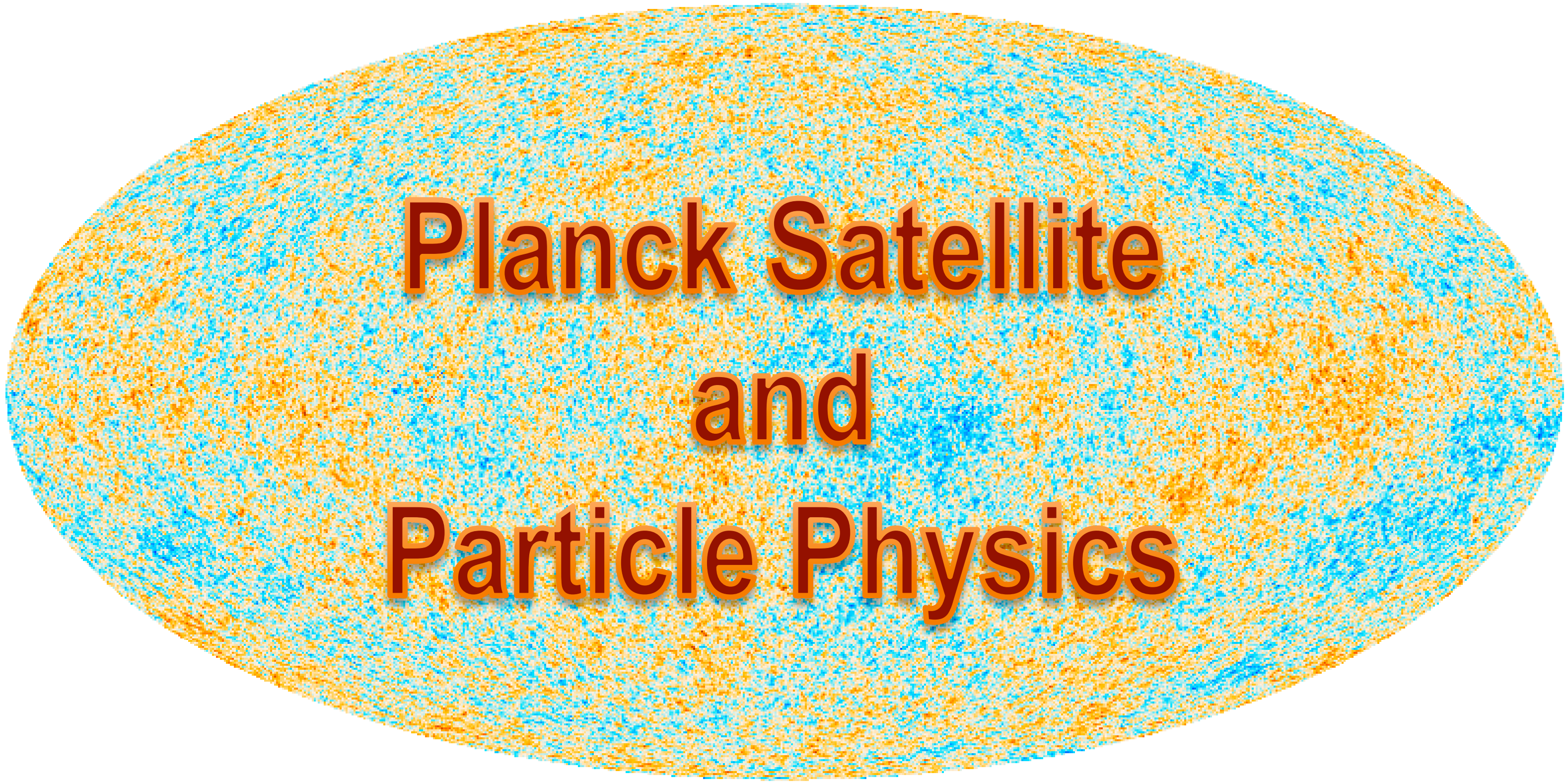
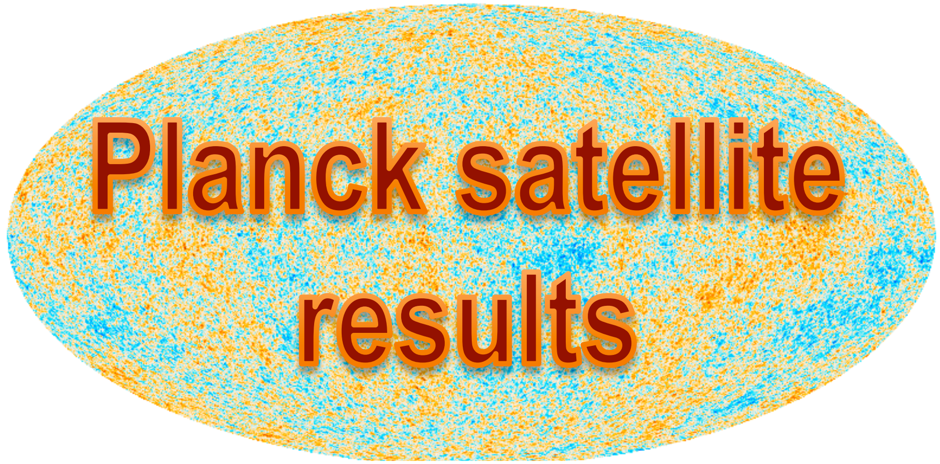
Planck Satellite and Particle Physics

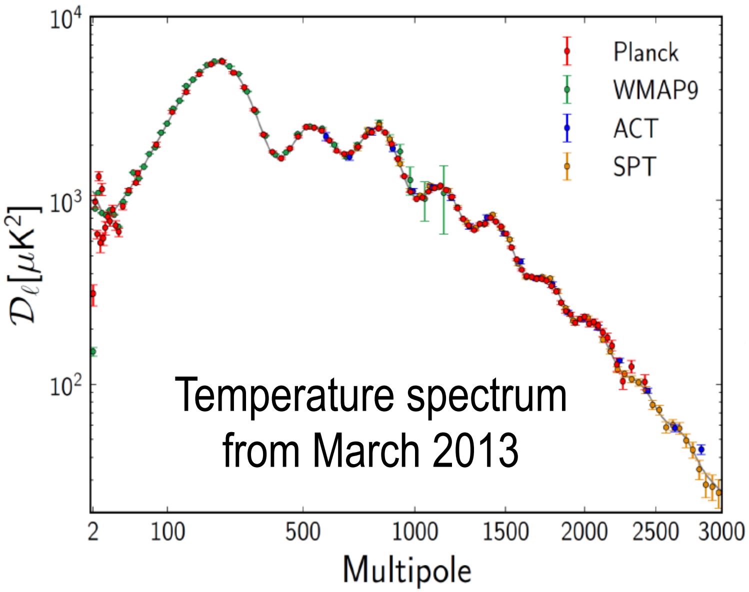


SEWM14, EPFL, 17.07.2014

Julien Lesgourgues (EPFL, CERN, LAPTh)

Planck satellite results





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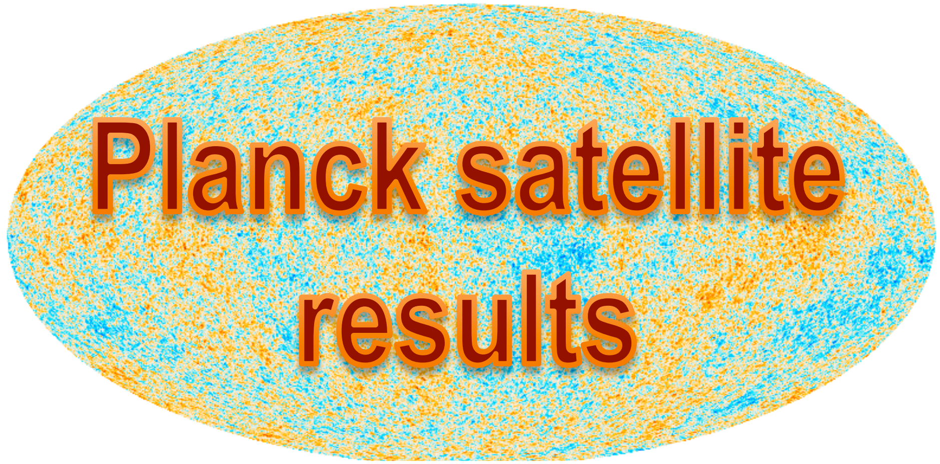
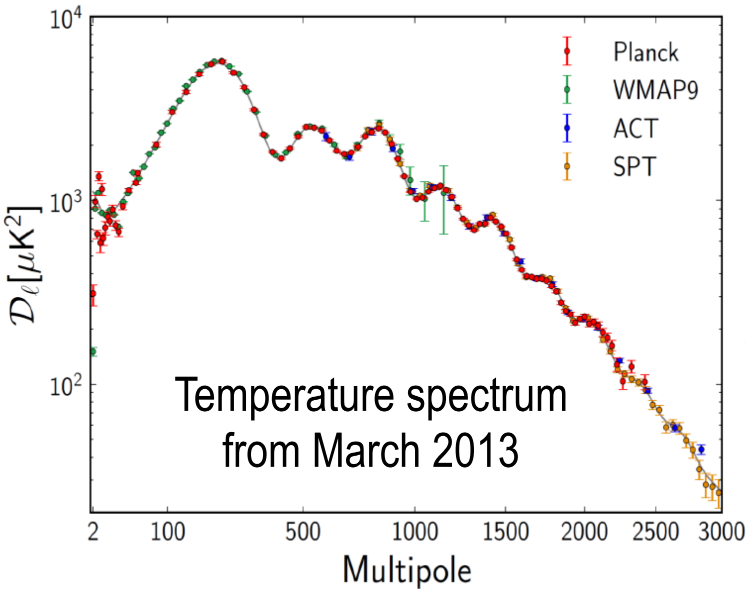
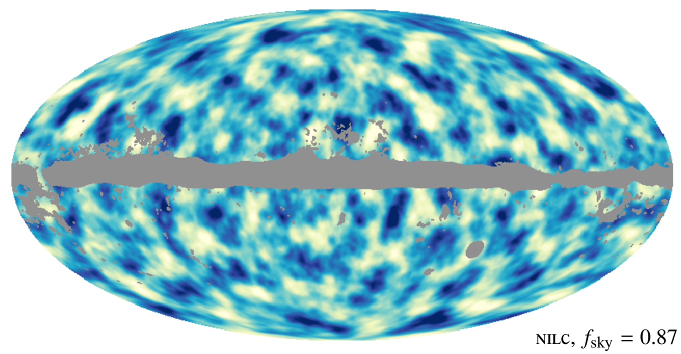


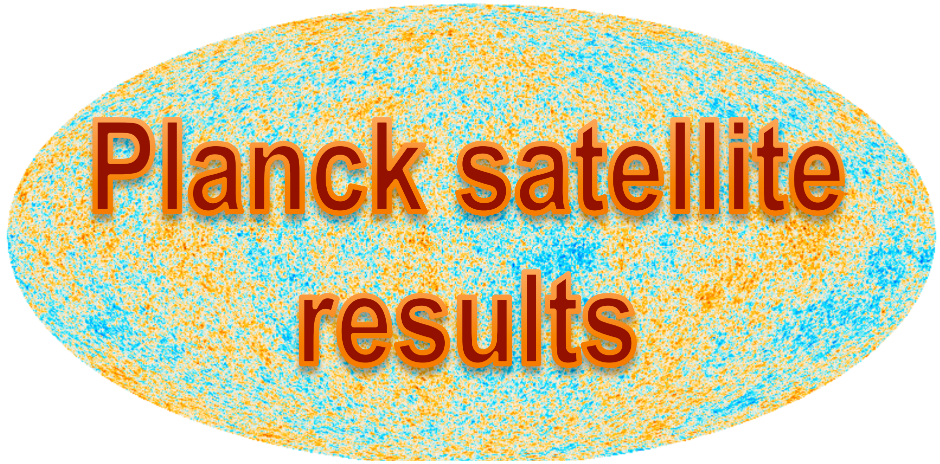


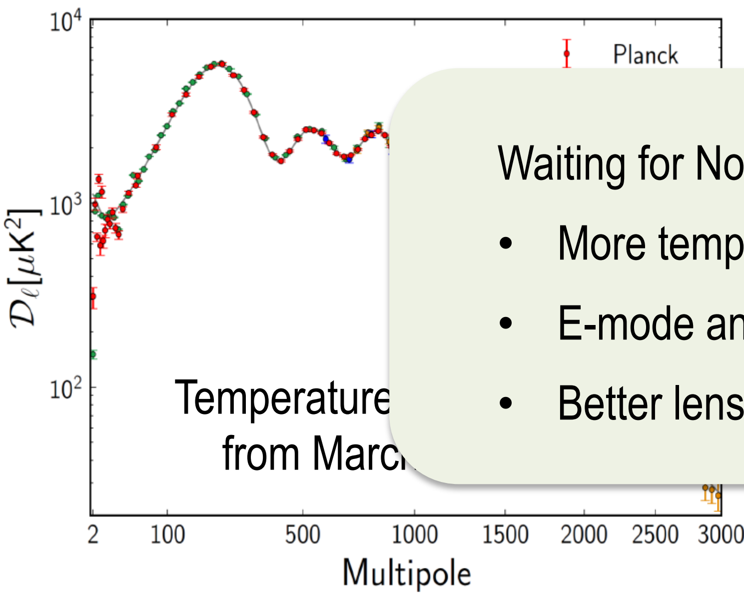
Temperature spectrum
from March 2013



Large Scale Structure
from CMB lensing

Planck satellite results





Temperature
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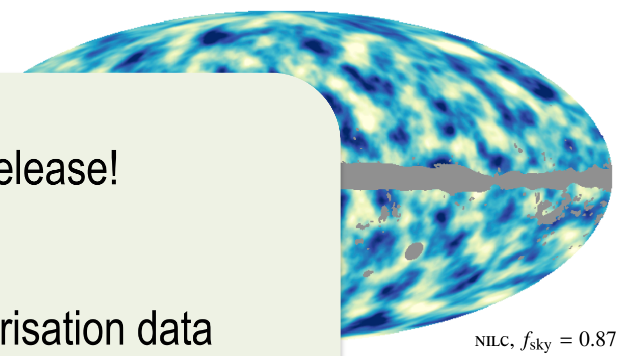


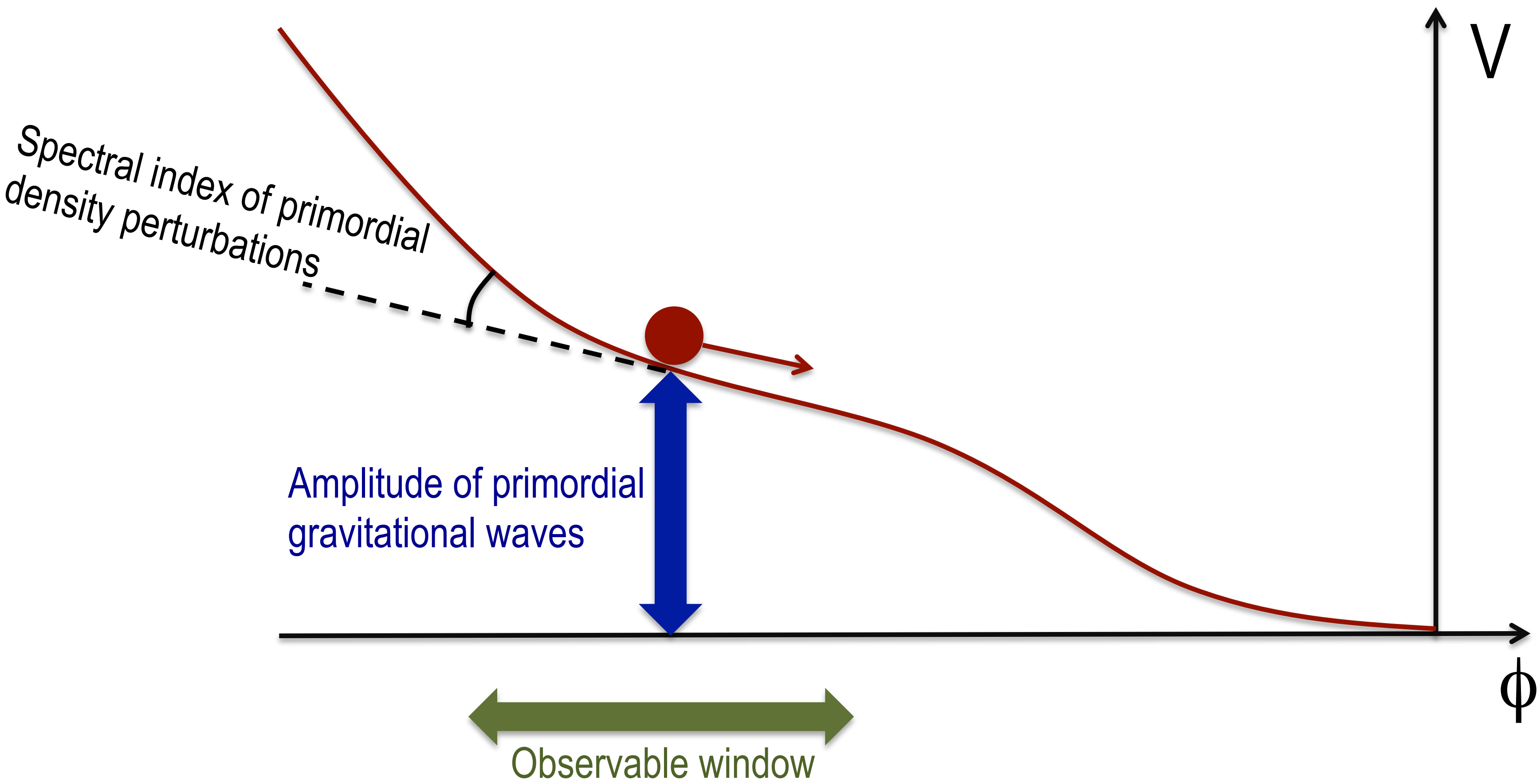
Structure
lensing

Waiting for November 2014 release!

- More temperature data
- E-mode and B-mode polarisation data
- Better lensing data

Energy scale of inflation

- Energy scale and dynamics of inflation:



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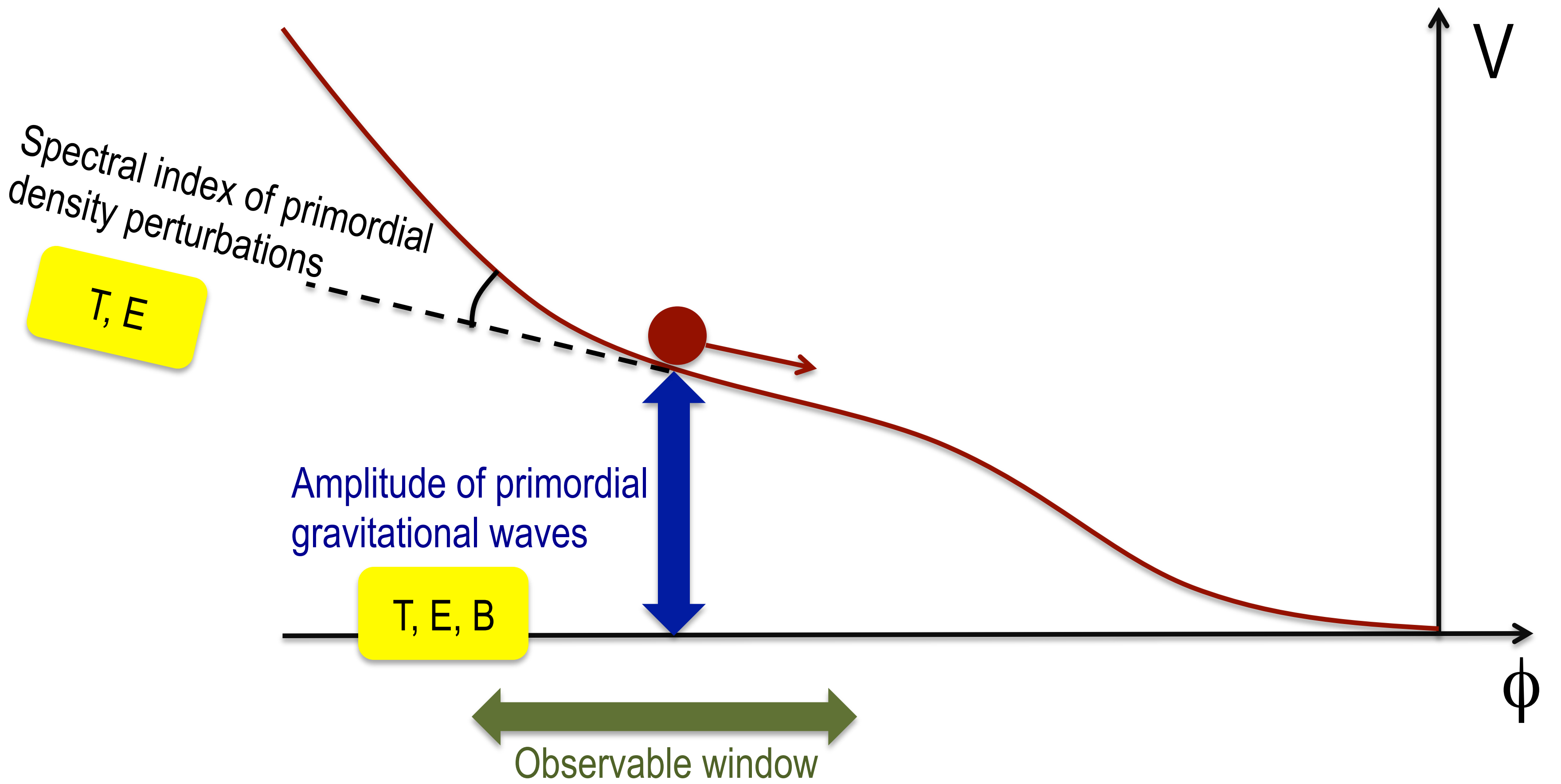
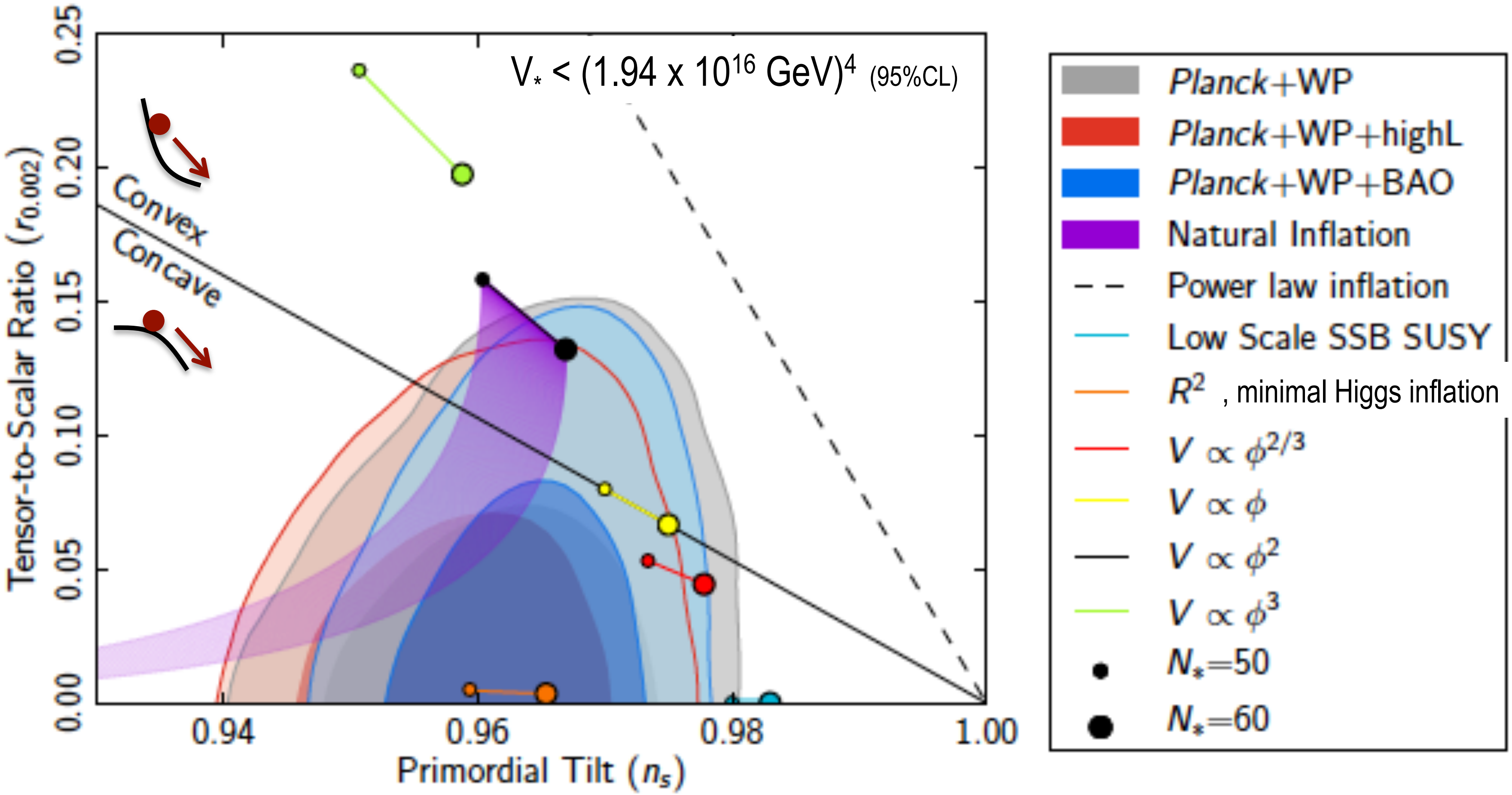
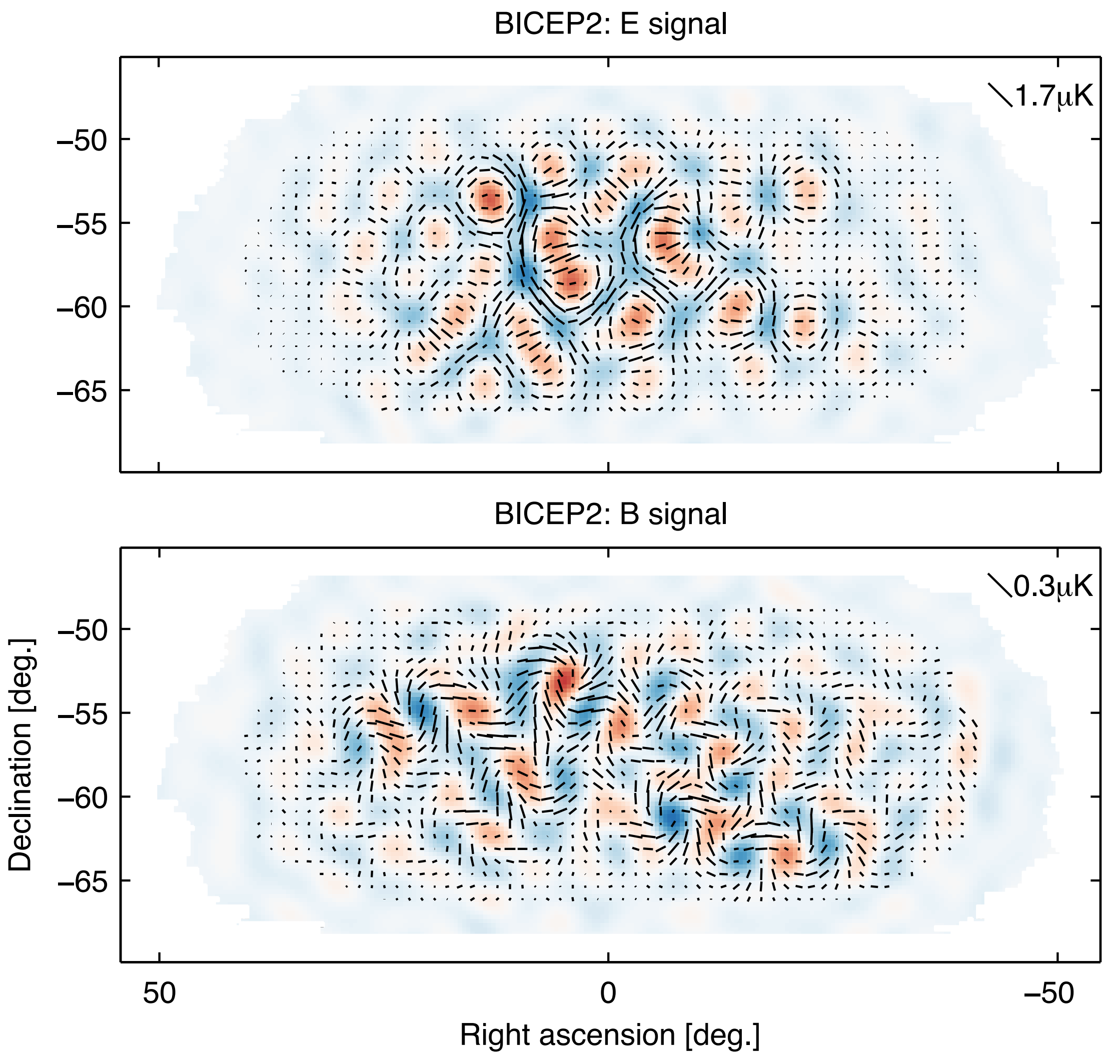


Inflationary model status in 2013

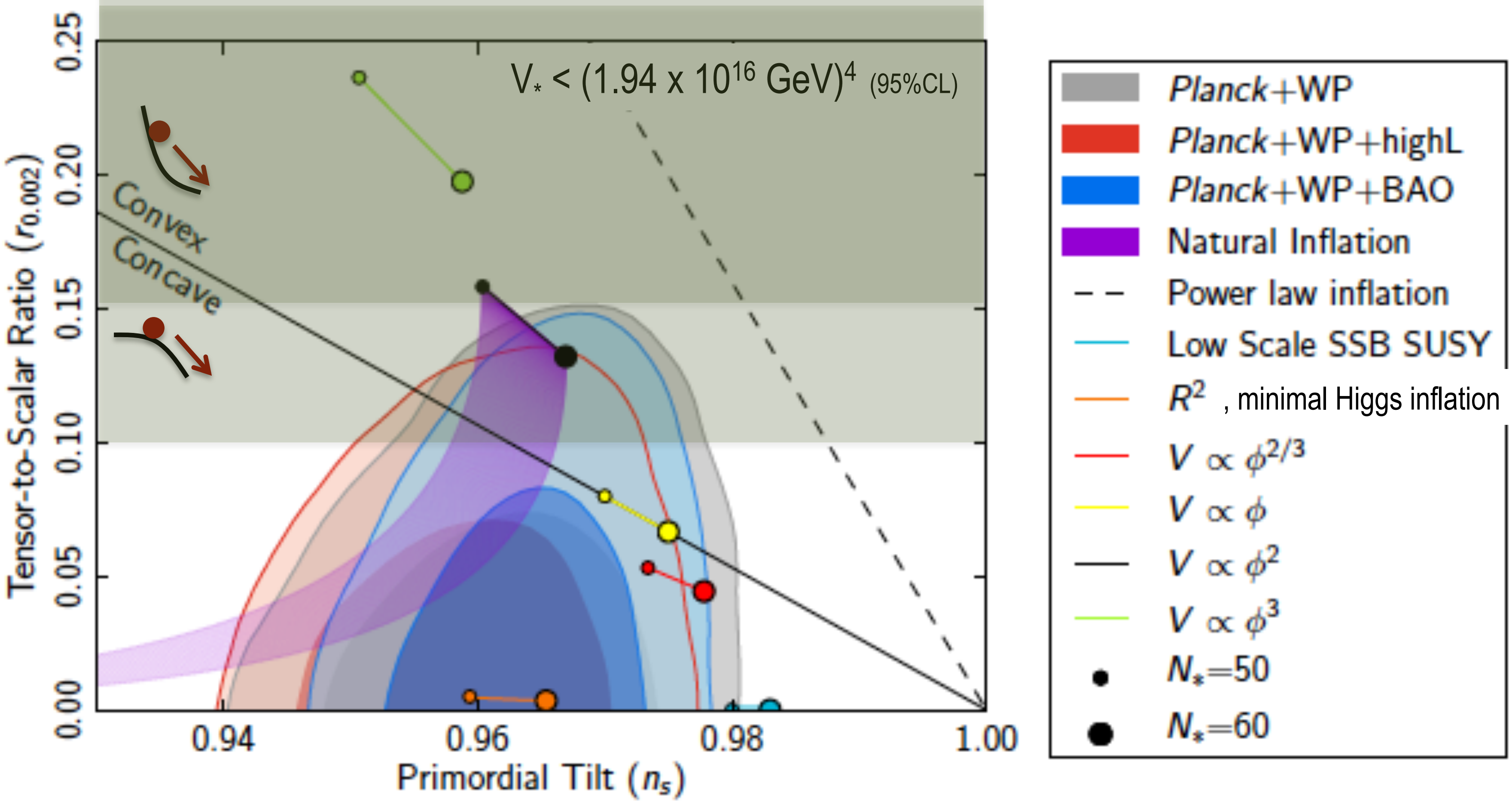


- Also OK: Hill-top with p=2 or p≥4; also disfavored: inverse power-law

March 2014: BICEP2



BICEP2 B-modes interpreted as gravity waves



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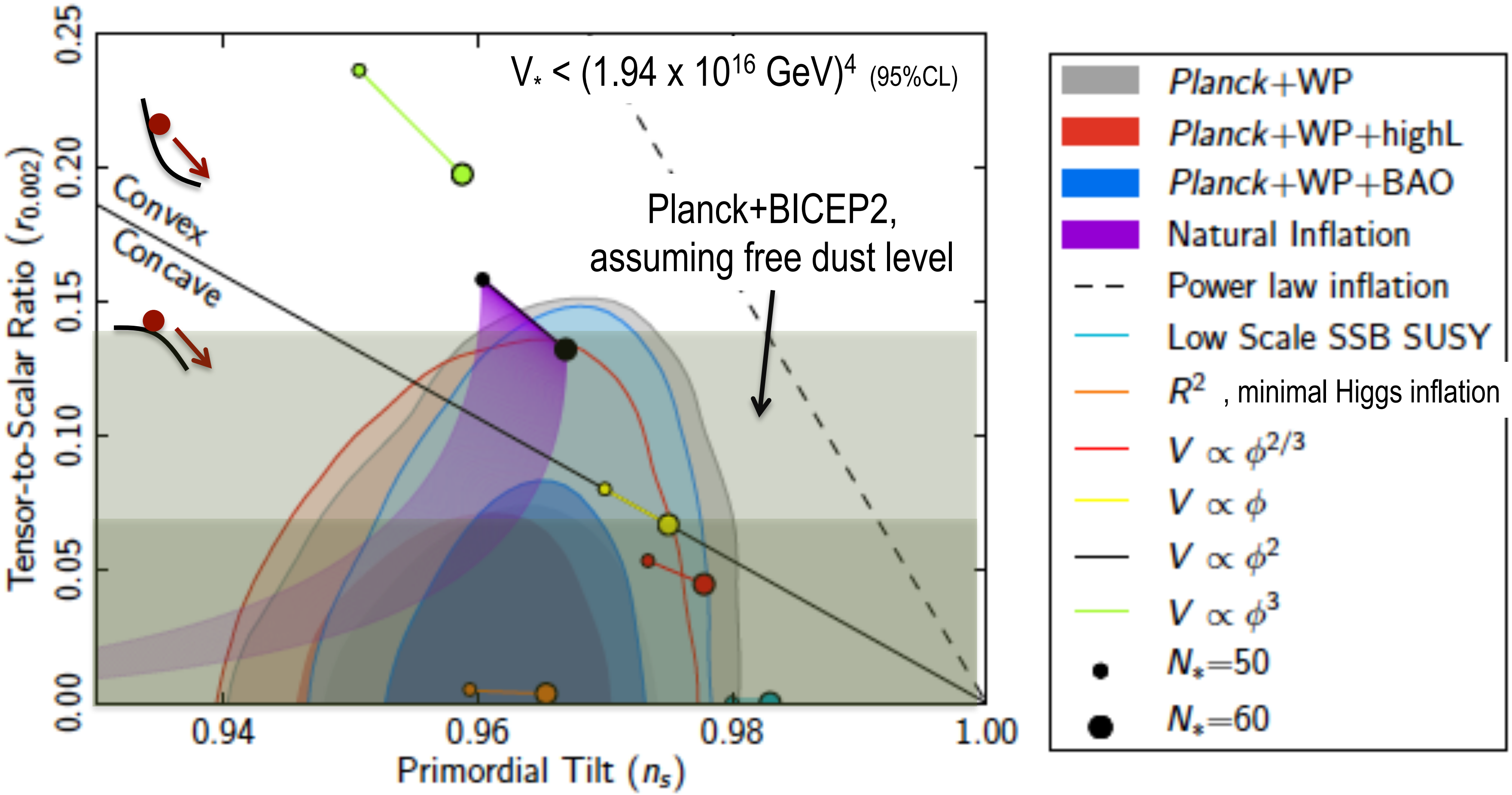
BICEP2 B-modes interpreted as dust + GW



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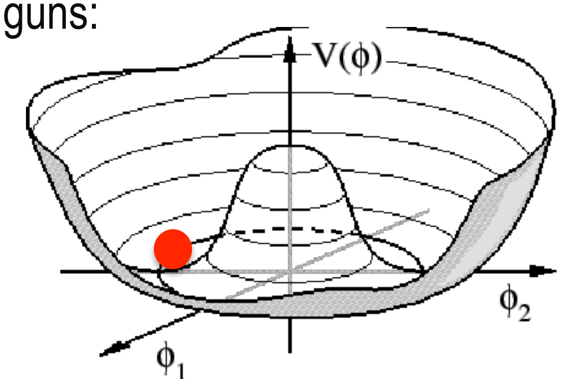
When will we know ?

- August/September 2015: Planck paper on level of polarised dust in BICEP2 region
- September/October 2015: joint Planck+BICEP2 paper on C_l^{BB} after dust removal
- November 2015: new Planck papers, using full Planck data + BICEP2 and other CMB data, with new r constraints from T, E, B
    - Situation could be conclusive (e.g. $r = 0.?? \pm 0.04$ at 1σ), or just improved bound (e.g. $r < 0.04$ at 1σ)
- Few years: other ground based experiments, → $\sigma(r) \sim 0.01$
- 15 years: Lite Bird, Core…. $\sigma(r) \sim 10^{-3} \rightarrow 10^{-4}$

If GW interpretation confirmed…

- Energy scale of inflation T~10^{16}GeV !!!
- Challenges for QFT (super-Planckian excursion), string theory, etc.
- Most probably, highest temperature in universe after reheating was T~$10^{13\text{-}15}$GeV !!! (no more "low-scale reheating", most particles thermalized)
- topological defects, phase transitions, magnetic fields…
- example of PQ axion: different (model-dependent) smoking guns:
  - 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:

- $H_{inflation} \sim 10^{14}$ GeV, $H_{reahting} \sim 10^{12\text{-}14}$ 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 $\qquad$ ($f_a \sim 7.5 \times 10^{10}$ GeV) $\qquad$ see arXiv:1405.1860

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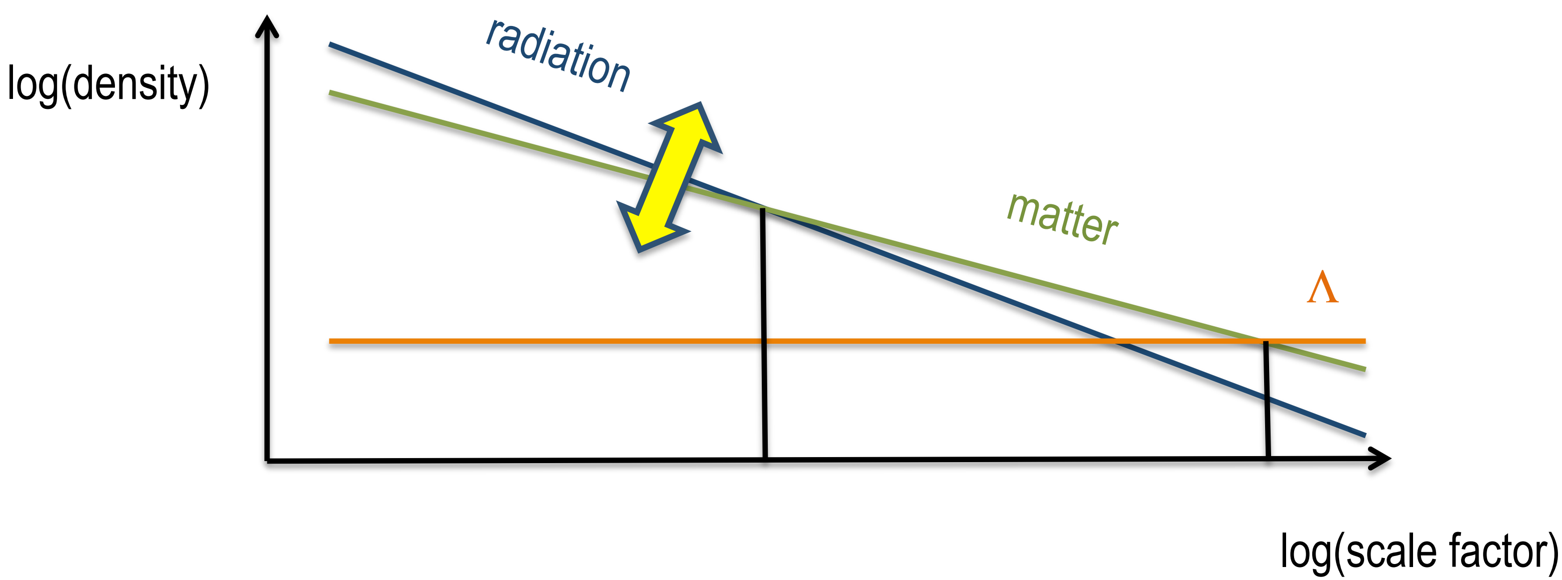
CERN

Neutrinos and other light/massless relic particles

Cosmology could probe light relics 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 $m \ll 0.01$eV]



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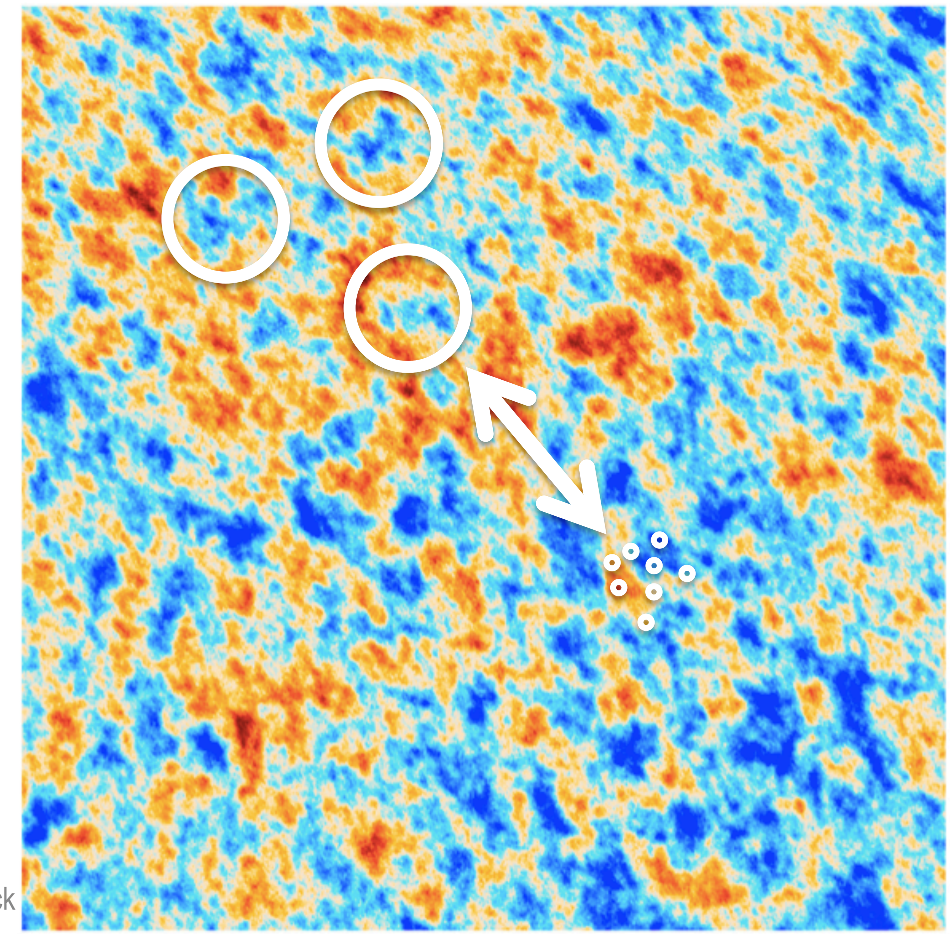

Several effects on CMB

- impact on expansion
- γ gravitational interactions

Cosmology could probe light relics if their density is sufficient:

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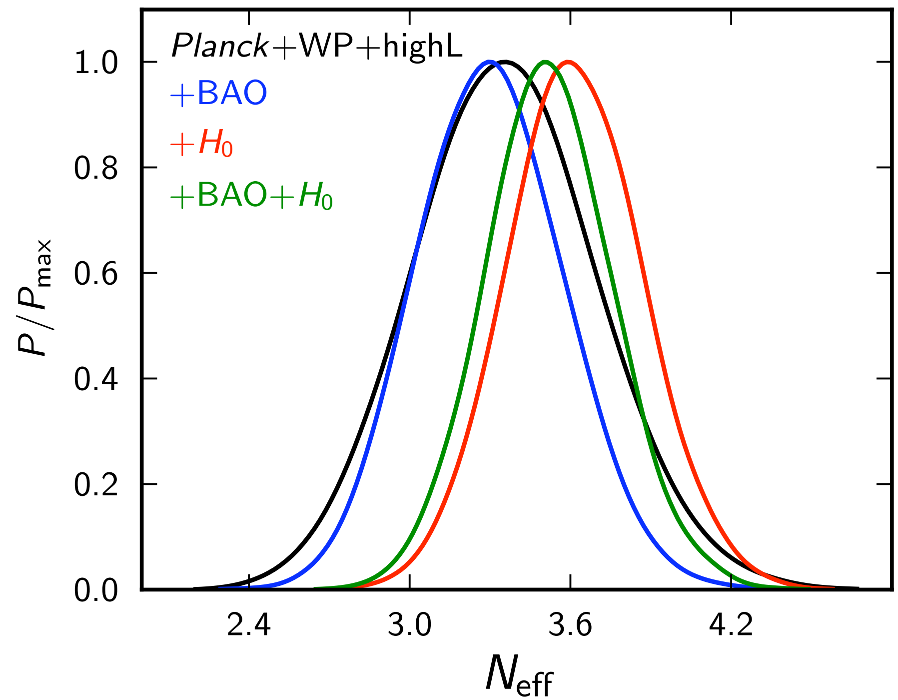
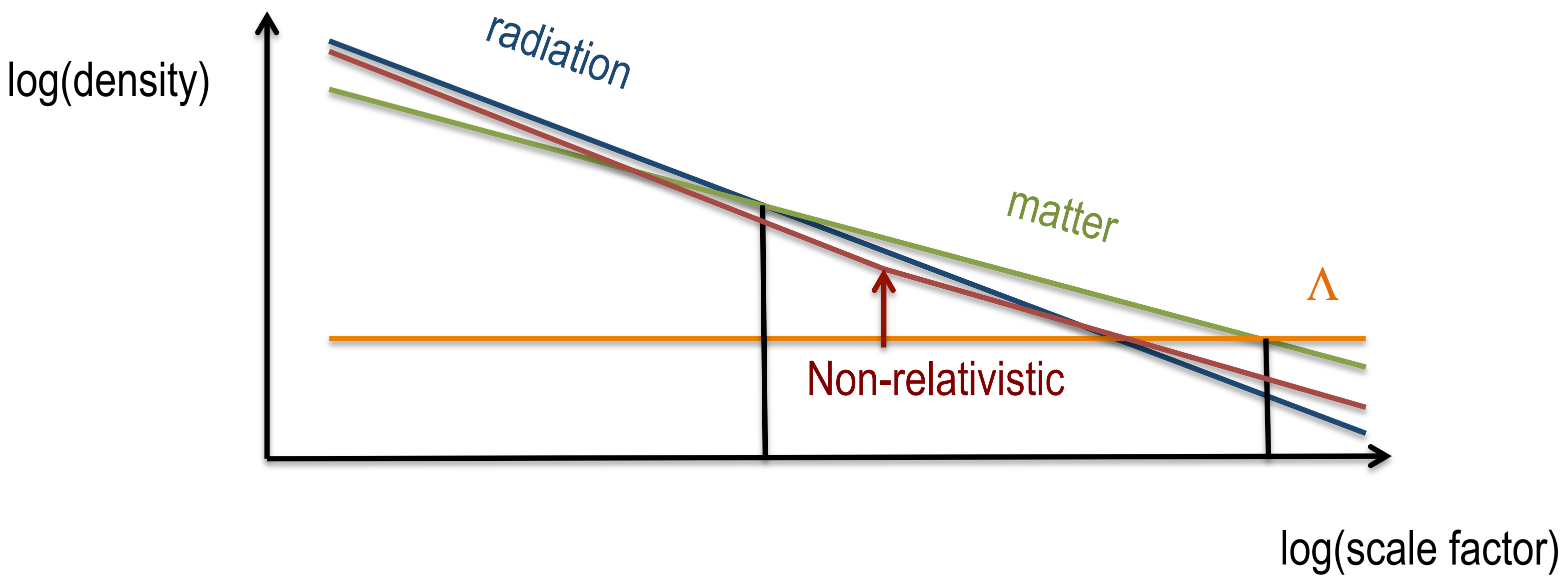
Planck compatible with 3

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



Cosmology could probe light relics 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]



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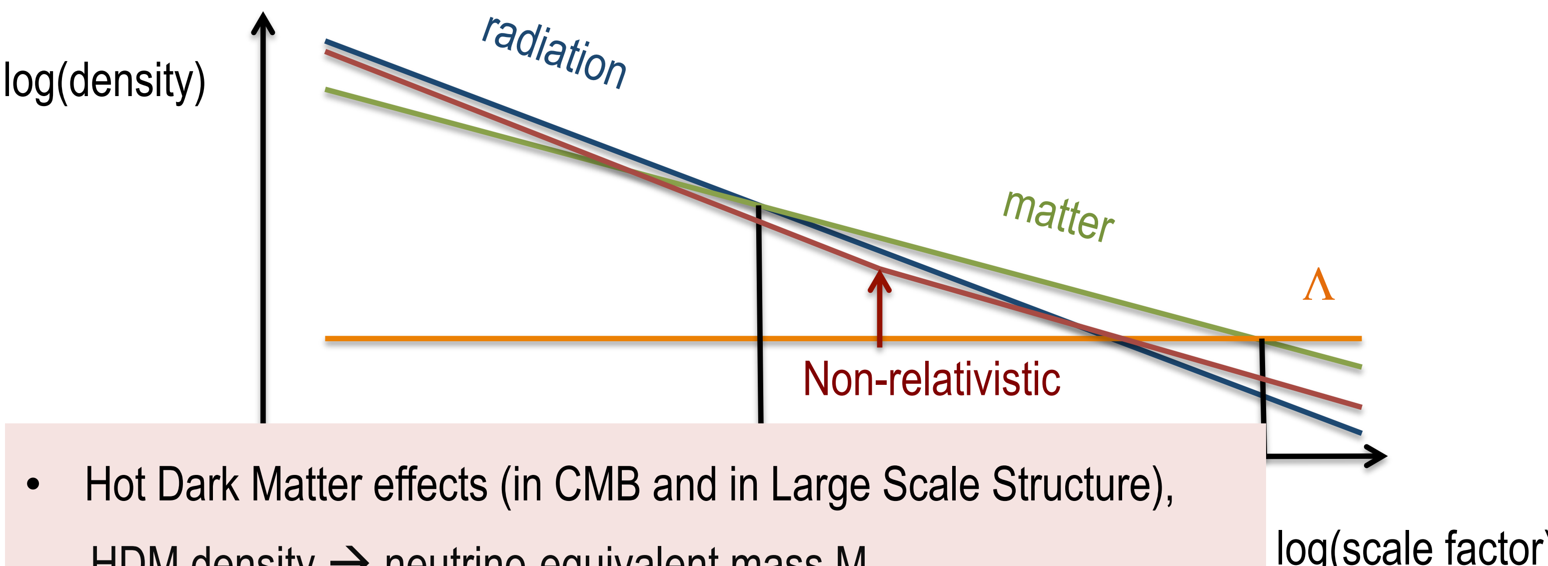

- Hot Dark Matter effects (in CMB and in Large Scale Structure), HDM density → neutrino-equivalent mass M_{eff}
- Enhancement of N_{eff} >1 if this mass comes not only from neutrinos

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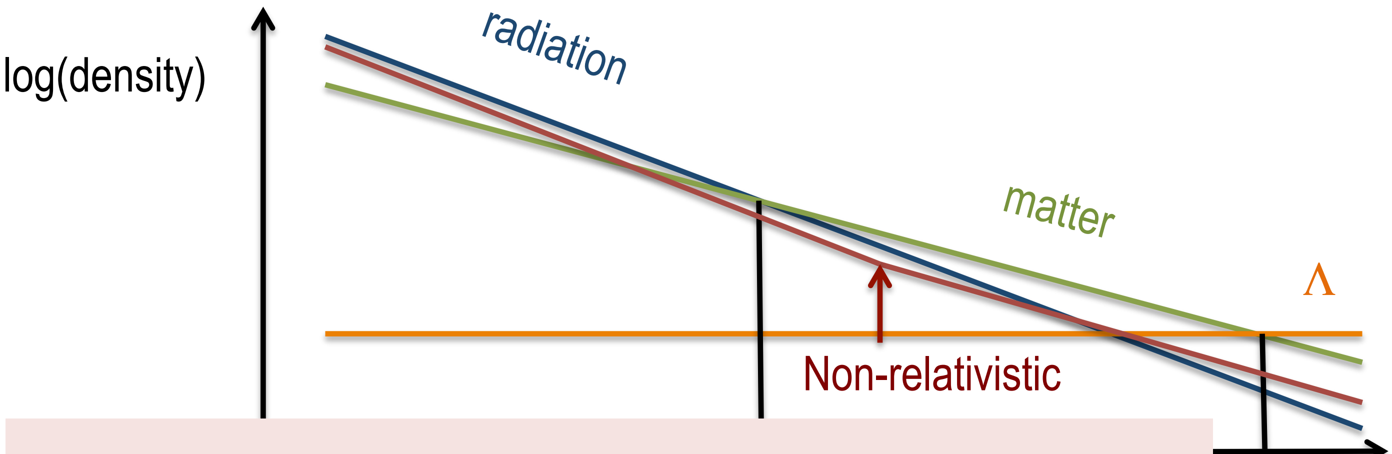


- Impact on N_{eff} >1
- Hot Dark Matter effects (in CMB a

HDM density → neutrino-equival M_{eff}

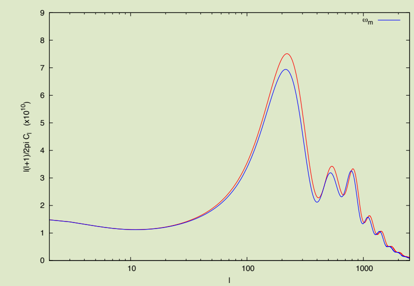
M_{eff} < 0.23 eV or M_{eff} ~ 0.3-0.5 eV ?

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

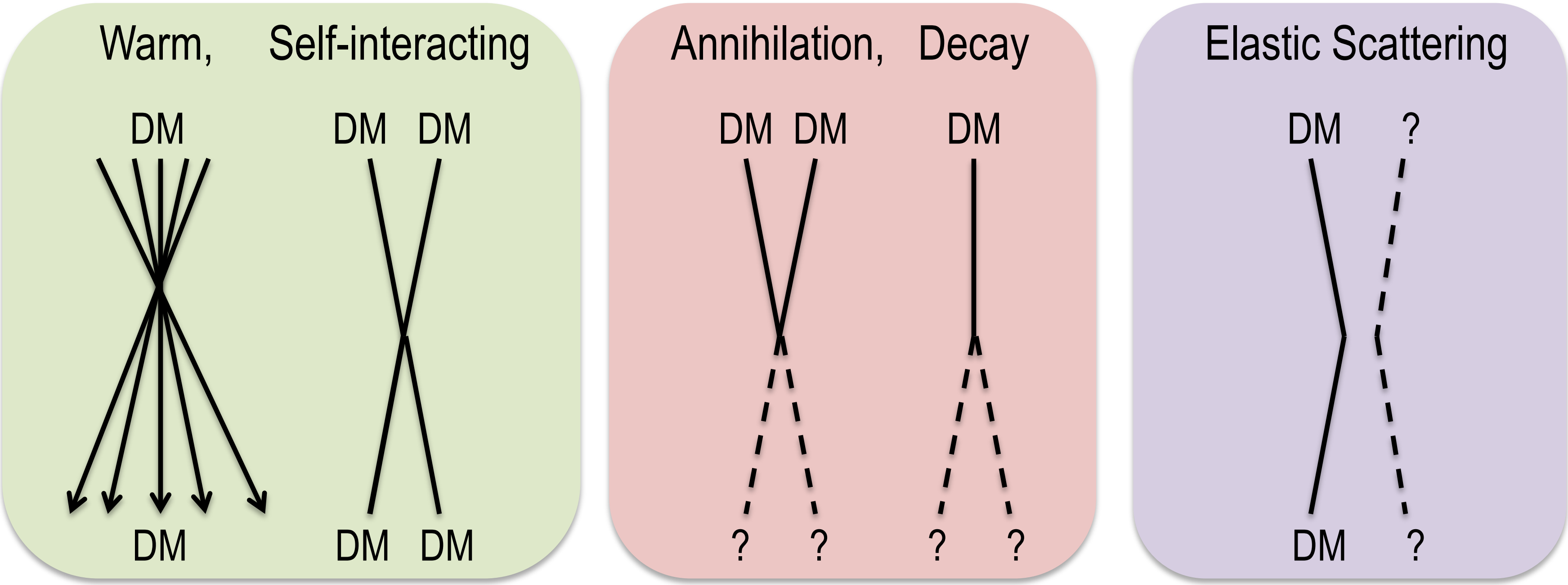
CMB/LSS and nature of (dominant) Dark Matter

- 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;
  - …

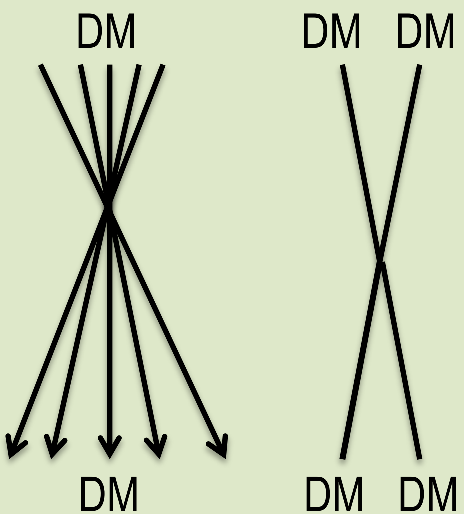
?

Possible properties of DM

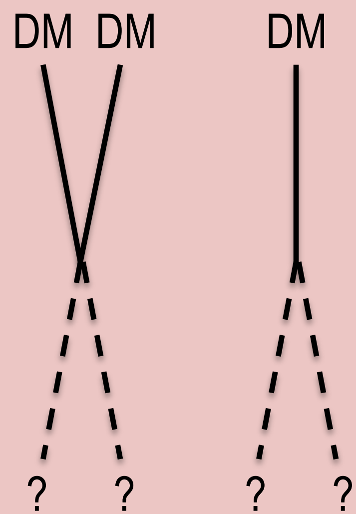


Possible properties of DM

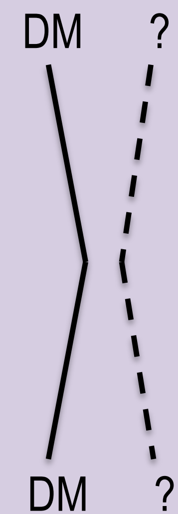
Warm, Self-interacting



Annihilation, Decay



Elastic Scattering

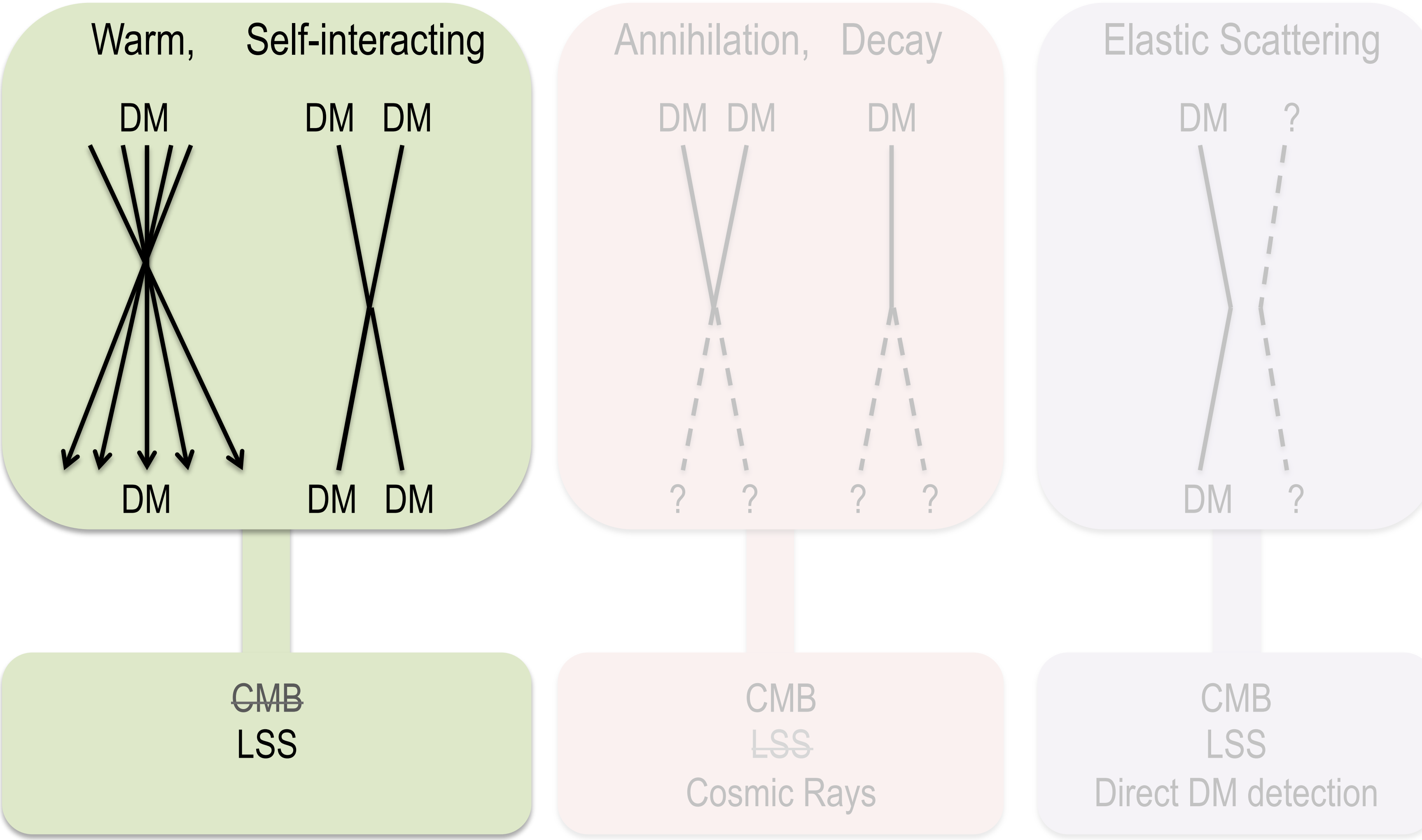


~~CMB~~
LSS

CMB
~~LSS~~
Cosmic Rays

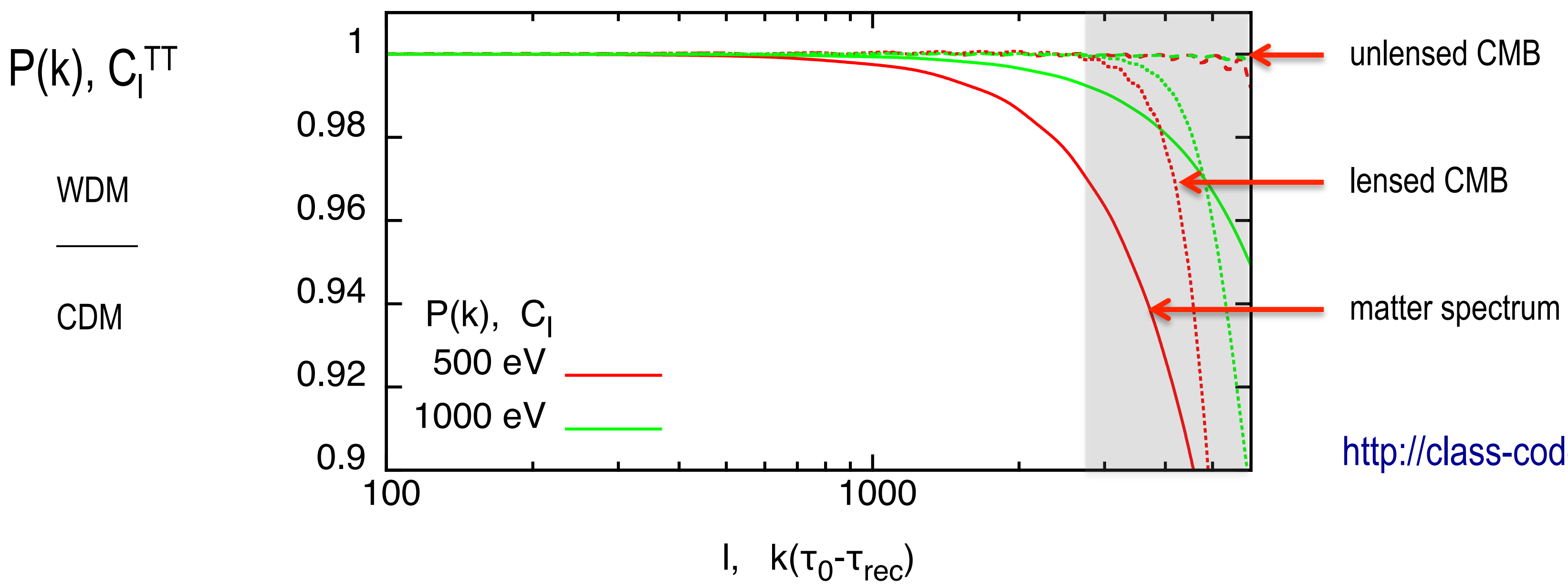
CMB
LSS
Direct DM detection

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)



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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**

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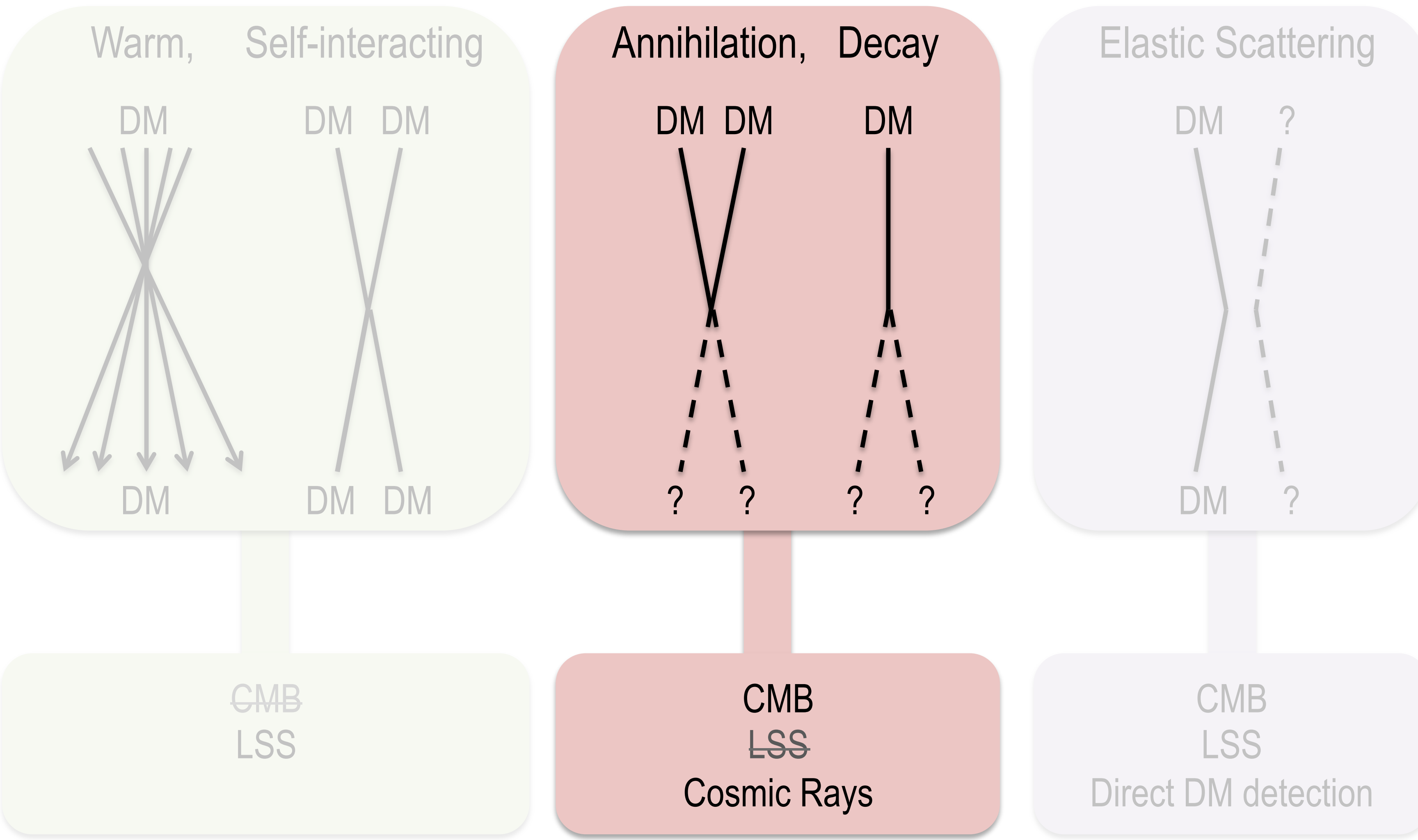
Decay in $\gamma+\nu_a$ constrains (m, θ)

- 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

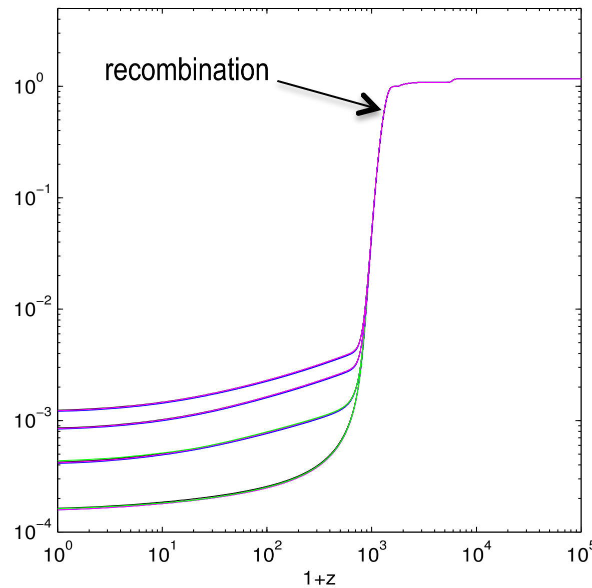
  (unless 100% in neutrinos)

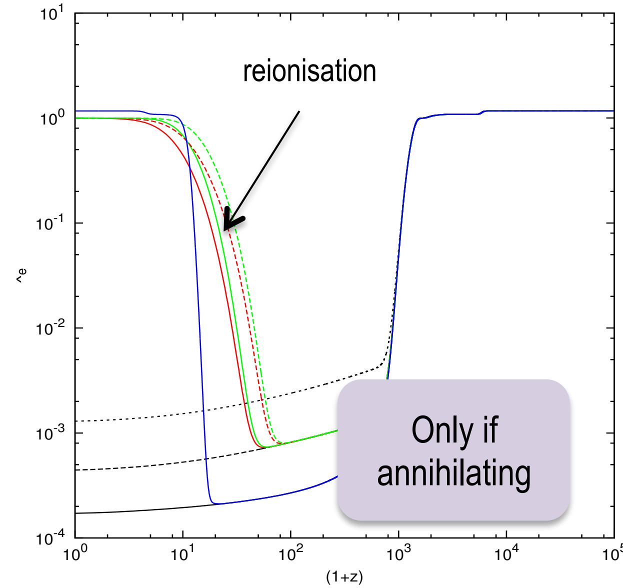
- Modification of recombination and reionisation history
- Effects depends on cross-section over mass σ/m or lifetime τ , and on annihilation/decay channel

- DM → neutrinos and/or lighter sterile species (dark sector)
  - Non-conservation of $\rho_m a^3$: direct effect on matter power spectrum, indirect effect on CMB (integrated Sachs-Wolfe effect)

Case 2: annihilating or decaying

ionisation fraction





1+z

1+z

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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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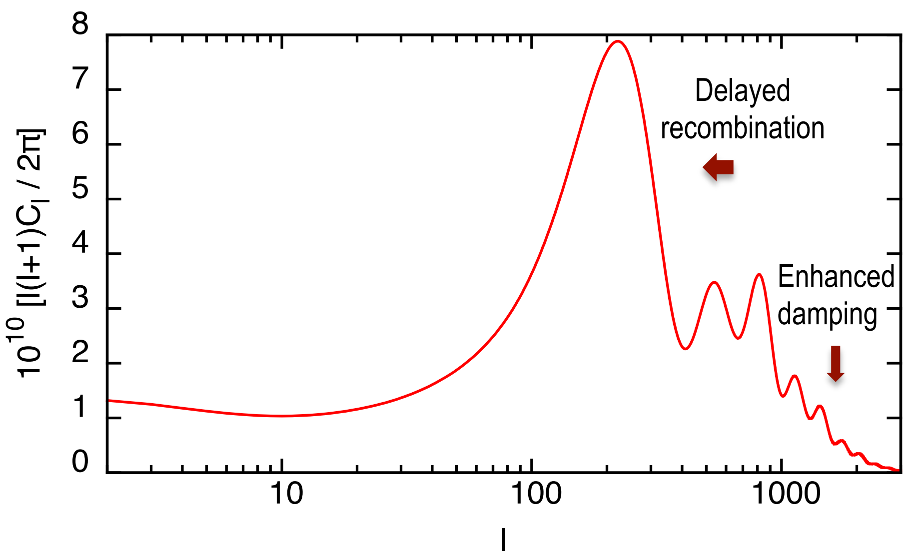

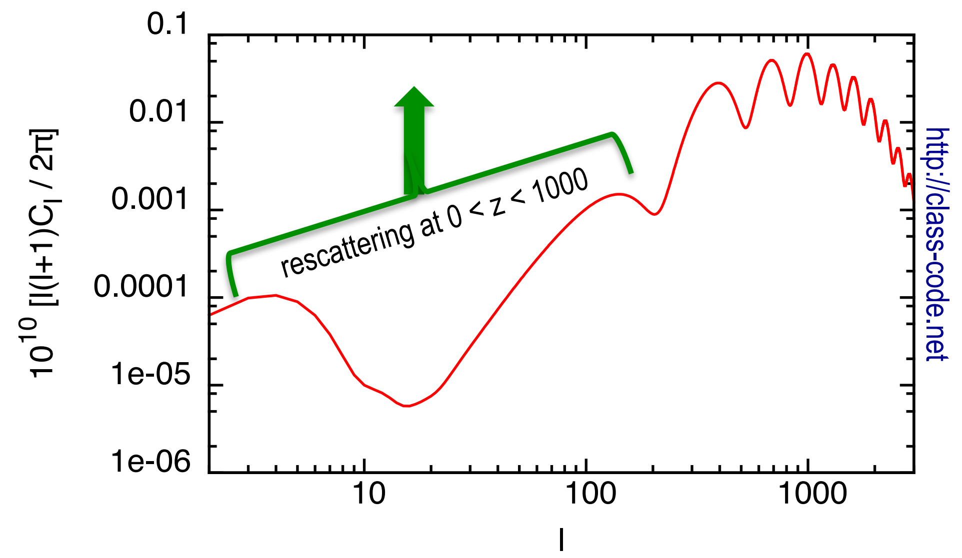

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Case 2: annihilating or decaying

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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

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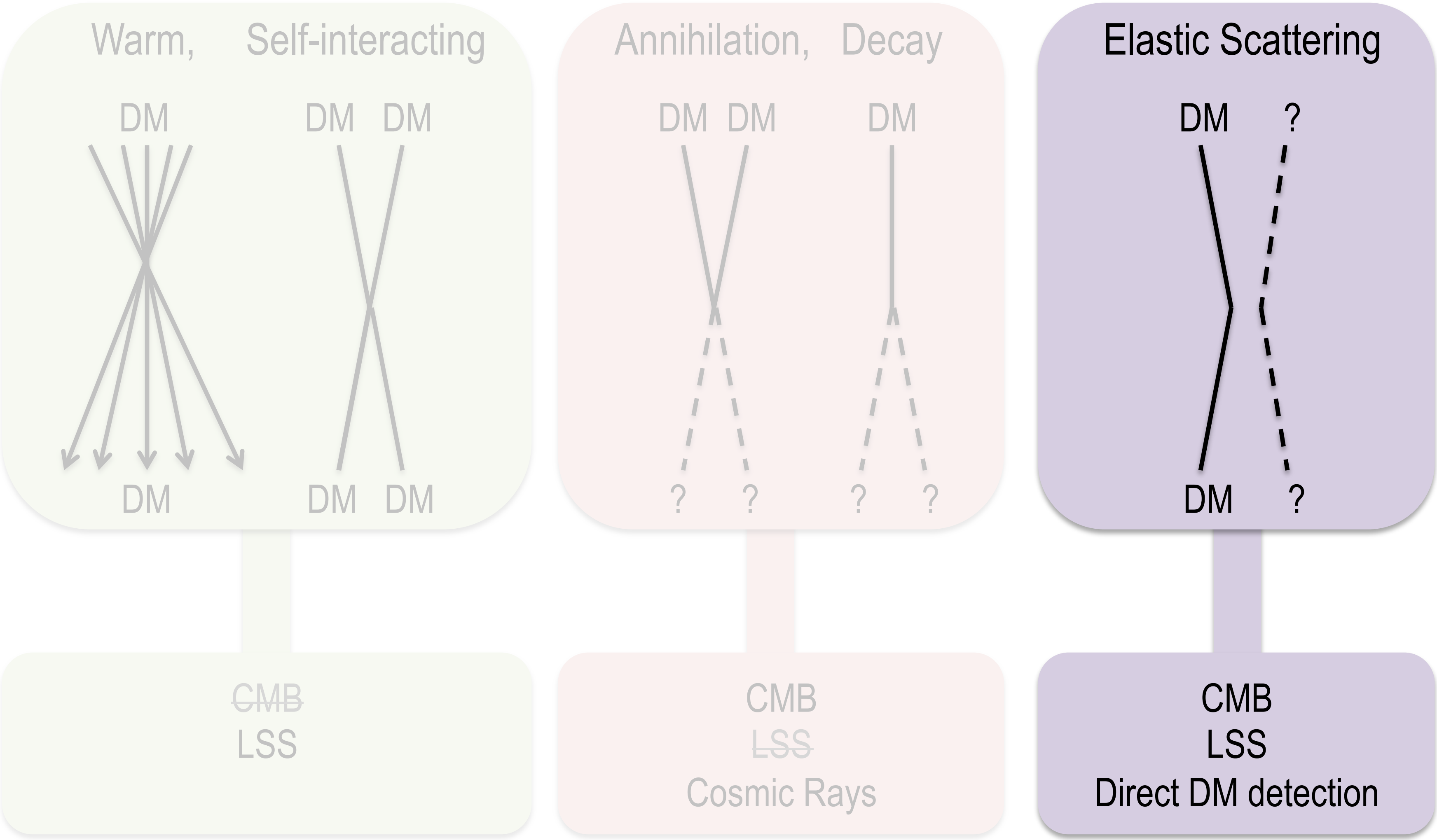
Decay into photons and charged particles: not as strong as cosmic ray bounds

Decay into neutrino or dark sector: T > 160 Gyr (95%CL) Audren et al. 2014

Case 3: DM interactions (elastic scattering)



Case 3: DM interactions (elastic scattering)

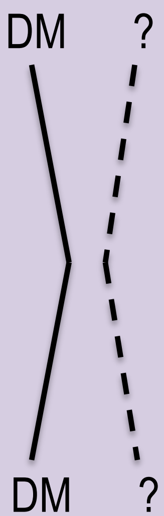
- For WIMPS: weak interactions (with quarks, neutrinos) too small to leave any signature on CMB/LSS

- 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



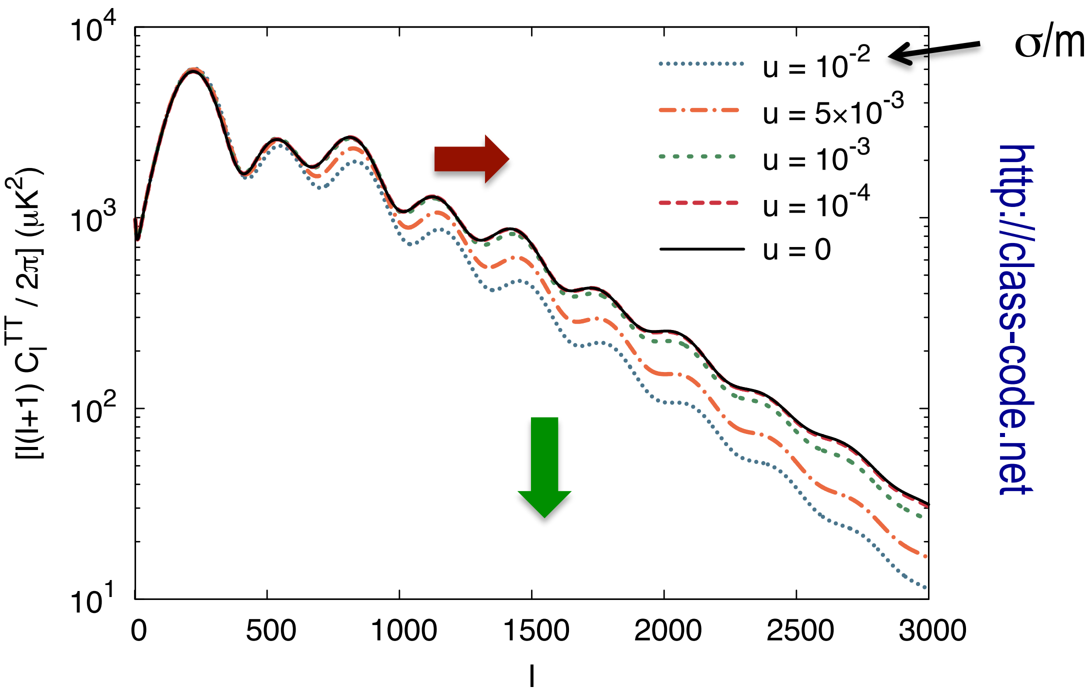
CMB
LSS
Direct DM detection

Case 3: DM interactions (elastic scattering)

- DM-photons

Wilkinson, JL & Boehm 1309.7588

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

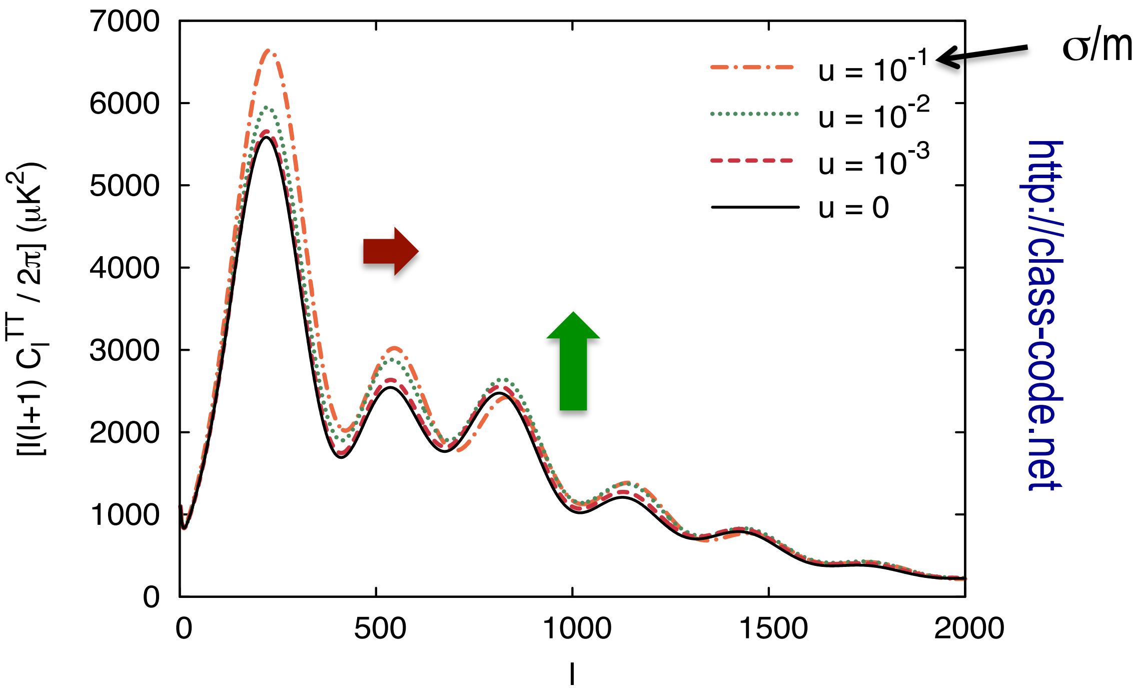


Case 3: DM interactions (elastic scattering)

- 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

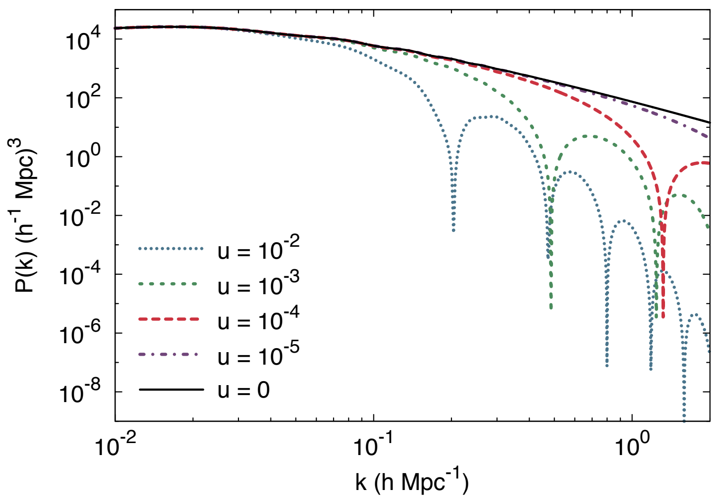
…

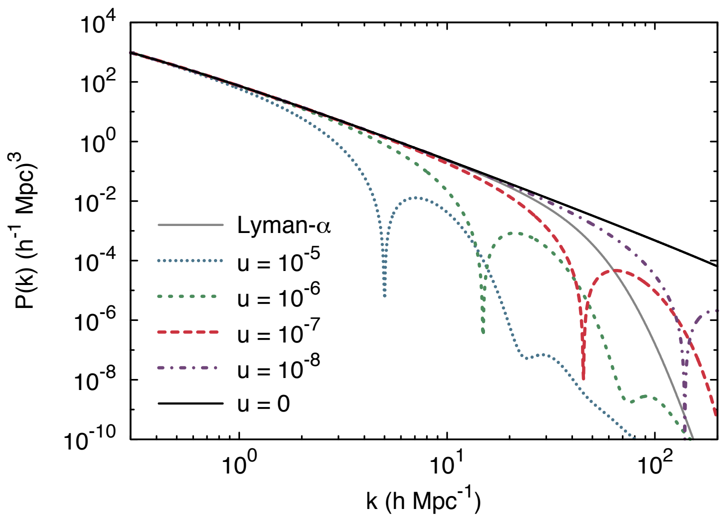
Case 3: DM interactions (elastic scattering)

Also effects in matter power spectrum:

DM-photons

DM-neutrinos





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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 light relic masses
- DM annihilation
- Plenty of other things…