Searching for Dark Matter Interactions in the CMB

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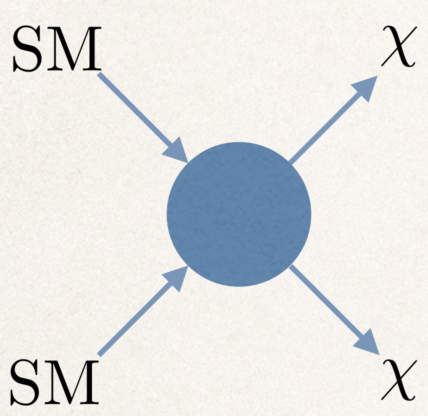
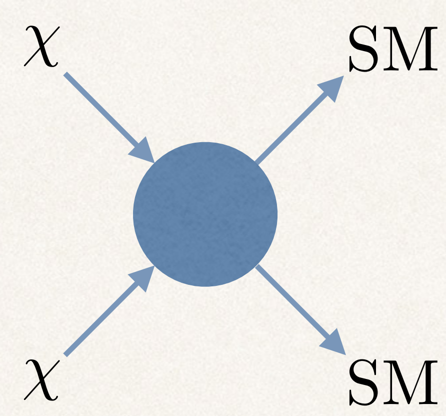
non-gravitational evidence of (particle)

Searching for ^ Dark Matter

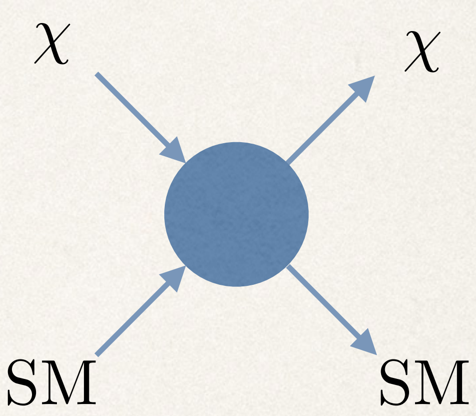
Production



Annihilation



Scattering



in particle physics

Collider | Indirect detection | Direct detection

in cosmology

Relic abundance | Energy injection | Momentum transfer

CMB vis-à-vis Direct Detection

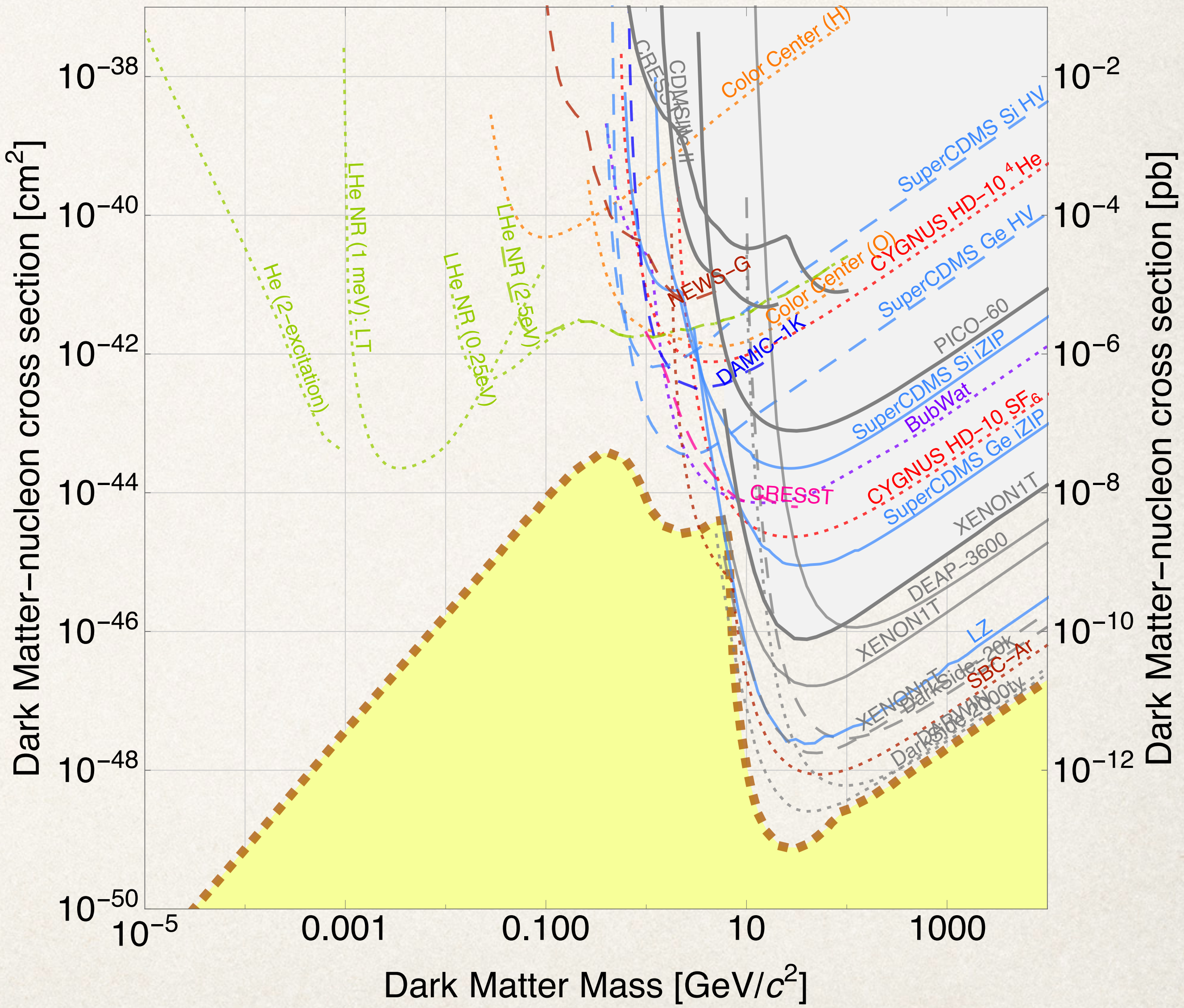
US Cosmic Visions (1707.04591)

For CMB:

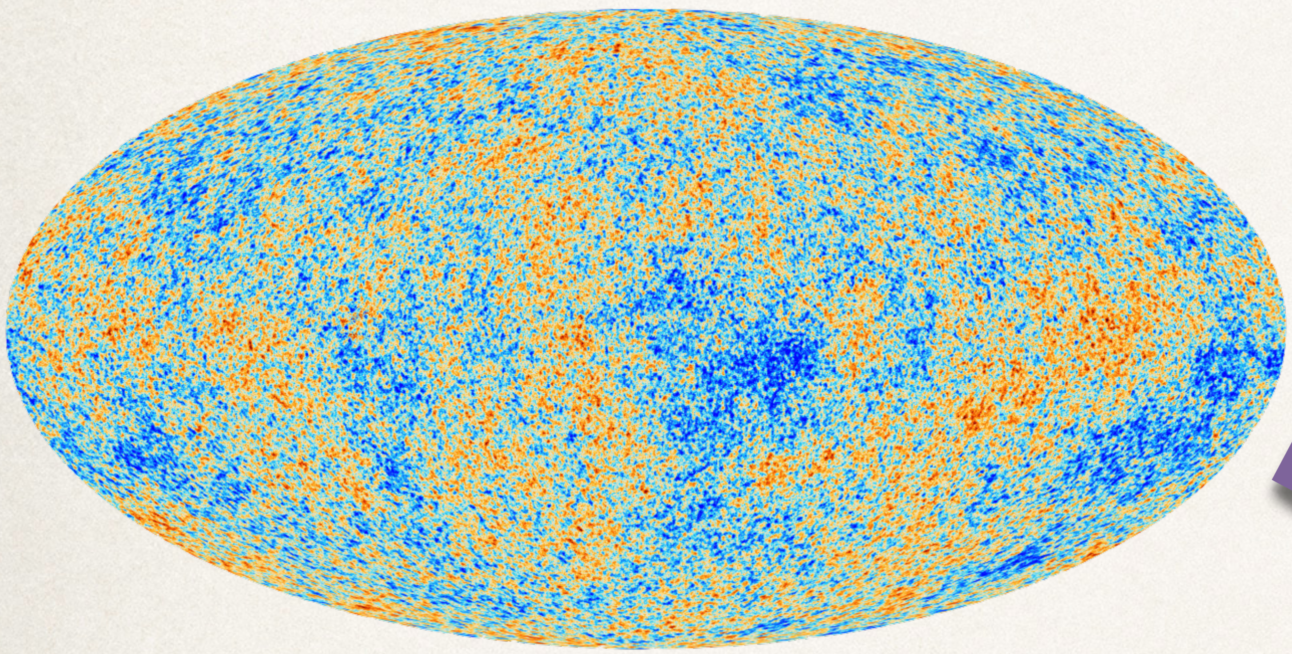
- Extend to masses < 1 GeV
- Constrain large cross sections (above direct detection ceiling)
- Independent of local halo properties

For both:

- Sensitivity to interaction structures beyond SI and SD cases



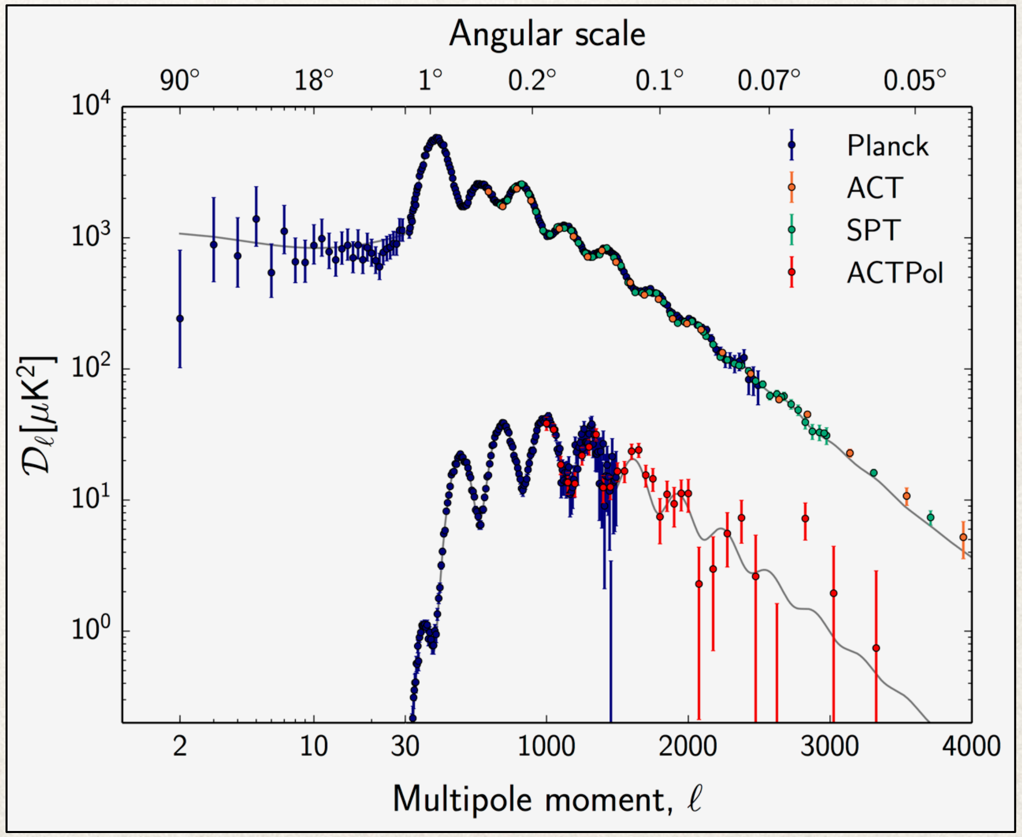
Cosmic Microwave Background



ESA and Planck Collaboration (2013)

$$\left\langle \frac{\delta T}{\bar{T}}(\hat{n}_1)\frac{\delta T}{\bar{T}}(\hat{n}_2)\right\rangle = \sum_{\ell,m,\ell',m'} \langle a_{\ell m} a^*_{\ell' m'}\rangle Y_{\ell m}(\hat{n}_1) Y_{\ell' m'}(\hat{n}_2)$$

$$\langle a_{\ell m} a^*_{\ell' m'}\rangle = \delta_{\ell\ell'}\delta_{mm'}C_\ell$$



Plot from E. Calabrese (for ACTPol)

Standard LCDM parameters:

$$\Omega_b h^2,\ \Omega_c h^2,\ h,\ \tau_{\rm reio},\ A_s,\ n_s$$

Consequences of Scattering

- Heat transfer due to scattering

$$\frac{dQ_\chi}{dt} = n_b \int d^3v_\chi d^3v_b f_\chi(\vec{v}_\chi) f_b(\vec{v}_b) \int \frac{d\sigma}{d\Omega} |\vec{v}_\chi - \vec{v}_b| \Delta E_\chi = \frac{3}{a} R'_\chi (T_b - T_\chi)$$

- Drag acceleration due to scattering

$$\frac{d\vec{V}_\chi}{dt} = \frac{n_b}{m_\chi} \int d^3v_\chi d^3v_b f_\chi(\vec{v}_\chi) f_b(\vec{v}_b) \int \frac{d\sigma}{d\Omega} |\vec{v}_\chi - \vec{v}_b| \Delta \vec{p}_\chi = \frac{1}{a} R_\chi (\vec{V}_b - \vec{V}_\chi)$$

- Consider scattering on protons
  (free and within helium nuclei)

Modified Boltzmann Equations

KB and Gluscevic (2017,2018), Dvorkin et al. (2014,2018), Sigurdson et al. (2004), Chen et al. (2002)

- 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

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

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

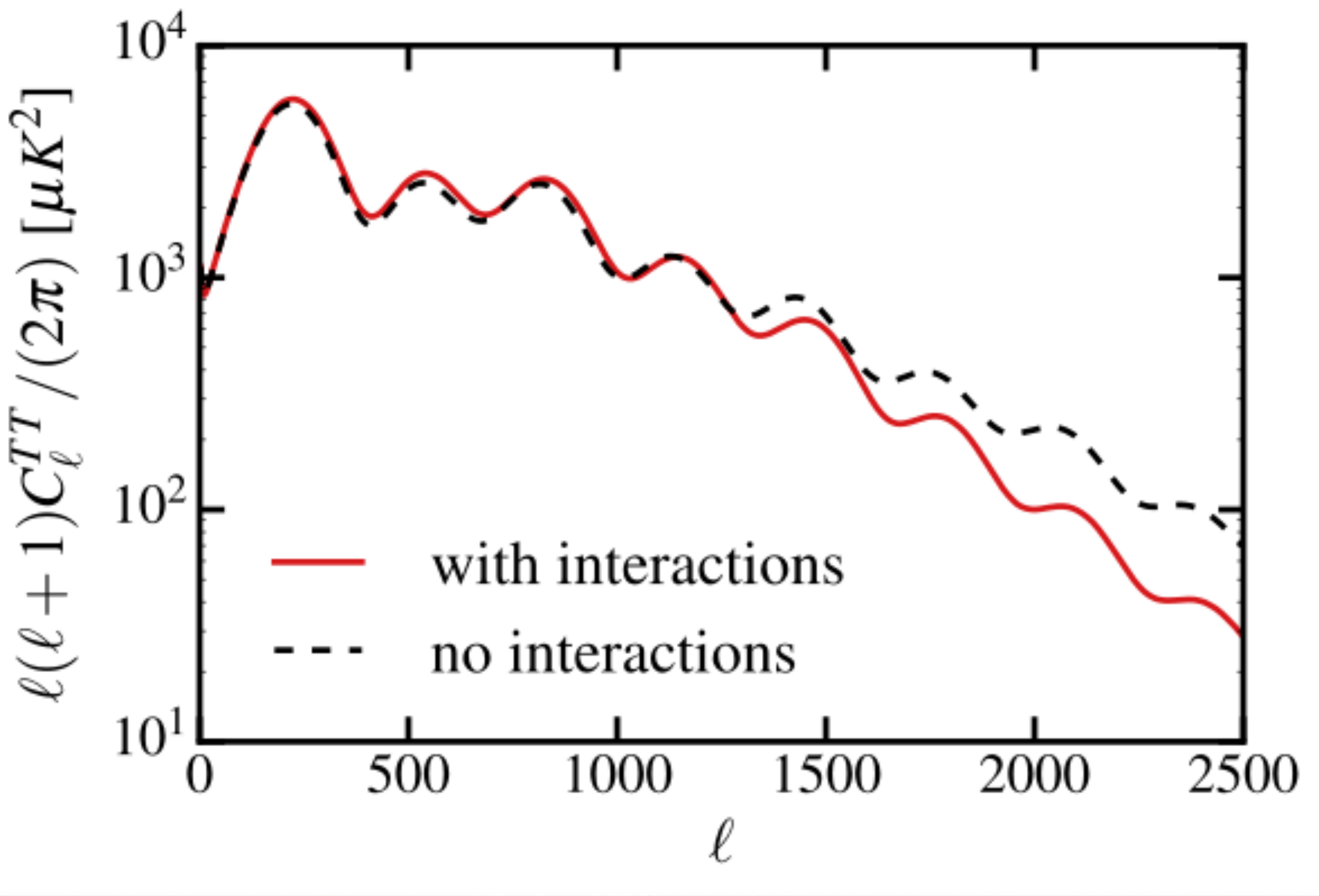
Rate of momentum transfer

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

- Implemented into CLASS/MontePython

Small-Scale Suppression

scattering → drag force → suppression



Rate Coefficients

$$\frac{dQ_\chi}{dt} = n_b \int d^3v_\chi d^3v_b f_\chi(\vec{v}_\chi) f_b(\vec{v}_b) \int \frac{d\sigma}{d\Omega} |\vec{v}_\chi - \vec{v}_b| \Delta E_\chi = \frac{3}{a} R'_\chi (T_b - T_\chi)$$

$$\frac{d\vec{V}_\chi}{dt} = \frac{n_b}{m_\chi} \int d^3v_\chi d^3v_b f_\chi(\vec{v}_\chi) f_b(\vec{v}_b) \int \frac{d\sigma}{d\Omega} |\vec{v}_\chi - \vec{v}_b| \Delta \vec{p}_\chi = \frac{1}{a} R_\chi (\vec{V}_b - \vec{V}_\chi)$$

Particle physics input?
Connect with direct detection.

Nonrelativistic EFT Operators

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

SI

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

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

SD

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

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

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

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

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

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

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

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

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

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

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

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

Single-Operator Cross Section

- Observables: $\vec{S}_\chi, \quad \vec{S}_N, \quad \frac{i\vec{q}}{m_N}, \quad \vec{v}^\perp = \vec{v} + \frac{\vec{q}}{2\mu_{\chi N}}$

$$|\vec{q}|^2 = 2\mu_{\chi N}^2 |\vec{v}|^2 (1 - \cos\theta)$$

Keep track of velocity dependence

$$\mathcal{O}_i \sim \left|\vec{v}^\perp\right|^\alpha \left(\frac{|\vec{q}|}{m_N}\right)^\beta$$

- Matrix element

DM response

$$\langle |\mathcal{M}|^2 \rangle_B = \frac{1}{m_v^4} \frac{4\pi}{2S_B + 1} \sum_{\tau,\tau'} \sum_k R_k^{\tau\tau'}\left(\vec{v}_B^{\perp 2}, \frac{|\vec{q}|^2}{m_N^2}\right) W_{B,k}^{\tau\tau'}\left(\frac{|\vec{q}|^2 a_B^2}{4}\right)$$

Nuclear response

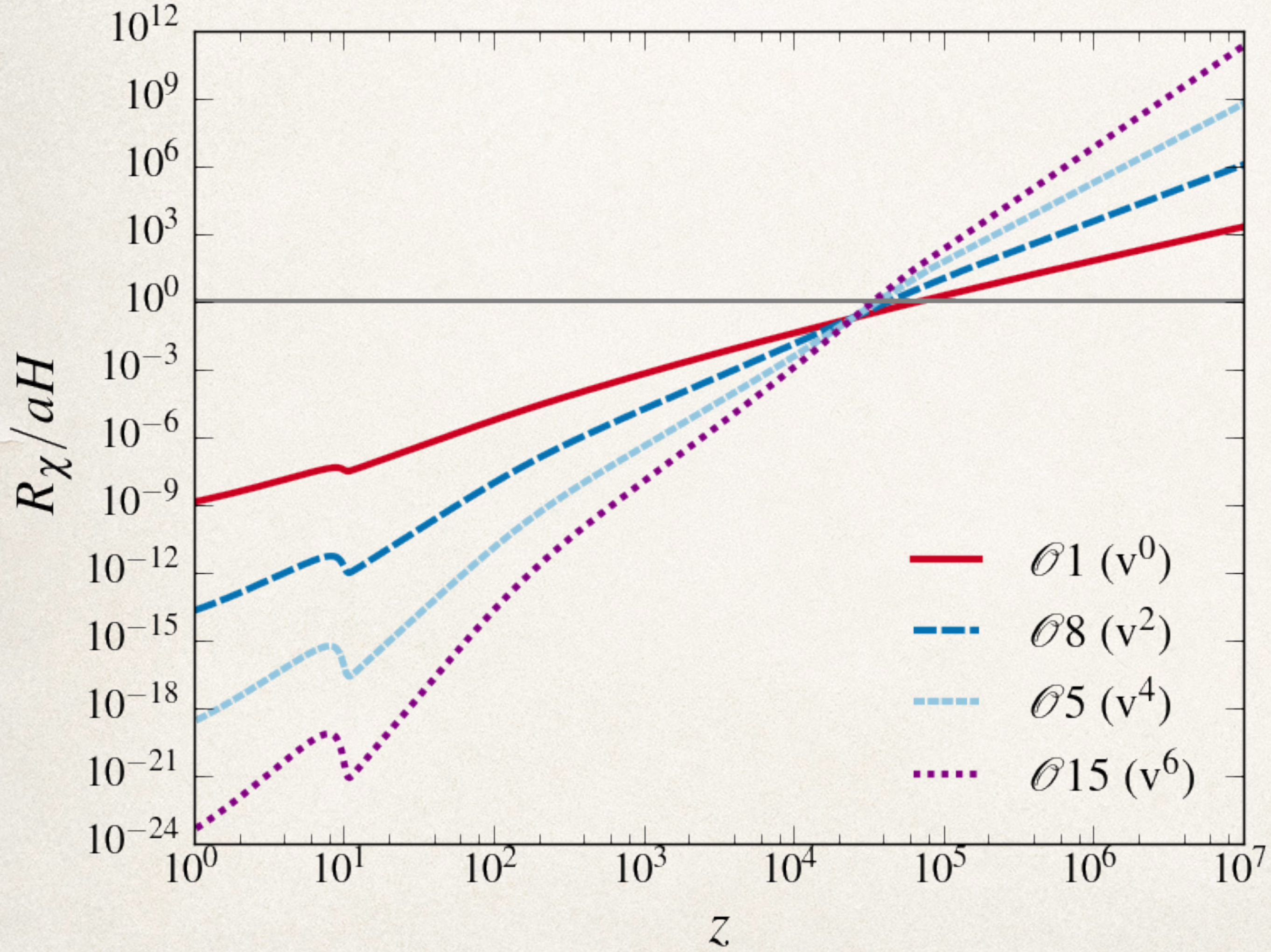
- Cross section

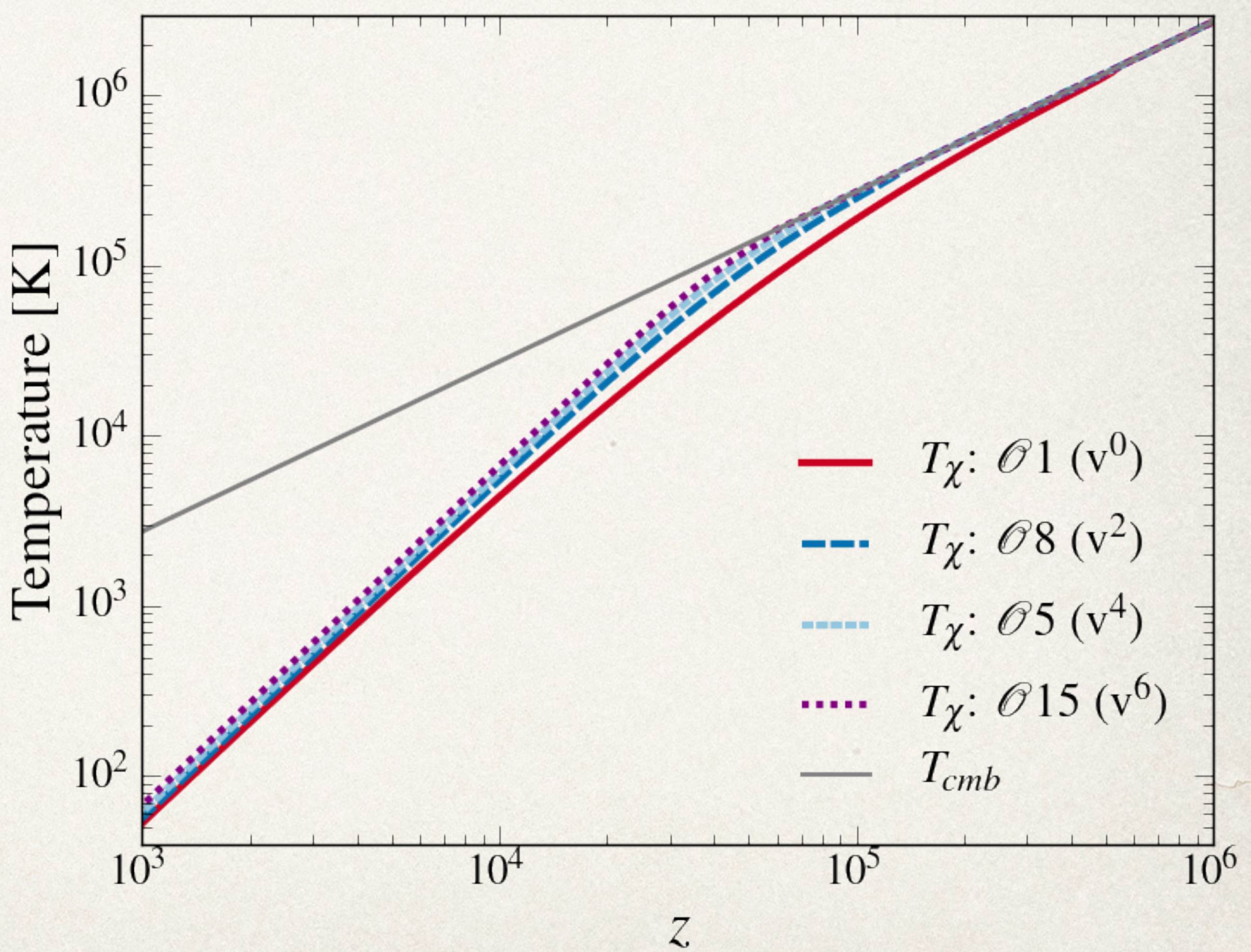
$$\sigma_B^{(i)}(v) = \widetilde{\sigma}_B^{(i)} v^{2(\alpha+\beta)} \times {}_1F_1(1+\beta, 2+\alpha+\beta; -2\mu_{\chi B}^2 a_B^2 v^2)$$

helium

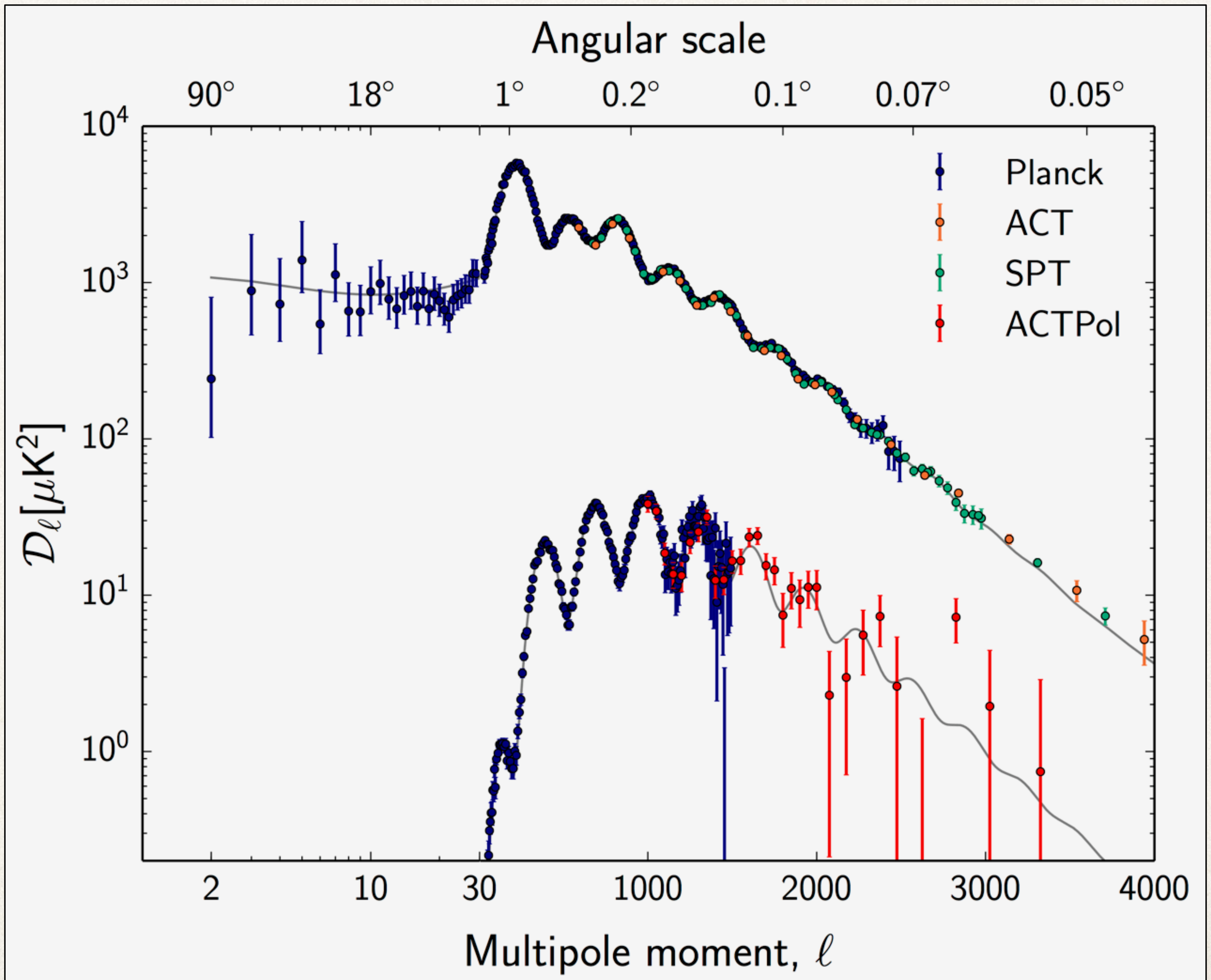
Rate Evolution

$$R_\chi \propto a\rho_b \sum_B \frac{Y_B}{m_\chi + m_B} \widetilde{\sigma}_B^{(i)} \left(\frac{T_b}{m_B} + \frac{T_\chi}{m_\chi} \right)^{1/2+\alpha+\beta} \times \left[1 + (2\mu_{\chi B} a_B)^2 \left(\frac{T_b}{m_B} + \frac{T_\chi}{m_\chi} \right) \right]^{-(2+\beta)}$$



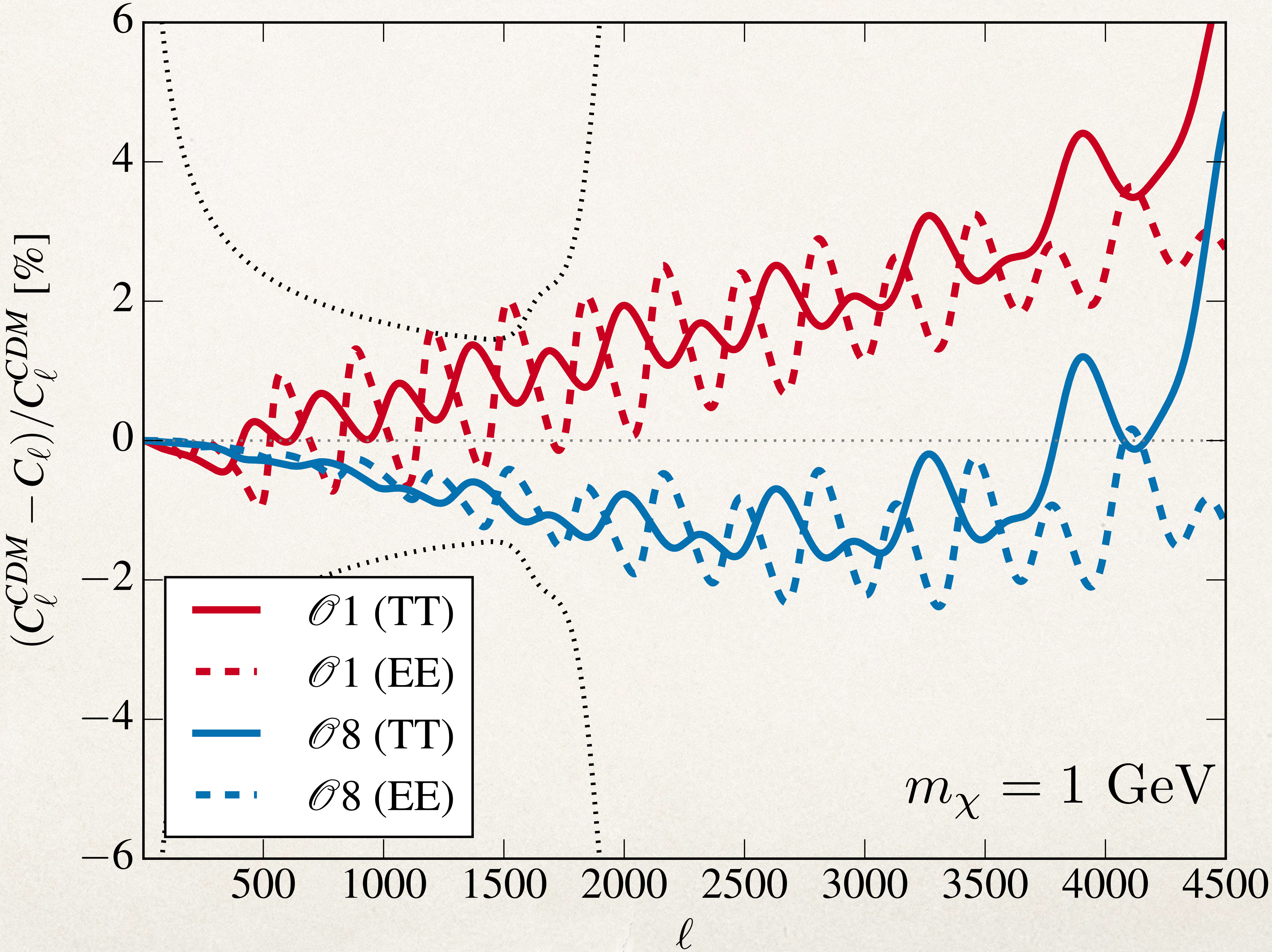


CMB Power Spectra



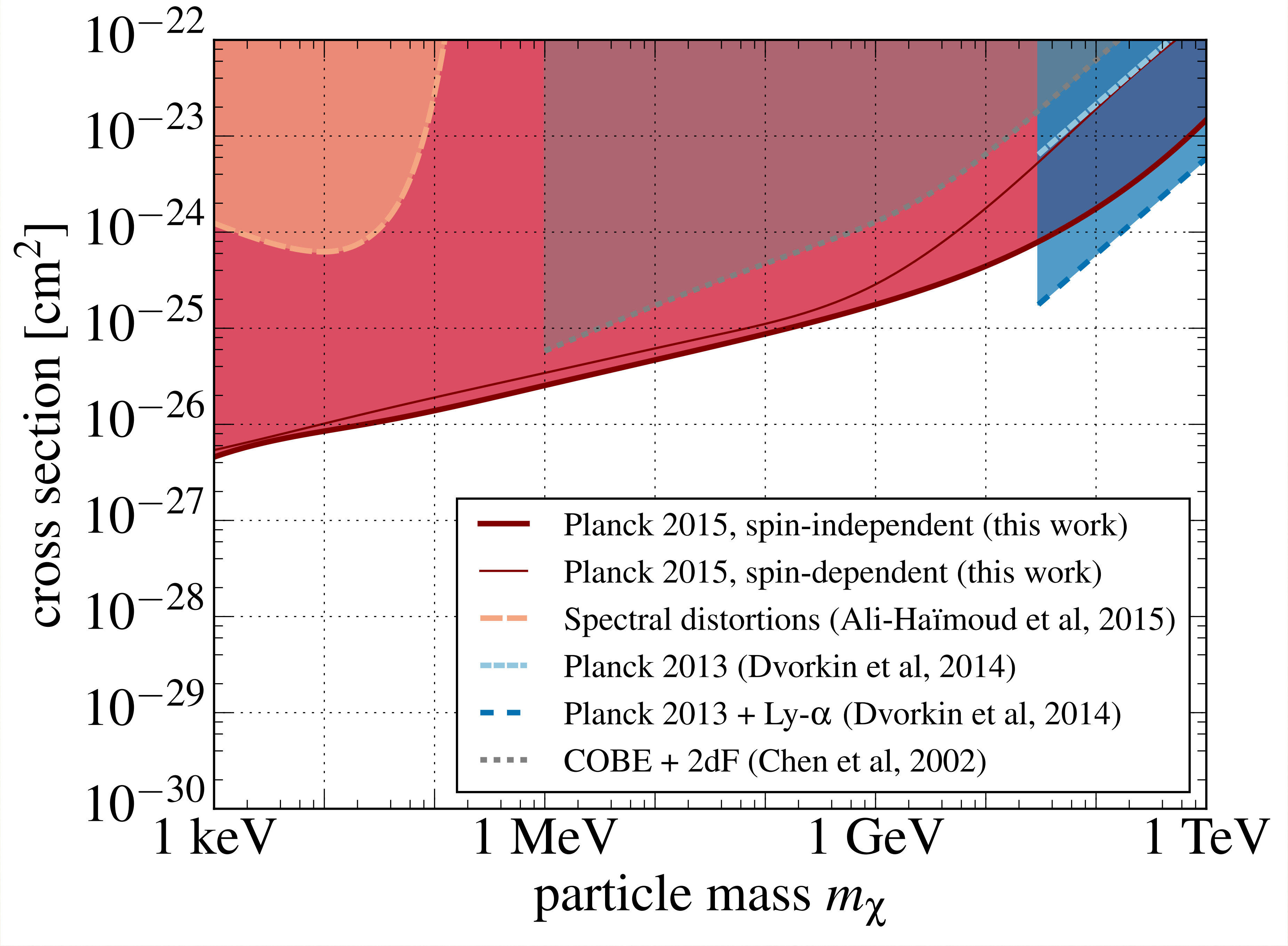
Plot from E. Calabrese (for ACTPol)

Spectrum Comparisons



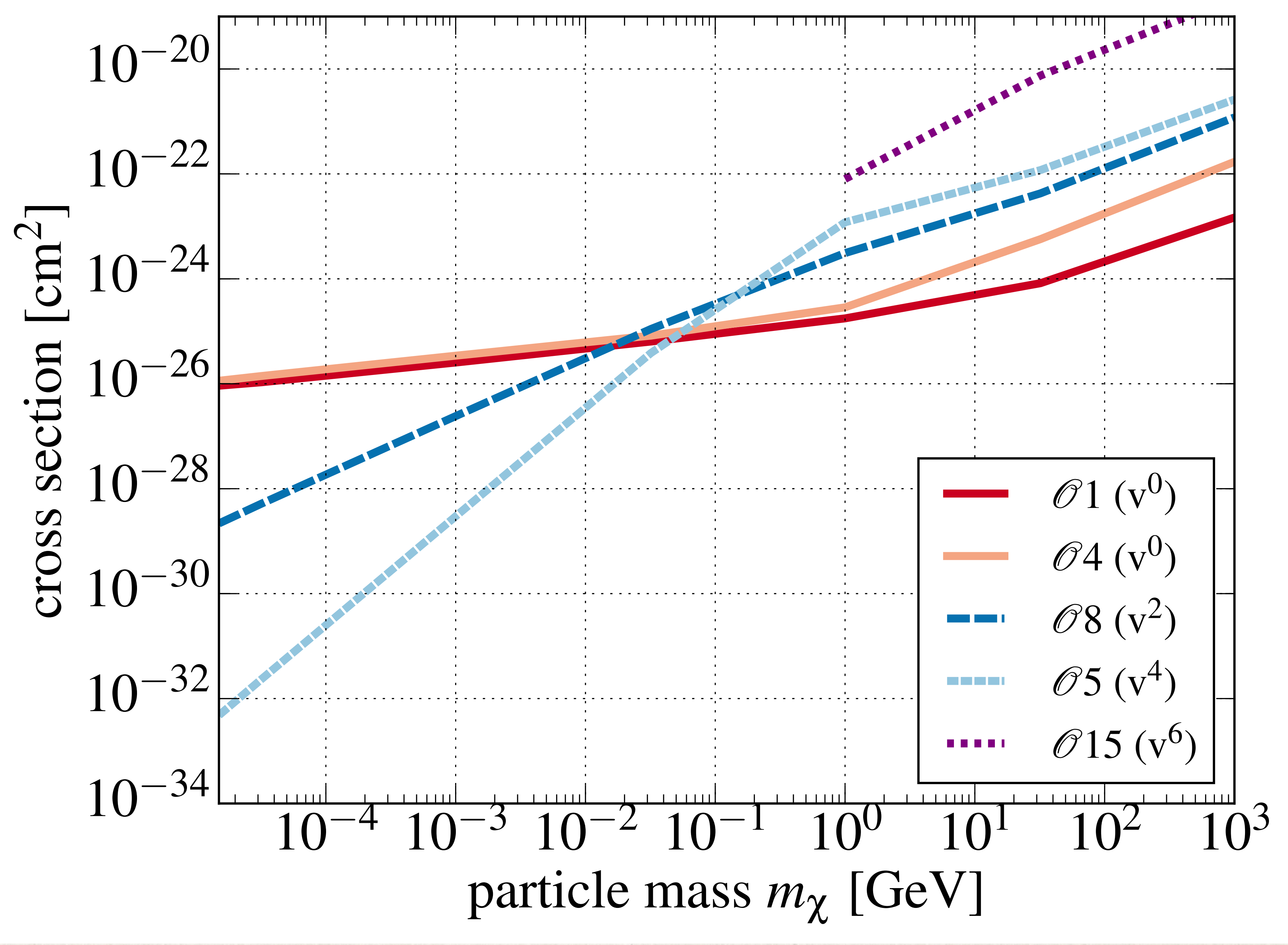
Constraints on SI and SD

Gluscevic and KB (1712.07133)



Constraint Comparison

KB and Gluscevic (1801.08609)



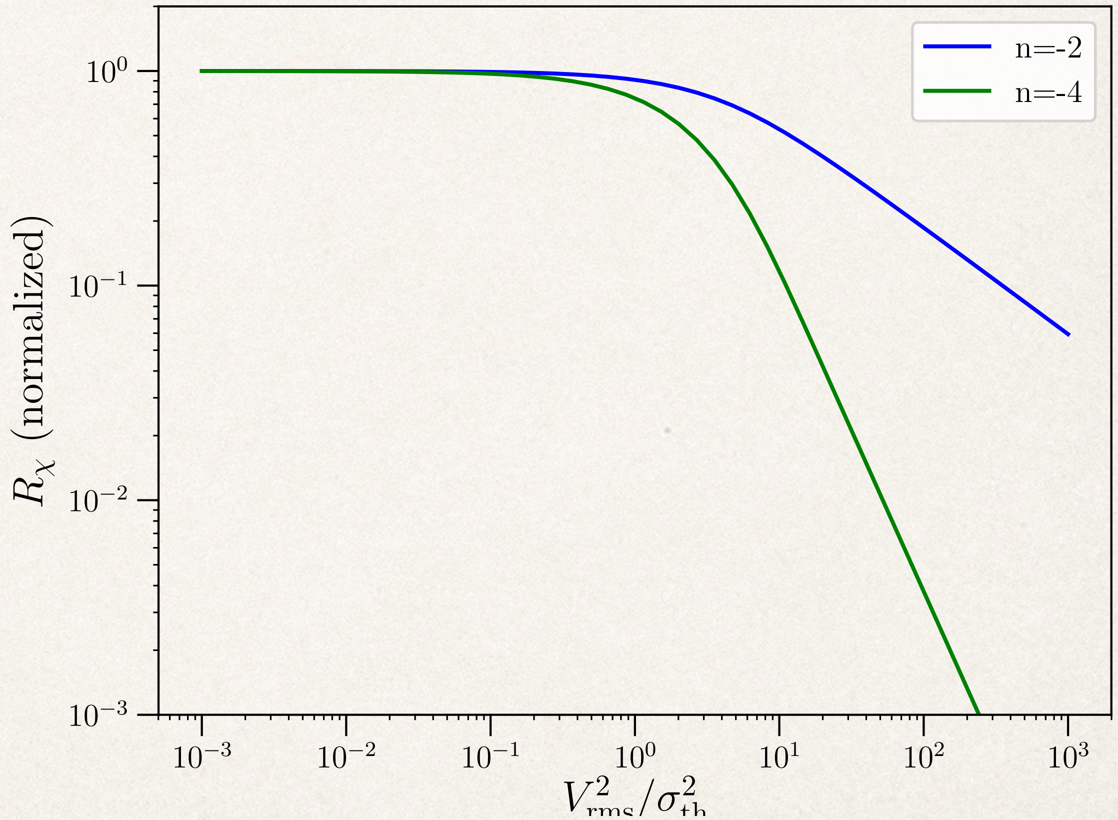
$v = (220 \text{ km/s})/c$

Light Mediators: v^{-2} and v^{-4}

- Expect cross section to be small at early times, when thermal velocities are large

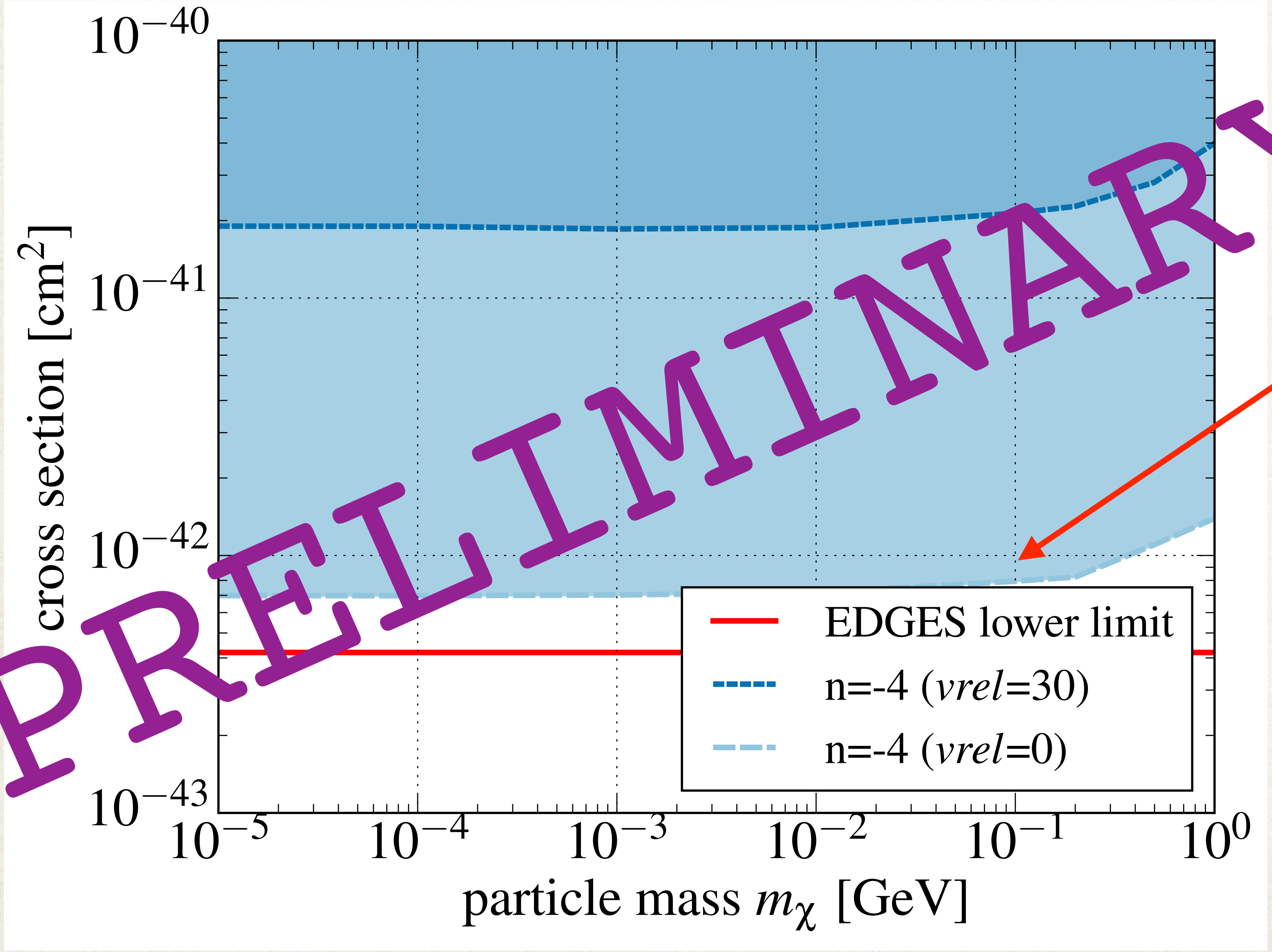
- Recall momentum-transfer rate

$$\frac{d\vec{V}_\chi}{dt} = \frac{1}{a} R_\chi (\vec{V}_b - \vec{V}_\chi)$$



- Difficulty: nonlinear equation ➤ Solution: use Vrms

Constraints for v^{-4}



steep rise in EDGES limit (not shown) above 0.1 GeV

More results soon to come!

Summary and Outlook

- Precision cosmology provides complementary searches for particle dark matter interactions
- Expect better constraints from ground-based CMB experiments that probe smaller scales
  - Planck+ACTPol joint analysis (upcoming)
  - Forecasts for AdvACT and CMB-S4 (in progress)
- Incorporate large-scale structure data (upcoming)
- Heightened interest in dark photon models from EDGES result; careful treatment of cosmological constraints is needed (in progress)