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Direct and Indirect Detection in Cosmology

Stöecker, Krämer, Lesgourgues, Poulin, arXiv:1801.01871 (JCAP, in press)
Barkana, nature25791
Bowman et al, nature25792

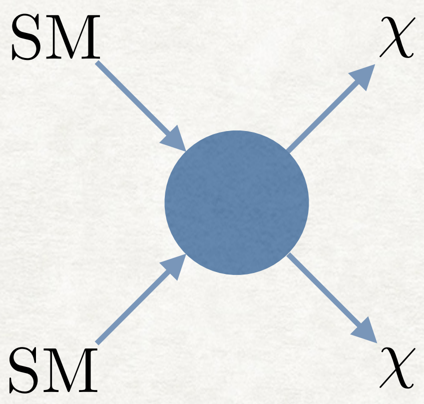
Vivian Poulin - Johns Hopkins University

LPSC, Grenoble
09 March 2018

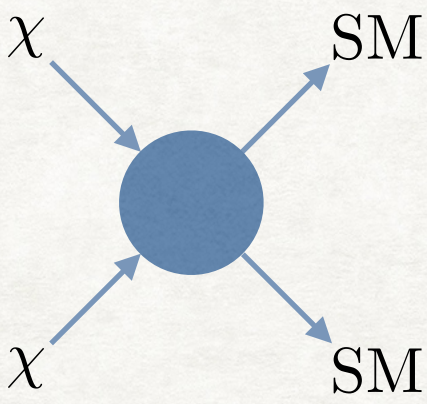
Searching for non-gravitational evidence of DM

Most of our searches are motivated by the WIMP miracle

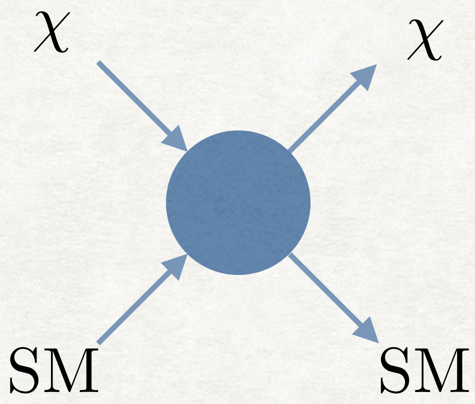
Production



Annihilation



Scattering



in particle physics

Collider

Indirect detection

Direct detection

in cosmology

Relic abundance

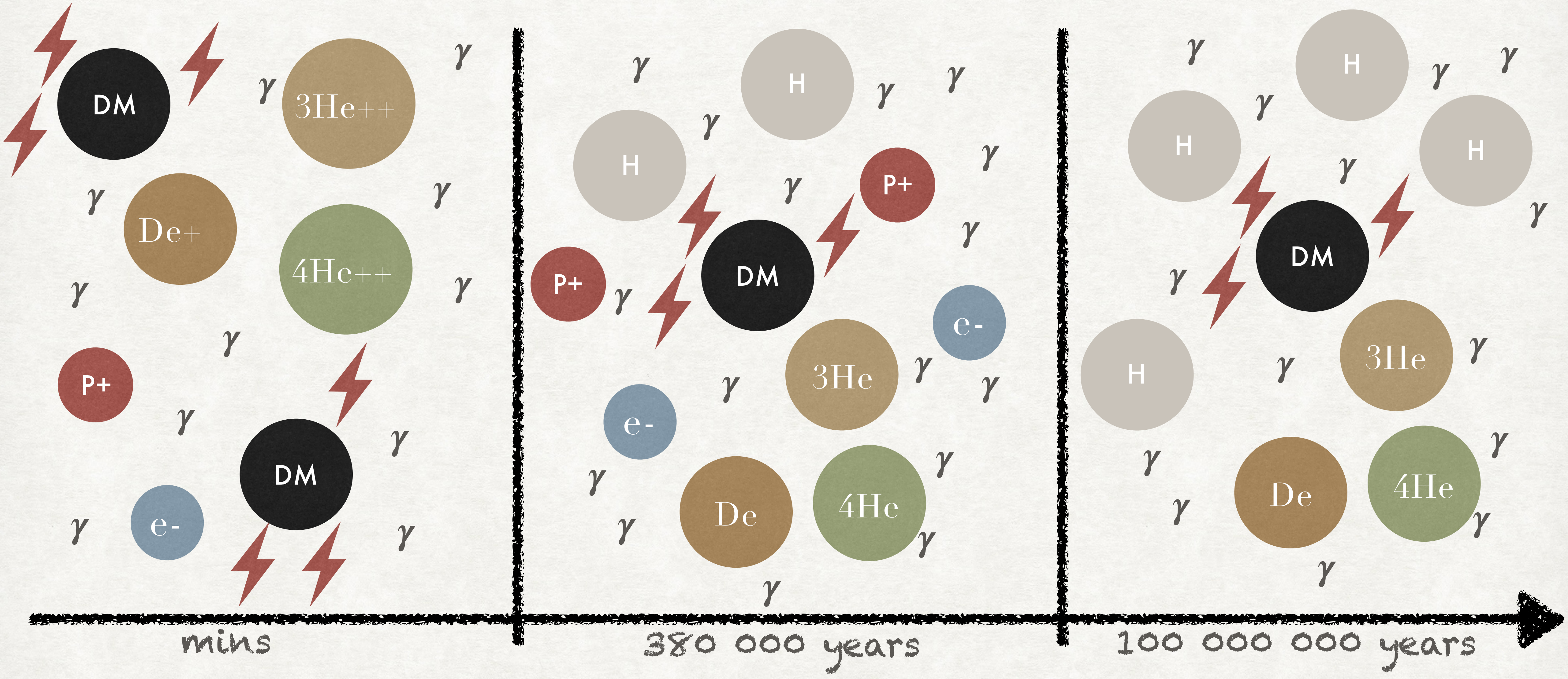
Energy injection

Momentum transfer

Naturally there are many other models motivated by alternative observations
(sterile neutrinos, ALP, Primordial Black Holes…)

Indirect detection in Cosmology

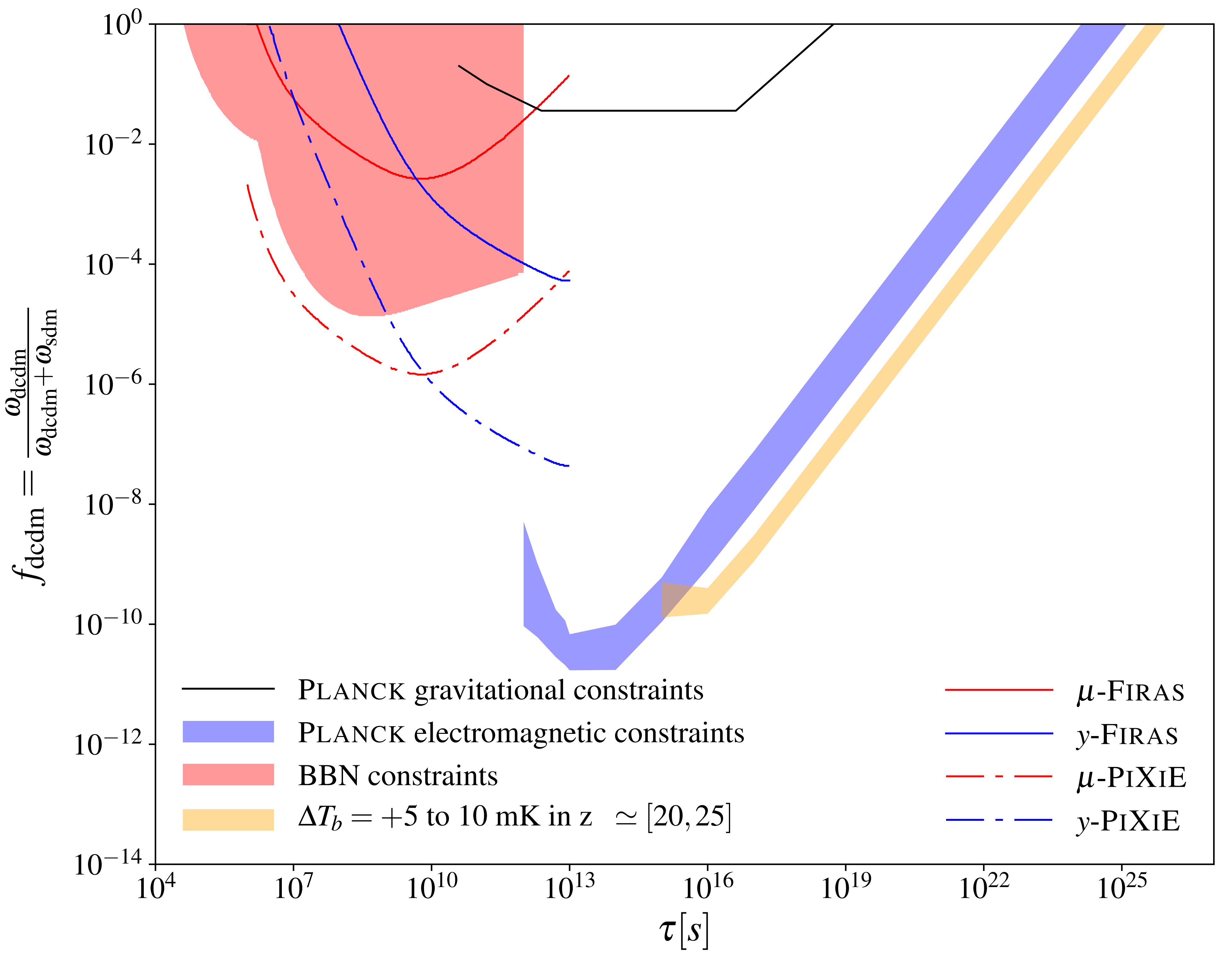
- Energy injection following relic WIMP annihilations can affect our various probes



- Destroy nuclei
- Affect the BB distribution
- Affect the recombination era
- Affect the 21cm signal

Constraints from various cosmological probes

VP, Lesgourgues, Serpico; 1610.10051

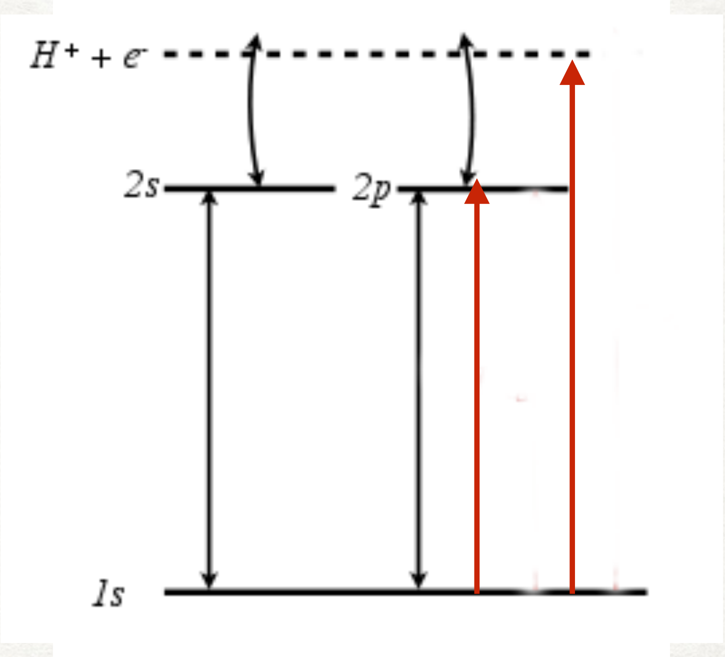


Energy injection impact recombination

$$\frac{dx_e}{dz} = \frac{1}{(1+z)H(z)}[R_s(z) - I_s(z) - I_X(z)]$$

$$\frac{dT_{\rm M}}{dz} = \frac{1}{1+z}\left[2T_{\rm M} + \gamma(T_{\rm M} - T_{\rm CMB}) + K_h\right]$$

$$I_X(z) \text{ and } K_h(z) \propto \left.\frac{dE}{dV\,dt}\right|_{\rm dep,c}$$



Toy model: the « three levels atom » developed by Peebles, 1969.
We use Recfast (seager et al. 1999) and HyRec (Ali-Haimoud et al. 2012).

Key quantity $dE/dVdt|_{dep,c}$:

- The energy deposition rate per unit volume in each channel: ionization, excitation and heating.
- Difficulty: the plasma is not necessarily efficient at absorbing energy!

What is in ExoCLASS?

$$\left.\frac{dE}{dV\,dt}\right|_{\mathrm{dep},c}(z) = f_c(z)\left.\frac{dE}{dV\,dt}\right|_{\mathrm{inj}}(z)$$

ExoCLASS calculates the energy deposited in each channel from:

- an energy injection history $dE/dVdt_{\mathrm{inj}}$.
- a set of "energy deposition function per channel" f(z), which requires to convolute the spectrum of electrons and photons with a set of transfer function T_c(z_inj,z_dep,E_inj) encoding the calorimetric properties of the plasma.

see Slatyer, 1506.03812

We have already implemented 4 energy injection histories:

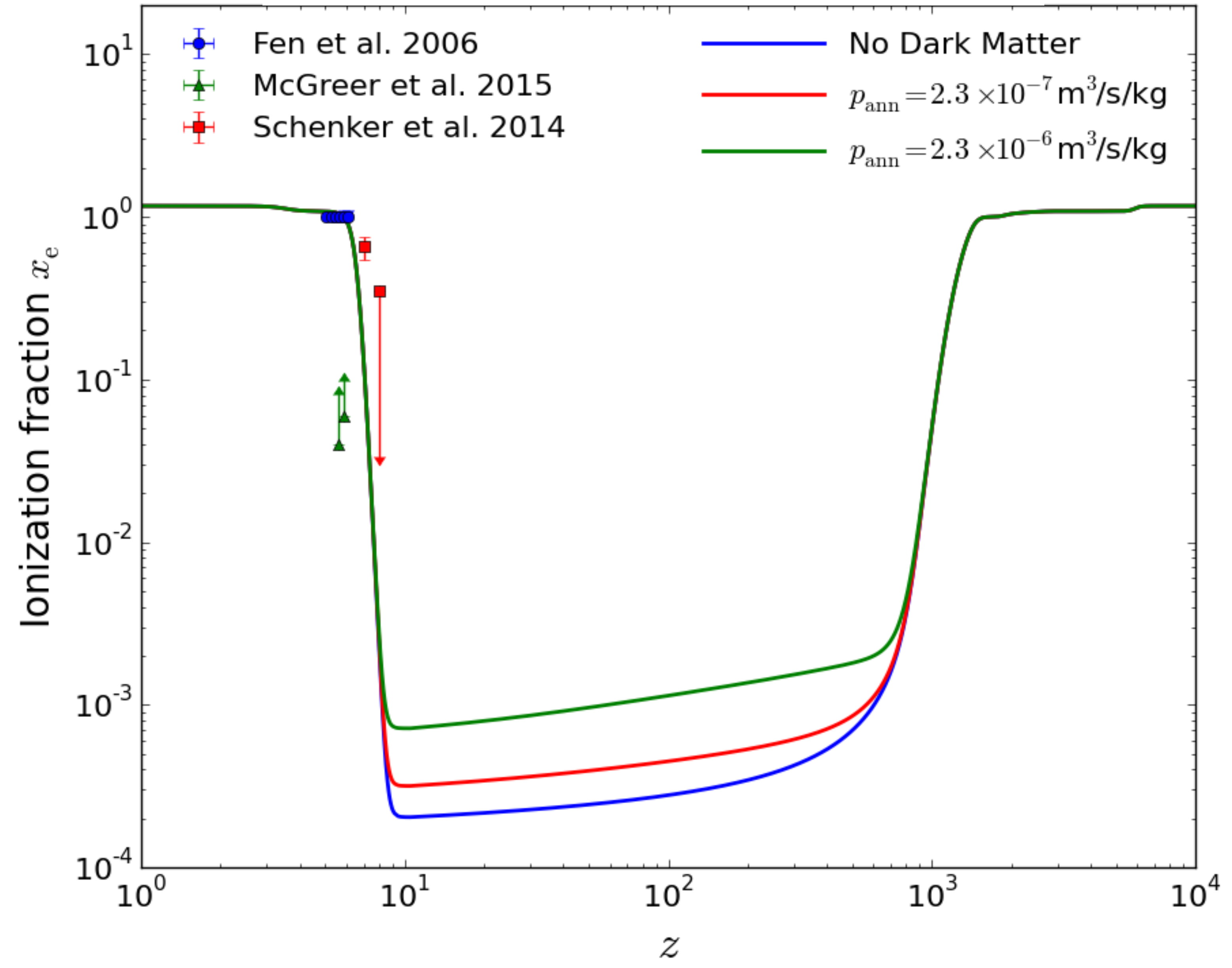
- annihilating DM including the effects of halo formation; *Poulin et al., 1508.01370*
- decaying DM, allowing small fraction with high decay rate; *Poulin et al., 1610.10051*
- low masses (~$[10^{13},10^{17}]$g) evaporating PBH (Hawking radiation); *Stoecker et al., 1801.01871*
- high masses (~$[1,10^{4}]$ Msun) accreting PBH (disk or spherical). *Poulin et al., 1707.04206*

DM annihilations

VP, Lesgourgues, Serpico; 1508.01370

see also Slatyer, 1506.03811

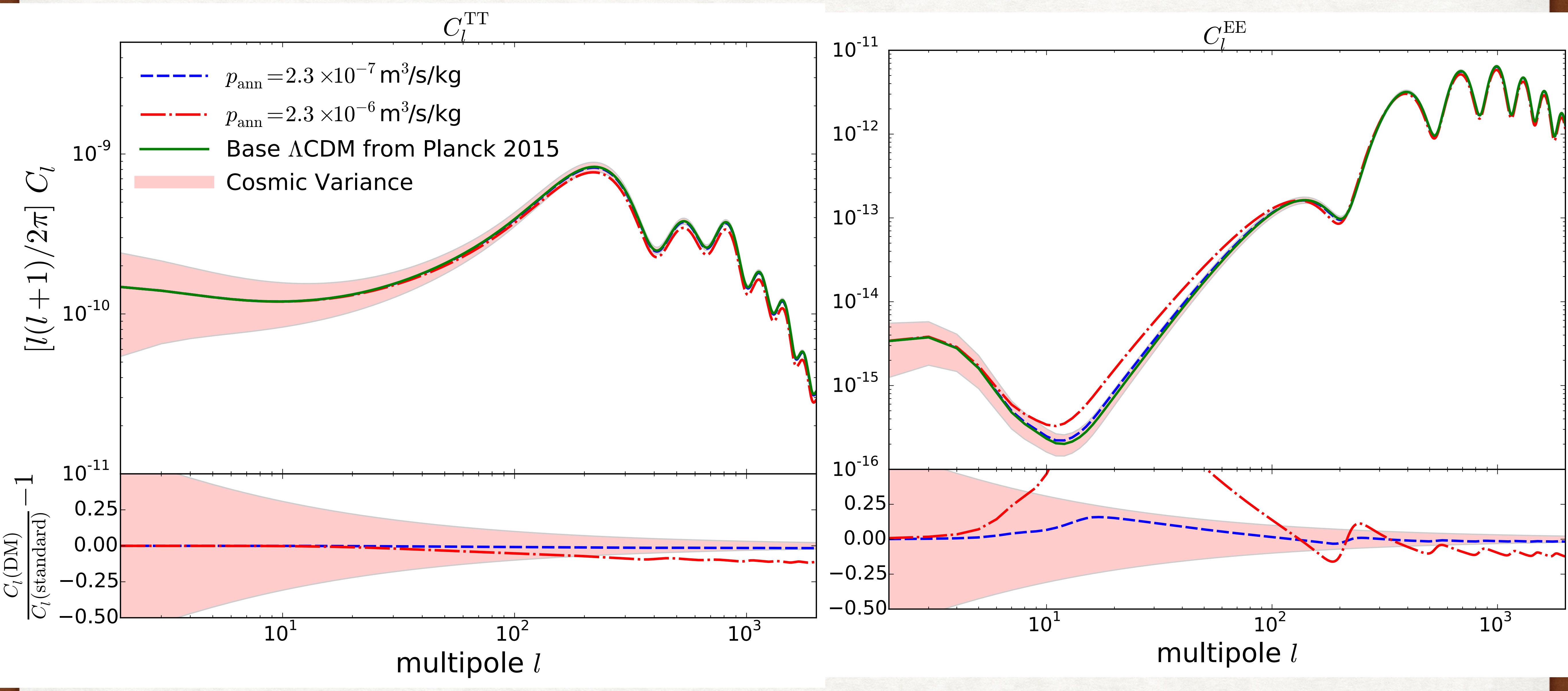
$$\left.\frac{\mathrm{d}^2E}{\mathrm{d}V\mathrm{d}t}\right|_{\mathrm{inj,\ smooth}} = \kappa\rho_c^2c^2\Omega_{\mathrm{CDM}}^2\,(1+z)^6\,\frac{\langle\sigma_{\mathrm{ann}}v\rangle}{m_{\mathrm{DM}}}$$



- DM annihilations delay the recombination and increase the freeze-out plateau

CMB power spectra

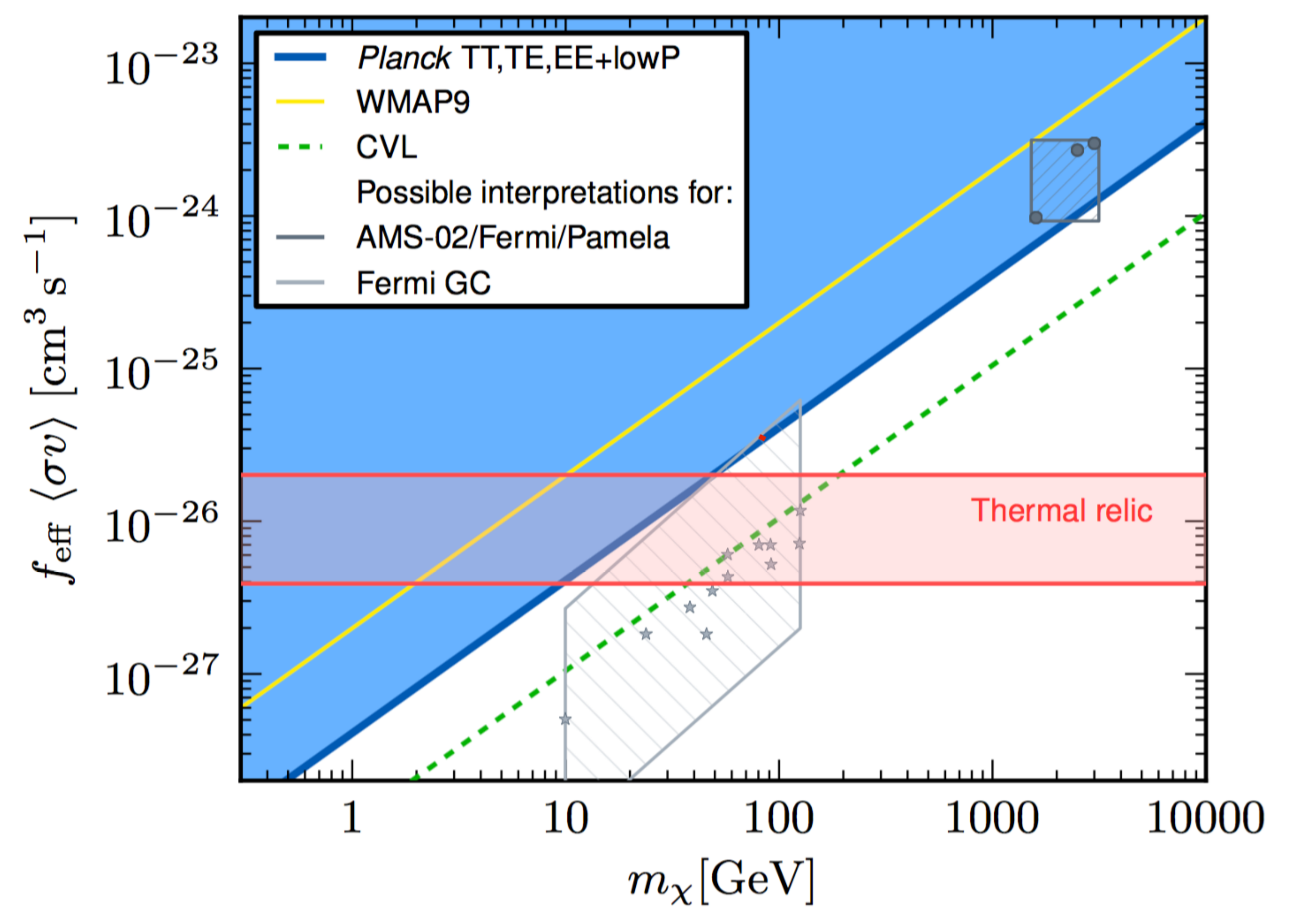
VP, Lesgourgues, Serpico; 1508.01370



- Recombination delay: shifts of the peak, more diffusion damping.
- Higher freeze-out plateau: reionisation bump higher, higher optical depth.

Planck 2015 results

Planck 2015, 1502.01589



$$p_{\rm ann} \equiv f_{\rm eff}\frac{\langle\sigma_{\rm ann}v\rangle}{m_{\rm DM}} < 3.4\times10^{-28}{\rm cm^3 s^{-1} GeV^{-1}}$$

$$\rm TT, TE, EE + lowP + lensing$$

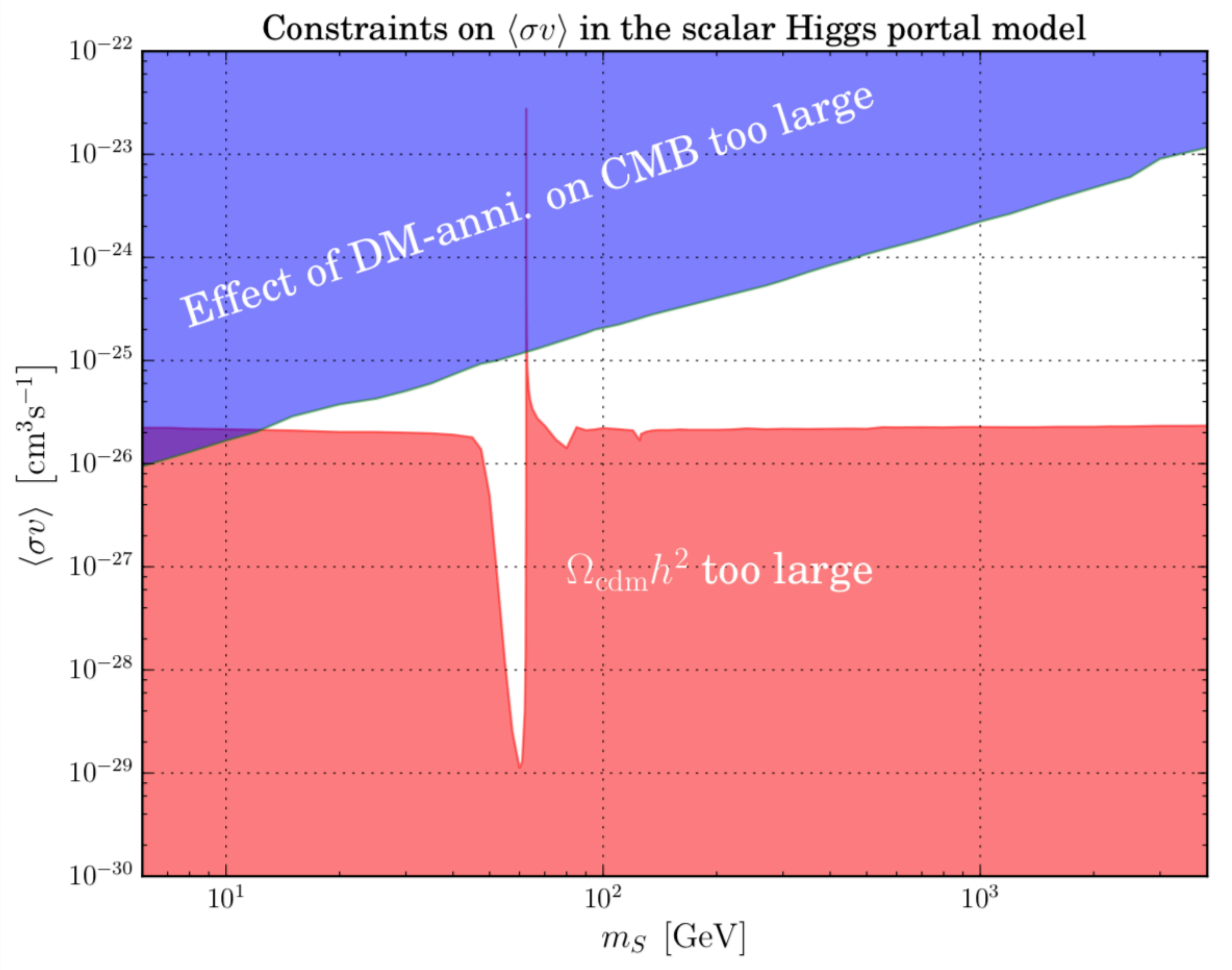
- Bounds in the effective "on the spot" approach: f(z) => f(z=600)

see also Slatyer, 1506.03811

Higgs portal model

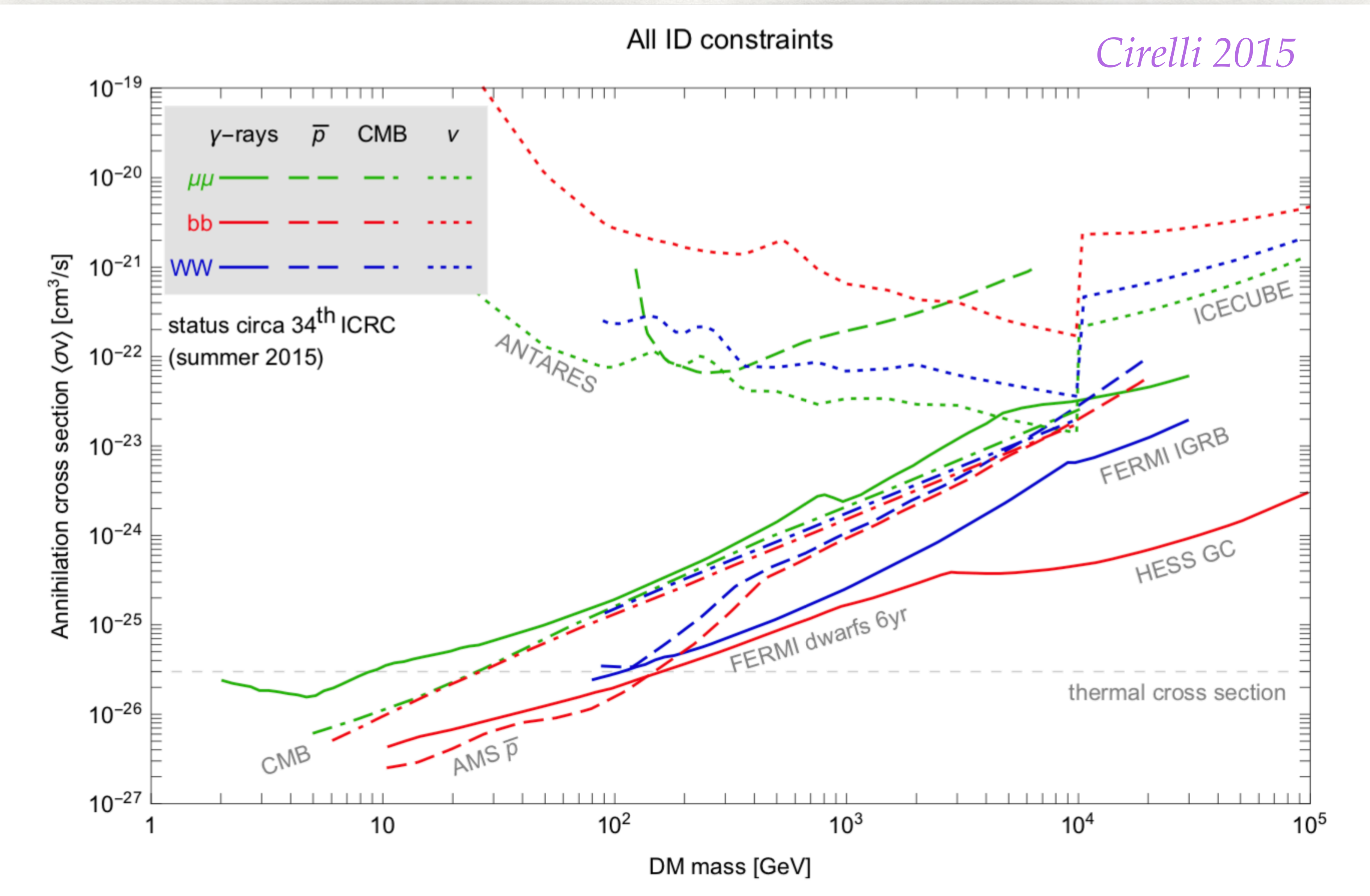
Stoecker, VP, et al., 1801.01871

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}\mu_S^2 S^2 - \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\lambda_{HS} S^2 H^\dagger H\,.$$



- A given model essentially fixes the value of $f_{\rm eff}$

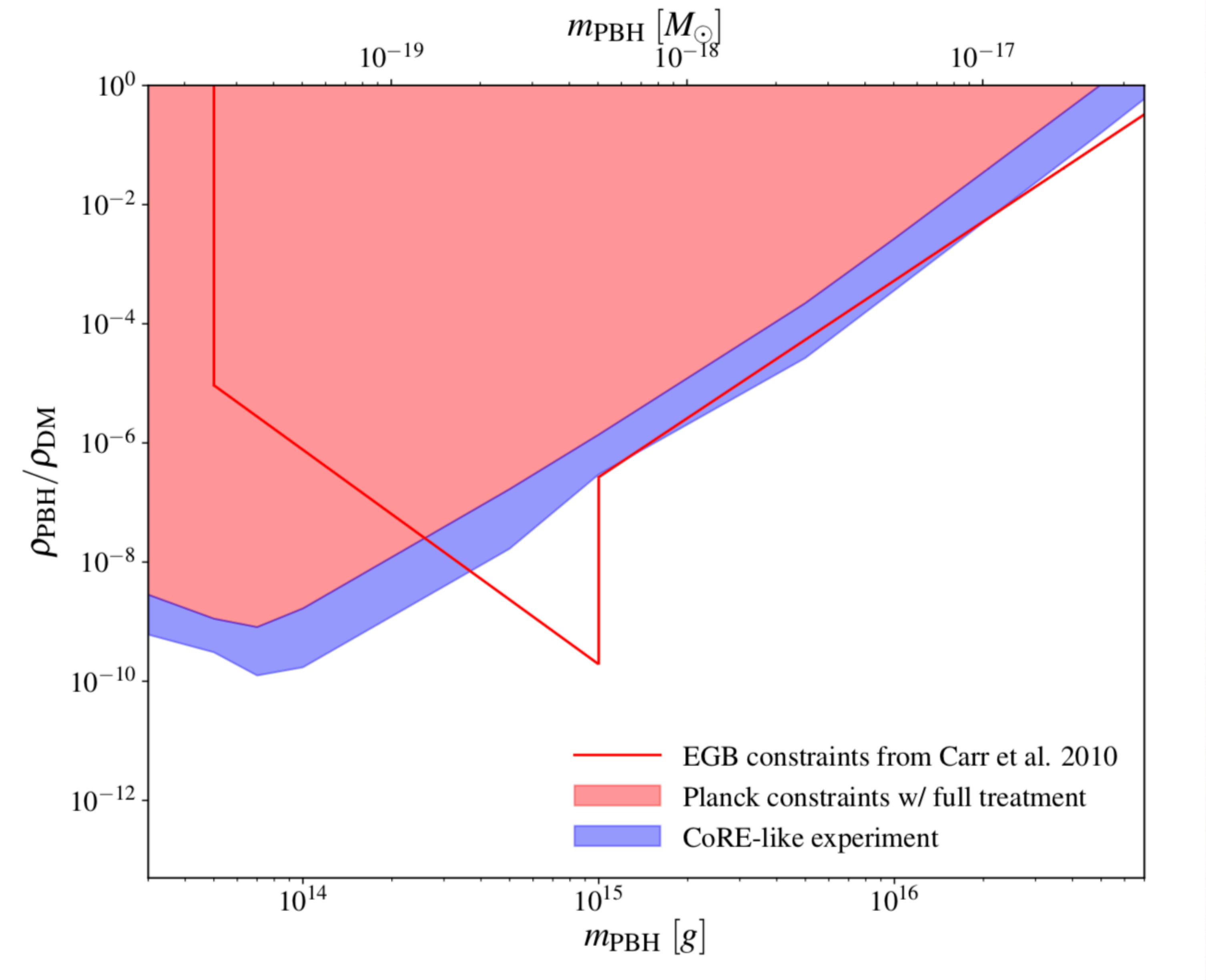
How does it compare to other probes?



- CMB is usually weaker except for: i) low masses (MeV); ii) pure electronic channels.
- CMB is not affected by propagation or DM profile uncertainties.

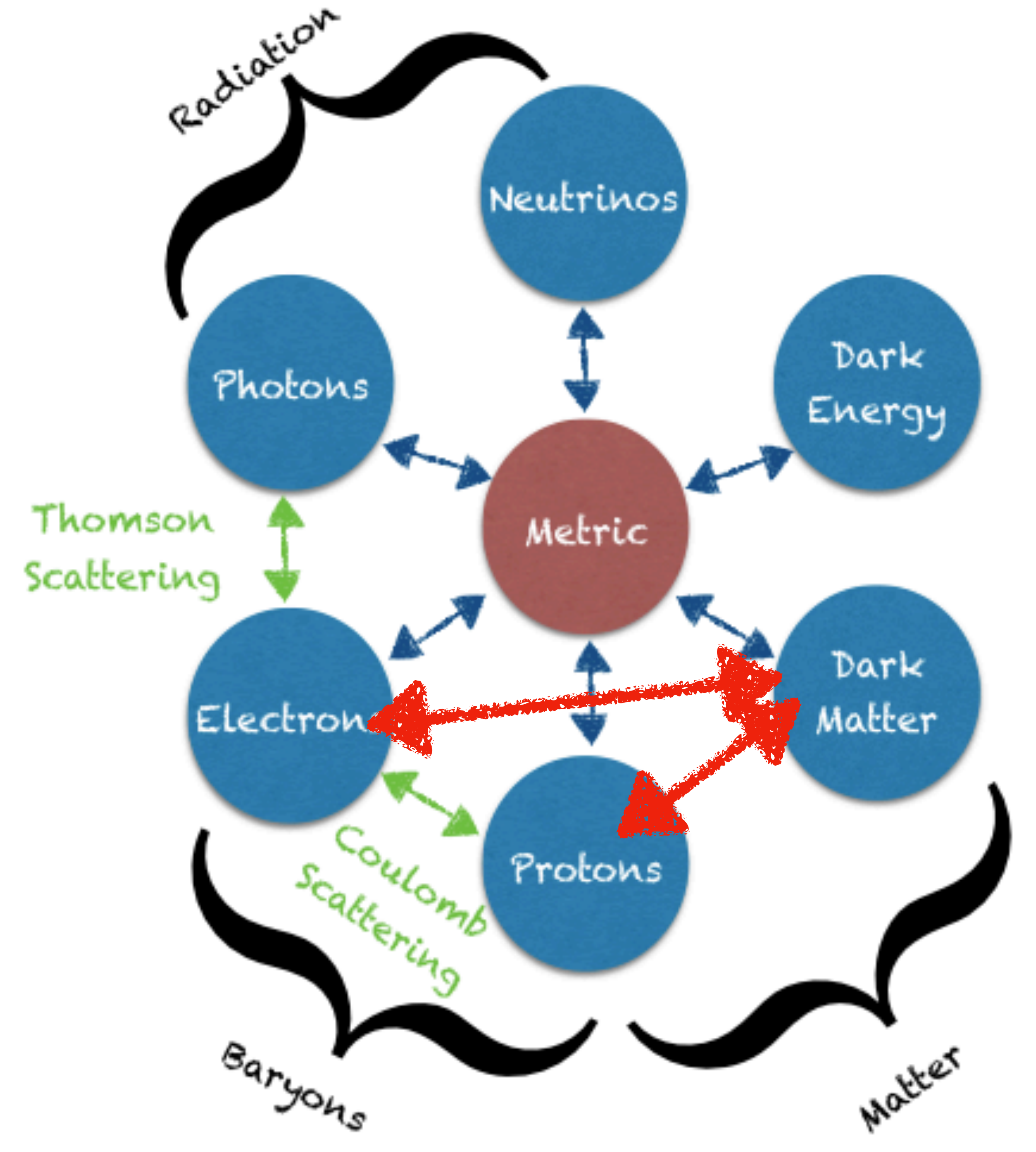
PBH evaporation

- We explicitely show that the "on-the-spot" approximation is bad: f(z) has a too strong z-dependence



See Stoecker, VP, et al., 1801.01871 for all details on evaporation rate and spectra

Direct Detection in Cosmology



Direct detection in Cosmology

Boddy & Gluscevic, 1712.07133, 1801.08609

- Temperature evolution

$$\dot{T}_\chi = -2\frac{\dot{a}}{a}T_\chi + 2R'_\chi(T_b - T_\chi)$$

$$\dot{T}_b = -2\frac{\dot{a}}{a}T_b + \frac{2\mu_b}{m_\chi}\frac{\rho_\chi}{\rho_b}R'_\chi(T_\chi - T_b) + \frac{2\mu_b}{m_e}R_\gamma(T_\gamma - T_b)\ ,$$

Rate of heat transfer

- Evolution of density and velocity perturbations

$$\dot{\delta}_\chi = -\theta_\chi - \frac{\dot{h}}{2} \qquad \dot{\theta}_\chi = -\frac{\dot{a}}{a}\theta_\chi + c_\chi^2 k^2 \delta_\chi + R_\chi(\theta_b - \theta_\chi)$$

$$\dot{\delta}_b = -\theta_b - \frac{\dot{h}}{2} \qquad \dot{\theta}_b = -\frac{\dot{a}}{a}\theta_b + c_b^2 k^2 \delta_b + R_\gamma(\theta_\gamma - \theta_b) + \frac{\rho_\chi}{\rho_b}R_\chi(\theta_\chi - \theta_b)$$

Rate of momentum transfer

$$\theta = i\vec{k}\cdot\vec{V}$$

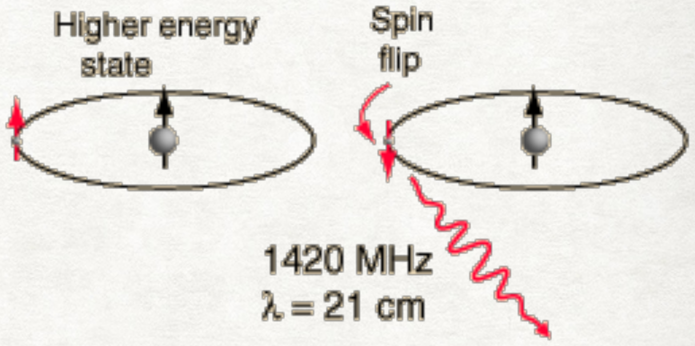
- The rates can be linked to the DD formalism:

$$\frac{d\vec{V}_\chi}{dt} = (1+z)R_\chi(\vec{V}_b - \vec{V}_\chi) = -\rho_b\sum_B \frac{Y_B}{m_\chi + m_B}\int d^3v\,\vec{v}[\sigma_{\mathrm{MT},B}(v)v]f(\vec{v})$$

momentum-transfer cross section

Slide taken from K. Boddy's talk

21 cm as a probe of DM-b scattering



- Hyperfine transition from neutral hydrogen
- Very sensitive probes of the Epoch of Reionization (EoR)
- Key quantities : Spin temperature Ts and differential brightness temperature Tb

$$\frac{n_1}{n_0} = 3e^{-E_{10}/k_B T_S}$$

$\Rightarrow$ Exc. = Des-exc.

$$T_S^{-1} = \frac{T_{\rm CMB}^{-1} + x_c T_K^{-1} + x_\alpha T_c^{-1}}{1 + x_c + x_\alpha}$$

scattering with CMB collision within the gas interaction with UV from stars

Compare patch of the sky with/without hydrogen clouds:

$$\delta T_b(\nu) = \frac{T_s - T_{\rm CMB}}{1+z}\left(1 - \exp(-\tau_{\nu 21})\right)$$

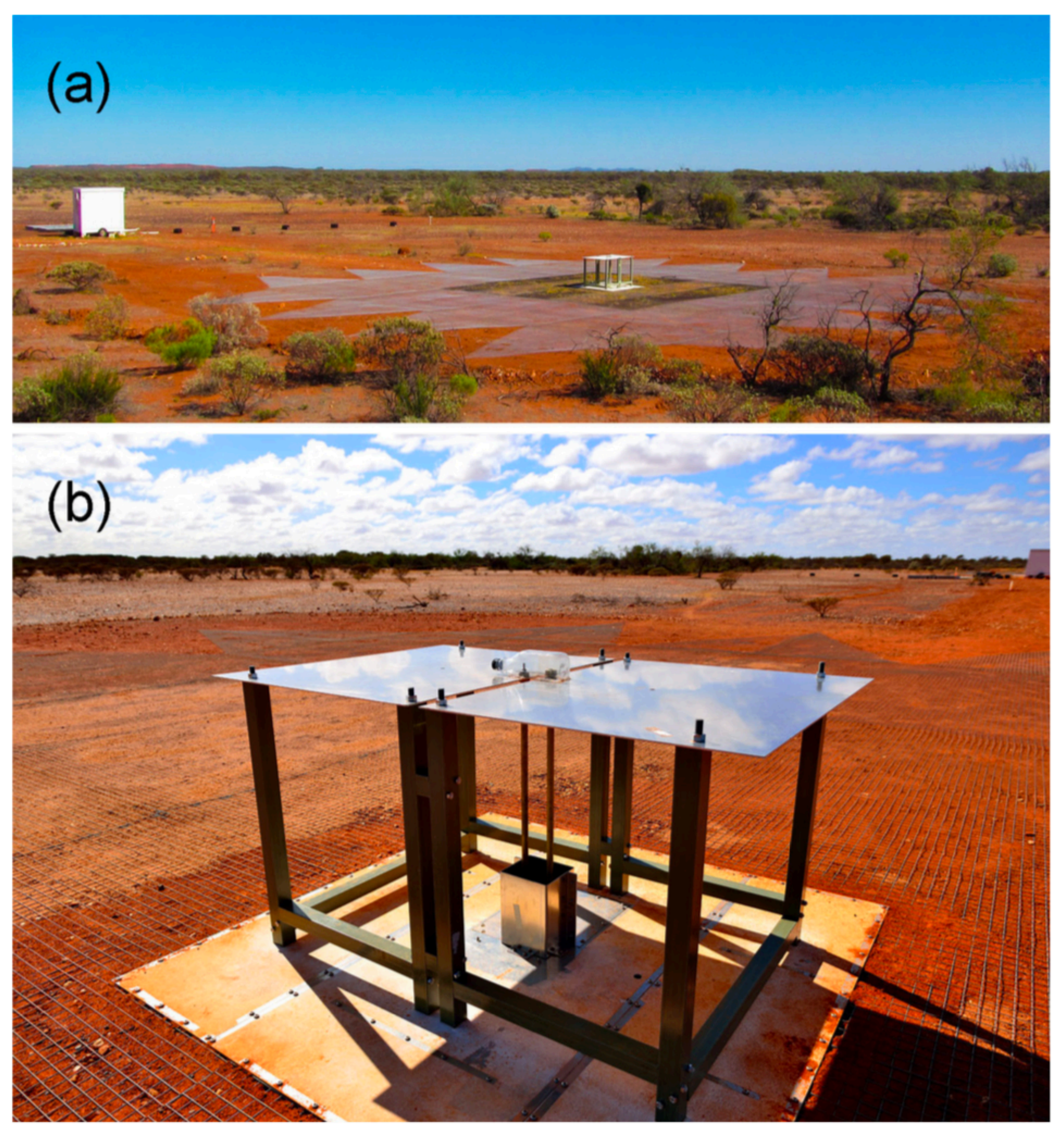
see e.g. Furlanetto et al. Phys.Rept. 433 (2006) 181-301

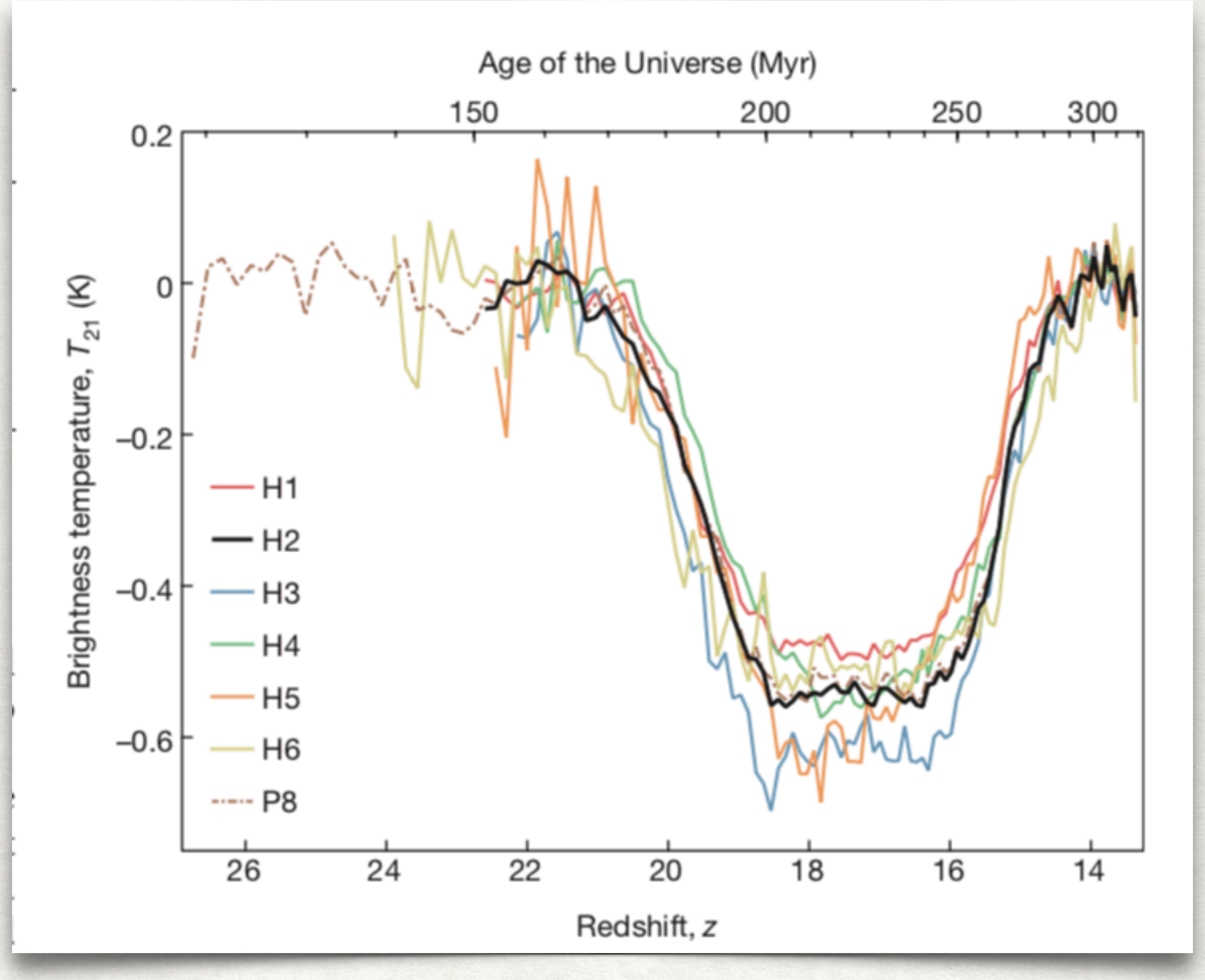
Difficulty = Huge astrophysical uncertainty below z ≈20
Stars can emits UV, ionizing photons and X-ray (heating)

21cm signal from EDGES

Bowman et al, nature25792

- EDGES is a broadband antenna (50-100 MHz) located in Western Australia
- The signal is much more (x2.5) in absorption than one expects.

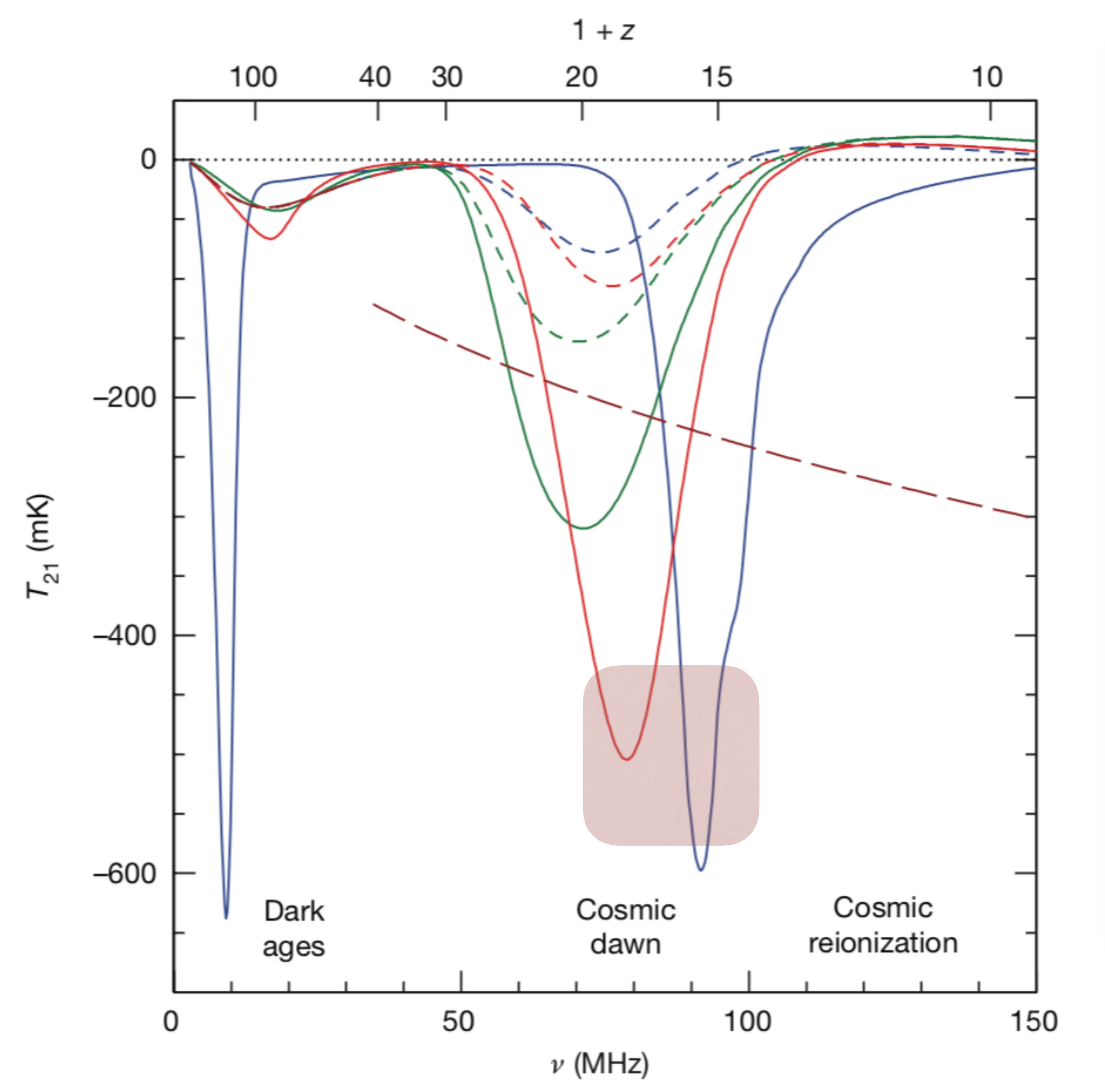


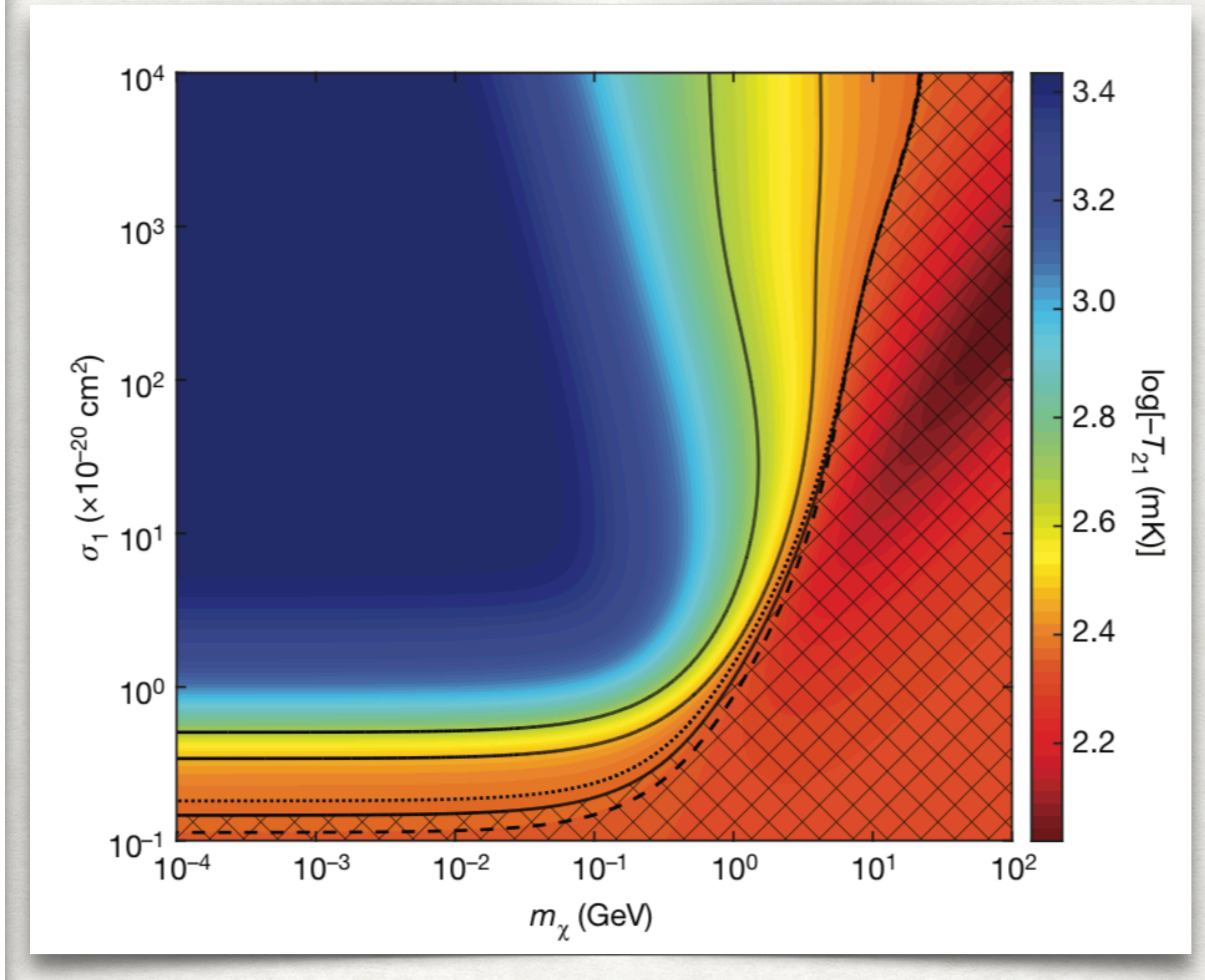


Have we discovered DM (again)?

Barkana, nature25791

- The gas is cooler than the pure adiabatic expansion. Scattering on CDM?
- requires a v^{-4} dependence to avoid other constraints! e.g. milli-charged DM.
- One subtlety: large DM-b relative velocity can heat the baryons.





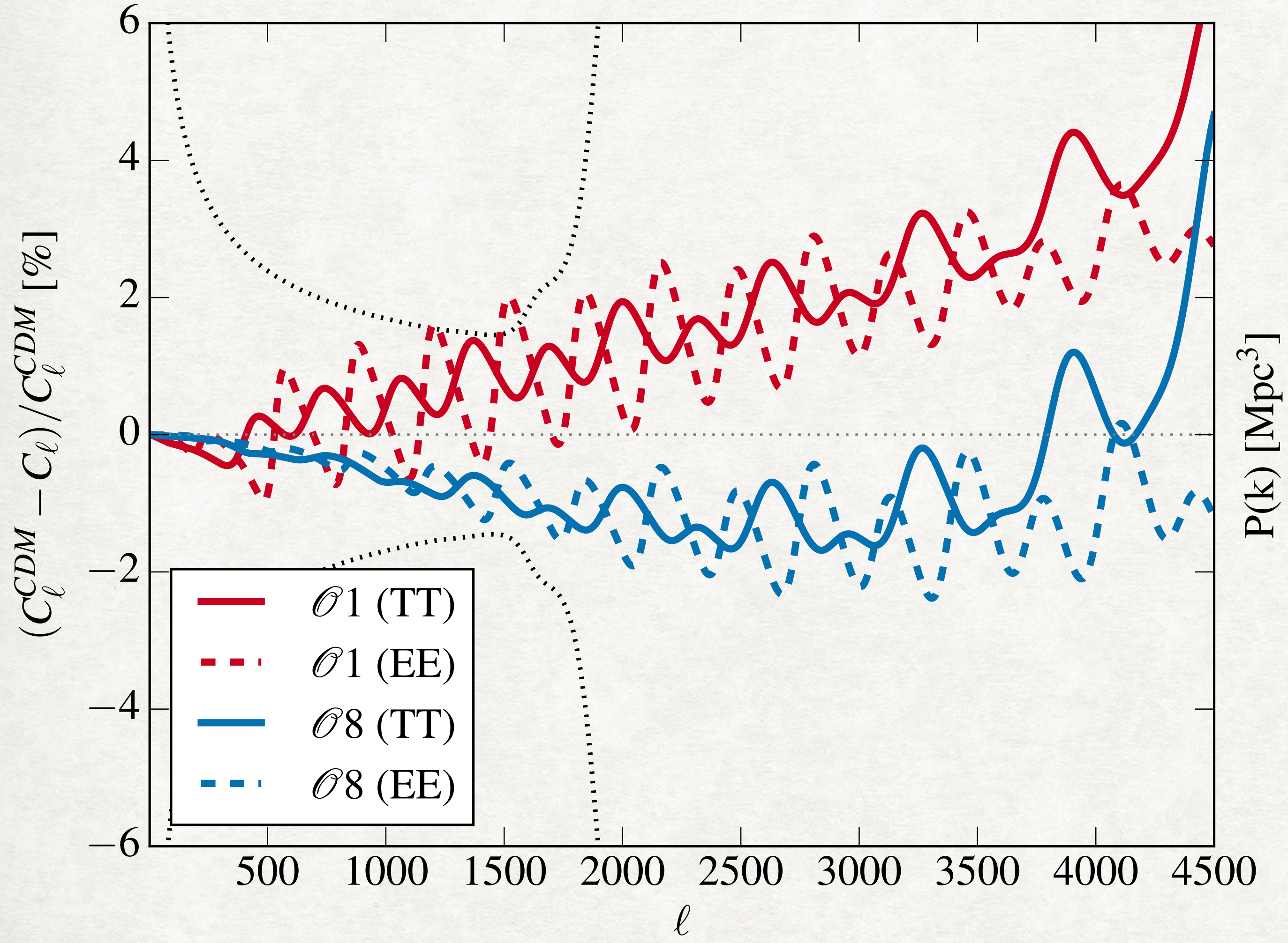
- favored DM properties are delimited by the full lines.

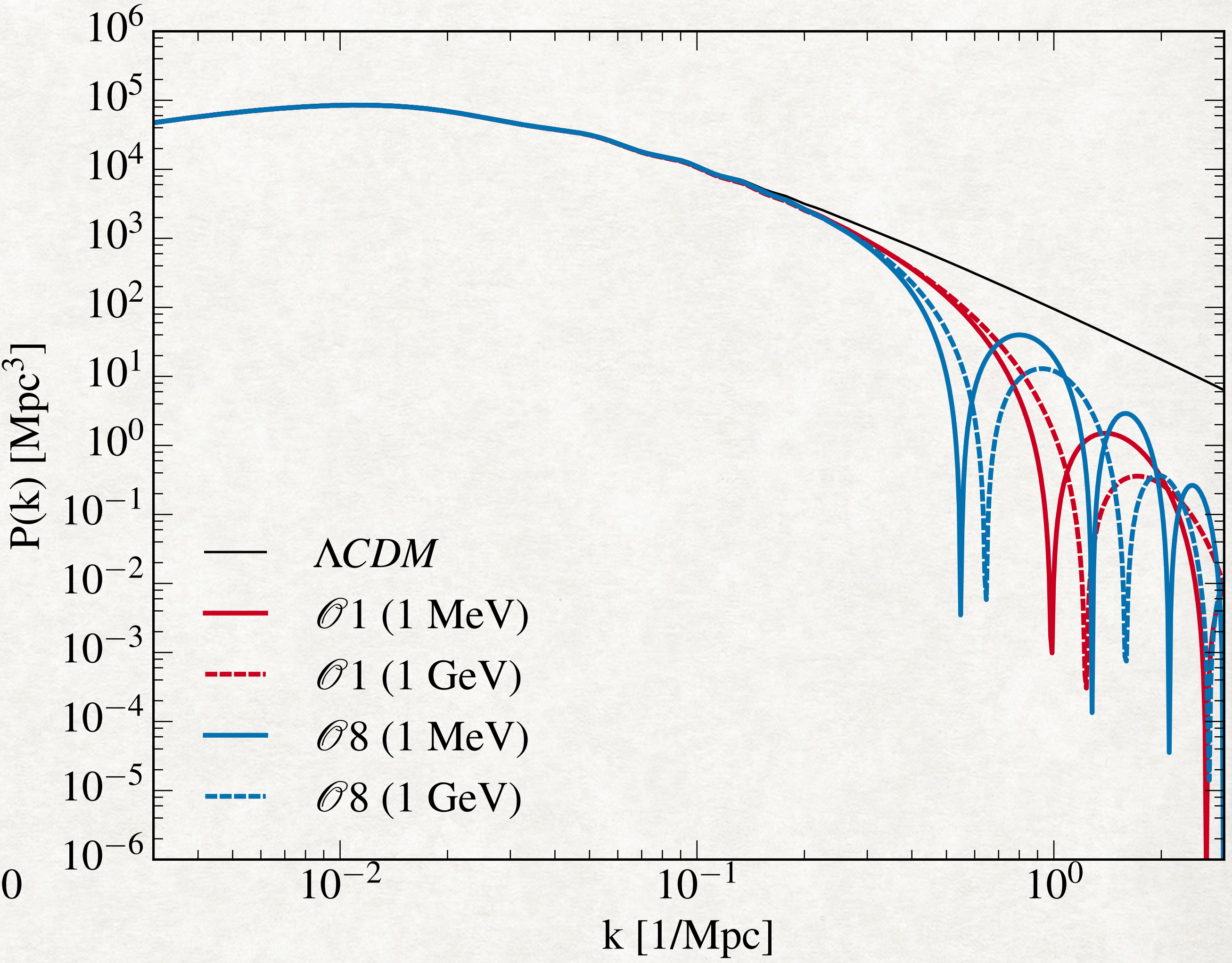
My next task: check the CMB/LSS

with K. Boddy and V. Gluscevic

- Boddy & Gluscevic 1801.08609: constraints on positive power of velocities.
- Xu et al, 1802.06788: Bad treatment of relative velocities and recombination

Currently I believe that such an interacting DM is still allowed





Boddy & Gluscevic, 1712.07133, 1801.08609

Conclusions

- We can perform both direct and indirect detection with the CMB: ExoCLASS. Constraints are competitive and/or complementary to galactic searches.

- An interesting DM-b signal has been seen in the 21cm: it will probably die (first experiment!) but it shows that data are coming! We ought to be ready.

Thank you!

Back Up

EFT Operator

Anand et al. (2014), Fitzpatrick et al. (2013), Fan et al. (2010)

$$\mathcal{H} = \sum_{\tau=0}^{1} \sum_{i=1}^{15} c_i^\tau \mathcal{O}_i t^\tau$$ (isospin basis)

$$\mathcal{O}_1 = 1_\chi 1_N$$

$$\mathcal{O}_3 = \vec{S}_N \cdot \left(\frac{i\vec{q}}{m_N} \times \vec{v}^\perp \right)$$

$$\mathcal{O}_4 = \vec{S}_\chi \times \vec{S}_N$$

$$\mathcal{O}_5 = \vec{S}_\chi \cdot \left(\frac{i\vec{q}}{m_N} \times \vec{v}^\perp \right)$$

$$\mathcal{O}_6 = - \left(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N} \right) \left(\vec{S}_N \cdot \frac{i\vec{q}}{m_N} \right)$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_9 = \vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{i\vec{q}}{m_N} \right)$$

$$\mathcal{O}_{10} = \vec{S}_N \cdot \frac{i\vec{q}}{m_N}$$

$$\mathcal{O}_{11} = \vec{S}_\chi \cdot \frac{i\vec{q}}{m_N}$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}^\perp \right)$$

$$\mathcal{O}_{13} = \left(\vec{S}_\chi \cdot \vec{v}^\perp \right) \left(\vec{S}_N \cdot \frac{i\vec{q}}{m_N} \right)$$

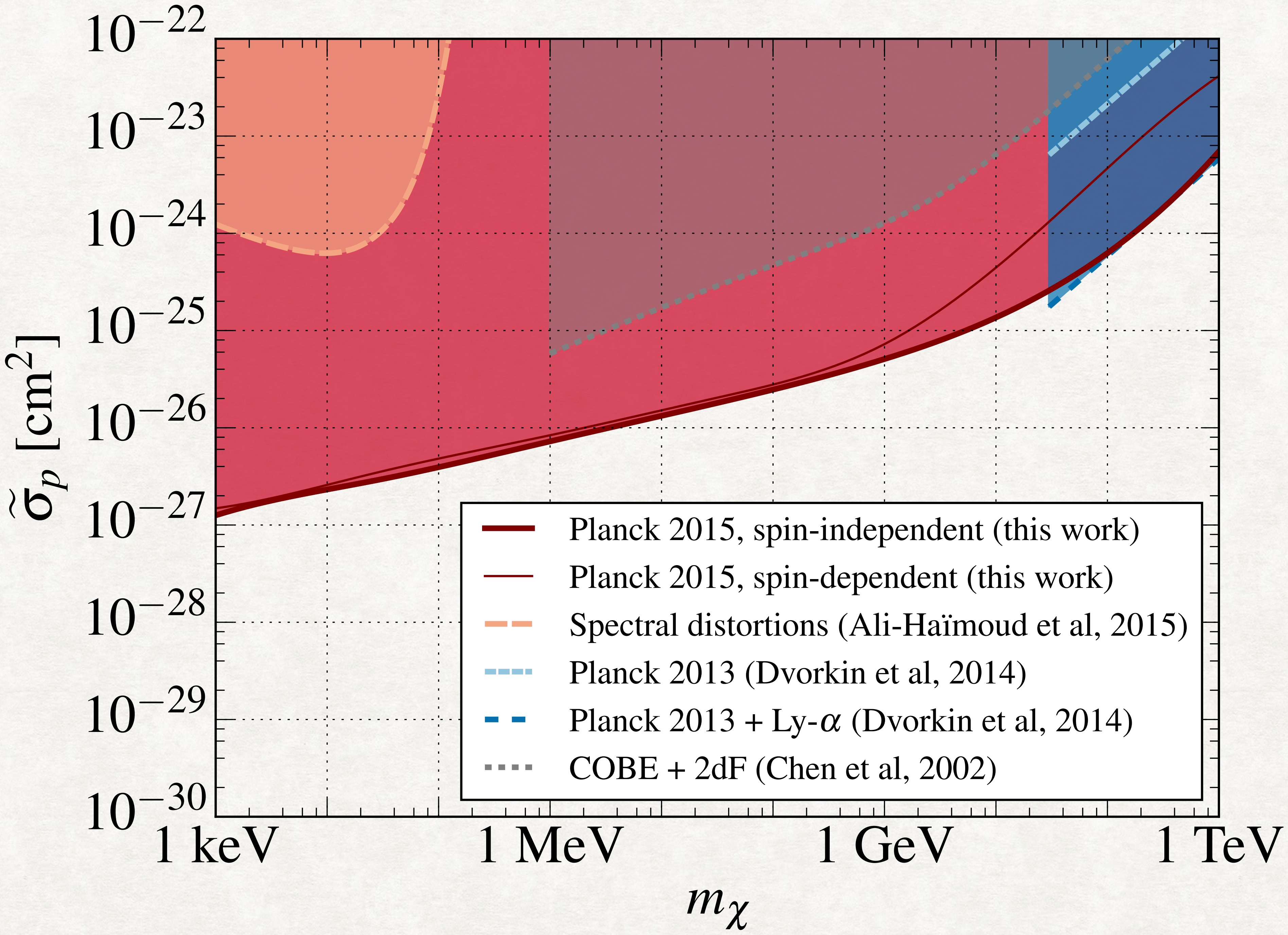
$$\mathcal{O}_{14} = \left(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N} \right) \left(\vec{S}_N \cdot \vec{v}^\perp \right)$$

$$\mathcal{O}_{15} = \left(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N} \right) \left[\left(\vec{S}_N \times \vec{v}^\perp \right) \cdot \frac{i\vec{q}}{m_N} \right]$$

Slide taken from K. Boddy's talk

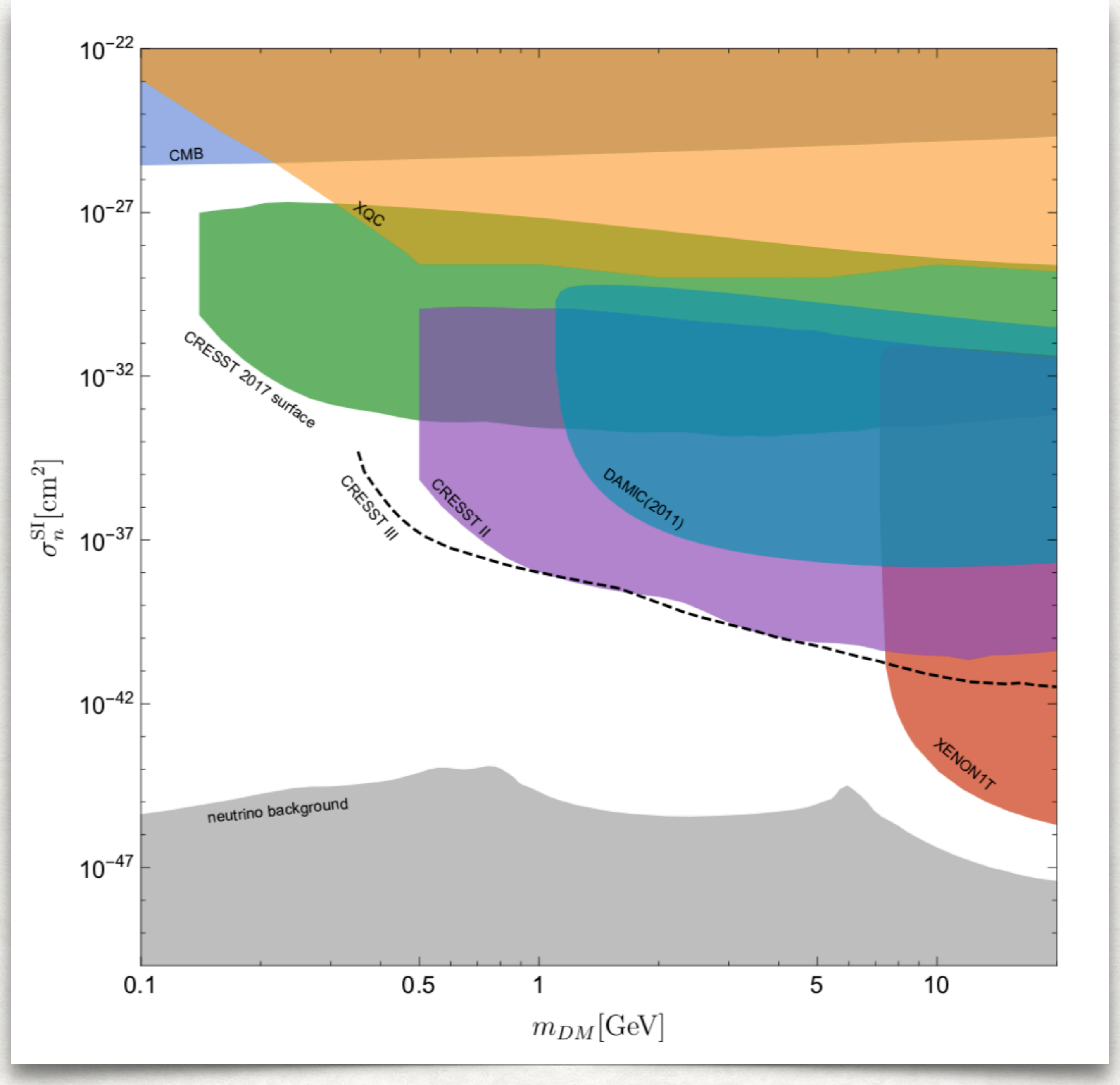
Constraints on SI and SD

Boddy & Gluscevic, 1712.07133, 1801.08609



Comparison with DD

Emken and Kouvaris 1802.04764



- Underground DD are shielded and insensitive to strongly interacting DM!
- The CMB extends constraints down to the KeV scale.