

Dark Matter-Baryon Scattering in Global 21cm Signal

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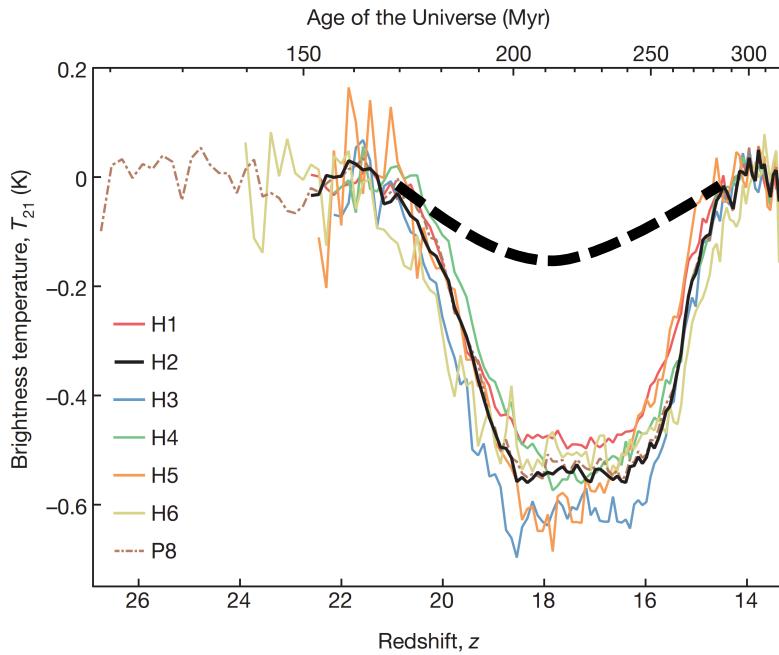


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Global 21 cm signal

- **EDGES result:** Bowman et al. Nature 555, 67 (2018)



- 1) Expect smaller 21 cm absorption between star-formation and reionization
 - 2) $z \sim 17, 78$ MHz
 - 3) $T_{21} \propto 1 - \frac{T_{rad}}{T_{spin}}$
- gas was colder, or background radiation was hotter

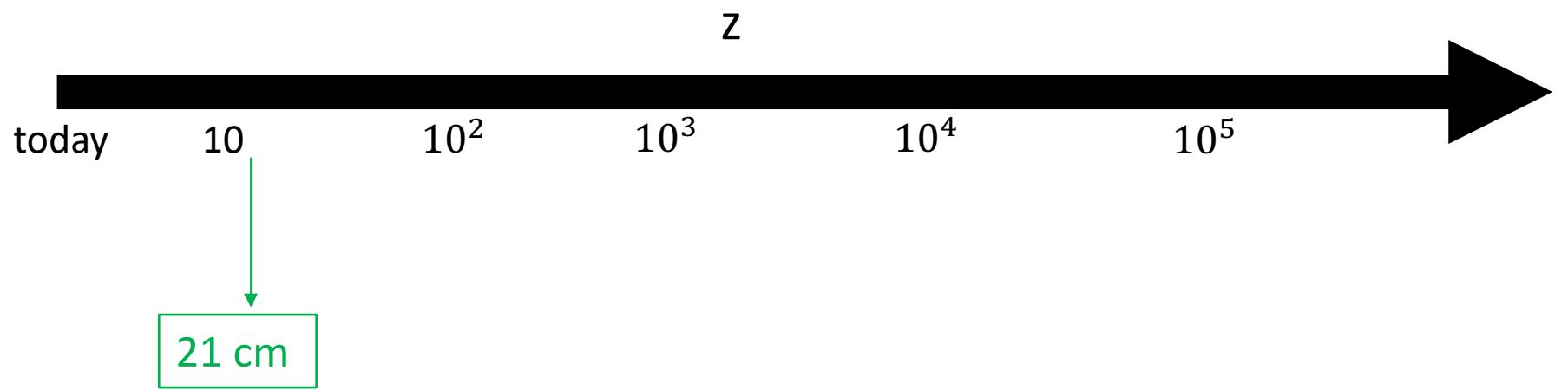
- Models:

Background radiation was hotter:

Light DM, axion, black hole

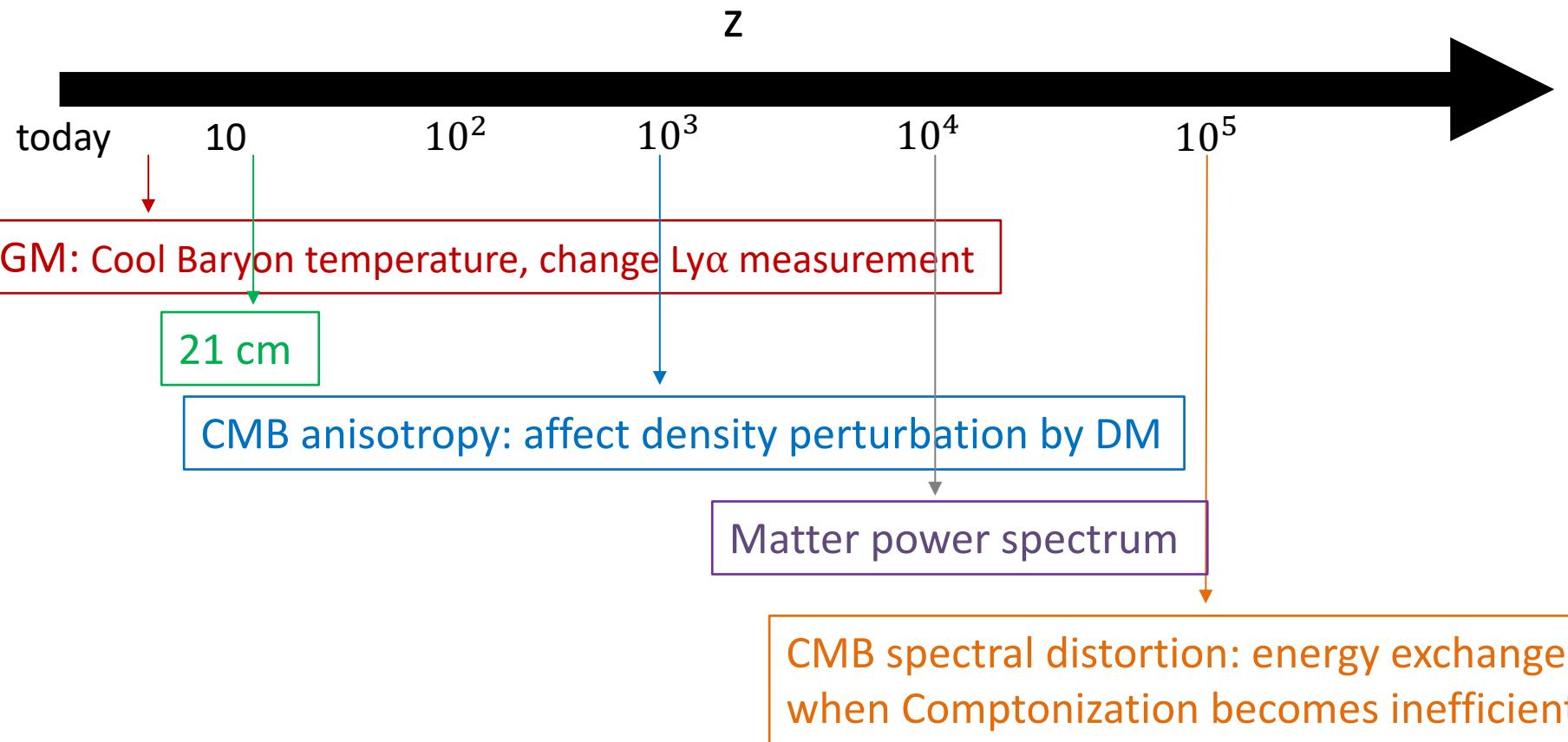
Gas was colder:

DM-Baryon scattering



Cosmological Constraints on DM-Baryon Scattering

- Walk through the history of cosmology



Cosmological Constraints on DM-Baryon Scattering

- Assume **velocity-dependent** elastic scattering:

$$\sigma = \sigma_0 v^n$$

v : DM and baryon relative velocity

n : -4 (light mediator), -2, 0...

IGM

- After reionization, IGM temperature evolution:

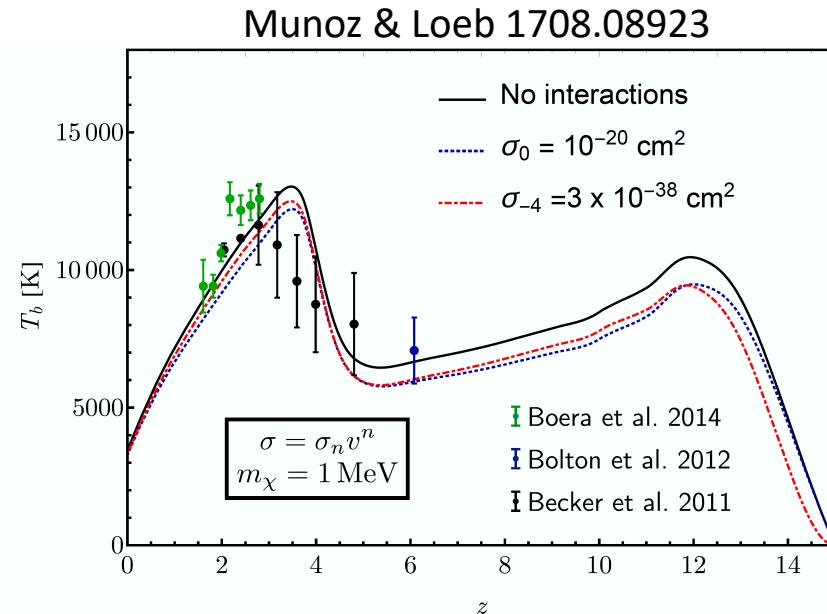
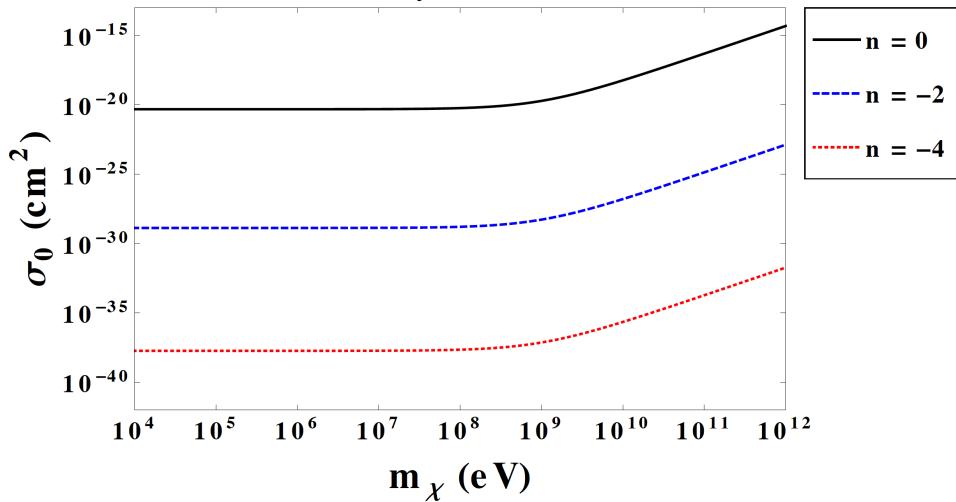
$$\dot{T}_b = Q_{adia} + Q_{CMB} + Q_{ph} + Q_{cooling} + Q_{DM-b}$$

- Roughly **constant** ΔT_b as a function of z in the presence of DM-Baryon scattering

$$\Delta T_b = \frac{2}{3} \int dt \Gamma_{b,\chi} (T_\chi - T_b)$$

- Ly α measurement: $\frac{\Delta T_b}{T_b} \lesssim 0.1$

Wu & Slatyer 1803.09734



CMB - formalism

- temperature & density evolution:

Temperature: $\dot{T}_\chi = -2\frac{\dot{a}}{a}T_\chi + \boxed{\frac{2m_\chi}{m_\chi + m_H} R_\chi (T_b - T_\chi)},$

$$\dot{T}_b = -2\frac{\dot{a}}{a}T_b + 2\frac{\mu_b}{m_e} R_\gamma (T_\gamma - T_b) + \boxed{\frac{2\mu_b}{m_\chi + m_H} \frac{\rho_\chi}{\rho_b} R_\chi (T_\chi - T_b)}.$$

Density: $\dot{\theta}_\chi = -\frac{\dot{a}}{a}\theta_\chi + c_\chi^2 k^2 \delta_\chi + \boxed{R_\chi (\theta_b - \theta_\chi)},$

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

where $R_\chi = \frac{ac_n\rho_b\sigma_0}{m_\chi + m_H} \left(\frac{T_b}{m_H} + \frac{T_\chi}{m_\chi} \right)^{\frac{n+1}{2}} F_{\text{He}}$

$$R_\chi \rightarrow \frac{ac_n\rho_b\sigma_0}{m_\chi + m_H} \left(\frac{T_b}{m_H} + \frac{T_\chi}{m_\chi} + \frac{V_{\text{rms}}^2}{3} \right)^{\frac{n+1}{2}} \text{(Bulk velocity)}$$

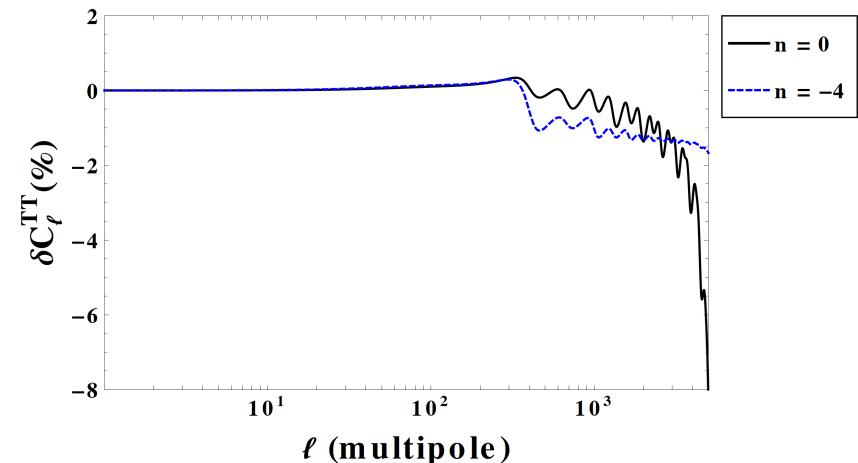
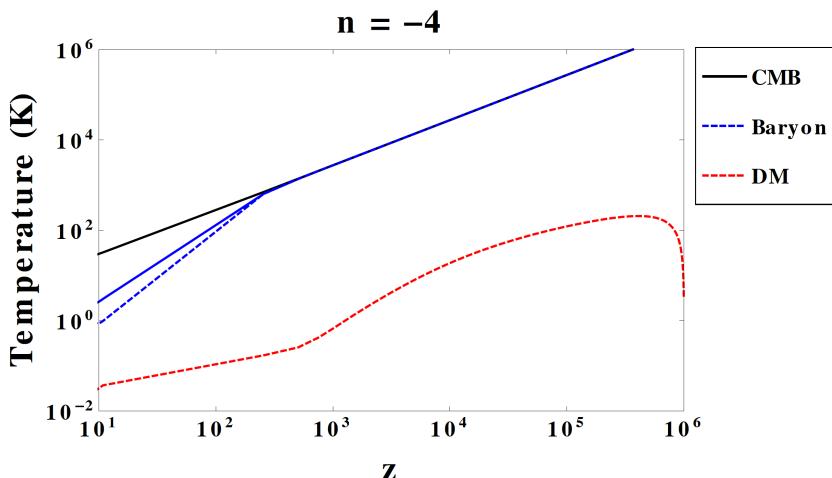
CMB - example

- Affect temperature & density evolution:

Temperature: cool baryon

Density: DM over-density feel pressure from plasma pressure
→ Modes within horizon will be suppressed

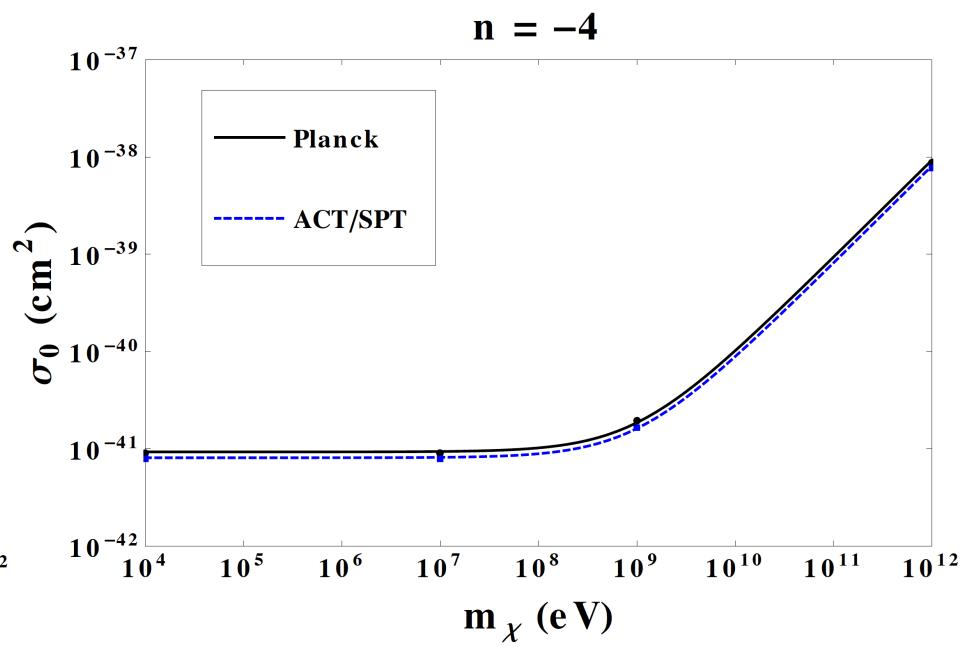
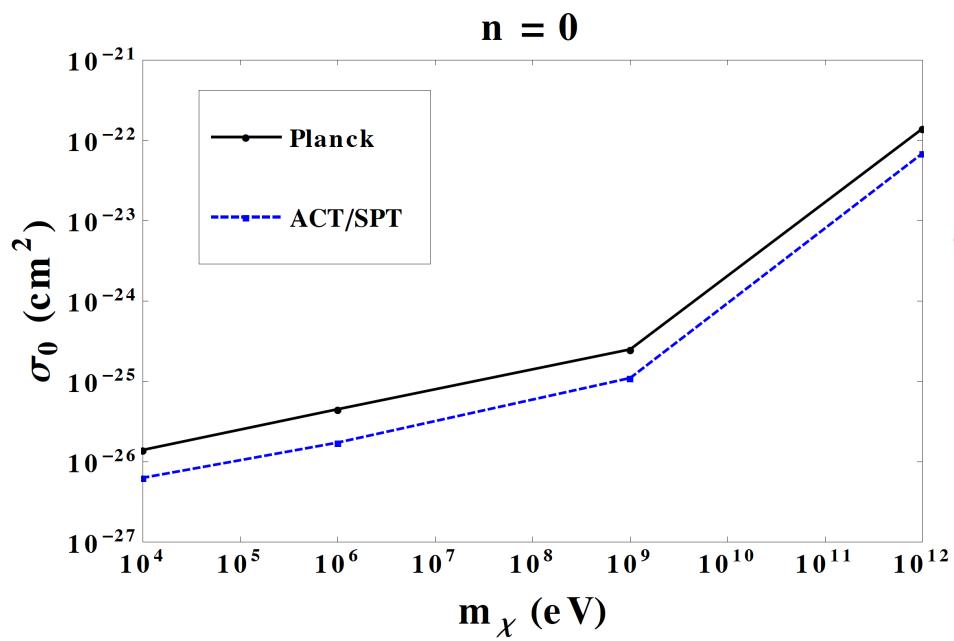
- Example



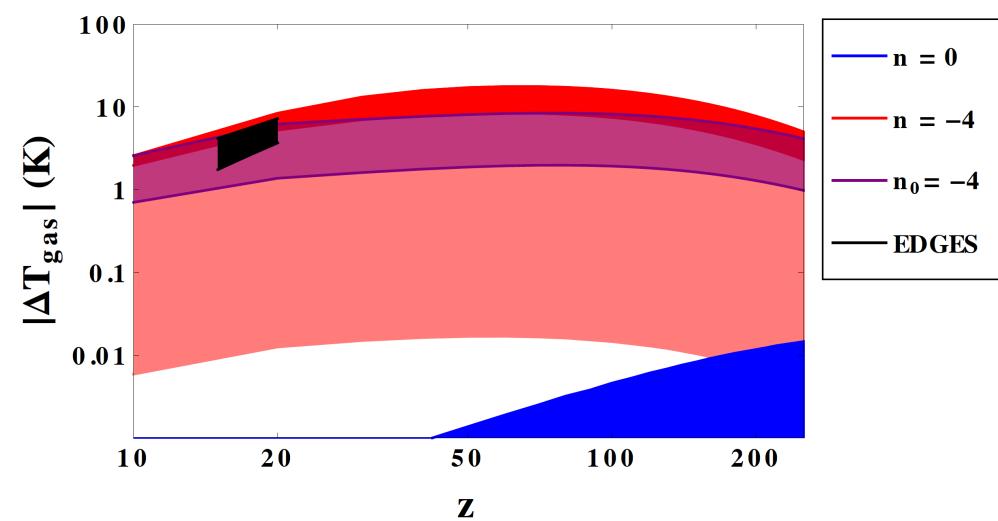
- 1) Photon & baryon tight coupled before $z \sim 150$
- 2) Minor effect

- 1) Dominant effect from high ℓ
- 2) Include ACT/SPT to $\ell = 5000$
- 3) Ly α is important for $n = 0$

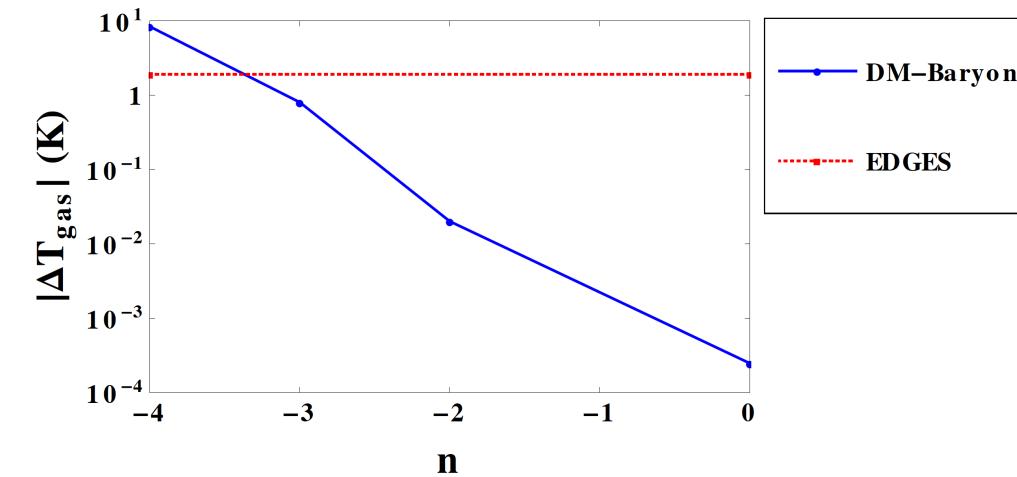
CMB - constraints



CMB – gas temperature



- 1) Maximal allowed xsec consistent with CMB
- 2) Gas temperature change as a function z
- 3) Broad band covers keV – TeV; Thin band covers sub-GeV
- 1) n vs n_0 : Bulk velocity



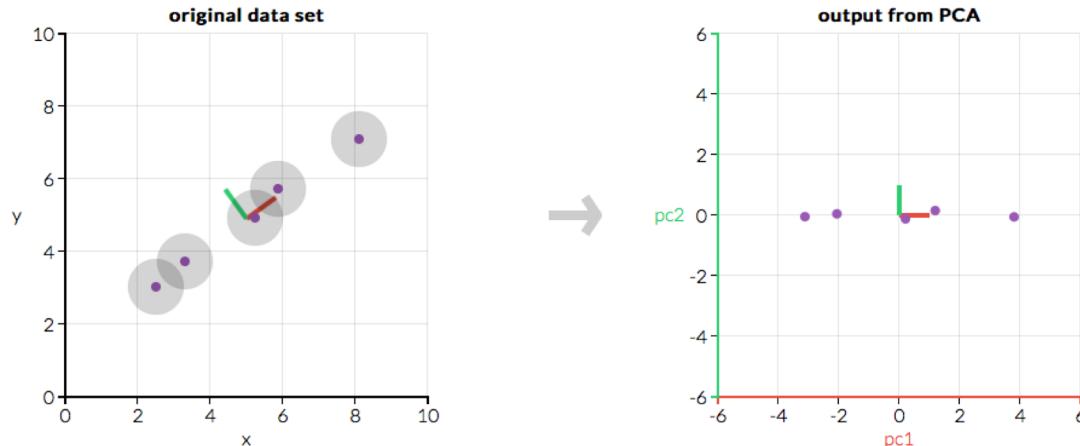
- 1) Maximal gas temperature consistent with CMB for different **velocity-dependence n**

CMB – PCA Intro

- Principal Component Analysis:

- Reduce dimension of the problem

- find the strong pattern in a dataset



DM-Baryon:

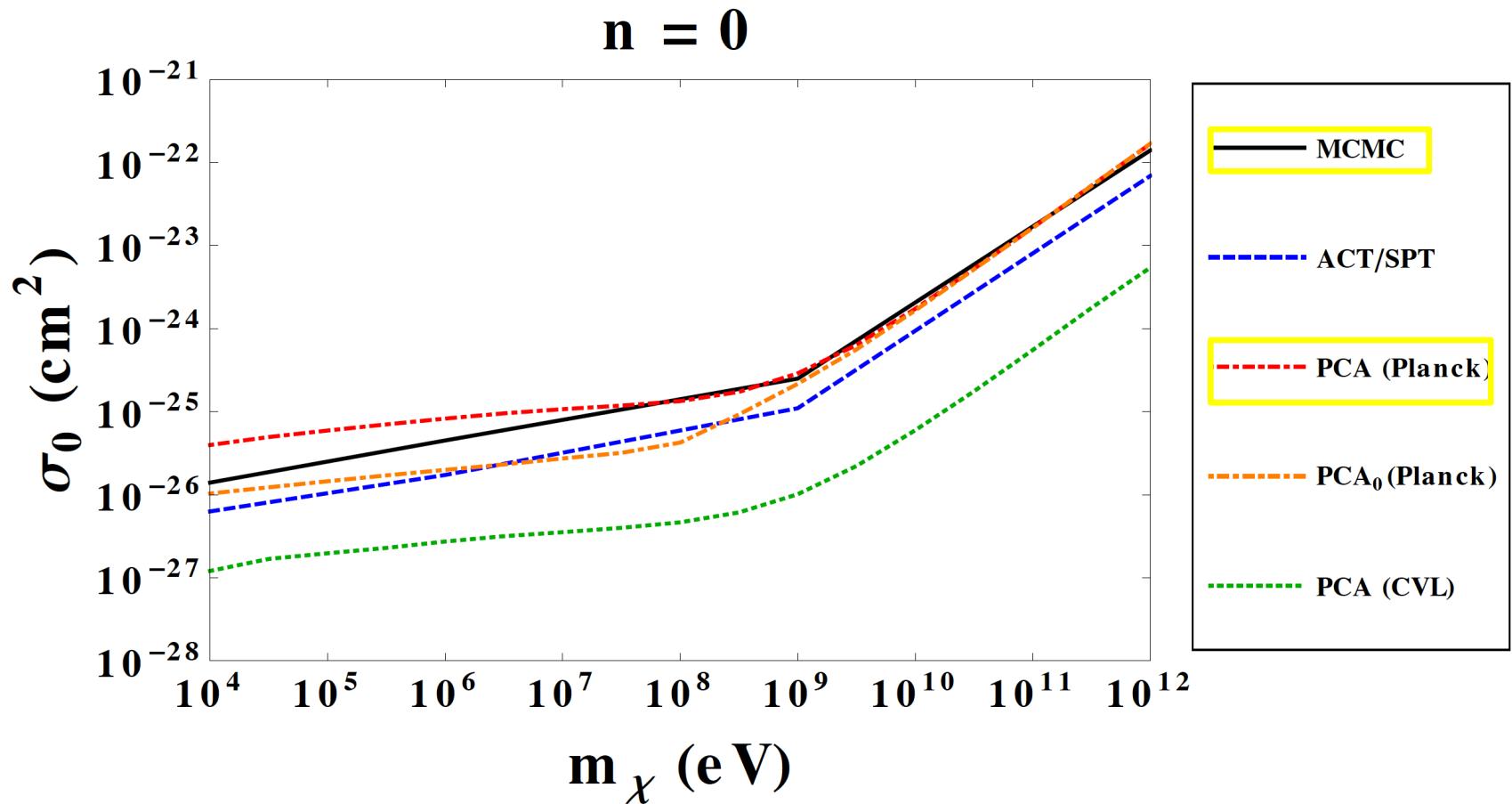
First 4 PCs capture over 90 % of variance:

Easy to estimate constraint on other velocity dependence

See examples in 1803.09734

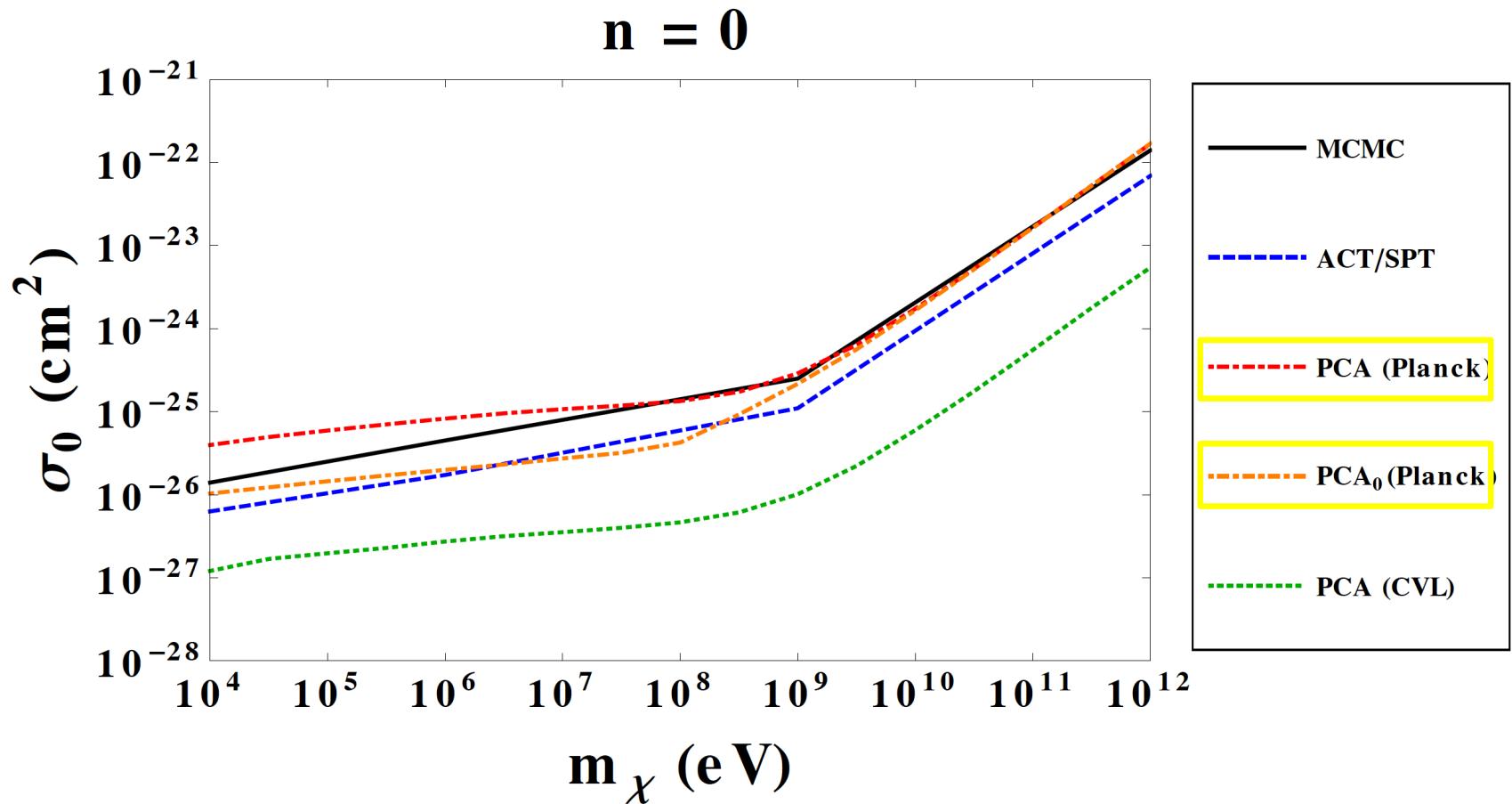
CMB – PCA & MCMC

- PCA validation:



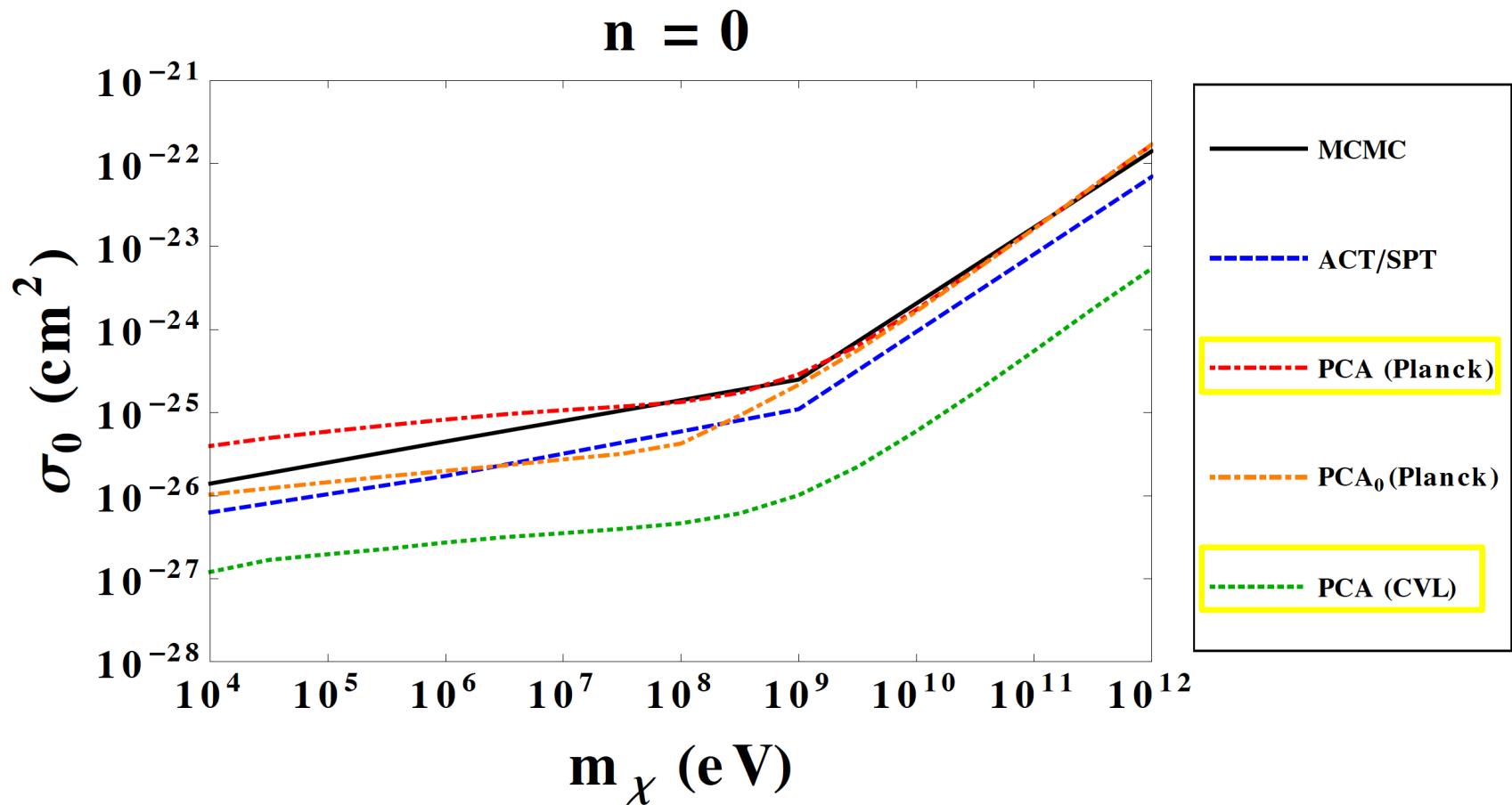
CMB – PCA & MCMC

- Bulk velocity:



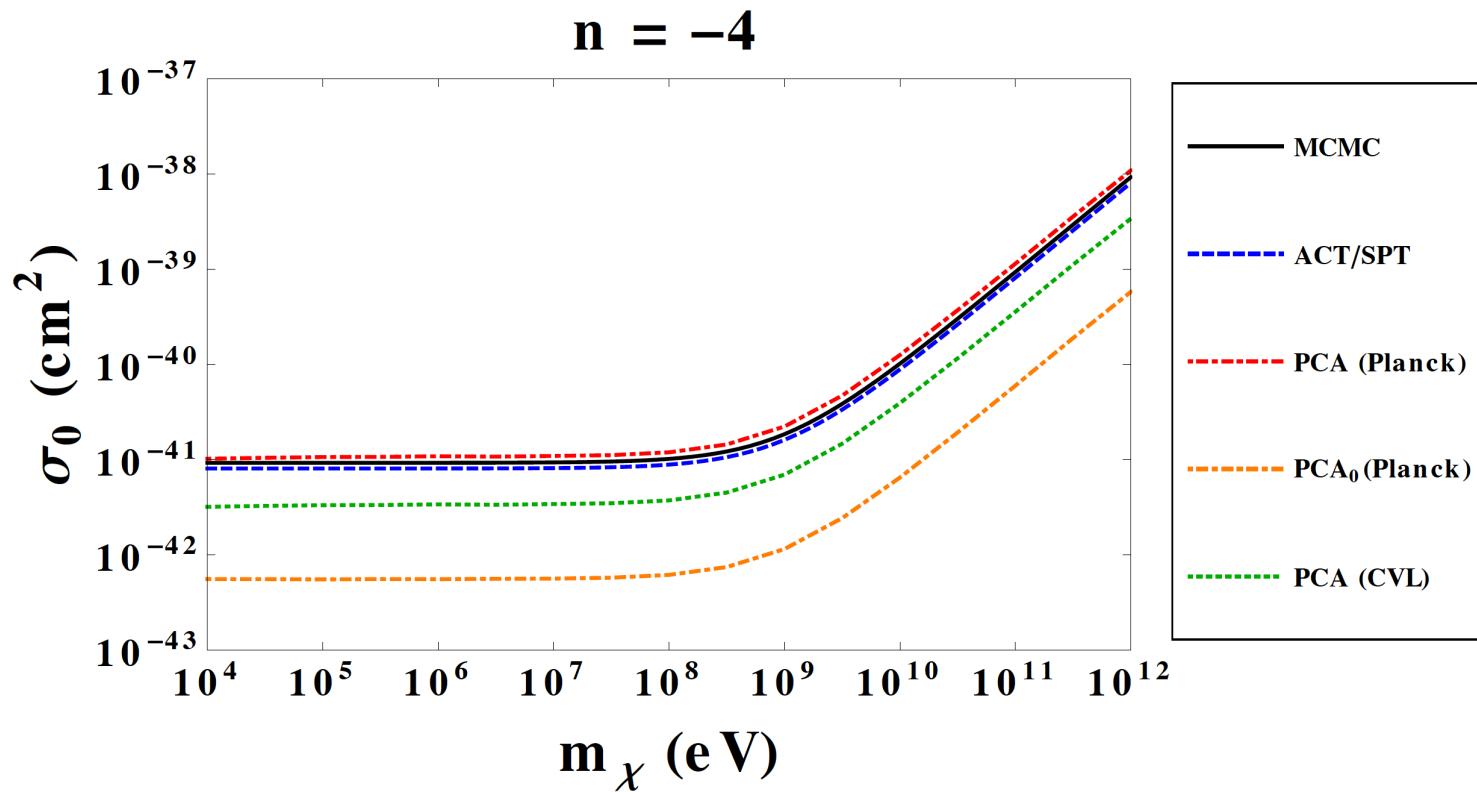
CMB – PCA & MCMC

- CVL improvement:



CMB – PCA & MCMC

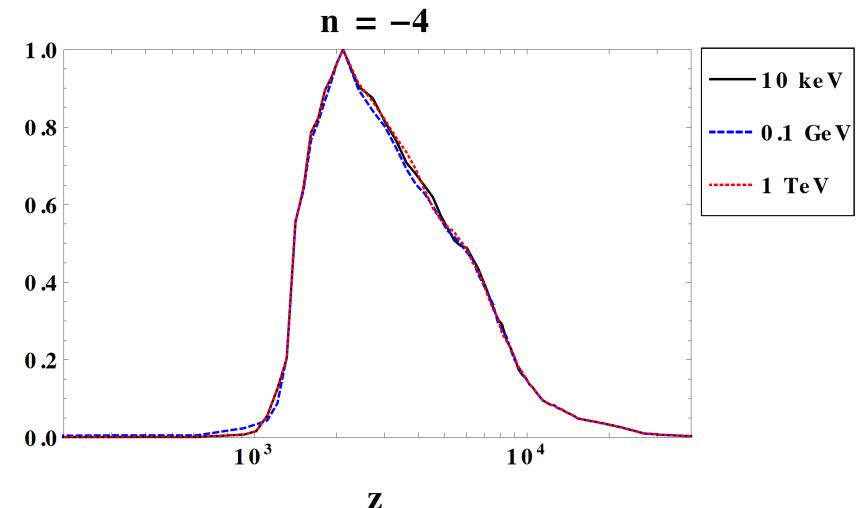
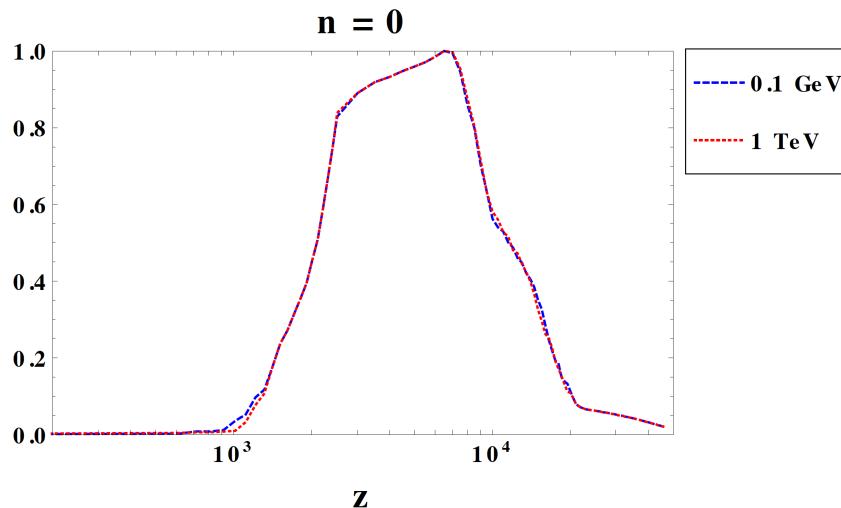
- constraints on $n = -4$:



Simple scaling: $\sigma_0 \lesssim 8.1 \times 10^{-42} \text{ cm}^2 \left(1 + \frac{m_\chi}{m_H}\right)$

CMB – redshift weighting

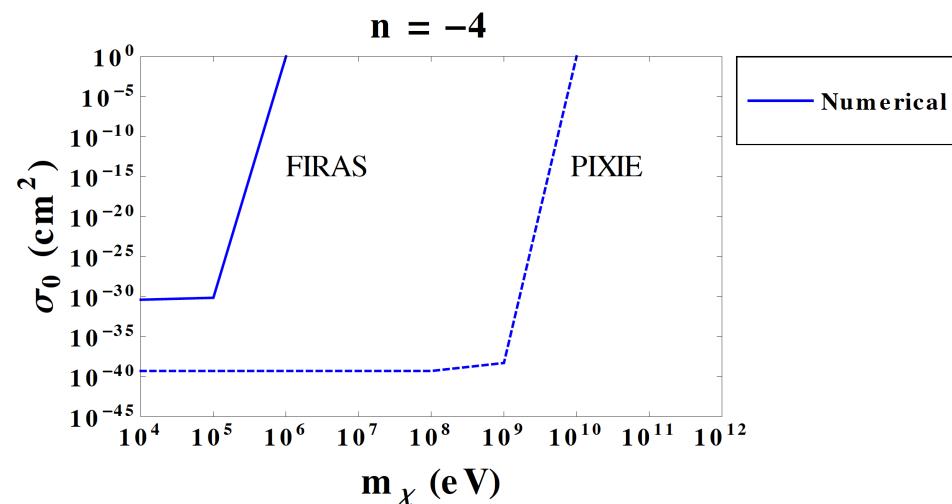
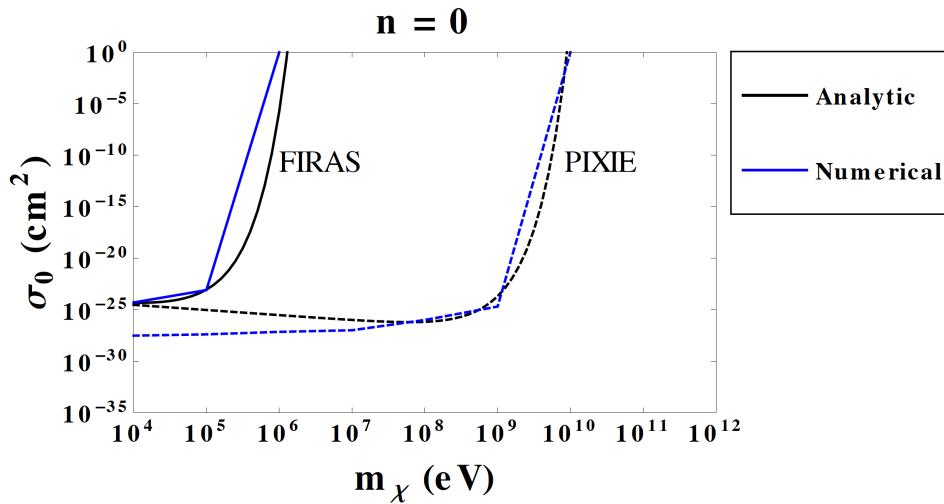
- Contribution from different redshift:



- 1) $n = 0$, σ is constant respect to velocity, **broadly peaked**
- 2) $n = -4$, lower redshift is **enhanced**
- 3) Both are independent of DM mass
- 4) Around $10^3 < z < 10^4$, corresponding to ℓ : hundreds - thousands
Smaller scale can be probed by matter power spectrum
(Ly α for $n = 0$) Xu, Dvorkin & Chael 1802.06788

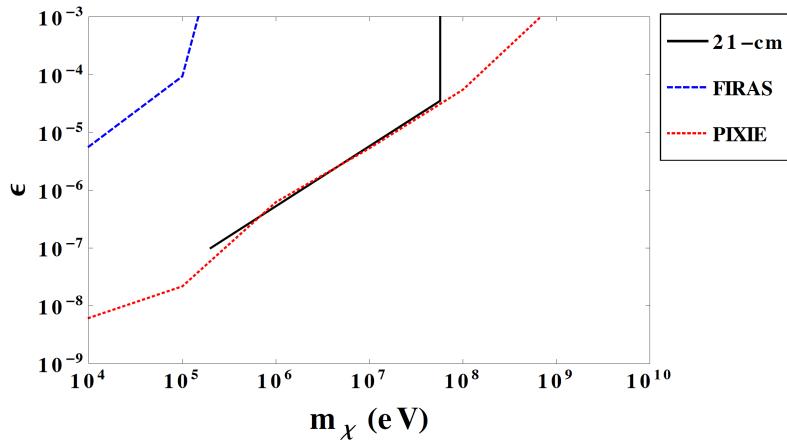
Spectral distortion

- Photon number changing process becomes inefficient for $z < 2 \times 10^6$
- Compton scattering can redistribute photon energy change by DM-baryon scattering
- μ -type distortion:
 - current exp: FIRAS -- 10^{-5} deviation from blackbody
 - future exp: PIXIE -- 10^{-8} deviation from blackbody



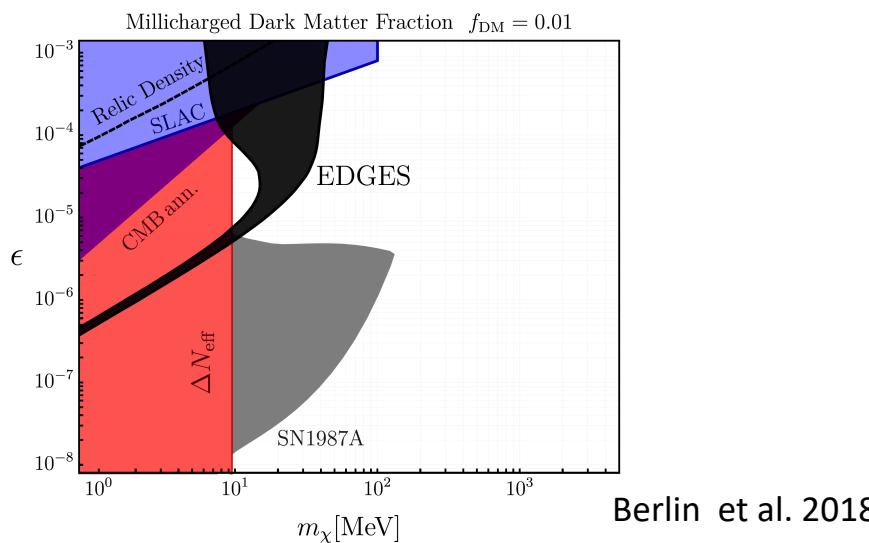
Millicharged DM

- Spectral distortion can be applied to millicharged DM



Assume 1% of DM are millicharged

- Other measurement:



Berlin et al. 2018

Summary

- DM-Baryon scattering is one of models to explain EDGES 21 cm signal
- Examine cosmological bounds from high to low redshift, CMB anisotropy provides stringent bound
- Under the context of DM-baryon scattering, only sub-GeV DM through light mediator is consistent
- Spectral distortion and other experiments are able to test (fractional) millicharged DM

Backup Slides

Bulk velocity

- Phase space distribution

$$f_\chi(\vec{v}_\chi) = n_\chi \frac{g_\chi}{(2\pi)^{3/2} \bar{v}_\chi^{3/2}} \exp \left[-(\vec{v}_\chi - \vec{V}_\chi)^2 / (2\bar{v}_\chi^2) \right]$$

$$f_B(\vec{v}_B) = n_B \frac{g_B}{(2\pi)^{3/2} \bar{v}_B^{3/2}} \exp \left[-(\vec{v}_B - \vec{V}_b)^2 / (2\bar{v}_B^2) \right]$$

where thermal velocity dispersion is $\langle (\Delta \vec{v})^2 \rangle = \langle (\vec{v}_\chi - \vec{v}_b)^2 \rangle = 3 \left(\frac{T_b}{m_b} + \frac{T_\chi}{m_\chi} \right)$

and the change rate is

$$\begin{aligned} \frac{d\vec{V}_\chi}{dt} &= -\frac{1}{m_\chi} \sum_B \int d^3 v_\chi d^3 v_B f_\chi(\vec{v}_\chi) f_B(\vec{v}_B) \int \frac{d\sigma}{d\Omega} |\vec{v}_\chi - \vec{v}_B| |\Delta \vec{p}_\chi| \\ &= -\sum_B \frac{g_B g_\chi \rho_B}{m_\chi + m_B} \frac{1}{(2\pi)^{3/2}} \frac{1}{(\bar{v}_B^2 + \bar{v}_\chi^2)^{3/2}} \int d^3 v \vec{v} [\sigma_{\text{MT}, B}^{(i)}(v) v] \exp \left\{ -\frac{[\vec{v} - (\vec{V}_\chi - \vec{V}_b)]^2}{2(\bar{v}_B^2 + \bar{v}_\chi^2)} \right\} \end{aligned}$$

1) in the limit $V_\chi^2 < \langle (\Delta \vec{v})^2 \rangle$: $\frac{d\vec{V}_\chi}{dt} = -\vec{V}_\chi \frac{c_n \rho_b \sigma_0 \left(\frac{\langle (\Delta \vec{v})^2 \rangle}{3} \right)^{\frac{n+1}{2}}}{m_\chi + m_b}$

2) in the limit $V_\chi^2 \gg \langle (\Delta \vec{v})^2 \rangle$: $\frac{d\vec{V}_\chi}{dt} = -\vec{V}_\chi \frac{\rho_b \sigma_0 |V_\chi|^{n+1}}{m_\chi + m_b}$

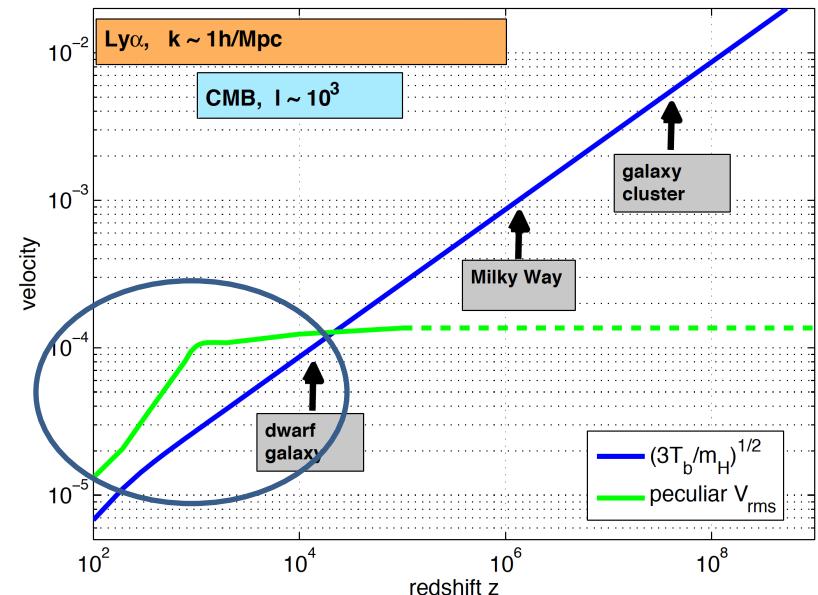
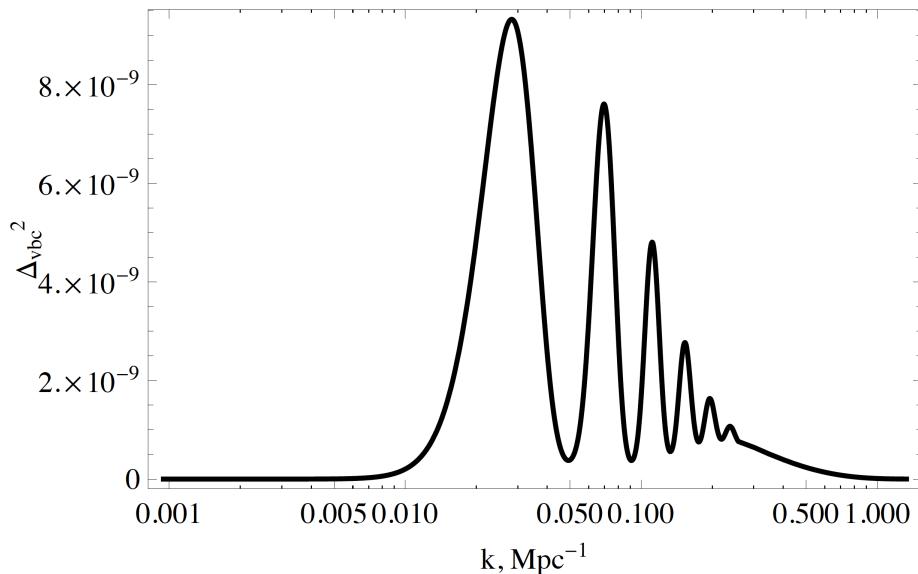
Compare $\dot{\theta}_\chi = -\frac{\dot{a}}{a} \theta_\chi + c_\chi^2 k^2 \delta_\chi + R_\chi (\theta_b - \theta_\chi),$

$$\begin{aligned} \dot{\theta}_b &= -\frac{\dot{a}}{a} \theta_b + c_b^2 k^2 \delta_b + R_\gamma (\theta_\gamma - \theta_b) \\ &\quad + \frac{\rho_\chi}{\rho_b} R_\chi (\theta_\chi - \theta_b), \end{aligned}$$

we get $R_\chi = \frac{a c_n \rho_b \sigma_0}{m_\chi + m_H} \left(\frac{T_b}{m_H} + \frac{T_\chi}{m_\chi} \right)^{\frac{n+1}{2}} F_{\text{He}}$ for case 1)

V_{rms} velocity

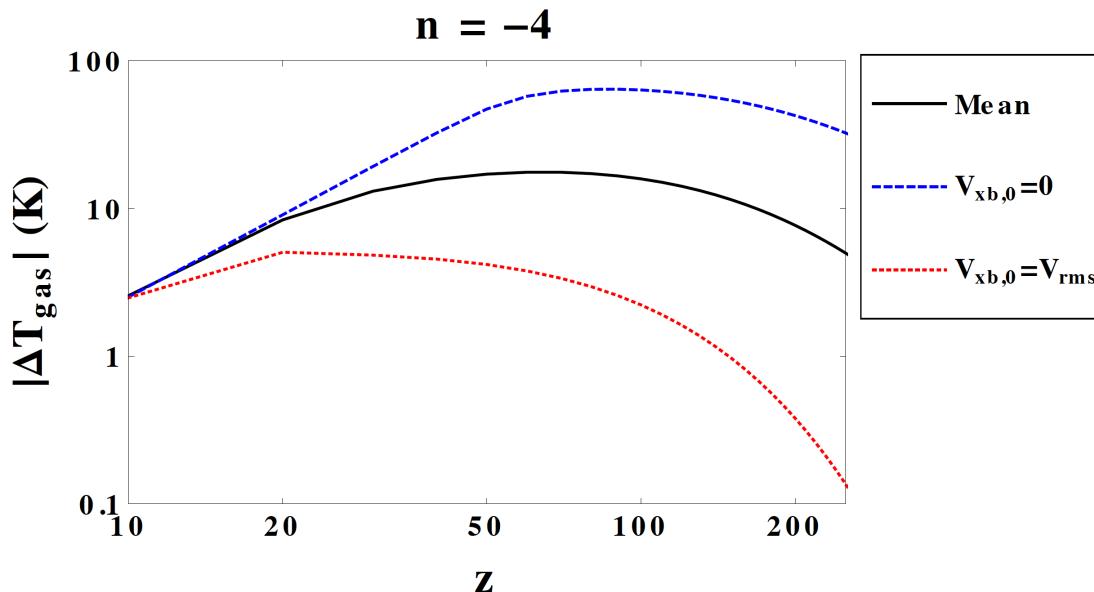
- V_{rms} :
$$V_{\text{RMS}}^2 = \left\langle \vec{V}_\chi^2 \right\rangle_\xi = \int \frac{dk}{k} \Delta_\xi \left(\frac{\theta_b - \theta_c}{k} \right)^2$$



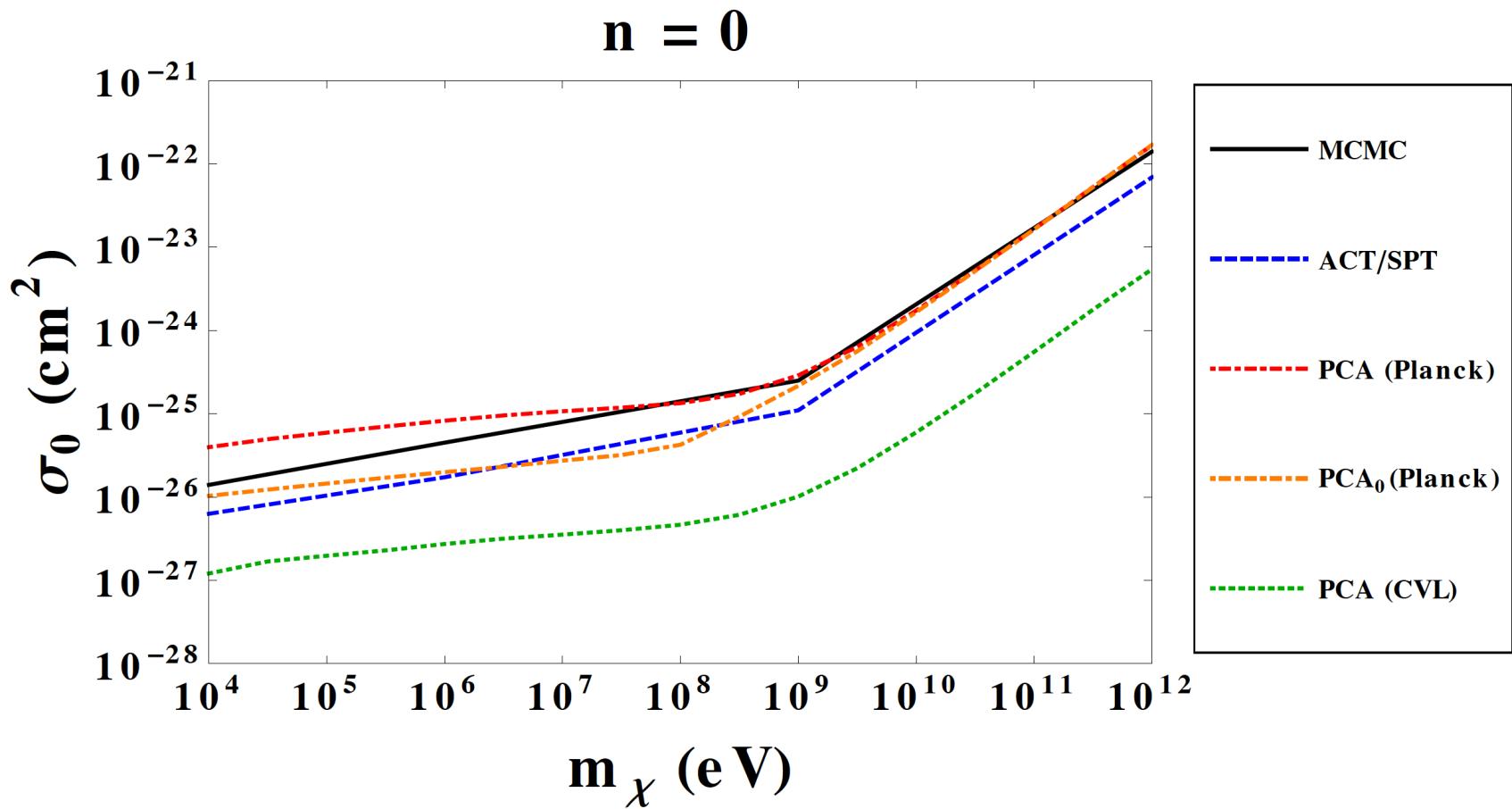
$$R_\chi \rightarrow \frac{ac_n \rho_b \sigma_0}{m_\chi + m_H} \left(\frac{T_b}{m_H} + \frac{T_\chi}{m_\chi} + \frac{V_{\text{rms}}^2}{3} \right)^{\frac{n+1}{2}}$$

Relative velocity

- At kinetic decoupling $z \sim 10$: $P(\mathbf{V}_{xb,0}) = \frac{e^{-3\mathbf{V}_{xb,0}^2/(2V_{rms}^2)}}{\left(\frac{2\pi}{3}V_{rms}^2\right)^{3/2}}$
where $V_{rms} \sim 10^{-4}$
- Assume same σ_0 , solve for velocity equation to late time with different initial condition:



CMB – PCA & MCMC



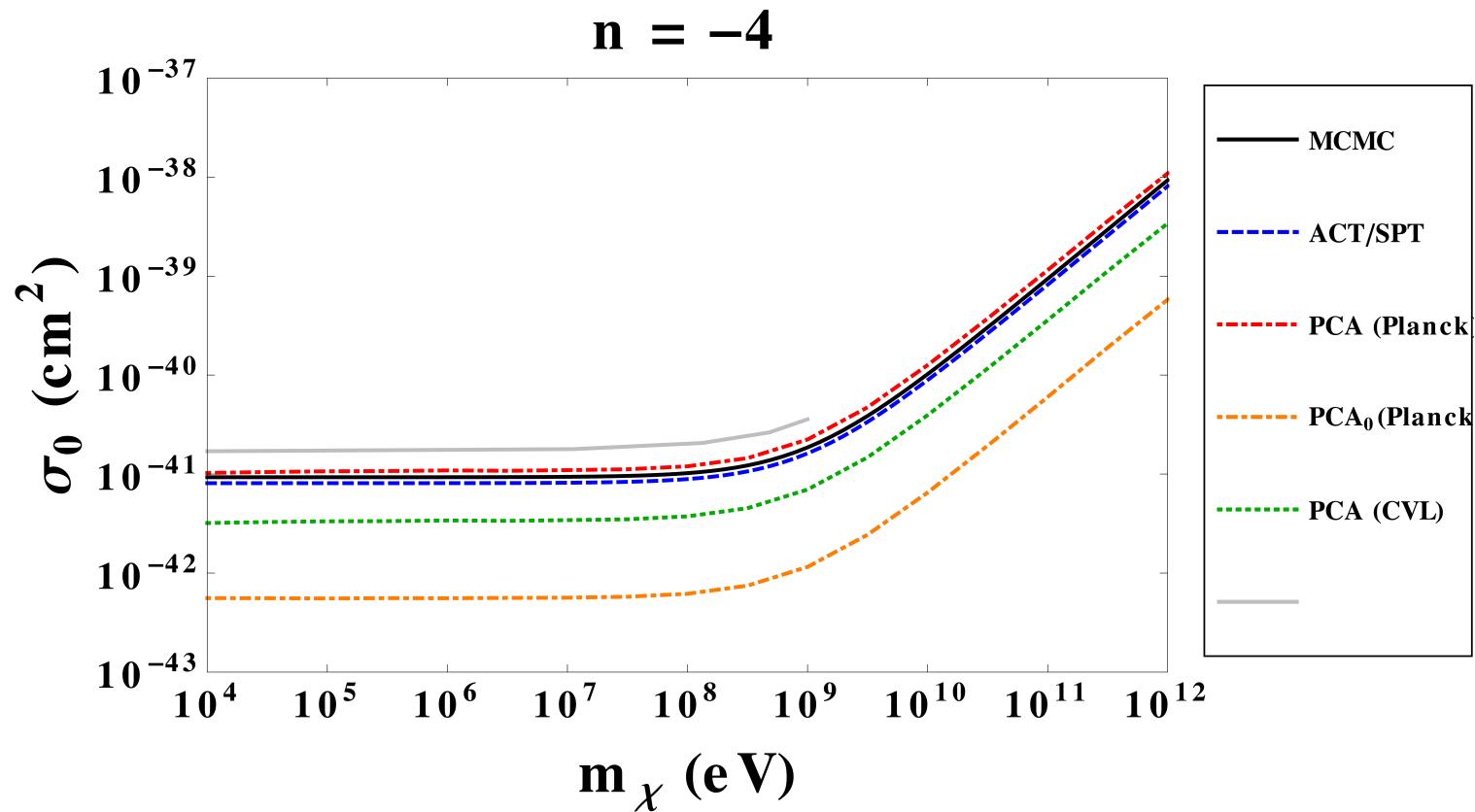
$$R_\chi = \frac{ac_n \rho_b \sigma_0}{m_\chi + m_H} \left(\frac{T_b}{m_H} + \frac{T_\chi}{m_\chi} \right)^{\frac{n+1}{2}} F_{\text{He}}$$

non-linear:

- 1) Scattering changes T_χ , and backreact to scattering rate
- 2) Important for high T_χ ($n=0$) and small m_χ

CMB – PCA & MCMC

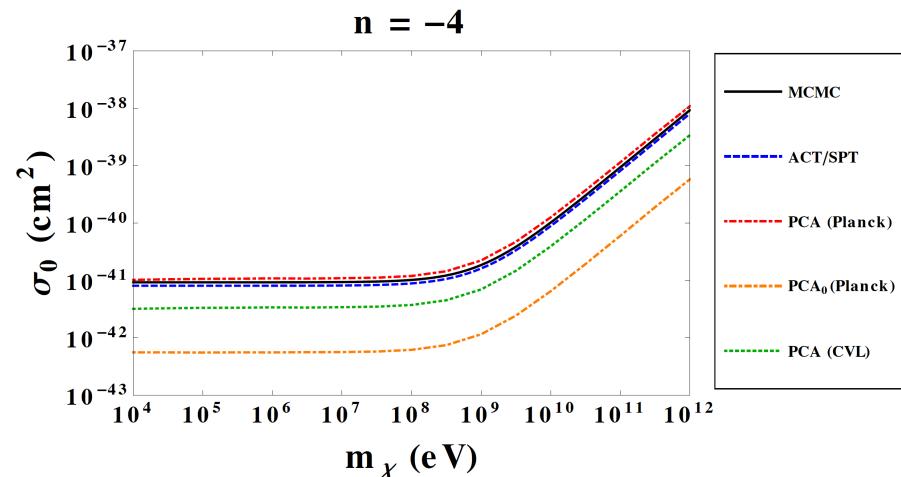
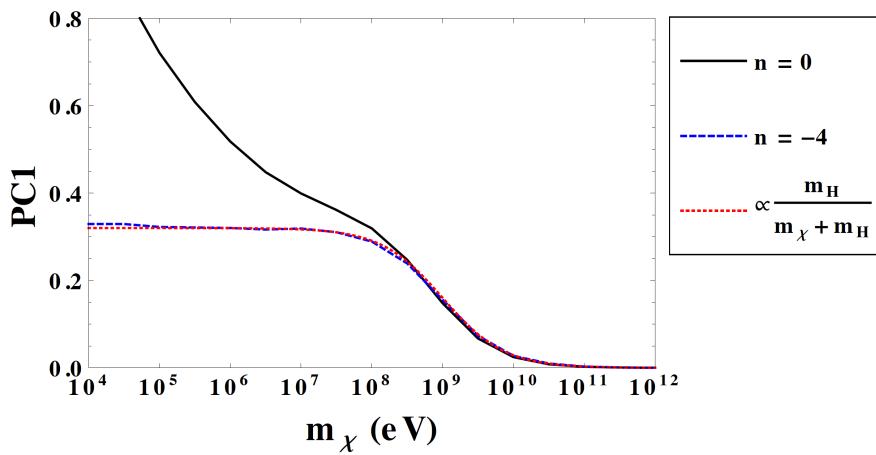
- constraints on $n = -4$:



Simple scaling: $\sigma_0 \lesssim 8.1 \times 10^{-42} \text{ cm}^2 \left(1 + \frac{m_\chi}{m_H}\right)$

CMB - scaling

- Principal Component Analysis:
 - 1) First 4 PC dominates over 90 %: Easy to give constraint on other n
 - 2) Simple scaling for n = -4:



DM is cold: $\sigma = \sigma_0(v_b)^n$

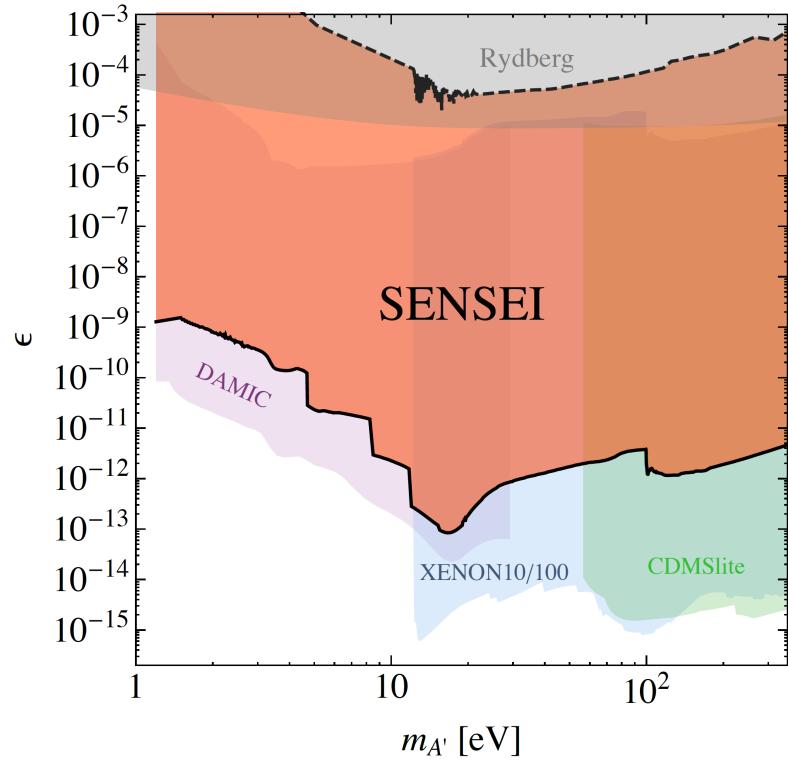
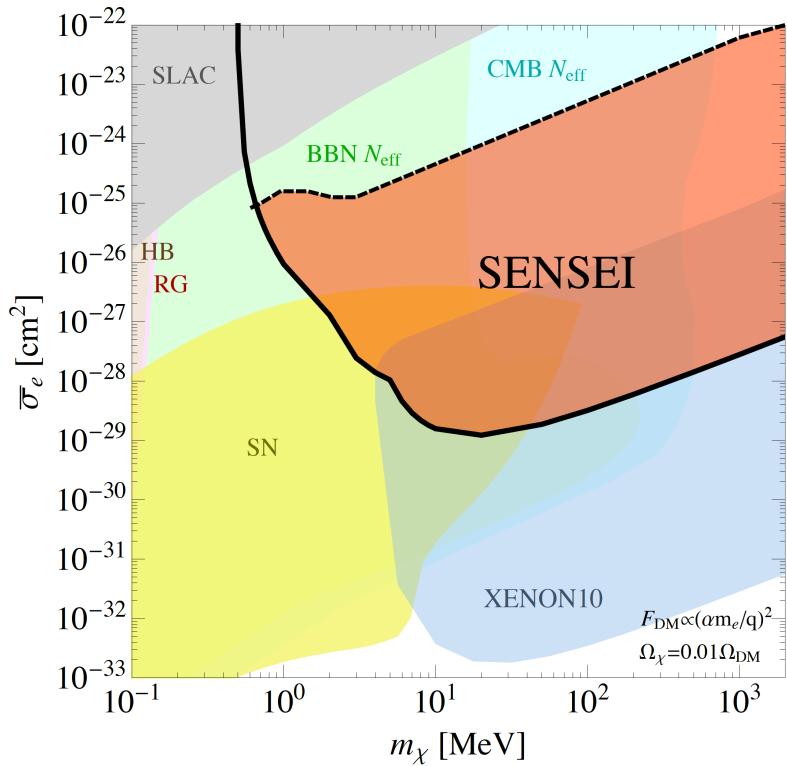
Momentum exchange per time: $\Delta p \sim m_\chi \Delta v \sim m_\chi v_{cm} \sim m_\chi \frac{m_b v_b}{m_\chi + m_b}$

Momentum exchange rate: $\Delta p (n_\chi \sigma) \sim \rho_\chi \frac{m_b v_b}{m_\chi + m_b} \sigma_0(v_b)^n \propto \frac{1}{m_\chi + m_b}$

→ Constraint on $\sigma_0 \lesssim 8.1 \times 10^{-42} \text{ cm}^2 \left(1 + \frac{m_\chi}{m_H}\right)$ for $n = -4$

Millicharged DM

- Direct measurement



SENSEI 2018