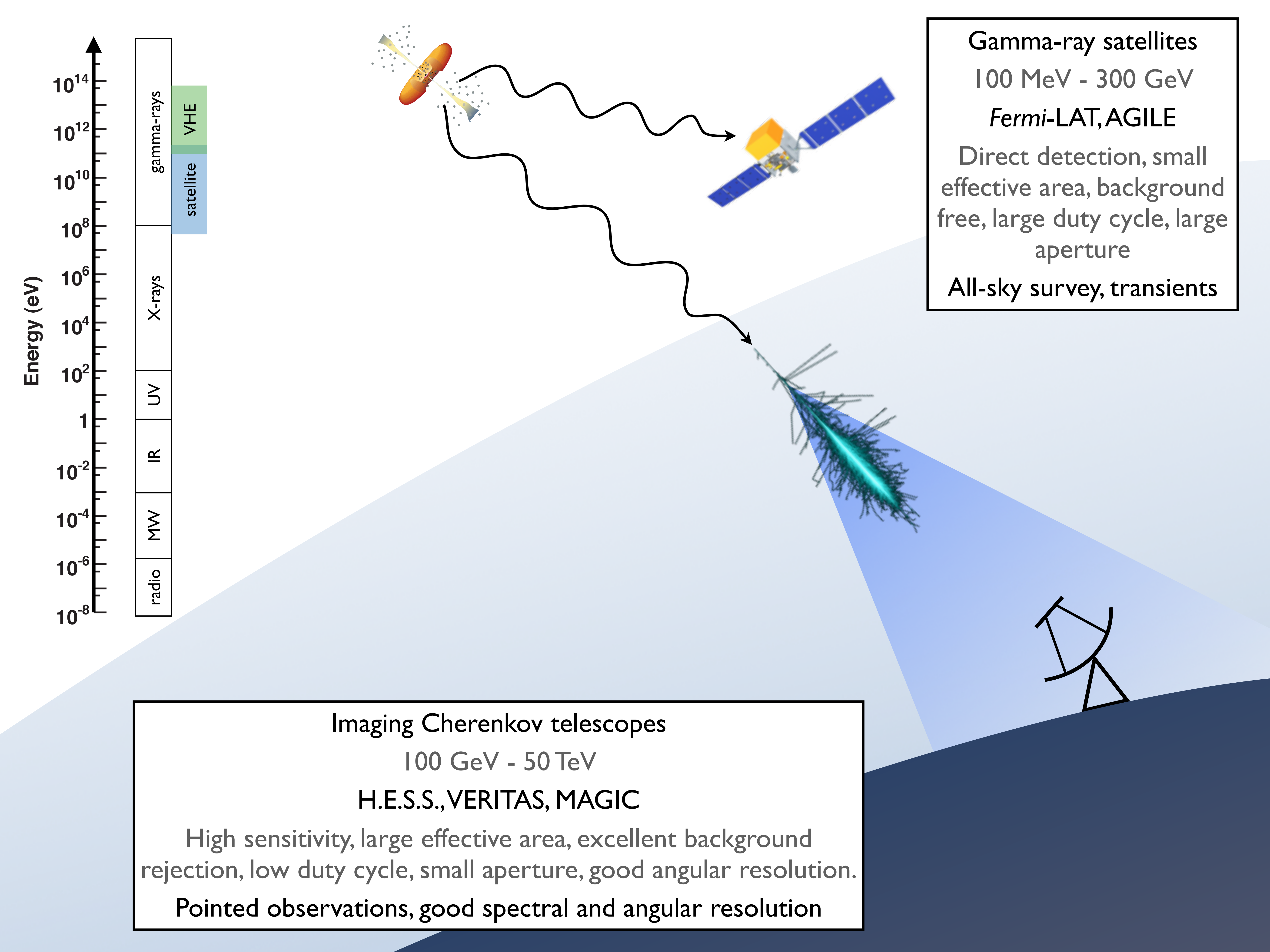
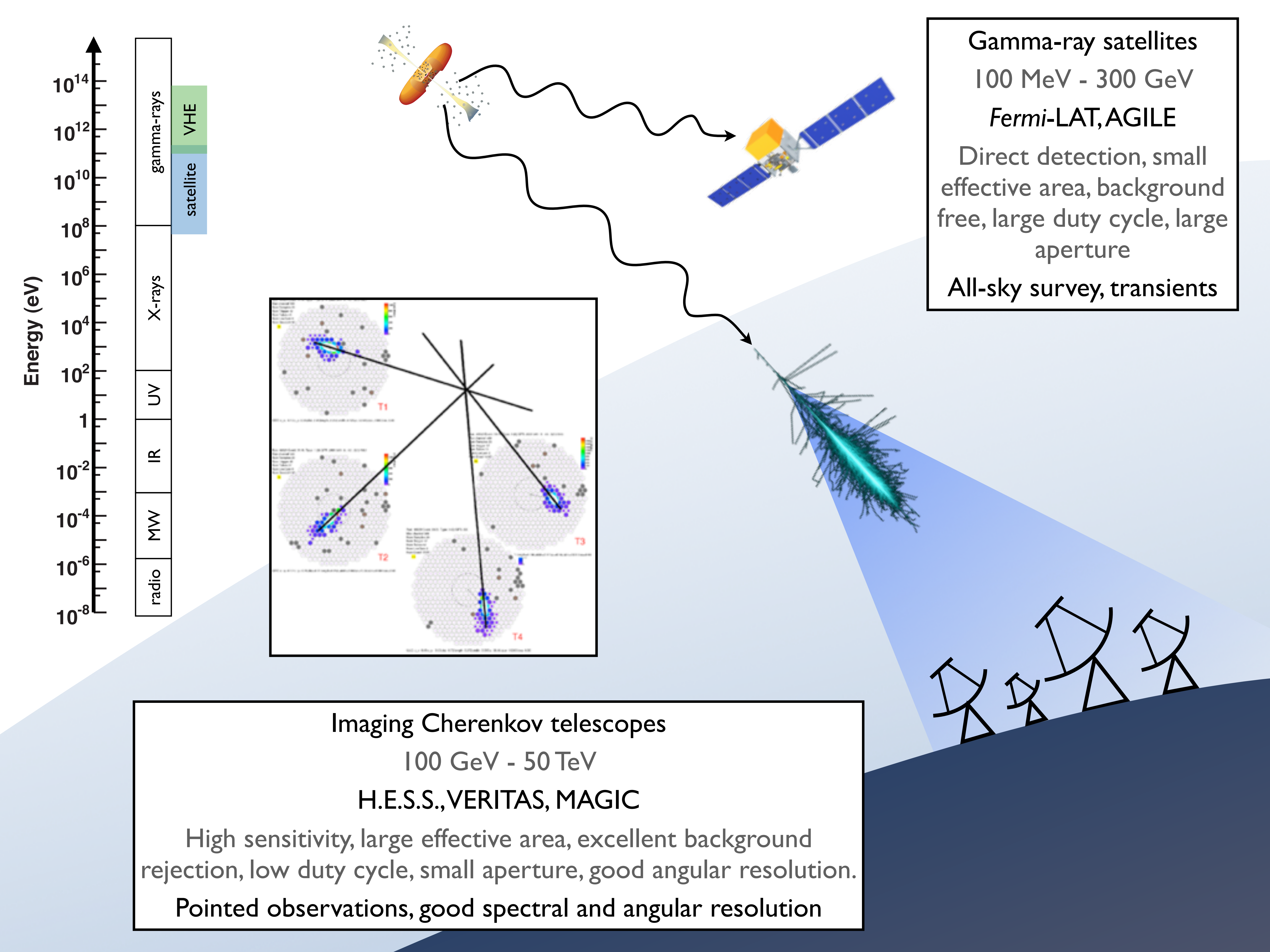
Imaging Atmopsheric Cherenkov Telescopes

Fermi School 2019
Lewes, DE


Energy (eV)
10^14
10^12
10^10
10^8
10^6
10^4
10^2
1
10^-2
10^-4
10^-6
10^-8
gamma-rays
X-rays
UV
IR
MW
radio
VHE
satellite
Gamma-ray satellites
100 MeV - 300 GeV
Fermi-LAT, AGILE
Direct detection, small effective area, background free, large duty cycle, large aperture
All-sky survey, transients
Imaging Cherenkov telescopes
100 GeV - 50 TeV
H.E.S.S., VERITAS, MAGIC
High sensitivity, large effective area, excellent background rejection, low duty cycle, small aperture, good angular resolution.
Pointed observations, good spectral and angular resolution



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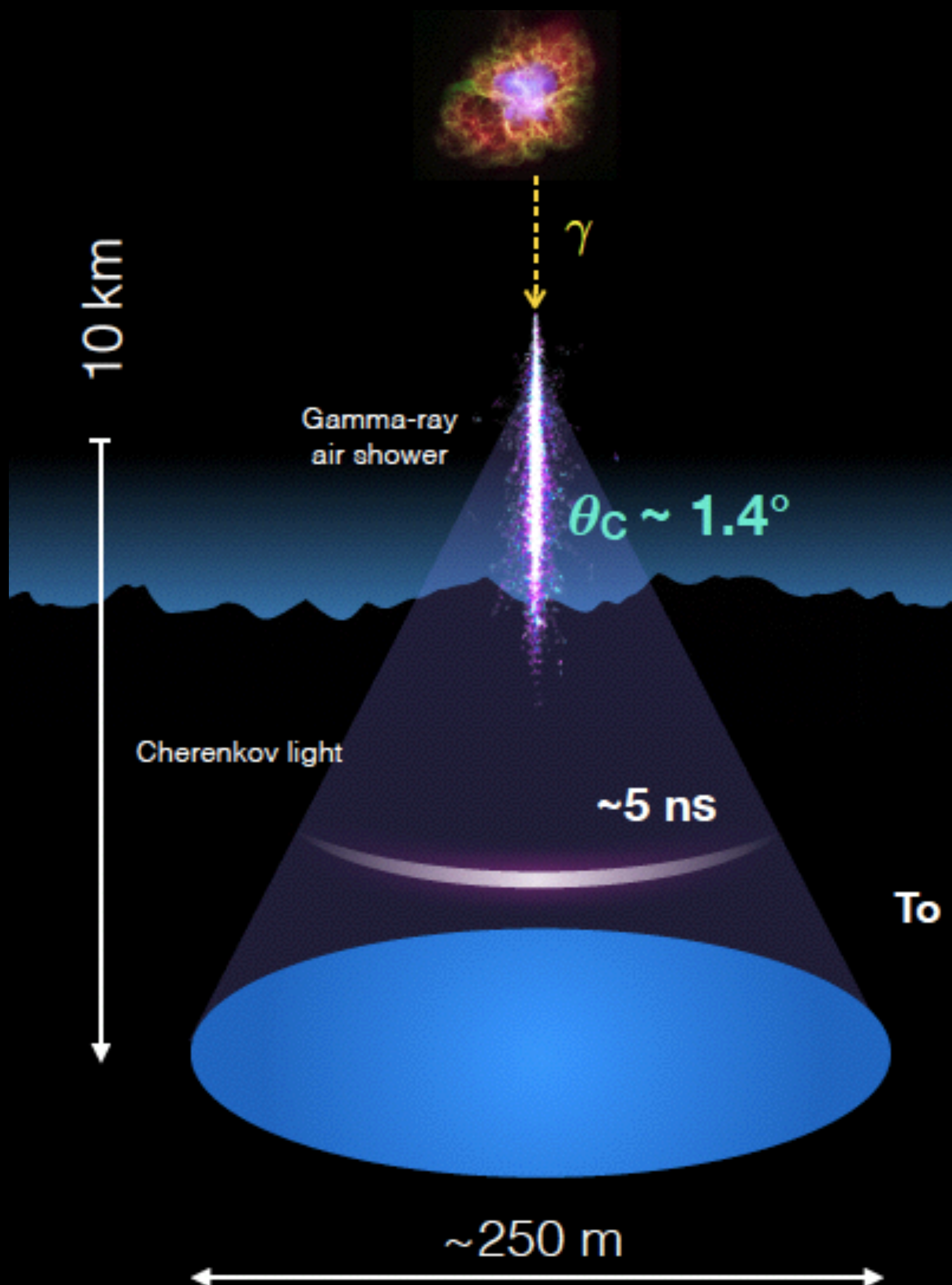
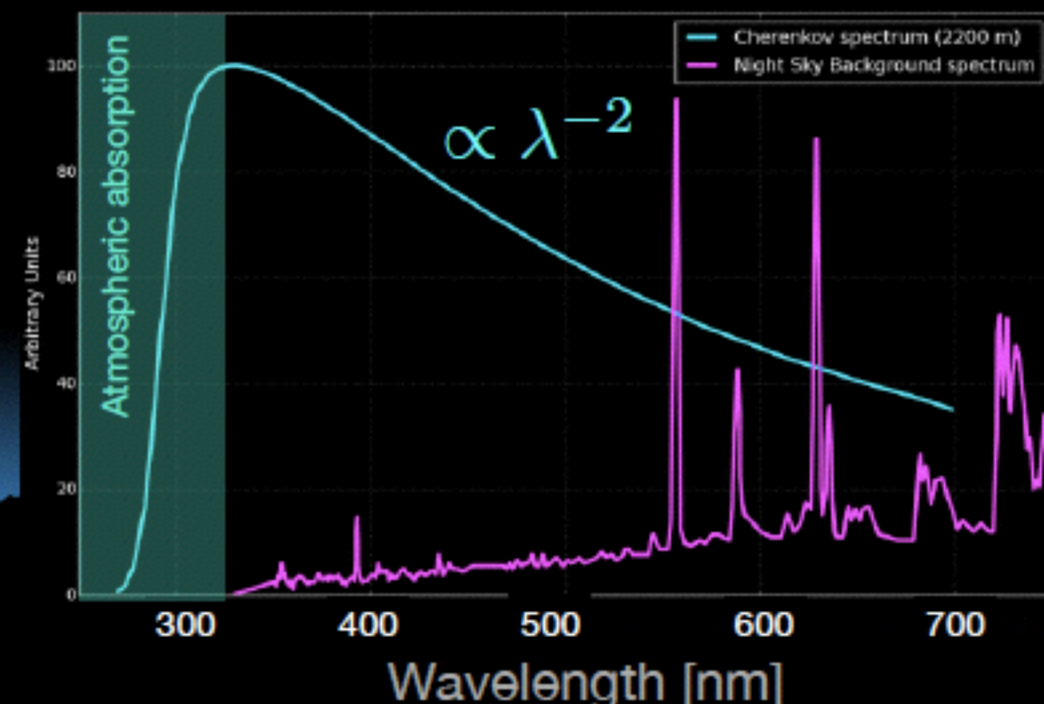
Imaging Atmospheric Cherenkov Telescopes



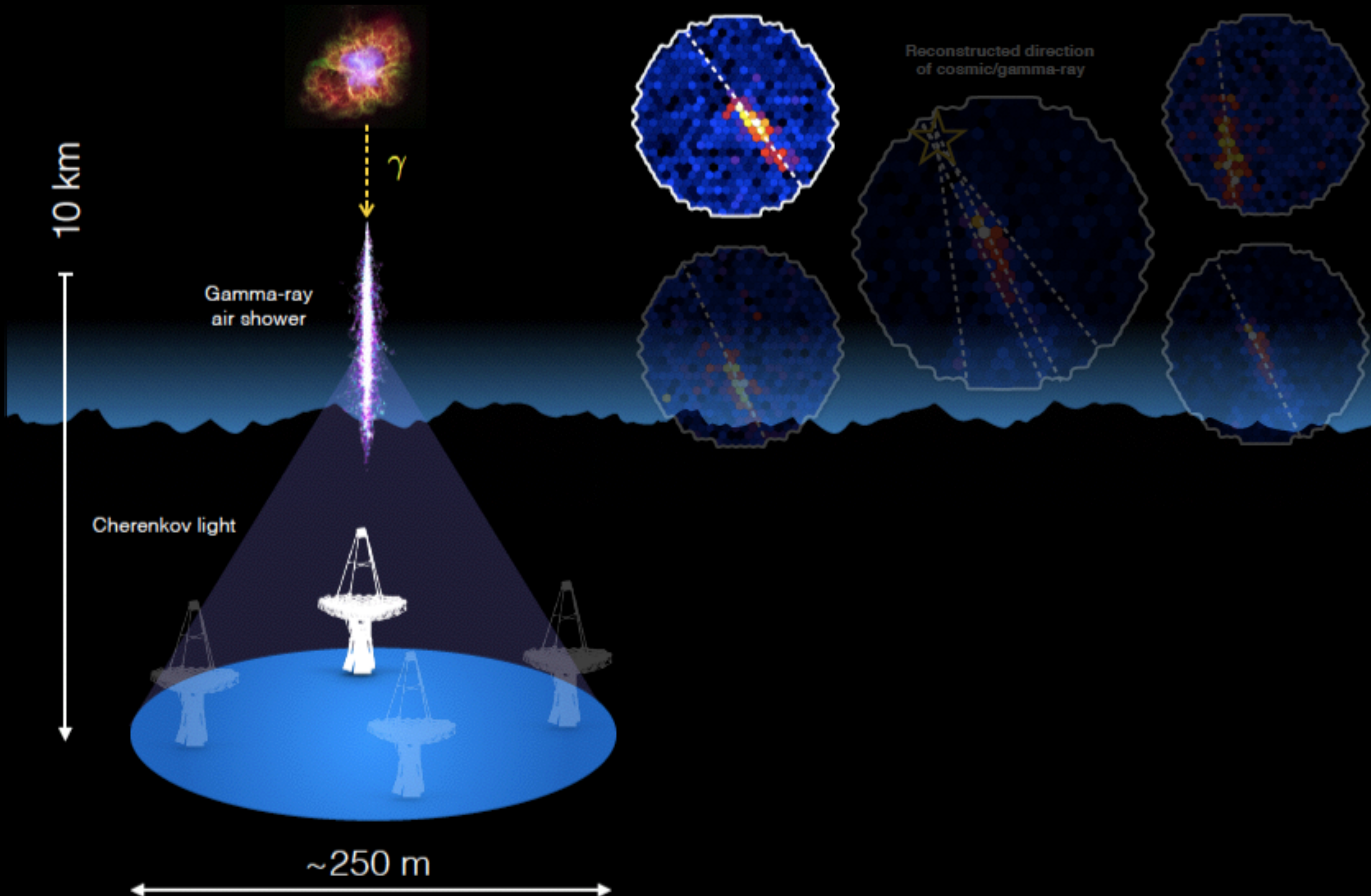


To detect air Cherenkov we need an instrument with:

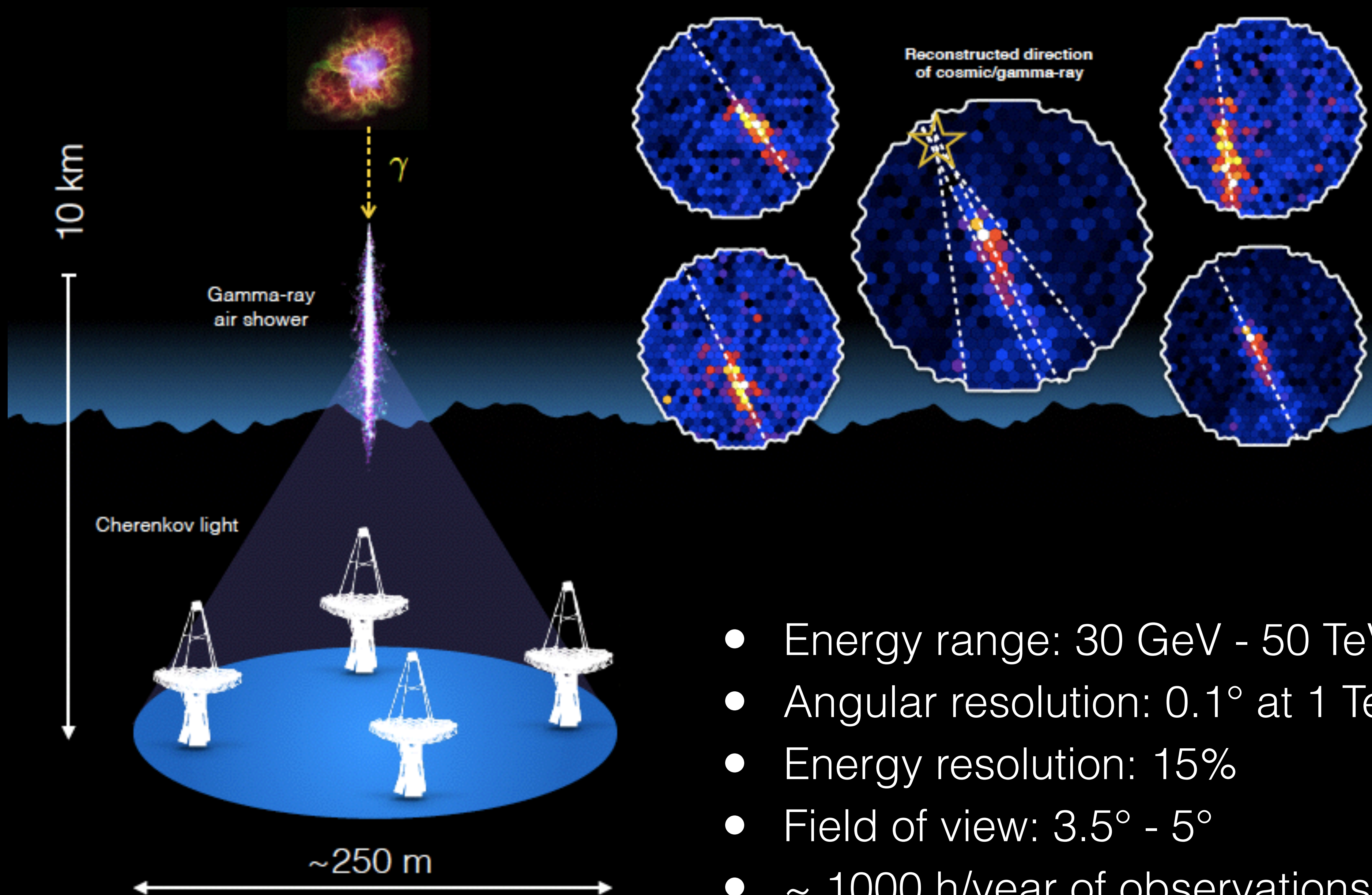
- Optical-UV sensitivity
- Large collection areas (*more Cherenkov photons*)
- Very fast, sensitive camera (*ns timing*)

Credit: Marcos Santander

Imaging Atmospheric Cherenkov Telescopes



Imaging Atmospheric Cherenkov Telescopes



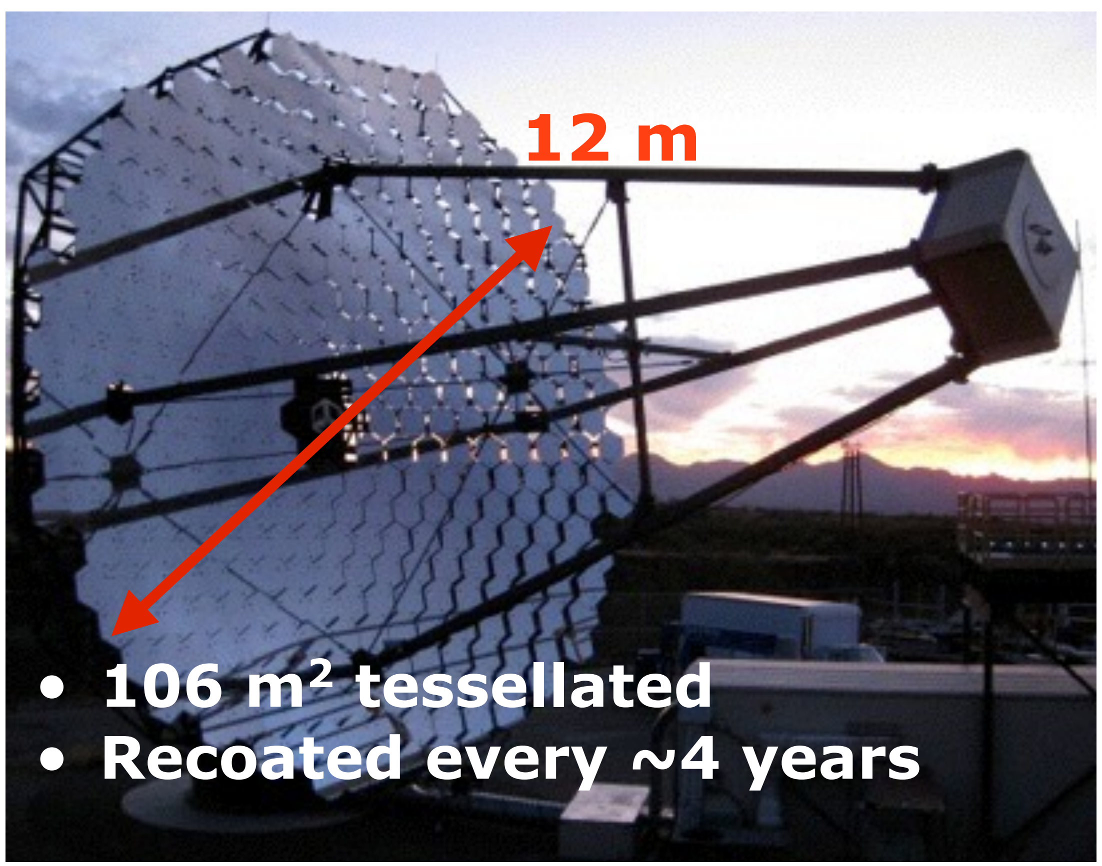
- Energy range: 30 GeV - 50 TeV
- Angular resolution: 0.1° at 1 TeV
- Energy resolution: 15%
- Field of view: 3.5° - 5°
- ~ 1000 h/year of observations.

IACTs in operation

VERITAS observatory

Located in Southern Arizona
4 telescopes, ~100m apart


• Situated at 1280m altitude at Whipple Observatory in Arizona


12 m
• 106 m² tessellated
• Recoated every ~4 years

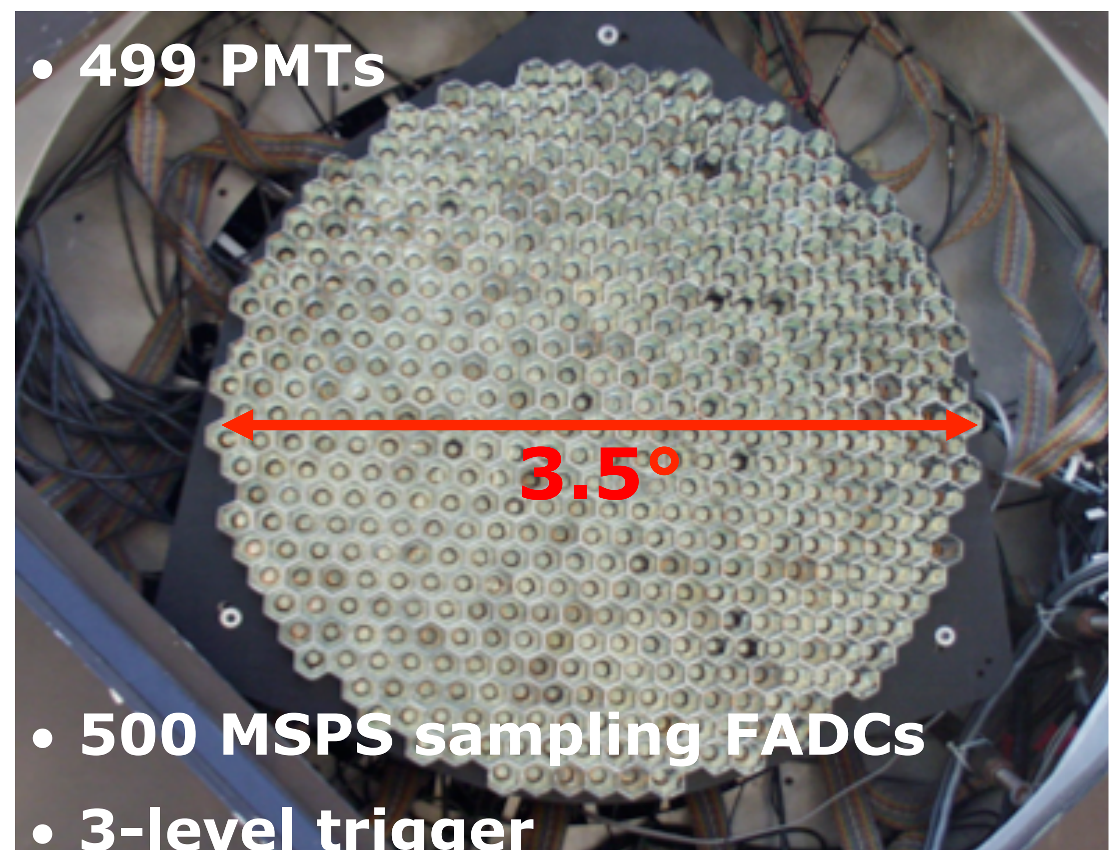
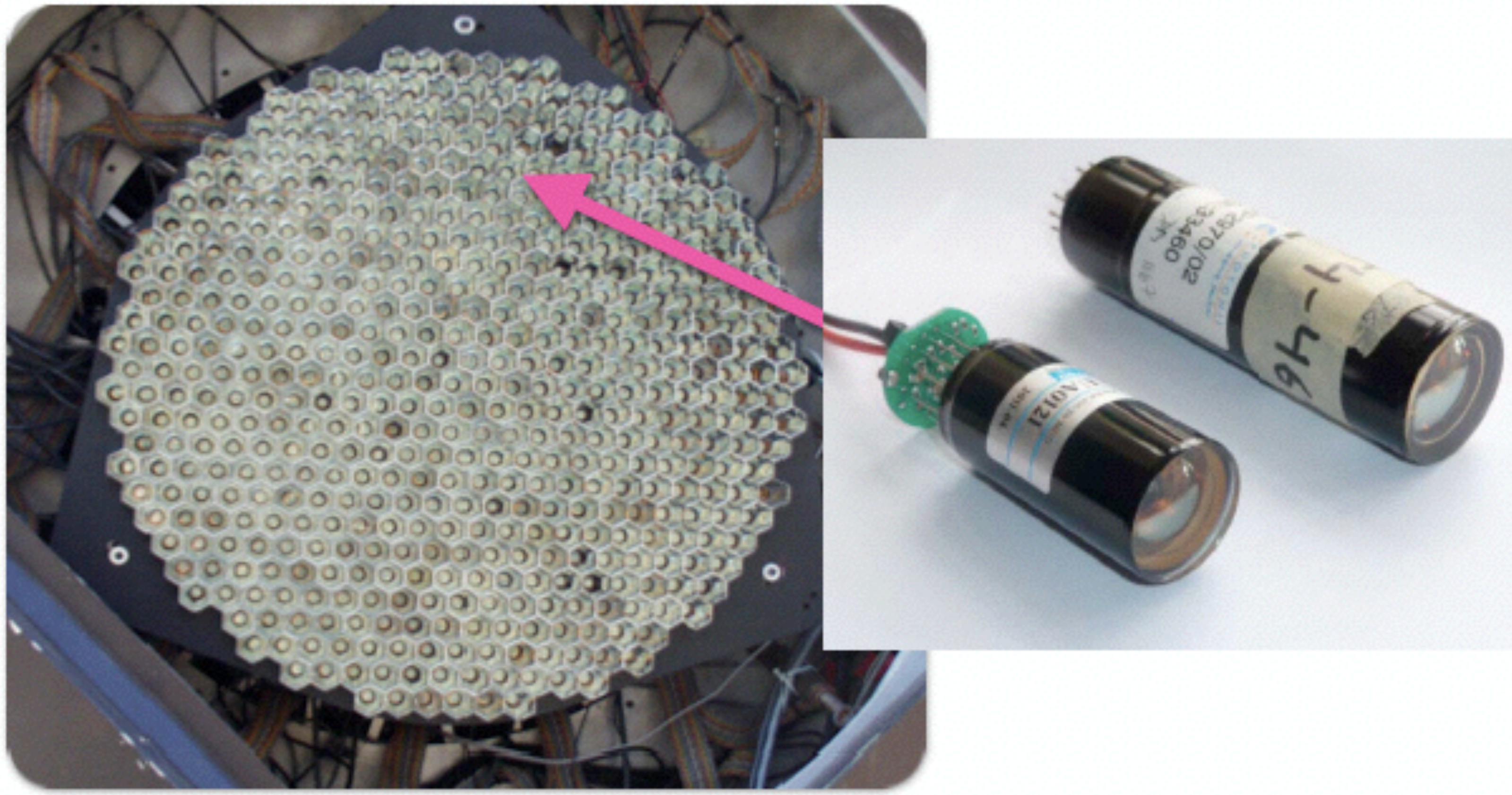
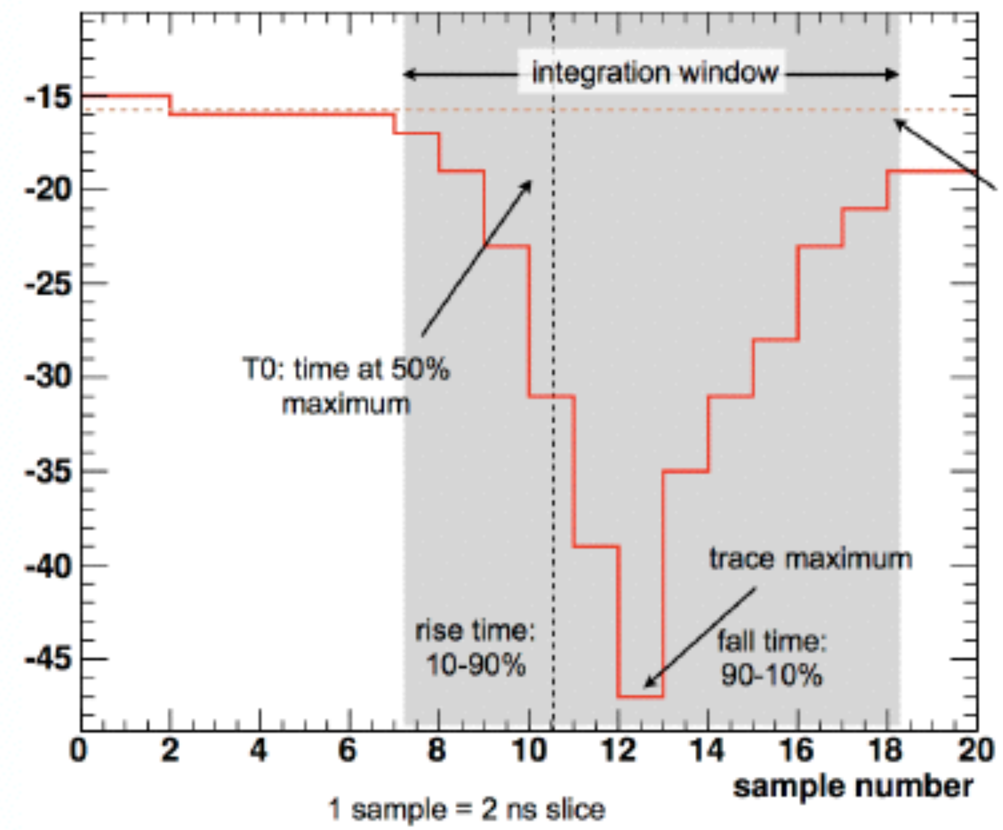
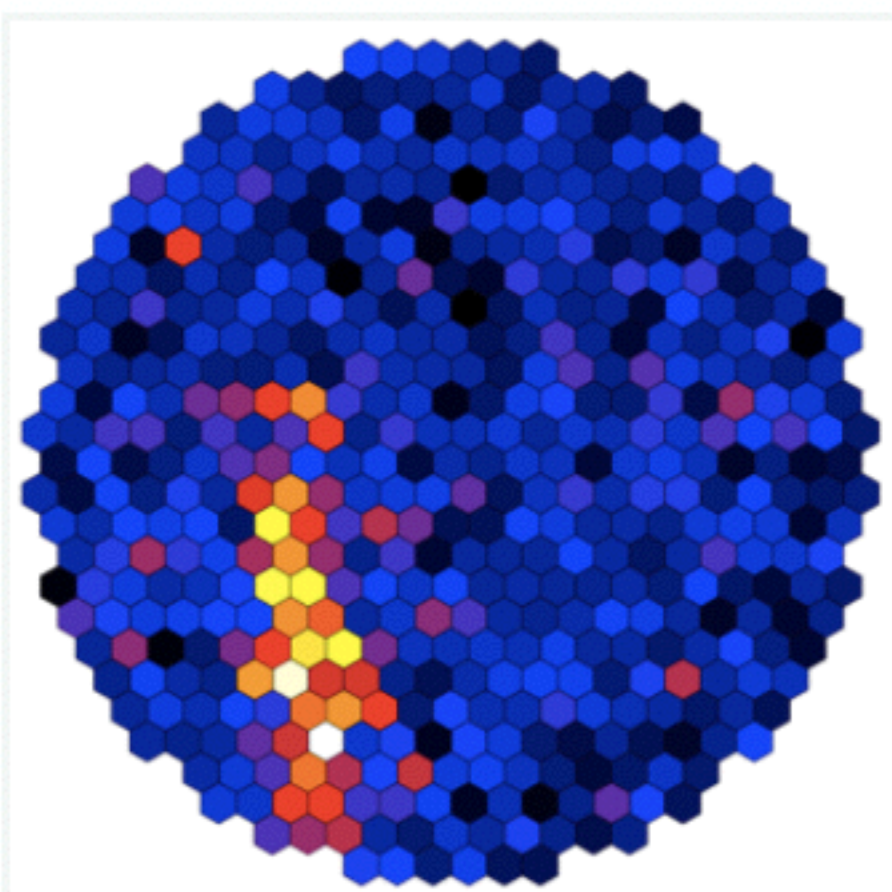

• 499 PMTs
3.5°
• 500 MSPS sampling FADCs
• 3-level trigger

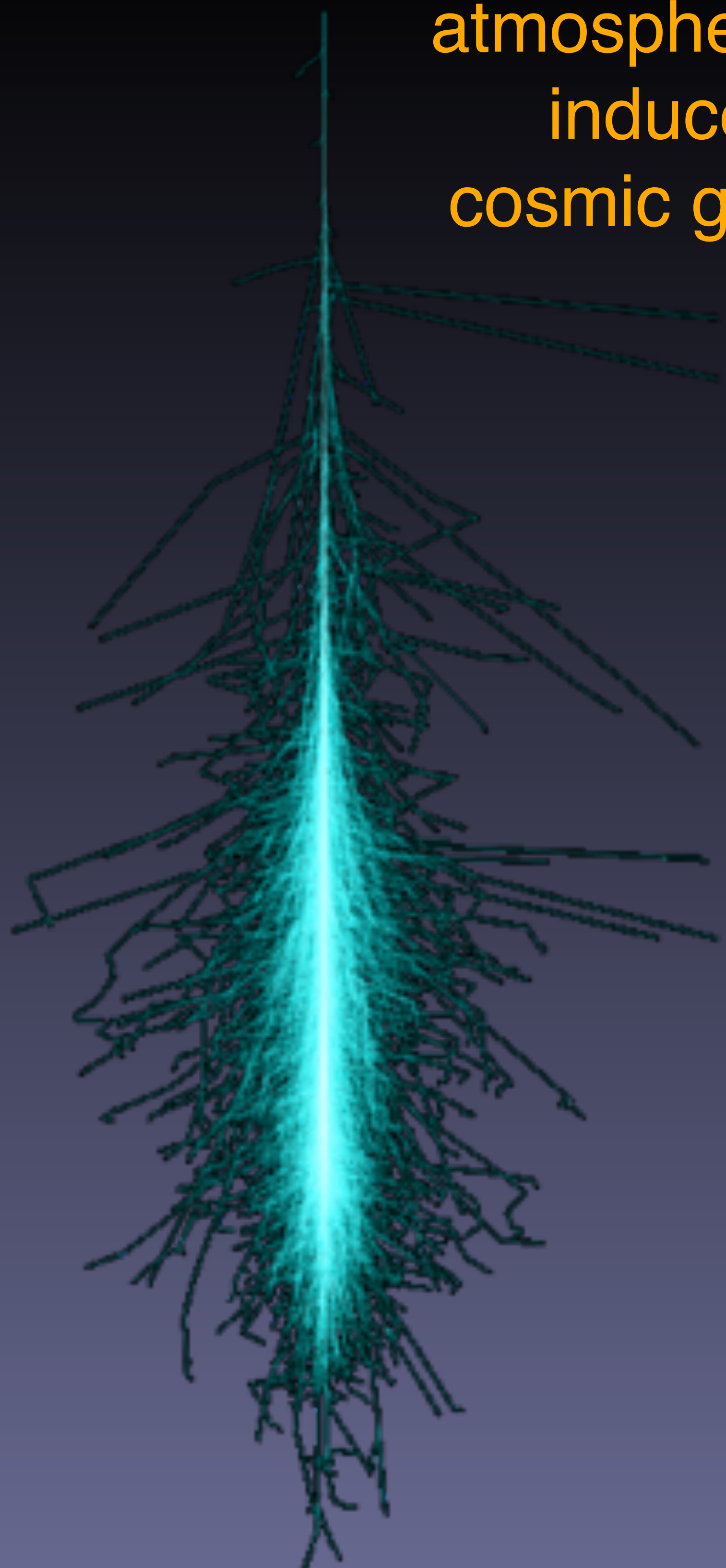
Image reconstruction

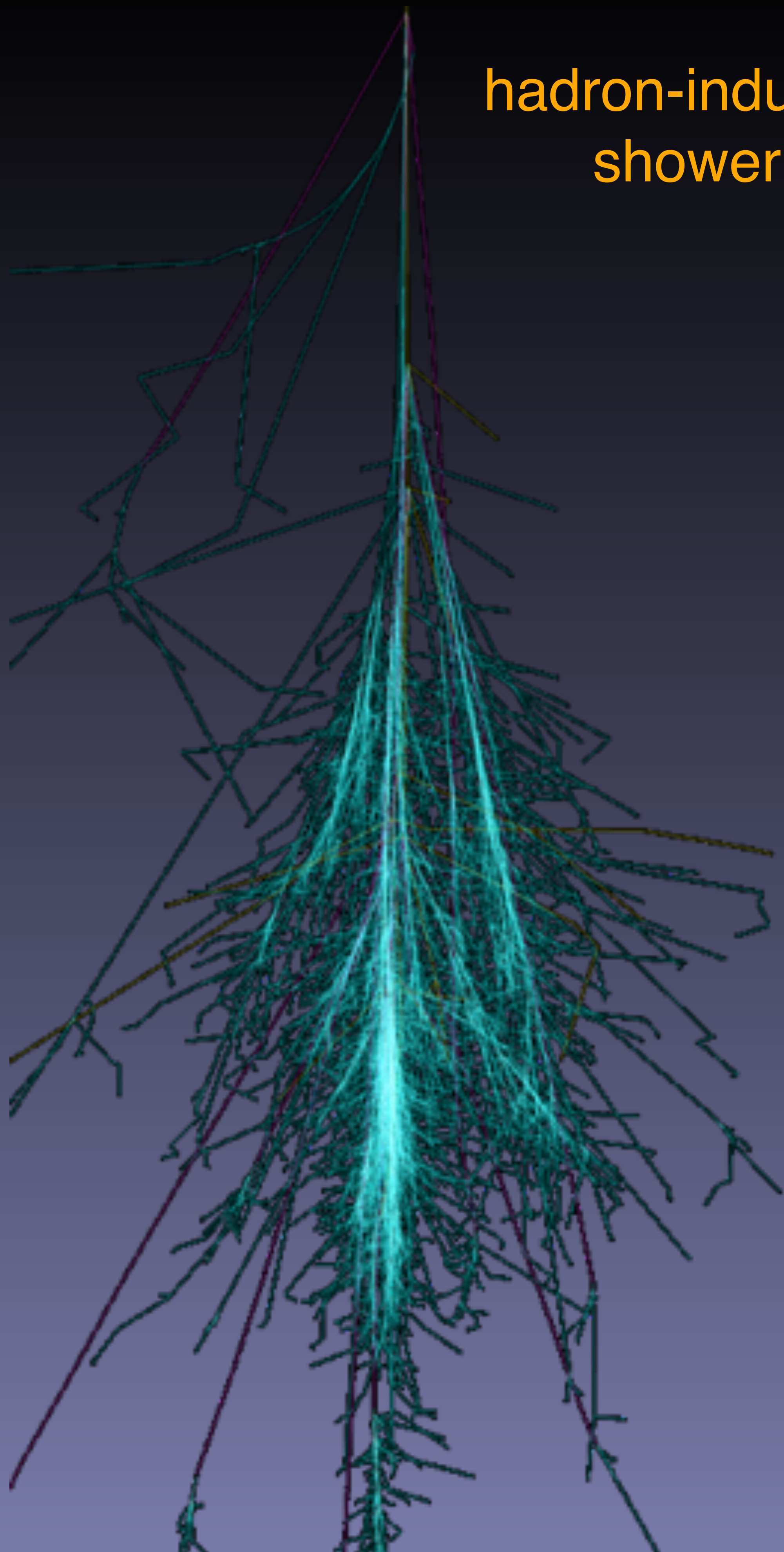




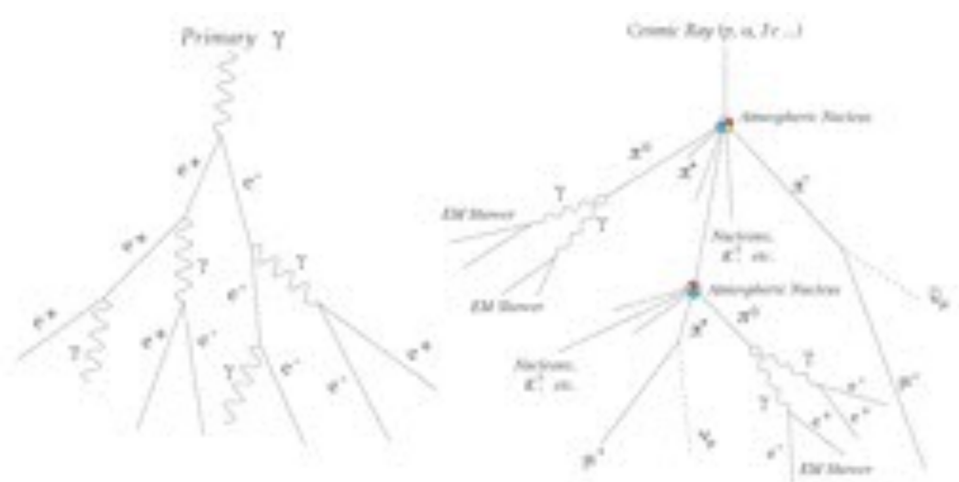


- PMT signals are digitized with fast ADCs with ~ns sampling.
- Total integrated charge is proportional to amount of light seen by PMT.
- *Three-level trigger*: PMT signal threshold (L1), pattern in camera with > 3 fired PMT within 8 ns (L2), at least two telescope within 50 ns (L3).
- Array event rate ~ 300 Hz.

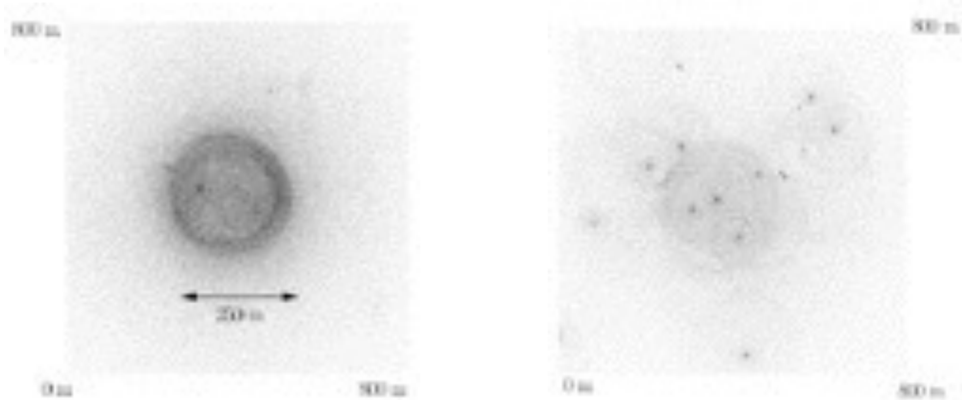

atmospheric shower
induced by a
cosmic gamma-ray


hadron-induced
shower

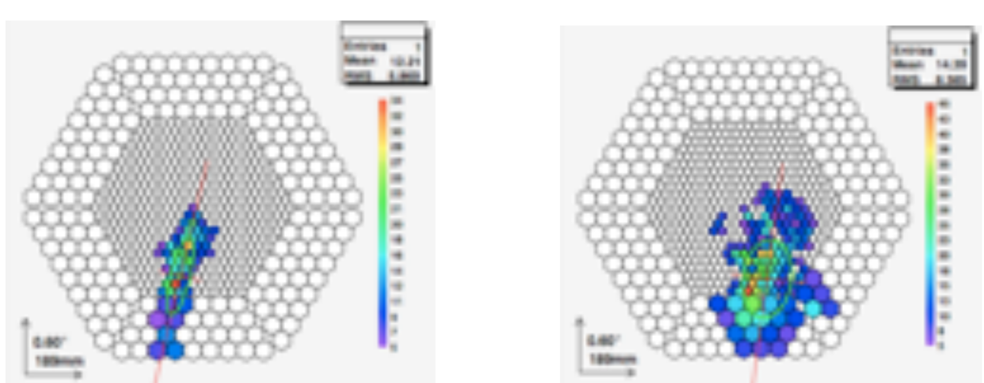
Background rejection



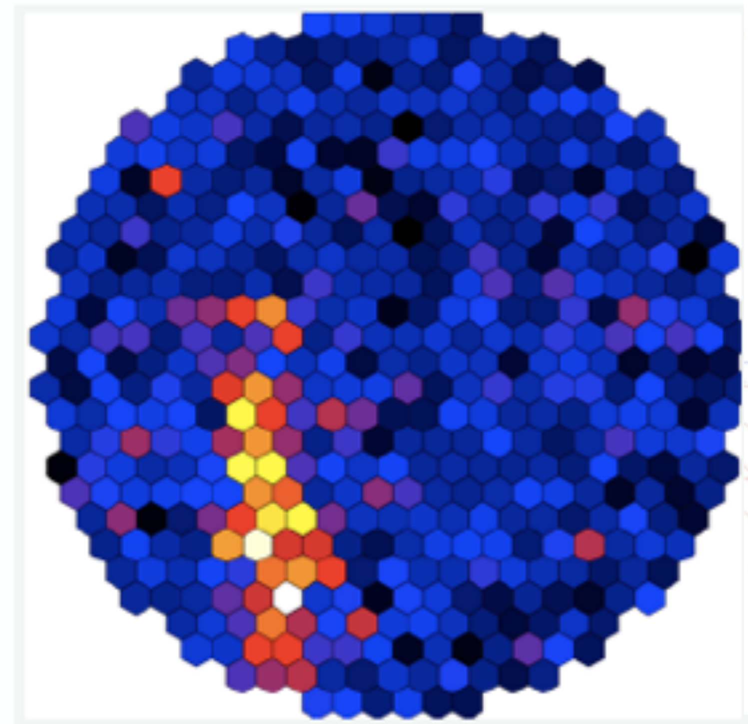
Sketch of the development of EAS

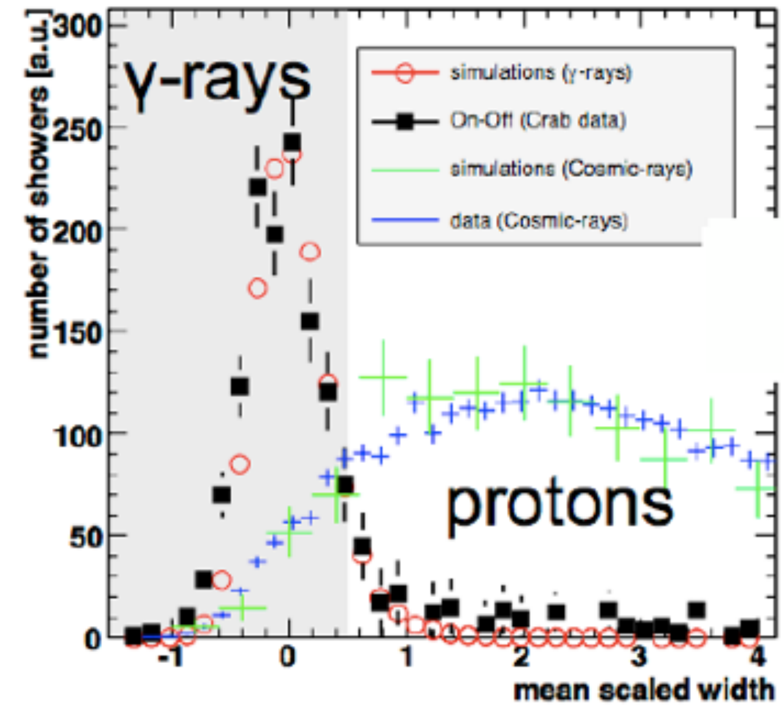


Cherenkov light distributions on the ground

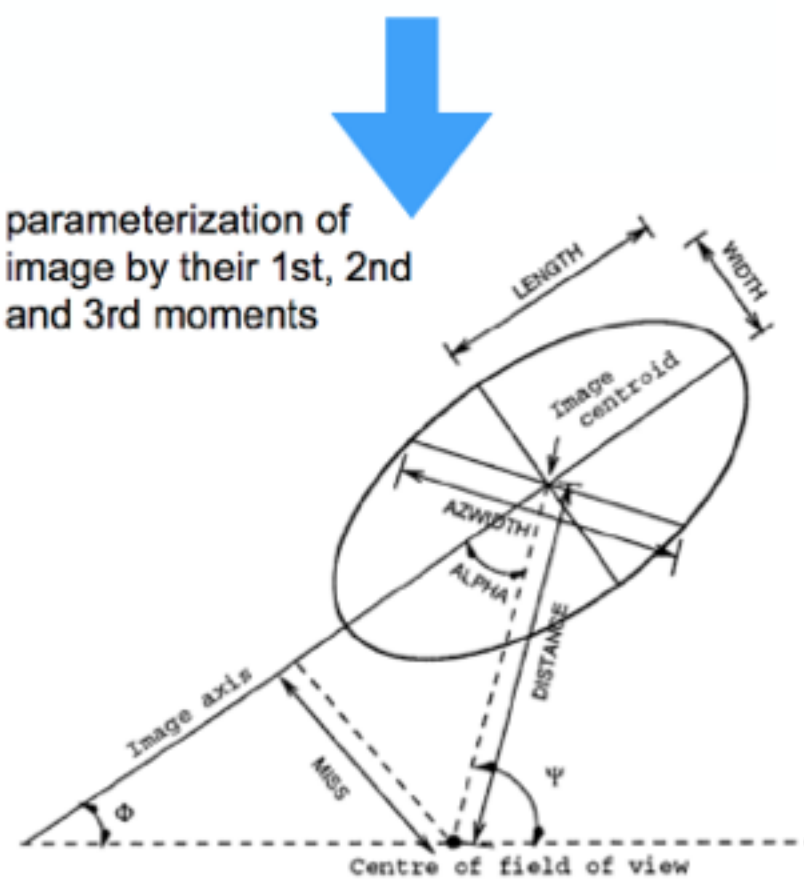


Cherenkov light distributions on the camera

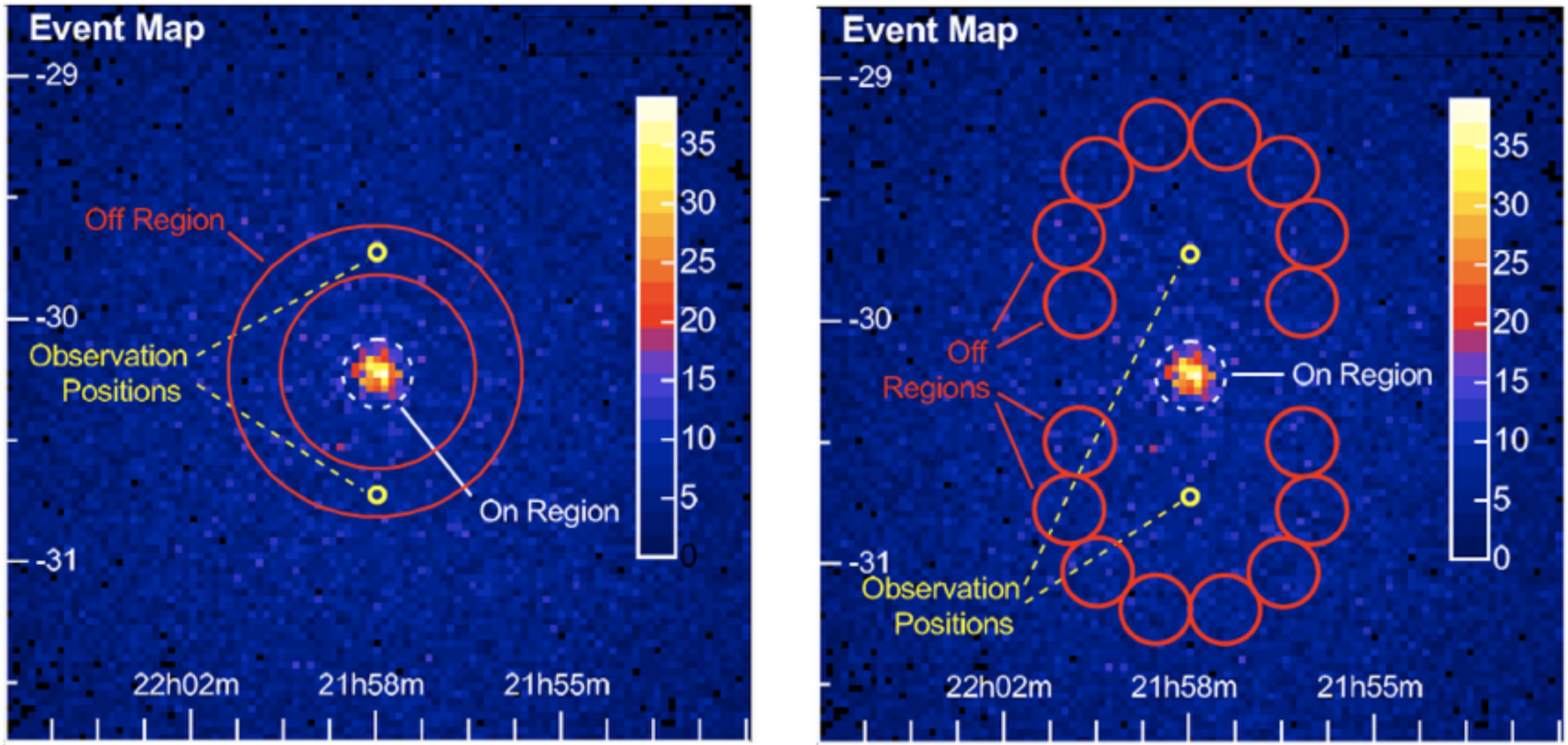




parameterization of image by their 1st, 2nd and 3rd moments



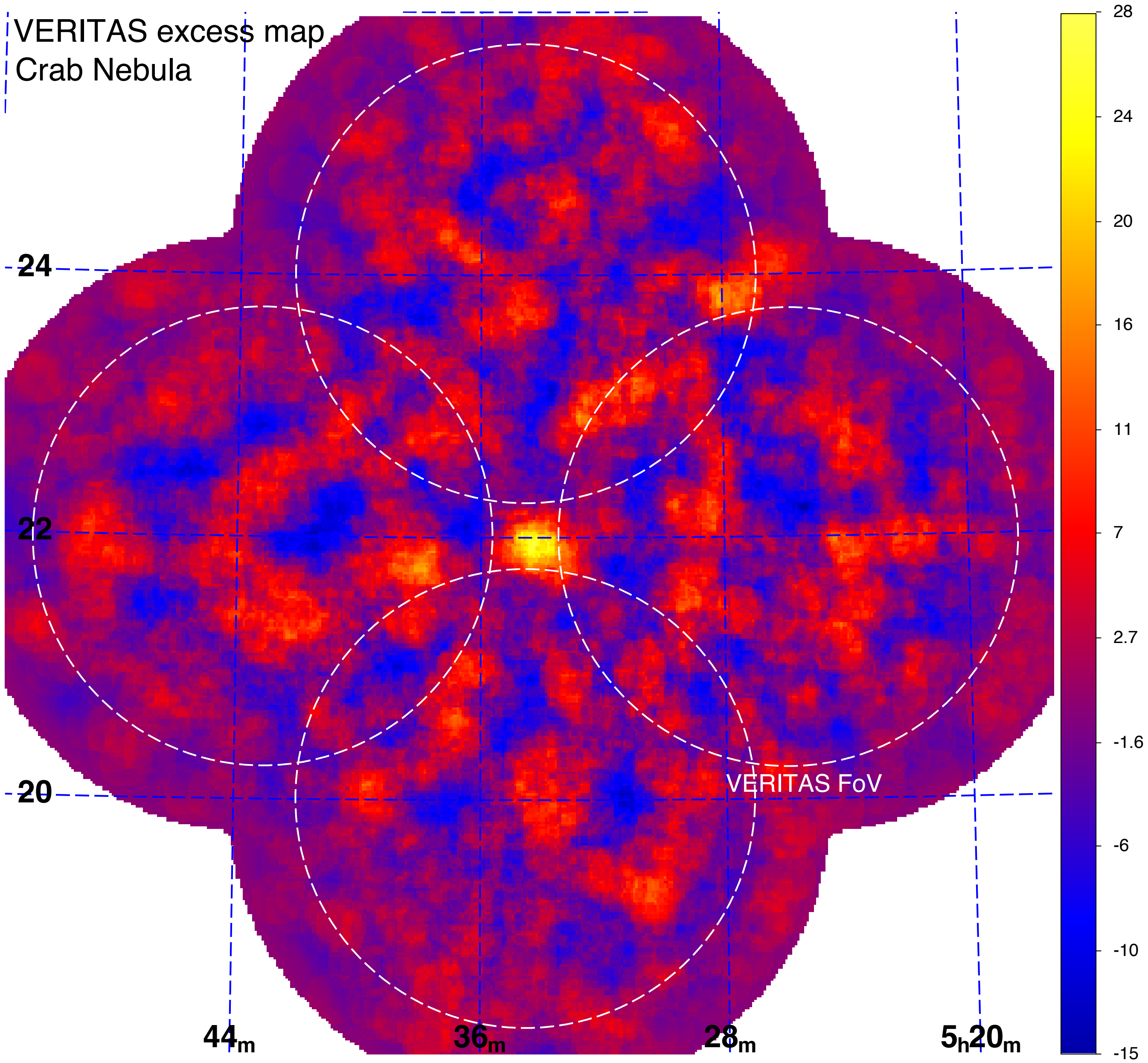
Background estimation

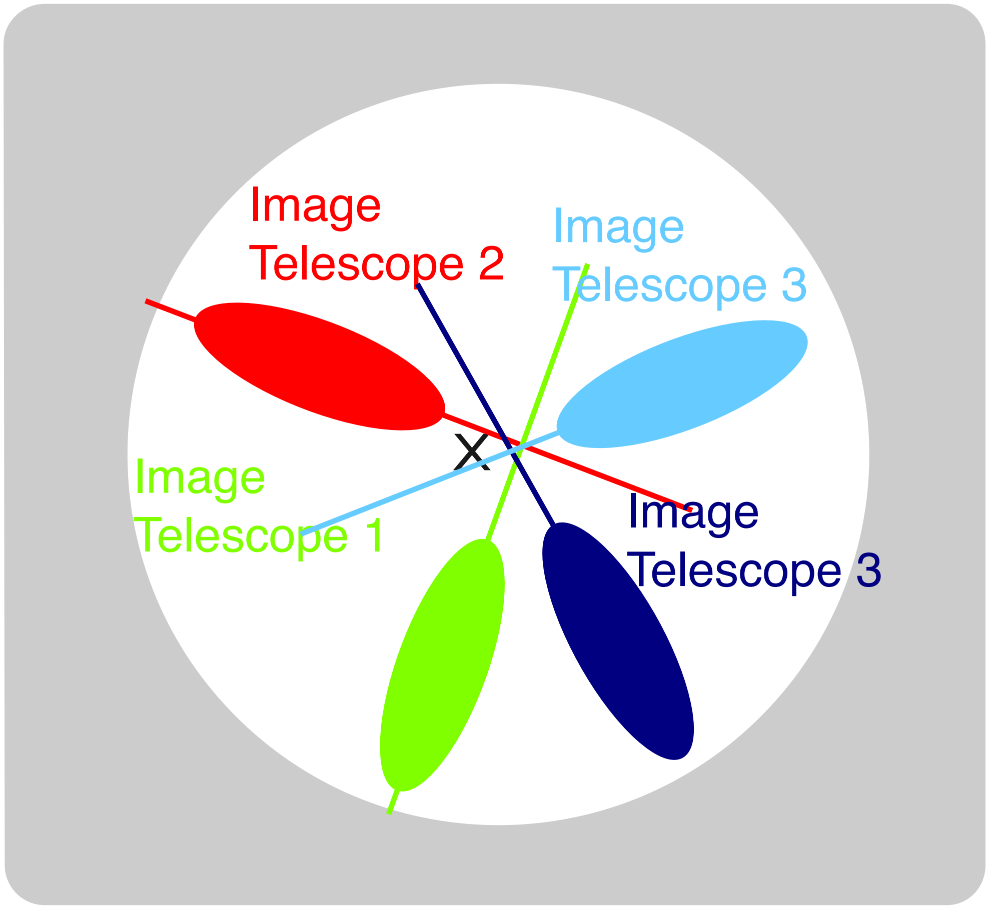


Berge, Funk & Hinton, 2007, A&A, 466, 1219

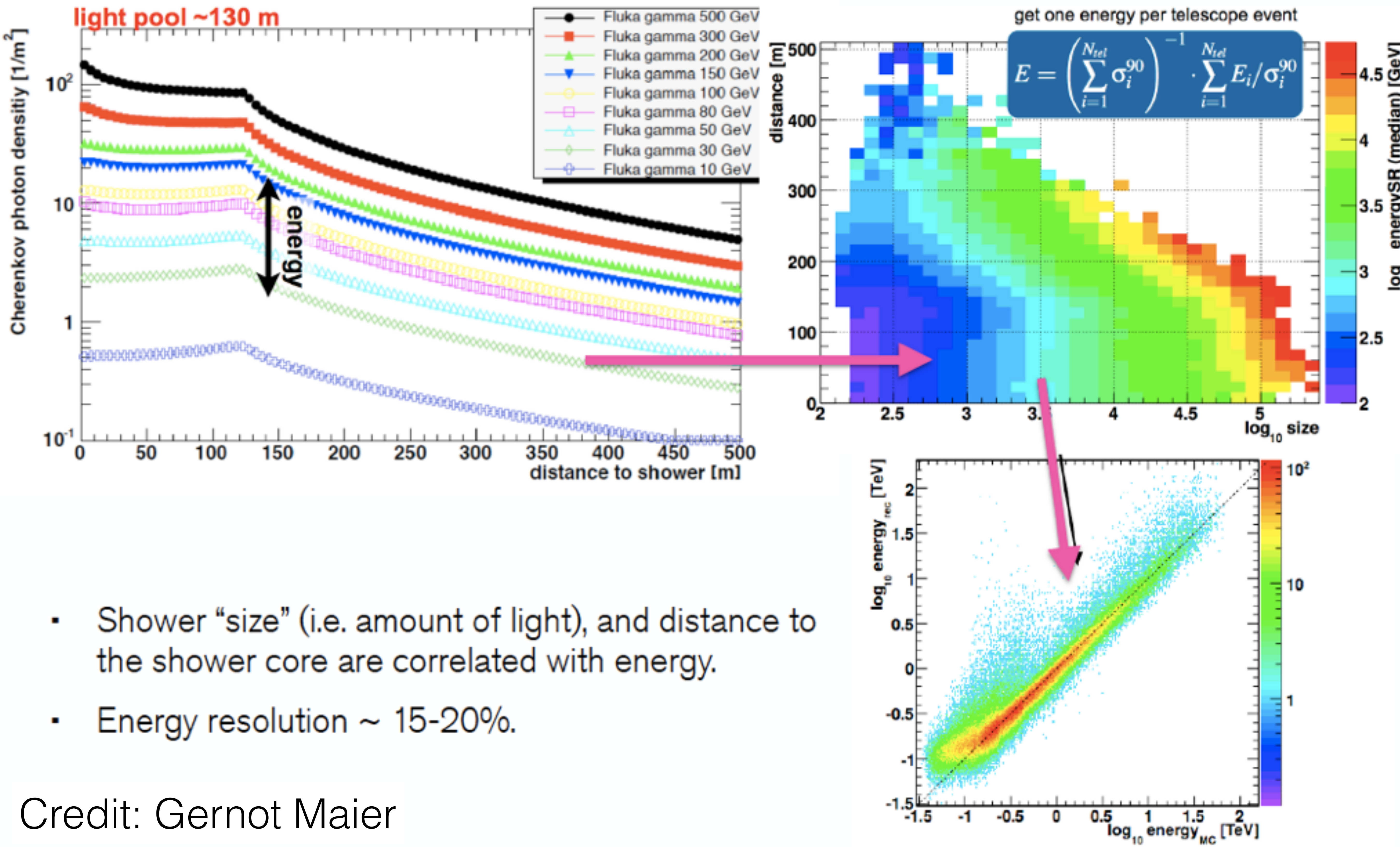
- The acceptance falls towards the edges of the camera.
- Sources are typically observed in wobble mode, where the source of interest is ~0.5° off of the camera center.

Source position reconstruction





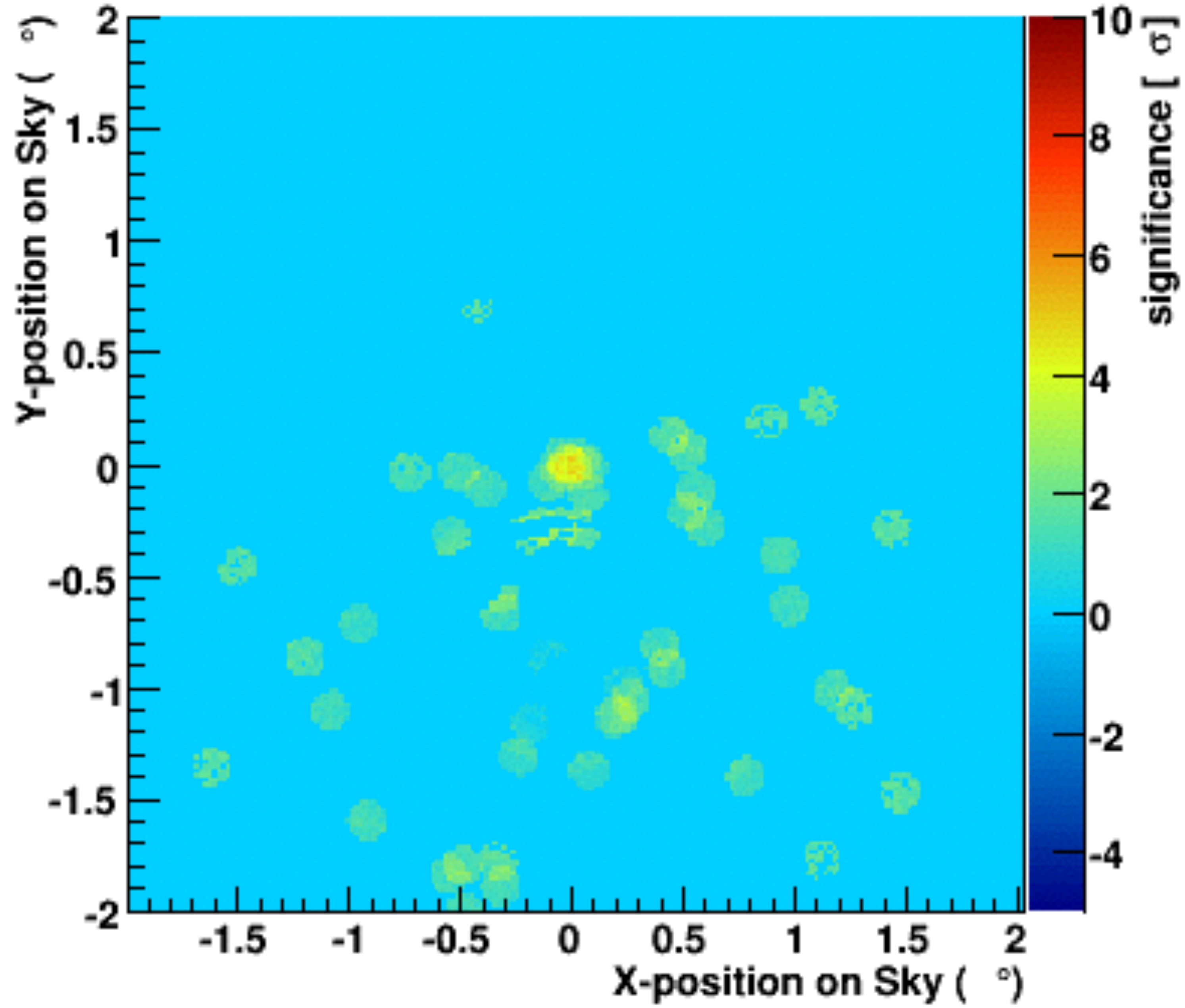
Energy reconstruction

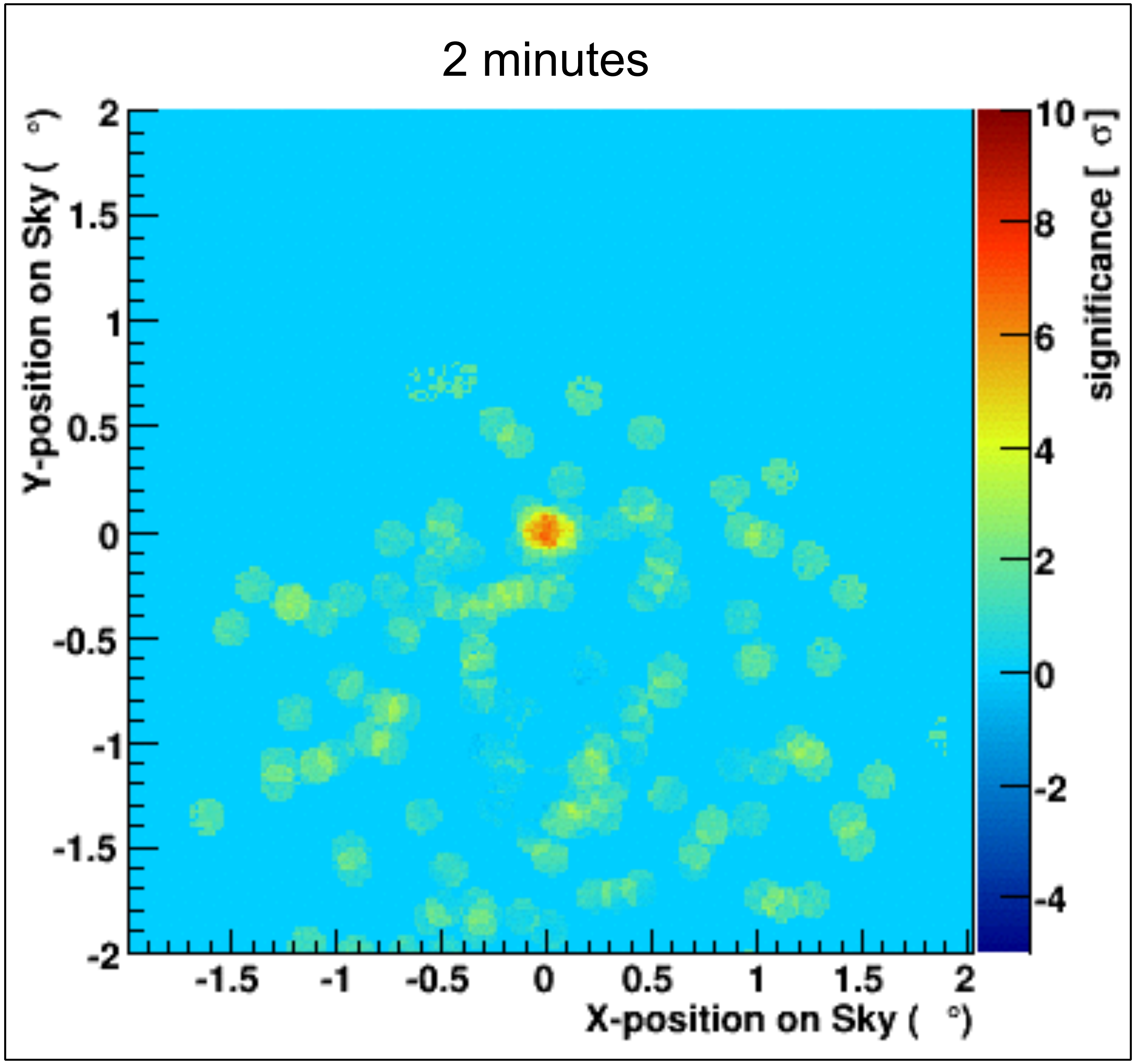


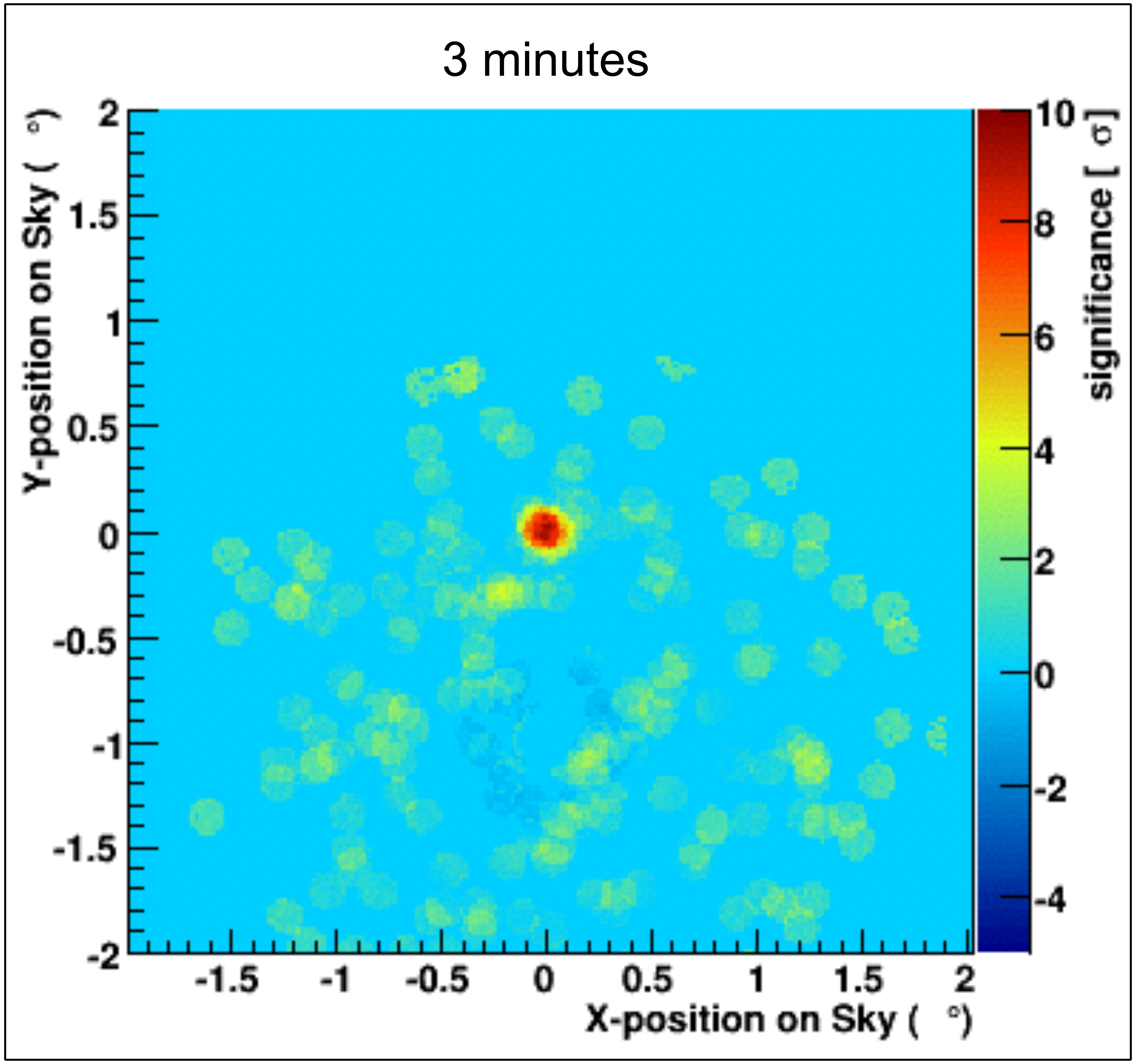
- Shower “size” (i.e. amount of light), and distance to the shower core are correlated with energy.
- Energy resolution ~ 15-20%.

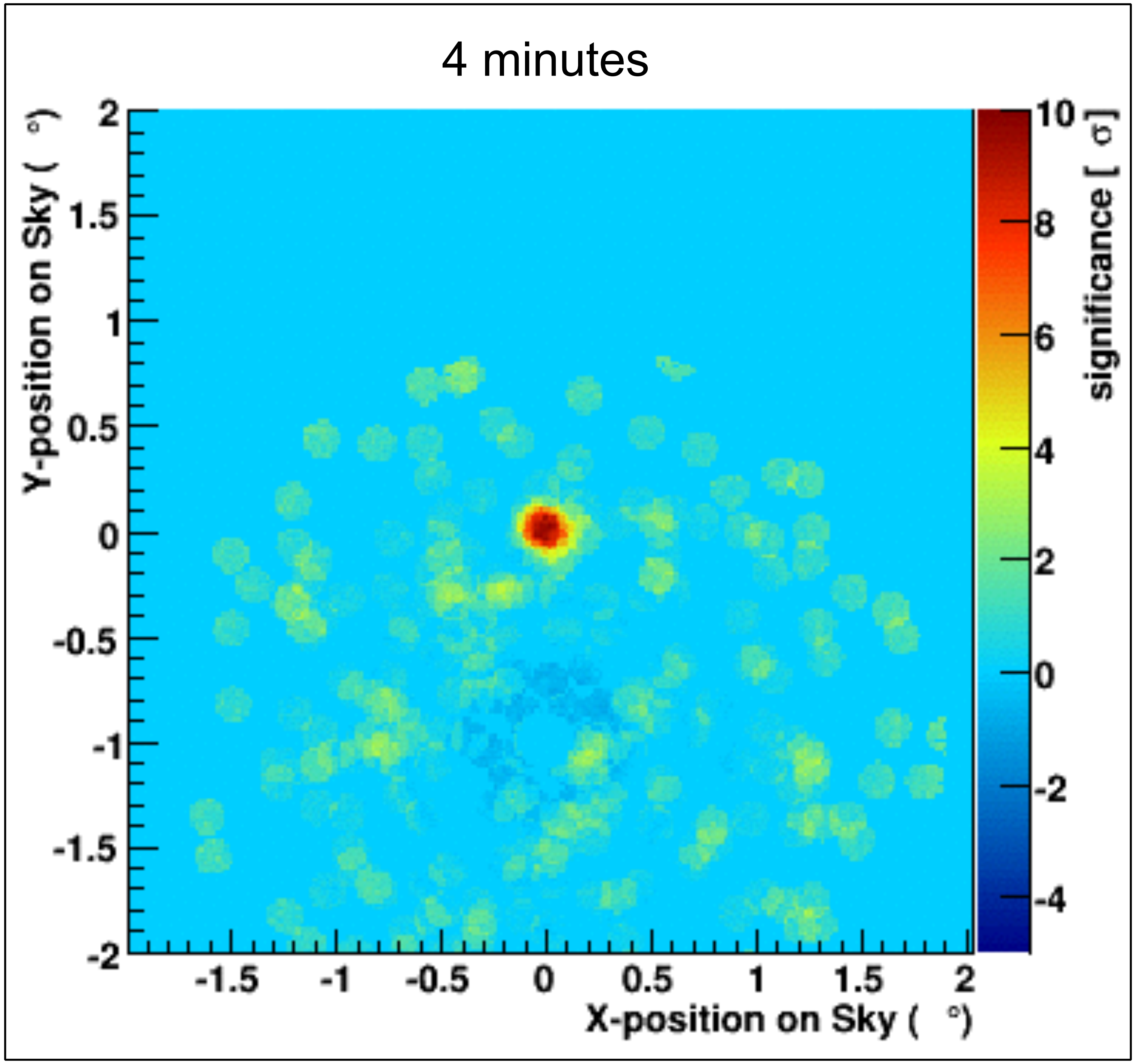
Credit: Gernot Maier

1 minute: detection

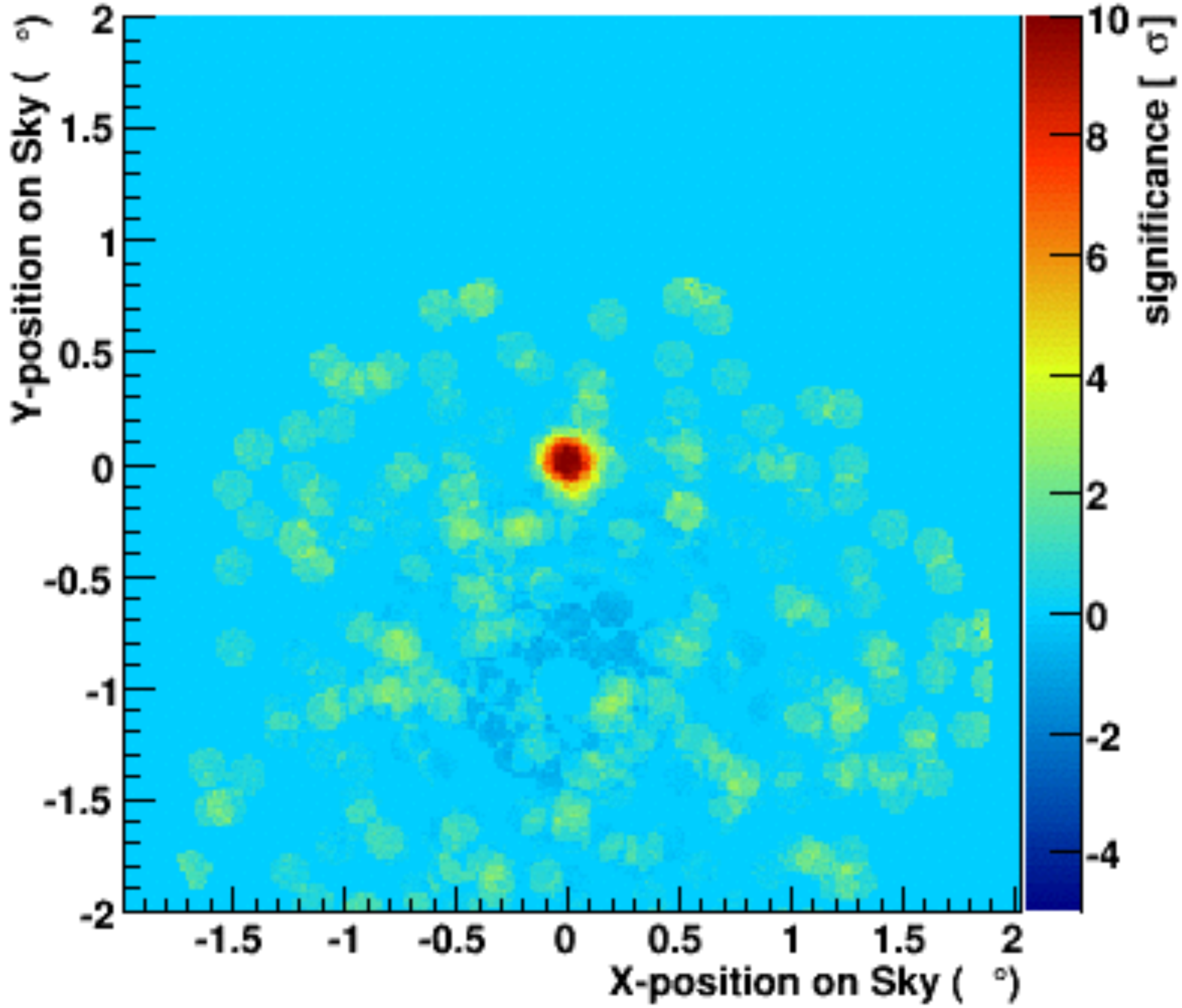


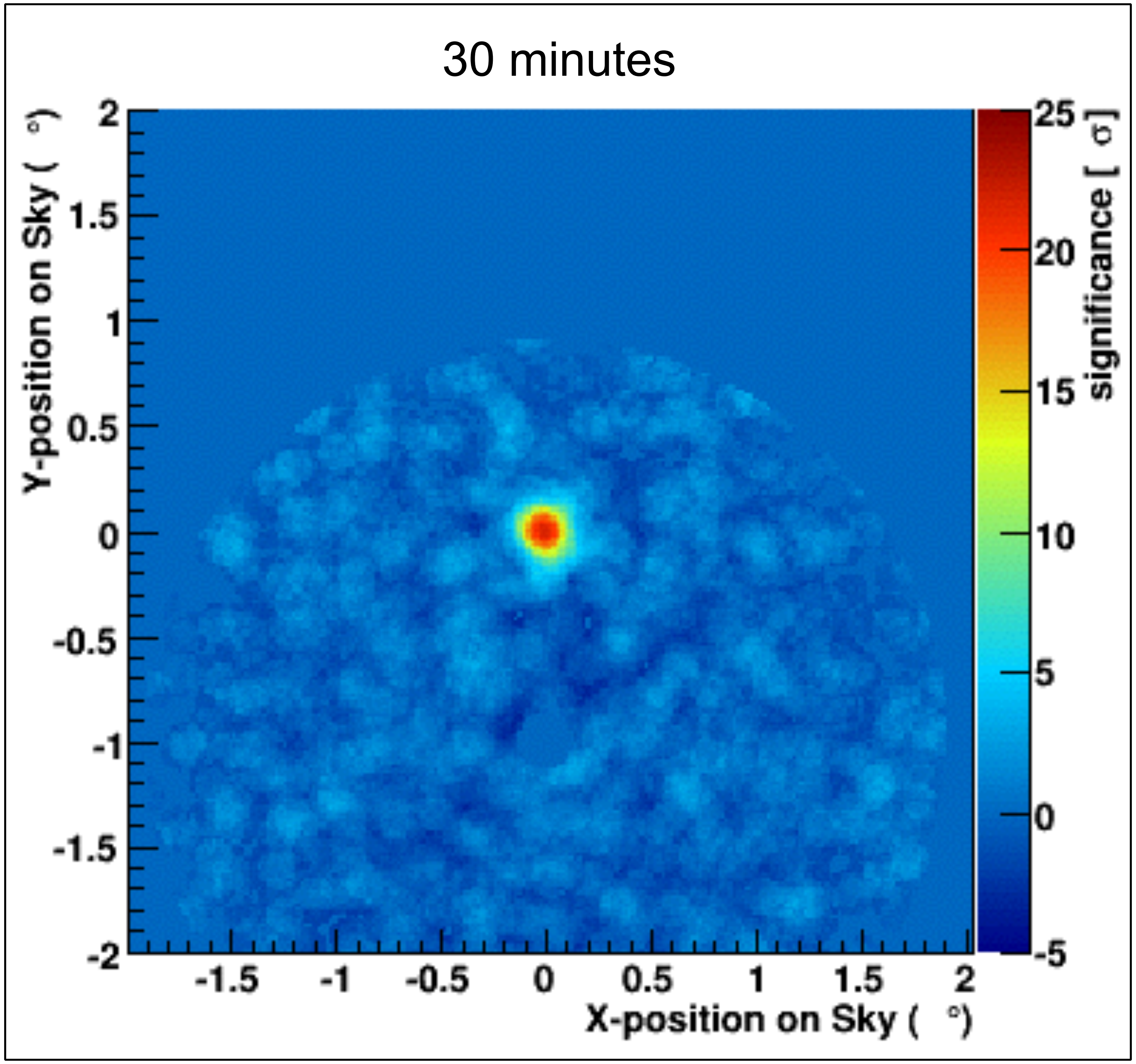

2 minutes
Y-position on Sky (°)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
X-position on Sky (°)
significance [σ]
10
8
6
4
2
0
-2
-4


3 minutes
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
Y-position on Sky (°)
-1.5
-1
-0.5
0
0.5
1
1.5
2
X-position on Sky (°)
10
8
6
4
2
0
-2
-4
significance [σ]

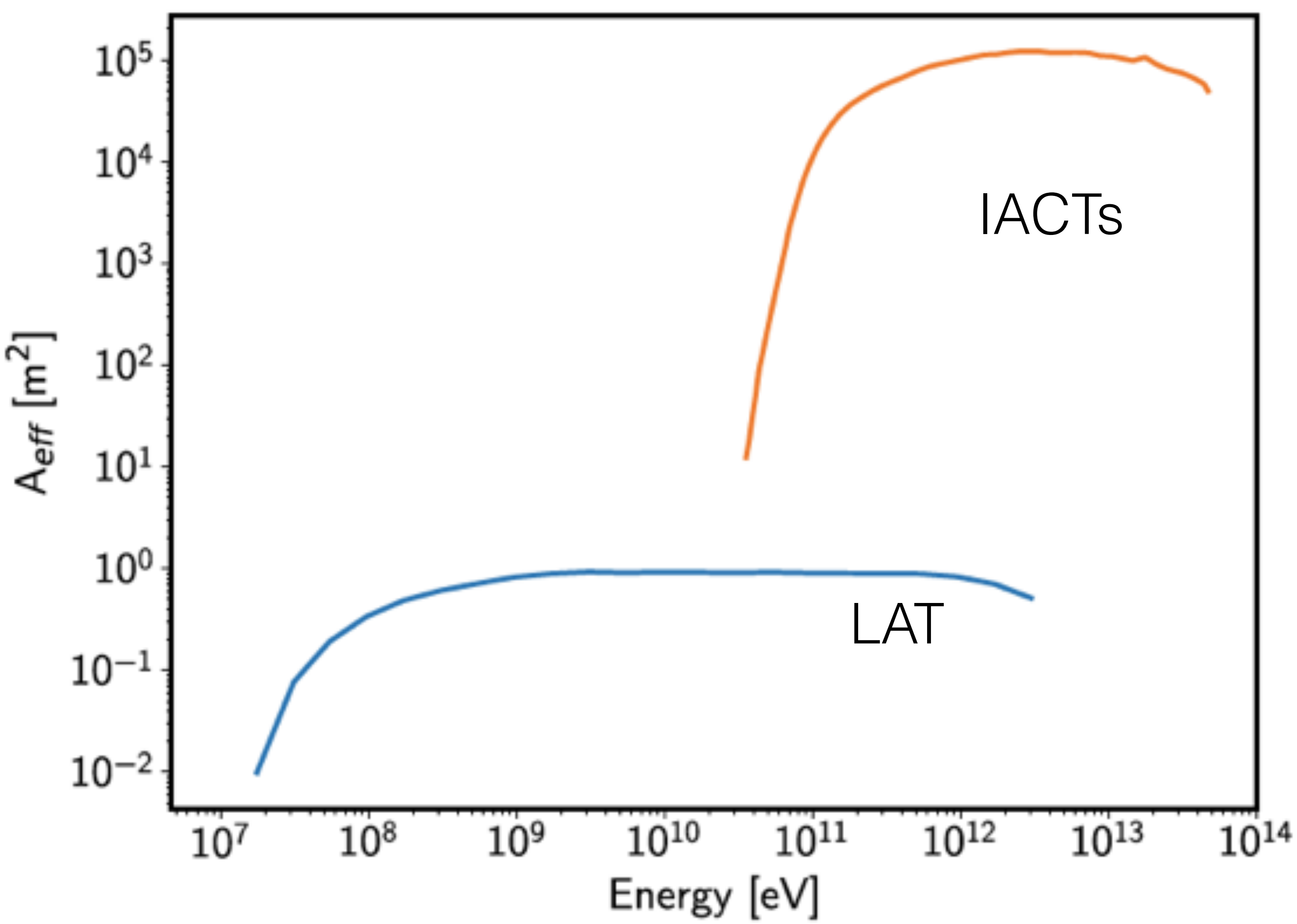

4 minutes
Y-position on Sky (°)
X-position on Sky (°)
significance [σ]
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
10
8
6
4
2
0
-2
-4

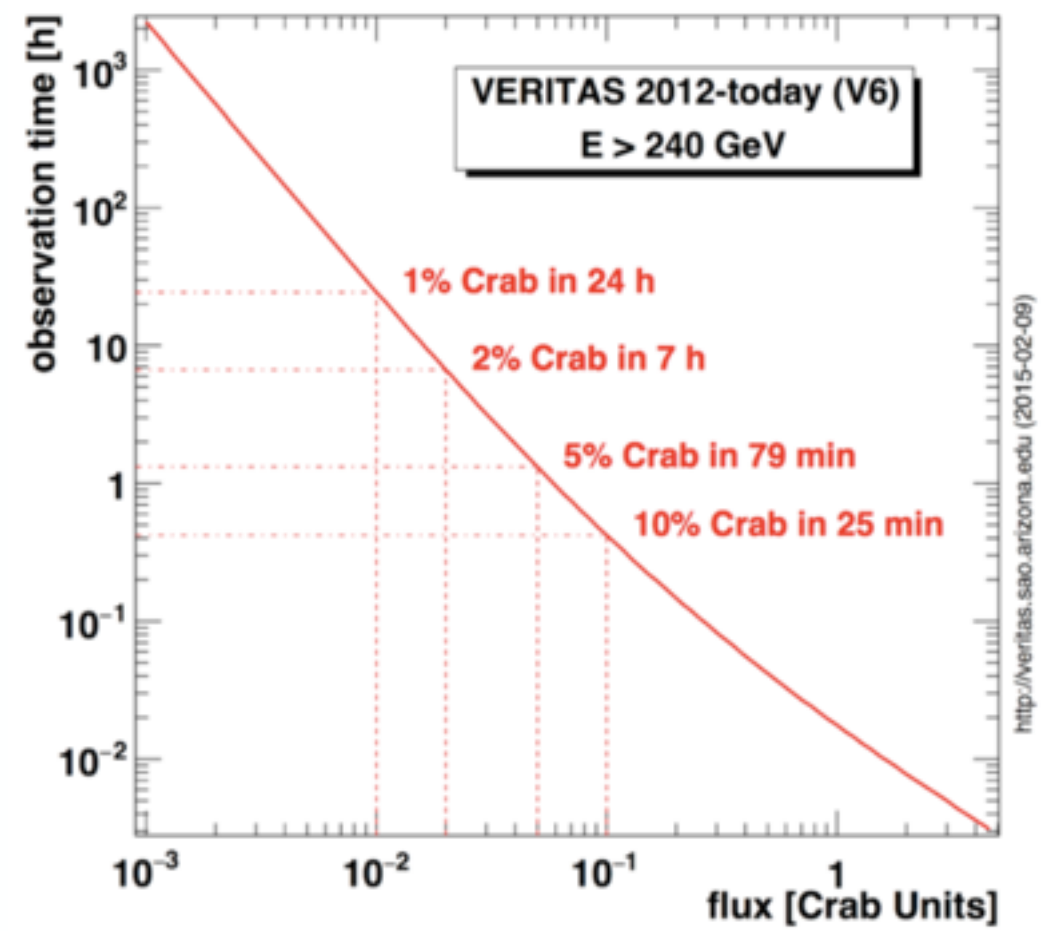
5 minutes: 10 σ




30 minutes
Y-position on Sky (°)
X-position on Sky (°)
significance [σ]
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
2
25
20
15
10
5
-5

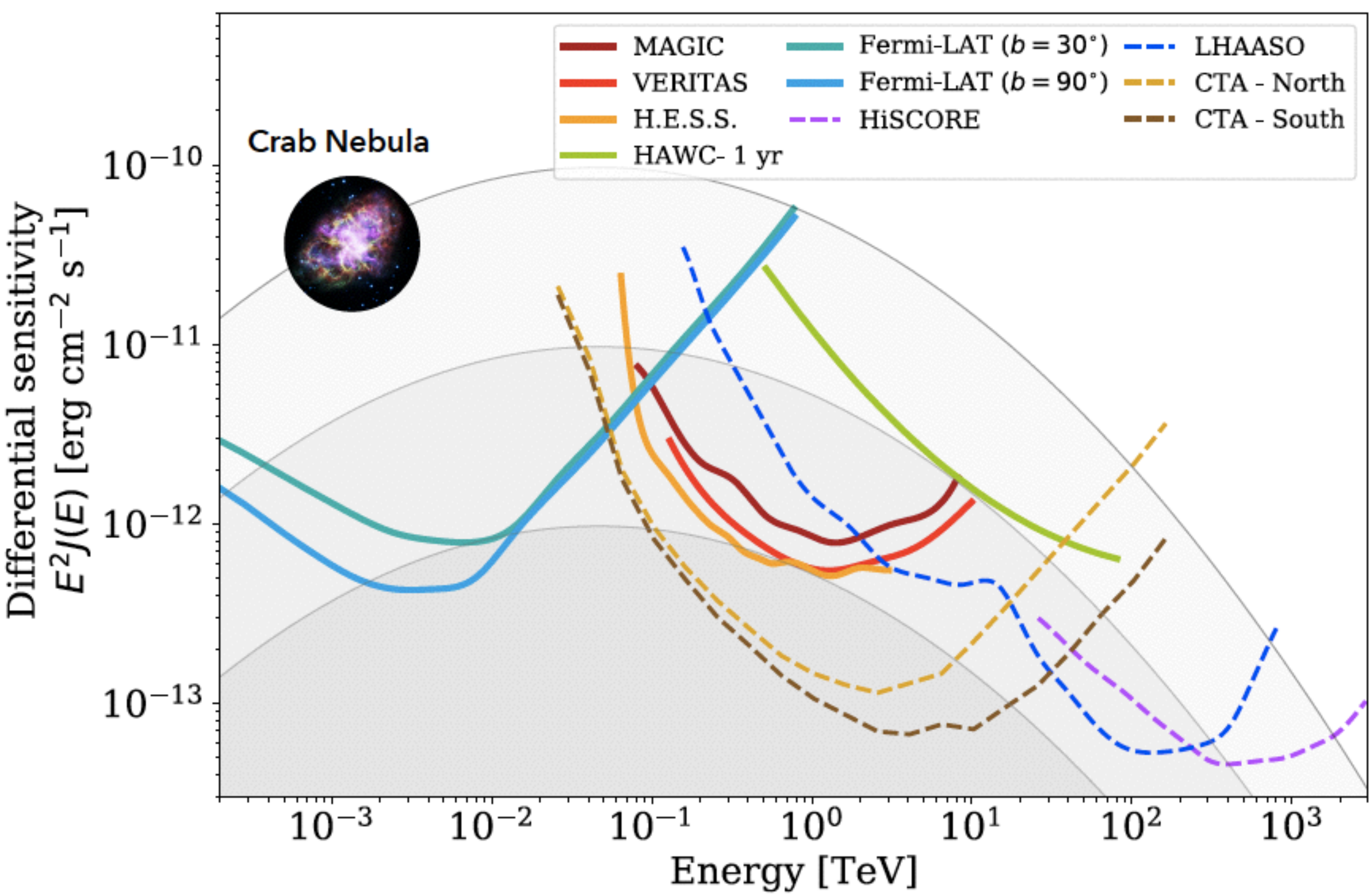
Effective area, sensitivity





Imagine a source with an energy spectrum dN/dE ~ E^{-2}.
You hope to detect fast variability, and will large photon statistics.
Are you better off with LAT data or IACT data?
Assume LAT detects 10 photons from the source at 10 GeV, how many 100 GeV photons will an IACT detect?

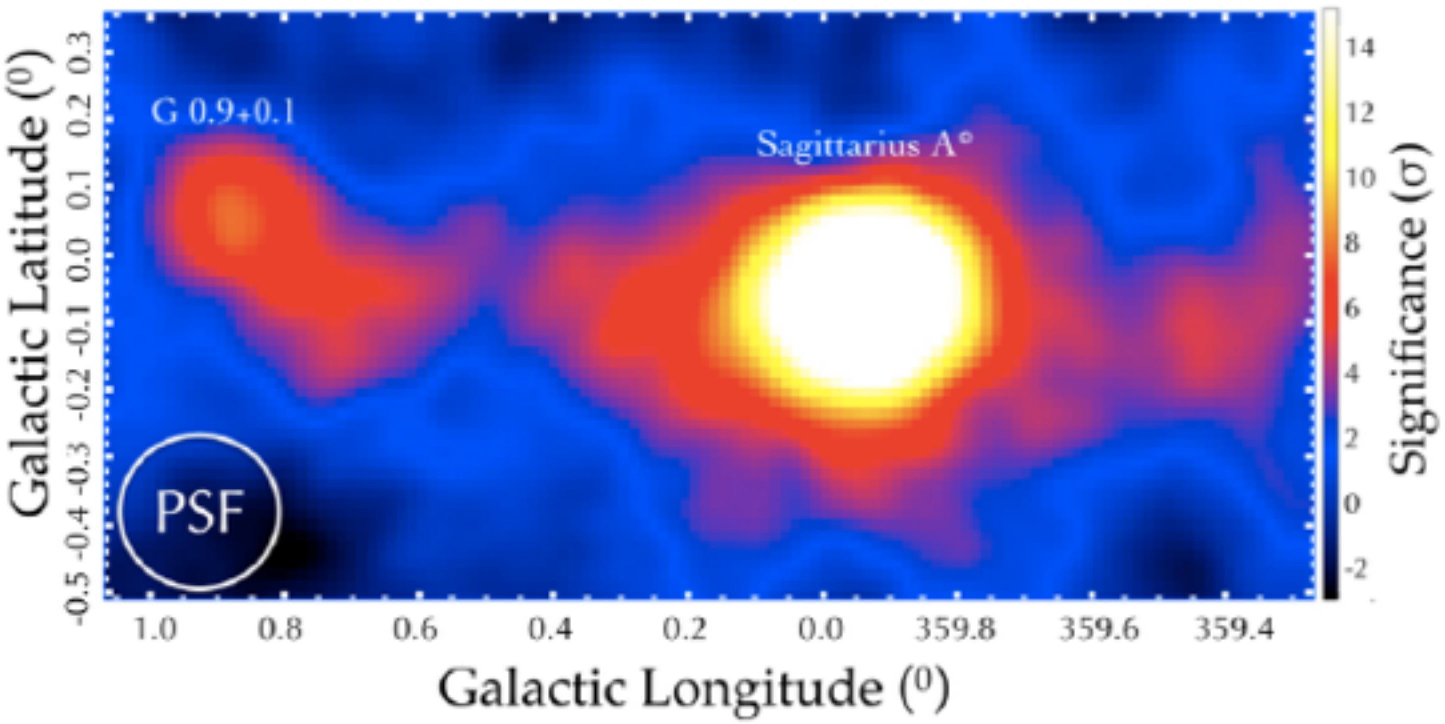
Effective area, sensitivity



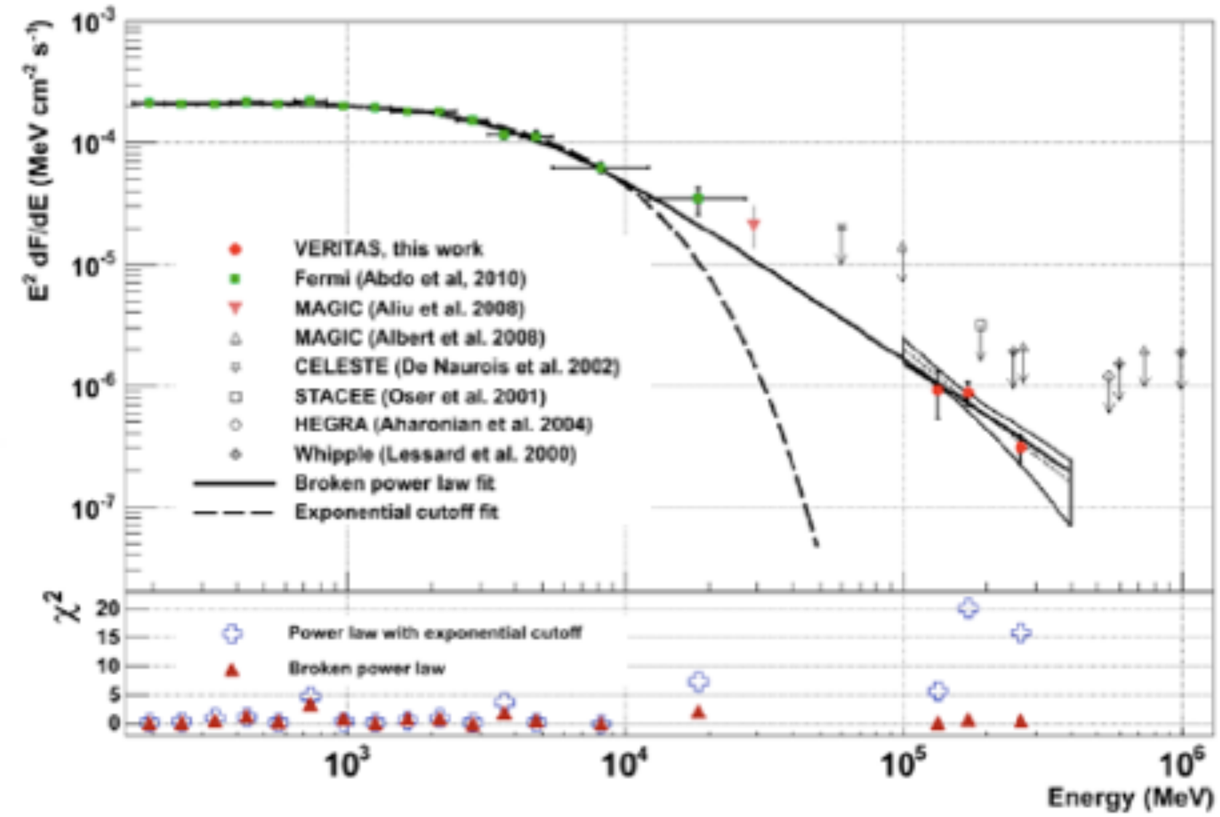
- Sensitivity: Point source for 50h of observation

IACT high-level products

Sky maps

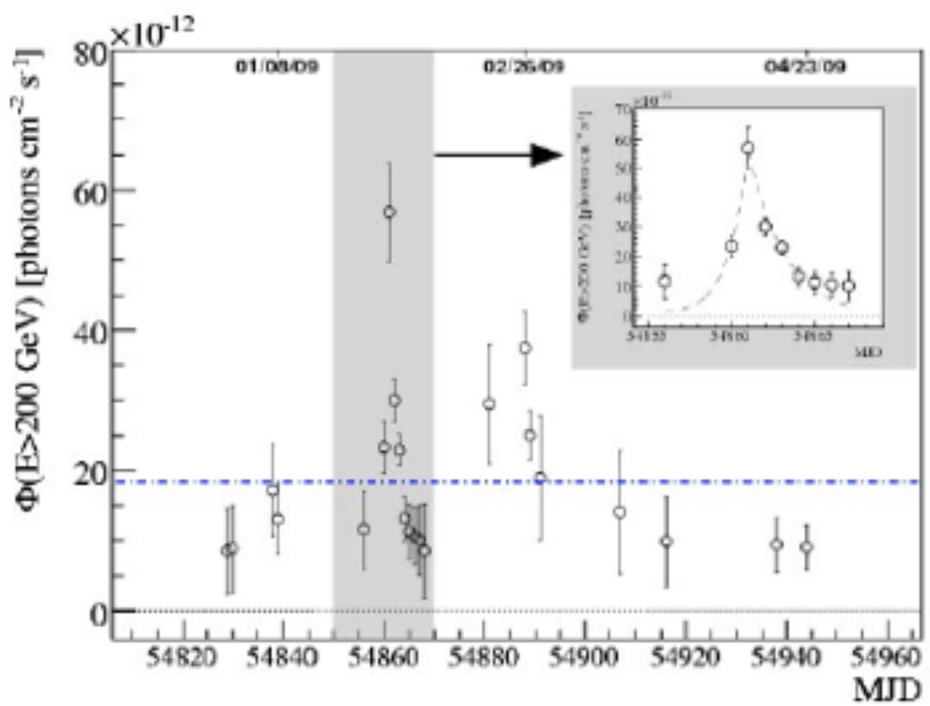


Spectra



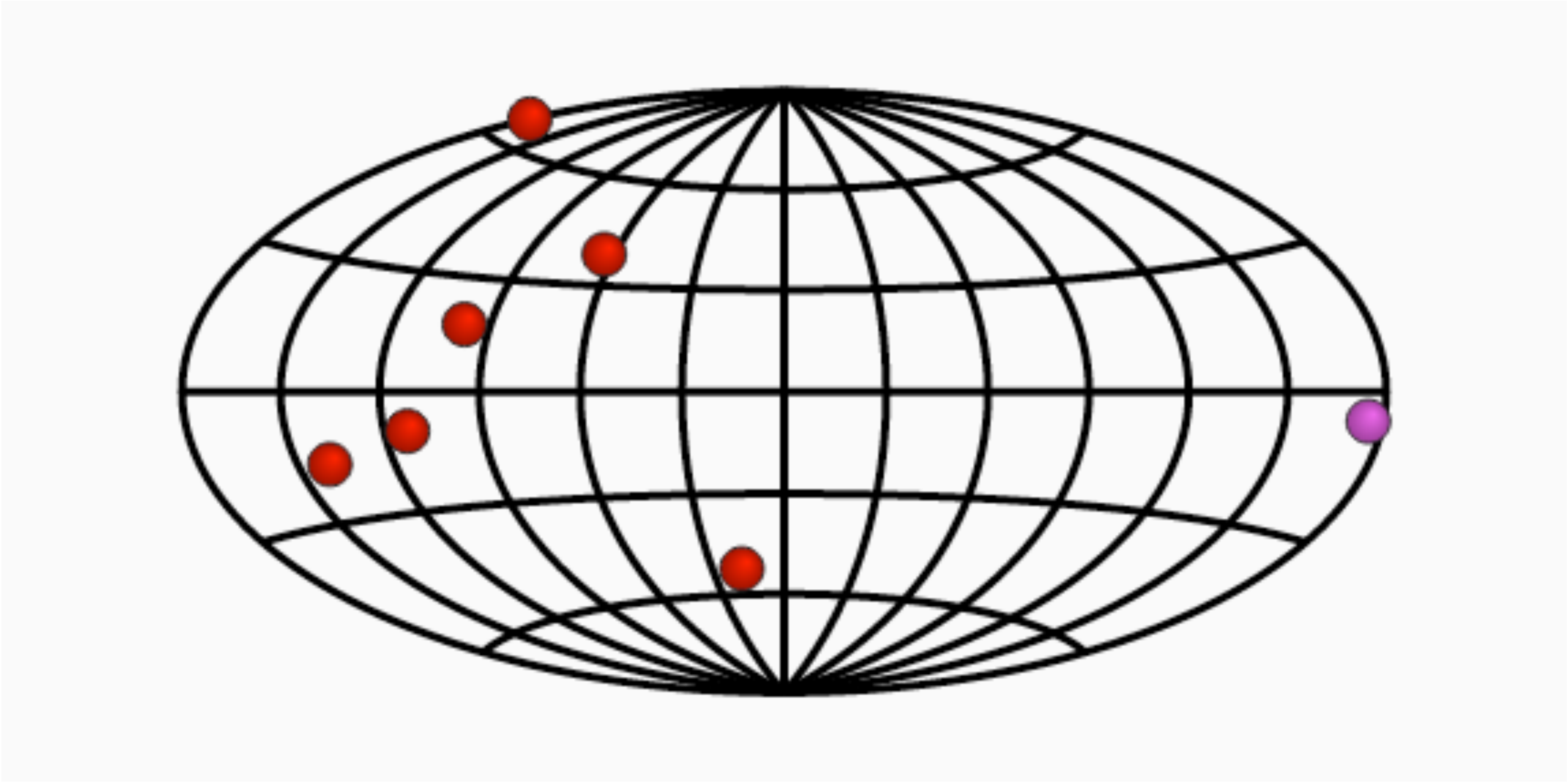
- Energetics of the source
- Constraints on emission models
- Upper limits

Light curves



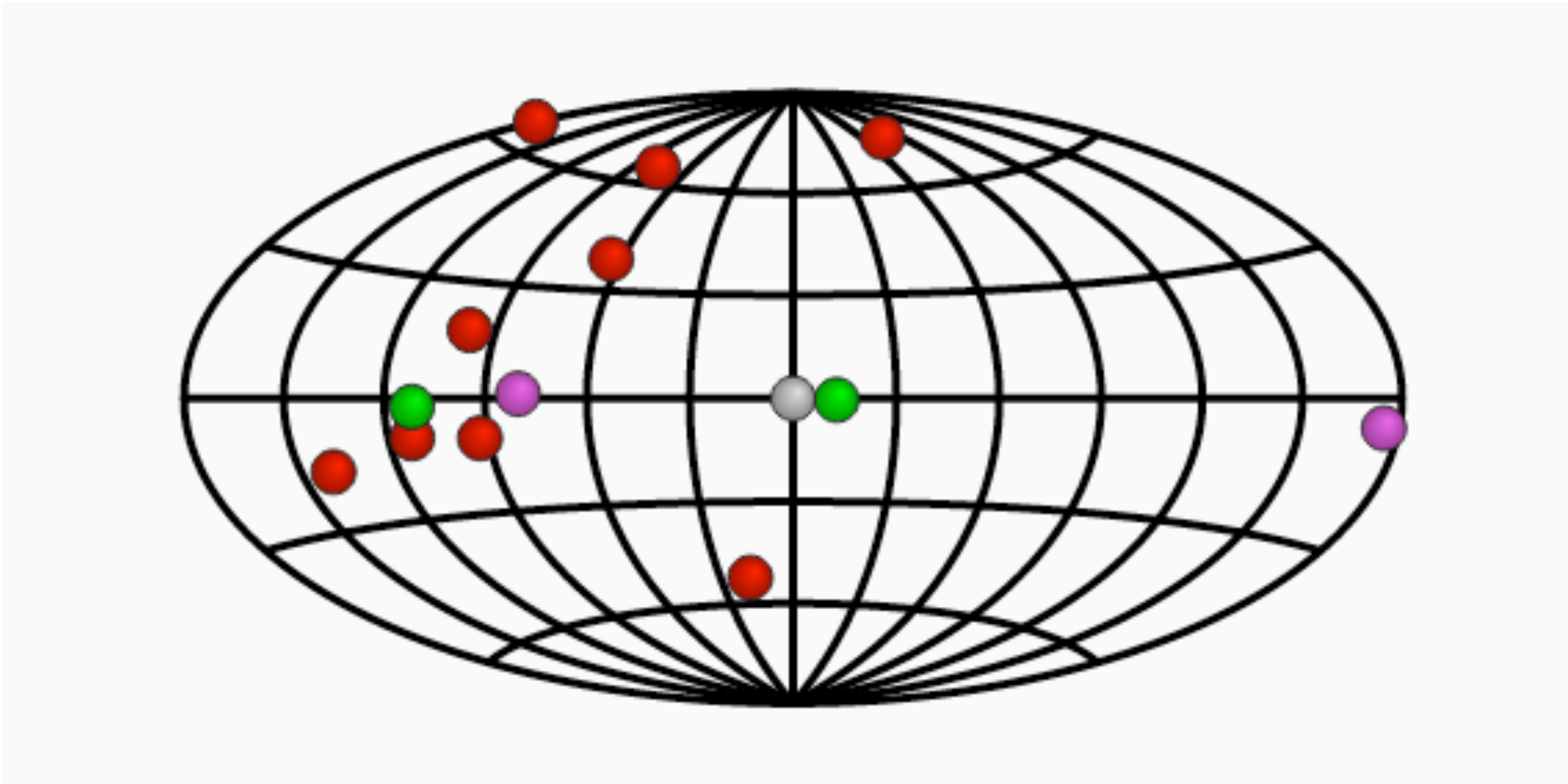
- Size of the emission region
- Correlation with MWL events

VHE gamma-ray sky



1999: 07 sources

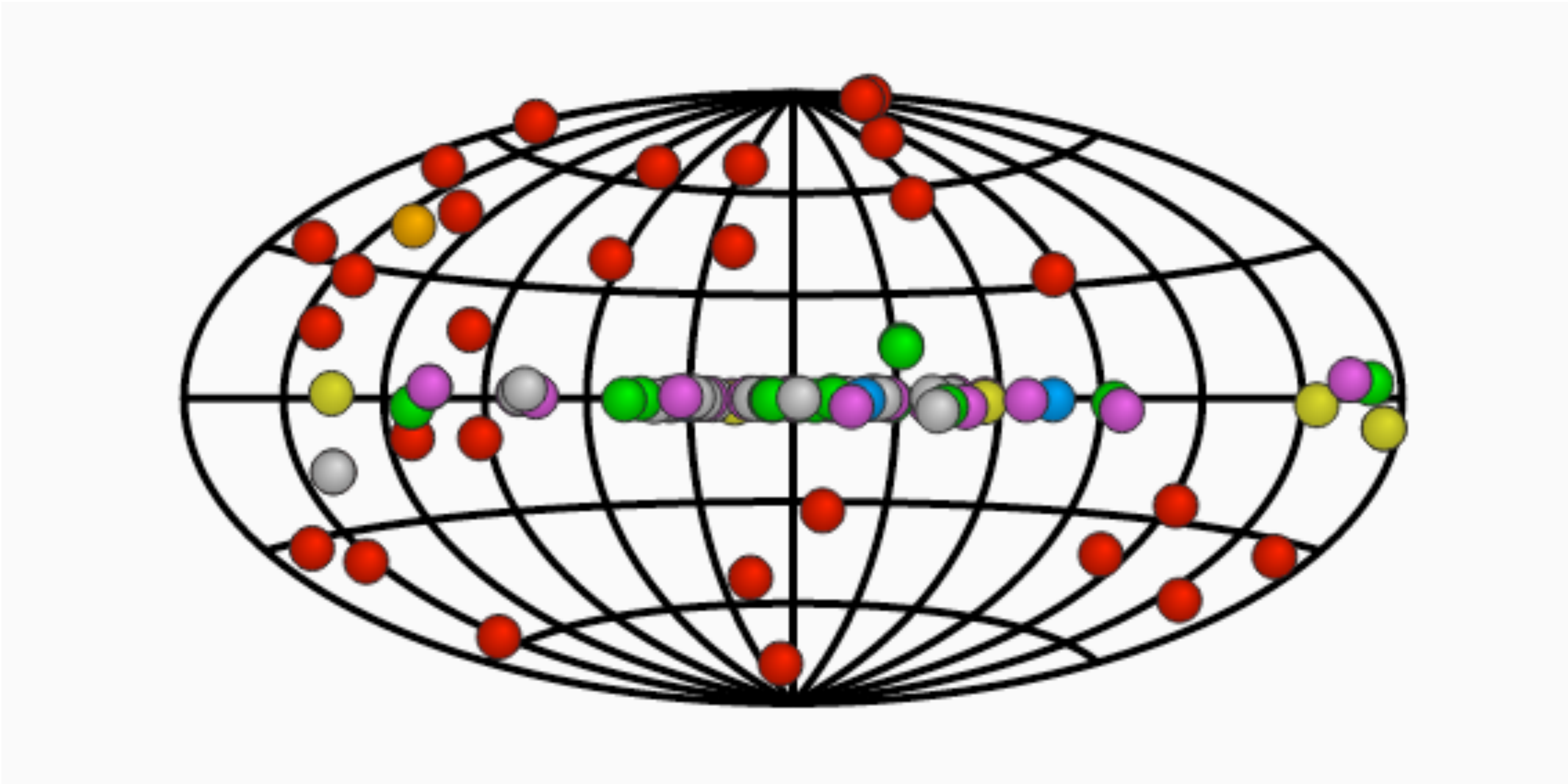
VHE gamma-ray sky



1999: 07 sources

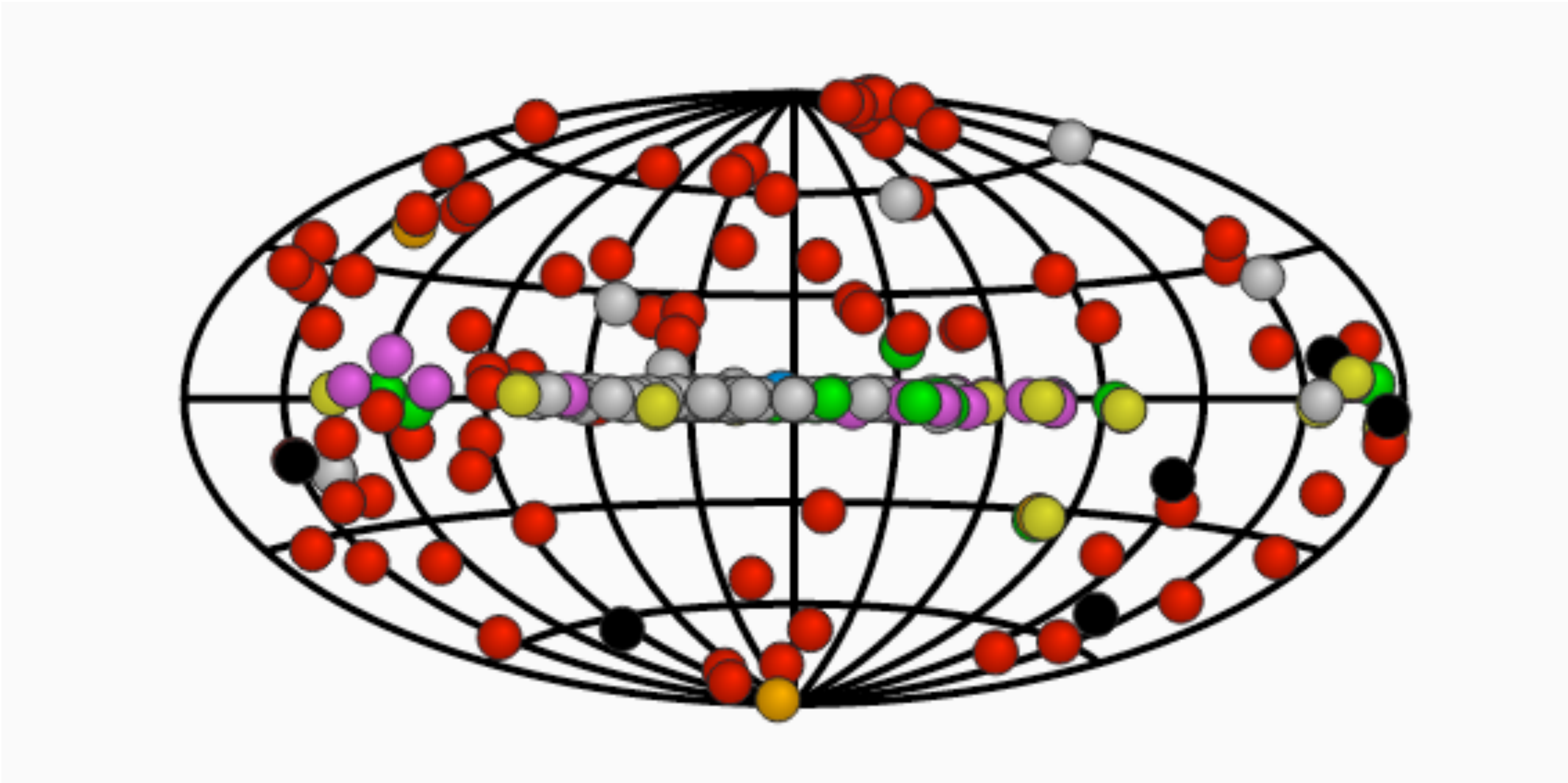
2004: 14 sources

VHE gamma-ray sky



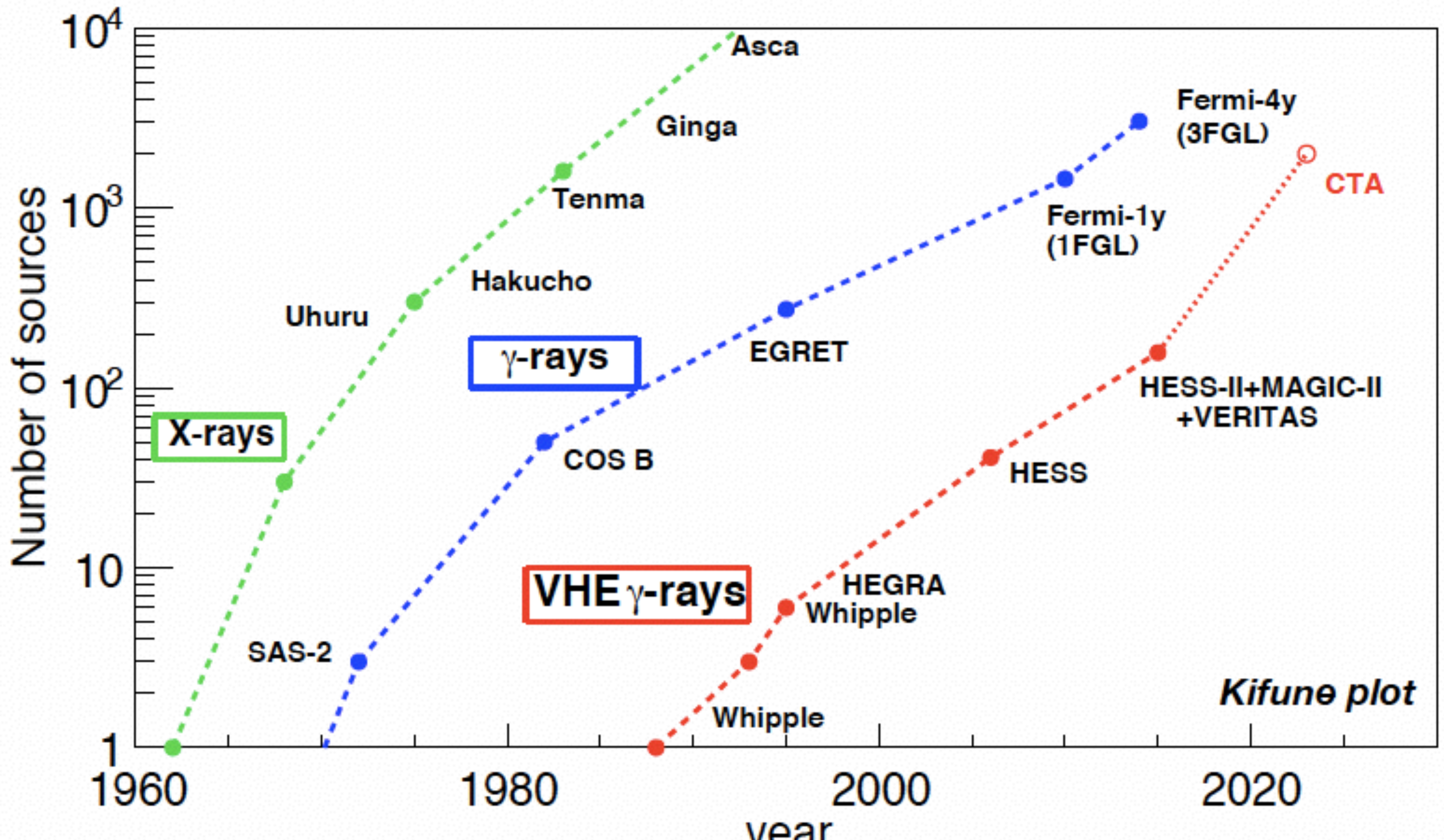
1999: 07 sources
2004: 14 sources
2009: 95 sources

VHE gamma-ray sky



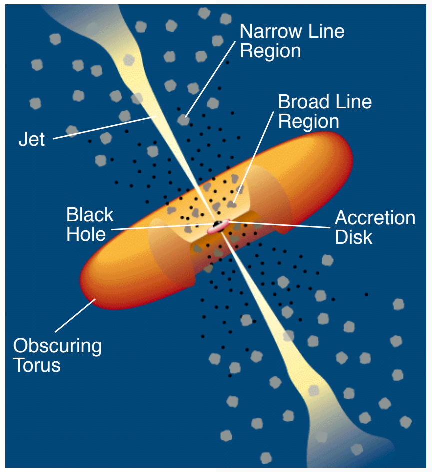
1999: 07 sources
2004: 14 sources
2009: 95 sources
Today: 224 sources

VHE gamma-ray sky

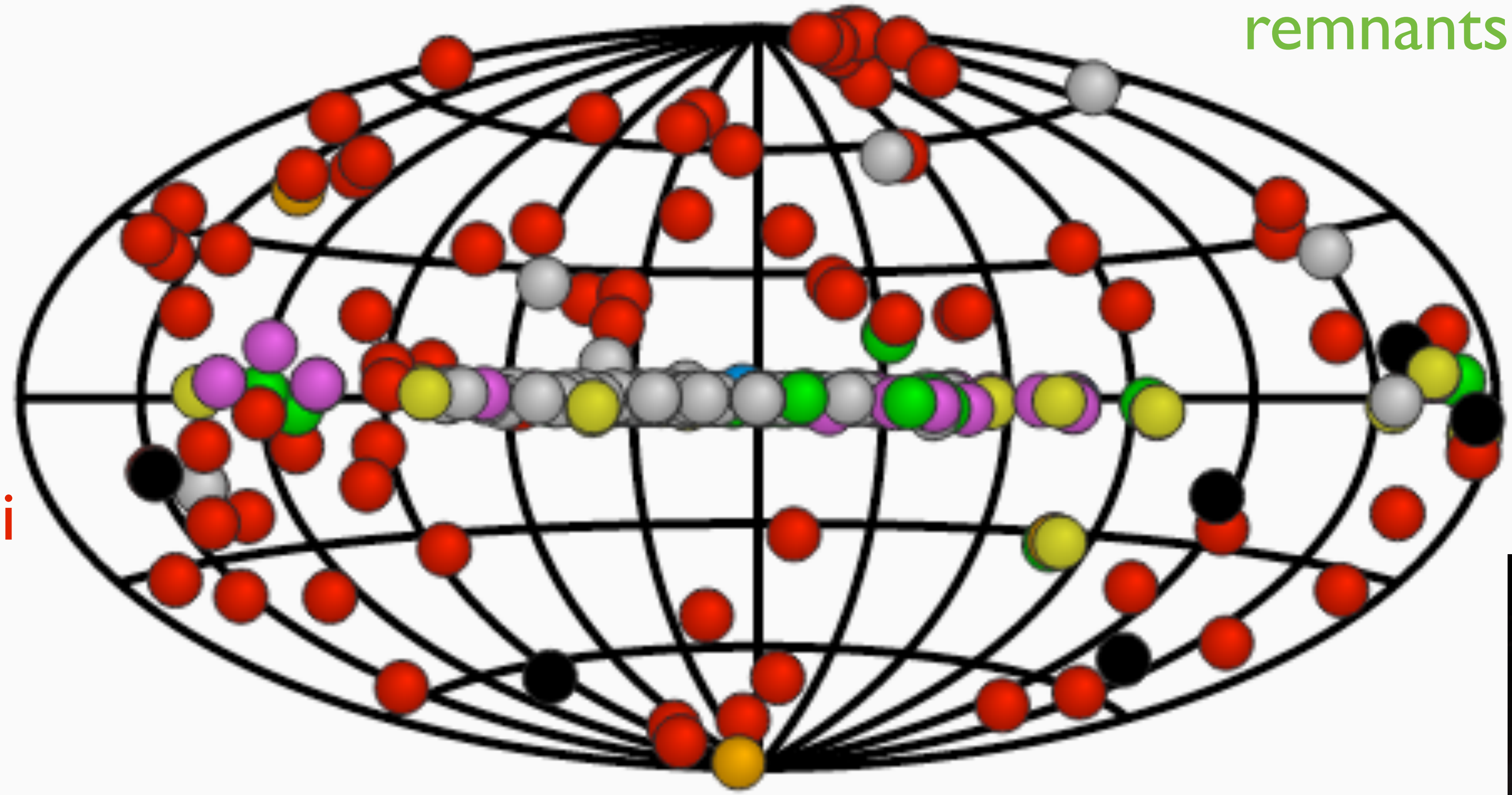


de Naurois & Mazin (2015)
arXiv/1511.00463

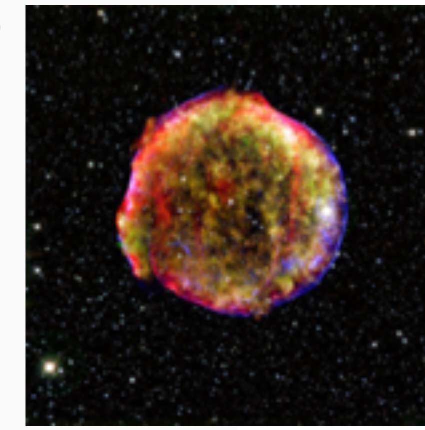
VHE gamma-ray sky



Active Galactic Nuclei

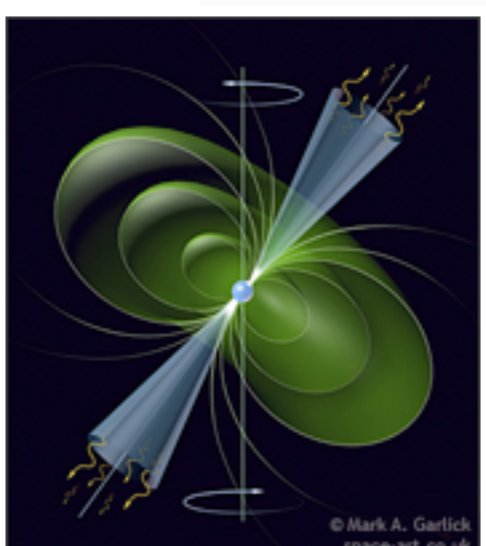


Supernova remnants



Starburst galaxies

Pulsar wind nebulae



X-ray binaries

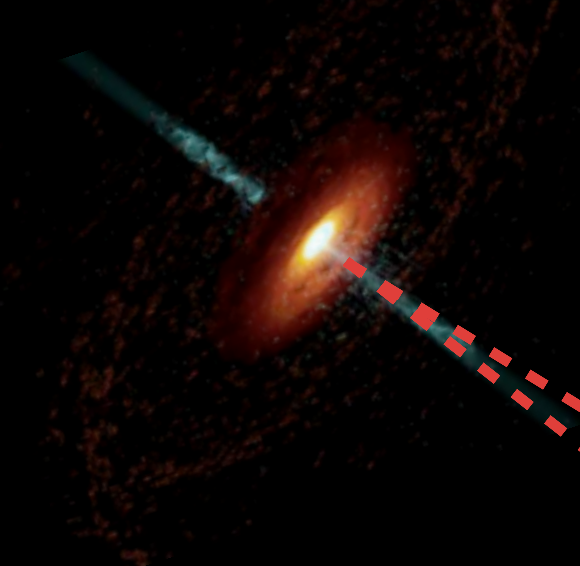
Gamma-ray burst

30

An Example of IACT science

that ties with the LAT measured isotropic background
and source populations…

- Probing the intergalactic medium with TeV blazars.



Aharonian, Coppi & Voelk
1994, ApJL, 423, 5

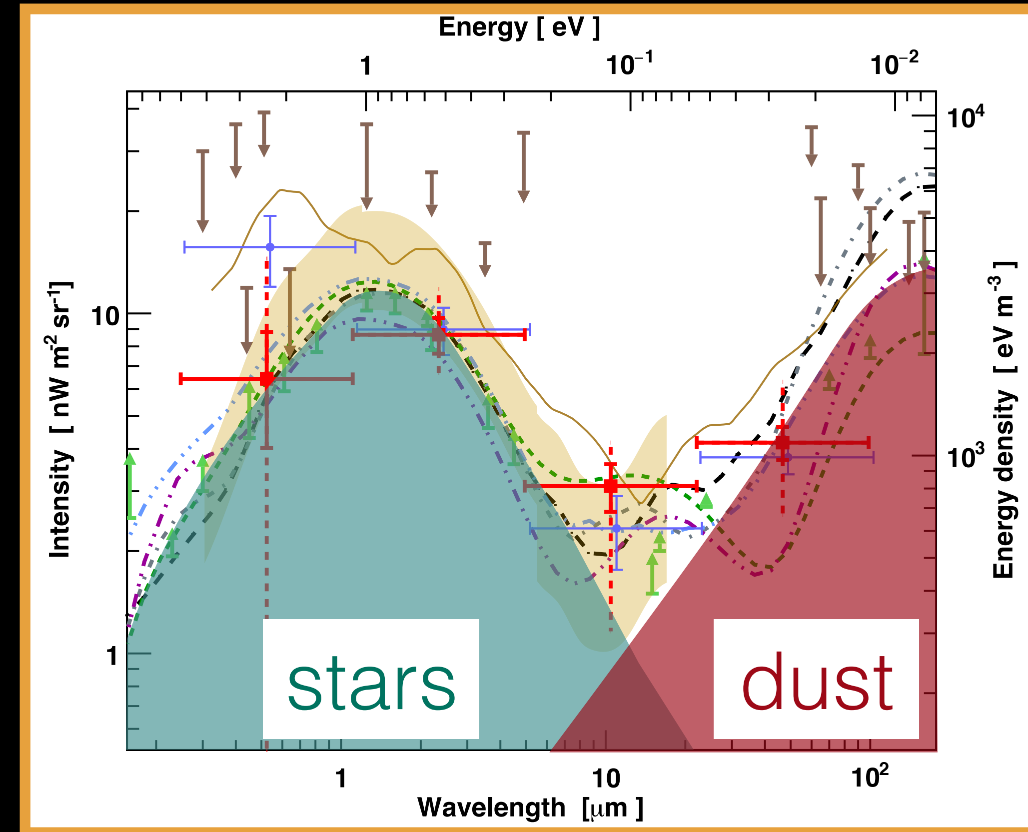
γ_{eV}

γ_{TeV}

$E = mc^2$

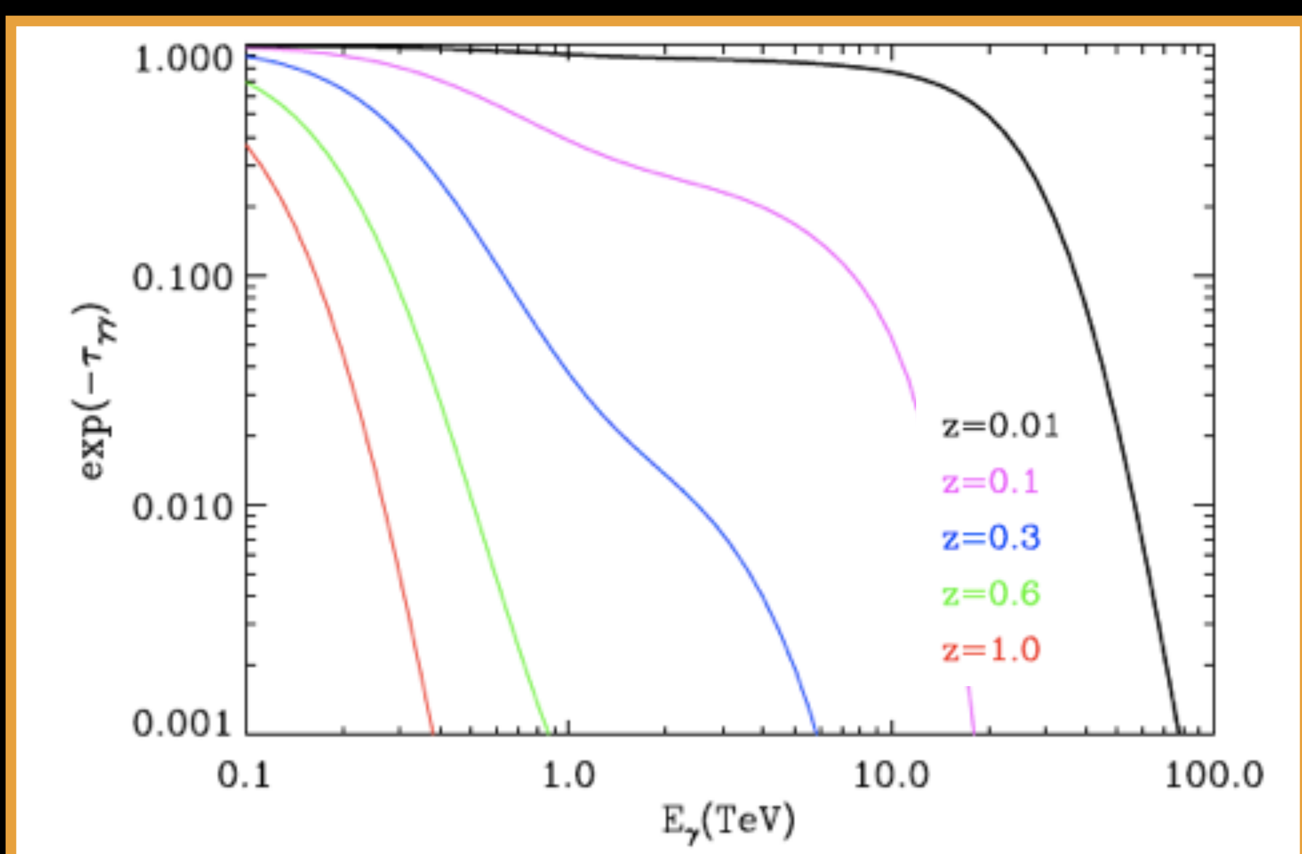
e^+

e^-



HESS Collaboration (2015)

Dwek & Krennrich (2013)

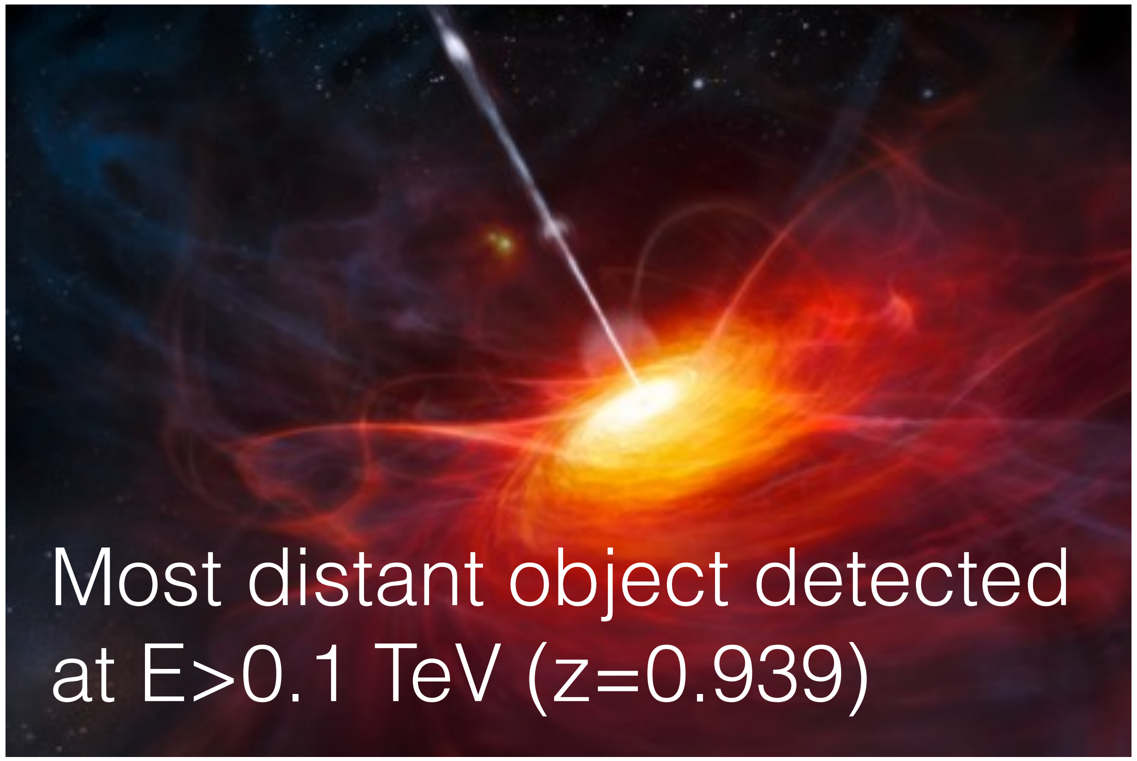


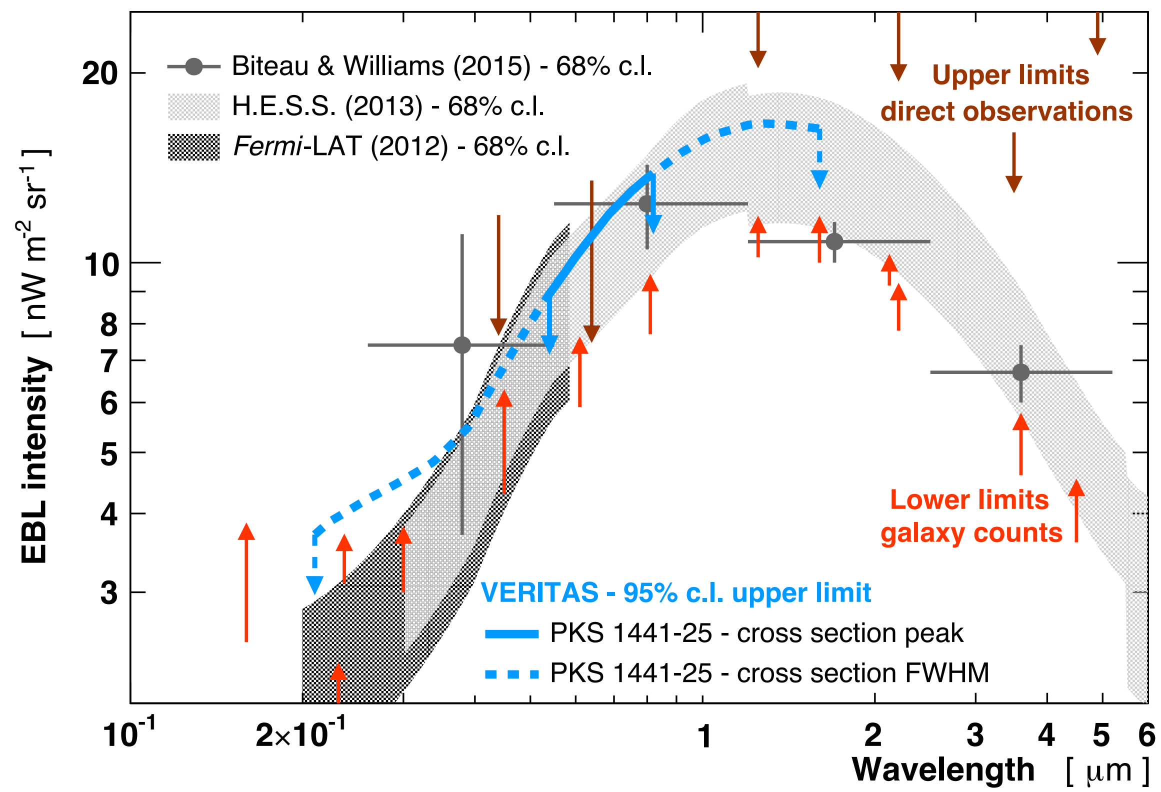
$$\gamma_{\mathrm{TeV}}\,\gamma_{\mathrm{eV}} \longrightarrow e^+\,e^-$$

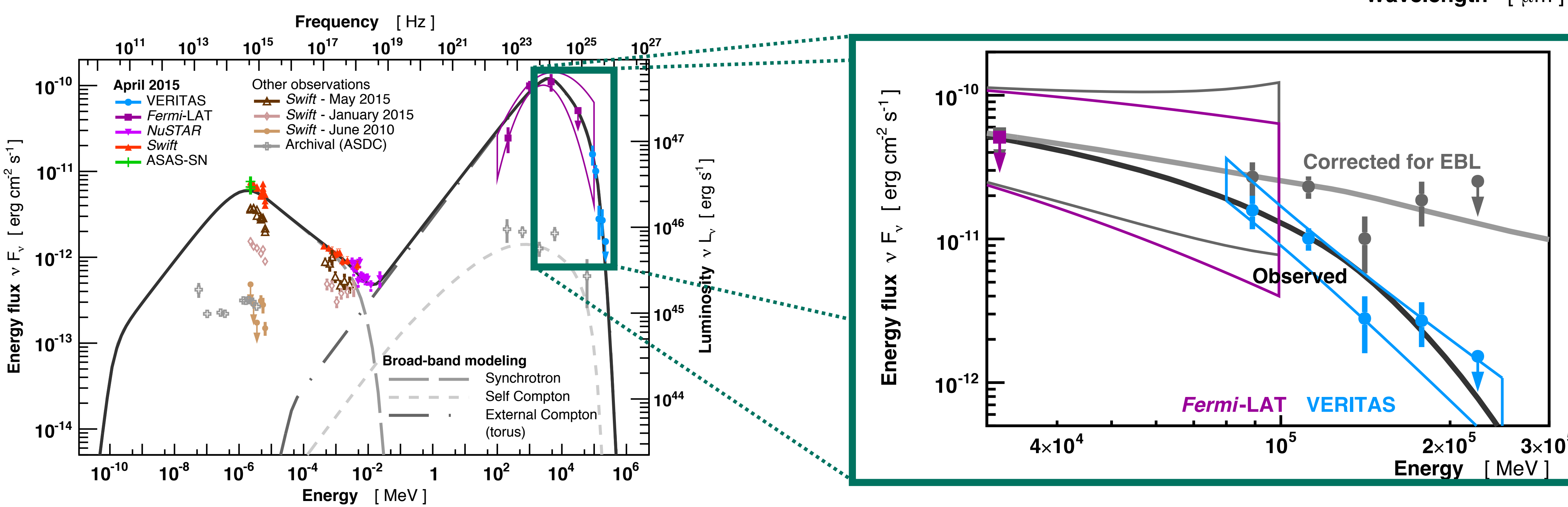
opacity to TeV
gamma rays

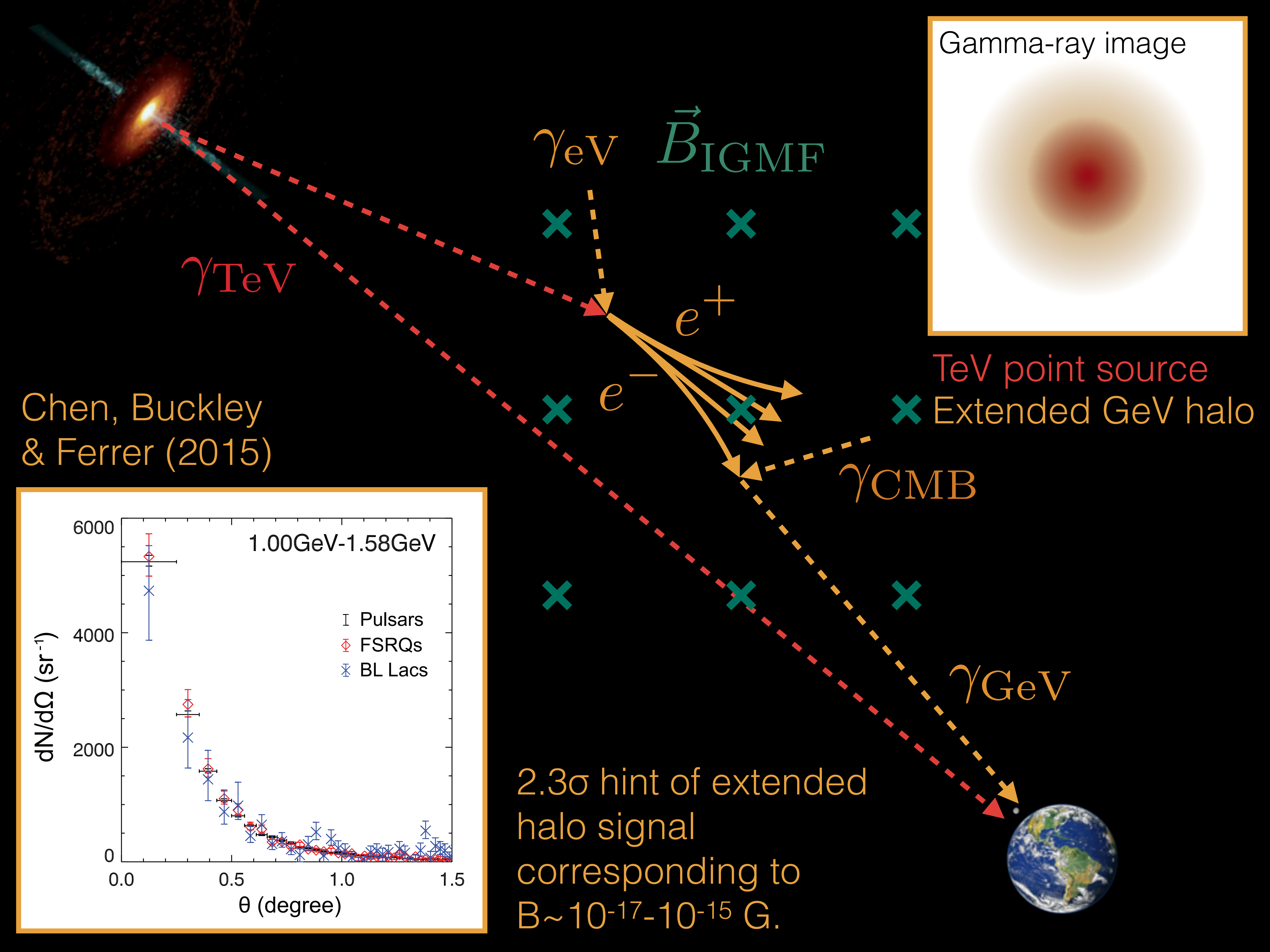
VERITAS detection of PKS 1441+25

VERITAS Collab. (incl. ME), ApJ Lett. (2015)





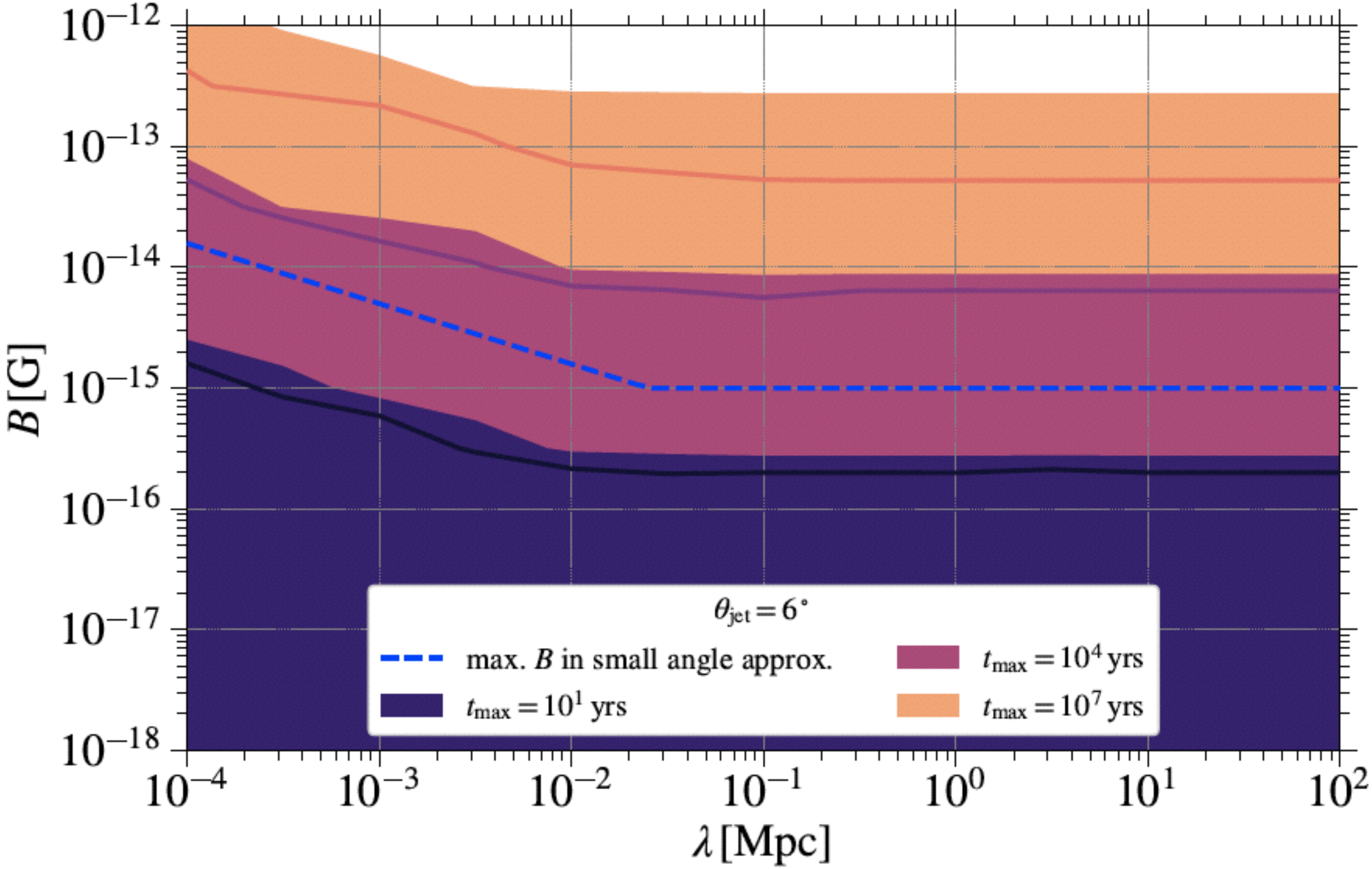


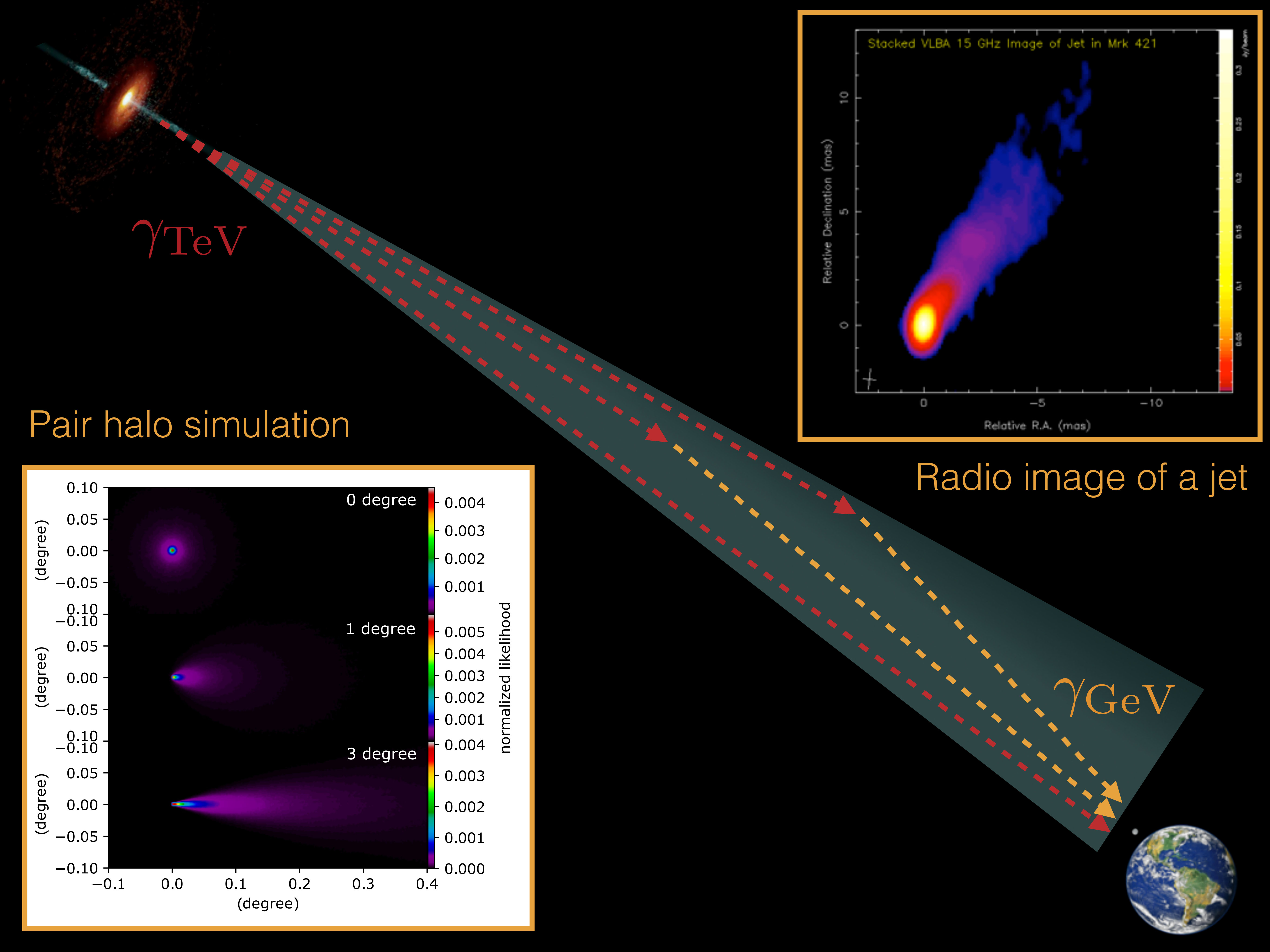


Gamma-ray image
γ_{eV}
$\vec{B}_{\mathrm{IGMF}}$
γ_{TeV}
e^+
e^-
TeV point source
Extended GeV halo
γ_{CMB}
Chen, Buckley & Ferrer (2015)
γ_{GeV}
1.00GeV-1.58GeV
Pulsars
FSRQs
BL Lacs
6000
4000
2000
0
0.0
0.5
1.0
1.5
dN/dΩ (sr^{-1})
θ (degree)
2.3σ hint of extended halo signal corresponding to $B \sim 10^{-17}$-10^{-15} G.

Halo searches

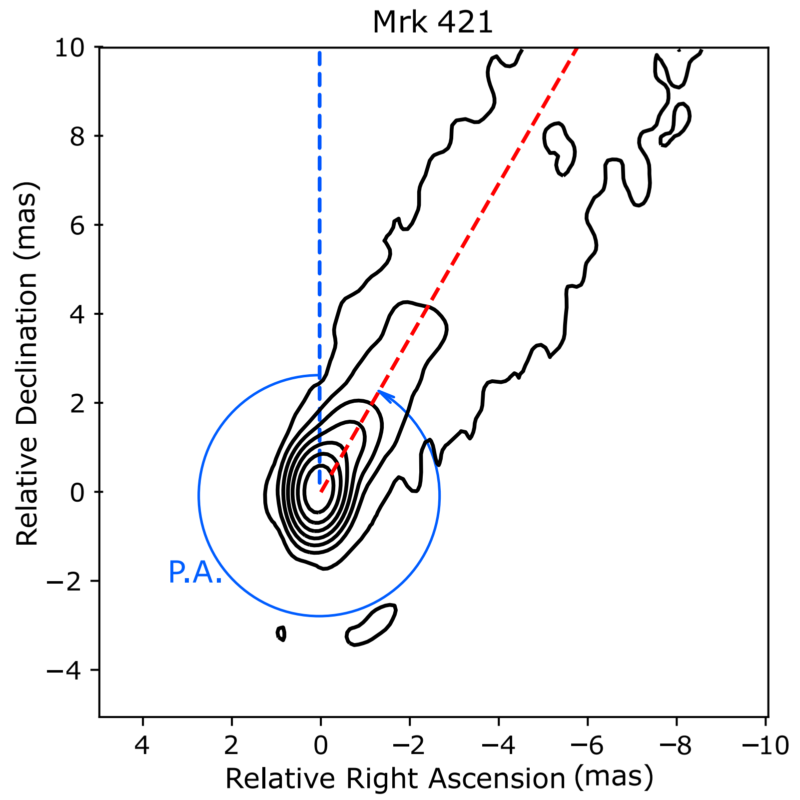
Ackermann et al. 2018, ApJS, 237, 32

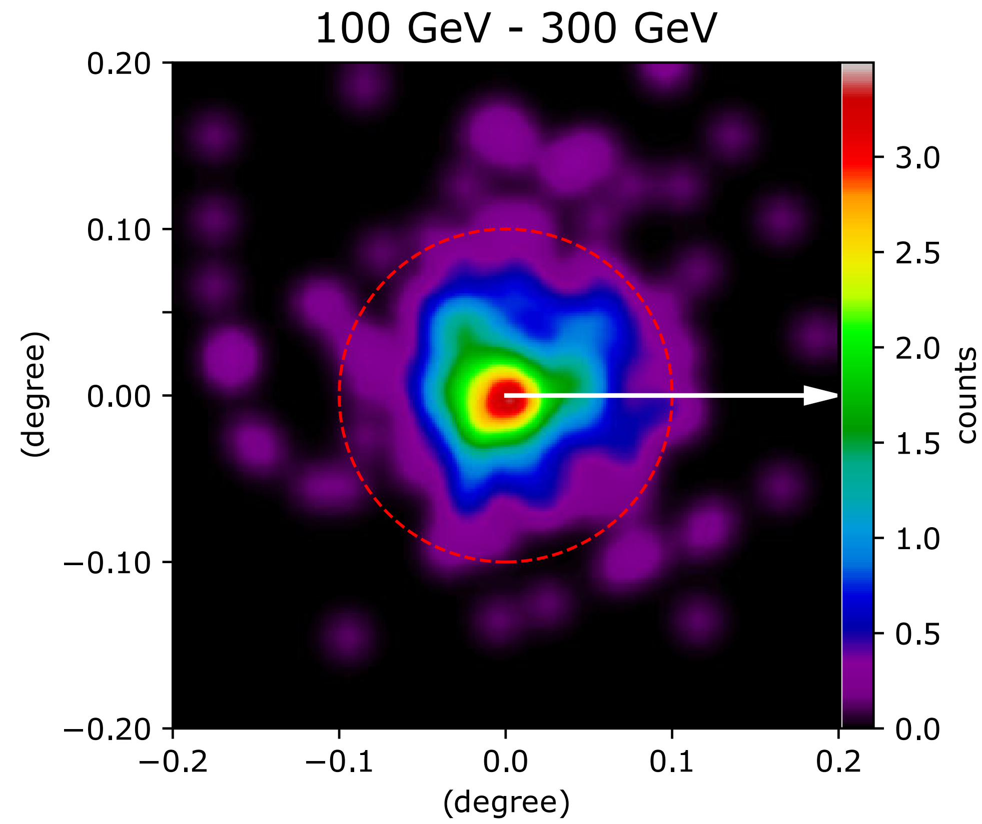




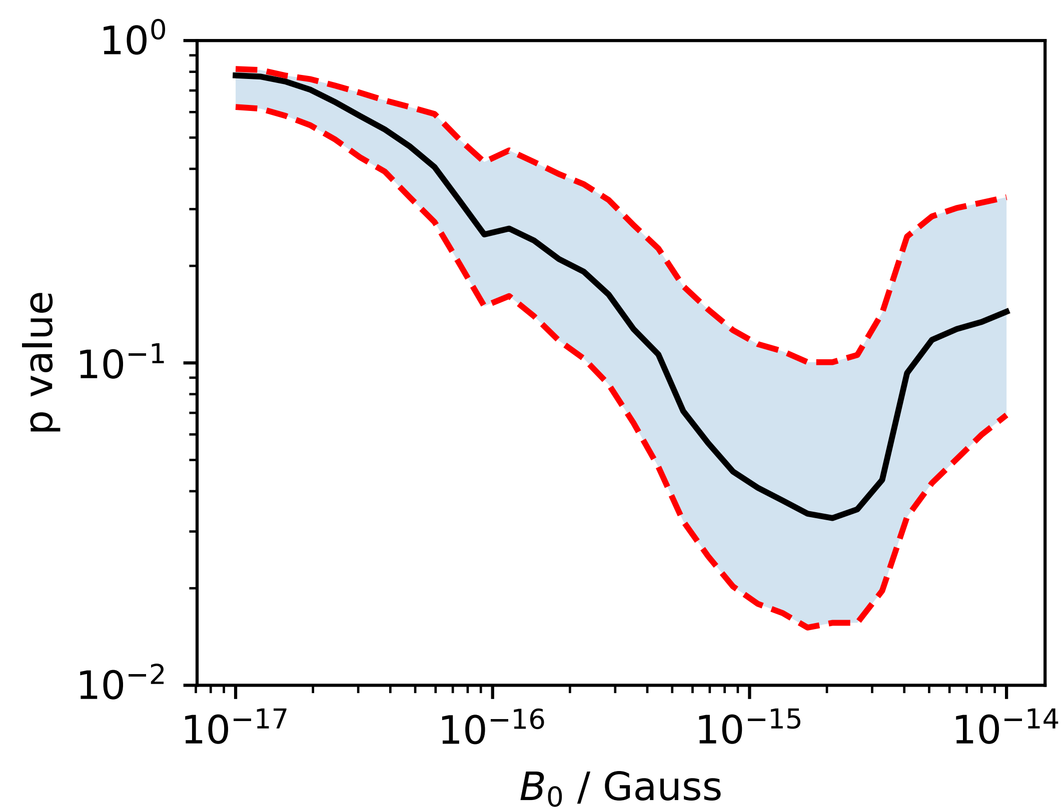
γTeV
Stacked VLBA 15 GHz Image of Jet in Mrk 421
Relative Declination (mas)
Relative R.A. (mas)
Radio image of a jet
Pair halo simulation
0 degree
1 degree
3 degree
(degree)
normalized likelihood
γGeV

Novel Search for TeV-Initiated Pair Cascades in the Intergalactic Medium



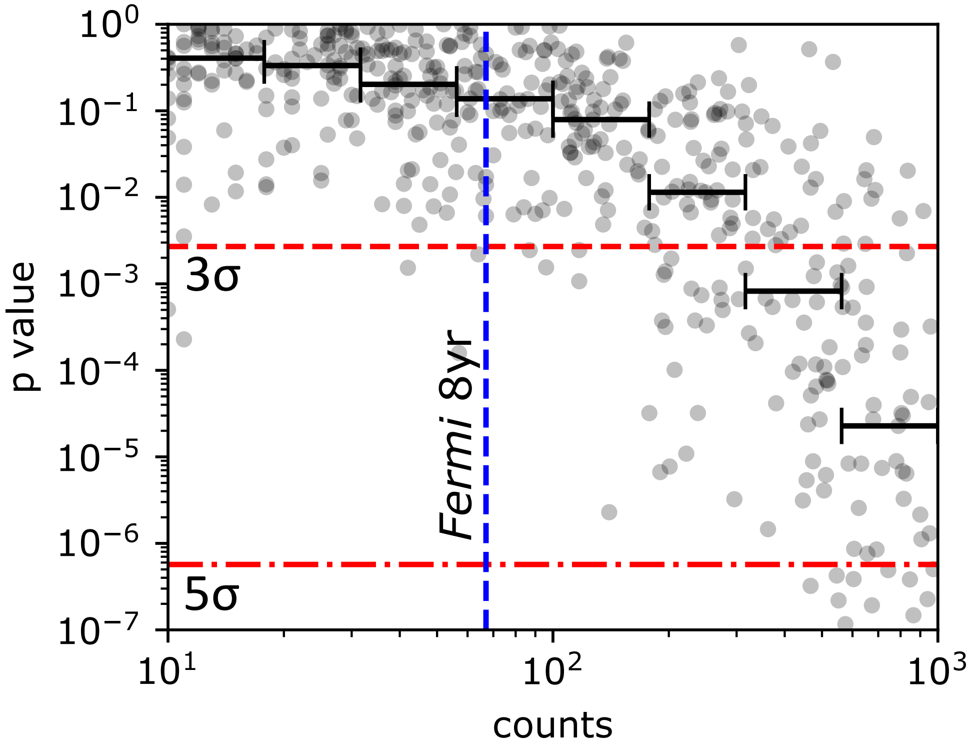


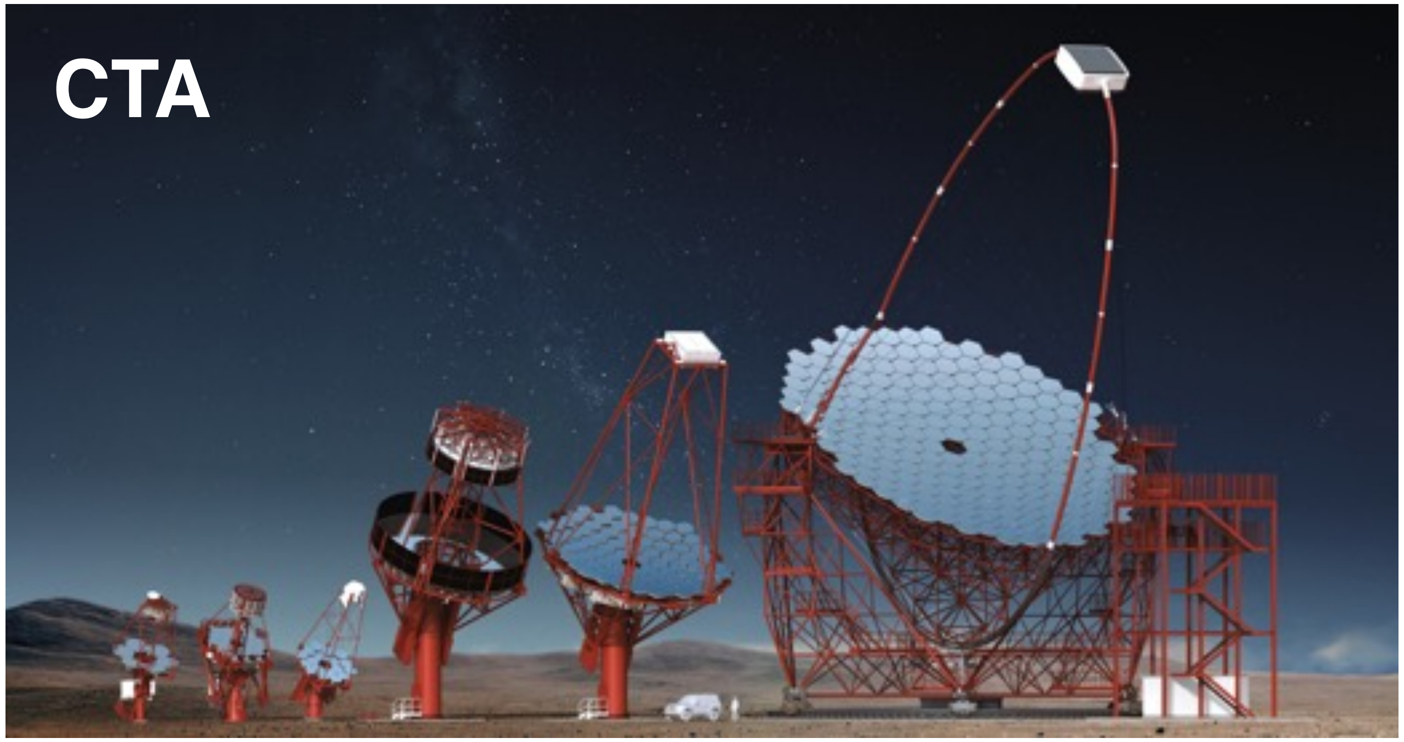
- Selected 12 TeV-emitting BL Lacs with measured radio morphology.
- Collected GeV data (Fermi-LAT), rotated and stacked the 12 maps.
- Likelihood ratio test using pair halo simulations.
- 2.0σ hint of extended halo signal corresponding to B~10^{-15} G.

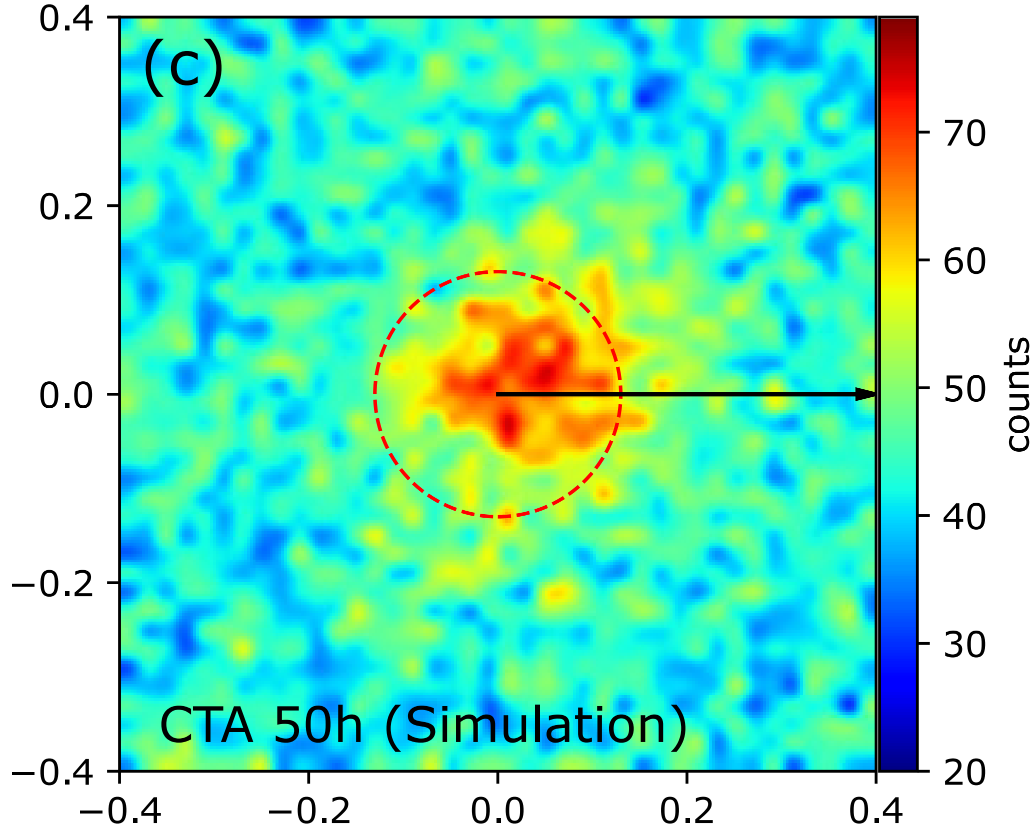


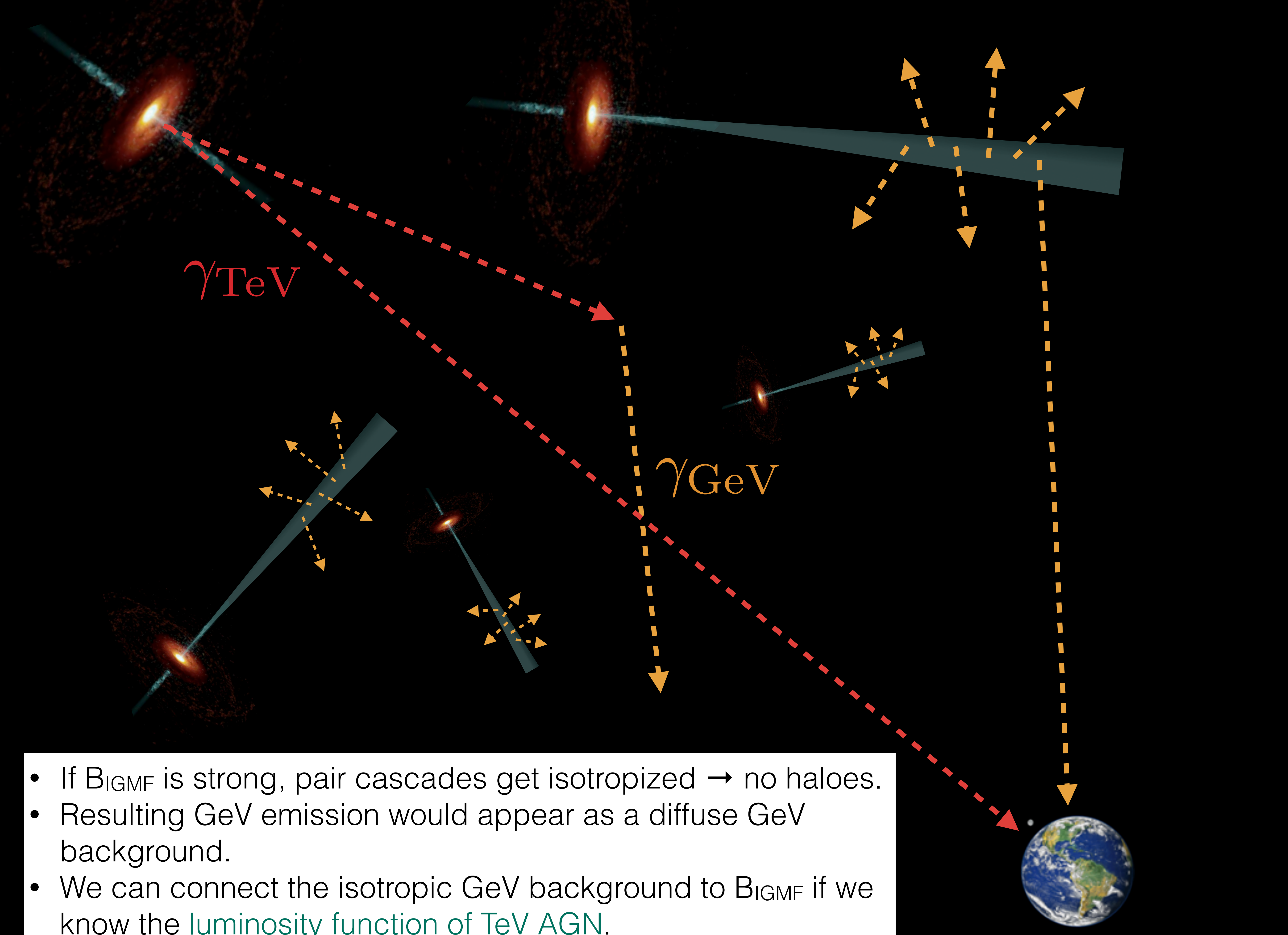
Novel Search for TeV-Initiated Pair Cascades in the Intergalactic Medium

- If the hint of signal is real, what would it take to confirm it?
  - About ×3 more Fermi-LAT data OR
  - About ×3 more suitable sources (TeV emitters with well-measured radio morphology) OR
  - A telescope with better angular resolution (CTA).





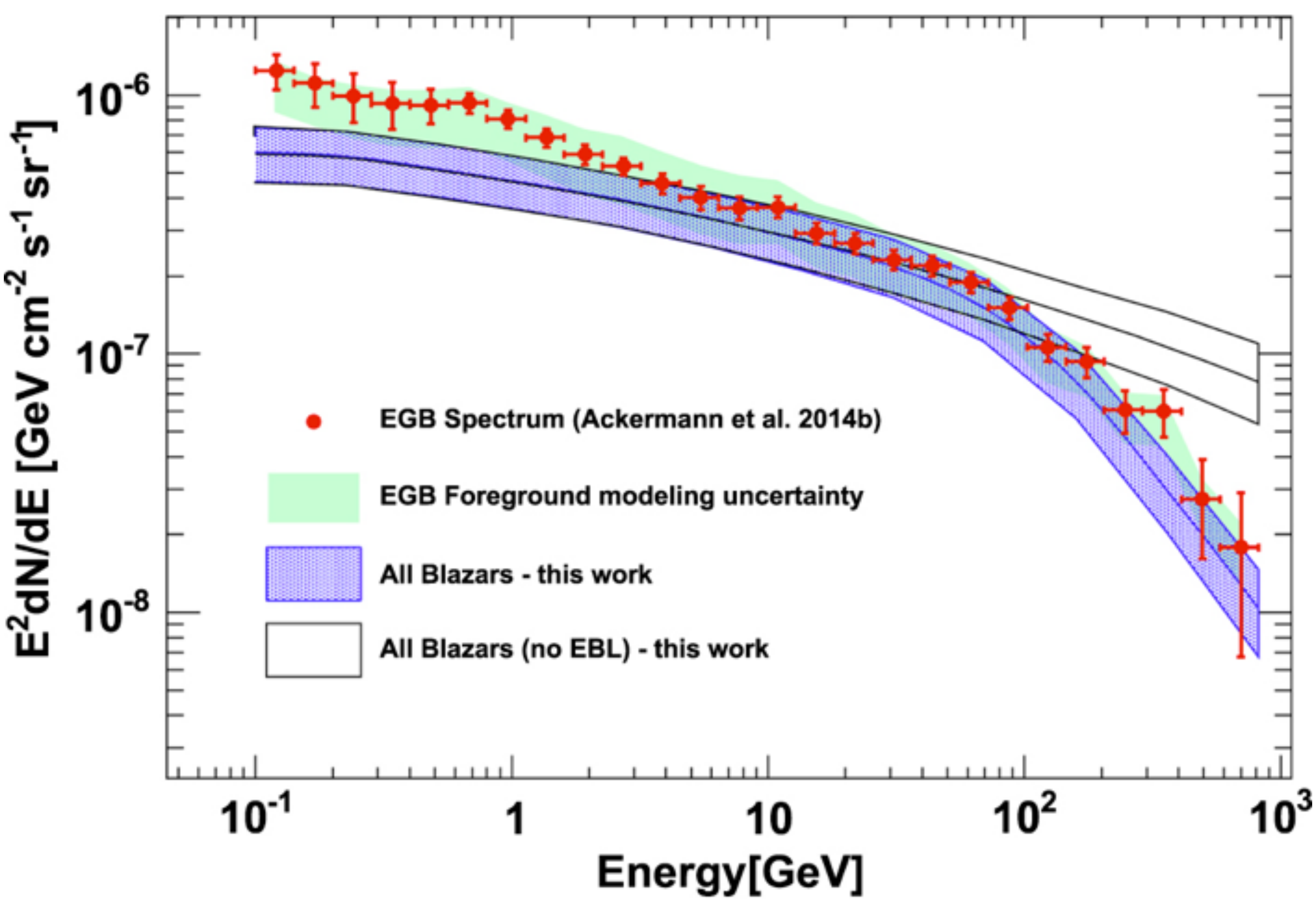




- If B_{IGMF} is strong, pair cascades get isotropized → no haloes.
- Resulting GeV emission would appear as a diffuse GeV background.
- We can connect the isotropic GeV background to B_{IGMF} if we know the luminosity function of TeV AGN.

GeV background, measured by LAT

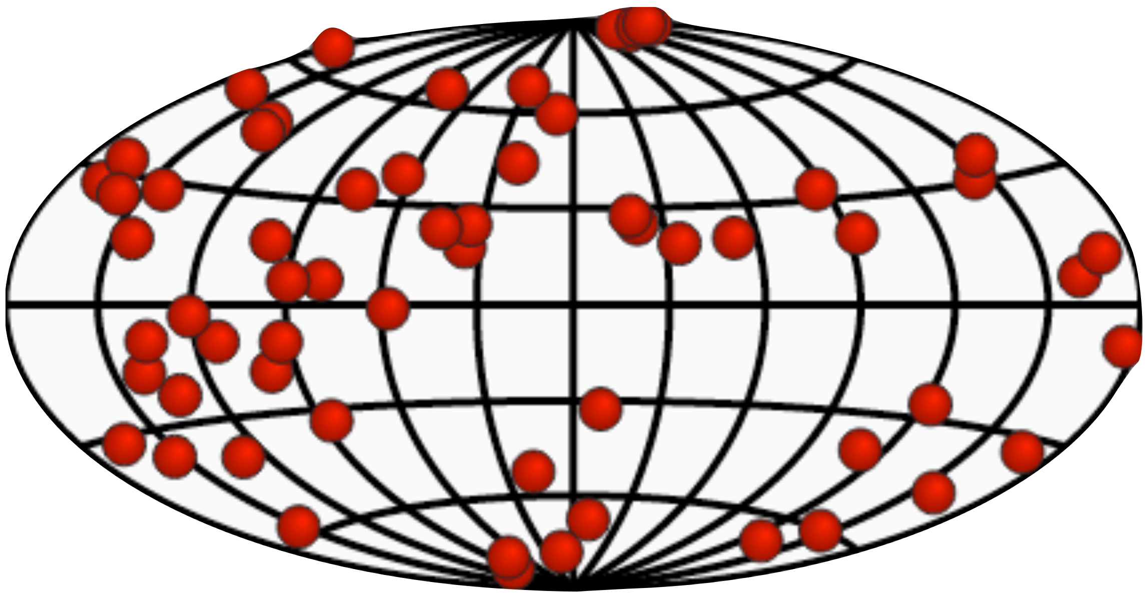
```
mymodel.makeModel('gll_iem_v07.fits', 'gll_iem_v07',
'iso_P8R3_SOURCE_V2_v1.txt', 'iso_P8R3_SOURCE_V2_v1')
```



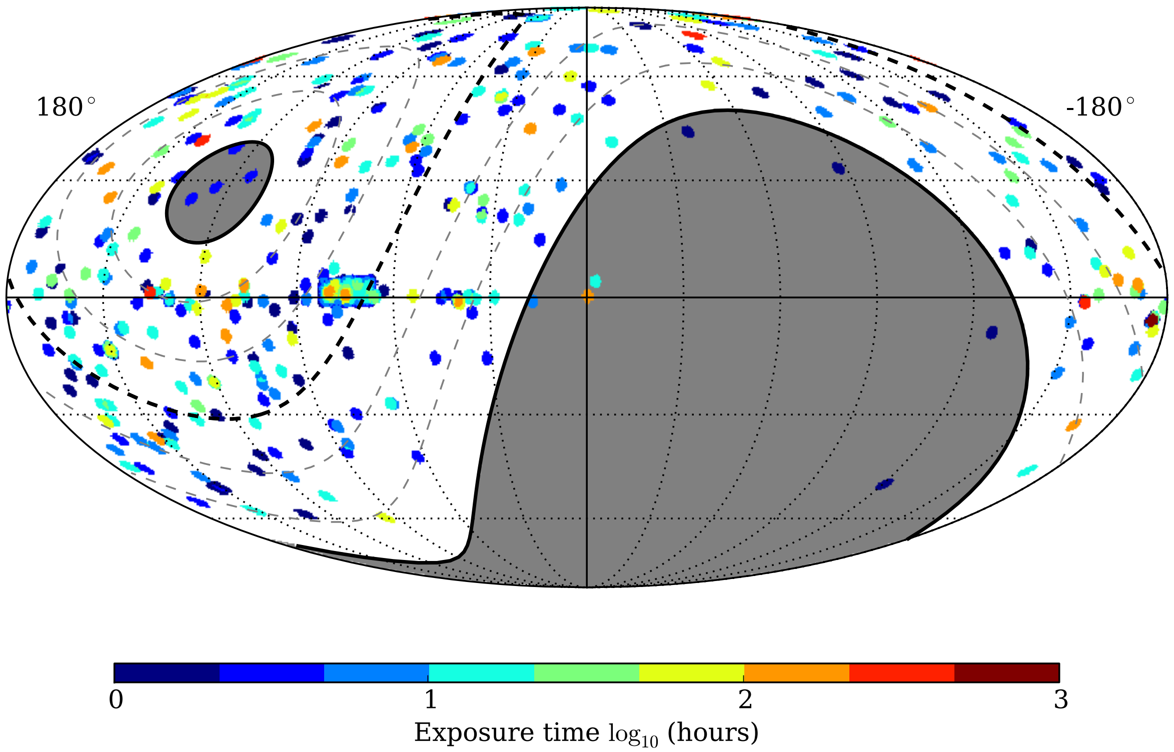
Ackermann et al. 2015, ApJ, 799, 86

Population of TeV BL Lacs

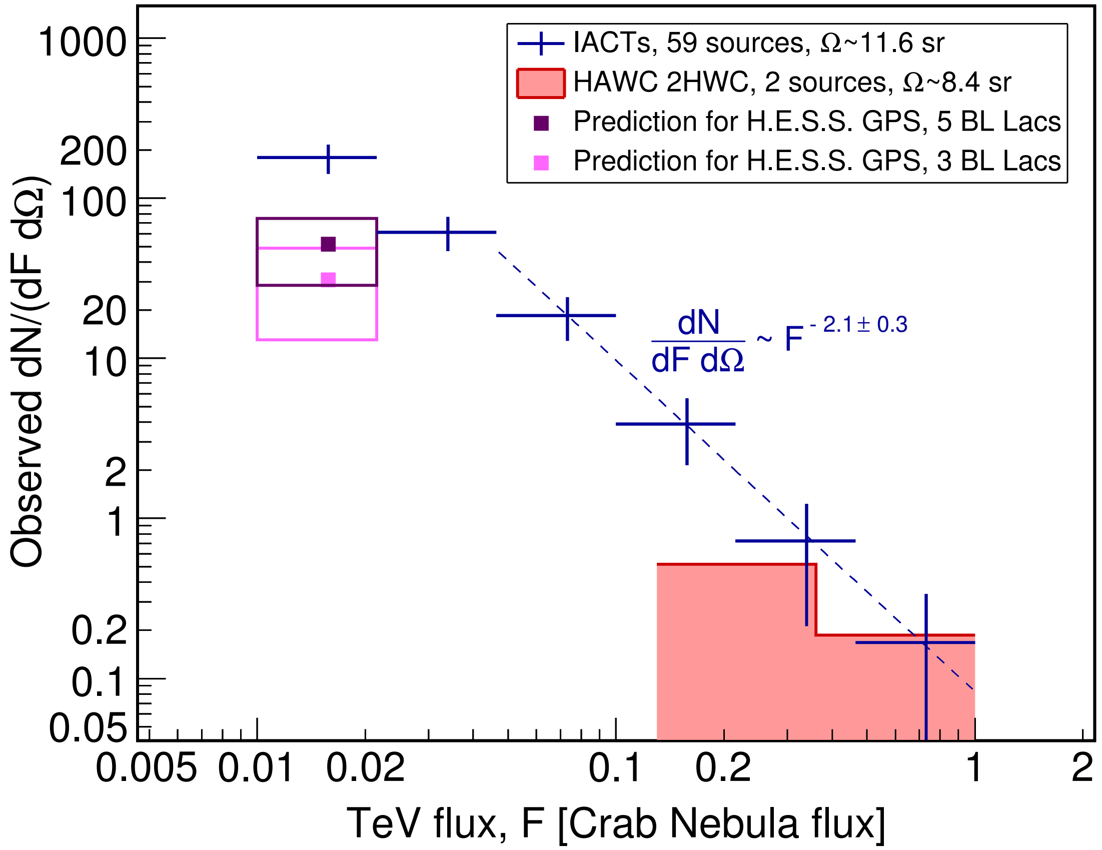
TeV AGN



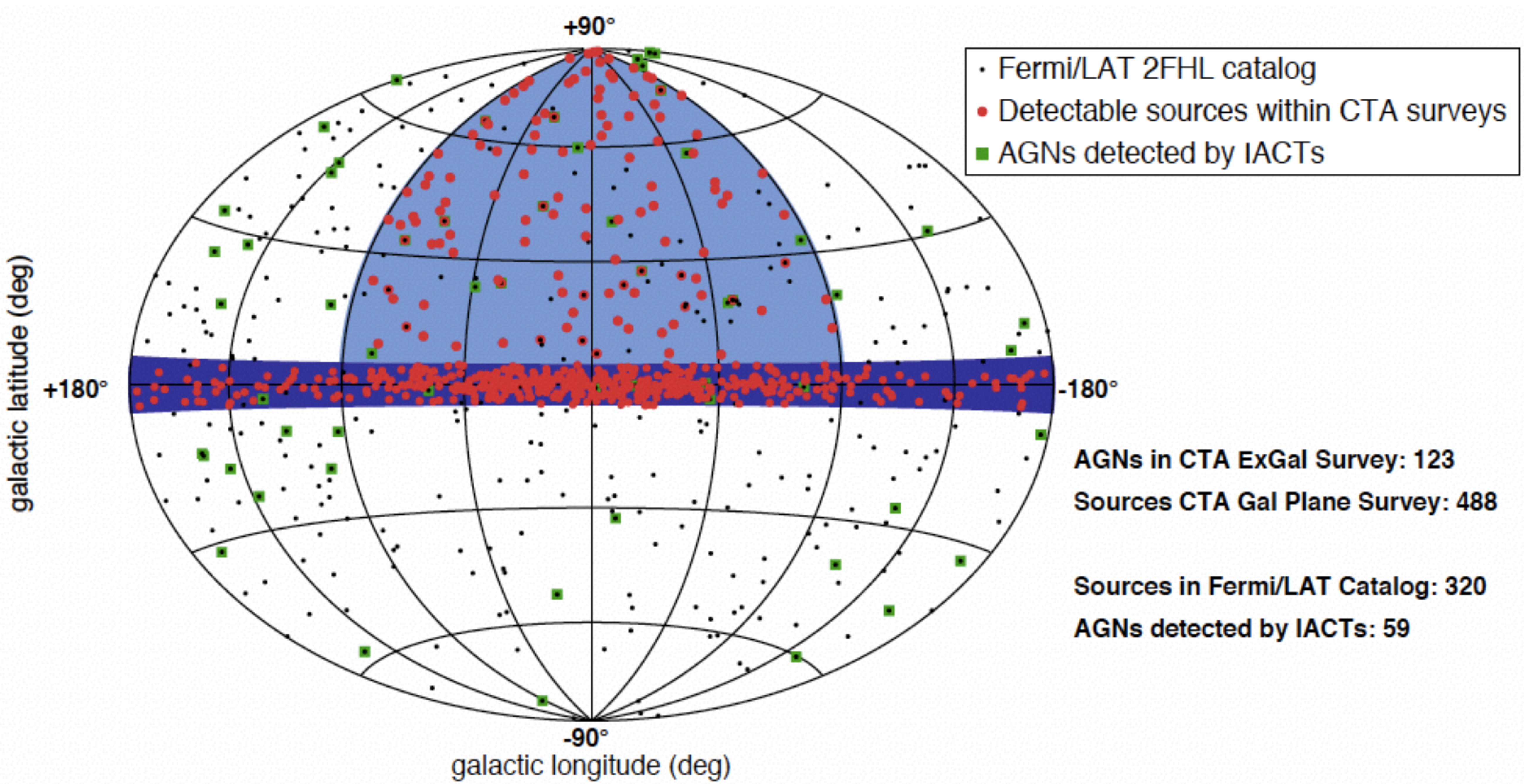
VERITAS exposure



- The luminosity function measures how many TeV BL Lacs are there per unit volume, and how bright they are.
- There are 62 TeV-detected BL Lacs, 45 in the northern hemisphere.
- Sky coverage is very inhomogeneous. The sample could be heavily biased.



Future, CTA extragalactic survey



- Unbiased survey of 25% of the sky in ~1000h.