The morphology of fluorescent emission from the IGM as a probe of dark matter properties

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Motivation

Need for a matter component weakly interacting with radiation to explain the rotation curve of galaxies or the rapid growth of high density fluctuations (missing mass)

—> Dark Matter

(Zwicky 1933, Rubin & Ford 1970, Peebles 1982)

Mass? Production mechanism? Self interactions? Decay modes?

The exact nature of dark matter is still a pivotal question of astrophysics!

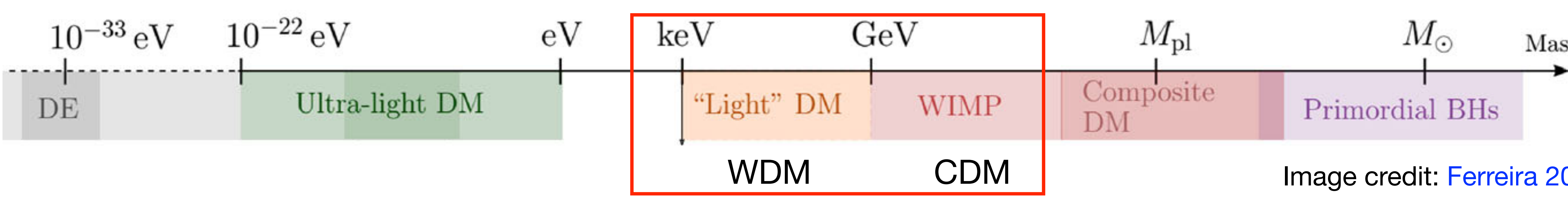
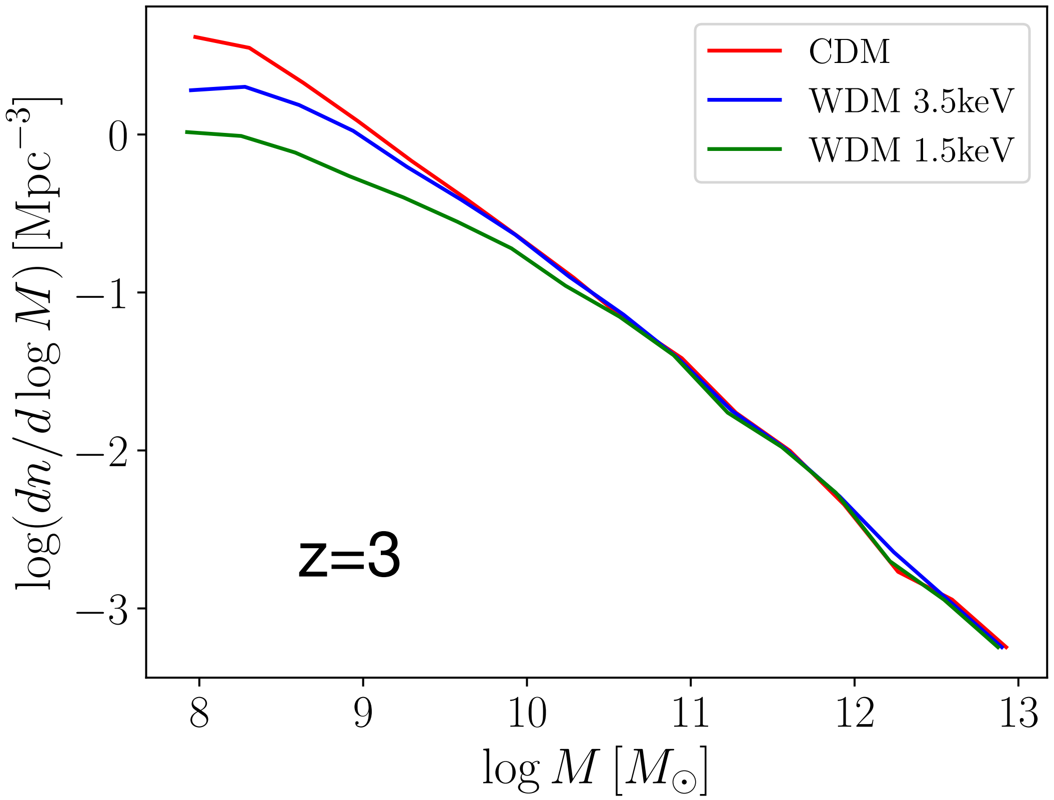


Image credit: Ferreira 2021

This work: **cold vs warm dark matter** (thermal relics)

Cold vs Warm Dark Matter

- **Cold dark matter** (CDM): currently preferred candidate, *m* ~ 100 GeV —> mean free path irrelevant for structure formation.
- **Warm dark matter** (WDM): *m* ~ few keV —> larger velocity dispersion & mean free path suppressing structure formation on small scales (Bond & Szalay 1983)



Some existing astrophysical constraints:

- Lya forest: m_{min} ~ 3 - 6 keV (e.g. Villasenor+ 2023, Irsic+ 2023). However, *degeneracy with thermal history of the Universe*
- (Ultra-)dwarf galaxies (e.g. Milky Way satellites): m_{min} ~ 2 - 4 keV (e.g. Newton+ 23) —> rely on *unknown physics of galaxy formation on smallest scales, observational difficulties*
- Gravitational lensing: m_{min} ~ 0.3 - 2 keV (e.g. Birrer+ 2017, Vegetti+ 2018, Ritondale+ 2019) but *degeneracies with the lens model, low statistics (for now)*

This work: new method to constrain the nature of dark matter using the morphology of IGM (diffuse gas) in emission

Dark matter and the IGM

- IGM loosely defined as all gas outside R_{vir}
- Distribution of cold (emitting) gas in IGM dominated by gravitational potential of DM —> near optimal tracer of the underlying dark matter density field —> possible to study the properties of dark matter
- Usually studied in absorption (e.g. Lya forest) but modern IFUs have revolutionised this allowing to observe the IGM **in emission** around bright QSOs at z ~ 2 - 4. Brightest emission at hydrogen **Ly-a frequency**

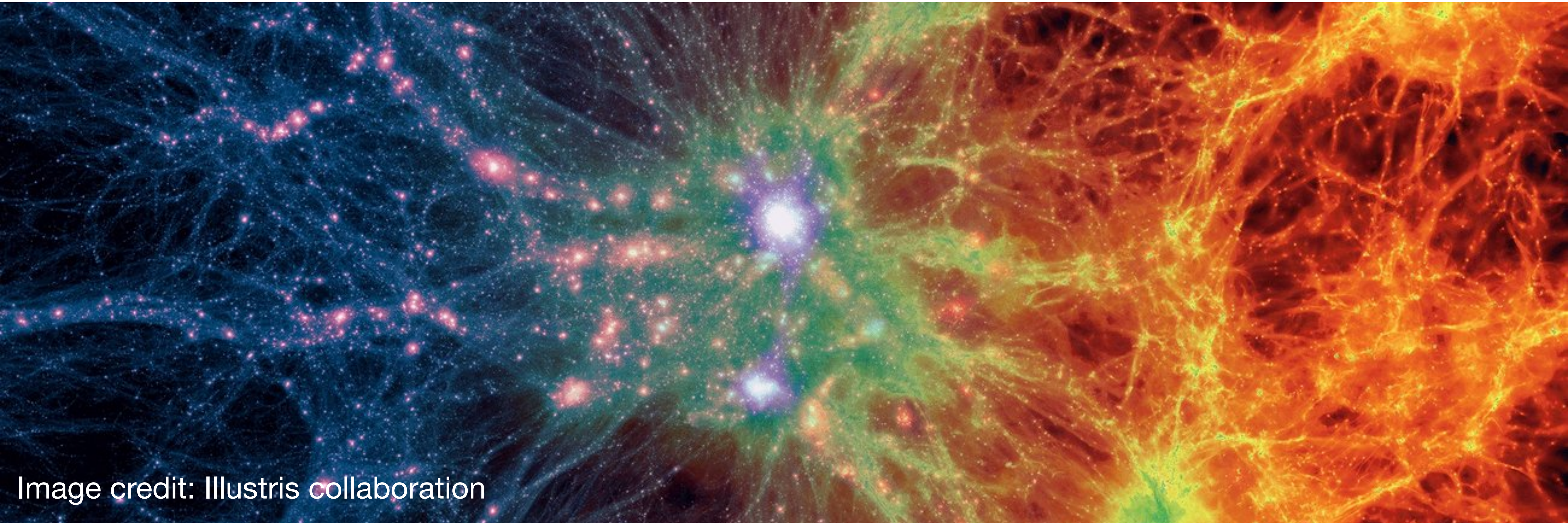
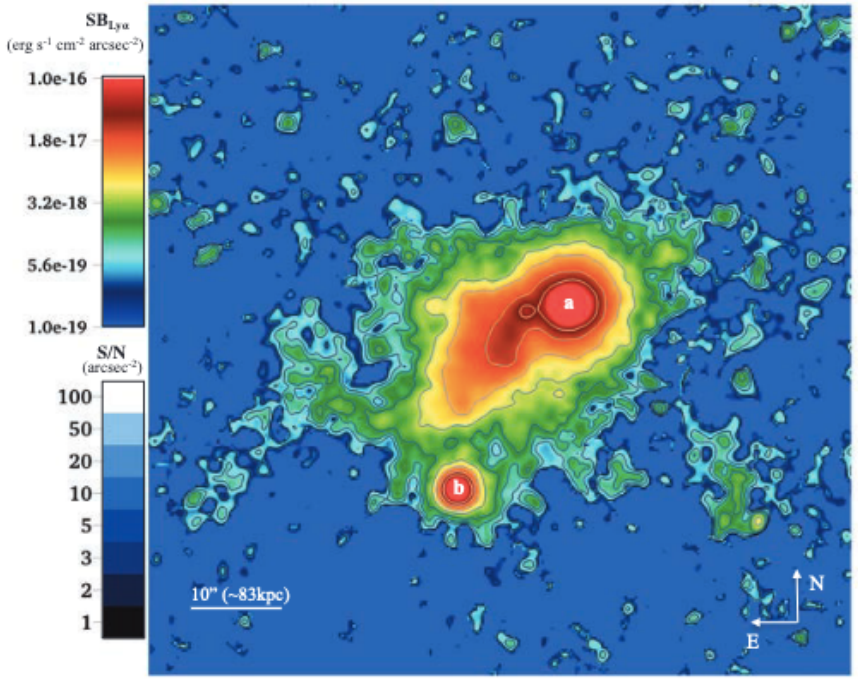
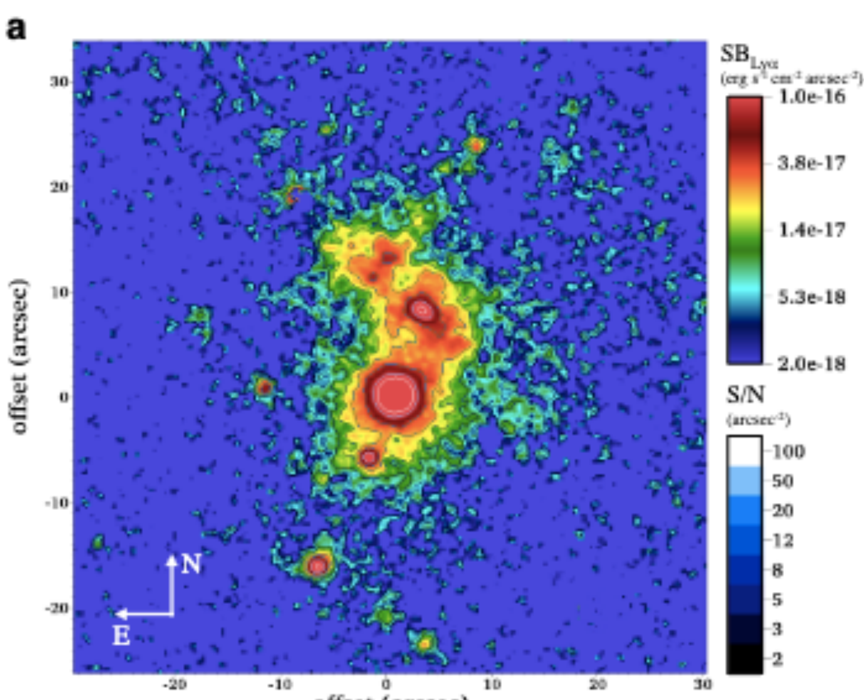


Image credit: Illustris collaboration

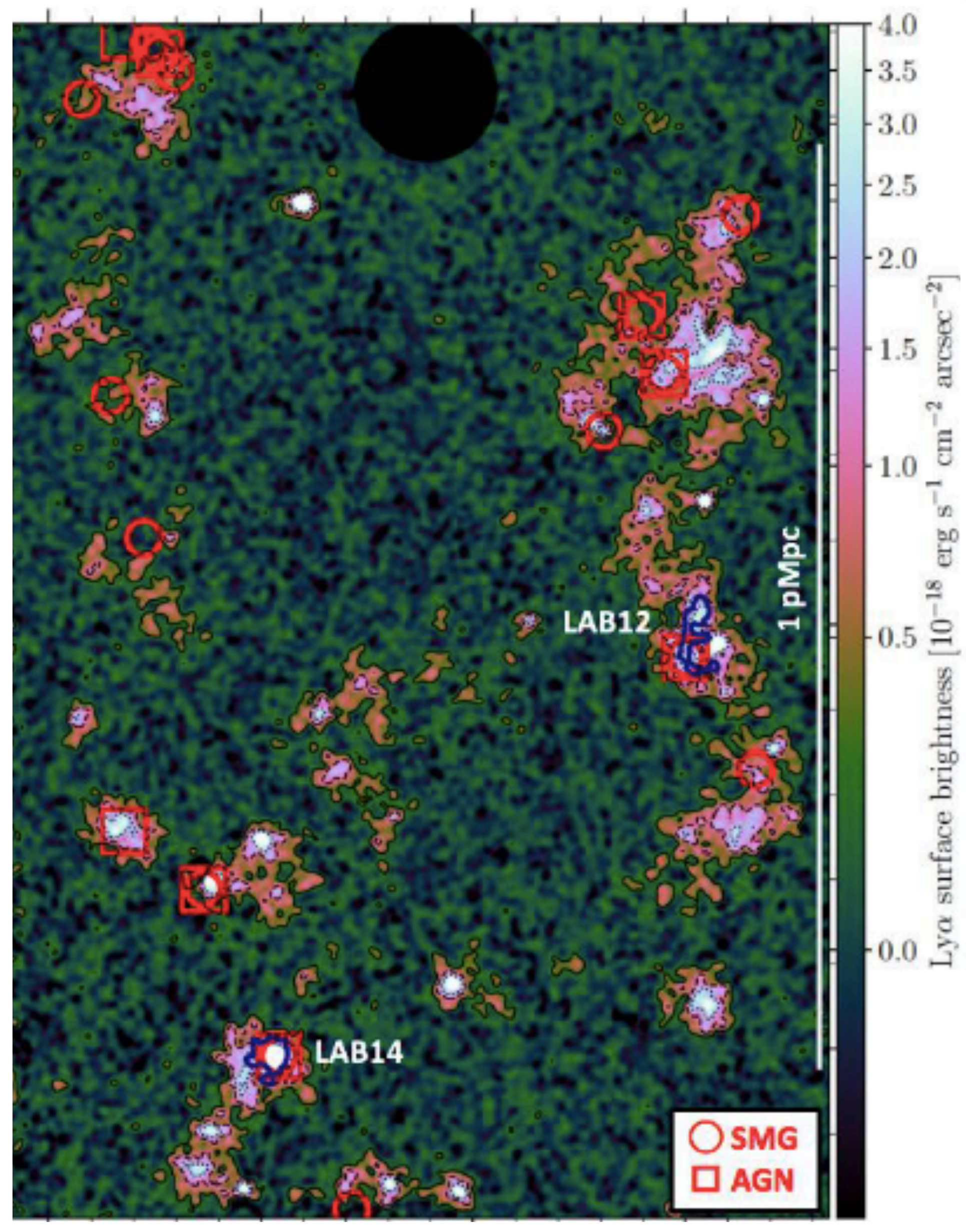
Giant Lya nebulae



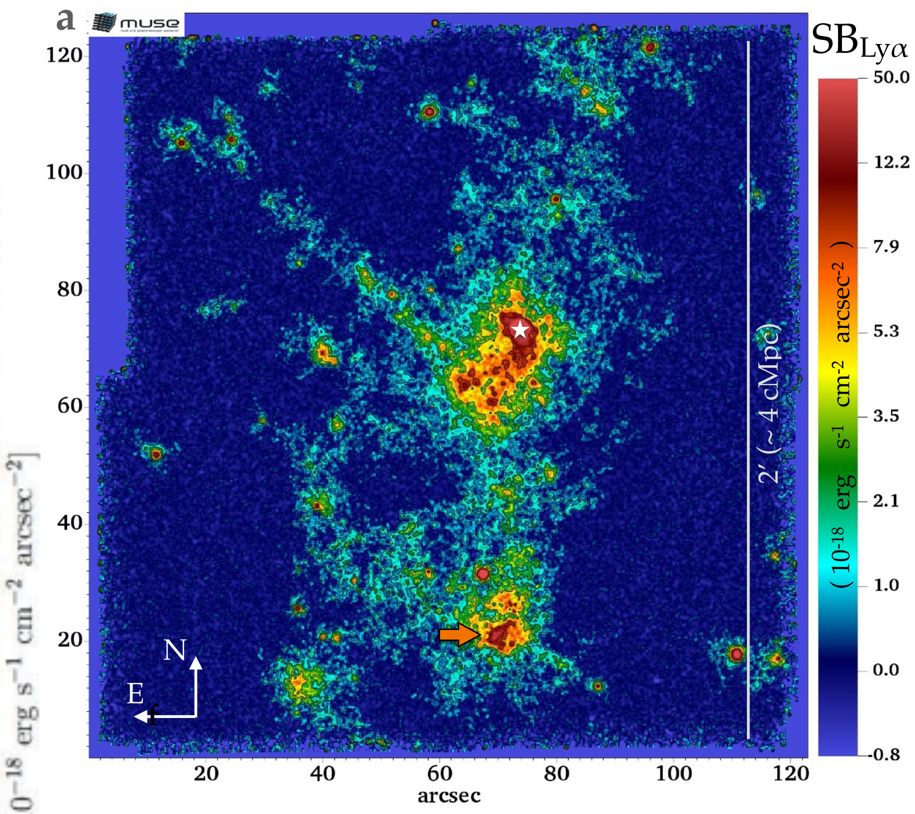
Cantalupo+ 2014



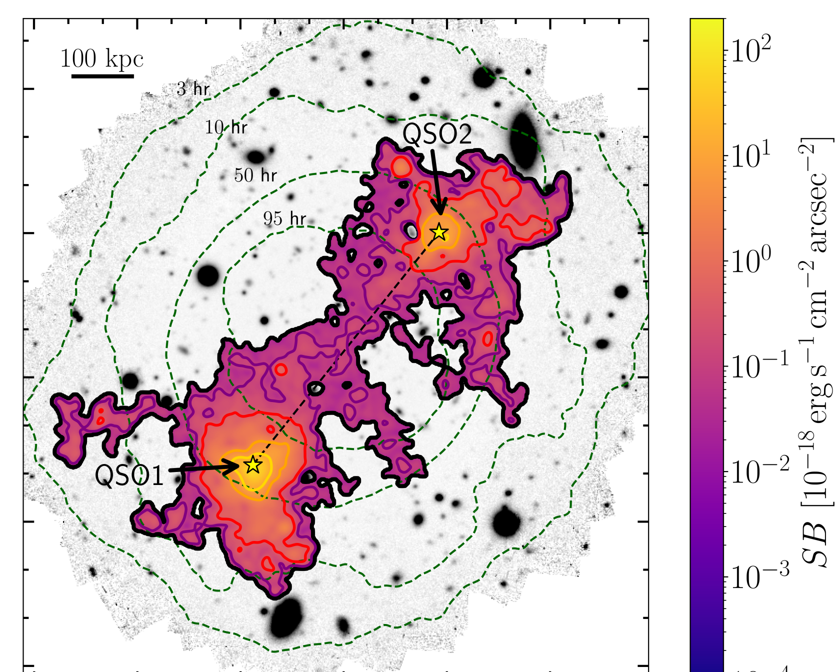
Hennawi+ 2015



Umehata+ 2019



Cantalupo+ in prep.



Tornotti+ 2024

See also Borisova+ 2016

Simulations

Objective: **simulate massive nodes of the cosmic web corresponding to giant Lya nebulae systems in warm and cold dark matter**.

We use 2 sets of simulations: DaLya (TL+ in prep.), HELLO (Waterval+ 2024)

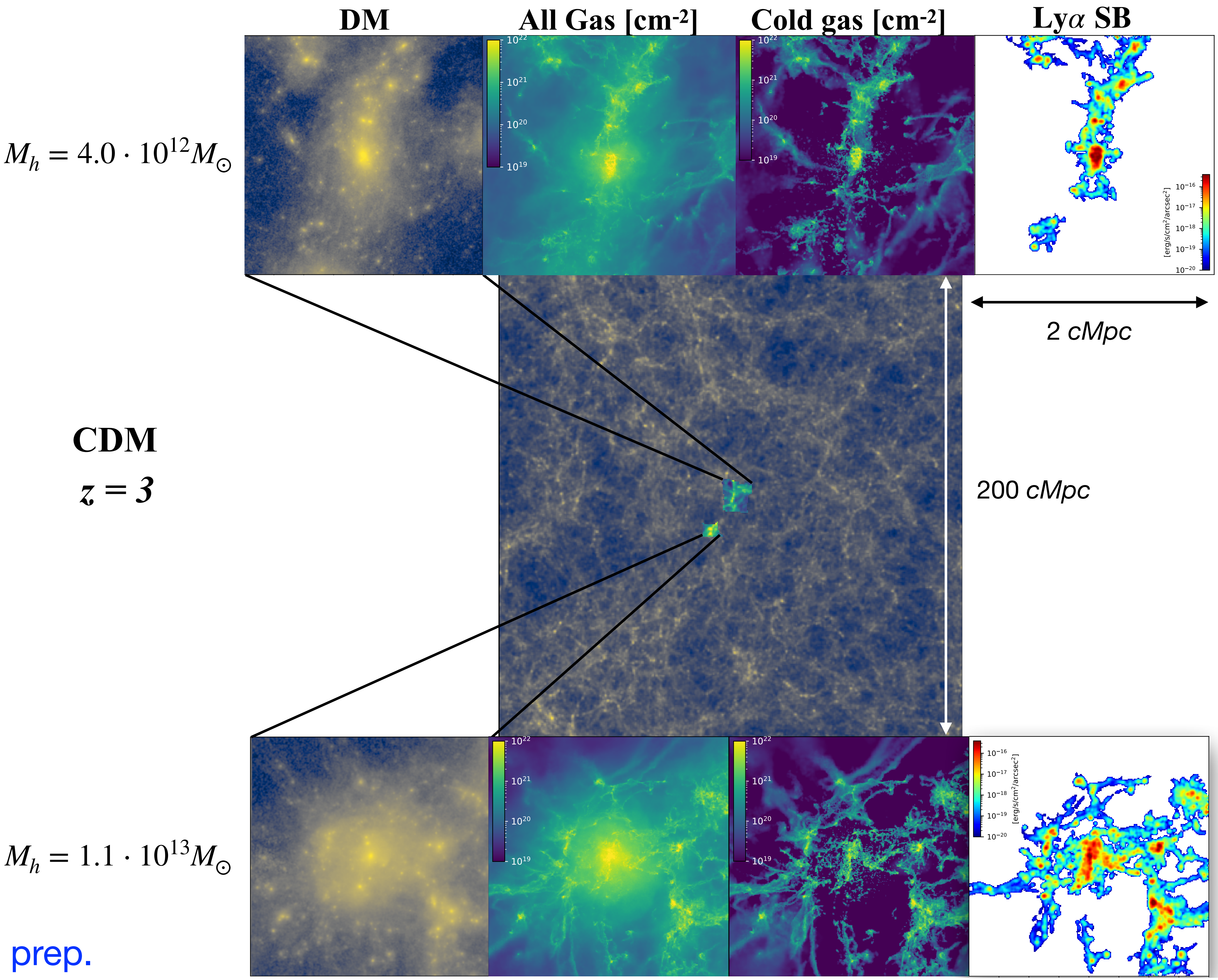
DaLya:

- Hydrodynamical *zoom-in* simulations with public code GIZMO (Hopkins 2015), Planck 2018 cosmology.
  ICs: MUSIC (Hahn+ 2011)
- Final gas mass resolution $\mathbf{m_b = 6.7}$ (1.0) $\mathbf{x\ 10^5\ M_\odot}$
- Simulate 2 protoclusters and their environment down to z ~ 3 to match MUSE observations, systems mass ~ $M_h \approx 10^{13} M_\odot$
- We run 3 dark matter models: CDM, WDM 3.5 keV, WDM 1.5 keV.
  WDM implemented as thermal relic with a cut-off power spectrum following Bode+ 2001, Viel+ 2005
- Each simulation requires 500k-1M cpu hours

Hydrodynamics in DaLya

- Galactic star formation above threshold n = 10 atoms/cm^3
  SFR ~ m_g/t_{dyn}
- SN feedback with mechanical winds (FIRE-2 model with enhanced kinetic energy, Hopkins+ 2017).
  No blackholes, so no AGN feedback (implemented in HELLO)
- Photoheating and photoionisation (reionization) from UV background from Faucher-Giguère 2020.
  Self-shielding in high density regions from Rahmati+ 2013 —> **gas in regions dense enough to be observable in emission self-shielded from UVB —> no degeneracy with thermal history of Universe**
- Follow 11 species up to Fe, and cooling by species down to T = 10^4 K following Wiersma+ 2009.
  Under 10^4 K, effective cooling based on total metallicity

The DaLya simulations



TL+ in prep.

Lya emission in maximum fluorescence limit and mock observations

In the case of maximal florescence, only emission mechanism is recombination, the surface brightness SB (= [lumnosity]/[unit area on sky]/ [unit area on detector]) is

$$SB_{\textbf{ion}} \propto \frac{1}{A}\int \alpha(T)\, n_H^2\, dV \propto \alpha(T) \cdot \langle n_H \rangle^2 \cdot L \cdot C$$

Cantalupo+ 2014, 2019

$C = \langle n_H^2 \rangle / \langle n_H \rangle^2$ clumping factor, and $\alpha(T) \rightarrow 0$ **for** $T > 10^5\, K$

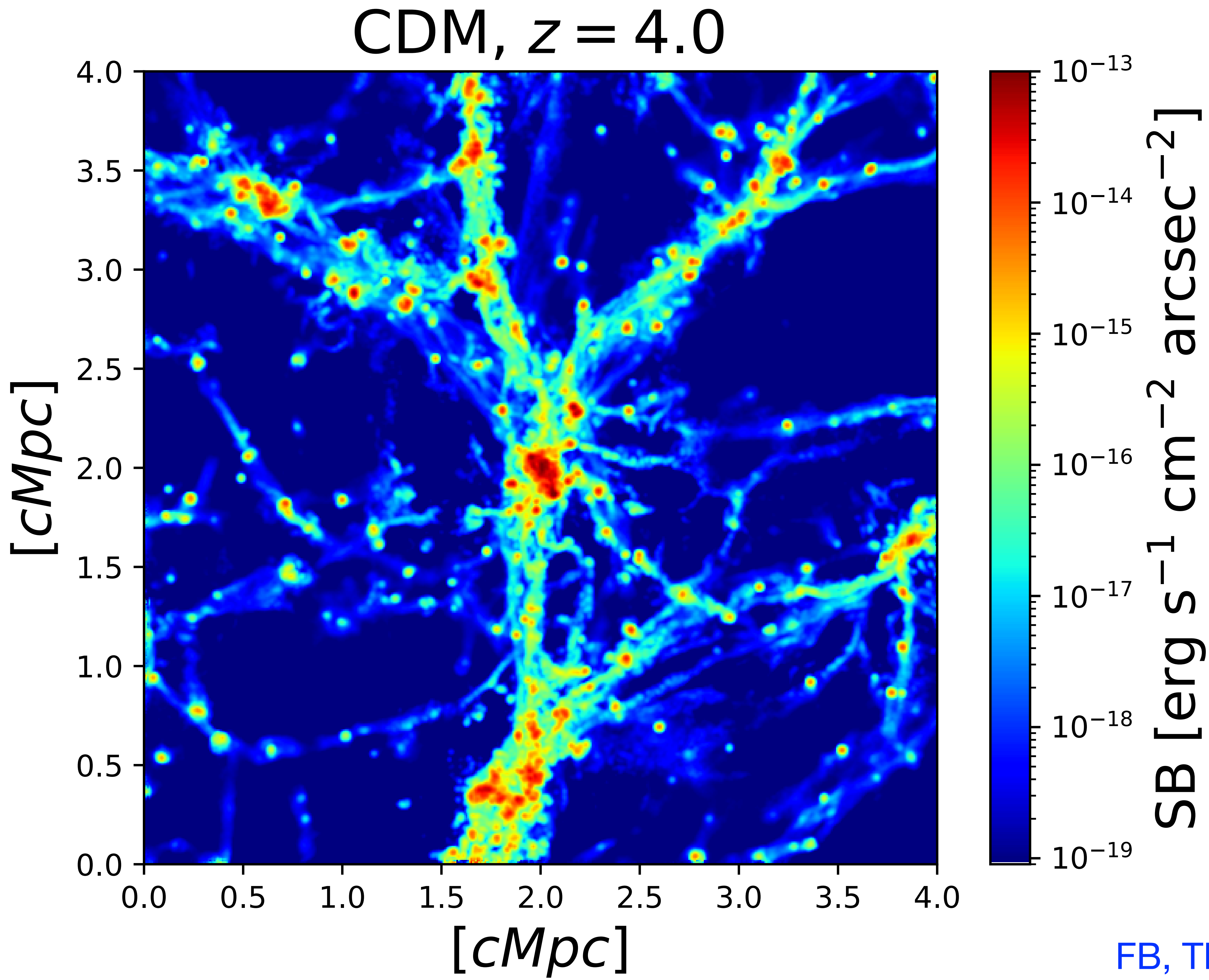
Dark matter properties impact the cold gas density and morphology in the IGM via gravitational interaction. This propagates to the observed Lya SB as $n_H{}^2$

From simulation outputs, assign particles on regular grid with correct kernel (cloud in cell problem) (P2C, Cantalupo+ in prep., de Beer+ 2023) and compute the Lya emissivity in maximum fluorescence limit (no radiative transfer).

Impose a photoheating floor due to the QSO at 5×10^4 K and remove contribution from ISM

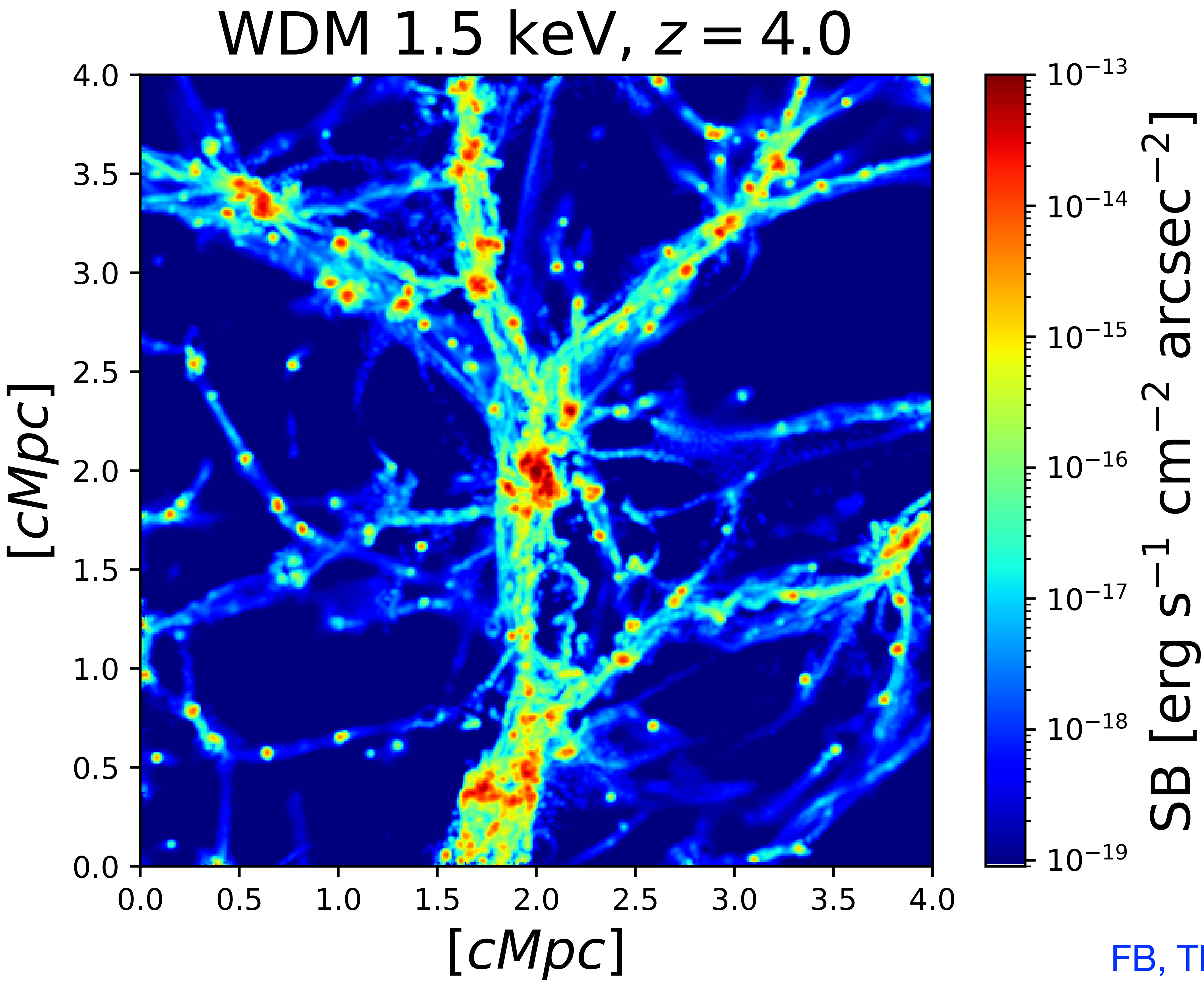
Create mock narrow band observations of Lya surface brightness by integrating along a line of sight, ev. adding seeing and noise (CubEx, MockOb, Cantalupo+ in prep., de Beer+ 2023)

DaLya - CDM vs WDM



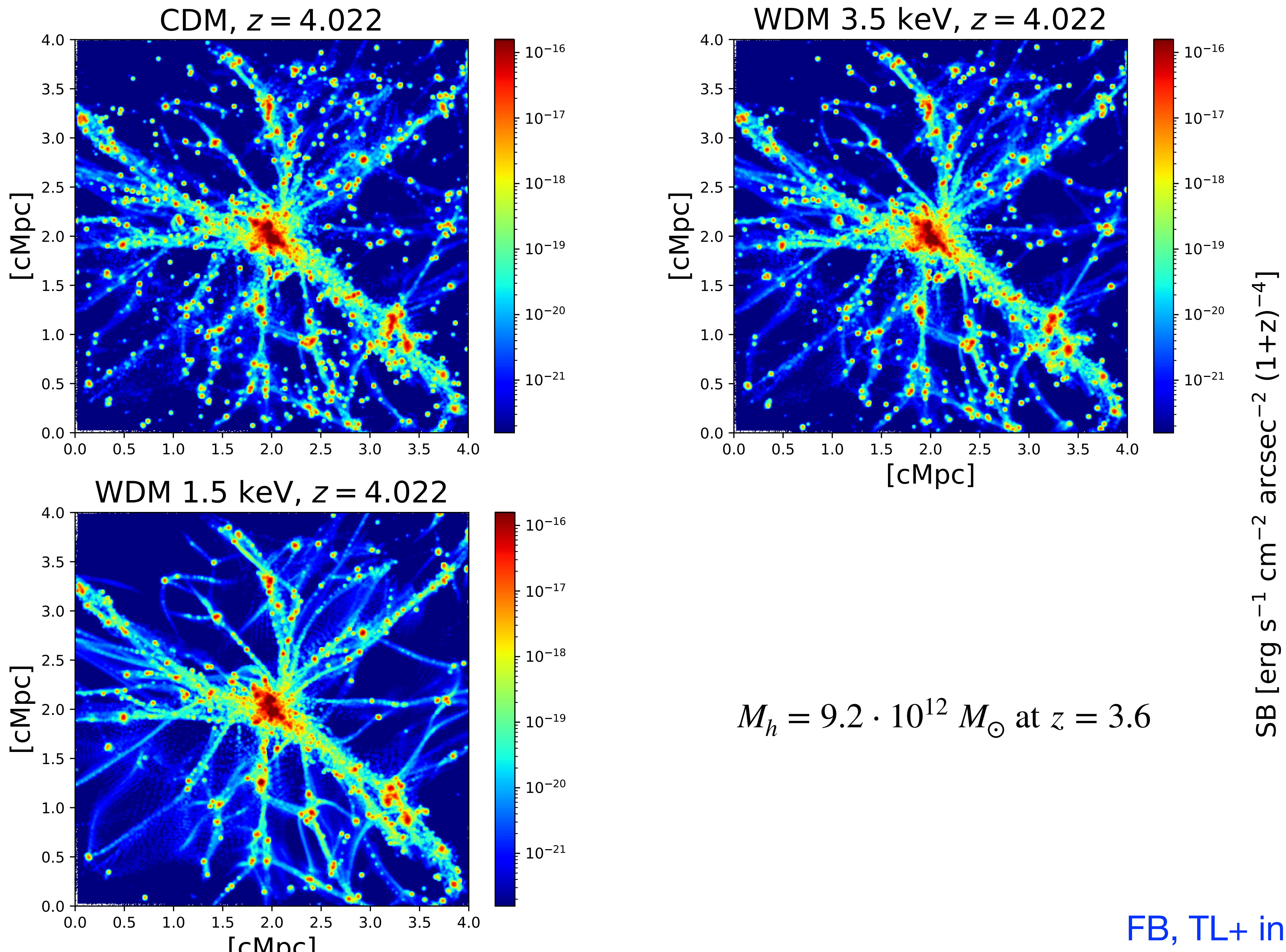
FB, TL+ in prep.

DaLya - CDM vs WDM



FB, TL+ in prep.

Comparison with HELLO



$M_h = 9.2 \cdot 10^{12}\ M_\odot$ at $z = 3.6$

FB, TL+ in prep.

Analysis: Minkowski functionals

- Measure size and connectivity of a subset E_{SB} of R^d (Minkowski 1903)
- In our case, d=2 and E_{SB} is the subset of all pixels above a SB threshold
- In that case, 3 MF that completely characterise the morphology of E_{SB}
- F, U and X are the surface, perimeter, and Euler characteristic (connectivity) of E_{SB}

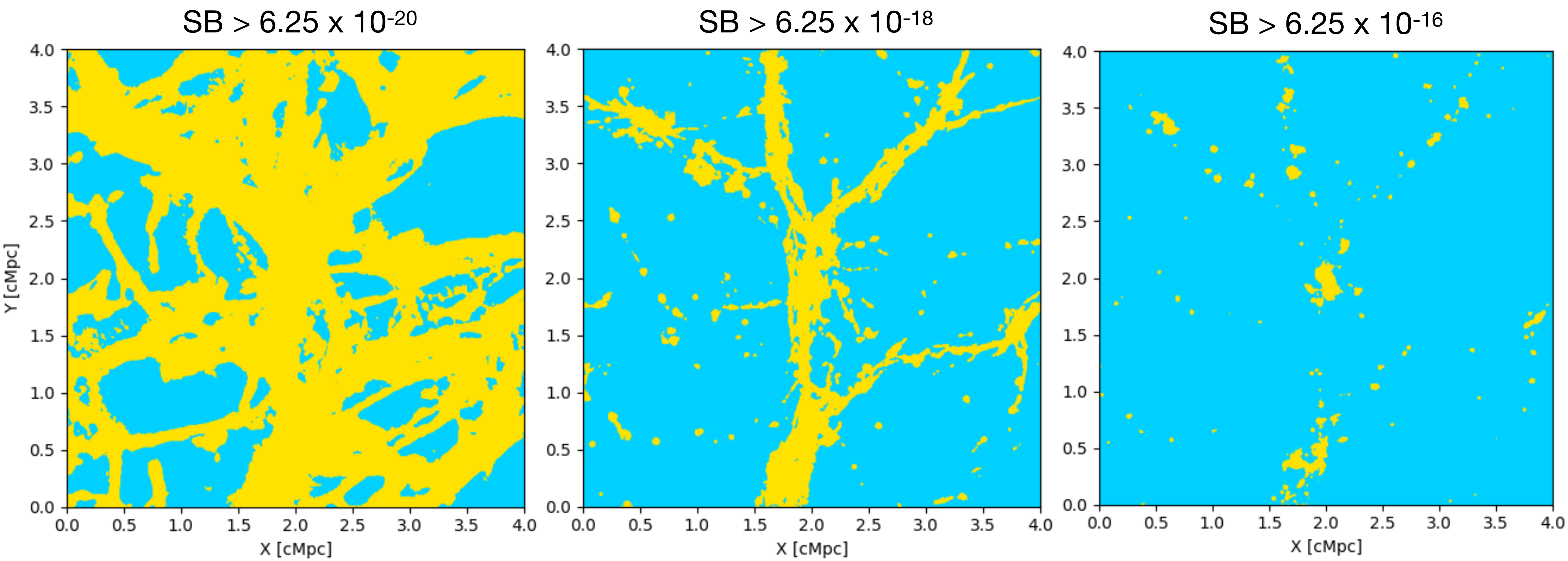
$$F(SB) = \int_{E_{SB}} dS, \qquad U(SB) = \int_{\partial E_{SB}} dl, \qquad \chi(SB) = \frac{1}{2\pi} \int_{\partial E_{SB}} \kappa dl$$

(we use the python package minkfncts2d to compute them efficiently)

Minkowski functionals

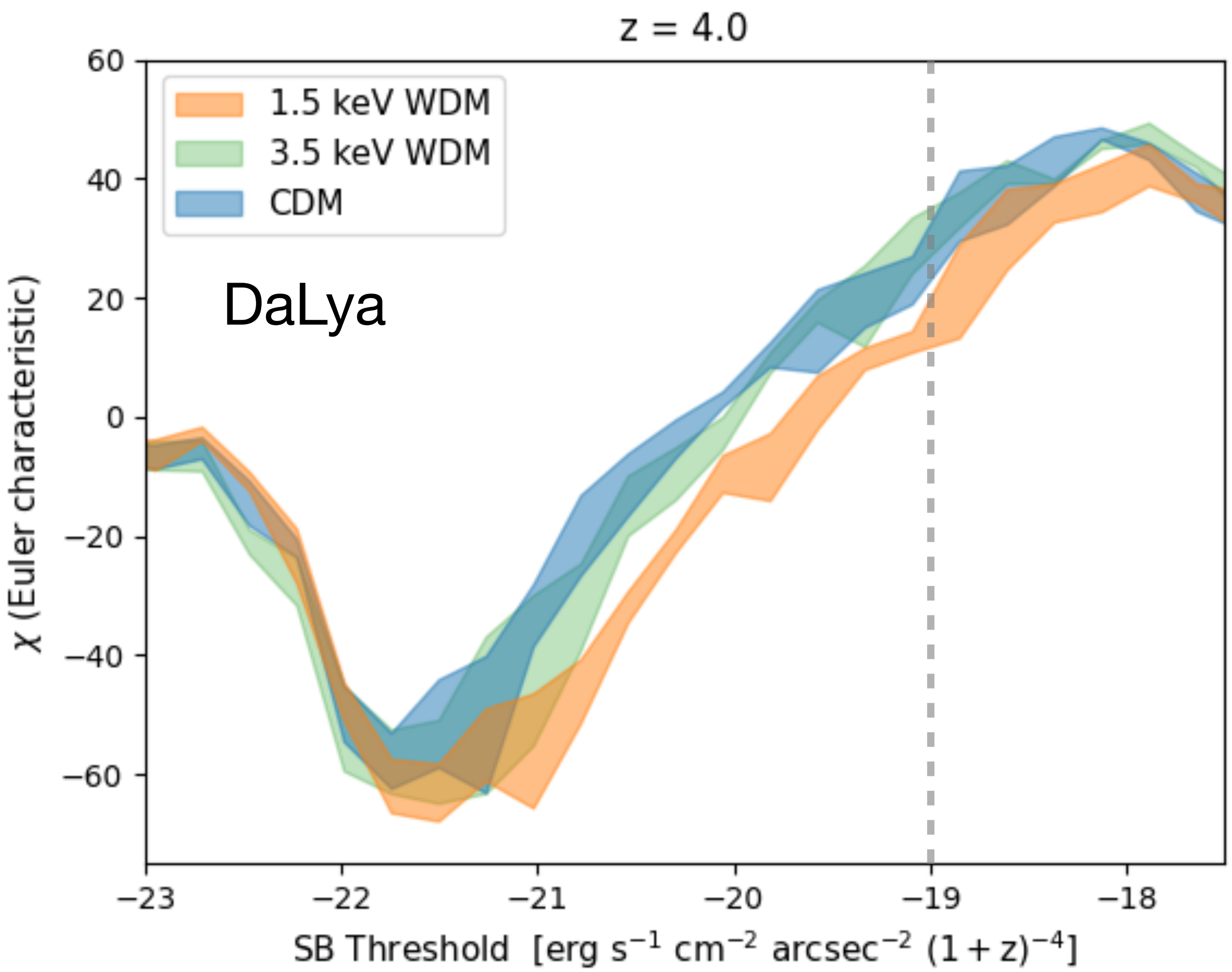
Compute the Minkowski functionals for the set of pixels above a varying SB threshold

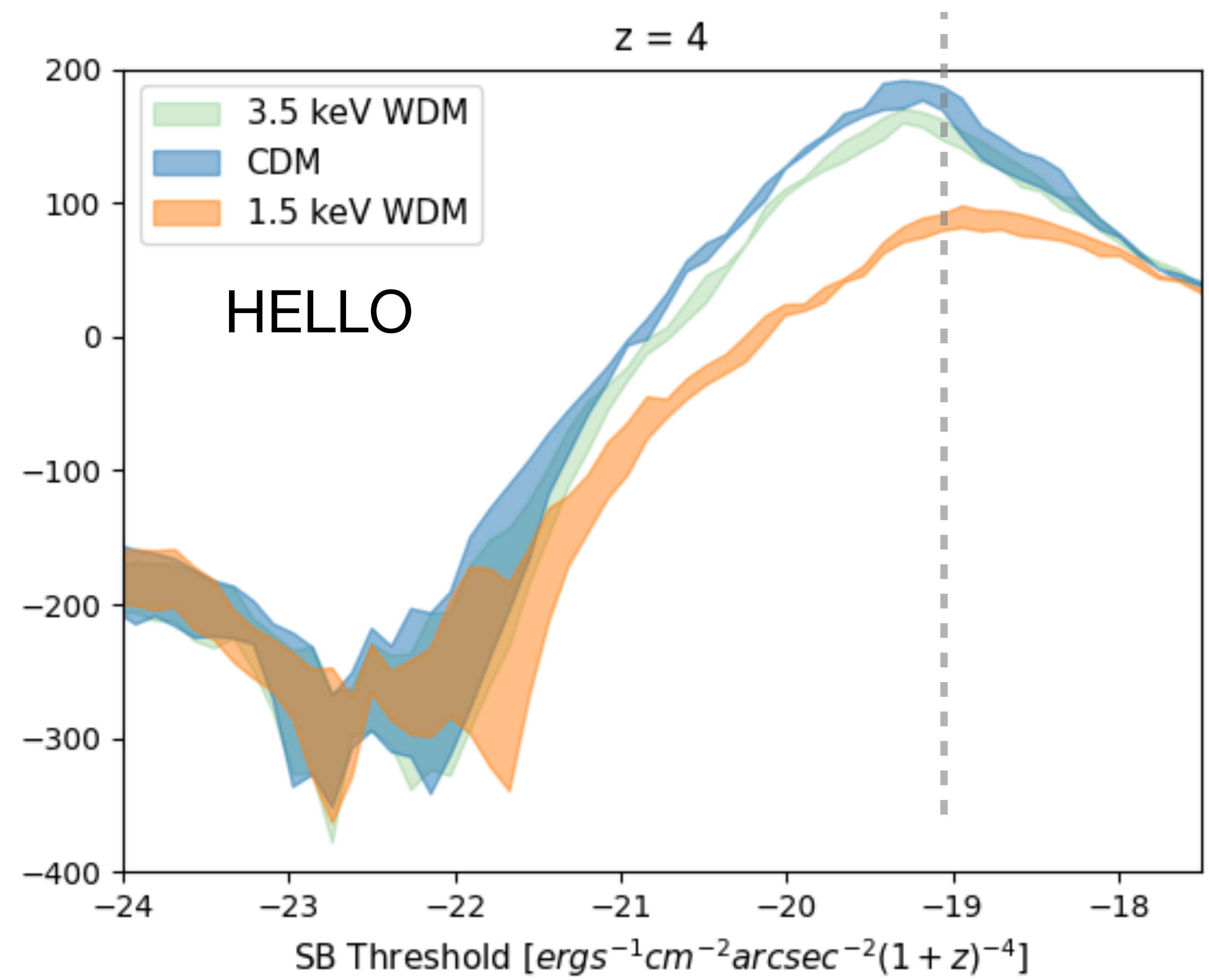
DaLya, CDM, $z = 4$



Minkowski functionals

Compute the Minkowski functionals for the set of pixels above a varying SB threshold





FB, TL+ in prep.

The connectivity displays clear differences between CDM and WDM at SB levels that are observables

Conclusions

- Development of high-resolution simulations of the IGM in protoclusters in different dark matter scenarios (DaLya)
- Morphological analysis of mock Lya observations shows quantitative differences between CDM and WDM.
- First steps towards using the IGM in emission to test dark matter models —> promising new way of constraining dark matter!

Future work:

- Systematic analysis of IGM with increased statistics.
- Robustly isolate the impact of DM from astrophysical processes (feedback)
- Additional analysis techniques: correlation functions, image recognition with AI,…
- Other dark matter models (SIDM, Fuzzy DM, …)
- Apply analysis to observations