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Search for gamma-ray halos around Fermi AGN

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Magnetic deflection and pair halos

E.g., Aharonian et al. (1994)

AGN

Earth

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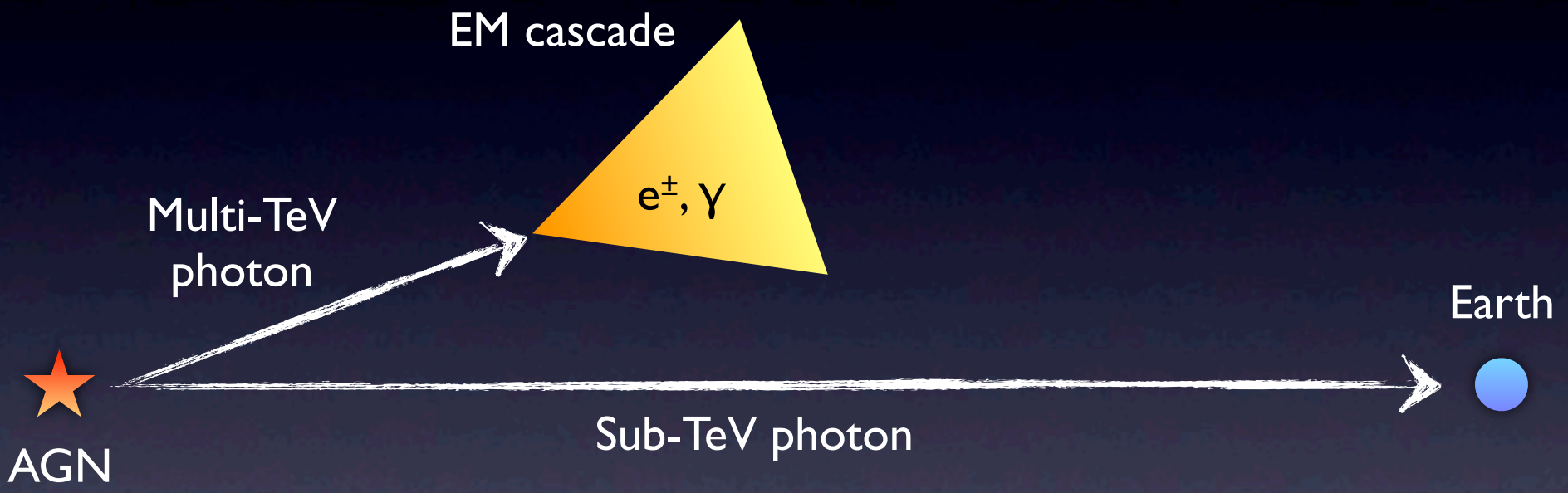

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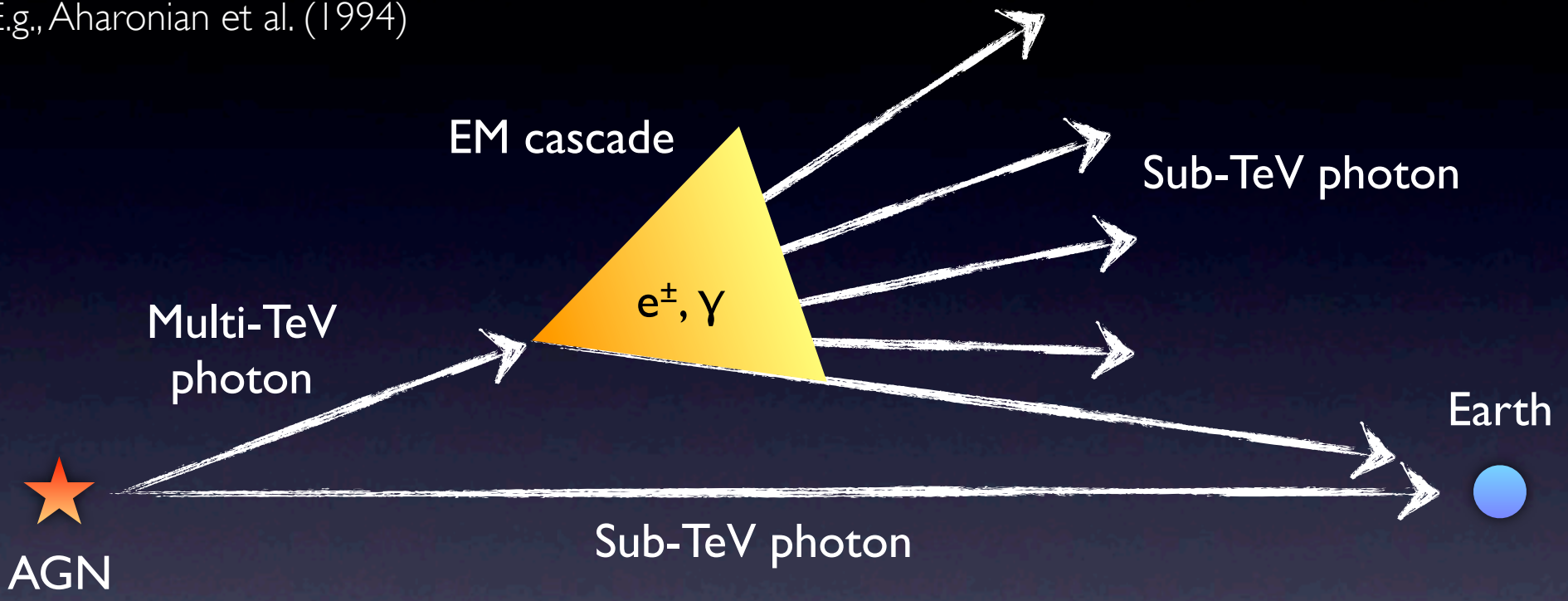

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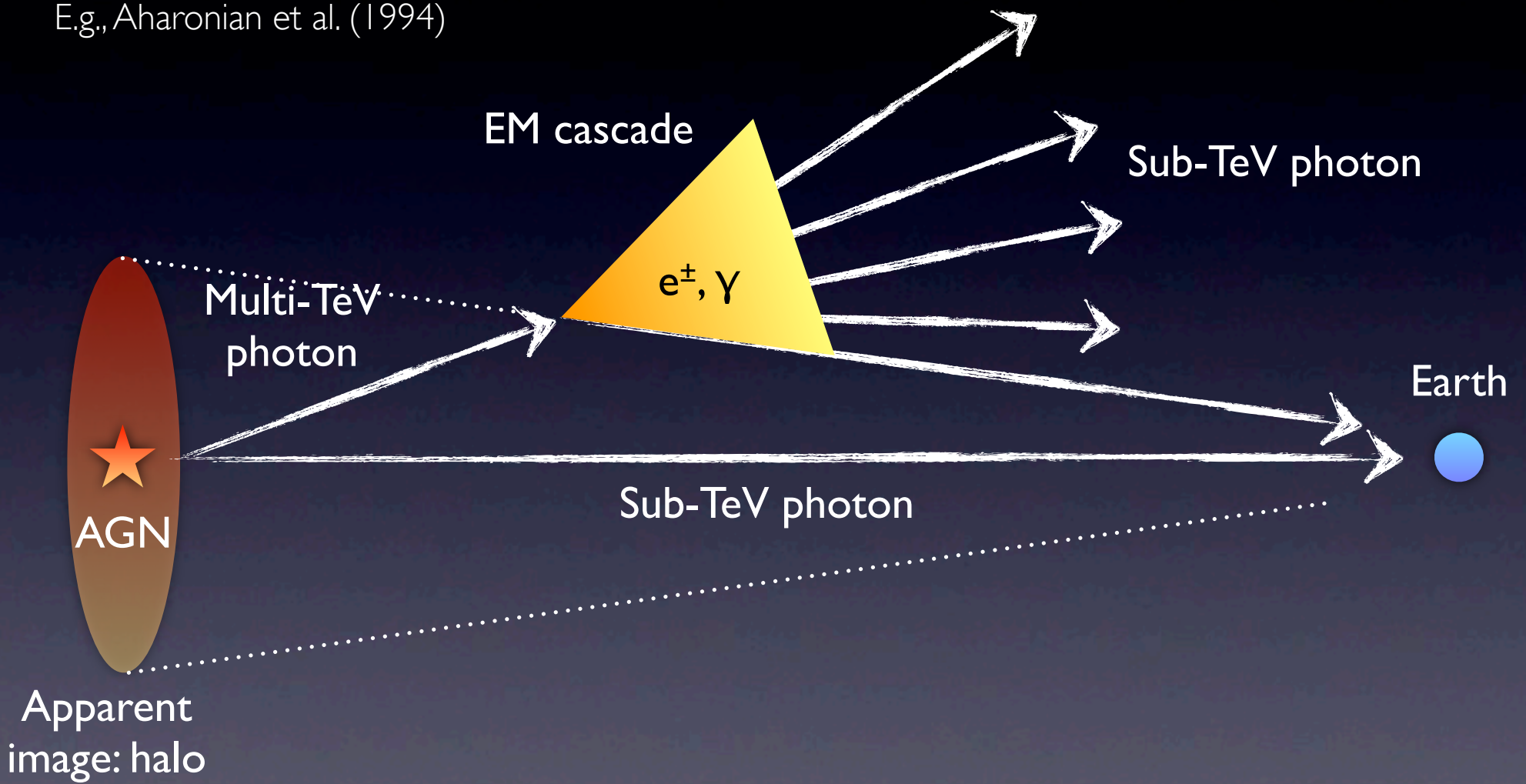

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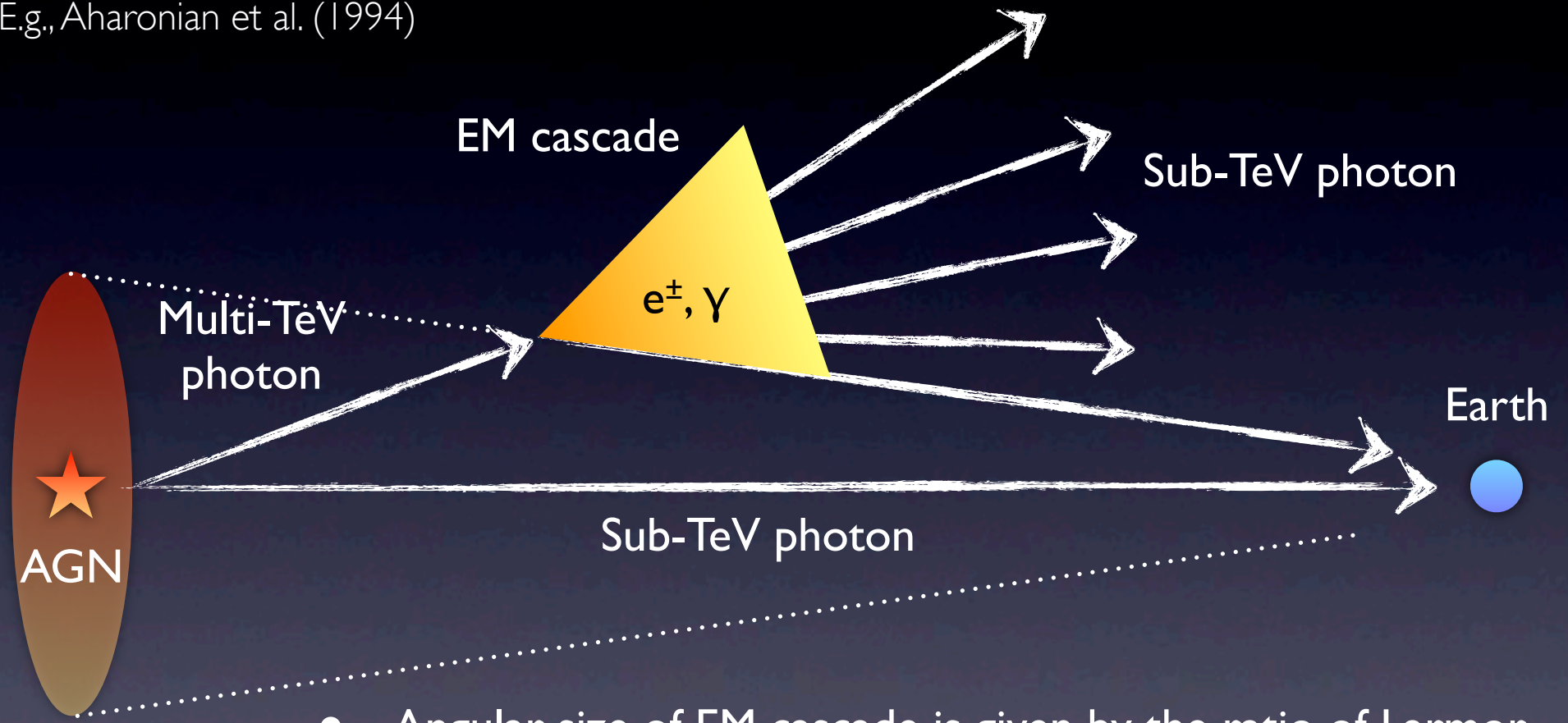

- Angular size of EM cascade is given by the ratio of Larmor radius and energy-loss length of pairs if correlation length is long enough

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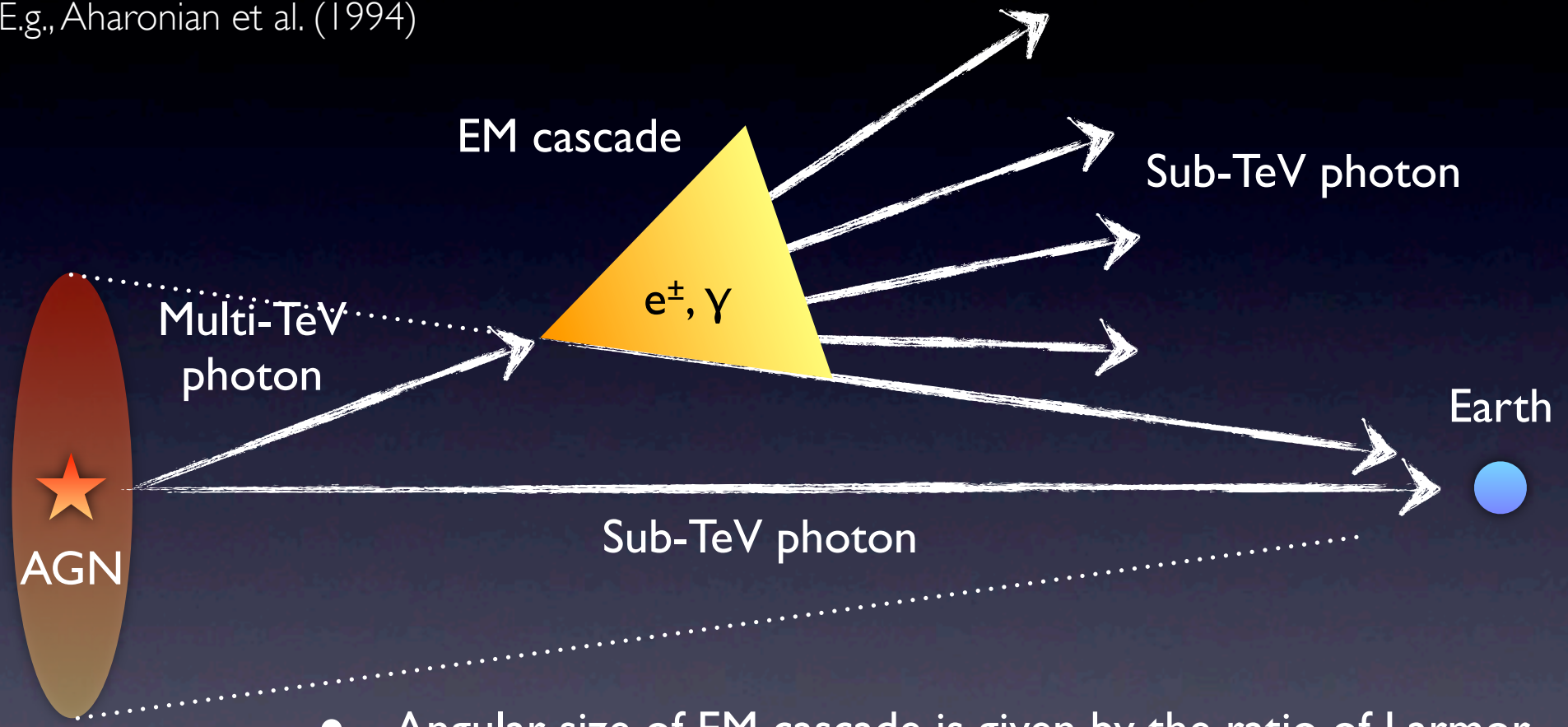
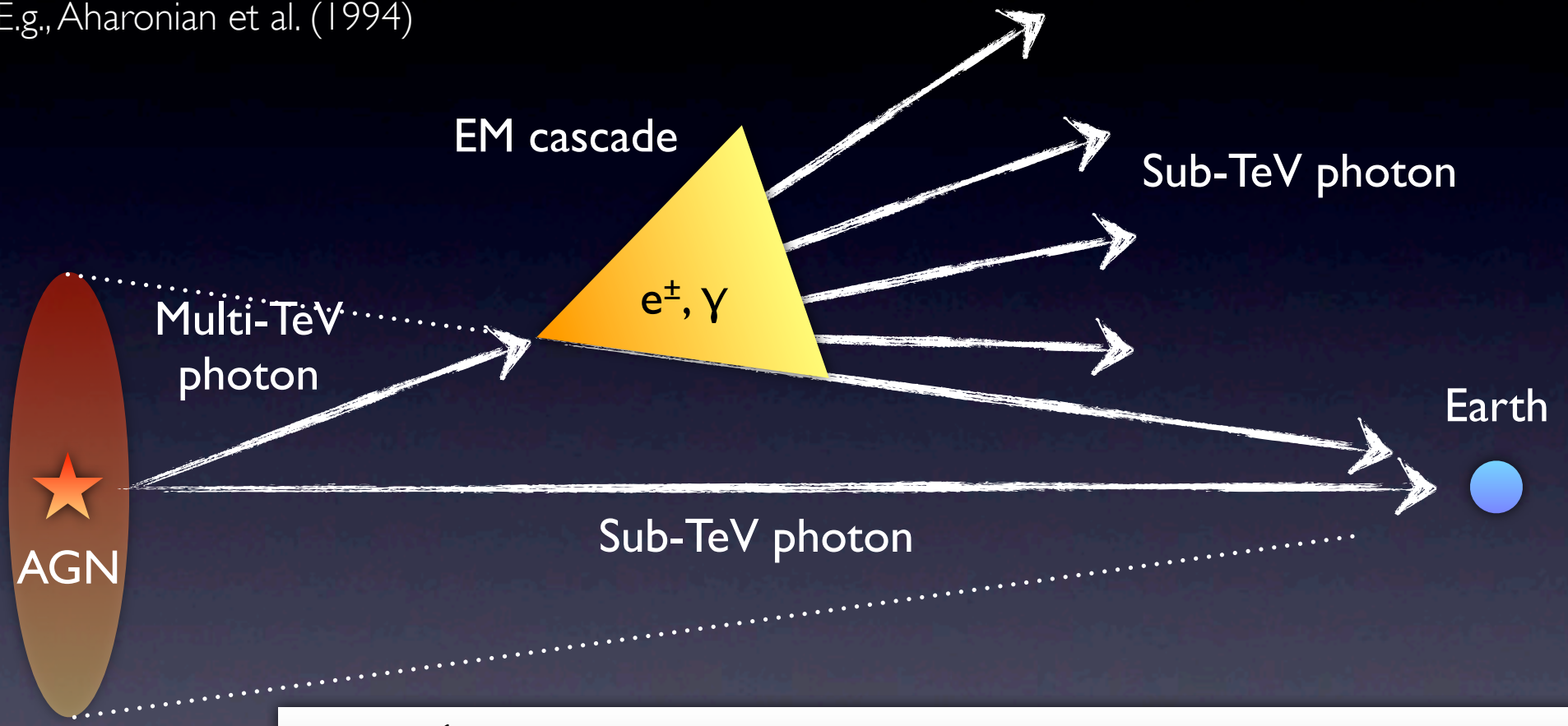


- Angular size of EM cascade is given by the ratio of Larmor radius and energy-loss length of pairs if correlation length is long enough
- In the opposite limit, pairs propagate through random walk

Magnetic deflection and pair halos

E.g., Aharonian et al. (1994)



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

Neronov & Semikoz (2009)

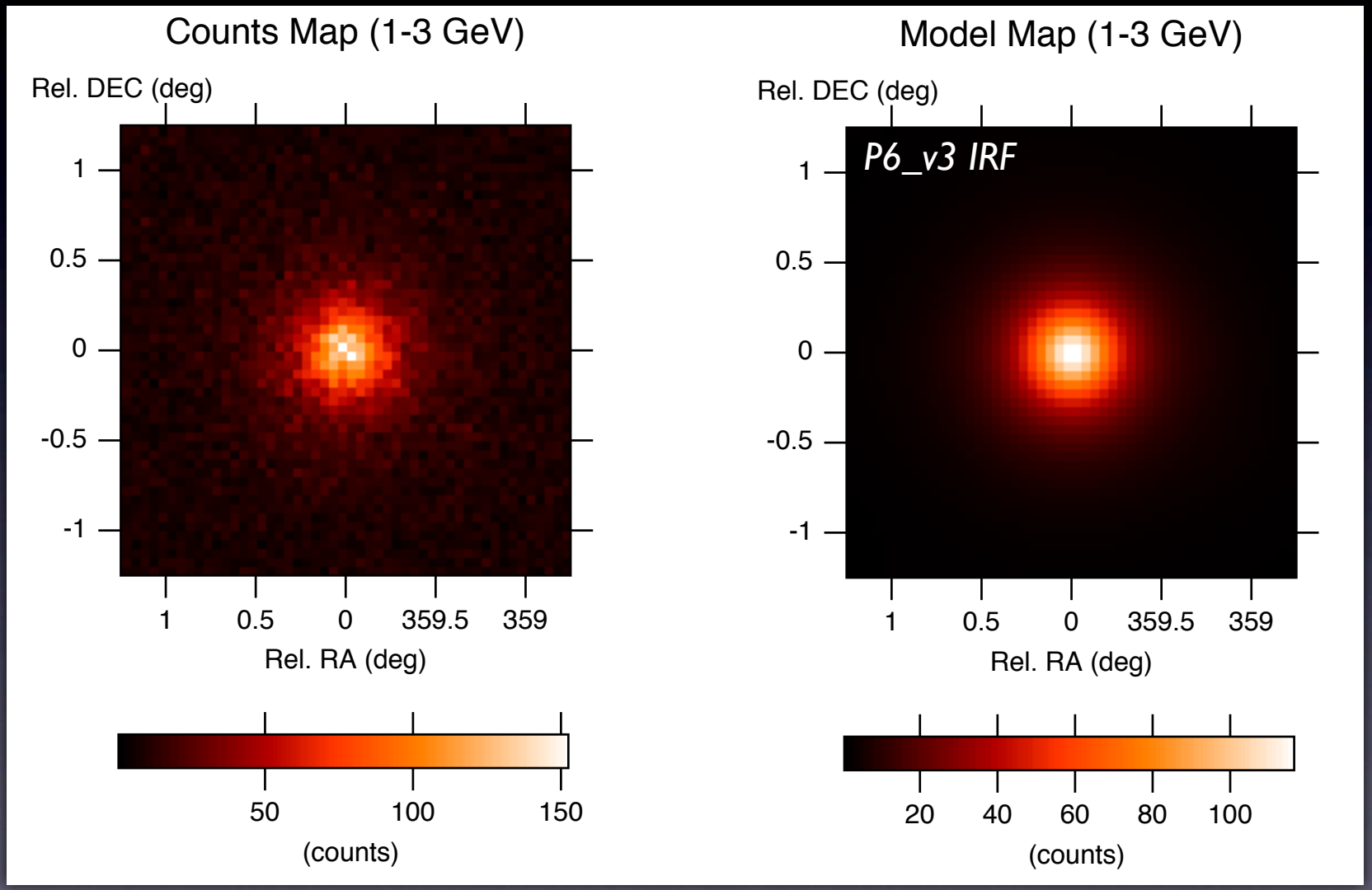
Search for gamma-ray halos

- Fermi LAT reported detection of ~700 AGN in its first point-source catalog (Abdo et al. 2010)
- Number of photons detected is not great for individual AGN, especially for high energies
- If many AGN images are stacked on top of each other, one can improve statistics dramatically
  - Pros: huge statistical advantage to beat the noise
  - Cons: lose information on individual AGN

More details of analysis

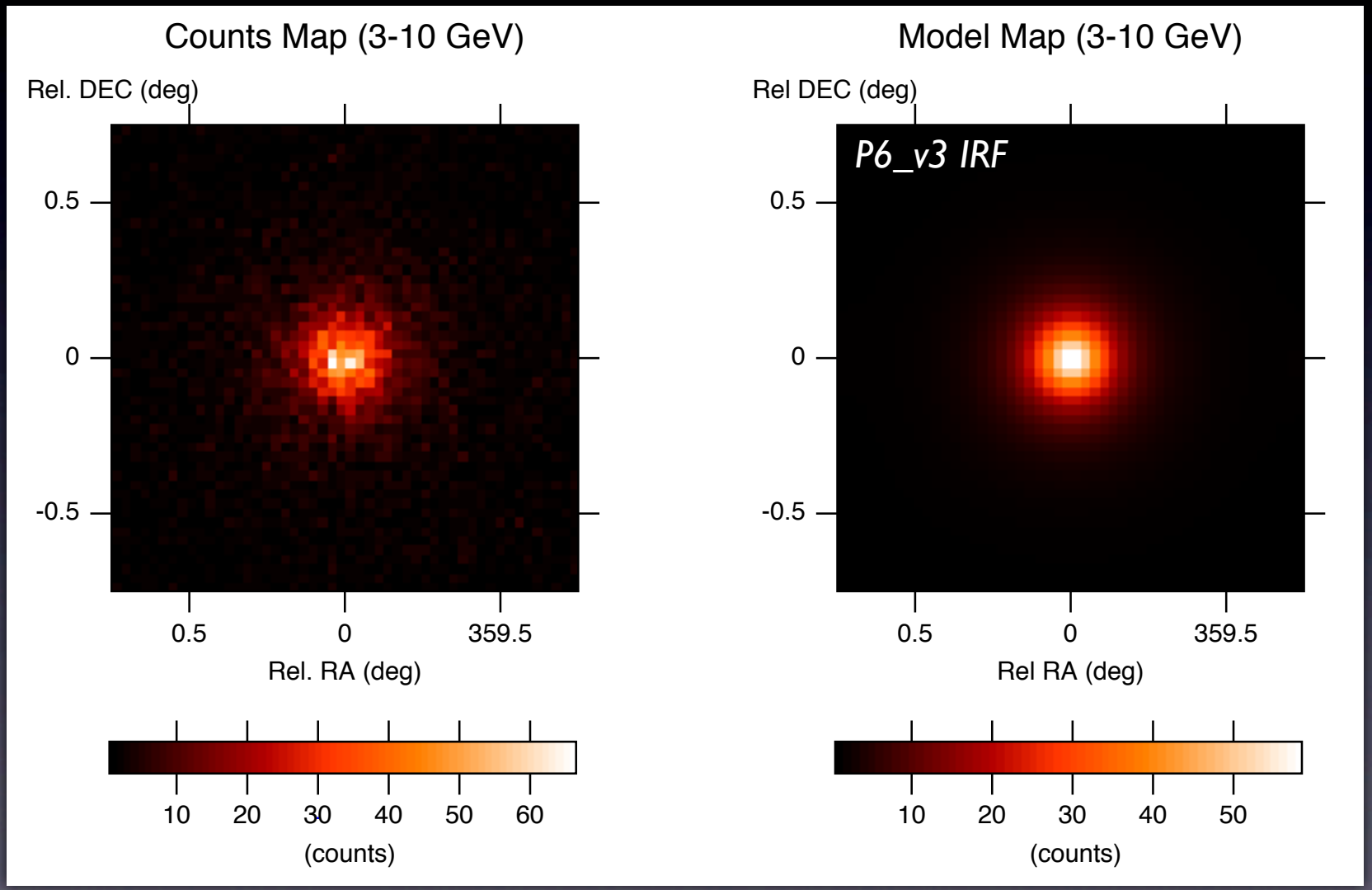
- Select photons from "diffuse" class event file (LAT_allsky_239557417_272868753_v01_Diffuse.fits) around AGN found in point source catalog (gll_psc_v02.fit)
- We use three energy bands: 1–3, 3–10, 10–100 GeV
- 170 AGN are selected as they yielded more than 4.1σ (TS>25) detection in the highest energy band, 10–100 GeV
  - Presumably these are hard AGN, producing lots of TeV photons that source halos
- We made both photon counts maps and expected model maps (using P6_v3 IRF) for individual AGN, and then staked them to make one stacked counts map and one stacked model map

Stacked maps: 1–3 GeV



Ando & Kusenko, arXiv:1005.1924 [astro-ph.HE]

Stacked maps: 3–10 GeV



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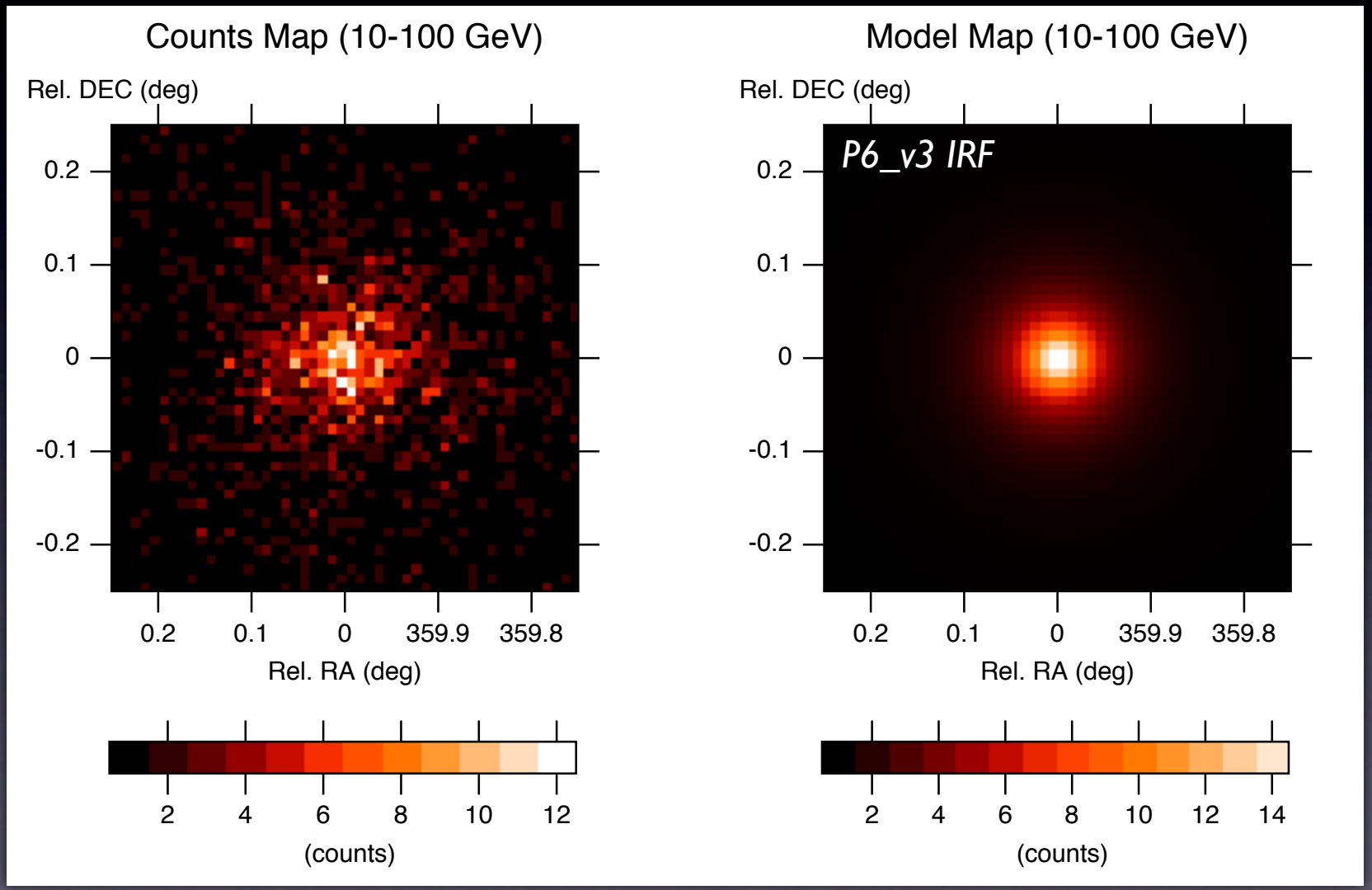
Stacked maps: 10–100 GeV



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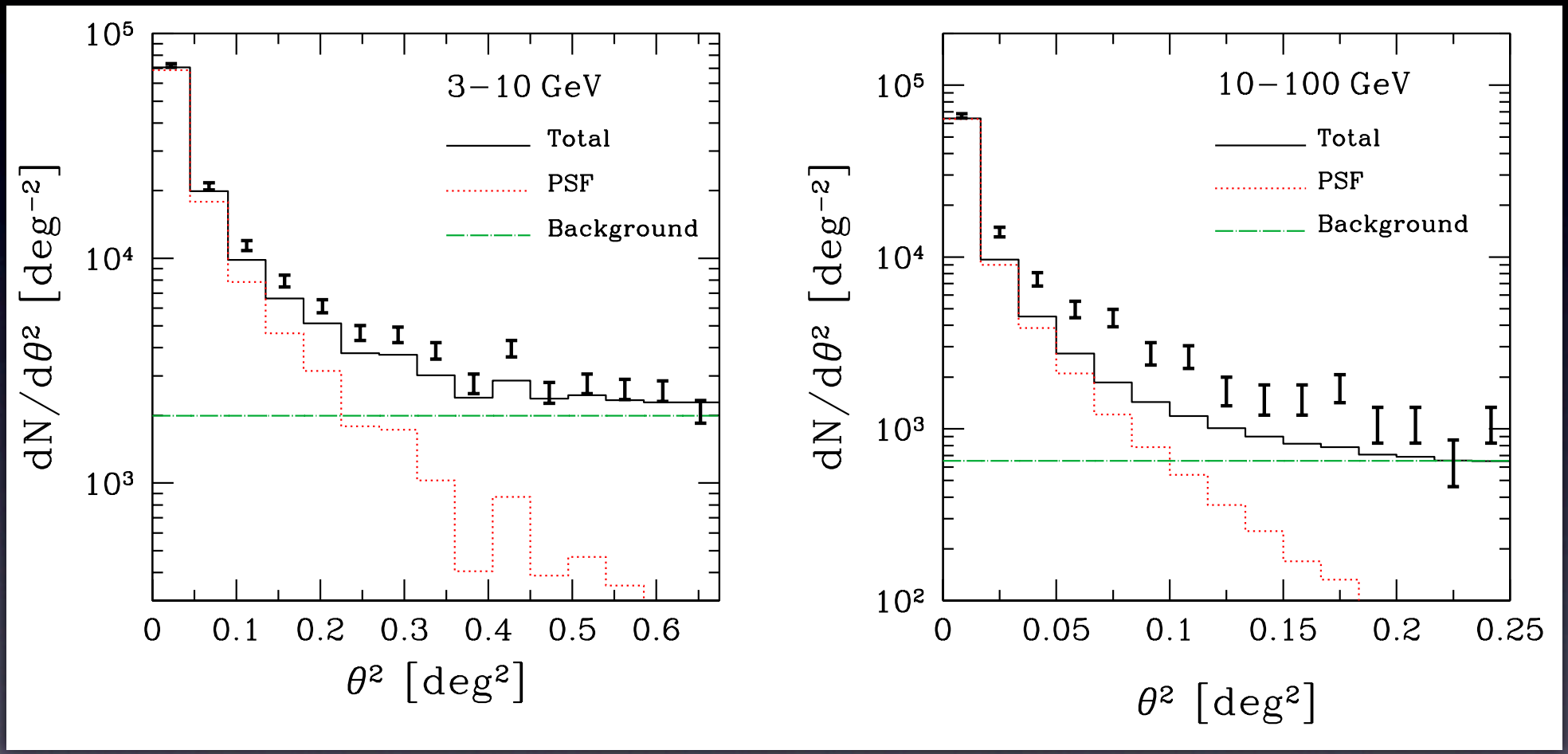
Is there anomalous excess? Yes!

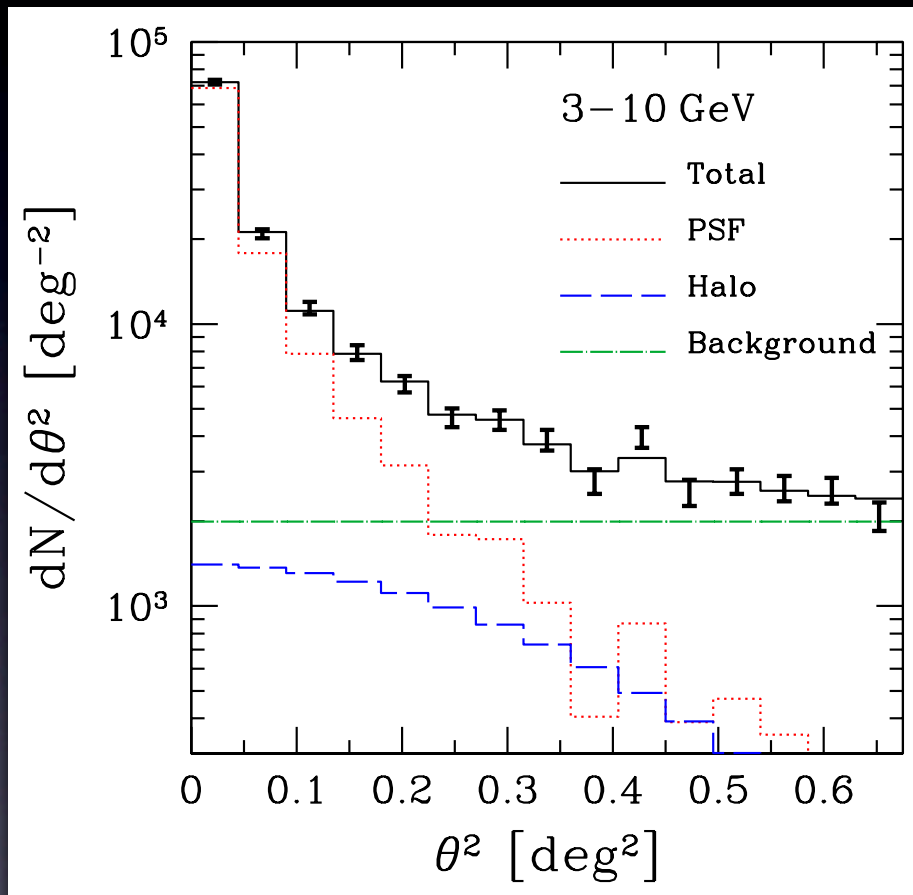


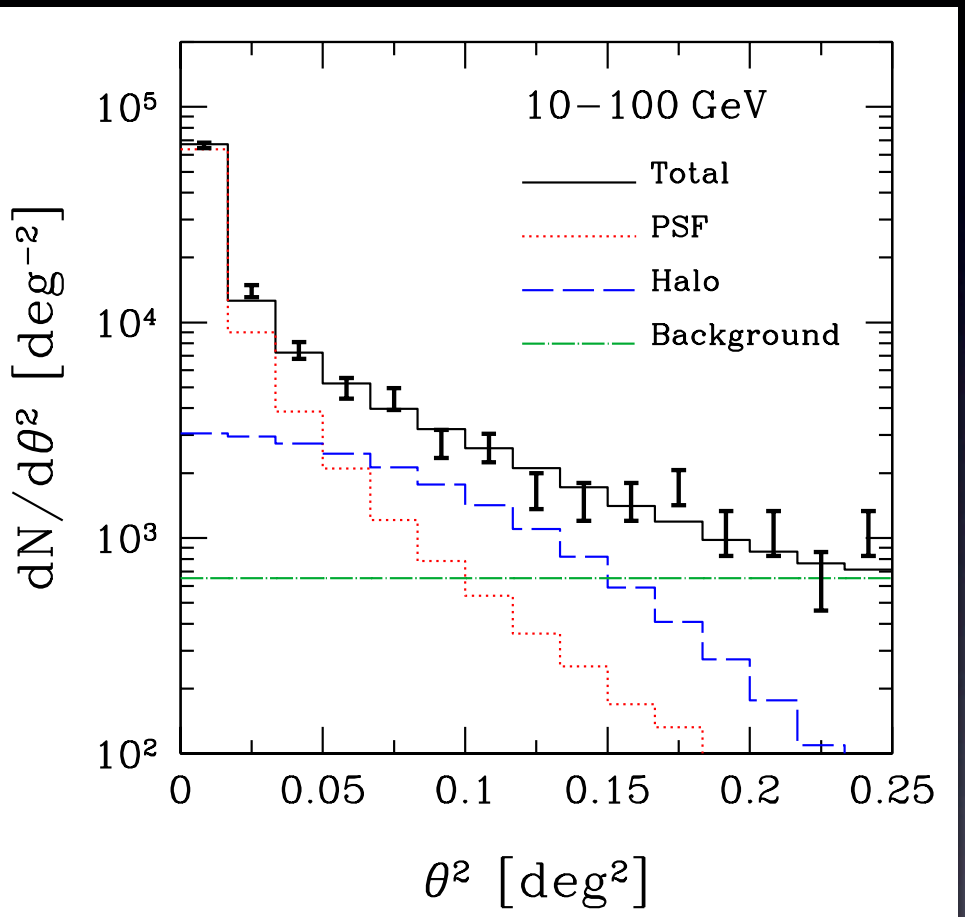
$\chi_{min}^2 = 69$; $N_{bin} = 22$

$\chi_{min}^2 = 140$; $N_{bin} = 15$

Gaussian halo component

Ando & Kusenko, arXiv:1005.1924 [astro-ph.HE]



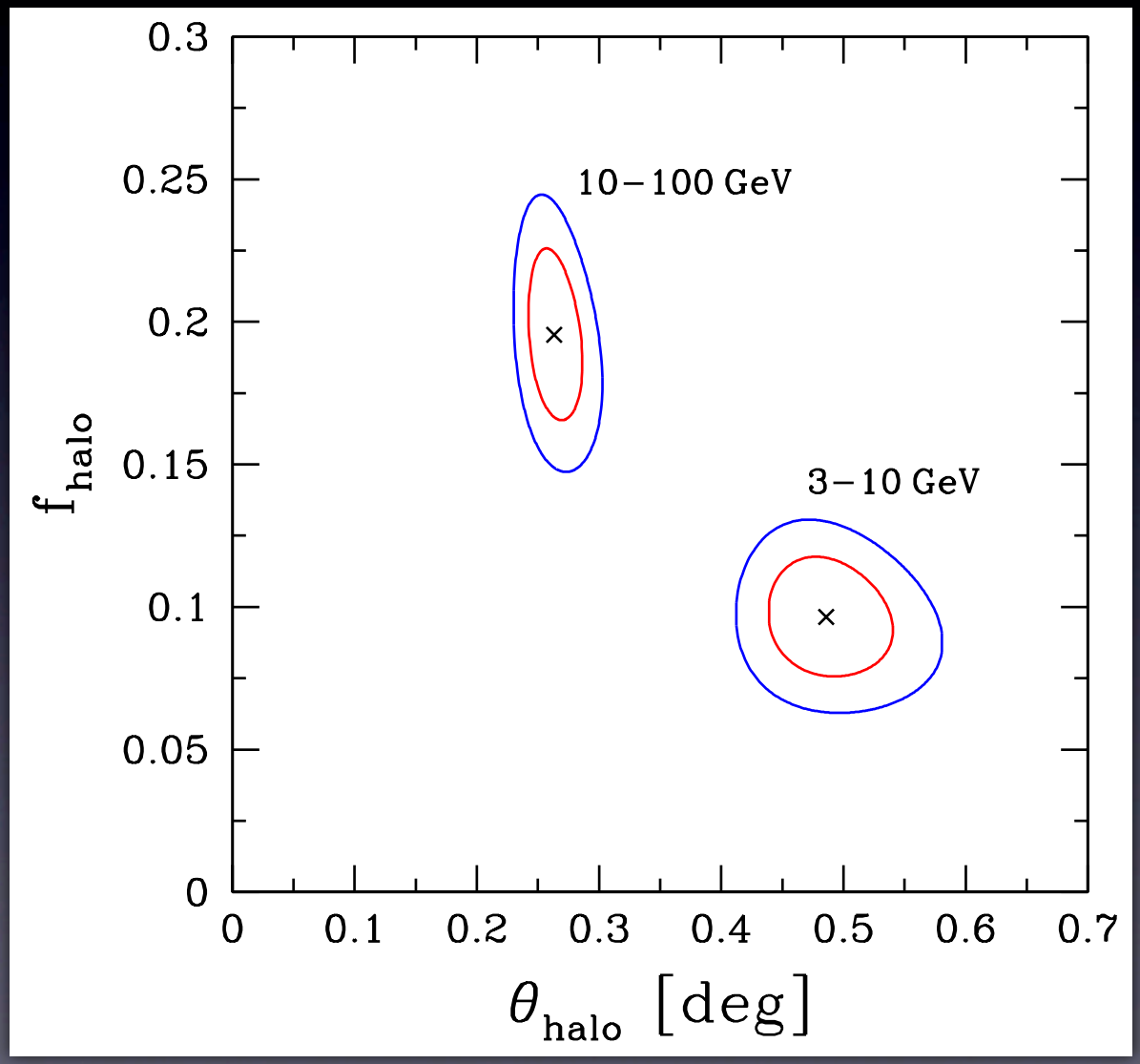


χ_{min}^2/DOF = 18.8/19

χ_{min}^2/DOF = 13.3/12

Halo properties and IGMF

Ando & Kusenko, arXiv:1005.1924 [astro-ph.HE]



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

Are the halos physical or instrumental?

Four possibilities

1. Pre-launch PSF is right, there are no halos
2. Pre-launch PSF is right, there are halos
3. Pre-launch PSF is wrong, there are no halos
4. Pre-launch PSF is wrong, there are halos

You can ask *(i) if pre-launch PSF is right or not*, or instead *(ii) if the halos are there or not*.

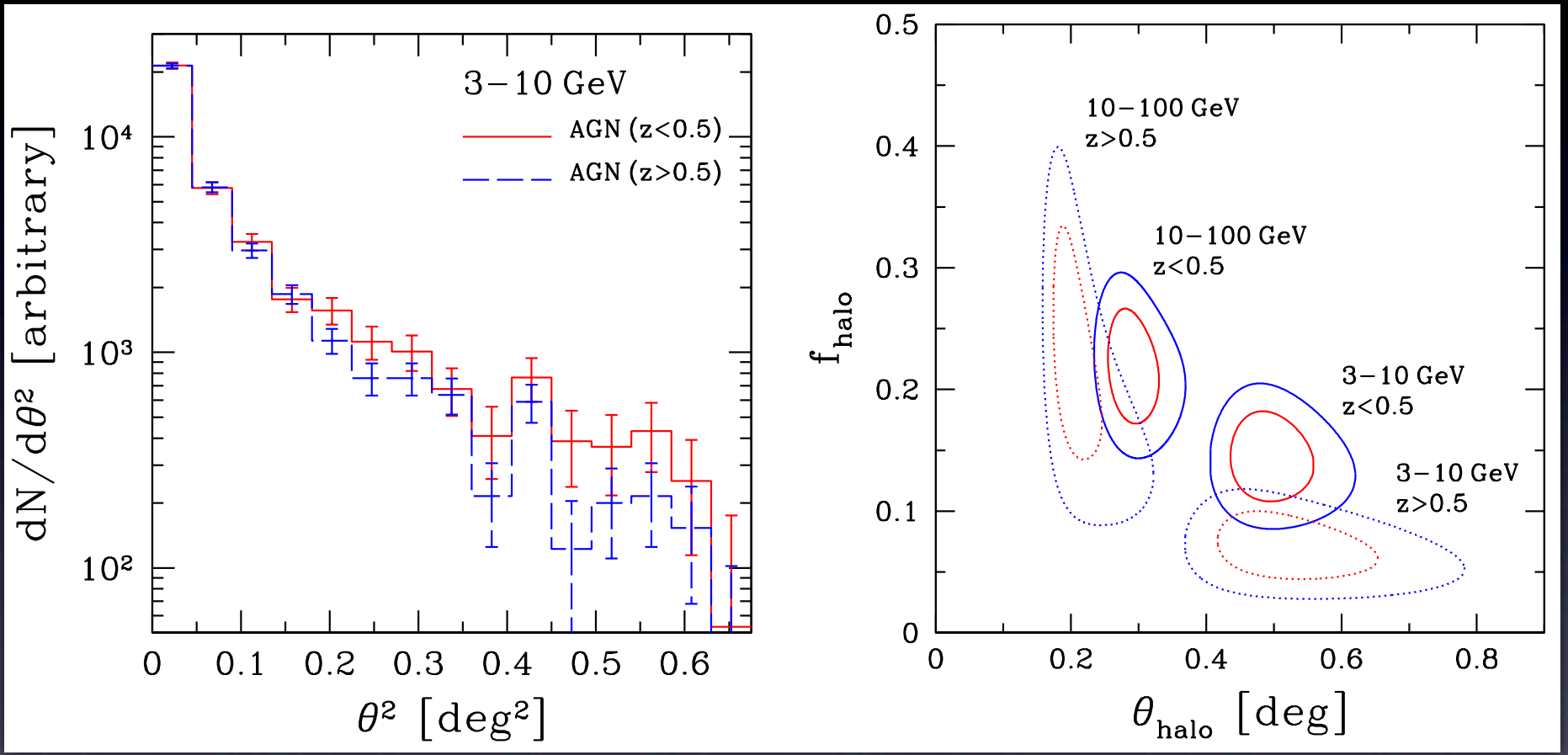
We prefer to answer the latter question and leave the former to others (e.g., Fermi team)!

Dependence on redshifts

- 99 AGN (among 170 total) have measured redshifts
  - 57 with $z < 0.5$; 42 with $0.5 < z < 2.5$
- Instrumental effects should not make any difference between nearby and distant populations

Redshift dependence

Ando & Kusenko, arXiv:1005.1924 [astro-ph.HE]



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

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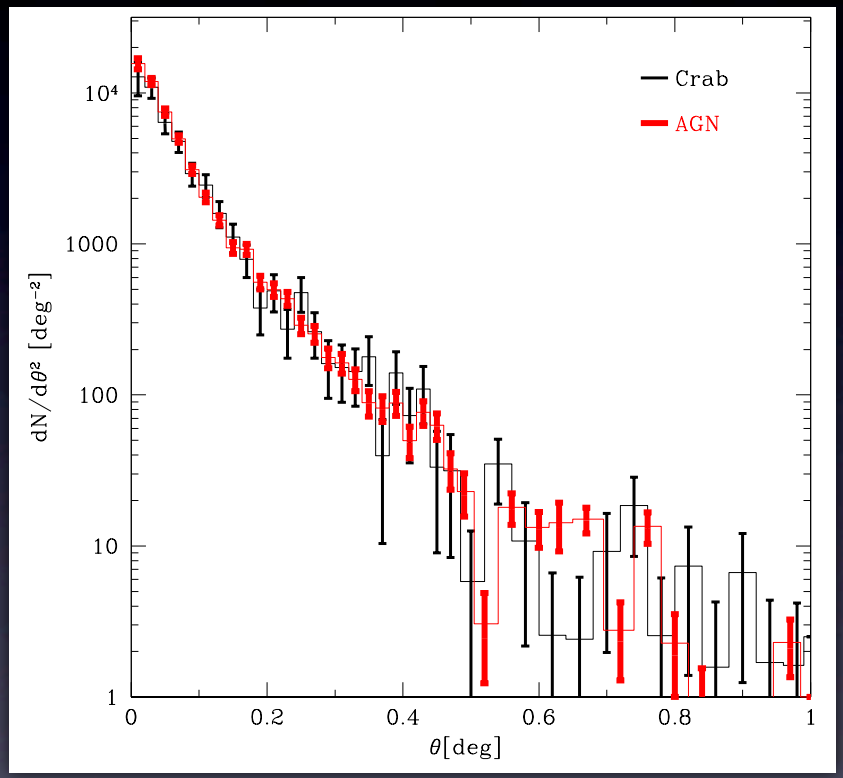
Redshift tests imply either possibility 2 or 4

Followup studies: More on instrumental effects

Neronov et al. (2010)



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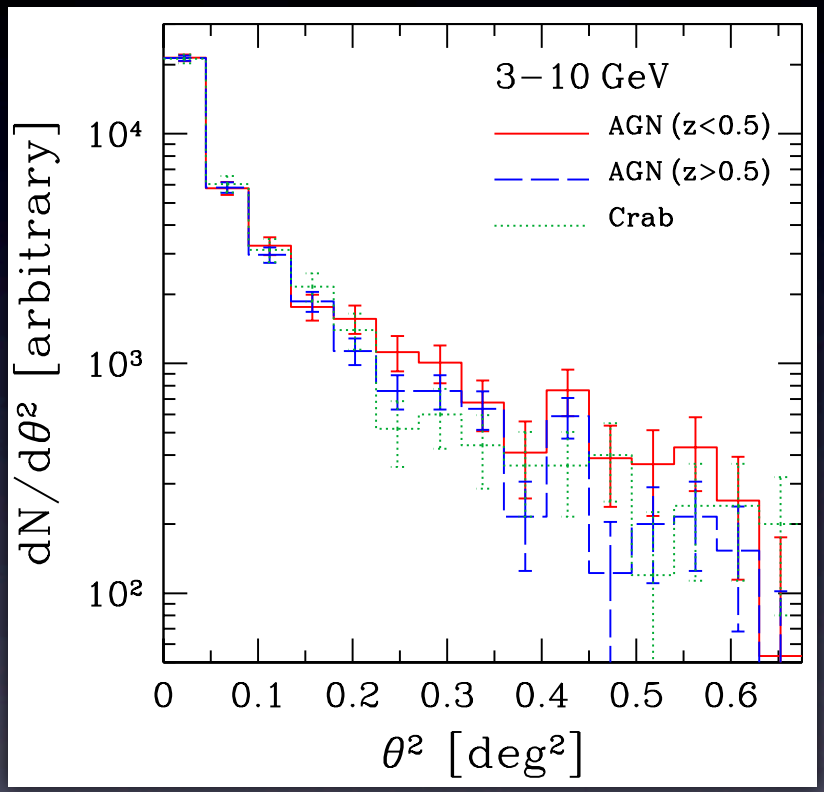
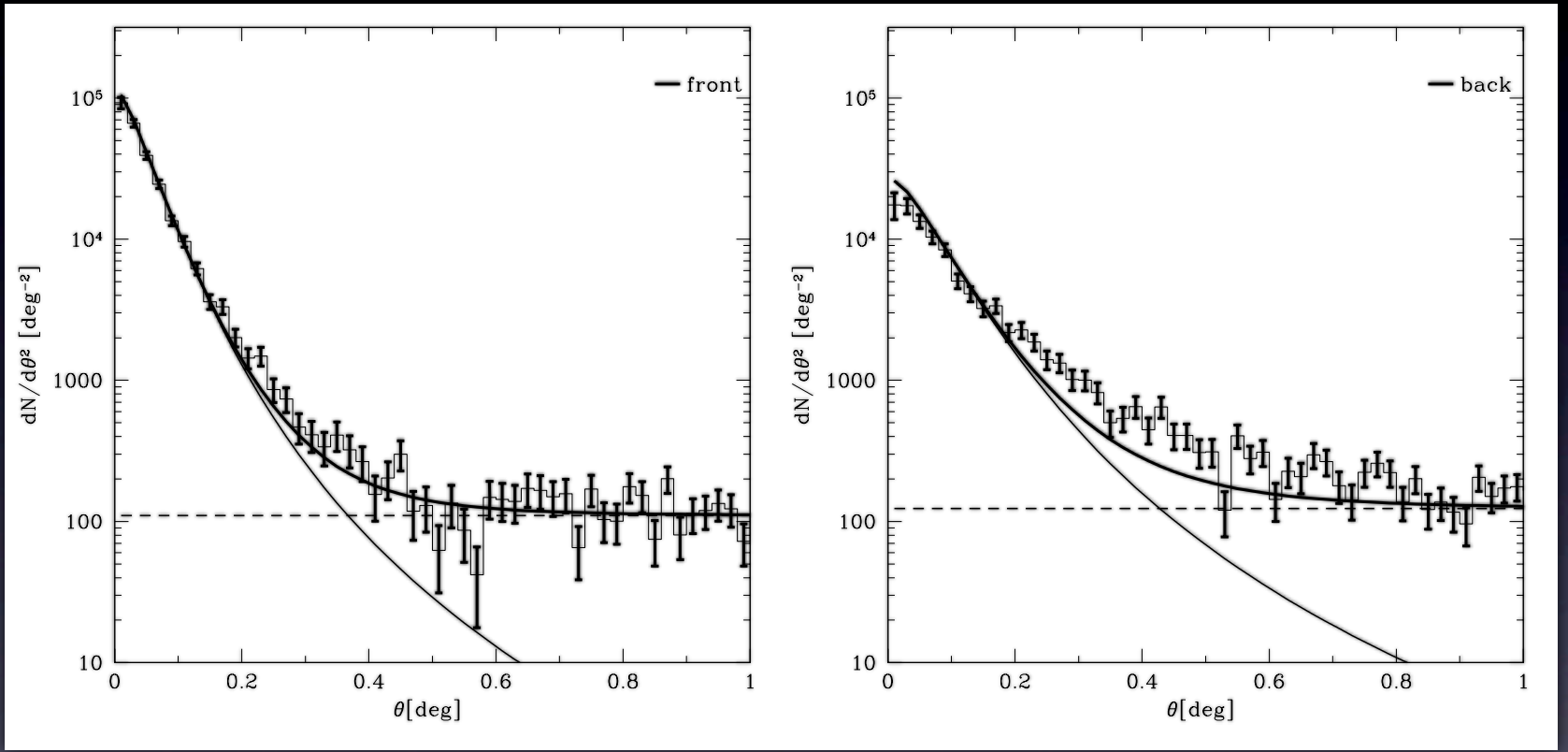


- Neronov et al. argue that Crab profile looks the same as AGN in 10–100 GeV band
- But in 3–10 GeV, where there are more photons, the Crab profile looks different from AGN

Followup studies: Front vs back issue

Neronov et al. (2010)



- Excesses are identified in both front-converted and back-converted photons, but are different
- There is some inaccuracy in pre-launch calibration of PSF

Official statement by Fermi

- Fermi made an official statement on their pre-launch PSF:

  * The LAT team confirms that the photon distributions in the stacked analysis of blazars that Ando & Kusenko performed are indeed broader than expected based on the P6_V3 Diffuse point-spread function (PSF), which is used in current team publications and released by the team via the FSSC

  * We had recognized that the PSF in flight was broader than expected at high energies; this was suggested in the caveats posted at the FSSC and noted in the 1FGL catalog paper

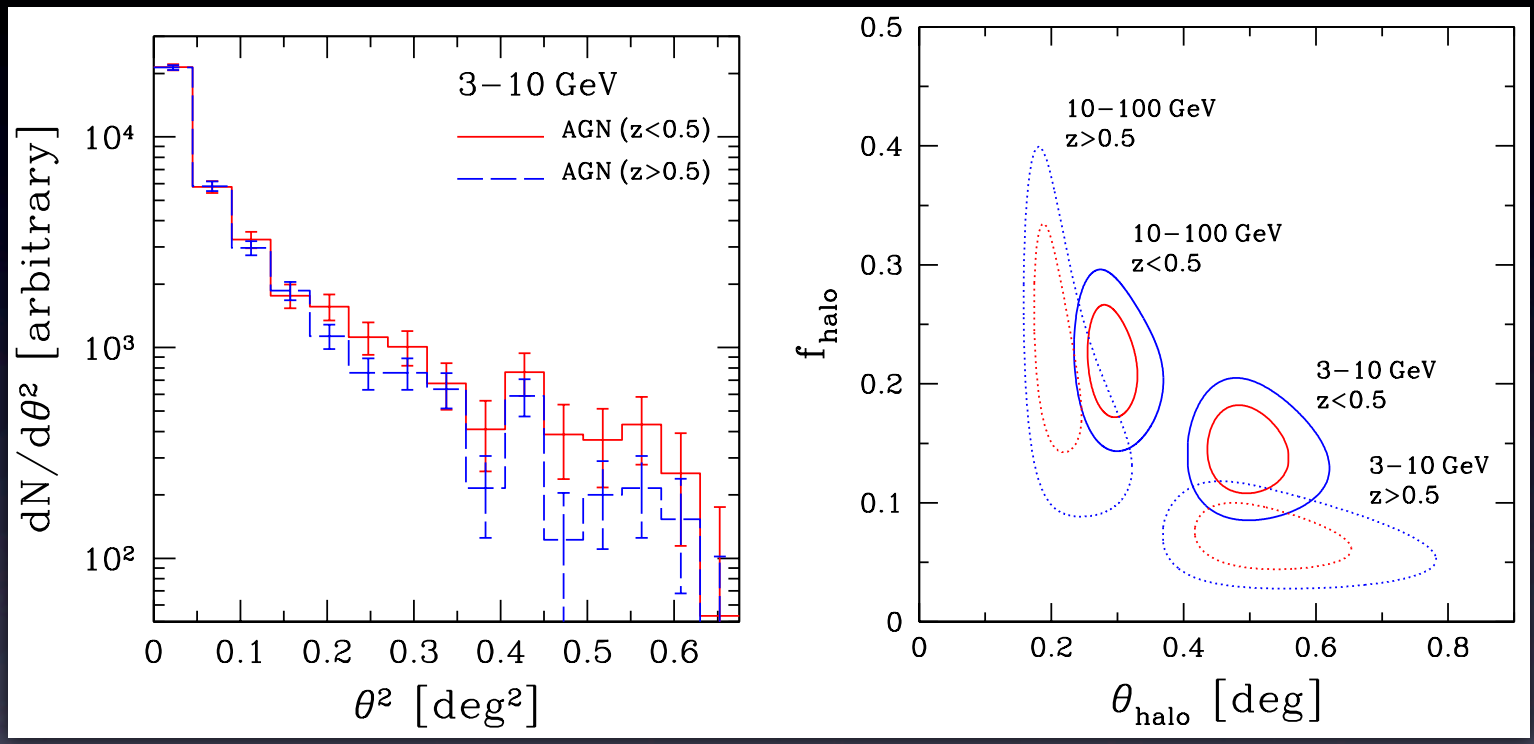
  * We are confident that the PSF at high energies is being mis-modeled in our Monte Carlo (MC) simulations of the LAT because we find similarly-broadened profiles in a stacked analysis of bright pulsars (Vela, Crab, and Geminga). The caveats posted on the FSSC page are being updated with this information

  * We have recently uncovered a deficiency in our MC simulation that may explain most, if not all, of the mismatch. We are working to deliver rapidly an 'in-flight' PSF that corrects for the effect while we proceed to fix the MC issue. Further instrument performance improvements are also under development

  * The redshift dependence of the photon distributions that Ando & Kusenko report can be understood in terms of spectral evolution of blazars (the $z>0.5$ blazars having softer spectra on average than for $z<0.5$), and the above-mentioned inaccuracy of the P6_V3 Diffuse PSF at high energies

Redshift/spectrum dependence

Ando & Kusenko, arXiv:1005.1924 [astro-ph.HE]



- Nearby AGN are harder (mostly BL Lac objects)
- No-halo scenario: PSF depends on energy, but PSF has to be increasing function of energy both in 3–10 GeV and 10–100 GeV bands
- Halo scenario: BL Lac emits more source (TeV) photons, thus making the image larger

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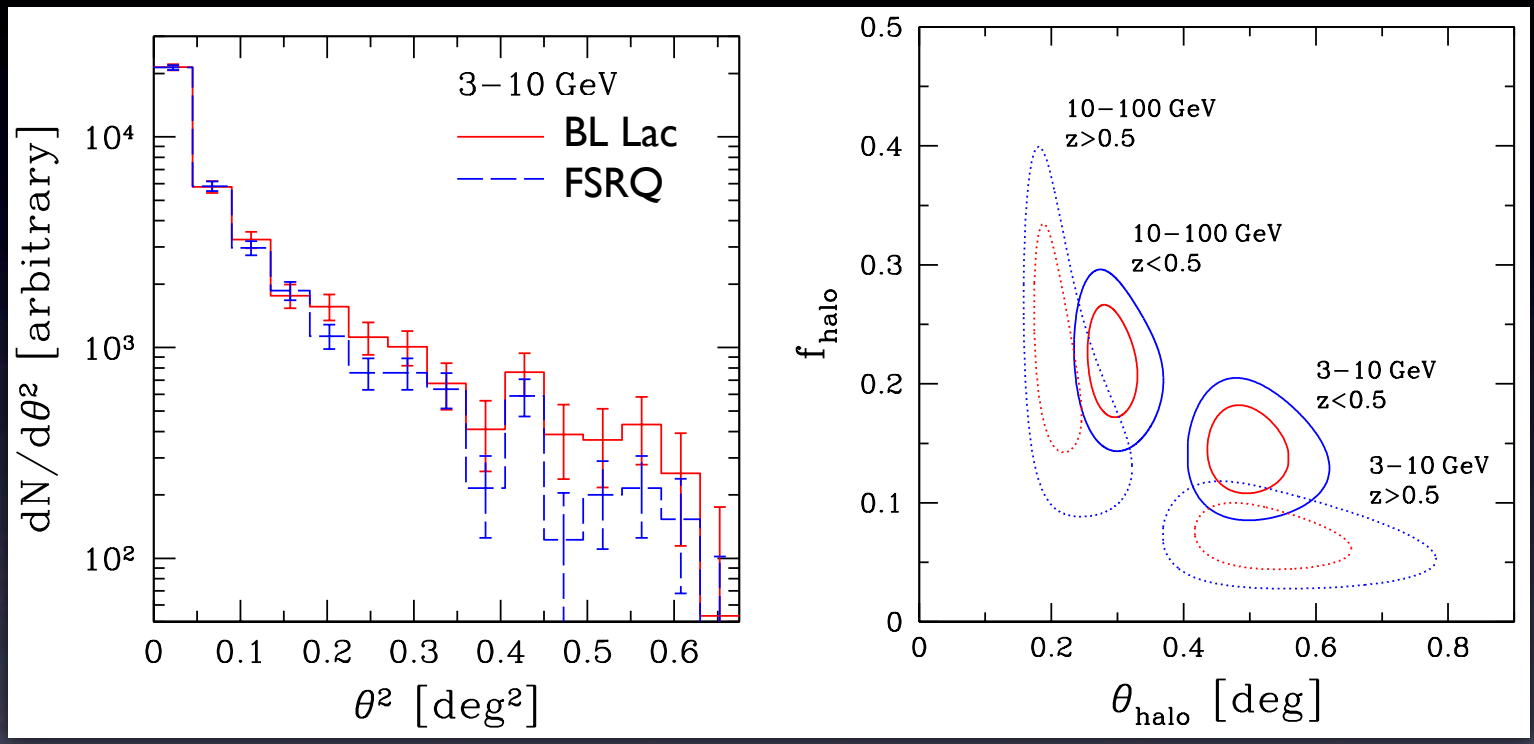

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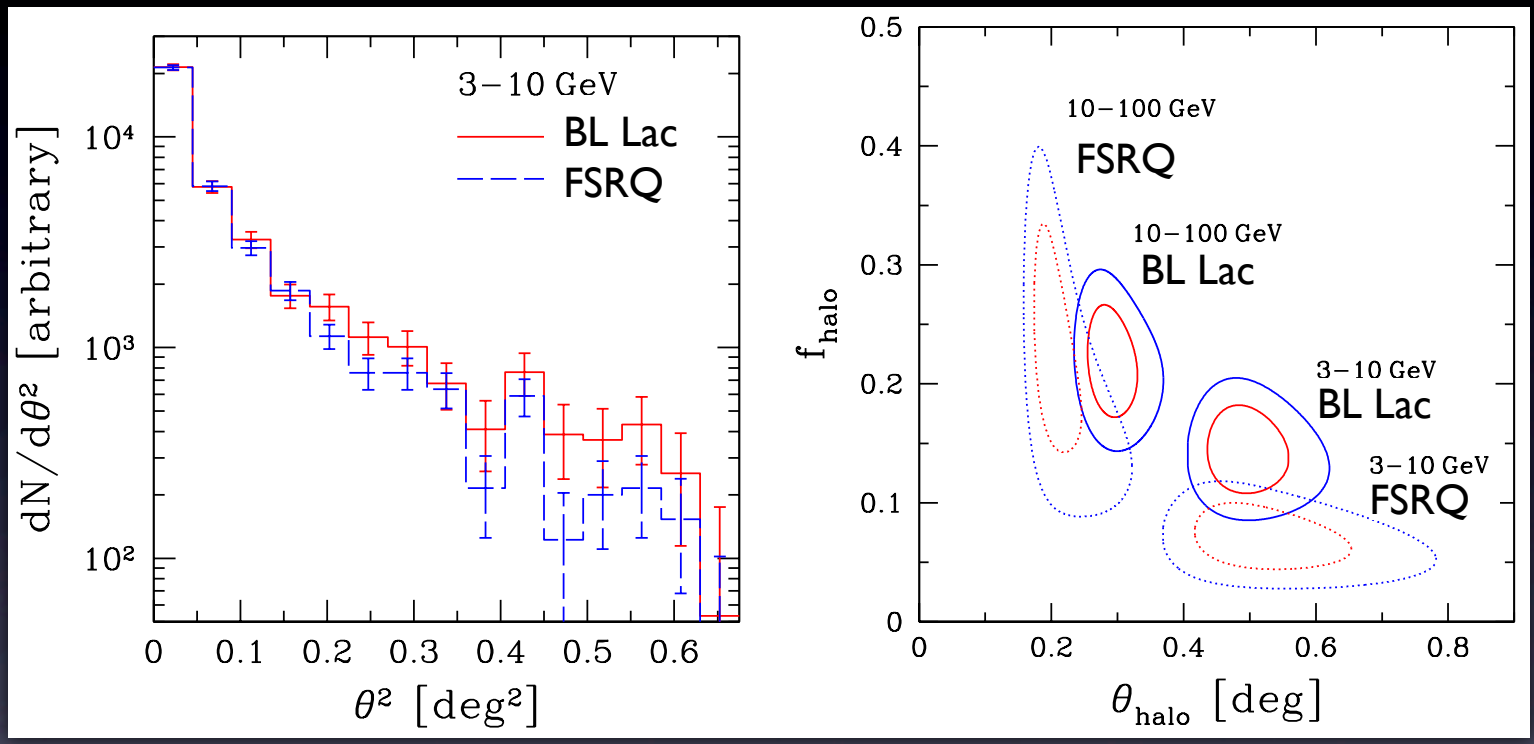

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Conclusions

- 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} gauss
- The image sizes are different for nearby/hard and distant/soft AGN populations (evidence against instrumental effects)
- This study triggered more careful calibration of LAT PSF, and P6_v3 PSF turned out to be mis-calibrated