Dark Ghosts
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Modeling dark matter substructure and annihilation boost for indirect searches

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Why subhalos?

- Dark matter halos contain lots of subhalos (as CDM predicts), so ***all*** the extragalactic halos are subject to the **substructure boost** of dark matter annihilation
- **Dwarfs are subhalos** (but condition of forming galaxies in them is not yet well understood)
- **WIMP accumulation** in the Sun may be affected
- Hence subhalos are relevant for **all the DM annihilation searches except for Galactic center region**

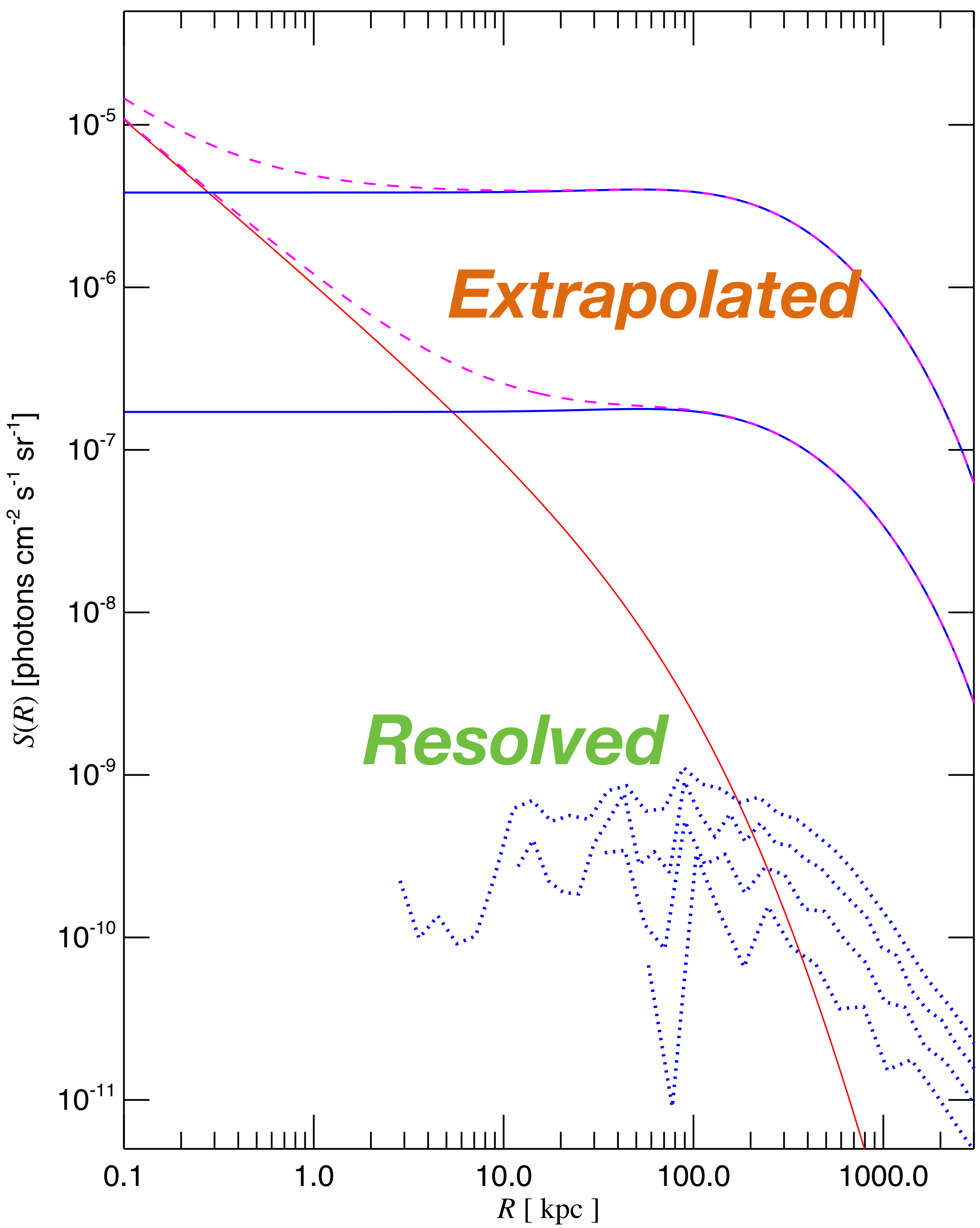
Annihilation boost

$$L(M) = [1 + B_{\rm sh}(M)]L_{\rm host}$$

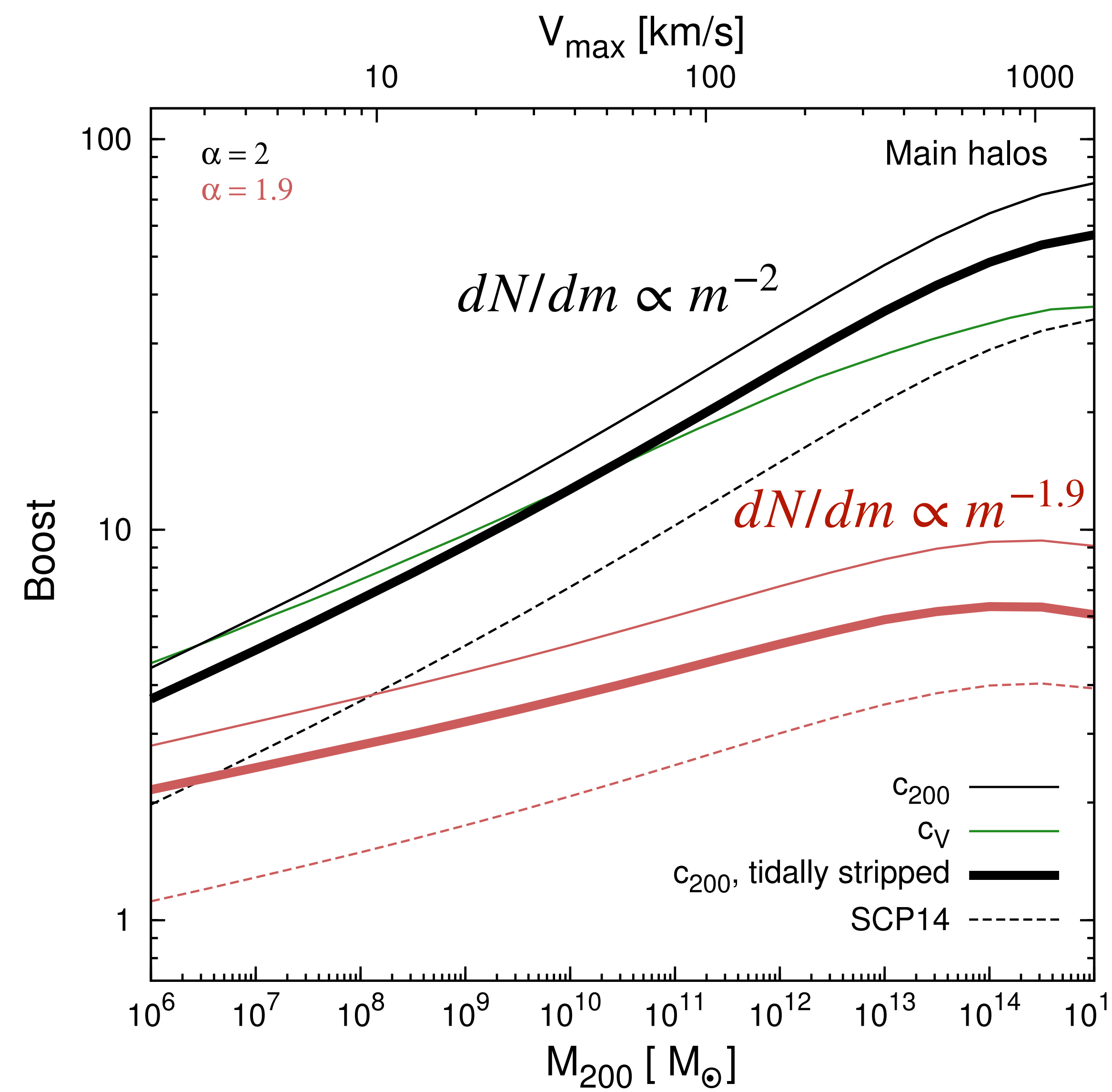
$$B_{\rm sh}(M) = \frac{1}{L_{\rm host}} \int dm \frac{dN_{\rm sh}}{dm} L_{\rm sh}(m)$$

http://wwwmpa.mpa-garching.mpg.de/aquarius/

How uncertain is the boost?



Gao et al., *Mon. Not. R. Astron. Soc.* **419**, 1721 (2012)



Moliné et al., *Mon. Not. R. Astron. Soc.* **466**, 4974 (2017)

- Very uncertain, of which we don't even have good sense
- **No way that it can be solved with numerical simulations**

Analytic model of subhalo evolution

- Complementary to numerical simulations
- Light, flexible, and versatile
- Can cover large range for halo masses (**micro-halos to clusters**) and redshifts (**z ~ 10 to 0**)
- **Physics-based** extrapolation
- Reliable if it is **tested compared with simulations** at resolved scales

Analytic model: Recipe

Structures start to form

↓

Smaller halos merge and accrete to form larger ones

↓

Subhalos experience mass loss

Initial condition: Primordial power spectrum

Extended Press-Schechter formalism

Modeling for tidal stripping and mass-loss rate

Formulation

$$L_{\rm sh}^{\rm total}(M, z) = \int dm \frac{dN}{dm} L_{\rm sh}(m)$$

Conventional formula

Formulation

$$L_{\rm sh}^{\rm total}(M, z) = \int dm_{\rm acc} \int dz_{\rm acc} \frac{d^2 N_{\rm sh}}{dm_{\rm acc} dz_{\rm acc}} L_{\rm sh}(z \,|\, m_{\rm acc}, z_{\rm acc})$$

Formulation

Accretion

$$L_{\rm sh}^{\rm total}(M, z) = \int dm_{\rm acc} \int dz_{\rm acc} \frac{d^2 N_{\rm sh}}{dm_{\rm acc} dz_{\rm acc}} L_{\rm sh}(z \,|\, m_{\rm acc}, z_{\rm acc})$$

Formulation

Accretion

$$L_{\rm sh}^{\rm total}(M,z) = \int dm_{\rm acc} \int dz_{\rm acc} \frac{d^2 N_{\rm sh}}{dm_{\rm acc} dz_{\rm acc}} L_{\rm sh}(z \,|\, m_{\rm acc}, z_{\rm acc})$$

Number of subhalos accreted at $z_{\rm acc}$ with mass $m_{\rm acc}$

Formulation

Accretion

Evolution

$$L_{\rm sh}^{\rm total}(M, z) = \int dm_{\rm acc} \int dz_{\rm acc} \frac{d^2 N_{\rm sh}}{dm_{\rm acc} dz_{\rm acc}} L_{\rm sh}(z \,|\, m_{\rm acc}, z_{\rm acc})$$

Number of subhalos accreted at $z_{\rm acc}$ with mass $m_{\rm acc}$

Formulation

Accretion **Evolution**

$$L_{\rm sh}^{\rm total}(M, z) = \int dm_{\rm acc} \int dz_{\rm acc} \frac{d^2 N_{\rm sh}}{dm_{\rm acc} dz_{\rm acc}} L_{\rm sh}(z \,|\, m_{\rm acc}, z_{\rm acc})$$

Number of subhalos accreted at $z_{\rm acc}$ with mass $m_{\rm acc}$

Luminosity of the subhalo at z

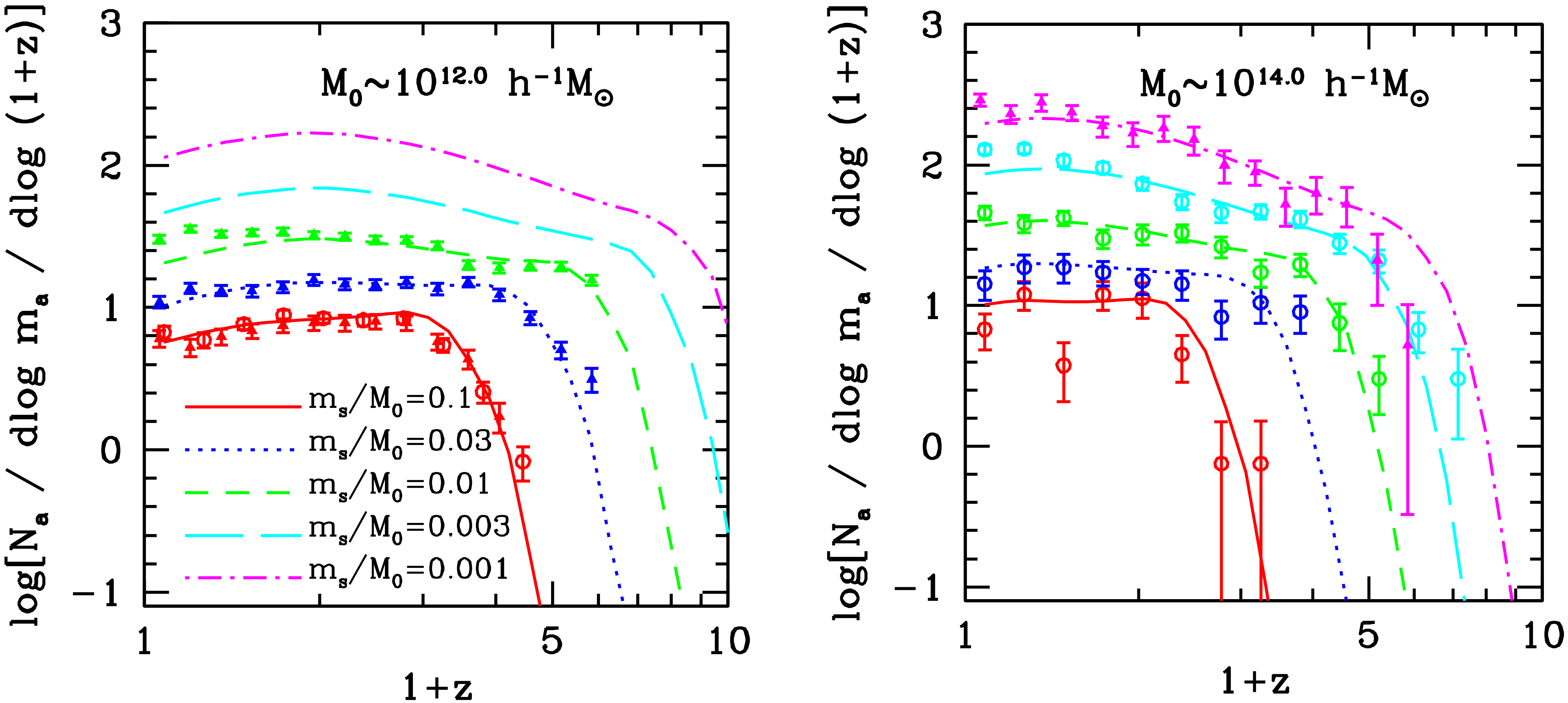
Halo formation and accretion history

- Based on spherical collapse model and **extended Press-Schechter formalism** (Yang et al. 2011)

$$\frac{d^2 N_{\rm sh}}{dm_{\rm acc} dz_{\rm acc}} \propto \frac{1}{\sqrt{2\pi}} \frac{\delta(z_{\rm acc}) - \delta_M}{(\sigma^2(m_{\rm acc}) - \sigma_M^2)^{3/2}} \exp\left[-\frac{(\delta(z_{\rm acc}) - \delta_M)^2}{2(\sigma^2(m_{\rm acc}) - \sigma_M^2)}\right]$$

- Primordial power spectrum + cutoff scale will change rms over-density $\sigma(M)$

Subhalo accretion rate



Yang et al., *Astrophys. J.* **741**, 13, (2011)

Infall distribution of subhalos:
Extended Press-Schechter formalism

$$\frac{d^2 N}{d \ln m_a d \ln(1+z_a)}$$

Formulation

Accretion

Evolution

$$L_{\rm sh}^{\rm total}(M,z) = \int dm_{\rm acc} \int dz_{\rm acc} \frac{d^2 N_{\rm sh}}{dm_{\rm acc} dz_{\rm acc}} L_{\rm sh}(z \,|\, m_{\rm acc}, z_{\rm acc})$$

Number of subhalos accreted at $z_{\rm acc}$ with mass $m_{\rm acc}$

Luminosity of the subhalo at z

Formulation

Accretion — **Evolution**

$$L_{\rm sh}^{\rm total}(M, z) = \int dm_{\rm acc} \int dz_{\rm acc} \frac{d^2 N_{\rm sh}}{dm_{\rm acc} dz_{\rm acc}} L_{\rm sh}(z \,|\, m_{\rm acc}, z_{\rm acc})$$

Number of subhalos accreted at $z_{\rm acc}$ with mass $m_{\rm acc}$

Luminosity of the subhalo at z

$$L_{\rm sh}(z \,|\, m_{\rm acc}, z_{\rm acc}) \propto \rho_s^2(z \,|\, m_{\rm acc}, z_{\rm acc}) r_s^3(z \,|\, m_{\rm acc}, z_{\rm acc}) \left\{ 1 - \frac{1}{[1 + r_t(z \,|\, m_{\rm acc}, z_{\rm acc})/r_s(z \,|\, m_{\rm acc}, z_{\rm acc})]^3} \right\}$$

Formulation

Accretion **Evolution**

$$L_{\mathrm{sh}}^{\mathrm{total}}(M,z) = \int dm_{\mathrm{acc}} \int dz_{\mathrm{acc}} \frac{d^2 N_{\mathrm{sh}}}{dm_{\mathrm{acc}} dz_{\mathrm{acc}}} L_{\mathrm{sh}}(z \,|\, m_{\mathrm{acc}}, z_{\mathrm{acc}})$$

Number of subhalos accreted at z_{acc} with mass m_{acc}

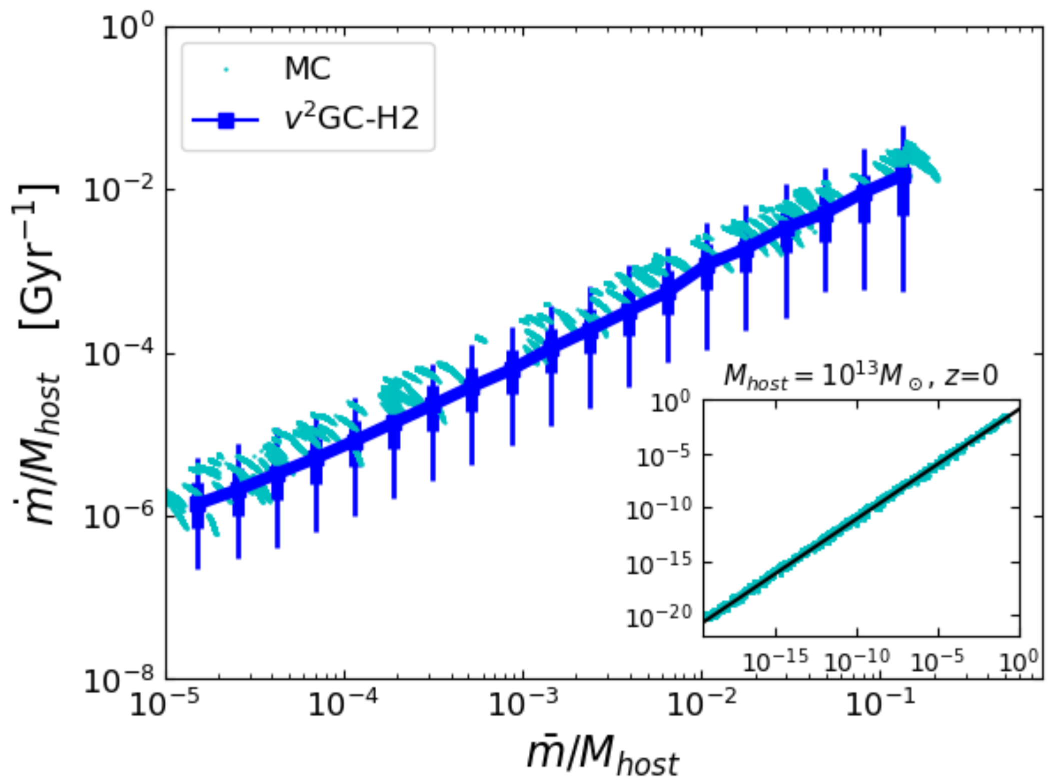
Luminosity of the subhalo at z

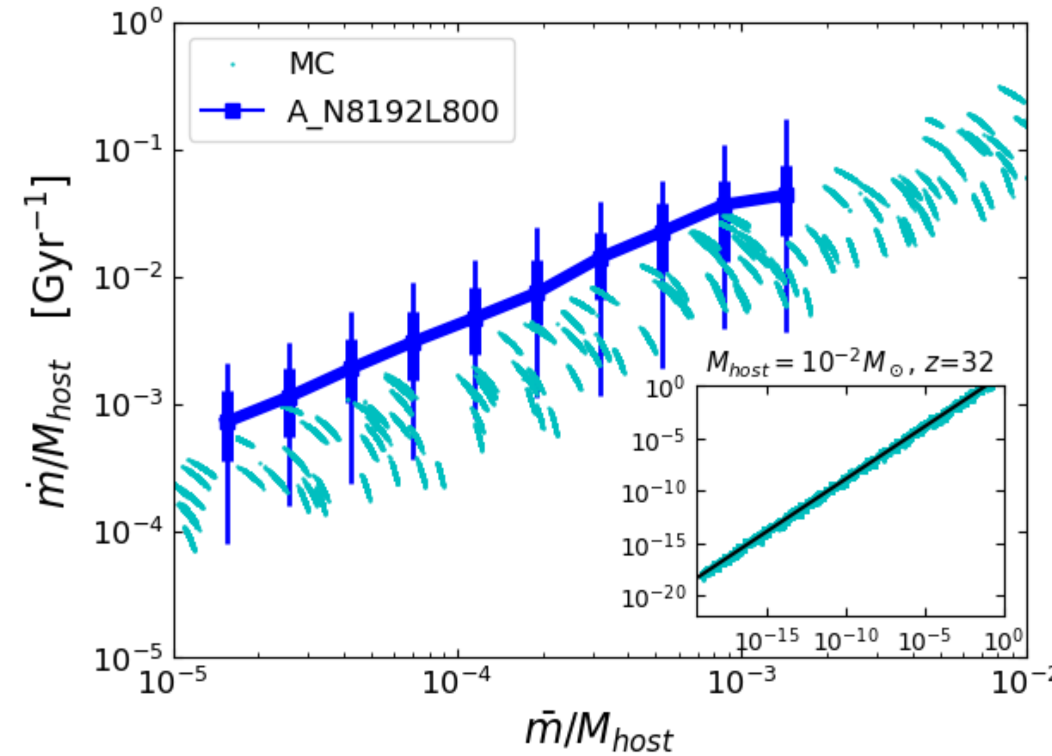
$$L_{\mathrm{sh}}(z \,|\, m_{\mathrm{acc}}, z_{\mathrm{acc}}) \propto \rho_s^2(z \,|\, m_{\mathrm{acc}}, z_{\mathrm{acc}}) r_s^3(z \,|\, m_{\mathrm{acc}}, z_{\mathrm{acc}}) \left\{ 1 - \frac{1}{[1 + r_t(z \,|\, m_{\mathrm{acc}}, z_{\mathrm{acc}})/r_s(z \,|\, m_{\mathrm{acc}}, z_{\mathrm{acc}})]^3} \right\}$$

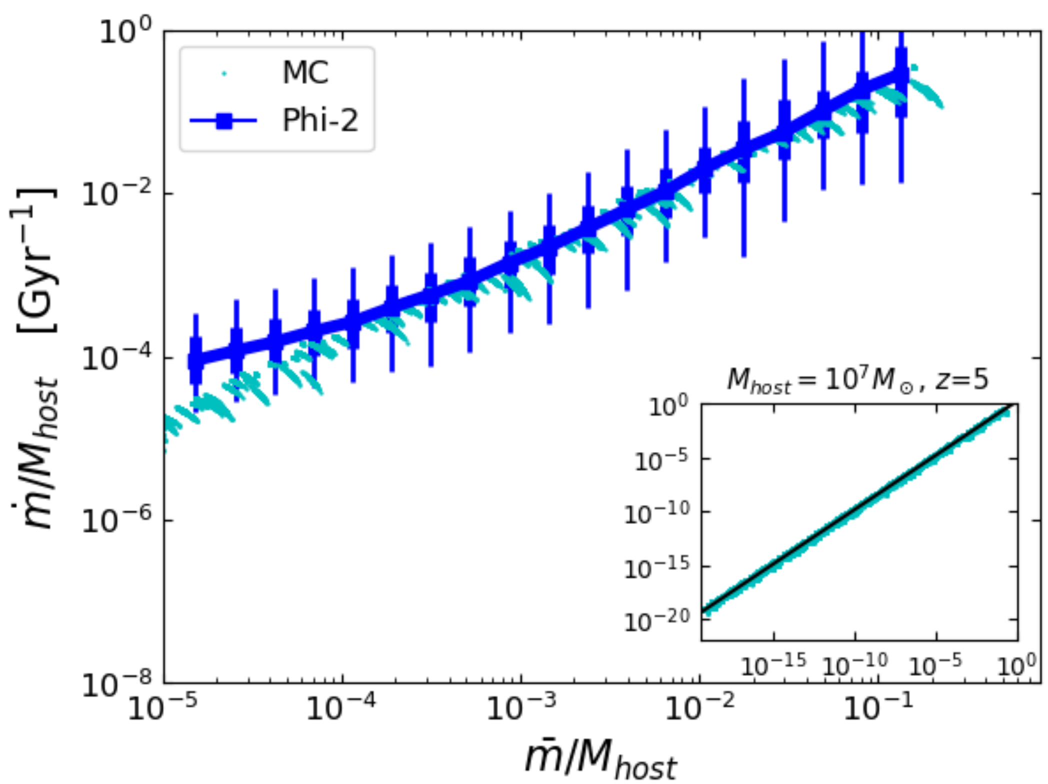
Parameters subhalo density profile **after tidal mass loss**

Subhalo mass loss

Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)



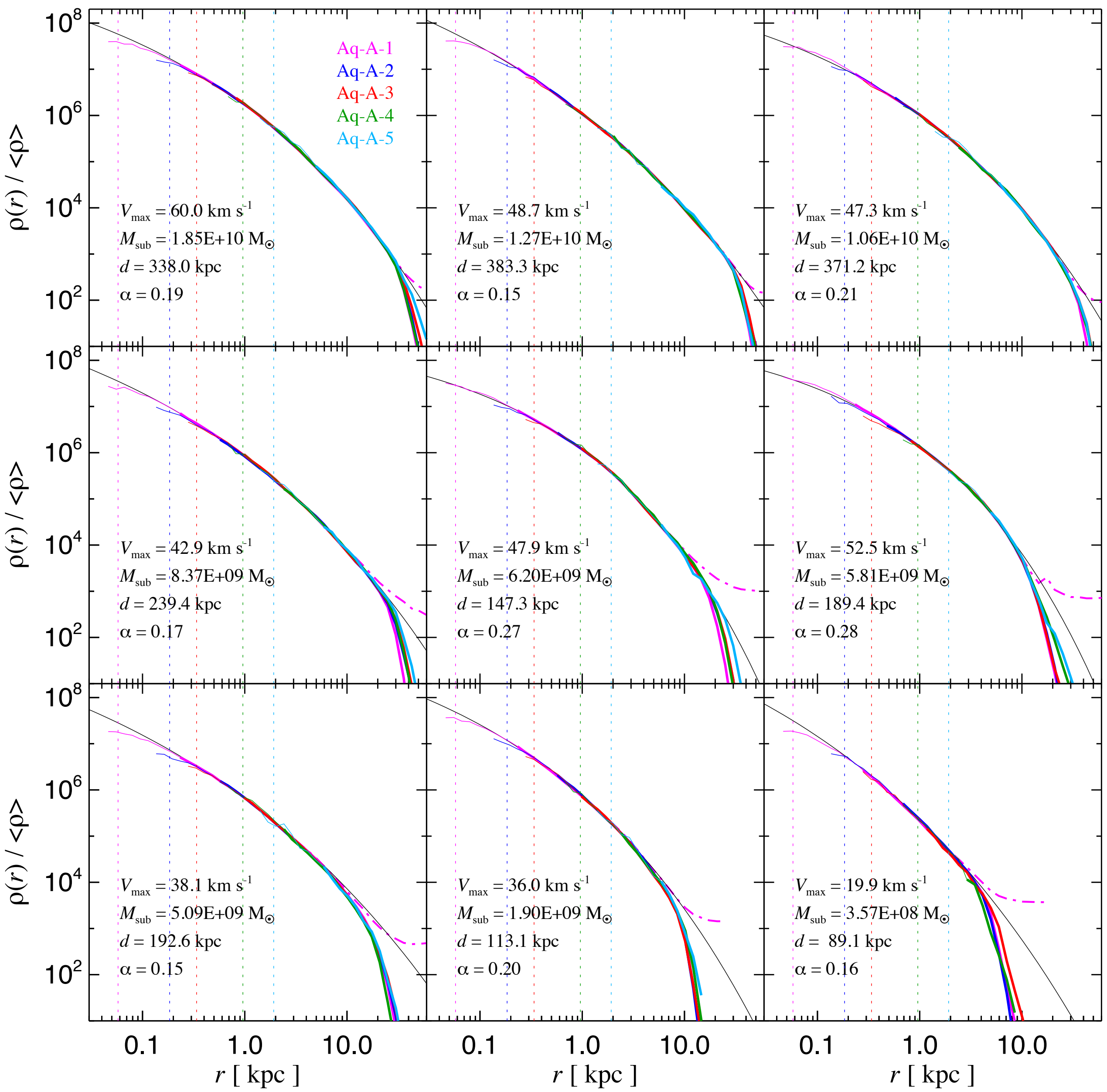




- Monte Carlo approach following Jiang & van den Bosch (2016)
  - Determine orbital energy and angular momentum
  - Assume the subhalo loses all the masses outside of its tidal radius instantaneously at its peri-center passage
- Mass-loss rate follows power law for wide range of *m/M*

Subhalo density profile after mass loss

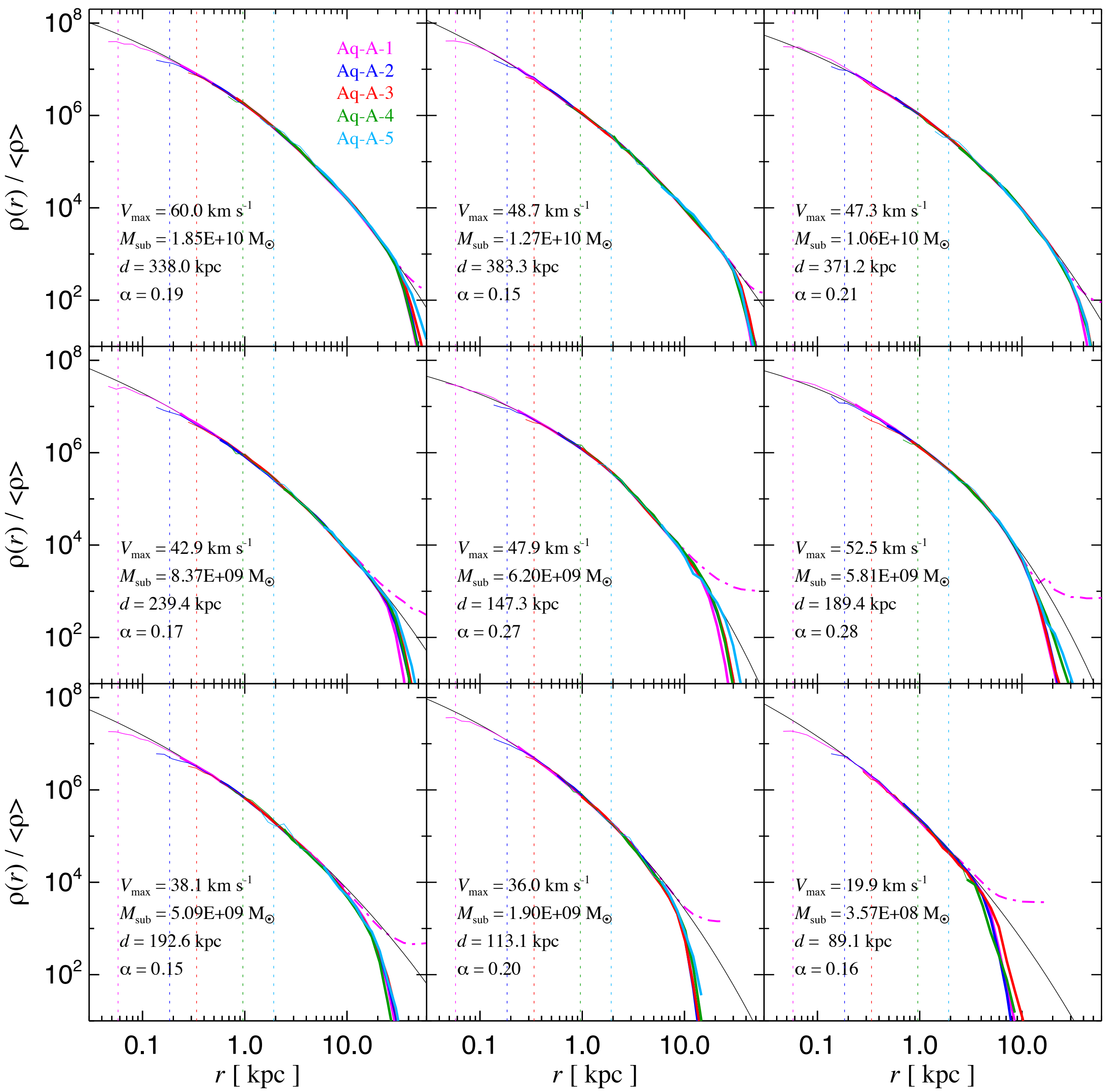
Springel et al., *Mon. Not. R. Astron. Soc.* **391**, 1685, (2008)



Truncated NFW

Subhalo density profile after mass loss

Springel et al., *Mon. Not. R. Astron. Soc.* **391**, 1685, (2008)

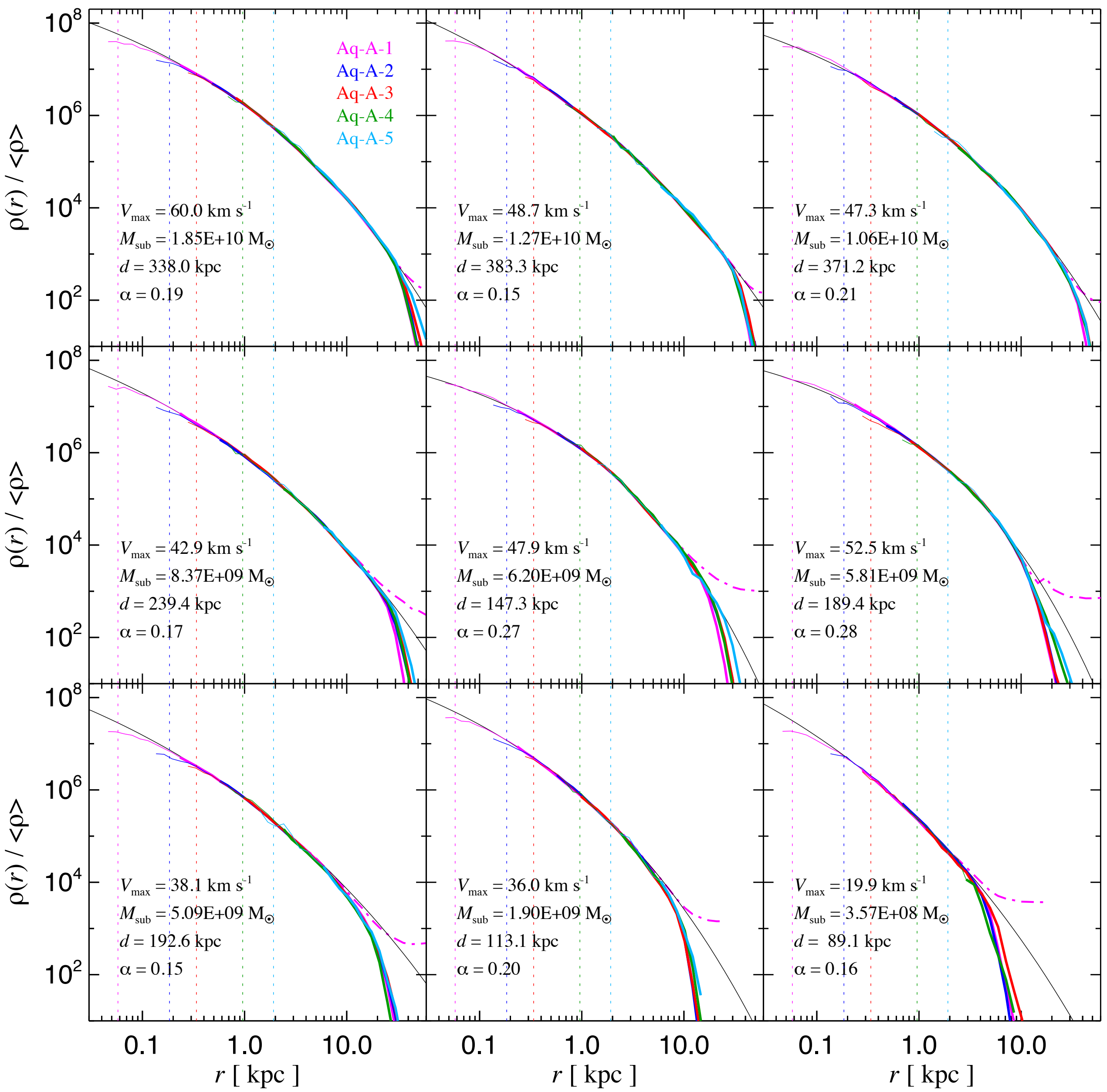


Truncated NFW

- Procedure

Subhalo density profile after mass loss

Springel et al., *Mon. Not. R. Astron. Soc.* **391**, 1685, (2008)

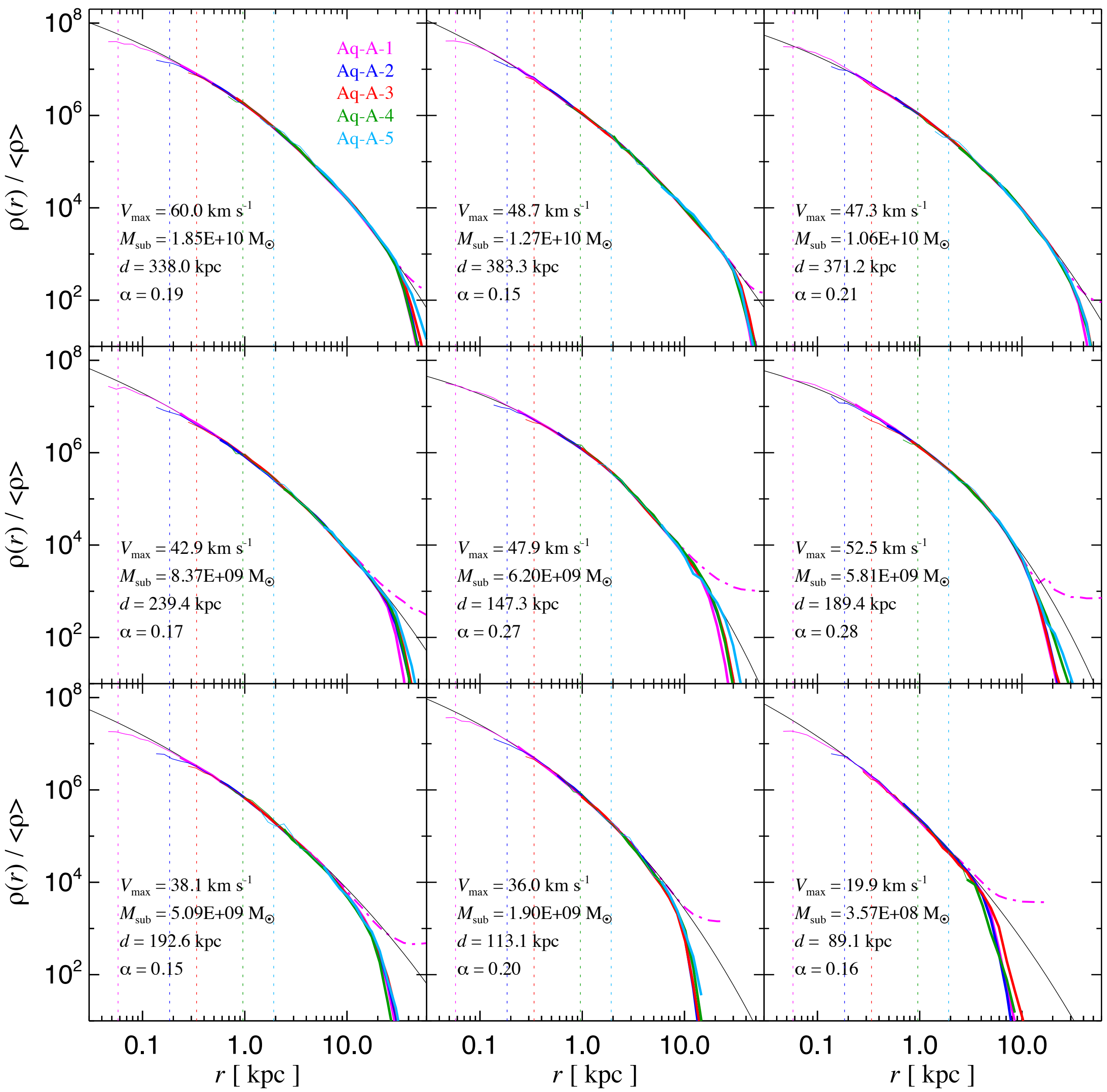


Truncated NFW

- Procedure
  1. Solve the differential equation from z_{acc} to z to get m

Subhalo density profile after mass loss

Springel et al., *Mon. Not. R. Astron. Soc.* **391**, 1685, (2008)

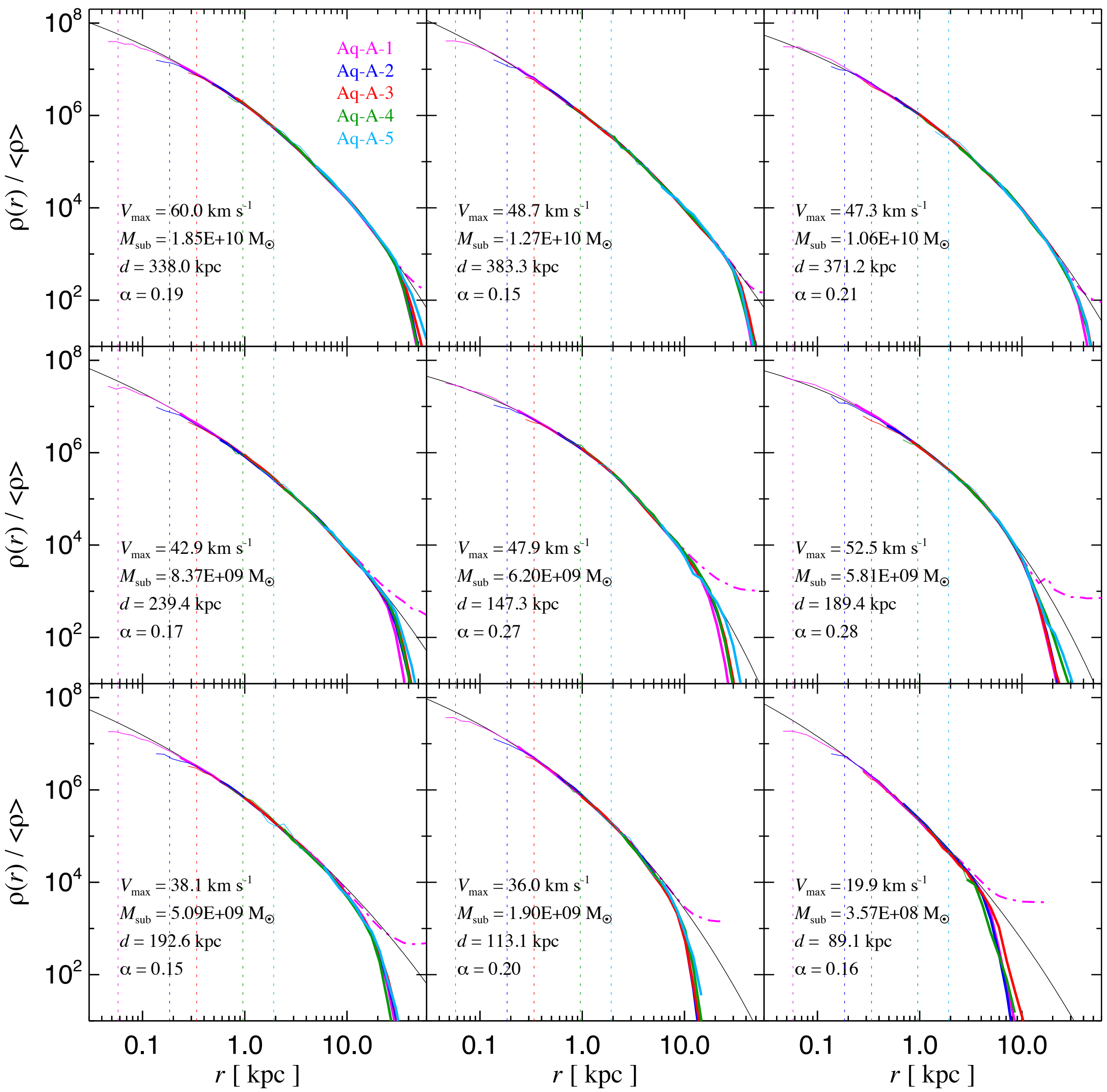


Truncated NFW

- Procedure
  1. Solve the differential equation from z_{acc} to z to get m
  2. Calculate $\boldsymbol{\rho_s}$ and $\boldsymbol{r_s}$ following Penarrubia et al. (2010)

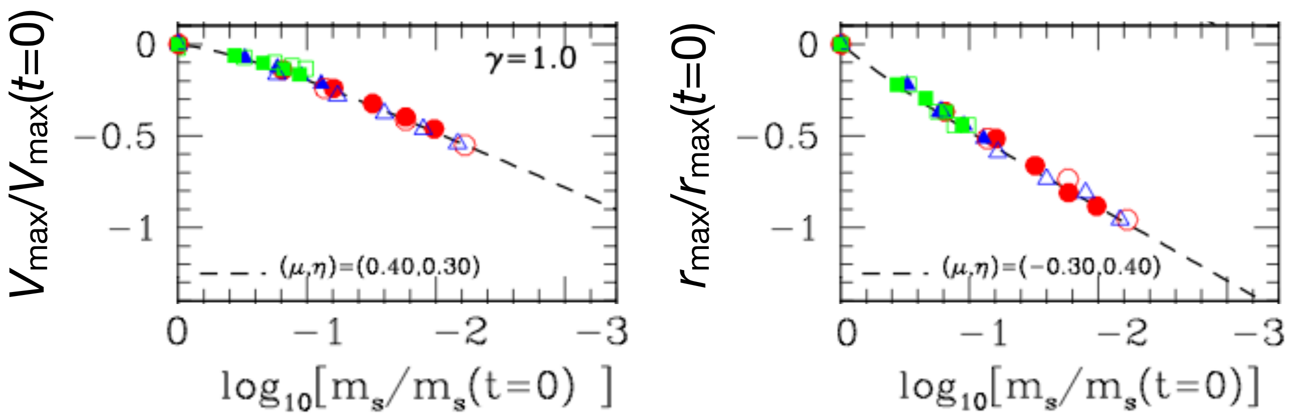
Subhalo density profile after mass loss

Springel et al., *Mon. Not. R. Astron. Soc.* **391**, 1685, (2008)



Truncated NFW

Penarrubia et al., *Mon. Not. R. Astron. Soc.* **406**, 1290, (2010)



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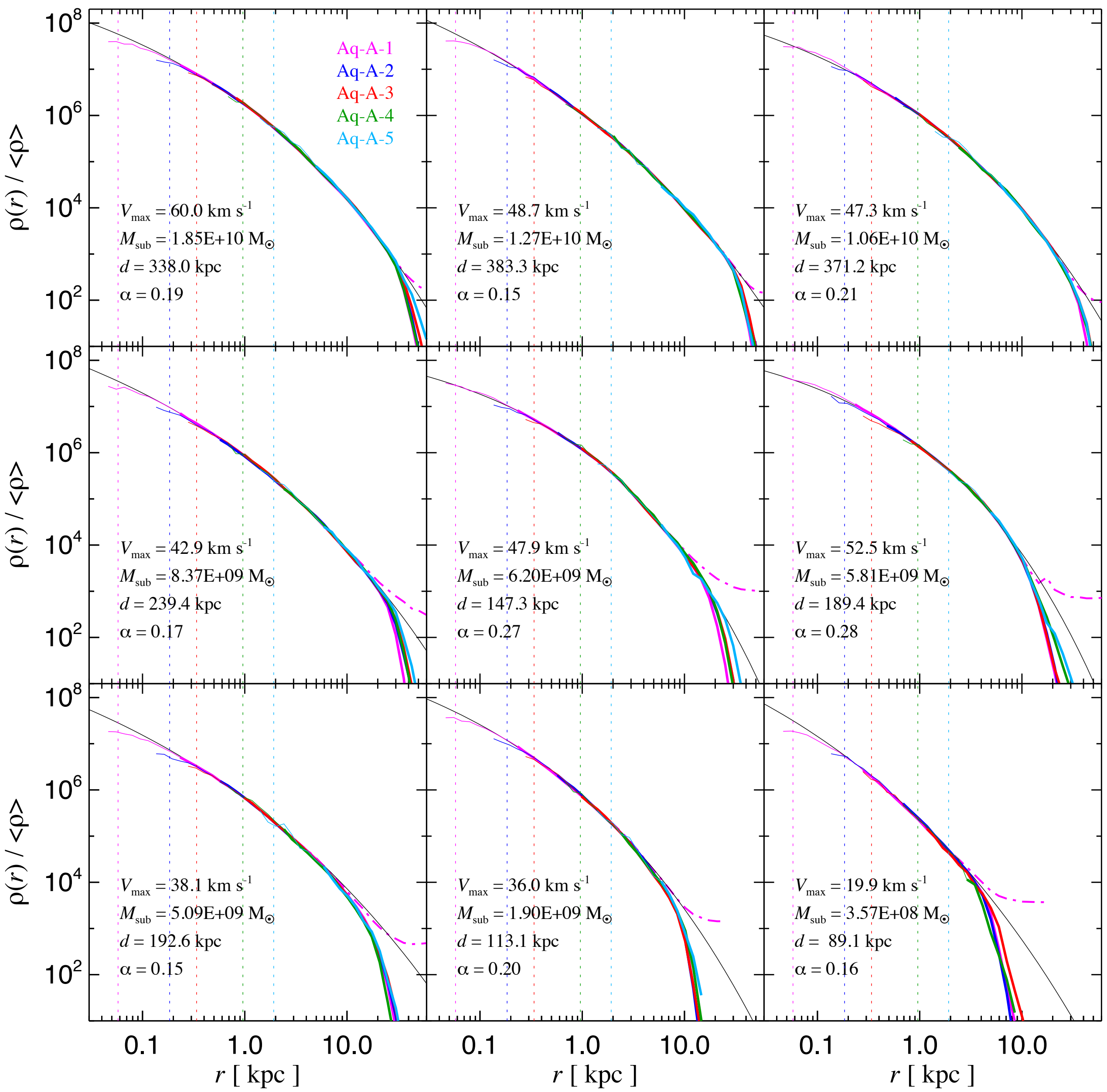
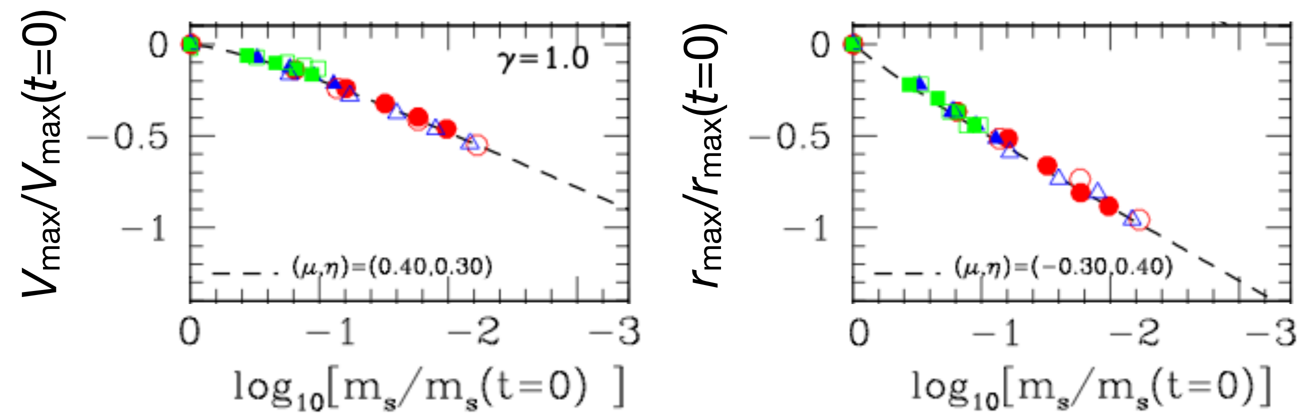
Subhalo density profile after mass loss

Springel et al., *Mon. Not. R. Astron. Soc.* **391**, 1685, (2008)



Truncated NFW

Penarrubia et al., *Mon. Not. R. Astron. Soc.* **406**, 1290, (2010)



- Procedure

1. Solve the differential equation from z_{acc} to z to get m
2. Calculate ρ_s and r_s following Penarrubia et al. (2010)
3. Obtain truncation radius r_t by solving

$$m = \int_0^{r_t} dr\ 4\pi r^2 \rho(r)$$

Formulation

Accretion

Evolution

$$L_{\rm sh}^{\rm total}(M,z) = \int dm_{\rm acc} \int dz_{\rm acc} \frac{d^2N_{\rm sh}}{dm_{\rm acc}dz_{\rm acc}} L_{\rm sh}(z\,|\,m_{\rm acc}, z_{\rm acc})$$

Number of subhalos accreted at $z_{\rm acc}$ with mass $m_{\rm acc}$

Luminosity of the subhalo at z

$$L_{\rm sh}(z\,|\,m_{\rm acc}, z_{\rm acc}) \propto \rho_s^2(z\,|\,m_{\rm acc}, z_{\rm acc}) r_s^3(z\,|\,m_{\rm acc}, z_{\rm acc}) \left\{ 1 - \frac{1}{[1 + r_t(z\,|\,m_{\rm acc}, z_{\rm acc})/r_s(z\,|\,m_{\rm acc}, z_{\rm acc})]^3} \right\}$$

Parameters subhalo density profile **after tidal mass loss**

Results

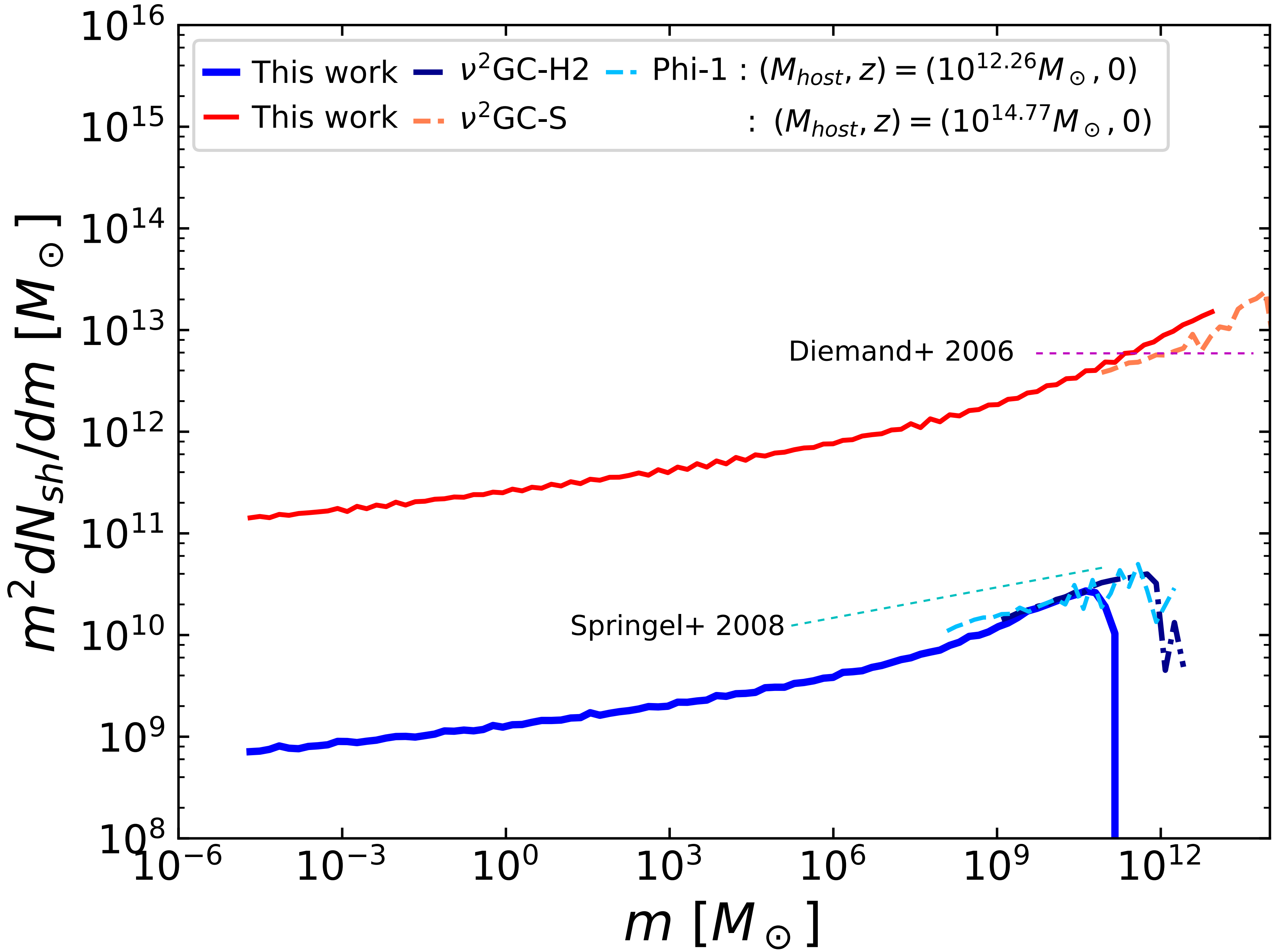
Comparison with simulations

Name		N	L	Softening	$m_{\rm p}$ ($M_\odot$)	Reference
ν^2GC-S	***Cluster***	2048^3	411.8 Mpc	6.28 kpc	3.2×10^8	[38, 44]
ν^2GC-H2	***Galaxy***	2048^3	102.9 Mpc	1.57 kpc	5.1×10^6	[38, 44]
Phi-1	***Dwarf***	2048^3	47.1 Mpc	706 pc	4.8×10^5	Ishiyama et al. (in prep)
Phi-2	***Dwarf***	2048^3	1.47 Mpc	11 pc	14.7	Ishiyama et al. (in prep)
A_N8192L800	***Micro***	8192^3	800.0 pc	2.0×10^{-4} pc	3.7×10^{-11}	Ishiyama et al. (in prep)

[38] Ishiyama et al., *Pulb. Astron. Soc. Jap.* **67**, 61 (2015)

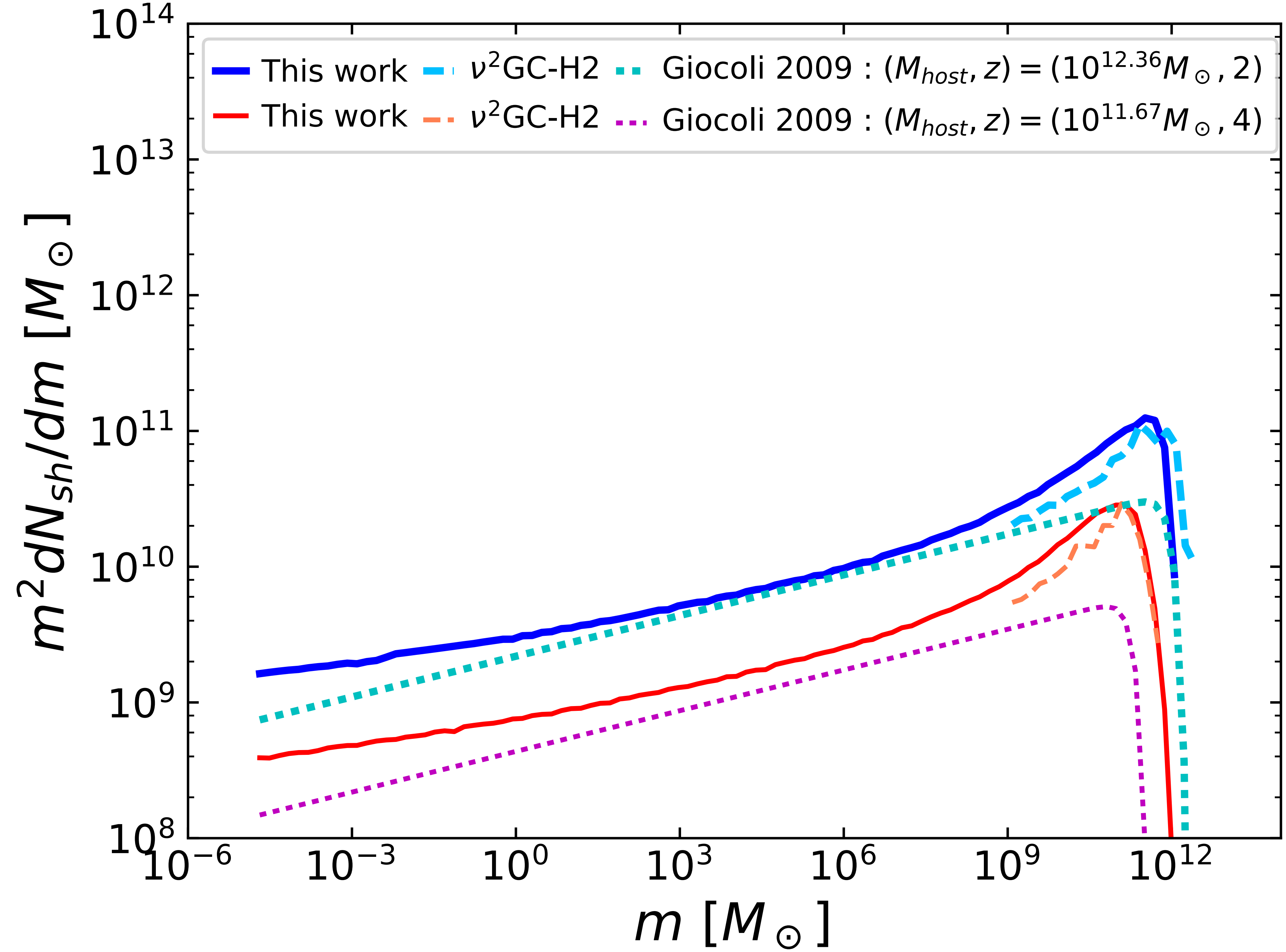
[44] Makiya et al., *Pulb. Astron. Soc. Jap.* **68**, 25 (2016)

Subhalo mass function: Clusters and galaxies



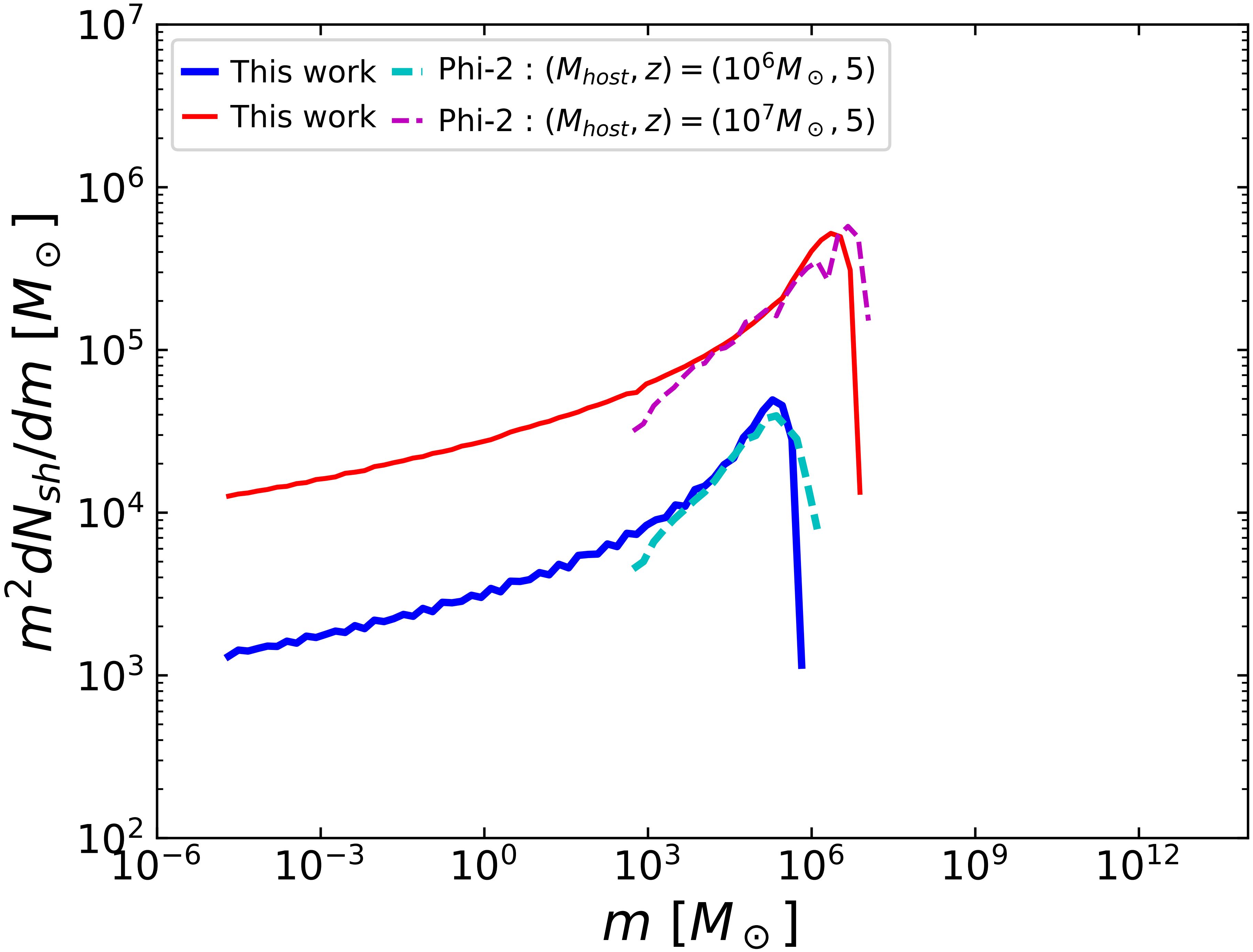
Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)

Subhalo mass function:
Galaxies at z=2,4



Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)

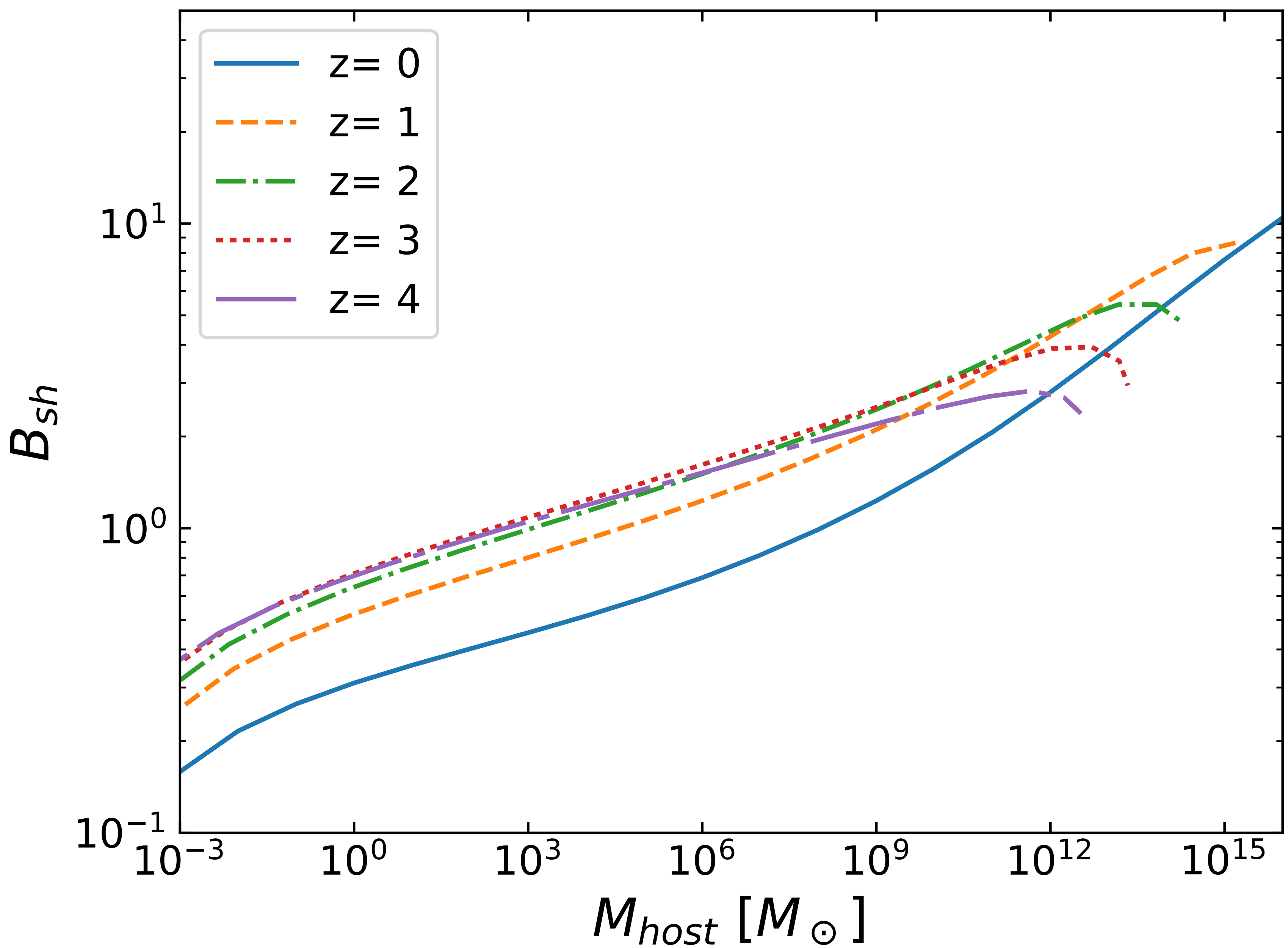
Subhalo mass function: Dwarfs at z=5



Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)

Annihilation boost

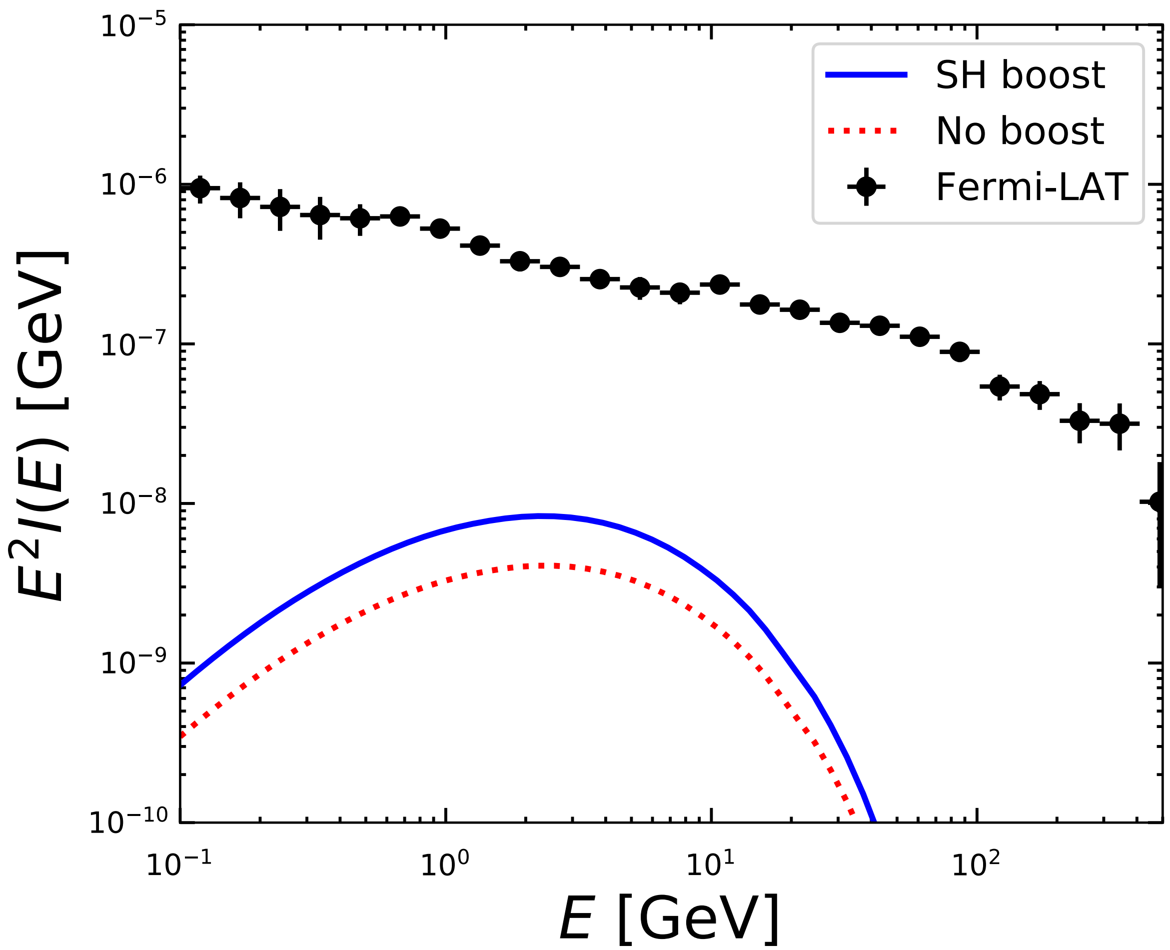
Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)

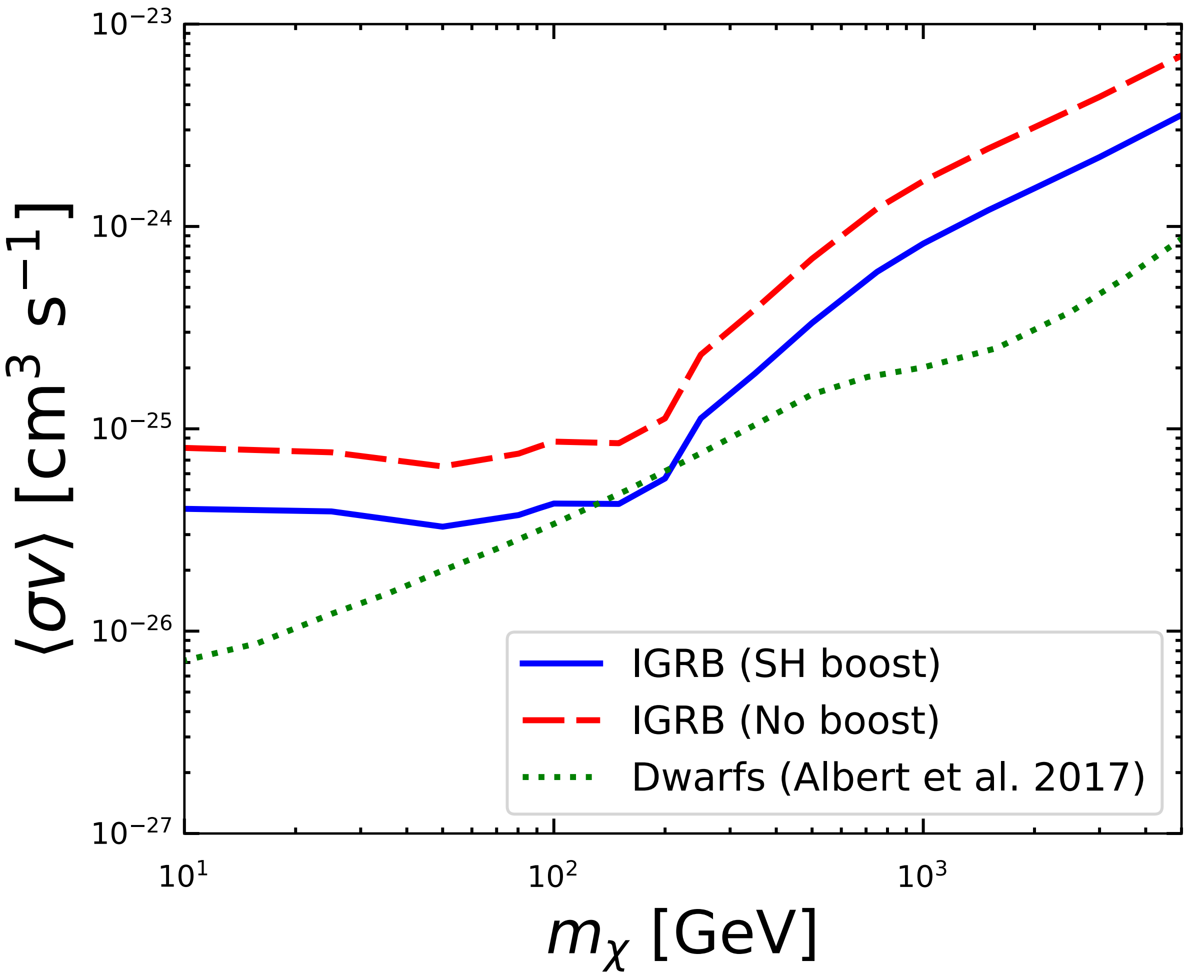


- Boost factors are higher at larger redshifts, but saturates after z = 1
- Boost can be as large as ~3 (10) for galaxies (clusters)
- For one combination of host mass and redshifts (M, z), the code takes **only ~O(1) min to calculate the boost** on a laptop computer

Application: IGRB

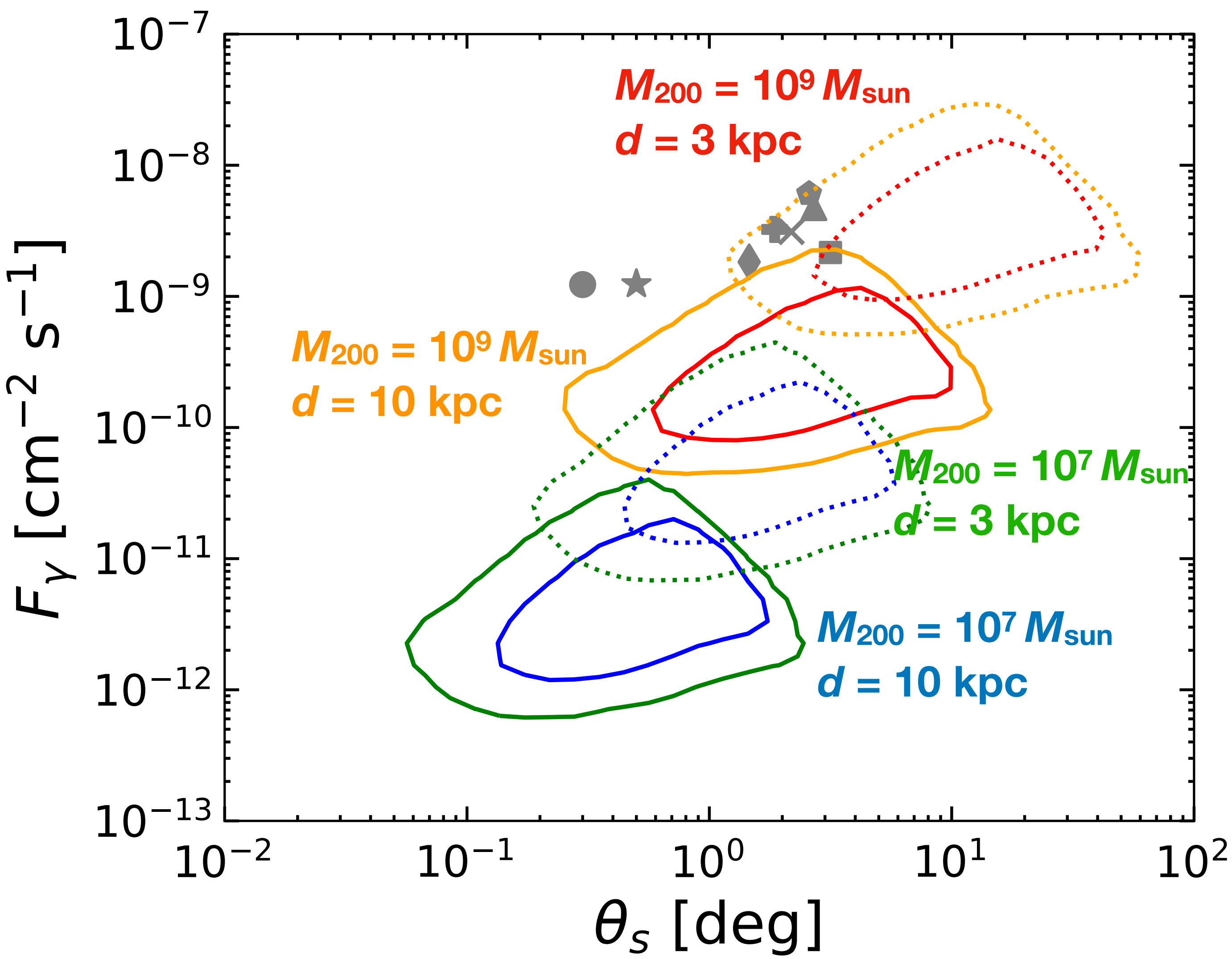
Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)





Application: Fermi unassociated sources

Ciuca, Kawata, Ando, Calore, Read, Mateu,
Mon. Not. R. Astron. Soc. **480**, 2284 (2018)



3FGL J2212.5+0703 (star), 3FGL J1924.8−1034 (circle), FHES J1501.0−6310 (pentagon), FHES J1723.5−0501 (diamond), FHES J1741.6−3917 (square), FHES J2129.9+5833 (cross), FHES J2208.4+6443 (plus), FHES J2304.0+5406 (square)

- Test of Fermi unassociated sources in light of *Gaia* non-detection: upper limit 10^9 $M_{\rm sun}$ within 20 kpc
- Analytic subhalo model enables to compute PDF of source extension and gamma-ray flux (for a fixed distance)

$$\langle \sigma v \rangle = 2 \times 10^{-26}\ \mathrm{cm^3\ s^{-1}}$$
$$m_\chi = 25\ \mathrm{GeV}$$

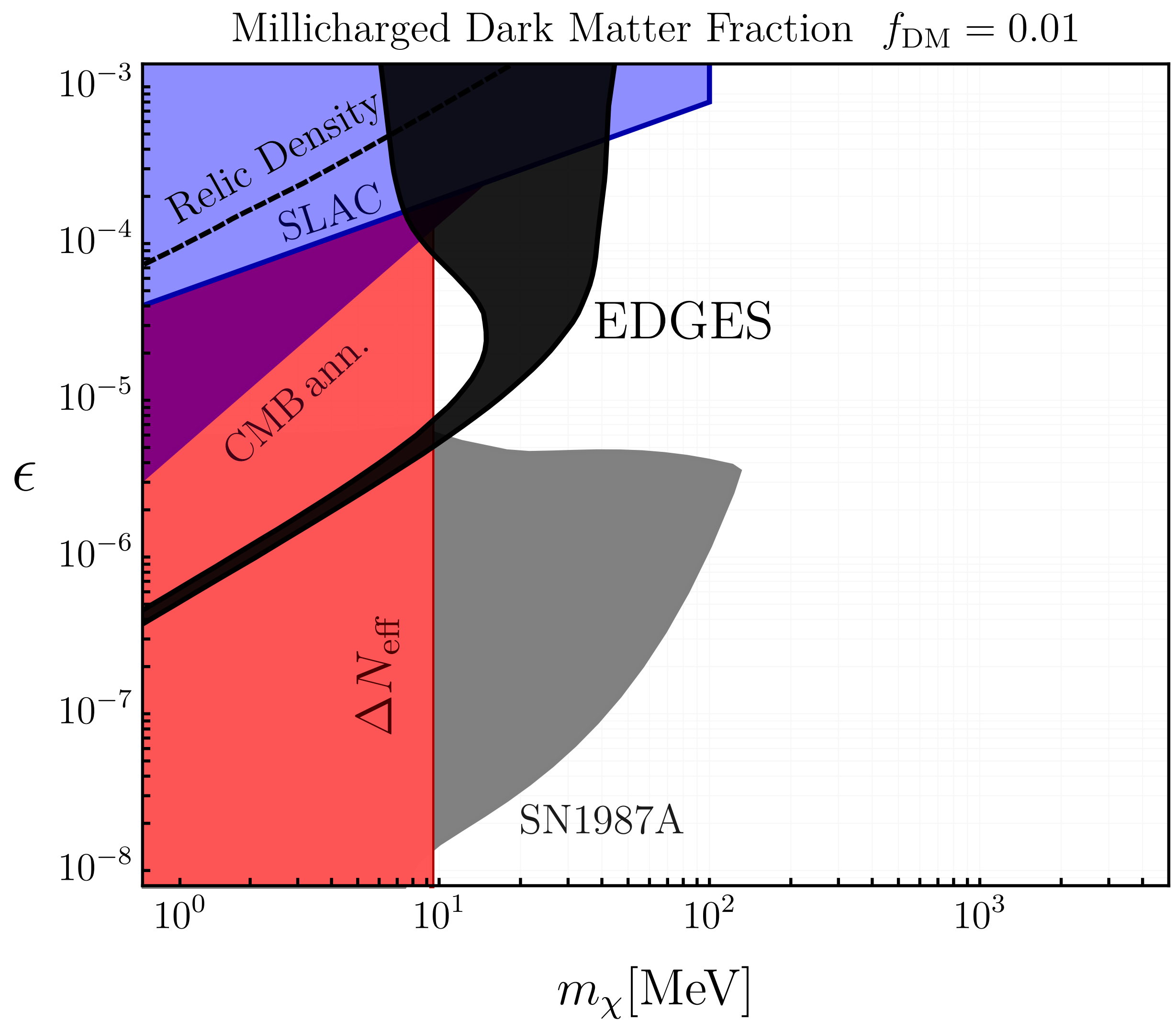
- Only they can be dark matter annihilation for 10^9 $M_{\rm sun}$ at d = 3 kpc
- This is unlikely because (1) probability is very small and (2) it will be depleted by the disk
- Conclusion: **no Fermi unassociated sources are subhalos**

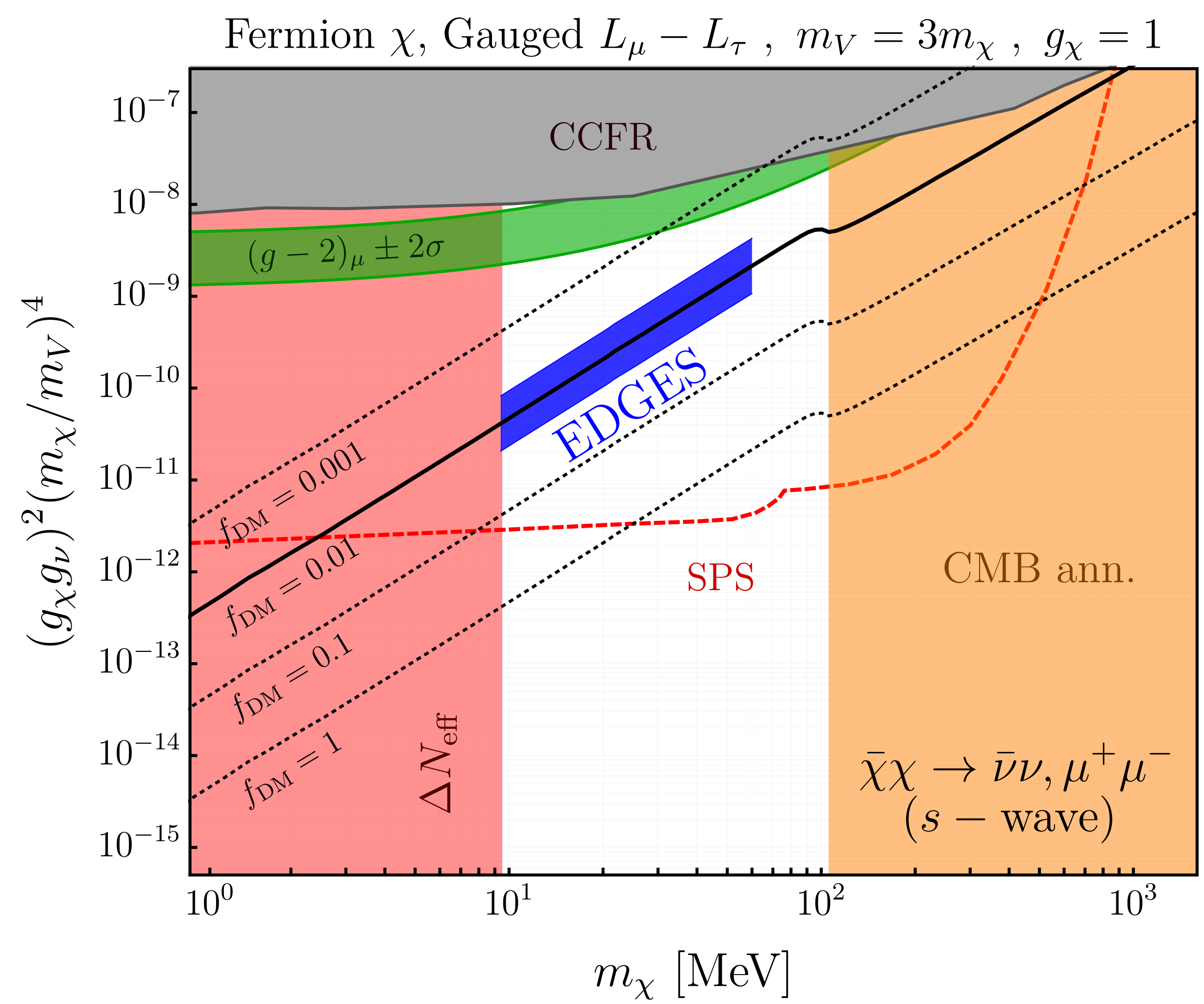
Application:

MeV neutrinos and implications for 21-cm measurements

Model to explain EDGES 21-cm obs

Berlin et al., *Phys. Rev. Lett.* **121**, 011102 (2018)

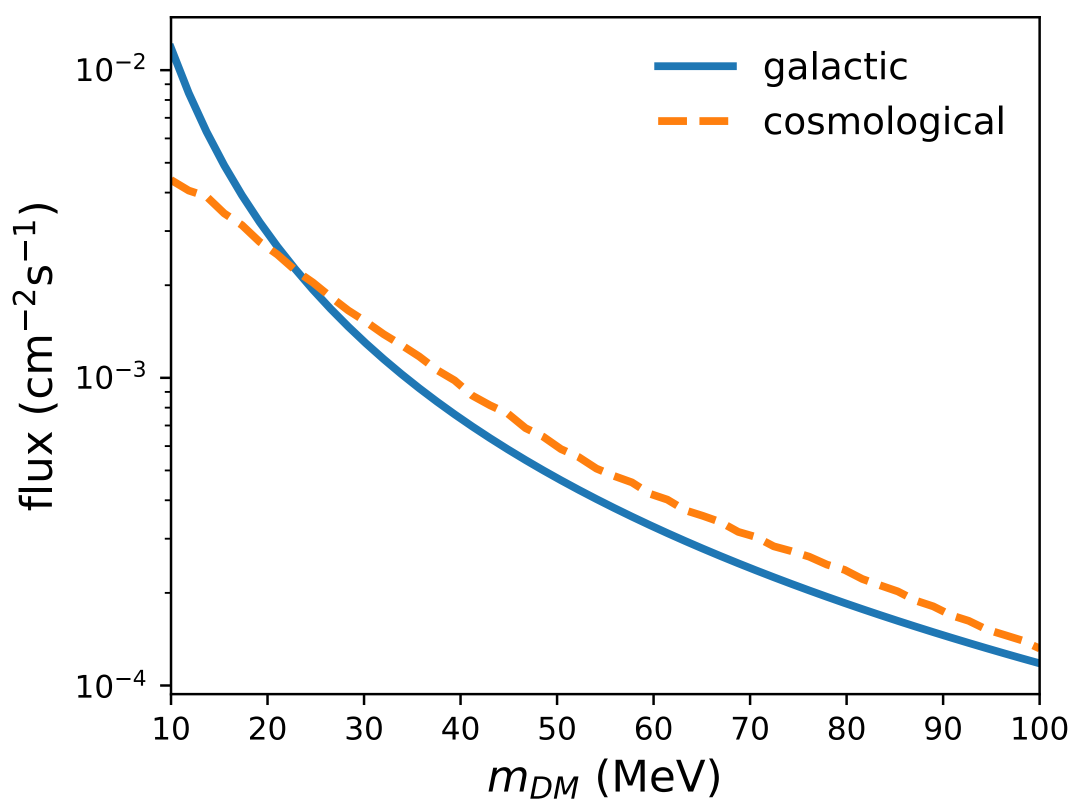


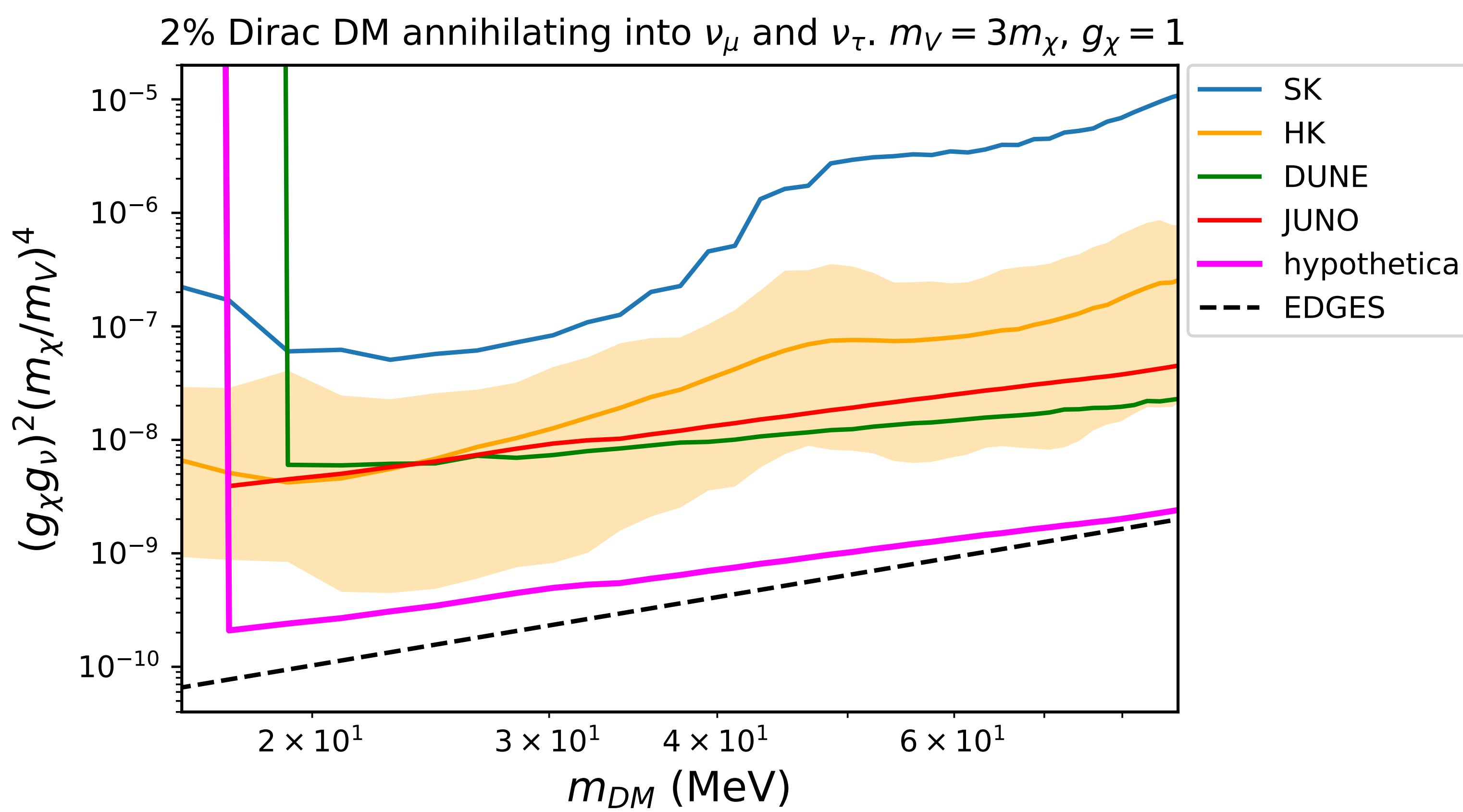


- $L_\mu - L_\tau$ gauge symmetry to explain relic density
- MeV dark matter annihilating into neutrino-antineutrino pairs still allowed

Neutrino constraints on MeV dark matter

Klop, Ando, *Phys. Rev. D* **98**, 103004 (2018)





- Similar contribution to neutrino flux from Galactic halo and cosmological halos (including substructure boost)
- EDGES regions might be reached with future neutrino telescopes

Conclusions

- Combining the distribution of subhalo accretion with the evolution afterwards, we can analytically model various subhalo quantities such as **mass function** and **annihilation boost factor**

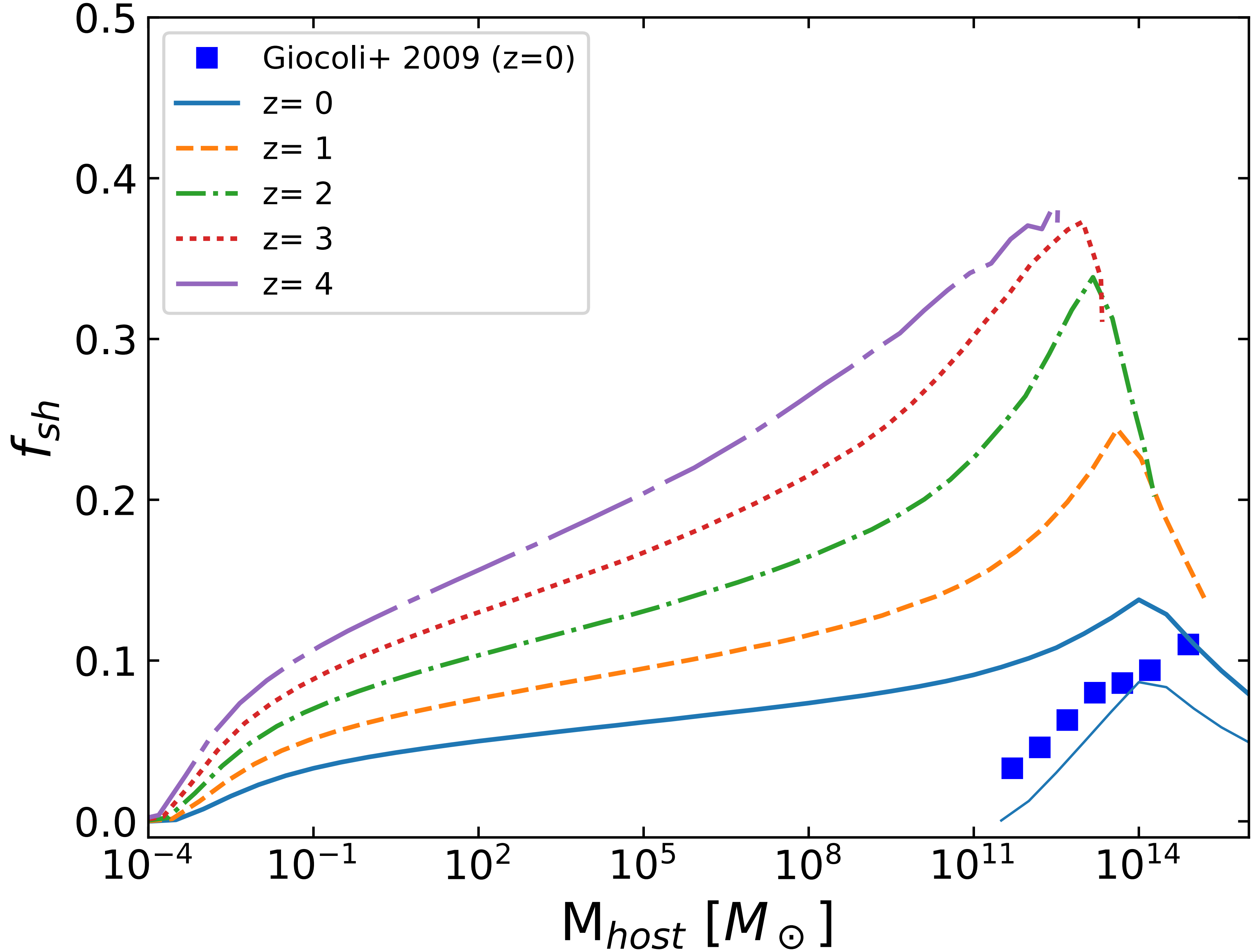
- The subhalo mass function appears to be in **good agreement** with results of numerical simulations for **wide range of masses and redshifts**

- The annihilation boost factors are predicted to be **~3 (10) for galaxy (cluster) halos**

- **The boost is not as uncertain as has been considered**

Backup slides

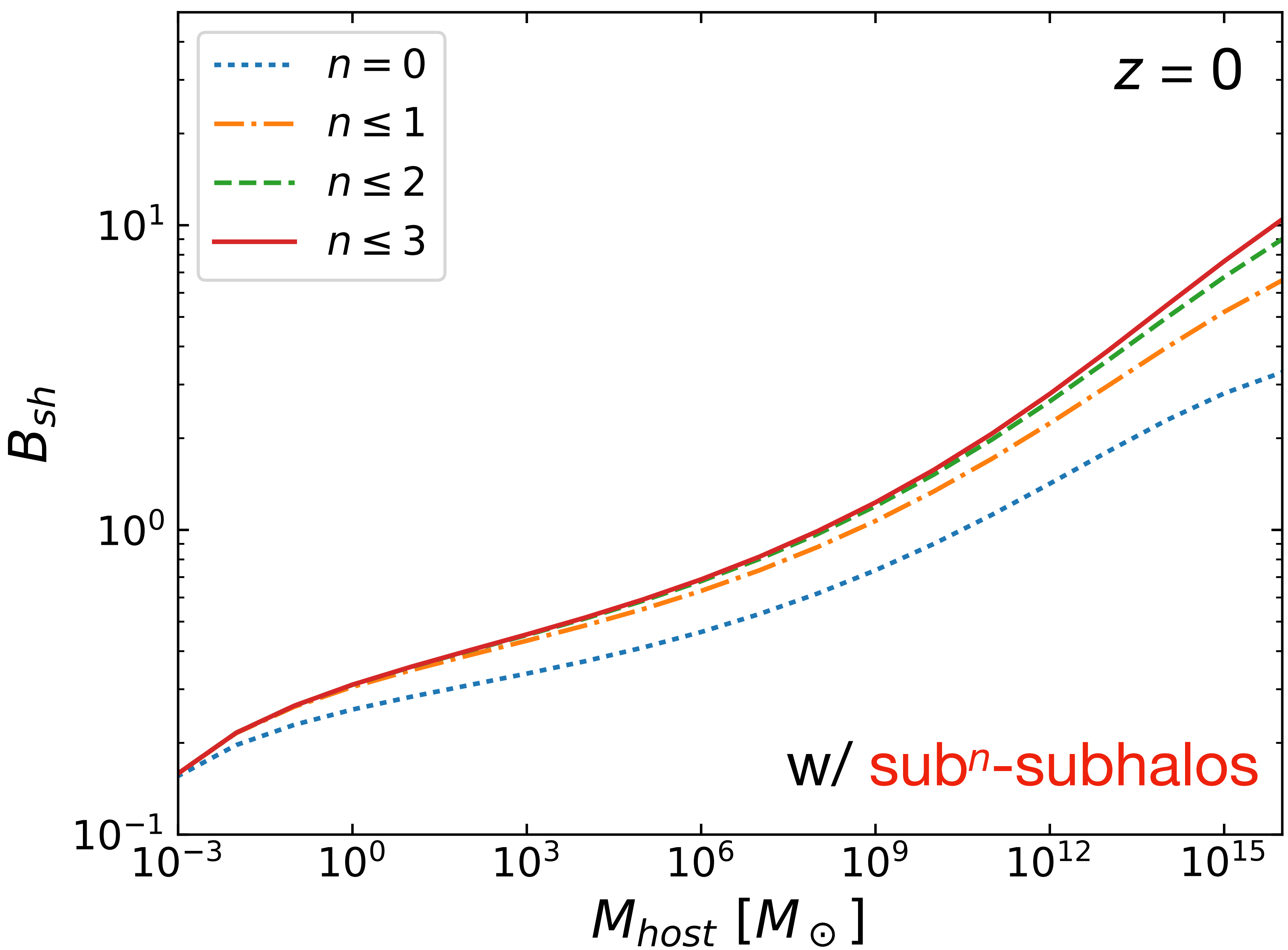
Subhalo mass function: Mass fraction in the subhalos



Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)

Annihilation boost

Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)



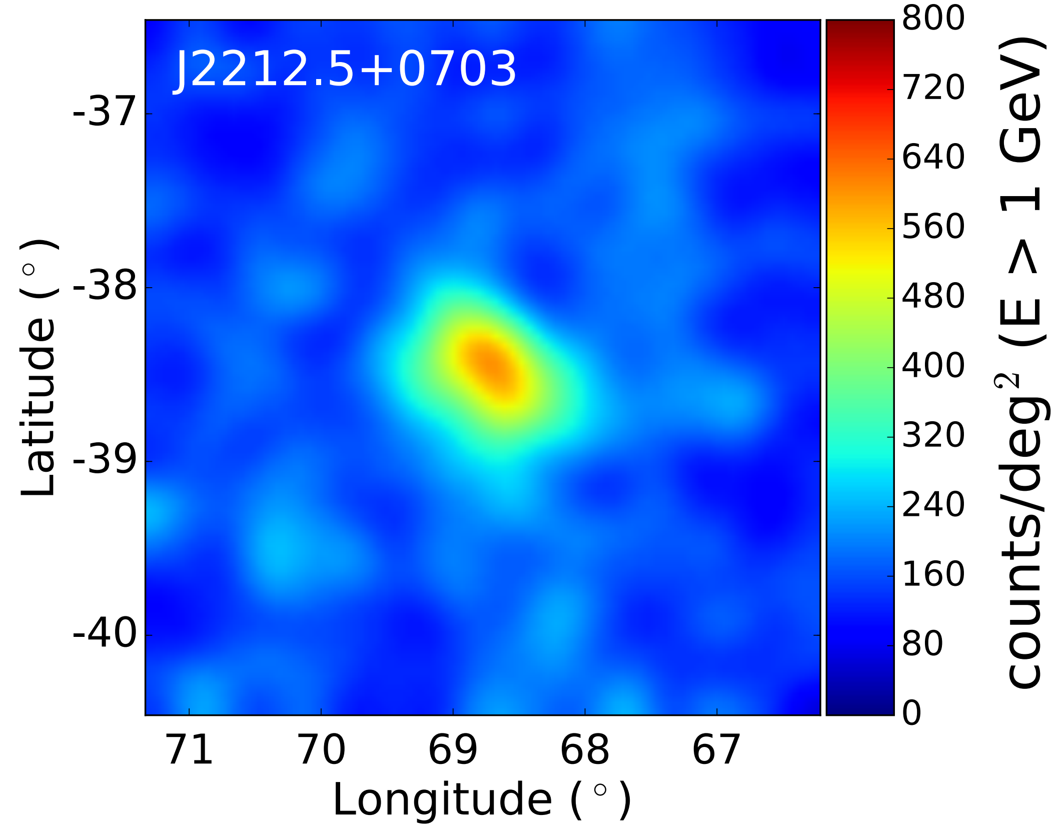
- Include effect of sub^n-subhalos iteratively
- They are assumed to be distributed following

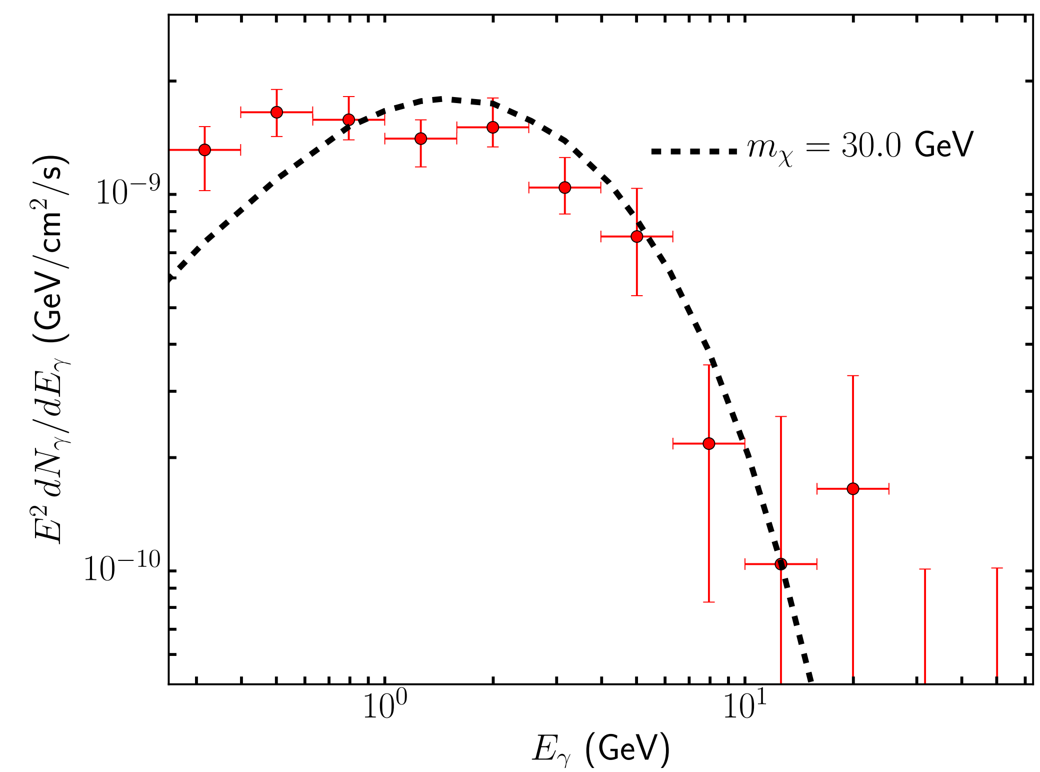
$$\propto [1 + (r/r_s)^2]^{-3/2}$$

- All the sub-subhalos outside of the tidal radius is assumed lost
- Important to include up to sub^2-substructures

Fermi unassociated sources

Bertoni et al., *JCAP* **1605**, 049 (2016)

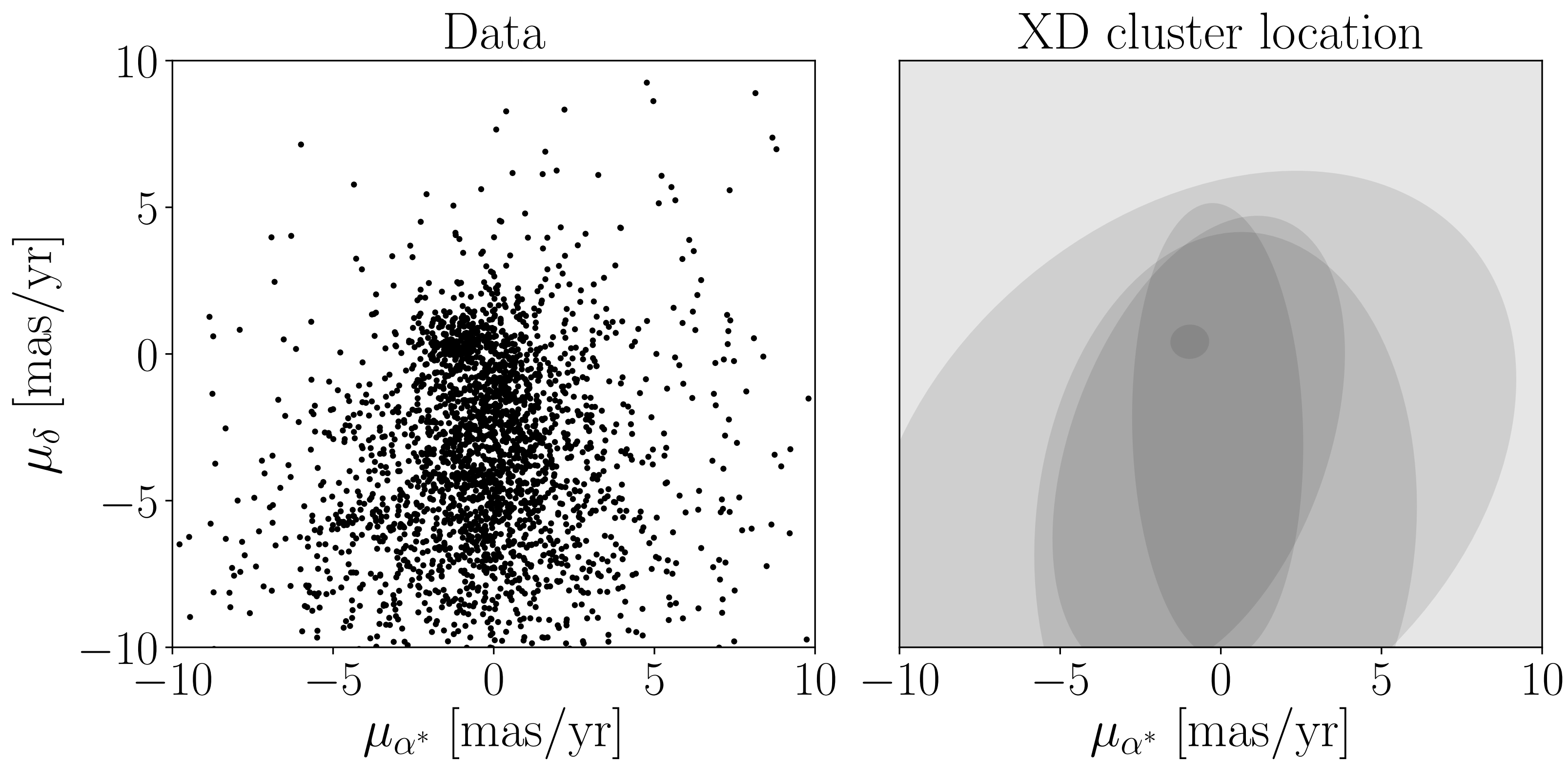




- There are several *extended* unassociated sources that might be compatible with dark matter annihilation from subhalos
- E.g., 3FGL J2212.5+0703 (Bertoni et al. 2016); 3FGL J1924+1034 (Xia et al. 2017)

Gaia DR2 search for subhalos

Simulation of 5000 M_{sun} stellar system at 10 kpc



Ciuca, Kawata, Ando, Calore, Read, Mateu, *Mon. Not. R. Astron. Soc.* **480**, 2284 (2018)

- No detection of dwarfs (subhalos) towards any of the 8 unassociated sources
- Gaia DR2 should be sensitive to subhalos with pre-infall mass of $>10^9$ M_{sun} within 20 kpc