CP3 Seminar
U. Catholique Louvain
22 February 2017

Anisotropy probes of dark matter annihilation

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Dark matter candidate: WIMP

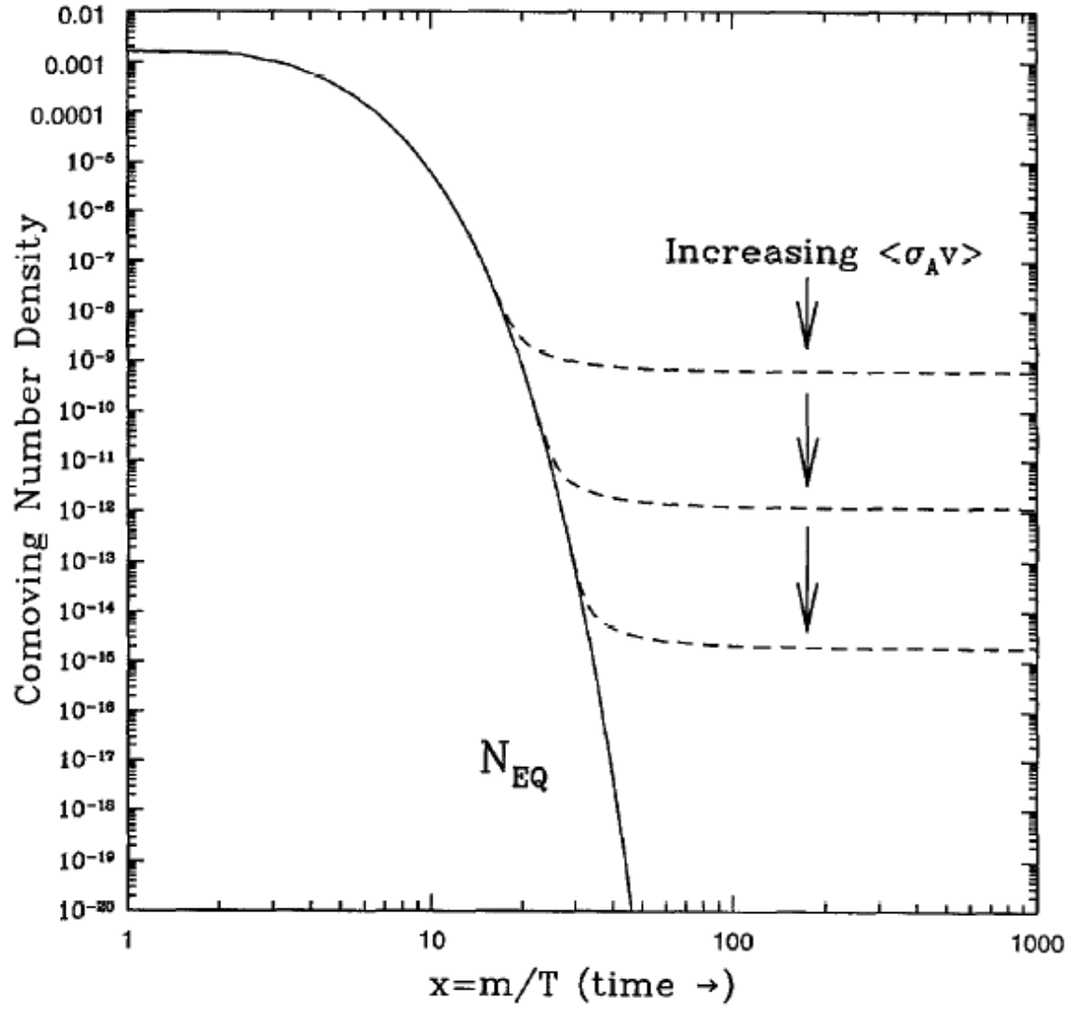
- Weakly Interacting Massive Particle (**WIMP**)

- Current dark matter density: determined by competition between Hubble expansion and annihilation (e.g., Steigman et al. 2012)

  - Later, expansion becomes too fast for WIMPs to annihilate (thermal freeze-out)

- WIMP models can naturally explain the relic abundance

- E.g., neutralino predicted by supersymmetry



$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

$$\langle \sigma_{\mathrm{ann}} v \rangle \sim \alpha^2 (100\ \mathrm{GeV})^{-2} \sim 3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$$

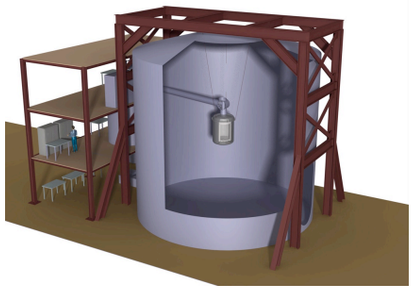
Three routes to DM



Collider production of dark matter; e.g., LHC

DM

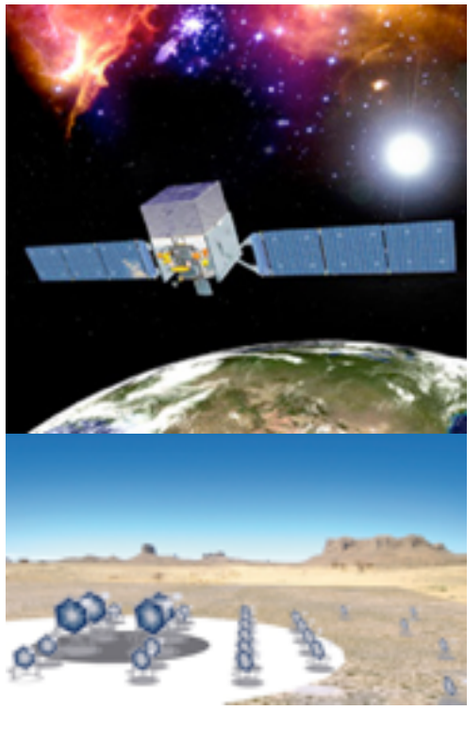
SM



Direct detection; e.g., XENON, LUX

DM

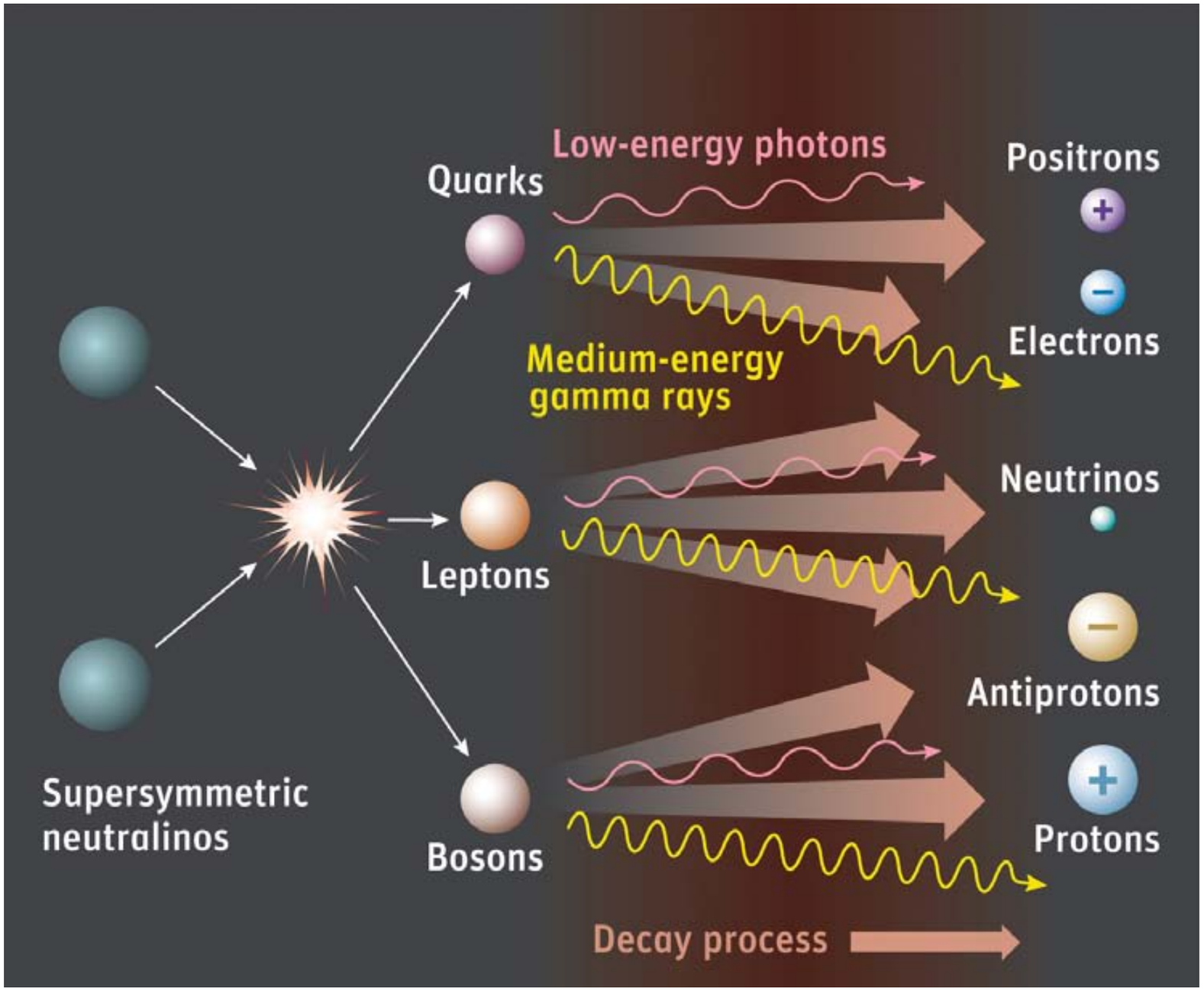
SM



Indirect detection; e.g., Fermi, CTA, IceCube

Dark matter annihilation

- WIMPs annihilate into standard model particles (photons, positrons, neutrinos, etc.)
- Each of these particles carry a fraction of WIMP mass energy (E ~ GeV–TeV)
- Annihilation rate is proportional to density squared
- And to annihilation cross section and relative velocity: $\sigma_{ann} v$



*Probe of **mass** and annihilation cross section (**interaction** with SM particles)*

The Galaxy

The Universe

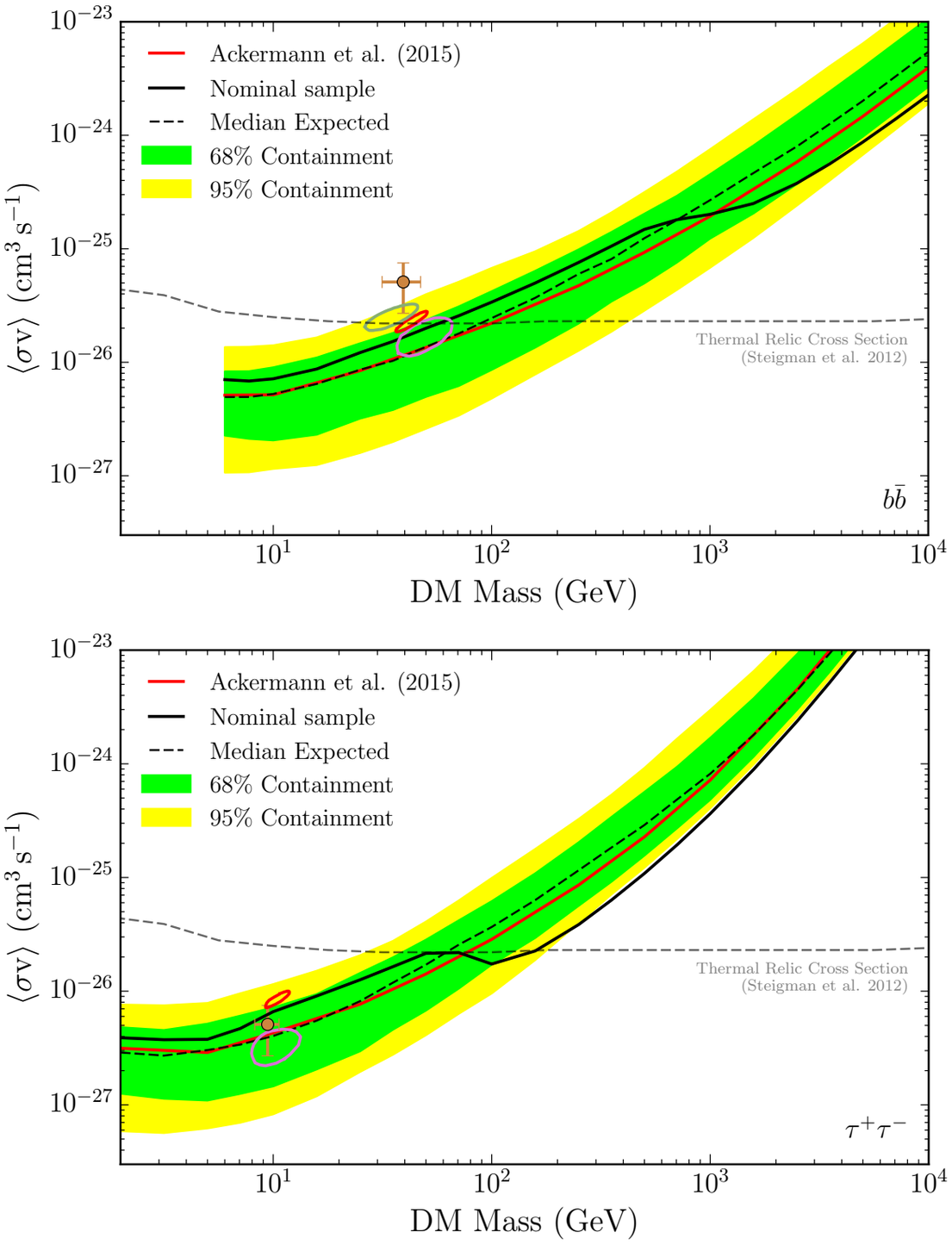
Millennium Run
10.077.696.000 particles

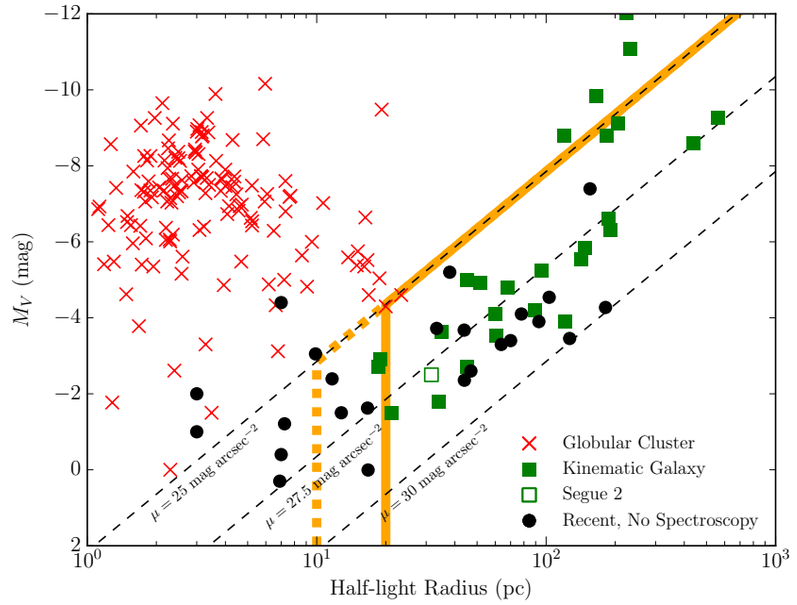
Galactic substructure
from Via Lactea II

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

Constraints from dwarf spheroidal galaxies

Fermi-LAT, arXiv:1611.03184 [astro-ph.HE]

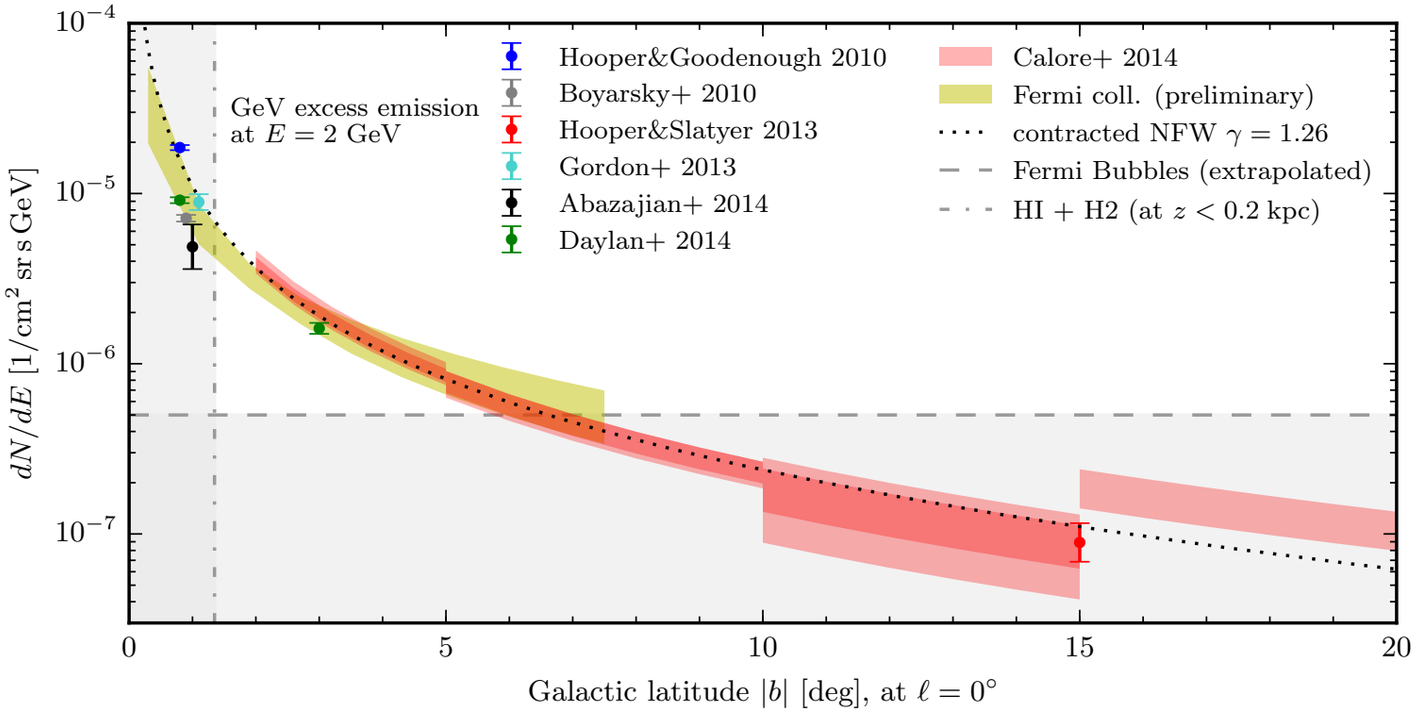


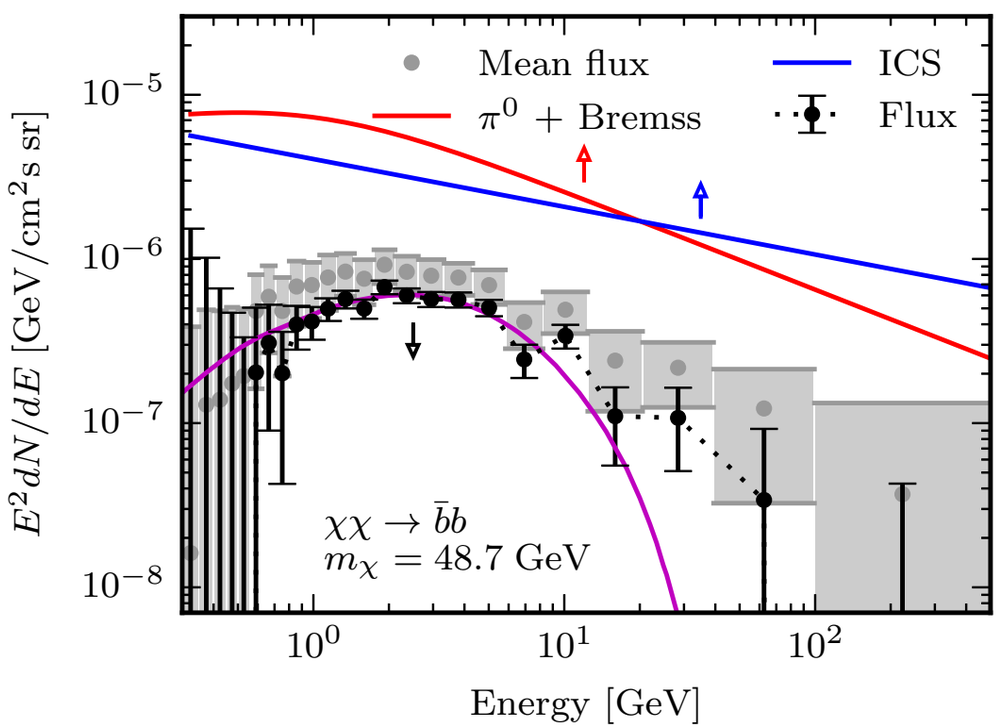


- Highly DM dominated system → suitable environment to test DM annihilation
  - Most robust constraints
- The latest results with PASS 8 data are pretty stringent
- They exclude the canonical cross section for WIMPs lighter than several tens of GeV
  - Nominal sample: 41 dwarfs
  - Ackermann et al. (2015):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

GeV excess: Signals of dark matter annihilation?

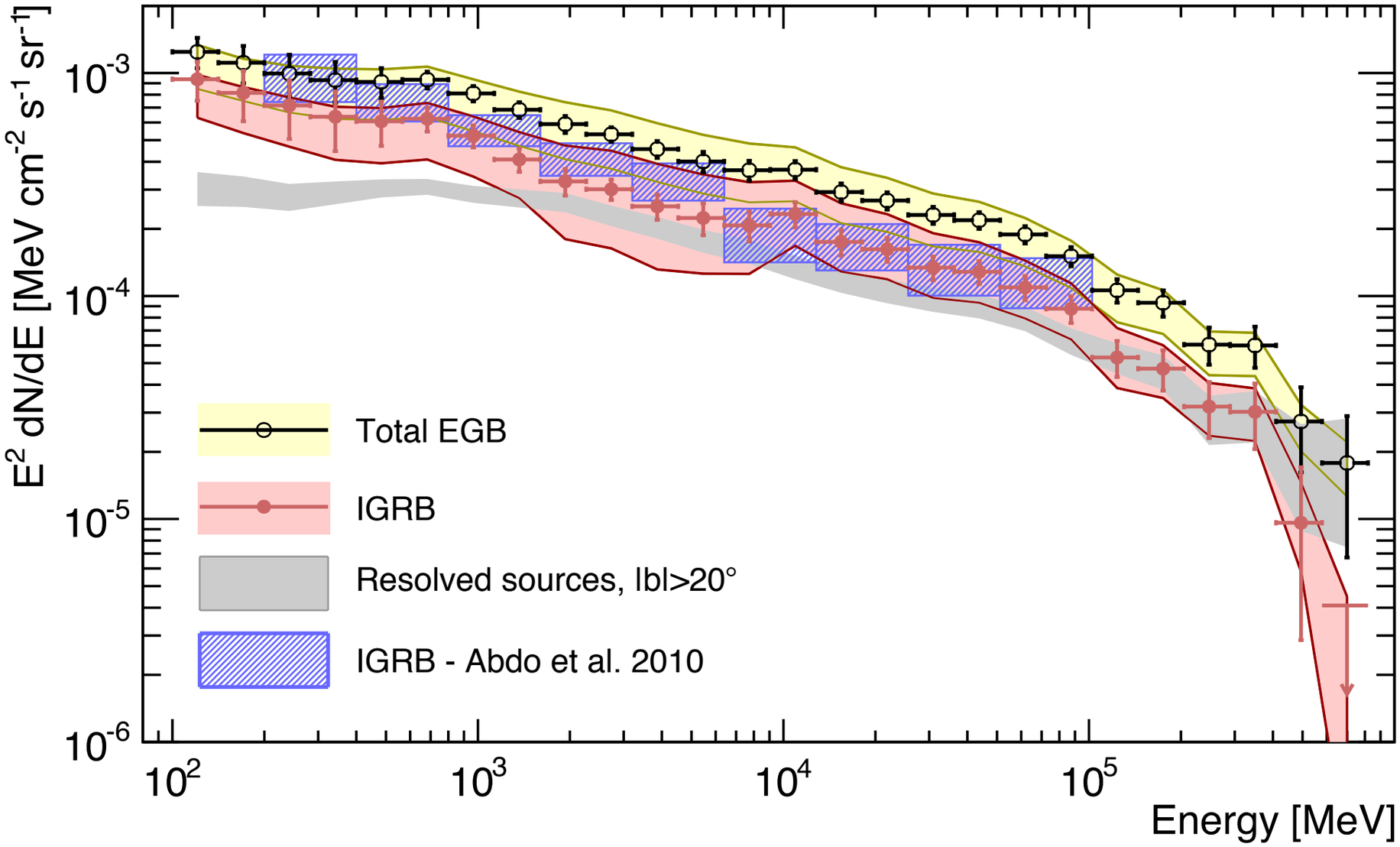
Calore et al., *Phys. Rev. D* **91**, 063003 (2015)





- Gamma-ray excess in GeV regime from the Galactic center (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}
- But more recent analyses (Bartels et al. 2015; Lee et al. 2015) suggest astrophysical source origin (e.g., millisecond pulsars)

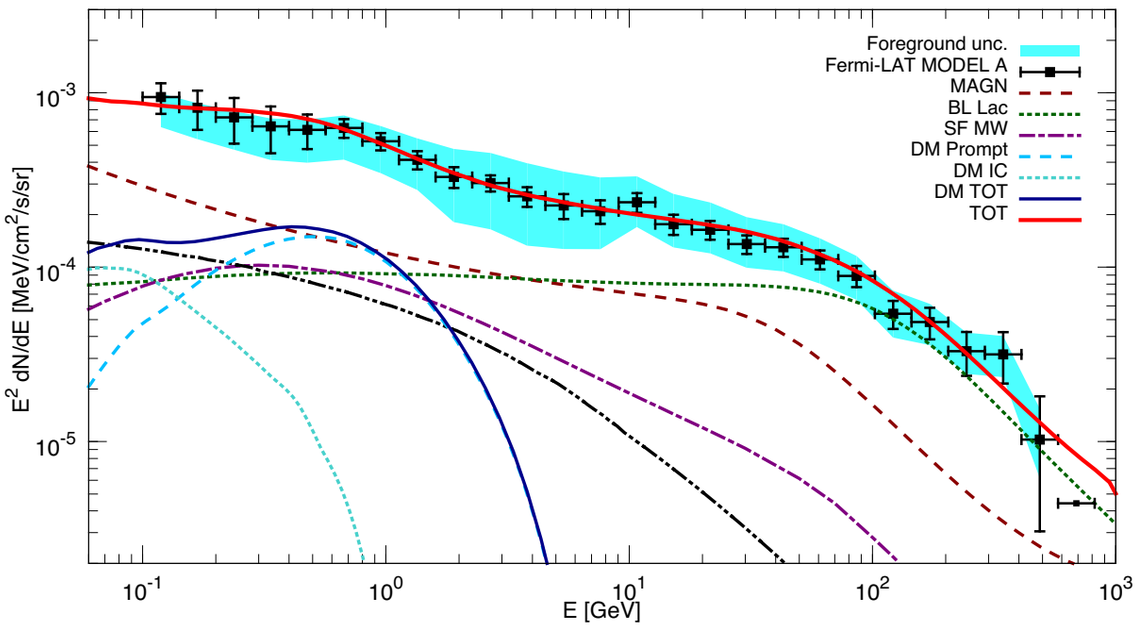
“Isotropic” gamma-ray background (IGRB)

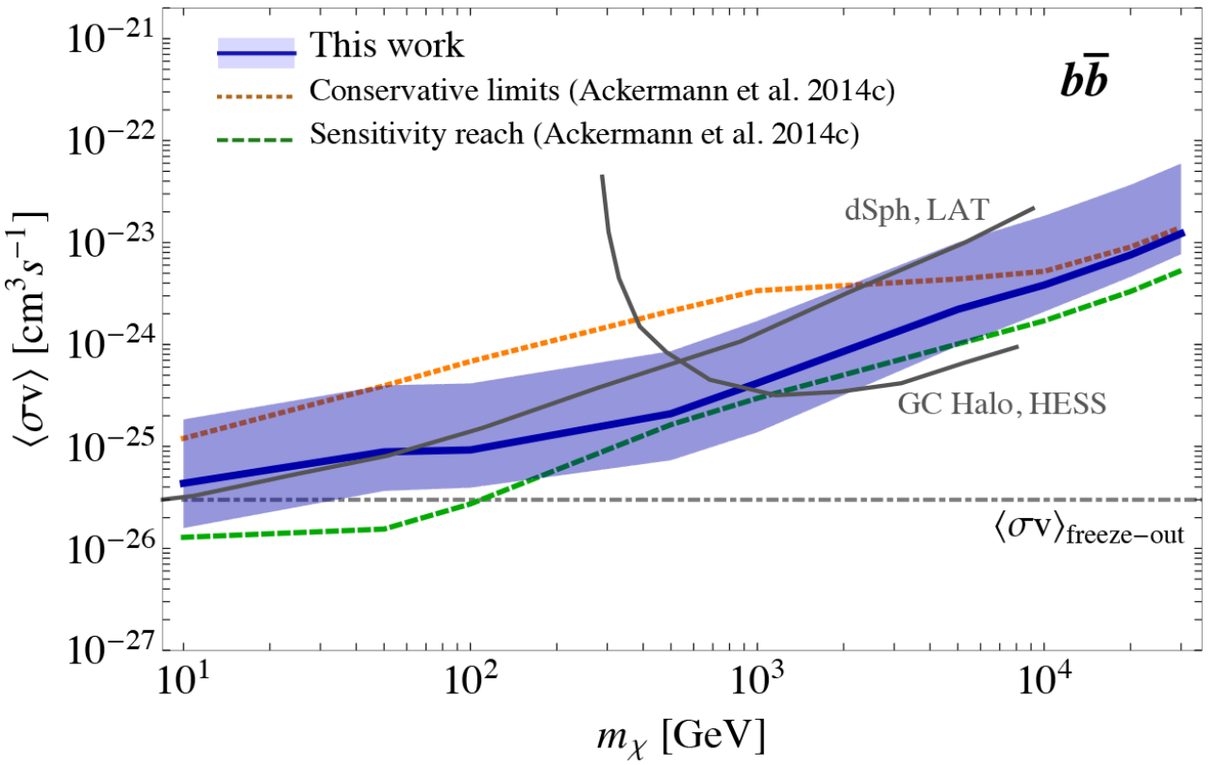


Fermi-LAT, *Astrophys. J.* **799**, 86 (2015)

Constraints from the gamma-ray background spectrum

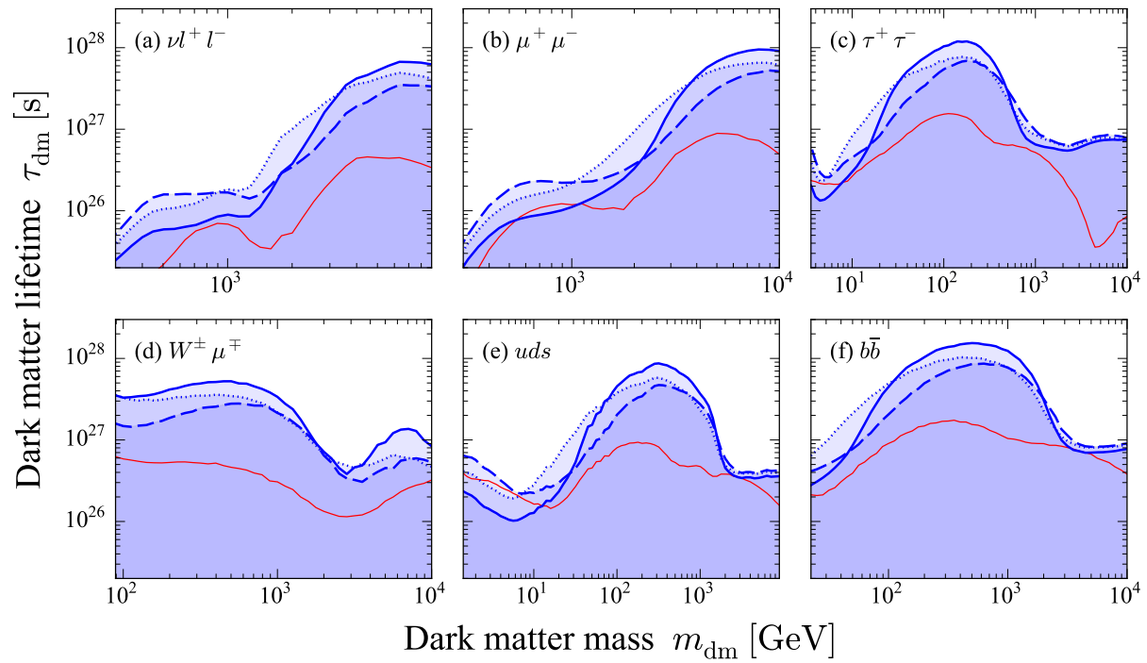
Di Mauro, Donato, *Phys.Rev. D* **91**, 123001 (2015)





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

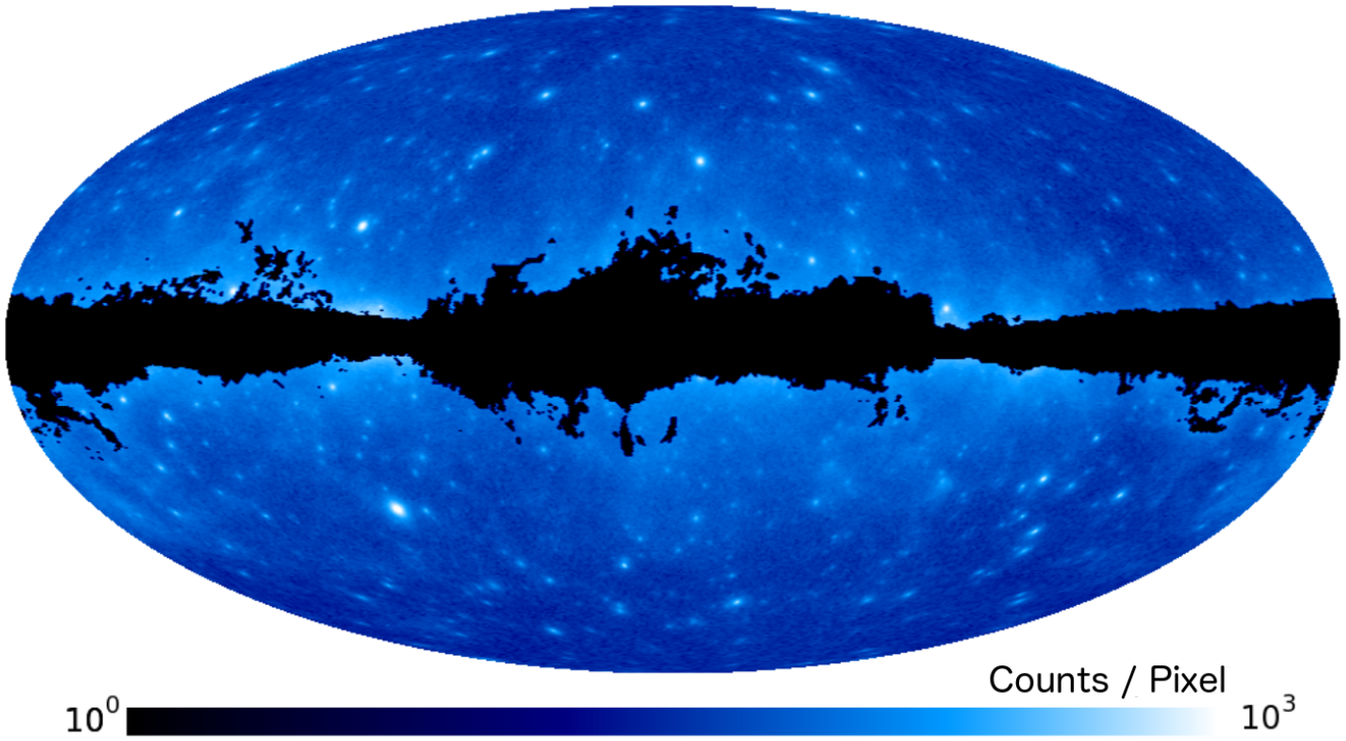
Ando, Ishiwata, *JCAP* **05**, 024 (2015)

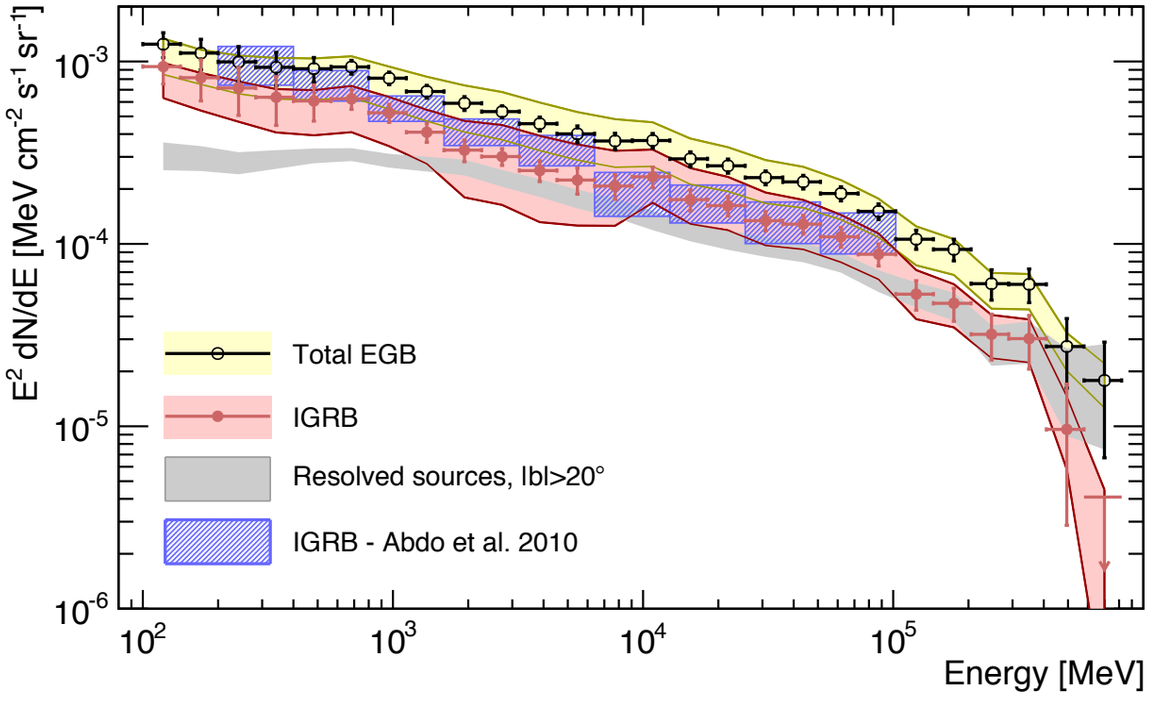


- **Annihilation**
  - Stringent constraints although with relatively large uncertainty (**subhalos**, discussed later)
- **Decay**
  - Stringent constraints (better than dwarf galaxies and galaxy clusters)

Anisotropy of the gamma-ray background

Fermi-LAT, Astrophys. J. **799**, 86 (2015)





- Number of gamma-ray photons (> 1 GeV) that Fermi collected: **> 5,000,000**
- Number of data of the gamma-ray background spectrum: **26**
- Loss of a lot of information → What else can one do?
  - **Anisotropy!**

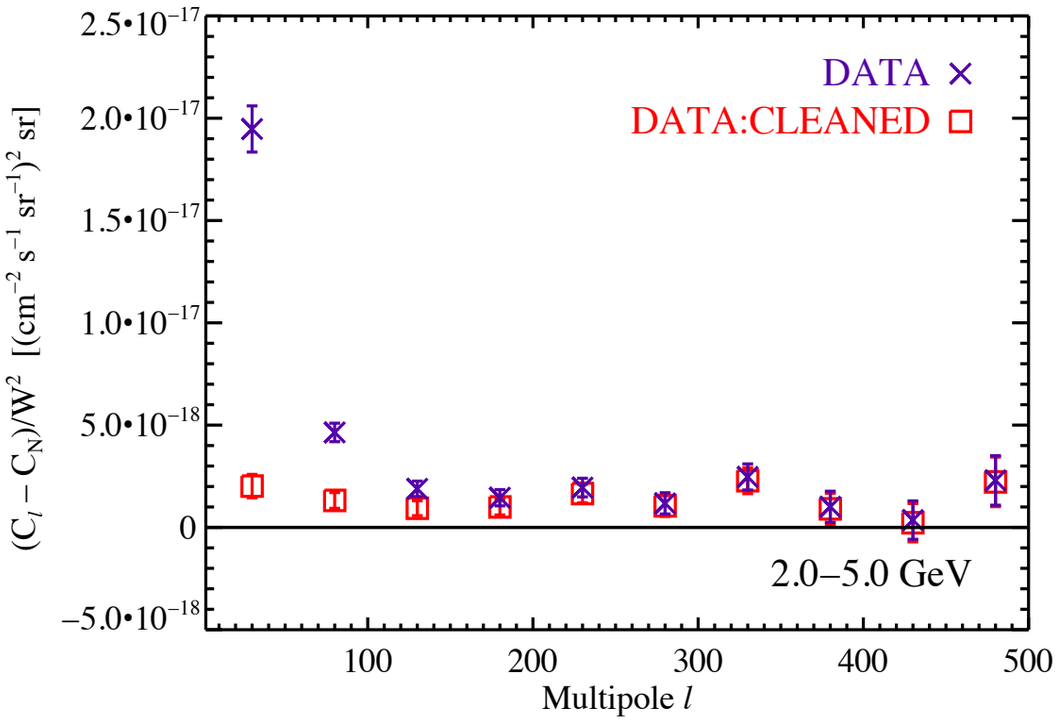
What can we learn from the gamma-ray background?

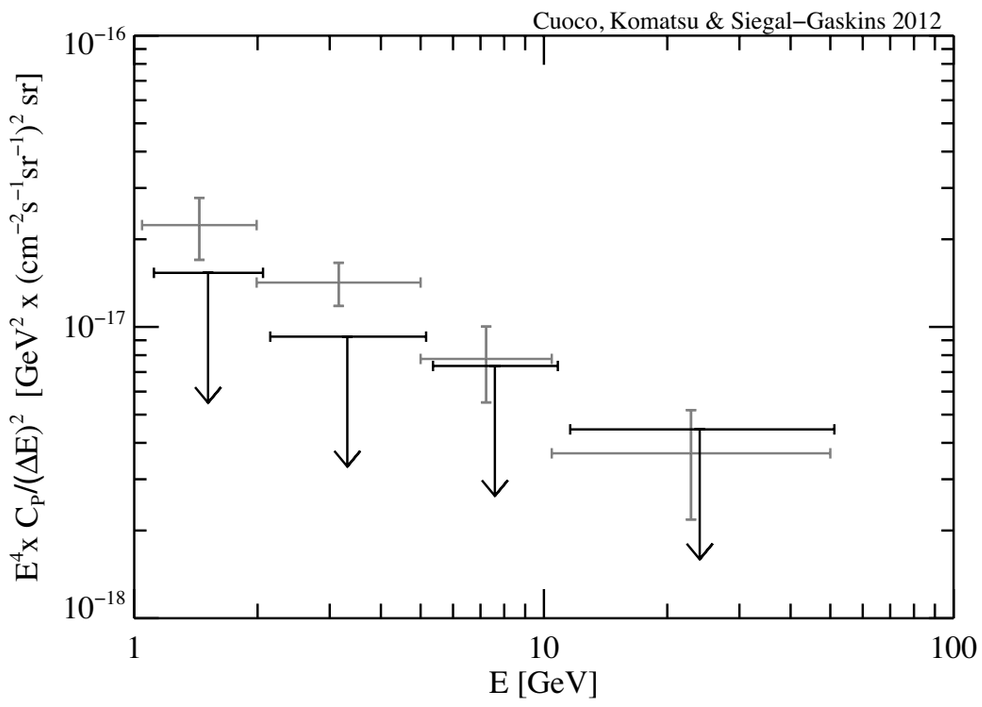
✓ **Energy**

- Intensity spectrum (Bergstrom et al. 1998)

- **Spatial clustering of sources**
  - Angular power spectrum (Ando & Komatsu 2006)
- **Redshift distribution of sources** → *tomography*
  - Cross correlation with dark matter tracers (Cosmic shear: Camera et al. 2013; Galaxy catalogs: Ando, Benoit-Lévy & Komatsu 2014)
- **Luminosity distribution of sources**
  - 1-point PDF of the gamma-ray flux (Lee, Ando & Kamionkowski 2009)

Angular power spectrum: Observations with Fermi

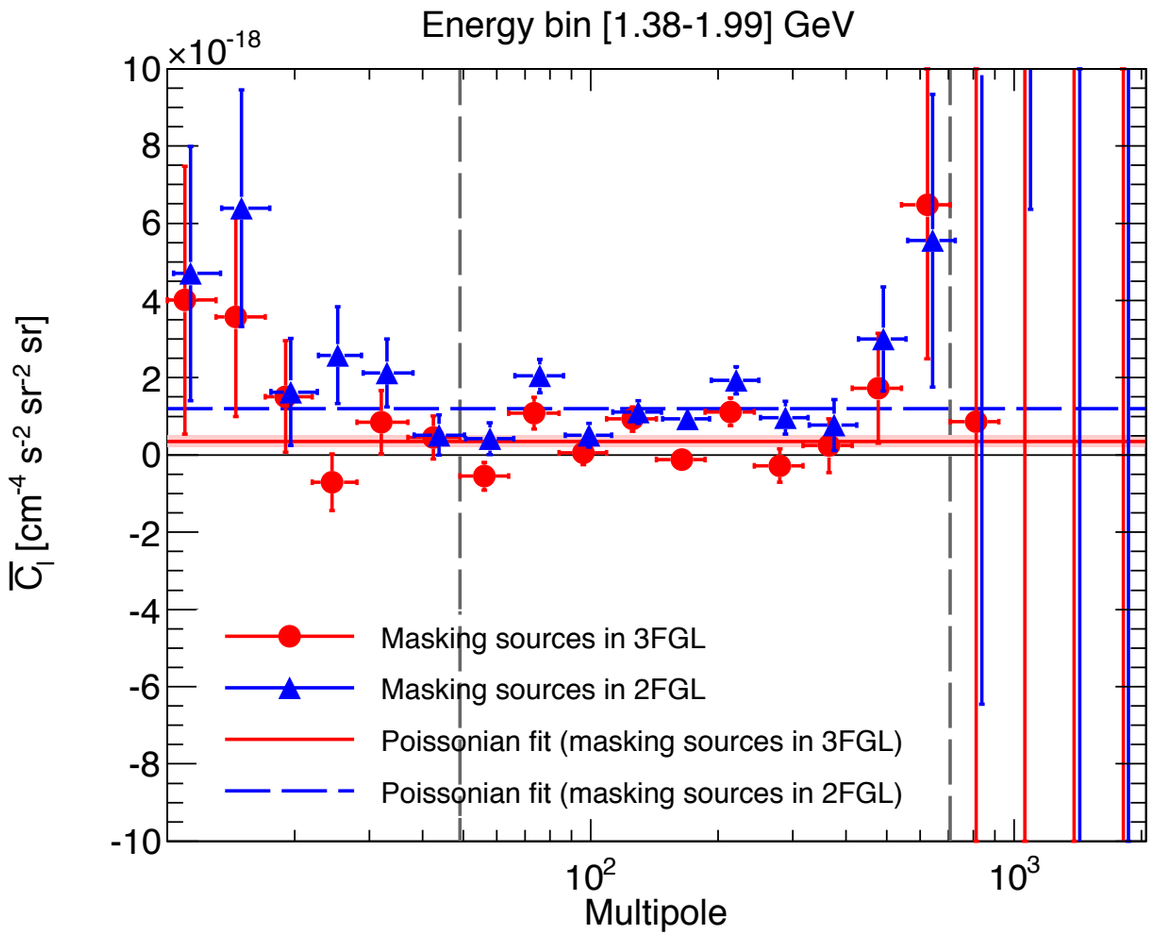




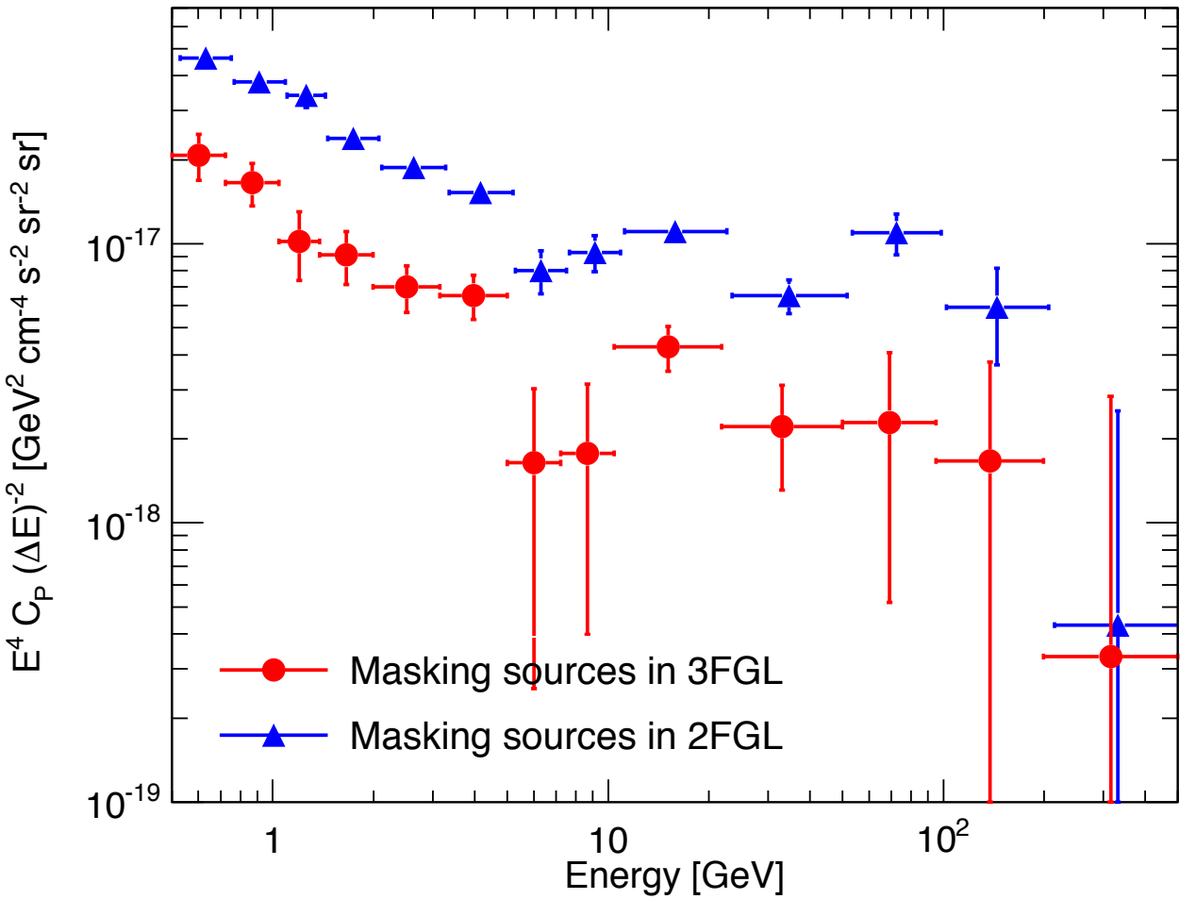
- Analysis of Fermi data for the angular power spectrum of the diffuse gamma-ray background in 2012 → **Discovery of anisotropies**
- Almost constant excess compared with shot noise of the photons at $100 < l < 500$
- Data are well **consistent with astrophysical expectations** (blazars; Ando et al. 2007)
- Upper limits on any other components (astrophysics or dark matter)

Fermi-LAT, *Phys. Rev. D* **85**, 083007 (2012)
Cuoco et al., *Phys. Rev. D* **86**, 063004 (2012)

Updated measurement on angular power

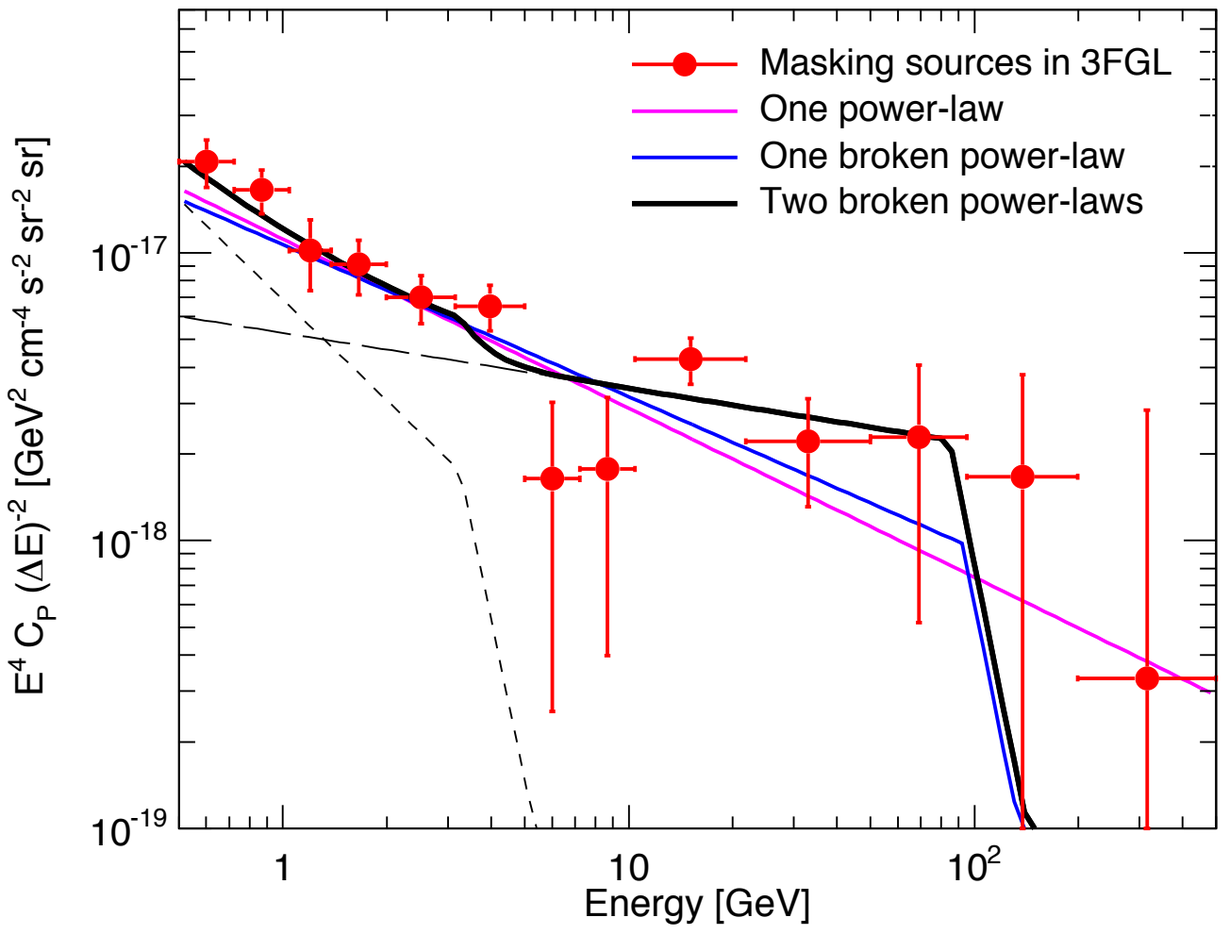


Fornasa et al. *Phys. Rev. D* **94**, 123005 (2016)



- 81 months of data, PASS 7 reprocessed, 13 energy bins between 500 MeV and 500 GeV, multipoles between 50 and 700
- Still consistent with “shot-noise” like spectrum

Phenomenological interpretation

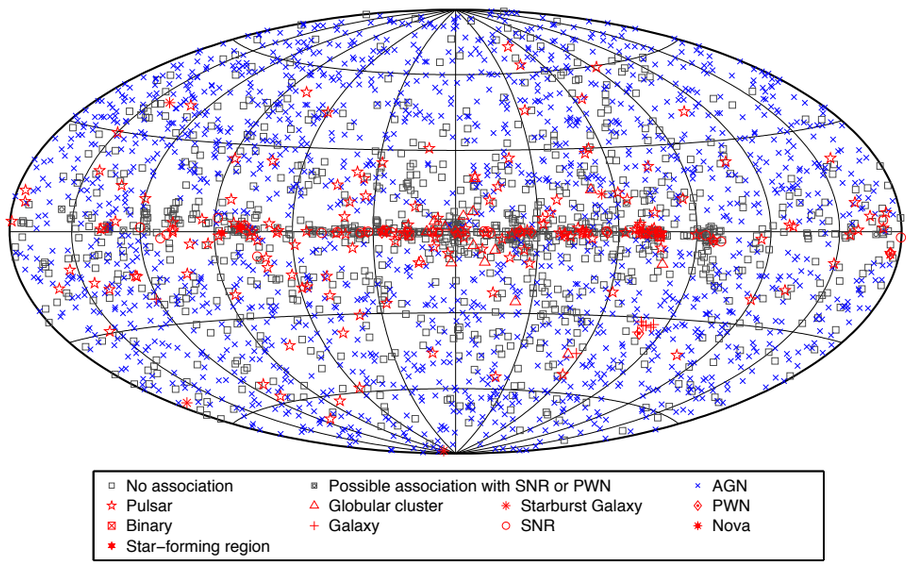


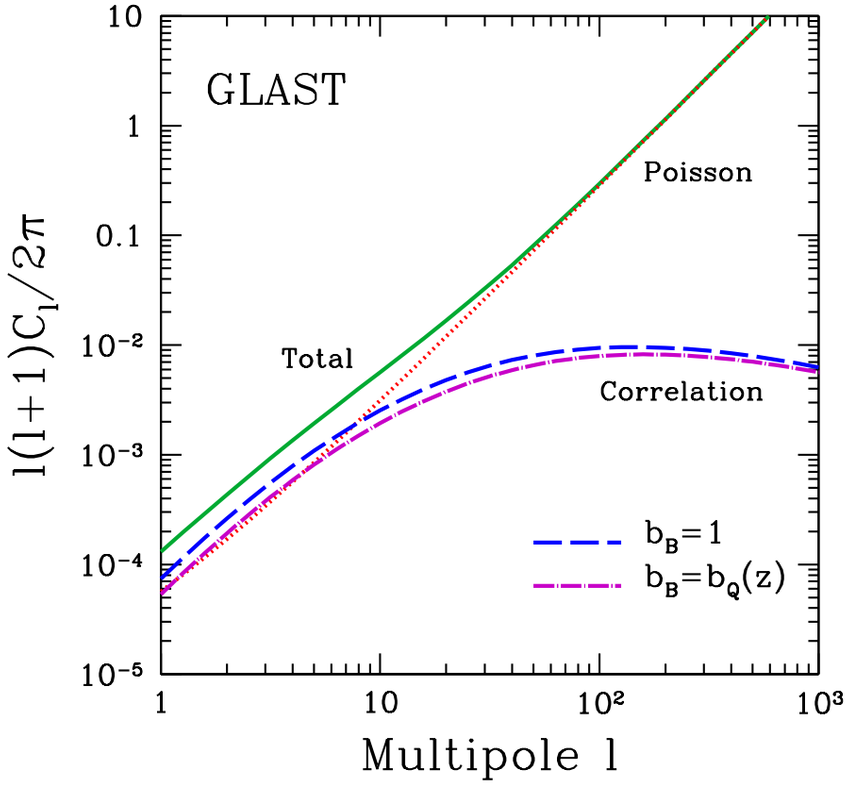
Fornasa et al. *Phys. Rev. D* **94**, 123005 (2016)

- One population (one single power-law) model does not fit the data well
- Data prefer two population models (two power laws, with at least one of them broken)
- Transition of power-law slope from 2.7 to 2.1 is seen
- ***What are they?*** **Can the data be entirely explained with the sources that we already know?**

Blazars as a dominant source of APS

Fermi-LAT, *Astrophys. J. Suppl. Ser.* **218**, 23 (2015)





Ando et al., *Phys. Rev. D* **75**, 063519 (2007)

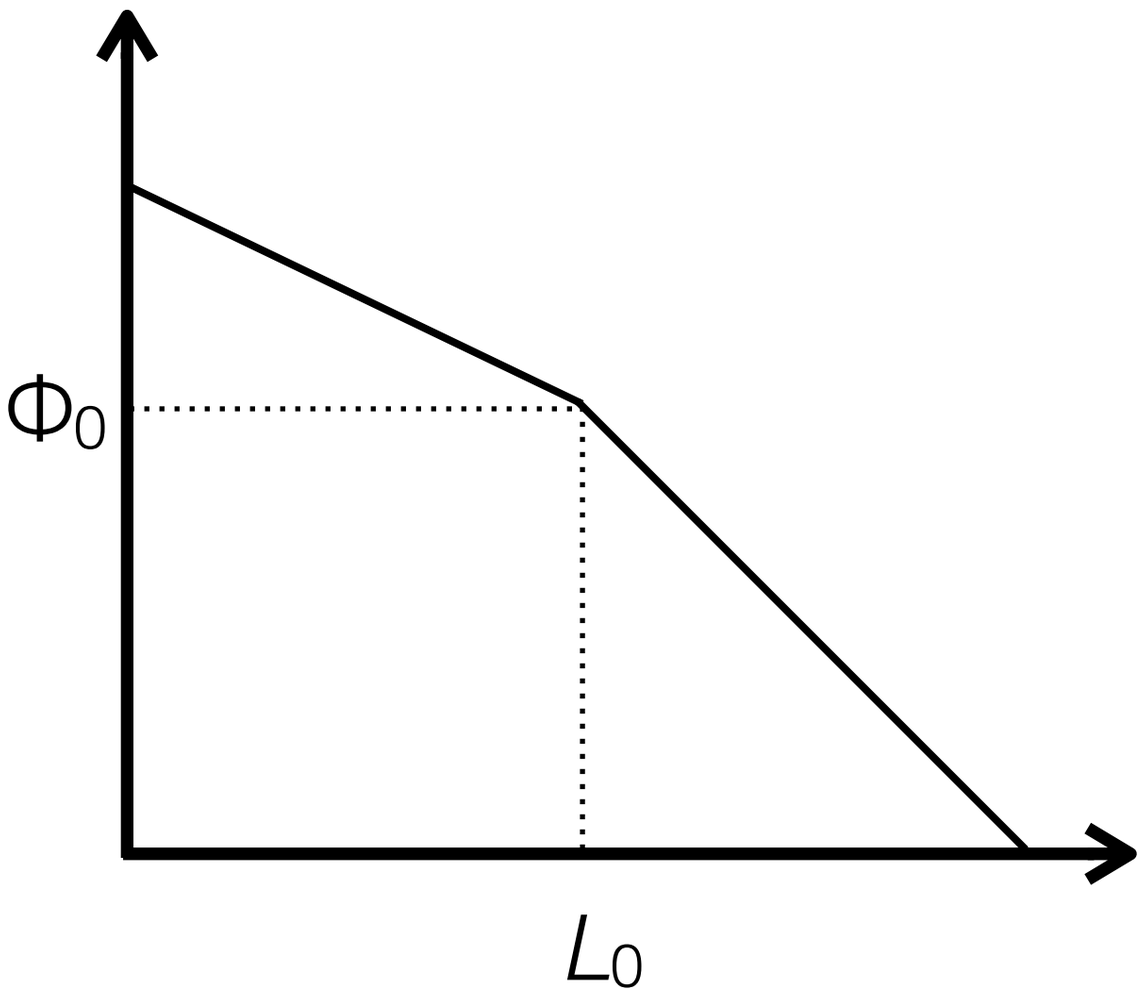
- Rule of thumb: **Poisson APS is dominated by brighter, less abundant sources**

- Blazars are a very bright, low-density gamma-ray source class, which are best studied with Fermi-LAT

- APS measurement in 2012 was well in consistent with blazar model alone (Ando et al. 2007)

- **Is this still the same for the new data? Can we learn blazar parameters?**

Gamma-ray luminosity function



- Gamma-ray luminosity function: number density of a source (i.e., blazar) per unit luminosity range $\Phi = dn/dL$

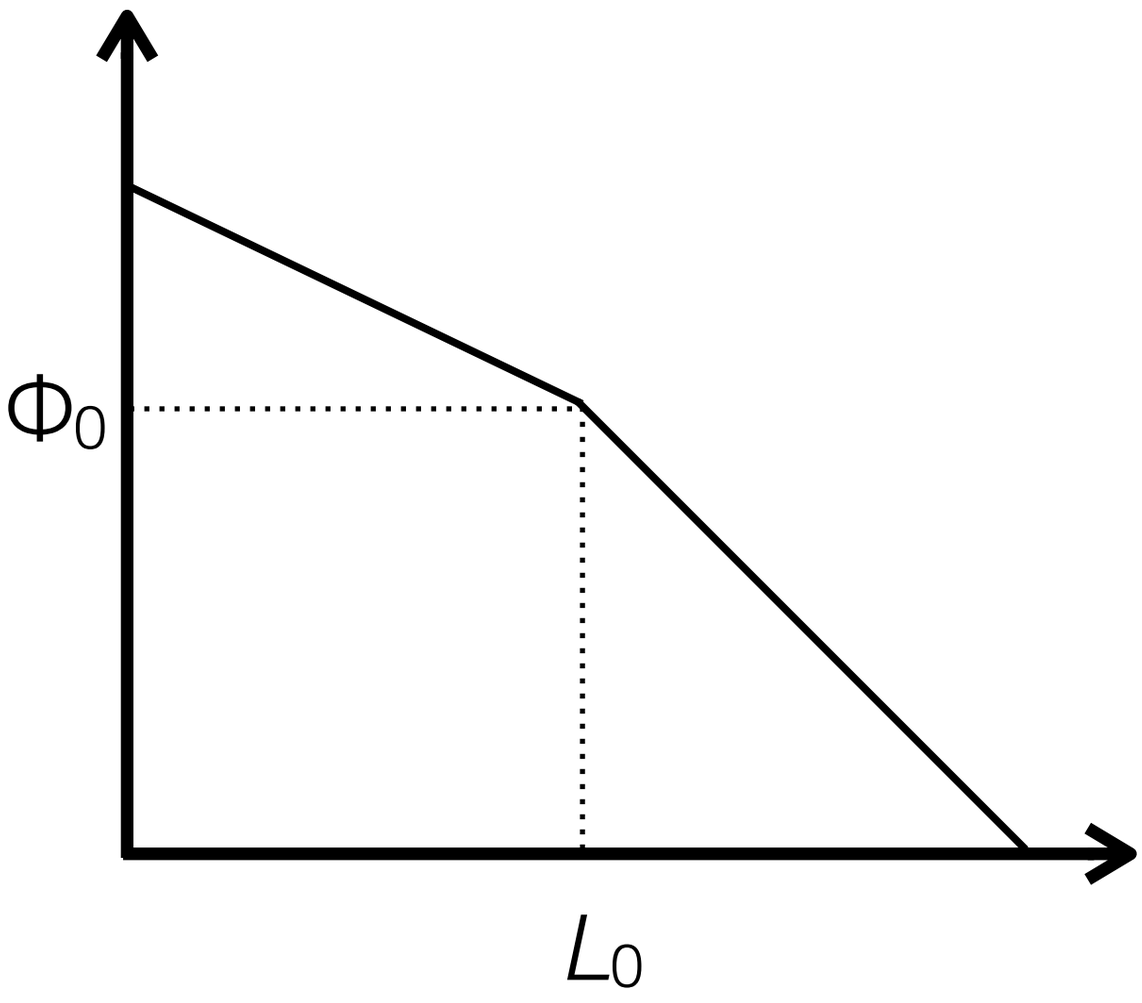
- It is typically modelled as a broken power law

- *Pure luminosity evolution (PLE)*: Only L_0 evolves with redshift z

- *Pure density evolution (PDE)*: Only Φ_0 evolves with z

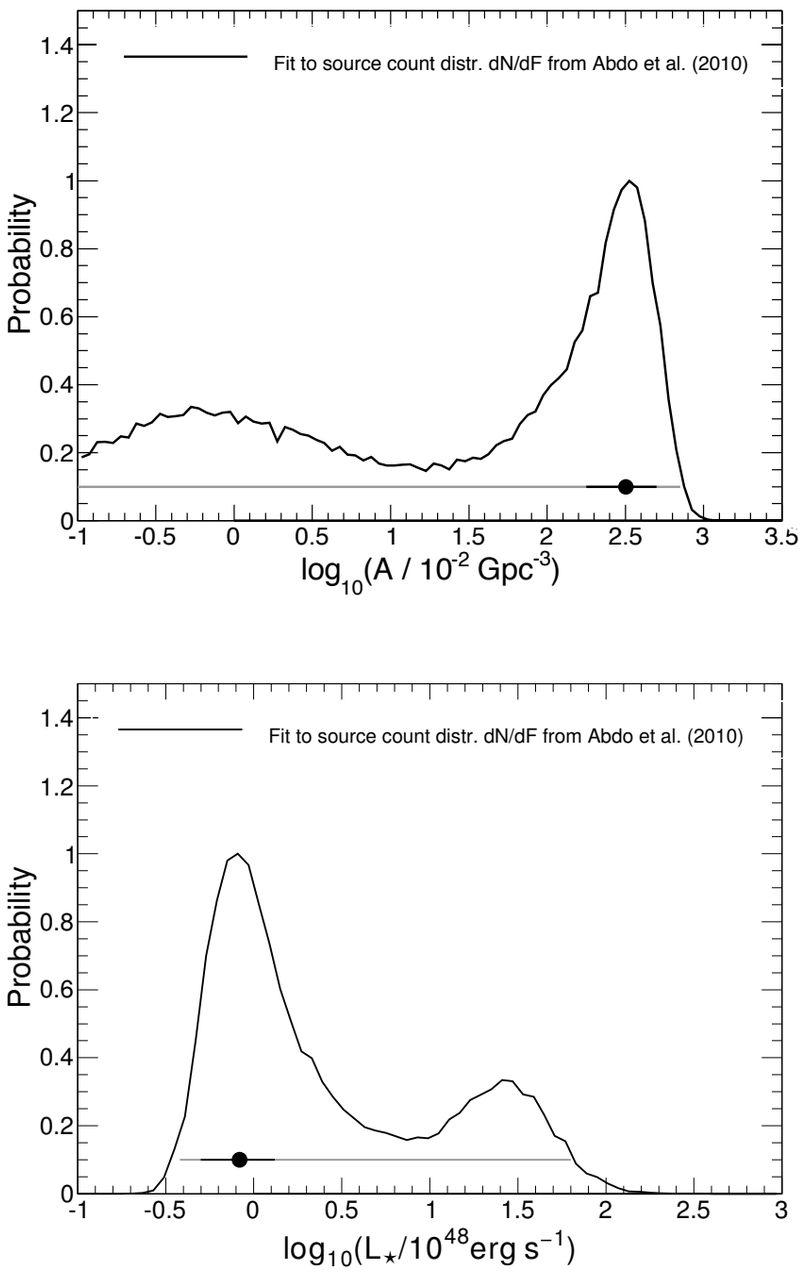
- ***Luminosity-dependent density evolution (LDDE)***: both L_0 and Φ_0 evolve with z

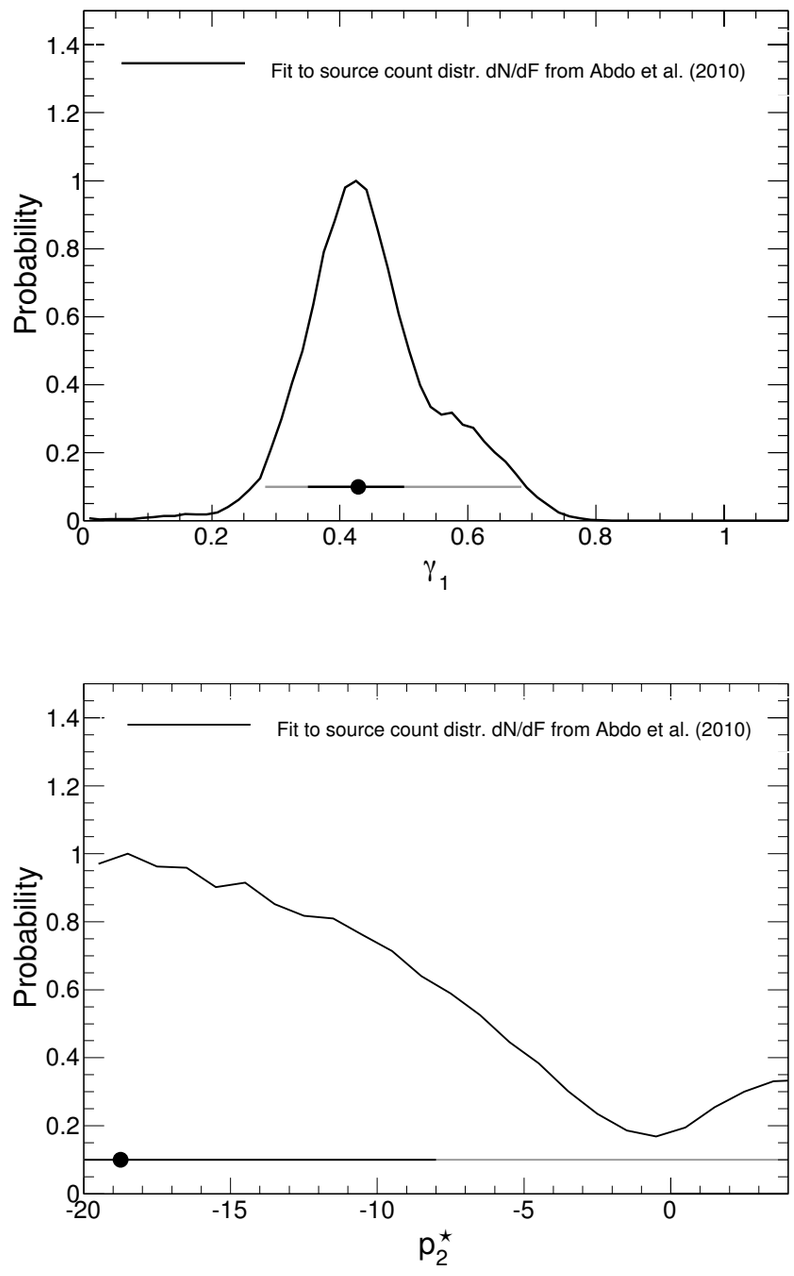
Procedure: Parameters to constrain



- Four free parameters (as from Ajello et al. 2015):
  - Overall normalization ***A***
  - Low-luminosity power-law slope γ_1
  - Break luminosity L_0 at $z = 0$
  - High-redshift power-law slope p_2^0
- Everything else is fixed to median of Ajello et al. (2015)
- Energy spectrum depends on luminosity (the less luminous, the harder); taking into account both FSRQs and BL Lacs

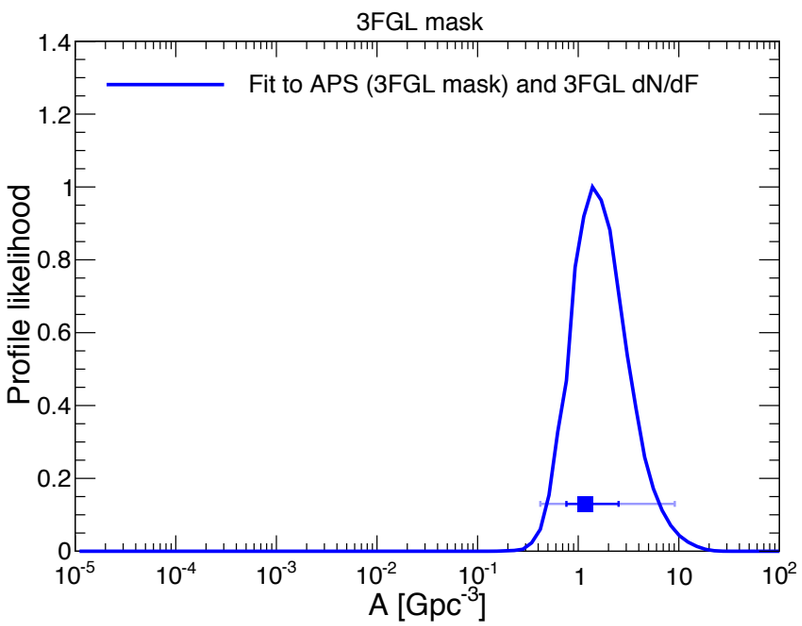
Test run: Fitting the flux distribution *dN/dF*

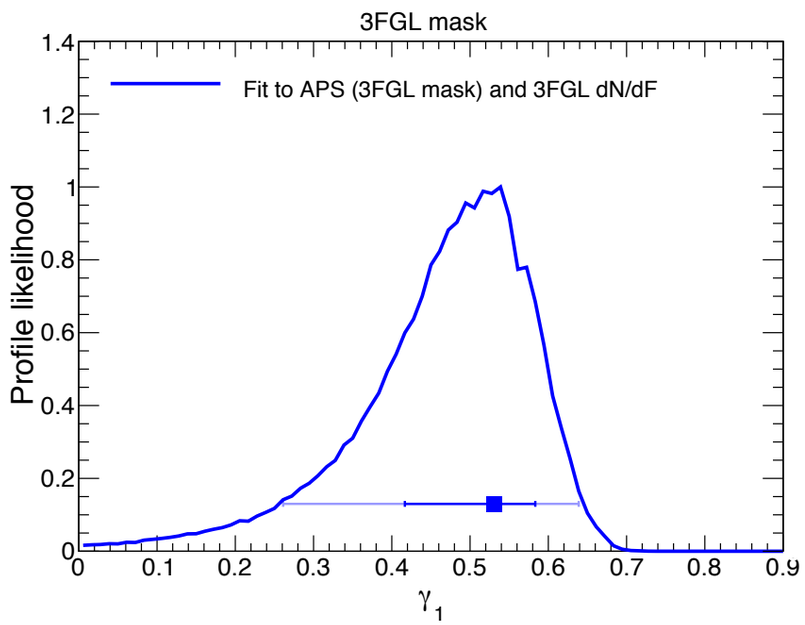


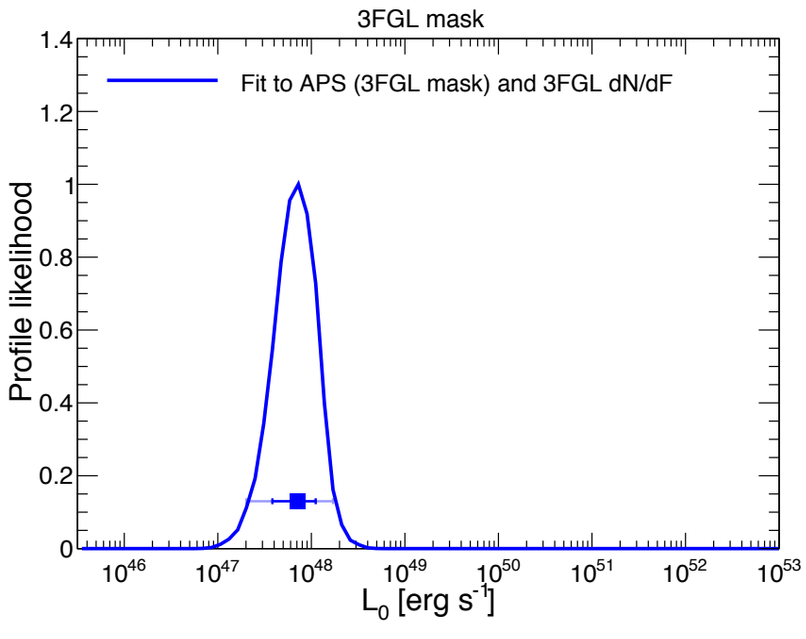


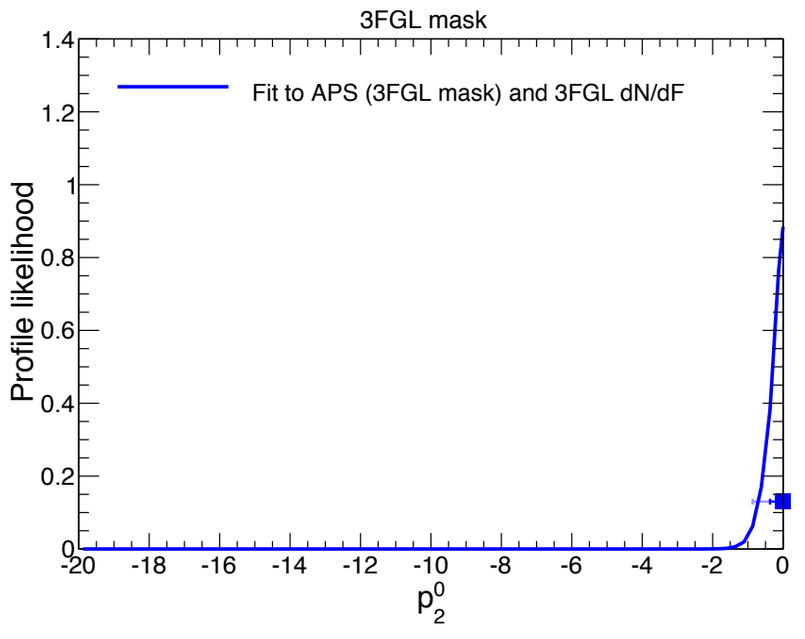
- Fitting 24 data points on *dN/dF* of all *detected* blazars in 1FGL
- Consistent with results by Ajello et al. (2015)
  - But they are weaker, as Ajello et al. (2015) fit both luminosity and redshift distributions
- Weak constraint on p_2^0
  - Cannot exclude positive evolution at high-z ($z > 1$)

Fitting both *dN/dF* and C_P







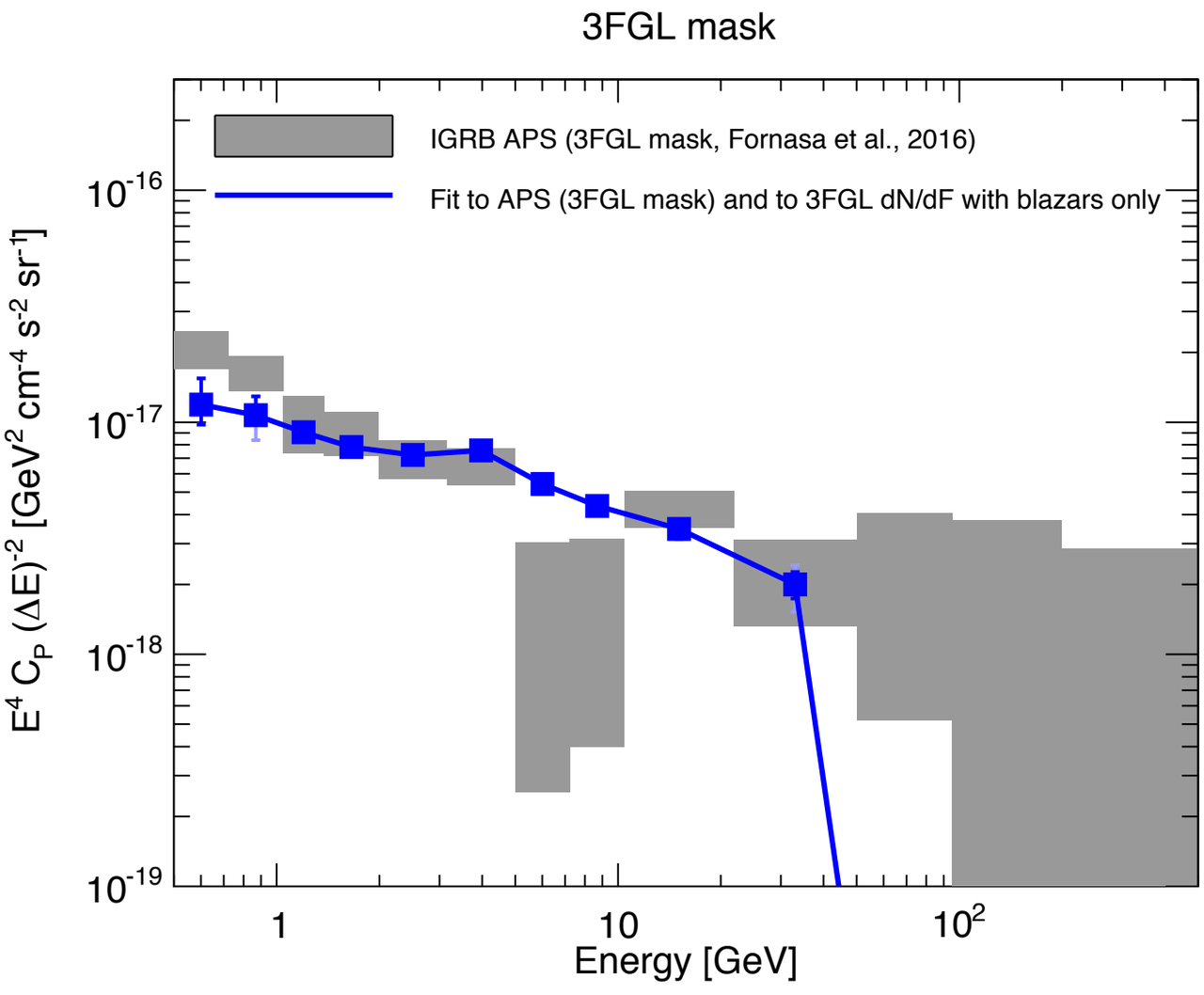


Fitting flux distributions of resolved blazars *dN/dF*, and angular power C_P of unresolved background

p_2* is clearly preferred to be positive!! (in tension with redshift distribution of blazars)

Ando, Fornasa, Fornengo, Regis, Zechlin, arXiv:1701.06988 [astro-ph.HE]

Resulting C_P and EGRB spectrum

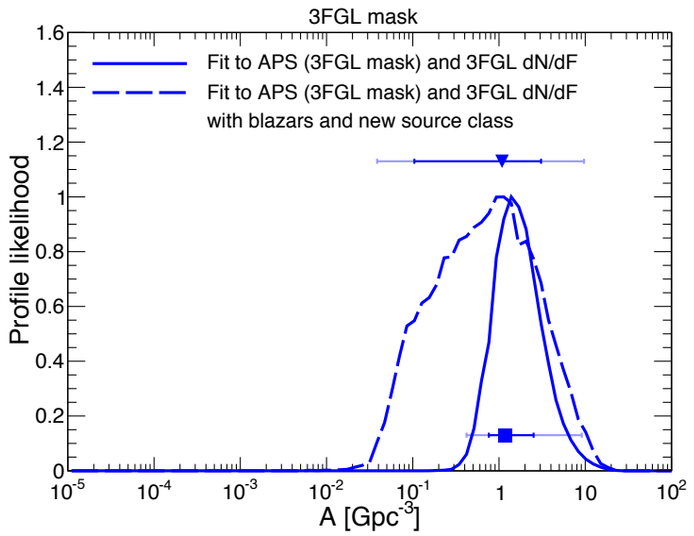


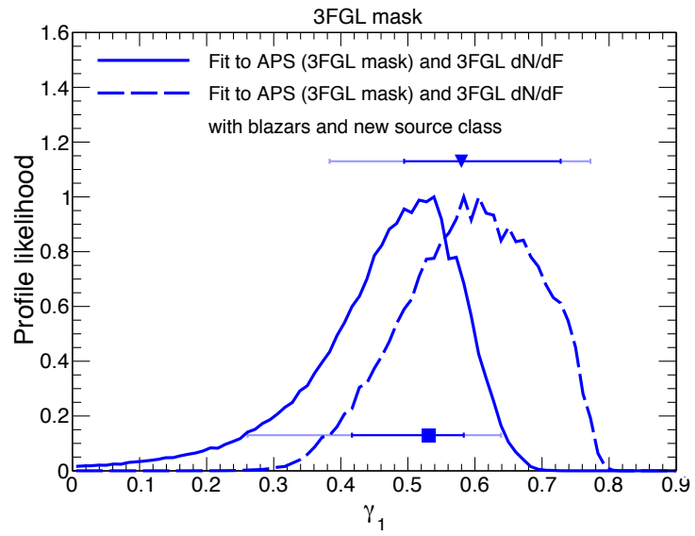
Ando, Fornasa, Fornengo, Regis, Zechlin, arXiv:1701.06988 [astro-ph.HE]

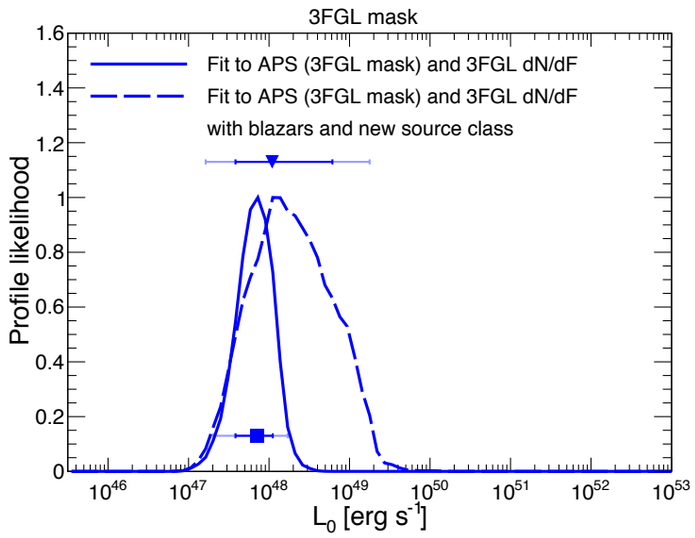
- Even the best-fit model of both *dN/dF* and C_P data does not provide good fit to C_P spectrum
  - χ^2/dof = 112.41/66 = 1.7
  - It clearly under-predicts data below 1 GeV
- ***This suggests a missing component at low-energy region (NEW!!)***

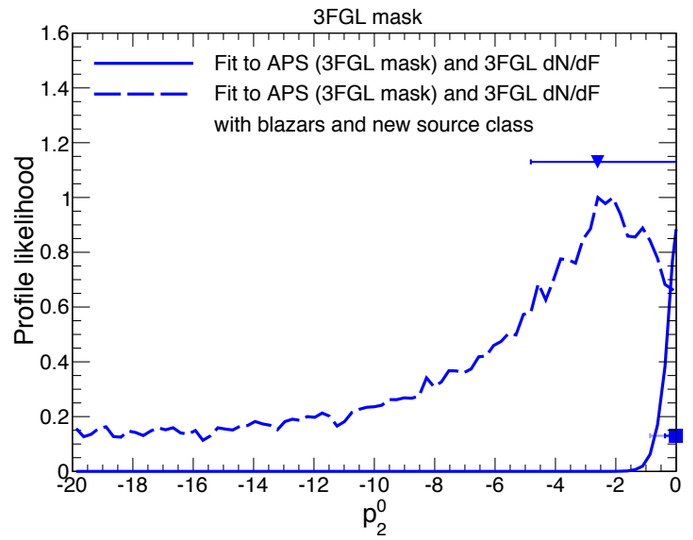
Adding a new source population

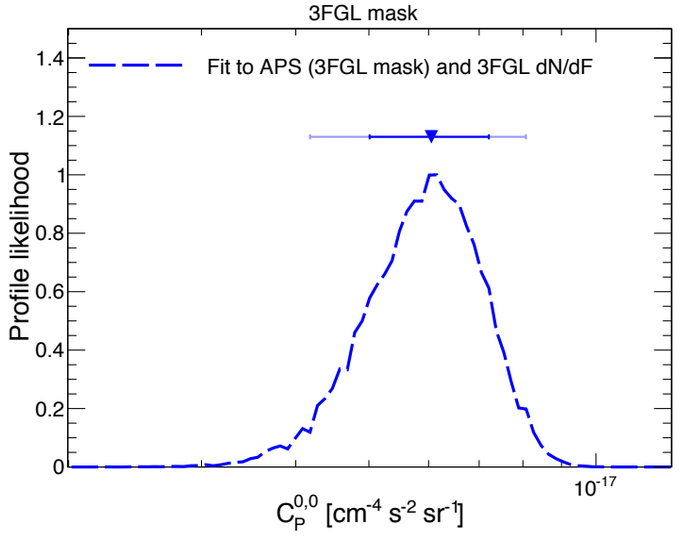
- Assume a single-power law energy spectrum
- Two additional free parameters:
  - Normalisation of C_P at the lowest energy bin
  - Spectral index Γ_{new}
- **The new source has to be soft: $\Gamma_{new} \sim 2.6–3.2$**
- Fits improve to χ^2/dof = 70.19/64 = 1.1 (*p*-value: 0.28)

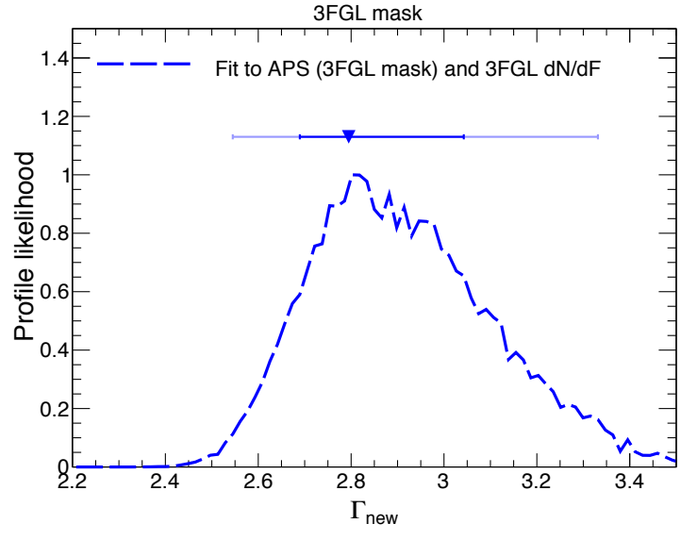






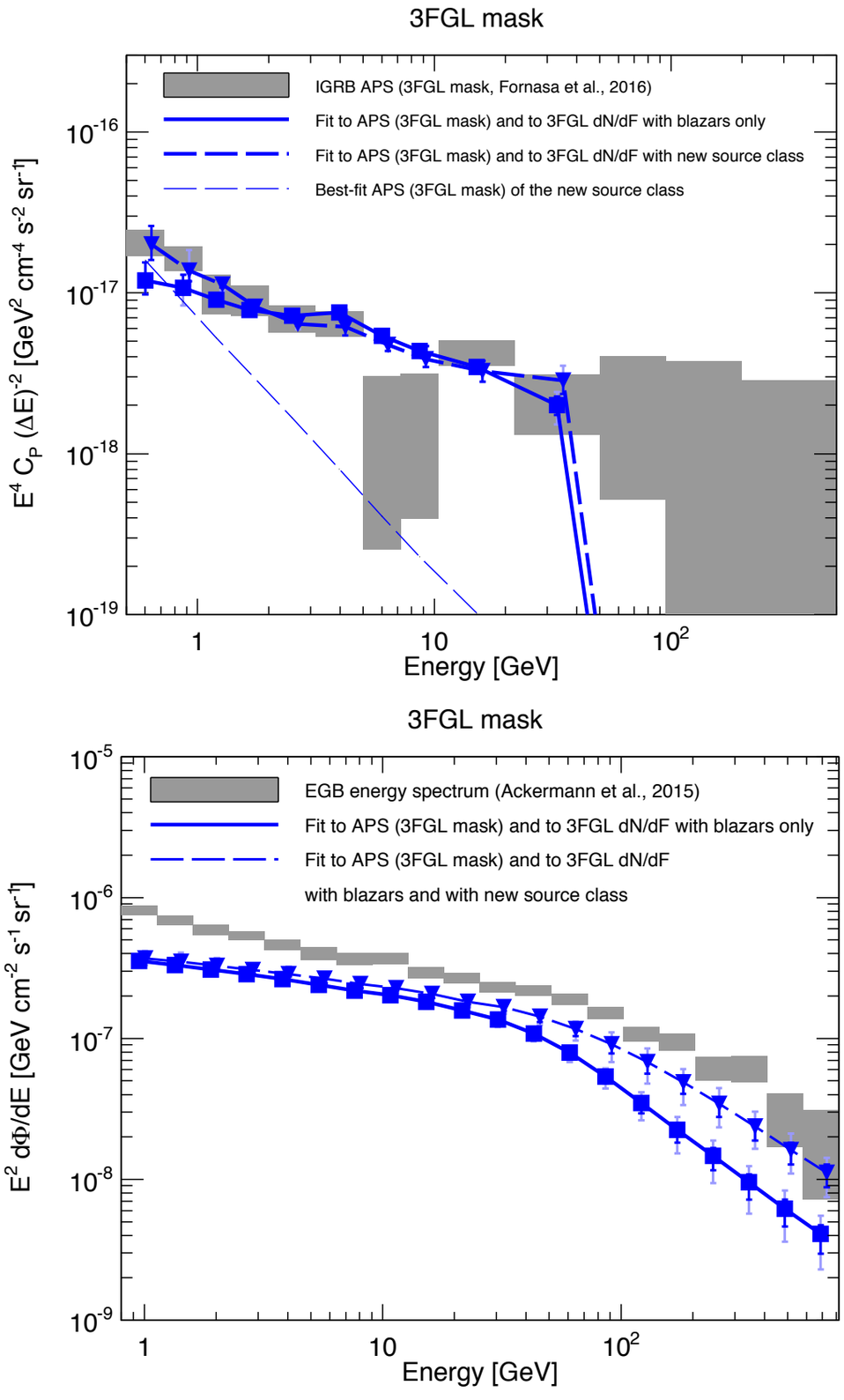






Ando, Fornasa, Fornengo, Regis, Zechlin, arXiv:1701.06988 [astro-ph.HE]

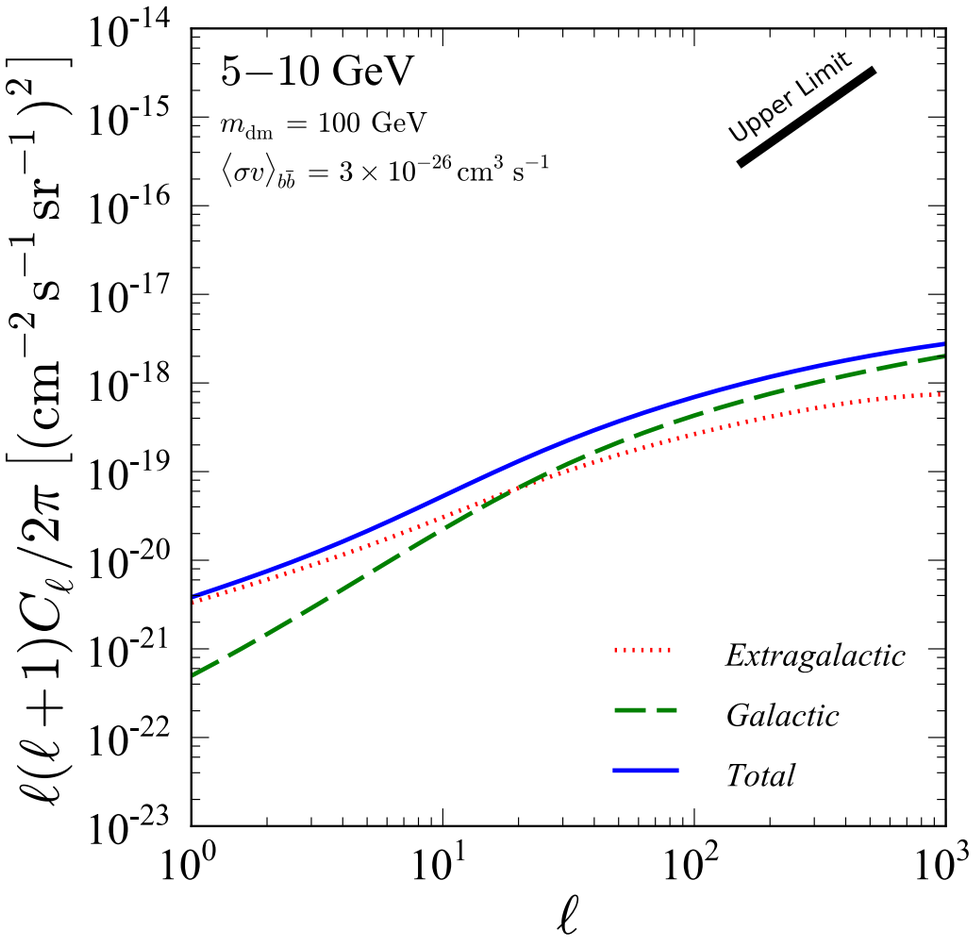
What are the sources? Star-forming galaxies?



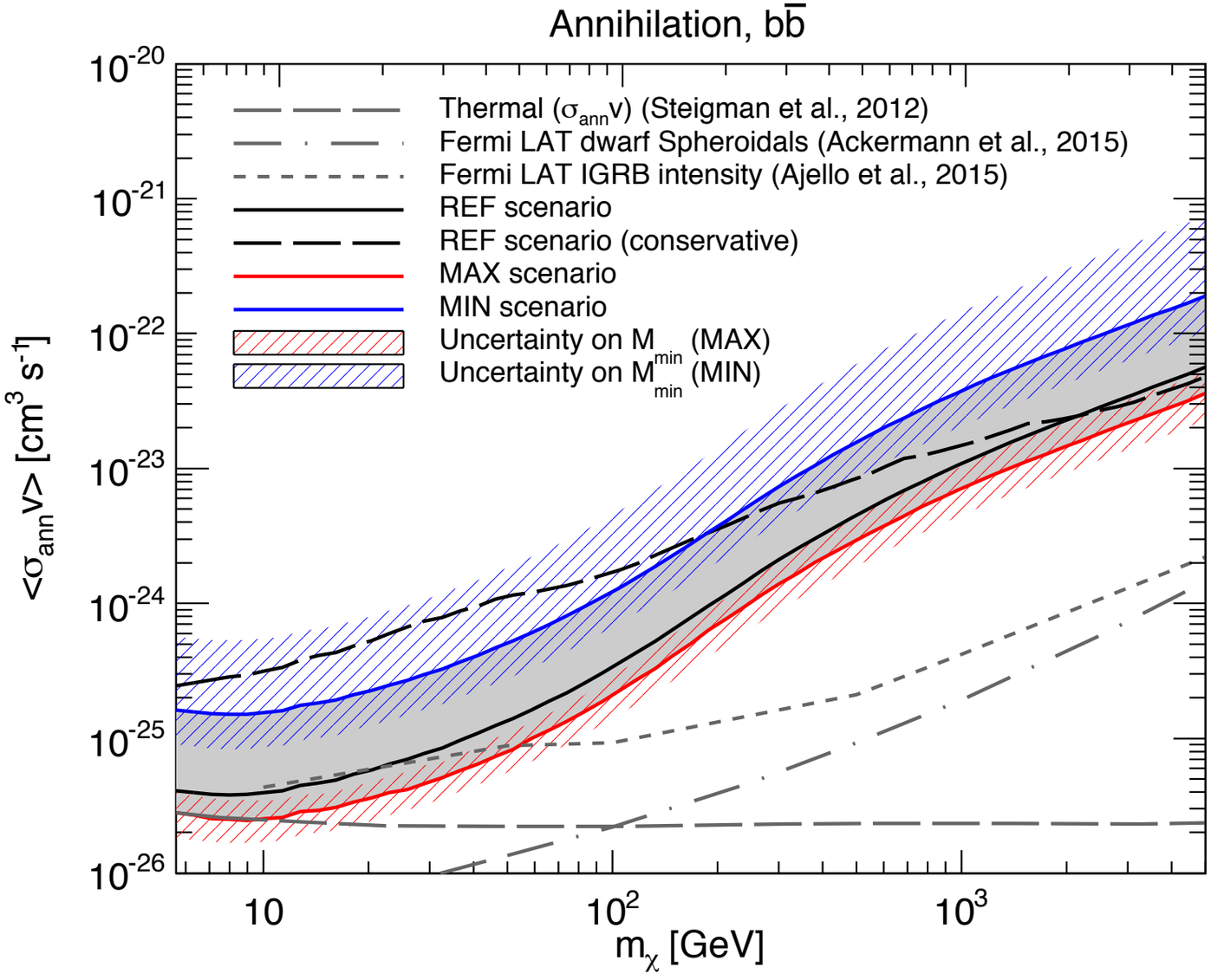
- There are other known populations that contribute to EGRB
  - Star-forming galaxies
  - Radio galaxies (misaligned AGNs)
- Soft spectrum ($E^{-2.8}$) suggests towards the former
- But C_P must be significantly smaller (by about 3 orders of magnitude; e.g., Ando & Pavlidou 2009, Tamborra et al. 2014)
- The population might be related to Fermi unassociated sources

Ando, Fornasa, Fornengo, Regis, Zechlin, arXiv:1701.06988 [astro-ph.HE]

Upper limits on the annihilation cross section



Ando, Komatsu, *Phys. Rev. D* **87**, 123539 (2013)



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

- Analysis including shot-noise components and dark matter
- Limits on annihilation cross section are comparable to spectral analysis at small masses

What can we learn from the gamma-ray background?

✓ **Energy**

- Intensity spectrum (Bergstrom et al. 1998)

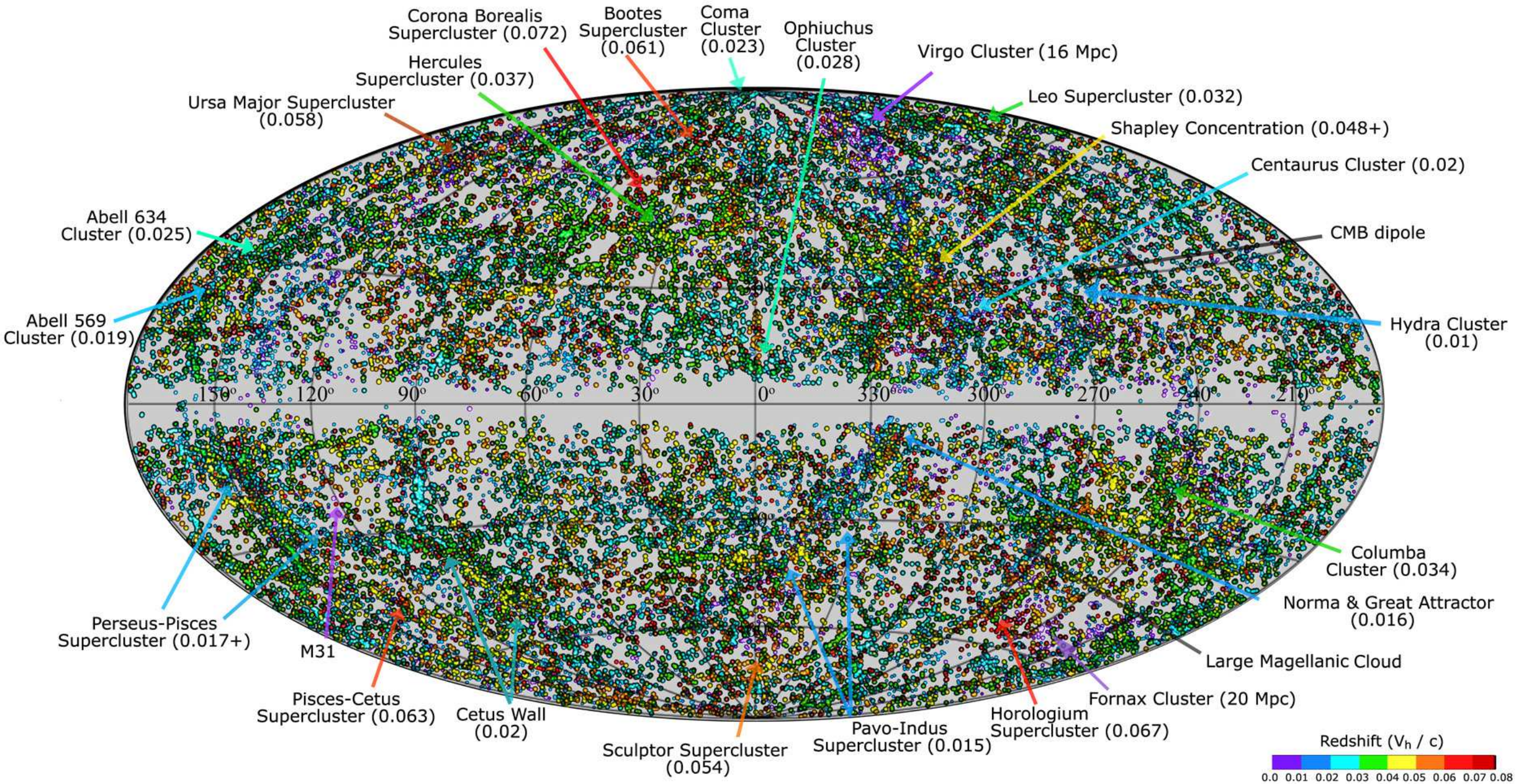
✓ **Spatial clustering of sources**

- Angular power spectrum (Ando & Komatsu 2006)

- **Redshift distribution of sources** → *tomography*
  - Cross correlation with dark matter tracers (Cosmic shear: Camera et al. 2013; Galaxy catalogs: Ando, Benoit-Lévy & Komatsu 2014)

- **Luminosity distribution of sources**
  - 1-point PDF of the gamma-ray flux (Lee, Ando & Kamionkowski 2009)

Cross correlation with galaxy catalogs

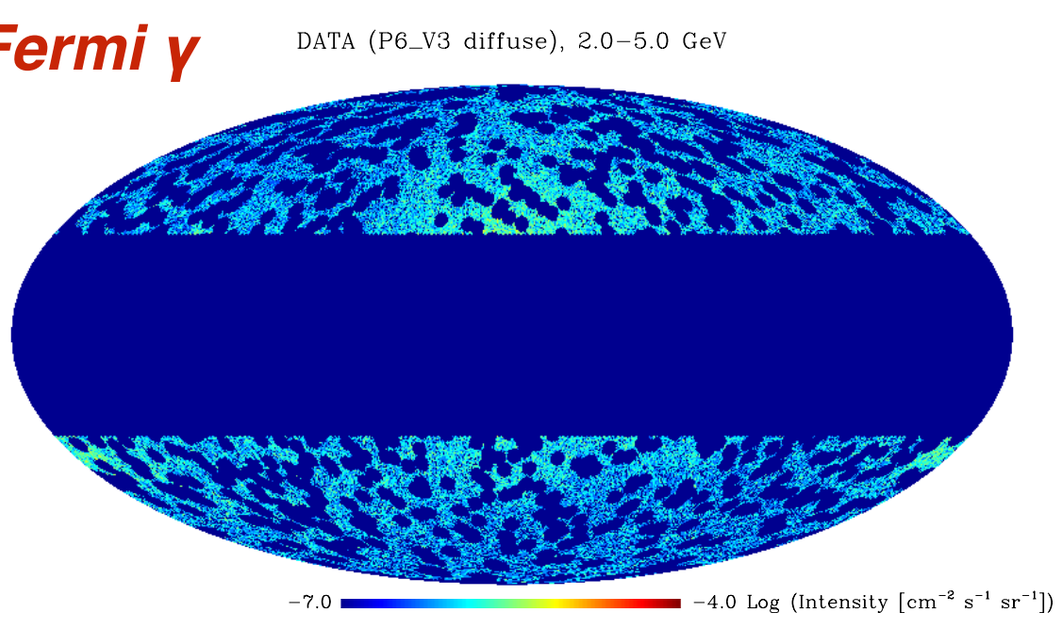


Huchra et al., *Astrophys. J. Suppl. Ser.* **199**, 26 (2011)

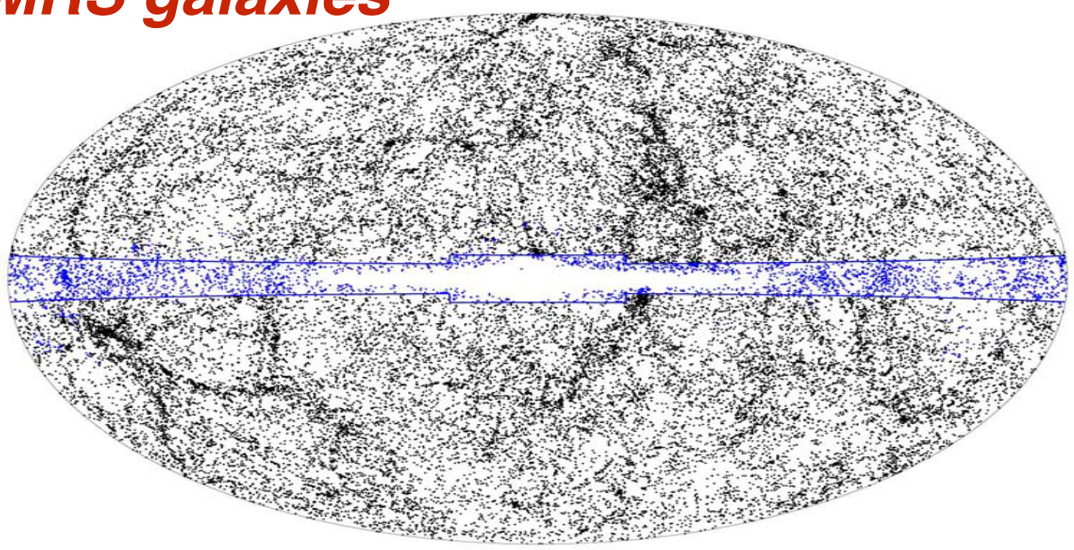
2MASS Redshift Survey; ***43000 galaxies up to z ~ 0.1***

Gamma-ray background tomography

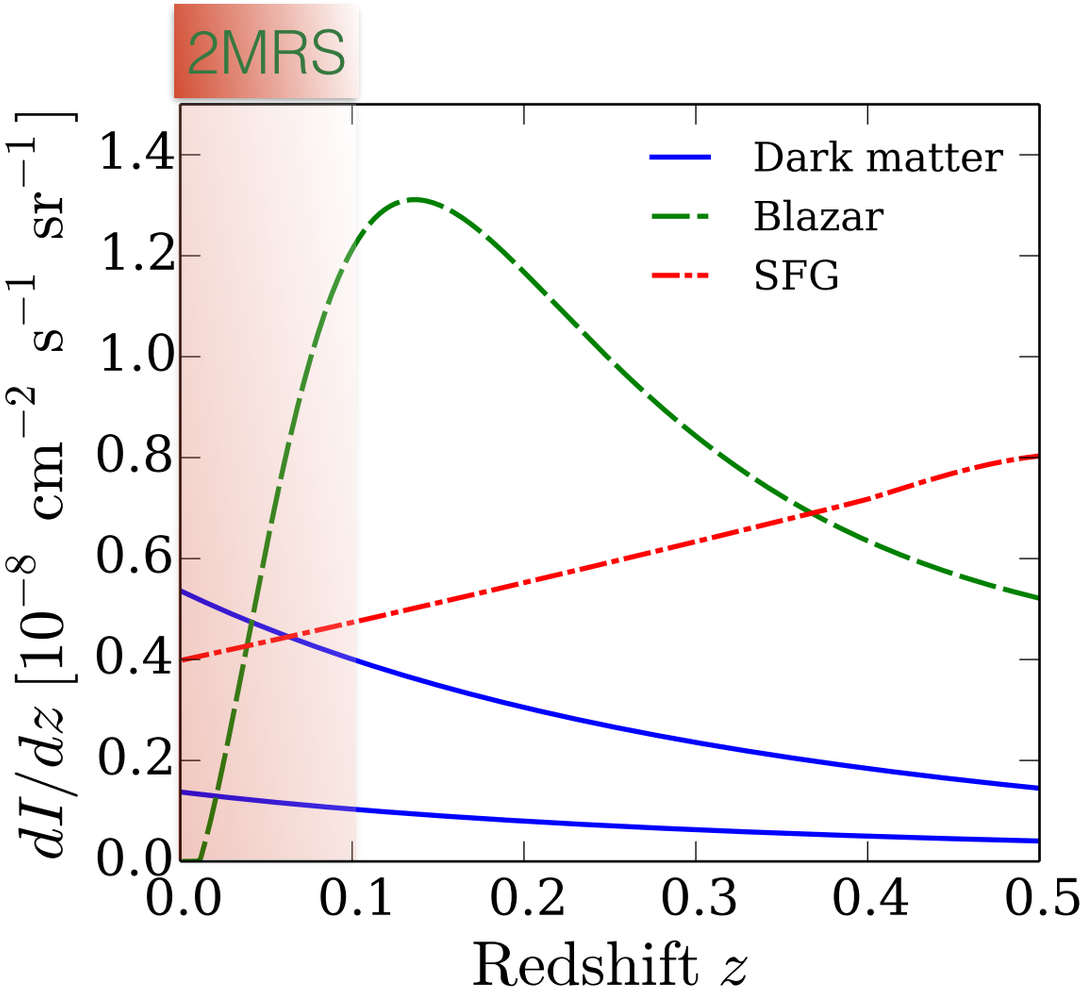
Fermi γ



2MRS galaxies



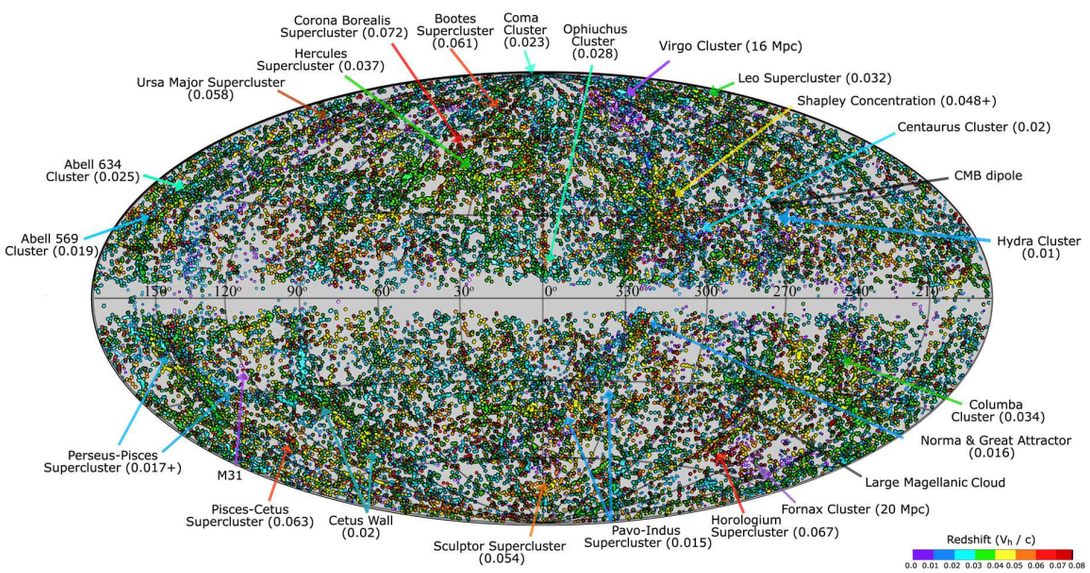
- Both γ and galaxies trace large-scale structure
- Two maps should resemble each other
- They don't, at least by eye.



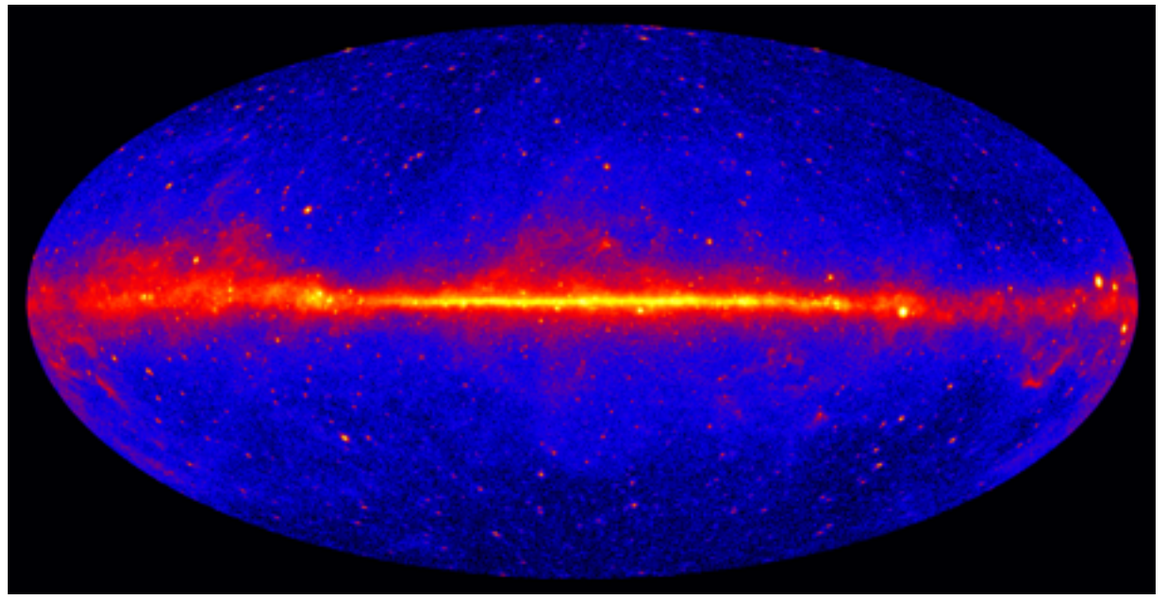
- ***DM contribution is relatively more important at z < 0.1***

- Cross-correlating with 2MRS galaxies will single out this redshift region!

Cross correlation with galaxy catalogs



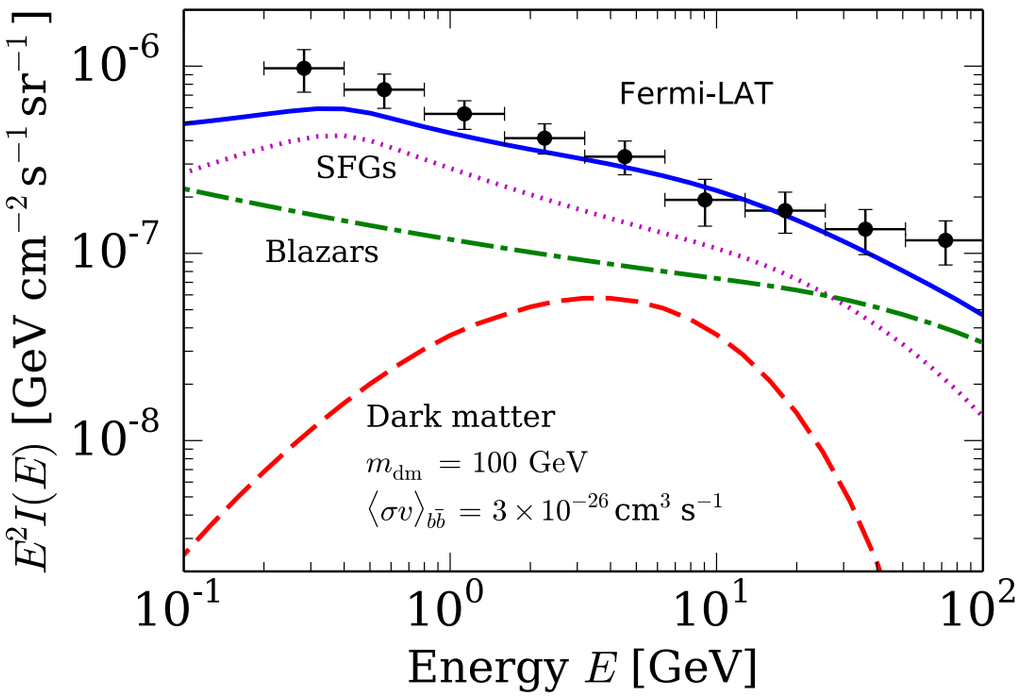
×



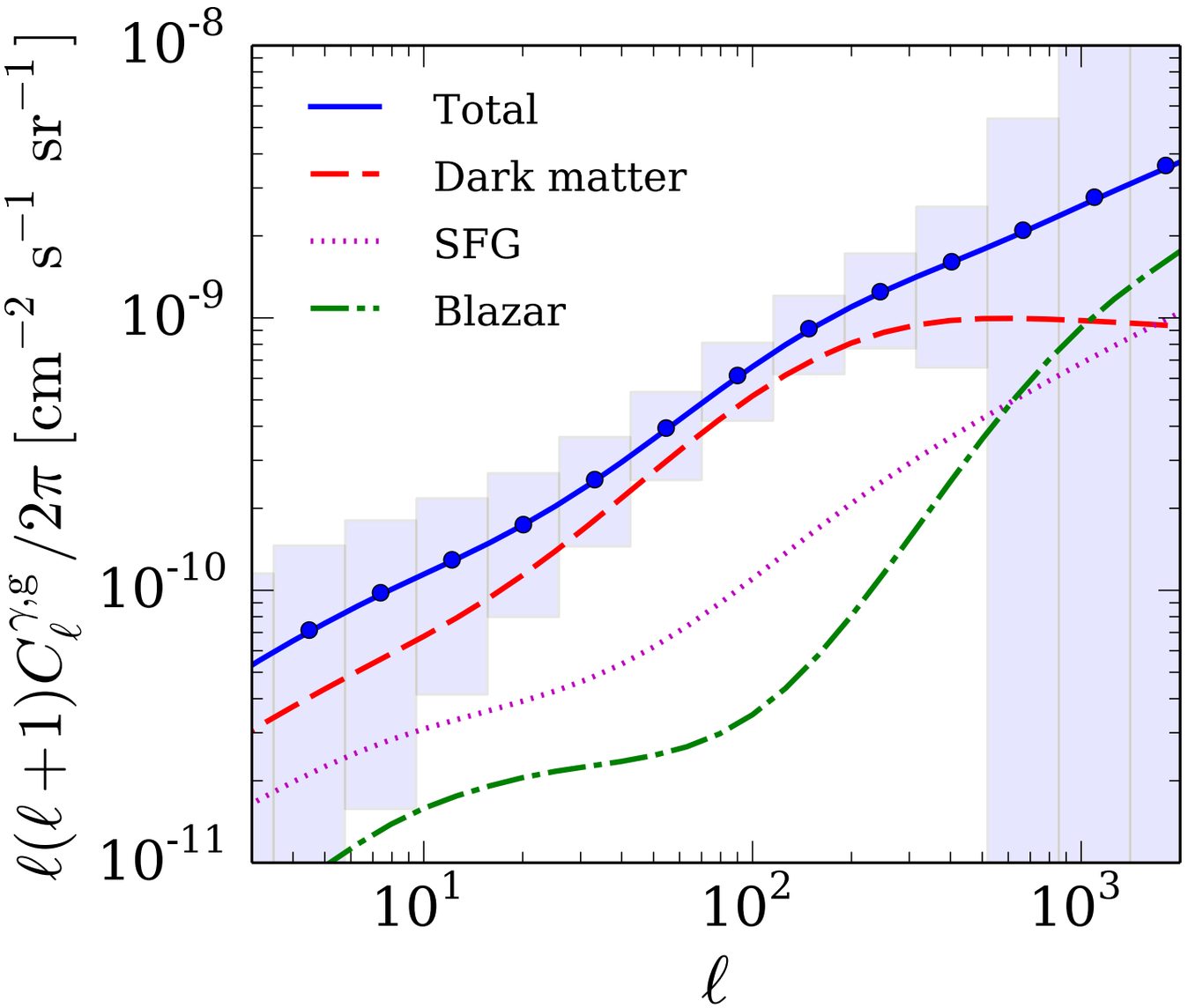
$$C_\ell^{\mathrm{DM,gal}} = \int \frac{d\chi}{\chi^2} W_{\mathrm{DM}}(\chi) W_{\mathrm{gal}}(\chi) P_{\delta^2,\mathrm{gal}}\left(k = \frac{\ell}{\chi}, \chi\right)$$

$$C_\ell^{\mathrm{astro,gal}} = \int \frac{d\chi}{\chi^2} W_{\mathrm{astro}}(\chi) W_{\mathrm{gal}}(\chi) P_{\delta,\mathrm{gal}}\left(k = \frac{\ell}{\chi}, \chi\right)$$

2MRS-gamma correlation



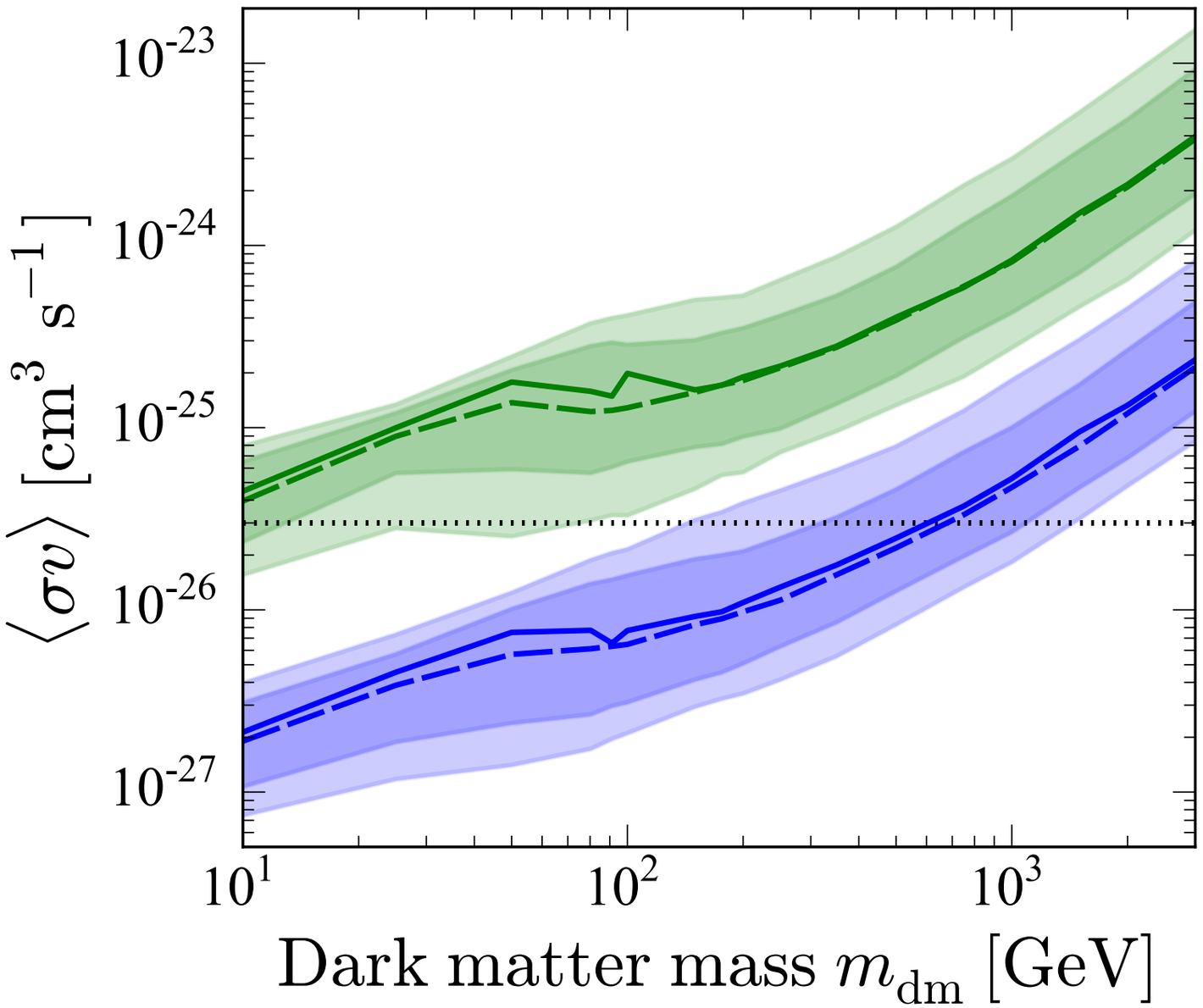
- **DM annihilation** shows **the largest correlation** with 2MRS galaxies
- Sensitivity is very good in order to exclude canonical cross section for thermal freeze-out mechanism



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

Fornengo, Regis, *Front. Phys.* **2**, 6 (2014)

Cross correlation: 5-year sensitivity

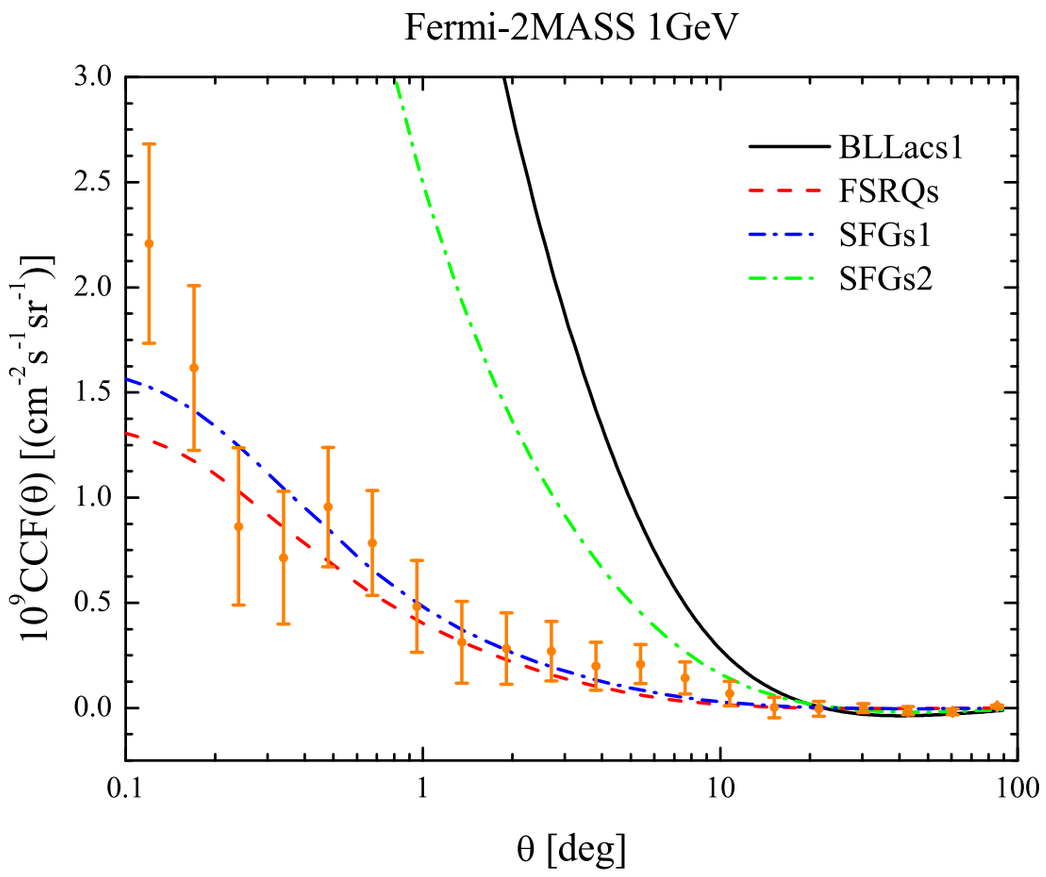


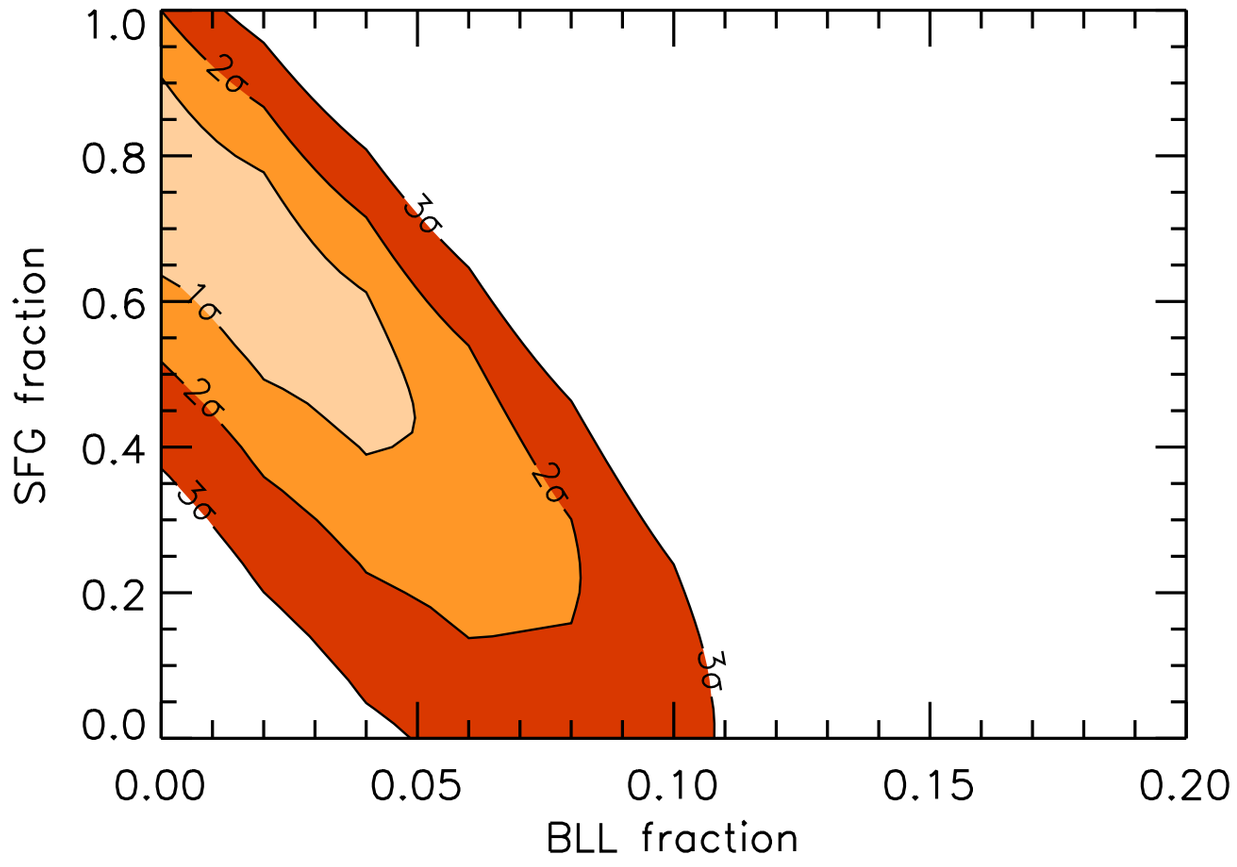
- Very powerful probe of DM
- Uncertainty regarding substructure boost is about one order of magnitude (Sanchez-Conde & Prada 2014 vs Gao et al. 2012)

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

Observations: Cross correlation with 2MASS galaxies

Xia et al., *Astrophys. J. Suppl. Ser.* **217**, 15 (2015)



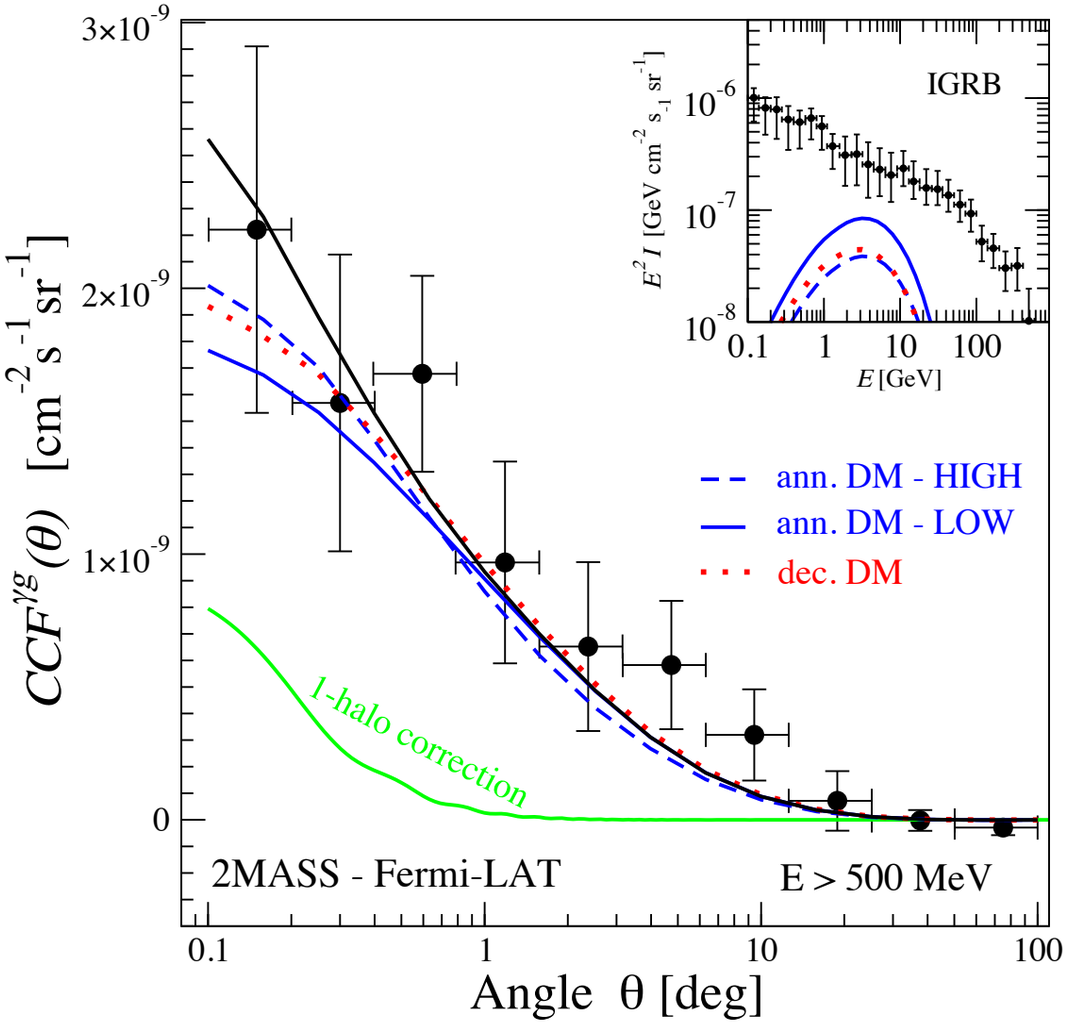


- Positive correlations with several catalogs (>3.5σ for 2MASS, NVSS, SDSS-QSO; >3σ for SDSS galaxies)

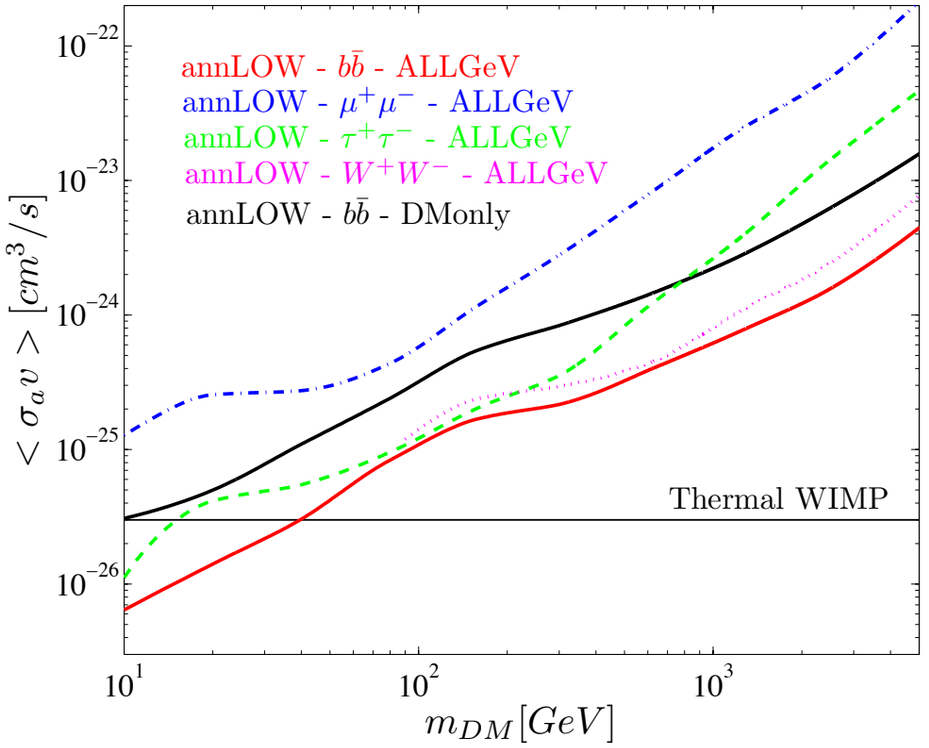
- Constraints on astrophysical components to the diffuse background (70% star-forming galaxies; blazars are subdominant)

Cross correlation with 2MASS: DM constraints

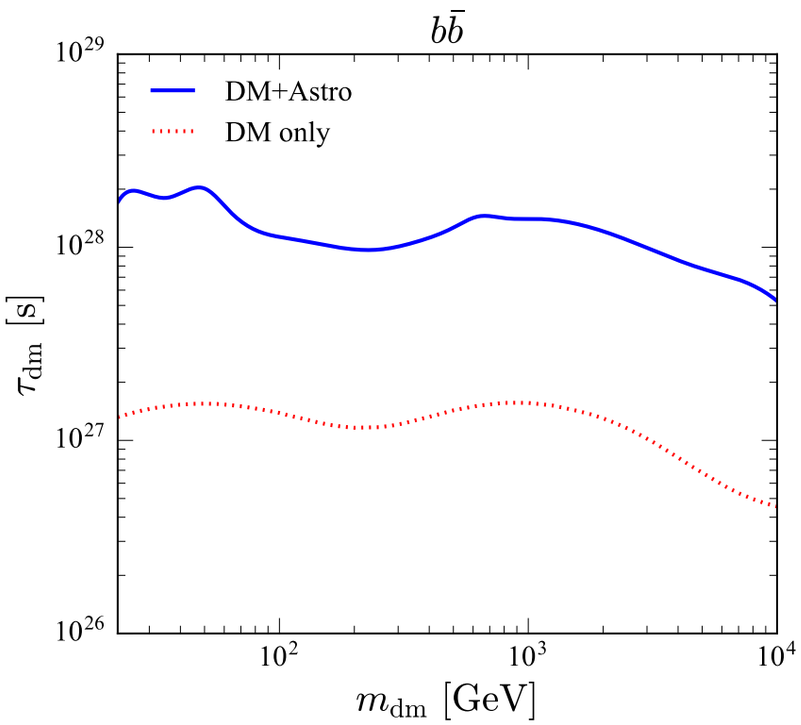
Regis et al., *Phys. Rev. Lett.* **113**, 241301 (2015)



- Very competitive bounds even in the DM only case

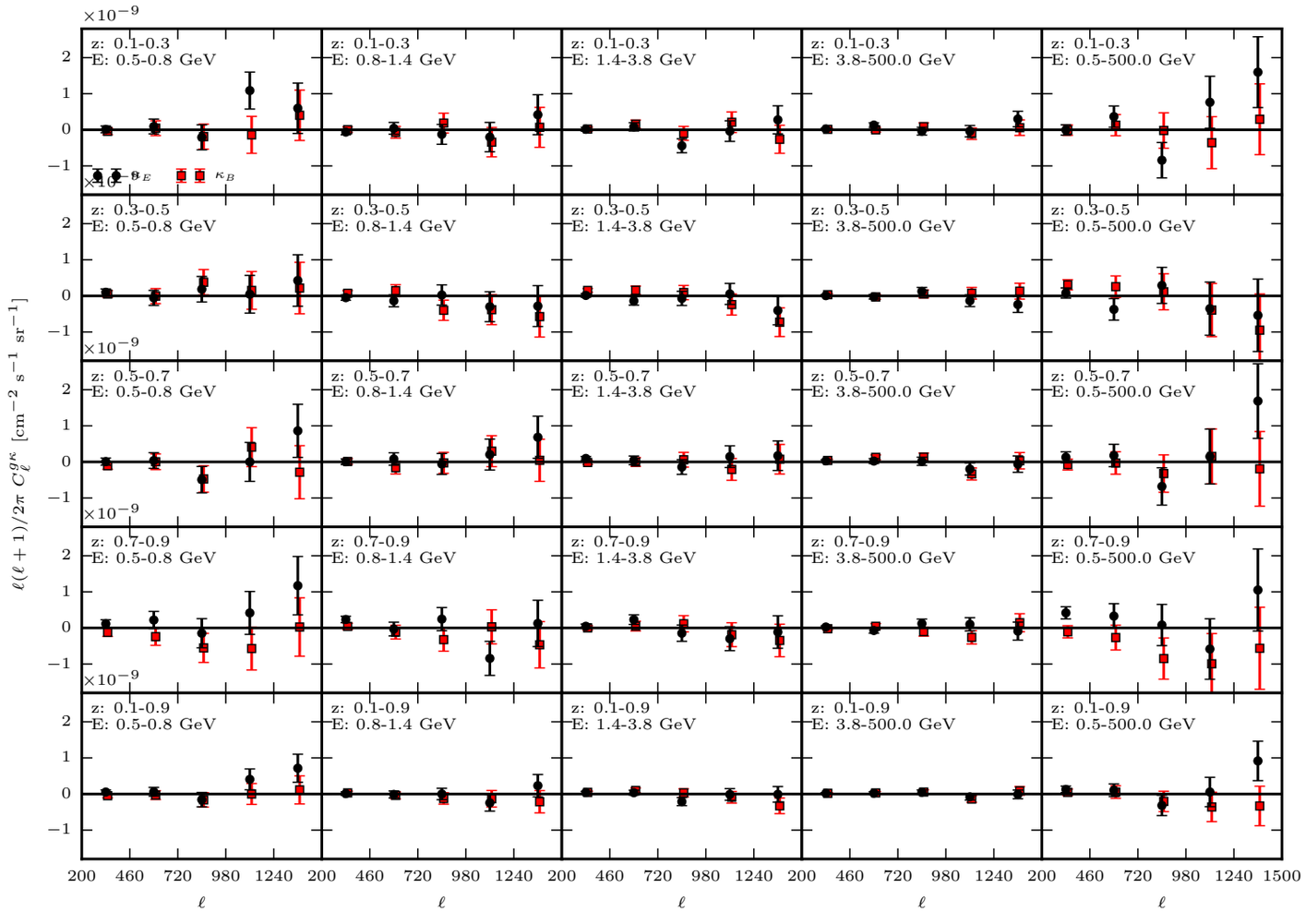


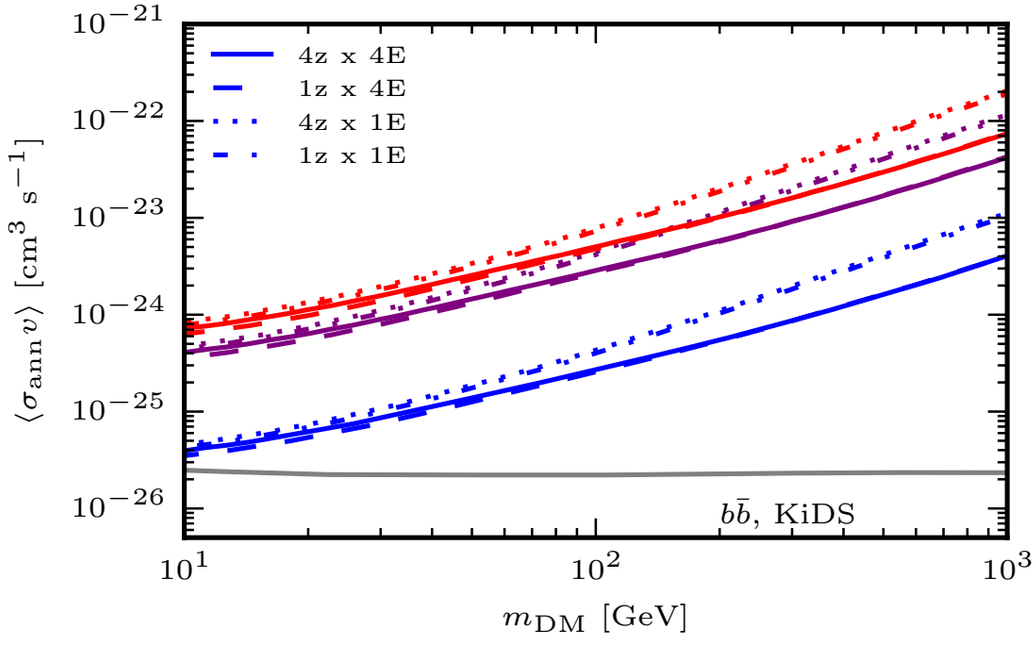
Cuoco et al., *Astrophys. J. Suppl. Ser.* **221**, 29 (2015)



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

Cross correlation with weak lensing data





Troster et al., arXiv:1611.03554 [astro-ph.CO]

- CFHTLenS/RCSLenS/KiDS
- No excess found

What can we learn from the gamma-ray background?

✓ **Energy**

- Intensity spectrum (Bergstrom et al. 1998)

✓ **Spatial clustering of sources**

- Angular power spectrum (Ando & Komatsu 2006)

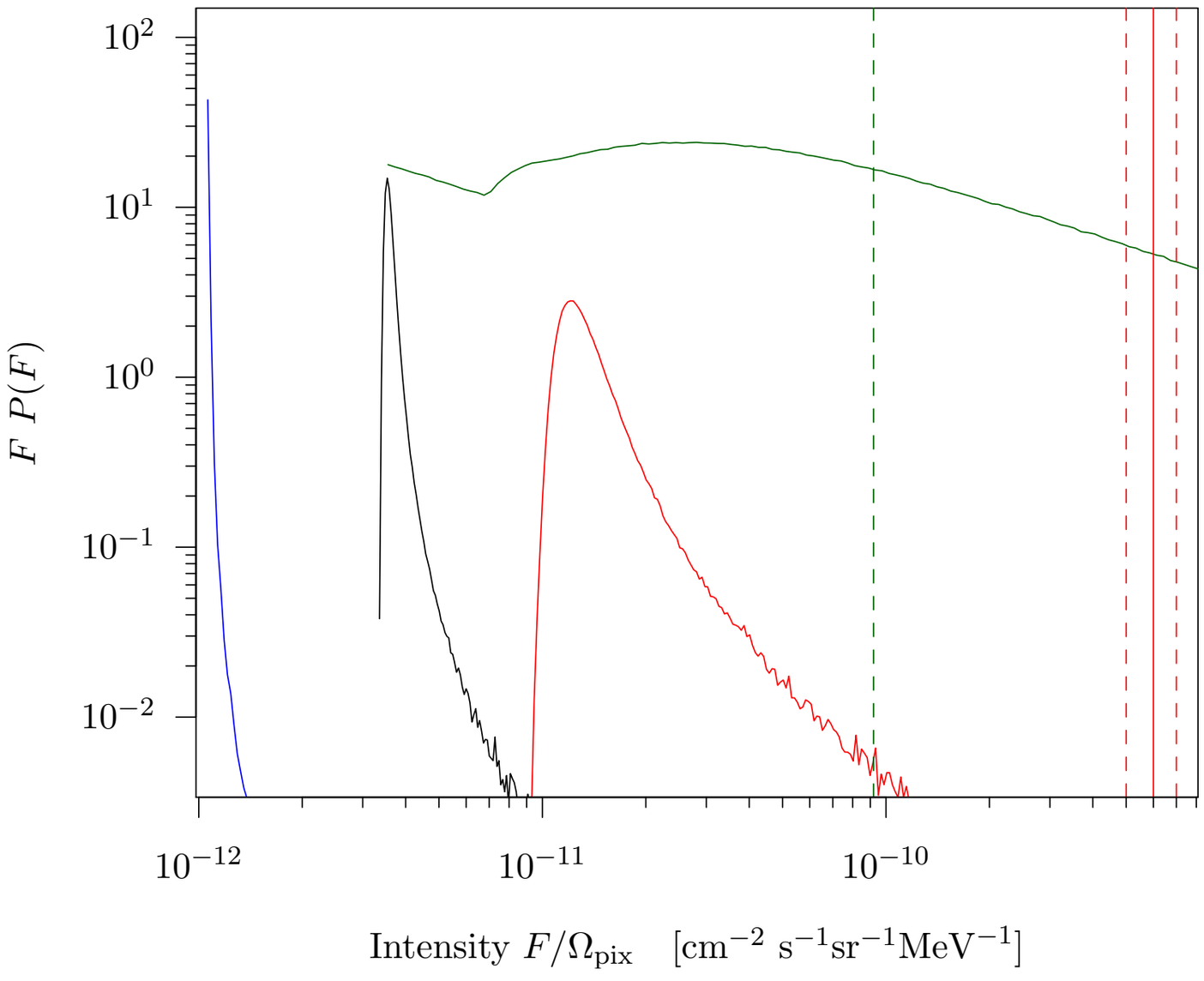
✓ **Redshift distribution of sources** → *tomography*

- Cross correlation with dark matter tracers (Cosmic shear: Camera et al. 2013; Galaxy catalogs: Ando, Benoit-Lévy & Komatsu 2014)

- **Luminosity distribution of sources**

- 1-point PDF of the gamma-ray flux (Lee, Ando & Kamionkowski 2009)

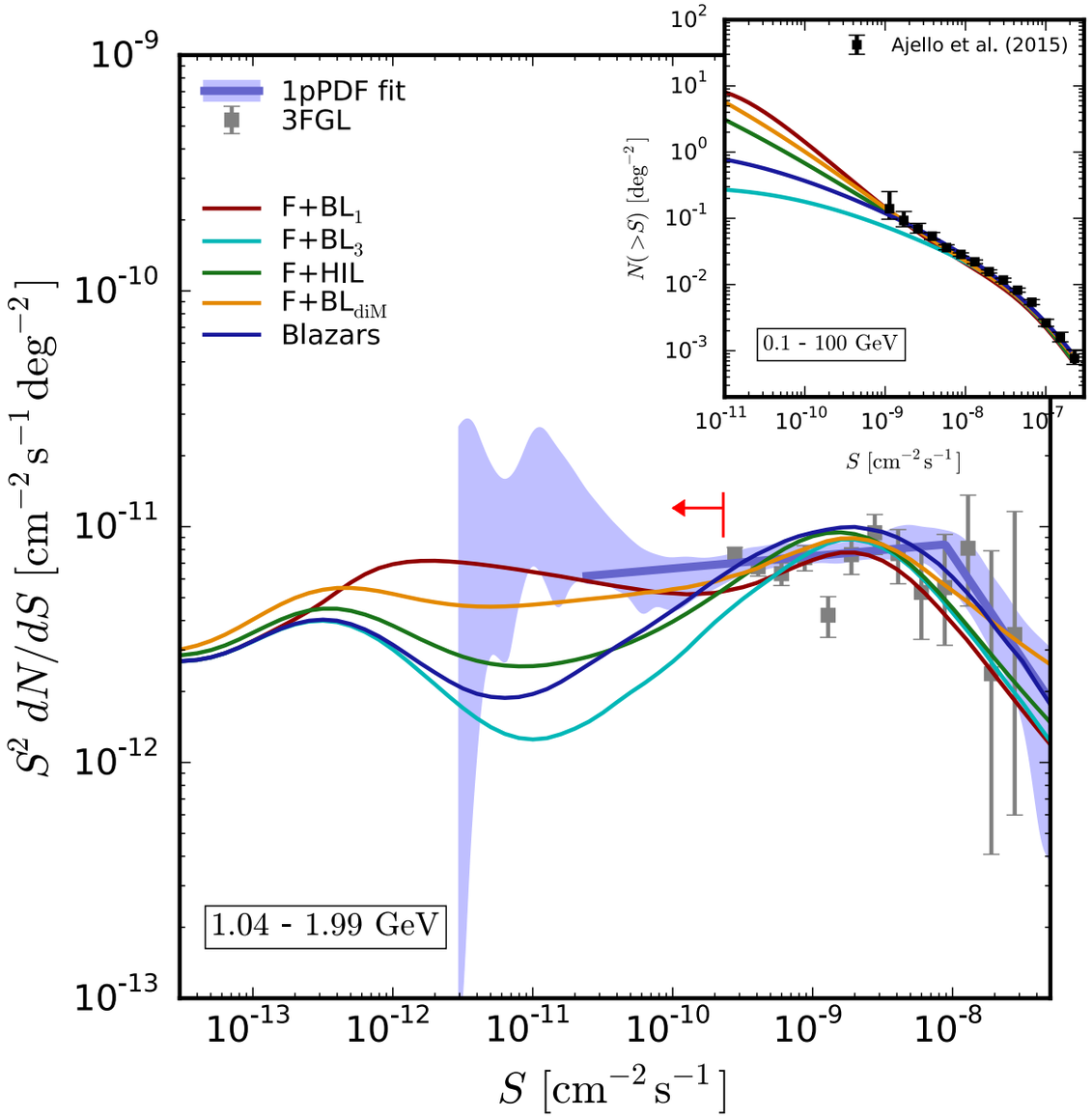
Flux PDF: Probe of luminosity distribution



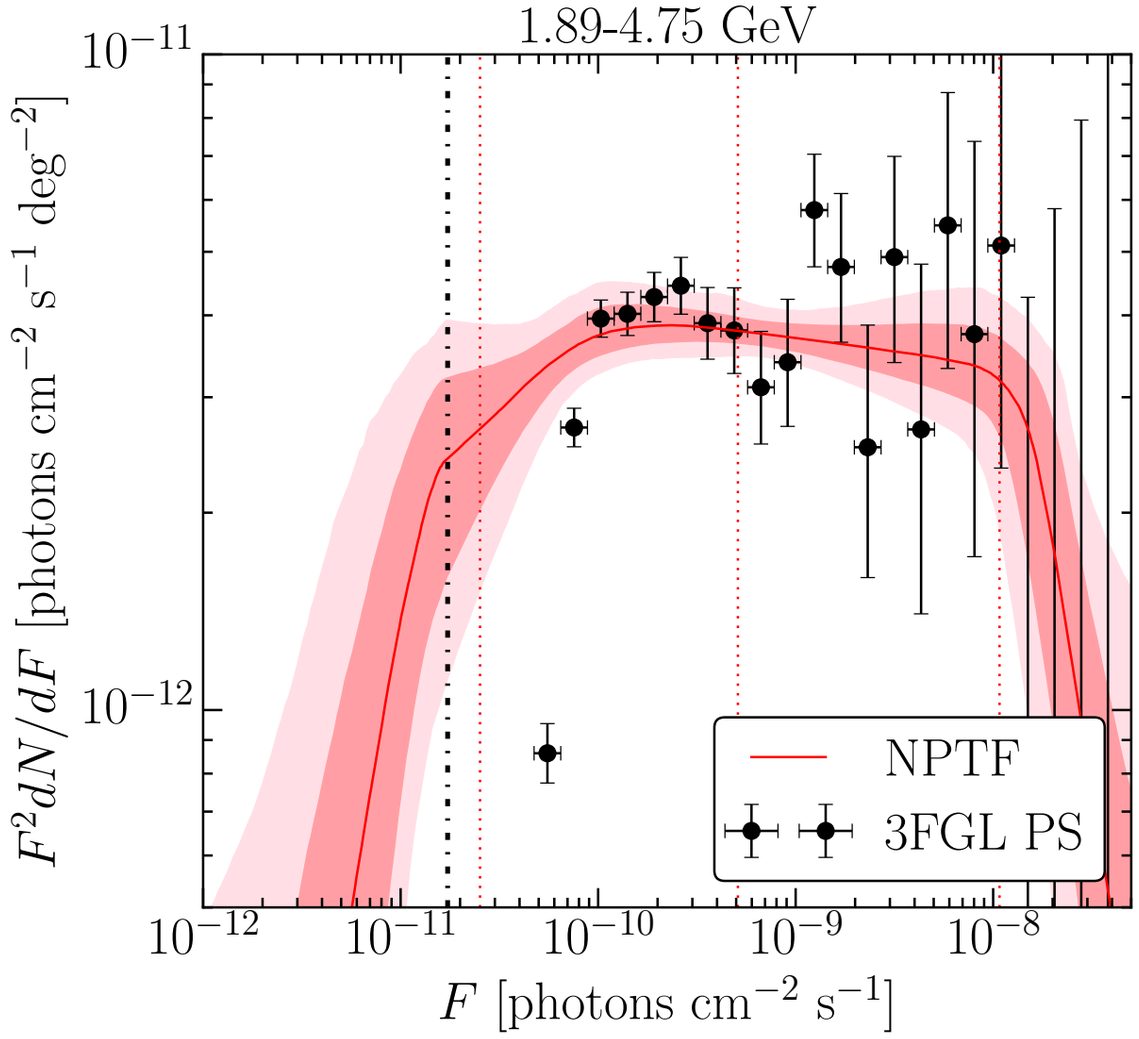
Feyereisen, Ando, Lee, *JCAP* **1509**, 027 (2015)

- Probability distribution function (PDF) of gamma-ray flux is a probe of luminosity function
- If the source is truly diffuse, then it is a delta function
- PDF for most astrophysical sources is power-law like
- Dark matter PDF is a Gaussian plus power-law tail
- Another diagnosis for dark matter

Analysis work of 1pPDF



Zechlin et al., *Astrophys. J.* **826**, L31 (2016)



Lisanti et al., *Astrophys. J.* **832**, 117 (2016)

Take-Home Message 1

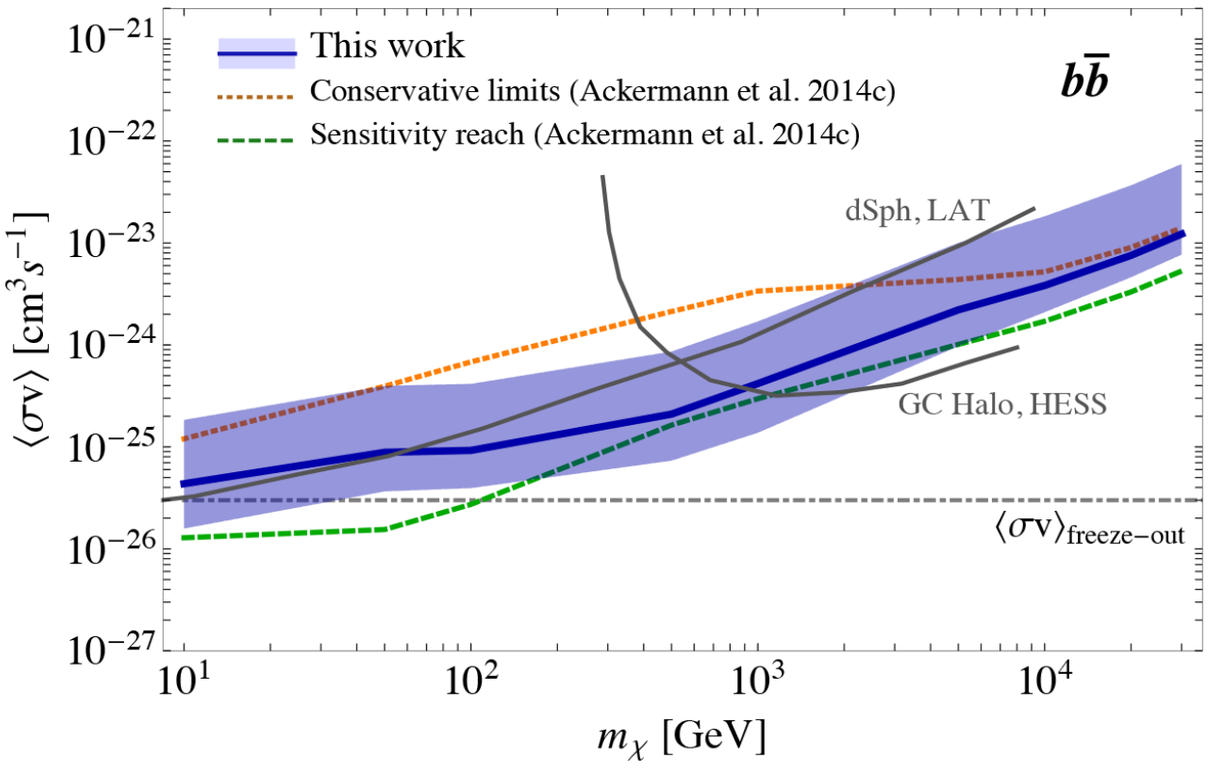
- Plenty of data of high-energy gamma rays enable analyses beyond energy spectrum of IGRB: ***Anisotropies***

- IGRB Anisotropy has started to be probed extensively and already shown some promise for the future
  - Angular power spectrum
  - PDF of gamma-ray flux
  - Cross correlation with nearby galaxy distribution

- Current constraints on dark matter from cross correlations with galaxy catalogs are already very strong

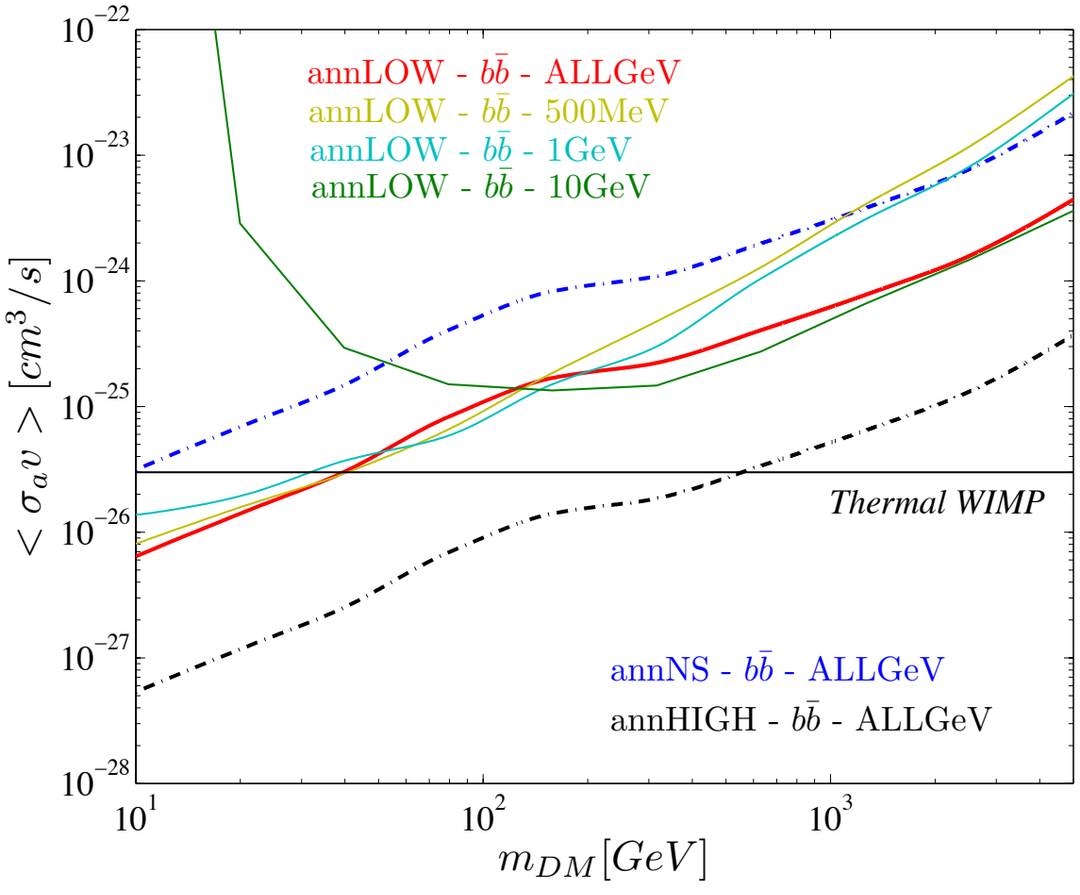
Uncertainty on subhalo boost

Measurement of EGRB spectrum



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

Measurement of EGRB-galaxy correlation



Cuoco et al., *Astrophys. J. Suppl.* **221**, 29 (2015)

- 1 order magnitude uncertainty related to **how little we know about subhalos**
- This is the main bottleneck that prevents EGRB measurement from being reliably trusted yet (compared with, e.g., dwarf galaxies)

Subhalo boost factor

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

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

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

Literature says

Numerical simulations of the dark universe: State of the art and the next decade

Michael Kuhlen [a,*], Mark Vogelsberger [b], Raul Angulo [c,d]

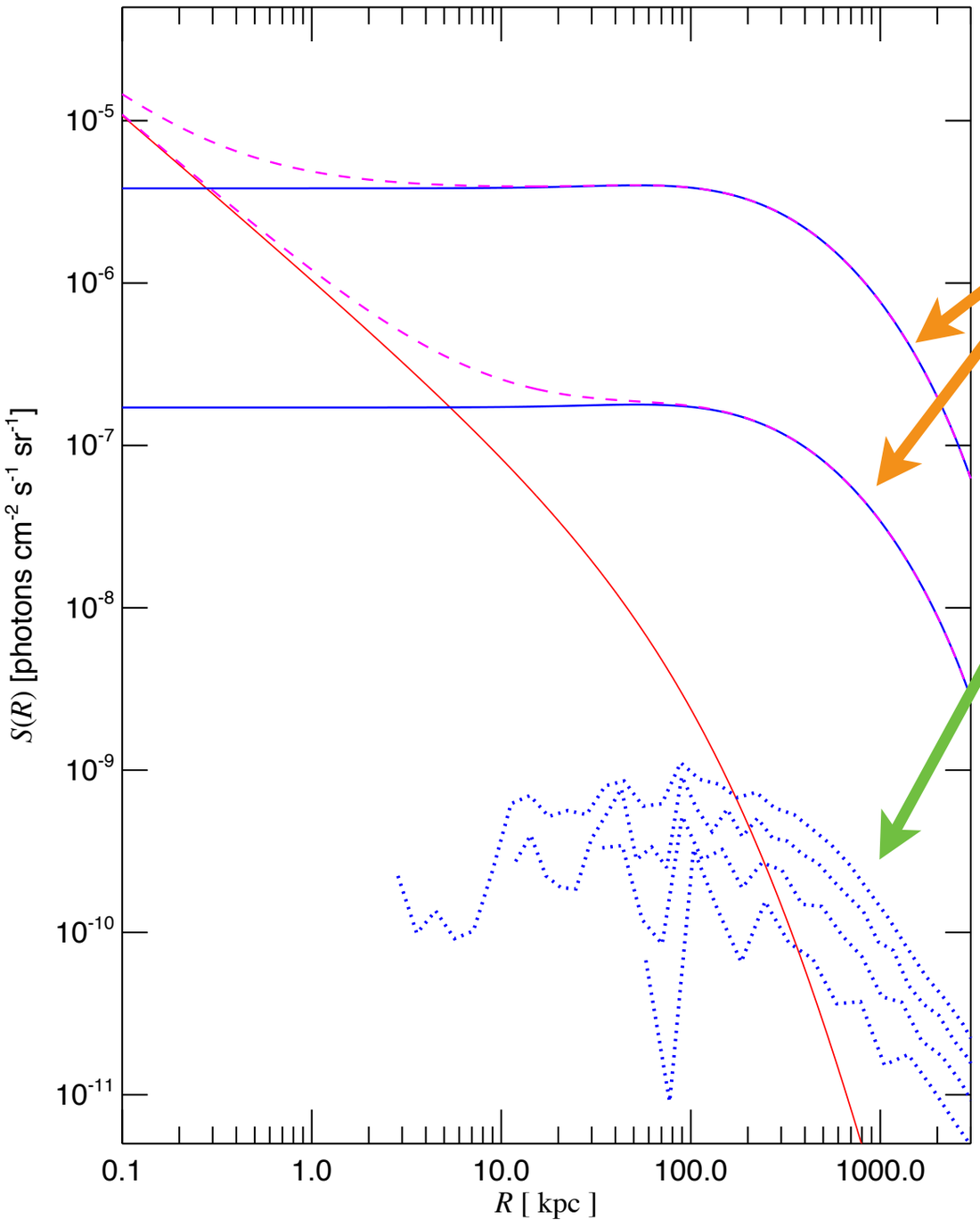
Dark Universe **1**, 50 (2012)

(b) Substructure boosts depend *sensitively* on subhalo properties many orders of magnitude below the resolution limit of state of the art simulations.

One approach to estimating the full substructure boost is to stay as close as possible to the results from ultra-high-resolution numerical simulations like Via Lactea II and Aquarius, by fitting the luminosity boost from all subhalos with mass greater than $M_{\rm min}$, $B(M_{\rm min}) = L(>M_{\rm min})/L_{\rm smooth}$, to a power law of $M_{\rm min}$ over the 4–5 decades of substructure mass that are currently resolved in the simulations, and then extrapolating this power law down to the free-streaming cutoff scale. This approach was taken, for example, by Springel et al. [135], who found $B(M_{\rm min}) \sim M_{\rm min}^{-0.226}$, and inferred a total boost factor for a Milky-Way-like halo of 230 for $M_{\rm min} = 10^{-6}$ $M_\odot$.

Another approach is to use the numerical simulation results only to constrain the mass function of subhalos, which is measured to be a power law, $dn/dM_{\rm sub} \sim M_{\rm sub}^{\alpha}$ with logarithmic slope $\alpha \simeq -1.9$ [44,45], and to use an analytical approach to determine the subhalo luminosity–mass relation down to the smallest mass halos [90,91,137]. The luminosity of

First approach: Power-law extrapolation of boost



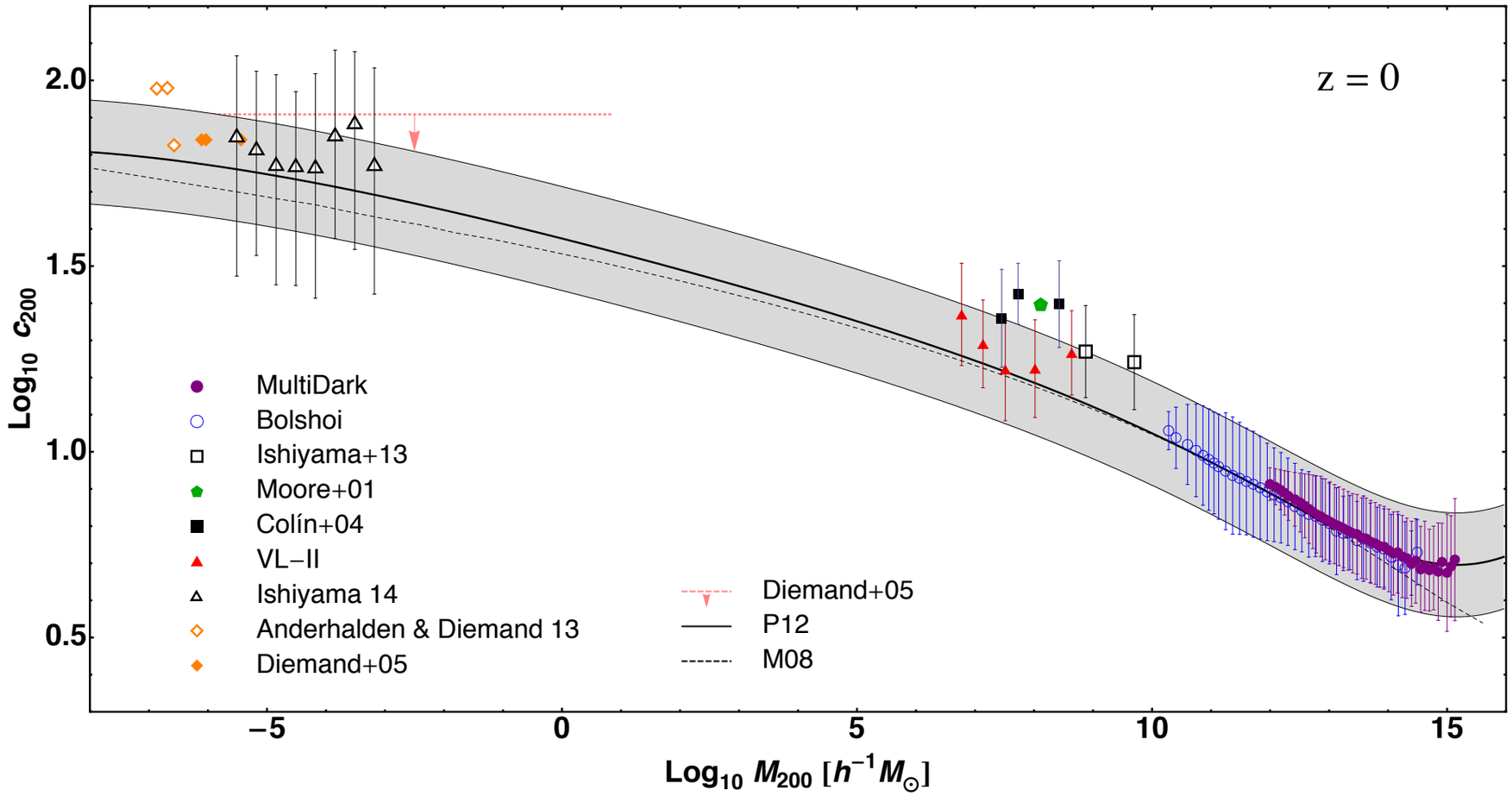
These are what's extrapolated

These are what's resolved

- Power-law extrapolation for more than 10 orders of magnitude
- Factor of 100 (1000) annihilation boost for galaxy (cluster) sized halos
- Very extreme assumption

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

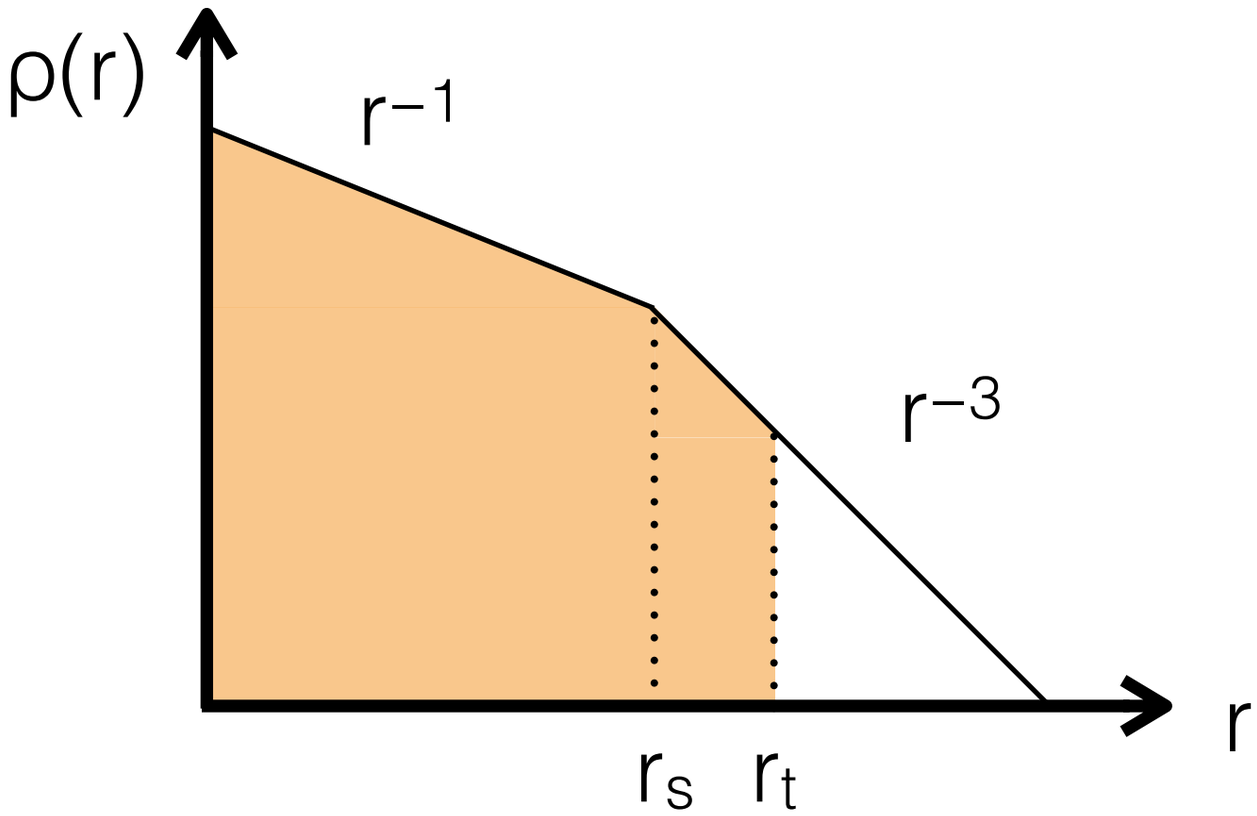
Second approach: analytic modeling

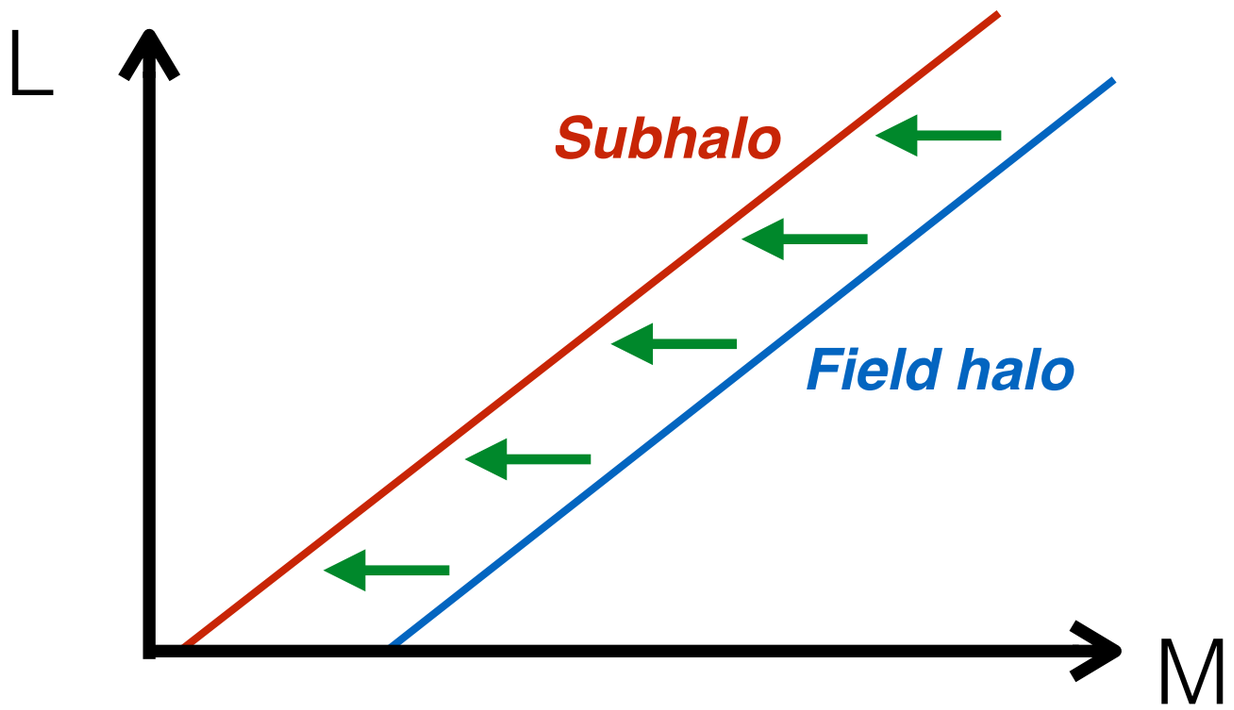


Sanchez-Conde, Prada, *Mon. Not. R. Astron. Soc.* **442**, 2271 (2014)

- Analytic modeling of mass-concentration relation, and hence subhalo mass-luminosity relation
- But this relation is for ***field halos***, not subhalos
- For same mass, *subhalos are much brighter than field halos*

Tidal stripping makes subhalos more “luminous”





- For field halos, most mass comes from radius larger than r_s
- But about 90% of annihilation happens within r_s
- Tidal stripping truncates density profile
- Mass of the suhalos gets reduced substantially, but luminosity is almost unchanged
- **This makes subhalos effectively more luminous than field halos!**

Semi-analytic modeling

Ingredients we need…

Mass accretion history of the host

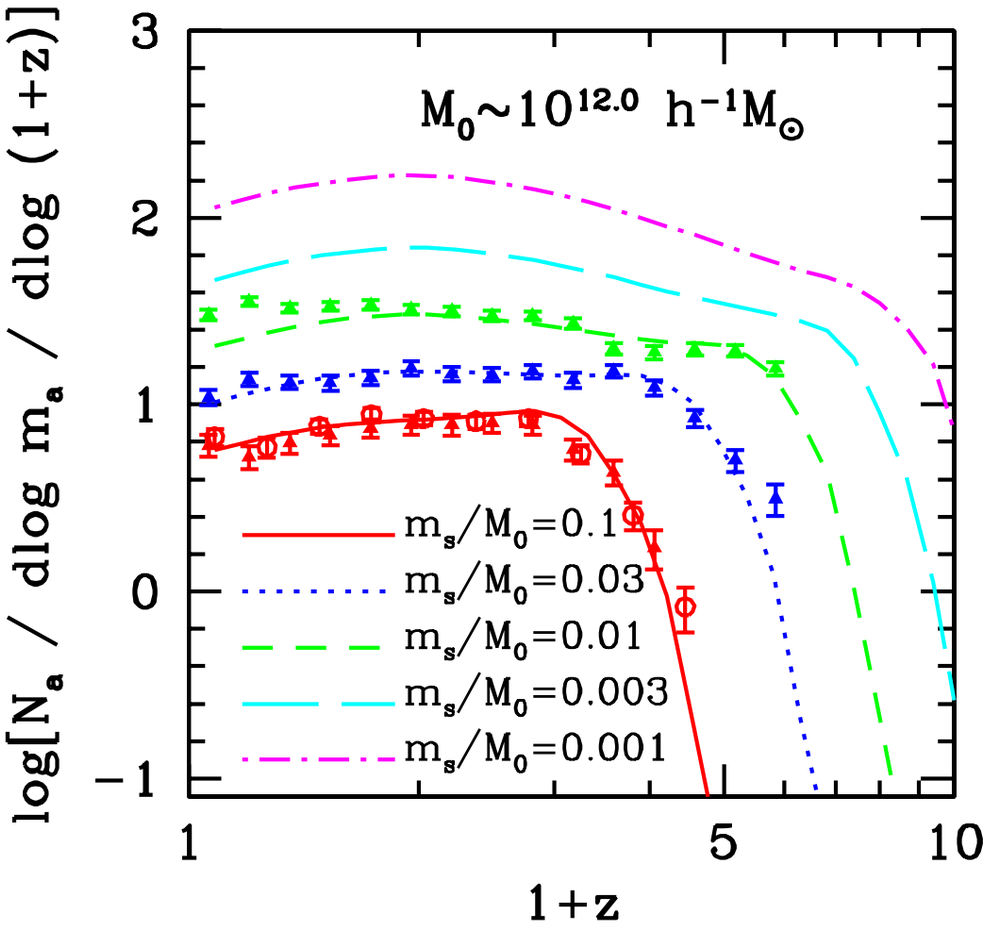
Initial density profile of subhalos

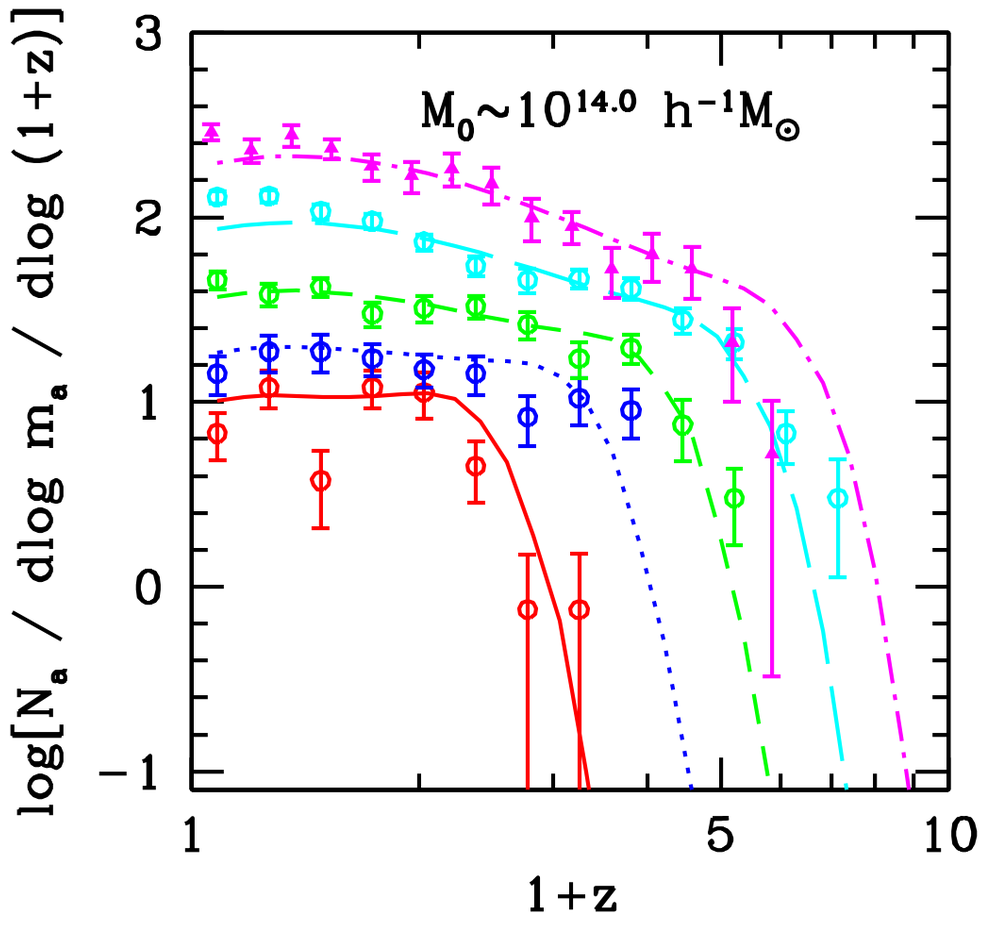


Mass-loss rate of subhalos

Infall distribution of subhalos

Subhalo accretion rate



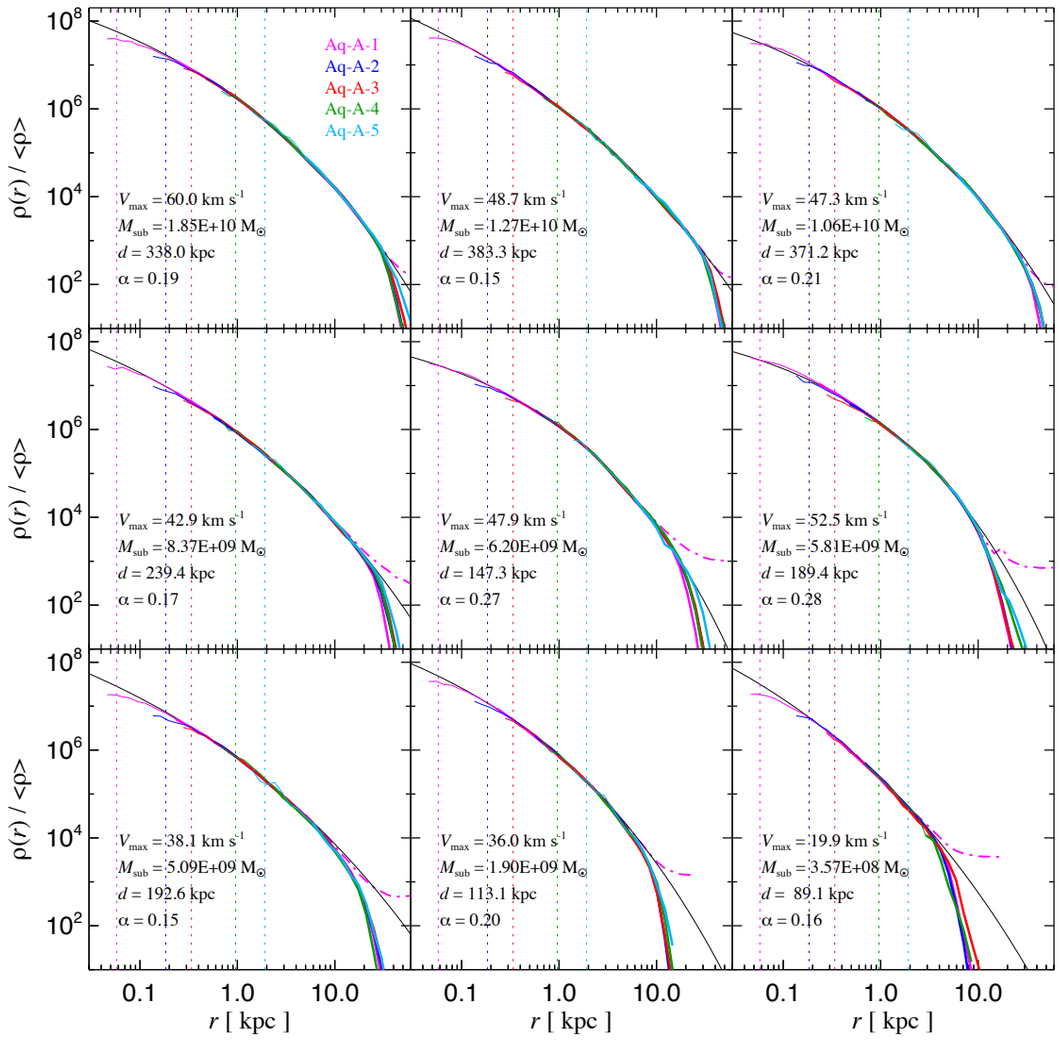


Yang et al., *Astrophys. J.* **741**, 13, (2011)

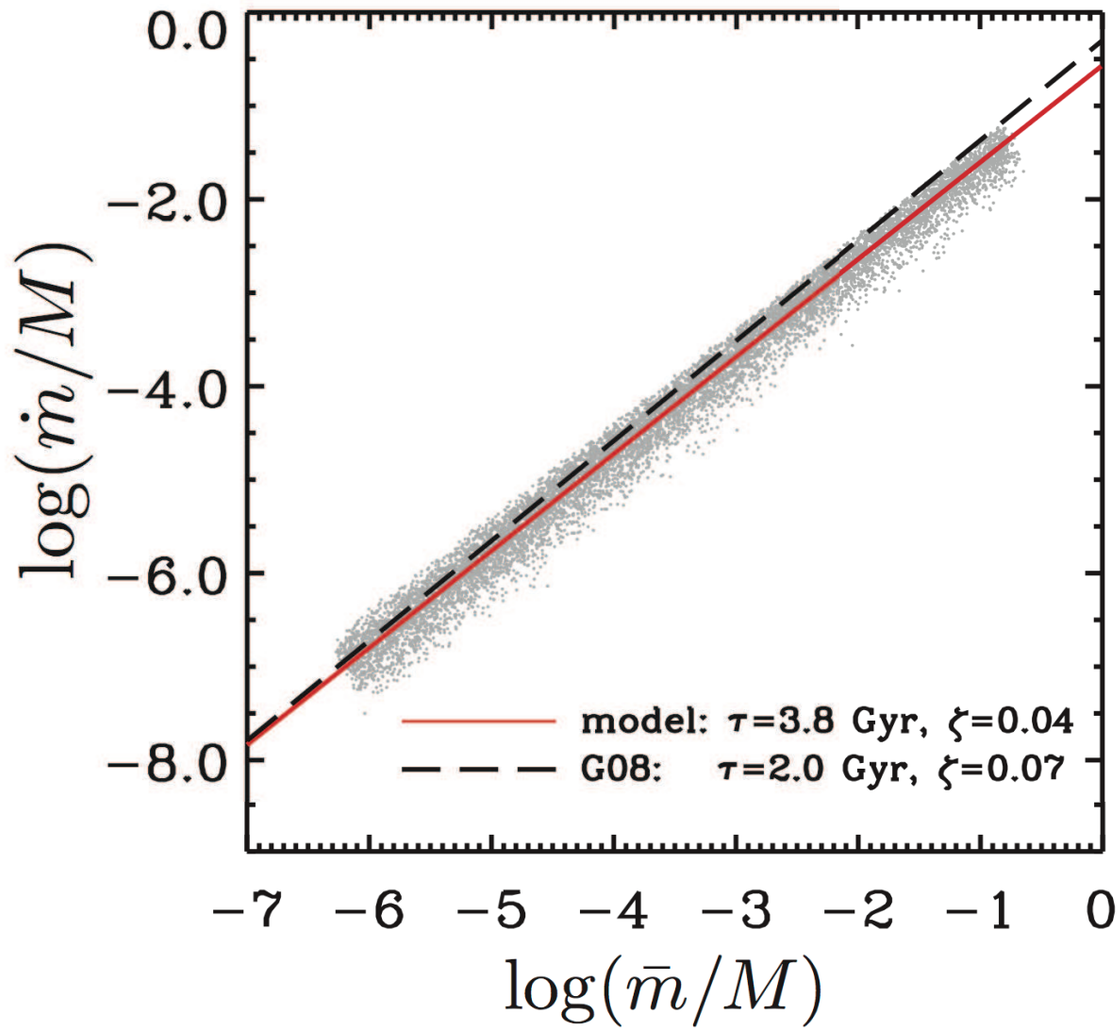
Infall distribution of subhalos:
Extended Press-Schechter formalism

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

Subhalo density profile and mass loss



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



Jiang, van den Bosch, arXiv:1403.6827 [astro-ph.CO]

Truncated NFW:
ρ_s and r_s hardly change

Mass-loss rate follows power law
Note: we extrapolate this relation down to 10^{-6} $M_\odot$

Summary of semi-analytic modeling

- EPS formalism tells us how many smaller halos accreted onto a main halo at given redshift (Yang et al. 2011)

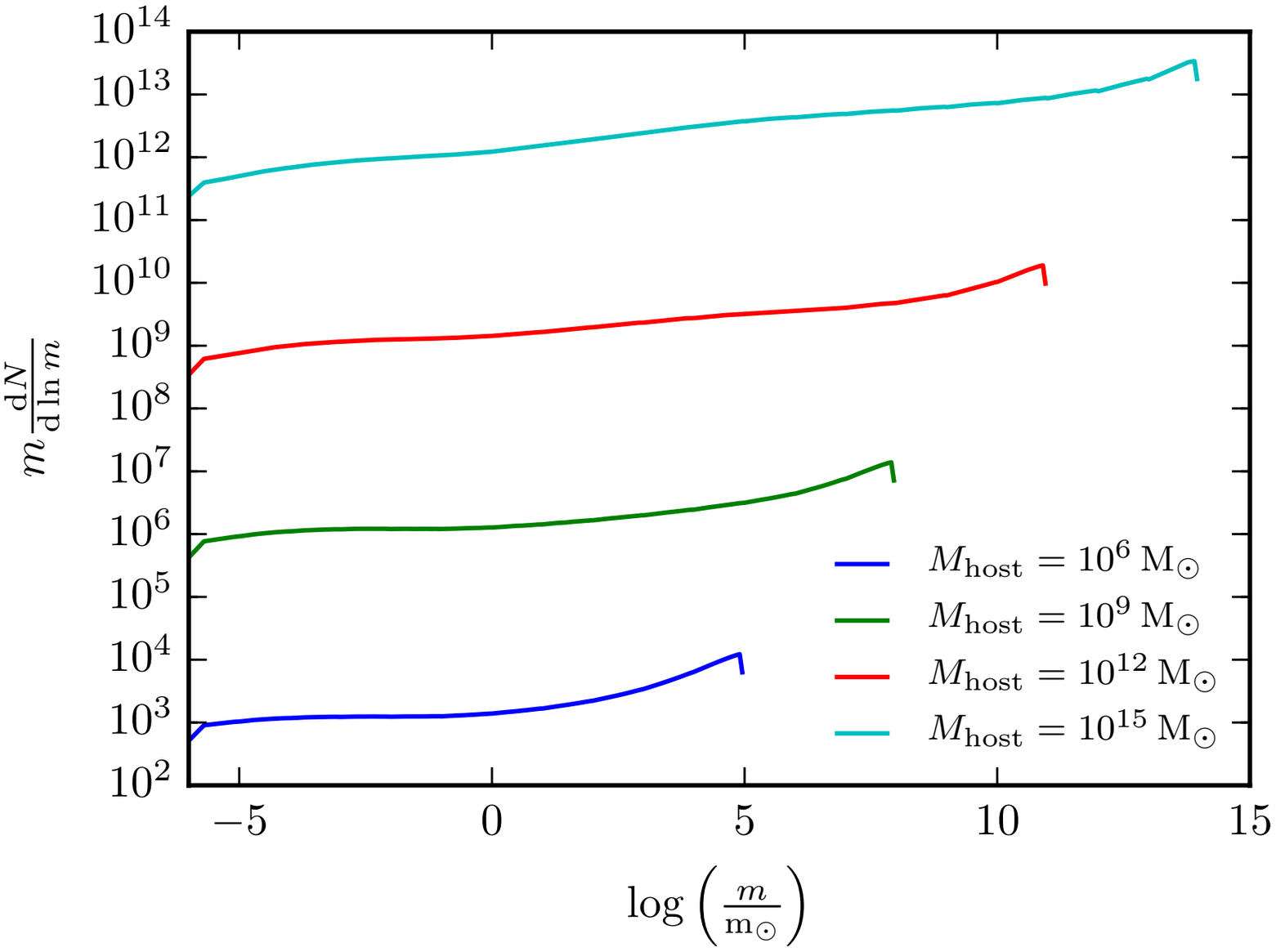
- We get density profile of these halos assuming that they are virialized shortly before; concentration-mass relation (Correa et al. 2014) determines the parameters such as ρ_s and r_s

- Solve equation for mass-loss rate of subhalos to get truncation radius r_t and evolved subhalo mass m_0, assuming ρ_s and r_s hardly change

- Obtain joint PDF for subhalo mass m_0 and $c_t = r_t/r_s$

$$\mathcal{P}(m_0, c_t) \propto \frac{d^2 N}{d\ln m_a d\ln(1+z_a)} \left| \frac{\partial(\ln m_a, \ln(1+z_a))}{\partial(m_0, c_t)} \right|$$

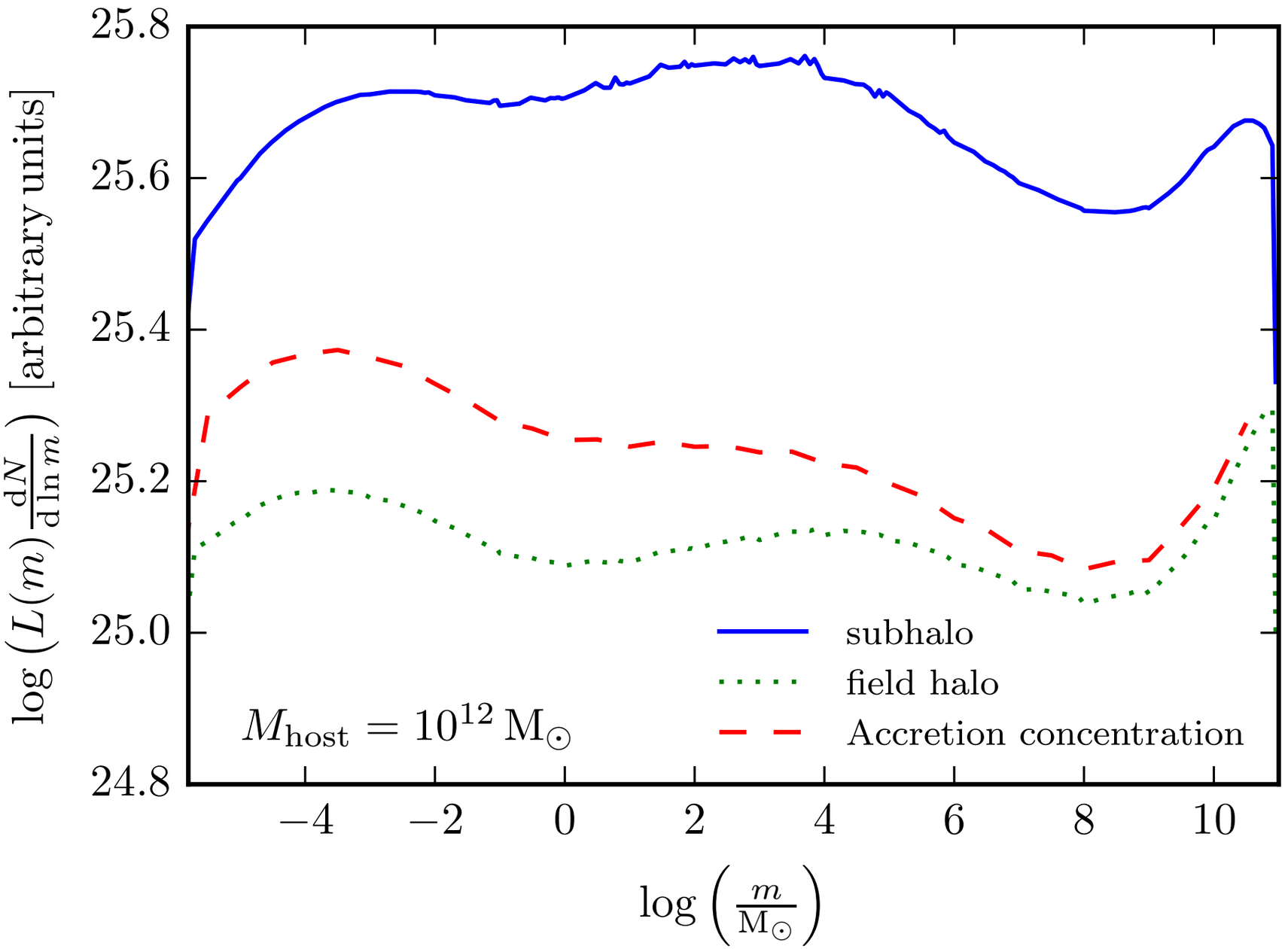
Results: Subhalo mass function



- Evolved subhalo mass function is consistent with simulation ($dN/dm_0 \sim m_0^{-1.9}$) down to free-streaming scale
- 10-20% of the total mass is confined in subhalos

Results: Luminosity of subhalos

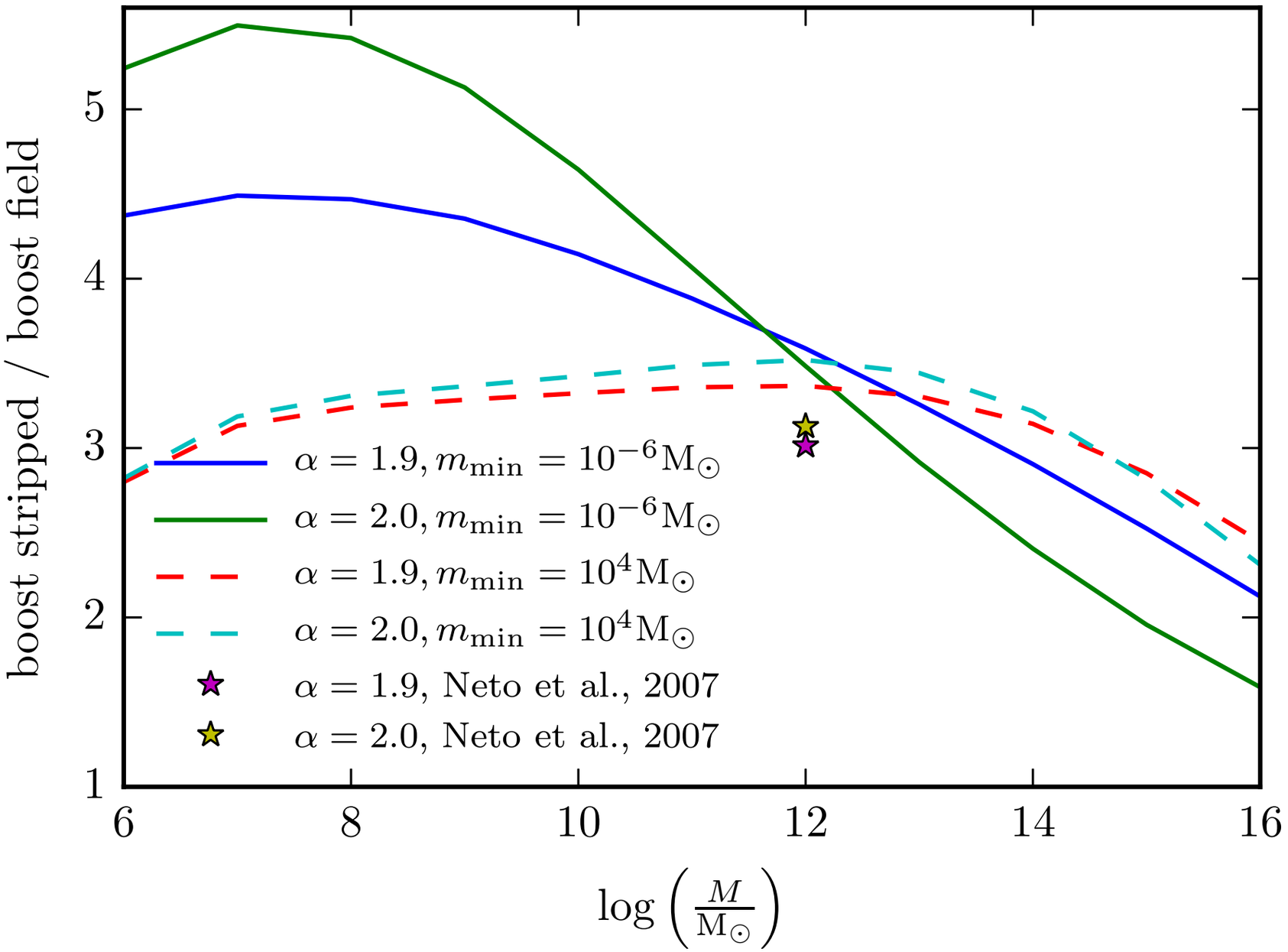
$$L_{\rm sh}(m) = \int_1^{c_{\rm max}} dc_t L_{\rm sh}(m, c_t) \mathcal{P}(m, c_t) \qquad L_{\rm sh}(m, c_t) \sim \rho_s^2 r_s^3 \left[1 - \frac{1}{(1+c_t)^3}\right]$$



- About **a factor of 3 enhancement** compared with the field-halo modeling, for all subhalo masses!!

Bartels, Ando,
Phys. Rev D **92**, 123508 (2015)

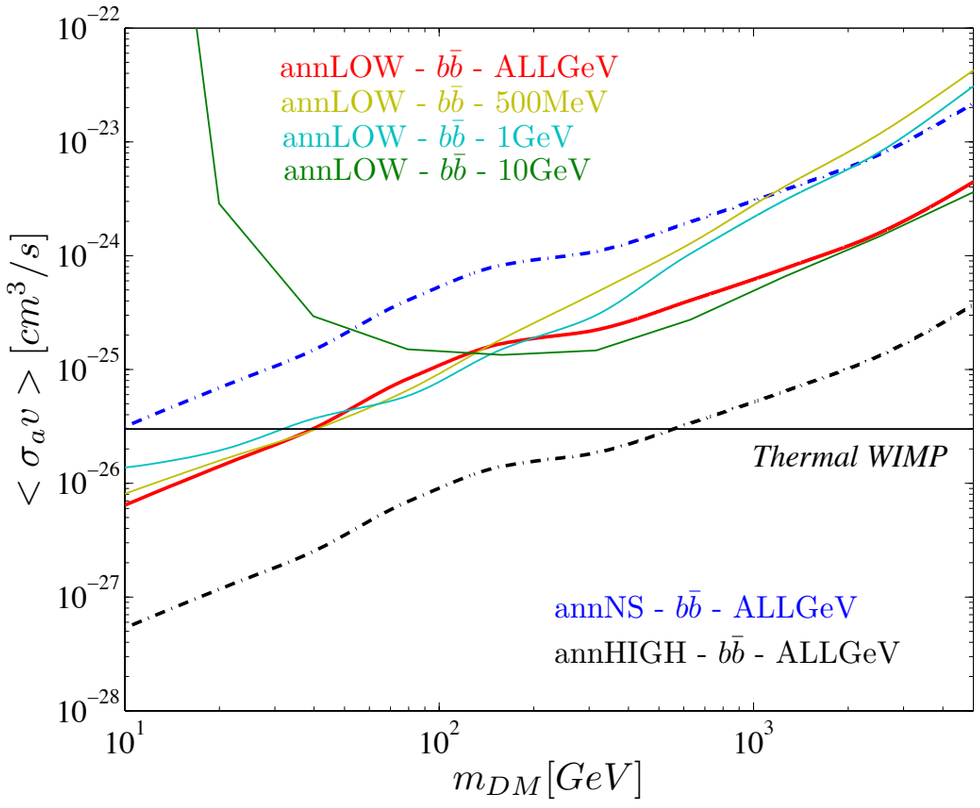
Annihilation boost



- Overall boost factor: **a factor of 2-5 enhancement** compared with field-halo modeling
- Stable against choice of subhalo mass function
- Stable against choice of concentration-mass relation for field halos

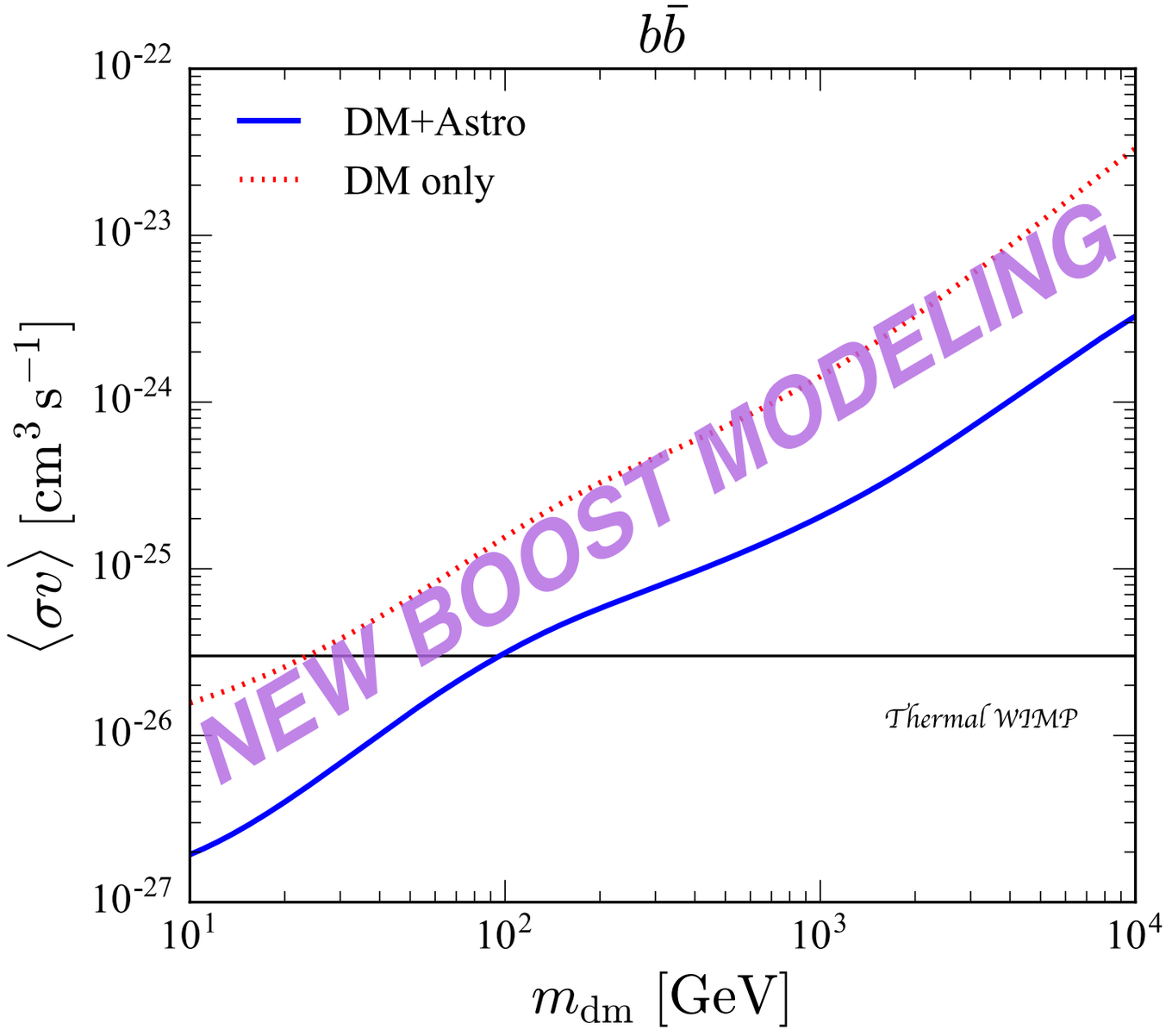
Bartels, Ando, *Phys. Rev D* **92**, 123508 (2015)

Tomographic constraints on annihilation cross section



Cuoco et al., *Astrophys. J. Suppl. Ser.* **221**, 29 (2015)

Solid: field-halo modeling
Dot-dashed: Power-law extrapolation



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

Take-home message 2

- Including tidal stripping when modeling subhalo boost is essential, and does ***improve the detection prospects of dark matter annihilation***
- Semi-analytic model shows a factor of 2-5 enhancement of the boost
    - The **same conclusions are obtained with independent studies** by Zavala, Afshordi (2016) and Moline et al. (2016) with two different approaches

Conclusions

- Rich gamma-ray data enable anisotropy analysis including **power spectrum** and **cross correlation** with galaxy catalogs

- Analysis of the latest power spectrum data implies **missing astrophysical sources below ~1 GeV** with soft spectrum

- Cross correlation with galaxy catalogs already gives **stringent constraints on annihilation cross section** or decay lifetime

- Interpretation is however limited due to **uncertainties on subhalos**, but at least, we showed that a conventional method to estimate ‘subhalo boost’ was overly conservative by a factor of 3