Constraints on the properties of νMSM dark matter using the satellite galaxies of the Milky Way

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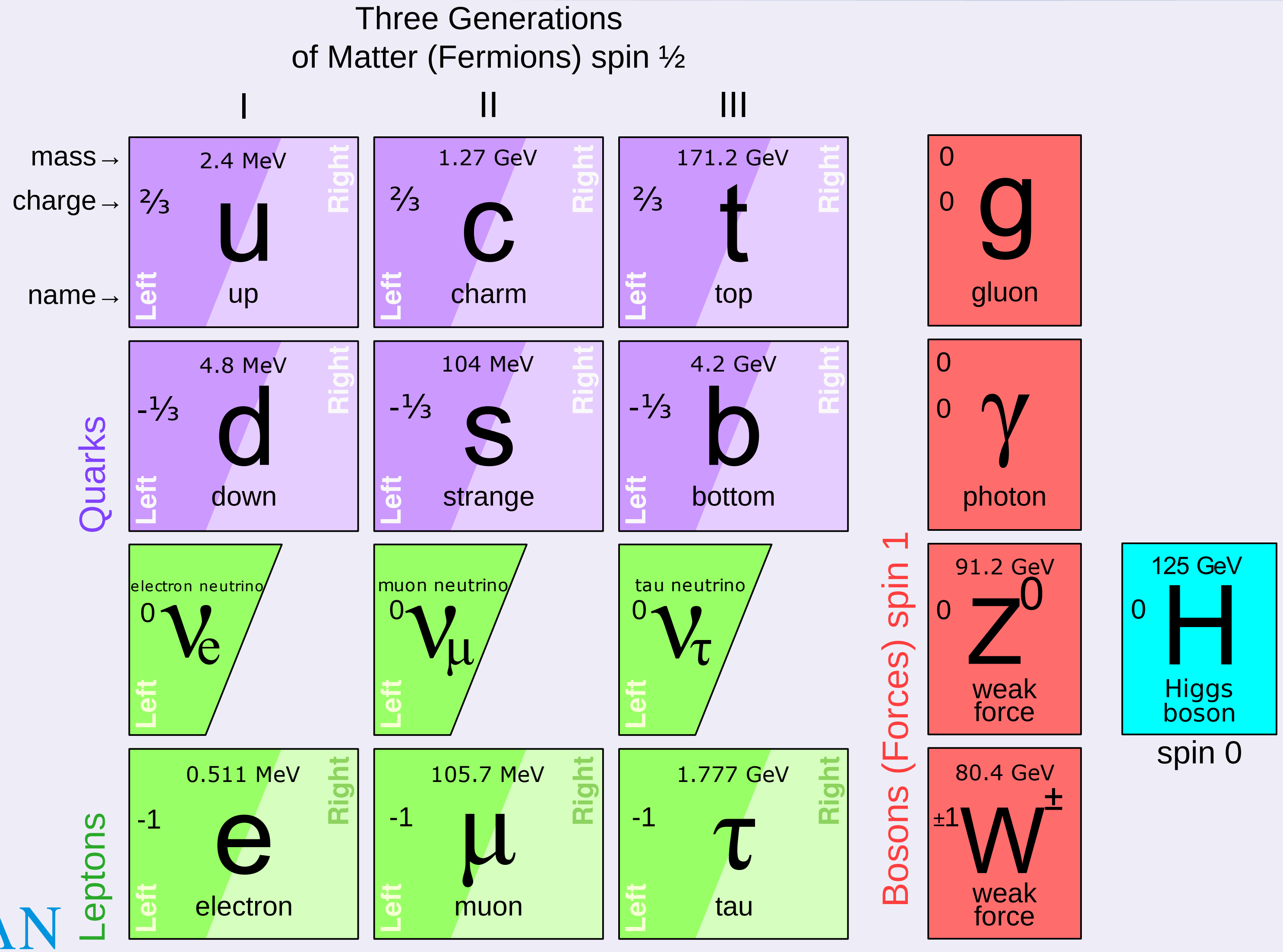
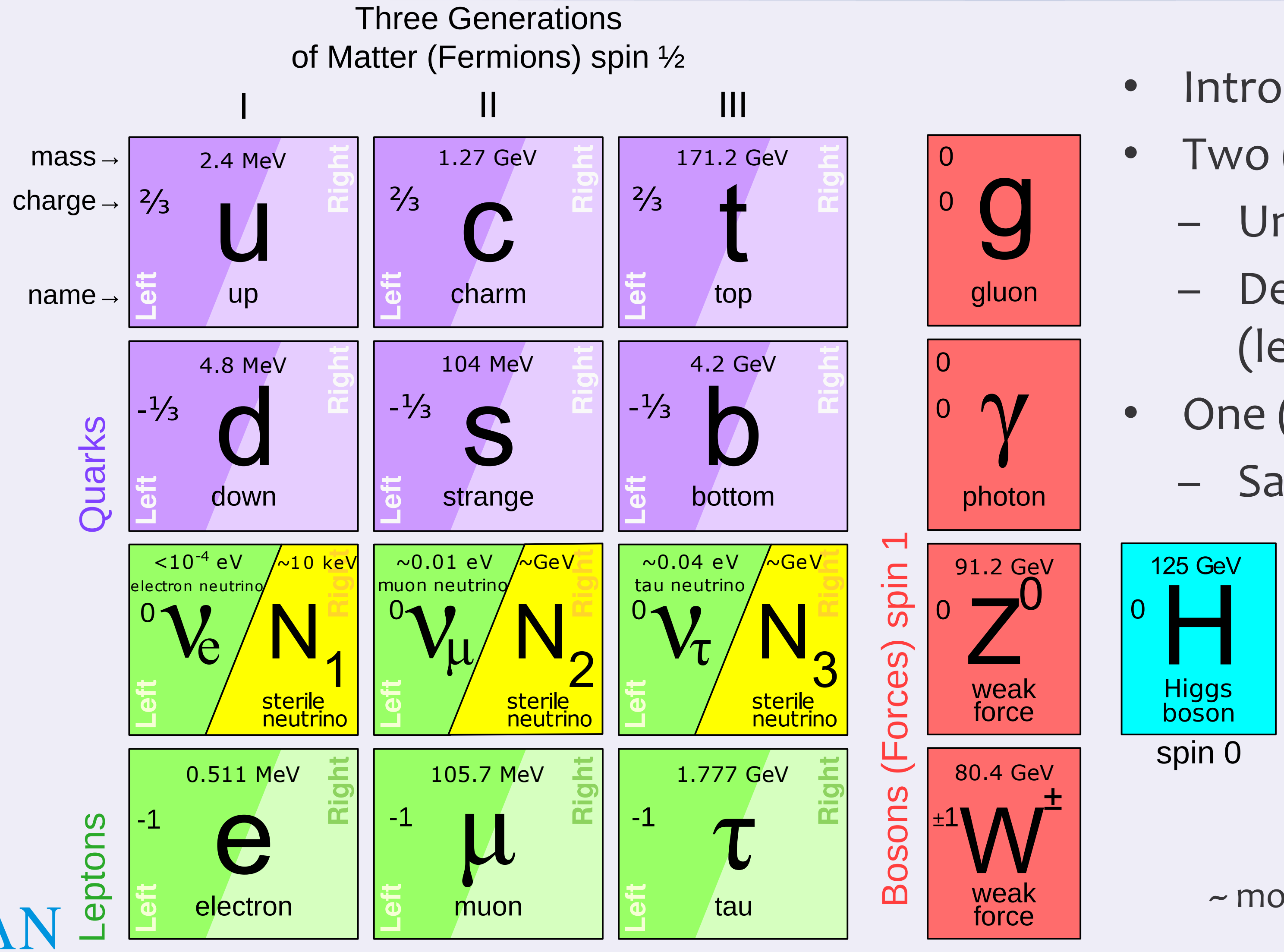
What is the νMSM*?

*Neutrino Minimal extension of the Standard Model



Adapted from Gninenko et al. (2012); arXiv: 1301.5516

What is the νMSM*?



*Neutrino Minimal extension of the Standard Model

- Introduces three massive sterile neutrinos
- Two (N_2 and N_3) are ~GeV scale
  - Unstable/short-lived
  - Decay into anti-leptons (lepton asymmetry)
- One (N_1) ~keV scale
  - Satisfies most requirements for DM candidates
    - Long-lived but unstable. Can radiatively decay into photon and active neutrino:

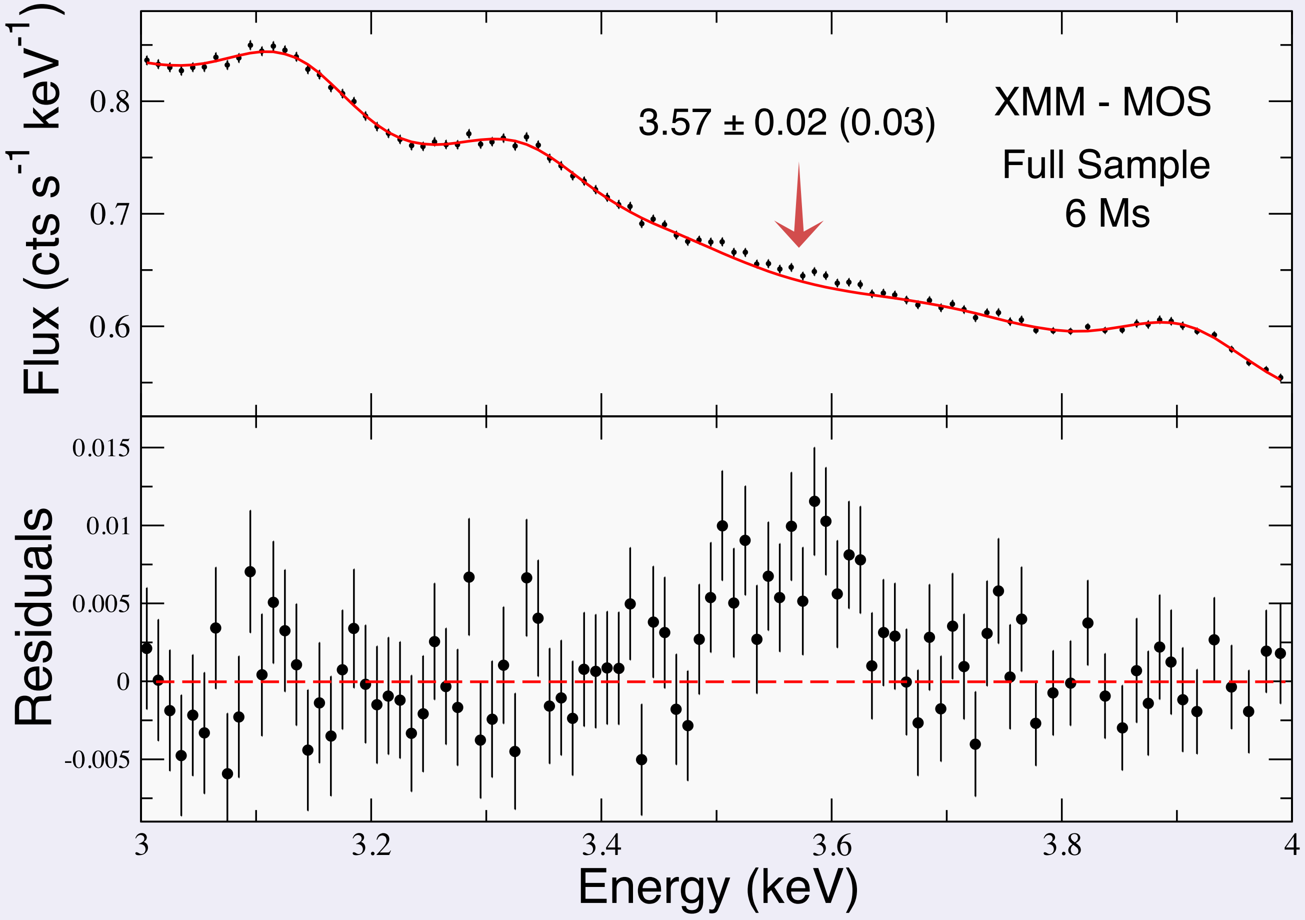
$$N_1 \rightarrow \gamma \upsilon_\alpha$$

~ monochromatic line in X-rays

Adapted from Gninenko et al. (2012); arXiv: 1301.5516

Unexplained problems the νMSM could solve

- Small active neutrino masses
- Leptogenesis
  - Lepton asymmetry resonantly enhances production of sterile neutrinos
  - Parametrized as *effective* mixing angle, θ_e
- Baryogenesis
  - Lepton asymmetry converts to baryon asymmetry
- Could explain 3.55 keV X-ray excess
  - Observed emanating from DM-dominated systems
  - No known astrophysical origin*
  - JAXA *XRISM* has better resolution

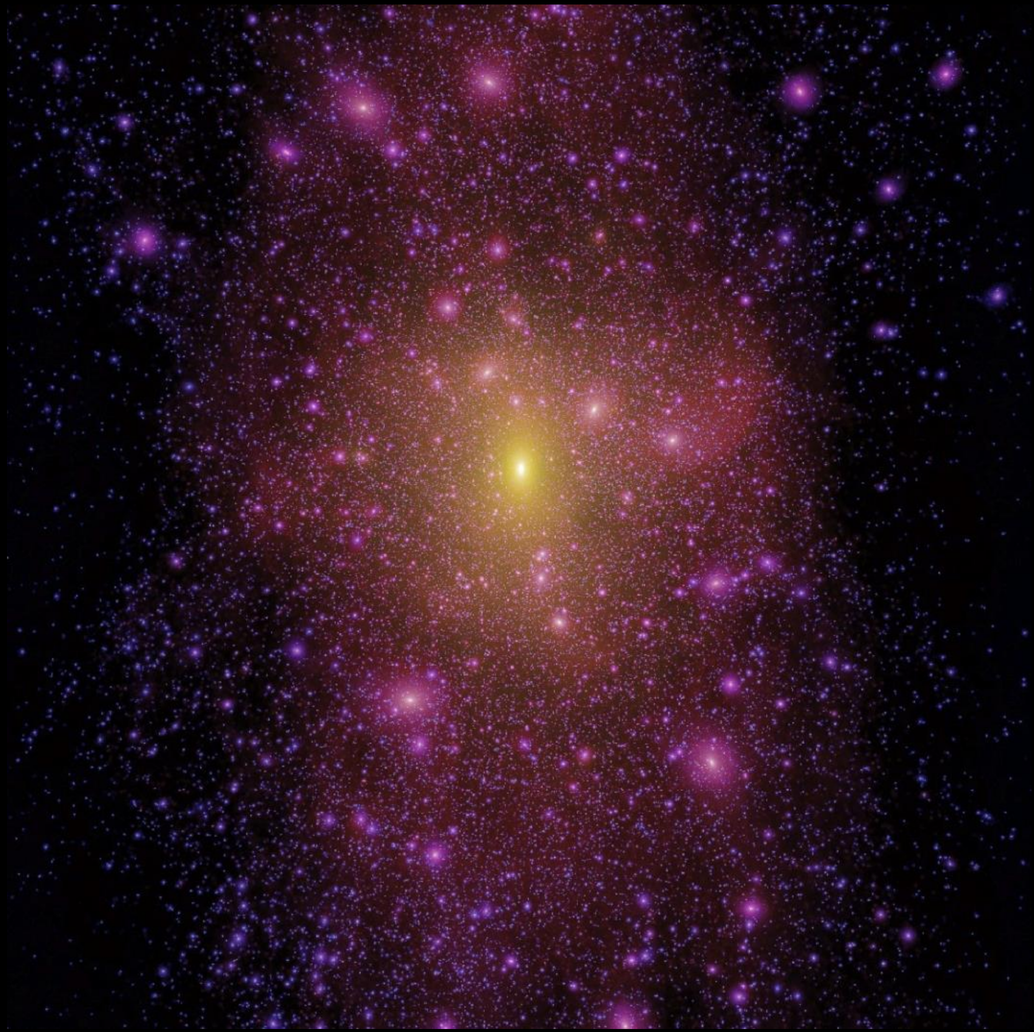


Adapted from Bulbul et al. (2014); arXiv: 1402.2301

*Perhaps charge exchange between sulphur ions and neutral ISM

Substructure and warm DM

Cold DM



Warm DM

Lovell et al. (2014); arXiv: 1308.1399

Assessing DM model viability

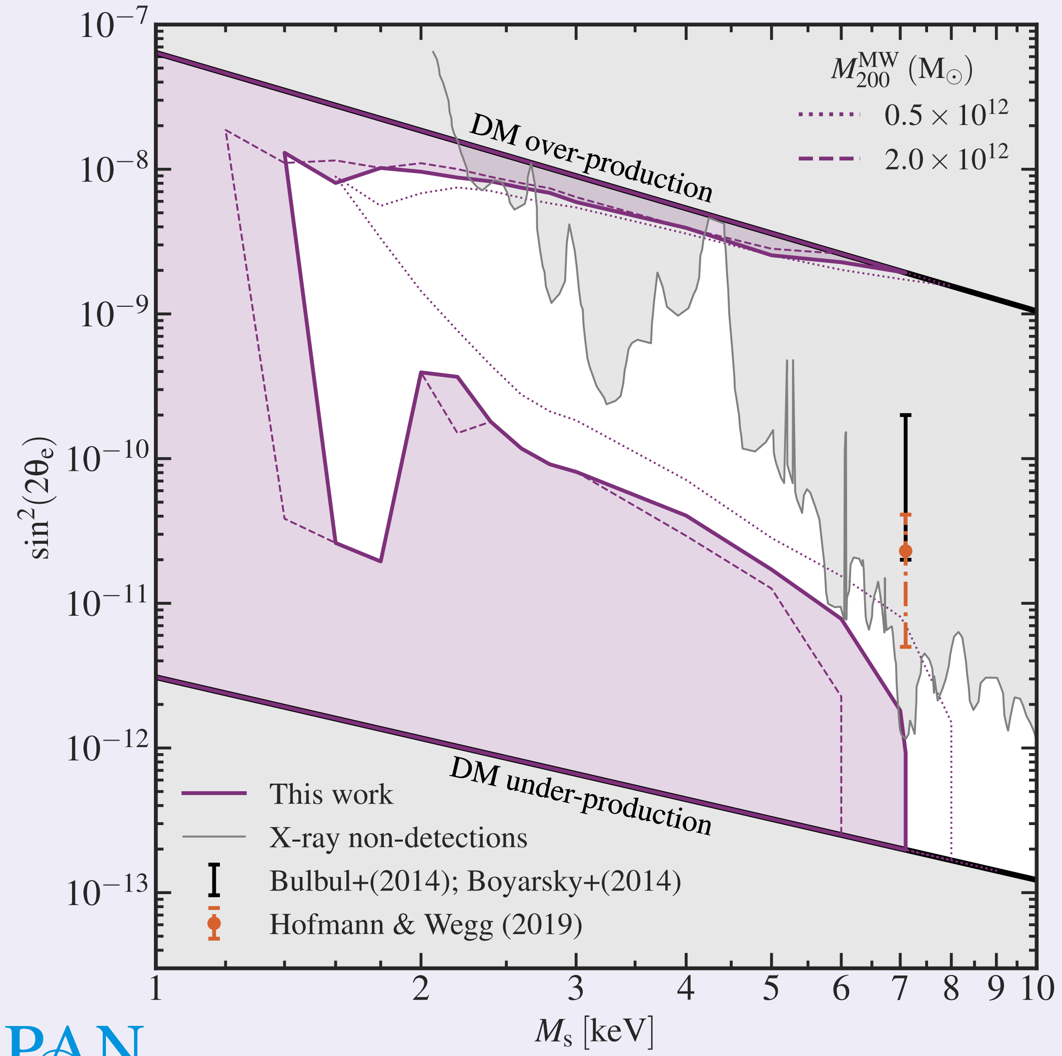
Need two ingredients:

- Total number of satellite galaxies around Milky Way (LSST will tell us this!)
  - Current surveys incomplete in depth and sky coverage
  - Model survey response and correct for incomplete observations to infer total population

Newton et al. (2018); arXiv: 1708.04247

- Predictions of the number of satellite galaxies in a Milky Way mass halo in a given DM model
  - Extended Press-Schechter formalism
  - Prescriptions to populate substructure with galaxies
    a. Assume all substructure hosts a galaxy
    b. Apply galaxy formation models

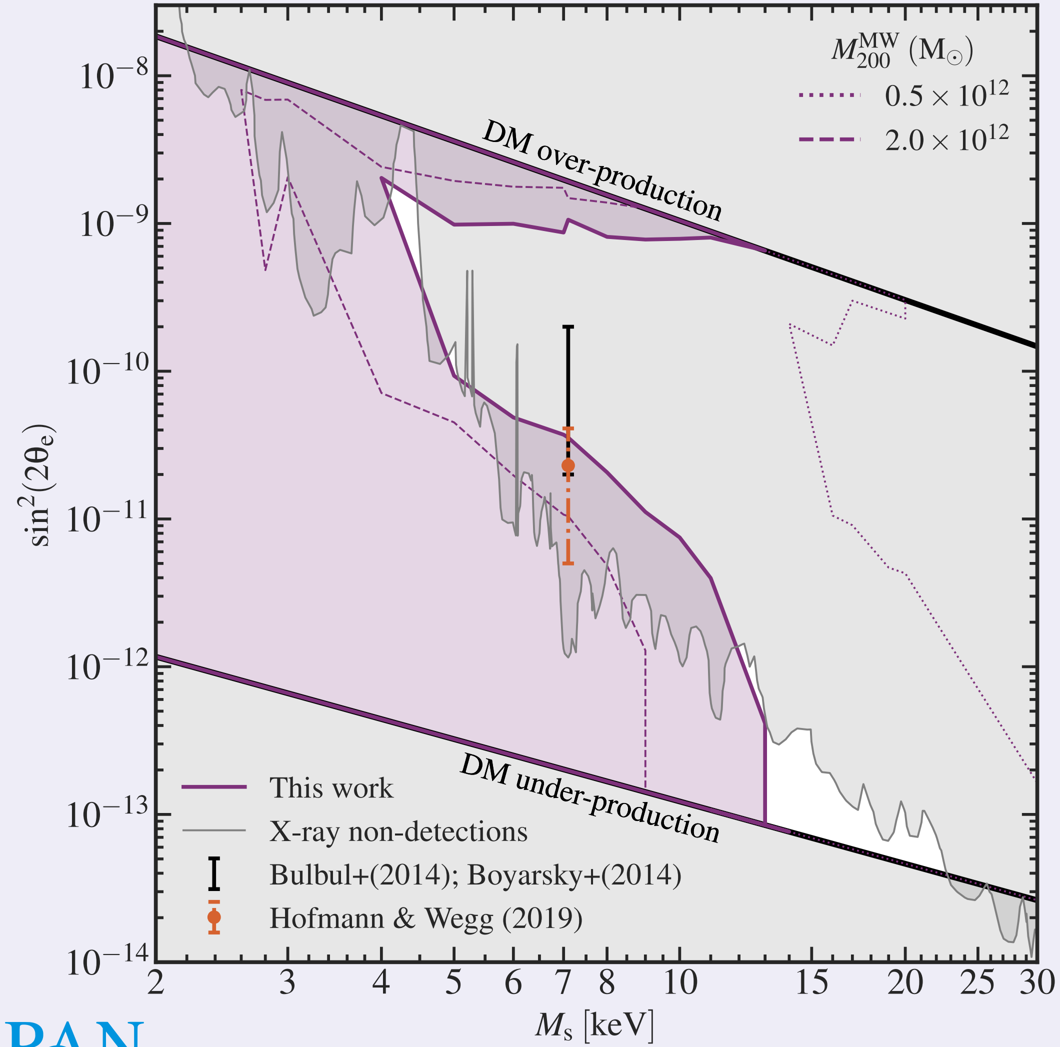
Constraints from substructure counts



- Assumptions
  - $N_{sat}^{MW} = 124^{+40}_{-27}$ (68% confidence; Newton+2018)
  - $M_{200}^{MW} = 1.17^{+0.21}_{-0.15} \times 10^{12}\ M_\odot$ (68% confidence; Callingham+2019)
  - *All* substructure hosts a galaxy
- Independent of galaxy formation physics
- Shaded area ruled out with ≥ 95% confidence
- More stringent constraints at lower M_{200}^{MW}
- Cannot exclude 7.1 keV νMSM (favoured by X-ray flux measurements) using satellite counts alone

O. Newton et al.; arXiv: 2408.16042

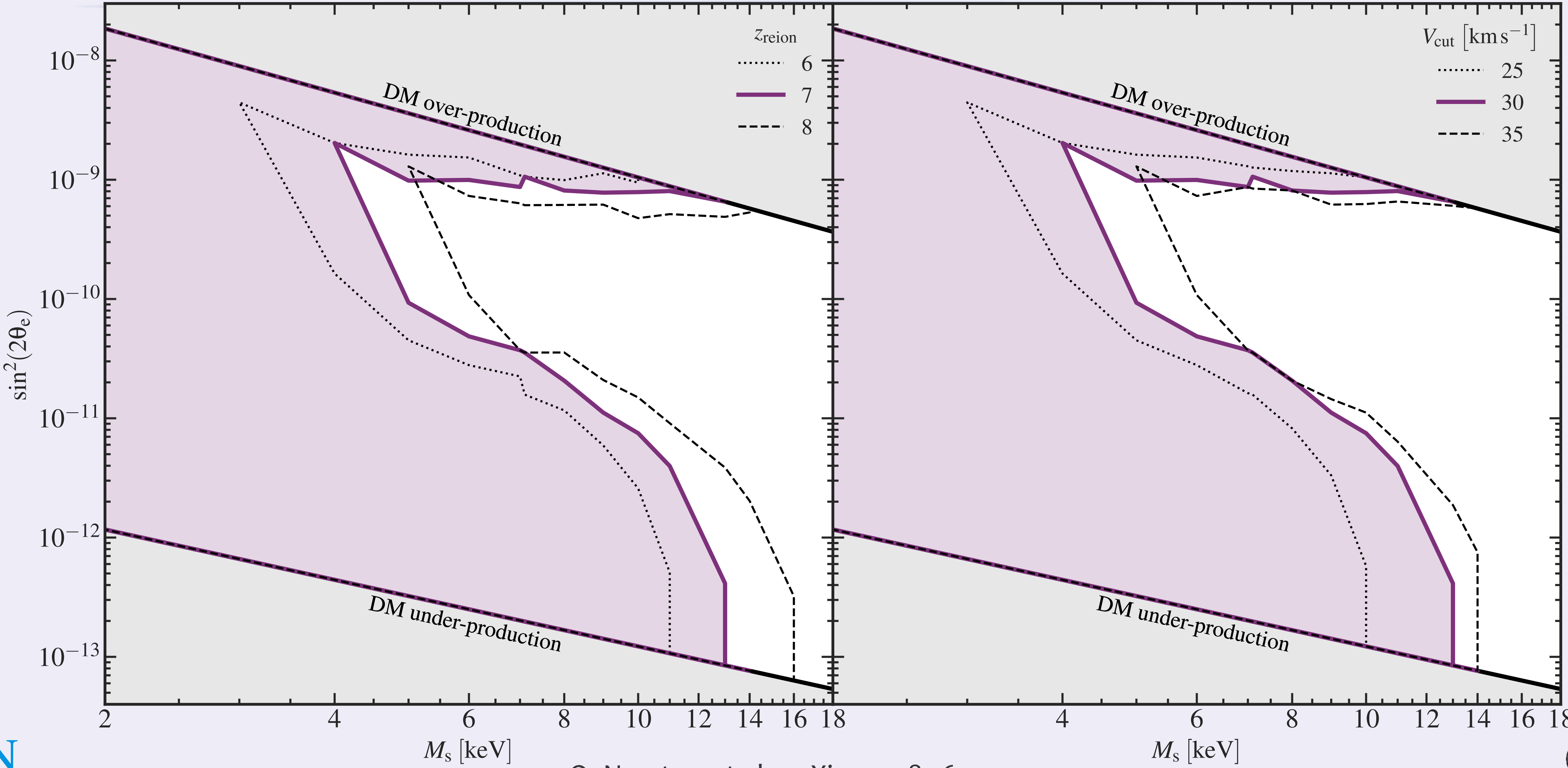
Constraints from galaxy formation



- Populate subhaloes with galaxies using Lacey+(2016) Galform model
- Reionization parametrized by:
  - z_{reion}: Redshift at which reionization is complete
  - V_{cut}: Gas cooling shuts down in haloes with $V_{\mathrm{circ}} < V_{\mathrm{cut}}$ at $z < z_{\mathrm{reion}}$
- Fiducial choices: $z_{\mathrm{reion}} = 7, V_{\mathrm{cut}} = 30\ \mathrm{km\ s^{-1}}$
  - Rule out part of favoured $M_s = 7.1$ keV parameter space with satellite counts alone
- Can explore how changing reionization affects constraints

O. Newton et al.; arXiv: 2408.16042

Changing reionization



O. Newton et al.; arXiv: 2408.16042

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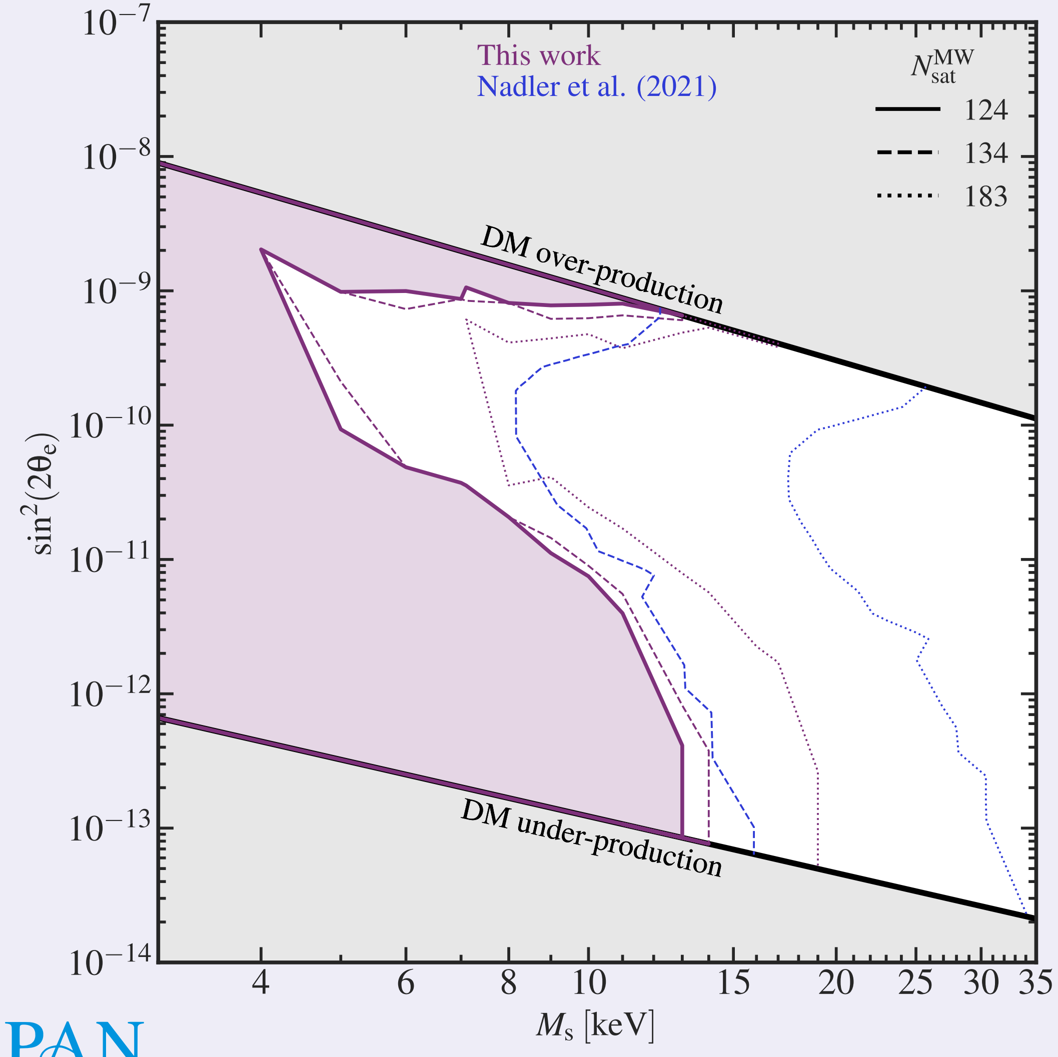
Sensitivity to number of MW satellites



- Several recent estimates of $N_{\rm sat}^{\rm MW}$ exist (Newton+2018; Nadler+2020)
- Nadler+2021
  - Subhalo Abundance Matching + analytic prescriptions to obtain thermal relic constraints
  - Convert thermal relic constraints to νMSM by matching half-mode mass between models
  - Compute νMSM power spectra based on Venumadhav+2016 momentum distributions
    - Systematically warmer than what we use (Ghiglieri & Laine 2015)
  - Differences in the number of orphans recovered

O. Newton et al.; arXiv: 2408.16042

Conclusions

- Non-linear regime is a powerful discriminator of viable DM models
  - Satellite count constraints will be affected by future LSST discoveries
- νMSM is a physically motivated extension to Standard Model. Explains:
  - Small masses of active neutrinos
  - Primordial lepton & baryon asymmetries
  - 3.55 keV X-ray excess
- We exclude parametrizations of MSM with:
  - $M_s \leq 1.4$ keV independently of galaxy formation physics
  - $M_s \leq 4$ keV assuming $z_{\rm reion} = 7$ and $V_{\rm cut} = 30$ km s^{-1}
  - $M_s = 7.1$ keV and $\sin^2 2\theta_e \leq 4 \times 10^{-11}$ or $\sin^2 2\theta_e \geq 10^{-9}$
- JAXA *XRISM* satellite will confirm (or refute) existence of the 3.55 keV line

O. Newton et al.; arXiv: 2408.16042

Requirements for dark matter candidates*

*Assuming a single particle species

Astrophysics

- Interacts via gravity
- No dependence on any other long-range forces on large astrophysical scales
- Must match observed relic abundance
- Non-relativistic at matter–radiation equality
- Dissipationless and collisionless (maybe)
- Large-scale behaviour similar to that predicted by ΛCDM/observed

Particle physics

- Very long-lived
- Electrically and colour-neutral
- Very weakly interacting with Standard Model particles
- Self-interactions/annihilations allowed
- Non-relativistic at early times

Resonant production

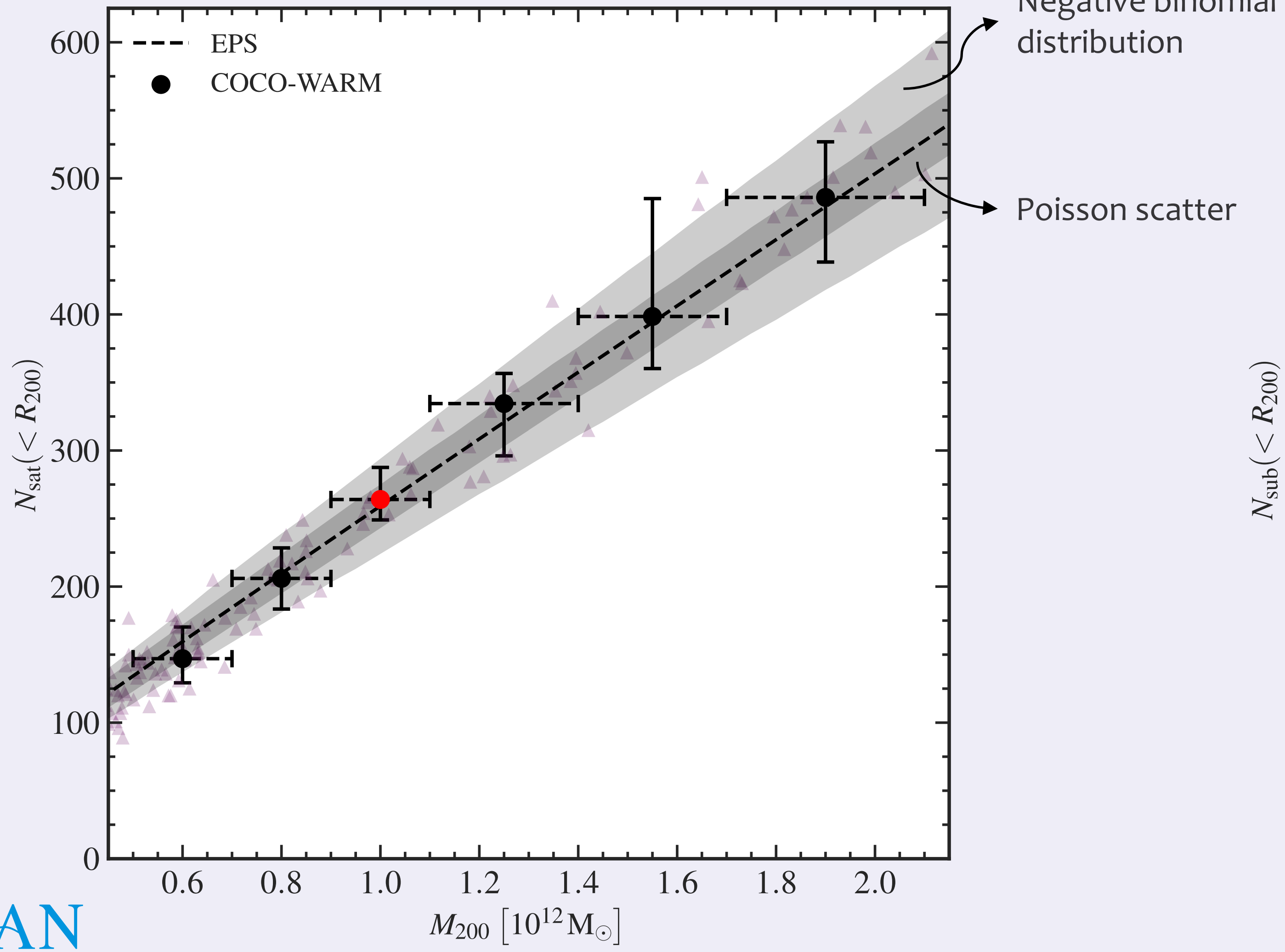
- Oscillation parameters of active neutrinos in a medium diverge from those *in vacuo*
  - Mikheyev–Smirnov–Wolfenstein (MSW) effect
- Analogous mechanism affects active–sterile mixing
  - Controlled by size of lepton asymmetry in primordial plasma

$$L_6 = 10^6 \frac{\left(n_{\nu_\mathrm{e}} - n_{\bar{\nu}_\mathrm{e}}\right)}{s}$$

  - Alternatively, can parametrize this as an *effective* mixing angle, θ_e
  - Lepton asymmetry resonantly enhances sterile neutrino production
  - Can affect momentum distribution of sterile neutrinos

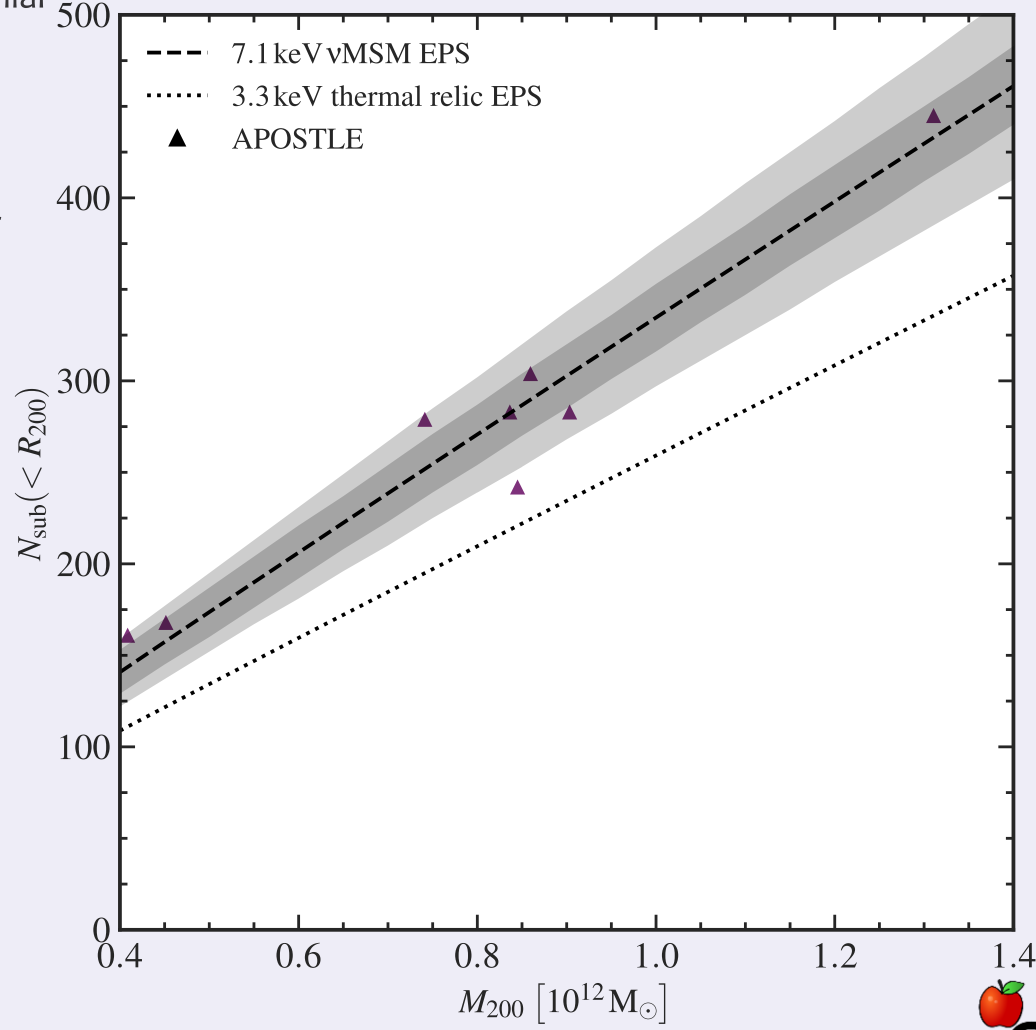
Estimates of substructure abundance

3.3 keV thermal relic



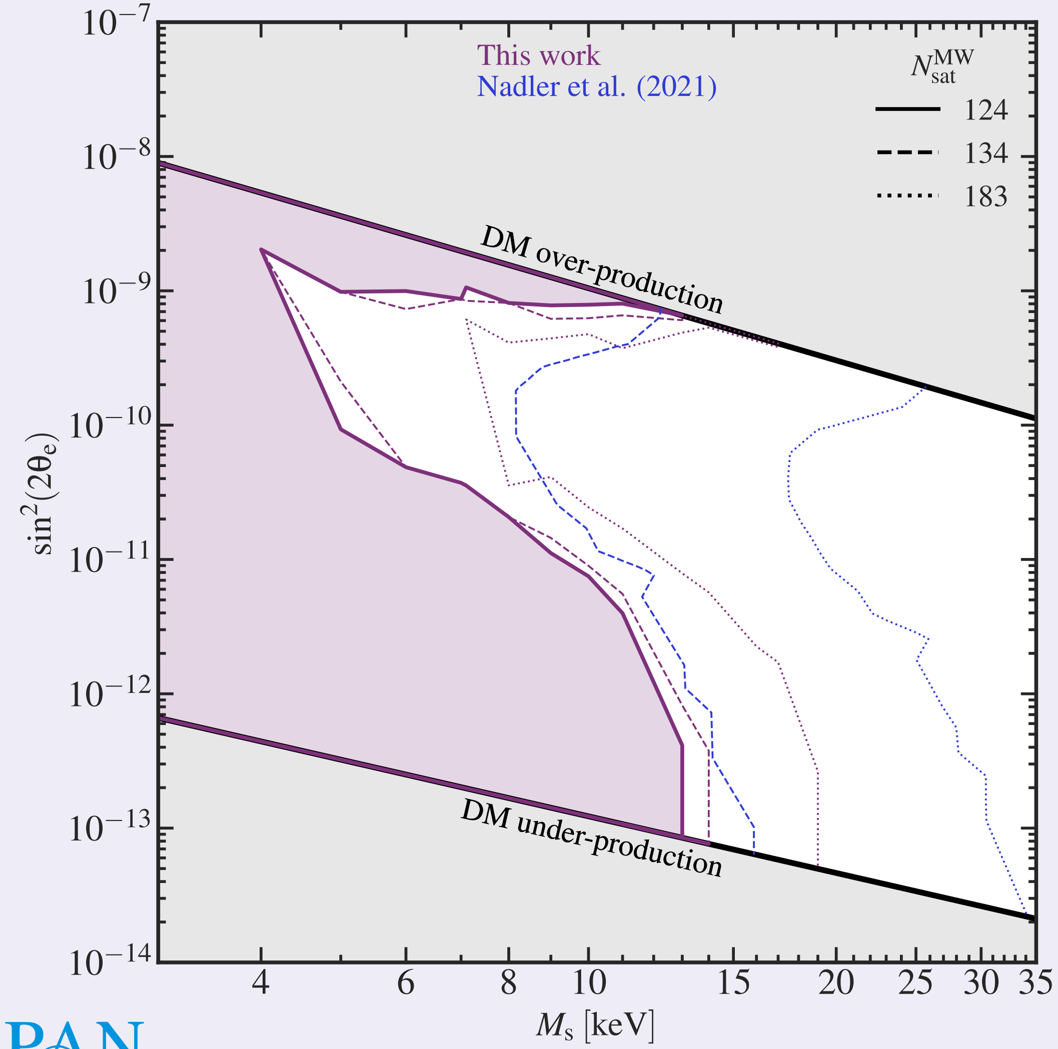
Newton et al. (2021); arXiv: 2011.08865

7 keV νMSM, $\sin^2 2\theta \approx 10^{-10}$



O. Newton et al.; arXiv: 2408.16042

Sensitivity to number of MW satellites



- Several recent estimates of $N_{\mathrm{sat}}^{\mathrm{MW}}$ exist (Newton+2018; Nadler+2020)
- Nadler+2021
  - Subhalo Abundance Matching + analytic prescriptions to obtain thermal relic constraints
  - Convert thermal relic constraints to νMSM by matching half-mode mass between models

$$M_{\mathrm{hm}} = \frac{4\pi}{3}\bar{\rho}\left(\frac{\pi}{k_{\mathrm{hm}}}\right)^3$$

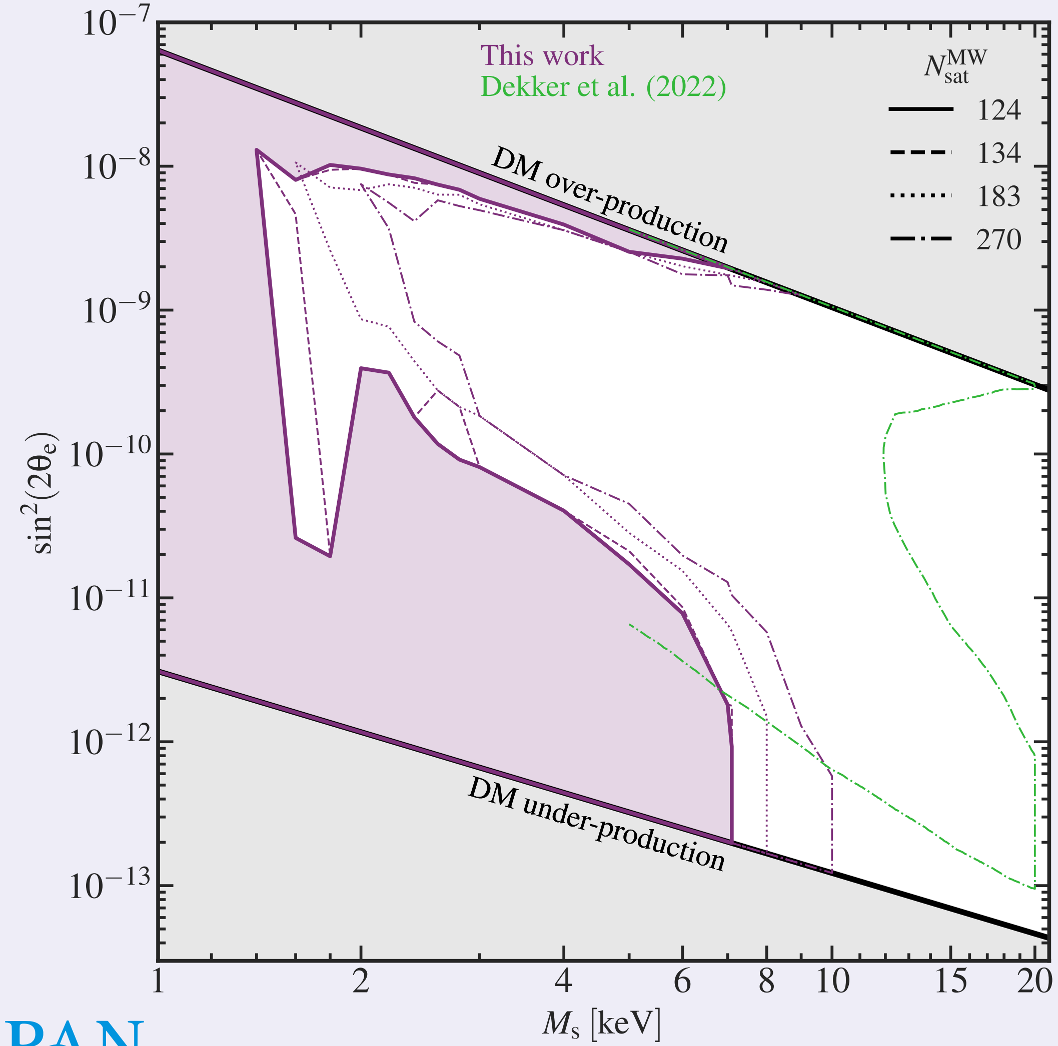
$\bar{\rho}$: Average matter density of the Universe

$$\sqrt{\frac{P_{\mathrm{WDM}}(k_{\mathrm{hm}})}{P_{\mathrm{CDM}}(k_{\mathrm{hm}})}} = 0.5$$

  - Compute νMSM power spectra based on Venumadhav+2016 momentum distributions
    - Consistently warmer than what we use

O. Newton et al.; arXiv: 2408.16042

Other work



- Estimate of $N_{\rm sat}^{\rm MW}$ too high (Nadler+2020)
- Dekker+2022
  - Use EPS
  - Adopt conservative constraint (all subhaloes host galaxies)
  - Also obtain power spectra using Venumadhav+2016 momentum distributions
    - Systematically warmer than ours

O. Newton et al.; arXiv: 2408.16042

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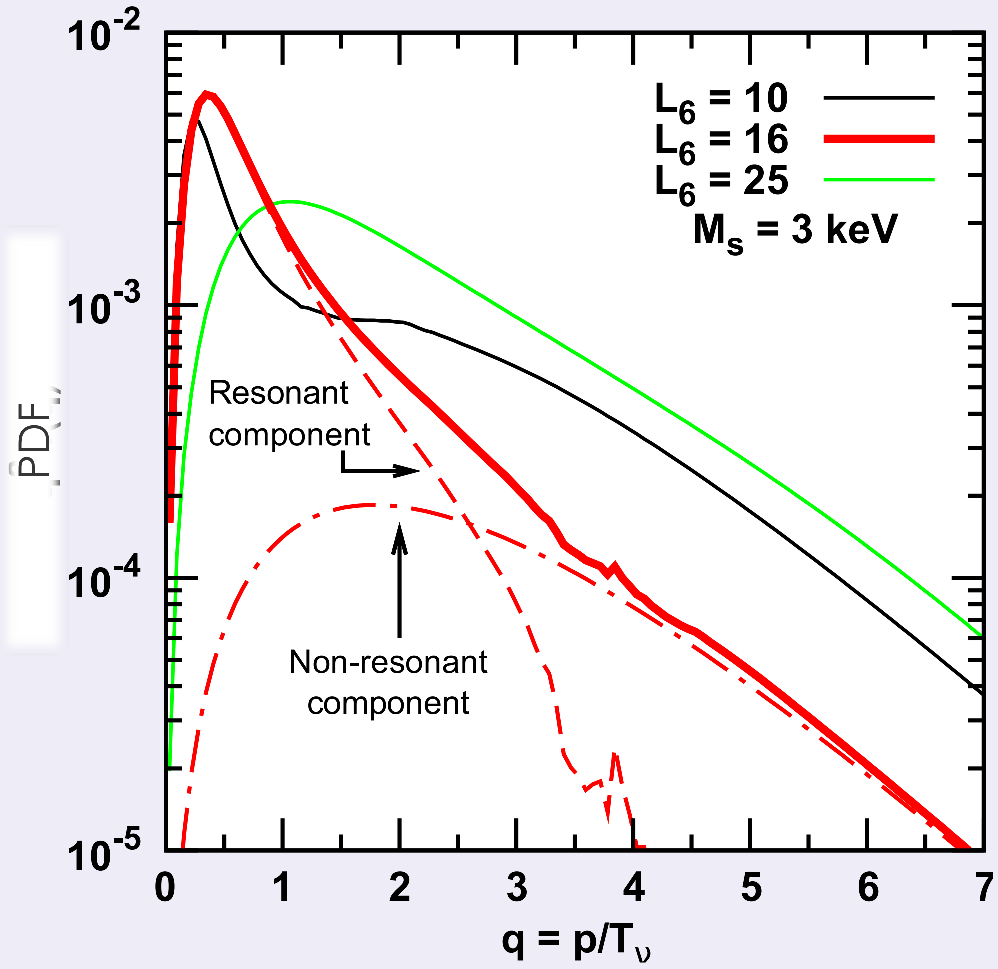
The problem with simulations

- Expensive
  - Illustris TNG50 required **130M CPUh** (~15,000 years of compute time)
- Slow exploration of parameter space
  - νMSM has two-dimensional parameter space: M_s and mixing angle
  - Require a simulation for each combination
  - Would need to re-run all simulations for each change to the hydrodynamics scheme
- Overall: **computationally infeasible** to explore parameter space with simulations

νMSM momentum distribution



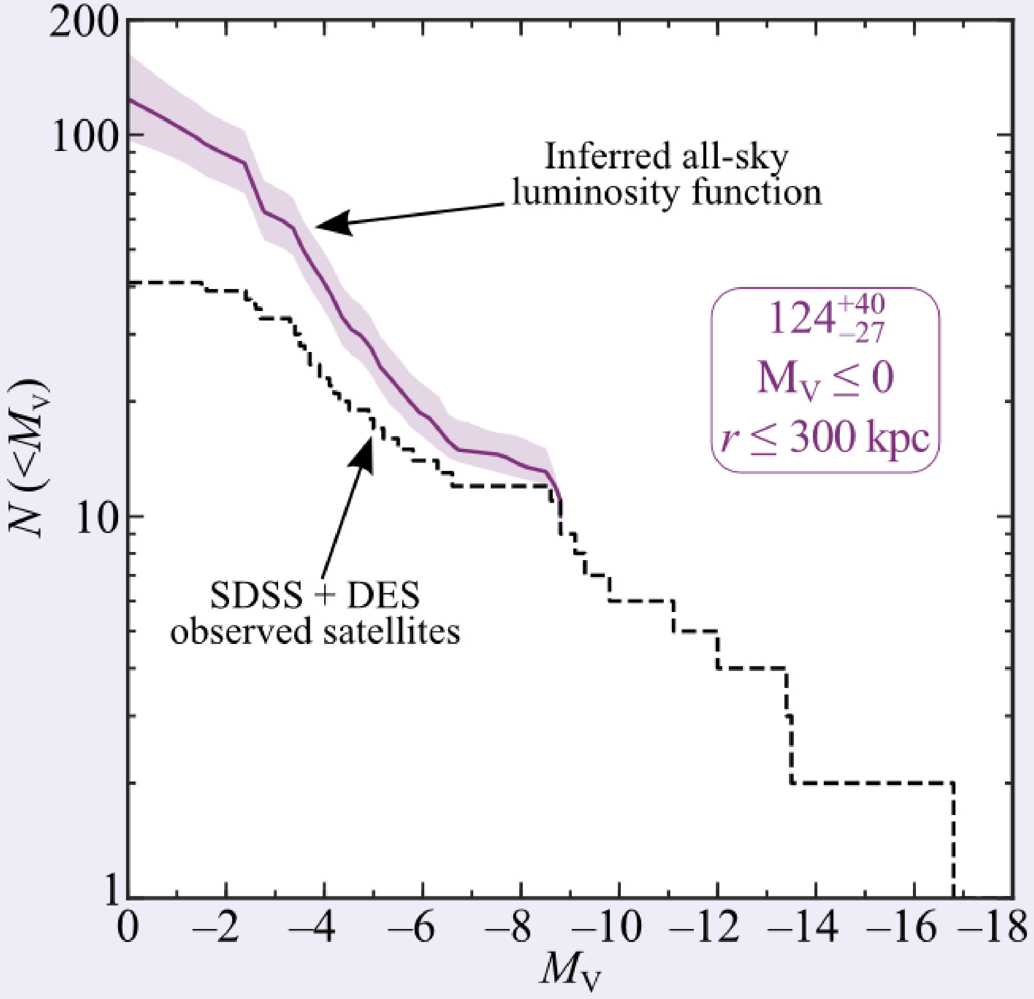
- q: Co-moving momentum; T_ν: Temperature of active neutrinos

$$L_6 = 10^6 \frac{(n_{\nu_e} - n_{\bar{\nu}_e})}{s}$$

- Non-resonant tails are self-similar at $q \geq 3$
- Non-monotonic behaviour with L_6 at fixed mass

Adapted from Boyarsky et al. (2009); arXiv: 0901.0011

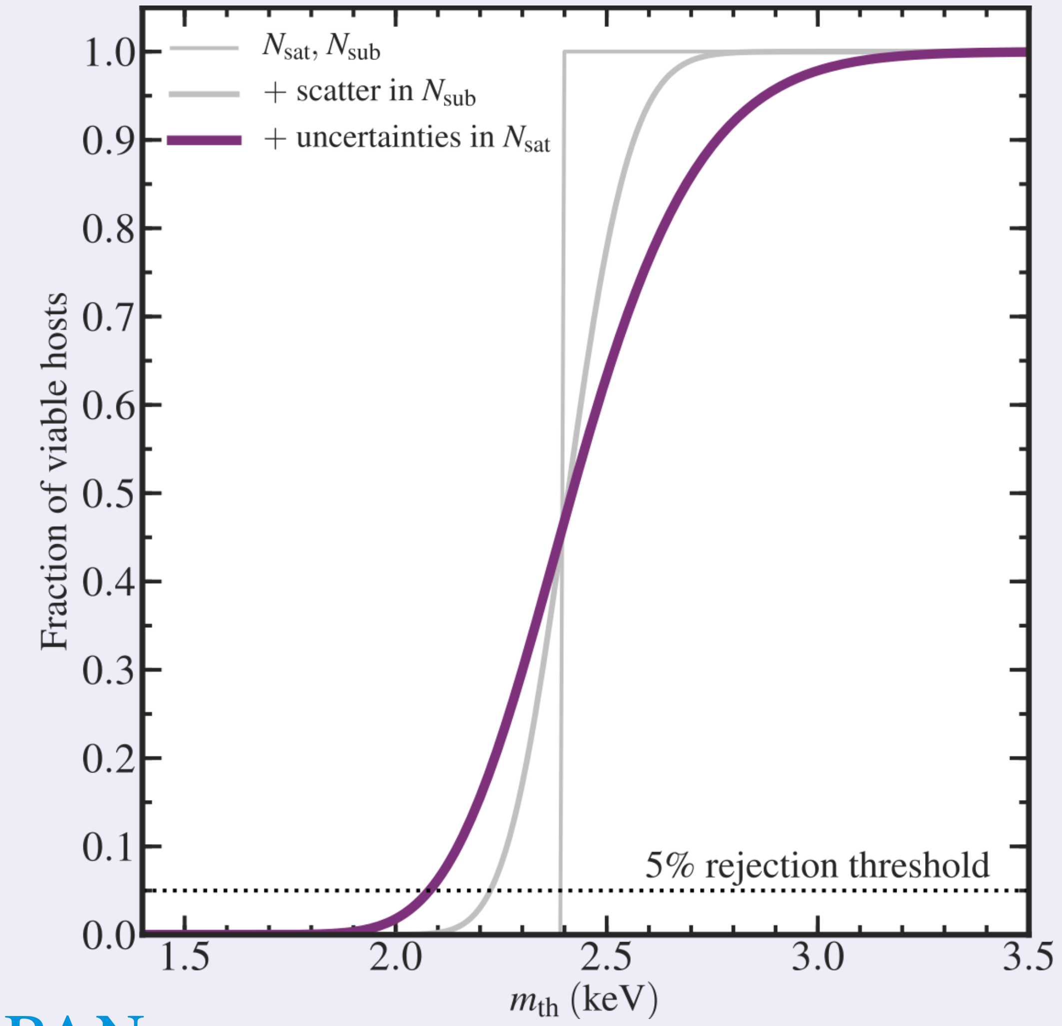
Satellite galaxies in the Milky Way



Newton et al. (2018); arXiv: 1708.04247

- Bayesian approach
- Model satellite distribution using $v_{\rm peak}$–selected subhaloes from Aquarius suite (Springel+2008)
- Use observations from SDSS and DES
  - Completeness characterized in the literature (Koposov+2008)
- Consistent with some follow-up estimates (e.g. Nadler+2020)

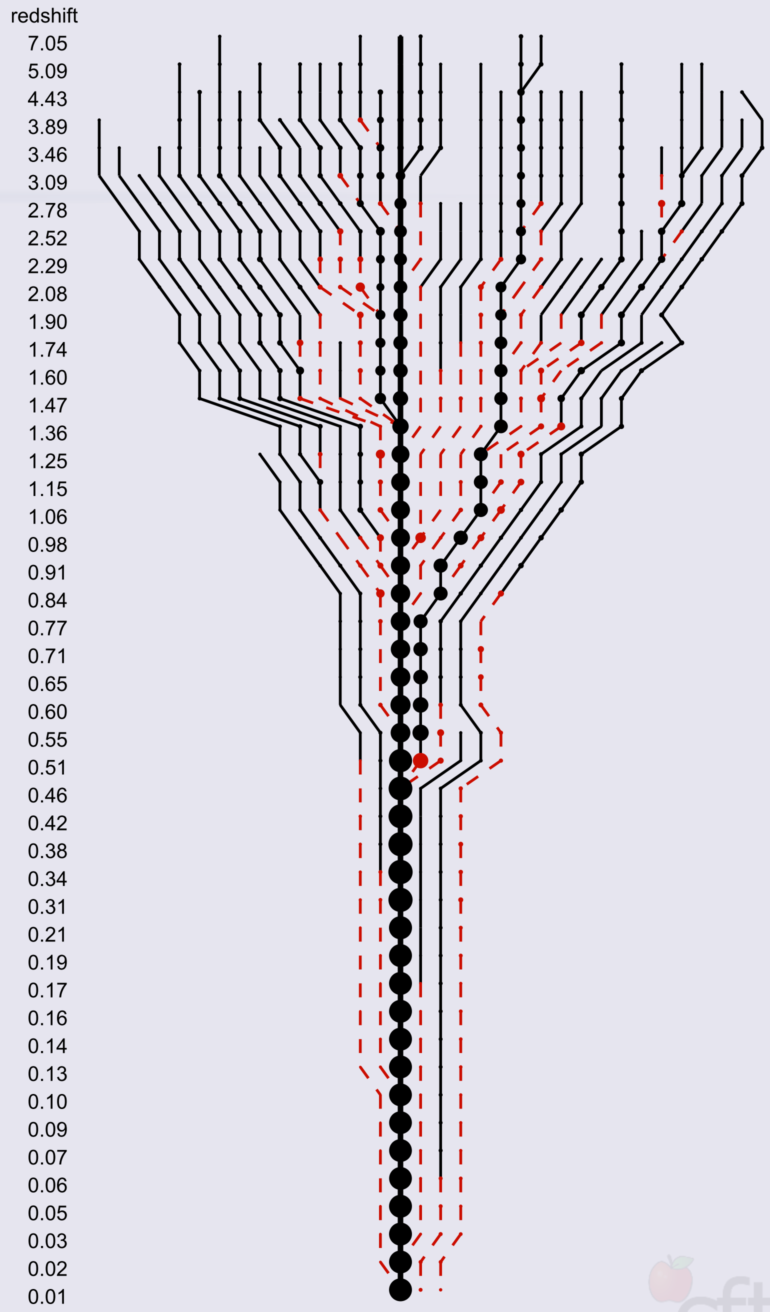
Setting the constraints



- Compare subhalo population with $N_{\mathrm{sat}}^{\mathrm{MW}}$
  - Independent of choice of galaxy formation physics
- Calculate fraction of systems with more subhaloes than is inferred from observations
- Rule out models with $f < 0.05$
- νMSM has 2-dimensional parameter space
  - Particle mass, M_s
  - Mixing angle, $\sin^2 2\theta$

Semi-analytic models of galaxy formation

- Rapidly explore different galaxy formation model prescriptions
- Based on DM halo merger trees
- Inexpensive compared to *N*–body/hydrodynamic simulations
- Implement many astrophysical processes
  - Shock heating/radiative cooling
  - Photoionization
  - Merging
  - Star formation (quiescent/burst)
  - Supernovae feedback (heating and winds)
  - AGN accretion and feedback
  - Chemical evolution
  - Stellar populations
  - Dust



Bullock et al. (2008); arXiv: 0811.0861