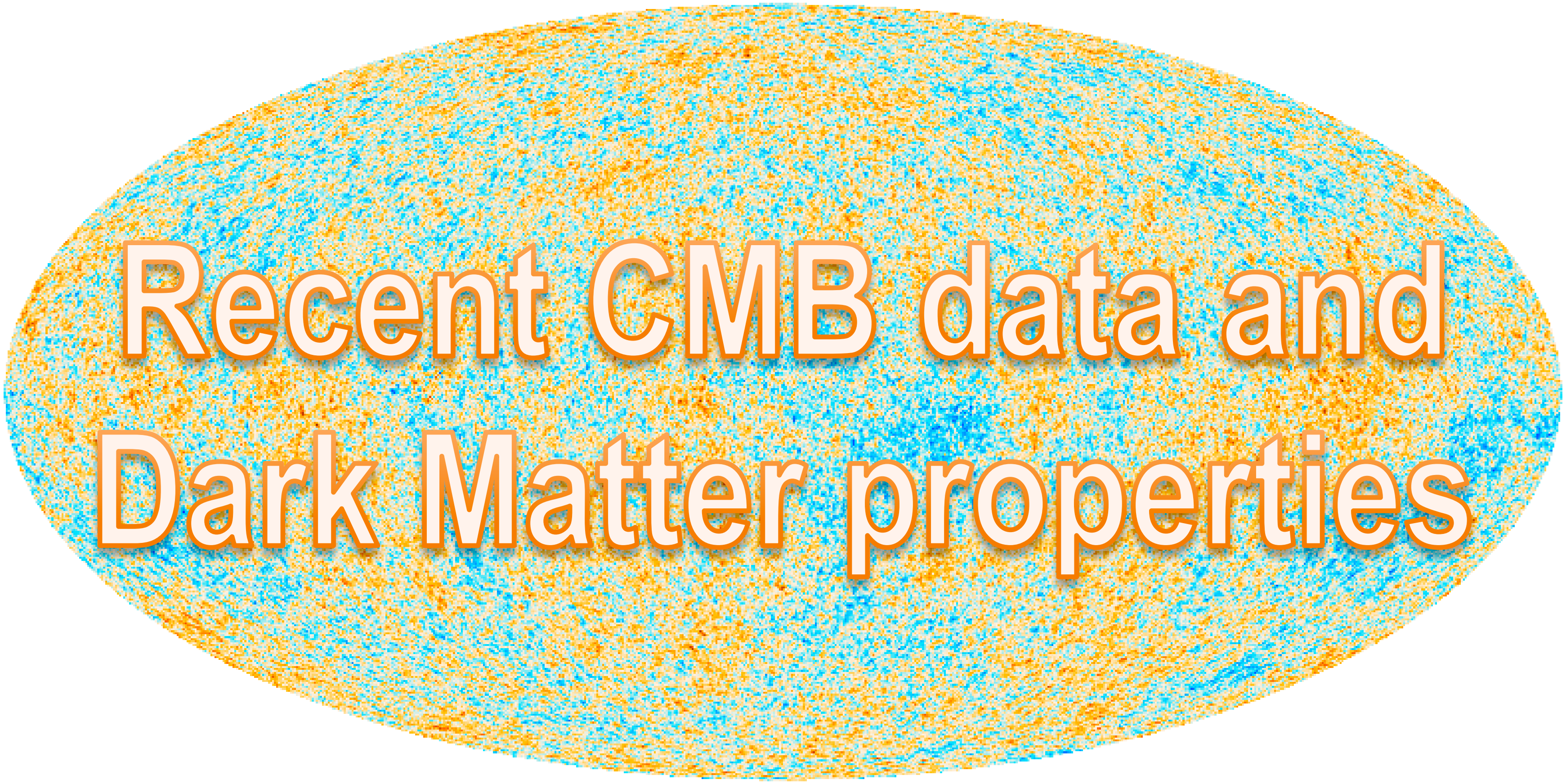
Recent CMB data and Dark Matter properties



XIX IFT Xmas Workshop, 12.12.2013

J. Lesgourgues (EPFL, CERN, LAPTh)

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planck

What could Dark Matter be made of ?

- Dominant component (observed) behaving like a cold component
  - CDM particles
  - Or WDM particles with high mass
  - Or several cold/warm particles

Totally unknown nature: WIMPS, non-weakly interacting; annihilating, decaying, stable; fluid, self-interacting… (non-particle, like modified gravity or scalar field DM are very constrained…)

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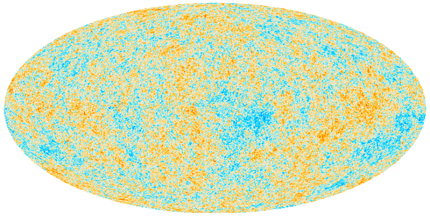
Totally unknown nature: WIMPS, non-weakly interacting; annihilating, decaying, stable; fluid, self-interacting… (non-particle, like modified gravity or scalar field DM are very constrained…)

- Subdominant component (not observed) not behaving like a cold component
  - Flavor neutrinos (theoretically motivated as small HDM component)
    - But mass not yet observed. Could in principle be unobservable, although…
  - Other light relics (sterile neutrinos, axions, etc…)



CMB as a probe of Dark Matter

- Evidence for missing mass of non-relativistic species (like rotation curves!)
  - CMB measures accurately: baryon density (first peaks asymmetry), time of radiation-matter equality (first peaks height)
  - ω_b~0.022, ω_m~0.142, need ω_{dm}~ 0.1199 ± 0.0027 (68%CL) : 44σ detection!

    Planck XVI 2013
  - In minimal cosmology (collisionless DM), this is the only effect (no probe of DM gravitational interactions)

    Weinberg 2002, Voruz, JL & Tram in prep.
  - Supported by Large Scale Structure (matter spectrum shape) and astrophysics

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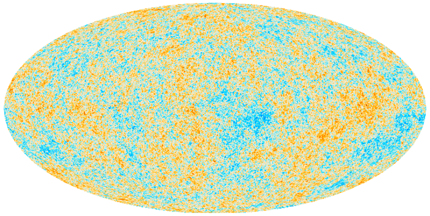

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  - Supported by Large Scale Structure (matter spectrum shape) and astrophysics
- Does it say anything more on DM properties?
  - Cold or warm ? No, LSS can say something, not CMB
  - Self-interactions ? - idem -
  - Completely stable, small annihilation rate or decay rate ? Yes
  - Very small interactions with other species ? Yes

CMB as probe of DM annihilation or decay

- DM annihilation
  - → hadrons, leptons, gauge bosons → … → electrons, neutrinos, photons
    - Ionization of thermal plasma
    - Heating of thermal plasma
    - Hydrogen excitation

    (unless 100% in neutrinos)
  - Modification of recombination and reionisation history

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  - Modification of recombination and reionisation history
  - Impact on CMB; results compete with DM indirect detection bounds

N. Padmanabhan and D. P. Finkbeiner 2005; L. Zhang, X.-L. Chen, Y.-A. Lei, and Z.-G. Si 2006; A. Natarajan and D. J. Schwarz 2008; A. V. Belikov and D. Hooper 2009; M. Cirelli, F. Iocco, and P. Panci 2009; S. Galli, F. Iocco, G. Bertone, and A. Melchiorri 2009; T. R. Slatyer, N. Padmanabhan, and D. P. Finkbeiner 2009; A. Natarajan and D. J. Schwarz 2010; S. Galli, F. Iocco, G. Bertone, and A. Melchiorri 2011; D. P. Finkbeiner, S. Galli, T. Lin, and T. R. Slatyer 2011; G. Hutsi, J. Chluba, A. Hektor, and M. Raidal 2011; A. Natarajan 2012; G. Giesen, J. Lesgourgues, B. Audren, Y. Ali-Haimoud 2012; T. Slatyer 2013; J. Cline and P. Scott 2013; C. Dvorkin, K. Blum and M. Zaldarriaga 2013; Planck XVI 2013; L. Lopez-Honorez, O. Mena, S. Palomares-Ruiz and A. Vincent 2013; Chluba 2013; S. Galli, T. Slatyer, M. Valdes and F. Iocco 2013; R. Diamanti, L. Lopez-Honorez, O. Mena, S. Palomares-Ruiz and A. Vincent 2013; M. Madhavacheril, N. Sehgal and T. Slatyer 2013;

CMB as probe of DM annihilation or decay

- DM decay
  - Should have similar effects
  - Probe DM lifetime instead of annihilation cross-section

    L. X.-L. Chen and M. Kamionkowski 2004; K. Ichiki, M. Oguri, and K. Takahashi 2004; L. Zhang, X. Chen, M. Kamionkowski, Z.-g. Si, and Z. Zheng 2007; S. Kasuya and M. Kawasaki 2007; S. Yeung, M. Chan, and M.-C. Chu 2012

  - But CMB constraints not as strong as those from cosmic ray

    N. F. Bell, A. J. Galea, and K. Petraki 2010; M. Cirelli, E. Moulin, P. Panci, P. D. Serpico, and A. Viana 2012

CMB and DM annihilation

- DM annihilation
  - f(z) = fraction of released energy going into ionization and heating at redshift z
  - Computed for wide range of WIMP candidates with different decay channels:

    f(z=2500)=0.2 to 0.9, f(z=0) 2 to 5 times smaller

T. R. Slatyer, N. Padmanabhan, and D. P. Finkbeiner 2009

$$\left.\frac{dE}{dV\,dt}\right|_{\mathrm{DM}}(z) = n_{pairs}\cdot P_{\mathrm{ann}}\cdot E_{\mathrm{ann}}\cdot f(z) = \frac{n_{\mathrm{DM}}}{2}\cdot\langle\sigma v\rangle\cdot n_{\mathrm{DM}}\cdot 2m_{\mathrm{DM}}c^2\cdot f(z)$$
$$= \rho_{\mathrm{c}}^2 c^2 \Omega_{\mathrm{DM}}^2 (1+z)^6 f(z)\frac{\langle\sigma v\rangle}{m_{\mathrm{DM}}}.$$

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$$p_{\mathrm{ann}}(z)$$

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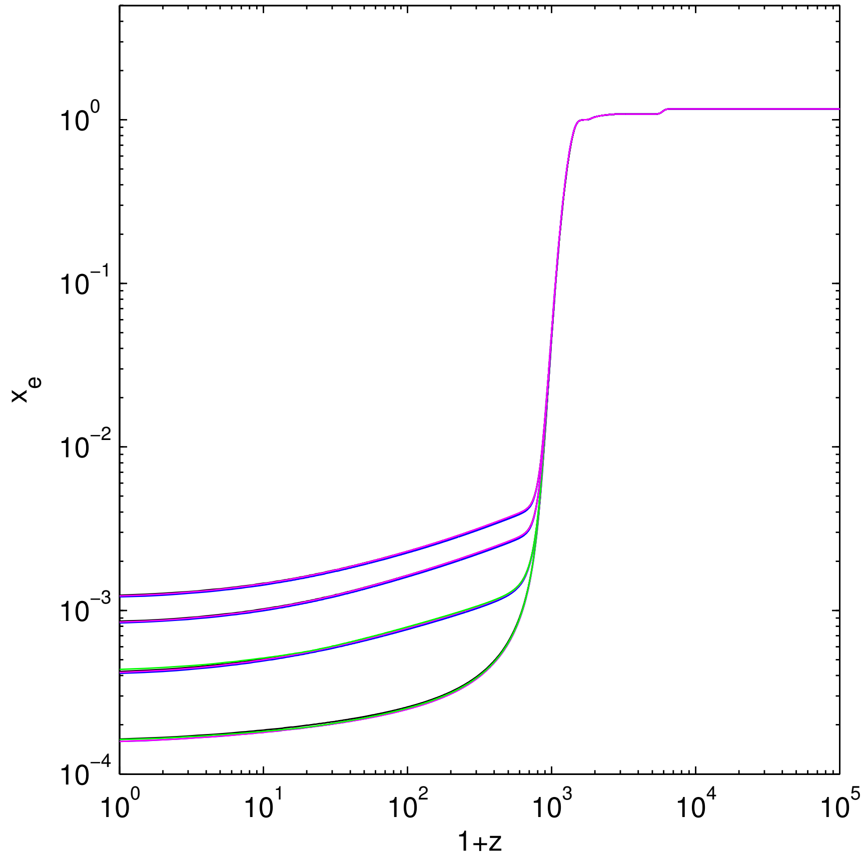
CMB and DM annihilation

- Ionization and excitation modify the recombination history

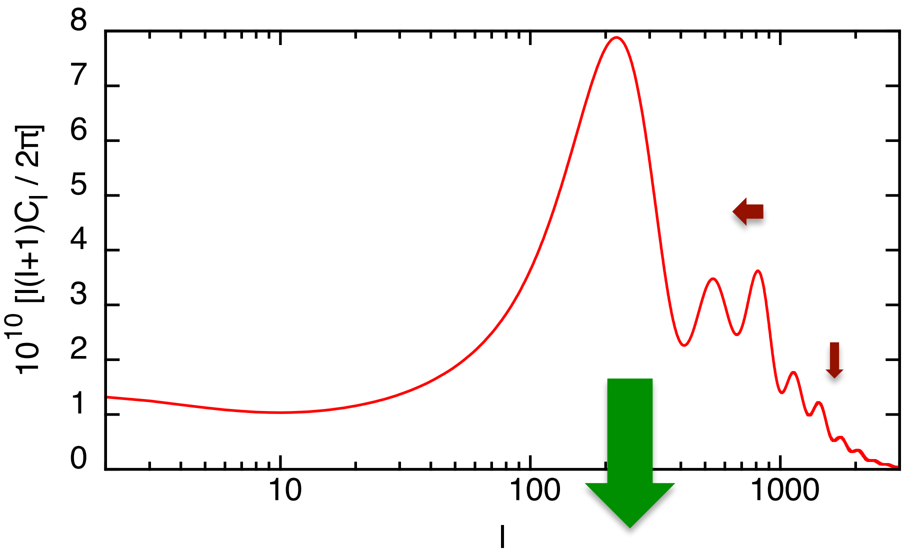
Ionisation fraction

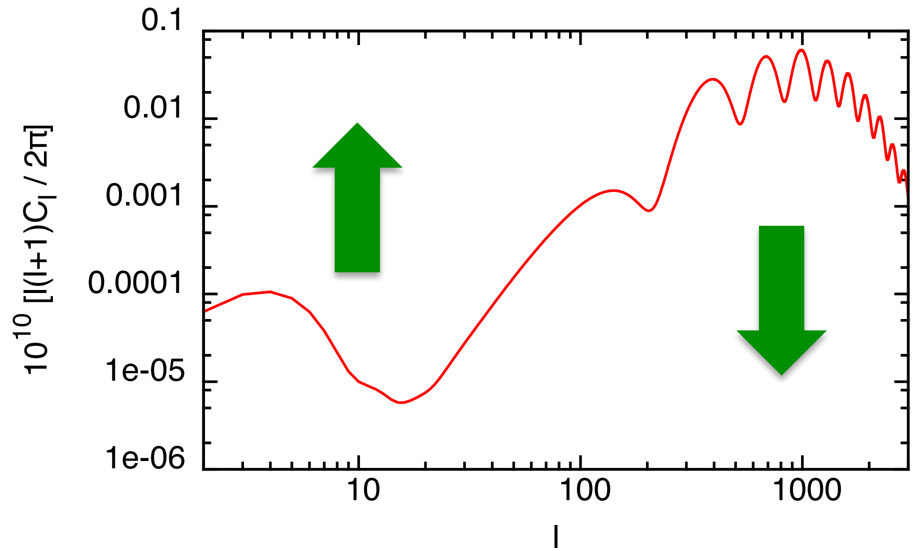


$$p_{\rm ann} = 0, 10^{-6}, 5\cdot 10^{-6} \text{ or } 10^{-5} \text{ m}^3\text{s}^{-1}\text{kg}^{-1}$$

CMB and DM annihilation

- DM annihilation effects:
  1. High z: { small delay in recombination: shift in peak scale
     slightly enhanced Thomson scattering rate: increased Silk damping
  2. Intermediate z: increased probability of rescattering:
     - suppression of CMB fluctuations on sub-Hubble scale,
     - regeneration of polarisation anisotropies near that scale (peaks near z=600)





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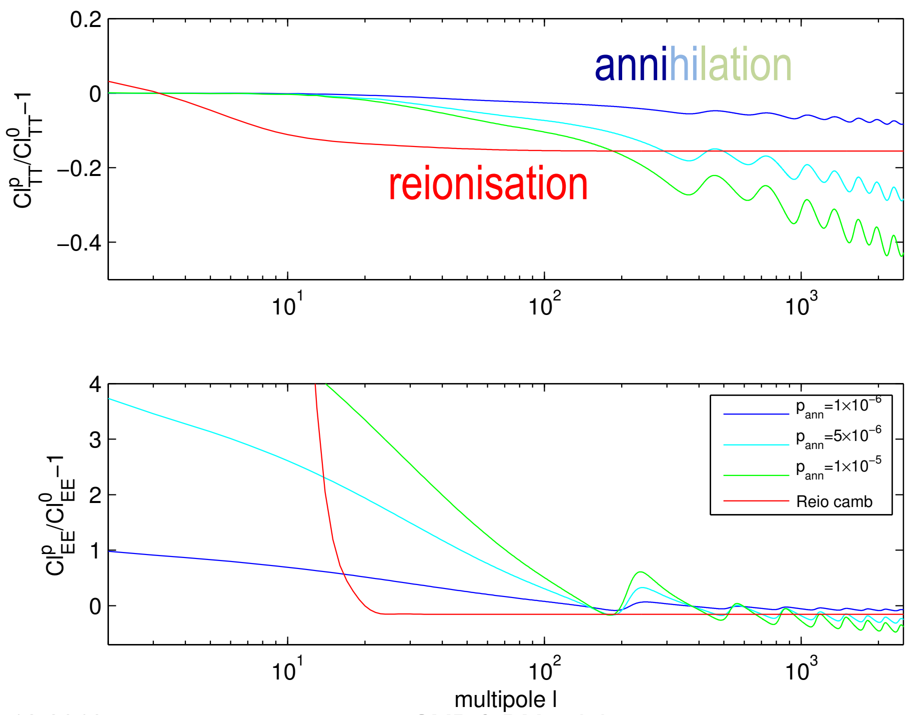
Relative impact:

- On temperature
- On polarisation



Different from reionisation:

- Higher redshift
- Smaller scales

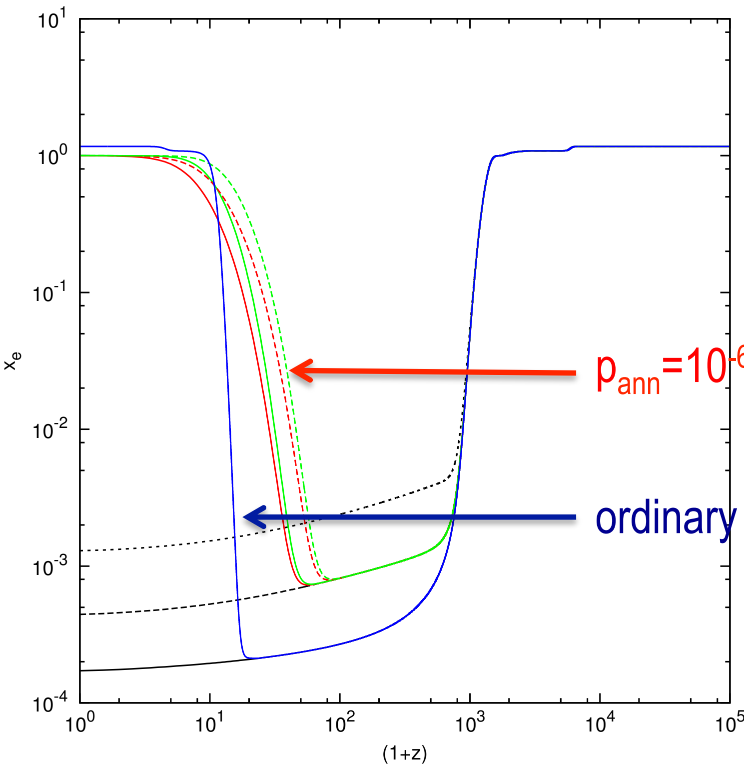
http://class-code.net

CMB and DM annihilation

- DM annihilation effects:
  3. Small z: { DM concentrates in halos, energy injection enhanced, contribution to reionisation

     … but lots of uncertainty on halo formation parameters

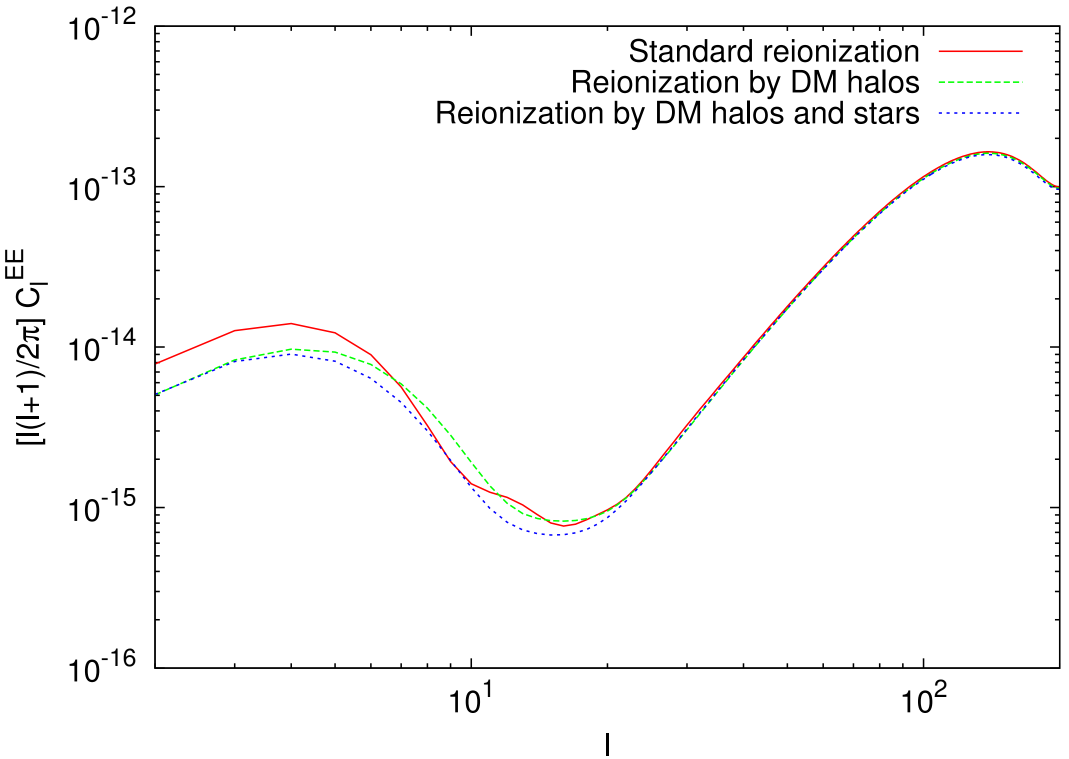
Ionisation fraction



CMB and DM annihilation

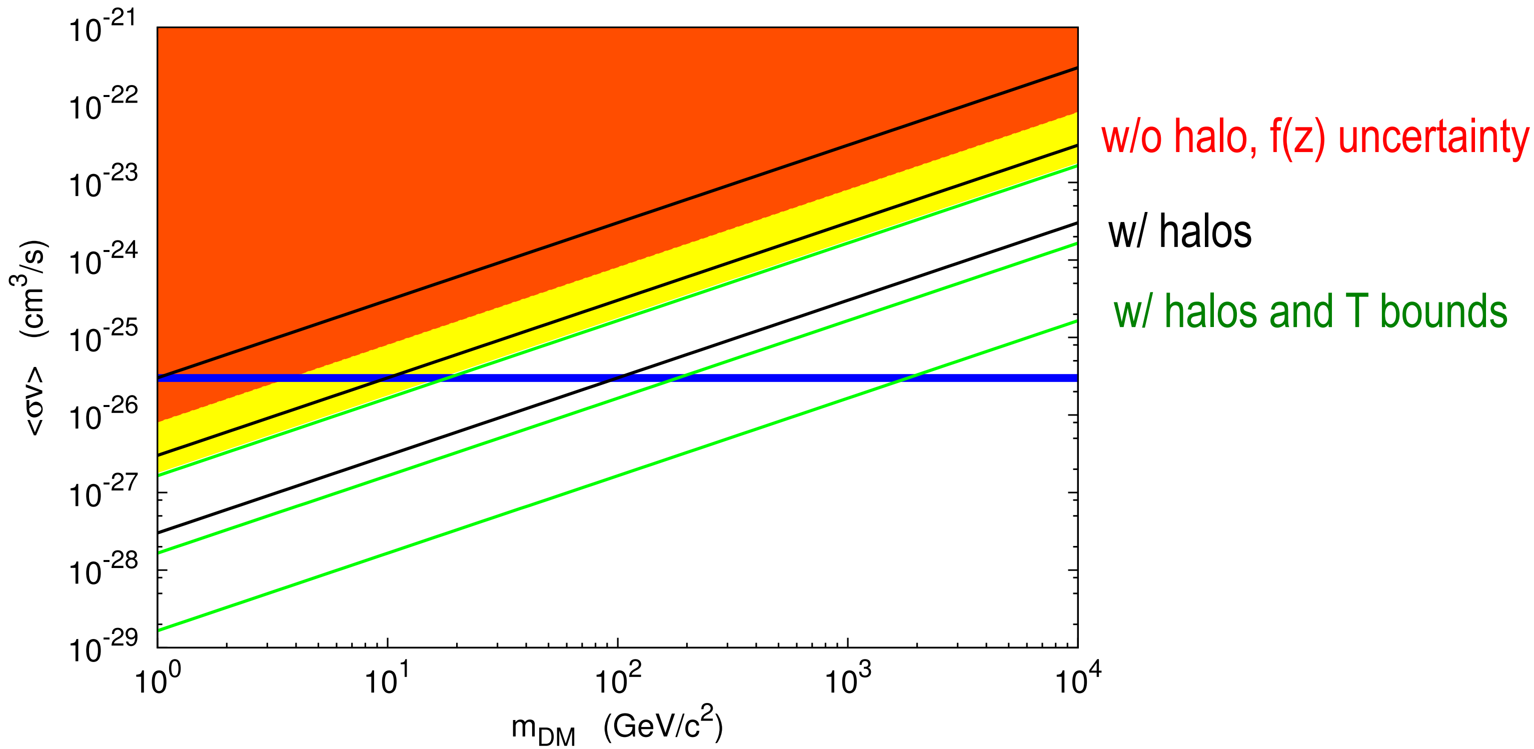
- DM annihilation effects:
  3. Small z: DM concentrates in halos,
     energy injection enhanced, contribution to reionisation
     … but lots of uncertainty on halo formation parameters

… and difficult to discriminate from star-induced reionization (maybe through T, quasars)



CMB and DM annihilation

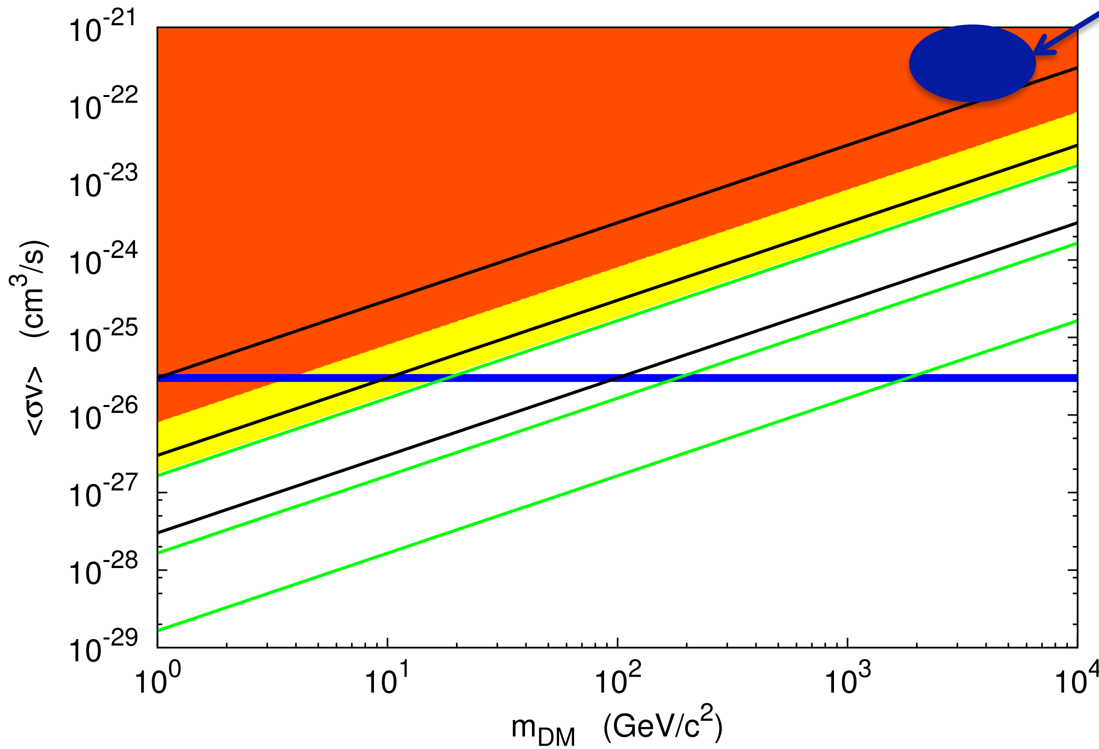
- WMAP bounds:



Giesen et al. 2012

CMB and DM annihilation

- WMAP results can exclude indirect-search-motivated models:



Giesen et al. 2012

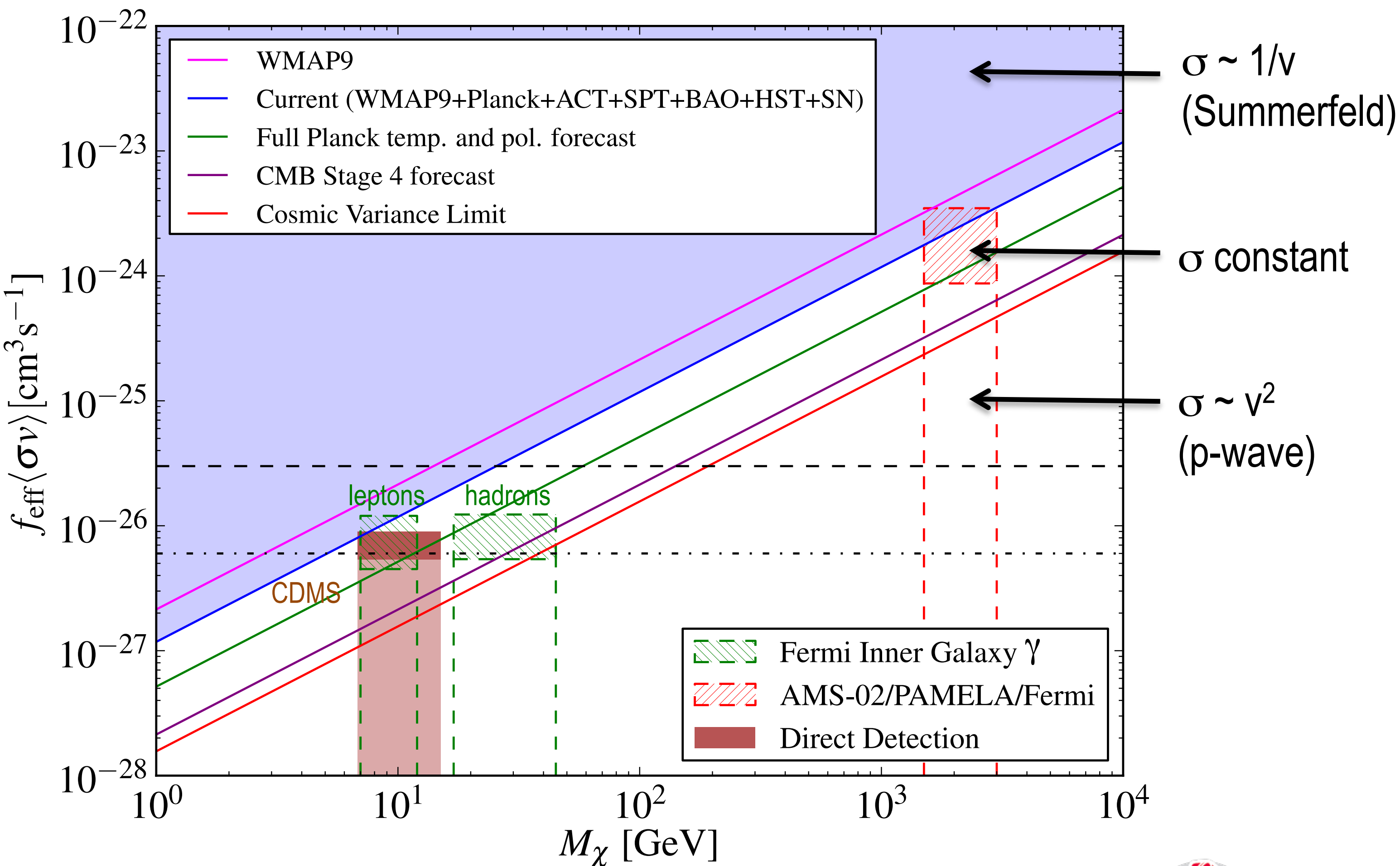
Candidate invoked to fit Pamela+Fermi positron anomaly, with Summerfeld enhancement leading to 10^{-24} today

Cirelli et al. 2009
Galli et al. 2009
Slatyer et al. 2009

CMB and DM annihilation

- Current limits and forecasts:

Madhavasheril et al. 2013



DM interactions with other particles

- DM scattering rate(s) probed by:
  - Relic density calculations
  - Indirect detection & CMB
  - Direct detection experiments

only annihilation or decay rate (Relic density calculations, Indirect detection & CMB)

mainly with quarks (Direct detection experiments)

limited mass range

DM interactions with other particles

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  - Relic density calculations } only annihilation
  - Indirect detection & CMB } or decay rate
  - Direct detection experiments mainly with quarks

  } limited mass range

  - Cosmological perturbations (CMB and Large Scale Structure power spectra)
    - Probes elastic cross-section with γ, b, ν,
    - "universal": for any mass, annihilating or decaying
    - negligible for standard WIMPs, but several models with larger interactions (millicharge, magnetic/dipole moment, …)
    - also model-dependent: need to assume redshift-dependence of σ

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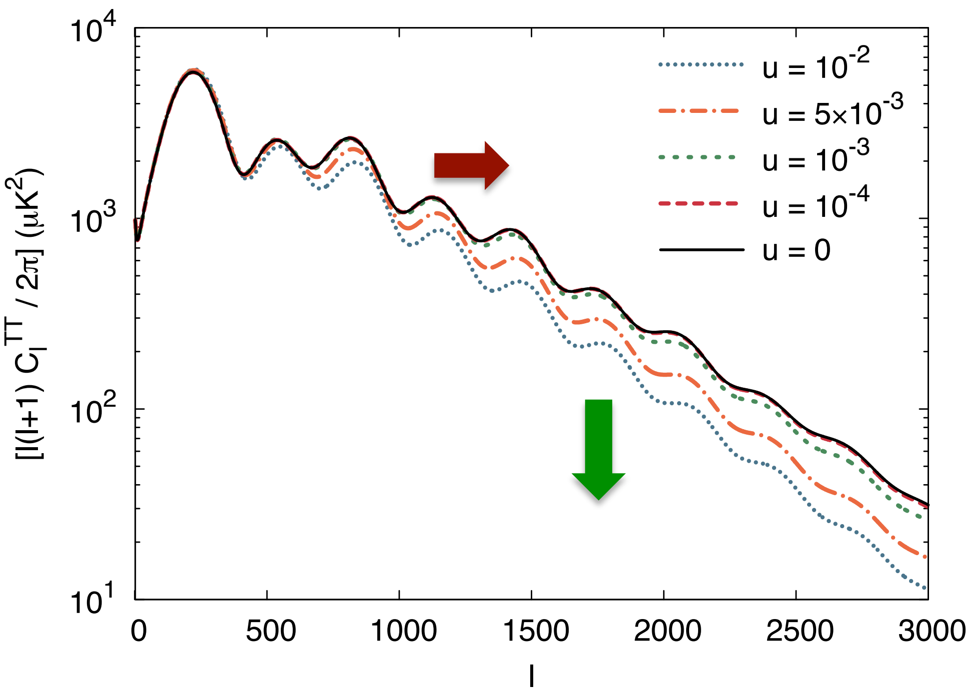
    - also model-dependent: need to assume redshift-dependence of σ
    - Collisional damping erasing CMB and/or matter fluctuations below given scale

C. Boehm, A. Riazuelo, S. H. Hansen and R. Schaeffer, 2001; X. I. Chen, S. Hannestad and R. J. Scherrer, 2002; K. Sigurdson, M. Doran, A. Kurylov, R. R. Caldwell and M. Kamionkowski, 2004, 2006; C. Boehm and R. Schaeffer, 2004; P. Serra, F. Zalamea, A. Cooray, G. Mangano and A. Melchiorri 2009; R. J. Wilkinson, J. Lesgourgues and C. Bœhm, 2013; C. Dvorkin, K. Blum, M. Kamionkowski 20013;

DM interactions with other particles

- DM-γ elastic scattering cross section $u \equiv \left[\frac{\sigma_{DM-\gamma}}{\sigma_{Th}}\right]\left[\frac{m_{DM}}{100\ \mathrm{GeV}}\right]^{-1}$

exemple with constant u :



http://class-code.net

+ Wilkinson et al. 1309.7588

- Extra diffusion damping, modified plasma sound speed
- SPT saw anomalous low damping tail! N_{eff}, tilt running… or interactions?

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- From first Planck release:

  - Constant u :

$$\begin{cases} u \leq 1.2 \times 10^{-4}\ \ (\mathrm{at}\ \ 68\%\ \ \mathrm{CL}) \\ \sigma_{\mathrm{DM}-\gamma} \leq\ 8 \times 10^{-31}\,(m_{\mathrm{DM}}/\mathrm{GeV})\ \mathrm{cm}^2 \end{cases}$$

    - Light (< GeV): at most weak. Interesting for DM not annihilating into SM (e.g. asymmetric)
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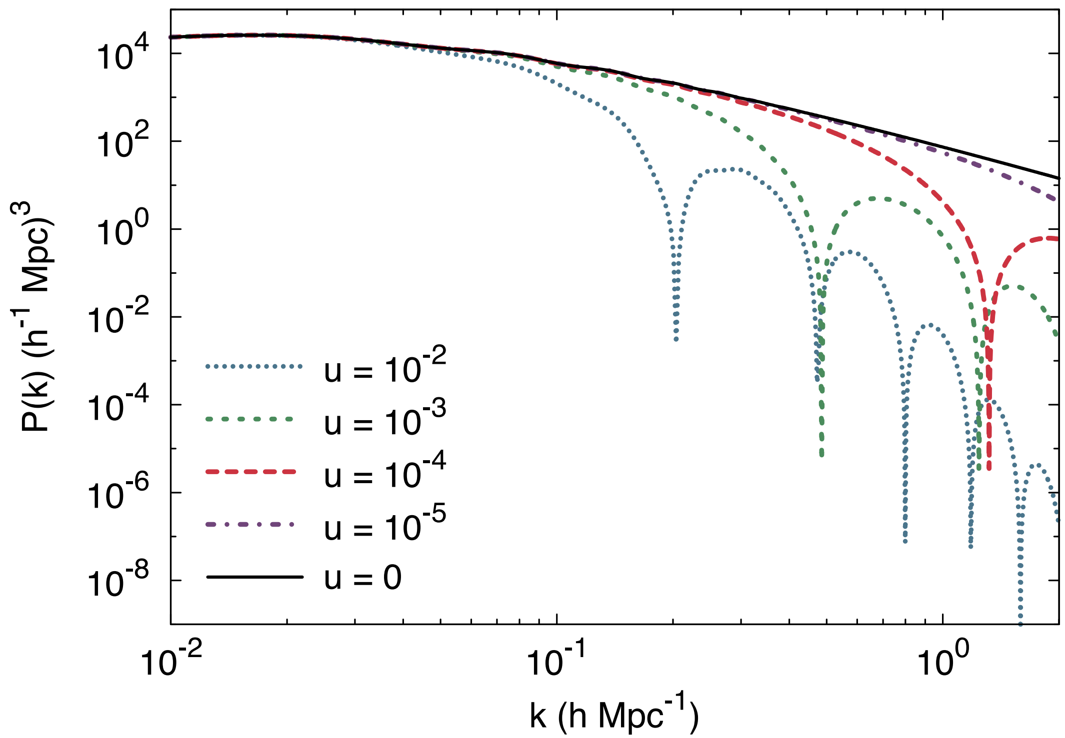
  - Increasing u ~ T^2 (dependence on photon energy): today

$$\sigma_{DM-\gamma} \leq\ 6 \times 10^{-40}\,(m_{DM}/\mathrm{GeV})\ \ \mathrm{cm}^2$$

(gives looser bounds at high redhsift)

DM interactions with other particles

- DM-γ elastic scattering cross section $u \equiv \left[\frac{\sigma_{DM-\gamma}}{\sigma_{Th}}\right]\left[\frac{m_{DM}}{100\ \mathrm{GeV}}\right]^{-1}$
- Potential progress with better foreground removal, polarisation, or large scale structure:



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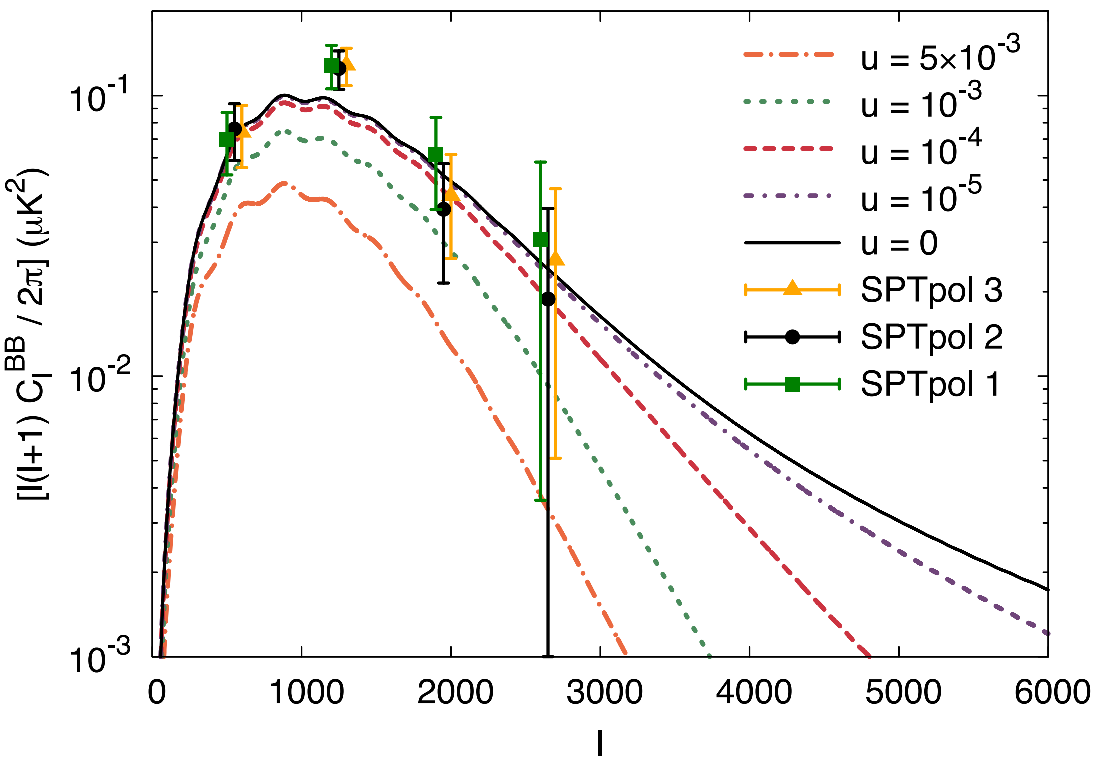

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DM interactions with other particles

- DM-b elastic scattering cross section after Planck — Dvorkin et al. 1311.2937

$\sigma \sim v^n$

n	CMB (95%CL, cm^2/g)	CMB + Lyman-α (95%CL, cm^2/g)	λ (MW)	
-4	1.8×10^{-17}	1.7×10^{-17}	27 Gpc	Millicharge
-2	3.0×10^{-9}	6.2×10^{-10}	738 Mpc	Dipole moment
-1	1.6×10^{-5}	1.4×10^{-6}	313 Mpc	
0	0.12	3.3×10^{-3}	138 Mpc	Massive boson (Yukawa)
+2	1.3×10^{5}	9.5×10^{3}	46 Mpc	

- SM-ν elastic cross-section: weaker bounds — Serra et al. 2009

Subdominant DM: Flavor neutrinos

Neutrino mass effect on CMB:

- $M_\nu = \Sigma m_\nu > 0.06$ eV (NH) or 0.1 eV (IH). At least two non-relativistic neutrinos today. But mass still below Planck sensitivity although there are anomalies…
- Neutrinos contribute to radiation at early time and non-relativistic matter at late time: $\omega_\nu = M_\nu$ / 94eV.

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- "effect of m_ν" depends on what is kept fixed.
- Leave both "early cosmology" and angular diameter dist. to decoupling invariant (fixing photon, cdm and baryon densities, while tuning H_0, Ω_Λ)

Flavor neutrinos

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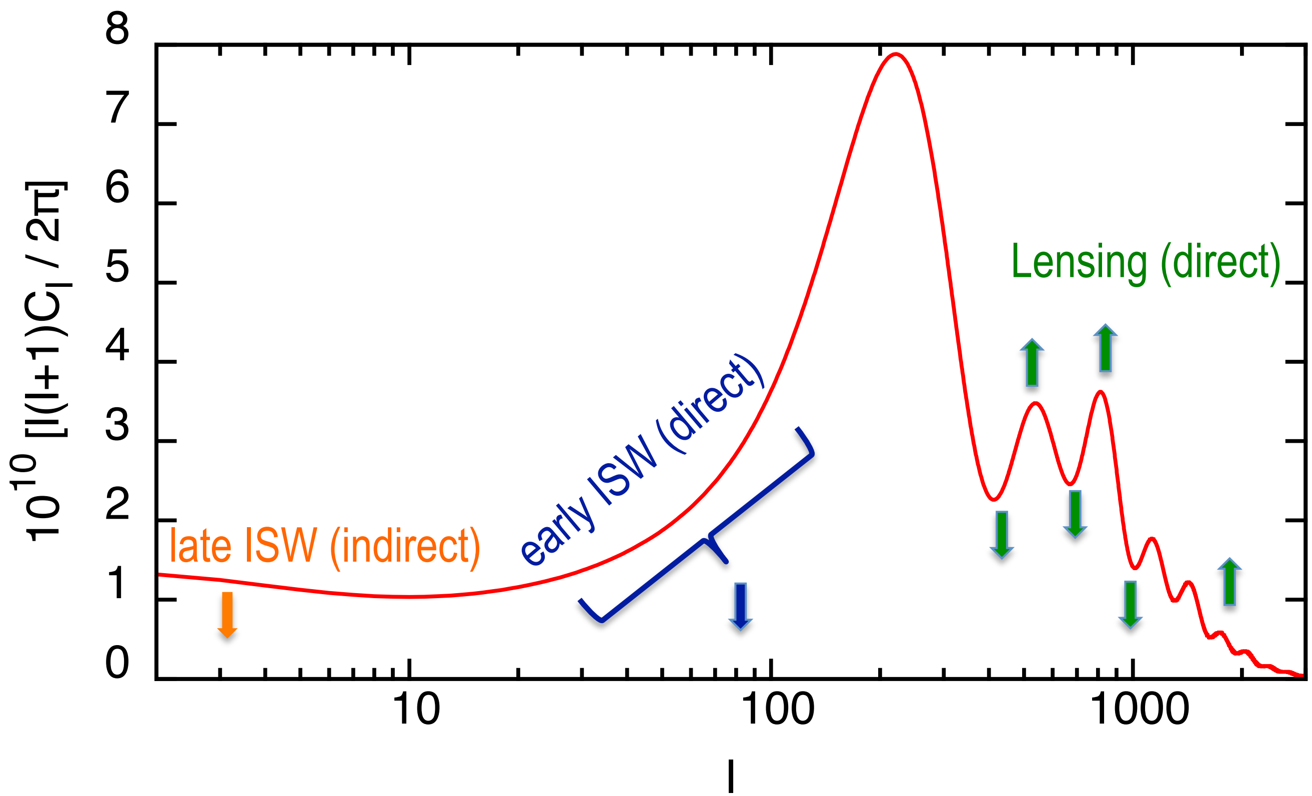
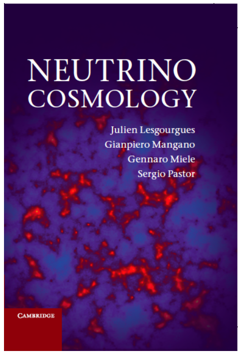




Lesgourgues, Mangano, Miele, Pastor, CUP 2013

Flavor neutrinos

Neutrino mass effect on CMB:

- not observed by Planck! Especially because spectrum has low peak contrast and would like even more lensing than in ΛCDM…

CMB alone (Planck+WP+HighL):

$\Sigma m_\nu < 0.66\text{eV}$ (95%CL)

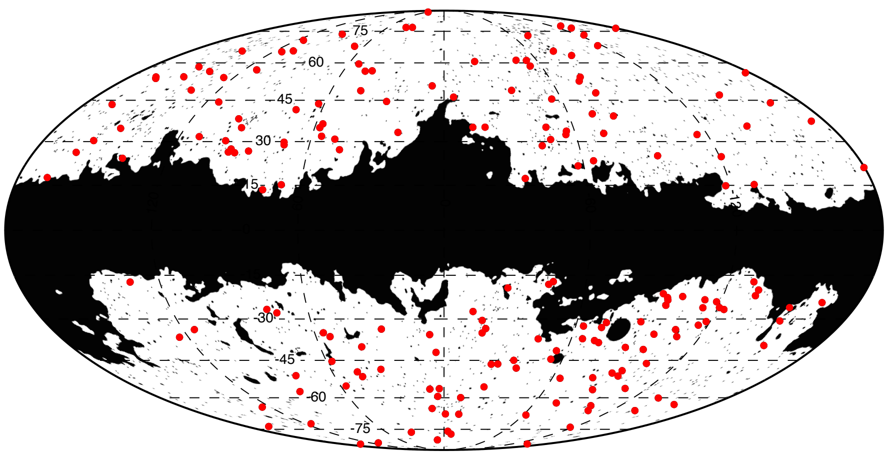
With BAO:

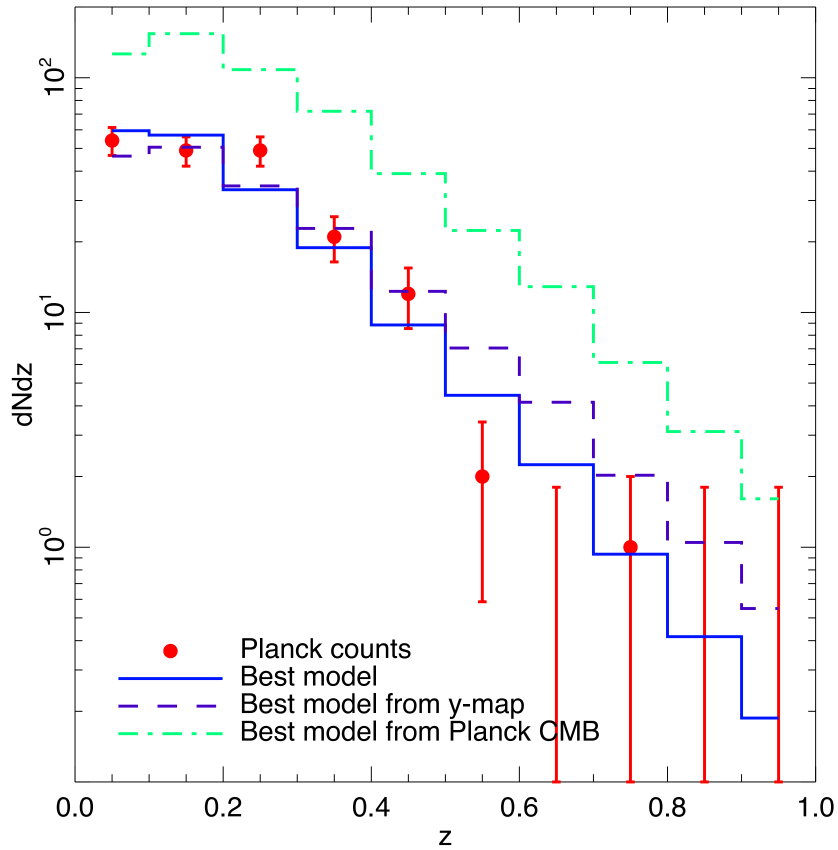
$\Sigma m_\nu < 0.23\text{eV}$ (95%CL)

- Compatible with bounds from galaxy surveys and Lyman-α
- Anomalies: lensing extraction, galaxy shear, cluster mass function

SZ cluster count

- Using SZ cluster count from Planck





Planck XX, 2013

SZ cluster count

- Using SZ cluster count from Planck, issue with bias parameter
  (bias between SZ flux Y and true mass)

Planck XX, 2013; Battye & Moss 2013;

… systematics or evidence for neutrino mass ?

Same issue with cluster count from other catalogues

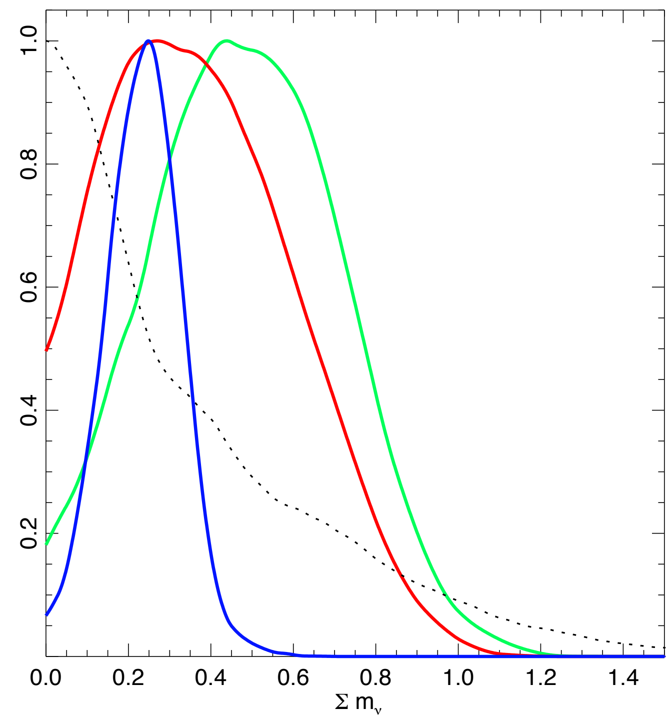
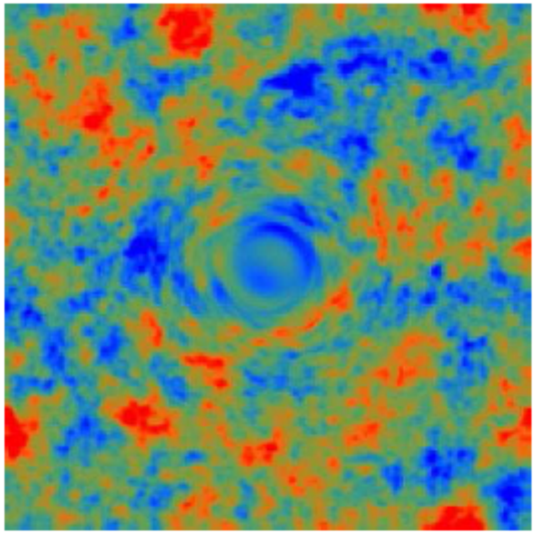


Fig. 12. Cosmological constraints when including neutrino masses $\sum m_\nu$ from: *Planck* CMB data alone (black dotted line); *Planck* CMB + SZ with $1 - b$ in [0.7, 1] (red); *Planck* CMB + SZ + BAO with $1 - b$ in [0.7, 1] (blue); and *Planck* CMB + SZ with $1 - b = 0.8$ (green).

Lensing extraction

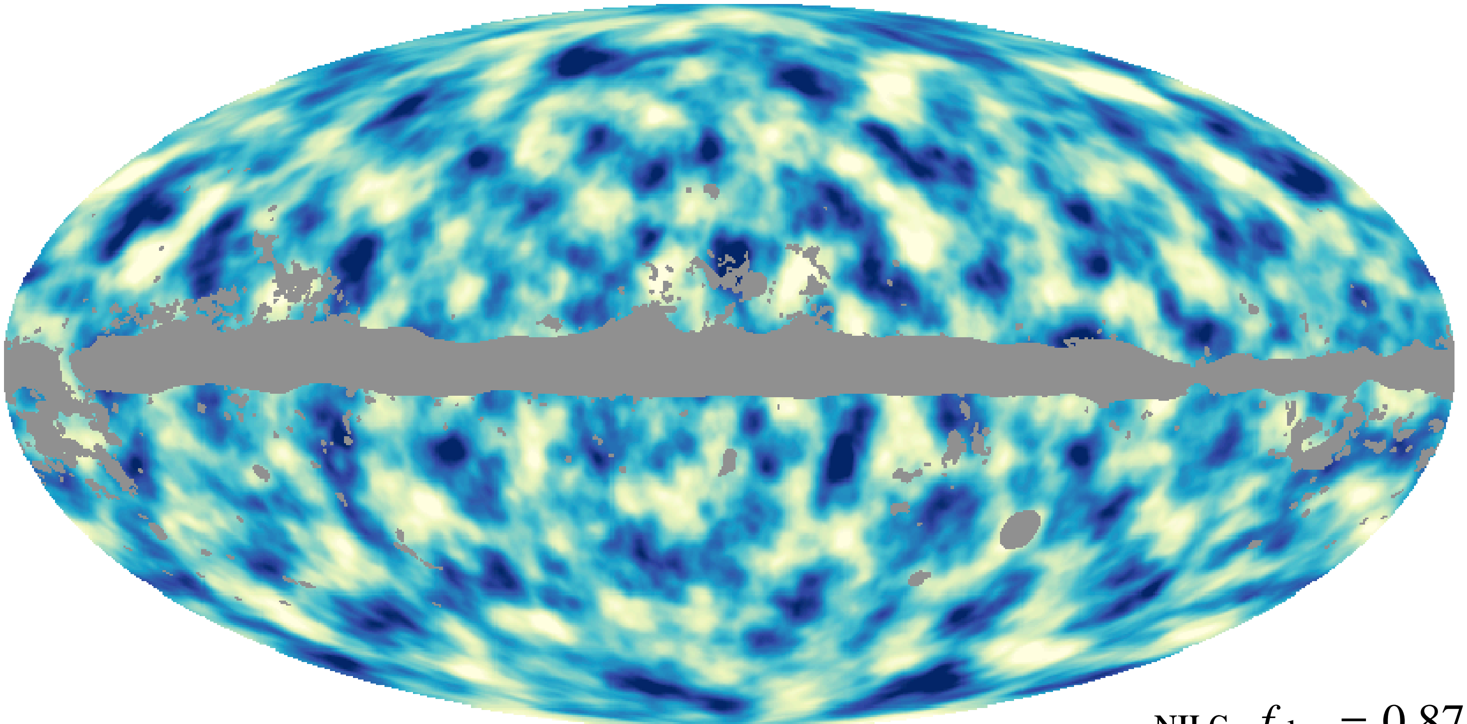
- exaggerated effect of a huge cluster:



- In fact, only 2'-3' deflections, coherent over large scales: invisible by eye
- Lensing potential = projected gravitational field (with some kernel: sensitive to structures at z~1-3)
- Induces non-gaussianity with very specific correlations. Can be extracted with specific "quadratic estimator" (= 4-point correlations)
- Proposed by Hu & Okamoto (2001)
First success in 2012 (SPT-ACT)

Lensing extraction

Lensing potential map:

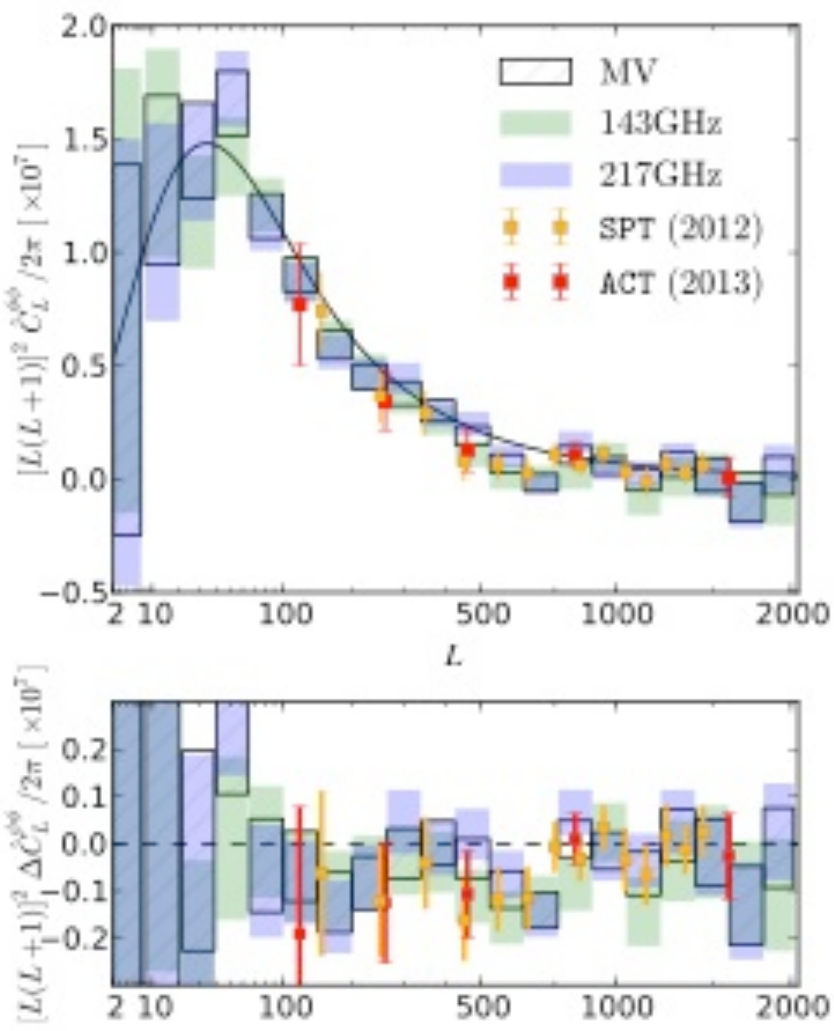


NILC, $f_{\rm sky} = 0.87$

Low signal-to-noise, but correlates at high level with different tracers of LSS (20 sigma with NVSS quasars, 10 sigma with SDSS LRG, 42 sigma with Planck's CIB)

Lensing extraction

- Lensing power spectrum consistent with ΛCDM
- Helps removing degeneracies and measuring extended model parameters with Planck alone



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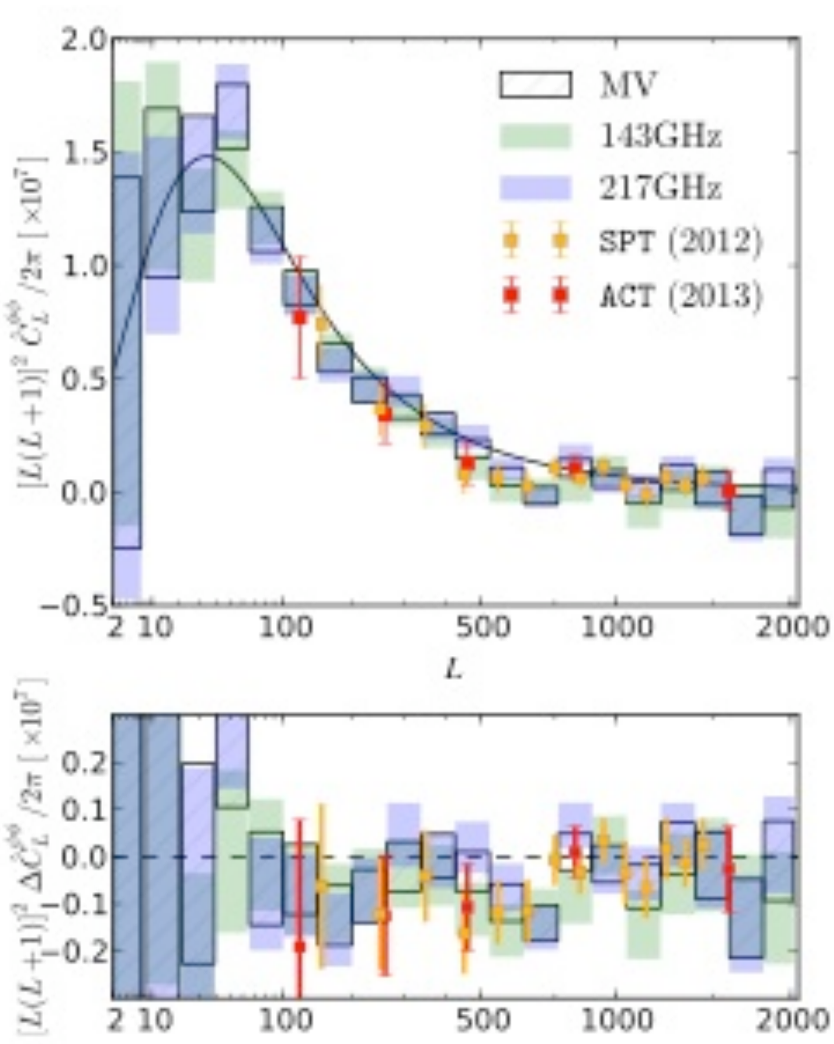
With lensing:

$\Sigma m_\nu < 0.85$eV (95%CL)



Other light relics

Anomalies could be related flavor neutrinos,

or to mass of other relics!!

Is N_{eff} > 3 ?

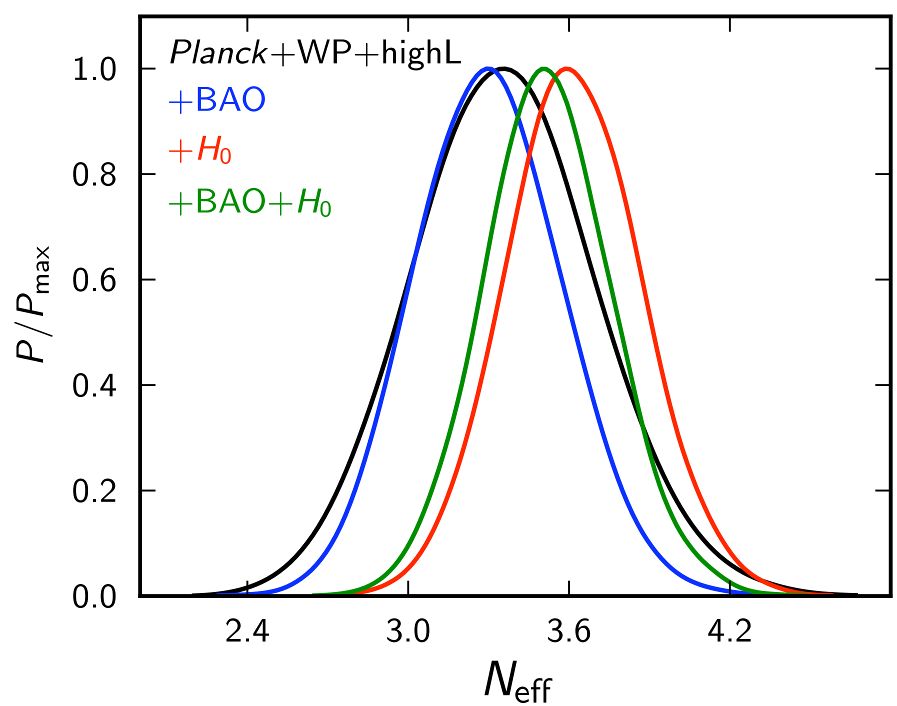
- N_{eff} constraints driven by CMB damping tail
  - WMAP+SPT see anomalously low tail: $N_{eff} > 3$ at 2 sigma
  - Planck and Planck+BAO well compatible with 3.046 at 1 sigma
  - Planck (+BAO) + HST : enforce higher H_0, hence also higher N_{eff}

CMB alone (Planck+WP+HighL)

$N_{eff} = 3.36 \pm 0.66$ (95%CL)

With lensing and BAO:

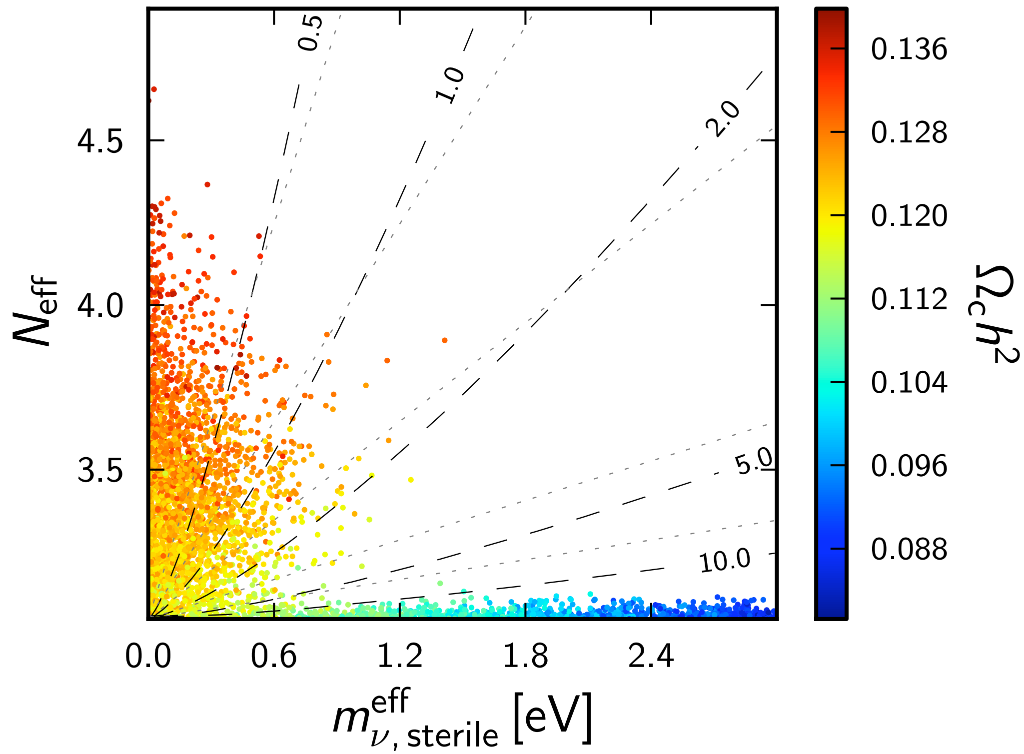
$N_{eff} = 3.30 \pm 0.52$ (95%CL)



Light sterile neutrinos

CMB only (Planck + WP + highL) analysis for 3+1 case:

Total neutrino density in early universe

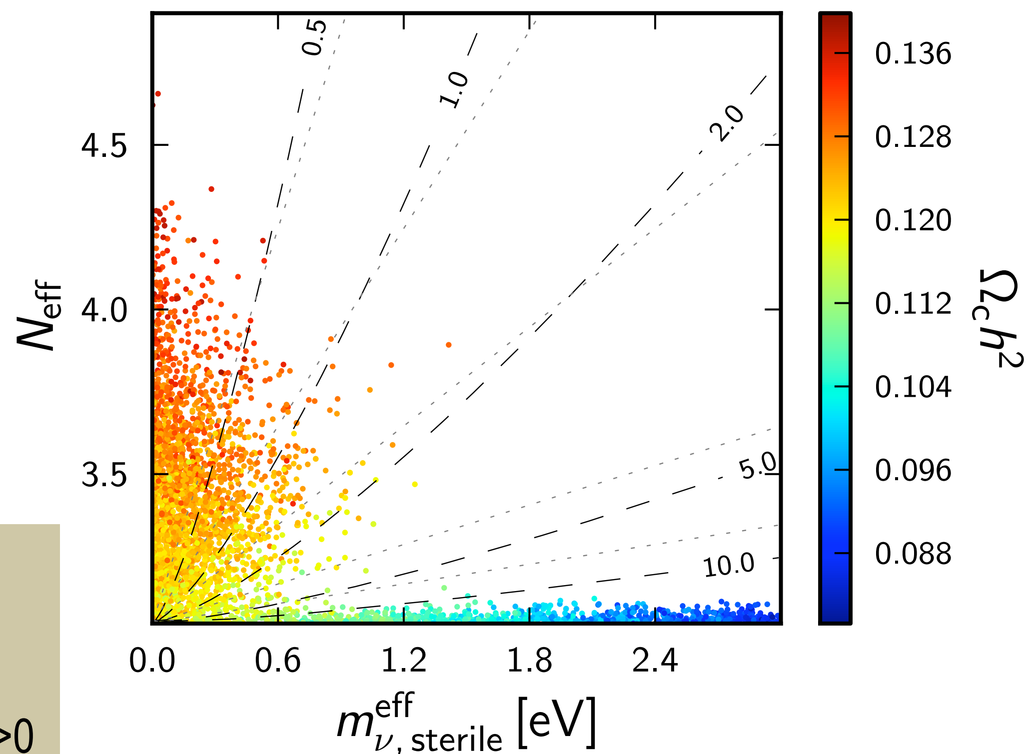


Sterile neutrino density today $\omega_{\nu s}$

Light sterile neutrinos

CMB only (Planck + WP + highL) analysis for 3+1 case:

Total neutrino density in early universe



Sterile neutrino density today $\omega_{\nu s}$

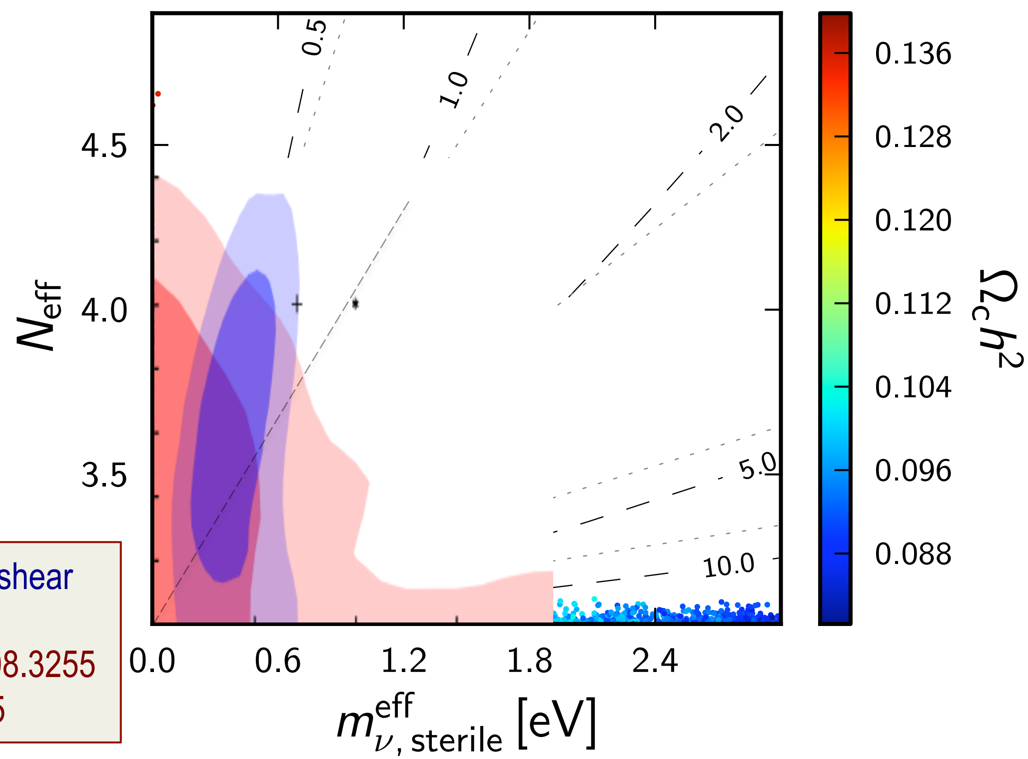
H0 would push Neff>3

SZ, Lensing extraction, cosmic shear would push m>0

Light sterile neutrinos

CMB only (Planck + WP + highL) analysis for 3+1 case:

Total neutrino density in early universe



Sterile neutrino density today $\omega_{\nu s}$

Using H0 + BAO + clusters + gal.shear

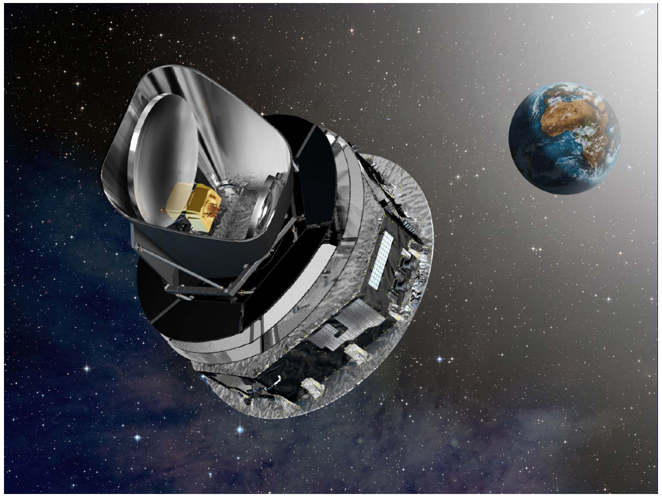
From Hamann & Hasenkamp 1308.3255
See also Wyman et al. 1307.7715

Conclusion

interplay between

cosmological perturbations and particle physics

even more rich than thought 15 years ago…



lot more to come from Planck

…

from next generation satellite (?) …

and from large scale structure!