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Searching for particle dark matter by cross-correlating gamma rays and large-scale structure

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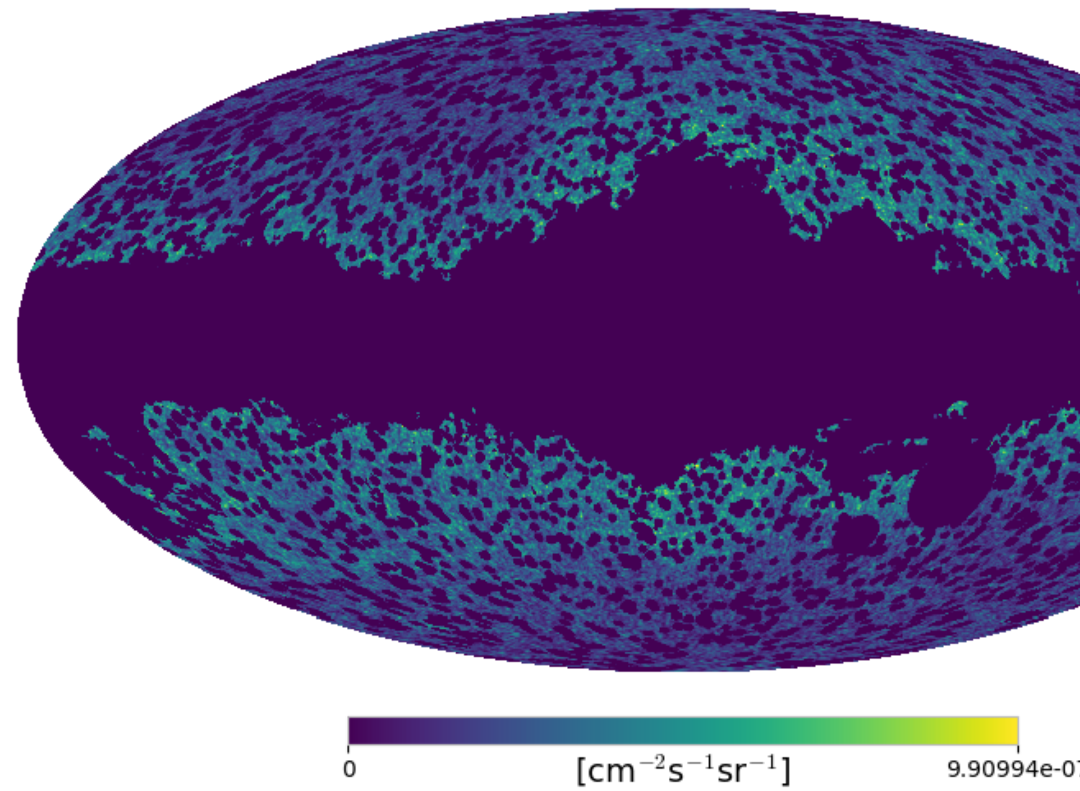
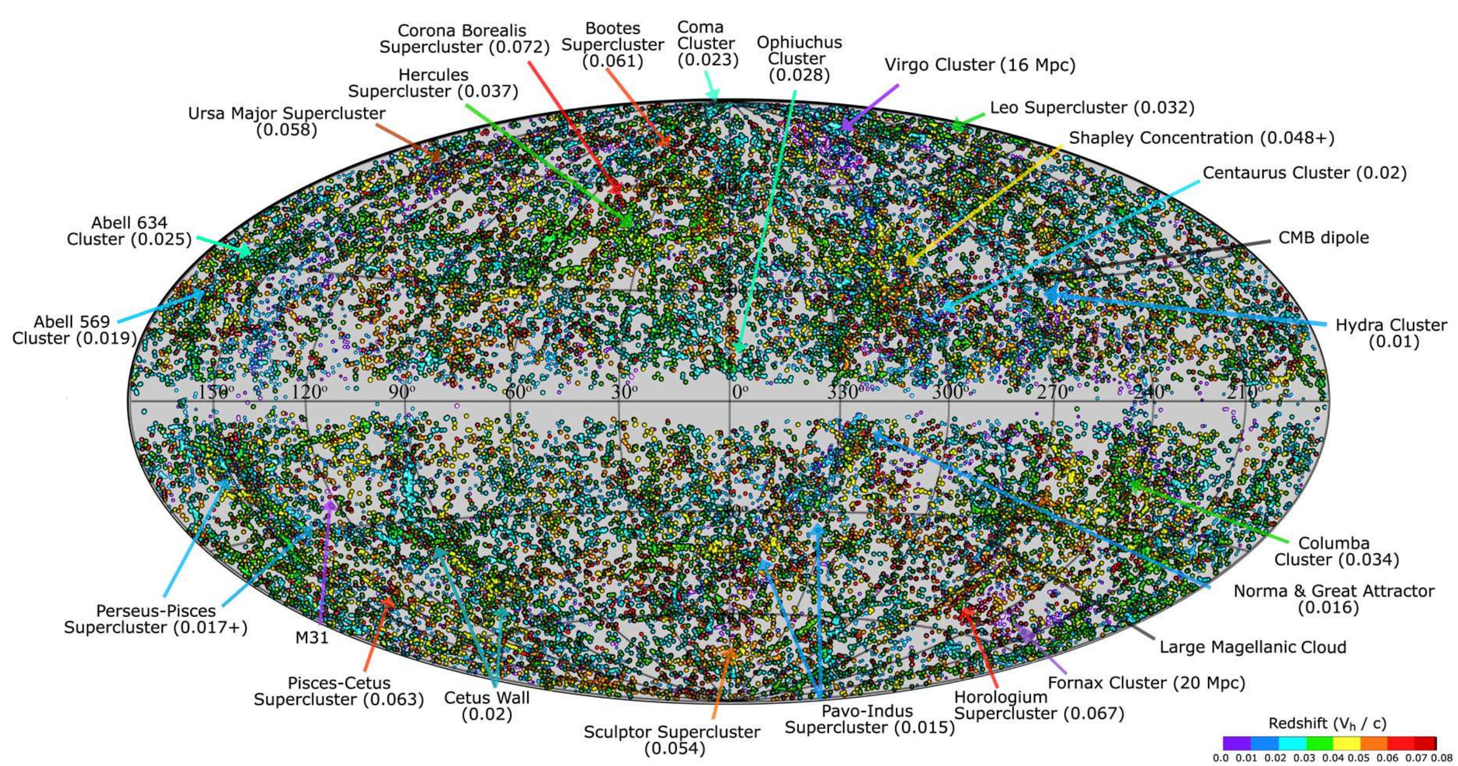
Gamma x large-scale structure

All the gamma-ray sources must trace large-scale structure in the Universe

Fermi-LAT, *Phys. Rev. Lett.* **121**, 241101 (2018)



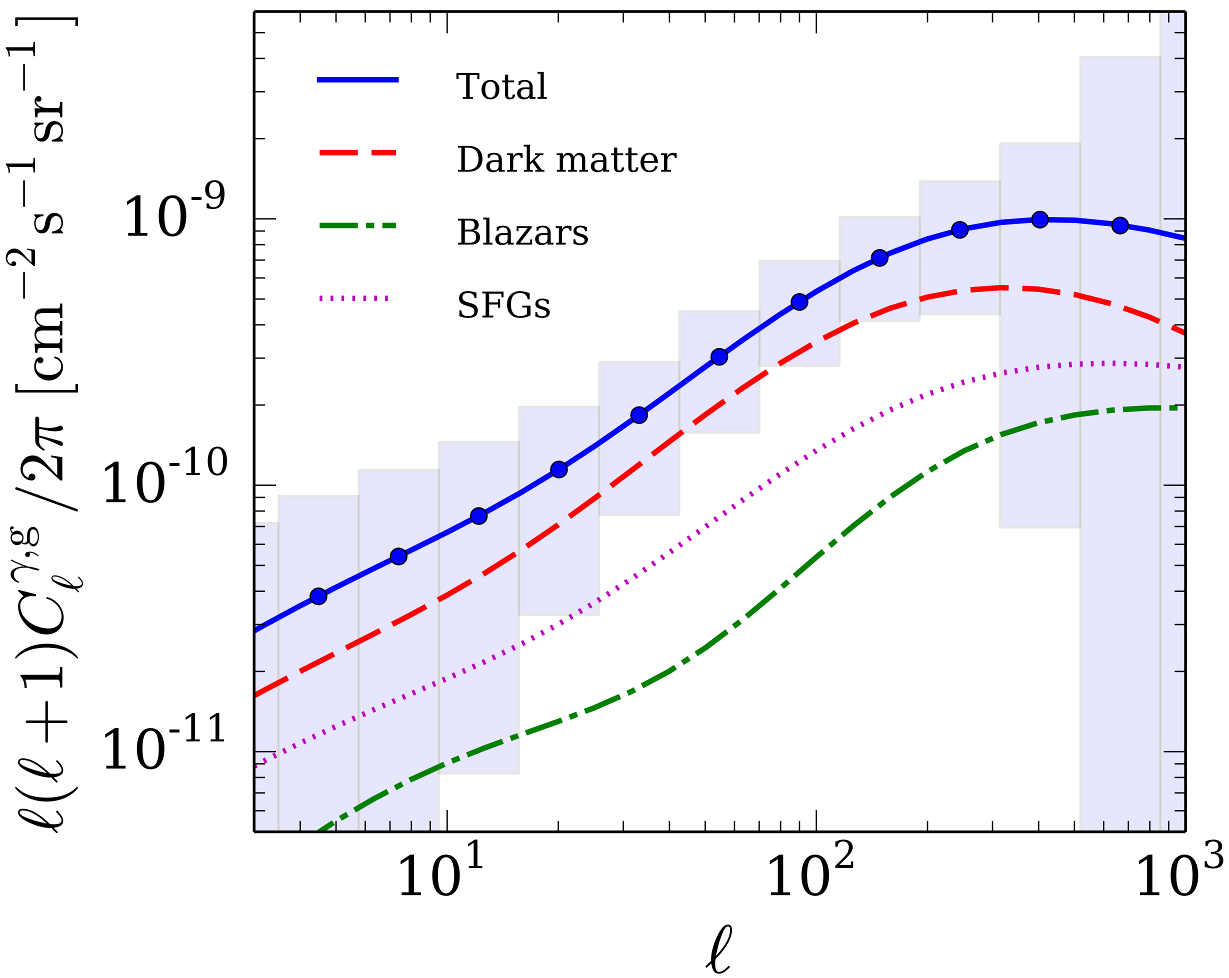
Huchra et al., *Astrophys. J. Suppl. Ser.* **199**, 26 (2011)



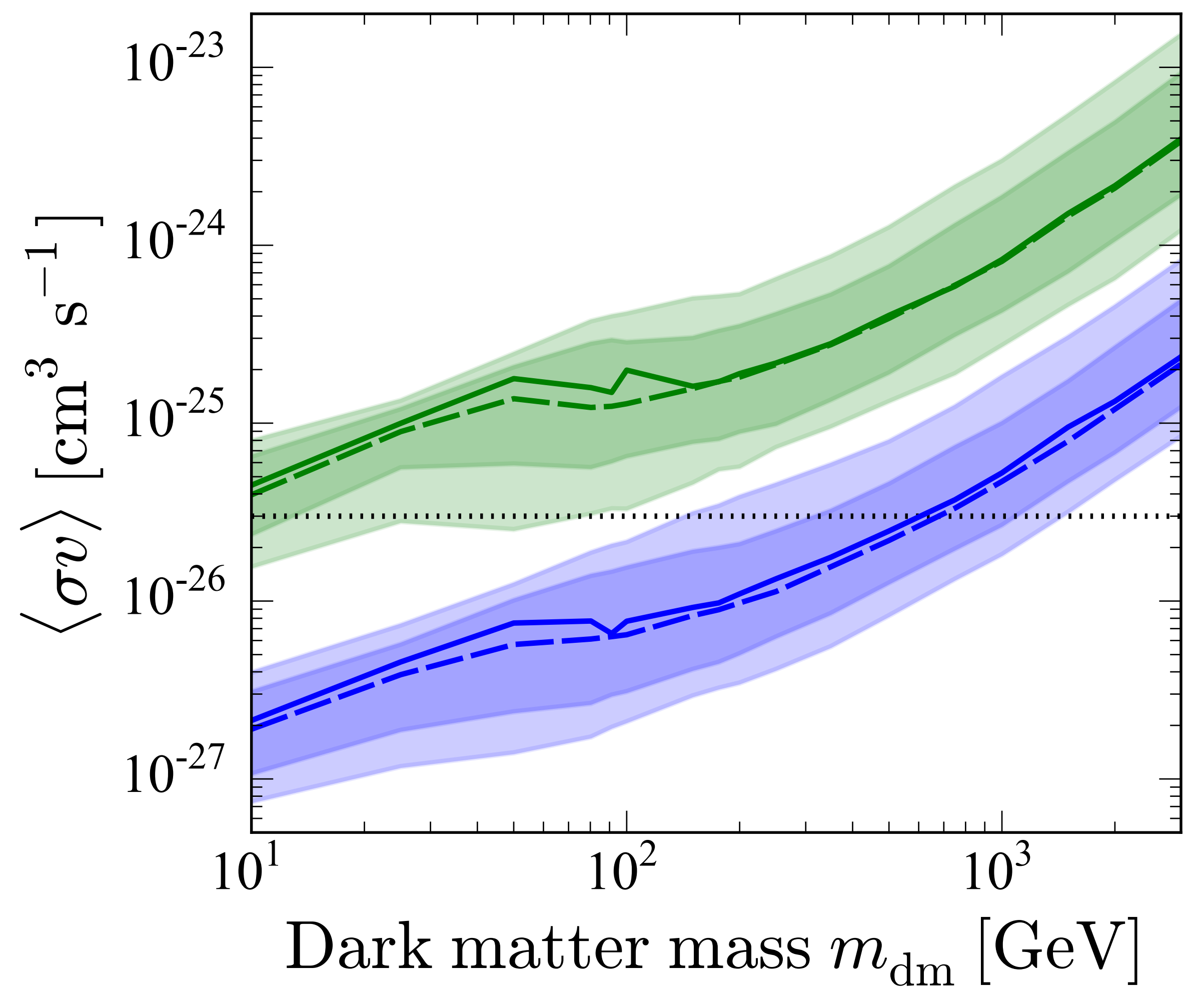
There has to be positive cross correlation

Cross correlation as efficient dark matter probe

Ando, Benoit-Lévy, Komatsu, *Phys. Rev. D* **90**, 023514 (2014)



Ando, *JCAP* **1410**, 061 (2014)



- Cross correlating with LSS proven to be efficient probe of particle DM
  - Utilize all available information (energy, spatial and redshift info) with efficient kernel
  - Astrophysical components are relatively suppressed
  - Interpretation is however limited by understanding of substructure

Contents

- Results of **cross-correlation analysis** between the **Fermi-LAT** gamma-ray data and **Dark Energy Survey (DES)** weak-lensing data

  Ammazzalorso, Gruen, Regis, Camera, Ando, Fornengo et al. *Phys. Rev. Lett.* (2020) [arXiv:1907.13484 [astro-ph.CO]]

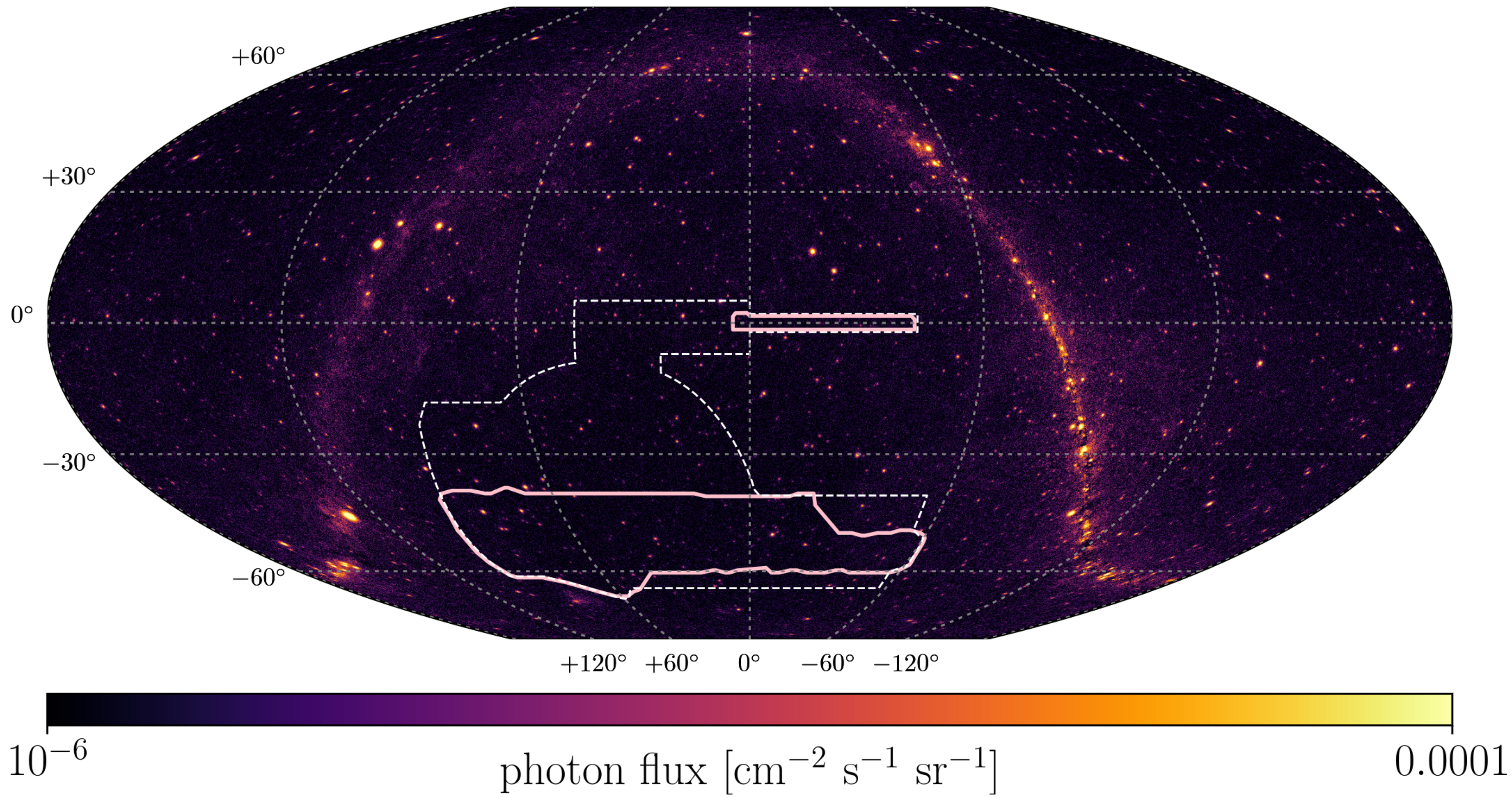
- **New models of dark matter subhalos** and annihilation boost

  Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)
  Ando, Ishiyama, Hiroshima, *Galaxies* **7**, 68 (2019)

- **New dwarf constraints** on dark matter annihilation

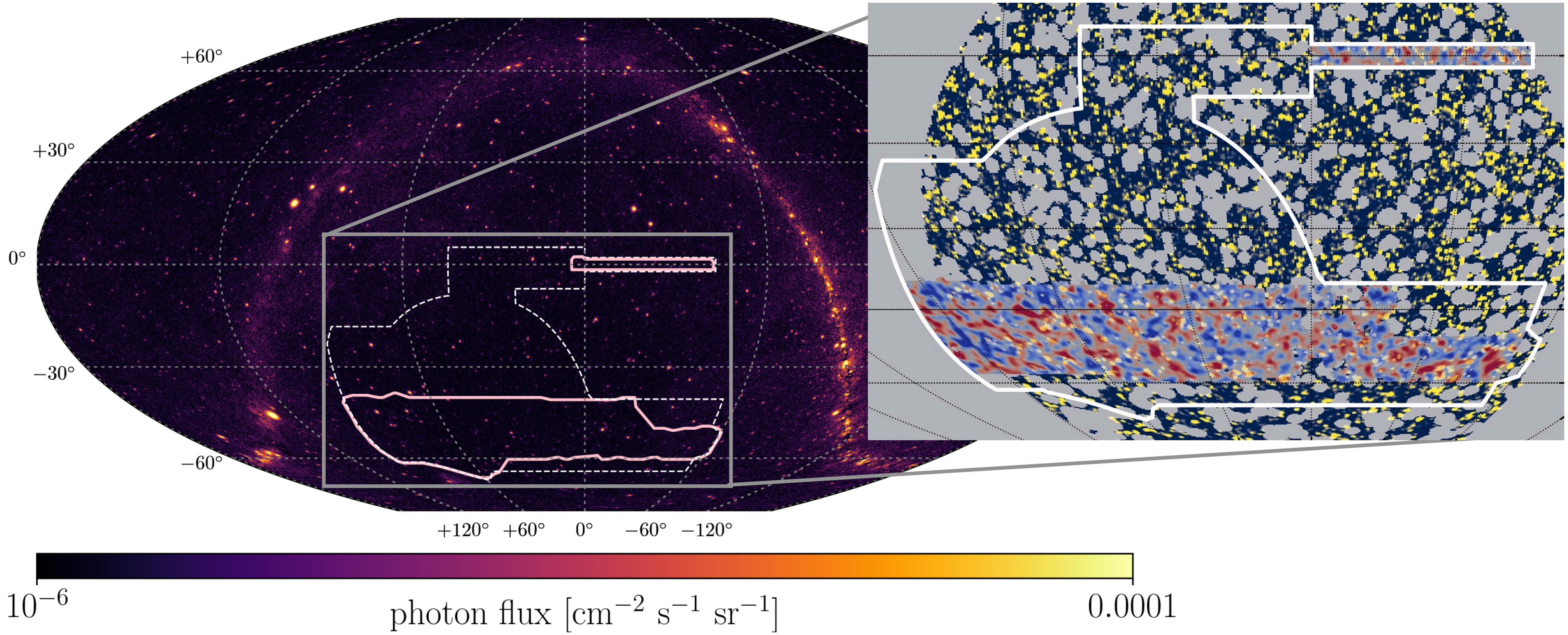
  Ando, Geringer-Sameth, Hiroshima, Hoof, Trotta, Walker, in preparation

Fermi-LAT x DES



- Cross correlation between 108 month Fermi-LAT data and DES shear measurements (Y1)
- Energies: 0.6-1000 GeV; Redshifts: 0.2-1.3

Fermi-LAT x DES



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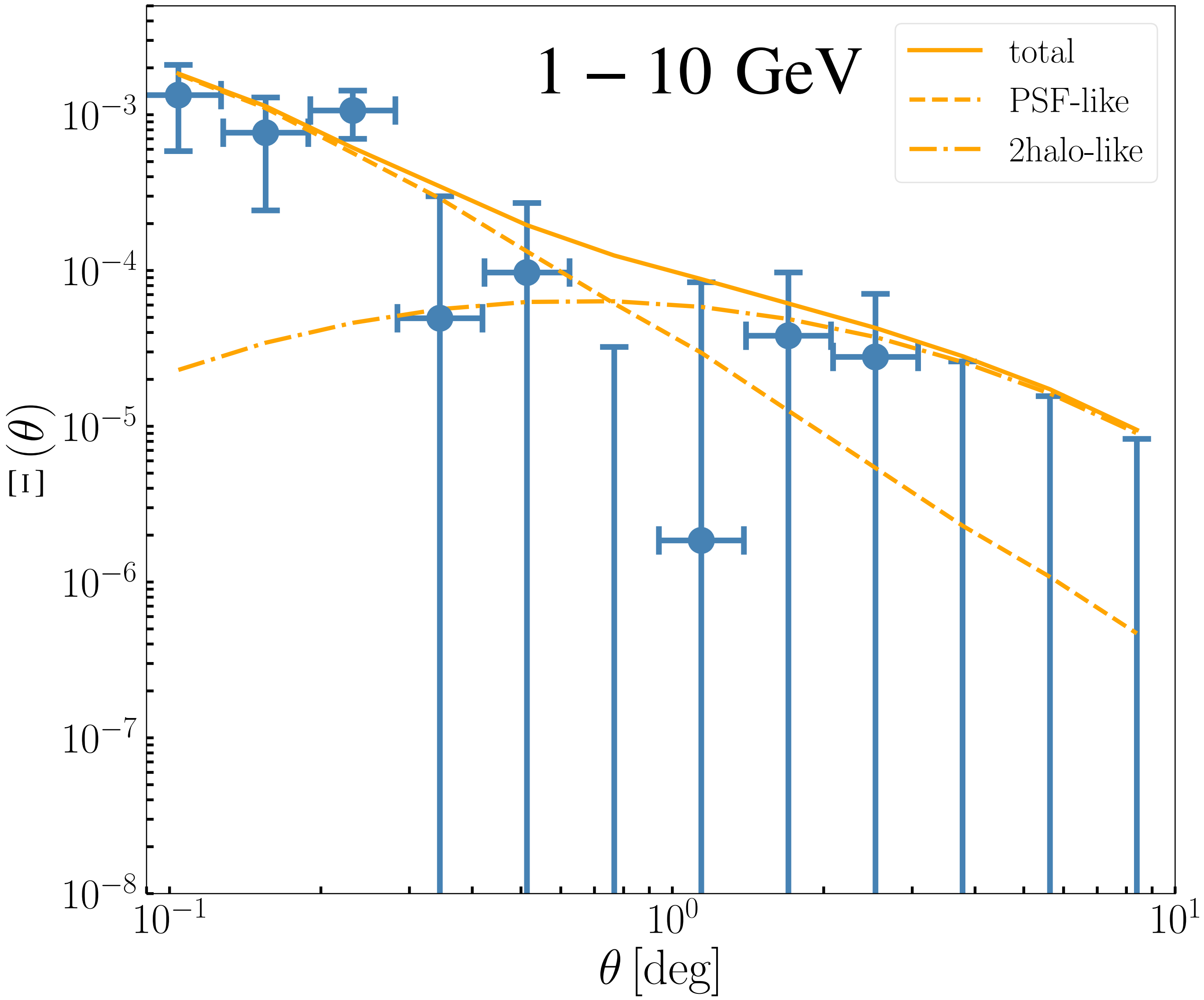
Fermi-LAT x DES

$$\Xi^{ar}(\theta) = \Xi^{\rm signal}_{\Delta\theta_h,\Delta E_a,\Delta z_r} - \Xi^{\rm random}_{\Delta\theta_h,\Delta E_a,\Delta z_r} = \frac{\sum_{i,j} e^r_{ij,{\rm t}} I^a_j}{R\sum_{i,j} I^a_j} - \frac{\sum_{i,j} e^r_{ij,{\rm t}} I^a_{j,{\rm random}}}{R\sum_{i,j} I^a_{j,{\rm random}}}$$



- Excess at < 0.3 deg
- **Phenomenological model**
  - PSF-like: Same sources contributing to both gamma-ray emission and shear
  - 2halo-like: Large-scale-structure distribution
- **Signal-to-noise ratio = 5.3**

Ammazzalorso et al. *Phys. Rev. Lett.* [arXiv:1907.13484 [astro-ph.CO]]

Fermi-LAT x DES

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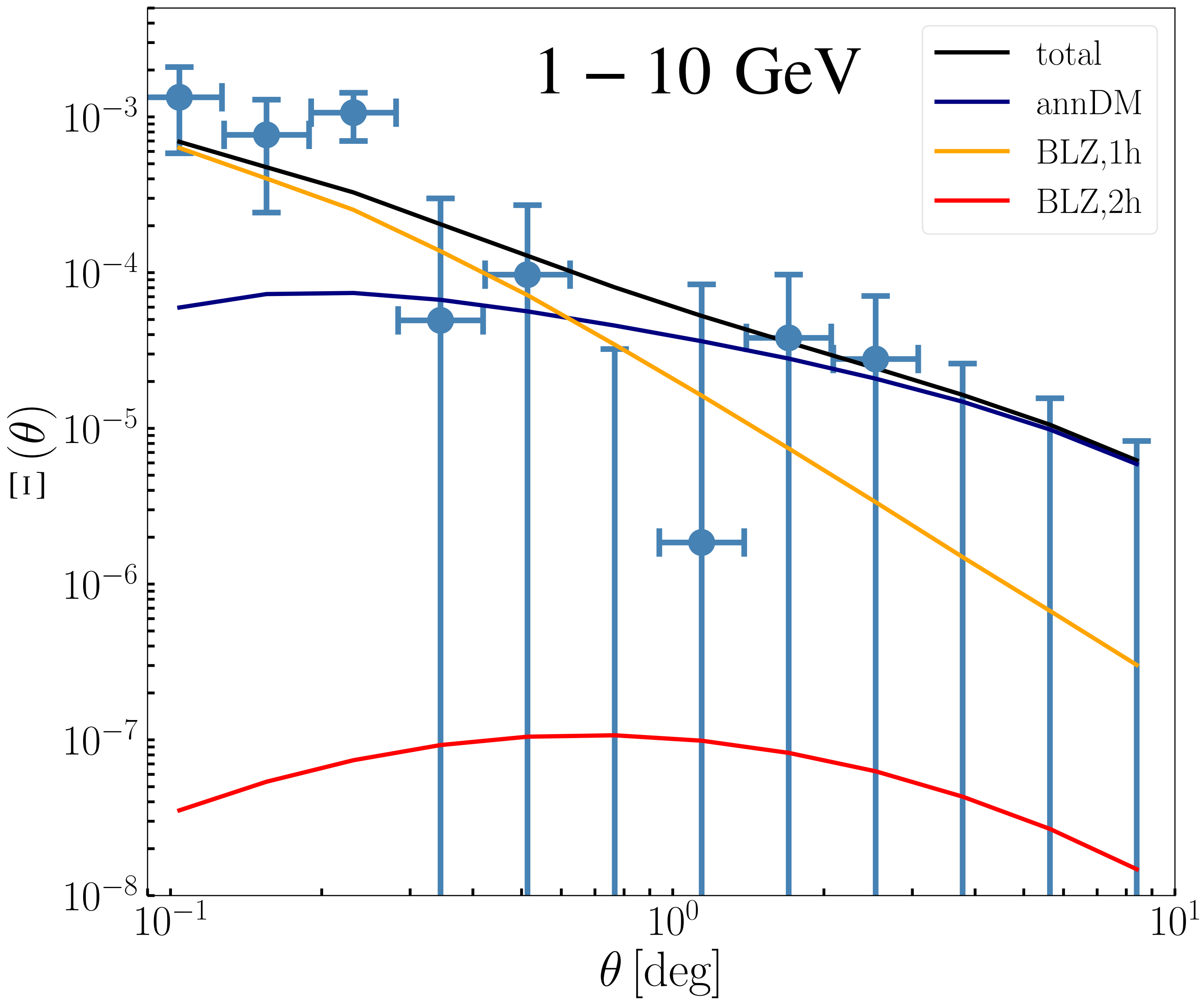
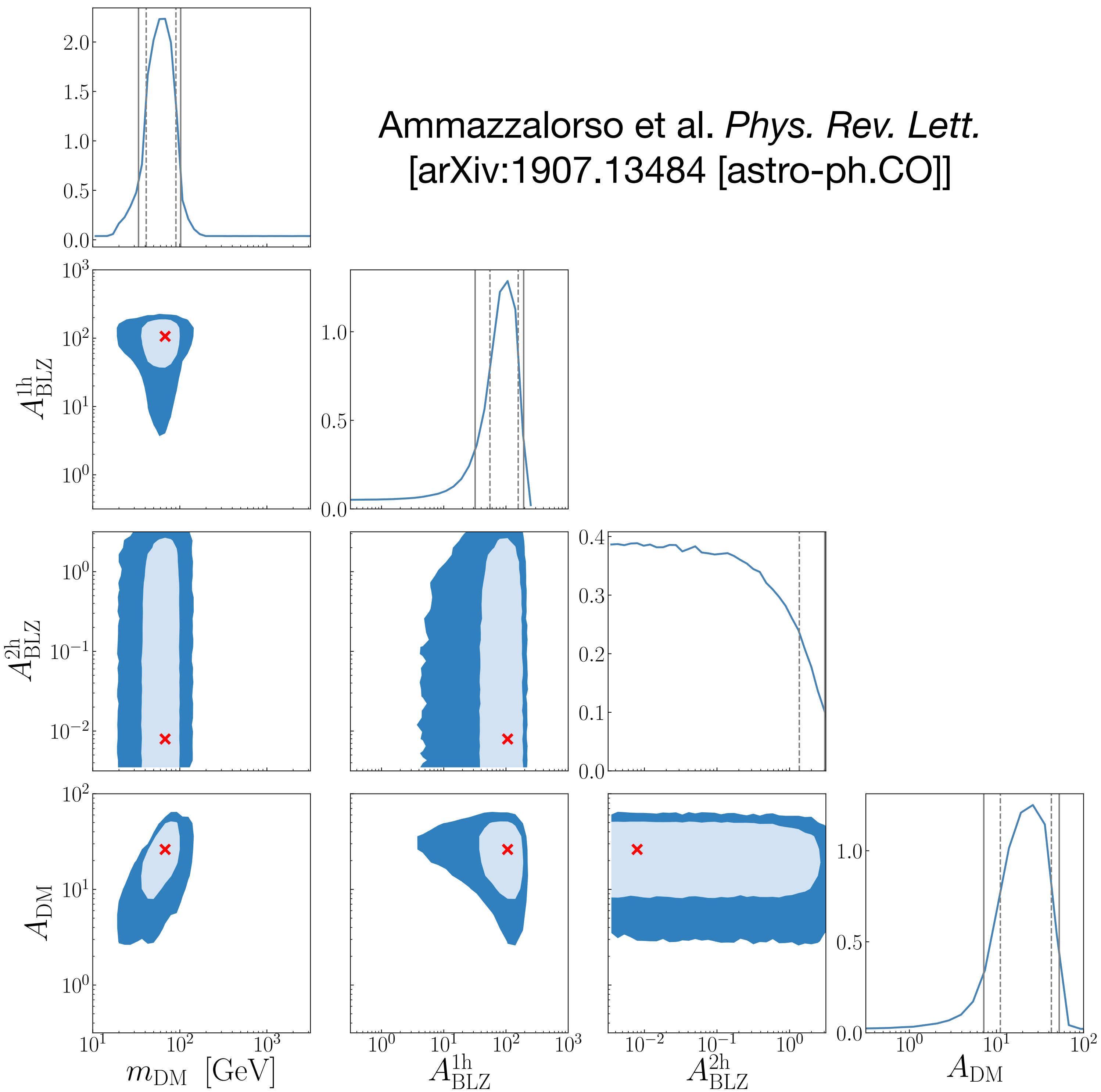


- Excess at < 0.3 deg
- **Physical model**
  - Astrophysical components (BLZ, mAGN, SFG)
  - Dark matter annihilation
- **Signal-to-noise ratio = 5.2**

Ammazzalorso et al. *Phys. Rev. Lett.* [arXiv:1907.13484 [astro-ph.CO]]

MCMC parameter scan



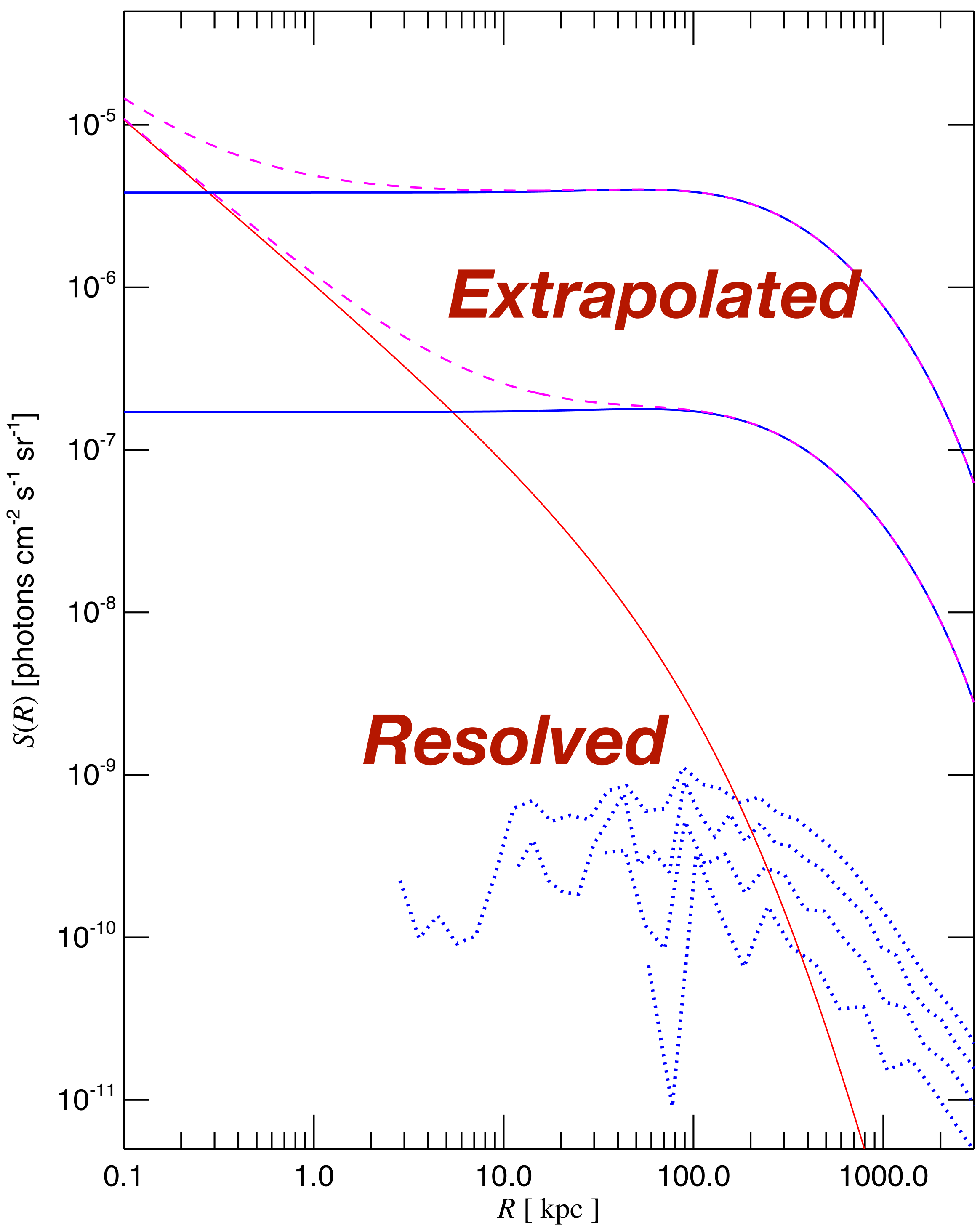
Ammazzalorso et al. *Phys. Rev. Lett.*
[arXiv:1907.13484 [astro-ph.CO]]

	$\tau^+\tau^-$	$b\bar{b}$
Significance	2.8σ	2.7σ
$\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}$	65^{+27}_{-23}	308^{+188}_{-120}
$\frac{\langle \sigma v \rangle}{\langle \sigma v \rangle_{\mathrm{th}}}$	26^{+17}_{-15}	78^{+67}_{-43}

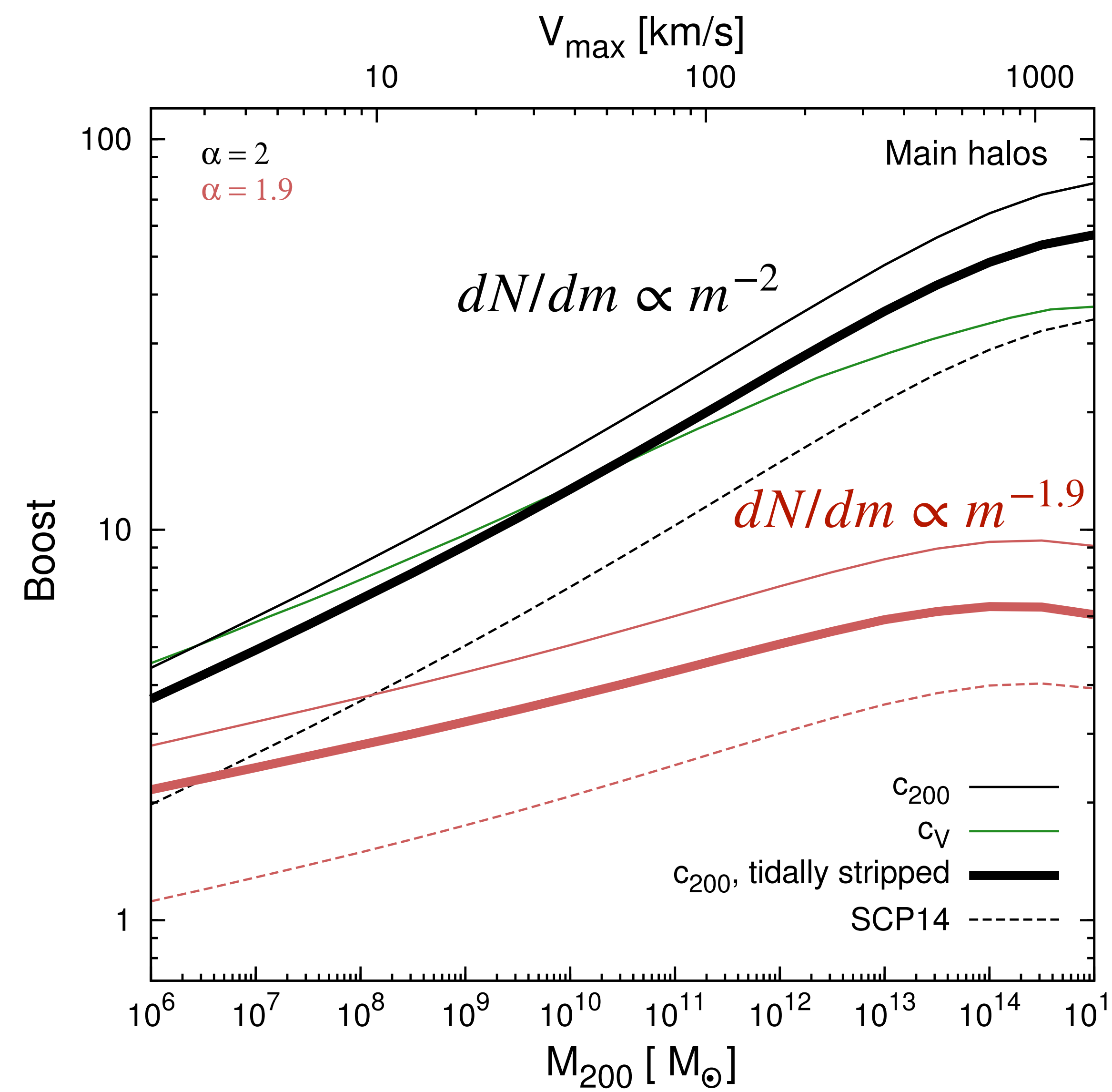
- Slight preference toward DM
- But required cross section is one order of magnitude larger, for **recent subhalo models** by Hiroshima et al. (2018); Ando et al. (2019)


Dark matter subhalos
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 modeling

Structures start to form

Initial condition: Primordial power spectrum

↓

Smaller halos merge and accrete to form larger ones

Extended Press-Schechter formalism

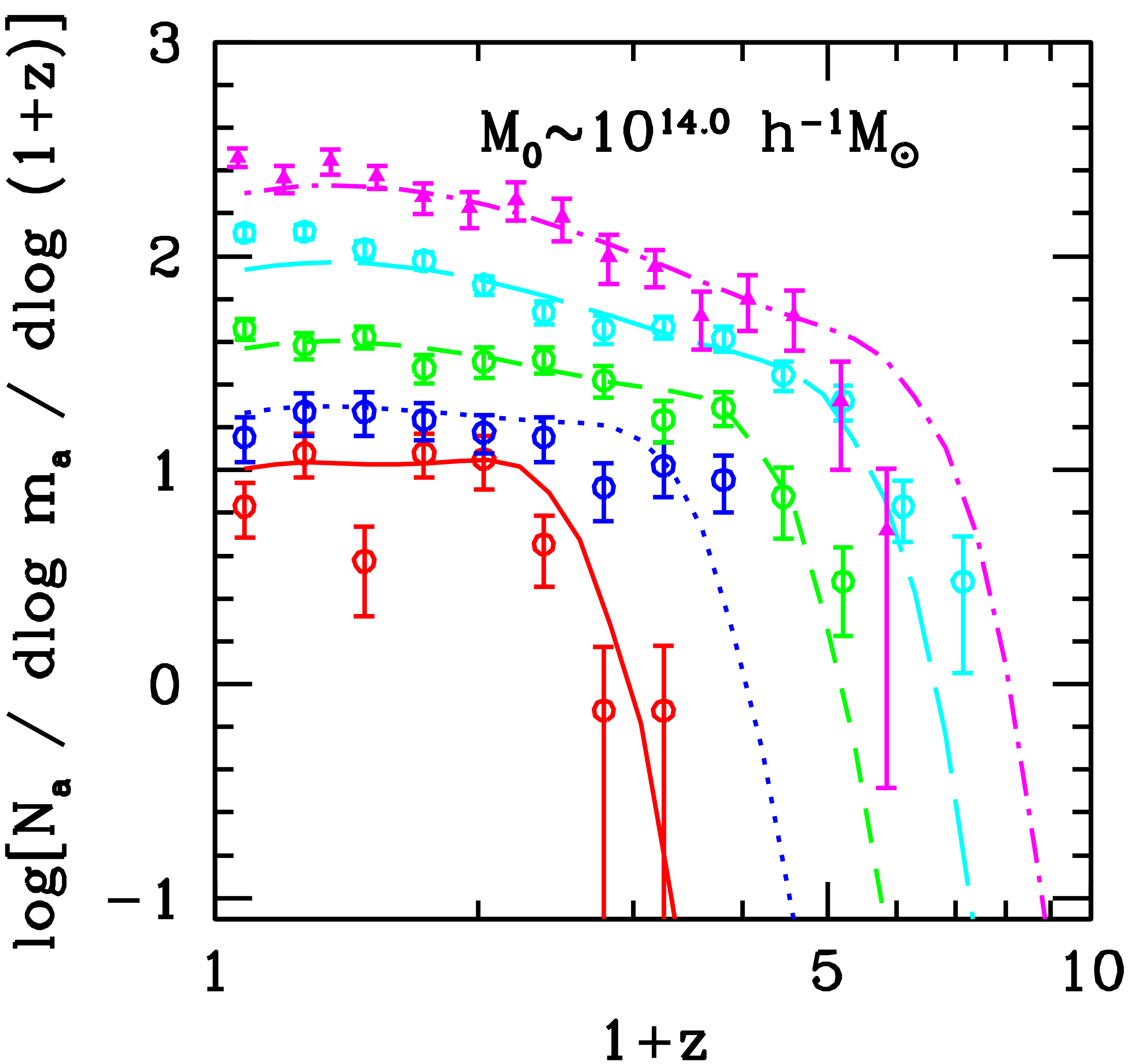
↓

Subhalos experience mass loss

Modeling for tidal stripping and mass-loss rate

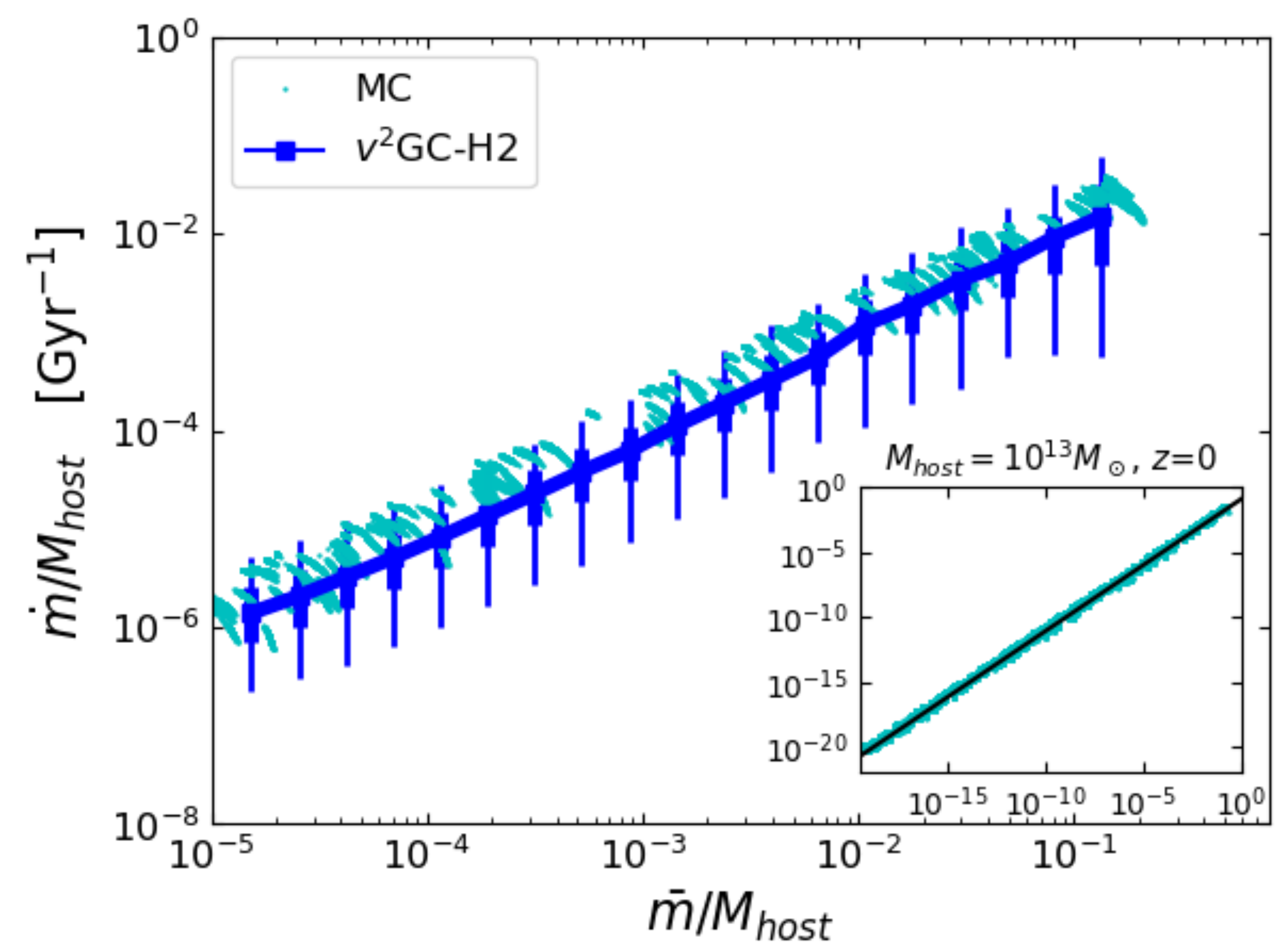
Model ingredients

Infall distribution of subhalos:
Extended Press-Schechter formalism



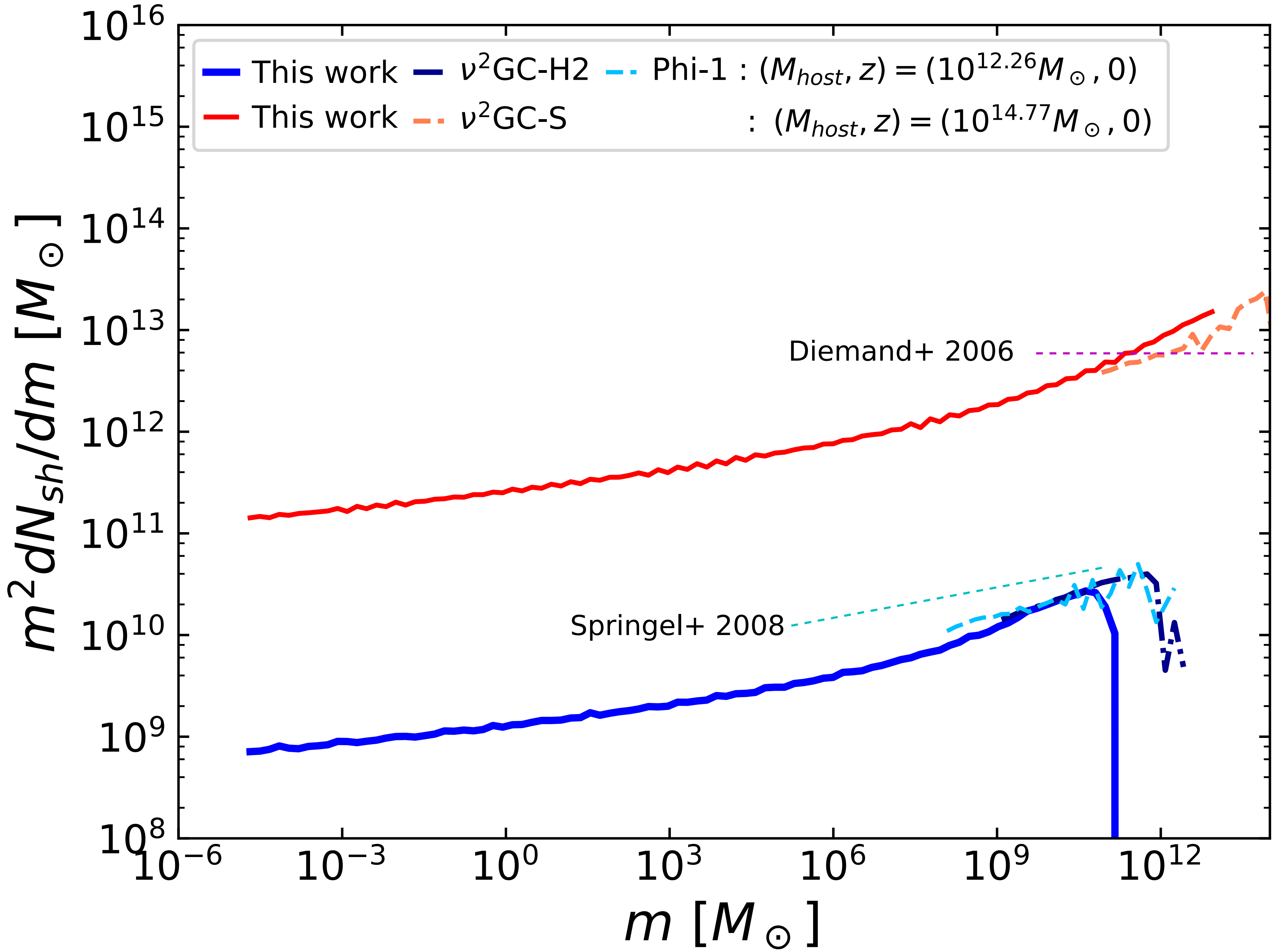
Yang et al., *Astrophys. J.* **741**, 13, (2011)

Modeling of tidal mass loss:
Monte Carlo calibrated with simulations



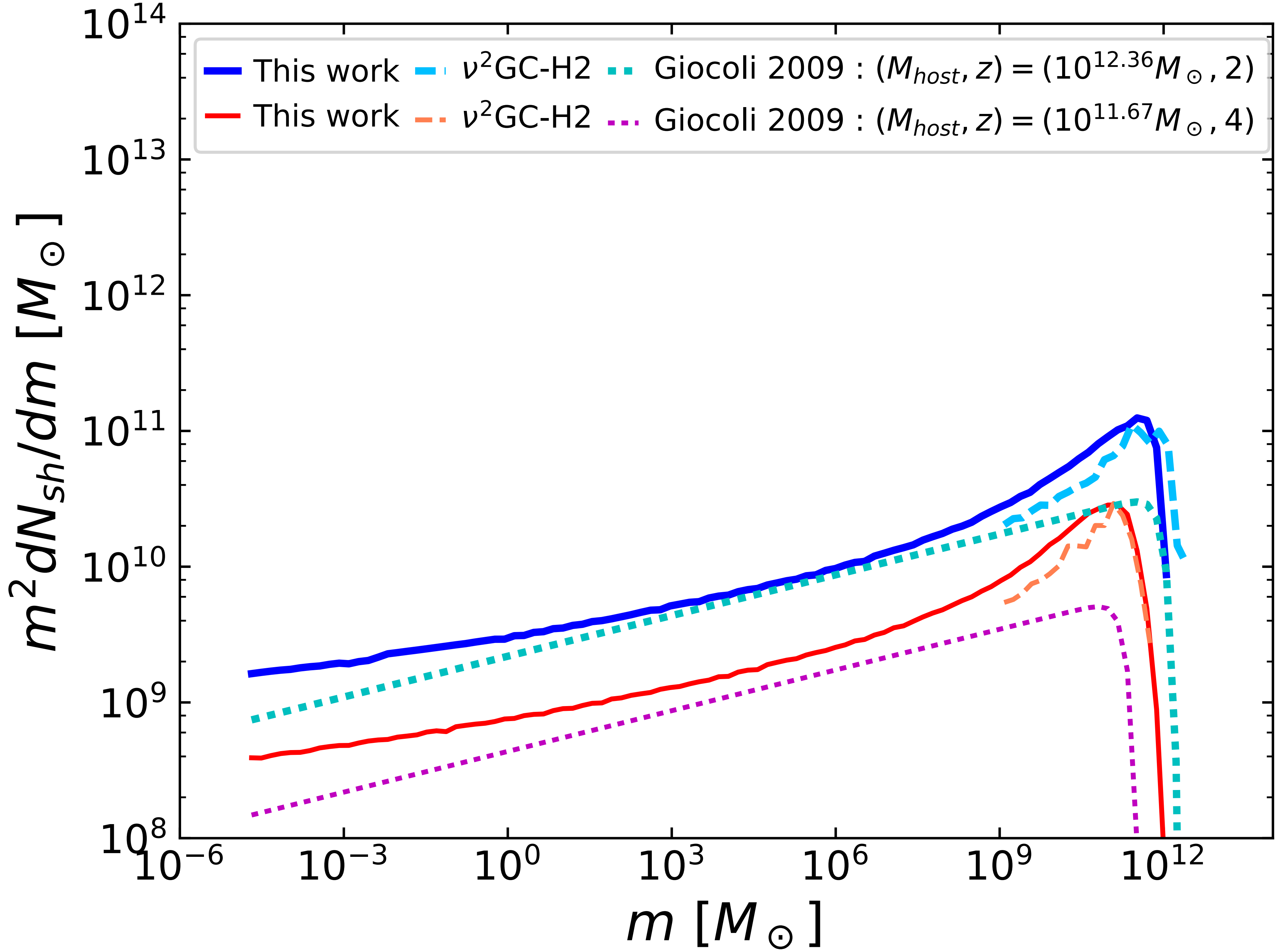
Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)

Subhalo mass function: Clusters and galaxies



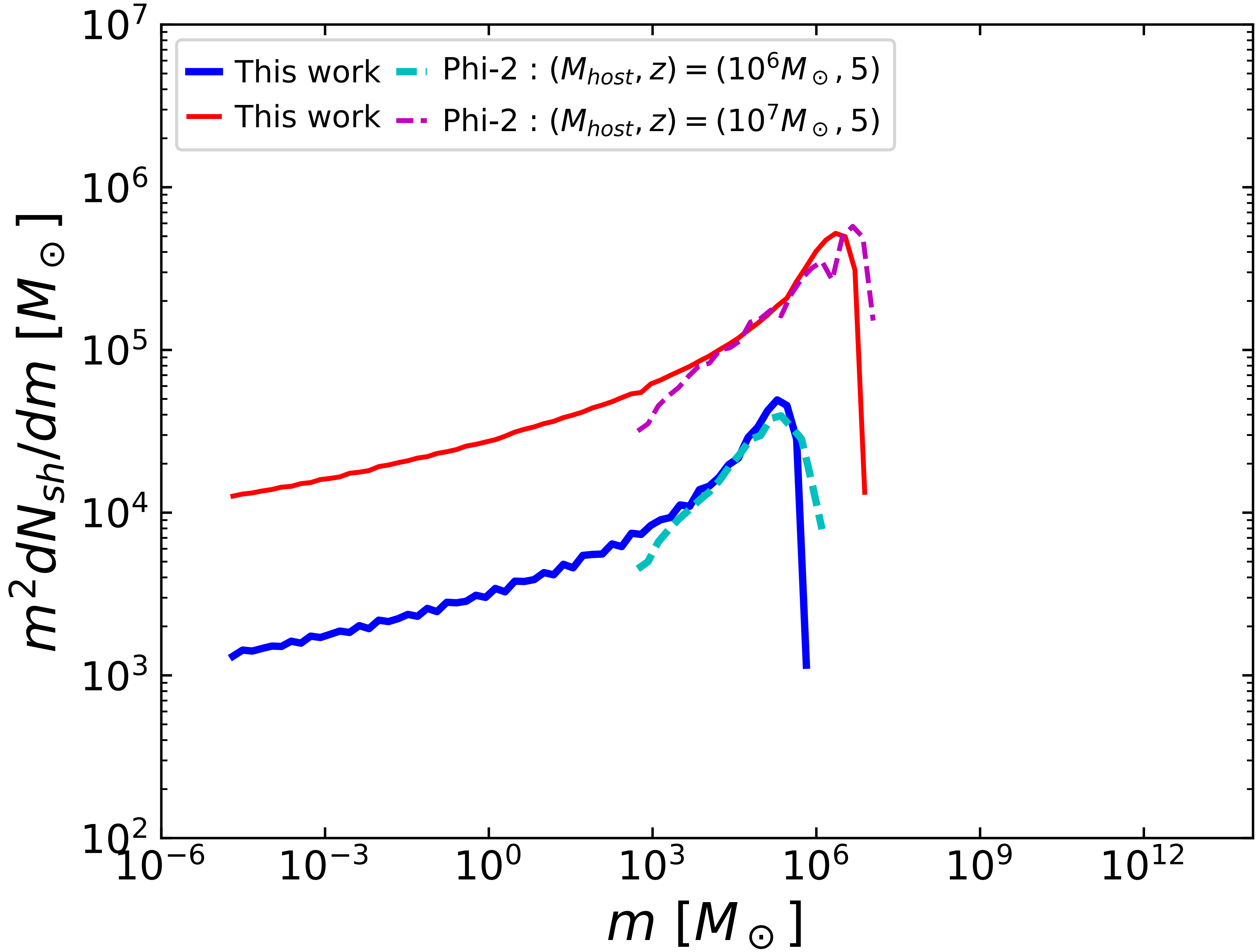
Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)

Subhalo mass function: Galaxies at z=2,4



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

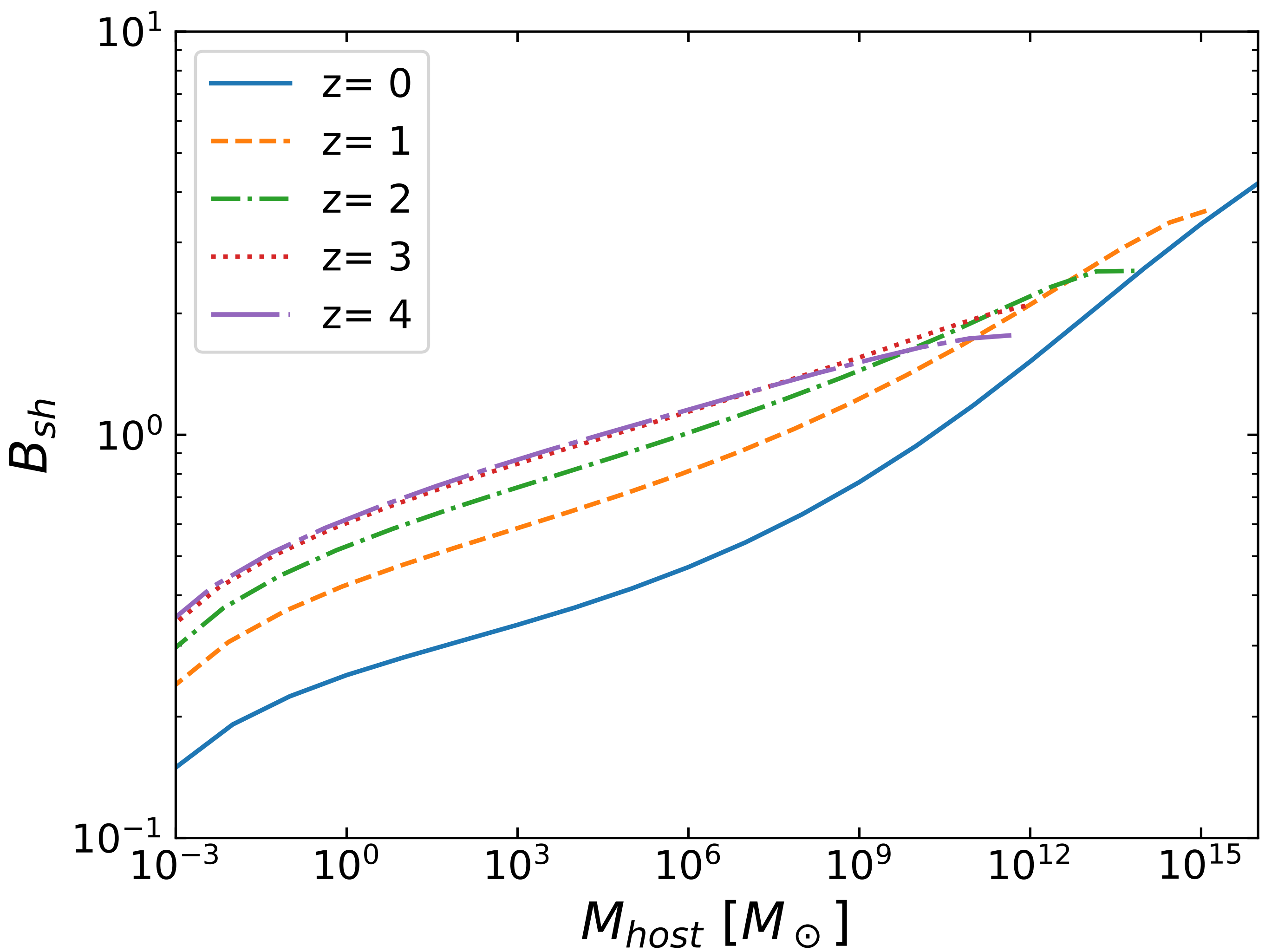
Subhalo mass function: Dwarfs at z=5



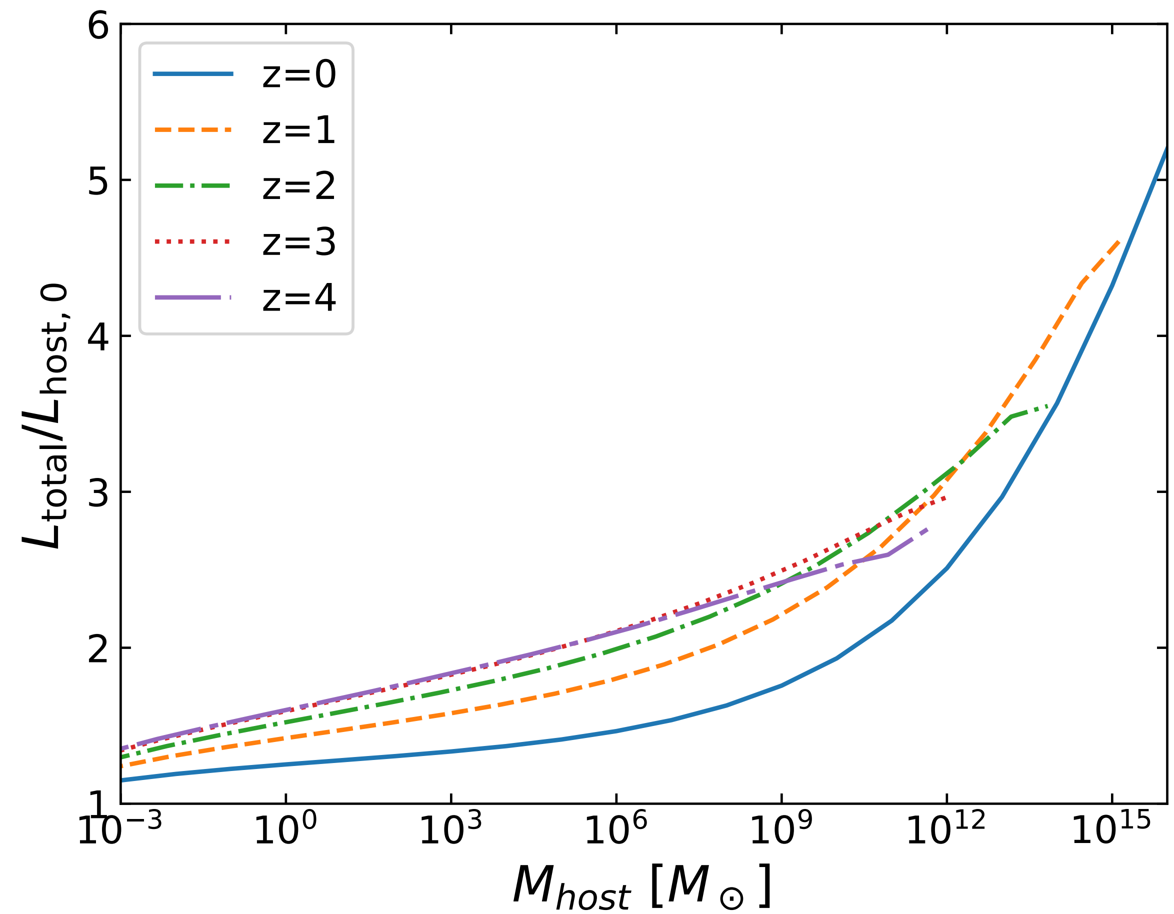
Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)

Annihilation boost

Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)
Ando, Ishiyama, Hiroshima, *Galaxies* **7**, 68 (2019)



w/ up to sub³-subhalos



- Boost can be as large as ~1 (3) for galaxies (clusters)
- 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

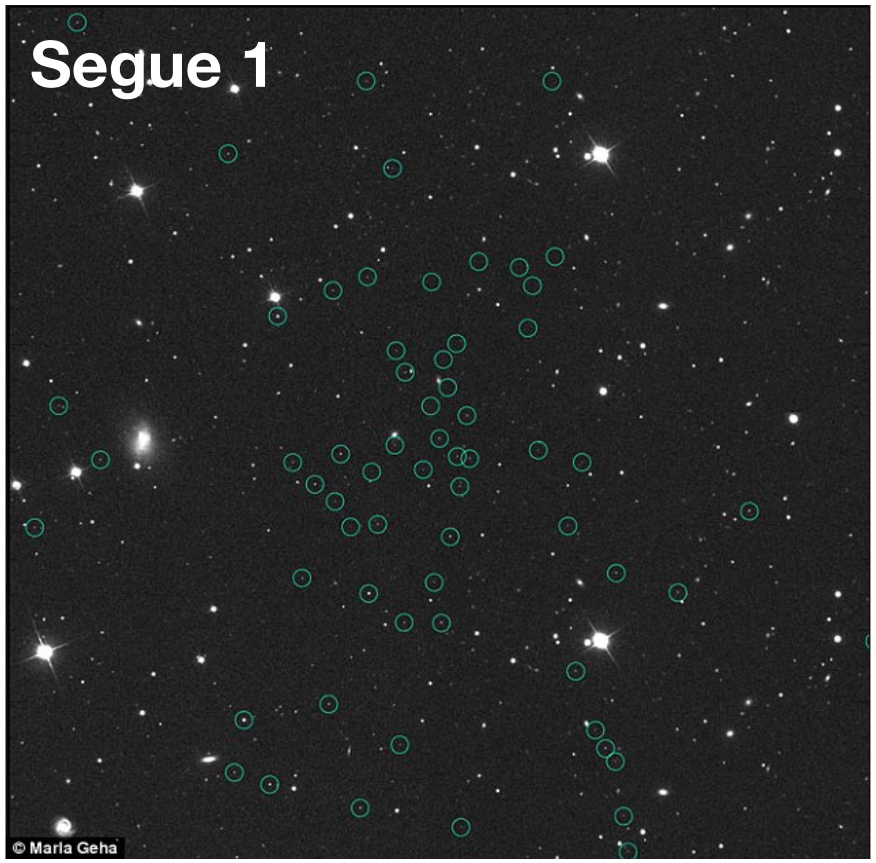
Implications for dwarf J factors

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} GeV^2/cm^5 or larger
- But *ultrafaint* dwarfs do not host many stars

Dwarf *J* factors



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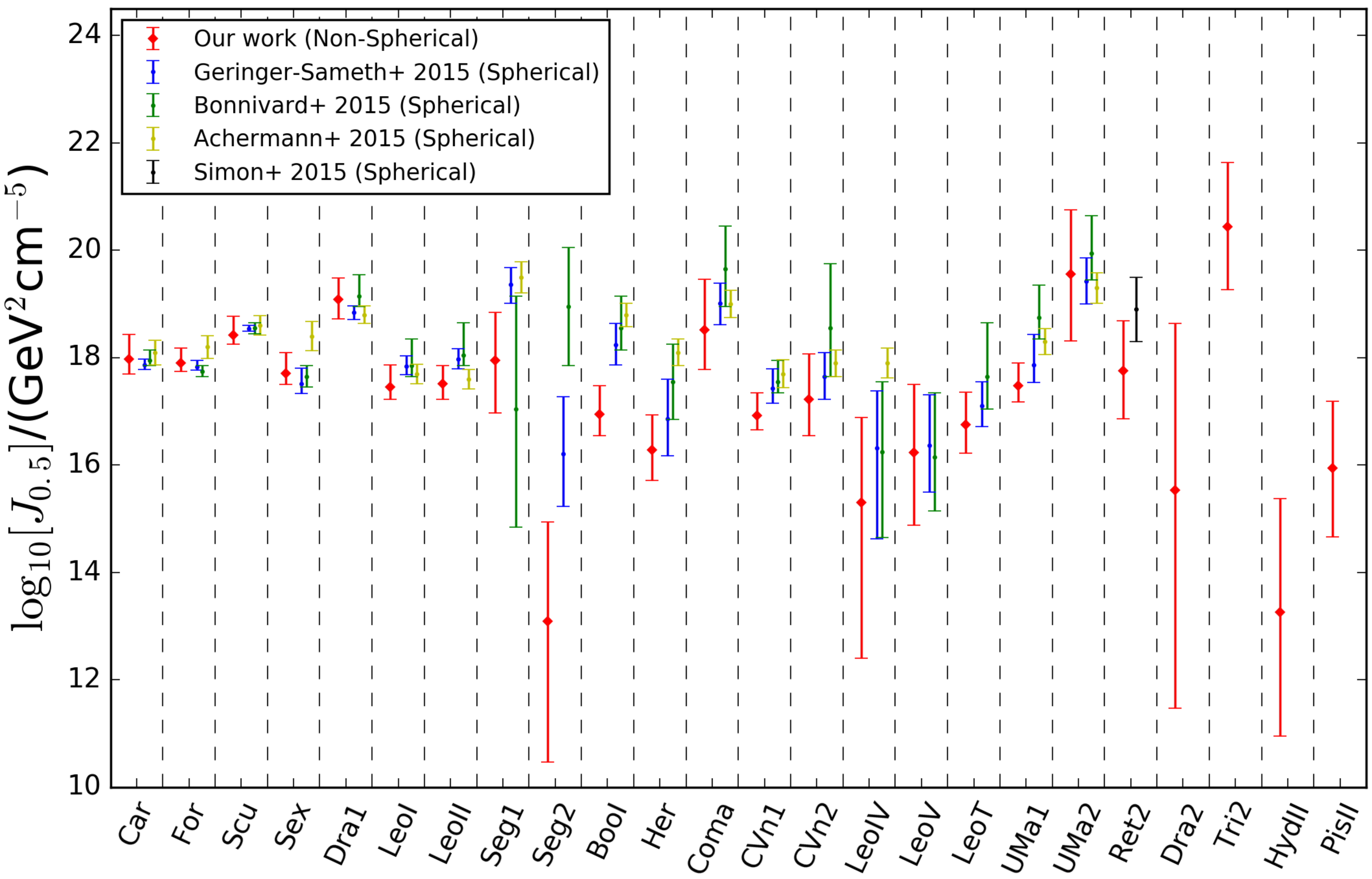
Dwarf *J* factors



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

Estimates of density profiles

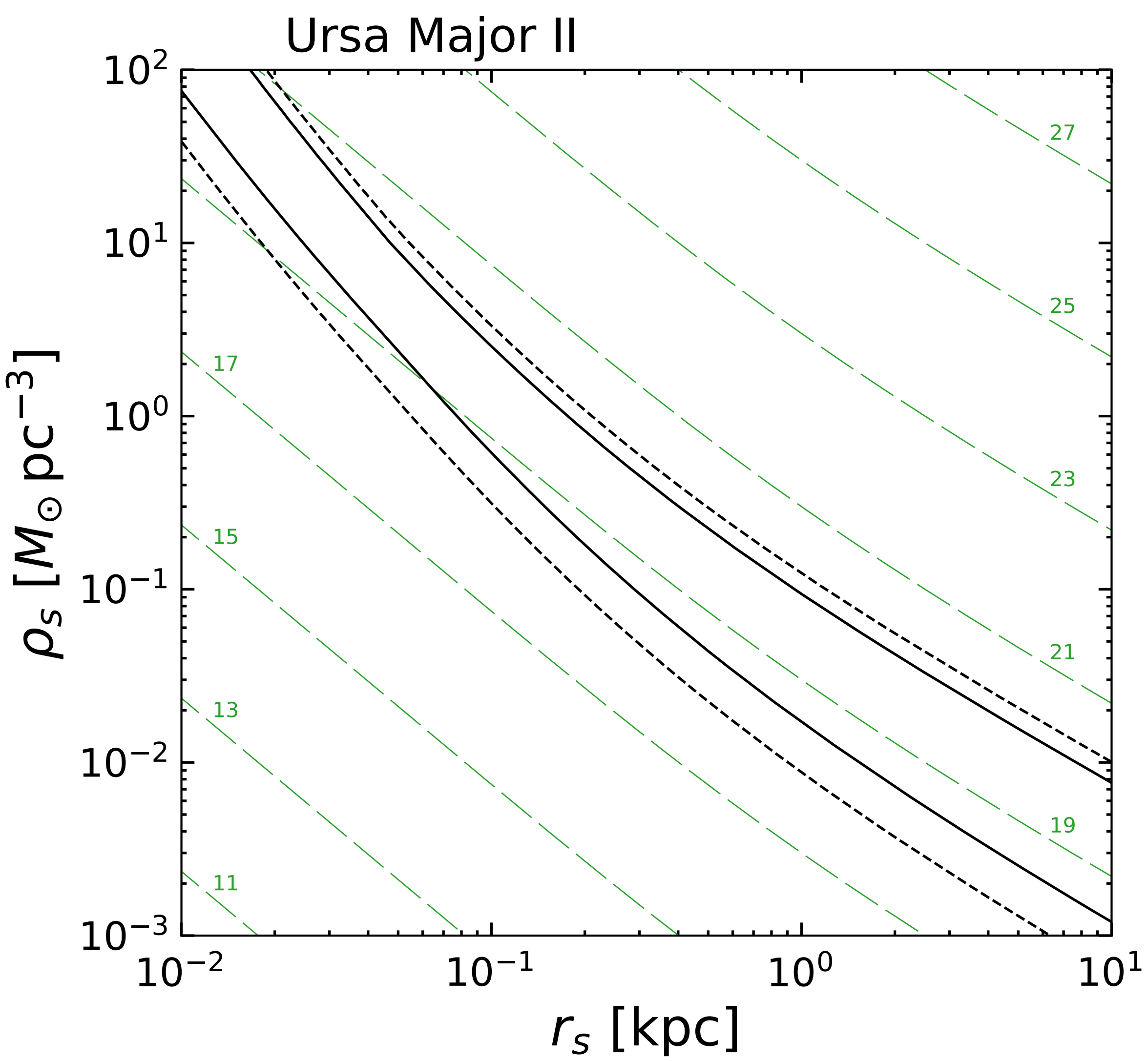
- Estimates of r_s and ρ_s usually rely on Bayesian statistics:

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

- 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)

Impact of *satellite prior*

Ando, Geringer-Sameth, Hiroshima, Hoof, Trotta, Walker, in preparation



- **Black: Likelihood contours**
- **Green: log [*J*/(GeV^2/cm^5)]**

- Having small data only does not break the degeneracy between r_s and ρ_s

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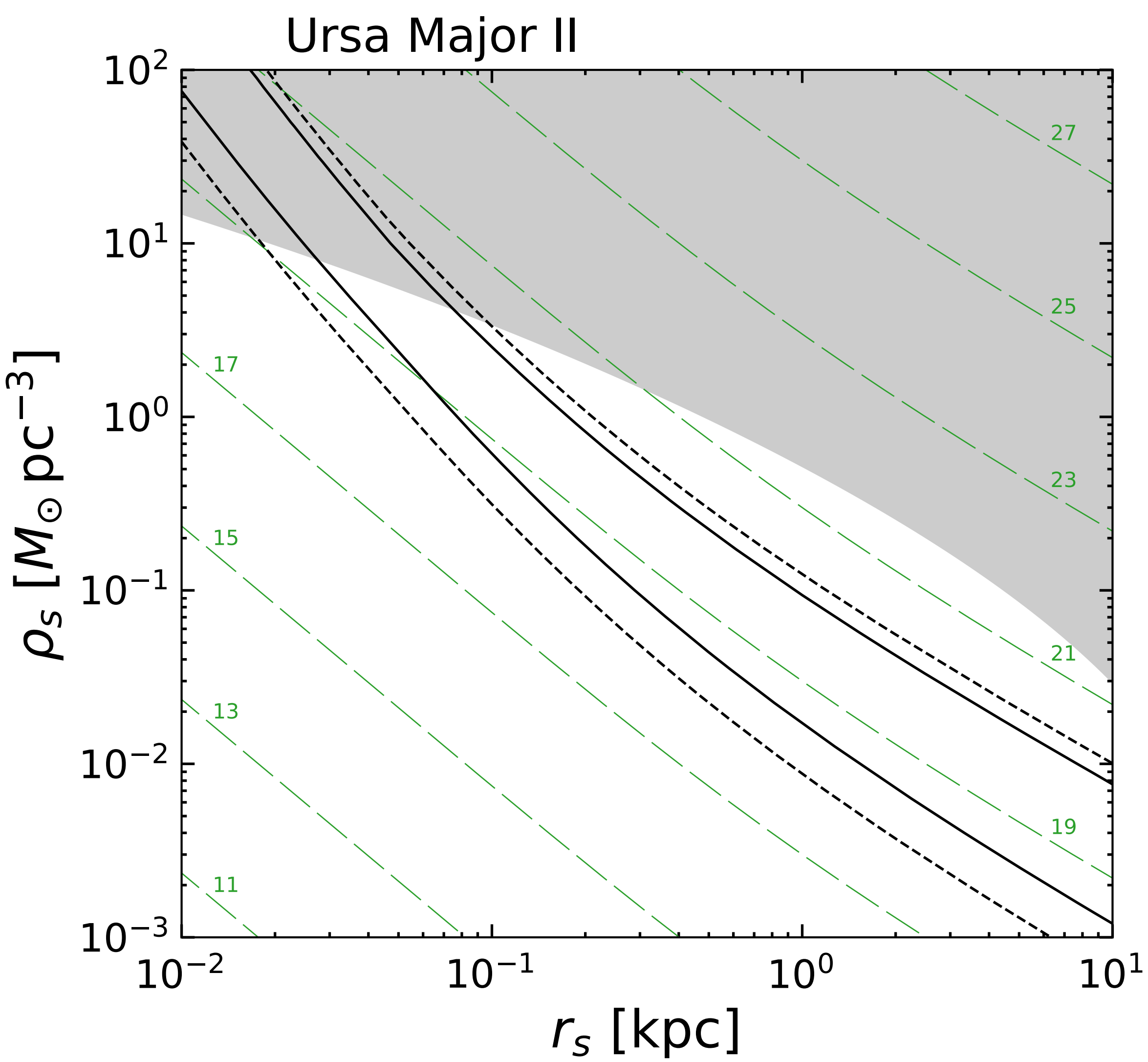

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- Having small data only does not break the degeneracy between r_s and ρ_s
- Cosmological arguments have been adopted to chop off upper regions of the parameter space (e.g., Geringer-Sameth et al. 2015)

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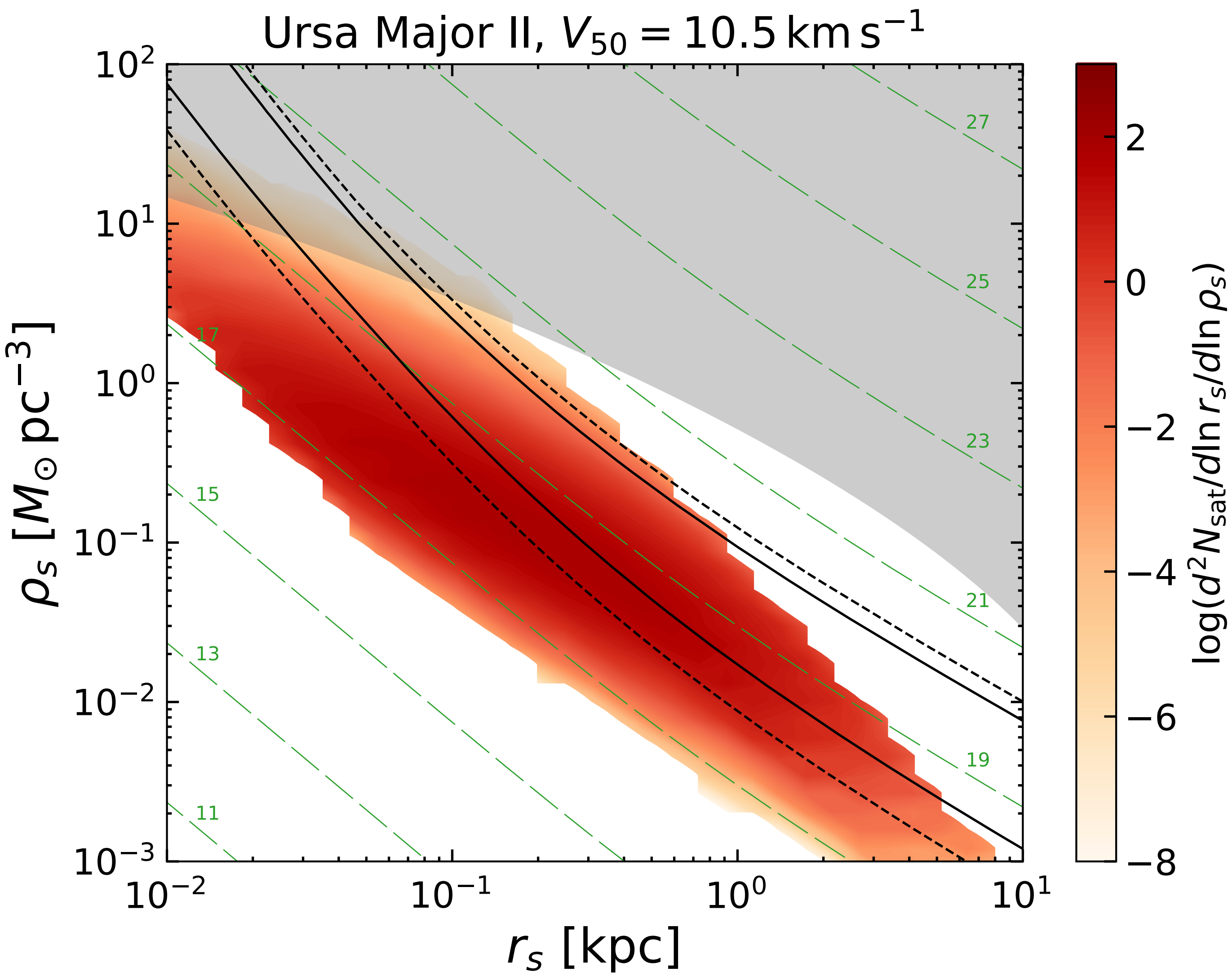

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- **Red: Prior density**

- Having small data only does not break the degeneracy between r_s and ρ_s
- Cosmological arguments have been adopted to chop off upper regions of the parameter space (e.g., Geringer-Sameth et al. 2015)
- Satellite prior does this job naturally as well as breaks the degeneracy

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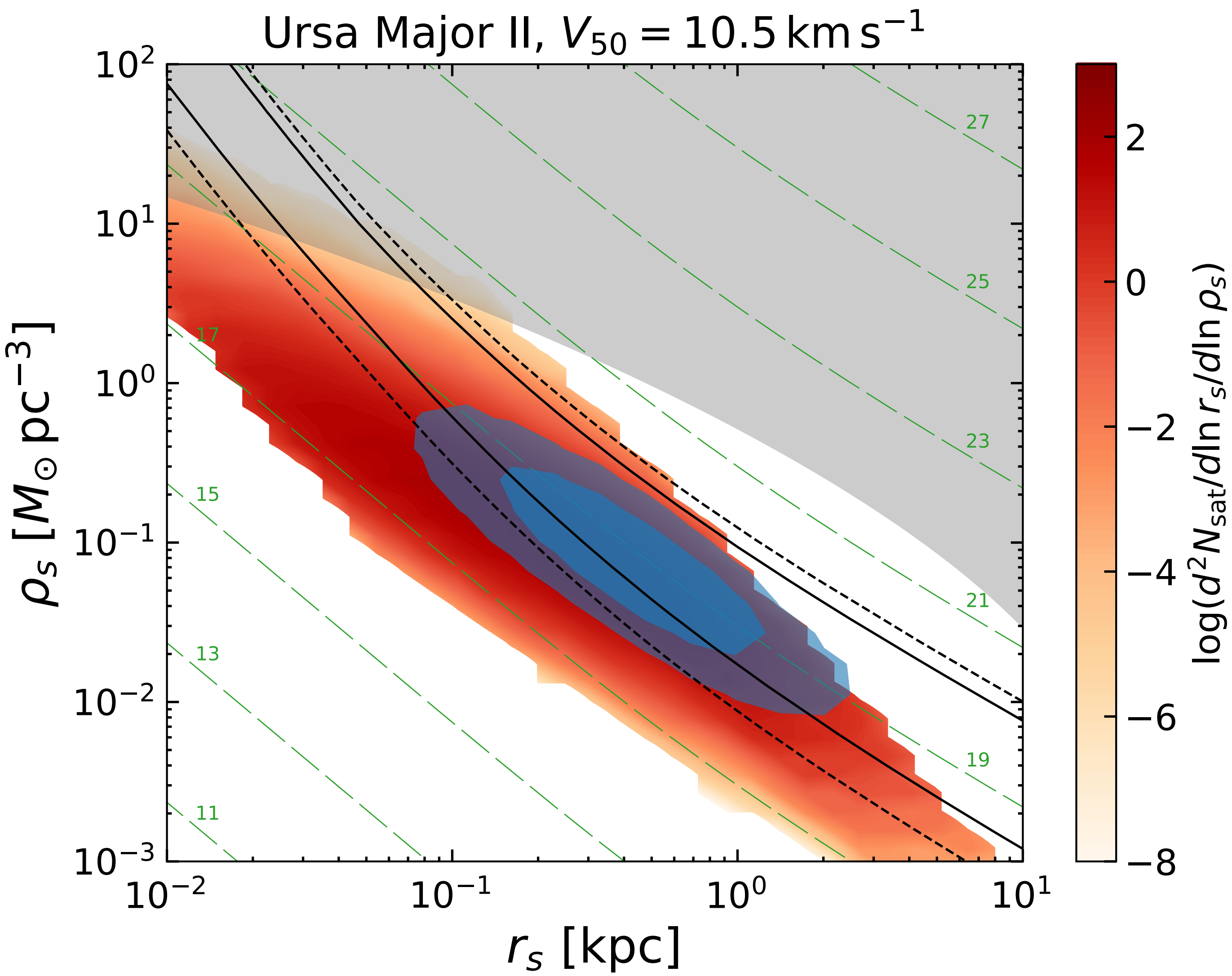

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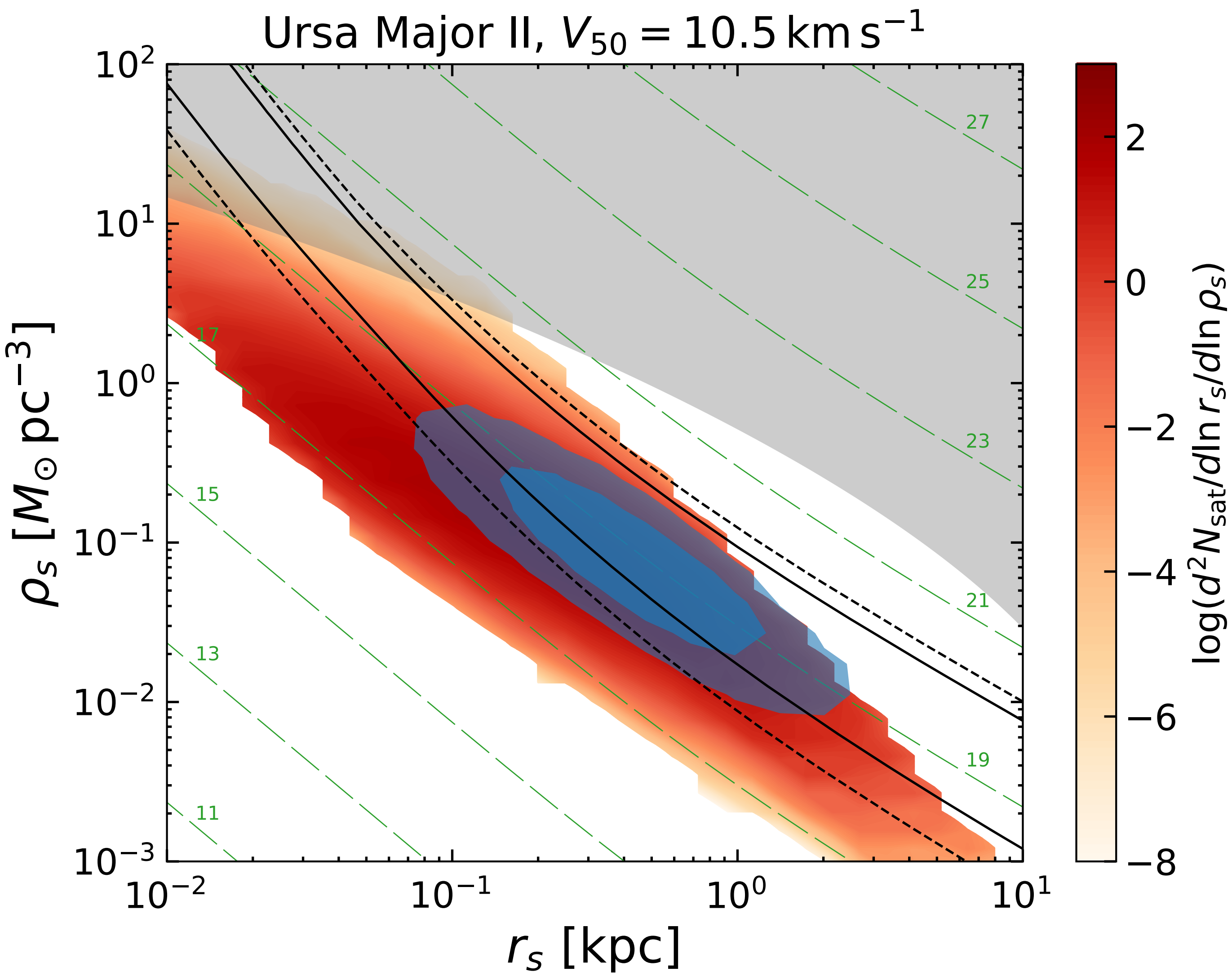

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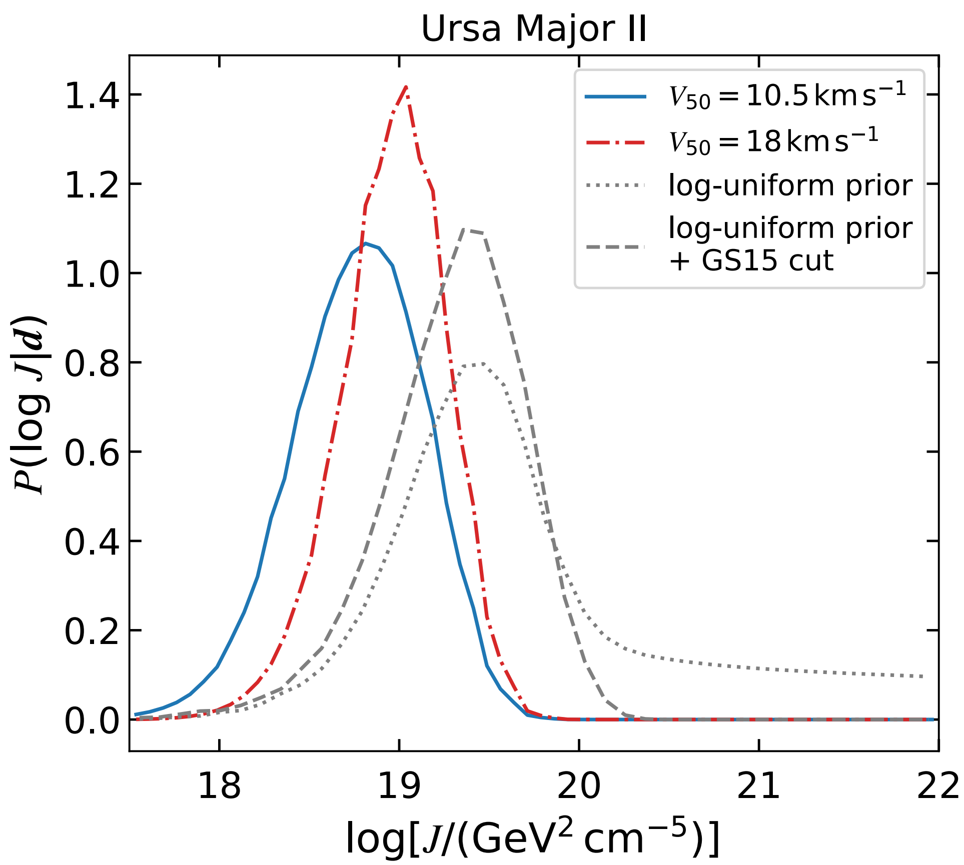
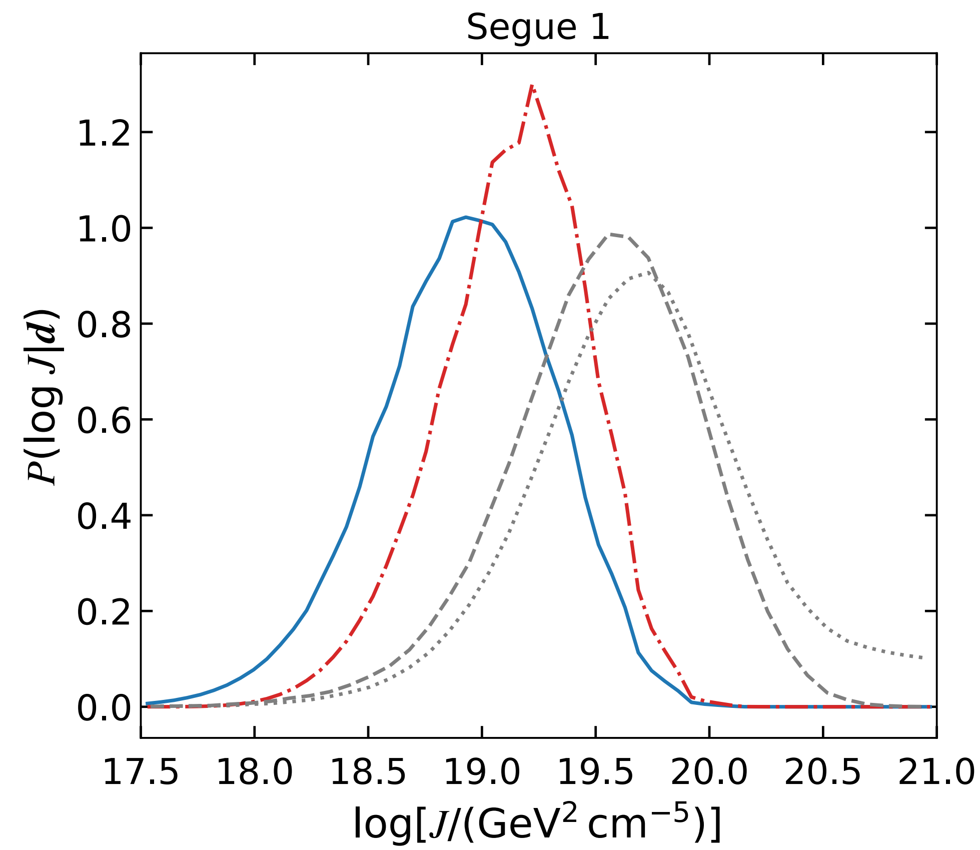
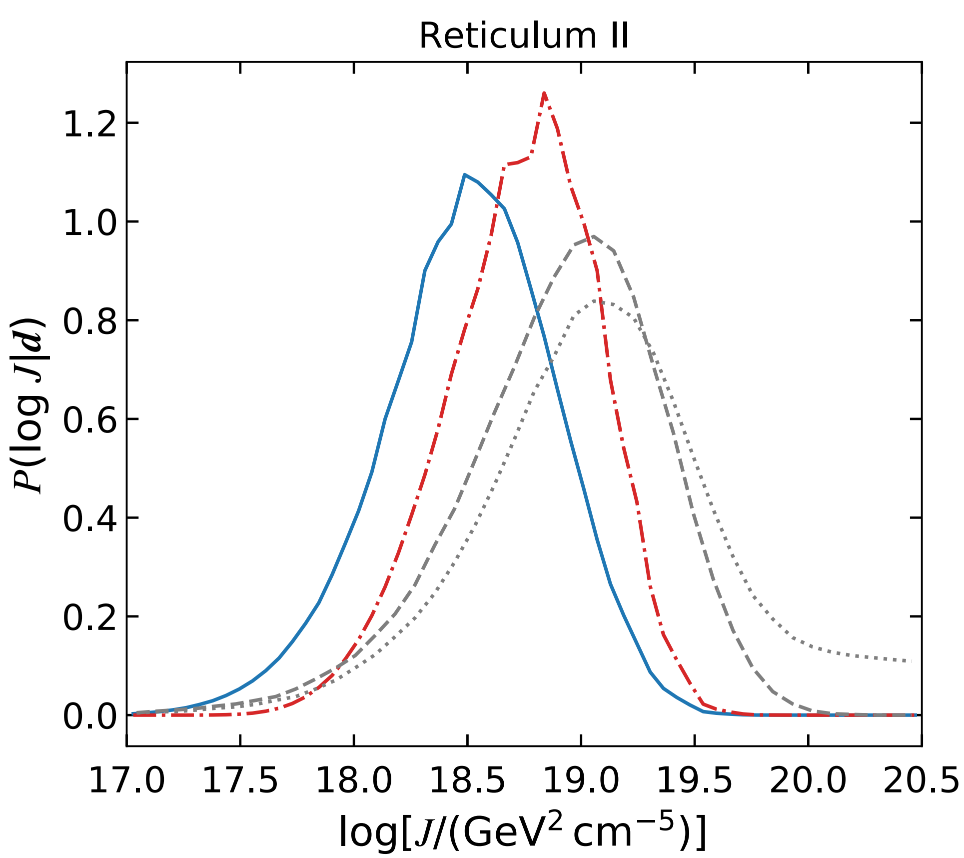
- Cosmological arguments have been adopted to chop off upper regions of the parameter space (e.g., Geringer-Sameth et al. 2015)
- Satellite prior does this job naturally as well as breaks the degeneracy
- This is hard to achieve with simulations as they are limited by statistics of finding dwarf candidates

Impact of *satellite prior*



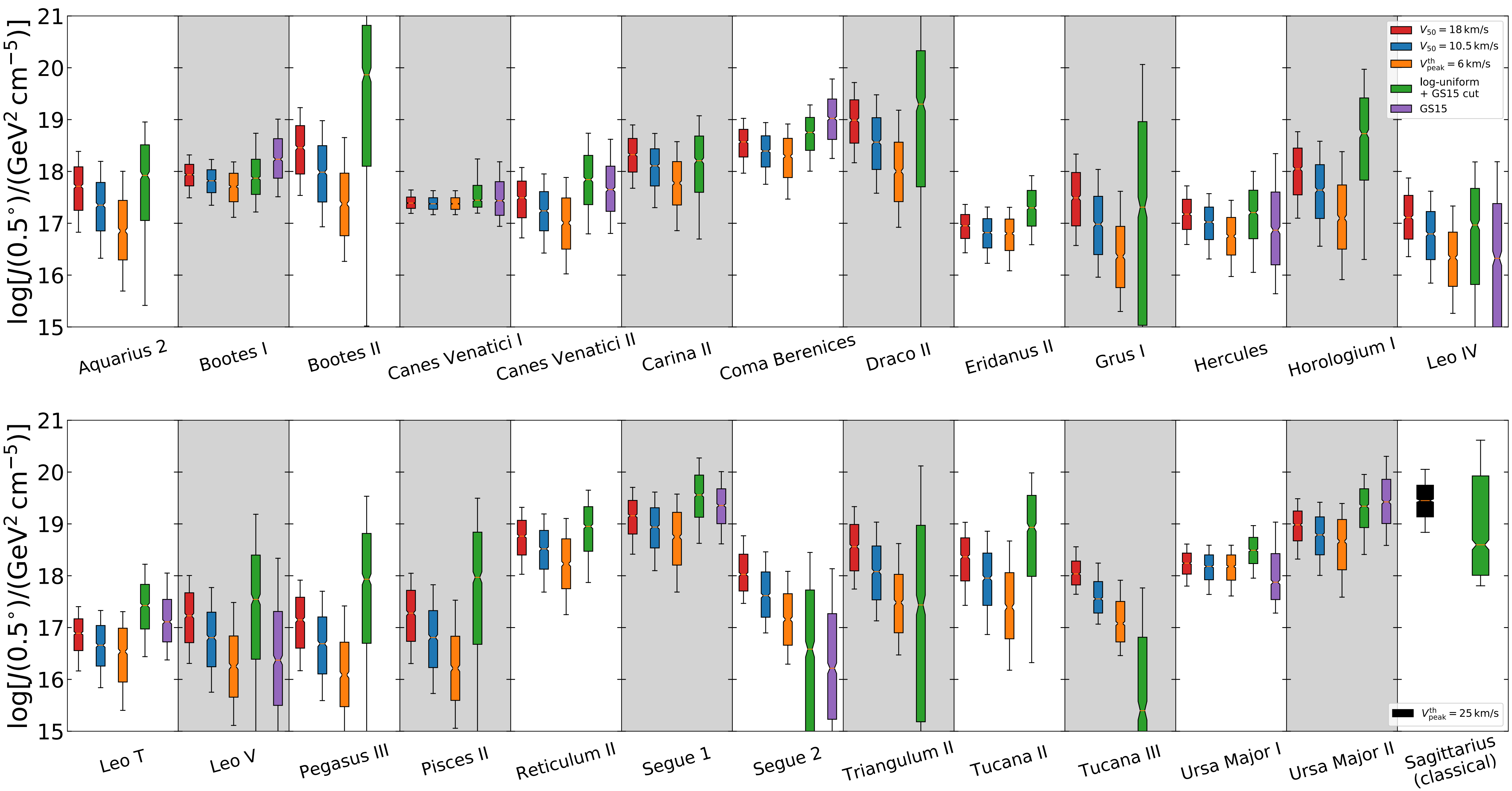


Ando, Geringer-Sameth, Hiroshima, Hoof, Trotta, Walker, in preparation



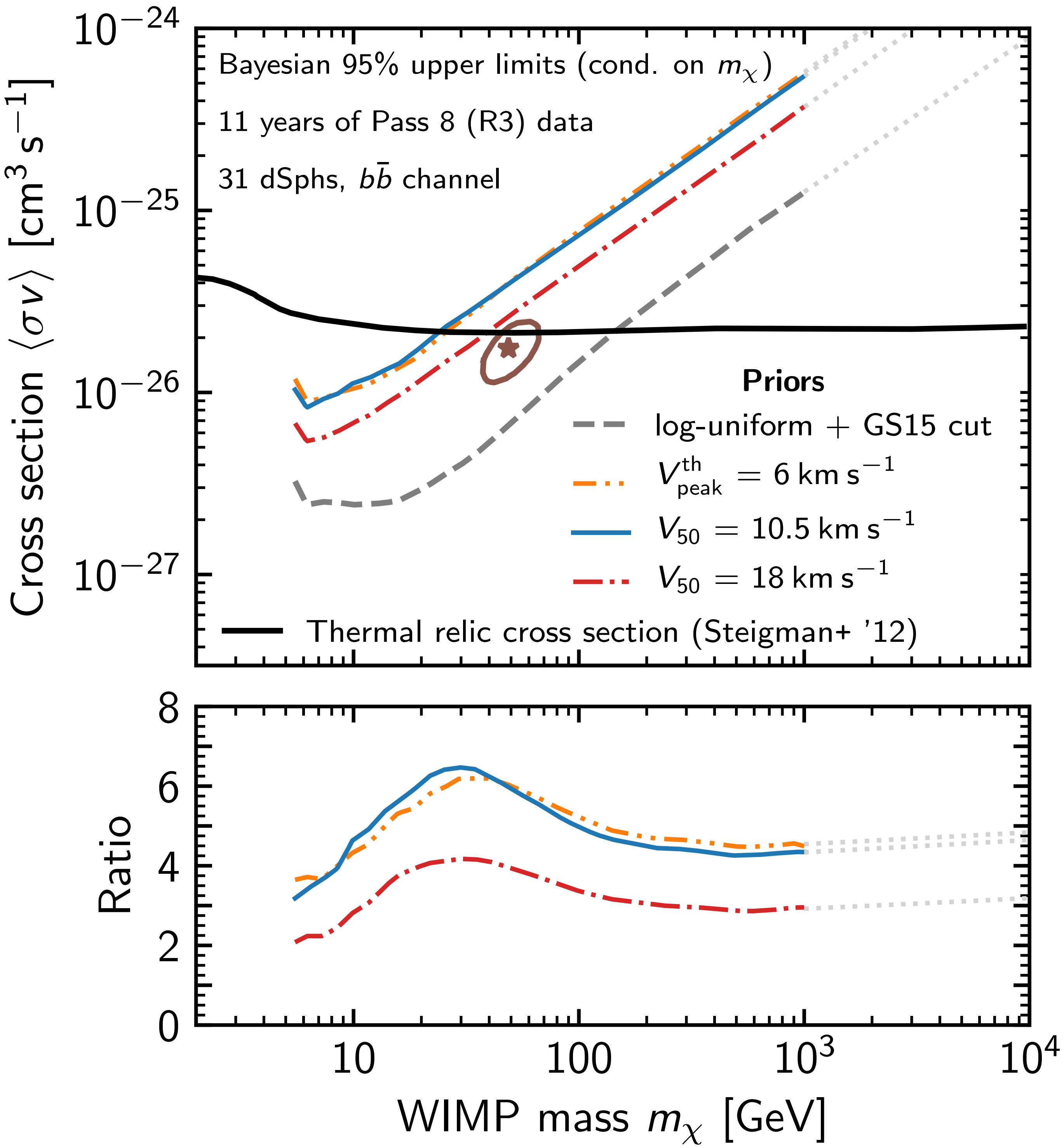
- Using satellite priors will systematically shift the *J* distribution toward lower values
- But this depends on satellite formation models

Impact of *satellite prior*



Ando, Geringer-Sameth, Hiroshima, Hoof, Trotta, Walker, in preparation

Cross section constraints



- Adopting satellite priors **weaken** the cross section constraints by **a factor of 2-7**
- The effect is relatively insensitive to condition of satellite formation: **robust prediction**
- Thermal cross section can be excluded only up to 20-50 GeV
- Also very relevant for wino dark matter targeted by CTA

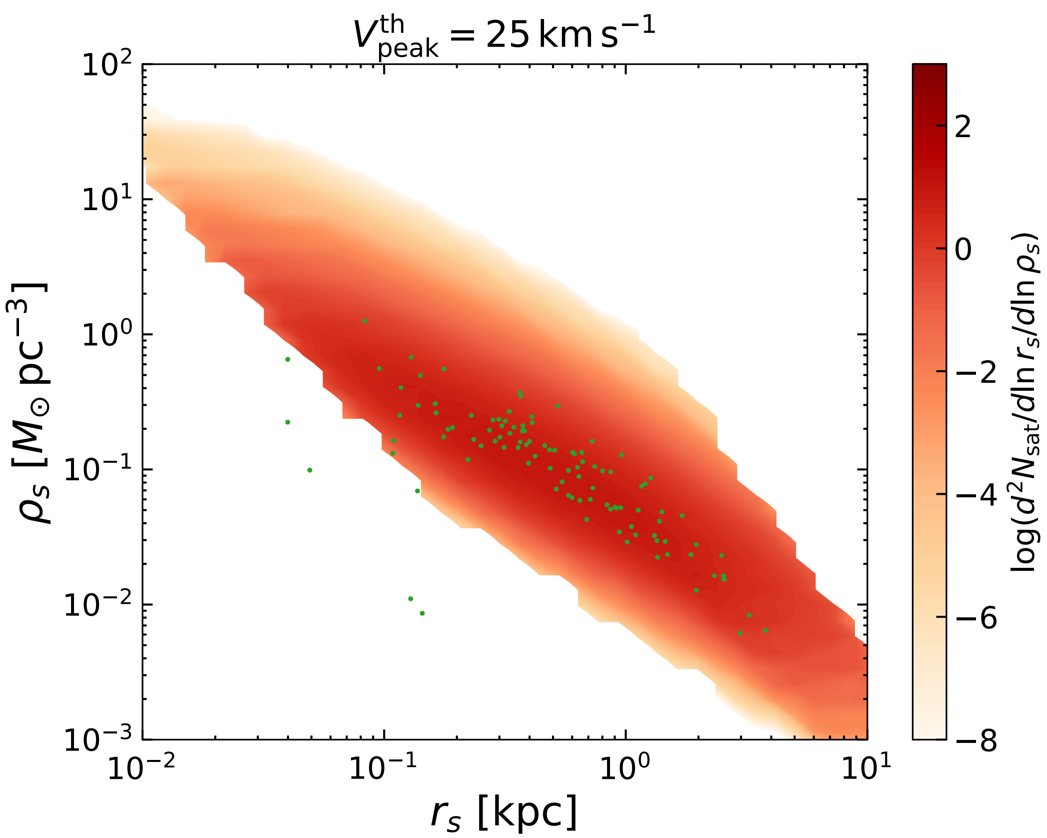
Ando, Geringer-Sameth, Hiroshima, Hoof, Trotta, Walker, in preparation

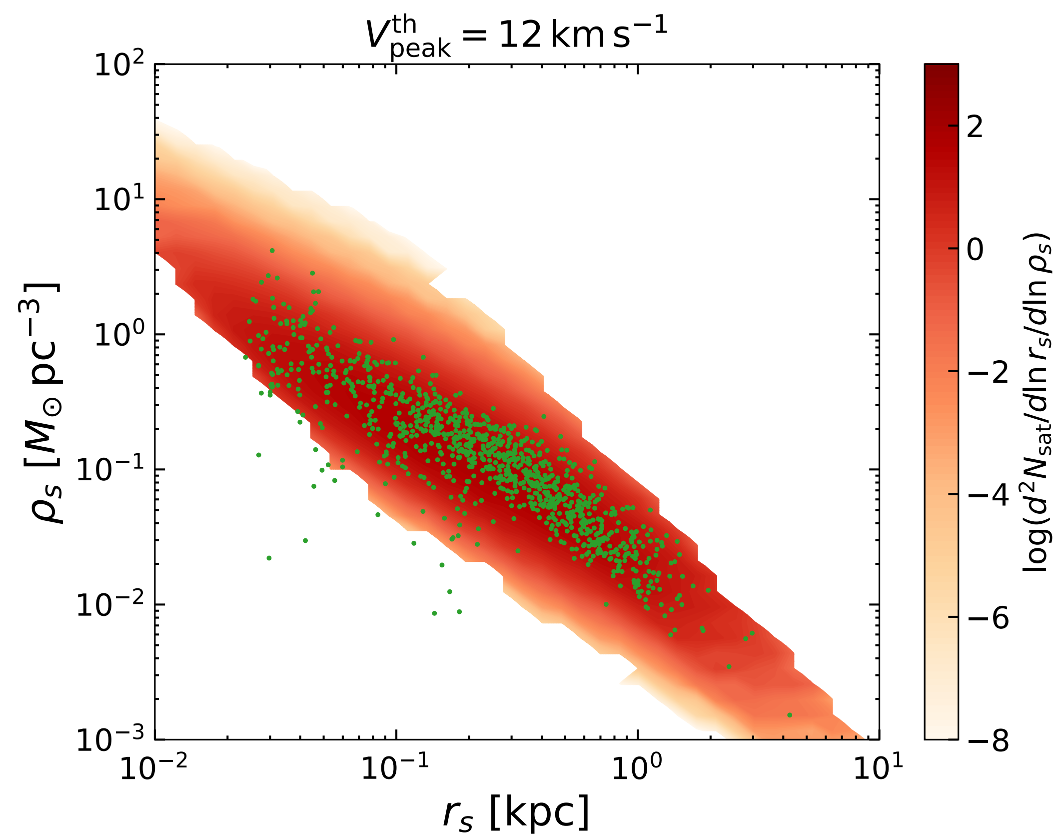
Conclusions

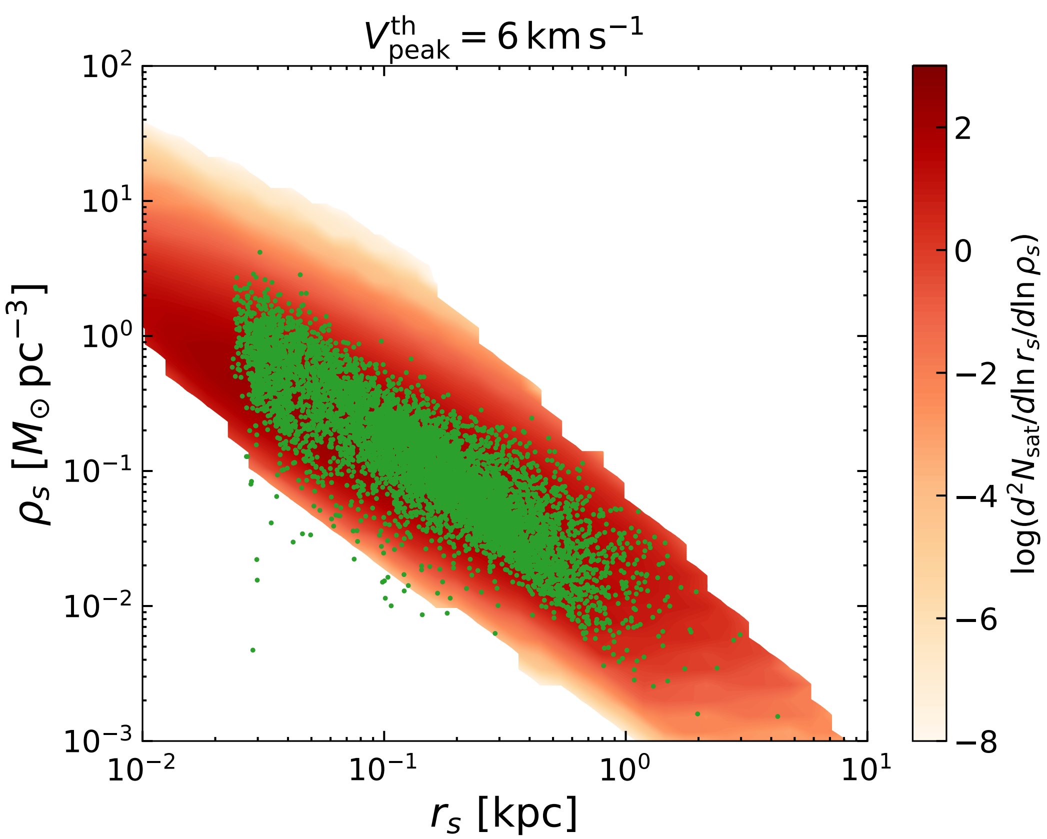
- **Correlation** between **gamma-ray** (Fermi-LAT) and **weak-lensing** (DES) data has been detected
- **Dark matter interpretation** is only **slightly preferred** over purely astrophysical scenario, but required cross section is very high and also depends how to model subhalos
- We developed **analytic models** which yielded relatively **modest annihilation boost** ~O(1) for galaxies
- Applying the same models **weakens the dwarf constraints** on the annihilation cross section **by a factor of 2-7**

Backup

Comparison with VL-II simulations







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