Bielefeld Kosmologie Tag, 19.05.2017

Cosmological constraints on the nature of Dark Matter

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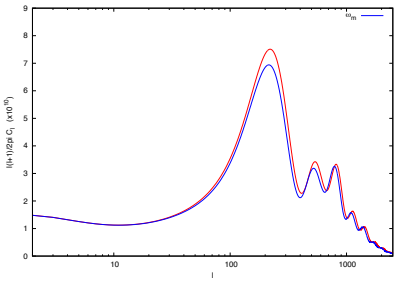
Dark Matter relic density

CMB: 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~0.0223, ω_m~0.1411, need ω_{dm}~ 0.1188 ± 0.0010 (68%CL) : 119σ detection!

Planck 2015

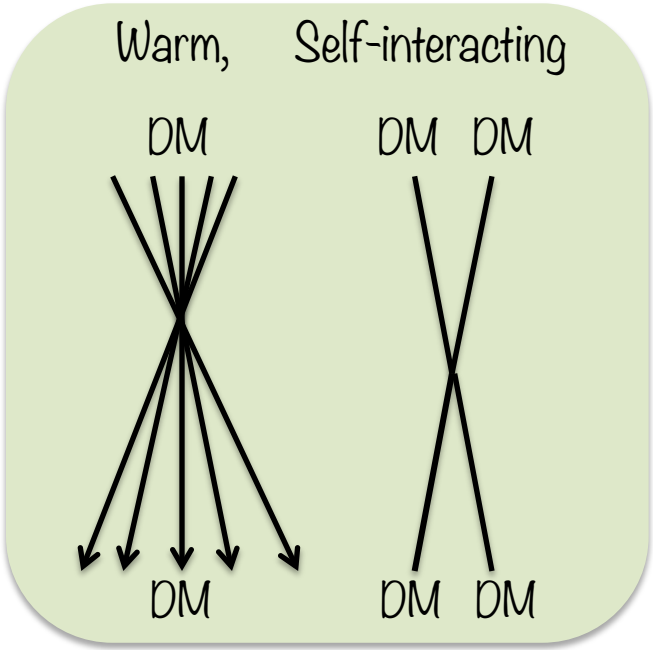
- Supported by Large Scale Structure (matter spectrum shape) and astrophysics

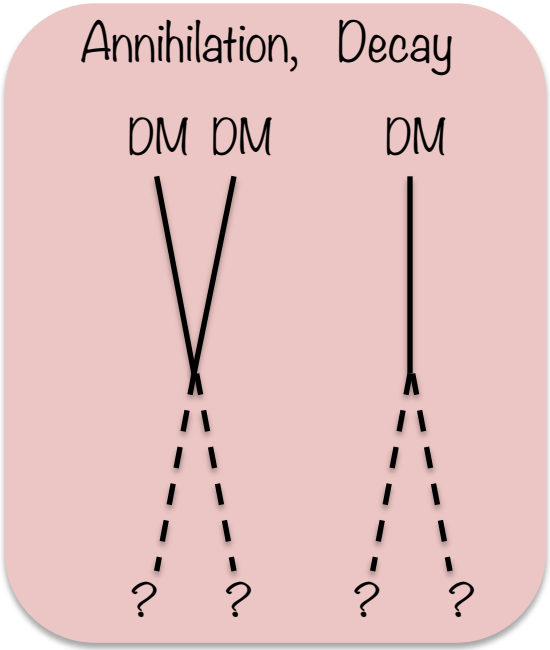
CMB/LSS and nature of (dominant) Dark Matter

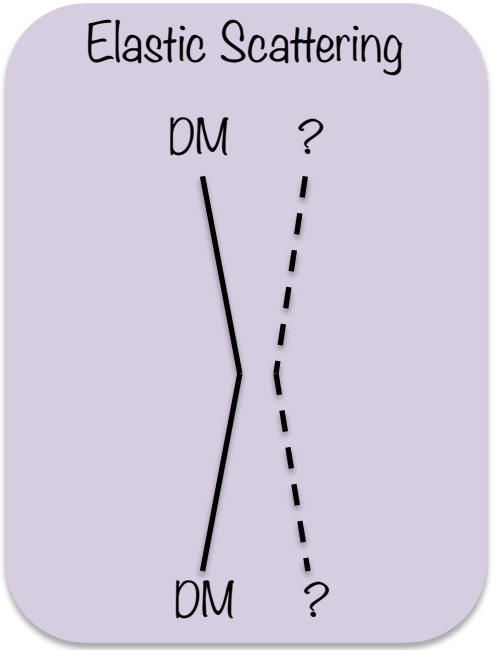
- For CMB and LSS: Dark Matter required to be
  - not interacting as much as ordinary electromagnetic interactions
  - not hot (small velocities)

- but totally unknown nature:
  - WIMPS, non-weakly interacting;
  - annihilating, decaying, stable;
  - cold or warm;
  - collisionless, self-interacting;
  - oscillating scalar field (axion);
  - Ultra-light scalar field (fuzzy dark matter)
  - ...

Possible properties of DM







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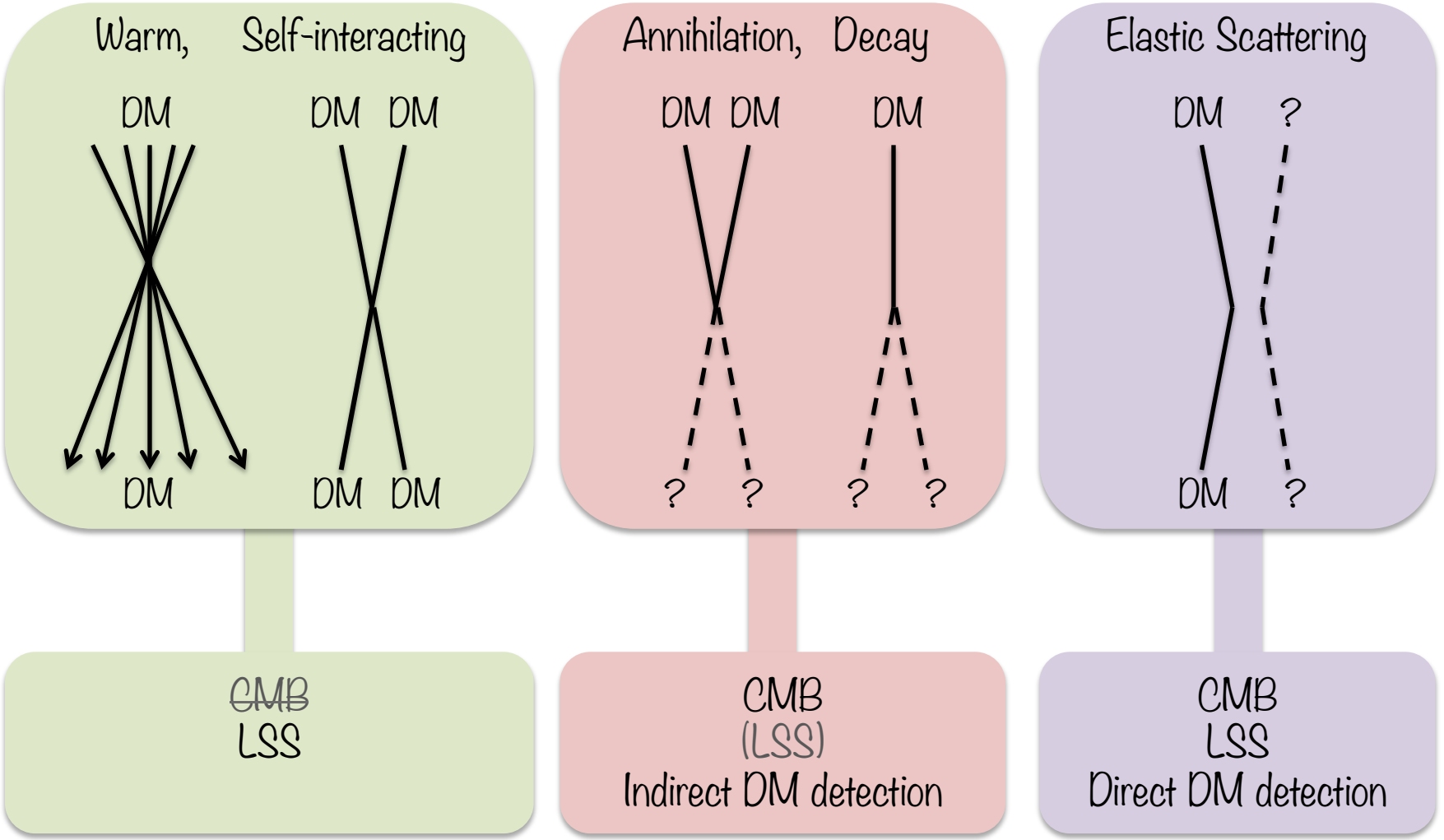
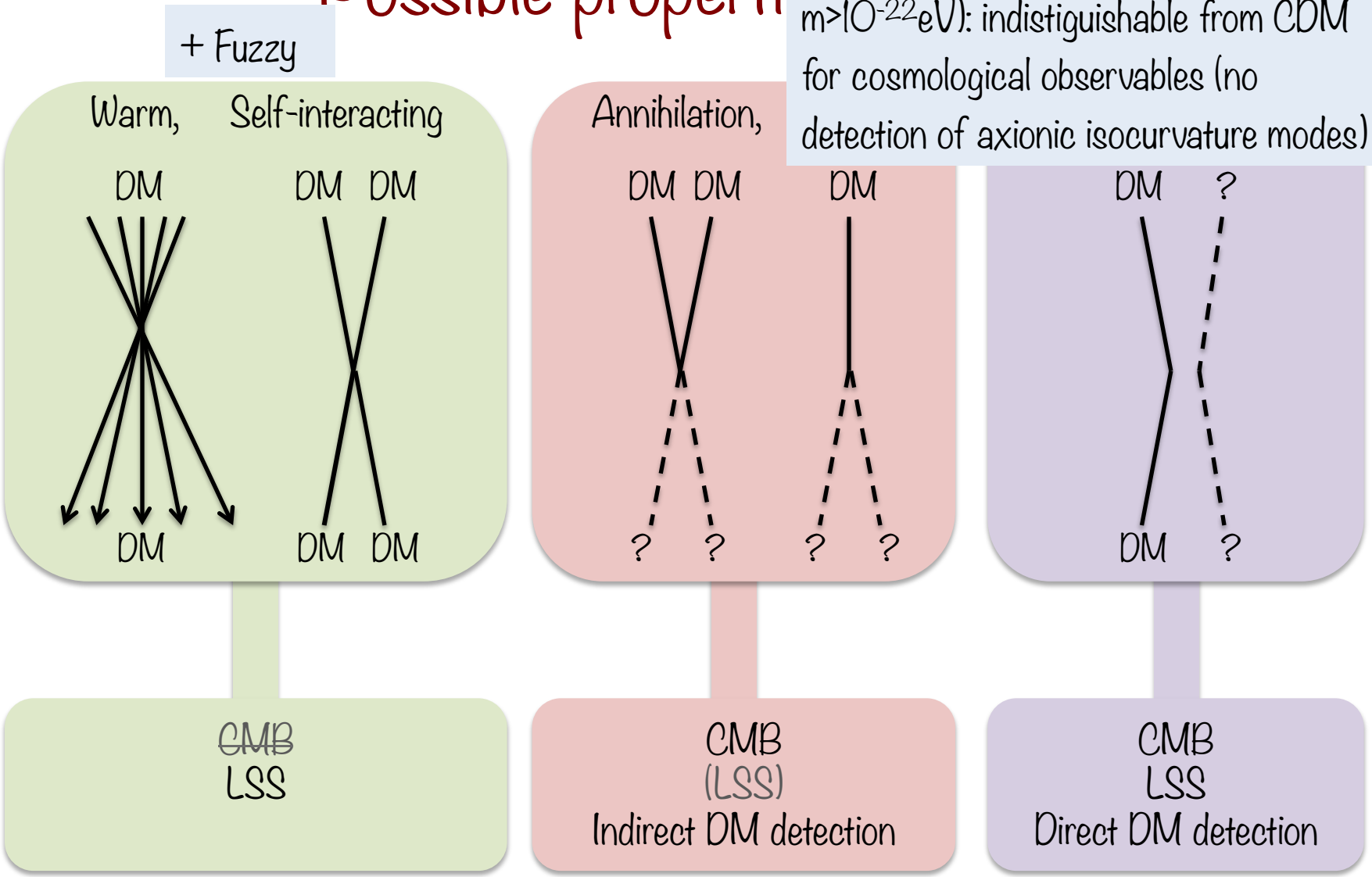


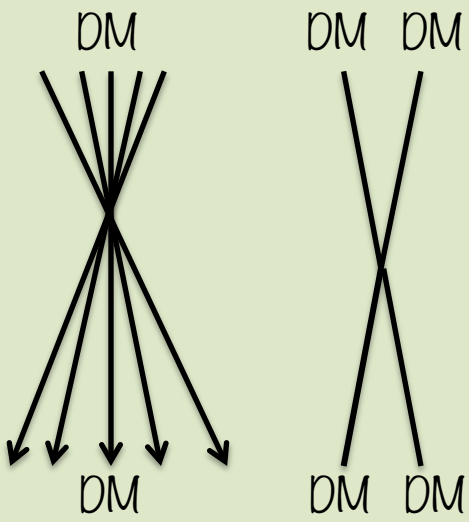
Possible properti

Oscillating scalar field (axion with $m>10^{-22}$eV): indistiguishable from CDM for cosmological observables (no detection of axionic isocurvature modes)



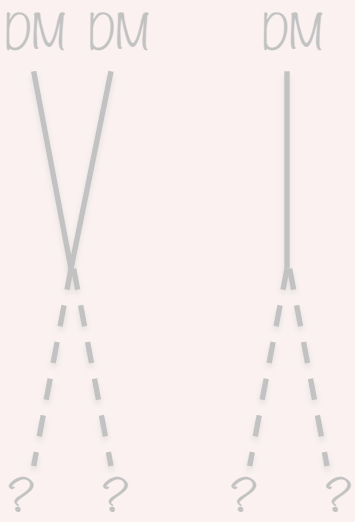
Possible properties of DM

Warm, Self-interacting



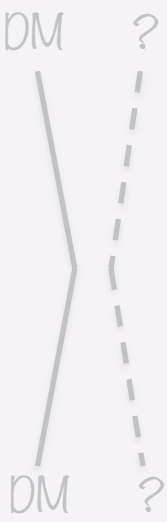
~~CMB~~
LSS

Annihilation, Decay



CMB
(LSS)
Cosmic Rays

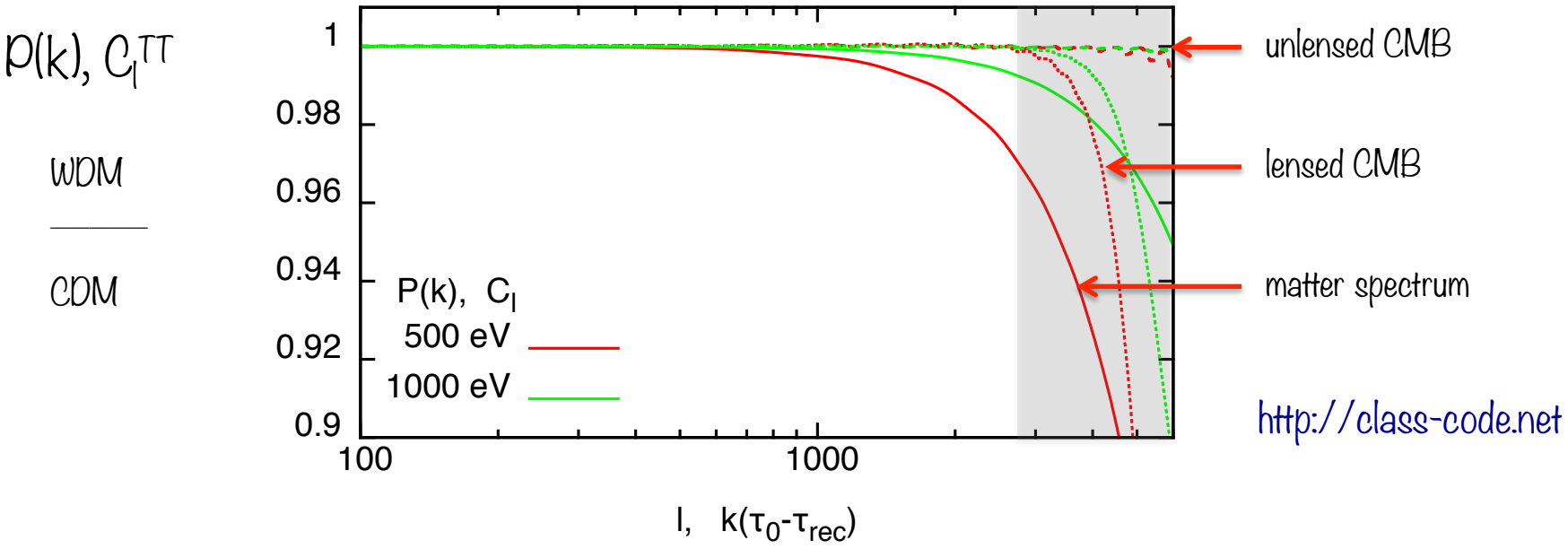
Elastic Scattering



CMB
LSS
Direct DM detection

Case I: 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

Weinberg 2003; Voruz et al., JCAP 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) Baur et al. 2015

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

  $m > 26$ keV (95%CL) Baur et al. 2015

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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

Bulbul et al. 1402.2301; Boyarsky et al. 1402.4119

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

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

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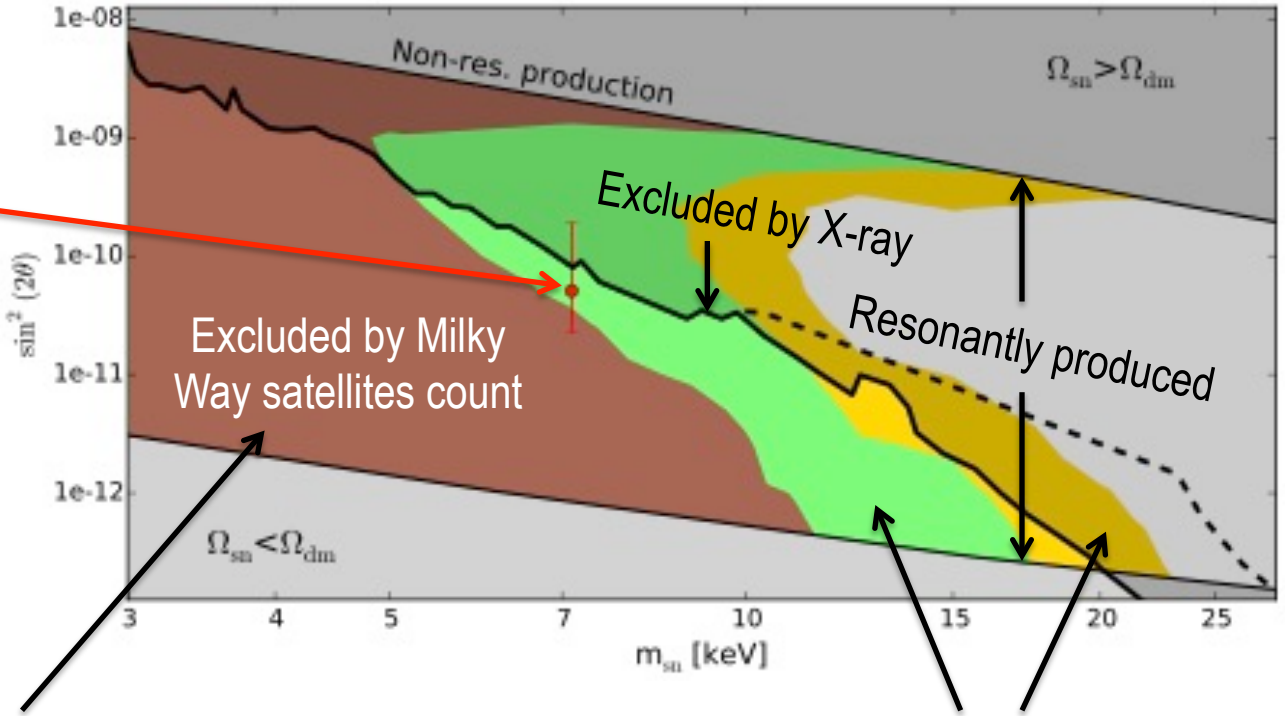
Case 1: warm or self-interacting

- Resonantly produced sterile neutrino also excluded by Lyα+X-ray according to Schneider 1601.07553



3.55keV line

Bounds assume sterile neutrinos accounting for all DM

Update by Cherry and Horiouchi 2017 now excludes 3.55keV line

Excluded by Lyα of Viel et al. 2013 / Baur et al. 2015, according to extrapolation method of Schneider; confirmed by Baur et al. in preparation

Case 1: warm or self-interacting

- Last chance for resonantly produced sterile neutrino as dominant DM component: a conspiracy with an underestimated systematics (IGM temperature evolution at high redhsift) Garzilli et al. 2015

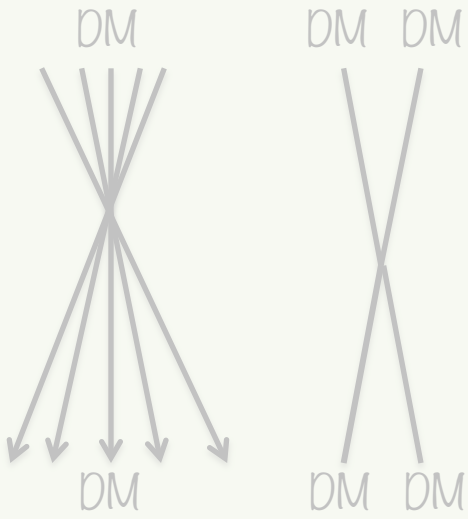
- Could still be a sub-dominant component; true for all these models of WDM, fuzzy DM, Ultra-light axions... Hlozek et al. 2016

- New methodology for Lyman-alpha and Milky way satellite constraints on warm dark matter, including RP sterile neutrinos, sterile neutrinos from particle decay, cold+warm DM, fuzzy DM and others: constraints on parameters of $T(k) = [1+(\alpha k)^\beta]^\gamma$

  Murgia et al. 2017

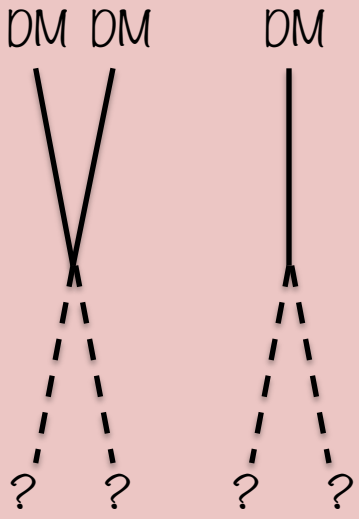
Possible properties of DM

Warm, Self-interacting



CMB
LSS

Annihilation, Decay



CMB
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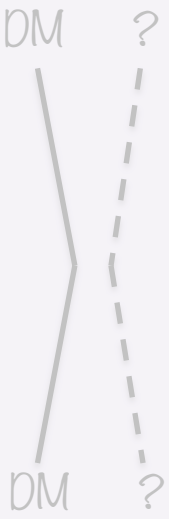


CMB
LSS
Direct DM detection

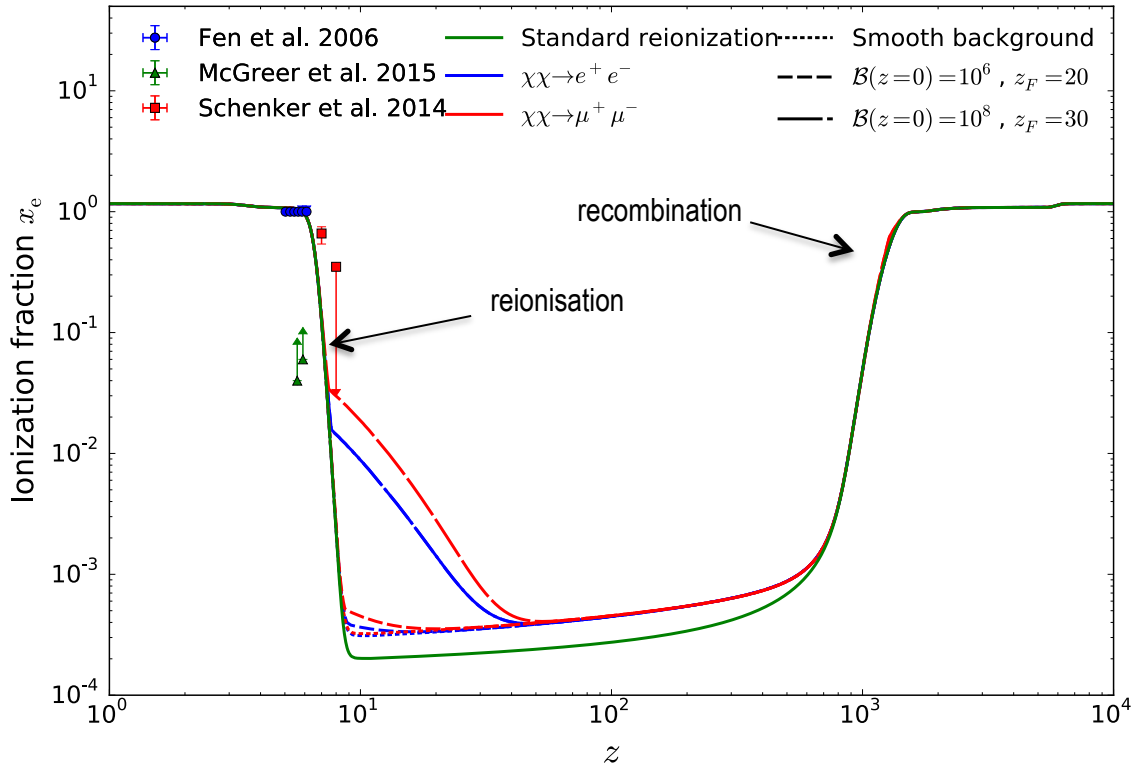
Case 2: annihilating or decaying

- DM → annihilation (or decay) in hadrons, leptons, gauge bosons → … → electrons, photons, protons
  - 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 t , and on annihilation/ decay channel

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

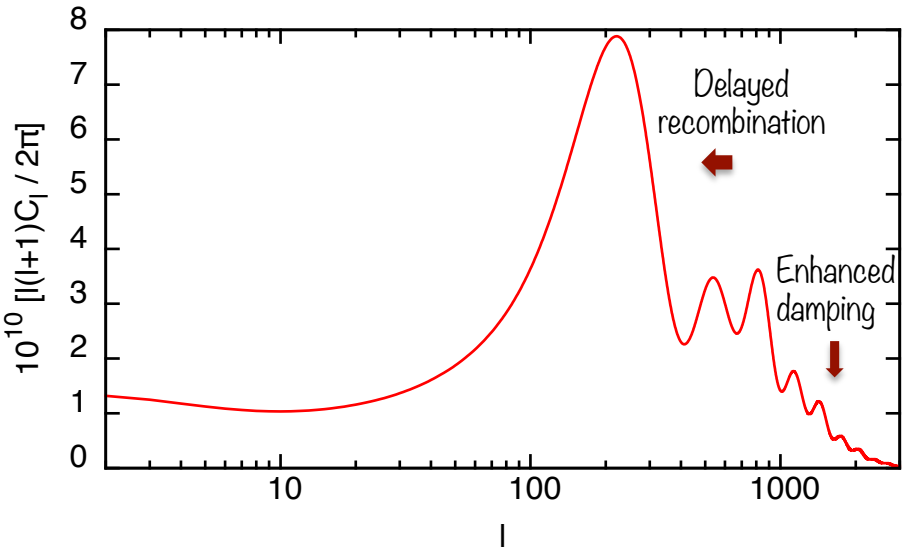
Case 2: annihilating or decaying

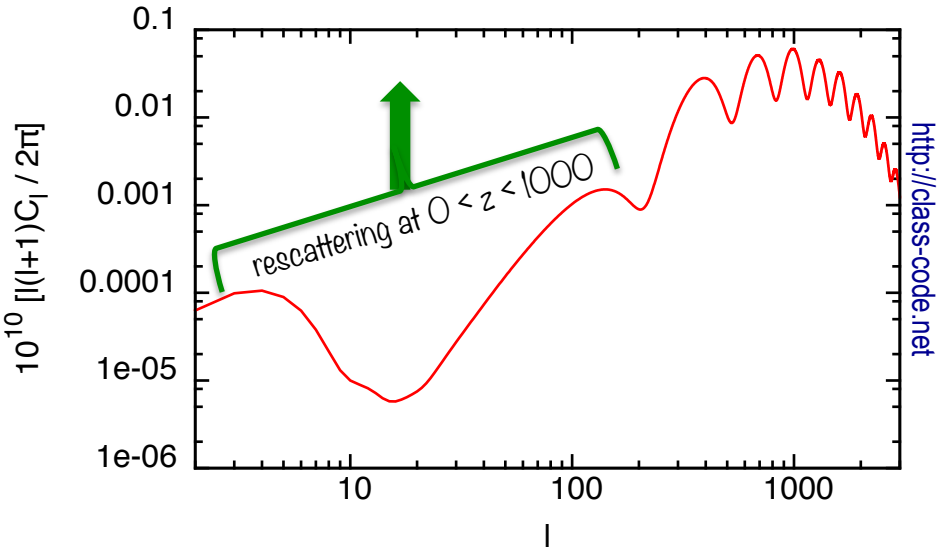


Modified thermal history in annihilation case

V. Poulin, P. Serpico, JL 2015
See also 1303.5094, etc.

Case 2: annihilating or decaying

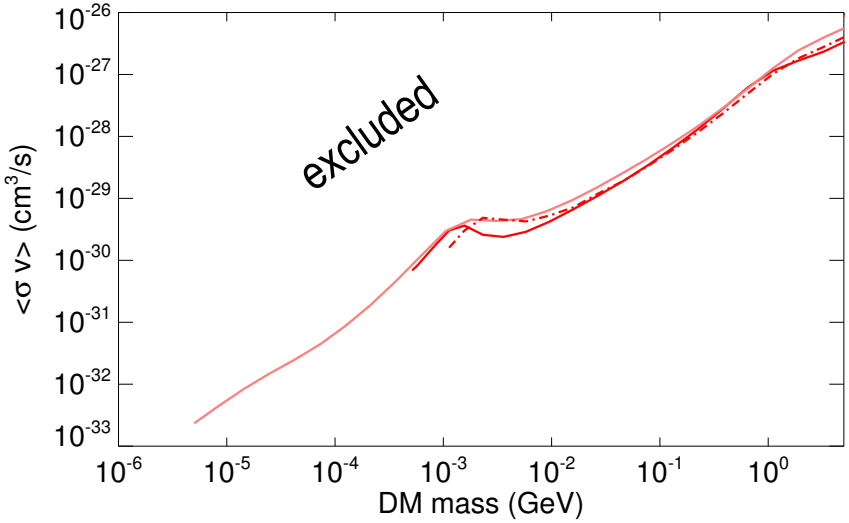




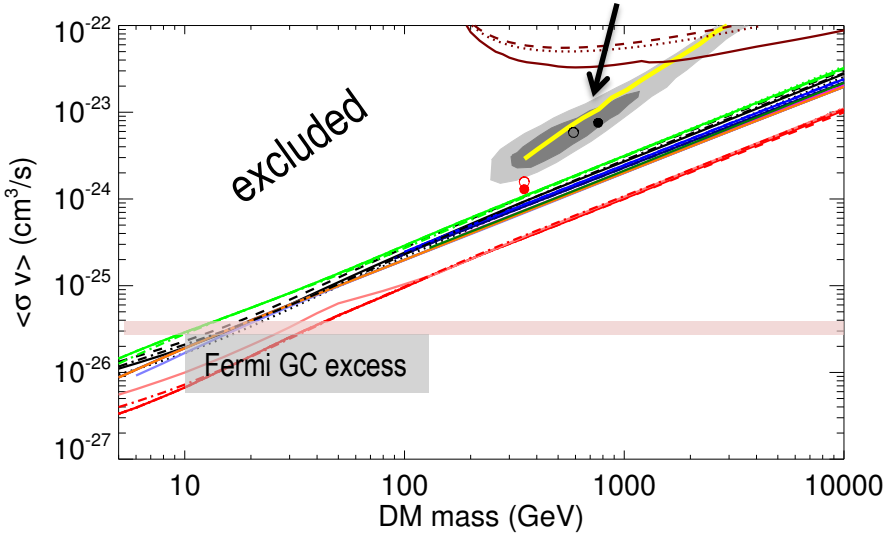
Modified CMB T and E spectrum in annihilation case

Quantity constrained by data: $f(z)\langle\sigma v\rangle/m$ or approx. $f_{eff}\langle\sigma v\rangle/m$ (depends on $z \sim 600$)

Case 2: annihilating or decaying

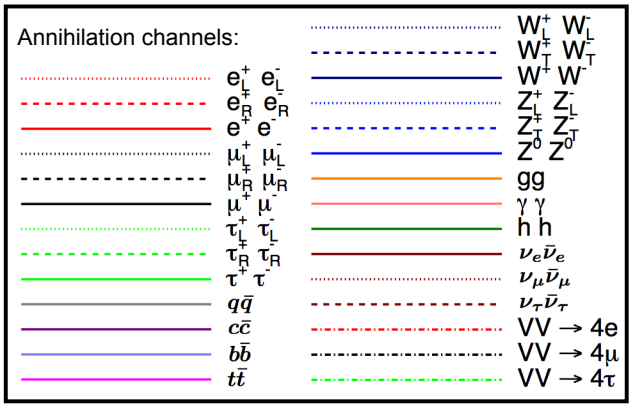


Pamela, Fermi, AMS-02
positron anomaly
(s-wave, Summerfeld enhanced)



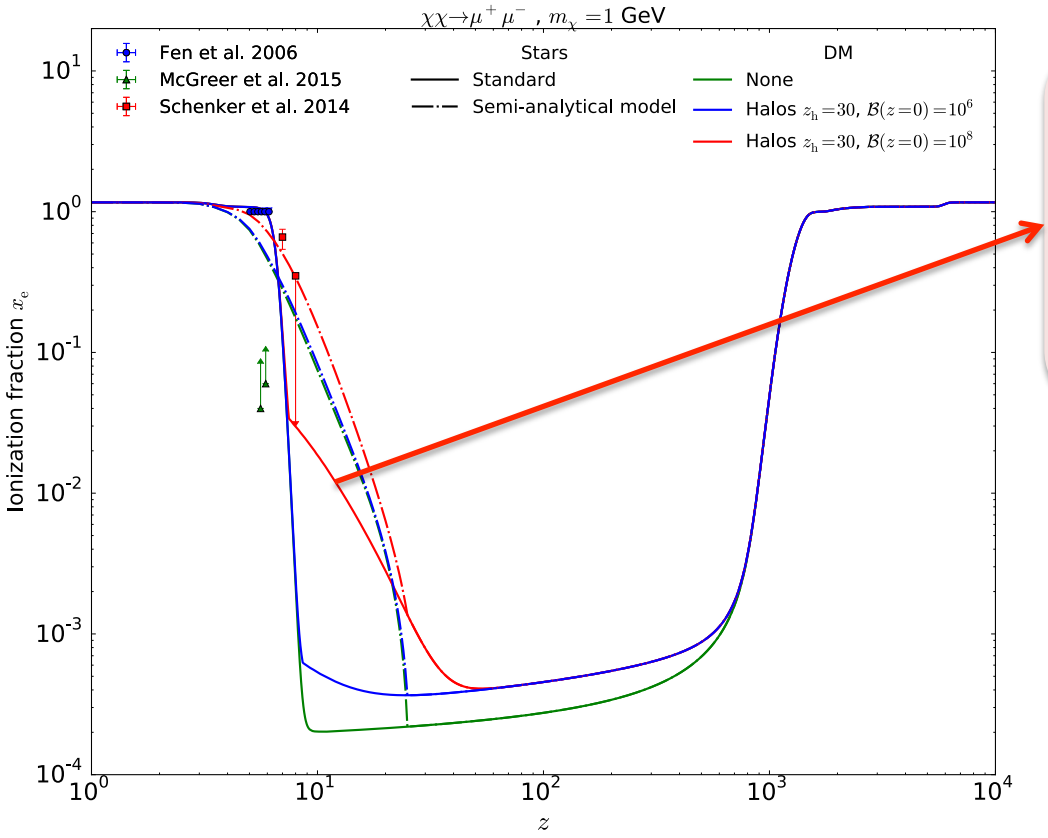
Thermal WIMP cross-section:
m > 10 to 40 GeV (95%CL) T. Slatyer 1506.03811

Potential x3 improvement with CMB satellite
CORE collaboration 1612.00021



Case 2: annihilating or decaying

- Specific role of DM annihilation in halos — V. Poulin, P. Serpico, JL 2015



Ionisation fraction vs. redshift

Contributes to τ_{reio} by <1%

Effect on C_l^{TT}, C_l^{EE} below cosmic variance

Large impact on T_{IGM}, maybe detectable?

Case 2: annihilating or decaying

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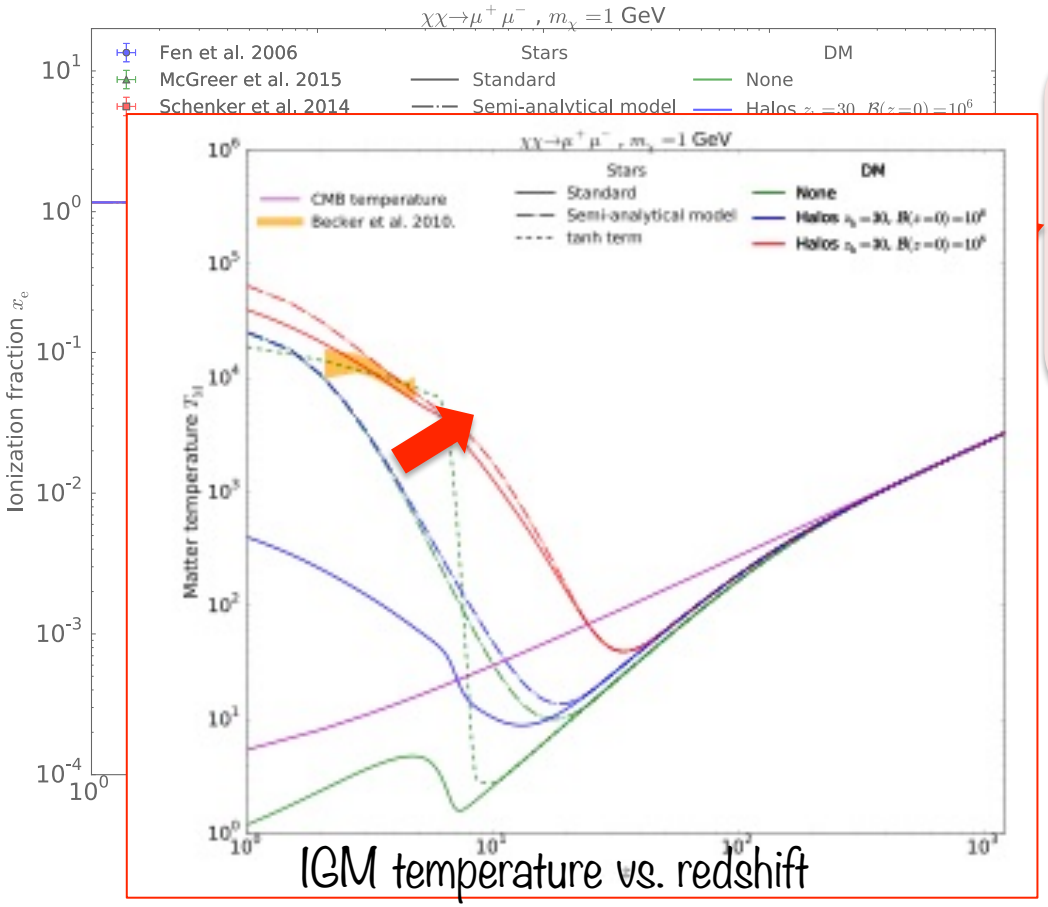


IGM temperature vs. redshift

Contributes to τ_{reio} by <1%

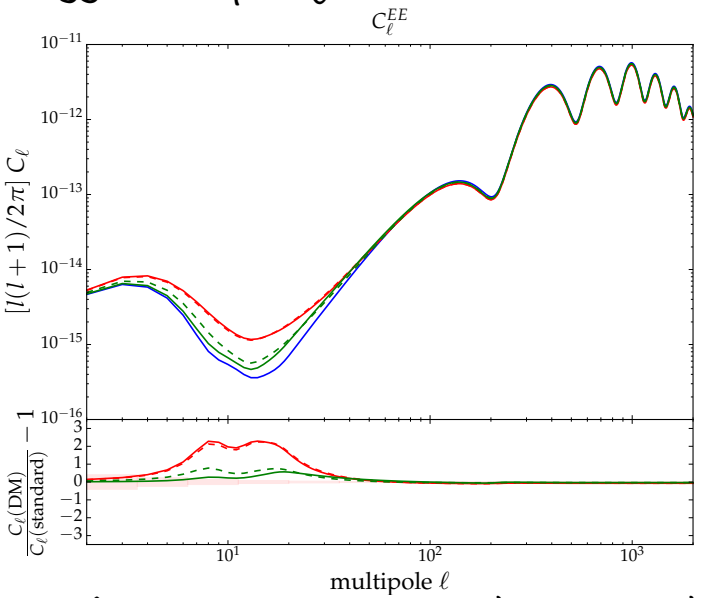
Effect on C_l^{TT}, C_l^{EE} below cosmic variance

Large impact on T_{IGM}, maybe detectable?

Case 2: annihilating or decaying
(electromagnetic effects)

Current and future bounds on decay rate from CMB only (DM decaying into SM particles other than neutrinos, heating/ionization/excitation of thermal plasma)

- If 100% of CDM is of decaying nature and all decay energy ends up in γ, e^+,e^-:
  - $< 5.3\ 10^{-26}\ s^{-1}$ (95%CL)
    Planck 2015 (TT,TE,EE + lowP+ lensing)
    Oldengott et al. 1605.03928;
    Poulin et al. 1610.10051
  - Factor 10 improvement with CORE [1612.00021]



Impact on reionisation history and large-angle CMB polarisation

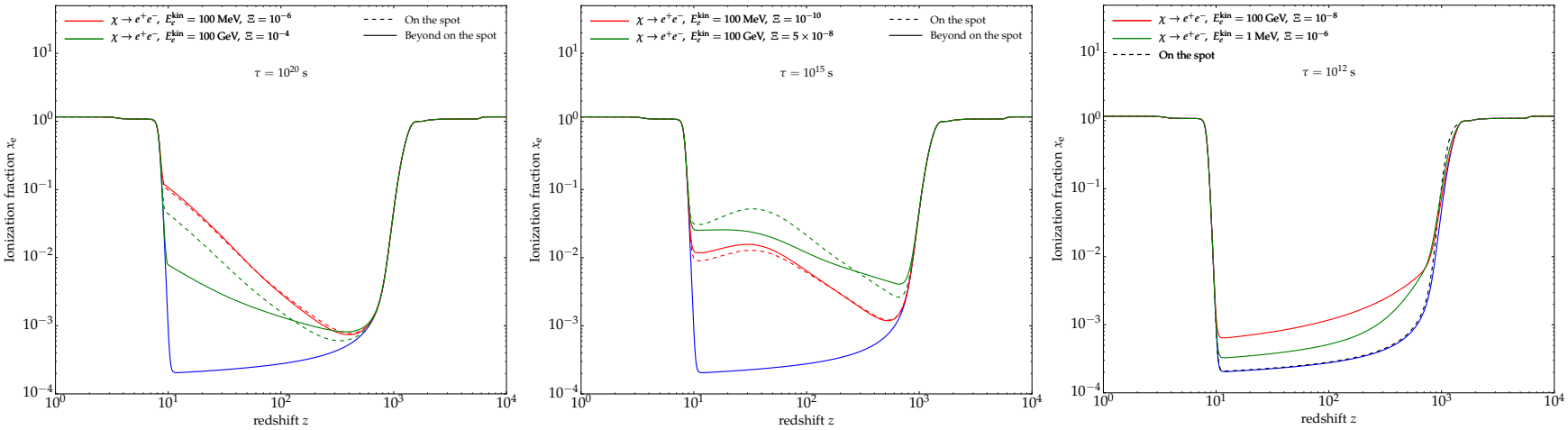
Case 2: annihilating or decaying
(electromagnetic effects)

Current and future bounds on decay rate from CMB only (DM decaying into SM particles other than neutrinos, heating/ionization/excitation of thermal plasma)

Effects depend on mass, lifetime, DM fraction and fraction of energy ending up in γ, e^+, e^-:

Different regimes / impacts on ionization history, CMB polarisation, etc.

Poulin et al. 1610.10051
see also Slatyer and Wu 2016



Case 2: annihilating or decaying
(electromagnetic effects)

Current and future bounds on decay rate from CMB only (DM decaying into SM particles other than neutrinos, heating/ionization/excitation of thermal plasma)

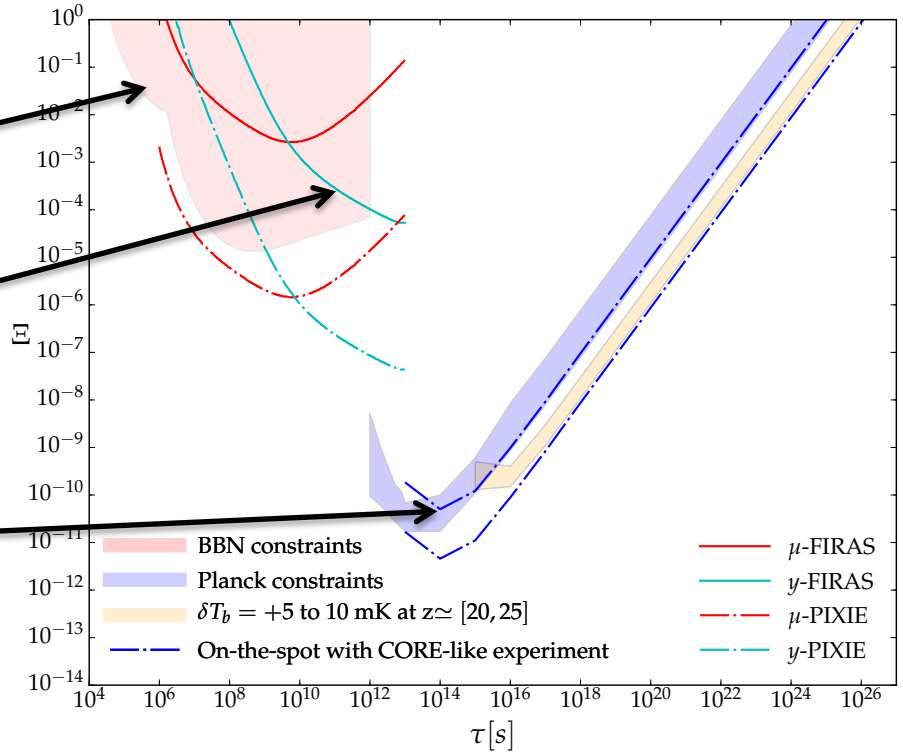
All effects captured by two parameters, injected energy density relative to DM energy density Ξ and lifetime τ:

Poulin et al. 1610.10051; see also Slatyer and Wu 2016

complementarity:

- with BBN
- with CMB spectral distorsions
- (also with cosmic rays at large z, m)

maximum CMB sensitivity when lifetime ~ z=300



Case 2: annihilating or decaying
(electromagnetic effects)

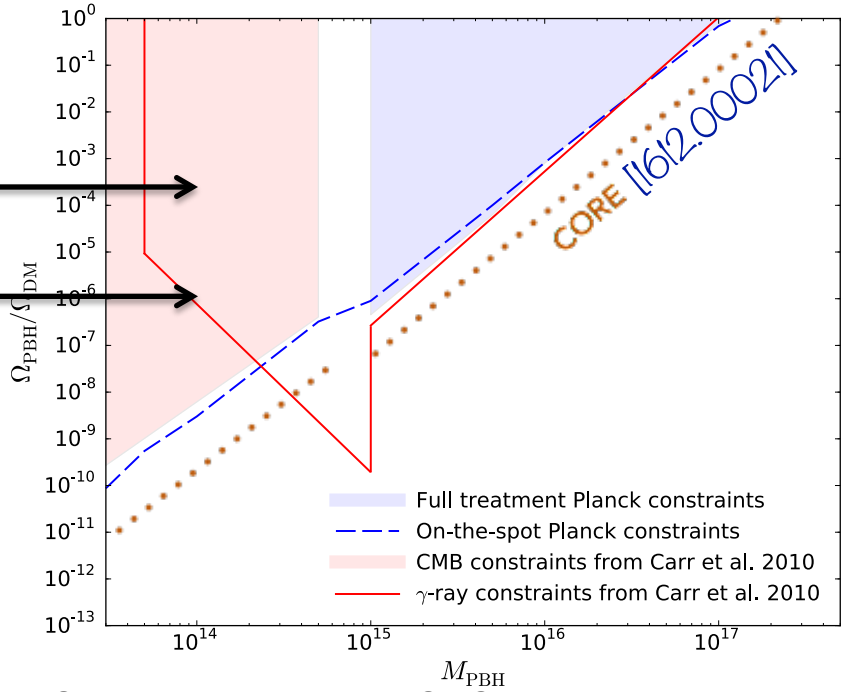
Current and future bounds on decay rate from CMB only (DM decaying into SM particles other than neutrinos, heating/ionization/excitation of thermal plasma)

Application to PBH of mass 10^{14}-10^{18}g being a fraction of DM (Hawking evaporation in different channels, depending on $T_{BH} \sim M^{-1}$)

Poulin et al. 1610.10051

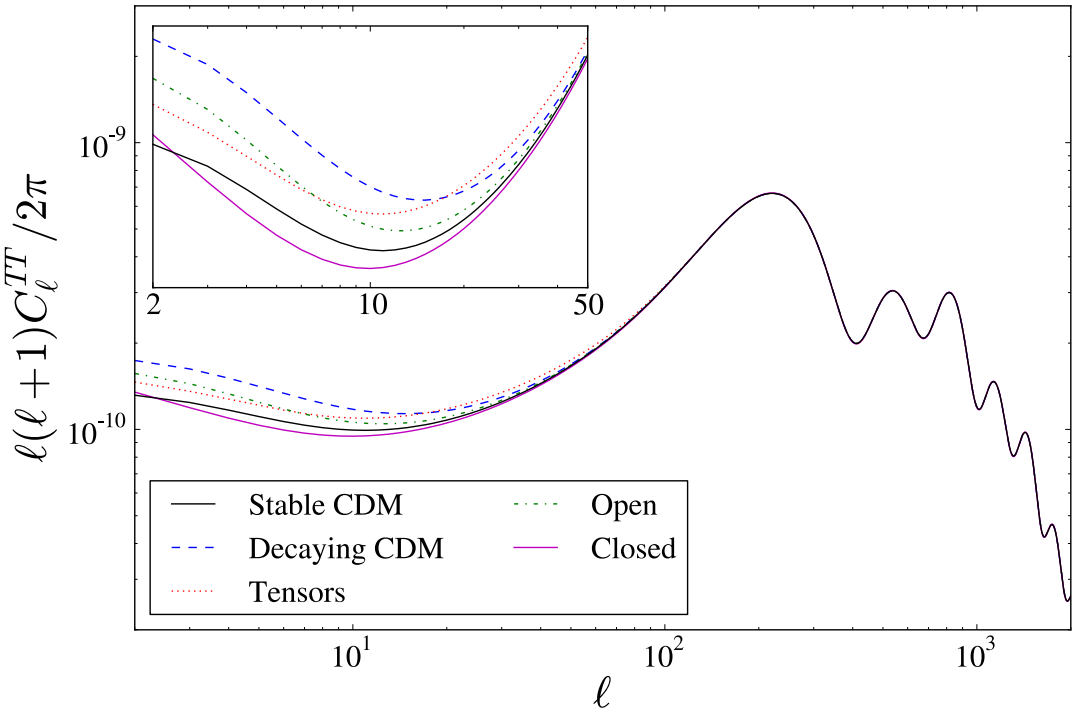
complementary to CMB spectral distorsions

and γ-ray background



Case 2: annihilating or decaying

(gravitational effects)



Audren et al. 2014

Modified CMB T and E spectrum in decaying case

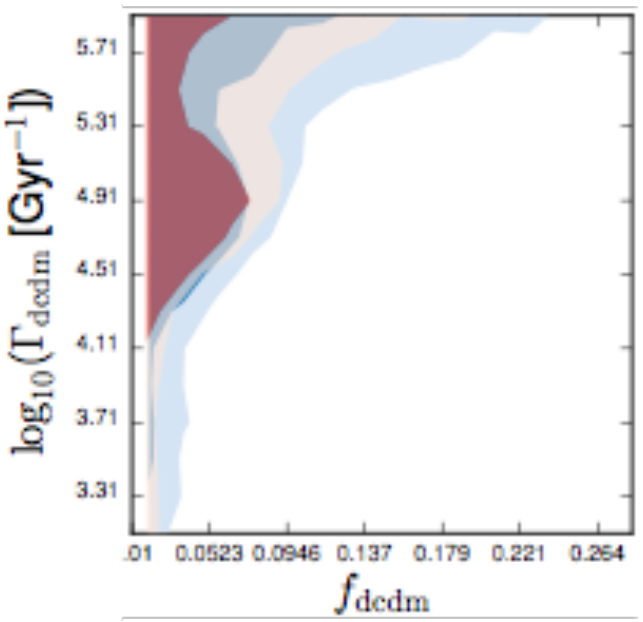
Planck 2015 implies $\tau > 160$ Gyr (95%CL) Poulin et al. 1606.02073

(Model-independent, includes decay in ν/DR)

Case 2: annihilating or decaying
(gravitational effects)

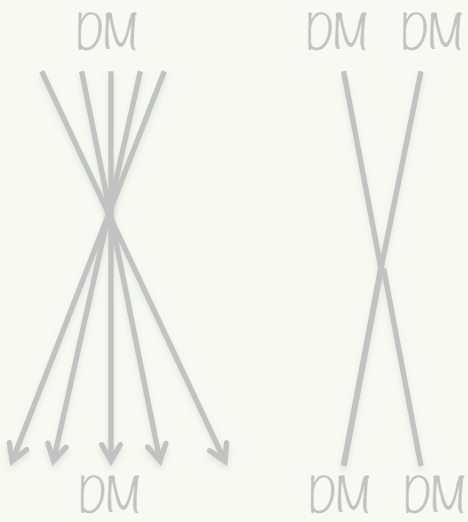
Models with stable CDM + decaying DM (parameters: $\tau_{dcdm} = 1/\Gamma_{dcdm}$ and f_{dcdm})
Different regimes! Poulin et al. 1606.02073

- Long lifetime (compared to recombination): late ISW
  $\tau_{dcdm} > 160 \times f_{dcdm}$ Gyr (95%CL)
- Shorter lifetimes: several different effects on CMB+LSS depending on lifetime versus recombination time
- e.g. for lifetimes between 10^5 yr and 10 Gyr: 4.2% of CDM may decay completely between photon decoupling and today



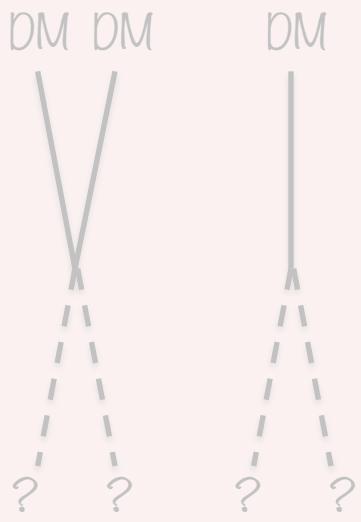
Possible properties of DM

Warm, Self-interacting



CMB
~~LSS~~

Annihilation, Decay



CMB
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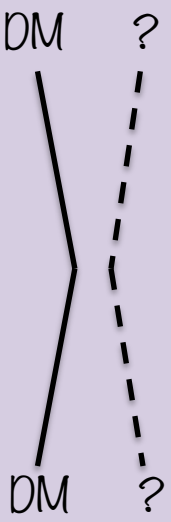
Cosmic Rays

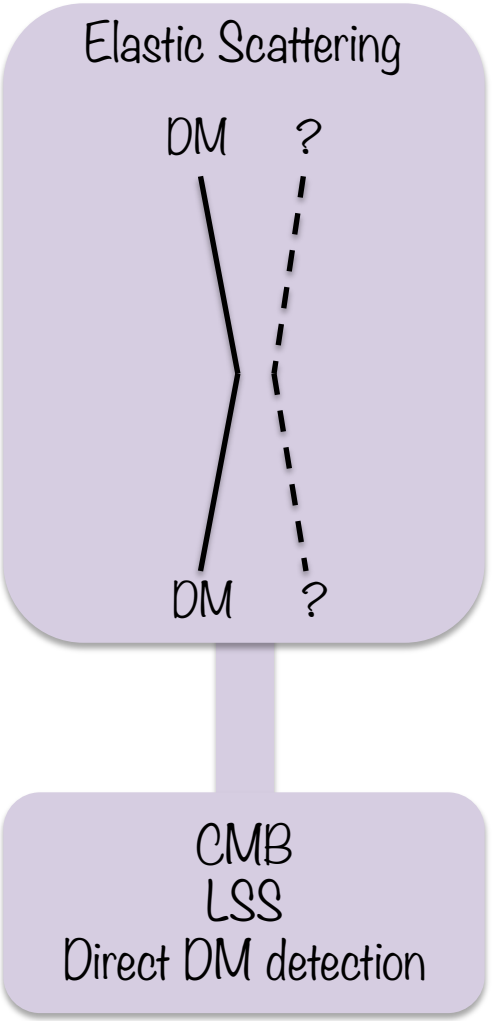
Elastic Scattering



CMB
LSS
Direct DM detection

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, magnetic/dipole moment, excited dark matter, asymmetric dark matter new gauge group and force...)
- Direct detection provide constraints, limited to quarks and to restricted mass range (e.g.do not include asymmetric DM)
- LHC constraints model-dependent (e.g. none for asymmetric DM)
- CMB/LSS constraints are universal



Case 3: DM interactions (elastic scattering)

- DM-photon
- DM-neutrino

$\sigma \sim$ const. (Thomson-like), momentum transfer rate* $\Gamma_{DM} \sim T^4$

$\sigma \sim v^2 \sim T^2$, $\Gamma_{DM} \sim T^6$

Wilkinson, JL & Boehm 1309.7588

Wilkinson, Boehm & JL, 1401.7597

(*) w.r.t proper time

- DM-baryons

$\sigma \sim v^n \sim T^{n/2}$, $\Gamma_{DM} \sim T^{n/2+3}$ Dvorkin, Blum, Kamionkowski 1311.2937

- DM-Dark Radiation

$\Gamma_{DM} \sim T^4$ Cyr-Racine, de Putter, Raccanelli, Sigurdson 1310.3278

$\Gamma_{DM} \sim T^2$ Buen-Abad, Marques-Tavares, Schmaltz, 1505.03542

General Cyr-Racine et al., 1512.05344

- DM-Dark Energy

...

Case 3: DM interactions (elastic scattering)

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$\sigma \sim v^2 \sim T^2$, $\Gamma_{DM} \sim T^6$

Wilkinson, JL & Boehm 1309.7588

Wilkinson, Boehm & JL, 1401.7597

*: per time

- DM-baryons

$\sigma \sim$ [illegible]

Dvorkin, Blum, Kamionkowski 1311.2937

- DM [illegible]radiation

$\Gamma_{DM} \sim T^4$ Cyr-Racine, de Putter, Raccanelli, Sigurdson 1310.3278

$\Gamma_{DM} \sim T^2$ Buen-Abad, Marques-Tavares, Schmaltz, 1505.03542

General Cyr-Racine et al., 1512.05344

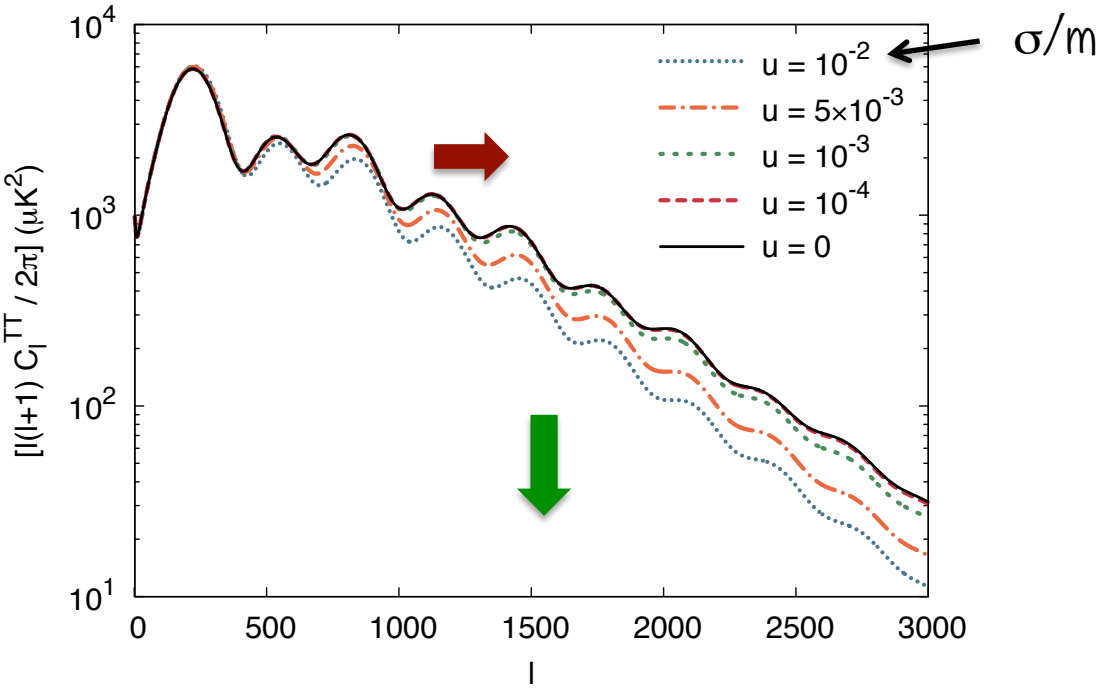
Each model requires special modifications to CLASS or CAMB, project to gather everything in future public CLASS version

- DM-Dark Energy

...

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)

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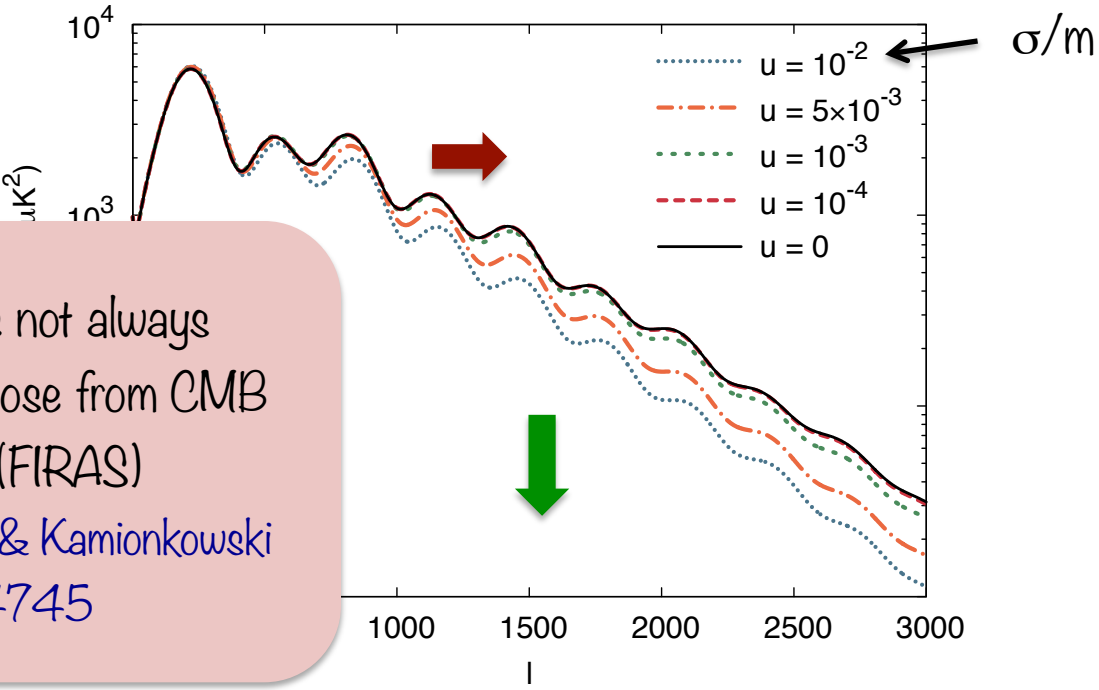


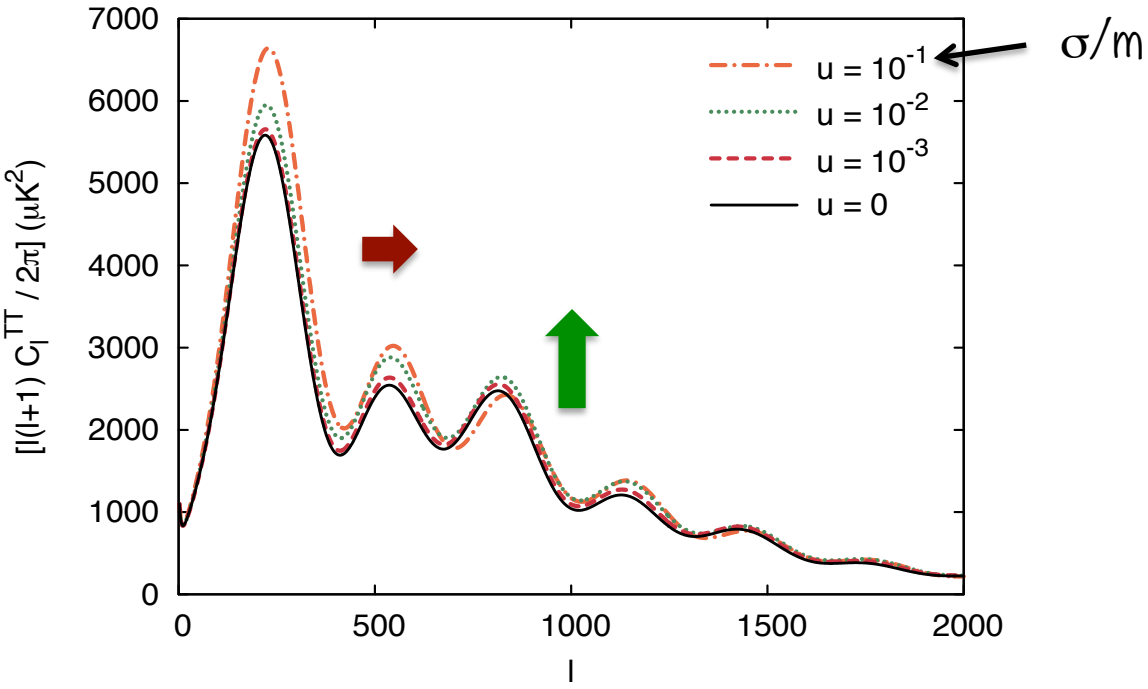
But constraints not always competitive with those from CMB distorsions (FIRAS)
Ali-Haimoud, Chluba & Kamionkowski 1506.04745

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)



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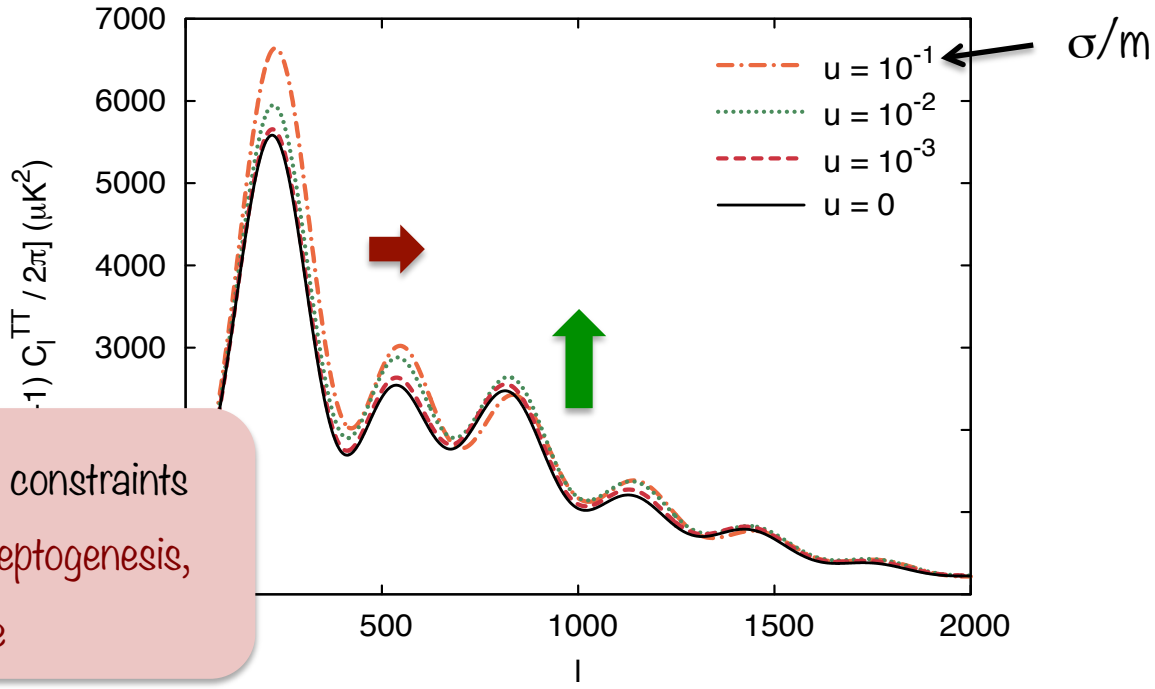


CMB/LSS provide constraints complementary to leptogenesis, IceCube

Case 3: DM interactions (elastic scattering)

Impact on matter power spectrum:

- Most models: $\Gamma_{DM} \sim T^p$ with $p>2$,

  while $H \sim T^2$ (Rad. Dom.) and $H \sim T^{3/2}$ (Matt. Dom.)
- Coupled at early time, then decoupled.

  Signature: exponential cut-off

  (+ oscillations for DM-photons, neutrinos, DR)

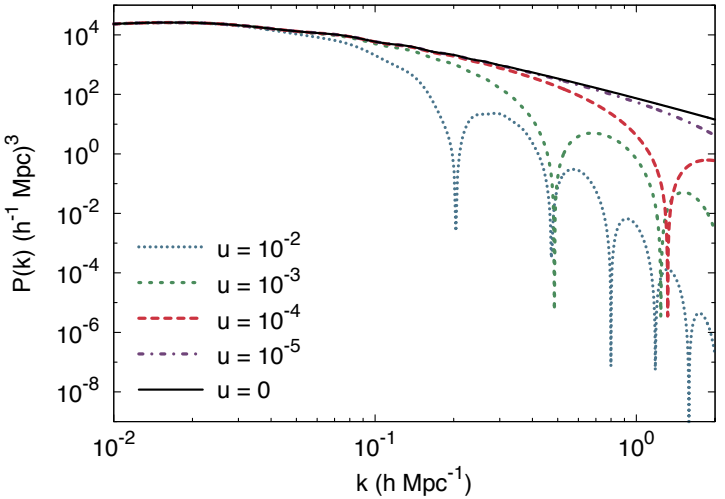
- When $\Gamma_{DM} \sim T^2$, constant effect during Rad. Dom.

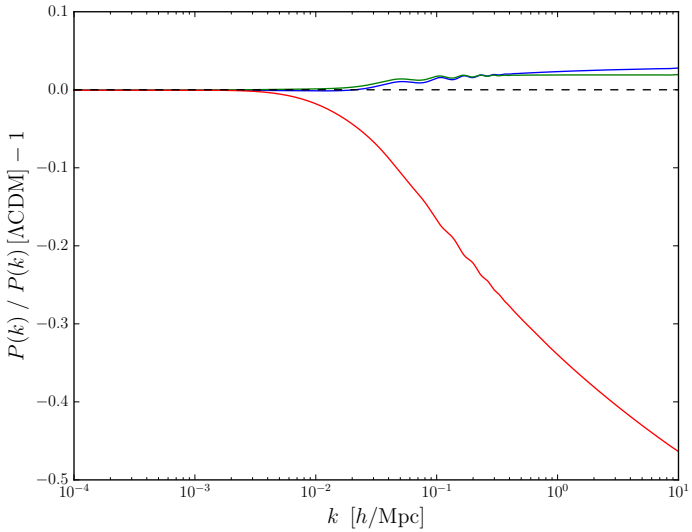
  (Dark Radiation drag on Dark Matter).

  Can be very small but cumulative, with no oscillations.

  Smoother than exponential.

  JL, Marques-Tavares, Schmaltz 1507.04351





Case 3: DM interactions (elastic scattering)

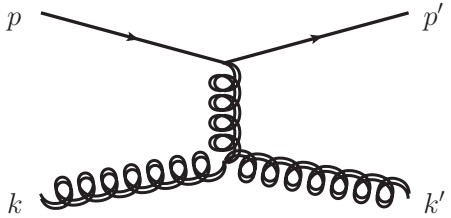
- Model of Marques-Tavares, Schmaltz, JL 2015 inspire by actual BSM models

  - dark gauge groupe SU(N)
  - DM has weak and dark interactions
  - DR = dark gluons, self-interacting, tiny mean free path, no viscosity

  - dark gauge group U(1)
  - DM has weak and dark interactions
  - DR = dark photon + massless fermions with dark charge, also self-interacting

Case 3: DM interactions (elastic scattering)

- Model of Marques-Tavares, Schmaltz, JL 2015 inspire by actual BSM models
- T-channel scattering of DM with gluons



gluons

- Euler equations

$$\dot{\theta}_{DM} = -\frac{\dot{a}}{a}\theta_{DM} + a\tau_c^{-1}(\theta_{DR} - \theta_{DM}) + k^2\psi$$
$$\dot{\theta}_{DR} = k^2\frac{\delta_{DR}}{4} + k^2\psi + \frac{3}{4}\frac{\rho_{DM}}{\rho_{DR}}a\tau_c^{-1}(\theta_{DM} - \theta_{DR})$$

- Momentum transfer rate $\dot{\vec{p}}_\chi = -a\tau_c^{-1}\,\vec{p}_\chi$ (dot: conformal time, rate: proper time)

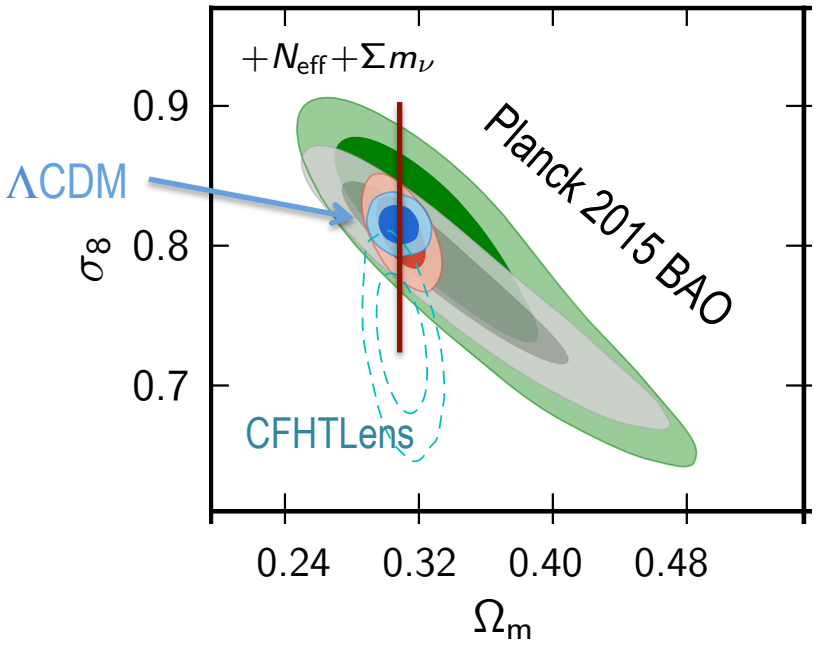
$$\dot{\vec{p}} = a\int\frac{d^3k}{(2\pi)^3}f(k)\frac{1}{4E_pk}\int\frac{d^3k'}{(2\pi)^3 2k'}\frac{d^3p'}{(2\pi)^3 2E'_p}(2\pi)^4\delta(p+k-p'-k')|M|^2(\vec{p}'-\vec{p})(1+f(k'))\ ,$$

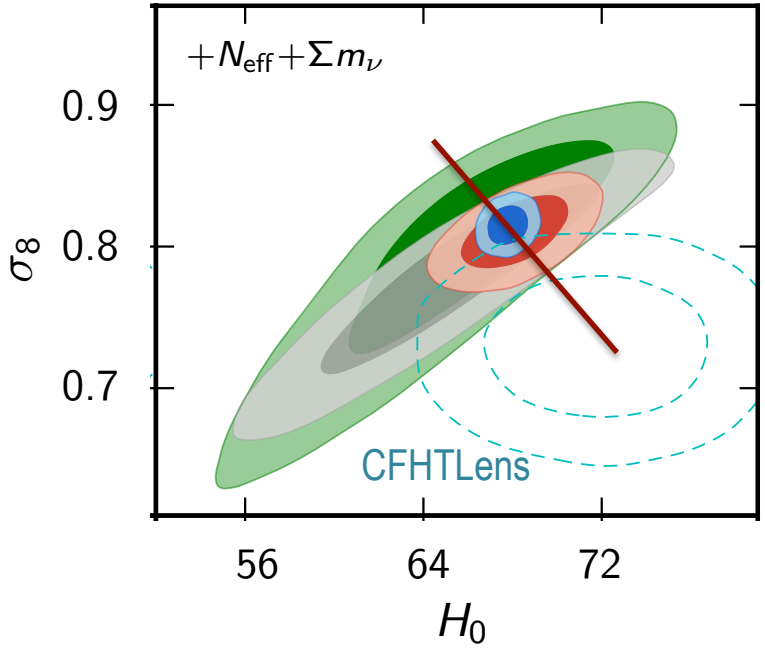
$$\Gamma_{DM} = \tau_c^{-1} = (N^2-1)\frac{\pi}{9}\alpha_d^2\log\alpha_d^{-1}\frac{T_{dr}^2}{M_\chi}$$

gluon T scaling like a^{-1}

Case 3: DM interactions (elastic scattering)

- Can explain tension with direct measurement of H_0 and low σ_8 anomaly: in Marques-Tavares et al. 2015, $\Delta\chi^2 \sim -12.7$ over ΛCDM, which is very difficult to achieve with simple ΛCDM extensions can (standard massive neutrinos, sterile neutrinos, decaying DM... extra CMB effects and wrong correlation with Ω_m, H_0)





- 3σ evidence for $\Gamma_{DM,0} \sim 10^{-21}$ s^{-1}

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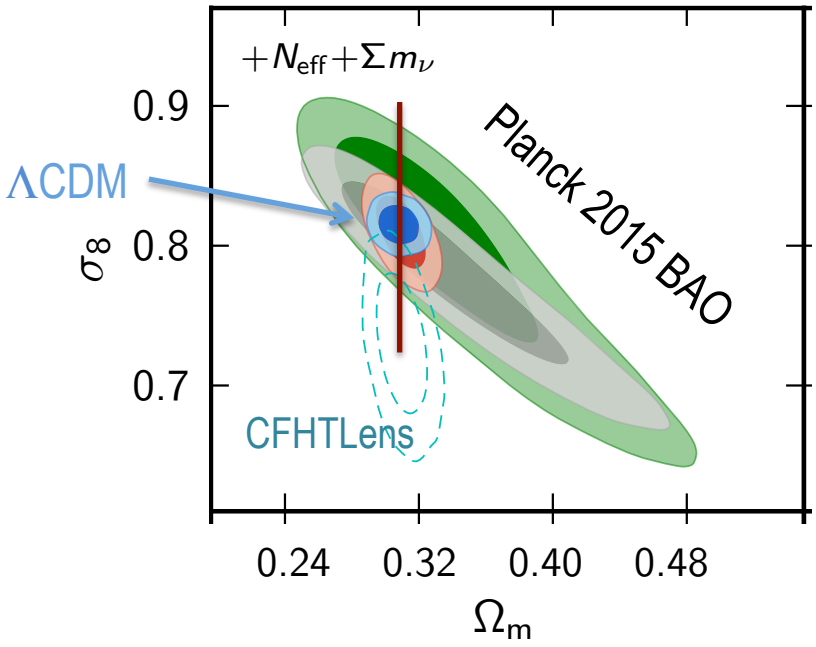
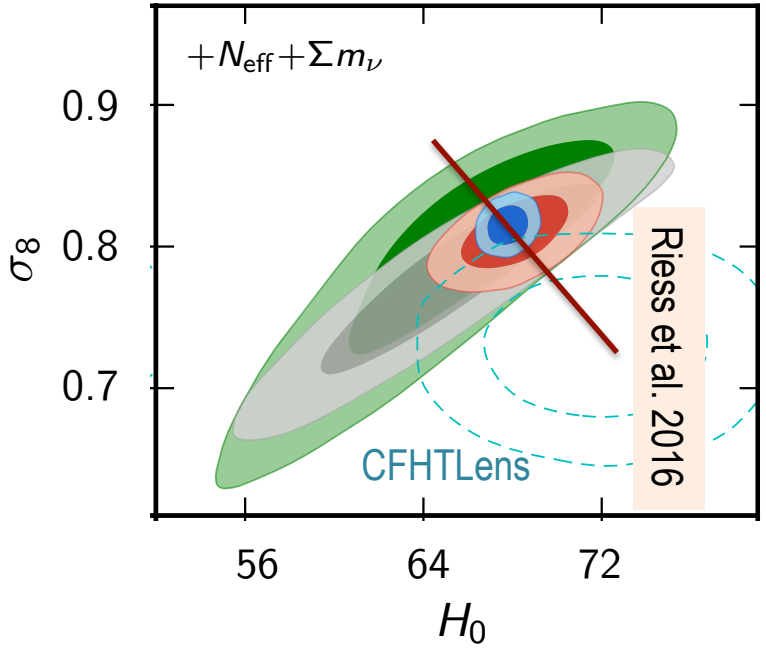




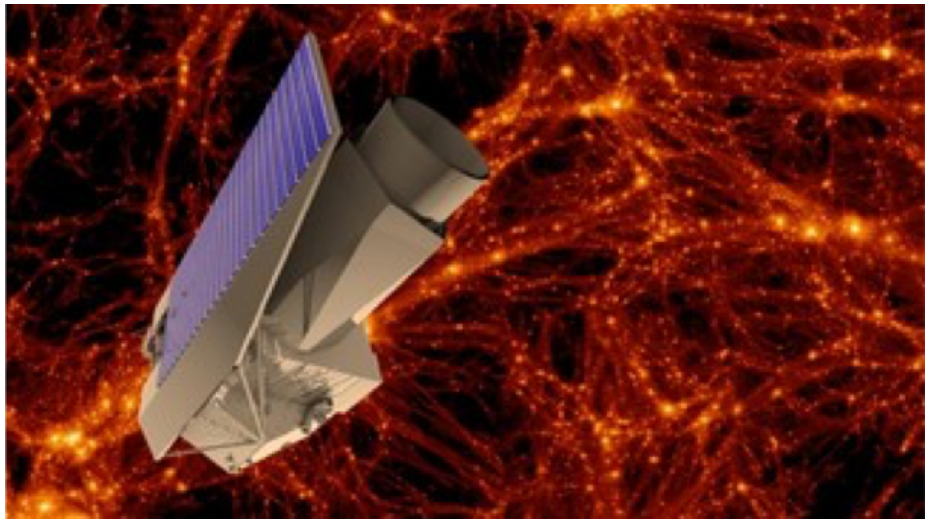
- 3σ evidence for $\Gamma_{DM,0} \sim 10^{-21}$ s^{-1} ; update in preparation (H_0, SDSS, ...)
- Other solution for H_0 : light sterile neutrinos with secret interactions (Archidiacono, hannestad et al....)

Prospects

Ground-based polarization experiments (CMB-stage IV); CMB anisotropy satellite ?

(LiteBird/Core+); CMB distorsion satellite? (PIXIE)

LSS from eBOSS, DES, Euclid, LSST, wFIRST, ..., 21cm survey of SKA

- incorporate all models in CLASS with unified parametrizations

- biggest challenge: N-body simulations to model non-linear effects in each case