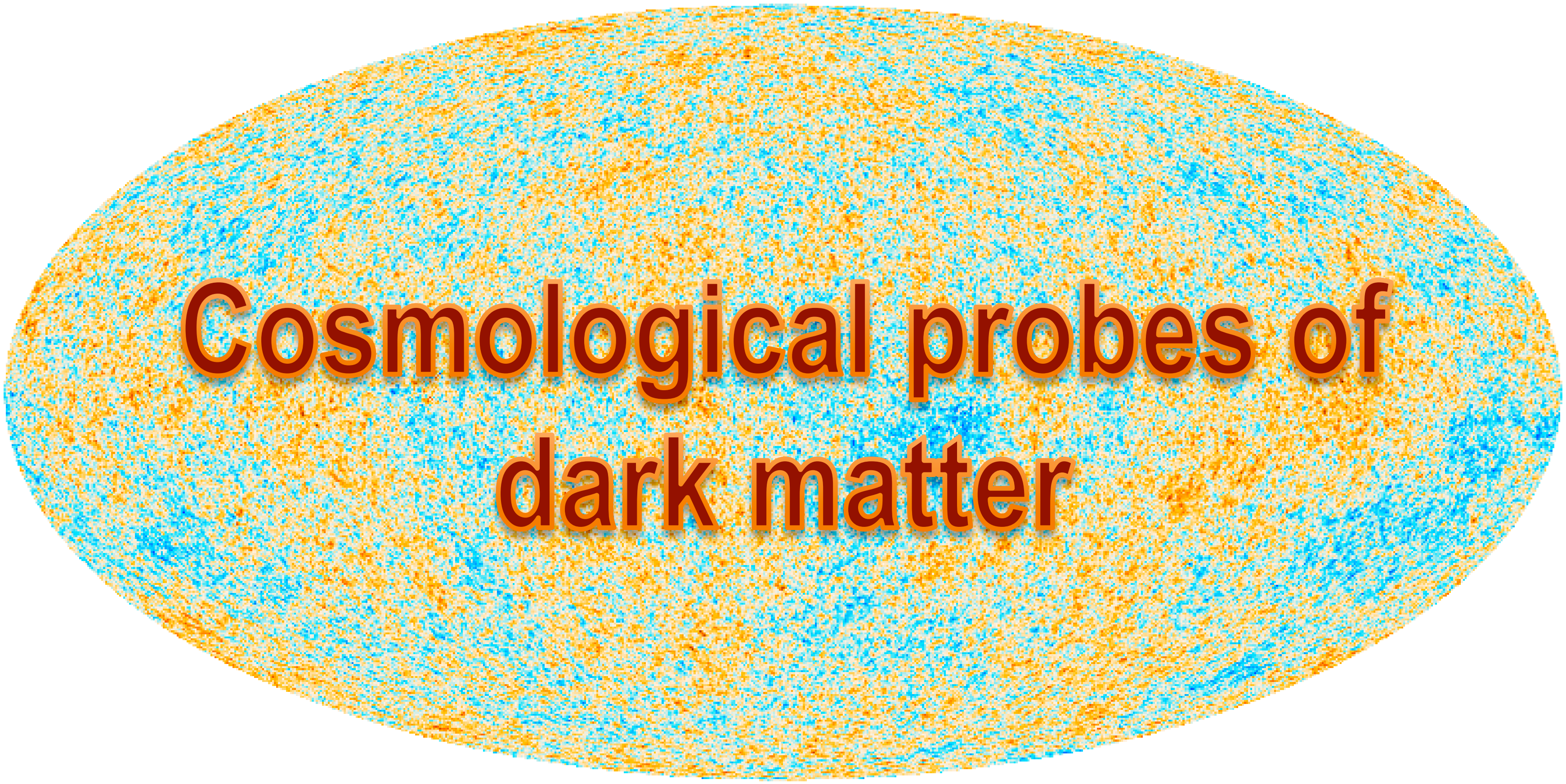

Cosmological probes of dark matter

Implications of the 125 GeV Higgs Boson, **LPSC Grenoble, 24.03.2014**

Julien Lesgourgues (EPFL, CERN, LAPTh)

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Cosmological model

Baryonic matter

Dominant Dark Matter component

Sub-dominant Dark Matter component (massive neutrinos, maybe extra light relics…)

Radiation (photons, maybe extra relativistic relics…)

Vacuum or Dark Energy

Generation mechanisms for primordial fluctuations, magnetic fields, etc.

Cosmological model

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Cosmological observations

- CMB maps (temperature, polarisation)
- Large Scale Structure (galaxy maps, lensing maps, Lyman-alpha spectra, cluster mass function)
- Primordial abundances (deuterium, helium…)
- Standard rulers, standard candles

Astrophysical observations

- Cosmic Rays (gamma-rays satellite, particle detectors in space, neutrino telescopes…)
- High-energy astrophysical phenomena: Supernovae, Gamma Ray Bursts, AGNs…
- Galactic structure (satellite, rotation curves…)

Laboratory experiments

- Accelerators (LHC) / DM direct detection
- Neutrino oscillation / beta decay experiments

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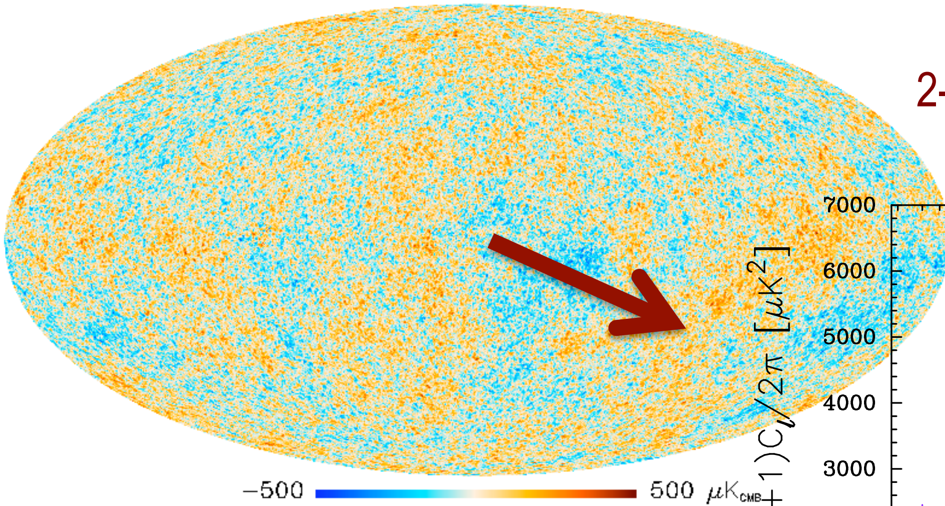
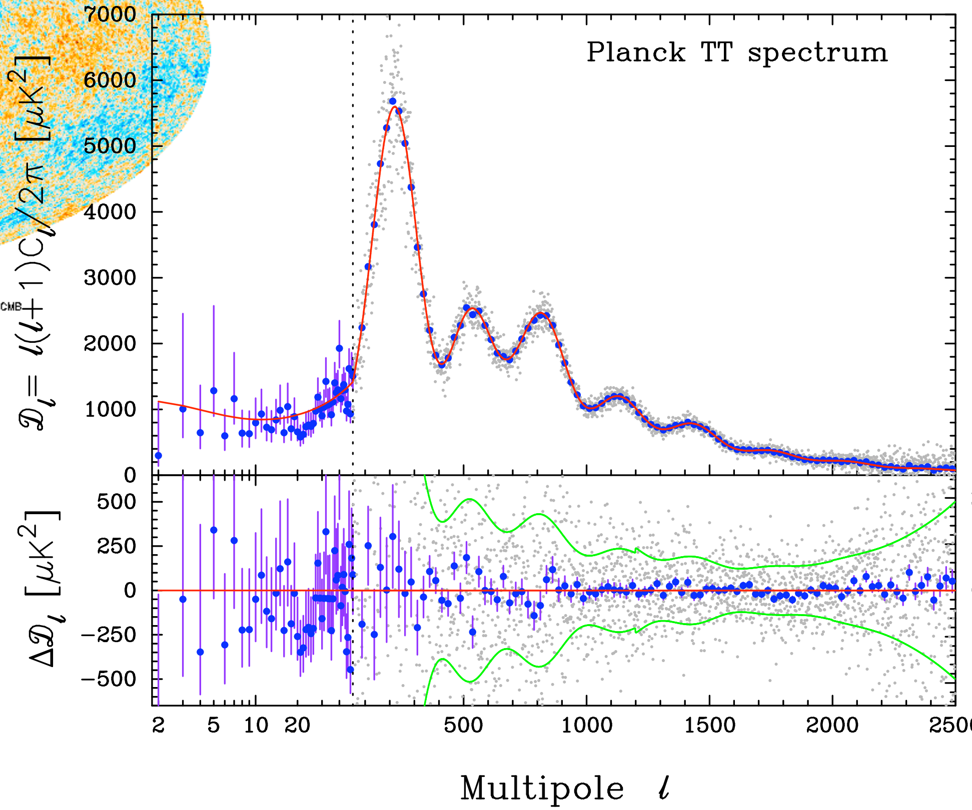
Cosmological observations: CMB temperature

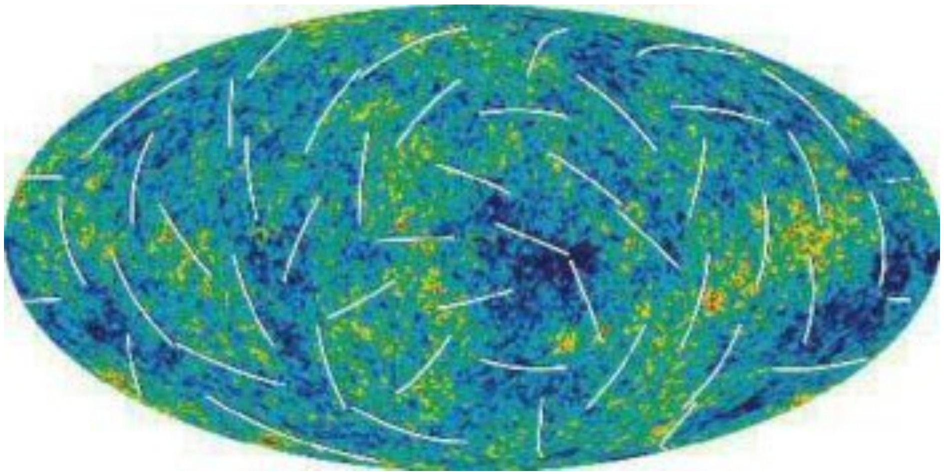


2-pt correlation function in harmonic space
= temperature spectrum



Overwhelming agreement
with predictions of minimal
ΛCDM model

Cosmological observations: CMB polarisation



WMAP

2-pt correlation function of polarisation
in harmonic space = polarisation spectrum

1 vector map = 2 scalar maps

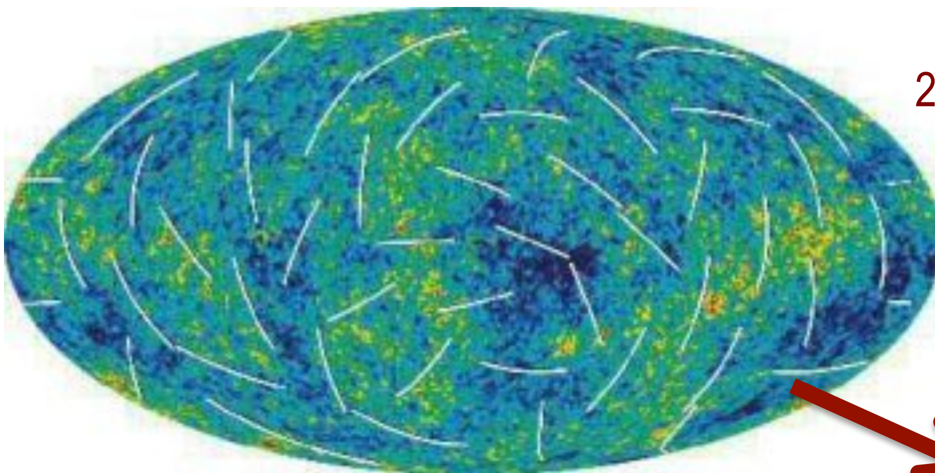
E-modes ← scalars (density fluct.)

E-modes ↓ lensing → B-modes

B-modes ← tensors (GW)

tensors (GW) → E-modes

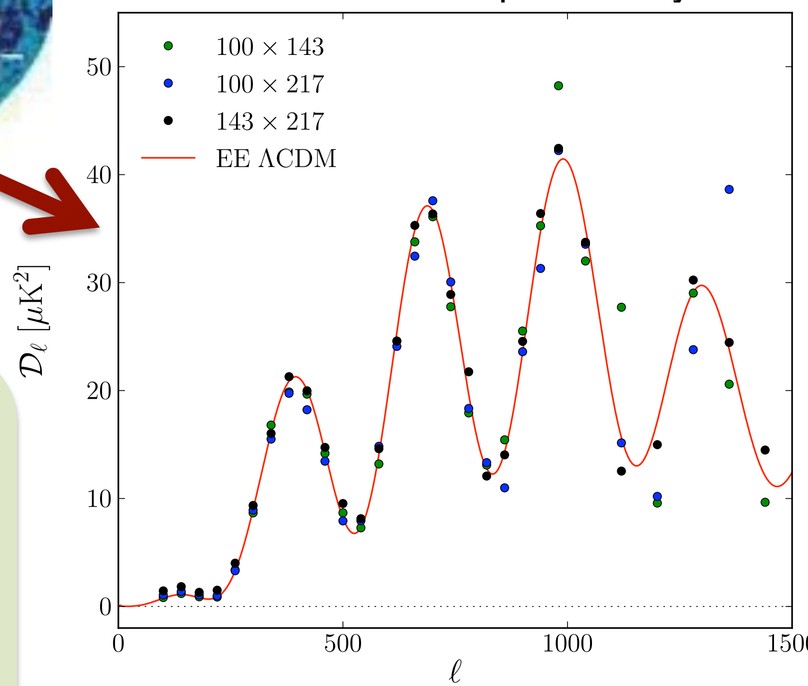
Cosmological observations: CMB polarisation



WMAP

2-pt correlation function of divergence potential in harmonic space = polarisation spectrum

Planck E-mode preliminary!!



1 vector map = 2 scalar maps

E-modes ← scalars (density fluct.)

lensing

B-modes ← tensors (GW)

Planck B-mode: low sensitivity, on-going analysis

Cosmological observations: CMB polarisation

The BICEP2 claim
arXiv:1403.3985

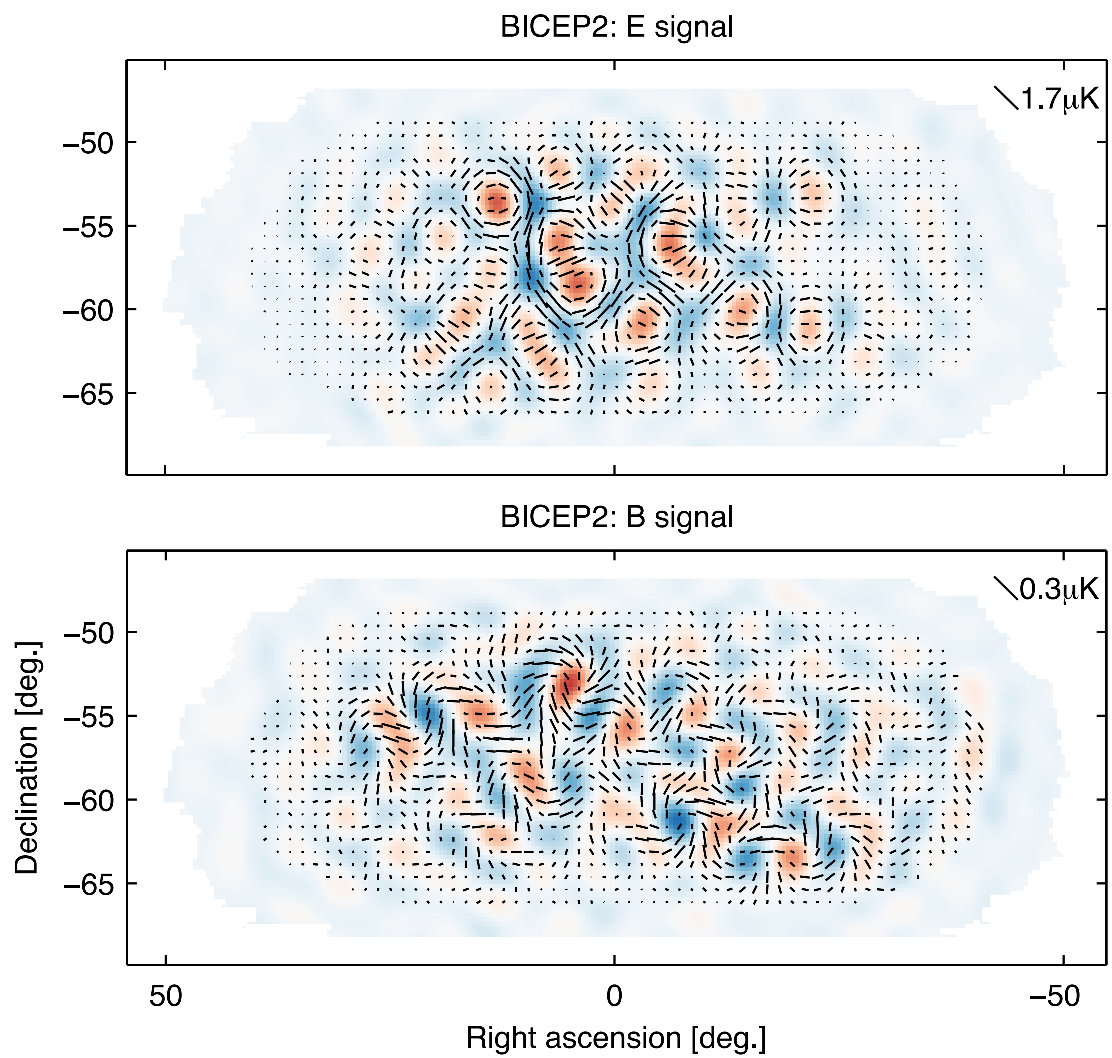
Detection of primordial B-modes !!!!!

r = T/S = 0.2

- GUT-scale inflation
- shift in most cosmological parameters

But :

3σ tension with Planck unless running, isocurv. modes, short inflation, etc.



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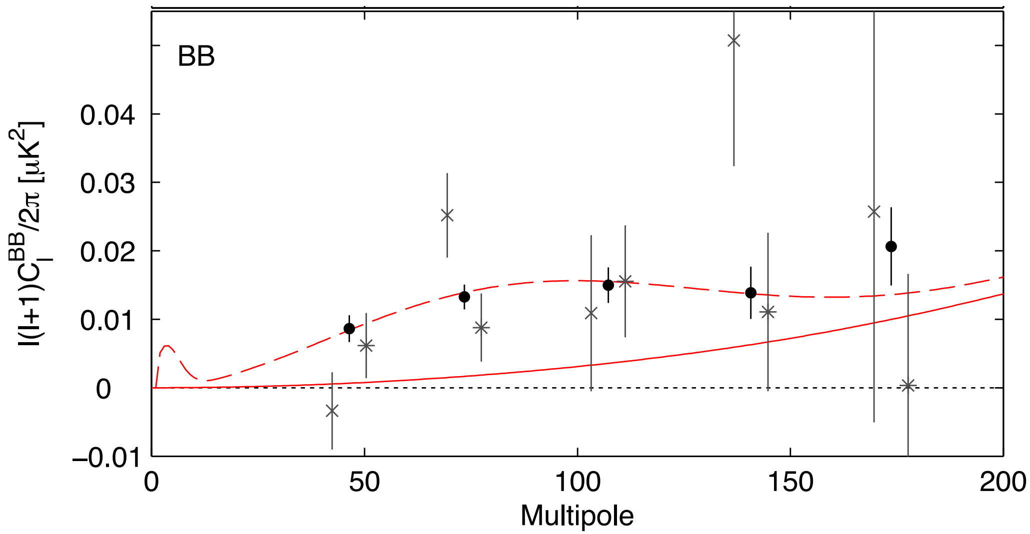


FIG. 7.— The BICEP2 *EE* and *BB* auto spectra (as shown in Figure 2) compared to cross spectra between BICEP2 and the 100 and 150 GHz maps from BICEP1. The cross spectrum points are offset horizontally for clarity.

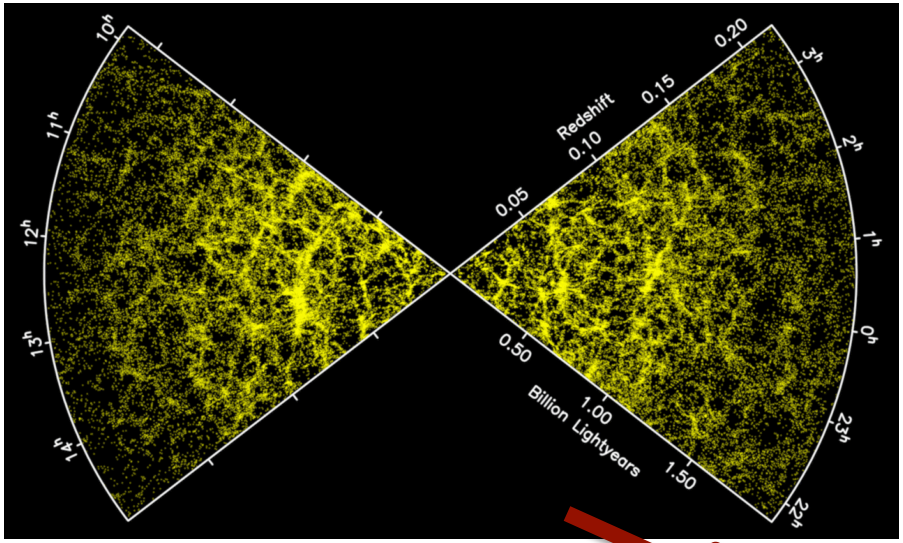
Significant detection only at 150Ghz so far…

Difficult to remove instrumental noise and foregrounds

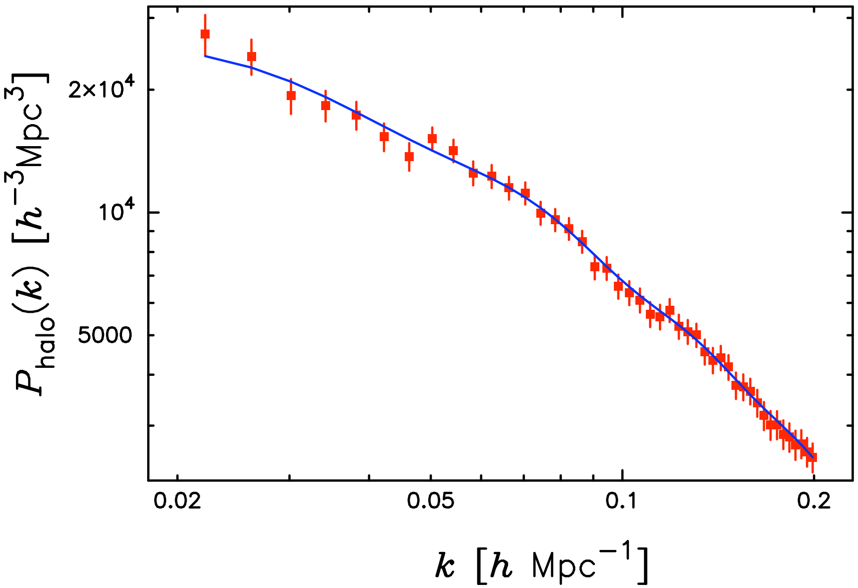
Planck will provide
- better TT+TE constraints
- comparable BB sensitivity
- dust maps

+ Keck Array, ACTpol, Ebex,…

Cosmological observations: LSS from galaxy maps

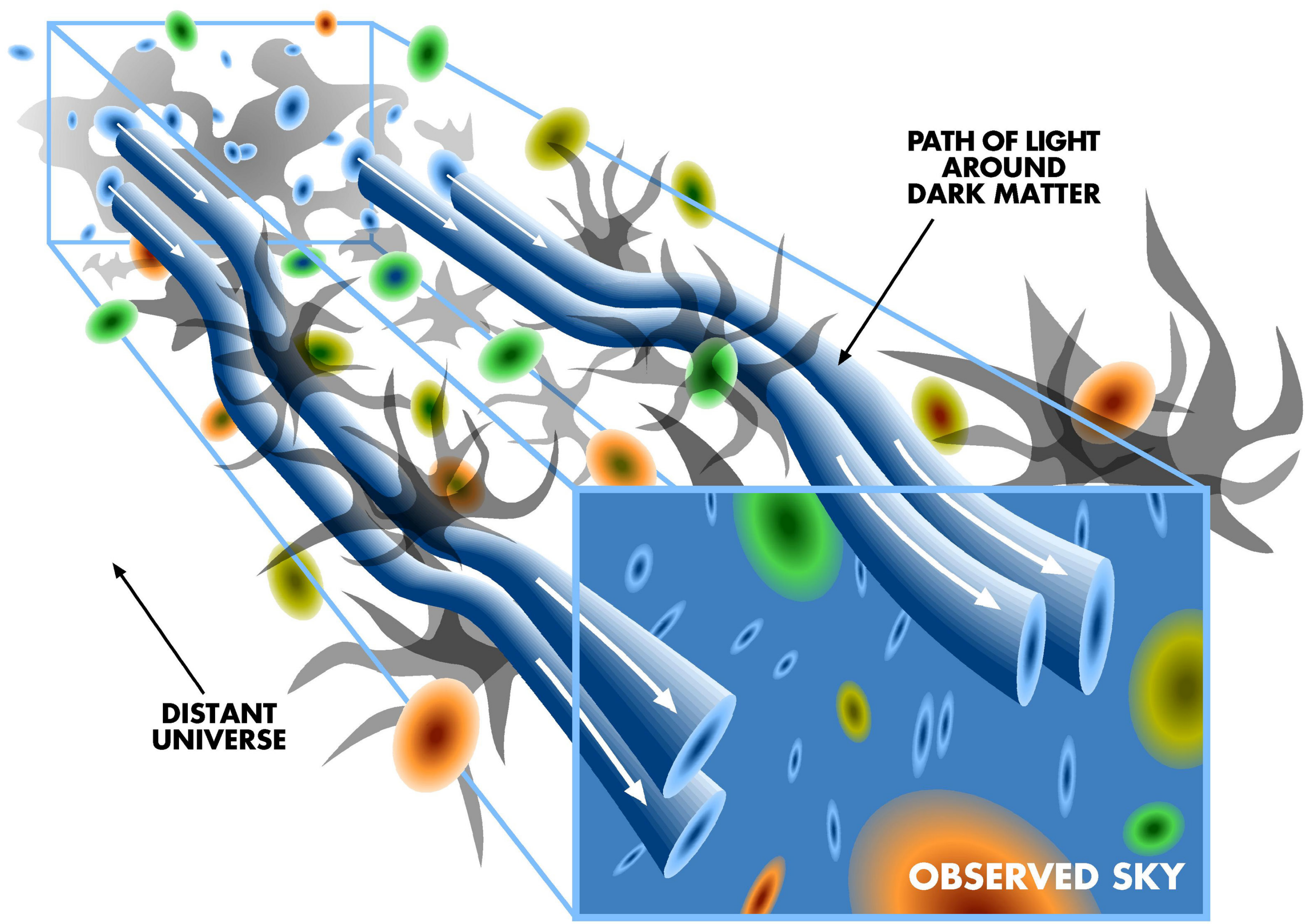


2-pt correlation function in Fourier space
= matter spectrum

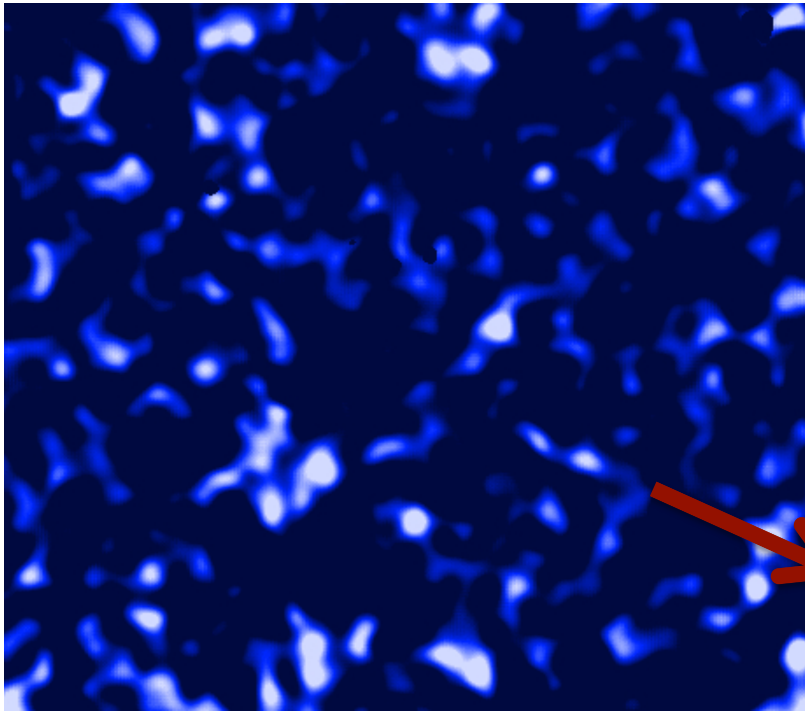


Excellent agreement with predictions of minimal ΛCDM model

Cosmological observations: LSS from lensing maps

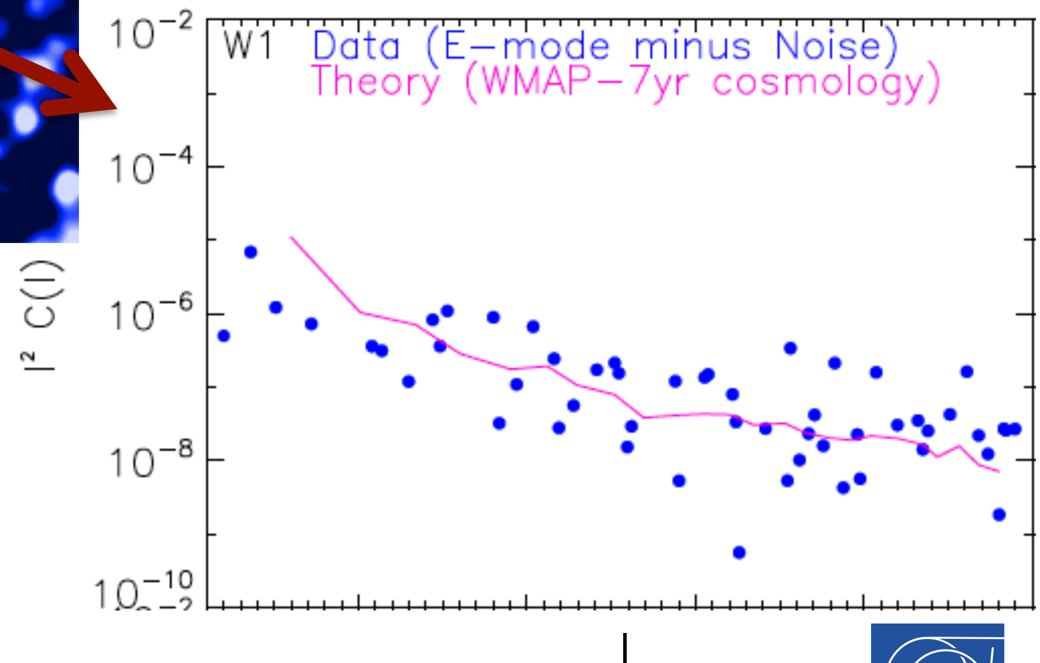


Cosmological observations: LSS from lensing maps

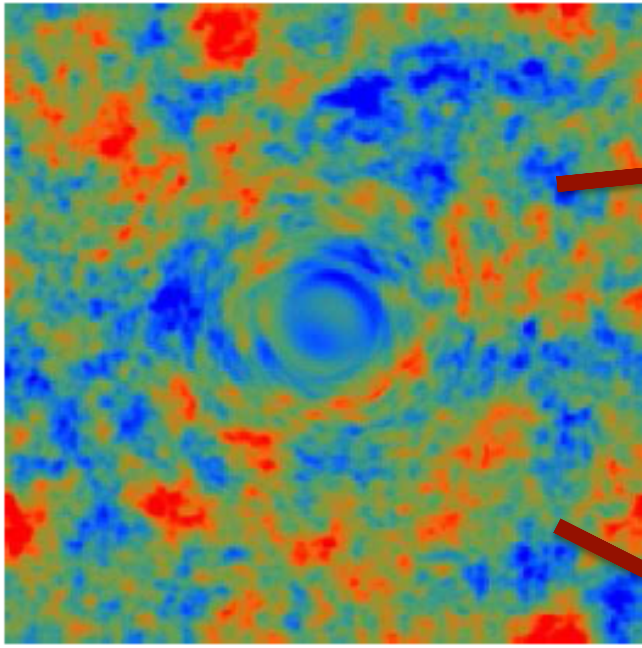


CFHTLens

2-pt correlation function of
Lensing potential in harmonic space
= lensing spectrum

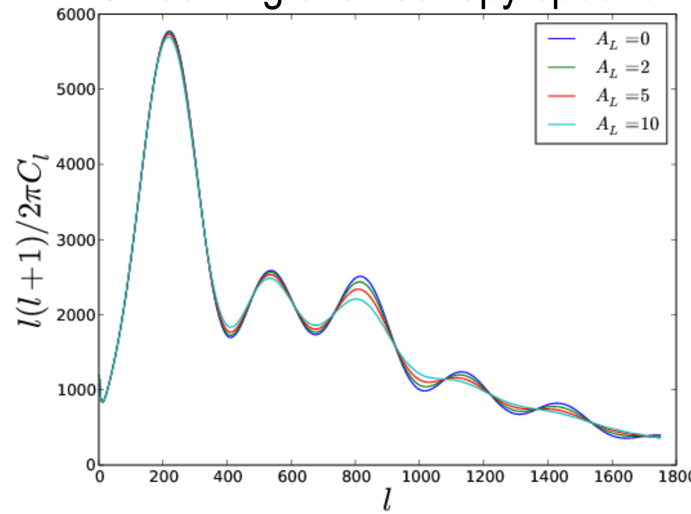


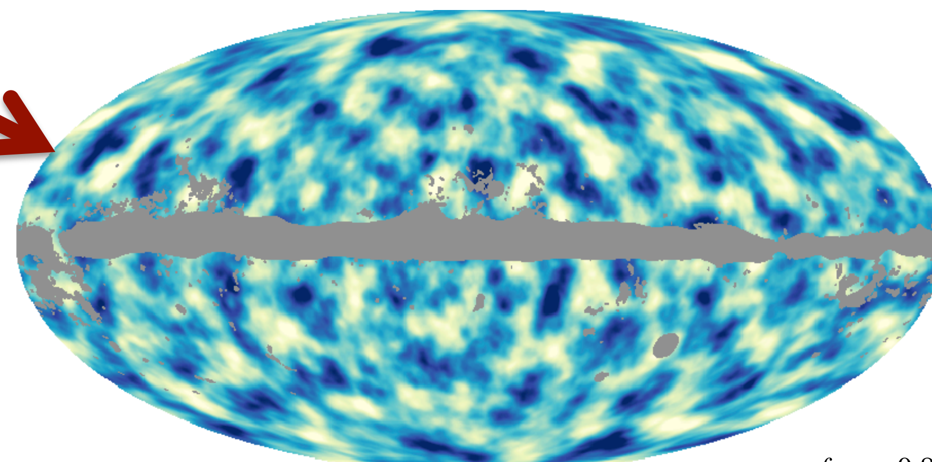
Cosmological observations: LSS from CMB lensing maps



Simulation of CMB lensing by huge cluster

Smoothing of anisotropy spectrum

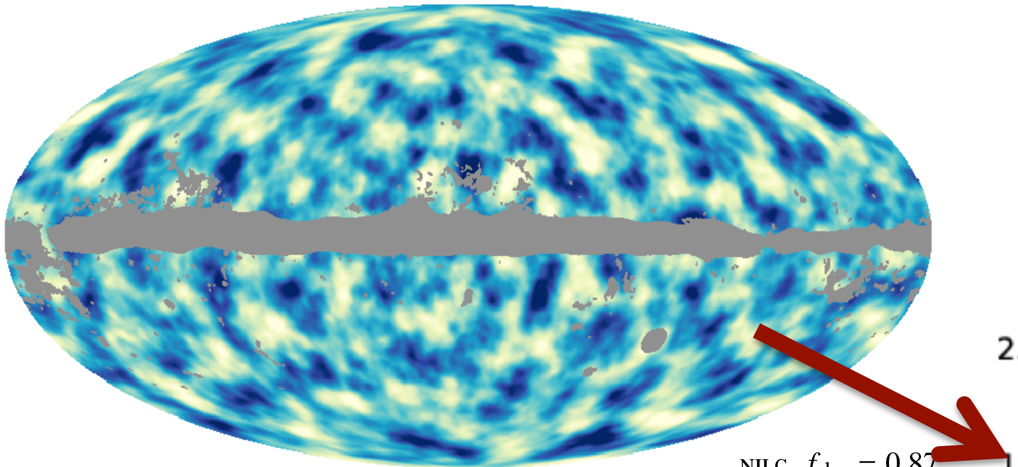




NILC, $f_{\rm sky} = 0.87$

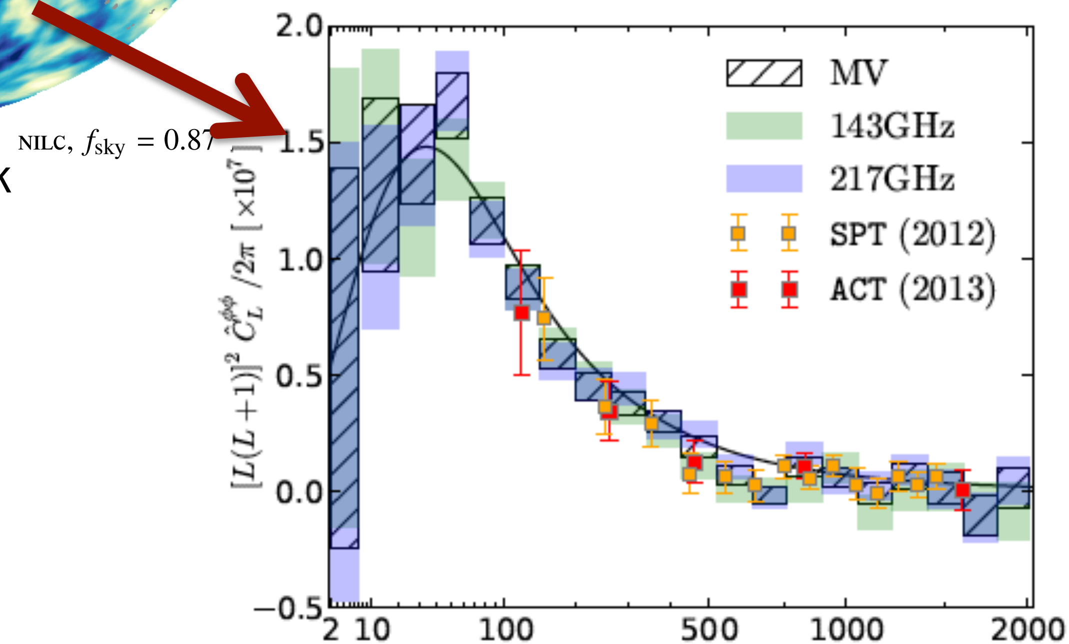
CMB lensing extraction by Planck

Cosmological observations: LSS from CMB lensing maps



CMB lensing extraction by Planck

2-pt correlation function of
CMB lensing potential in harmonic space
= CMB lensing spectrum



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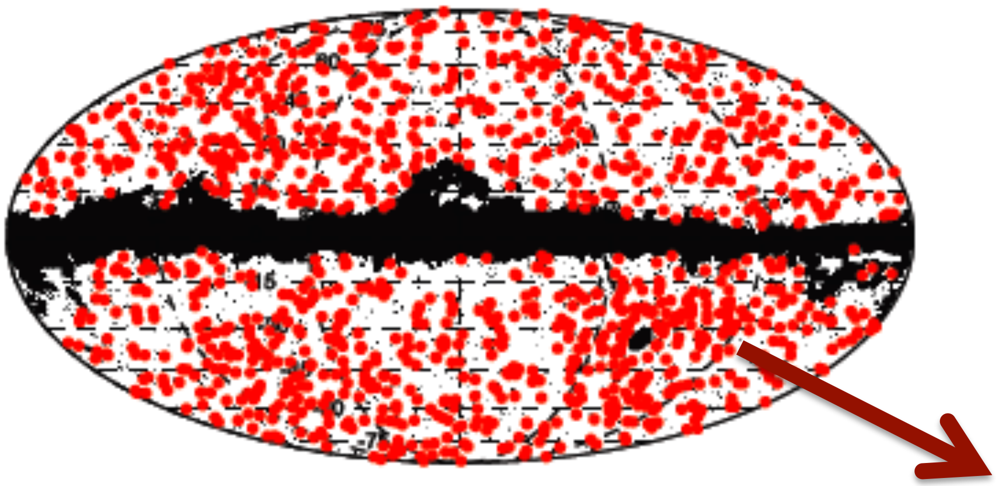
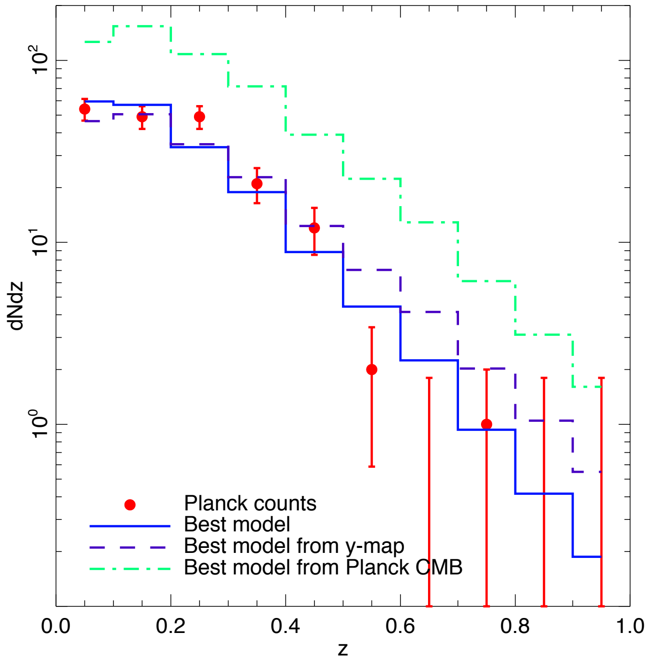
Cosmological observations: LSS from cluster mass function

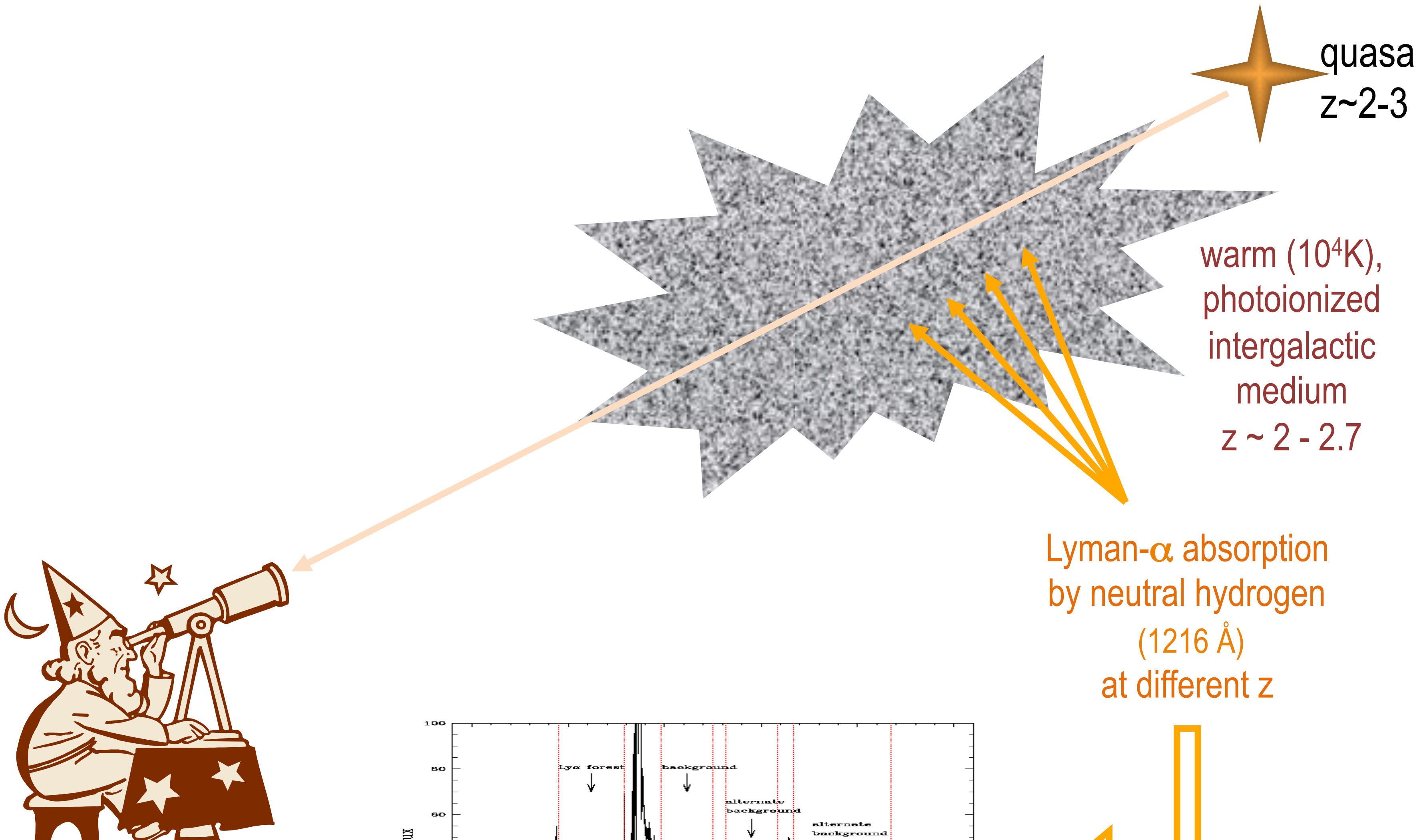


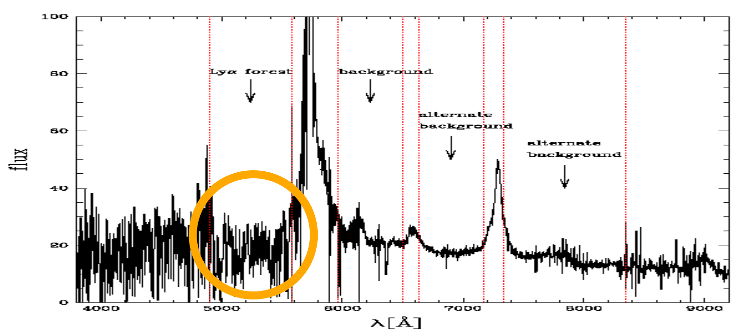
SZ cluster map from Planck

Histogram of number (or mass) versus redhsift



Cosmological observations: LSS from Lyman-α forests





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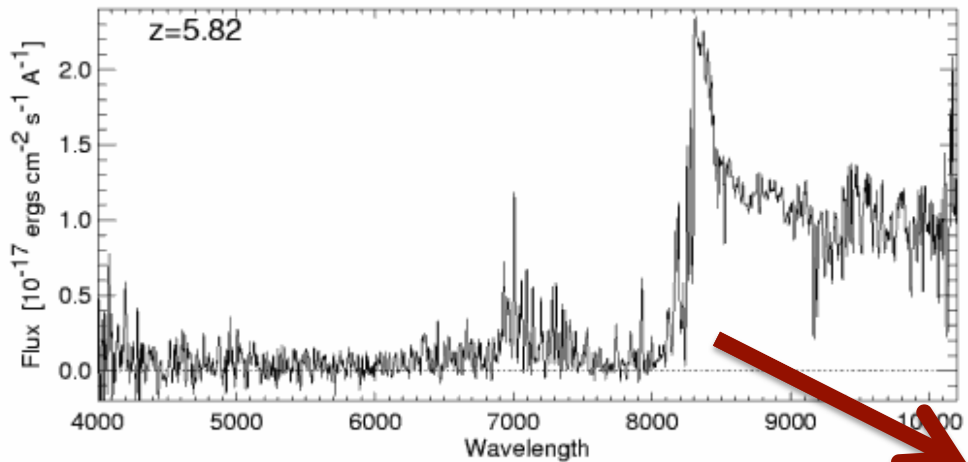
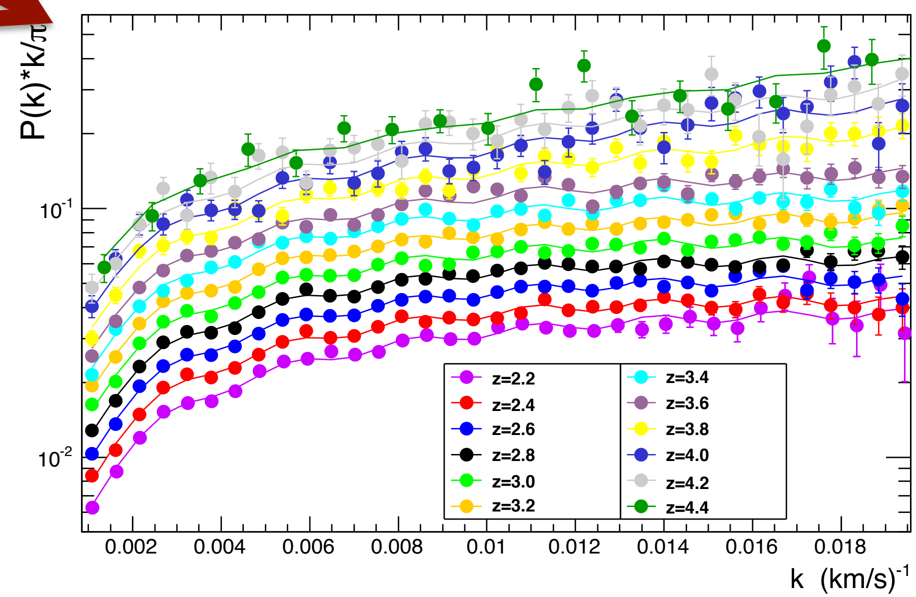
Cosmological observations: LSS from Lyman-α forests



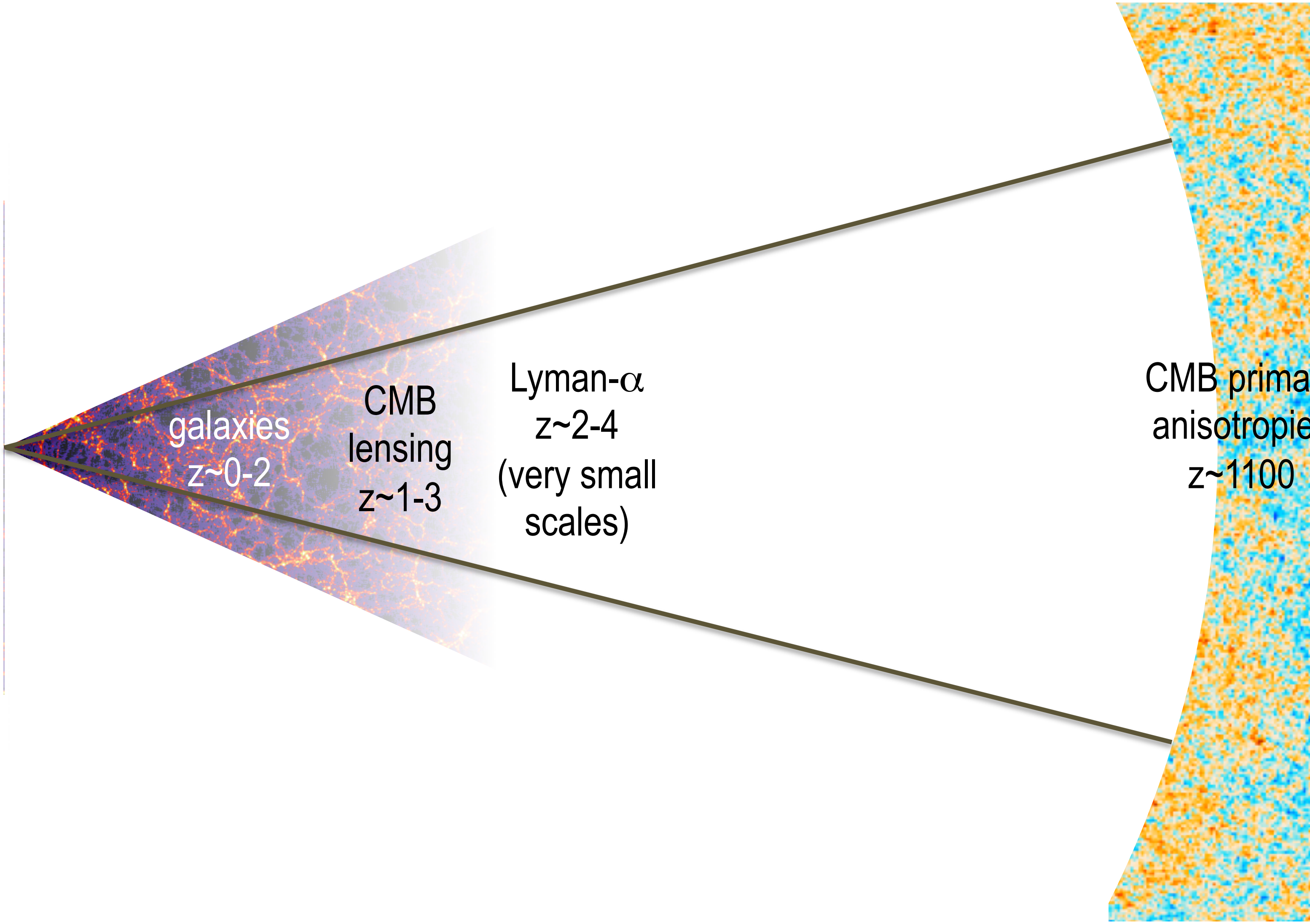
Quasar spectrum from SDSS

Flux power spectrum
(related to 1-D matter spectrum)



Palanque-Delabrouille et al., 1306.5896

Observations probe very different times and scales

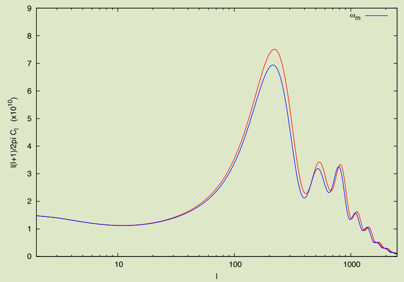


Dominant DM component

CMB = best probe of Dark Matter

Evidence for missing mass of non-relativistic species (like rotation curves!)

CMB measures accurately:



- baryon density (first peaks asymmetry),
- total matter density (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

- Supported by Large Scale Structure (matter spectrum shape) and astrophysics

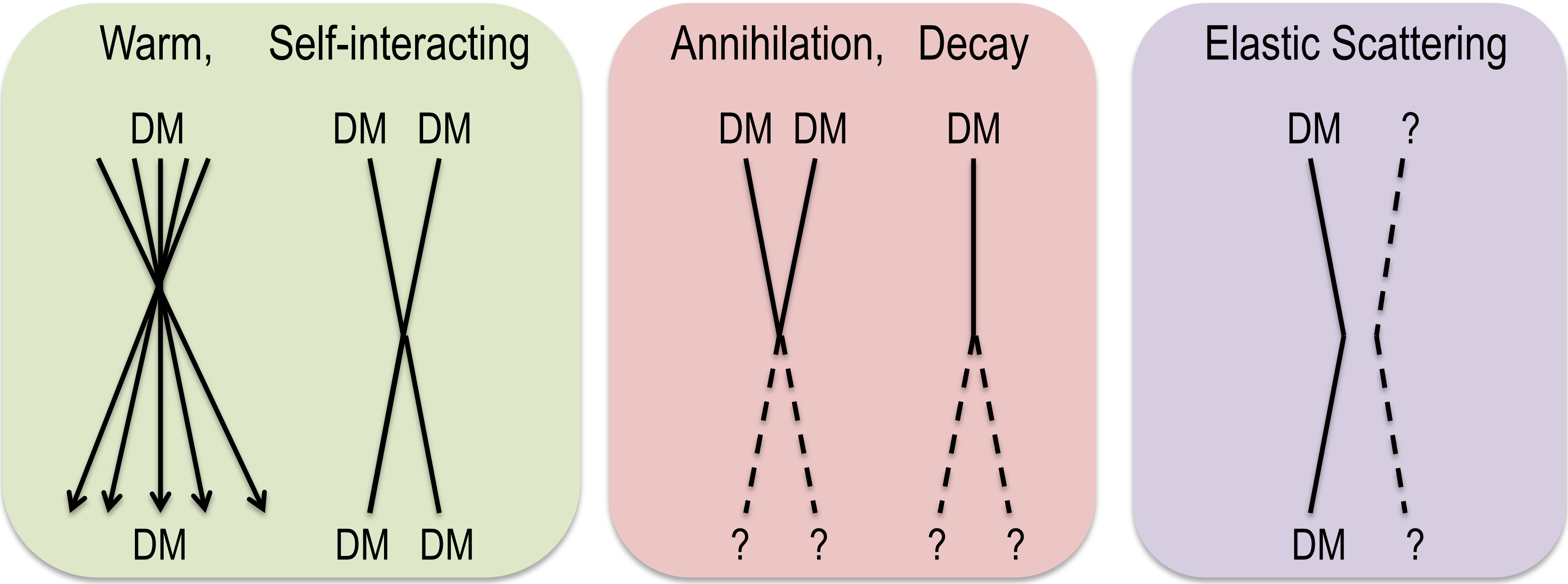
CMB/LSS and nature of (dominant) Dark Matter

- For CMB and LSS: Dark Matter required to be
  - not interacting as much as ordinary electromagnetic interactions
  - not hot (small velocities)

- but totally unknown nature:
  - WIMPS, non-weakly interacting;
  - annihilating, decaying, stable;
  - cold or warm;
  - collisionless, self-interacting;
  - oscillating scalar fields;
  - …

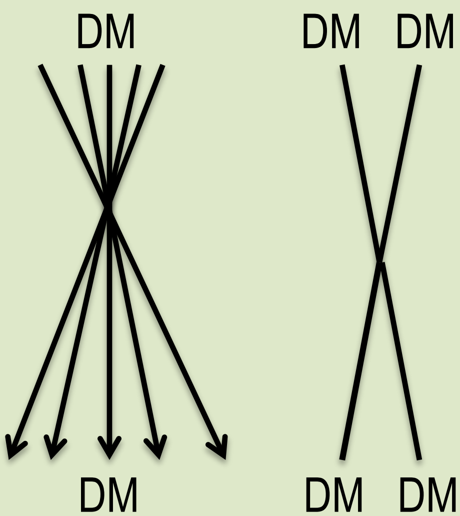
?

Possible properties of DM

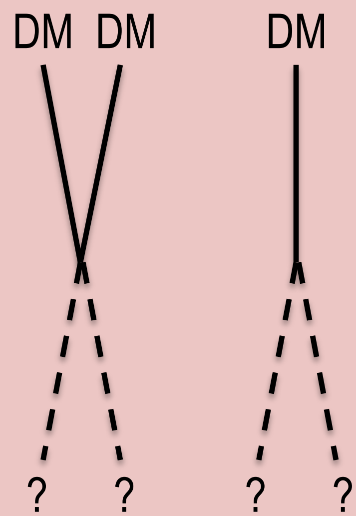


Possible properties of DM

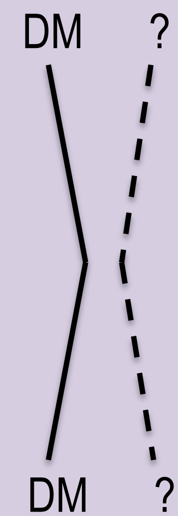
Warm, Self-interacting



Annihilation, Decay



Elastic Scattering

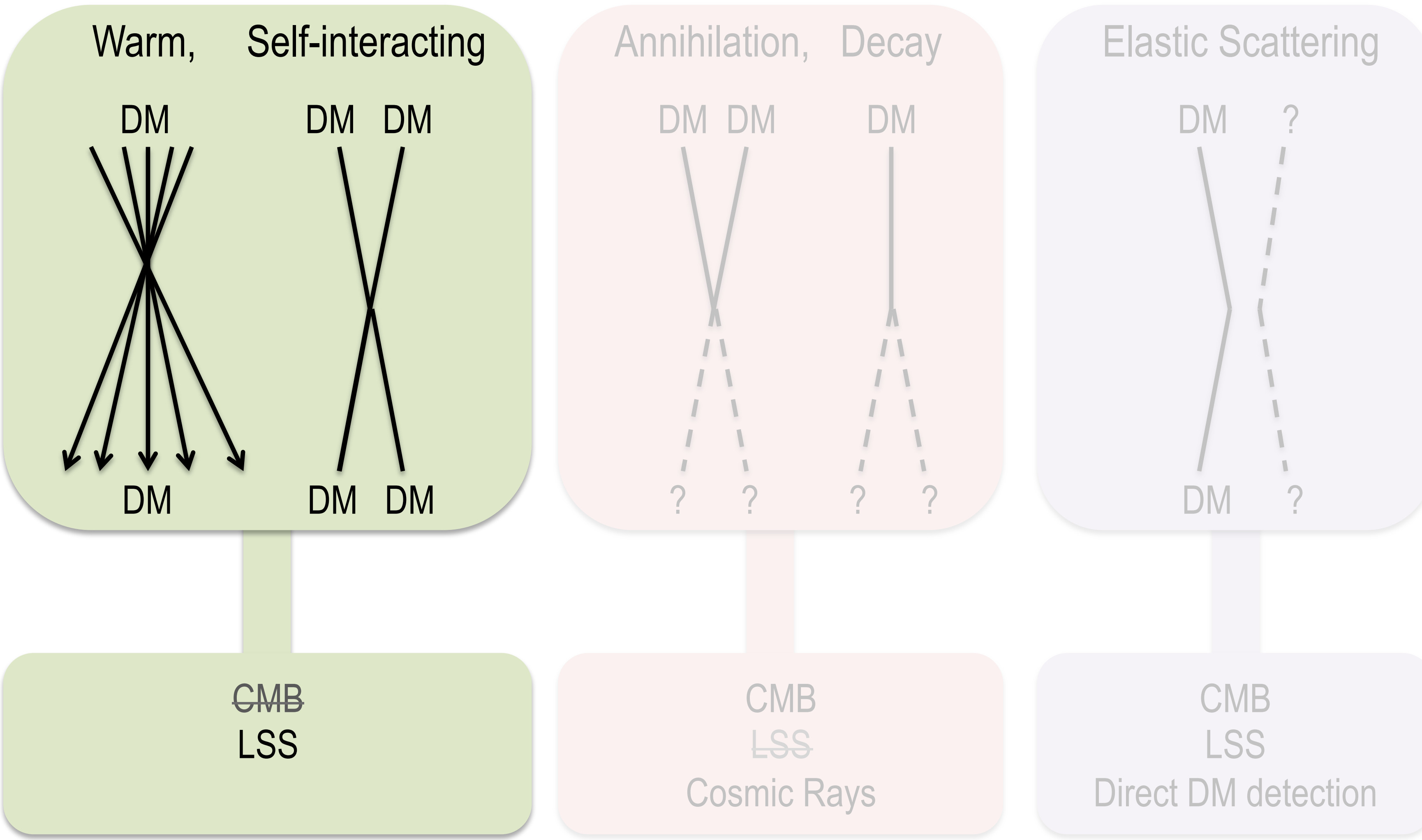


~~CMB~~
LSS

CMB
~~LSS~~
Cosmic Rays

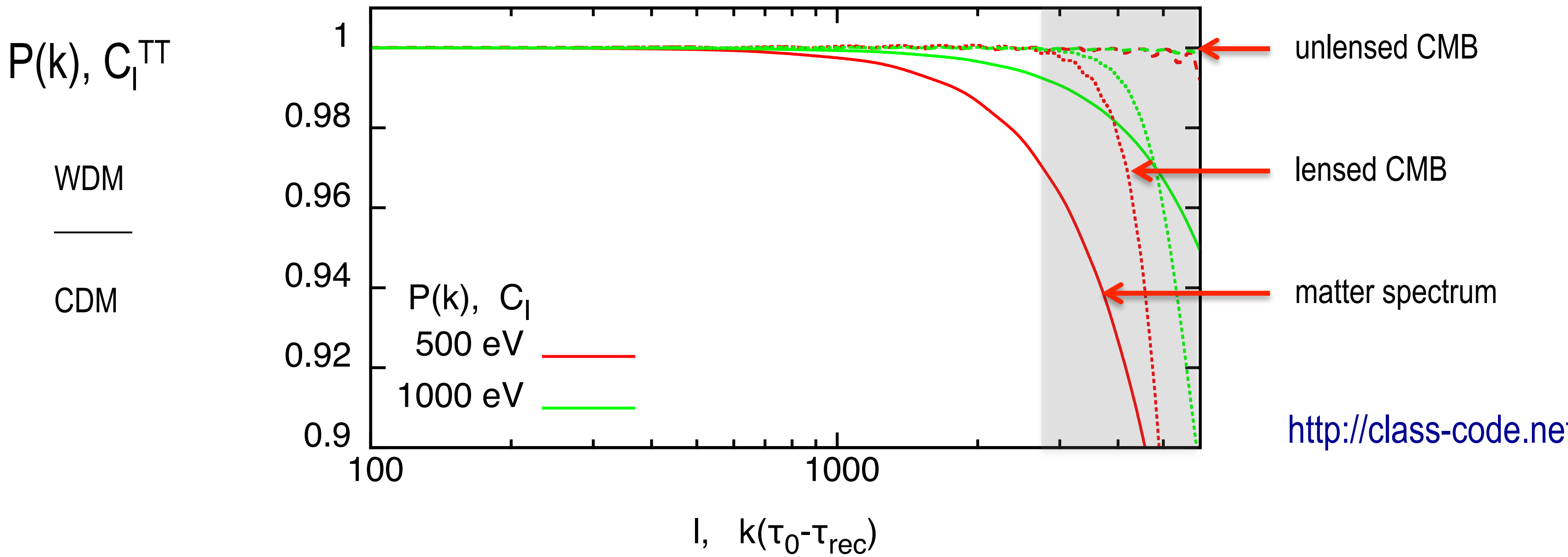
CMB
LSS
Direct DM detection

Case 1: warm or self-interacting



Case 1: warm or self-interacting

CUT-OFF in matter power spectrum (not in CMB spectrum on same scales)



CUT-OFF SCALE depends on velocity dispersion (<p>/m) or sound speed

The effective gravitational decoupling between dark matter and the CMB
Luc Voruz, Julien Lesgourgues, and Thomas Tram, JCAP, arXiv:1312.5301

Case 1: warm or self-interacting

- best constraints from Lyman-alpha: $\langle p \rangle/m \sim T/m <$ …

- Thermal WDM: T given by $\Omega_{DM} \sim 0.23$:

  m > 4 keV (95%CL) Viel et al. 2007, 2013

- Non-resonantly produced sterile neutrinos: T given by T_ν :

  m > 28 keV (95%CL) Viel et al. 2007, 2013

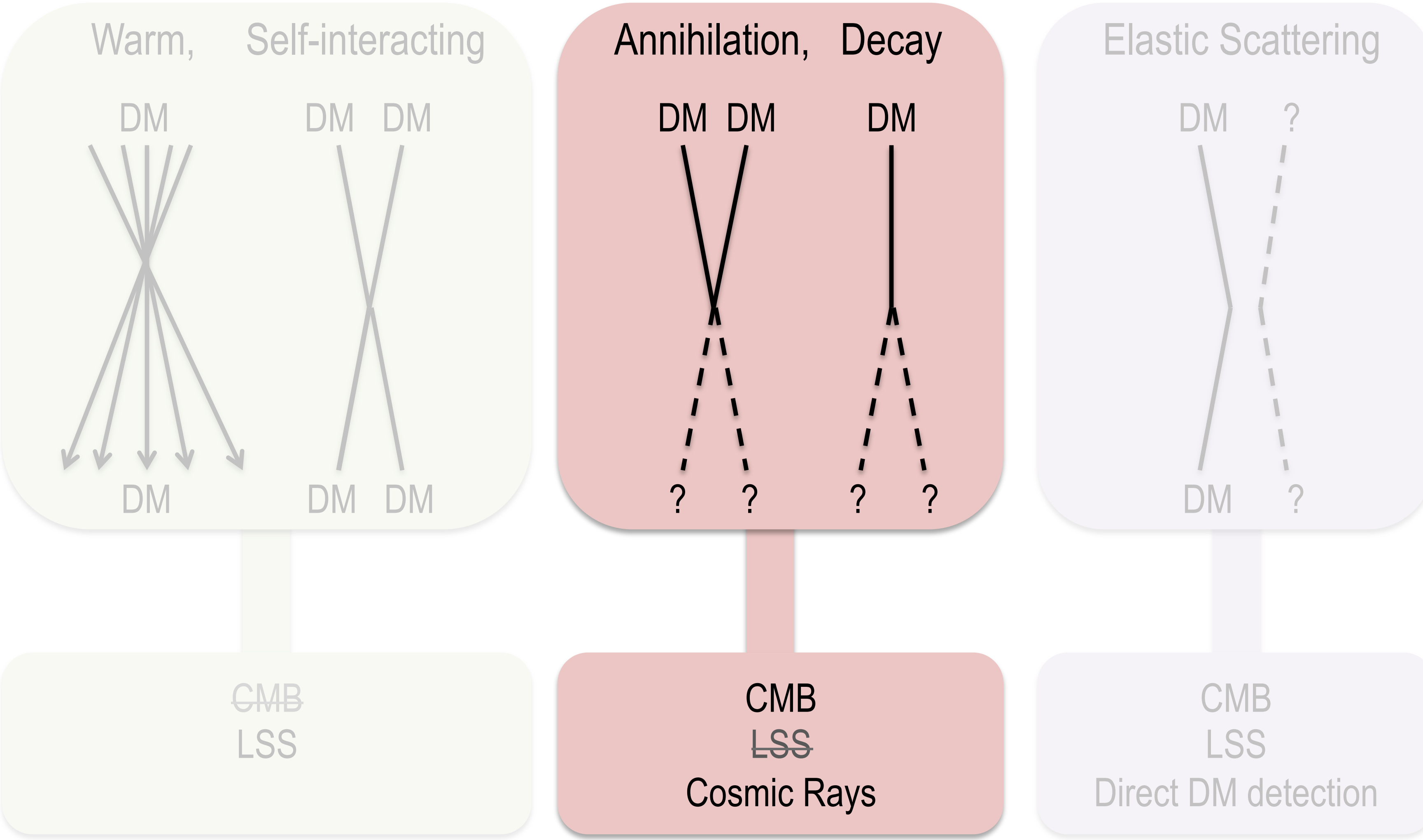
- Resonantly produced sterile neutrino: like CDM+WDM. Loose bound :

  m > 2 keV (95%CL) Boyarsky et al. 2009

- X-ray bounds exclude NRP sterile neutrino
- X-ray line at 3.5 keV: 3σ evidence for sterile neutrinos with m = 7 keV

Bulbul et al. 1402.2301; Boyarsky et al. 1402.4119

Case 2: annihilating or decaying



Case 2: annihilating or decaying

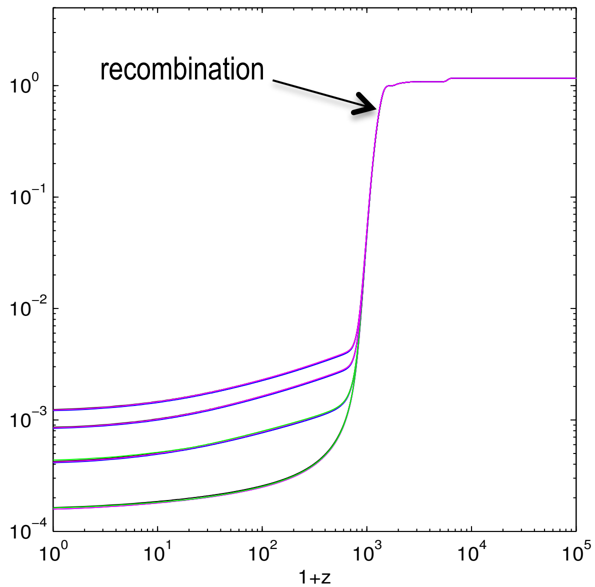
- DM → hadrons, leptons, gauge bosons → … → electrons, neutrinos, photons
  - Ionization of thermal plasma
  - Heating of thermal plasma
  - Hydrogen excitation

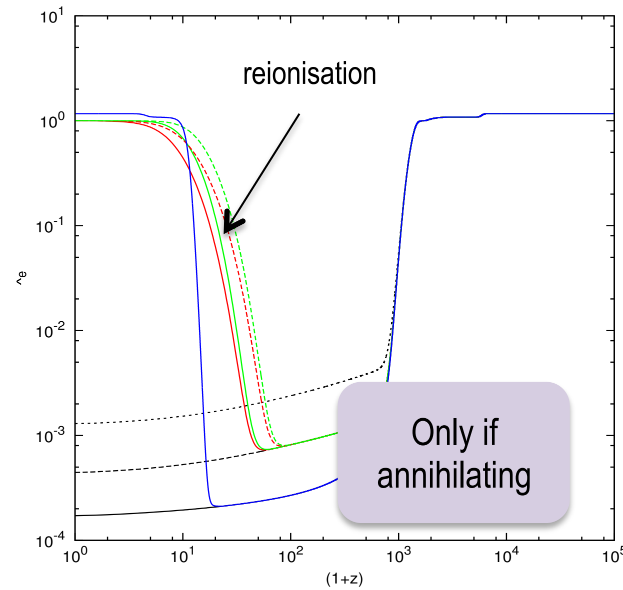
  } (unless 100% in neutrinos)

- Modification of recombination and reionisation history
- Effects depends on σ/m or τ , and on annihilation/decay channel

Case 2: annihilating or decaying

ionisation fraction





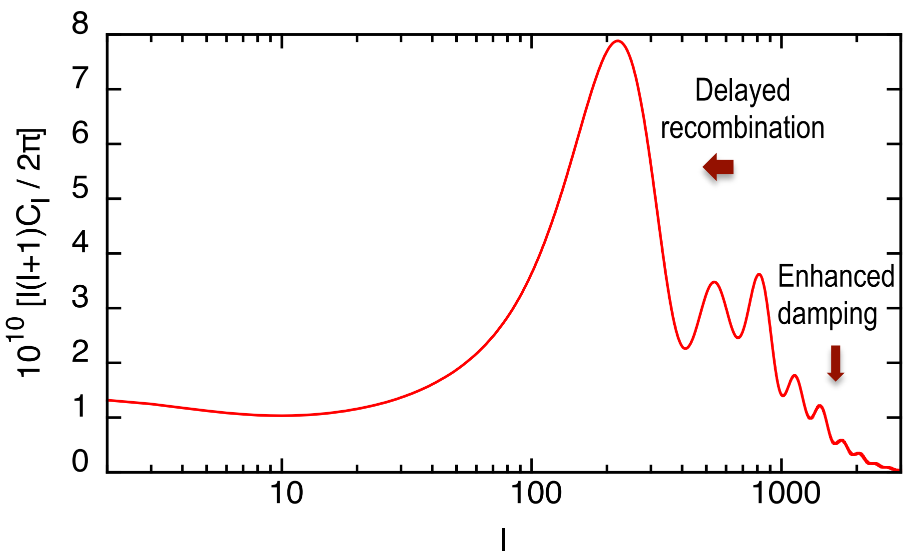
1+z

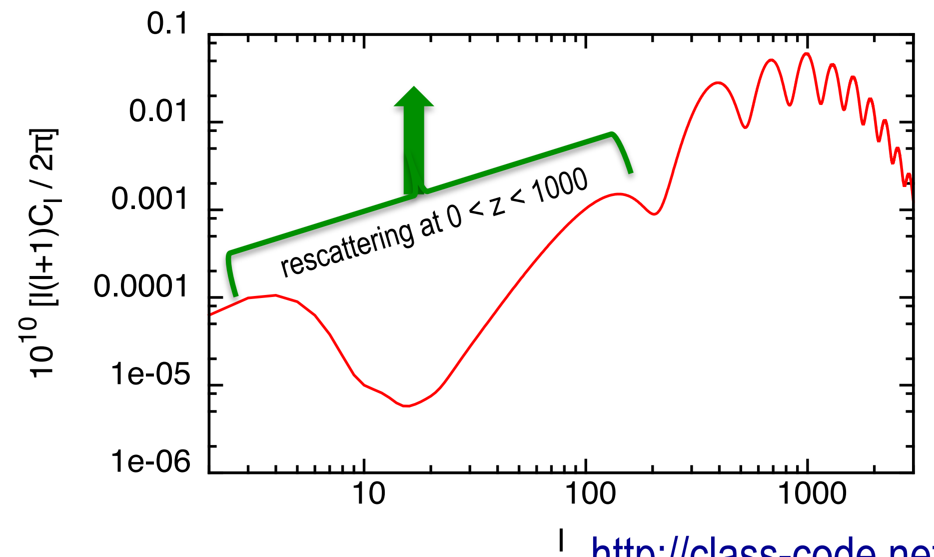
1+z

http://class-code.net

CMB photons shedding light on Dark Matter
G. Giesen, J. Lesgourgues, B. Audren, Y. Ali-Haimoud 2012, JCAP, **arXiv:1209.0247**

Case 2: annihilating or decaying





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CMB photons shedding light on Dark Matter
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Case 2: annihilating or decaying

- Bounds from WMAP7/9 and Planck 2003 very similar — Madhavasheril et al. 2013
- progress expected with Planck polarisation

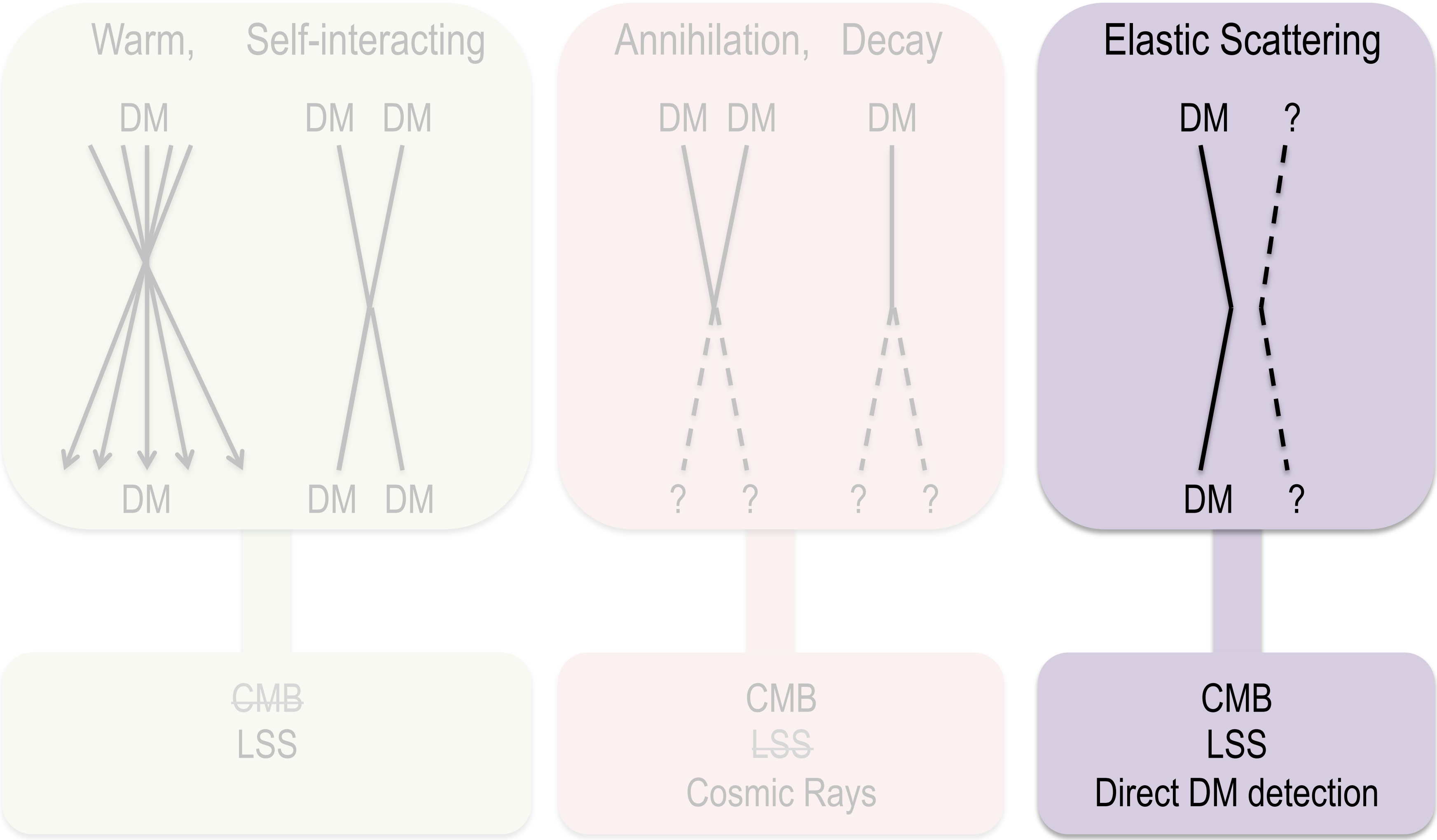
Annihilation: VERY INTERESTING RESULTS compared to direct/indirect detection

- Currently excludes DM intepretation of AMS/Pamela positron anomaly if annihilation is Sommerfeld-enhanced (m~TeV)
- Marginal agreement with Fermi anomaly (inner galaxy) (m~20-40 GeV), but can be excluded with Planck polarisation
- … unless DM annihilation cross-section enhanced in halos (p-wave)
- … conclusions based on recombination effects, not reionisation

Decay:

- … not as strong as cosmic ray bounds (unless for specific decay channels)

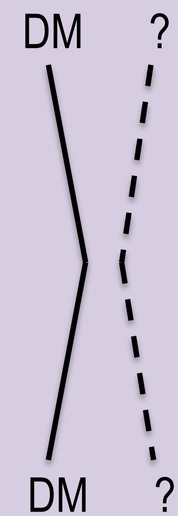
Case 3: DM interactions (elastic scattering)



Case 3: DM interactions (elastic scattering)

- For WIMPS: weak interactions (with quarks, neutrinos) too small to leave any signature on CMB/LSS
- More generally: many reasonable DM models predict interactions with photons / baryons / neutrinos / other dark species with intermediate strength between weak and electromagnetic (minicharged, asymmetric, magnetic/dipole moment, …)
- Direct detection provide constraints, limited to quarks and to restricted mass range
- CMB/LSS constraints are universal

Elastic Scattering



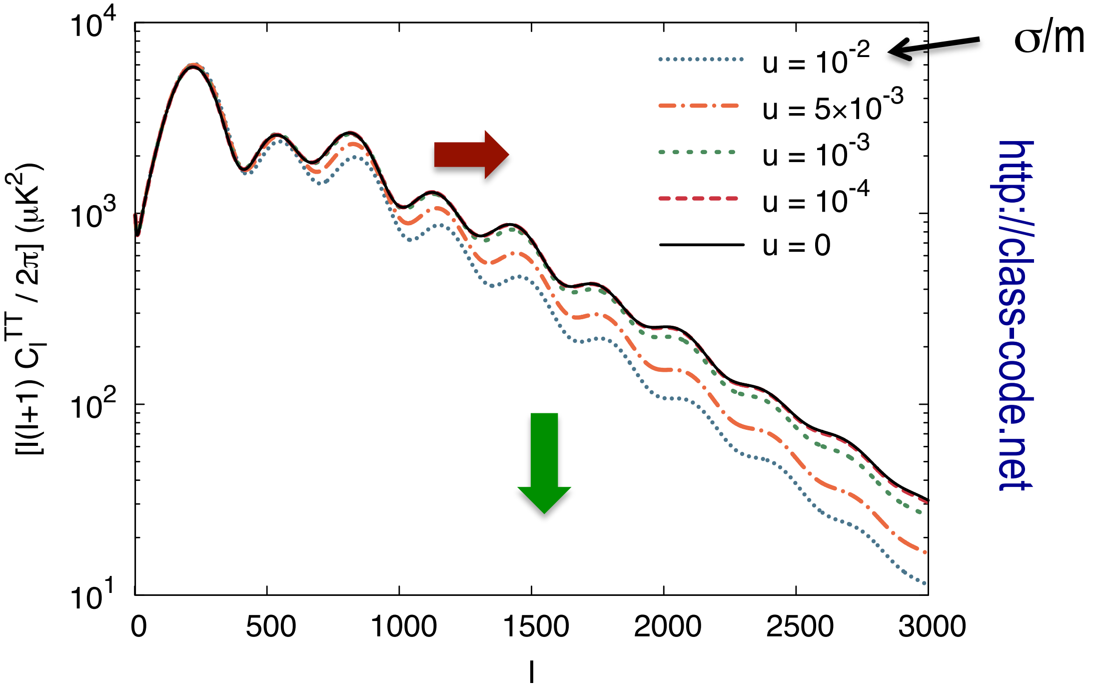
CMB
LSS
Direct DM detection

Case 3: DM interactions (elastic scattering)

- DM-photons

Wilkinson, JL & Boehm 1309.7588

- Collisional damping erasing CMB and/or matter fluctuations below given scale

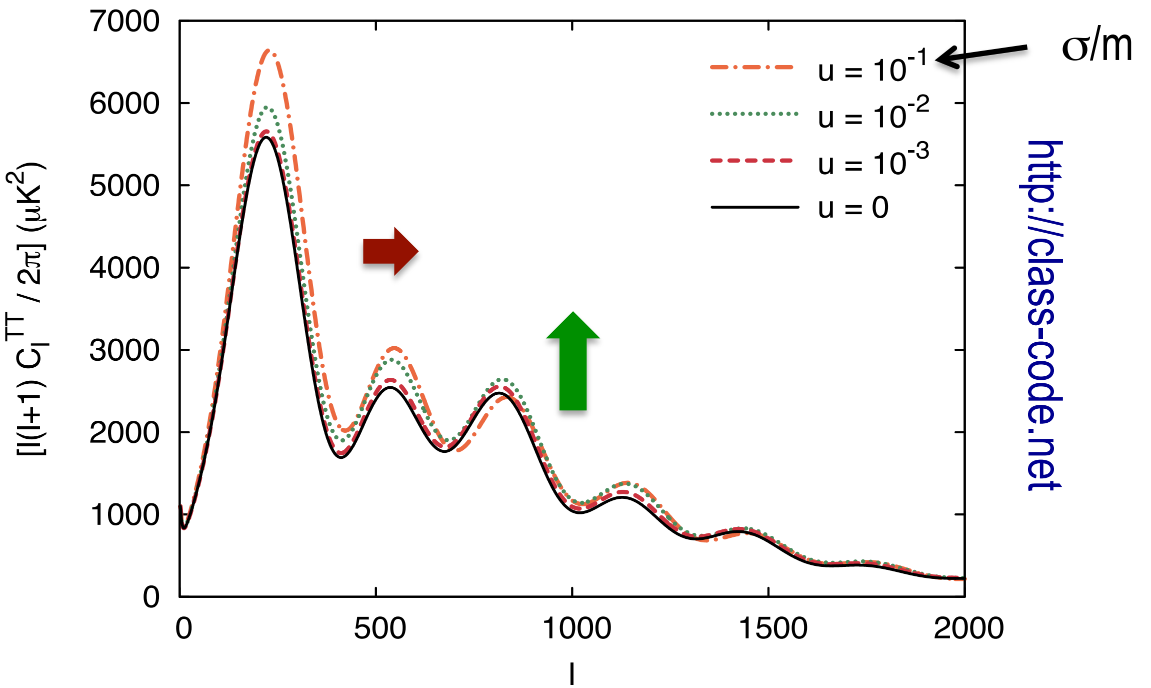


Case 3: DM interactions (elastic scattering)

- DM-neutrinos

Wilkinson, Boehm & JL, 1401.7597

- Neutrino cluster more due to their interactions, more gravity boost of photon-baryon fluid
- higher damping tail (dominant effect for small cross section)



Case 3: DM interactions (elastic scattering)

- DM-baryons

Dvorkin, Blum, Kamionkowski 1311.2937

- DM-Dark Radiation

Cyr-Racine, de Putter, Raccanelli, Sigurdson 1310.3278

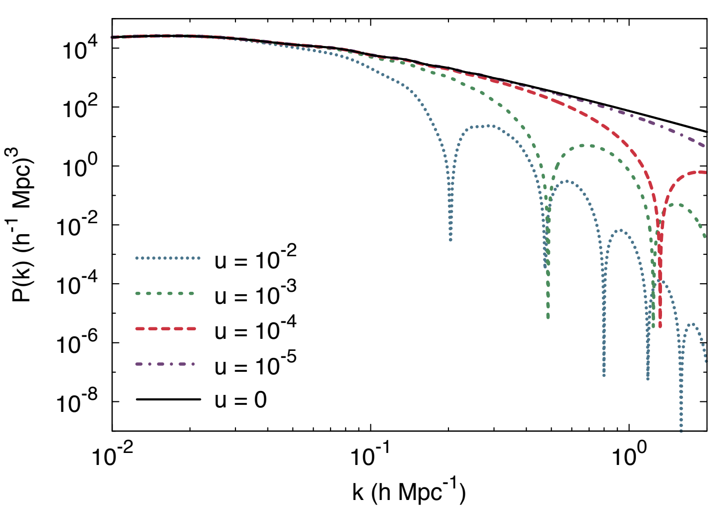
- DM-Dark Energy

…

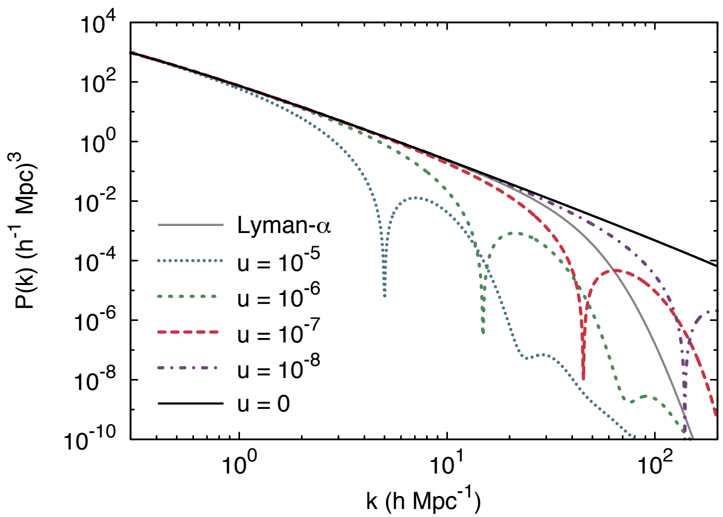
Case 3: DM interactions (elastic scattering)

Also effects in matter power spectrum:

DM-photons



DM-neutrinos



http://class-code.net

CMB bounds can be tightened by Lyman-α

Case 3: DM interactions (elastic scattering)

NO INTERACTION DETECTED but interesting results for particle physics…

- DM-γ interaction :
  - Light (< GeV): at most weak interactions.
    Interesting for DM not annihilating into SM (e.g. asymmetric DM)
  - Heavy (>GeV): DM can interact significantly more than with weak interactions

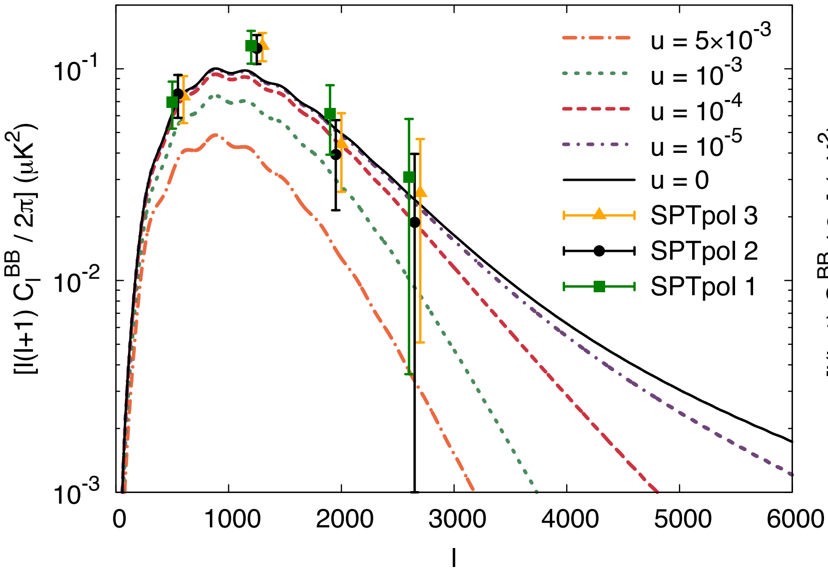
- DM-ν interaction :
  - Upper bound close to predictions of model with coupling between scalar dark matter and neutrinos, giving DM relic density and neutrino masses (radiative corrections)

Boehm, Farzan, Hambye, Palomarez-Ruiz & Pascoli 2008

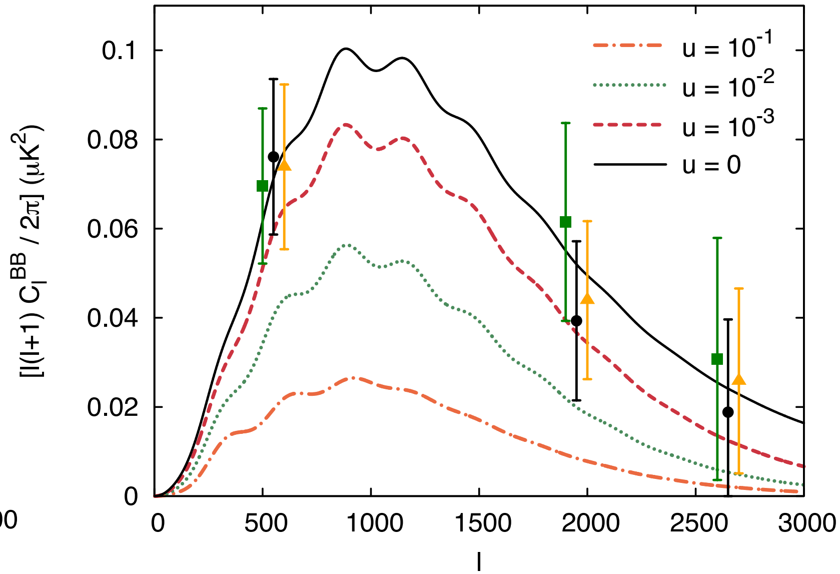
Case 3: DM interactions (elastic scattering)

Potential progress with polarisation, including B modes:

DM-photon



DM-neutrino



(collisonal damping + lensing and E-B conversion)

Even current SPT bound not very far from Planck TT bounds!

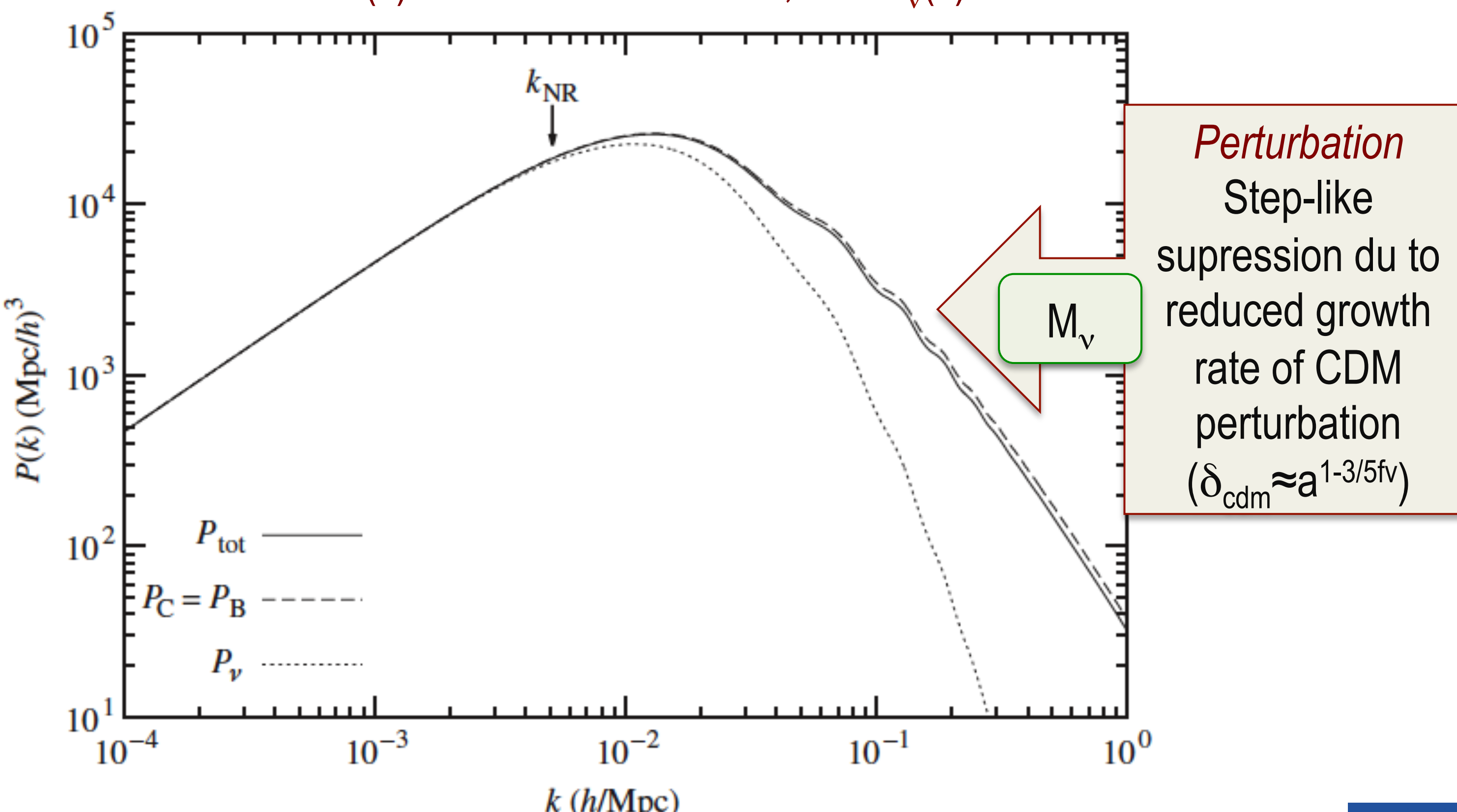
Subdominant DM component
(not observed)
not behaving like a cold component

Measuring neutrino masses

- Leaving both "early cosmology" and angular diameter dist. to decoupling invariant

  fixing photon, cdm and baryon densities, while tuning H_0, Ω_Λ

P(k) massive vs massless, and $P_\nu(k)$:

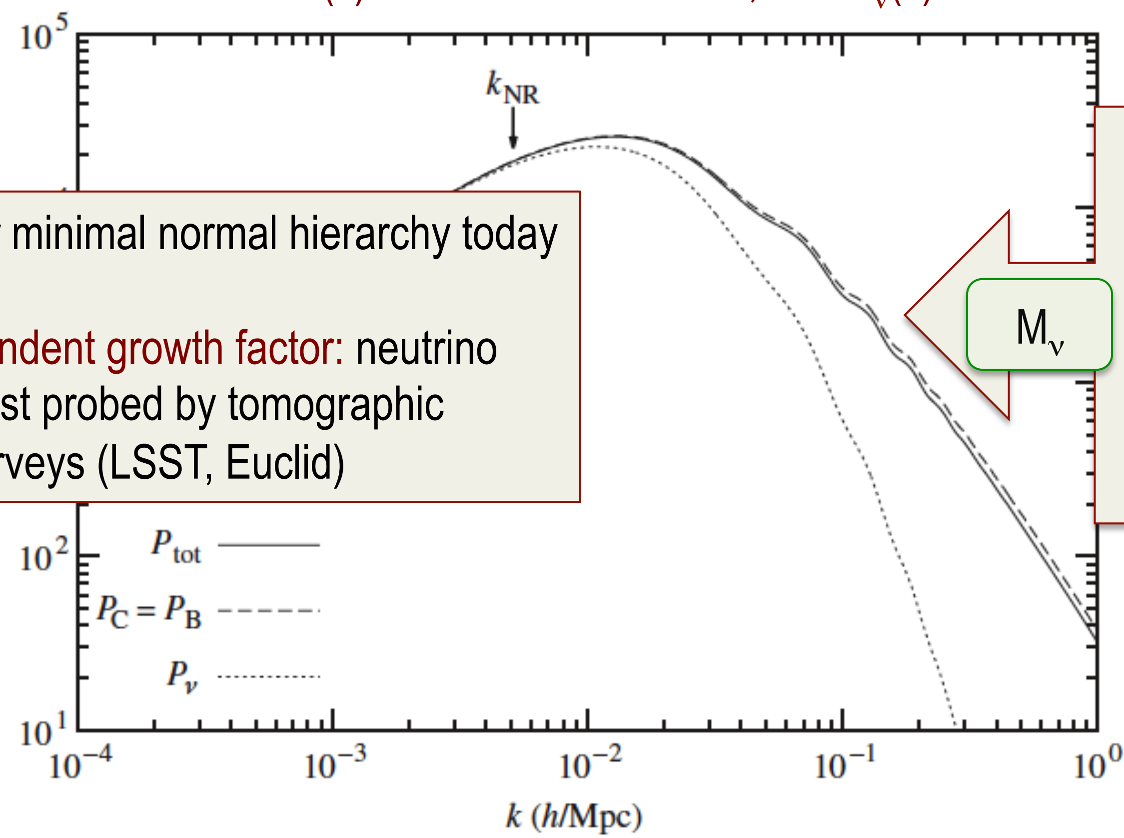


Effect of neutrino masses on matter spectrum

- Leaving both "early cosmology" and angular diameter dist. to decoupling invariant

  fixing photon, cdm and baryon densities, while tuning H_0, Ω_Λ

P(k) massive vs massless, and $P_\nu(k)$:



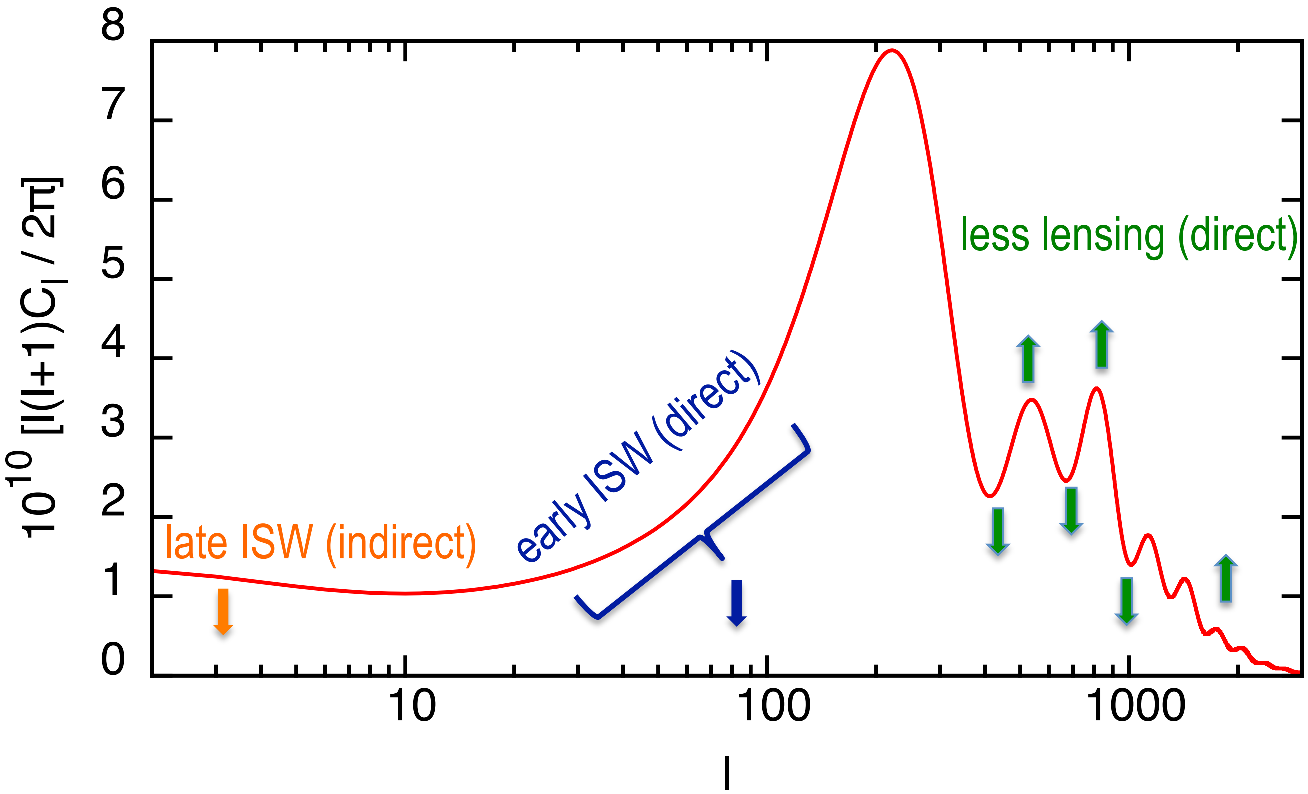
At least 5% for minimal normal hierarchy today

Scale-dependent growth factor: neutrino mass best probed by tomographic surveys (LSST, Euclid)

Perturbation
Step-like supression du to reduced growth rate of CDM perturbation ($\delta_{cdm} \approx a^{1-3/5 f\nu}$)

Effect of neutrino mass on CMB

- Leave both "early cosmology" and $d_A(z_{dec})$ invariant (fixing photon, cdm and baryon densities, while tuning H_0, Ω_Λ)



Current constraints

95%CL

- Planck+WP alone: $M_{\nu} < 0.66$ eV (twice better than WMAP) from non-observation of eISW depletion + strong smoothing of the peaks (actually more lensing than in LCDM preferred…)
- adding H0: $M < 0.18$ eV
- adding BAO: $M < 0.23$ eV
- but lensing extraction compatible with large value
- SZ cluster count prefers non-zero value
- CFHTLens also prefers non-zero value

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Current constraints

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- adding BAO: $M_\nu < 0.23$ eV

95%CL

- but lensing extra[illegible] compatible with large value
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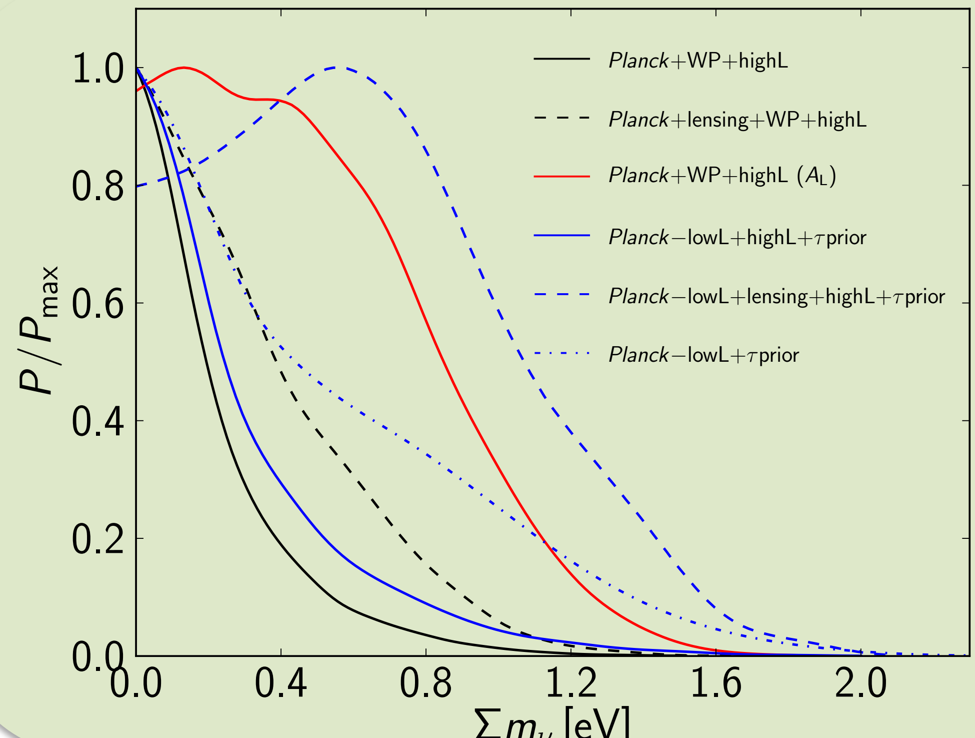

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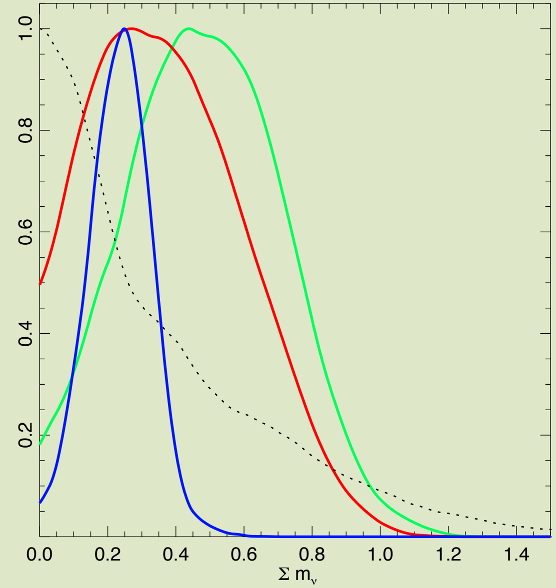

Fig. 12. Cosmological constraints when including neutrino masses $\sum m_\nu$ from: *Planck* CMB data alone (black dotted line); *Planck* CMB + SZ with $1 - b$ in [0.7, 1] (red); *Planck* CMB + SZ + BAO with $1 - b$ in [0.7, 1] (blue); and *Planck* CMB + SZ with $1 - b = 0.8$ (green).

Current constraints

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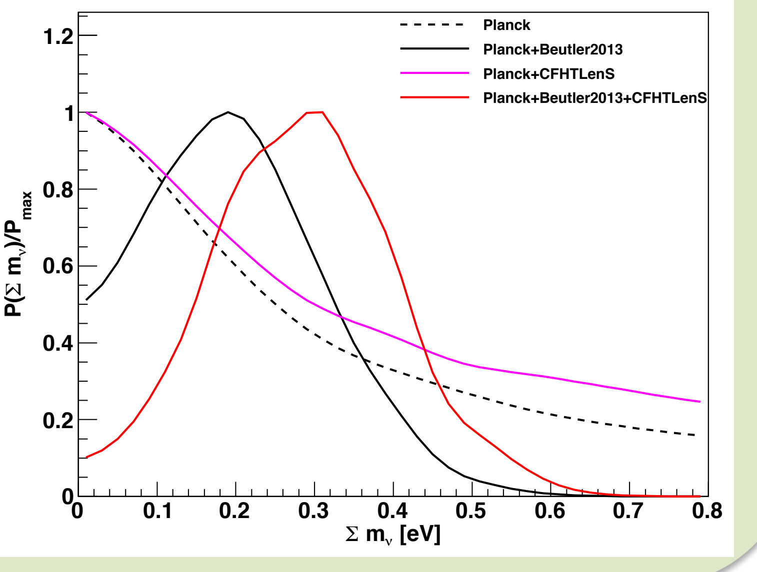
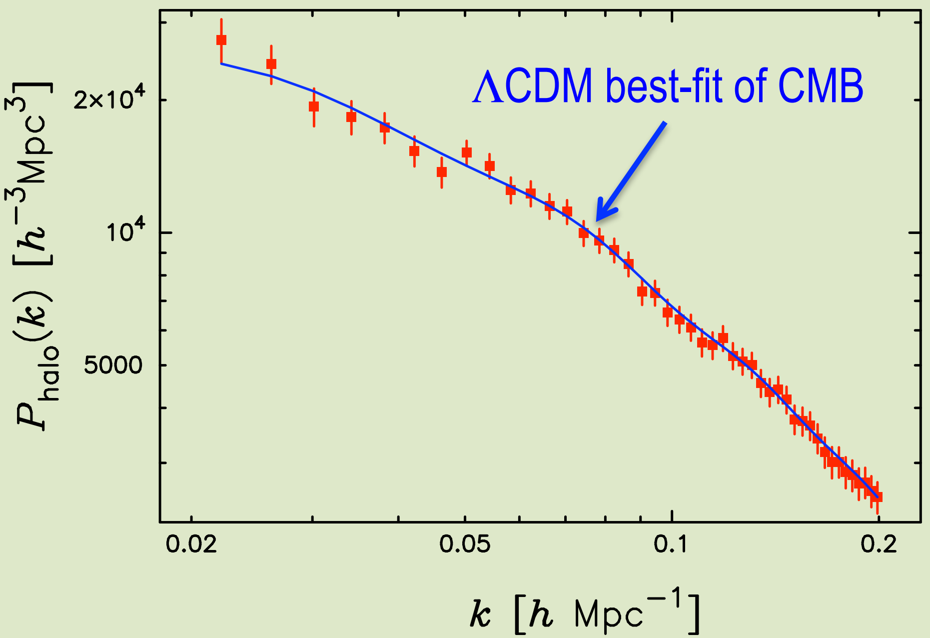
- adding BAO: M_ν < 0.23 eV
- but lensing extraction compatible with larger value
- SZ cluster count prefers non-zero value ~ 0.3 eV
- CFHTLens also slightly prefers non-zero value
- SDSS also prefers 0.3 eV at 2σ (1403.4599)



Current constraints

Most probably issue with systematics…



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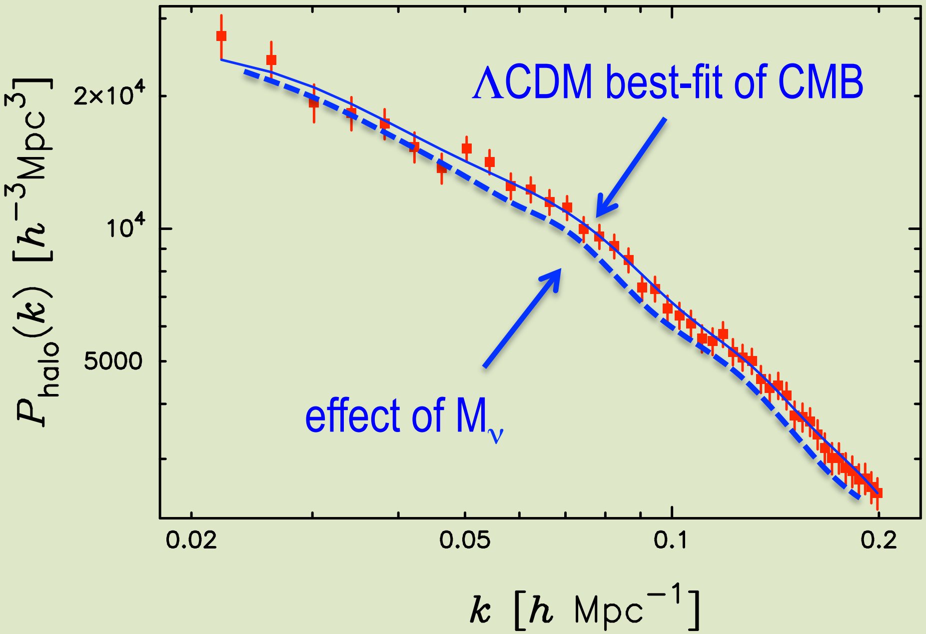

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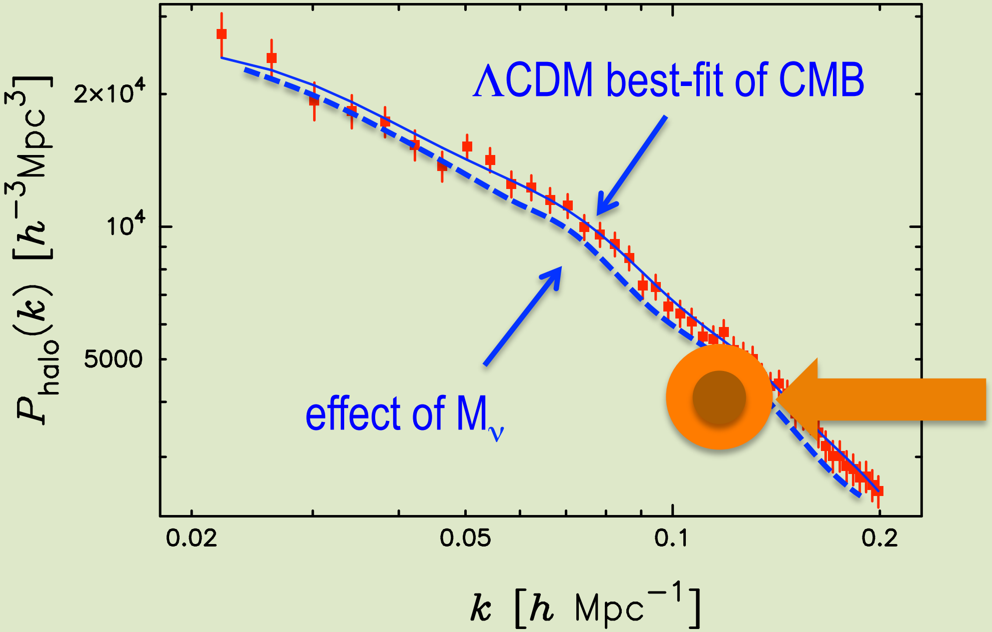
Current constraints

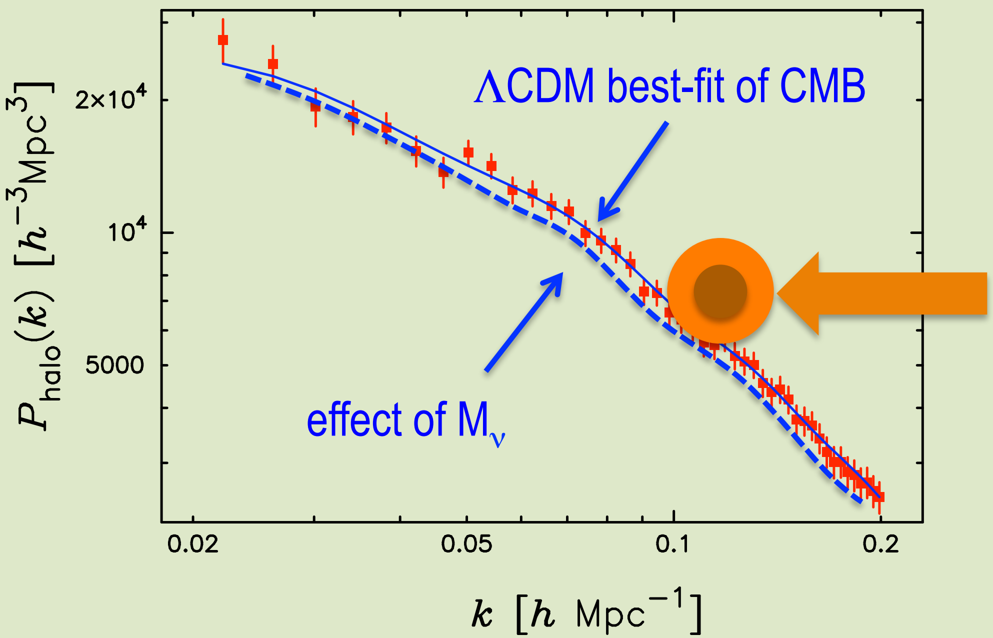
Most probably issue with systematics…



Any experiment seeing low amplitude favors high neutrino mass but conflicts CMB TT (CMB lensing, clusters, CFHTLens, BOSS 1403.4599)

Current constraints

Most probably issue with systematics…

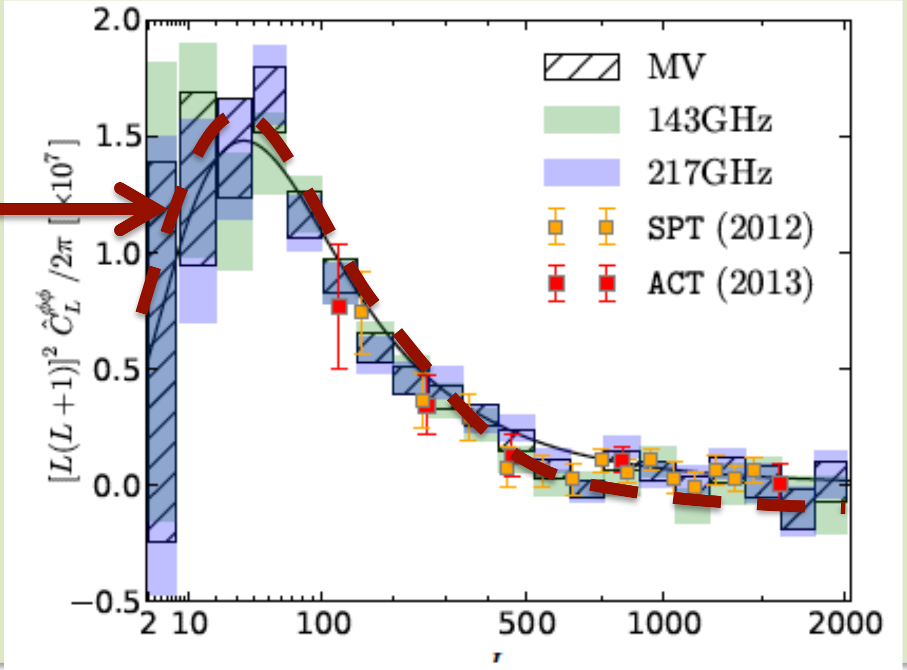


Any experiment seeing high amplitude disfavors high neutrino mass (SDSS Ly-α of 2006)

Current constraints

Difficult to reconcile all dataset with new model…

This would reconcile CMB TT, lensing, clusters, but not Lyα



Current constraints

Who is more affected by unknown systematics?

- Planck TT low-l, Planck high-l, Lyα ???

then maybe $M_\nu \sim 0.3$ eV

- CMB lensing extraction, clusters, cosmic shear ???

then maybe $M_\nu \sim 0.06 - 0.17$ eV

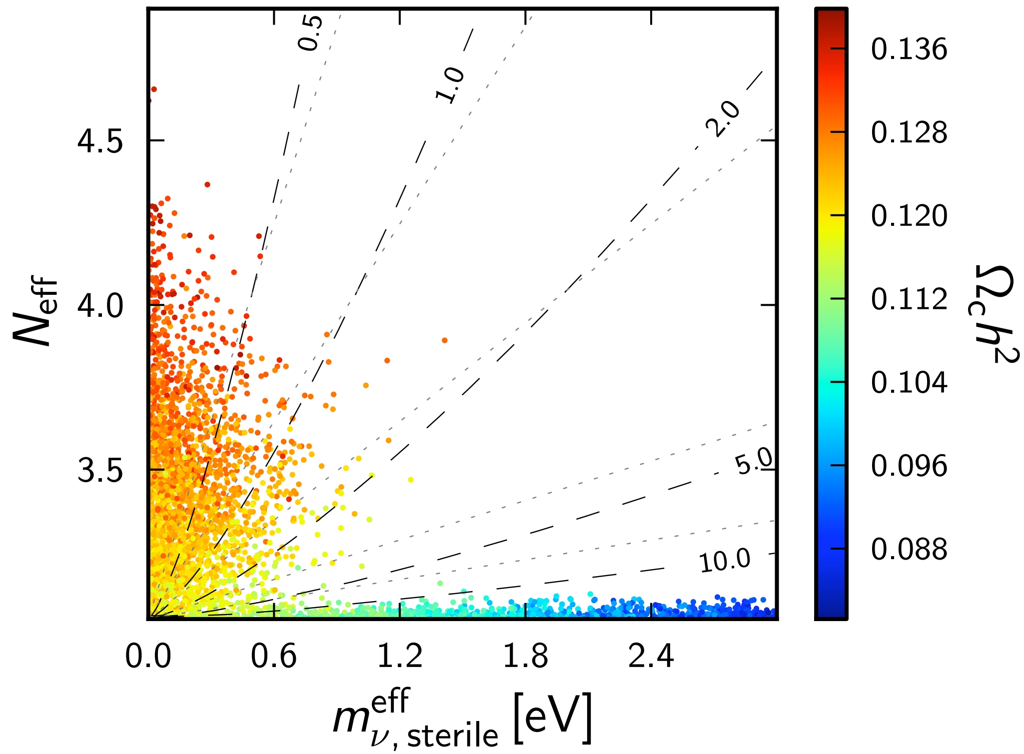
We will know at some point!

new data from CMB, BOSS, eBOSS, DES, LSST, Euclid, 21cm…

If there is such a mass, could it come instead from extra relics?

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

Total neutrino density in early universe



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

If there is such a mass, could it come instead from extra relics?

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

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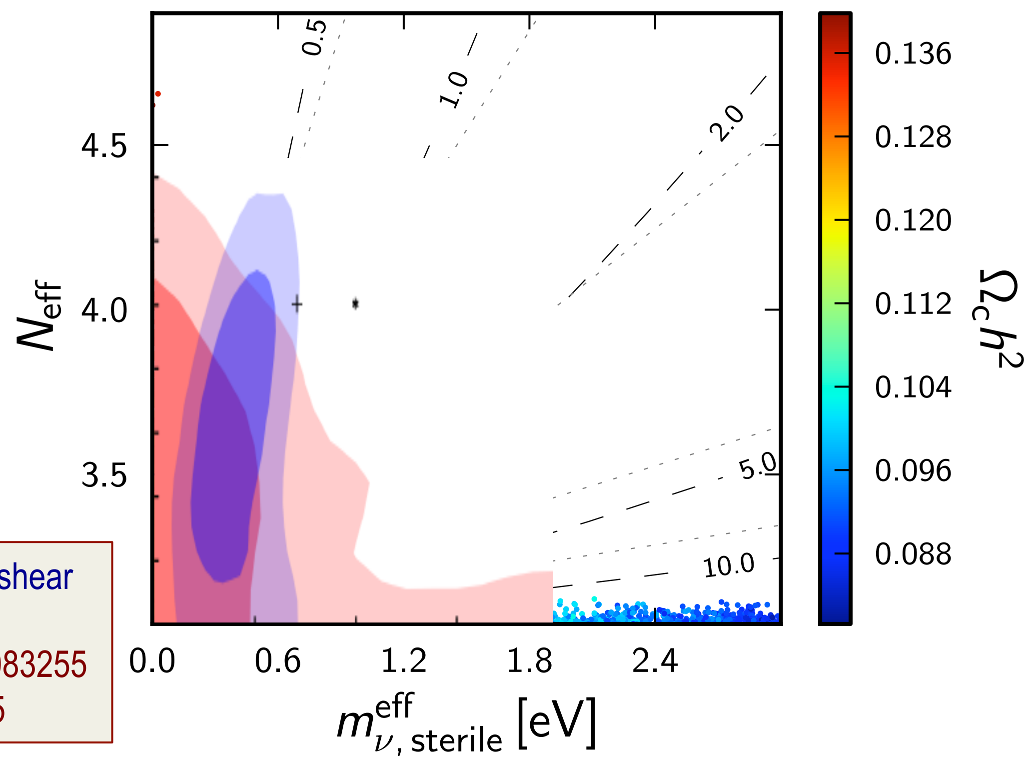

Sterile neutrino density today $\omega_{\nu s}$

Using H0 + BAO + clusters + gal.shear

From Hamann & Hasenkamp 13083255
See also Wyman et al. 1307.7715

Conclusion

Interplay between cosmological perturbations and particle physics even richer than thought 15 years ago…

CMB sensitive to tiny effects (small neutrino mass, small enhancement of radiation density, tiny annihilation rate or elastic cross-section)

lot more to come from Planck …

… from CMB satellite of next generation (?) …

…. and from large scale structure:

Ly-α of (e)BOSS, galaxy/lensing surveys, 21cm surveys