Cosmological constraints on the velocity-dependent Baryon-Dark matter coupling

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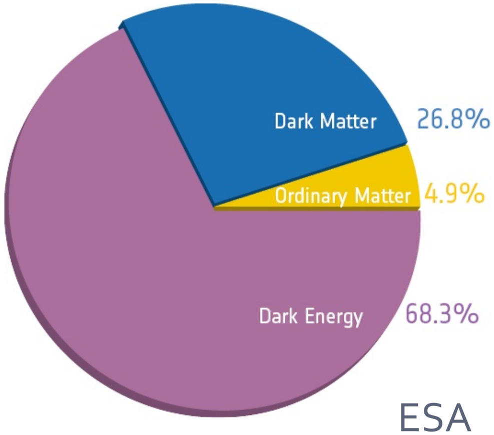
Introduction

- The modern cosmology indicates that the usual baryonic matter is forming only 5% of the today's energy budget of our universe.
- And the rest 95% is formed from unknown dark matter and dark energy.
- Although there are a lot of astronomical evidences which suggesting the existence of the dark matter, to reveal its nature is still a main goal of the modern cosmology.
- Usually, we assume the cold dark matter.
  - only a gravitational coupling with the baryon



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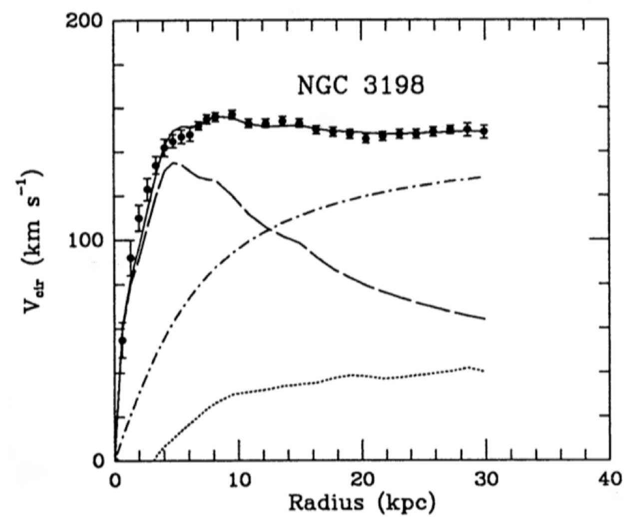

Begeman+ 1991

Introduction

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- Here, we focus on a question "how dark is dark?".
- We consider an extra non-gravitational coupling between the baryon and the dark matter components which can be naturally realized by some dark matter models.
- Those models predict a scattering cross section as a power-law of the baryon-DM relative velocity.

$$(\text{cross section}) \propto v^n$$

- Deferent n-values correspond to deferent dark matter models.
  - n = -4: fractional electric charge — Melchiorri+ 2007
  - n = ±2: electric and magnetic dipole moment — Sigurdson+ 2004
  - n = -1: Yukawa potential — Arkani-Hamed+ 2009, Buckley+ 2010
  - n = 0: velocity-independent scattering — Chen+ 2002

Introduction

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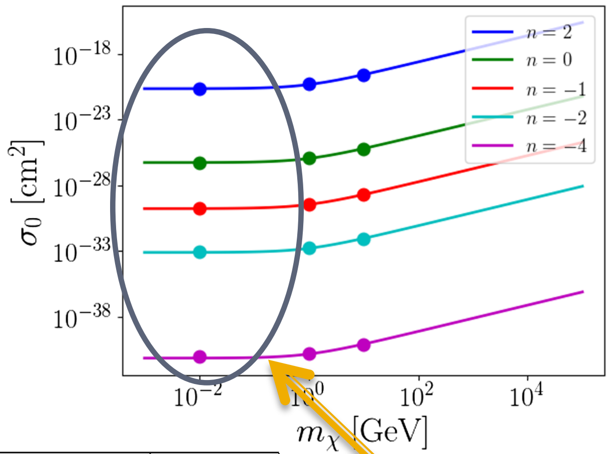
- Previous works

Dvorkin+ 2014: **CMB+Lya, $m_x \gg m_H$**

n	CMB (95%CL, cm^2/g)	CMB + Lyman-α (95%CL, cm^2/g)
-4	1.8×10^{-17}	1.7×10^{-17}
-2	3.0×10^{-9}	6.2×10^{-10}
-1	1.6×10^{-5}	1.4×10^{-6}
0	0.12	3.3×10^{-3}
+2	1.3×10^{5}	9.5×10^{3}

Xu+ 2018: **CMB+Lya, m_x > 10 MeV**



Boddy+ 2018: **CMB only, m_x > 10 keV**

	10 keV	**1 MeV**	**10 MeV**	**100 MeV**	**200 MeV**	**500 MeV**	**1 GeV**
$n = -4$	1.7e-41	1.7e-41	1.7e-41	1.9e-41	2.1e-41	2.6e-41	3.5e-41
$n = -2$	2.3e-33	2.3e-33	2.4e-33	2.6e-33	2.8e-33	3.6e-33	4.9e-33

No mass dependency?

Our study focus on the DM mass below ~ 10 keV, and put constraints by using CMB + Lya data

Baryon-dark matter coupling

- Effects on the cosmology
  - Background thermal history
  - Perturbation evolution

Background temperature

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- The baryon gas temperature could be affected by baryon-DM coupling.

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

Expansion of the universe | Thomson scattering | **Baryon-DM coupling**

$$\mu_b = m_H\left(\frac{n_H + 4n_{He}}{n_H + n_{He} + n_e}\right)$$

- The dark matter temperature is

$$\dot{T}_\chi = -2\frac{\dot{a}}{a}T_\chi + \frac{2m_\chi}{m_\chi + m_b}R_\chi(T_b - T_\chi)$$

- Coupling rate: Thomson scattering, baryon-DM coupling

$$R_\gamma = \frac{4\rho_\gamma}{3\rho_b}an_e\sigma_T$$

$$R_\chi = c_n\frac{a\rho_b\sigma_0}{m_\chi + m_b}\left(\frac{T_b}{m_b} + \frac{T_\chi}{m_\chi} + \frac{V_{\rm RMS}^2}{3}\right)^{\frac{n+1}{2}}$$

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

Background temperature

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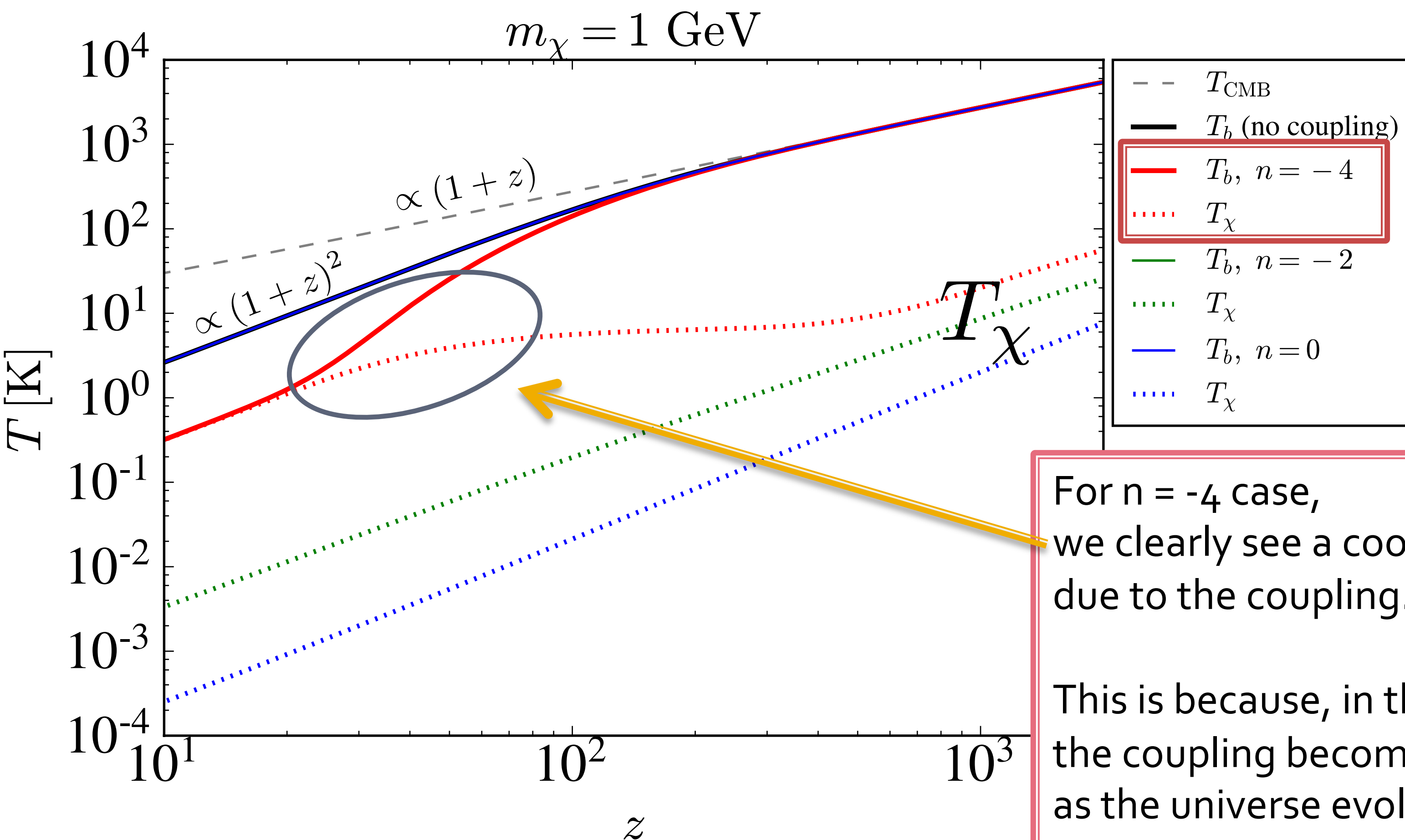

For n = -4 case,
we clearly see a cooling of T_b
due to the coupling.

This is because, in this case,
the coupling becomes stronger
as the universe evolves and
the temperature decreases.

Perturbation equations

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- Boltzmann equations also modified as follows:

$$\dot{\delta}_b = -\theta_b + 3\dot{\phi}, \quad \dot{\delta}_\chi = -\theta_\chi + 3\dot{\phi}$$

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

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

Perturbation evolutions are also modified by baryon-DM coupling.

- Coupling rate (again):

$$R_\chi = c_n \frac{a\rho_b\sigma_0}{m_\chi + m_b}\left(\frac{T_b}{m_b} + \frac{T_\chi}{m_\chi} + \frac{V_{\mathrm{RMS}}^2}{3}\right)^{\frac{n+1}{2}}$$

Therefore, DM's evolution could be prevented by this coupling because the baryon-photon coupling.

Perturbation equations

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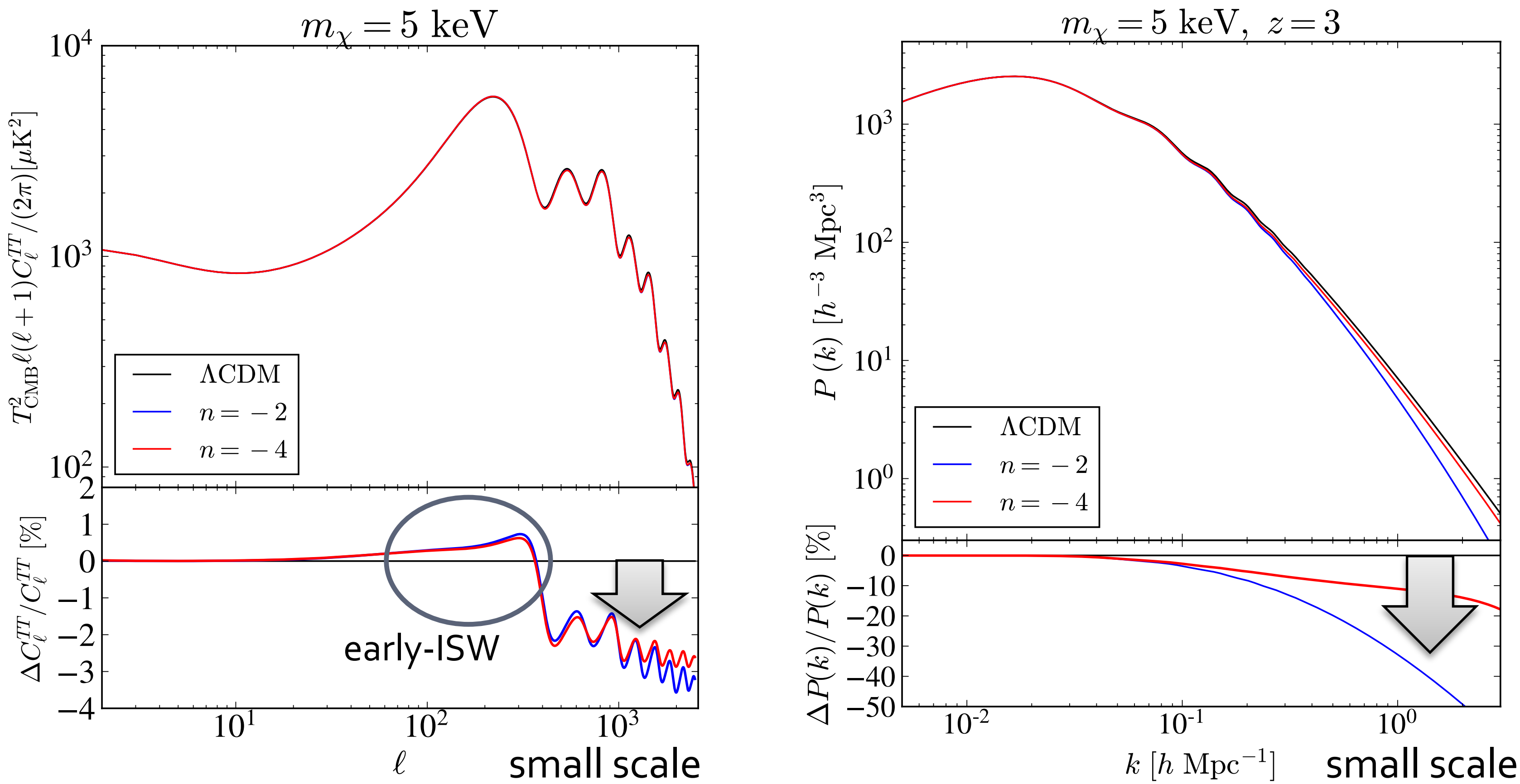
CMB temperature C_ℓ | **Matter power spectrum**



Warm dark matter effect

- If the dark matter particle mass is below ~MeV, an additional relativistic effect cannot be neglected anymore and the perturbation evolution changes from the CDM case.

- This effect erases a small scale P(k), which is similar to a warm dark matter case.
- We use an approximated form of P(k) to include the WDM dumping effect on the P(k).

$$P_{WDM}(k) = T_\chi^2(k) P_{CDM}(k)$$

$$T_\chi(k) = [1 + (\alpha k)^\nu]^{-\mu}$$

where,

$$\alpha = a \left(\frac{m_\chi}{1\mathrm{keV}}\right)^b \left(\frac{\Omega_\chi}{0.26}\right)^c \left(\frac{h}{0.7}\right)^d \quad h^{-1}\mathrm{Mpc}$$

a = 0.189, b = -0.858, c = -0.136
d = 0.692, v = 2.25, µ = 3.08

Colin+ 2008

Warm dark matter effect

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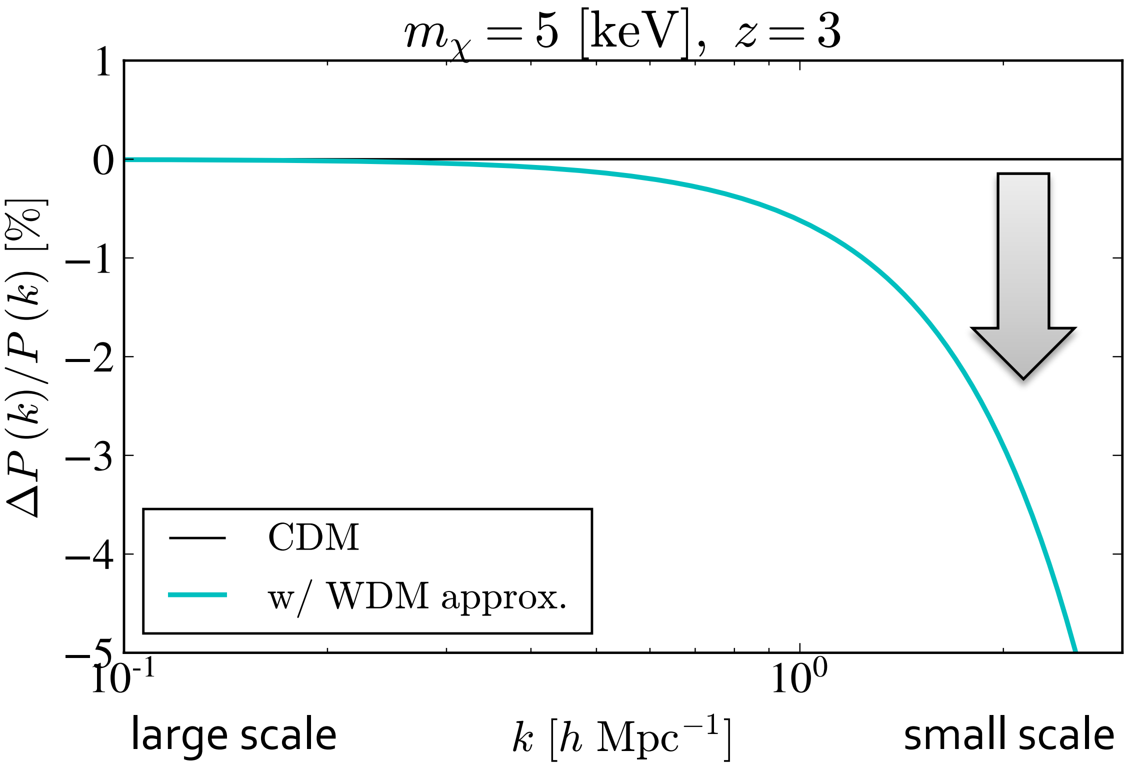
- Residual plot between CDM and WDM approx. cases.



Suppression due to a free-streaming effect with DM mass 5 keV.

We apply this effect in addition to the baryon-DM coupling effect.

Result

- The constraint on the **baryon-DM coupling**
  - Method and Data
  - Results of the constraint

Method and Data

- CLASS (class-code.net)
  - To compute CMB angular power spectra and matter power spectrum.
- Monte python (montepython.net)
  - To analyze data by using the Markov chain Monte Carlo (MCMC) method.
- Data
  - Planck 2015: TT, lowP, lensing -> C_ℓ
  - SDSS: Lyman-α-forest (McDonald+ 2006) -> $P(k)$ at k~1, z=3

Result: constraint on σ_0

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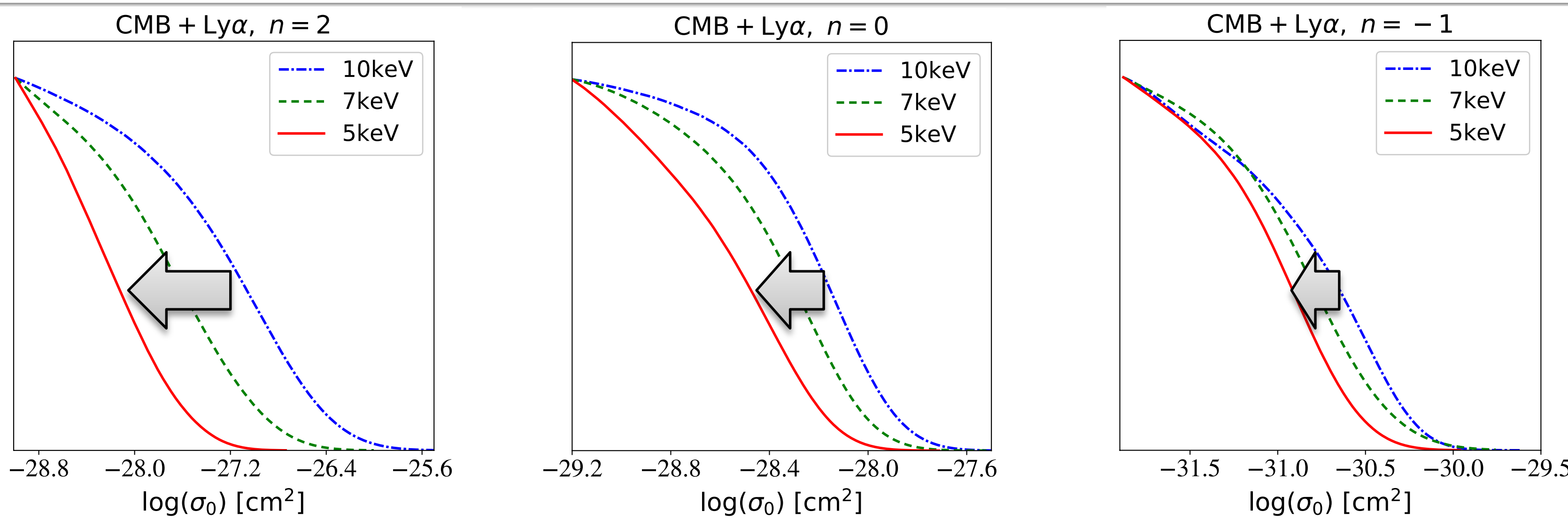

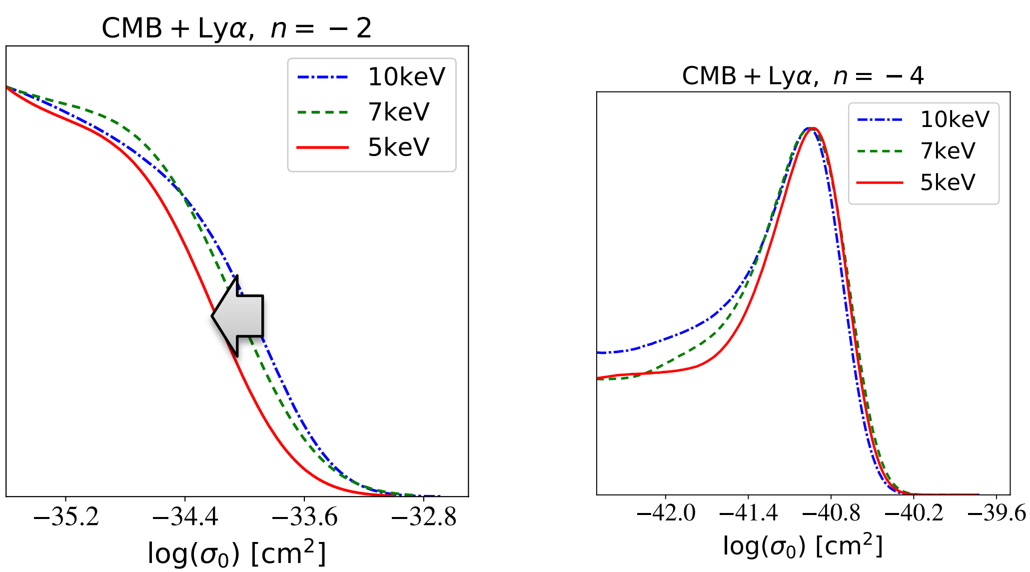

- **Constraints are getting tighter if we take a smaller DM mass.**
- For n=-4 case, there is no mass dependency. It's already limited by CMB alone constraint.

Summary

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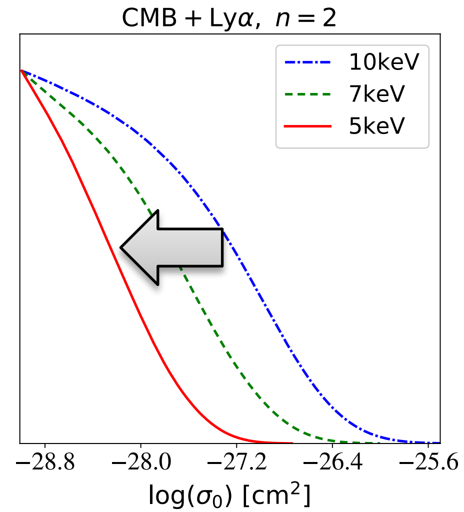
- We put constraint on the cross section of the baryon-DM coupling.

- Those couplings induce
  - lower baryonic gas temperature,
  - suppression of the small scale P(k),
  - multiple effects on the C_ℓ (dumping, early-ISW).

- We got the tighter constraint on the cross section of the coupling if we consider the DM mass below 10 keV.



Thank you for your attention.

Back up

Coupling rate vs. Resdshift

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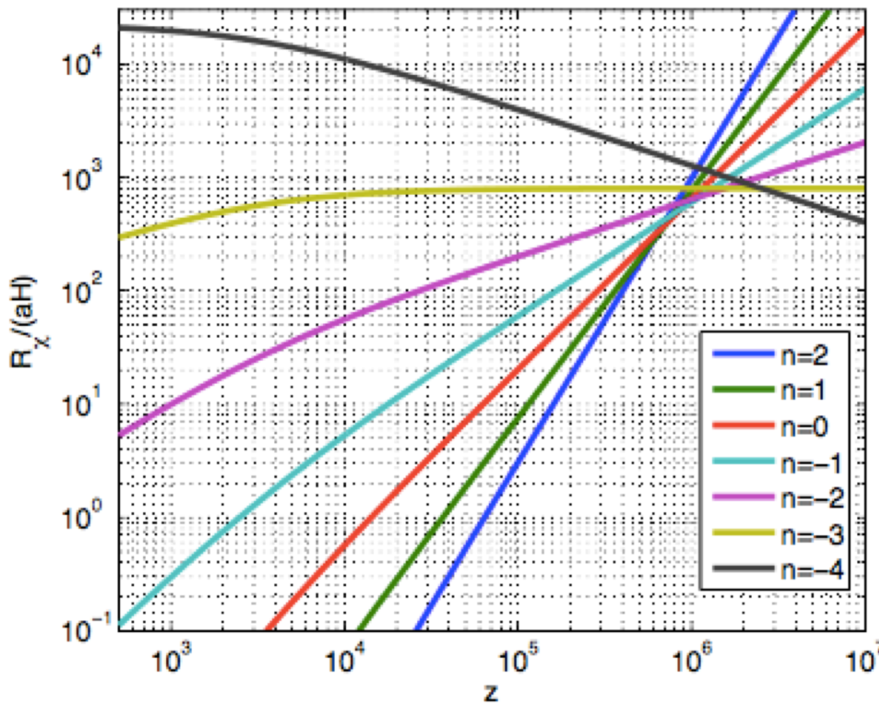
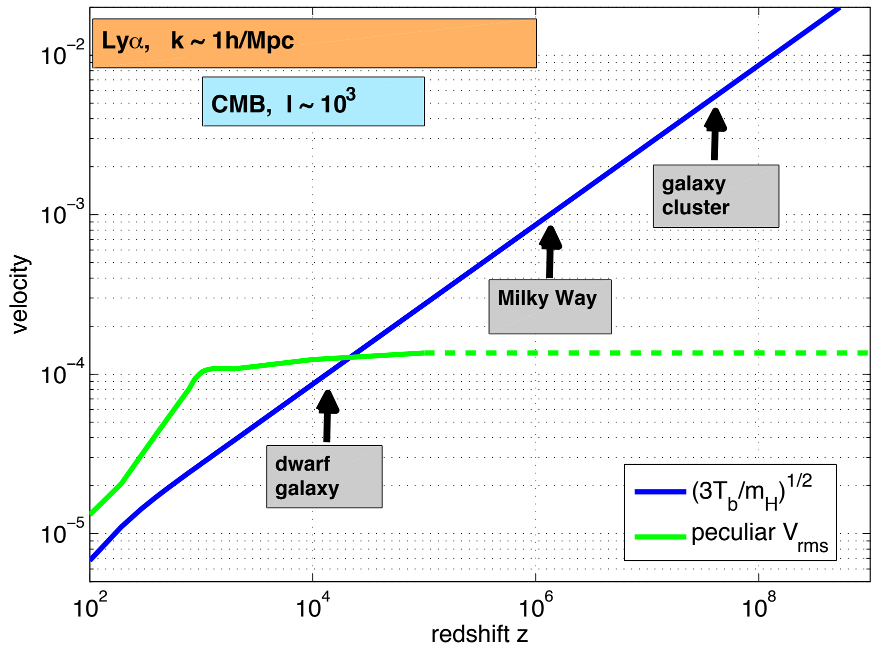
$$R_\chi = c_n \frac{a\rho_b\sigma_0}{m_\chi + m_b}\left(\frac{T_b}{m_b} + \frac{T_\chi}{m_\chi} + \frac{V_{\rm RMS}^2}{3}\right)^{\frac{n+1}{2}}$$



Dvorkin+ 2014



$$V_{\rm RMS}^2 \equiv \langle V_\chi^2 \rangle \simeq \begin{cases} 10^{-8} & z > 10^3 \\ 10^{-8}\left(\frac{(1+z)}{10^3}\right)^2 & z \leq 10^3 \end{cases} .$$

Dvorkin+ 2014

Xu+ 2018

IC of the DM temperature

- It depends on its velocity dependency *n.*

- For n > -3 cases, we use the following expression.

$$T_\chi = \begin{cases} T_b, & R_\chi \frac{m_\chi}{m_\chi + m_b} > aH \\ T_{dec}\left(\frac{a_{dec}}{a}\right)^2, & R_\chi \frac{m_\chi}{m_\chi + m_b} < aH \end{cases}$$

- For n = -4 case, we start from $T_\chi = 0$, because the effect of the coupling is very weak in the early epoch so that we consider its temperature is already sufficiently small in an epoch we study here (z < 10^6).

Lyman-α forest data

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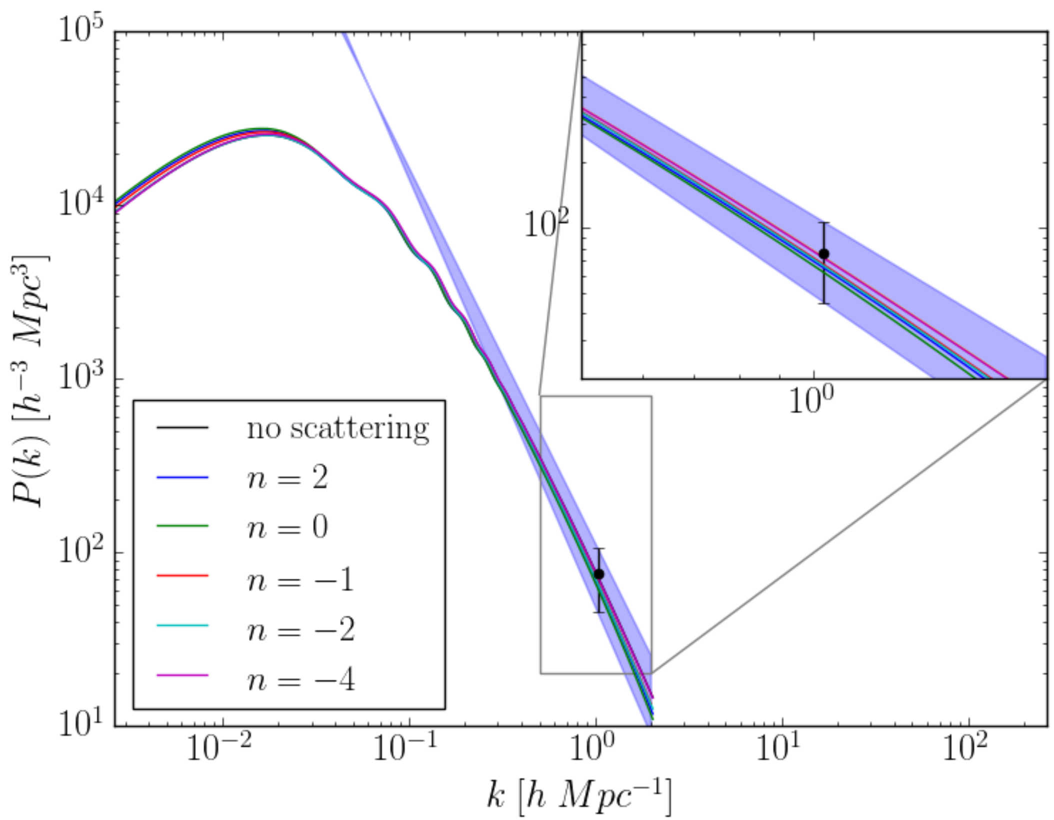
- Lyman-α data: amplitude, tilt, curvature of P(k) at k~1, z=3



Xu+ 2018

Perturbation evolution

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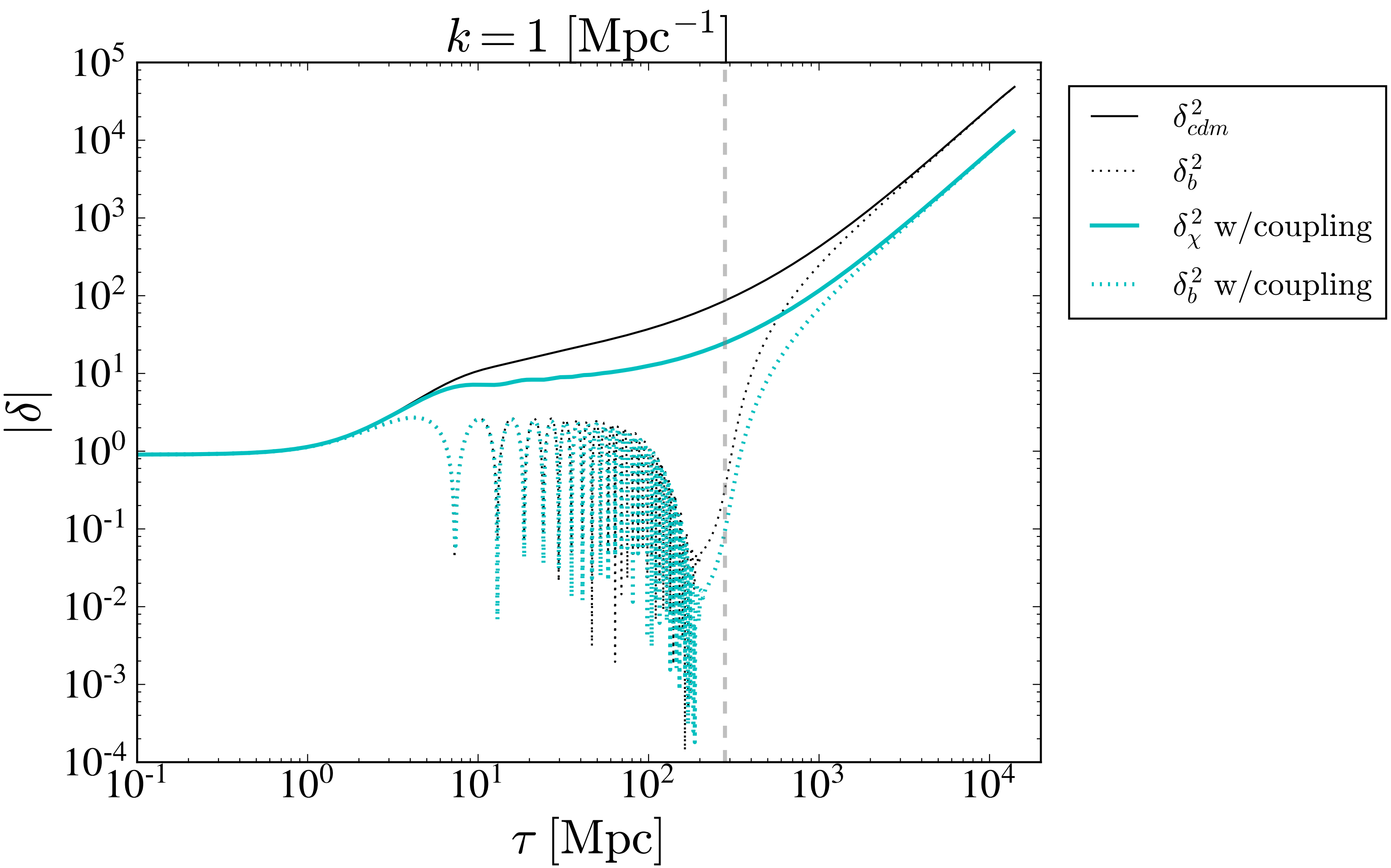

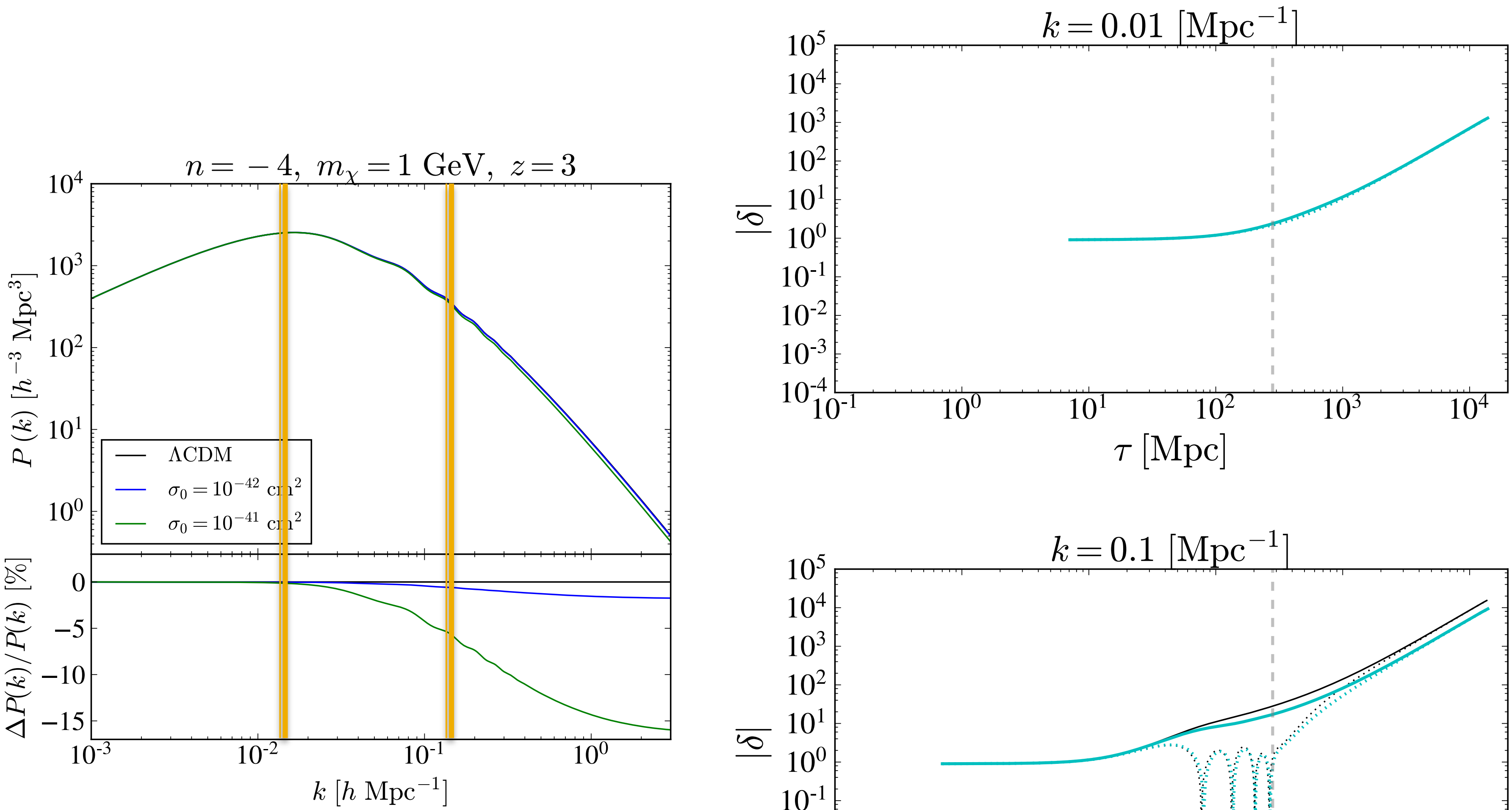

$n = -4,\ m_\chi = 1$ GeV$,\ z = 3$
$P(k)\ [h^{-3}\ \mathrm{Mpc}^3]$
ΛCDM
$\sigma_0 = 10^{-42}$ cm^2
$\sigma_0 = 10^{-41}$ cm^2
$\Delta P(k)/P(k)$ [%]
$k\ [h\ \mathrm{Mpc}^{-1}]$
$k = 0.01\ [\mathrm{Mpc}^{-1}]$
$|\delta|$
τ [Mpc]
$k = 0.1\ [\mathrm{Mpc}^{-1}]$
$|\delta|$
τ [Mpc]

CMB temperature fluctuation

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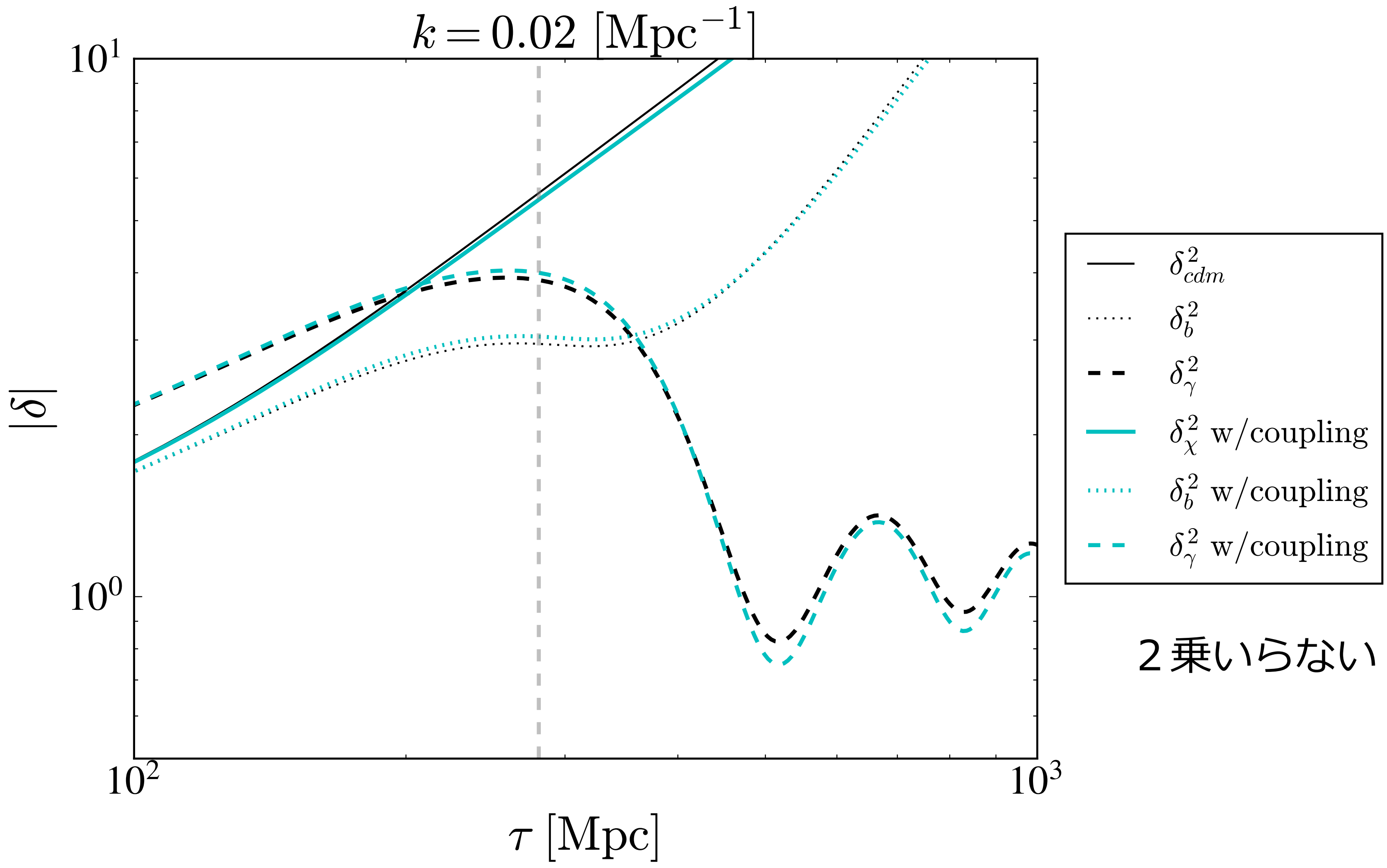

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Warm dark matter effect

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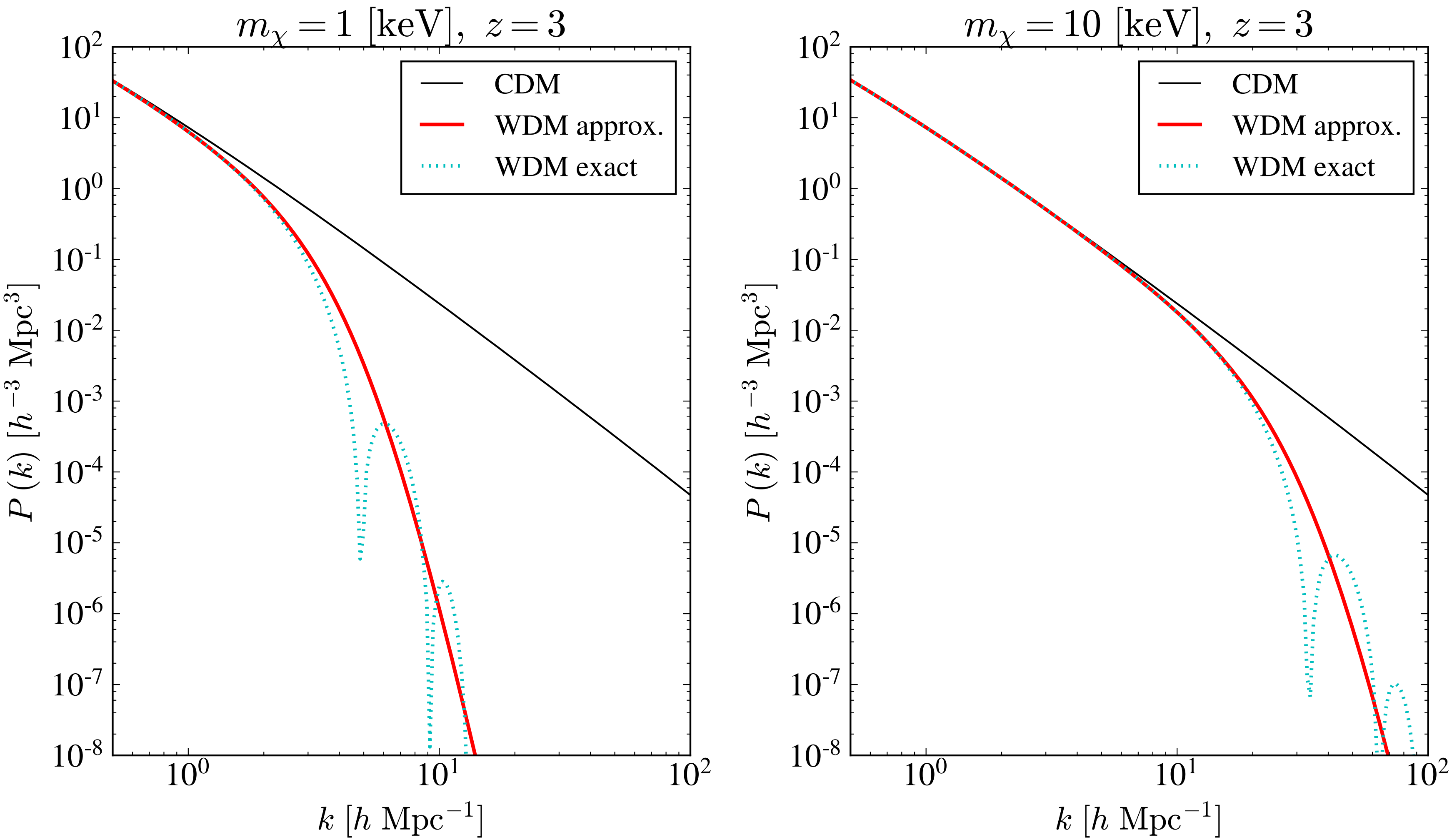

Velocity-dependent Baryon-DM coupling

- Model: **millicharged dark matter**
  - dark matter has a fractional electric charge.

$$q = \epsilon e \quad (\epsilon \ll 1)$$

- The cross-section of the baryon-DM scattering is

Introduction

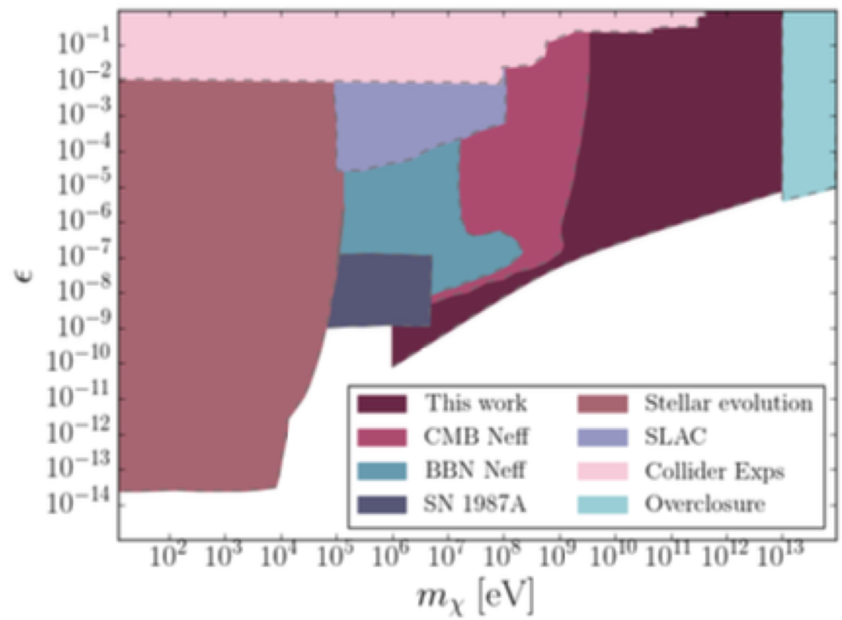

FIG. 12: Constraints from this work on millicharged DM scattering (corresponding to the $n = -4$ scenario) in $\epsilon - m_\chi$ space compared to bounds from other areas: cooling of giants, white dwarfs, and supernovae and constraints on N_{eff} from BBN and CMB [38, 72], overclosure of the Universe [87] and various collider experiments [35, 73, 74, 87]. We have assumed here that all DM is millicharged.

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