Particle Astrophysics Seminar
Fermilab, December 13, 2010

Gamma-ray probes of new physics

Particle dark matter and intergalactic magnetic fields

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Gamma-ray astrophysics

- Nature, growth, and environment of black holes

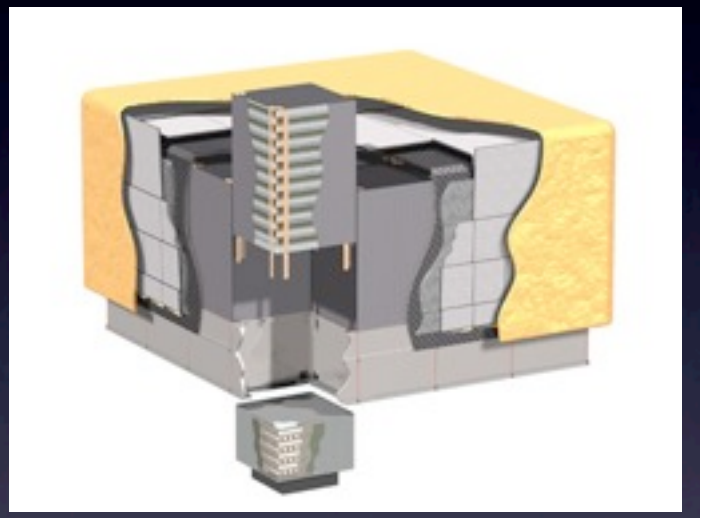
  Both stellar size and galaxy size

  Probed together with neutrinos and gravitational waves

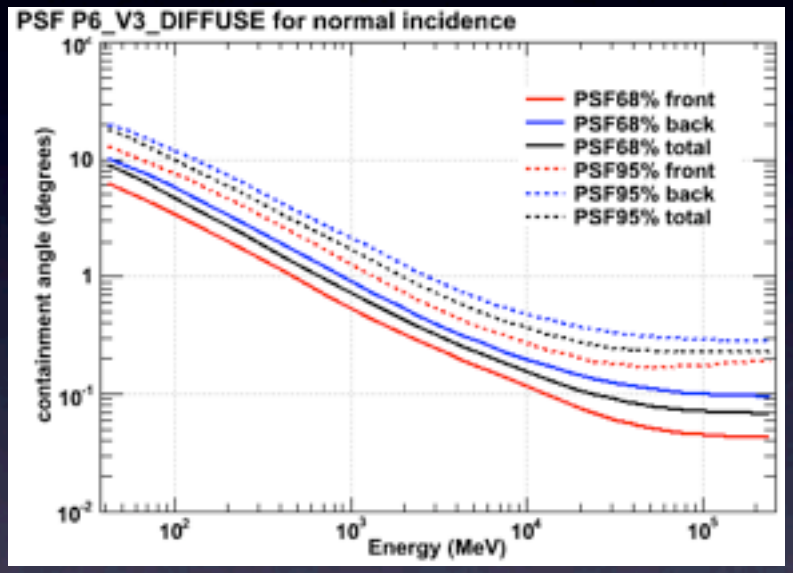
- Origins of ultrahigh-energy cosmic rays
- Radiation mechanisms of astrophysical sources
- Nature of particle dark matter
- Magnetic fields in intergalactic space

Fermi Gamma-Ray Space Telescope

Large Area Telescope (LAT)

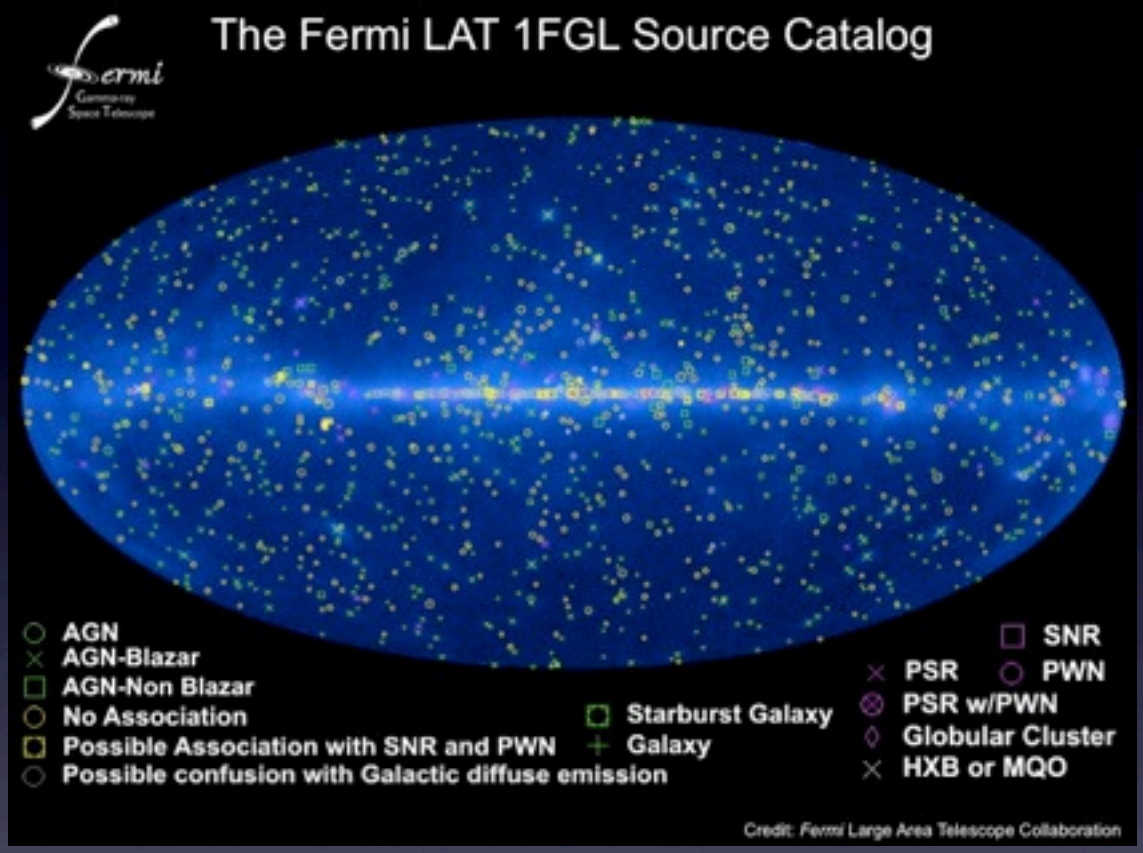


Pre-launch PSF (P6_v3)



- Launched in summer 2008
- Collect photons from all sources in the entire sky
- Sensitive to photons between ~20 MeV and 300 GeV
- Angular resolution gets sub-degree for > 1 GeV

All-sky gamma-ray map from Fermi-LAT



http://fermi.gsfc.nasa.gov/

- 11-month source catalog includes 1451 sources (Abdo et al. 2010)
- Enabling detailed studies of many astrophysical sources
- AGNs are the dominant source population; others include pulsars, pulsar wind nebulae, SNR, X-ray binaries, micro-quasars, starbursts, and many unidentified sources

Plan of this talk

- Angular power spectrum of the gamma-ray background from dark matter annihilation

  Ando, Komatsu, *Phys. Rev. D* **73**, 023521 (2006)

  Ando, Komatsu, Narumoto, Totani, *Phys. Rev. D* **75**, 063519 (2007)

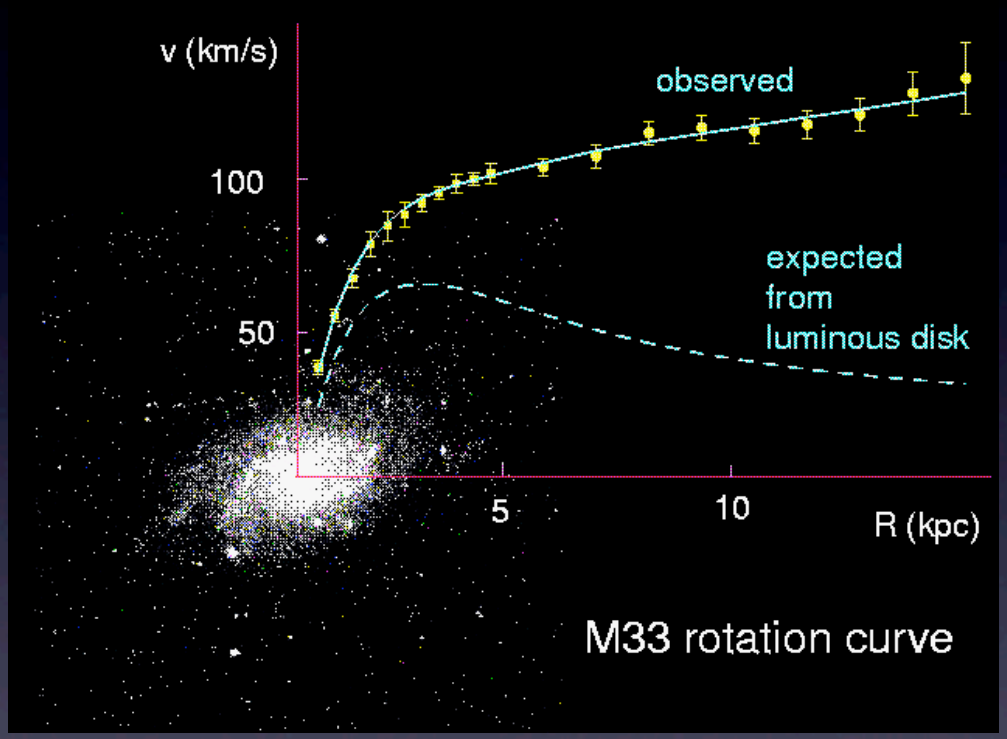
  Ando, *Phys. Rev. D* **80**, 023520 (2009)

- Search for gamma-ray halos around Fermi AGNs and intergalactic magnetic fields

  Ando, Kusenko, *Astrophys. J.* **722**, L39 (2010)

Nonbaryonic dark matter

Bergstrom, *Rep. Prog. Phys.* **63**, 793 (2000)



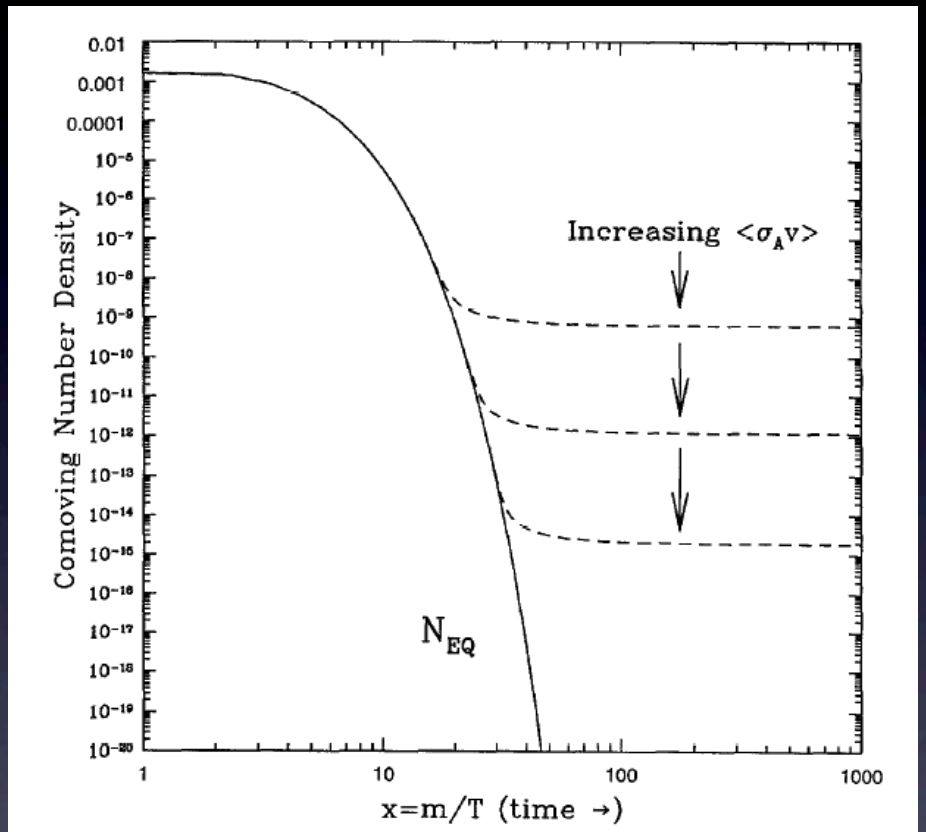
Bullet cluster (1E0657-56)

- Many observations indicate presence of *nonbaryonic dark matter*
  - Galaxy rotation curves, galaxy clusters, gravitational lensing, CMB anisotropy, etc.
- ~80% of total matter in the Universe

Identity: WIMP?

- Dark matter is considered to be "cold," with heavy masses (~GeV–TeV scale)
- It is called WIMP (weakly interacting massive particle)
- WIMP with weak-scale interactions naturally explains the relic density
- E.g., supersymmetric neutralino

Jungman, Kamionkowski, Griest, *Phys. Rep.* **267**, 195 (1996); Bertone, Hooper, Silk, *Phys. Rep.* **405**, 279 (2005)



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

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

Search for signals of WIMP

- Scattering of WIMP dark matter on target nuclei

  Direct detection

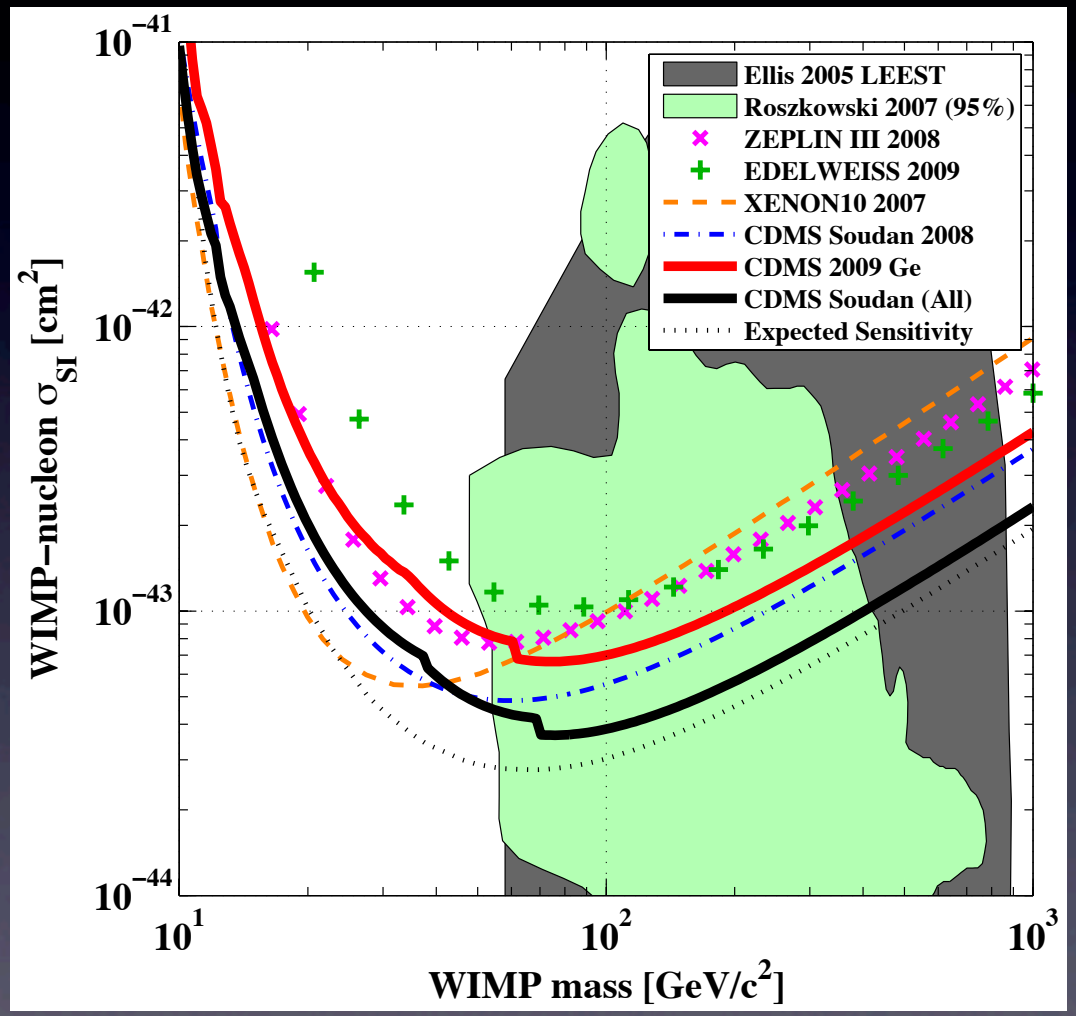
- Annihilation into visible particles (gammas, positrons, neutrinos, ...)

  Indirect detection

Another important feature:

✓ WIMPs may form substructure with scales down to ~ Earth mass

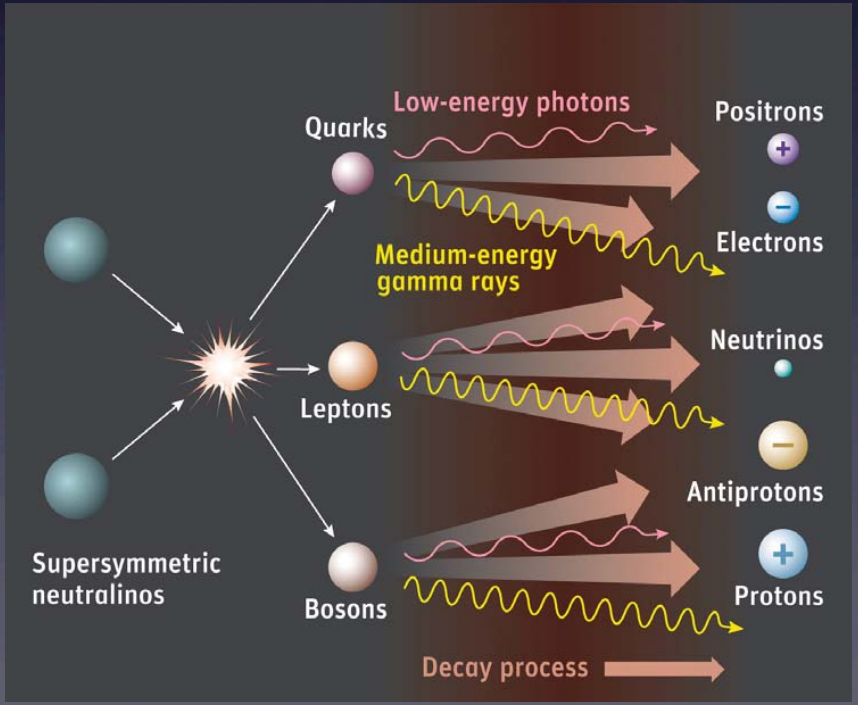
will boost both direct and indirect signals



CDMS, Ahmed et al., *Science* **327**, 1619 (2010)

Dark matter annihilation

- WIMPs may annihilate into standard model particles (photons, neutrinos, etc.)
- Energy of product particles is fractions of WIMP mass (E ~ GeV–TeV)
  - High-energy experiments are necessary
- Ongoing projects
  - Fermi, ACTs (γ, $e^{\pm}$)
  - PAMELA, ATIC ($e^{\pm}$)
  - IceCube (ν)



Where to look for annihilation signature

- Galactic center
- Galactic halo distribution
- Nearby dwarf galaxies (substructure)
- Galaxy clusters
- Diffuse gamma-ray background

Contributions from both Galactic subhalos and large-scale structure

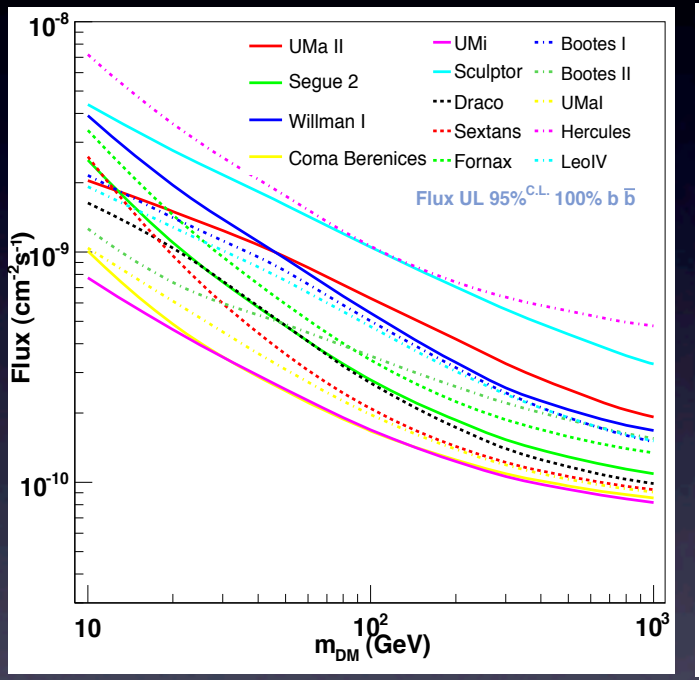
Dark matter substructure seen by simulations

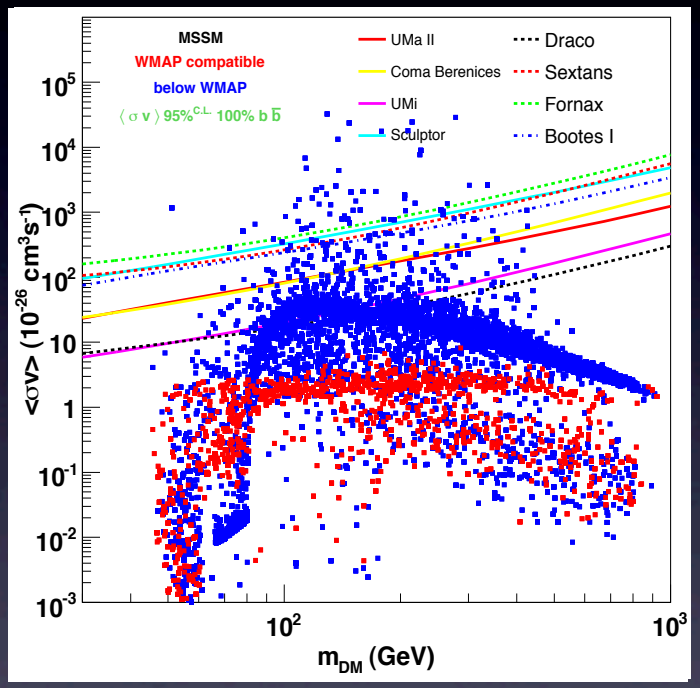
e.g., Diemand, Kuhlen, Madau, *Astrophys. J.* **657**, 262 (2007)

Search for dark matter in dwarf galaxies

Fermi-LAT, Abdo et al., *Astrophys. J.* **712**, 147 (2010)

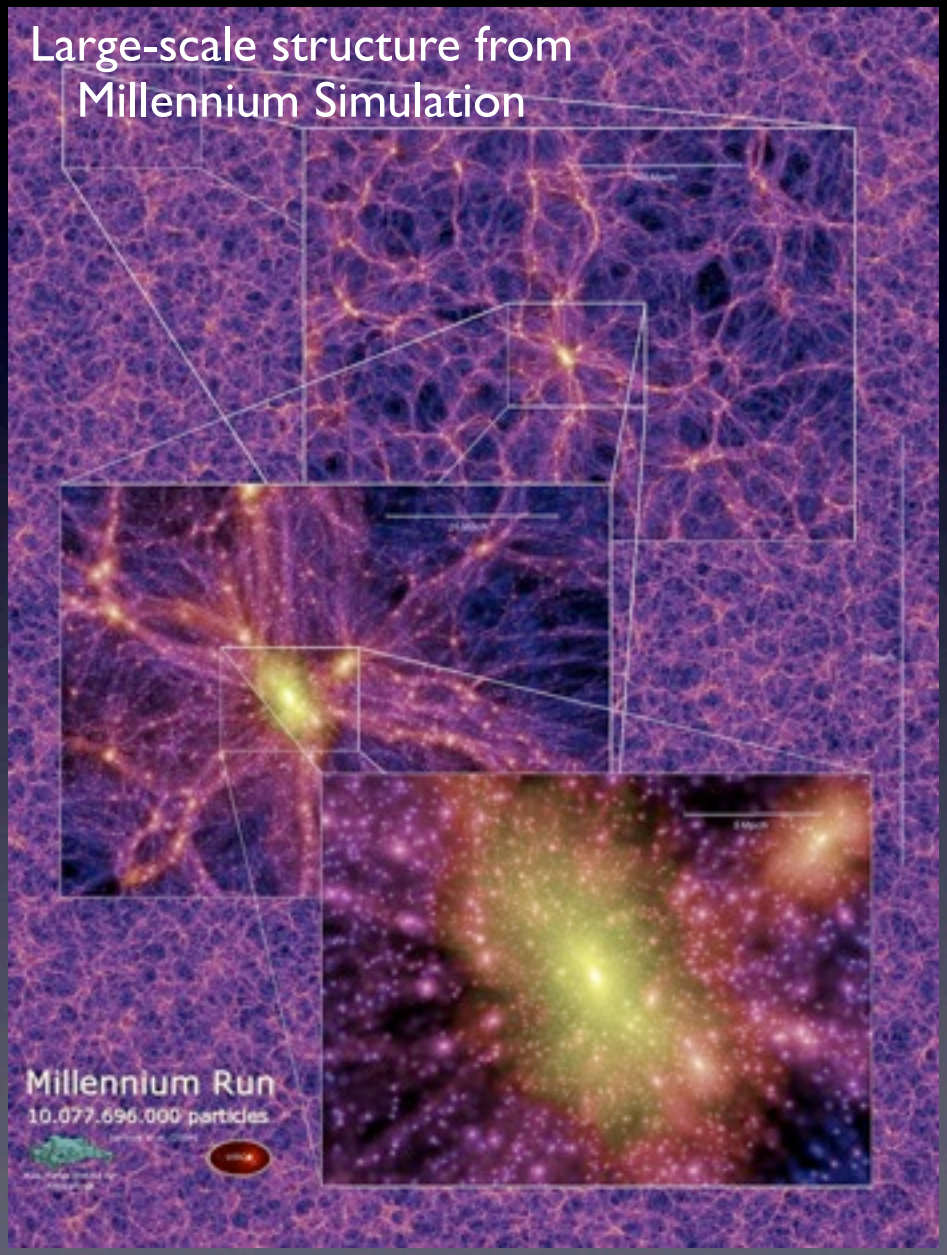
Name	Distance (kpc)	year of discovery	$M_{1/2}/L_{1/2}$ ref. 8
Ursa Major II	30± 5	2006	4000^{+3700}_{-2100}
Segue 2	35	2009	650
Willman 1	38± 7	2004	770^{+930}_{-440}
Coma Berenices	44± 4	2006	1100^{+800}_{-500}
Bootes II	46	2007	18000??
Bootes I	62±3	2006	1700^{+1400}_{-700}
Ursa Minor	66± 3	1954	290^{+140}_{-90}
Sculptor	79± 4	1937	18^{+6}_{-5}
Draco	76± 5	1954	200^{+80}_{-60}
Sextans	86± 4	1990	120^{+40}_{-35}
Ursa Major I	97±4	2005	1800^{+1300}_{-700}
Hercules	132±12	2006	1400^{+1200}_{-700}
Fornax	138± 8	1938	$8.7^{+2.8}_{-2.3}$
Leo IV	160±15	2006	260^{+1000}_{-200}

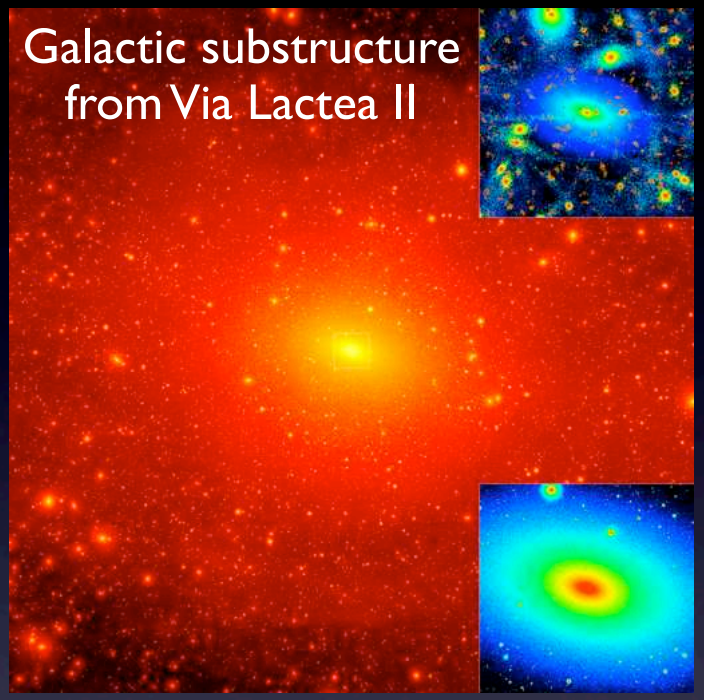




- No detection so far, constraining $\langle\sigma v\rangle < 10^{-25}$ cm^3 s^{-1}, but starting to constrain some SUSY parameters

Gamma-ray background from dark matter

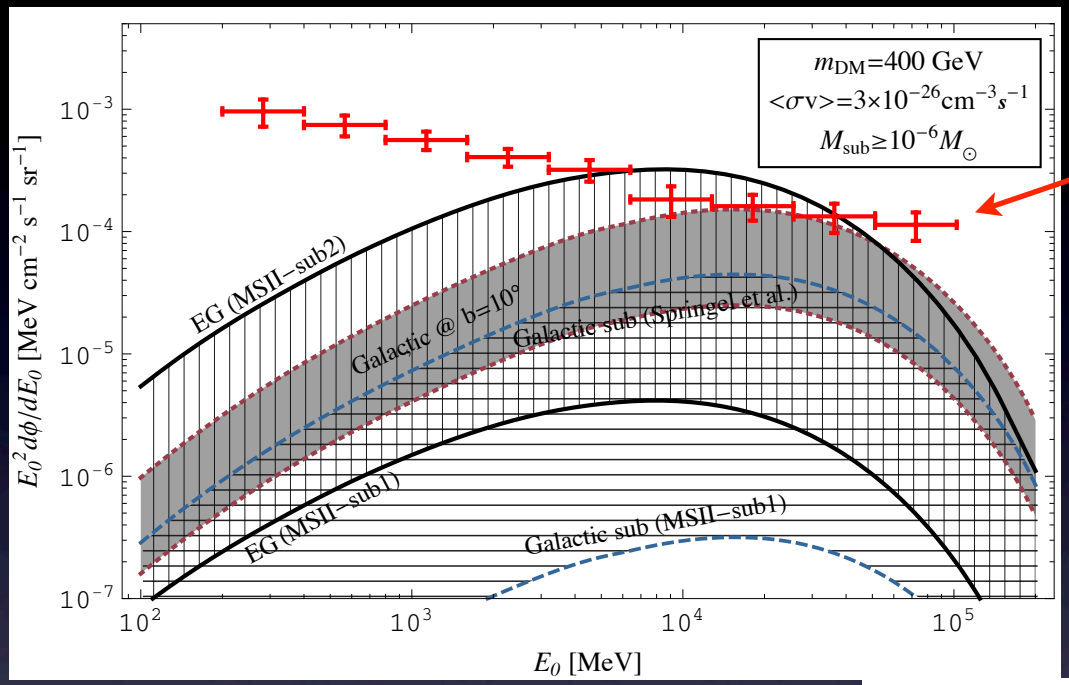




Diemand et al., *Nature* **454**, 735 (2008)

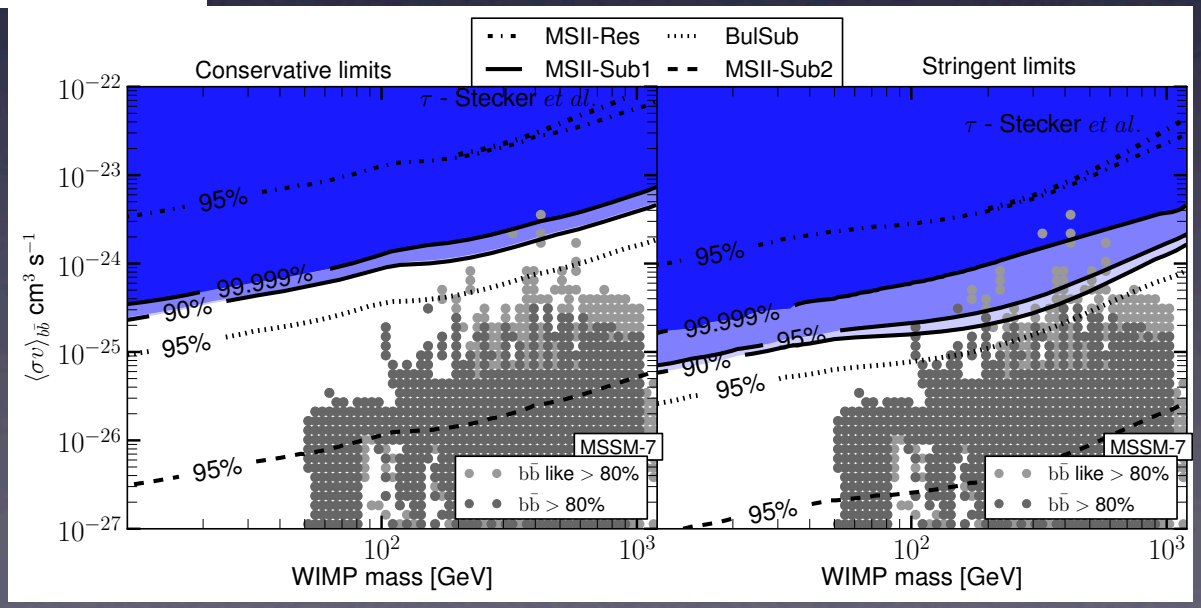
- Dark matter is annihilating everywhere!
- It gives contribution to the gamma-ray background

Fermi 1st year result on cosmological annihilation

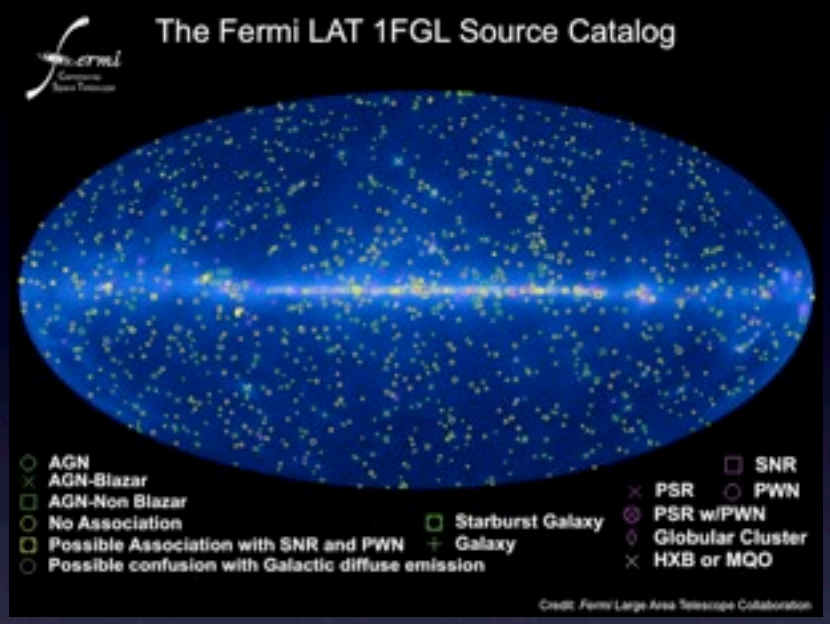


Spectrum of "isotropic" gamma-ray background

Fermi-LAT, Abdo et al., *JCAP* **04**, 014 (2010)

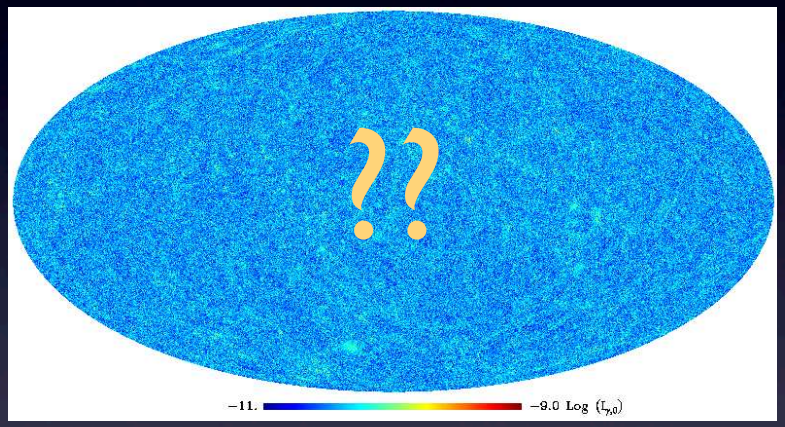


Diffuse gamma-ray background



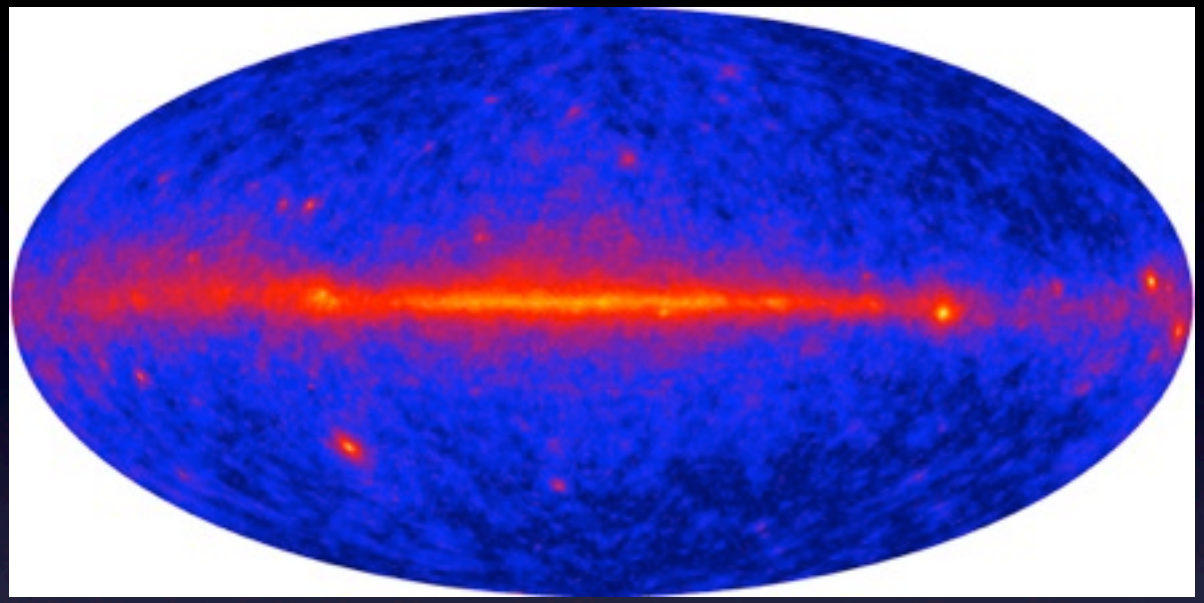
Remove all the identified sources

Zavala, Springel, Boylan-Kolchin, *MNRAS* **405**, 593 (2010)



- What would the gamma-ray background map look like?
- What information on dark matter can we extract from the gamma-ray map, and how?

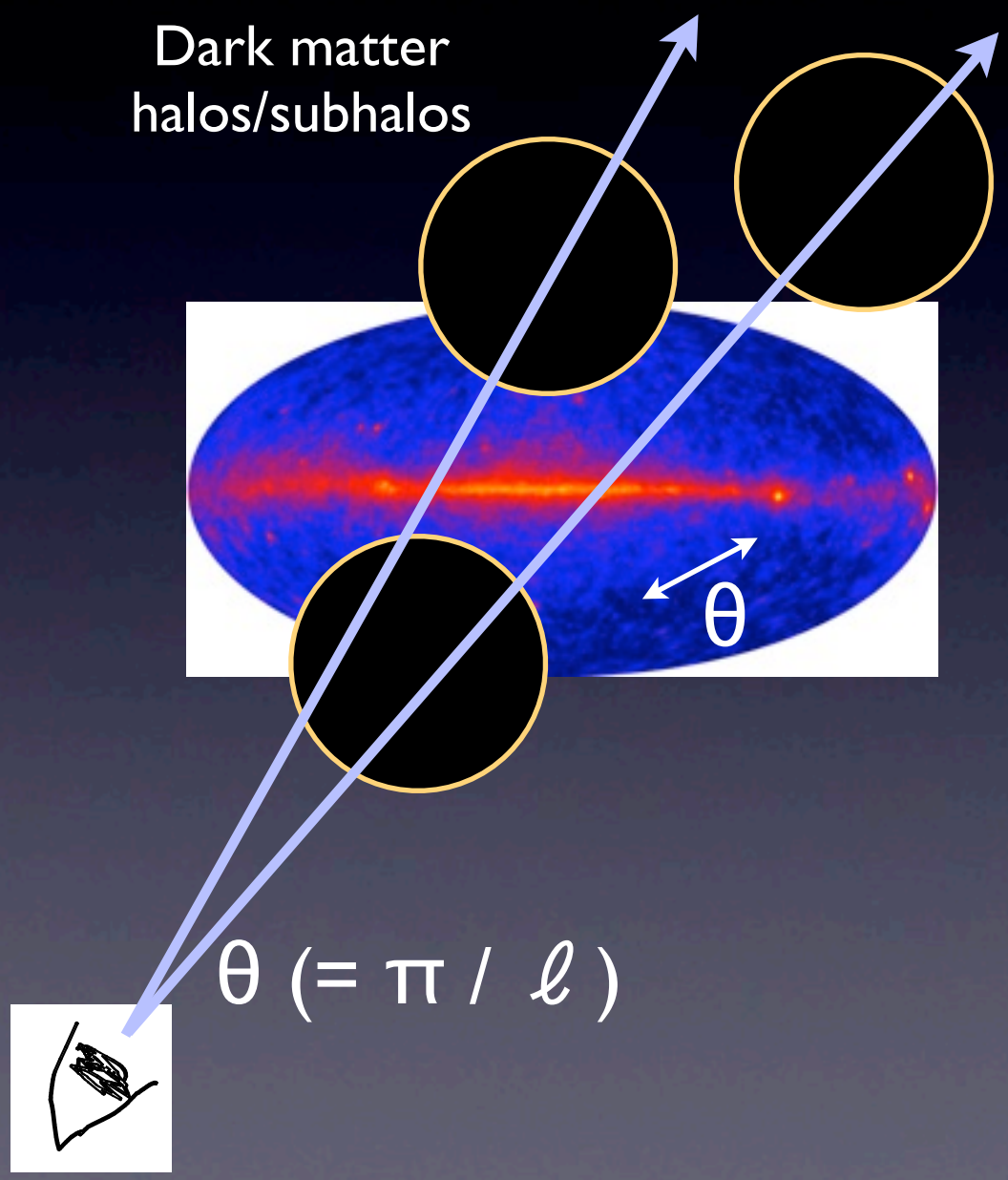
Gamma-ray background anisotropy



- Fermi obtains all-sky gamma map with high angular resolutions
- It enables analysis of angular power spectrum
- Clustering feature of gamma-ray sources can be studied
  - Different between DM and astrophysical sources

E.g., Ando, Komatsu, *Phys. Rev. D* **73**, 023521 (2006)

Angular power spectrum

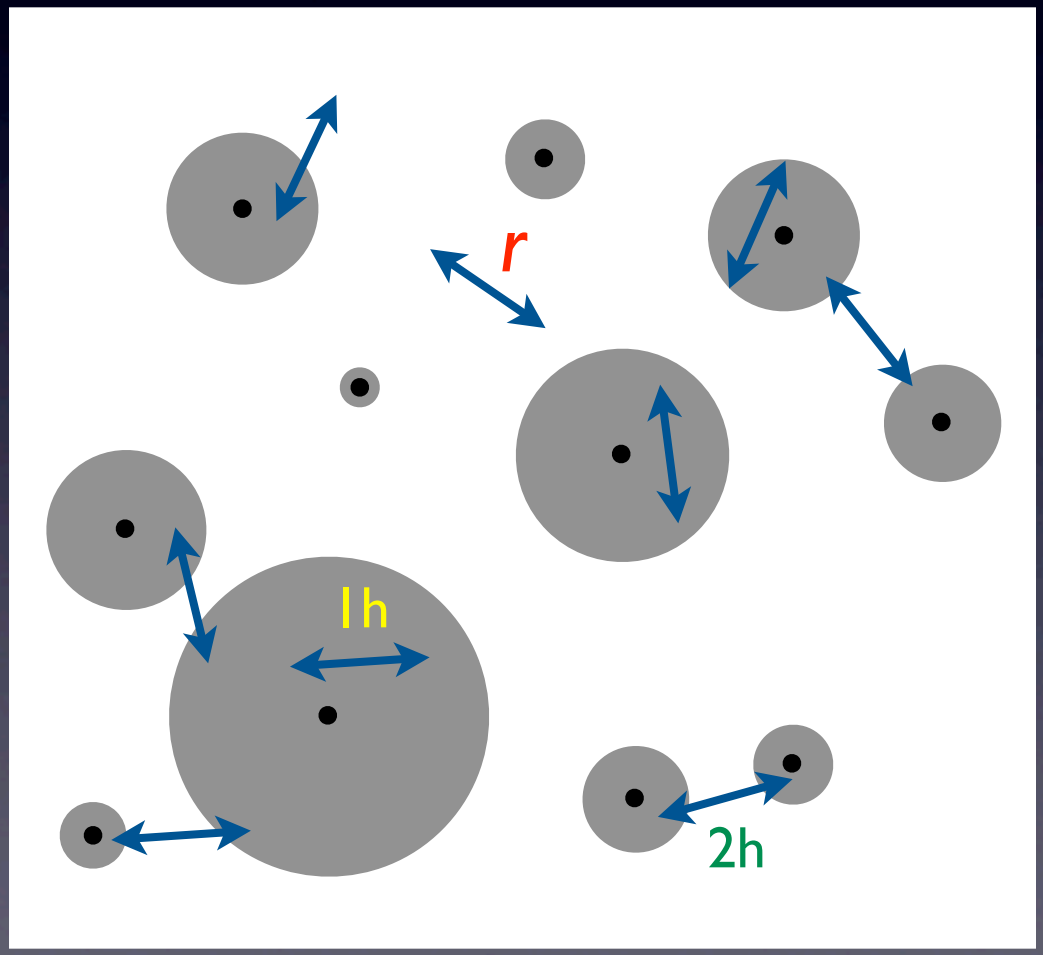


- Correlate intensities from two directions separated by θ
- Take spherical harmonic expansion → square of coefficient: power spectrum
- Multipole ℓ is related to θ through $\theta = \pi / \ell$
- We need to know how the halos are distributed, mass function, and density profiles
- We apply "halo model" to compute the power spectrum

Halo model

Scherrer & Bertschinger (1991); Seljak 2000

- Analytic prescription to get matter/galaxy power spectrum including nonlinear regime



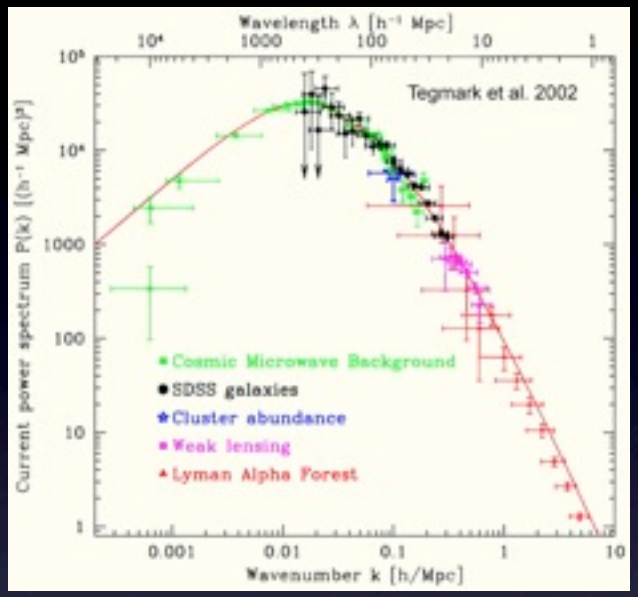
- Procedure

1. Distribute halo *seeds* following linear matter power spectrum
2. Surround each halo seed by NFW density profile
3. Evaluate $\langle\delta(\mathbf{x})\delta(\mathbf{y})\rangle$ as a function of $r = |\mathbf{x}-\mathbf{y}|$

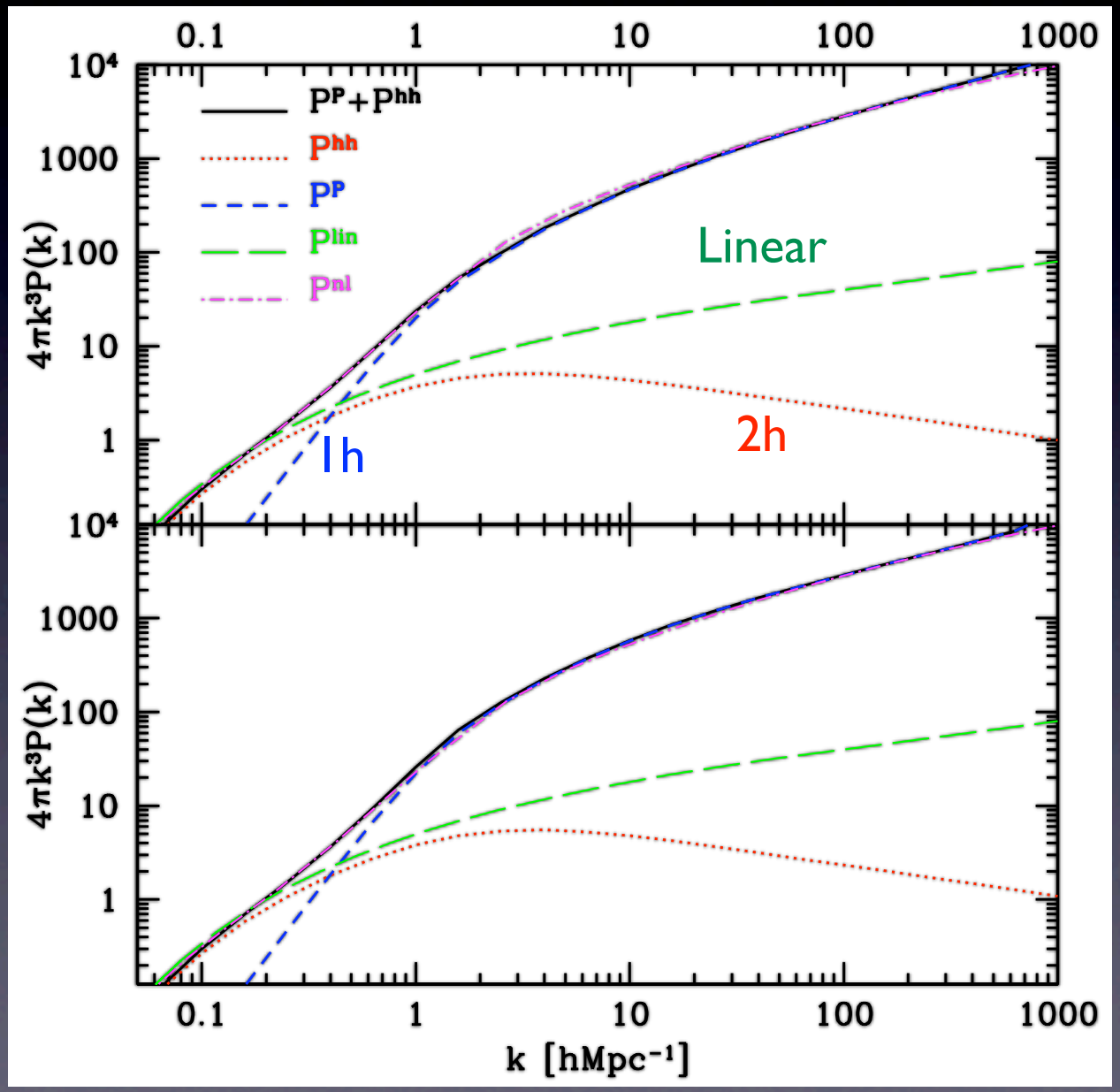
   There are 1-halo and 2-halo terms

4. Go to Fourier space to get $P(k)$

Power spectrum by halo model



Seljak., *MNRAS* **318**, 203 (2000)



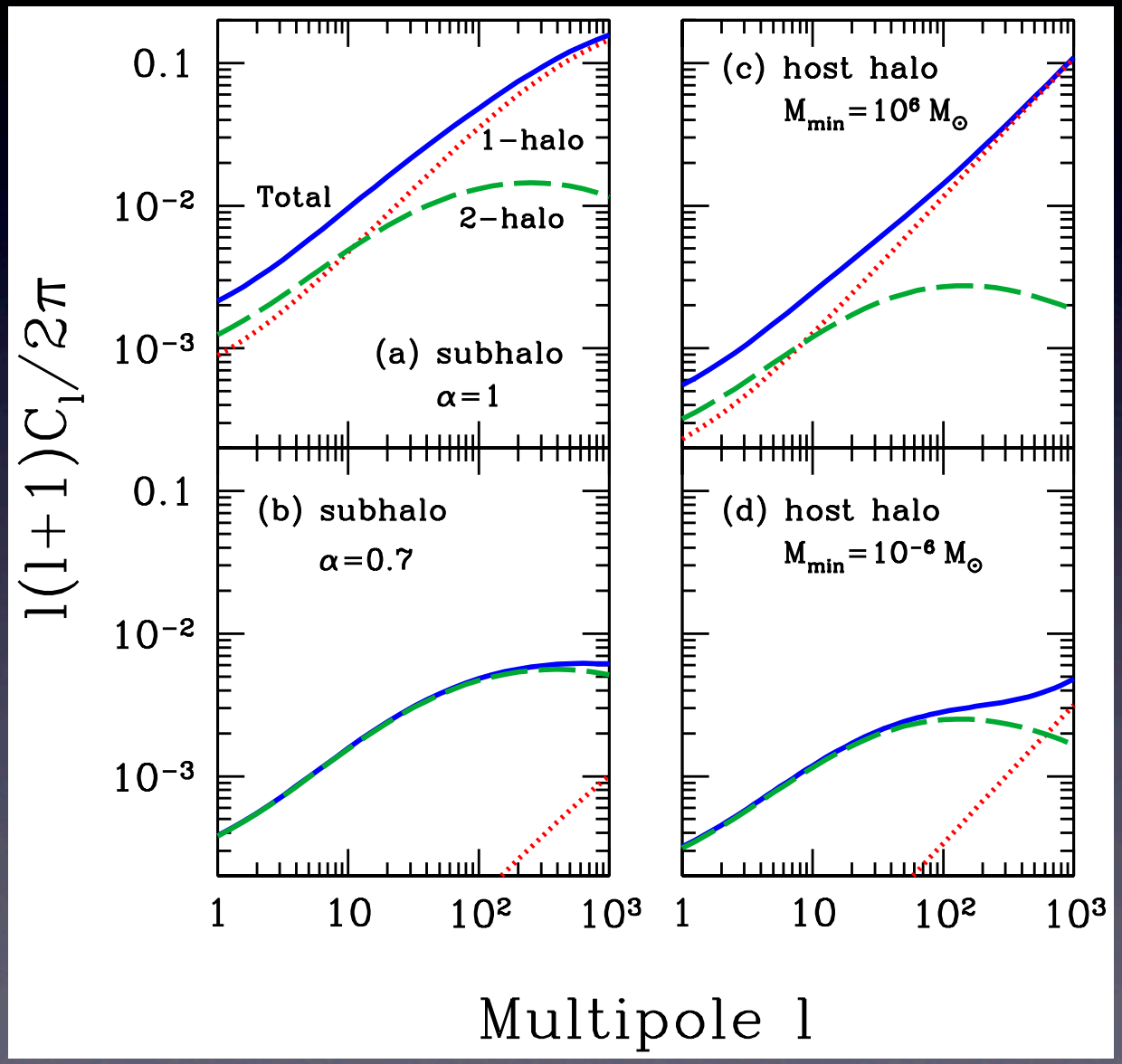
- Halo model provides good fit to the nonlinear power spectrum
- 1-halo term dominates at small scales (large *k*)

Apply halo model to gamma-ray background

	Matter power spectrum	Gamma-ray background from extragalactic halos
Seed distribution	Follows linear power spectrum	Follows linear power spectrum
Correlating quantity	ρ	$L \sim \rho^2$ (smooth halo) ρ (clumpy halo)
Spatial dimension	3D	2D (projected)

Anisotropy due to extragalactic halos

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



- DM mass: 100 GeV, gamma energy: 10 GeV
- Subhalo dominated case
  - Number of subhalos in host halo

$$\langle N|M\rangle \propto M^{\alpha}$$

- Host-halo dominated case
  - Minimum mass as a free parameter

Error estimate

- Total power spectrum is given by signal (s) and background (b) components with suppression due to fractional contributions to mean intensity (f_s and f_b; $f_s + f_b = 1$)

$$C_\ell^{\rm tot} = f_s^2 C_\ell^s + f_b^2 C_\ell^b + 2 f_s f_b C_\ell^{\rm cross}$$

  - This has unique dependence on f_s
  - Even if DM is subdominant in mean intensity, it could excel in angular power spectrum!

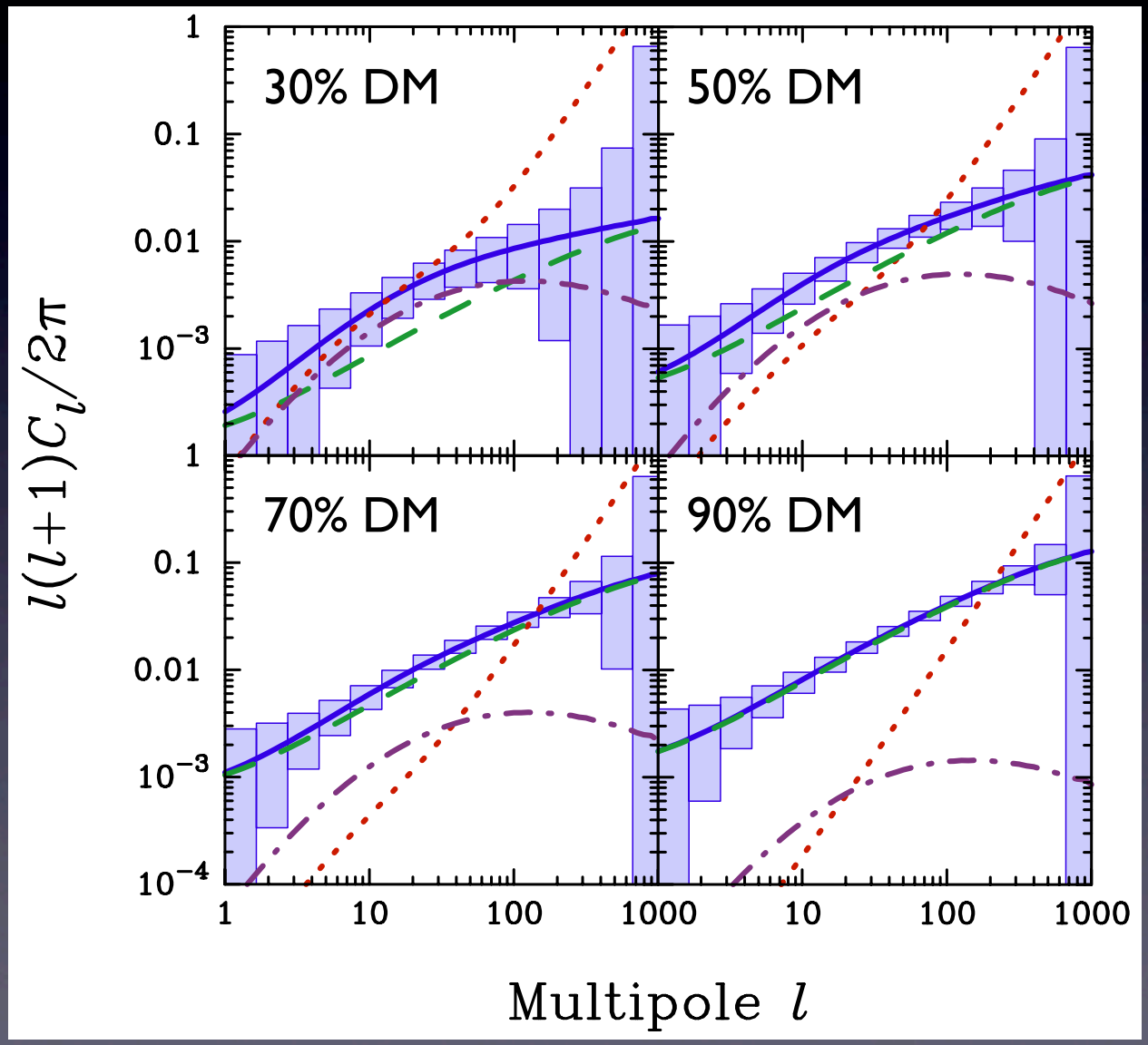
- Errors on signal are given by

$$\delta C_\ell = \sqrt{\frac{2}{(2\ell+1)\Delta l}} \left(C_\ell^{\rm tot} + \frac{C_N}{W_\ell^2} \right)$$

C_N: error due to finiteness of photon count
W_ℓ : error due to finite angular resolution

Detectability of the angular power spectrum

Ando, Komatsu, Narumoto, Totani, *Phys. Rev. D* **75**, 063519 (2007)



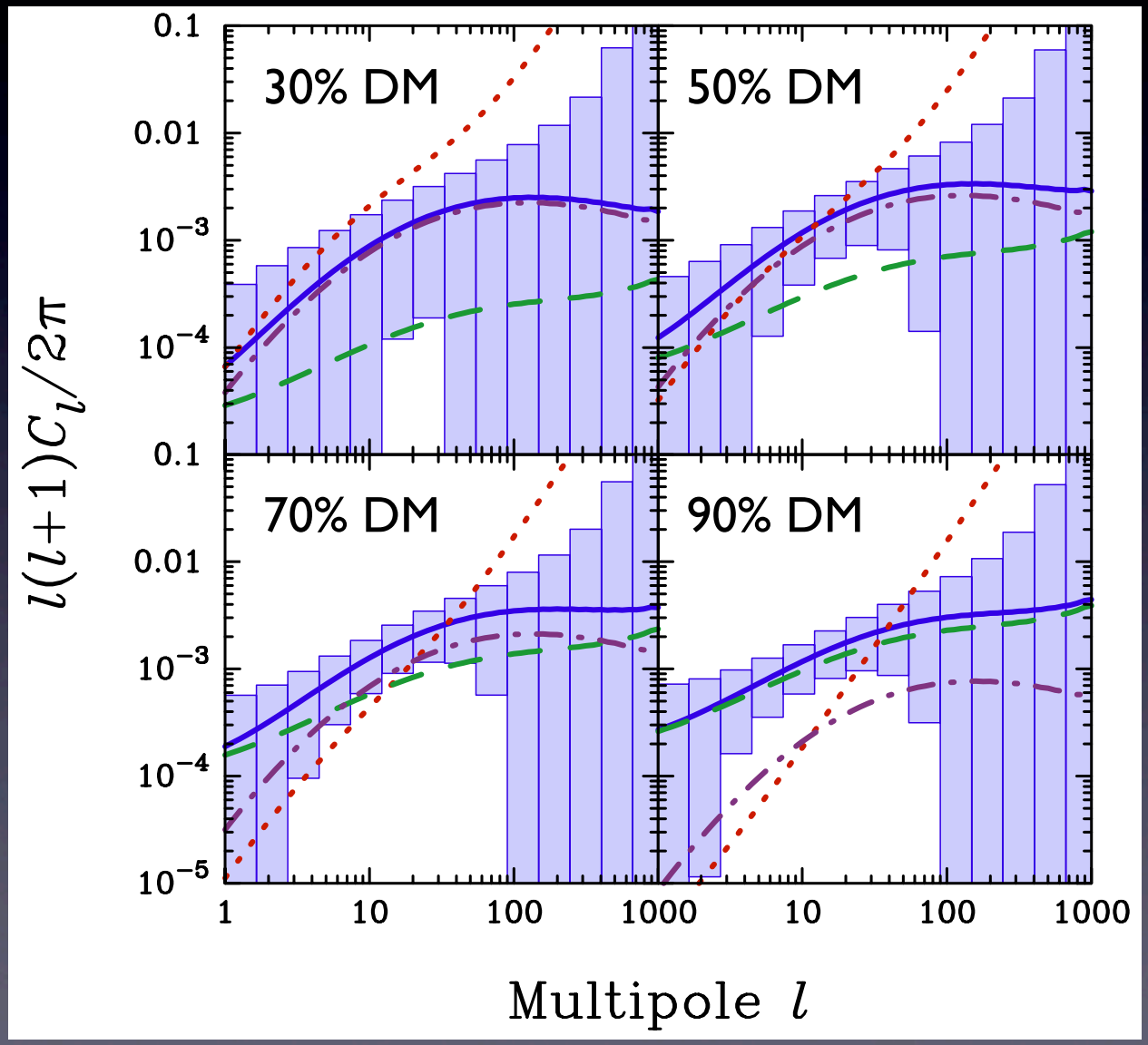
"Subhalo-dominated"

Dark matter signal
Dark matter correlation
Blazar background
Dark matter-blazar cross correlation

- Dark matter mass: 100 GeV
- At 10 GeV for 2-yr exposure
- Blazar component is easily discriminated
  - Blazar power spectrum is nearly independent of energy

"No substructure" or "smooth halo" limit

Ando, Komatsu, Narumoto, Totani, *Phys. Rev. D* **75**, 063519 (2007)



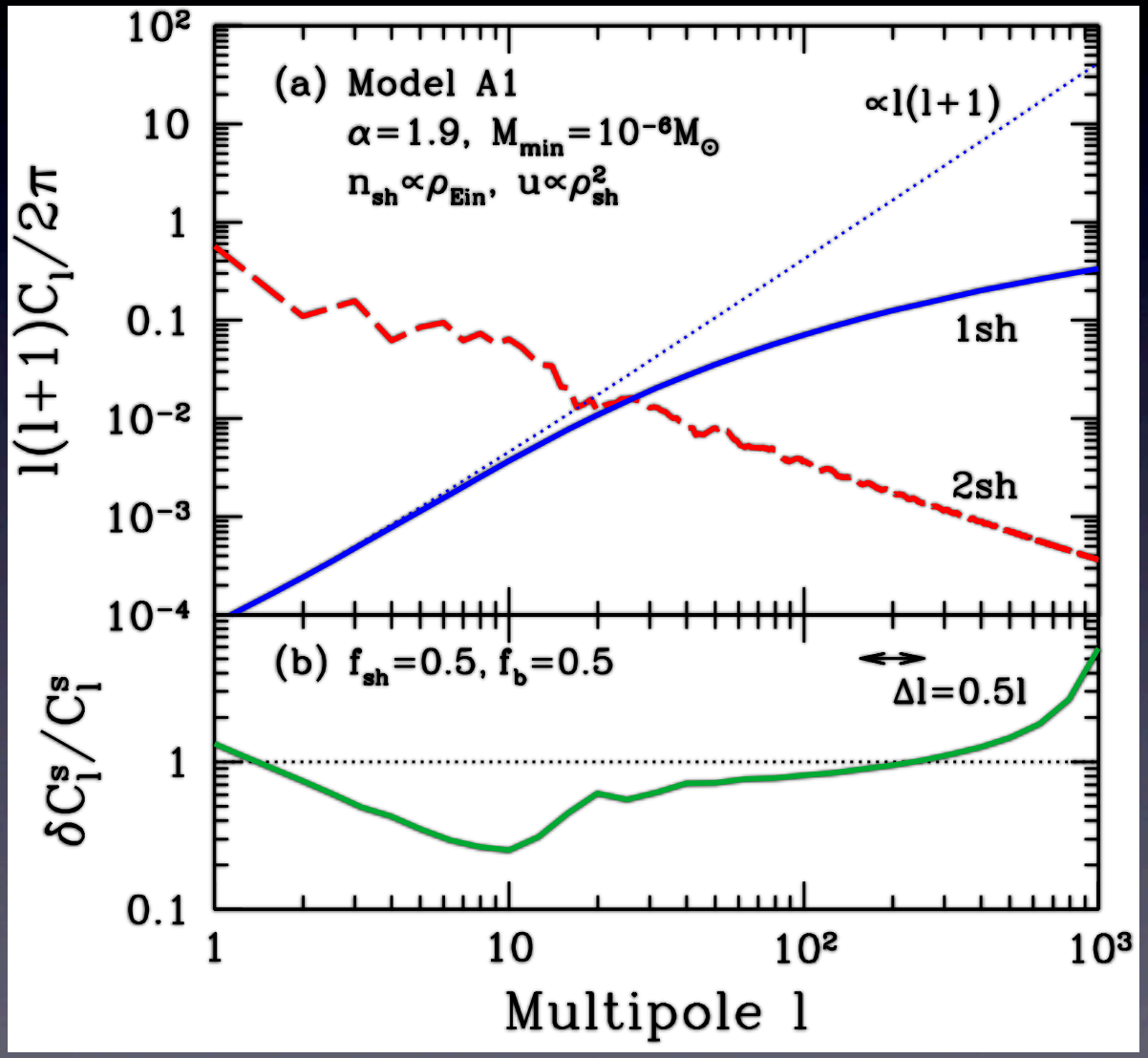
"Host-halo-dominated"

Dark matter signal
Dark matter correlation
Blazar background
Dark matter-blazar cross correlation

- $M_{min} = 10^{-6} M_{sun}$
- Our best estimate: "If DM annihilation contributes > 30% of the mean intensity, Fermi should be able to detect DM anisotropy"

Anisotropy due to Galactic subhalos

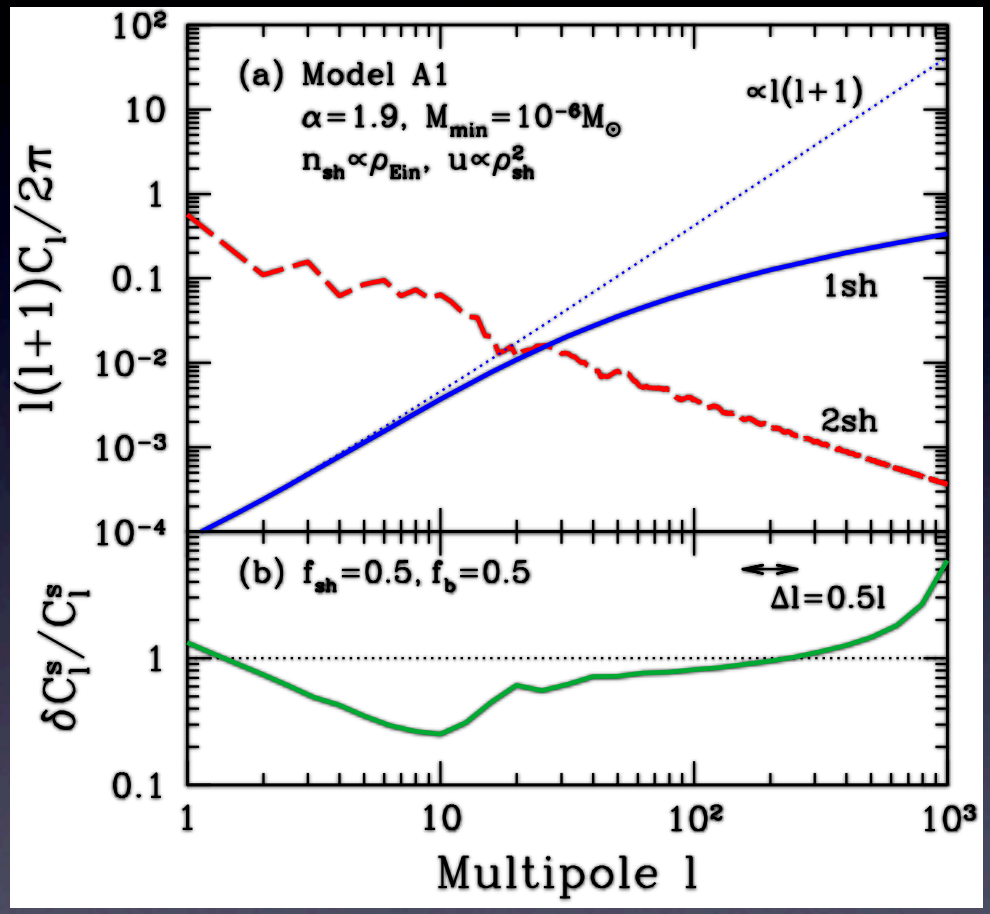
Ando, *Phys. Rev. D* **80**, 023520 (2009)

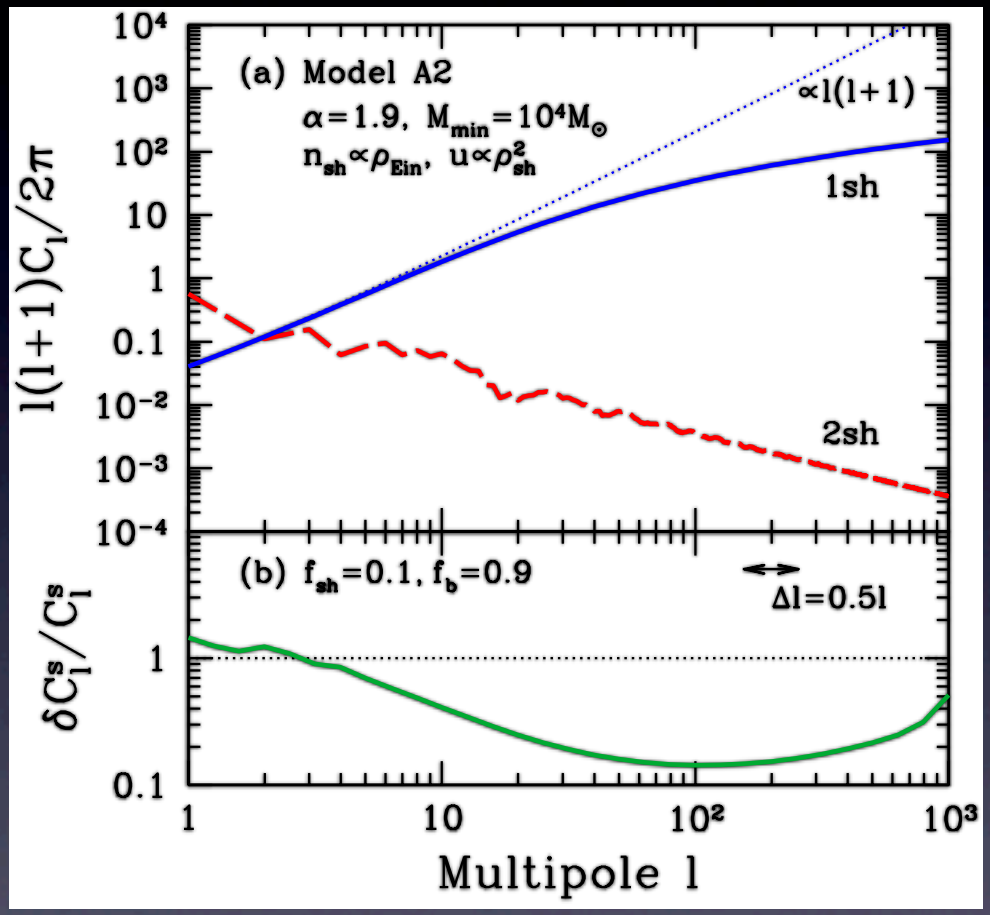


- $M_{min} = 10^{-6} M_{sun}$
- 1sh term dominates at smaller scales
- Deviation from shot noise is due to spatial extention of subhalos
- Good chance of detection if 50:50 mixture with blazars

Dependence on minimum mass

Ando, *Phys. Rev. D* **80**, 023520 (2009)

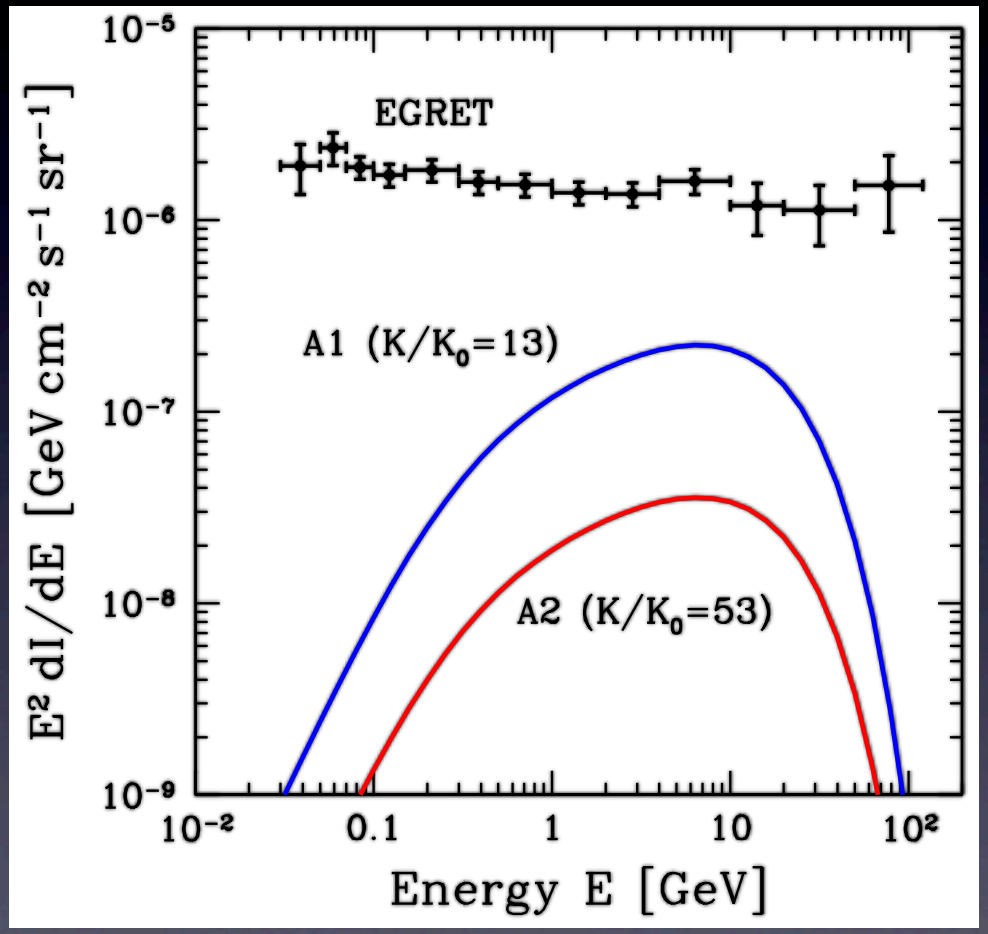




- If M_{min} = 10^4 M_{sun}, we get larger anisotropies
- Even with 10%, dark matter component can be easily detected

Parameters for anisotropy detection

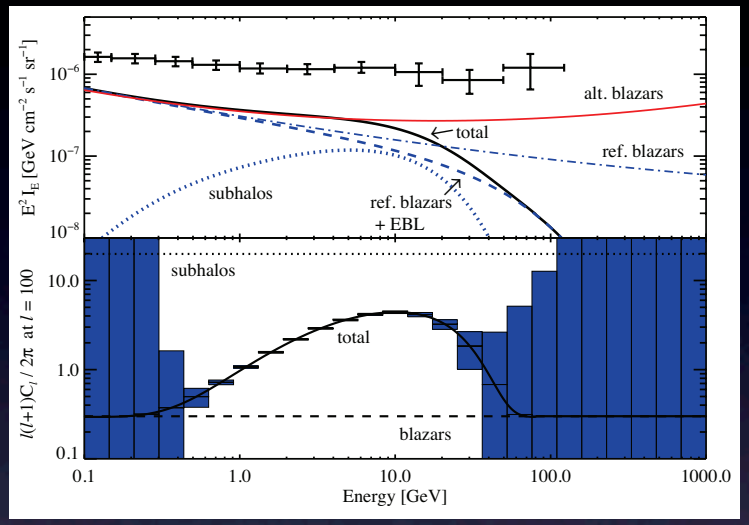
	A1	A2
I_{sh} / I_{obs}	0.24	0.038
Boost	13	53
Associated N_{sh}	0.64	4.0

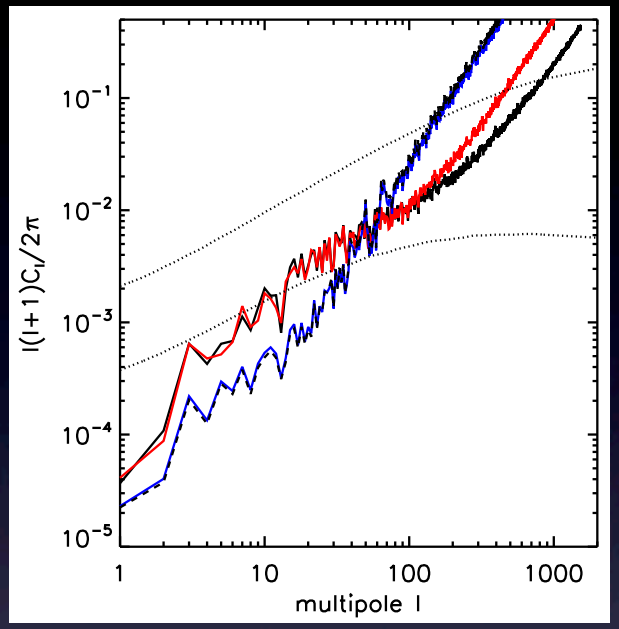


- Even if the subhalo contribution is subdominant in the mean intensity, it can excel in the anisotropy
- This could provide stronger probe of subhalos than detection as single gamma-ray sources

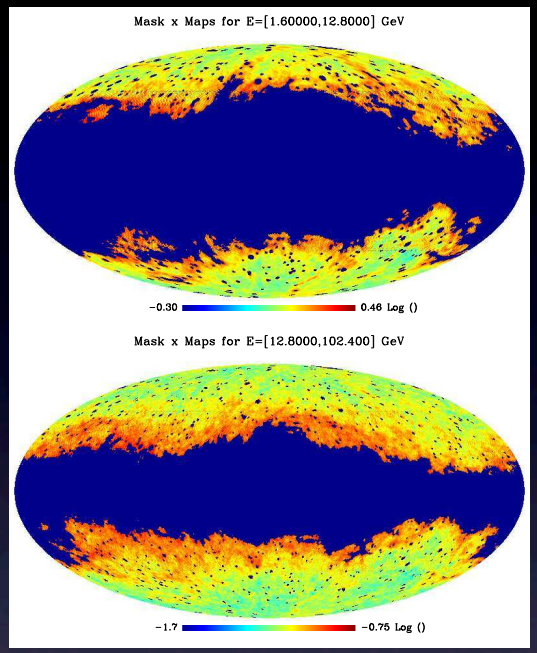
Followup studies

Siegal-Gaskins, Pavlidou (2009)





Zavala, Springel, Boylan-Kolchin (2010)



Cuocco et al. (2010)

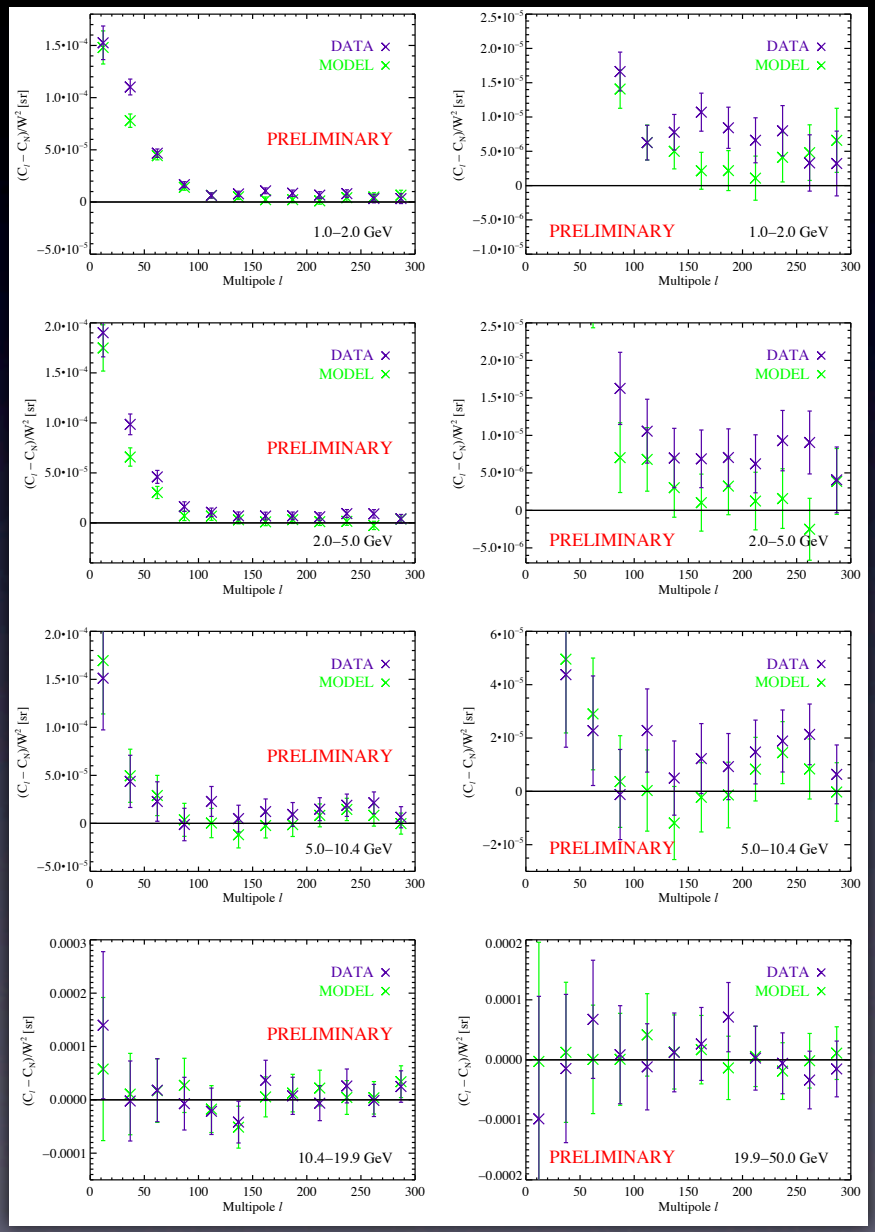
- **Dark matter annihilation**

  Cuocco et al. 2007, 2008; Siegal-Gaskins 2008; Zhang, Sigl 2008; Taoso et al. 2008; Fornasa et al. 2009; Siegal-Gaskins, Pavlidou 2009; Zavala et al. 2010; Hensley et al. 2010; Ibarra et al. 2010; Cuocco et al. 2010; Zhang et al. 2010

- **Astrophysical sources**

  Miniati et al. 2007; Ando, Pavlidou 2009; Siegal-Gaskins et al. 2010

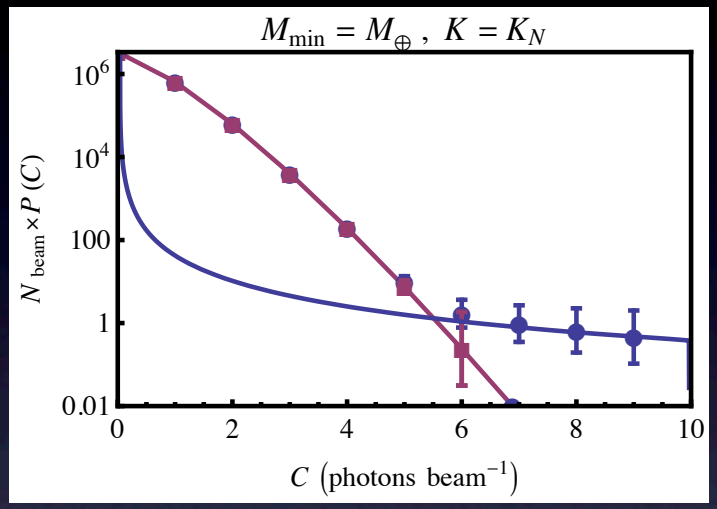
Fermi preliminary results on anisotropy



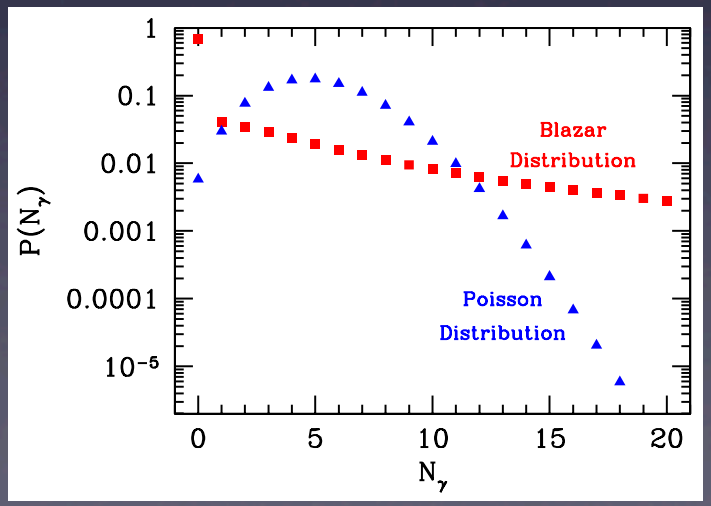
Fermi-LAT & Komatsu, arXiv:1012.1206

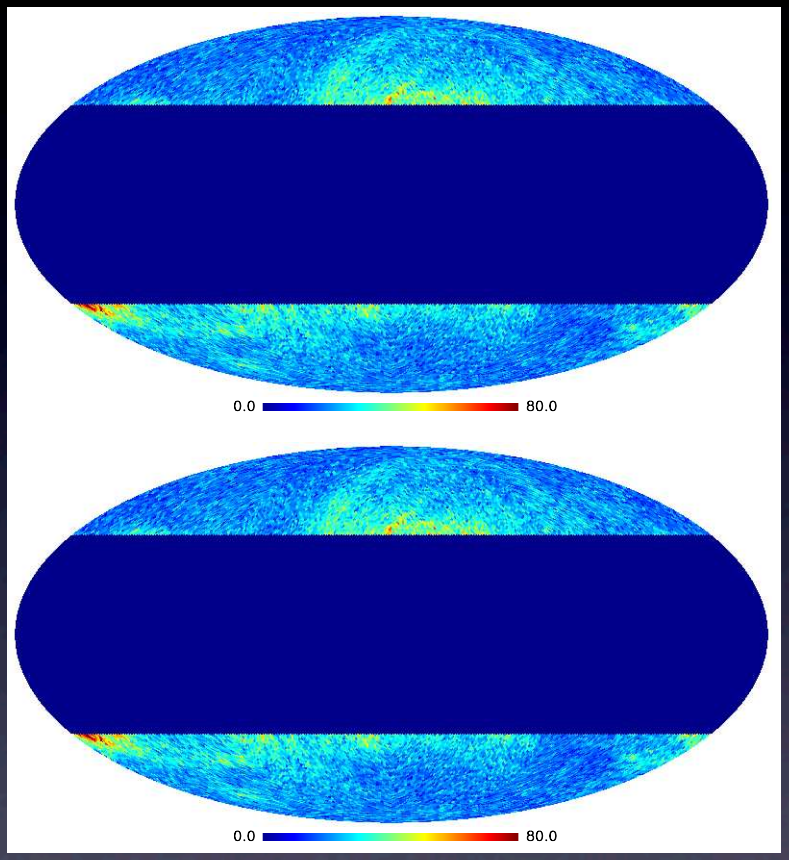
1-point statistics: flux PDF

Lee, Ando, Kamionkowski, *JCAP* **07**, 007 (2009)



Dodelson et al., *Phys. Rev. D* **80**, 083504 (2009)





Baxter et al., *Phys. Rev. D* **82**, 123511 (2010)

- Another diagnostic different for different origin

Summary

- Fermi will provide information on the origin of the gamma-ray background through anisotropy
  - This isn't just for dark matter, but *anything* contributing considerably
- From angular power spectrum, we see that if extragalactic DM component is > 30%, Fermi should discriminate it from blazars' in anisotropy
- Galactic subhalos might give larger power spectrum, and so detection would be more promising
- This series of research is now expanding farther, including energy dependence of power spectrum, 1-point PDF, etc.

Plan of this talk

- Angular power spectrum of the gamma-ray background from dark matter annihilation

  Ando, Komatsu, *Phys. Rev. D* **73**, 023521 (2006)

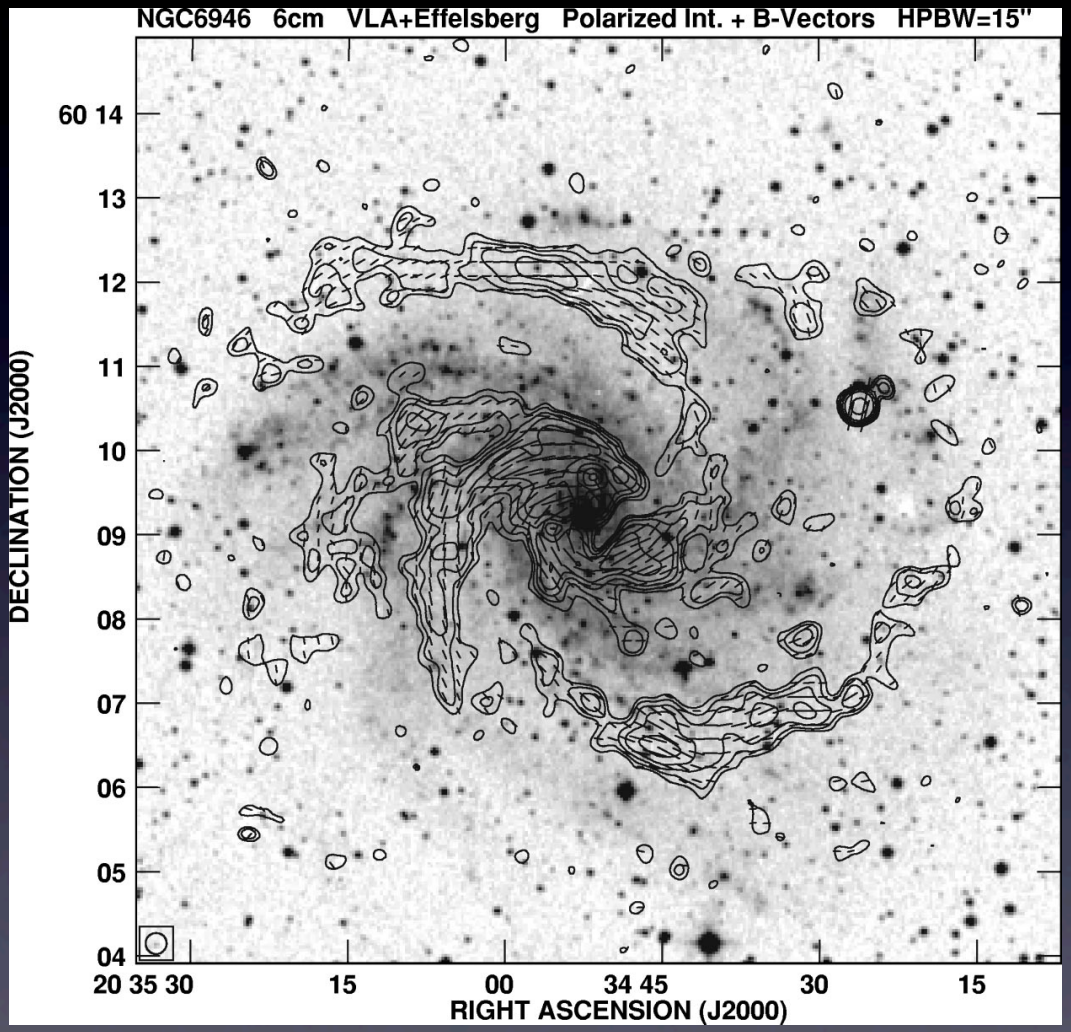
  Ando, Komatsu, Narumoto, Totani, *Phys. Rev. D* **75**, 063519 (2007)

  Ando, *Phys. Rev. D* **80**, 023520 (2009)

- Search for gamma-ray halos around Fermi AGNs and intergalactic magnetic fields

  Ando, Kusenko, *Astrophys. J.* **722**, L39 (2010)

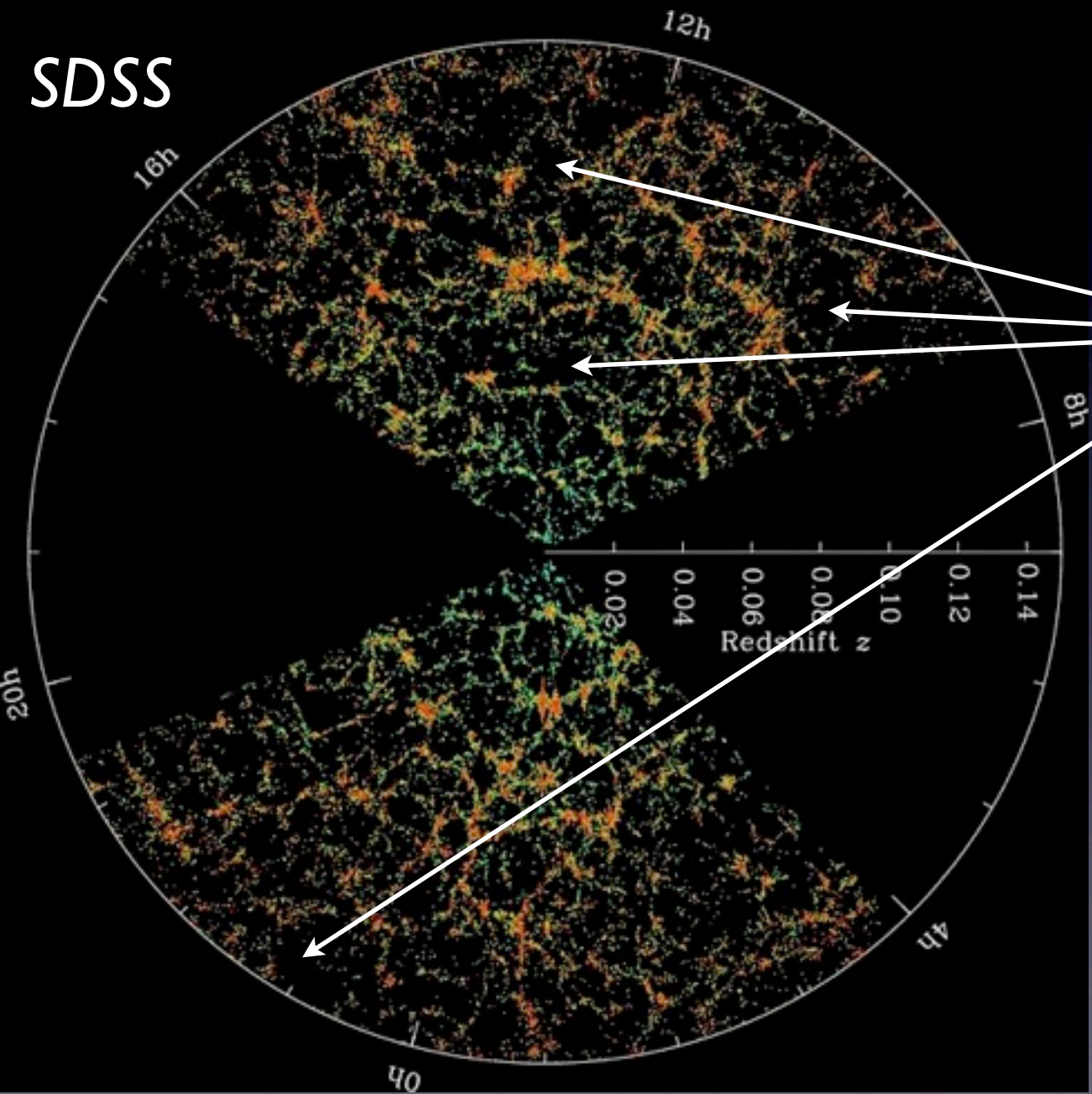
Magnetic fields in galaxies and galaxy clusters



B-filed configuration by polarized synchrotron intensity (Beck & Hoernes 1996)

- Astronomical probes
  - Faraday rotation
  - Synchrotron from radio halos
  - Polarization of optical light (Davis-Greenstein effect)
- Measured strength: ~1–10 μG
- Galactic dynamo as an amplifying mechanism
  - The "seed" fields could be as small as ~10^{-30}–10^{-20} G
- Where can we find seeds of galactic fields?

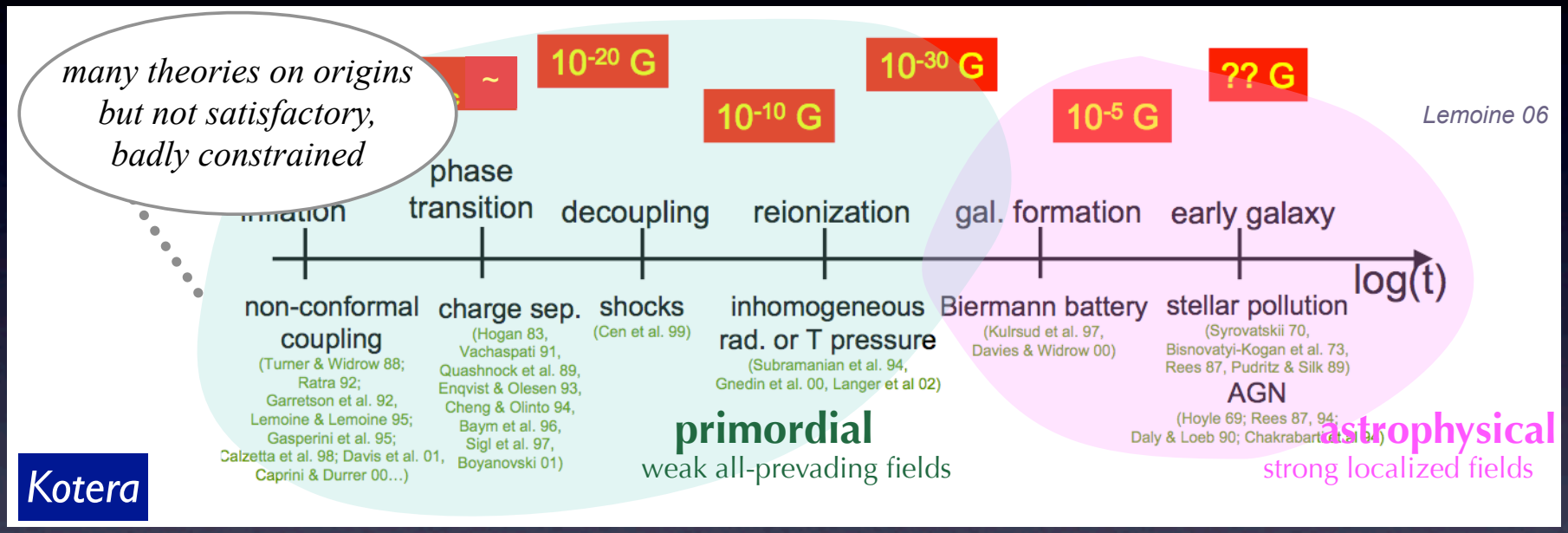
Intergalactic magnetic fields (IGMFs)



Are there magnetic fields in intergalactic space (or voids)?

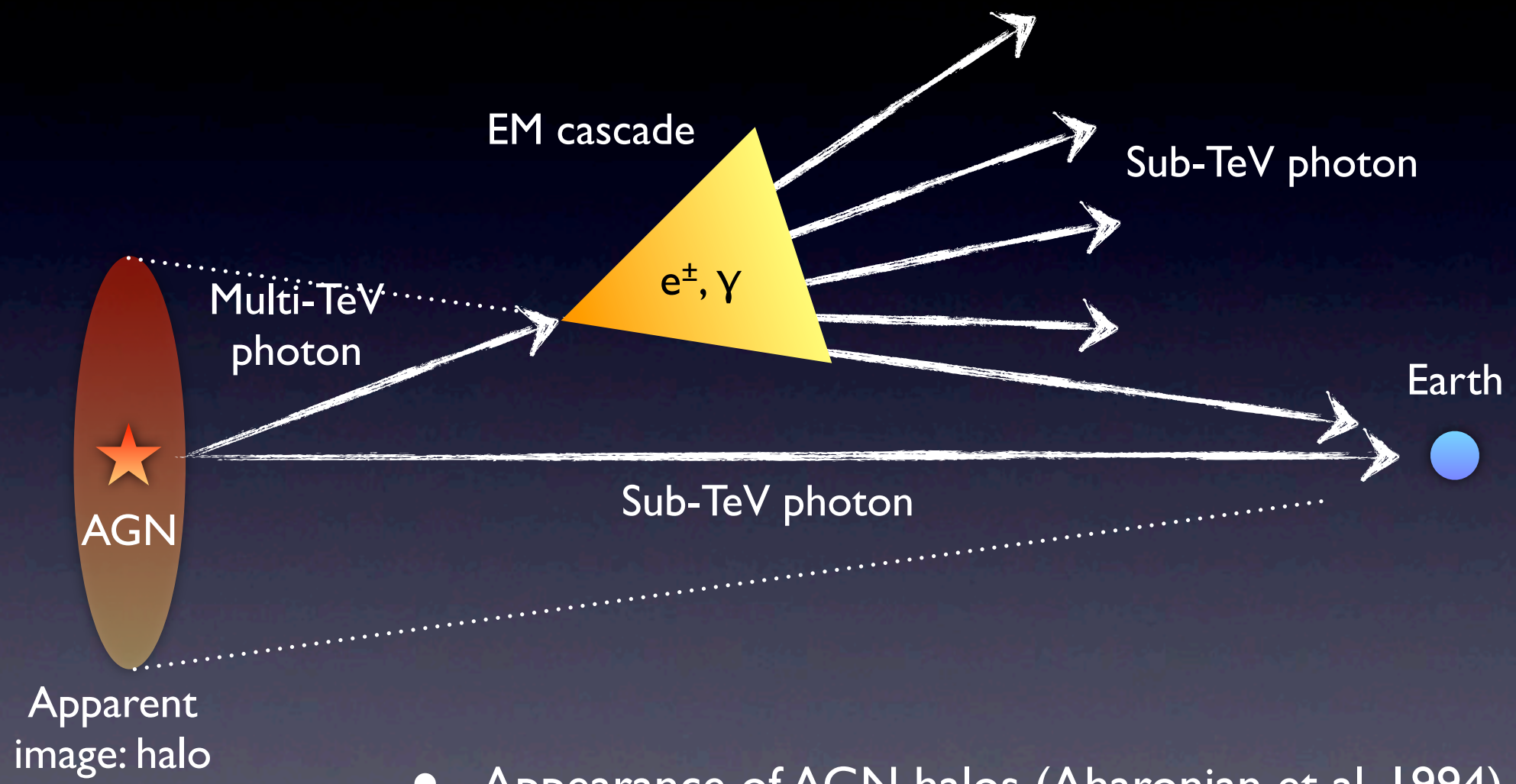
Intergalactic magnetic fields (IGMFs)

- How are they generated?



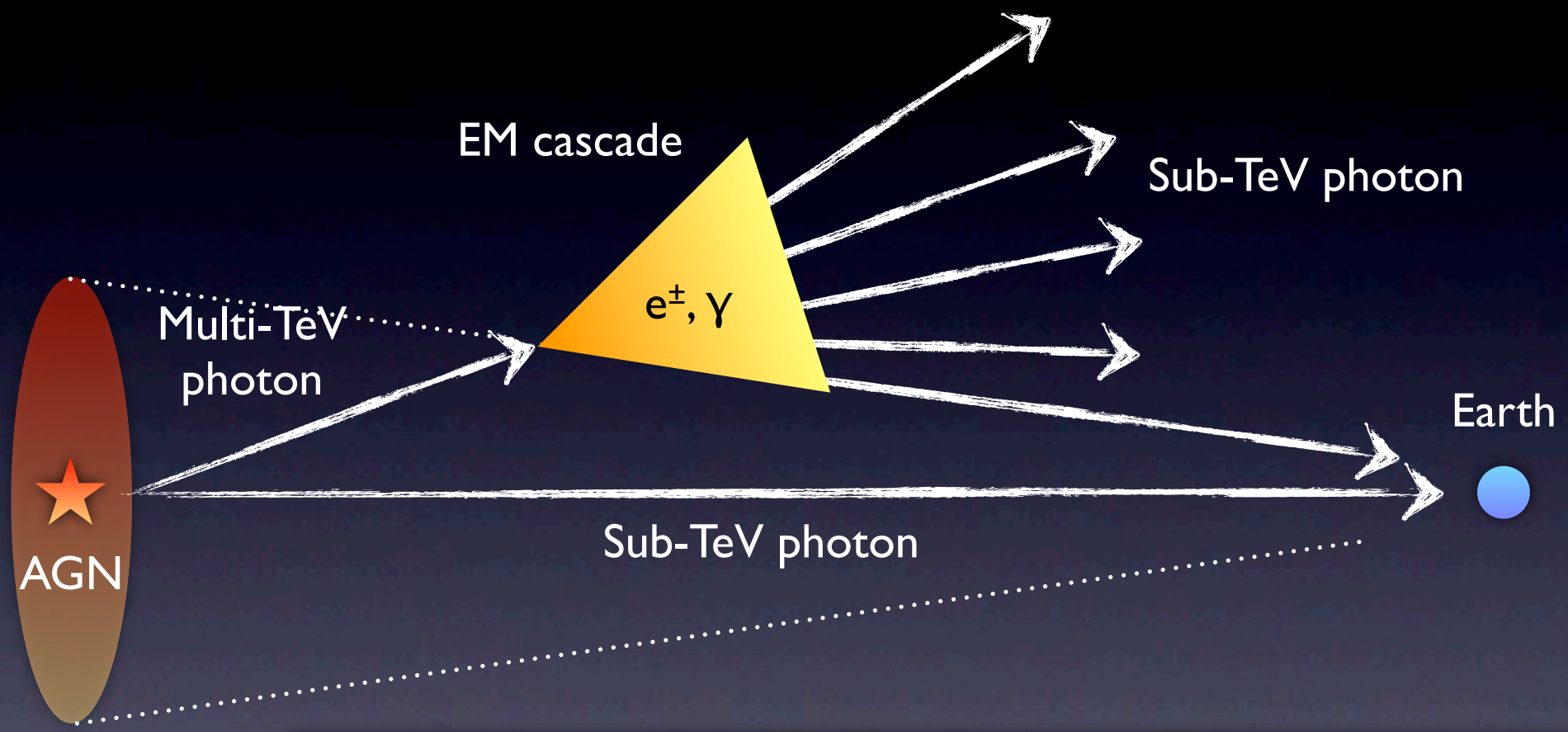
- Upper bounds: $B_{\mathrm{IGMF}} \lesssim 10^{-9}$ G
  - Late Universe: Faraday rotation measure
  - Early Universe: CMB, Big-Bang nucleosynthesis

Gamma-ray probes of IGMFs



- Appearance of AGN halos (Aharonian et al. 1994)
- Delay of arrival time (Plaga 1995)

Magnetic deflection and pair halos



Apparent image: halo

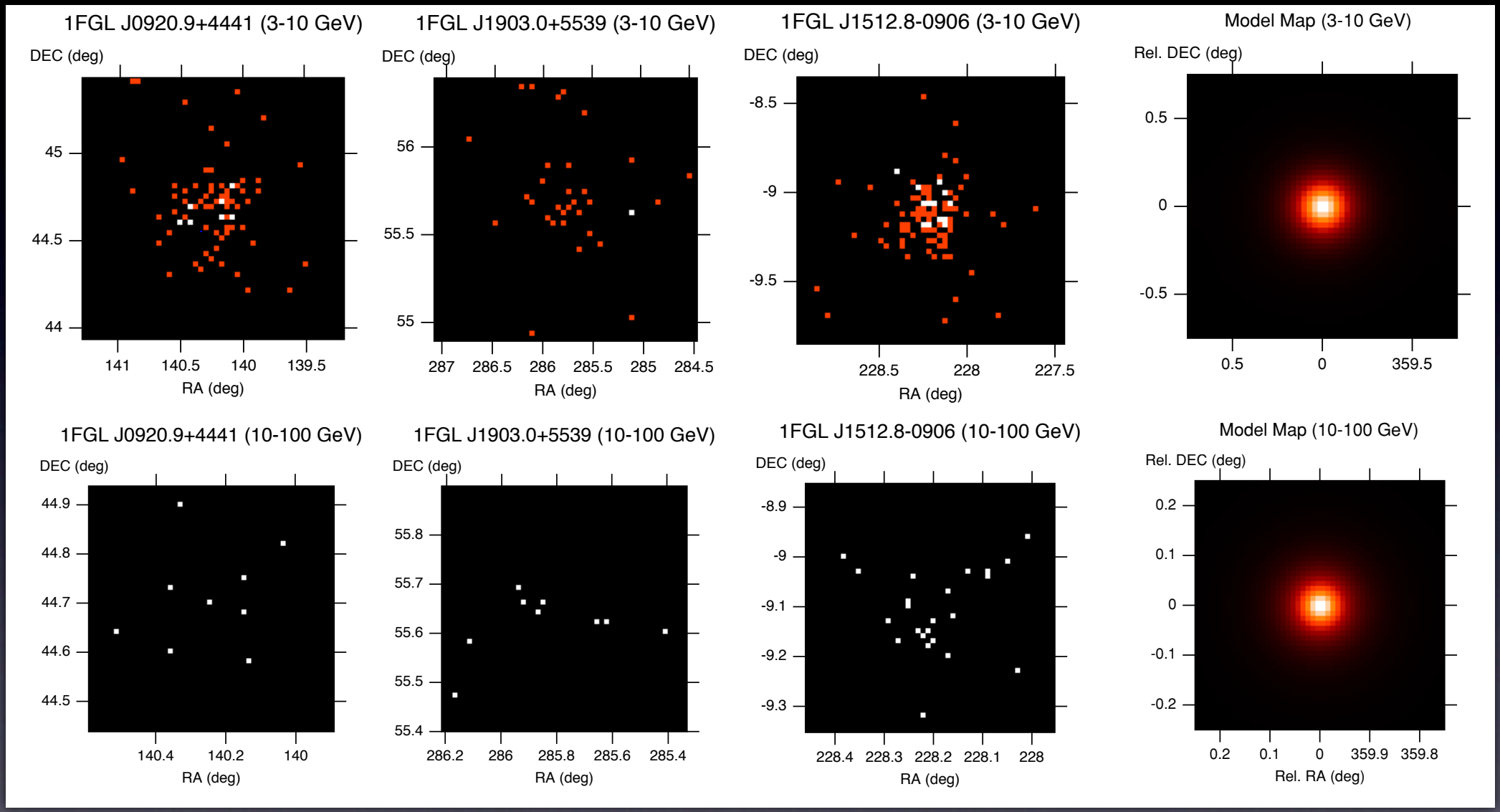
$$\theta_{\rm halo} = \begin{cases} 5^\circ (1+z)^{-2} \tau^{-1} \left(\frac{E_\gamma}{10\ \rm GeV}\right)^{-1} \left(\frac{B}{10^{-15}\ \rm G}\right), & \text{for } \lambda_B \gg D_e \\ 0.4^\circ (1+z)^{-1/2} \tau^{-1} \left(\frac{E_\gamma}{10\ \rm GeV}\right)^{-3/4} \left(\frac{B}{10^{-15}\ \rm G}\right) \left(\frac{\lambda_B}{1\ \rm kpc}\right)^{1/2}, & \text{for } \lambda_B \ll D_e \end{cases}$$

Neronov & Semikoz (2009)

Details of analysis

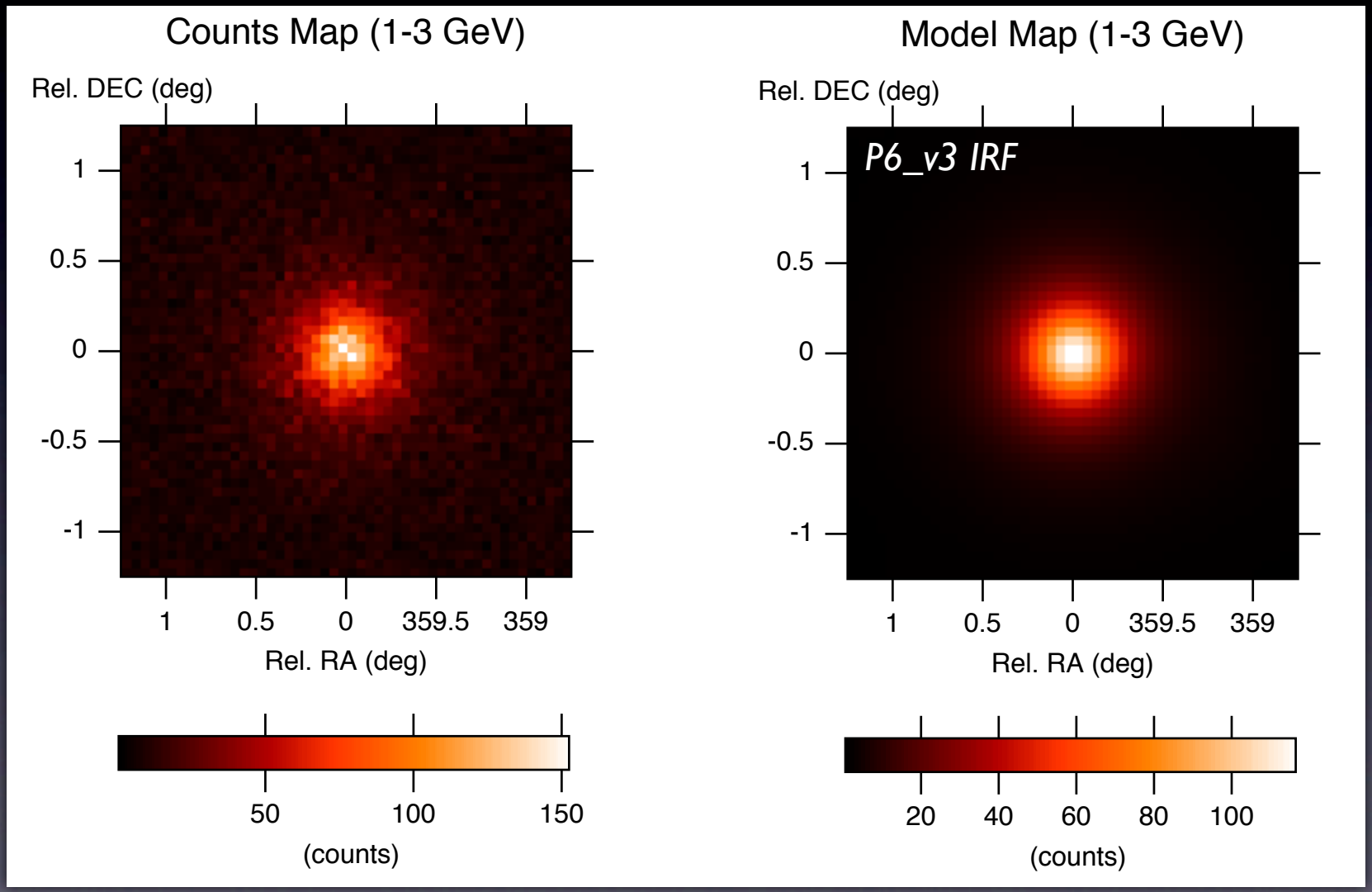
- Select photons from 1-year "diffuse" class event file (*LAT_allsky_239557417_272868753_v01_Diffuse.fits*)
  - List of individual photons from all sky; information on arrival directions, time, energy, etc.
  - "Diffuse class": purest data recommended for most of analysis (charged-particle contamination is minimum)
- We use three energy bands: 1–3, 3–10, 10–100 GeV
- 170 AGNs are selected from the 11-month point-source catalog (*gll_psc_v02.fit*)
  - They yielded more than 4.1σ (TS>25) detection in the highest energy band, 10–100 GeV
  - Presumably these are hard AGNs, producing lots of TeV photons that source halos
- We make both photon counts maps and expected model maps (using *P6_v3 IRF*)

Gamma-ray maps for individual AGNs



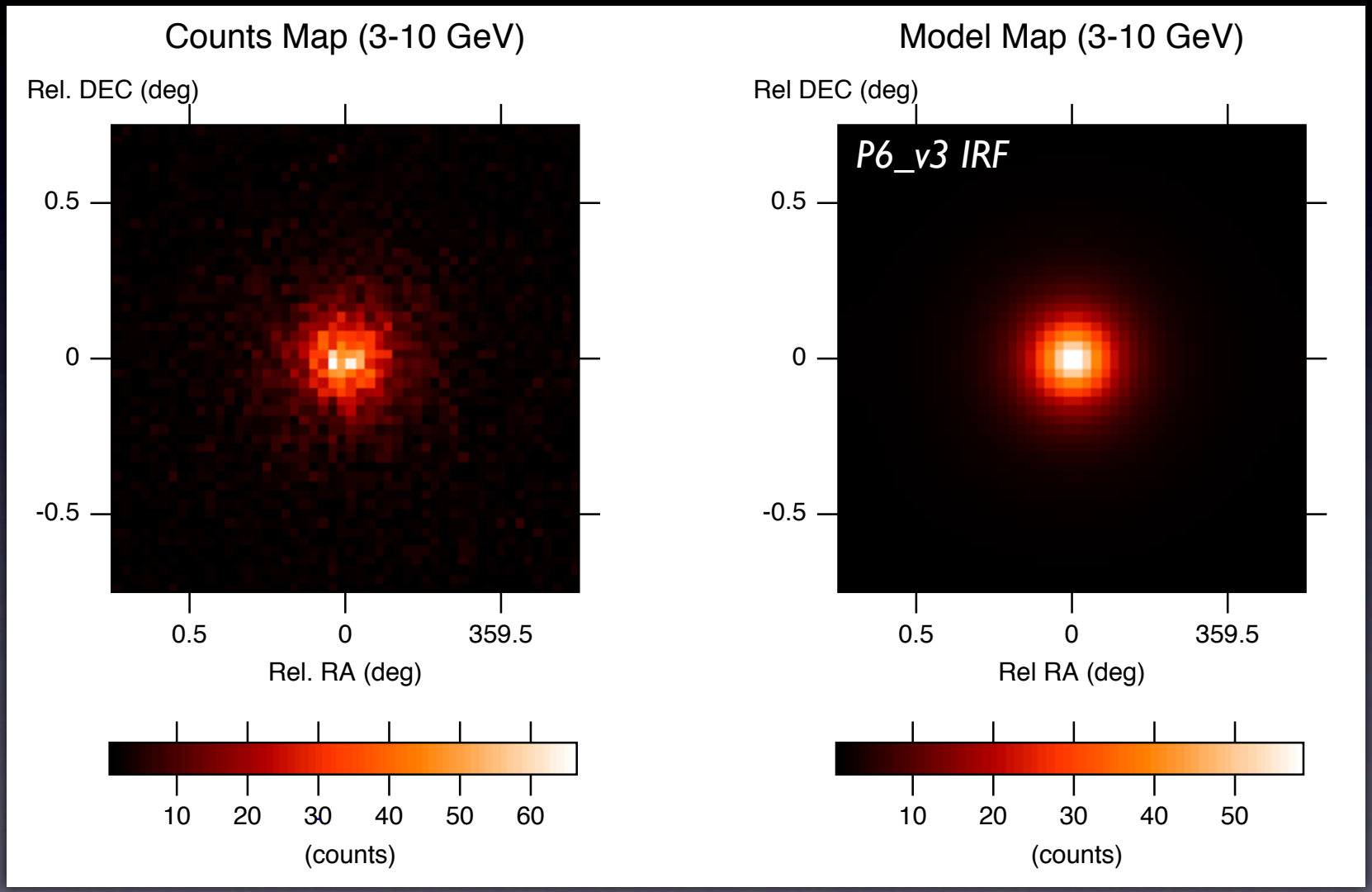
- It is not possible to compare data with PSF models → need stacking

Stacked maps: 1–3 GeV



Ando & Kusenko, *Astrophys. J.* **722**, L39 (2010)

Stacked maps: 3–10 GeV



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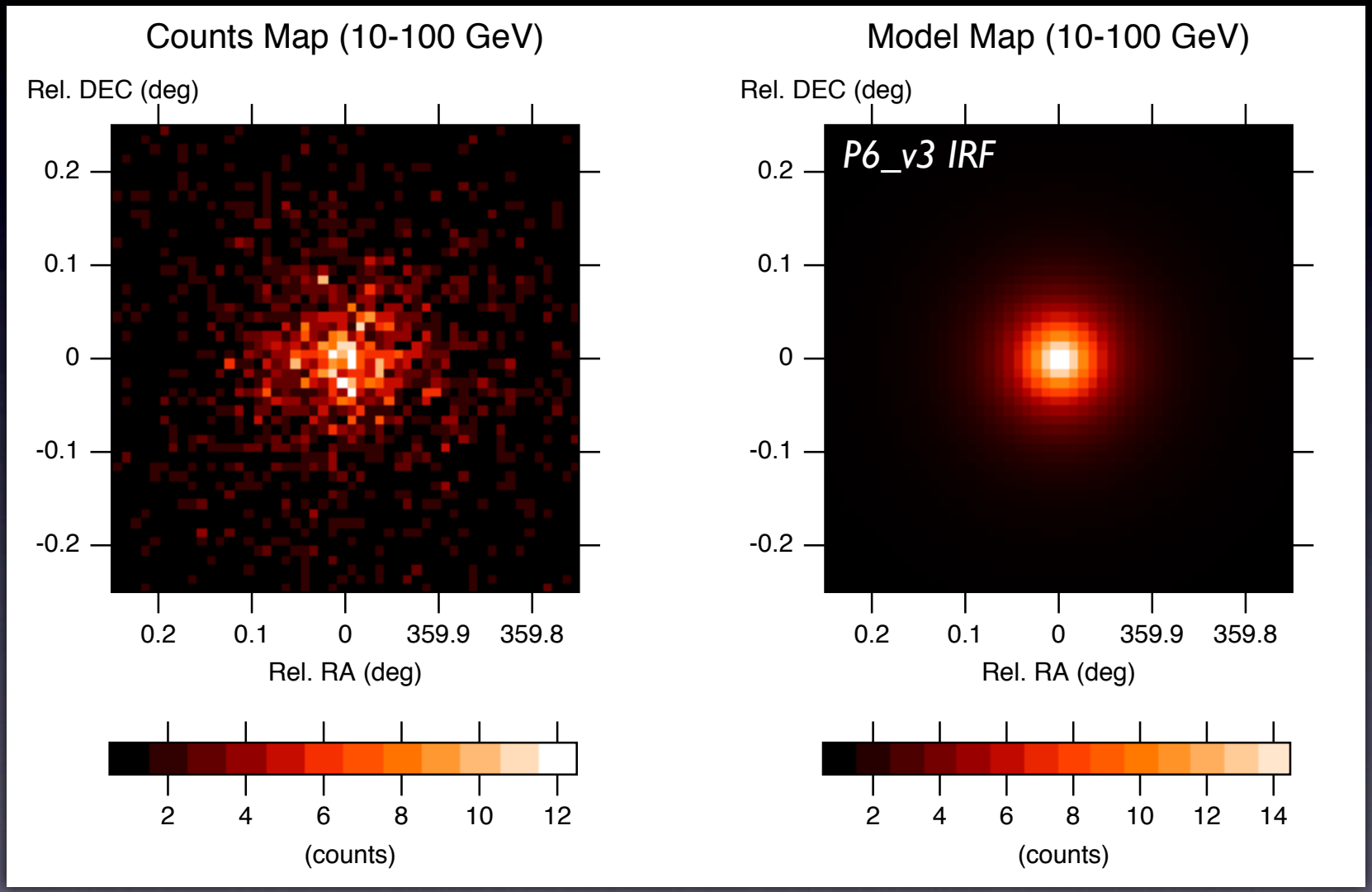
Stacked maps: 10–100 GeV



Ando & Kusenko, *Astrophys. J.* **722**, L39 (2010)

Is there anomalous excess? Yes!

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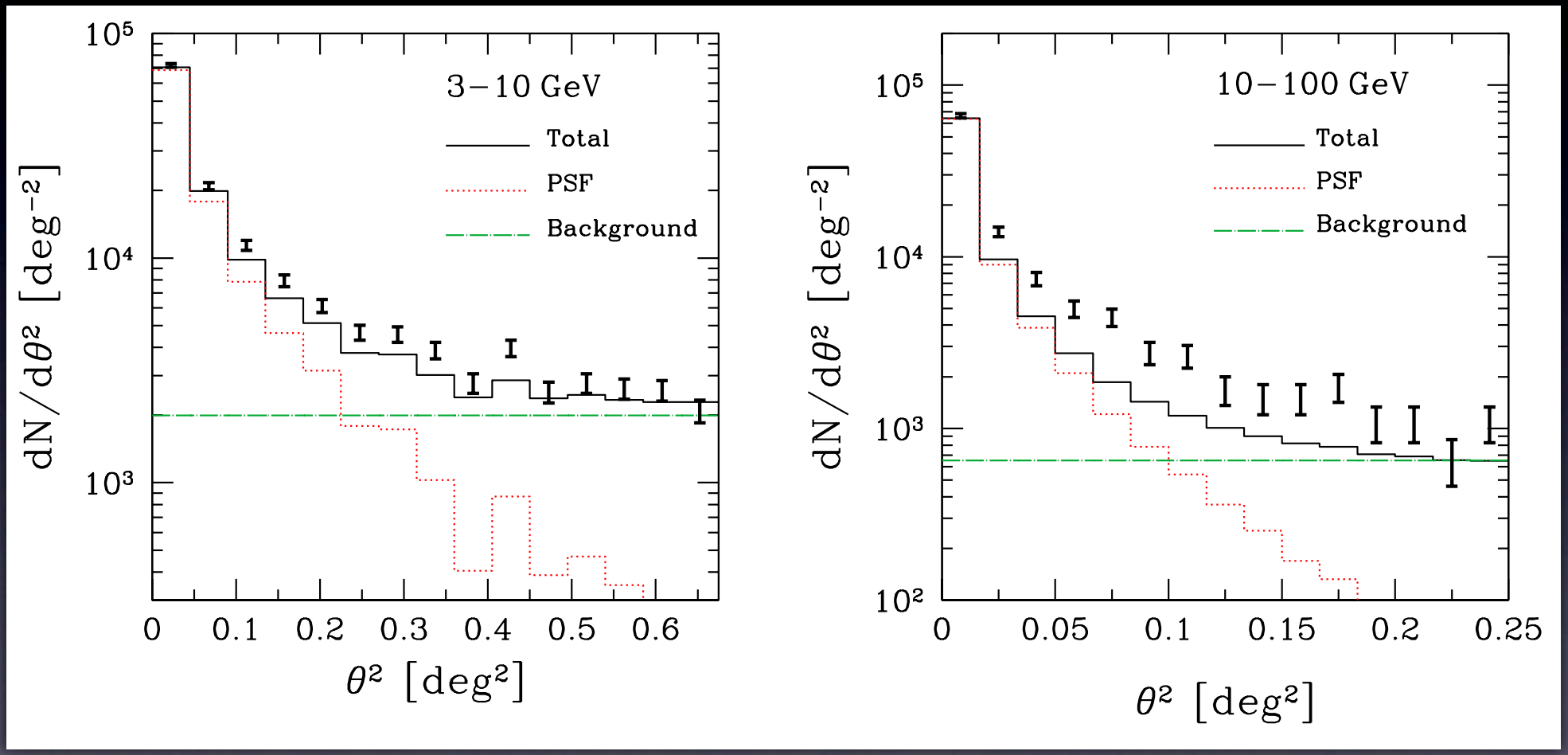

χ_{min}^2/DOF = 66/20

χ_{min}^2/DOF = 62/13

Gaussian halo component

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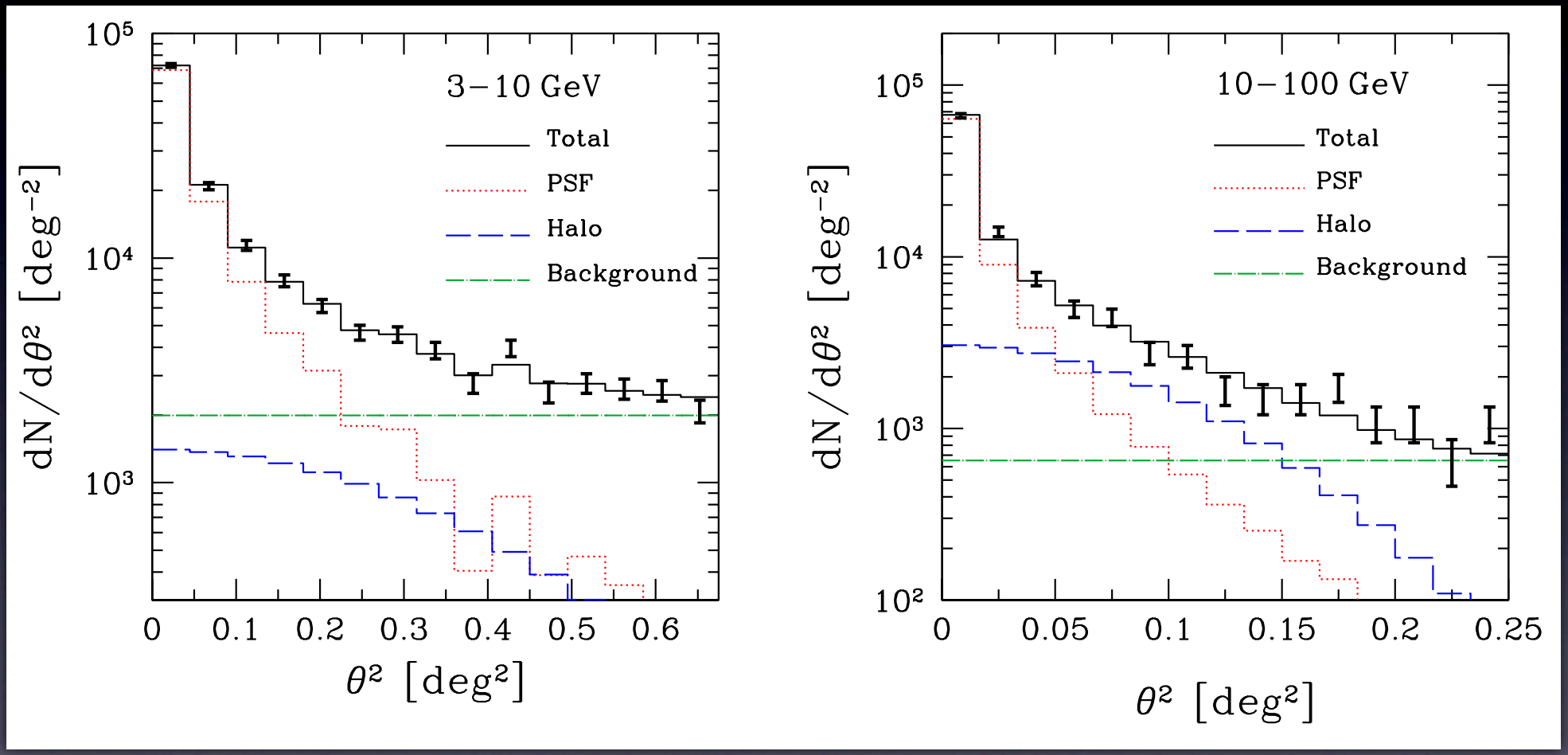

χ_{min}^2/DOF = 18.8/19

χ_{min}^2/DOF = 13.3/12

Halo properties and IGMF

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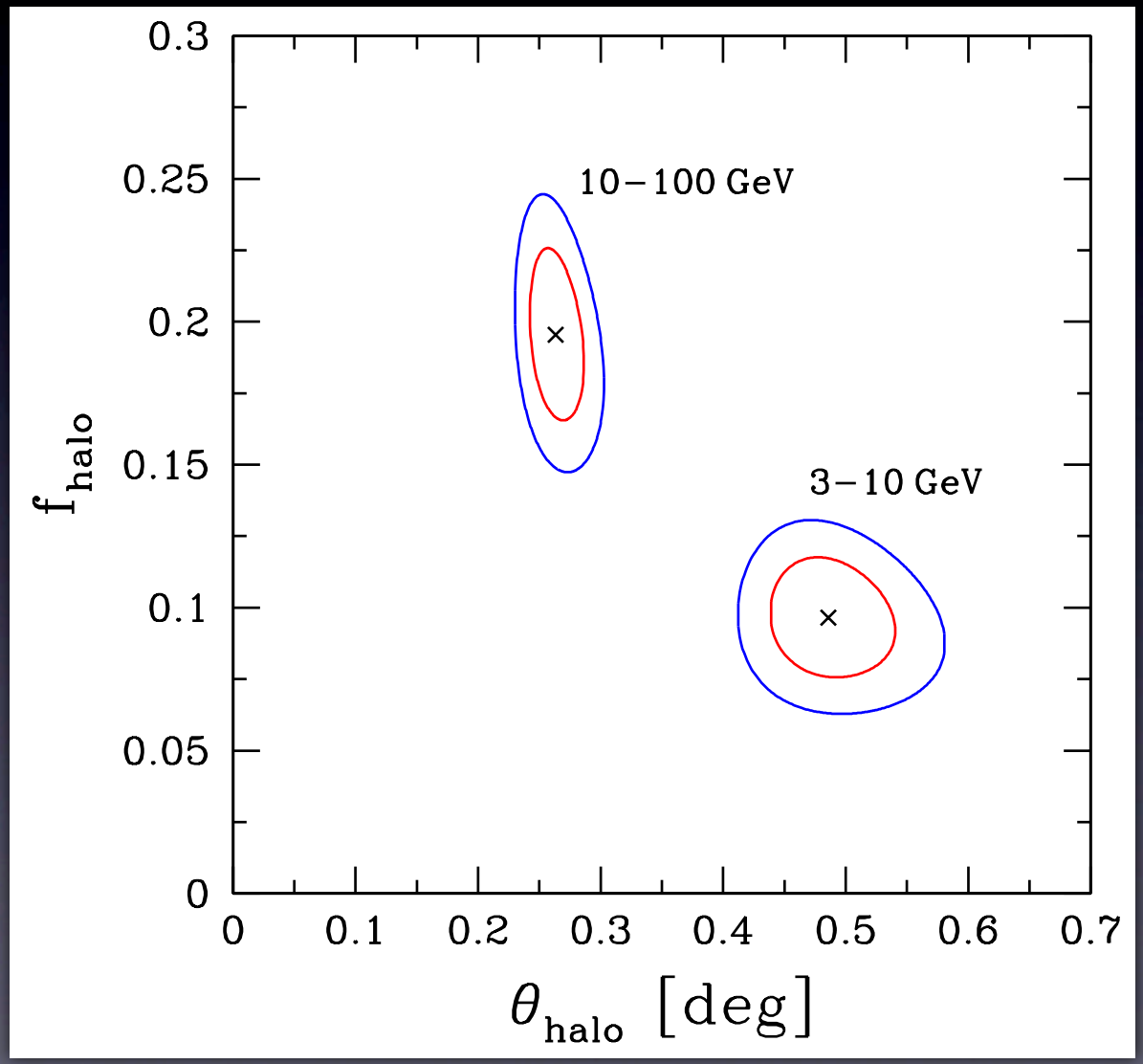

- 68%, 95% CL contours for halo size θ_{halo} and fractional number of halo photons f_{halo}
- The halo sizes and energy dependence imply $B \approx 10^{-15}$ G

Are the "halos" physical or instrumental?

Two tests against instrumental effects

1. Dependence on redshifts

   - 57 AGNs for $z < 0.5$
   - 42 AGNs for $0.5 < z < 2.5$

2. Comparison with the Crab pulsar (point source)

Instrumental effects should not make any difference in both tests

Redshift dependence

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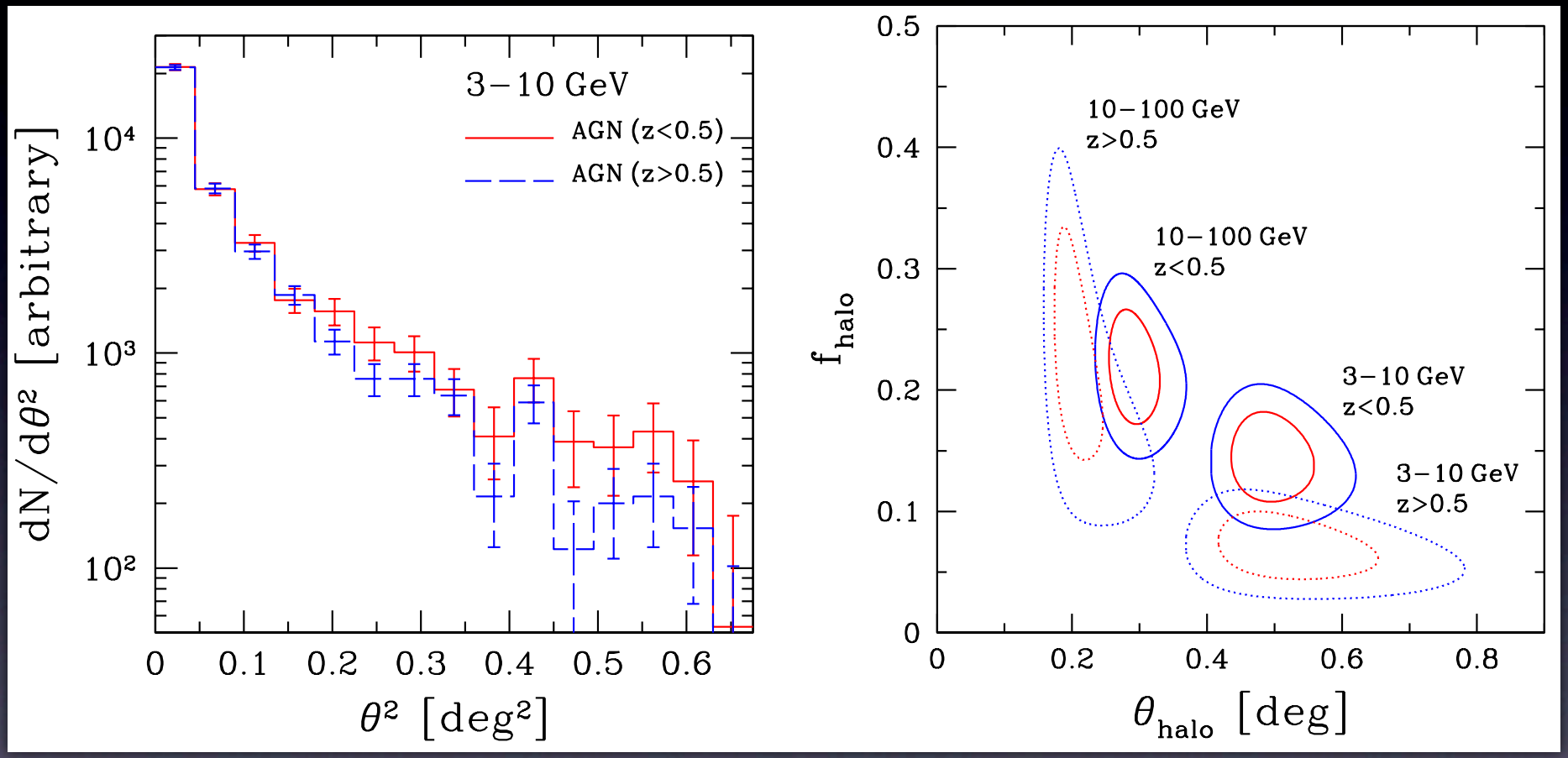
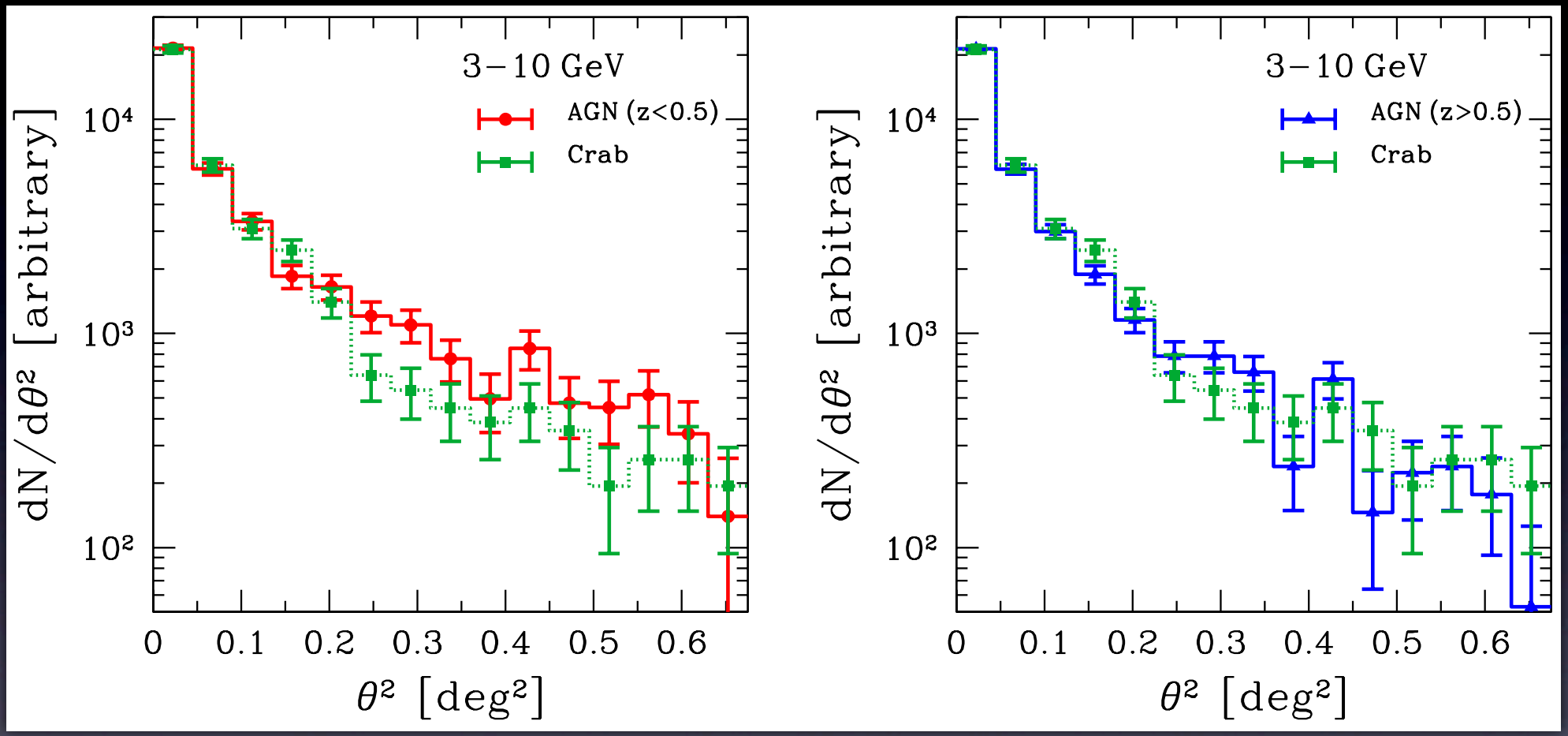


- Nearby AGNs are more extended — as expected from the pair halo scenario, but not from instrumental effects

Comparison of AGN and Crab profiles



- Backgrounds have been estimated from θ^2 = 1.8–2.25 deg^2 and subtracted
- Nearby AGNs are even more extended than Crab
- Distant AGN profile is consistent with the Crab profile

Summary

- Stacked 170 (hard spectrum) AGN images
- Found anomalous excess compared with the latest (P6_v3) PSF
- Can be interpreted as IGMF, with amplitude around 10^{-15} G
- The image sizes are different for nearby/hard and distant/soft AGN populations (evidence against instrumental effects)
- Nearby/hard AGNs are more extended than Crab, but distant/soft ones are consistent with Crab
- Some work on GeV–TeV spectra also supports femto-Gauss IGMF
- This study accelerated post-launch calibration of LAT PSF

Implications

- Astronomy; Plasma Physics
  - How to generate micro-Gauss fields in galaxies and galaxy clusters from femto-Gauss IGMF (e.g., galactic dynamo)
  - How to generate IGMFs from astrophysical activities (e.g., Biermann battery)
- Cosmology; Particle Physics
  - Magnetogenesis in the early Universe, such as QCD, electroweak phase transitions, and inflation
  - Imprint of IGMF on CMB, BBN, etc.
- High-Energy Astrophysics
  - Measurement of (constraint on) femto-Gauss IGMFs
  - Origins of halos; photons or cosmic rays?