Realistic estimation for the detectability of Dark Matter Galactic sub-halos in the Fermi-LAT 3FGL and 2FHL catalogs

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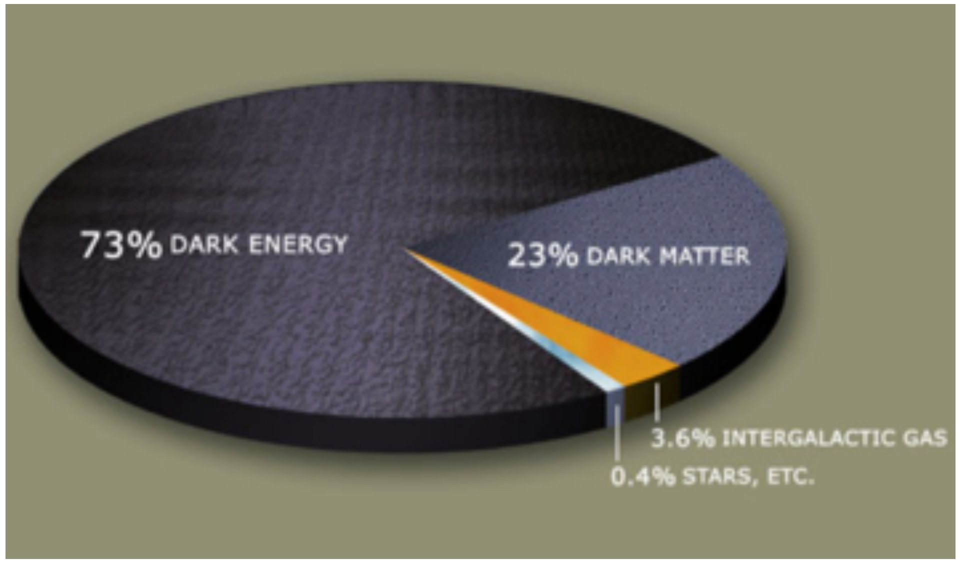
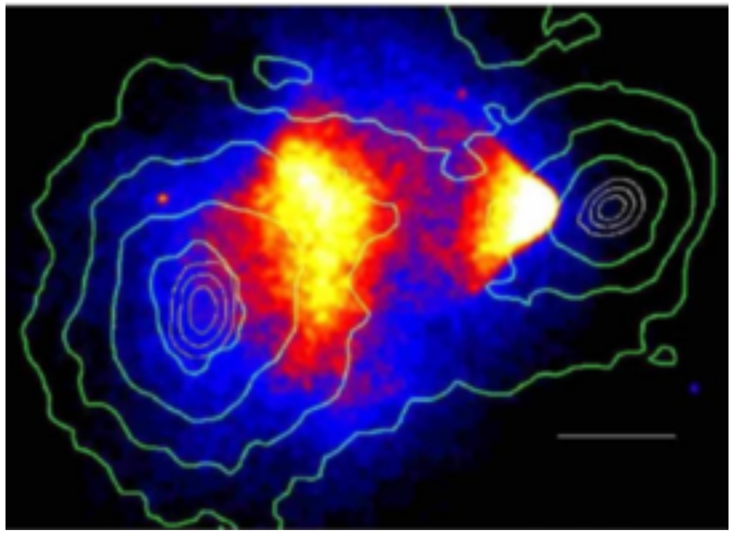
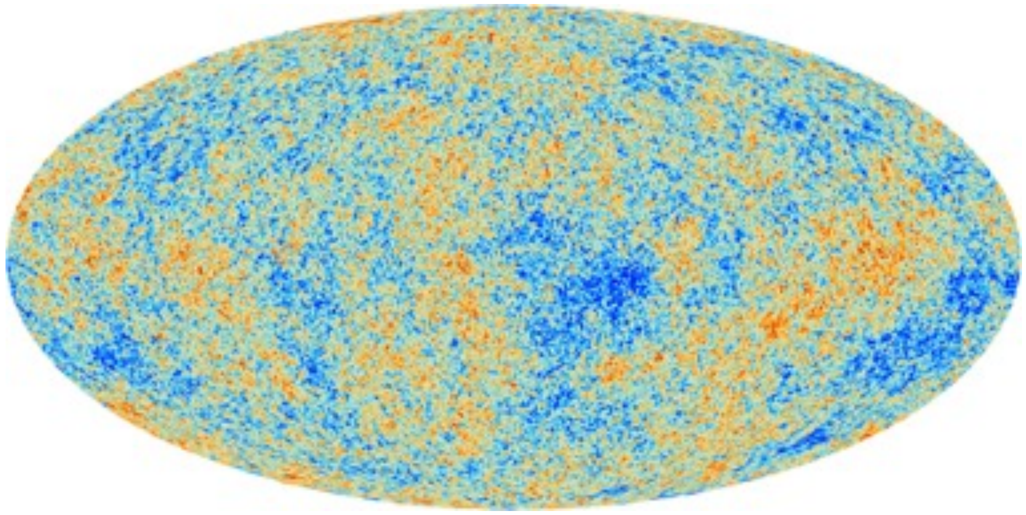
ECRS Turin September 4-9, 2016

EVIDENCES FOR EXISTENCE OF DM



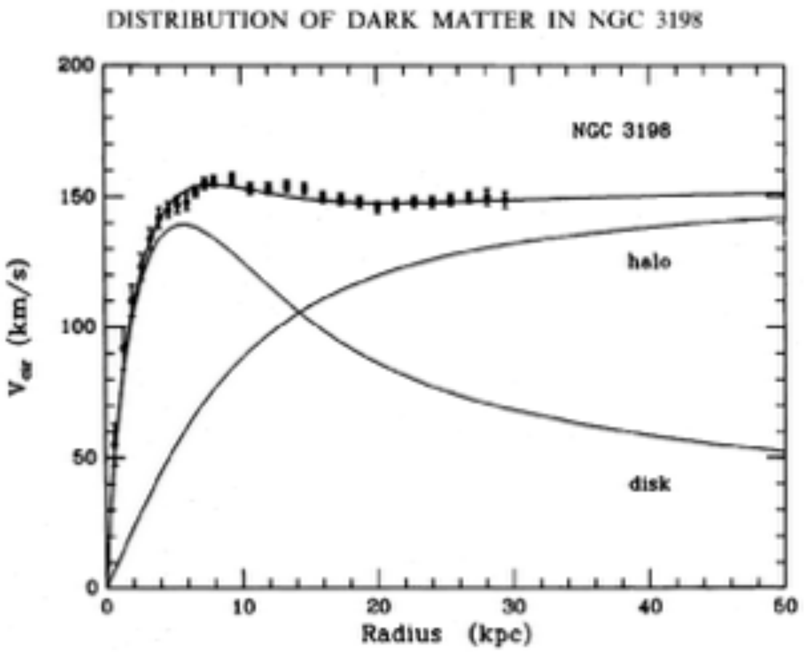
physics.stackexchange.com





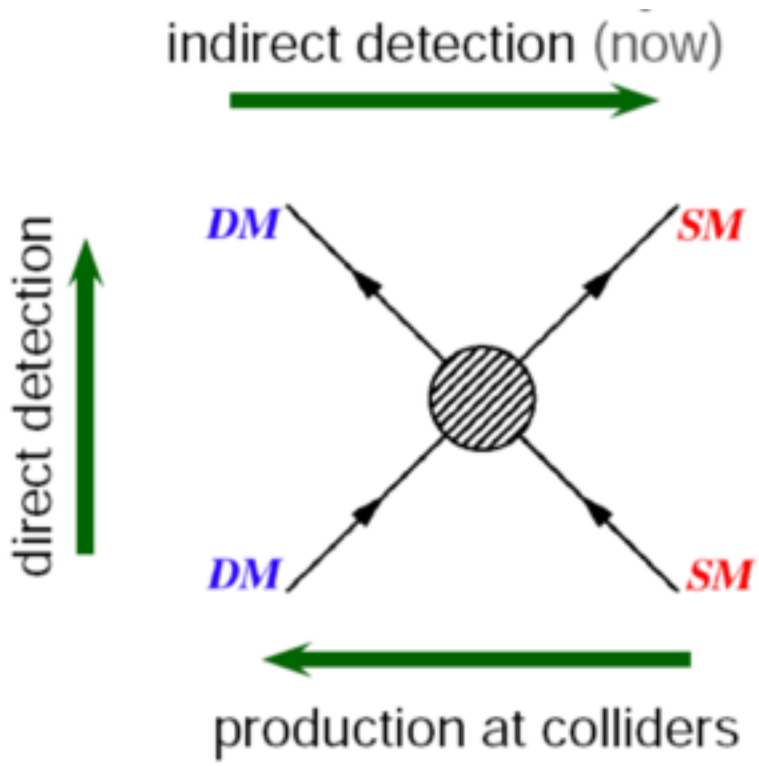
www.esa.int

bustard.phys.nd.edu

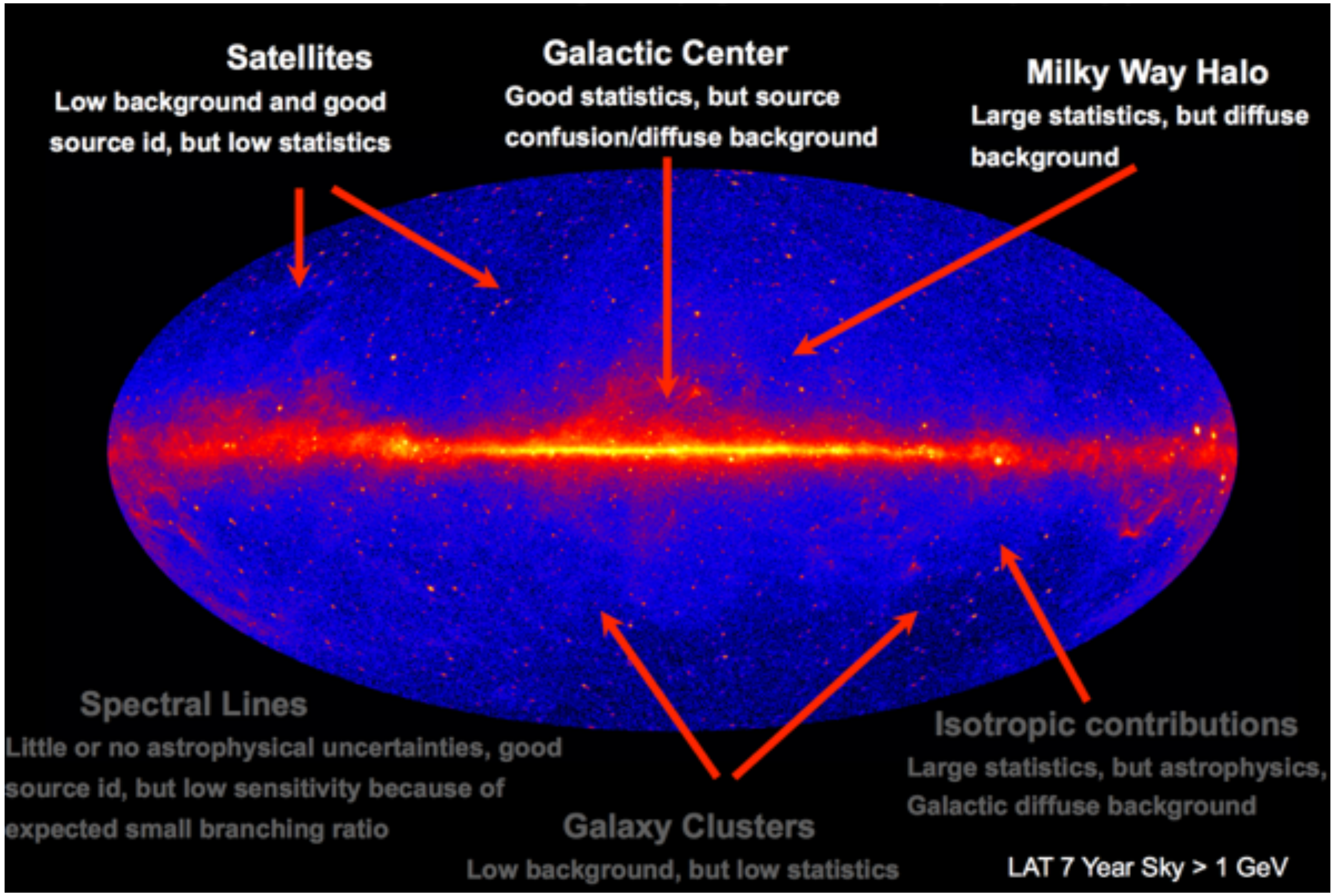


earthsky.org

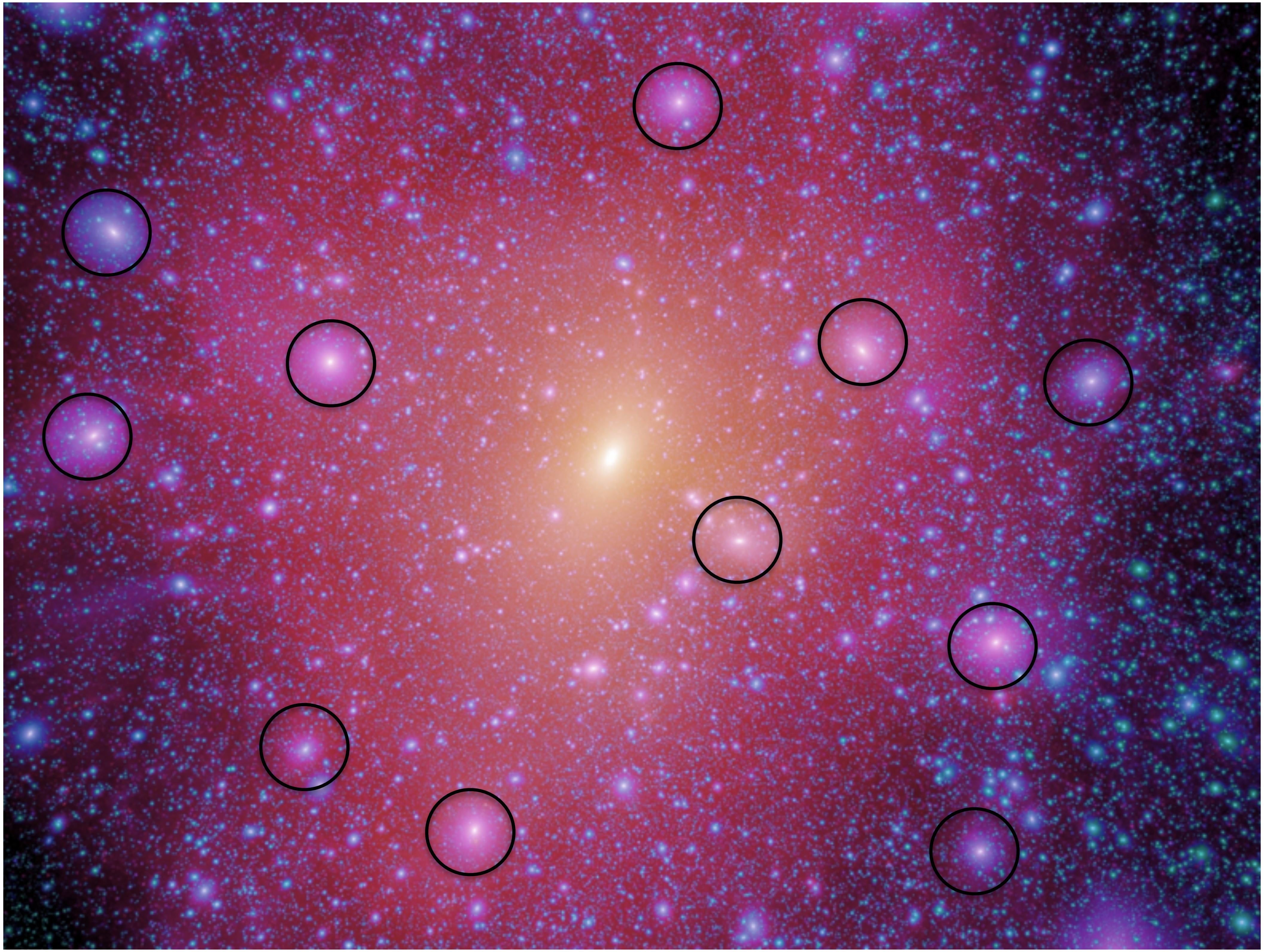
DETECTION STATEGIES



See e.g. E. Charles et al. 2016



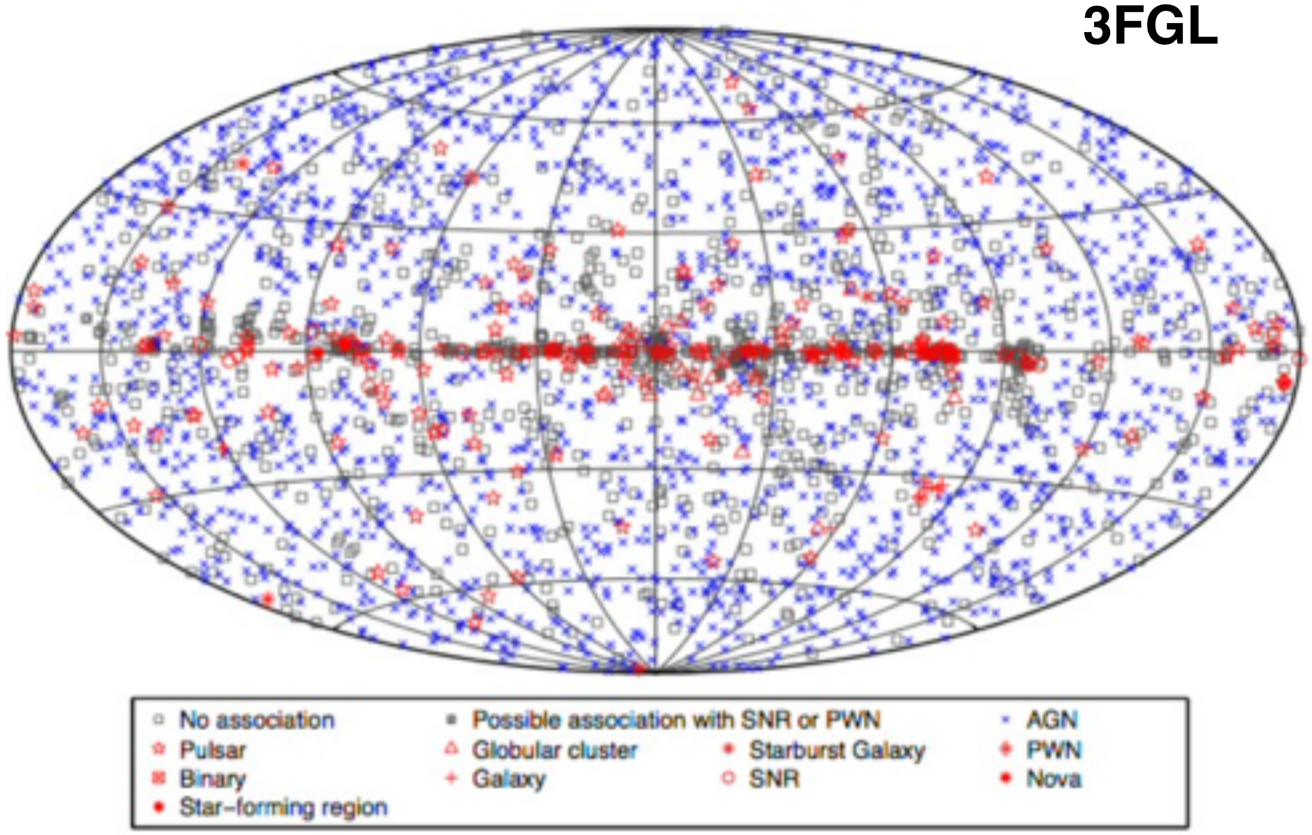
NUMERICAL SIMULATIONS



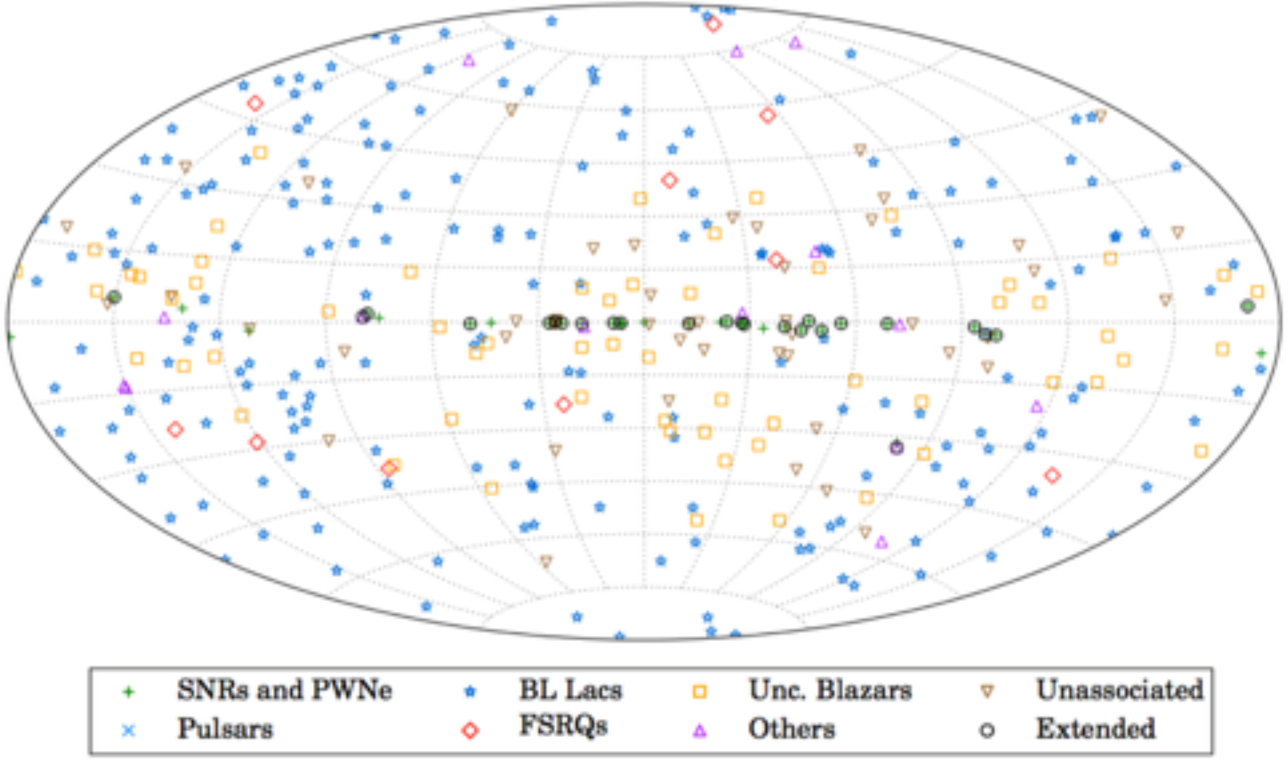
Springel et al. 2008

DETECTION STRATEGY

- The Fermi-LAT Collaboration released the **3FGL** (Acero et al. 2015)**:** 4 years, **0.1 – 300 GeV** with Pass 7 data. **3000 sources (**at a latitude $|b| > 20^\circ$ mainly AGN).
- Fermi-LAT also recently released the **2FHL** (Ackermann et al. 2015)**:** 360 sources detected with 80 months of exposure time and between **50 – 2000 GeV**.
- In both catalogues, a large fraction of sources remain **unassociated**: about **15% in the 2FHL** and **30% in the 3FGL.**
- Hence, unassociated sources are point-like gamma-ray emitters detected as such by the LAT, but lacking association with astrophysical objects known in other wavelengths. Interestingly, the sample of unassociated sources in the Fermi-LAT catalogues might already contain gamma-ray emitting DM SHs.



3FGL



2FHL

NEW WITH RESPECT TO PREVIOUS PAPERS

- Previous works have already addressed this issue (see Bertoni et al. 2015 and . Schoonenberg et al. 2014), examining the 3FGL source catalogue and modelling the DM SHs distribution in a Milky Way (MW) like galaxy, based on the N-body simulation Via Lactea II and Aquarius.
- New of this analysis:

  A. The prediction of the DM SHs gamma-ray signal is based on one of the most recent cosmological numerical simulations that includes baryonic physics **Hydro Aquarius (Marinacci et al. 2015).** For the first time, we model the signal as expected in both hydrodynamic and pure-DM simulations of the Milky Way and we compare the results, quantifying possible differences.

  B. The **3FGL and 2FHL Fermi-LAT** catalogues are used simultaneously, the advantage being a wider DM mass coverage.

  C. Instead of using a fixed detection threshold, as usually done, we provide a realistic estimation for the sensitivity of the LAT to the DM flux from SHs at high-latitude as a function of DM annihilation channel, mass and Galactic latitude. We show that the accurate determination of the sensitivity to DM spectra leads to significant differences with respect to a fixed flux threshold.

  D. We estimate the detectability of extended DM SHs comparing the extension of gamma-ray emission from DM interaction with the minimum extension detected in the 3FGL catalogue.

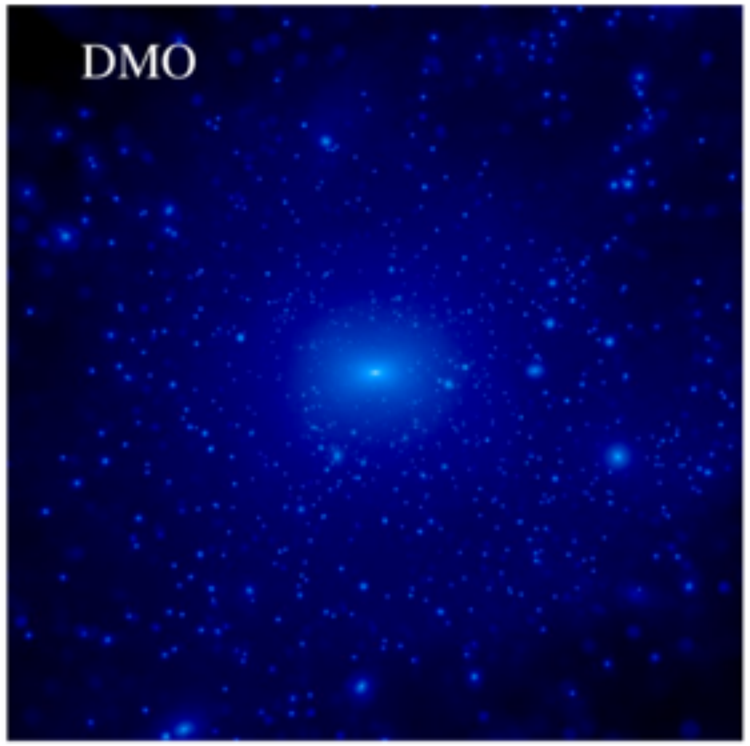
SETUP OF SIMULATIONS

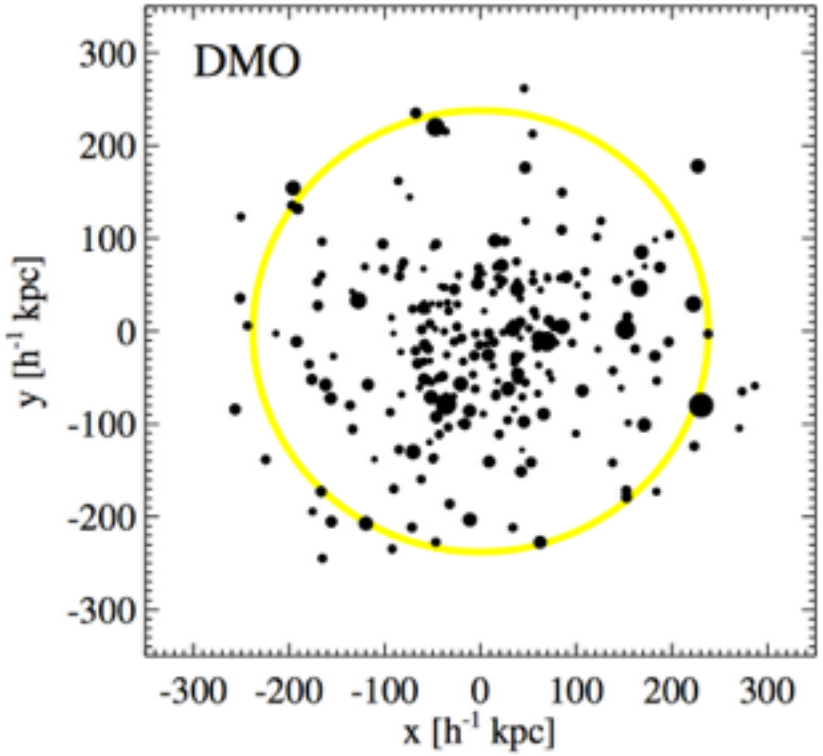
Baryonic impact on the dark matter distribution in Milky Way-size galaxies and their satellites

Q. Zhu, F. Marinacci, M. Maji, Y. Li, V. Springel and L. Hernquist

2015 arXiv:1506.05537

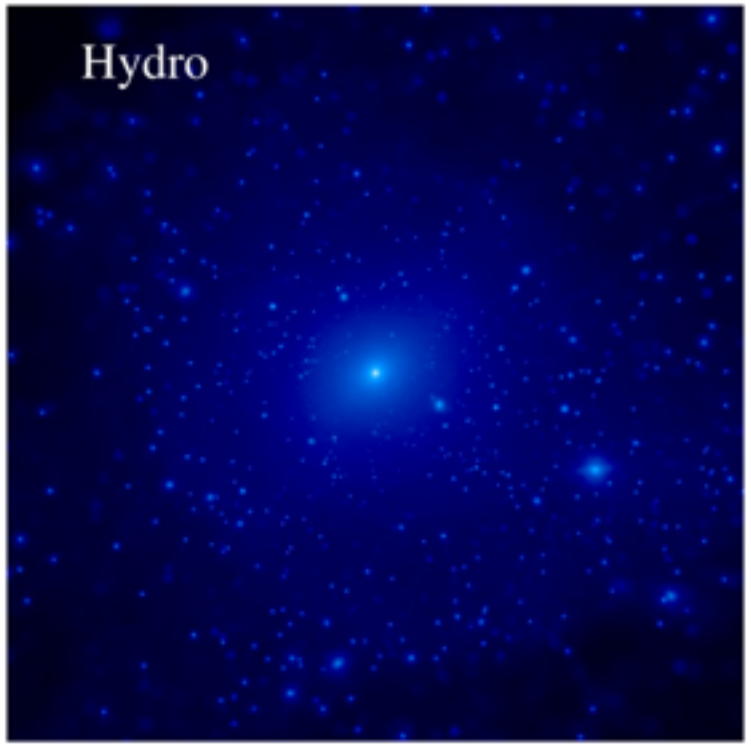
Spatial distribution of SHs

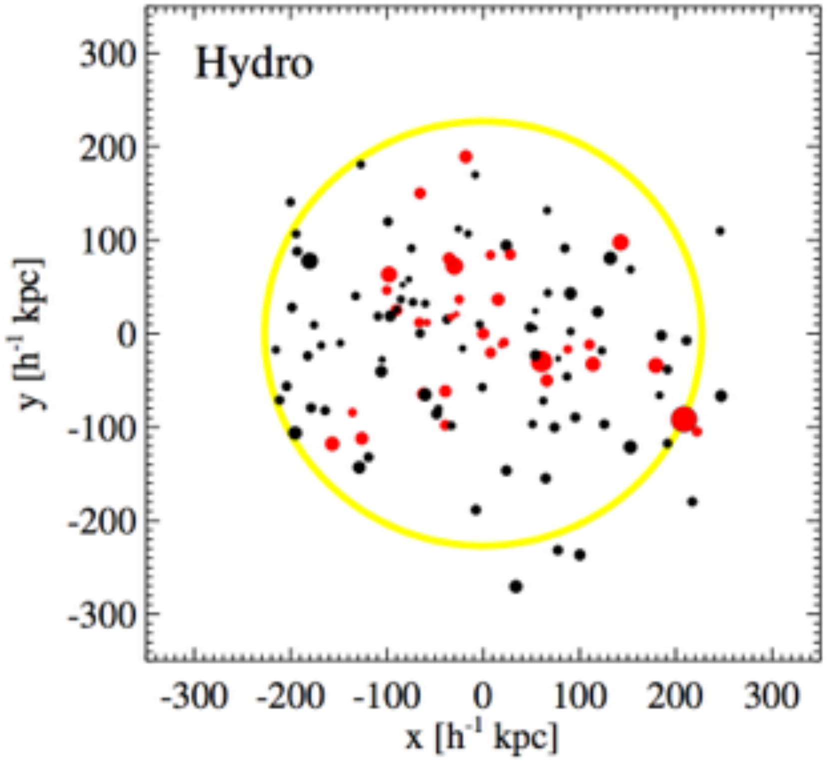




Zoom-in simulation of MW-sized disk galaxies with Illustris implementation of baryons, same initial conditions of Aquarius.

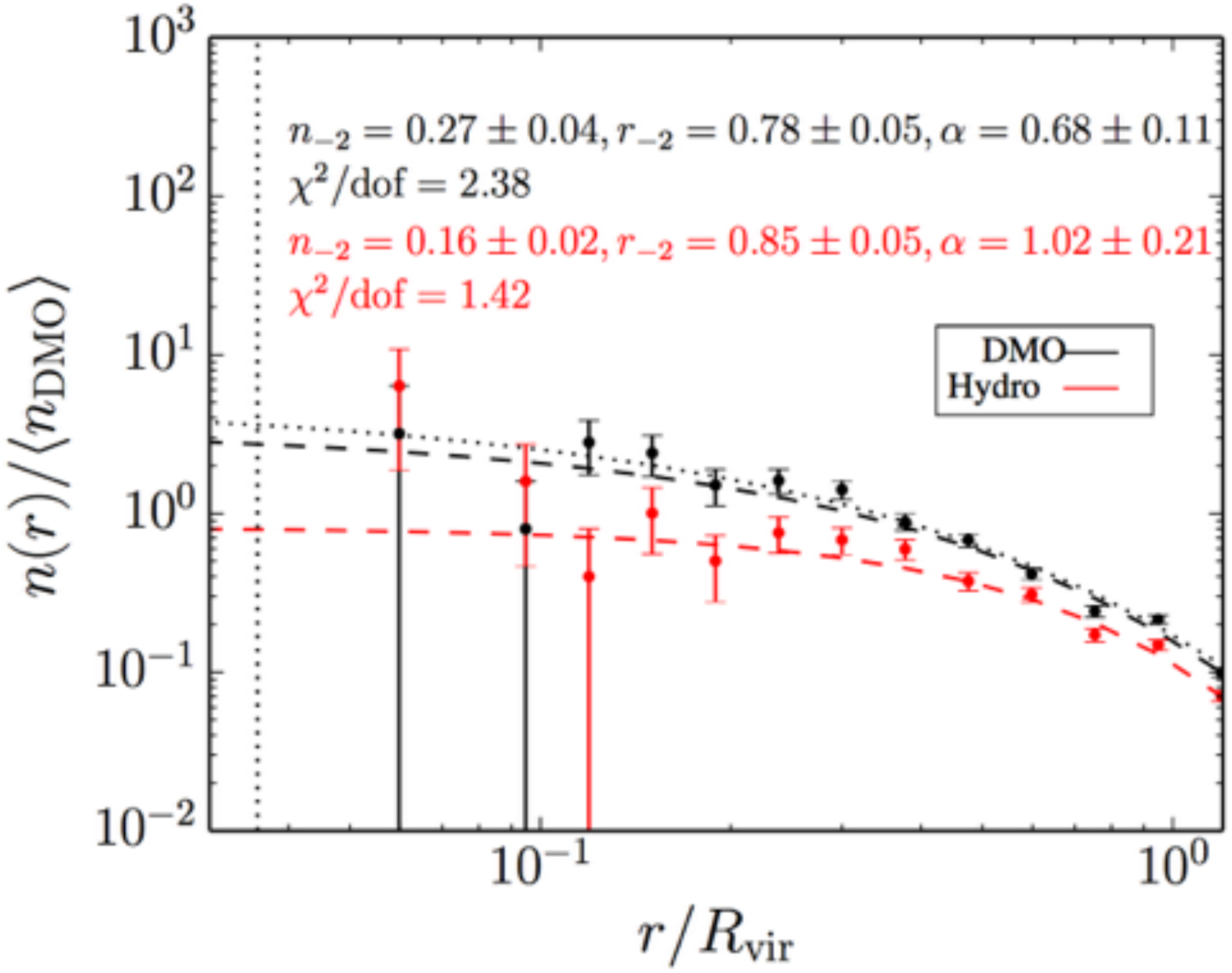
Marinacci+MNRAS'14





- Fewer SHs in the Hydro simulation.
- Low-mass SHs depleted in the Hydro simulation.
- Depletion mostly near the center.

Spatial distribution of SHs: DM-only vs Hydro



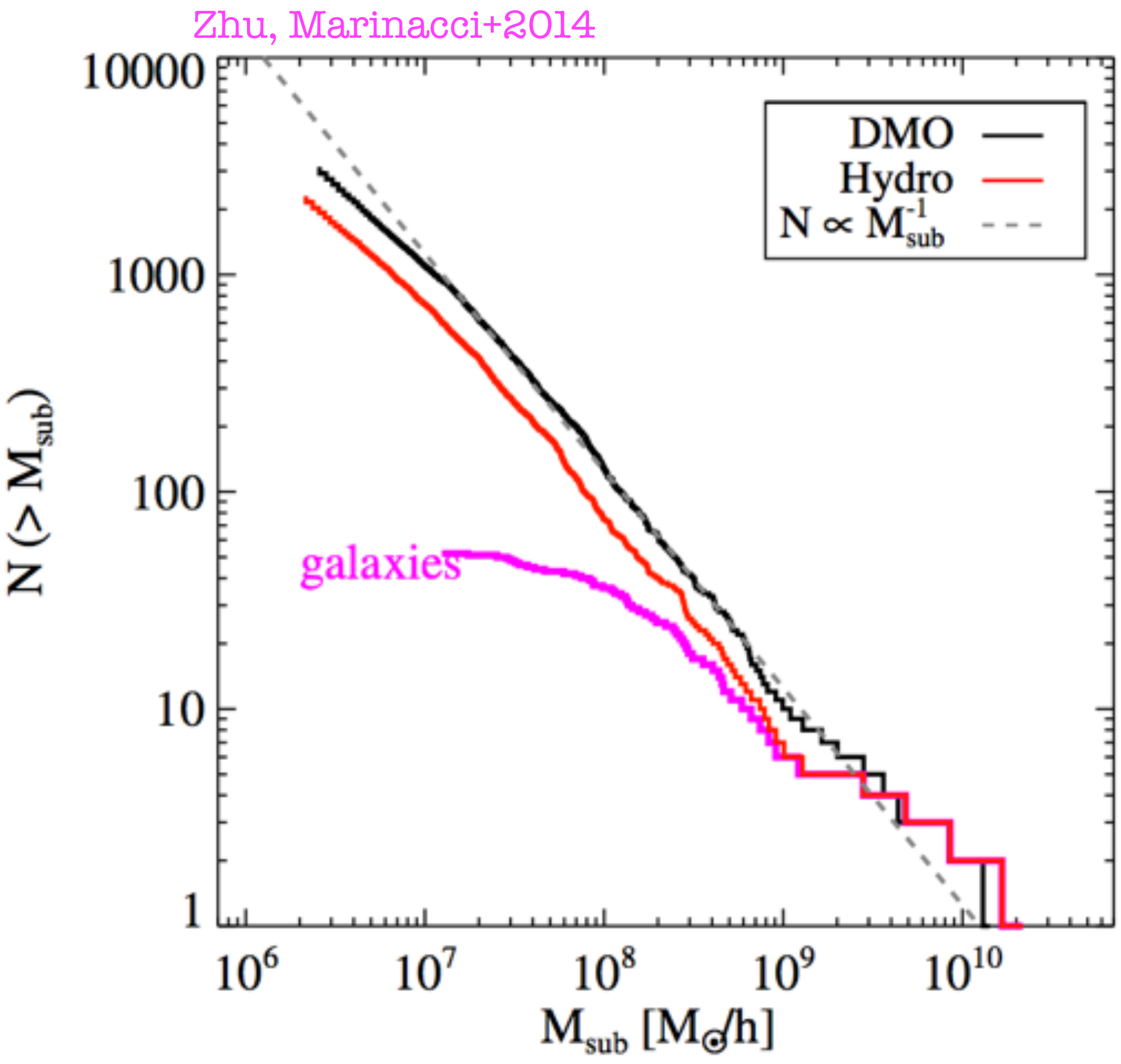
Einasto fitting function

$$n(r)/\langle n \rangle_{\mathrm{DMO}} = n_{-2} \exp\left\{ -\frac{2}{\alpha}\left[\left(\frac{r}{r_{-2}}\right)^{\alpha} - 1\right]\right\}$$

Data sets for DMO and Hydro simulations of

- Radial abundance lower for Hydro simulation, mostly in the central region.
- Offset larger for massive SHs (flatter profile).
- V_{max} (M_{SH}) dependence of radial distribution — stronger for Hydro simulation.

Mass distribution of SHs

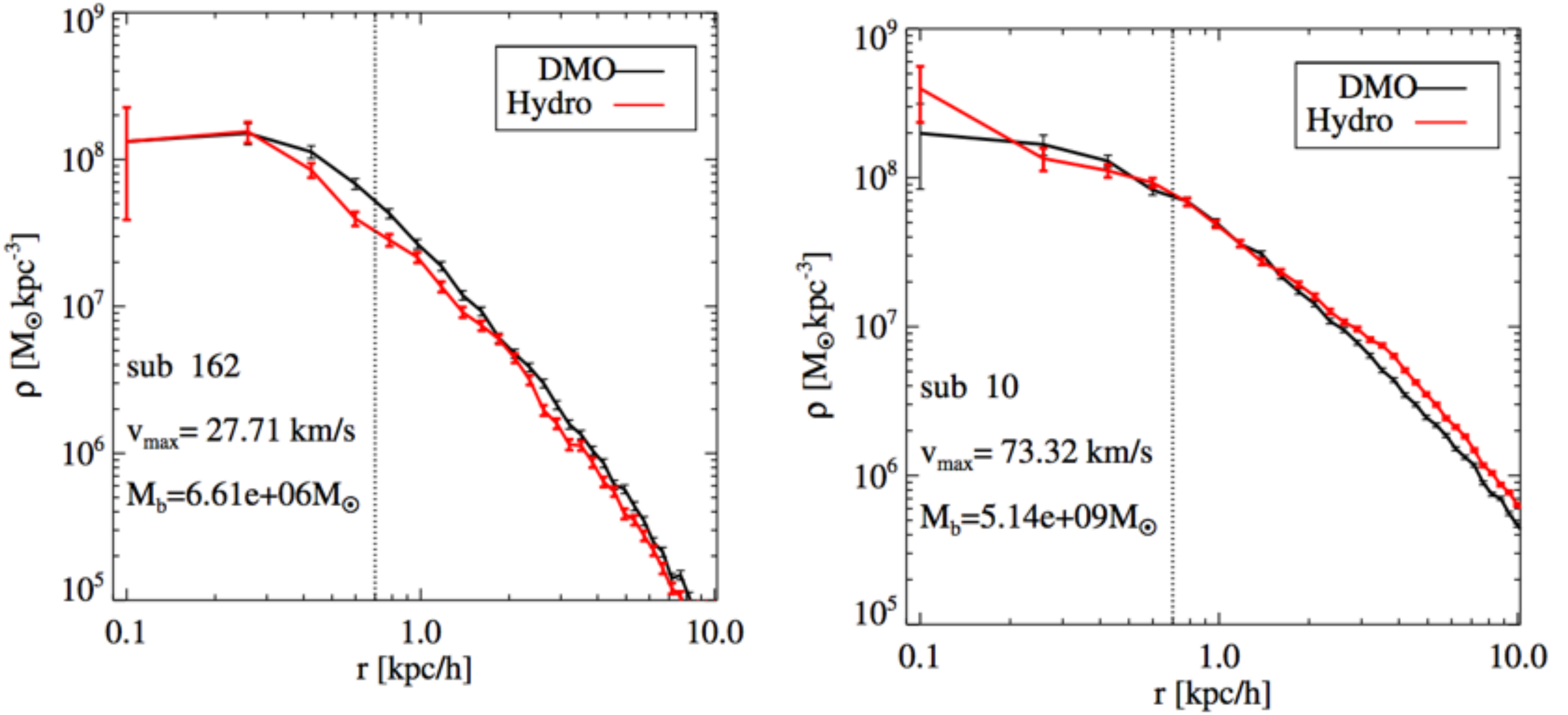


- Mass distribution slope consistent with DMO simulation.
- 30% reduction in the total number of SHs in Hydro simulation.

Dark matter profile of individual SHs

"[…] the density profiles of SHs from the Hydro simulation match their DMO counterparts quite closely."

Zhu, Marinacci+2014

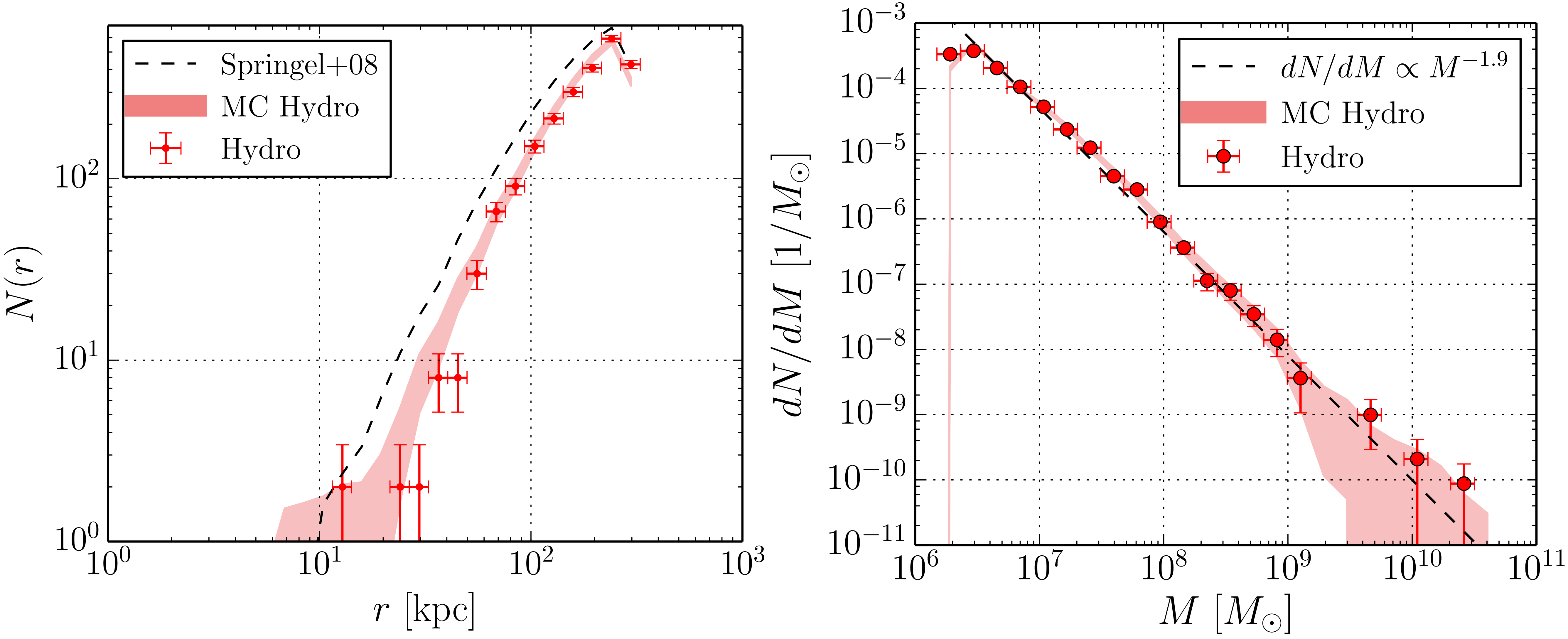


How do we model SHs?

- Concentration - Mass relation fron Aquarius simulation.
- Einasto DM density profile, α = 0.16.

Springel+MNRAS'08

Setting up the Monte Carlo



100 MC realisations
~3000 SHs for single DMO realization
~2000 SHs for single Hydro realization

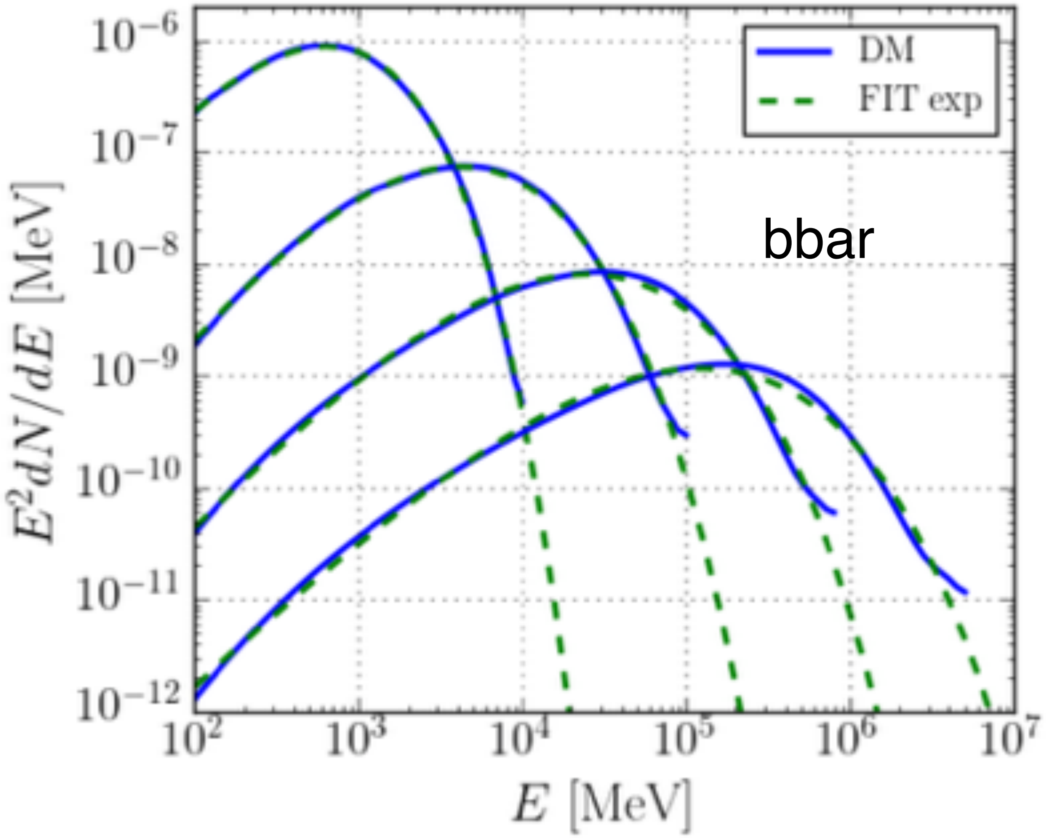
GAMMA RAYS FROM DM SHs

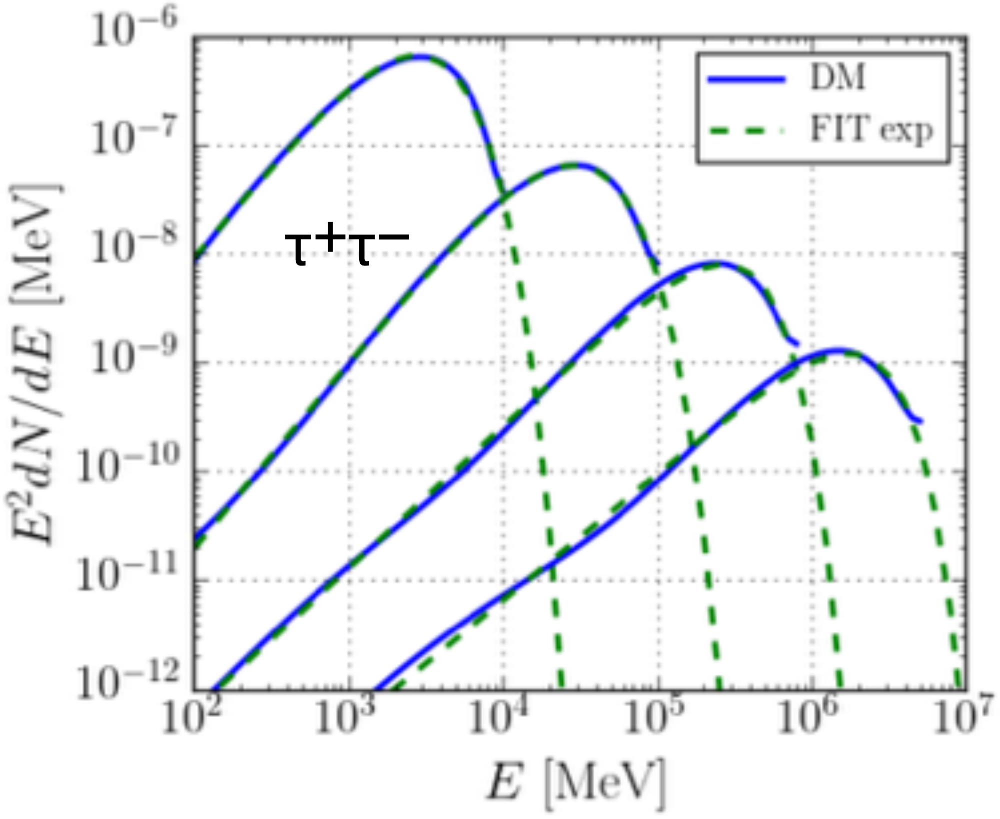
Estimation for the flux sensitivity

- DM particle annihilation produces gamma-rays through direct emission, the so-called **prompt** mechanism, and through indirect processes, such as the **Inverse Compton or bremsstrahlung.**
- Usually different primary annihilation channels are studied assuming a branching ratio of 100% in each channel separately.
- Here, we take into account one typical hadronic channel, bbar, and the leptonic channel that gives the largest DM gamma-ray flux, i.e. $\tau^+\tau^-$. In these channels, the most important gamma-ray emission mechanism is the prompt one.
- We consider the gamma-ray spectra from DM annihilation from Cirelli et al. 2011 (Pythia 8).

$$S_{[E_1,E_0]} = \frac{\langle \sigma v \rangle}{8\pi M_{\mathrm{DM}}^2} \mathcal{I}_{[E_1,E_0]} \mathcal{J}$$

$$\frac{dN_{\mathrm{DM}}}{dE} = K \left(\frac{E}{E_0}\right)^{-\alpha} \exp\left(-\left(\frac{E}{E_{\mathrm{cut}}}\right)^{\beta}\right)$$



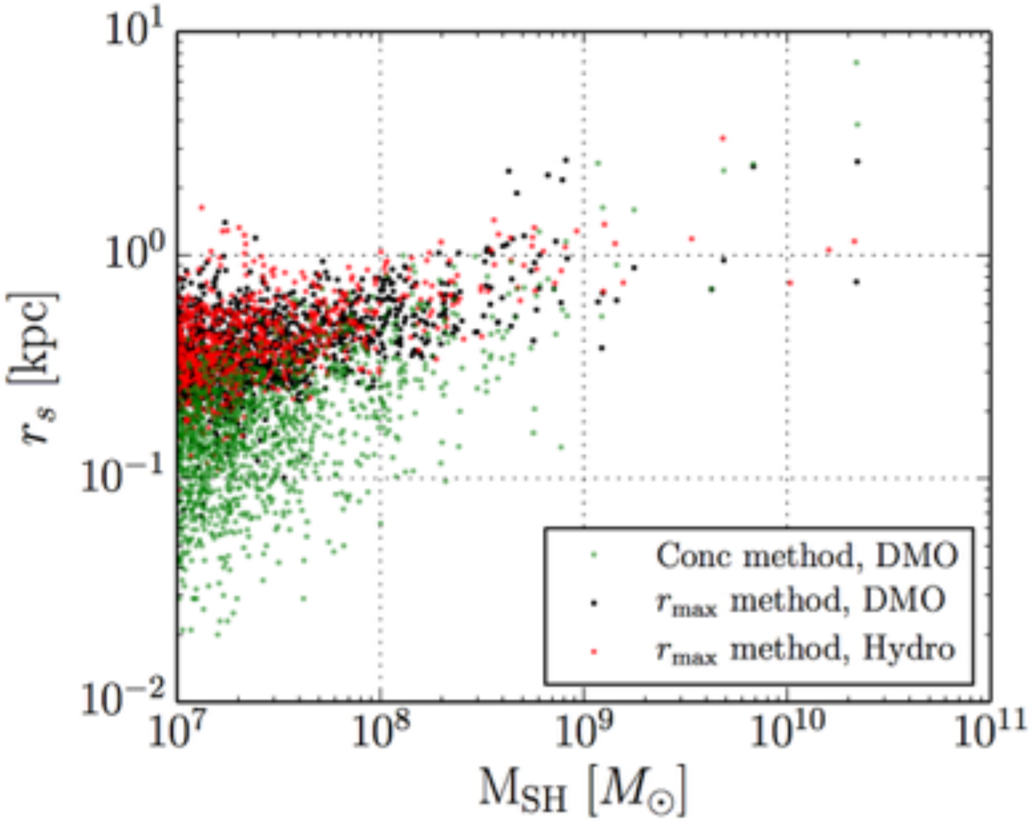


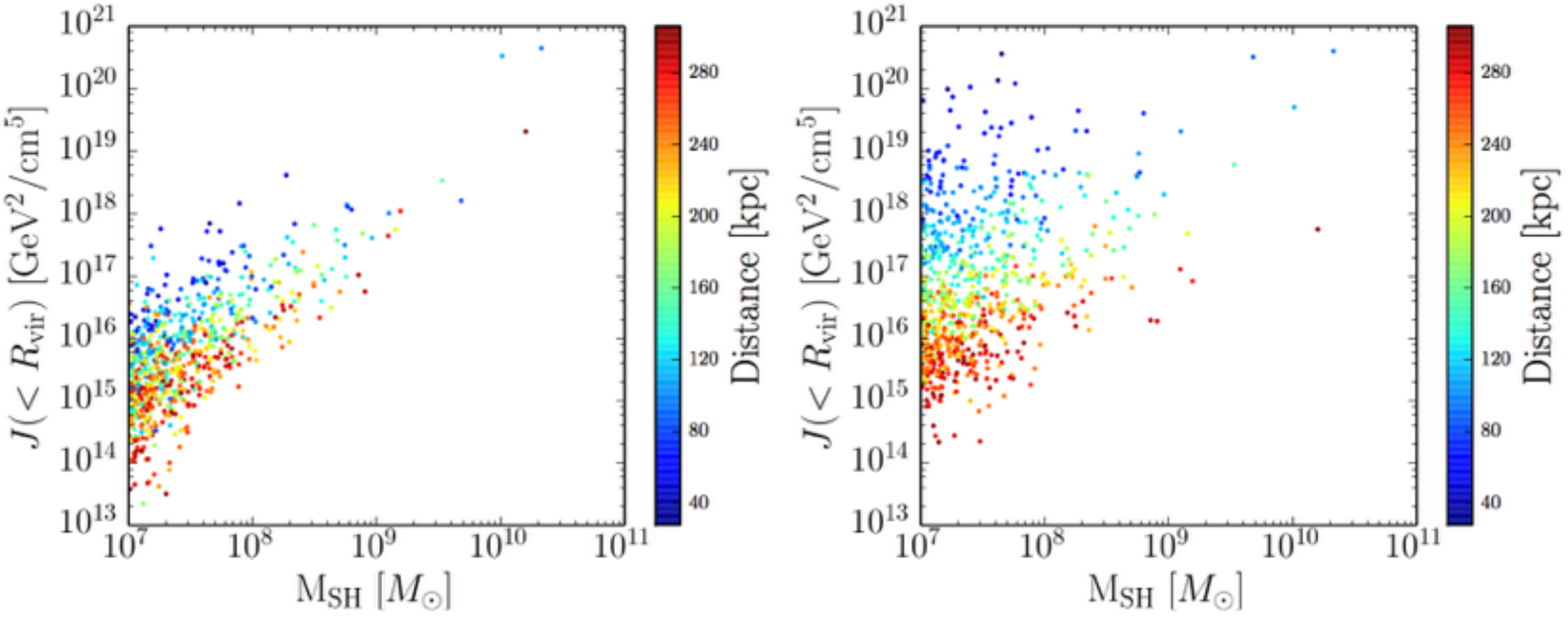
M_{DM} = 10, 100, 800, 5000 GeV

J FACTORS FOR ‘Rmax' and ‘conc' methods

For the computation of r_S, we follow two approaches:

- **“r_{max} method”**: As for the first method, we extract the value of r_{max} from the real statistical distribution of r_{max} as derived by the original simulation data.
- **“Conc method”:** In the second scenario we compute r_S using a fit of the SH concentration-mass relation in different N-body simulations (Moline’ et al. 2016).





SENSITIVITY FOR THE DETECTION OF DM SHs

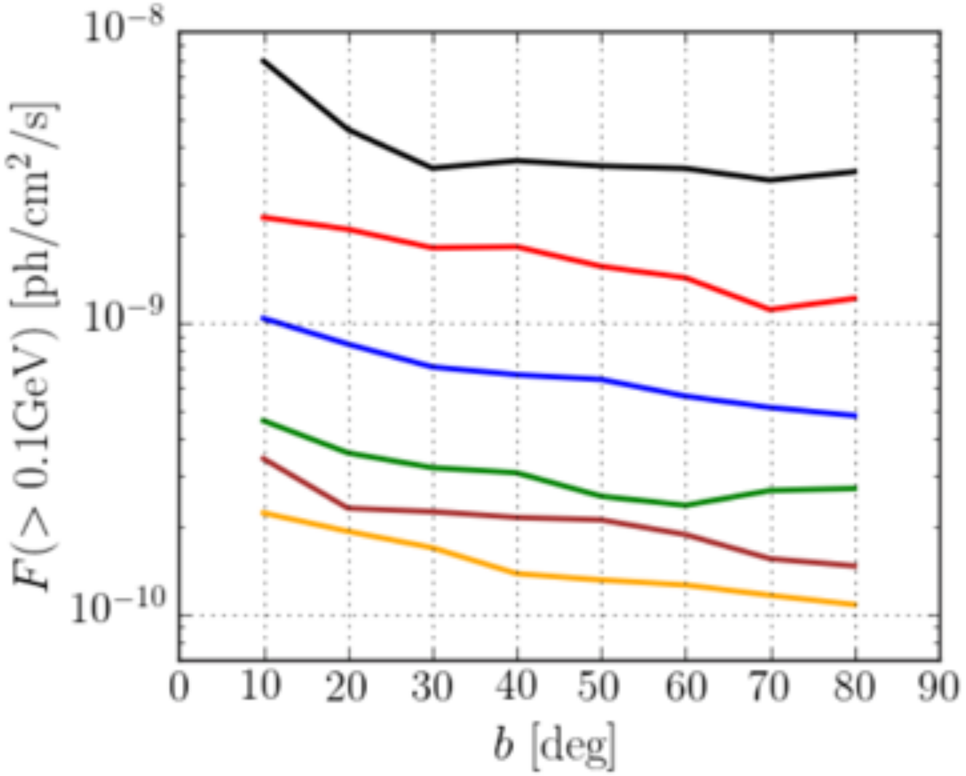
Estimation for the flux sensitivity

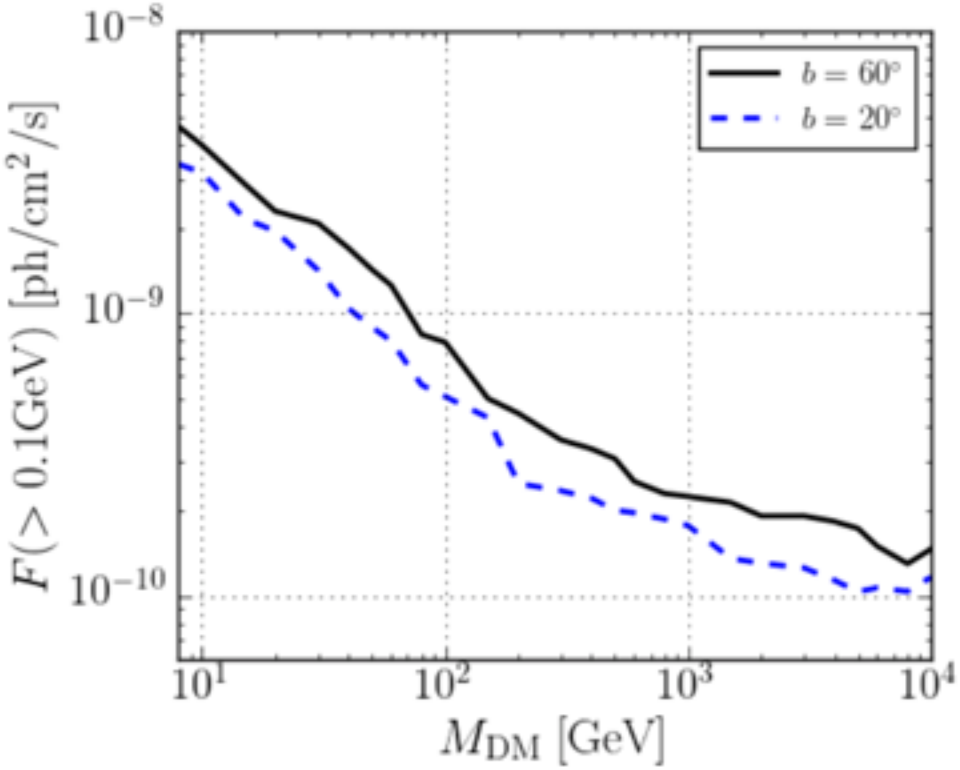
- Estimate the **sensitivity flux** to detect a DM sub-halos as a function of **DM mass** and **Galactic latitude (b)**.
- The **sensitivity flux** is the flux for which **TS=25**.
- For each DM mass I simulate DM subhalos with **different fluxes** and at different latitudes **[10,20,30,40,50,60,70,80] deg.**
- I simulate also the GDE and isotropic components taking the reference models for the 3FGL and 2FHL catalogs.
- The data analysis details (exposure time, energy range, IRFs,…) are the same as in the 3FGL and 2FHL catalogs.
- Given these maps that contain the GDE, isotropic emission and the flux from the DM halo, I launched the **detection pipeline** (gtselect, gtmktime, gtbin, gtsrcmap, gtlike).
- I find so for each mass and for each latitude the flux for which the TS=25.

MDM = 8 (black), 30 (red), 80 (blue), 300 (green), 600 (brown), 1200 (orange) GeV

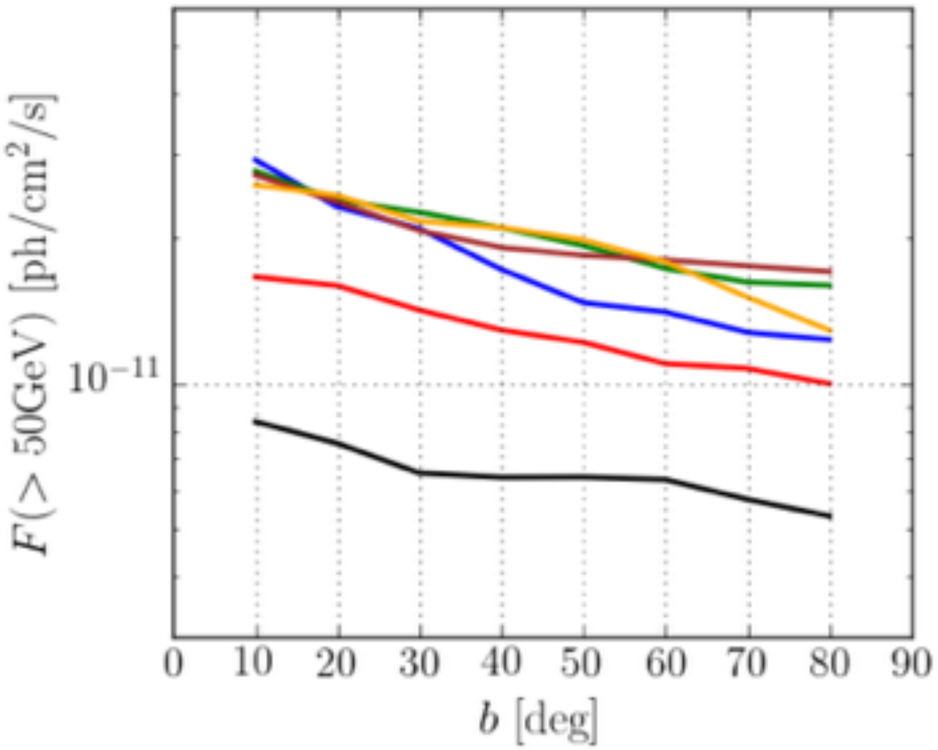
3FGL

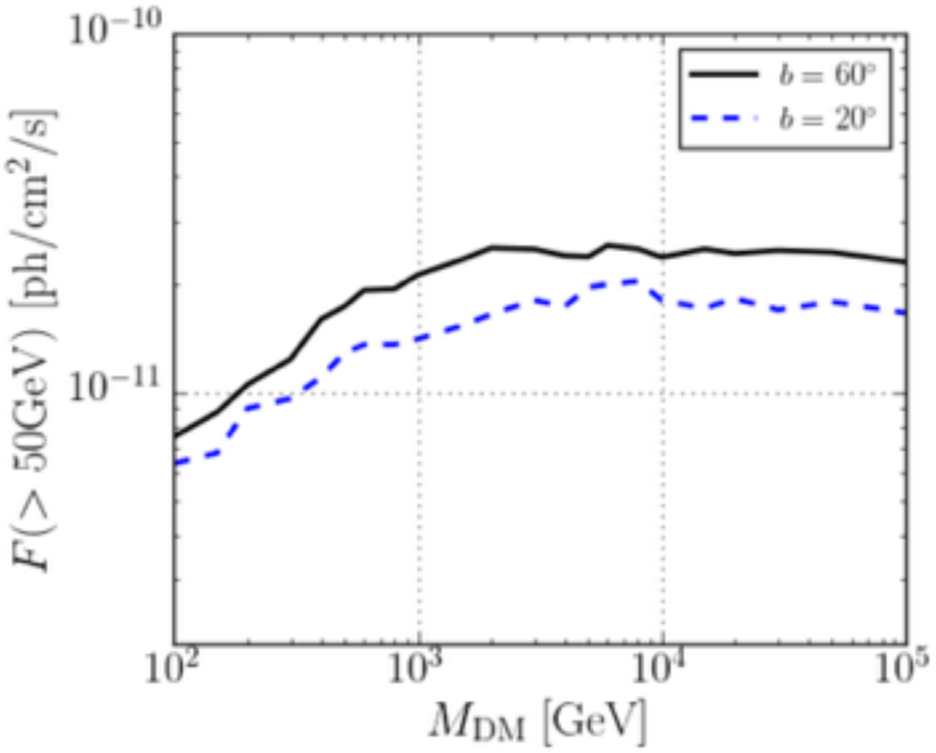
Flux sensitivity threshold as a function of DM mass for b = 20 and 60 of the SH.





2FHL





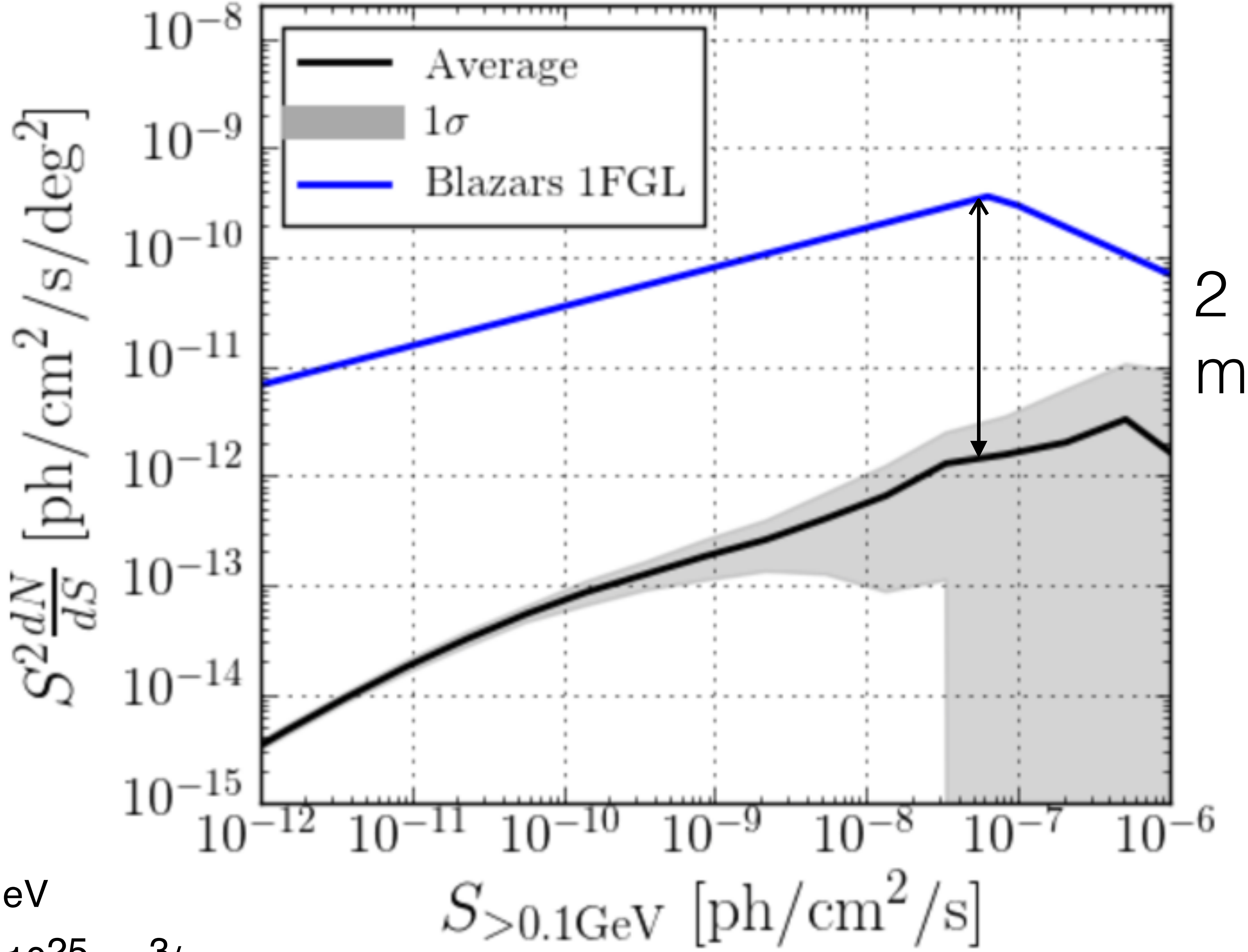
MDM = 100 (black), 400 (red), 1000 (blue), 4000 (green), 8000 (brown), 20000 GeV (orange)

Flux sensitivity threshold as a function of DM mass for b = 20 and 60 of the SH.

3FGL CATALOG

Source count distribution of SHs

‘Conc’ METHOD



2 orders of magnitude

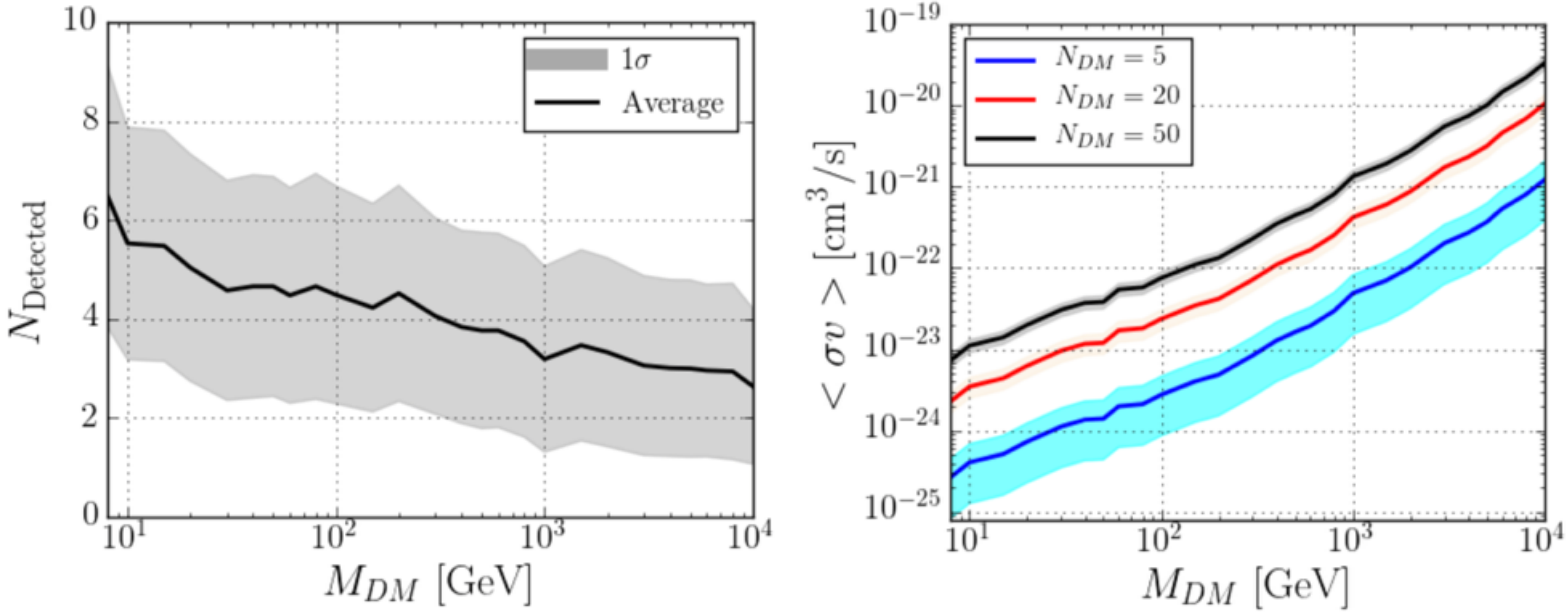
MDM=100 GeV

<sigma v> = 10^{25} cm^3/s.

SHs Hydro simulation vs detected blazars

Number of detected clumps

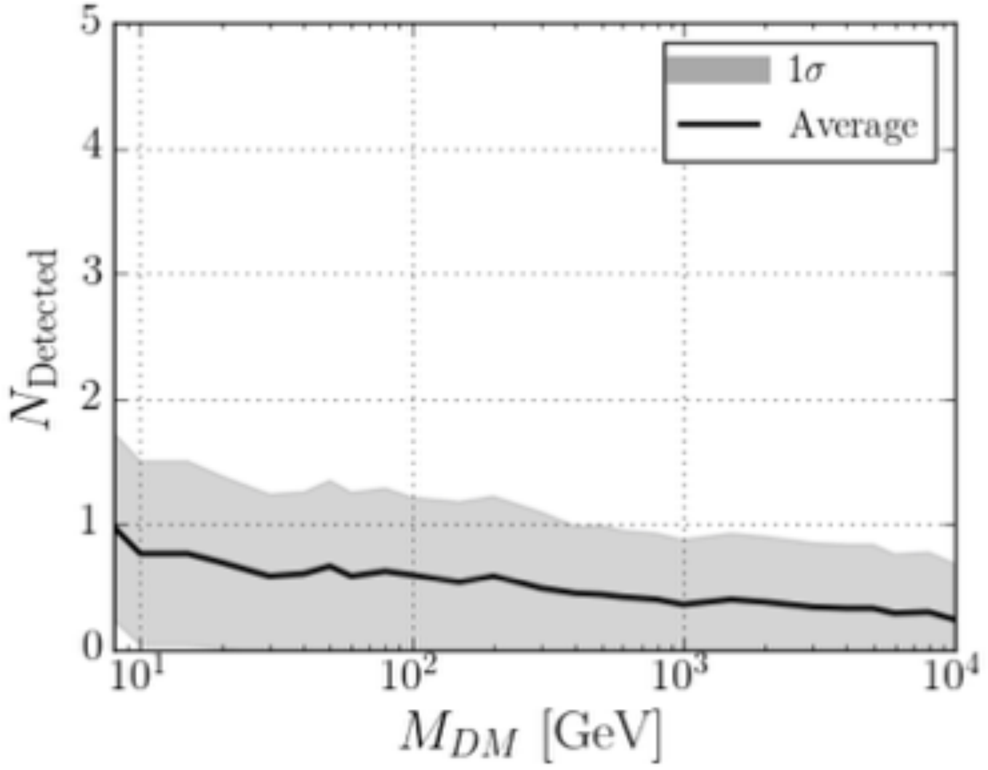
<sigma v> —> Pass 8 dwarf limits Ackermann et al. 2015

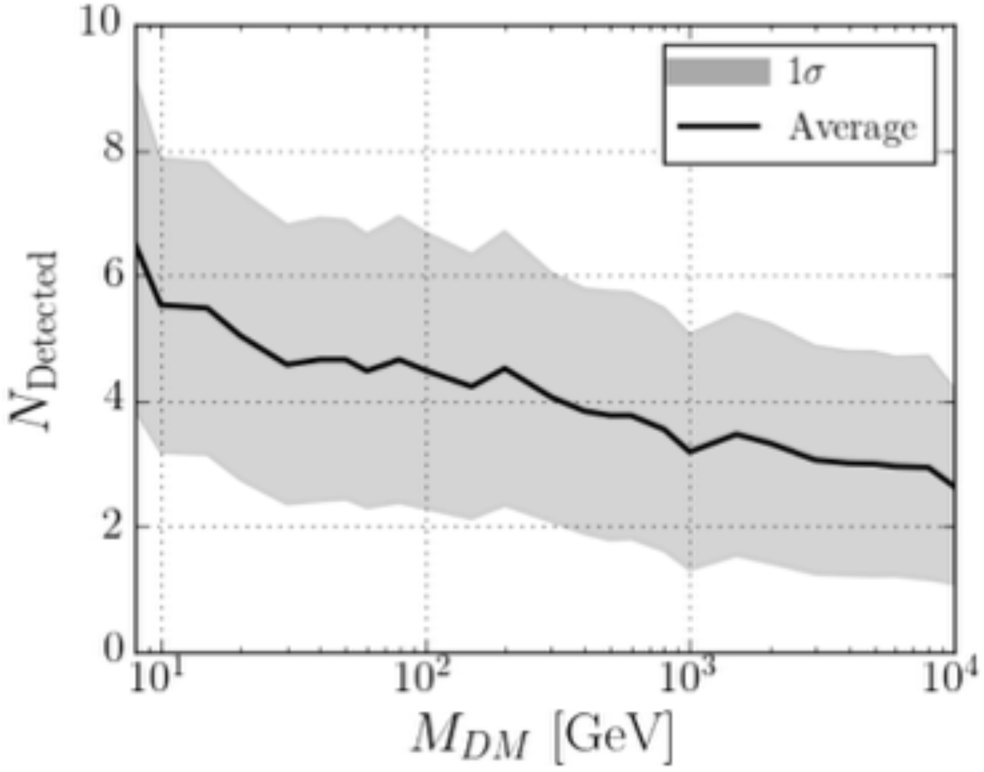


‘Conc’ METHOD

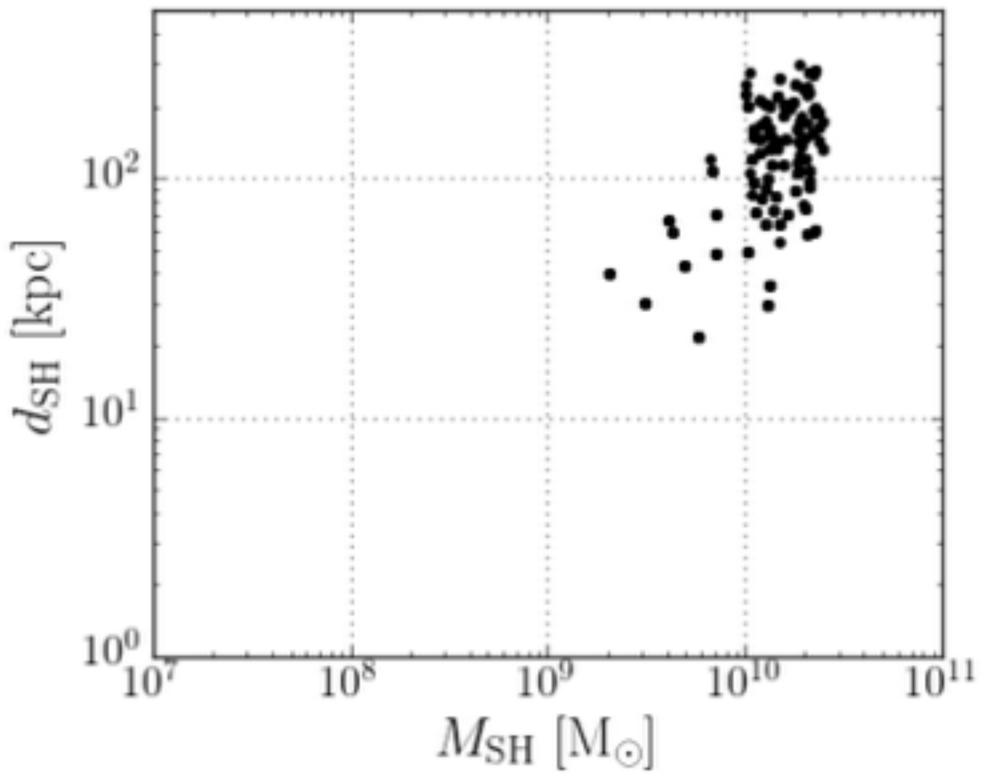
a few clumps could be among unassociated 3FGL sources

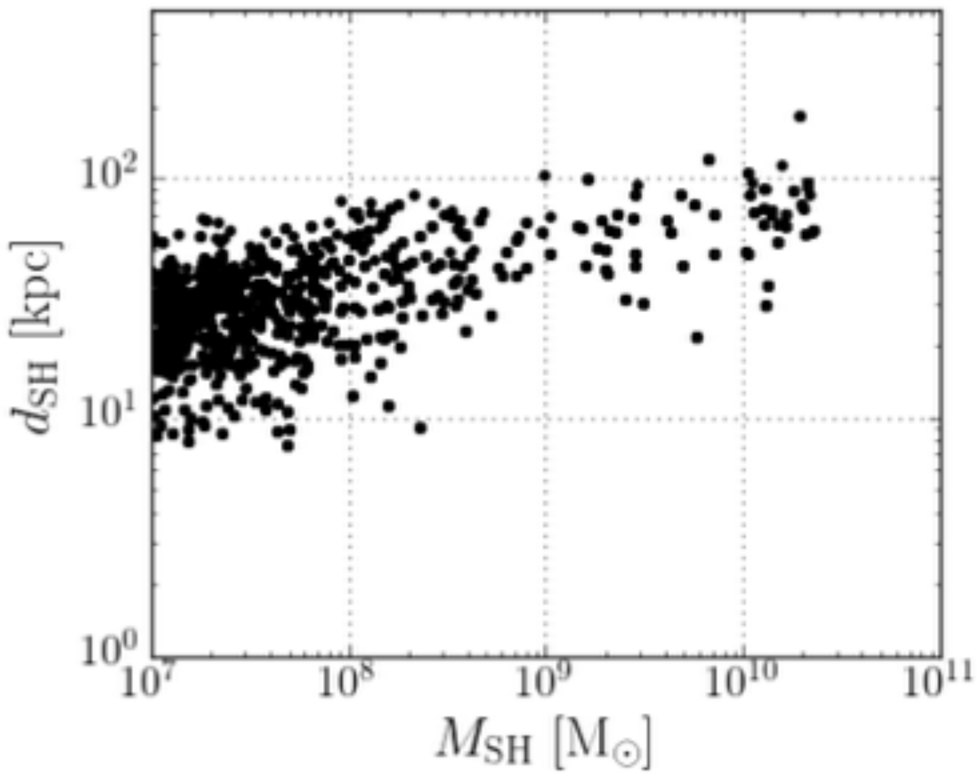
COMPARISON BETWEEN ‘Rmax' AND ‘Conc’ METHODS





<sigma v> —> Pass 8 dwarf limits Ackermann et al. 2015





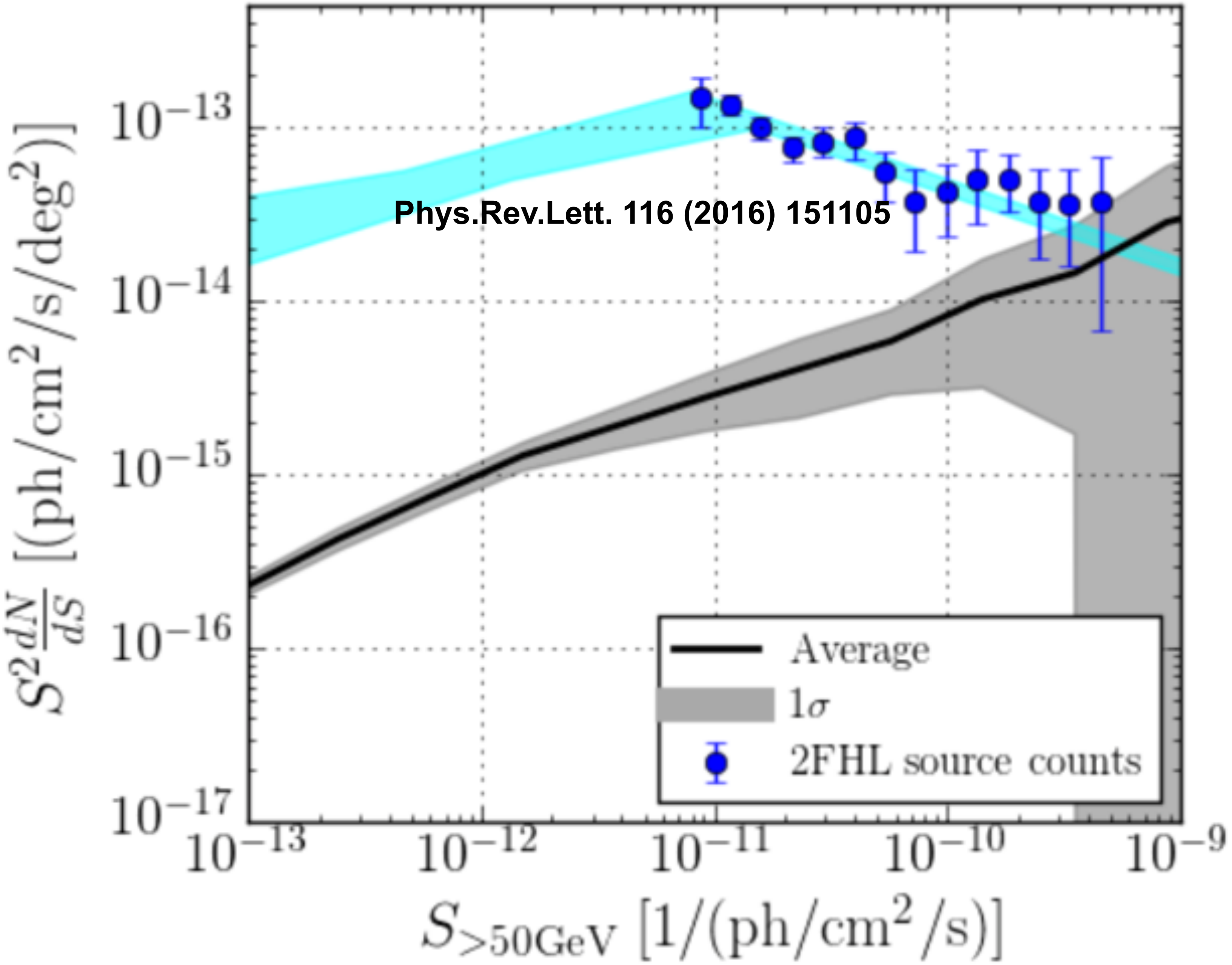
‘Rmax’ METHOD

‘Conc’ METHOD

2FHL CATALOG

Source count distribution of SHs

'Conc' METHOD



Phys.Rev.Lett. 116 (2016) 151105

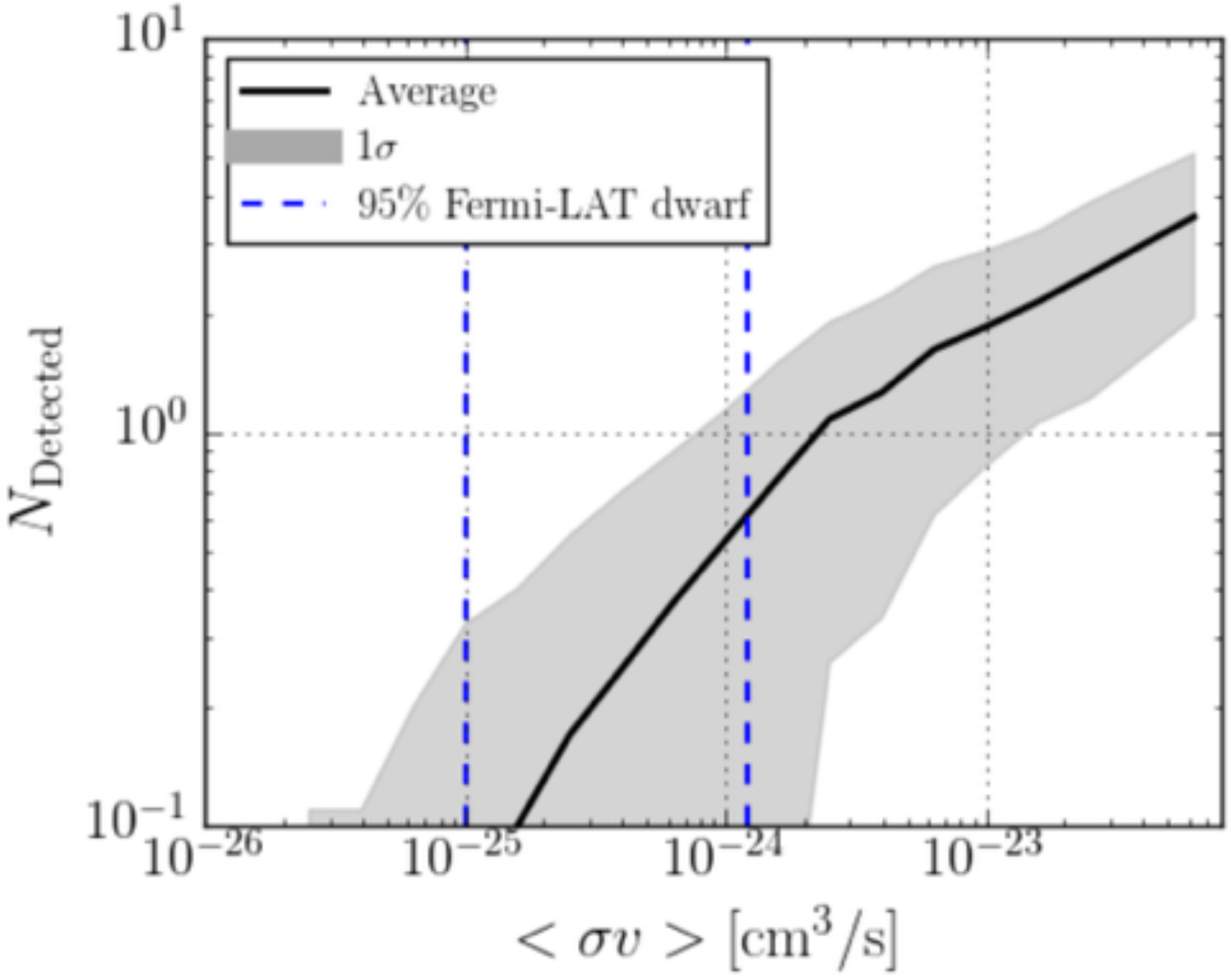
MDM=100 GeV

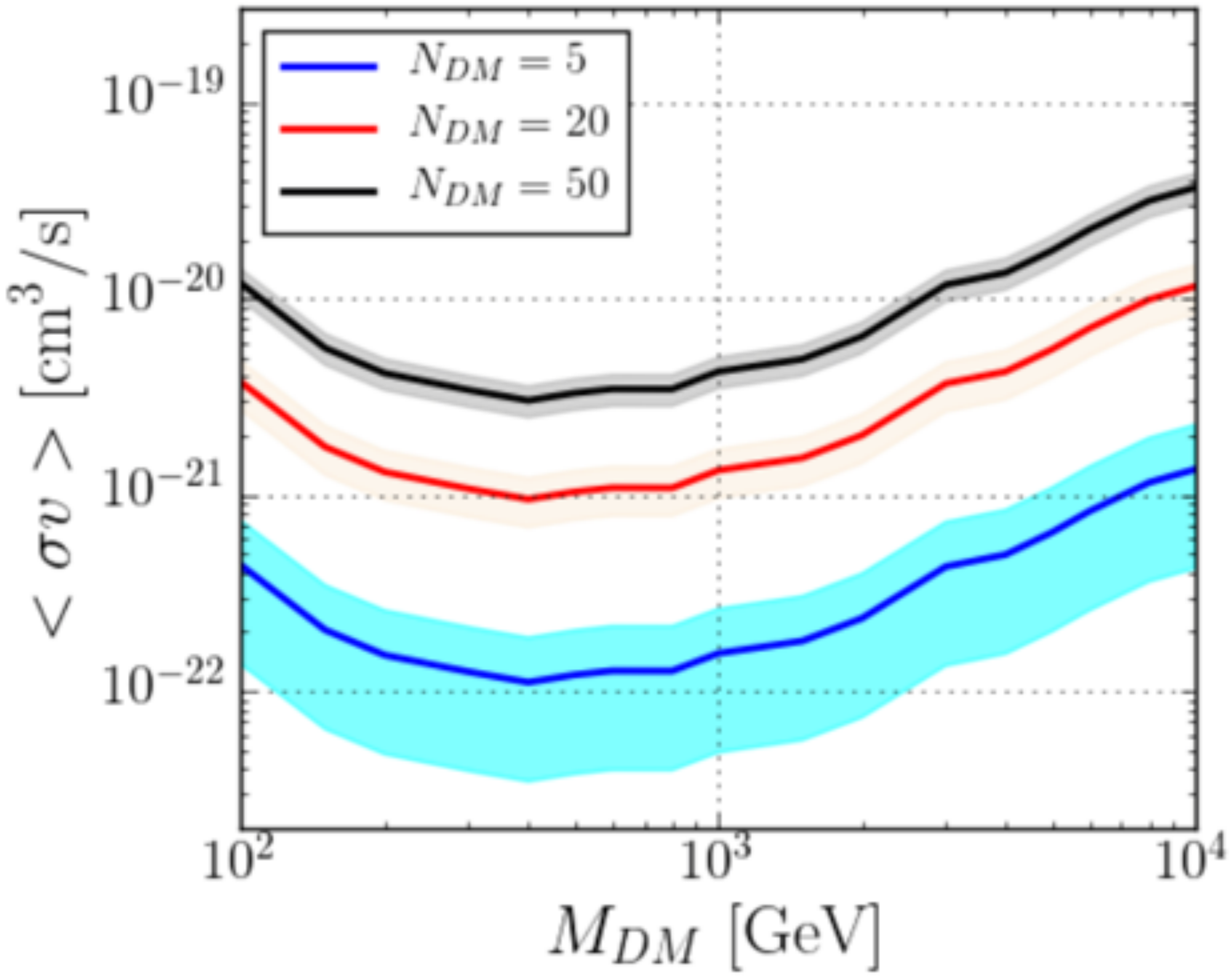
<sigma v> = 10^{25} cm^3/s.

SHs Hydro simulation vs detected blazars

Number of detected clumps

‘Rmax’ METHOD



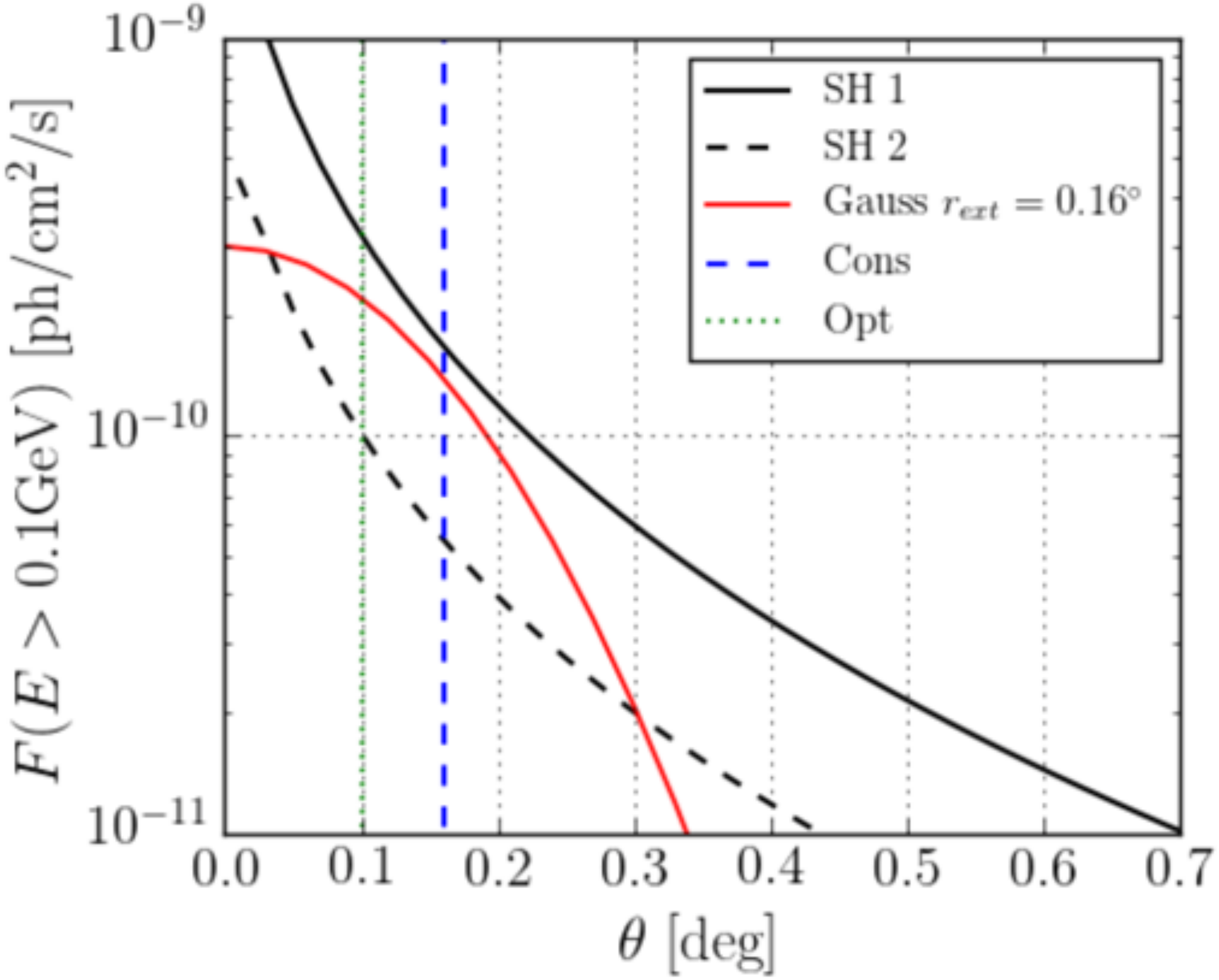


a few clumps could be among unassociated 2FHL sources

DETECTING EXTENDED DM SHs

We follow two approaches:

- A **conservative** one, where we take as a reference angle for the SH spatial extension the size of W44 (**r_{ext} = 0.16 deg**) and
- a more **optimistic** choice where we consider the average value of Conf_68_Semiminor for sources with TS = 25 in the 3FGL (**r_{ext} = 0.10 deg**). This is nevertheless not too optimistic, if we consider that with Pass 8 PSF 3 there is an improvement with respect to the 3FGL (Pass 7) of at least a factor of two in the containment angle
- For each simulation – on average over all simulations Hydro:(r_{max} method) and for M_{DM} = 40 GeV and annihilation into bbar – we find **0.3 extended** sources when conditioned to **r_{ext} = 0.16 deg**, while using the optimistic approach (r_{ext} = 0.10 deg) we get **1 extended source** per realization.



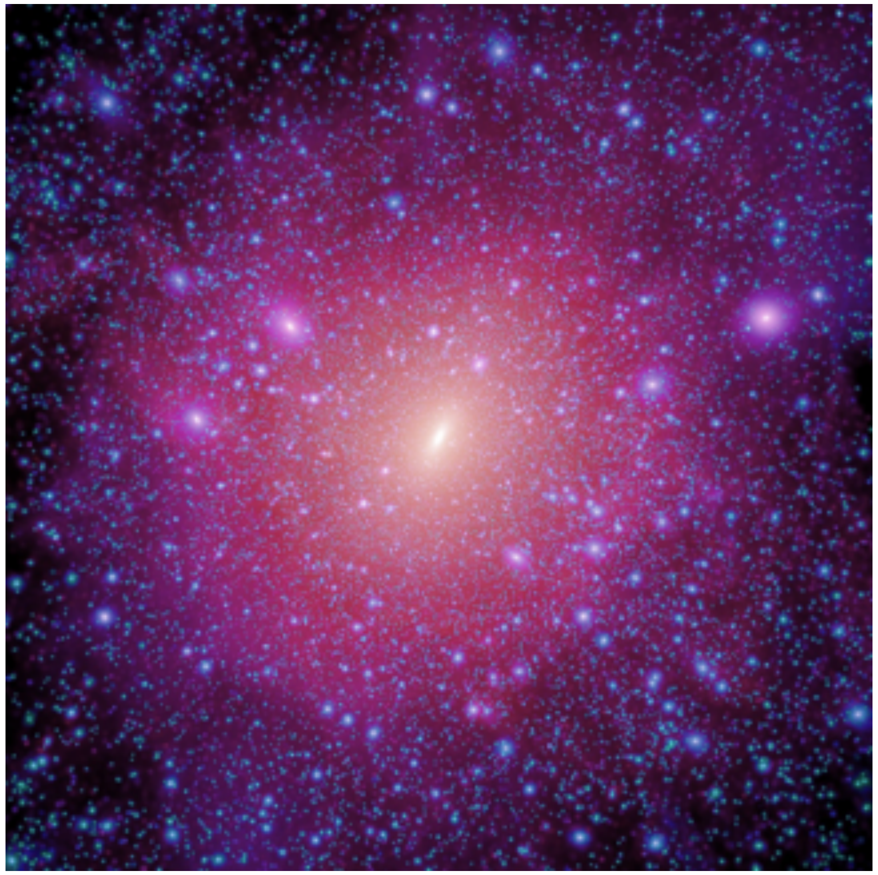
SUMMARY

- First realistic estimation of the detectability of Galactic DM SHs with the Fermi-LAT, in both the **3FGL and 2FHL catalogues**.
- Based on one of the most recent hydrodynamic simulations, the **Hydro-Aquarius** simulation (Marinacci et al. 2014-2015), we have modeled the spatial and mass distribution of SHs in a Milky Way-like Galaxy. We have generated Monte Carlo realizations of the Galactic SH population for two different scenarios corresponding to the hydrodynamic and pure DM case.
- Assuming a typical SH concentration-mass relation, derived by recent N-body simulations (the **"Conc method"**), or relying on the real statistical distribution of r_S as obtained in the original hydrodynamic simulation (the **"r_S method"**) leads to considerable differences in the J -factor, and hence in the results of our analysis.
- The results show that the largest number of detectable SHs, that might already be among the unassociated sources of the 3FGL catalogue, is at most **6 ± 2 for M_{DM} = 8 GeV (**"Conc method" and <sigma v> fixed Ackermann et al. 2015). The prediction for the 2FHL catalogue is lower: $N_{Detected} = 0.2 \pm 0.3$ for M_{DM} = 10 TeV.
- Assuming values of <sigma v> consistent with the current limits from dwarf galaxies, we have also found that the SHs source count distribution is strongly suppressed with respect to the observed flux distribution of AGN in both the 3FGL and 2FHL.
- Finally we have shown that at most there could be on average one SH detected as extended in the 3FGL.

BACKUP SLIDES

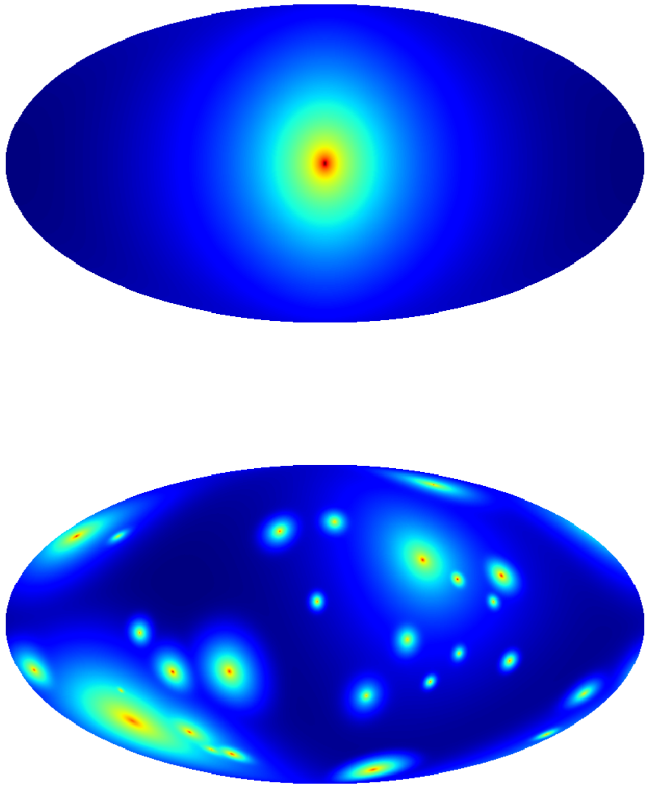
DM N-BODY SIMULATIONS

Aquarius DM N-body simulation



Springel+ MNRAS'08

Expected gamma-ray flux



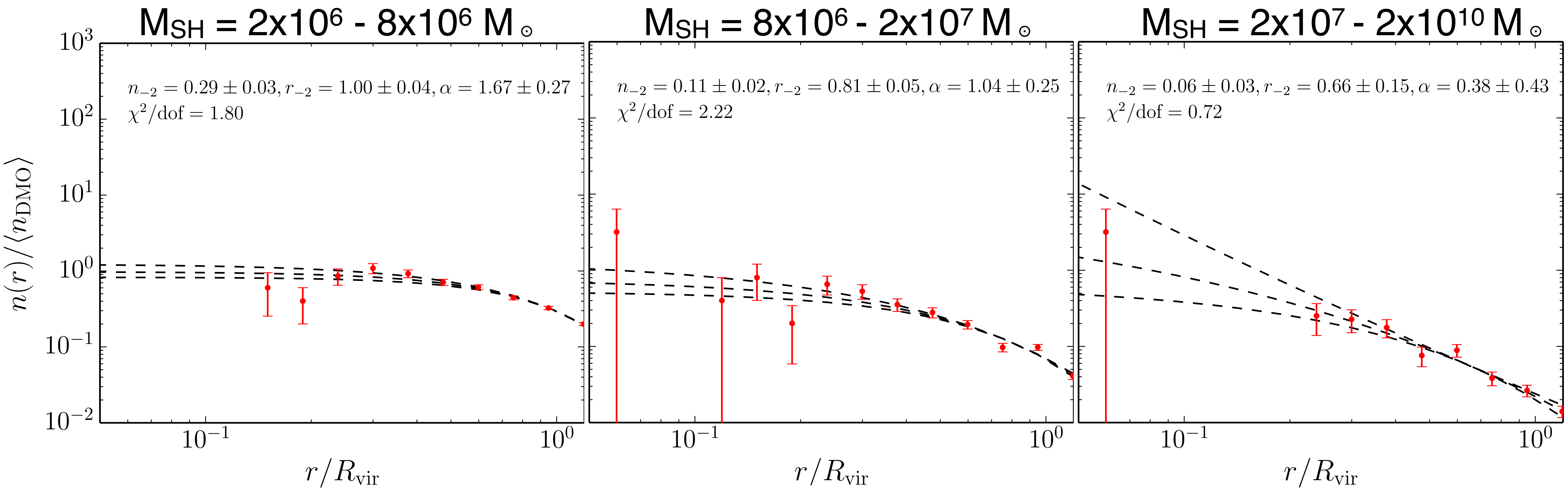
Main halo

Sub-haloes (SHs)

Calore+ MNRAS'14

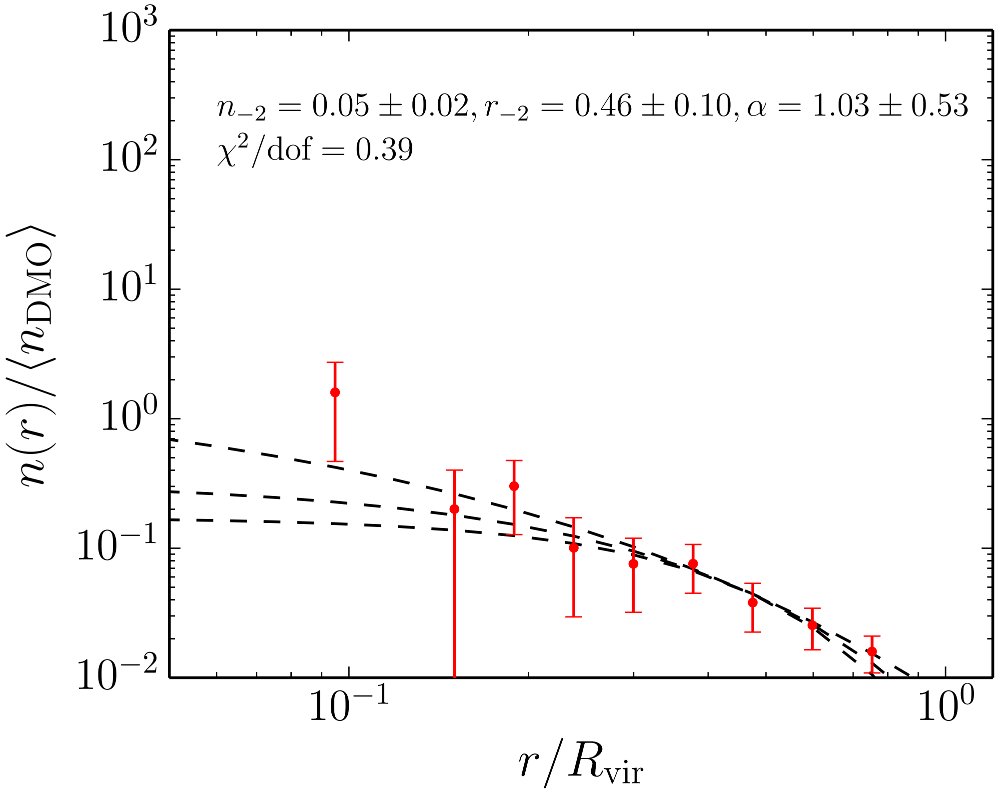
Radial distribution of SHs

Dark SHs



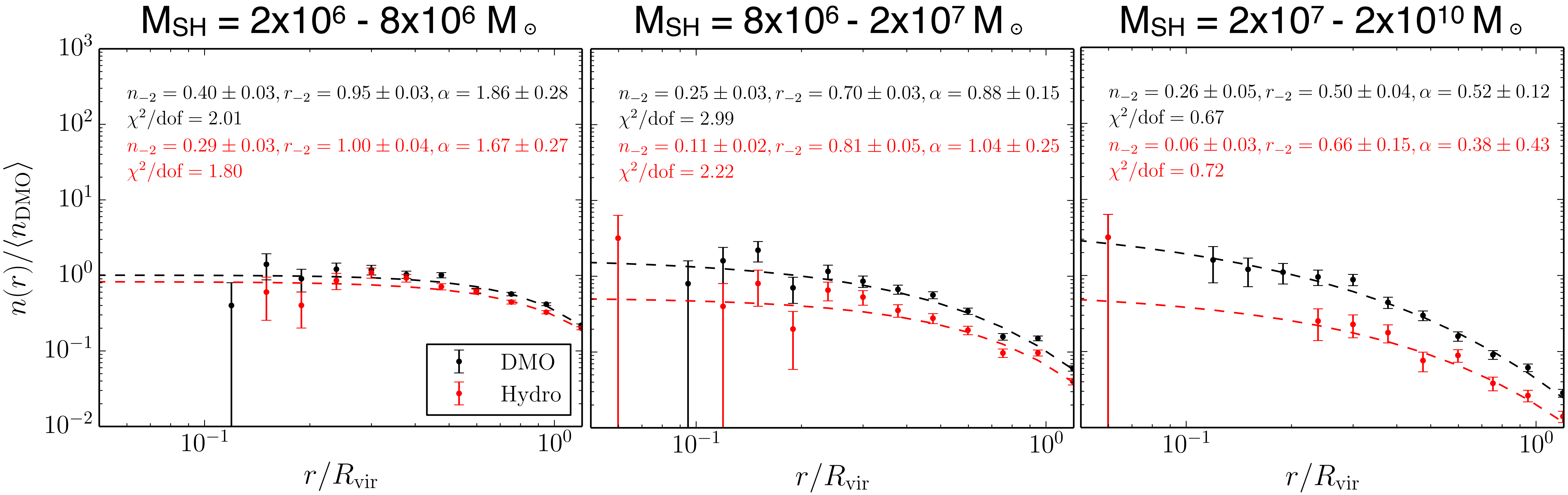
Luminous SHs

M_{SH} = 2x10^6 - 2x10^{10} M$_\odot$



Radial distribution of SHs

Dark SHs



$M_{SH} = 2x10^{6} - 8x10^{6}\ M_{\odot}$

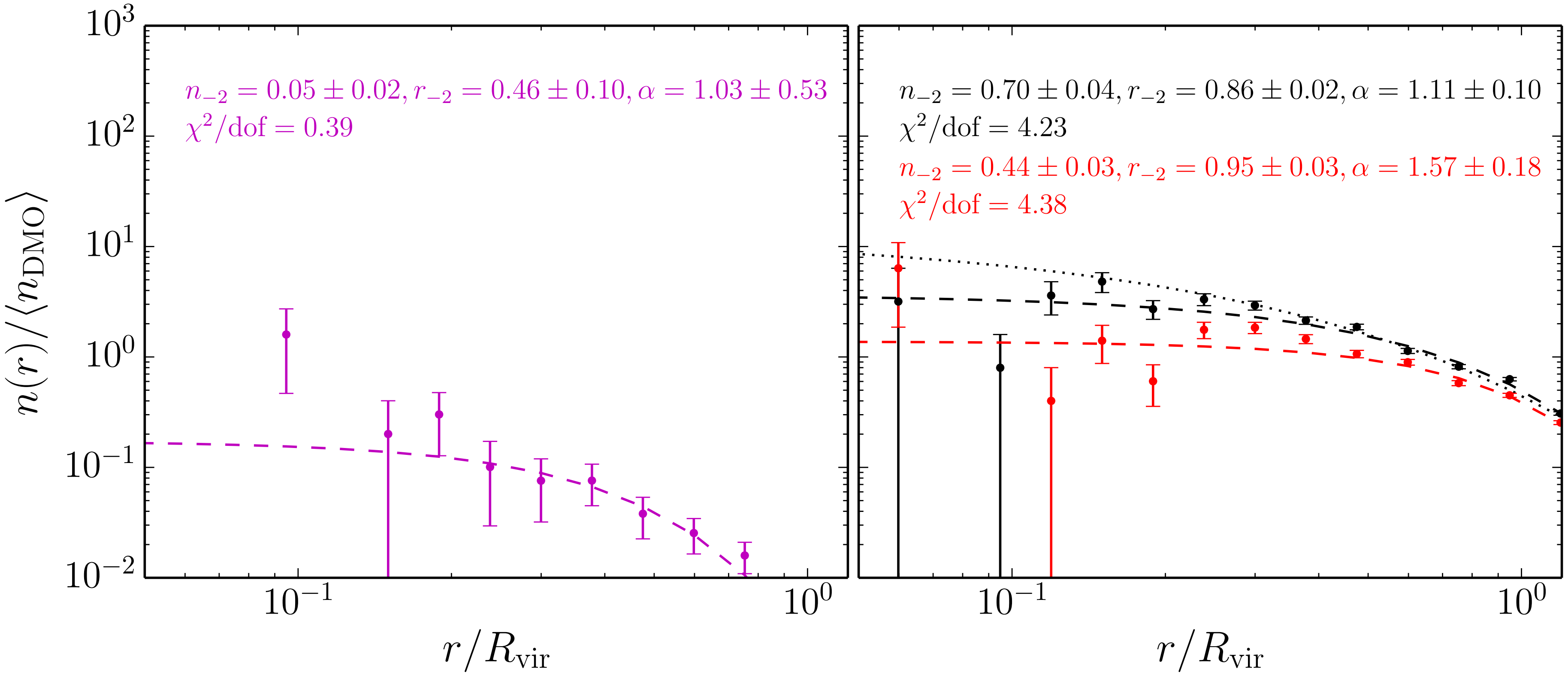
$M_{SH} = 8x10^{6} - 2x10^{7}\ M_{\odot}$

$M_{SH} = 2x10^{7} - 2x10^{10}\ M_{\odot}$

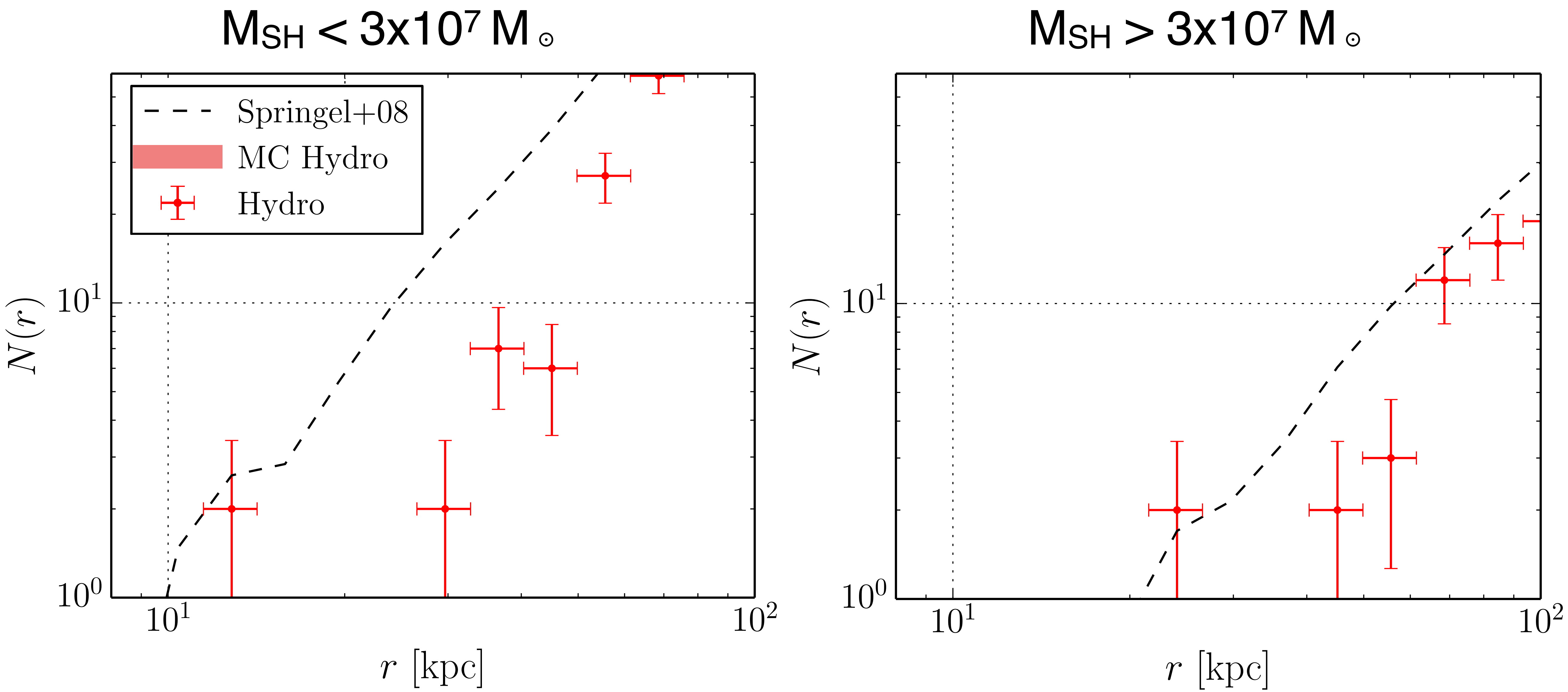
Luminous SHs

$M_{SH} = 2x10^{6} - 2x10^{10}\ M_{\odot}$

$\alpha_{\mathrm{Springel08}} = 0.678$

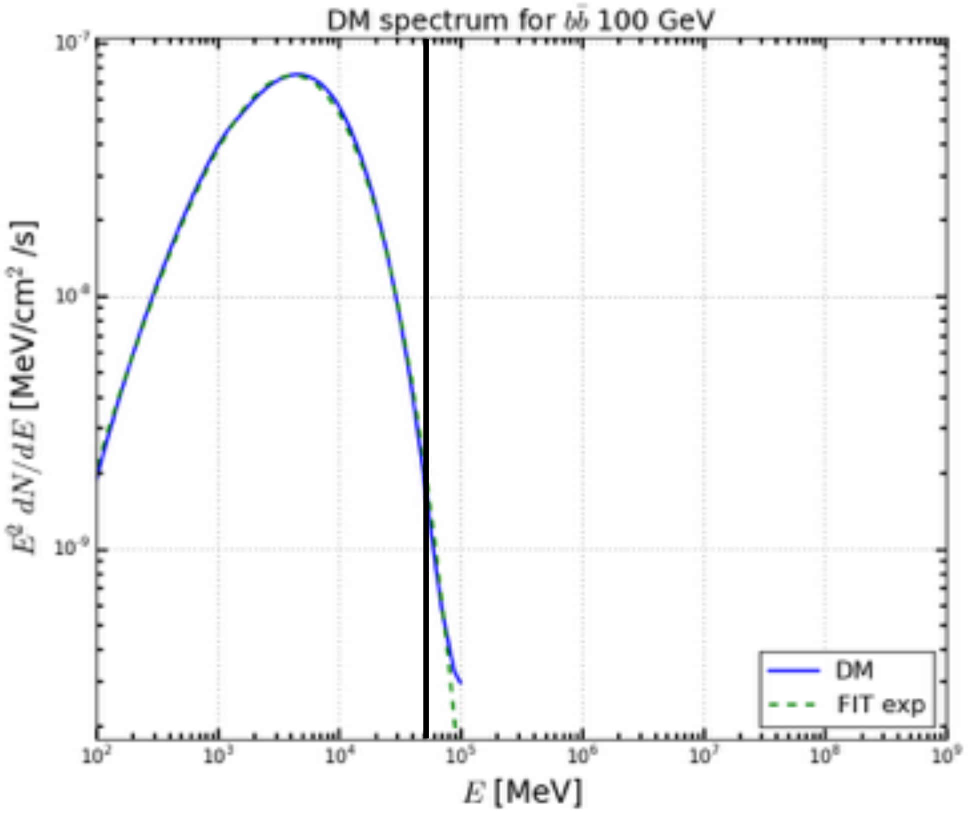


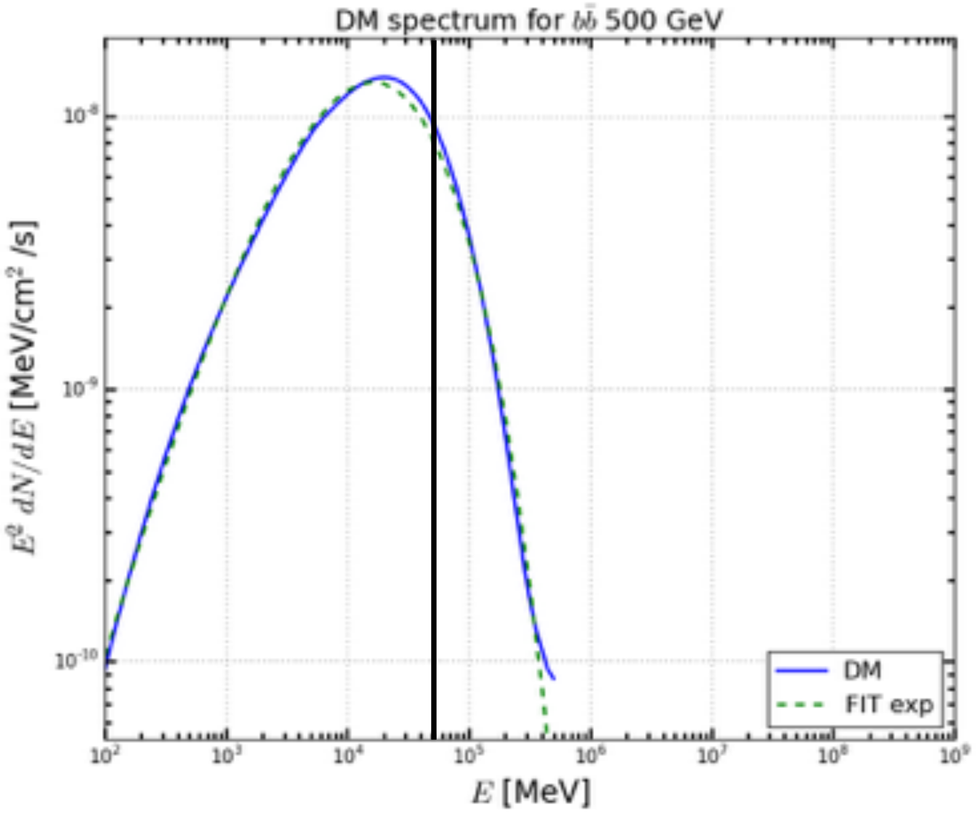
Setting up the Monte Carlo

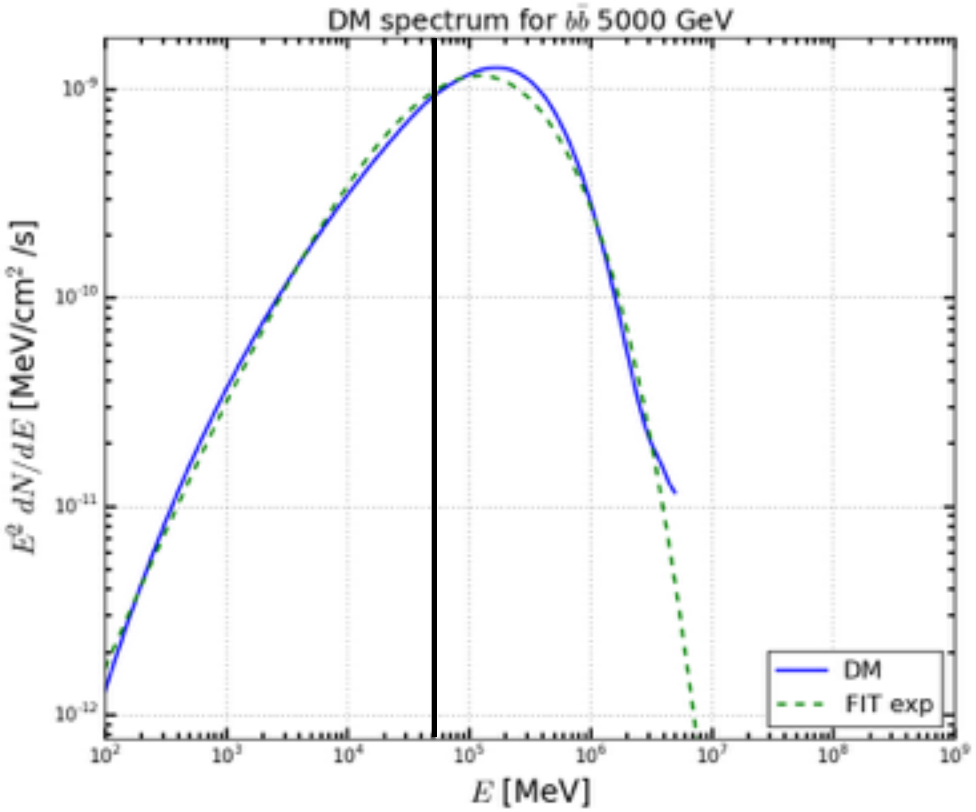


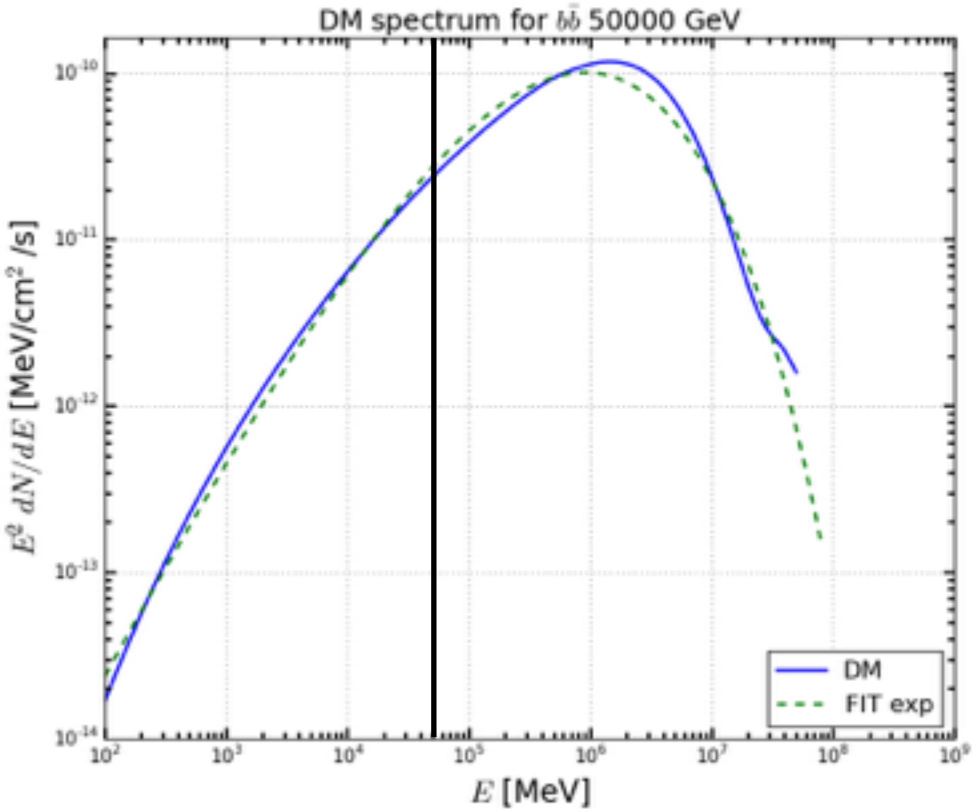
Depletion of low-mass SHs in the center in the Hydro simulation.

DM spectra 2FHL









Anisotropy from SHs: Poisson term

m_{DM} = 100 GeV

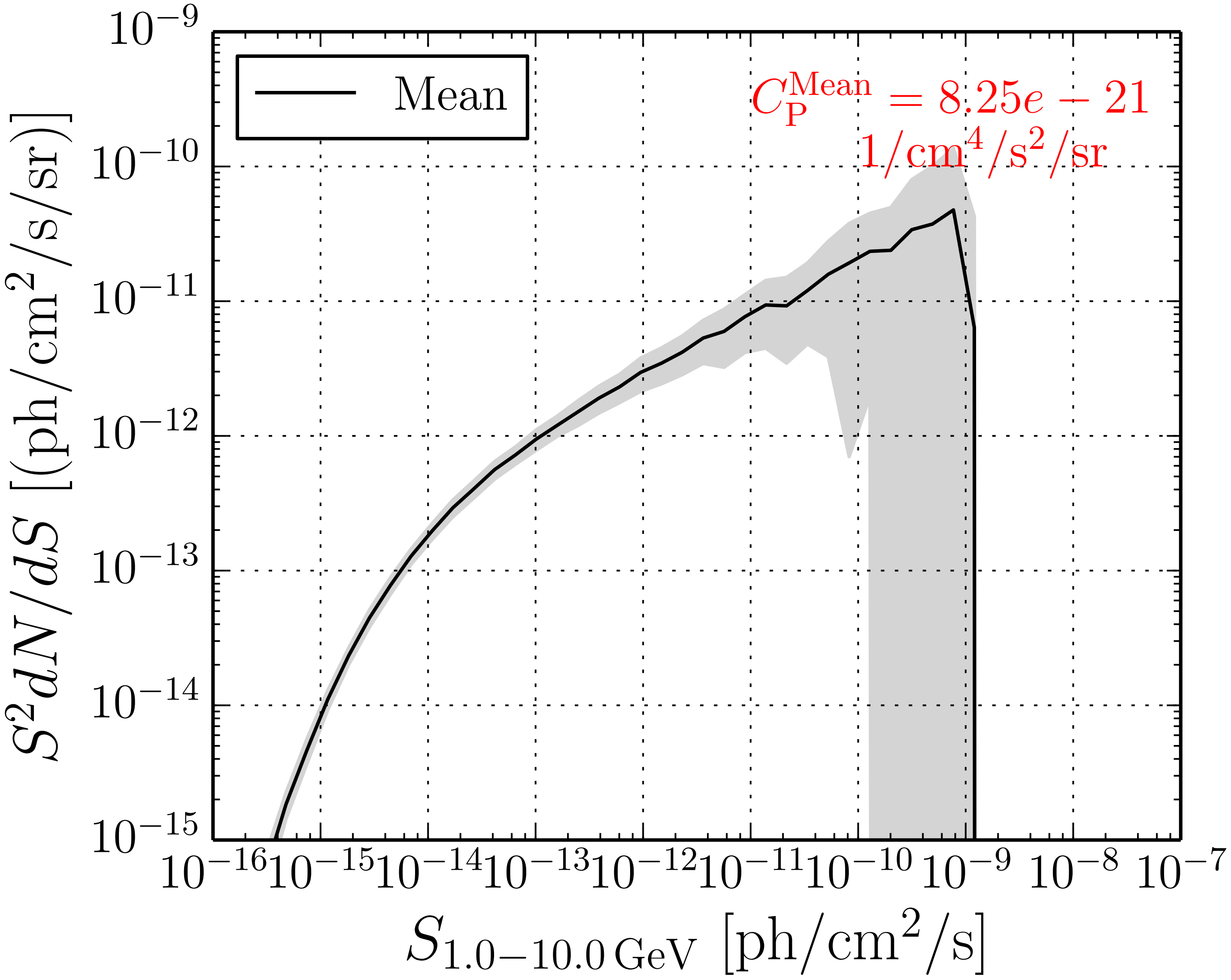
$\langle \sigma v \rangle$ from dSph limits

$$C_P = \int_0^{S_t} \frac{dN}{dS} S^2 \, dS$$

Cuoco+PRD'12

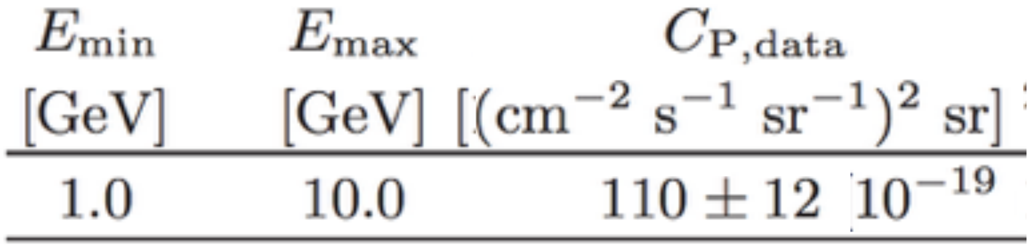
Detection threshold:

1×10^{-9} ph/cm^2/s



2012 *Fermi*-LAT results

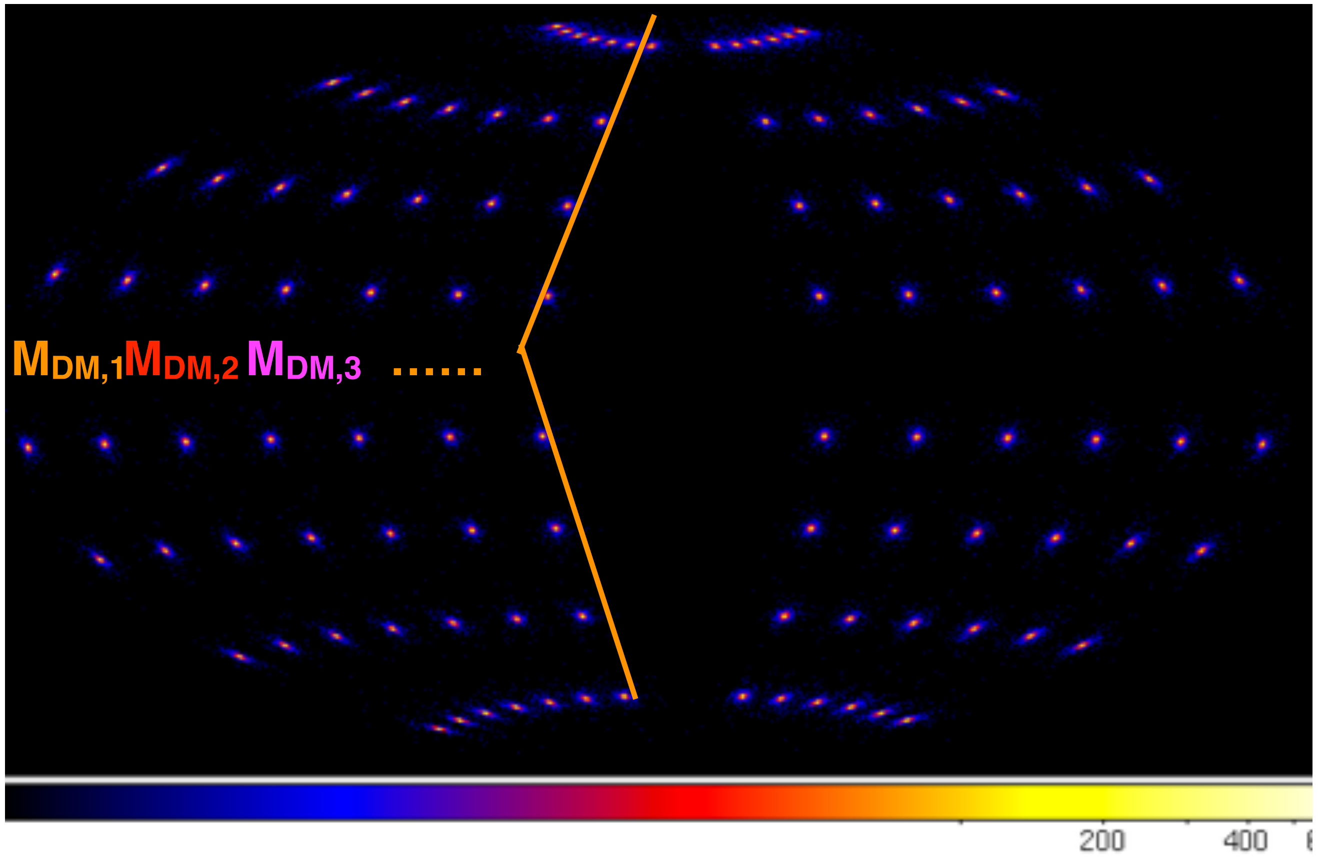
Ackermann+PRD'12



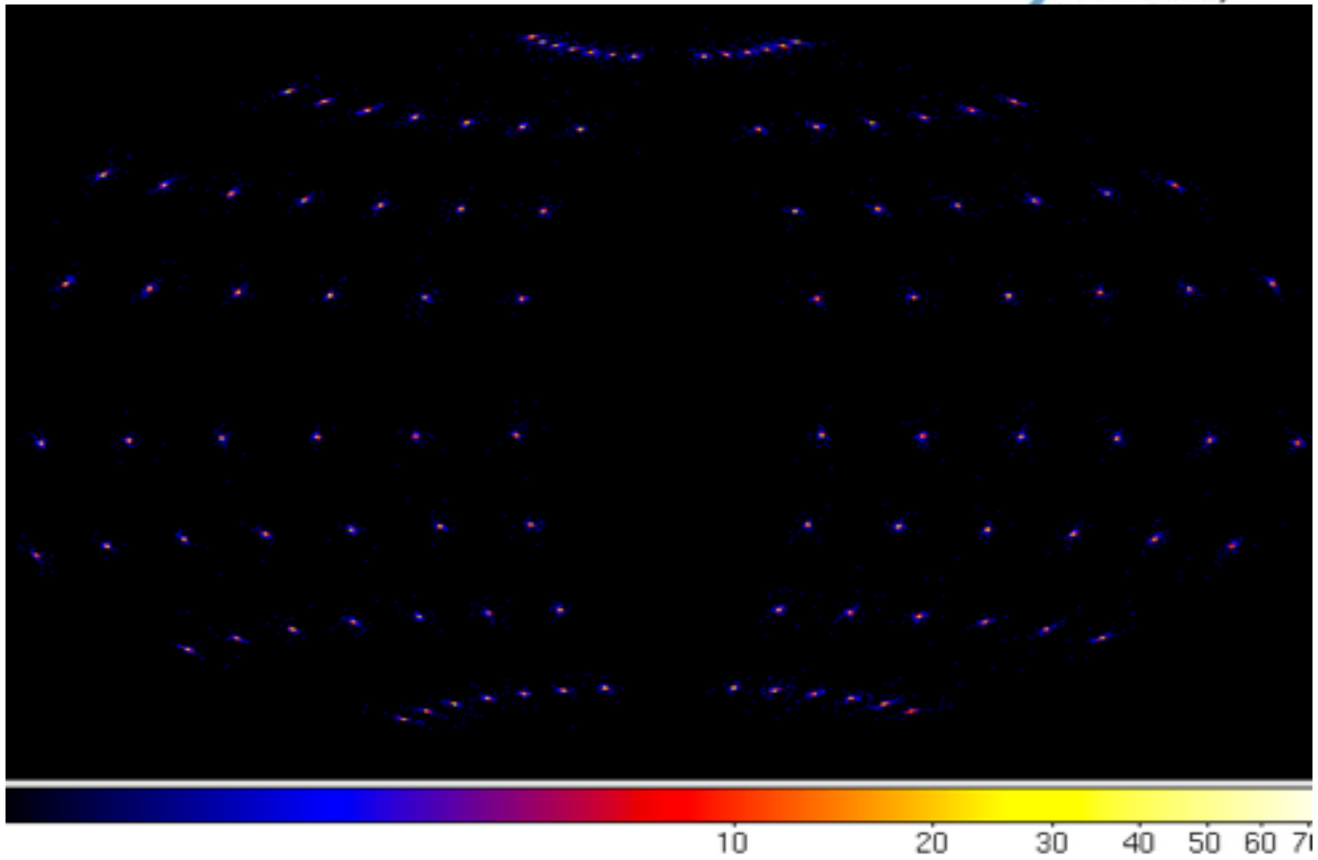
E_{min} [GeV]	E_{max} [GeV]	$C_{\mathrm{P,data}}$ [(cm^{-2} s^{-1} sr^{-1})^2 sr]
1.0	10.0	110 ± 12 10^{-19}

Simulated maps

$F_1=10^{-8}$ ph/cm^2/s



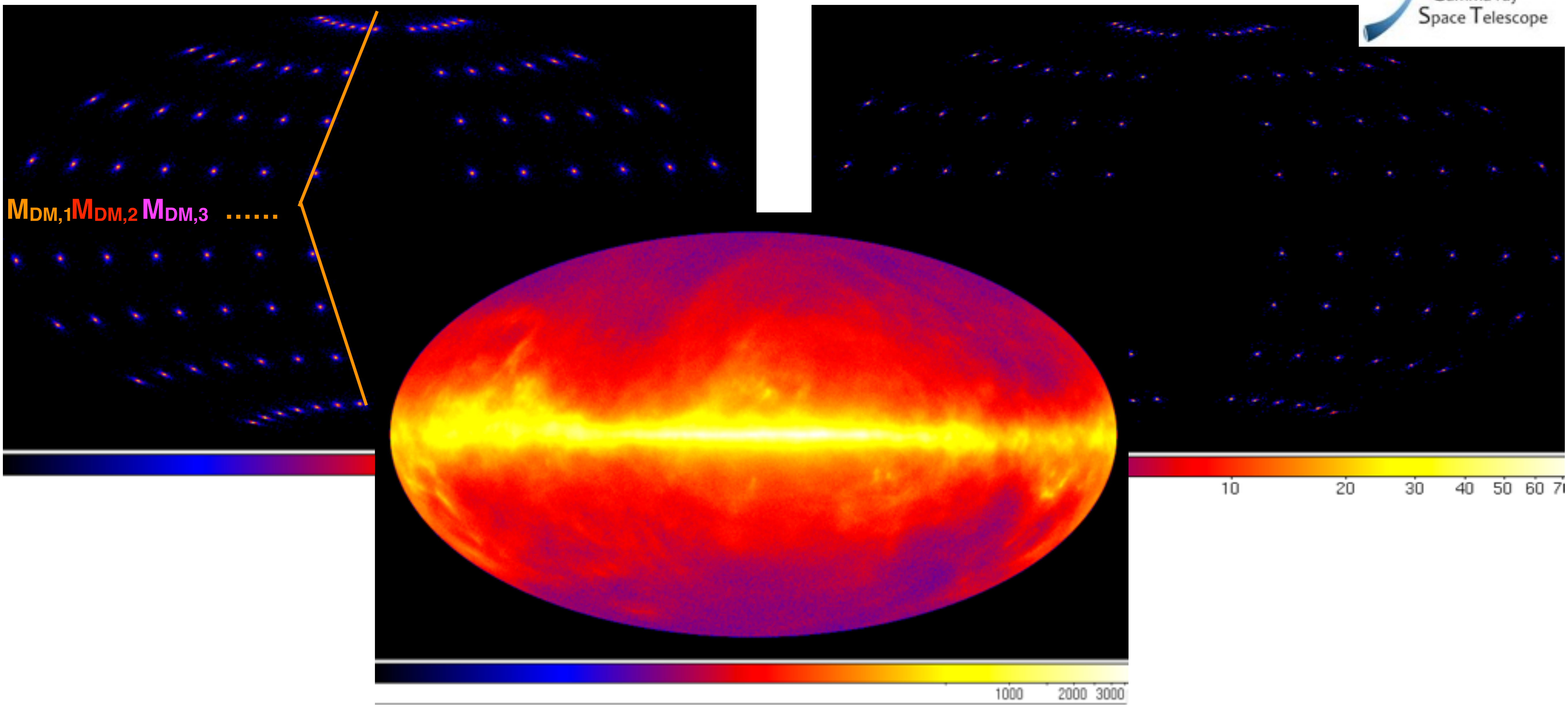
$F_2=10^{-9}$ ph/cm^2/s



$F_1=10^{-8}$ ph/cm^2/s

Simulated maps

$F_2=10^{-9}$ ph/cm^2/s

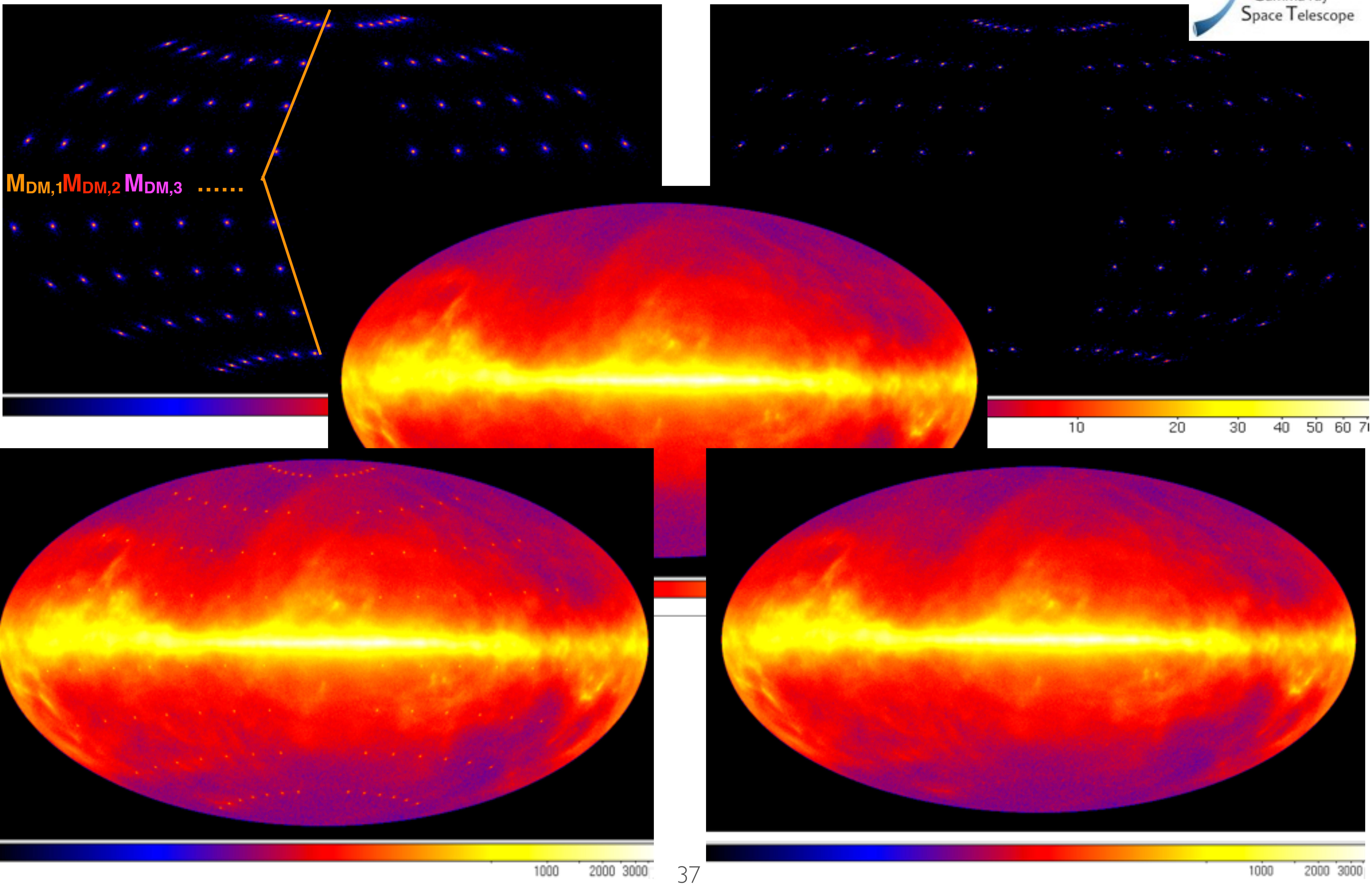


$F_1=10^{-8}$ ph/cm^2/s

Simulated maps

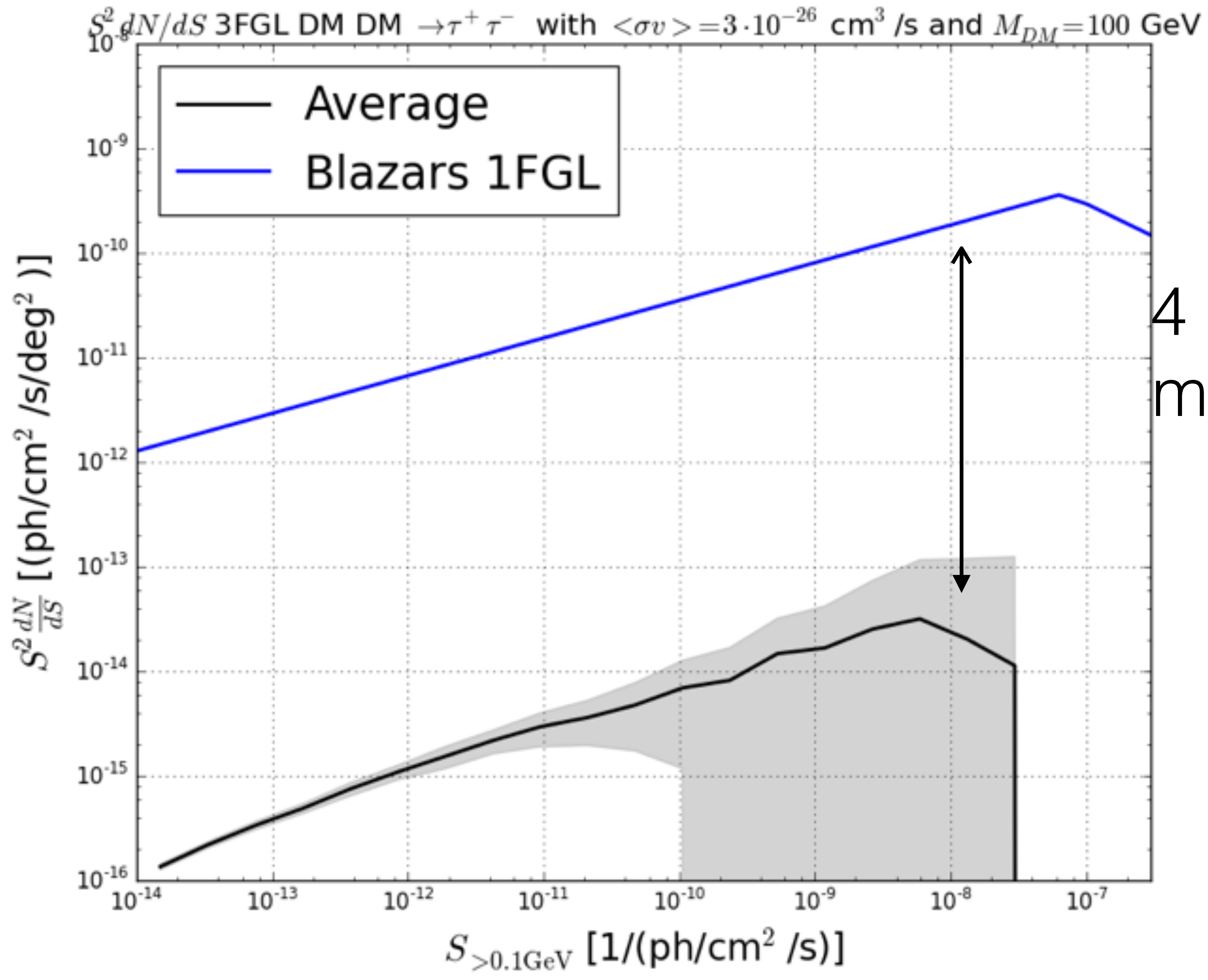
$F_2=10^{-9}$ ph/cm

Fermi Gamma-ray Space Telescope



tau

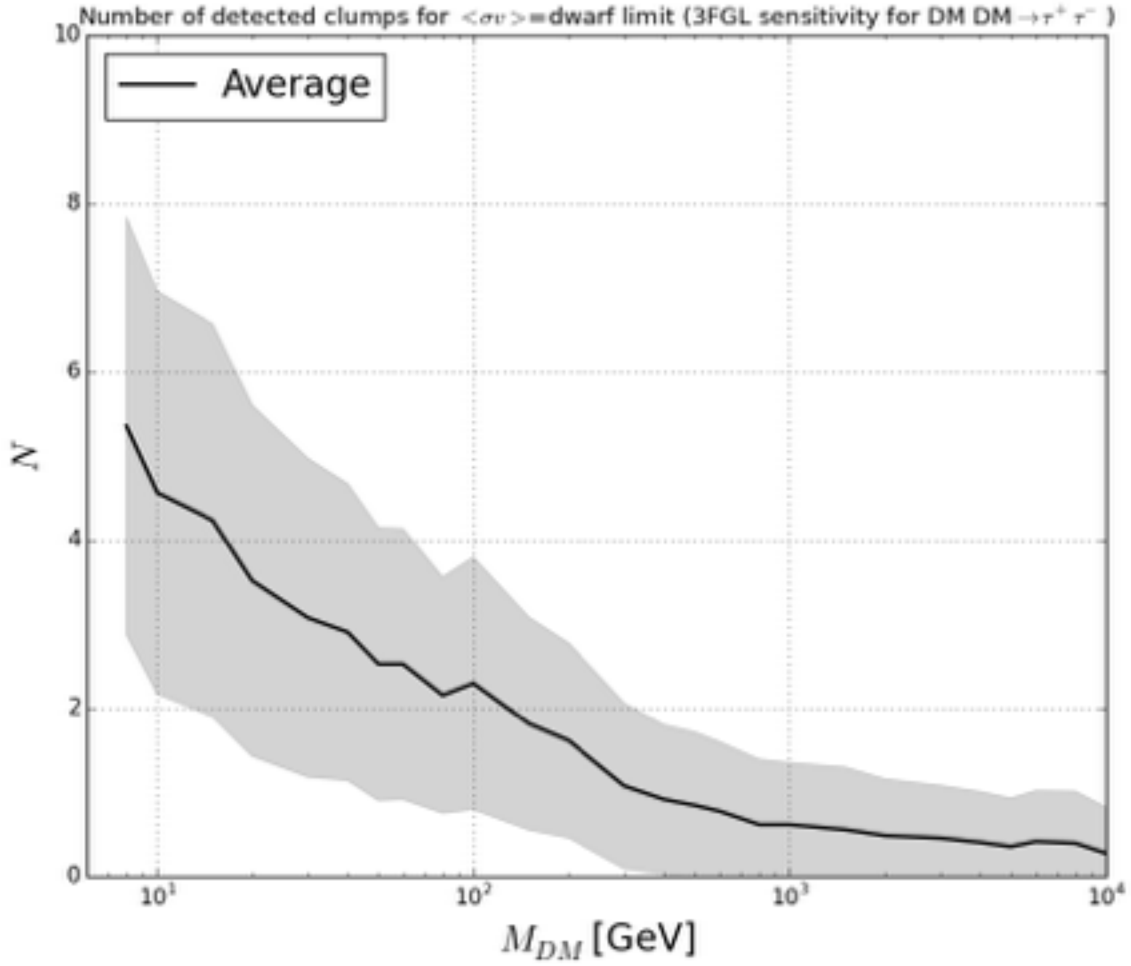
Source count distribution of SHs

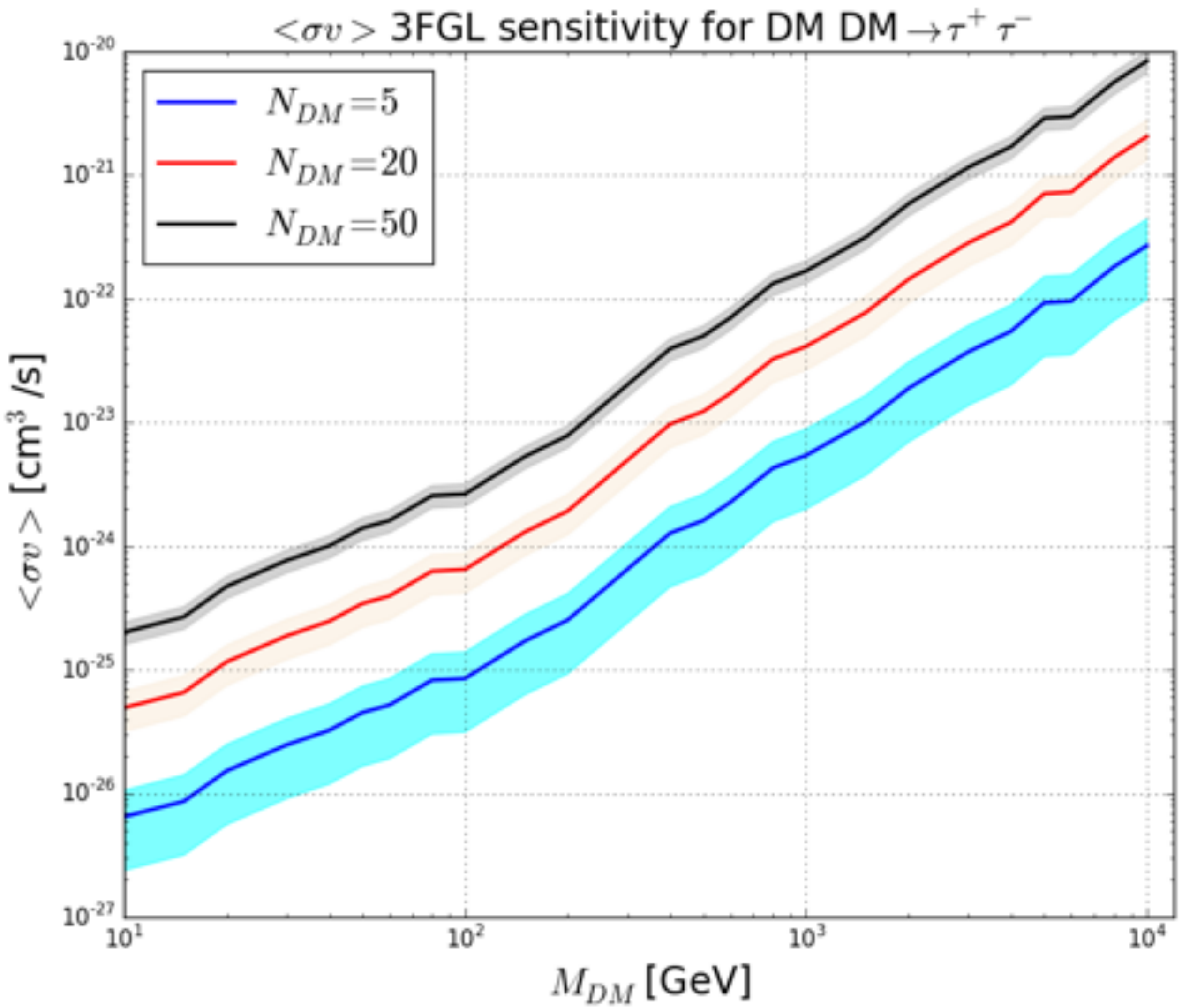


4 orders of magnitude

SHs Hydro simulation vs detected blazars

Number of detected clumps



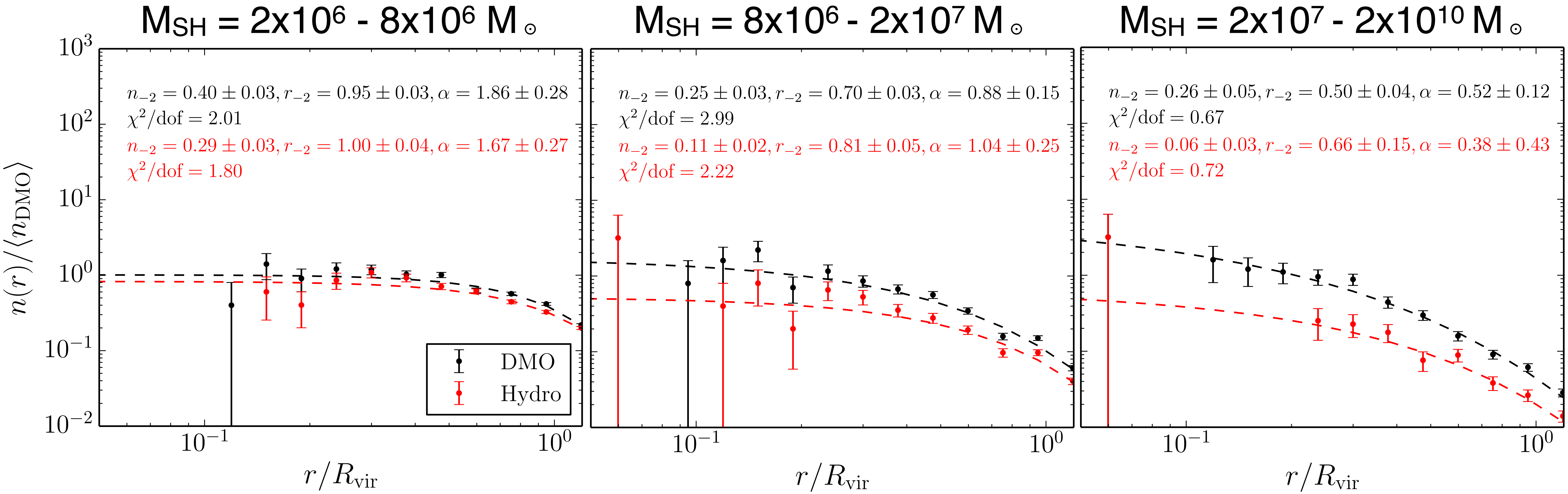


a few clumps could be among unassociated 3FGL sources

Radial distribution of SHs

Fermi Gamma-ray Space Telescope

Dark SHs


M_{SH} = 2x10^6 - 8x10^6 $M_\odot$

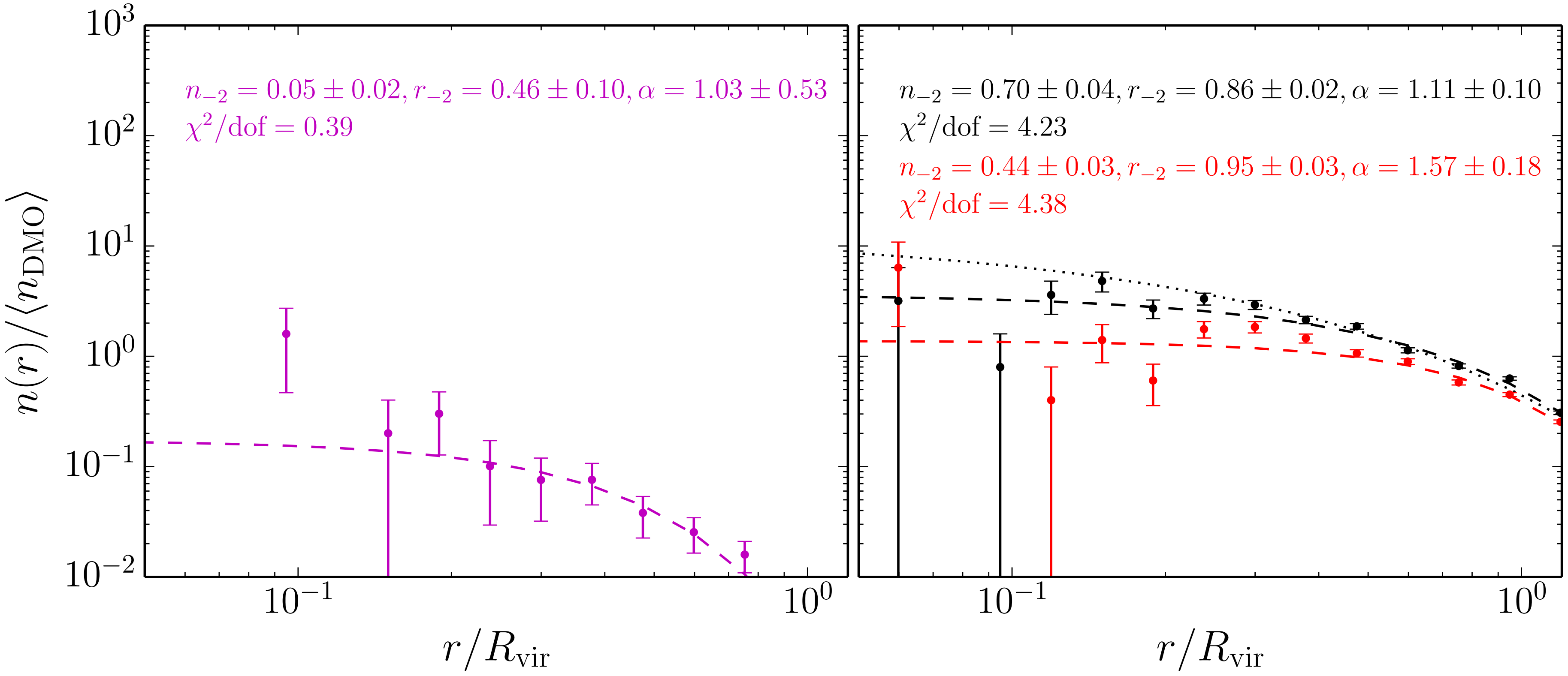
M_{SH} = 8x10^6 - 2x10^7 $M_\odot$

M_{SH} = 2x10^7 - 2x10^{10} $M_\odot$

Luminous SHs

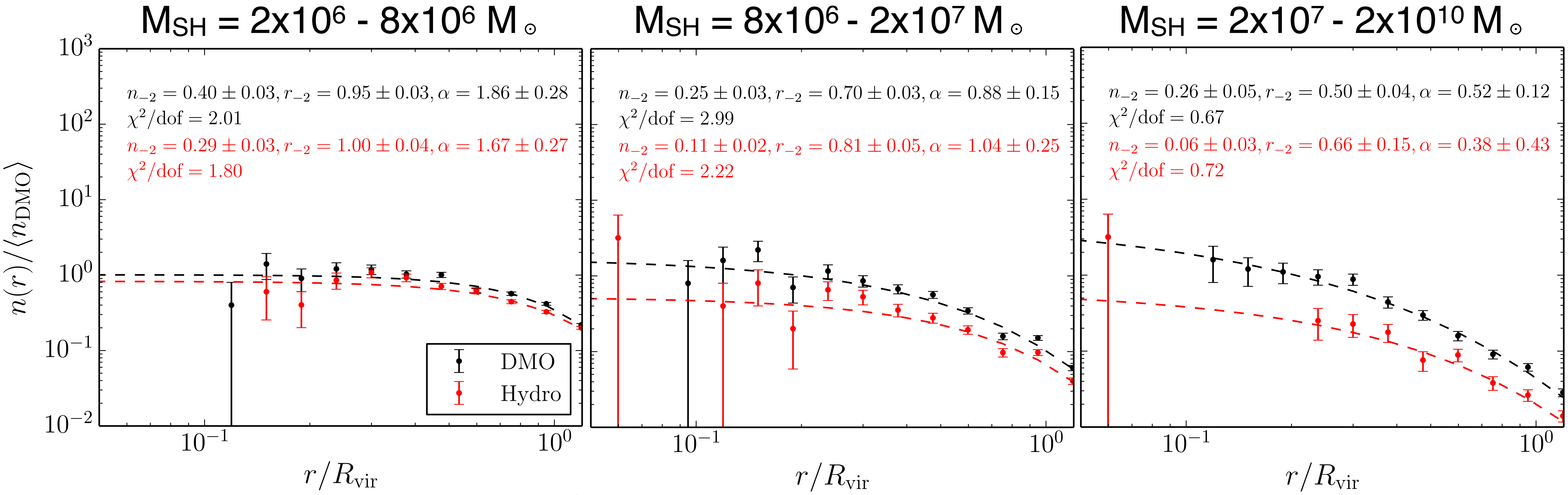
M_{SH} = 2x10^6 - 2x10^{10} $M_\odot$

$\alpha_{\mathrm{Springel08}} = 0.678$



Radial distribution of SHs

Dark SHs



M_{SH} = 2x10^6 - 8x10^6 M$_\odot$

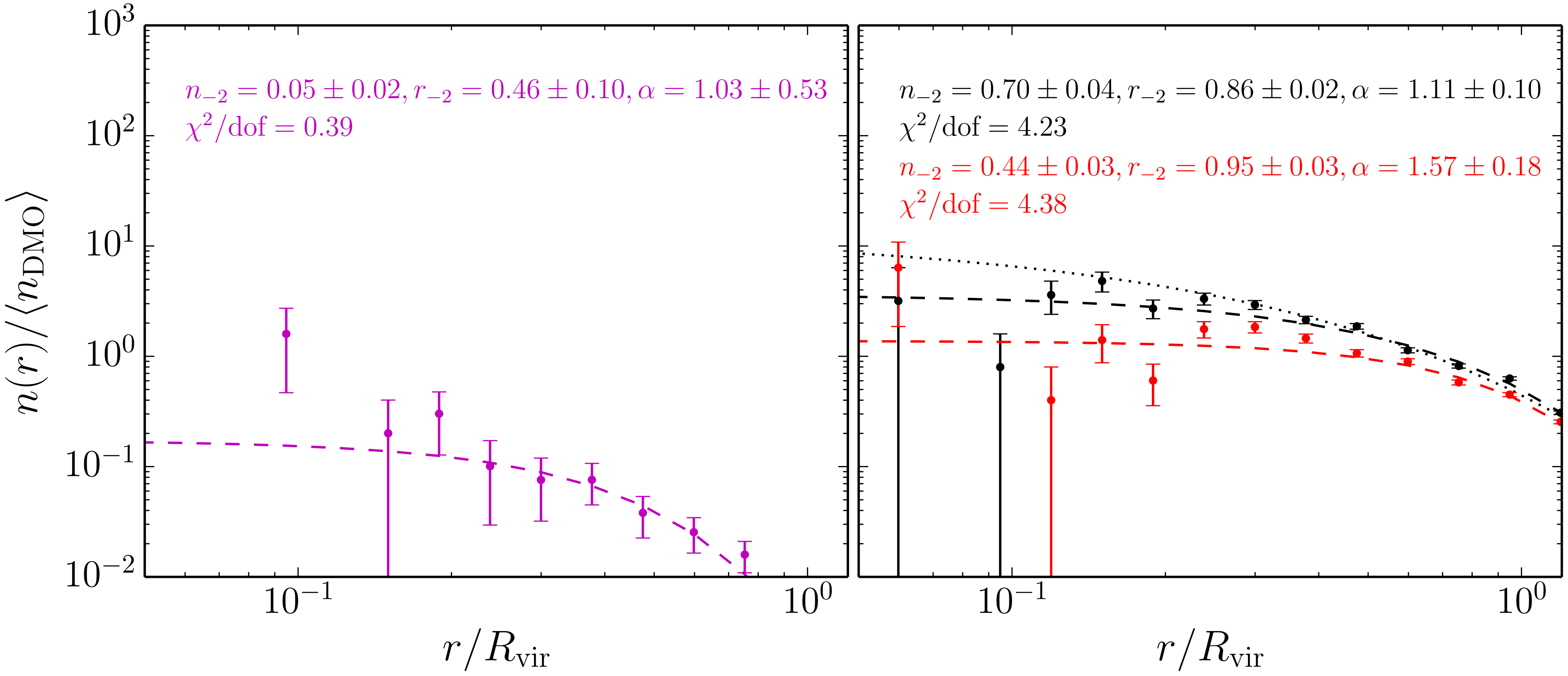
M_{SH} = 8x10^6 - 2x10^7 M$_\odot$

M_{SH} = 2x10^7 - 2x10^{10} M$_\odot$

Luminous SHs

M_{SH} = 2x10^6 - 2x10^{10} M$_\odot$

$\alpha_{\rm Springel08}$ = 0.678



Moline' et al. 2016