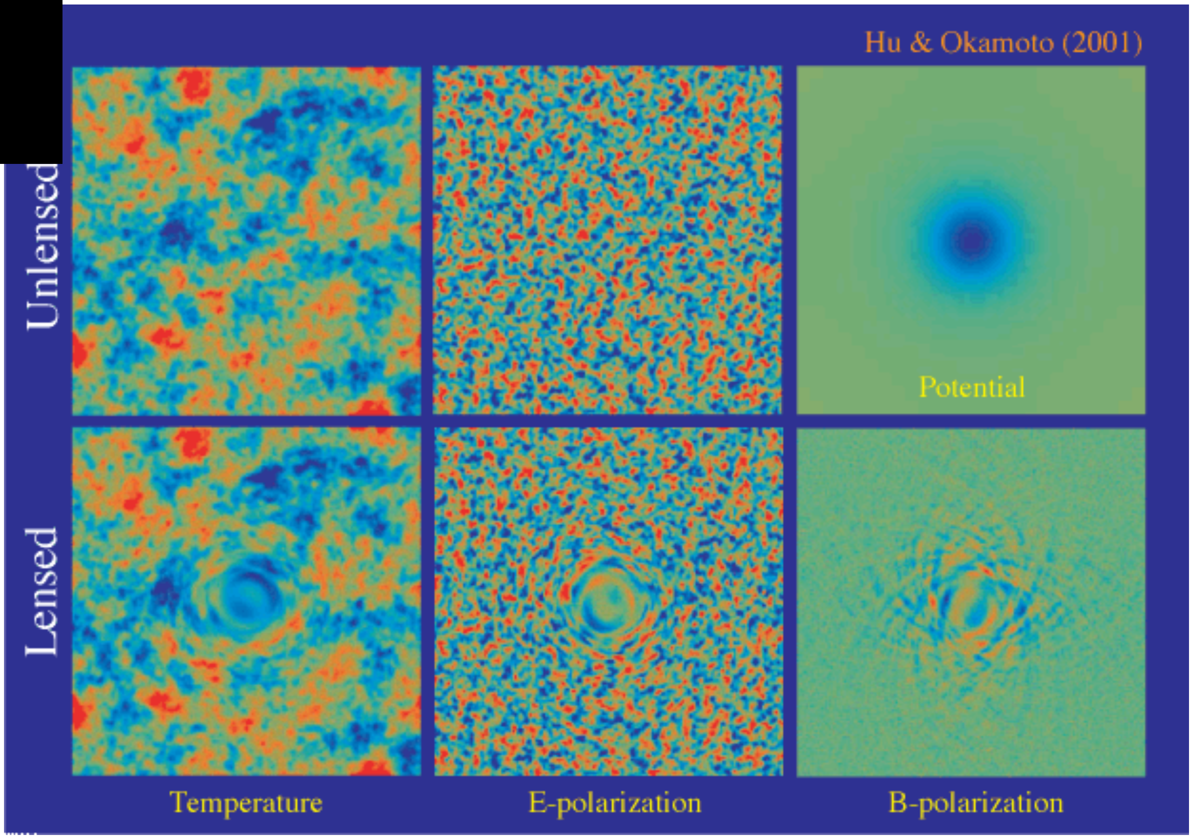
CMB Lensing



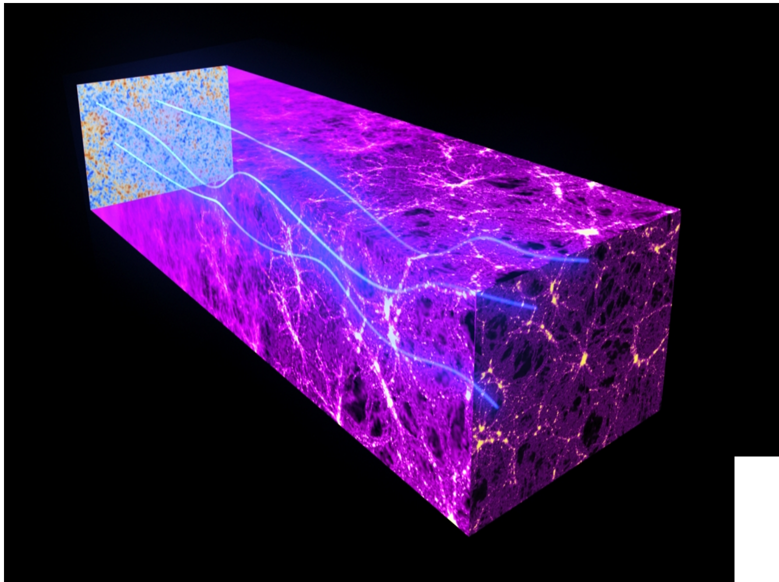
The CMB anisotropy pattern is distorted ("blurred") by the weak lensing effect due to the intervening structures between us and the last scattering surface



The effect is relevant at small scales (~ % effect at sub-degree scales) and results in a smearing of the power spectrum at high multipoles. It also induces a non-gaussian signal.

CMB lensing probes the matter distribution of the Universe.

CMB Lensing



The CMB anisotropy pattern is distorted ("blurred") by the weak lensing effect due to the intervining structures between us and the last scattering surface

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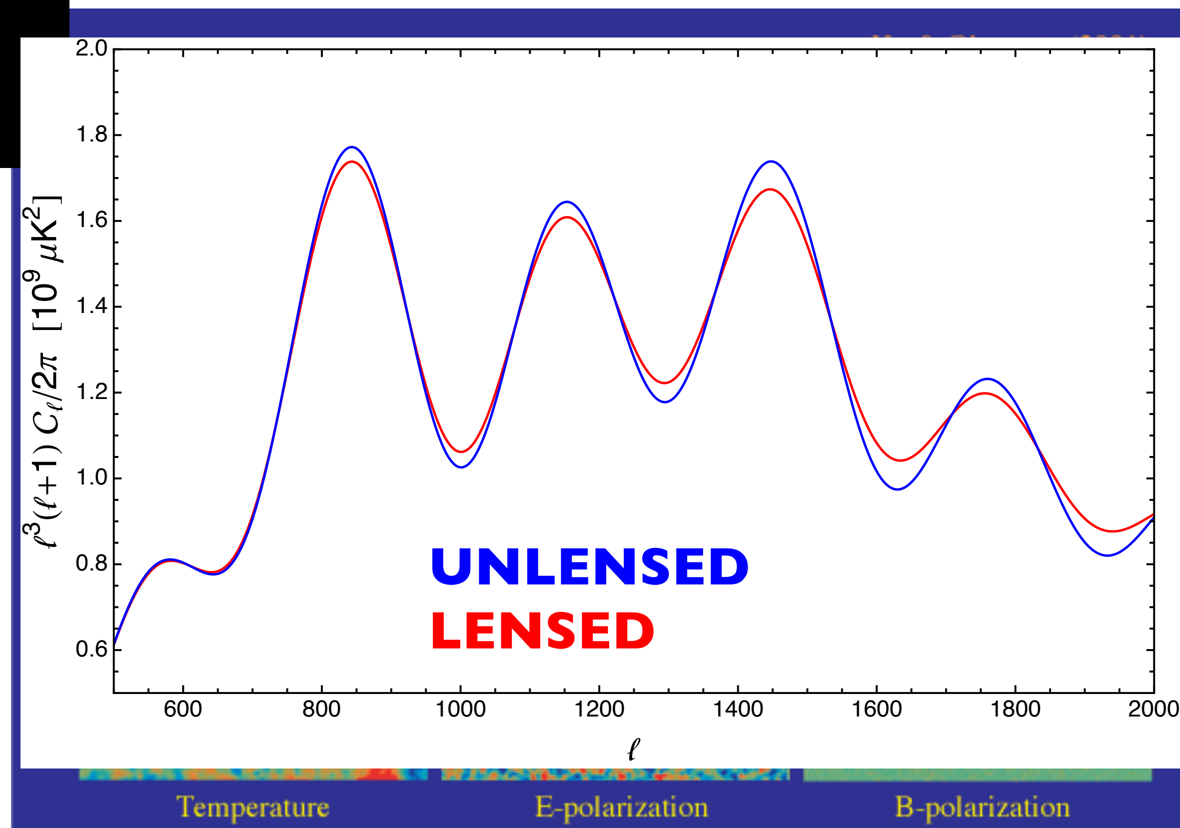
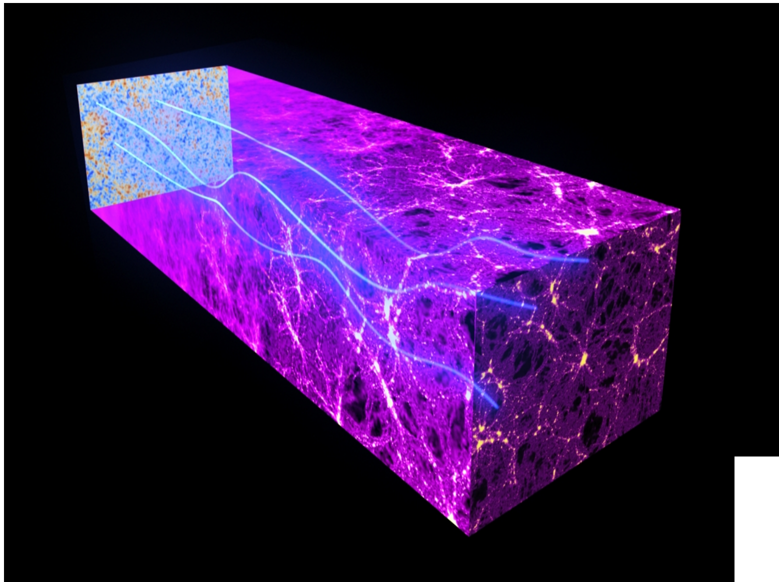
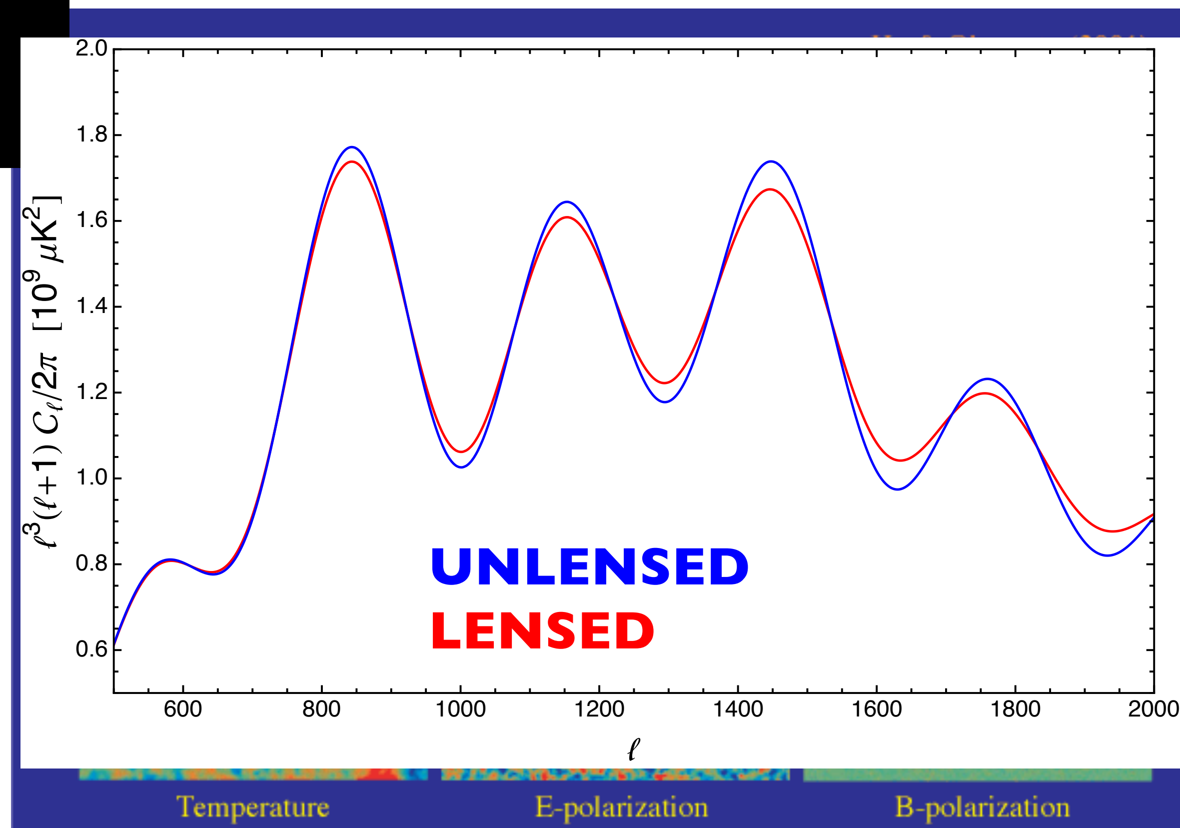


CMB Lensing



Light neutrinos (both active and sterile) are free streaming, so they suppress clustering at small scales.

This means **less** lensing since matter is distributed more smoothly.



The effect is larger for larger neutrino density, and thus for larger neutrino mass.

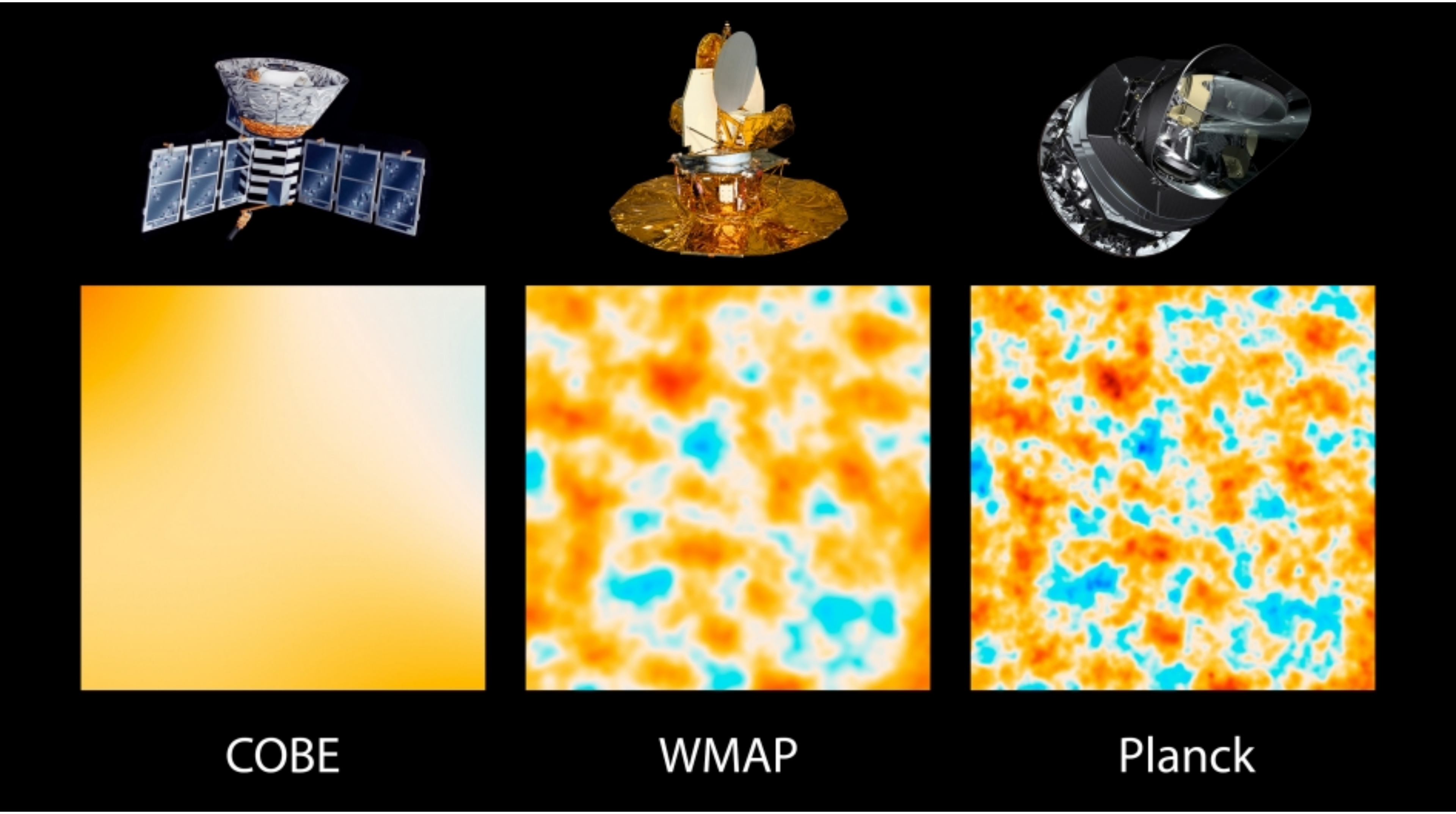
For active neutrinos

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{94.1\ \mathrm{eV}}$$

THE PLANCK SATELLITE

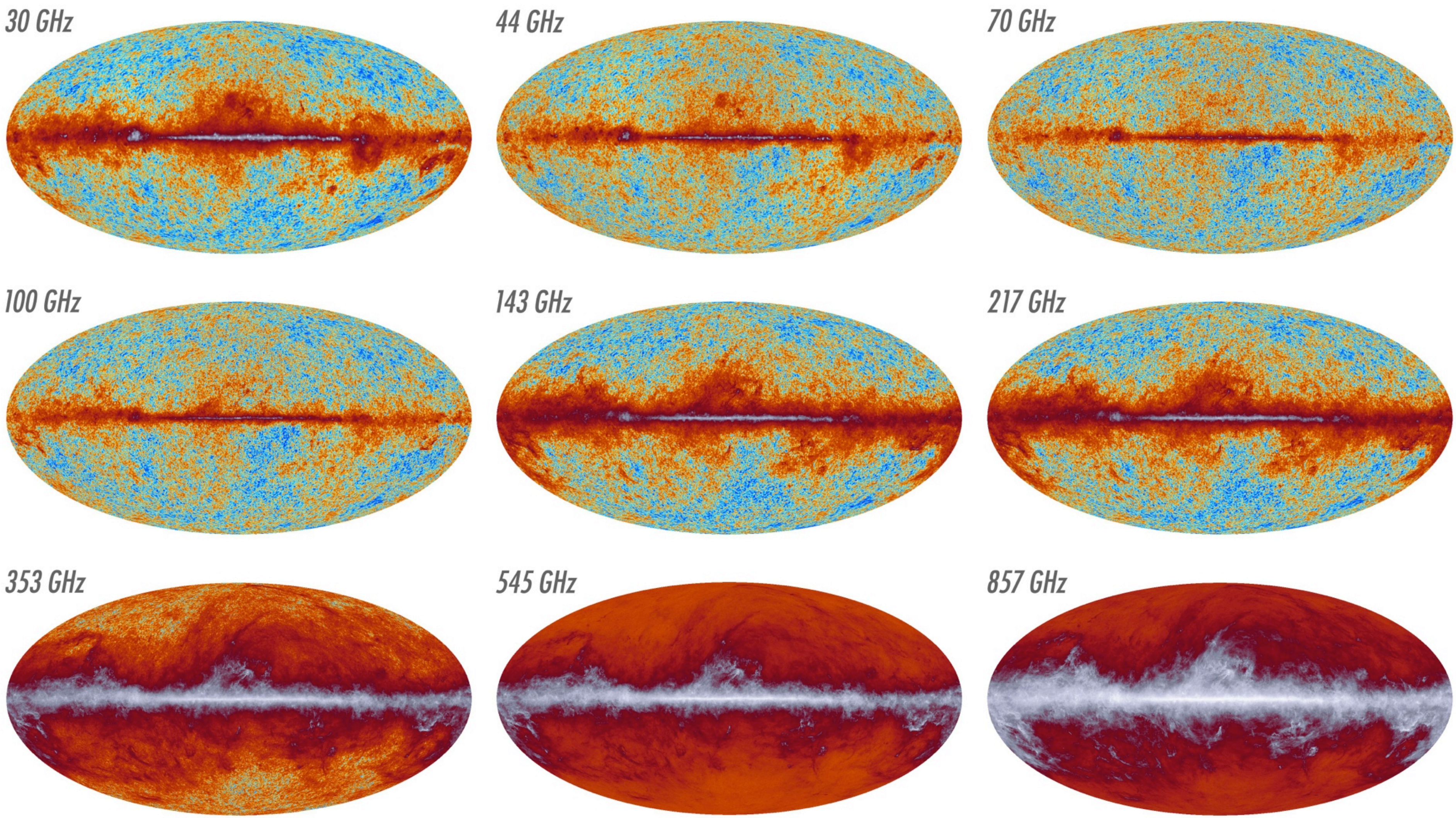
- Third-generation ESA satellite dedicated to the CMB
- observed the sky continously from 12 August 2009 to 23 October 2013
- Scientific payload: array of 74 detectors in nine frequency bands between ~ 30 GHz and ~ 1 THz
- angular resolution between 30′ and 5′, $\Delta T/T \sim 2 \times 10^{-6}$
- Low Frequency Instrument (LFI): pseudo-correlation radiometers observing at 30, 44, 70 GHz
- High Frequency Instrument (HFI): bolometers observing at 100, 143, 217, 353, 545 and 857 GHz
- observed the mw sky for ~ 30 (HFI) and 48 (LFI) months
- first cosmological release in May 2013, using the "nominal mission" temperature data (15.5 months of observations)
- second cosmological release in Feb 2015: full mission temperature and polarization
- third and final release in 2017

Comparison with forerunners

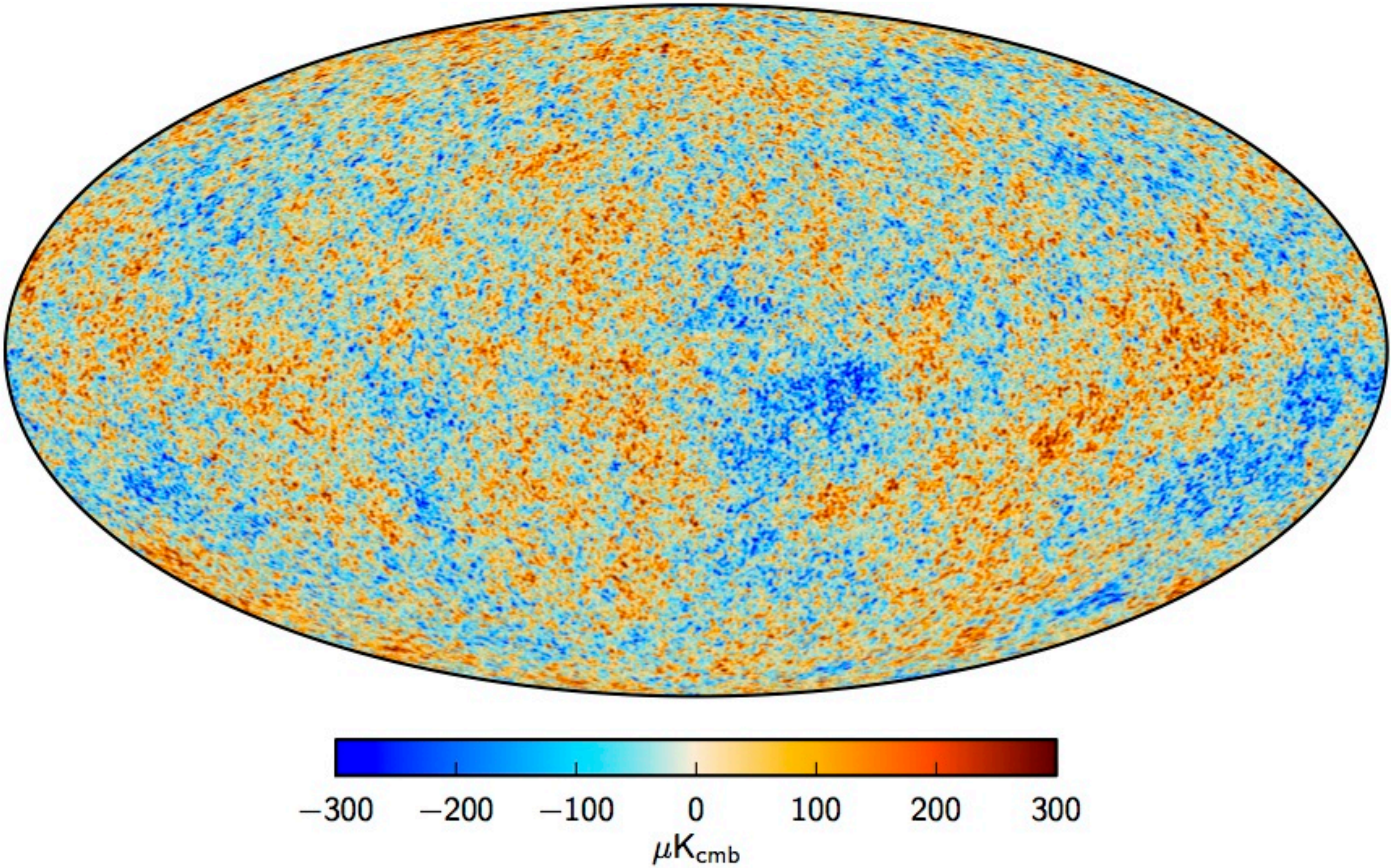


THE MICROWAVE SKY

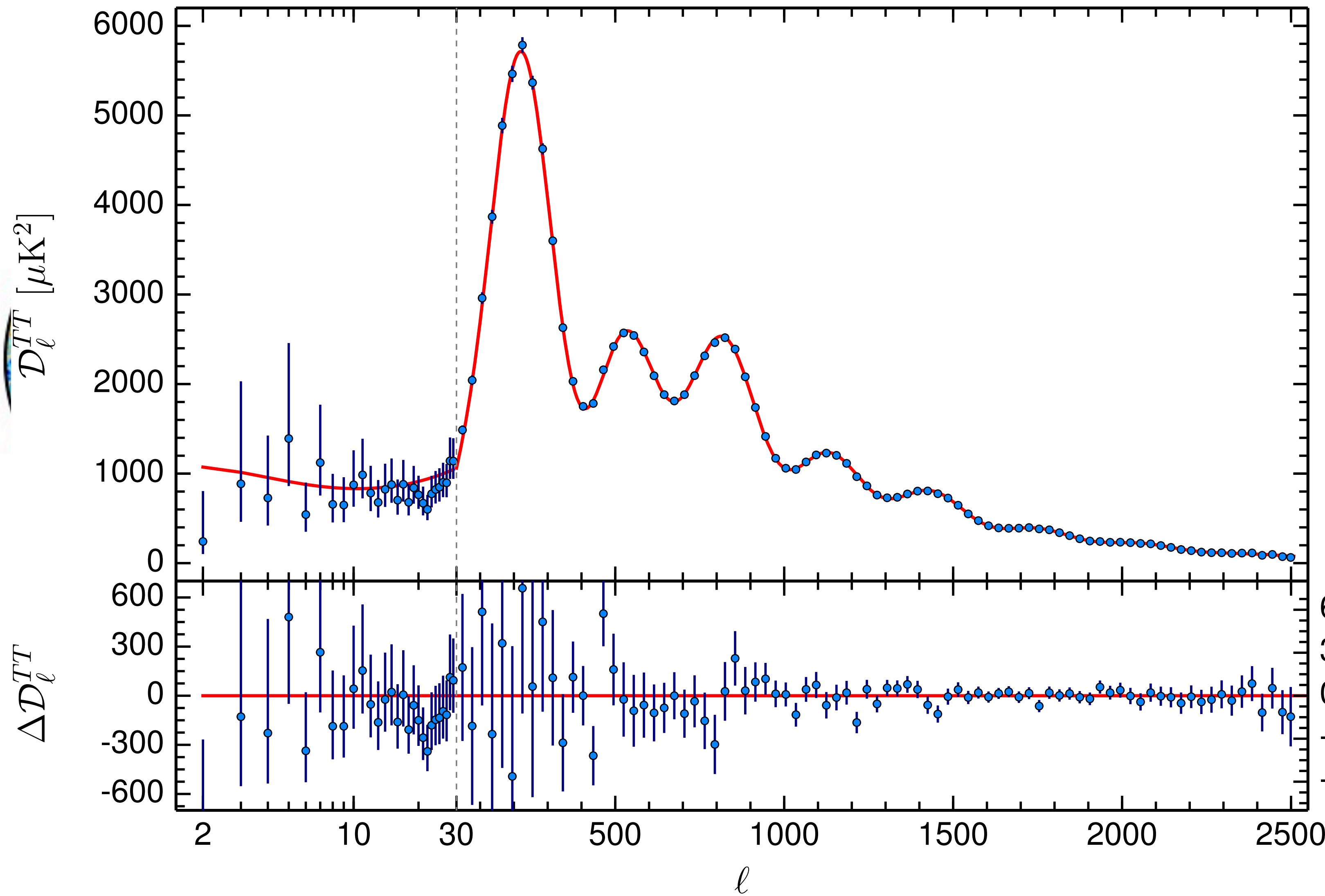
The 2015 Planck view of the sky



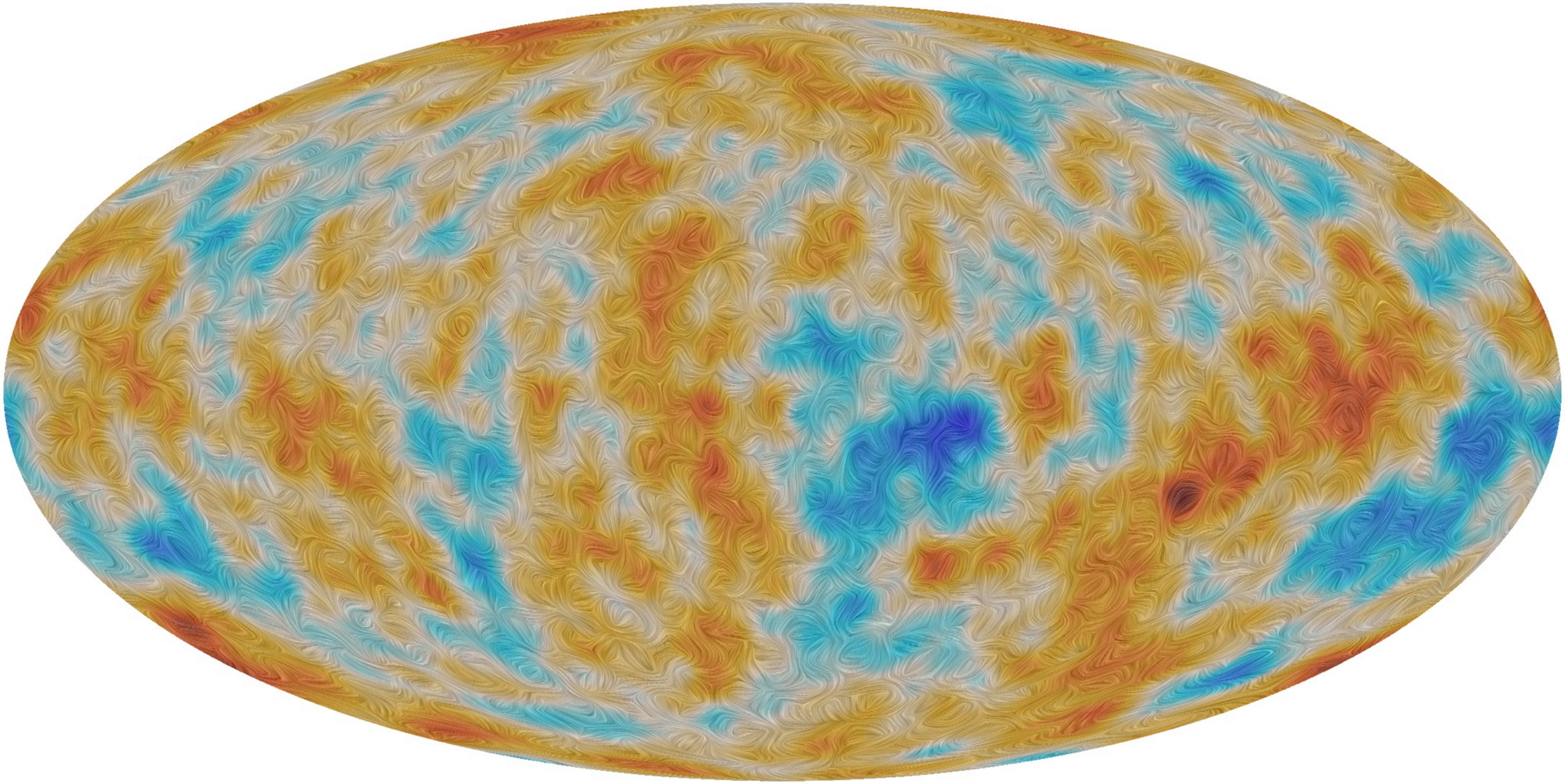
PLANCK 2015 TEMPERATURE MAP



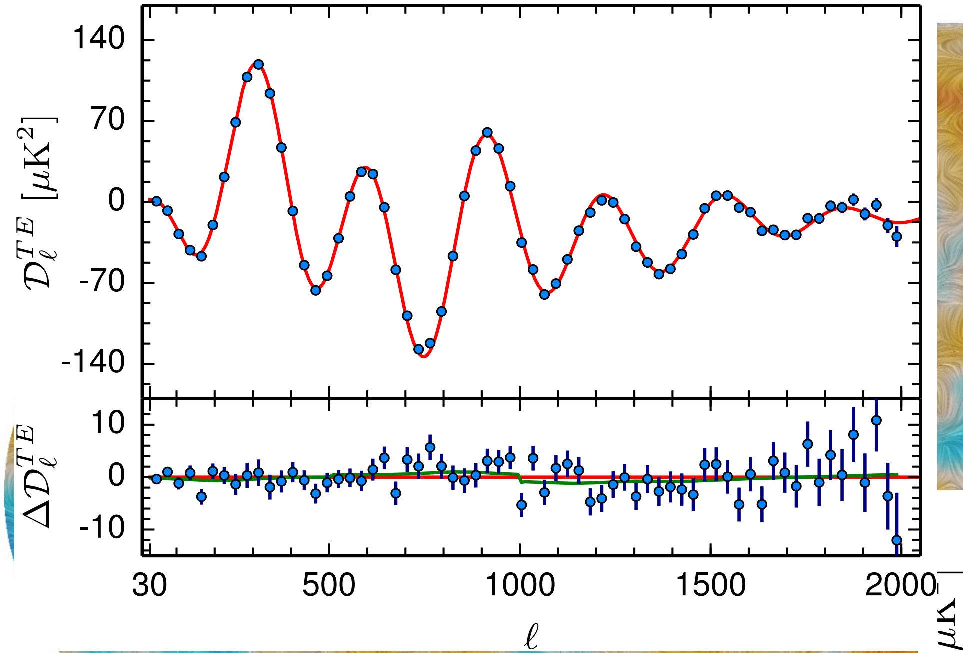
TT Power spectrum

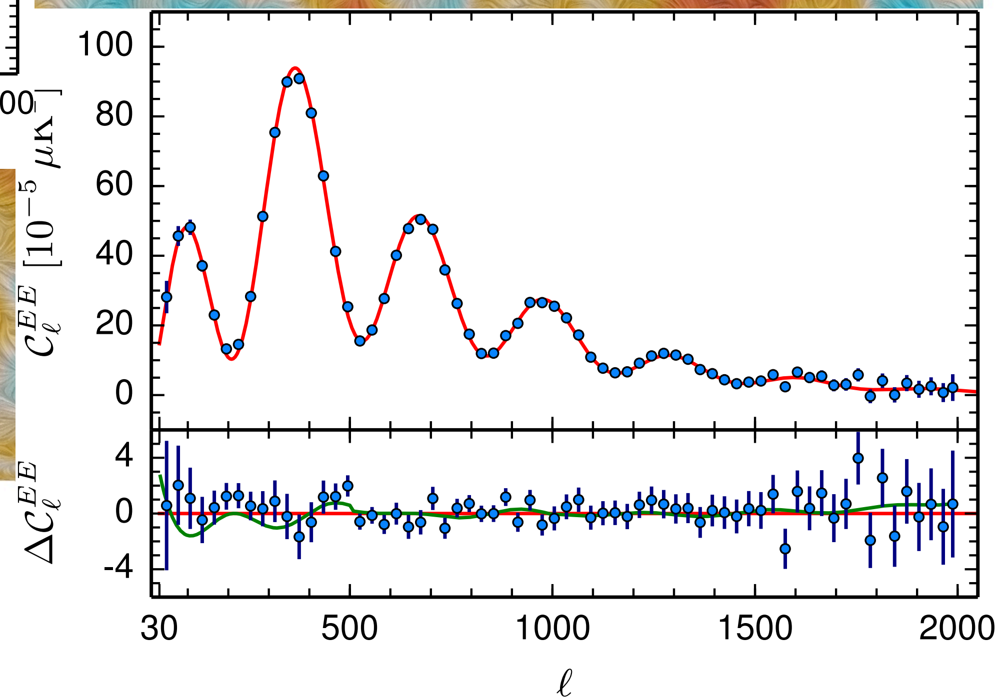


Planck 2015 CMB polarization map



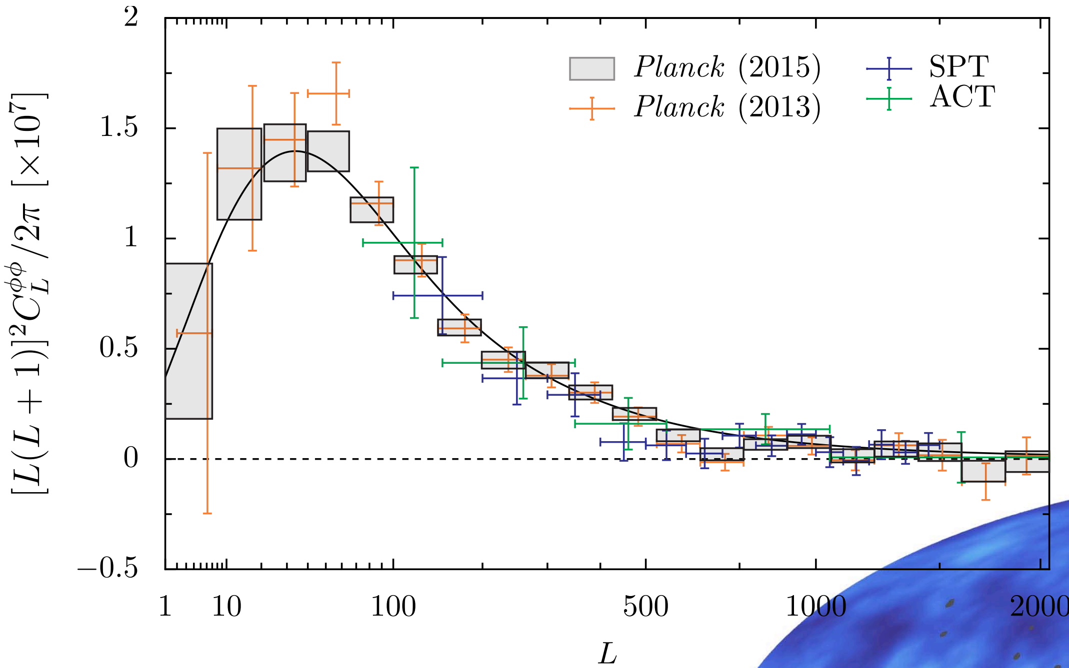
TE and EE power spectra



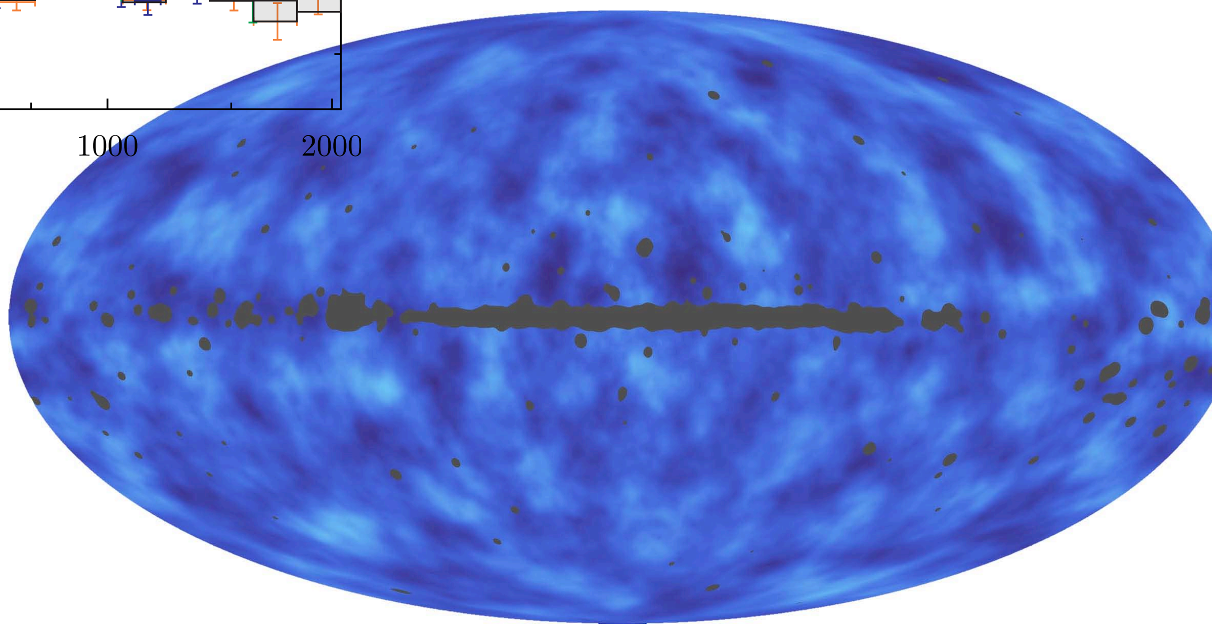


Red curves are fitted to the TT spectrum only!!

Lensing potential reconstruction



Non-gaussian signal induced by the CMB lensing (can be seen in the CMB 4-point correlation function)



Allows to reconstruct the map of the lensing potential (and its spectrum).

STERILE NEUTRINO PARAMETERIZATION

A full description of the sterile sector would require to specify (for each sterile species) its mass m_s and the **full form of the distribution function.**

Two notable cases are often considered:

- thermally distributed with arbitrary temperature T_s;
- à la Dodelson-Widrow: distributed proportionally to active neutrinos with an arbitrary scaling factor χ_s (depends on the mixing angle).

This two models are equivalent from the point of view of cosmological observations as they can be remapped in the same effective model

Sterile neutrino parameterization

In this phenomenological reparameterization

$$m_s^{\text{eff}} \equiv \left(94.1\, \Omega_s h^2\right)\ \text{eV}$$

Effective mass (sets non-relativistic energy density)

Effective number of degrees of freedom (sets relavistic energy density)

$$\Delta N_{\text{eff}} = \begin{cases} (T_s/T_\nu)^4 & \text{thermal} \\ \chi_s & \text{DW} \end{cases}$$

To go back to the real mass:

$$m_s = \begin{cases} m_s^{\text{eff}}\,(T_s/T_\nu)^{-3} = m_s^{\text{eff}}/\Delta N_{\text{eff}}^{3/4} & \text{thermal} \\ m_s^{\text{eff}}/\chi_s = m_s^{\text{eff}}/\Delta N_{\text{eff}} & \text{DW} \end{cases}$$

Planck constraints on massless sterile neutrinos

Planck constraints on N_{eff} alone (can be regarded as a massless limit for the sterile)

$$N_{\text{eff}} = 3.13 \pm 0.32 \quad \text{(PlanckTT+lowP)}$$

$$N_{\text{eff}} = 3.15 \pm 0.23 \quad \text{(PlanckTT+lowP+BAO)}$$

$$N_{\text{eff}} = 2.99 \pm 0.20 \quad \text{(PlanckTT,TE,EE+lowP)}$$

$$N_{\text{eff}} = 3.04 \pm 0.18 \quad \text{(PlanckTT,TE,EE+lowP+BAO)}$$

(uncertainties are 68% CL)

Planck 2015 XVI

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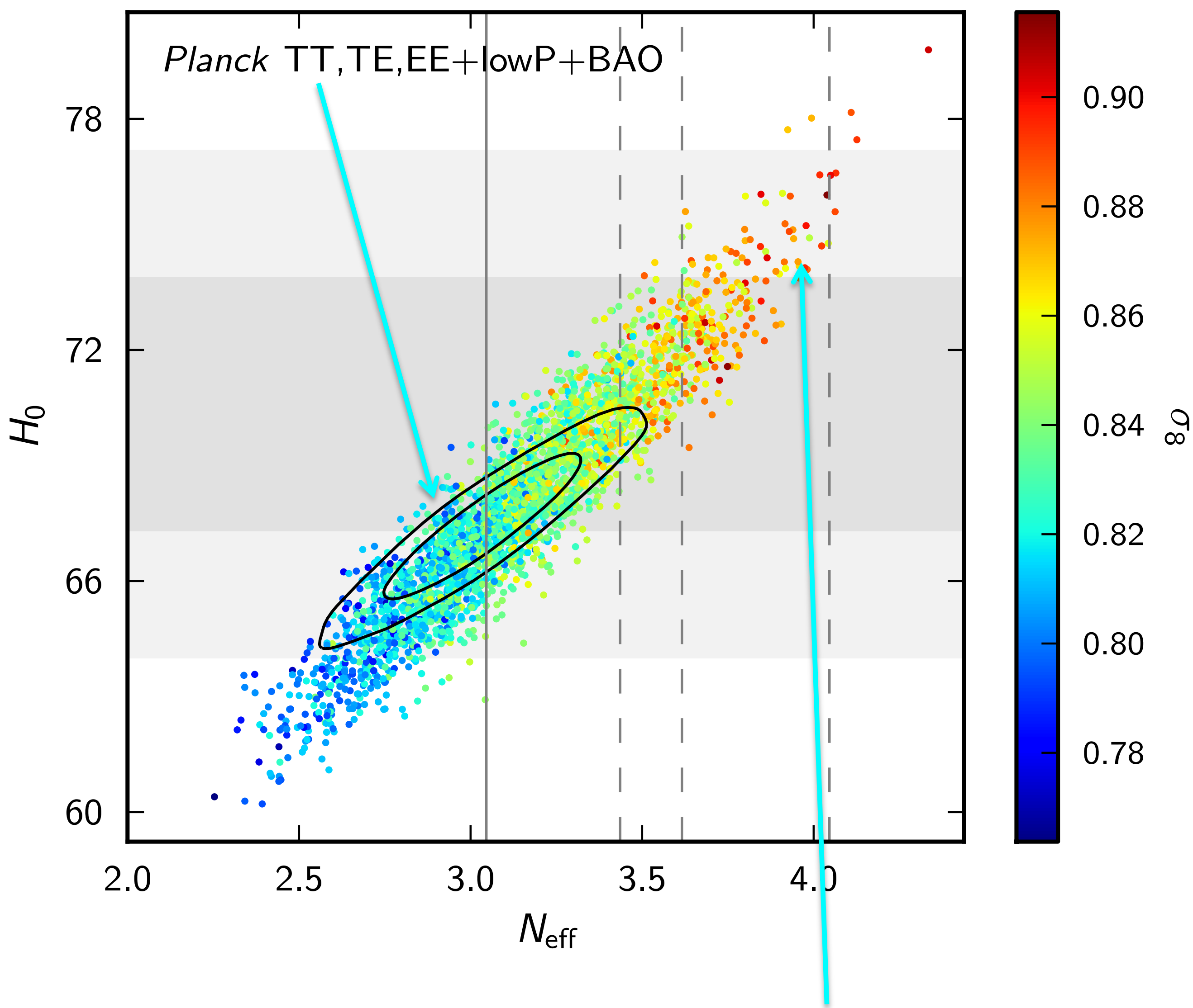
(uncertainties are 68% CL)

N_{eff} = 4 (i.e., one extra thermalized neutrino)
is excluded at between ~ 3 and 5 sigma.

Planck 2015 XVI

PLANCK CONSTRAINTS ON MASSLESS STERILE NEUTRINOS

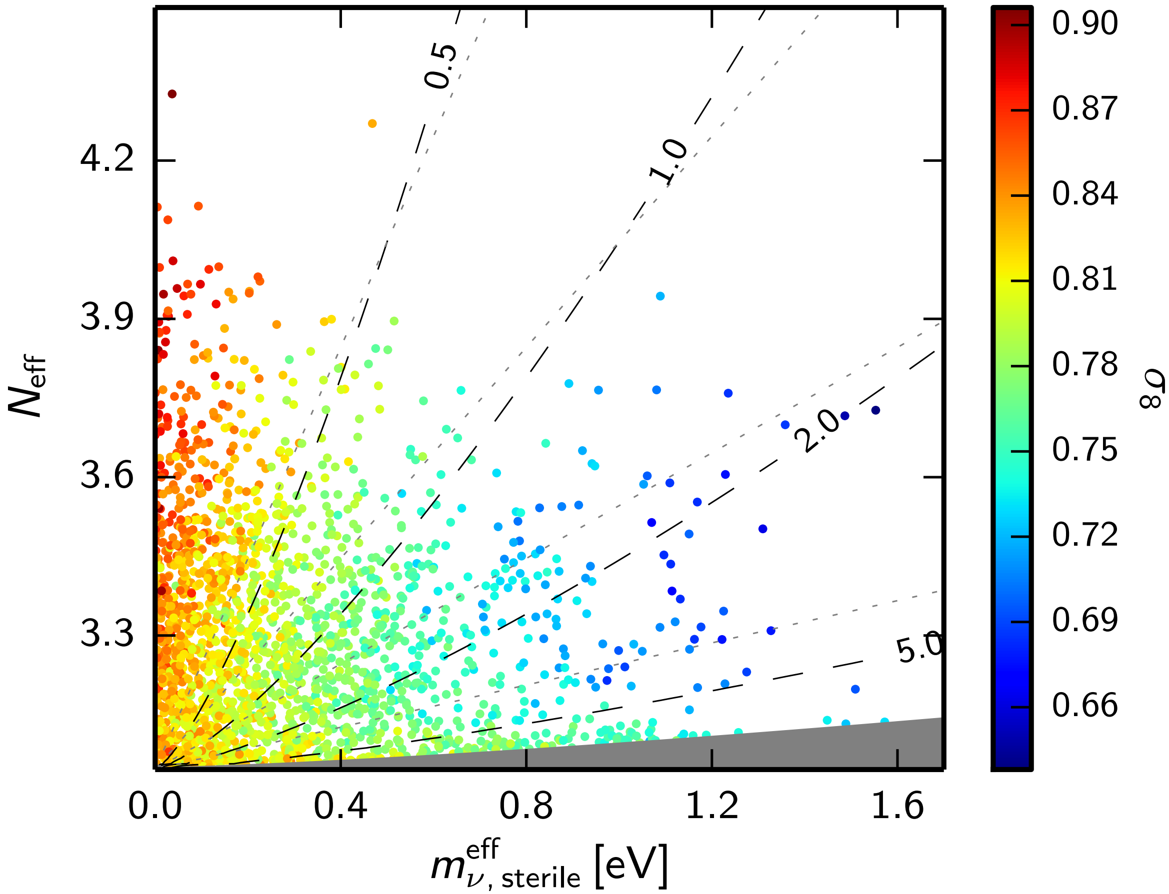


Higher values of N_{eff} can help relieve the tension with astrophysical measurements of H_0

However, they imply a larger σ_8 and thus worsen the tension with LSS probes.

Planck 2015 XVI

PLANCK CONSTRAINTS ON MASSIVE STERILE NEUTRINOS



Planck TT+lowP+lensing+BAO

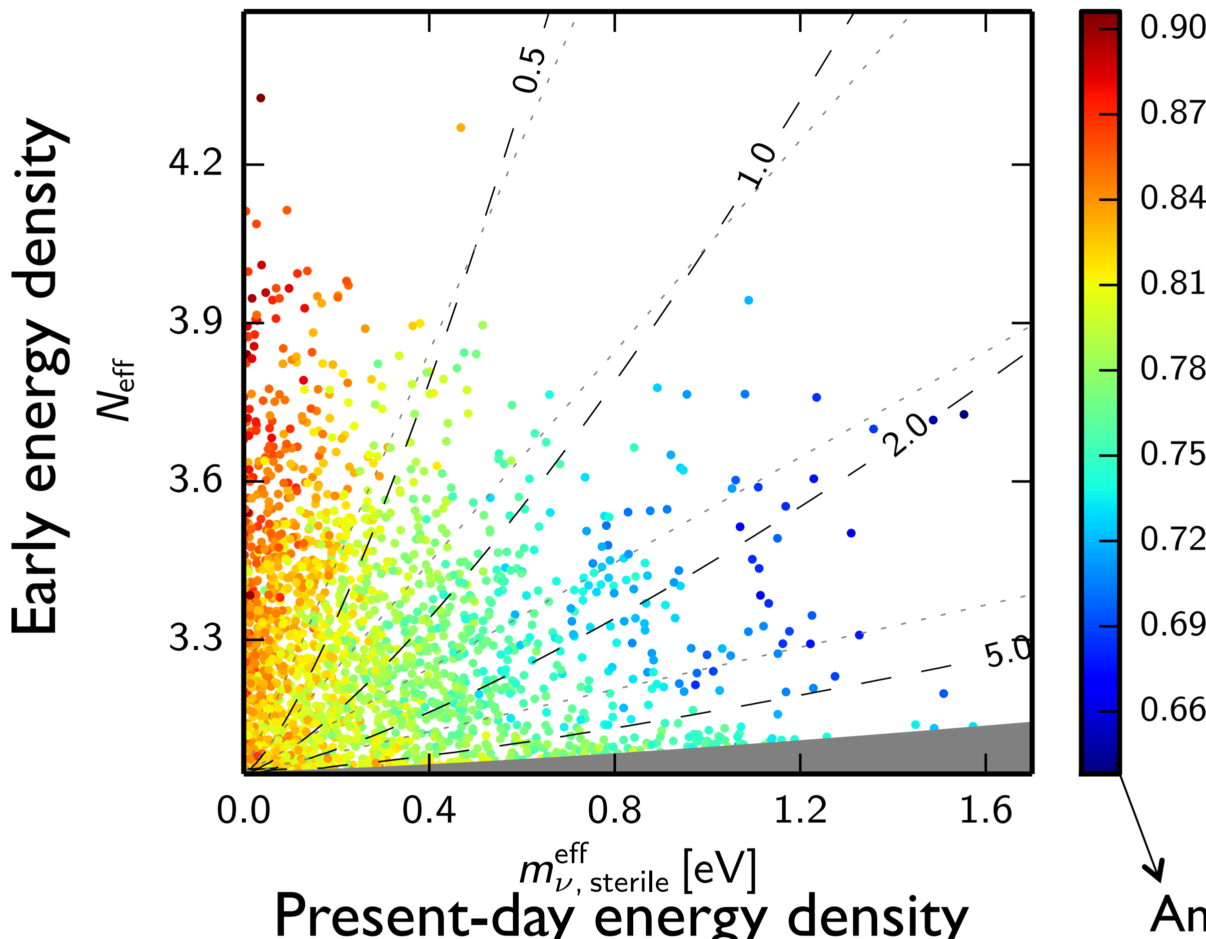
$N_{\mathrm{eff}} < 3.7$

$m^{\mathit{eff}}_{\mathit{sterile}} < 0.52$ eV

One sterile eigenstate; total active mass fixed to 0.06 eV

Planck 2015 XVI

Planck constraints on massive sterile neutrinos



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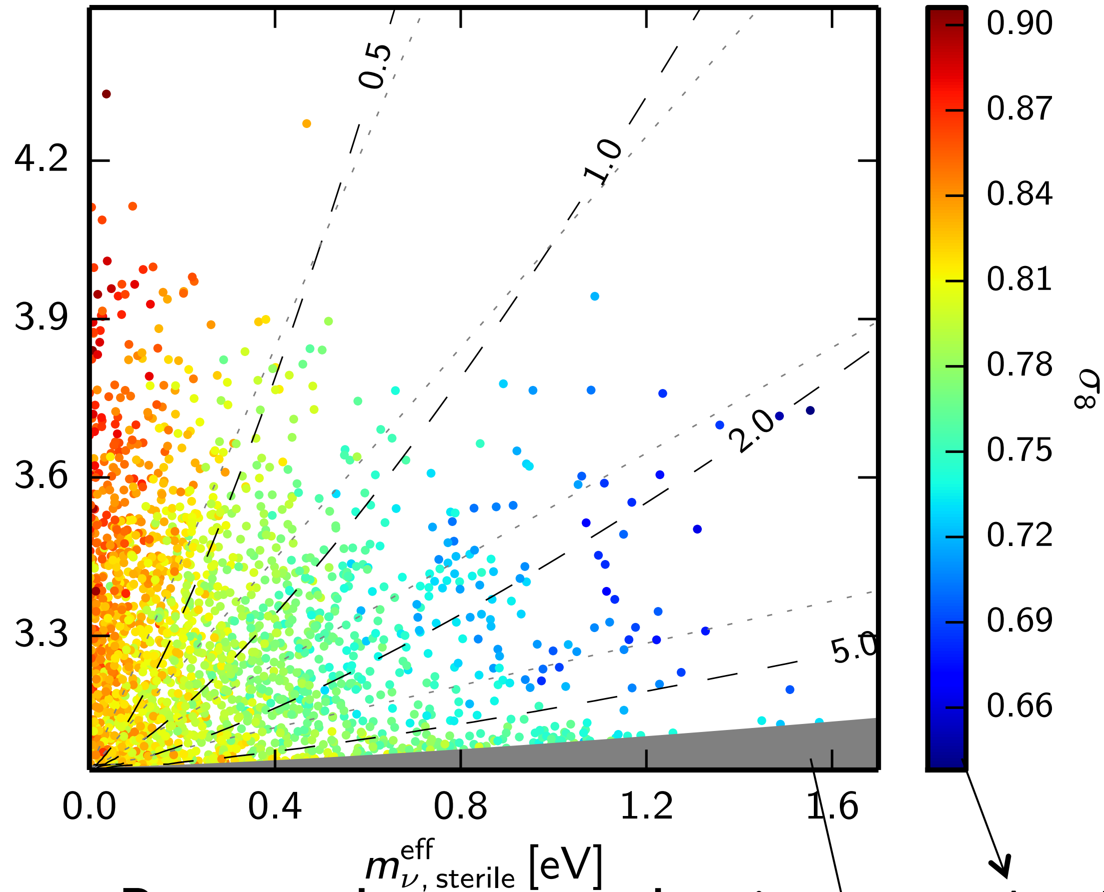
Amplitude of density fluctuations

Planck constraints on massive sterile neutrinos



Early energy density

Present-day energy density

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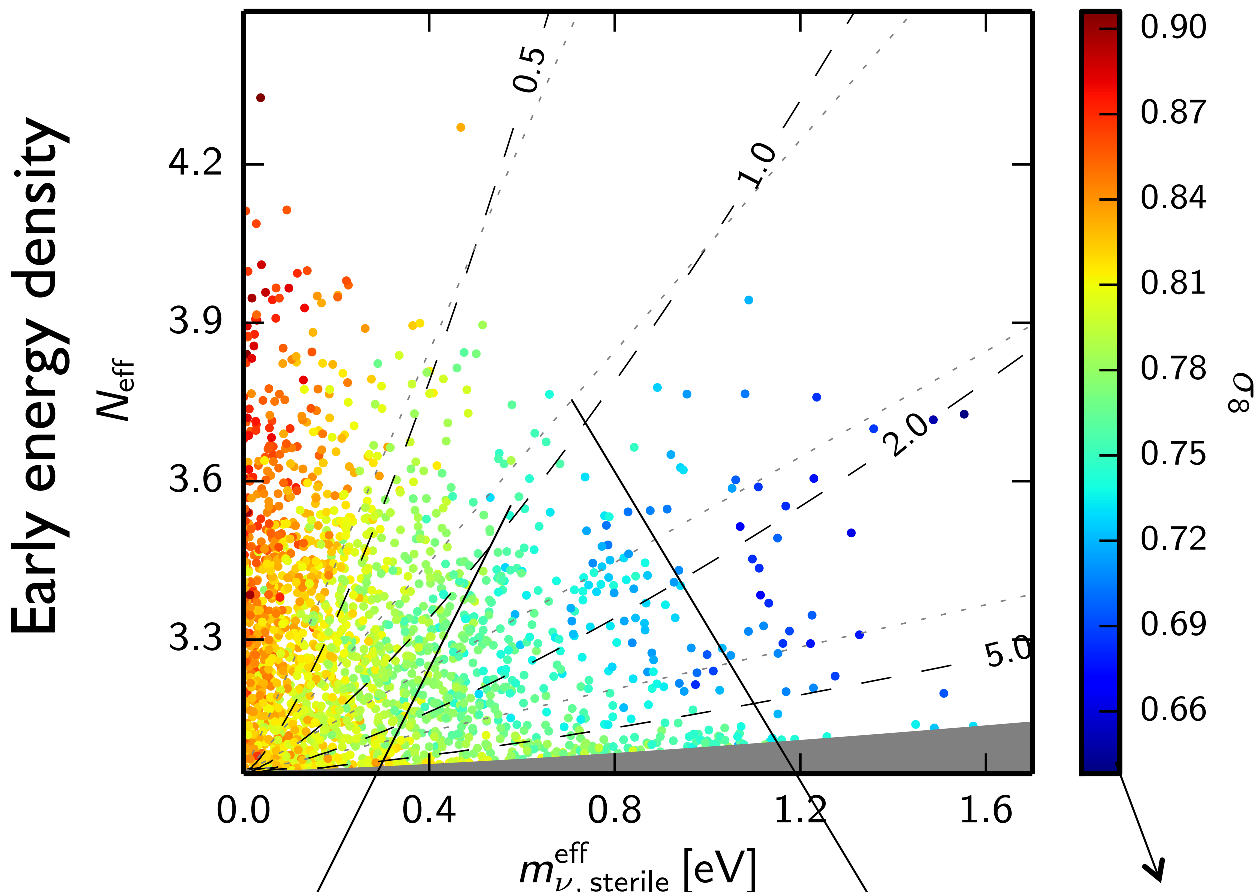
One sterile eigenstate; total active mass fixed to 0.06 eV

Amplitude of density fluctuations

Behaves like warm/cold DM

PLANCK CONSTRAINTS ON MASSIVE STERILE NEUTRINOS



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One sterile eigenstate; total active mass fixed to 0.06 eV

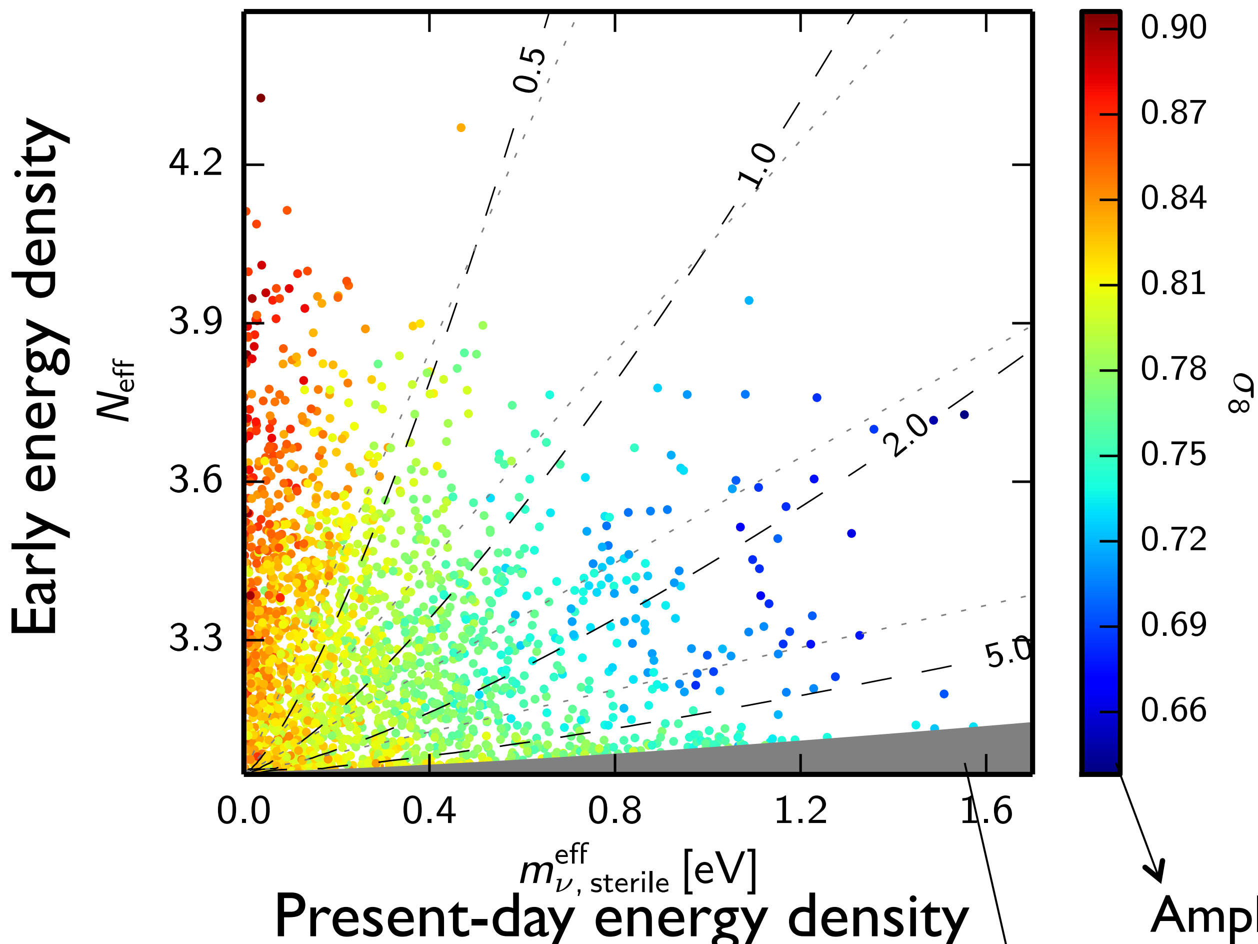
Present-day energy density

Amplitude of density fluctuations

Lines of constant m_s (thermal)

Lines of constant m_s (DW)

PLANCK CONSTRAINTS ON MASSIVE STERILE NEUTRINOS



Planck TT+lowP+lensing+BAO

$N_{\rm eff} < 3.7$

$m^{eff}{}_{sterile} < 0.52$ eV

$m^{eff}{}_{s} < 0.38$ eV

restricting to m_s (thermal) < 2 eV

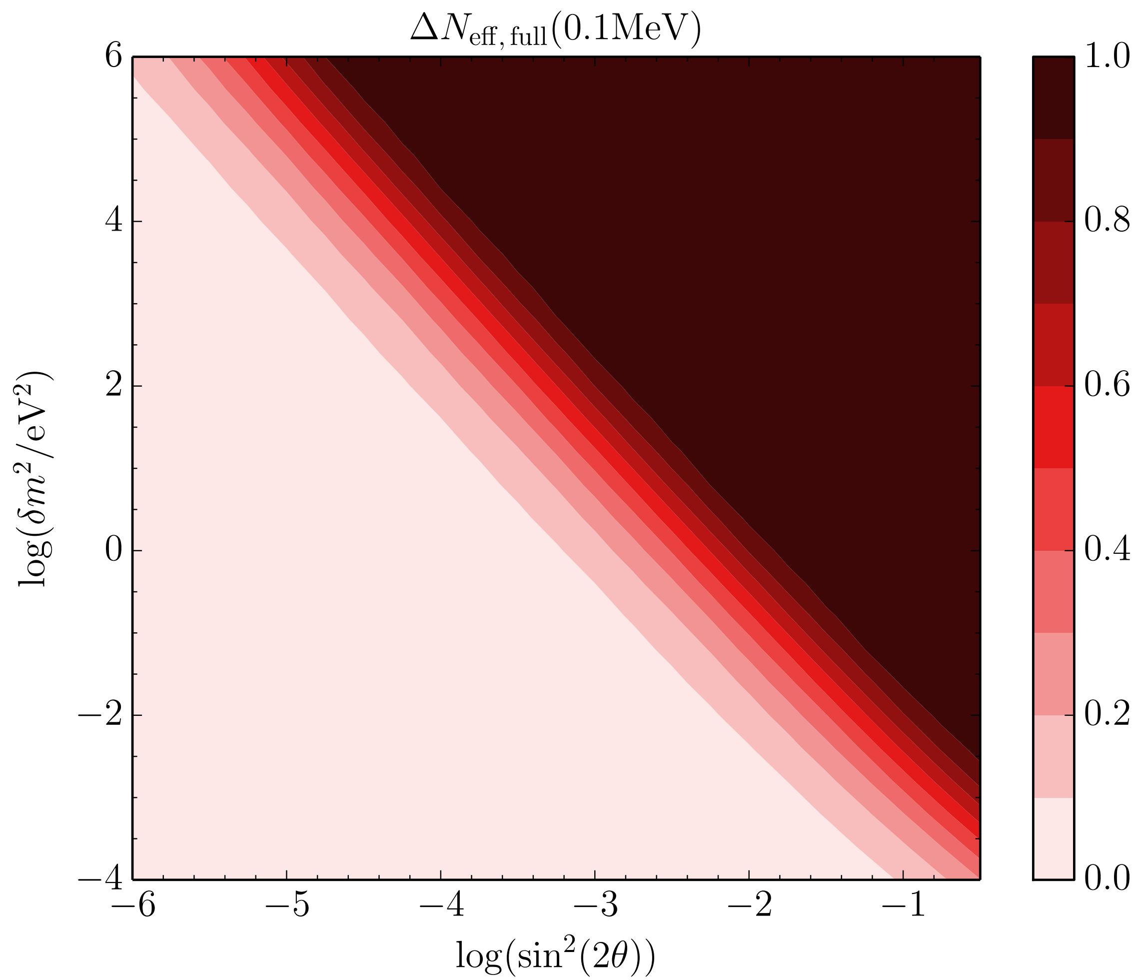
Amplitude of density fluctuations

Behaves like warm/cold DM

1 eV for the real mass is allowed by Planck.

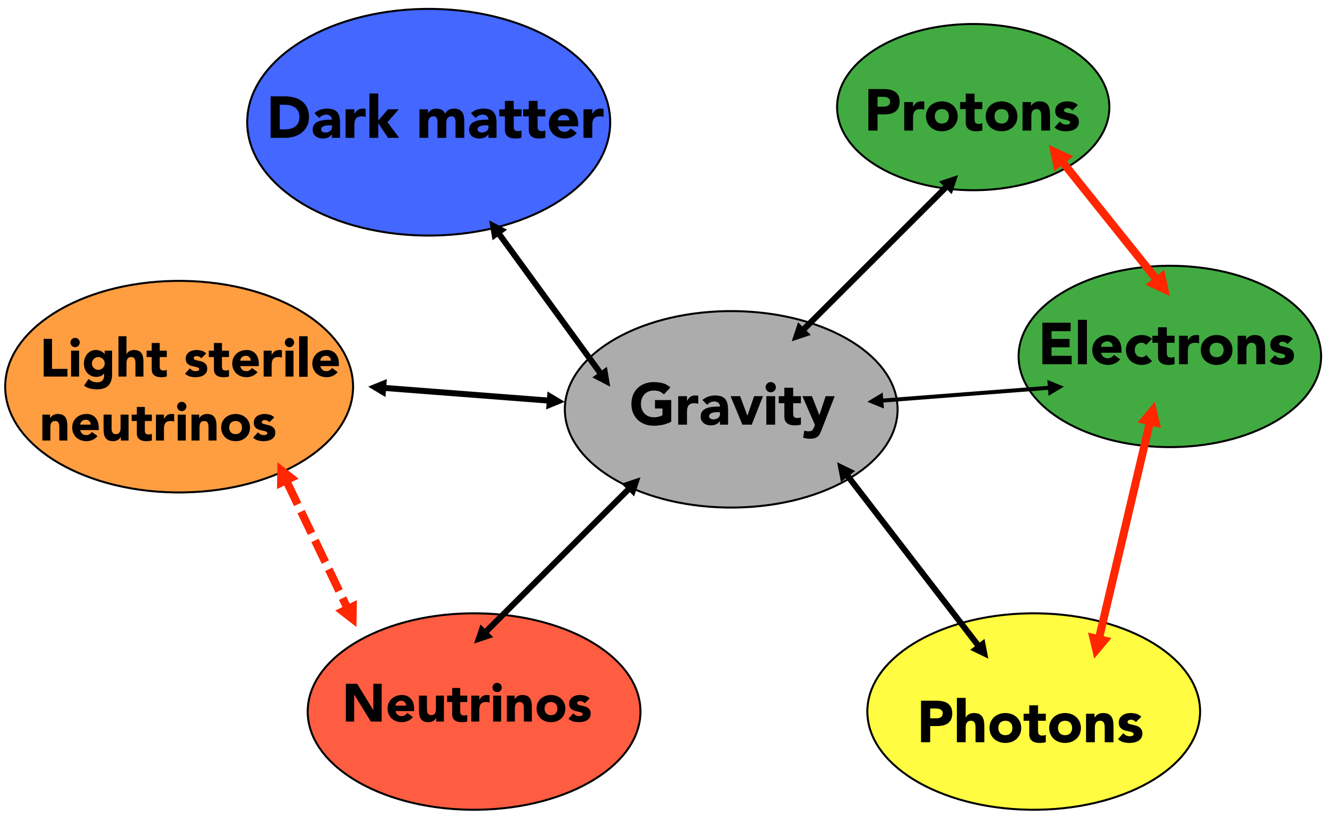
However, for m_s ~ 1eV and $\sin^2 2\theta$ ~ 0.1 (the preferred SBL solution) full thermalization (ΔN_{eff} ~ 1) is expected.

This is at odds with Planck constraints



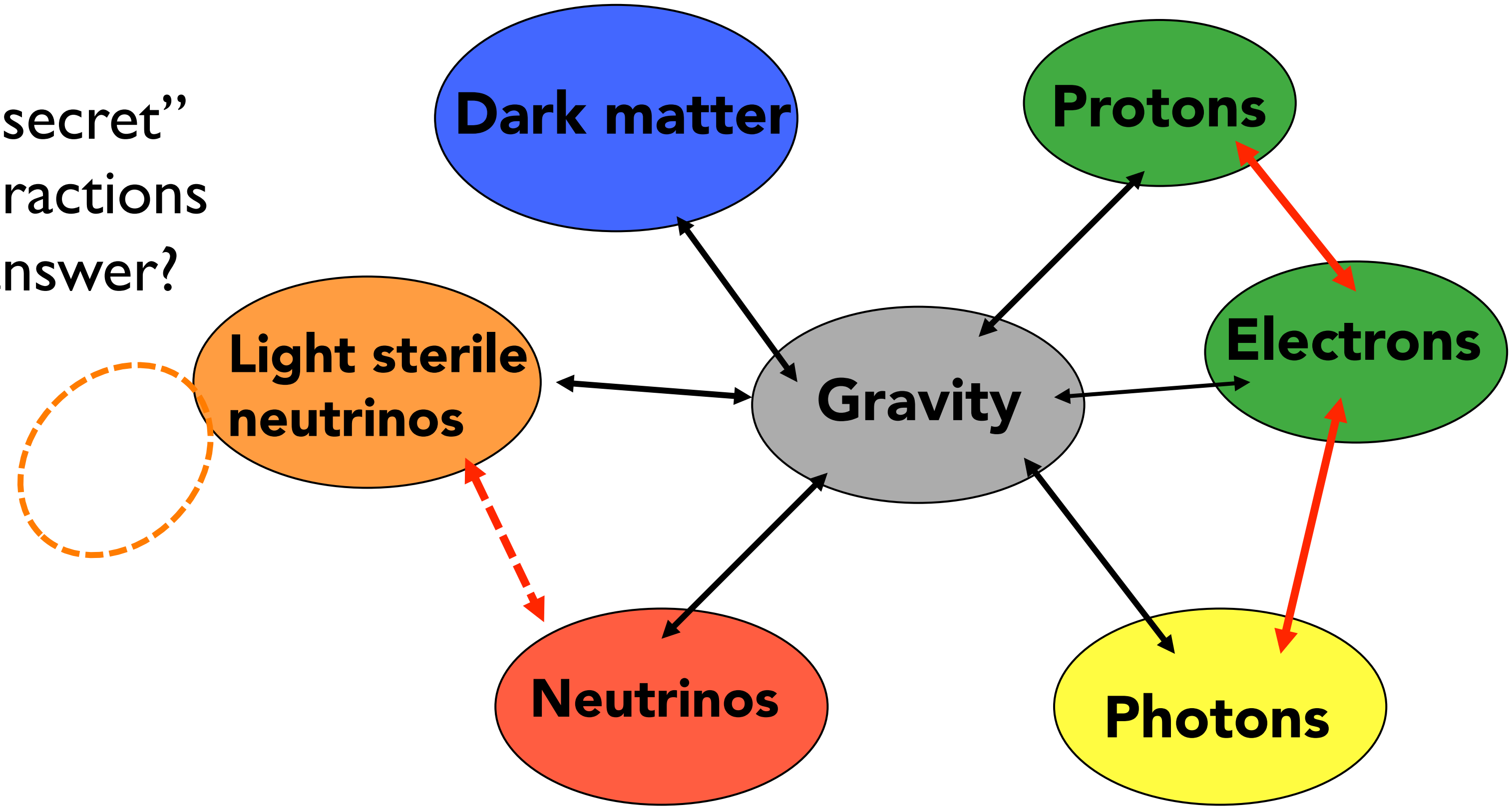
Hannestad et al. 2015

Cosmology and sterile neutrinos



COSMOLOGY AND STERILE NEUTRINOS

Maybe "secret" self-interactions are an answer?



Both scalar- and vector– mediated interactions have been considered in the literature to avoid thermalization (see e.g. Archidiacono et al. 2014; Mirizzi et al. 2014)

Summary

- The standard ΛCDM can explain all present cosmological observations
- Light sterile neutrinos are a hot component and would both provide extra energy density in the early Universe, and suppress matter fluctuations at small scales
- Planck CMB observations are consistent with no light species beyond the three active neutrinos
- However, sterile neutrinos with sub-eV effective mass and subthermal abundance are allowed by CMB observations…
- …BUT the SBL-preferred solution would lead to full thermalization
- Could there be a loophole? E.g., additional BSM interactions for steriles?

BACKUP SLIDES