Dark matter astroparticle constraints from high-z galaxies

Presented by **Giovanni Gandolfi**

Cosmology 2023 in Miramare
29/8/2023

Aim of the talk:

To showcase a **novel way** to to **constrain** different Dark Matter models based on determinations of the **cosmic star formation rate density** at high redshifts ($z>4$).

Outline:

- Introduction
- Data set & methods
- Results
- Forecast for JWST
- Conclusions and future prospects

What is **Dark Matter** ?

Particle with a weak/negligible interaction with baryons (no detection so far!) except through **gravity**.

Cold Dark Matter (CDM)

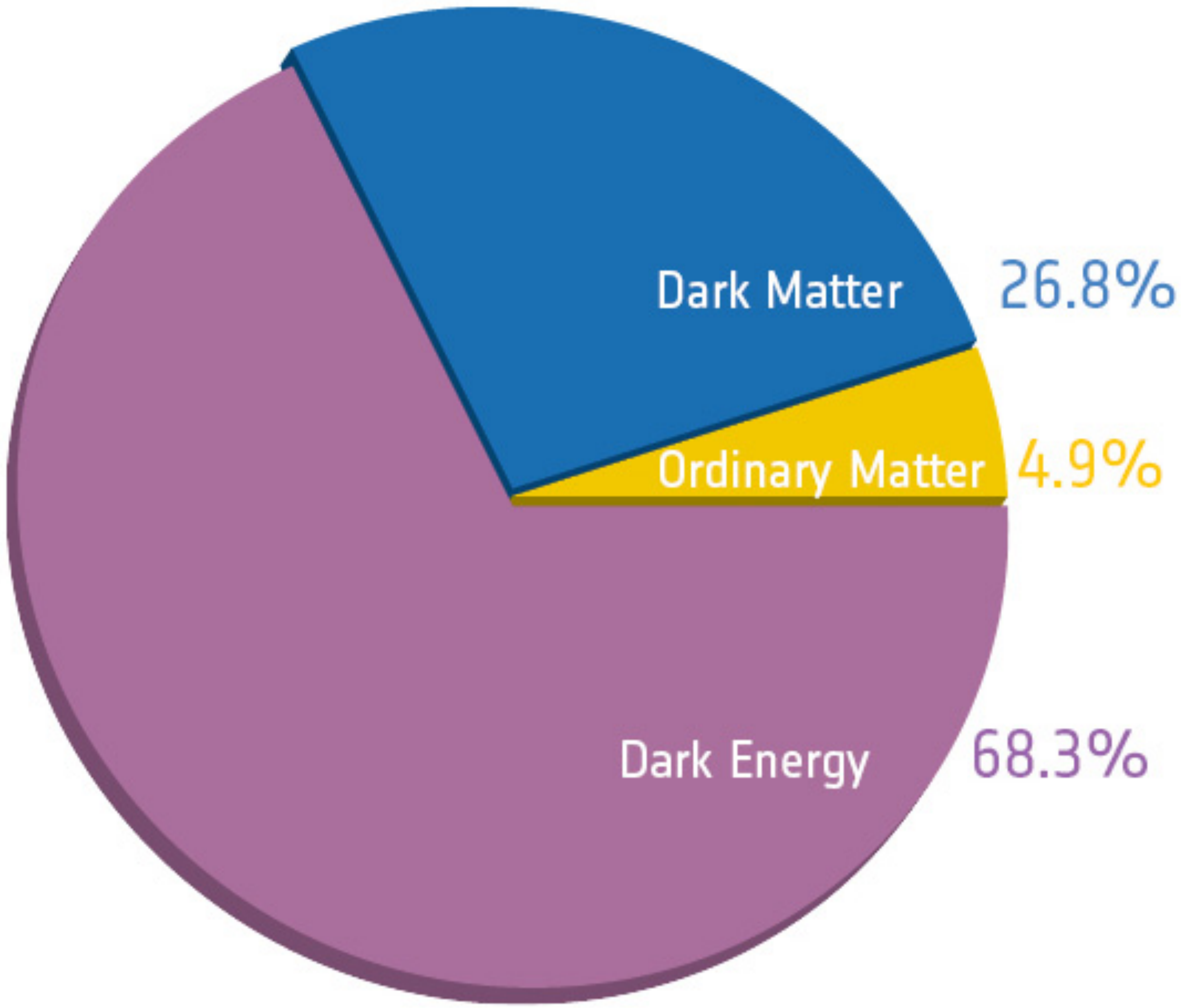
GeV mass, non-relativistic, negligible free-streaming velocities.

Successes on cosmological scales:

CMB, LSS, BBN nucleosynthesis, BAOs, etc.

Issues on galactic scales:

core cusp-controversy, # and dynamical properties of MW satellites, dynamical relationships between baryons and DM



... issues addressable within the CDM framework (dynamical friction, baryonic/AGN feedback). Or **non-standard DM particle candidates**?

Warm Dark Matter (WDM)

Thermal relics, $m_\chi \sim O(\text{keV})$, non-negligible free streaming velocities

Fuzzy Dark Matter (ψDM)

Bose-Einstein Condensate of ultralight axions with $m_\chi \sim O(10^{-22}\ \text{eV})$

Self-Interacting Dark Matter (SIDM)

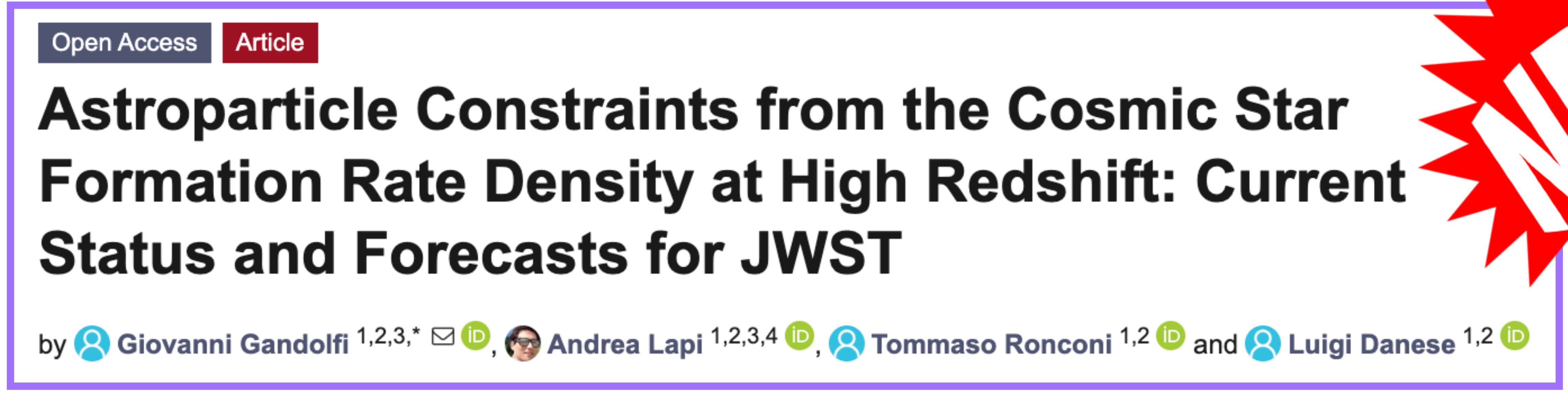
$10 < m_\chi < 250$ MeV, $\sigma_{\chi\chi}/m_\chi \sim 0.1\text{-}1\ \text{cm}^2/\text{g}$ (cf. ETHOS), kinetic T_χ at decoupling

As a consequence of their **characteristics** (free-streaming, quantum effects, dark sector interactions):

- Reduced number of **sub-haloes**
- **Flatter** inner density profile
- DM power spectrum will be **suppressed** on small scales!

Indirect constraints of DM properties:

- Lyman-α forest (Viel+13, Irsic+17a,b, Villasenor+22)
- High-z galaxy counts (Pacucci+13, Menci+16, Shirasaki+21, Sabti+22)
- γ-ray bursts (De Souza+12, Lapi+17)
- Cosmic reionization (Barkana+01, Lapi+15, Dayal+17, Carucci+19, Lapi+22)
- Gravitational lensing (Vegetti+18, Ritondale+18)
- Integrated 21 cm data (Carucci+15, Boyarsky+19, Chatterjee+19, Rudakovskyi+20)
- γ-ray emission (Bringmann+17, Grand+22)
- Fossil records of the Local Group (Weisz+14, Weisz+17)
- Dwarf galaxy profiles and scaling relations (Calabrese+16, Burkert 2020)
- Milky Way satellite galaxies (Kennedy+14, Horiuchi+14, Lovell+16, Nadler+21, Newton+21)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Astroparticle Constraints from the Cosmic Star Formation Rate Density at High Redshift: Current Status and Forecasts for JWST

by Giovanni Gandolfi [1,2,3,*], Andrea Lapi [1,2,3,4], Tommaso Ronconi [1,2] and Luigi Danese [1,2]

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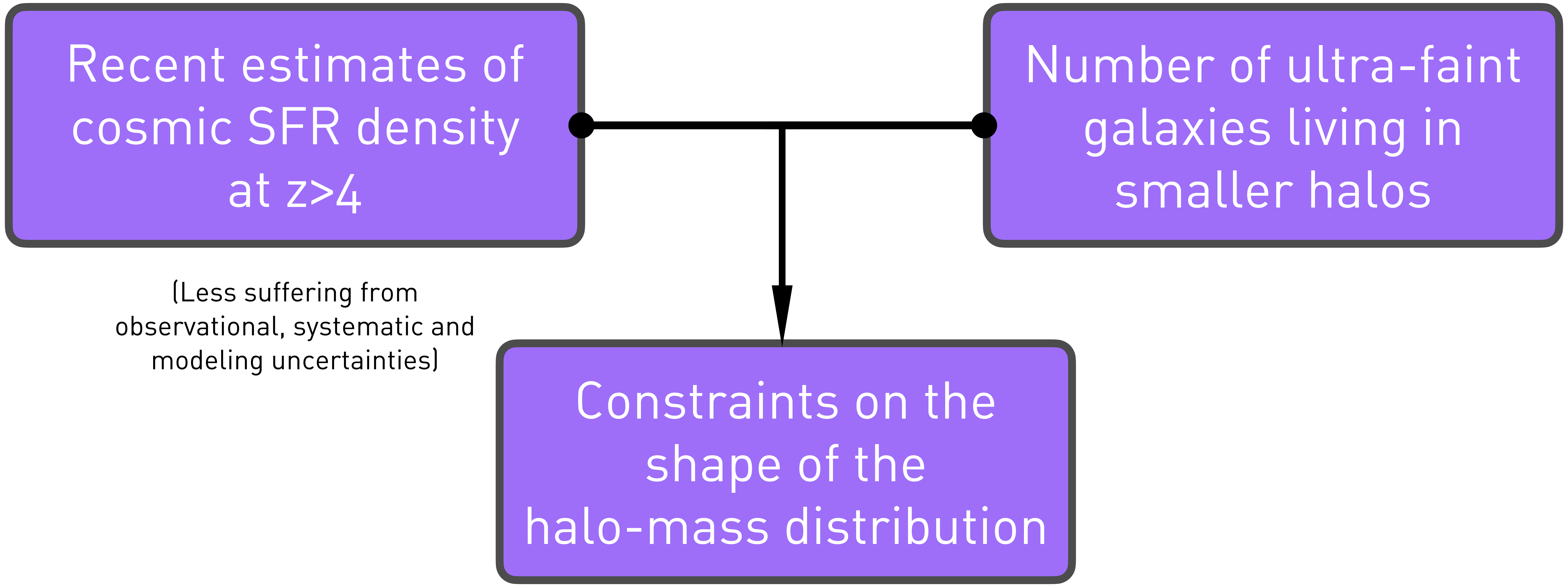


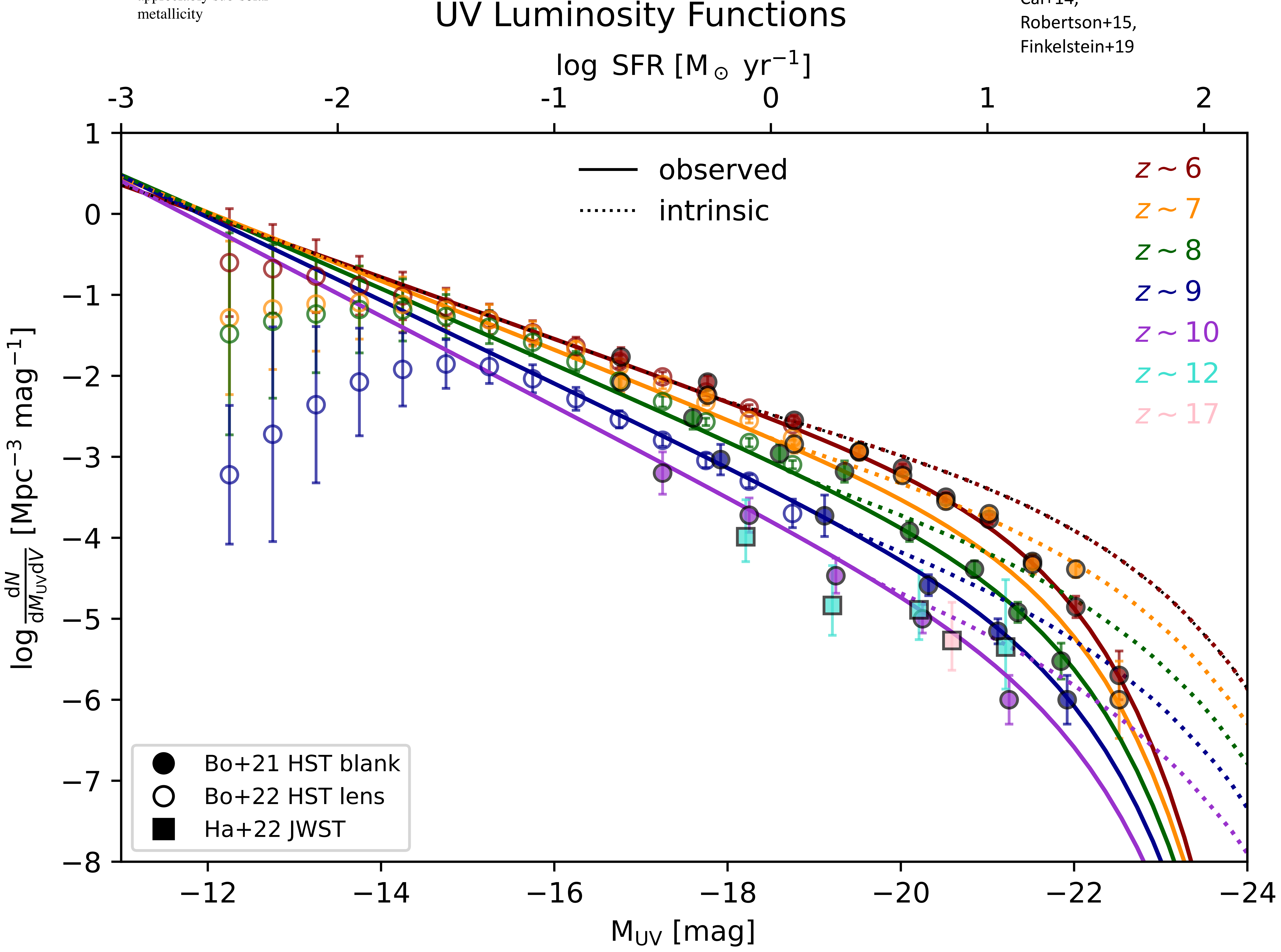
STEP 1
Binned UV luminosity function

- HST blank field data (Oesch+18, Bouwens+21; $M_{UV} \leq -17$, $6 < z < 10$, 1600 Å) - **filled circles** (binned)
- HST lensed sources (HFF clusters, Bowens+22; $M_{UV} \leq -12.5$) - **open circles** (binned) tracing a **flattening**
- JWST early results (Harikane+22, z > 12) - **squares**
- Corresponding **Schechter** functions - **solid lines**
- Correction for **dust** extinction (as in Meurer&Calzetti 1999 and Bouwens+14) - **dashed lines**

Chabrier IMF, age & 10^8 years, and appreciably sub-solar metallicity

$$\log \mathrm{SFR}\left[M_\odot \mathrm{year}^{-1}\right] \approx -0.4\left(M_{UV} + 18.5\right)$$

Kennicut+12, Madau 12, Cai+14, Robertson+15, Finkelstein+19



SCHECHTER LUMINOSITY FUNCTION

$$\frac{\mathrm{d}N}{\mathrm{d}M_{\mathrm{UV}}\mathrm{d}V} = \phi^{\star}\frac{\ln(10)}{2.5}10^{-0.4\left(M_{\mathrm{UV}} - M^{\star}_{\mathrm{UV}}\right)(\alpha+1)}e^{-10^{-0.4\left(M_{\mathrm{UV}} - M^{\star}_{\mathrm{UV}}\right)}}$$

$$\begin{cases} \alpha \approx -1.95 - 0.11(z-6) & \text{(faint end slope)} \\ M^{\star}_{\mathrm{UV}} \approx -21.04 - 0.05(z-6) & \text{(characteristic magnitude)} \\ \phi^{\star} \approx 3.8 \times 10^{-4-0.35(z-6)-0.027(z-6)^2}\ \mathrm{Mpc}^{-3} & \text{(normalization)} \end{cases}$$

(Redshift evolution of the parameters comes from Bouwens+21 and Bouwens+22, consistent!)

STEP 2
Calculate SFR density from UV luminosity function

$$\rho_{\rm SFR}(z) = \int_{-\infty}^{\min\left[M_{\rm UV}^{\rm obs},\, M_{\rm UV}^{\rm lim}\right]} {\rm d}M_{\rm UV} \frac{{\rm d}N}{{\rm d}M_{\rm UV}{\rm d}V} {\rm SFR}$$

- **M^{obs}_{UV}**: faintest limit probed by observations (-13 for Bouwens+22 or -17 for Harikane+22)
- **M^{lim}_{UV}**: limit magnitude down to which the luminosity function is steeply increasing (i.e., after which we consider the SFR density to be negligible)

Uncertain quantity! Bouwens+22 provides the most stringent limits (ruling out the presence of a turnover in the luminosity function brightward of -15.5).

STEP 2
Calculate SFR density from UV luminosity function

$$\rho_{\rm SFR}(z) = \int_{-\infty}^{\min\left[M_{\rm UV}^{\rm obs}, M_{\rm UV}^{\rm lim}\right]} {\rm d}M_{\rm UV} \frac{{\rm d}N}{{\rm d}M_{\rm UV}{\rm d}V} {\rm SFR}$$

At magnitudes **fainter** than **$M^{\rm lim}_{\rm UV}$**: the luminosity function can flatten/bend because:

- **Galaxy formation processes** becoming inefficient in small haloes (e.g. photo suppression by the UV bkg, inefficiency in atomic cooling...)
- The **microscopic nature of DM** generating a suppression of the power spectrum at small scales

+ underlying assumption of an IMF (Chabrier), does not affect such constraints (Lapi+22)

$$\Theta = \{M_{\rm H}^{\rm GF}, X\}$$

STEP 3

Consider the halo mass function for each DM model

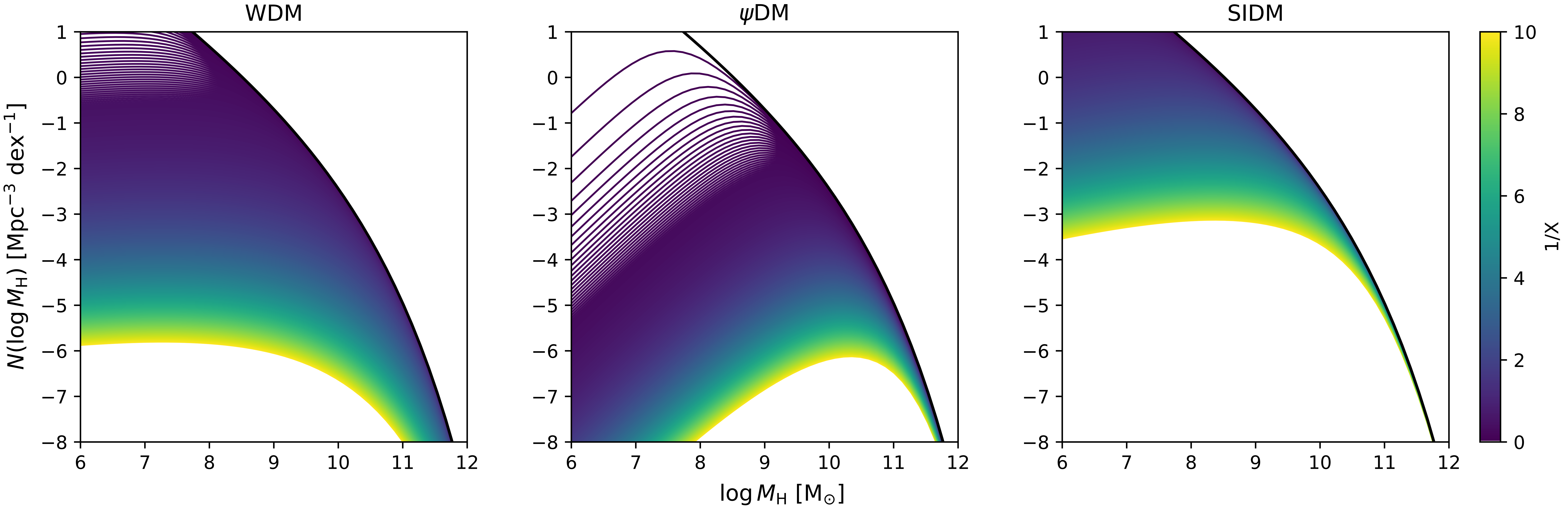
$$\frac{\mathrm{d}N}{\mathrm{d}M_\mathrm{H}\mathrm{d}V} = \frac{\mathrm{d}N_\mathrm{CDM}}{\mathrm{d}M_\mathrm{H}\mathrm{d}V}\left[1+\left(\frac{M_\mathrm{H}^\mathrm{cut}}{M_\mathrm{H}}\right)^{\beta}\right]^{-\gamma}$$

CDM HMF from the COLOSSUS Python package (Diemer 2018)

Scenario	β	γ	Cut-off mass $M_\mathrm{H}^\mathrm{cut}$	Ref.
WDM	1.0	1.16	$\approx 1.9\times10^{10}\mathrm{M}_\odot\,(m_X/\mathrm{keV})^{-3.33}$	Schneider+12
ψDM	1.1	2.2	$\approx 1.6\times10^{10}\mathrm{M}_\odot\,(m_X/10^{-22}\mathrm{eV})^{-1.33}$	Schive+16
SIDM	1.0	2.34	$\approx 7\times10^{7}\mathrm{M}_\odot\,(T_X/\mathrm{keV})^{-3}$	Huo+18

(From detailed simulations, not semi-analytical models based on the excursion set formalism)
(Schneider+13, Lapi & Danese 2015, Springel 2022)

Halo mass functions at ref. z = 10



- **CDM** - black solid line
- **WDM flattens** wrt CDM, decimation occurs at smaller halo masses for decreasing particle mass (CDM behavior recovered for the particle mass tending to infinity)
- Similar behavior in other scenarios (**FDM** - strong reduction/absence of small halo masses)

STEP 4
Link UV magnitudes and halo masses

We use a simple **abundance matching** technique (Aversa+15, Moster+18, Cristofari & Ostriker 2019, Behroozi+20)

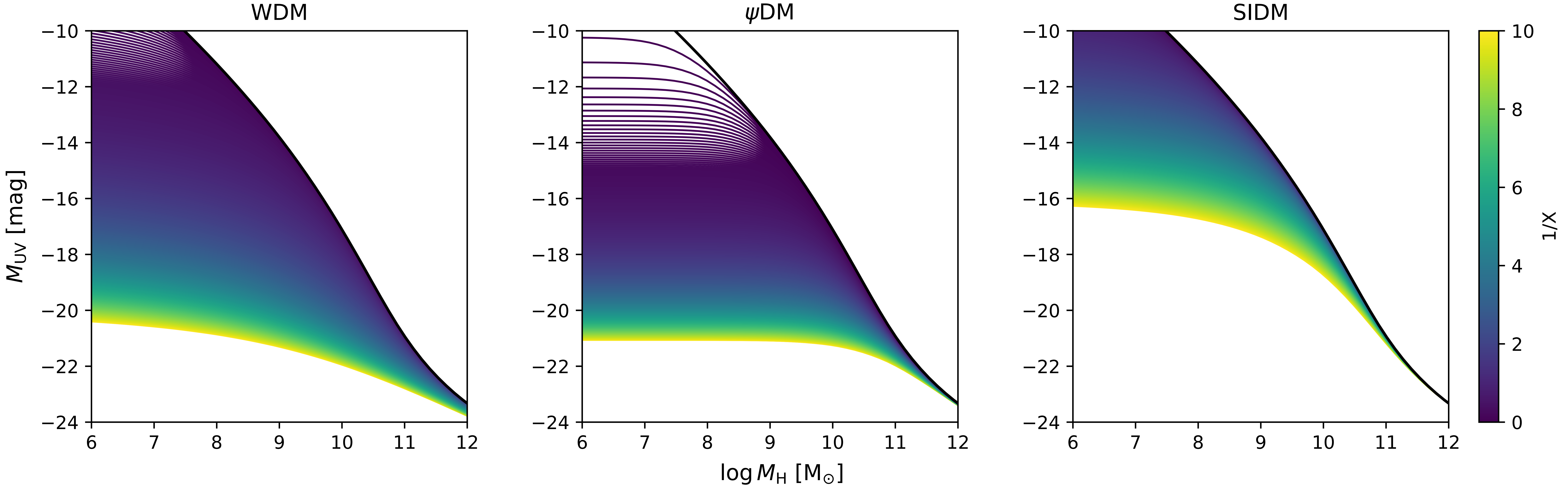
We match the cumulative number densities in galaxies and haloes:

$$\int_{M_{\rm H}}^{+\infty} {\rm d}M'_{\rm H} \frac{{\rm d}N}{{\rm d}M'_{\rm H}{\rm d}V}\left(M'_{\rm H}, z \mid X\right) = \int_{-\infty}^{M_{\rm UV}} {\rm d}M'_{\rm UV} \frac{{\rm d}N}{{\rm d}M'_{\rm UV}{\rm d}V}\left(M'_{\rm UV}, z\right)$$

This implicitly defines a **relation** between M_{UV} and M_H at a given z and given X

X is the **specific property** of DM that determines its behavior for $M_H < M_H^{cut}$ (m or T_x for SIDM)

M_{UV} - M_H relation at z=10 (for different X)



- WDM: flattening for lower m. For high m, the relation becomes indistinguishable from CDM
- The relation barely depends on z (for z>6) at a given m, because the cosmic evolution of the UV luminosity function and the halo mass function mirror each other (Bouwens+21)
- Other models are similar, but the flattening is more abrupt (e.g. FDM, see HMF)

Analysis

Compute the **cosmic SFR density** integrating the UV lum. functions down to a magnitude limit

$$M_{\rm UV}^{\rm lim}(M_{\rm H}^{\rm GF}, z\,|\,X)$$

Cosmic SFR density constrained by HST UV luminosity function data; early JWST UV luminosity function; GRB counts data from Fermi (Kistler+09) and (sub)mm luminosity function data from ALMA (Gruppioni+20)

We perform a **Bayesian MCMC fit** (flat priors + gaussian likelihood, 10^4 steps and 200 walkers)
The $M_{\rm obs}^{\rm UV}$ we consider the minimum observational magnitude limit in each dataset.

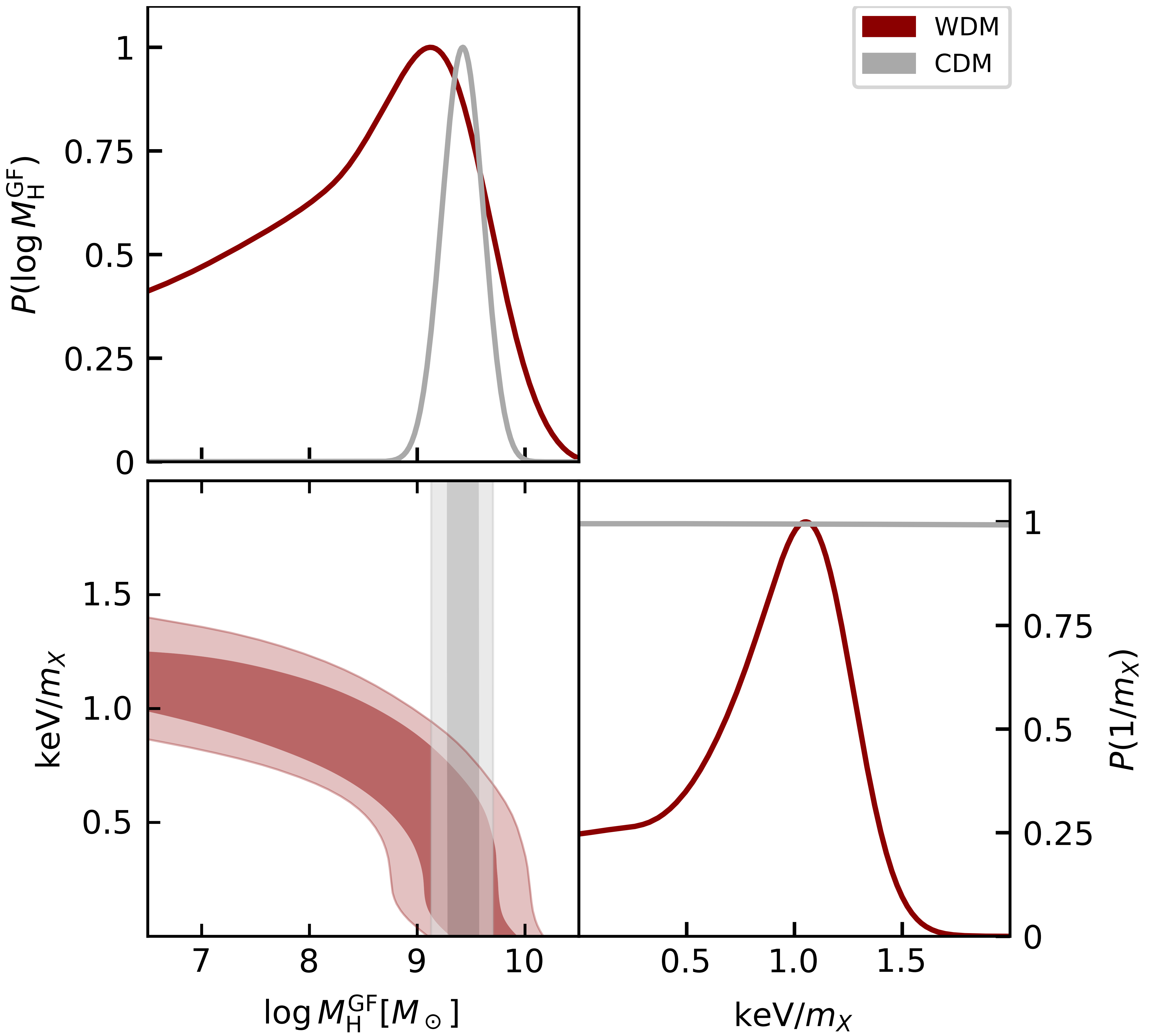
$$\theta = \{M_{\rm H}^{\rm GF}, X\}$$

$$M_{\rm UV}^{\rm lim} \begin{cases} M_{\rm H}^{\rm GF} \in [6,11] \\ 1/X \in [0,10] \end{cases}$$

$$\mathscr{L}(\theta) \equiv -\sum_i \chi_i^2(\theta)/2 \qquad \mathscr{P}(\theta) \propto \mathscr{L}(\theta)\pi(\theta)$$

$$\chi_i^2 = \sum_j \left[\mathscr{M}\left(z_j, \theta\right) - \mathscr{D}\left(z_j\right)\right]^2 / \sigma_{\mathscr{D}}^2\left(z_j\right)$$

Warm Dark Matter



- **CDM**: $\log M_H^{GF}\left[M_\odot\right] \approx 9.4^{+0.2(+0.4)}_{-0.1(-0.4)}$

  $M_{UV}^{lim} \approx -14.7$ (see Finkelstein+19)

  (Close to the photo-suppression mass expected by the intense UV bkg during reionization)

- **WDM**: **degeneracy** between particle mass and halo mass.

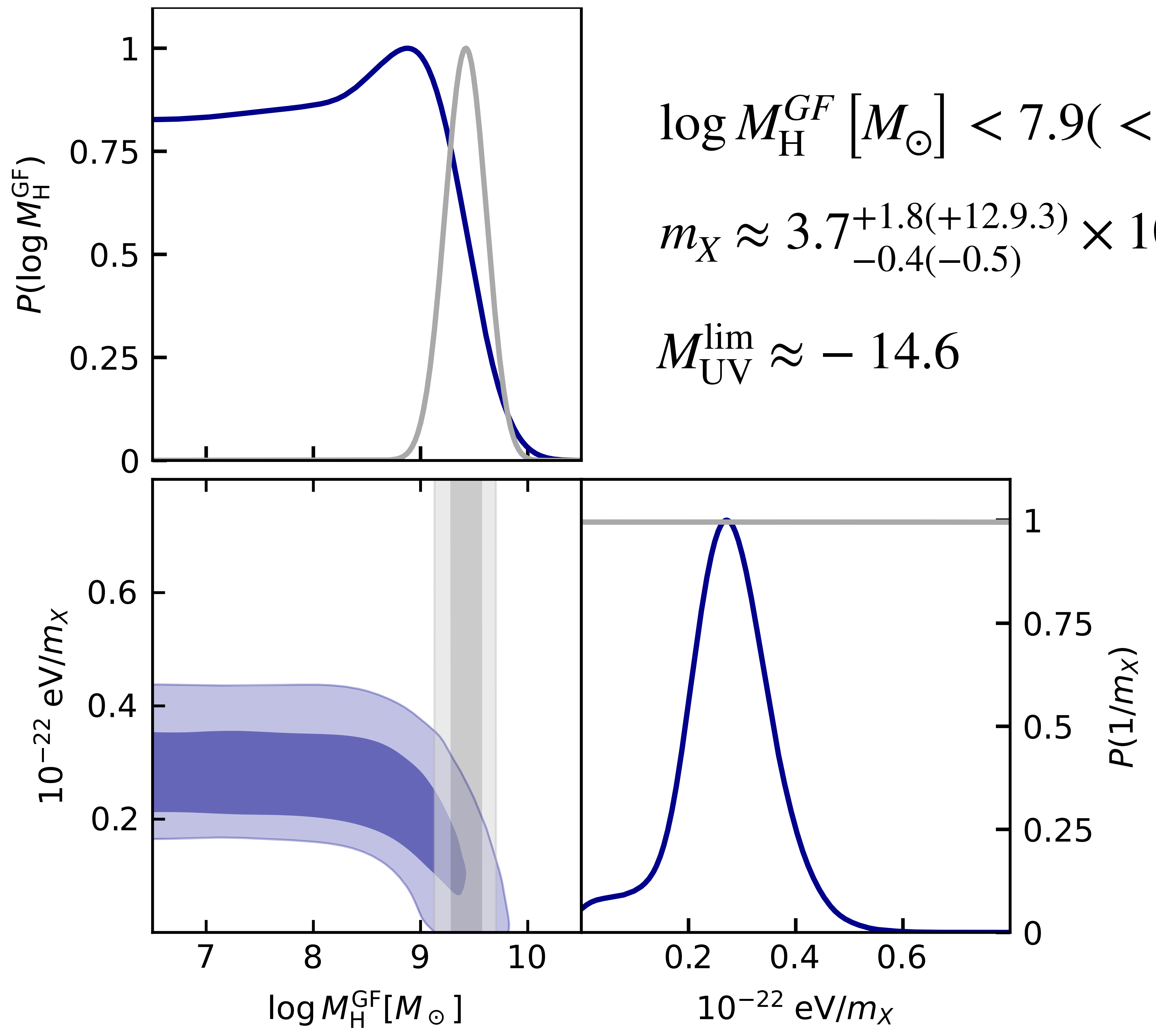
$$\log M_H^{GF}\left[M_\odot\right] \approx 7.6^{+2.2(+2.3)}_{-0.9(-3.3)}$$

$$m_X \approx 1.2^{+0.3(11.3)}_{-0.4(-0.5)}\ \text{keV}$$

$$M_{UV}^{lim} \approx -13.3$$

Posterior peaks at **keV scale**, which solves issues of CDM (missing satellites, cusp-core) - but beware of the posterior **tail**!.

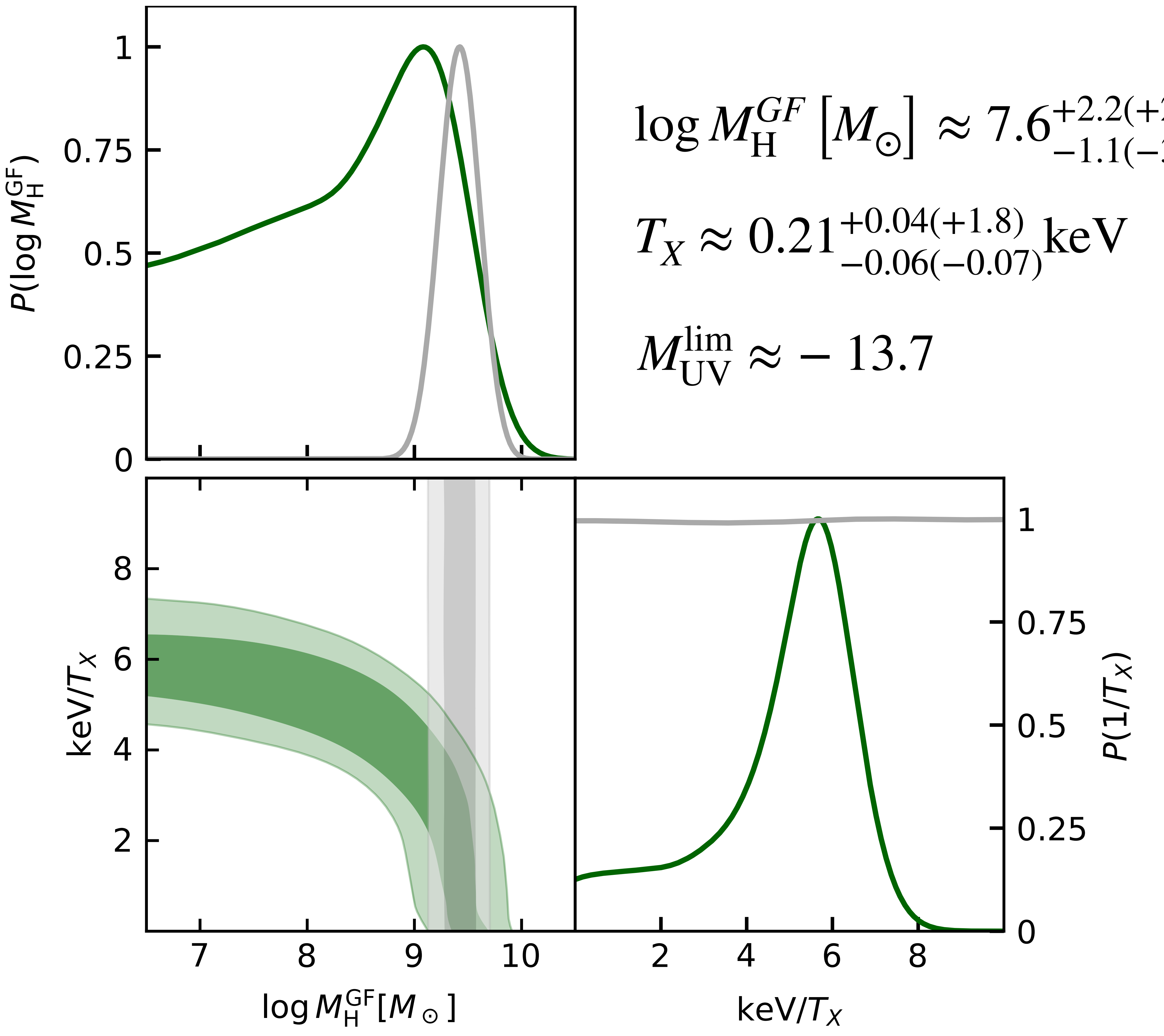
Fuzzy Dark Matter & Self-Interacting Dark Matter



$$\log M_{\rm H}^{GF}\left[M_\odot\right] < 7.9(< 9.3)$$

$$m_X \approx 3.7^{+1.8(+12.9.3)}_{-0.4(-0.5)} \times 10^{-22}{\rm eV}$$

$$M_{\rm UV}^{\rm lim} \approx -14.6$$



$$\log M_{\rm H}^{GF}\left[M_\odot\right] \approx 7.6^{+2.2(+2.3)}_{-1.1(-3.2)}$$

$$T_X \approx 0.21^{+0.04(+1.8)}_{-0.06(-0.07)}{\rm keV}$$

$$M_{\rm UV}^{\rm lim} \approx -13.7$$

Scenario	$M_{\mathrm{H}}^{\mathrm{GF}}$	**X**	**BIC**	**DIC**
CDM	$9.4^{+0.2\,(+0.4)}_{-0.1\,(-0.4)}$	–	≈ 31	≈ 13
WDM	$7.6^{+2.2\,(+2.3)}_{-0.9\,(-3.3)}$	$1.2^{+0.3\,(+11.3)}_{-0.4\,(-0.5)}$	≈ 33	≈ 14
ψDM	$< 7.9\,(< 9.3)$	$3.7^{+1.8\,(+12.9)}_{-0.9\,(-1.4)}$	≈ 33	≈ 14
SIDM	$7.6^{+2.2\,(+2.3)}_{-1.1\,(-3.2)}$	$0.21^{+0.04\,(+1.8)}_{-0.06\,(-0.07)}$	≈ 33	≈ 14
CDM + JWST forecast				
WDM + JWST forecast				
ψDM + JWST forecast				
SIDM + JWST forecast				

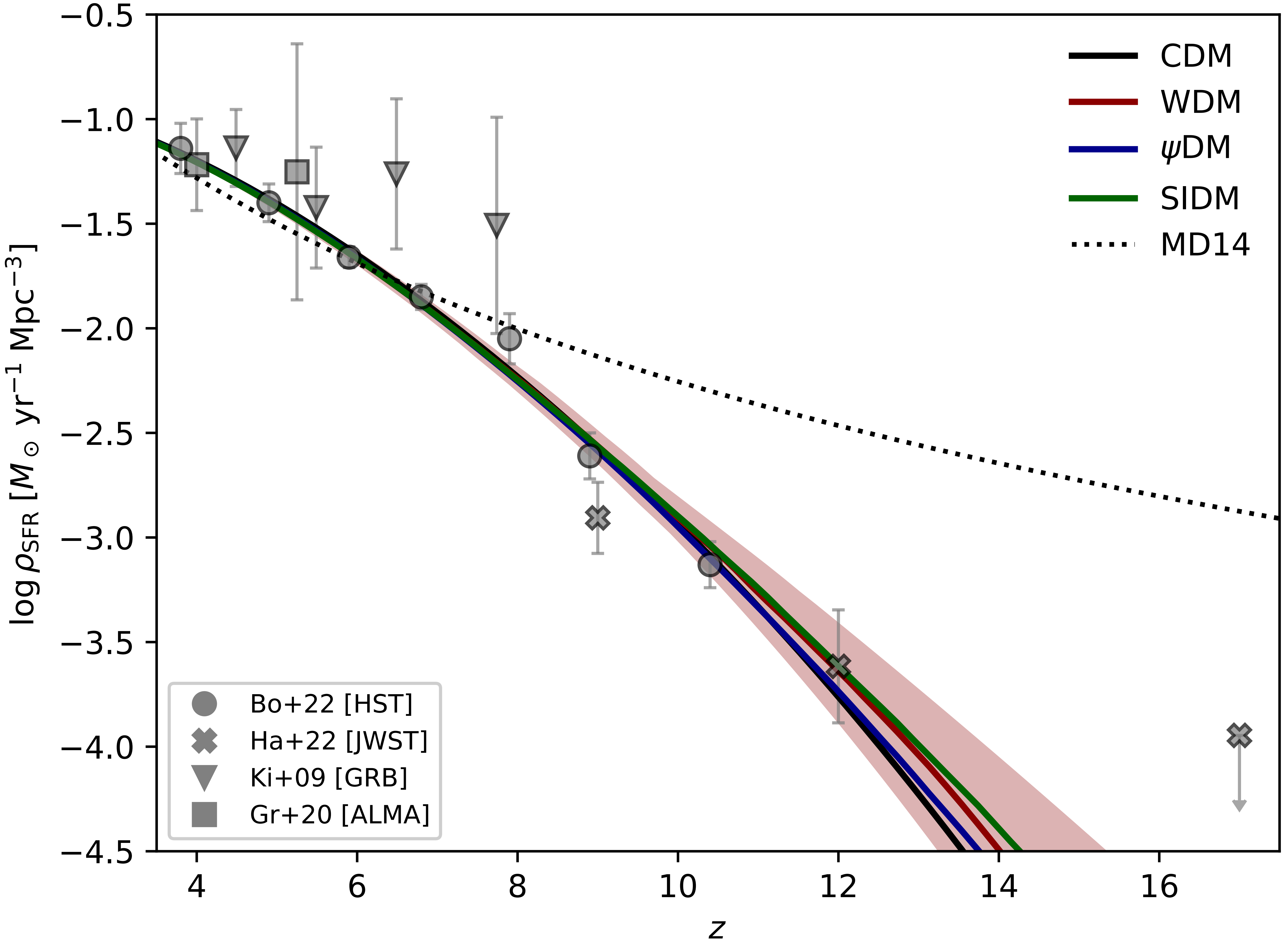
Spoilers!

$$\mathrm{BIC} \equiv -2 \ln \mathscr{L}_{\max} + N_{\mathrm{par}} \ln N_{\mathrm{data}}$$

$$\mathrm{DIC} \equiv -2 \log \mathscr{L}(\bar{\theta}) + 2p_D$$

$$p_D \approx -2\overline{\log \mathscr{L}(\theta)} - 2 \log \mathscr{L}(\bar{\theta})$$

Cosmic Star Formation Rate Density



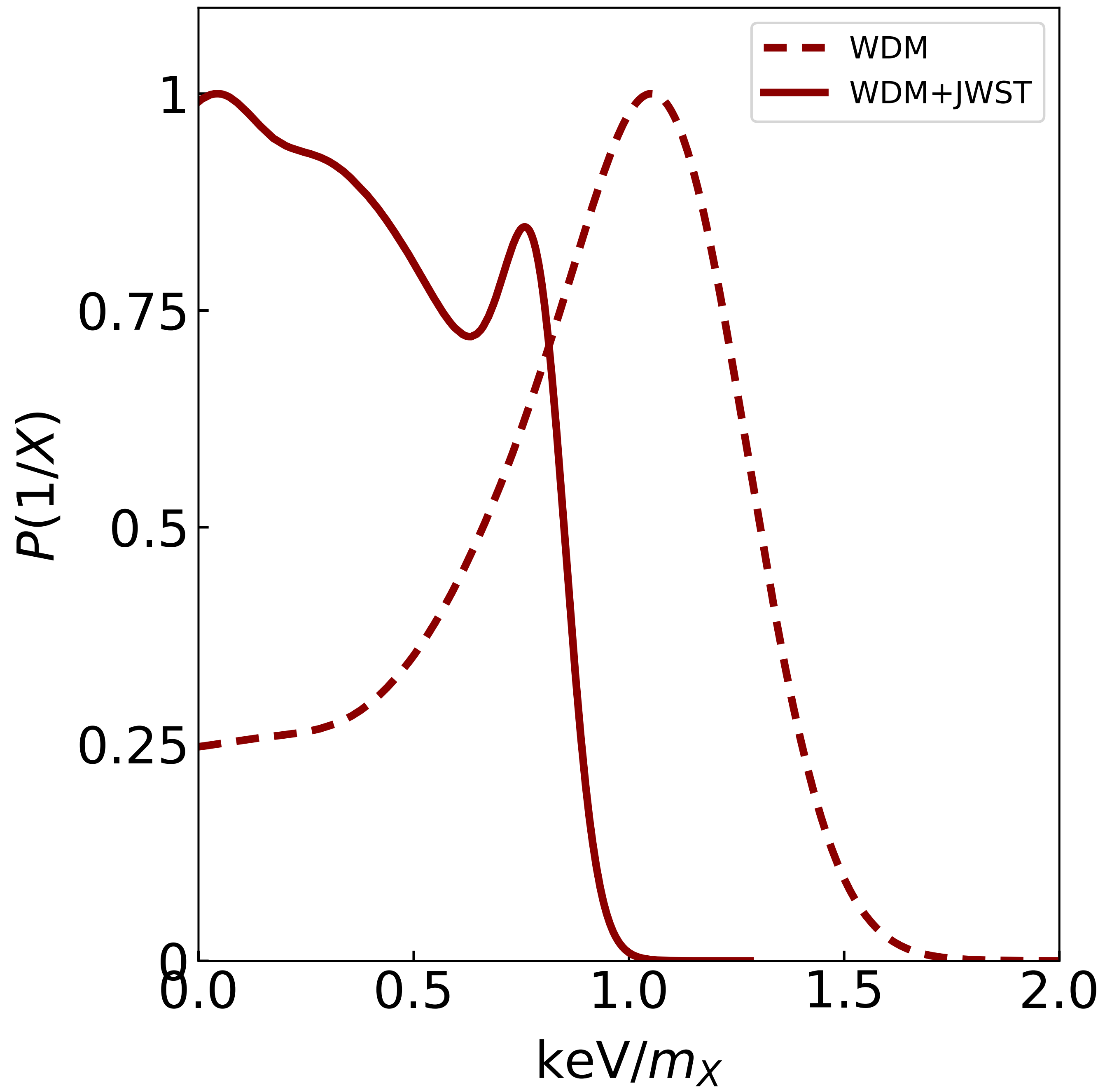
- Best fit VS observed cosmic SFR density (with 95% credible interval)
- DM scenarios are consistent with each other within **2 sigma**
- **JWST data** (9 < z < 12, crosses) around the same values of HST ones but referring to UV luminosities integrated to -17 VS -13.

What if the JWST data are confirmed and extended to ultra-faint magnitudes?

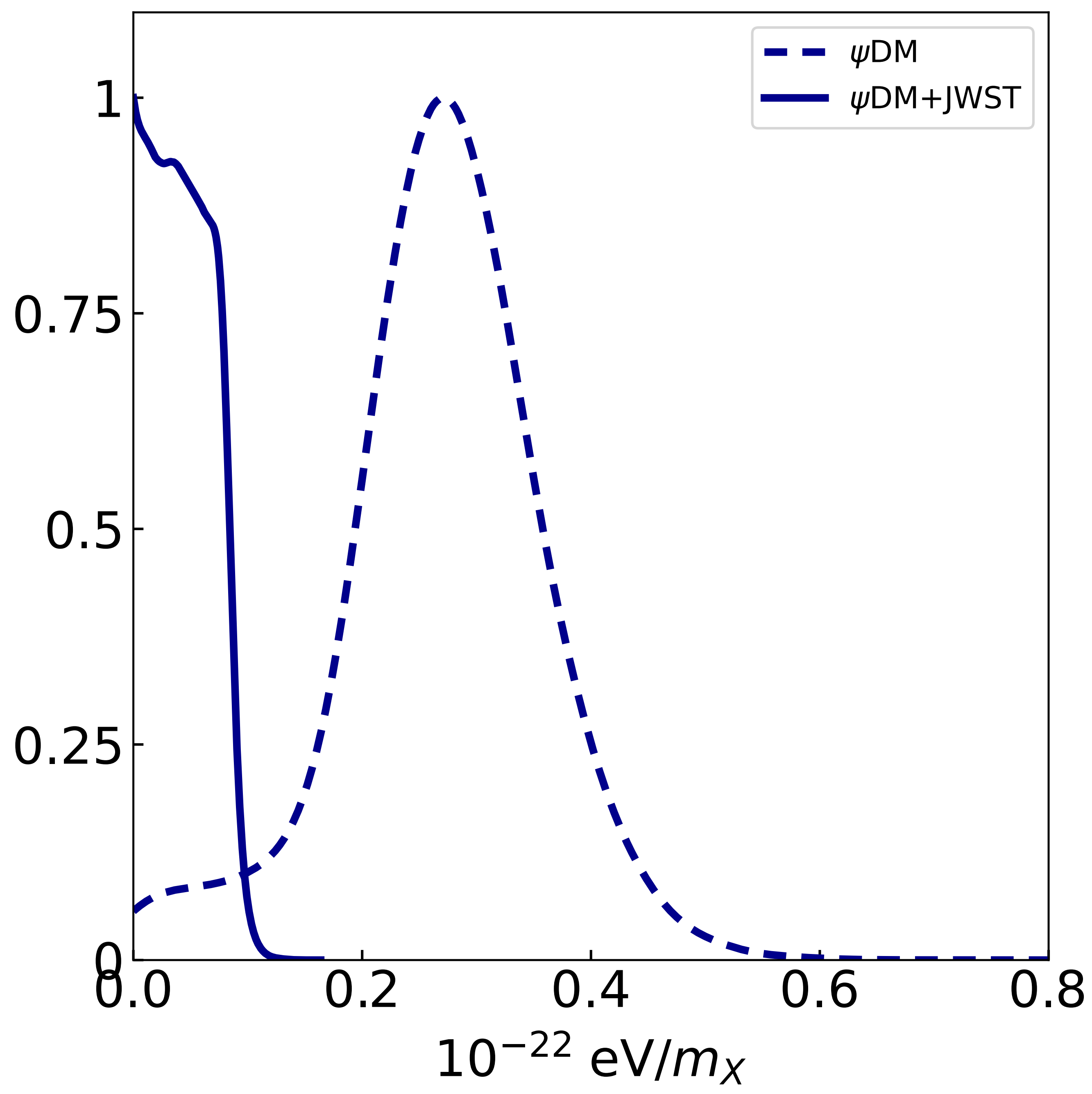
Cosmic Star Formation Rate Density

- We scaled up by 0.4 dex the UV luminosity estimate by JWST (Harikane+22) at z>9 to reflect the same increase in cosmic SFR density of the HTS data when integrating the UV luminosity function from -17 to -13
- We assign relative uncertainty to JWST data comparable to the HST one

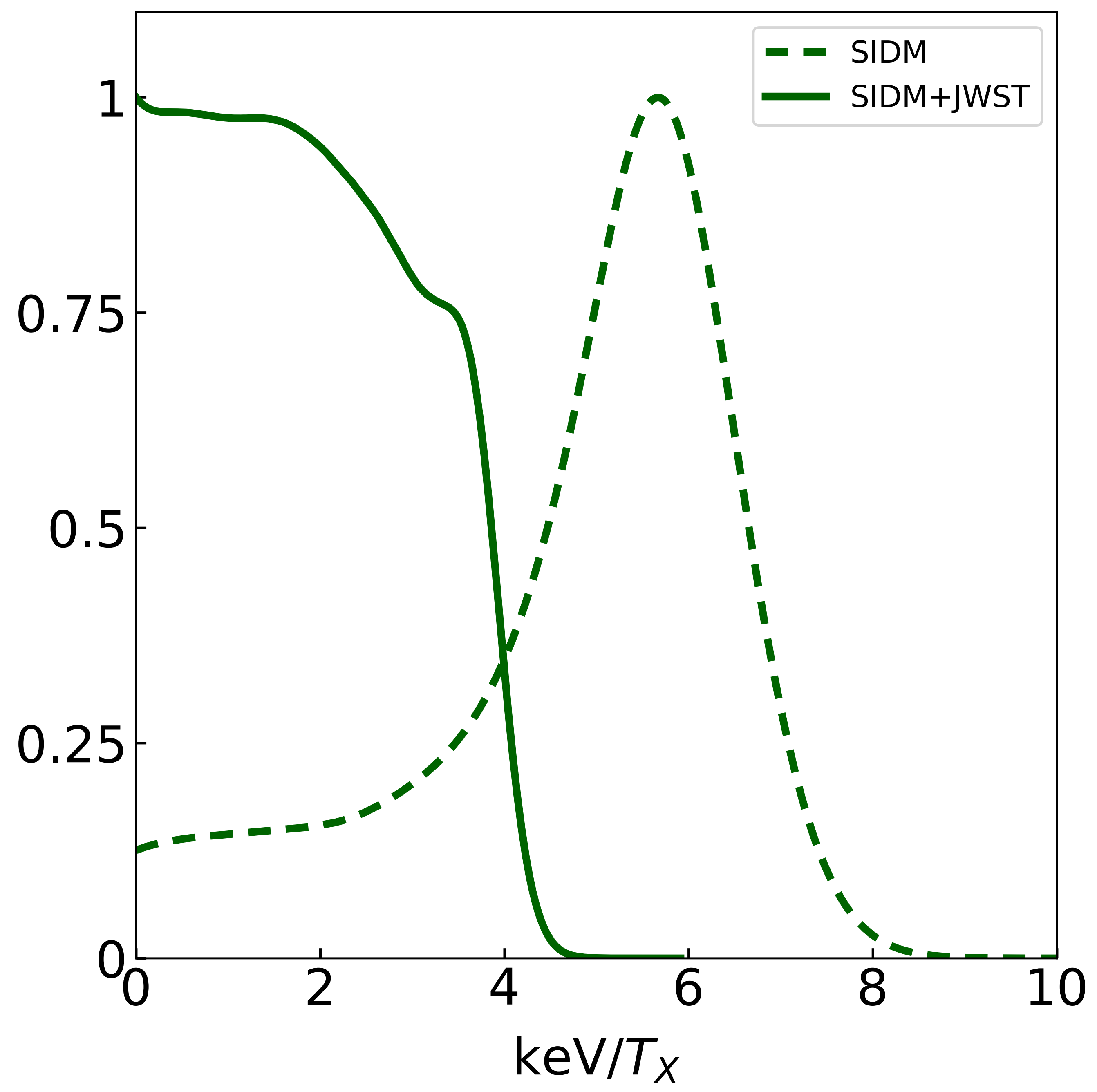
The **higher SFR density** predicted by JWST data goes **in tension** with the suppression of small scales of the power spectrum by alternative DM scenarios



$$m_X \gtrsim 1.8(1.2)\mathrm{keV}$$



$$m_X \gtrsim 17.3(12)\times 10^{-22}\mathrm{eV}$$



$$T_X > 0.4(0.3)\mathrm{keV}$$

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ψDM	$< 7.9\,(< 9.3)$	$3.7^{+1.8\,(+12.9)}_{-0.9\,(-1.4)}$	≈ 33	≈ 14
SIDM	$7.6^{+2.2\,(+2.3)}_{-1.1\,(-3.2)}$	$0.21^{+0.04\,(+1.8)}_{-0.06\,(-0.07)}$	≈ 33	≈ 14
CDM + JWST forecast	$< 7.2\,(< 8.5)$	–	≈ 89	≈ 130
WDM + JWST forecast	$< 6.6\,(< 8.2)$	$> 1.8\,(> 1.2)$	≈ 87	≈ 125
ψDM + JWST forecast	$6.2^{+1.3}_{-1.3}\,(< 8.2)$	$> 17.3\,(> 12)$	≈ 92	≈ 135
SIDM + JWST forecast	$< 6.8\,(< 8.3)$	$> 0.4\,(> 0.3)$	≈ 89	≈ 130

Take home message:

Our analysis highlights the relevance of upcoming ultra-faint galaxy surveys in the (pre)reionization era via JWST as a direct probe for

a) The astrophysics of galaxy formation at small scales
b) The microscopic nature of DM

Future prospects:

- Update the forecasts with state-of-the-art determinations of CSFRD estimates
- Find, characterize and secure high-z galaxies candidates (e.g. w/ CEERS)

Thank you!

Bouwens+21

Most **comprehensive** estimation of the rest-frame **UV luminosity function** (from z=2 to z=9) with HST data (> 24.000 sources!).

It uses all of the non-clusters extragalactic legacy fields including:

- Hubble Ultra Deep Field (**HUDF**)
- **Hubble Frontier** parallel fields
- All five **CANDLES** fields (total survey of 1136 $arcmin^2$)
- ERS WFC3/UVIS observations (150 $arcmin^2$ area in the GOODS North/South regions)

Bouwens+22

Determination of the rest-frame UV luminosity function (z=2-9) with lensed galaxies found behind the HFF clusters (> 2500 galaxies) reaching extremely low luminosities (> -14).

Faint end slope results are fully consistent (z=2-9) with blank field studies (Bouwens+21)

(Sub)mm ALMA data

Gruppioni+20: sample of **56 sources** serendipitously detected in ALMA band 7 as part of the **ALPINE** program. These sources were used to derive an estimate for the total infrared luminosity function and to estimate the cosmic star formation rate density up to z=6.

GRB counts

Kistler+09: with GRBs we are witnessing the **death of massive, short-lived stars**. Given their intrinsic intensity, it is possible to infer the star formation rate to very early times (not unbiased tracers of cosmic SFR!).