Cosmological Constraints on Dark Matter Interactions with Ordinary Matter

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arXiv:2107.12377: w/ Rouven Essig, David McKeen, and Yi-Ming Zhong
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Nov 16/15 2021

Outline

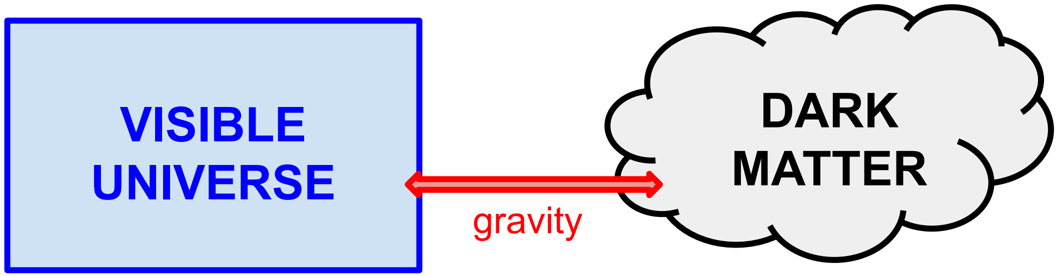
1. Motivation
2. Dark Matter – baryon interactions
3. Datasets
4. Results
5. Conclusions

I. Motivation

Dark Matter

Evidence (relies on gravity)

- Galactic rotation curves
    - MOND? Cf. 1910.06345, 2008.04065, etc. etc.
- Bullet Cluster
- Distance Ladder (SNe)
- Cosmic Microwave Background



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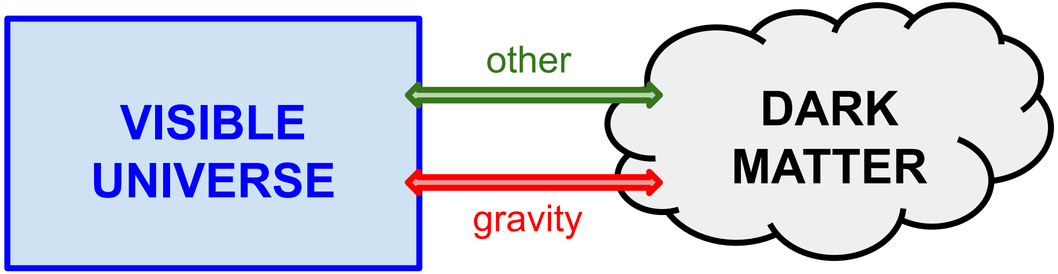
Dark Matter

Searches (beyond gravity!)

- Direct Detection
- Indirect Detection
- Collider Physics
  - (search for "*invisibles*")
- **Cosmology**
  - *Complementary!*
    - at different times and scales
    - independent of attenuation, thresholds, local densities or distributions, coherent scalings...



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ΛCDM

$\rho_\gamma \quad \rho_\nu \quad \rho_b \quad \rho_c \quad \rho_\Lambda$

ΛCDM

"baryons": SM matter

ρ_γ ρ_ν ρ_b ρ_c ρ_Λ

"cold dark matter"

ΛCDM+

ρ_γ ρ_ν ρ_b ρ_c ρ_Λ

other interactions

II. Dark Matter–baryon interactions

DMb

total dark matter

$\rho_\gamma \quad \rho_\nu \quad \rho_b \quad \rho_\chi \quad \rho_c \quad \rho_\Lambda$

other interactions

Dark Matter – baryon interactions (DMb) $\chi B \to \chi B$

B: baryon species (***p*** or ***e***)

- Momentum-Transfer cross section: $\sigma_{\mathrm{T}}^{\chi B} = \int_{-1}^{+1} \mathrm{d}\cos\theta_* \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_*}(1 - \cos\theta_*)$
- **Phenomenological** parameterization: $\sigma_{\mathrm{T}}^{\chi B} = \sigma_n^{\chi B} v_{\mathrm{rel}}^n$

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Particle physics origin:

- ***n=0:*** contact interactions (i.e. heavy mediator)
- ***n=-2:*** dipole-moment
- ***n=-4:*** Coulomb-like (e.g. light mediator)
- **n>0:** [Nguyen et al. ‘21] non-Maxwell Boltzmann [Ali-Haimoud ‘18 & ‘21]

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Fluid Description: temperature

$$\dot{T}_\chi = (\Lambda\text{CDM}) + 2R'_\chi(T_b - T_\chi)$$

$$\dot{T}_b = (\Lambda\text{CDM}) + 2\frac{\rho_\chi}{\rho_b}\frac{\mu_b}{m_\chi}R'_\chi(T_\chi - T_b)$$

[Dvorkin et al. ‘13;
Muñoz et al. ‘15]

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cooling expansion
(***b***: photon bath thermal contact)

[Dvorkin et al. '13;
Muñoz et al. '15]

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"friction" term: drives them to equilibrium

[Dvorkin et al. '13; Muñoz et al. '15]

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DMb heat exchange rate: $R'_\chi \propto f(m_\chi, m_B)\, n_B\, \sigma_n^{\chi B}\, u_B^{n+1}$

[Dvorkin et al. ‘13; Muñoz et al. ‘15]

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$$\text{rate} \sim \langle n\,\sigma\,v\rangle$$

DMb heat exchange rate:

$$R'_\chi \propto f(m_\chi, m_B)\, n_B\, \sigma_n^{\chi B}\, u_B^{n+1}$$

velocity dispersion

baryon species number density

[Dvorkin et al. ‘13; Muñoz et al. ‘15]

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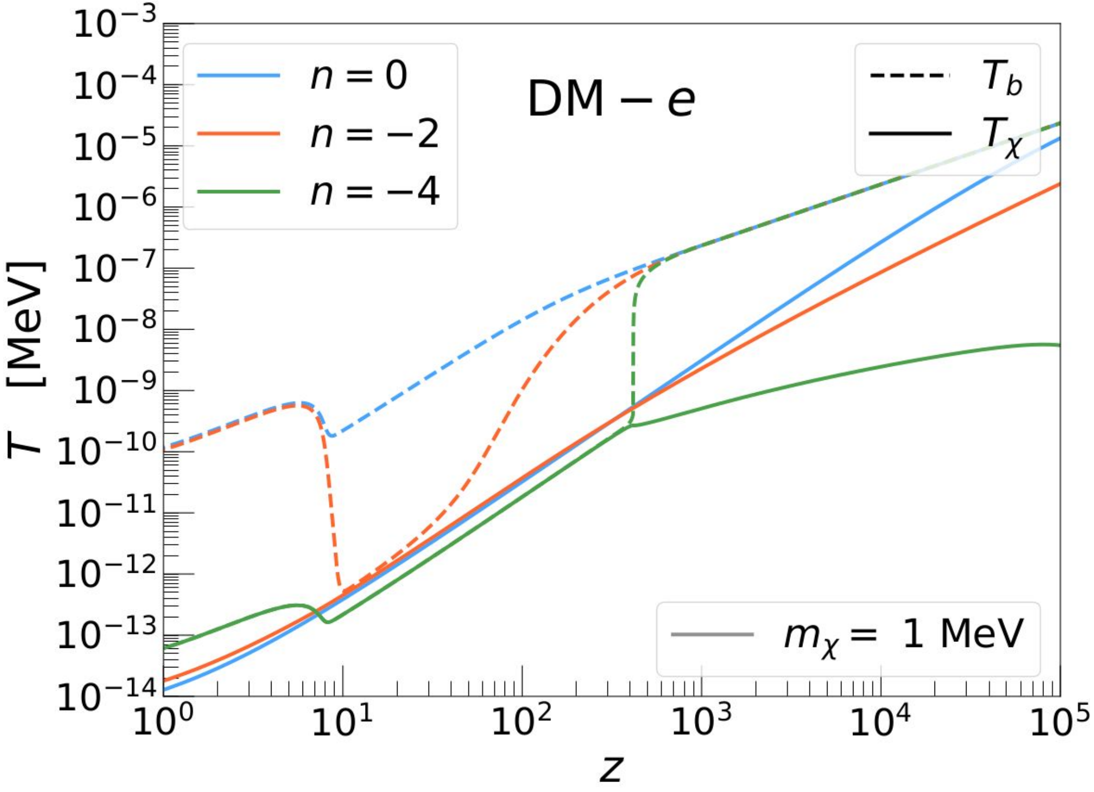

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Fluid Description: perturbations

Velocity divergence: θ *(related to momentum in stress-energy tensor)*

Fluid Description: perturbations

Velocity divergence: θ

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[Dvorkin et al. ‘13;
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Hubble expansion, Poisson source,
fluid sound speed

[Dvorkin et al. ‘13;
Muñoz et al. ‘15]

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rate $\sim \langle n\,\sigma\,v\rangle$

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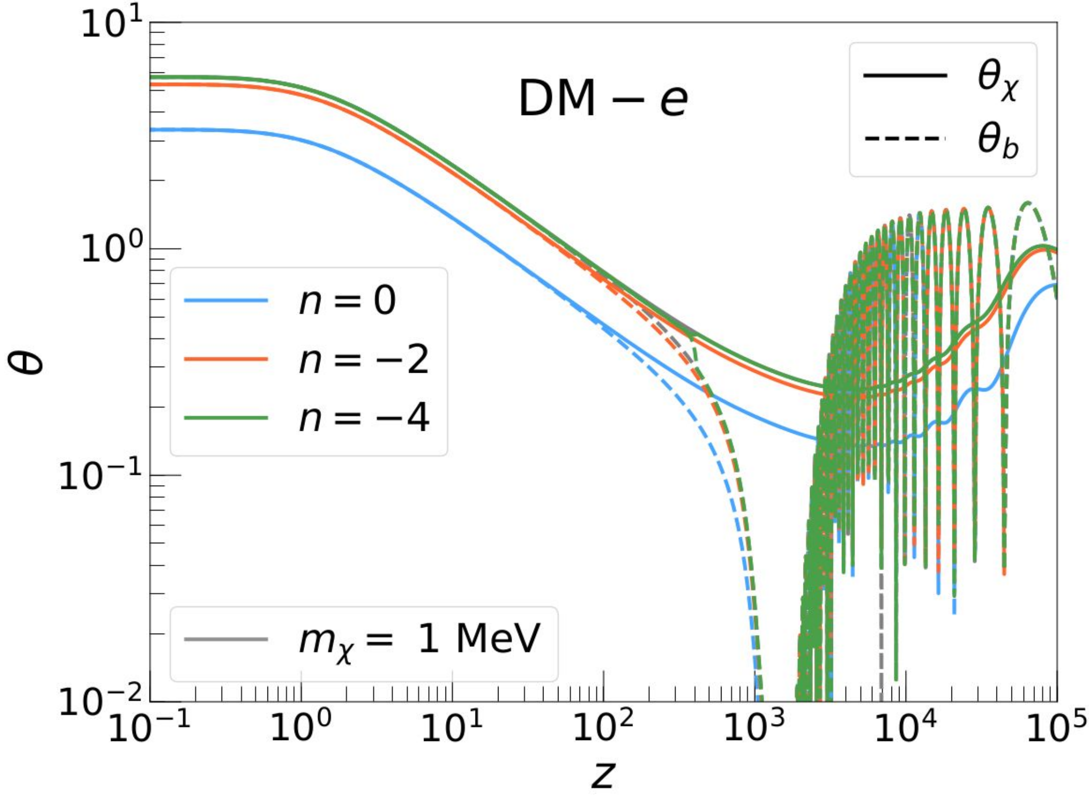

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DMb: impact on observables

1. Implement DMb:
    - In temperature evolution
    - In perturbations evolution (e.g. velocity divergence)
2. Compute impact on observables
    - Cosmic Microwave Background (TT, TE, EE, lensing)
    - Matter Power Spectrum
3. Contrast with data
4. Place bounds

$$\begin{aligned}\dot{T}_\chi &= (\Lambda\mathrm{CDM}) + 2R'_\chi(T_b - T_\chi)\\ \dot{T}_b &= (\Lambda\mathrm{CDM}) + 2\frac{\rho_\chi}{\rho_b}\frac{\mu_b}{m_\chi}R'_\chi(T_\chi - T_b)\end{aligned}$$

$$\begin{aligned}\dot{\theta}_\chi &= (\Lambda\mathrm{CDM}) + R_\chi(\theta_b - \theta_\chi)\\ \dot{\theta}_b &= (\Lambda\mathrm{CDM}) + \frac{\rho_\chi}{\rho_b}R_\chi(\theta_\chi - \theta_b)\end{aligned}$$

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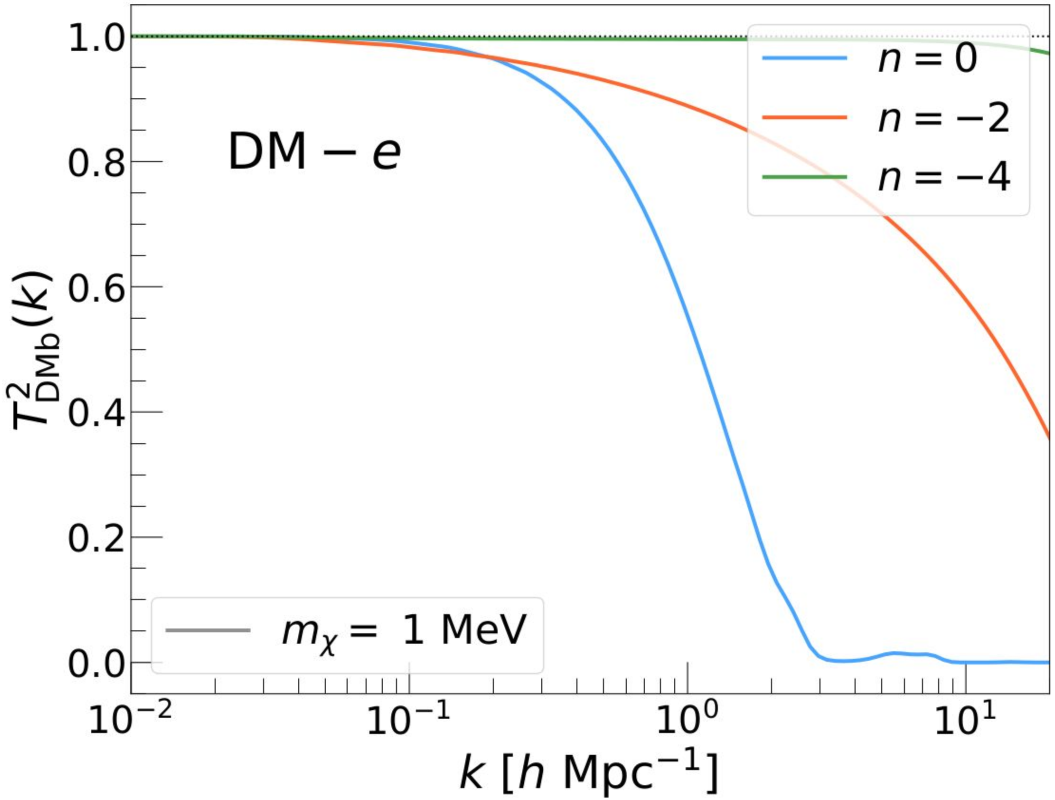
DMb impact: Matter Power Spectrum

$$T^2_{\mathrm{DMb}}(k) = \frac{P_{\mathrm{DMb}}(k)}{P_{\Lambda\mathrm{CDM}}(k)}$$



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DMb models: parameters

$$\{\ B,\ n,\ f_\chi,\ m_\chi,\ \sigma_n\ \}$$

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DMb models: parameters

$$\{\ B,\ n,\ f_\chi,\ m_\chi,\ \sigma_n\ \}$$

$$= \sigma_n^{\chi B}$$

$$\sigma_T = \sigma_n v^n$$

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DMb models: parameters

$$\{\, \underbrace{B}_{p \quad e},\ n,\ f_\chi,\ m_\chi,\ \sigma_n \,\}$$

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DMb models: parameters

$$\{\ B,\ n,\ f_\chi,\ m_\chi,\ \sigma_n\ \}$$

p ***e***

ignored in literature

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DMb models: parameters

$$\{\ B,\ n,\ f_\chi,\ m_\chi,\ \sigma_n\ \}$$

$$\sigma_T = \sigma_n v^n$$

0 -2 -4

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DMb models: parameters

$$\{\ B,\ n,\ \underbrace{f_\chi}_{\boxed{\frac{\rho_\chi}{\rho_{\rm dm}^{\rm tot}}}},\ m_\chi,\ \sigma_n\ \}$$

100%   1%

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DMb models: parameters

$$\{\ B,\ n,\ f_\chi,\ \underbrace{m_\chi}_{\text{10 keV — 100 GeV}},\ \sigma_n\ \}$$

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DMb models: parameters

$$\{\ B,\ n,\ f_\chi,\ m_\chi,\ \underbrace{\sigma_n}_{\textbf{bounds!}}\ \}$$

arXiv:2107.12377

DMb models: parameters

$$\{\ B,\ n,\ f_\chi,\ m_\chi,\ \sigma_n\ \}$$

- ***B***: ***p***, ***e***
- ***n***: ***0*** (e.g. heavy mediator), ***-2*** (e.g. dipole), ***-4*** (e.g. light mediator)
- f_χ: ***100%***, ***1%***
- m_χ: ***10 keV—100 GeV***
- σ_n: ***bounds!***

code publicly available: github.com/ManuelBuenAbad/class_dmb

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III. Datasets

Datasets

- **Cosmic Microwave Background + Baryon Acoustic Oscillations (CMB+BAO)**
  - CMB: anisotropies on the temperature and polarization of CMB photons, lensing of the same
  - BAO: imprint of baryon plasma oscillations on galactic two-point correlation functions
- **Lyman–α forest**
  - Lyman–α absorption lines in spectra of Quasars due to intergalactic hydrogen.
  - Hydrogen traces matter distribution
- **Milky Way Subhalos (MWS)**
  - Abundance of Milky Way subhalos depends on matter power spectrum

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CMB + BAO

- **Data:**
  - CMB
    - Planck 2018 TT+TE+EE anisotropies
    - Planck 2018 lensing
  - BAO
    - 6dFGS
    - SDSS
- **Method:**
  - MontePython MCMC scan: 95% C. R. bounds on $\boldsymbol{\sigma_n}$, at fixed $\boldsymbol{m_\chi}$, for the choices of $\boldsymbol{B}$, $\boldsymbol{n}$, $\boldsymbol{f_\chi}$.

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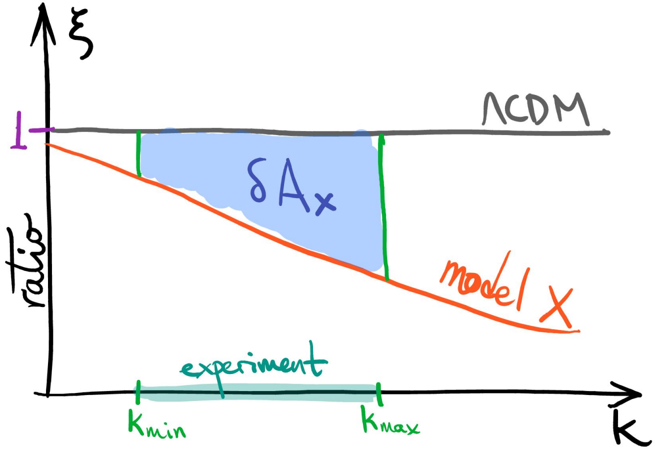
Lyman-α



- **Data:**
  - HIRES/MIKE
  - XQ-100
  - ***0.5 h/Mpc < k < 20 h/Mpc***
- **Method:**
  - ***Area criterion***: for model X: if $\delta A_X > \delta A_{\rm ref} \Rightarrow \text{reject } X$
    - area under suppression curve: ratio of matter power spectra
  - Correlates strongly with bounds from MCMC scans (aided by hydrodynamical simulations) applied to data [Murgia, Irsic, & Viel '18]
  - Reference value: **0.31** (corresponds to WDM model 95% C. R.: $\boldsymbol{m_{WDM} = 5.3}$ ***keV***)

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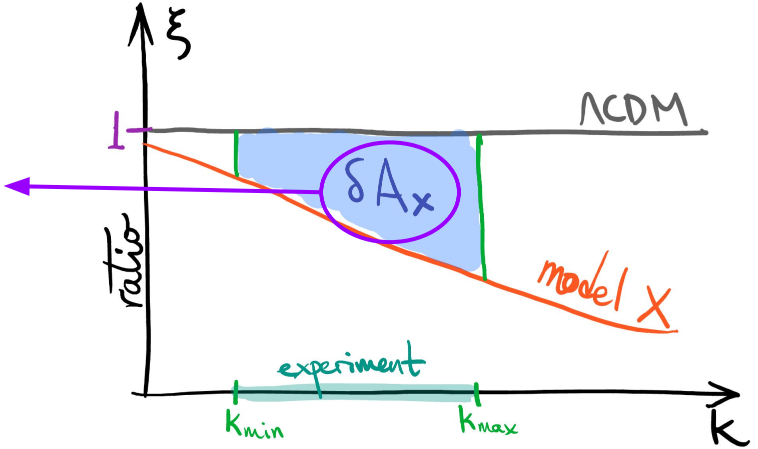
Lyman-α

area difference
w.r.t. ΛCDM

$$\delta A_X \equiv \frac{A_{\Lambda\mathrm{CDM}} - A_X}{A_{\Lambda\mathrm{CDM}}}$$



- **Data:**
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MWS

- **Data:**
  - Luminous Milky Way satellite galaxies
    - SDSS
    - DES
    - PanSTARSS
- **Method:**
  - Compare to bounds on WDM: 95% C. R.: $\boldsymbol{m_{WDM} > 6.5\ keV}$ [DES Collab. Nadler et al. '20]
  - ***Half-mode:*** $\boldsymbol{T_{DMb} = T_{WDM} = 50\%}$
  - ***Fixed k:*** $\boldsymbol{T_{DMb} = T_{WDM}}$ at $\boldsymbol{k=130\ h/Mpc}$ ($\boldsymbol{T_{WDM} \sim 2\%}$)

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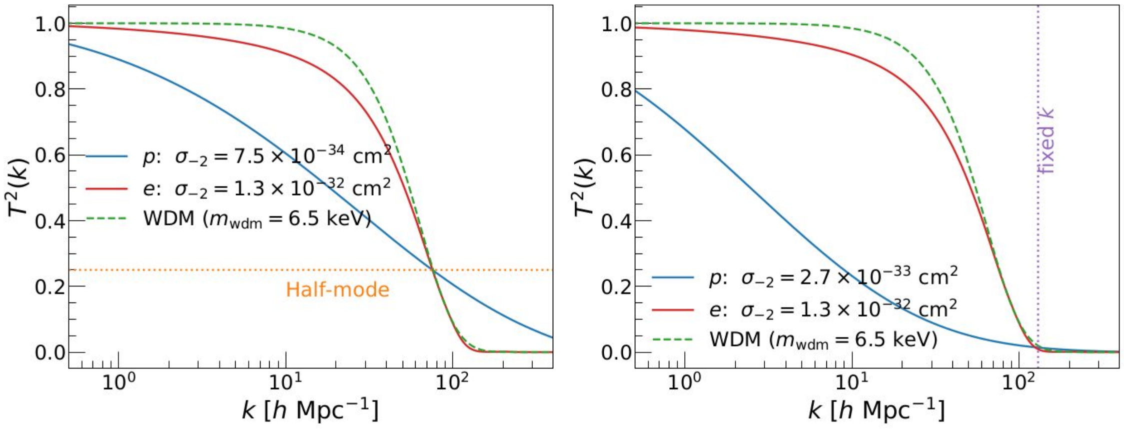
MWS

- **Data:**
  - Luminous Milky Way satellite
    - SDSS
    - DES
    - PanSTARSS



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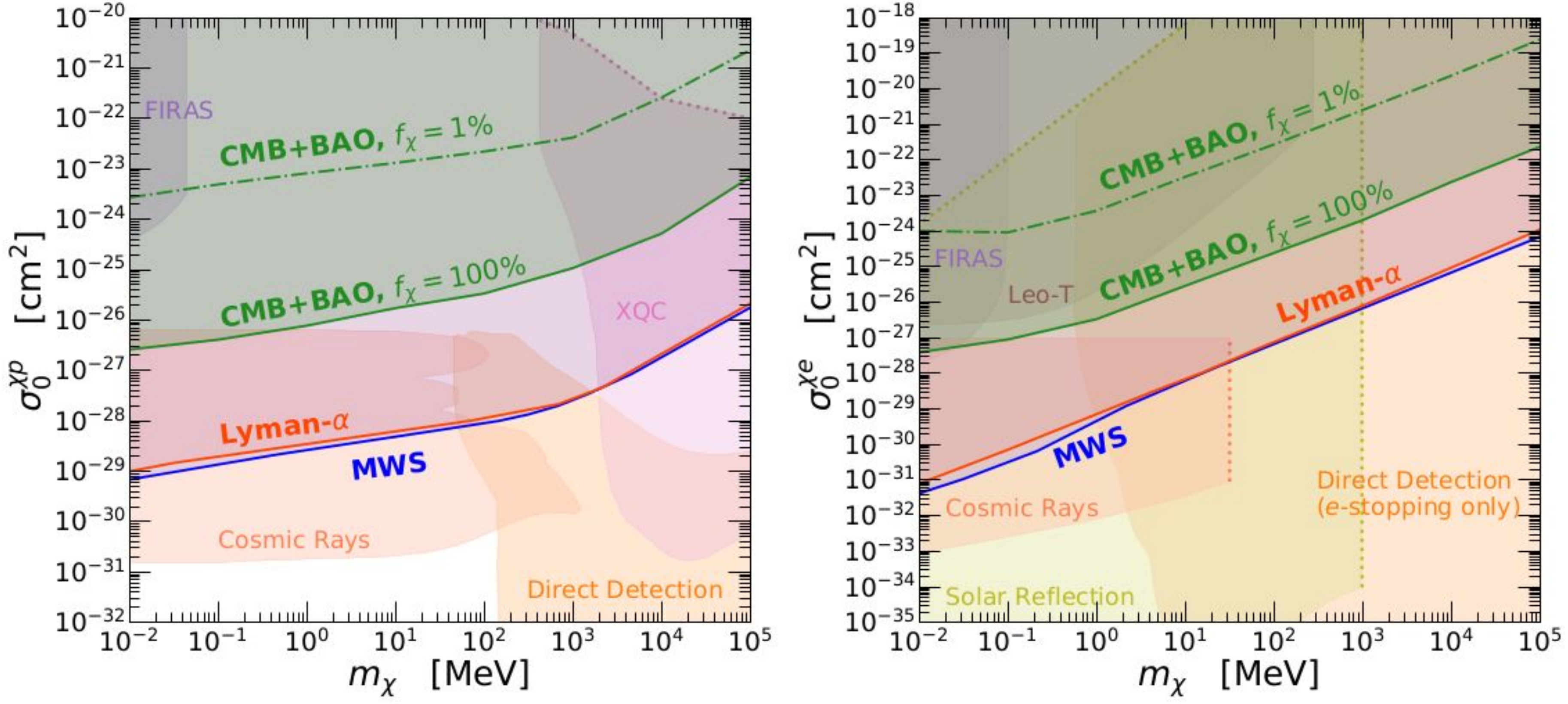
  - ***Fixed k: T_{DMb} = T_{WDM}*** at ***k=130 h/Mpc*** (***T_{WDM}~2%***)

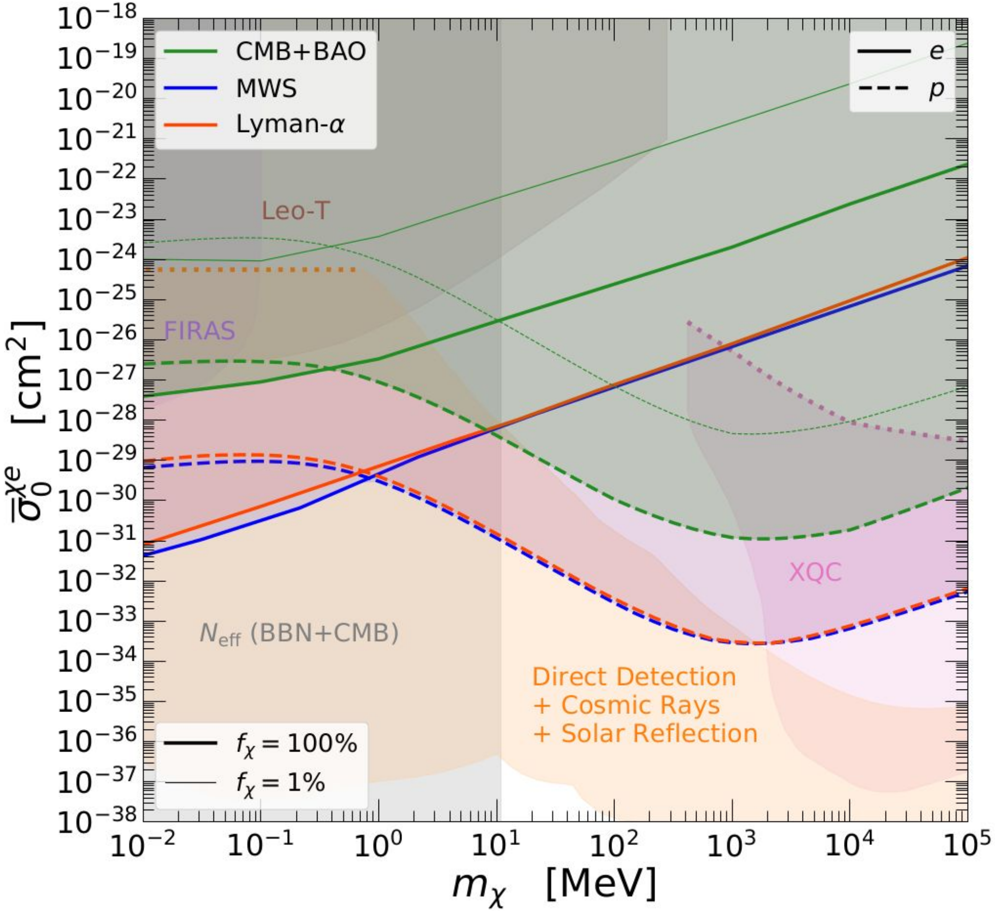
[arXiv:2107.12377](https://arxiv.org/abs/2107.12377)

IV. Results



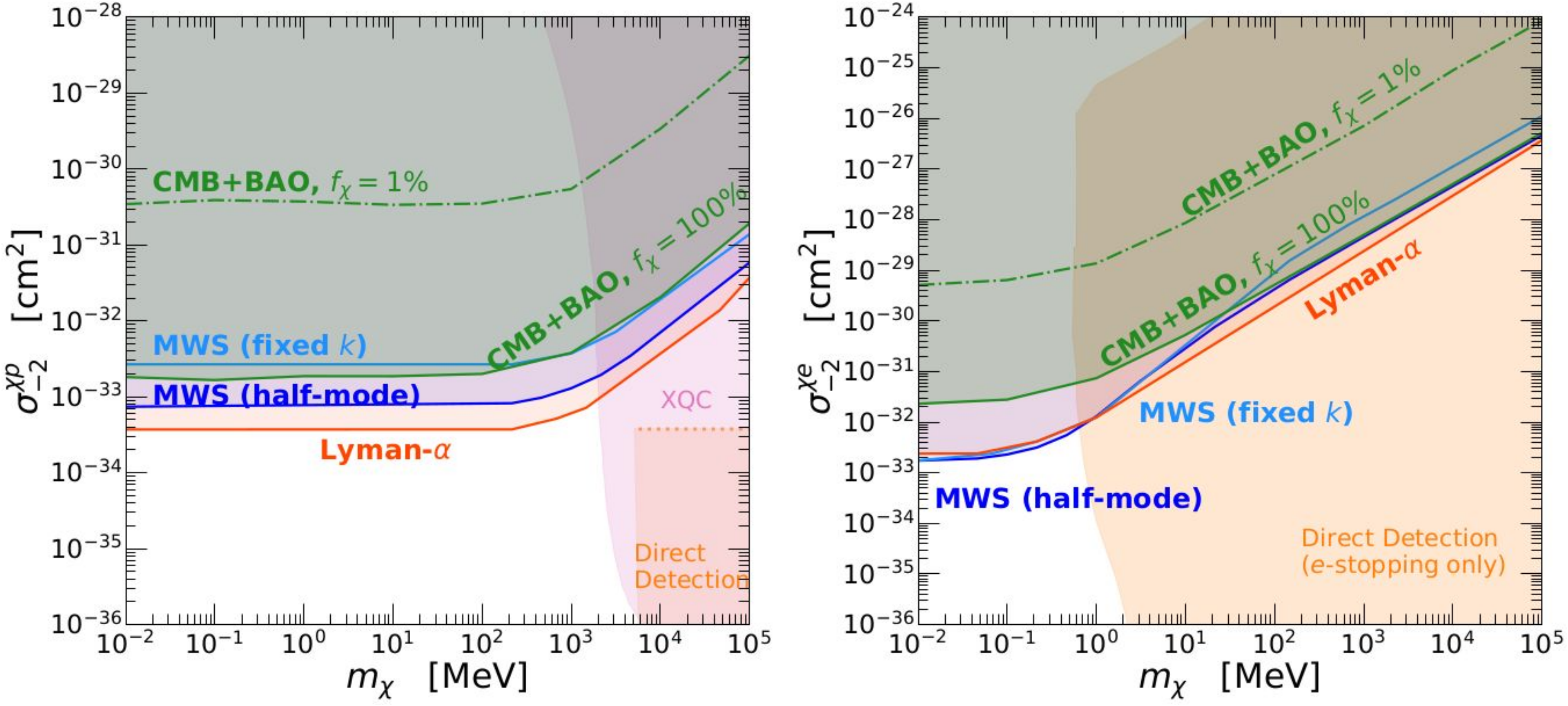
n=0 (phenomenological)

$$\bar{\sigma}_0^{\chi B} = \sigma_0^{\chi B}$$



$$\bar{\sigma}_n^{\chi e} = \frac{\mu_{\chi e}^2}{\mu_{\chi p}^2}\,\bar{\sigma}_n^{\chi p}$$

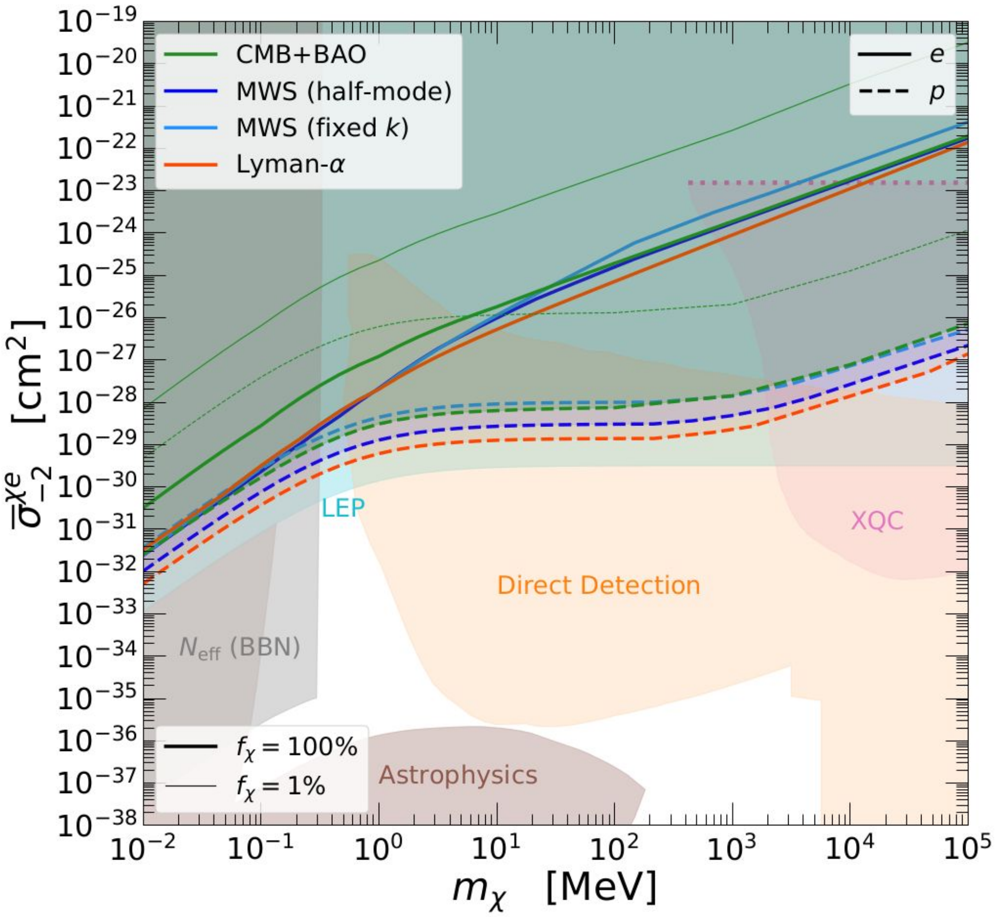
n=0 (heavy mediator)



n=-2 (phenomenological)

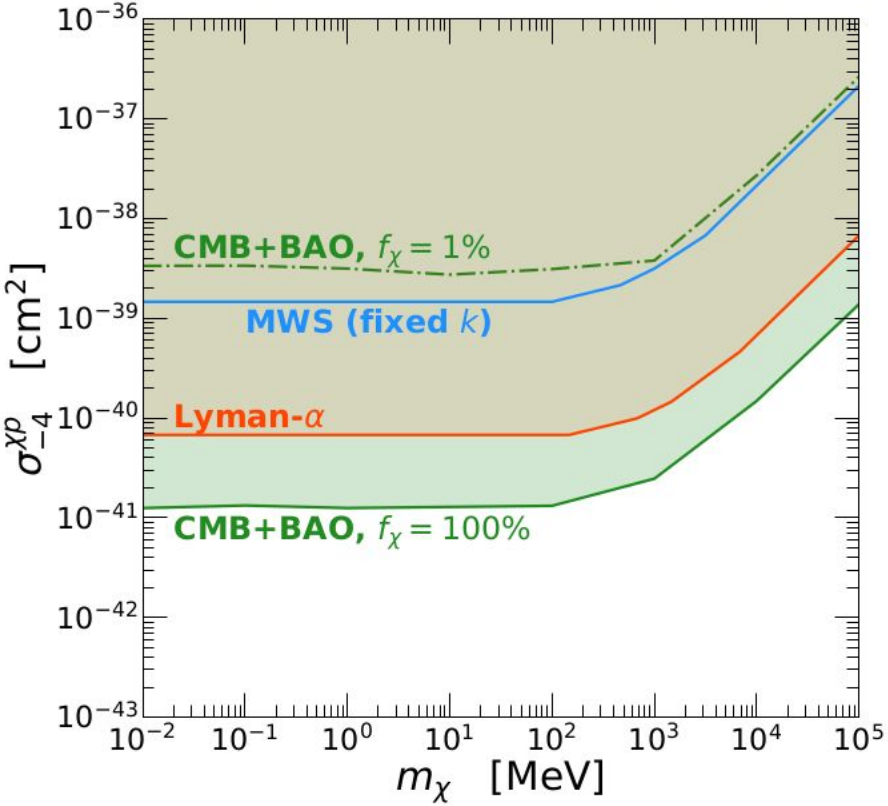
$$\bar{\sigma}_{-2}^{\chi B} = \frac{2\mu_{\chi B}^2}{q_{\rm ref}^2}\sigma_{-2}^{\chi B}$$

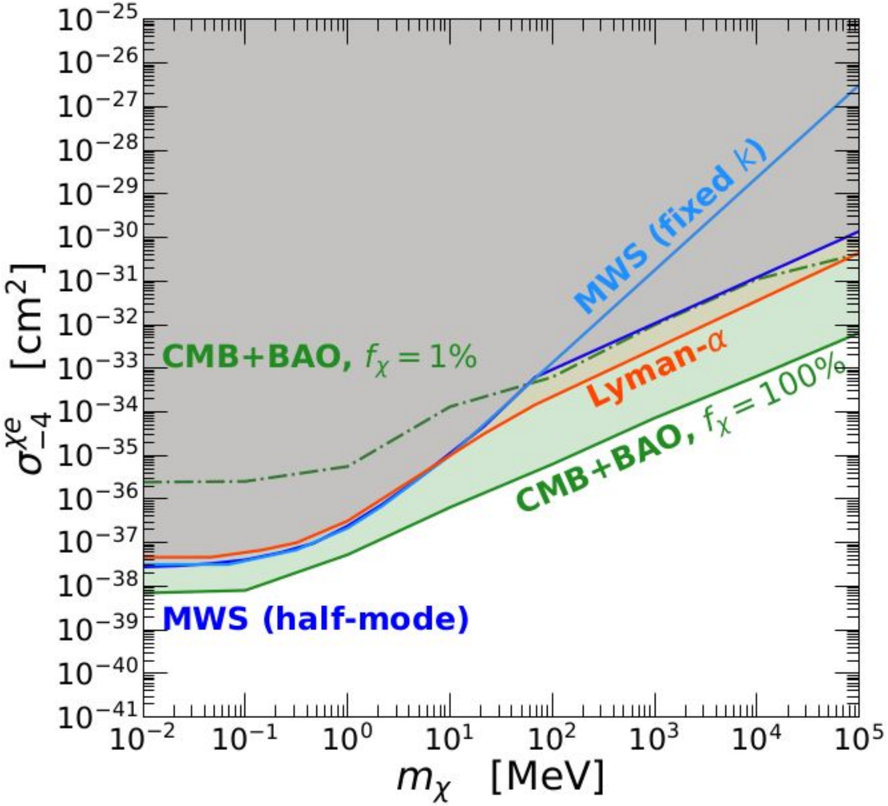
$$q_{\rm ref} = \alpha m_e$$



$$\bar{\sigma}_n^{\chi e} = \frac{\mu_{\chi e}^2}{\mu_{\chi p}^2}\bar{\sigma}_n^{\chi p}$$

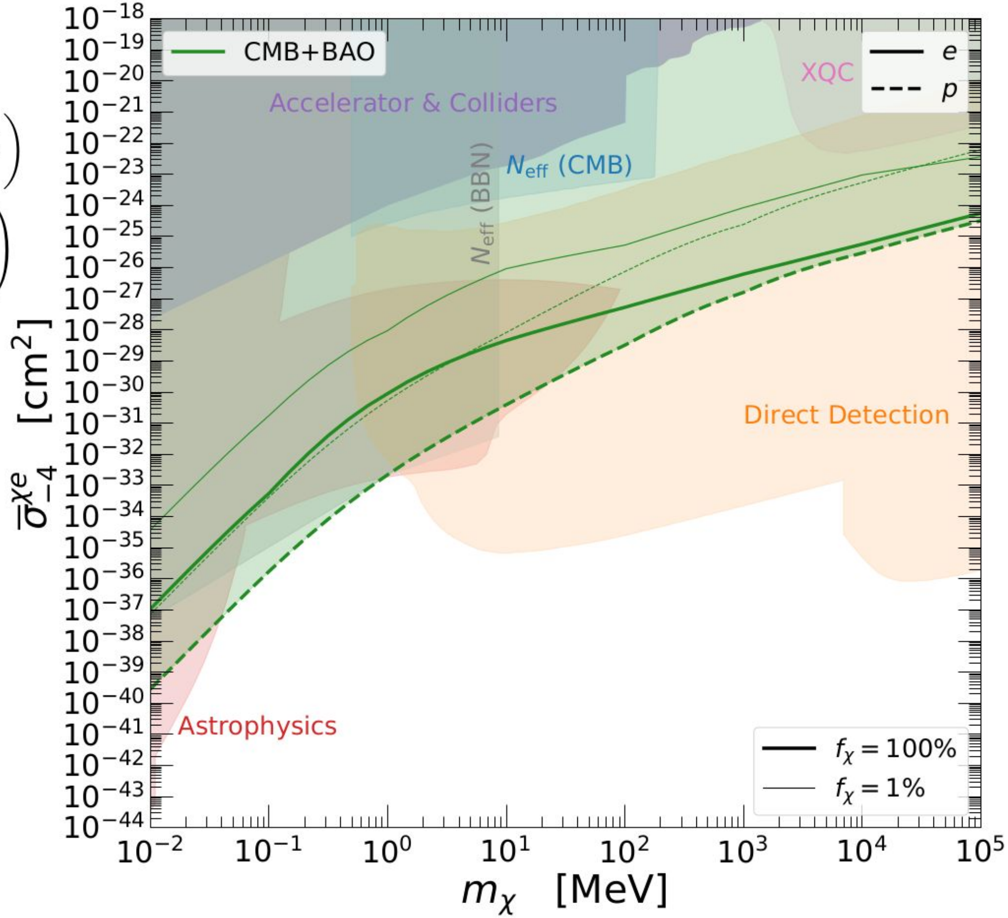
n=-2 (dipole moment)





n=-4 (phenomenological)

$$\sigma_{\mathrm{T}}^{\chi B} \approx \frac{2\pi\epsilon^2\alpha\alpha_\chi\mu_{\chi B}^2}{p_{\mathrm{CM}}^4} \ln\left(\frac{4p_{\mathrm{CM}}^2}{m_{\mathrm{D}}^2}\right)$$
$$= \frac{2\pi\epsilon^2\alpha\alpha_\chi}{\mu_{\chi B}^2 v_{\mathrm{rel}}^4} \ln\left(\frac{4\mu_{\chi B}^2 v_{\mathrm{rel}}^2}{m_{\mathrm{D}}^2}\right)$$



$$\bar{\sigma}_n^{\chi e} = \frac{\mu_{\chi e}^2}{\mu_{\chi p}^2}\,\bar{\sigma}_n^{\chi p}$$

n=-4 (light mediator)

V. Conclusions

Conclusions

- DM-p & DM-e constraints from cosmology
  - First time: DM-e, area criterion Lyman–α
  - Updated: Planck, Lyman–α, MWS
  - Full temperature evolution
  - Phenomenological & Particle Physics
- Complementary to DM Direct Detection
  - Closed some gaps
- The future of *darkness* is **bright**!
  - CMB-S4, CMB-HD
  - 21 cm, newer MWS, *Gaia*
  - Call for: hydrodynamical simulations with DMb

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Backup Slides

$$\dot{T}_\chi = -2\mathcal{H}T_\chi + 2R'_\chi\left(T_b - T_\chi\right) \ ,$$

$$\dot{T}_b = -2\mathcal{H}T_b + 2\frac{\mu_b}{m_e}R_\gamma\left(T_\gamma - T_b\right) + 2S\frac{\mu_b}{m_\chi}R'_\chi\left(T_\chi - T_b\right)$$

$$R'_\chi \equiv a\sum_B \frac{Y_B\,\rho_b m_\chi}{\left(m_\chi + m_B\right)^2}\sigma_n^{\chi B} c_n u_B^{n+1}$$

$$S \equiv \frac{\rho_\chi}{\rho_b}$$

$$u_B \equiv \left(\frac{T_b}{m_B} + \frac{T_\chi}{m_\chi} + \frac{\langle V_{\rm bulk}^2\rangle}{3}\right)^{\frac{1}{2}}$$

$$\begin{aligned}\langle V_{\rm bulk}^2\rangle = V_{\rm RMS}^2 &\simeq 10^{-8} \quad \text{for } z > 10^3 \ , \\ &\simeq 10^{-8}\left(\frac{1+z}{1+10^3}\right)^2 \text{for } z \le 10^3\end{aligned}$$

Temperature Equations

$$\dot{\theta}_{\rm cdm} = -\mathcal{H}\theta_{\rm cdm} + k^2\psi \ ,$$

$$\dot{\theta}_\chi = -\mathcal{H}\theta_\chi + k^2\psi + c_\chi^2 k^2 \delta_\chi + R_\chi\left(\theta_b - \theta_\chi\right) \ ,$$

$$\dot{\theta}_b = -\mathcal{H}\theta_b + k^2\psi + c_s^2 k^2 \delta_b + R_\gamma(\theta_\gamma - \theta_b) + S R_\chi\left(\theta_\chi - \theta_b\right)$$

$$R_\chi \equiv a \sum_B \frac{Y_B \rho_b}{m_\chi + m_B} \sigma_n^{\chi B} c_n u_B^{n+1}$$

$$S \equiv \frac{\rho_\chi}{\rho_b}$$

$$u_B \equiv \left(\frac{T_b}{m_B} + \frac{T_\chi}{m_\chi} + \frac{\langle V_{\rm bulk}^2 \rangle}{3}\right)^{\frac{1}{2}}$$

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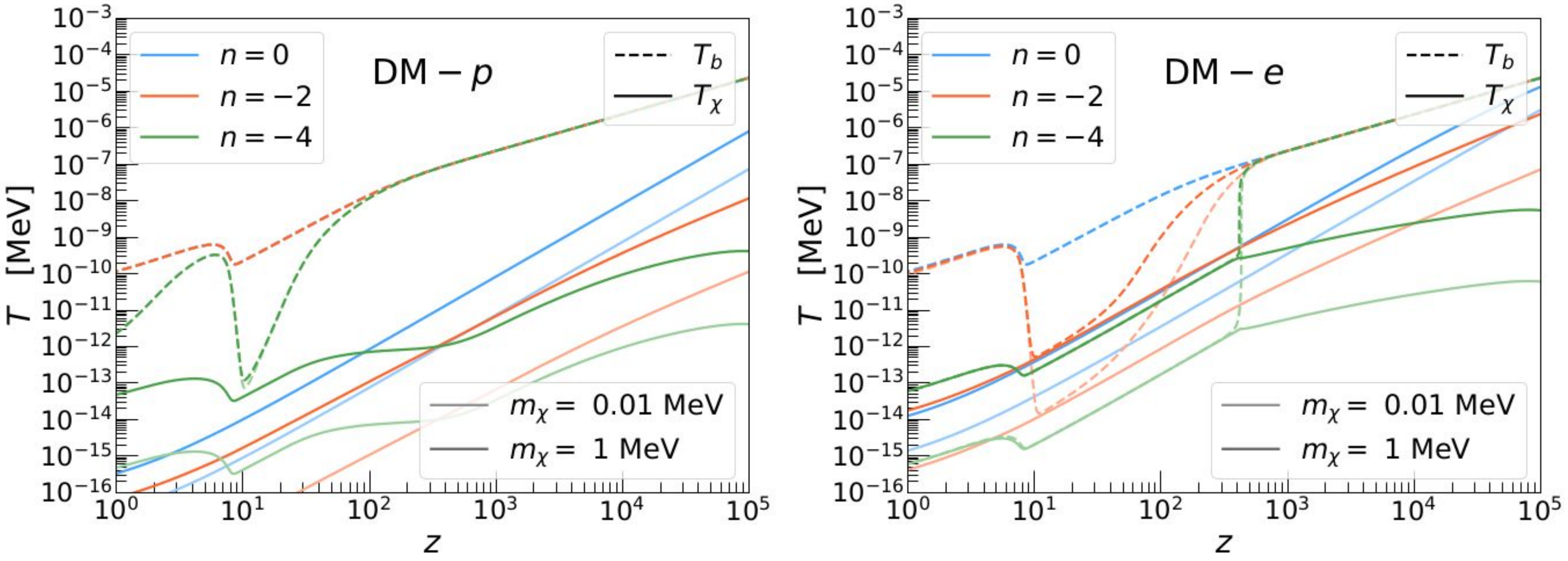
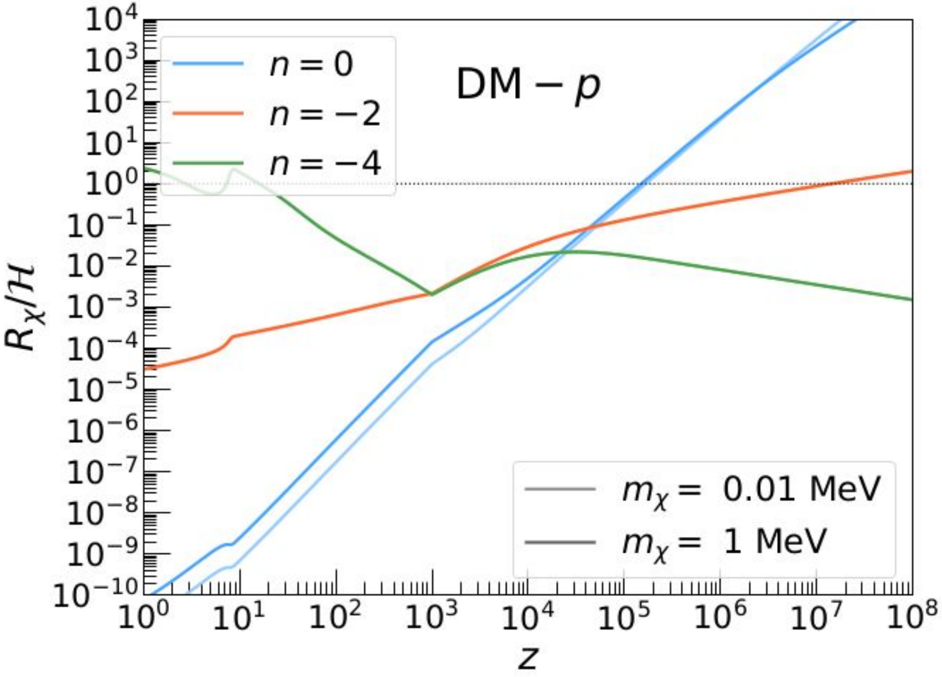
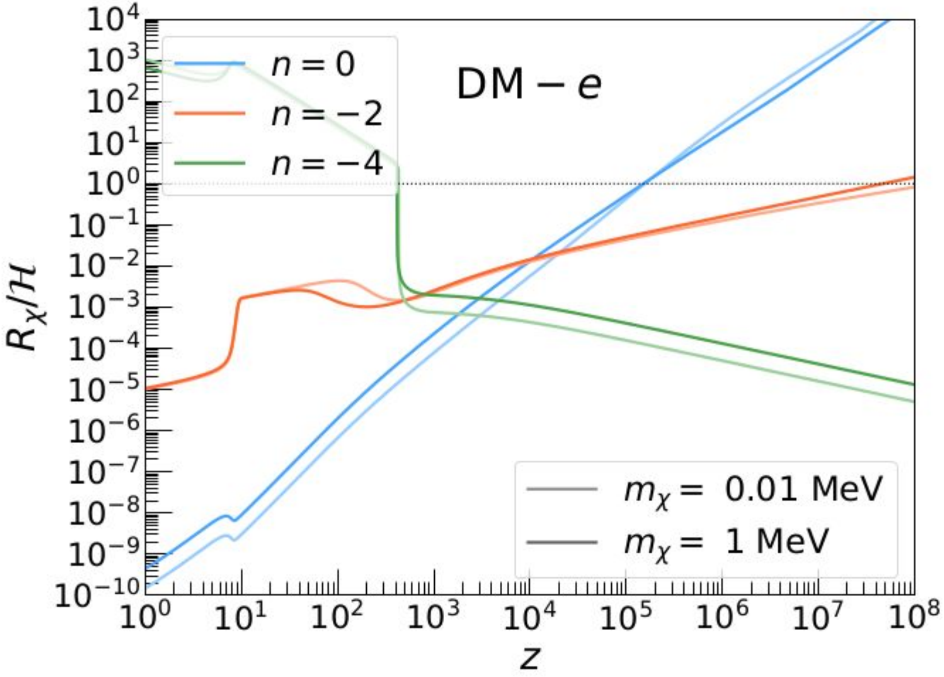
Perturbation Equations

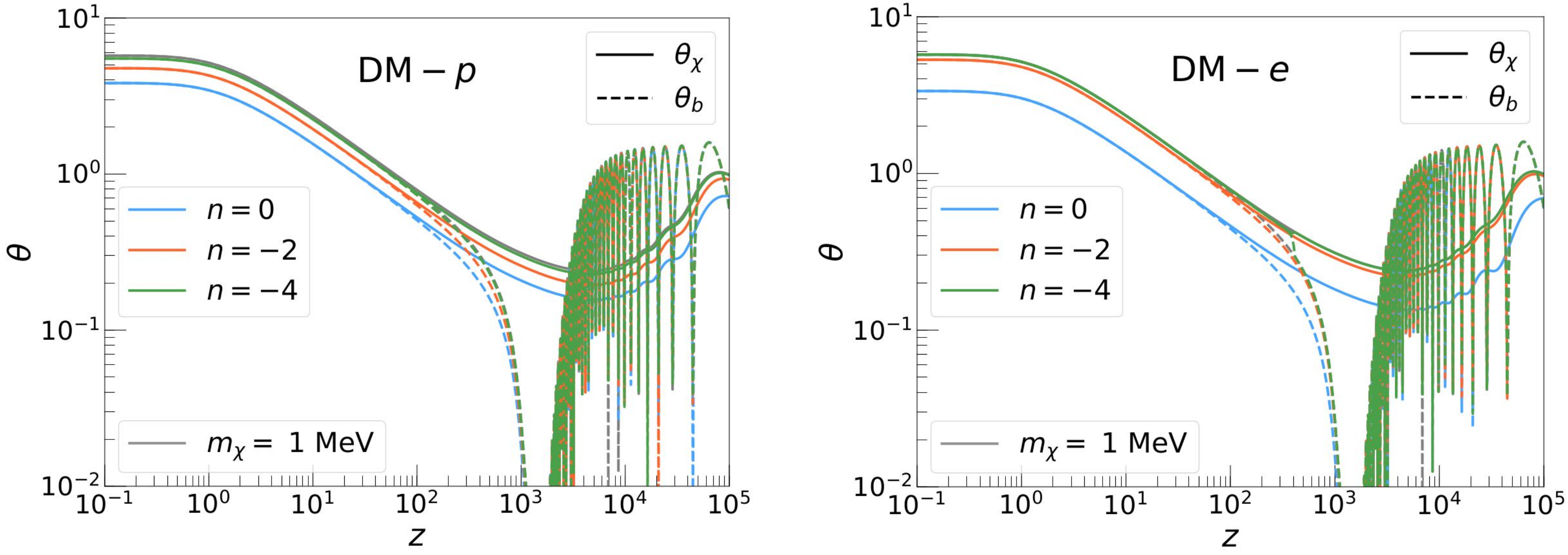


Temperature





Momentum-transfer rate



Perturbations

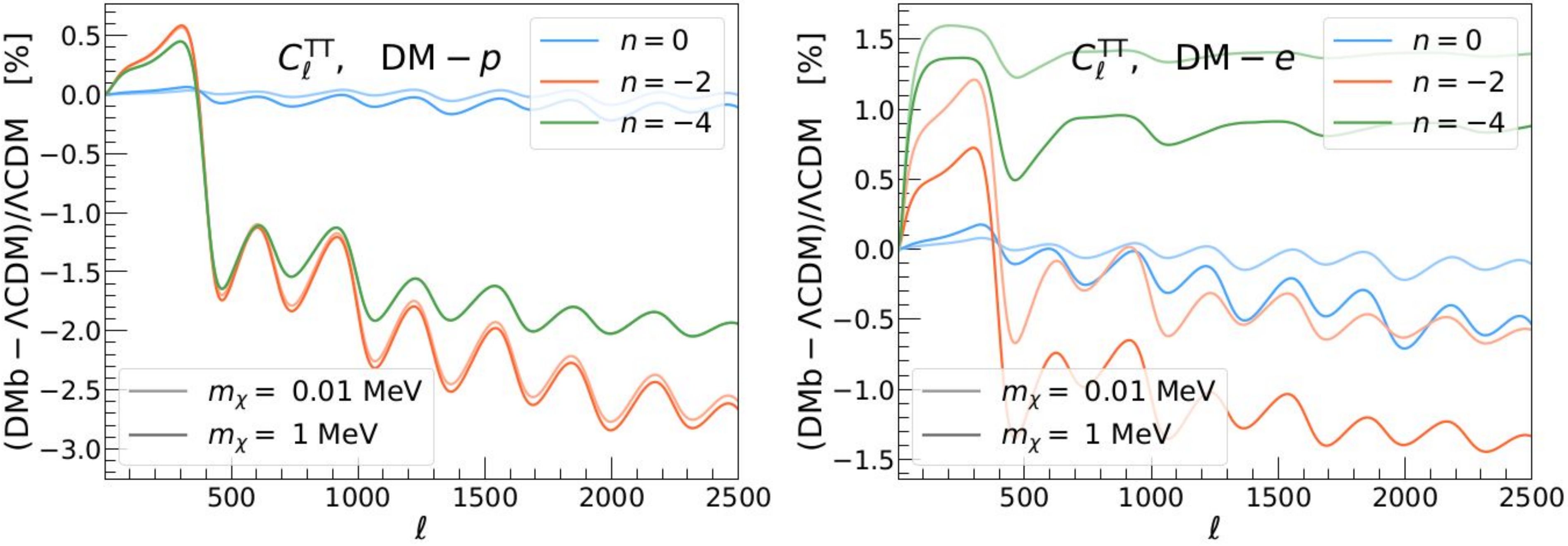
$$\kappa(\tau) \equiv \int_{\tau}^{\tau_0} \mathrm{d}\tau' \ \dot{\kappa}(\tau') \ , \quad \text{the optical depth,}$$

$$\dot{\kappa}(\tau) \equiv a n_e \sigma_{\mathrm{Thomson}} = \frac{3}{4}\frac{\rho_b}{\rho_\gamma} R_\gamma \ , \quad \text{the Thomson scattering rate,}$$

$$g(\tau) \equiv -\dot{\kappa} e^{-\kappa} \ , \quad \text{the visibility function.}$$

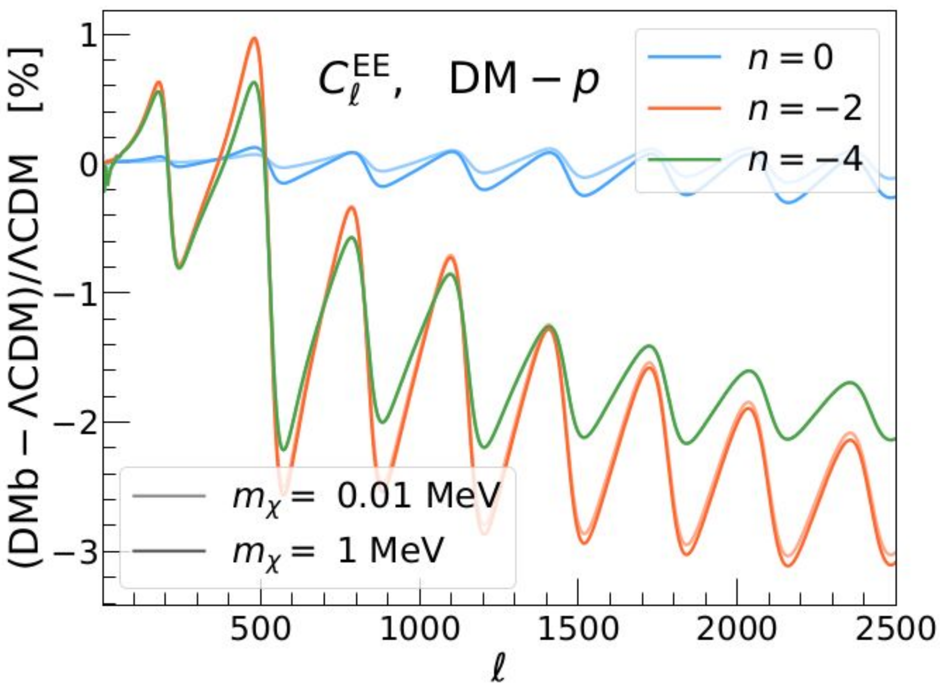
$$S_{\mathrm{T}}(k,\tau) = g(\tau) \ \left(\frac{\delta_\gamma}{4} + \psi\right) + \frac{1}{k^2}\frac{\mathrm{d}\left(g(\tau)\theta_b\right)}{\mathrm{d}\tau} + e^{-\kappa}\left(\dot{\psi} + \dot{\phi}\right) \ ,$$

$$S_{\mathrm{E}}(k,\tau) = \frac{3}{4} g(\tau) \ \left(2\sigma_\gamma + G_{\gamma 0} + G_{\gamma 2}\right) \ ,$$

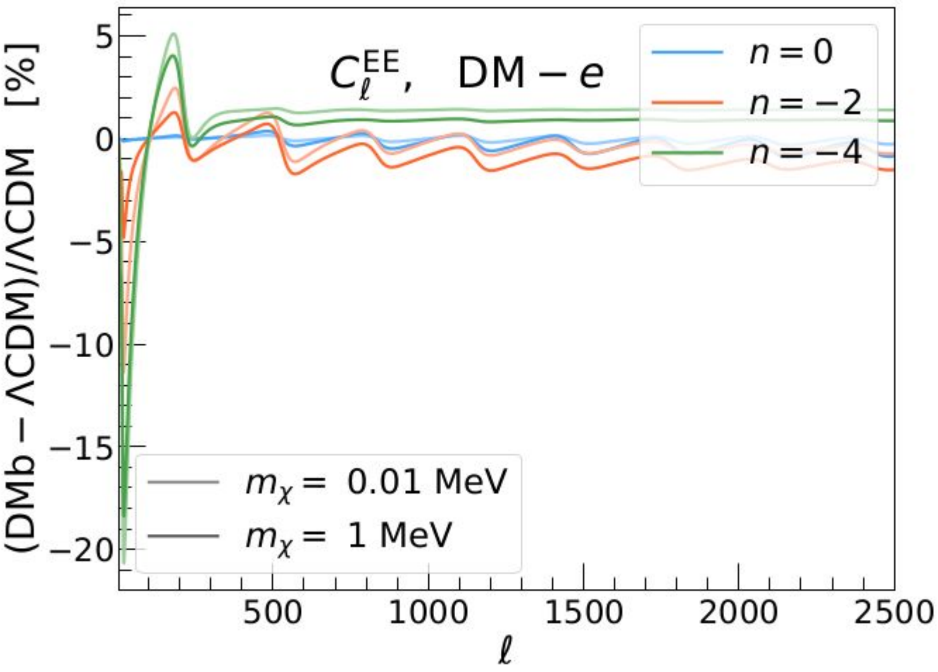


C_ℓ^{TT}, DM − p
$n = 0$
$n = -2$
$n = -4$
$m_\chi =$ 0.01 MeV
$m_\chi =$ 1 MeV
(DMb − ΛCDM)/ΛCDM [%]
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
500
1000
1500
2000
2500
ℓ
C_ℓ^{TT}, DM − e
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5

TT spectra

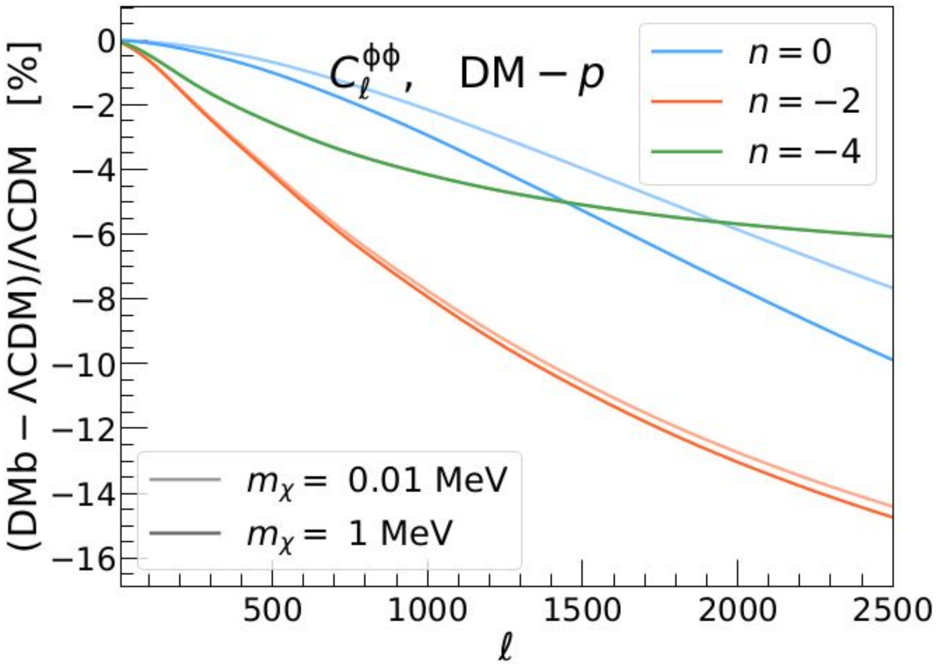


C_ℓ^{EE}, DM − p
n = 0
n = −2
n = −4
m_χ = 0.01 MeV
m_χ = 1 MeV
(DMb − ΛCDM)/ΛCDM [%]
ℓ

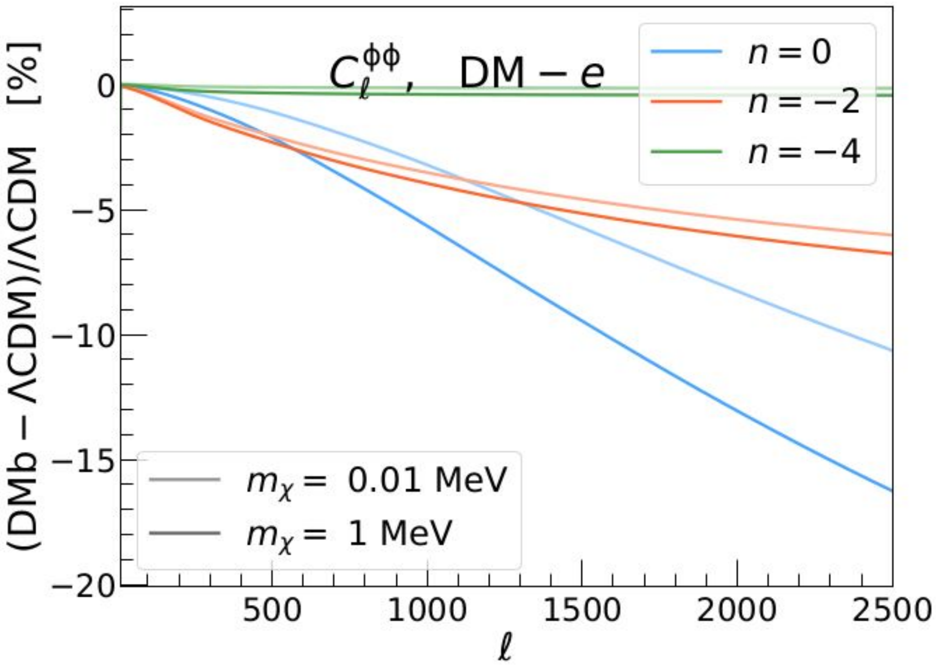


C_ℓ^{EE}, DM − e
n = 0
n = −2
n = −4
m_χ = 0.01 MeV
m_χ = 1 MeV
(DMb − ΛCDM)/ΛCDM [%]
ℓ

EE spectra

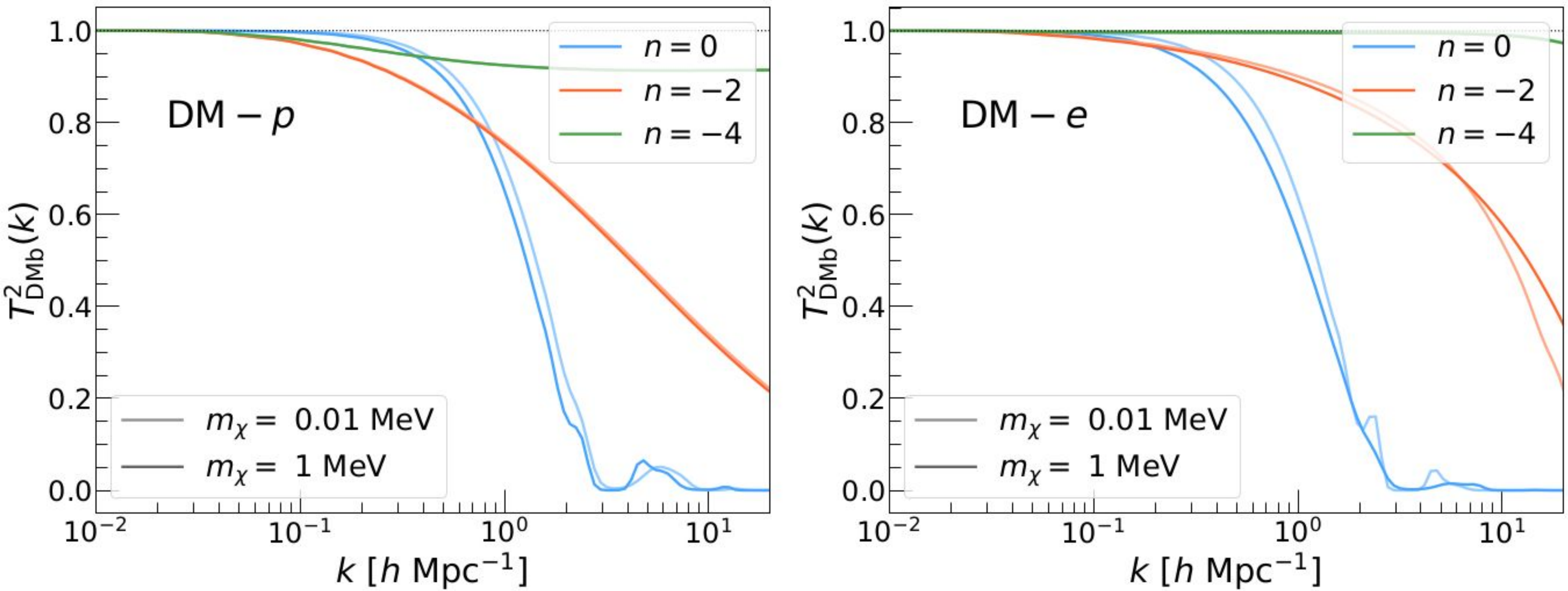


$C_\ell^{\phi\phi}$, DM − p
n = 0
n = −2
n = −4
m_χ = 0.01 MeV
m_χ = 1 MeV
(DMb − ΛCDM)/ΛCDM [%]
0
−2
−4
−6
−8
−10
−12
−14
−16
500
1000
1500
2000
2500
ℓ



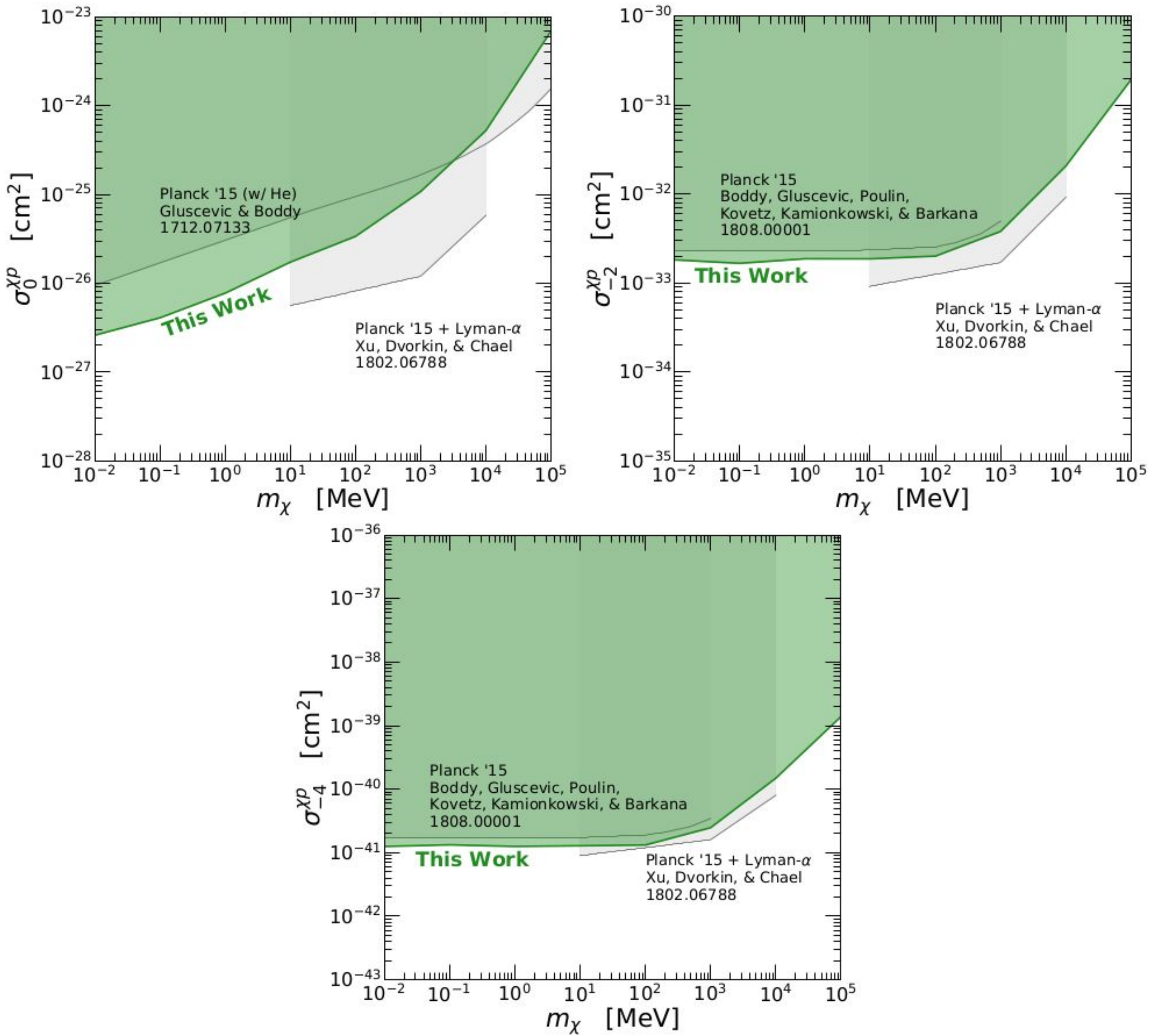
$C_\ell^{\phi\phi}$, DM − e
n = 0
n = −2
n = −4
m_χ = 0.01 MeV
m_χ = 1 MeV
(DMb − ΛCDM)/ΛCDM [%]
0
−5
−10
−15
−20
500
1000
1500
2000
2500
ℓ

φφ spectra



Transfer power

$$T^2_{\mathrm{DMb}}(k) = \frac{P_{\mathrm{DMb}}(k)}{P_{\Lambda\mathrm{CDM}}(k)}$$



Planck '15 (w/ He)
Gluscevic & Boddy
1712.07133
This Work
Planck '15 + Lyman-α
Xu, Dvorkin, & Chael
1802.06788
$\sigma_0^{\chi p}$ [cm^2]
m_χ [MeV]
Planck '15
Boddy, Gluscevic, Poulin,
Kovetz, Kamionkowski, & Barkana
1808.00001
This Work
Planck '15 + Lyman-α
Xu, Dvorkin, & Chael
1802.06788
$\sigma_{-2}^{\chi p}$ [cm^2]
m_χ [MeV]
Planck '15
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This Work
Planck '15 + Lyman-α
Xu, Dvorkin, & Chael
1802.06788
$\sigma_{-4}^{\chi p}$ [cm^2]
m_χ [MeV]

CMB+BAO

$$\text{if}\quad \delta A_X > \delta A_{\rm ref} \Rightarrow \text{reject}\ X$$

$$\delta A_X \equiv \frac{A_{\Lambda\rm CDM} - A_X}{A_{\Lambda\rm CDM}}$$

$$A_X \equiv \int_{k_{\rm min}}^{k_{\rm max}} \mathrm{d}k\ \xi_X(k)$$

area under suppression

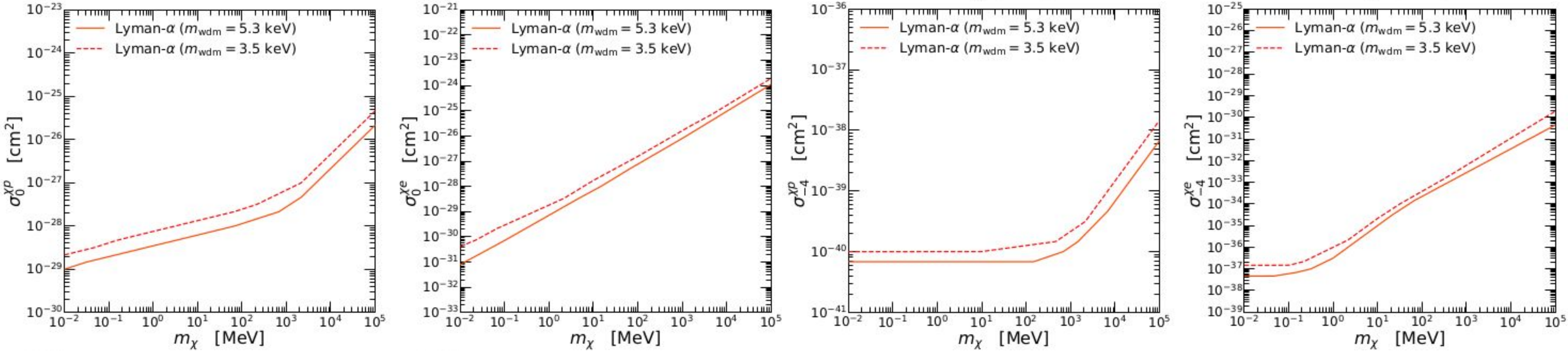
$$\xi_X(k) \equiv \frac{P_{\rm 1D}^X(k)}{P_{\rm 1D}^{\Lambda\rm CDM}(k)}$$

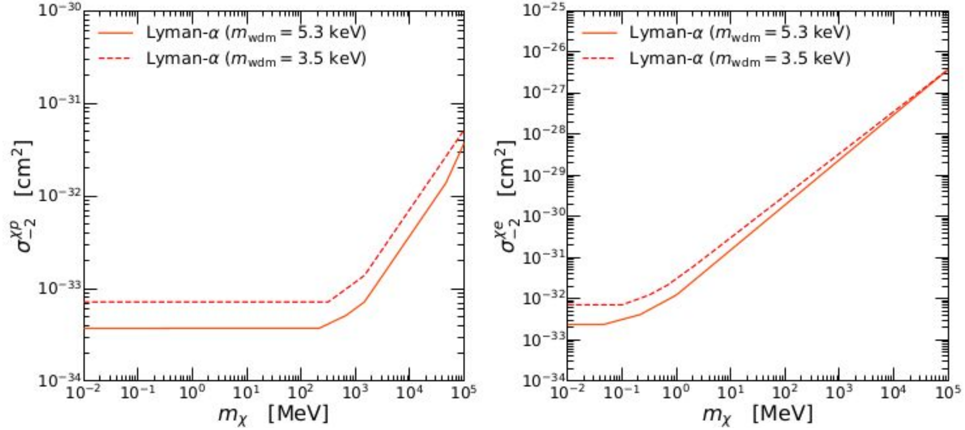
suppression

$$P_{\rm 1D}(k) \equiv \frac{1}{2\pi}\int_k^{\infty} \mathrm{d}k'\ k' P(k')$$

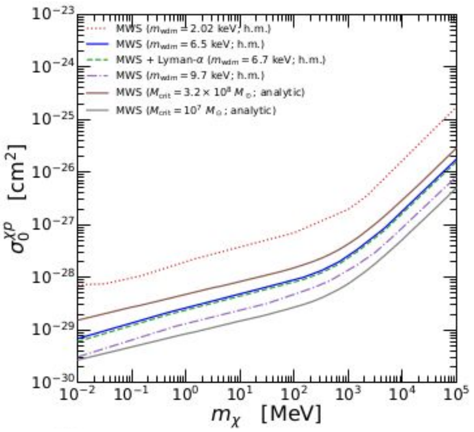
1D matter power spectrum

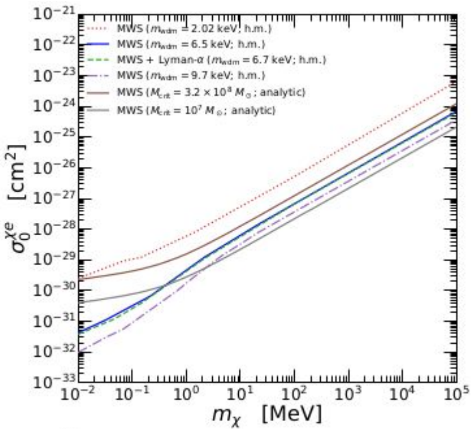
Area criterion

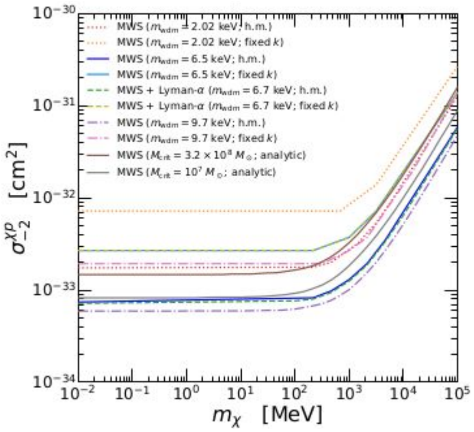

Lyman-α ($m_{\rm wdm}$ = 5.3 keV)
Lyman-α ($m_{\rm wdm}$ = 3.5 keV)
$\sigma_0^{\chi p}$ [cm^2]
$\sigma_0^{\chi e}$ [cm^2]
$\sigma_{-4}^{\chi p}$ [cm^2]
$\sigma_{-4}^{\chi e}$ [cm^2]
m_χ [MeV]

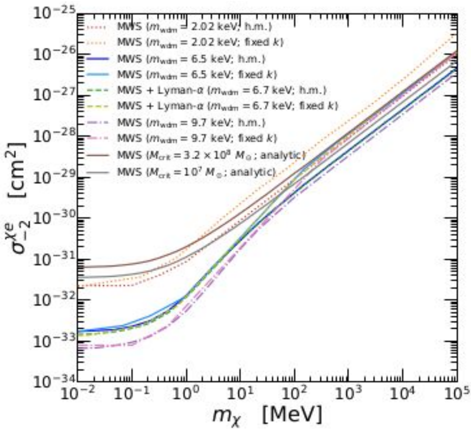

Lyman-α ($m_{\rm wdm}$ = 5.3 keV)
Lyman-α ($m_{\rm wdm}$ = 3.5 keV)
$\sigma_{-2}^{\chi p}$ [cm^2]
$\sigma_{-2}^{\chi e}$ [cm^2]
m_χ [MeV]

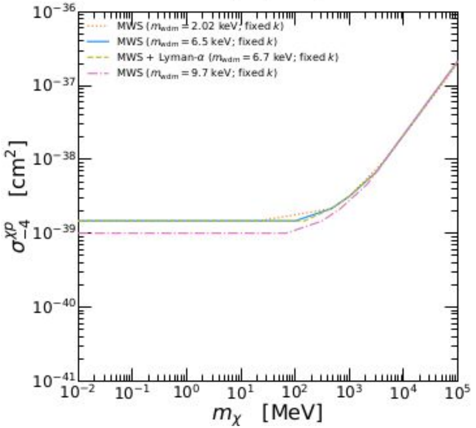
Lyman−α

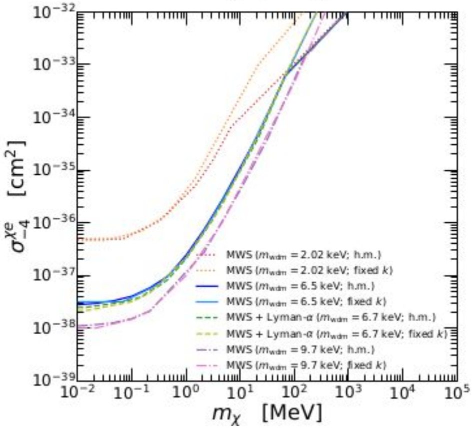

MWS ($m_{\rm wdm} = 2.02$ keV; h.m.)
MWS ($m_{\rm wdm} = 6.5$ keV; h.m.)
MWS + Lyman-α ($m_{\rm wdm} = 6.7$ keV; h.m.)
MWS ($m_{\rm wdm} = 9.7$ keV; h.m.)
MWS ($M_{\rm crit} = 3.2 \times 10^8\, M_\odot$; analytic)
MWS ($M_{\rm crit} = 10^7\, M_\odot$; analytic)
$\sigma_0^{\chi p}$ [cm^2]
m_χ [MeV]


MWS ($m_{\rm wdm} = 2.02$ keV; h.m.)
MWS ($m_{\rm wdm} = 6.5$ keV; h.m.)
MWS + Lyman-α ($m_{\rm wdm} = 6.7$ keV; h.m.)
MWS ($m_{\rm wdm} = 9.7$ keV; h.m.)
MWS ($M_{\rm crit} = 3.2 \times 10^8\, M_\odot$; analytic)
MWS ($M_{\rm crit} = 10^7\, M_\odot$; analytic)
$\sigma_0^{\chi e}$ [cm^2]
m_χ [MeV]


MWS ($m_{\rm wdm} = 2.02$ keV; h.m.)
MWS ($m_{\rm wdm} = 2.02$ keV; fixed k)
MWS ($m_{\rm wdm} = 6.5$ keV; h.m.)
MWS ($m_{\rm wdm} = 6.5$ keV; fixed k)
MWS + Lyman-α ($m_{\rm wdm} = 6.7$ keV; h.m.)
MWS + Lyman-α ($m_{\rm wdm} = 6.7$ keV; fixed k)
MWS ($m_{\rm wdm} = 9.7$ keV; h.m.)
MWS ($m_{\rm wdm} = 9.7$ keV; fixed k)
MWS ($M_{\rm crit} = 3.2 \times 10^8\, M_\odot$; analytic)
MWS ($M_{\rm crit} = 10^7\, M_\odot$; analytic)
$\sigma_{-2}^{\chi p}$ [cm^2]
m_χ [MeV]


MWS ($m_{\rm wdm} = 2.02$ keV; h.m.)
MWS ($m_{\rm wdm} = 2.02$ keV; fixed k)
MWS ($m_{\rm wdm} = 6.5$ keV; h.m.)
MWS ($m_{\rm wdm} = 6.5$ keV; fixed k)
MWS + Lyman-α ($m_{\rm wdm} = 6.7$ keV; h.m.)
MWS + Lyman-α ($m_{\rm wdm} = 6.7$ keV; fixed k)
MWS ($m_{\rm wdm} = 9.7$ keV; h.m.)
MWS ($m_{\rm wdm} = 9.7$ keV; fixed k)
MWS ($M_{\rm crit} = 3.2 \times 10^8\, M_\odot$; analytic)
MWS ($M_{\rm crit} = 10^7\, M_\odot$; analytic)
$\sigma_{-2}^{\chi e}$ [cm^2]
m_χ [MeV]


MWS ($m_{\rm wdm} = 2.02$ keV; fixed k)
MWS ($m_{\rm wdm} = 6.5$ keV; fixed k)
MWS + Lyman-α ($m_{\rm wdm} = 6.7$ keV; fixed k)
MWS ($m_{\rm wdm} = 9.7$ keV; fixed k)
$\sigma_{-4}^{\chi p}$ [cm^2]
m_χ [MeV]


MWS ($m_{\rm wdm} = 2.02$ keV; h.m.)
MWS ($m_{\rm wdm} = 2.02$ keV; fixed k)
MWS ($m_{\rm wdm} = 6.5$ keV; h.m.)
MWS ($m_{\rm wdm} = 6.5$ keV; fixed k)
MWS + Lyman-α ($m_{\rm wdm} = 6.7$ keV; h.m.)
MWS + Lyman-α ($m_{\rm wdm} = 6.7$ keV; fixed k)
MWS ($m_{\rm wdm} = 9.7$ keV; h.m.)
MWS ($m_{\rm wdm} = 9.7$ keV; fixed k)
$\sigma_{-4}^{\chi e}$ [cm^2]
m_χ [MeV]

MWS