Astroparticle constraints from high-z galaxies

Presented by **Giovanni Gandolfi** (SISSA, Trieste, Italy)

CORFU2023 - Workshop on Future Accelerators
28/4/2023

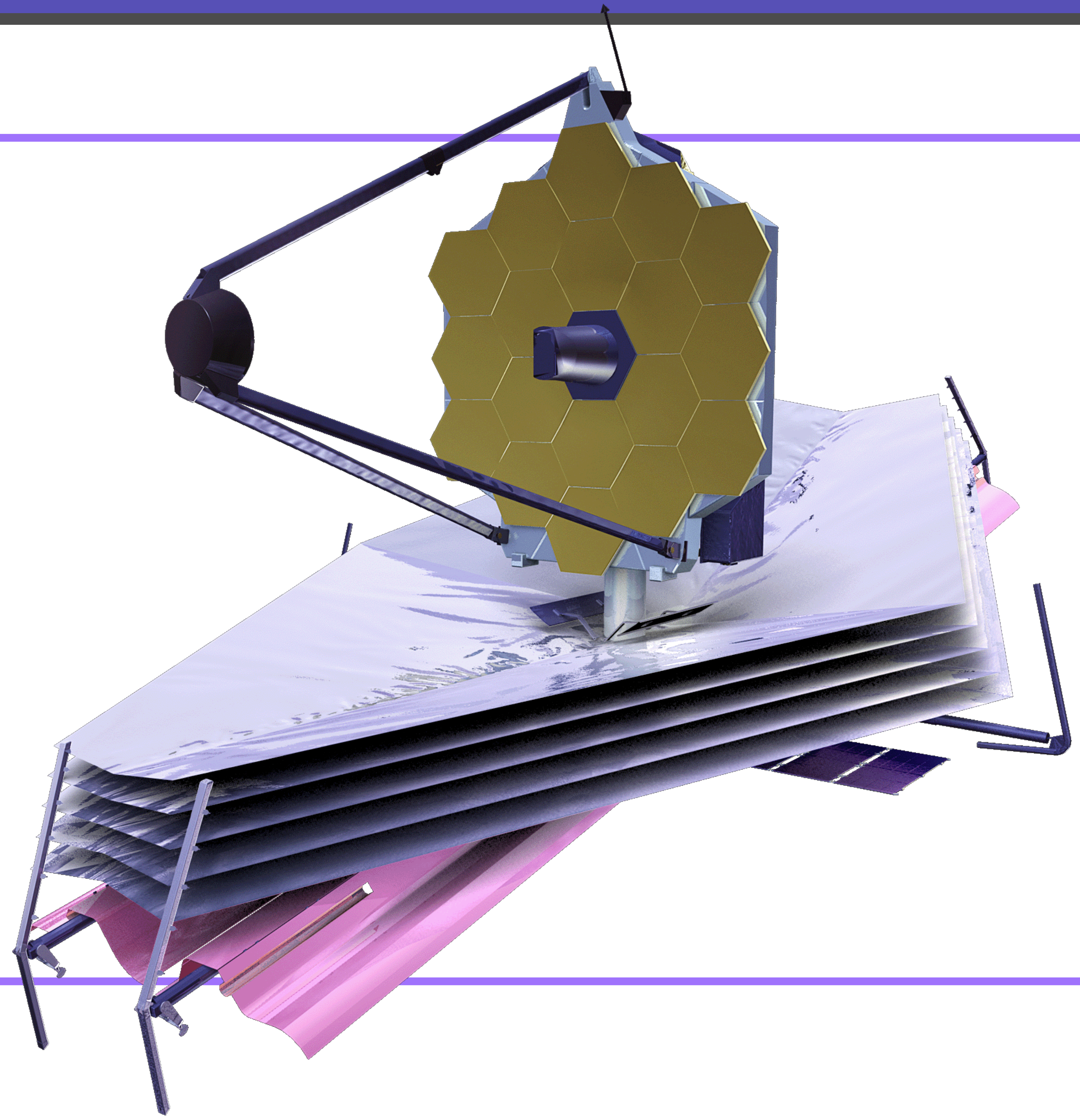
Image credits: CERN

Aim of the talk:

- Review the **state of the art** of astrophysical DM searches and current DM **paradigms**,
- Present **a new way** to constrain DM's APP with cutting-edge instruments & data

Outline:

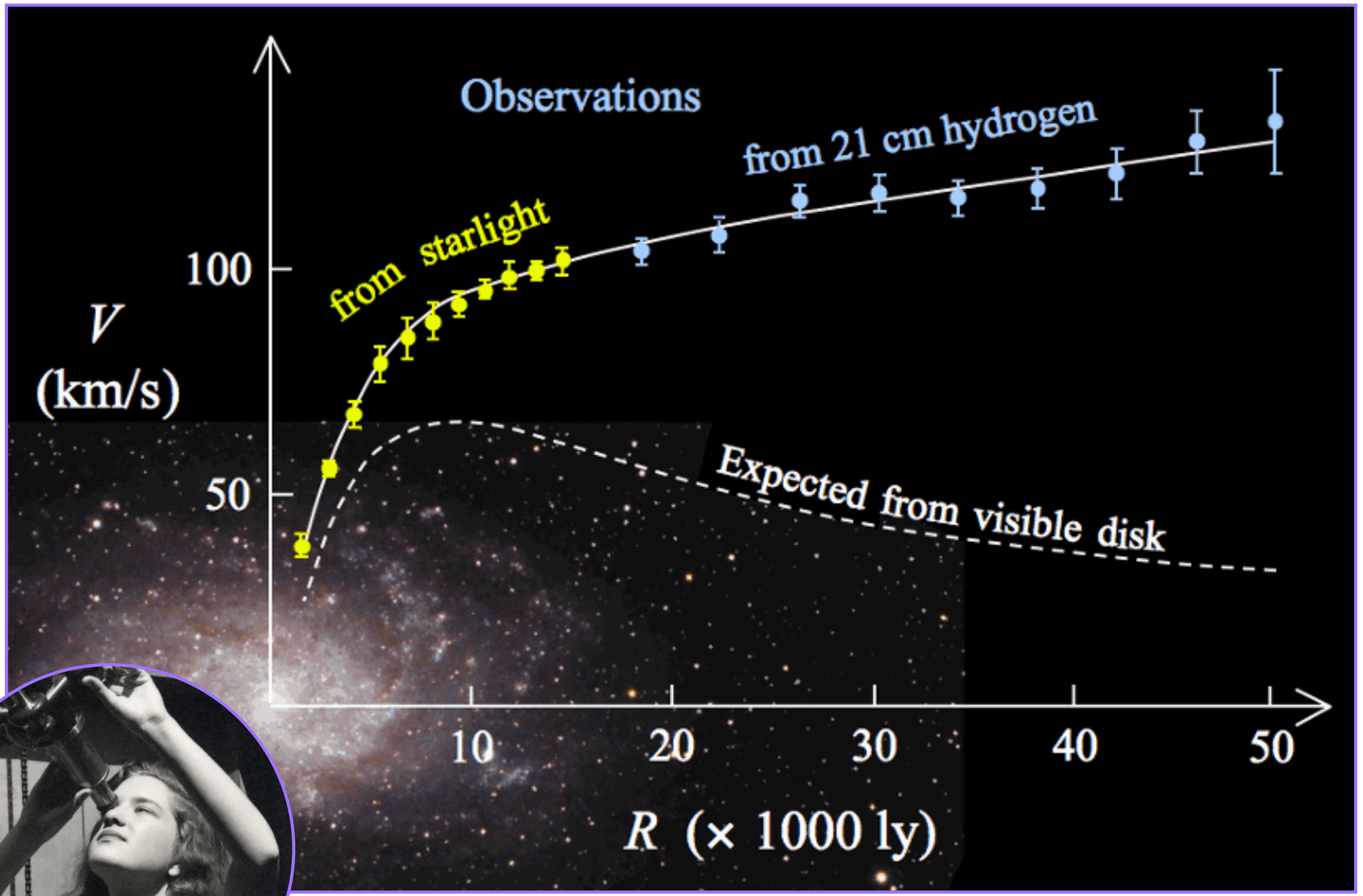
- Introduction (origin of DM)
- DM (astro) state of the art
- High-z galaxy and DM
- Conclusions and future prospects



Dark Matter - story of an idea:

- **1930s**: Fritz Zwicky finds a discrepancy between motion vs light inferred mass of the Coma Cluster. Creates the term "dunkle materie"
- **1970s**: V. Rubin & K. Ford detect a discrepancy between the observed vs. theoretical rotation curve of the Andromeda Galaxy.

This missing mass is interpreted as **Dark Matter**!



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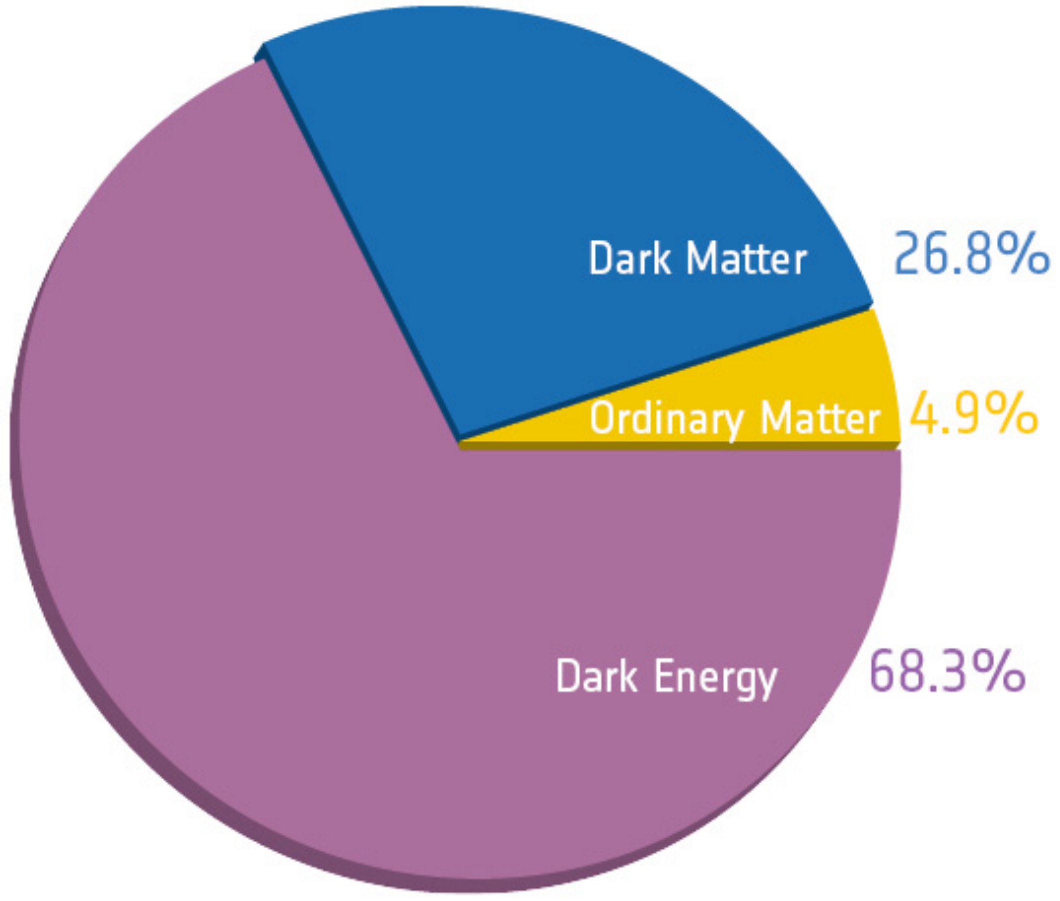
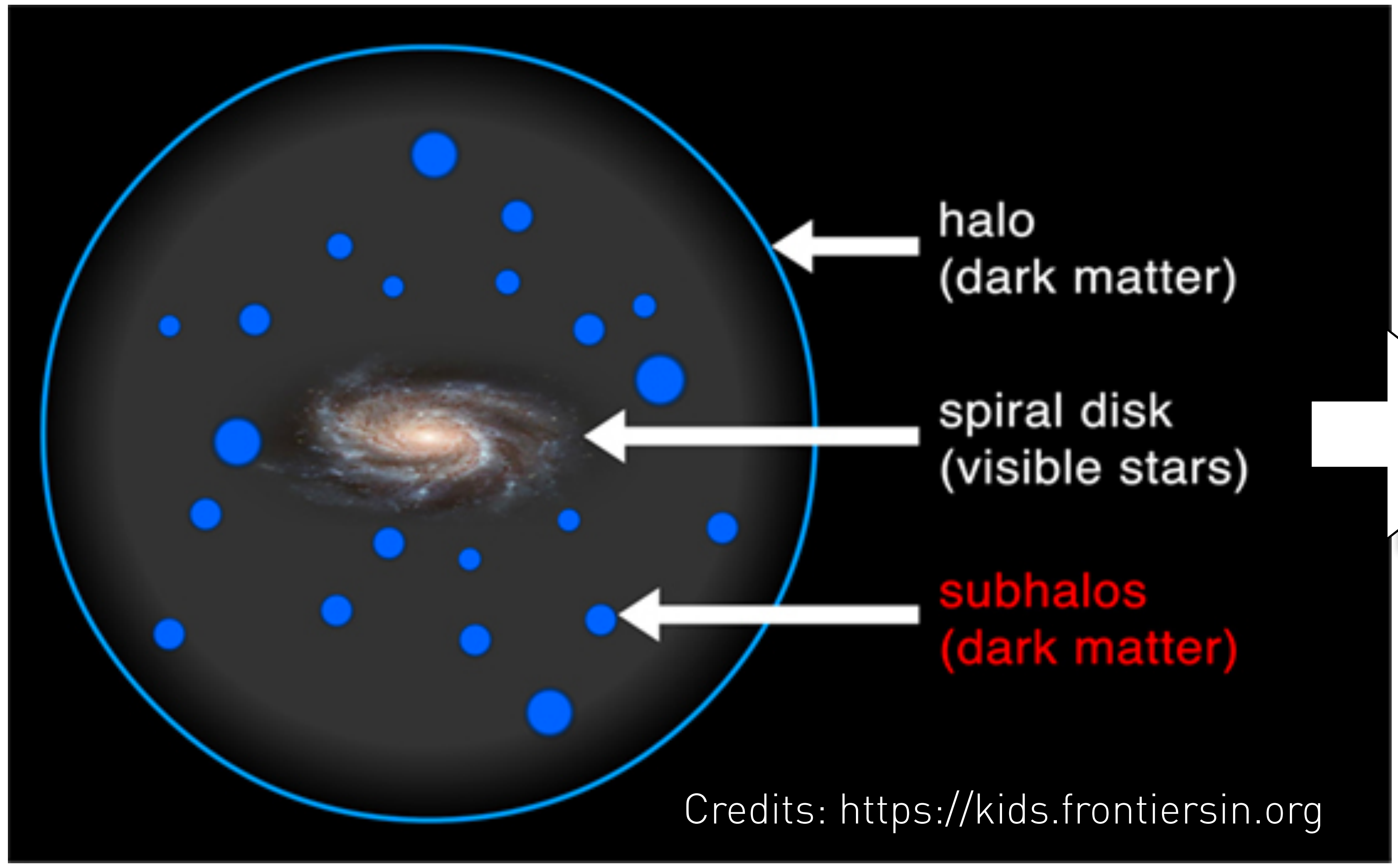
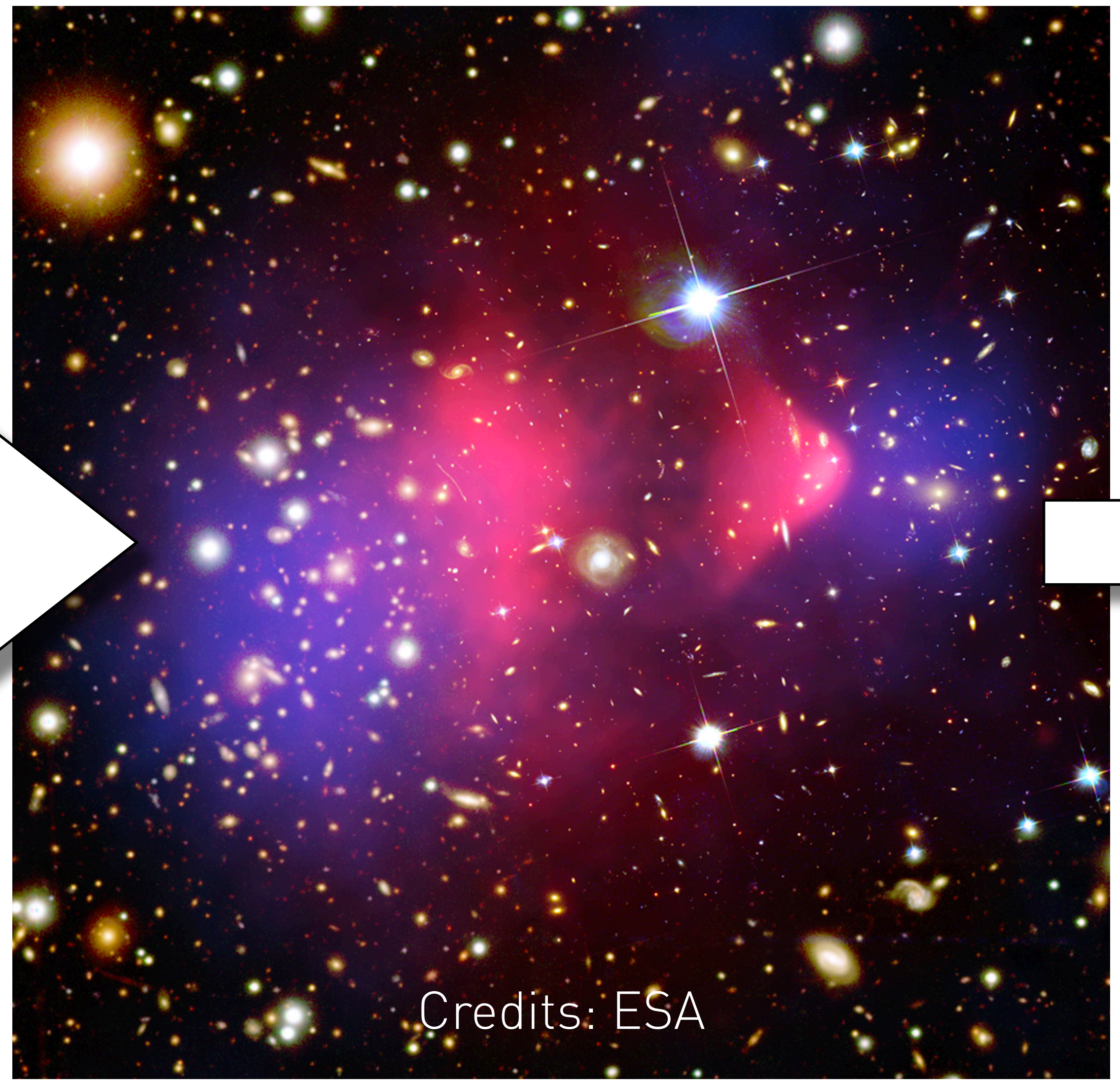
State of the art

- Astro & cosmo probes constrained **baryons** to be ~ **15% of total matter** in the Universe
- DM general characteristics: particle with **weak/negligible interaction** with baryons except with **gravity**
- DM is a crucial ingredient in **structure formation**





Credits: https://kids.frontiersin.org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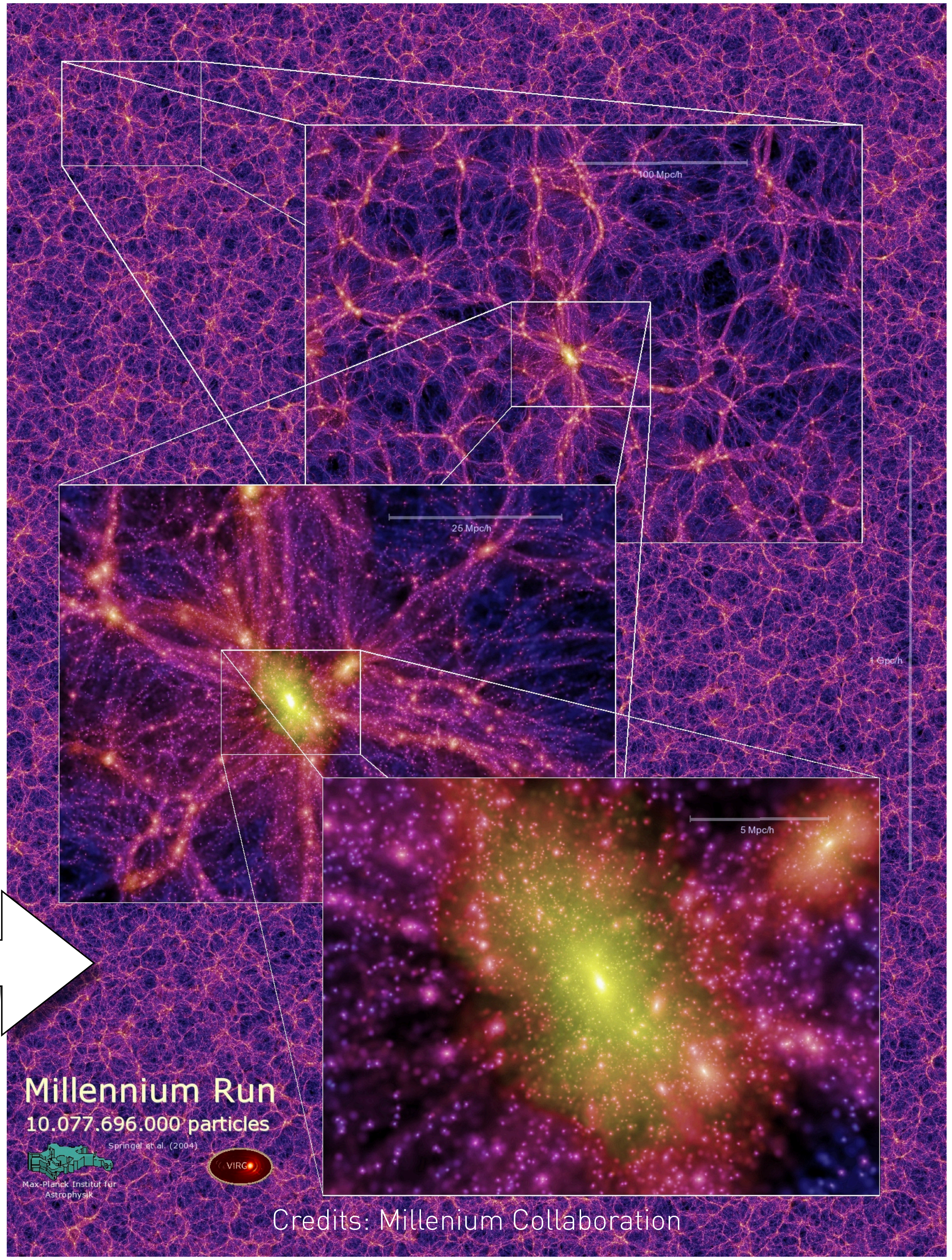


Credits: Millenium Collaboration

Cold Dark Matter (CDM)

DM interpretation in the concordance cosmological model (ΛCDM)

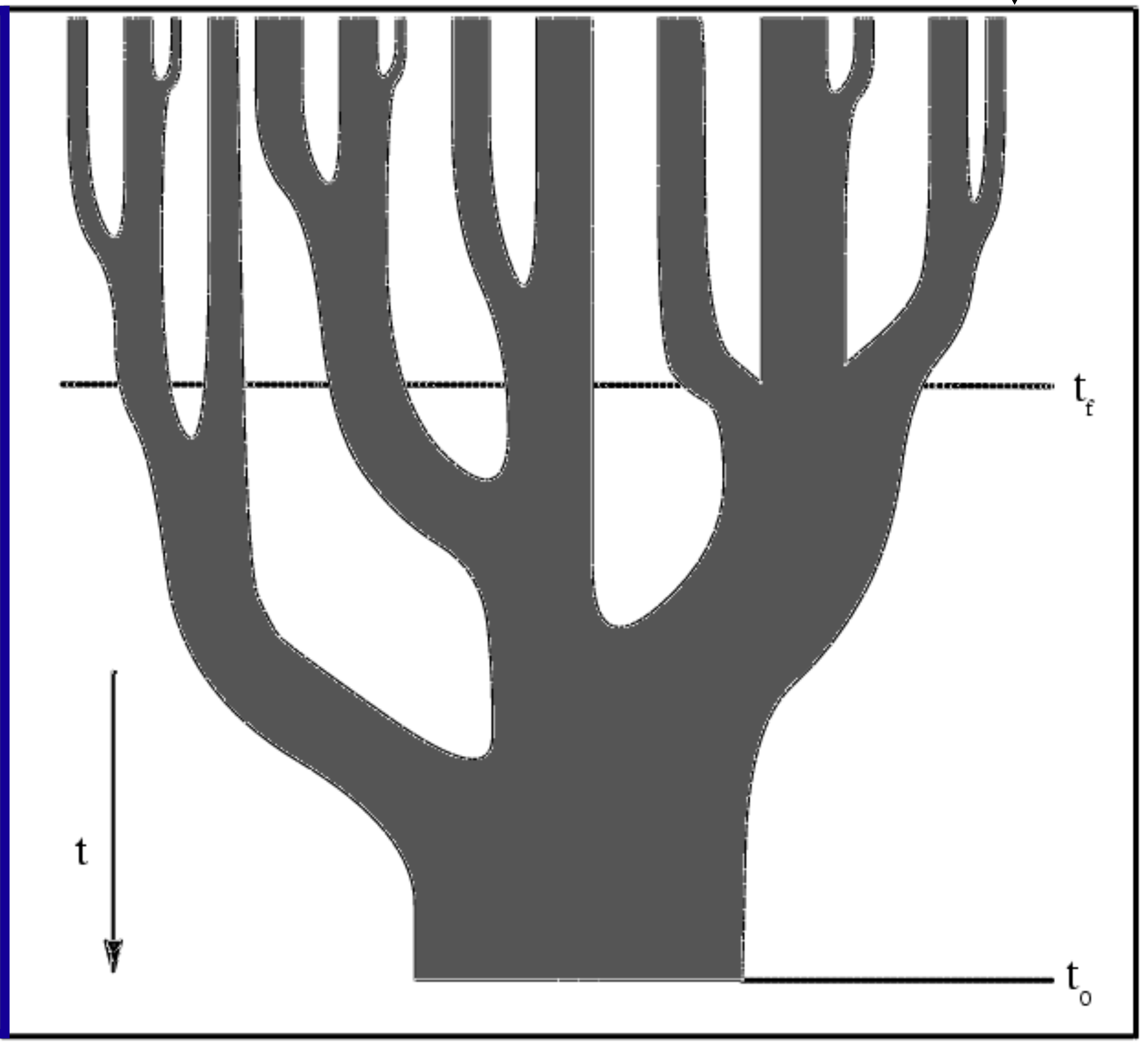
- "Cold" = **non-relativistic** at the epoch of decoupling
- Dissipationless, collisionless
- WIMPs (GeV), PBHs, axions
- Negligible free-streaming velocities, **hierarchical structure formation** w/ stochastic merging

CDM strengths: cosmology

- Structure of the **Cosmic Microwave Background**
- The **large scale structures** in the distribution of galaxies
- Abundances of chemical in the **Big Bang Nucleosynthesis**
- Prediction of **Baryonic Acoustic Oscillations**
- Statistics of **weak gravitational lensing**

CDM weaknesses: galactic scales

- Discrepancies with **simulations** (core-cusp problem, missing satellites problem, angular momentum problem, too-big-to-fail problem)
- Interplay between **baryons** and **DM** inside galaxies
- Tension with unexpected **high-z massive galaxies** found by JWST?



Credits: Lacey and Cole MNRAS 262 627 1993

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 particles with $m_\chi \sim O(10^{-22}\ \text{eV})$

Self-Interacting Dark Matter (SIDM)

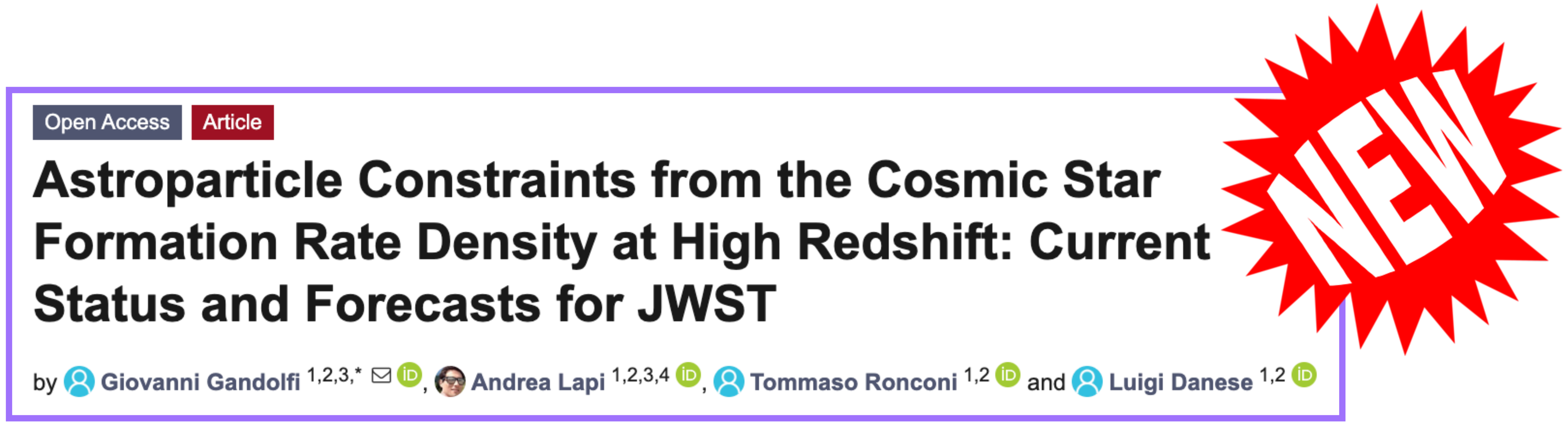
$10 < m_\chi < 250$ MeV, $\sigma_{\chi\chi}/m_\chi \sim 0.1\text{-}1\ \text{cm}^2/\text{g}$ (cf. ETHOS), kinetic T_χ at decoupling

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

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

Astrophysical probes of DM particle 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)


Open Access Article

Astroparticle Constraints from the Cosmic Star Formation Rate Density at High Redshift: Current Status and Forecasts for JWST

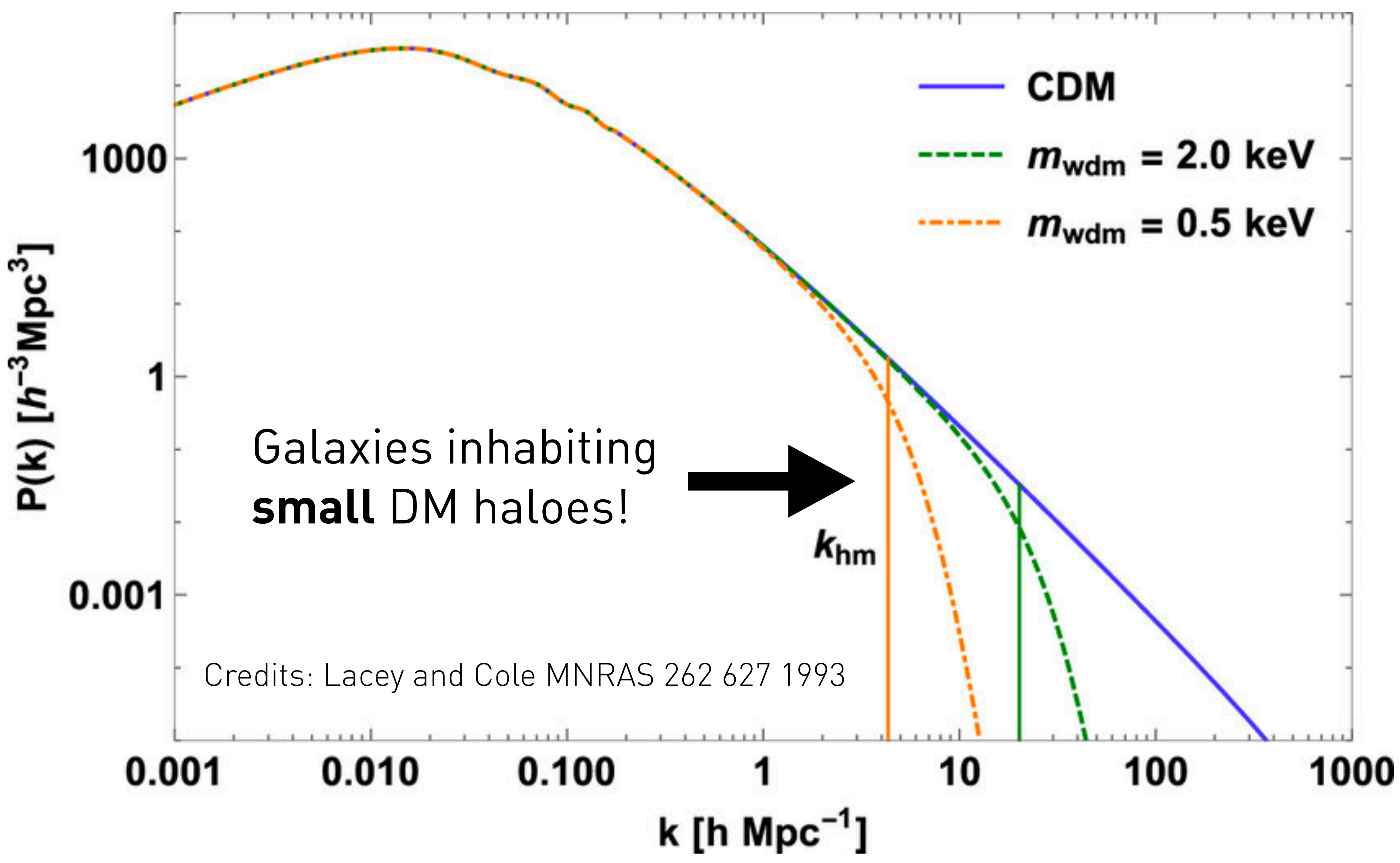
by Giovanni Gandolfi [1,2,3,*], Andrea Lapi [1,2,3,4], Tommaso Ronconi [1,2] and Luigi Danese [1,2]

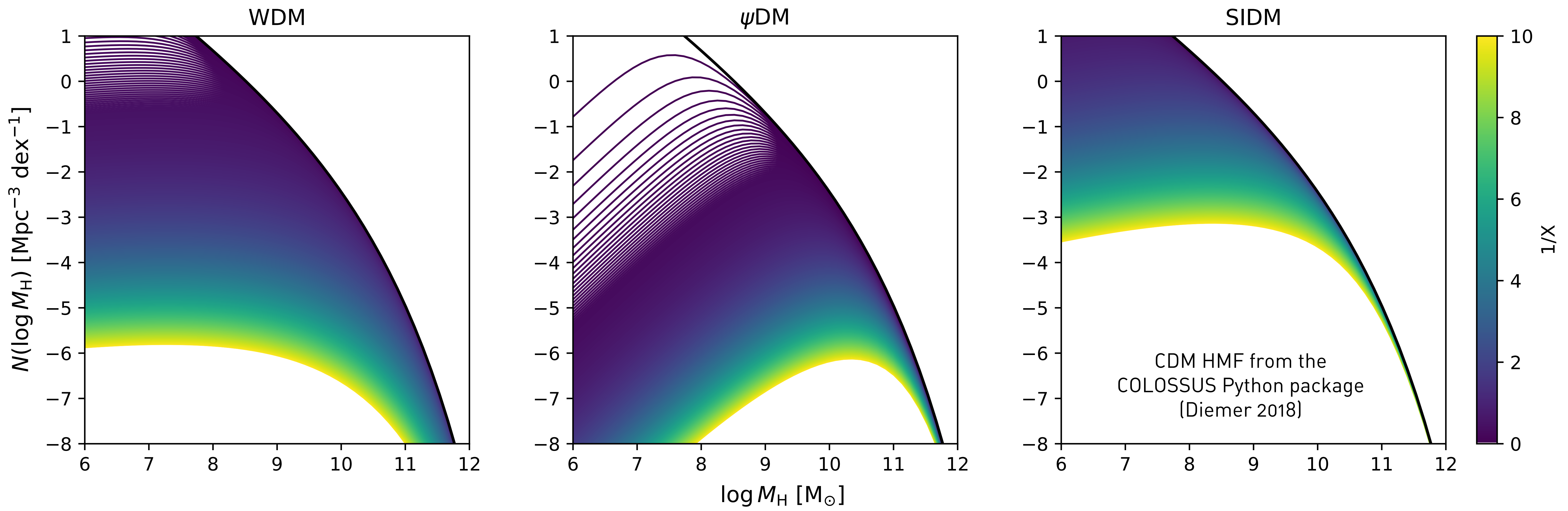
Small scales suppression

CDM vs alternative models: **suppression** on **small scales** of DM power spectrum due to free-streaming, quantum pressure, dark sector interactions

Different APP can **hinder** the formation of **low mass DM haloes**!

Best understood via the DM **halo mass function**
Below: DM HMF at a reference z = 10





$$\frac{dN}{dM_H dV} = \frac{dN_{CDM}}{dM_H dV}\left[1 + \left(\frac{M_H^{cut}}{M_H}\right)^{\beta}\right]^{-\gamma}$$

... but can we **observe** DM's HMF?

Observing the invisible?

Can we observe **DM's HMF?**

... no! But we can use another observable: the (UV) **luminosity function** of galaxies!

Luminosity function:
Number of galaxies with a given luminosity/magnitude in a certain band per volume unit

M_{UV} - M_H relation
at given z and given X

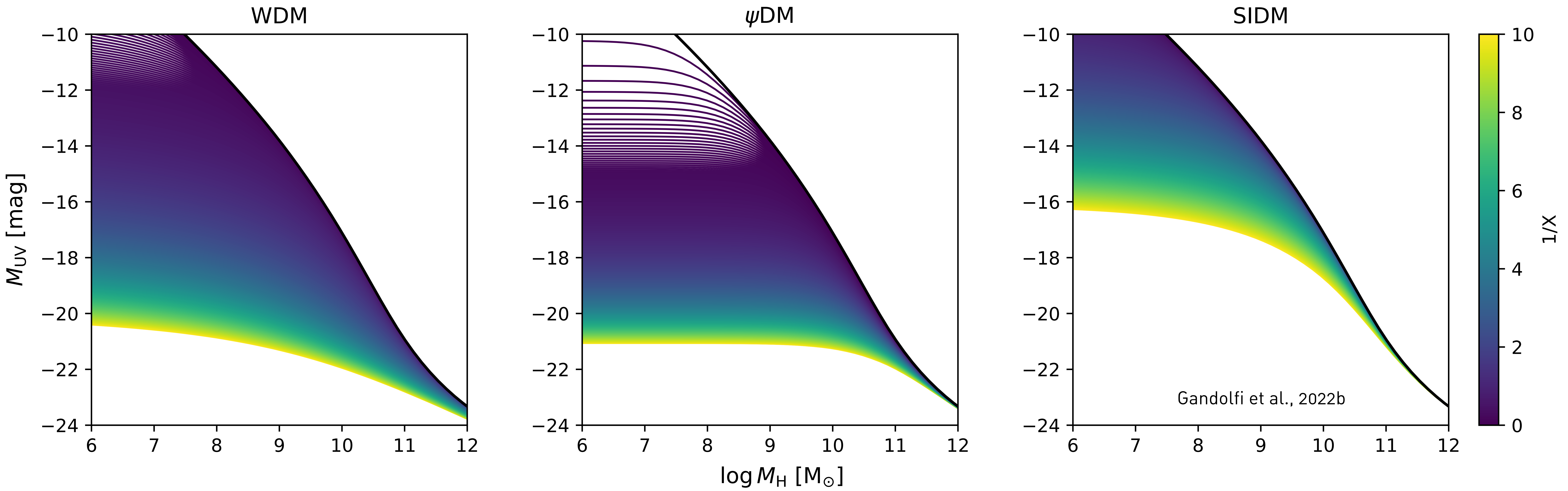
DM HMF:
Number of DM haloes with a given mass per volume unit

Abundance matching: matching the cumulative number densities in galaxies and haloes

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

Aversa+15, Moster+18, Cristofari & Ostriker 2019, Behroozi+20

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)

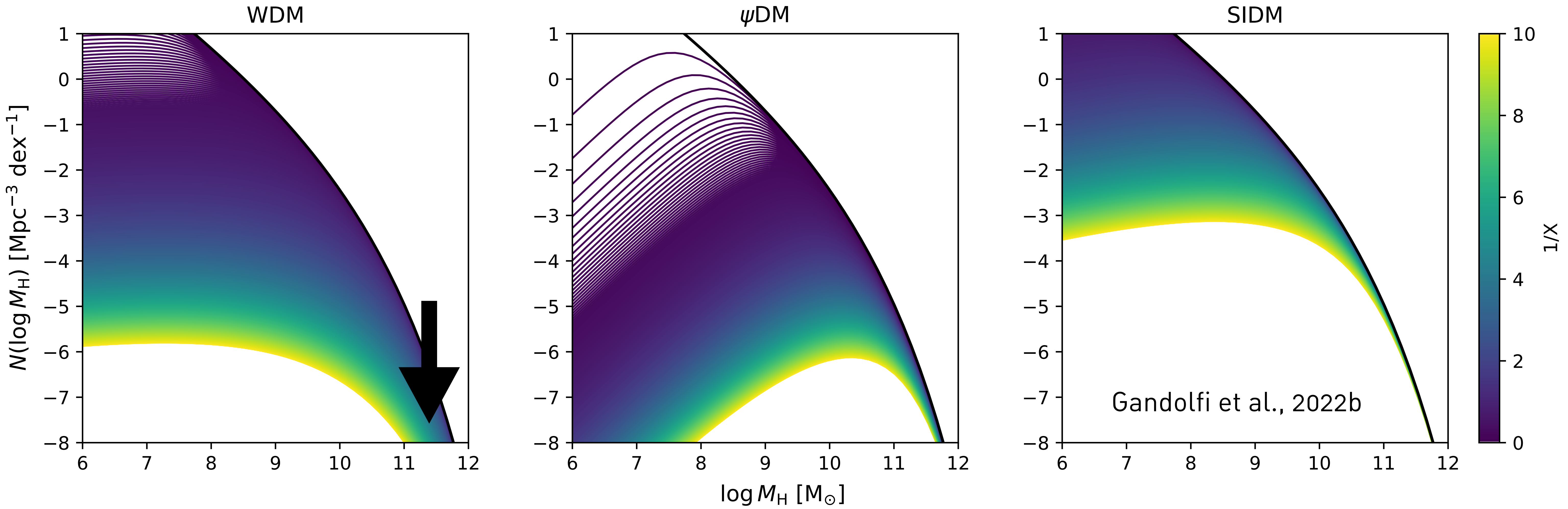
Where to look?

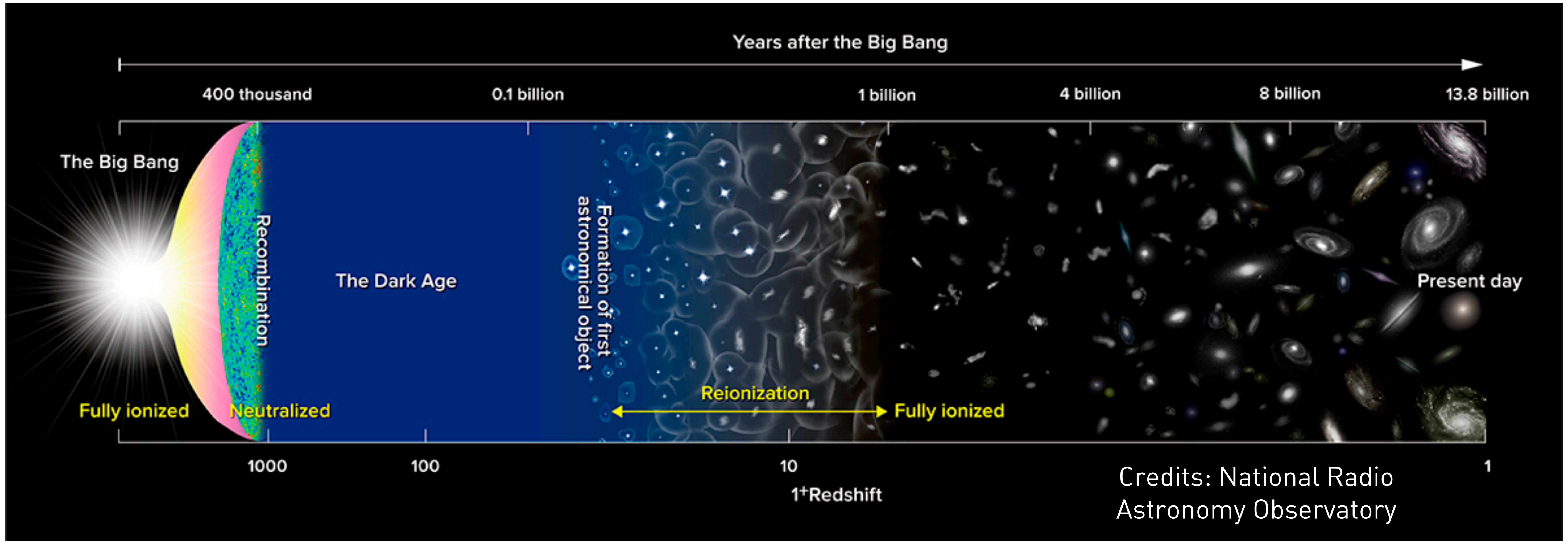
How to constrain the **low mass end** of DM's power spectrum?

We need **faint galaxies** inhabiting small mass DM haloes.

The number of high mass DM haloes is always **depressed** at very high redshift (see z=10 DM's HMFs above).

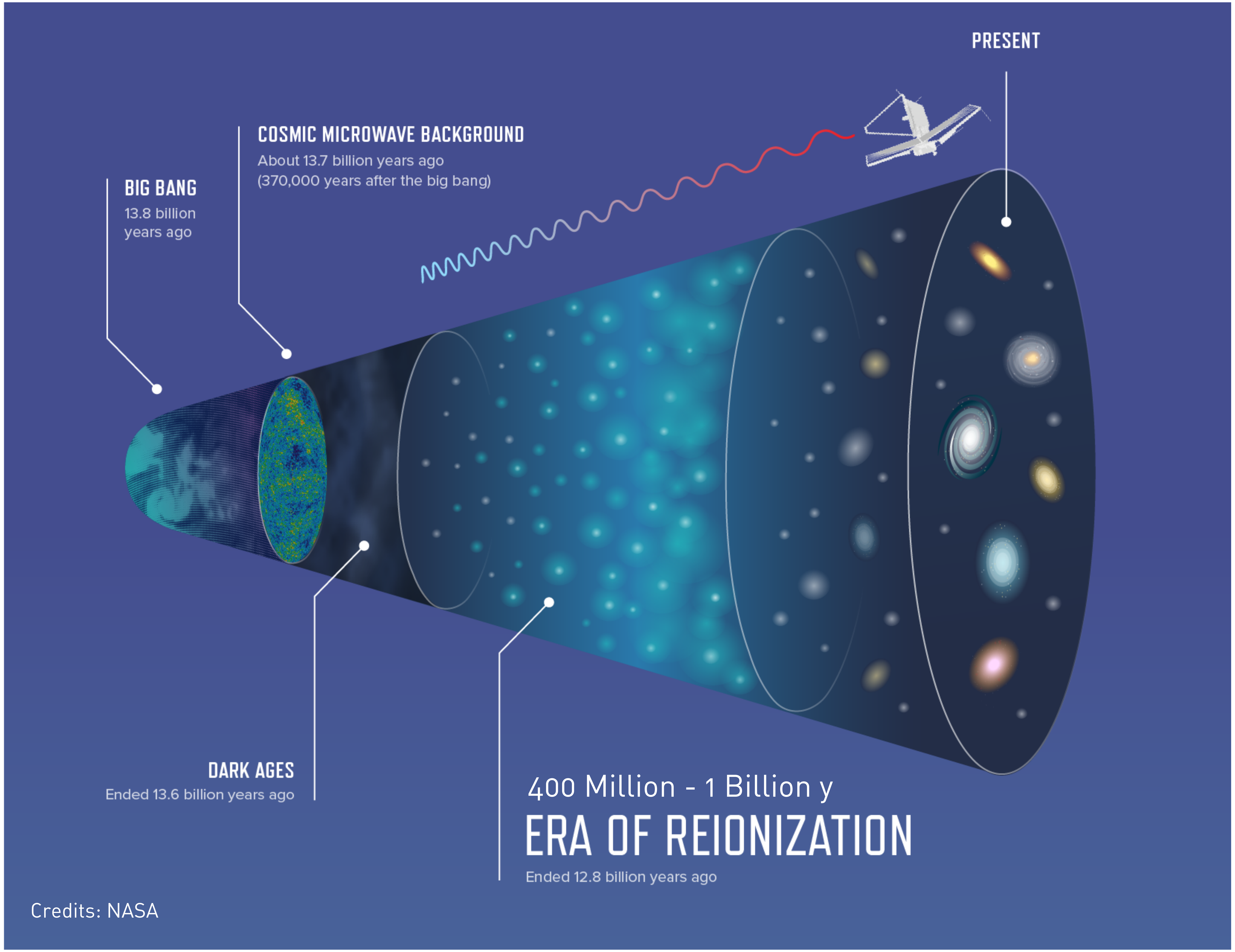
We can **peer into the early Universe** in search of early, ultra-faint primordial galaxies with **brand new technologies.**





Credits: National Radio Astronomy Observatory


Credits: NASA/ESA


PRESENT
COSMIC MICROWAVE BACKGROUND
About 13.7 billion years ago
(370,000 years after the big bang)
BIG BANG
13.8 billion
years ago
DARK AGES
Ended 13.6 billion years ago
400 Million - 1 Billion y
ERA OF REIONIZATION
Ended 12.8 billion years ago
Credits: NASA

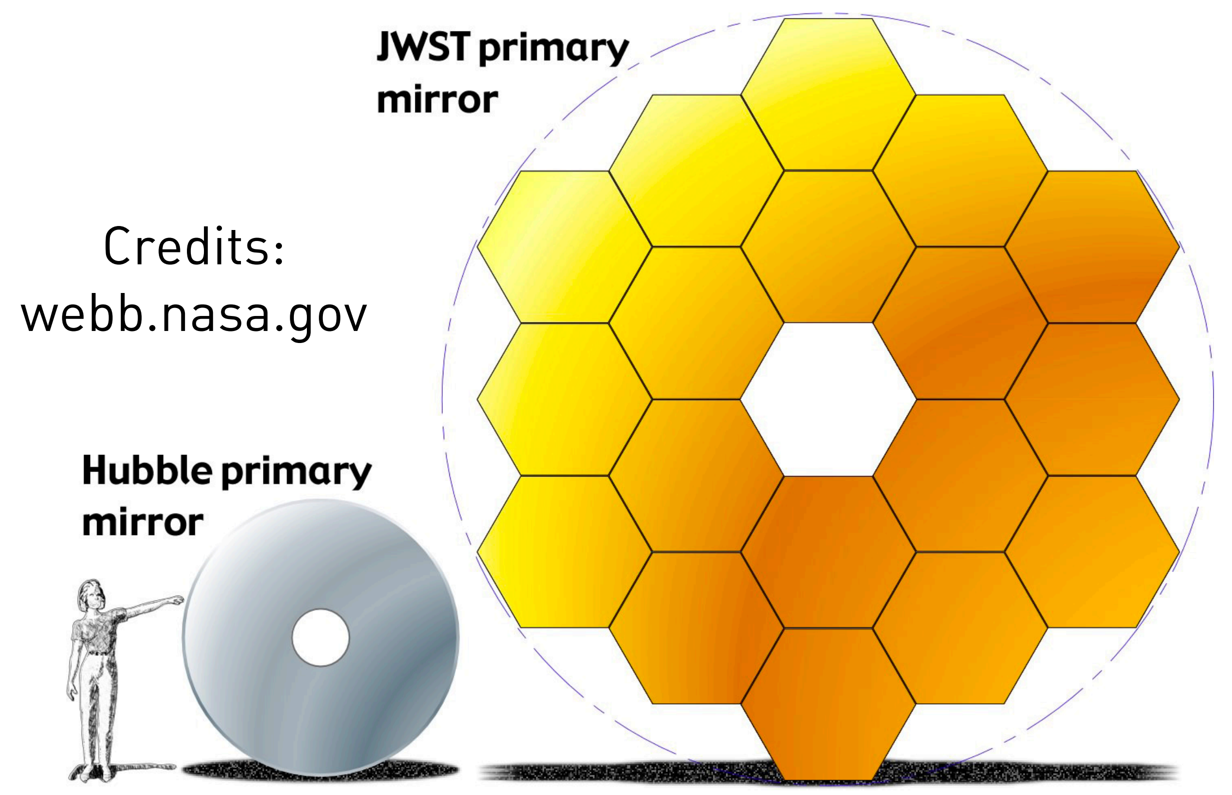
Peering into the early Universe

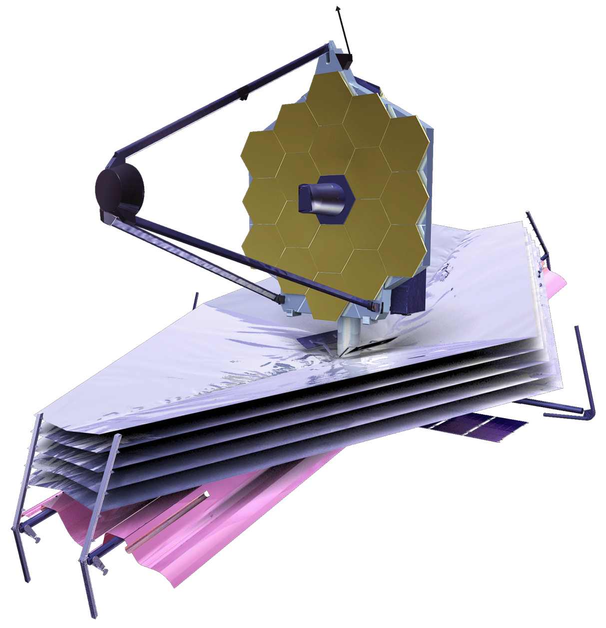
JWST is HST successor: 6x collecting area & larger FOV (15x) wrt HST, **unmatched sensitivity & resolution** in the (N+M)IR band!

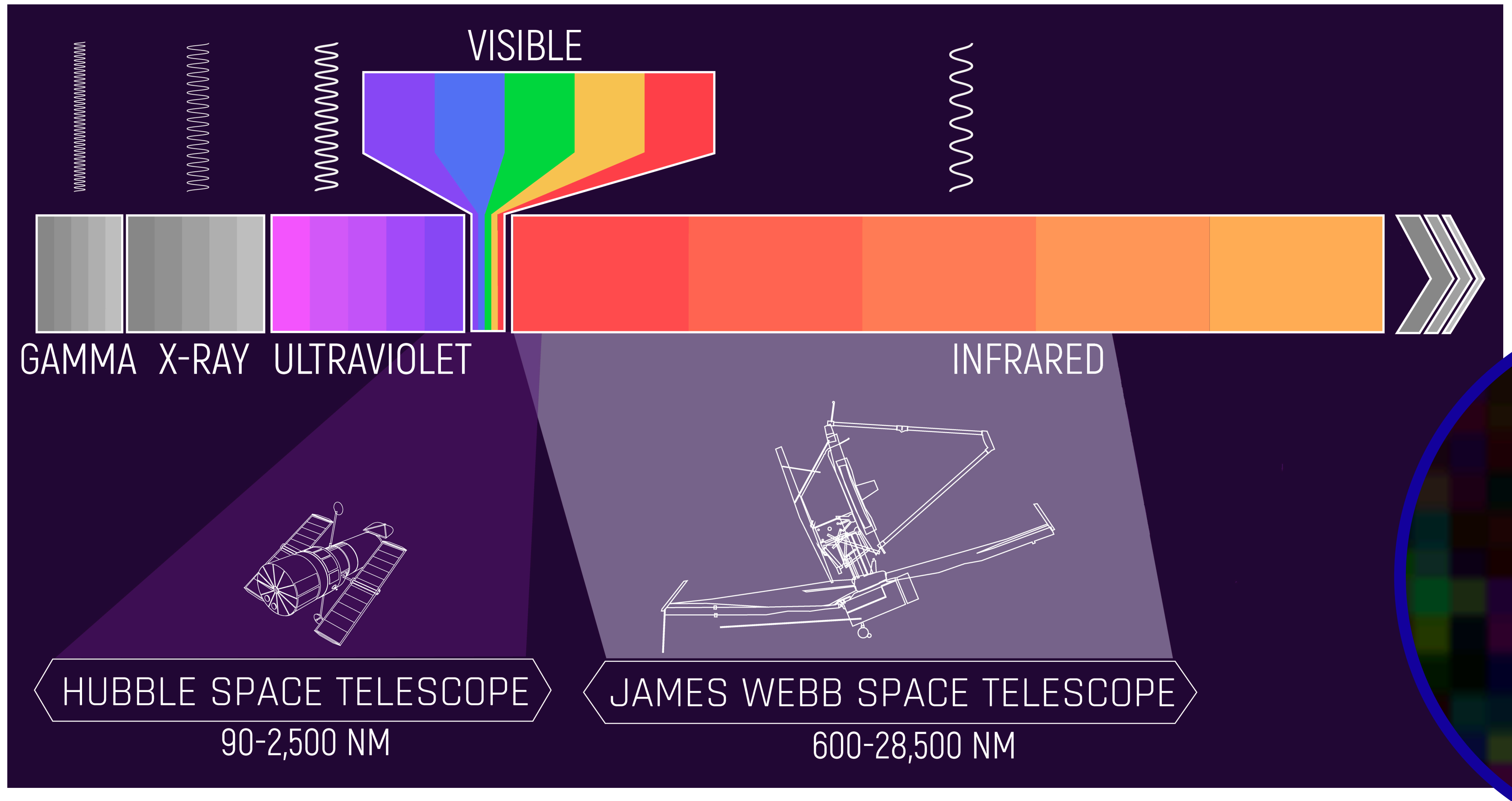
Near-Infrared Camera (NIRCam): JWST's primary imager with a resolution of 0.07 arcsec @ 2 μm (c.a. double of HST's WFC3) and covering longword wavelengths than HST's cutoff.

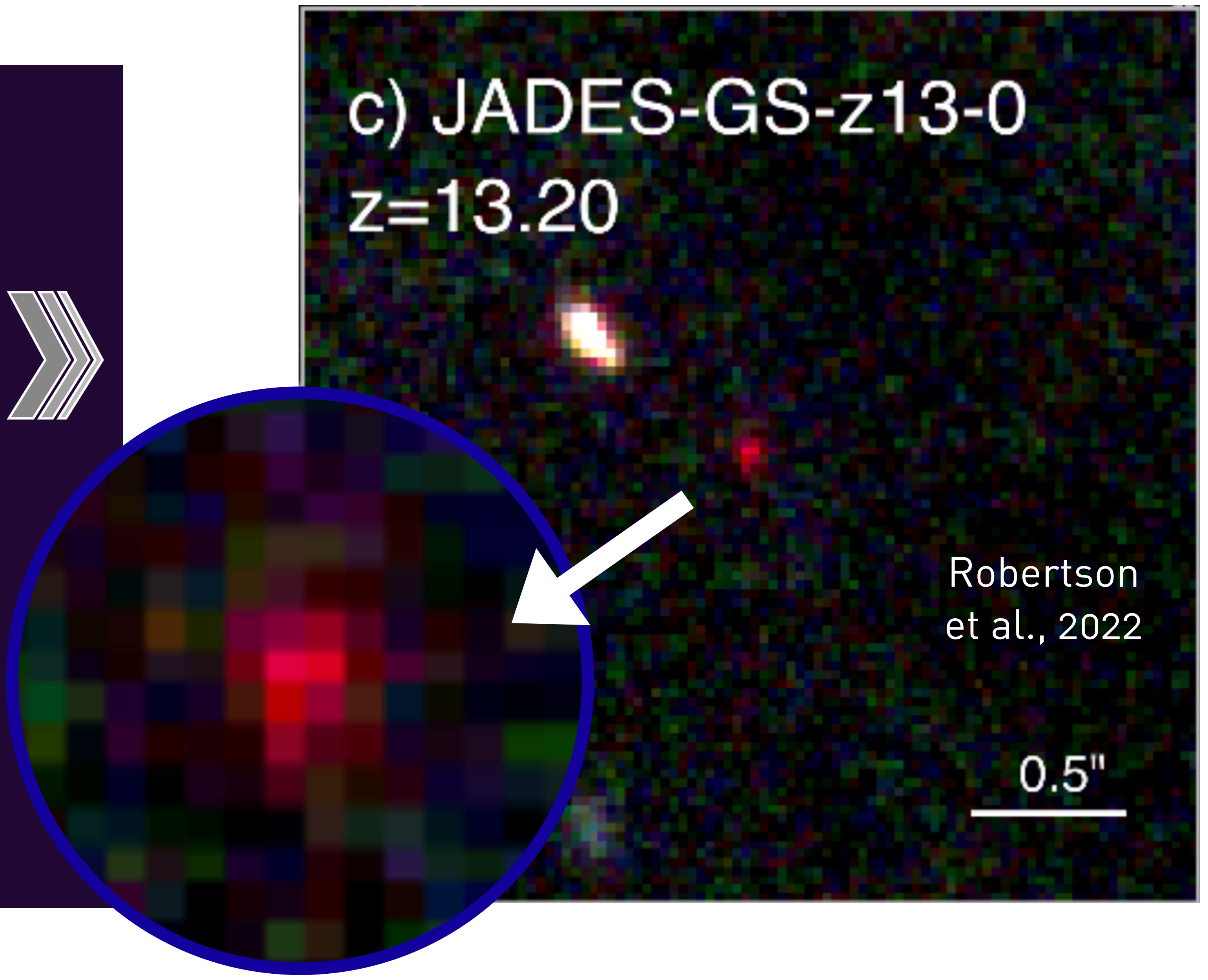
Since July 14th 2022, **over 100 z > 11 galaxy candidates** were revealed by JWST (up to z~16 [CEERS-93316] and z~17 [S5-z17-1]).

(Adams+23, Castellano+22, Donnan+22, Finkelstein+22a, Morishita & Stiavelli+22, Naidu+22a, Atek+23, Yan+23, Rodighiero+23)









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Astroparticle Constraints from the Cosmic Star Formation Rate Density at High Redshift: Current Status and Forecasts for JWST

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Cosmic star formation rate density

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

- The cosmic SFR is a very basic astrophysical quantity that suffers less from observational, systematic and modeling uncertainties.
- $\mathbf{M^{obs}_{UV}}$: faintest limit probed by observations (depends on the dataset considered)
- $\mathbf{M^{lim}_{UV}}$: limit magnitude down to which the luminosity function is steeply increasing (i.e., after which we consider the SFR density to be negligible)

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

- **Galaxy formation processes** becoming inefficient in small haloes (e.g. photo suppression by the UV bkg, ...)
- 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)

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

The analysis

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

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

Datasets: cosmic SFR density constrained by **HST UV luminosity function data** (Bouwens+21,+22); **early JWST UV luminosity function** (Harikane+22); GRB counts data from Fermi (Kistler+09) and (sub)mm luminosity function data from ALMA (Gruppioni+20)

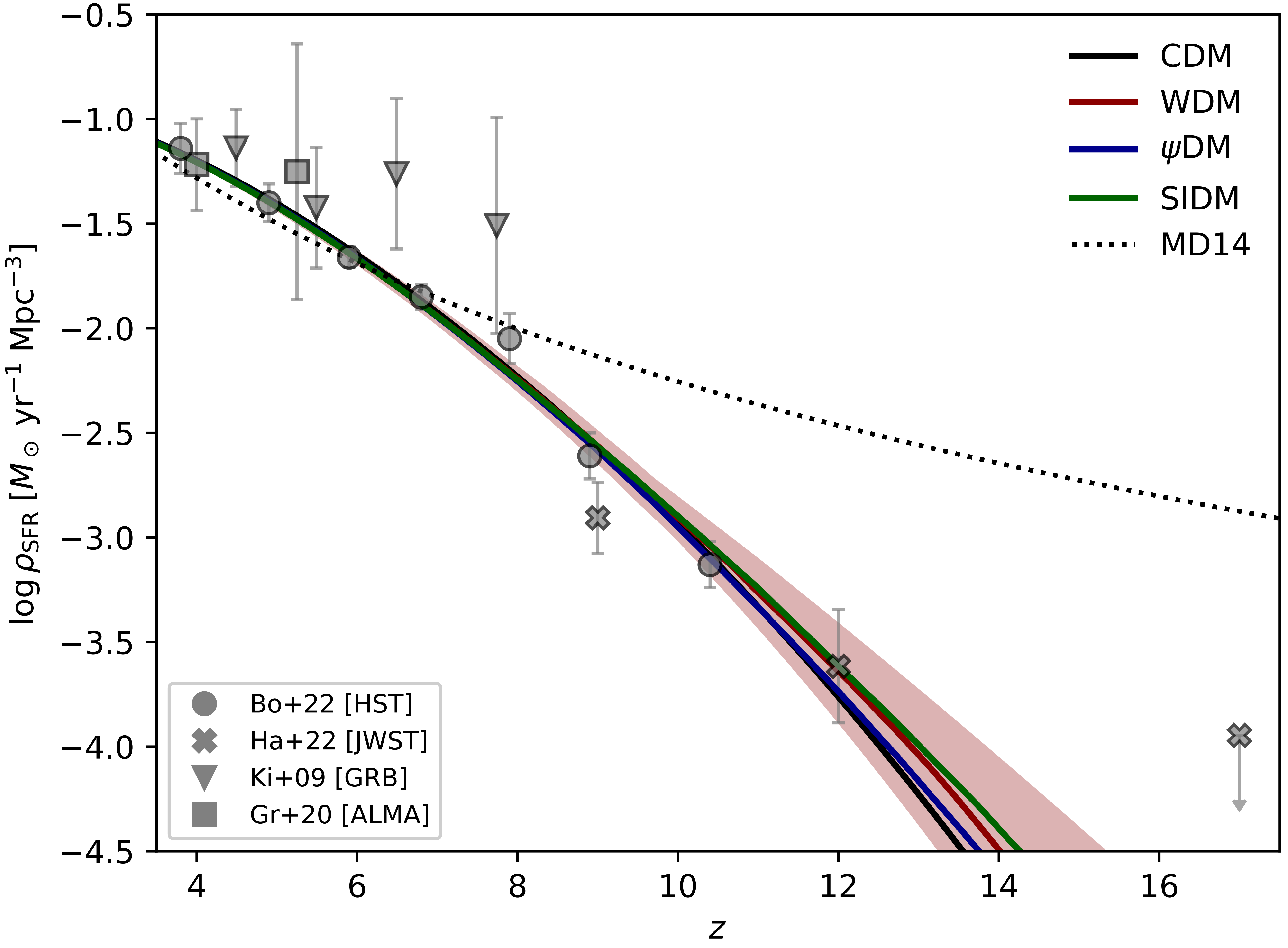
We perform a **Bayesian MCMC fit** (flat priors + gaussian likelihood, 10^4 steps and 200 walkers)
The $M_{\rm obs}^{\rm UV}$ we consider the minimum observational magnitude limit in each dataset.

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

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

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

Cosmic star formation rate density (results)

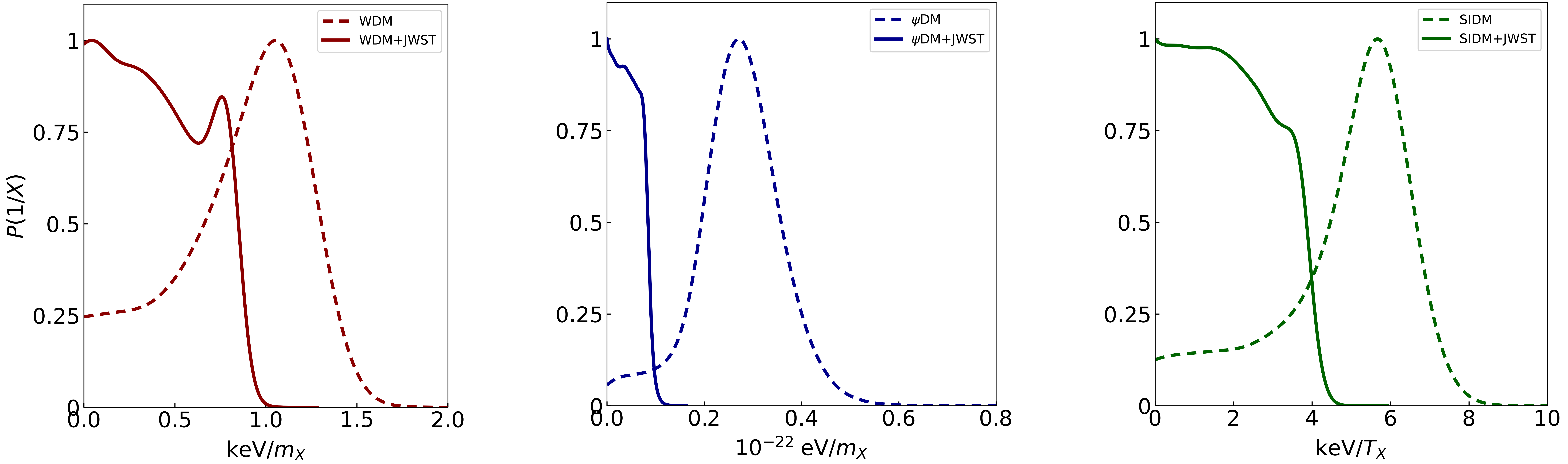


- Best fit VS observed cosmic SFR density (with 95% credible interval)
- DM scenarios are consistent with each other within **2 sigma**
- **JWST data** (9 < z < 12, crosses) around the same values of HST ones but referring to UV luminosities integrated to -17 VS -13.

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

Cosmic star formation rate density (results)

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



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

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

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

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

- New **JWST data** are coming as new high-z galaxies / local ultra-faint objects are discovered!
- New technology to study the dark sector (e.g. **Euclid**, scheduled for launch in **July 2023**).

Backup Slides

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)

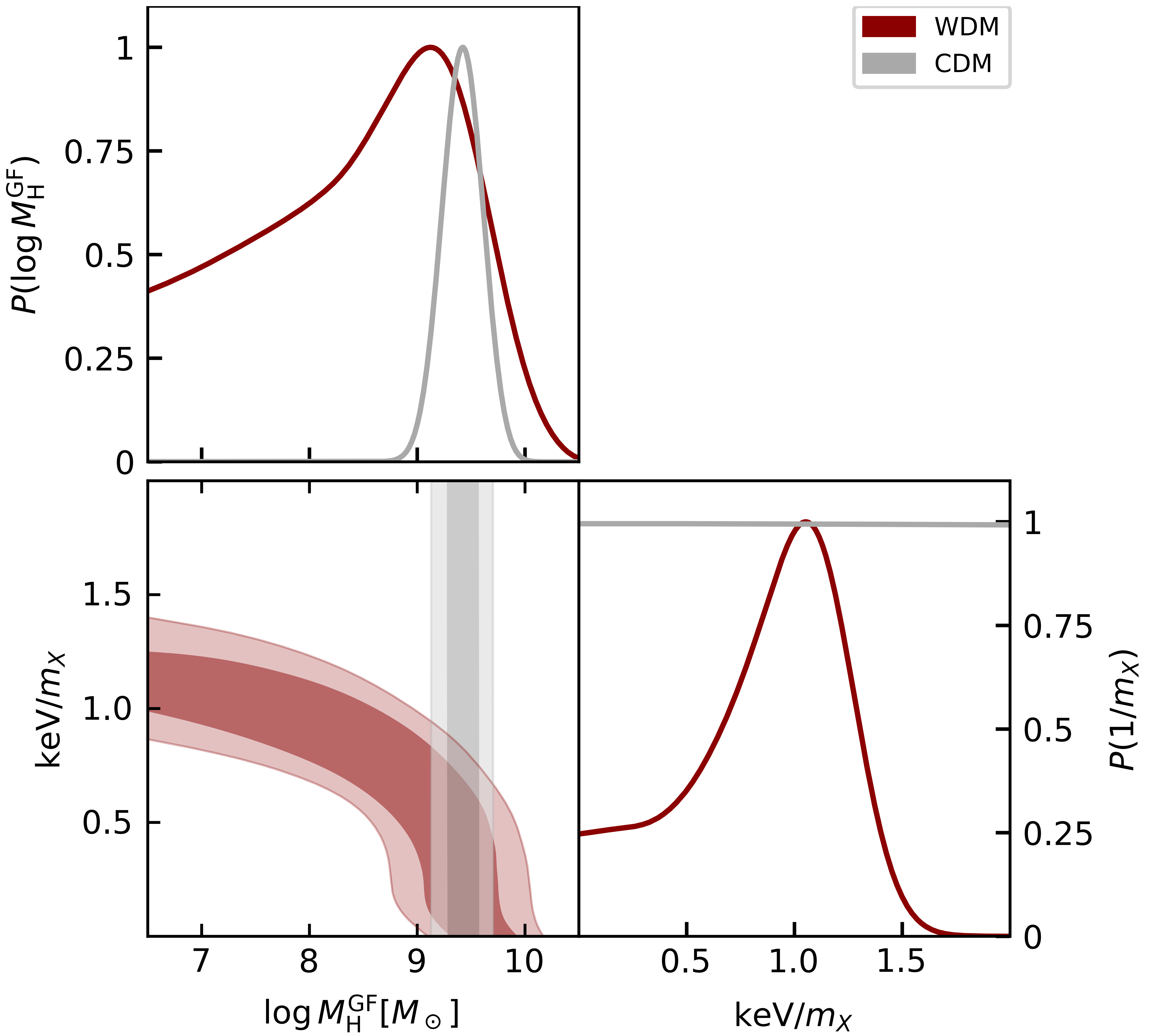
(Sub)mm ALMA data

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!).

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.

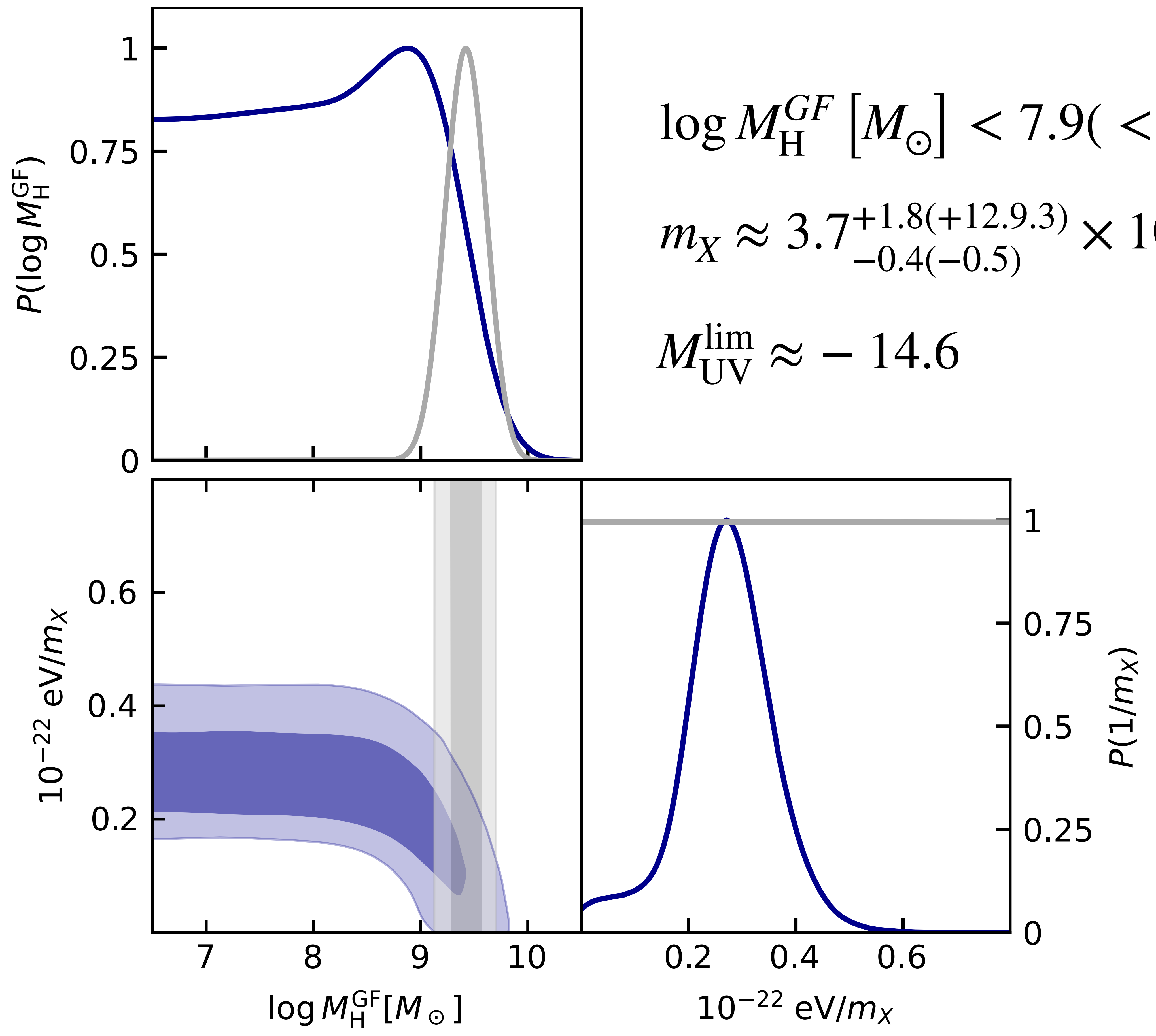
$$\log M_H^{GF} \left[M_\odot\right] \approx 7.6^{+2.2(+2.3)}_{-0.9(-3.3)}$$

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

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

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

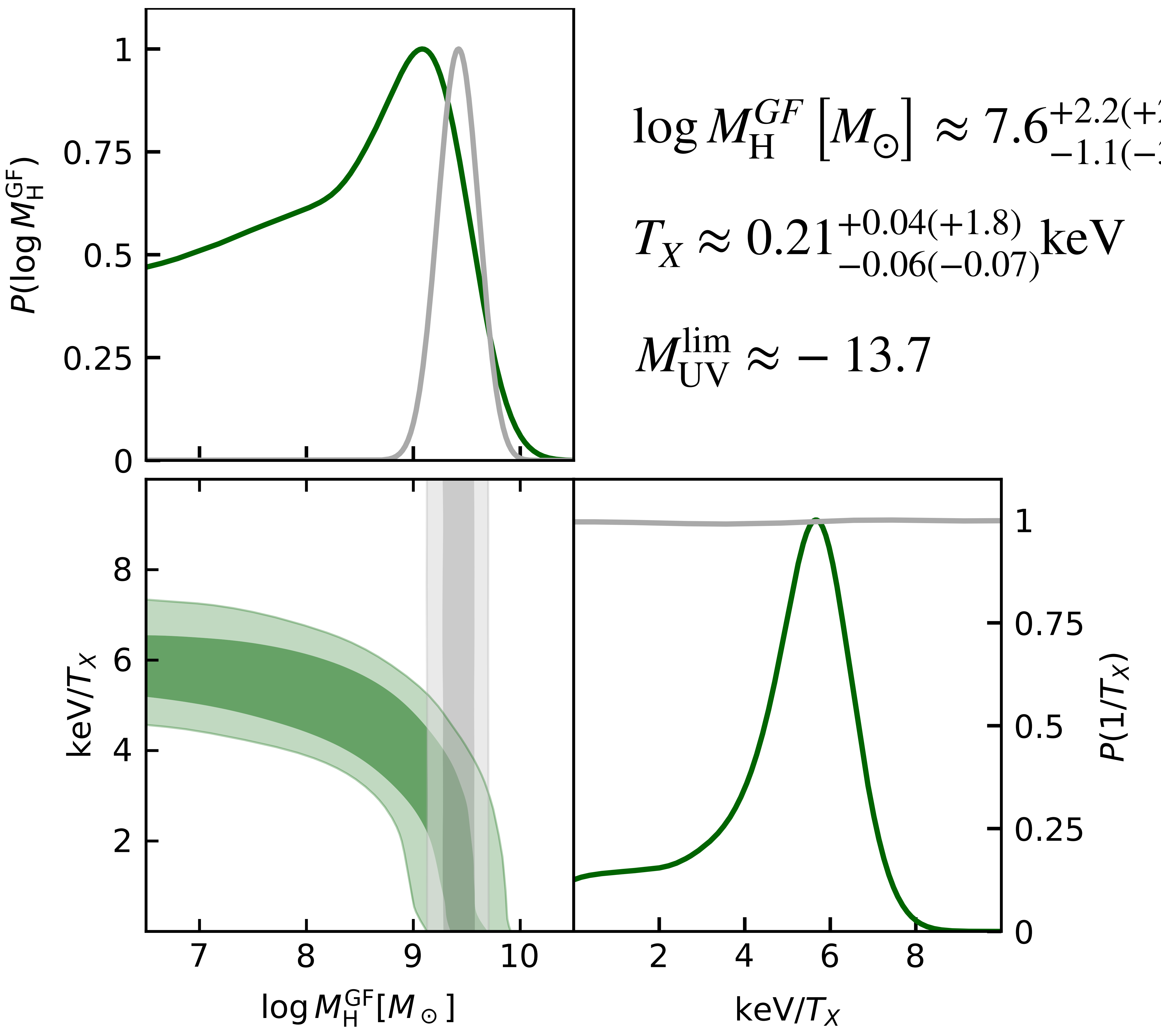
Fuzzy Dark Matter & Self-Interacting Dark Matter



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

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

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



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

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

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