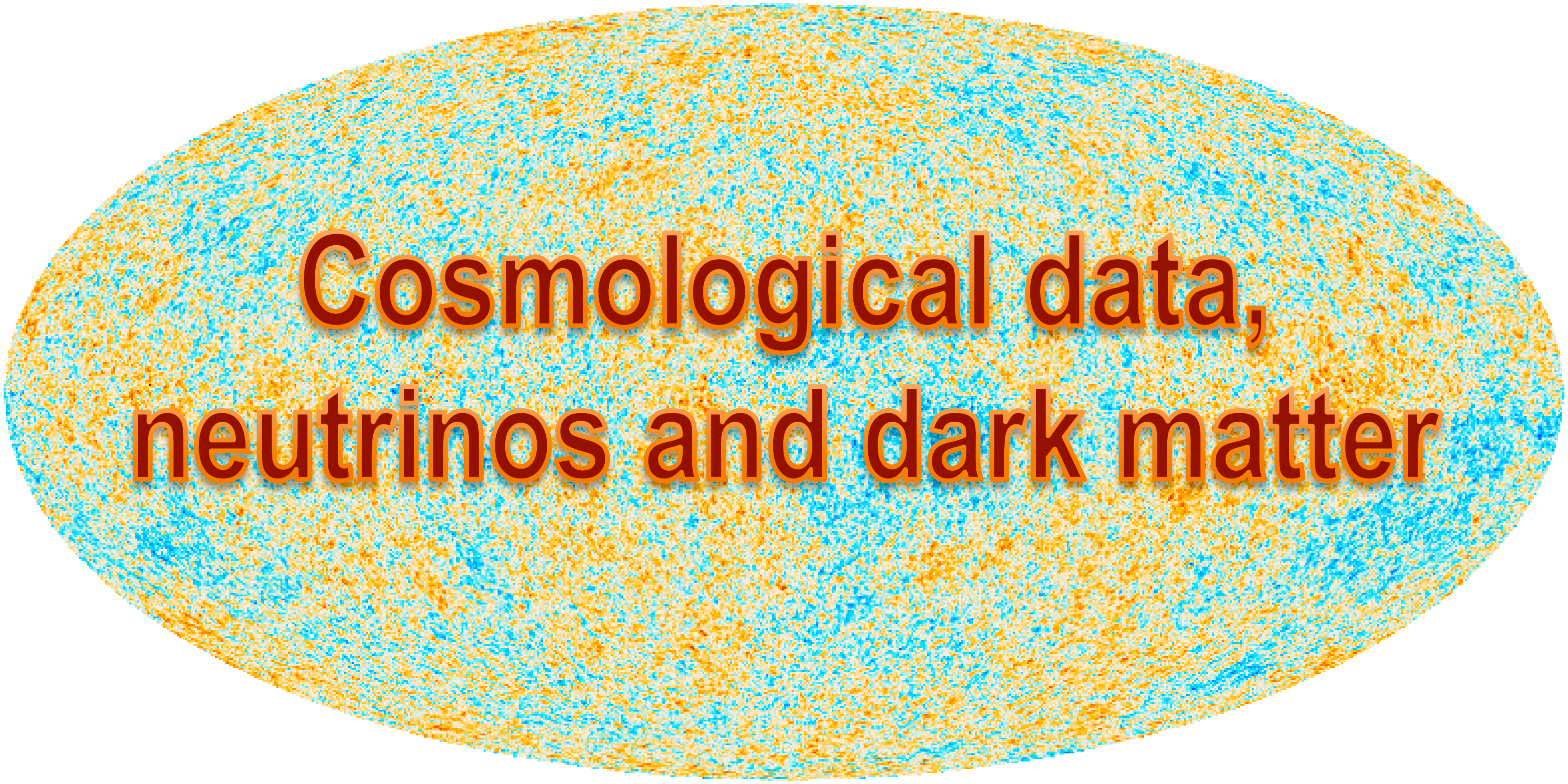
Cosmological data, neutrinos and dark matter



SPP, CEA, Saclay, 3.03.2014

Julien Lesgourgues (EPFL, CERN, LAPTh)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

CERN

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

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 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

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 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…

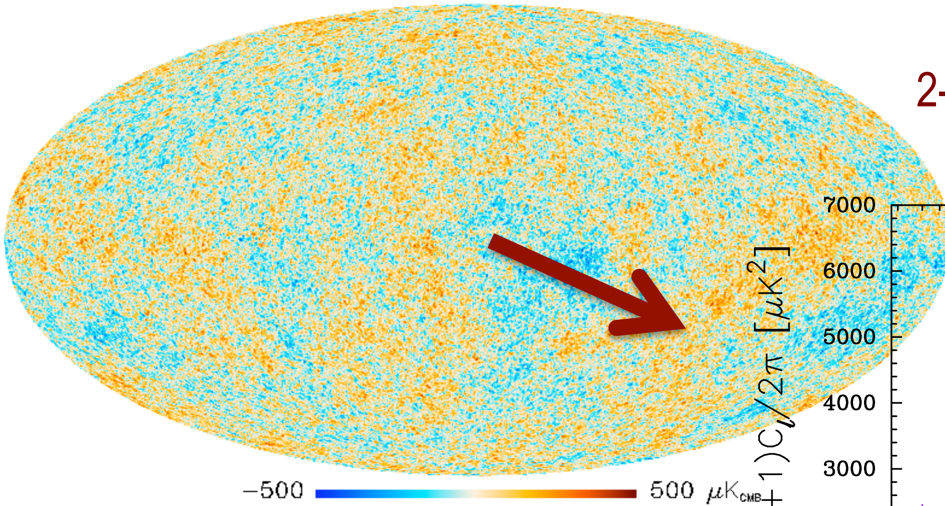
Galactic structure (satellite, rotation curves…)

Laboratory experiments

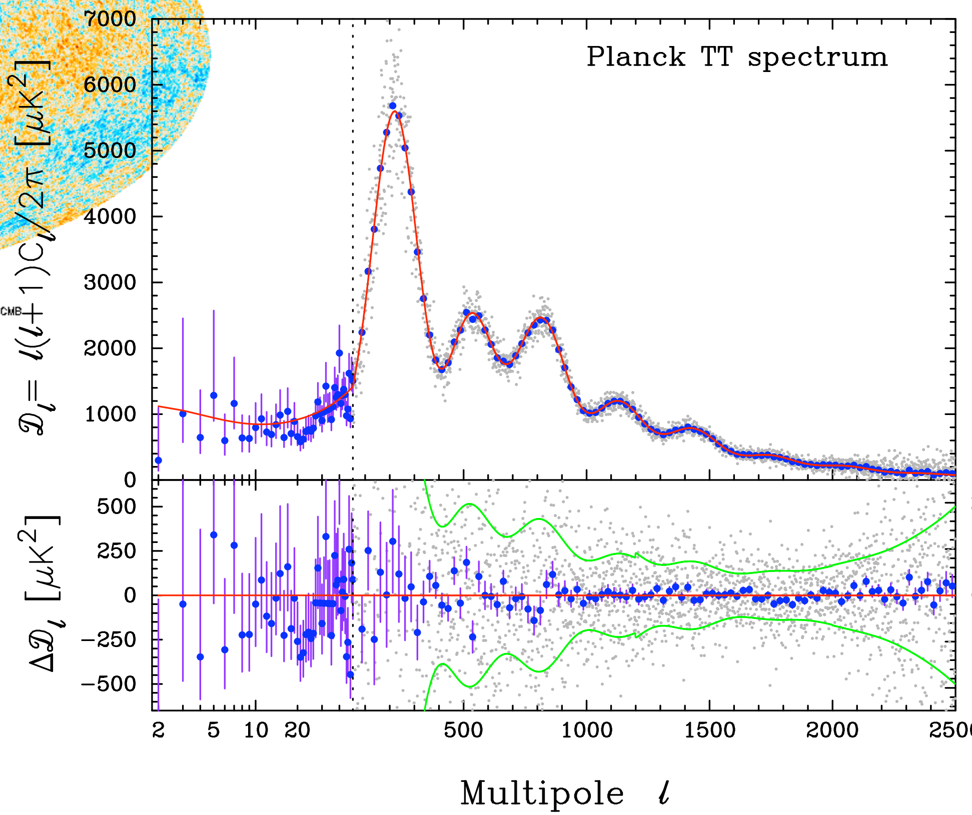
Accelerators (LHC) / DM direct detection

Neutrino oscillation / beta decay experiments

Cosmological observations: CMB temperature

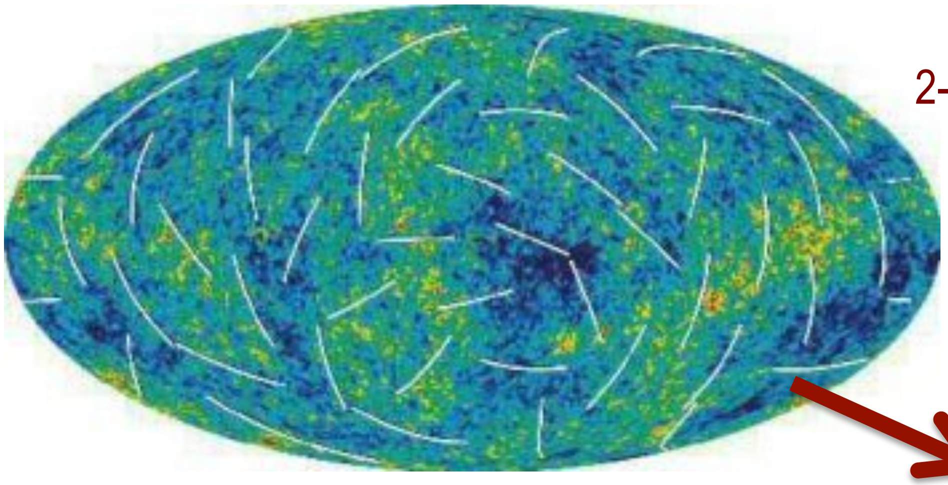


2-pt correlation function in harmonic space
= temperature spectrum



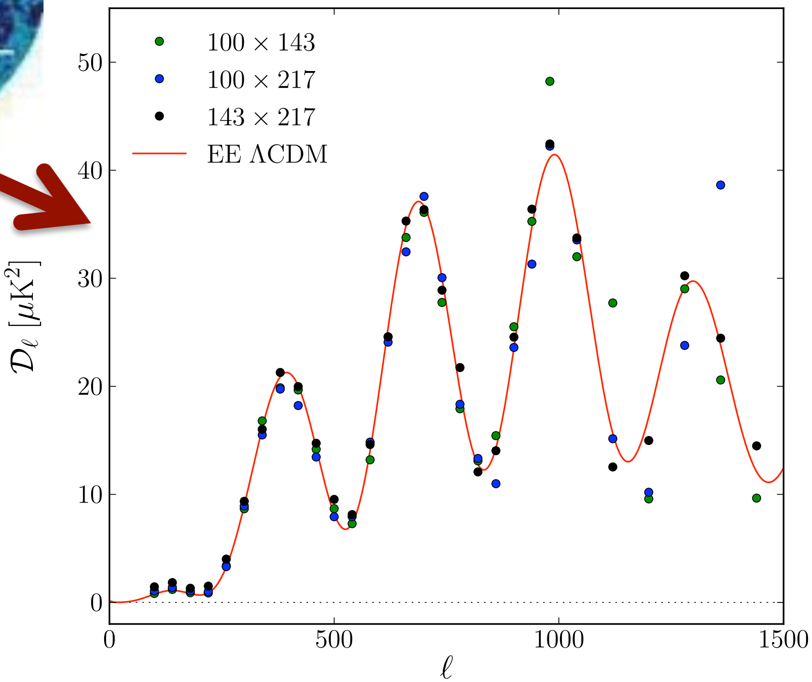
Overwhelming agreement with predictions of minimal ΛCDM model

Cosmological observations: CMB polarisation



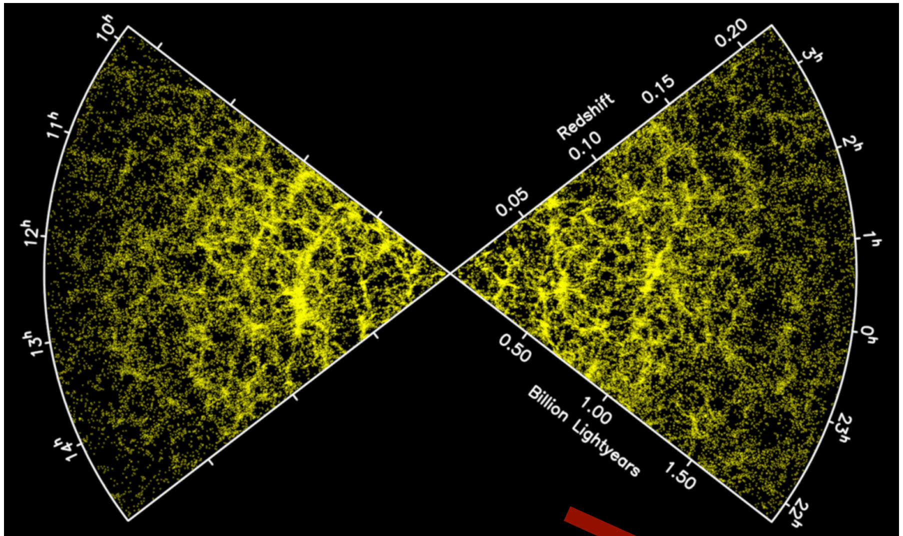
WMAP

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

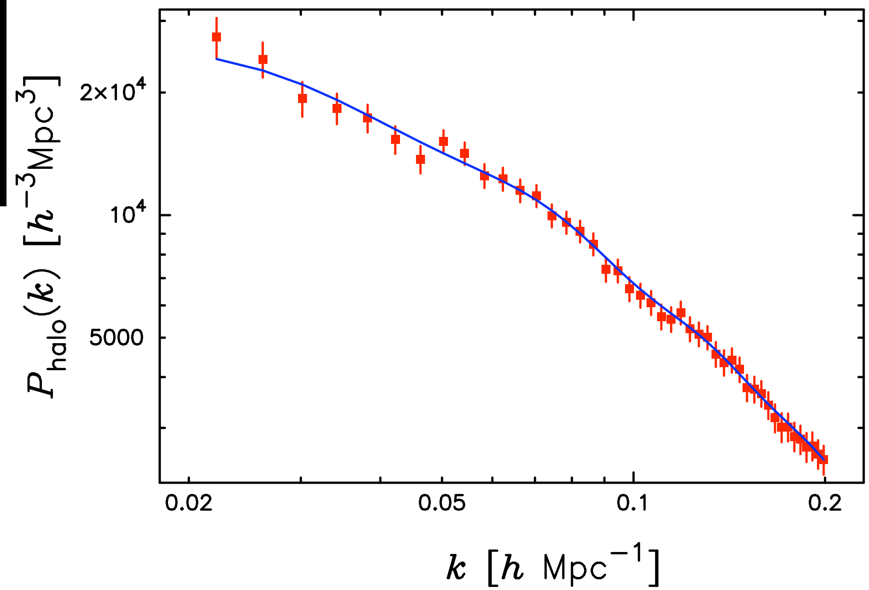


Planck preliminary!!

Cosmological observations: LSS from galaxy maps

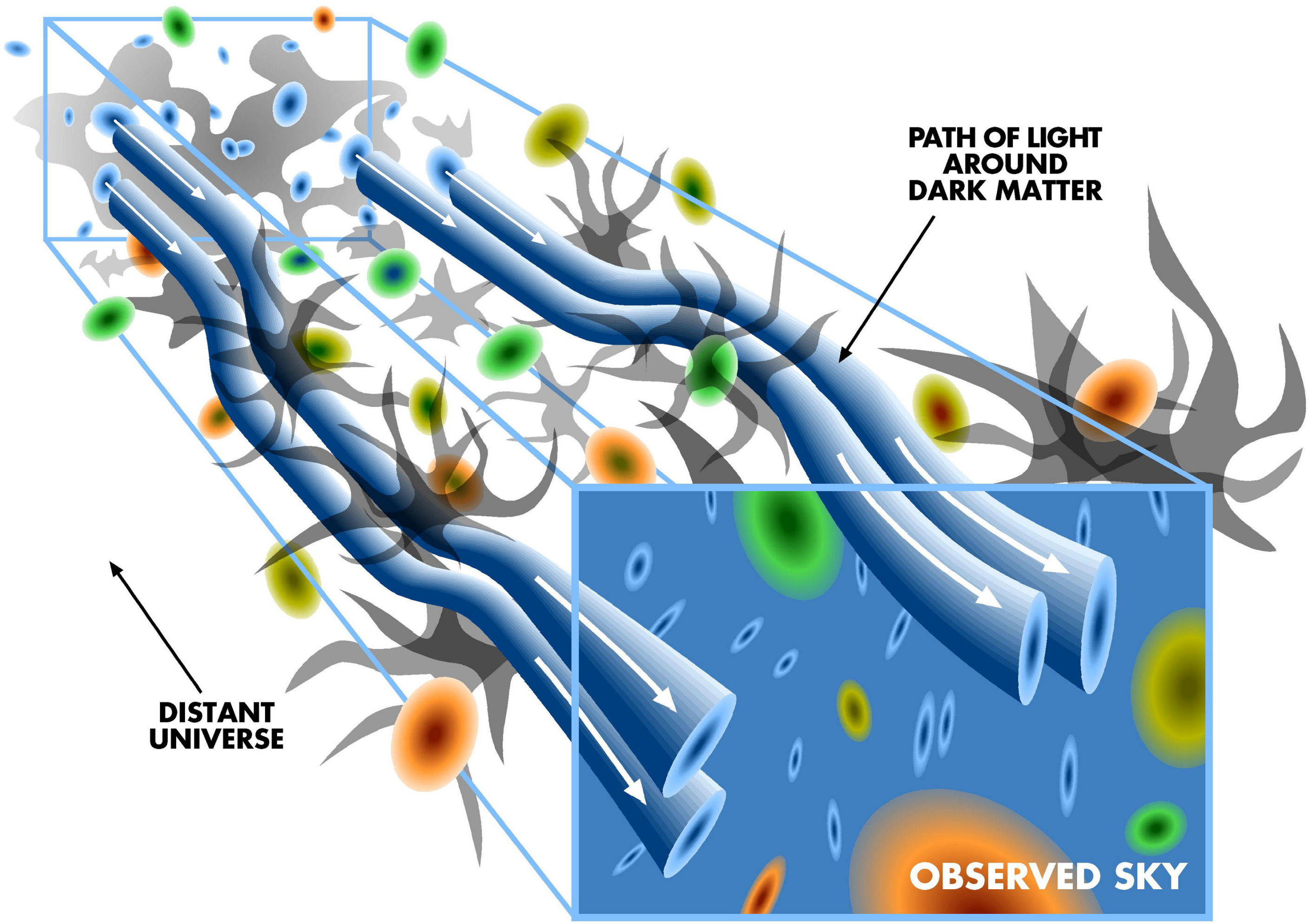


2-pt correlation function in Fourier space
= matter spectrum

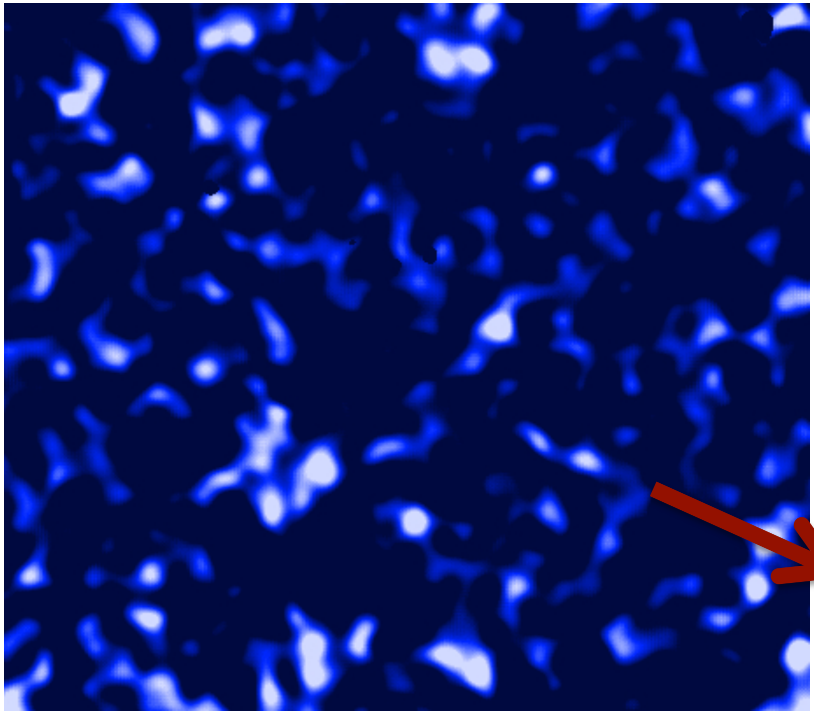


Excellent agreement with predictions of minimal ΛCDM model

Cosmological observations: LSS from lensing maps

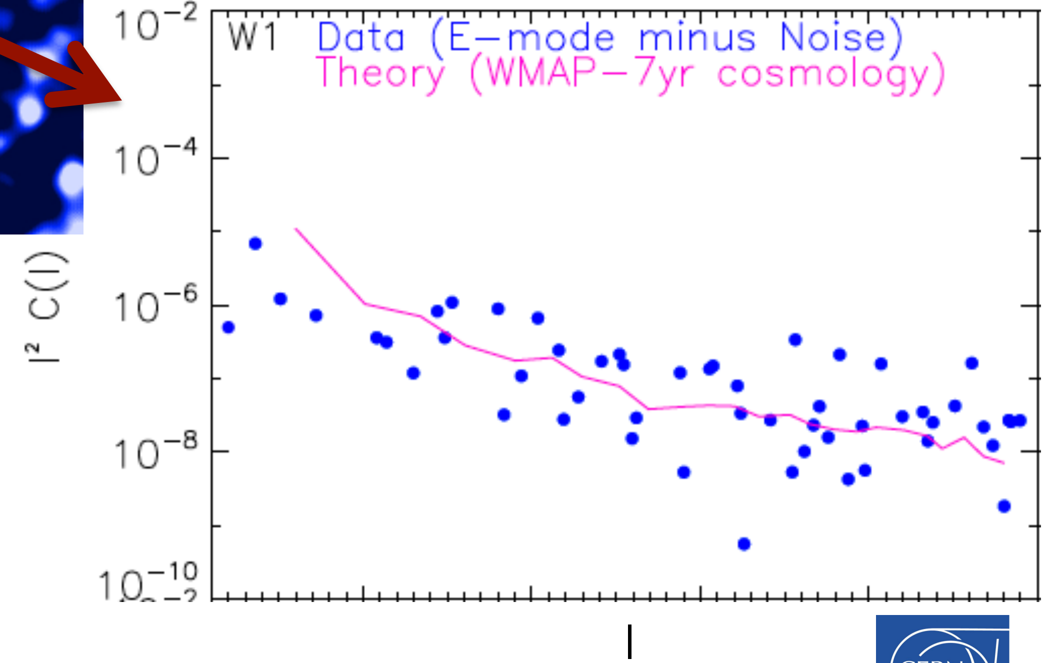


Cosmological observations: LSS from lensing maps

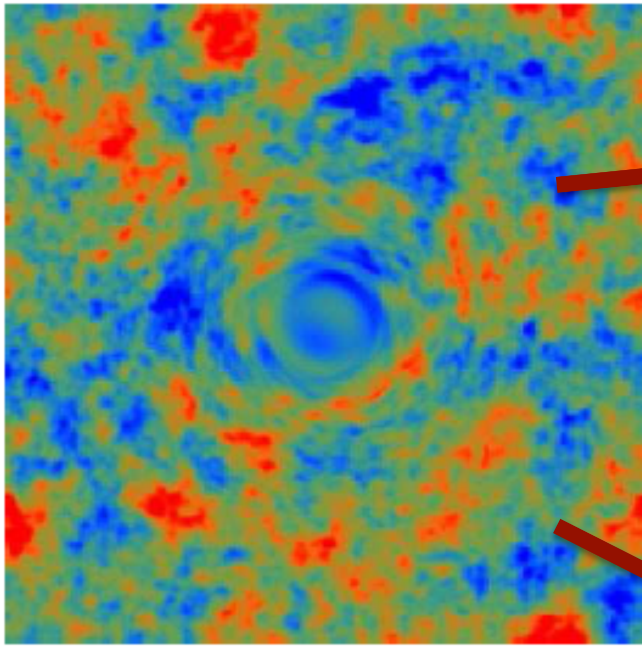


CFHTLens

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

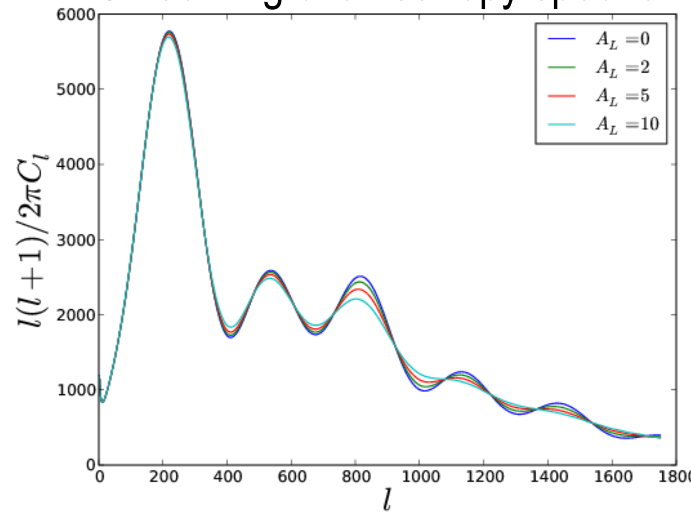


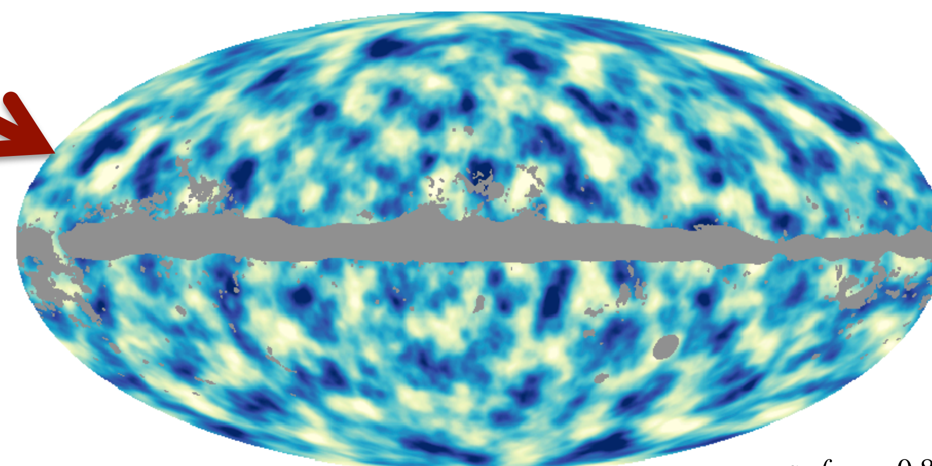
Cosmological observations: LSS from CMB lensing maps



Simulation of CMB lensing by huge cluster

Smoothing of anisotropy spectrum

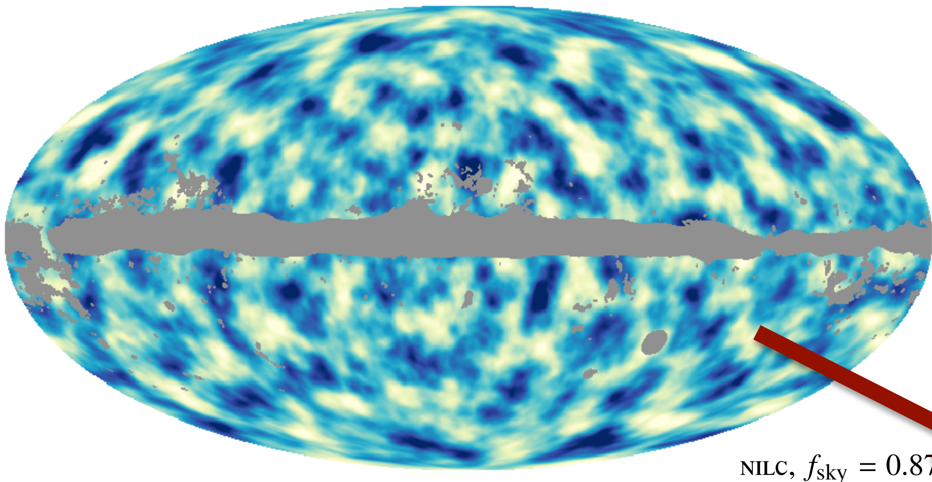




NILC, $f_{\rm sky} = 0.87$

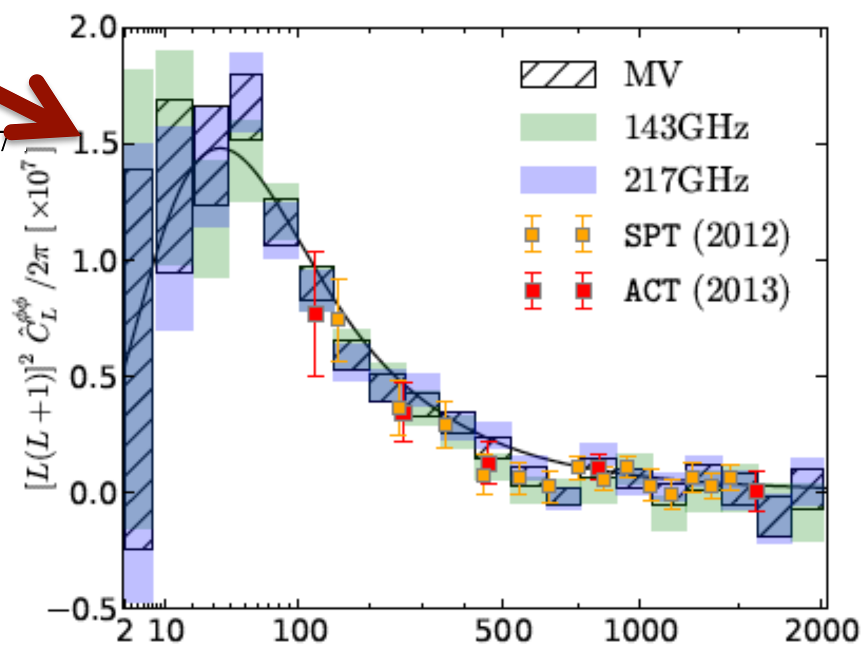
CMB lensing extraction by Planck

Cosmological observations: LSS from CMB lensing maps

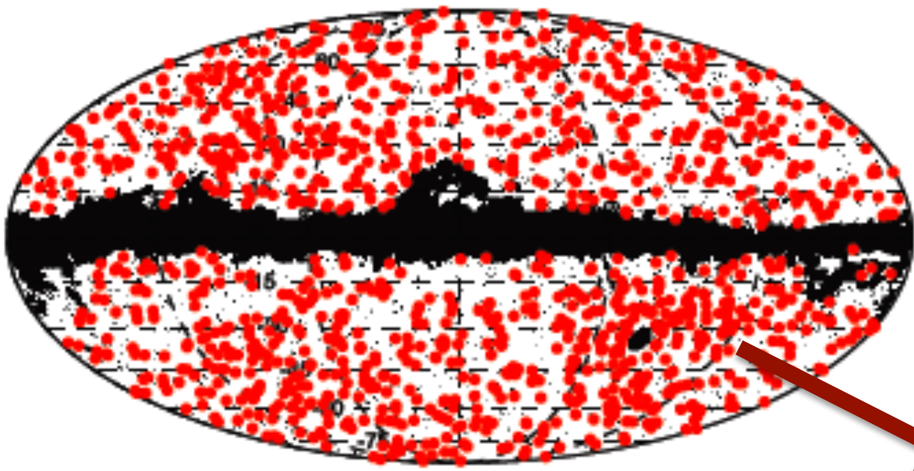


CMB lensing extraction by Planck

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

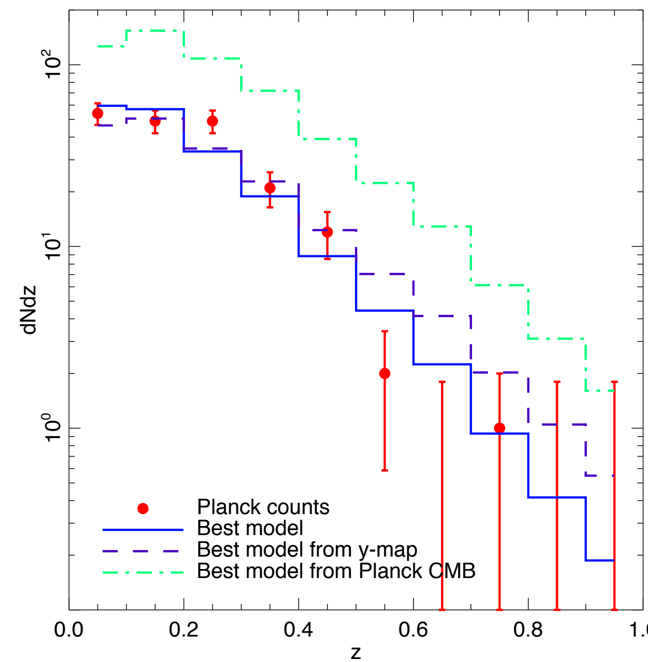


Cosmological observations: LSS from cluster mass function

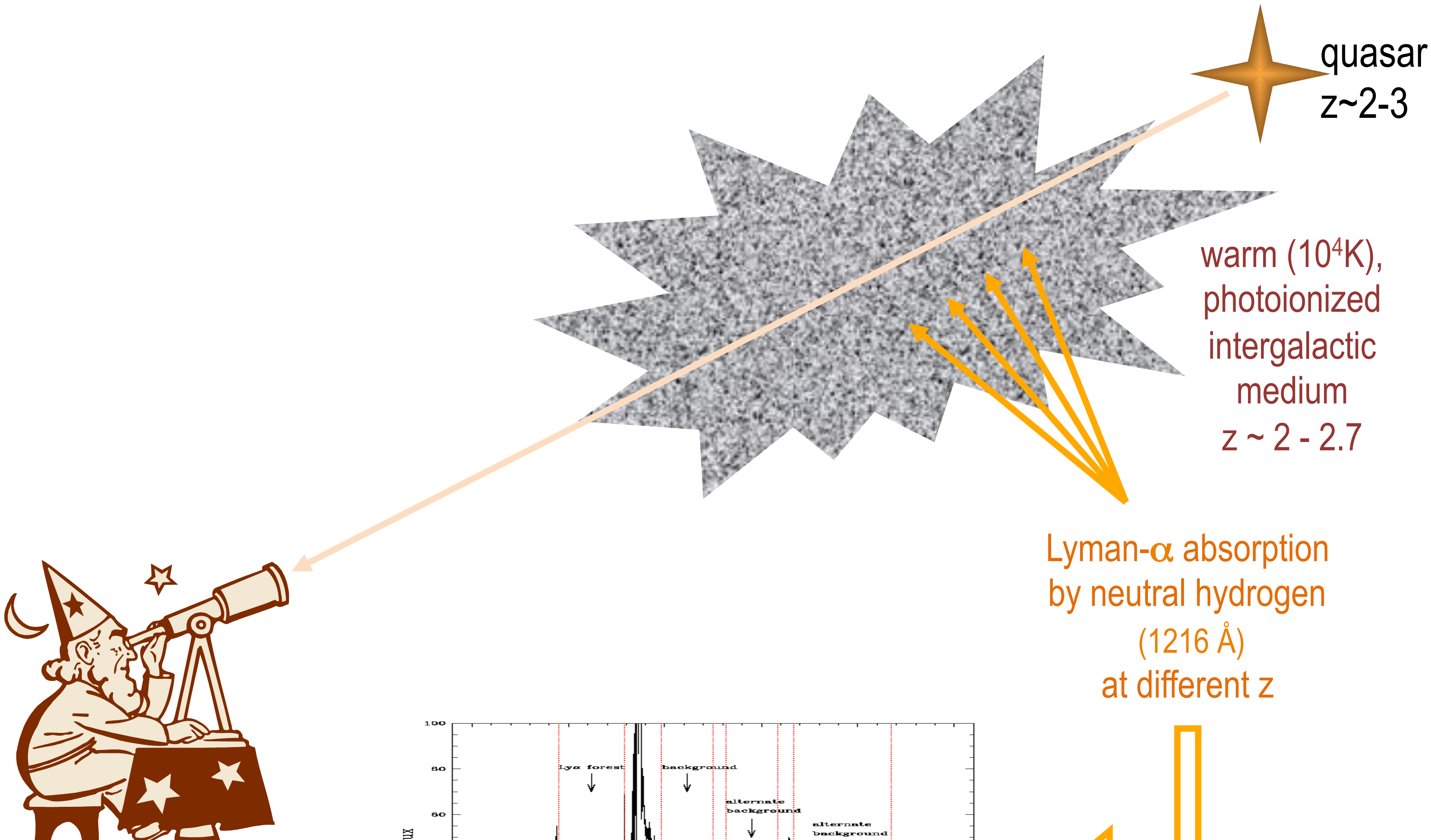


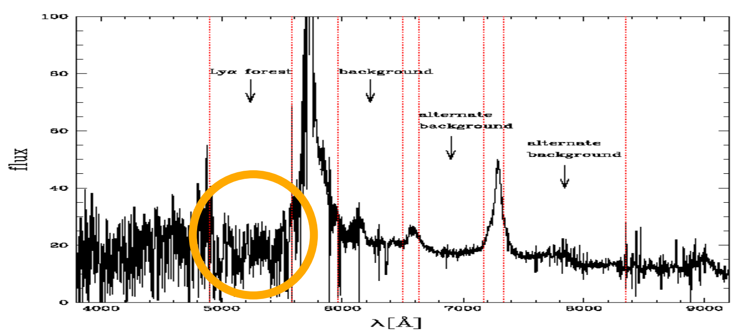
SZ cluster map from Planck

Histogram of number (or mass) versus redhsift

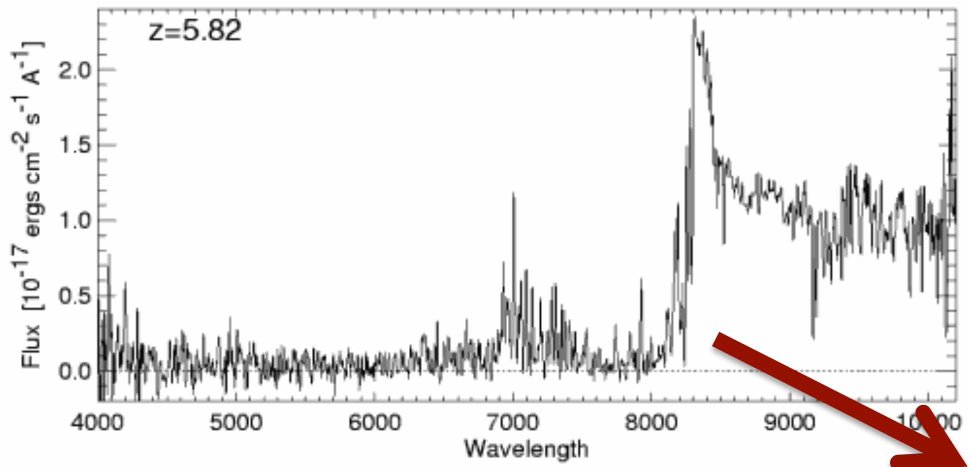


Cosmological observations: LSS from Lyman-α forests



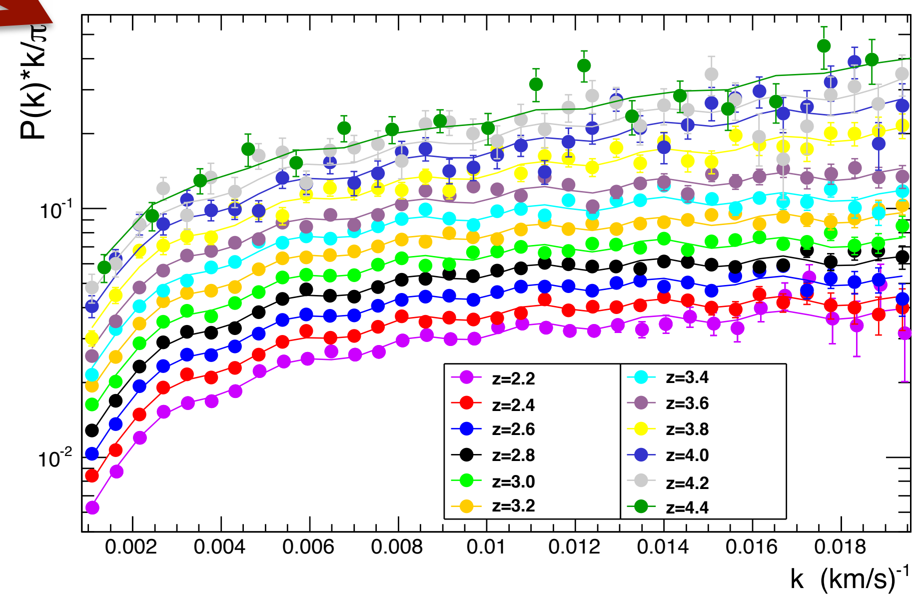


Cosmological observations: LSS from Lyman-α forests



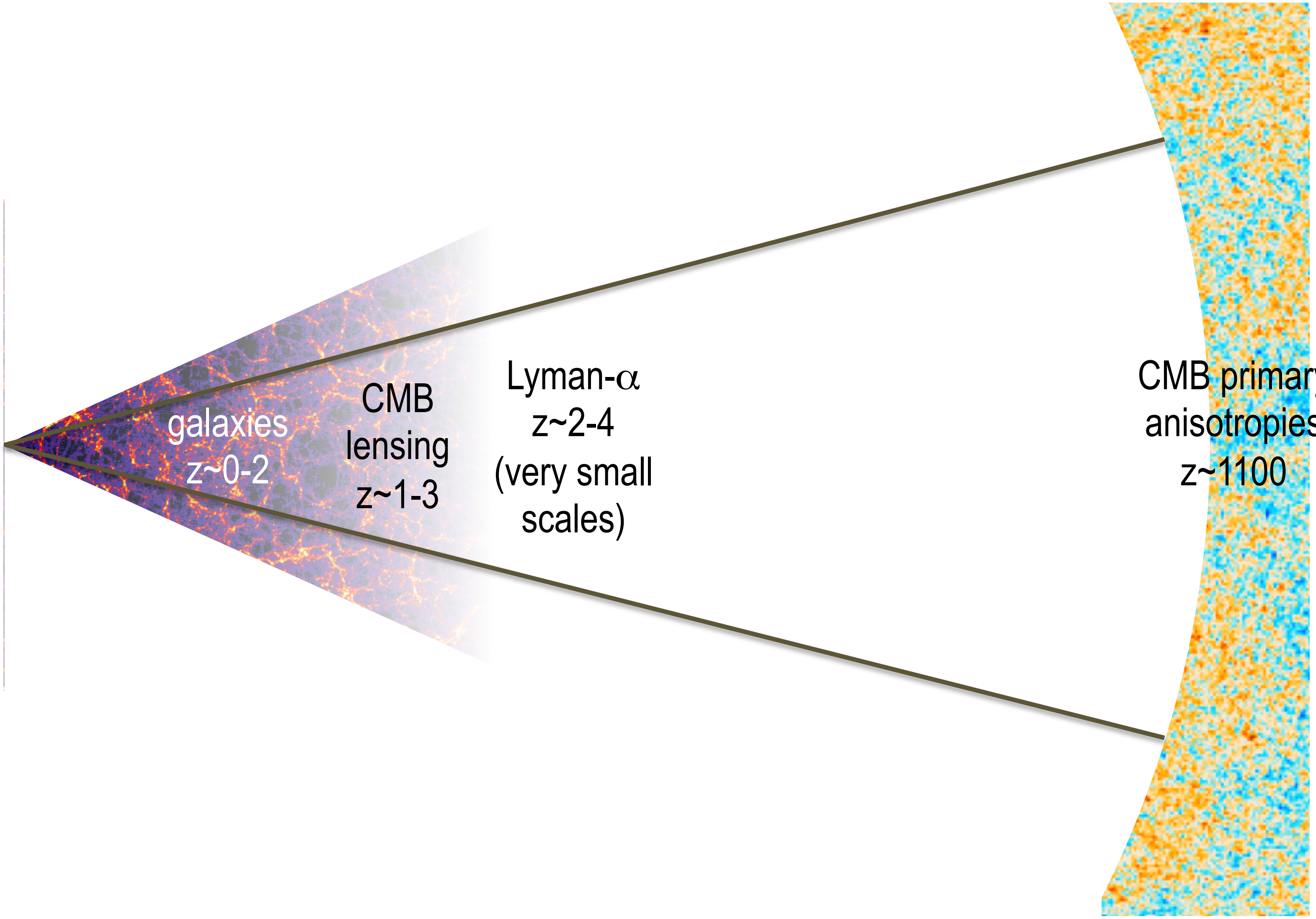
Quasar spectrum from SDSS

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



Palanque-Delabrouille et al., 1306.5896

Observations probe very different times and scales



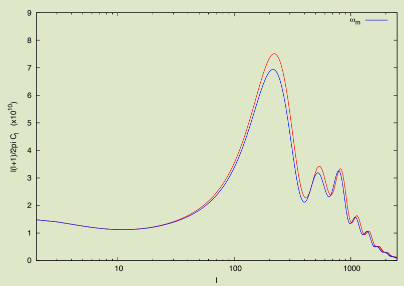
Dominant DM component

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

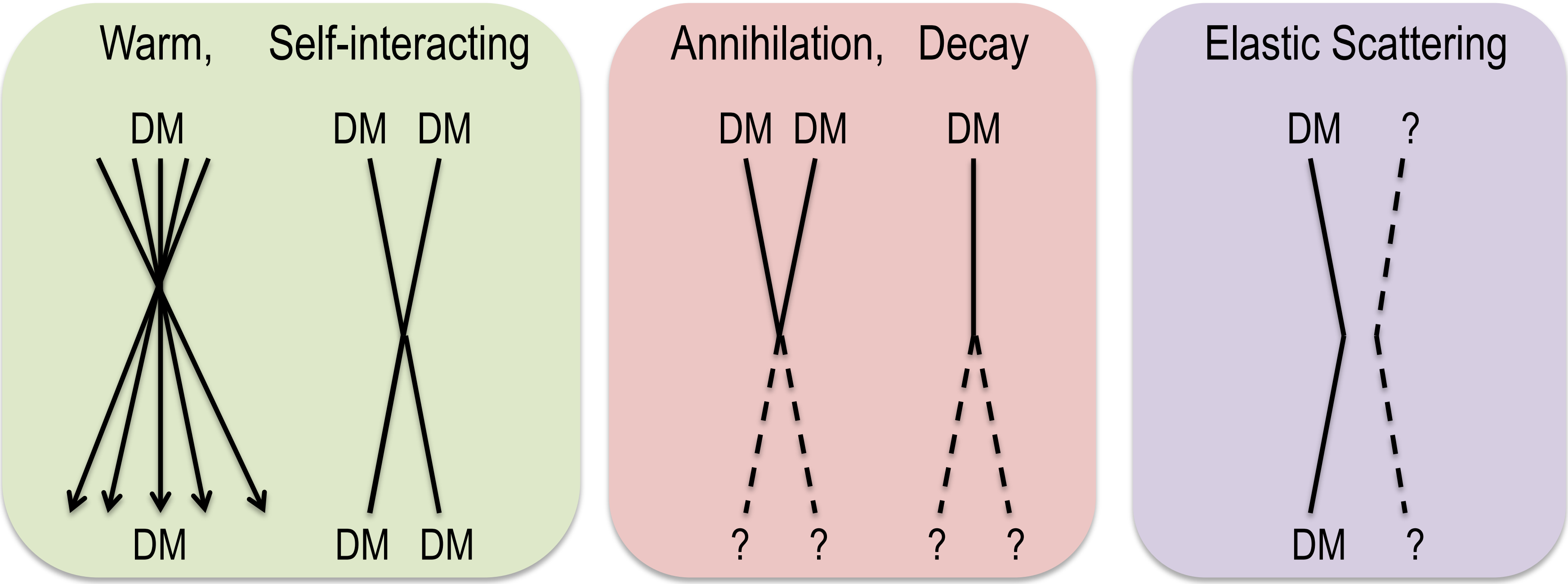
CMB/LSS and nature of (dominant) Dark Matter

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

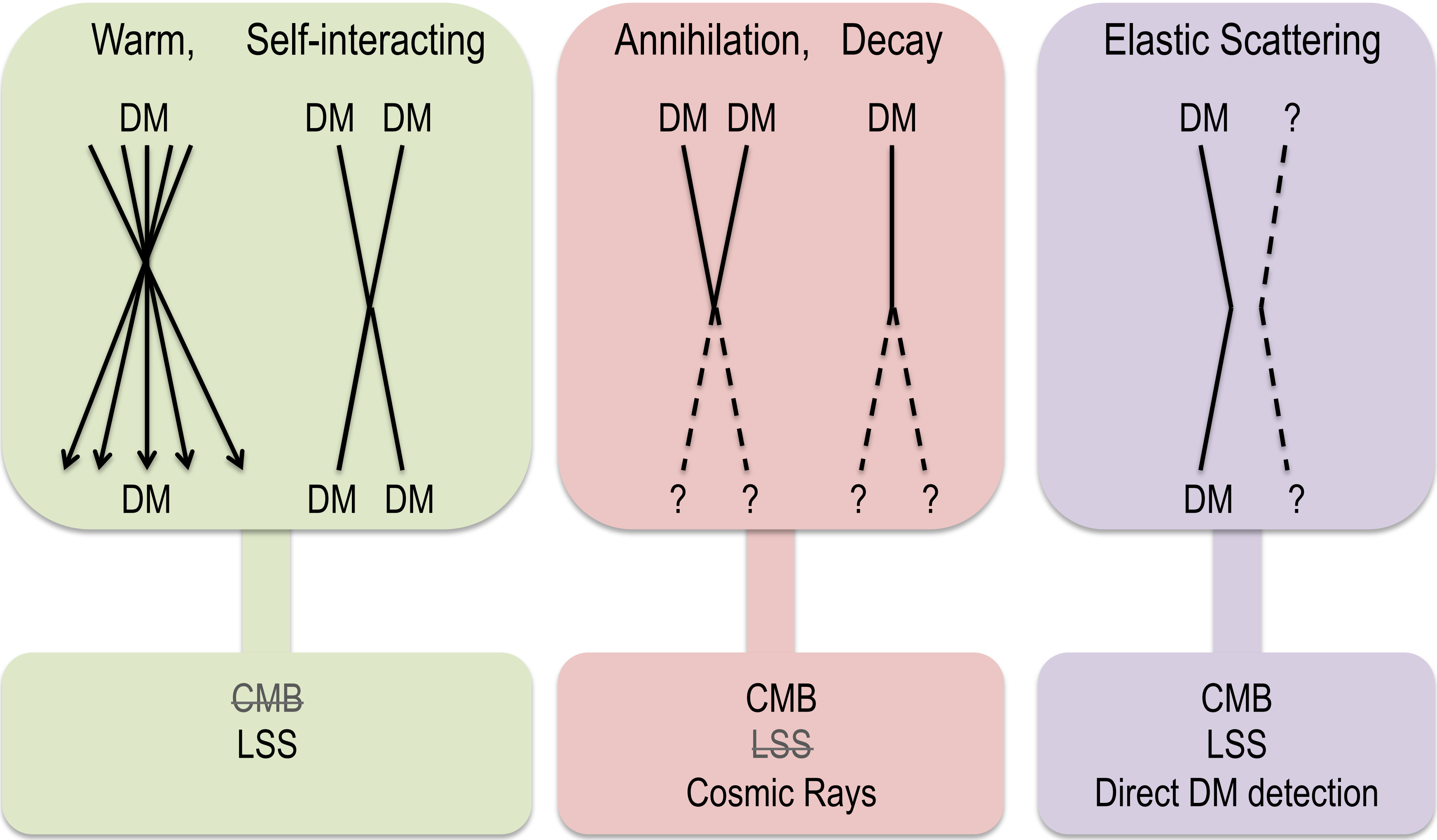
- but totally unknown nature:
  - WIMPS, non-weakly interacting;
  - annihilating, decaying, stable;
  - cold or warm;
  - collisionless, self-interacting;
  - oscillating scalar fields;
  - …

?

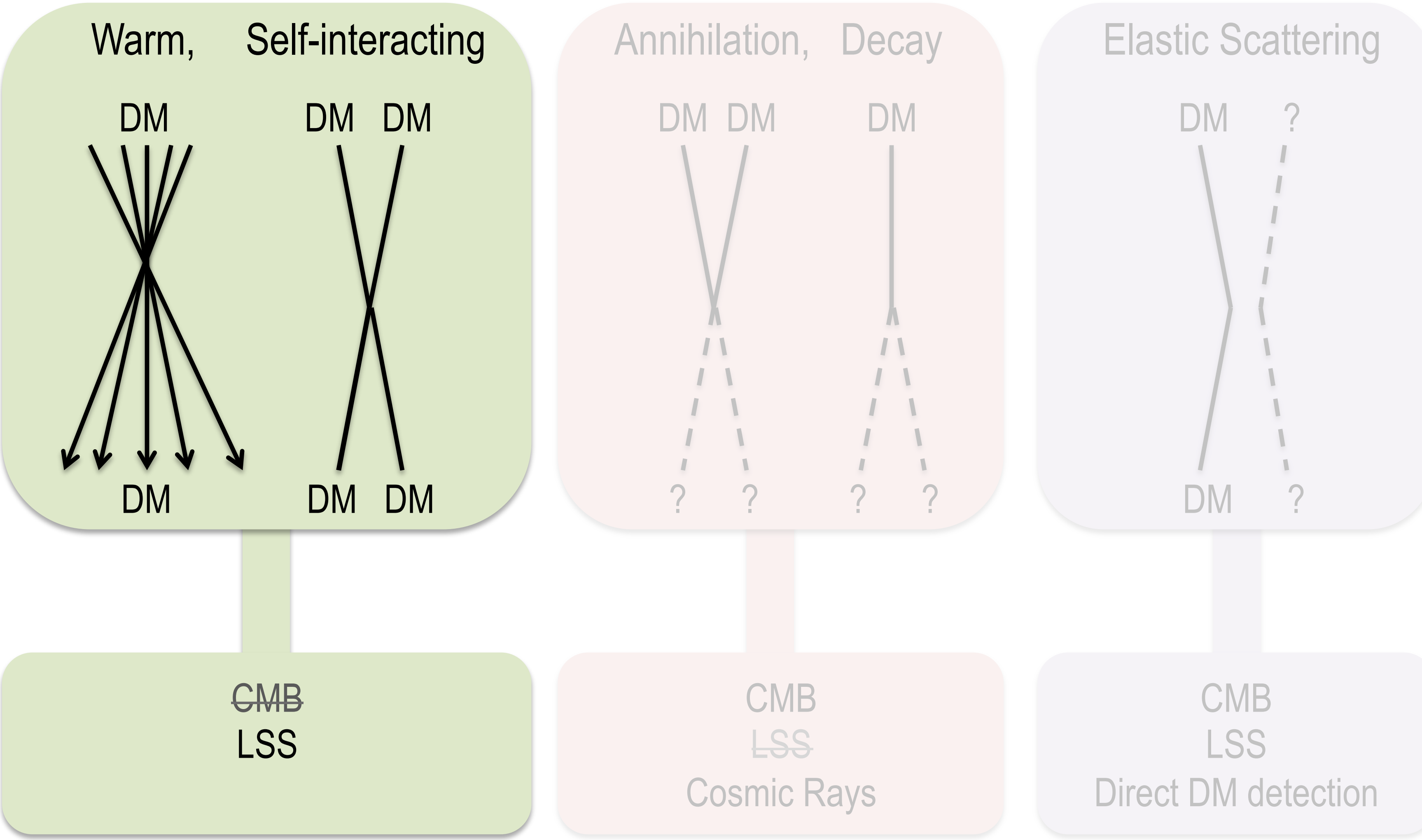
Possible properties of DM



Possible properties of DM

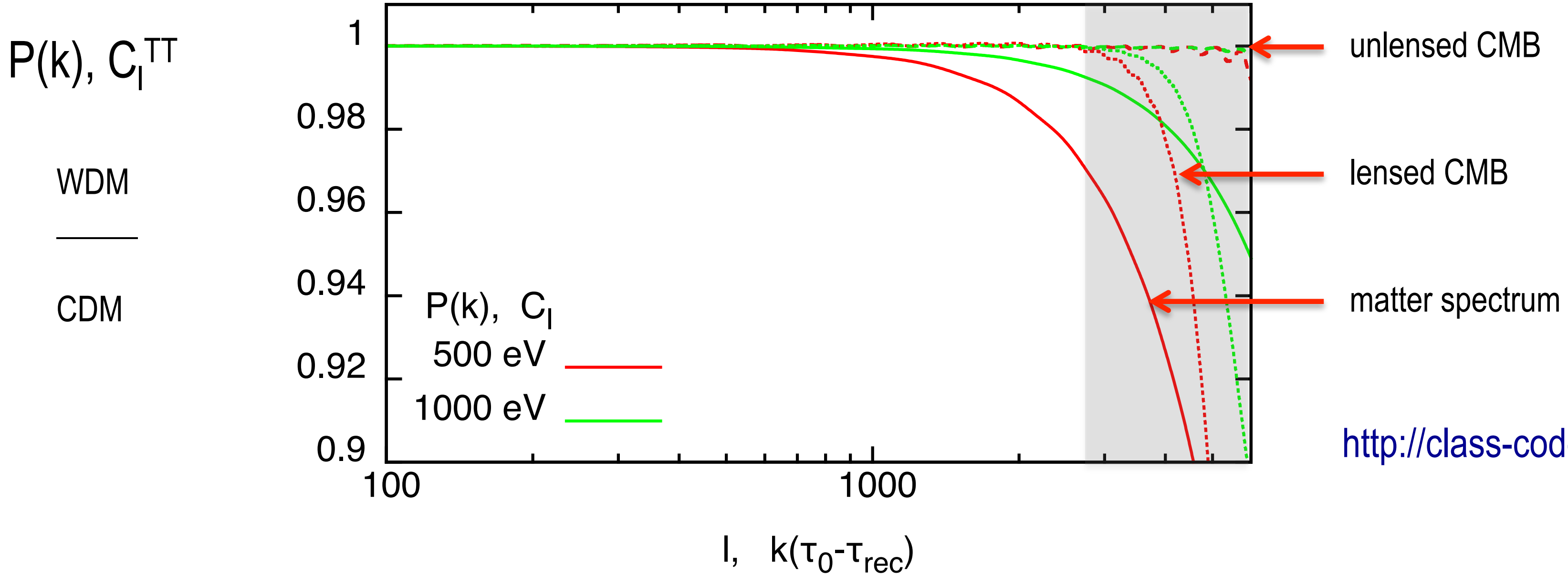


Case 1: warm or self-interacting



Case 1: warm or self-interacting

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



http://class-code.net

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: <p>/m ~ 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

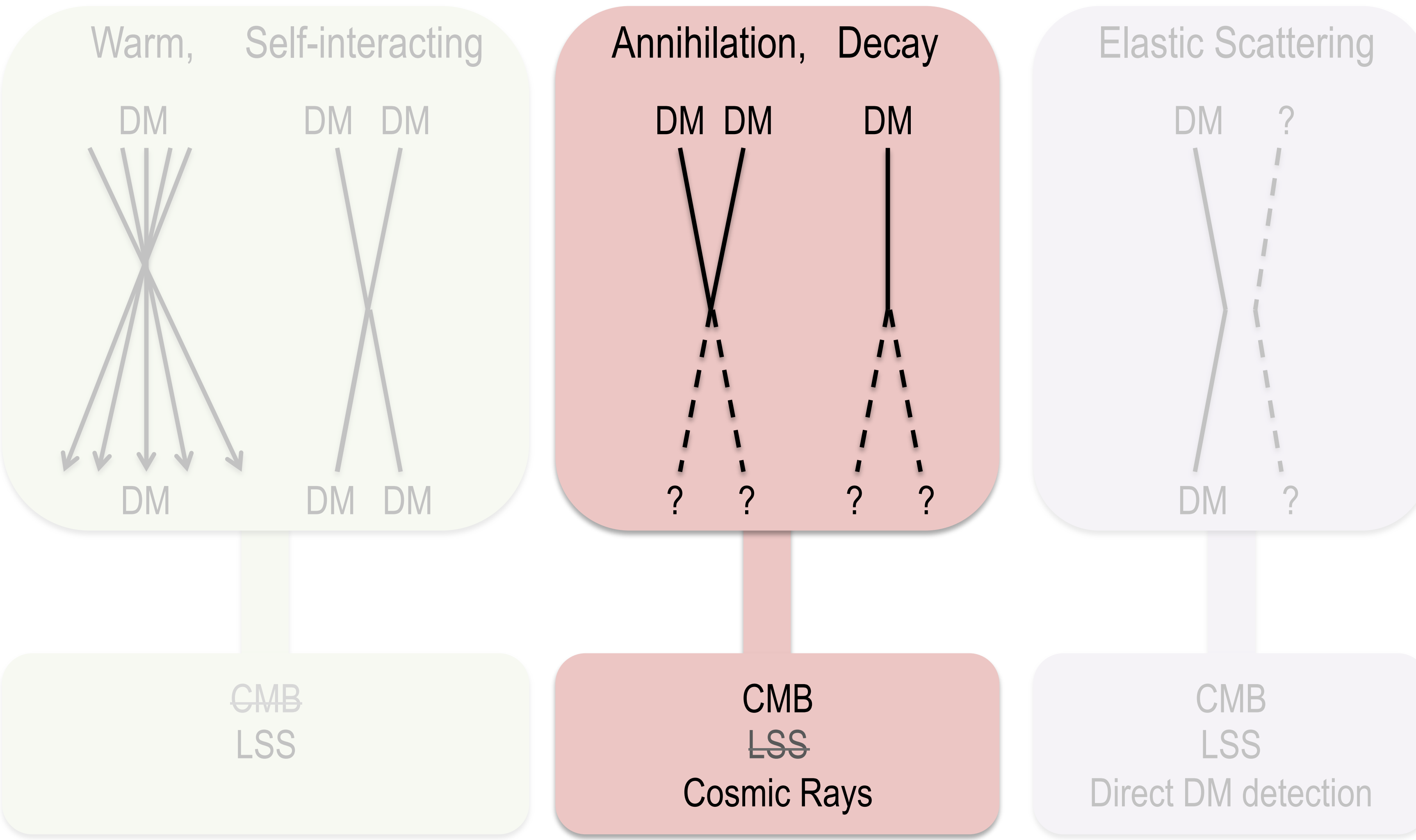
- Resonantly produced sterile neutrino: like CDM+WDM. Loose bound :

  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

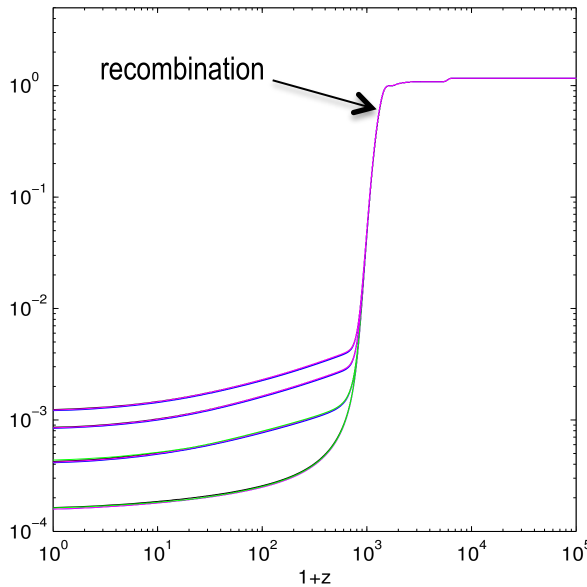
- DM → hadrons, leptons, gauge bosons → … → electrons, neutrinos, photons
  - Ionization of thermal plasma
  - Heating of thermal plasma
  - Hydrogen excitation

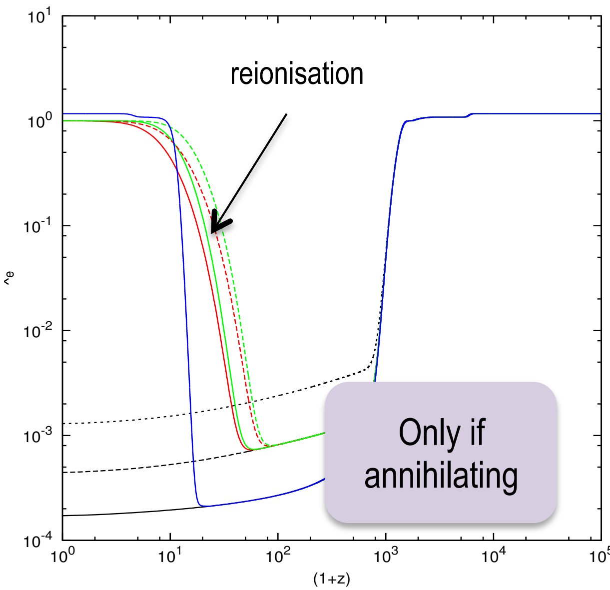
  (unless 100% in neutrinos)

- 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

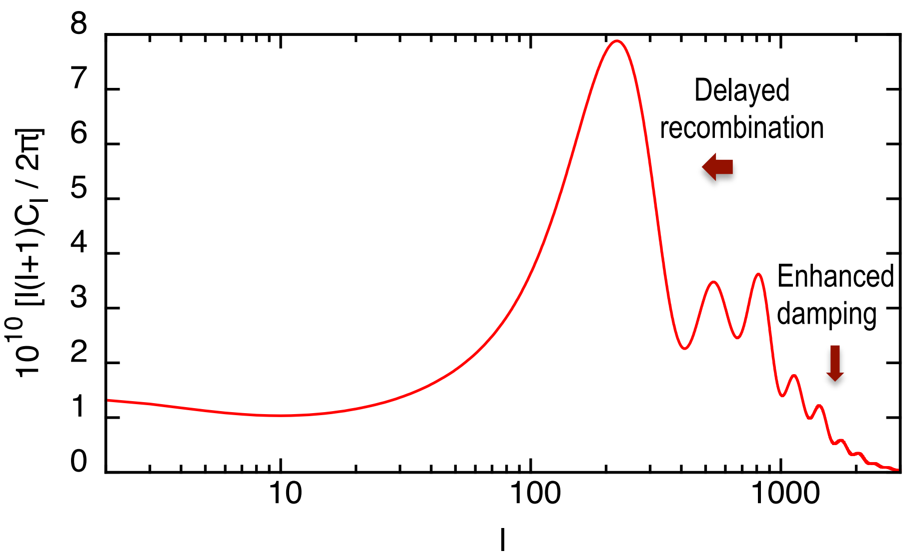
CMB photons shedding light on Dark Matter

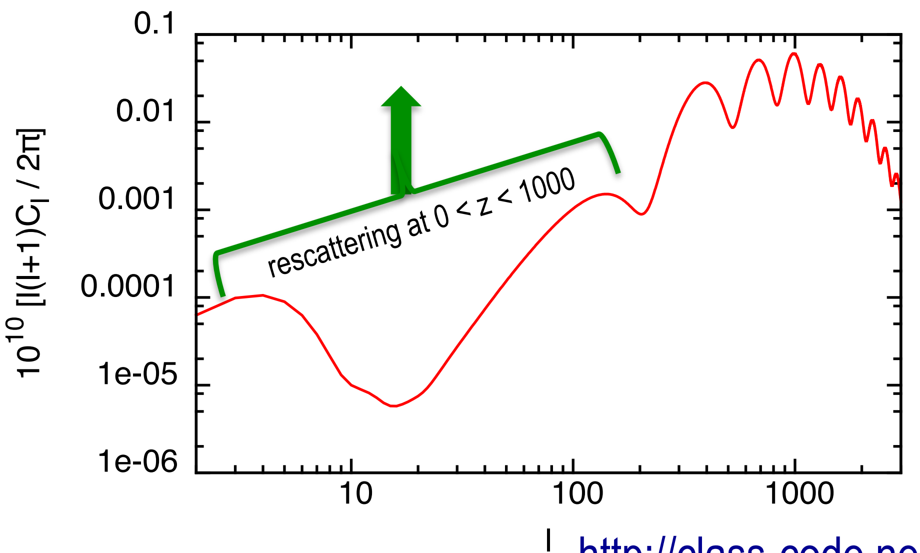
G. Giesen, J. Lesgourgues, B. Audren, Y. Ali-Haimoud 2012, JCAP, **arXiv:1209.0247**

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

CERN

Case 2: annihilating or decaying





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

- Bounds from WMAP7/9 and Planck 2003 very similar;
- progress expected with Planck polarisation

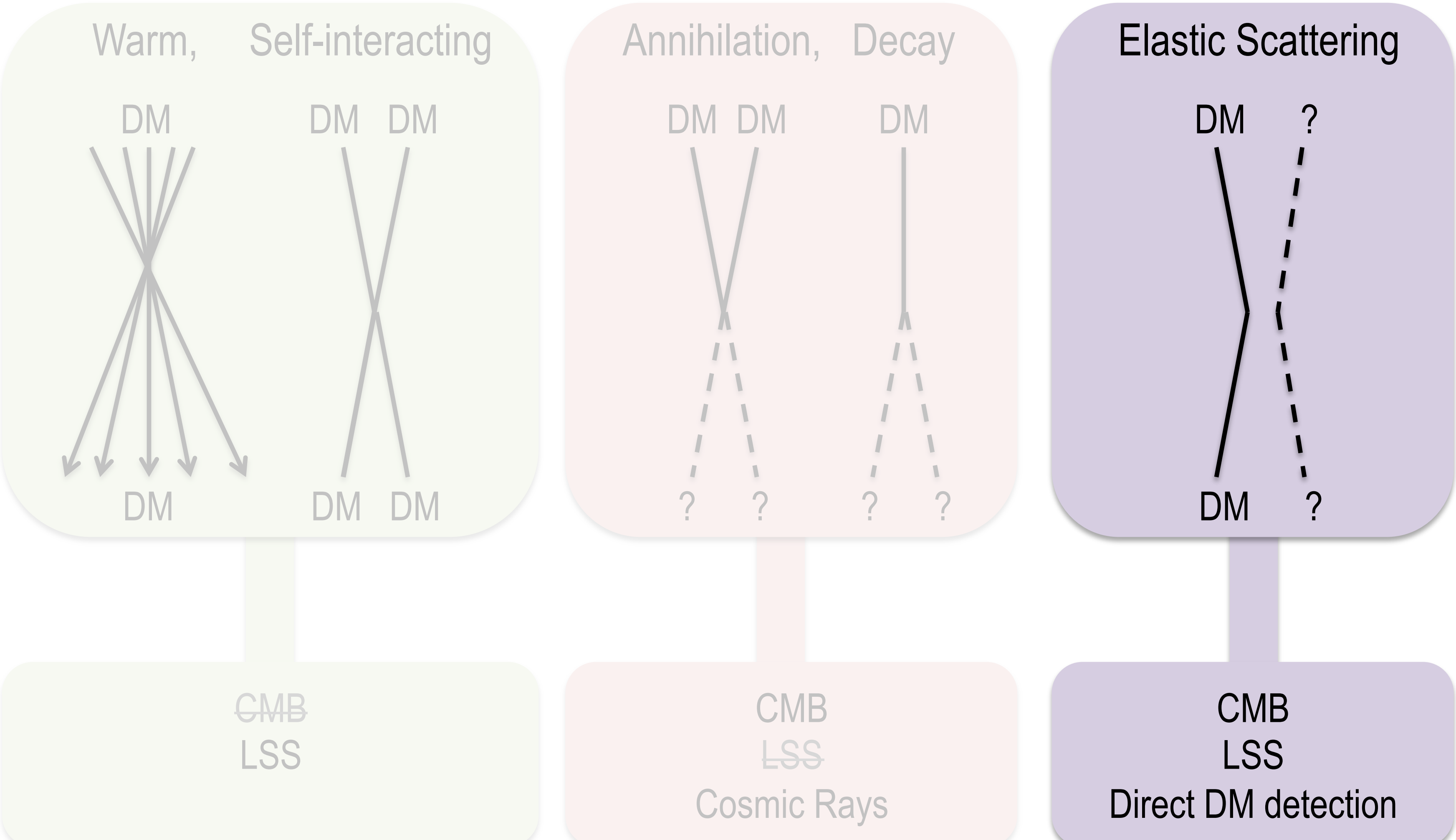
Annihilation: VERY INTERESTING RESULTS compared to direct/indirect detection

- Currently excludes DM intepretation of Pamela anomaly if annihilation is Sommerfeld-enhanced
- Marginal agreement with CDMS direct detection claim and Fermi anomaly, 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)

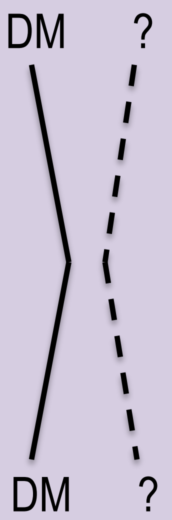
- For WIMPS: weak interactions (with quarks, neutrinos) too small to leave any signature on CMB/LSS

- 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



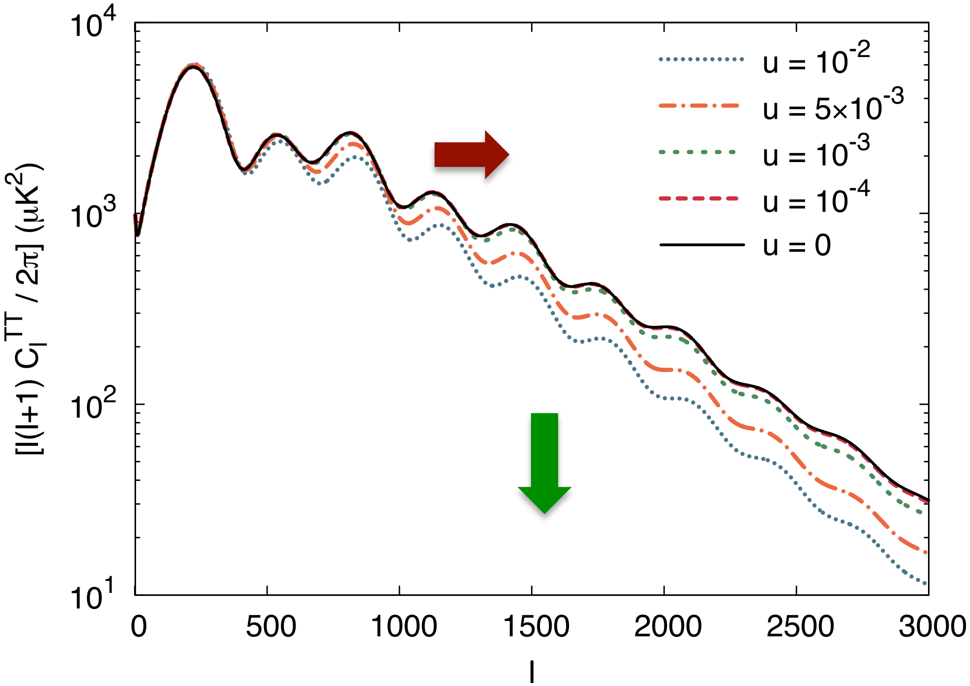
CMB
LSS
Direct DM detection

Case 3: DM interactions (elastic scattering)

- DM-photons

Wilkinson, JL & Boehm 1309.7588

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



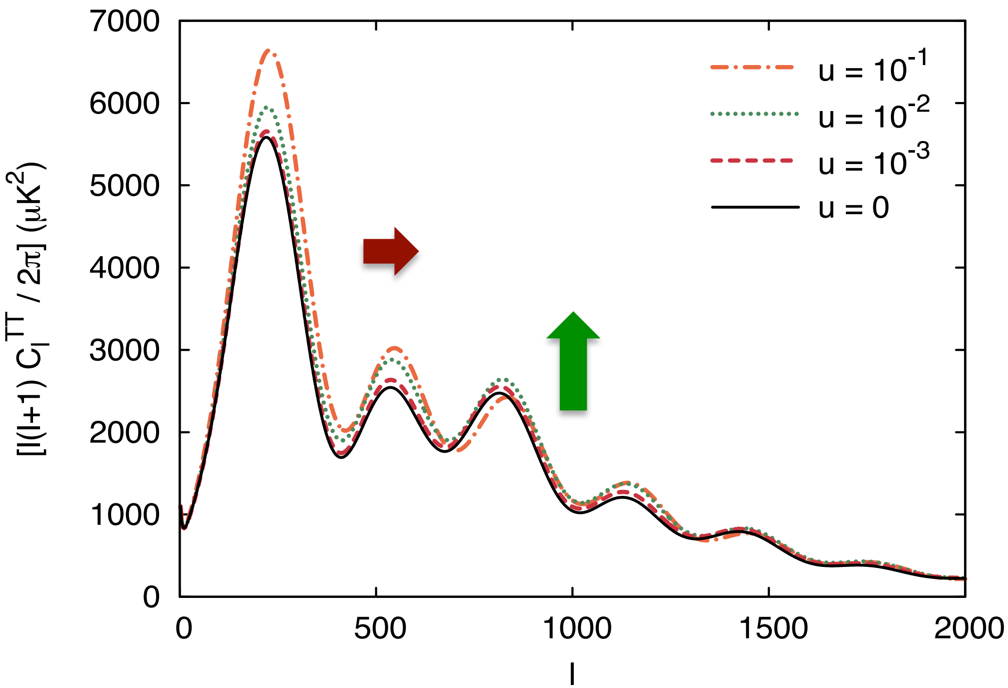
http://class-code.net

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)



http://class-code.net

Case 3: DM interactions (elastic scattering)

- DM-baryons

Dvorkin, Blum, Kamionkowski 1311.2937

- DM-Dark Radiation

Cyr-Racine, de Putter, Raccanelli, Sigurdson 1310.3278

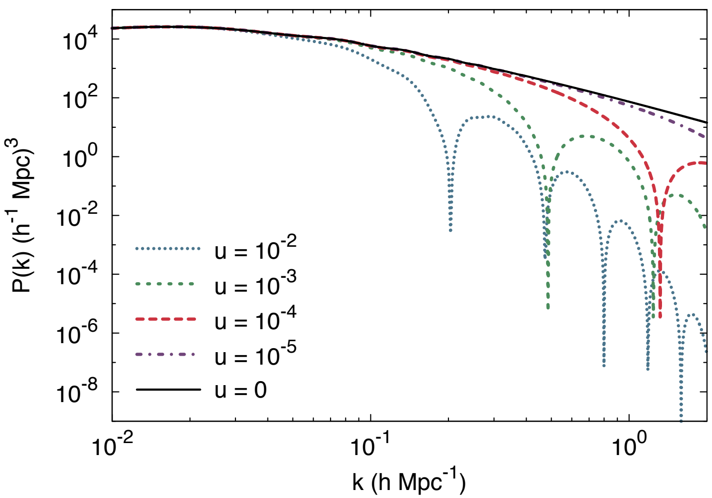
- DM-Dark Energy

…

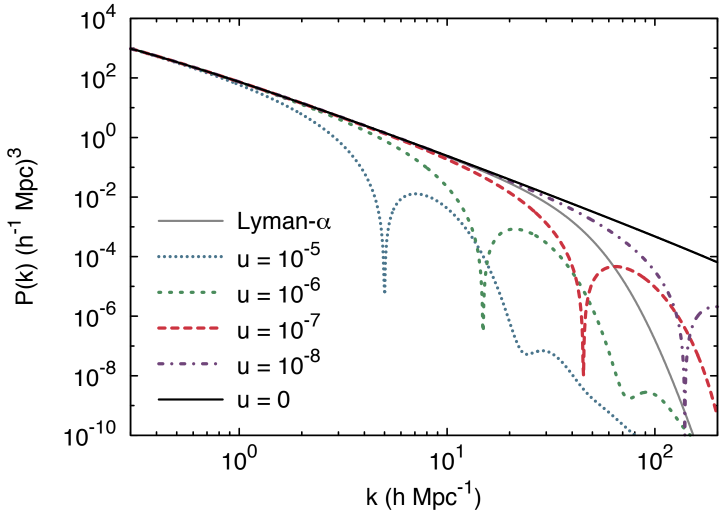
Case 3: DM interactions (elastic scattering)

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

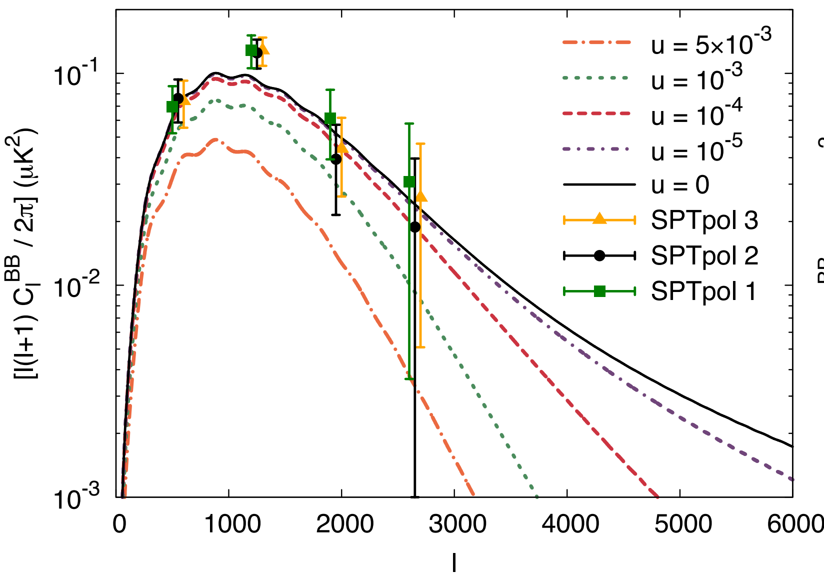
- DM-ν interaction :
  - Upper bound close to predictions of model with coupling between scalar dark matter and neutrinos, giving DM relic density and neutrino masses (radiative corrections)

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

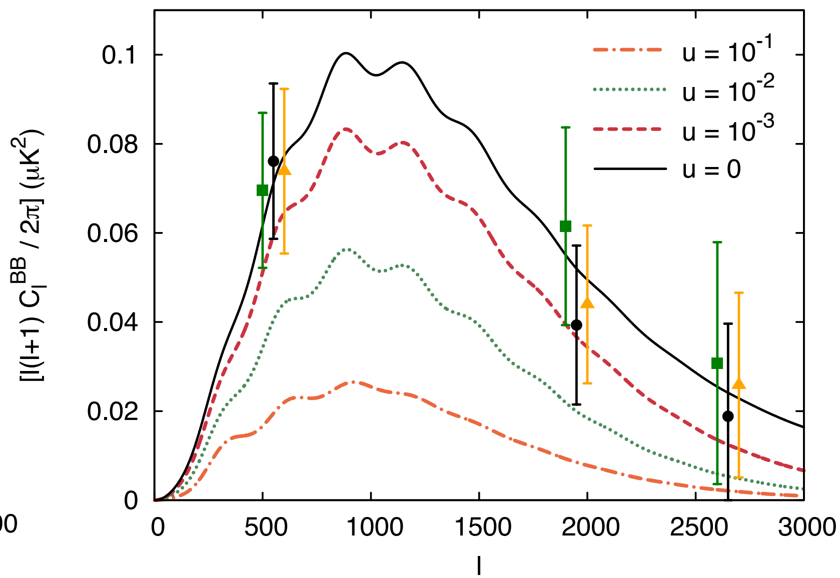
Case 3: DM interactions (elastic scattering)

Potential progress with polarisation, including B modes:

DM-photon



DM-neutrino



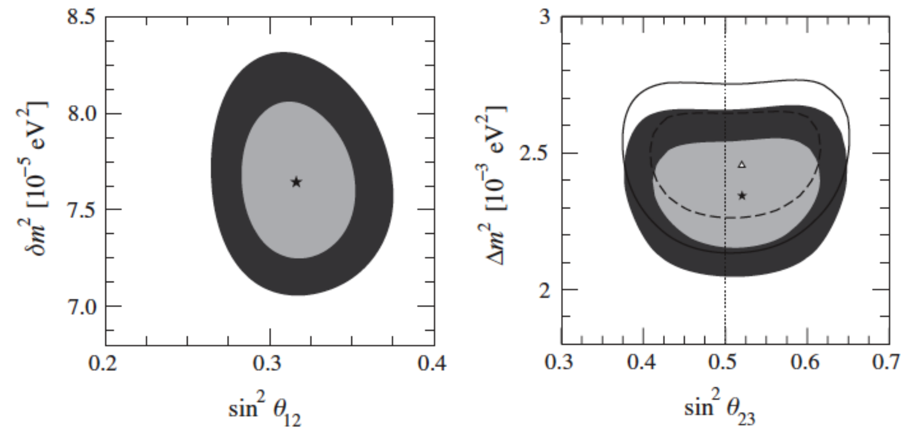
(collisonal damping + lensing and E-B conversion)

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

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

Mass of flavor neutrinos

- Neutrinos have a mass :



  - Neutrino oscillations in early universe : almost irrelevant for cosmology
  - Dirac/Majorana mass : completely irrelevant for cosmology
  - $T \ll m_\nu$: non-relativistic : effects in CMB / LSS

Measurement of m_ν with CMB / LSS

Measuring neutrino masses with CMB/LSS

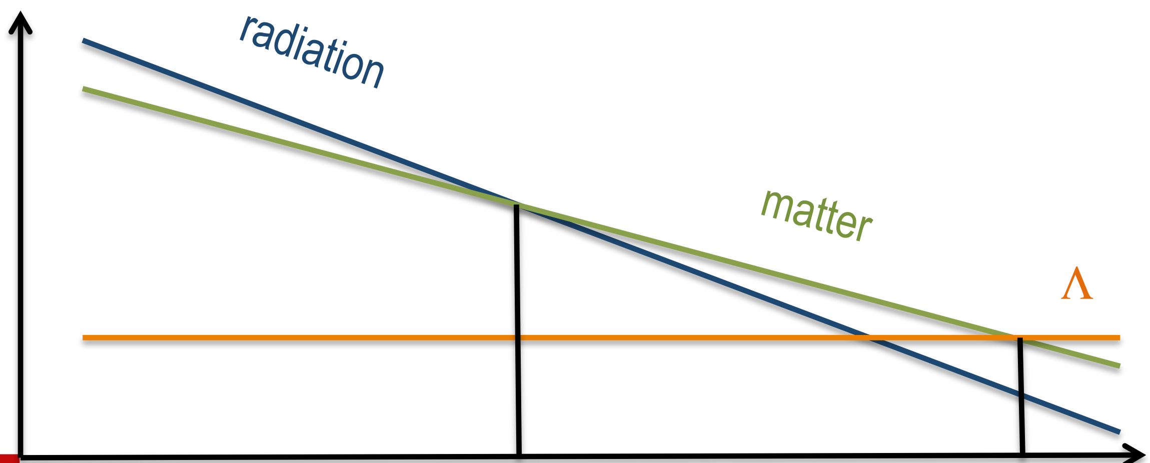
- Neutrinos contribute to radiation at early time and non-relativistic matter at late time: $\omega_\nu = M_\nu / 94\text{eV}$.
- $M_\nu = \Sigma m_\nu > 0.06$ eV (NH) or 0.1 eV (IH). At least two non-relativistic neutrinos today.
- If $m_\nu < 0.6$ eV, neutrinos are relativistic at decoupling. Claim that CMB can only probe higher masses is wrong for several reasons.

Measuring neutrino masses with CMB/LSS

- Neutrinos contribute to radiation at early time and non-relativistic matter at late time: $\omega_\nu = M_\nu / 94\text{eV}$.
- $M_\nu = \Sigma m_\nu > 0.06$ eV (NH) or 0.1 eV (IH). At least two non-relativistic neutrinos today.
- If $m_\nu < 0.6$ eV, neutrinos are relativistic at decoupling. Claim that CMB can only probe higher masses is wrong for several reasons.
- "effect of m_ν" depends on what is kept fixed.

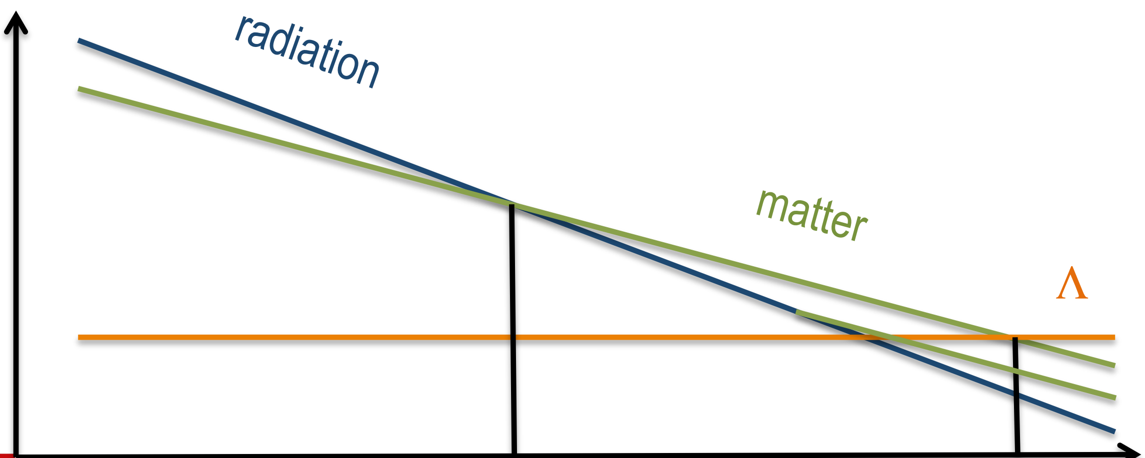
Measuring neutrino masses with CMB/LSS

- Neutrinos contribute to radiation at early time and non-relativistic matter at late time: $\omega_\nu = M_\nu / 94\text{eV}$.
- $M_\nu = \Sigma m_\nu > 0.06$ eV (NH) or 0.1 eV (IH). At least two non-relativistic neutrinos today.
- If $m_\nu < 0.6$ eV, neutrinos are relativistic at decoupling. Claim that CMB can only probe higher masses is wrong for several reasons.
- "effect of m_ν" depends on what is kept fixed.
- Leave both "early cosmology" and angular diameter dist. to decoupling invariant:



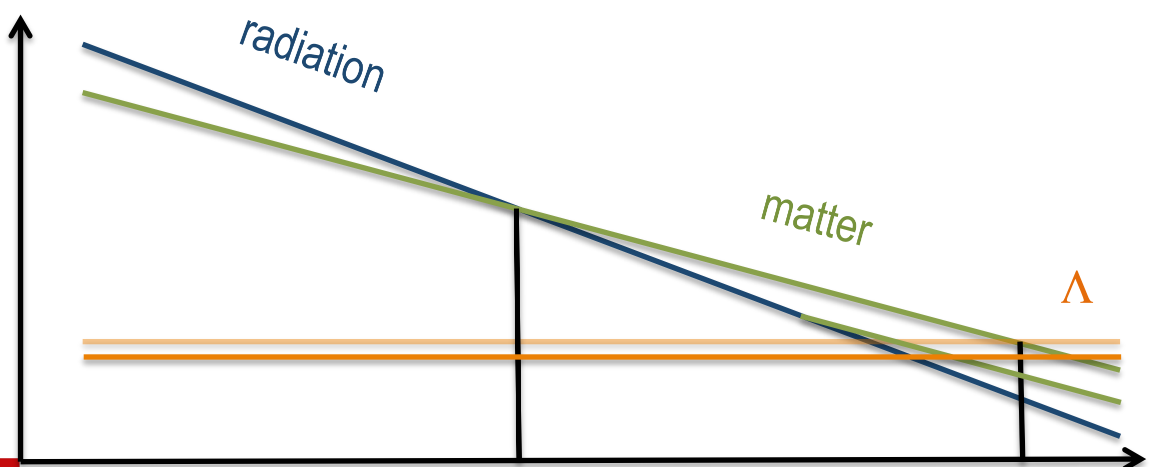
Measuring neutrino masses with CMB/LSS

- Neutrinos contribute to radiation at early time and non-relativistic matter at late time: $\omega_\nu = M_\nu / 94\text{eV}$.
- $M_\nu = \Sigma m_\nu > 0.06$ eV (NH) or 0.1 eV (IH). At least two non-relativistic neutrinos today.
- If $m_\nu < 0.6$ eV, neutrinos are relativistic at decoupling. Claim that CMB can only probe higher masses is wrong for several reasons.
- "effect of m_ν" depends on what is kept fixed.
- Leave both "early cosmology" and angular diameter dist. to decoupling invariant:



Measuring neutrino masses with CMB/LSS

- Neutrinos contribute to radiation at early time and non-relativistic matter at late time: $\omega_\nu = M_\nu / 94\text{eV}$.
- $M_\nu = \Sigma m_\nu > 0.06$ eV (NH) or 0.1 eV (IH). At least two non-relativistic neutrinos today.
- If $m_\nu < 0.6$ eV, neutrinos are relativistic at decoupling. Claim that CMB can only probe higher masses is wrong for several reasons.
- "effect of m_ν" depends on what is kept fixed.
- Leave both "early cosmology" and angular diameter dist. to decoupling invariant:



Measuring neutrino masses

- Neutrinos contribute to radiation at early time and non-relativistic matter at late time: $\omega_\nu = M_\nu / 94\text{eV}$.
- $M_\nu = \Sigma m_\nu > 0.06$ eV (NH) or 0.1 eV (IH). At least two non-relativistic neutrinos today.
- If $m_\nu < 0.6$ eV, neutrinos are relativistic at decoupling. Claim that CMB can only probe higher masses is wrong for several reasons.
- "effect of m_ν" depends on what is kept fixed.
- Leave both "early cosmology" and angular diameter dist. to decoupling invariant:

  - Possible by fixing photon, cdm and baryon densities, while tuning H_0, Ω_Λ
  - then increase in m_ν goes with decrease in H_0: negative correlation between the two
  - "base model" in Planck has (0.06, 0, 0) eV masses: shifts best-fitting H_0 by -0.6 h/km/Mpc with respect to massless case

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

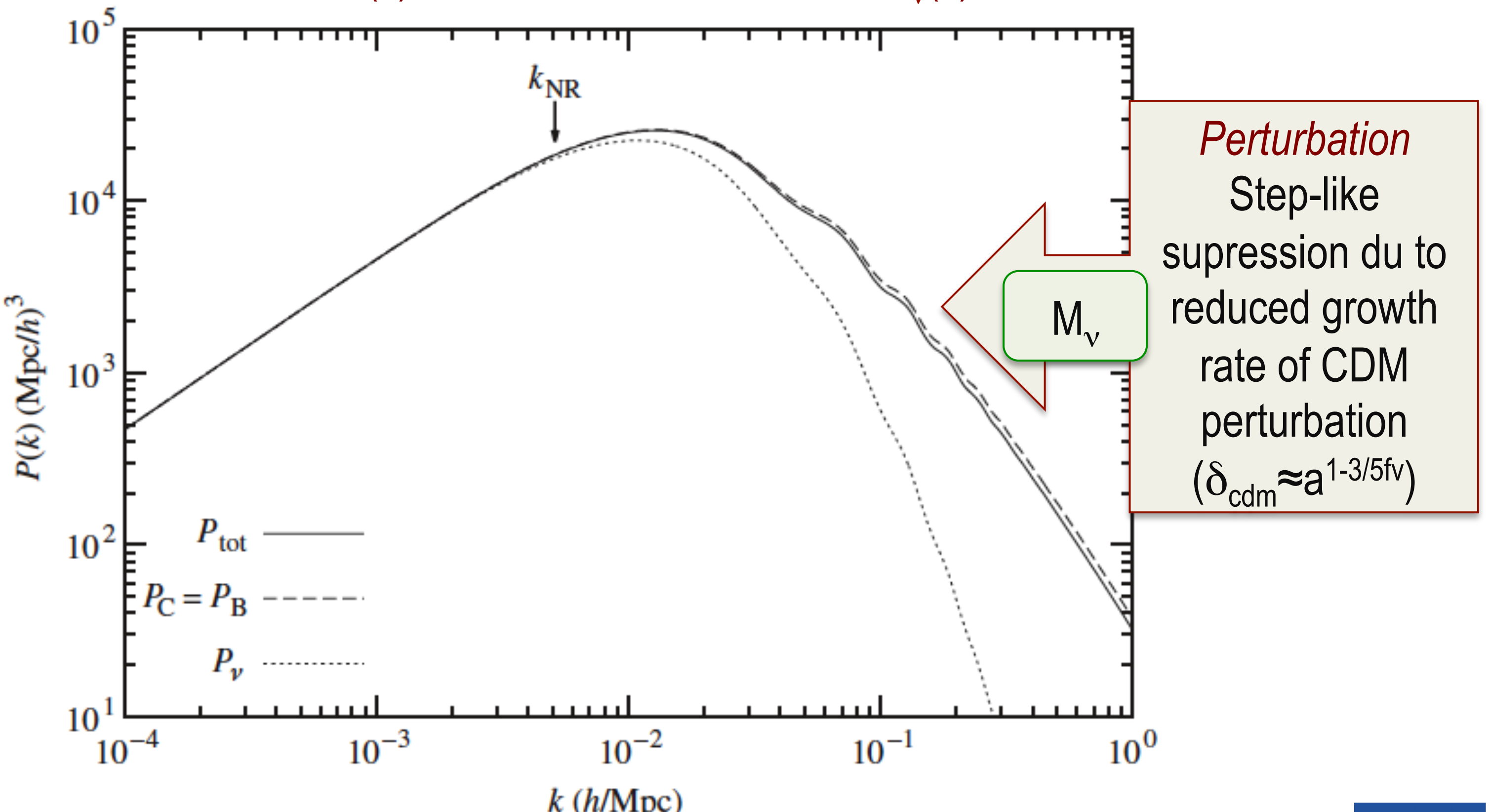
CERN

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 $P_\nu(k)$:



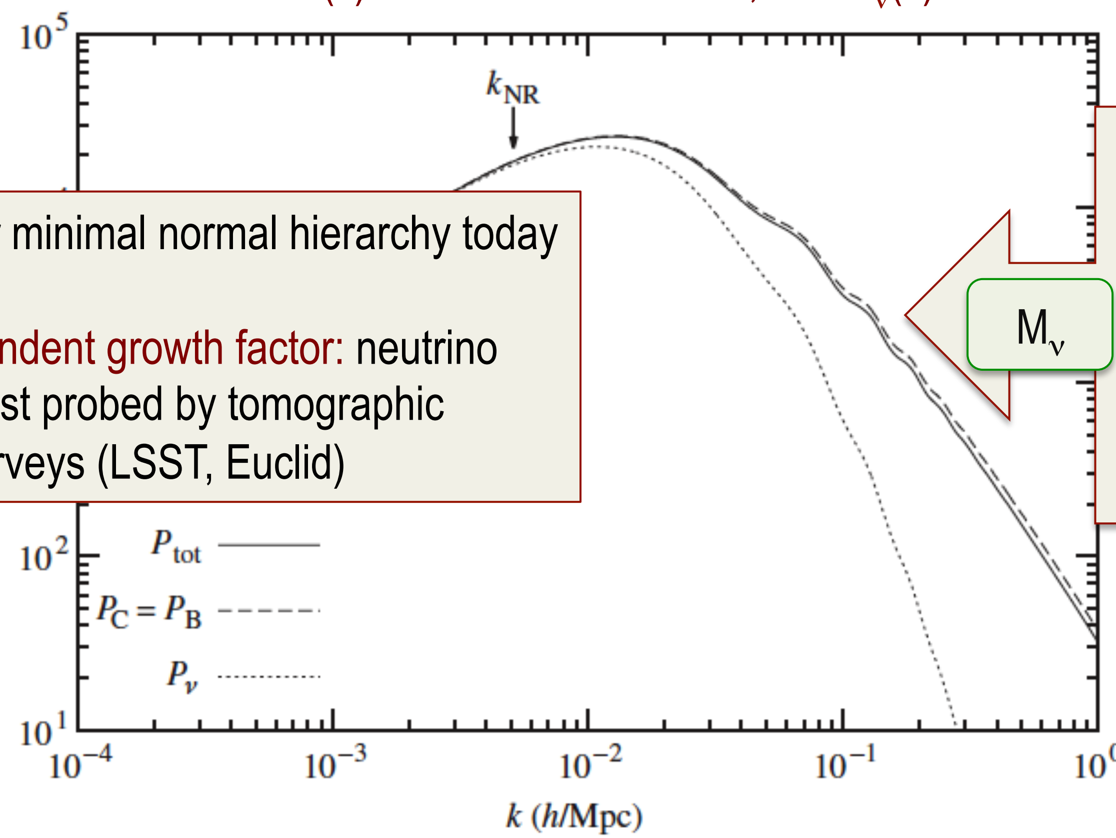
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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_ν(k):



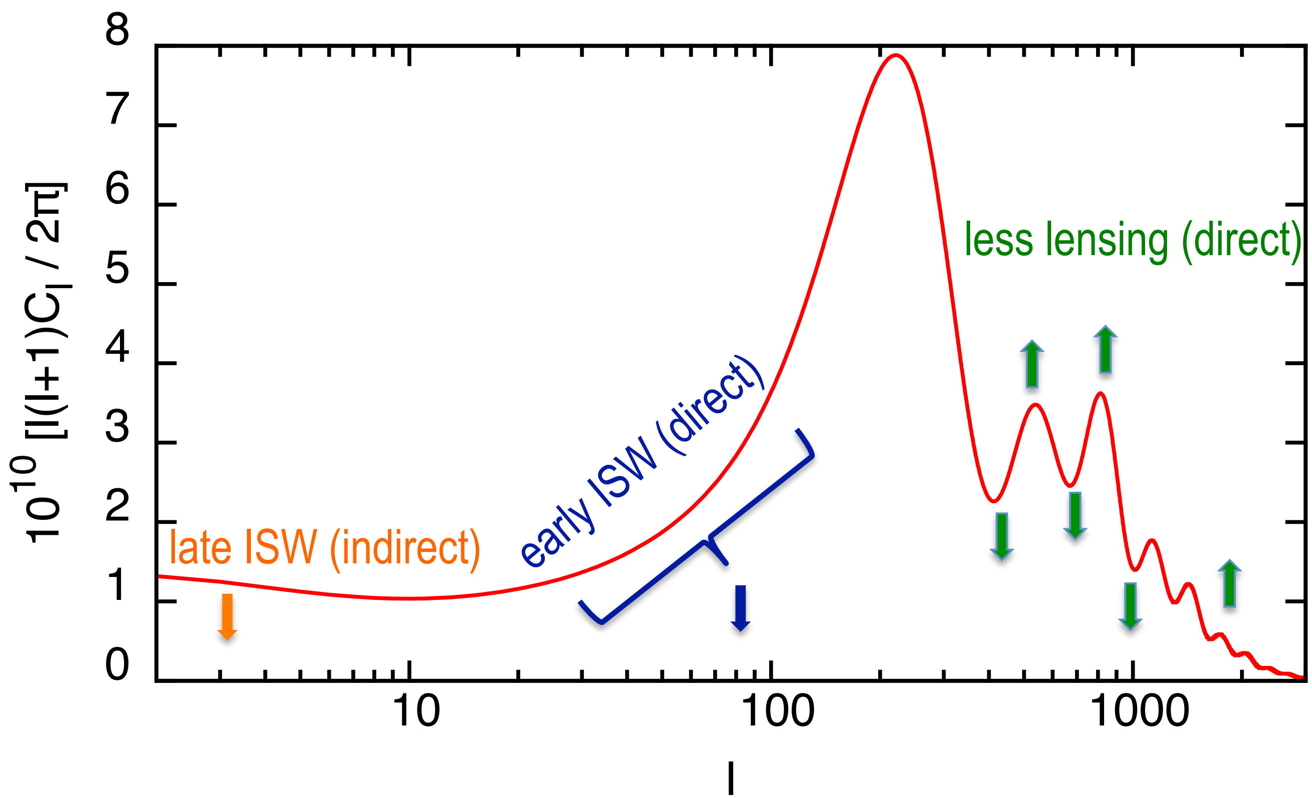
At least 5% for minimal normal hierarchy today

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
($\delta_{cdm} \approx a^{1-3/5fv}$)

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: $\boxed{M_\nu < 0.66\ \mathrm{eV}}$ (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

Current constraints

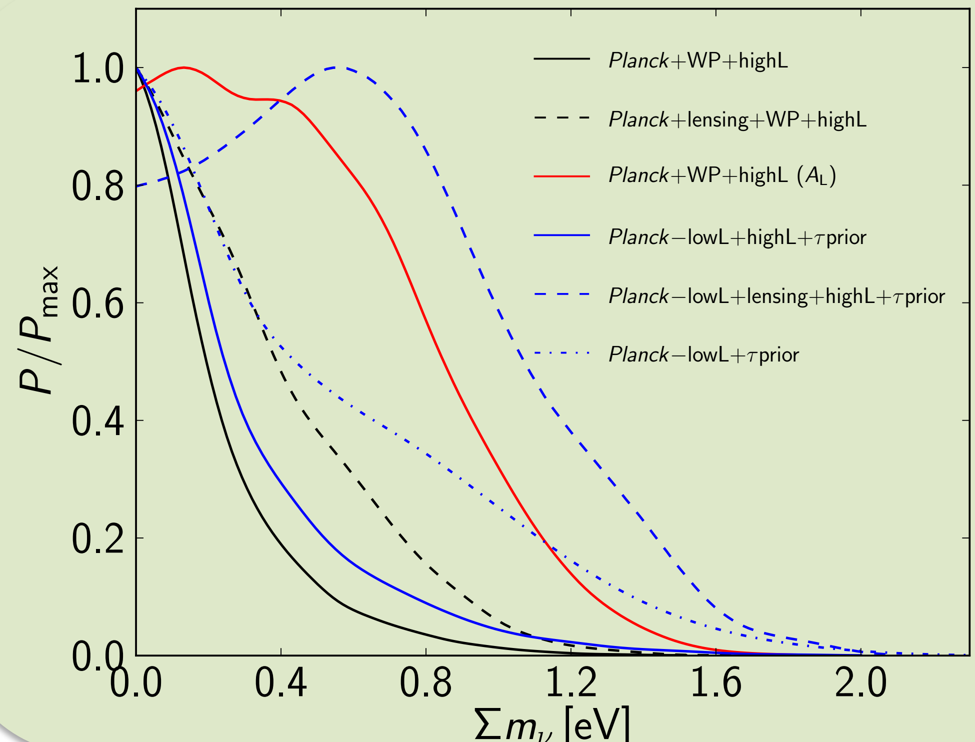
- Planck+WP alone: M_ν < 0.66 eV (twice better than WMAP) from non-observation of eISW depletion + strong smoothing of the peaks (actually more lensing than in LCDM preferred…)
- adding H0: M_ν < 0.18 eV
- adding BAO: $\boxed{M_\nu < 0.23 \text{ eV}}$

95%CL

- but lensing extra[illegible]ompatible with large value
- SZ cluster count prefers non-zero value
- CFHTLens also prefers non-zero value

Current constraints

- Planck+WP alone: M_ν < 0.66 eV (twice better than WMAP) from non-observation of eISW depletion + strong smoothing of the peaks (actually more lensing than in ΛCDM preferred…)
- adding H0: M_ν < 0.18 eV
- adding BAO: M_ν < 0.23 eV
- but lensing extraction compatible with larger value…
- CFHTLens also prefers non-zero valu



Current constraints

- Planck+WP alone: M_ν < 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_ν < 0.18 eV
- 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 prefers non-zero value

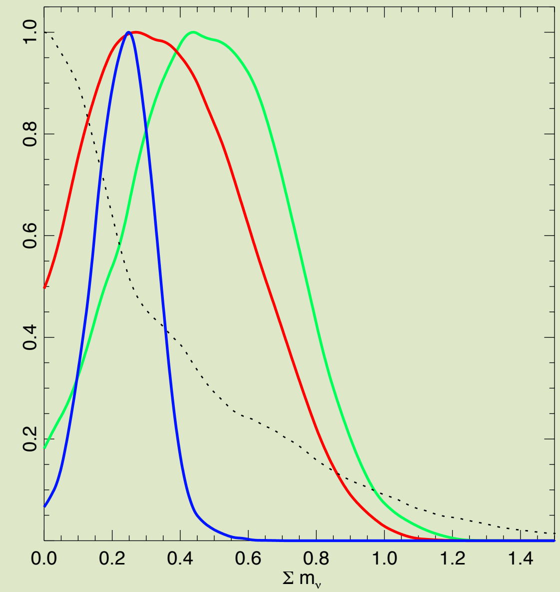


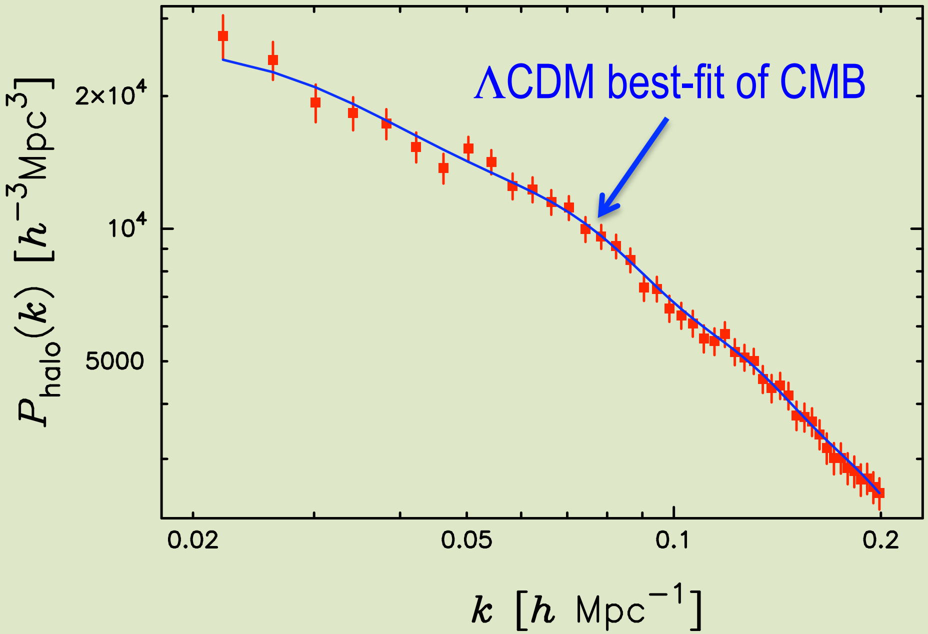
Fig. 12. Cosmological constraints when including neutrino masses $\sum m_\nu$ from: *Planck* CMB data alone (black dotted line); *Planck* CMB + SZ with $1-b$ in [0.7, 1] (red); *Planck* CMB + SZ + BAO with $1-b$ in [0.7, 1] (blue); and *Planck* CMB + SZ with $1-b = 0.8$ (green).

Current constraints

- Planck+WP alone: M_ν < 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_ν < 0.18 eV
- 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

Current constraints

Most probably issue with systematics…

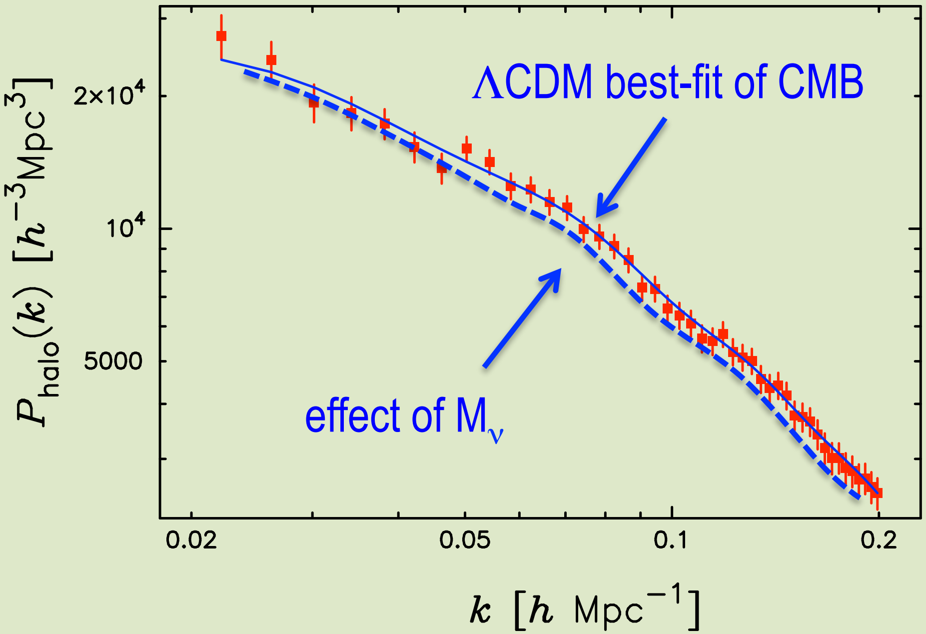


ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

CERN

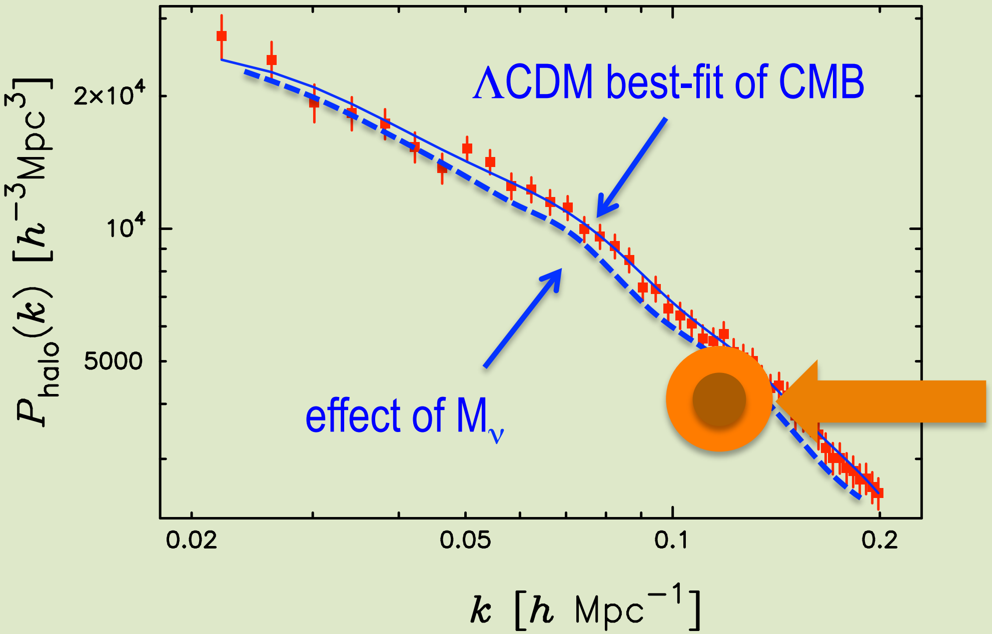
Current constraints

Most probably issue with systematics…



Current constraints

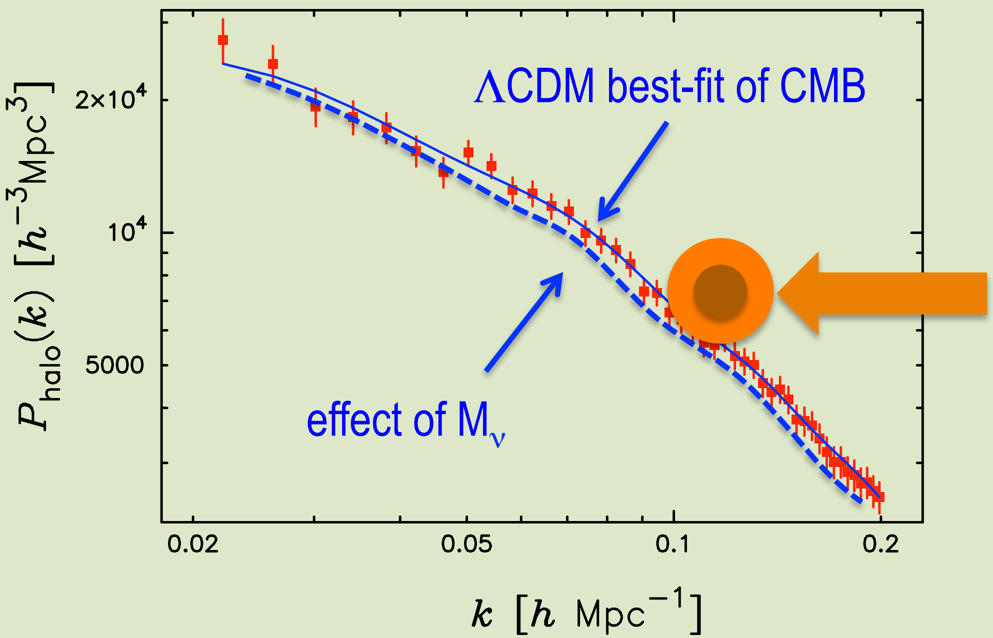
Most probably issue with systematics…



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

Current constraints

Most probably issue with systematics…

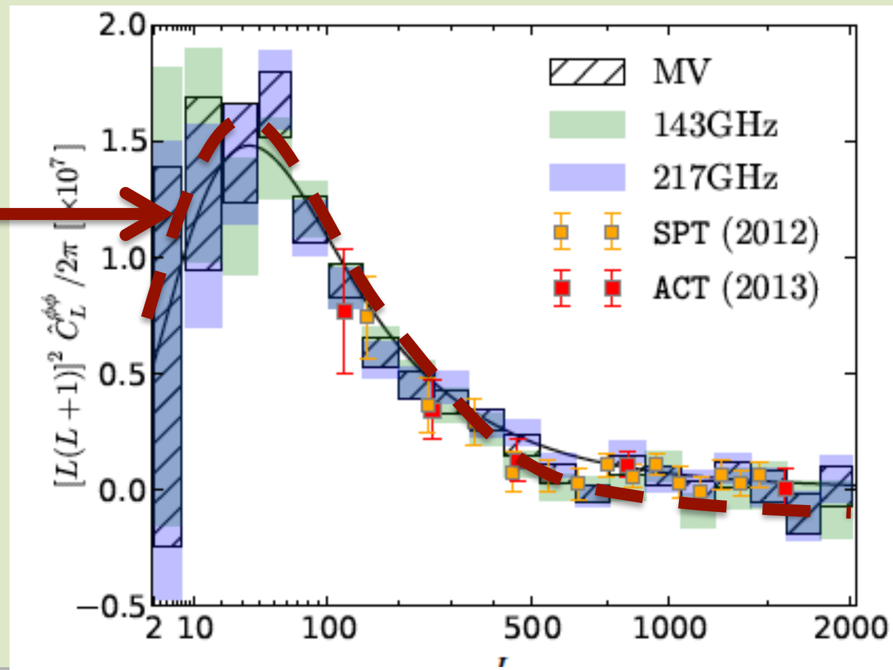


Any experiment seeing high amplitude disfavors high neutrino mass (SDSS Ly-α of 2006)

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_ν ~ 0.3 eV

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

then maybe M_ν ~ 0.06 – 0.17 eV

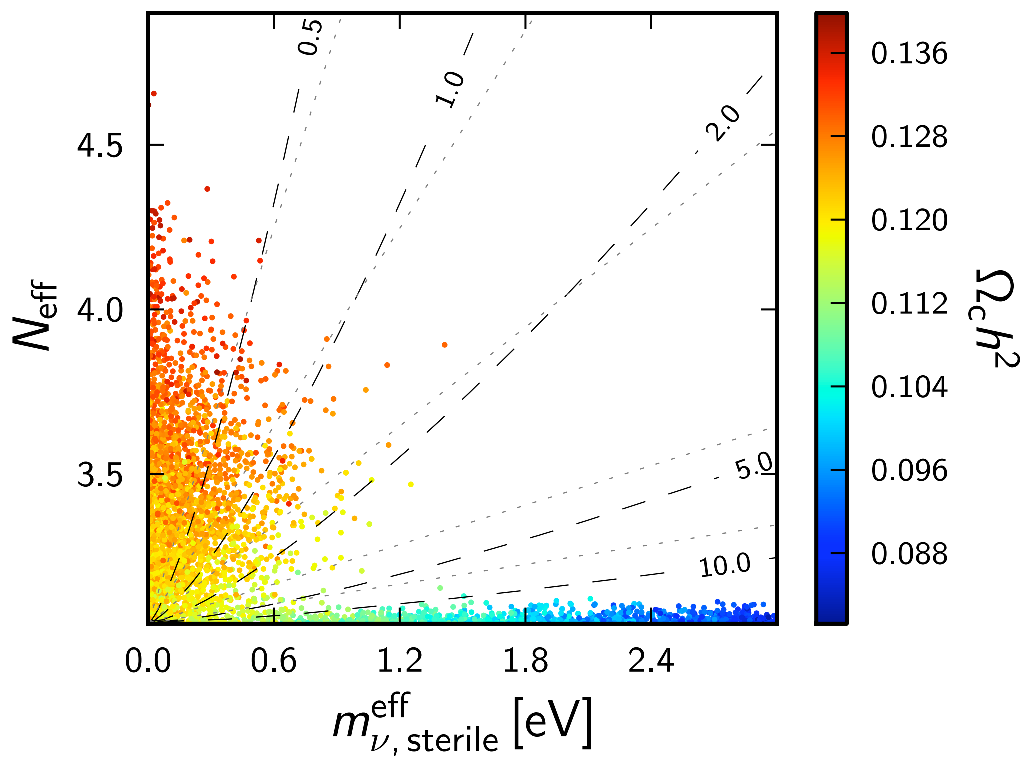
We will know at some point!

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

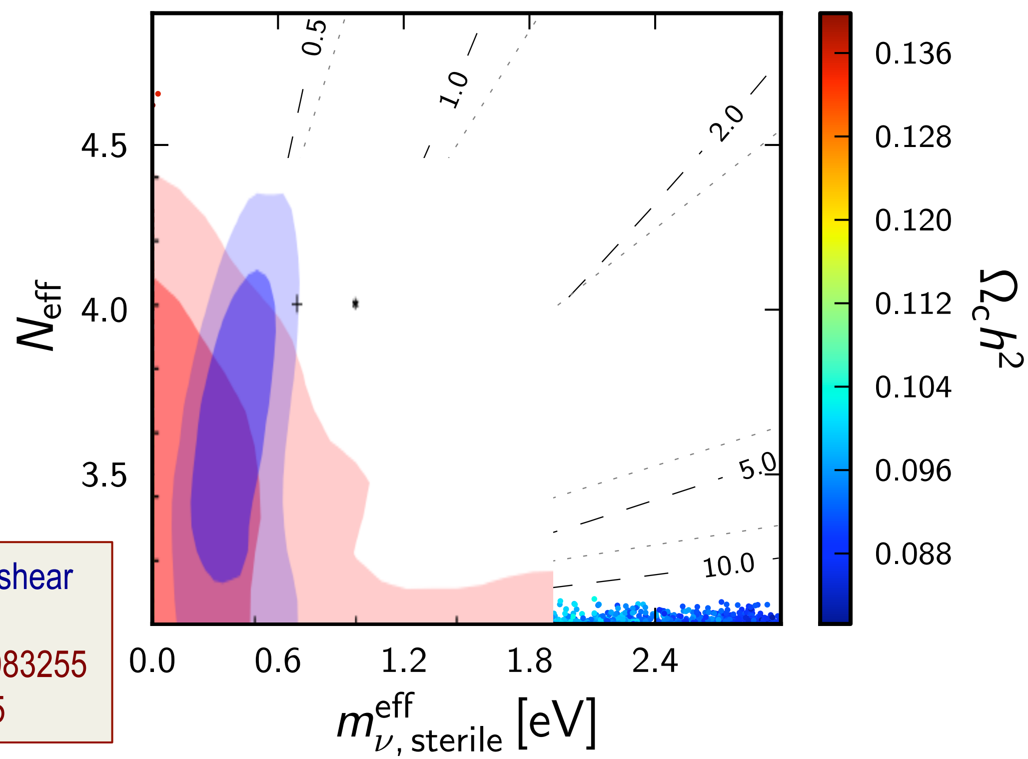


Sterile neutrino density today $\omega_{\nu s}$

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

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

Total neutrino density in early universe



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