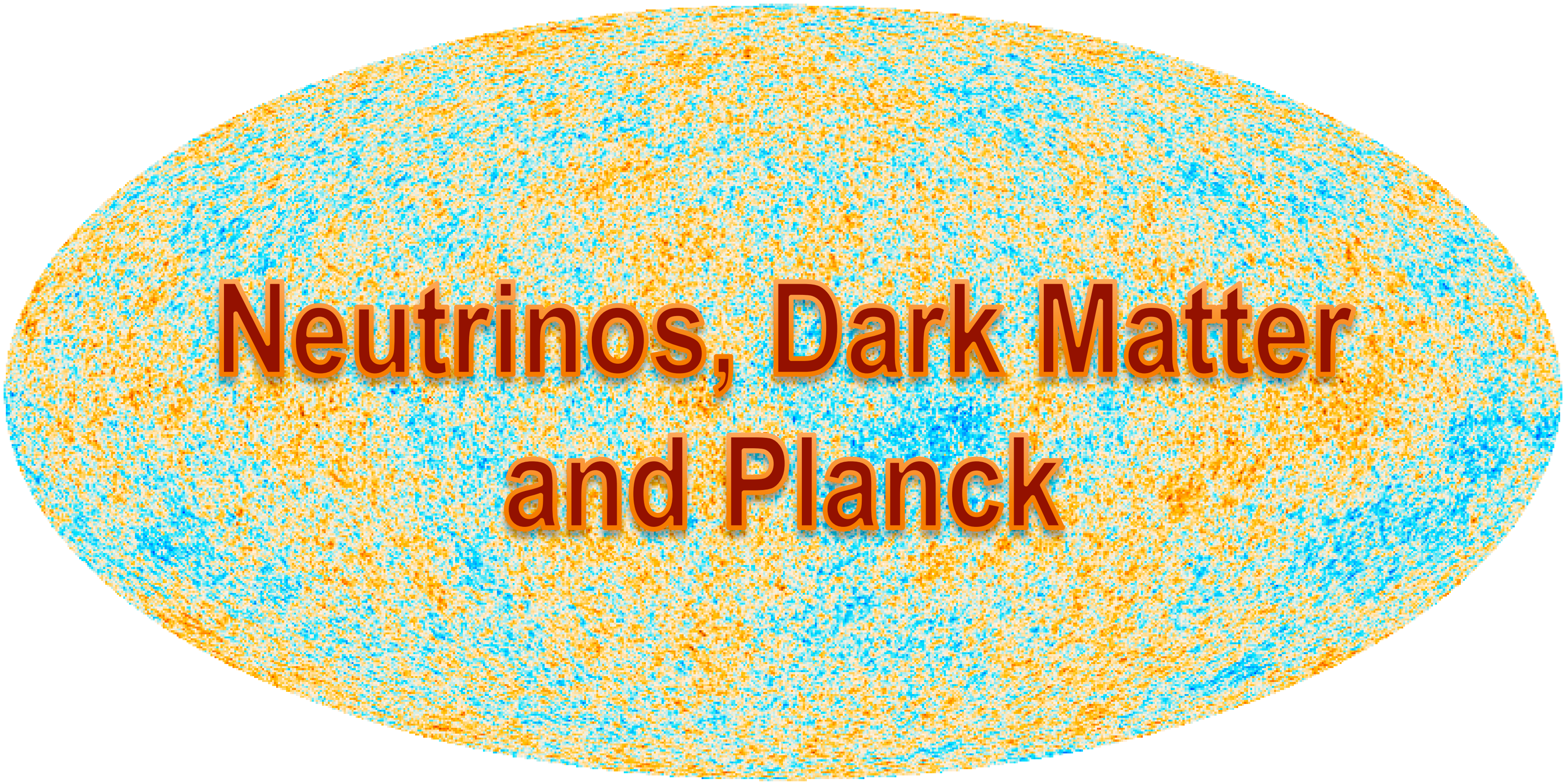

Neutrinos, Dark Matter and Planck

Planck 2014, Paris, 26.05.2014

Julien Lesgourgues (EPFL, CERN, LAPTh)

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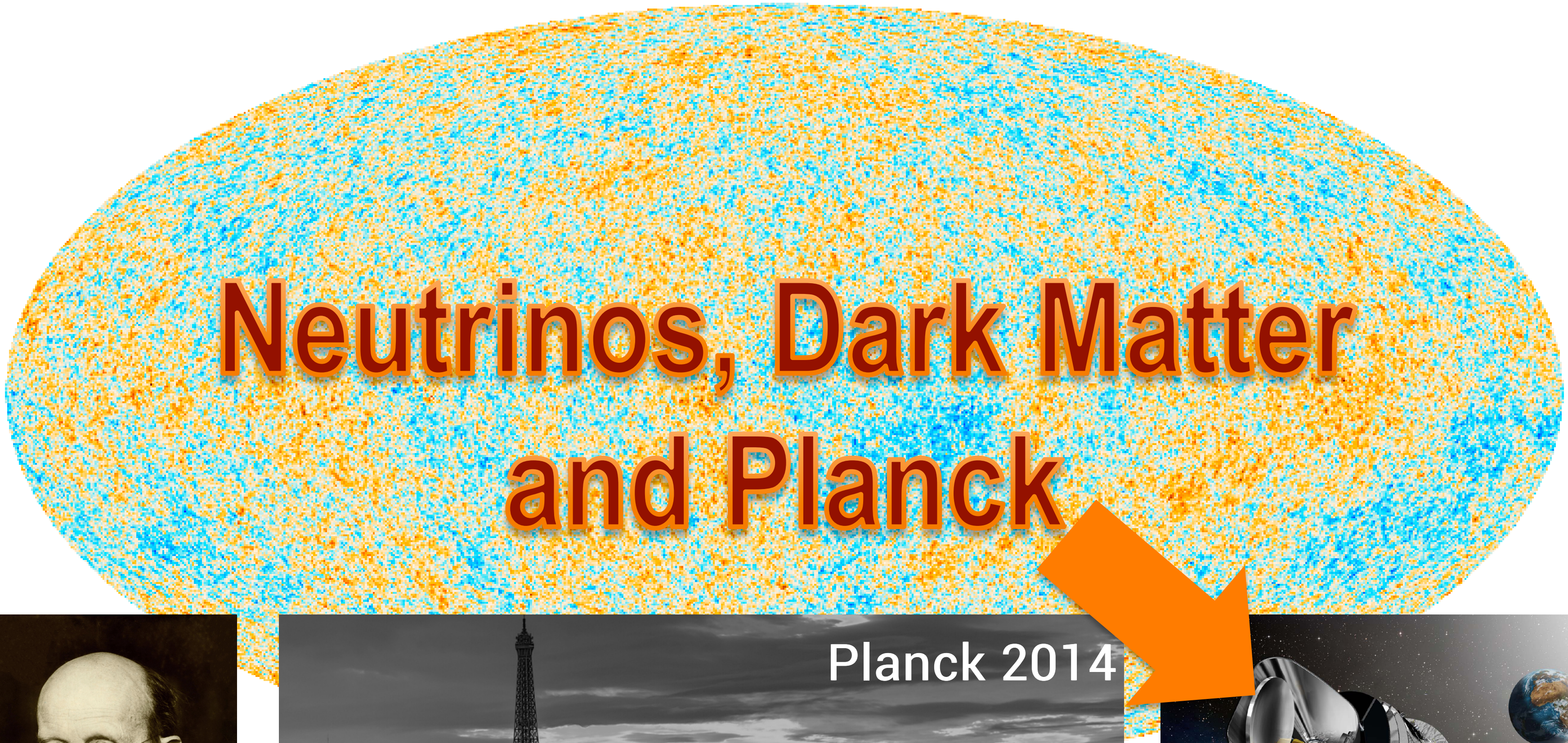
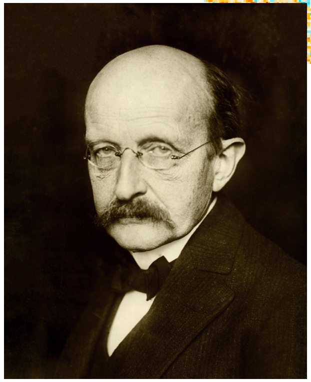
Neutrinos, Dark Matter and Planck





~ 1 year after 1st Planck release and ~ 6 months before 2nd Planck release…

What can we say on relic particles in the universe?

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ν

- Absolute neutrino mass scale
- Neutrino density, other relics
- Neutrino-antineutrino asymmetry

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- Absolute neutrino mass scale
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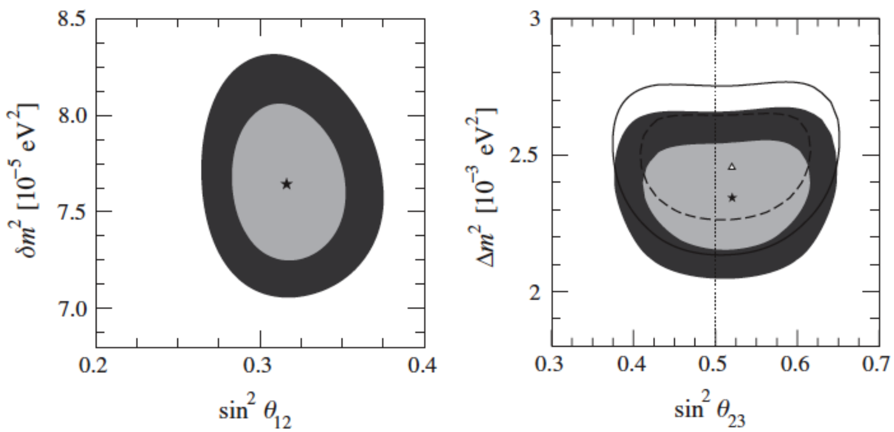
DM

- DM existence
- DM "coldness"
- DM annihilation/decay rate
- DM scattering cross-section with other relics

Absolute neutrino mass scale & CMB

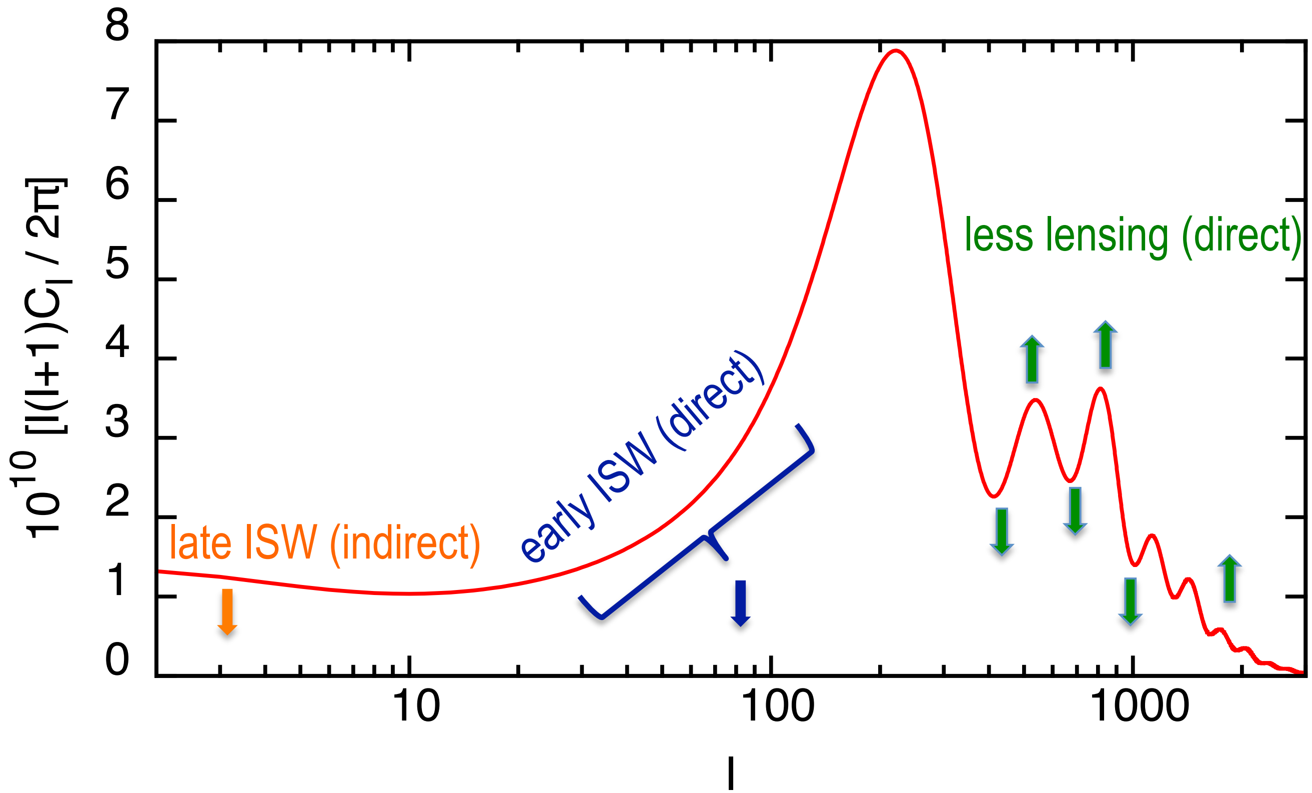
- main unknown parameter to complete our understanding of active neutrinos!
- $M_\nu = \Sigma m_\nu > 0.06$ eV (NH) or 0.1 eV (IH)



- Neutrinos contribute to radiation at early time and non-relativistic matter at late time: $\omega_\nu = M_\nu / 94$eV.
- If $m_\nu < 0.6$ eV, neutrinos are relativistic at decoupling, still CMB/LSS effects

Absolute neutrino mass scale & CMB

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

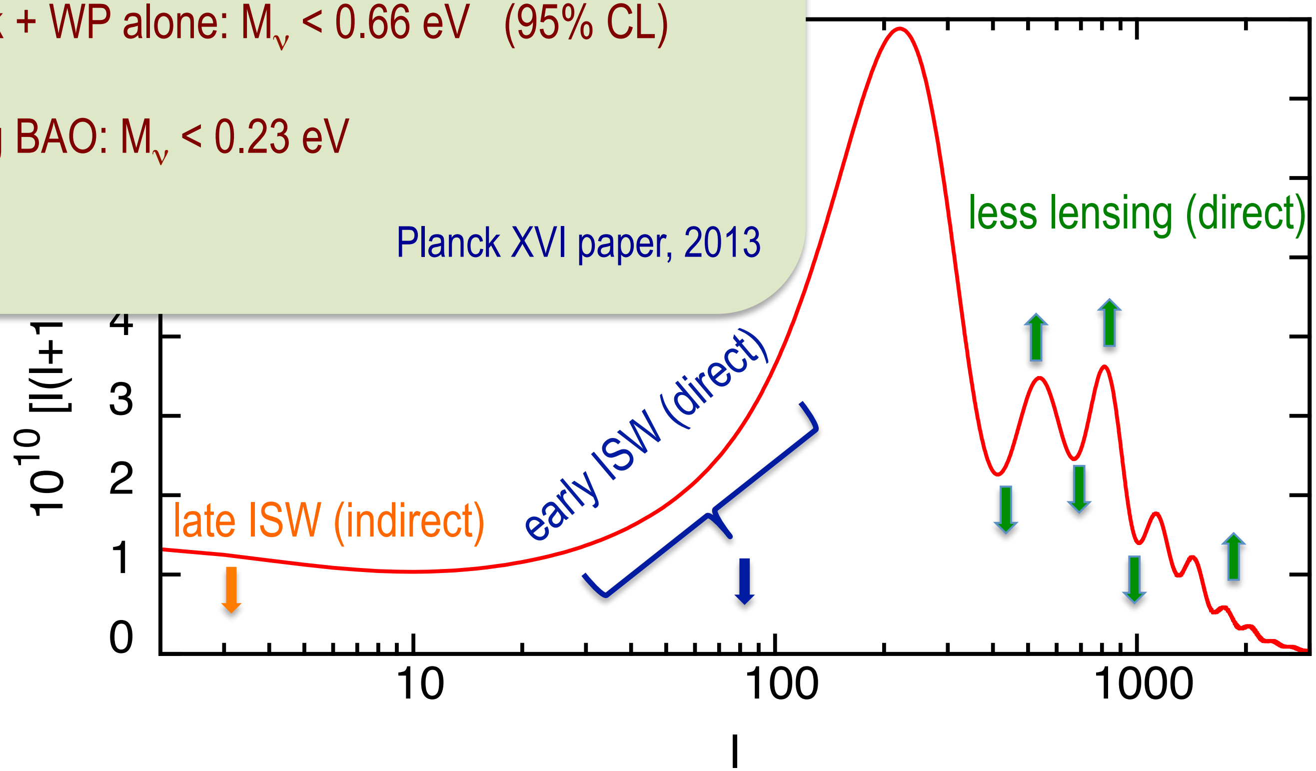


Absolute neutrino mass scale & CMB

- Not observed by Planck (within error bars)!
- Planck + WP alone: $M_\nu < 0.66$ eV   (95% CL)
- adding BAO: $M_\nu < 0.23$ eV

Planck XVI paper, 2013

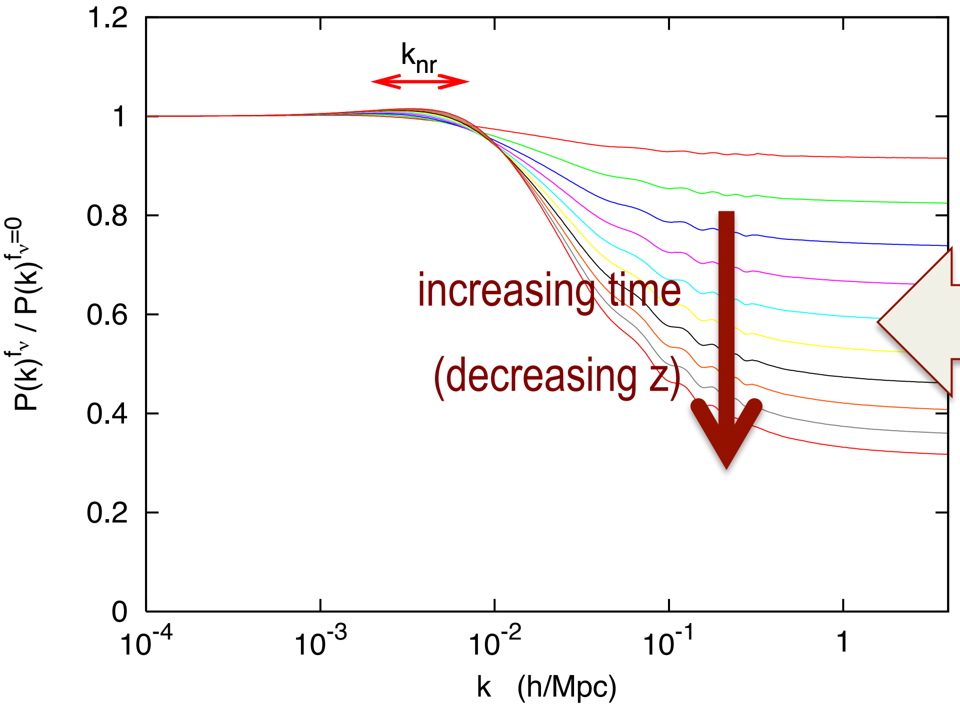
and $d_A(z_{dec})$ invariant   (fixing photon, cdm and baryon



Absolute neutrino mass scale & LSS

- small scales: neutrino free-streaming (large velocity dispersion)
- shifts balance between gravity and expansion, reduced growth rate of baryon+DM perturbations ($\delta_{cdm} \approx a^{1-3/5f\nu}$)

P(k) massive / massless, at several redshifts



Time-dependent step-like suppression

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Future: measurements of P(k,z) over many scales and redshifts (tomography)

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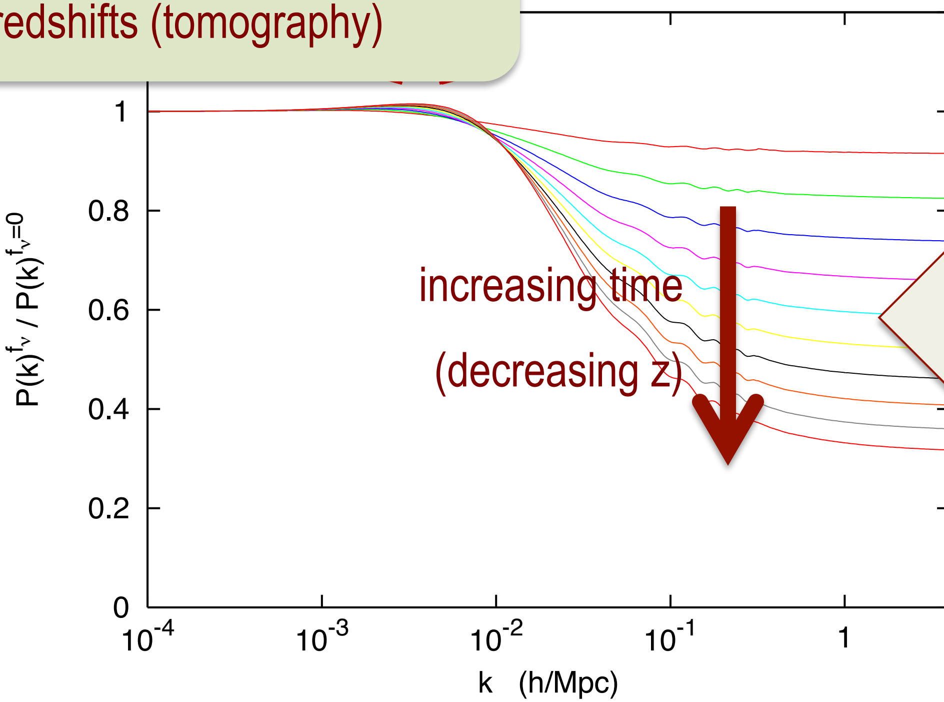

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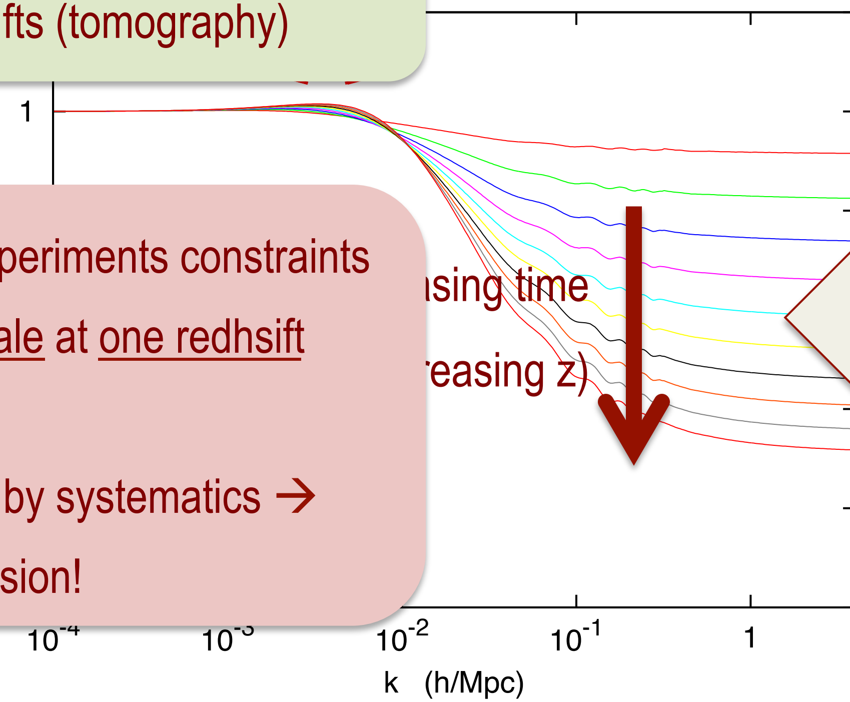


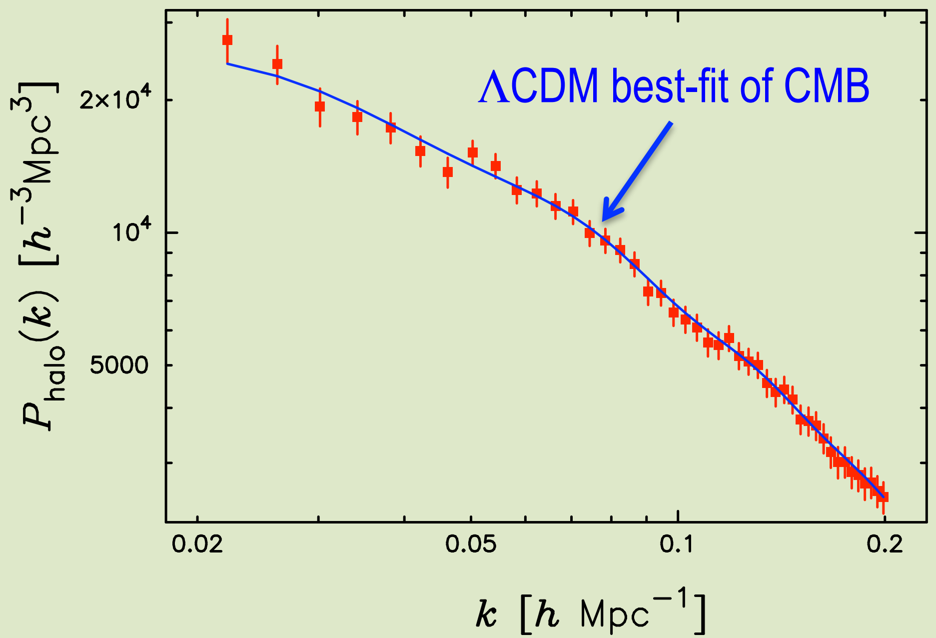
Present: each LSS experiments constraints essentially <u>one scale</u> at <u>one redhsift</u>

Results dominated by systematics → confusion!

Time-dependent step-like suppression

Current constraints

Most probably issue with systematics…



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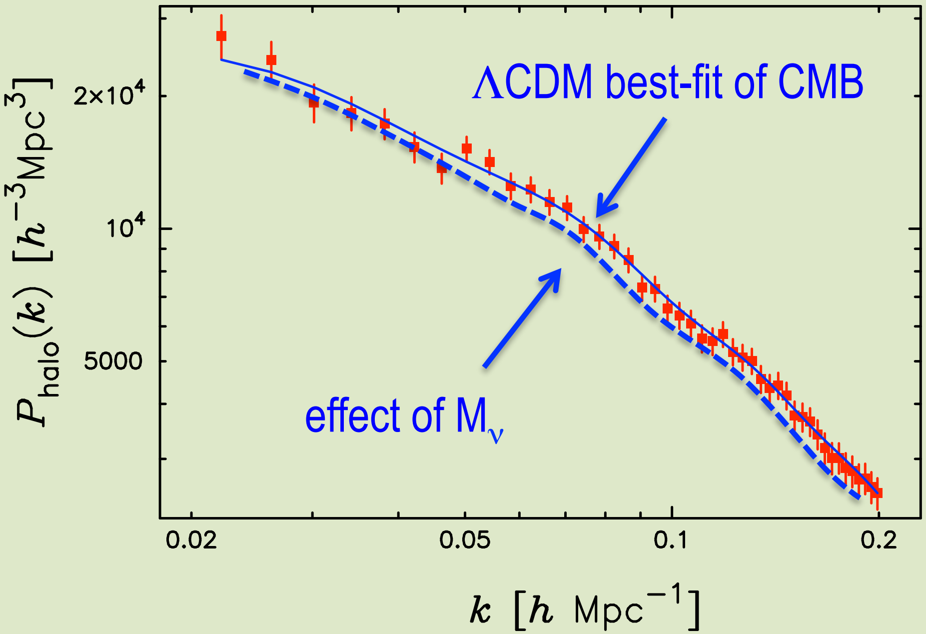

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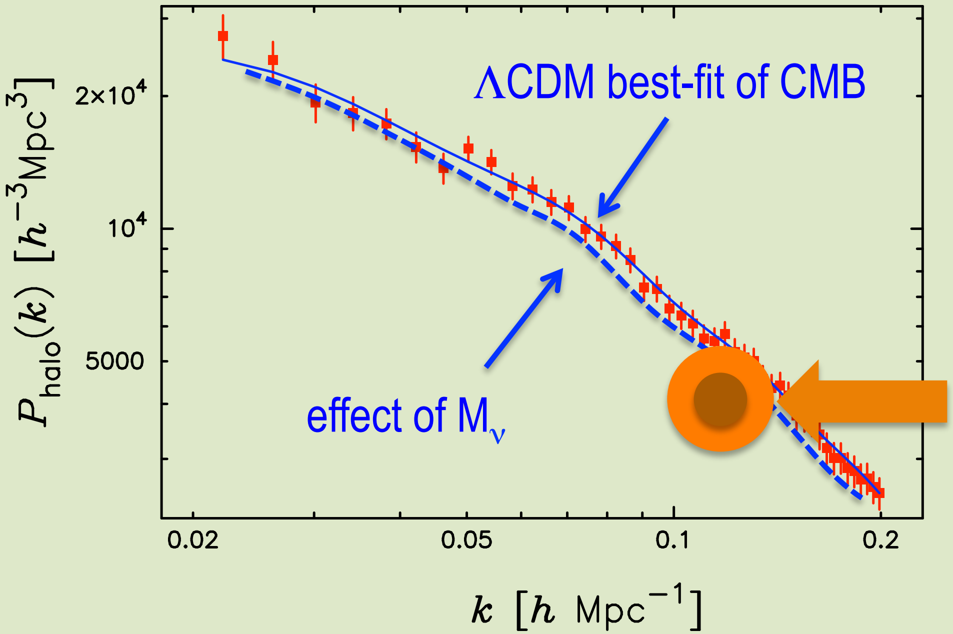


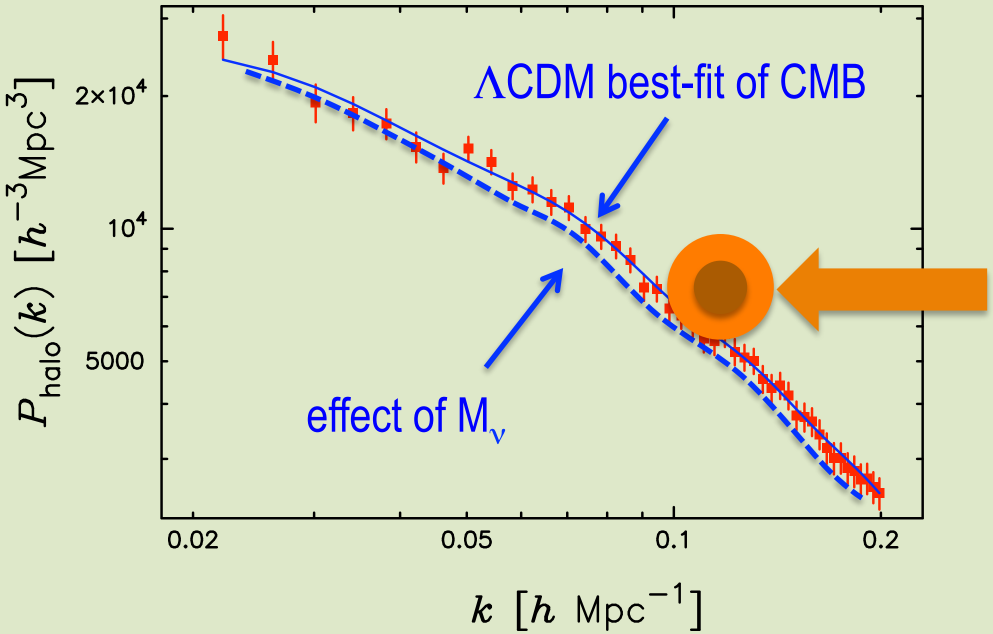
Any experiment seeing low amplitude favors high neutrino mass but conflicts CMB TT

- CMB lensing,
- (SZ) clusters,
- CFHTLens weak lensing,
- BOSS red.-space dist.

Claims for M_ν~0.3eV – 0.8eV

Current constraints

Most probably issue with systematics…



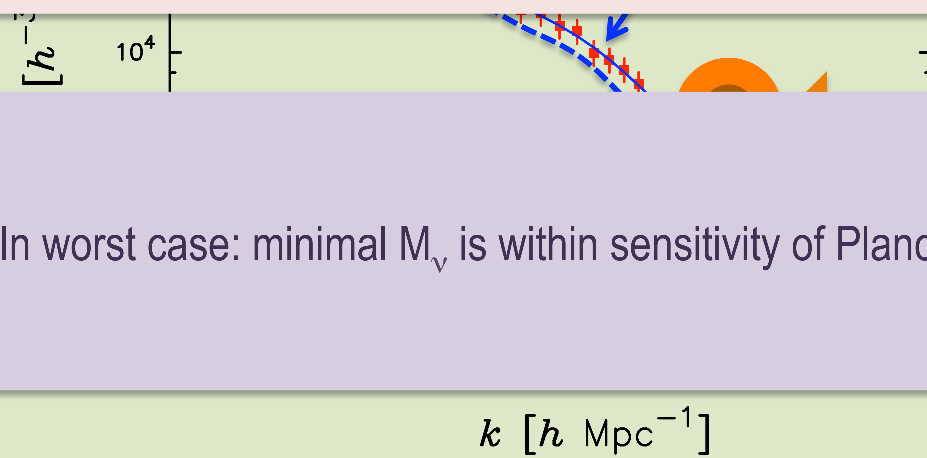
Any experiment seeing high amplitude disfavors high neutrino mass:

- SDSS Ly-α of 2006

Current constraints

Need better data!

Full Planck, full BOSS, eBOSS, DES, LSST, Euclid, Core, 21cm…



Any experiment seeing
high amplitude disfavors
mass
2006)

In worst case: minimal M_ν is within sensitivity of Planck+Euclid

Similar comments and conclusions for relic radiation density…

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- N_{eff} is a parameter for the relativistic density in general: $\omega_r = [1+0.227N_{eff}]\ \omega_\gamma$
- Could be related to non-standard neutrino decoupling (low-T reheating), neutrino chemical potential, any other light relic, … even dark radiation (e.g. Slava's)

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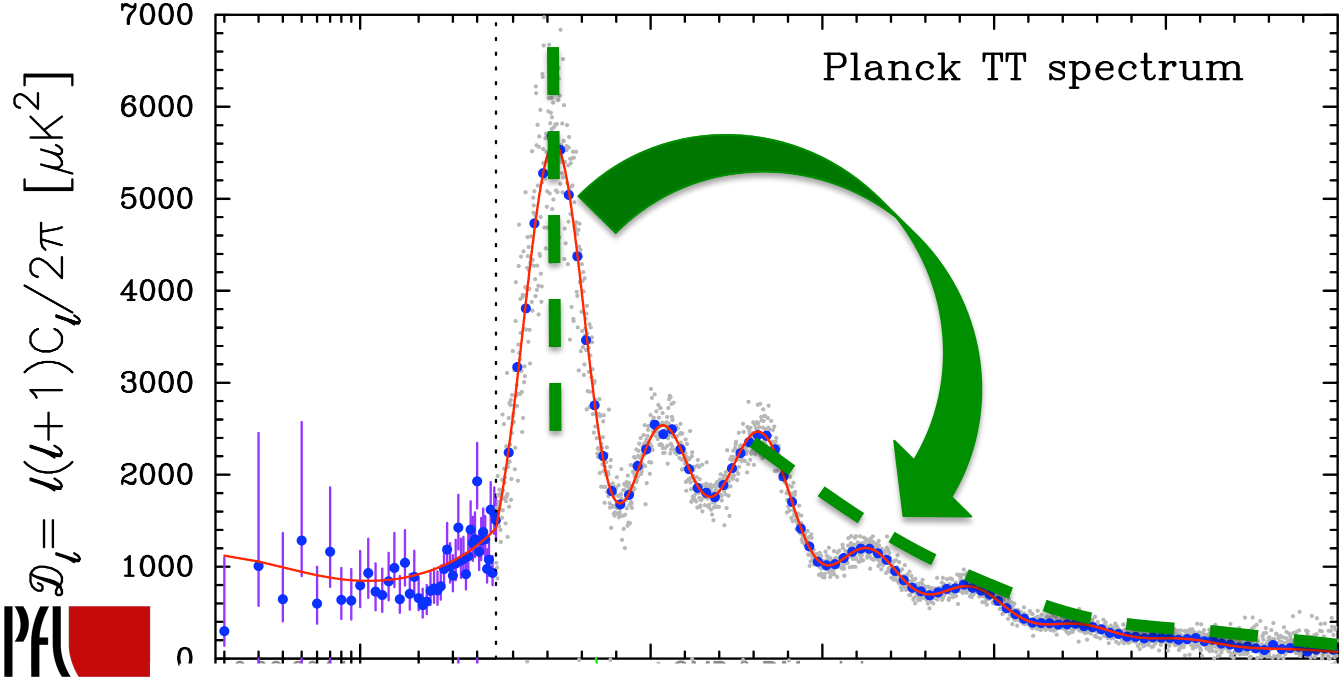
- Probed by damping scale w.r.t peak scale



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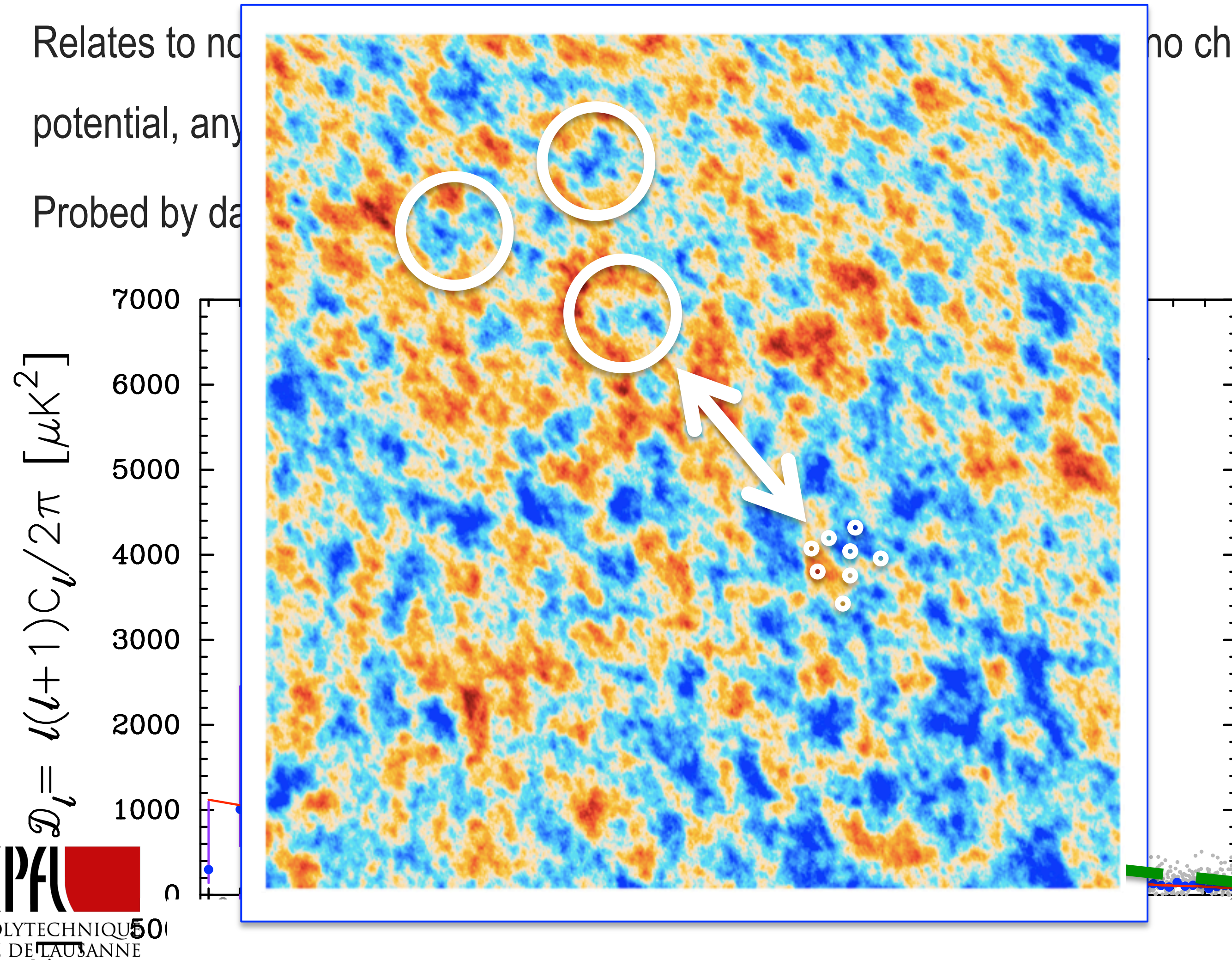
Similar comments and conclusions for relic radiation density…

- N_{eff} is a parameter for the relativistic density in general: $\omega_r = [1+0.227N_{eff}]\,\omega_\gamma$
- Relates to no… no chemical potential, any…
- Probed by da…



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Measuring N_{eff}

CMB alone (Planck+WP+HighL)

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

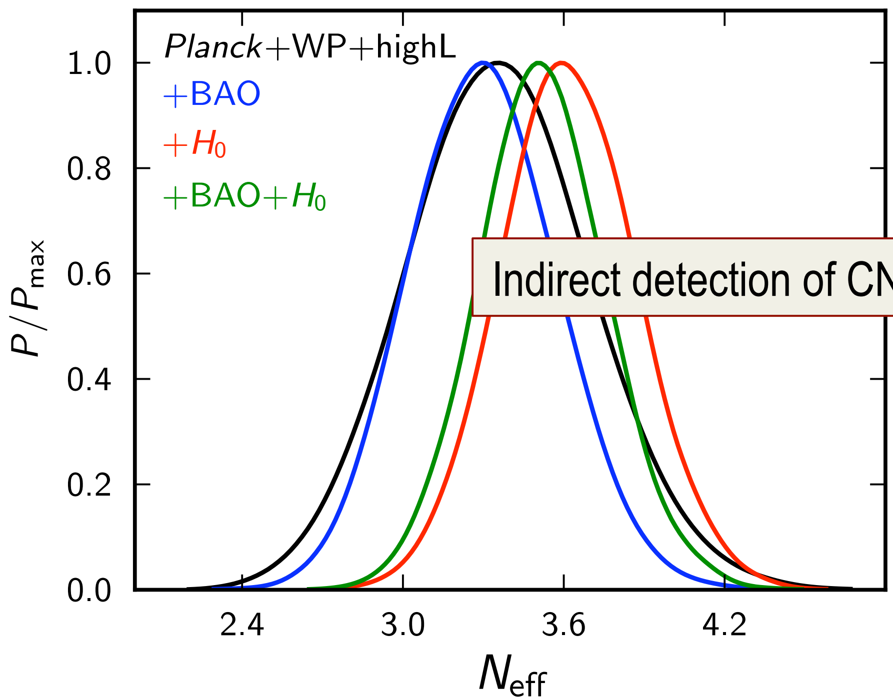
With lensing and BAO:

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

With H_0:

$N_{eff} = 3.62 \pm 0.49$ (95%CL)

Large r from BICEP2 would favor large N_{eff}… but let's wait for data at more than one frequency !



Indirect detection of CNB at 10 sigma

What if N_{eff}>3 and M_ν >0 are detected ?

- Cosmological observables sensitive to different mass splittings in that case:
- may find evidence for mass being in active neutrino sector or in extra relic sector
- Probing: light sterile neutrino scenario, thermal axion, etc.
- (mass ~ 0.3 eV, or more if non-thermalised)

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Could N_{eff}>3 be related to neutrino chemical potentials?

- best constraints from combination of BBN data with knowledge of neutrino mixing parameters
- large mixing solution with large θ_{13} (RENO, Daya-Bay)
- very small asymmetry, n_ν < 0.06 at T~10 MeV , ΔN_{eff} at most 0.04 …

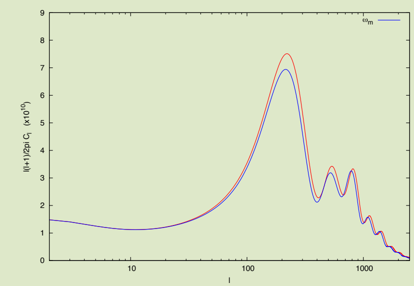
Franca et al. PRD86 023517 (2012)

Dominant Dark Matter 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;
  - …

?

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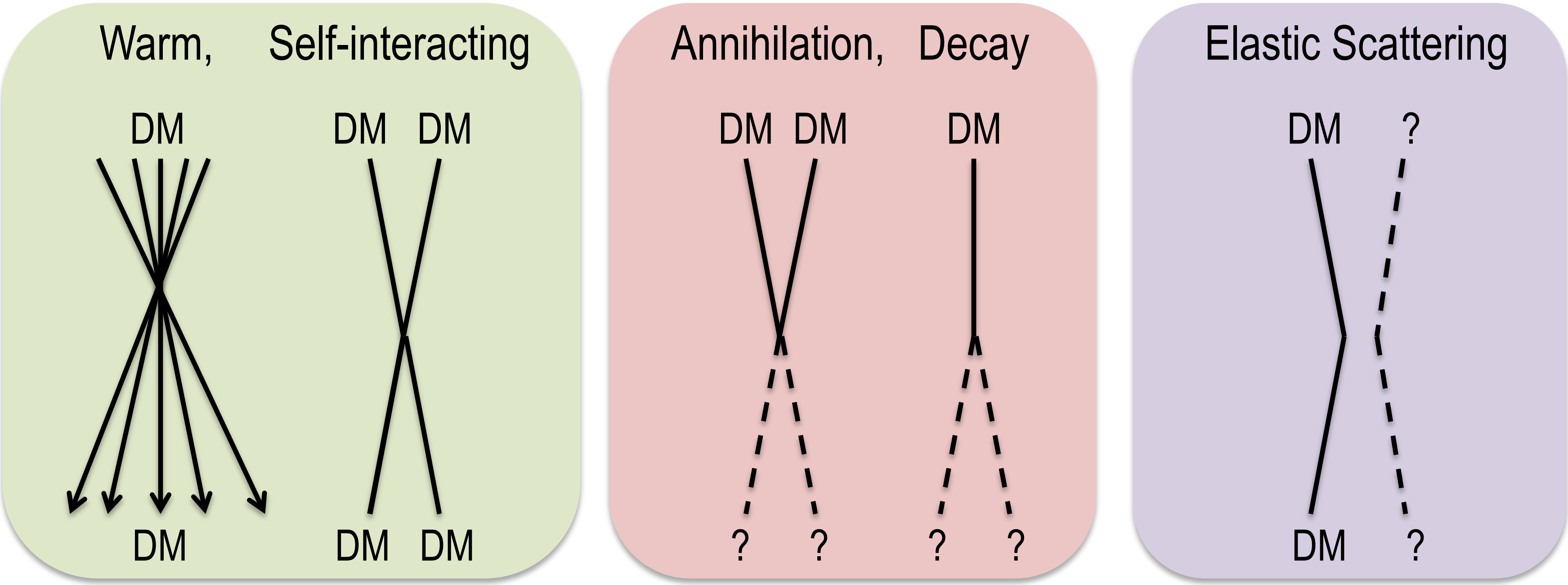
Possible properties of DM



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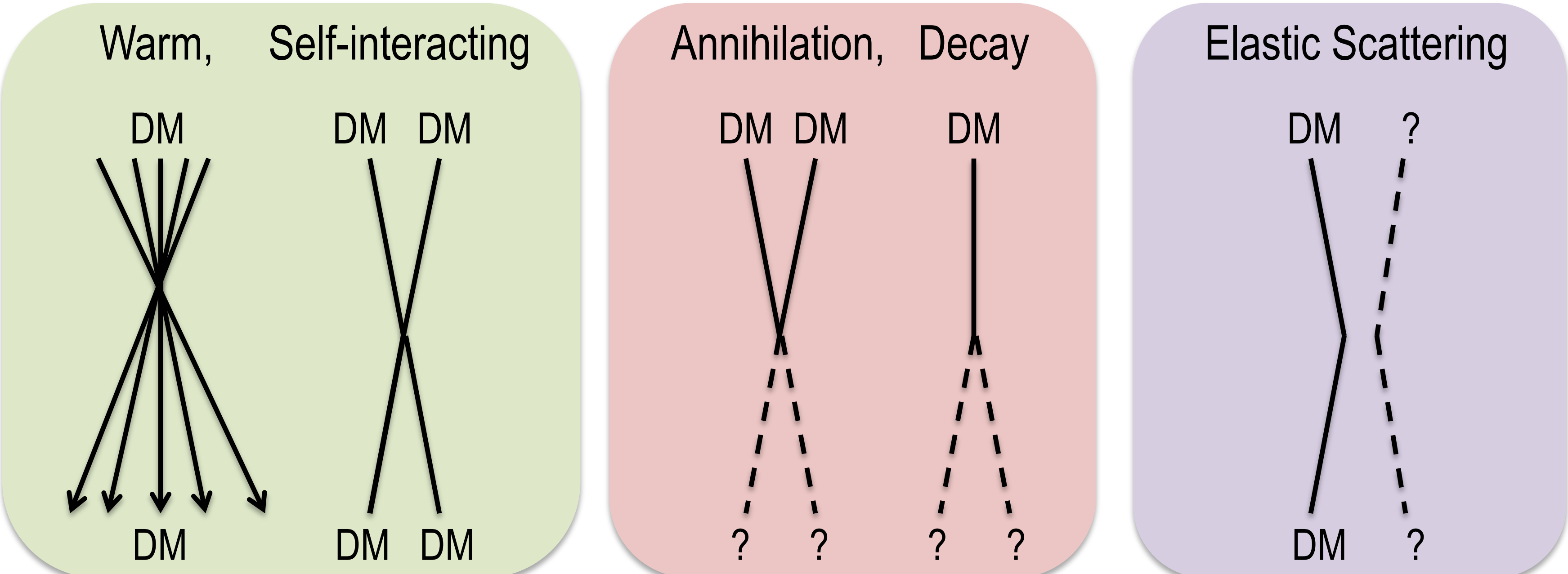
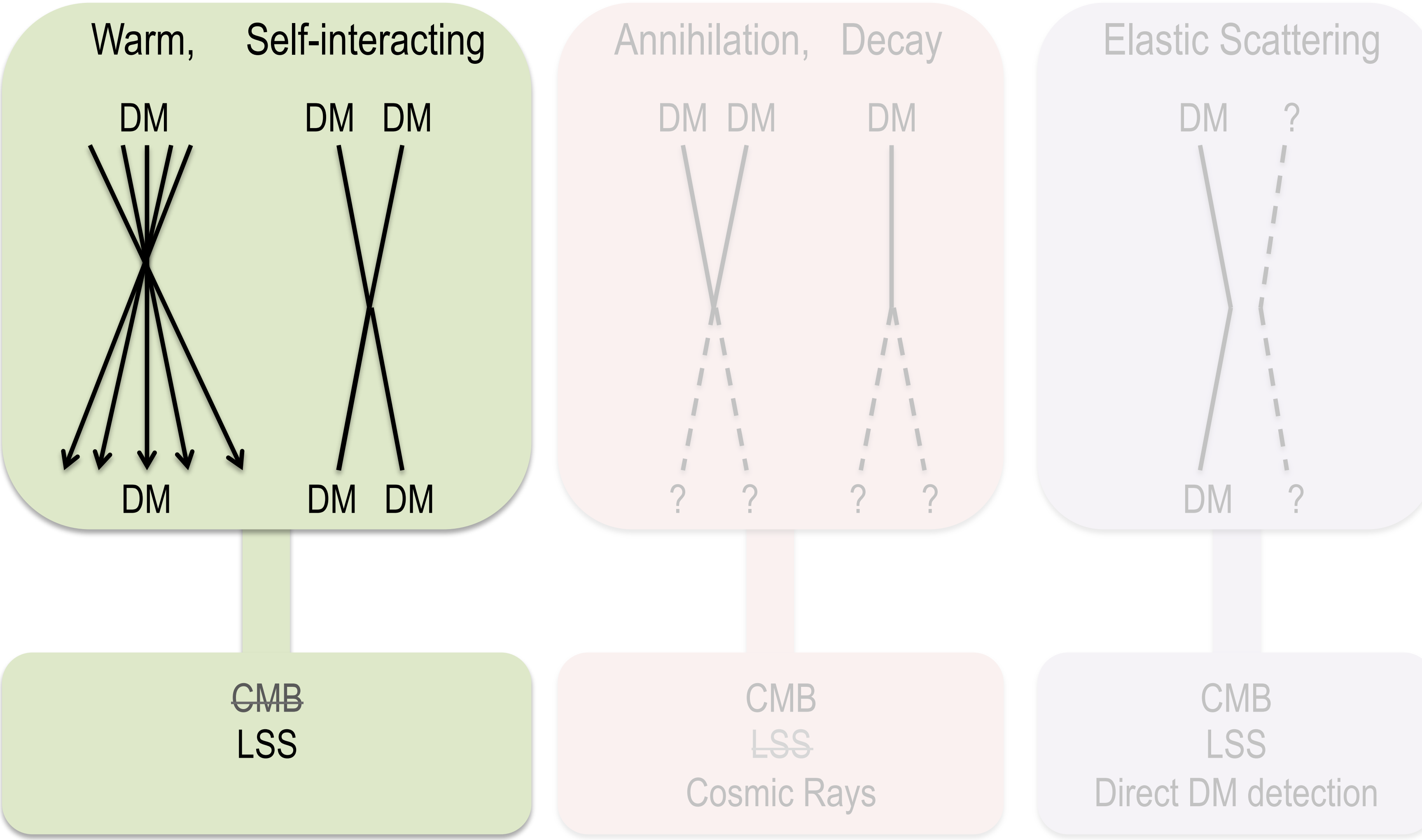


~~CMB~~
LSS

CMB
~~LSS~~
Cosmic Rays

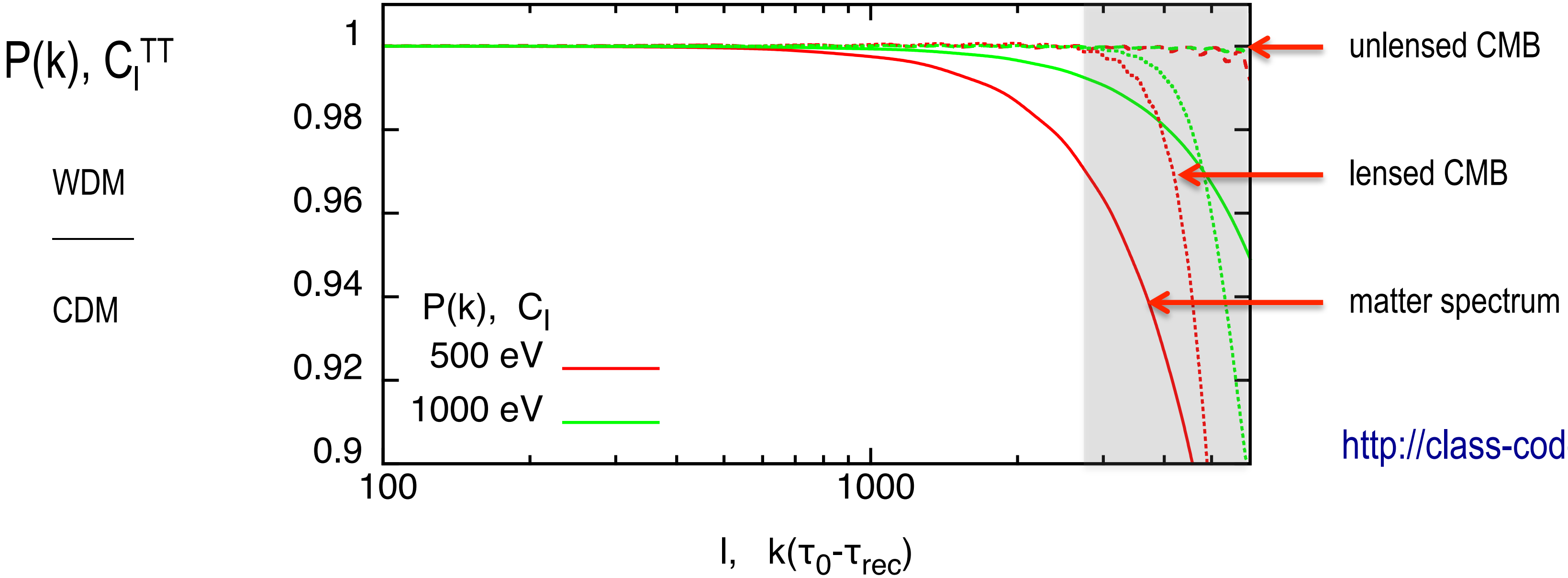
CMB
LSS
Direct DM detection

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)



http://class-code.net

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

Effective gravitational decoupling between dark matter and the CMB

Voruz et al., 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 :

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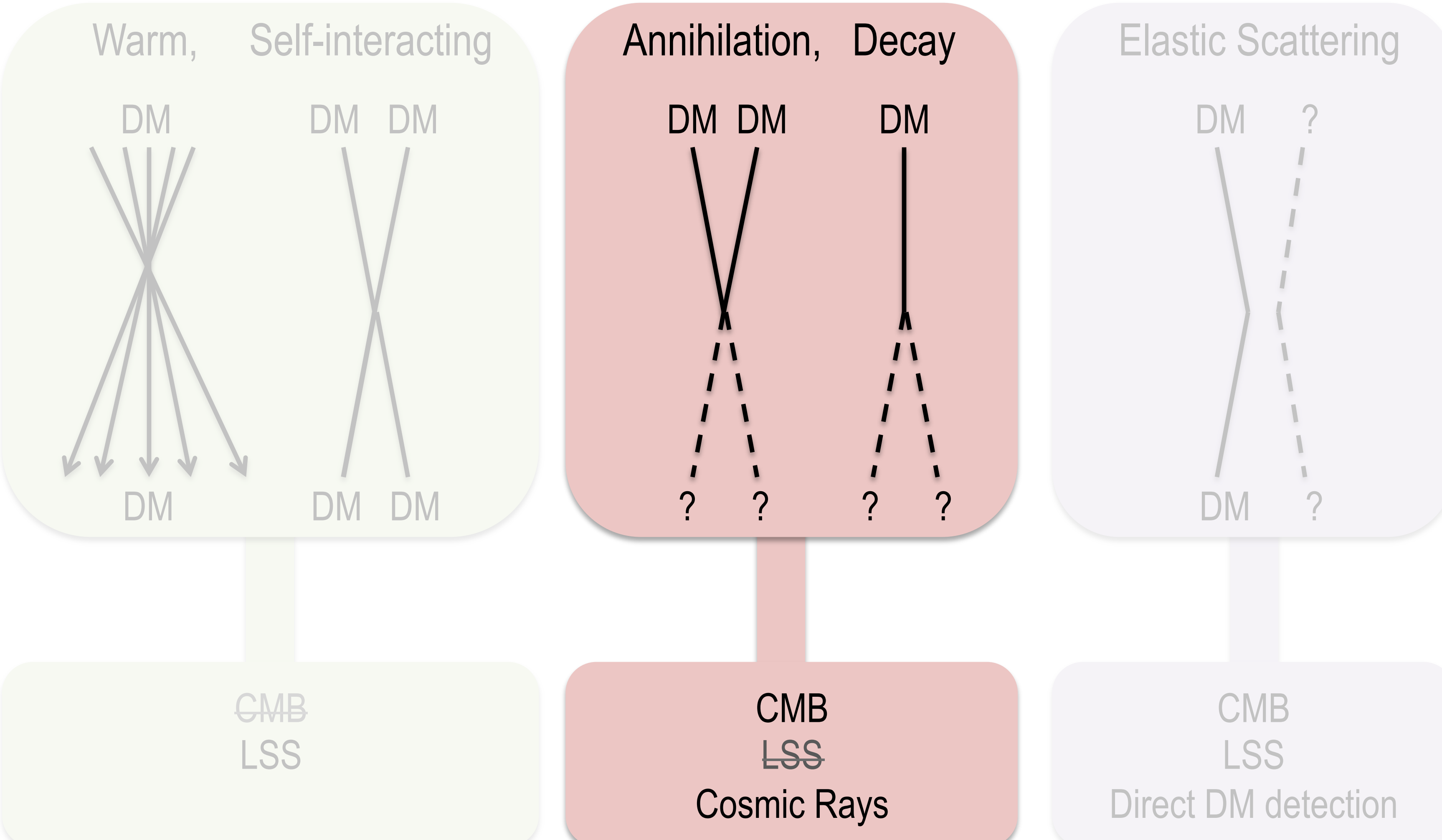
Decay in $\gamma+\nu_a$ constrains (m, θ)

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

Connection with leptogenesis! Bulbul et al. 1402.2301; Boyarsky et al. 1402.4119

Case 2: annihilating or decaying



Case 2: annihilating or decaying

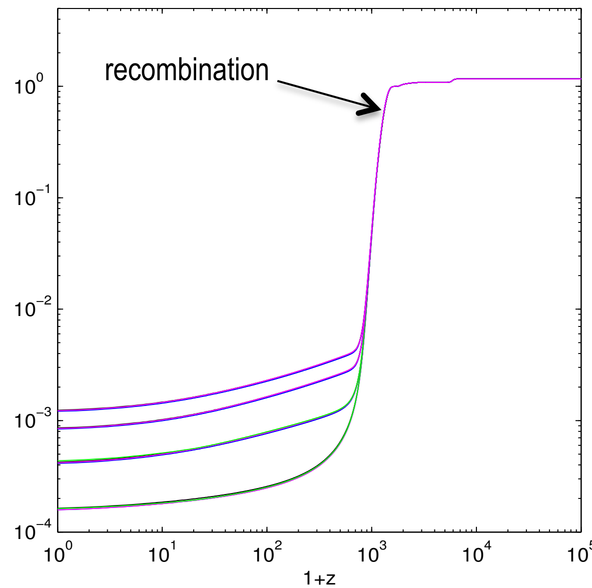
- DM → hadrons, leptons, gauge bosons → … → electrons, neutrinos, photons
  - Ionization of thermal plasma
  - Heating of thermal plasma
  - Hydrogen excitation

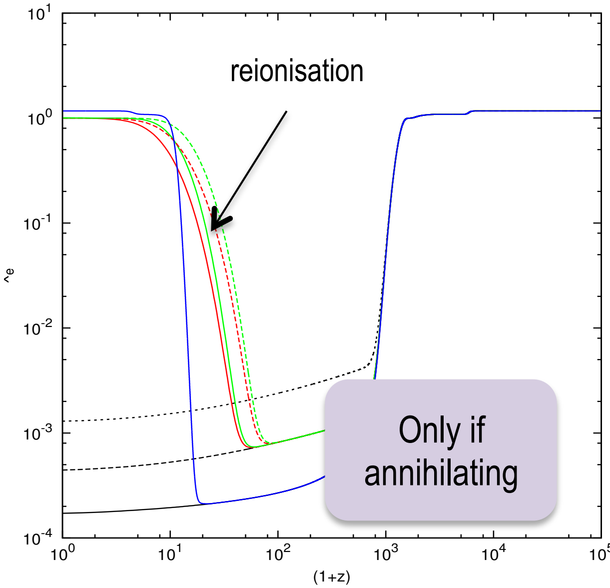
  (unless 100% in neutrinos)

- Modification of recombination and reionisation history
- Effects depends on cross-section over mass σ/m or lifetime τ , and on annihilation/ decay channel

Case 2: annihilating or decaying

ionisation fraction





1+z

1+z

http://class-code.net

Naselsky et al. 2001; Padmanabhan & Finkbeiner 2005; Mapelli et al. 2006; Zhang et al. 2006; Natarajan & Schwarz 2008; Belikov & Hooper 2009; Cirelli et al. 2009; Galli et al. 2009; Slatyer et al. 2009; Natarajan & Schwarz 2010; Galli et al. 2011; Finkbeiner et al. 2011; Hutsi et al. 2011; A. Natarajan 2012; Giesen et al. 2012; Slatyer 2013; Cline & Scott 2013; Dvorkin et l. 2013; Planck XVI 2013; Lopez-Honorez et al. 2013; Chluba 2013; Gali et al. 2013; Diamanti et al. 2013; Madhavacheril et al. 2013;

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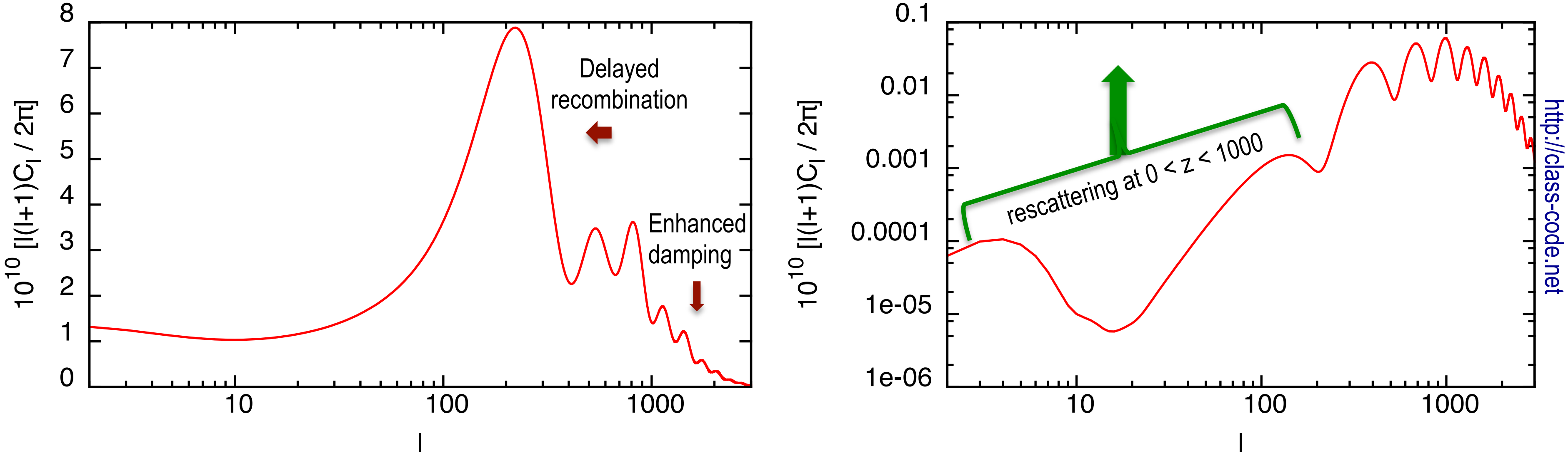

Naselsky et al. 2001; Padmanabhan & Finkbeiner 2005; Mapelli et al. 2006; Zhang et al. 2006; Natarajan & Schwarz 2008; Belikov & Hooper 2009; Cirelli et al. 2009; Galli et al. 2009; Slatyer et al. 2009; Natarajan & Schwarz 2010; Galli et al. 2011; Finkbeiner et al. 2011; Hutsi et al. 2011; A. Natarajan 2012; Giesen et al. 2012; Slatyer 2013; Cline & Scott 2013; Dvorkin et l. 2013; Planck XVI 2013; Lopez-Honorez et al. 2013; Chluba 2013; Gali et al. 2013; Diamanti et al. 2013; Madhavacheril et al. 2013;

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- Bounds from WMAP7/9 and Planck 2003 very similar Madhavasheril et al. 2013
- m>10GeV for thermal wimp; progress expected with Planck polarisation

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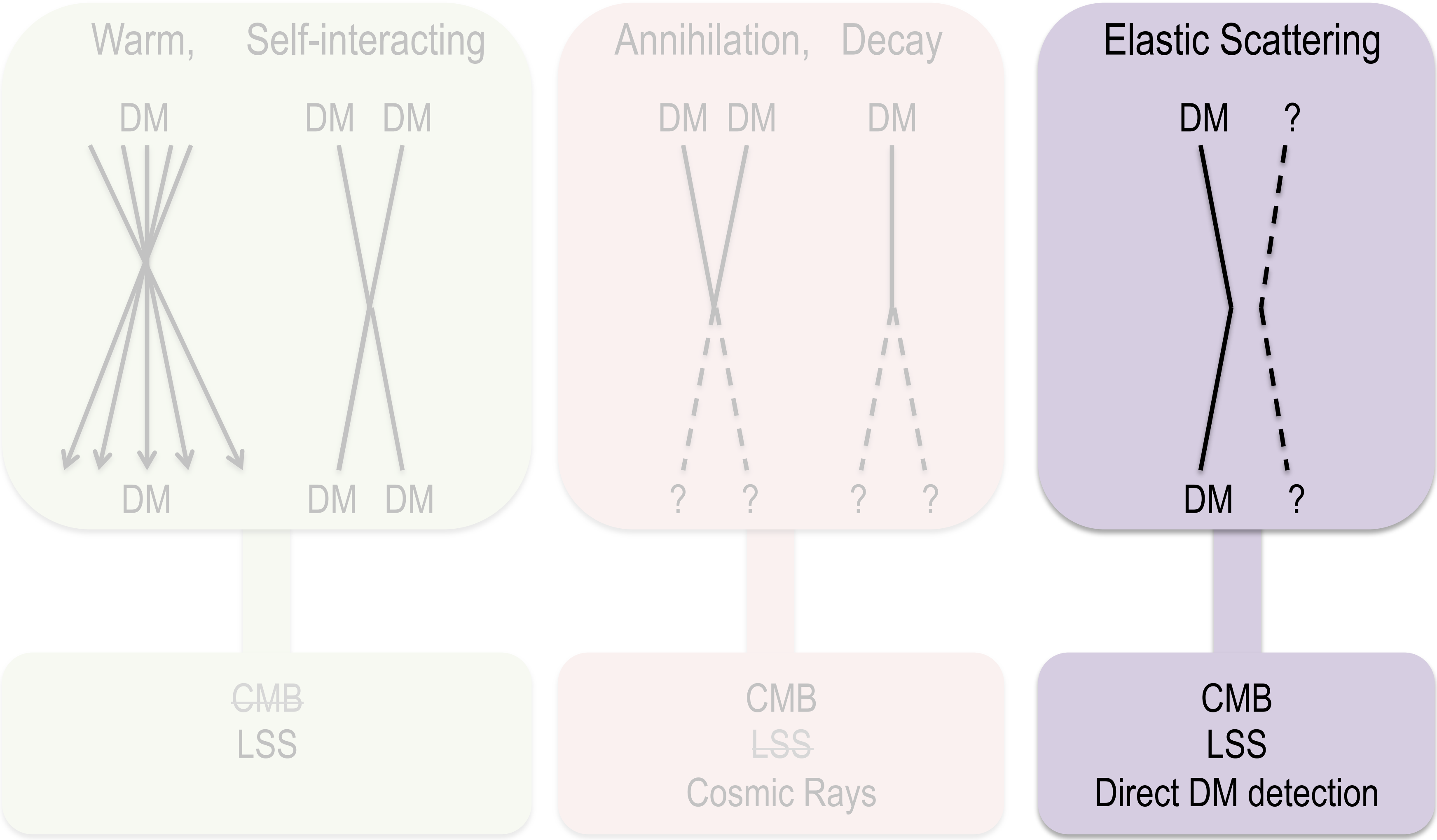
Annihilation: VERY INTERESTING RESULTS compared to direct/indirect detection

- 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)



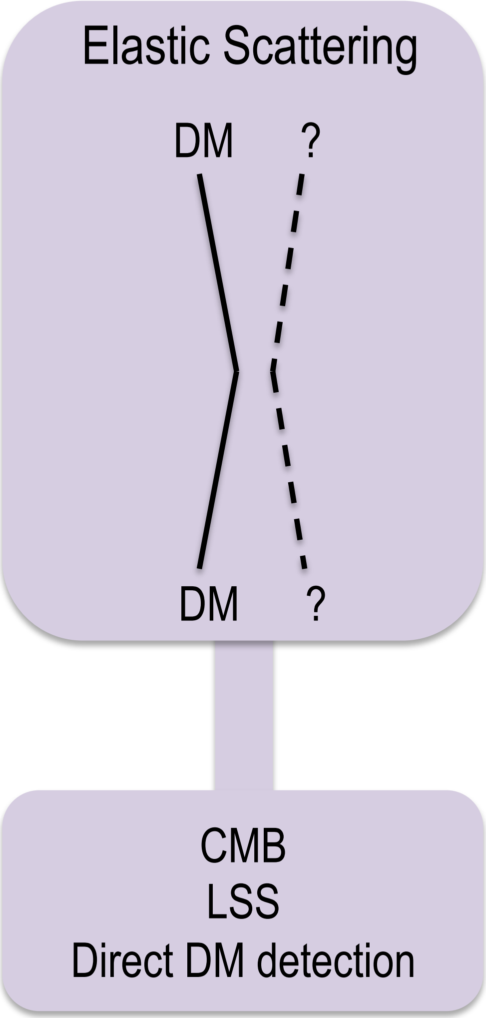
Case 3: DM interactions (elastic scattering)

- 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

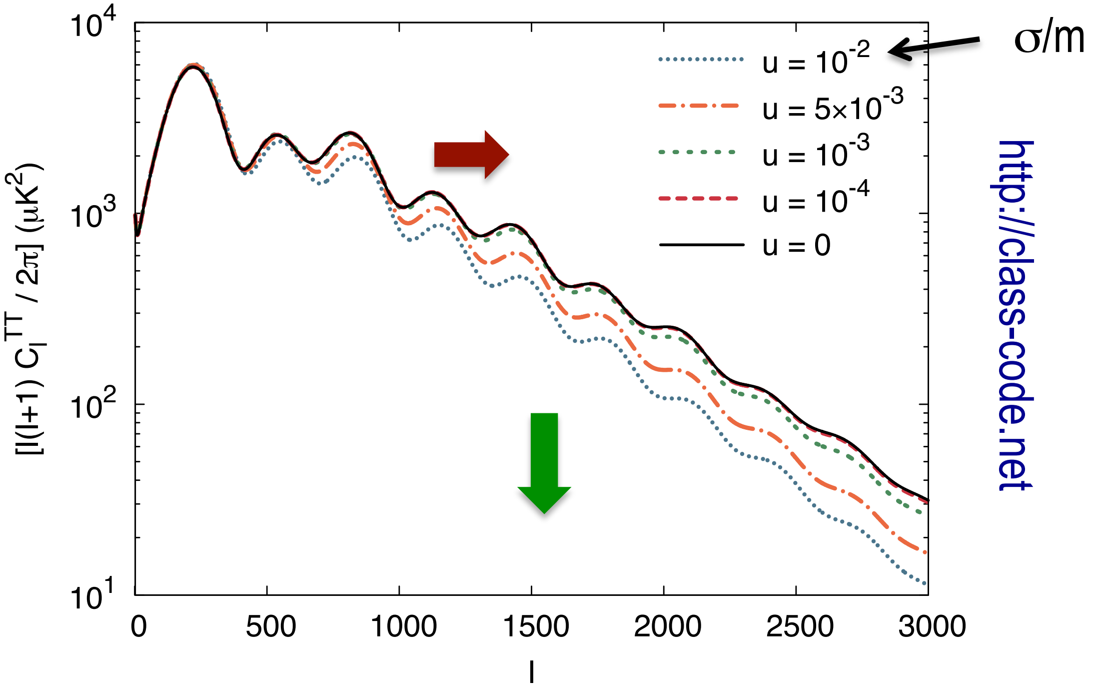


Case 3: DM interactions (elastic scattering)

- DM-photons

Wilkinson, JL & Boehm 1309.7588

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

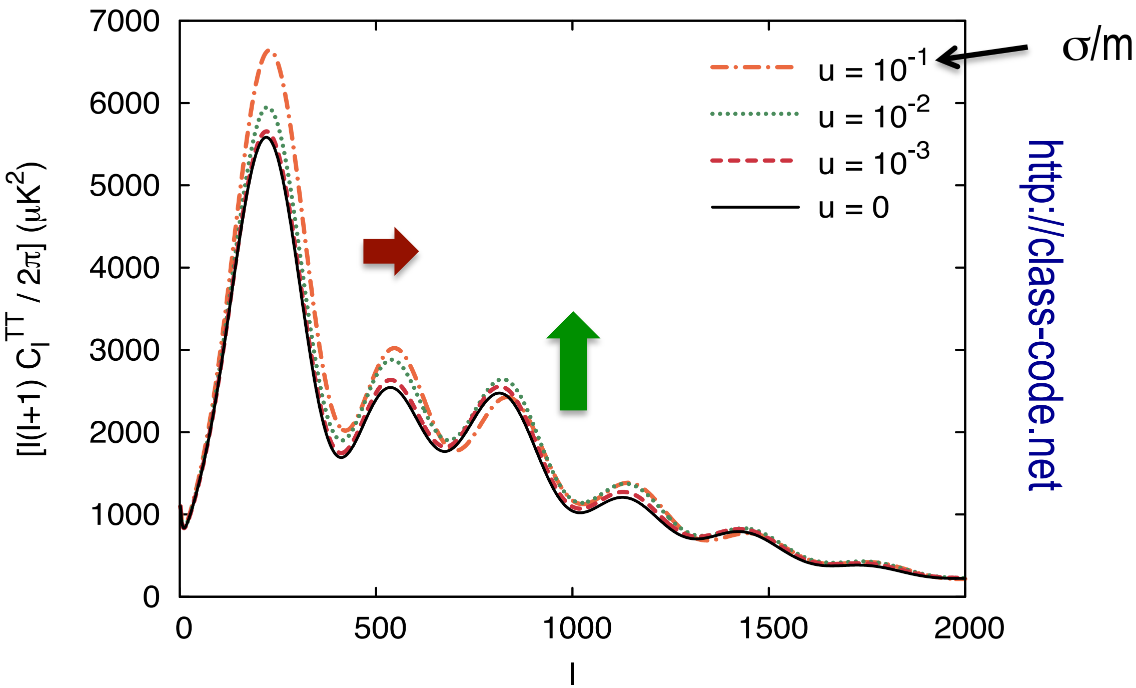


Case 3: DM interactions (elastic scattering)

- 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

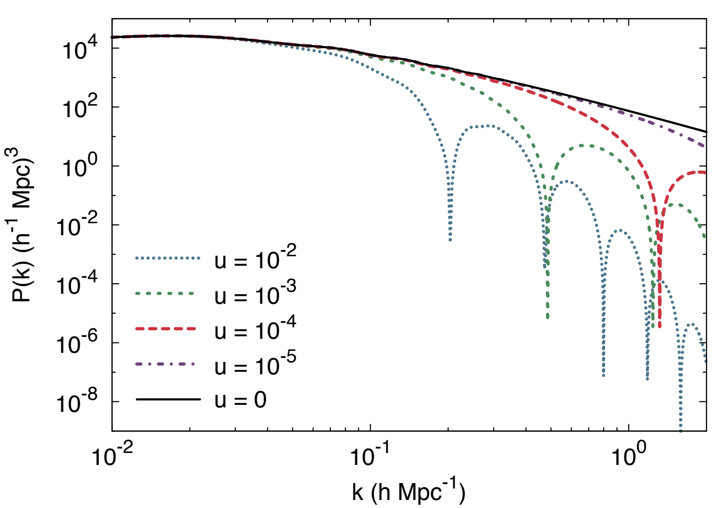
- DM-Dark Energy

…

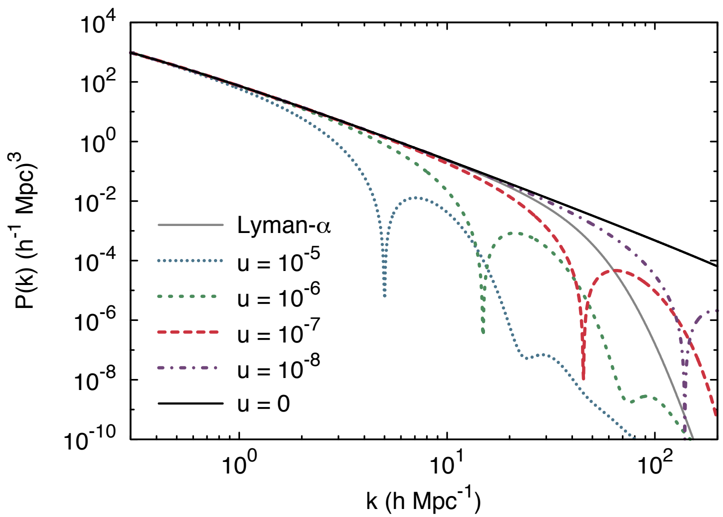
Case 3: DM interactions (elastic scattering)

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 potentially interesting results for particle physics… and astrophysics… [See Celine Boehm's talk]

- 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

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, …