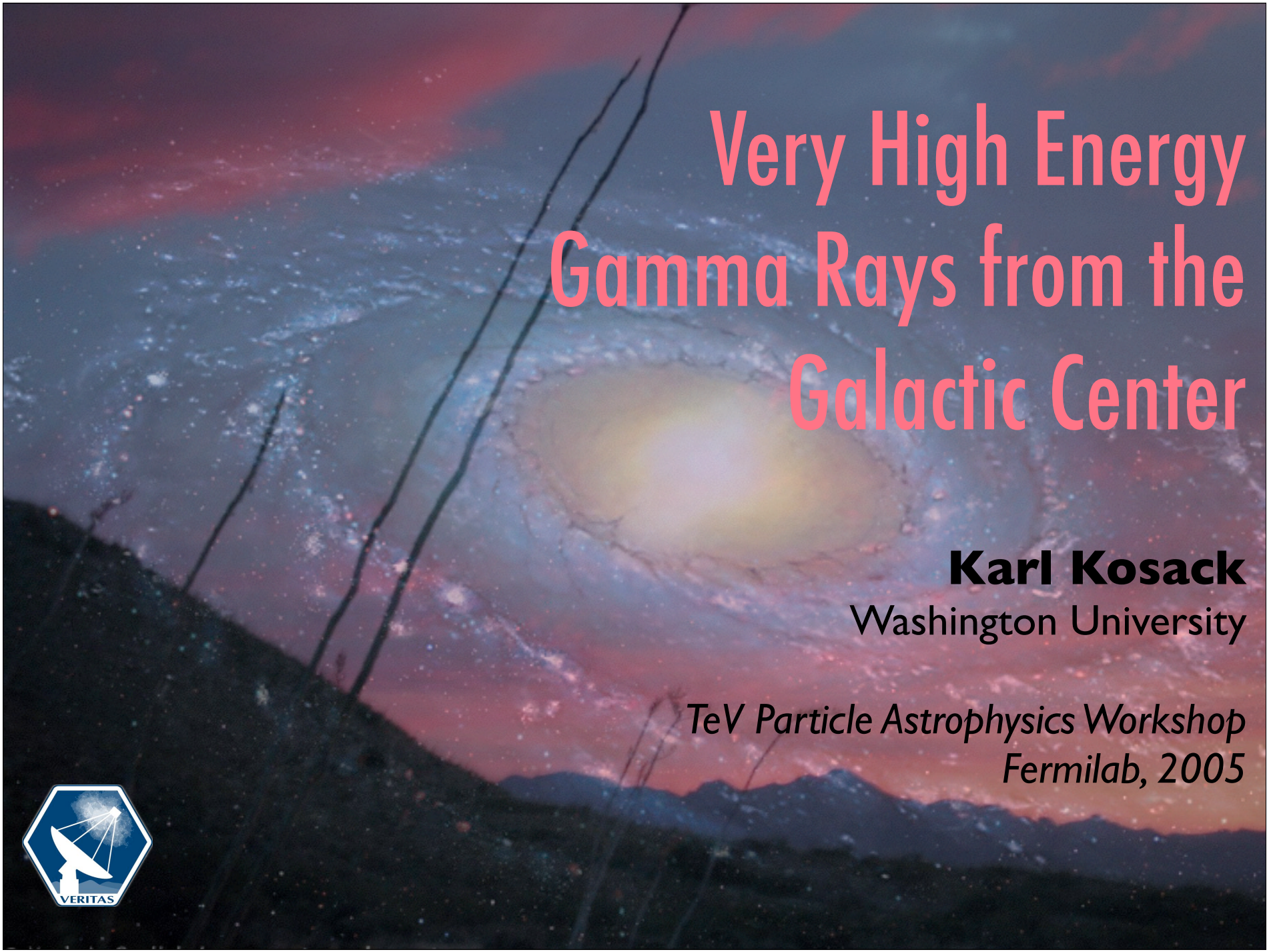


Very High Energy Gamma Rays from the Galactic Center

Karl Kosack
Washington University

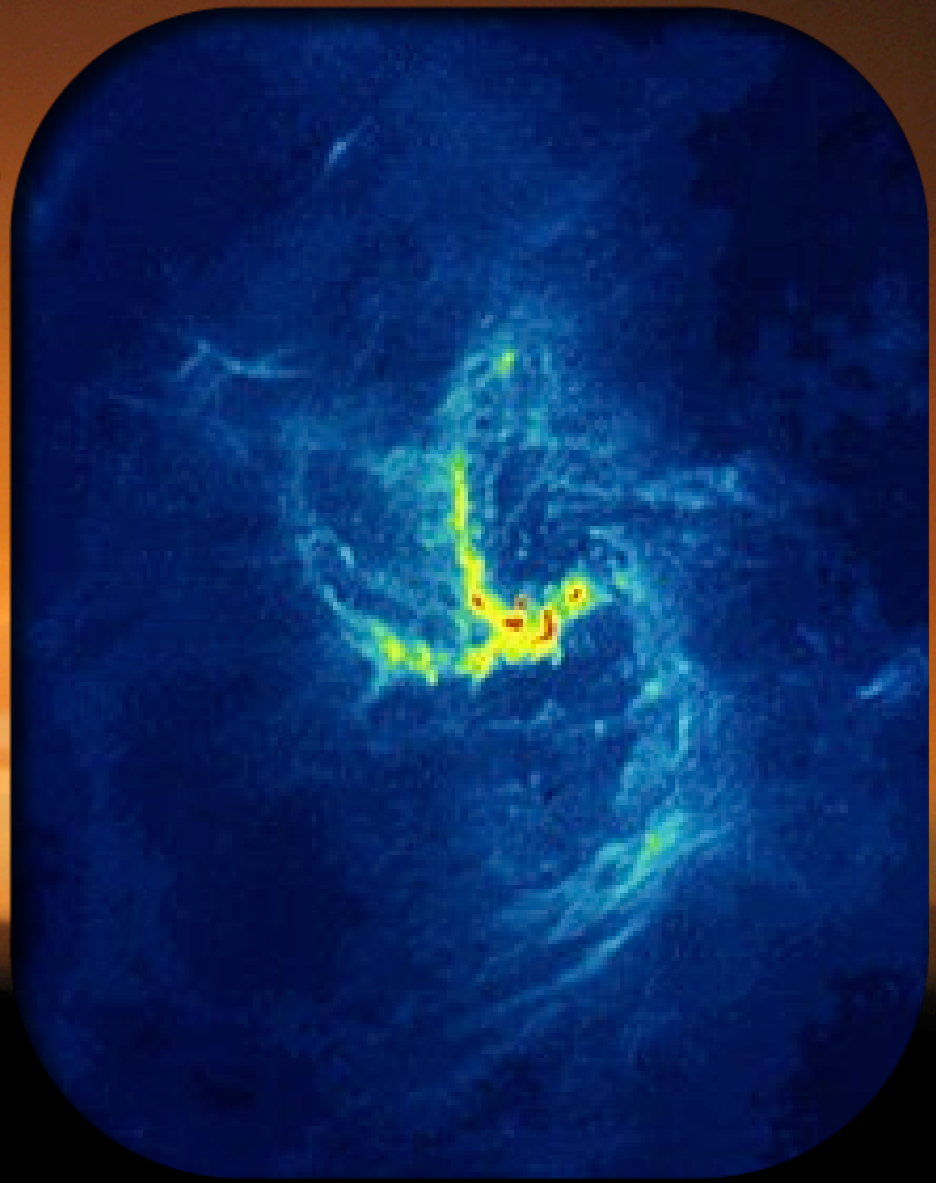
TeV Particle Astrophysics Workshop
Fermilab, 2005

Overview

- **The Galactic Center is the most likely place to look for gamma rays from Dark Matter.**
- **Multiple gamma-ray telescopes have independently seen TeV and GeV emission from the Galactic Center region**
  - GeV EGRET source, Whipple/HESS source, CANGAROO source
- **Origin of the emission is unknown:**
  - Dark Matter annihilation?
  - Astrophysical source?

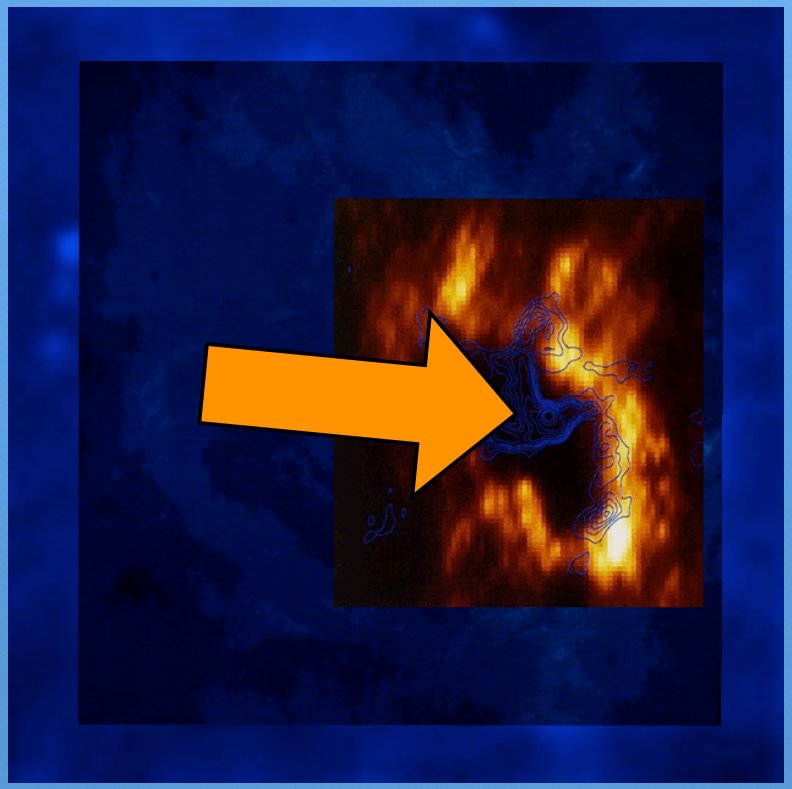
Outline

- The Galactic Center
- Instrument & Technique
- Analysis
- Results
- Emission Mechanisms
- Discussion



Galactic Center:

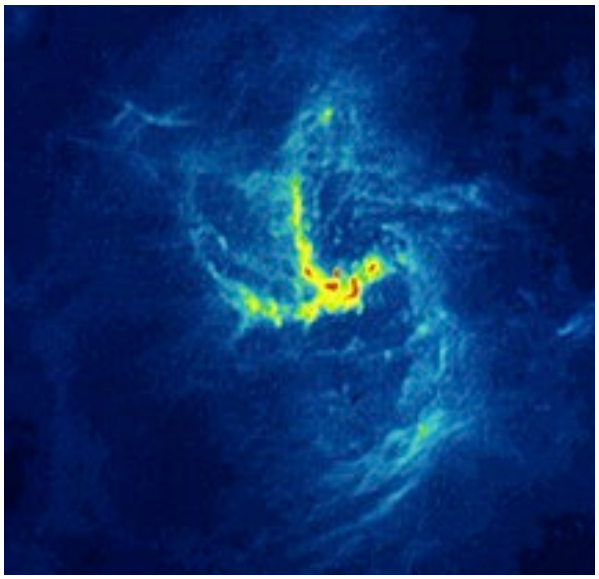
What's there?

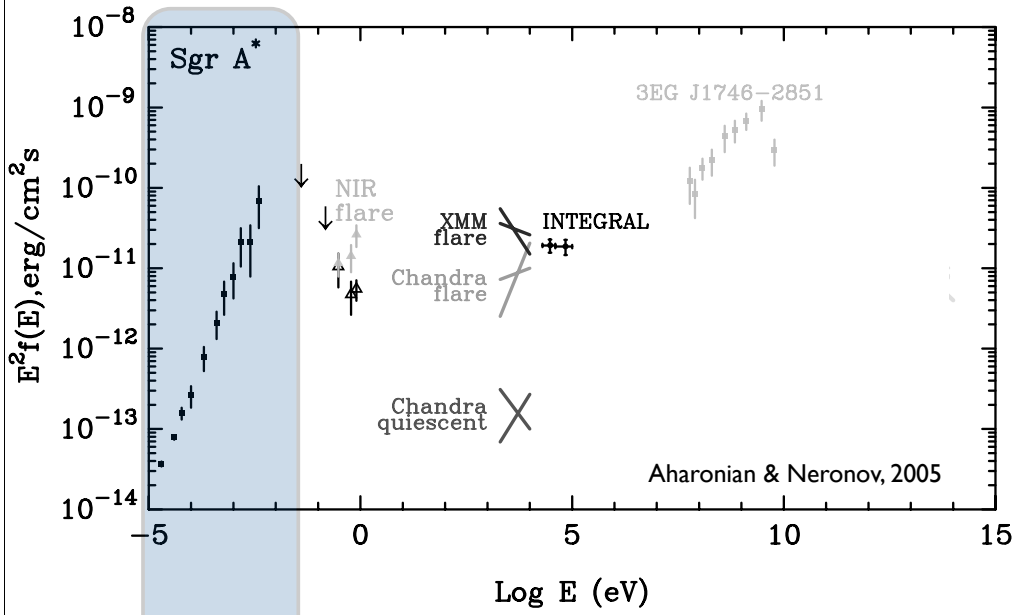


2 pc

- **Sagittarius A East**
  - Massive Supernova Remnant
- **Sagittarius A West**
  - Spiral-shaped Hot Gas Cloud
- **Sagittarius A***
  - Extremely bright radio-source
  - Supermassive Black Hole
- **Center of Galactic Dark Matter Halo**

Credits: Image visualized by Raymond Plante, NCSA/Univ. of Illinois

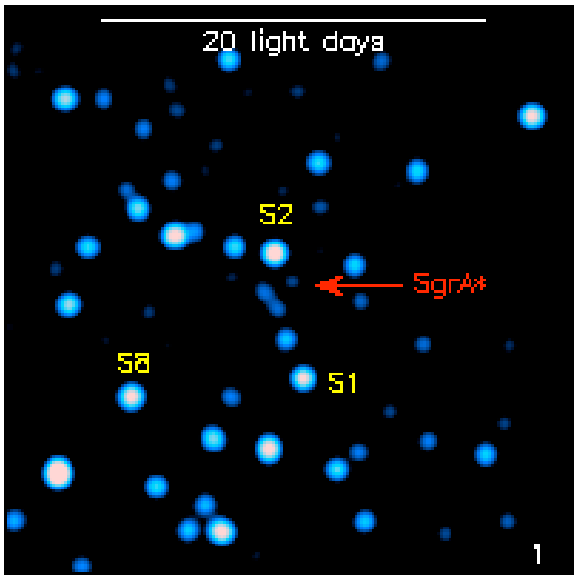


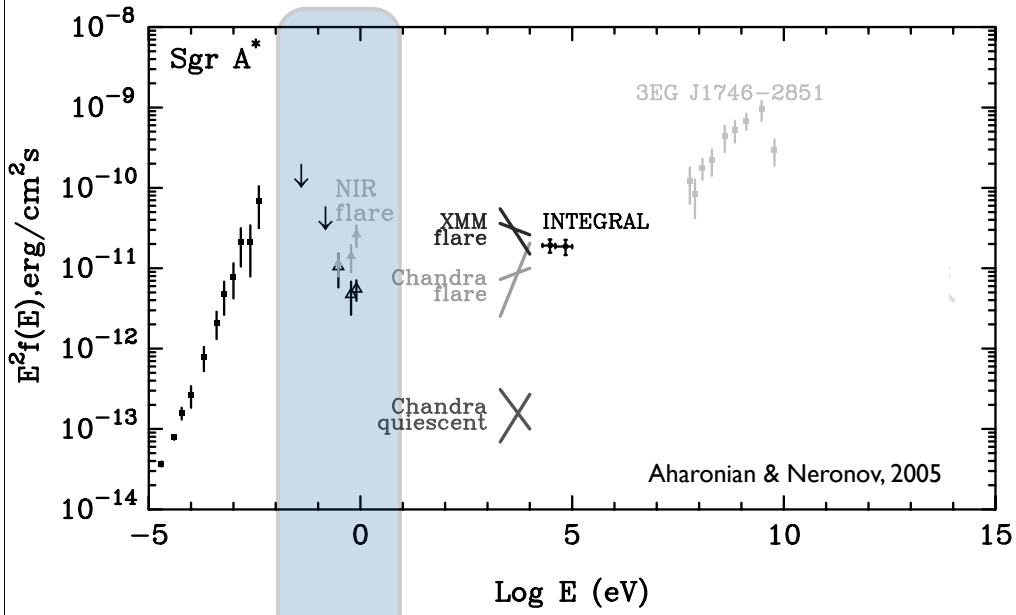


- **$L_{radio} \approx 10^{36}$ erg/s**
- **Spectrum**
  - $F(E) \approx E^{1/3}$
  - cutoff at 10^{12} Hz
  - sub-mm bump
- **Variability:**
  - ≈100 Days, 20% change in amplitude
  - $R < 20\ R_s$

Radio

Sgr A*

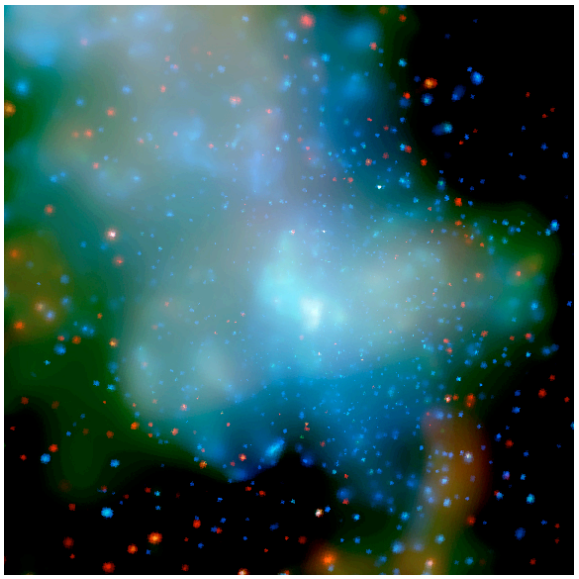


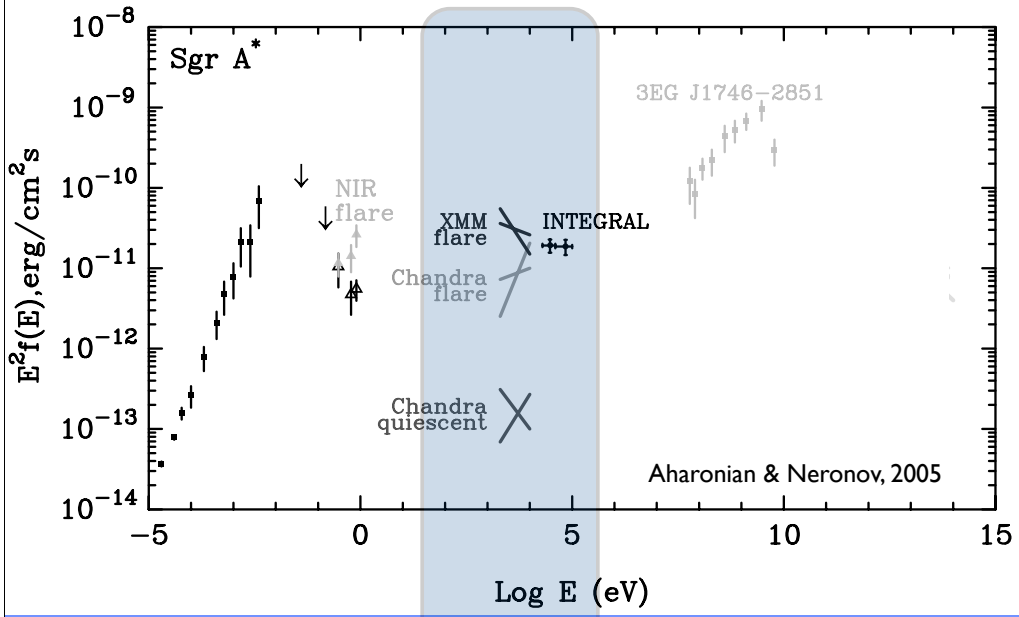


- **Quiescent Emission**
  - within 20 mas of Sgr A*
- **IR Flaring**
  - 30-50 min timescale
  - Structure on 17 minute scales
  - Implies: emission process within 3-4 Schwarzschild radii = 1/5 AU

Infrared

Sgr A*



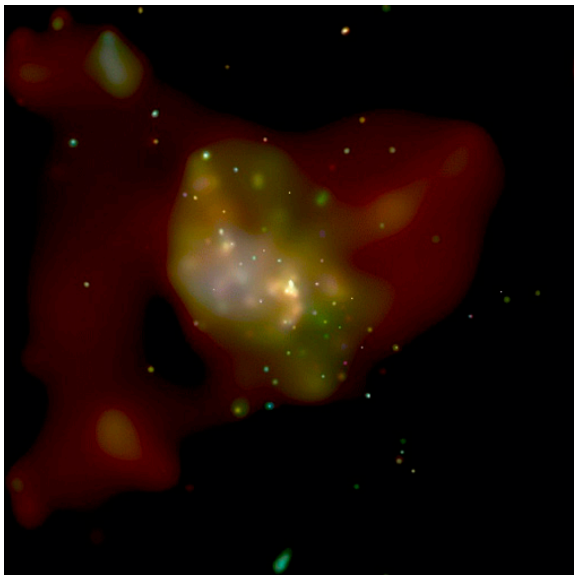


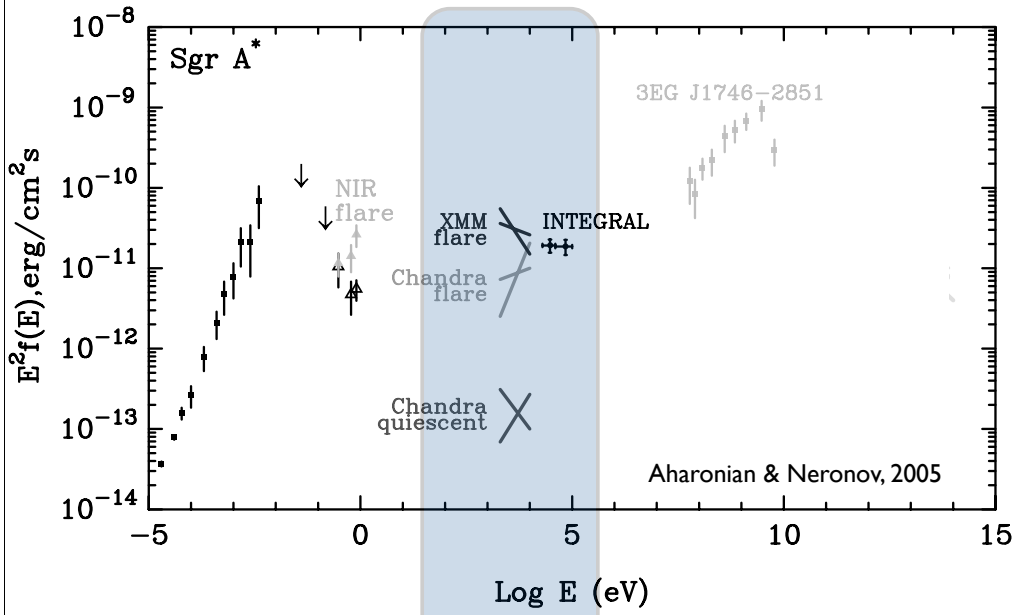
Quiescent Emission

- Point source within 0.2 arcsec of Sgr A*
- Extended emission out to 1.4 arcsec
- $L = 2.4 \times 10^{33}$ erg/s
- $F(E) \approx E^{-2.7}$

X-Ray

Sgr A*



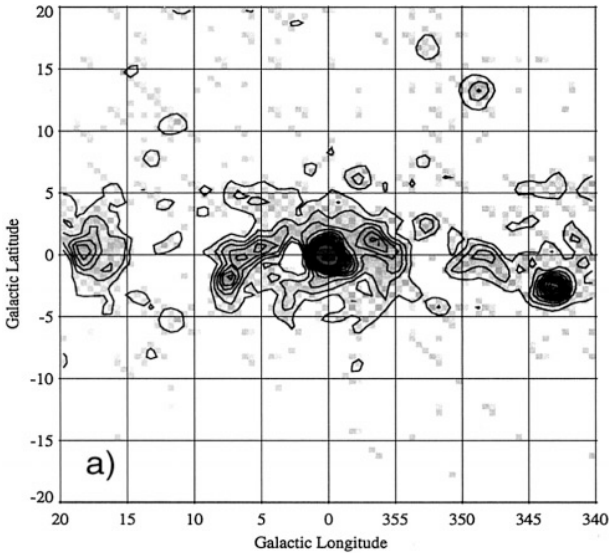


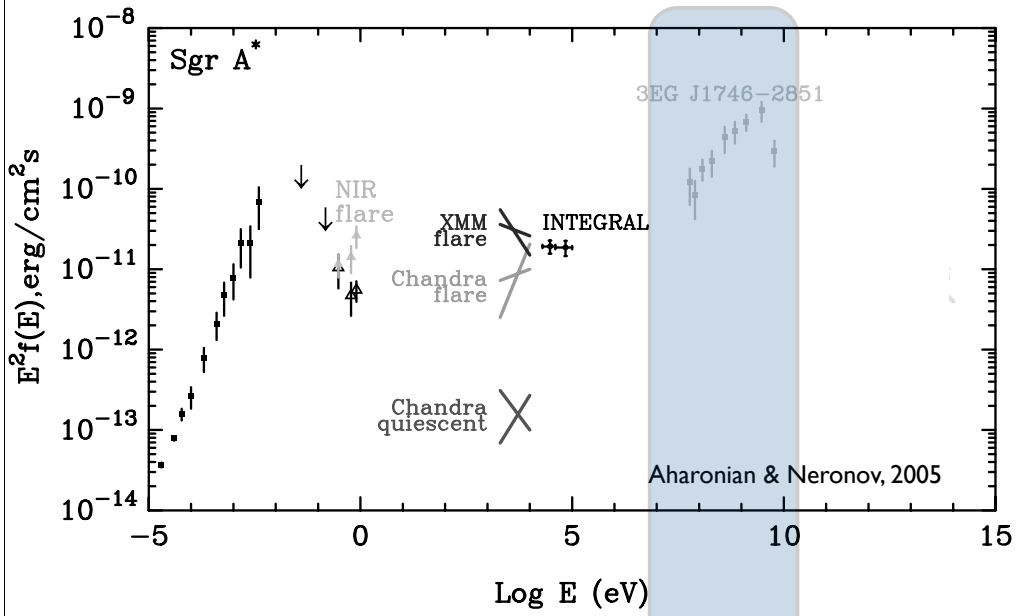
Flaring

- Chandra/XMM
  - 200 s flares, daily
  - 10 min doubling time
  - R < 20 Rs (≈ 1 AU)
- Integral:
  - 40m flare
  - central 10′

X-Ray

Sgr A*





- **Exceeds SgrA* luminosity in other wavebands by order of magnitude**

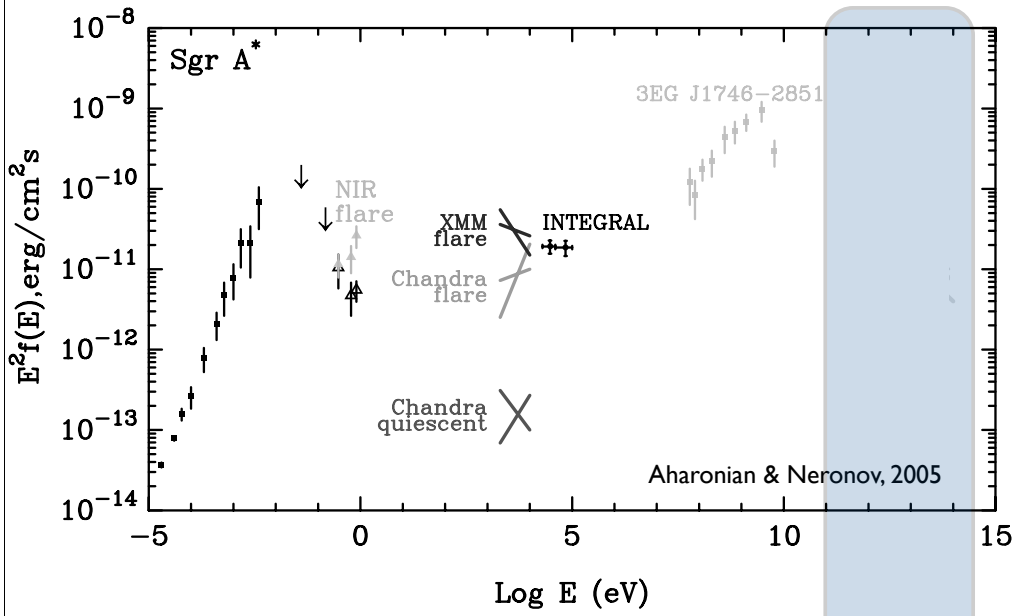
$$F(E) = \begin{cases} (2.2 \pm 0.01) \times 10^{-10} (E/1900\ \mathrm{MeV})^{-1.30 \pm 0.03} & (E < 1900\ \mathrm{MeV}) \\ (2.2 \pm 0.01) \times 10^{-10} (E/1900\ \mathrm{MeV})^{-3.1 \pm 0.2} & (E > 1900\ \mathrm{MeV}) \end{cases}$$

- **Too big error-box to associate with SgrA***
  - Re-analysis (Hooper and Dingus (2002), Pohl (2004) show it is OFFSET from Sgr A*
- **GLAST will help here...**

GeV Gamma Sgr A*

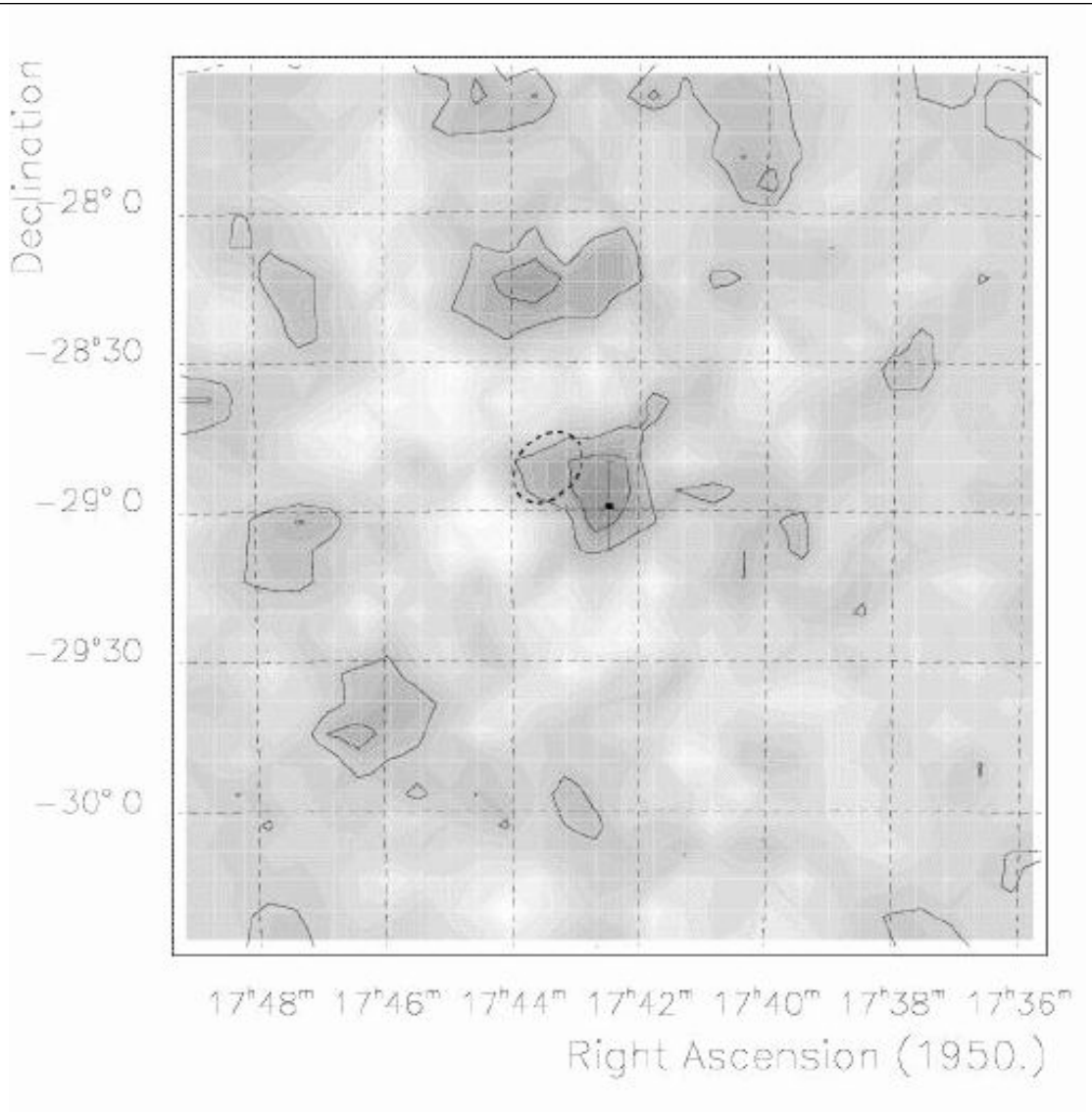
?

- **Unexplored until recently...**



TeV Gamma?

Sgr A*



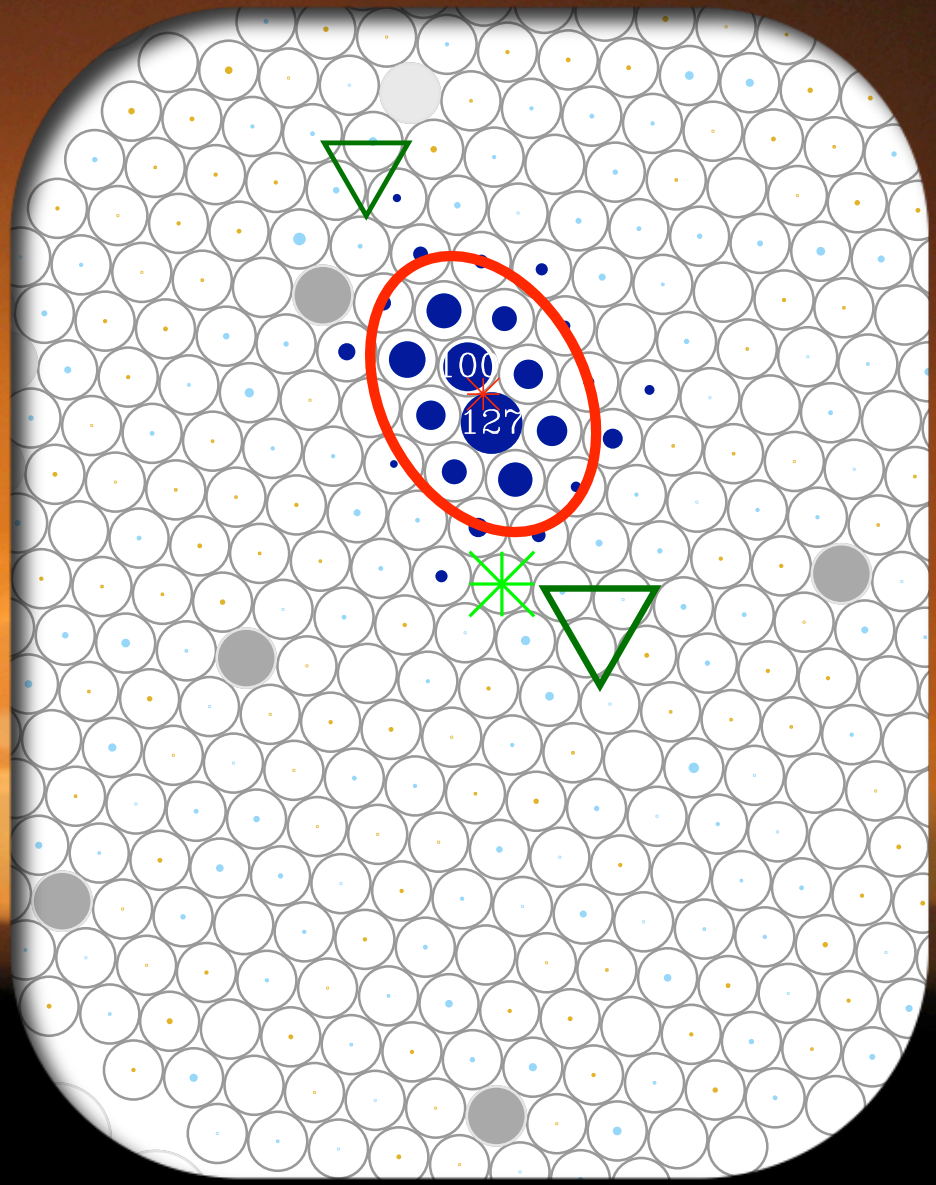
Small excess seen at Galactic Center position in 1997 Whipple data.

Buckley et al., 1997
Proceedings of the 25th International
Cosmic Ray Conference

Old Observations

Outline

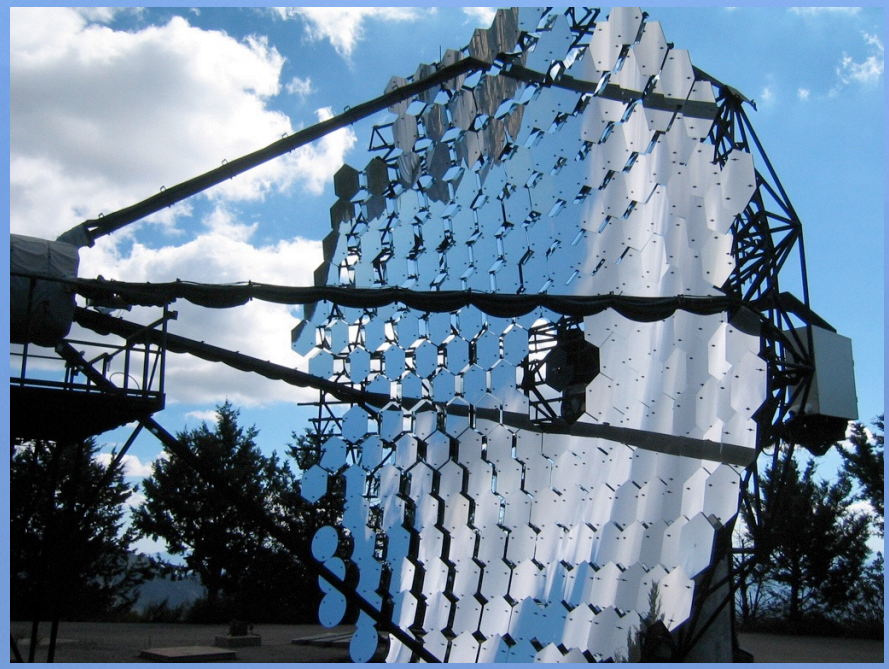
- The Galactic Center
- Instrument & Technique
- Analysis
- Results
- Emission Mechanisms
- Discussion

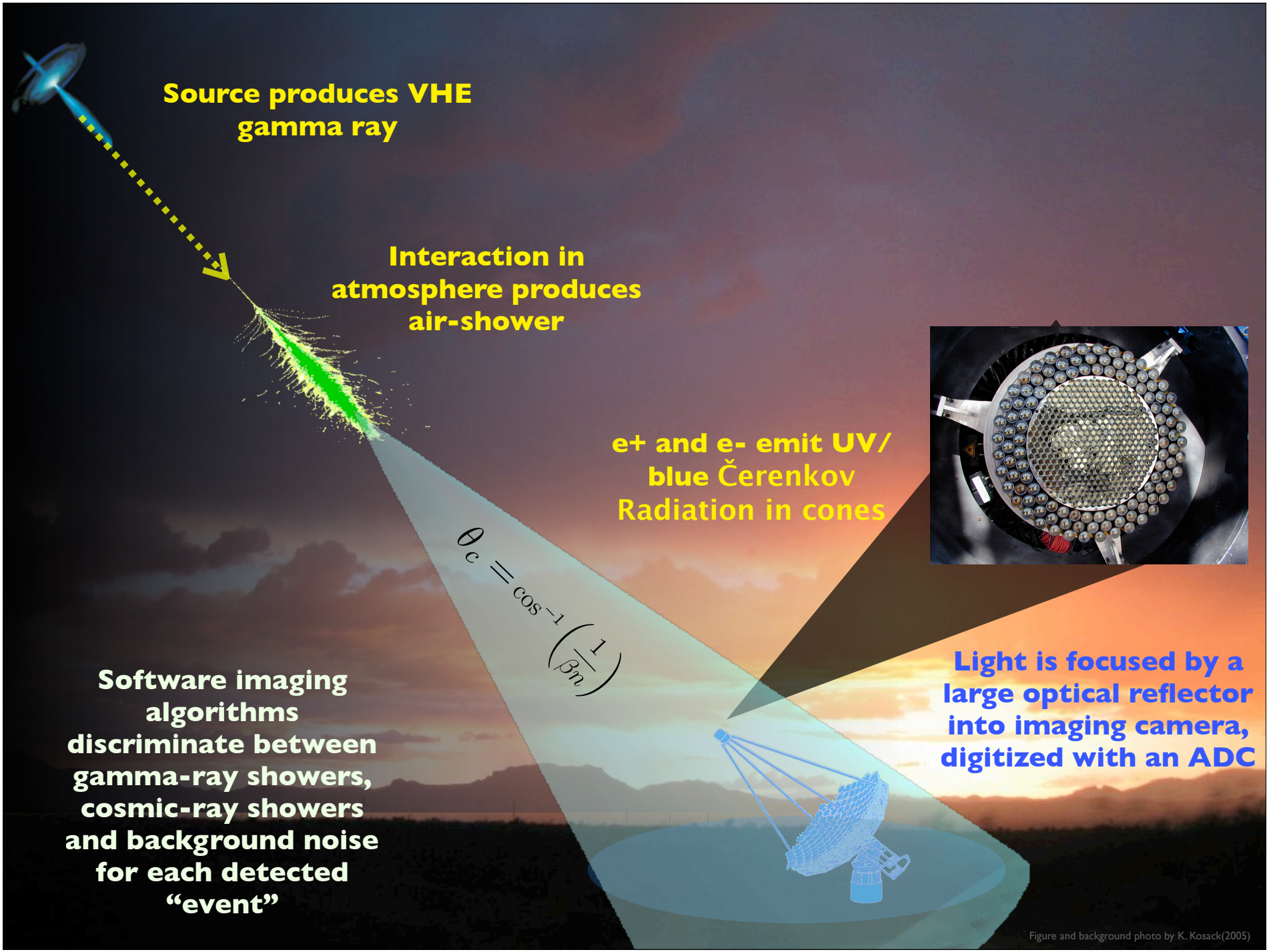


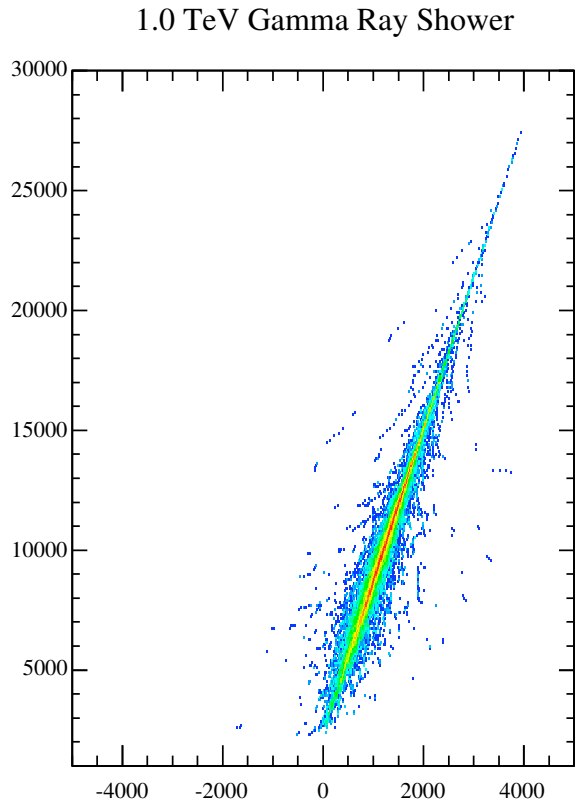
Detecting Gamma Rays:

The Atmospheric Cherenkov Technique

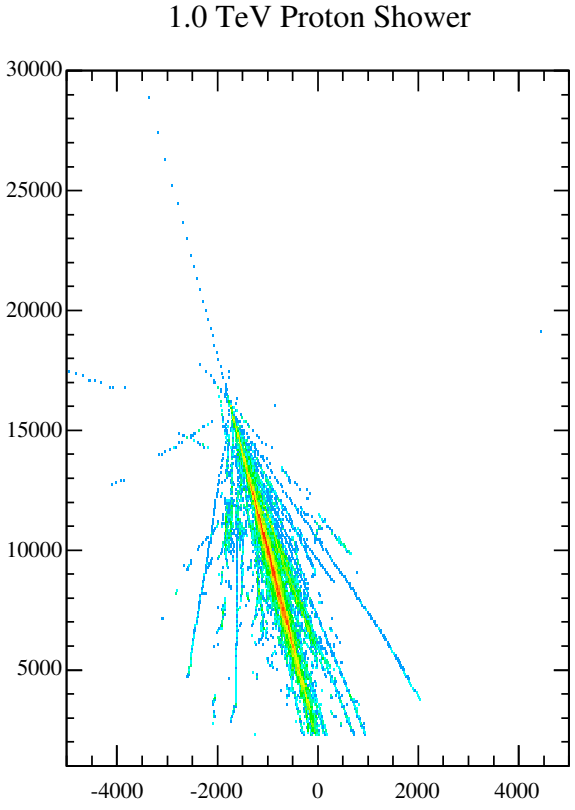
- **Problems?**
  - Can't use traditional focusing optics with gamma rays.
  - Earth's atmosphere is opaque to gamma rays.
- **Solution:**
  - Very-High-Energy particles interact in the atmosphere, producing Extensive Air Showers
  - Earth's atmosphere is a particle detector: a Cherenkov radiator.



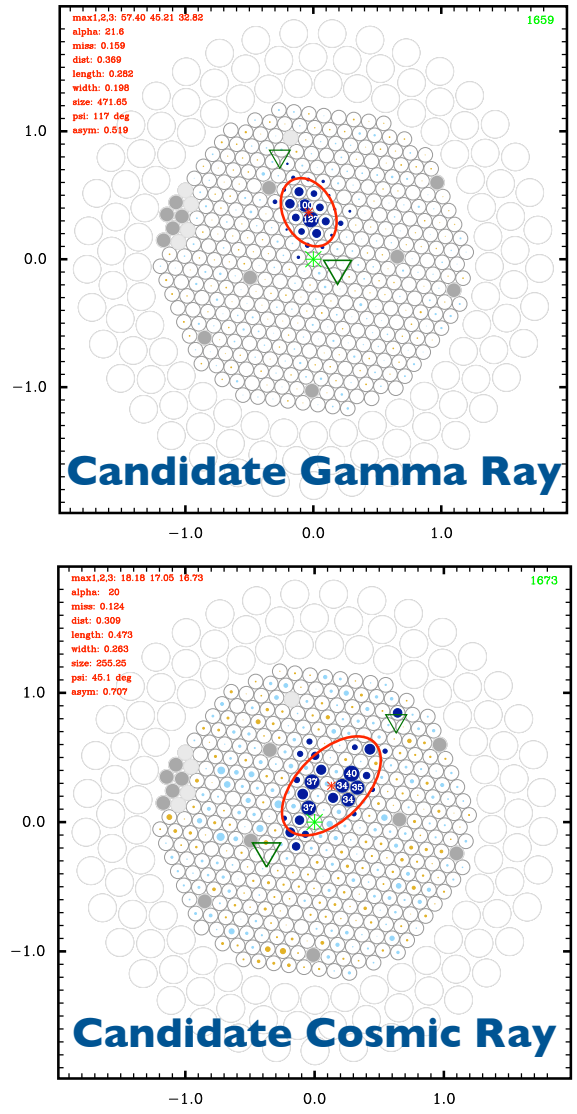

Source produces VHE gamma ray
Interaction in atmosphere produces air-shower
e+ and e- emit UV/ blue Čerenkov Radiation in cones
$\theta_c = \cos^{-1}\left(\frac{1}{\beta n}\right)$
Light is focused by a large optical reflector into imaging camera, digitized with an ADC
Software imaging algorithms discriminate between gamma-ray showers, cosmic-ray showers and background noise for each detected "event"
Figure and background photo by K. Kosack(2005)



(Signal)



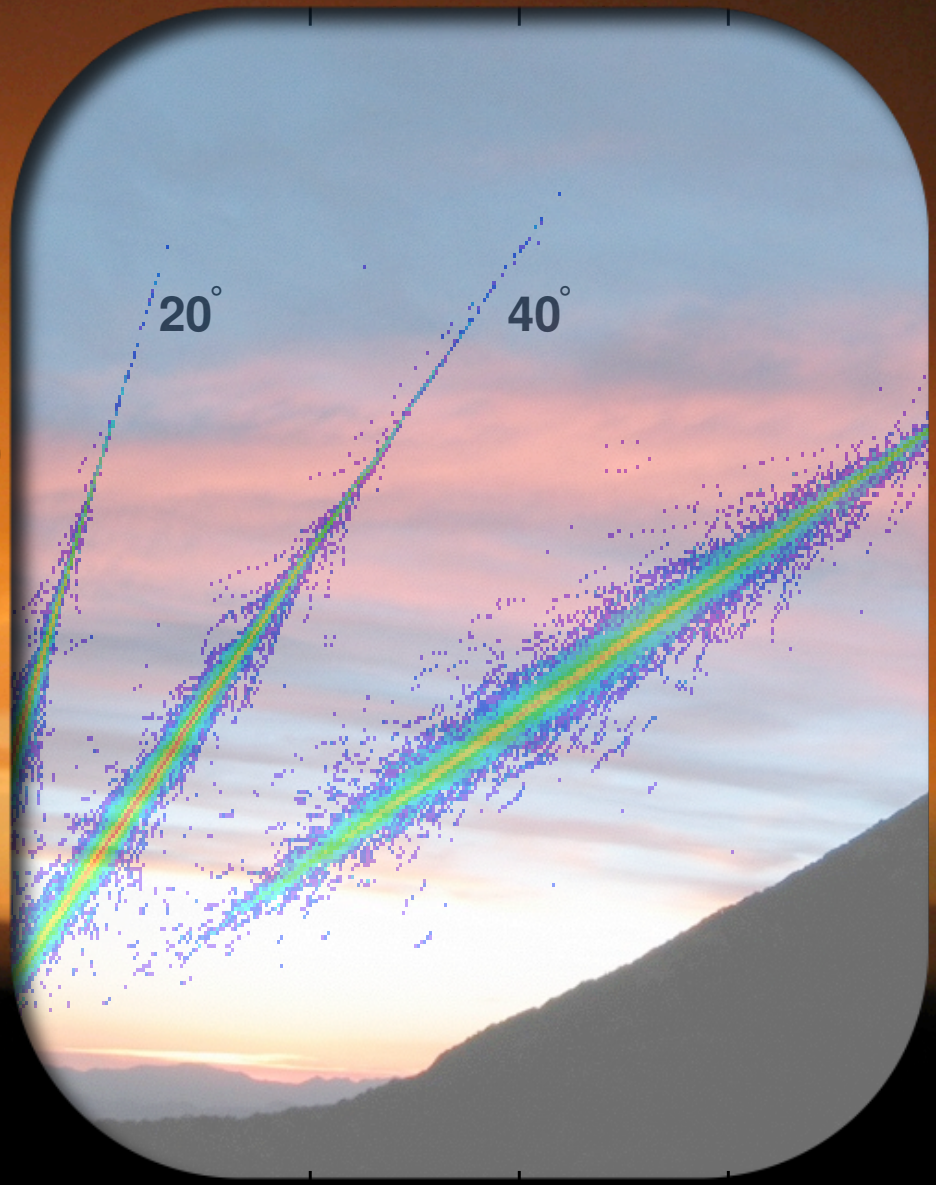
(Background)



Gamma-Ray vs Cosmic-Ray Showers

Outline

- The Galactic Center
- Instrument & Technique
- **Analysis**
- Results
- Emission Mechanisms
- Discussion



Galactic Center Analysis Challenges:

(with the Whipple Telescope)

- **Multiple Observing Seasons (≈10 years of data!)**
  - Only visible in May-July, ≈1 hour per night
  - Instrument upgraded several times
- **Large Zenith Angle Observations (θ=60°)**
  - Standard Gamma-Ray Selection Criteria Need Modification
  - Telescope Pointing Error at low elevation
- **Unknown Source**
  - Did not expect emission, no one obvious mechanism. Original motivation: Dark Matter, so we chose to look at Sgr A* position

A Priori Assumptions

- Problem: **Flux, Position, and Emission mechanism uncertain.**
  - Easy to bias analysis toward detection!
- Solution: **Don't look at the Galactic Center.**
  - Develop and optimize selection criteria and calibrations using **Crab Nebula data only**.
  - Only in the end apply analysis to Galactic Center to prevent biasing

Outline

- The Galactic Center
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- Analysis
- **Results**
- Emission Mechanisms
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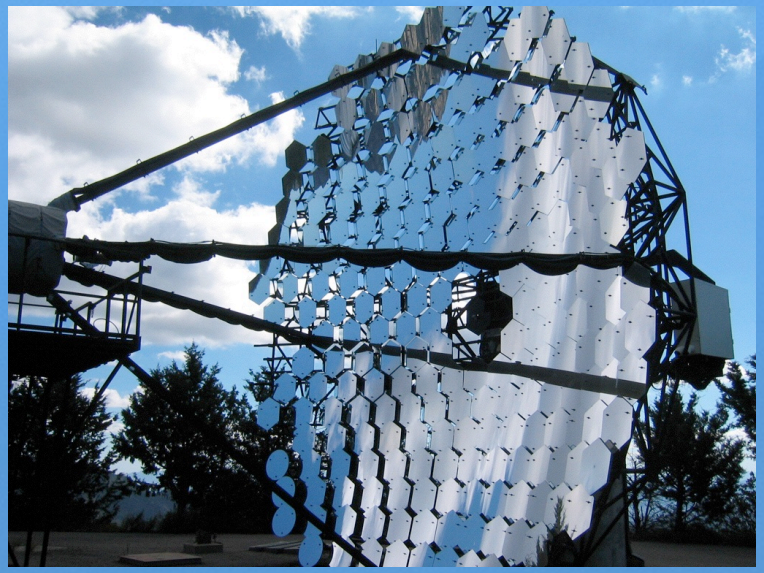
Whipple Telescope Observations

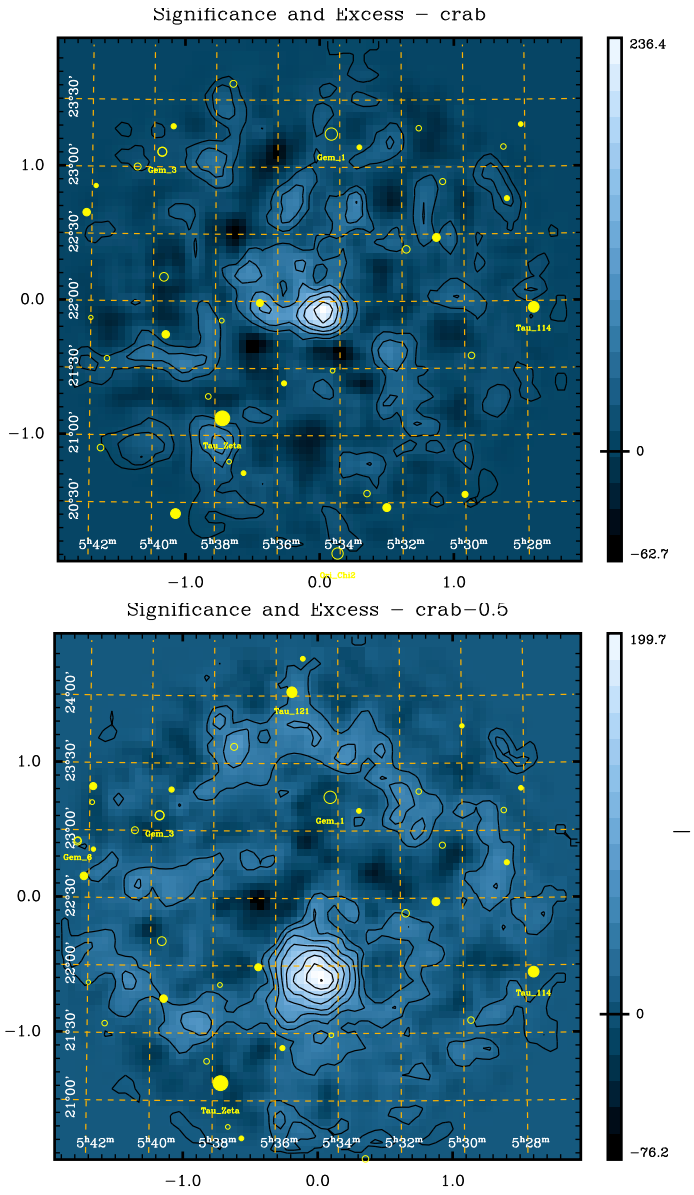


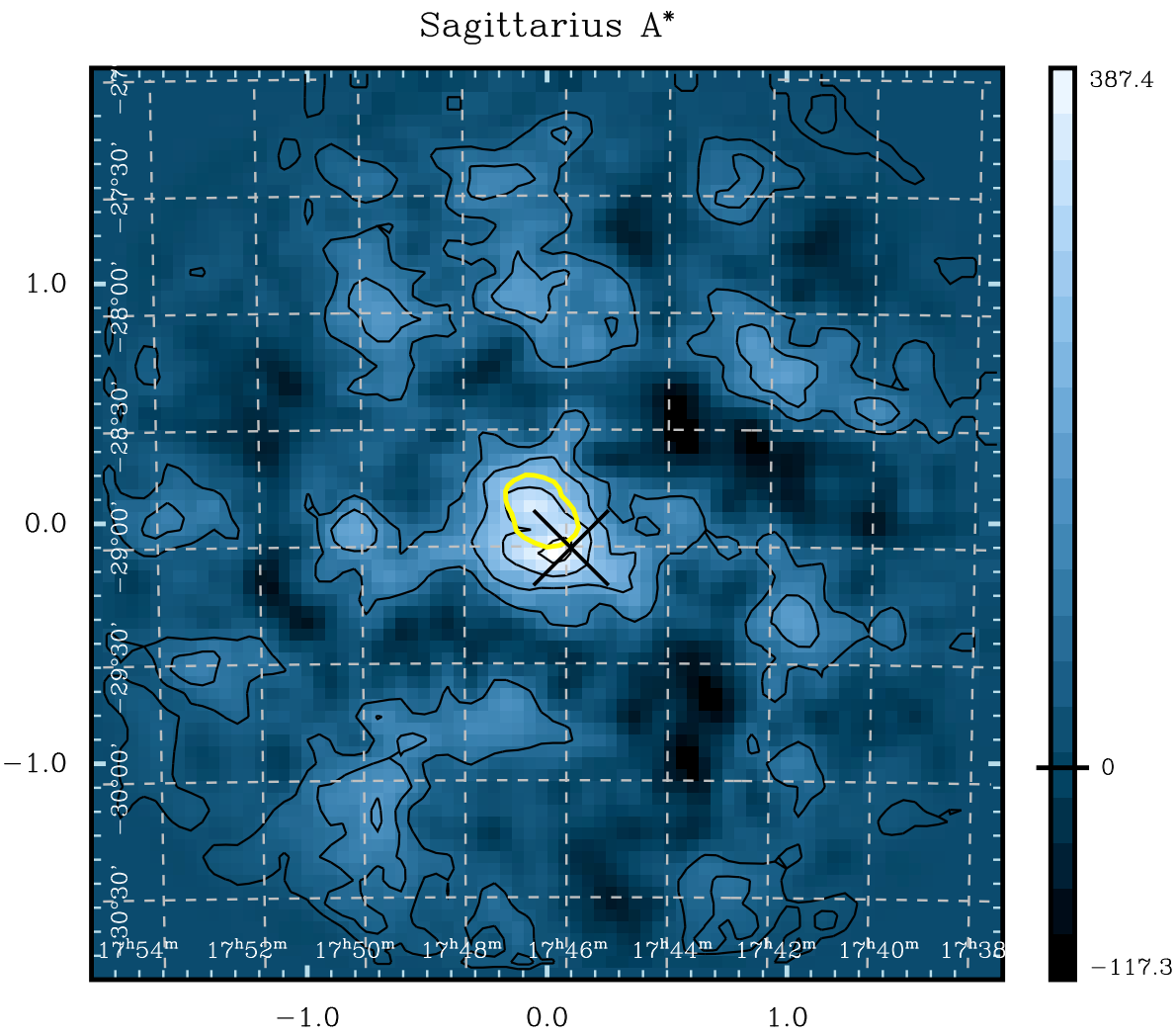
Observations

- 31 Hours (ON-source)
- 1995-2003

Analysis

- Seasonal gain corrections
- LZA Camera Geometry Corrections
- 2 Nearby stars used to measure and correct for pointing offset (0.1°)
- Zenith-angle and energy independent gamma-ray selection cuts

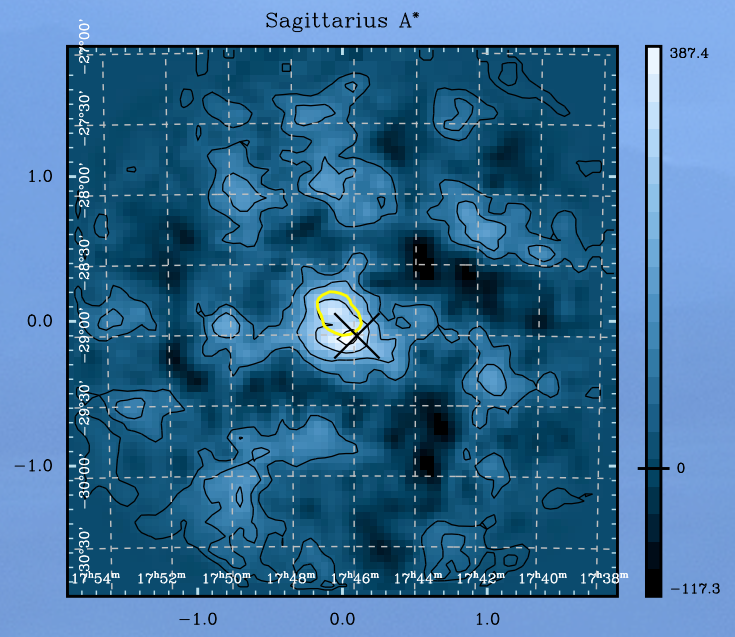




Gamma-Ray Sky Plot

Flux

- **Normalized to Crab Nebula at peak energy of 2.8 TeV:**
  - $(5.3 \pm 1.9) \times 10^{-9}$ m^{-2} s^{-1} TeV^{-1}
  - 22% of Crab Flux (at 4x distance)
- **Consistent with Point source within 15 arcmin (95% confidence)**



Independent Observations

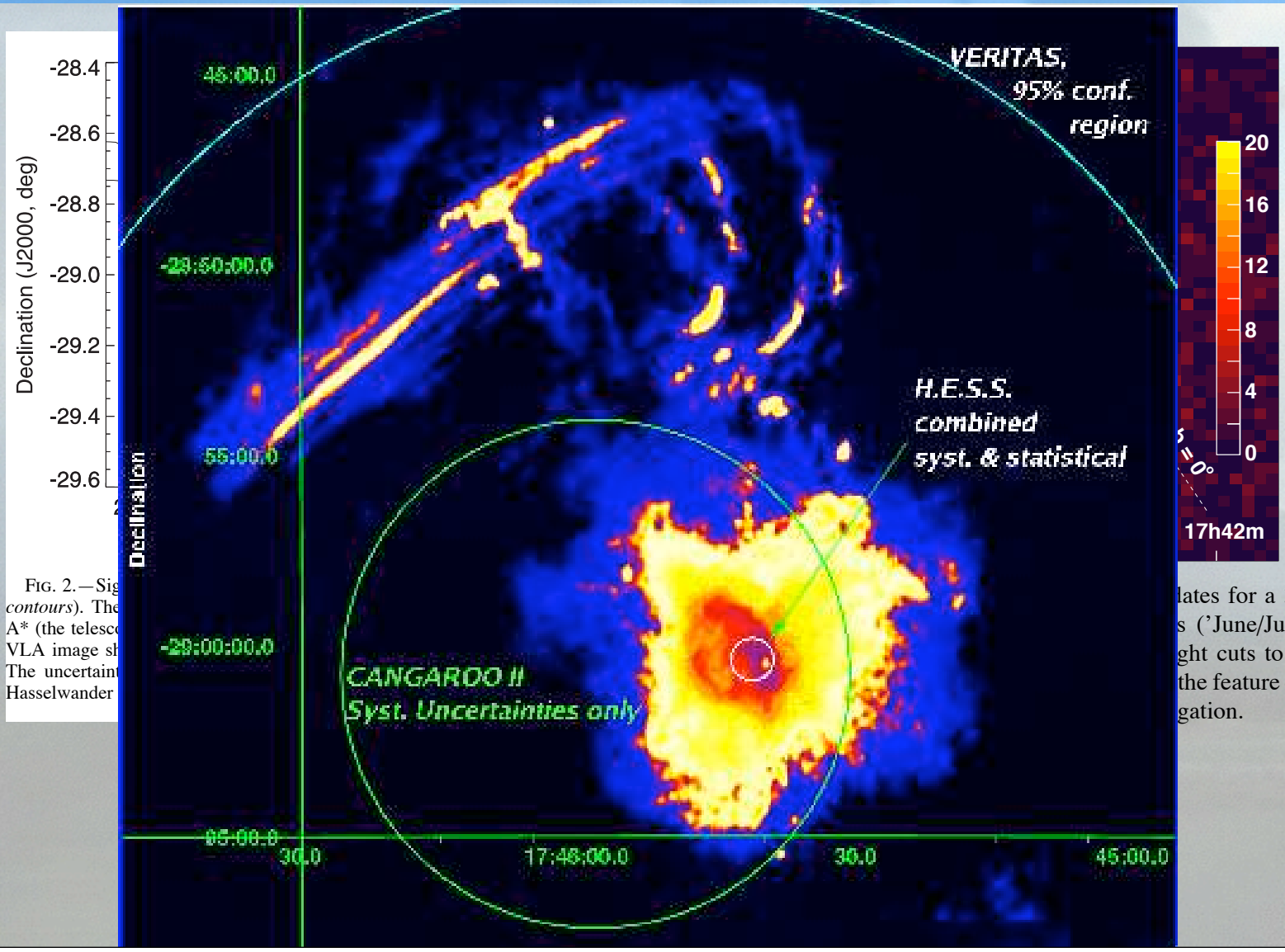


FIG. 2.—Sig
contours). The
A* (the telesc
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the feature extend-
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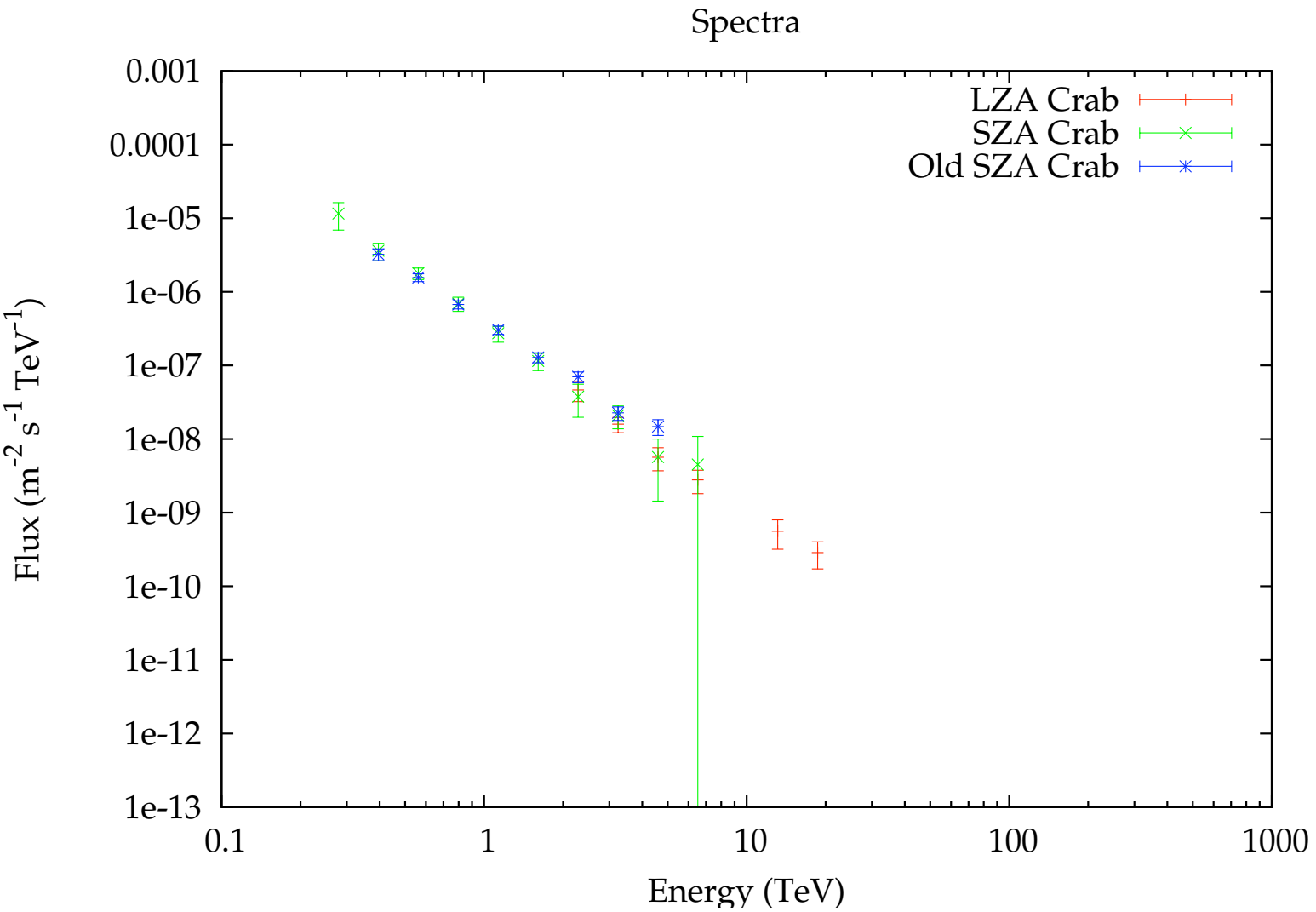
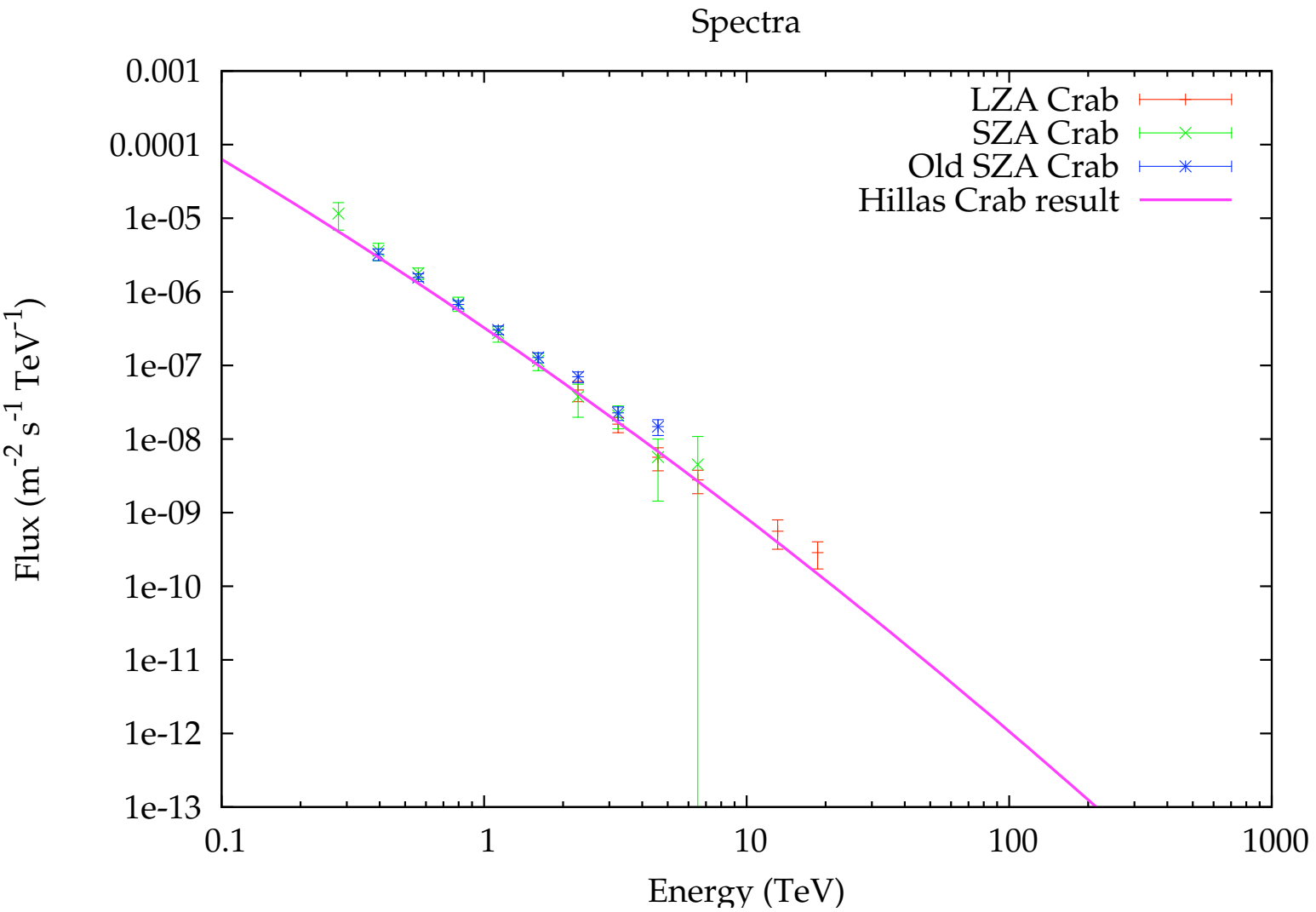
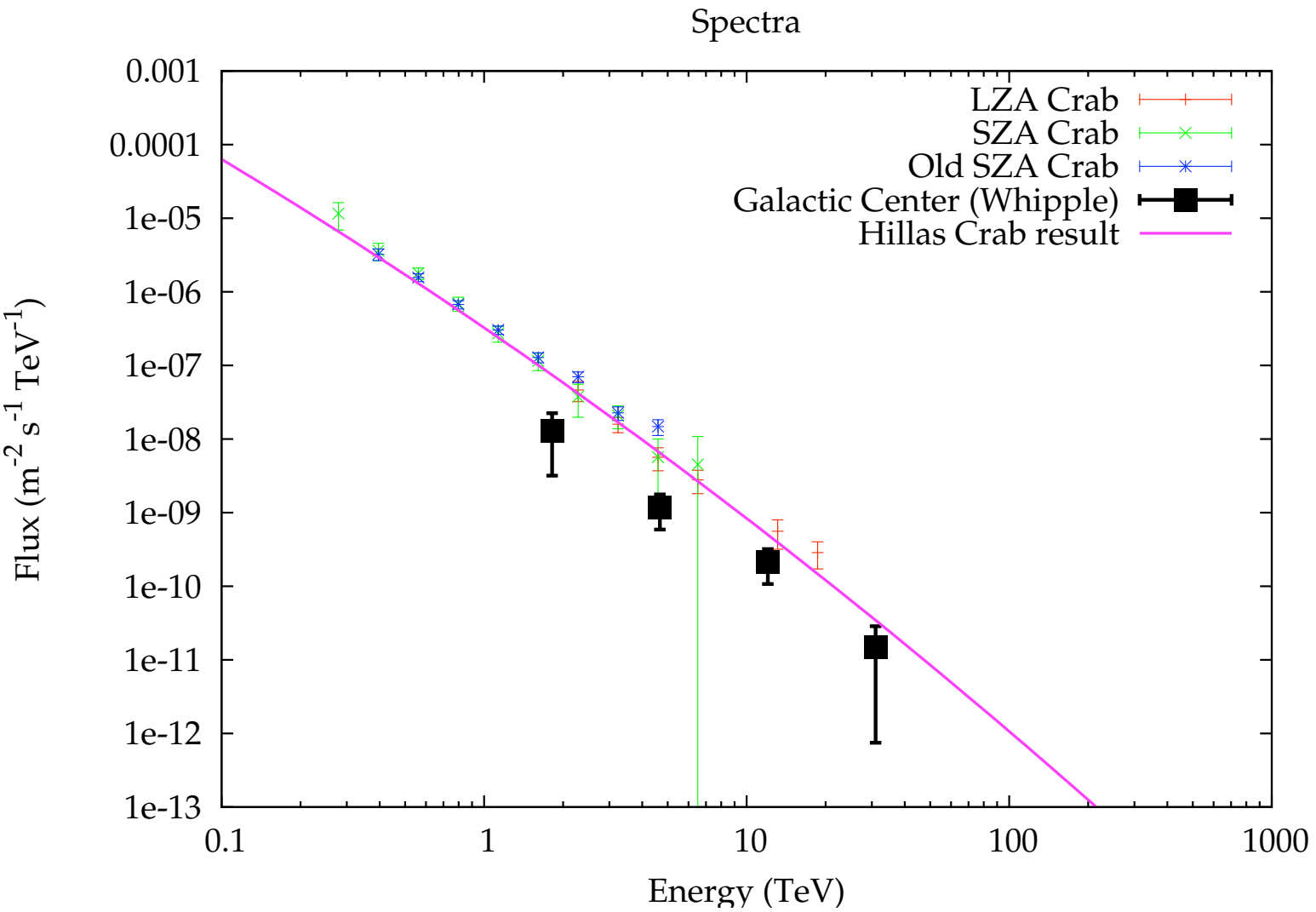

Spectra
LZA Crab
SZA Crab
Old SZA Crab
Flux (m-2 s-1 TeV-1)
0.001
0.0001
1e-05
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
1e-13
0.1
1
10
100
1000
Energy (TeV)

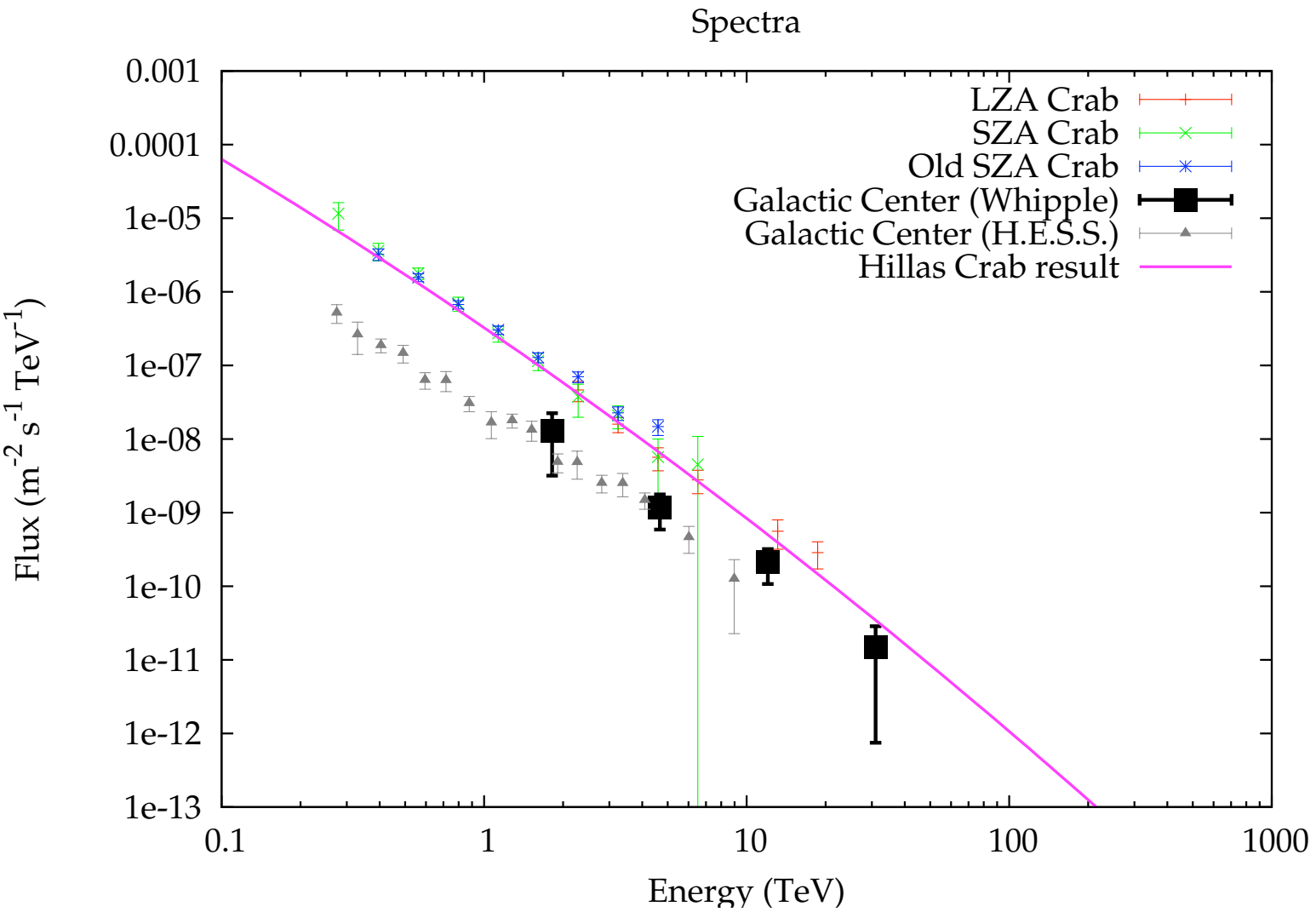
Spectrum


Spectra
LZA Crab
SZA Crab
Old SZA Crab
Hillas Crab result
Flux (m-2 s-1 TeV-1)
Energy (TeV)
0.001
0.0001
1e-05
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
1e-13
0.1
1
10
100
1000

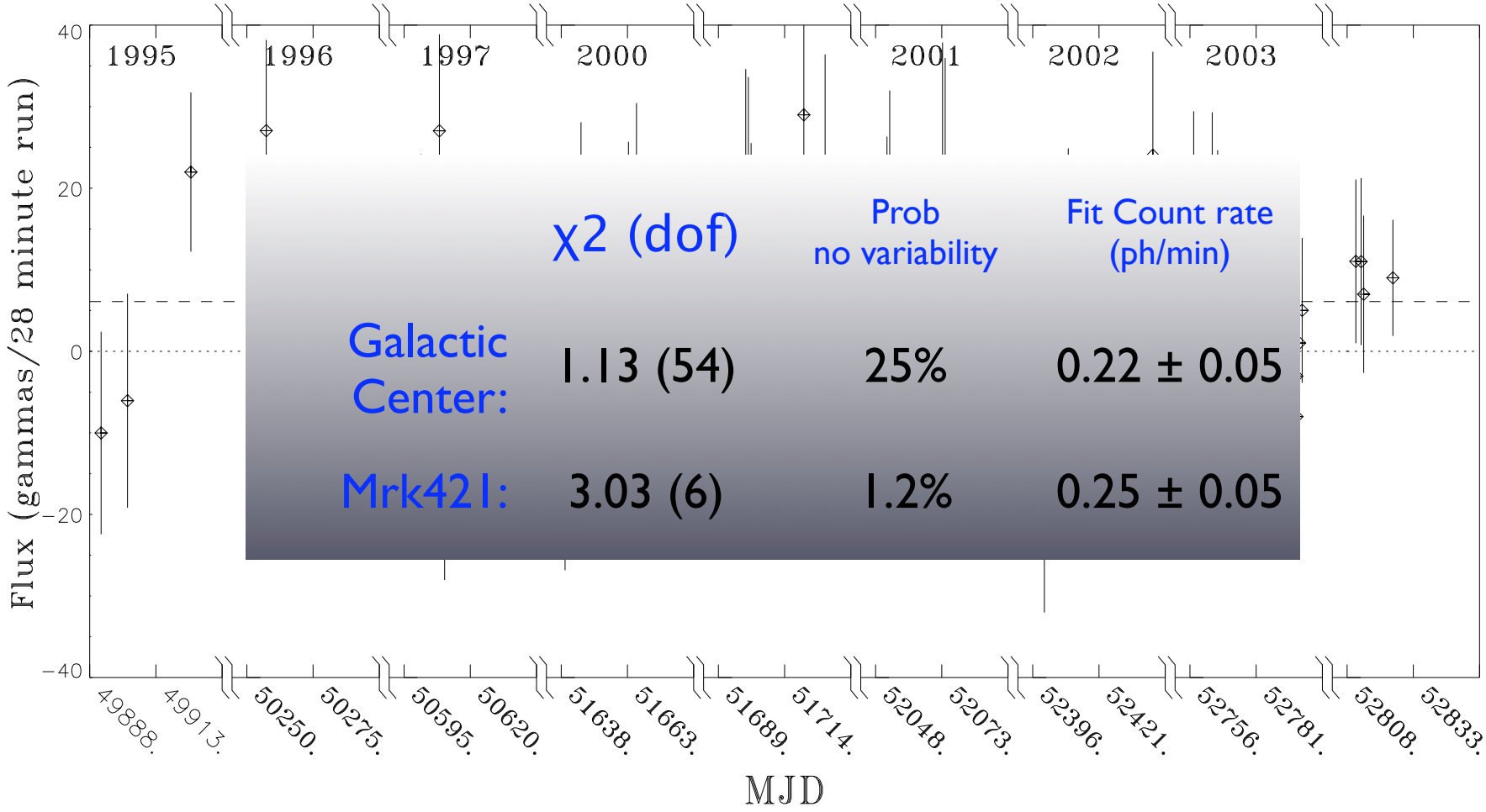
Spectrum


Spectra
LZA Crab
SZA Crab
Old SZA Crab
Galactic Center (Whipple)
Hillas Crab result
Flux (m-2 s-1 TeV-1)
Energy (TeV)
0.001
0.0001
1e-05
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
1e-13
0.1
1
10
100
1000

Spectrum

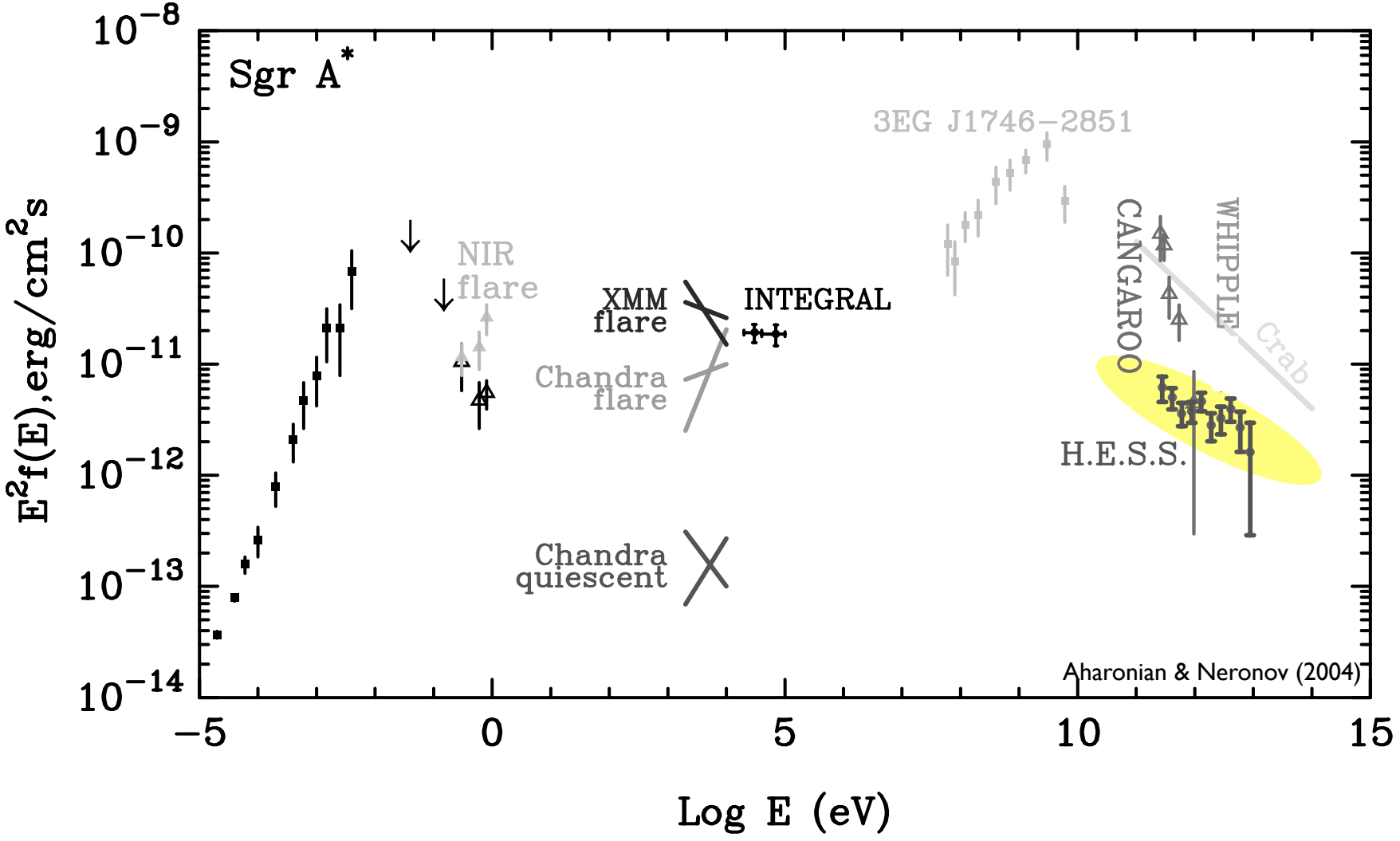

Spectra
LZA Crab
SZA Crab
Old SZA Crab
Galactic Center (Whipple)
Galactic Center (H.E.S.S.)
Hillas Crab result
Flux (m-2 s-1 TeV-1)
Energy (TeV)
0.001
0.0001
1e-05
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
1e-13
0.1
1
10
100
1000

Spectrum



	χ2 (dof)	Prob no variability	Fit Count rate (ph/min)
Galactic Center:	1.13 (54)	25%	0.22 ± 0.05
Mrk421:	3.03 (6)	1.2%	0.25 ± 0.05

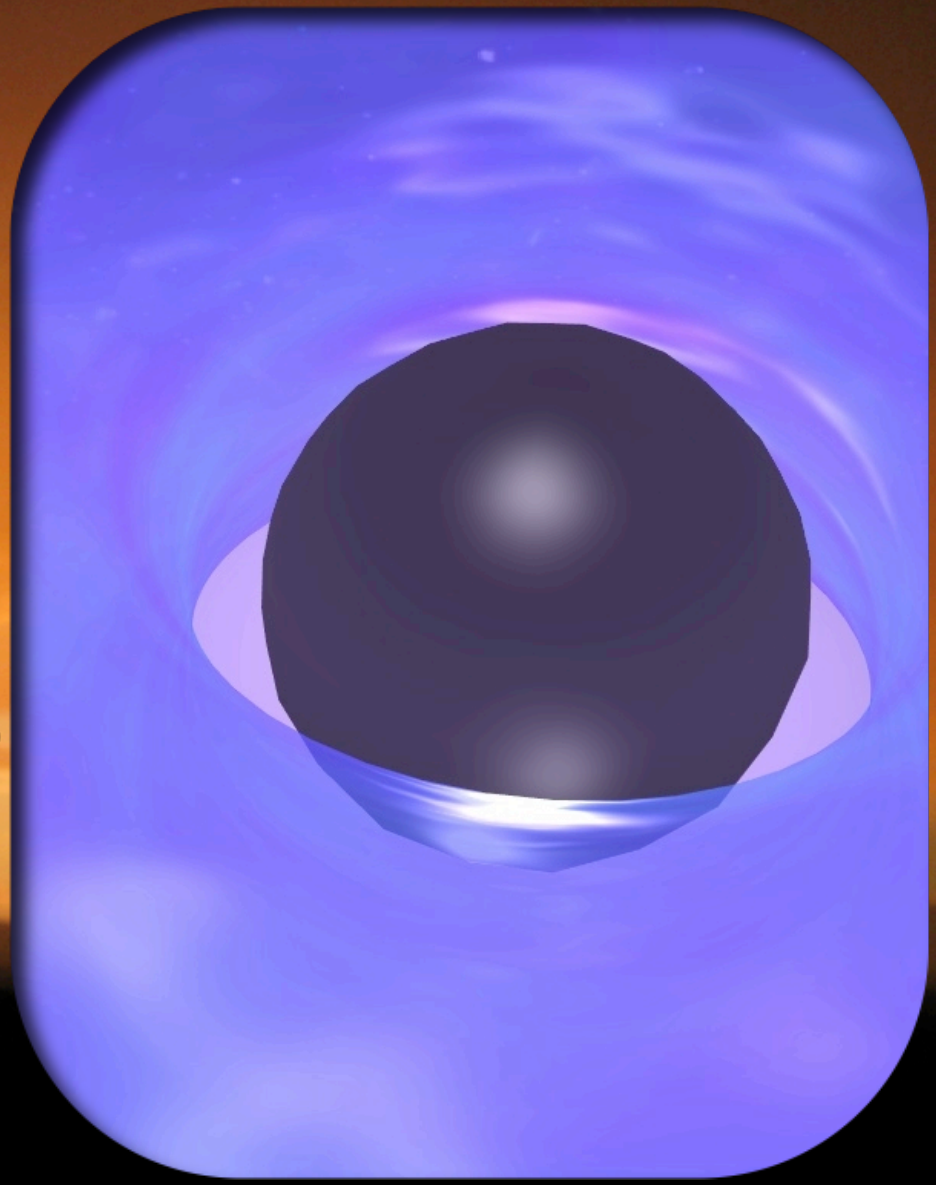
Variability



The Full Spectrum

Outline

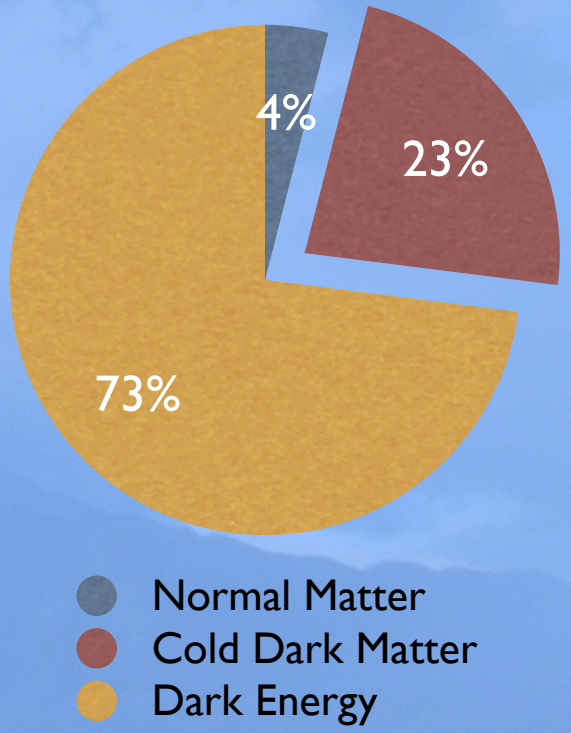
- The Galactic Center
- Instrument & Technique
- Analysis
- Results
- **Emission Mechanisms**
- Discussion



Weakly Interacting Massive Particle (WIMP)

- Creation/Annihilation determine density
- Early Universe: in equilibrium
- Later: Universe expands, annihilation rate drops, fall out of equilibrium: **Freeze-Out** ($T_f \approx m_x/20$)
- Relic abundance of WIMP consistent with Dark Matter density measurements.

Dark Matter



Galaxy Rotation: DM exists (in halo)

CMBR + BB nucleosynthesis: It's non-baryonic

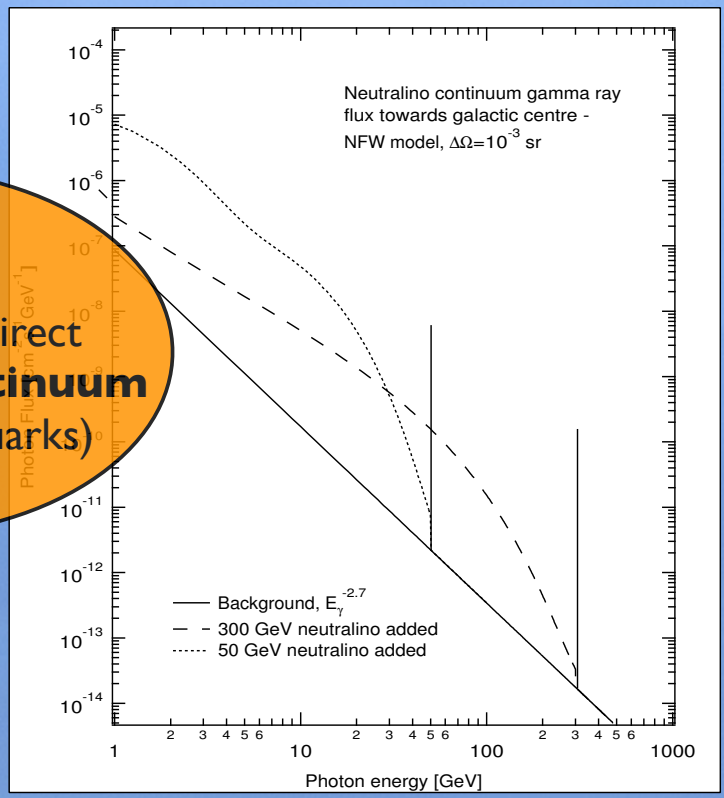
Structure Formation: It's Cold

Dark Matter Annihilation

- **Must be stable, non-baryonic**
- **Nothing in Standard Model works**
- **Supersymmetry provides natural candidate: Neutralino**
  - stable
  - weakly interacting
  - mass ≈ GeV - TeV
  - Annihilates to Gamma Rays

Signature:

Expect a **line** (direct annihilation) + **continuum** (annihilation to quarks)

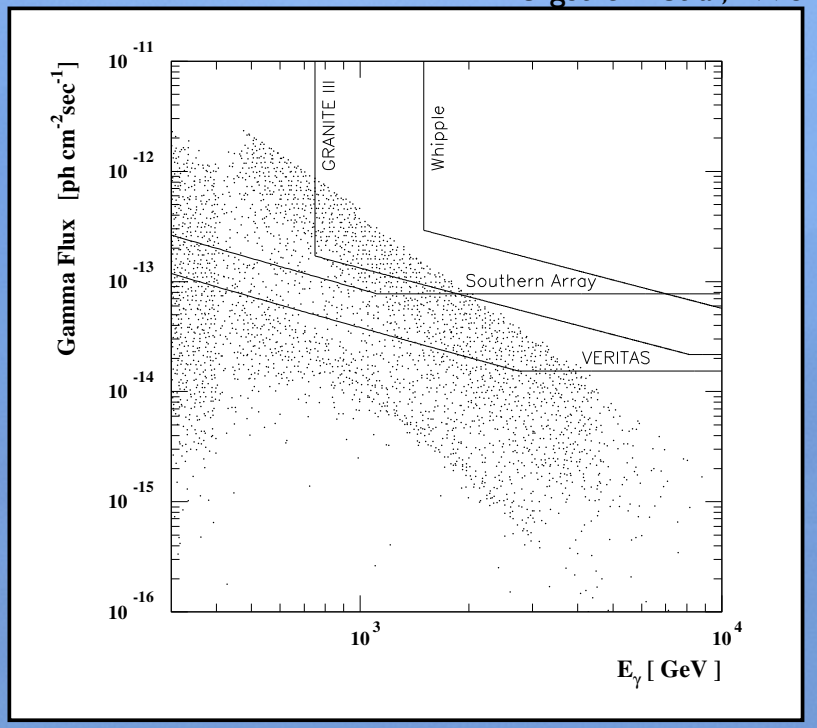


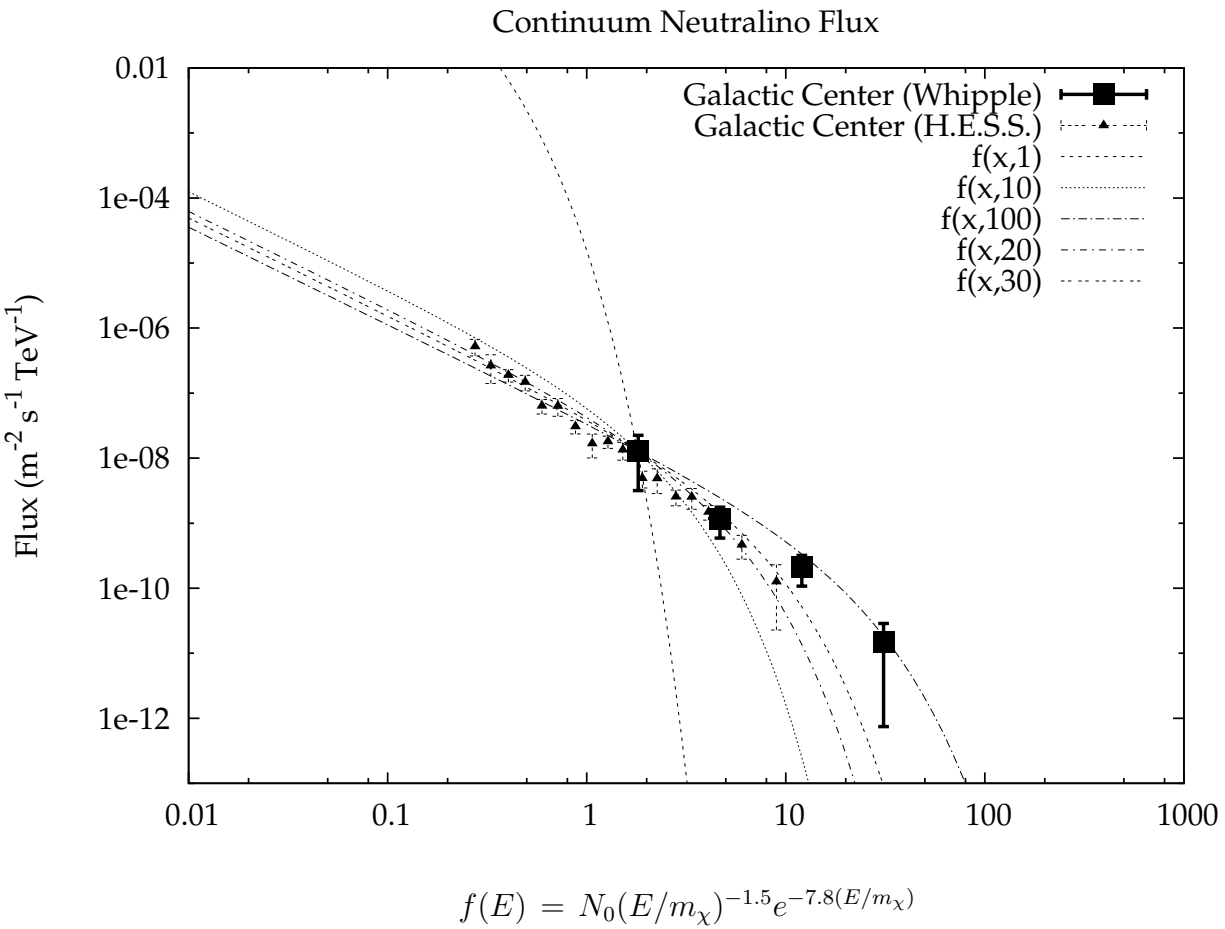
- Dark Matter in galaxies is in form of spherical halo
- Halo density highest near Galactic Center
- $$\rho(r) = \frac{\rho_c}{(r/r_s)\,(1 + r/r_s)^2}$$
- Power-law cusp at r=0
- Intensity ∝ ρ^2
- Annihilation may be visible

Could we see it?

Maybe!

Bergstrom et al, 1998





$$f(E) = N_0 (E/m_\chi)^{-1.5} e^{-7.8(E/m_\chi)}$$

- $m_x \approx$ 20-100 TeV
- GUT theory + cosmological constraints: $m_x <$ TeV

  [Ellis et. al (2004)]
- A problem for WIMP DM? Maybe.

Neutralinos?

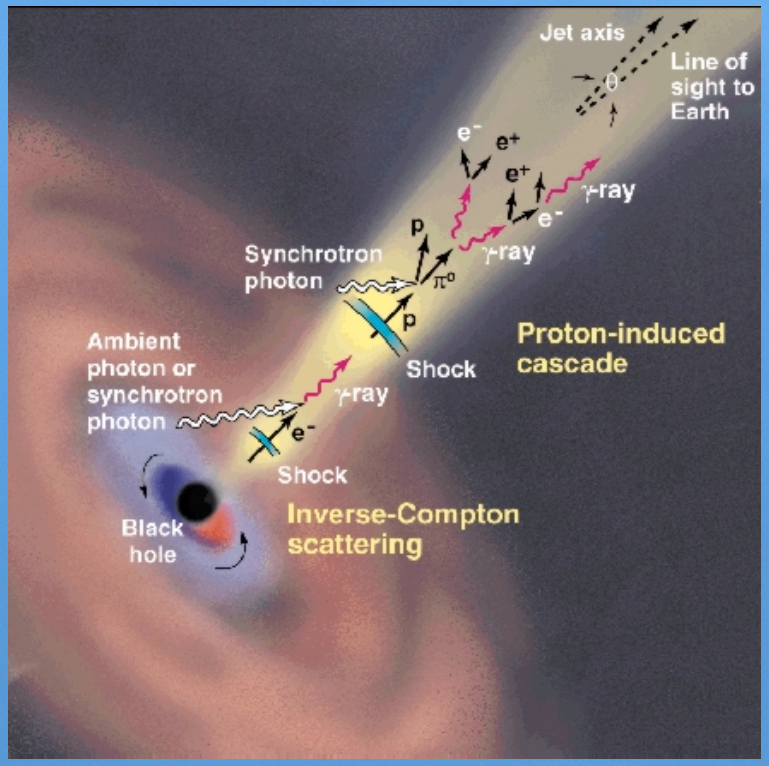
An AGN?

Active Galactic Nuclei:

- Outshine host galaxy
- Accretion Powered (Supermassive Black Hole with Accretion Disc)
- Jets (relativistic outflow)
- Well-established TeV sources
- Broad emission (Radio - TeV)
- Variability (flaring)

- **Galactic Center isn't very active, but may share some characteristics/ processes**
- **Black Hole + evidence for Accretion + flaring at lower energies**
- **Radiatively-inefficient accretion process**
- **Current model: Black Hole Plerion Model** (see C. Dermer talk on Friday)

How do AGN produce TeV Photons?



Buckley (1998)

- **Synchroton-Self-Compton (SSC)**
  - Fermi Shock Acceleration produces VHE electrons
  - Emit lower energy photons by synchrotron emission
  - Inverse Compton (IC) Up-Scattering to TeV
- **Proton-induced cascades**
  - Photo-meson interactions
  - Synchrotron (req. large B-field)
  - Proton-Proton interactions

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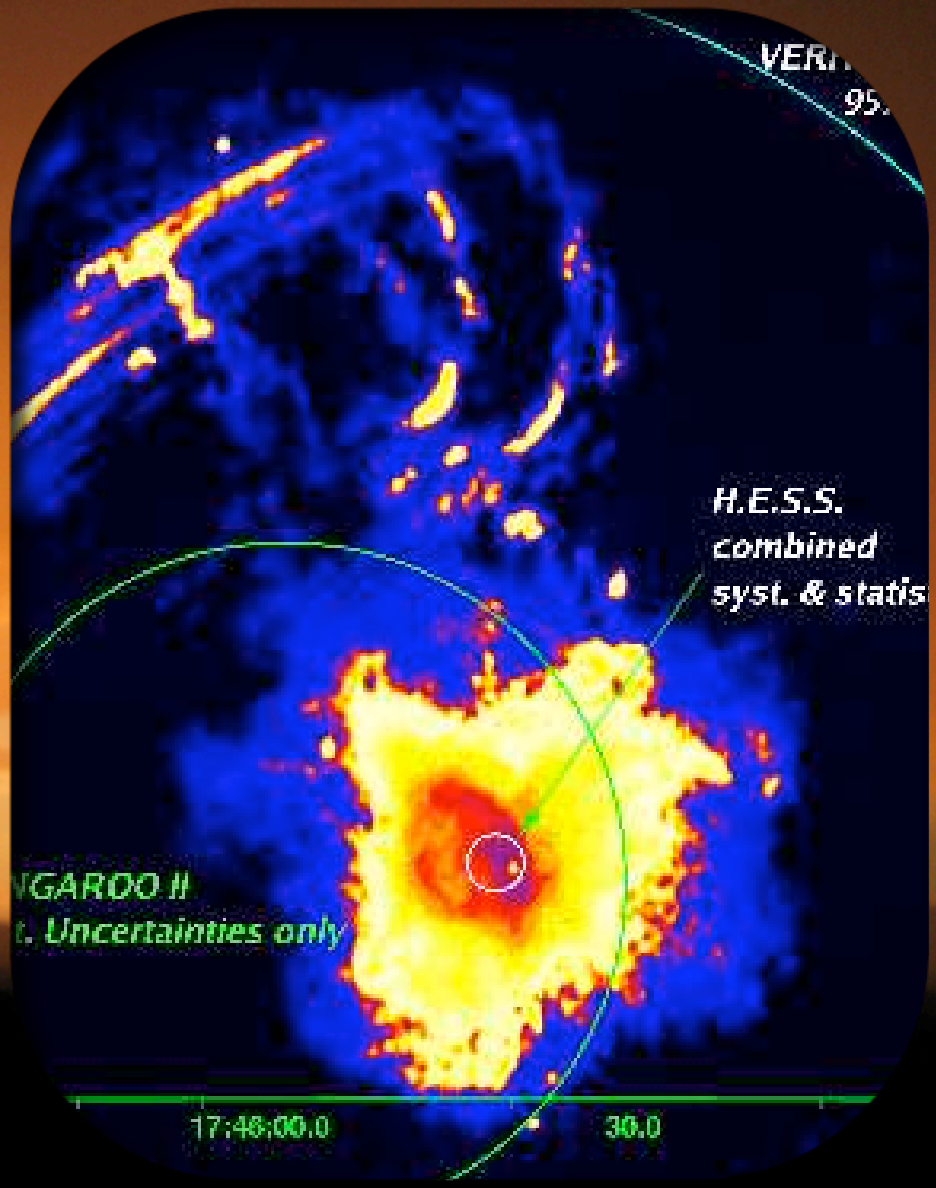
- Emission Mechanisms
- Discussion



The Future

- **How high does spectrum extend? Evidence for line emission?**
- **Variability? (multi-wavelength correlations)**
  - Single TeV flare would eliminate possibility of DM annihilation!
- **Source(s)?**
  - Resolve difference between: Whipple/ HESS, CANGAROO, EGRET
- **Next-Gen Telescopes:**
  - **TEV**: VERITAS, HESS, MAGIC
  - **GEV**: GLAST