Probing Dark Matter-Baryon Interactions using JWST Early Galaxies

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Ongoing work with **Ranjini Mondol**, **Abhijeet Singh**, and **Ranjan Laha**

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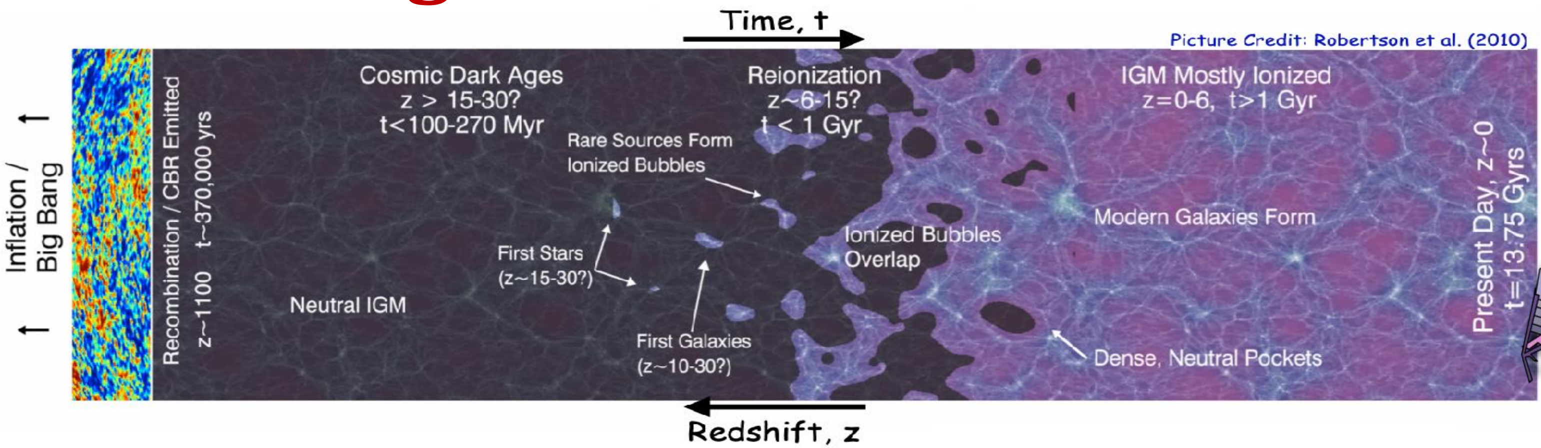
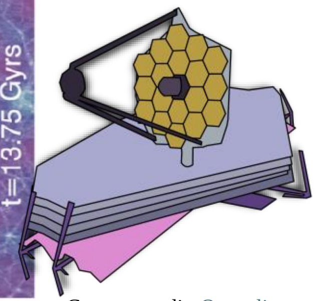
Contents

1. What we observe using JWST (James Webb Space Telescope)?

2. How can we use this observation to probe DM-baryon interaction?

Observing the Earliest Galaxies





Cartoon credit: Openclipart

Earlier galaxies are star-forming and host younger stars. Younger stars are hotter and emit mostly in UV. (A fiducial wavelength for this purpose is 150 nm)

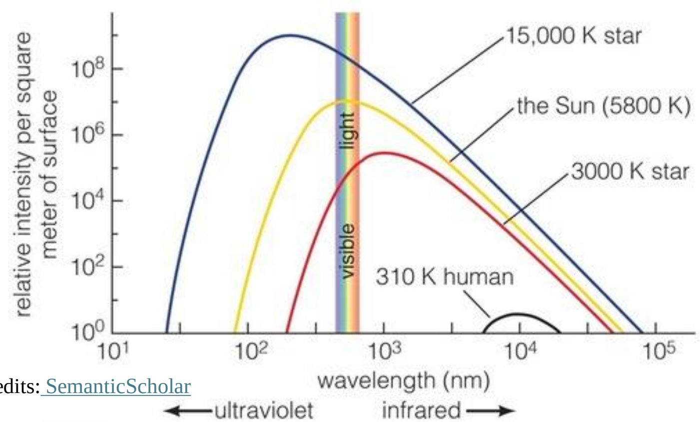


Fig credits: SemanticScholar

We observe these galaxies in near-IR.

Hubble can observe $\lambda \lesssim 1.6\ \mu m$
JWST can observe $\lambda \lesssim 5\ \mu m$ in NIR

JWST can look at higher redshift galaxies!

Farthest galaxy observed by HST: GN-z11 ($z \simeq 11.09$)

JWST has already observed galaxies at $z \simeq 12$ and higher!

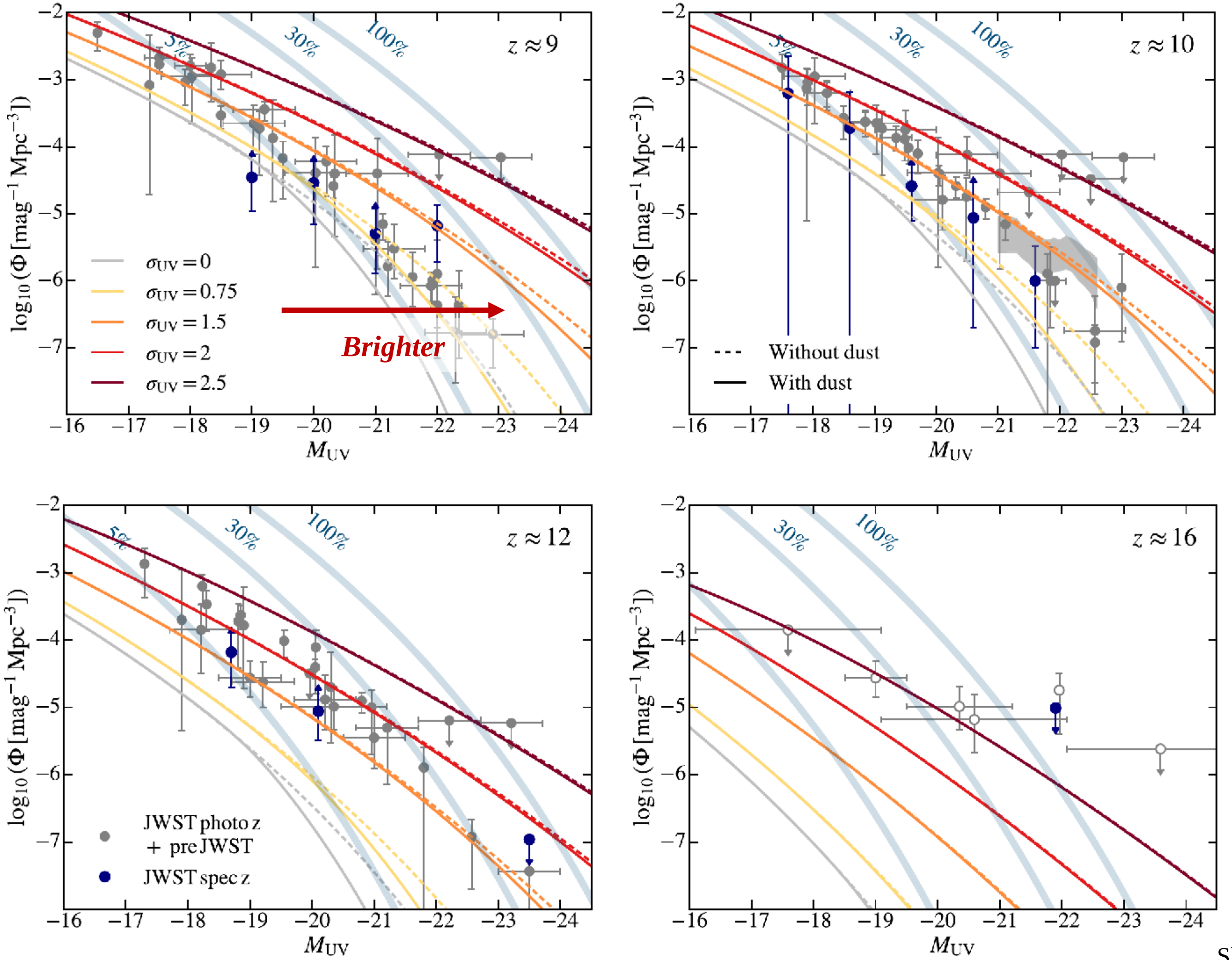
UV Luminosity Function

$$\Phi(M_{\mathrm{UV}})$$

Number of galaxies per unit volume of space, with UV magnitude between M_{UV} and $M_{UV} + dM_{UV}$: $\Phi(M_{\mathrm{UV}}).\mathrm{d}M_{\mathrm{UV}}$

UV magnitude is defined in terms of the luminosity at wavelength 150 nm (in the rest frame of the galaxy)

JWST has observed many bright galaxies at z ~ 9 – 16



Shen et al (2023), arXiv:2305.05679

High z measured photometrically, using Lyman-break technique.

Redshifts of some galaxies were later confirmed using spectroscopy.

These high-redshift galaxies are apparently much more numerous than expected from pre-JWST measurements at high-redshift.

Slide idea: Priyank Parashari, Ranjan Laha

Pre-JWST expectations

Low-redshift observations
Hubble, Spitzer observe galaxies at redshifts $\lesssim 10$

Reionization
First stars and galaxies produce UV radiation and ionize the neutral hydrogen.
Lyα forest tells us about reionization history

Hierarchical structure formation
Halos form *bottom-up* : smaller halos form first, larger halos form later.

At high z, we expect less halos to have collapsed/merged

Cosmological simulations
Predicts first stars: $z \sim 15 - 30$
First galaxies: $z \sim 15 - 30$

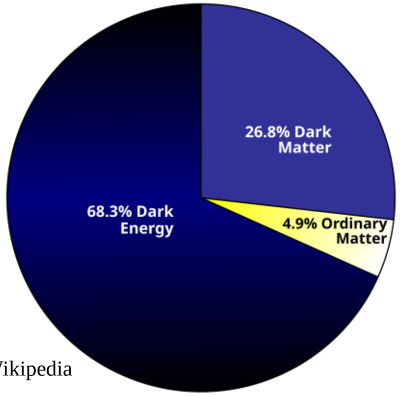
When we observe earlier galaxies with JWST, we find many more bright galaxies than we expected (extrapolated from pre-JWST models).

Proposed solutions:
Change the Astrophysical Models

Top-heavy initial stellar mass function	Yung et al., *MNRAS* 2024
Low dust attenuation in high-redshift galaxies	Ferrara et al., *MNRAS* 2023
Feedback-free starburst	Dekel et al., *MNRAS* 2023
Bursty star-formation and high variability	Shen et al., arXiv:2305.05679
Non-stellar sources of UV radiation	Inayoshi et al., *ApJL* 2022

What if, we instead changed the cosmological model?

Changing the Cosmological Model



Credit: Wikipedia

Energy budget of the ΛCDM model

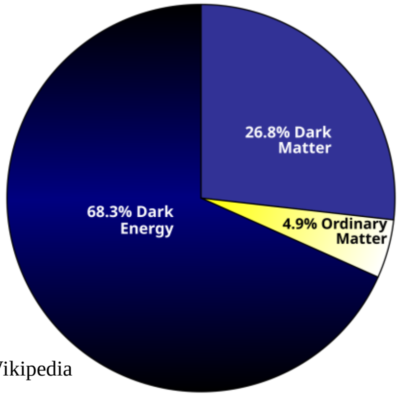
The standard ΛCDM model explains almost all observations on large scales. But it is not the perfect model –

- Tensions: H_0 tension, σ_8 tension
- Not quite satisfactory at smaller scales (core-cusp problem, missing satellites problem etc.)
- The two components (dark matter and dark energy) that make up **~95%** of the Universe have largely unknown properties.

Alterations to the ΛCDM model (some examples)

- Early Dark Energy (EDE)
- Warm Dark Matter (WDM)
- Self-Interacting Dark Matter (SIDM)
- Dark Matter - Standard Model interactions
- Modifying the Primordial Power Spectrum

Changing the Cosmological Model



Credit: Wikipedia

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Some of these models predict more galaxies at high redshifts (compared to ΛCDM)!

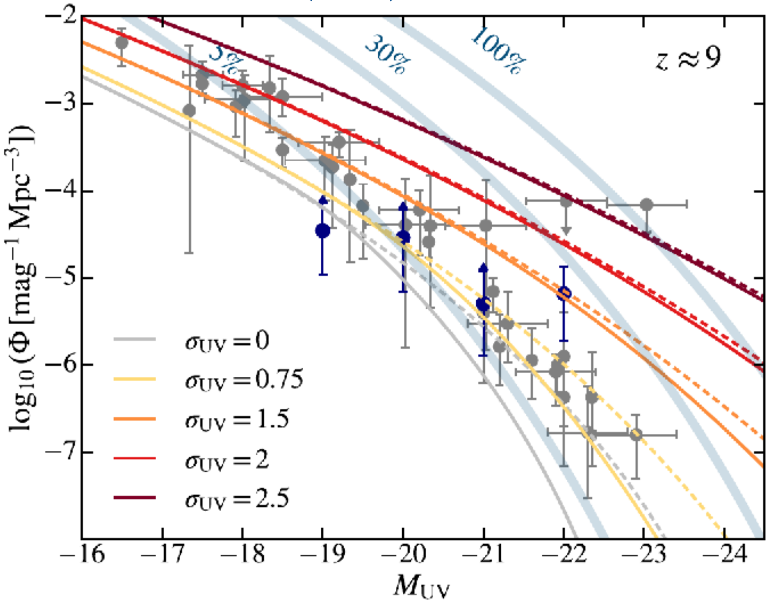
Do Early Galaxies contradict ΛCDM?

Likely not.

- Astrophysical uncertainties are large for early galaxies. Variability could be very important. (Shen et al. (2023), arXiv:2305.05679)

- Changing cosmology/matter power spectrum also changes other data at similar redshifts, e.g., HST data. (Parashari and Laha, *MNRAS* 526 (2023) 1, L63; Sabti, et al., *PRL* 132 (2024) 6, 061002)

Shen et al (2023), arXiv:2305.05679



Can we obtain new constraints on Dark Matter using Early Galaxies?

Alterations to the ΛCDM model

- Early Dark Energy (EDE)
- Warm Dark Matter (WDM)
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- Dark Matter - Standard Model interactions
- Modifying the Primordial Power Spectrum
- …

DM-proton interaction

DM-electron interaction

DM-photon interaction

DM-neutrino interaction

Dark Matter-Standard Model (DM-SM) interactions generically predict lesser number of early galaxies

Our Model: Dark Matter - Baryon scattering

DM scatters elastically with protons/electrons.
(For simplicity, consider only one interaction, say with electrons)

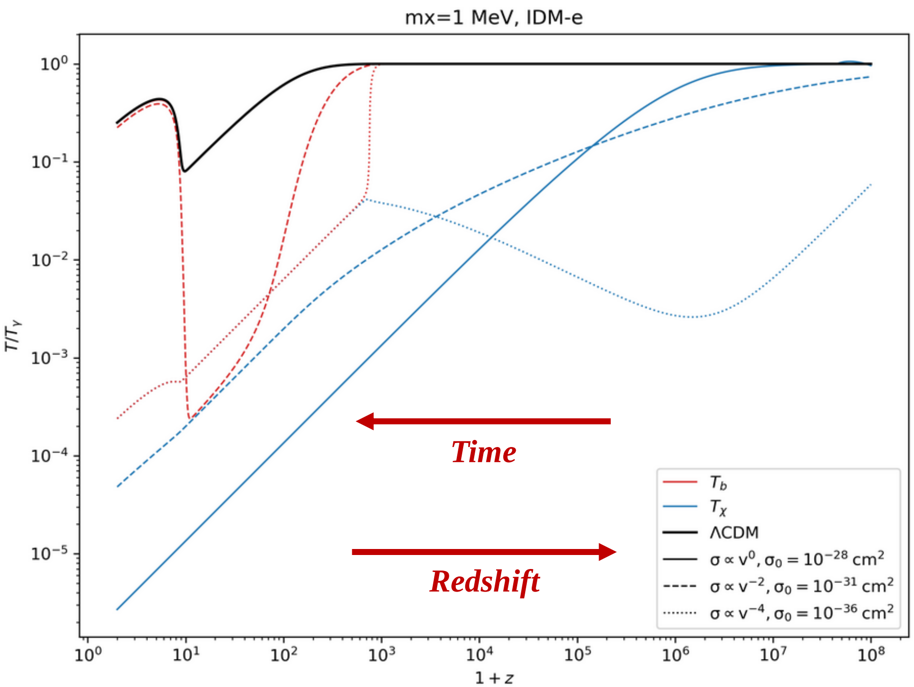
Momentum transfer: Effect of drag – DM can be pulled out of potential wells.

Heat transfer: DM can become warmer

Interaction cross-section: $\sigma = \sigma_n v^n$

- $n = 0$: Heavy-mediator/contact interaction
- $n = -1$: Yukawa potential
- $n = -2$: Dipole interaction
- $n = -4$: Light-mediator/long-range/Coulomb interaction

For $n > -3$, DM decouples from baryons at some high redshift ($z \gtrsim 10^4$).
For lower n, DM can recouple with baryons at low redshift (late Universe)

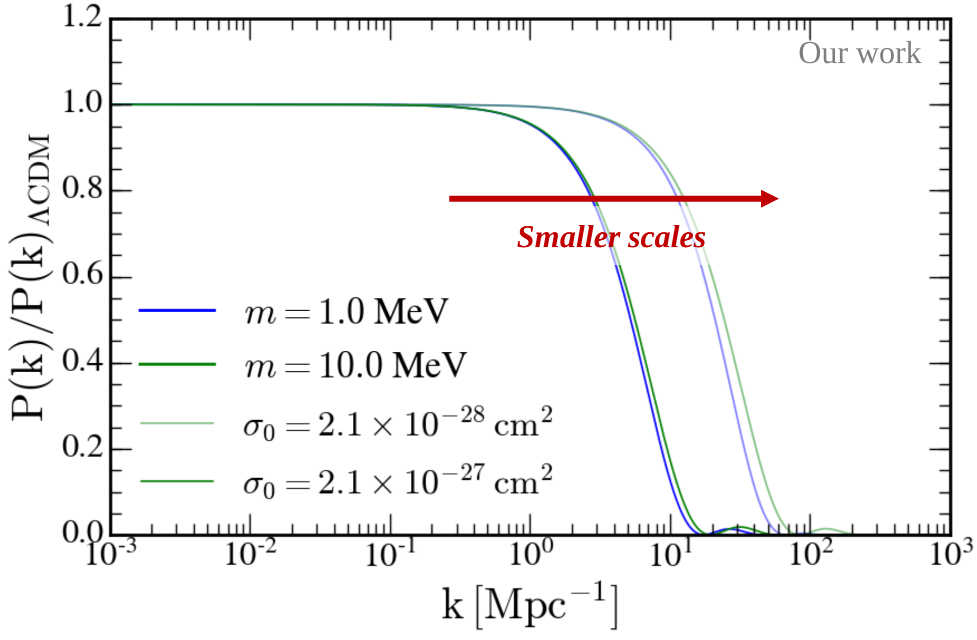


Our work (in progress)

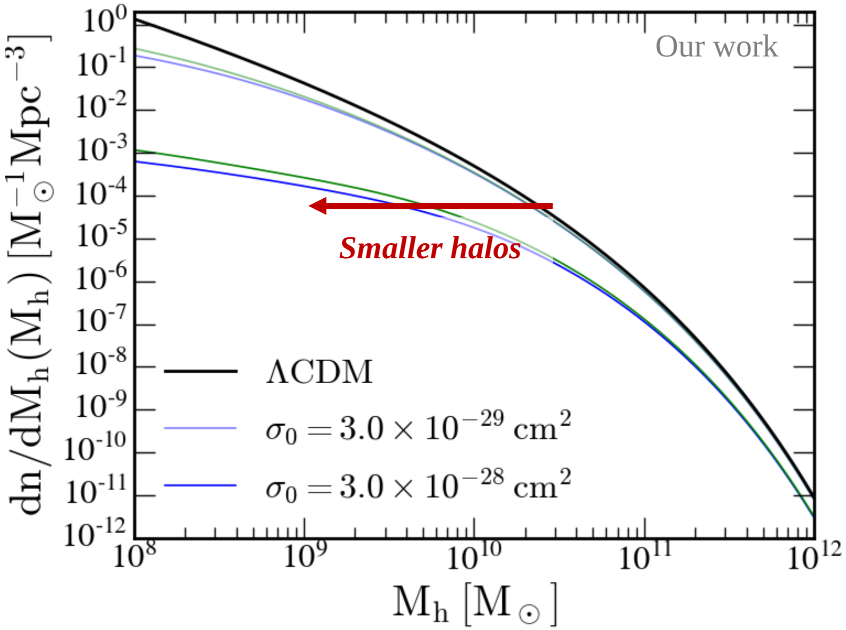
Example: Effect of DM-electron interaction on Cosmology

Assumption: Velocity-independent momentum-transfer cross-section

Matter power spectrum is suppressed at small scales by collisional damping



Hence, less number of small-mass halos



*Here ΛCDM indicates no DM-electron interaction

From Halo Mass to UV Luminosity

Halo mass

↓

Mass accretion rate

$$\dot{M}_{\rm halo} = C\left(\frac{M_{\rm halo}}{10^{12} M_\odot h^{-1}}\right)^{\gamma} \frac{H(z)}{H_0}$$

$$\gamma = 1.000 + 0.329a - 0.206a^2$$

$$\log_{10} C = 2.730 - 1.828a + 0.654a^2$$

↓

Star Formation Rate (SFR)

$$\mathrm{SFR} = \epsilon_\star \mathrm{f_b} \dot{\mathrm{M}}_{\rm halo}$$

$$\epsilon_\star(M_{\rm halo}) = \frac{2\epsilon_0}{(M_{\rm halo}/M_0)^{-\alpha} + (M_{\rm halo}/M_0)^{\beta}}$$

(Star Formation Efficiency)

↓

UV Luminosity

$$L_\nu^{\rm UV} = \frac{1}{\kappa_{\rm UV}} \mathrm{SFR}$$

$$\kappa_{\rm UV} = 0.72 \times 10^{-28}\ \mathrm{M_\odot.yr^{-1}.erg^{-1}.s.Hz}$$

↓

Dust-corrected UV luminosity

$$M_{\rm UV}^{\rm obs} = M_{\rm UV} + A_{\rm UV}$$

$$A_{\rm UV} = -0.34(21 + M_{\rm UV}^{\rm obs}) + 0.79$$

UV Variability – major factors

- Accretion rate of halo is not uniform
- Bursty star-formation: Star formation in short-lived ‘bursts’. Irregular, clumpy morphology (observed in high-z galaxies)
- Also, variable amount of dust

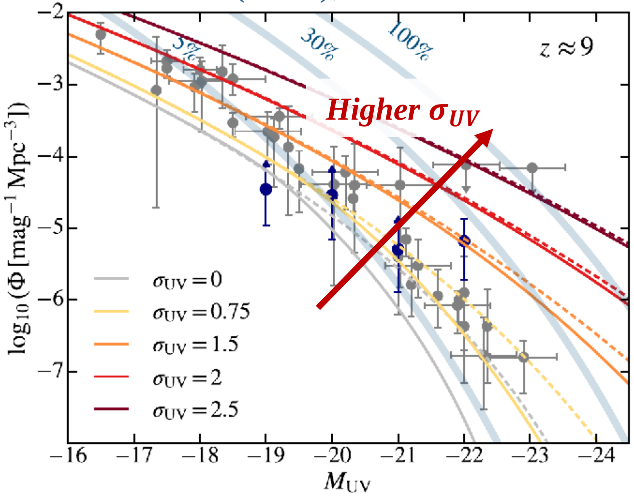
Combined effect: Log-normal spread in UV luminosity for a given halo mass

$$\text{Spread in } M_{\mathrm{UV}} \equiv \sigma_{\mathrm{UV}} \approx 0.5 - 2.0$$

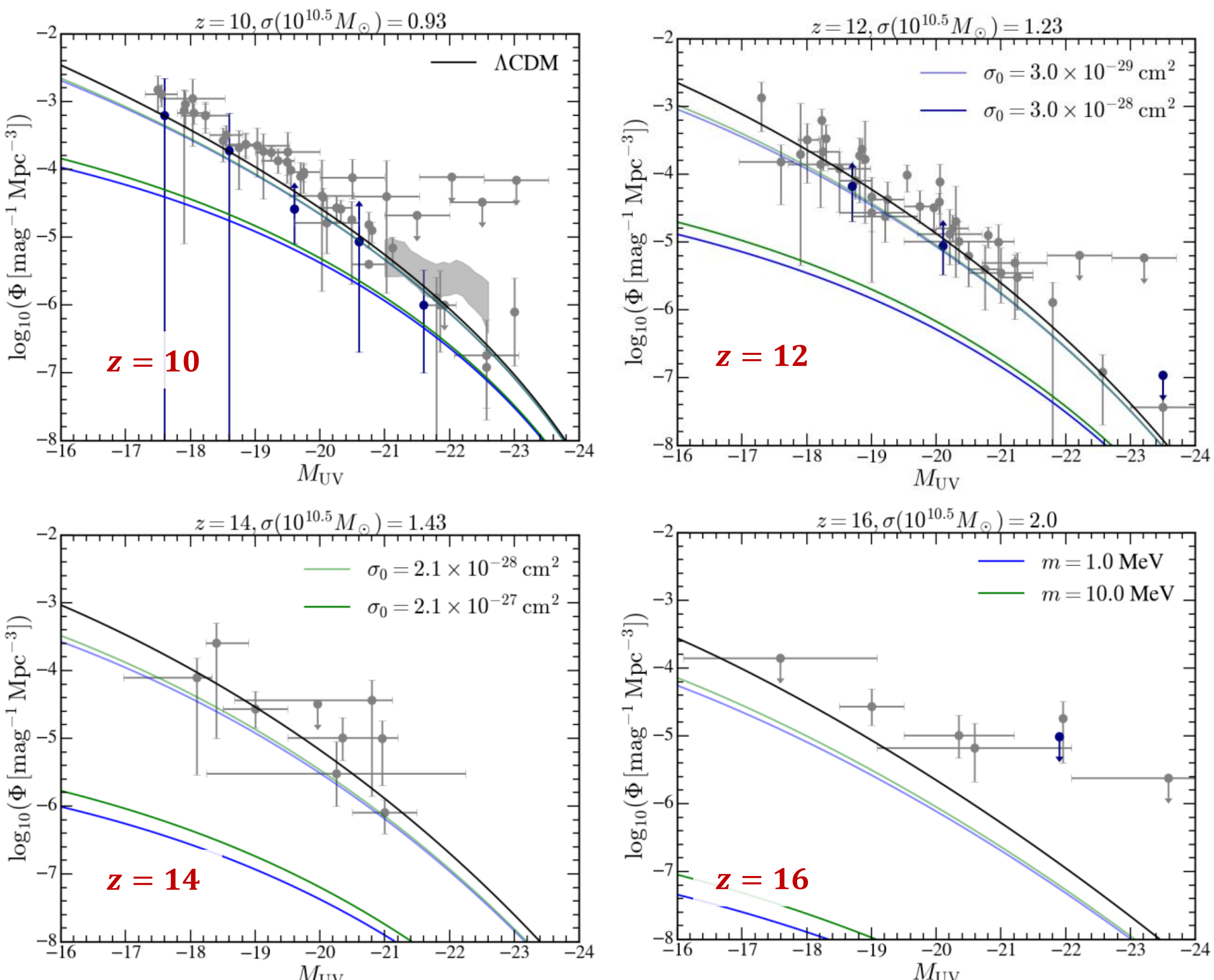
Variability leads to higher UV luminosity function!

This is simply because more low-mass galaxies are upscattered than high-mass galaxies down-scattered (HMF is monotonically decreasing function)

Shen et al (2023), arXiv:2305.05679



DM-SM interaction predicts less number of Early Galaxies!



Our work

We assume a benchmark astrophysical model at each redshift, and change the interaction cross-section.

Benchmark model chosen so that ΛCDM (with no interactions) fits the JWST data best.

Larger interaction cross-sections lead to more suppression of UVLF compared to ΛCDM.

Suppression stronger at higher redshifts.

Summary

1. JWST has observed more numerous early, bright galaxies than we expected.
2. Early galaxies may be accommodated by changing astrophysical models.
3. DM-SM interactions can suppress the power spectrum and halo mass function at the relevant scales.
4. We can get observable effects on the UVLF from DM-SM interactions, which allows us to get limits of interaction strengths.
5. UVLF at high z can be a new probe of DM properties.
6. Future JWST observations should improve such constraints.

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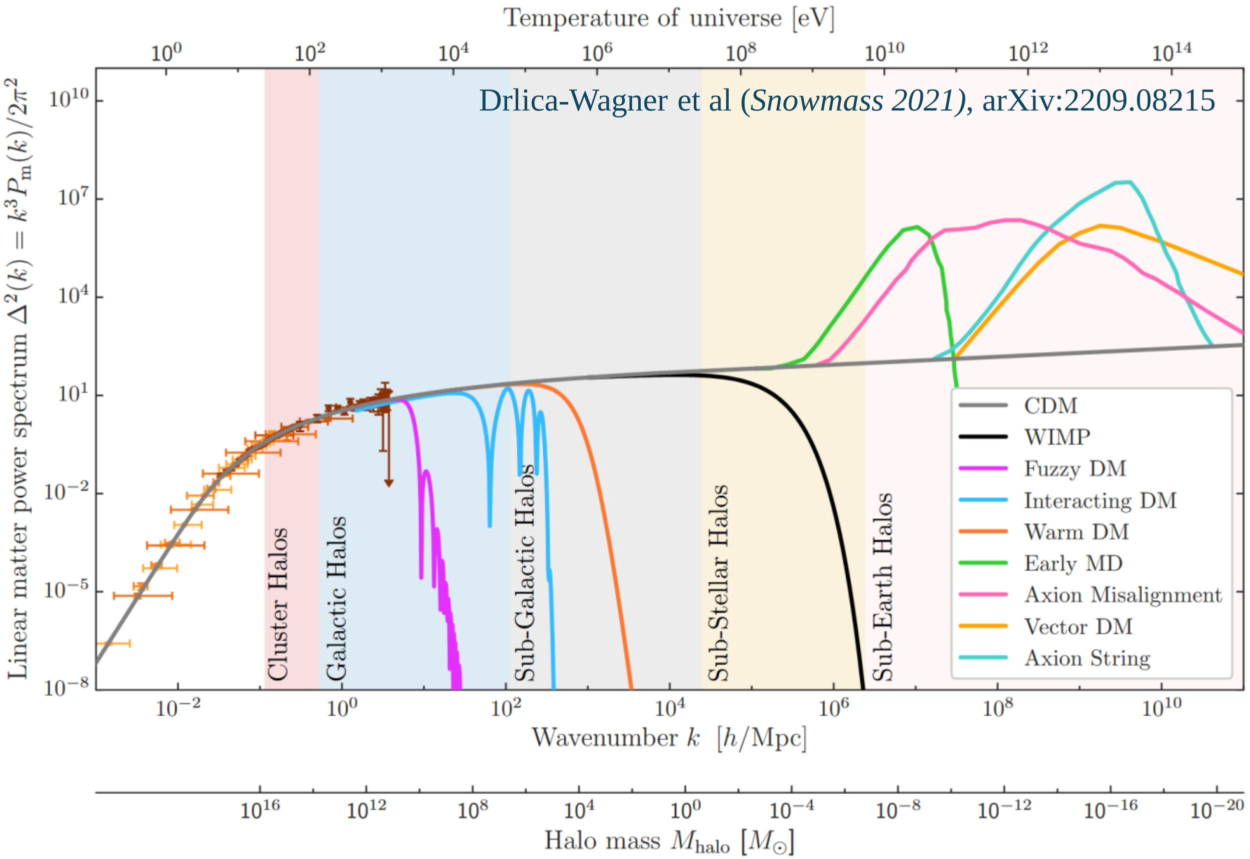
Power spectrum suppression

Typical processes involved in matter power spectrum suppression:

1. Free streaming: Dark matter such as WDM escapes from halos
2. Collisional damping Dark matter-baryon interaction prevents collapse

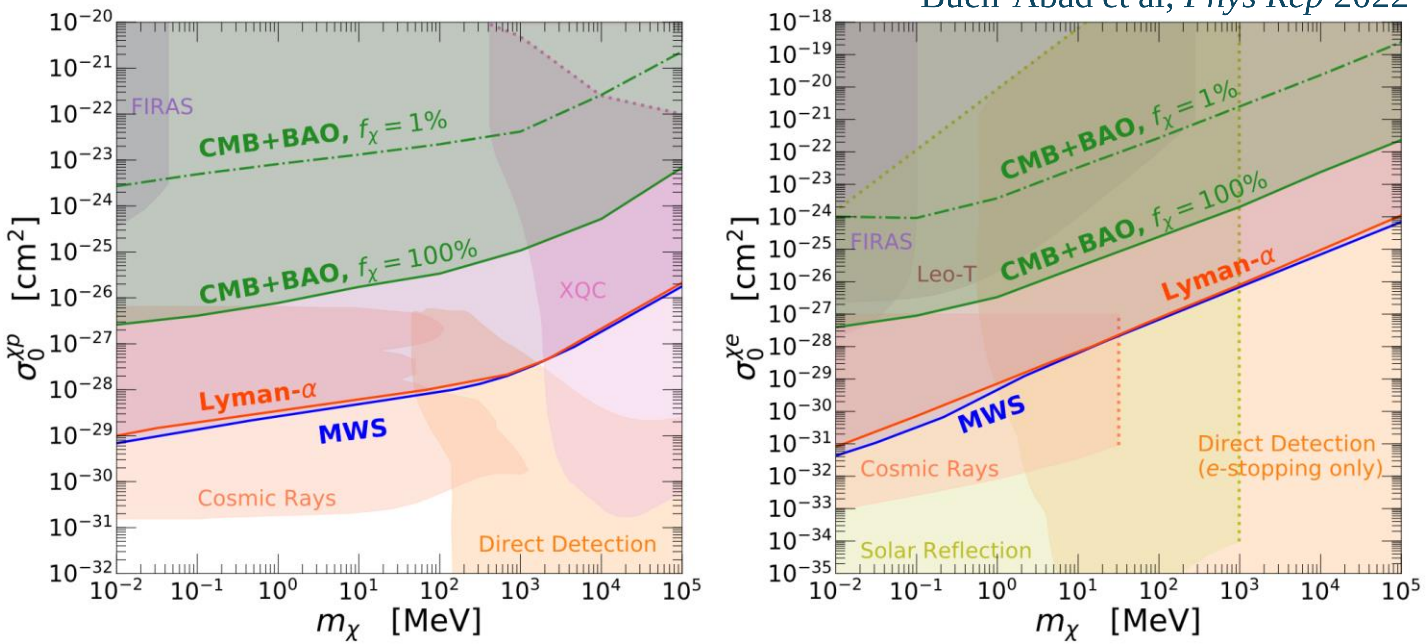
Both processes are stronger at smaller scales



Present limits on DM-baryon interaction

$$n = 0$$

Buen-Abad et al, *Phys Rep* 2022



DM-proton

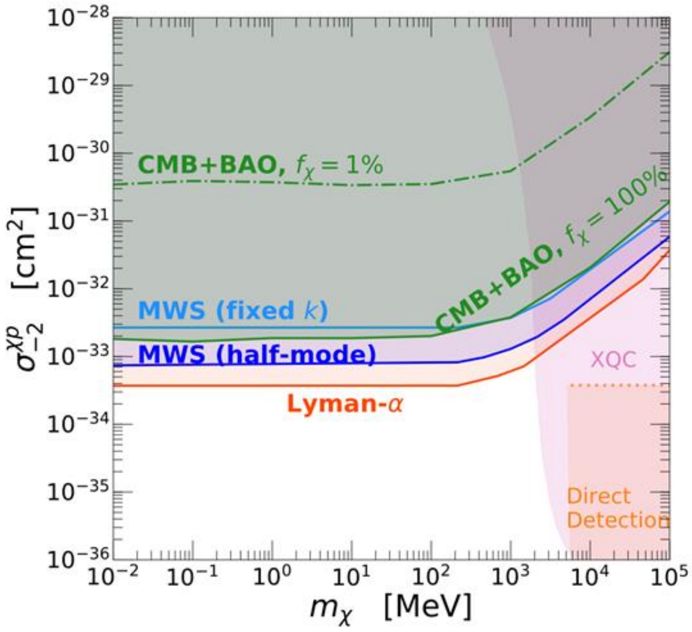
DM-electron

Our limits (in progress) will be close to Lyman alpha limits

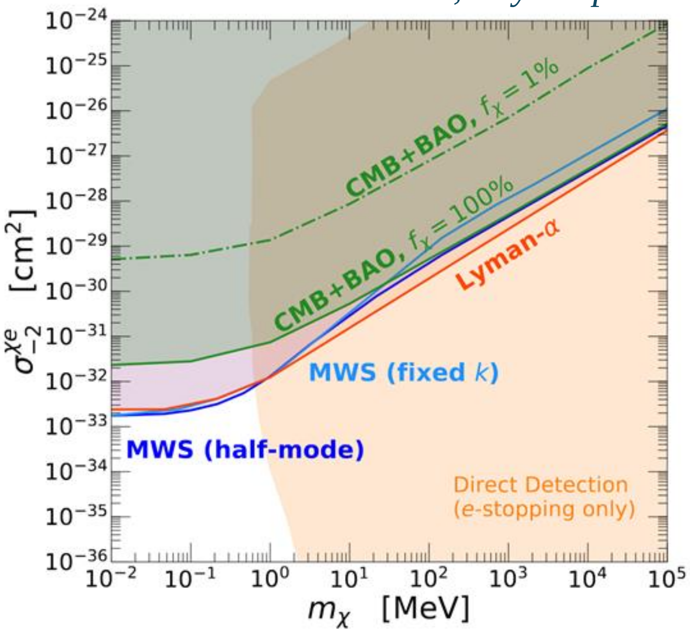
Present limits on DM-baryon interaction

$$n = -2$$

Buen-Abad et al, *Phys Rep* 2022



DM-proton



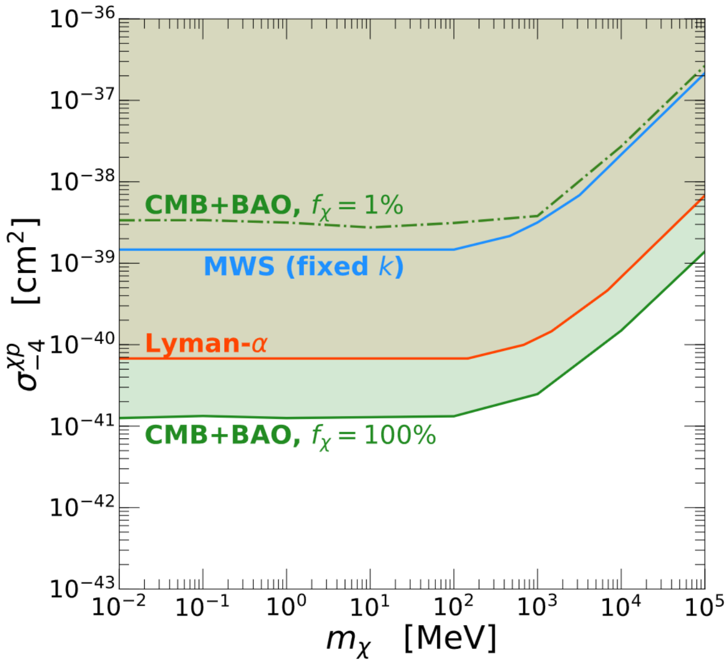
DM-electron

Our limits (in progress) will be close to Lyman alpha limits

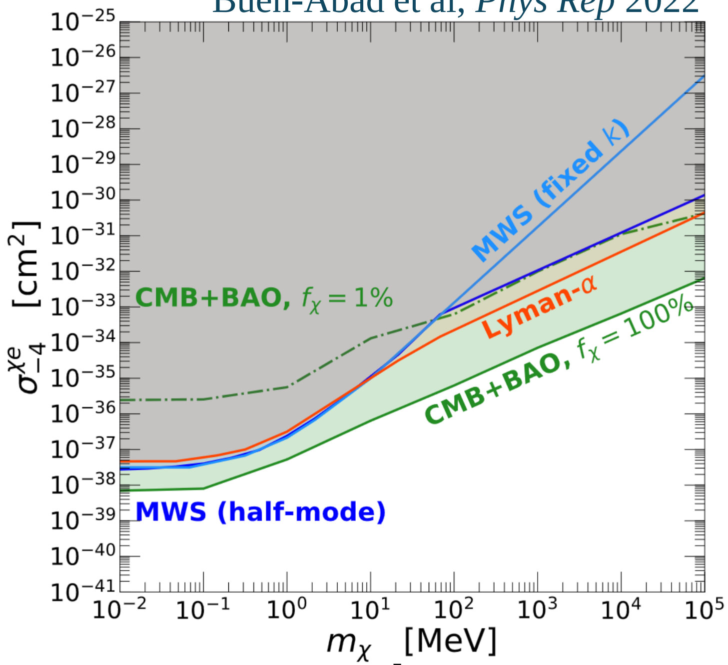
Present limits on DM-baryon interaction

$$n = -4$$

Buen-Abad et al, *Phys Rep* 2022



DM-proton



DM-electron

Our limits (in progress) will be close to Lyman alpha limits

Formalism: DM-electron Interaction

Continuity equation

$$\begin{cases} \dot{\delta}_\chi = -\theta_\chi + 3\dot{\phi} \\ \dot{\delta}_b = -\theta_b + 3\dot{\phi} \end{cases}$$

Euler equation

$$\begin{cases} \dot{\theta}_\chi = -aH\theta_\chi + k^2 c_\chi^2 \delta_\chi + R_{\chi-b}(\theta_b - \theta_\chi) + k^2\psi \\ \dot{\theta}_b = -aH\theta_b + k^2 c_b^2 \delta_b + R_{b-\chi}(\theta_\chi - \theta_b) \\ \qquad + R_{b-\gamma}(\theta_\gamma - \theta_b) + k^2\psi \end{cases}$$

Temperature evolution

$$\begin{cases} \dot{T}_\chi = -2aHT_\chi + 2R'_{\chi-b}(T_\gamma - T_\chi) \\ \dot{T}_b = -2aHT_b + 2R'_{b-\chi}(T_\chi - T_b) + 2R'_{b-\gamma}(T_\gamma - T_b) \end{cases}$$

Solved using ***`class_dmb`***

Interaction rate

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

Sound speed

$$c_i^2 = \frac{k_B T_i}{\mu}\left(1 - \frac{1}{3}\frac{\mathrm{d}\ln T_i}{\mathrm{d}\ln a}\right)$$

Halo Mass Function

Number of DM halos per unit mass interval per unit volume

$$\boxed{\frac{\mathrm{d}n}{\mathrm{d}\ln M} = M\frac{\rho_m}{M^2} f(\sigma(M)) \left|\frac{\mathrm{d}\ln\sigma}{\mathrm{d}\ln M}\right|}$$

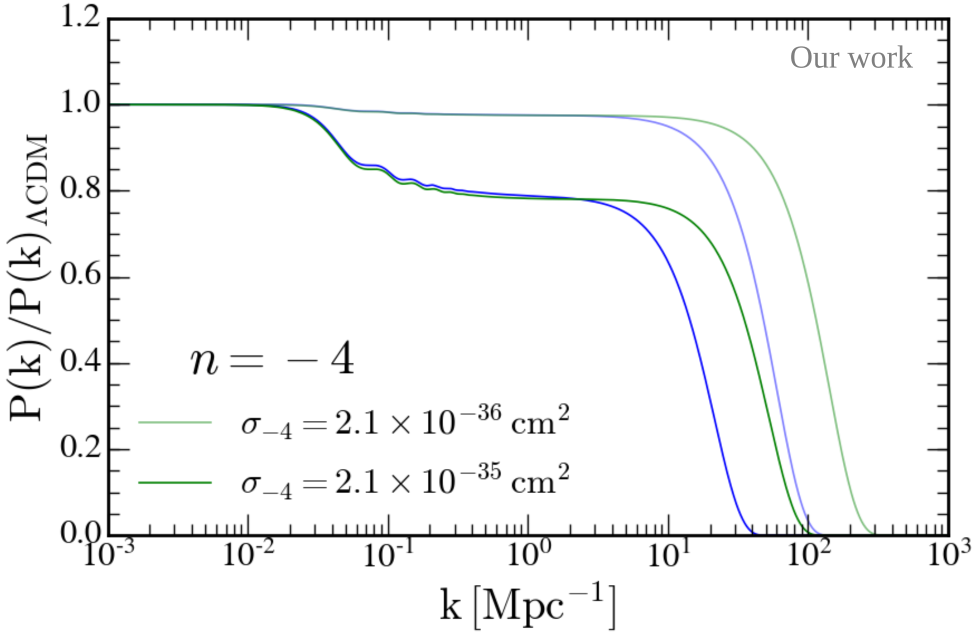
Sheth-Tormen fitting function: $f(\sigma) = A\sqrt{\frac{2a}{\pi}}\left[1+\left(\frac{\sigma^2}{a\delta_c^2}\right)^p\right]\frac{\delta_c}{\sigma}\exp\left(-\frac{a\delta_c^2}{2\sigma^2}\right)$

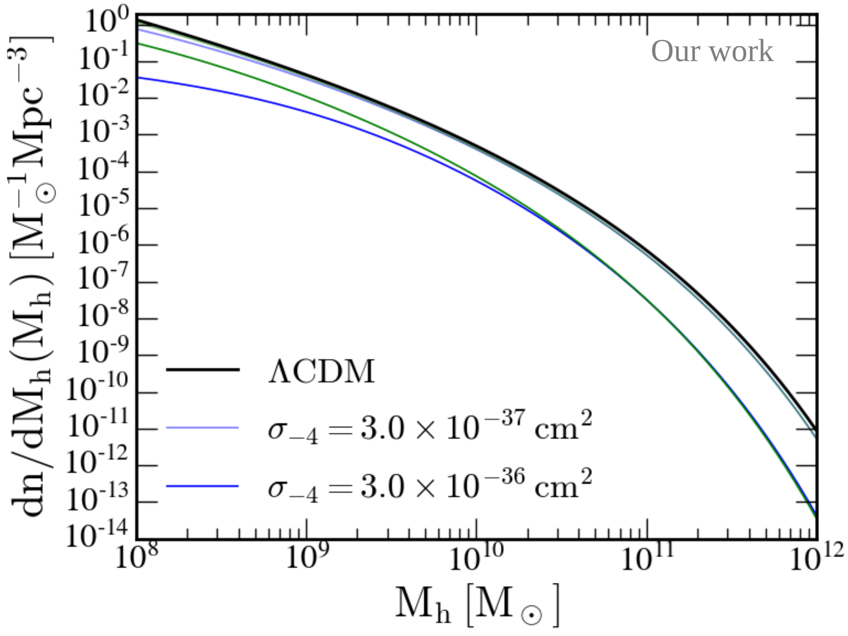
Variance of fluctuations: $\sigma^2(R) = \frac{1}{2\pi^2}\int_0^\infty \mathrm{d}k\, k^2 W^2(kR) P(k)$

Top-hat filter function: $W(kR) = \frac{3}{(kR)^3}(\sin(kR) - kR\cos(kR))$

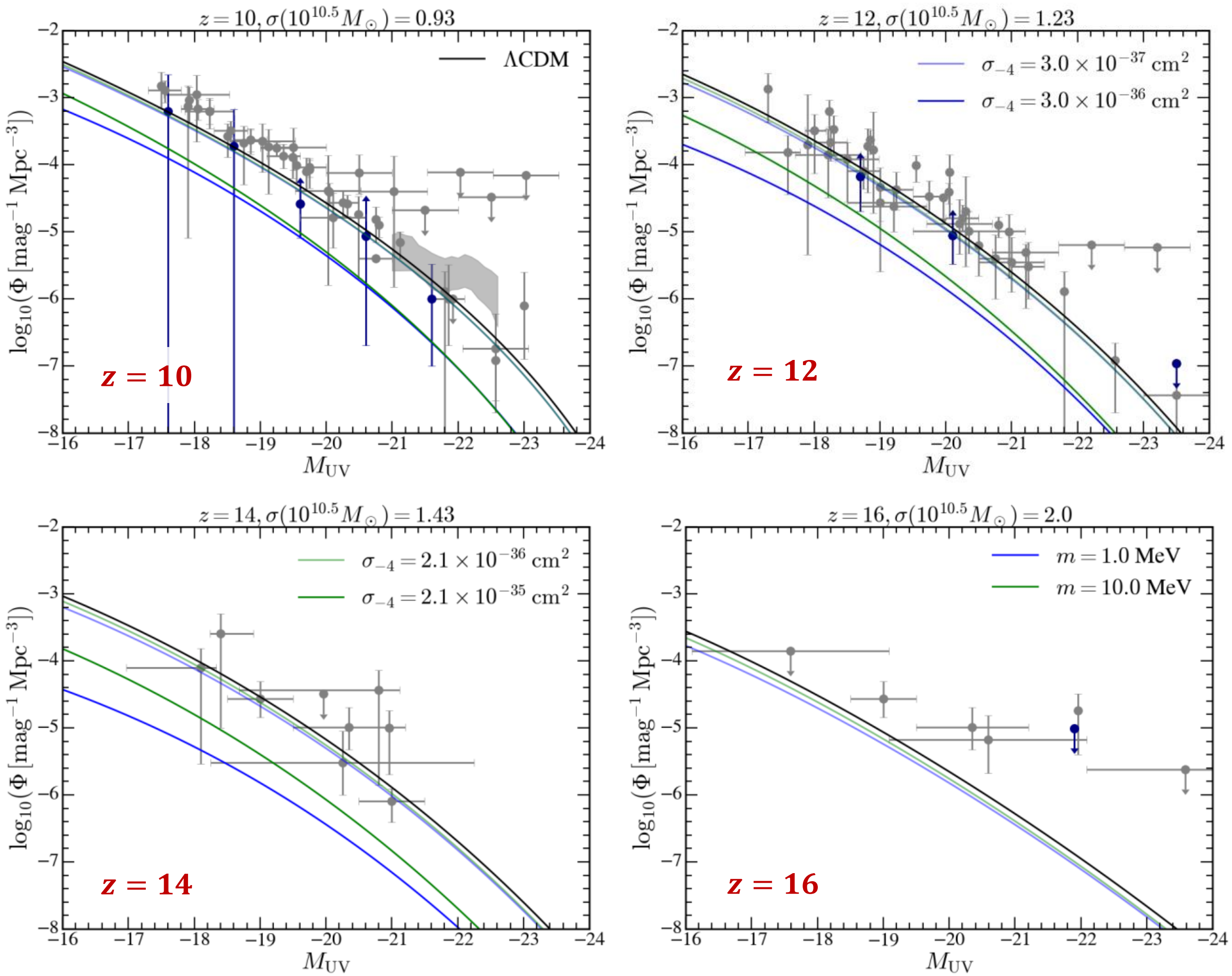
Effect of DM-electron interaction on Cosmology: *Coulomb-like* Interactions

$$\sigma \propto v_{\rm rel}^{-4}$$





Coulomb-like interactions and Early Galaxies



Our work