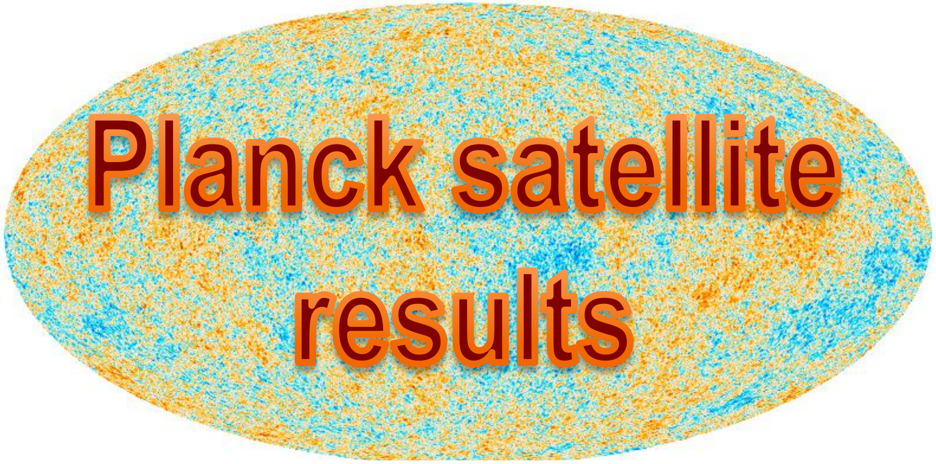
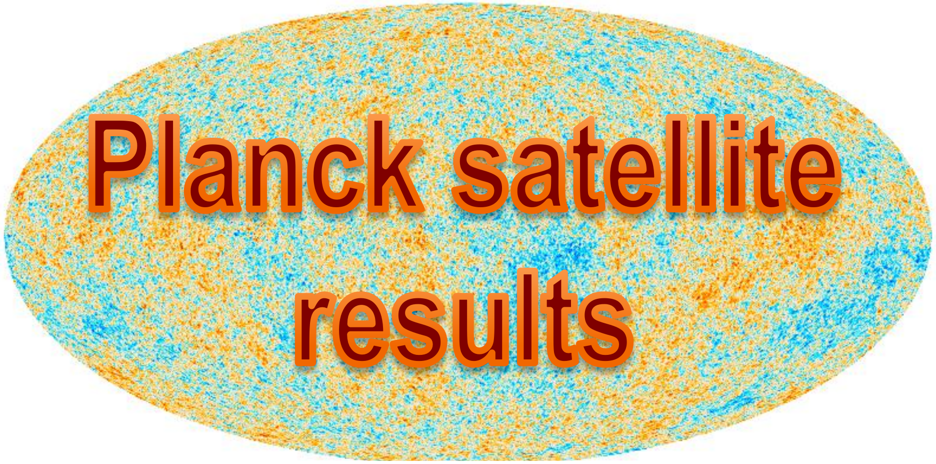


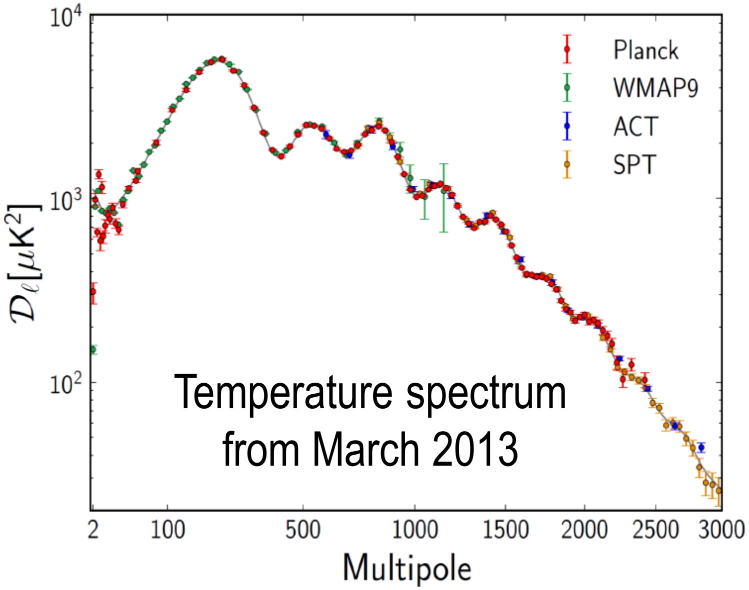
Planck satellite results

10th Patras Workshop, CERN, 3.07.2014

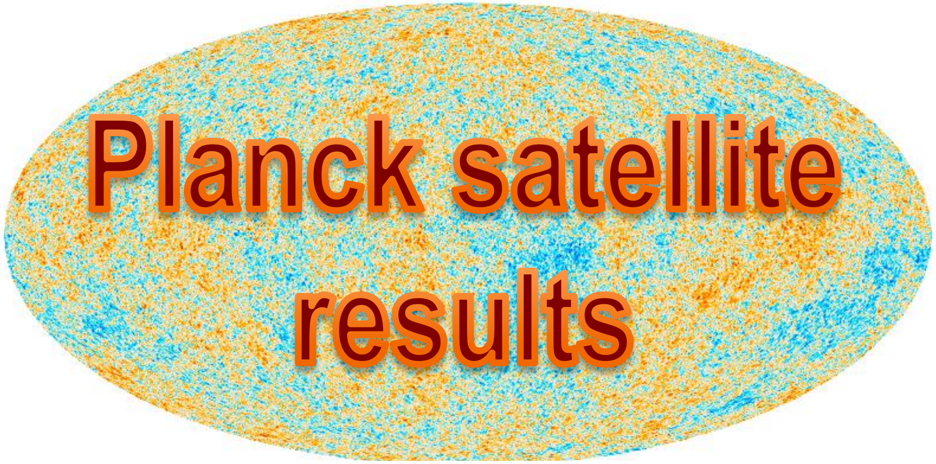
Julien Lesgourgues (EPFL, CERN, LAPTh)

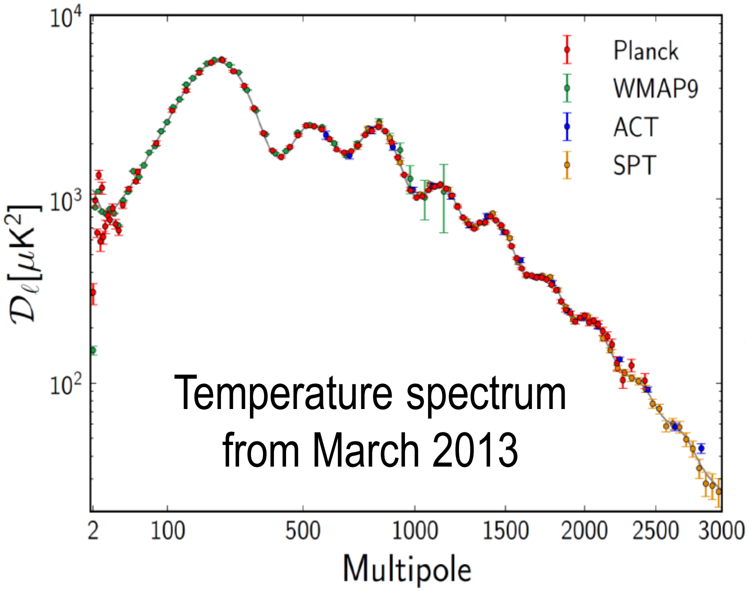
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE


Planck satellite results

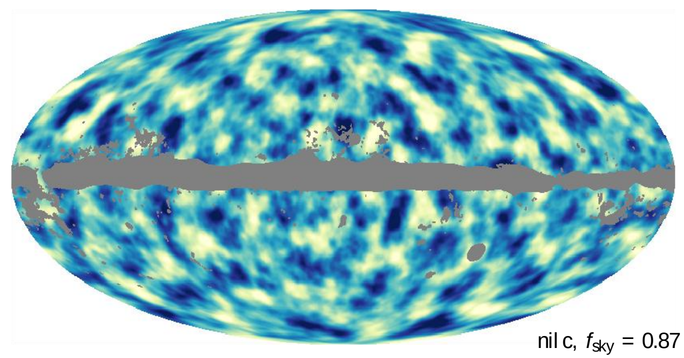

10^4
10^3
10^2
$\mathcal{D}_\ell[\mu K^2]$
Planck
WMAP9
ACT
SPT
Temperature spectrum
from March 2013
2
100
500
1000
1500
2000
2500
3000
Multipole

Planck satellite results



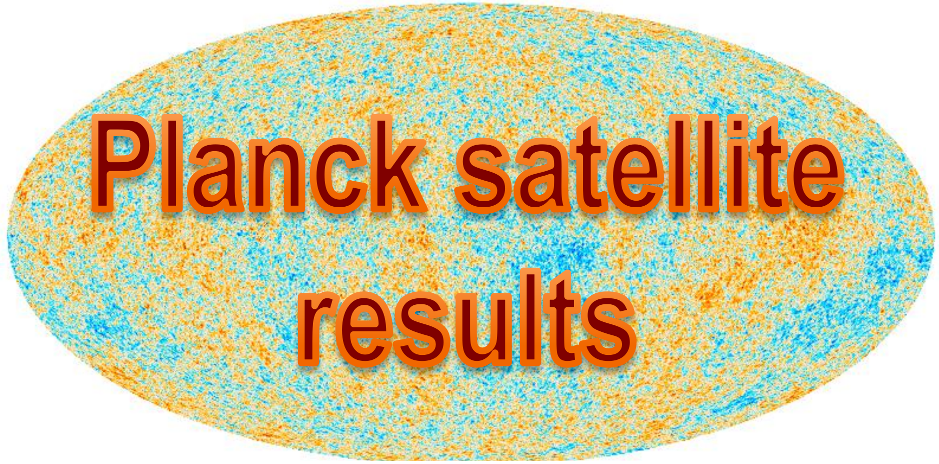


Temperature spectrum from March 2013



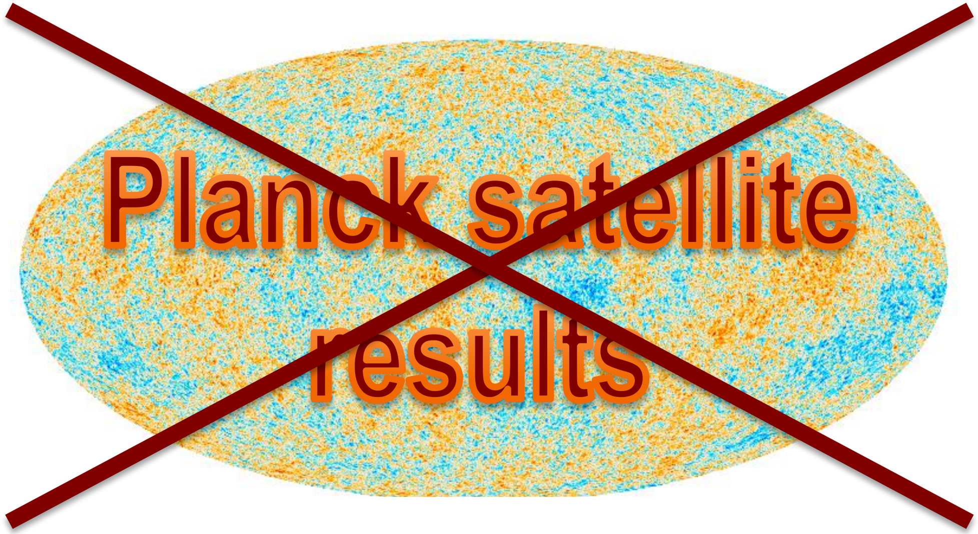
Large Scale Structure from CMB lensing

Planck satellite results



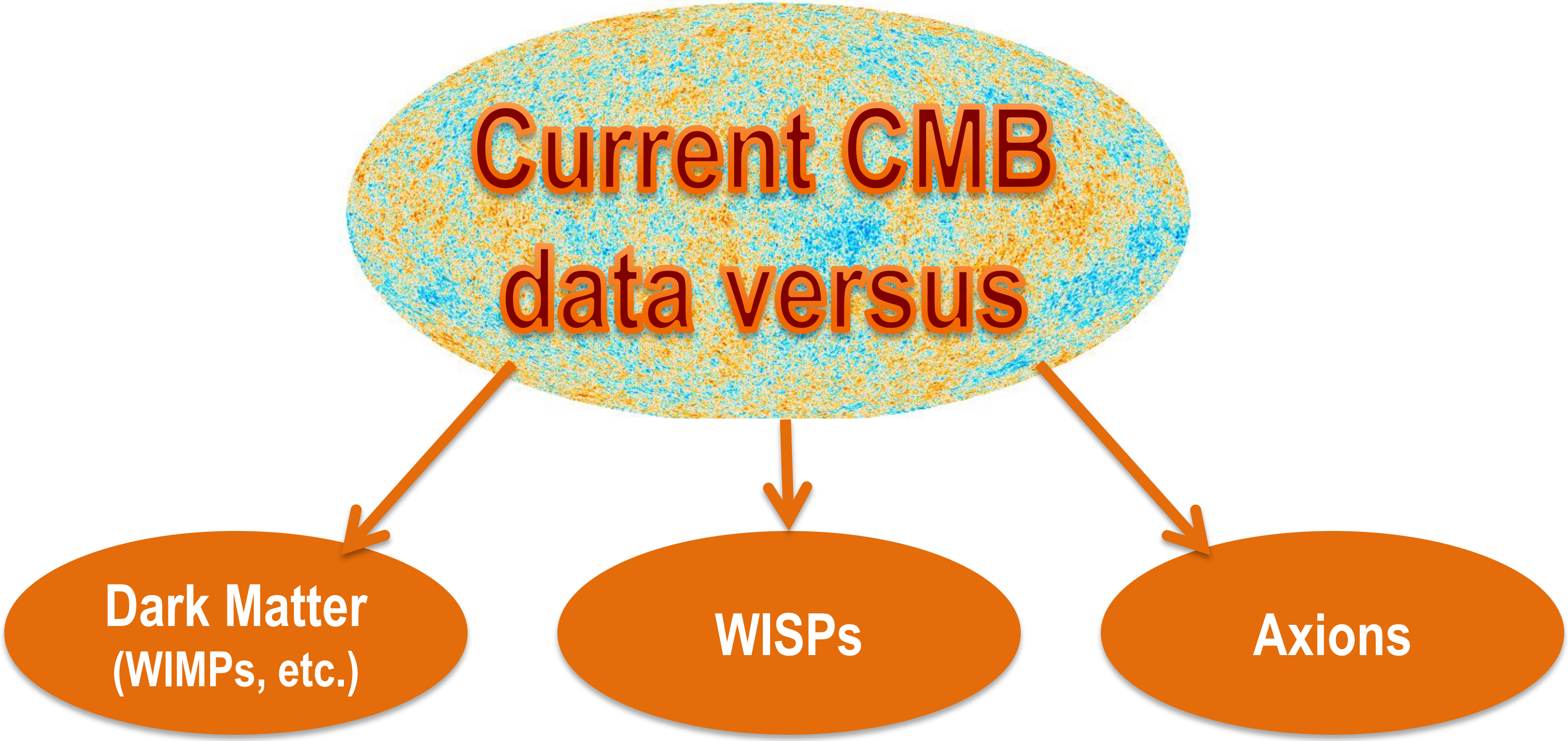
Waiting for November 2014 release!

- More temperature data
- E-mode and B-mode polarisation data
- Better lensing data
- Statement on polarised forgrounds in BICEP2 region might come before



10th Patras Workshop, CERN, 3.07.2014

Julien Lesgourgues (EPFL, CERN, LAPTh)



10th Patras Workshop, CERN, 3.07.2014

Julien Lesgourgues (EPFL, CERN, LAPTh)

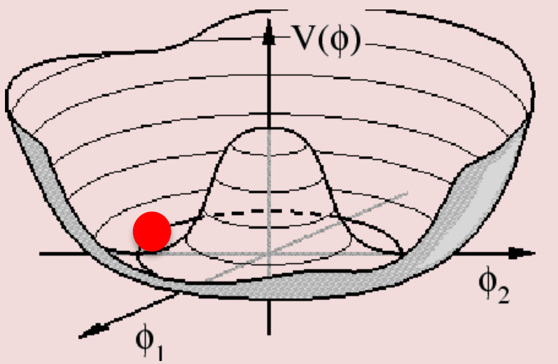
QCD axion

Constraints on energy scale of inflation (tensor modes in CMB Temperature and Polarisation), and indirectly on reheating scale:

- Is PQ broken before/after inflation?
- Can it be restored during inflation by quantum fluctuations?
- Can it be restored after reheating by thermal fluctuations?

Leads to different smoking guns (but model-dependent)

- Axion quantum fluctuations during inflation: Isocurvature modes?
- Axionic dark matter from misalignement angle, or contribution from axionic string decays?



If we don’t believe BICEP2:

- PQ symmetry may break down before inflation
- axion-induced isocurvature perturbations may survive if PQ not restored during inflation or reheating
- Axion density from misalignement angle ONLY
- Relation between $\Omega_a h^2$ and f_a (unless anthropic suppression of θ_a)
- Then Planck non-detection of isocurvature modes gives:

$$H_I \leq 0.87 \times 10^7 \text{ GeV} \left(\frac{f_\mathrm{a}}{10^{11} \text{ GeV}} \right)^{0.408}$$

If we believe BICEP2:

- $H_{infl} \sim 10^{14}$ GeV
- PQ symmetry breaks down after inflation
- No axion-induced isocurvature perturbations
- Axion density from misalignement angle θ_a + axionic string decay
- Relation between $\Omega_a h^2$ and f_a (order-of-magnitude relation, θ_a being unknown, but no possible anthropic suppression)
- Assuming all CDM is axions and typical θ_a:

$m_a \sim 80\ \mu$eV ($f_a \sim 7.5 \times 10^{10}$ GeV) see arXiv:1405.1860

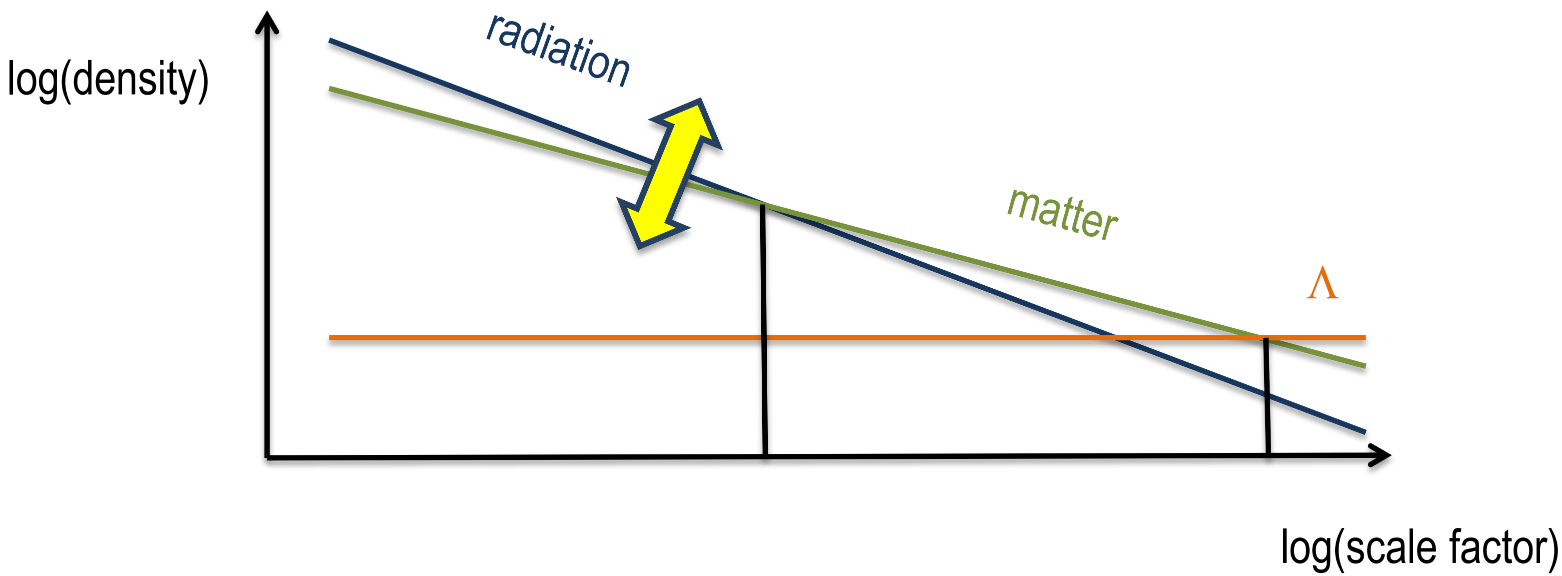
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Weakly Interacting Sub-eV Particles

Cosmology could probe WISPs if their density is sufficient:

1) to contribute to a fraction of radiation during radiation domination: N_{eff}

[e.g. ultra relativistic relics with $T \sim T_\gamma$ and $m << 0.01eV$]



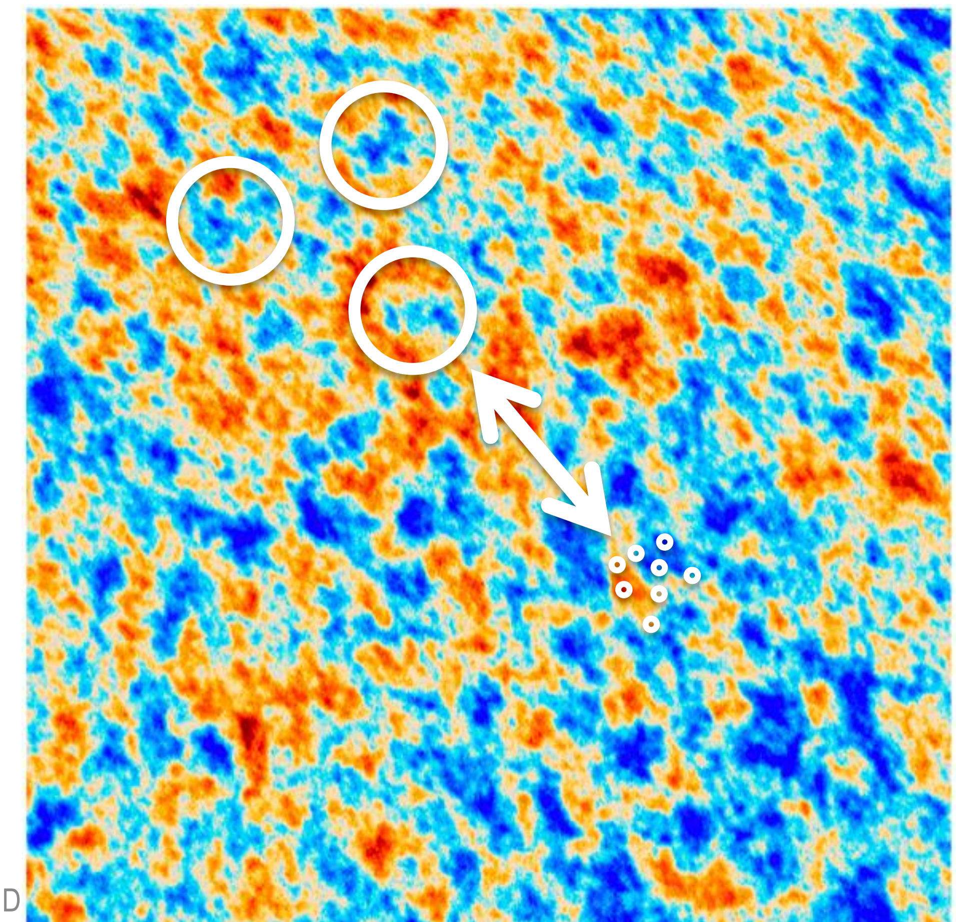
Cosmology could probe WISPs if their density is sufficient:

1) to contribute to a fraction of radiation during radiation domination: N_{eff}

[e.g. ultra relativistic relics with $T \sim T_\gamma$ and $m \ll 0.01eV$]

Several effects on CMB

- impact on expansion
- γ gravitational interactions



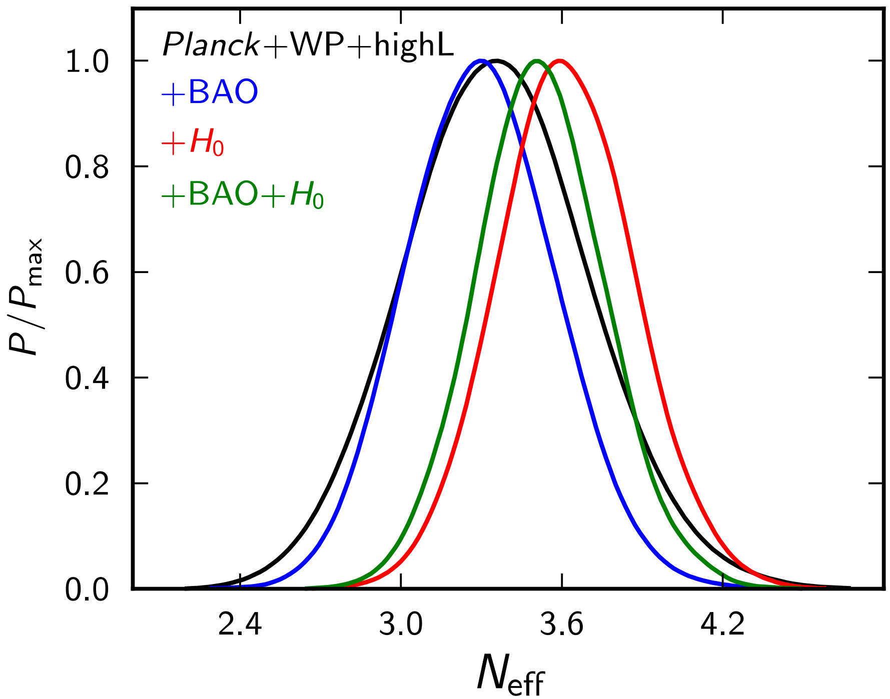
Cosmology could probe WISPs if their density is sufficient:

1) to contribute to a fraction of radiation during radiation domination: N_{eff}

[e.g. ultra relativistic relics with $T \sim T_\gamma$ and $m << 0.01eV$]

Planck compatible with 3

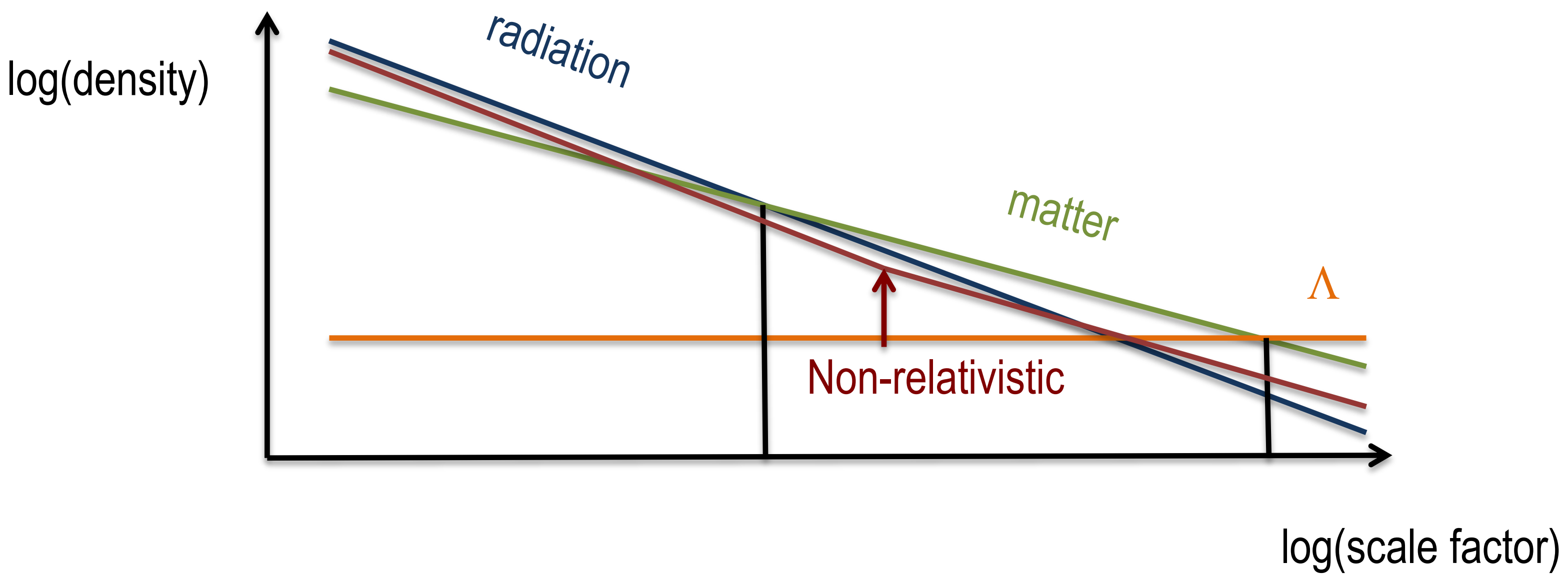
$N_{eff} > 3$ = way to release tension with H_0



Cosmology could probe WISPs if their density is sufficient:

2) To contribute to radiation during RD and matter during MD (hot dark matter fraction)

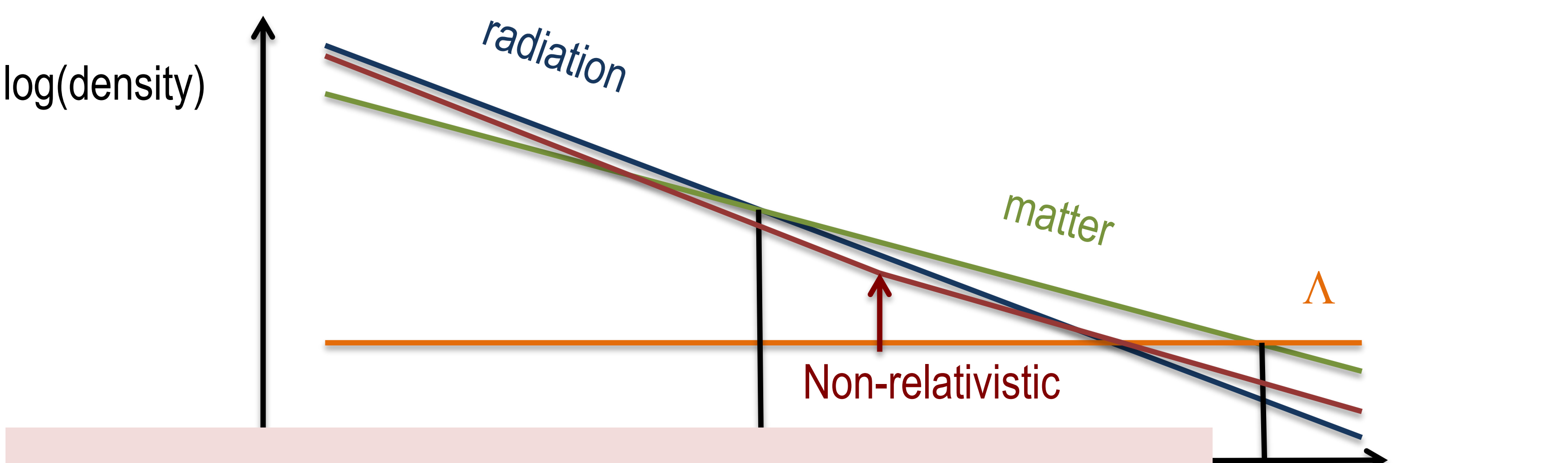
[e.g. sterile neutrinos with ~ 1 eV and (nearly) thermalised]



Cosmology could probe WISPs if their density is sufficient:

2) To contribute to radiation during RD and matter during MD (hot dark matter fraction)

[e.g. sterile neutrinos with ~ 1 eV and (nearly) thermalised]



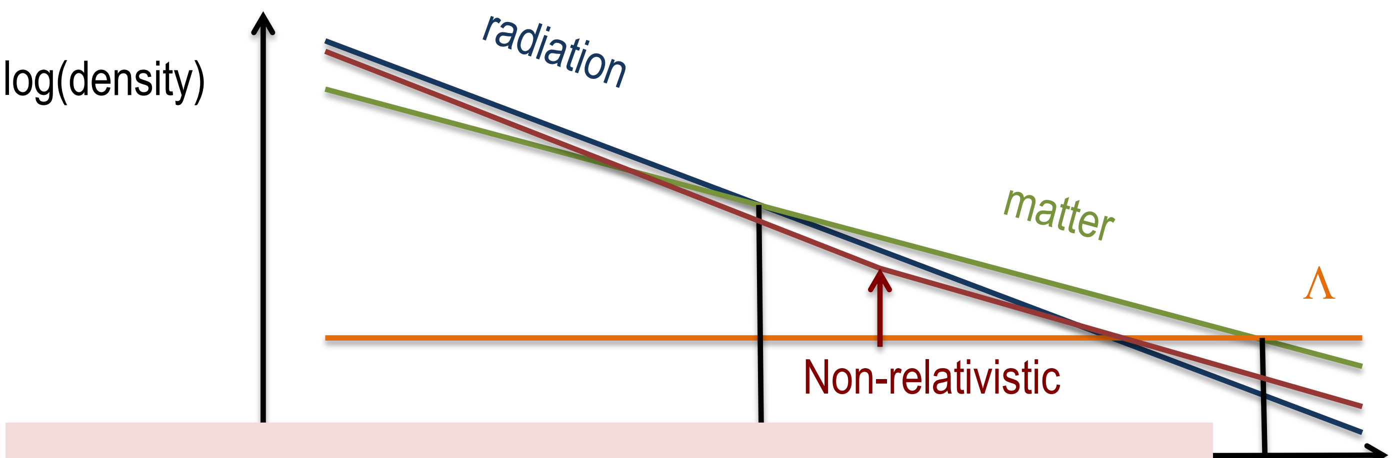
- Impact on N_{eff} >1
- Hot Dark Matter effects (in CMB and in Large Scale Structure),

  HDM density → neutrino-equivalent mass M_{eff}

Cosmology could probe WISPs if their density is sufficient:

2) To contribute to radiation during RD and matter during MD (hot dark matter fraction)

[e.g. sterile neutrinos with ~ 1 eV and (nearly) thermalised]



- Impact on $N_{eff} > 1$
- Hot Dark Matter effects (in CMB a

HDM density → neutrino-equival M_{eff}

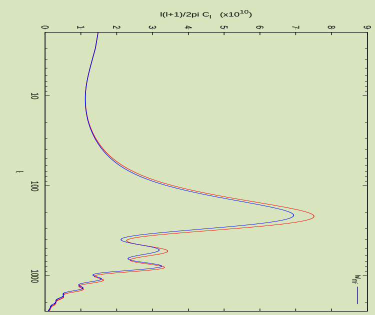
$M_{eff} < 0.23$ eV or $M_{eff} \sim 0.3\text{-}0.5$ eV ?

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

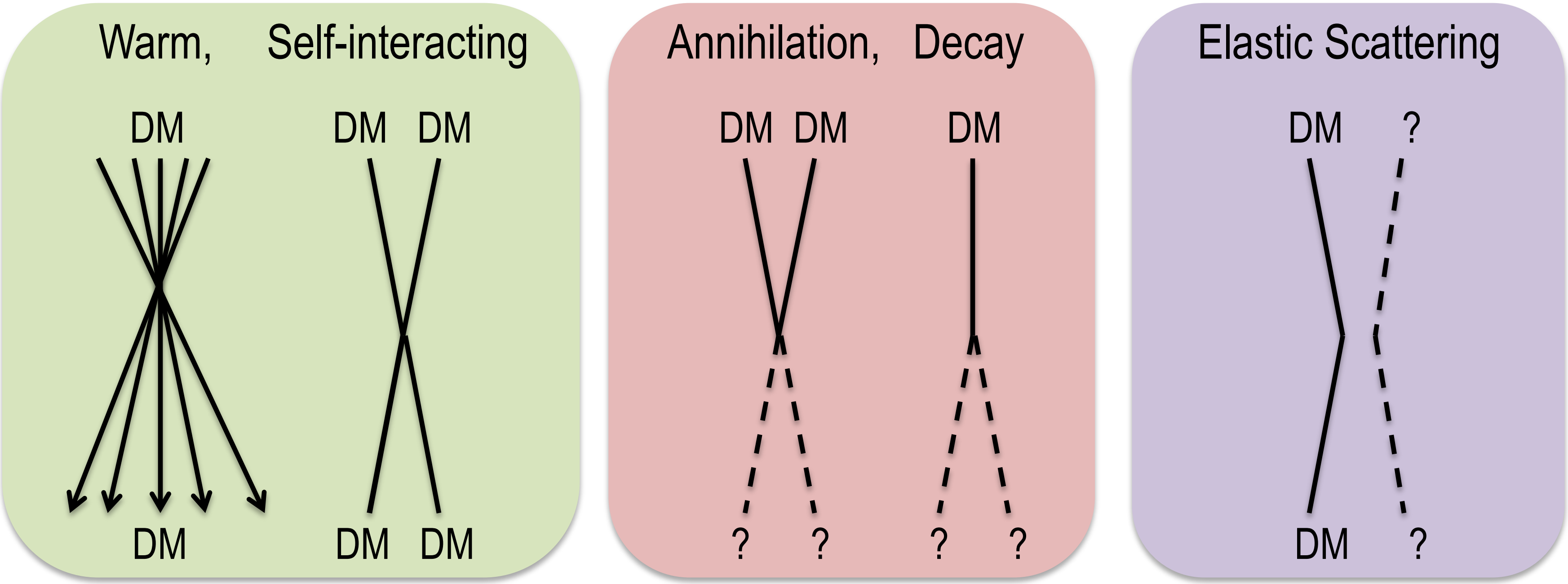
CMB/LSS and nature of (dominant) Dark Matter

- 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;
  - …

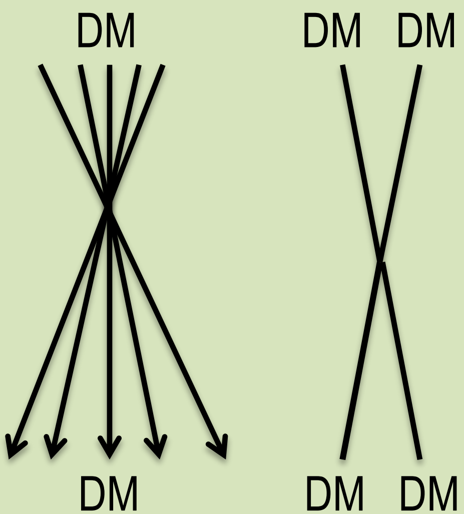
?

Possible properties of DM



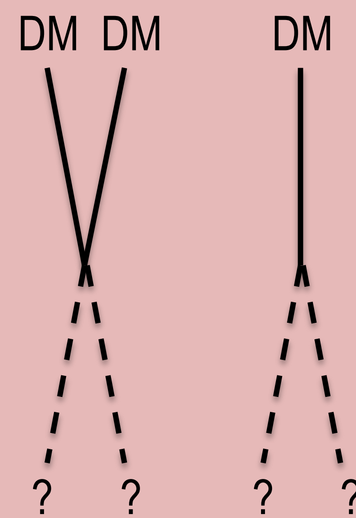
Possible properties of DM

Warm, Self-interacting



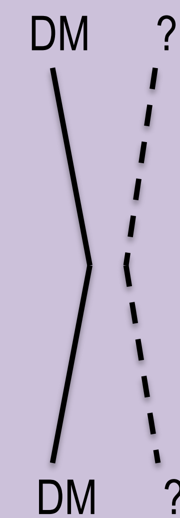
~~CMB~~
LSS

Annihilation, Decay



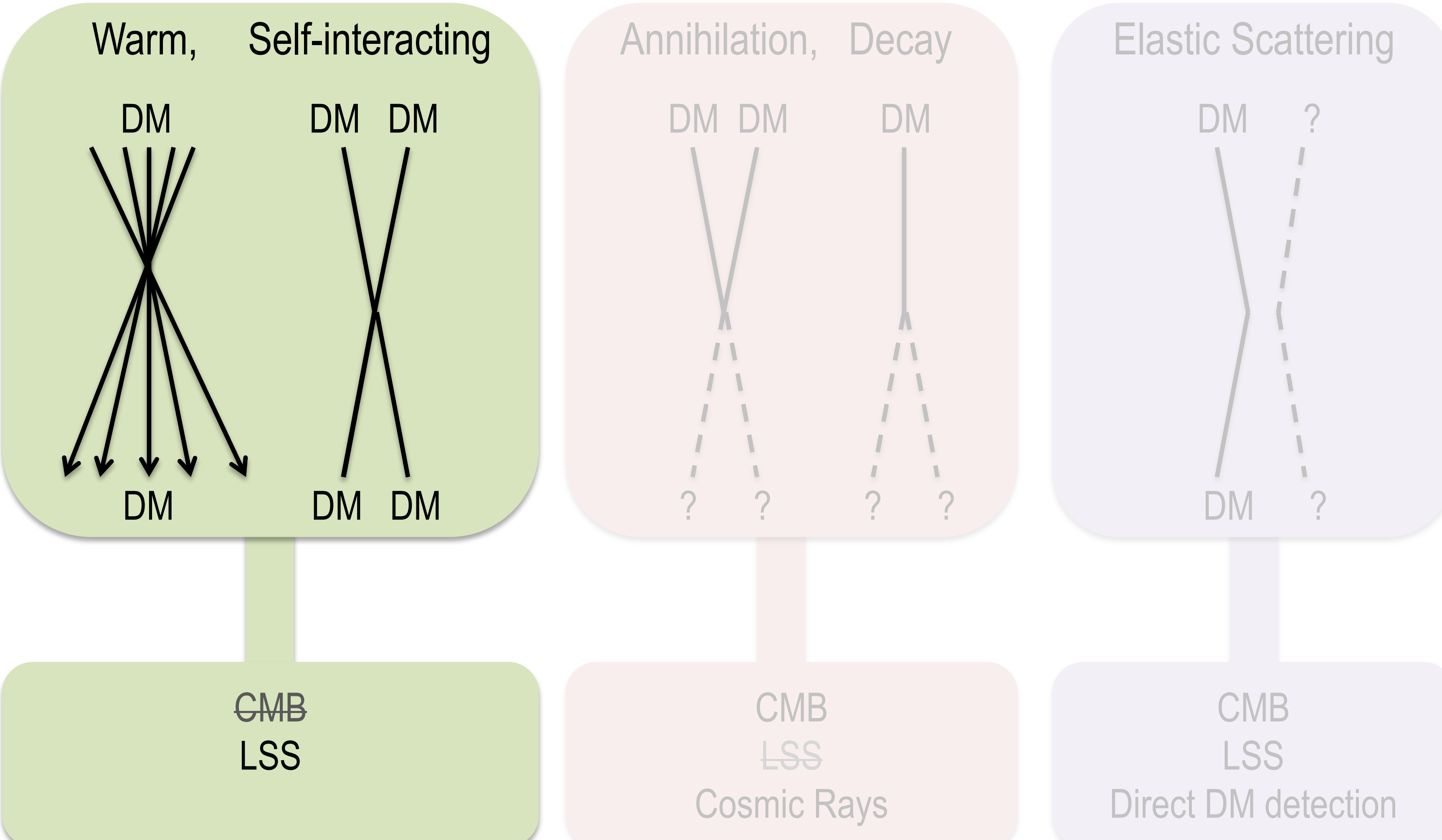
CMB
~~LSS~~
Cosmic Rays

Elastic Scattering



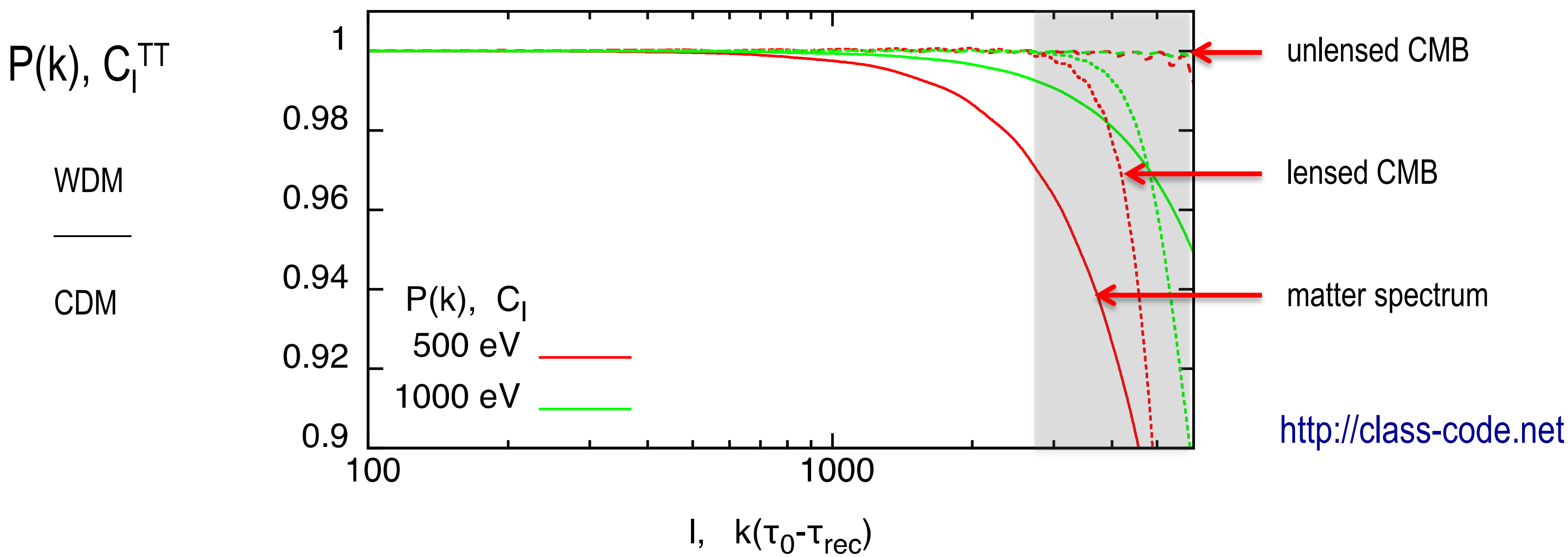
CMB
LSS
Direct DM detection

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

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 Ω_{DM} ~ 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

Case 1: warm or self-interacting

- best constraints from Lyman-alpha: <p>/m ~ T/m < …

- Thermal WDM: T given by Ω_{DM} ~ 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 :

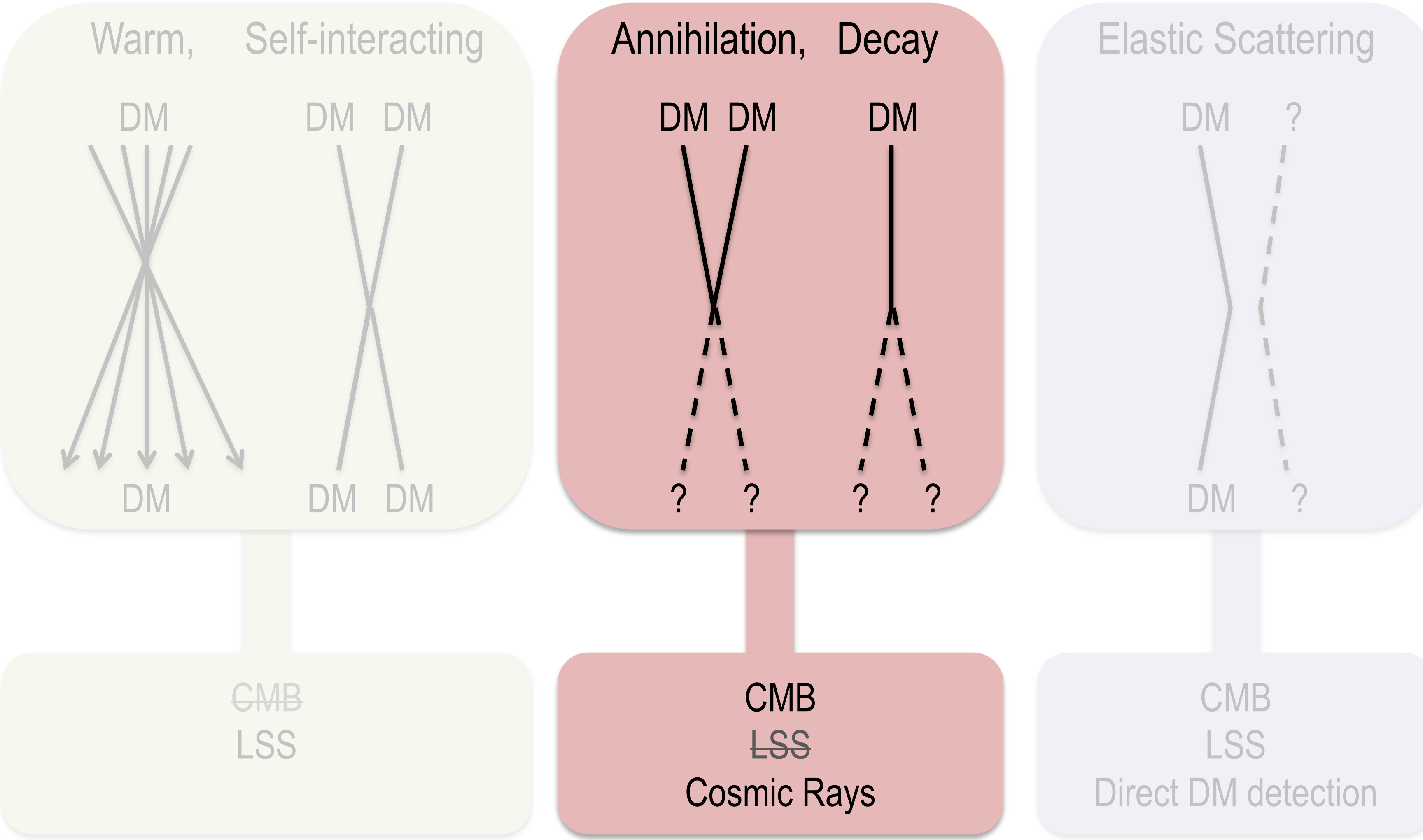
  m > 2 keV (95%CL) Boyarsky et al. 2009

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

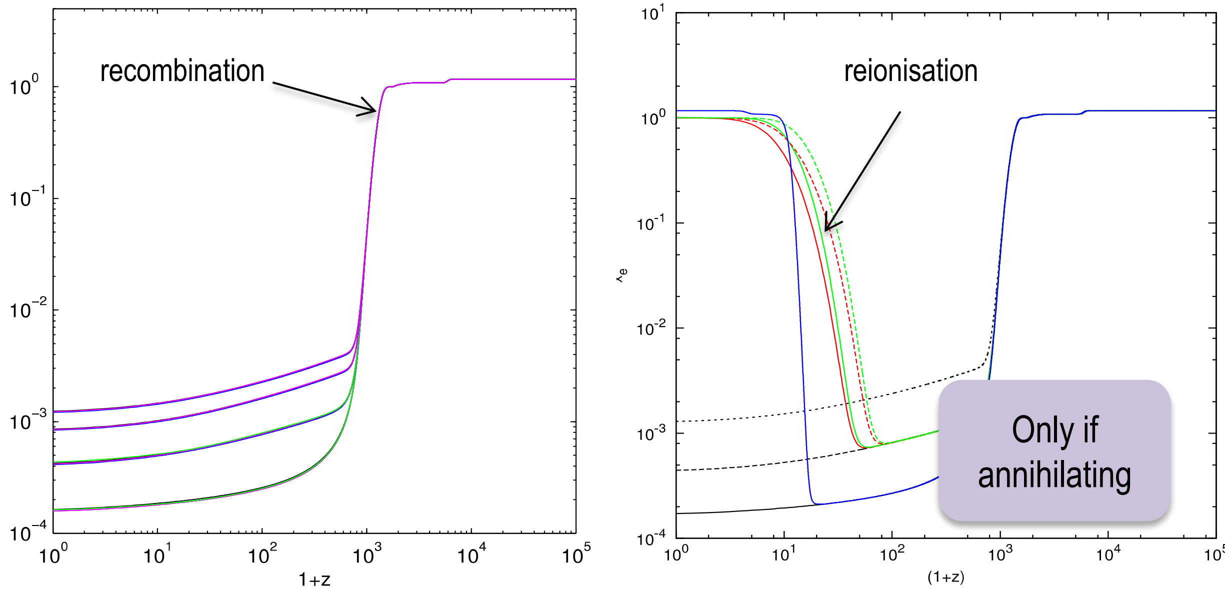
- DM → hadrons, leptons, gauge bosons → … → electrons, neutrinos, photons
  - Ionization of thermal plasma
  - Heating of thermal plasma
  - Hydrogen excitation

  } (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

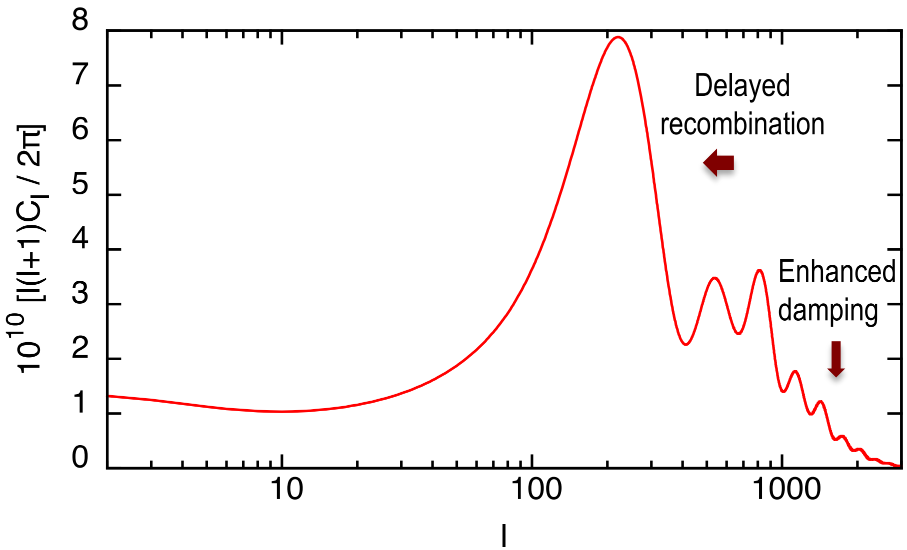
1+z

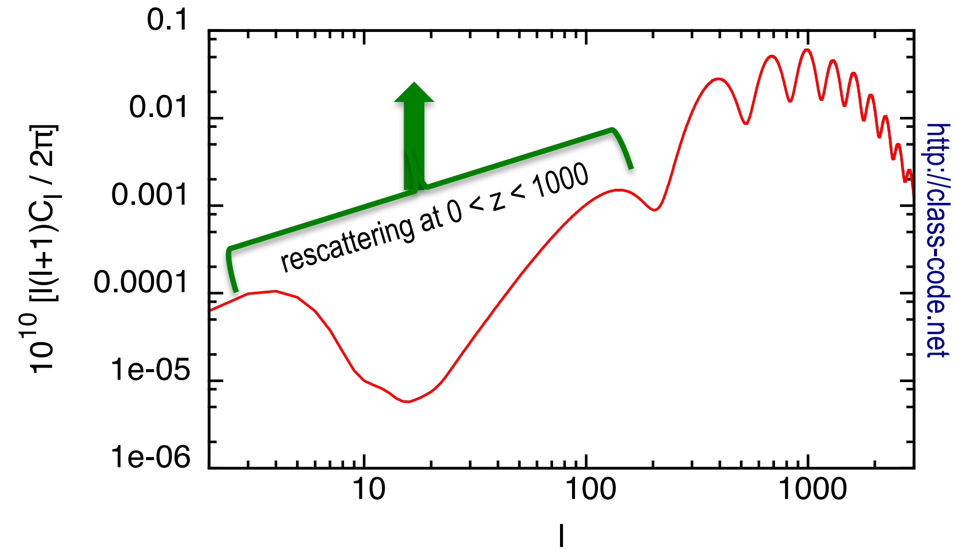
http://class-code.net

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;

Adams et al. 1998; Hansen & Haiman 2004; Chen & Kamionkowski 2004; Ichiki et al. 2004; Zhang et al. 2007; Kasuya & Kawasaki 2007; Yeung et al. 2012; Cirelli et al. 2012

Case 2: annihilating or decaying





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;

Adams et al. 1998; Hansen & Haiman 2004; Chen & Kamionkowski 2004; Ichiki et al. 2004; Zhang et al. 2007; Kasuya & Kawasaki 2007; Yeung et al. 2012; Cirelli et al. 2012

Case 2: annihilating or decaying

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

Case 2: annihilating or decaying

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

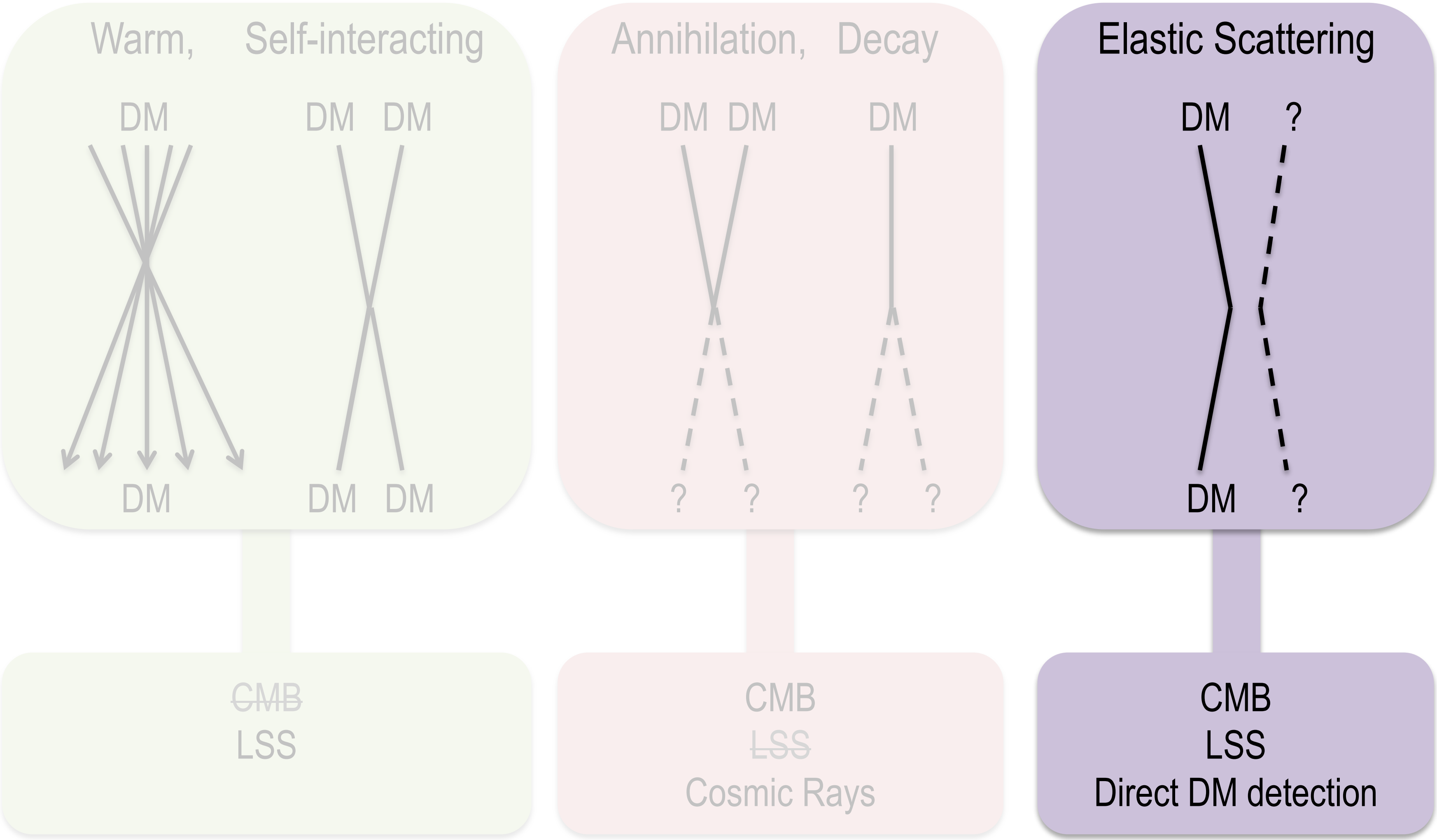
Annihilation: VERY INTERESTING RESULTS compared to direct/indirect detection

- 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)

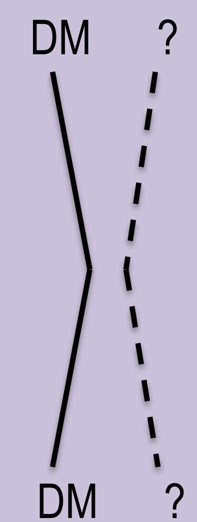
Case 3: DM interactions (elastic scattering)



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



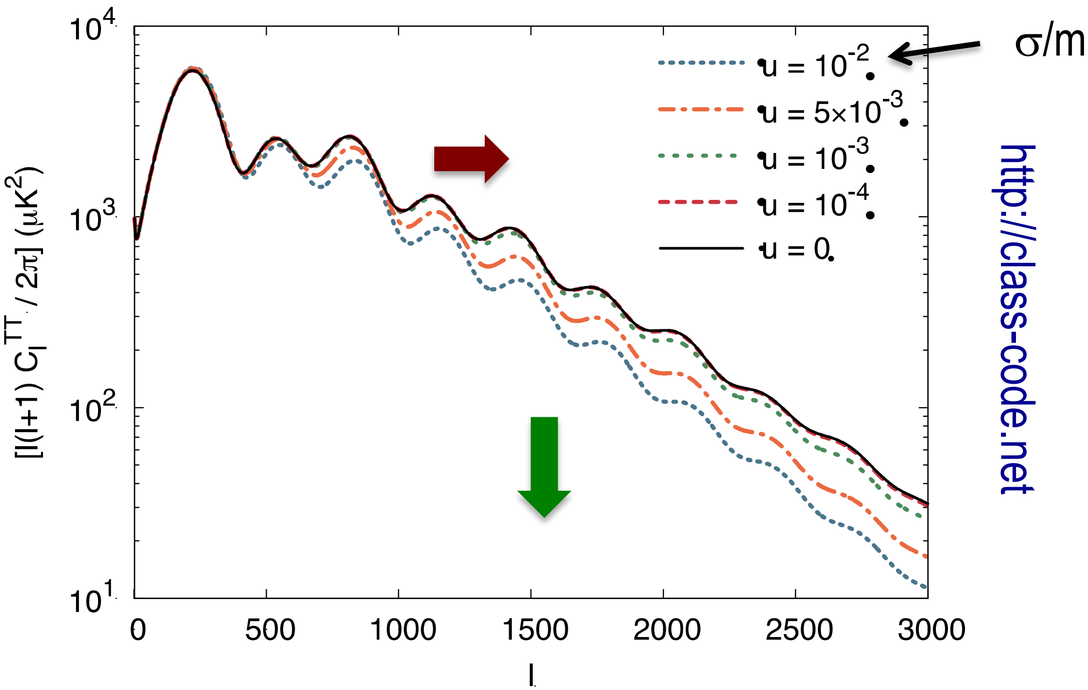
CMB
LSS
Direct DM detection

Case 3: DM interactions (elastic scattering)

- DM-photons

Wilkinson, JL & Boehm 1309.7588

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

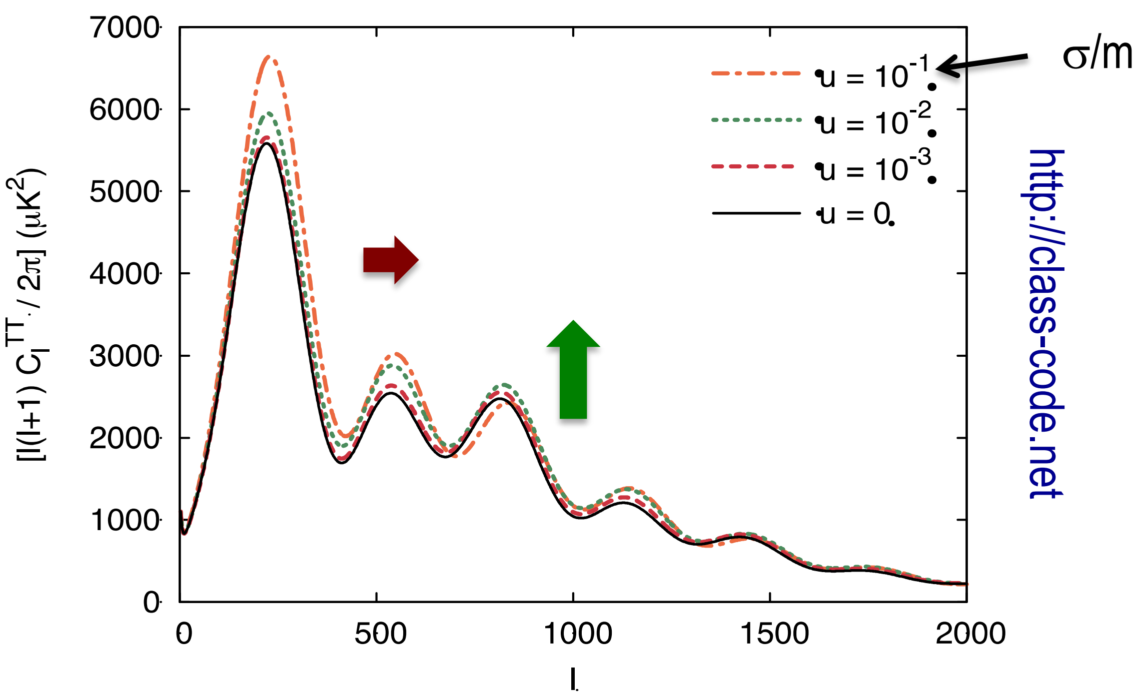


Case 3: DM interactions (elastic scattering)

- 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)



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

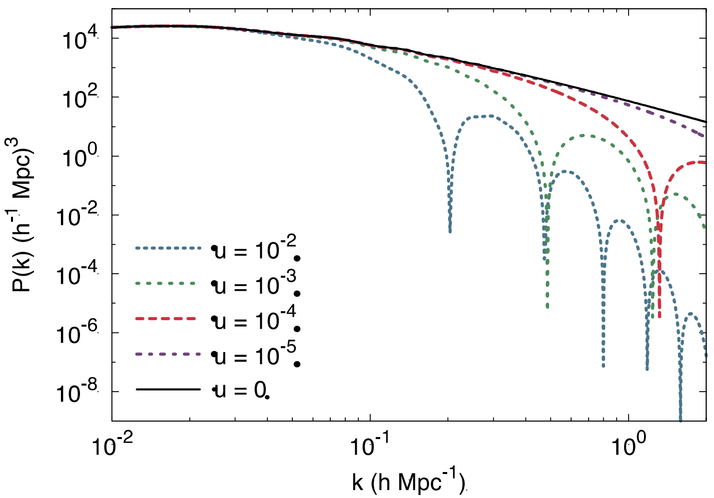
- DM-Dark Energy

…

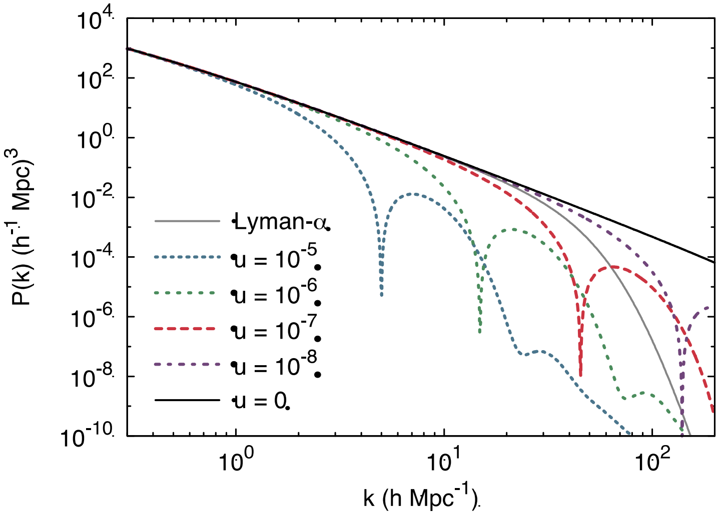
Case 3: DM interactions (elastic scattering)

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 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

Planck 2014 release expected to shed more light on

- Energy scale of inflation (BICEP = dust or GWs?)
- N_{eff}, Neutrino and WISPs masses
- DM annihilation
- Plenty of other things…