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Dark Secrets of Baryons: Illuminating Dark Matter-Baryon Interactions with JWST

Accepted in *Phys. Rev. Lett.*, arXiv:2511.02906

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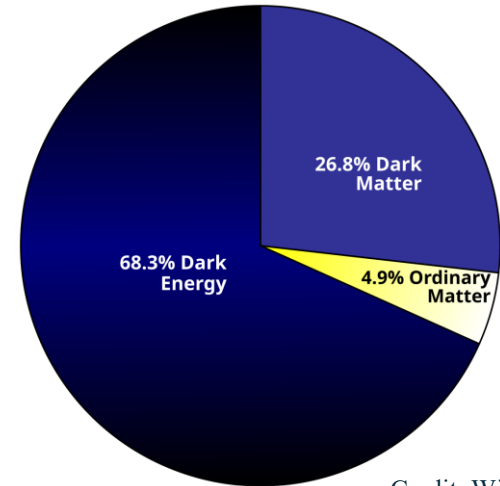
2026 Phenomenology Symposium
University of Pittsburgh, May 12, 2026

Outline

- Dark Matter and Galaxies
- What has the **James Webb Space Telescope (JWST)** seen?
- How we use JWST observations of early galaxies to probe DM-SM interactions
 - Methods
 - Results

Dark Matter

- Comprises 27% of the Universe
- Interacts via gravity
- Other interaction forces?

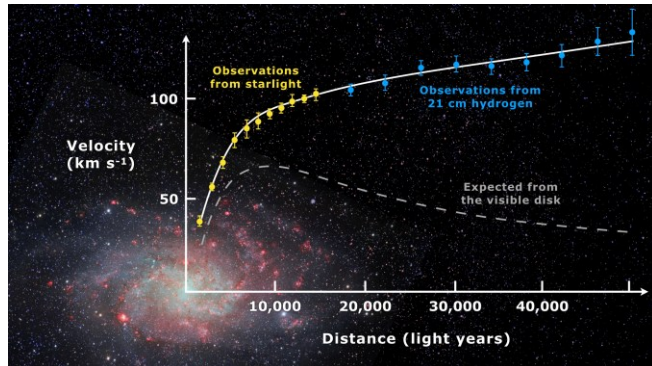


Credit: Wikipedia

Energy budget of the Λ CDM model

Evidence for Dark Matter

Rotation curves of galaxies are flat



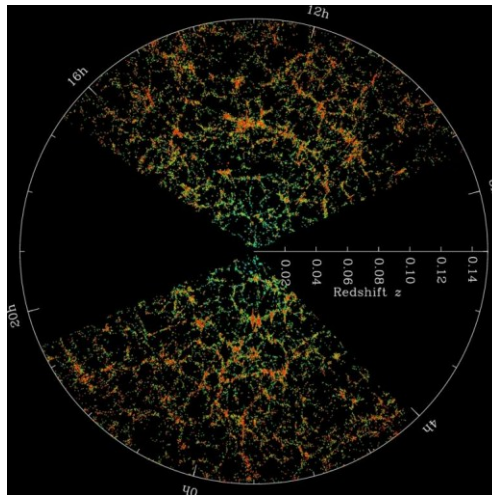
Wikipedia

Bullet cluster



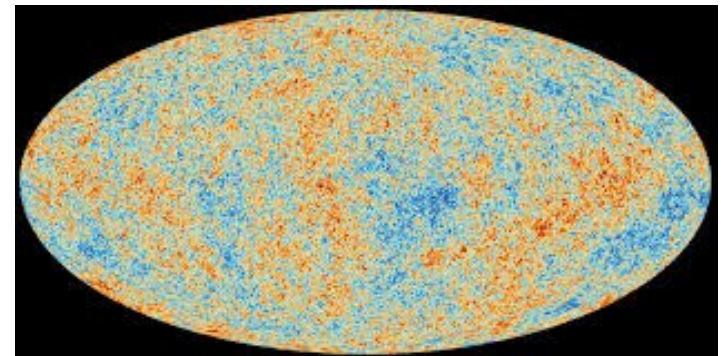
ESA

Large-Scale Structure

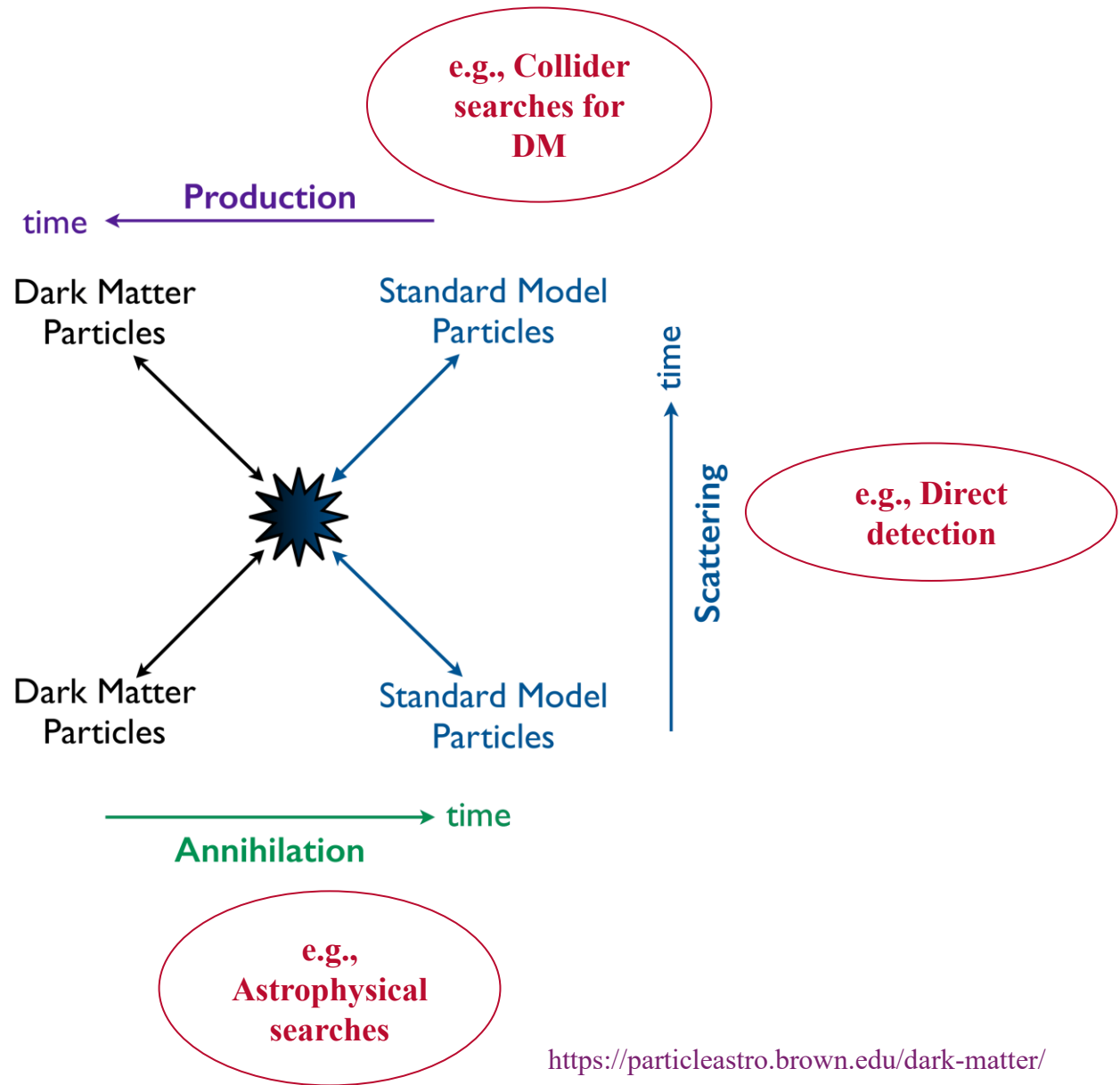


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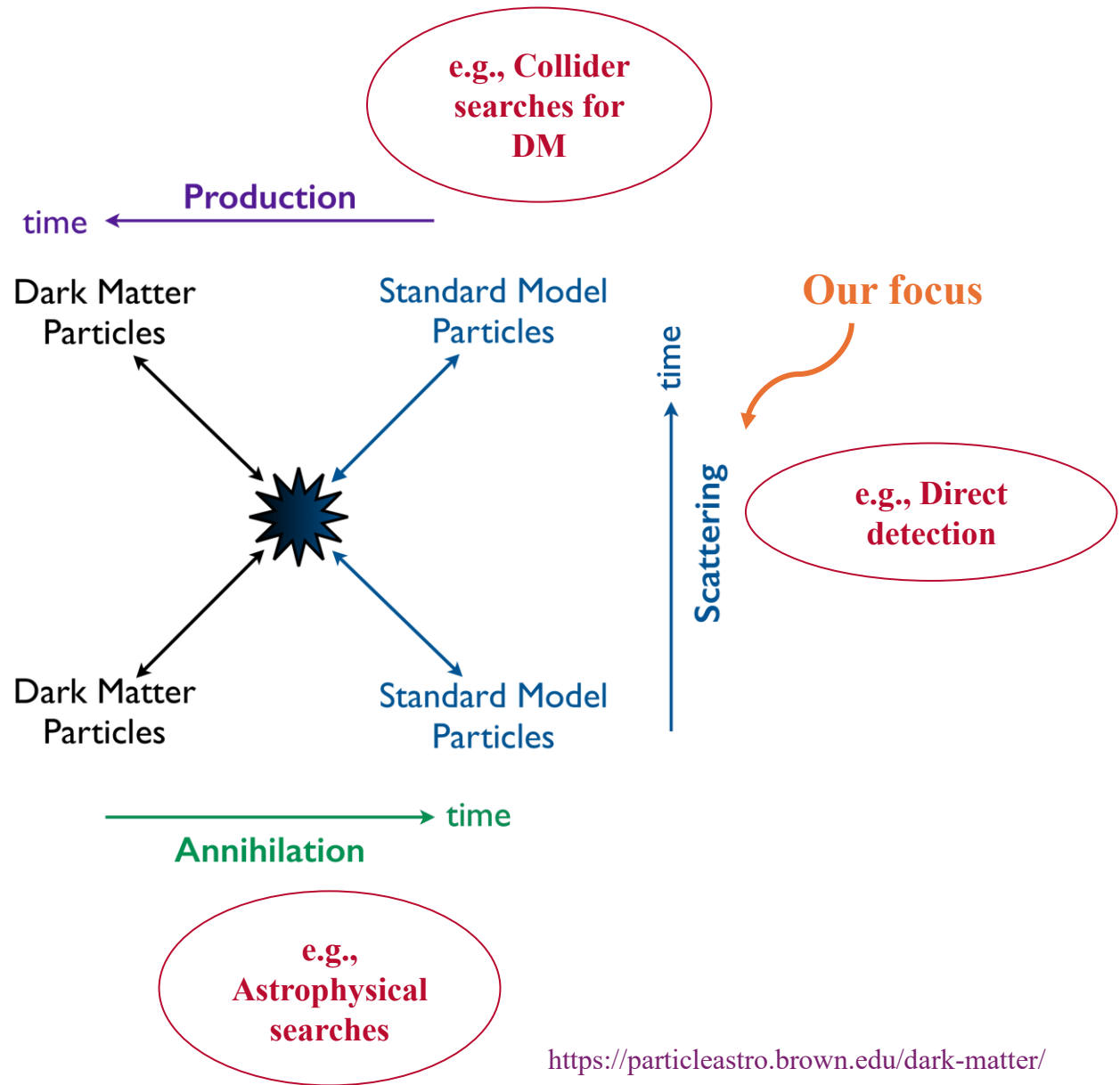
Cosmic Microwave Background



ESA/Planck



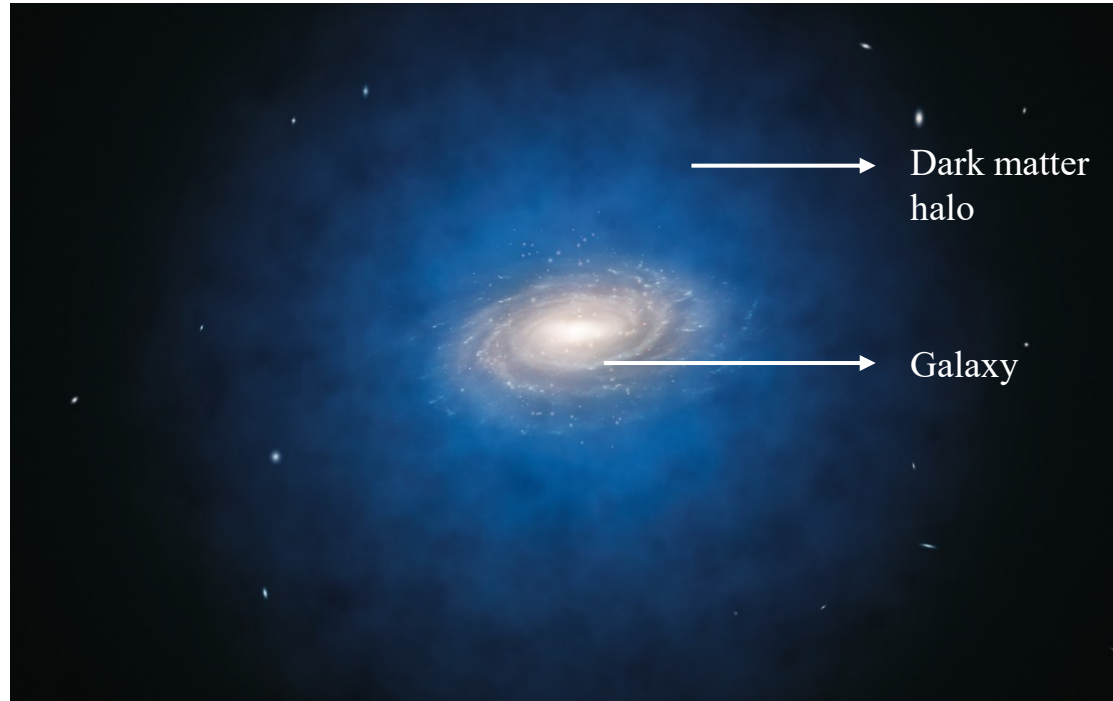
<https://particleastro.brown.edu/dark-matter/>



<https://particleastro.brown.edu/dark-matter/>

How does Dark Matter affect galaxies?

Dark Matter halos host galaxies



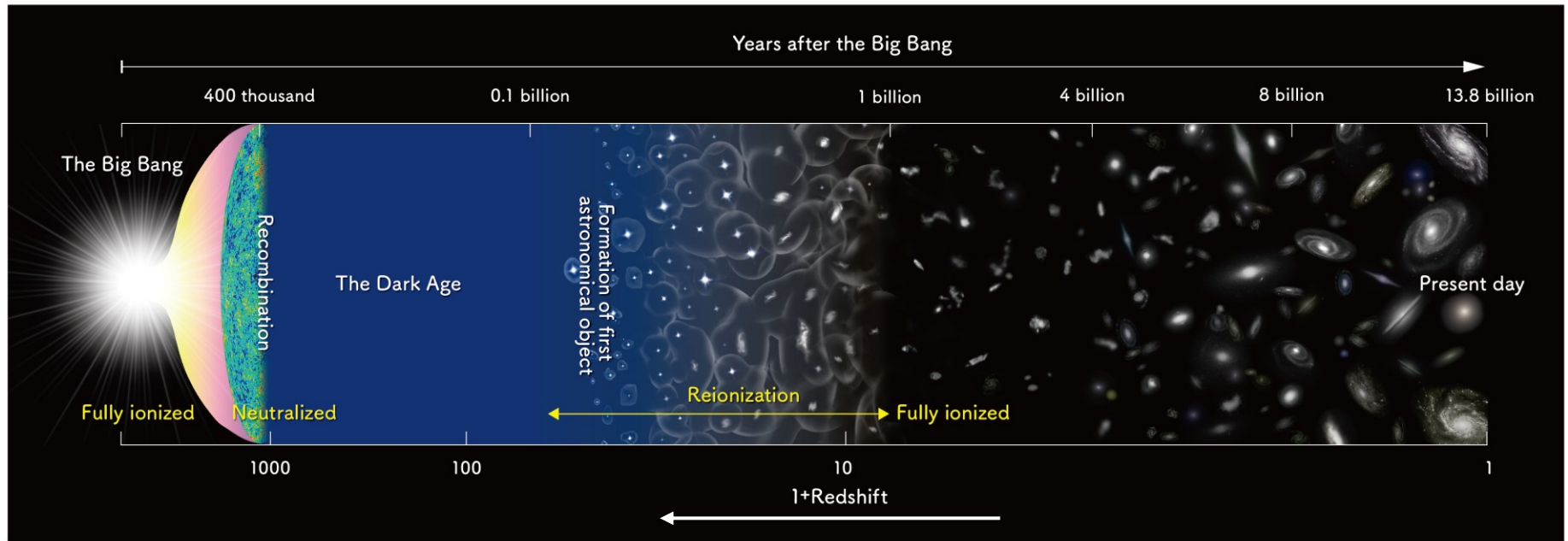
Credits: ESO

Galaxy formation requires Dark Matter

- Dark matter distribution in the early Universe has over- and under-densities (**perturbations**)
- Overdensities **collapse** into halos under gravity
- Halos **accrete baryonic matter** and form small galaxies
- They **grow into larger galaxies** by:
 - Accretion
 - Mergers

What has JWST Observed?

Cosmic Evolution



$$\lambda_{\text{obs}} = (1 + z)\lambda_{\text{emitted}}$$

Credits: NAOJ

High redshift \equiv Earlier in cosmological time

Star-forming galaxies emit Ultraviolet light

Luminosity of a young stellar population is dominated by high-mass stars which emit primarily in UV

UV emission traces star-formation

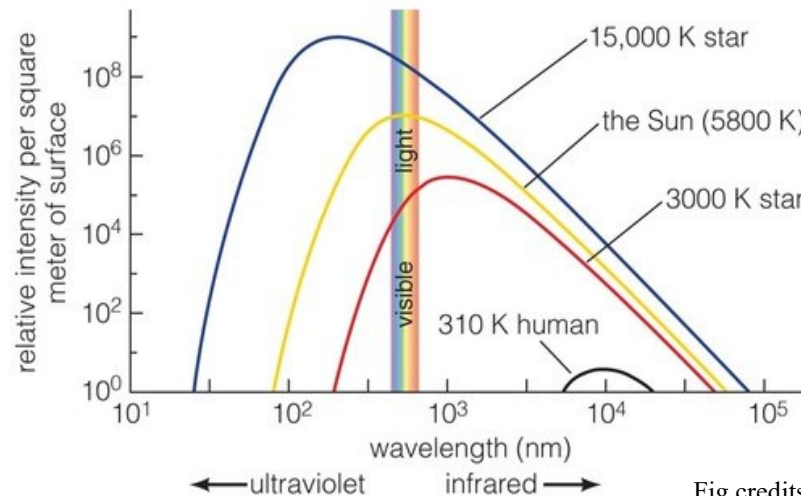


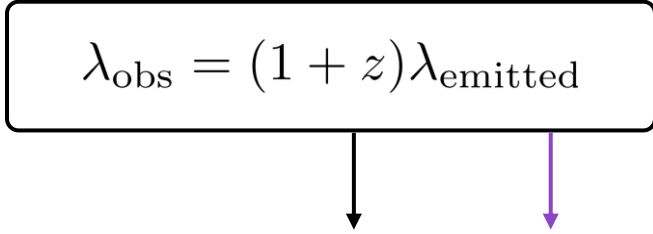
Fig credits: [SemanticScholar](#)

UV Luminosity

$L_{\nu,UV}$ is the specific luminosity (per unit frequency interval)
defined at a wavelength **150 nm** in rest-frame of the galaxy

Observed in infra-red for high-redshifts:

$$\lambda_{\text{obs}} = (1 + z)\lambda_{\text{emitted}}$$


$$1650 \text{ nm} = (1+10) \times 150 \text{ nm}$$

JWST and Early Galaxies



Credits: webbtelescope.org

James Webb Space Telescope

JWST has **discovered numerous early galaxies** at redshifts ≥ 12

For comparison, the farthest galaxy observed by Hubble is at $z = 11$

JWST has already observed galaxies at $z = 14$

(e.g., **MoM-z14, JADES-GS-z14-0**)

UV Luminosity Function (UVLF)

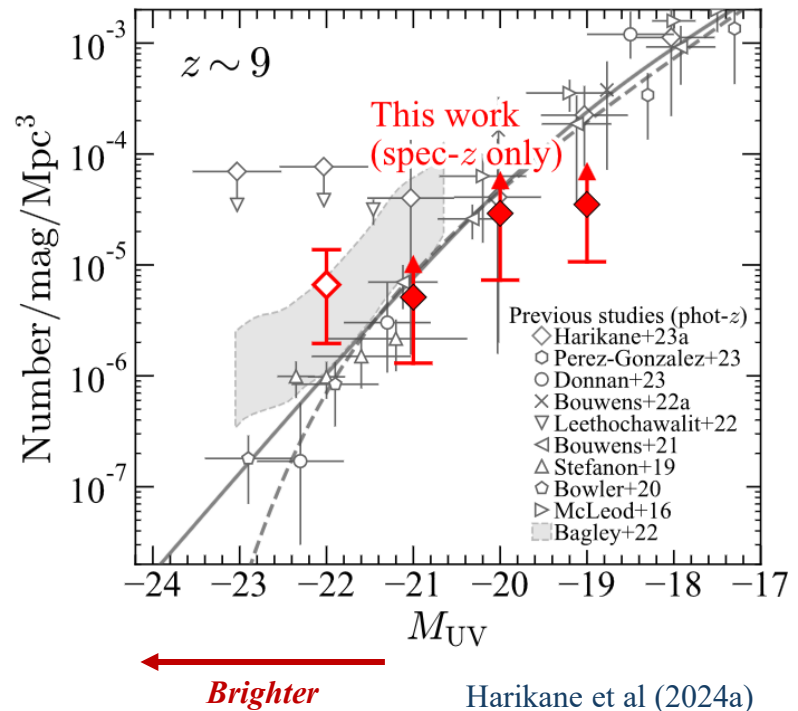
Quantifies the number density of galaxies

Number of galaxies:

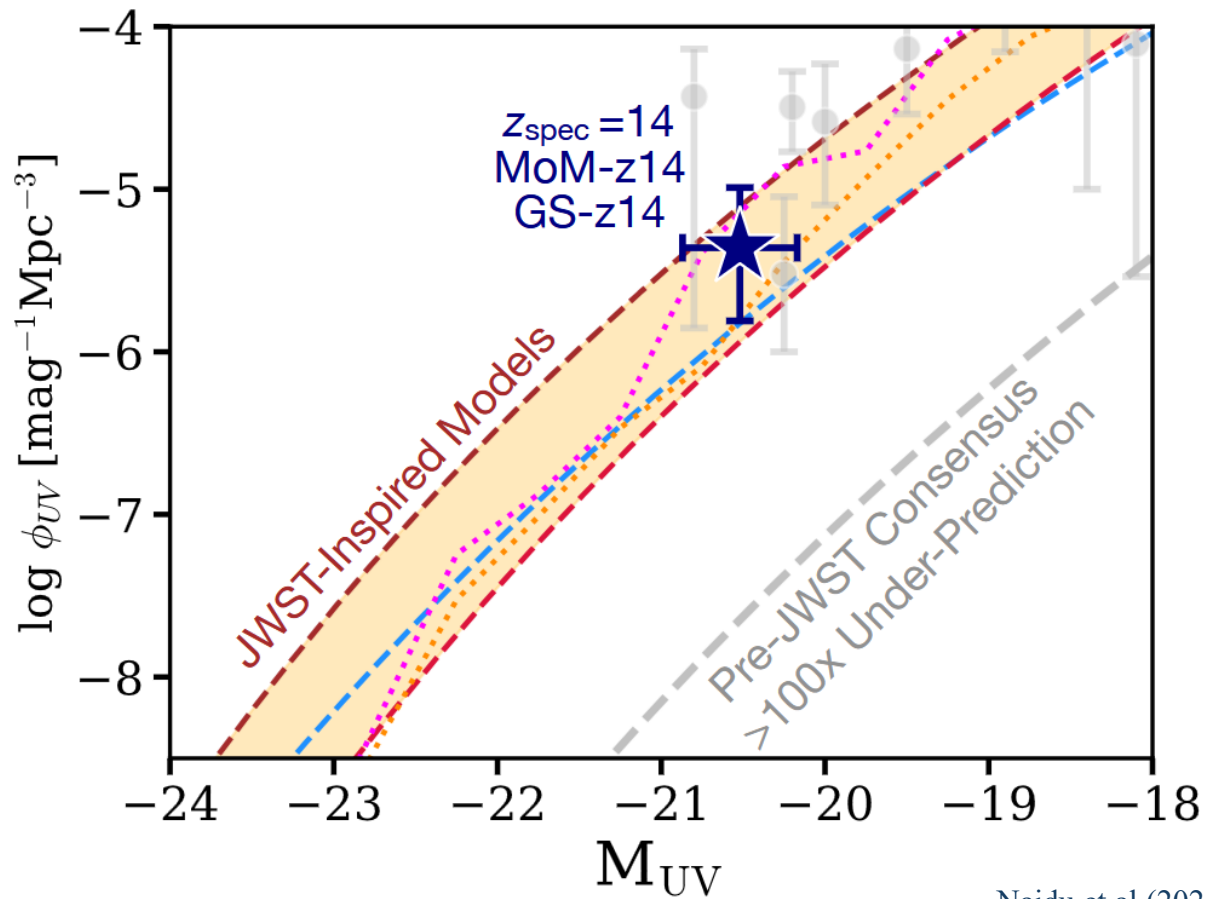
- per unit volume
- per unit interval of M_{UV}

$$dn = \phi_{UV}(M_{UV}, z)dM_{UV}$$

$$\log_{10} \left(\frac{L_{\nu}^{UV}}{\text{erg s}^{-1}} \right) = 0.4(51.63 - M_{UV})$$



Measurements of UVLF at high z



Naidu et al (2025)


Can we use these UVLF measurements to probe
the nature of Dark Matter?

DM Interaction with Standard Model

- Strength of non-gravitational DM-SM interactions **must be ‘very low’**.
- Such **interactions have been constrained** using various probes:
 - Direct detection
 - Indirect detection
 - From cosmological observables such as CMB or LSS

Our Model: Dark Matter - Baryon scattering

To a cosmologist,
both are 'baryons'



DM scatters elastically with **protons/electrons** due to a non-gravitational force.


For simplicity, consider only one interaction, say with protons

1. **Momentum transfer:** Drag force on DM
2. **Heat transfer:** DM becomes warm-*ish*

Cross-section in phenomenological models

[Cross section] [velocity-dependence]

$\sigma \propto v^0$  **Contact interactions**, Interactions via heavy mediator

$\sigma \propto v^{-2}$  Electric *dipole-like* interactions

$\sigma \propto v^{-4}$  *Coulomb-like* interactions, Interactions via ultralight mediator

We look at velocity dependences $n = 0, -2, -4$ in our work

Methods

1. Fluid Equations for Dark Matter

Start with density fluctuations

$$\delta := \frac{\delta\rho}{\bar{\rho}}, \quad \theta := \nabla \cdot \mathbf{v}$$

Density contrast

Divergence
of velocity

Continuity $\dot{\delta}_\chi = -\theta_\chi + 3\dot{\phi}$

Pressure term: DM
is no longer cold

Momentum
transfer

Euler $\dot{\theta}_\chi = -aH\theta_\chi + k^2 c_\chi^2 \delta_\chi + R_{\chi-b}(\theta_b - \theta_\chi) + k^2 \psi$

Heat Flow $\dot{T}_\chi = -2aHT_\chi + 2R'_{\chi-b}(T_\gamma - T_\chi)$

Heat transfer

Power Spectrum

Define the matter power spectrum (2-point correlation function):

$$\langle \delta_m(\mathbf{k}, z) \delta_m(\mathbf{k}', z) \rangle = \delta_D(\mathbf{k} + \mathbf{k}') P_m(k, z)$$

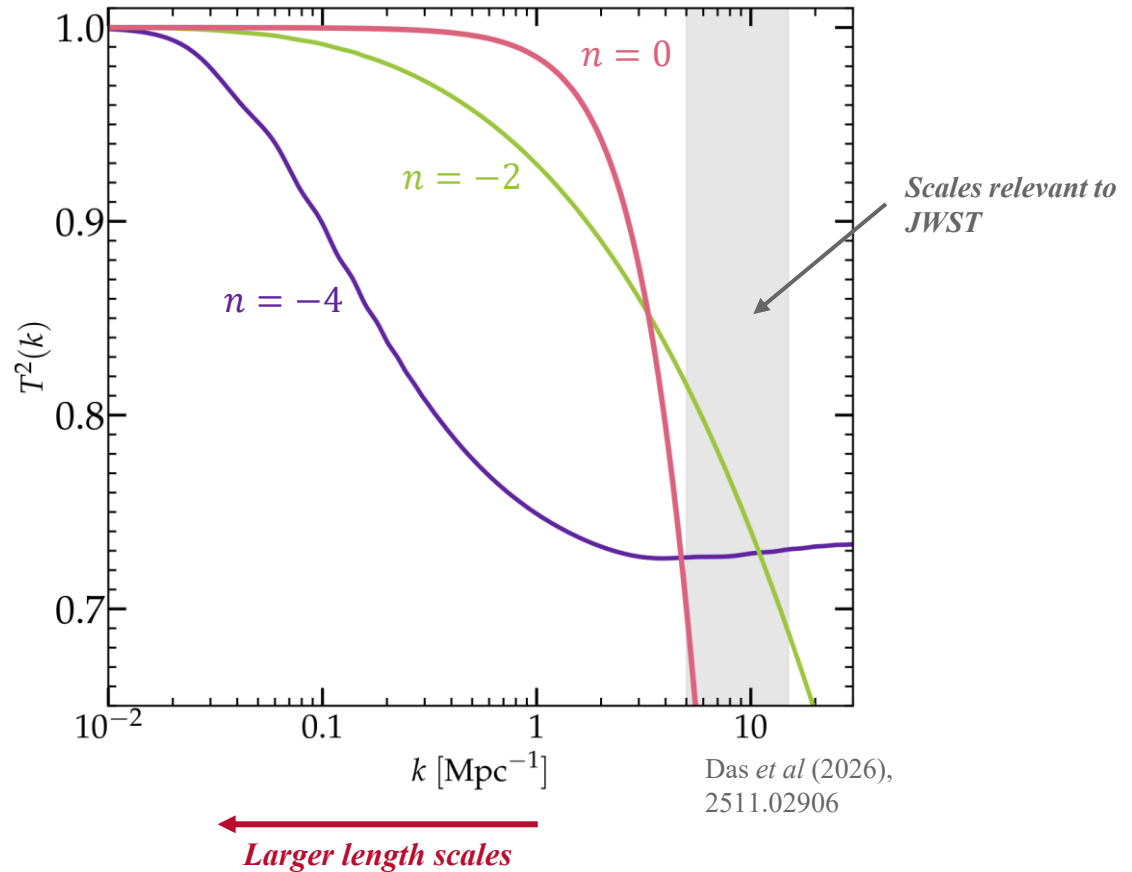
Quantifies the ‘strength’ or ‘power’ of density fluctuations at a given scale

DM-baryon interaction will thus suppress $P(k)$ at large k

Suppression of small-scale structure

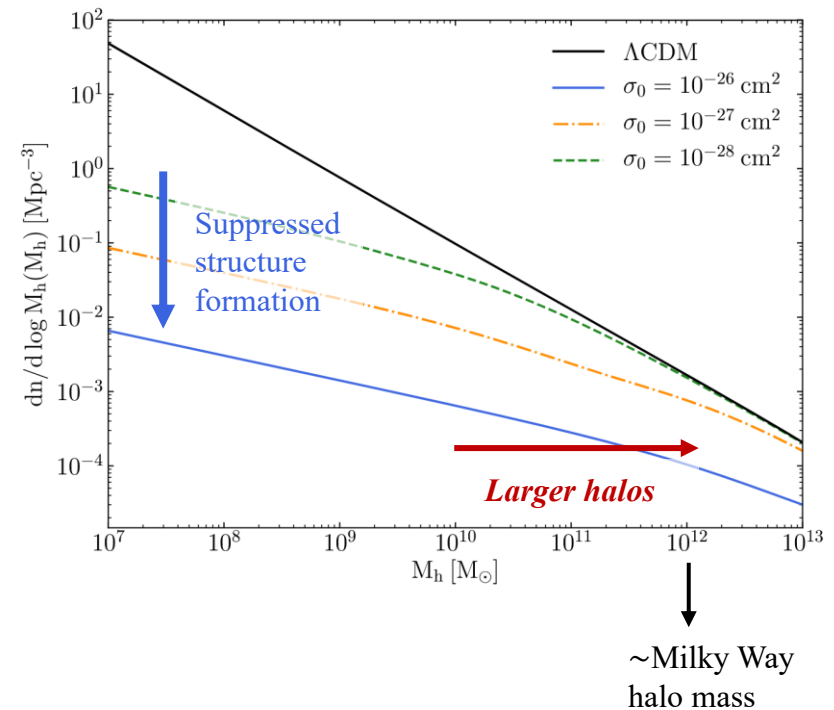
$$T^2(k) = \frac{\boxed{P(k)}}{\boxed{P(k)_{\Lambda\text{CDM}}}}$$

Interacting DM
No interactions



2. Halo Mass Function

- Halo Mass Function (HMF) is the distribution of DM halos in the space of halo masses.
- Defined as the number of DM halos:
 - per unit volume
 - per unit interval of halo mass
- Calculating the HMF: extended Press-Schechter formalism
- Top-hat window function, Sheth-Tormen fitting function



3. From Halo Mass to UV Luminosity

Empirical astrophysical models

Halo mass

Mass accretion rate

$$\frac{\dot{M}_h}{M_\odot \text{ yr}^{-1}} = \beta(z)(M_{h,12}E(z))^{\alpha(z)},$$

$$\alpha(z) = 0.858 + 1.554a - 1.176a^2$$

$$\log \beta(z) = 2.578 - 0.989a - 1.545a^2$$

Star Formation Rate (SFR)

$$\text{SFR} = \text{SFE} \cdot f_b \cdot \dot{M}_h$$

$$\epsilon_\star(M_h) = \frac{\epsilon_0}{(M_h/M_0)^{-\alpha_\star} + (M_h/M_0)^{-\beta_\star}}$$

UV Luminosity

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

$$\kappa_{\text{UV}} = 0.72 \times 10^{-28} \text{ M}_\odot \cdot \text{yr}^{-1} \cdot \text{erg}^{-1} \cdot \text{s} \cdot \text{Hz}$$

Chabrier IMF

Dust-corrected UV luminosity

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

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

UV Variability / Stochasticity

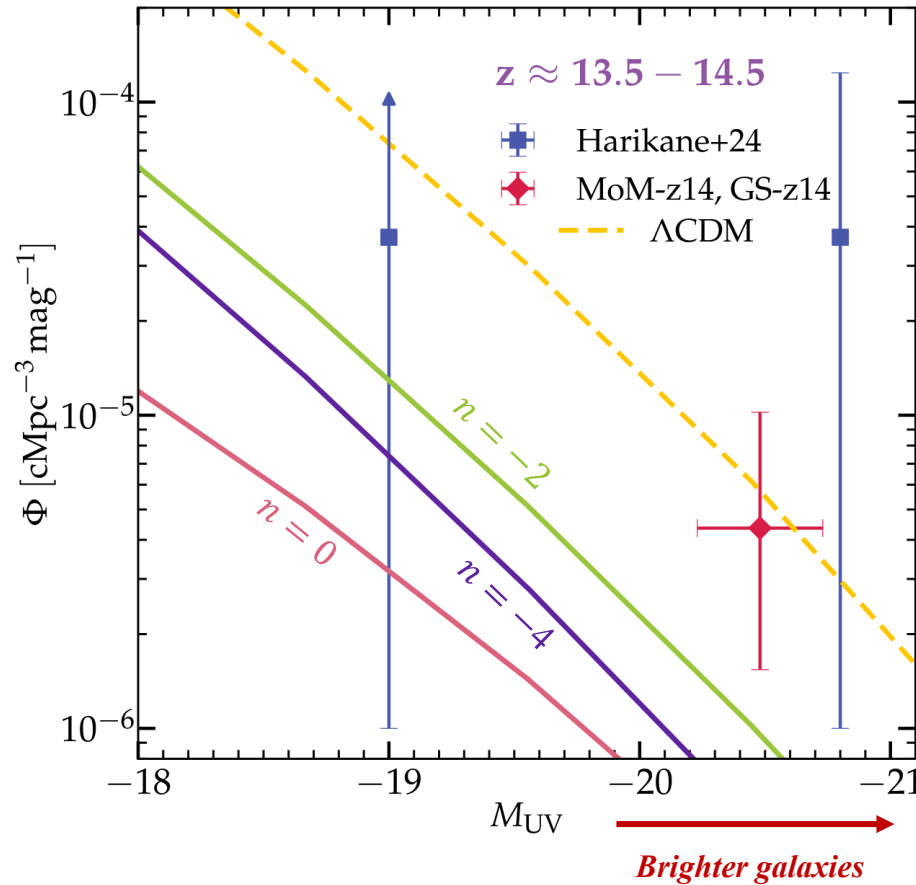
If astrophysics was deterministic: *One-to-one* relation between halo mass and luminosity

- Star-formation can be **bursty** instead of continuous.
- Mass accretion rate and dust can vary stochastically

One-to-one relation is broken: Magnitude is distributed over some median value

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

Suppression of Galaxy UV Luminosity Function



Das *et al* (2026),
2511.02906

Obtaining constraints on the DM-baryon interactions

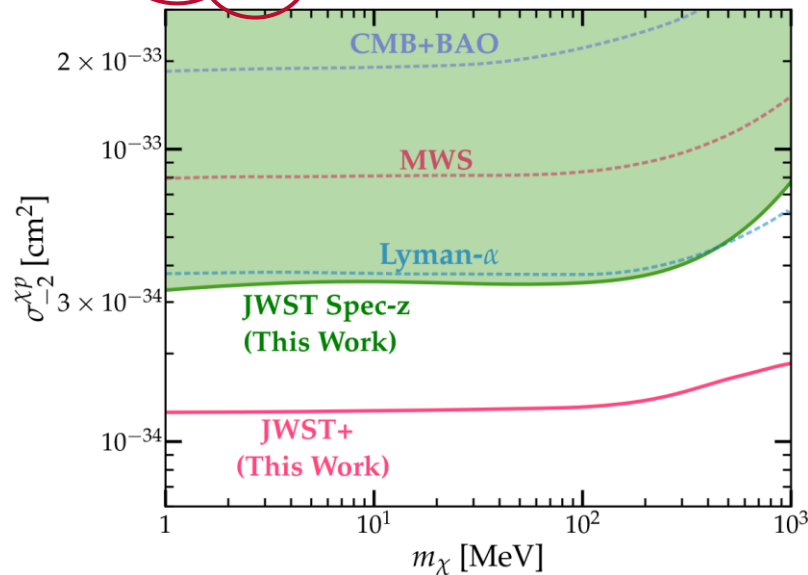
Large cross-sections above a certain cutoff are ‘disfavoured’ by the JWST data

To calculate this cutoff value, we vary cosmological and astrophysical parameters, including the cross-section, and sample the posterior using the MCMC sampler **MontePython**

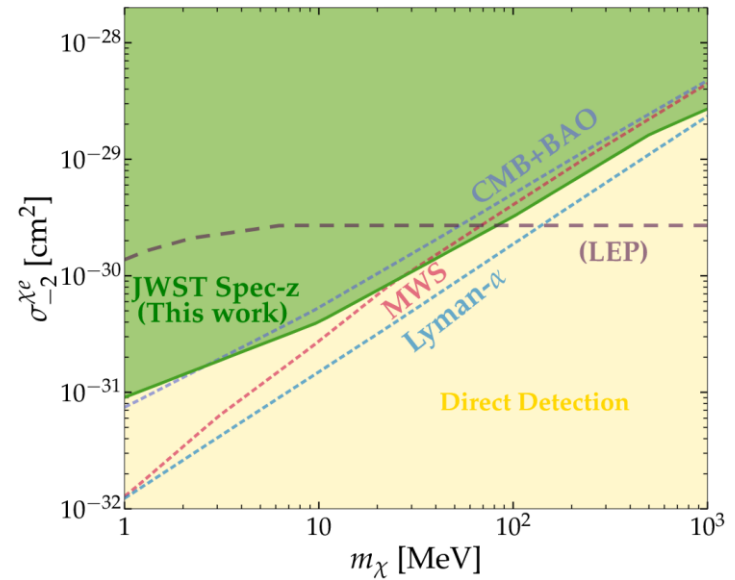
Constraints on 'Dipole-like' Interactions

Strongest constraints till date

$$\sigma_{\chi B} \propto v^{-2}$$



DM-proton interaction



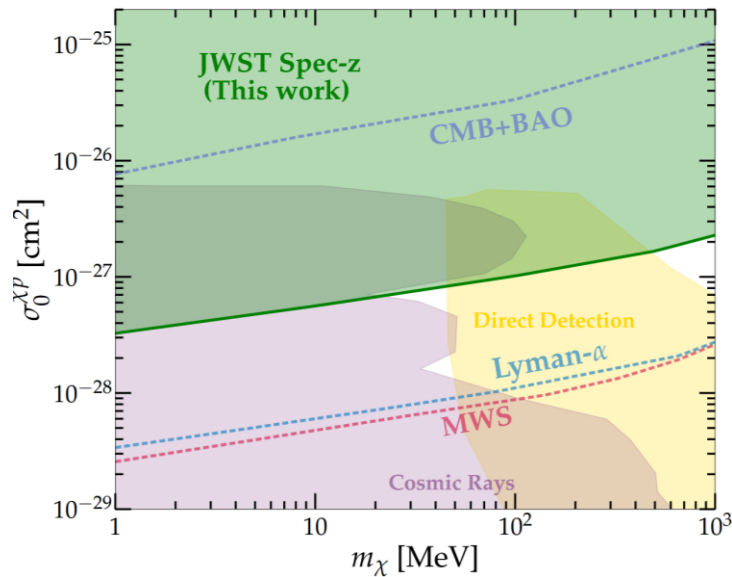
DM-electron interaction

Existing constraints taken from 2107.12377 (Buen-Abad et al) and 2107.12380 (Nguyen et al)

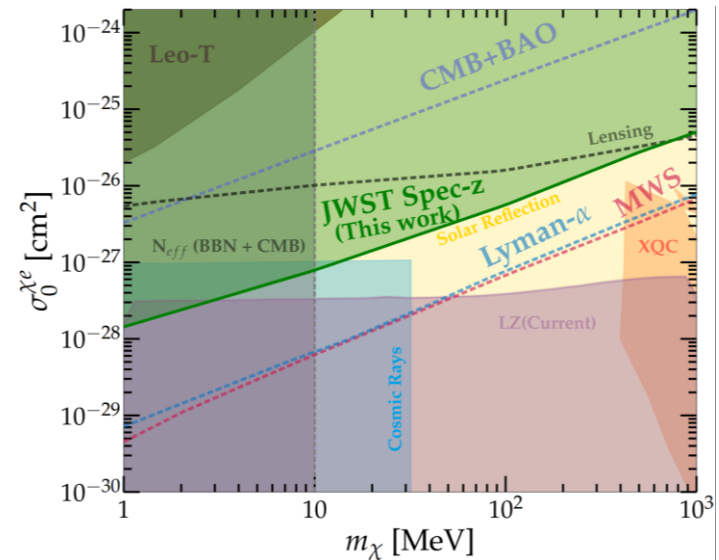
Das *et al* (2026)
2511.02906

Constraints on 'Contact' Interactions

$$\sigma_{\chi B} \propto v^0$$



DM-proton interaction



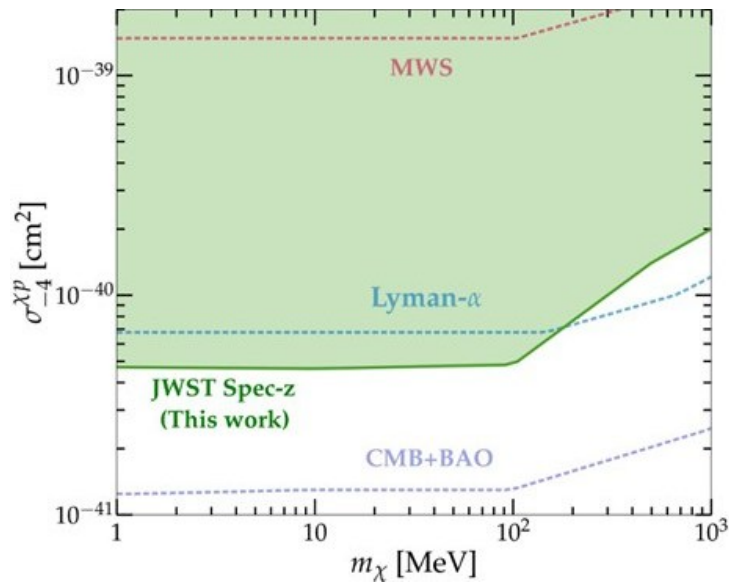
DM-electron interaction

Existing constraints taken from 2107.12377 (Buen-Abad et al) and 2107.12380 (Nguyen et al)

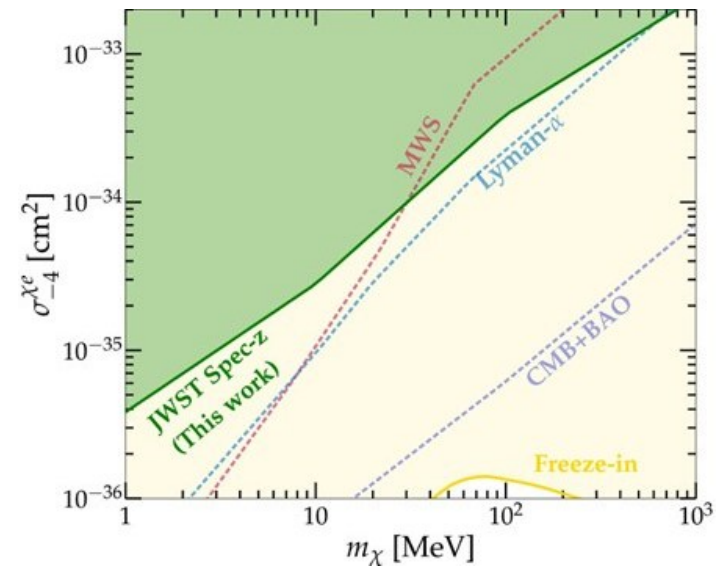
Das *et al* (2026)
2511.02906

Constraints on 'Coulomb-like' Interactions

$$\sigma_{\chi B} \propto v^{-4}$$



DM-proton interaction



DM-electron interaction

Existing constraints taken from 2107.12377 (Buen-Abad et al) and 2107.12380 (Nguyen et al)

Das *et al* (2026)
2511.02906

Summary

Read the paper here:



- Dark Matter Interactions with Standard Model particles (e.g., baryons: protons and electrons) can suppress structure formation and ultimately **reduce the number of observed galaxies**.
- High-redshift observations from JWST show no signs of suppressed structure formation, thus imposing **strong upper limits on interaction cross-section**.
- We obtain **strongest-till-date upper limits on dipole-like interaction cross-section**, and competitive limits on other phenomenological models, with data from **just about 40 galaxies!**
- More detailed observations can further constrain DM-SM interactions.

Thank you !!

Contact: das.536@osu.edu

Backup slides

Spectroscopic redshift determination

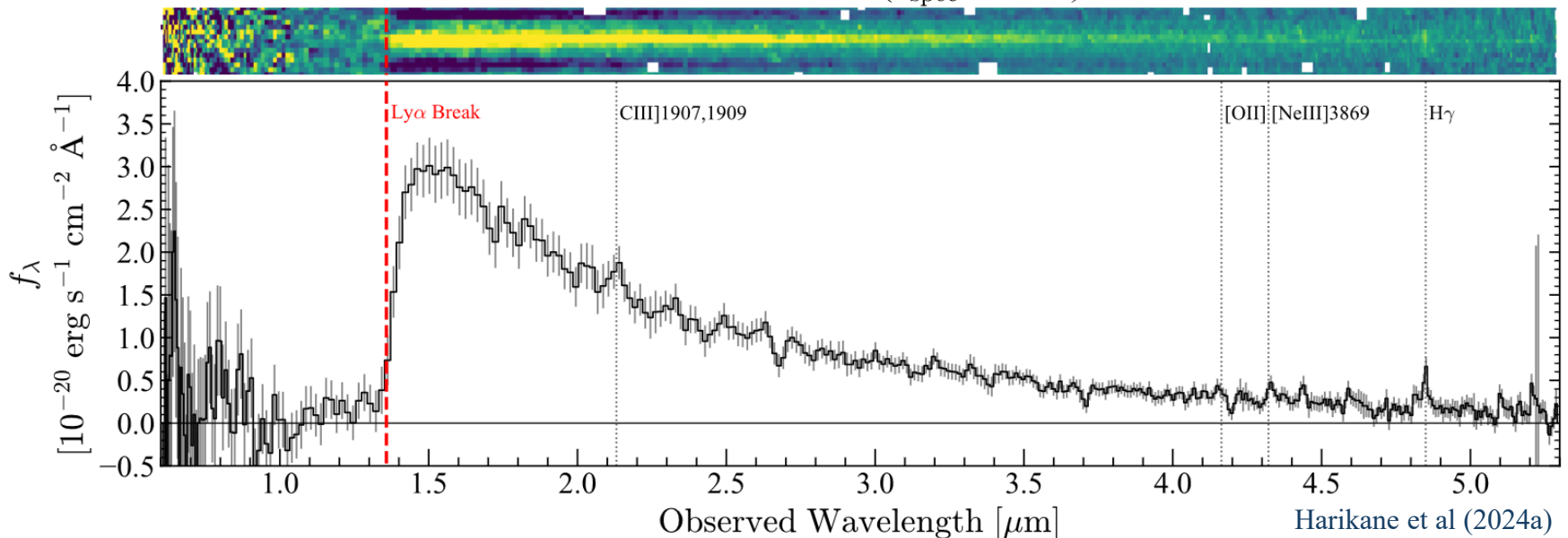
Spectral features from galaxies such as:

1. Lyman break
2. Emission lines

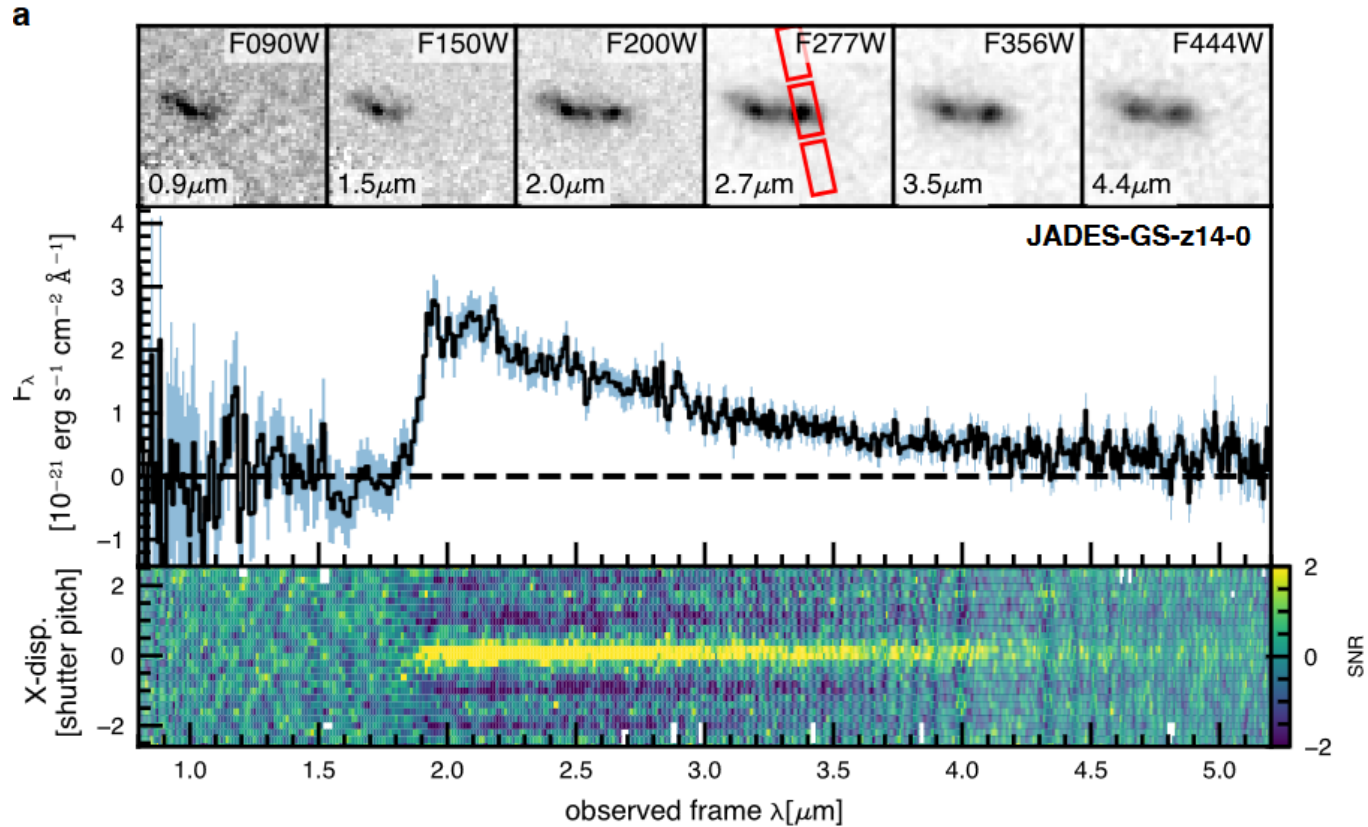
$$\lambda_{\text{obs}} = (1 + z)\lambda_{\text{emitted}}$$

MACS0647-JD ($z_{\text{spec}} = 10.17$)

JWST NIRSpec



JWST Galaxies at $z=14$

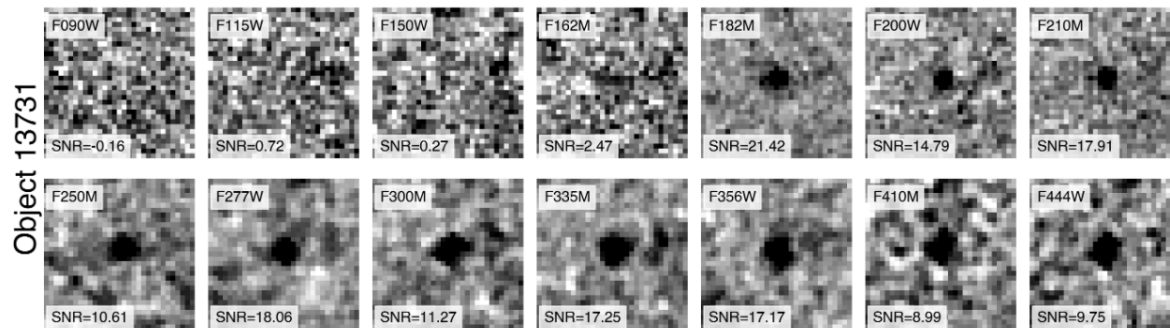
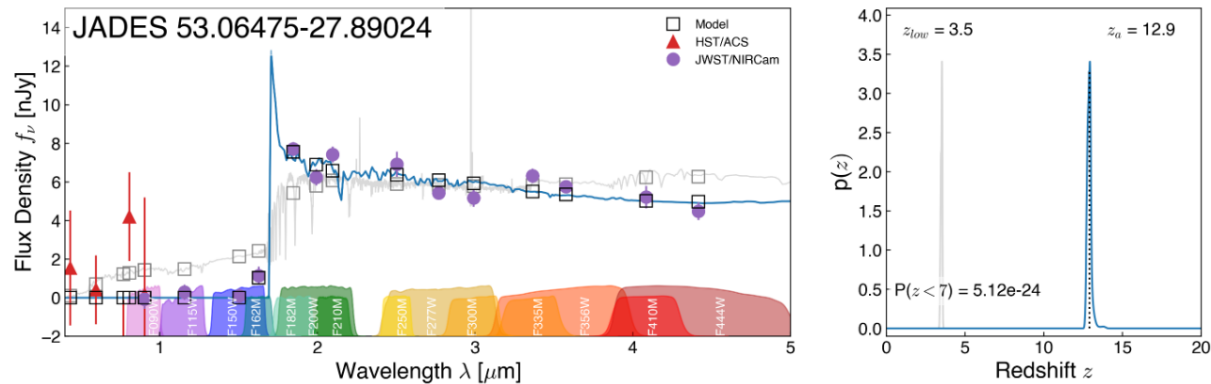


Carniani et al (2024a)

Photometric redshift determination

Lyman-break method

$$\lambda_{\text{obs}} = (1 + z)\lambda_{\text{emitted}}$$



JWST NIRCam
Robertson et al (2024)

We observe Early Galaxies in Infrared

$$\lambda_{\text{obs}} = (1 + z)\lambda_{\text{emitted}}$$

$$1650 \text{ nm} = (1+10) \times 150 \text{ nm}$$

ESA



Hubble

115 - 1700 nm

2.4 m mirror

space.com

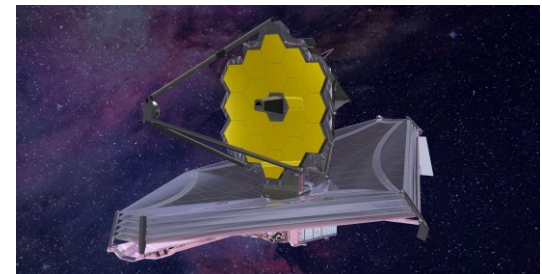


Spitzer

3000 - 180000 nm

0.85 m mirror

webbtelescope.org



James Webb

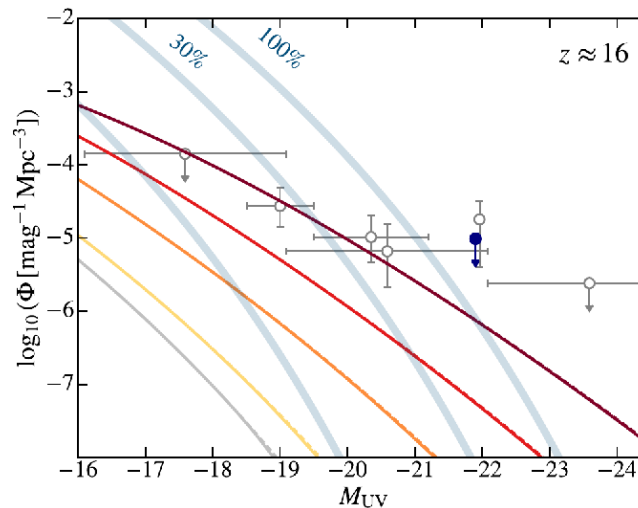
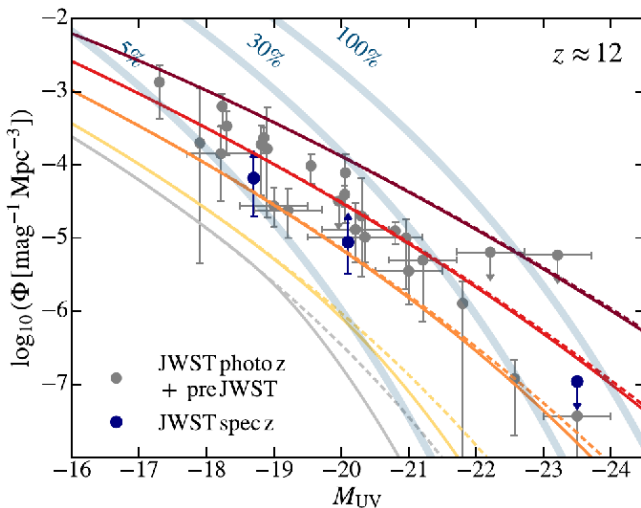
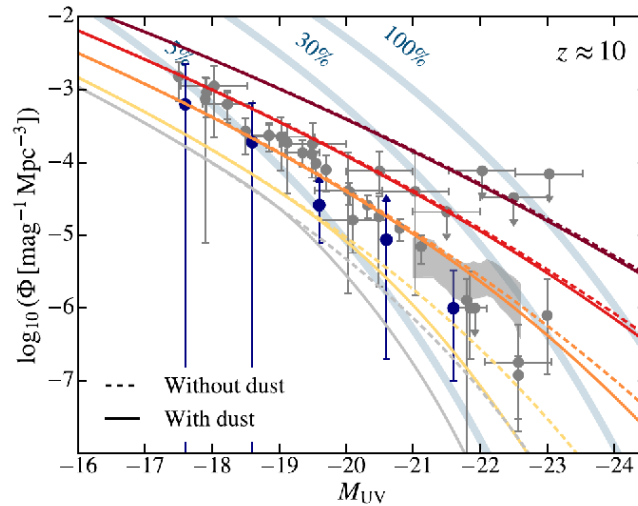
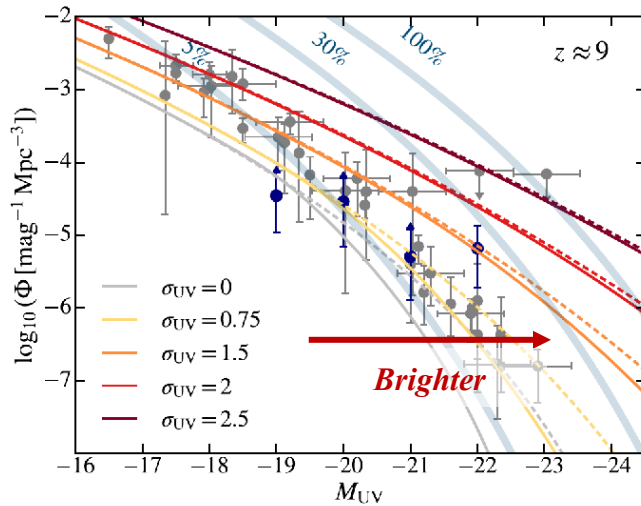
600 - 28500 nm

6.5 m mirror

Priors for JWST Likelihood

	Parameter	Prior
Cosmological parameters	$\log_{10} \sigma_n^{\chi^2 B}$	Uniform ^a
	Ω_χ	$\mathcal{U}[0.0, 0.3]$
	$\omega_b \times 10^2$	$\mathcal{N}(2.233, 0.036)$
	n_s	$\mathcal{N}(0.9649, 0.0042)$
	$A_s \times 10^9$	$\mathcal{N}(2.1, 0.03)$
Astrophysical parameters	α_\star	$\mathcal{U}[0.0, 3.0]$
	β_\star	$\mathcal{U}[0.0, 3.0]$
	$\log_{10} \epsilon_0$	$\mathcal{U}[-3.0, 0.0]$
	$\log_{10} M_0$	$\mathcal{U}[7.0, 11.0]$
	$\sigma_{UV}(10^{10.5} M_\odot)$	$\mathcal{U}[0.001, 3.0]$
	M	$\mathcal{U}[-21, -18]$

JWST has observed many bright galaxy candidates at $z \sim 9 - 14$



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.

Pre-JWST expectations

Low-redshift observations

Hubble, Spitzer observe galaxies at redshifts $\lesssim 10$

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

Reionization

First stars and galaxies produce UV radiation and ionize the neutral hydrogen.

$\text{Ly}\alpha$ forest tells us about reionization history

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).

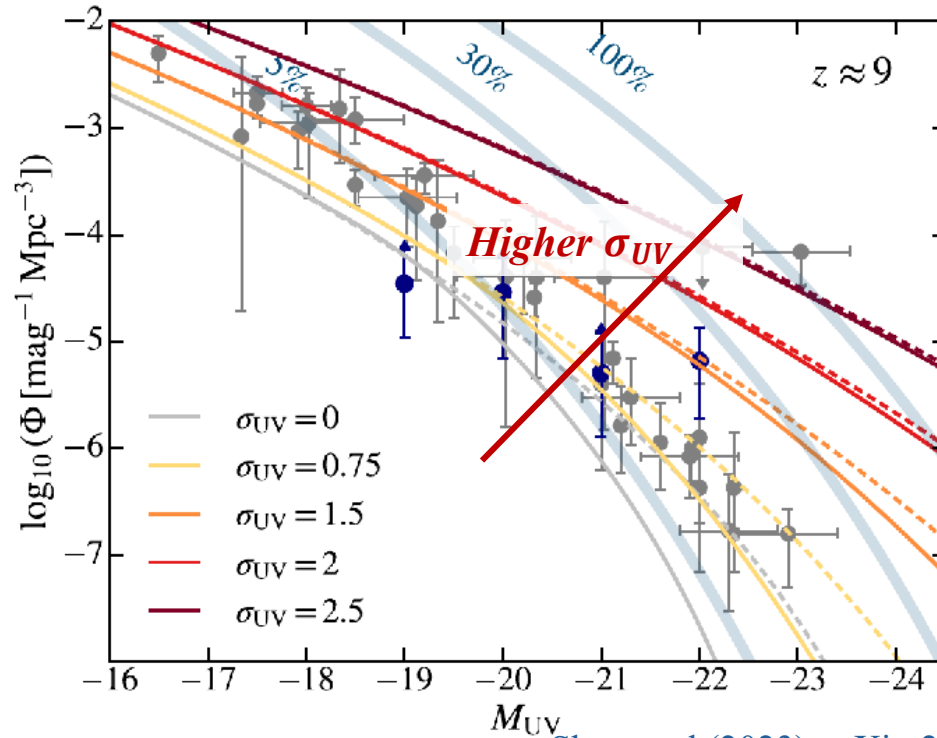
Proposed solutions: Change the Astrophysical Models

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

What if, we instead changed the cosmological model?

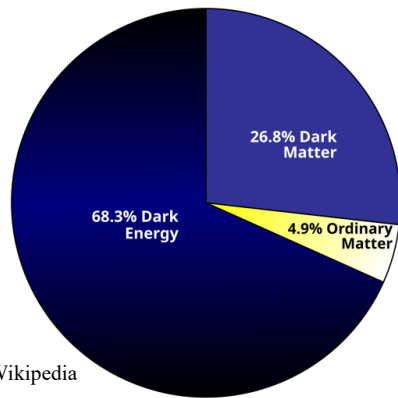
Variability leads to higher UV luminosity function!

This is simply because more low-mass galaxies become *over-bright* than high-mass galaxies becoming *under-bright* (HMF is monotonically decreasing function)



Shen et al (2023), arXiv:2305.05679

Changing the Cosmological Model



Credit: Wikipedia

Energy budget of the Λ CDM model

The standard Λ CDM 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 Λ CDM 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

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

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

Alterations to the Λ CDM model

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

DM-proton interaction

DM-electron interaction

DM-photon interaction

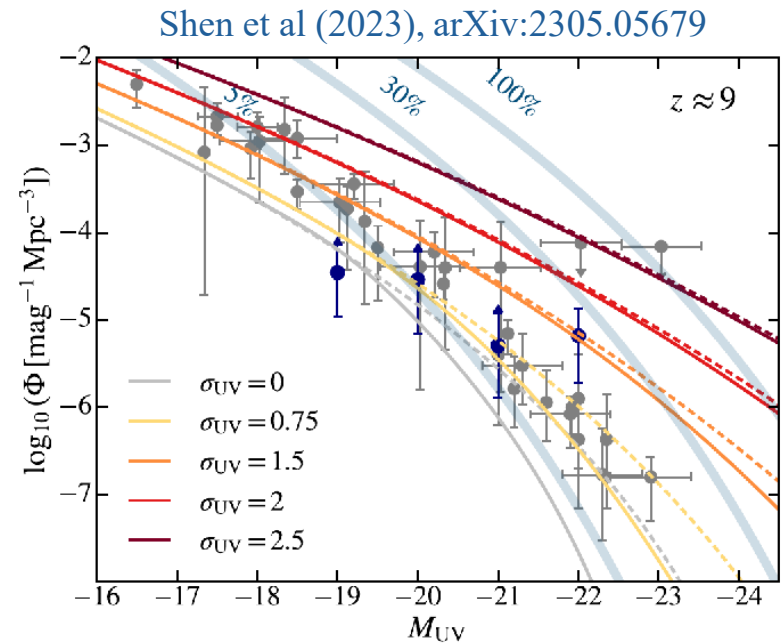
DM-neutrino interaction

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

Do Early Galaxies contradict Λ CDM?

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)



Continuity equation for DM

$$\dot{\delta}_\chi = -\theta_\chi + 3\dot{\phi}$$

$$\left(\delta := \frac{\delta\rho}{\bar{\rho}}, \quad \theta := \nabla \cdot \mathbf{v} \right)$$

Density contrast Divergence of velocity

Derivatives taken w.r.t.
conformal time τ

$$\frac{d}{d\tau} = a \frac{d}{dt}$$

Local expansion
of the Universe

Density dilution
due to flow

The Euler equation for DM

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

Velocity dilution
from uniform
Hubble expansion

Pressure term

Momentum exchanged
with baryons

Gravity

Sound speed

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

Interaction rate

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

Heat transfer to DM

$$\dot{T}_\chi = -2aHT_\chi + 2R'_{\chi-b}(T_b - T_\chi)$$

↓
Cooling in
adiabatic expansion

↓
Heat exchanged
with baryons

$$R'_{\chi-b} = \frac{m_\chi}{m_\chi + m_B} R_{\chi-b}$$

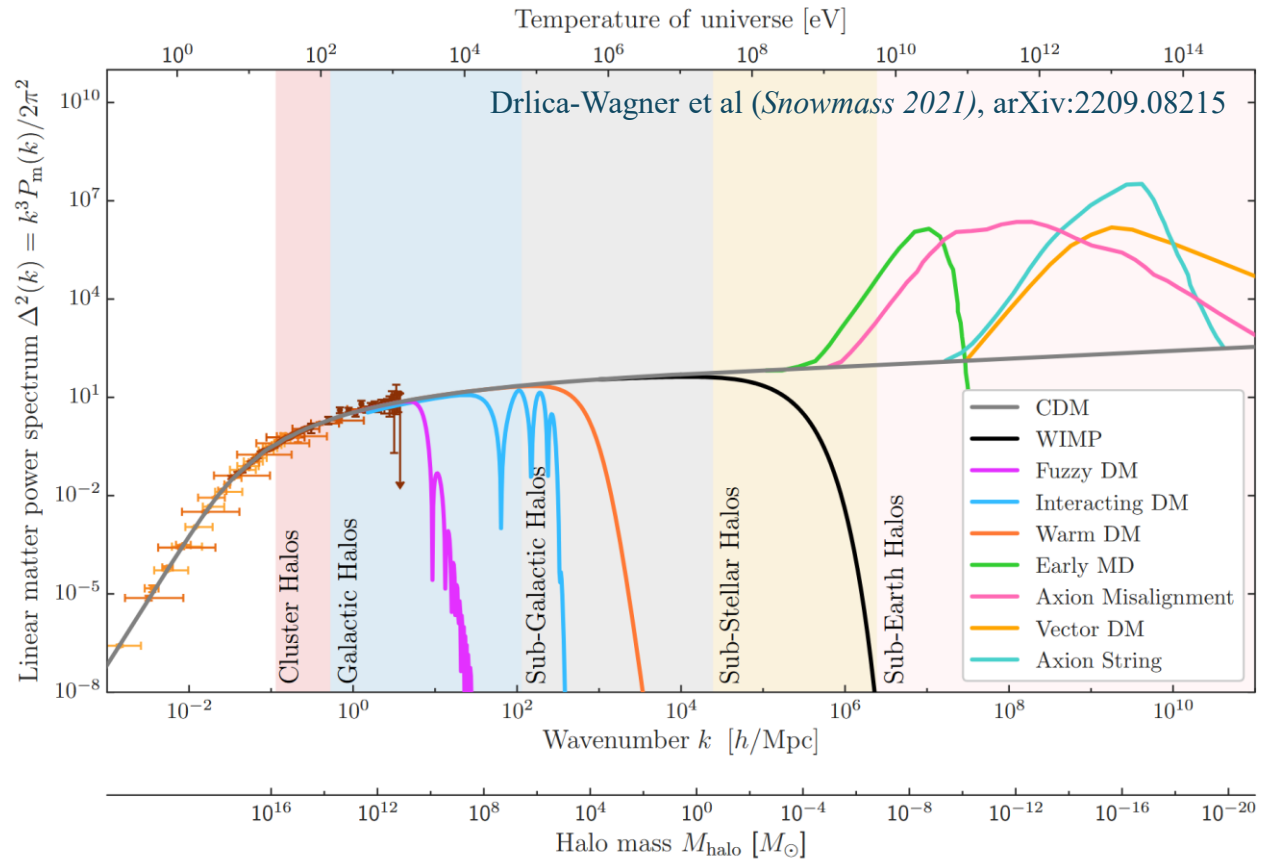
↑ Heat transfer rate constant ↑ Momentum transfer rate constant

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



Extended Press-Schechter Formalism

Variance of (smoothed) density contrast over a sphere of radius R

$$\sigma_m^2(R) = \frac{1}{2\pi^2} \int dk k^2 W^2(kR) P_m(k)$$

Choice of window function: $W(\mathbf{x}, R) = \frac{3}{4\pi R^3}, \quad |\mathbf{x}| < R$ (Top-hat filter)

Halo Mass Function (HMF): $\frac{dn}{dM} = \frac{\rho_m}{M^2} f(\sigma(M)) \left| \frac{d \ln \sigma}{d \ln M} \right|$

f is the Sheth-Tormen fitting function for an ellipsoidal collapse model:

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

Mass-dependence of constraint

Dark matter heavier than baryons:

$$\sigma_{\text{lim}} \propto m_{\chi}, \quad m_{\chi} \gg m_B$$

Dark matter lighter than baryons:

$$\sigma_{\text{lim}} \propto m_{\chi}^{1/4}, \quad m_{\chi} \ll m_B$$

Comes from consideration of decoupling redshift

Why this variation with mass?

1. Dark matter much heavier than baryons

Decoupling at redshift z_{dec}

$$aH(z_{\text{dec}}) = R_{\chi-b}(z_{\text{dec}})$$
$$H_0 \sqrt{\Omega_r} (1 + z_{\text{dec}}) = (1 + z_{\text{dec}})^{5/2} \frac{Y_B \rho_{b0} c_0 \sigma_0}{m_\chi} \left(\frac{T_0}{m_B} \right)^{1/2}$$

For DM-proton scattering:

$$z_{\text{dec}} \simeq 10^4 \left(\frac{\sigma_0 / m_\chi}{2 \times 10^{-24} \text{ cm}^2 \text{ GeV}^{-1}} \right)^{-2/3}$$

$$\sigma_{\text{lim}} \propto m_\chi, \quad m_\chi \gg m_B$$

Our work (in prep.)

Why this variation with mass?

2. Dark matter much lighter than baryons

Thermal decoupling

$$aH(z_{\text{dec}}^{\text{th}}) = R'_{\chi-b}(z_{\text{dec}}^{\text{th}})$$

$$T_{\chi} = T_b$$

Kinetic decoupling

$$aH(z_{\text{dec}}^{\text{kin}}) = R_{\chi-b}(z_{\text{dec}}^{\text{kin}})$$

$$T_{\chi} \lesssim T_b$$

For $m_{\chi} \gtrsim m_B$ these two are simultaneous

For $m_{\chi} \ll m_B$ thermal decoupling takes place before kinetic decoupling:

$$R'_{\chi-b} = \frac{m_{\chi}}{m_{\chi} + m_B} R_{\chi-b}$$

Why this matters:

$$T_{\chi} \propto (1+z) \quad \text{before thermal decoupling}$$

$$T_{\chi} \propto (1+z)^2 \quad \text{after thermal decoupling}$$

Kinetic decoupling:

$$aH(z_{\text{dec}}^{\text{kin}}) = R_{\chi-b}(z_{\text{dec}}^{\text{kin}})$$

For DM-proton scattering:

$$z_{\text{dec}}^{\text{kin}} \simeq 10^4 \left[\frac{\sigma_0}{2 \times 10^{-24} \text{ cm}^2} \left(\frac{1 \text{ GeV}}{m_\chi} \right)^{1/4} \right]^{-2/3}$$

$$\sigma_{\text{lim}} \propto m_\chi^{1/4}, \quad m_\chi \ll m_B$$

Our work (in prep.)