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 et al. — *Phys. Rev. D 104, 023021 (2021)*

Introduction

- ΛCDM scenario: Structure forms through hierarchical merging of dark matter haloes
- Numerical predictions: Observed structure above ~1 Mpc is well explained by CDM

  Small scale observations challenge CDM (Bullock & Boylan-Kolchin (2017))

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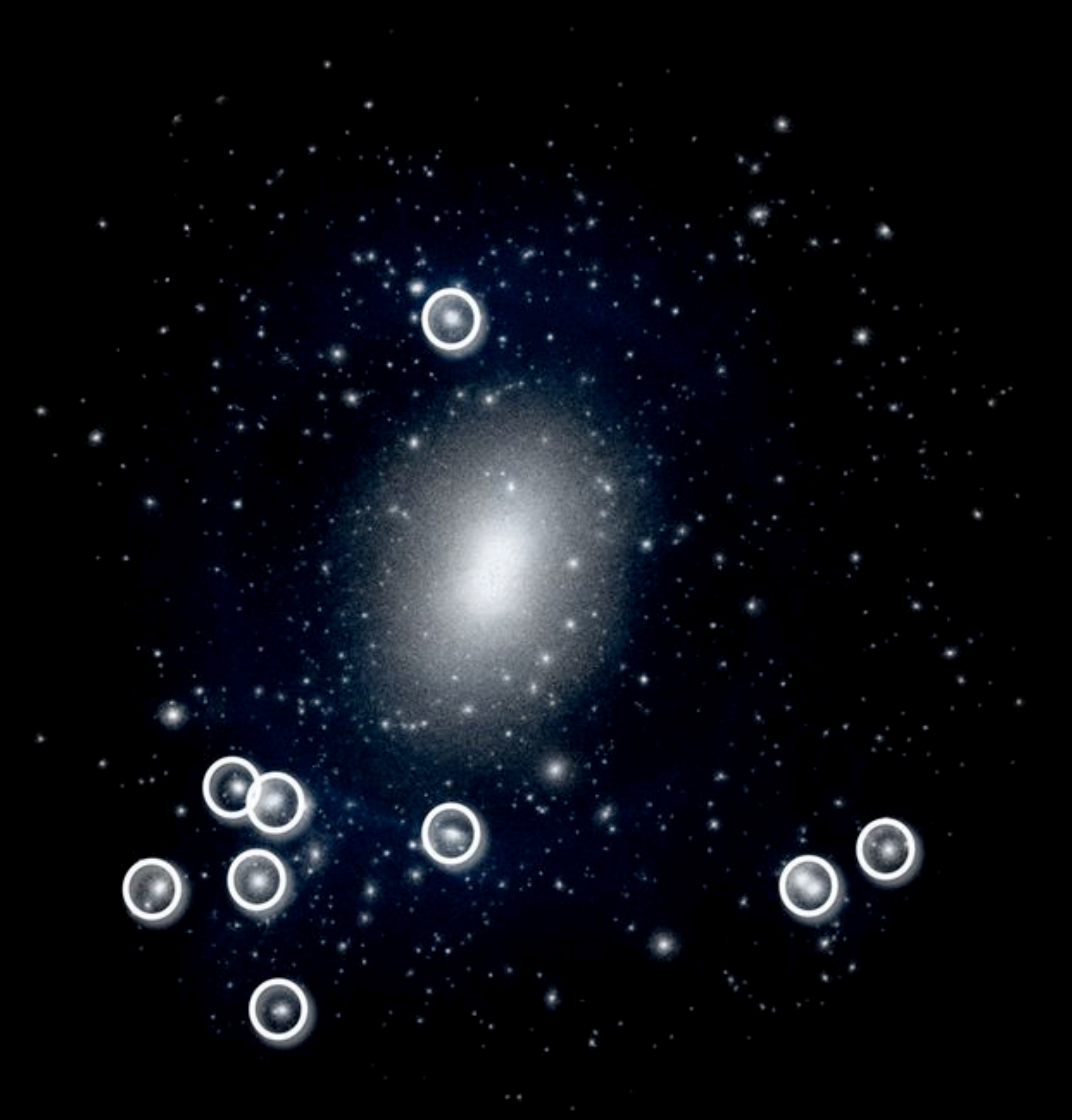
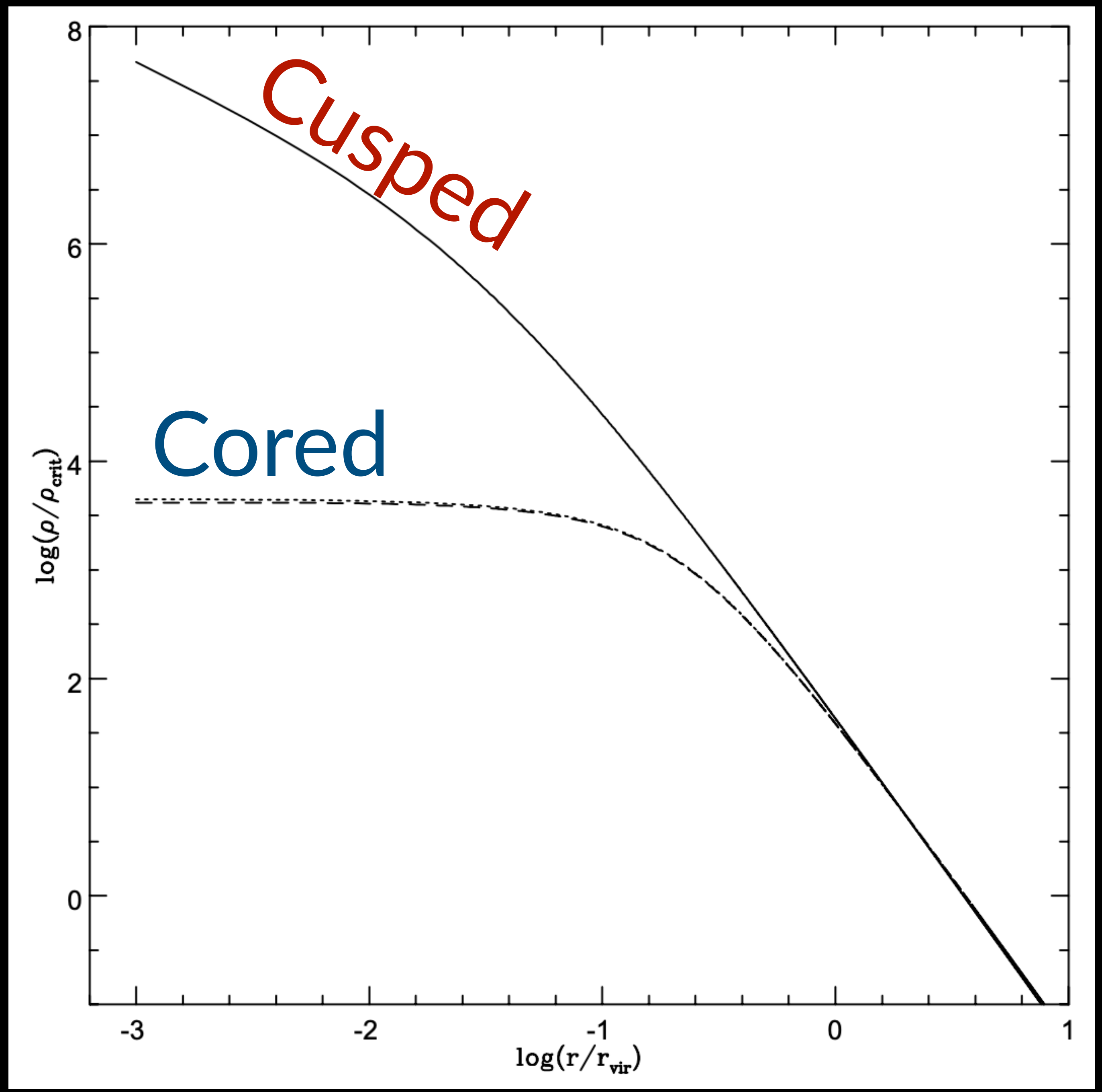
  Small scale observations challenge CDM (Bullock & Boylan-Kolchin (2017))

  - Cusp-core problem
  - Too-big-to-fail
  - Missing satellite problem



Weinberg et al. (2013)

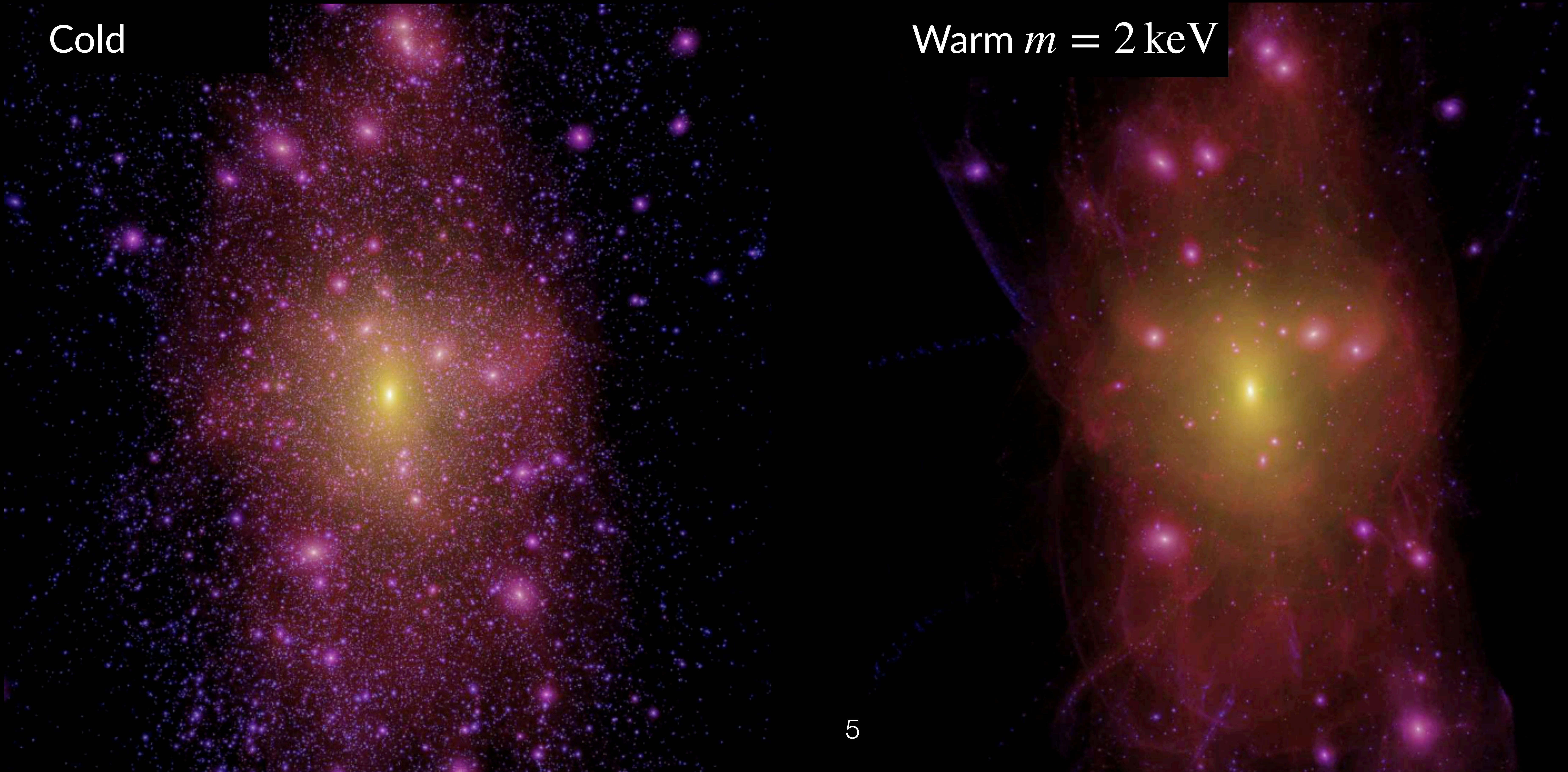


Popolo et al. (2009)

Introduction

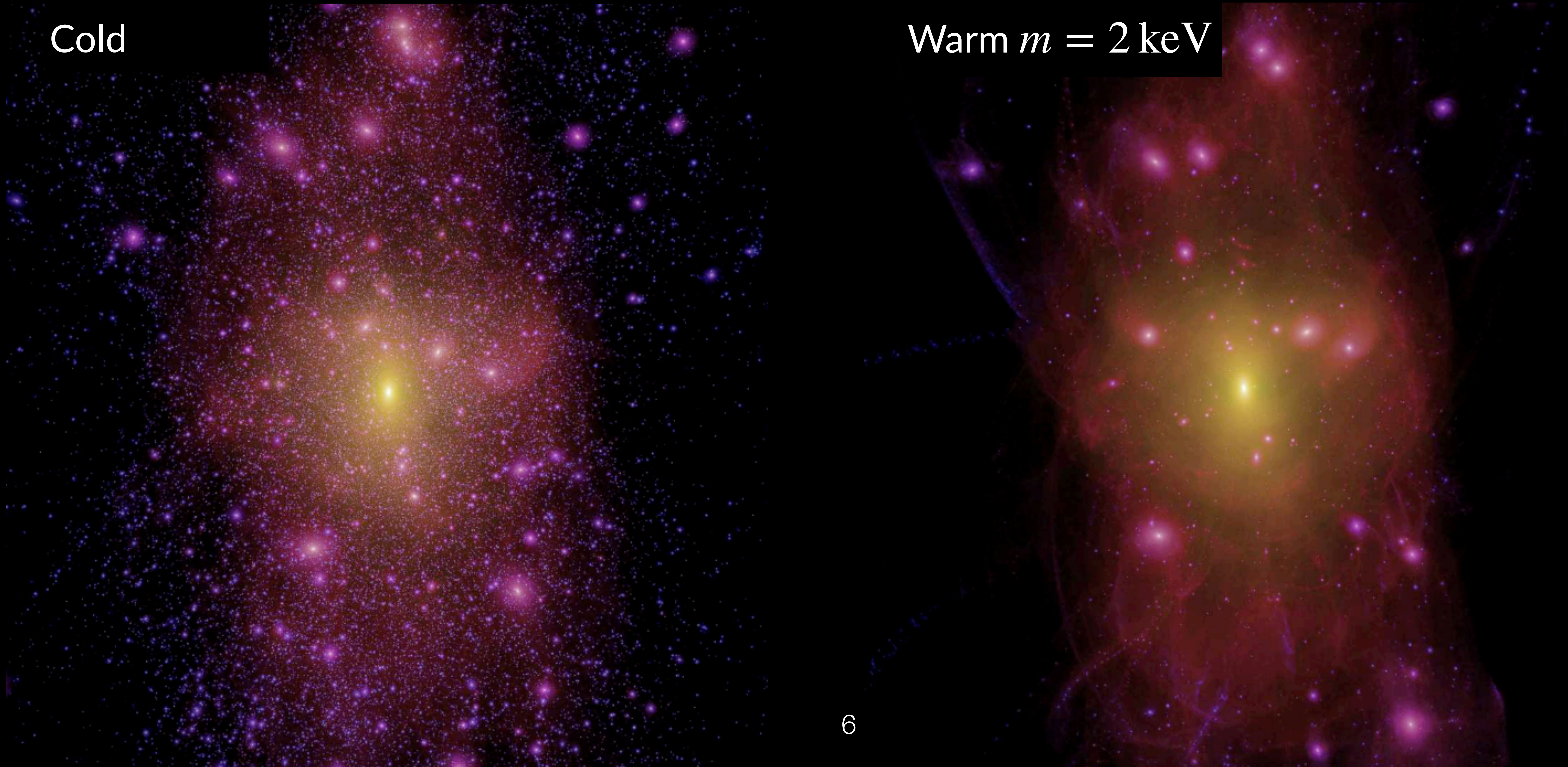
- ΛCDM scenario: Structure forms through hierarchical merging of dark matter haloes
- Numerical predictions: Observed structure above ~1 Mpc is well explained by CDM
  Small scale observations challenge CDM (Bullock & Boylan-Kolchin (2017))
- Solutions: Baryonic physics
  Non-cold dark matter: Warm dark matter (sterile neutrinos, axionlike particles)

- Warm dark matter as a solution?



Lovell et al. (2014)

- Warm dark matter as a solution?
- Probe small scales: Abundance of Milky-Way satellites
- Need subhalo model: Numerical simulations / Analytical model

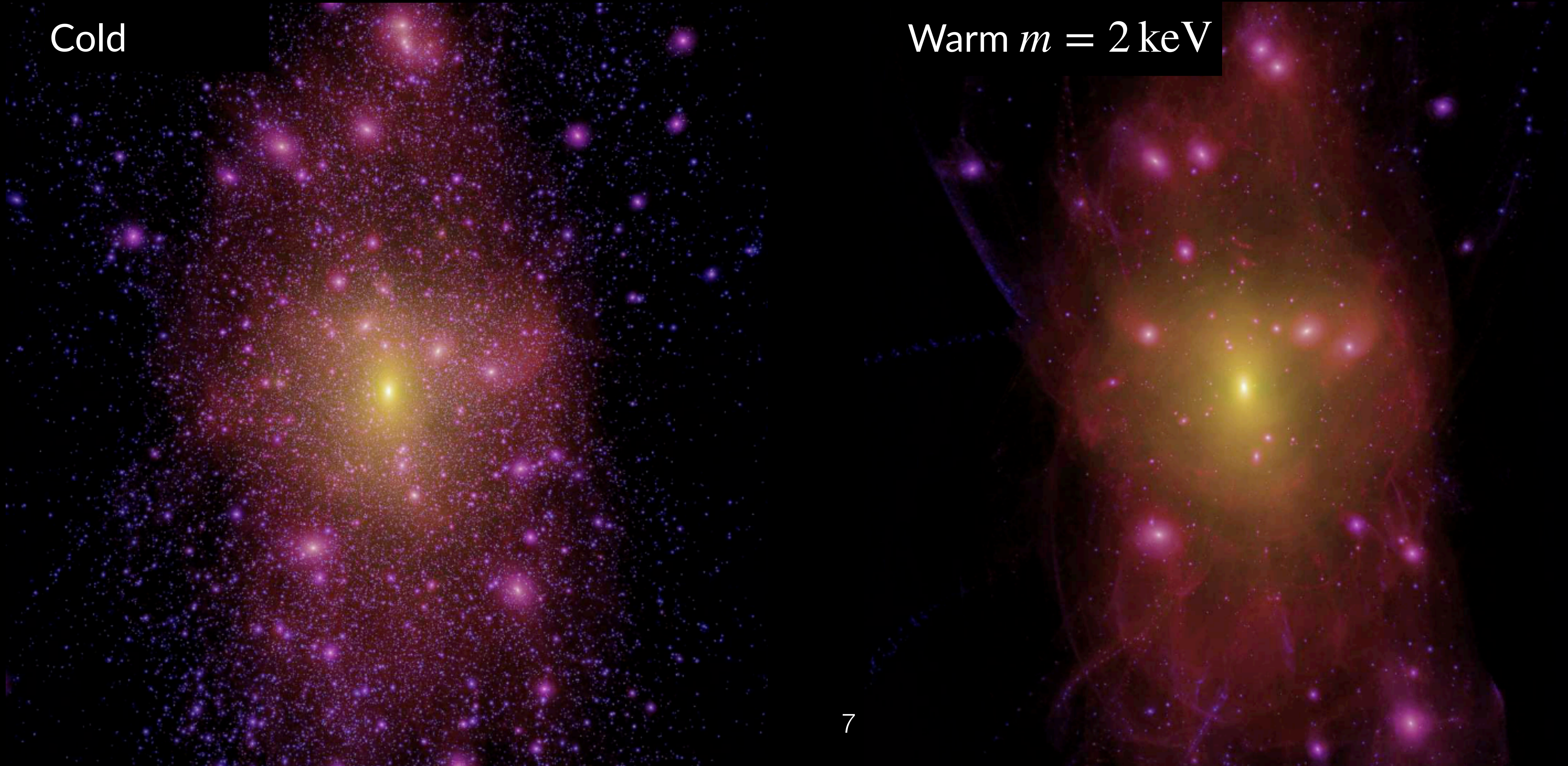


Lovell et al. (2014)

- Warm dark matter as a solution?
- Probe small scales: Abundance of Milky-Way satellites
- Need subhalo model: Numerical simulations / Analytical model

Numerical simulations → Limited to numerical resolution

Analytical model → Fast & flexible



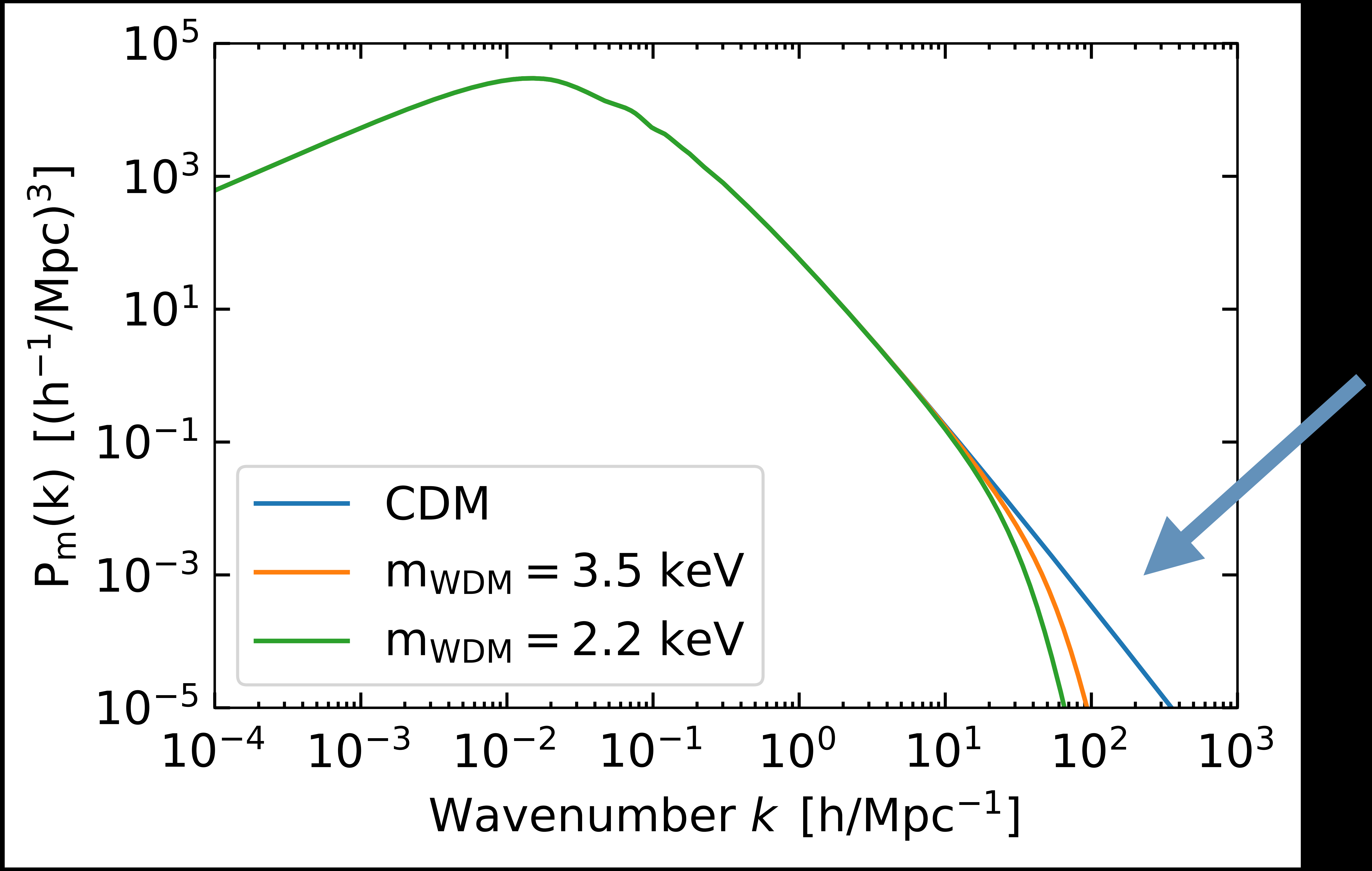
Lovell et al. (2014)

Analytical Model

Semi-Analytical SubHalo Inference Modeling — SASHIMI

1. Structure forms — Matter Power spectrum

Thermal WDM (Viel et al. (2011))



Warm particles suppress small scale perturbations

2. Dark matter haloes accrete

Halos are formed through gravitational collapse above $\delta(z) > \delta_c$

Extended Press-Schechter: Analytical expressions for the accretion history

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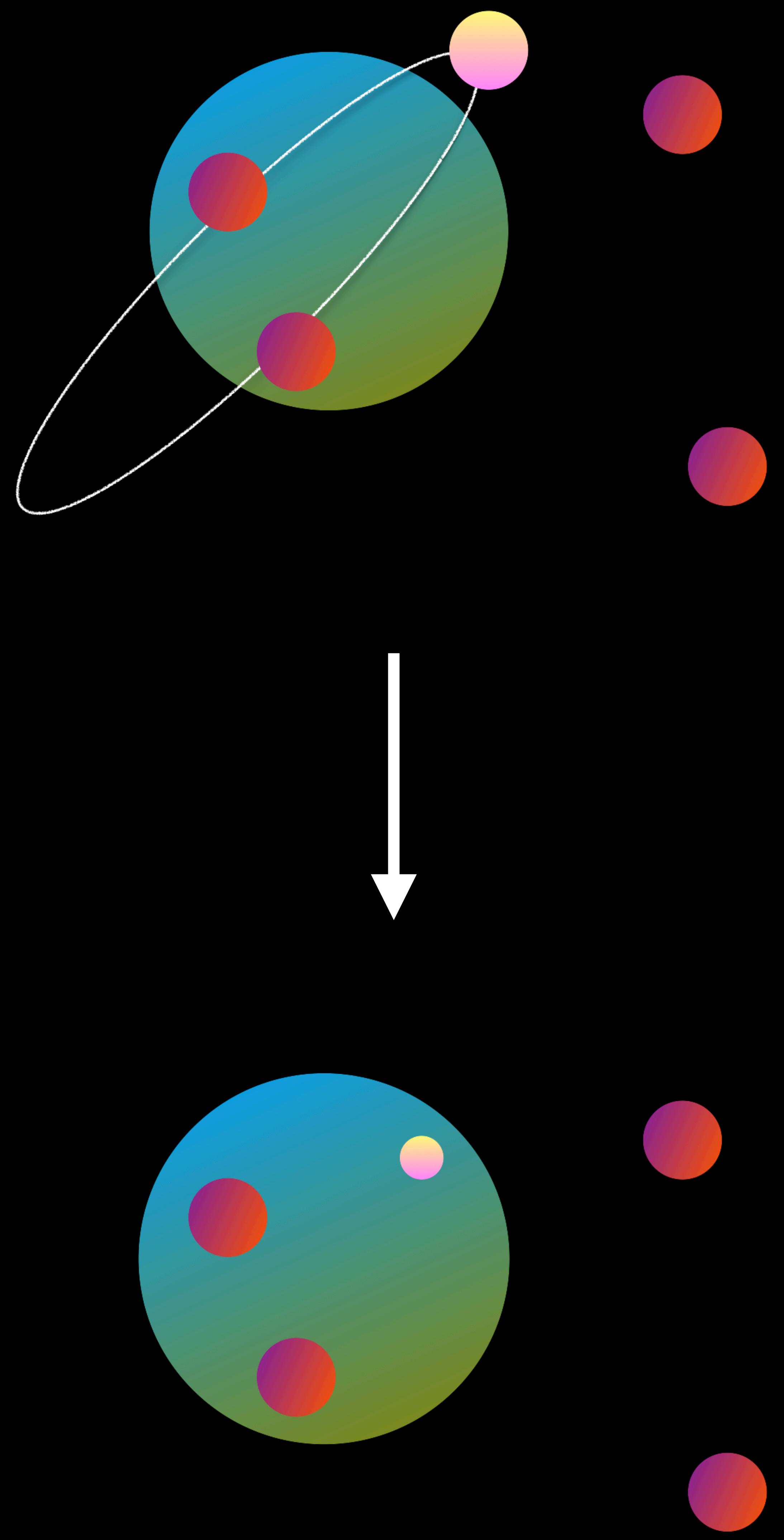
Halos are formed through gravitational collapse above $\delta(z) > \delta_c$

Extended Press-Schechter: Analytical expressions for the accretion history

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

3. Subhaloes evolve in time



Average mass-loss due to Tidal Stripping *(Hiroshima+ 2018, Van den Bosch+ 2005)*

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

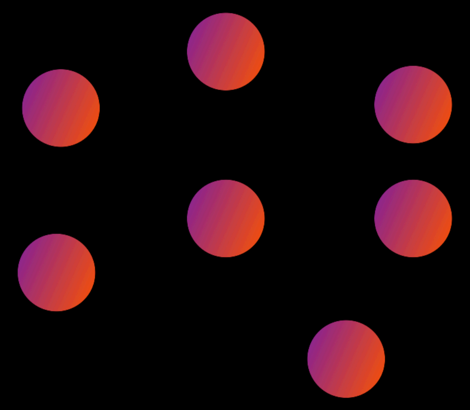
→ Mass stripped at pericenter after first orbital period T_r beyond r_t

Obtain (ρ_s, r_s, r_t) before and after tidal stripping

Remove completely disrupted subhalos

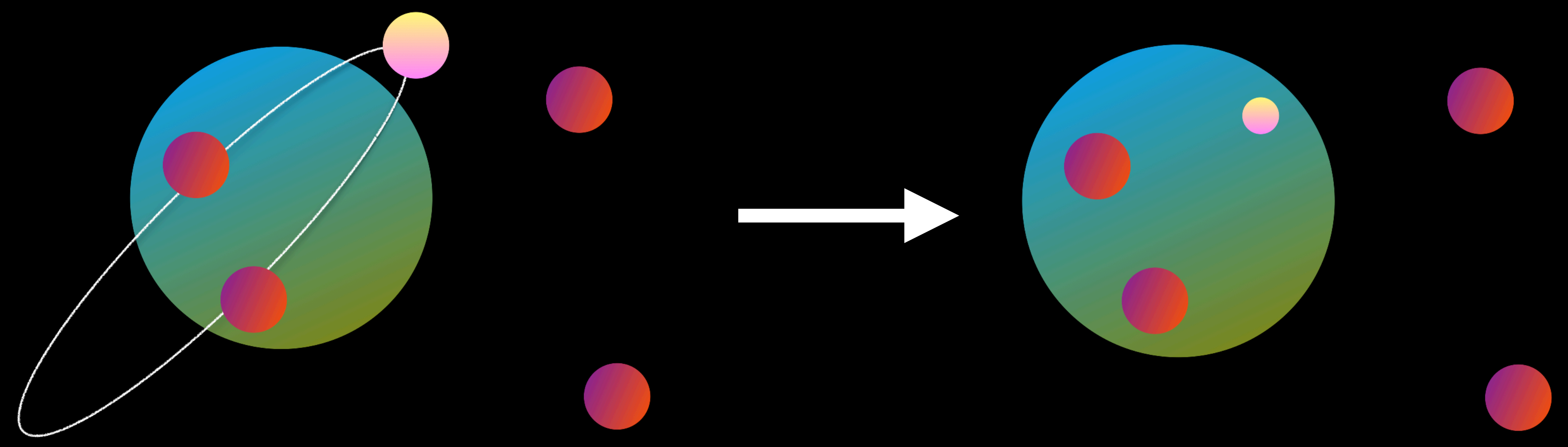
SASHIMI

1. Structure forms



2. Dark matter haloes accrete

3. Subhaloes evolve in time



SASHIMI

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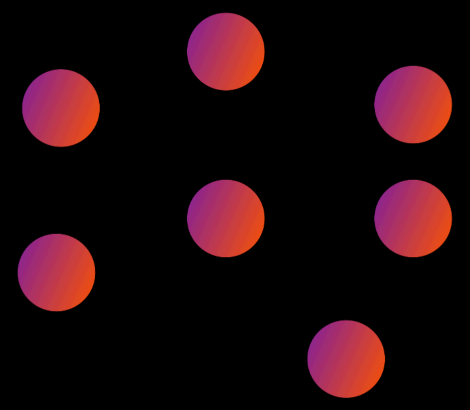

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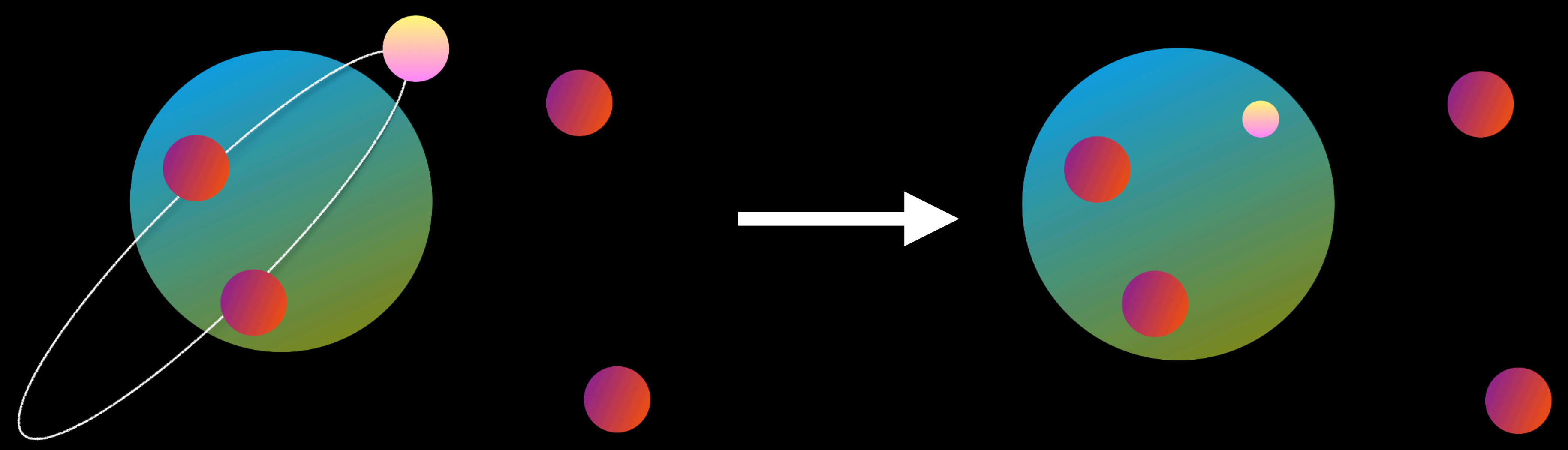

4. Satellite galaxies form within

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

SASHIMI

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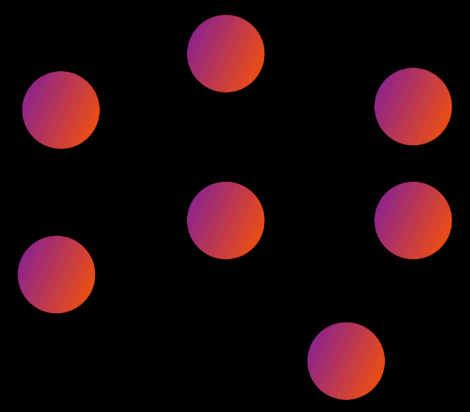

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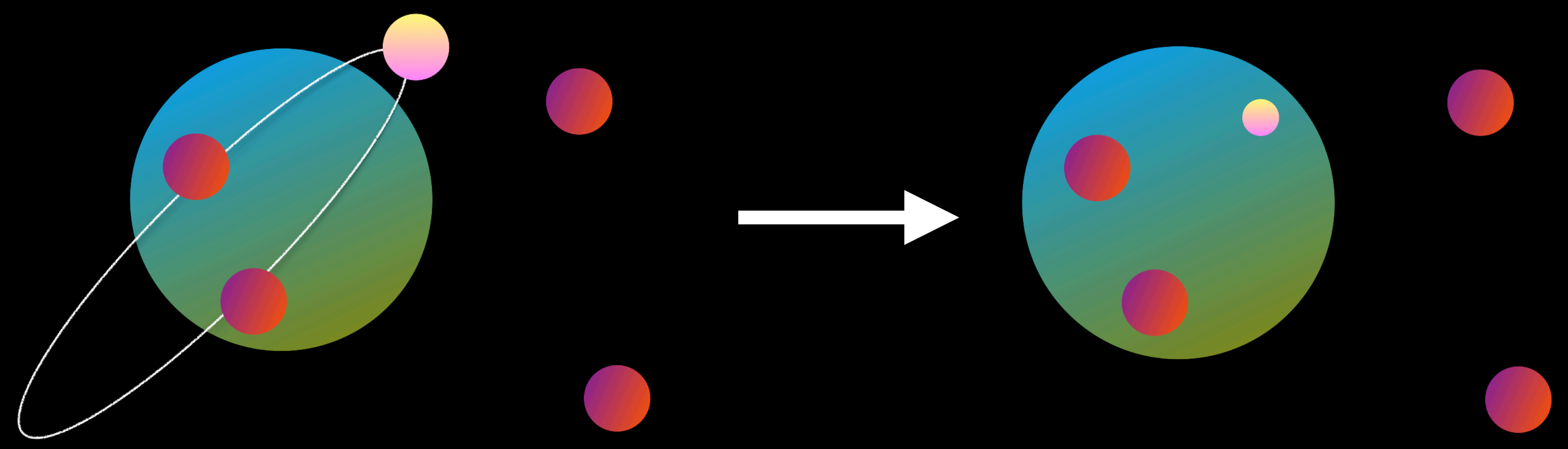
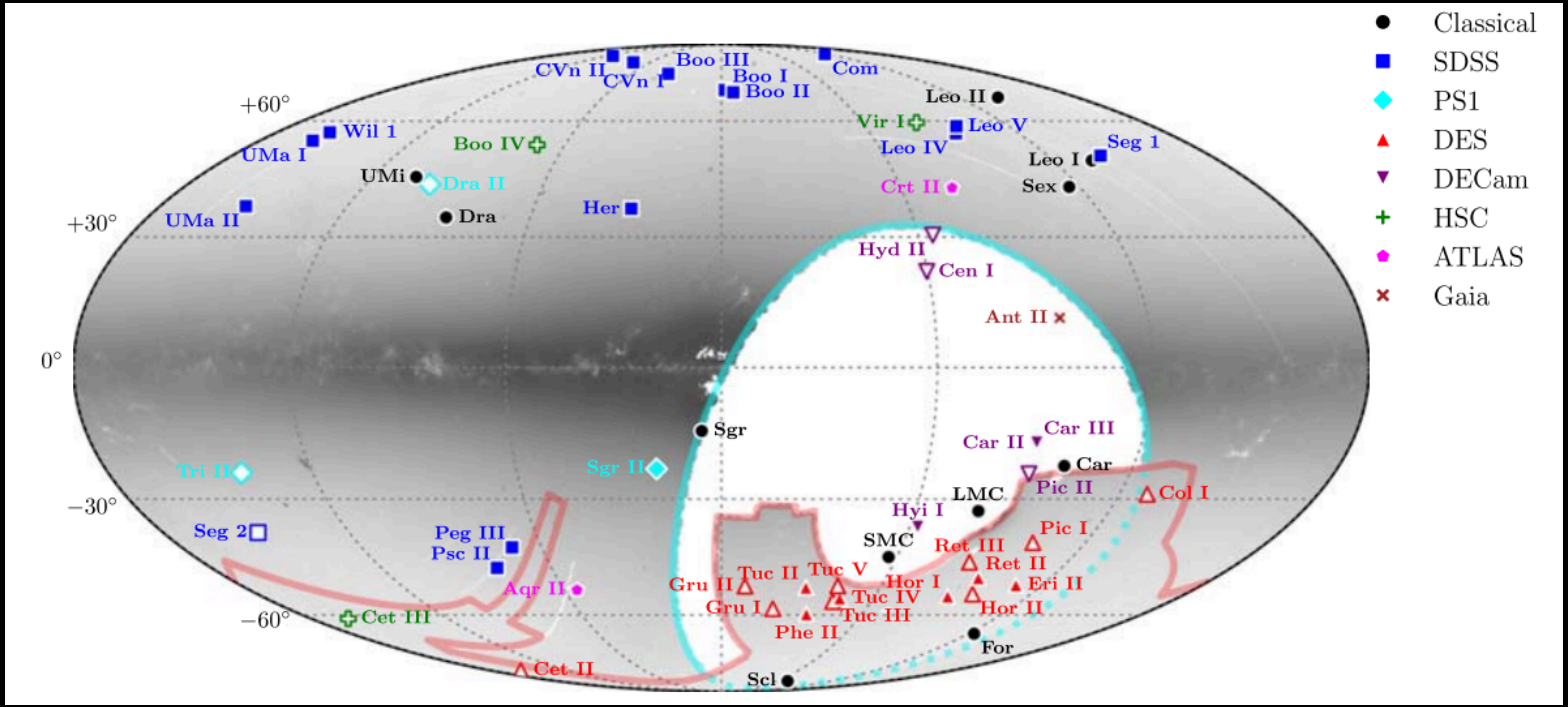


4. Satellite galaxies form within

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

5. Integrate to obtain total number of satellites in the Milky-Way

Observed satellites in the Milky Way



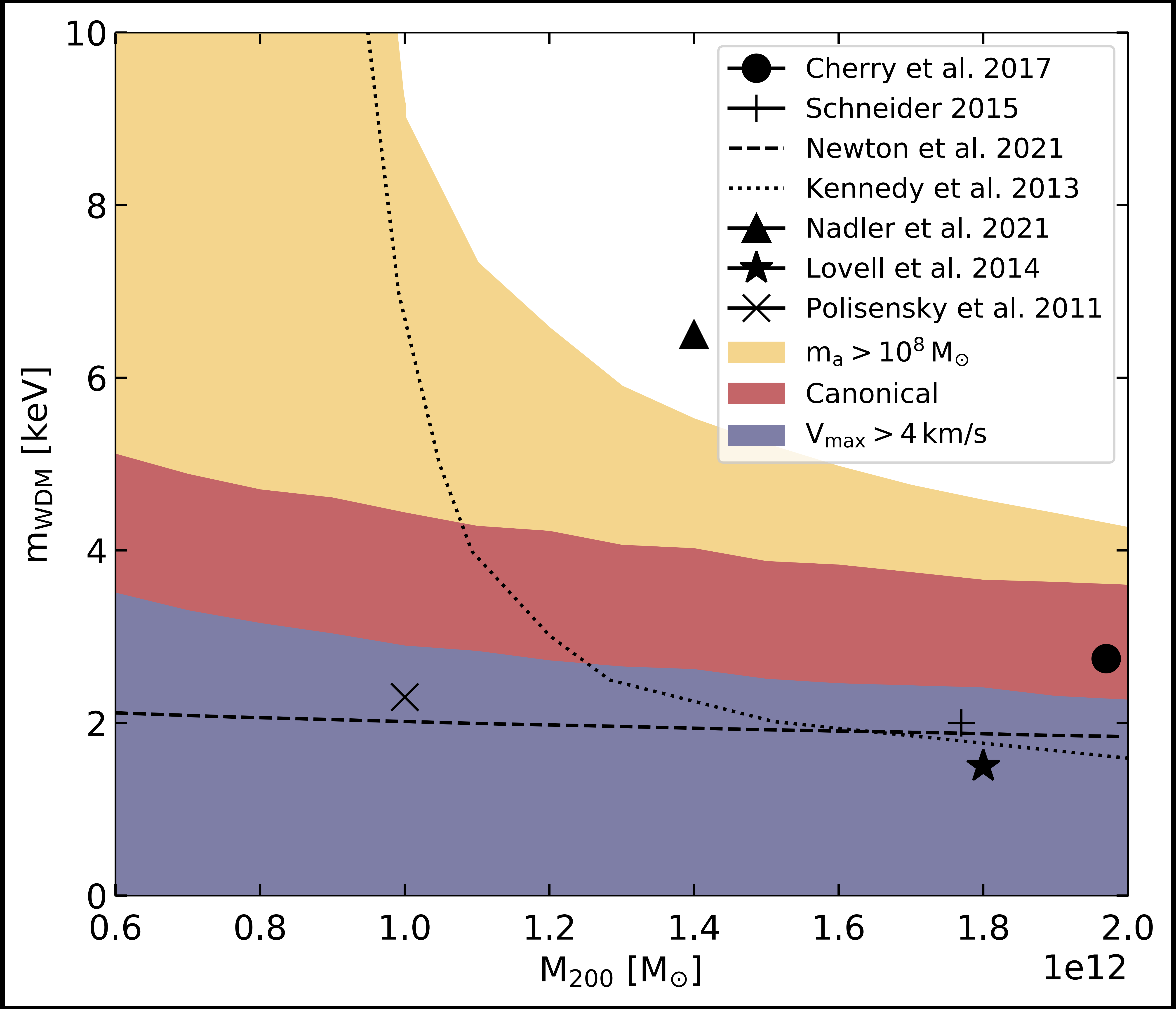
Drlica-Wagner et al. (2020)

- DES & Pan-STARRS1 observe ultra-faint satellite galaxies with ~80% sky coverage.
- Correct for detectability of satellites

270 satellites after correction

- Rule out WDM models that produce too few satellites at 95% CL

Warm dark matter Constraints



All subhalos host satellite galaxies

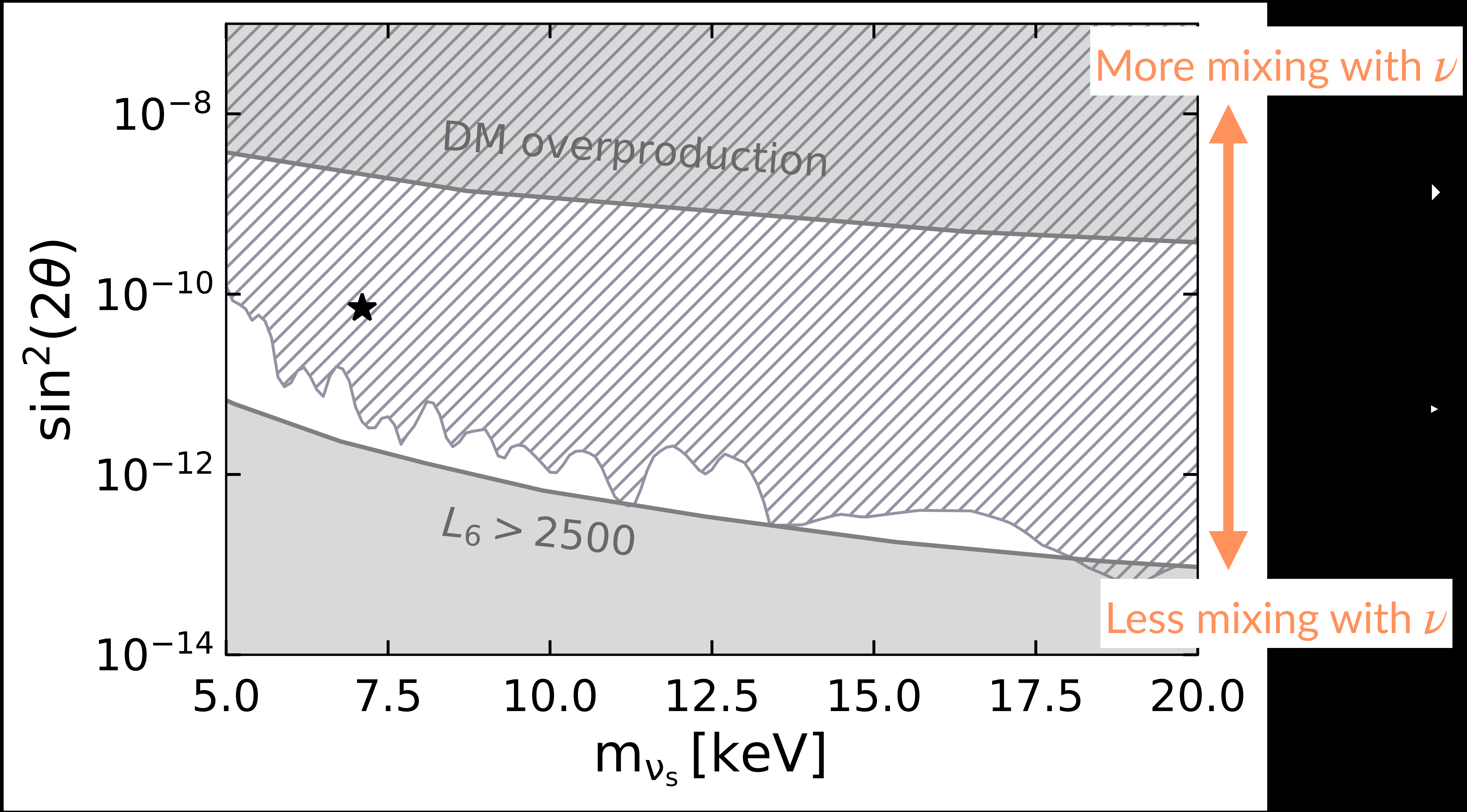
- Exclude WDM mass at 95% CL

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

- Model-independent constraints

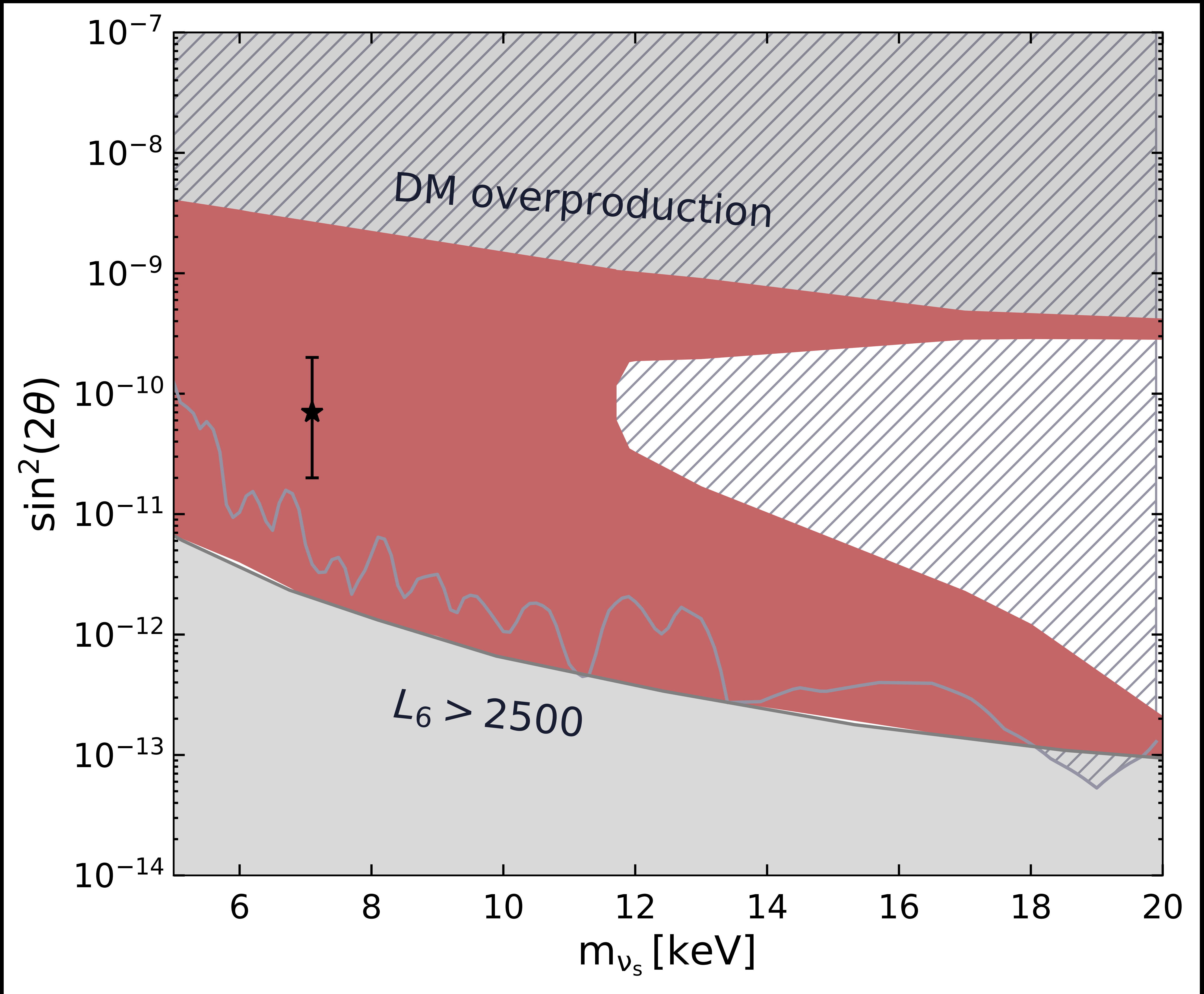
Dekker et al. (2021)

Sterile Neutrino: Current constraints



- Produced through mixing $\sin^2(2\theta)$ with neutrinos (non-thermal)
- Enhanced by lepton asymmetry *(Shi&Fuller 1999)*

Sterile Neutrino Constraints



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

All subhalos host satellite galaxies

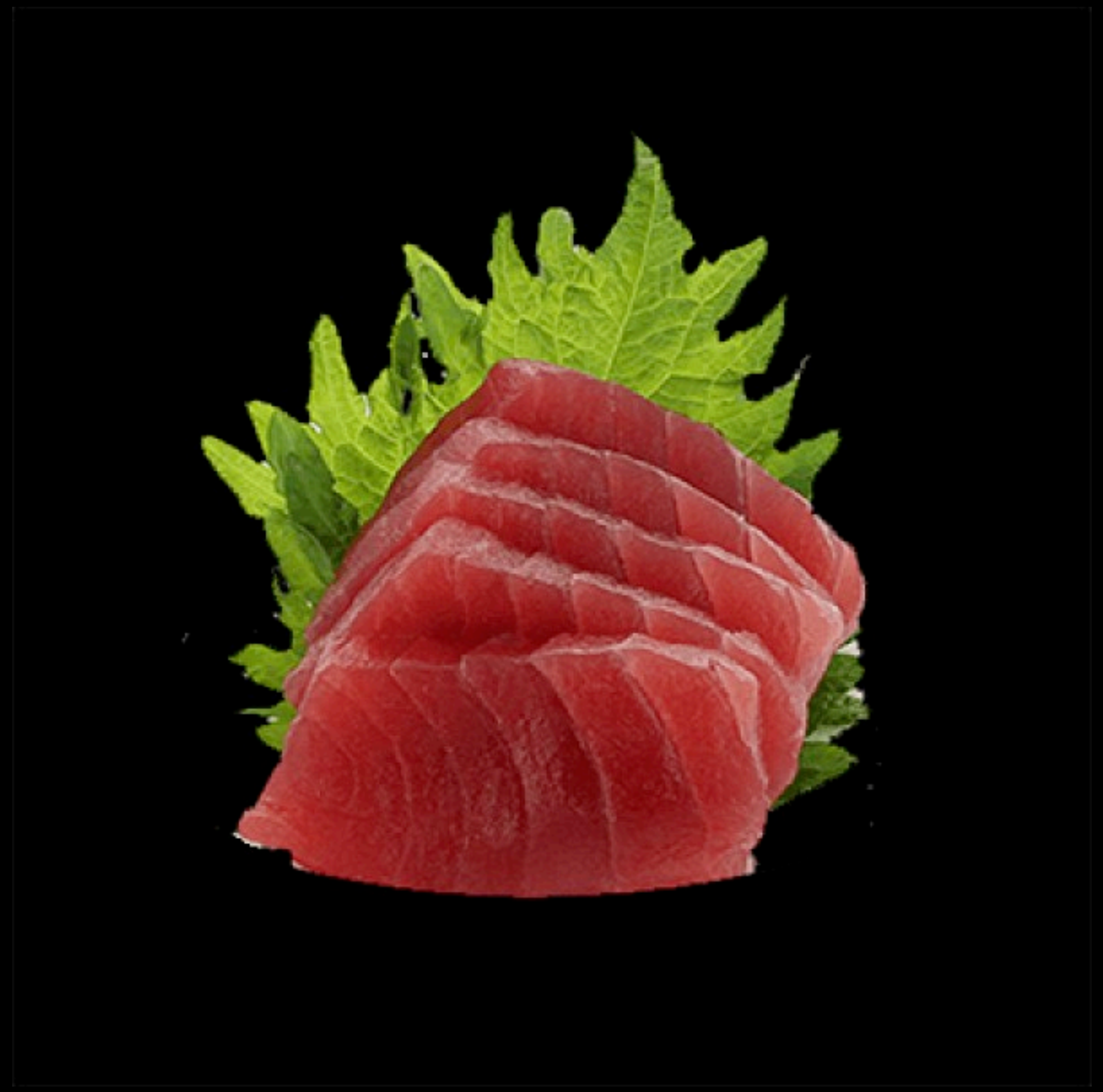
Constraints at 95% CL

Exclude sterile neutrino mass <12 keV

Dekker et al. (2021)

Codes publicly available on Github

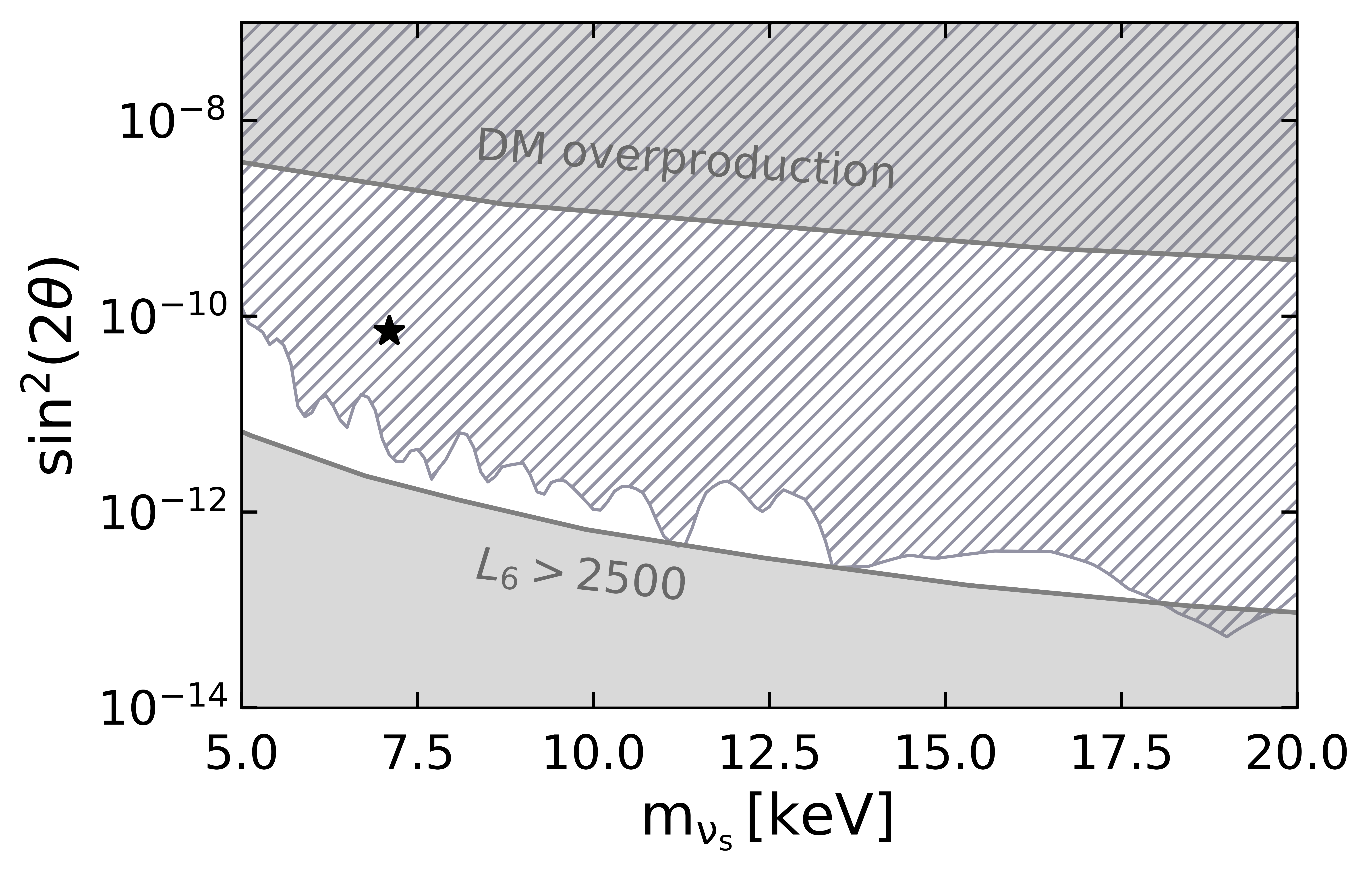
SASHIMI — Semi-Analytical SubHalo Inference ModelIng



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

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

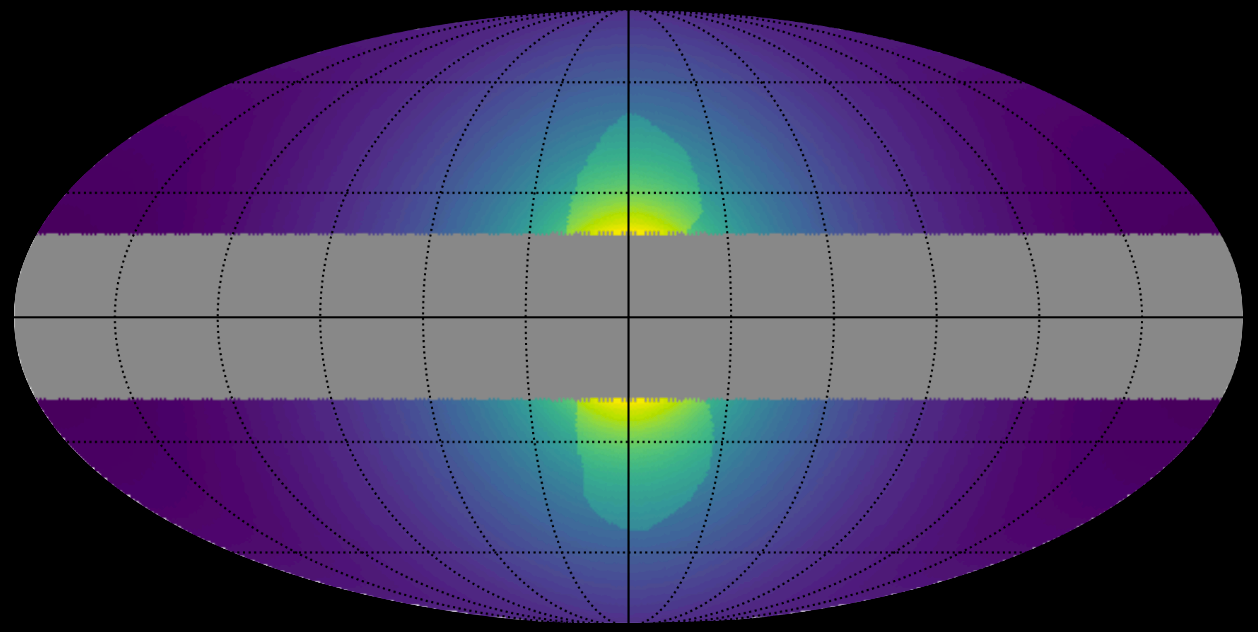
Sterile Neutrino Constraints — X-ray observations



X-ray constraints

Theory

- Sterile neutrino decay $\nu_s \rightarrow \nu_a + \gamma$
- Improve with eROSITA: All-sky X-ray survey (4 years)
- Studied diffuse emission from Galactic halo



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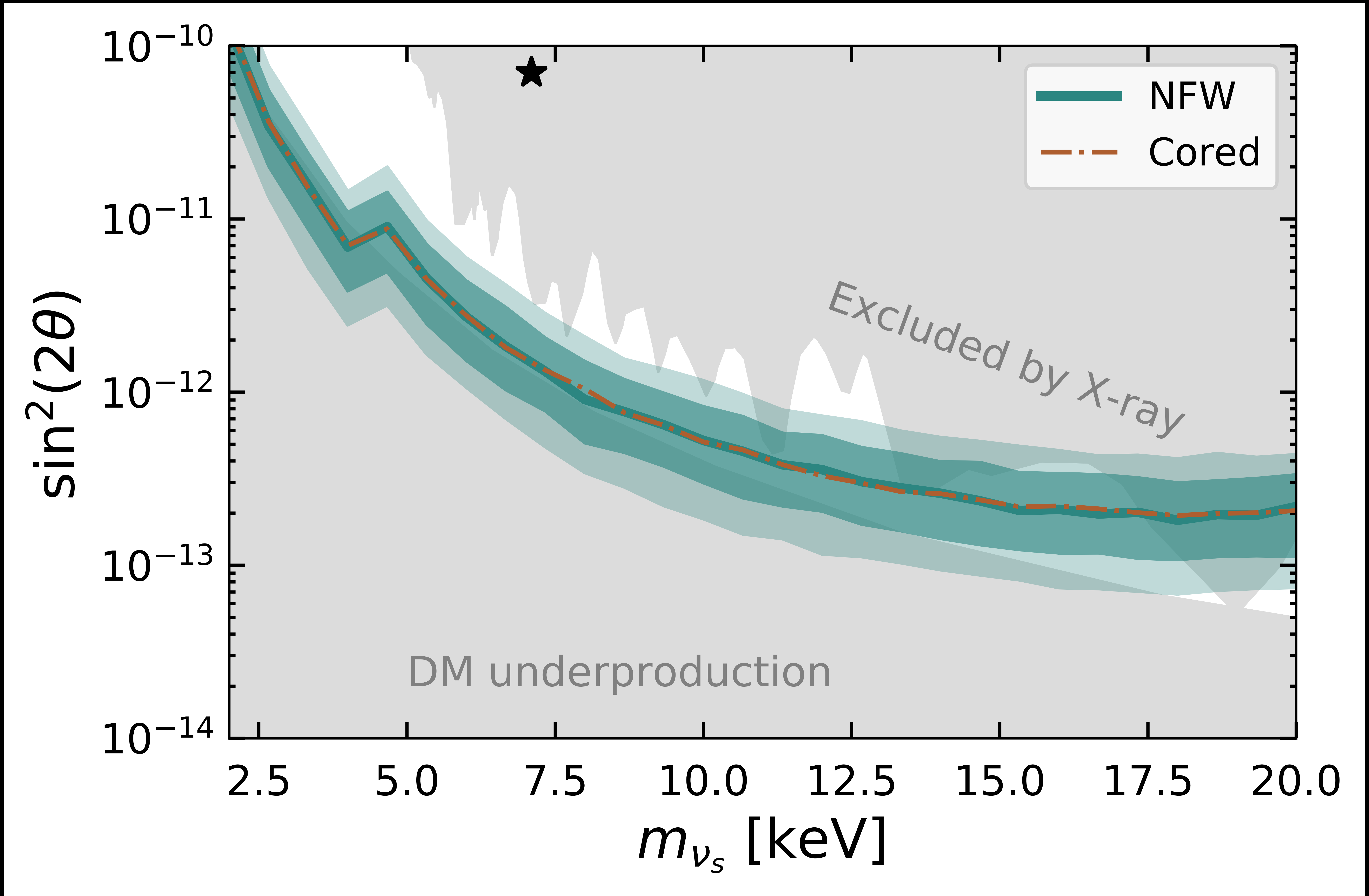
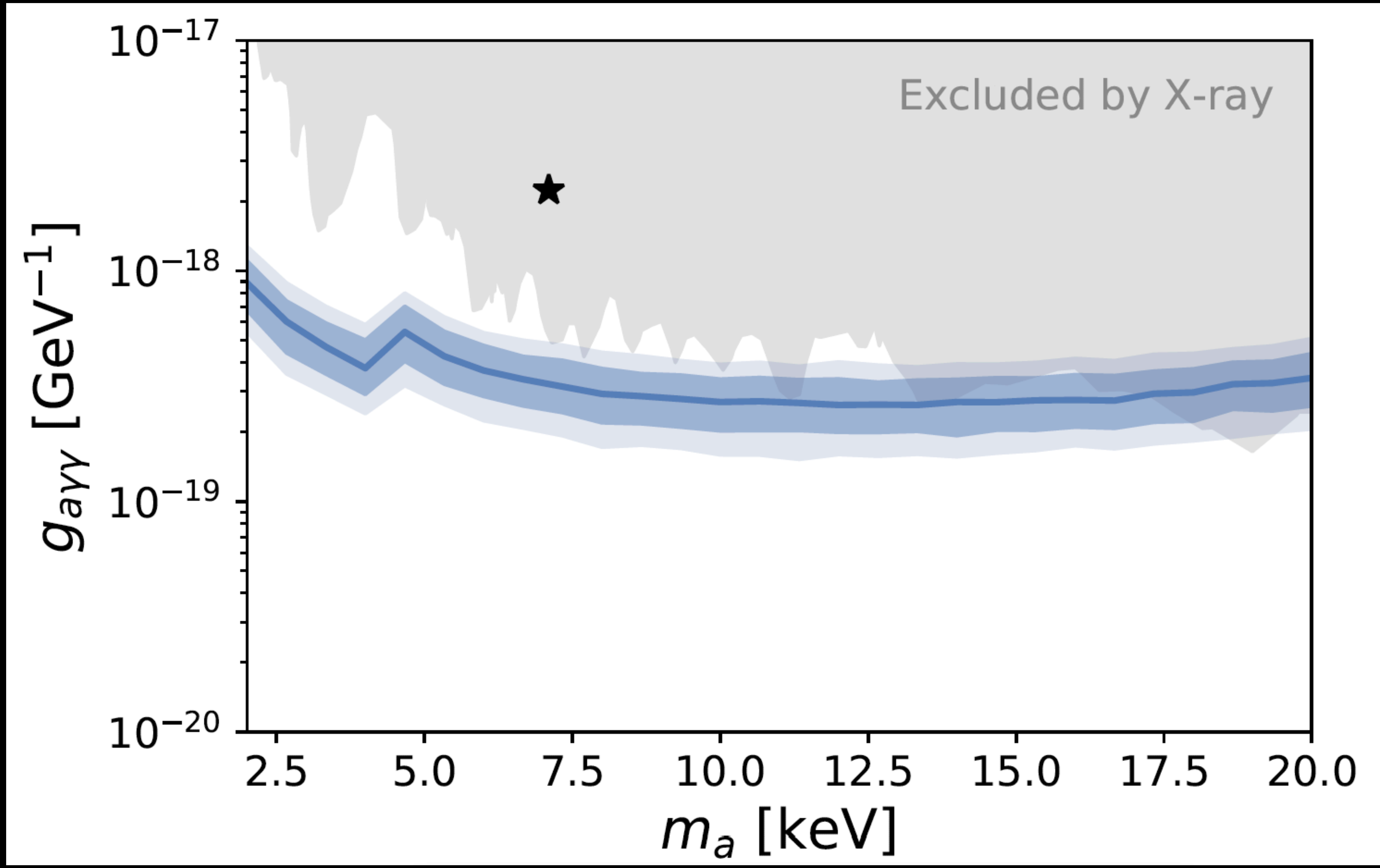
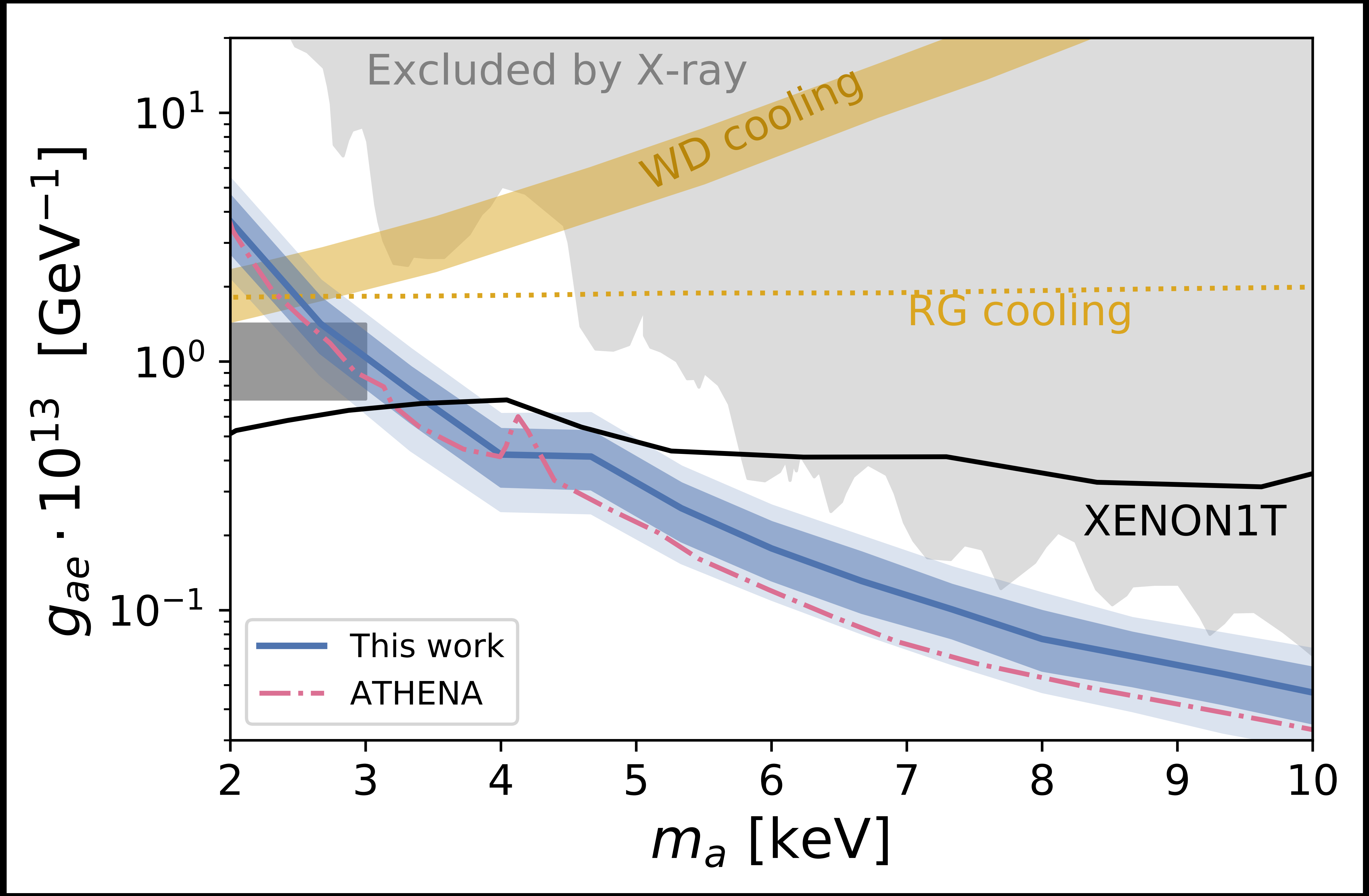


Dekker et al. (2020)

Sensitivity axion-like particle





Dekker et al. (2020)

Summary

- Semi-analytical model *SASHIMI*
- Codes are publicly available
- 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 from X-ray emission with eROSITA

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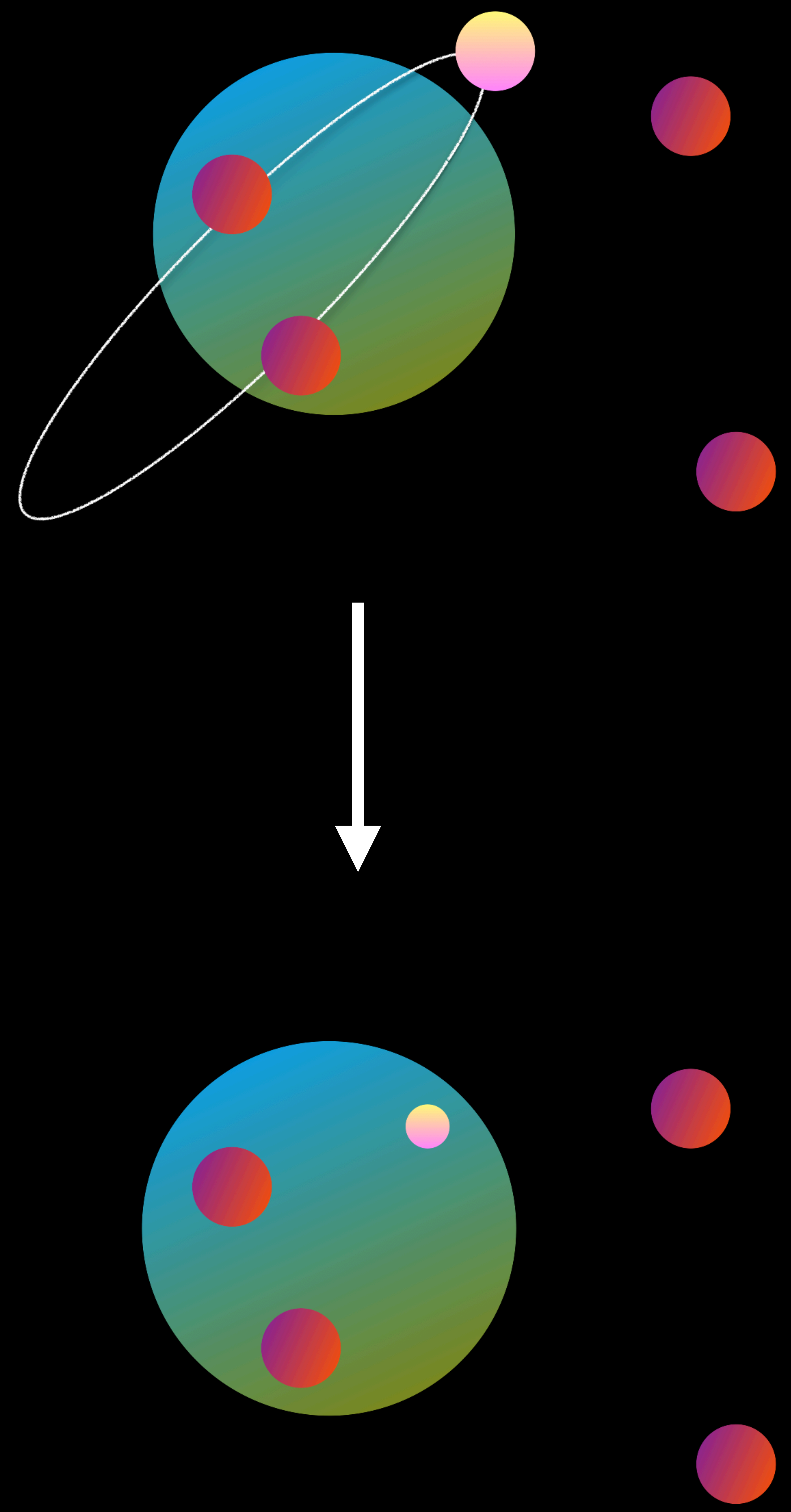
Thank you!

Back-up slides

Tidal stripping



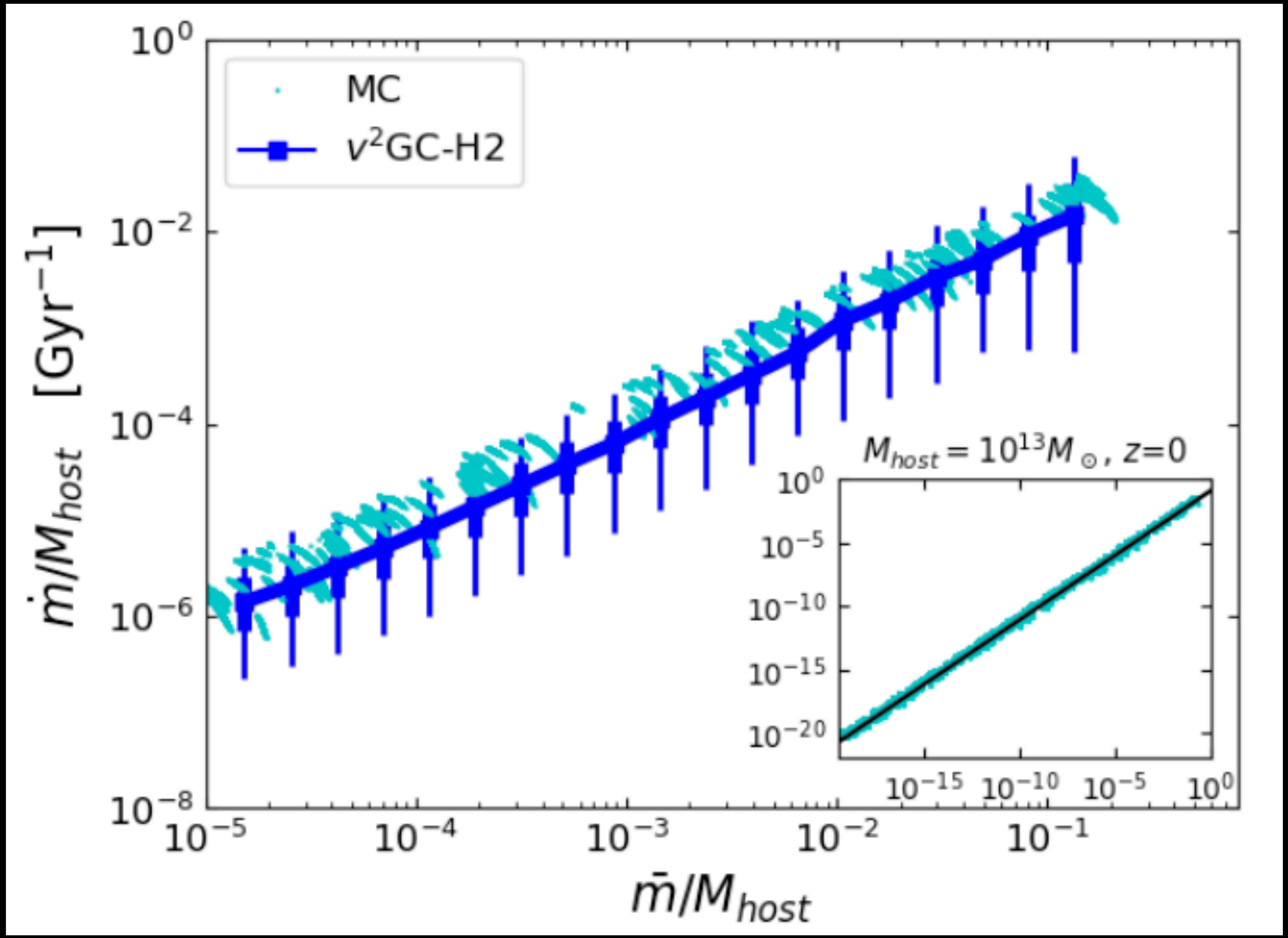
- Van den Bosch et al. (2005) present analytical description for the average mass loss rate of dark matter haloes

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

- 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)

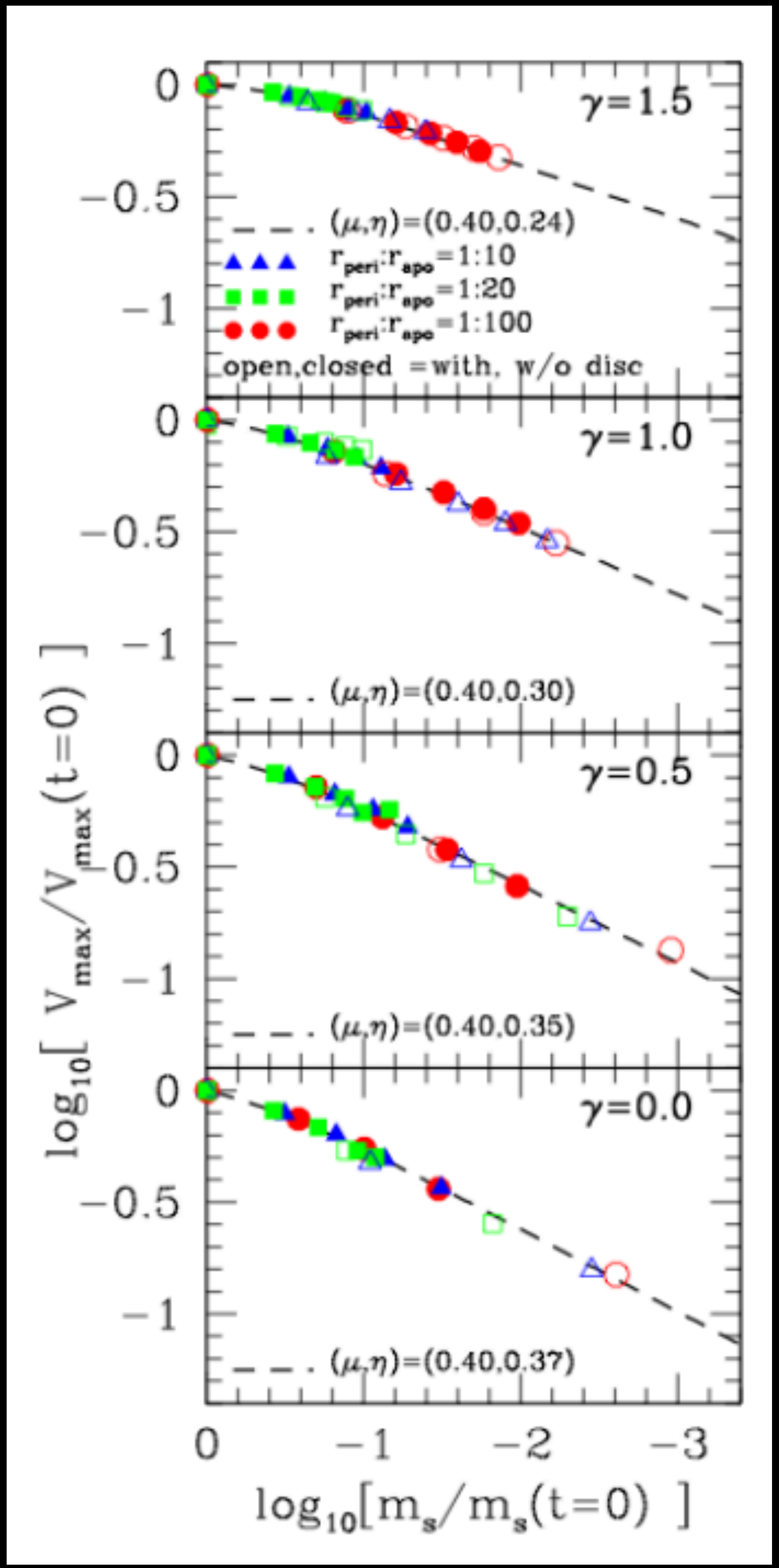
Agreement for CDM with numerical simulations

↓

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)

Evolved subhalo mass function

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$$\frac{dN(m|M,z)}{dm} = \int d\ln m_a \int dz_a \underbrace{\frac{d^2N}{d\ln m_a dz_a}}_{\text{EPS}} \times \int dc_a \underbrace{P(c_a|m_a,z_a)}_{\text{Log-normal distribution for concentration}} \underbrace{\delta(m - m(z|m_a,z_a,c_a)}_{\text{Mass-loss}},$$

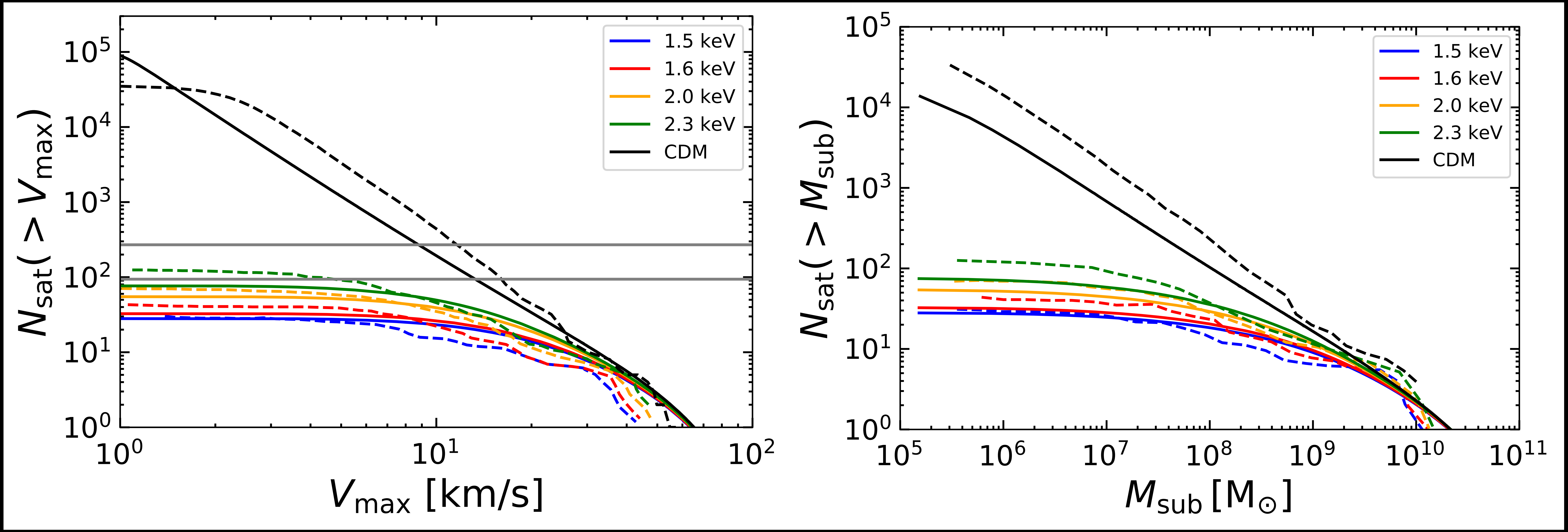
EPS

Mass-loss

Log-normal distribution for concentration

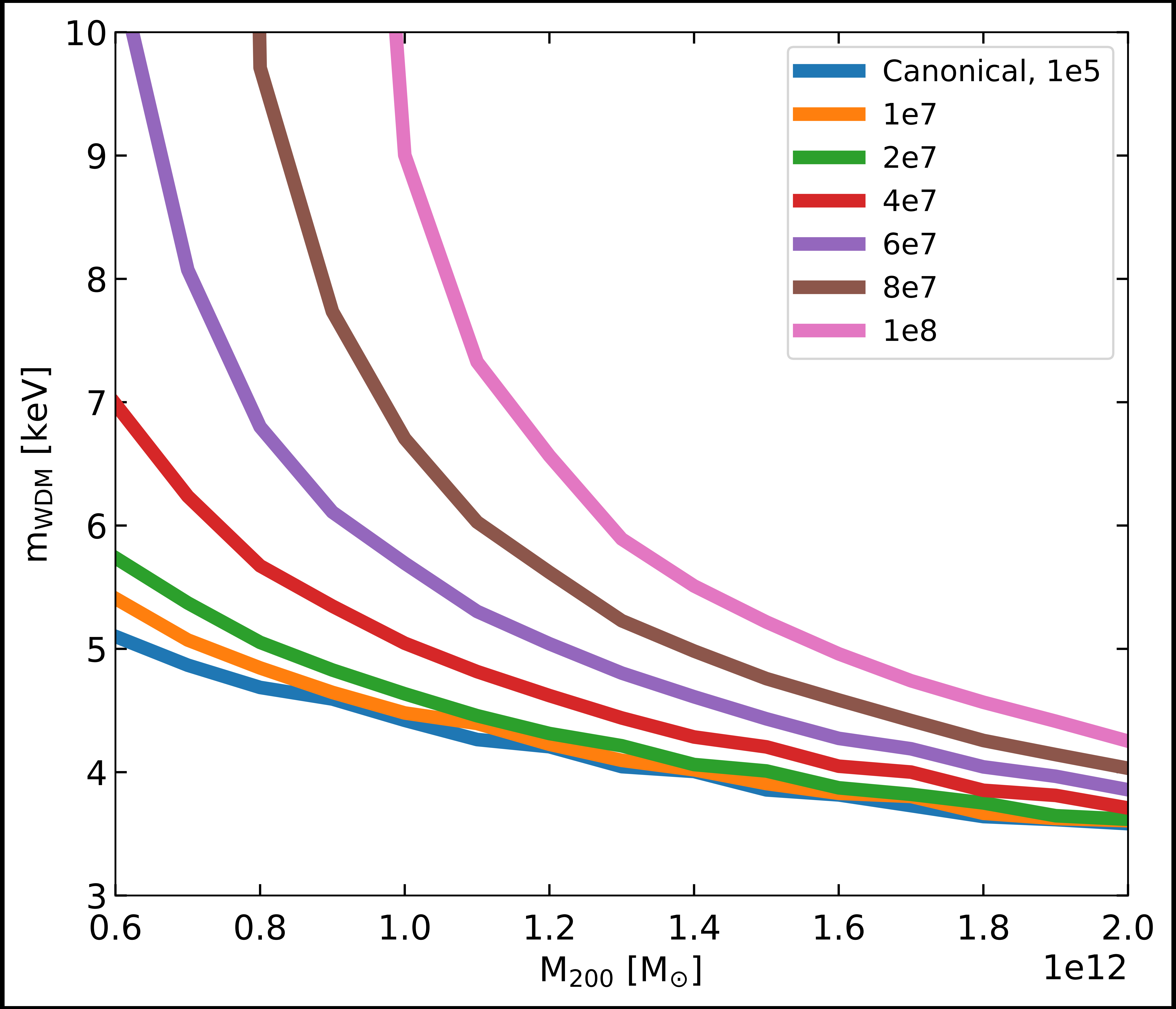
Comparison with numerical simulation

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



Dekker et al. (2021)

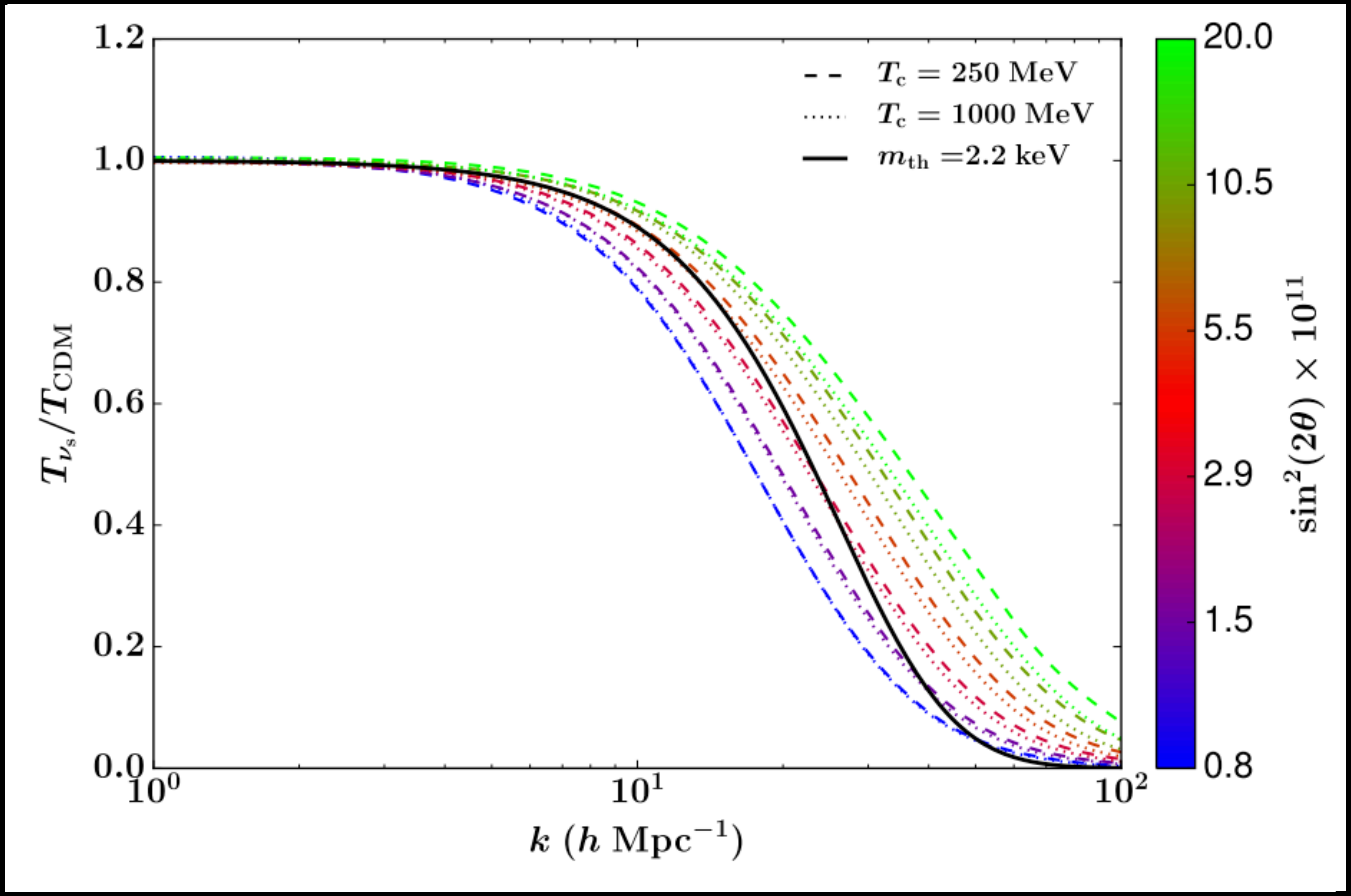
Minimum peak mass



Dekker et al. (2021)

Matter Power Spectrum

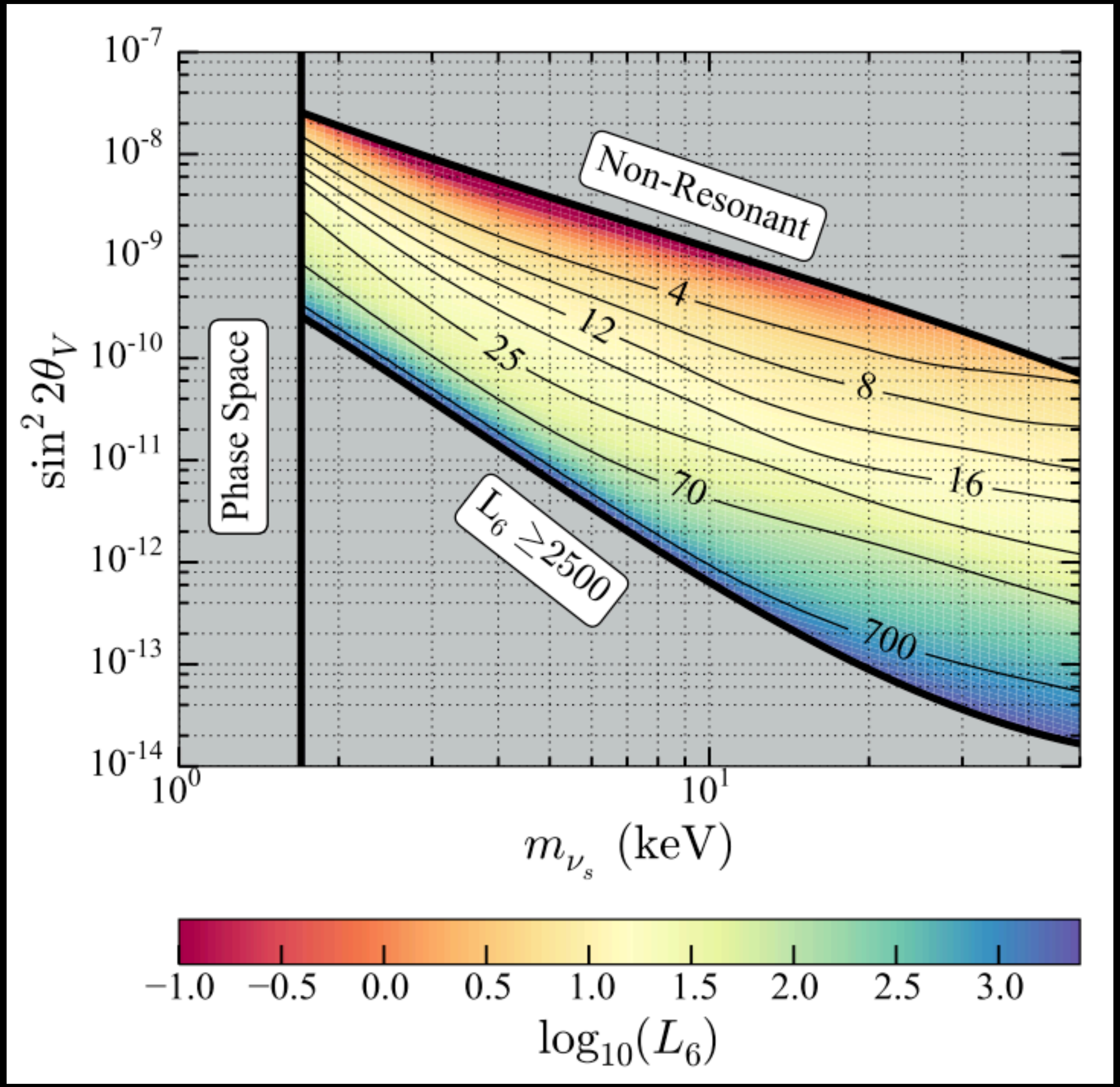
Sterile neutrino (Venumadhav et al. (2015))



- 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)

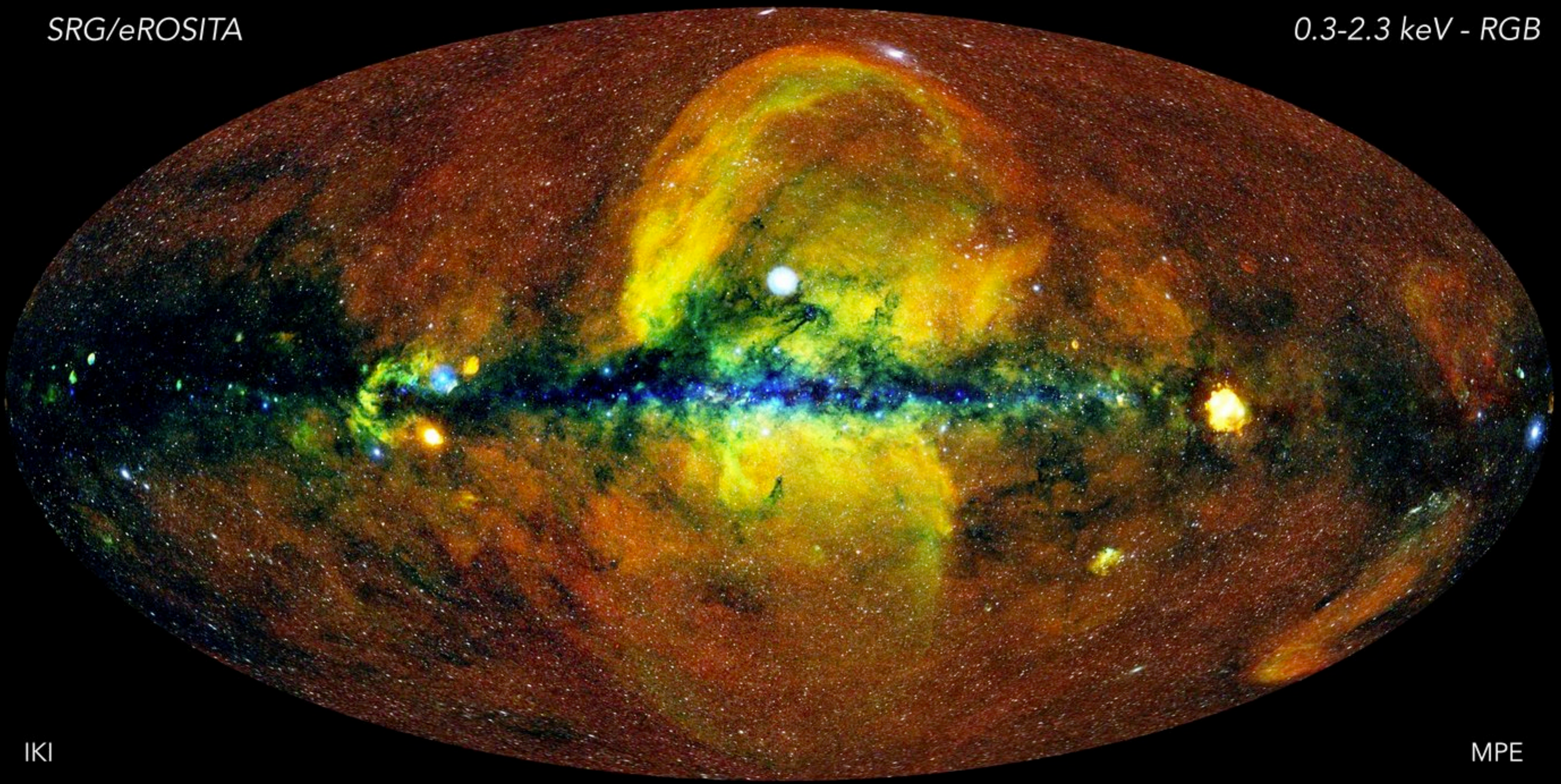
Matter Power Spectrum

Cherry et al. (2017)



For each set of parameter $(\sin^2(2\theta), m_{\nu_s})$ scan over lepton asymmetry to get the correct dark matter abundance

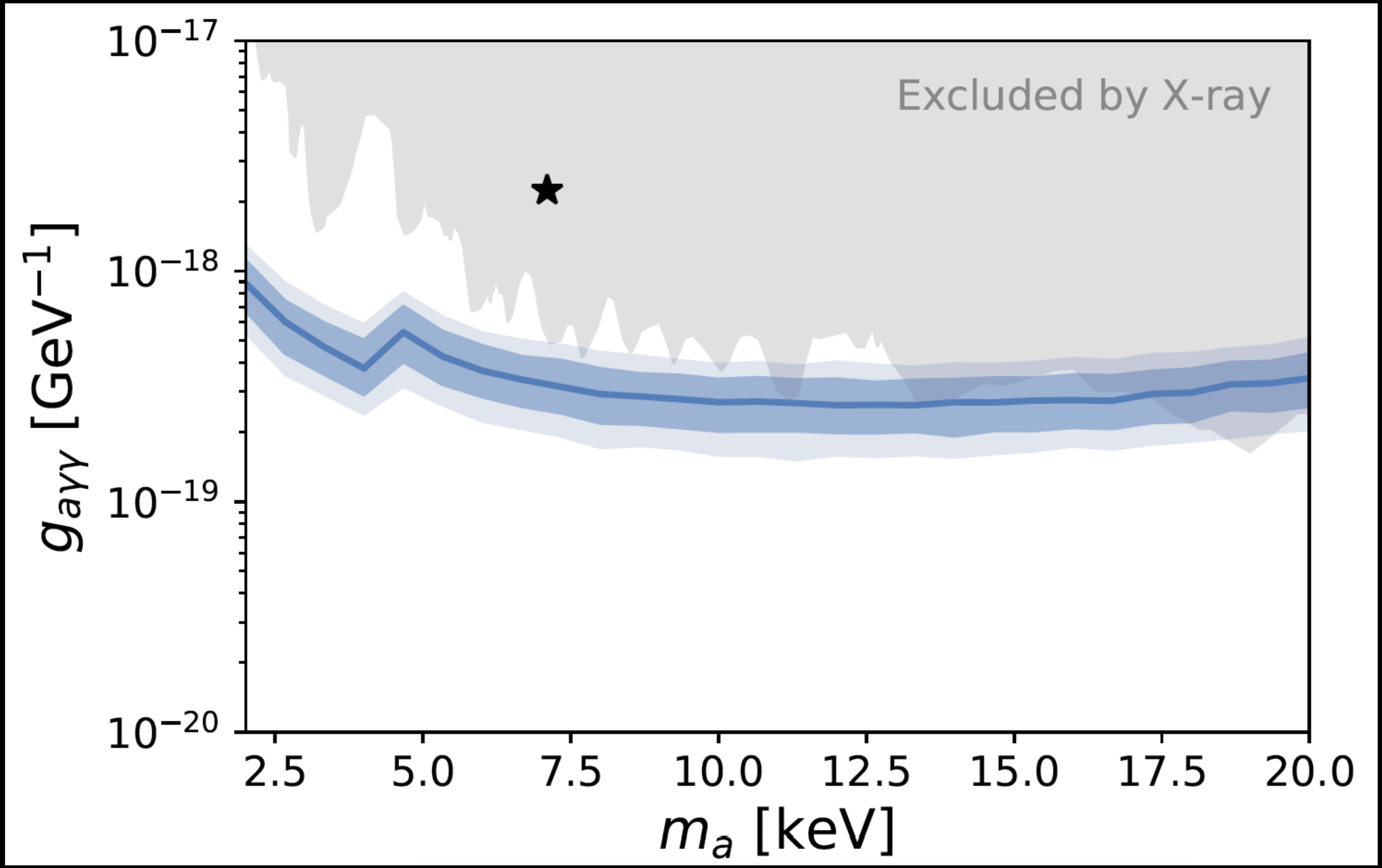
- First all-sky X-ray mission since ROSAT
- ~25 times better sensitivity
- Good energy/angular resolution *(Predehl et al. 2021)*
- Launched July 2019



Axion-like particle dark matter

Median, 68% and 95%

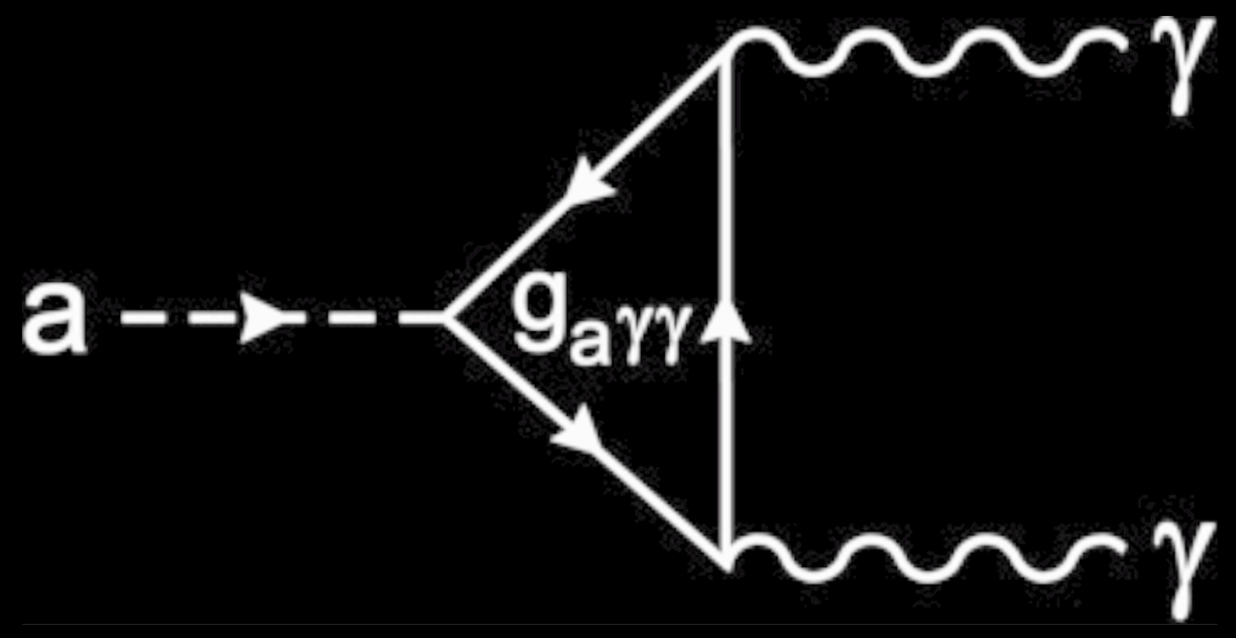
Excluded regions



Dekker et al. (2020)

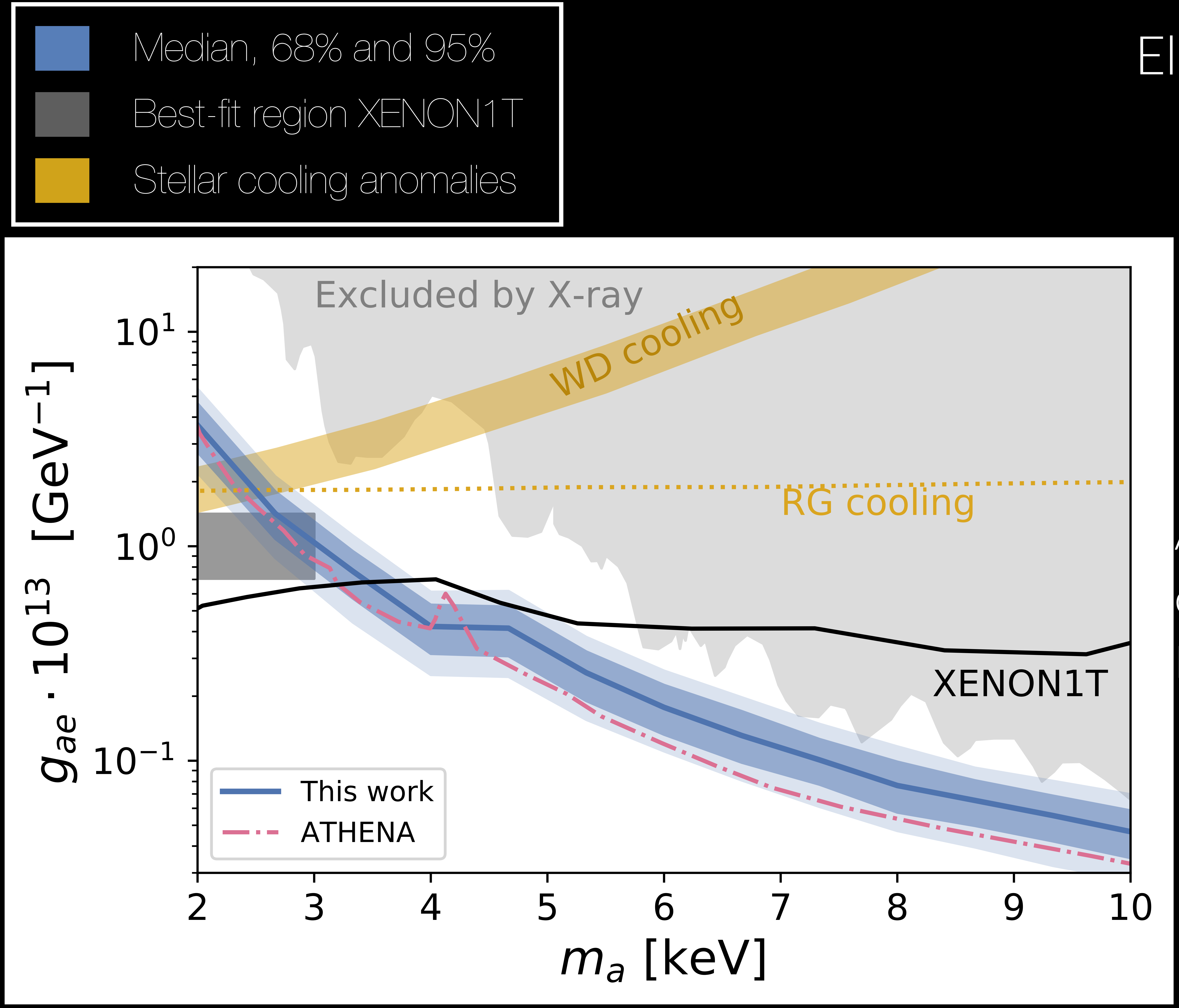
Applicable to any DM candidate that produces monochromatic X-ray line

ALP well motivated by theories beyond the SM



Axion-like particle dark matter

Electron coupling



Dekker et al. (2020)

XENON1T excess explained by ALP at

↓

ALP coupling to SM particles is already constrained by X-ray observations: Photon production needs to be suppressed

↓

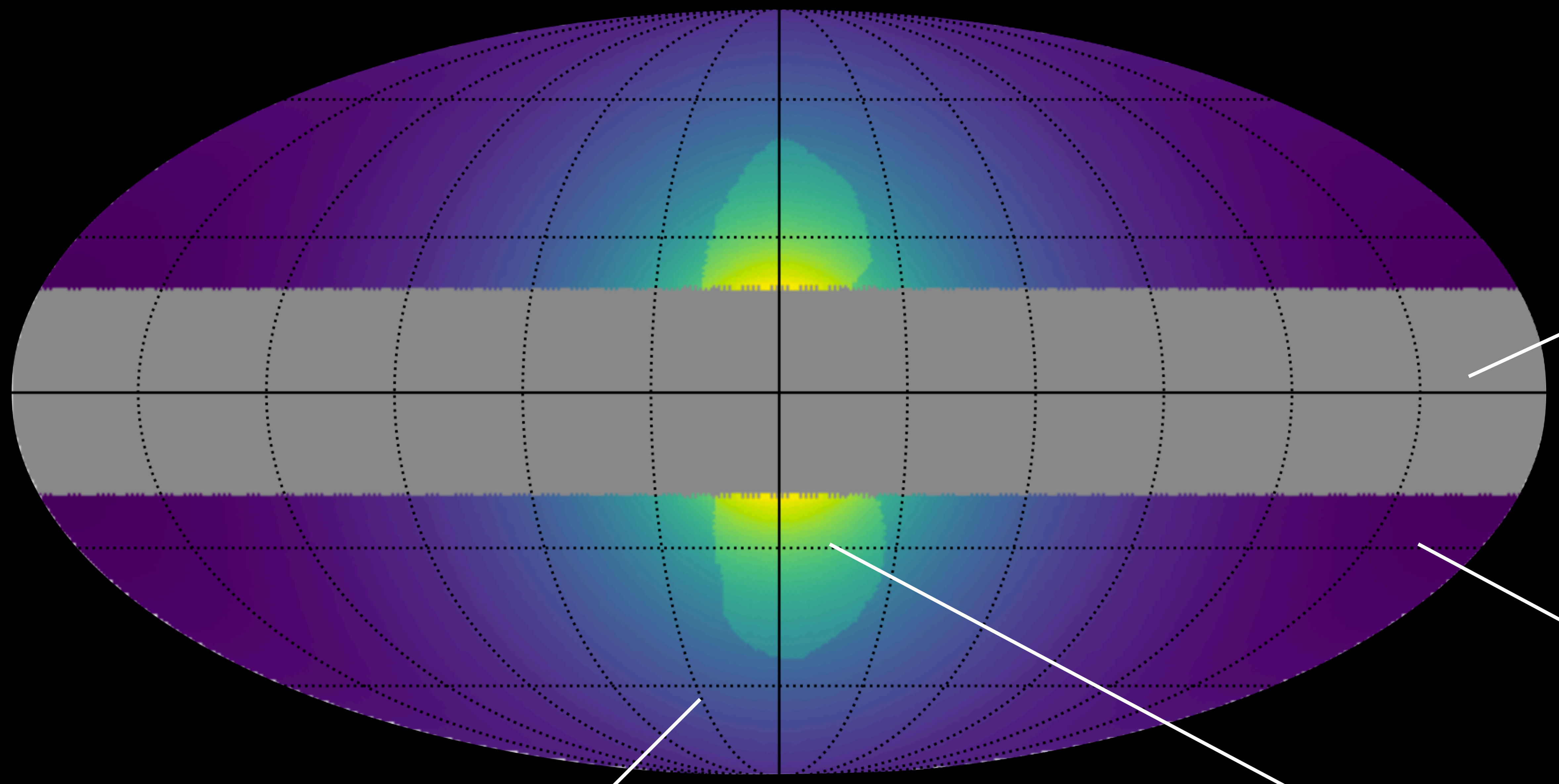
Anomaly free symmetry model

(Takahashi et al (2020),

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)

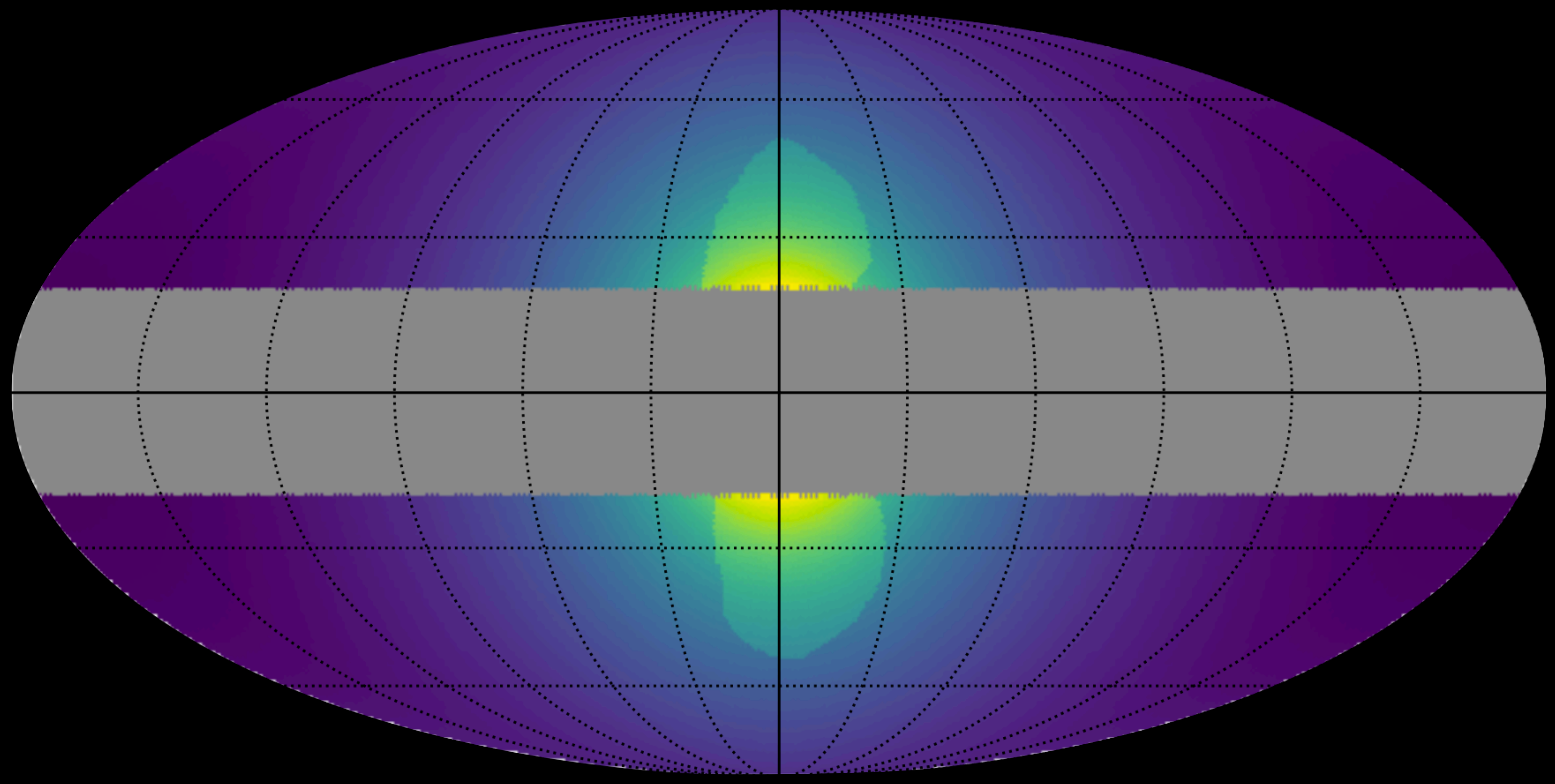
Isotropic components

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

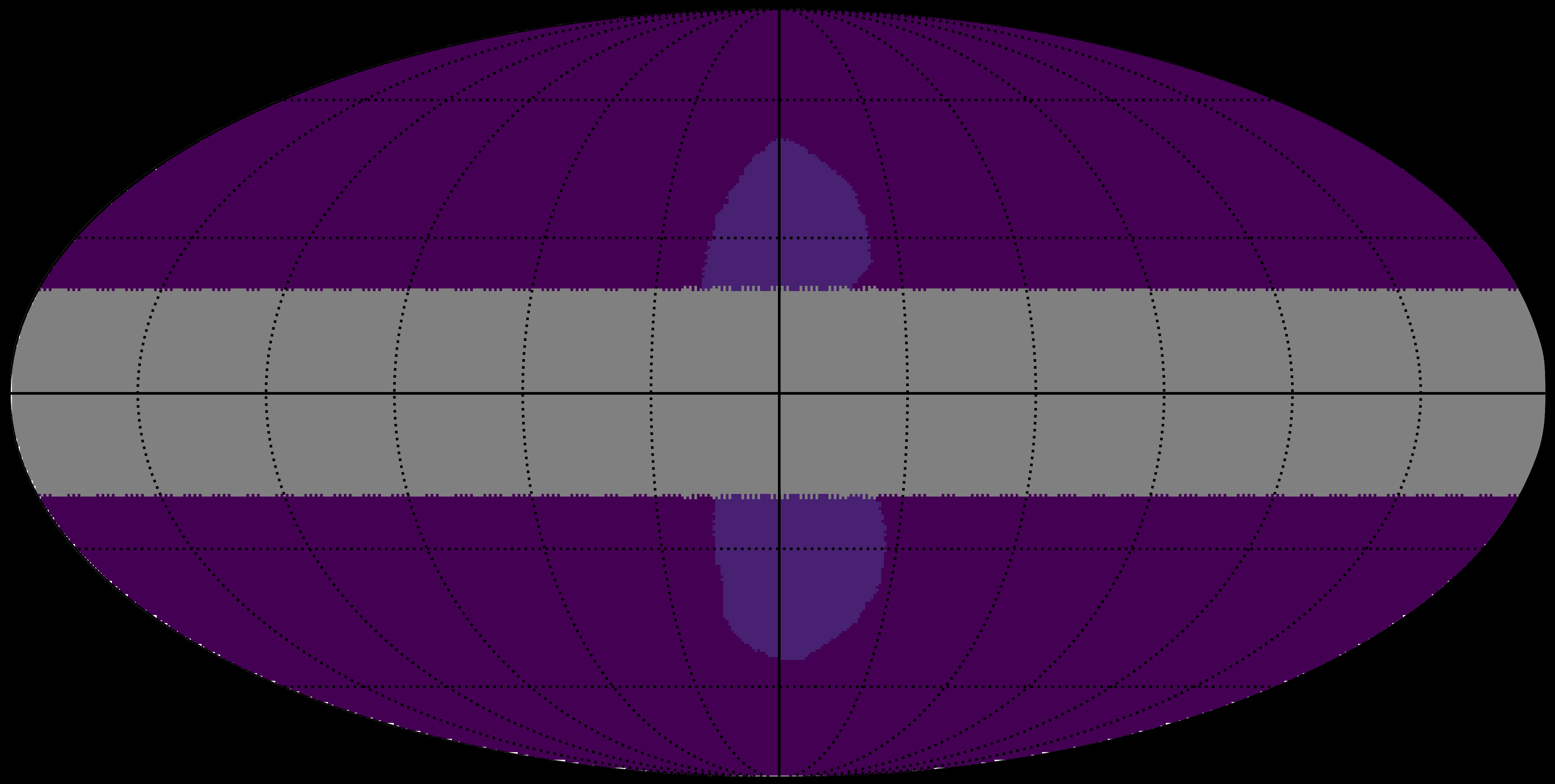
X-ray count sky maps

2.5 ks eROSITA exposure

Model



Mock data sets



Generate mock data sets

Joint likelihood analysis — Obtain upper limits at 95% CL