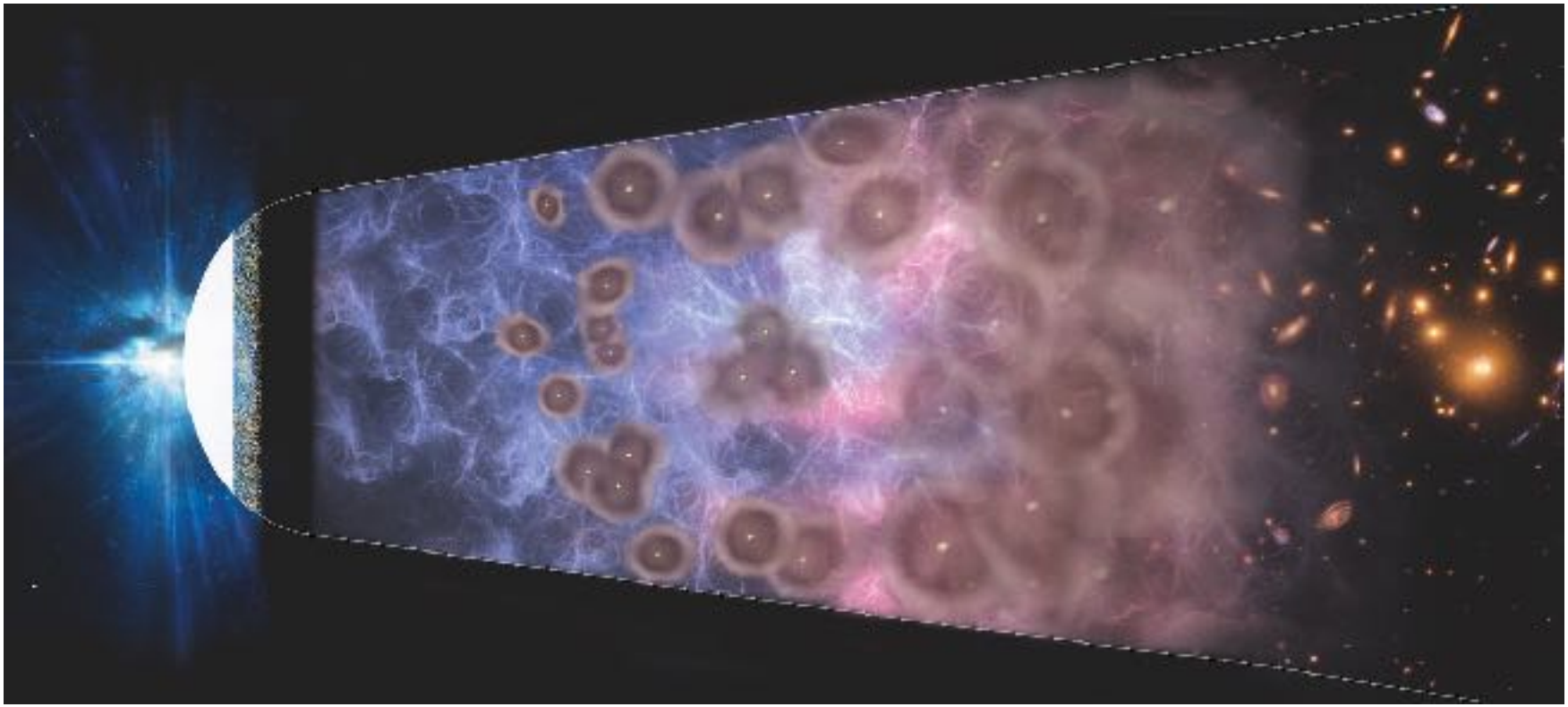
Early galaxy formation and its implications for dark matter, 21cm cosmology and multi-messenger astronomy

Pratika Dayal



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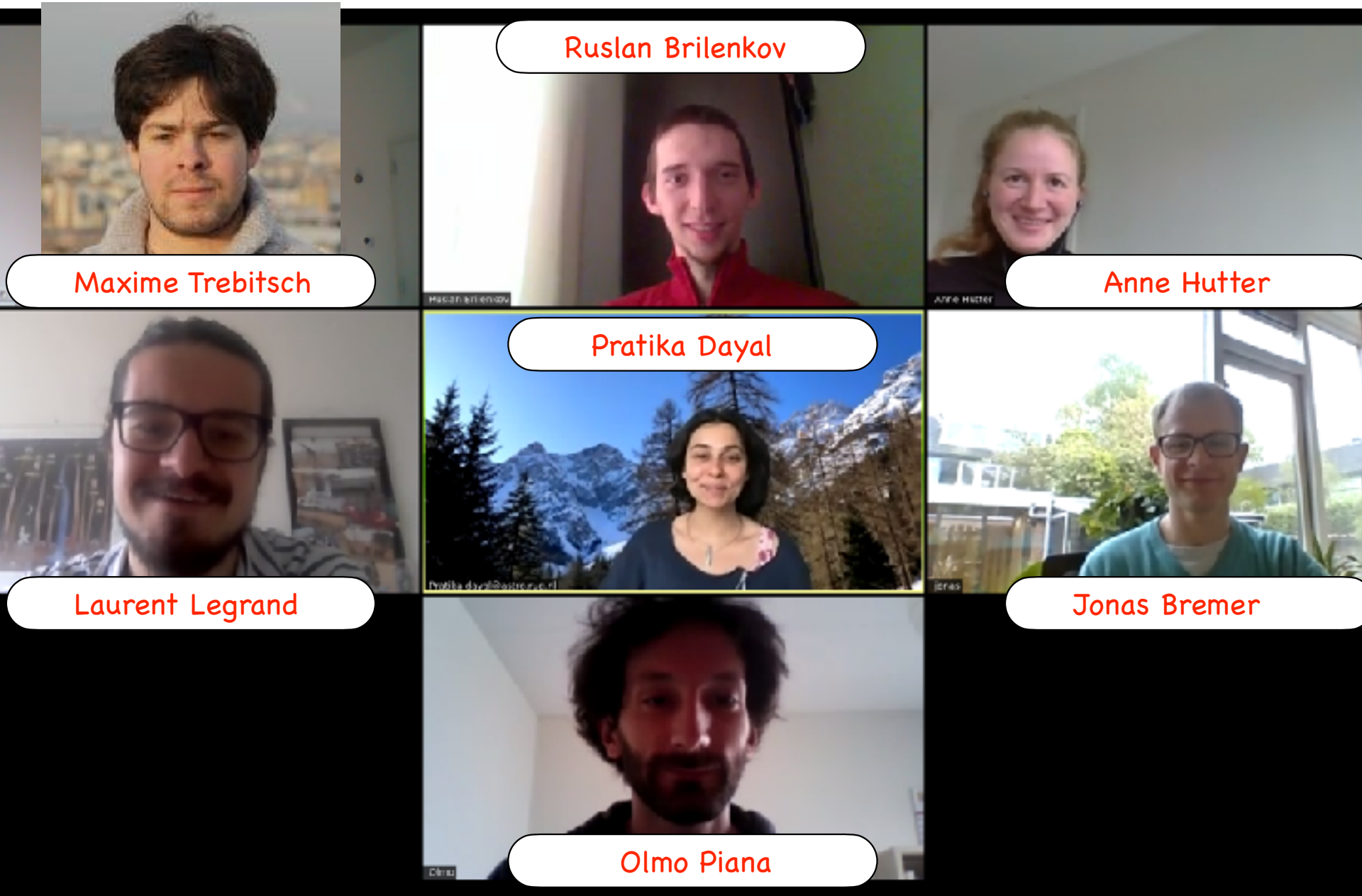
The team in Groningen



Key collaborators and collaborations

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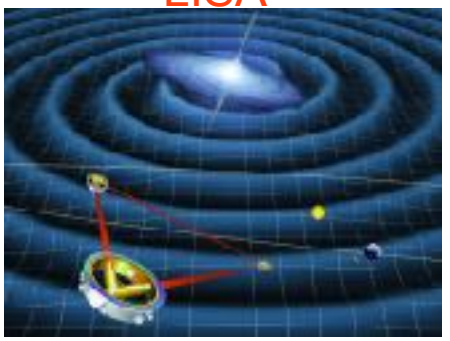
Marta Volonteri: Observatory of Paris, France
Gustavo Yepes: Universita Autonoma di Madid, Spain…

LISA



EUCLID

The outstanding challenges

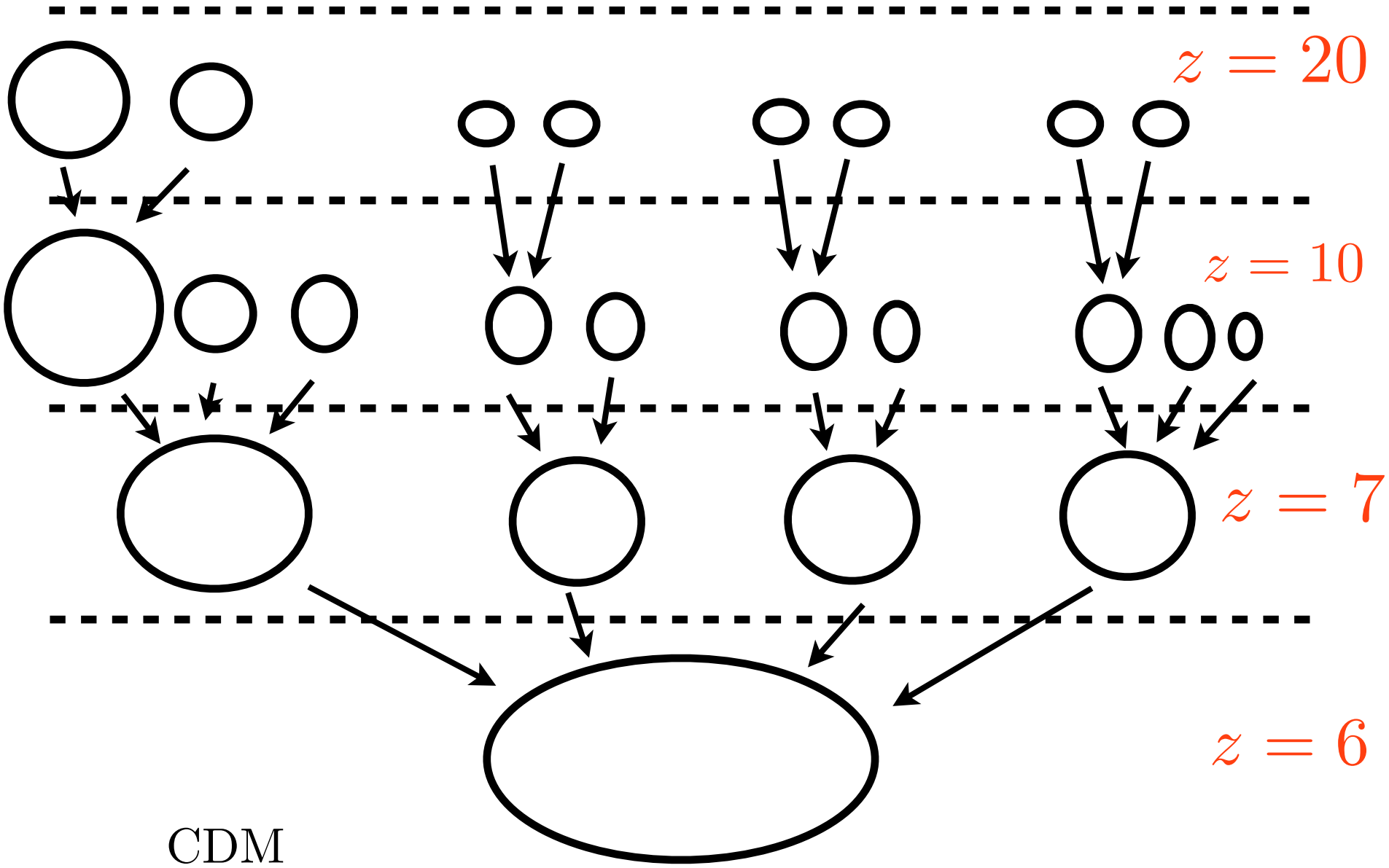
- Hints on the (warm) nature of dark matter using early galaxies

- Hints on (warm) nature of dark matter using 21cm data

- Early galaxies and GW events from LISA

Hints on the (warm) nature of dark matter using early galaxies and 21cm data

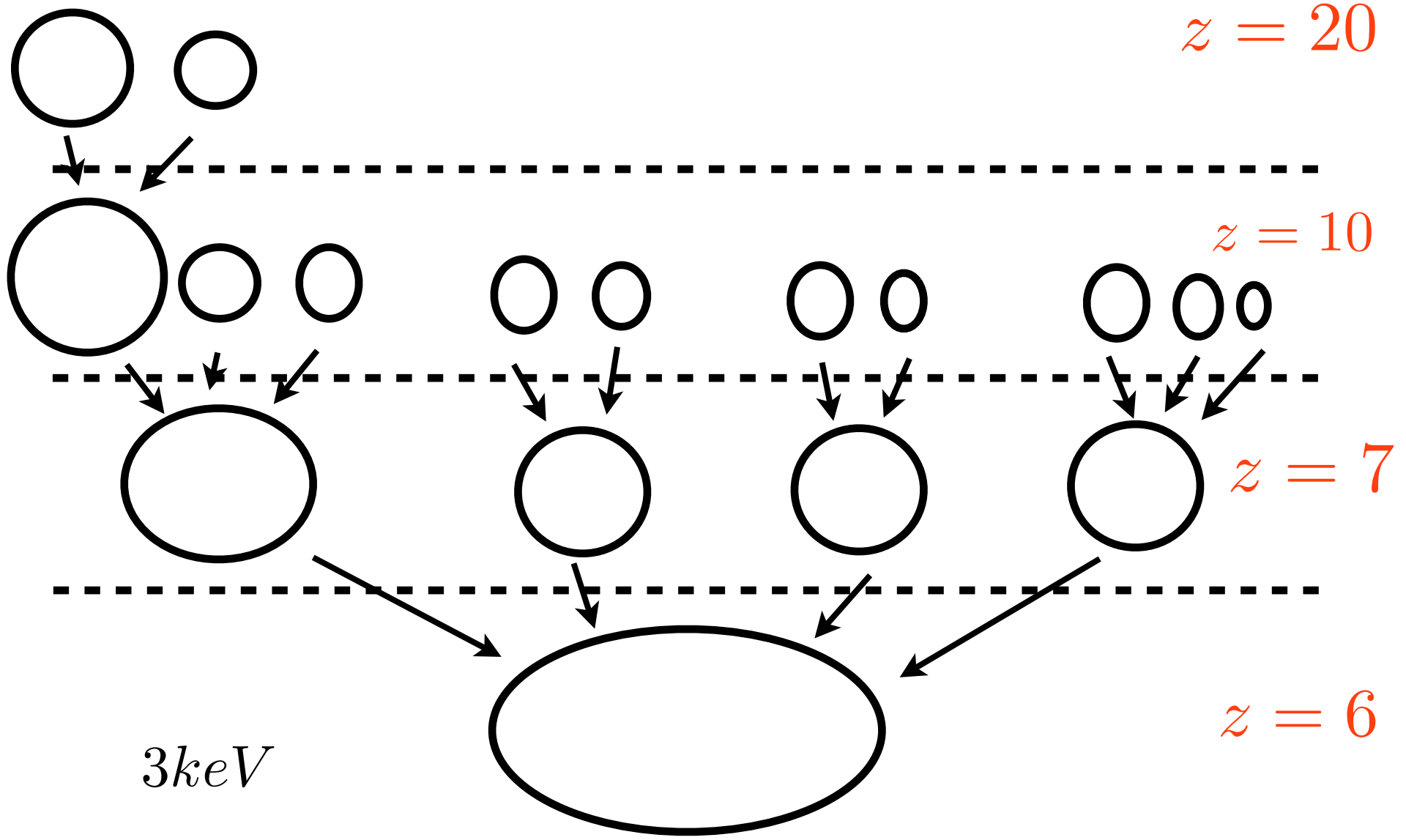
Hierarchical structure formation in CDM



CDM

Mass roughly ~100 GeV

Lighter the WDM particle, more is the suppression of small scale structure



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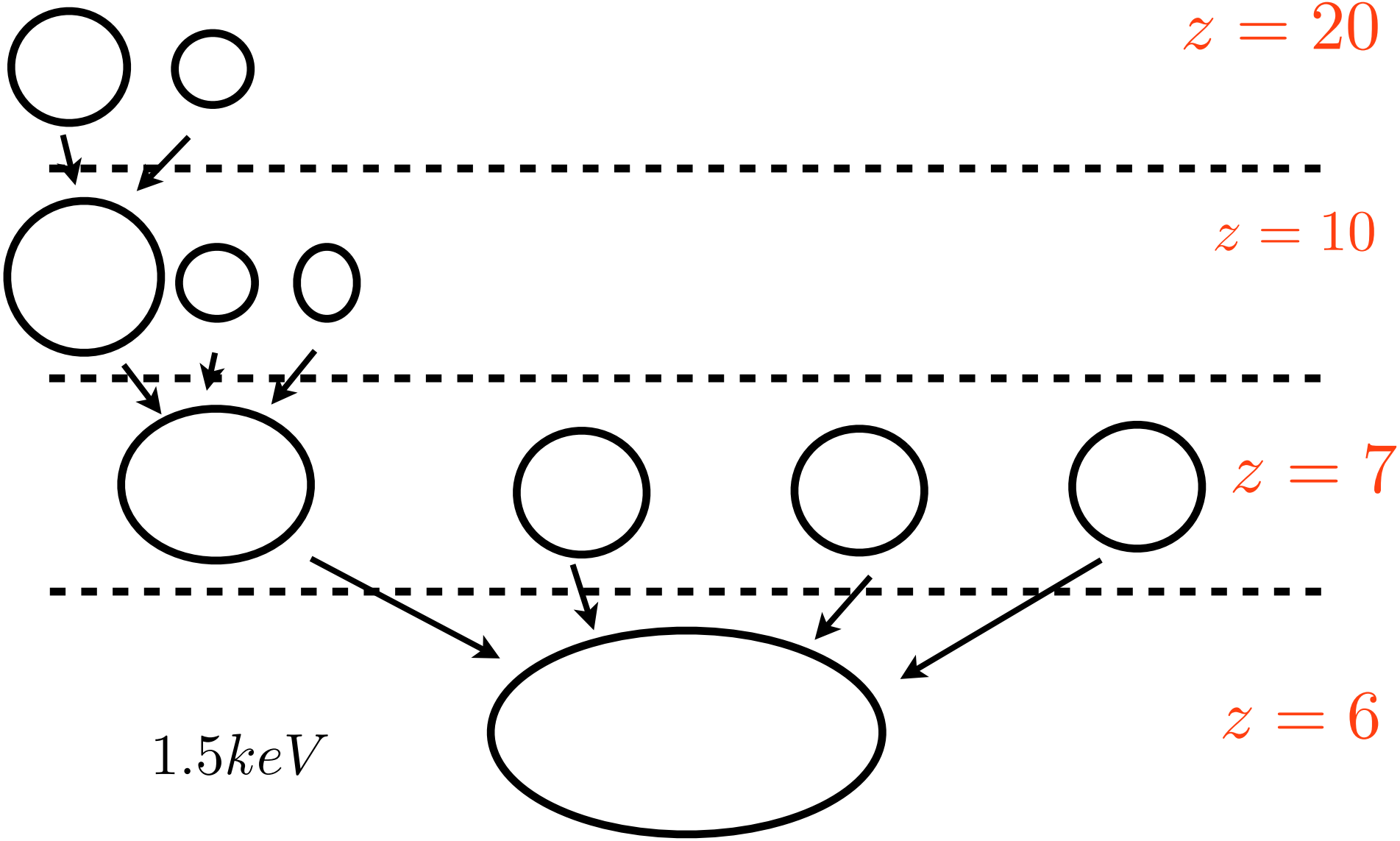
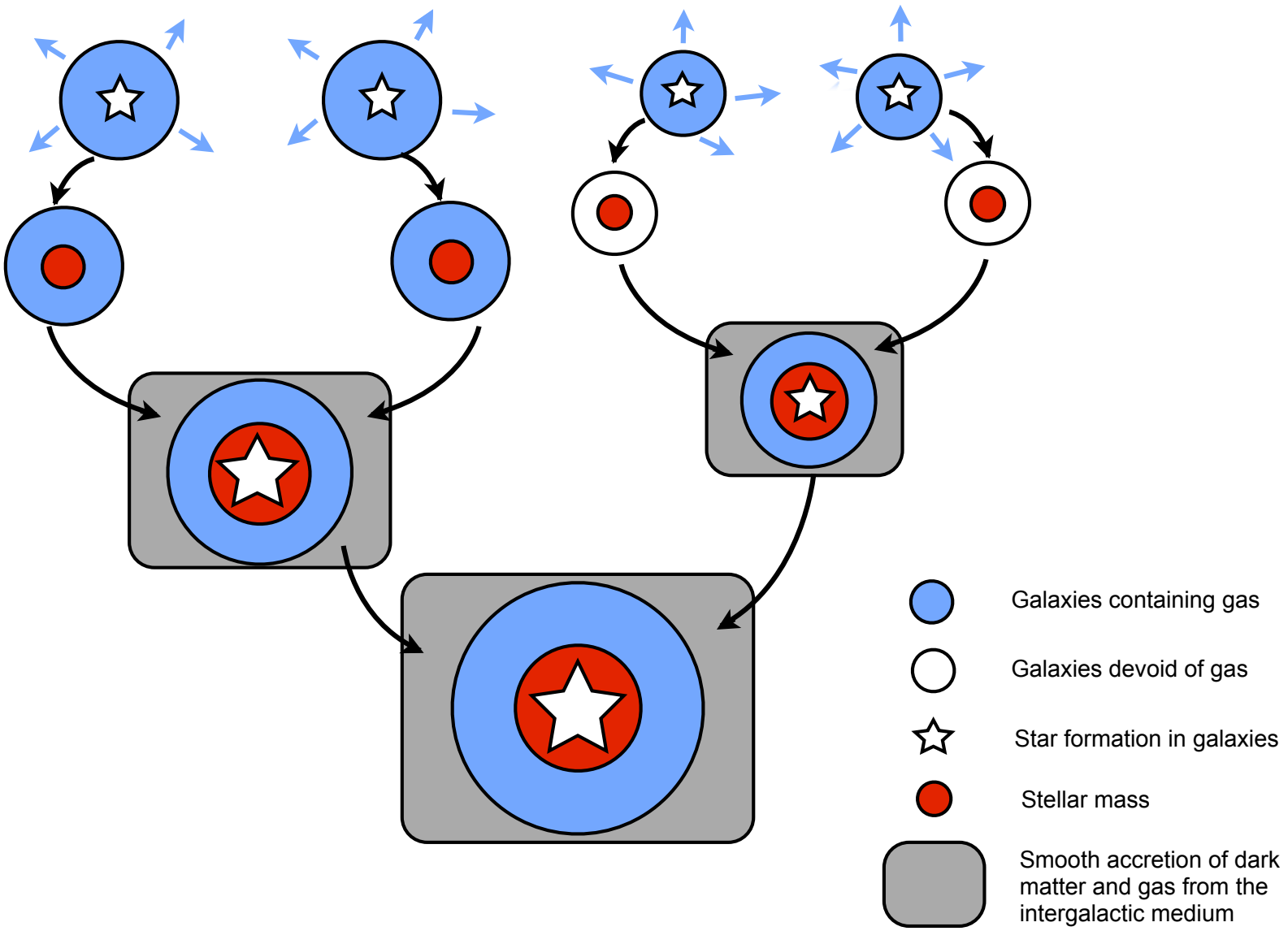


Since the merger tree starts building up later in WDM models..



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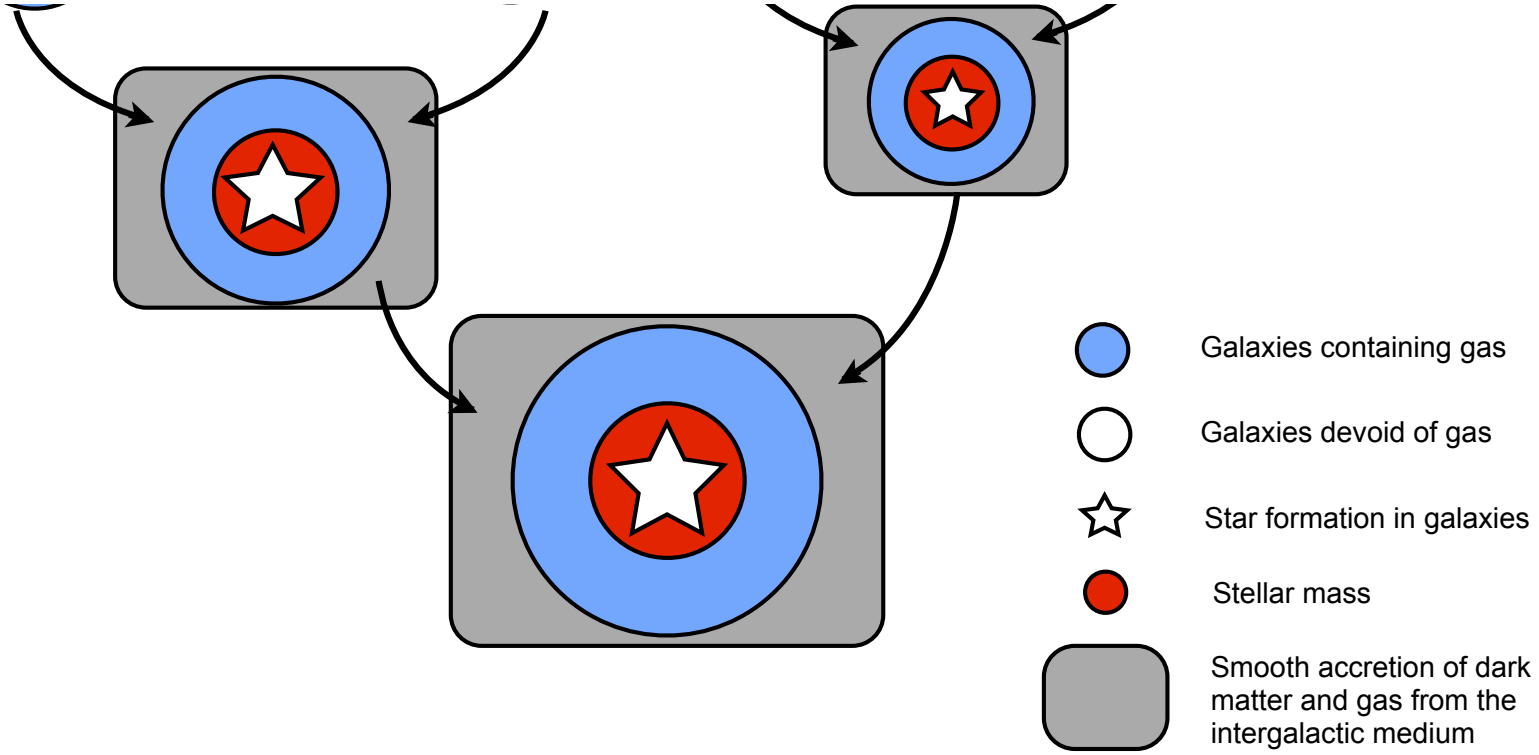
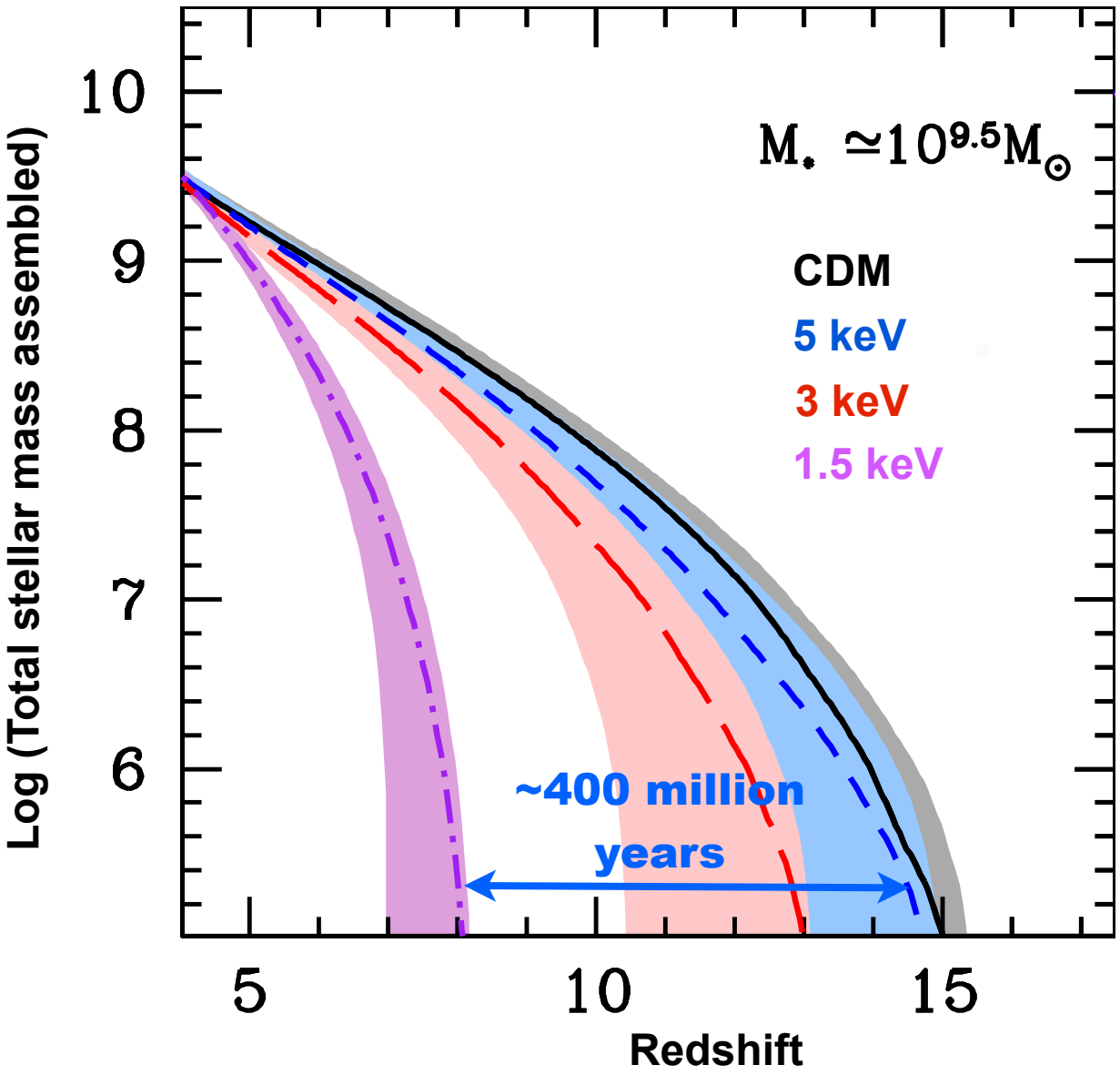


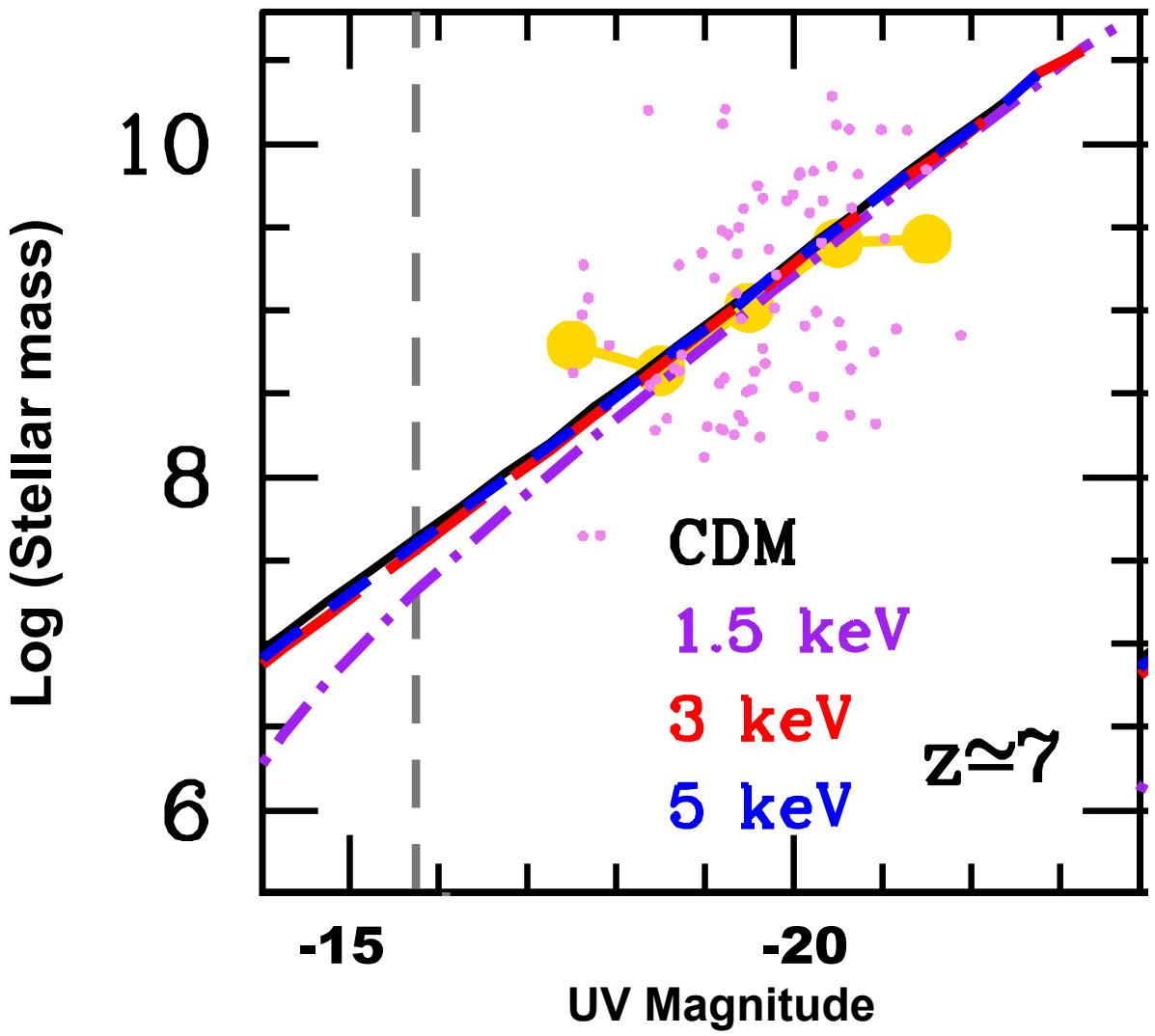
..it leads to a delayed assembly of stellar mass



Galaxies assemble faster in 1.5 keV WDM models compared to CDM. This is because they start off bigger and are less feedback limited as a consequence.

PD+2015, ApJ, 806, 67

Mass-to-light ratios are cosmology dependent!

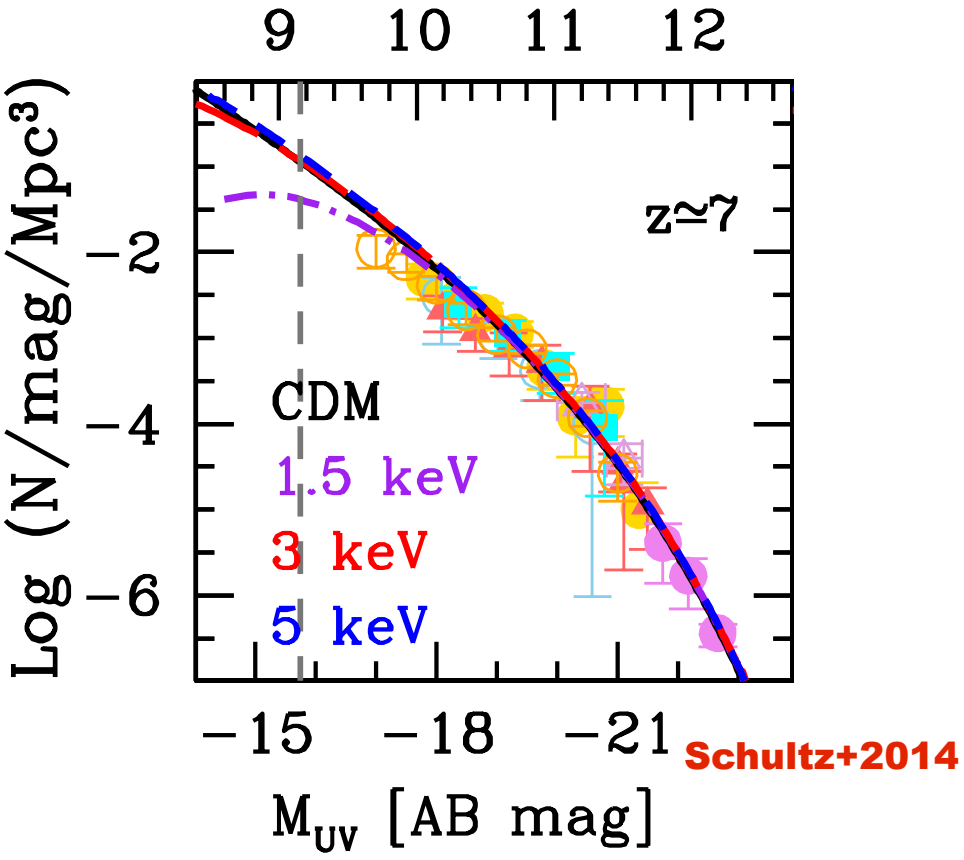


PD+2015, ApJ, 806, 67;

Light WDM models show lower M/L ratios (i.e. more luminosity per unit stellar mass) compared to CDM

UV LFs in Cold versus Warm DM models

Scaling Halo mass function



Schultz+2014

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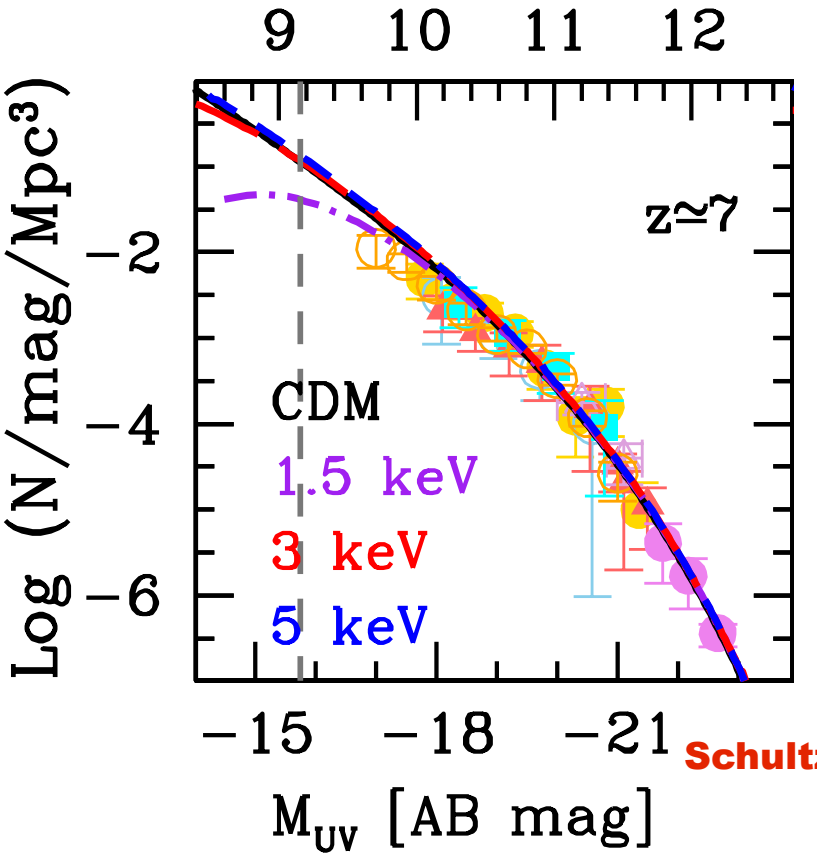
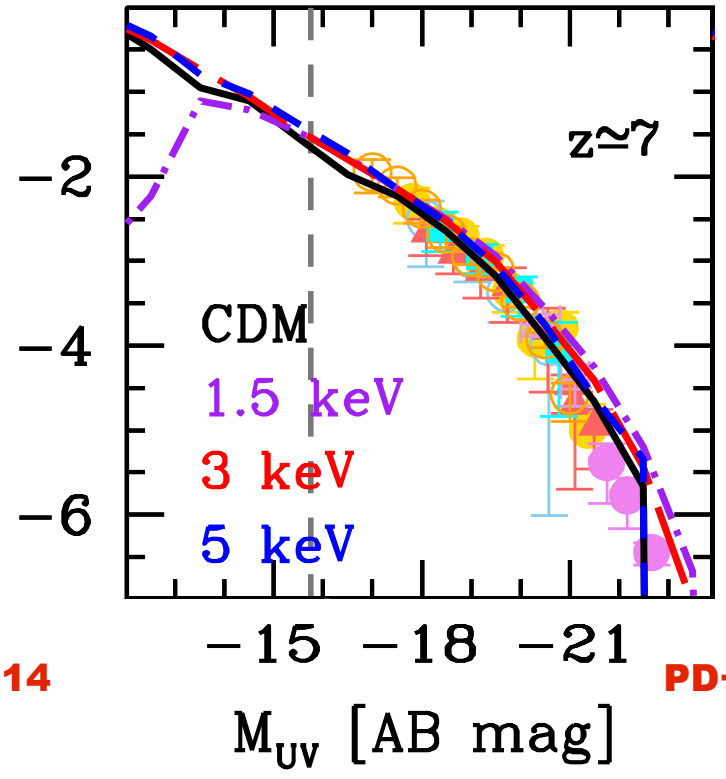


Schultz+2014

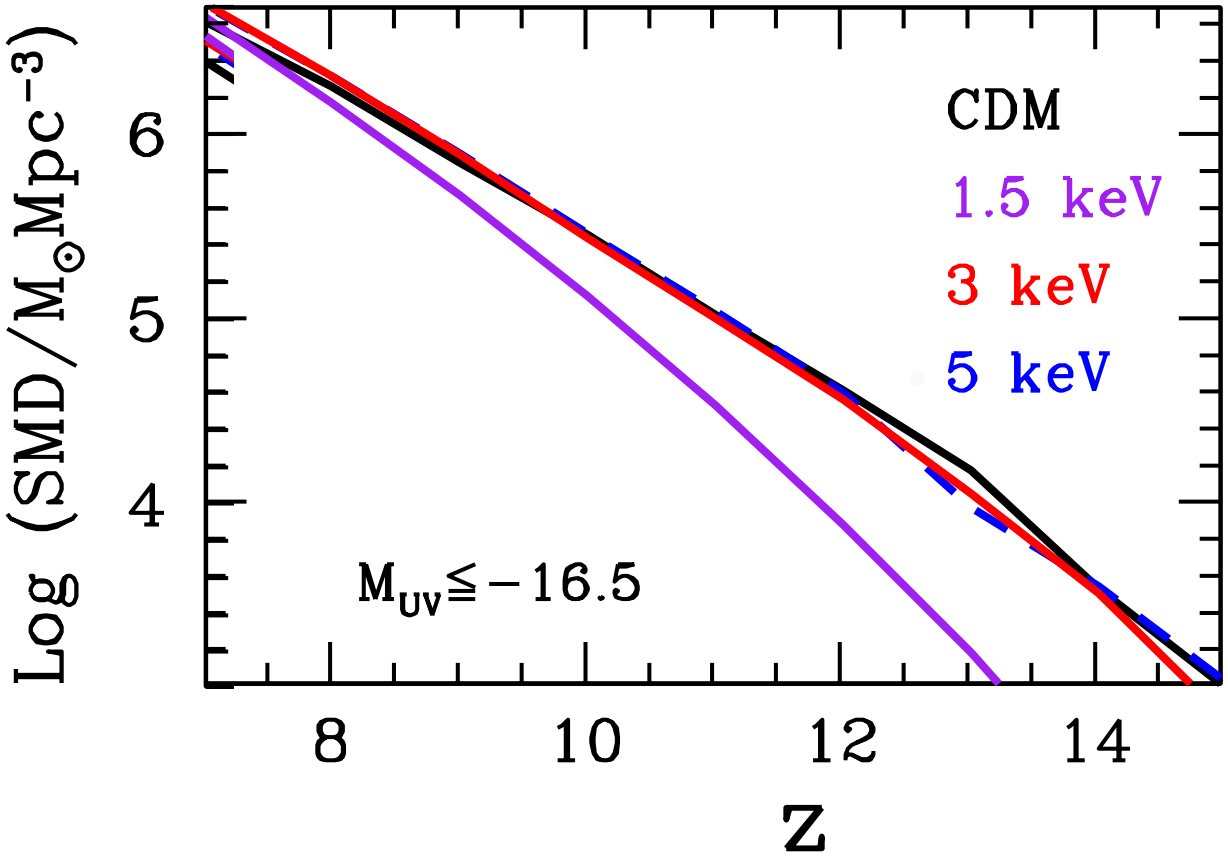
Fiducial model



PD+2015

Including baryons (and SF) decreases the difference between CDM and 1.5 keV WDM models

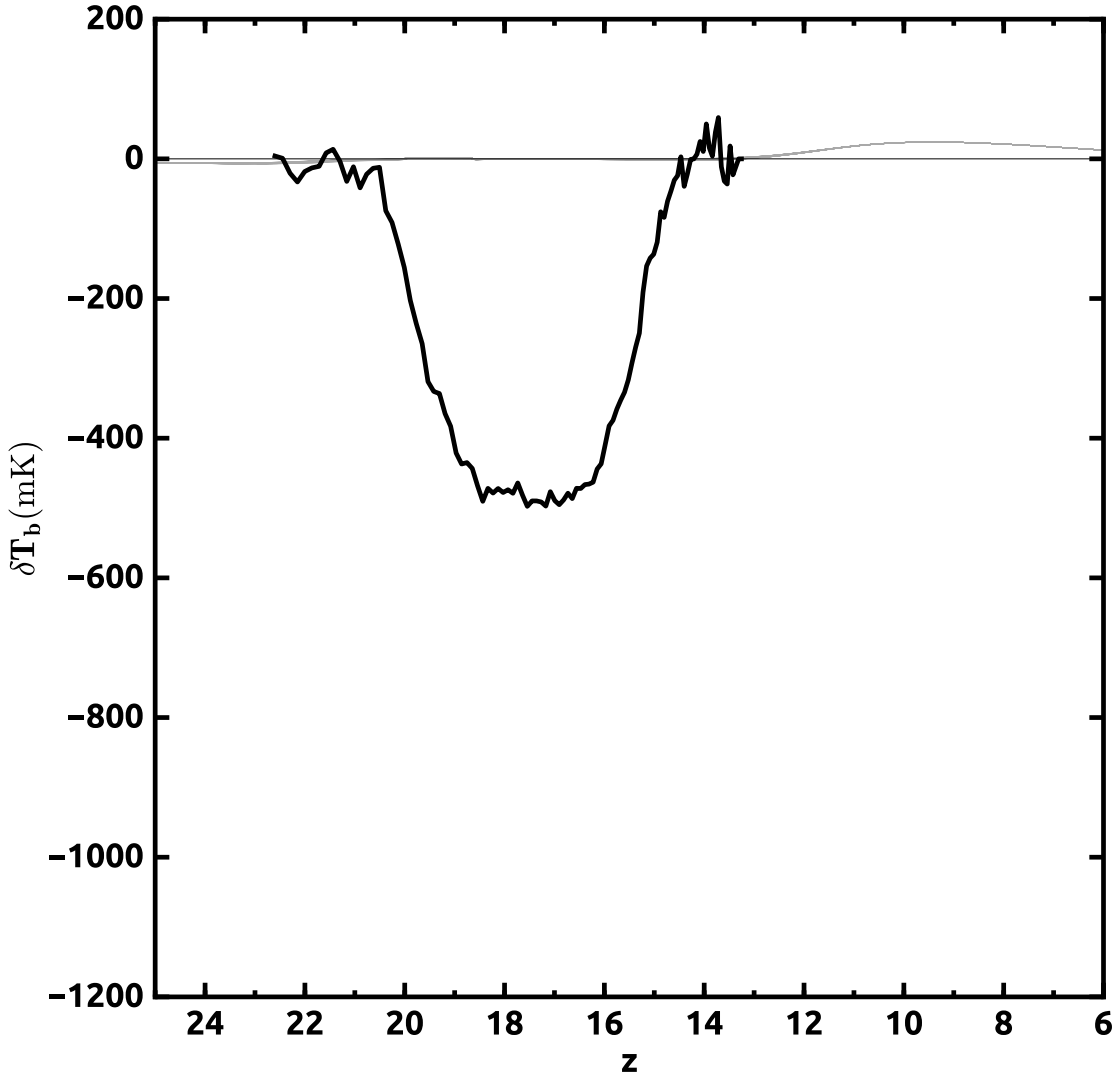
Observational imprints of light WDM particles: buildup of the cosmic stellar mass density



Redshift evolution of stellar mass density with JWST-detectable galaxies can allow constraints on WDM mass of about 2keV

PD+2015, ApJ, 806, 67;
PD+2017, ApJ, 836, 16

Sky-averaged absorption 21cm signal (EDGES)



Bowman et al., 2018, Nature, 555, 67

21cm signal redshift and amplitude scale with star formation rate density

$$\delta T_b(\nu) = \frac{T_S(z) - T_\gamma(z)}{1+z}\left(1 - e^{-\tau}\right) \qquad \text{where} \qquad T_S^{-1} = \frac{T_\gamma^{-1} + x_c T_k^{-1} + x_\alpha T_\alpha^{-1}}{1 + x_c + x_\alpha},$$

Coupling coefficients: $$x_c = \frac{T_*}{A_{10} T_\gamma} \sum_{i=\mathrm{H,e,p}} \kappa_{10}^{\mathrm{H}-i} T_k n_i, \quad x_\alpha = 1.81 \times 10^{11} (1+z)^{-1} S_\alpha \frac{J_\alpha}{\mathrm{cm^{-2} s^{-1} Hz^{-1} sr^{-1}}}$$

Gas kinetic temperature: $$\frac{\mathrm{d}T_k}{\mathrm{d}z} = \frac{2T_k}{1+z} - \frac{2}{3H(z)(1+z)} \sum_i \frac{\epsilon_i}{k_B n}.$$

Compton

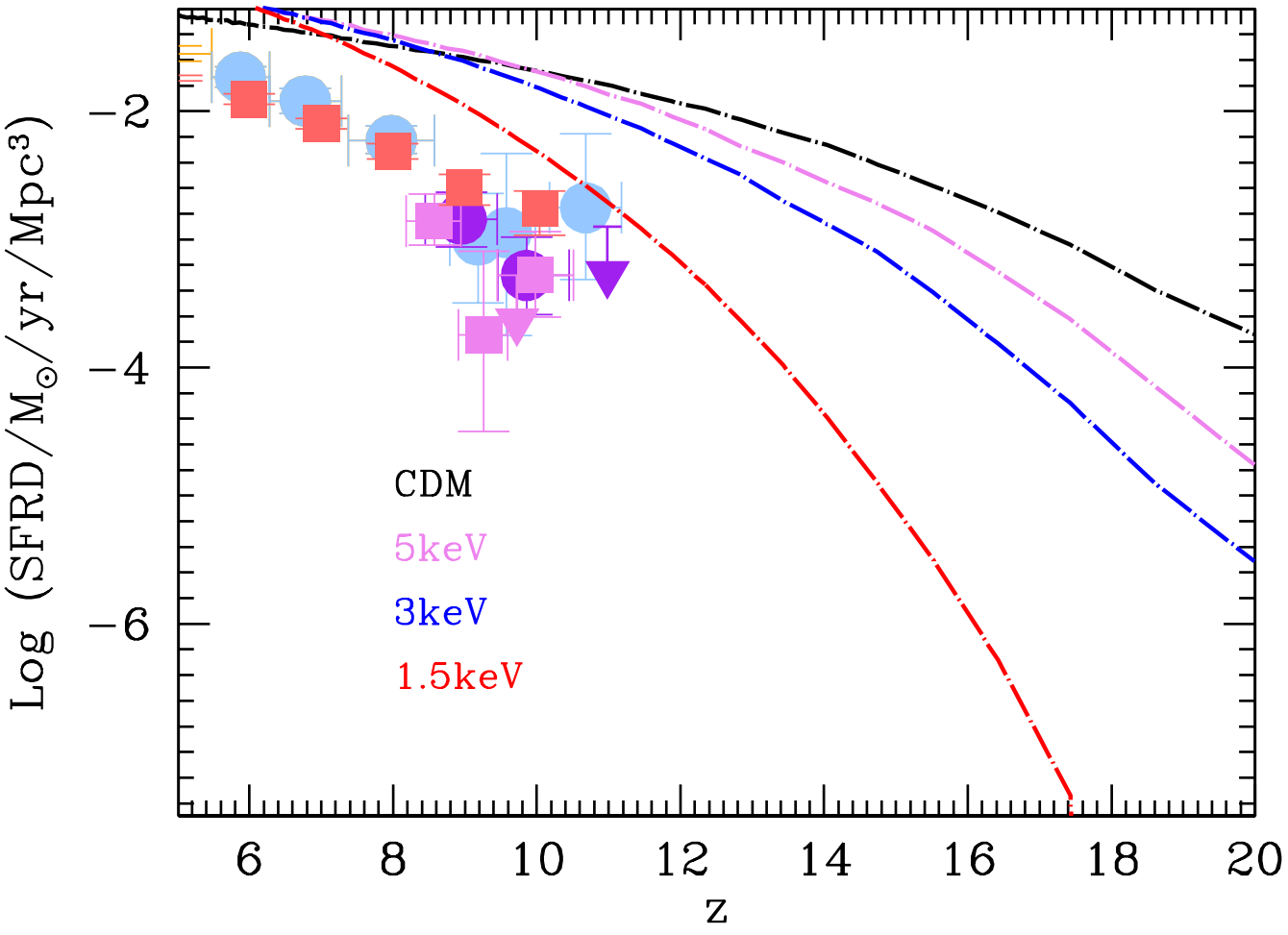
$$\frac{2\epsilon_{comp}}{3 n k_B} = \frac{\chi_e}{1 + \chi_e + f_{He}} \frac{8\sigma_T u_\gamma}{3 m_e c} (T_\gamma - T_k)$$

X-rays

$$\epsilon_X = 3.4 \times 10^{33} f_h \; f_X \; \frac{\dot{\rho}_*}{\mathrm{M_\odot \; yr^{-1} \; Mpc^{-3}}},$$

Excess radio background: $$\epsilon_R(z) = f_R \times 10^{22} \times \frac{\dot{\rho}_*(z)}{\mathrm{M_\odot \; yr^{-1} \; Mpc^{-3}}} \mathrm{Js^{-1} Hz^{-1} Mpc^{-3}}$$

Build-up of cosmic SFRD cosmology-dependent



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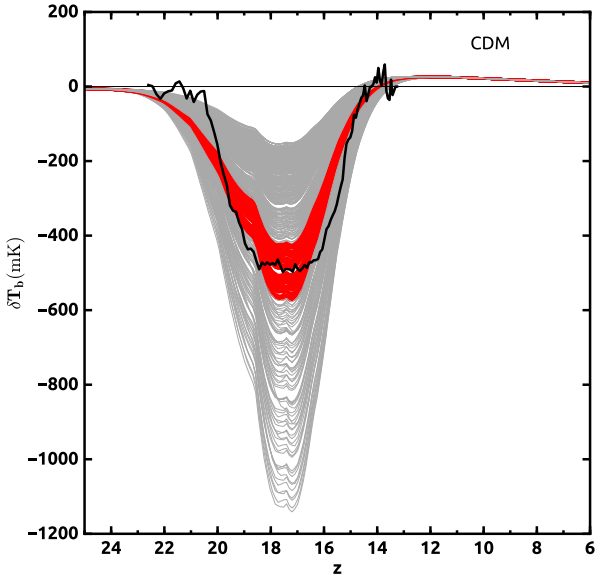
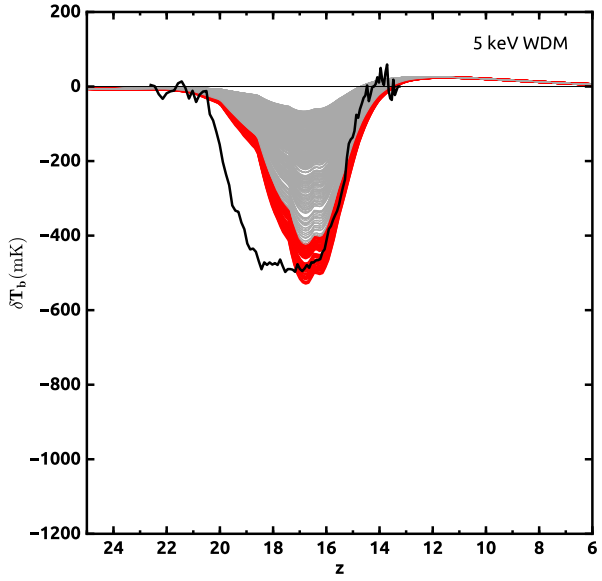
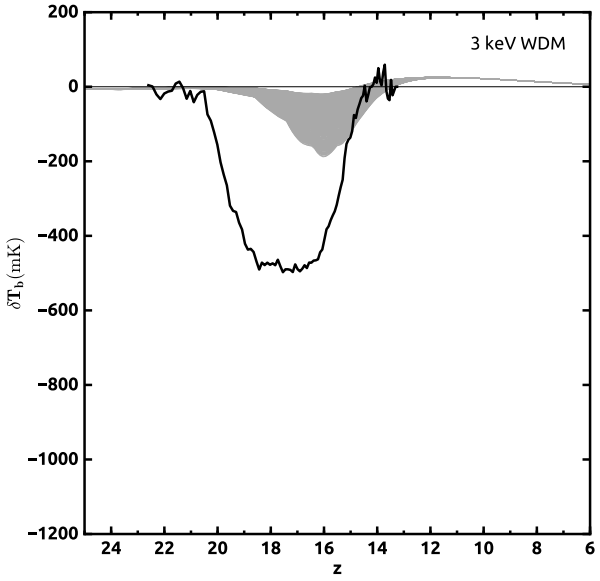
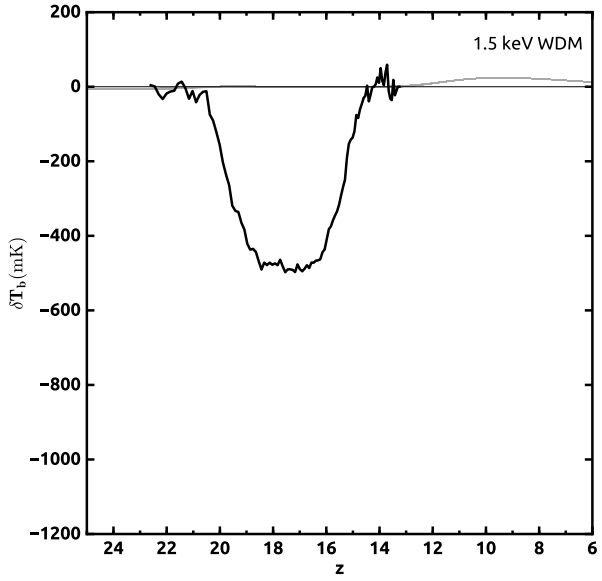
Ruling out light (<3 keV) WDM using 21cm EDGES data









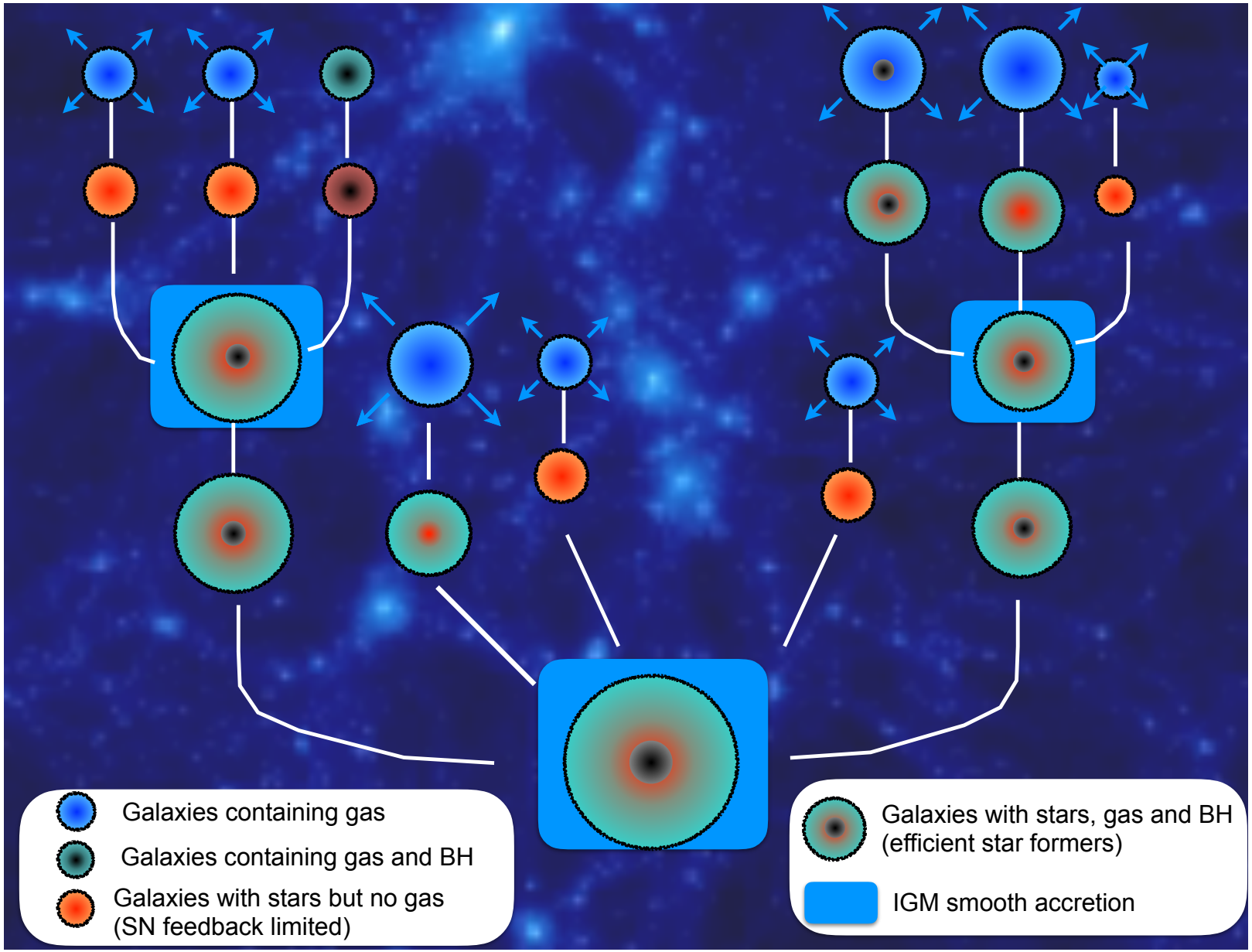
- Matching to amplitude of EDGES requires an excess radio background.
- The dearth of star formation at z>18 in <3 keV WDM modes allows them to be ruled out using EDGES data, even allowing X-ray heating and an excess radio background

Atrideb Chatterjee

Chatterjee, PD+2019, MNRAS, 487, 3560

GWs from the first billion years

The theoretical framework: DELPHI



DELPHI; PD et al. 2019

The key physics explored

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Two types of BH seeds
- stellar (PopulationIII) and direct collapse black holes (based on strength of Lyman alpha background)

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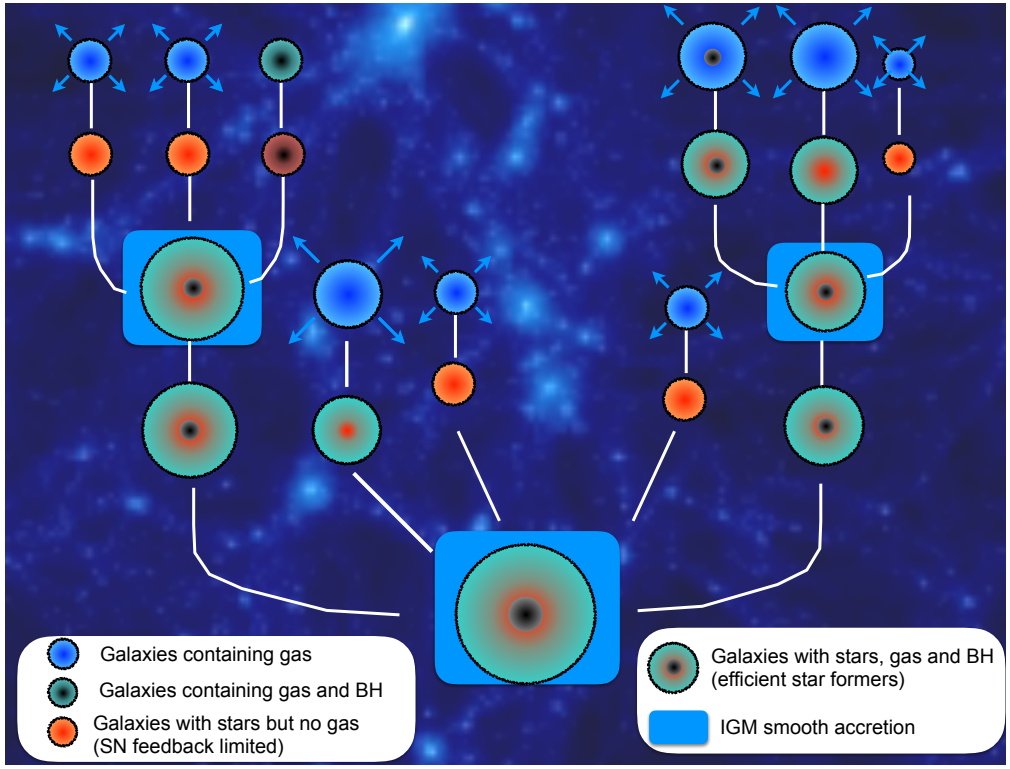
Black hole growth regulated by both halo mass and gas availability (due to the impact of Supernova and reionization feedback)

Impact of instantaneous versus (dynamically) delayed galaxy mergers on the black hole merger rate

DELPHI; PD et al. 2019

Baselining the model against all available high-z data



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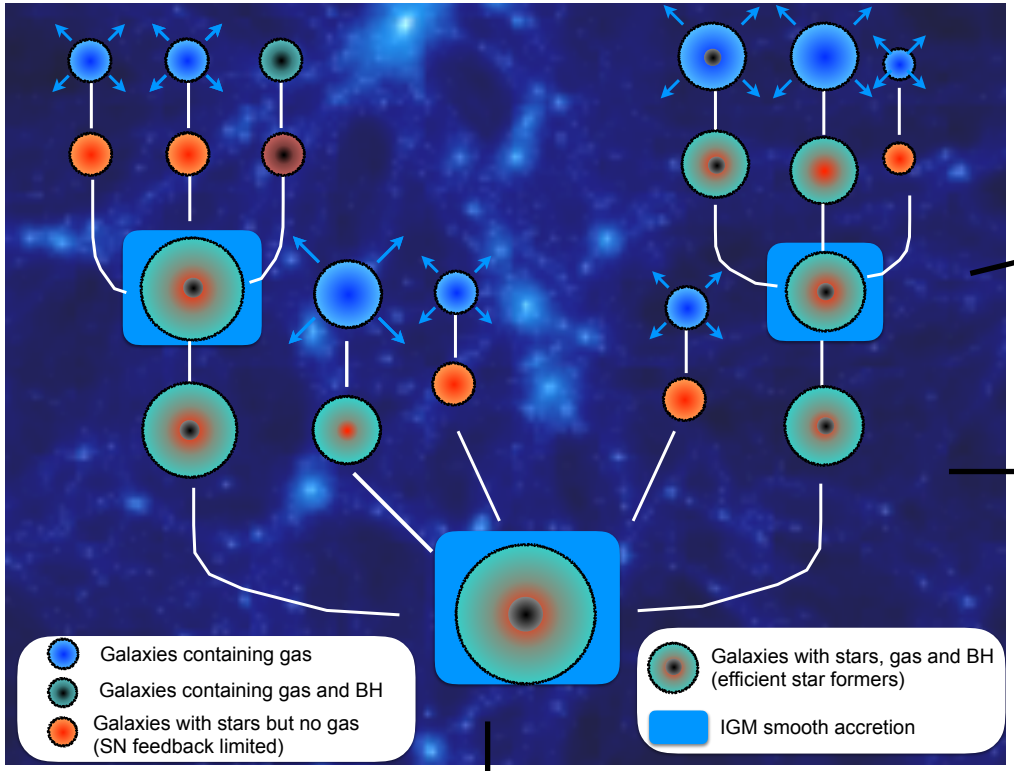
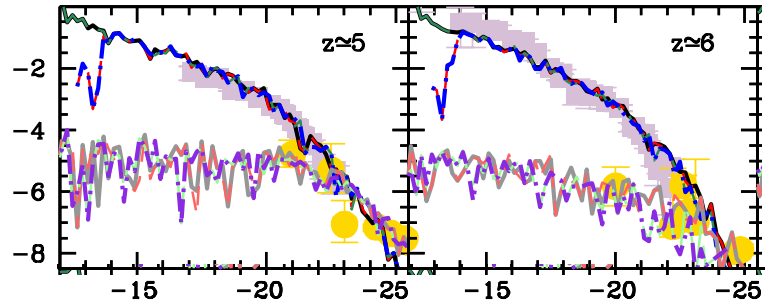
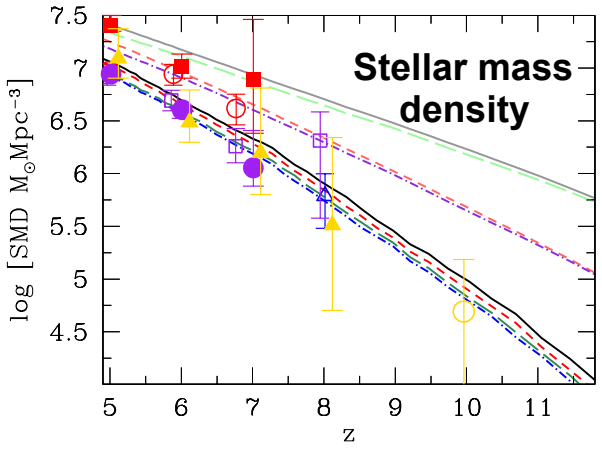
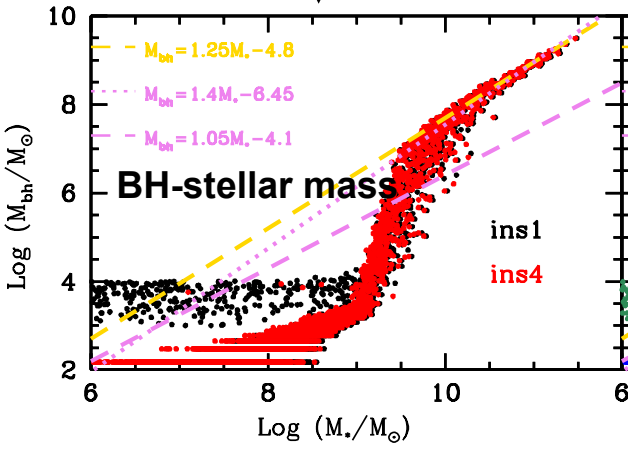
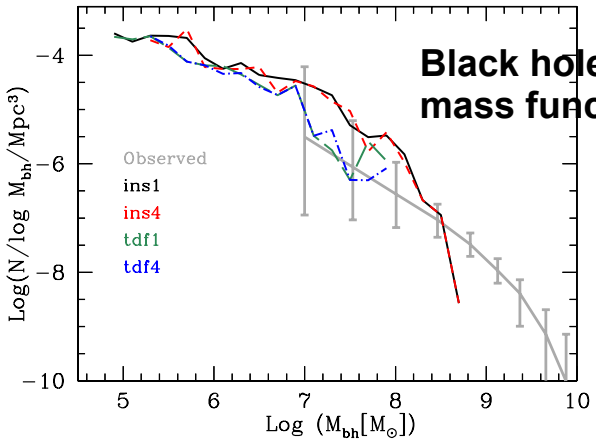


Ultra Violet Luminosity Function









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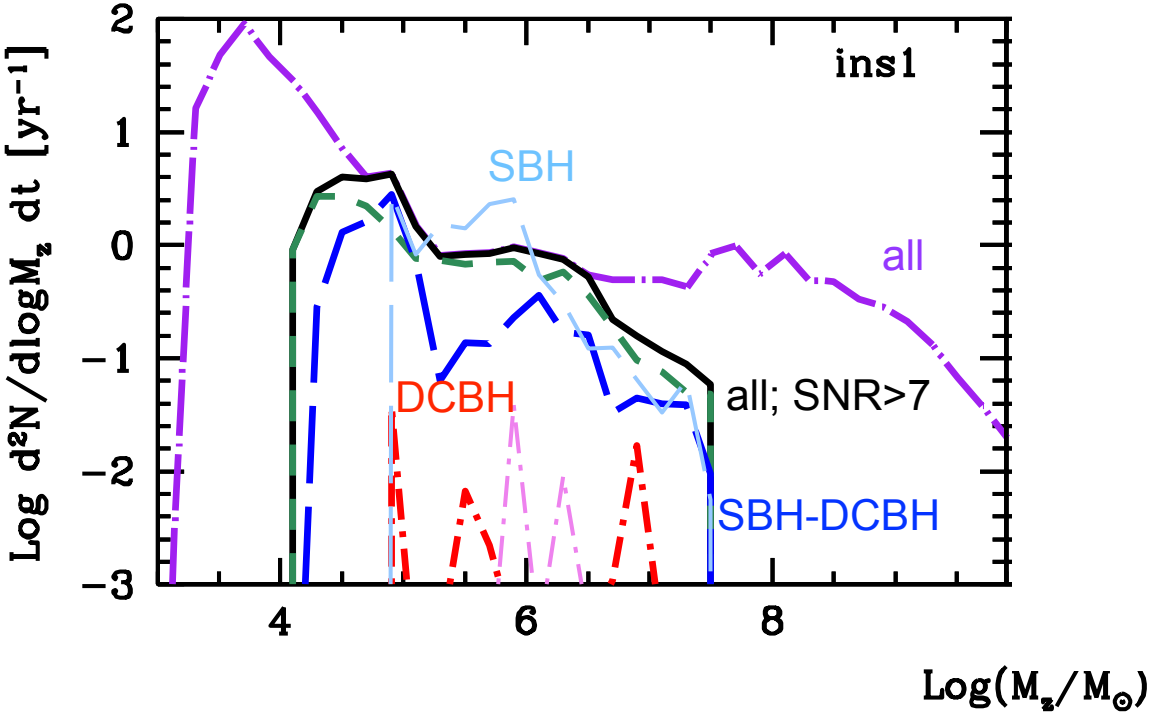
PD et al. 2019

The LISA-detectable GW event rate as function of mass



• LISA will preferentially detect BHs with mass $M_{BH} \sim 10^{4-7} M_{\odot}$. In *fiducial case (ins1) m*ost detectable mergers are those from SBH-SBH, followed by SBH-DCBH mergers. DCBH-DCBH mergers negligible.

• Although same mass range true for the *tdf4 model, d*ue to delayed mergers + reionization feedback, importance of DCBH-SBH mergers decreases. No detectable DCBH-DCBH mergers (with SNR>7).

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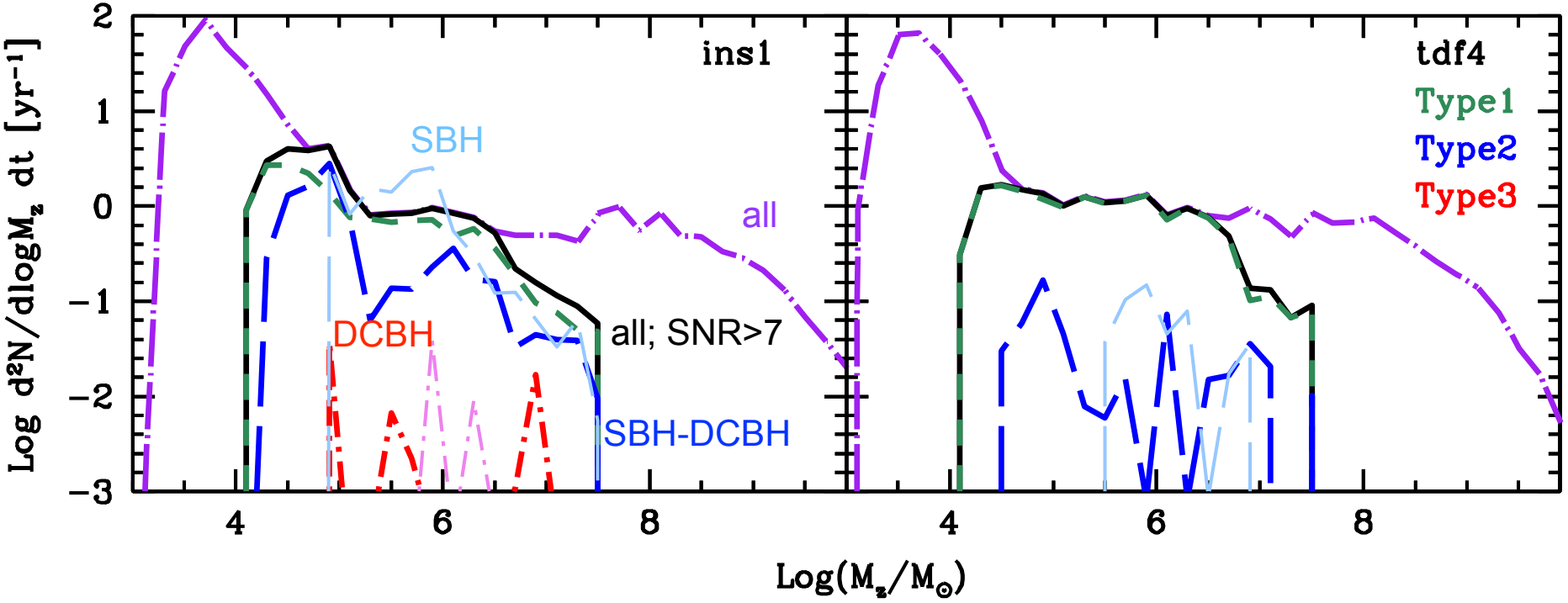

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The emerging picture..

- **High-z Universe is being explored to ever greater depths, providing constraints on both global and individual galaxy properties.**

- **Galaxy assembly delayed in very light WDM models (e.g. 1.5 keV).**

- **Since halos start of bigger (and hence less feedback limited) in light WDM models, it leads to a change in global quantities (SMD) as well as M/L ratios for individual galaxies - can be constrained with JWST.**

- **Metal enrichment of the IGM delayed and slightly lower in light WDM models.**

- **Edges data rules out light (<3 keV) WDM models.**

- **LISA will preferentially detect BHs with mass $M_{BH} \sim 10^{4-7} M_{\odot}$ at z>5.**