@TeVPA - Kingston, Canada - 10/8/2022

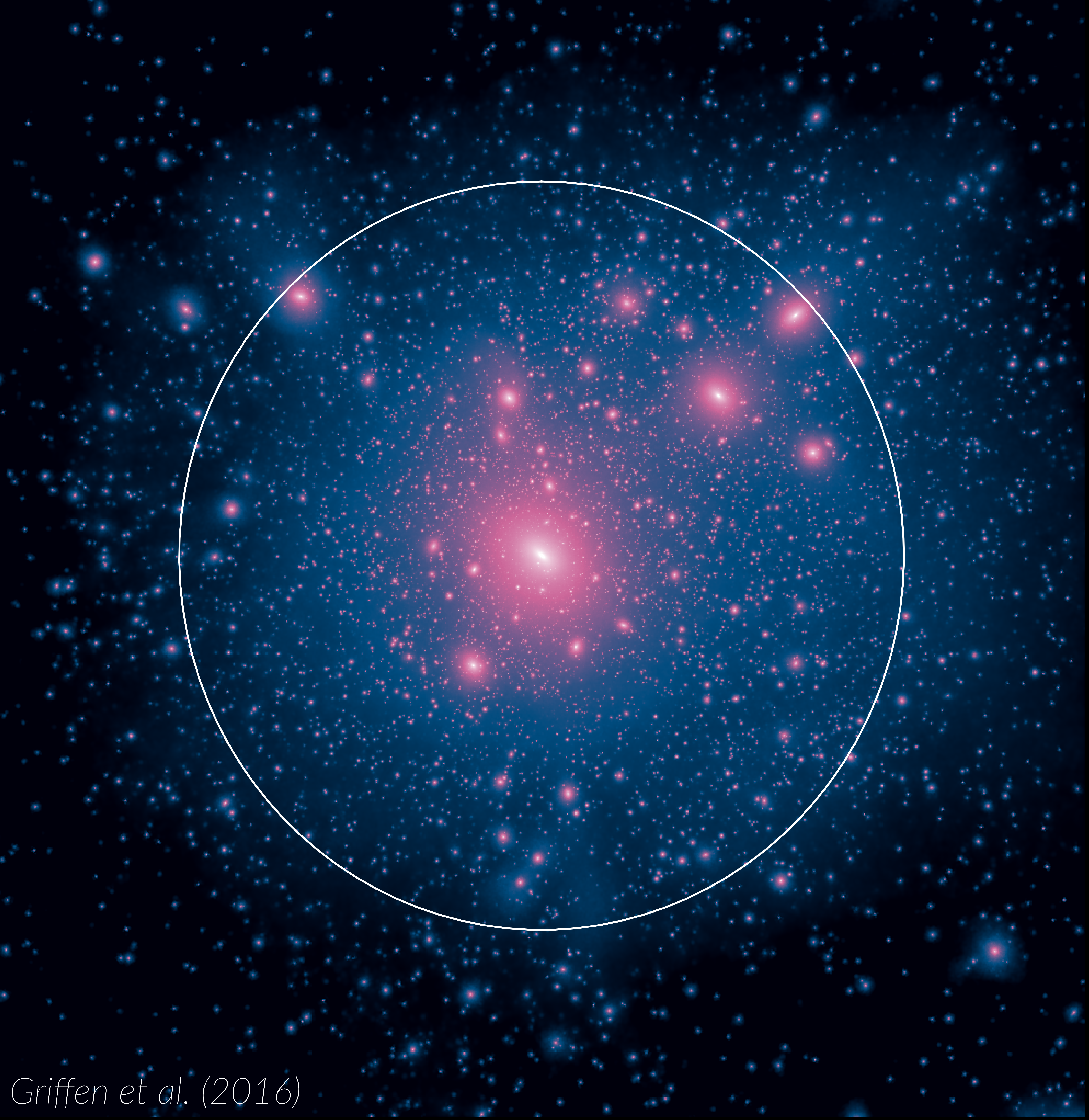
Warm dark matter searches from the Galactic halo

Ariane Dekker — PhD at GRAPPA/University of Amsterdam

A. Dekker, S. Ando, C.A. Correa, K.C.Y. Ng — arXiv: 2111.13137
A. Dekker, E. Peerbooms, F. Zimmer, K.C.Y. Ng, S. Ando — Phys. Rev. D 104, 023021 (2021)

UNIVERSITY OF AMSTERDAM

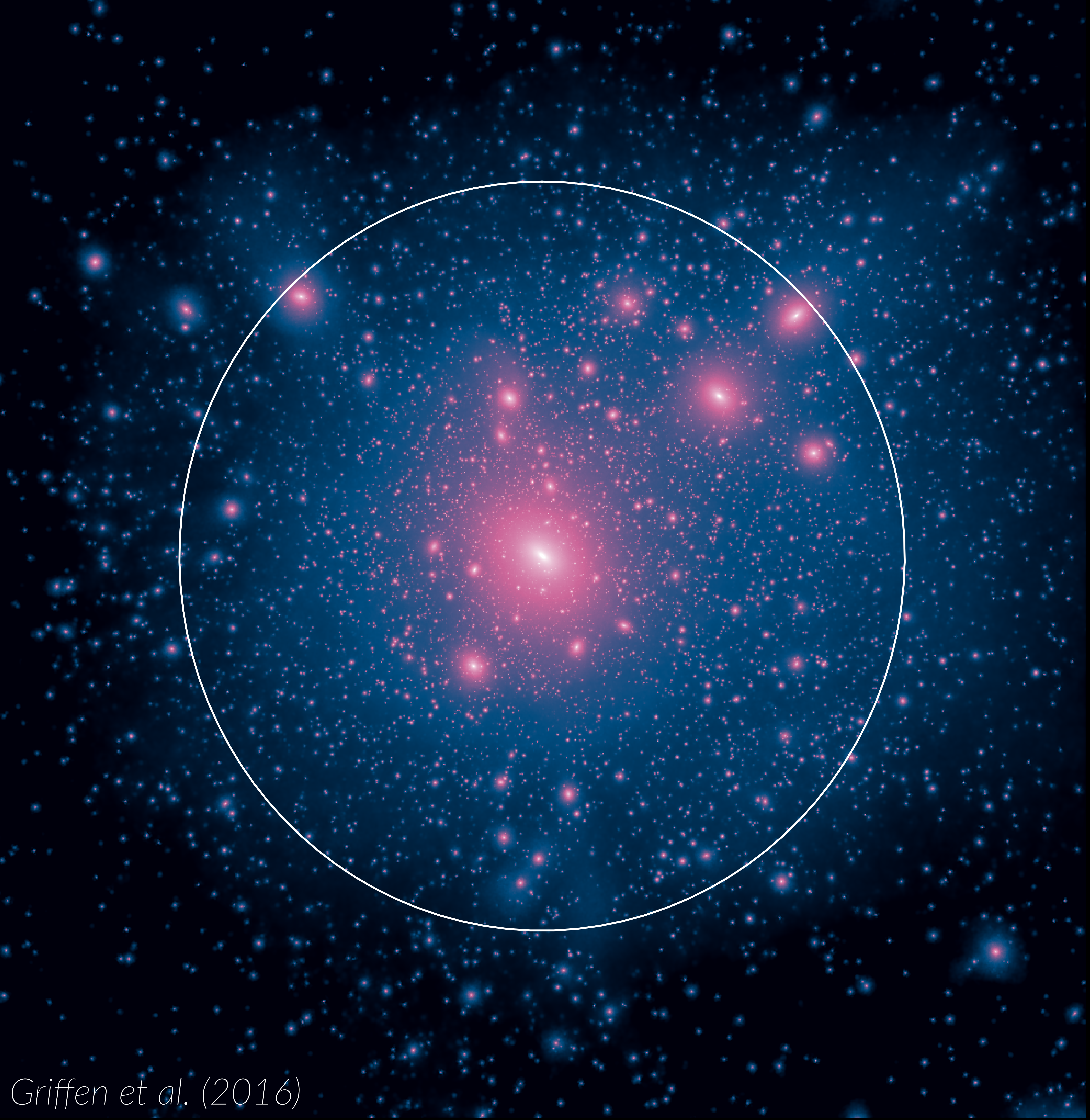
GRAPPA
GRavitation AstroParticle Physics Amsterdam



Why the galactic dark matter halo?

1)

- Milky-Way is embedded in a large dark matter halo
- Hosts smaller dark matter halos (subhalos)
- Abundance of substructure to distinguish between dark matter models



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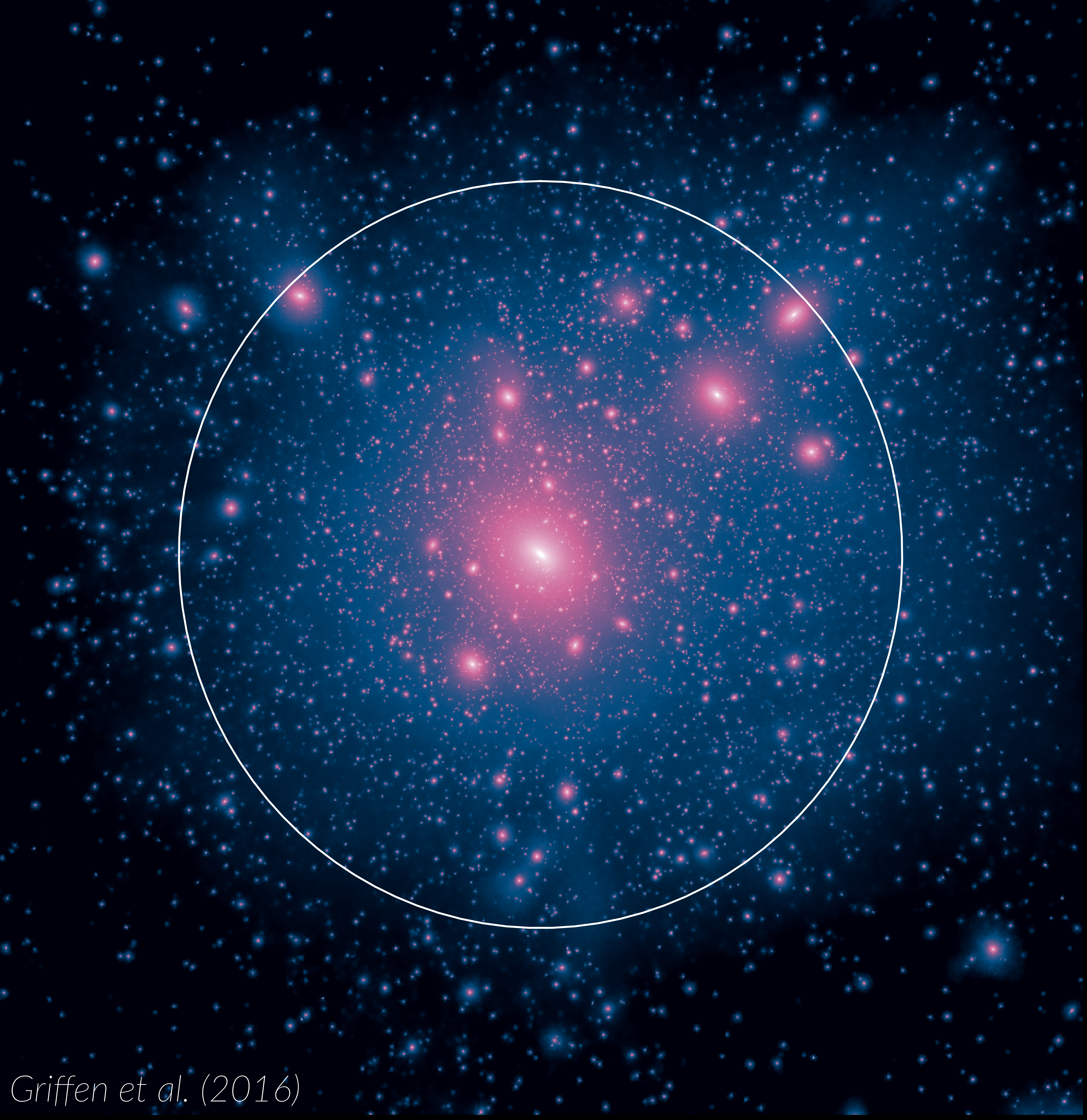
- Dark Matter can decay into SM particles
- Highest flux observable on Earth from Galactic halo
- Ideal for indirect dark matter searches



Griffen et al. (2016)

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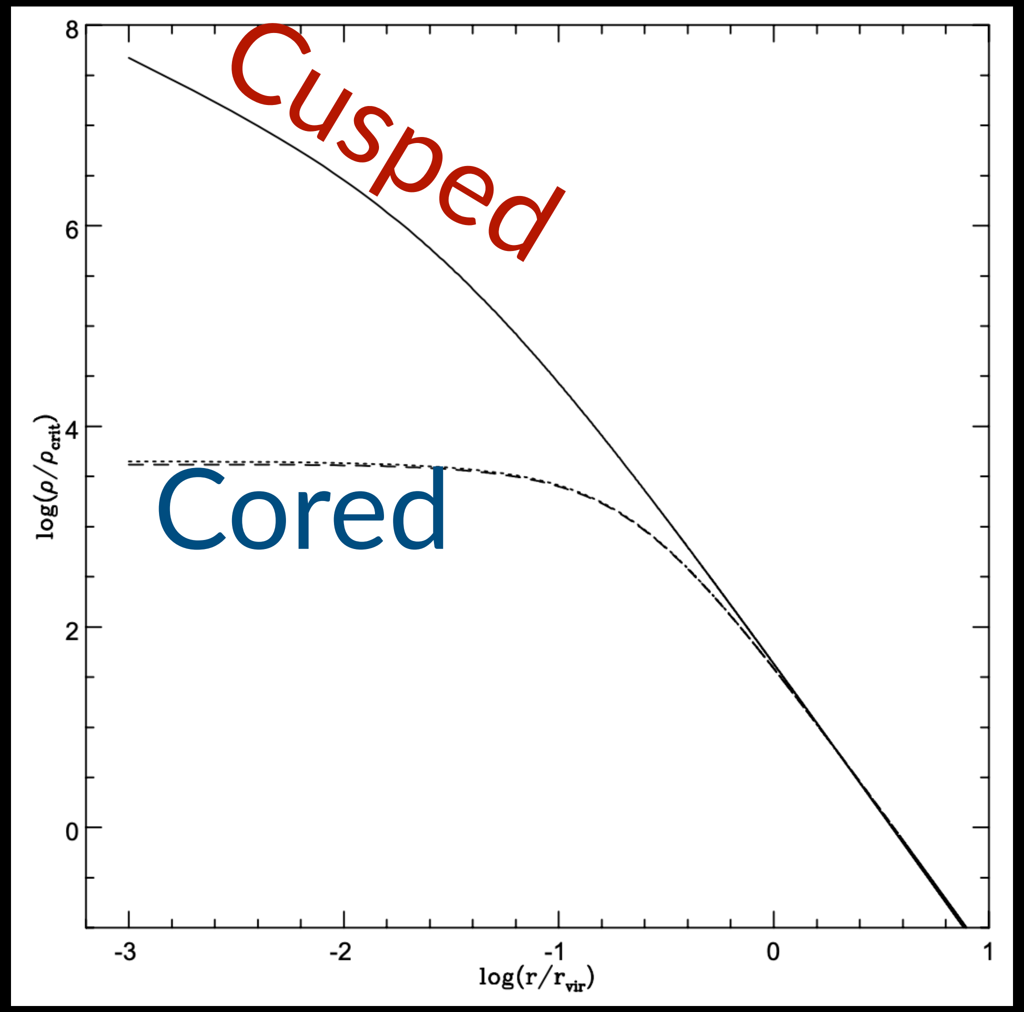
Small scale observations

- ΛCDM successful on reproducing the large scale structures in the Universe
- However, DM-only N-body simulations find discrepancies with observations at small scales (below ~1 Mpc)

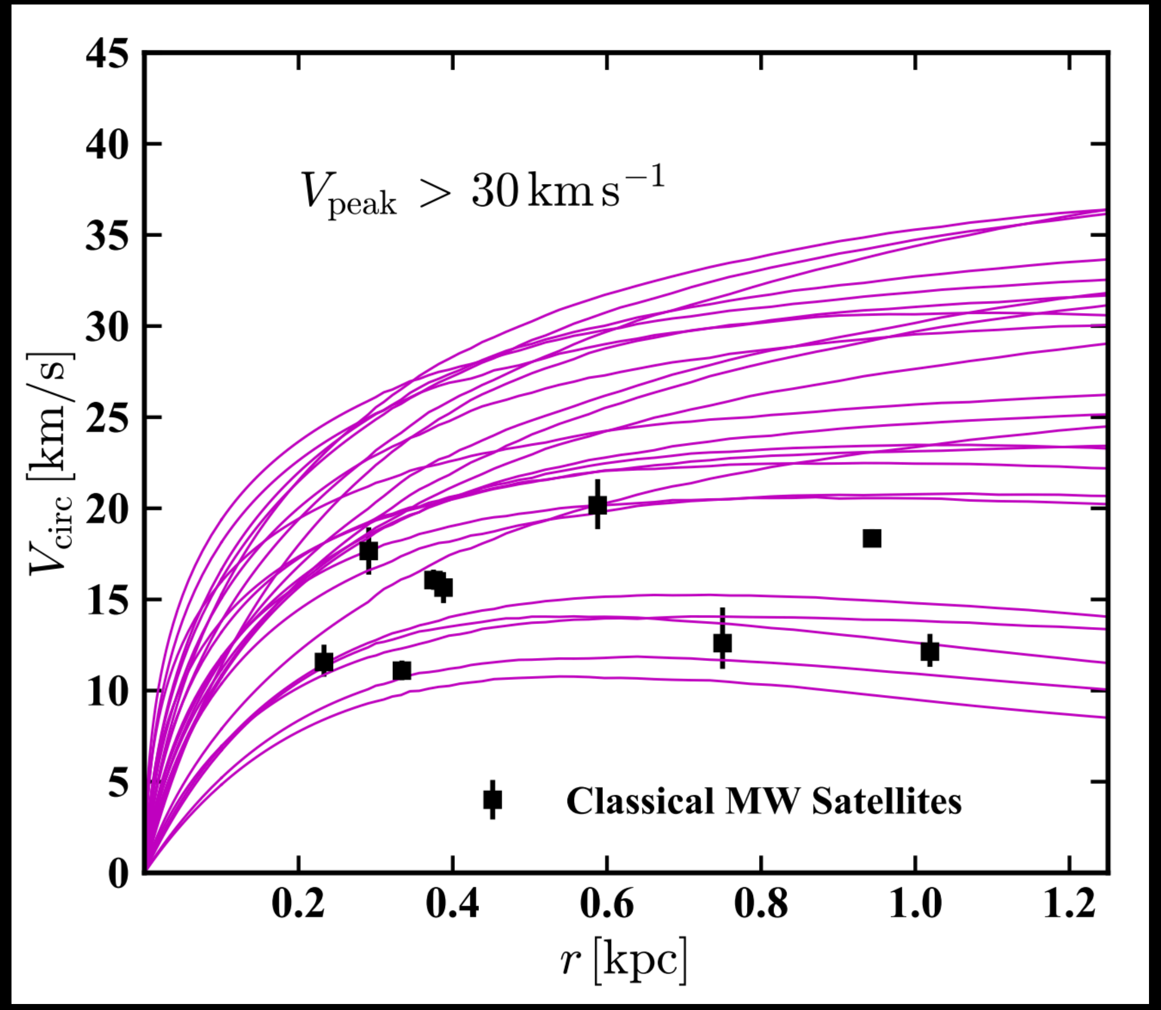
Small scale discrepancies

Cusp/core



Popolo et al. (2009)

Too-big-to-fail

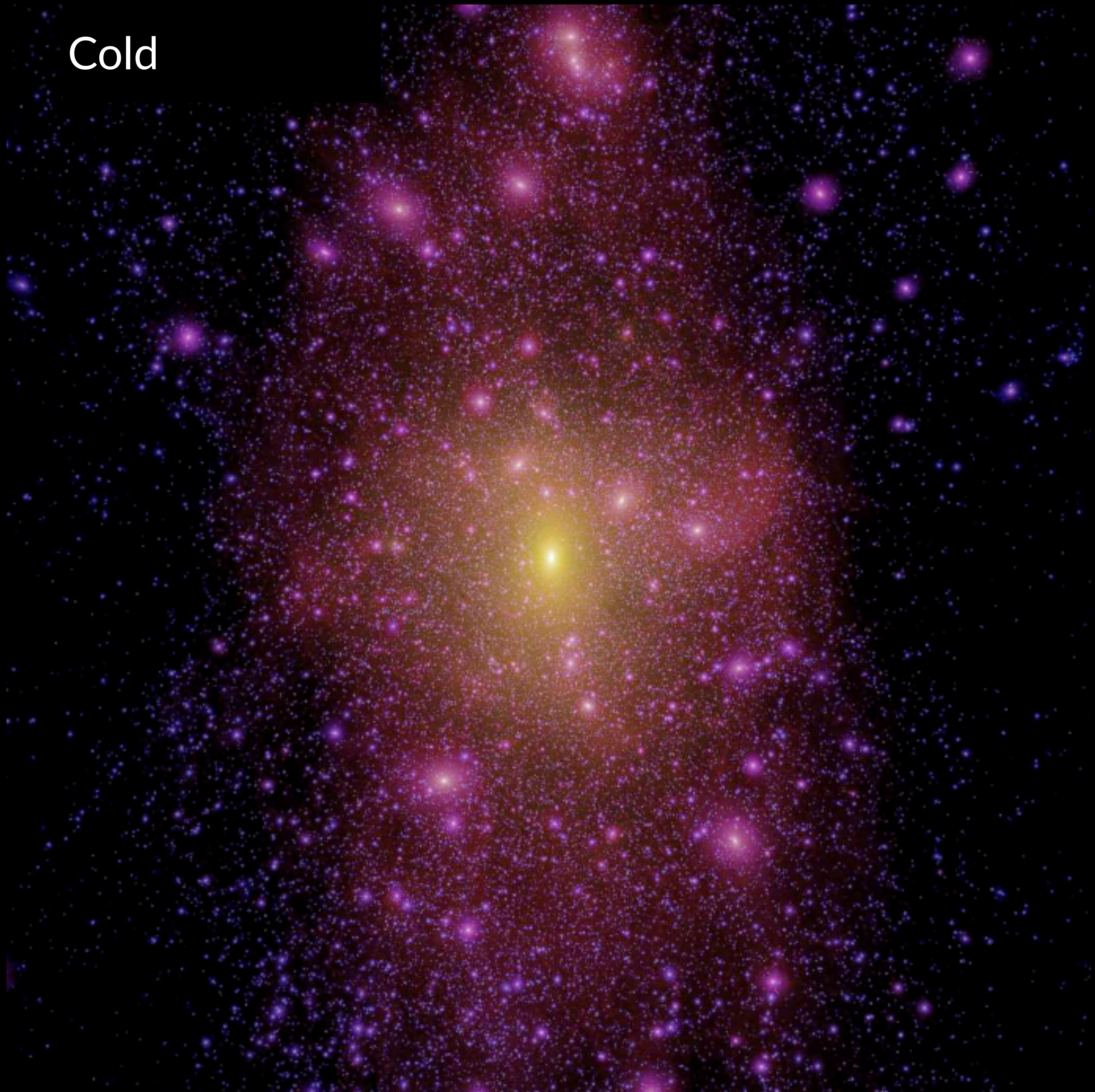


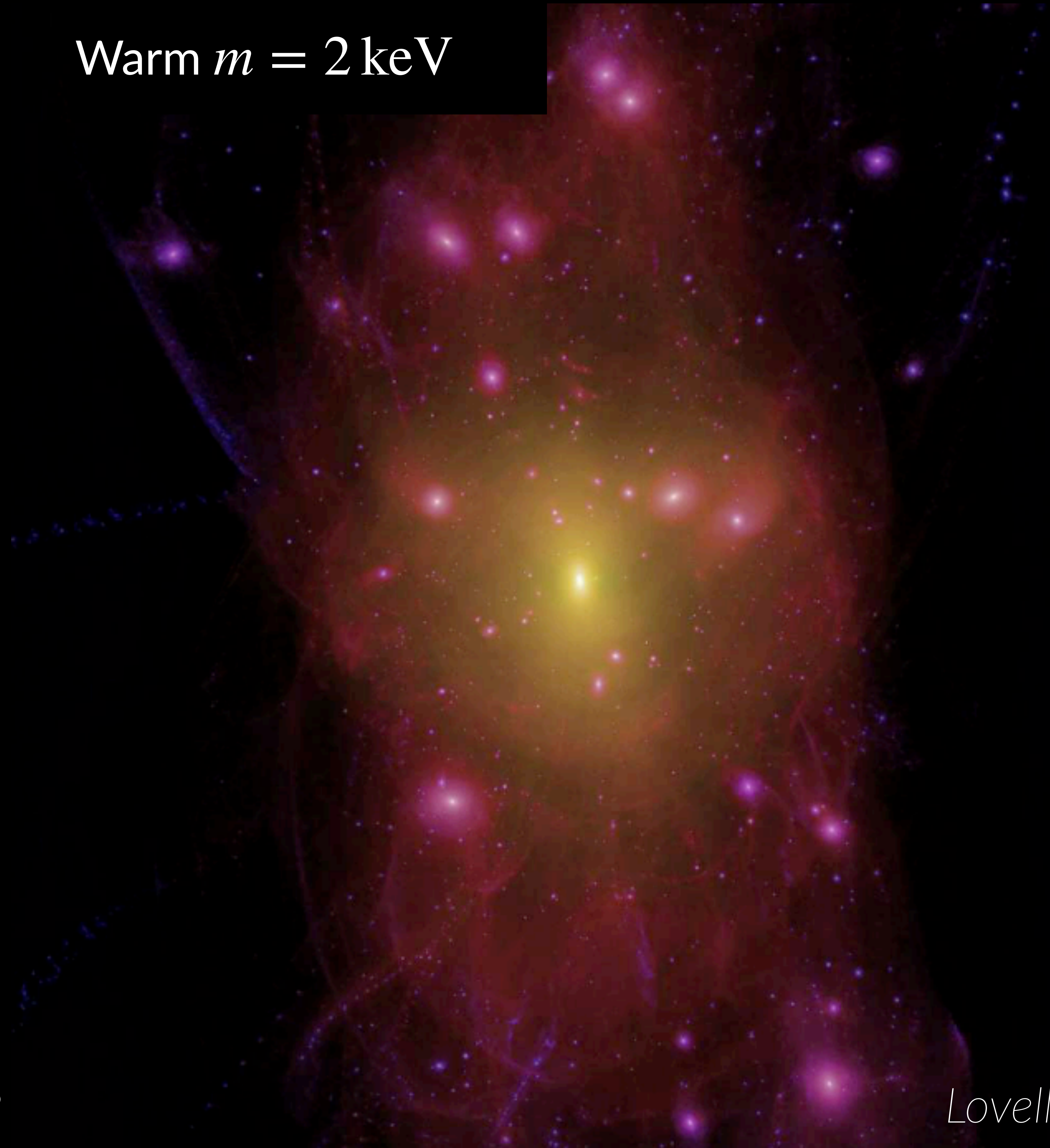
Bullock et al. (2017)

Missing satellites

Weinberg et al. (2013)

- Solutions: Baryonic physics / non-CDM (such as **Warm Dark Matter**)

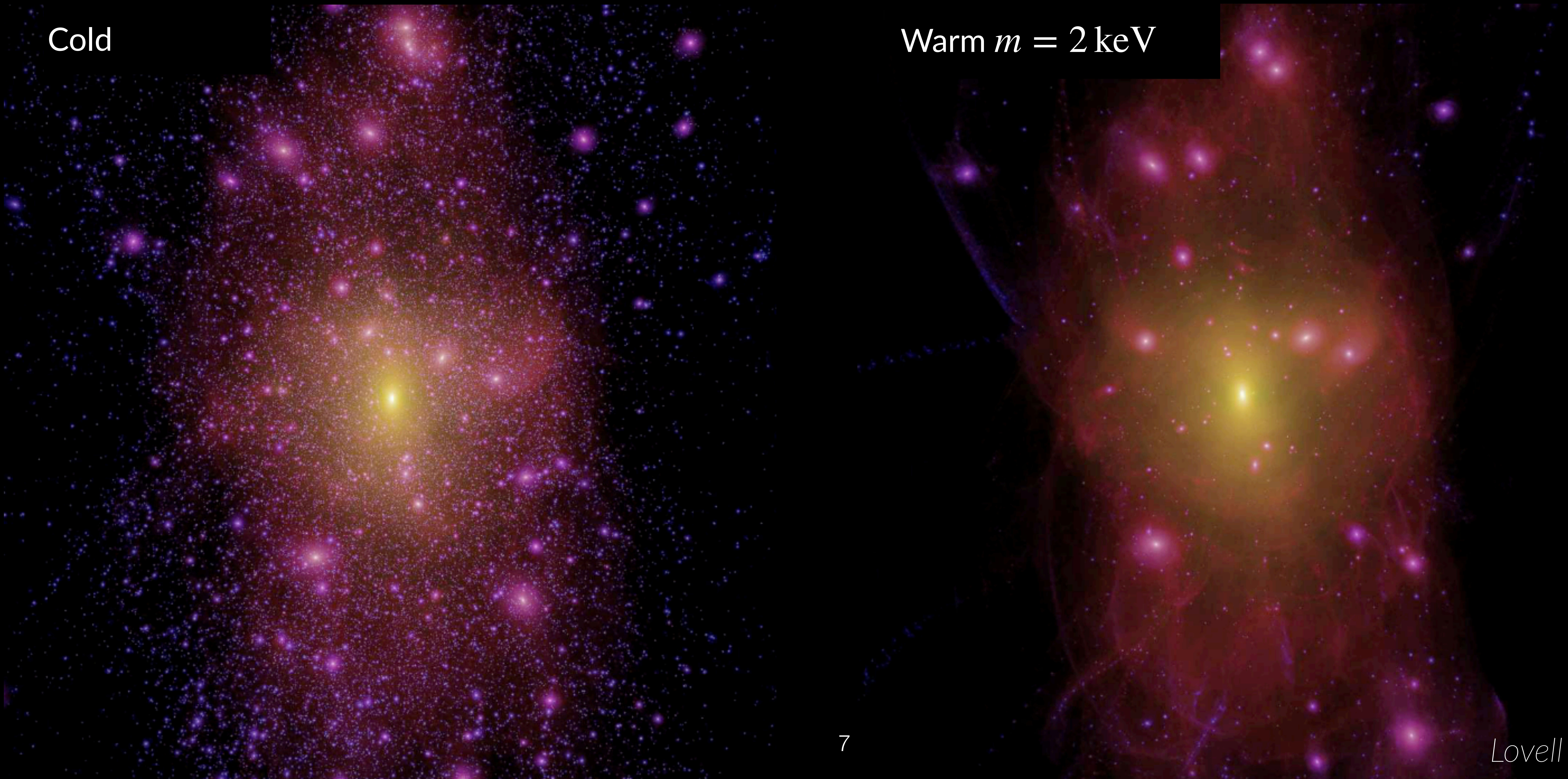




Lovell et al. (2014)

- Solutions: Baryonic physics / non-CDM (such as **Warm Dark Matter**)

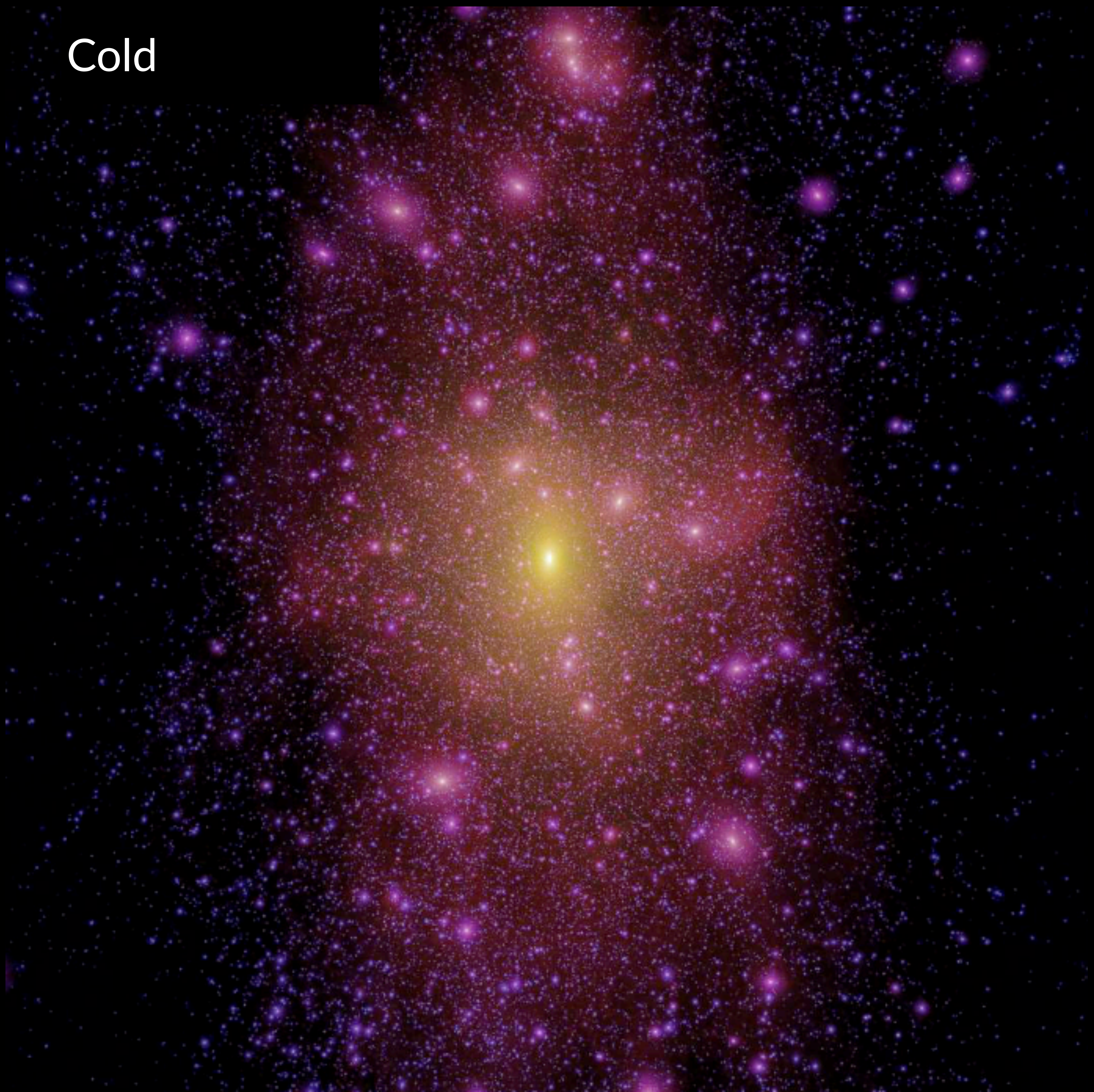
  ↘ supernova feedback / ionisation processes

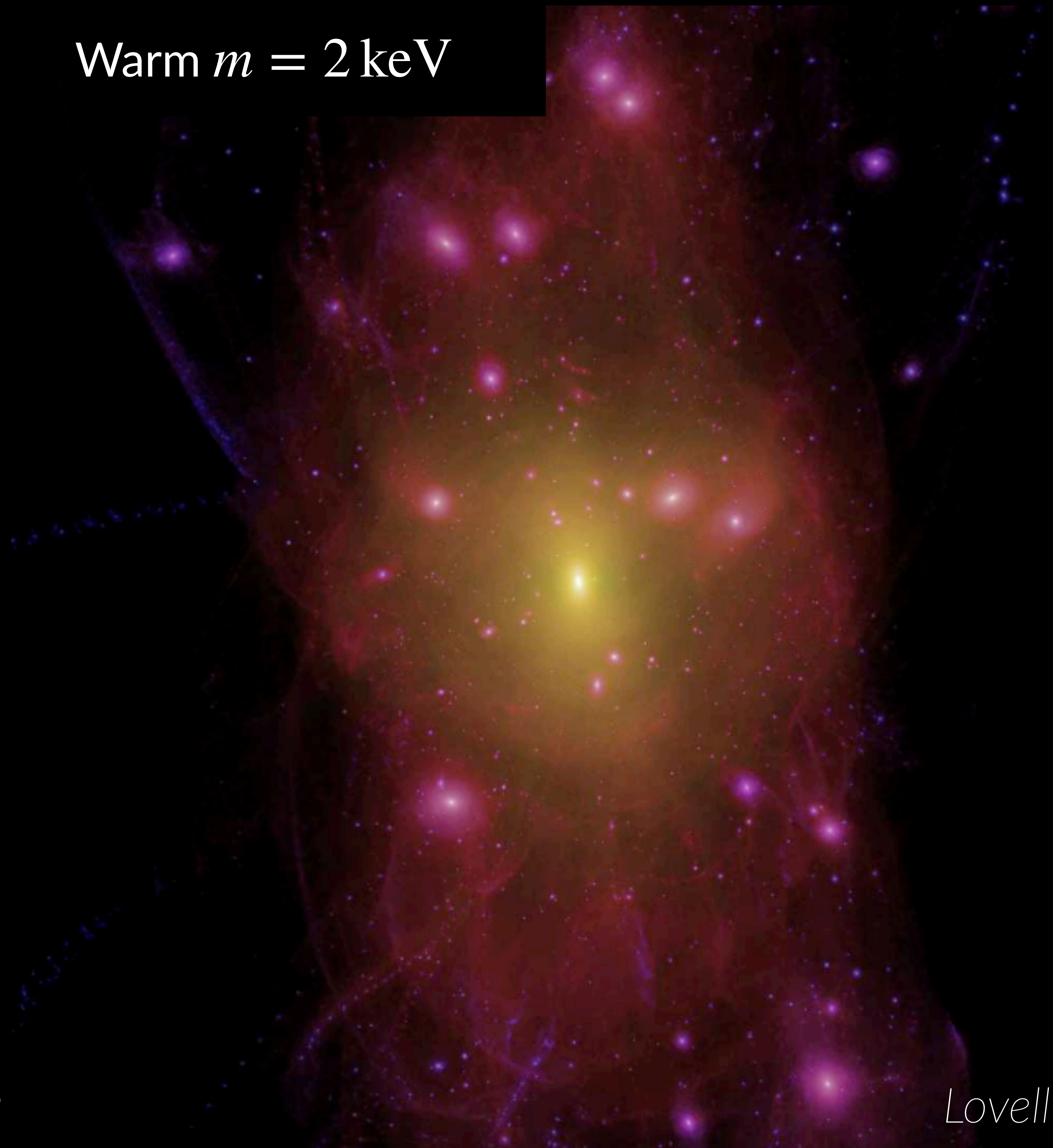


Lovell et al. (2014)

- Solutions: Baryonic physics / non-CDM (such as **Warm Dark Matter**)

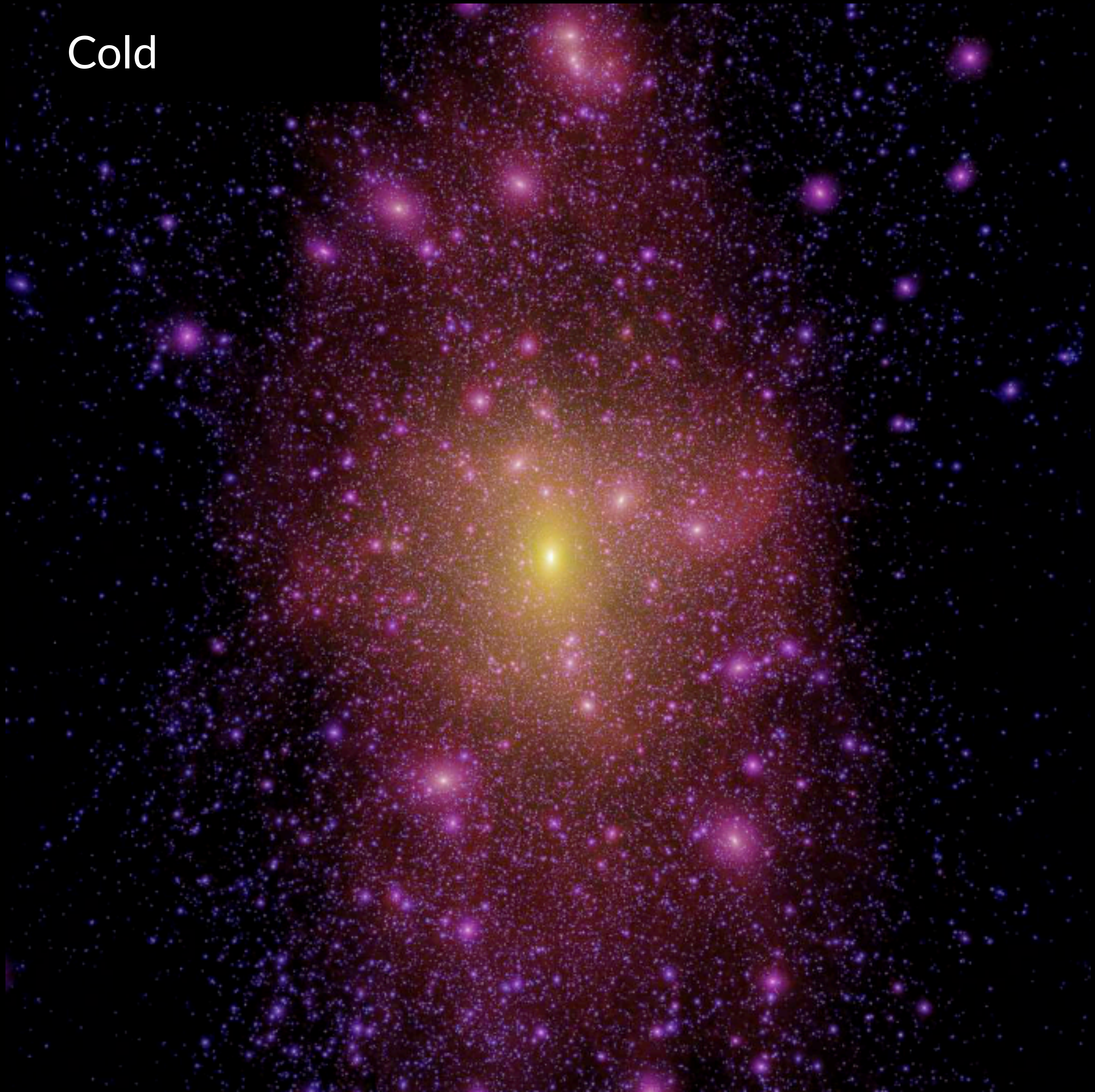
Free-streaming effects

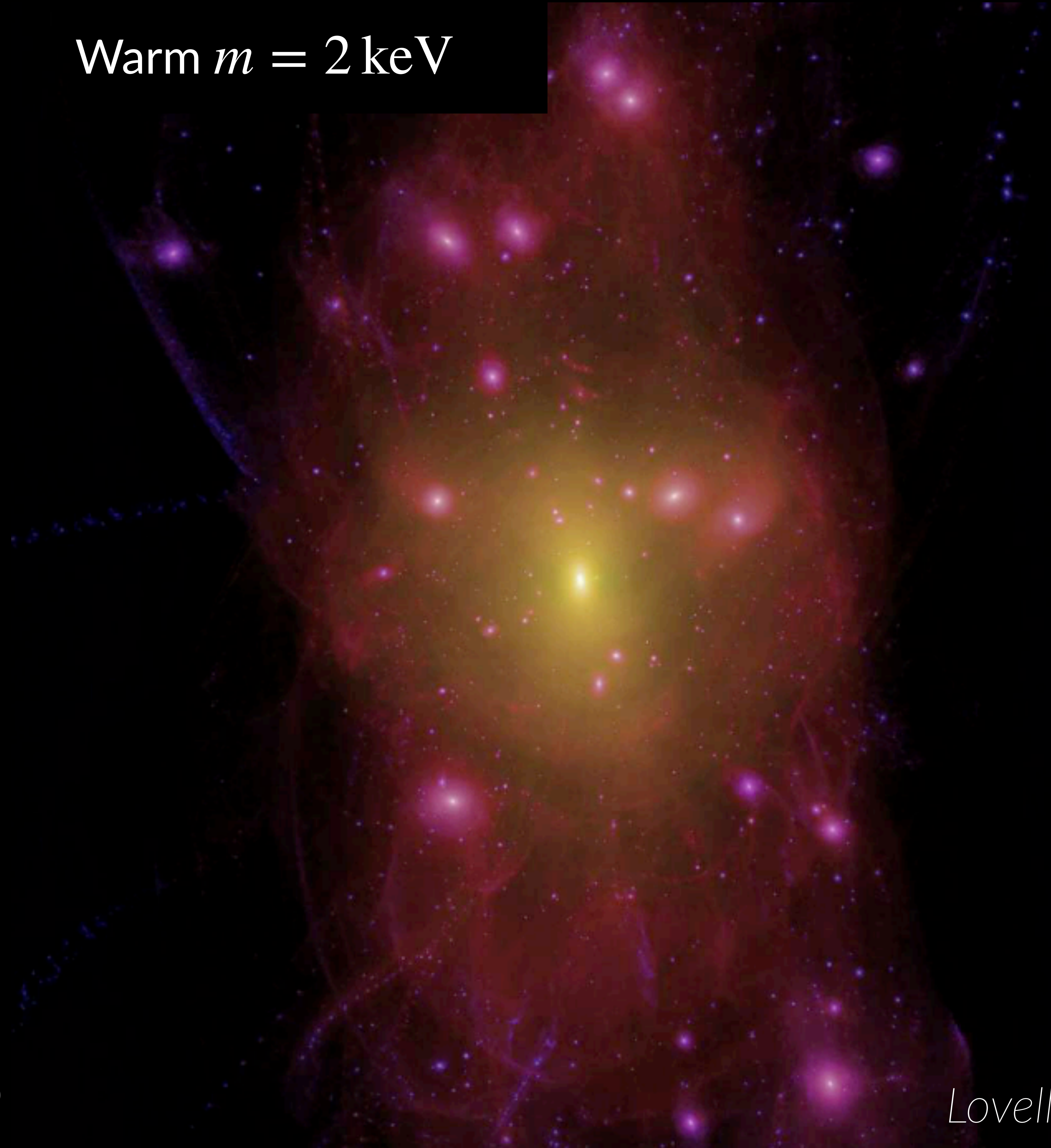




Lovell et al. (2014)

- Solutions: Baryonic physics / non-CDM (such as **Warm Dark Matter**)
- Probe small scales: Abundance of Milky-Way satellites





Lovell et al. (2014)

- Solutions: Baryonic physics / non-CDM (such as **Warm Dark Matter**)
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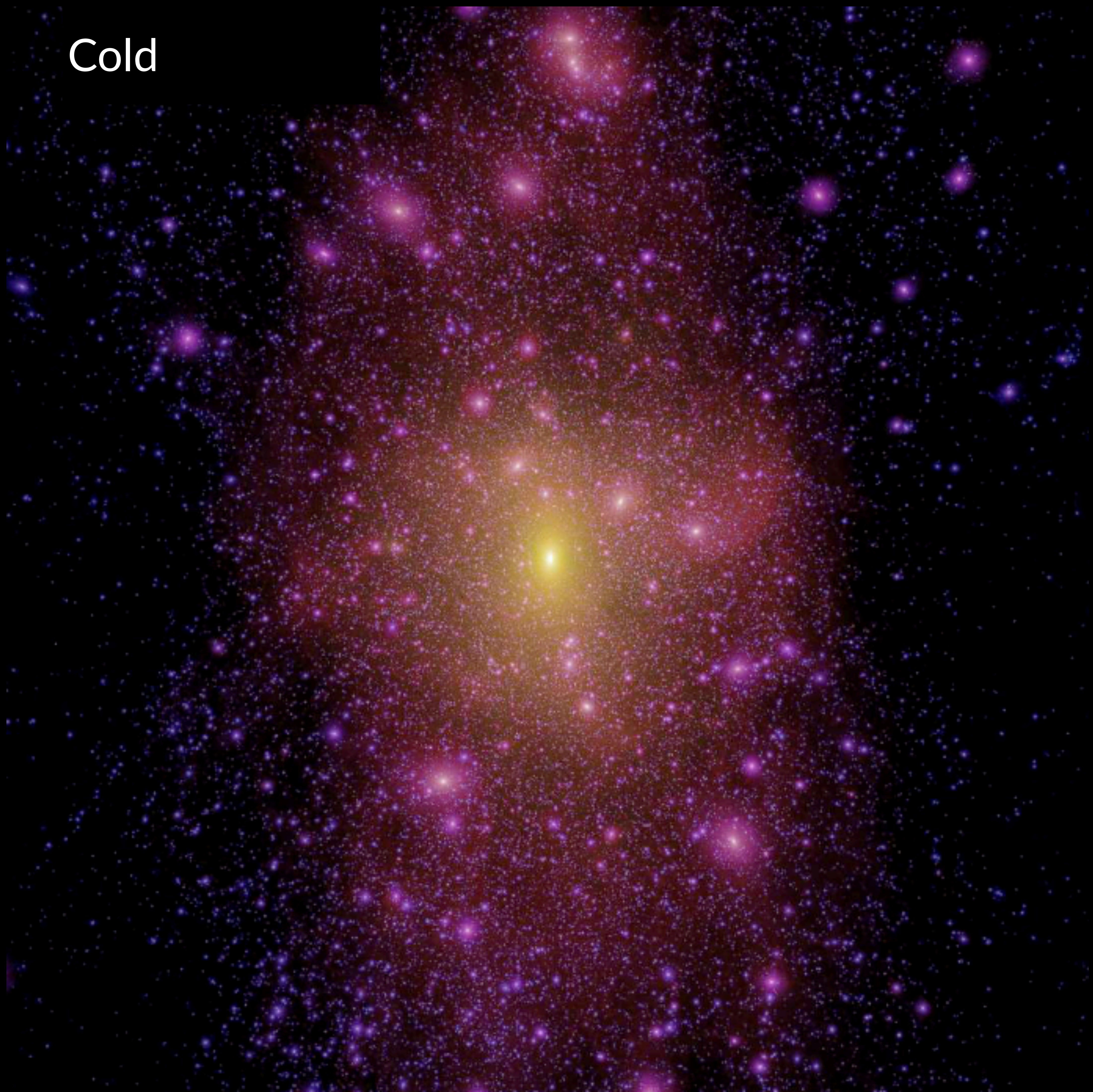
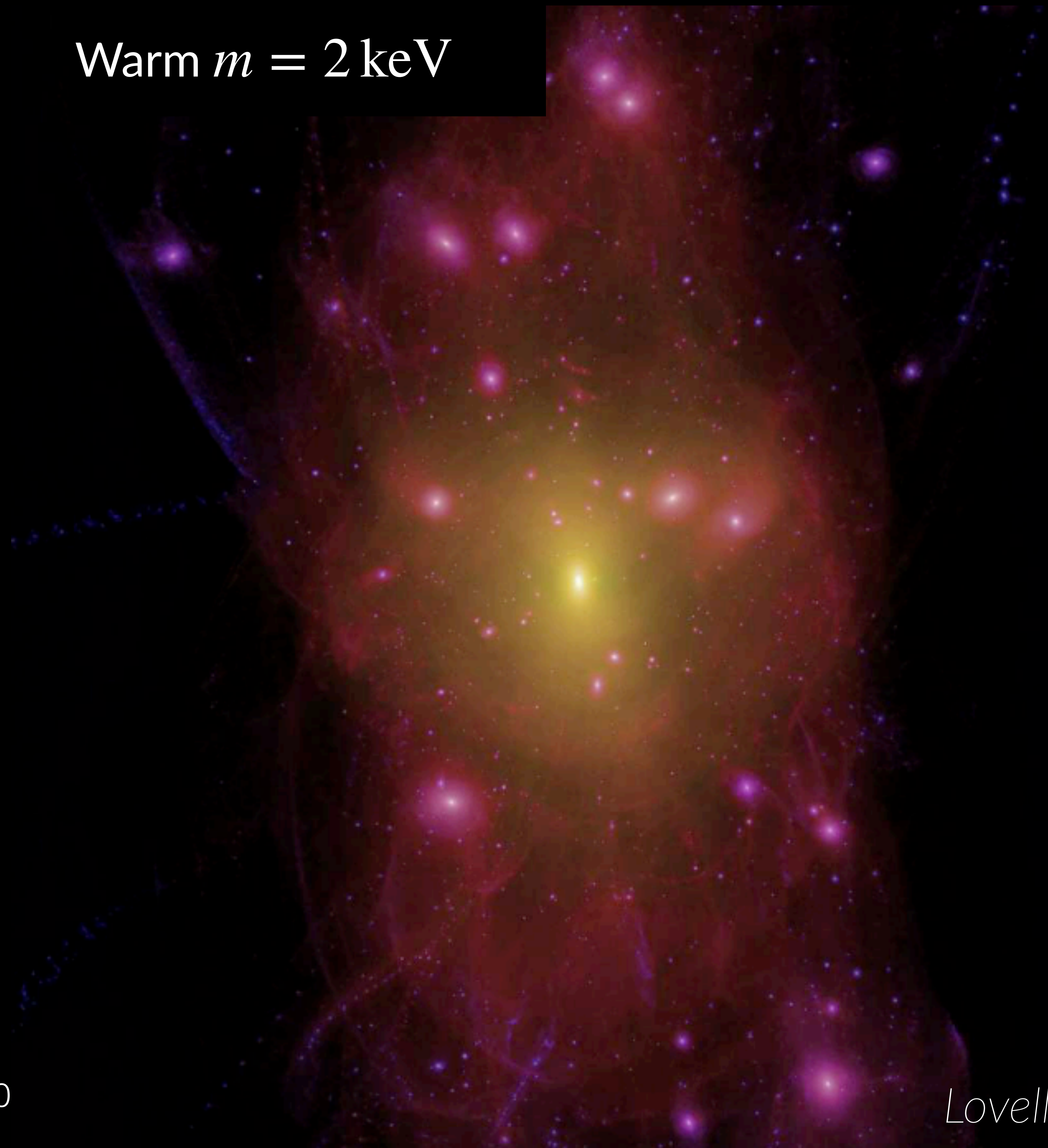
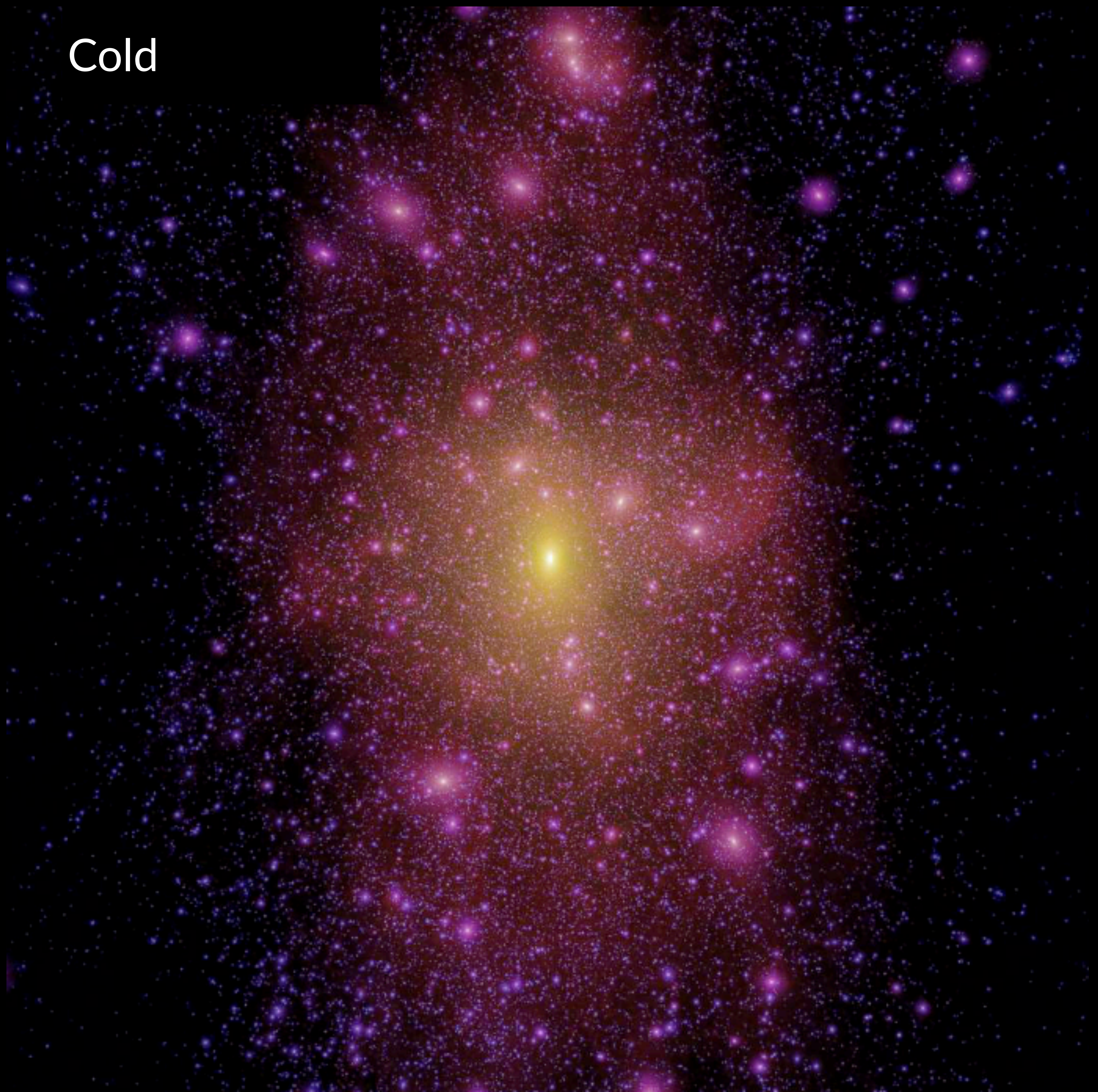
- Subhalo modelling: Numerical simulations / **Analytical model**

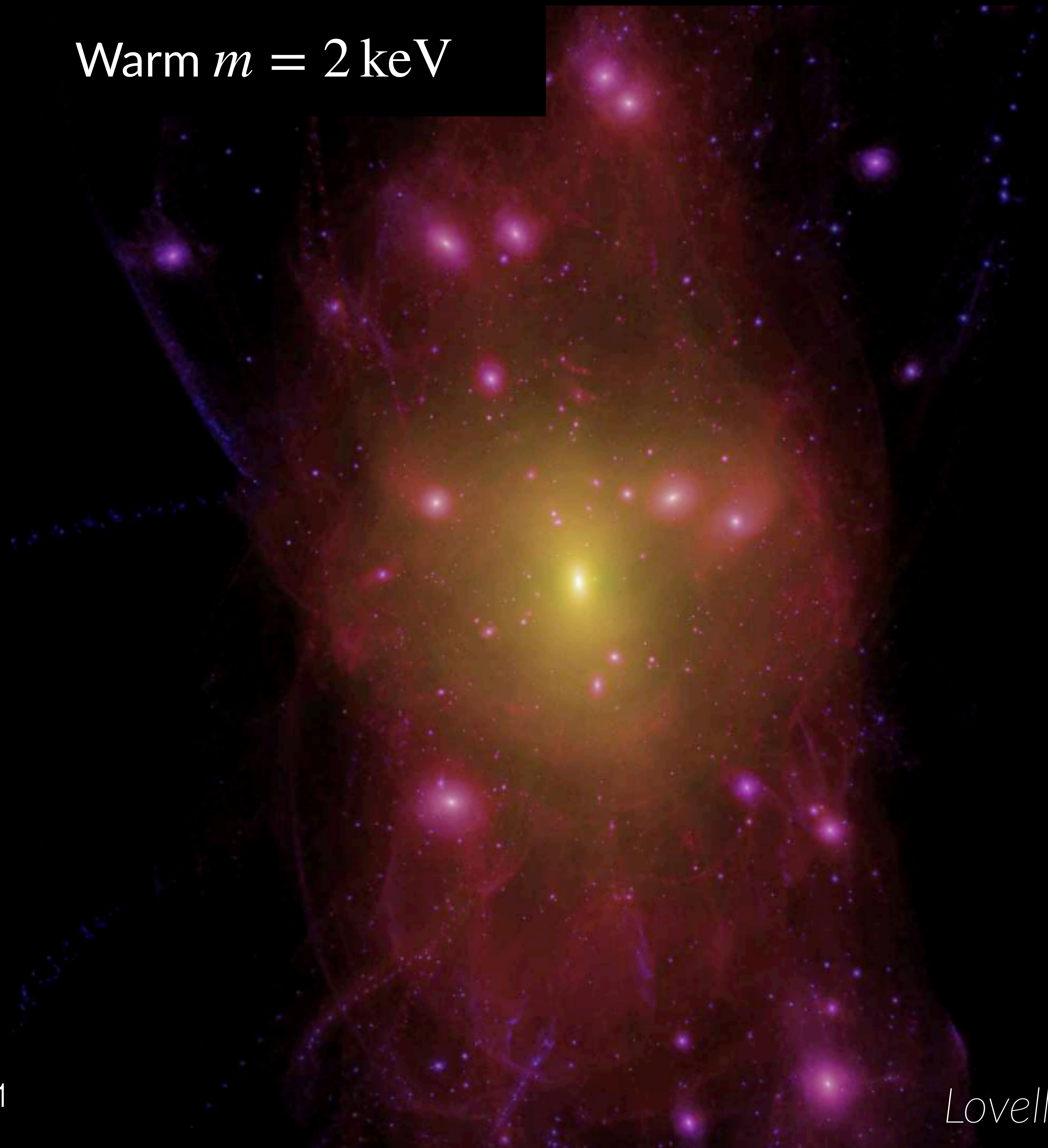




Lovell et al. (2014)

- Solutions: Baryonic physics / non-CDM (such as **Warm Dark Matter**)
- Probe small scales: Abundance of Milky-Way satellites
- Subhalo modelling: Numerical simulations / **Analytical model** → Fast & flexible



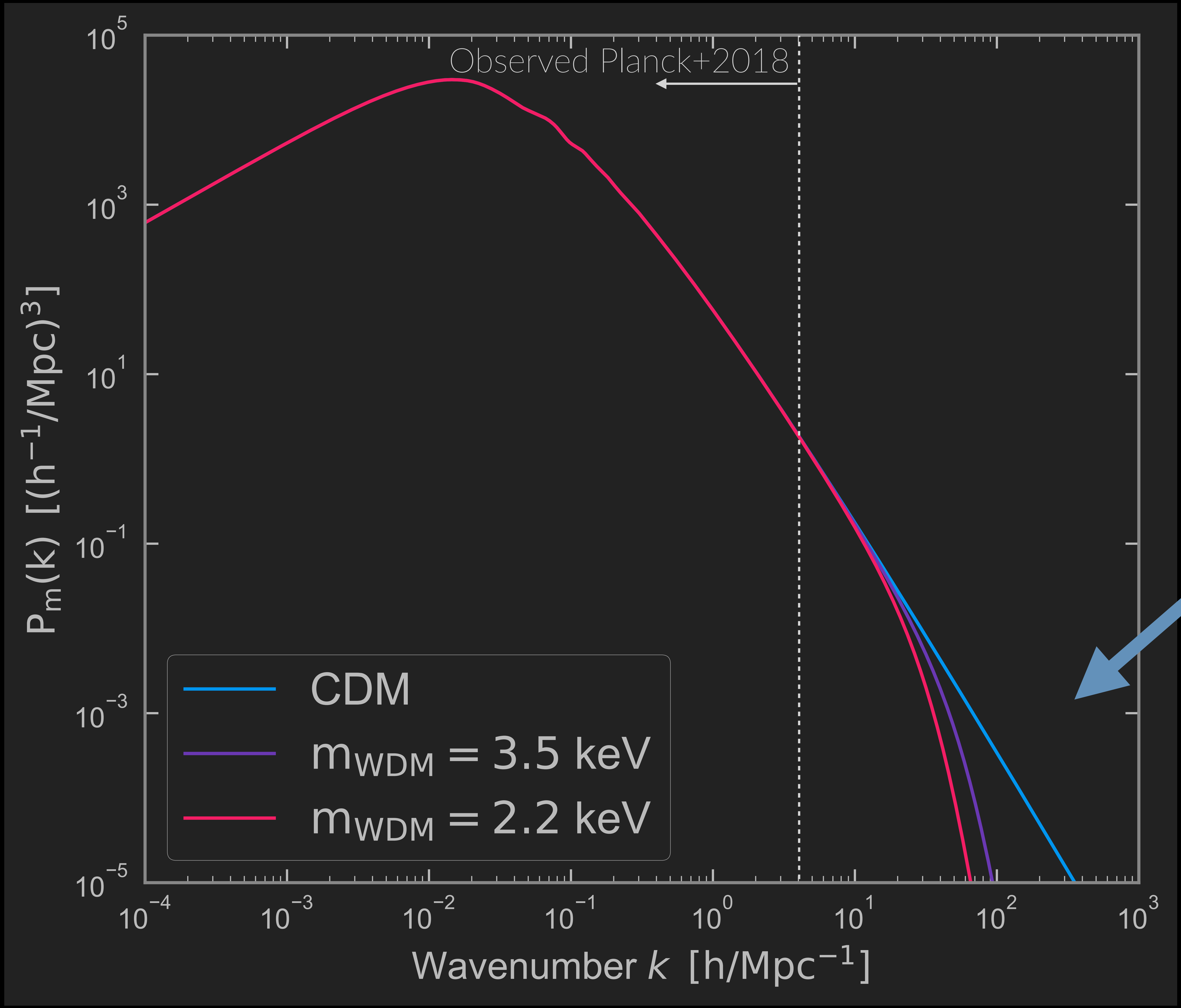


Lovell et al. (2014)

SASHIMI

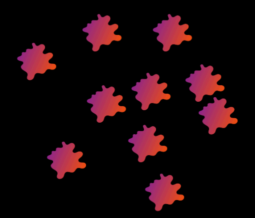
Semi-Analytical SubHalo Inference Modeling

1. Structure forms — Matter Power spectrum

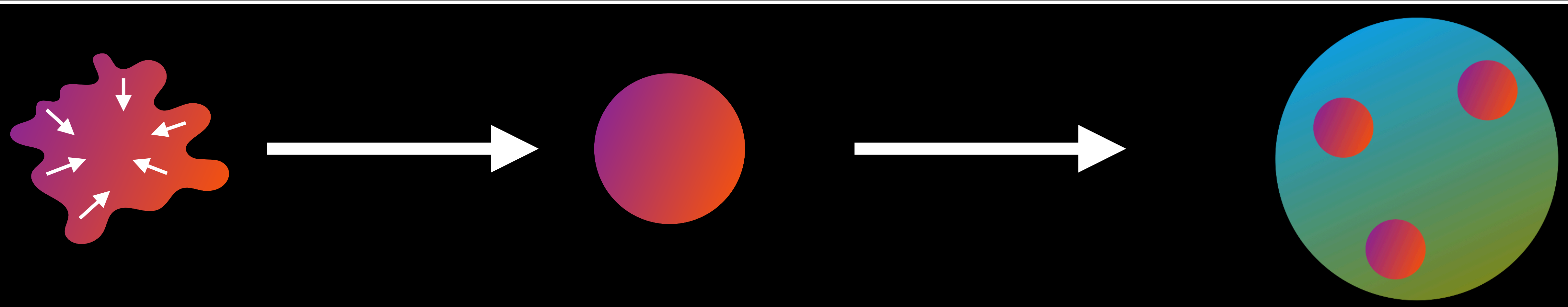


Warm particles suppress small scale perturbations

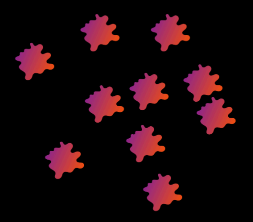
Thermal WDM (Viel+2011)



2. Dark matter haloes accrete



- Halos are formed through gravitational collapse above $\delta(z) > \delta_c$
- Analytical expressions for the accretion history based on the Extended Press-Schechter



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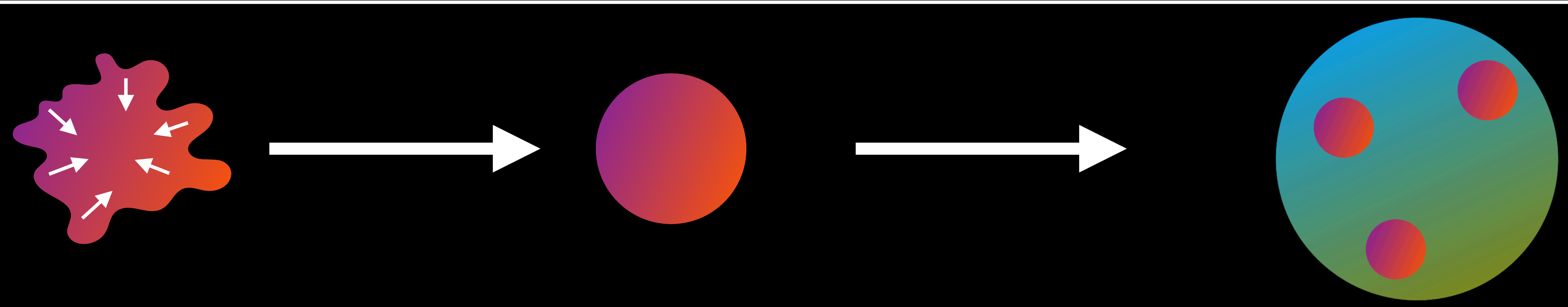

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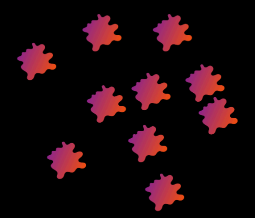
- Subhalo mass function: $$\frac{d^2N}{d\ln m\,dz} = f(S,\delta\,|\,S_0,\delta_0)\frac{dS}{dm}\frac{d\bar{M}}{dz}$$

Number of subhaloes with (m, z) at accretion within host M



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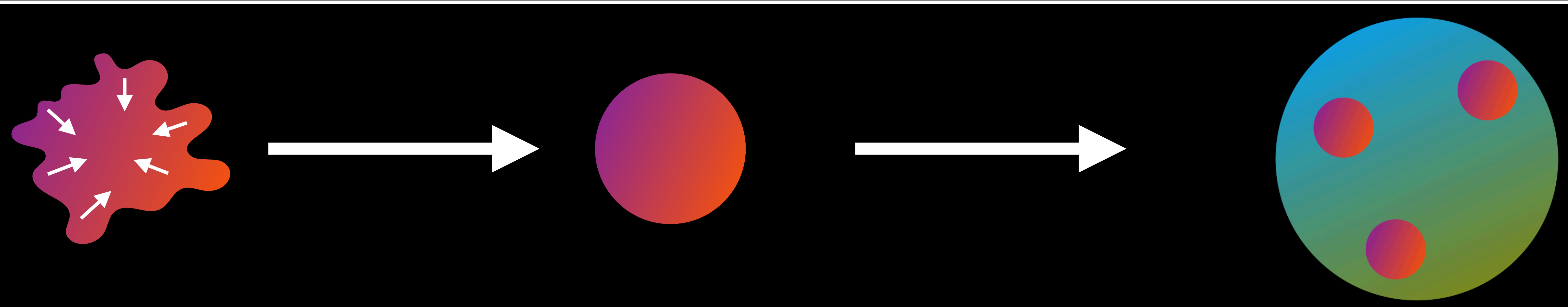

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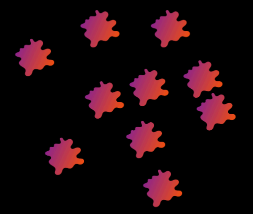
Mass fraction of subhalos in certain volume (based on EPS, *Yang+ 2011*)



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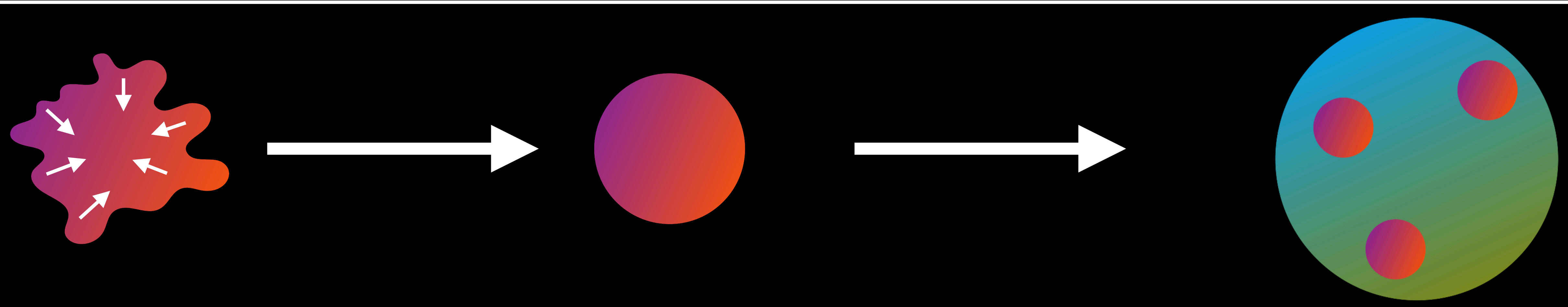

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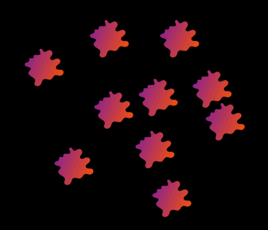
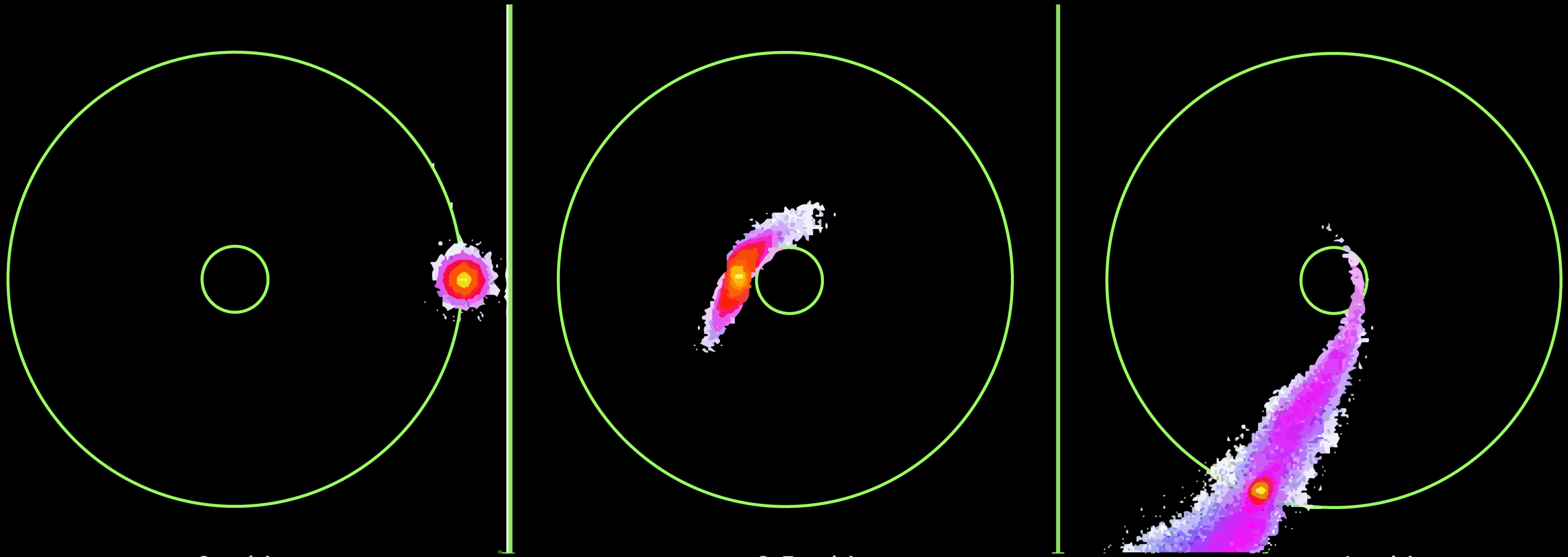
Main branch of host halo evolves

1. Structure forms



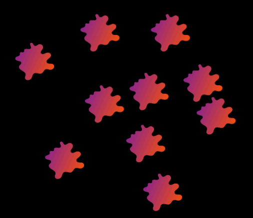
2. Dark matter haloes accrete

3. Subhaloes evolve in time



t=0 orbit t=0.5 orbit t=1 orbit

Hayashi+ 2003



3. Subhaloes evolve in time

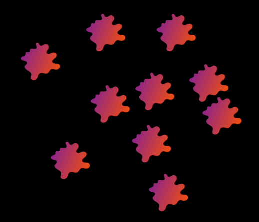
- Incorporate average mass-loss due to tidal stripping (Hiroshima+ 2018, Van den Bosch+ 2005)

$$\frac{dm}{dt} = \frac{m - m(r_t)}{T_r}$$

→ Mass stripped at pericenter after first orbital period T_r beyond r_t

- Internal properties change: (ρ_s, r_s, r_t) before and after tidal stripping
- Remove completely disrupted subhalos $(r_t < 0.77 r_s)$

1. Structure forms



2. Dark matter haloes accrete

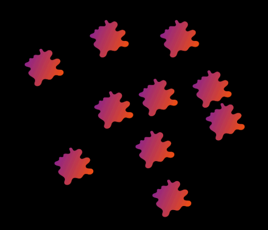
3. Subhaloes evolve in time

Evolved Subhalo mass function:

$$\frac{dN(m\,|\,M,z)}{dm} = \int d\ln m_a \int dz_a \frac{d^2N}{d\ln m_a dz_a} \times \int dc_a P(c_a\,|\,m_a,z_a)\delta(m - m(z\,|\,m_a,z_a,c_a))$$

Extended Press-Schechter formalism

1. Structure forms



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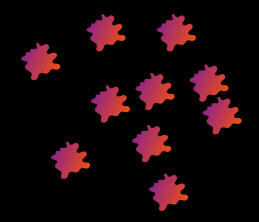
Log-normal distribution for concentration (Ludlow+ 2016)



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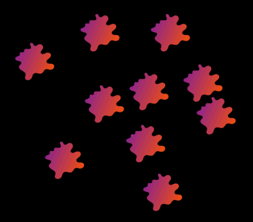
Mass-loss

1. Structure forms



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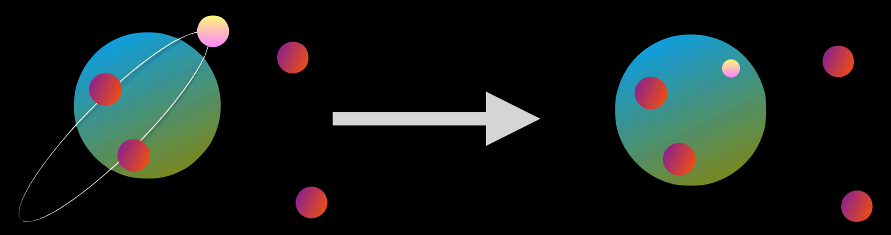
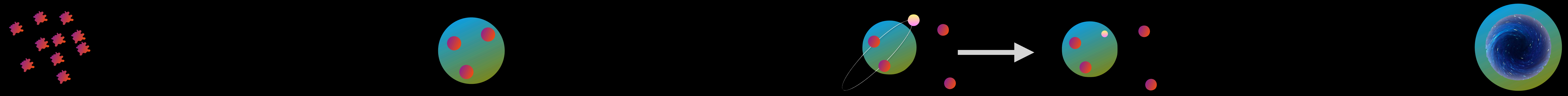


4. Satellite galaxies form within

Galaxy formation physics is model-dependent

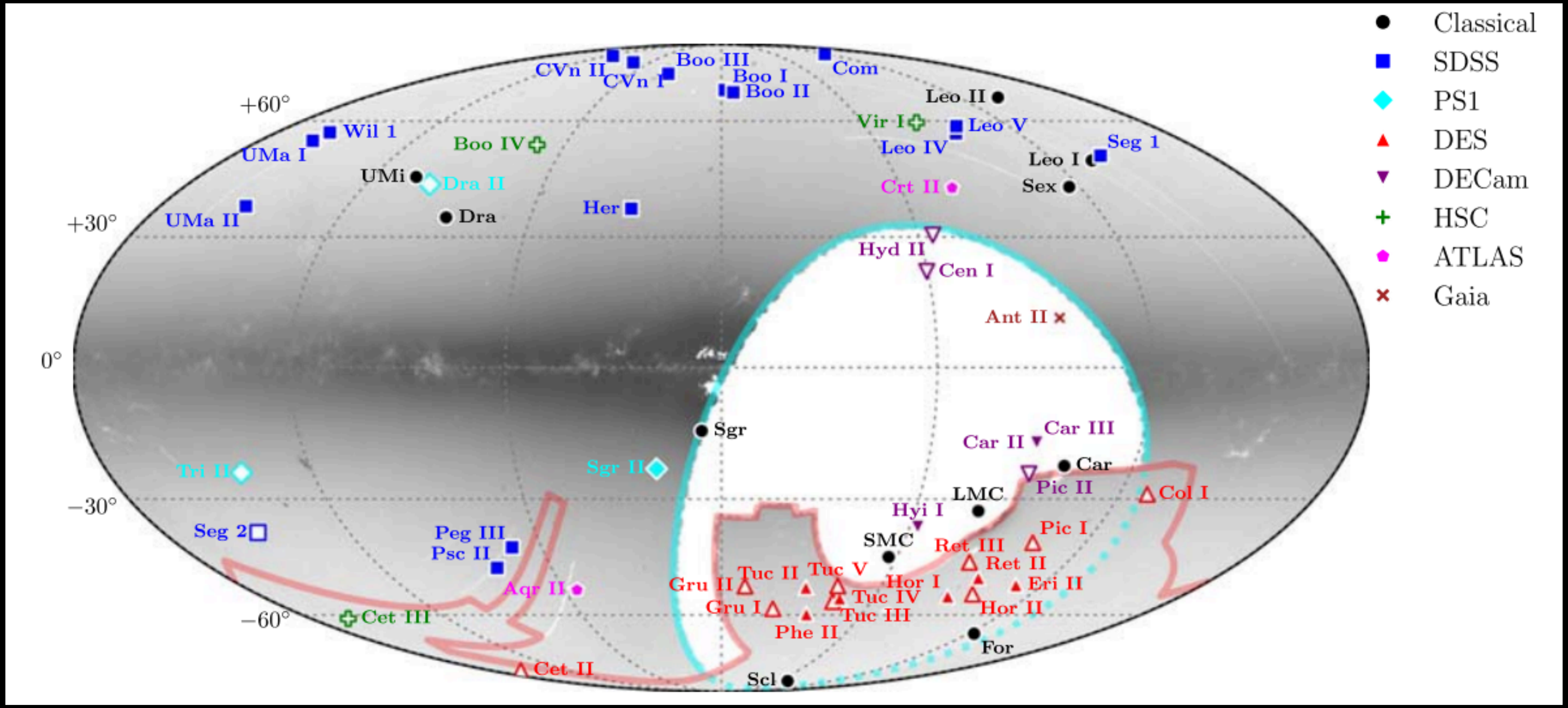
- All subhalos host satellites (canonical)
- Galaxy formation threshold (mass, circular velocity)



5. Obtain total number of satellites in the Milky-Way

- Integrate evolved subhalo mass function

Observed satellites in the Milky Way



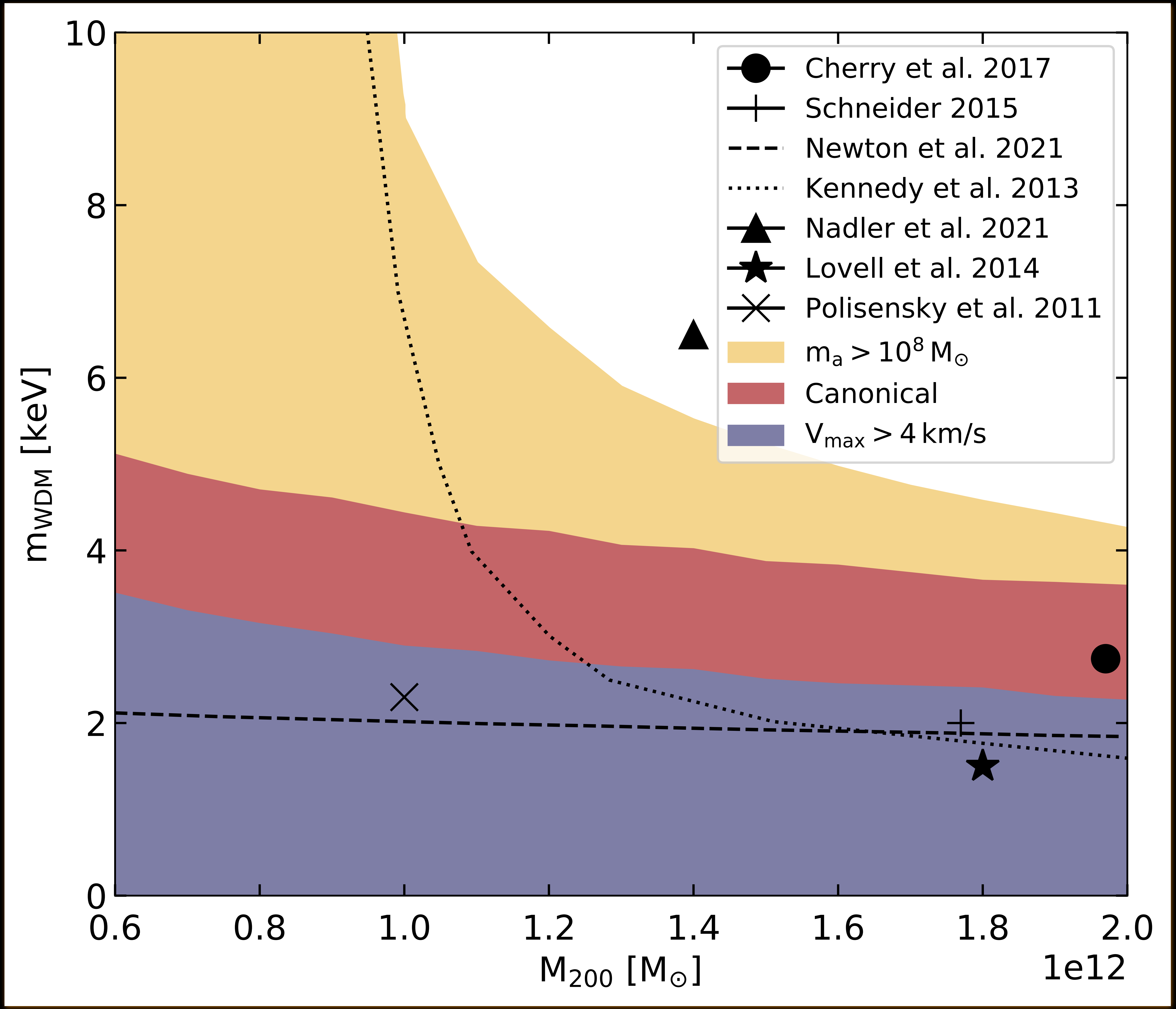
Drlica-Wagner et al. (2020)

DES & Pan-STARRS1 observe ultra-faint satellite galaxies with ~80% sky coverage.

270 satellites after completeness correction

We exclude warm dark matter models that produce too few satellites with SASHIMI at 95% confidence level.

Warm dark matter: Constraints



Dekker et al. (2021)

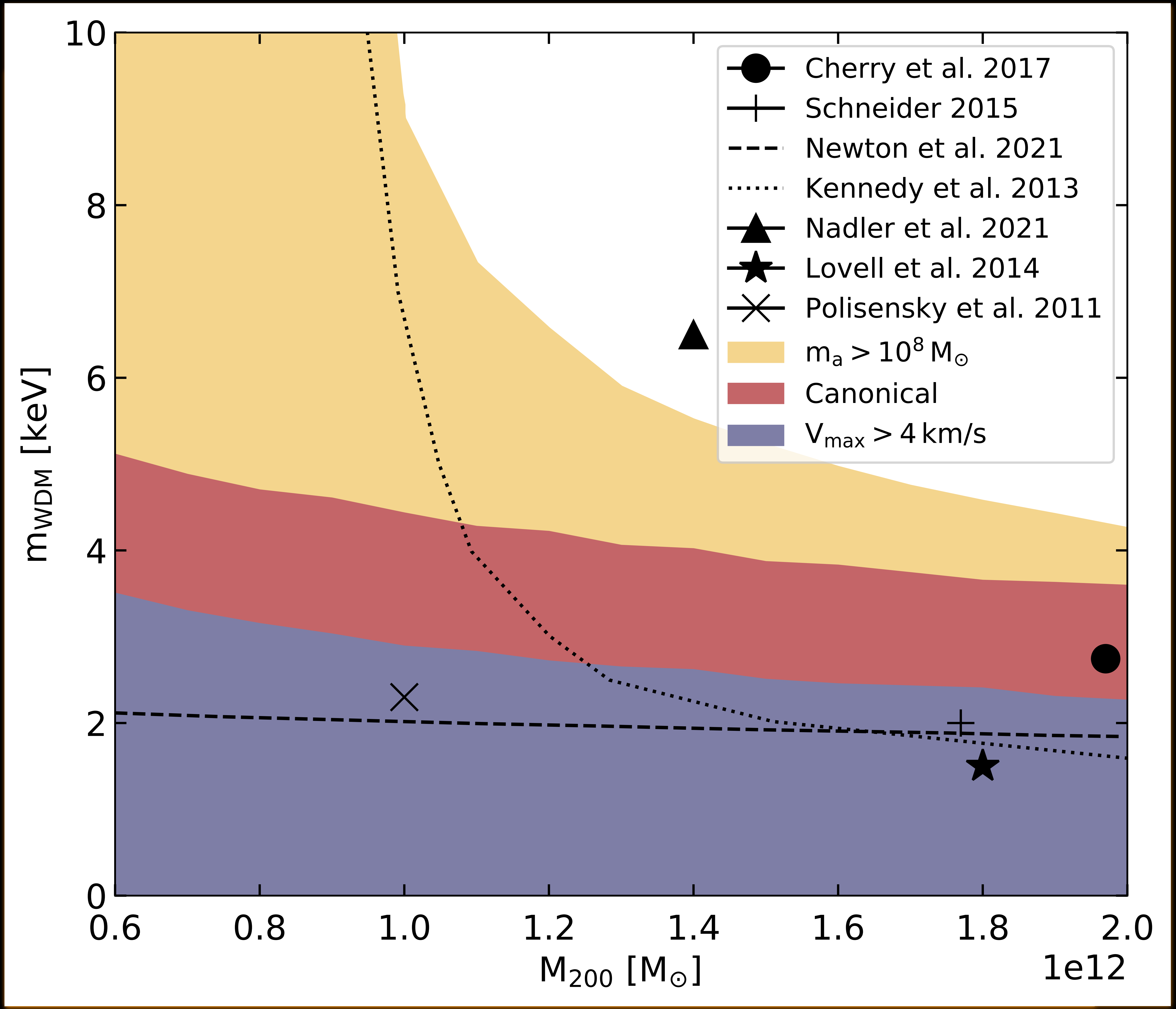
All subhalos host satellite galaxies

- Exclude WDM mass at 95% CL

$$m_{WDM} > 3.5 - 5\,\mathrm{keV}$$

- Model-independent constraints

Warm dark matter: Constraints

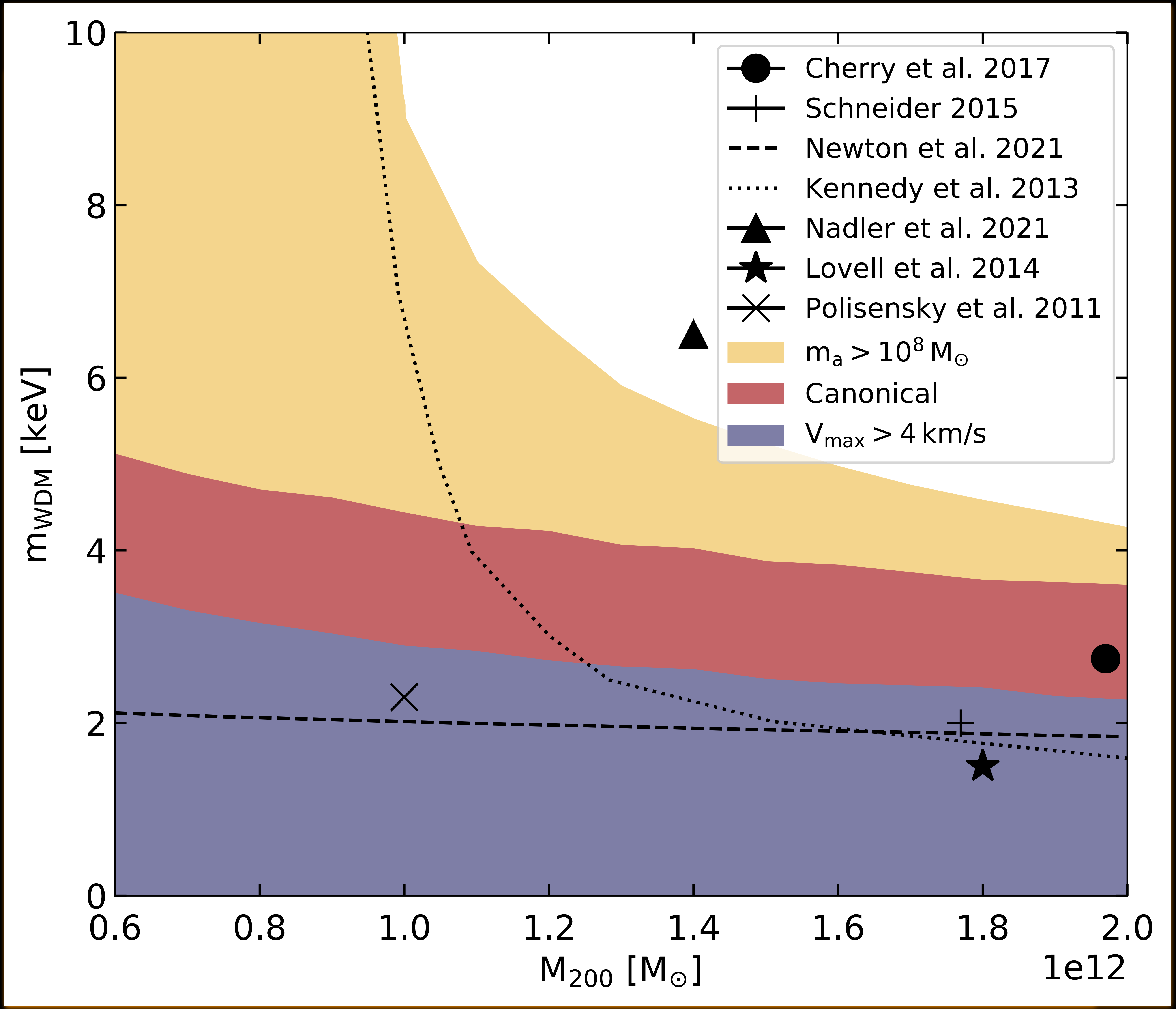


Dekker et al. (2021)

Galaxy formation threshold on mass

$$M_{sh} > 10^8\,\mathrm{M}_\odot$$

Warm dark matter: Constraints



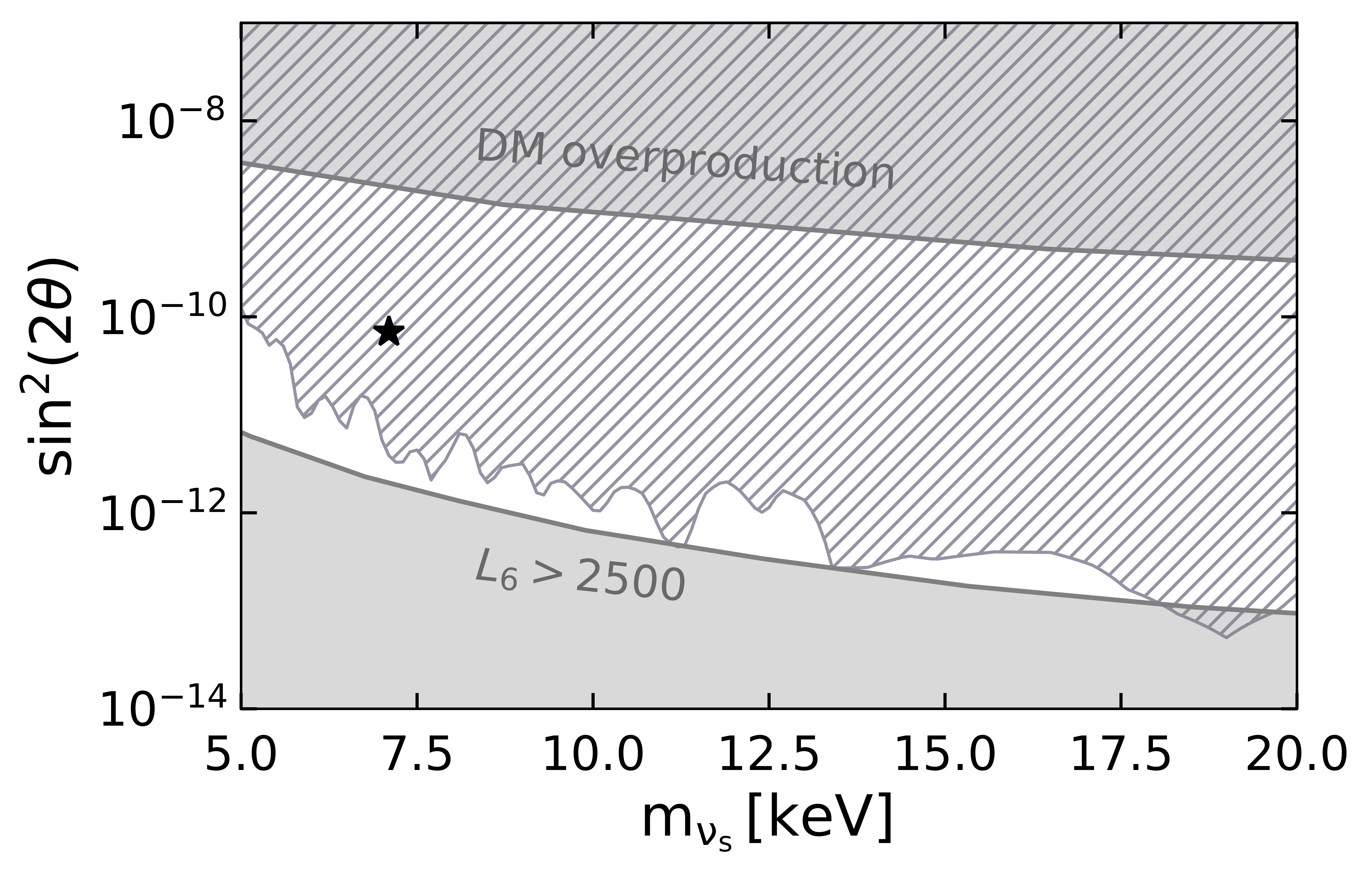
Dekker et al. (2021)

■ Galaxy formation threshold on maximum circular velocity

- Subset of 94 satellites with kinematic data (Simon 2019)
- $v_{max} > 4$ km/s (Leo V)

Sterile Neutrino: Current constraints

More mixing with ν

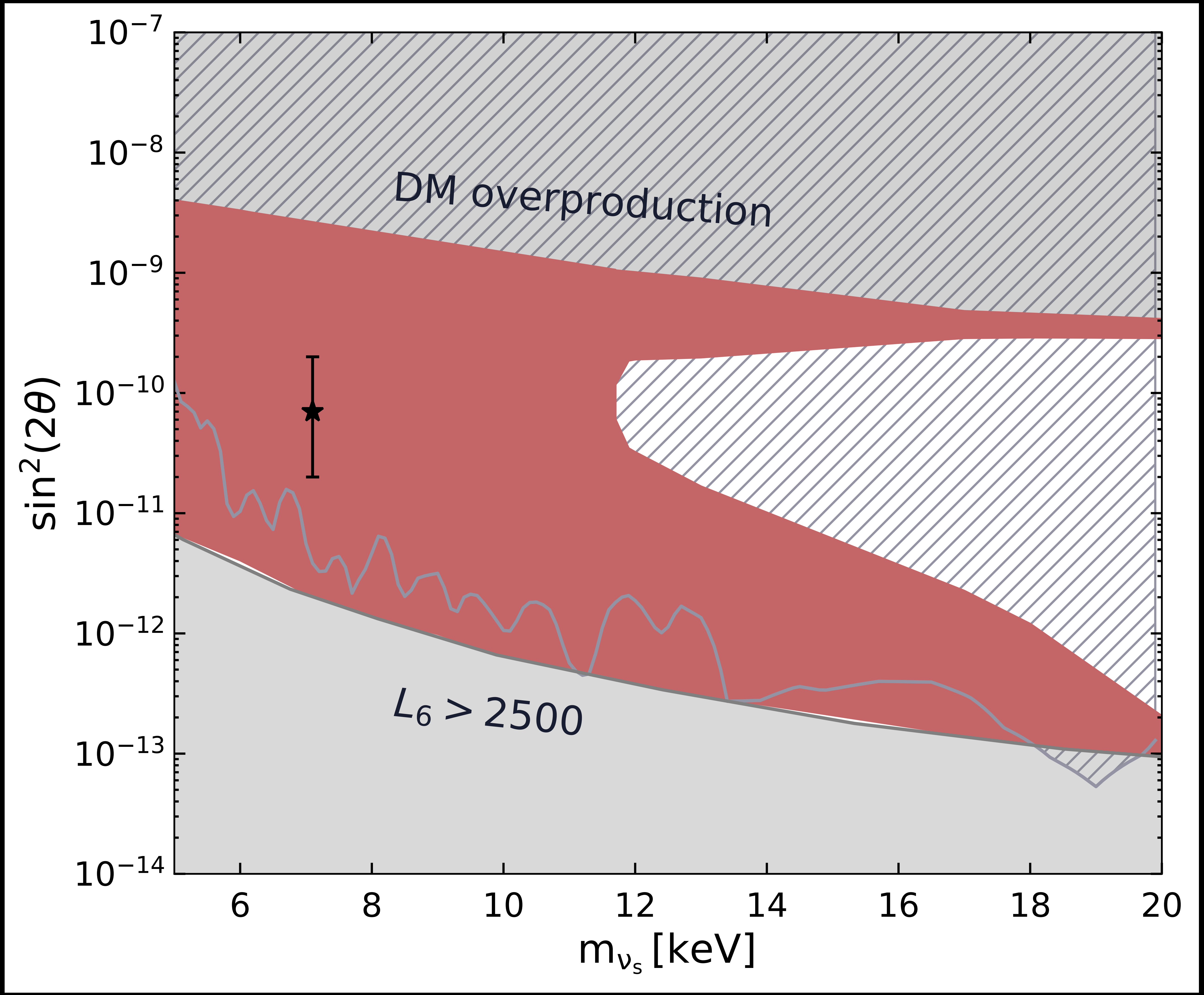


Less mixing with ν

- Well-motivated WDM candidate
- Produced through mixing $\sin^2(2\theta)$ with neutrinos
- Enhanced by lepton asymmetry *(Shi&Fuller 1999)*

X-ray constraints — (Foster+ 2021, Cherry+ 2017, Ng+ 2019)
Theory — (Serpico+ 2005)
★ **3.5 keV line** — (Bulbul+ 2014, Dessert+ 2020)

Sterile Neutrino Constraints



Dekker et al. (2021)

$$M_{\rm MW} = 10^{12}\ M_\odot$$

All subhalos host satellite galaxies

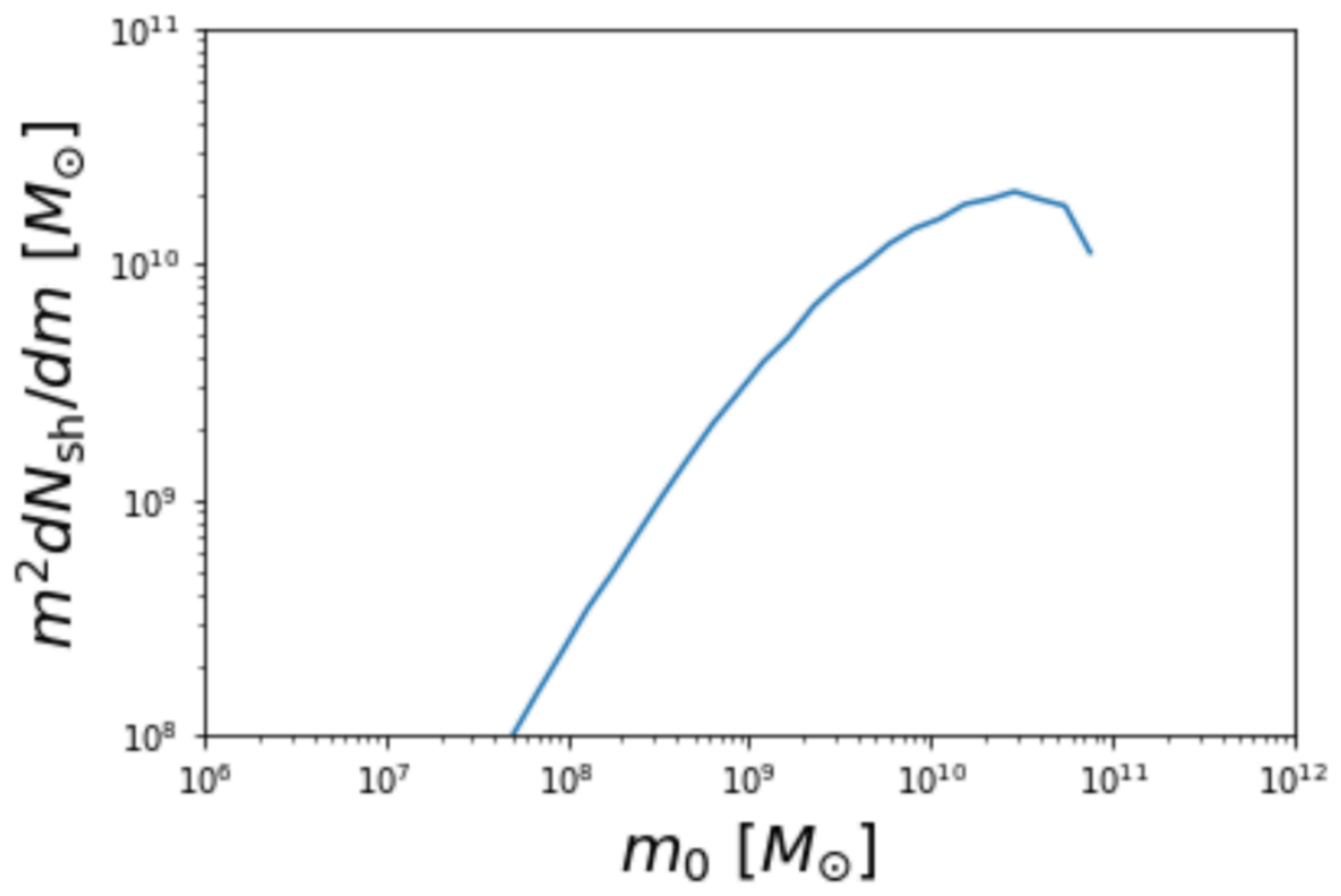
Constraints at 95% CL

Exclude sterile neutrino mass <12 keV

Codes SASHIMI publicly available on GitHub*

```
m, dNdm = sh.subhalo_distr(Mhost_0)

plt.loglog(m,m**2*dNdm)
plt.xlim(1e6,1e12)
plt.ylim(1e8,1e11)
plt.xlabel(r'$m_0$ [$M_{\odot}$]',fontsize=20)
plt.ylabel(r'$m^{2} dN_{\rm sh}/dm$ [$M_{\odot}$]',fontsize=20)
plt.show()
```



* https://github.com/shinichiroando/sashimi-w

https://github.com/shinichiroando/sashimi-c

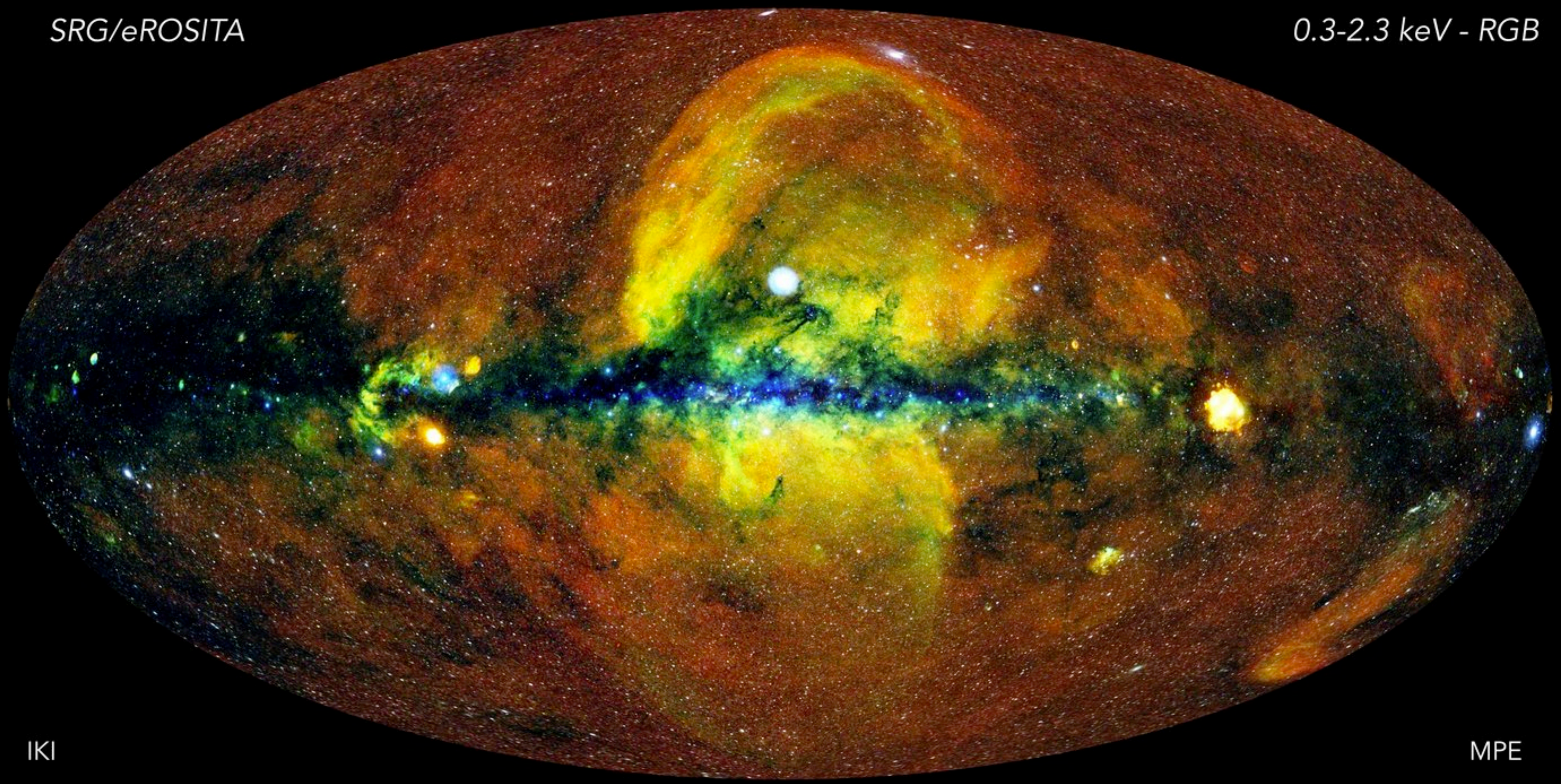
Contact: a.h.dekker@uva.nl

2) Indirect searches

Complementary searches for sterile neutrinos through X-ray observations

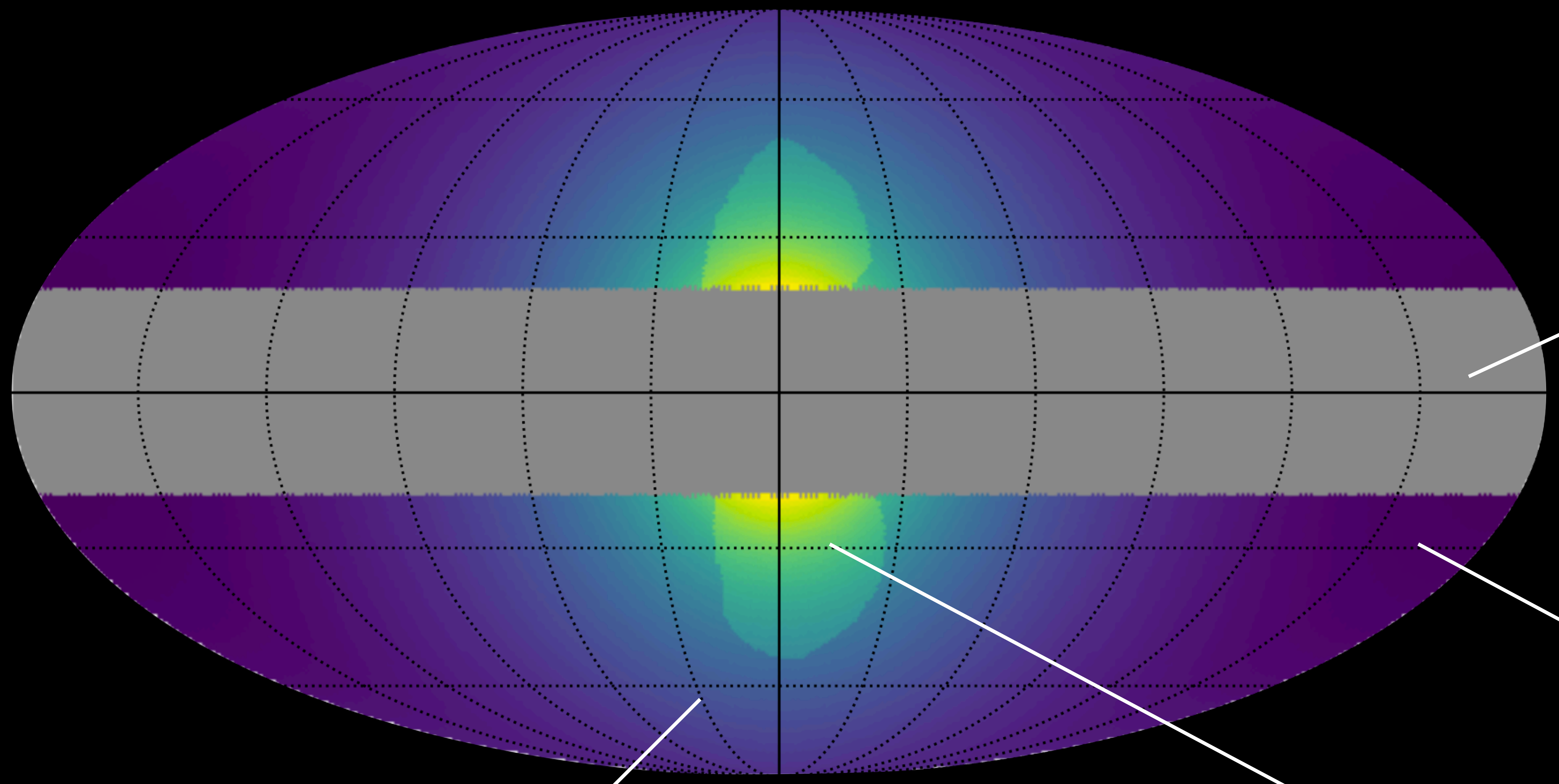
Sterile neutrino: Indirect searches with X-rays

- Sterile neutrino decays into monochromatic X-ray line $\nu_s \rightarrow \nu_a + \gamma$
- eROSITA: All-sky X-ray survey (4 years)
- Studied diffuse emission from Galactic halo



X-ray count sky maps

2.5 ks eROSITA exposure



Remove Galactic plane with |b|<20

Decay signal from the Galactic halo

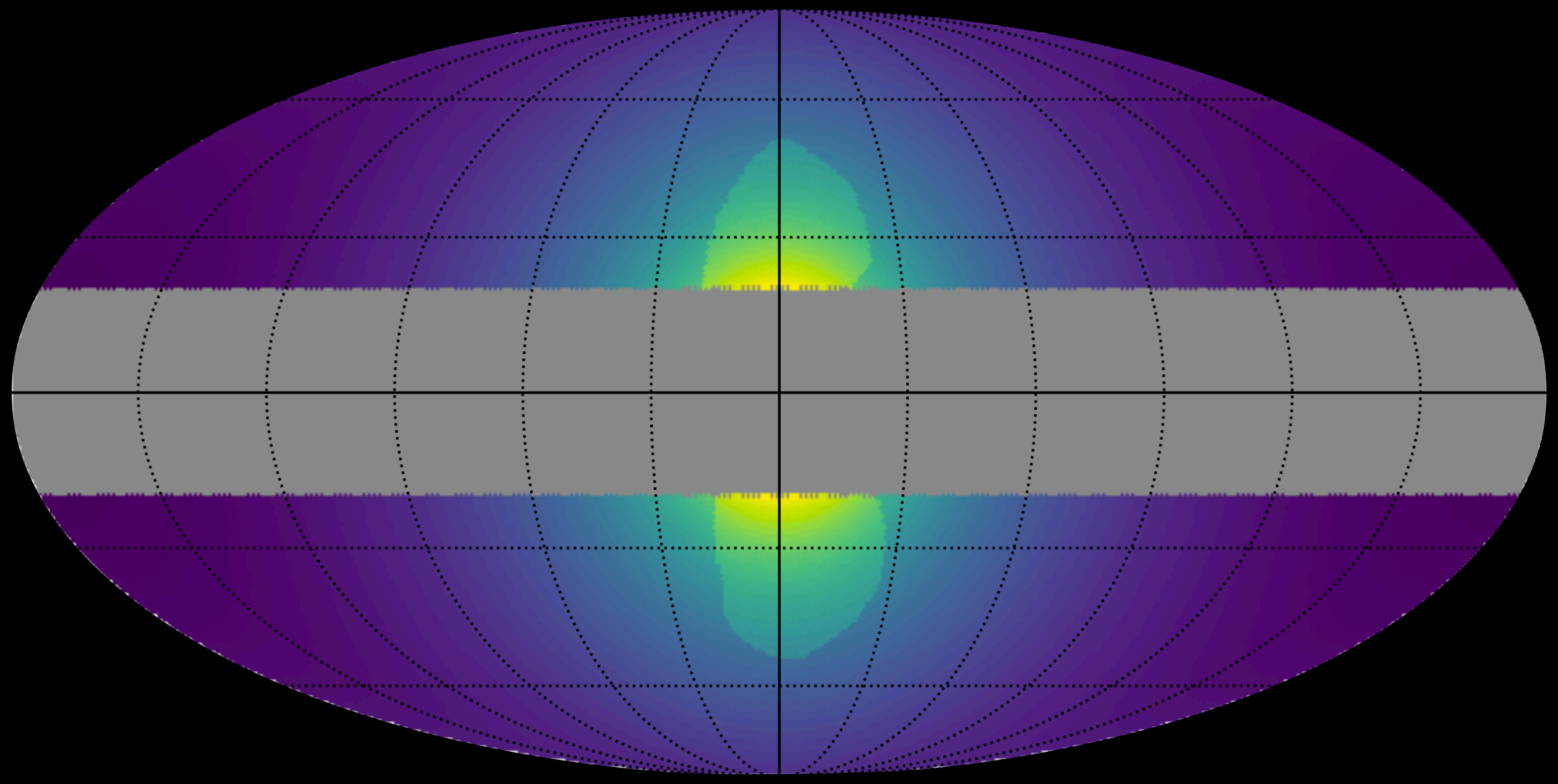
$m_{\nu_s} = 9\mathrm{keV}, \Gamma_{\nu_s} = 10^{-28}\mathrm{s}^{-1}$

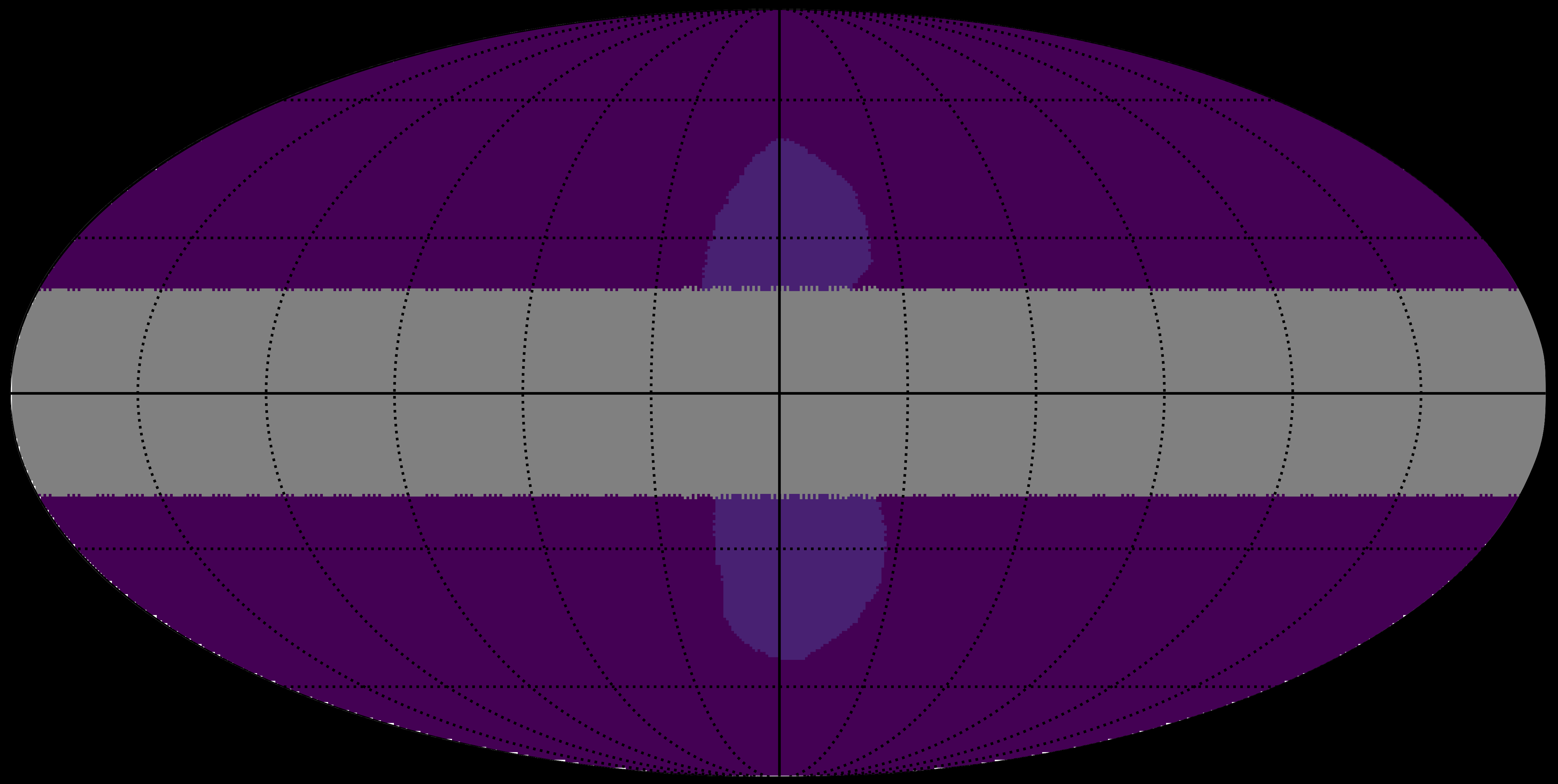
X-ray bubbles
(Predehl et al. 2020)

Isotropic components
- Cosmic X-ray background (Lumb et al. 2002)
- eROSITA's detector
- Extragalactic dark matter signal

X-ray count sky maps

2.5 ks eROSITA exposure

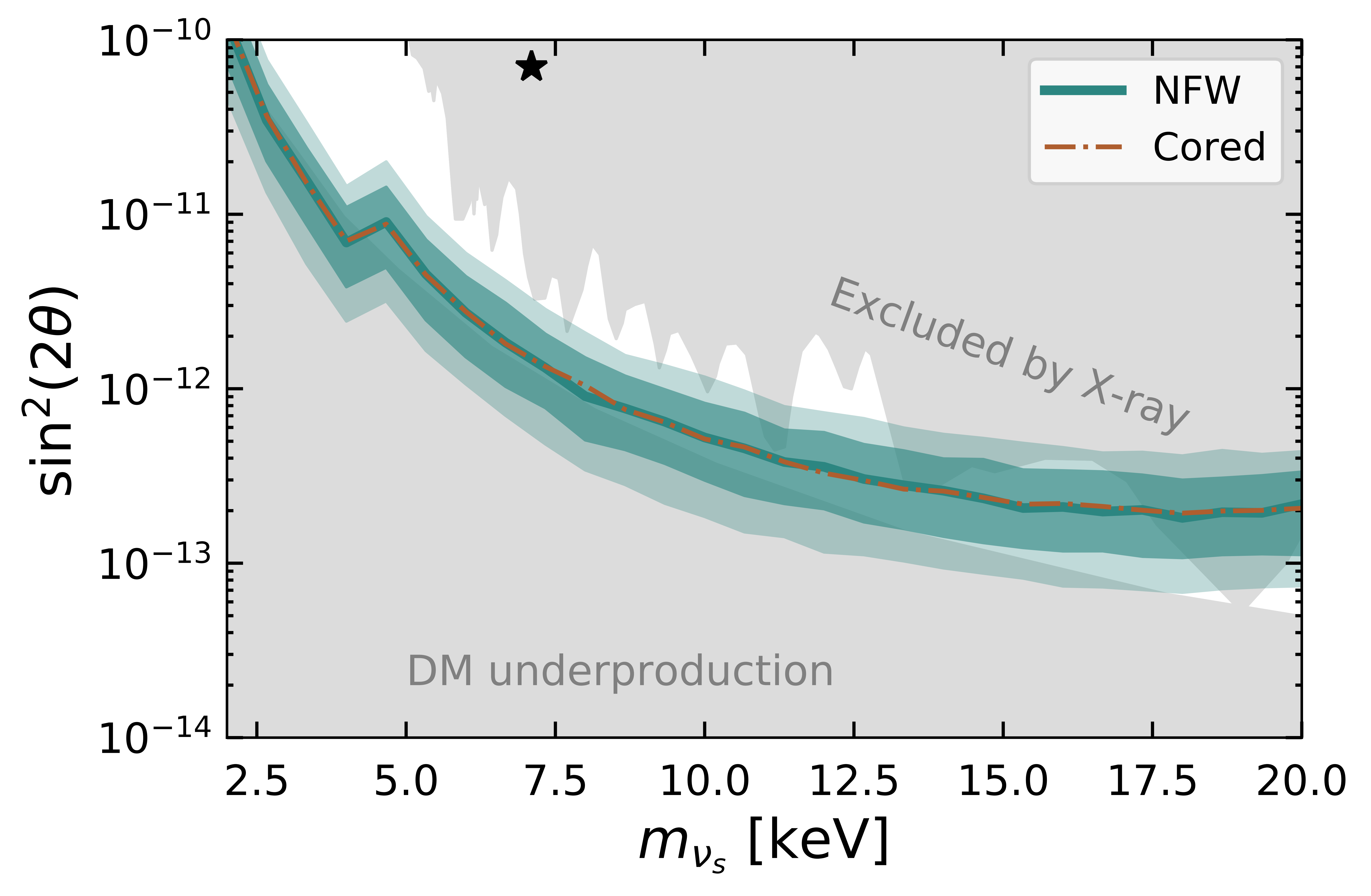




Generate mock data sets

Joint likelihood analysis — Obtain upper limits at 95% CL

Sterile Neutrino Constraints: X-ray observations



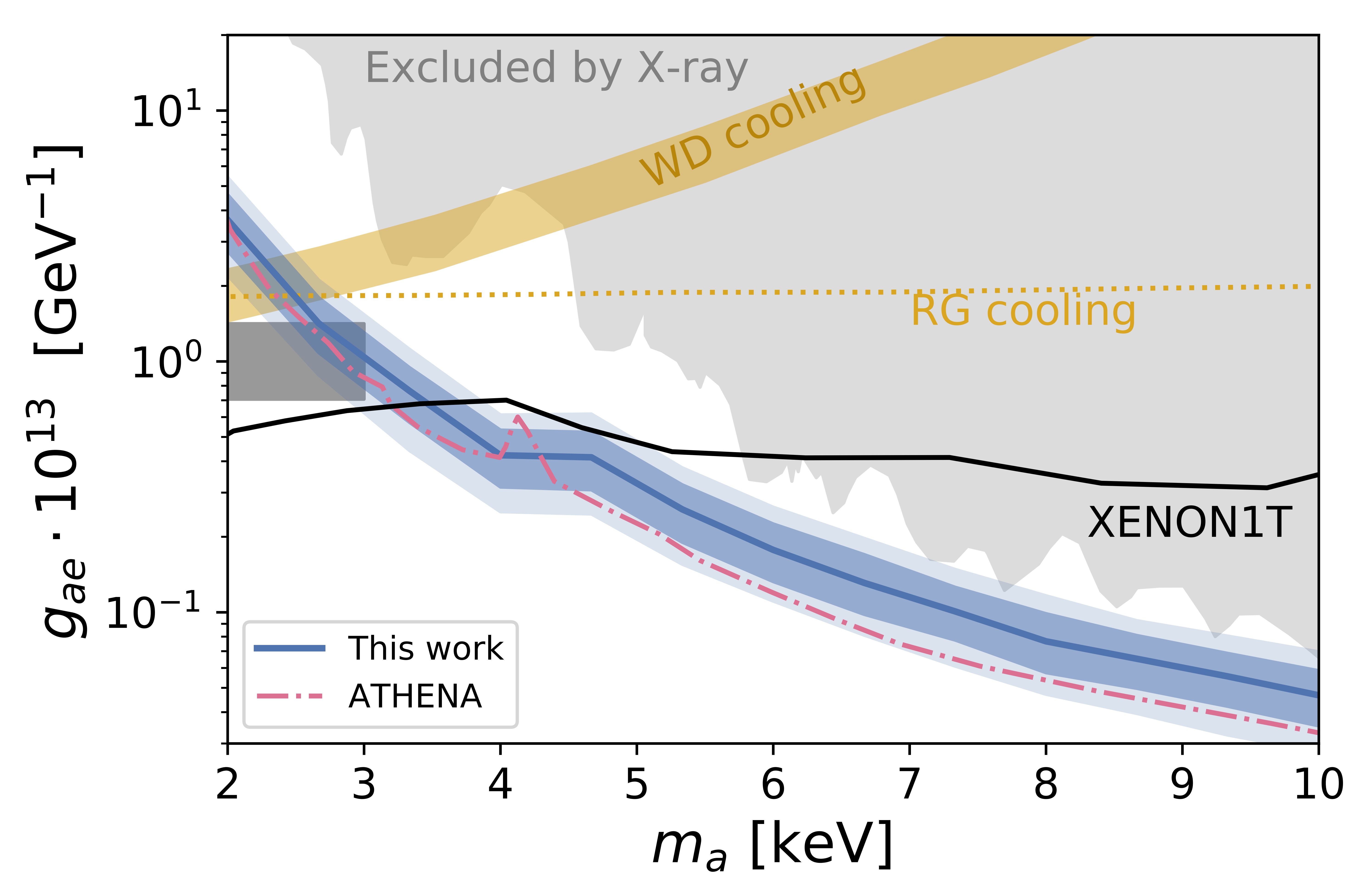
Dekker et al. (2021)

Median, 68% and 95% containment regions

Excluded regions (Foster et al. 2021, Cherry et al. 2017, Ng et al. 2019)

★ 3.5 keV line

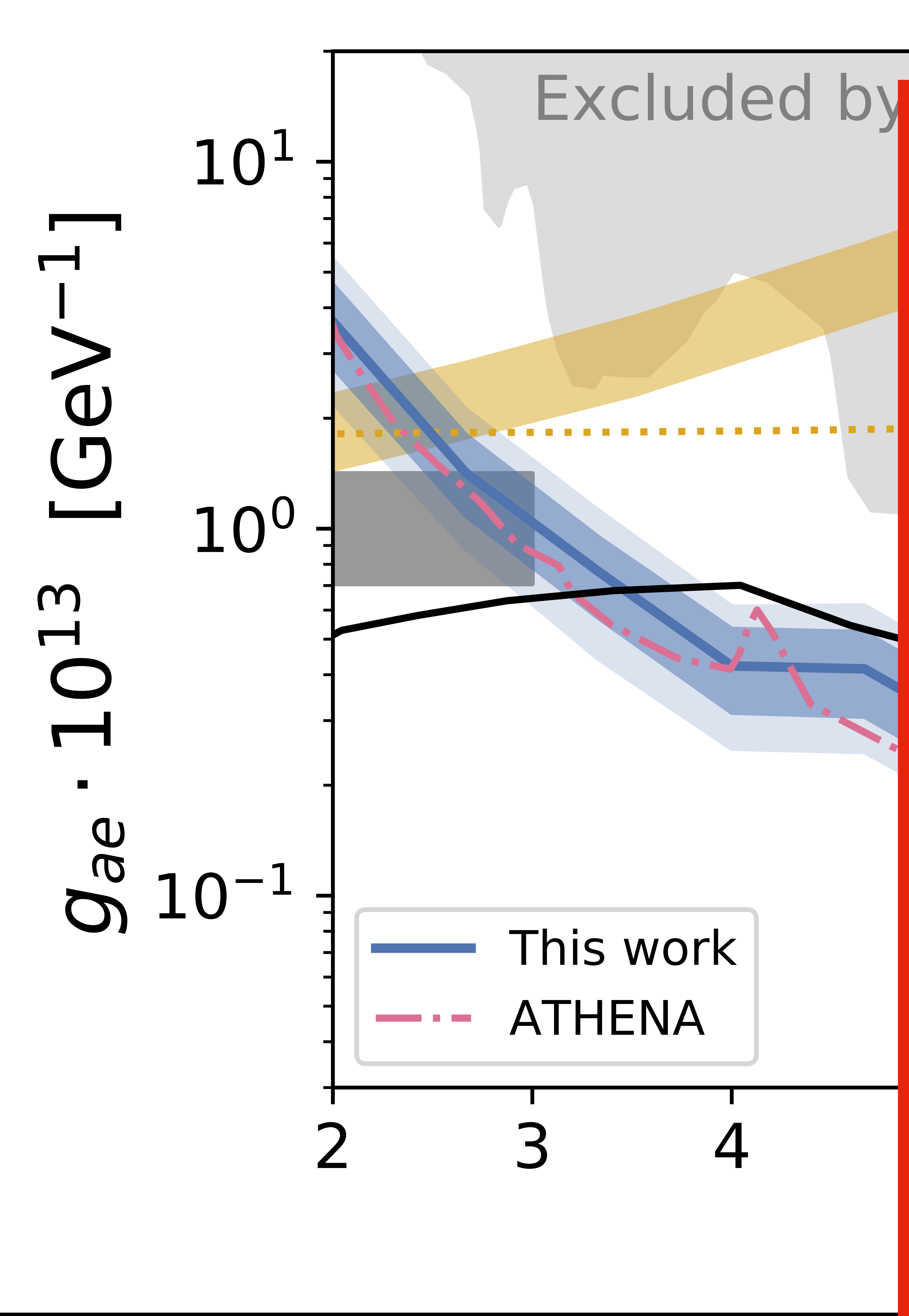
Axion-like particle Constraints: X-ray observations



Dekker et al. (2021)

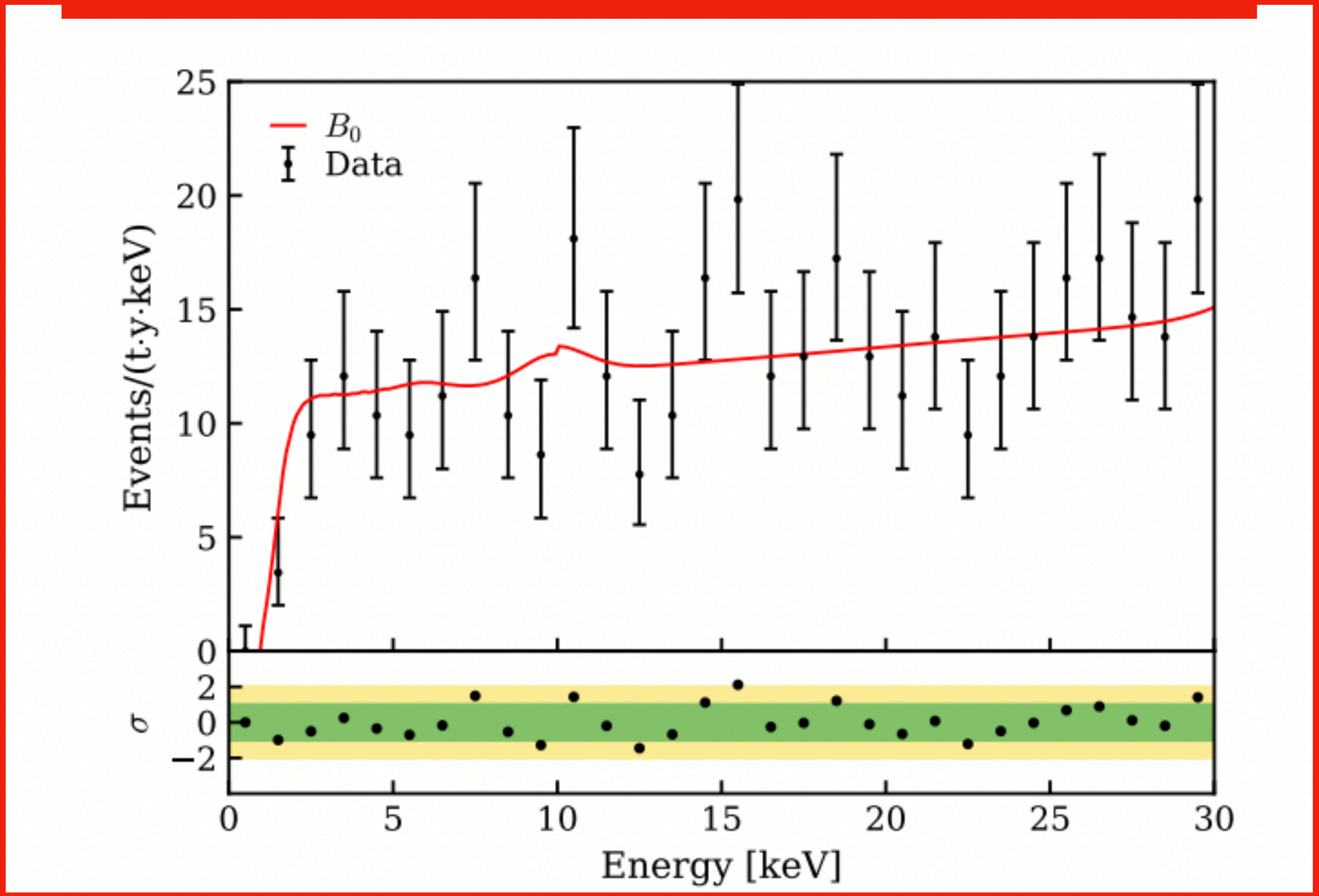
XENON1T excess explained by ALP at 3σ *(Aprile et al. 2020)* ??

Axion-like particle Constraints: X-ray observations



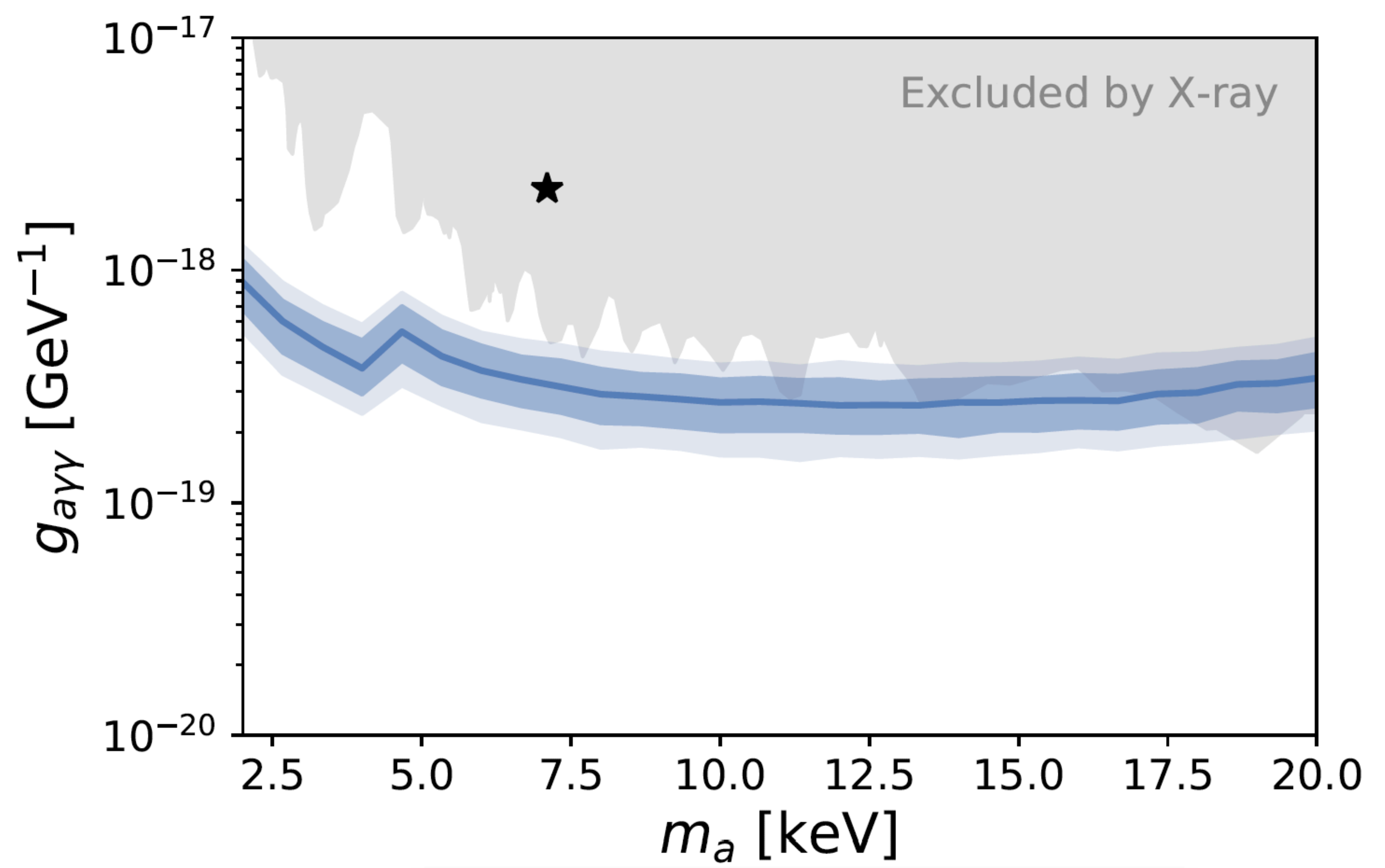
Dekker et al. (2021)

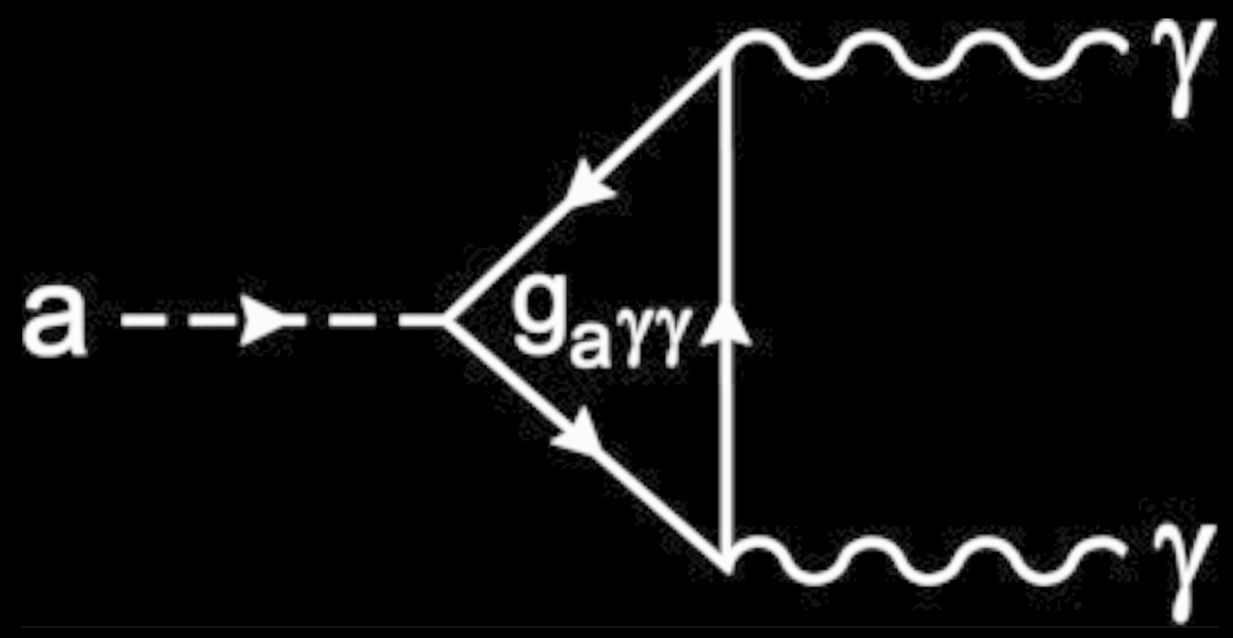
Knut Moraa presented at IDM2022 excess gone!



ed by
20) ??

Axion-like particle Constraints: X-ray observations





Median, 68% and 95%

Excluded regions

Dekker et al. (2021)

Summary

- Semi-analytical model *SASHIMI* publicly available on GitHub

- Rule out WDM models based on satellite counts in the Milky Way

$$m_{WDM} > 4.4\,\mathrm{keV},\, m_{\nu_s} > 12\,\mathrm{keV} \text{ for } M_{\mathrm{MW}} = 10^{12}\mathrm{M}_\odot$$

- Complementary results with eROSITA X-ray observations

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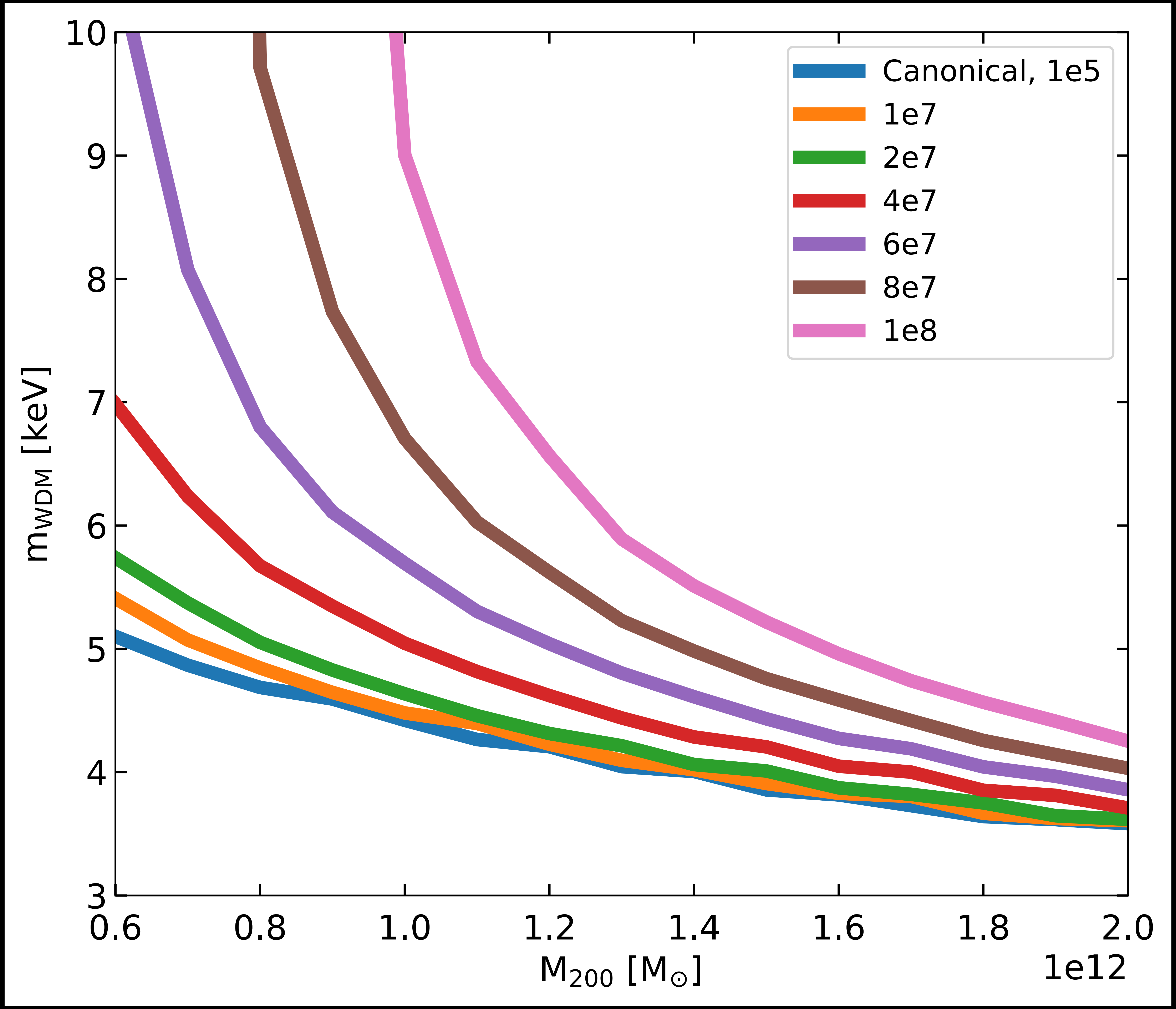
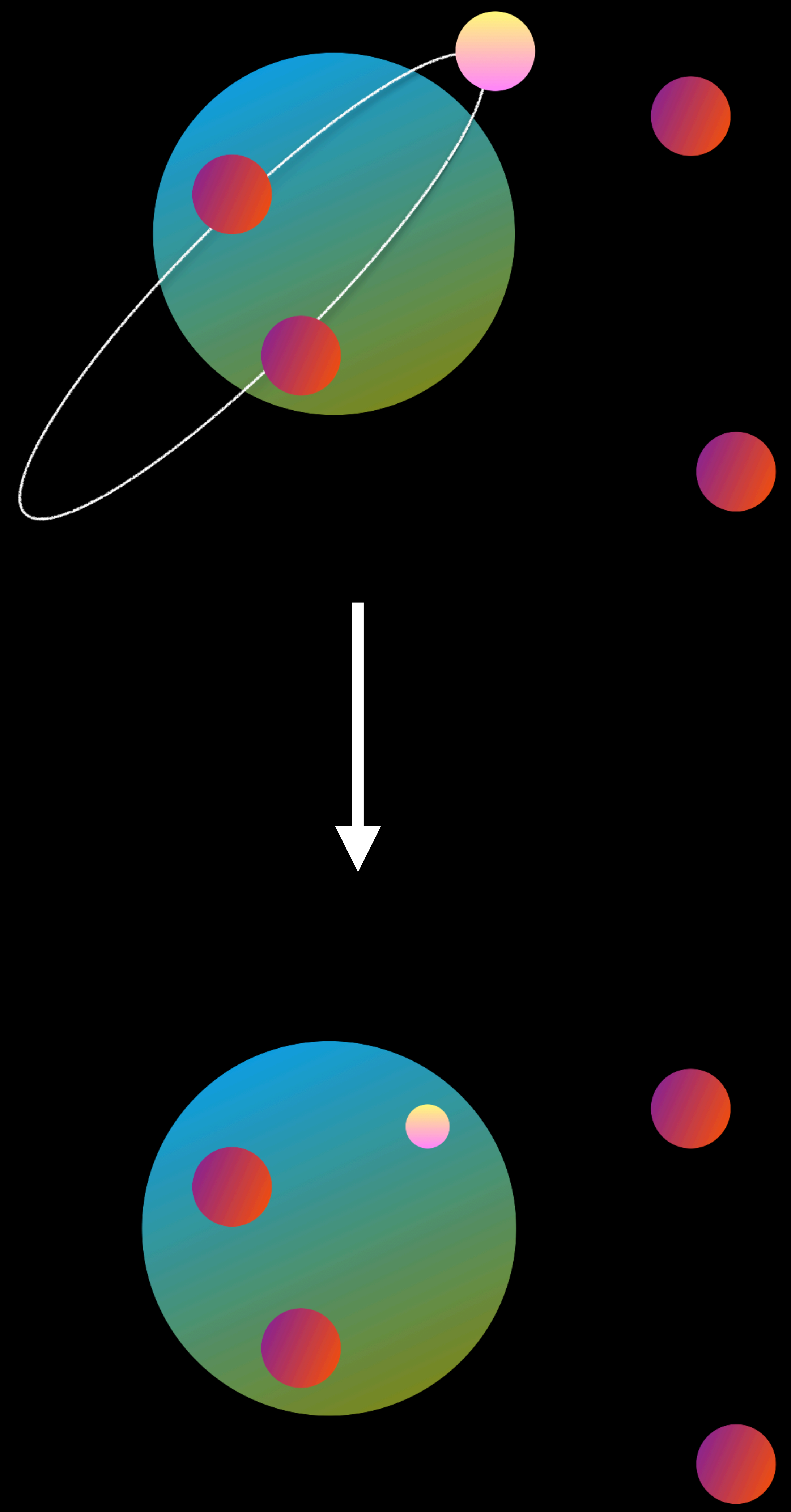
Thank you!

Minimum peak mass



Dekker et al. (2021)

Tidal stripping



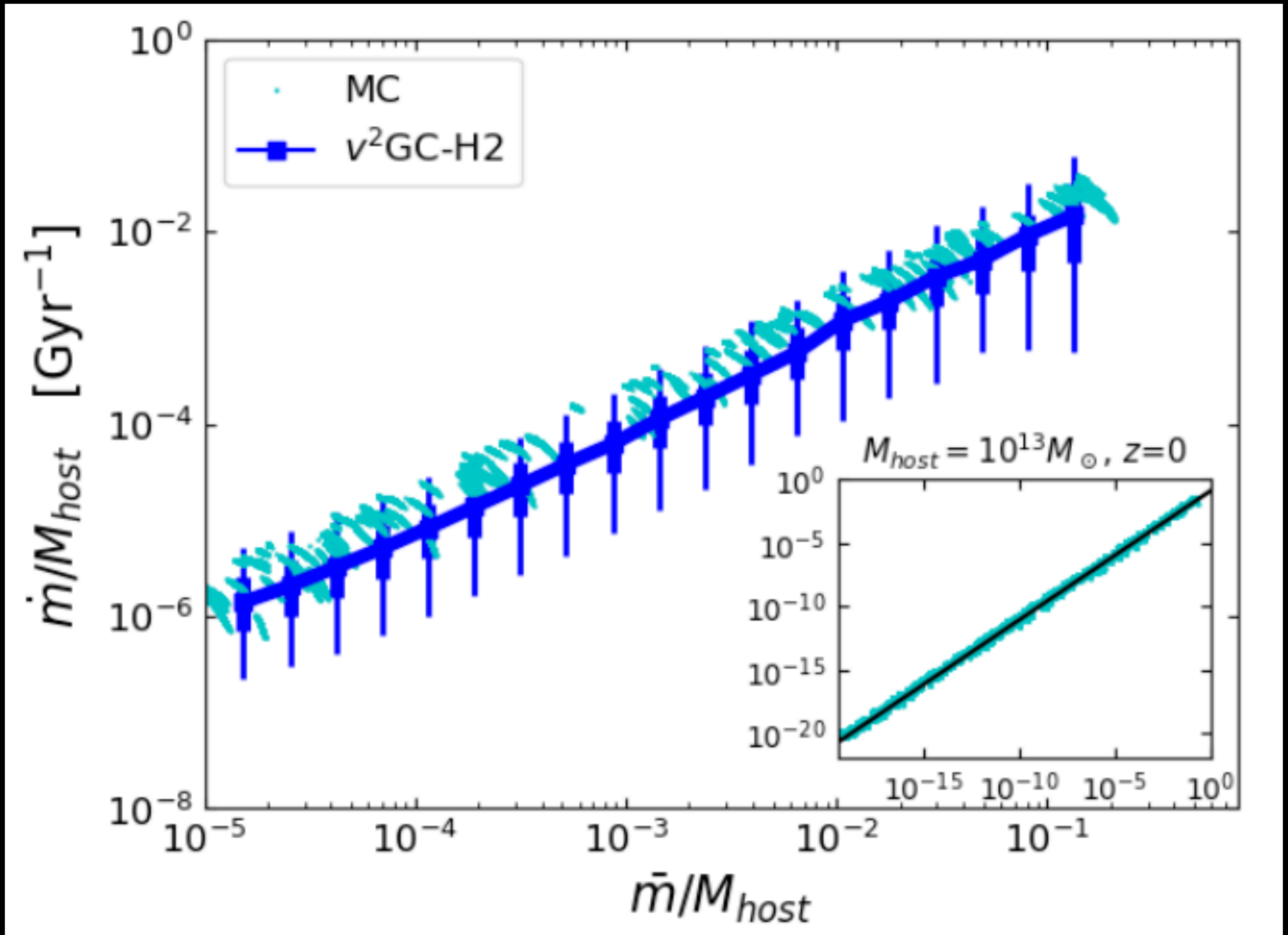
- Van den Bosch et al. (2005) present analytical description for the average mass loss rate of dark matter haloes

$$\frac{dm(z)}{dt} = -A\frac{m(z)}{\tau_{dyn}}\left(\frac{m}{M_{host}}\right)^{\zeta}$$

- Hiroshima et al. (2018) consider toy model for the average mass loss of a subhalo

$$\frac{dm}{dt} = \frac{m - m(r_t)}{T_r}$$

Tidal stripping



Hiroshima et al. (2018)

Agreement for CDM with numerical simulations

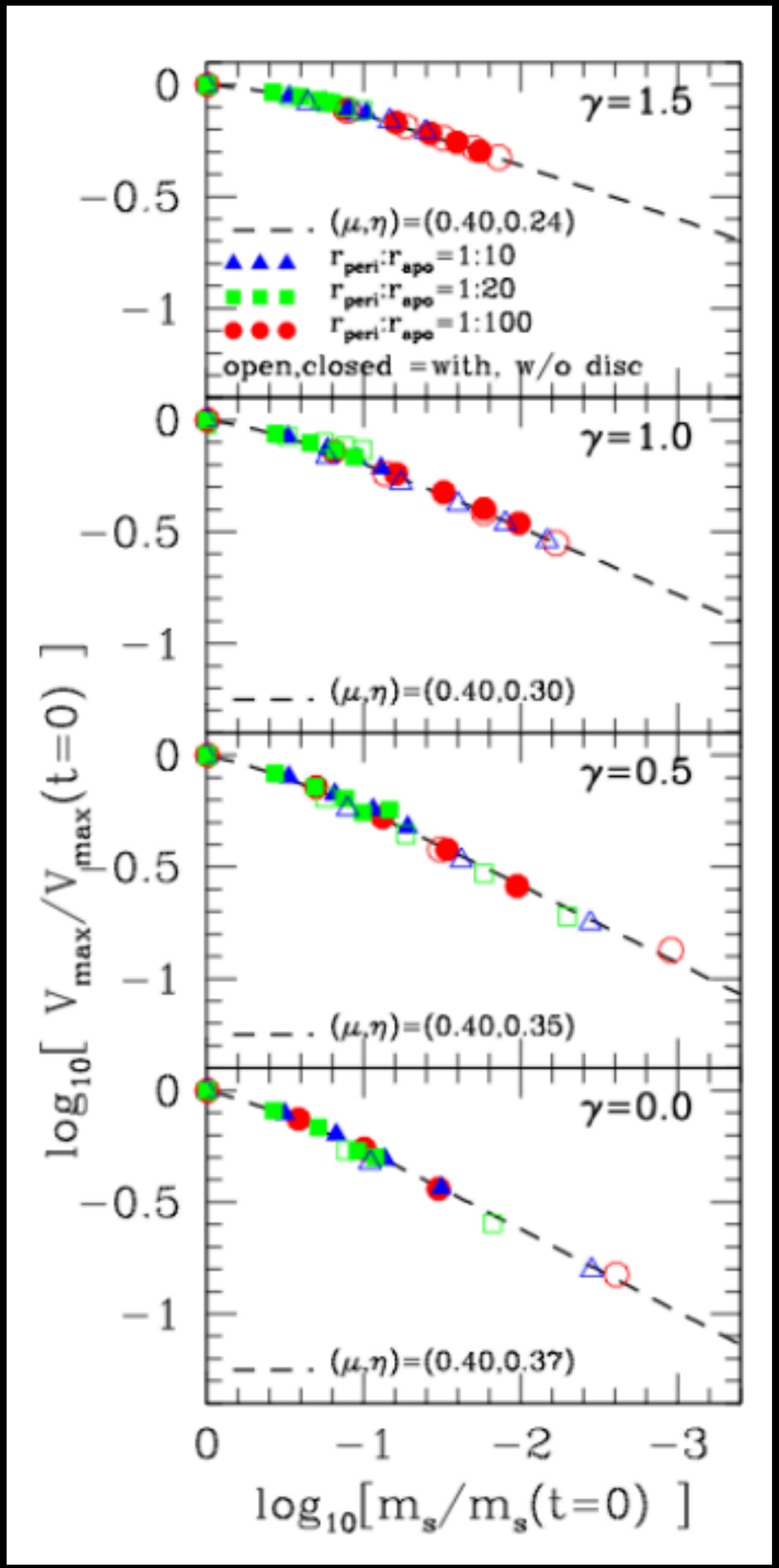
↓

Adopt toy model to get (A, ζ) for WDM

Evolved subhalo mass function

- After tidal stripping the internal structure of a subhalo changes
- Determine (ρ_s, r_s, r_t) at accretion for given (c, m, z)
- Obtain (ρ_s, r_s, r_t) after tidal stripping
- Subhalos with $r_t < 0.77\, r_s$ are completely disrupted

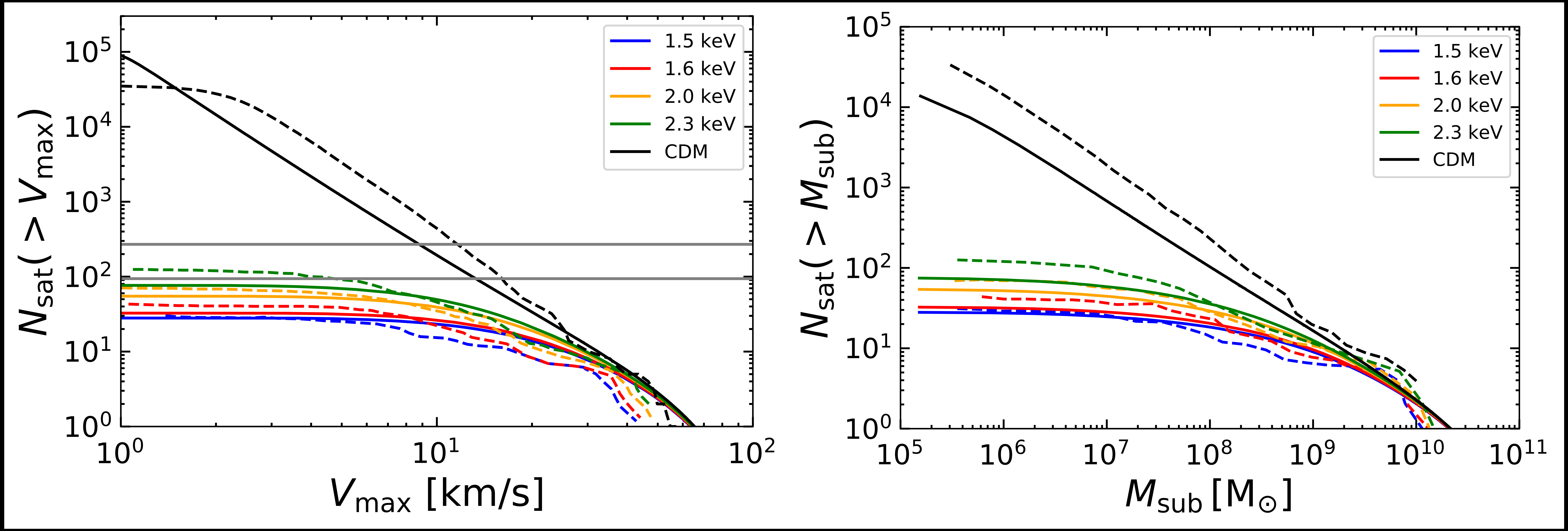
Evolution of V_{max} and r_{max} as a function of mass loss fraction



Penarrubia et al. (2010)

Comparison with numerical simulation

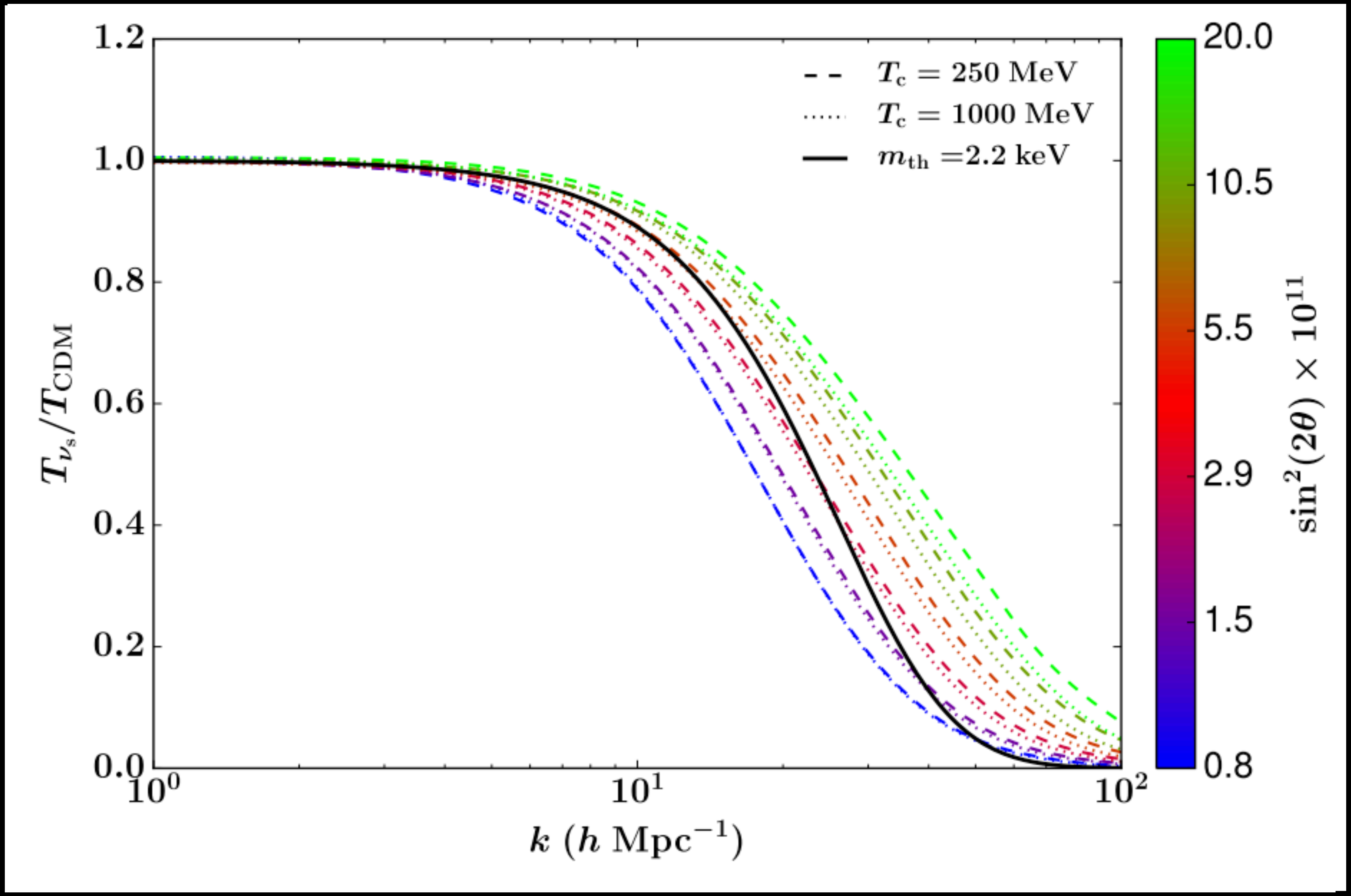
$$M_{host} = 1.8 \times 10^{12} M_{\odot}$$



Dekker et al. (2021)

Matter Power Spectrum

Sterile neutrino (Venumadhav et al. (2015))



- Produced through mixing $\sin^2(2\theta)$ with neutrinos (non-thermal)
- Lepton asymmetry enhances resonant oscillations $\nu_{e,\mu,\tau} \rightarrow \nu_s$ (Shi & Fuller 1999)

Structure formation

Dark matter haloes are formed by perturbations in the matter density field $\delta(x) = \rho(x)/\bar{\rho} - 1$

Spherical collapse model: $\delta(z) > \delta_c \approx 1.686$

Press-Schechter formalism

δ follows a random walk over x

Positions that cross δ_c form a halo

Nr density of haloes with mass M = Nr density of peaks above δ_c smoothed over M

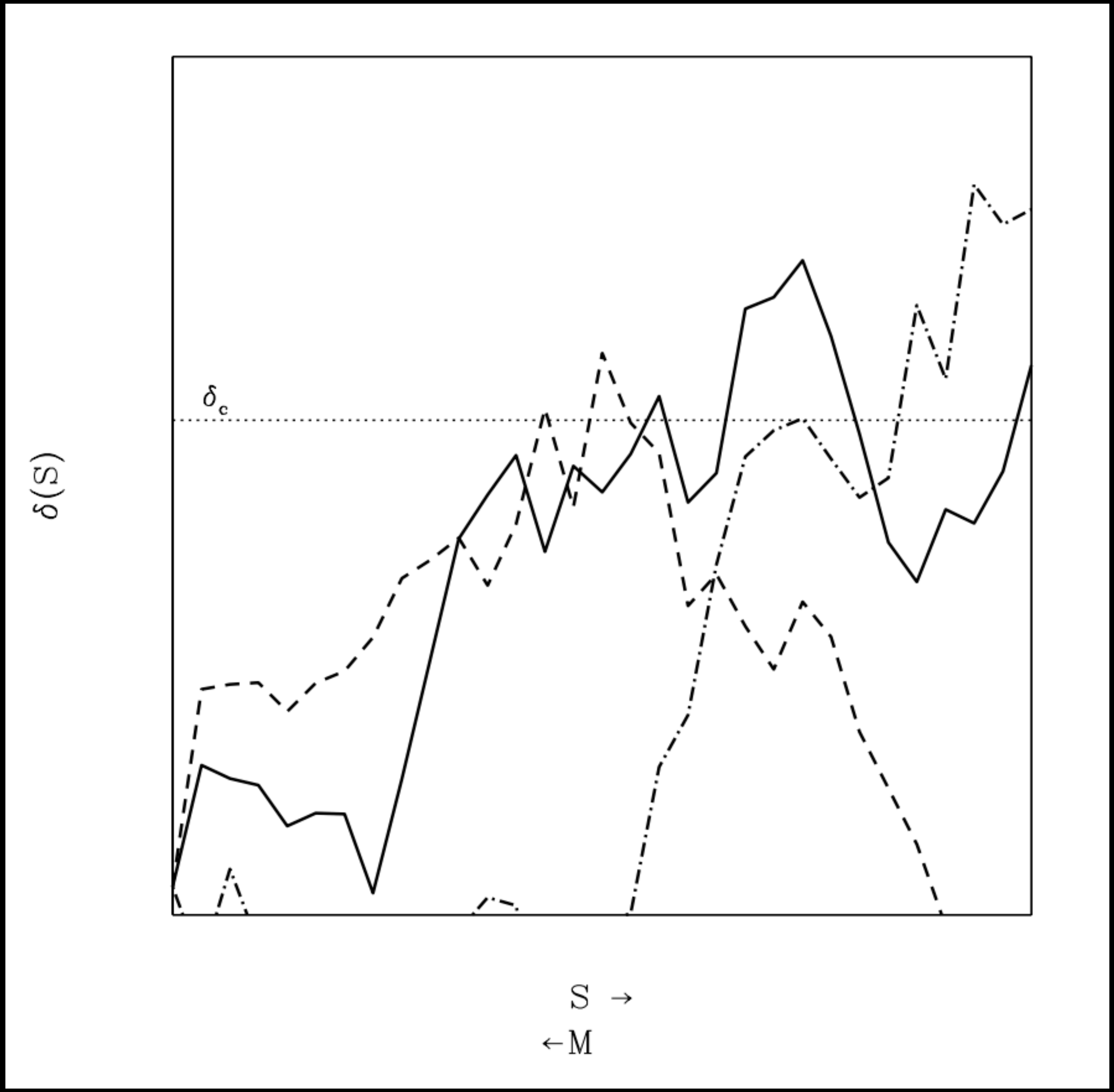
Structure formation

Extended Press-Schechter formalism

δ follows a random walk in (S, δ_S)-space for fixed $\boldsymbol{x}$

Each trajectory starts at (0,0): Largest possible halo mass

Obtain the fraction of mass inside a halo of mass M at redshift z



Zentner (2006)