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Kavli IPMU, 4 June 2019

Understanding halo substructure for indirect dark matter searches

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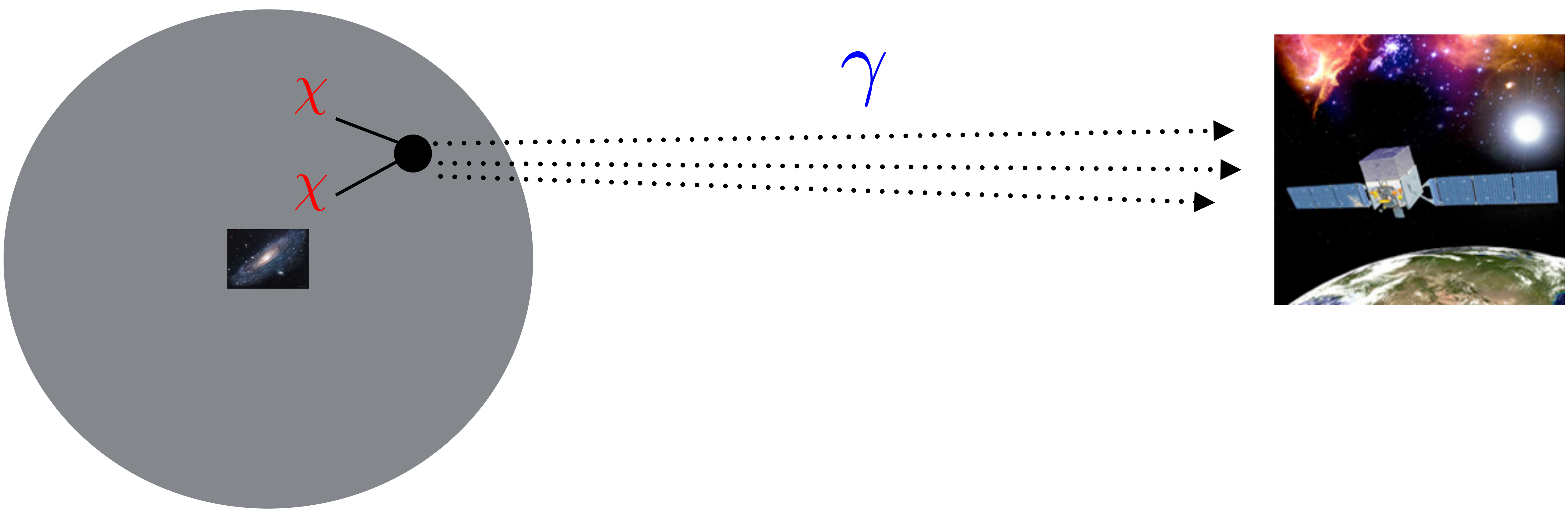
GRAPPA GRavitation AstroParticle Physics Amsterdam

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Indirect dark matter searches

Particle physics **Astrophysics**

$$I_\gamma(E_\gamma, \psi) = \overbrace{\frac{1}{2}\frac{\langle \sigma v \rangle}{m_\chi^2}\frac{dN_{\gamma,\mathrm{ann}}}{dE_\gamma}}^{\text{Particle physics}}\;\overbrace{\frac{1}{4\pi}\int d\ell\;\rho_\chi^2(r[\ell,\psi])}^{\text{Astrophysics}}$$



Density profiles of dark matter halos

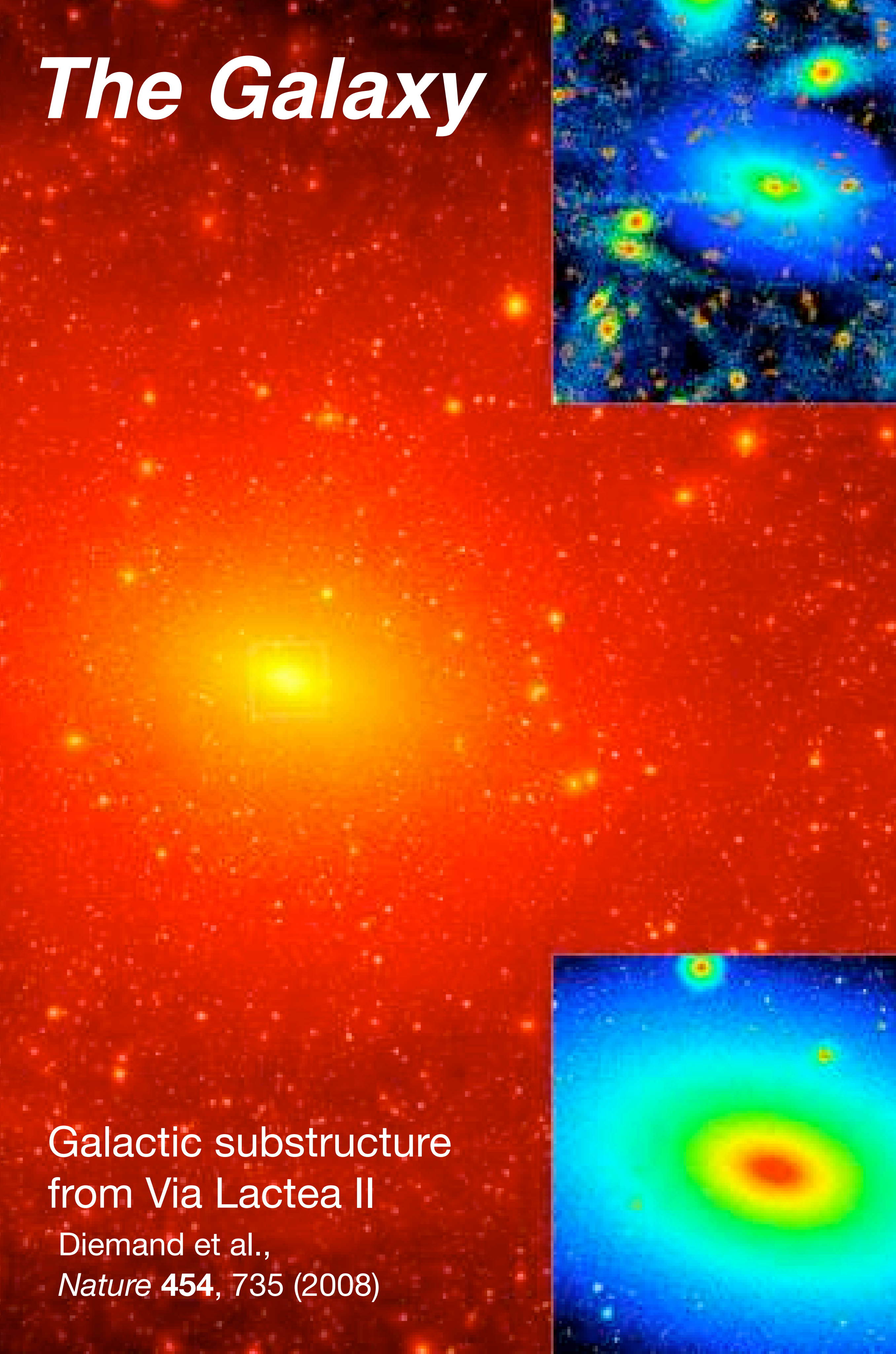
- Numerical simulations find that density profiles are well fitted with Navarro-Frenk-White (NFW) profile:

$$\rho(r) = \frac{\rho_s}{(r/r_s)(r/r_s + 1)^2}$$

- There are two parameters: r_s and ρ_s, both of which are functions of halo mass

- This is also supported by various observations (lensing measurements of galaxy clusters, etc.)

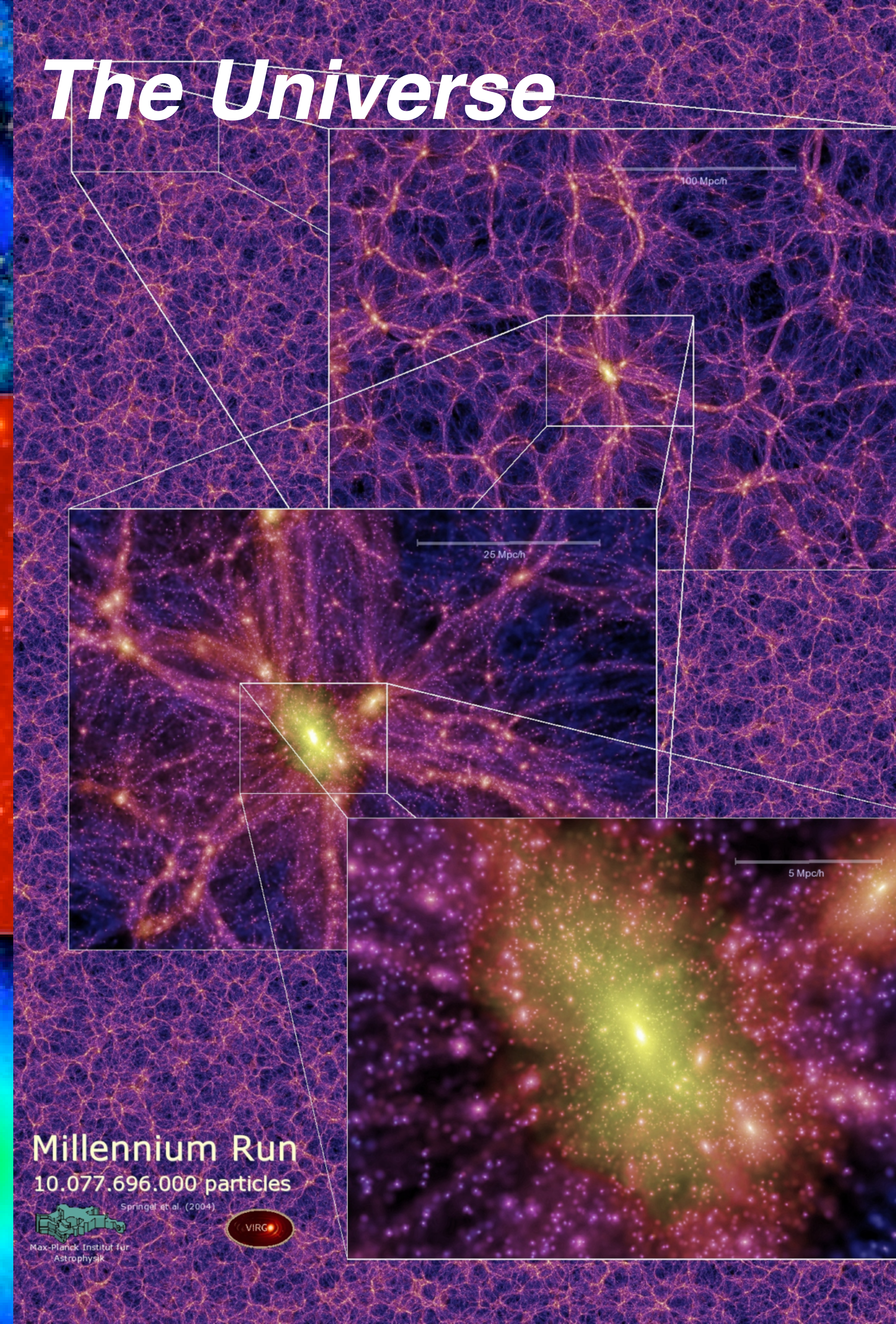
The Galaxy



Galactic substructure from Via Lactea II

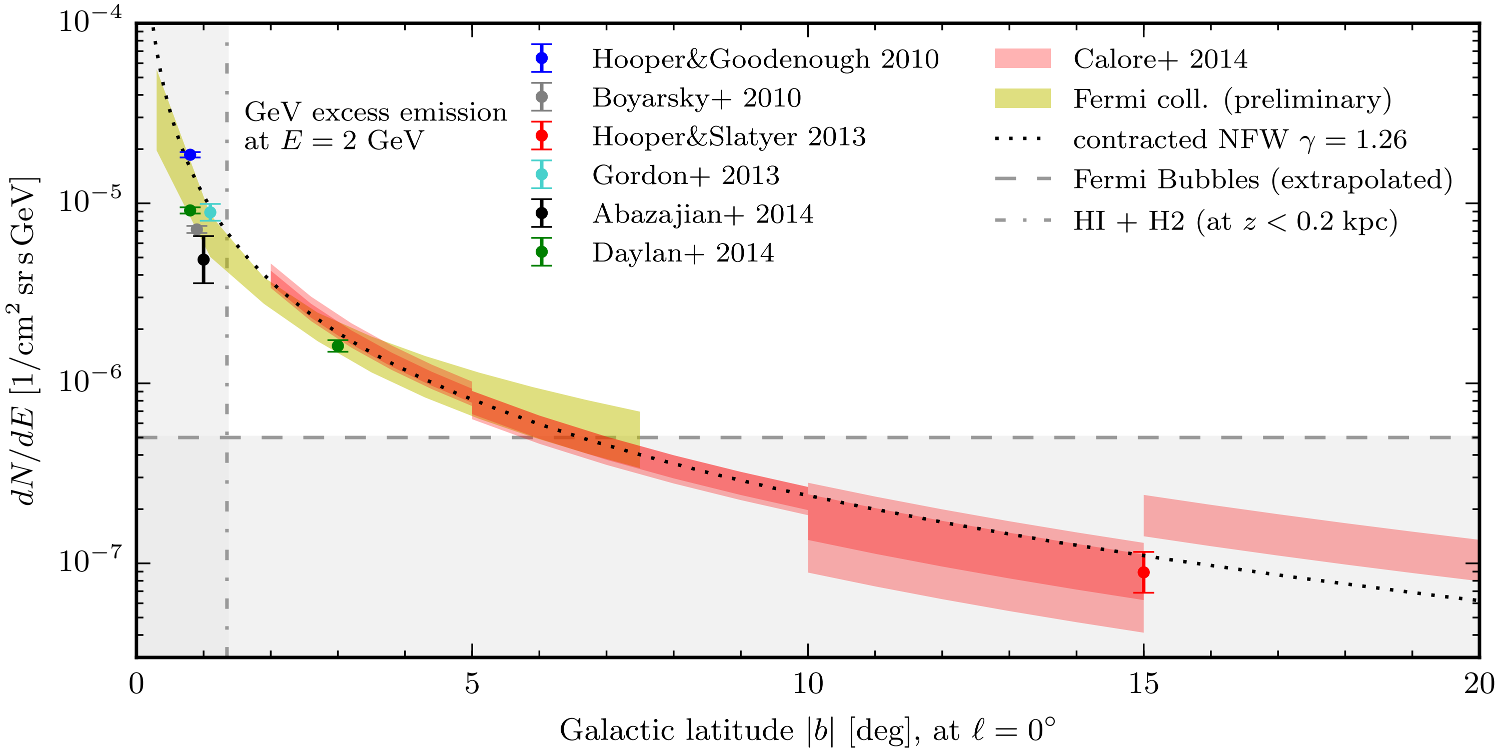
Diemand et al., *Nature* **454**, 735 (2008)

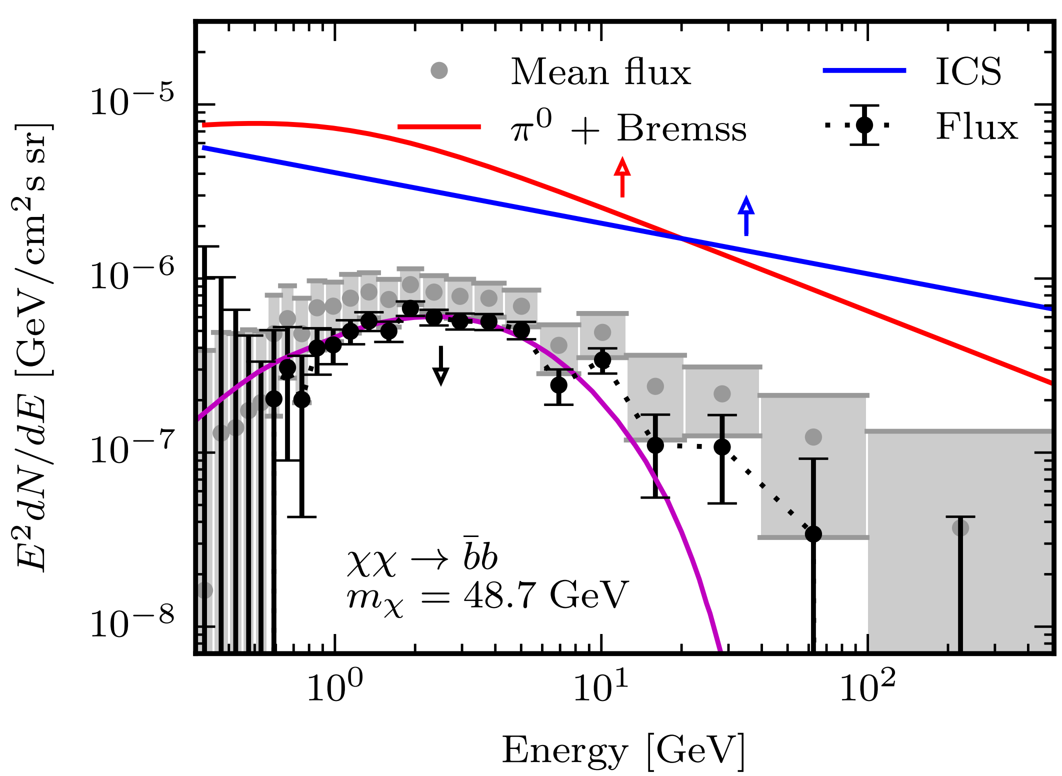
The Universe



GeV excess: Signals of dark matter annihilation?

Calore et al., *Phys. Rev. D* **91**, 063003 (2015)

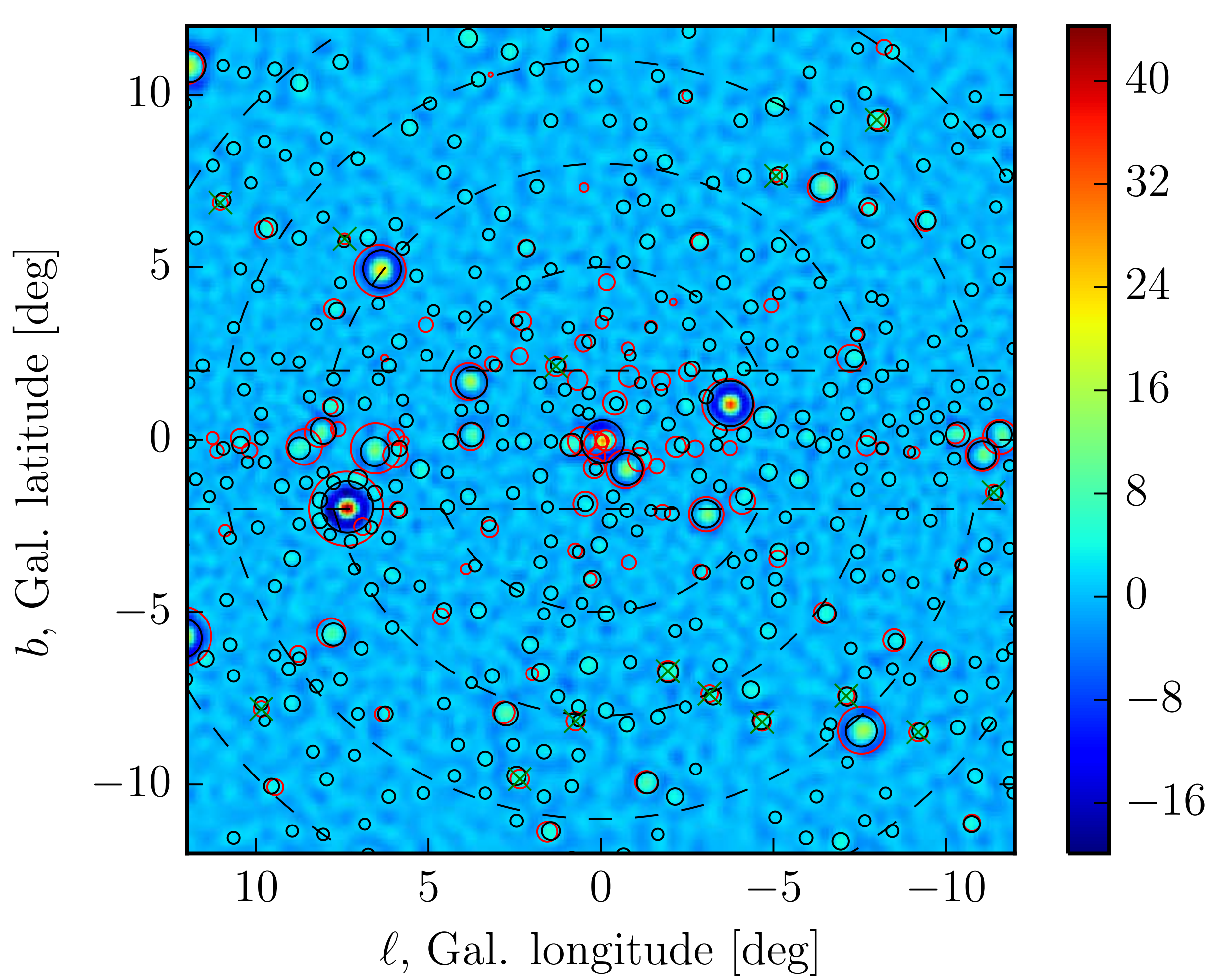




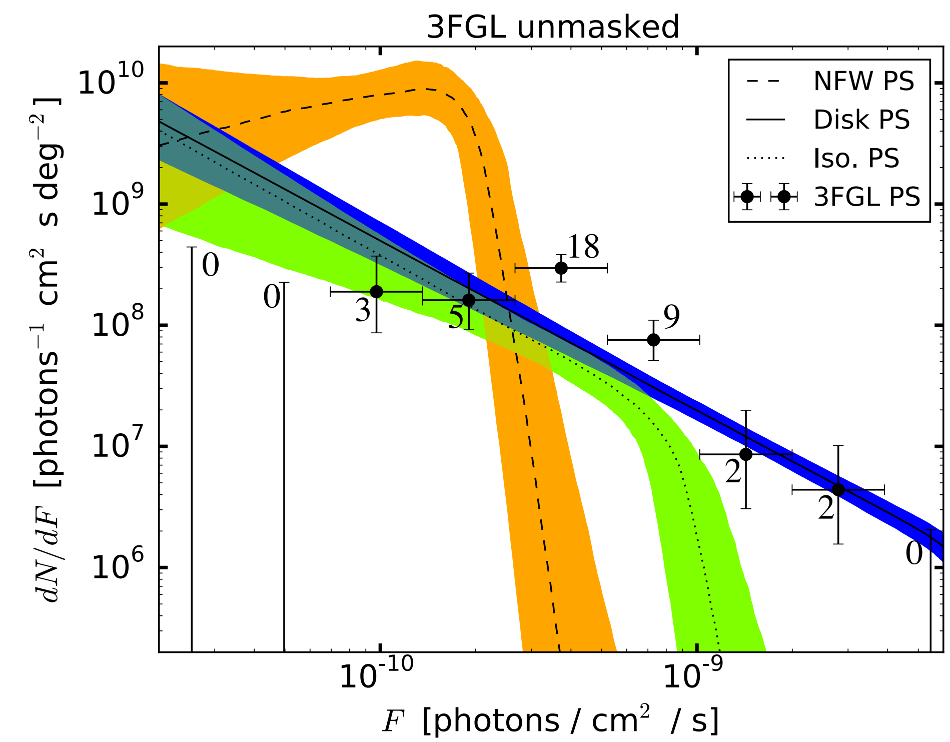
- Gamma-ray excess in GeV regime from the Galactic centre (many sigma) of unknown origin
- Brightness profile is consistent with NFW^2 (with inner slope of –1.26)
- Spectral shape is also consistent with expectation from annihilation
  - mass: ~50 GeV
  - cross section: ~2×10^{-26} cm^3 s^{-1}

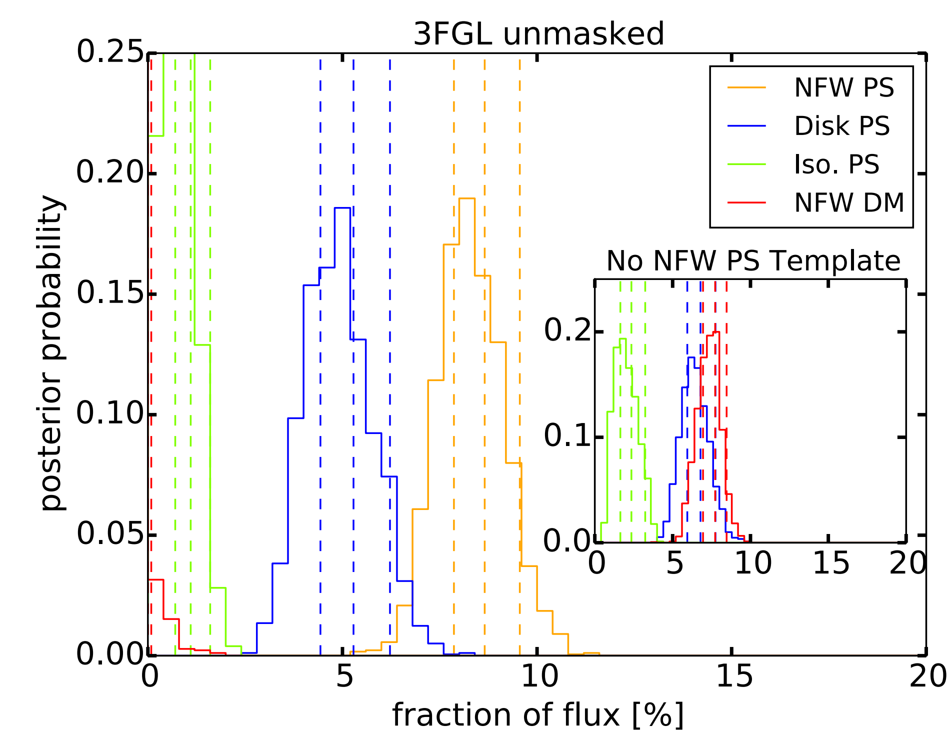
GeV excess: Evidence for astrophysical point sources?

Bartels et al., *Phys. Rev. Lett.* **116**, 051102 (2016)



- Two analyses (wavelet/flux distribution) both point towards point-source origin of the GeV excess
- The excess might be caused by unresolved astrophysical sources

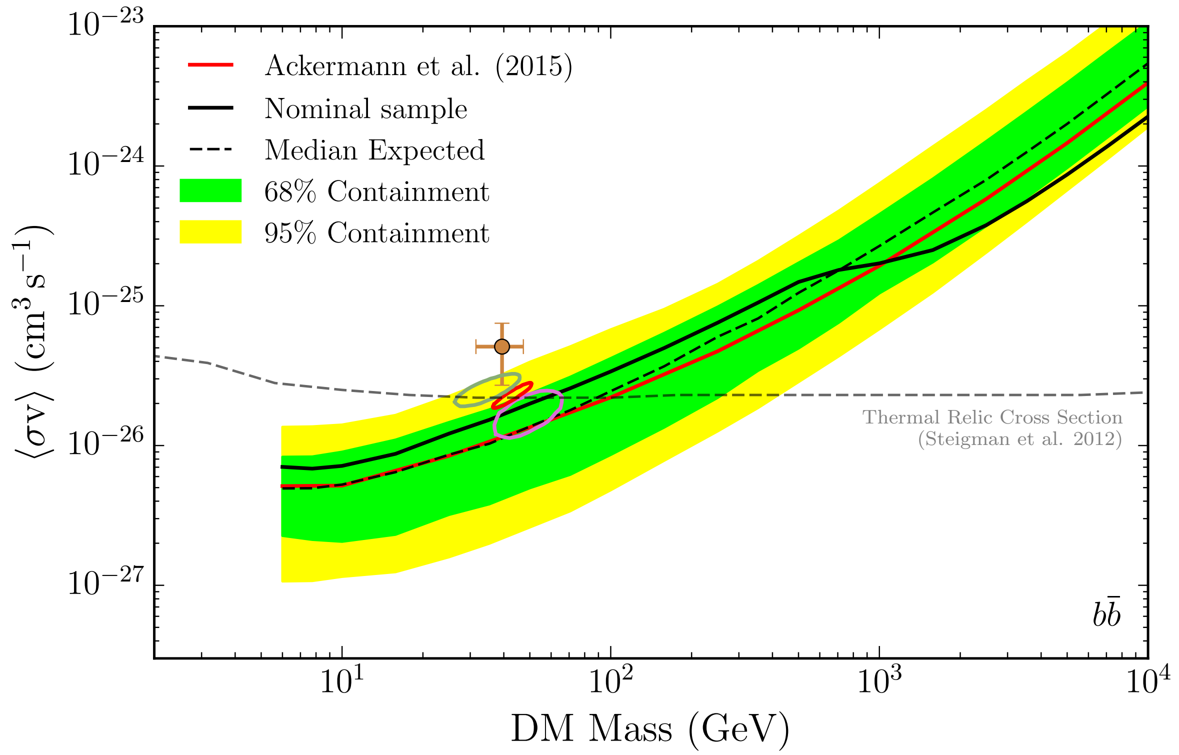


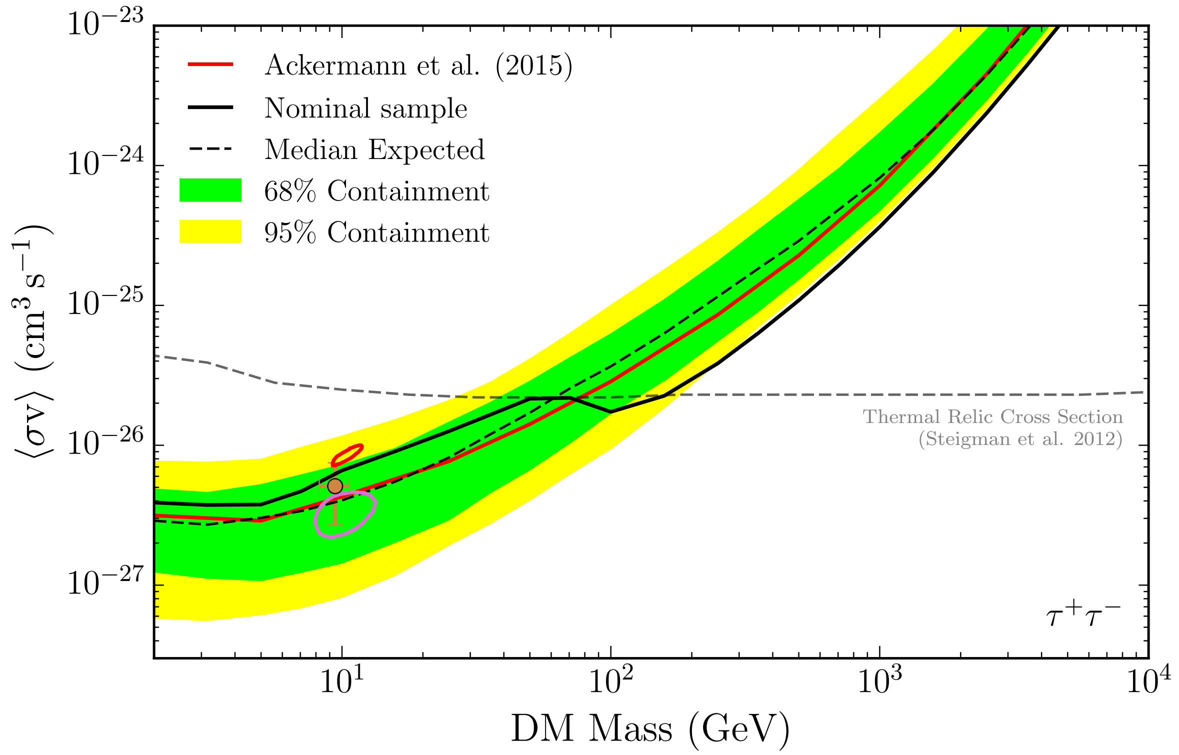


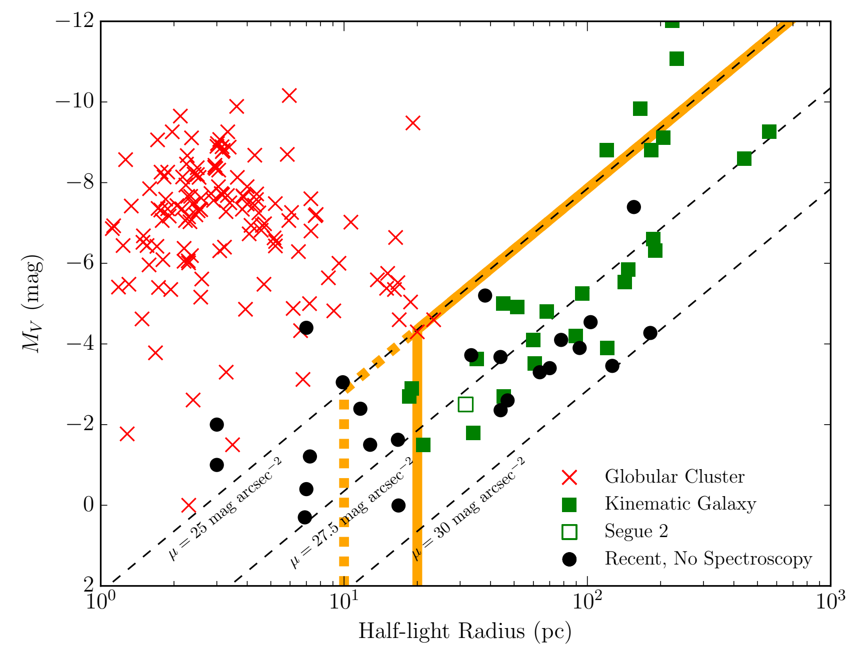
Lee et al., *Phys. Rev. Lett.* **116**, 051103 (2016)

DM constraints from dwarf spheroidal galaxies

Fermi-LAT, *Astrophys. J.* **834**, 110 (2017)

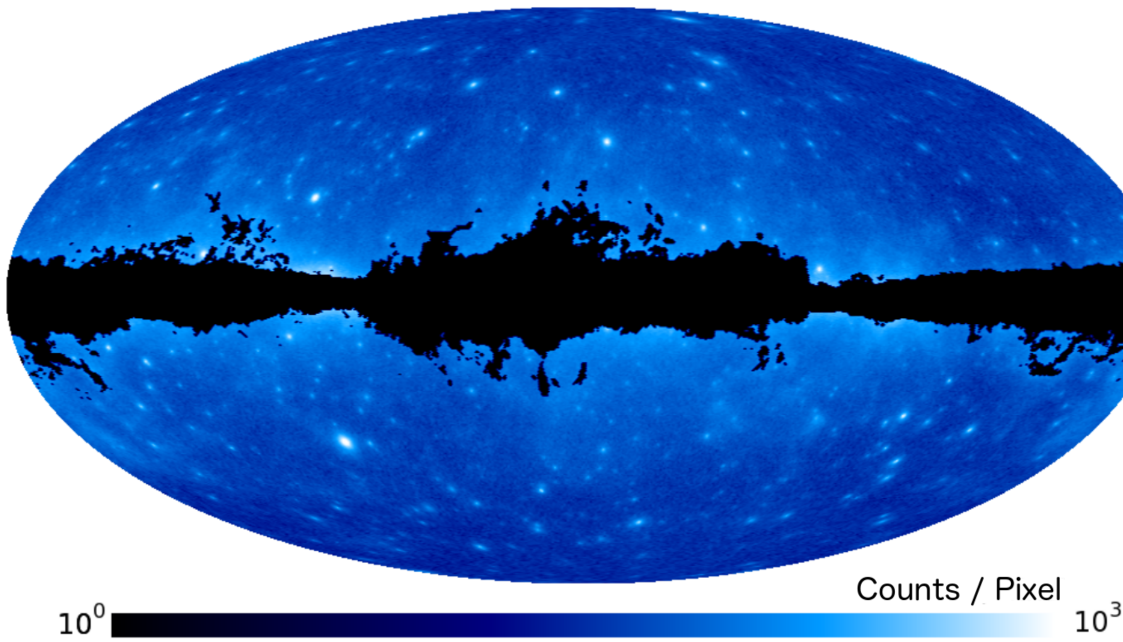




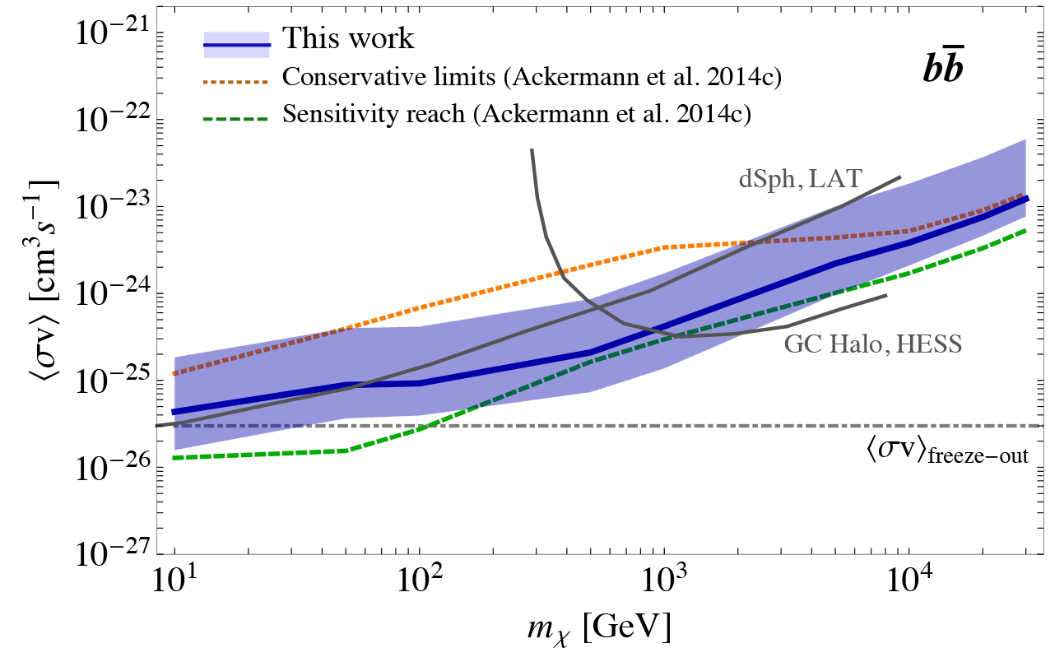


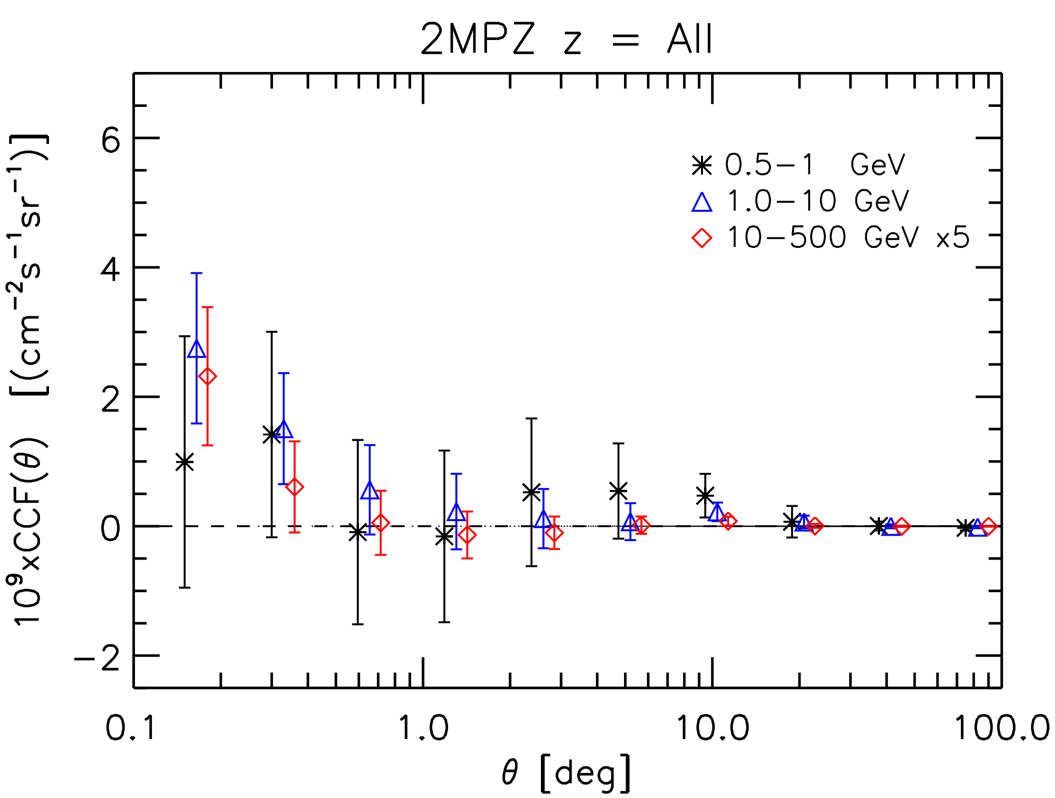
- Highly DM dominated system → suitable environment to test DM annihilation
  - Most robust constraints
- The latest results with PASS 8 data are pretty stringent
- They exclude the canonical cross section for WIMPs lighter than several tens of GeV
  - Nominal sample: 41 dwarfs
  - Ackermann et al. (2015): 15 dwarfs

Unresolved gamma-ray background

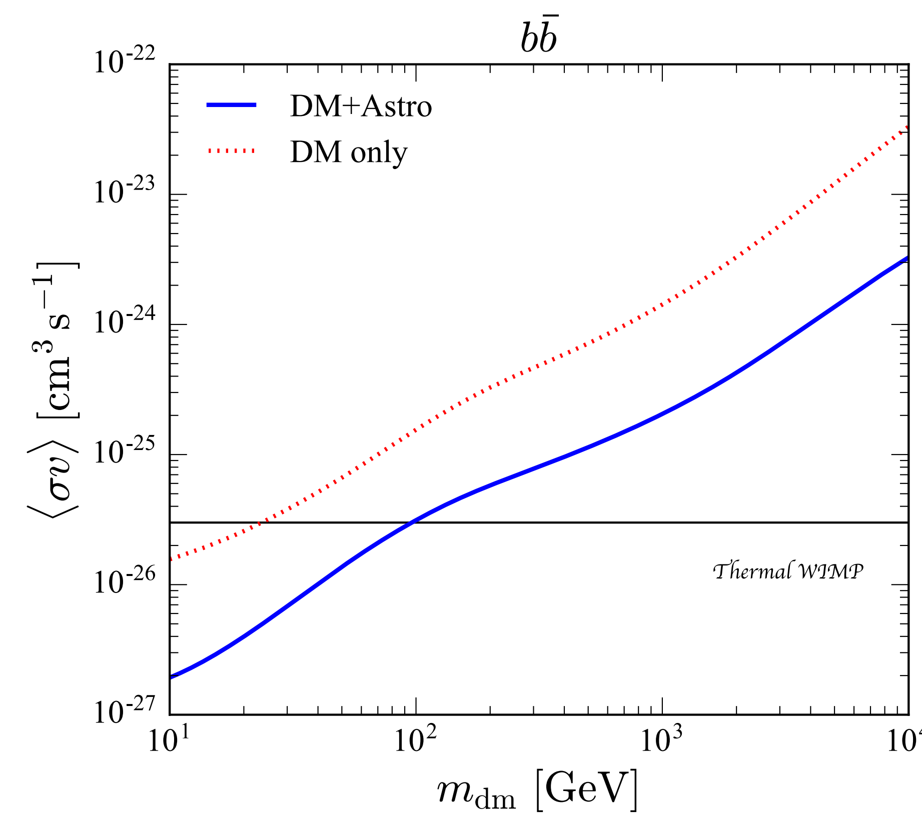


Ajello et al., *Astrophys. J.* **800**, L27 (2015)





Cuoco et al., *Astrophys. J. Suppl. Ser.* **232**, 10 (2017)



Ando, Ishiwata, *JCAP* **1606**, 045 (2016)

Dark matter subhalos

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

Why subhalos?

- **Dwarf galaxies from in 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
- Hence subhalos are relevant for **all the indirect DM searches except for Galactic center region**
- **Subhalo statistics** is important discriminant of different dark matter candidates (cold, warm, self-interacting?)

Annihilation boost

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

$$B_{\rm sh}(M) = \frac{1}{L_{\rm host}(M)} \int dm \frac{dN}{dm} L_{\rm sh}(m)[1 + B_{\rm ssh}(m)]$$

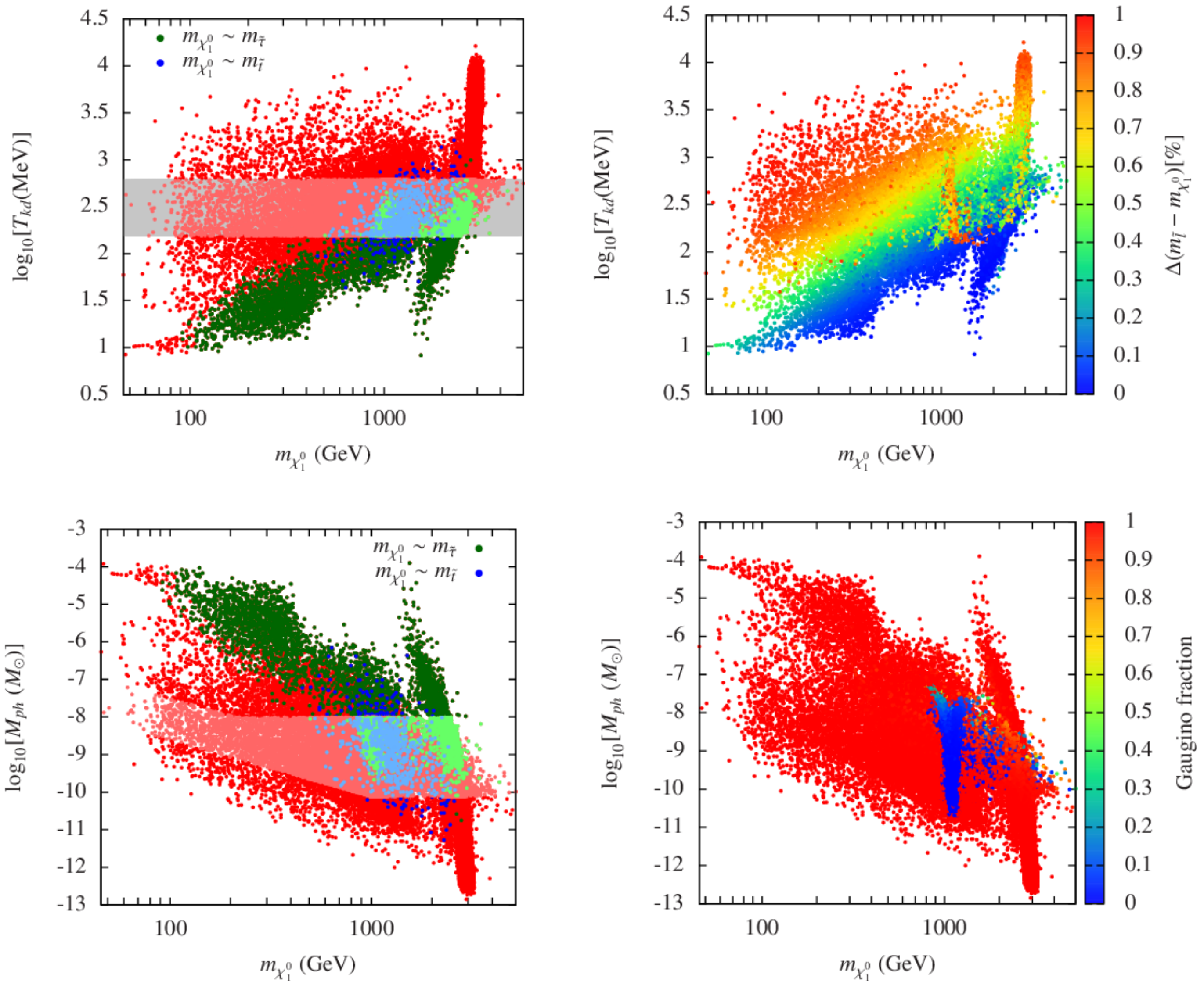
http://wwwmpa.mpa-garching.mpg.de/aquarius/

Motivation for physics

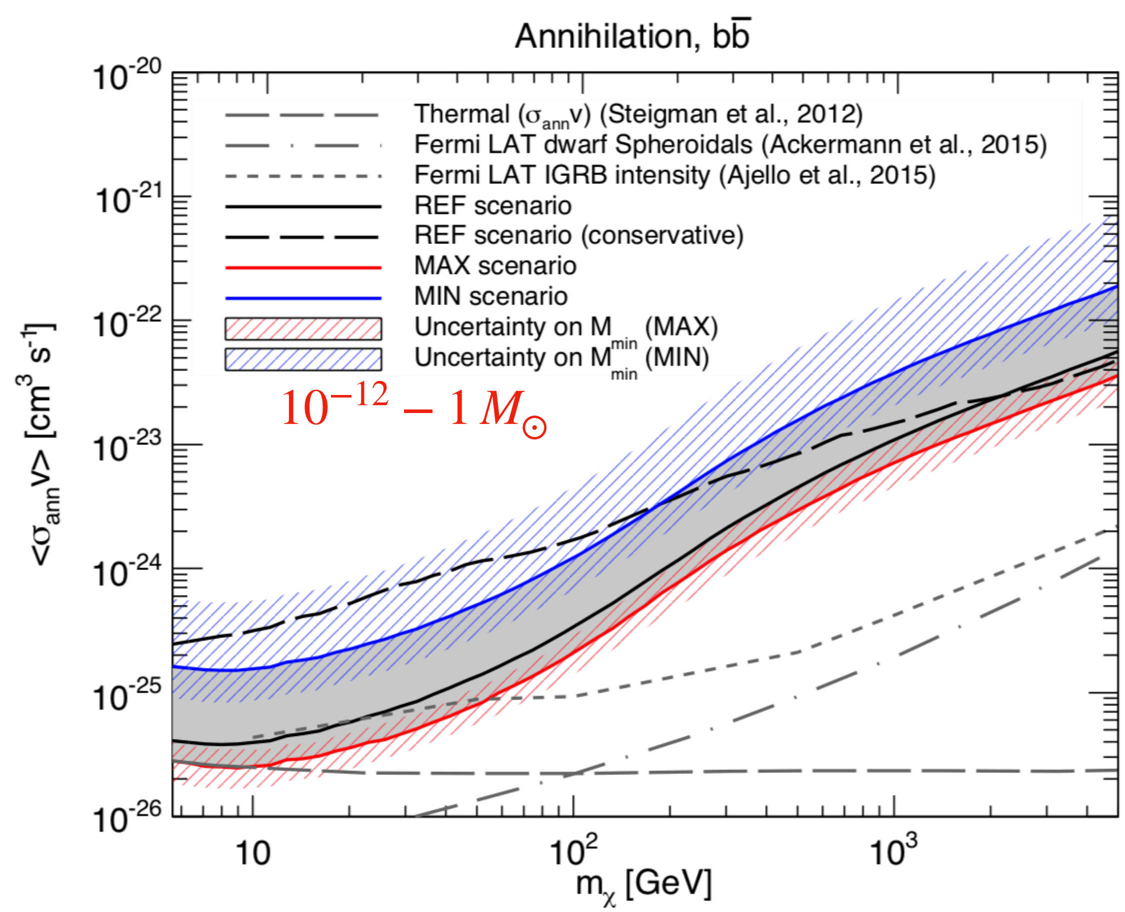
- Help increase the rate of dark matter annihilation
- Mass of smallest halos is determined by scattering between dark matter and SM particles (**kinetic decoupling** + free-streaming)
- Boost factor depends on **primordial power spectrum at small scales**

Impact of the smallest structure

Diamanti, Cabrera-Catalan, Ando, *Phys. Rev. D* **92**, 065029 (2015)



Fornasa et al. *Phys. Rev. D* **94**, 123005 (2016)

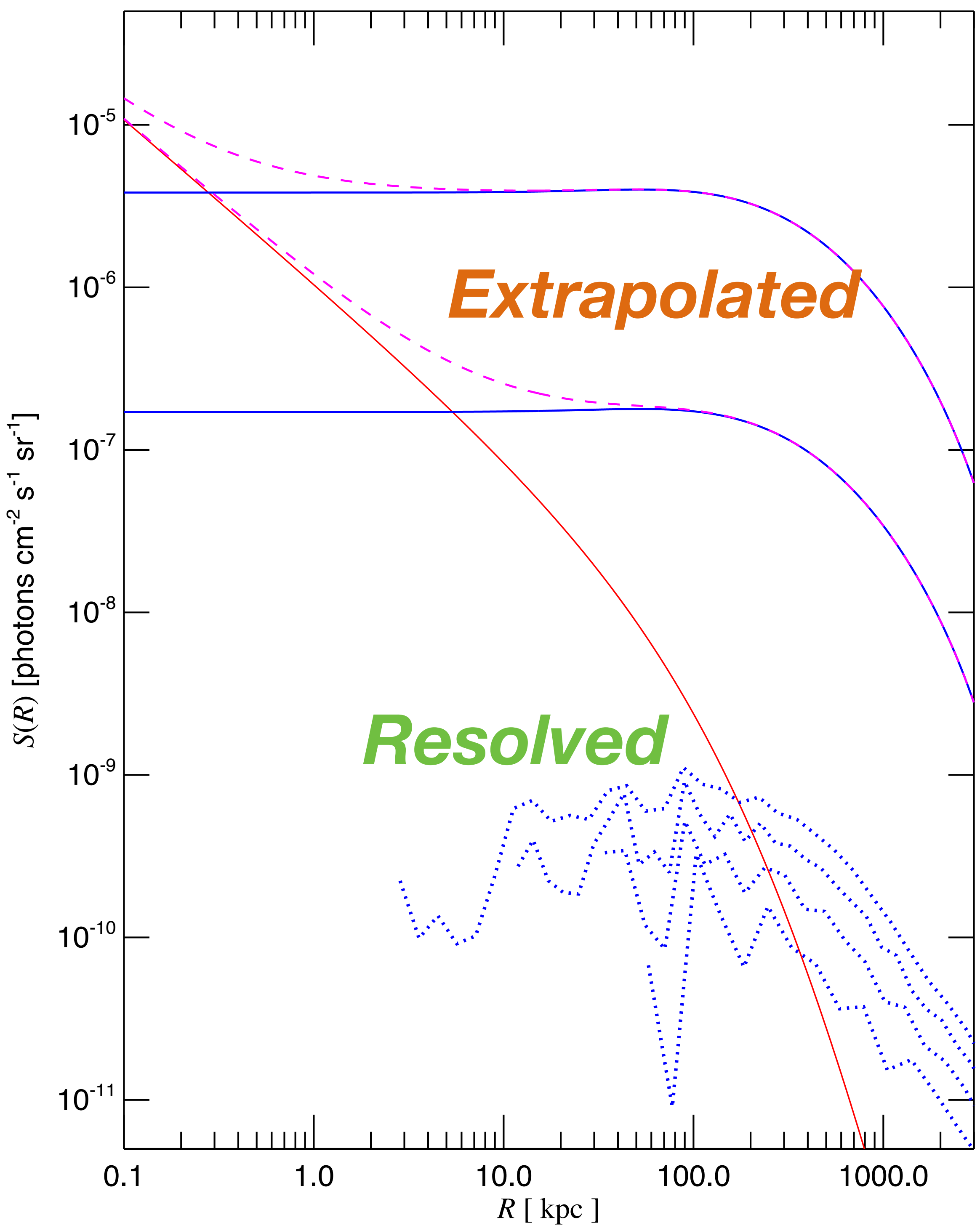


- MCMC parameter scan for 9-parameter MSSM

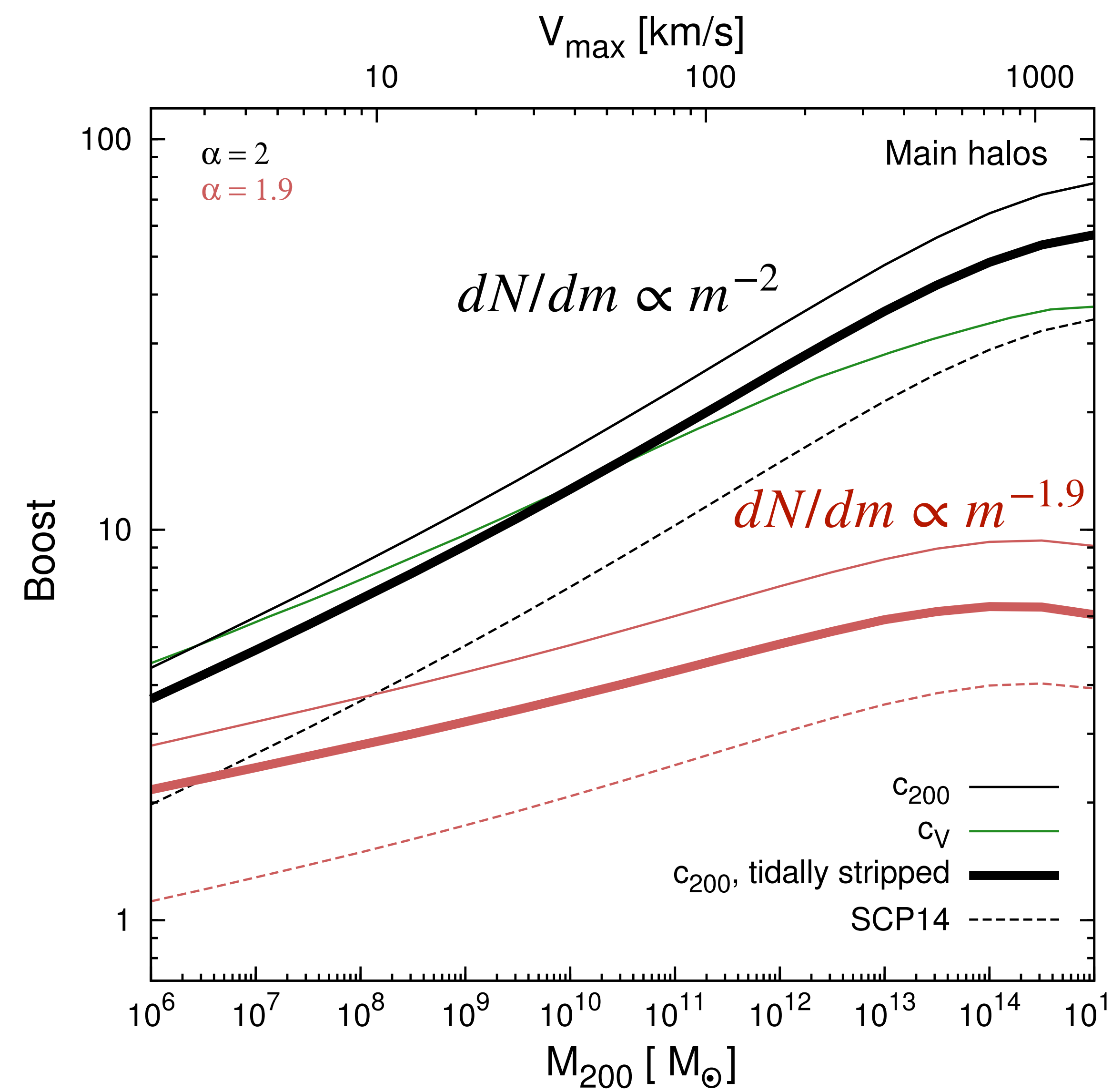
Typical smallest halo mass:

$$10^{-12} - 10^{-4} M_\odot$$

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 models 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 **calibrated with simulations** at resolved scales

Content

- Model description and test against numerical simulations 1803.07691 1903.11427
- Application to indirect dark matter searches
  - **Annihilation boost factor** 1803.07691 1903.11427
  - ***Satellite prior*** for dwarf *J*-factor estimates In progress
  - Prospects for **LSST dwarfs** 1905.07128
  - Gaia searches for subhalo counterparts in **Fermi unassociated sources** 1805.02588

Collaborators

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Analytic modeling

Structures start to form

Initial condition:
Primordial power spectrum

Smaller halos merge and accrete to form larger ones

Extended Press-Schechter formalism

Subhalos experience mass loss

Modeling for tidal stripping and mass-loss rate

Formulation

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

Conventional formula

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

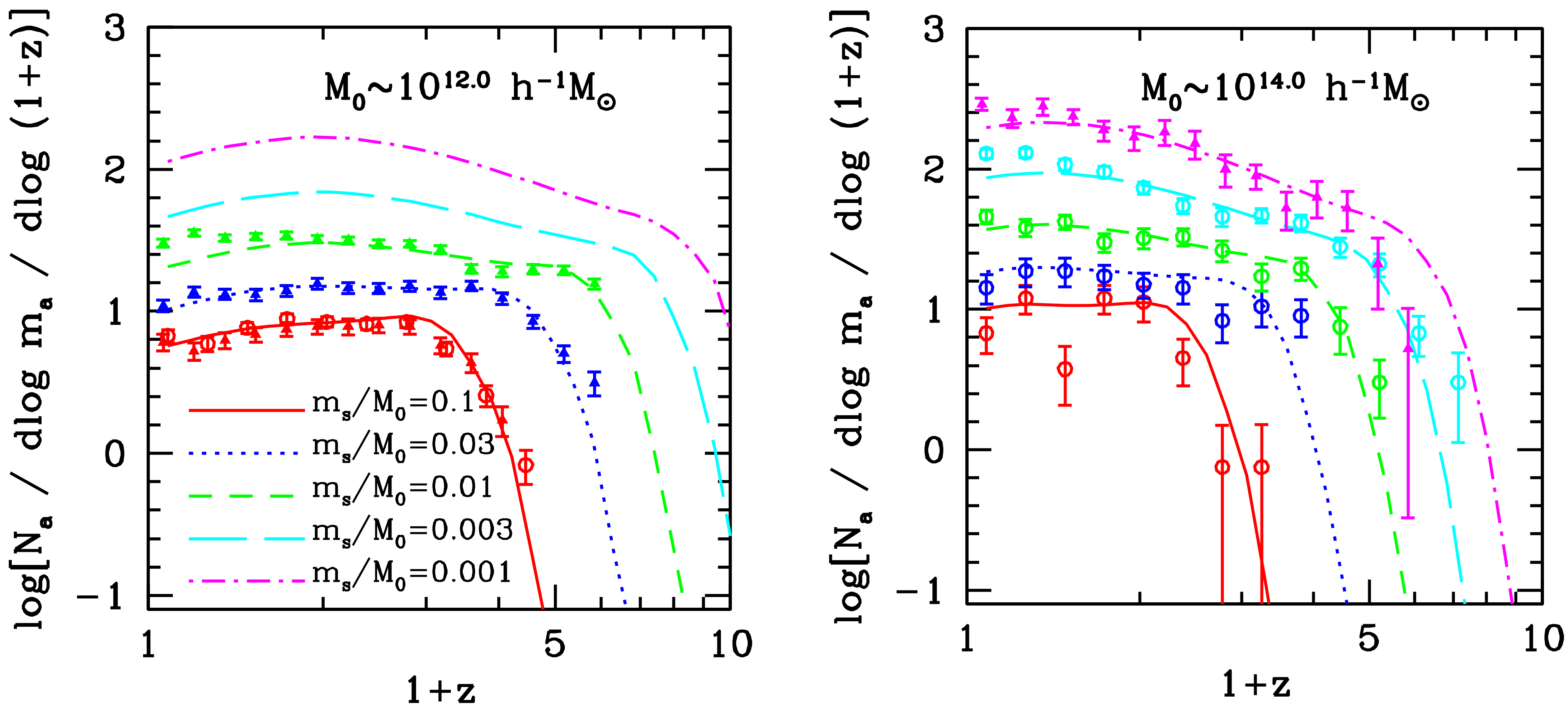
Halo formation and accretion history

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

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

- Primordial power spectrum + cutoff scale will change rms over-density σ(*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

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

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

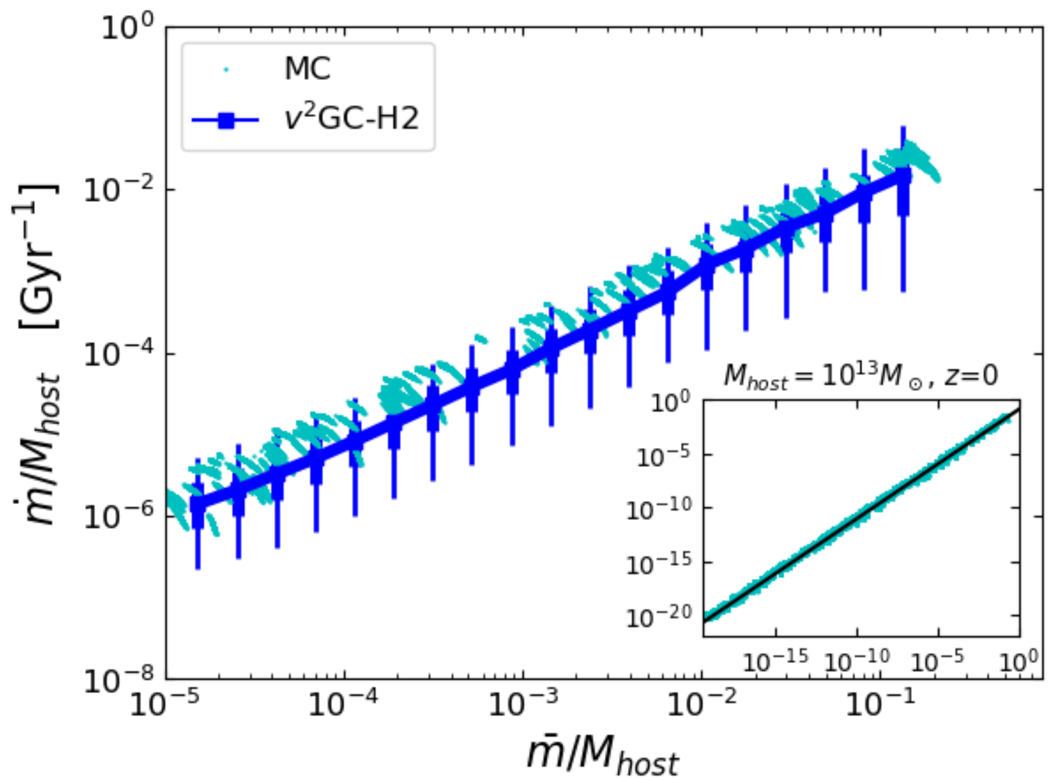
Luminosity of the subhalo at z

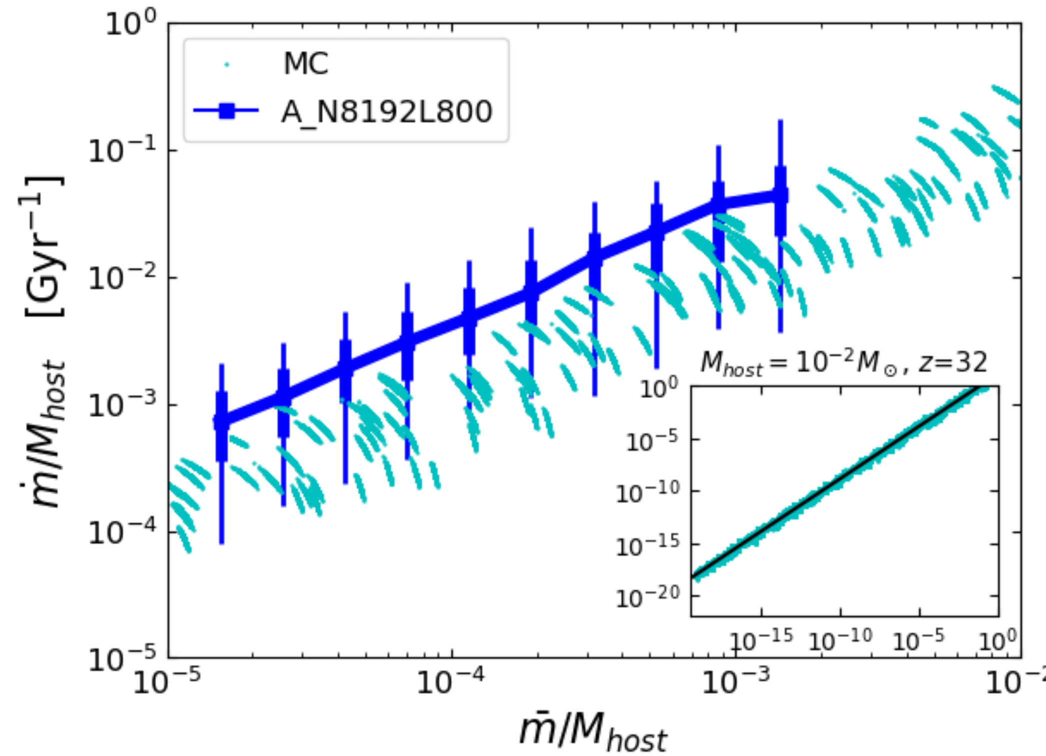
$$L_{\rm sh}(z\,|\,m_{\rm acc}, z_{\rm acc}) \propto \rho_s^2(z\,|\,m_{\rm acc}, z_{\rm acc}) r_s^3(z\,|\,m_{\rm acc}, z_{\rm acc}) \left\{ 1 - \frac{1}{[1 + r_t(z\,|\,m_{\rm acc}, z_{\rm acc})/r_s(z\,|\,m_{\rm acc}, z_{\rm acc})]^3} \right\}$$

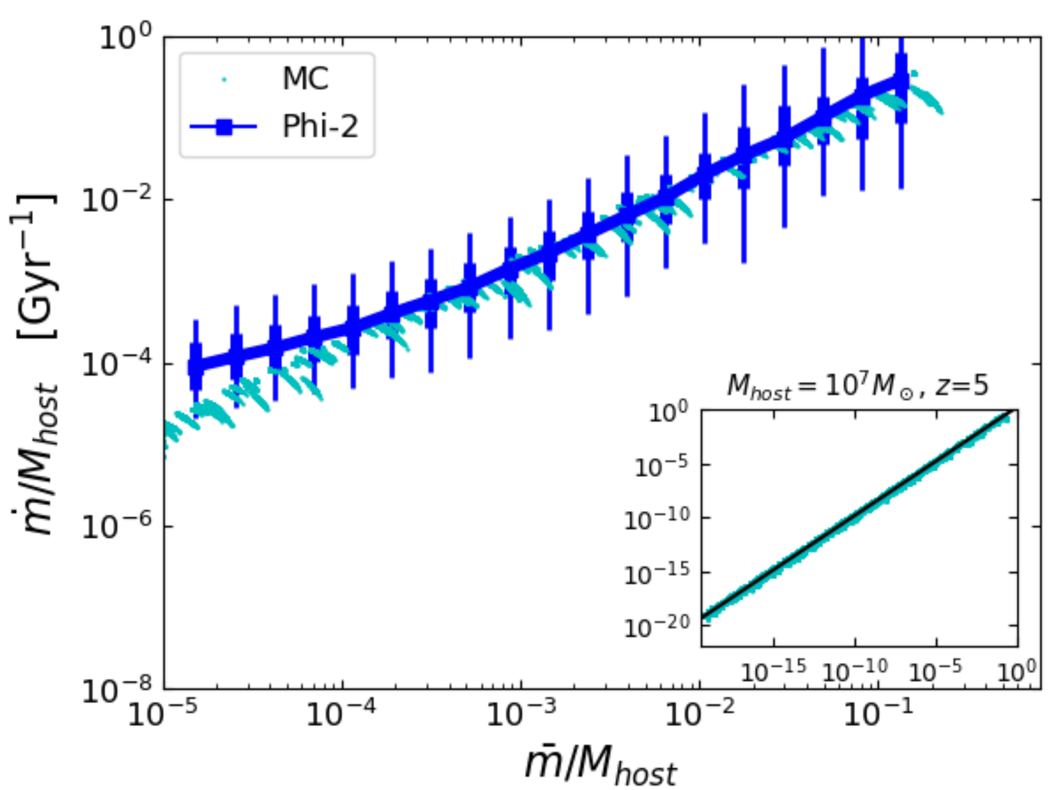
Parameters subhalo density profile **after tidal mass loss**

Subhalo mass loss

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



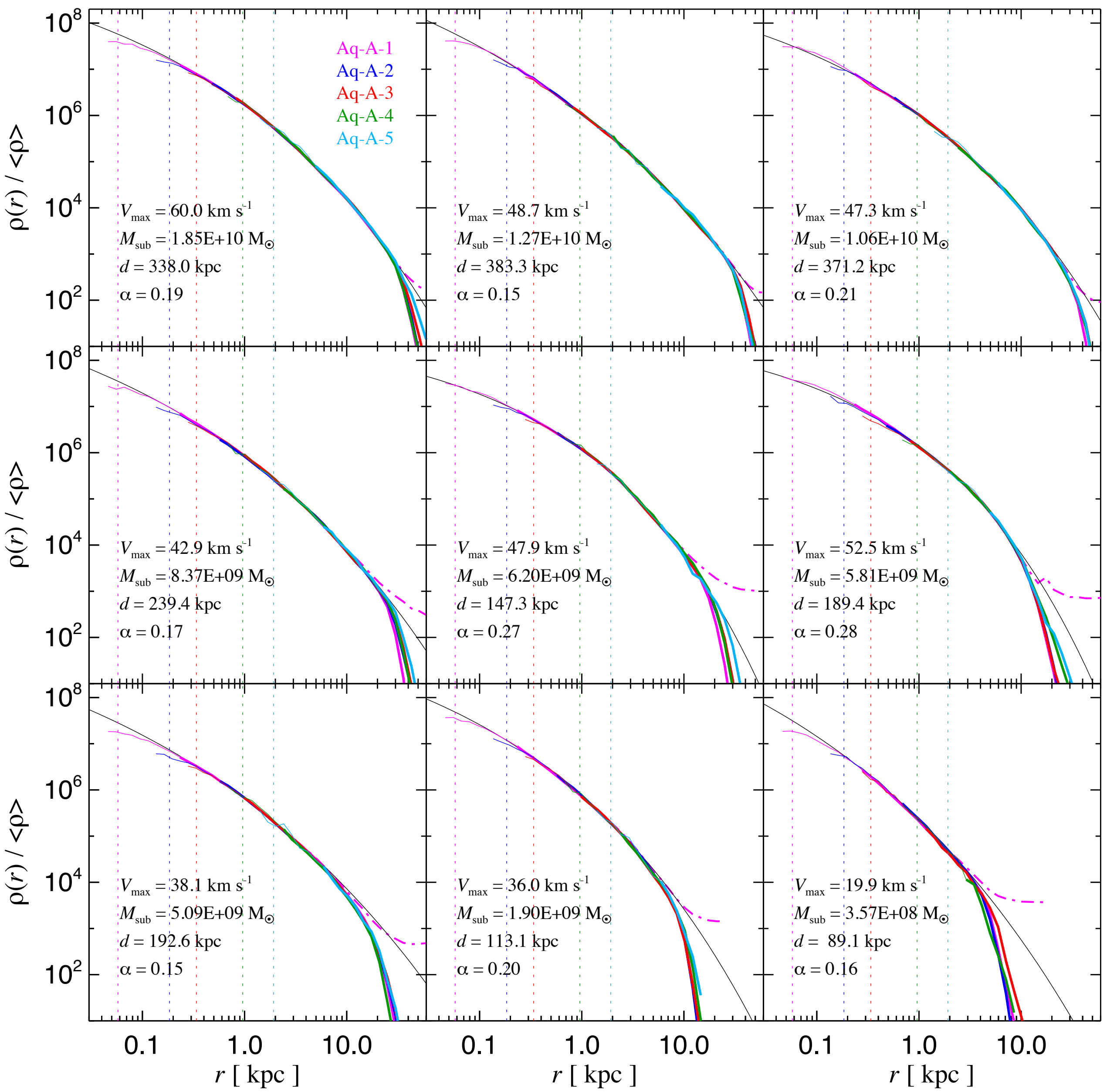




- Monte Carlo approach following Jiang & van den Bosch (2016)
  - Determine orbital energy and angular momentum
  - Assume the subhalo loses all the masses outside of its tidal radius instantaneously at its peri-center passage
- Mass-loss rate follows power law for wide range of *m/M*

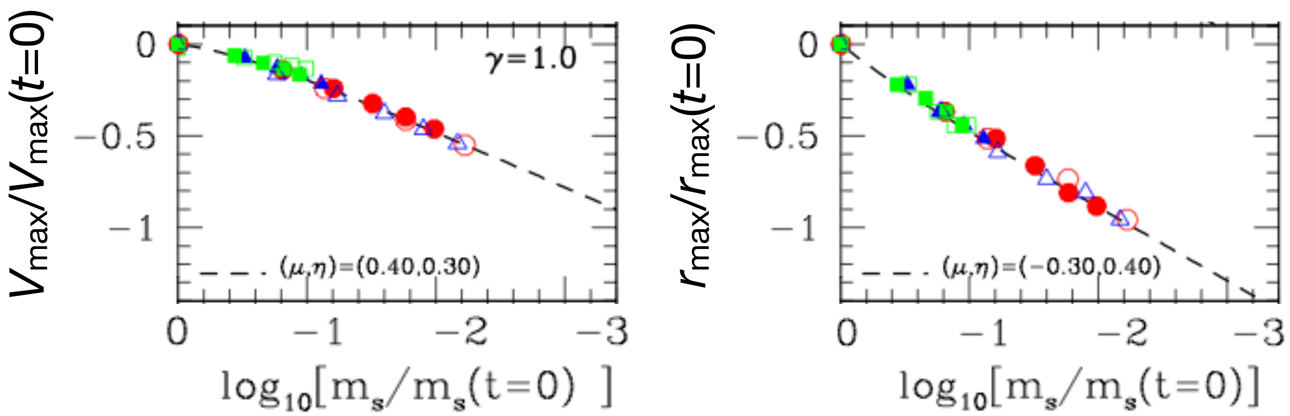
Subhalo density profile after mass loss

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



Truncated NFW

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 $\boldsymbol{\rho_s}$ and $\boldsymbol{r_s}$ following Penarrubia et al. (2010)
3. Obtain truncation radius $\boldsymbol{r_t}$ by solving

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

Results

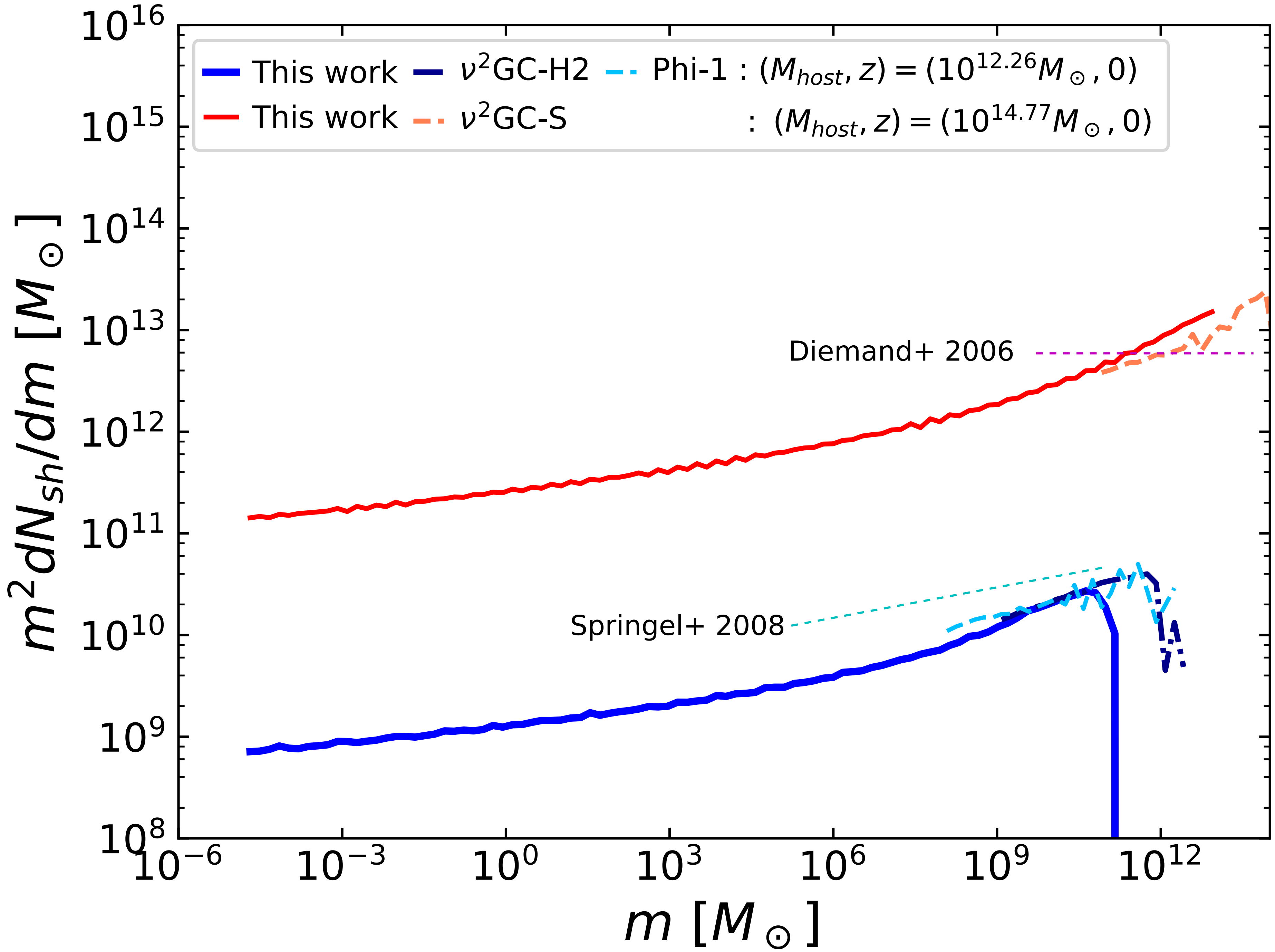
Subhalo mass function and annihilation boosts

Comparison with simulations

Name		N	L	Softening	m_{p} ($\mathrm{M}_{\odot}$)	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)

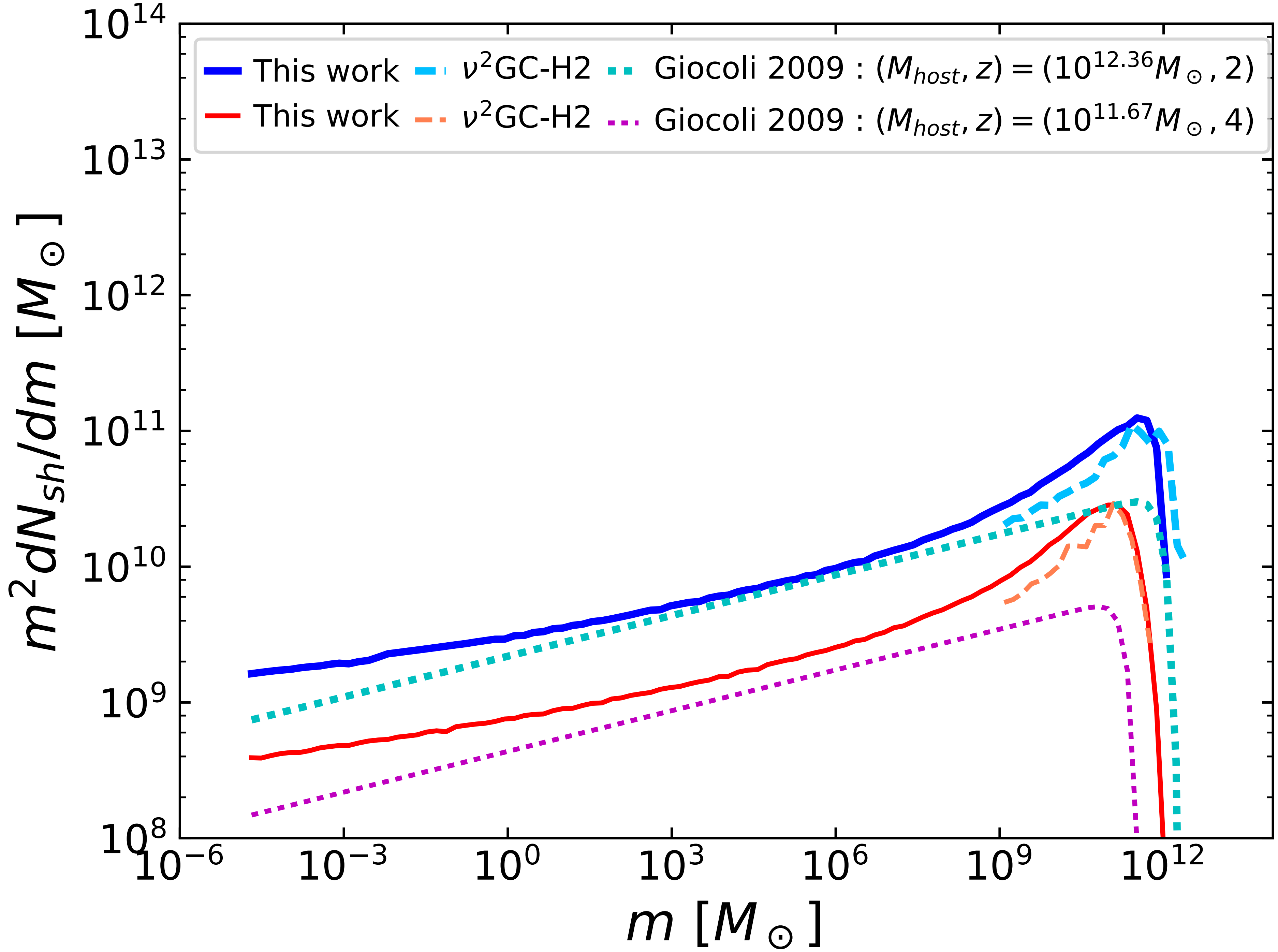
[38] Ishiyama et al., *Pulb. Astron. Soc. Jap.* **67**, 61 (2015)
[44] Makiya et al., *Pulb. Astron. Soc. Jap.* **68**, 25 (2016)

Subhalo mass function: Clusters and galaxies



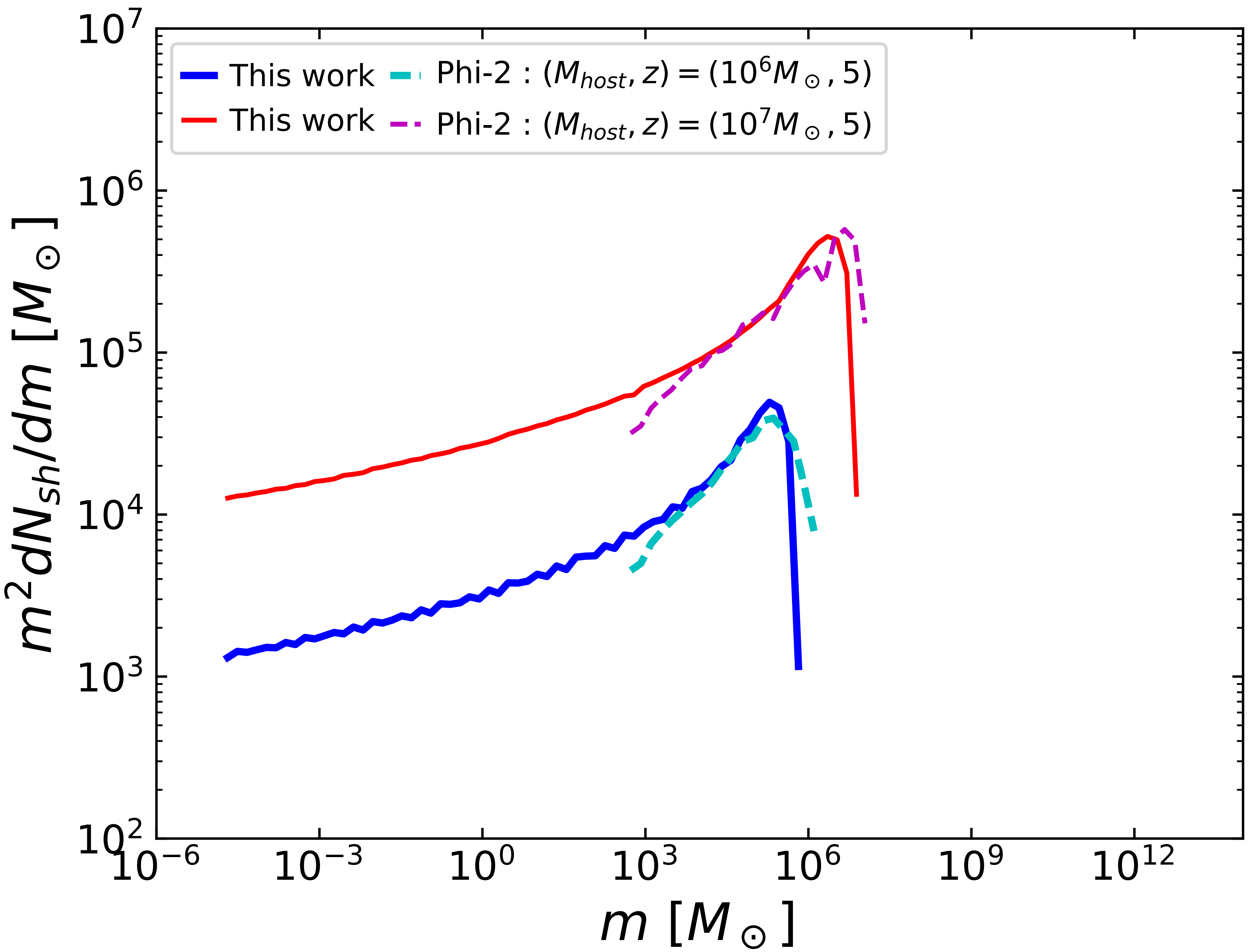
Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)

Subhalo mass function: Galaxies at z=2,4



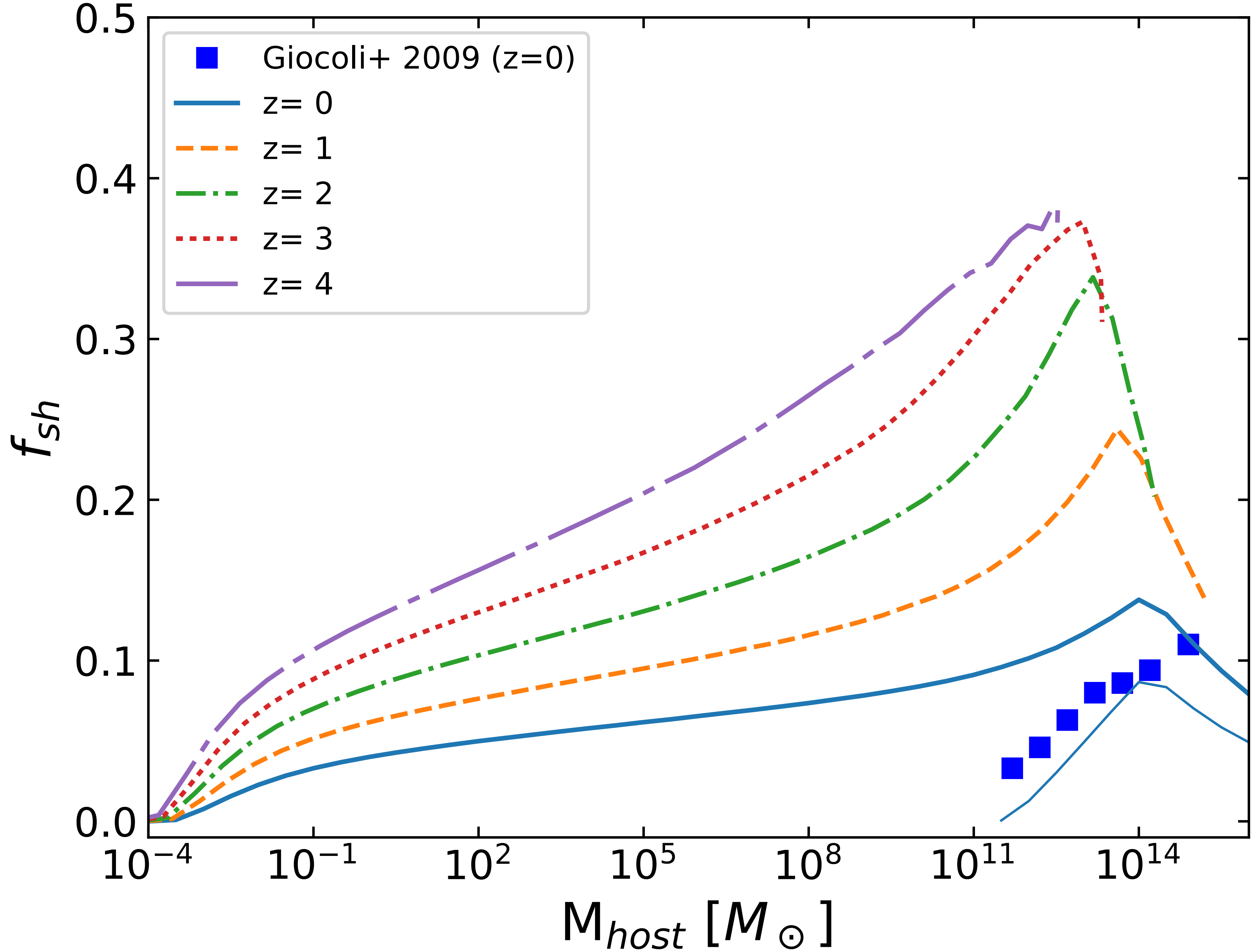
Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)

Subhalo mass function: Dwarfs at z=5



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

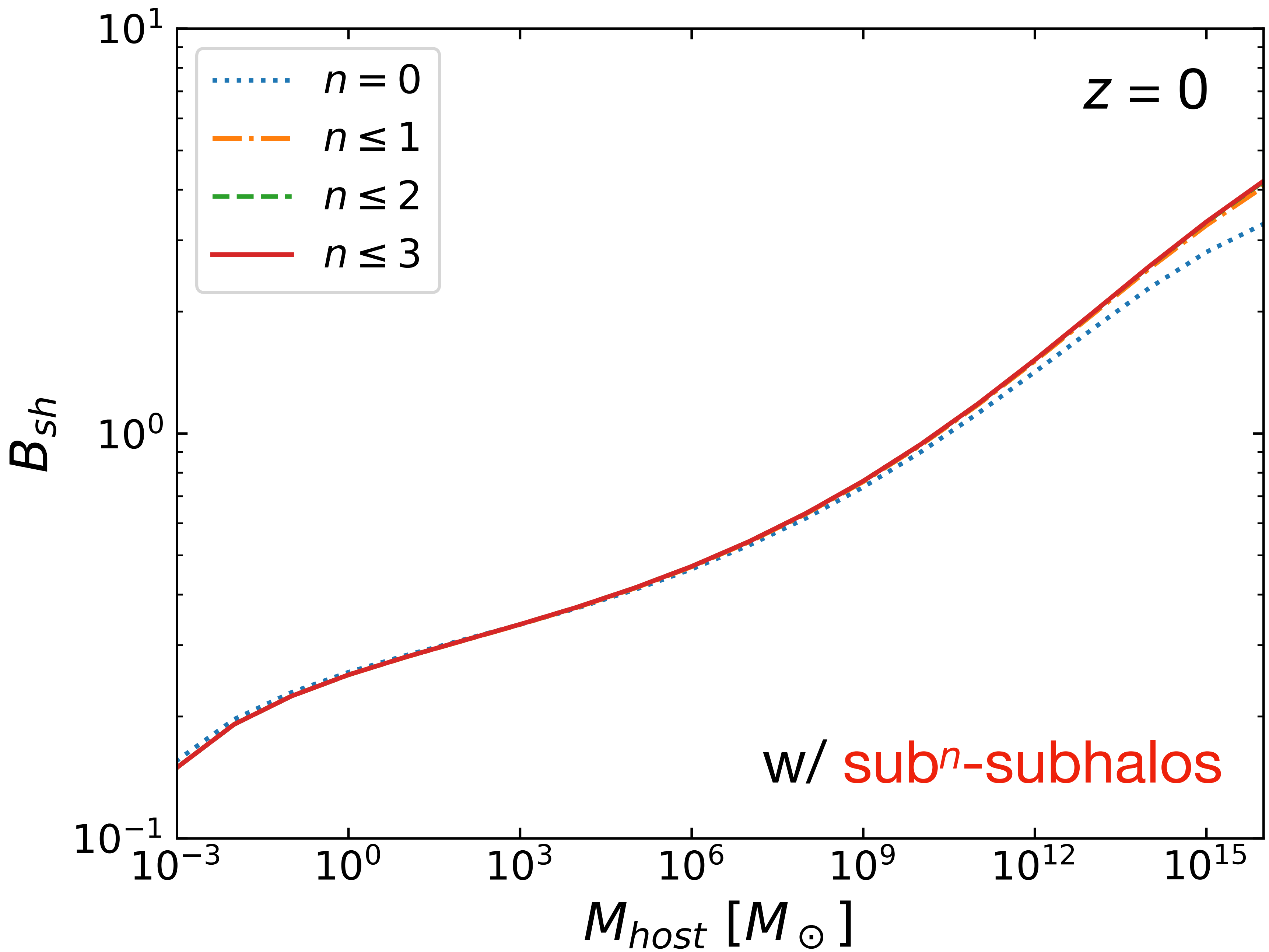
Subhalo mass function: Mass fraction in the subhalos



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

Annihilation boost

Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)
Ando, Ishiyama, Hiroshima, arXiv:1903.11427 [astro-ph.CO]



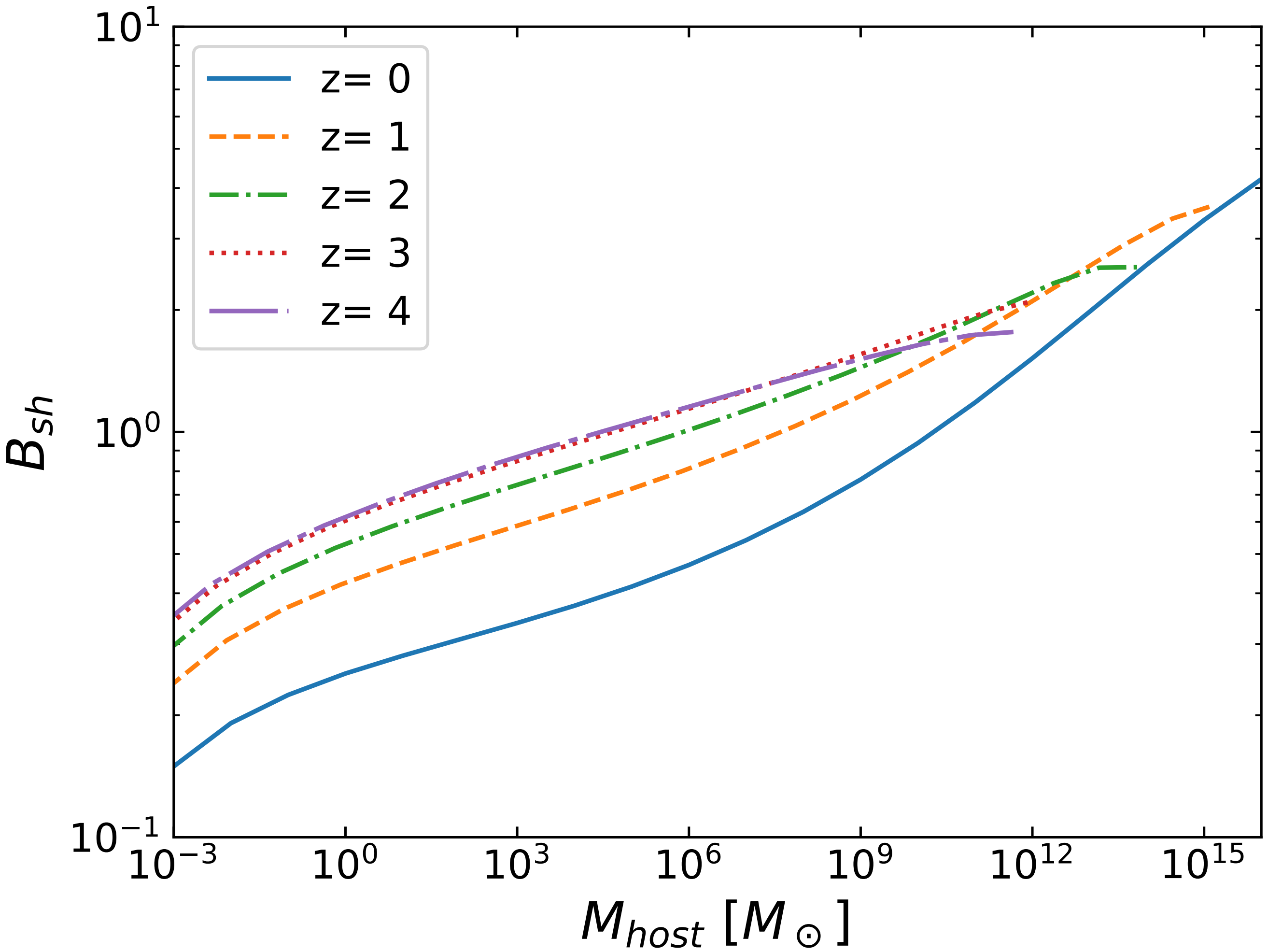
- Include effect of sub^n-subhalos iteratively
- They are assumed to be distributed following

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

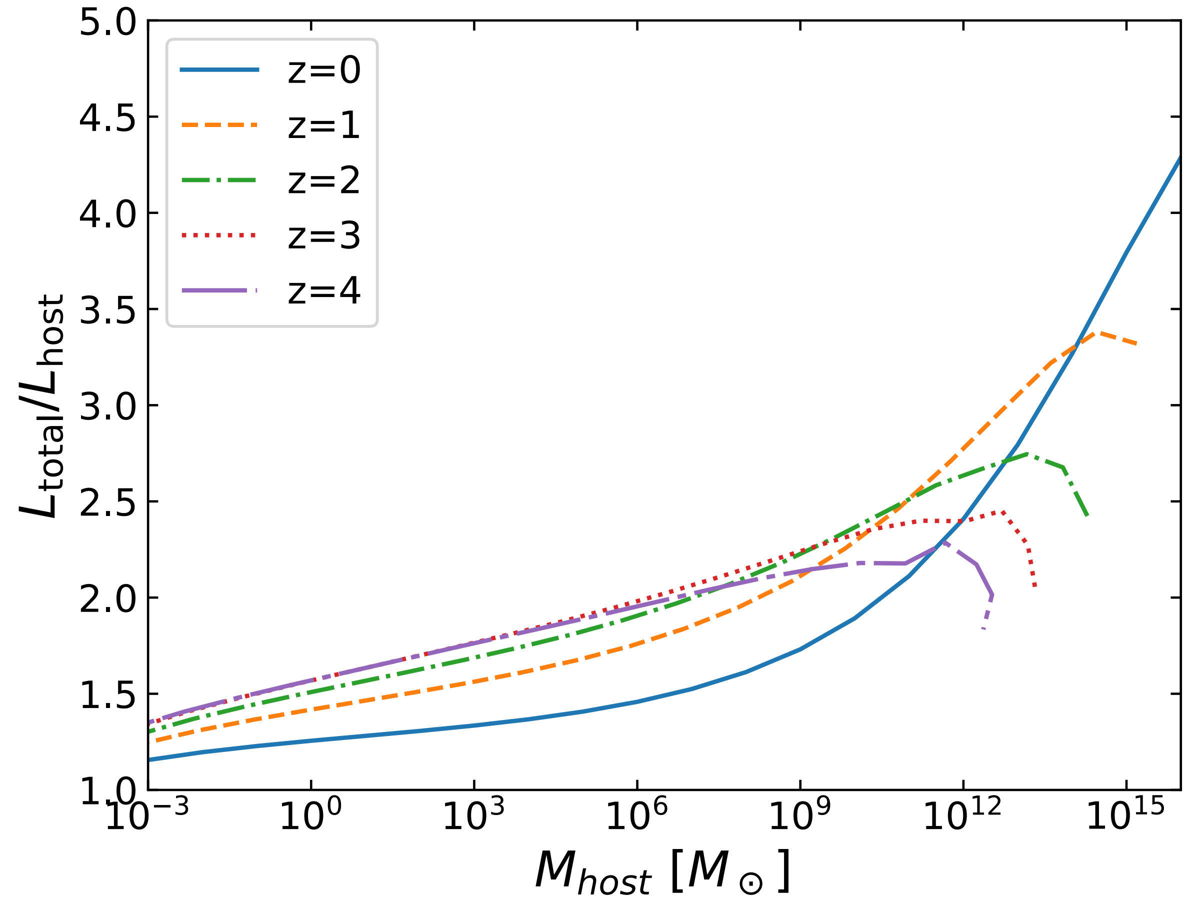
- All the sub-subhalos outside of the tidal radius is assumed lost
- Important to include up to sub-substructures
- Boost can be as large as ~1 (3) for galaxies (clusters)

Annihilation boost

Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)
Ando, Ishiyama, Hiroshima, arXiv:1903.11427 [astro-ph.CO]



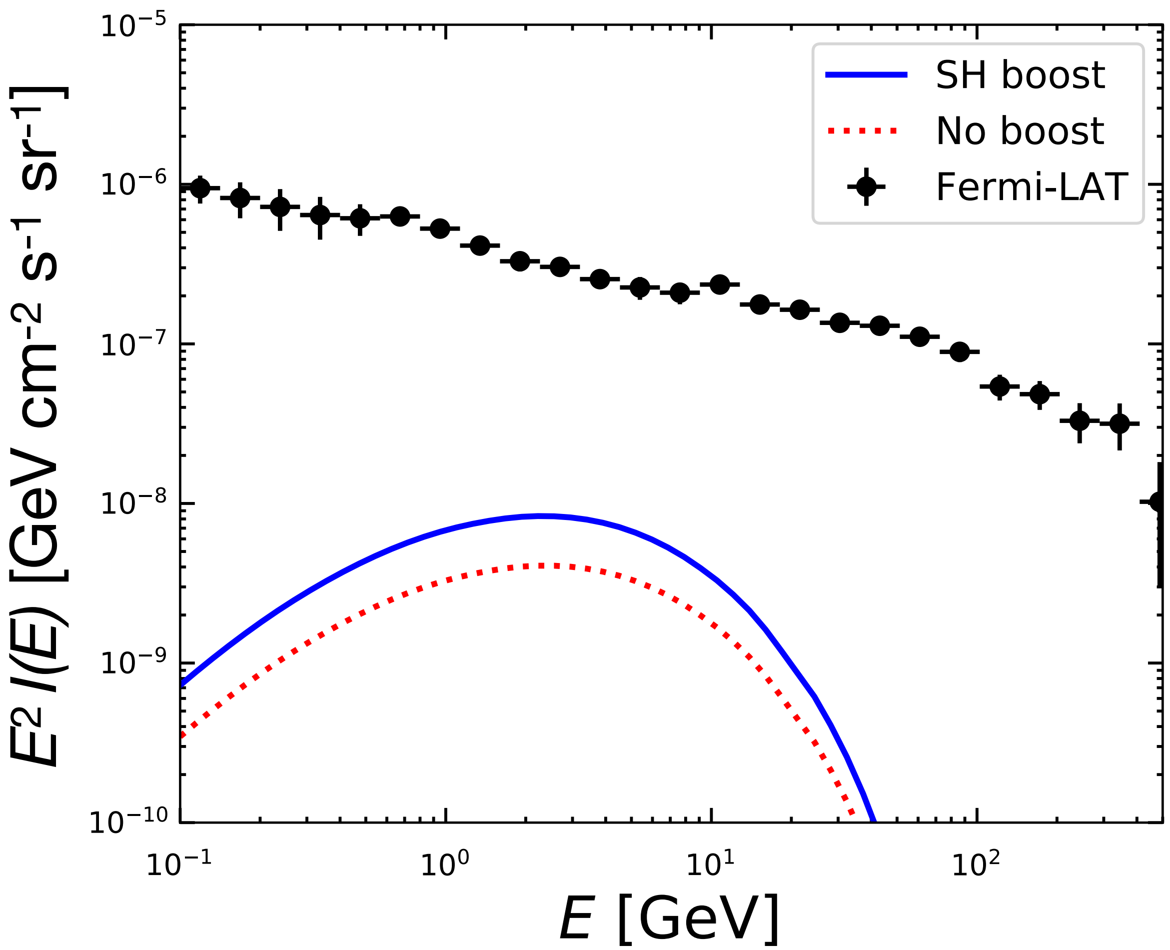
w/ up to sub³-subhalos

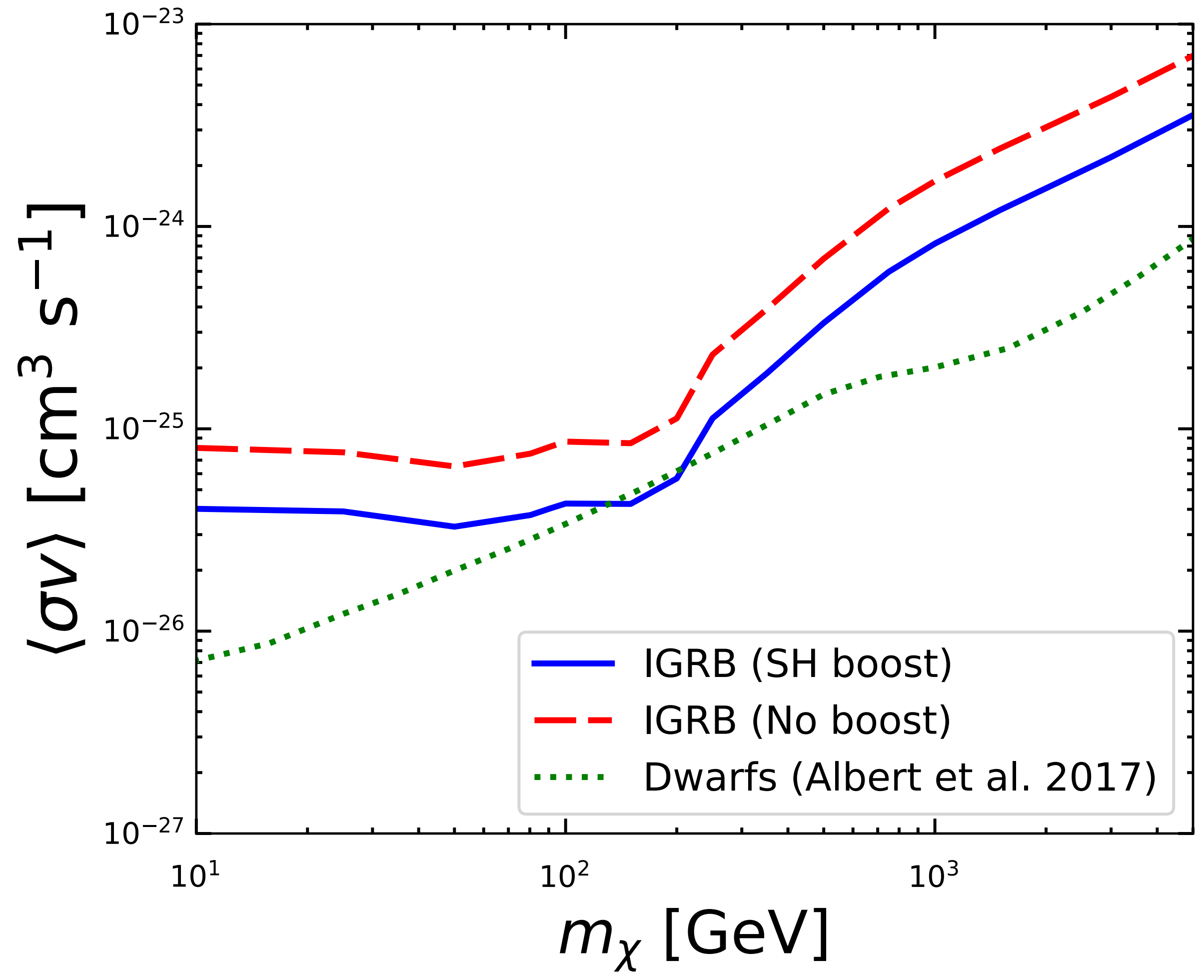


- Boost factors are higher at larger redshifts, but saturates after z = 1
- For one combination of host mass and redshifts (*M*, *z*), the code takes **only ~O(1) min to calculate the boost** on a laptop computer

Application: IGRB

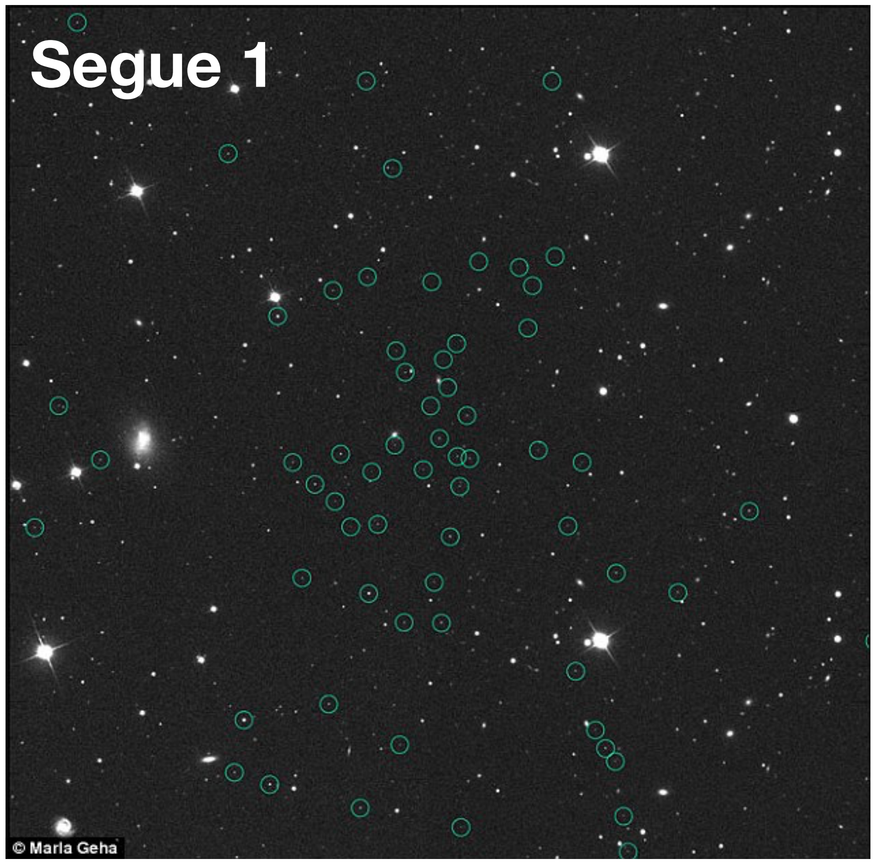
Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)





Implications for dwarf J factors

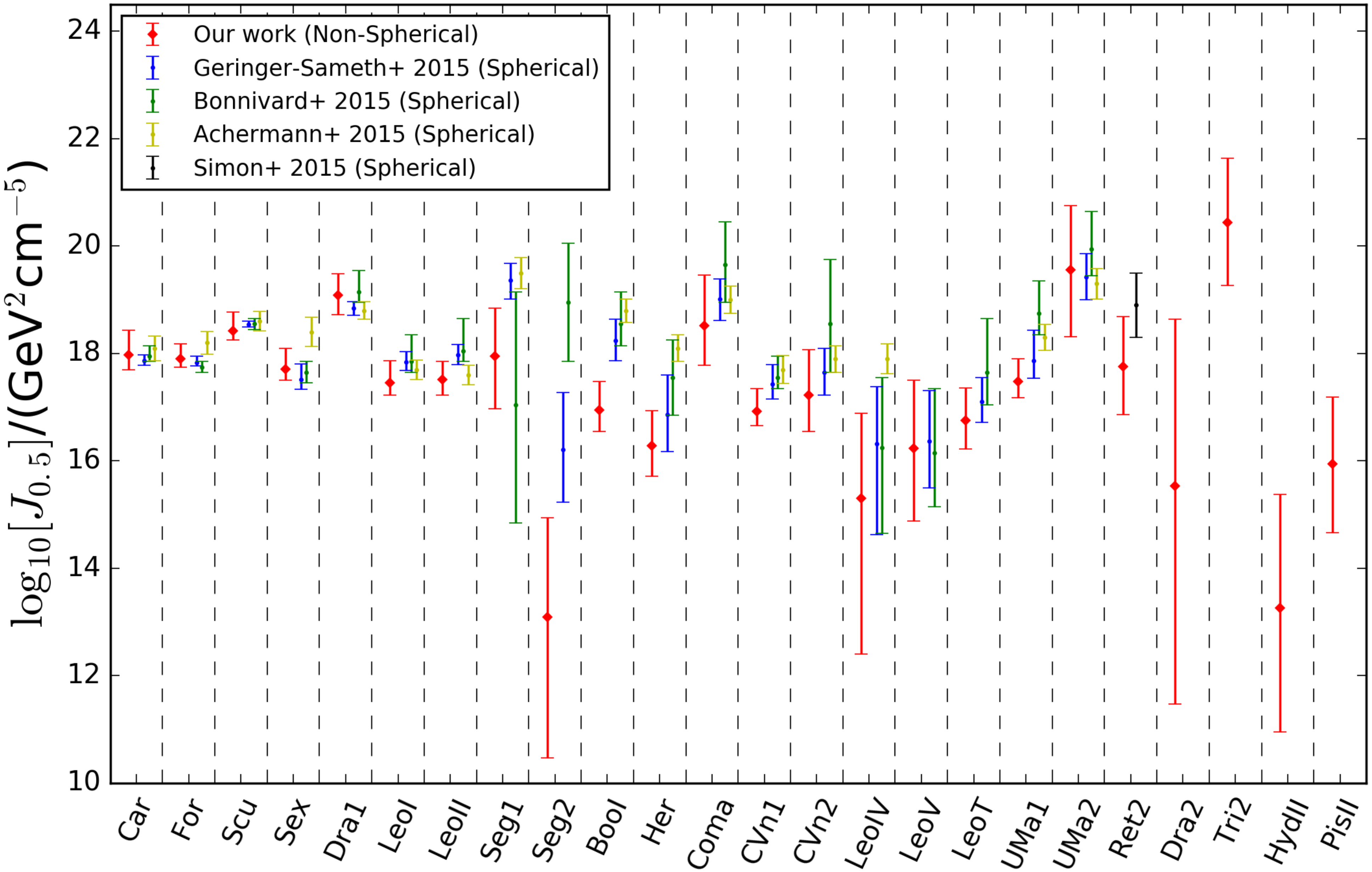
Dwarf J factors



$$J = \int d\Omega \int d\ell \, \rho^2(r(\ell, \Omega))$$

- Estimates of density profiles and hence J factors of dwarf galaxies are based on stellar kinematics data
- J factors of promising dwarfs are ~10^{19} $\mathrm{GeV^2/cm^5}$ or larger
- But *ultrafaint* dwarfs do not host many stars

Dwarf J factors



Hayashi et al., *Mon. Not. R. Astron. Soc.* **461**, 2914 (2016)

Estimates of density profiles

- Estimates of r_s and ρ_s usually rely on Bayesian statistics:

$$P(r_s, \rho_s \,|\, \mathbf{d}) \propto P(r_s, \rho_s) \mathscr{L}(\mathbf{d} \,|\, r_s, \rho_s)$$

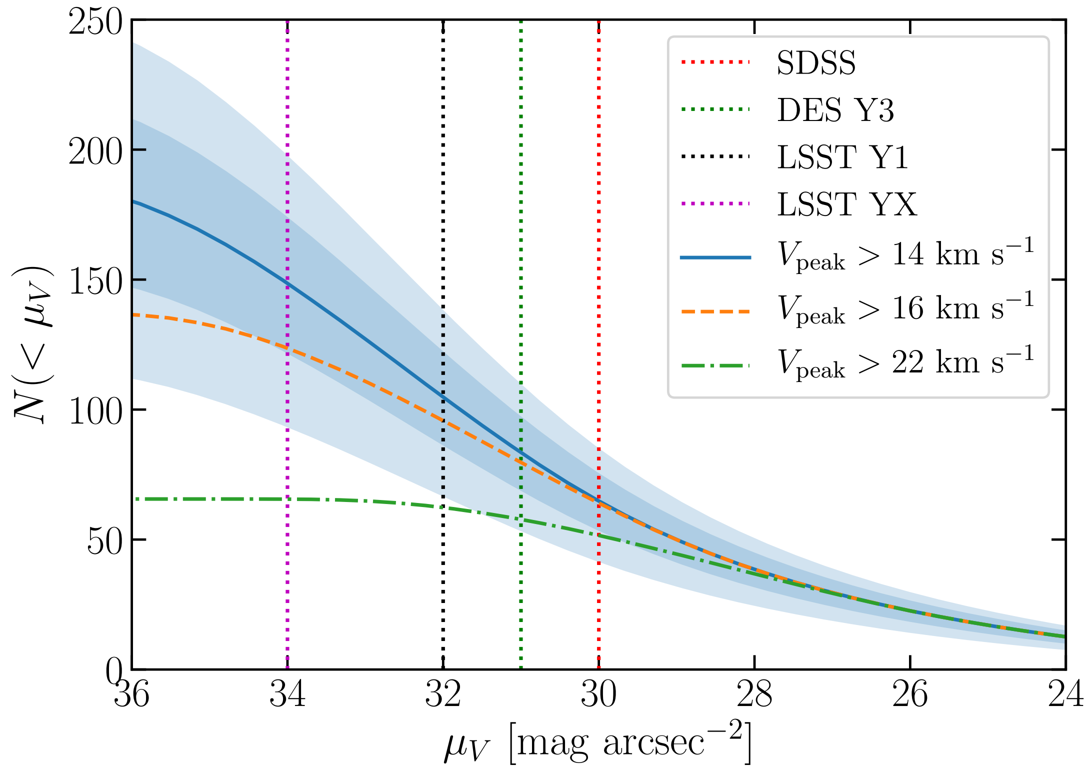
- If data are not constraining, **the posterior depends on prior choices**

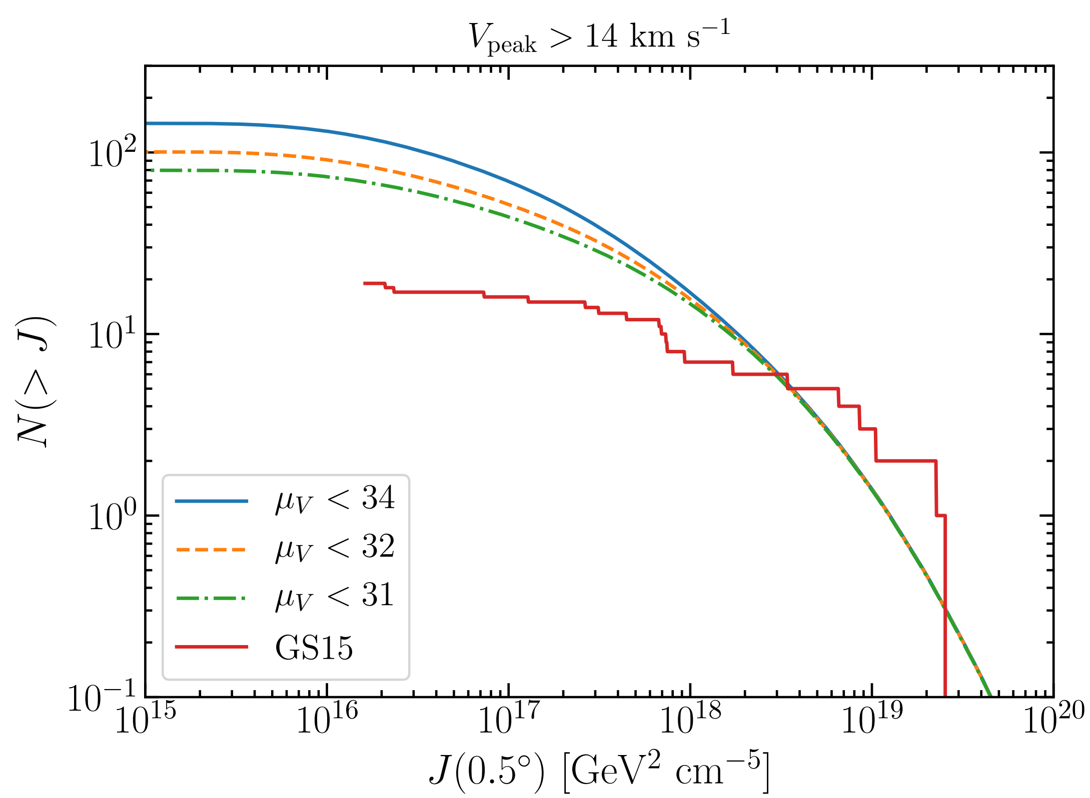
- Usually **log-uniform priors** are chosen for both r_s and ρ_s

- Doing frequentist way is very challenging, which is done only for *classical* dwarfs (Chiappo et al. 2016, 2018)

Three slides skipped in this uploaded version as they contain preliminary results…

Prospects for LSST

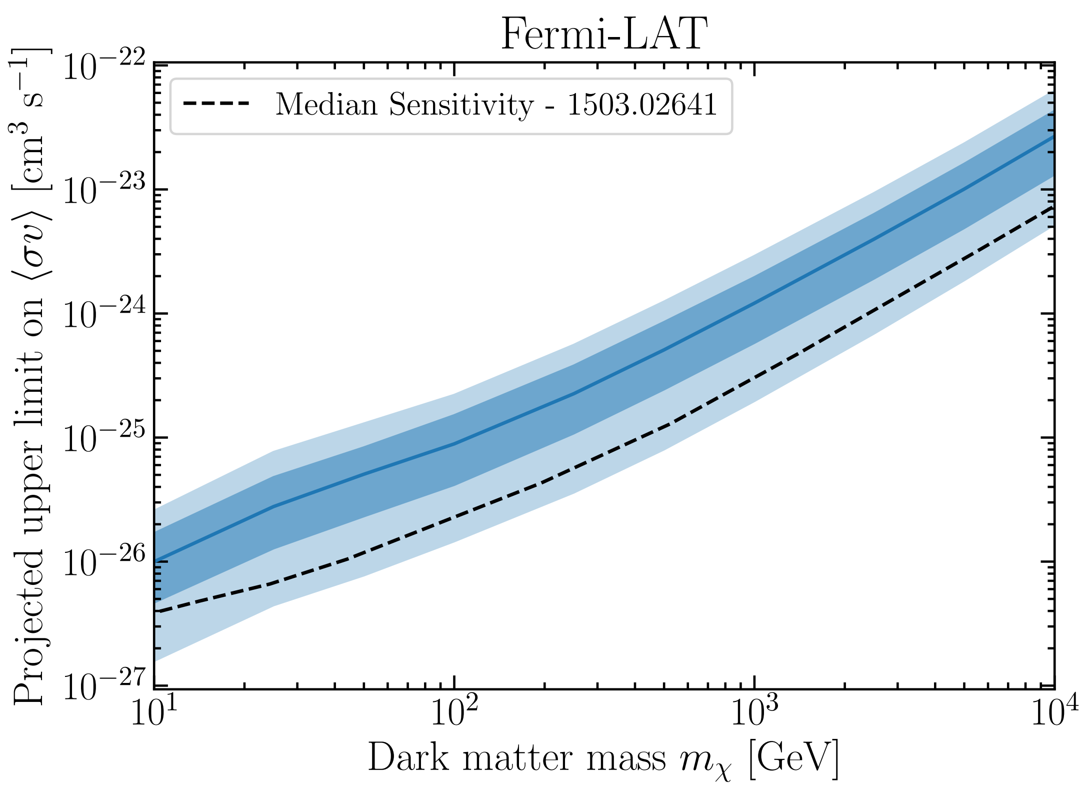


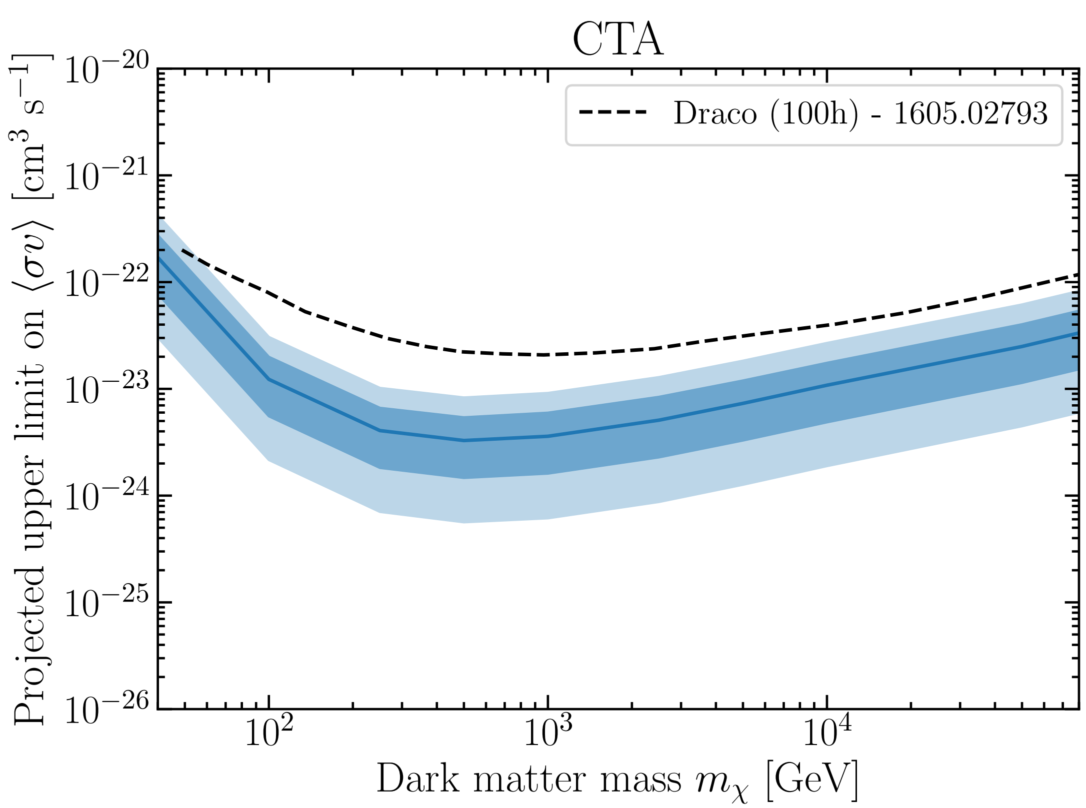


Ando et al., arXiv:1905.07128 [astro-ph.CO]

- LSST will cover nearly half the sky and expected to discover many dwarf galaxies
- Our subhalo models with simple phenomenological prescription of forming satellites predict several tens to hundred dwarfs to be discovered with LSST
- **High-*J* tail is dominated by Poisson uncertainty**, making other uncertainties (e.g., MW mass measurements) less of an issue
- **LSST wouldn't dramatically increase the number of dwarfs with very high *J* factors**

Prospects for LSST





Ando et al., arXiv:1905.07128 [astro-ph.CO]

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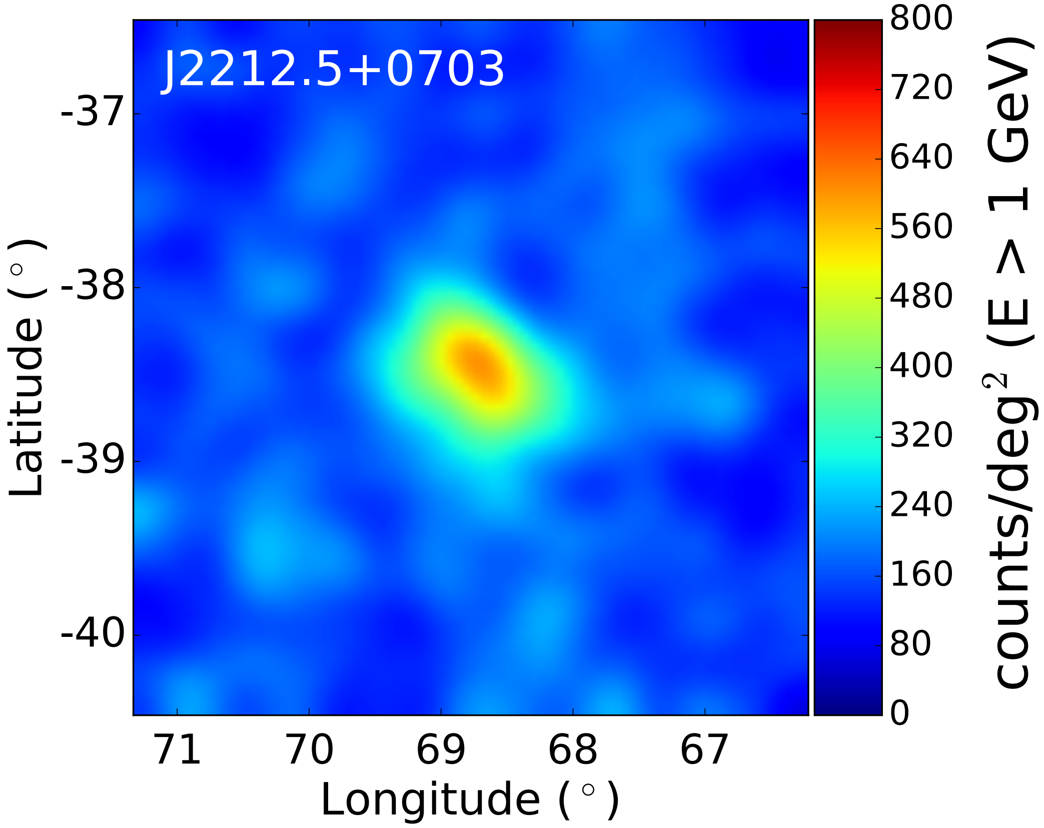
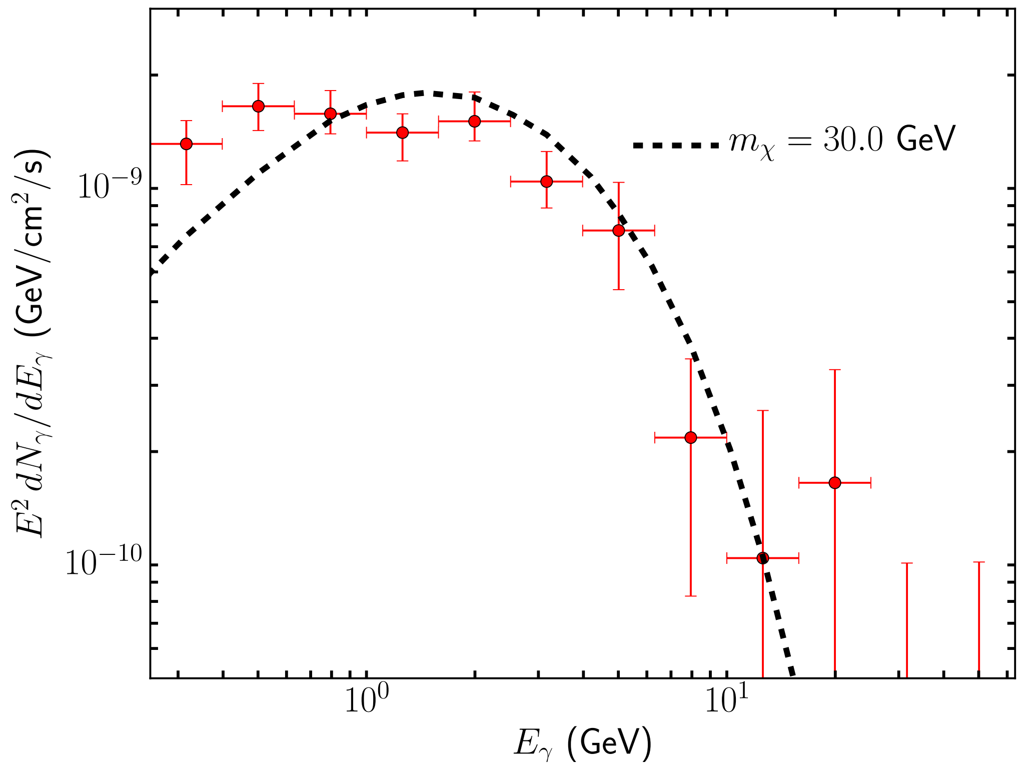
- **High-*J* tail is dominated by Poisson uncertainty**, making other uncertainties (e.g., MW mass measurements) less of an issue
- **LSST wouldn't dramatically increase the number of dwarfs with very high *J* factors**

Implication for Fermi unassociated sources

Fermi unassociated sources

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



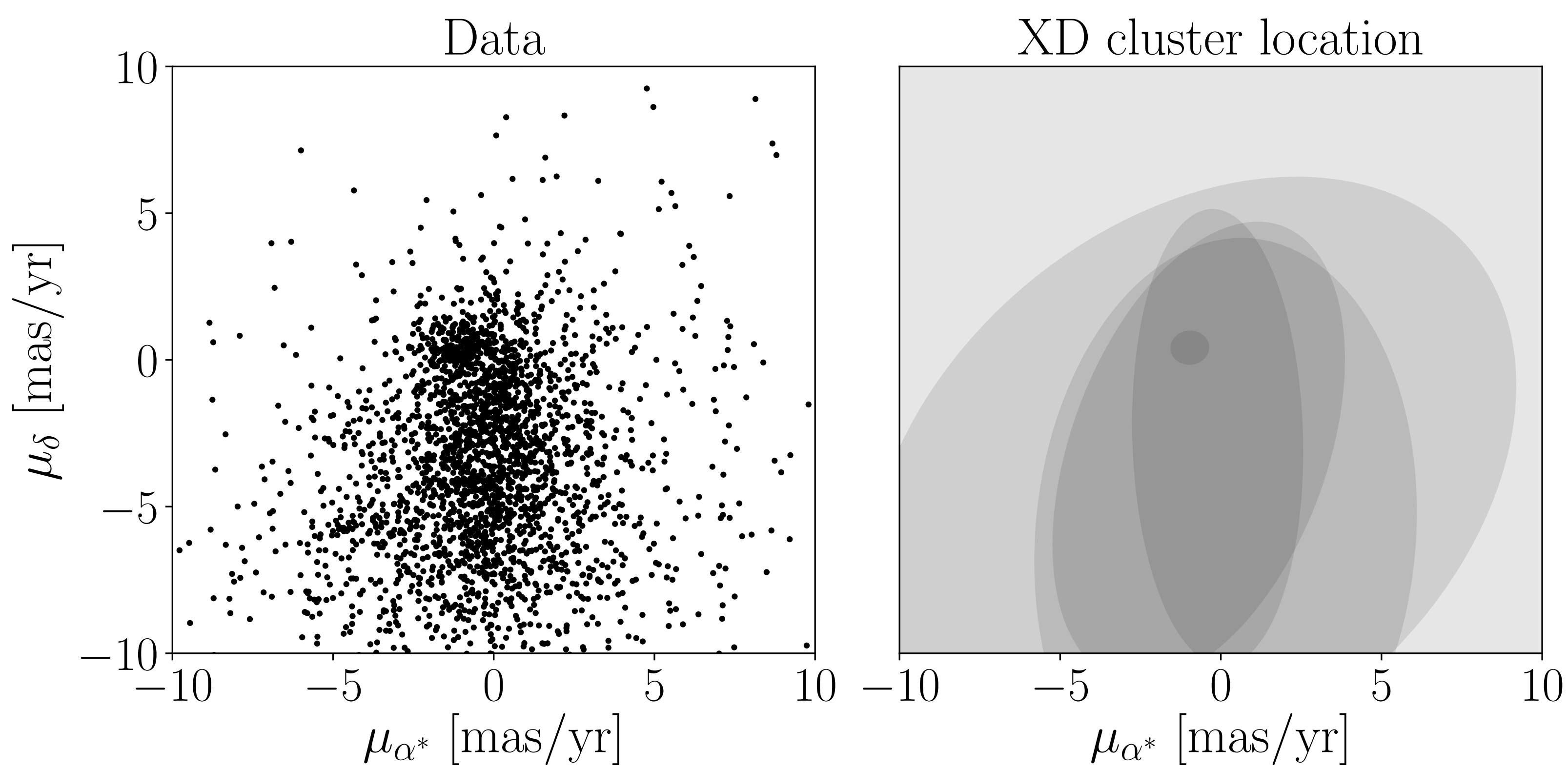


- There are several *extended* unassociated sources that might be compatible with dark matter annihilation from subhalos

- 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

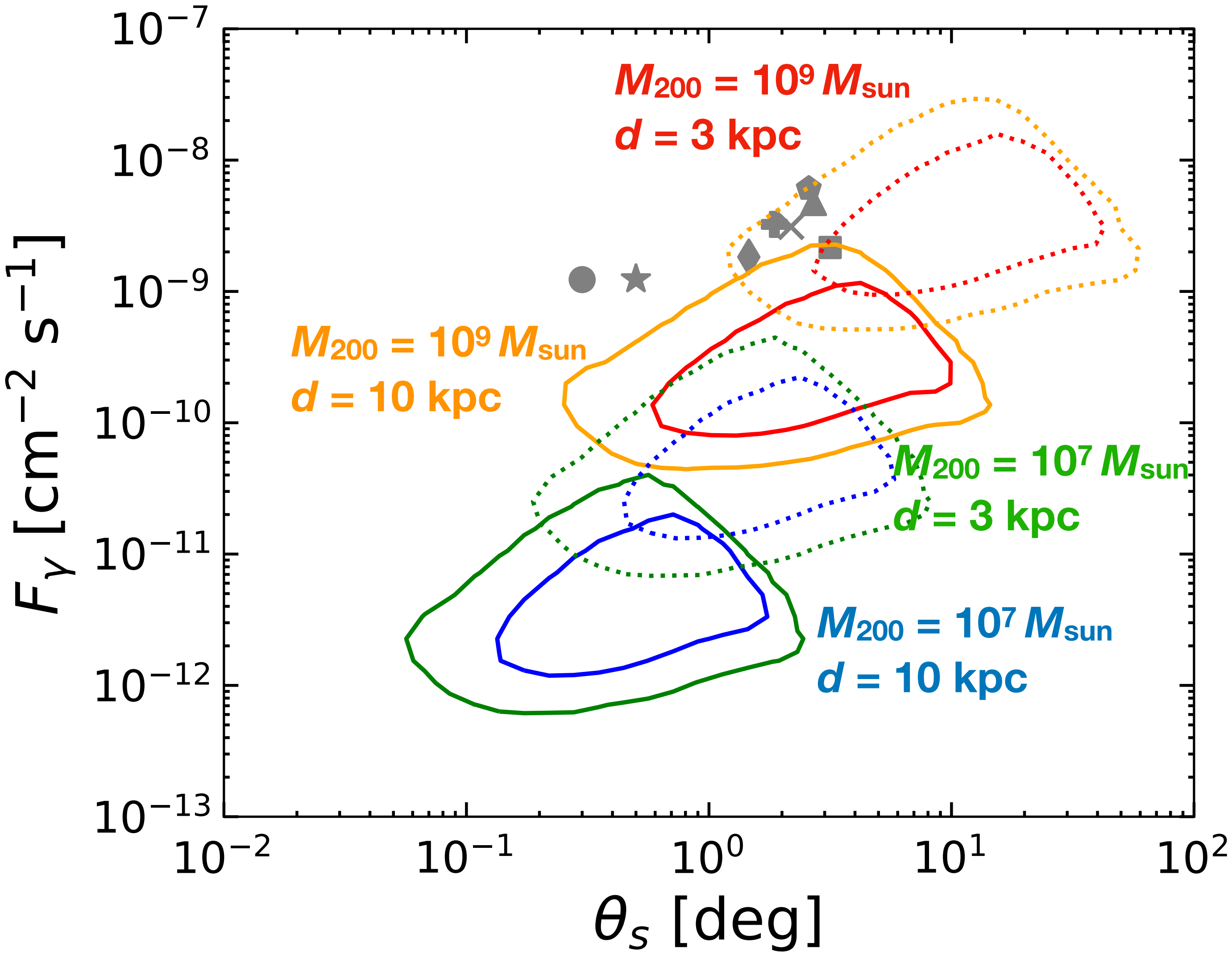


Ciuca, Kawata, Ando, Calore, Read, Mateu, *Mon. Not. R. Astron. Soc.* **480**, 2284 (2018)

- 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

Implication of *Gaia* non-detection

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)

- 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**

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 **~1 (3) for galaxy (cluster) halos**
- The models enable to compute **first realistic prior distribution for the dwarf J estimates**, which we find smaller than previously thought for the most promising ultrafaint dwarf galaxies
- **LSST will find tens to hundred new dwarfs**, but cross section limits are unlikely improved in a drastic manner
- The model can be used to **reject the possibility of dark matter annihilation for Fermi unassociated sources**