GRAPPA
GRavitation AstroParticle Physics Amsterdam

Perspectives on the Extragalactic Frontier
ICTP, Trieste
3 May 2016

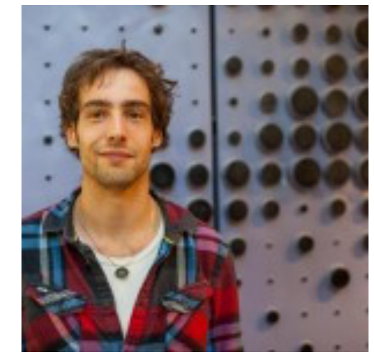
Extragalactic gamma-ray background
Implications for dark matter subhalos and neutrinos

Shin'ichiro Ando
GRAPPA, University of Amsterdam

This talk is based on…

1. “*Boosting the annihilation boost: Tidal effects on dark matter subhalos and consistent luminosity modeling*”

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



2. “*Tomographic Constraints on High-Energy Neutrinos of Hadronuclear Origin*”

   S. Ando, I. Tamborra, F. Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

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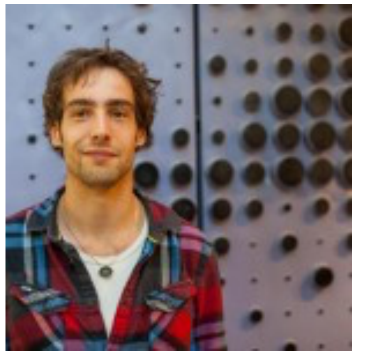

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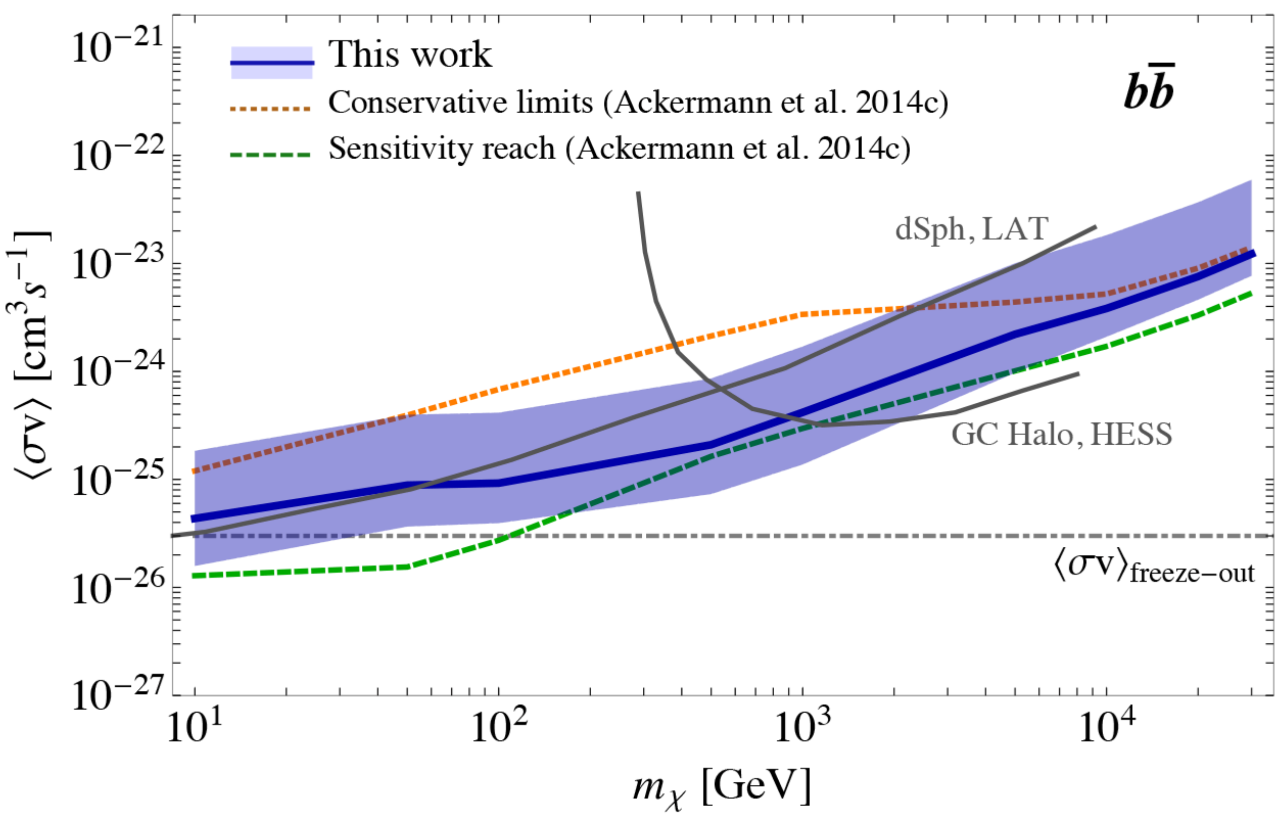
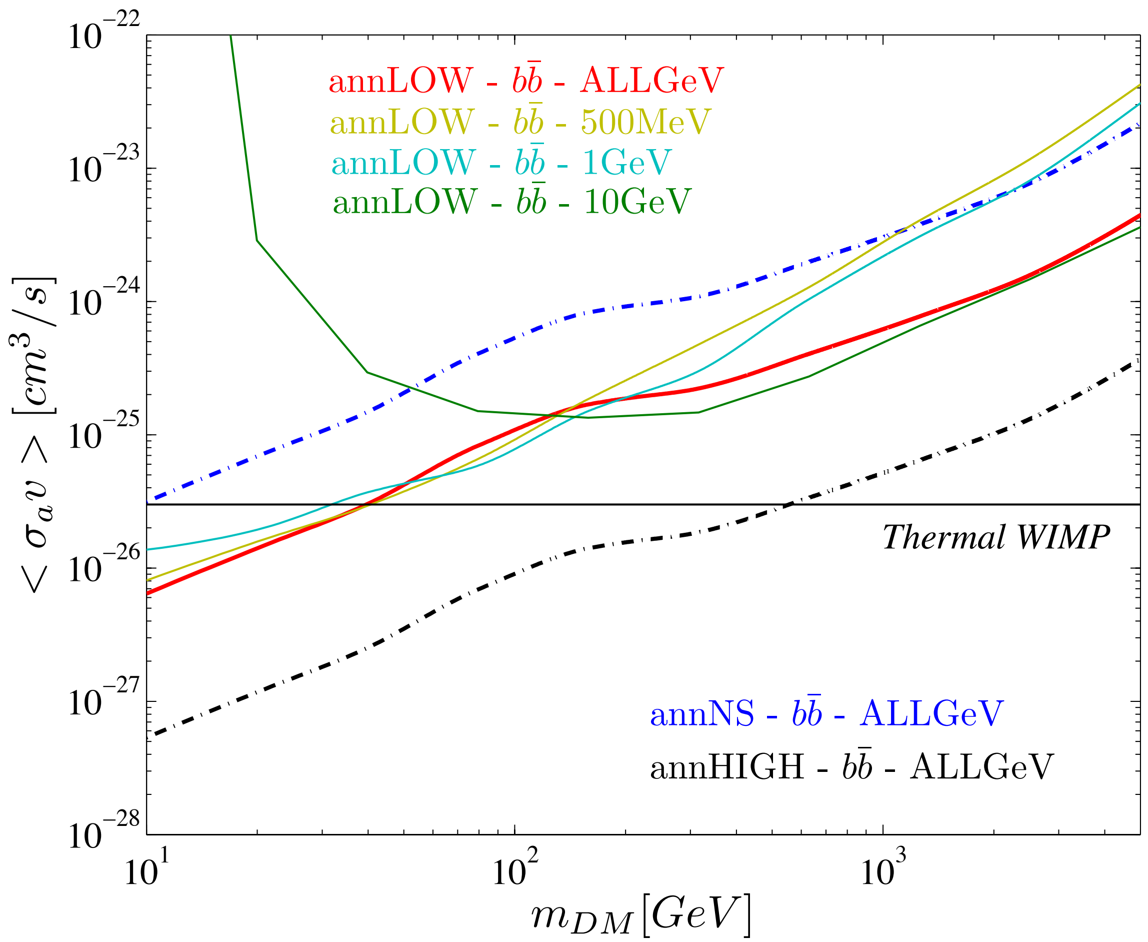
Uncertainty on subhalo boost

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]

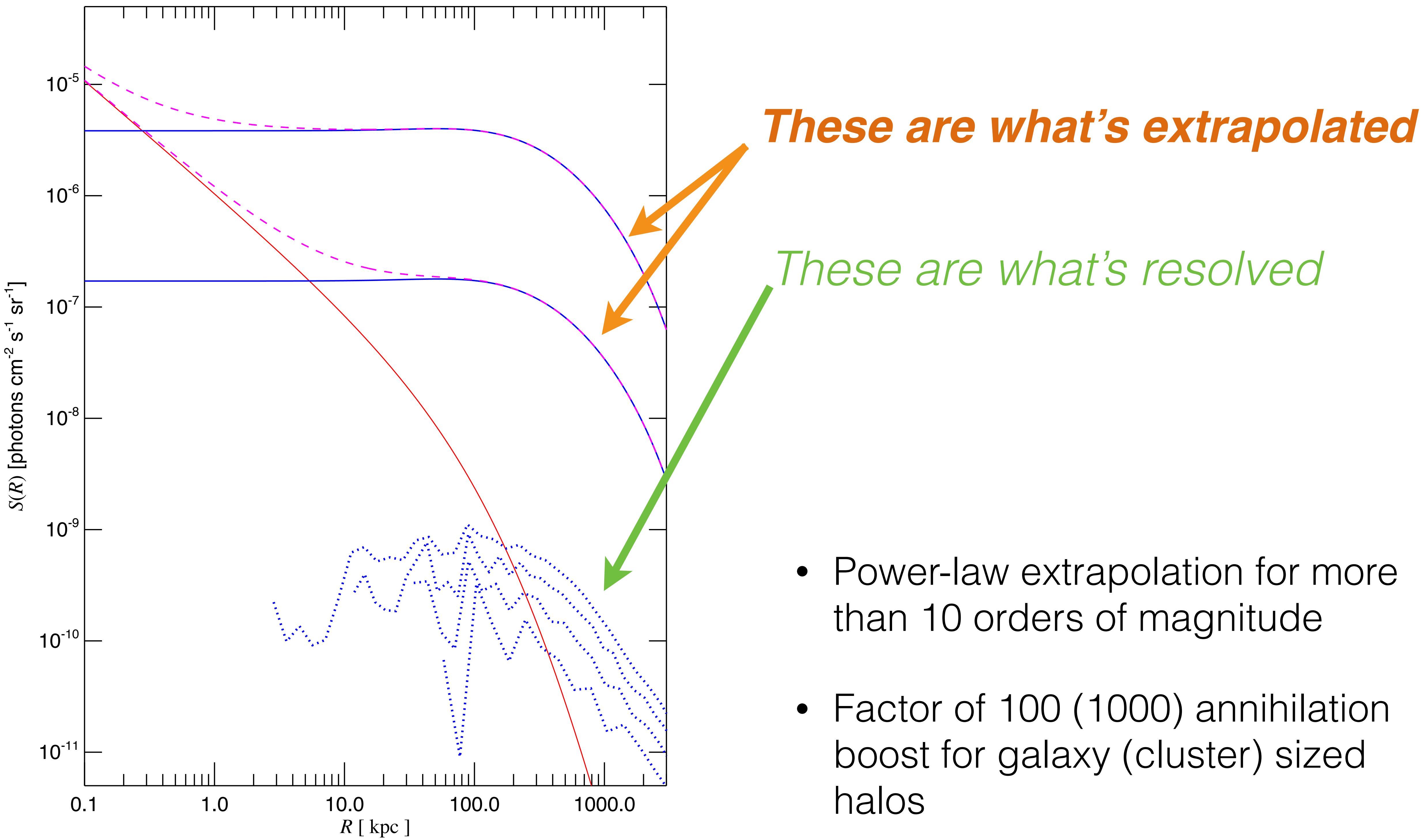
Dark Universe **1**, 50 (2012)

(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 $M_{\rm min} = 10^{-6}\ {\rm M}_\odot$.

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

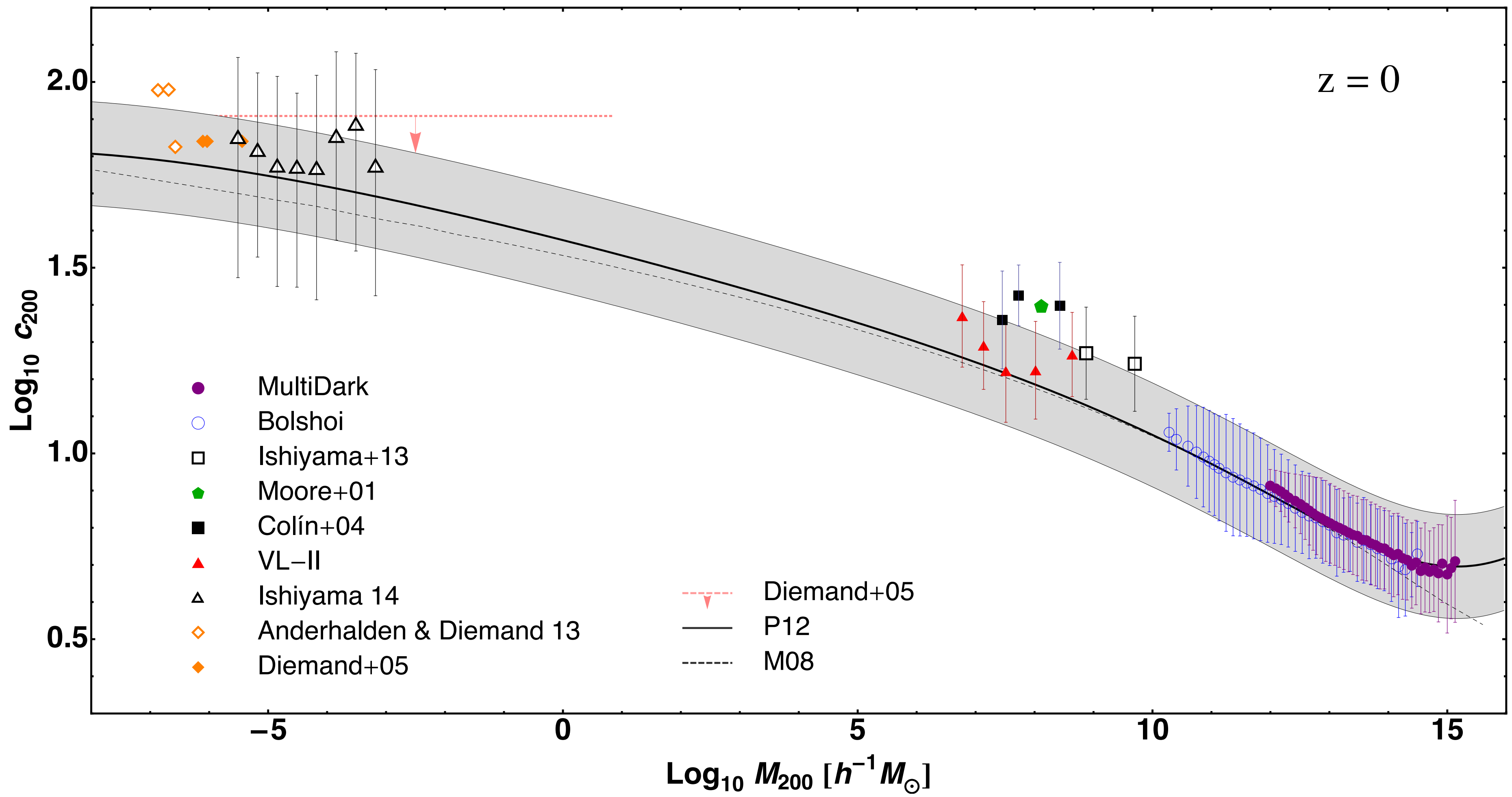
First approach: Power-law extrapolation of boost



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

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

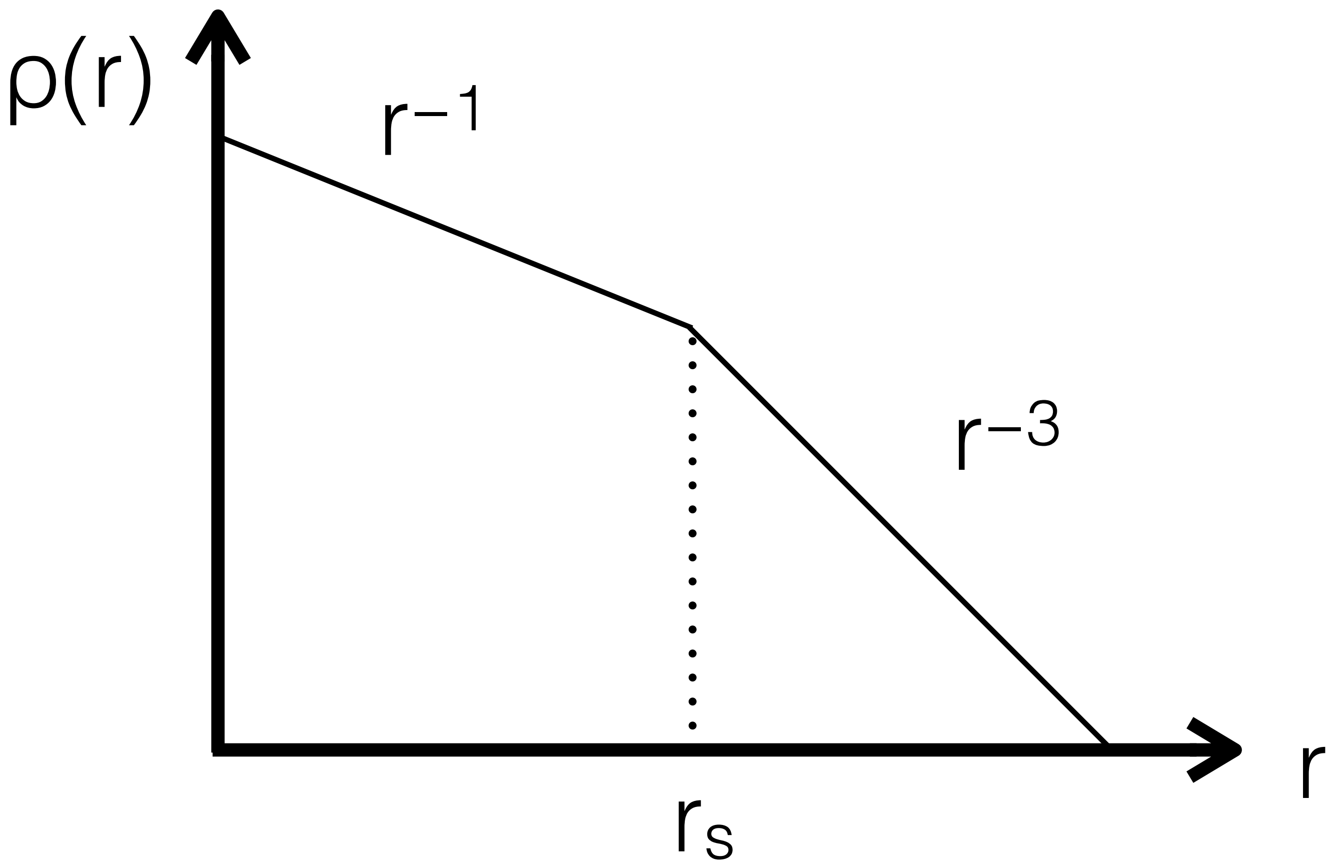
Second approach: analytic modeling

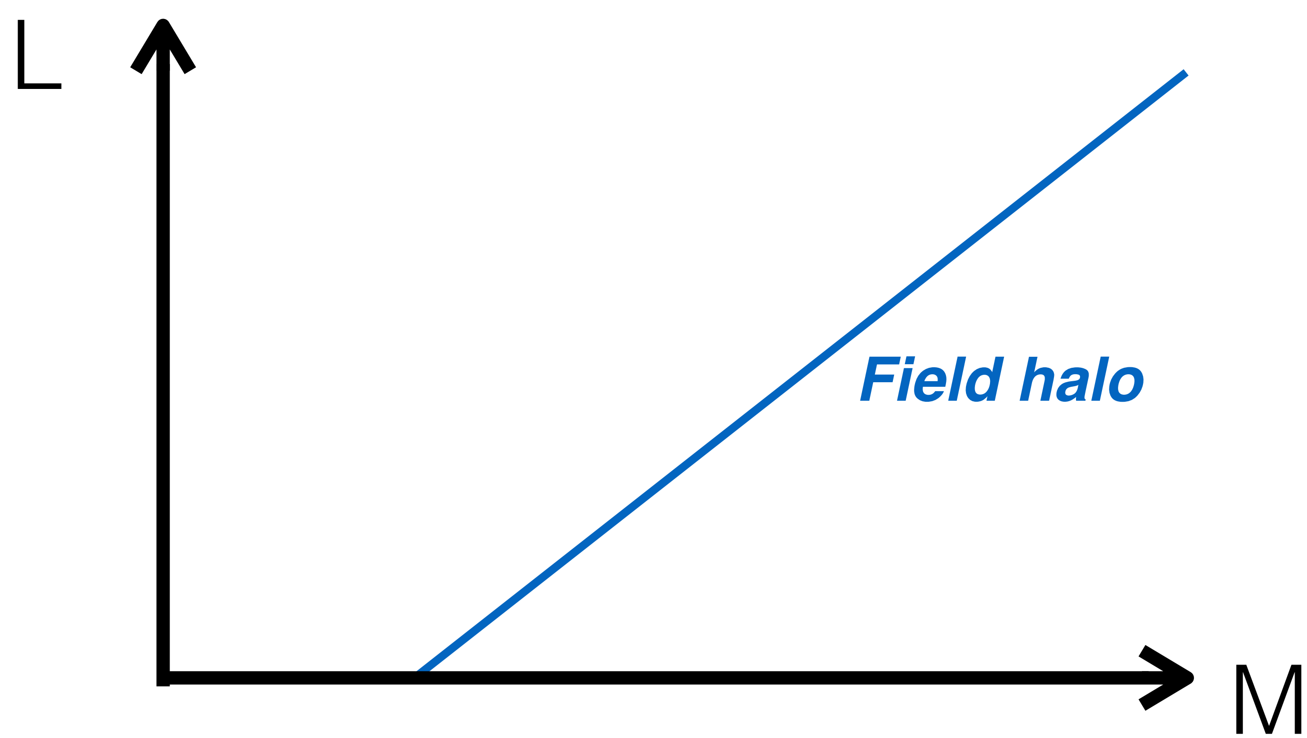


Sanchez-Conde, Prada, *Mon. Not. R. Astron. Soc.* **442**, 2271 (2014)

- 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"





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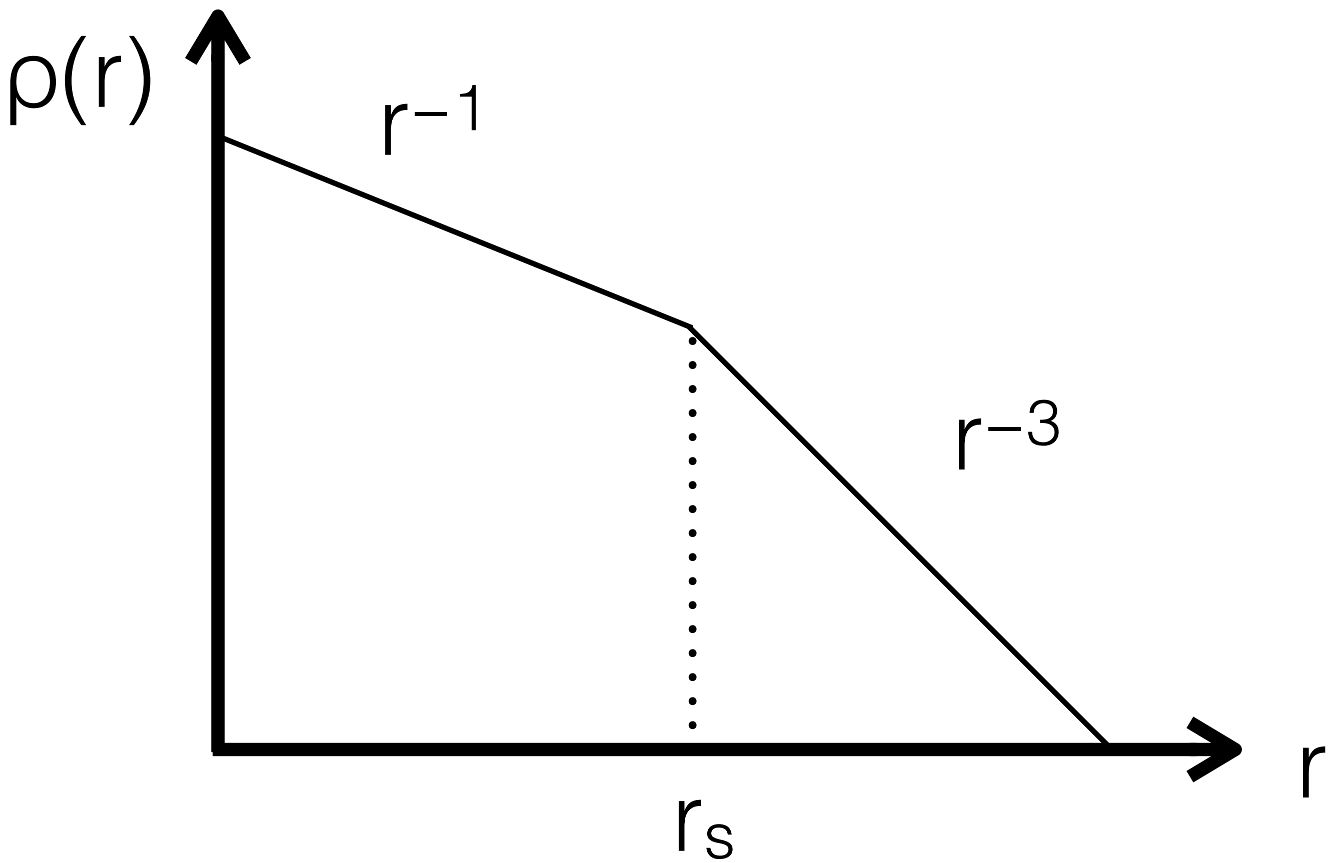

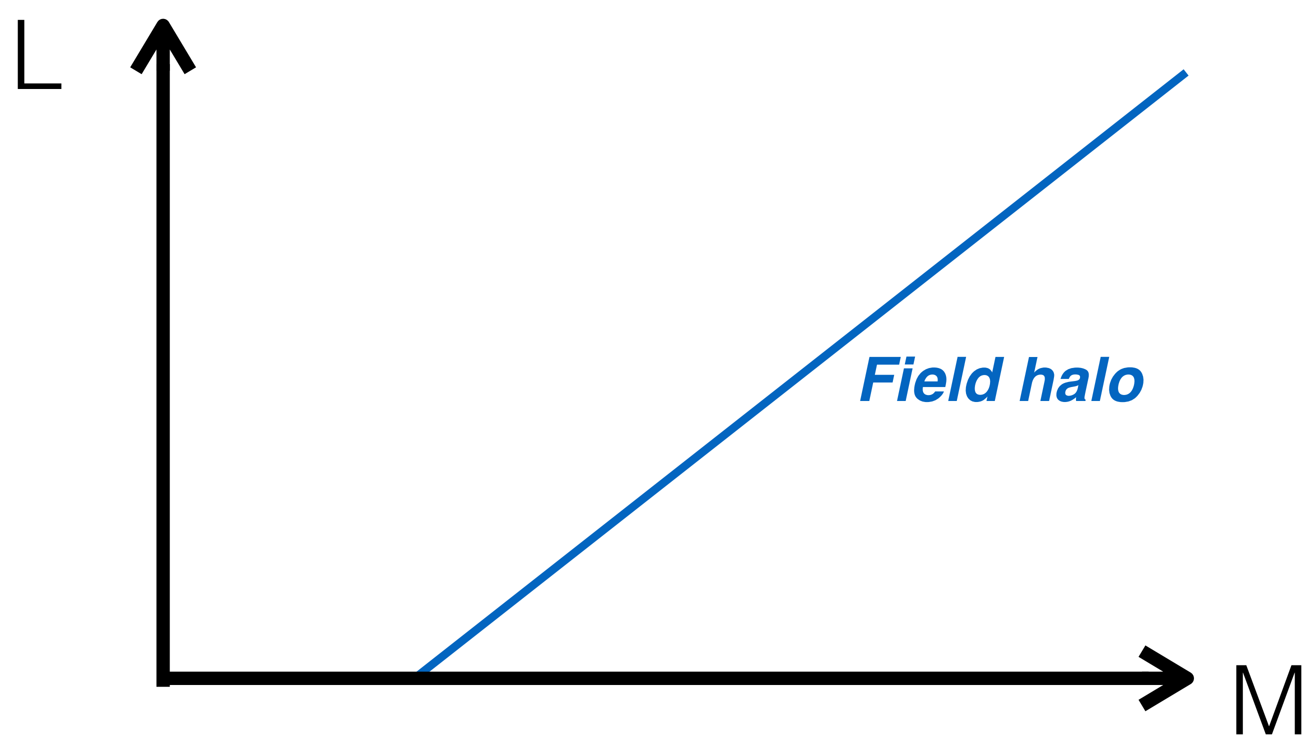

- For field halos, most mass comes from radius larger than r_s
- But about 90% of annihilation happens within r_s

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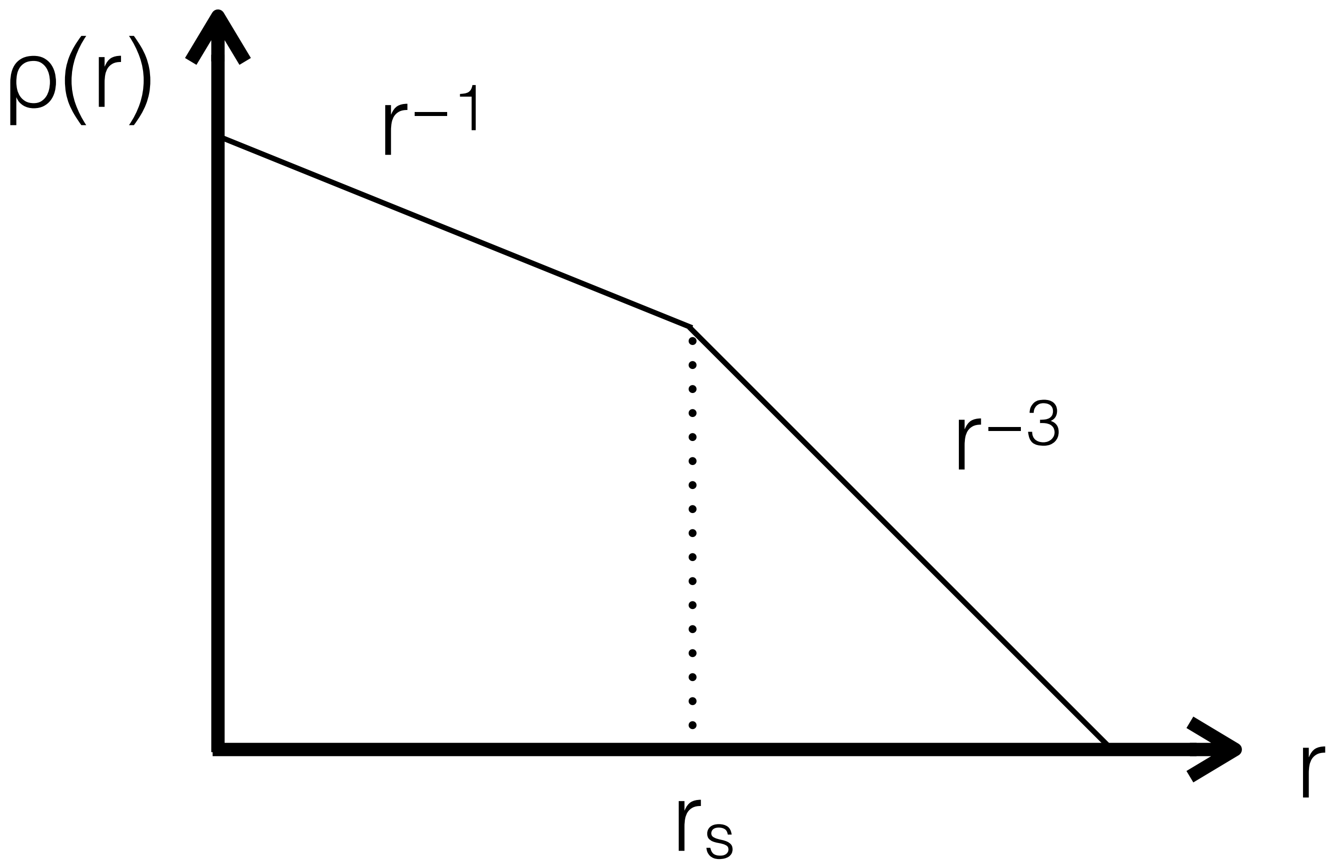

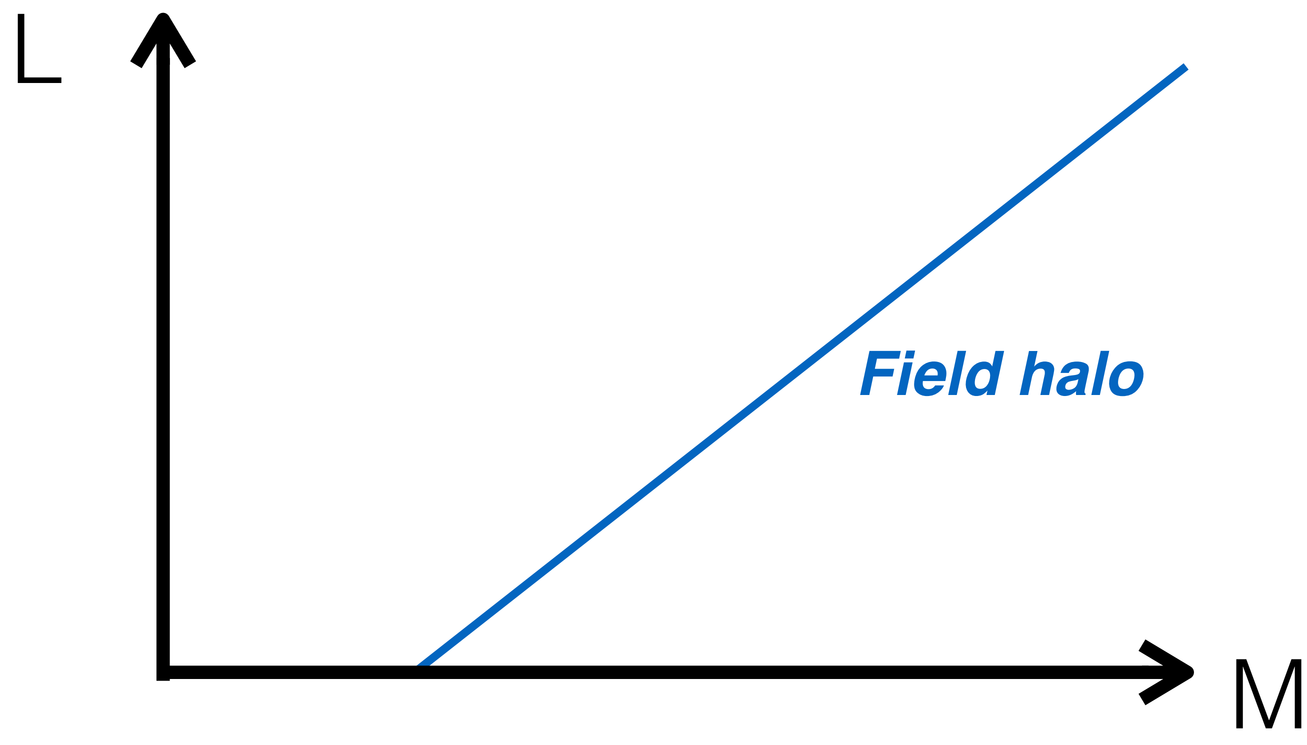

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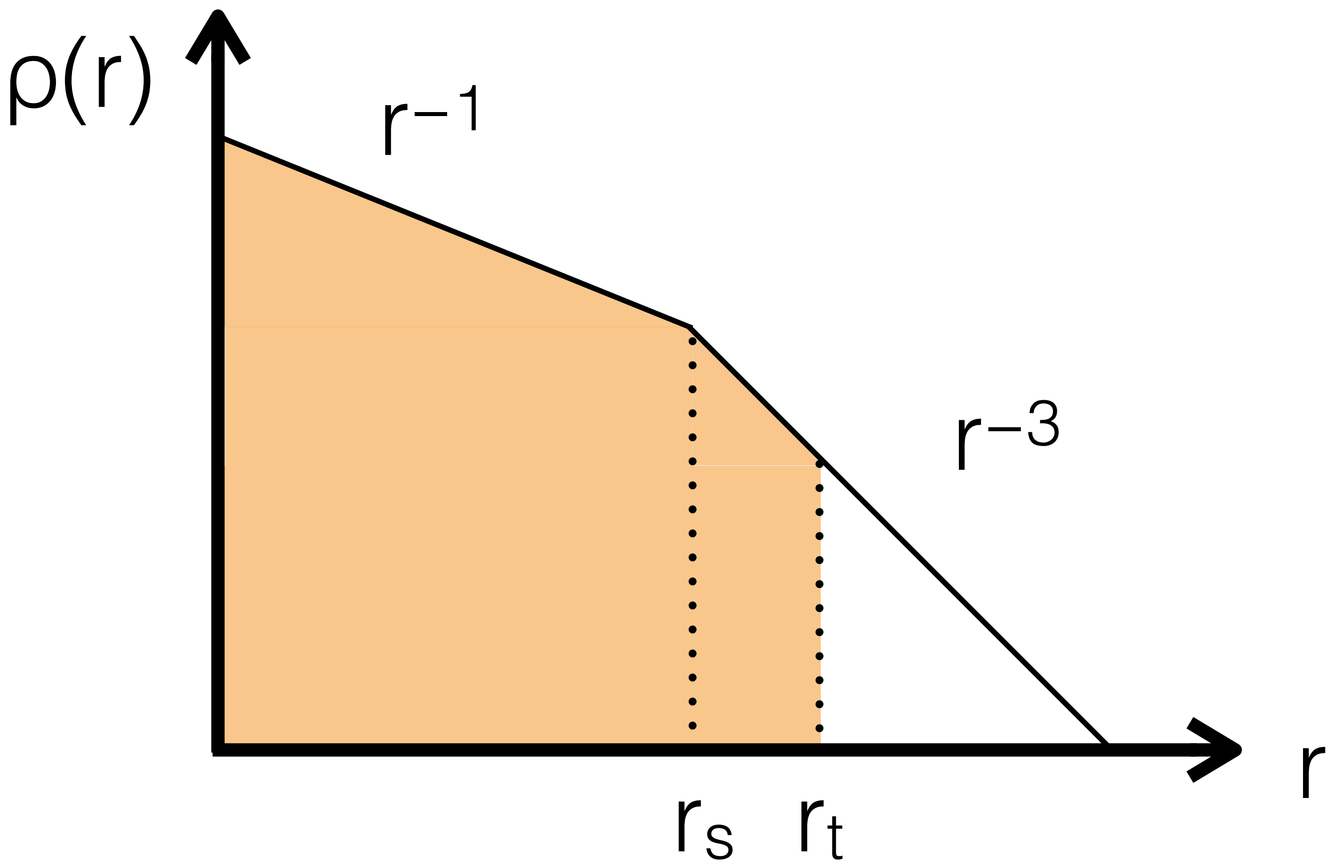

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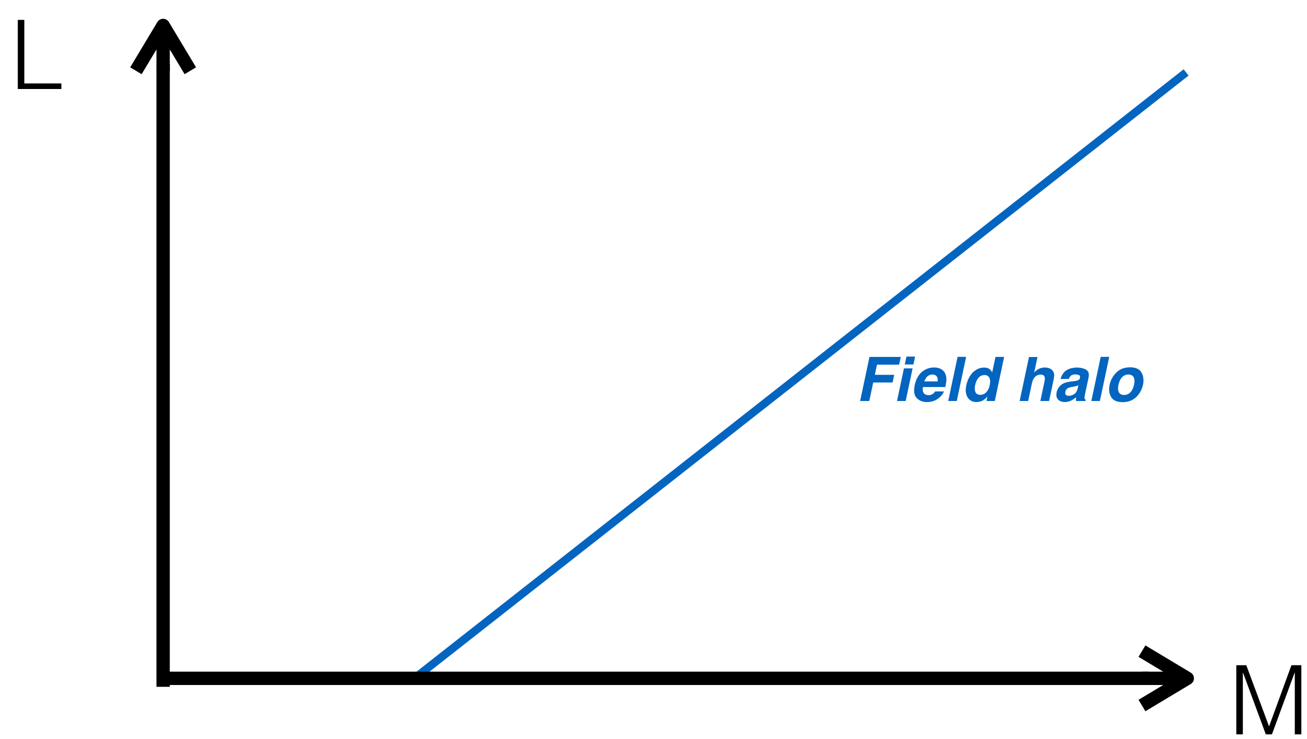

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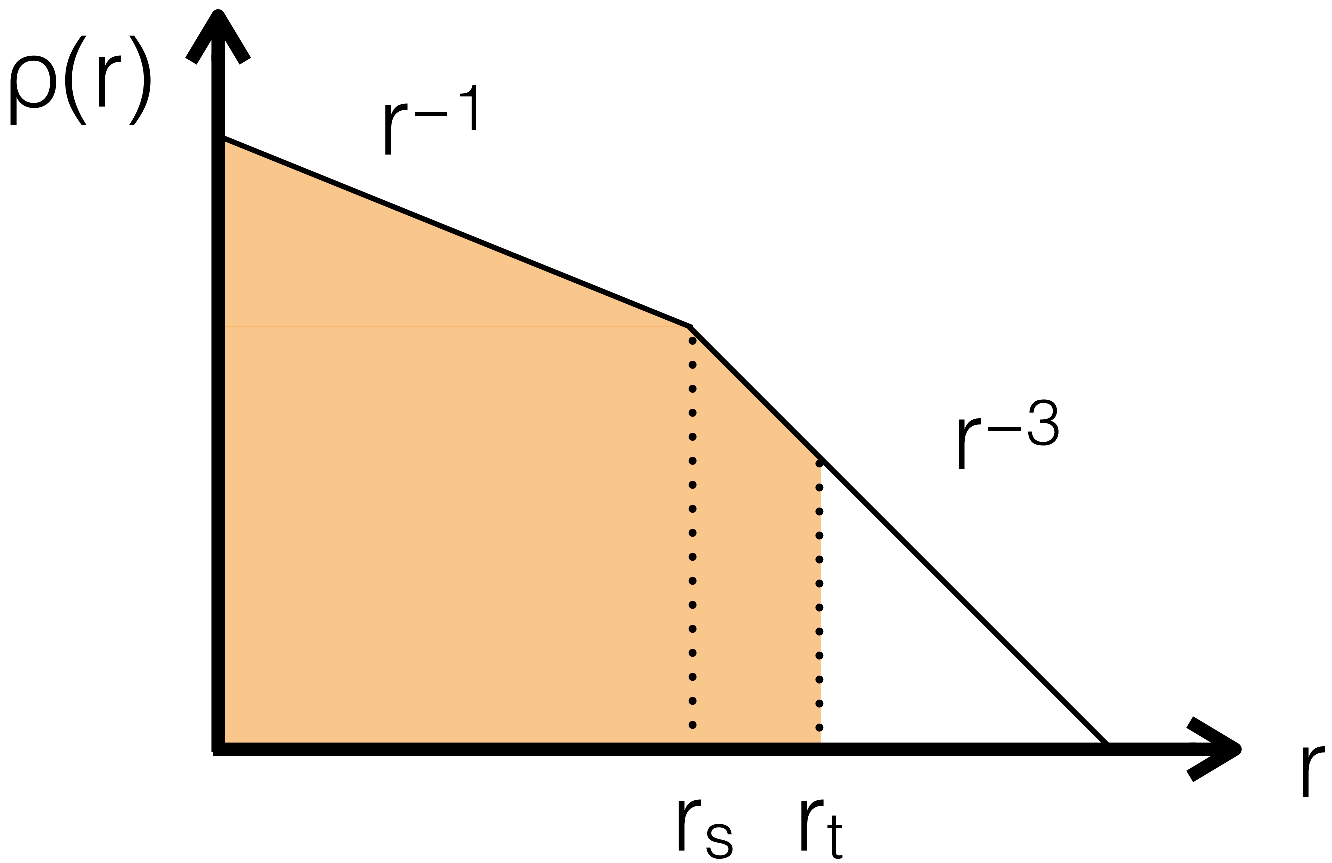

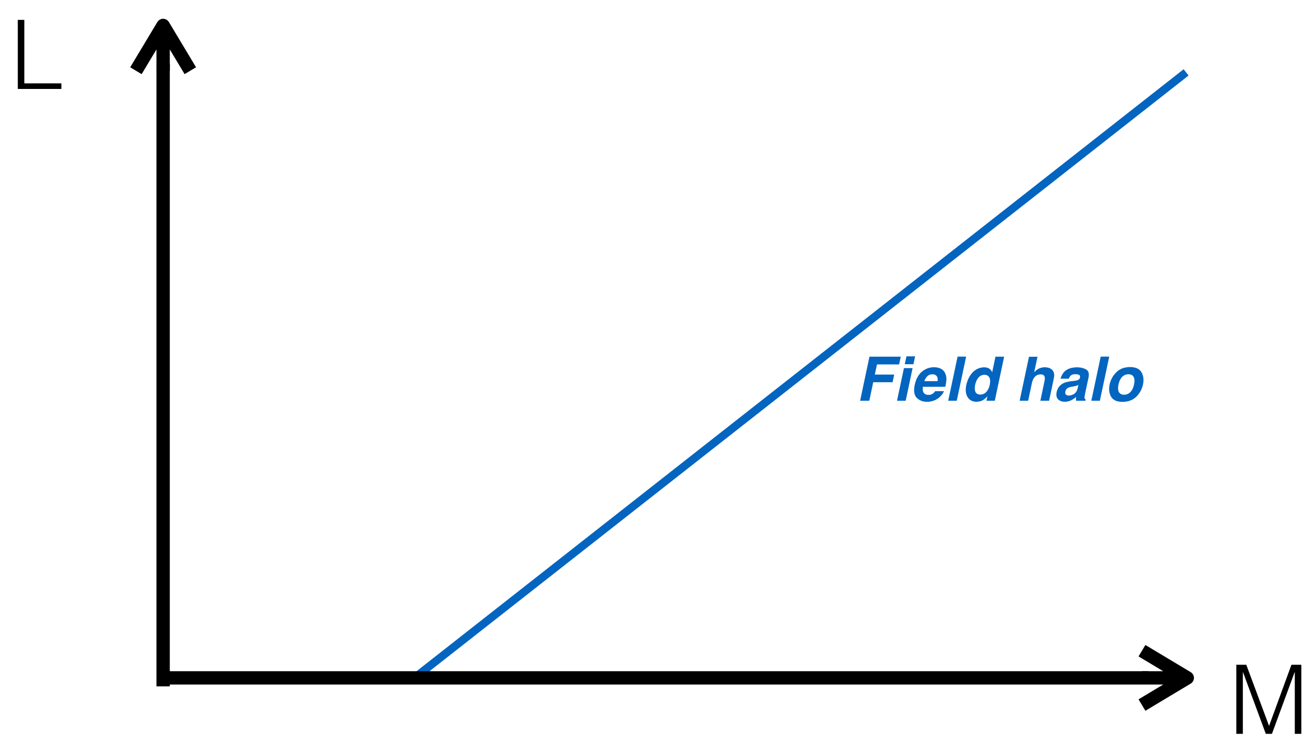

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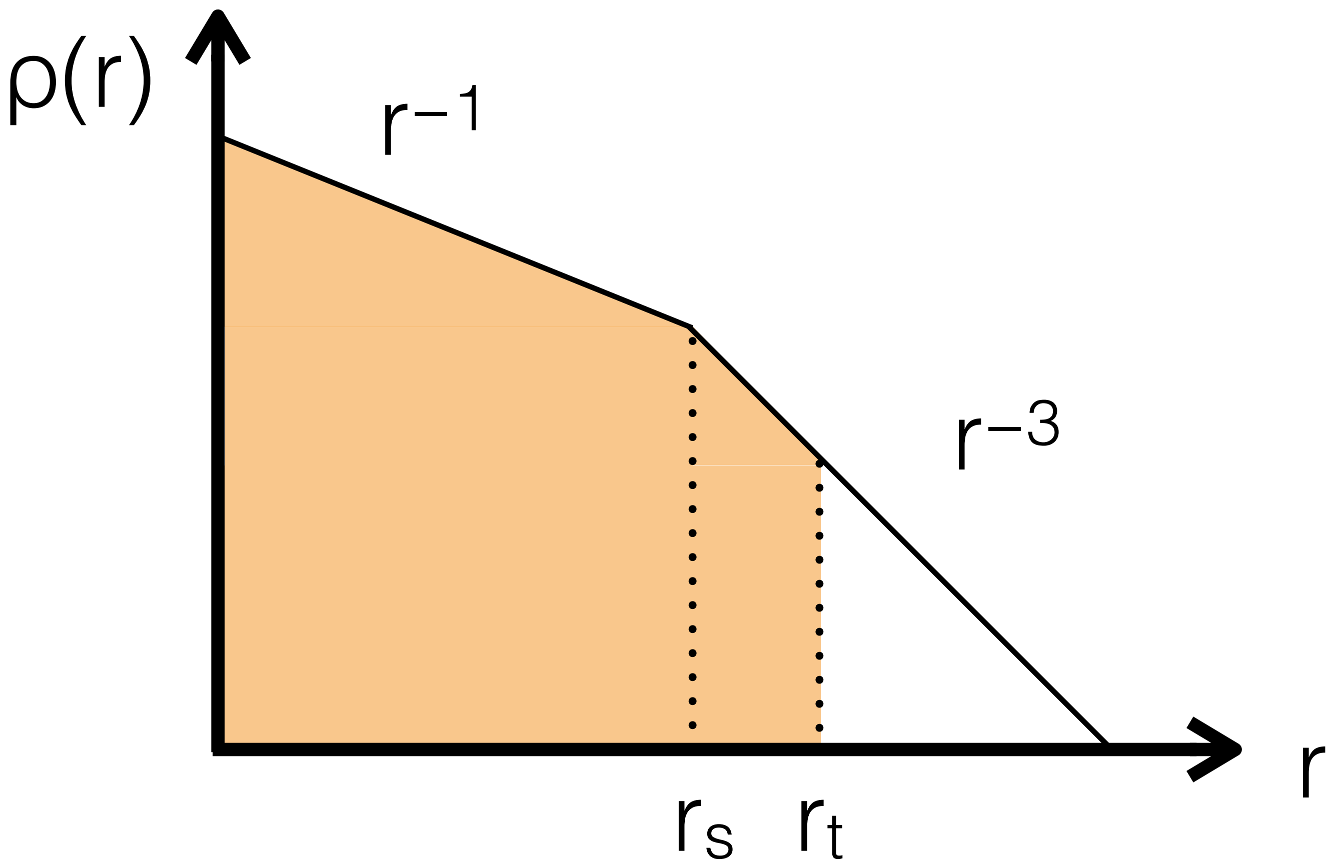

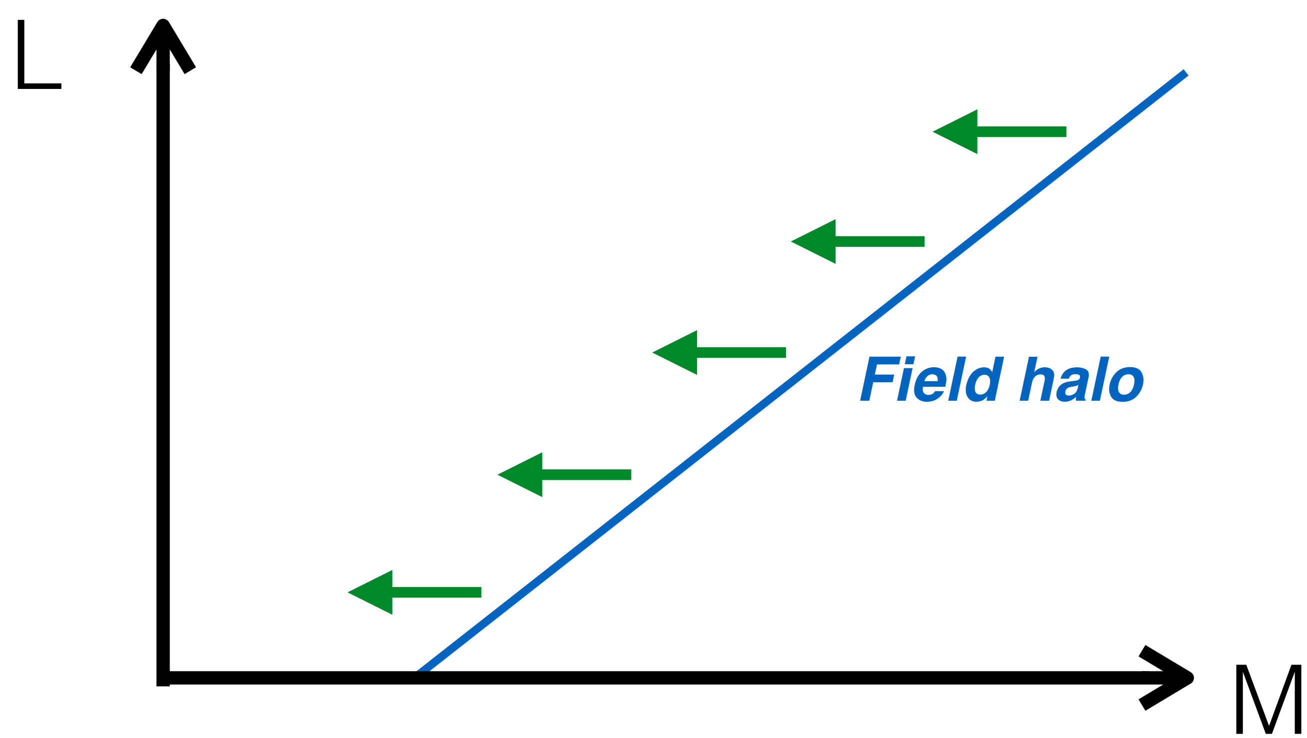

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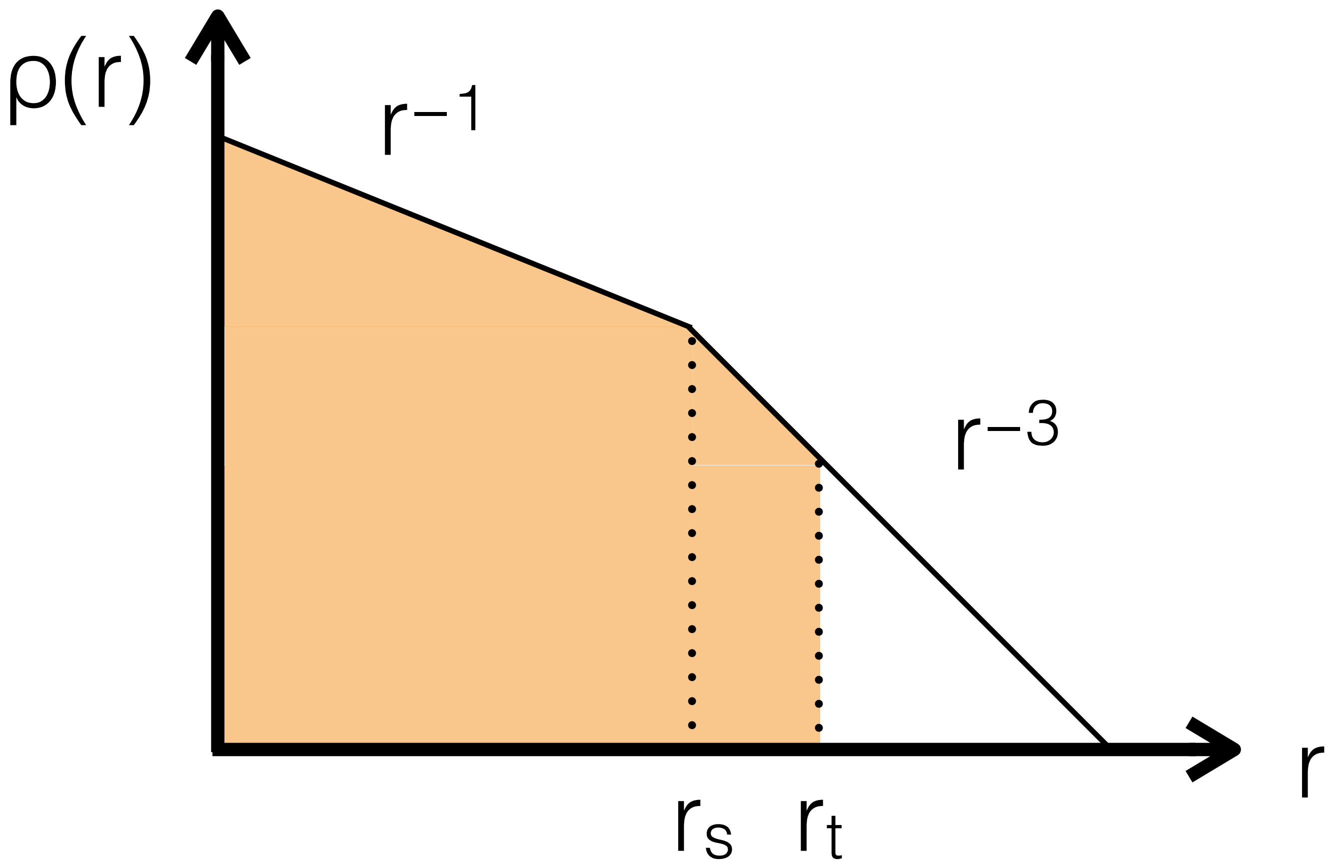

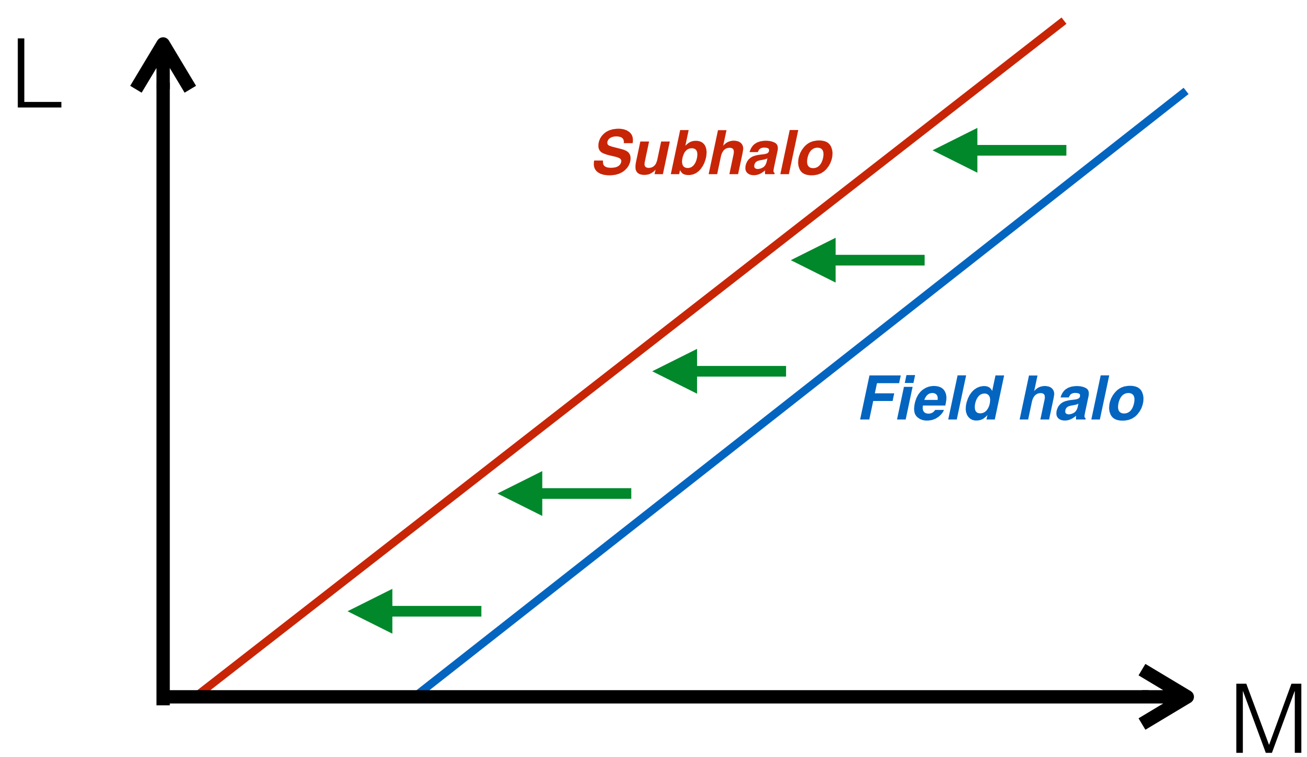

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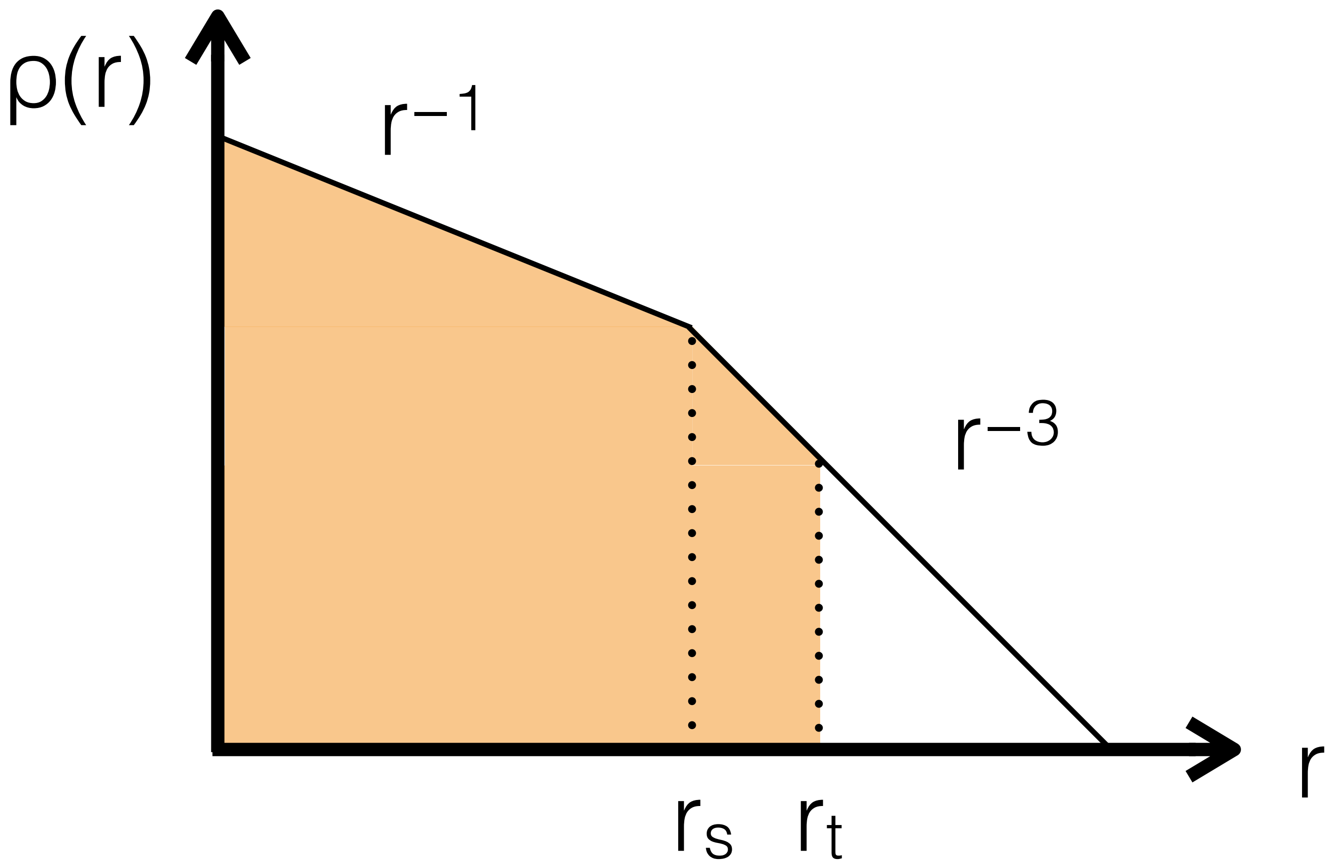

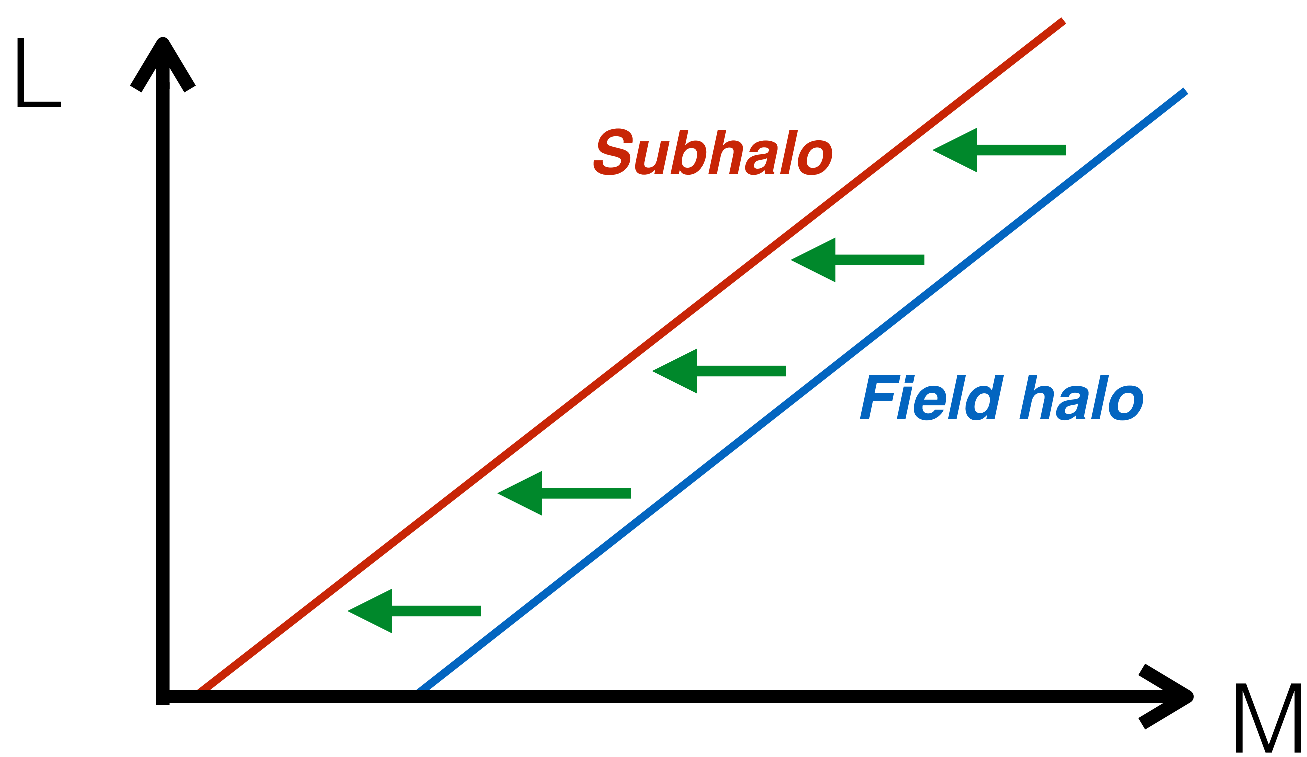

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- But about 90% of annihilation happens within r_s
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  - Mass of the suhalos gets reduced substantially, but luminosity is almost unchanged
  - **This makes subhalos effectively more luminous than field halos!**

Goal

Calculate subhalo boost consistently by taking tidal effects into account

What is the quantitative difference from field halo modeling or phenomenological extrapolation?

Semi-analytic modeling

Ingredients we need…

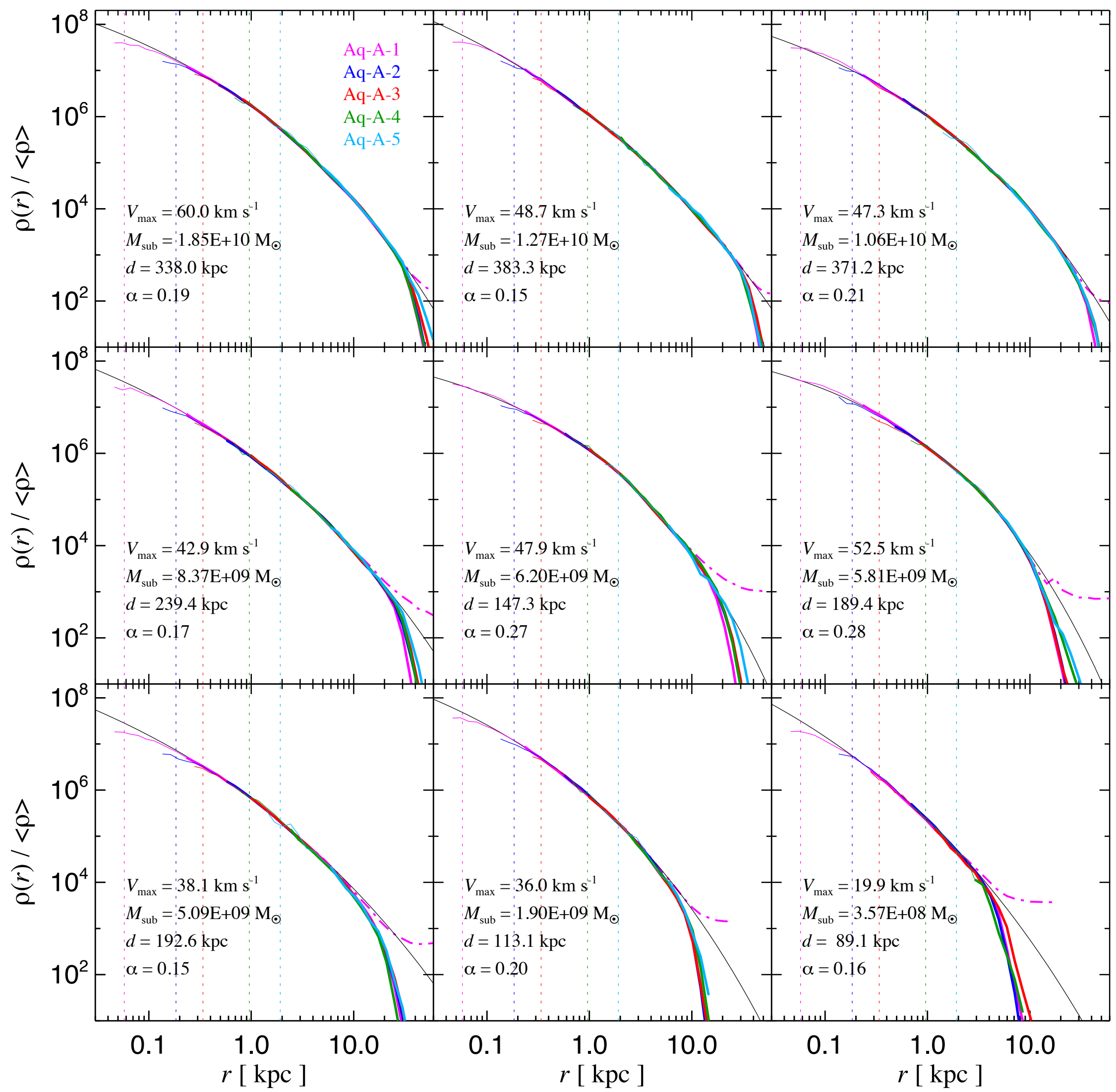
Mass accretion history of the host

Initial density profile of subhalos

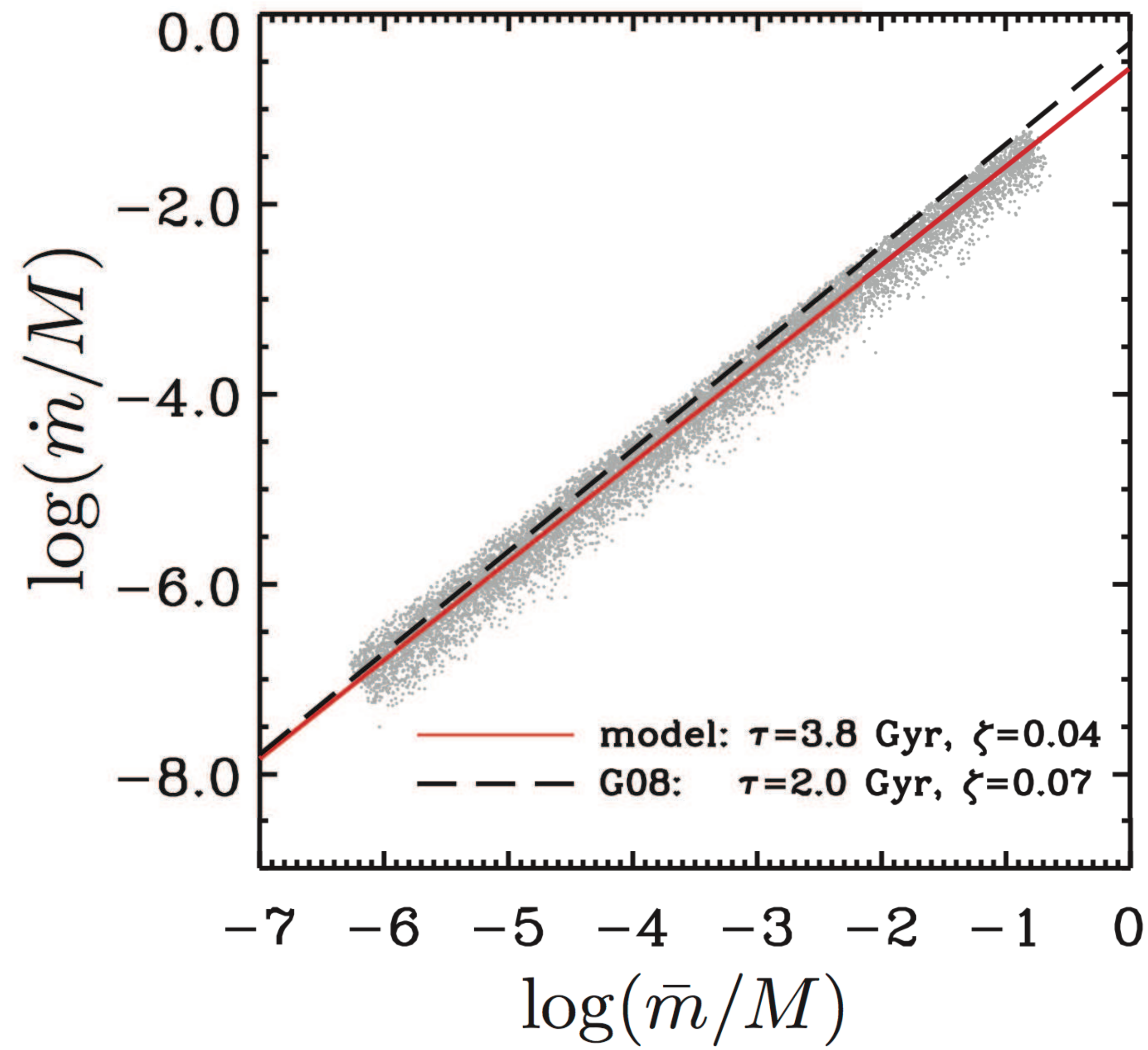
Mass-loss rate of subhalos

Infall distribution of subhalos

Subhalo density profile and mass loss



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

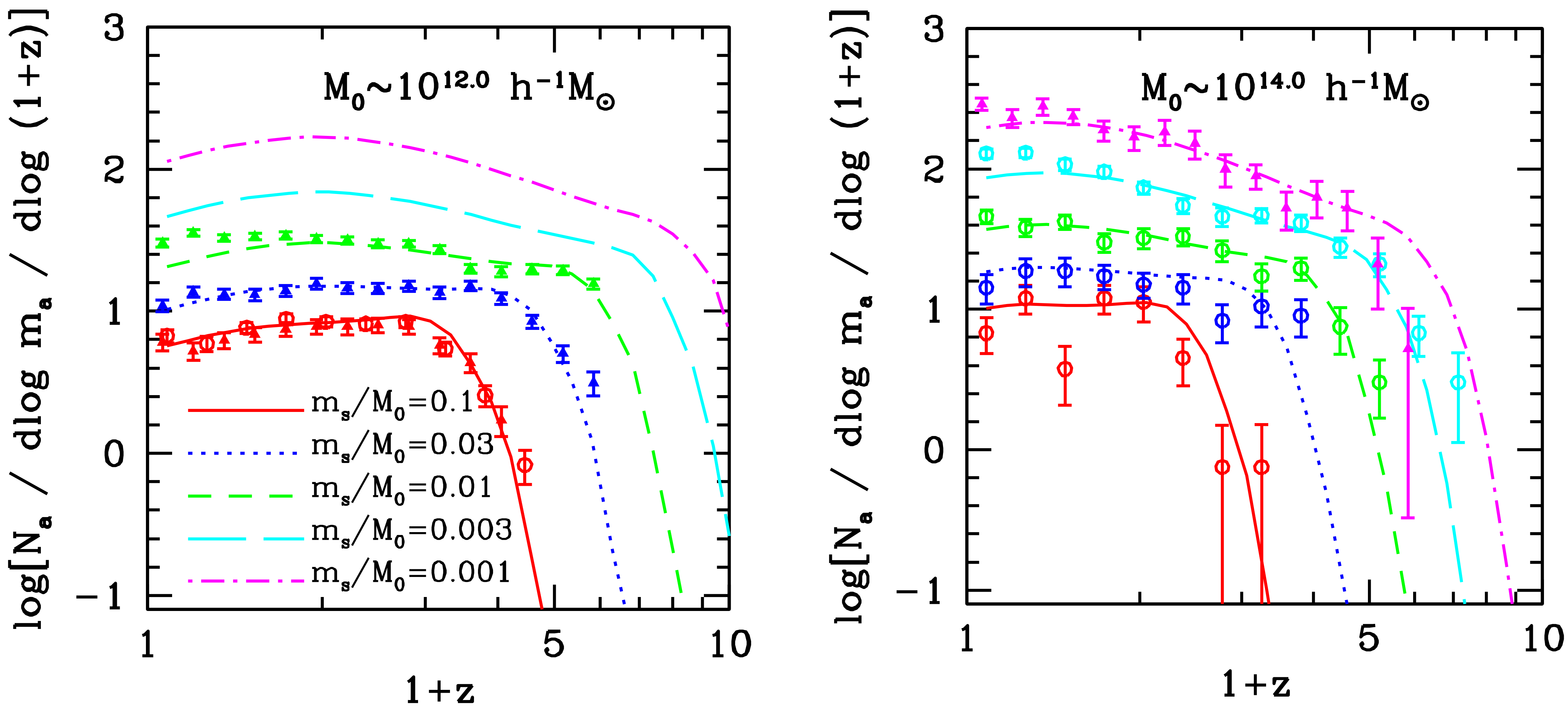


Jiang, van den Bosch, arXiv:1403.6827 [astro-ph.CO]

Truncated NFW:
ρ_s and r_s hardly change

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

Subhalo accretion rate



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

Infall distribution of subhalos:
Extended Press-Schechter formalism

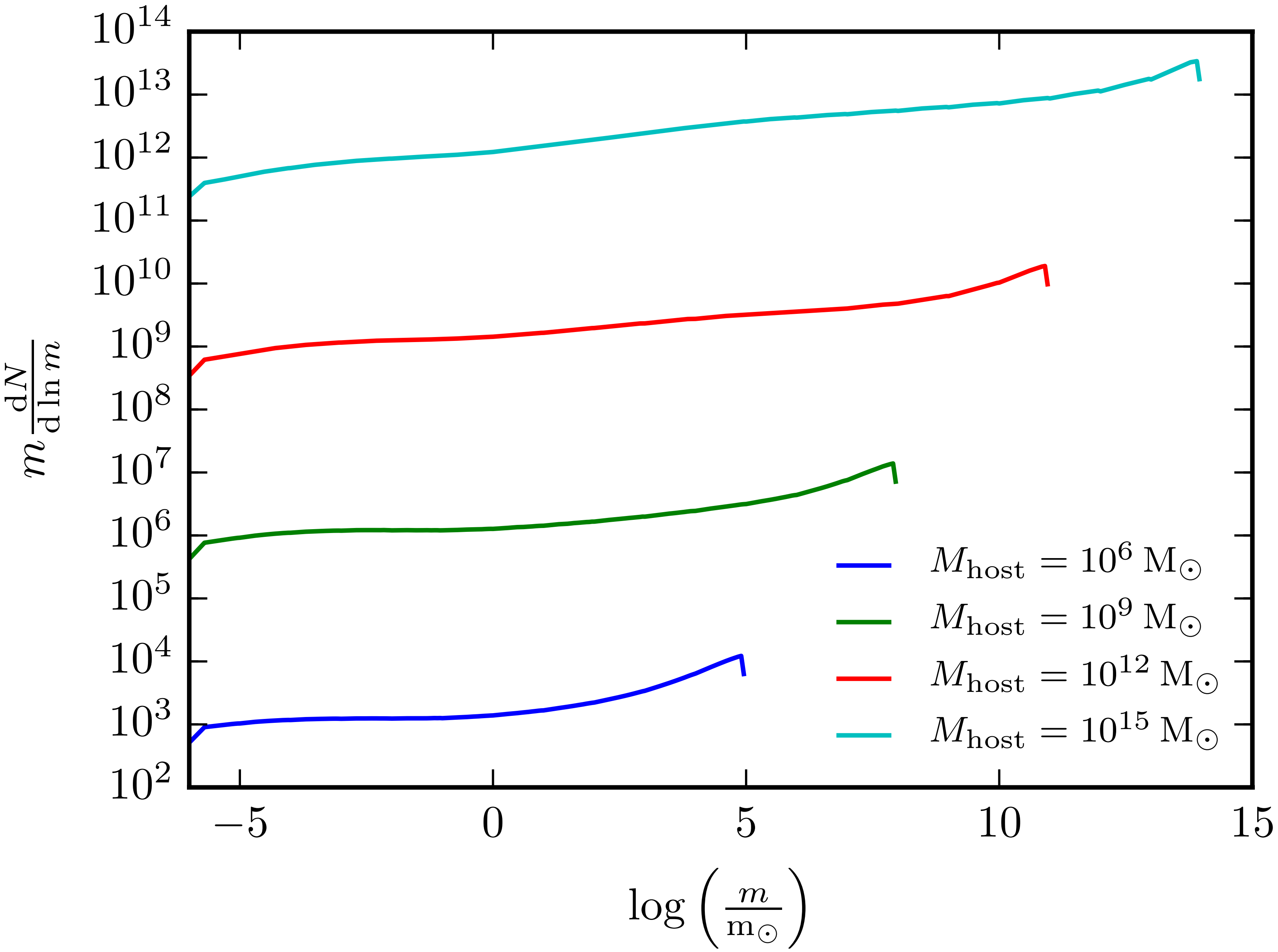
$$\frac{d^2 N}{d\ln m_a d\ln(1+z_a)}$$

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 $c_t = r_t/r_s$

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

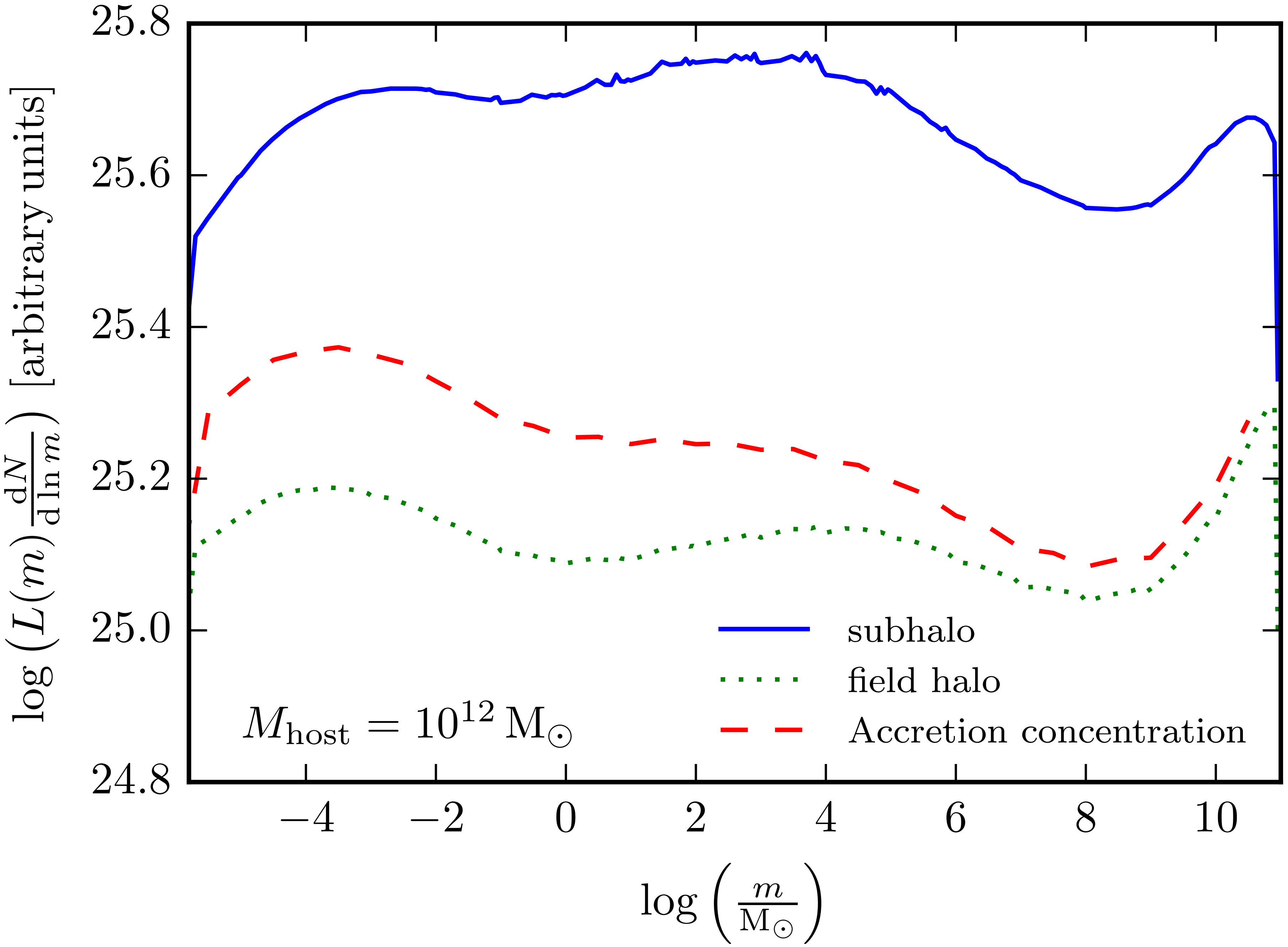
Results: Subhalo mass function



- 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

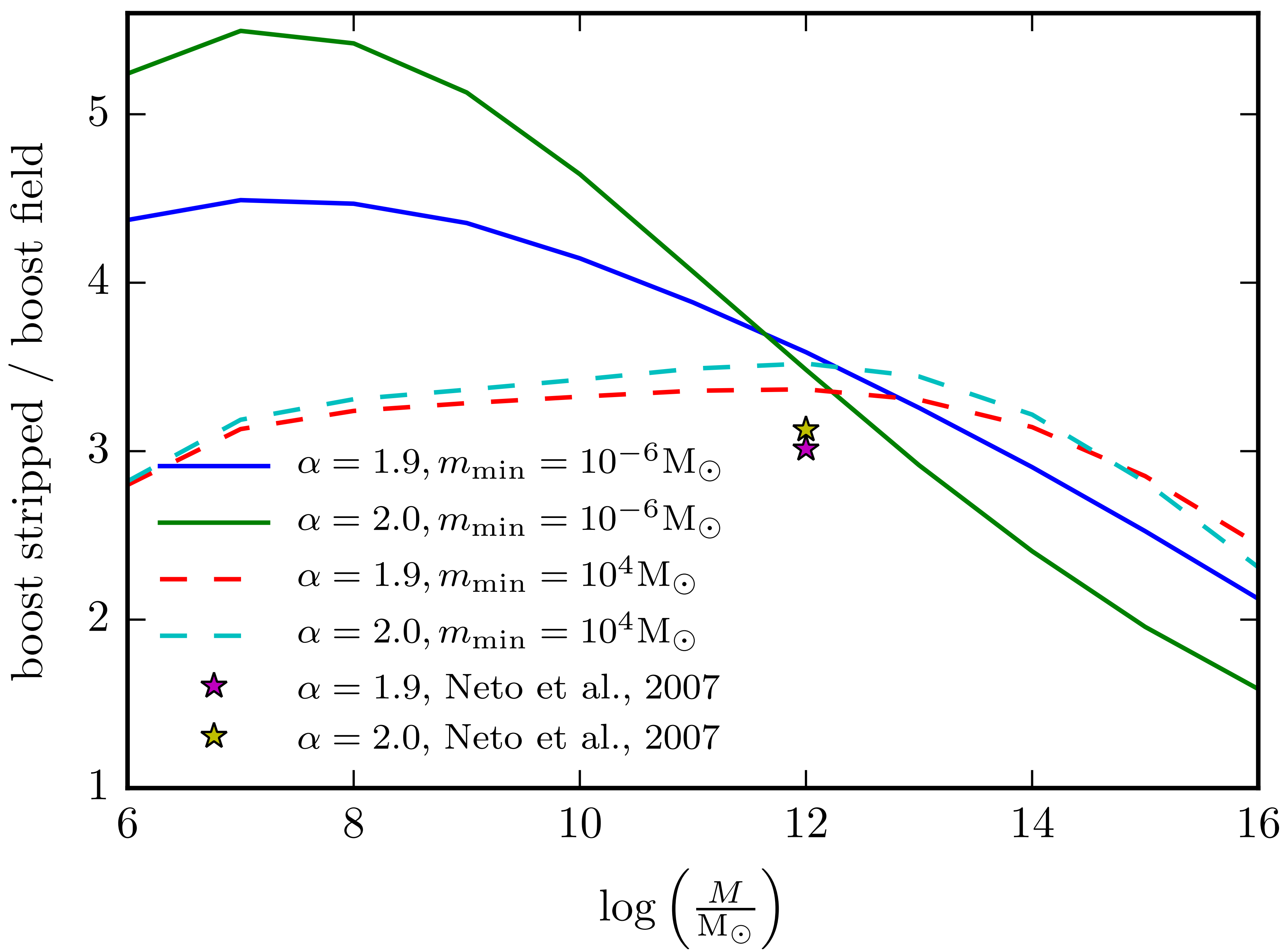
$$L_{\rm sh}(m) = \int_1^{c_{\rm max}} dc_t L_{\rm sh}(m, c_t)\mathcal{P}(m, c_t) \qquad L_{\rm sh}(m, c_t) \sim \rho_s^2 r_s^3 \left[1 - \frac{1}{(1+c_t)^3}\right]$$



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

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

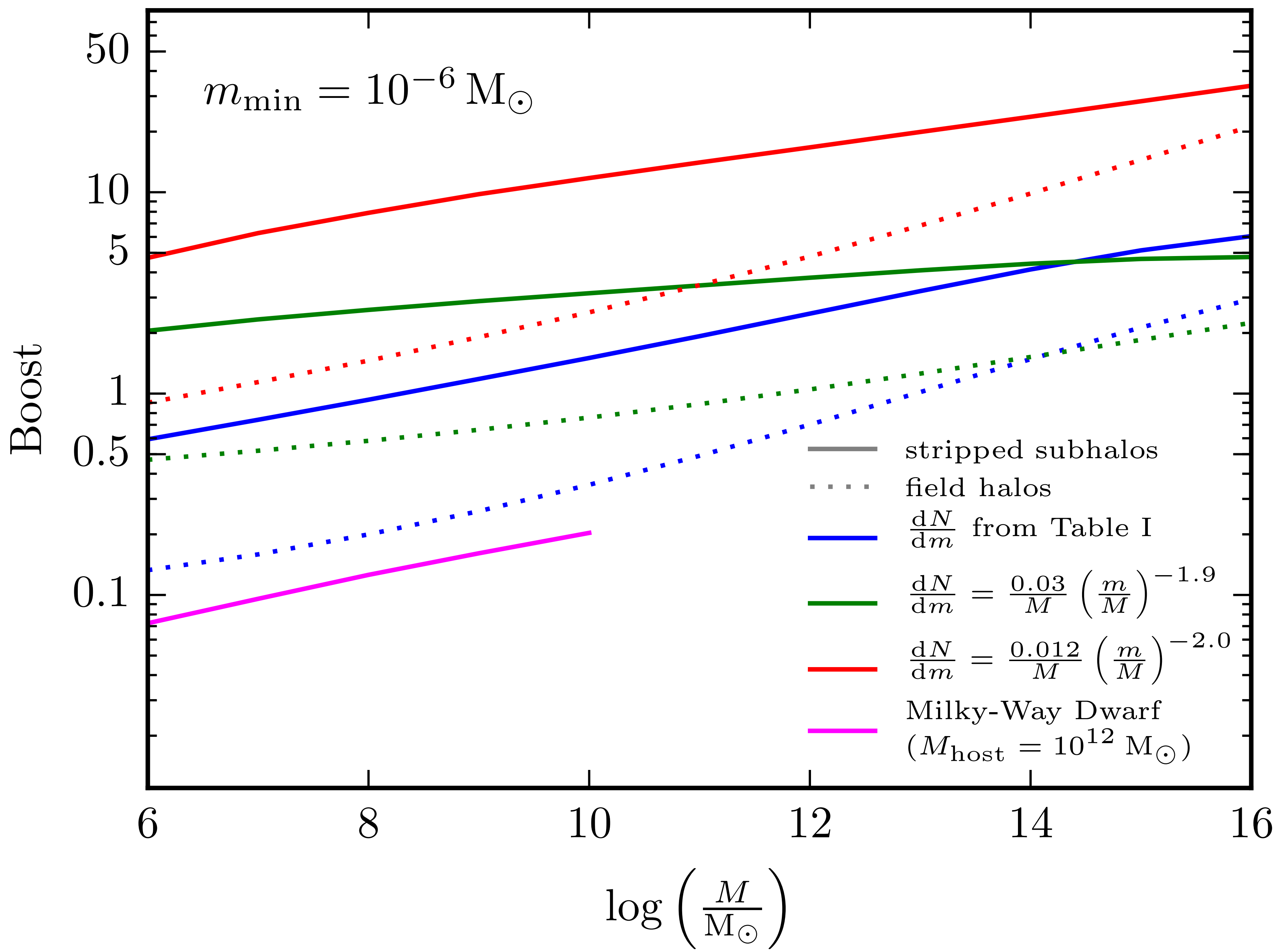
Annihilation boost



- 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

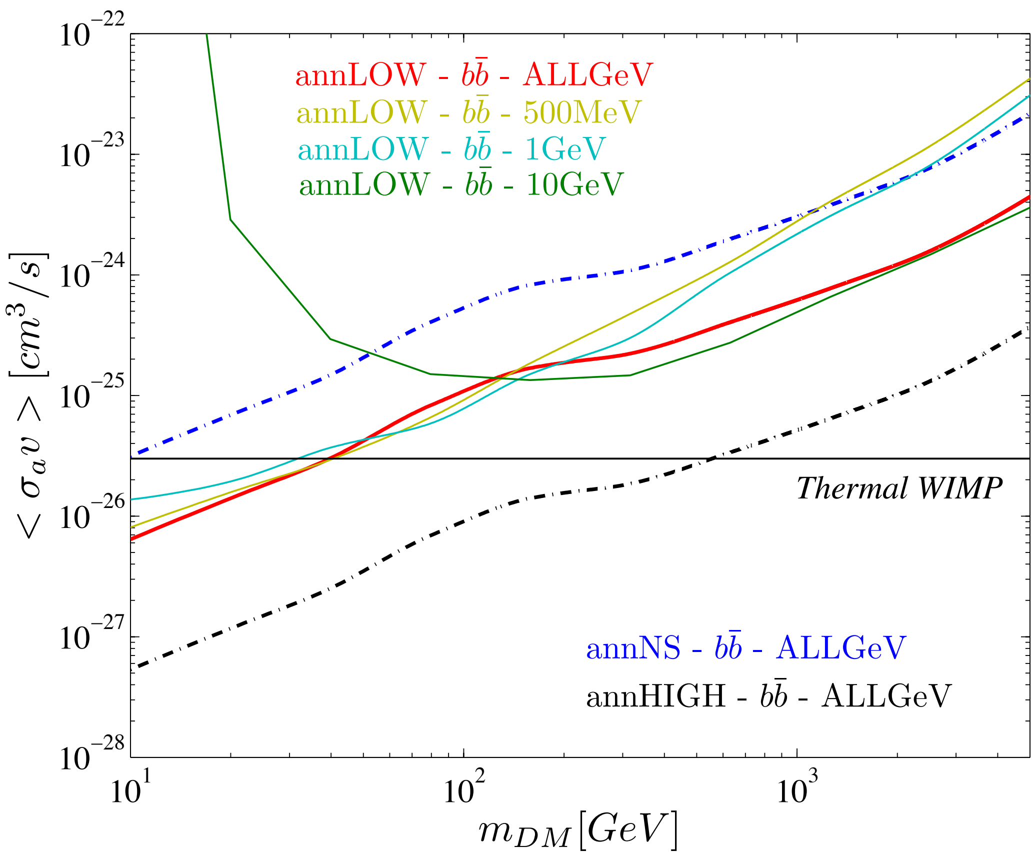
Bartels, Ando, *Phys. Rev D* **92**, 123508, (2015)

Annihilation boost



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

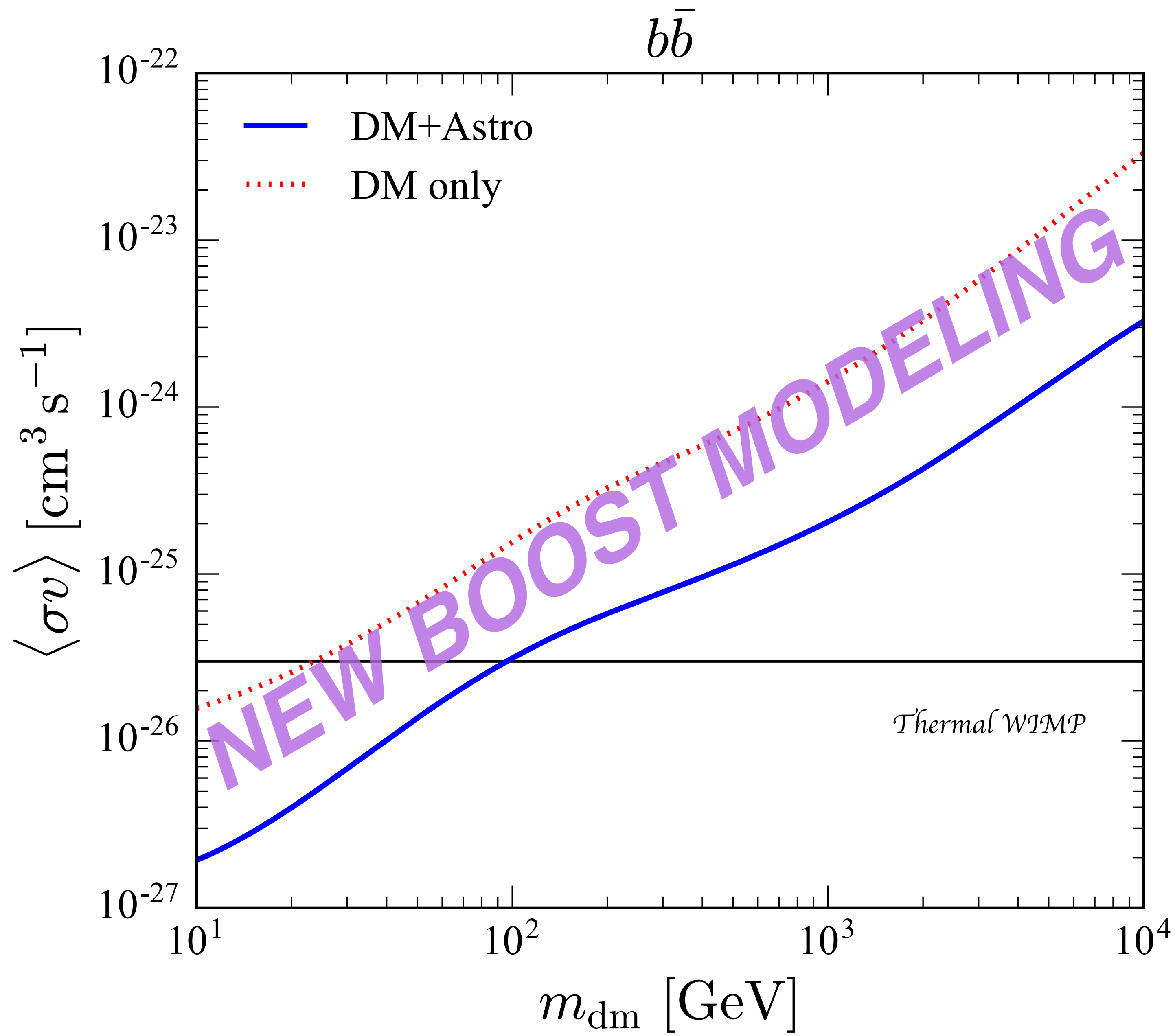
Tomographic constraints on annihilation cross section



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

Solid: field-halo modeling

Dot-dashed: Power-law extrapolation



Ando, Ishiwata, arXiv:1604.02263 [hep-ph]

Take-home message 1

- 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
- **A quick recipe for simple-minded physicists:**
  - **Take your favorite models for subhalo mass function and concentration-mass relation for field halos**
  - **Compute boost factor assuming that there are no tidal stripping**
  - **Multiply this boost by 3, to accommodate the stripping effect**

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

2. "*Tomographic Constraints on High-Energy Neutrinos of Hadronuclear Origin*"

   S. Ando, I. Tamborra, F. Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

This work is

- **NOT** about
  - yet another modeling of whatever sources they are for IceCube neutrinos
- But, it is
  - ***model-independent*** study of any generic source of both gamma rays and neutrinos (i.e., **hadronuclear** source)

Two origins of high-energy neutrinos

Photohadron $p + \gamma \rightarrow \pi^0, \pi^\pm$

Usually, protons have to be very energetic, making pions very energetic too

Hadronuclear $p + p \rightarrow \pi^0, \pi^\pm$

Interaction can happen for low-energy protons

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$$\pi^0 \rightarrow 2\gamma$$

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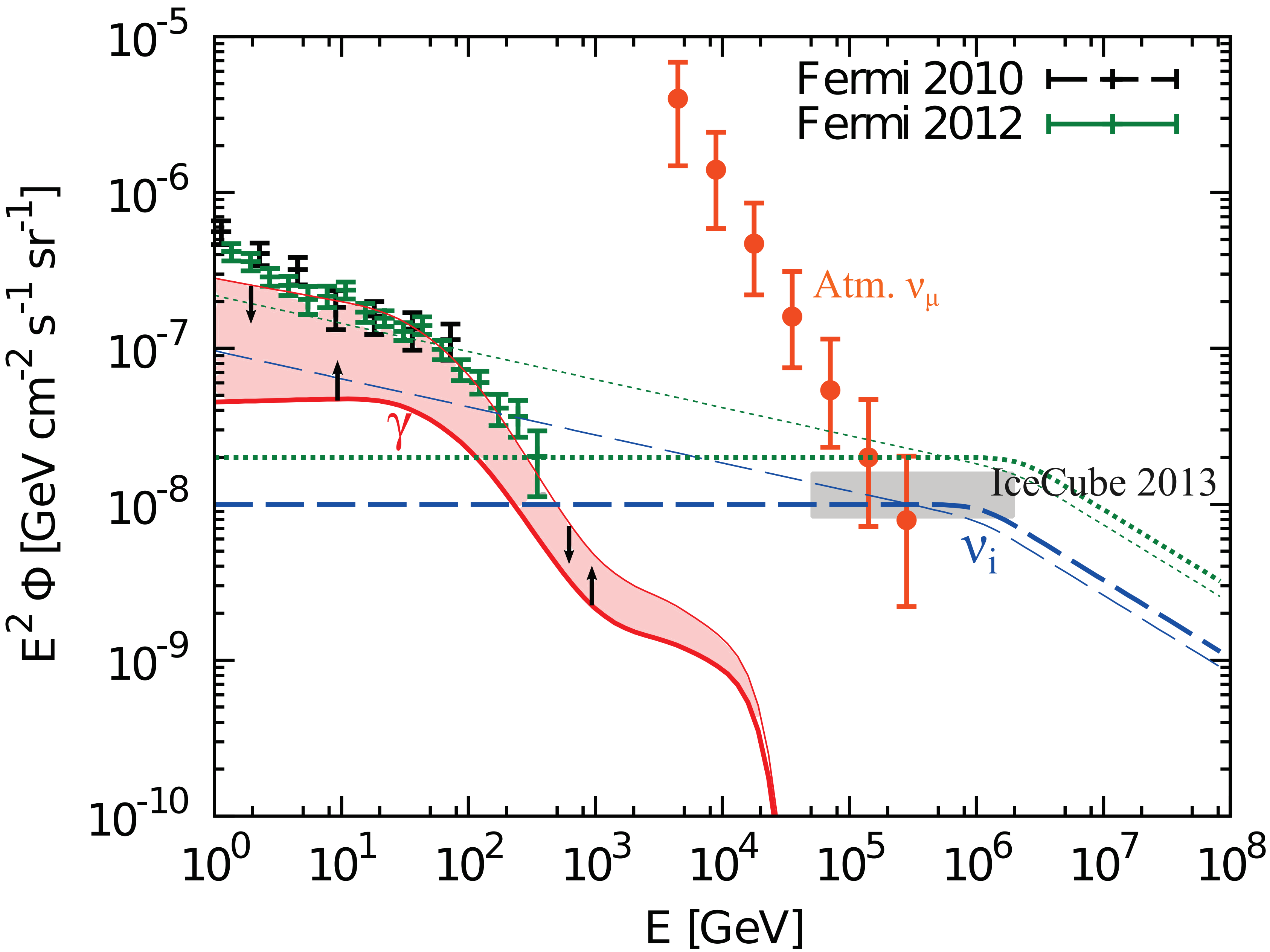
Any (optically thin) hadronuclear sources will produce both neutrinos and gamma rays down to GeV energies

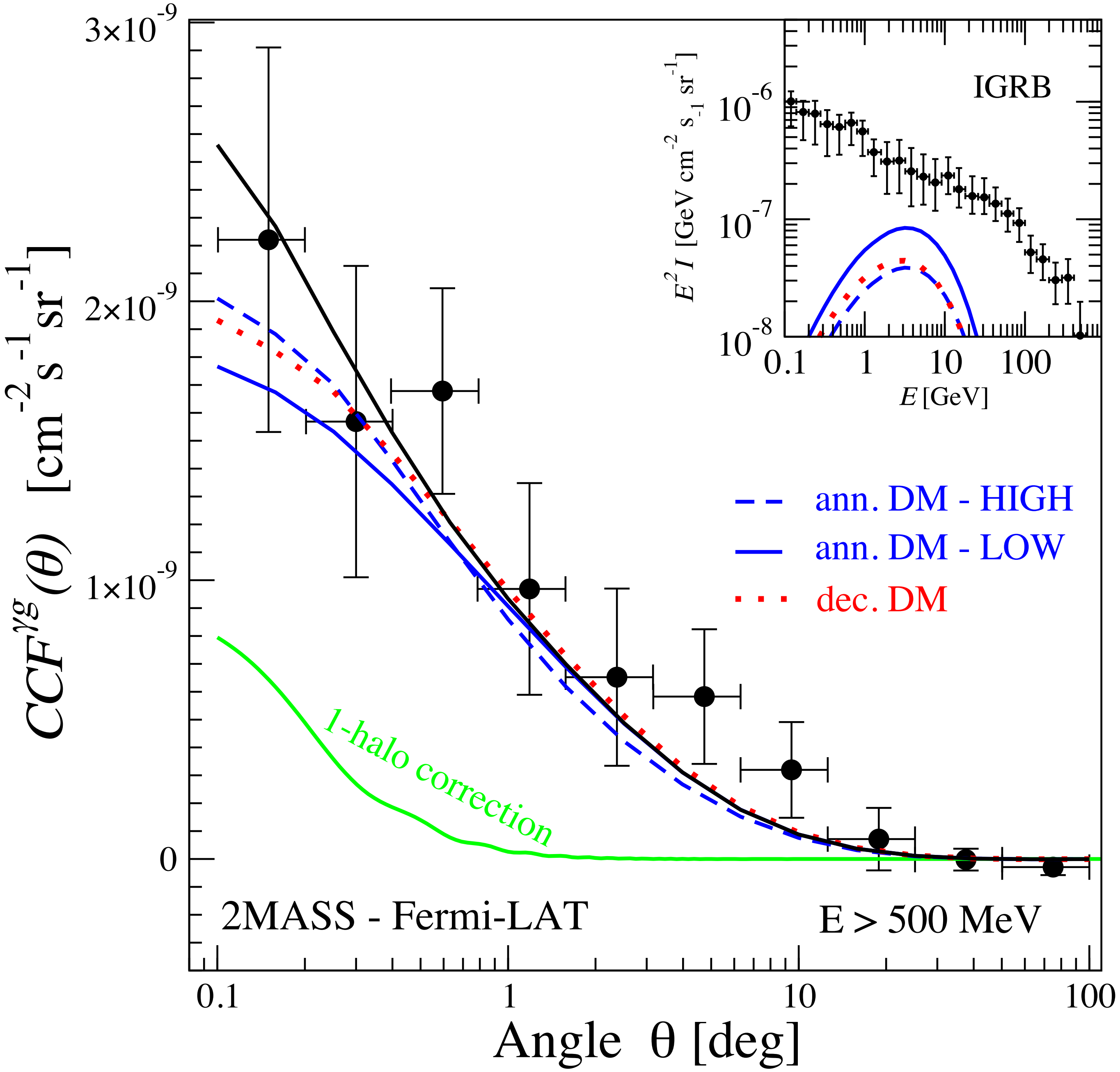
Spectral constraints

Murase, Ahlers, Lacki, *Phys. Rev. D* **88**, 121301 (2013)



- If IceCube neutrinos are explained by hadronuclear sources, they will also produce GeV gamma rays
- These cannot overshoot the Fermi-LAT measurement of IGRB
- Implication: Spectrum cannot be softer than $E^{-2.2}$

Cross correlation between IGRB and galaxies



Regis et al., *Phys. Rev. Lett.* **114**, 241301 (2015)

- Yet another probe of gamma-ray sources due to recent measurements of cross correlations between IGRB and galaxy catalogs
- Proven to be strong probe of dark matter annihilation or decay
- *This can also be applied to neutrino sources if they are of hadronuclear origin!*

Assumptions

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1. Energy **spectrum** is power law

$$\frac{dN}{dE} \propto E^{-\alpha}$$

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$$\mathcal{E} \propto (1+z)^{\delta}, \text{ for } z < 1.5$$

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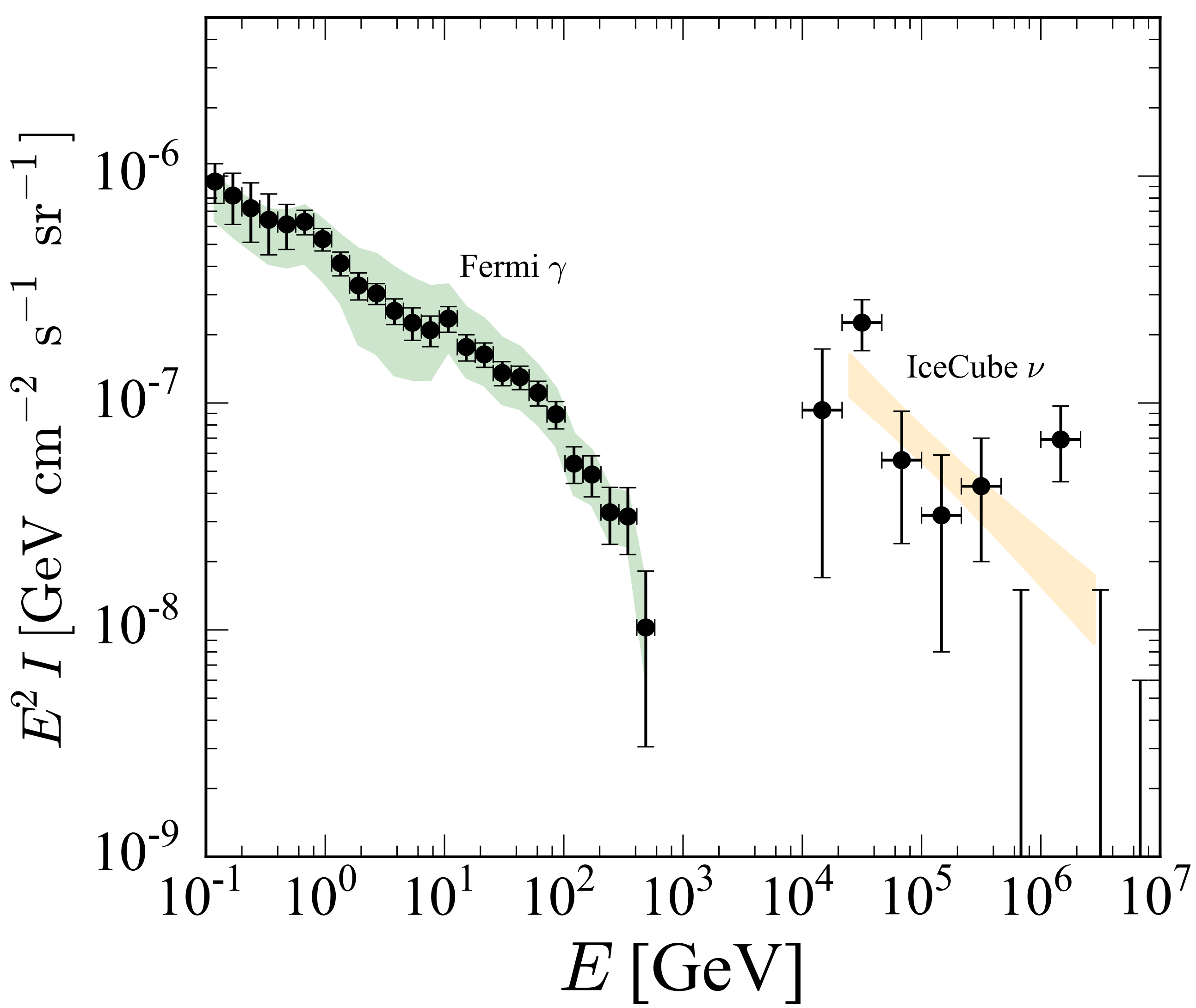
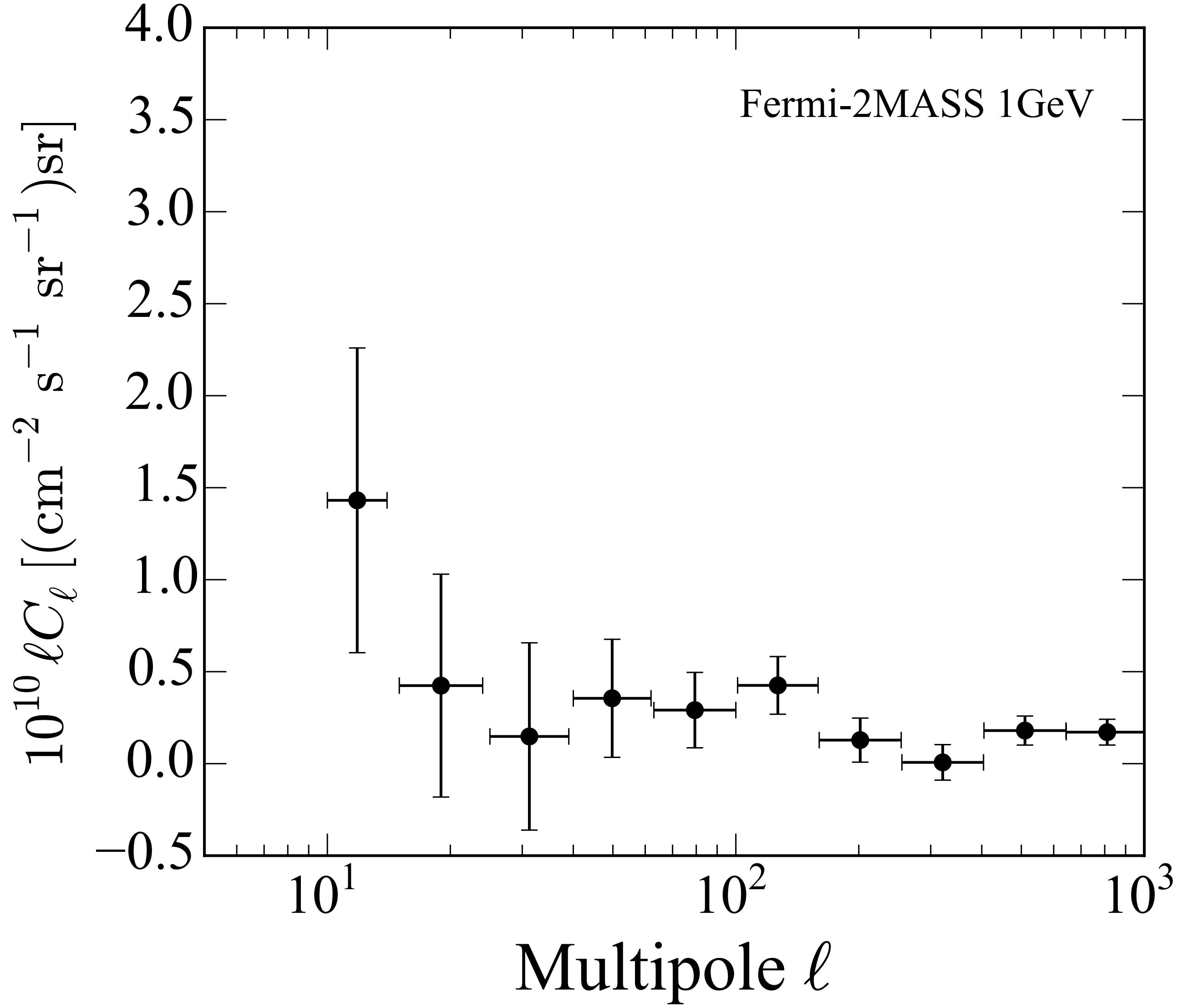
3. Sources **trace underlying dark matter** distribution in an unbiased way

$$P_{\gamma \mathrm{g}}(k,z) = b_{\gamma} b_{\mathrm{g}} P_{\mathrm{m}}(k,z) \ \text{with } b_{\gamma} = 1$$

Spectral constraints





Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

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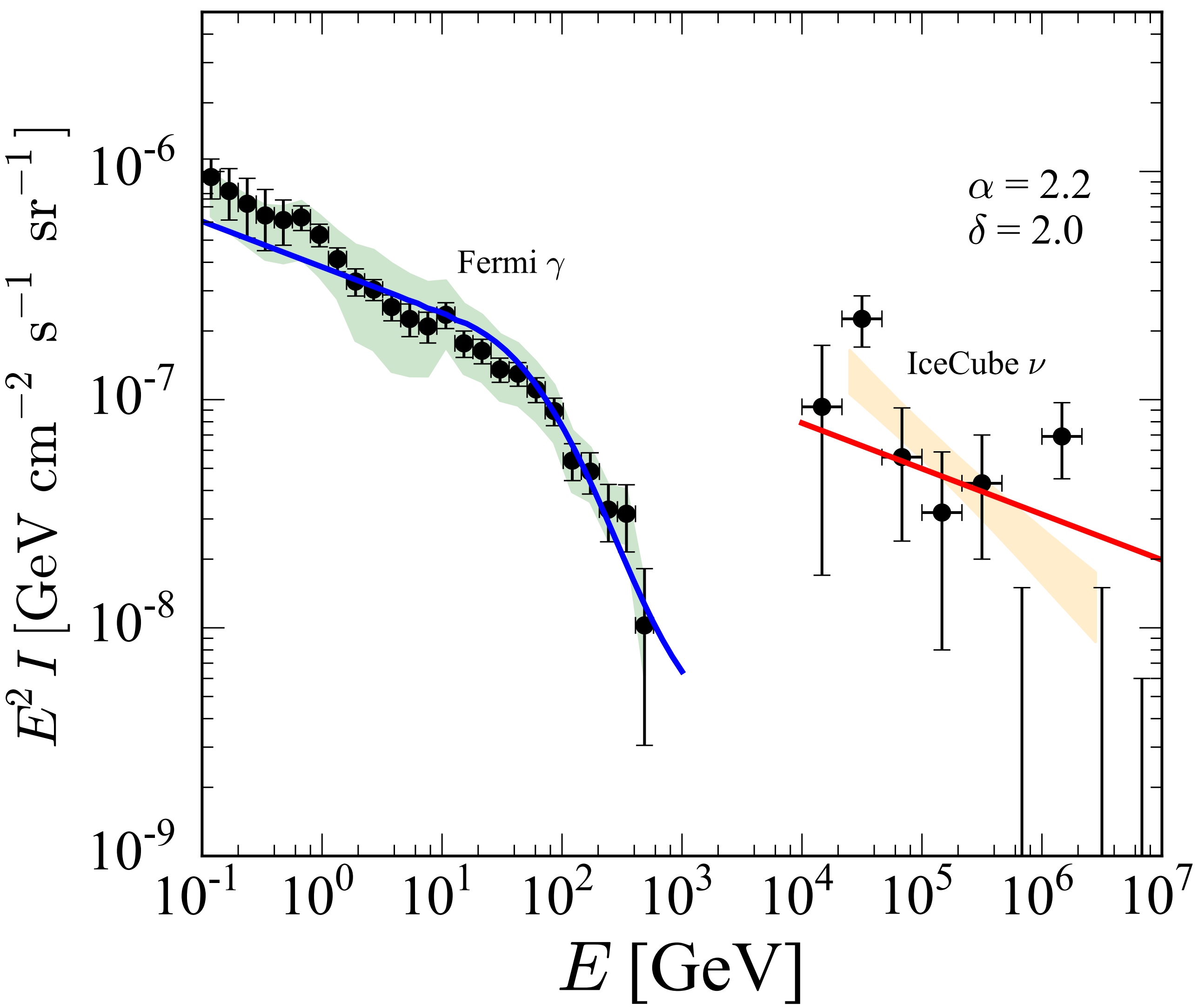

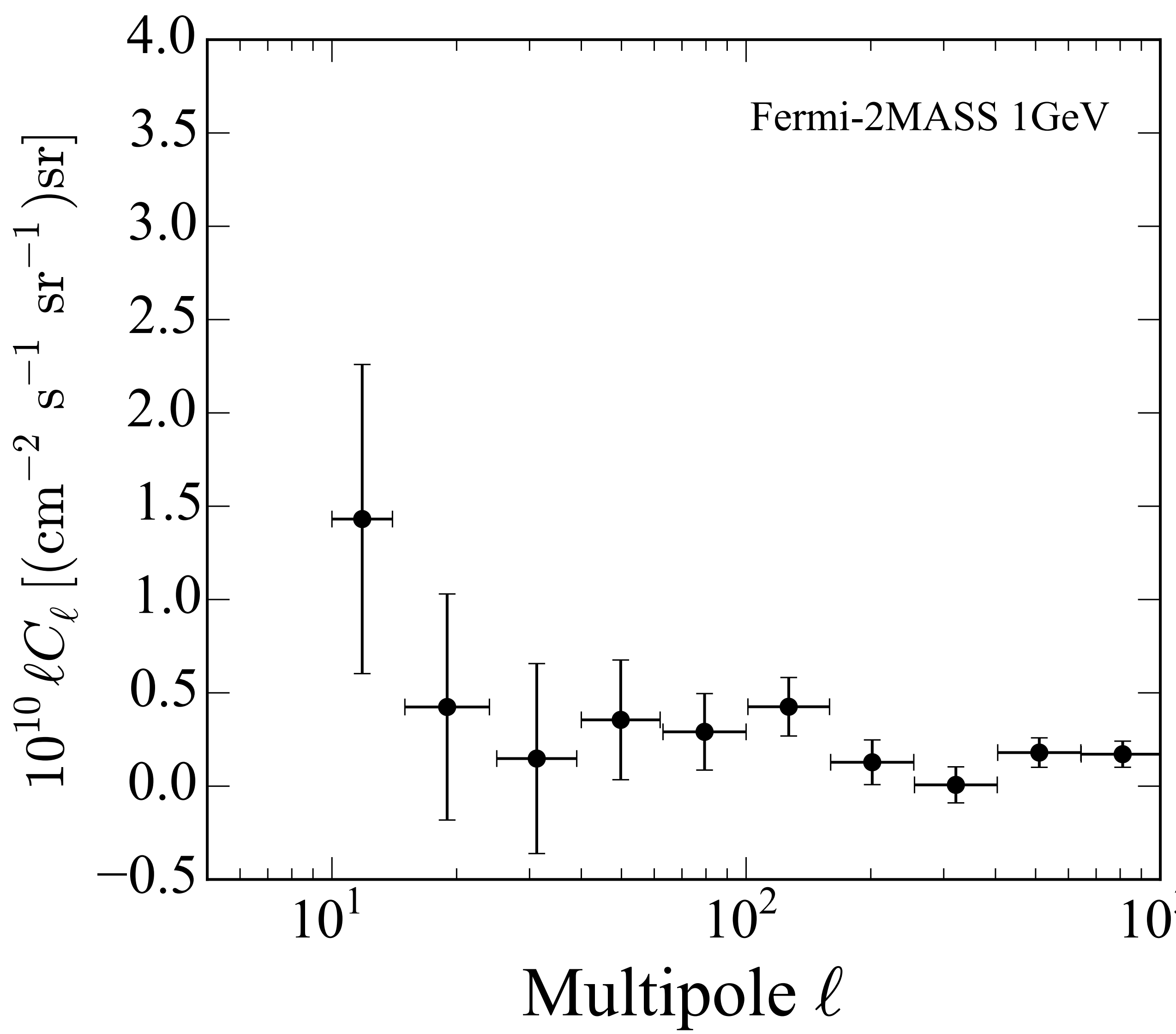

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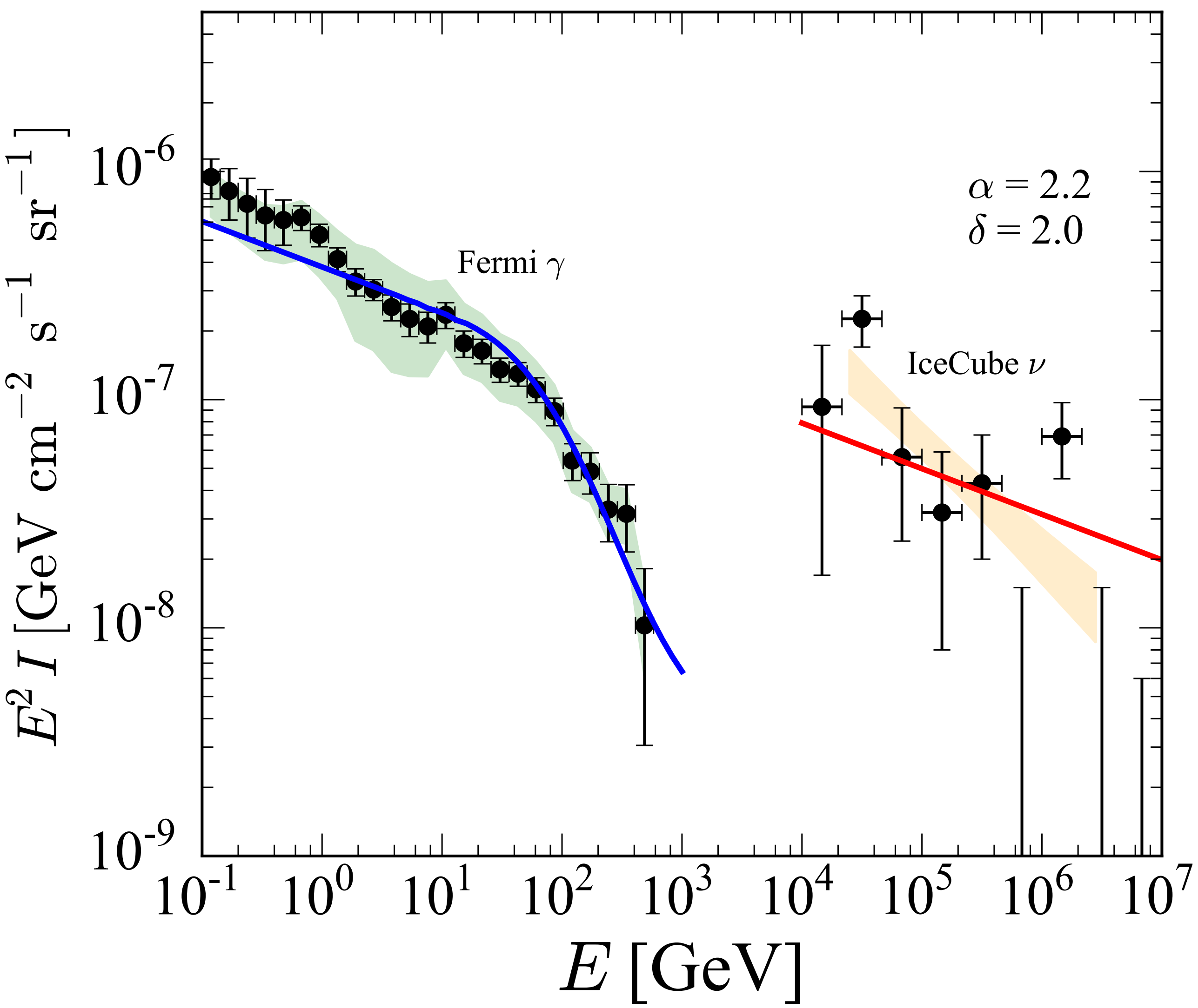

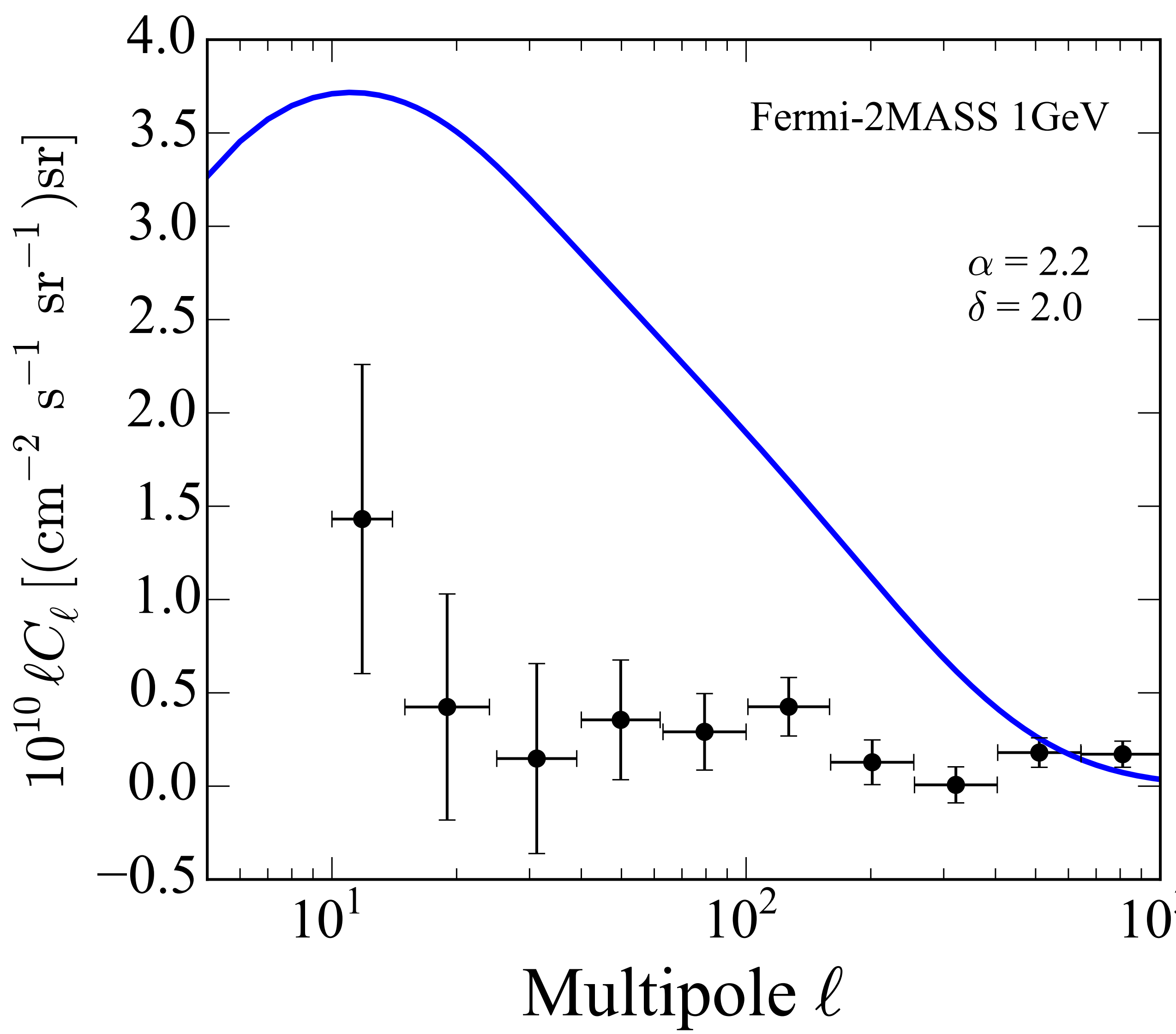

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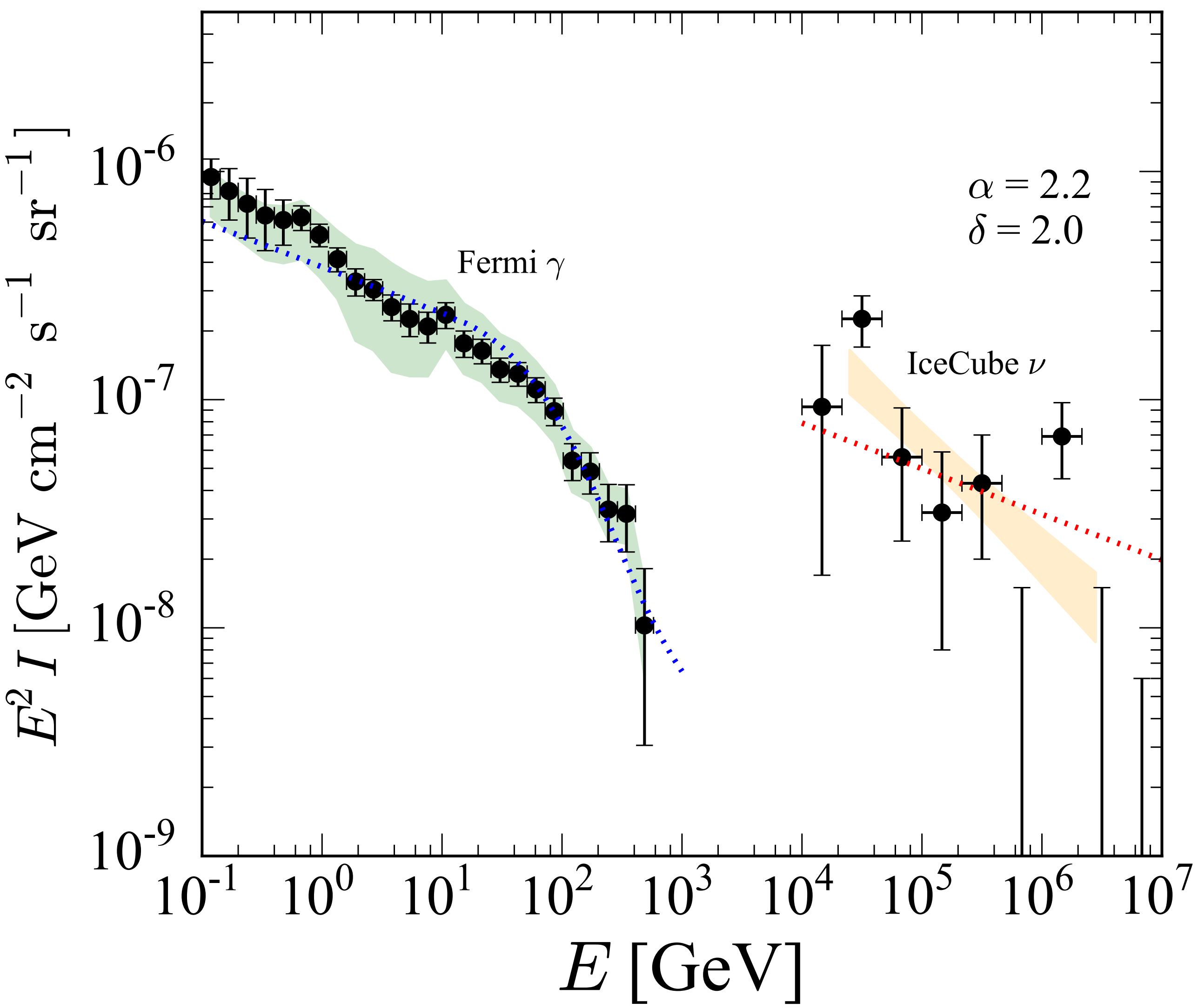
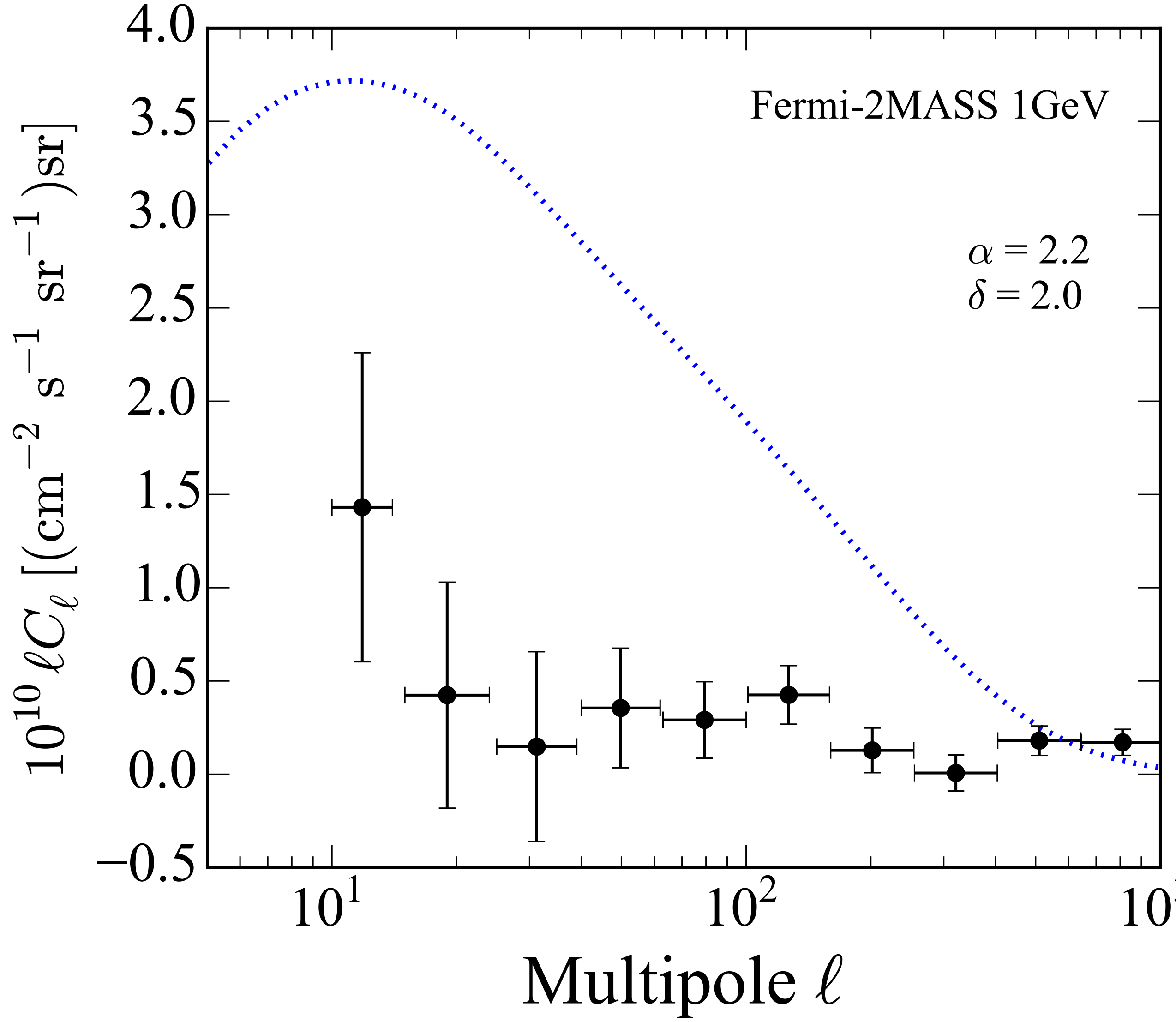
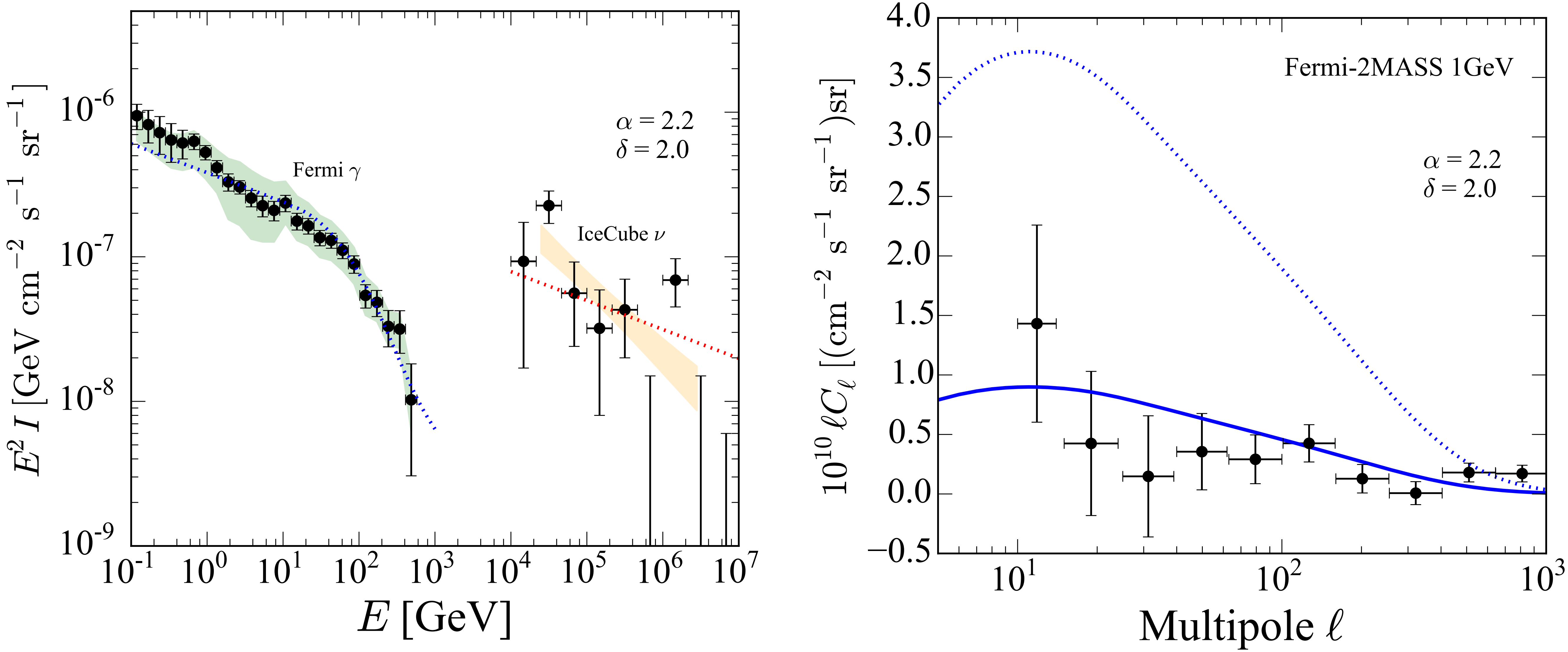
Tomographic constraints





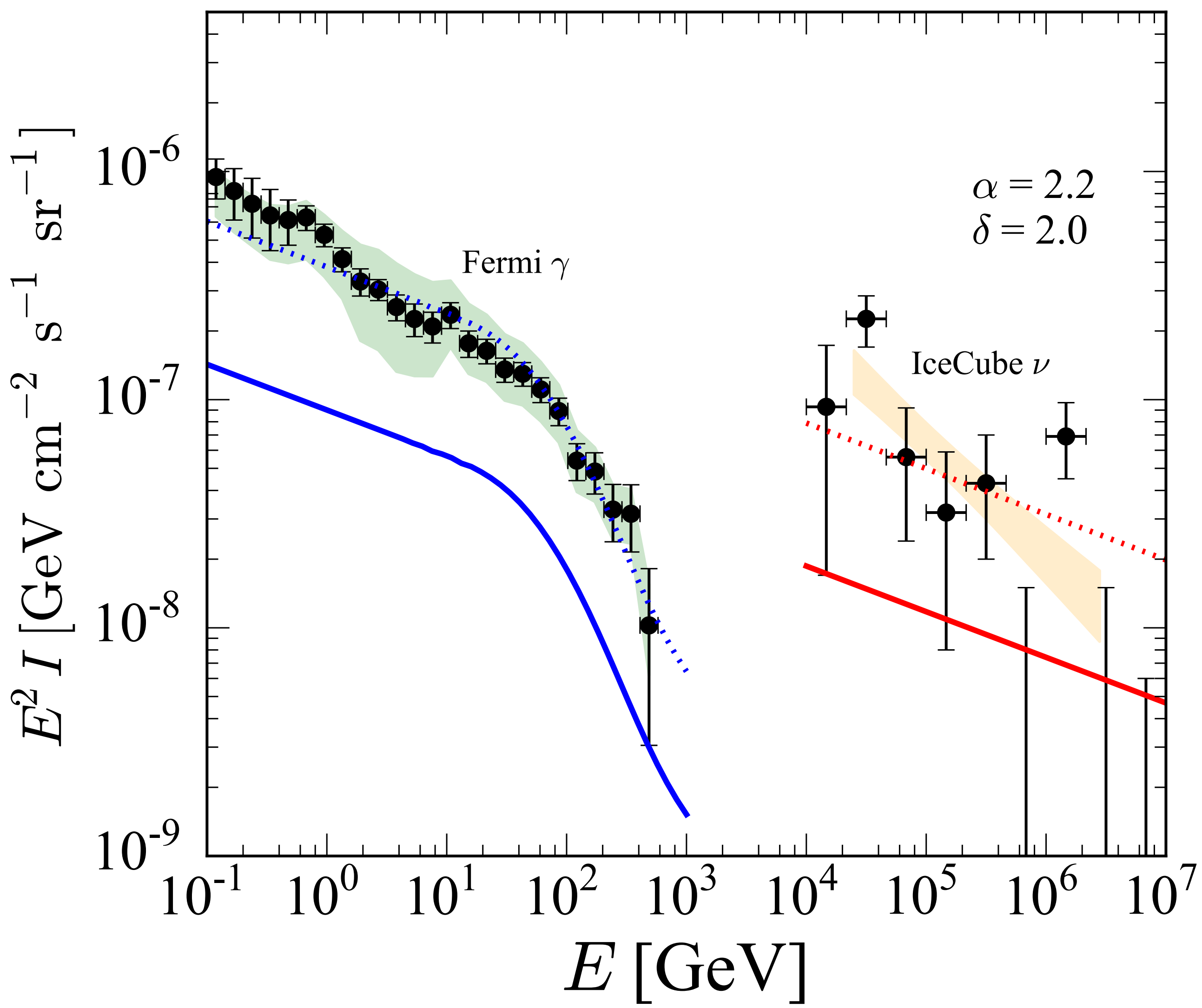
Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

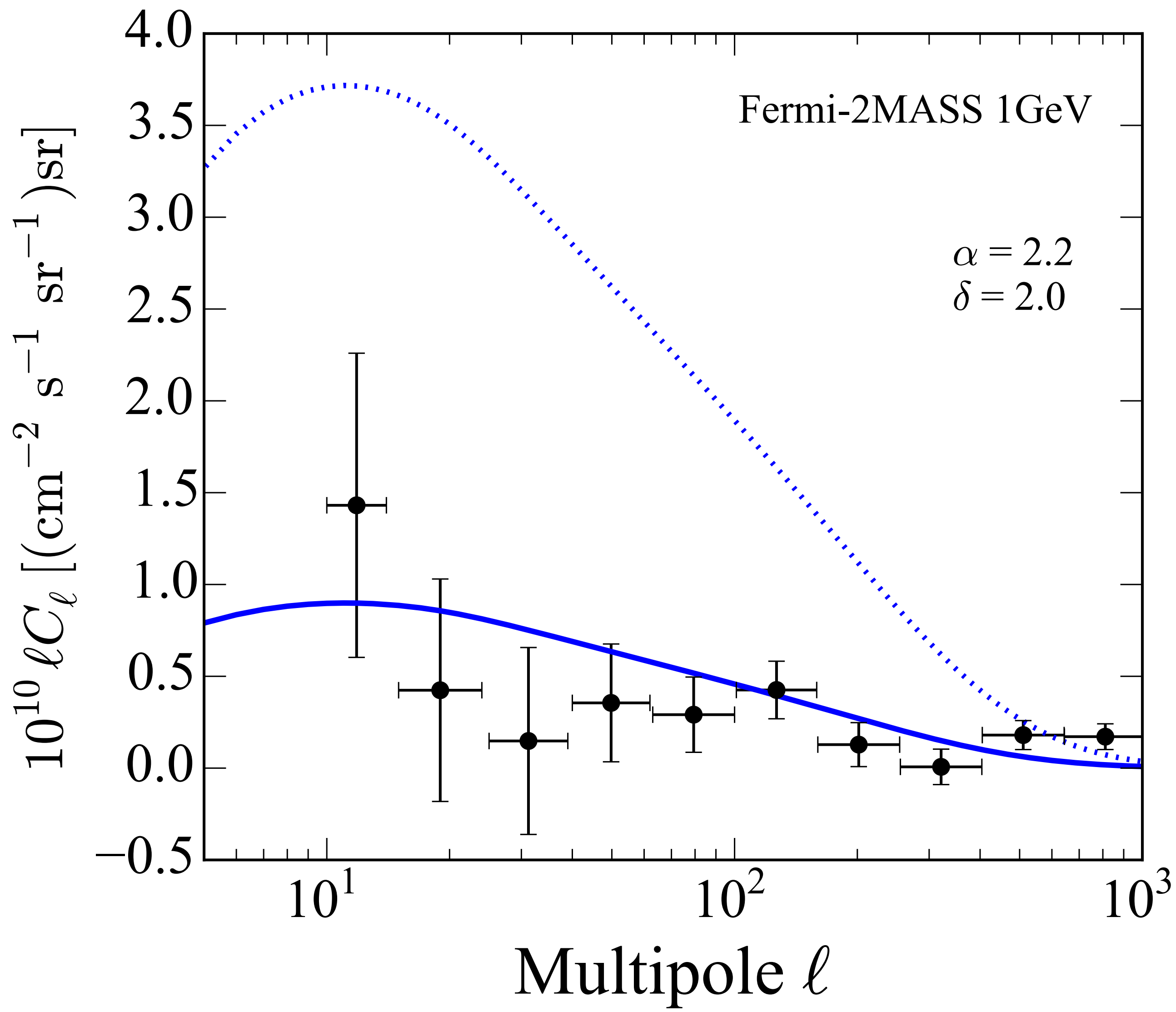
Tomographic constraints



Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

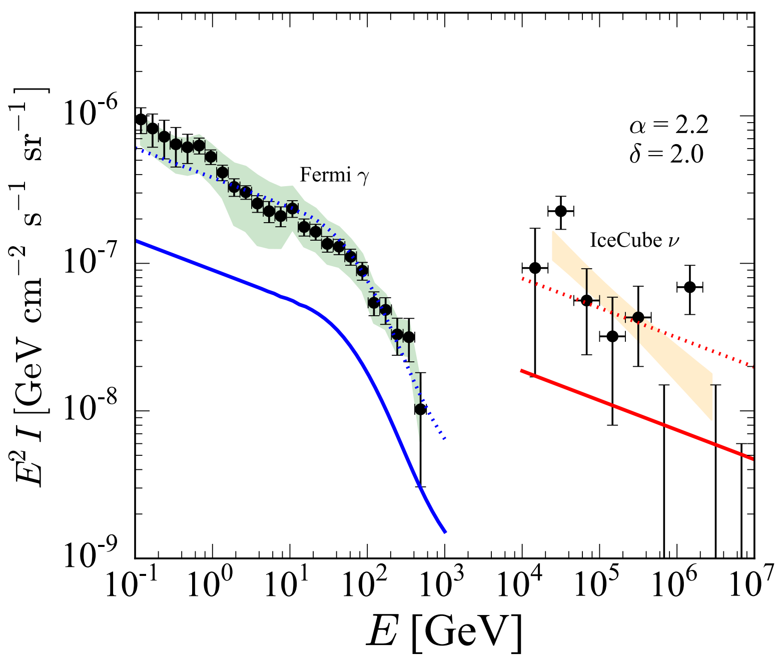
Tomographic constraints

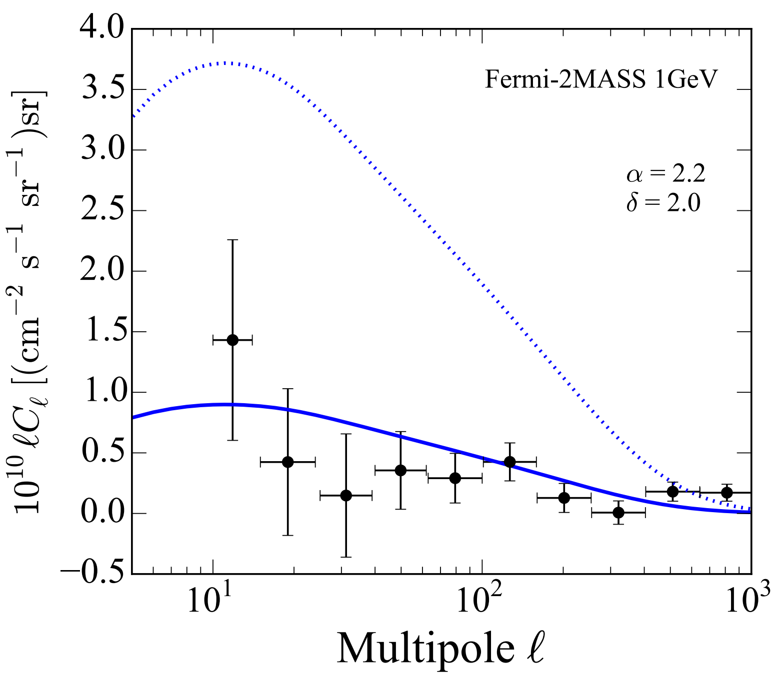




Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

Dependence on **α** and **δ**

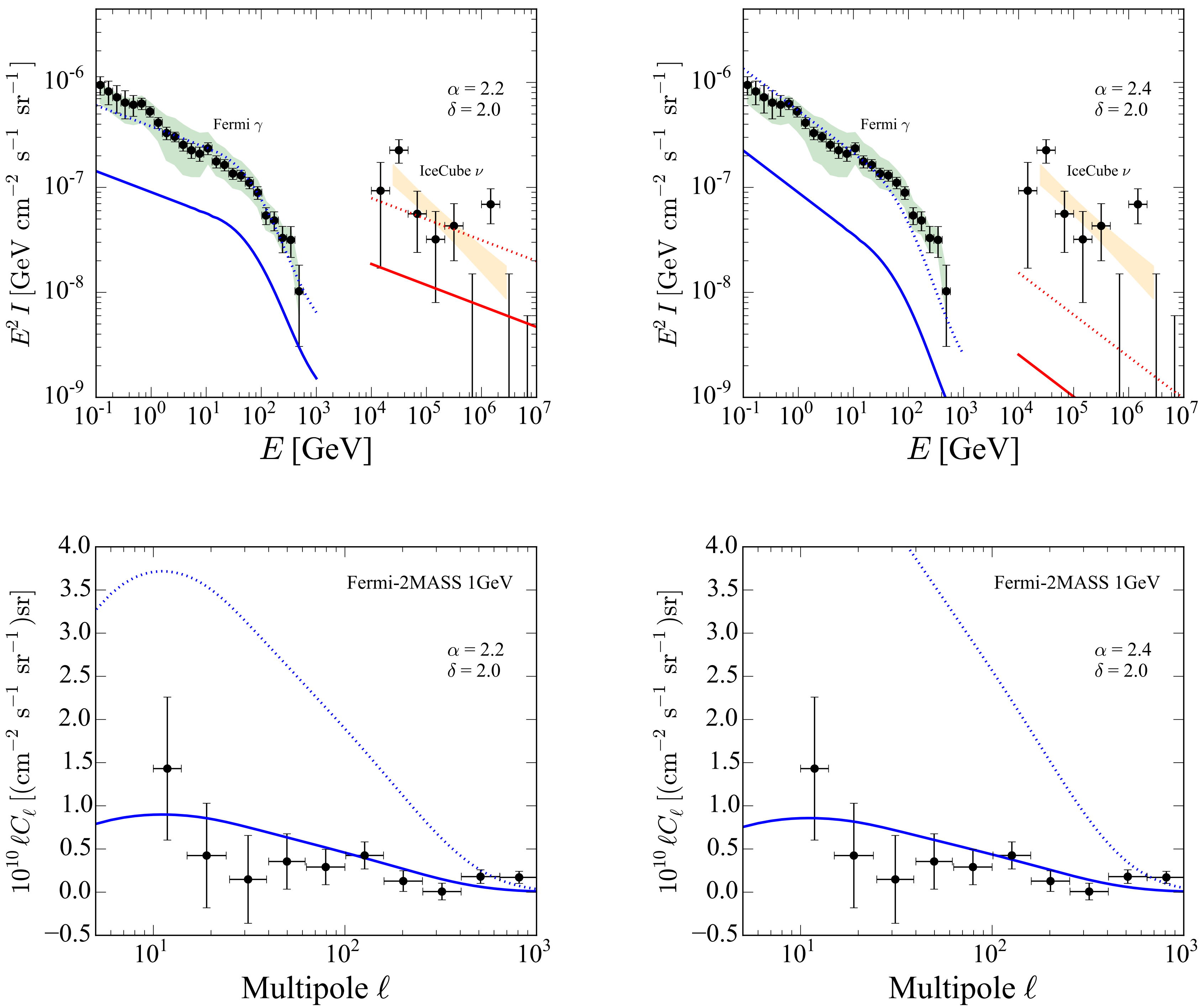




Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

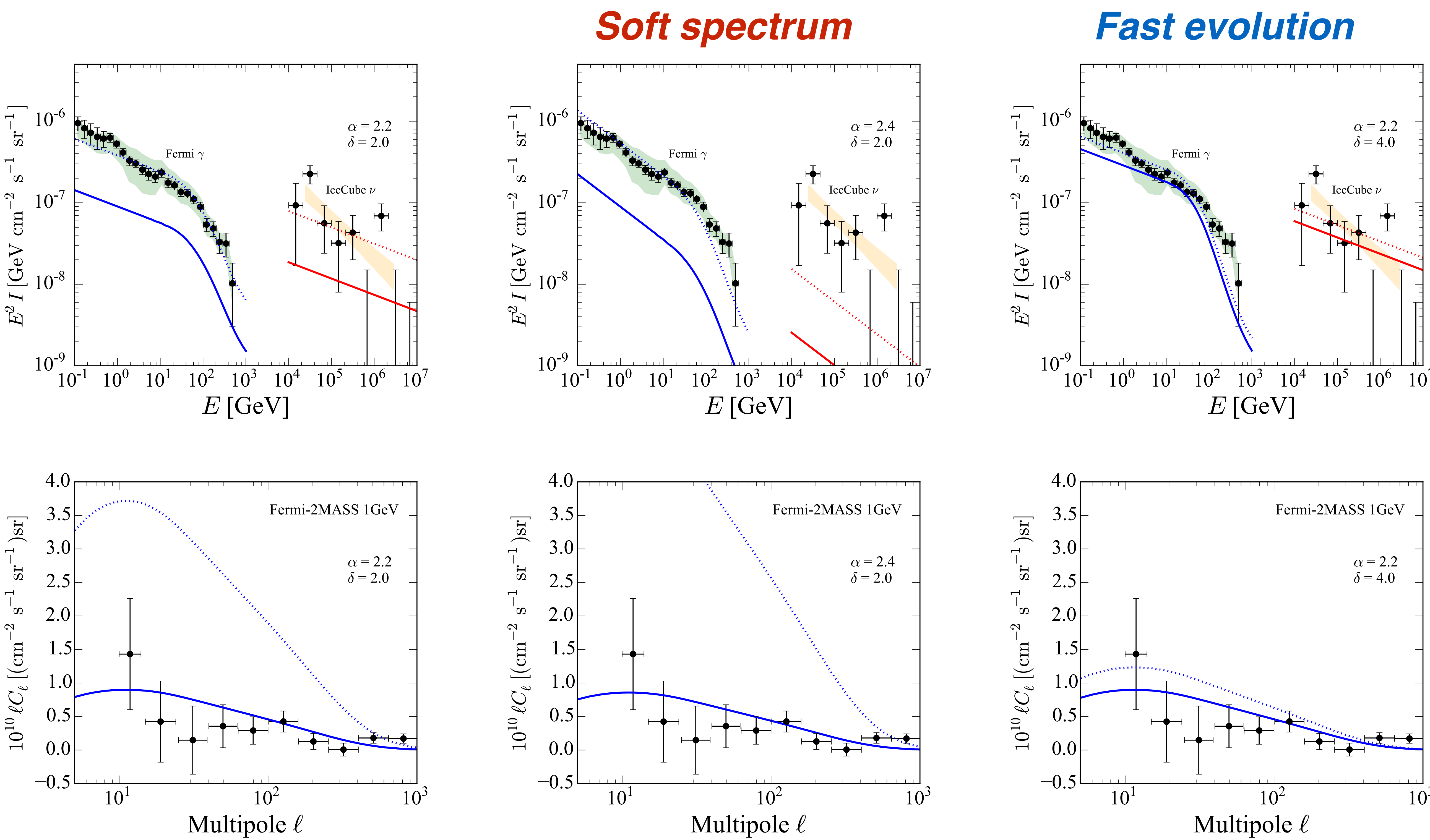
Dependence on **α** and **δ**

Soft spectrum



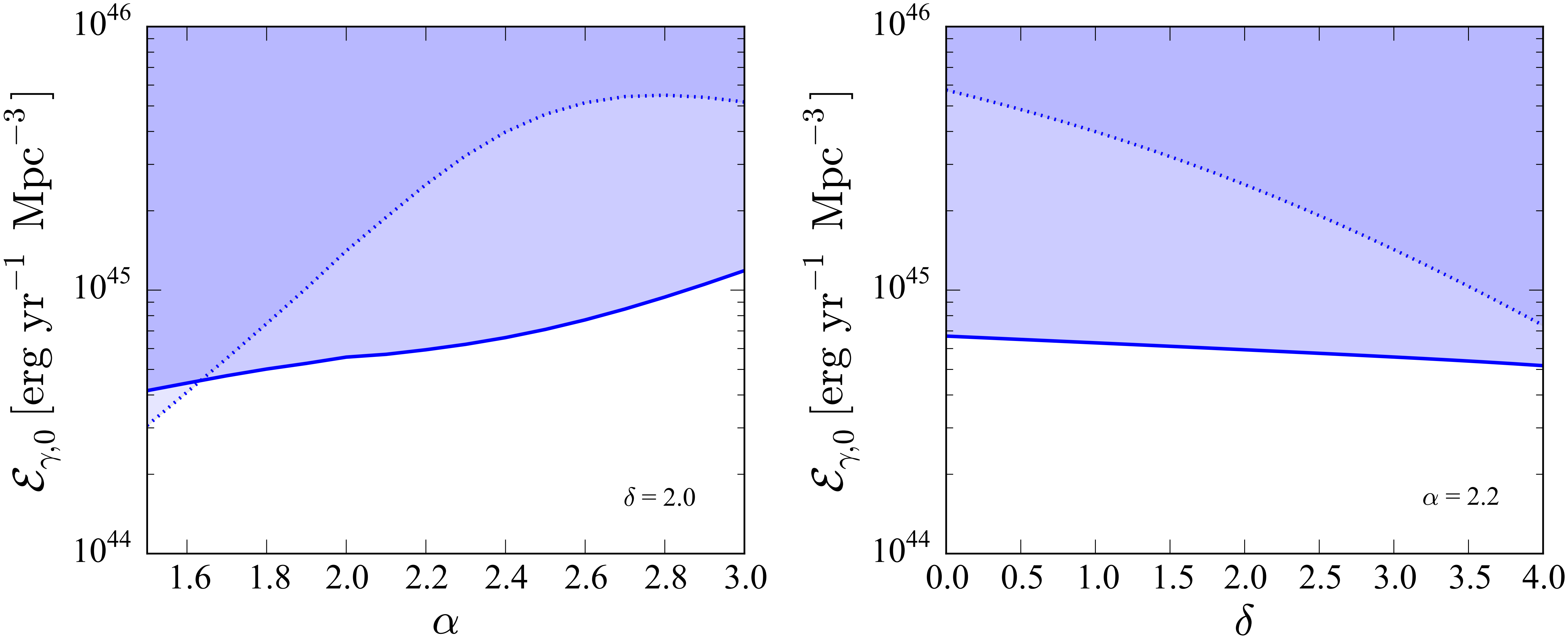
Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

Dependence on **α** and **δ**



Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

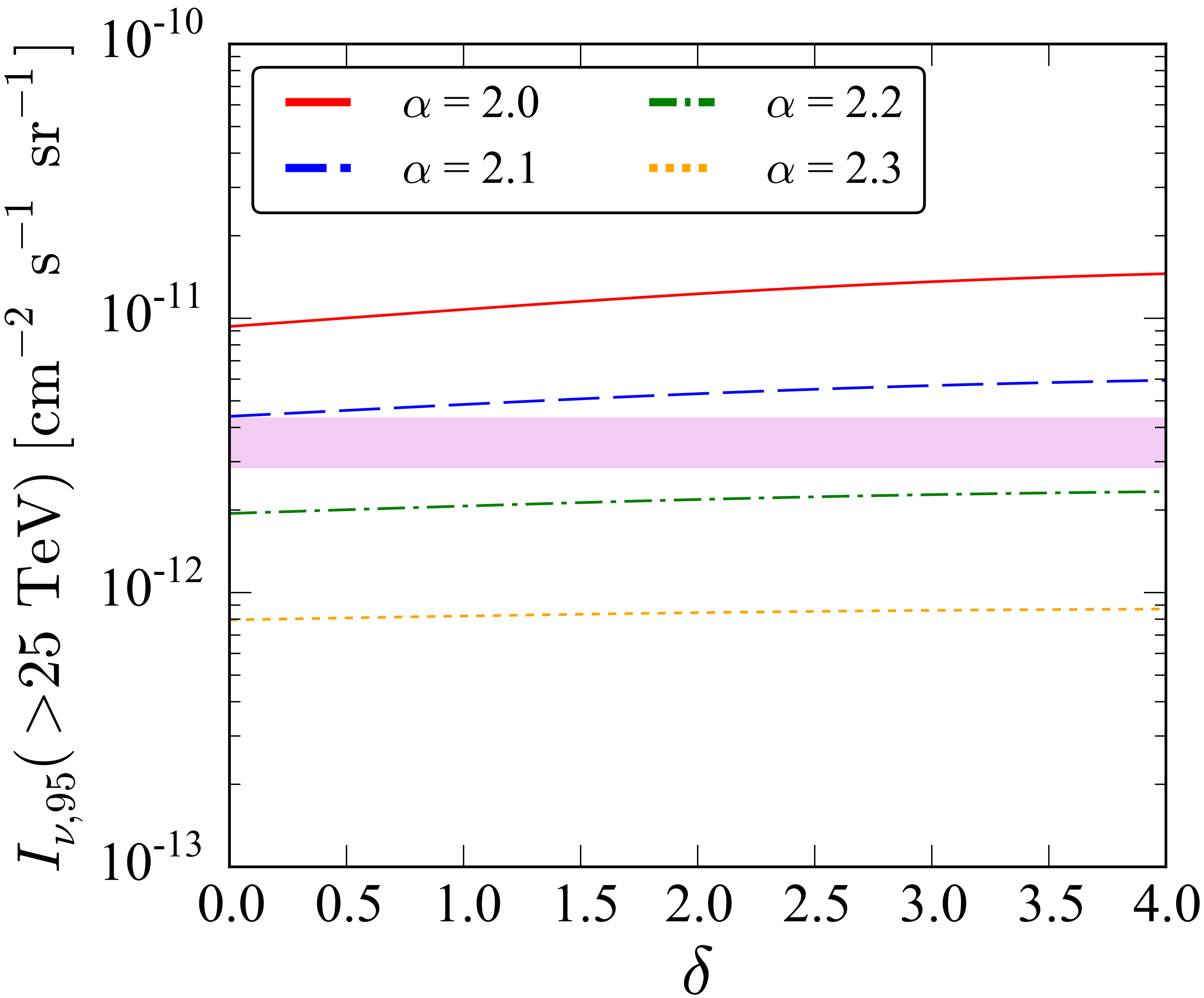
Constraints on gamma-ray luminosity density



Cross-correlation data give constraints tighter by ***up to 1 order of magnitude***!

Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

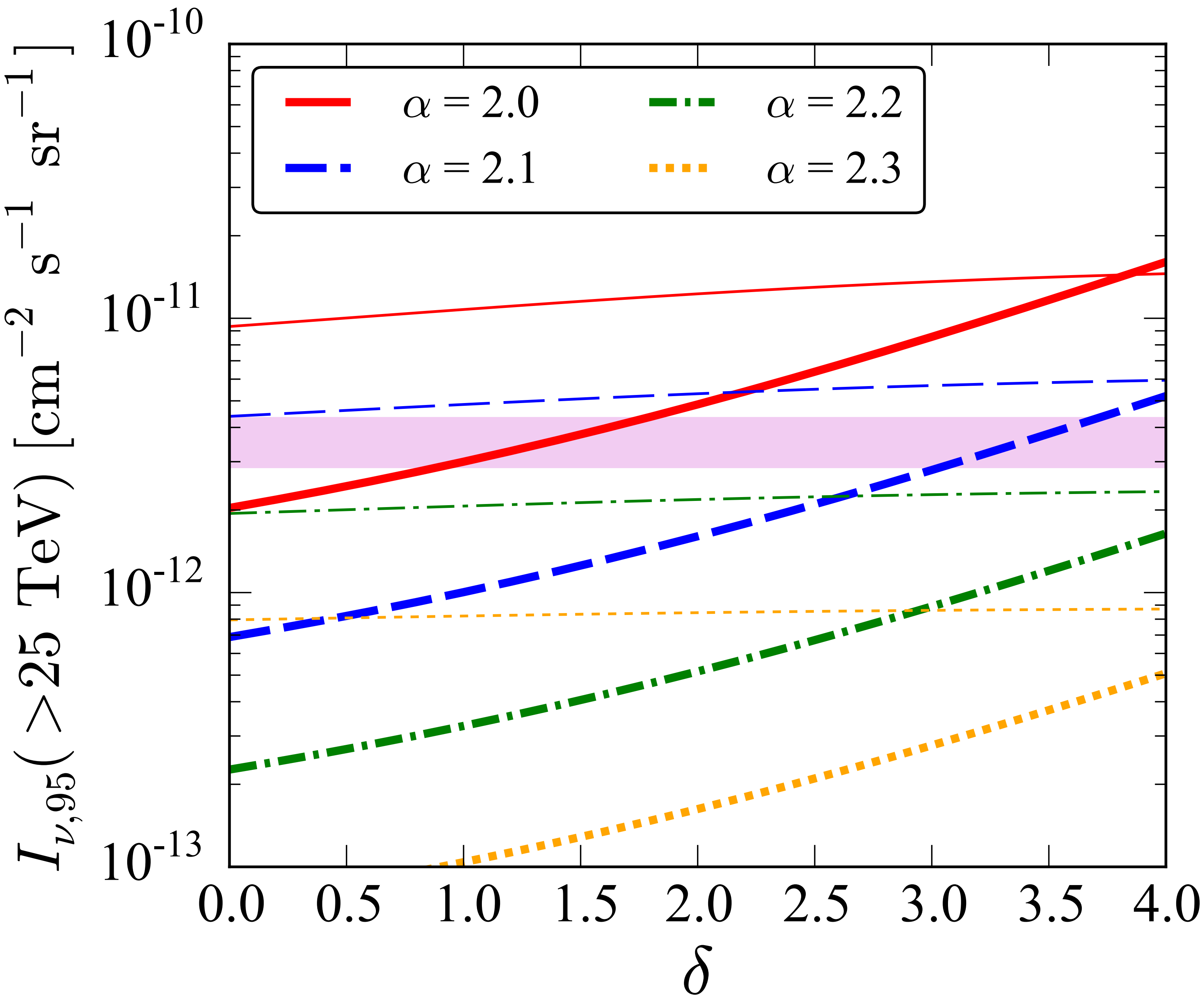
Constraints on high-energy neutrinos



- Spectral constraints: α has to be smaller than ~2.2

Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

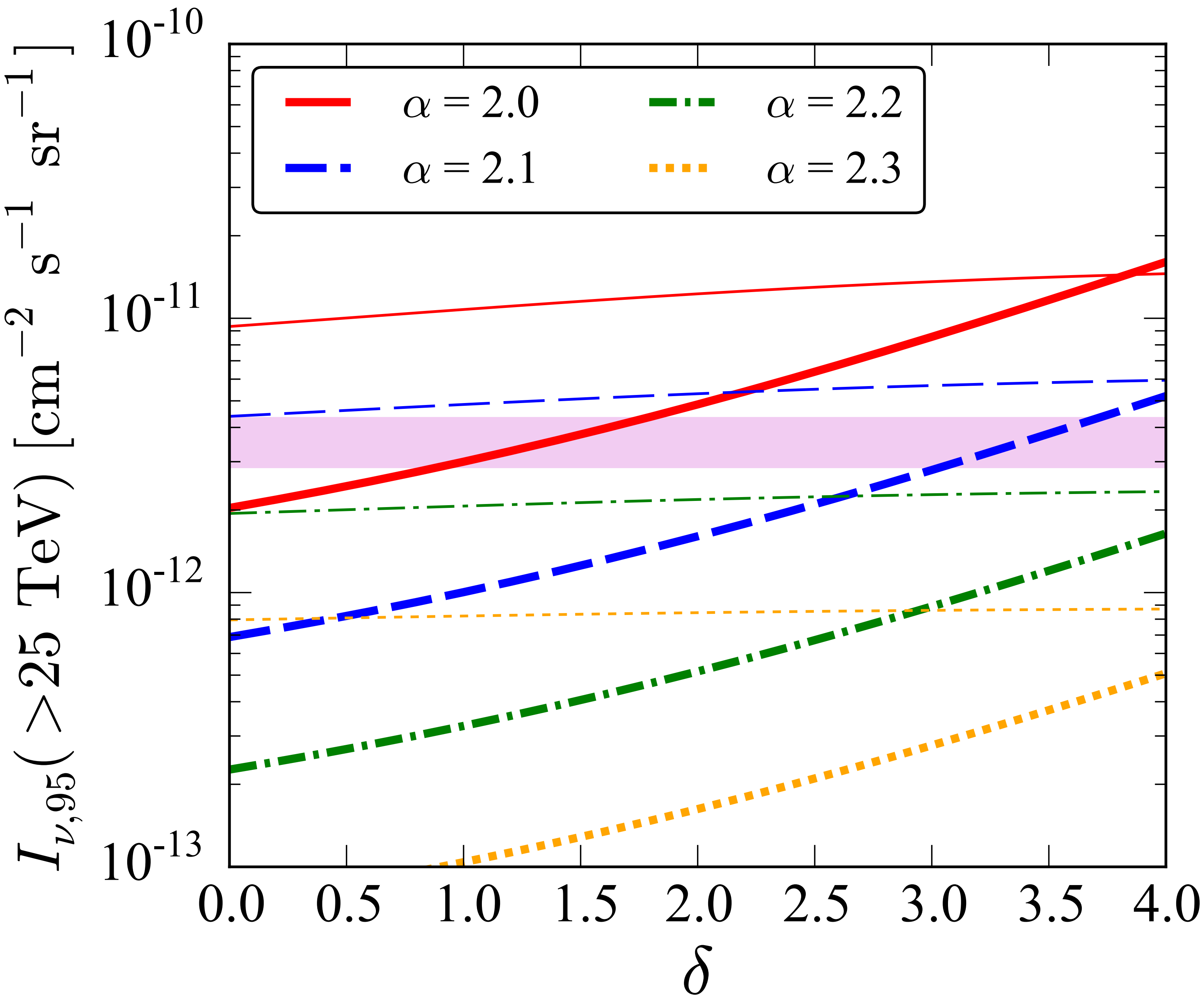
Constraints on high-energy neutrinos



- Spectral constraints: α has to be smaller than ~2.2
- Tomographic constraints:

Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

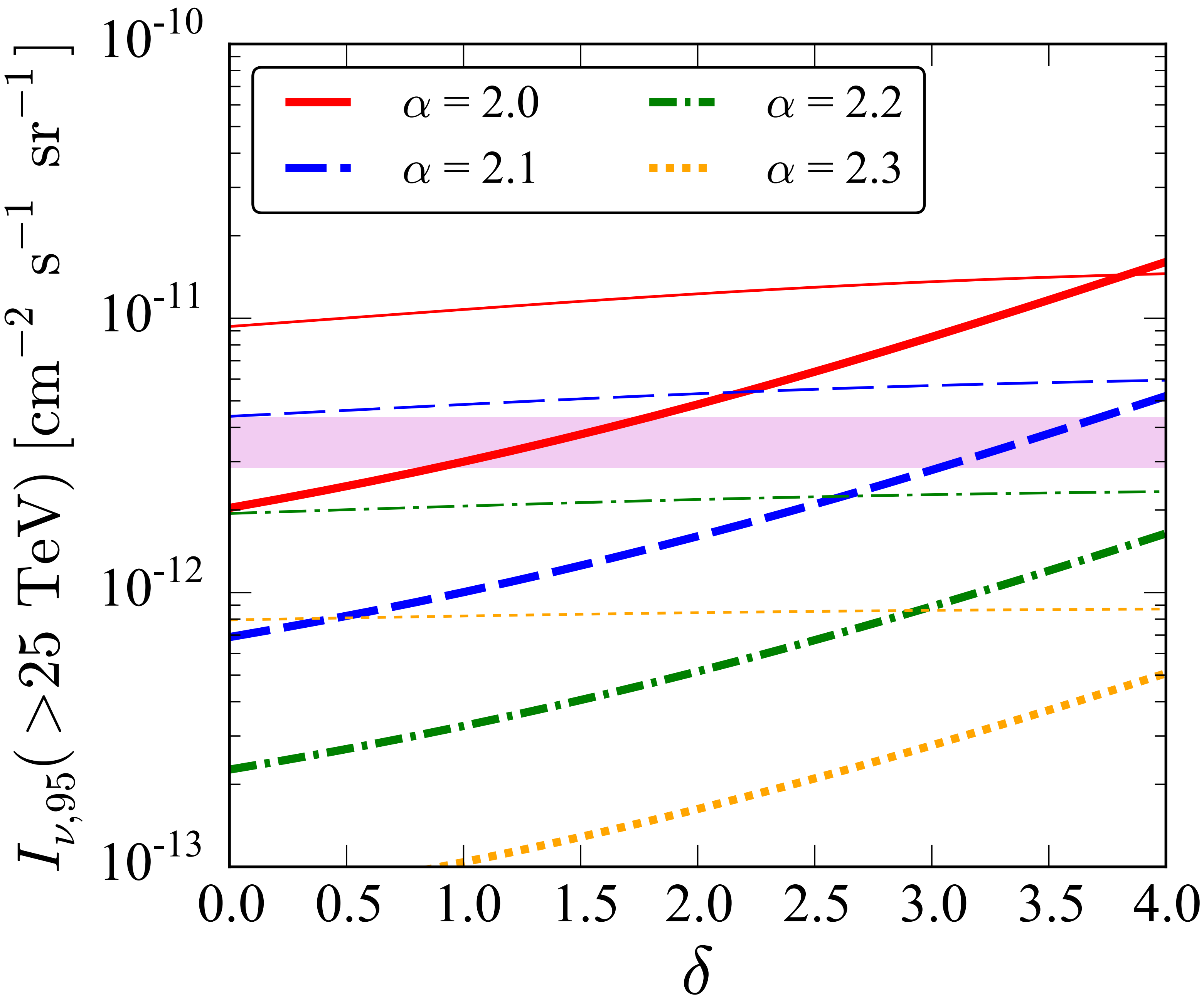
Constraints on high-energy neutrinos



- Spectral constraints: α has to be smaller than ~2.2
- Tomographic constraints:
  - If δ is smaller than ~3, source with spectrum softer than $E^{-2.1}$ is disfavored

Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

Constraints on high-energy neutrinos

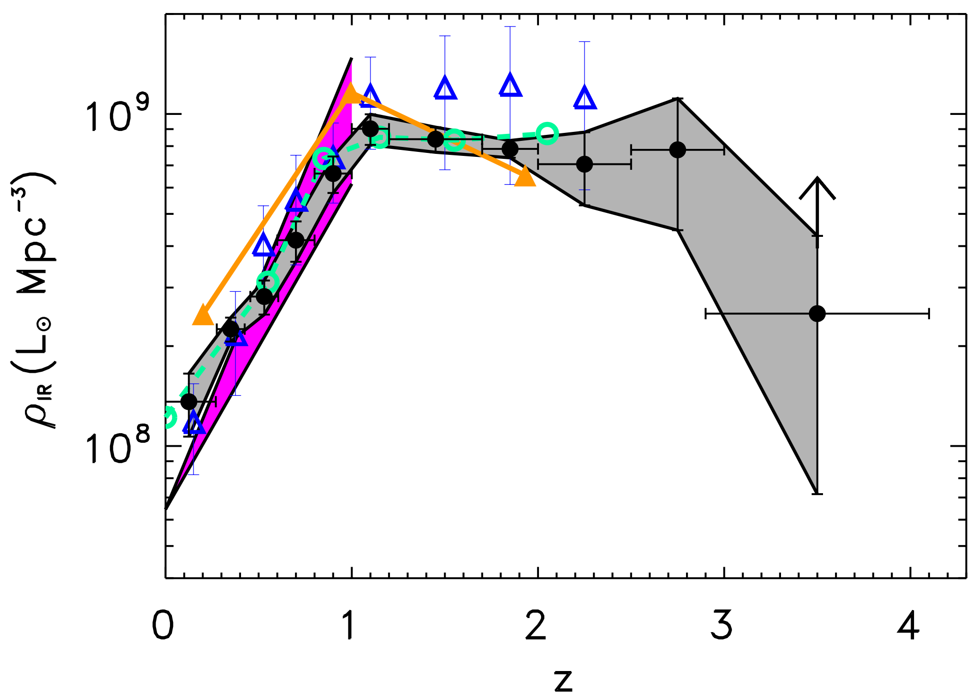


- Spectral constraints: α has to be smaller than ~2.2
- Tomographic constraints:
  - If δ is smaller than ~3, source with spectrum softer than $E^{-2.1}$ is disfavored
- If δ ~ 4, both spectral and tomographic data give comparable constraints

Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

Possible pp sources

Star-forming/starburst galaxies



- No direct measurement of δ yet
- Infrared luminosity density suggests δ ~ 3–4

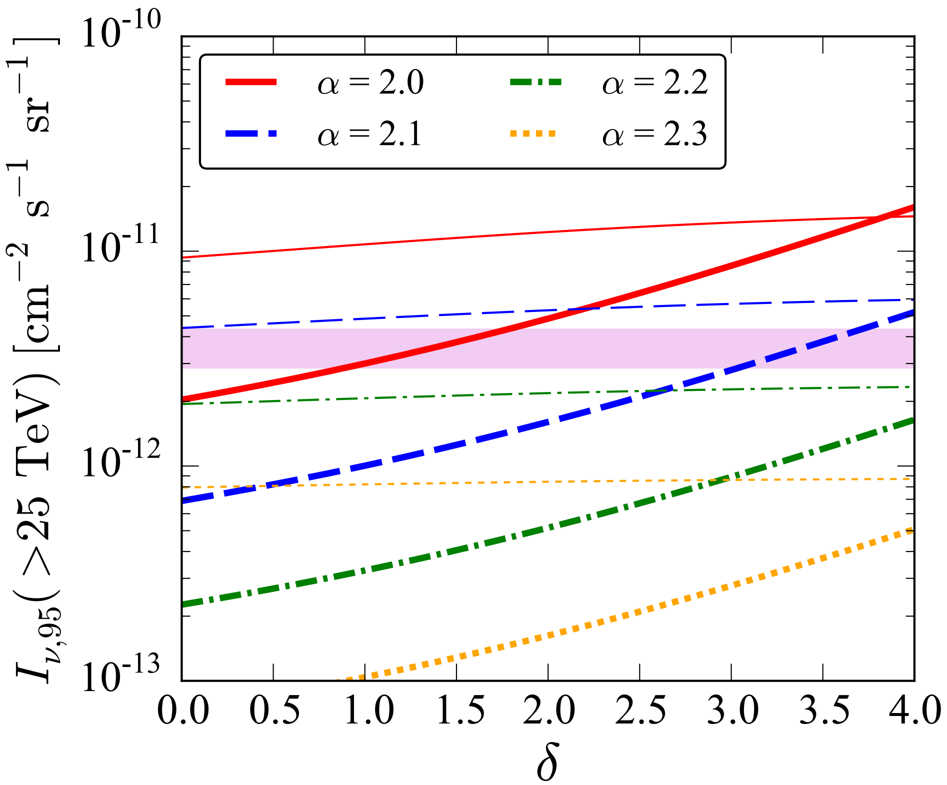
Gruppioni et al., *Mon. Not. R. Astron. Soc.* **432**, 23 (2013)

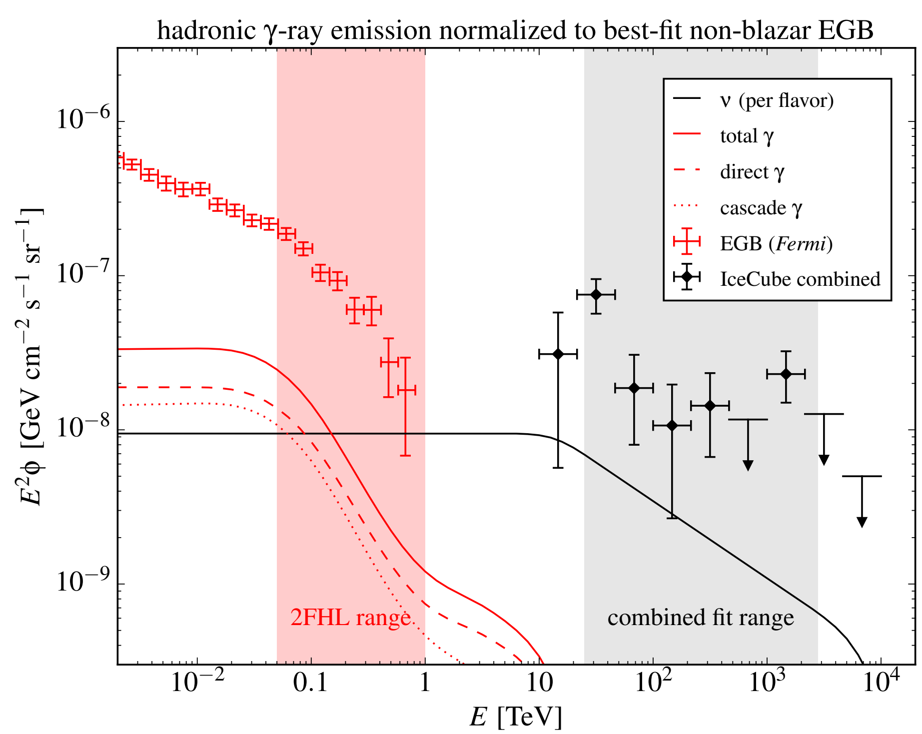
Clusters of galaxies

- Cosmic rays accelerated through large-scale-structure shocks or provided by sources (AGNs, galaxies)
- In both cases, δ is very small (i.e., clusters are found only in low-z)
- Very strongly disfavored; also independent constraints from radio number counts (Zandanel, Tamborra, Gabici, Ando, 2014)

What if blazars explain most IGRB data?

Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)





Bechtol et al., arXiv:1511.00688 [astro-ph.HE]

- Blazars might be responsible for ~85% of IGRB spectrum above 50 GeV (Fermi-LAT, 1511.00693)
  - If so, only very hard sources (α ~ 2) with fast evolution are allowed as the origin of the IceCube neutrinos
- Maybe such hard sources are disfavored by IceCube data??
  - If so, any pp sources are highly disfavored

Take-home message 2

- Hadronuclear (pp) interaction is a prime channel for production of high-energy neutrinos
- Contribution to IceCube neutrinos (TeV−PeV) can be constrained with Fermi-LAT gamma-ray data (GeV−TeV)
- New tomographic constraints are obtained with the galaxy-gamma cross-correlation measurements
- They exclude soft sources with relatively slow redshift evolution much more strongly than spectral constraints
- Sources with fast evolution (including starbursts) are still allowed, but they must have hard spectrum (E^{-2}) that can be tested