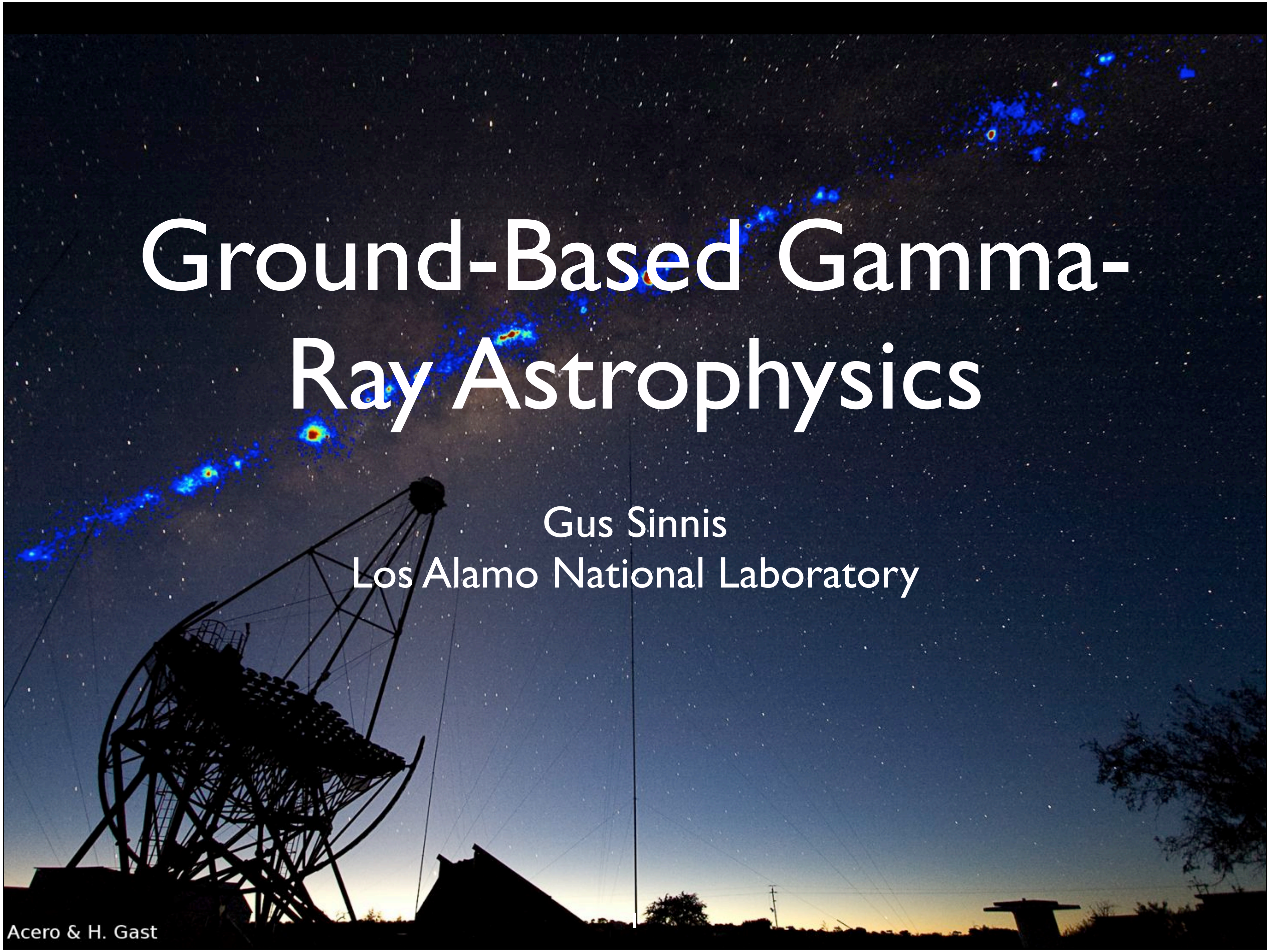
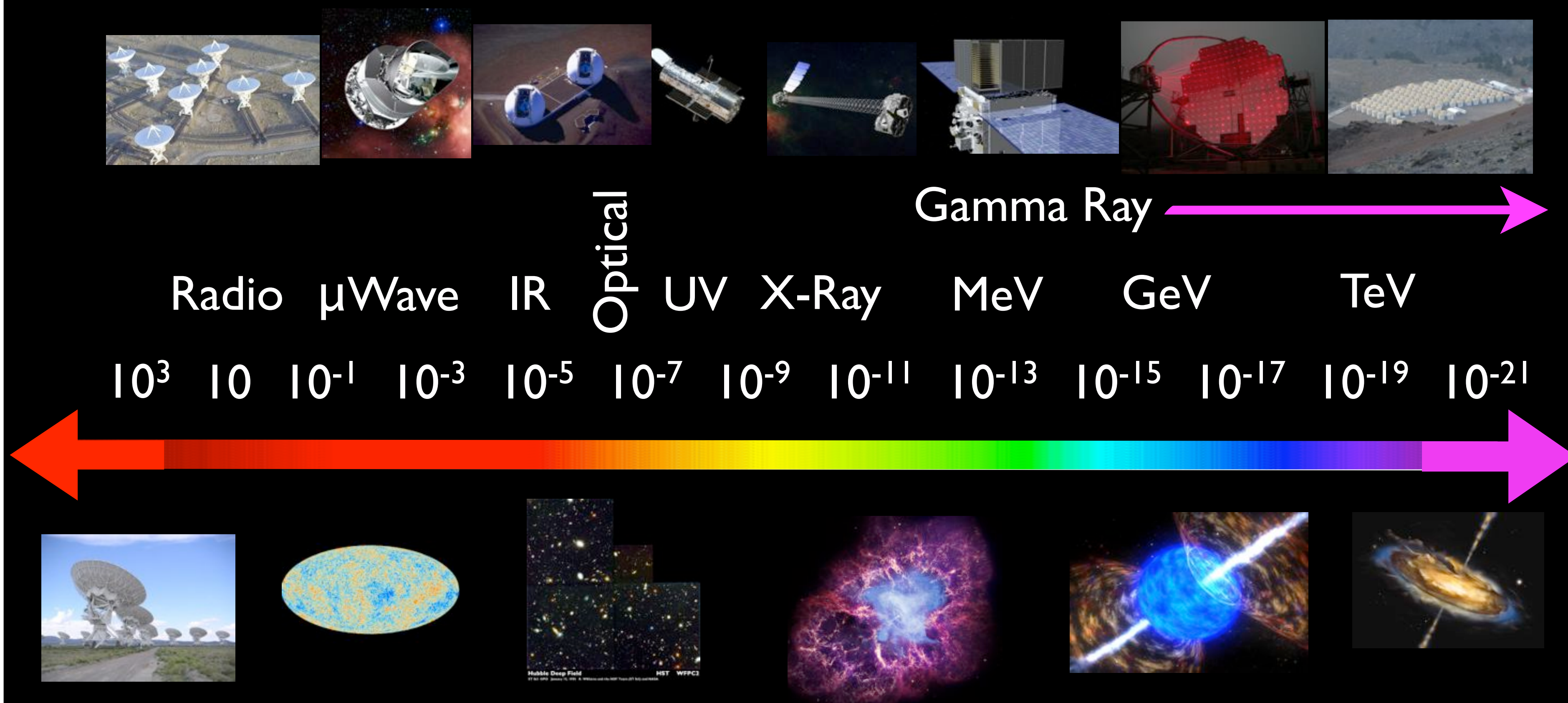
Ground-Based Gamma-Ray Astrophysics

Gus Sinnis
Los Alamo National Laboratory



The Electromagnetic Spectrum



Pulsars
Radio Galaxies

CMB

Stars, galaxies
Dark Energy

Compact objects
Particle
acceleration

Particle acceleration, Gamma Ray Bursts, Active Galaxies, Cosmic Ray Origins, Lorentz Invariance, Dark Matter

Goals of TeV Astrophysics

- Cosmic Particle Acceleration
  - Origin of cosmic rays
  - Understand astrophysical jets and extreme environments
- Cosmology
  - Measure the extragalactic background light
  - Sum of all UV, optical, and infrared radiation emitted since the Big Bang
- Search for new physics
  - Dark matter (indirect detection of annihilation or decay products)
  - Measure intergalactic magnetic fields (origins in primordial field)
  - Search for violations of Lorentz invariance

Gamma Ray Telescopes

Atmospheric Cherenkov Telescopes
H.E.S.S./VERITAS/MAGIC

50 GeV - 100 TeV
Large Area
Excellent background rejection
Small Aperture/Low Duty Cycle

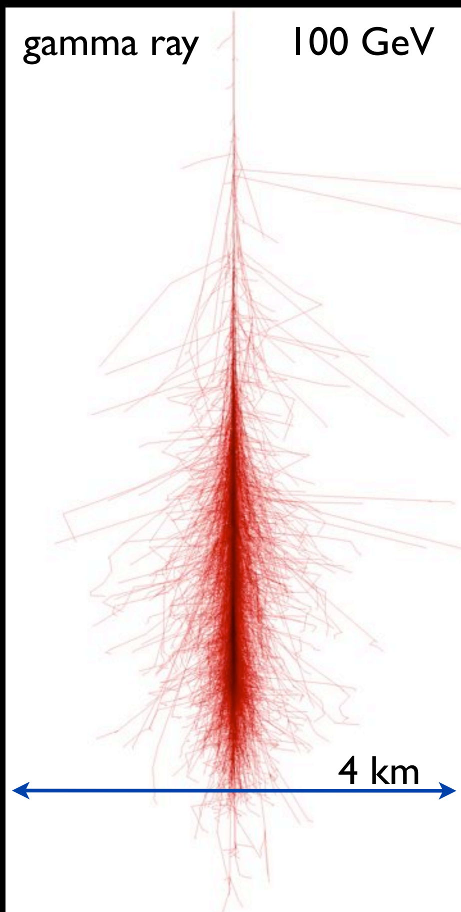
Study known sources
Deep surveys of limited regions
Source morphology (SNRs)
Fast transients (AGN flares)

EAS Arrays
Milagro/Tibet/ARGO

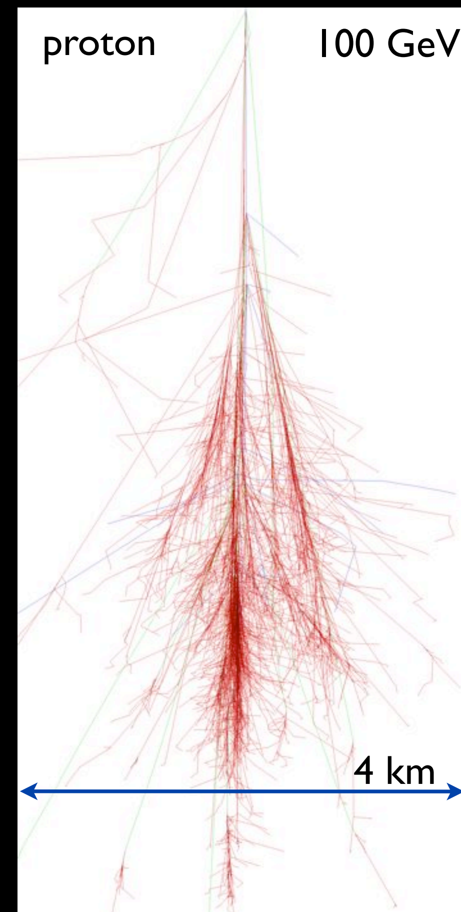
100 GeV - 100 TeV
Large Area
Good background rejection
Large Aperture & Duty Cycle

Sky survey & monitoring
Extended Sources
Transients (GRBs, AGN flares)
Highest Energies (>10 TeV)

Extensive Air Showers

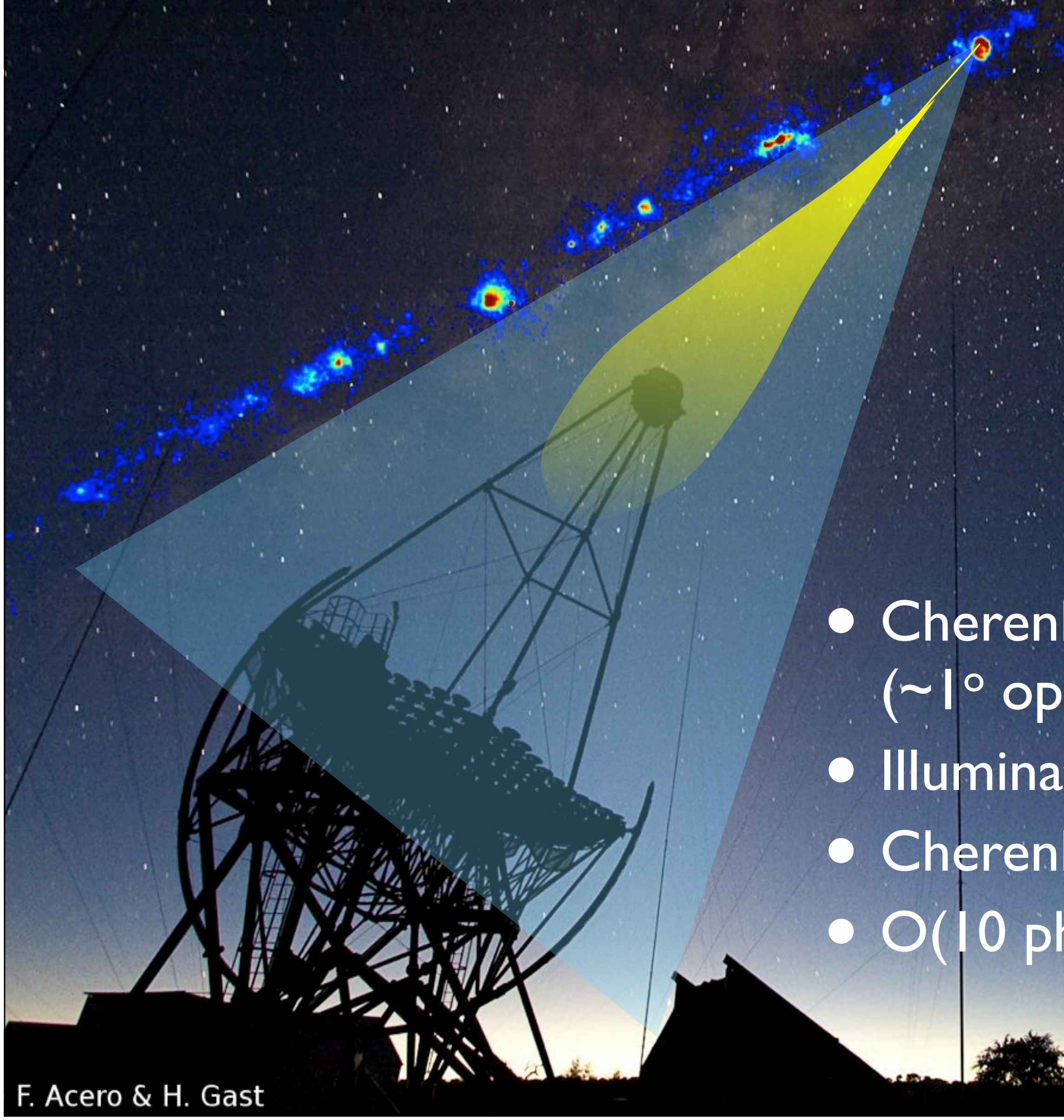


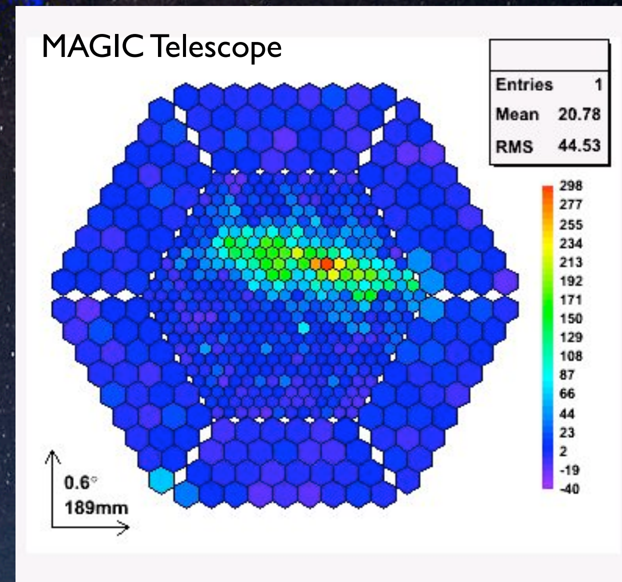
- γ showers almost purely e-m and relatively compact
- Hadronic showers contain muons (~30/TeV)
- Both have core of energetic particles
- Ground-based VHE telescopes must distinguish protons from photons



F. Schmidt, "CORSIKA Shower Images", http://www.ast.leeds.ac.uk/~fs/showerimages.html

Imaging Atmospheric Cherenkov Telescopes





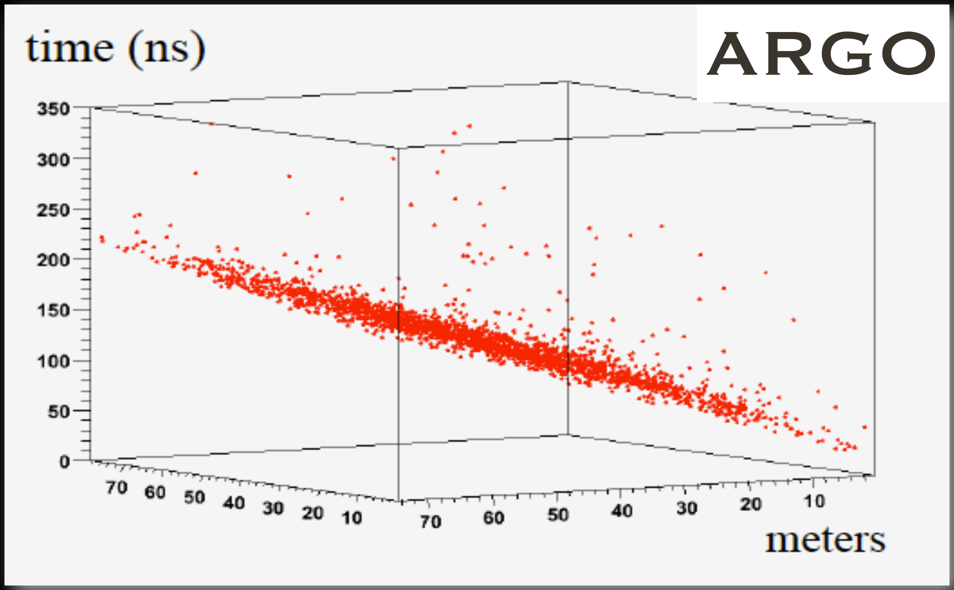
- Cherenkov light beamed forward (~1° opening angle)
- Illuminates ~100,000 m^2 on ground
- Cherenkov flash lasts ~few ns
- O(10 photons/m^2) @ 1 TeV

F. Acero & H. Gast

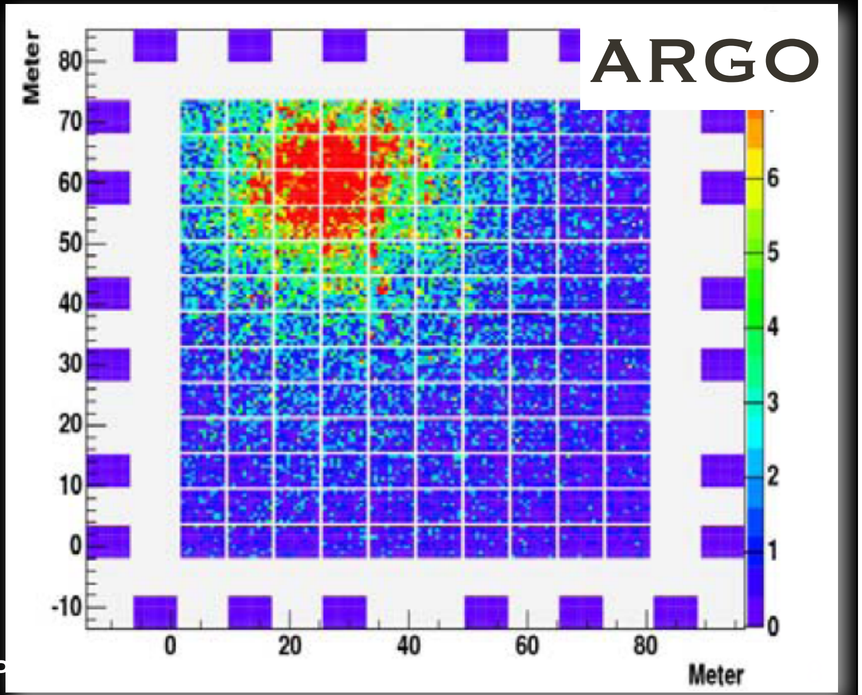
Extensive Air Shower Arrays

- Detect particle that survive to ground level
- Scintillation detector arrays sparsely instrument the ground <2% coverage
- Water detectors (or RPC carpet) can densely sample the shower particles (~50% particles detected)
- Water will also convert gamma rays to electrons/positrons (gamma rays dominate the particles on ground ~6:1)
- Deep water detector (≳4m) can serve as muon detector

Angular and Energy Reconstruction

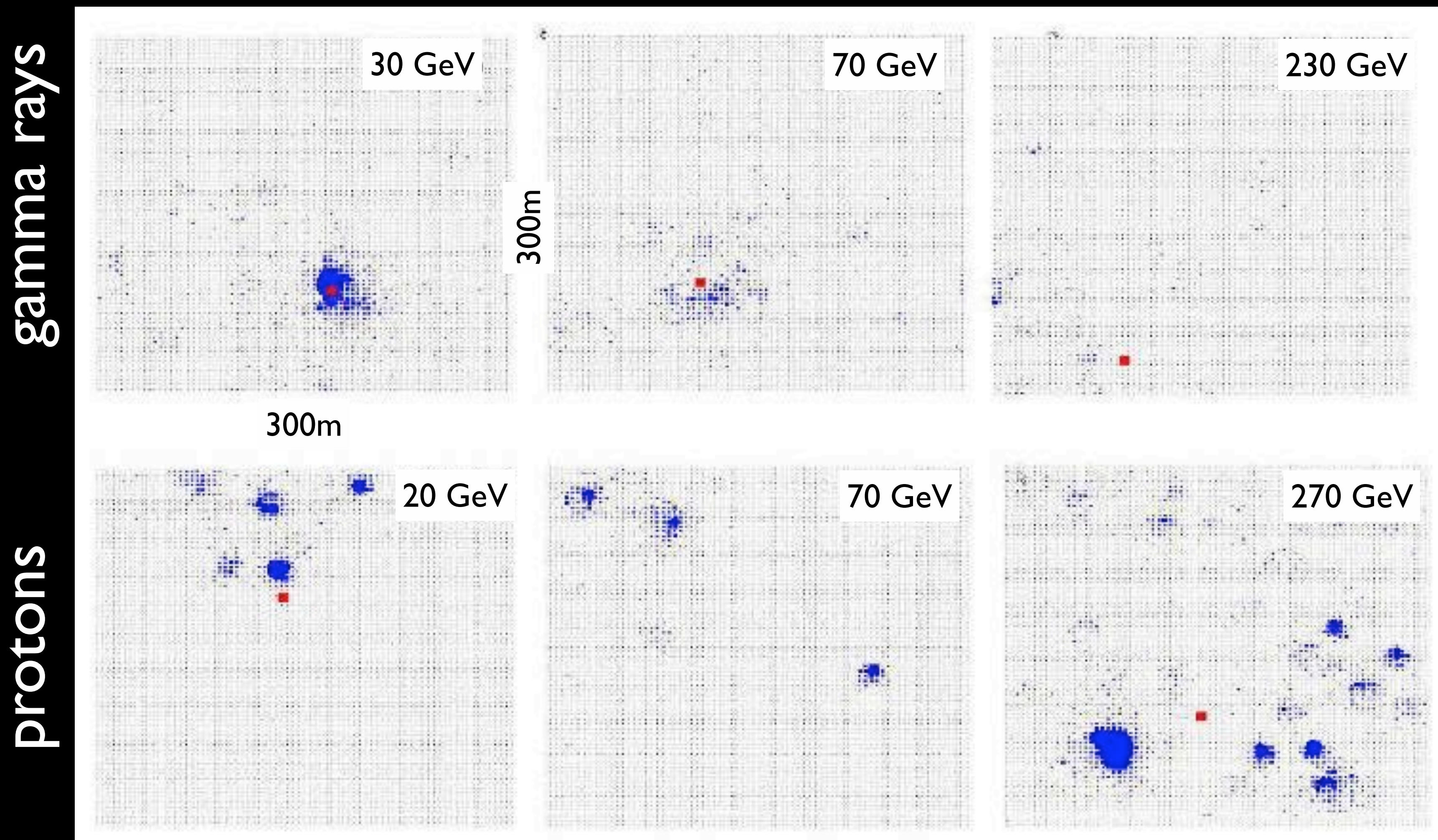


Direction via timing
(~ns timing yields 0.2°-1° resolution)



Primary energy via energy at ground
(shower fluctuations dominate resolution ~40%)

Background Rejection

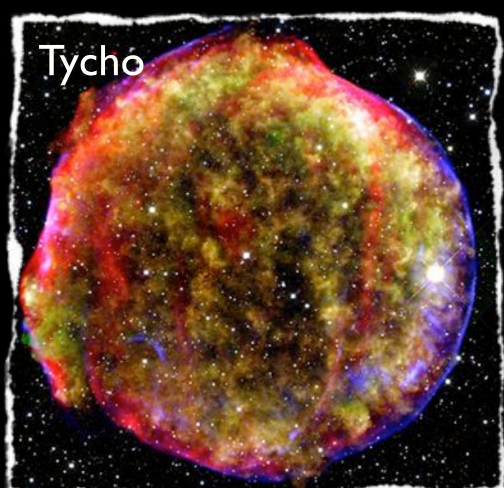


VHE Instruments

Galactic Gamma-Ray Sources

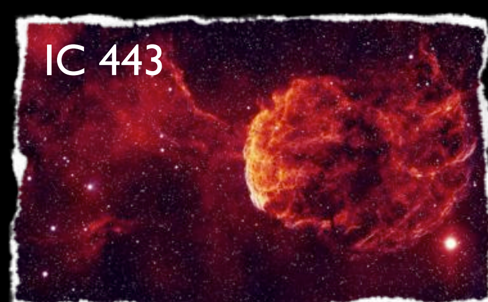
PWN

SNR



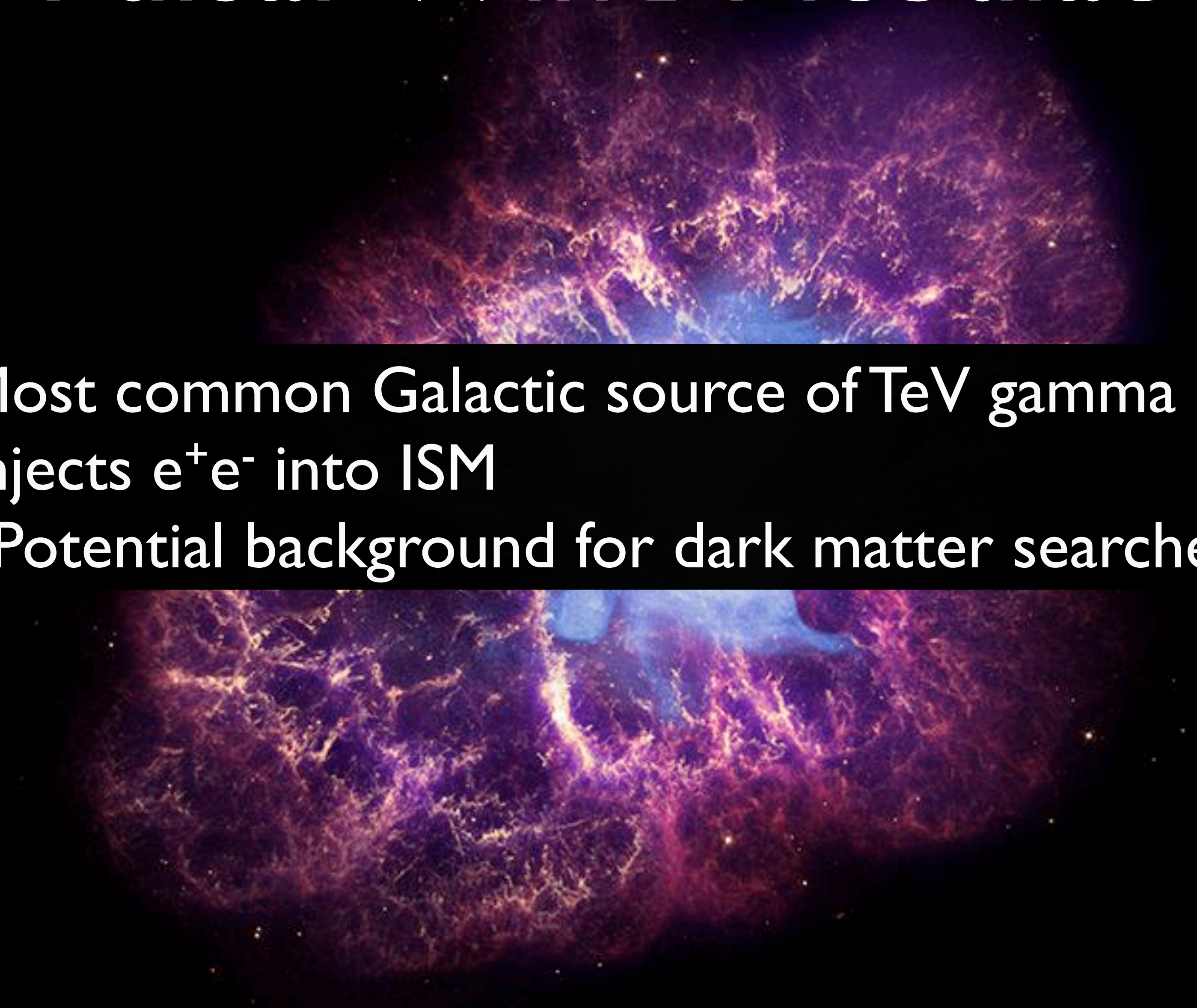
Globular Clusters

SNR/Molecular Clouds



38 PWN/PSR
30 UNID
13 SN Shell
9 SNR/Mol. Cloud
8 binaries
4 massive star clusters
2 Star Forming Regions
1 Cataclysmic Variable
1 Globular Cluster

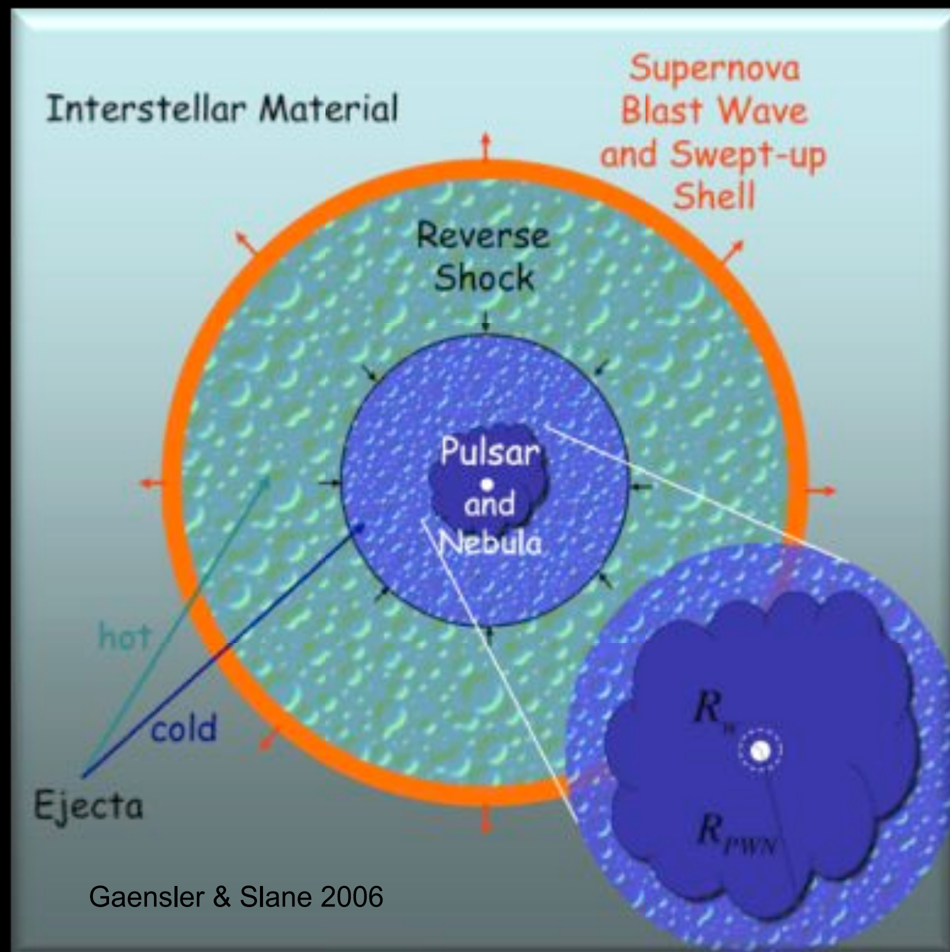
Pulsar Wind Nebulae



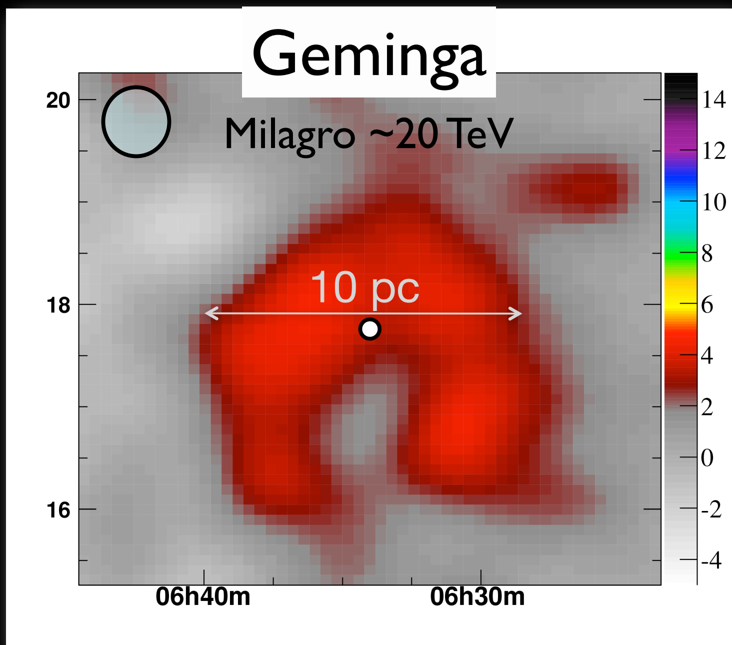
- Most common Galactic source of TeV gamma rays
- Injects e^+e^- into ISM
  - Potential background for dark matter searches

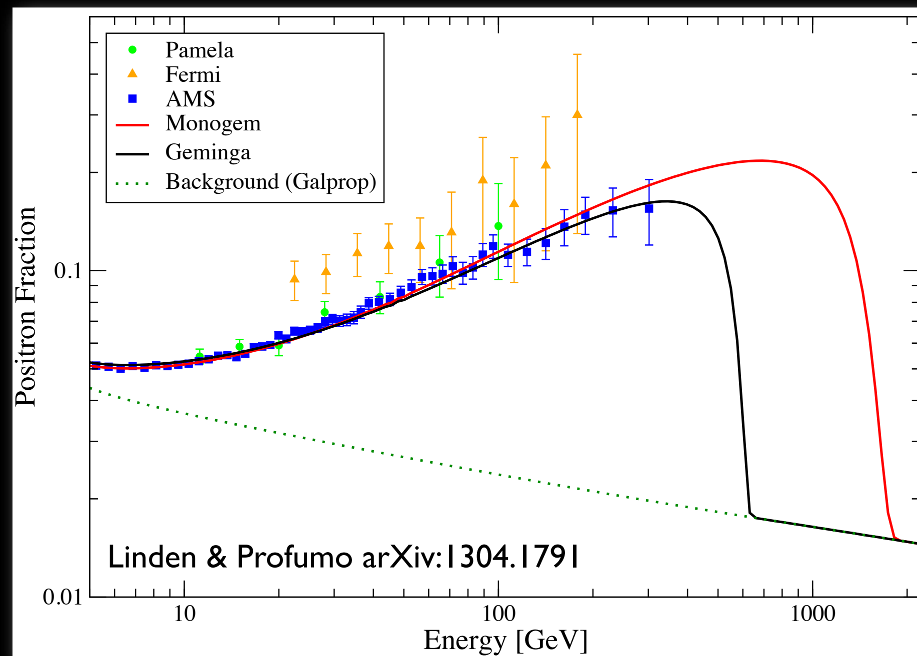
Pulsar Wind Nebulae

- Rapidly spinning neutron star powers a cold relativistic electron-positron wind
- Wind termination shock accelerates e^+e^-
- Inverse Compton reactions lead to production of VHE gamma rays
- Over time nebula expands, magnetic field weakens, and e^+e^- are released into the ISM



PWN: Positron Generators

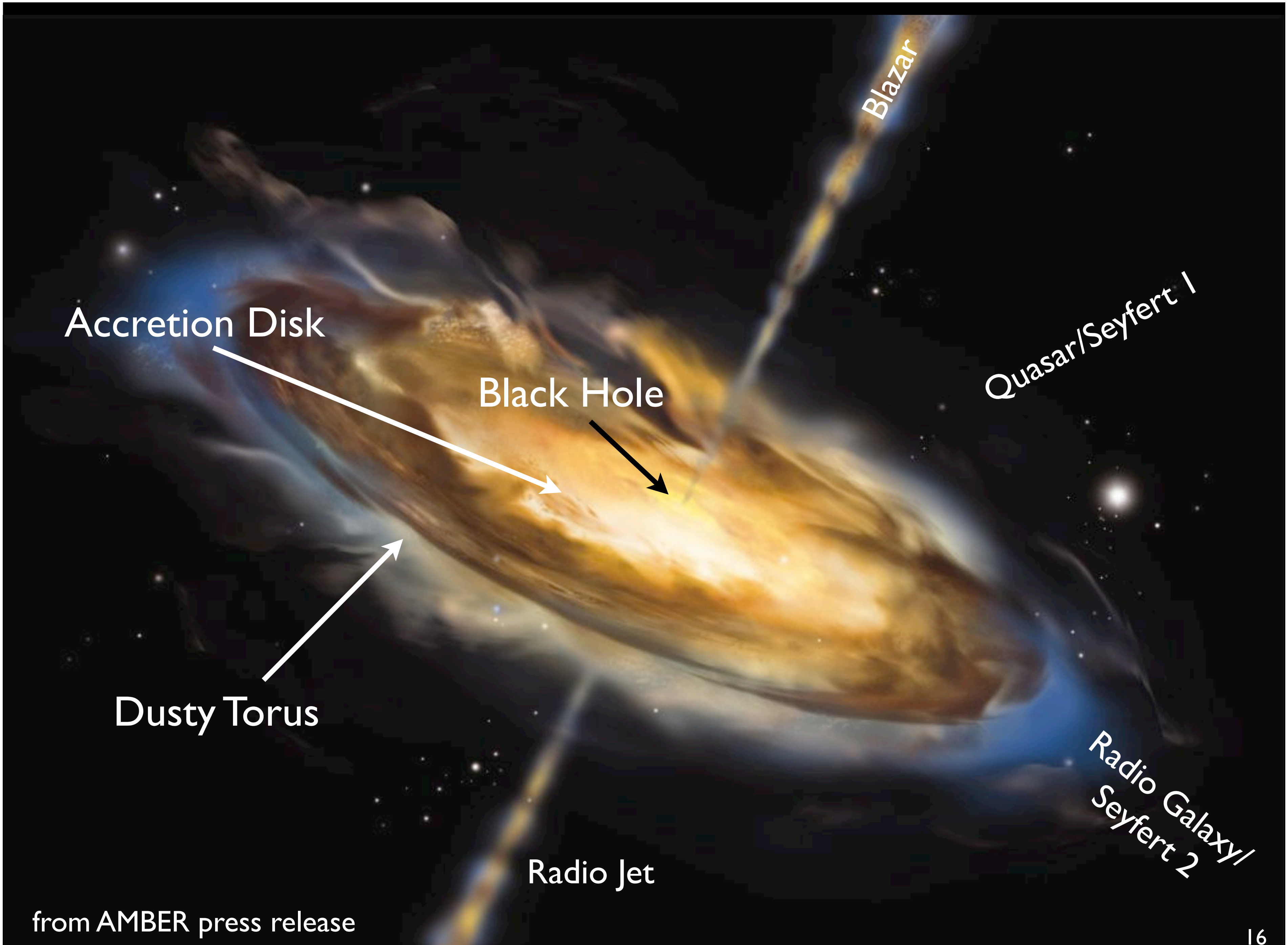




- Geminga (~300,000 yrs at ~200 pc) and Monogem (100,000 yrs at ~300 pc) are good candidates
- Milagro detected an extended gamma ray source (3^o) coincident with the Geminga pulsar (~10^{32} ergs/sec) at ~20 TeV. Most likely seeing the PWN.

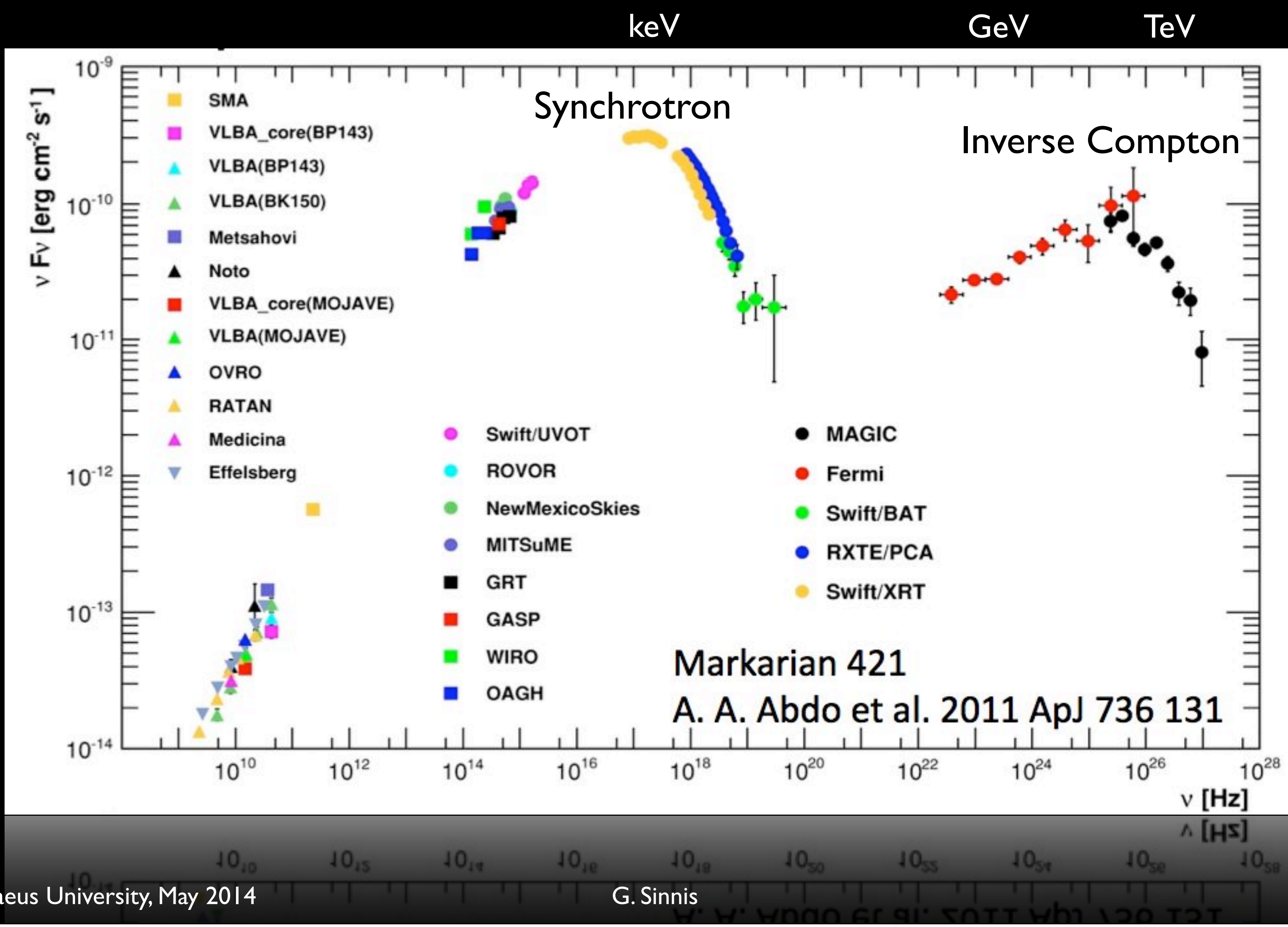
Extragalactic Gamma Rays

- Active Galaxies (57 detected in VHE band)
- Gamma Ray Bursts (not yet detected from ground)
  - Extragalactic Background Light
  - Primordial Magnetic Fields
  - Axion-like Particle Searches
  - Lorentz Invariance Violation

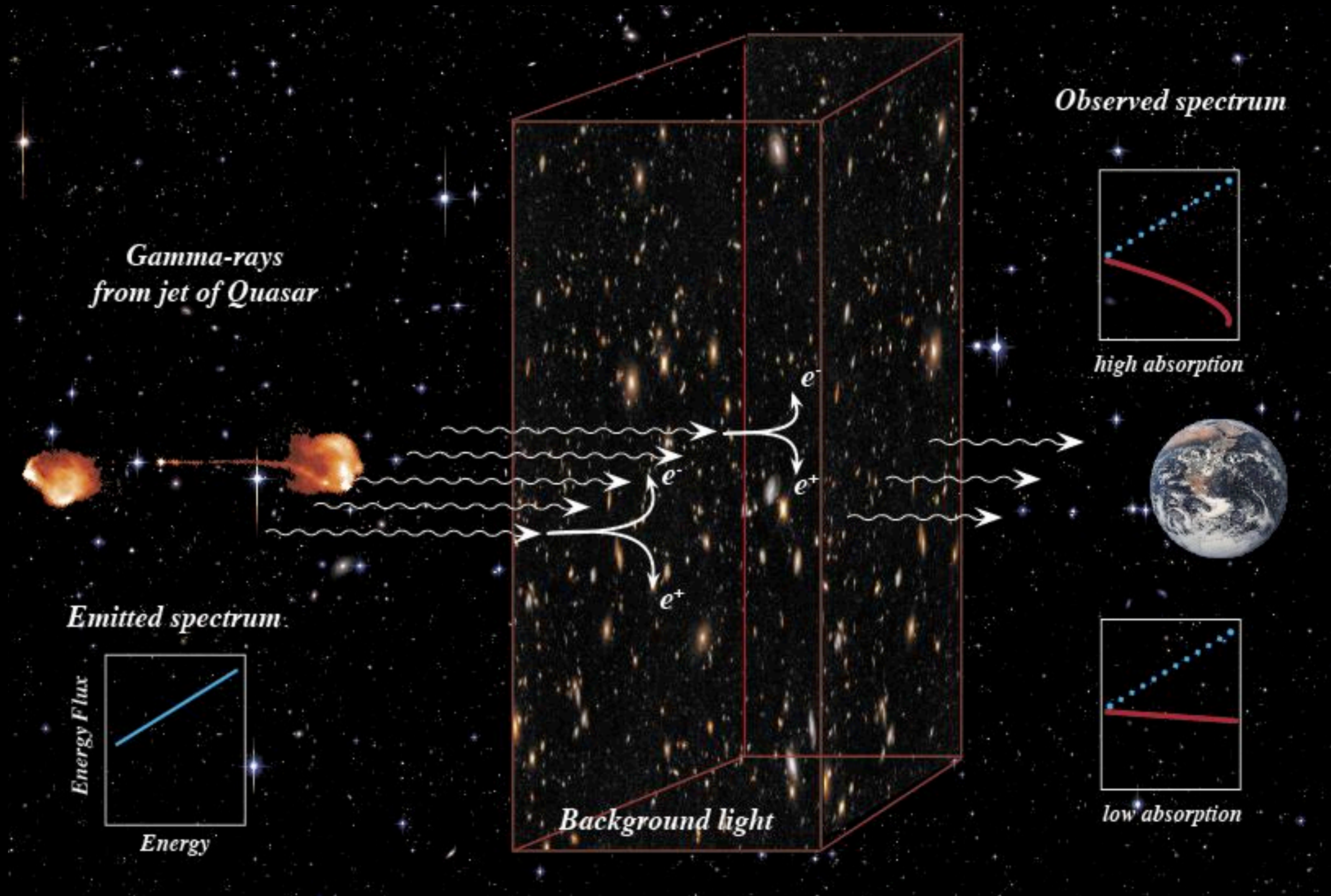


from AMBER press release

AGN Spectral Energy Distribution



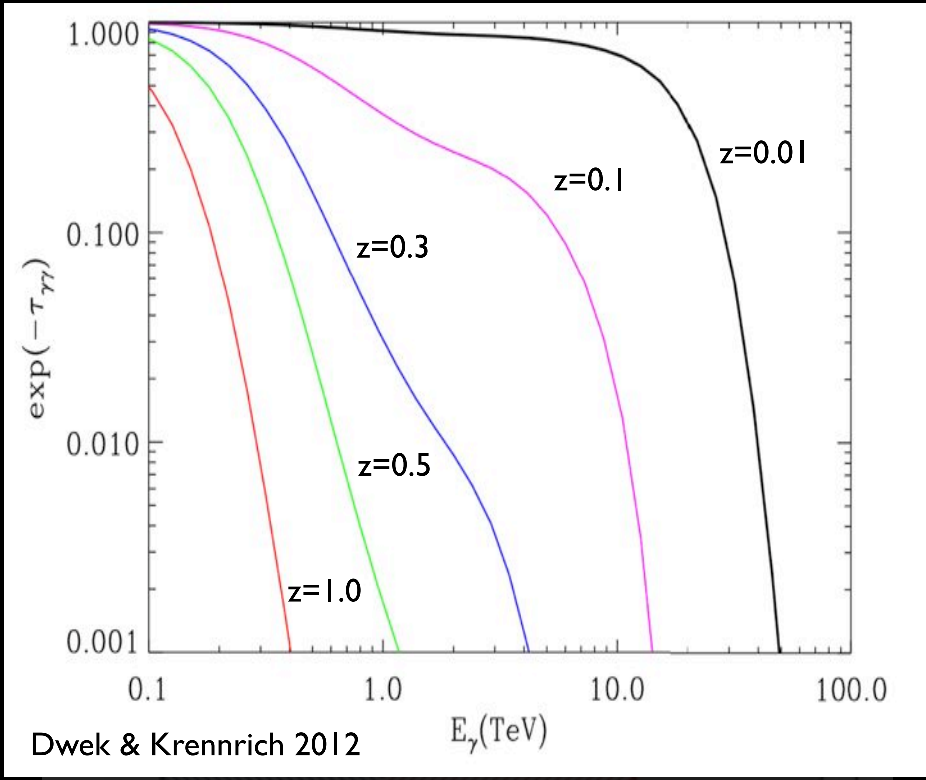
Extragalactic Background Light



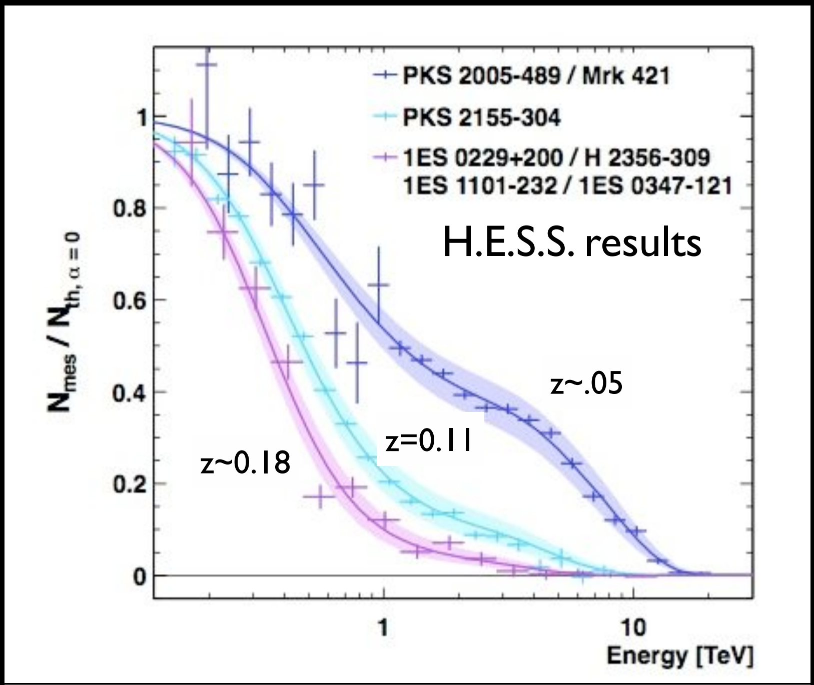
from CTA and MPI

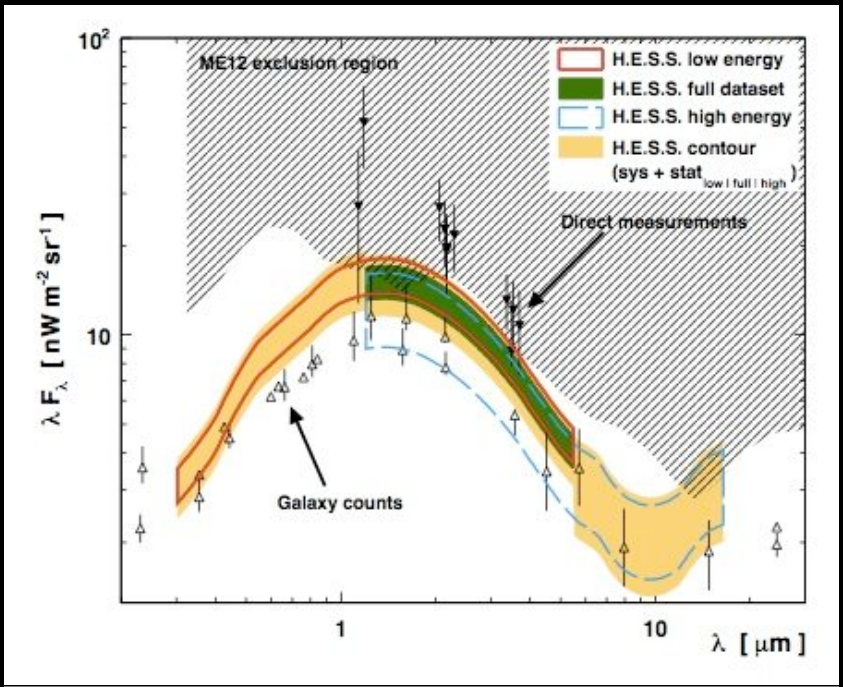
The EBL

- The sum of all UV, optical, and IR radiation emitted over the history of the universe
- Main contributions from stars and light re-radiated by dust
- Direct measurement difficult due to local backgrounds (zodiacal light)
- Gamma-ray absorption measurements are the best way to measure EBL
- EBL is useful tool for probing other physics
  - Axion-like particles
  - UHECR accelerators
  - IGMFs



EBL Measurements



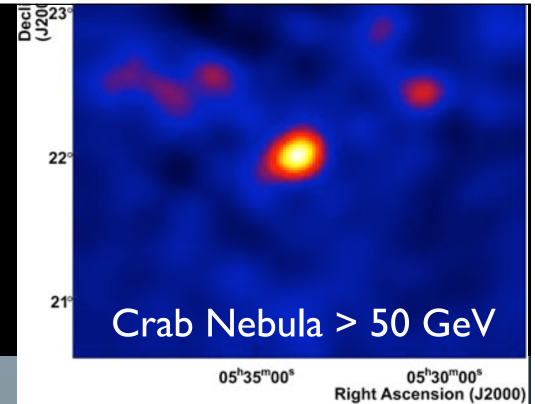


- H.E.S.S. has measured the EBL from 2~1-10 microns
- Fermi has measured the EBL below 0.2 micron (3±1 nW m^{-2} sr^{-1} at z=1)
- These values are close to the lower bounds set by Galaxy counts
- Large star formation rates at the end of the cosmic dark ages excluded

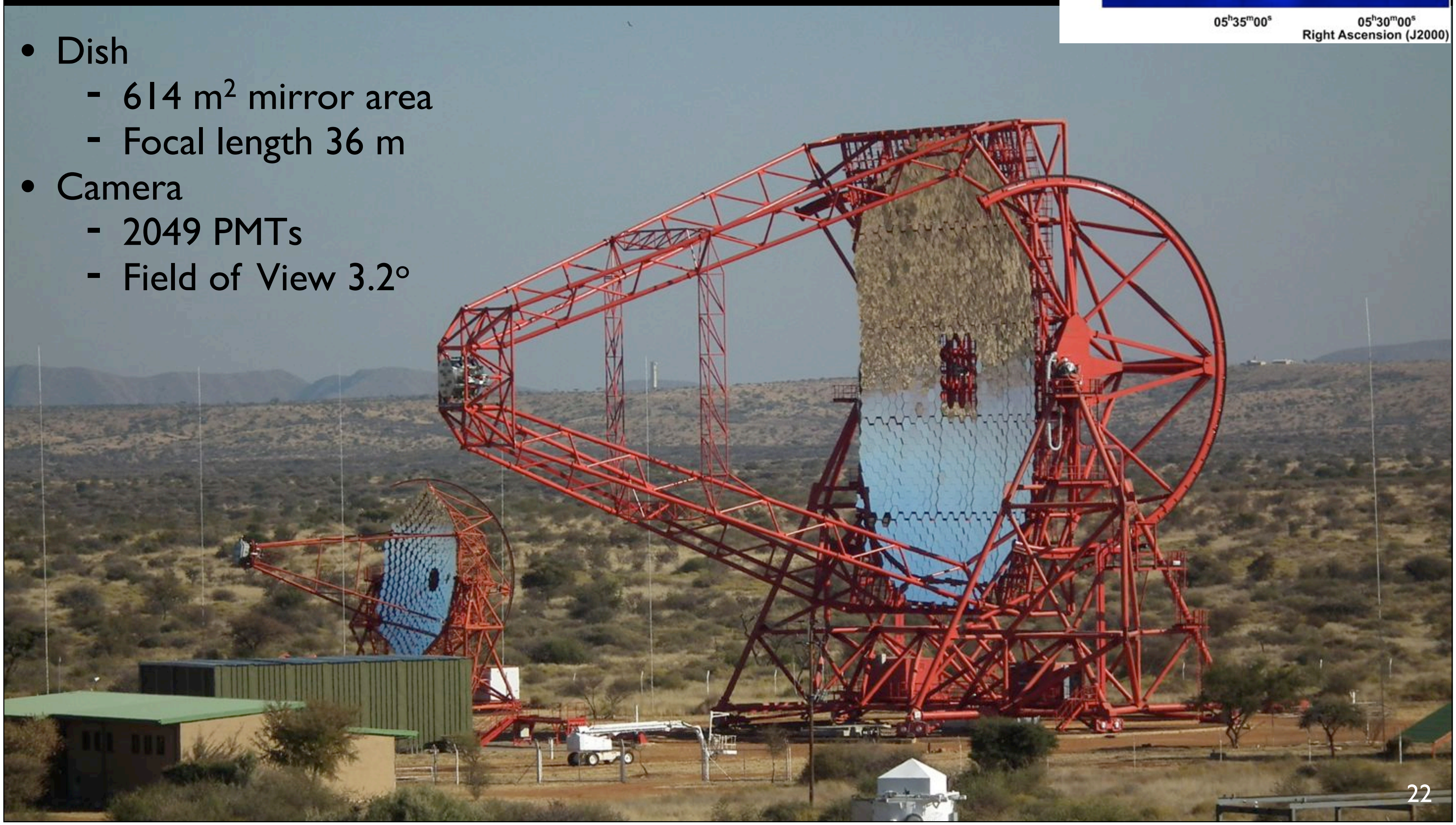
Future Facilities

- H.E.S.S. II - 30 meter dish at H.E.S.S. site
- HAWC - air shower array
  - HAWC-111 operating since August 2013
  - 300-tank array complete September 2014
- LHAASO - air shower array
  - See talk by Zhen Cao (Friday a.m.)
- CTA - Imaging Atmospheric Cherenkov Telescope Array
  - See talk by J. Knödlseder (this session)

H.E.S.S. II



- Dish
  - 614 m^2 mirror area
  - Focal length 36 m
- Camera
  - 2049 PMTs
  - Field of View 3.2°

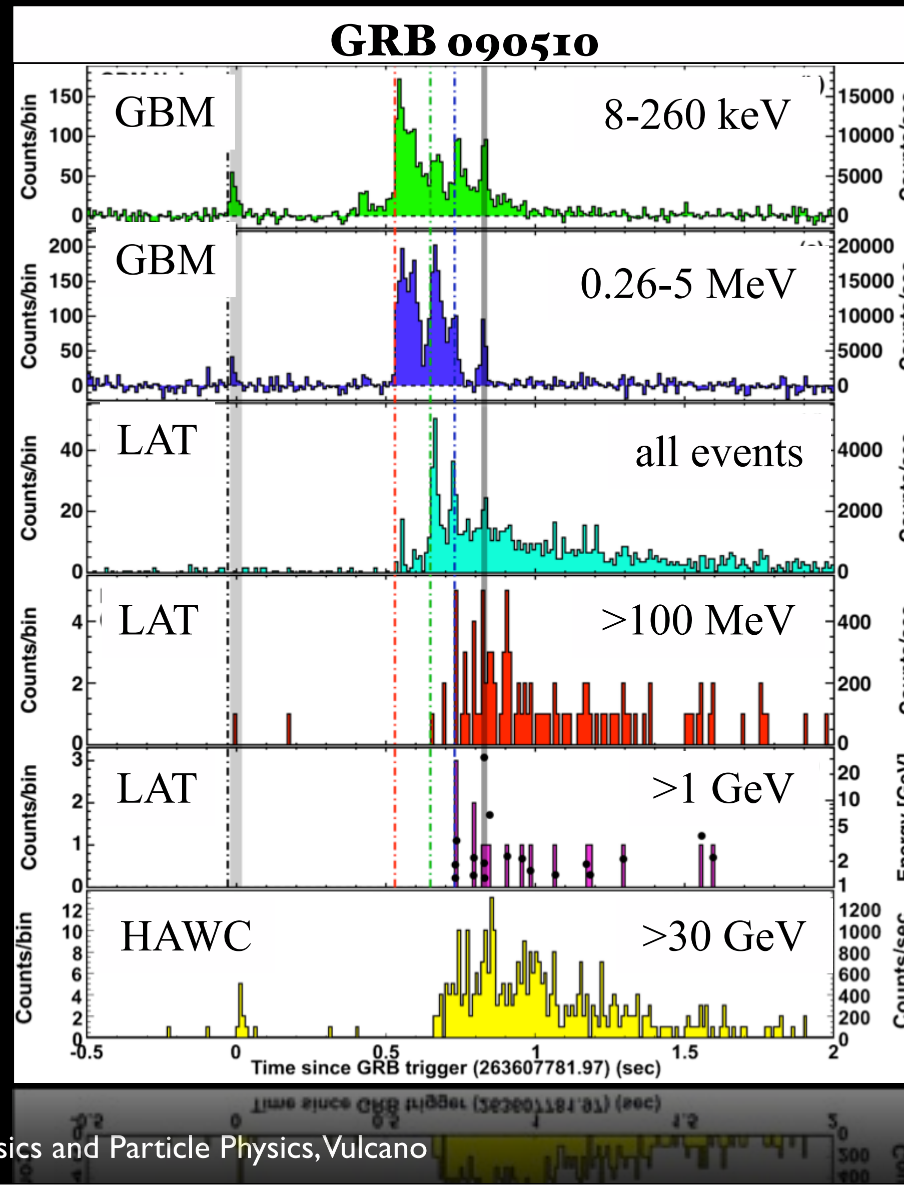


HAWC

- Sierra Negra, Mexico (19^{o} north, 97^{o} west)
- High elevation (4100m)
- ~22,000 m^2 area (also muon detector)
- ~10-15x more sensitive than Milagro

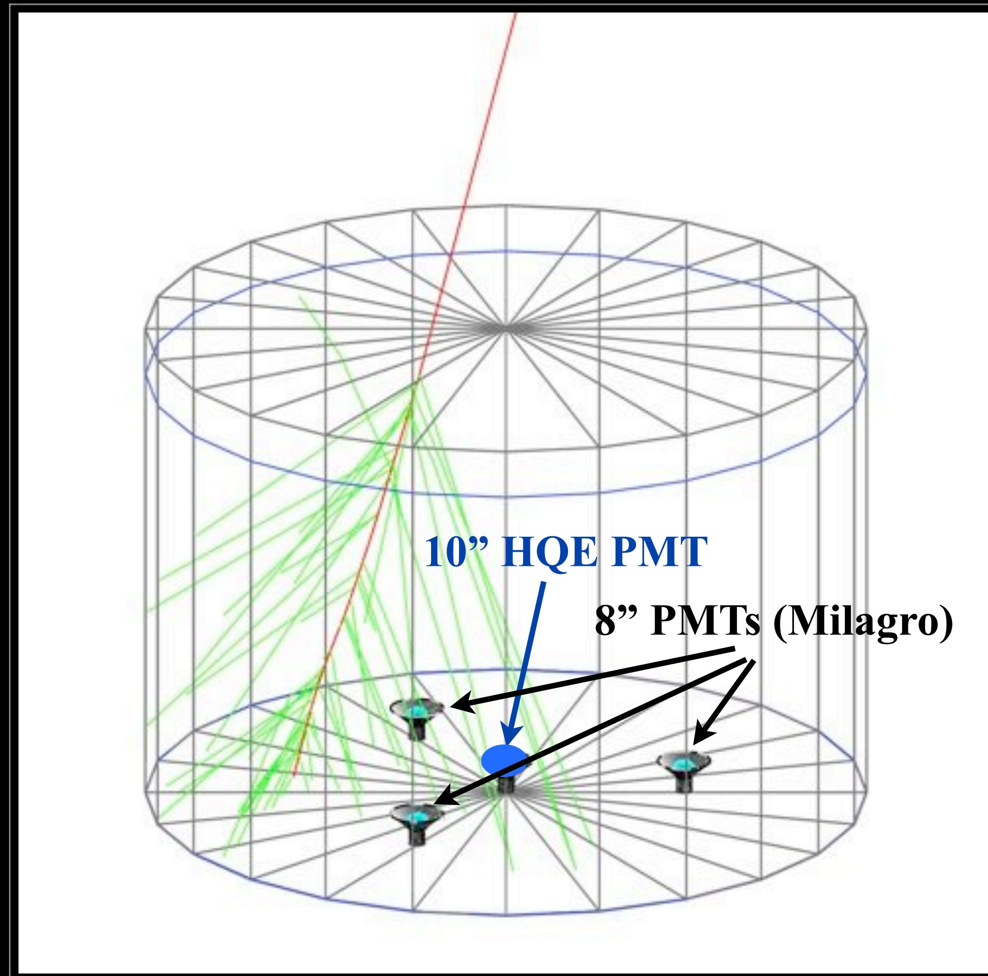
HAWC Science Goals

- 8 sr sky survey
- VHE Transients
  - AGN, GRB
- Cosmic-ray origins
- Fundamental physics
  - TeV-scale DM
  - IGMF (~10^{-16} Gauss)
  - Q-Balls (~10^{15} GeV DM)
- Multi-wavelength and Multi-messenger campaigns

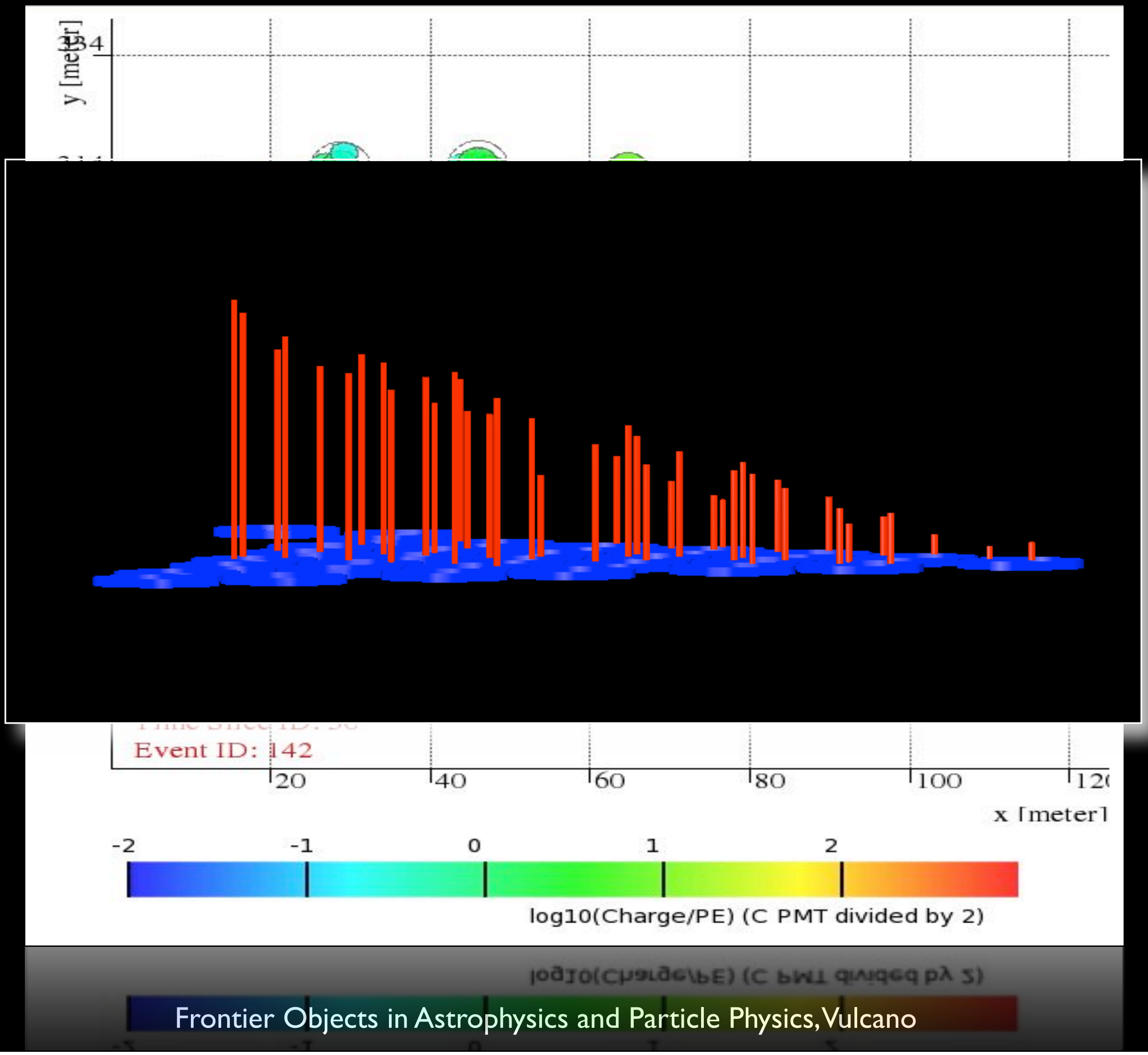


HAWC Design

- 300 steel tanks
- 4 PMTs/tank
- No hardware trigger
  - all hits (1/4 PE threshold) readout
  - software trigger
  - ~500 MBytes/sec
- Retain all data for 24 hrs (40 TBytes)
- Reconstructed data ~600 TBytes/yr

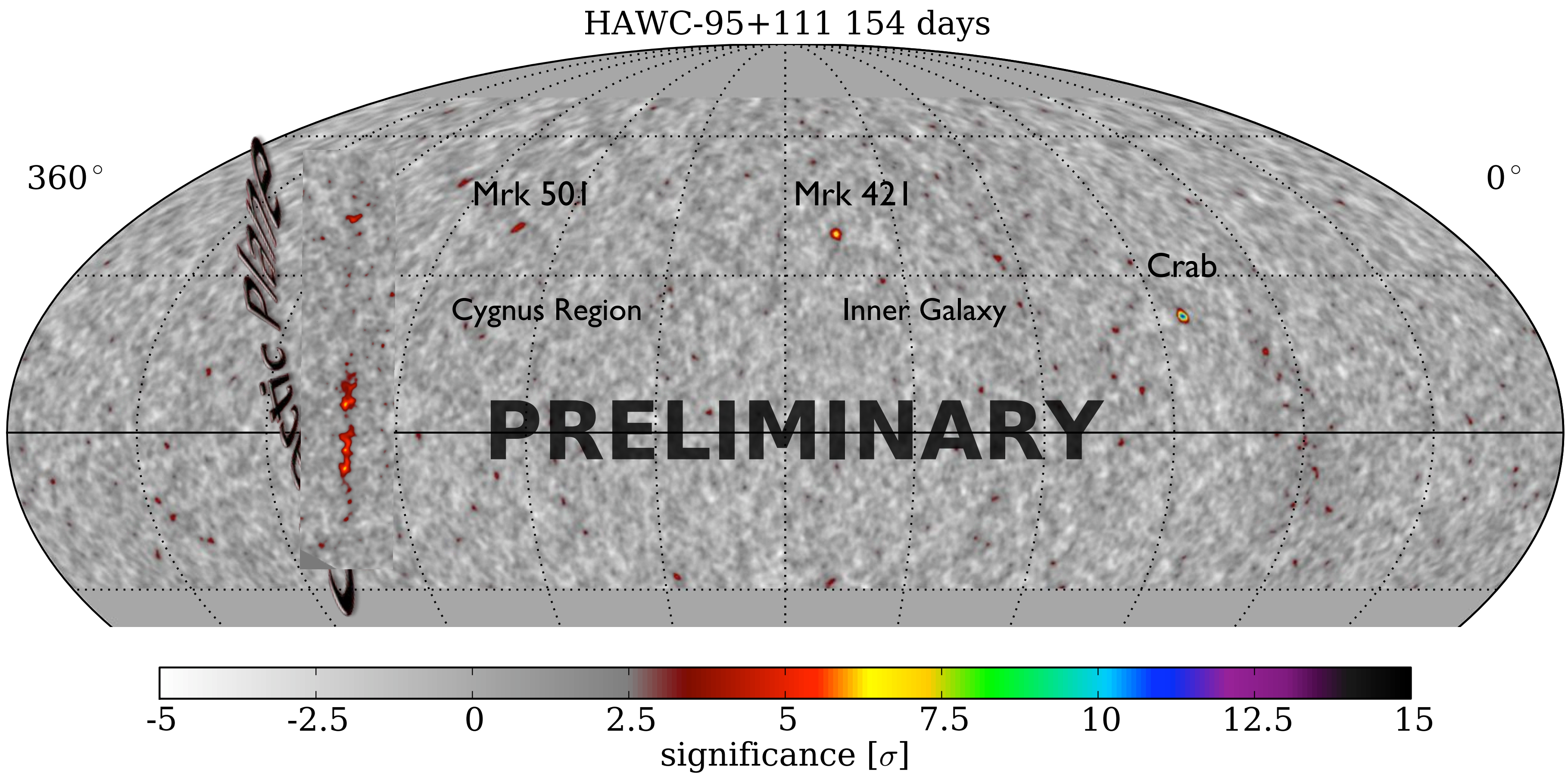


HAWC Event

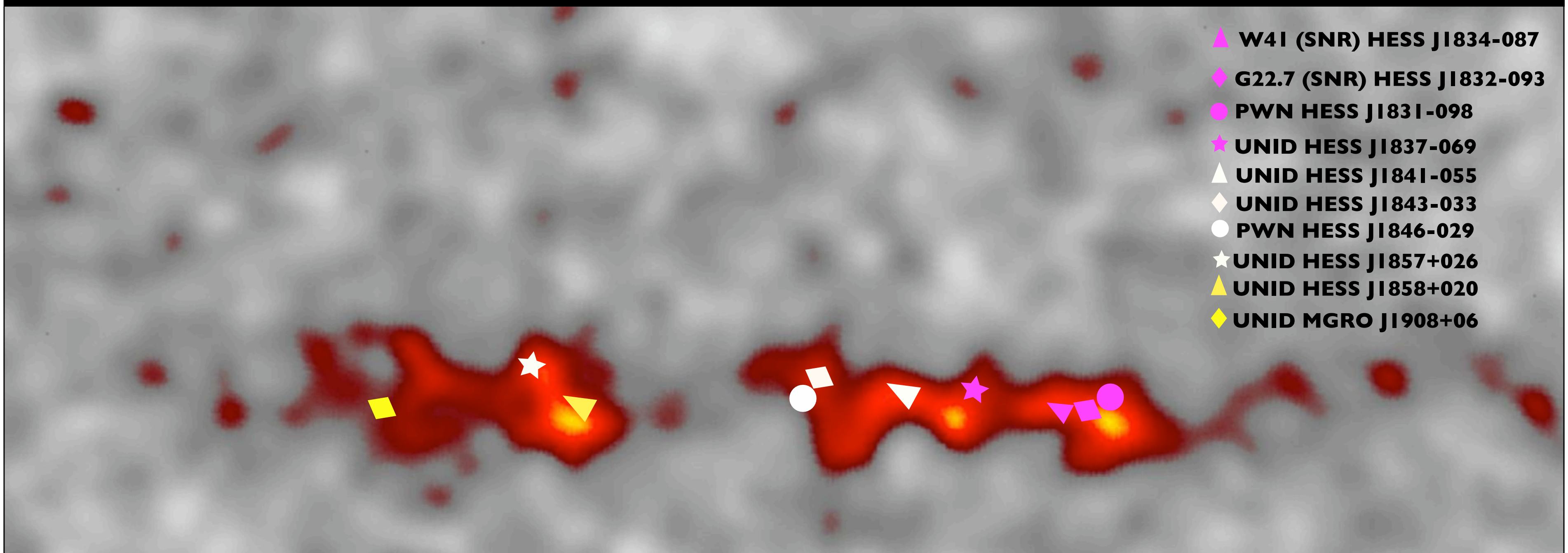


y [meter]
Event ID: 142
20
40
60
80
100
x [meter]
-2
-1
0
1
2
log10(Charge/PE) (C PMT divided by 2)

HAWC-111 Sky


HAWC-95+111 154 days
360°
0°
Mrk 501
Mrk 421
Crab
Cygnus Region
Inner Galaxy
PRELIMINARY
-5
-2.5
0
2.5
5
7.5
10
12.5
15
significance [σ]

The Inner Galaxy



A complex region supernova remnants, molecular clouds, PWN, ...

Summary

- Gamma-Ray experimental techniques have made enormous progress in the past 25 years
- Complementarity of all-sky and pointed instruments
- Now have ~150 sources in the TeV band
  - Large diversity of source classes
  - Have begun to probe fundamental physics: Dark Matter, EBL, IGMF, ALPs, & Lorentz invariance violation
- Future facilities promise large ~10x increase in sensitivity
  - Expect ~1000 sources (high precision)
  - See CTA and LHASSO talks
- HAWC is now operating and will soon be complete - sky survey in the TeV regime.

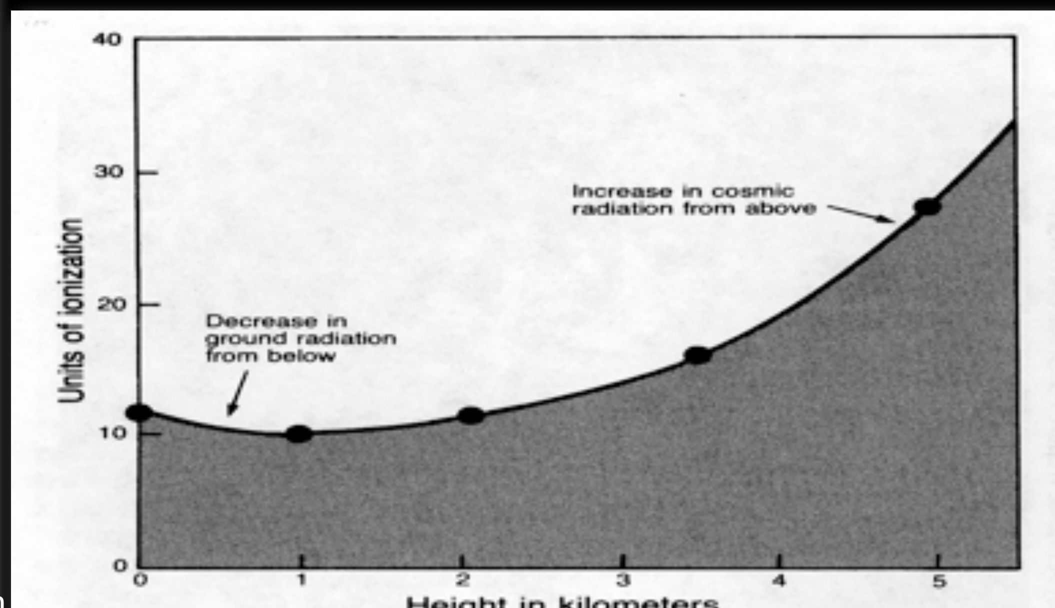
Thanks To

Stefan Funk, Werner Hofmann, Jamie Holder, Christian Stegmann, Rene Ong, David Williams, Cao Zhen

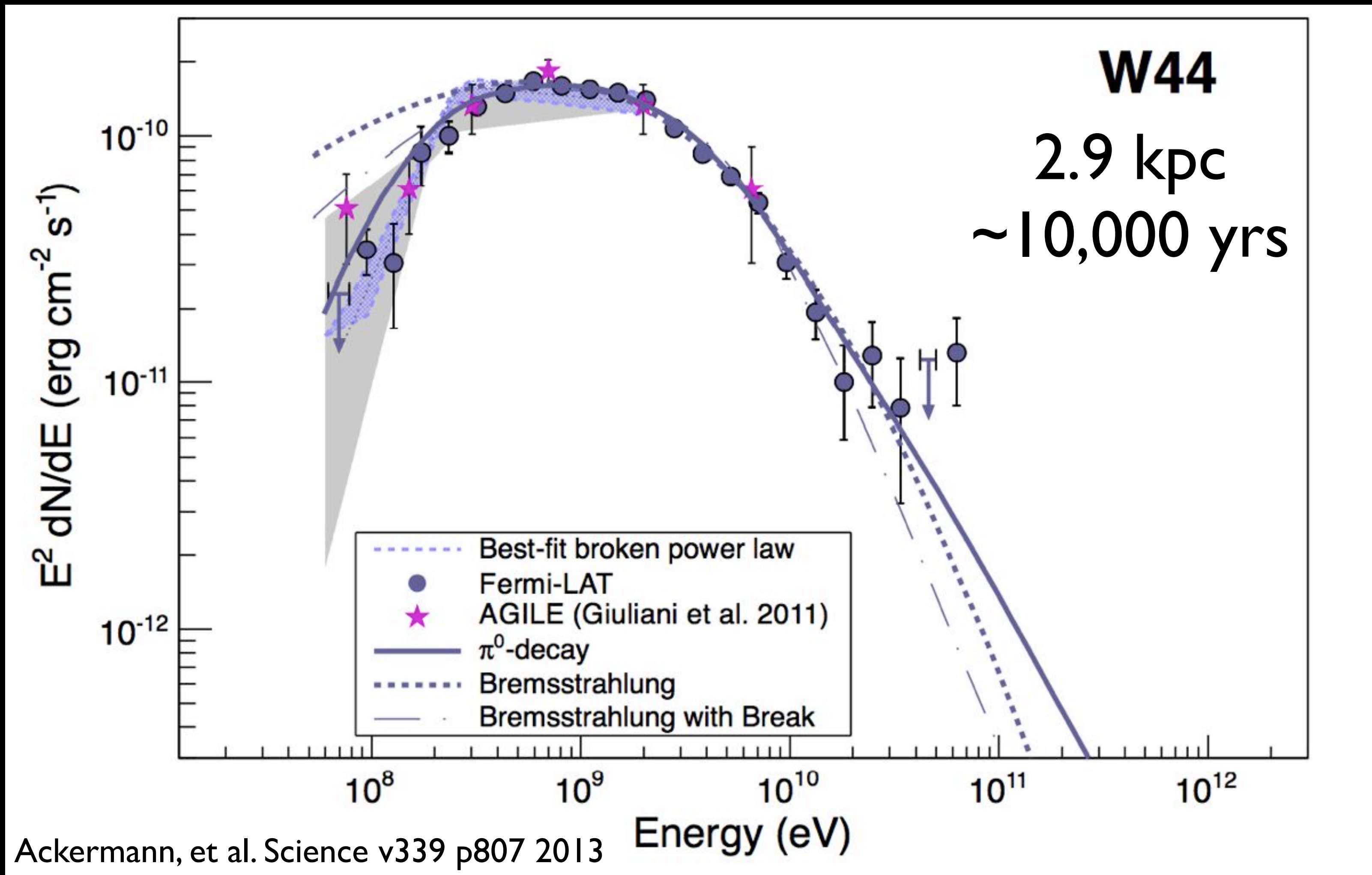
Back Up

Cosmic Ray Origins

- V. Hess 1911-1912 balloon flights determined cosmic origin of background radiation
- "We still do not know what processes out in the deep fastnesses of space give rise to this radiation. ... no one has yet been able to provide any detailed explanation of how these rays - over a thousand times more powerful than the strongest radioactivity - come into being." - V. Hess 1936 Nobel acceptance speech

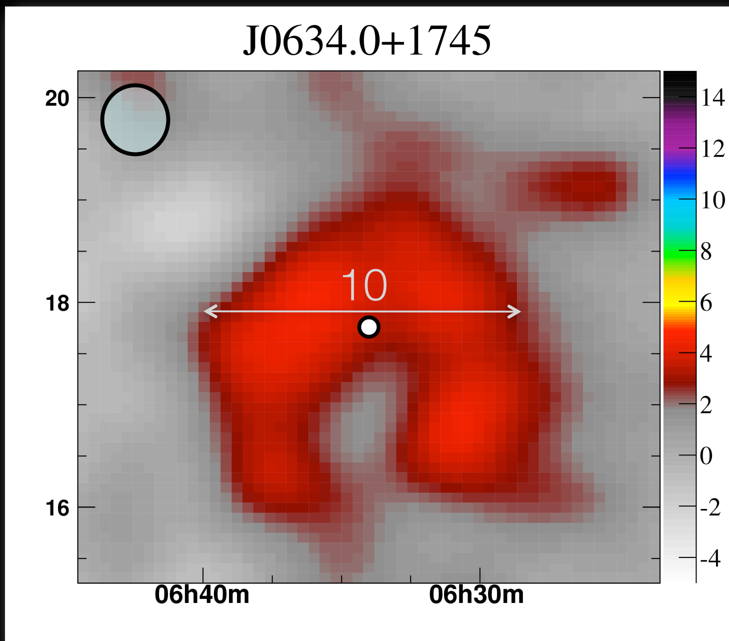


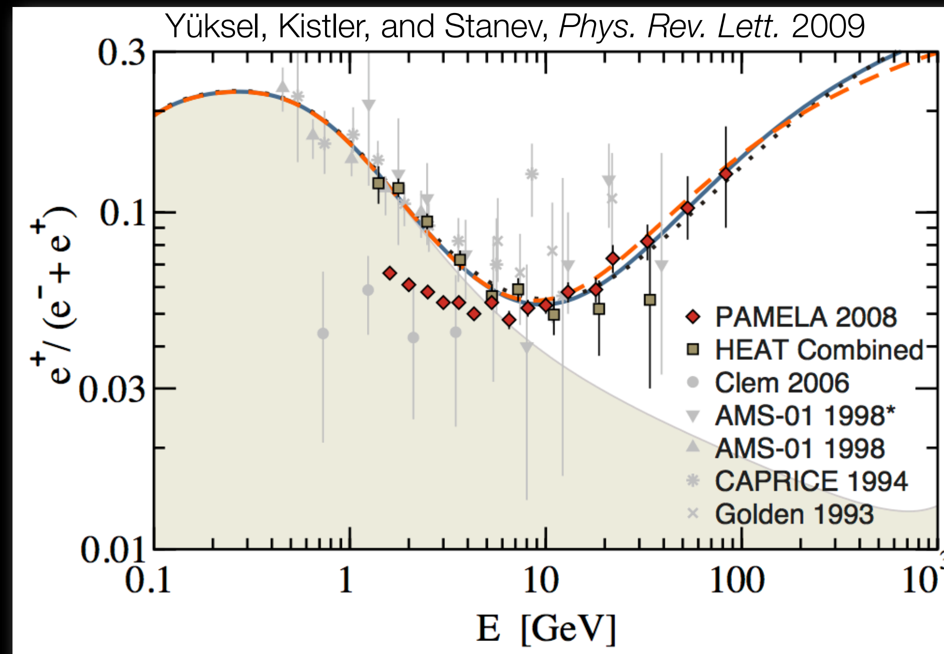
Cosmic-Ray Acceleration in SN Remnants



Ackermann, et al. Science v339 p807 2013

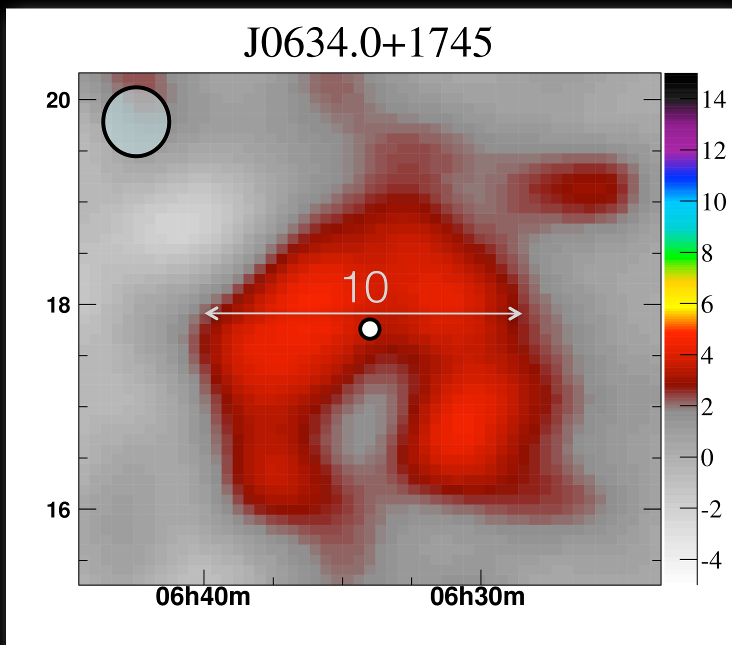
Geminga

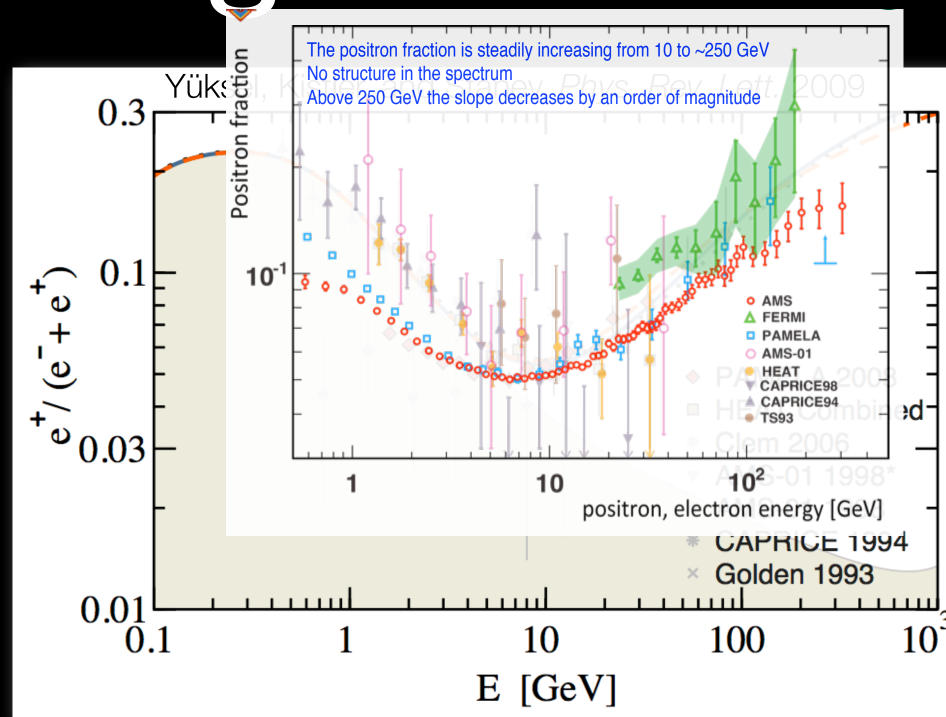




- Geminga is an old (~300,000 yrs) nearby (~200 pc) pulsar
- Milagro detected an extended gamma ray source (3°) coincident with the Geminga pulsar (~10^{32} ergs/sec) at ~20 TeV. Most likely seeing the PWN.
- The observed gamma-ray flux (IC from CMB) from Milagro yields an e^+e^- flux (~10^{45} ergs/sec) that can explain the increasing e^+ fraction (Yuksel, et al.)

Geminga





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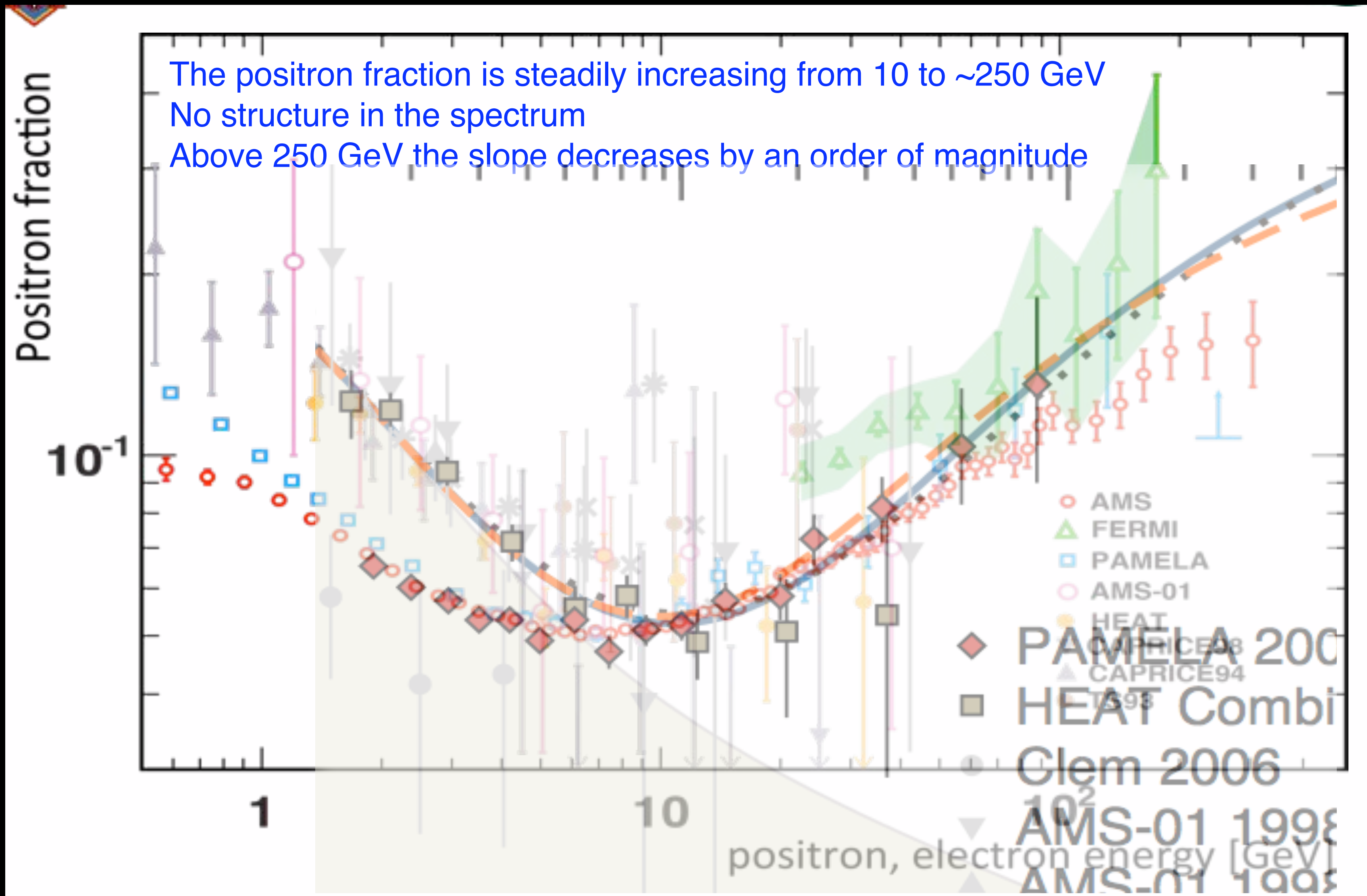
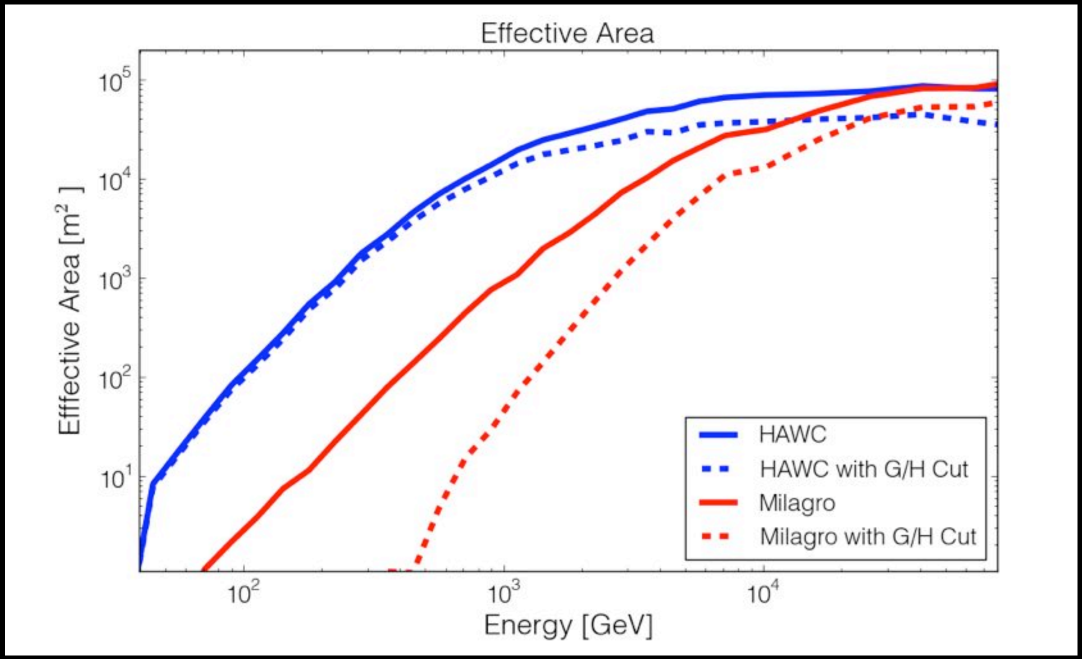
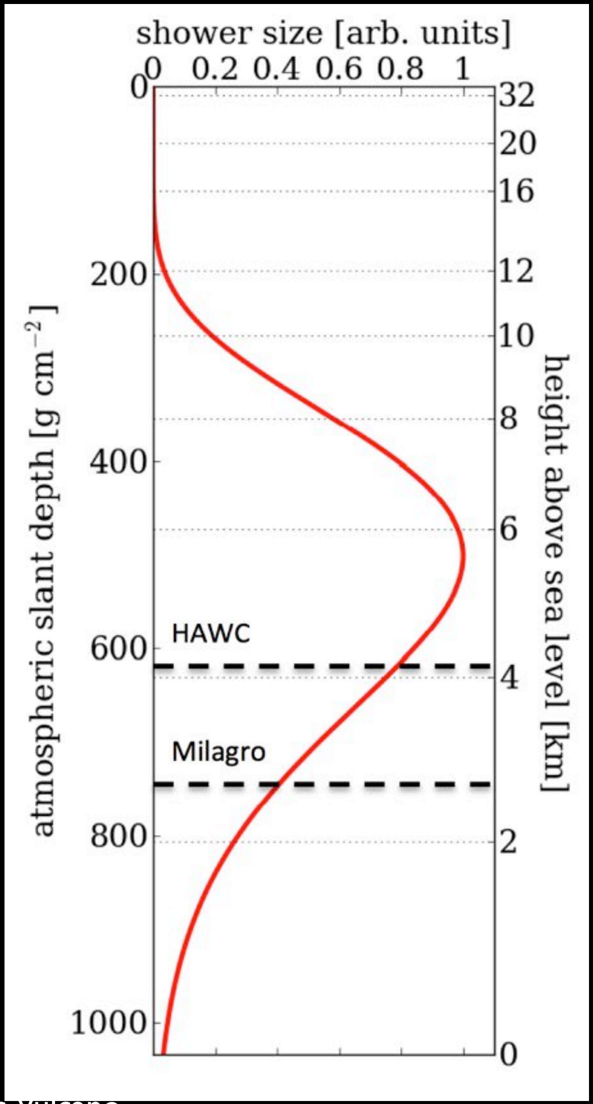
The positron fraction is steadily increasing from 10 to ~250 GeV
No structure in the spectrum
Above 250 GeV the slope decreases by an order of magnitude



HAWC Improvements

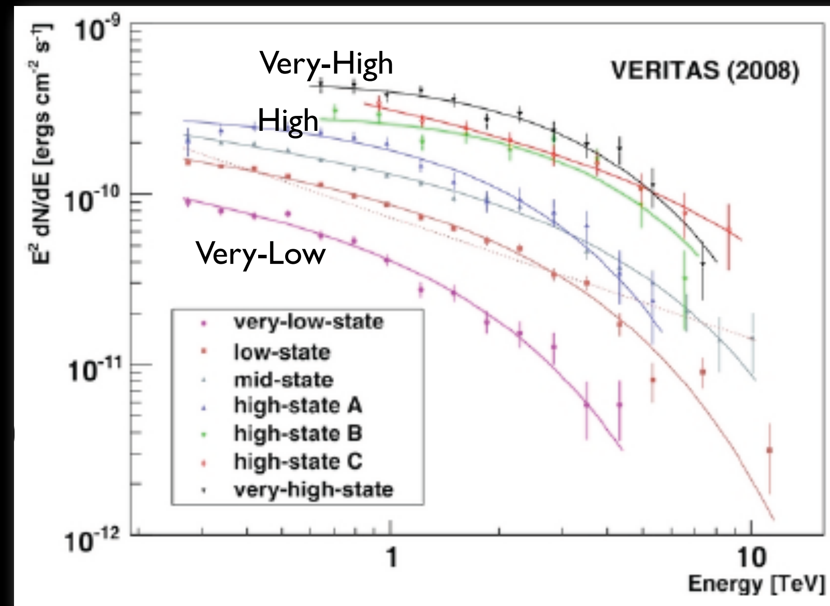
- High altitude 4100m asl
- Large, 22,000 m^2 muon detector
- Optical isolation

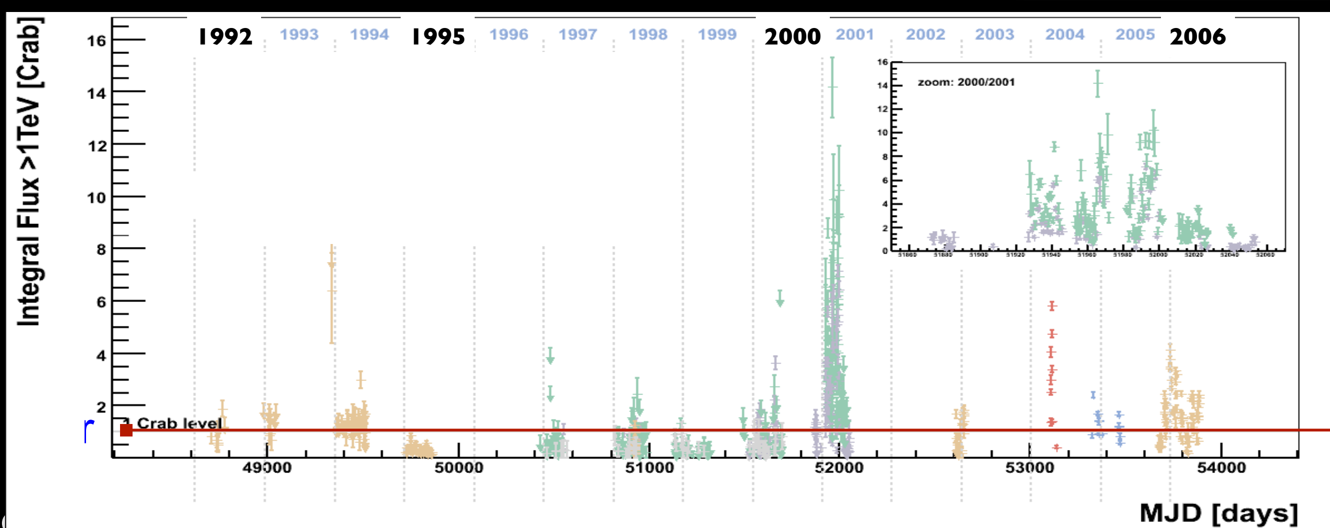




Active Galaxies

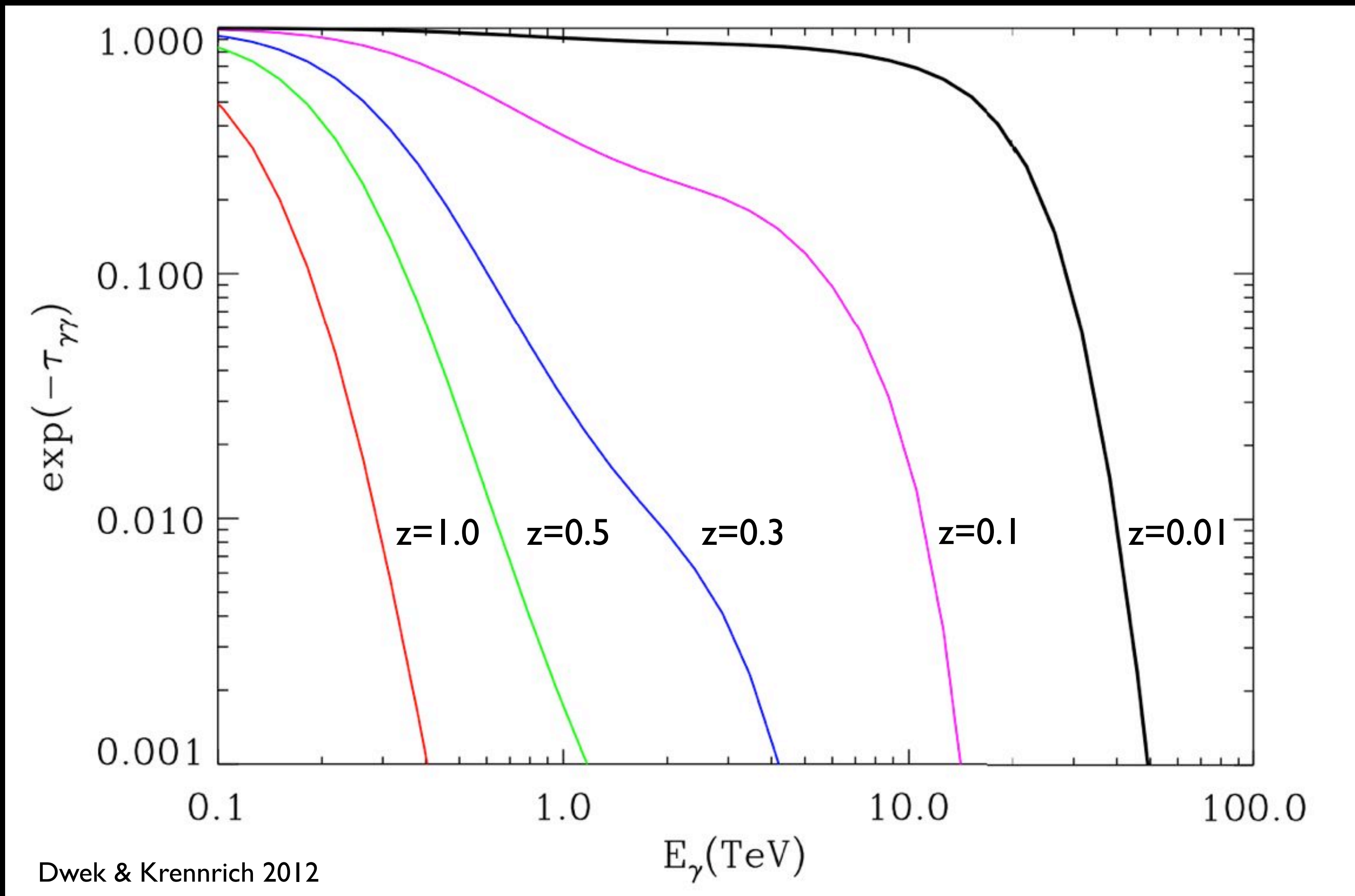
- >50 AGN detected at TeV energies
- >1000 AGN detected by Fermi-LAT
- HAWC will observe 8 sr of the sky every day
- Mrk-421 detectable:
  - "very-high-state" in 30 minutes (8σ)
  - "high state" 1 day
  - "very-low-state" 1 month



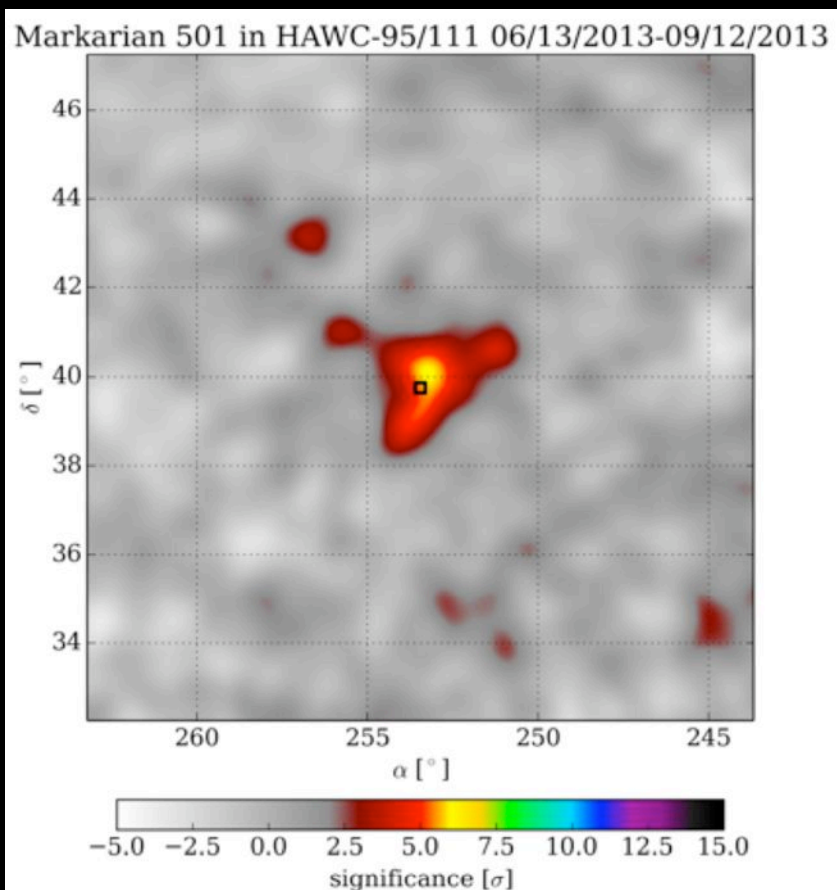


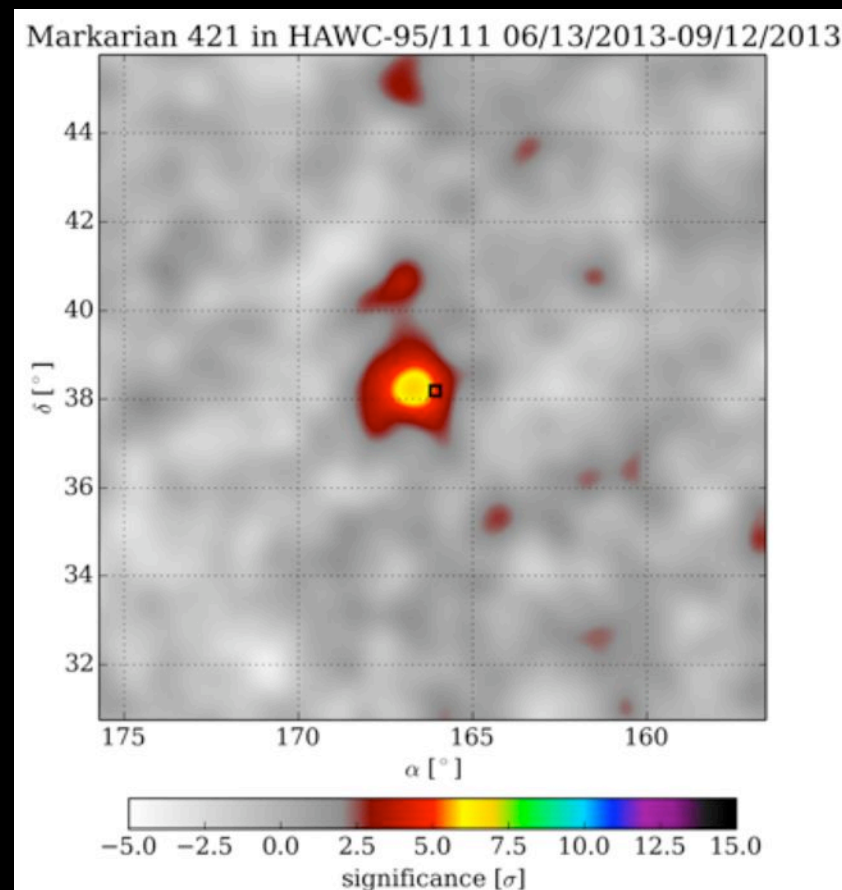
HAWC 1-day sensitivity

Spectral Distortion



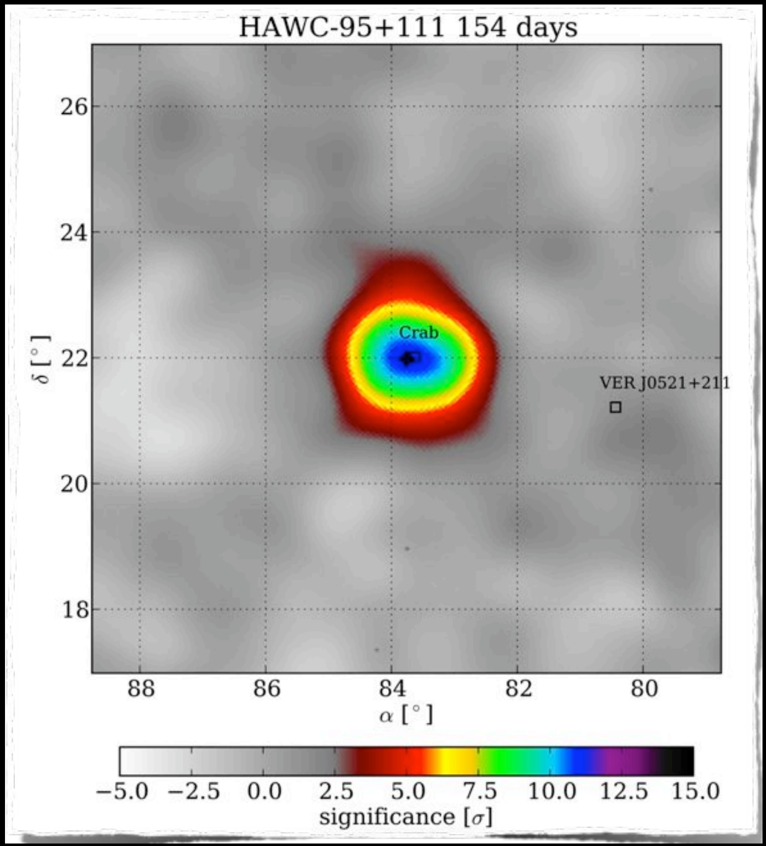
Mrk 501 and Mrk 421





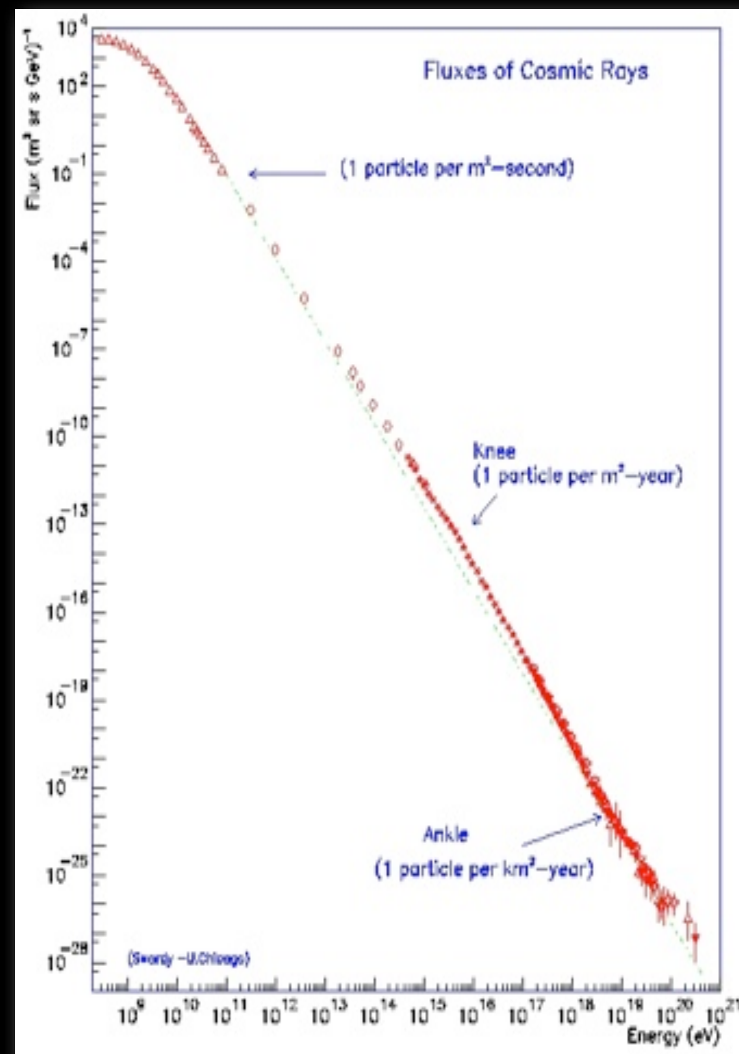
Crab Nebula

- 154 days data
- 11σ at Crab location
- High-energy data not included



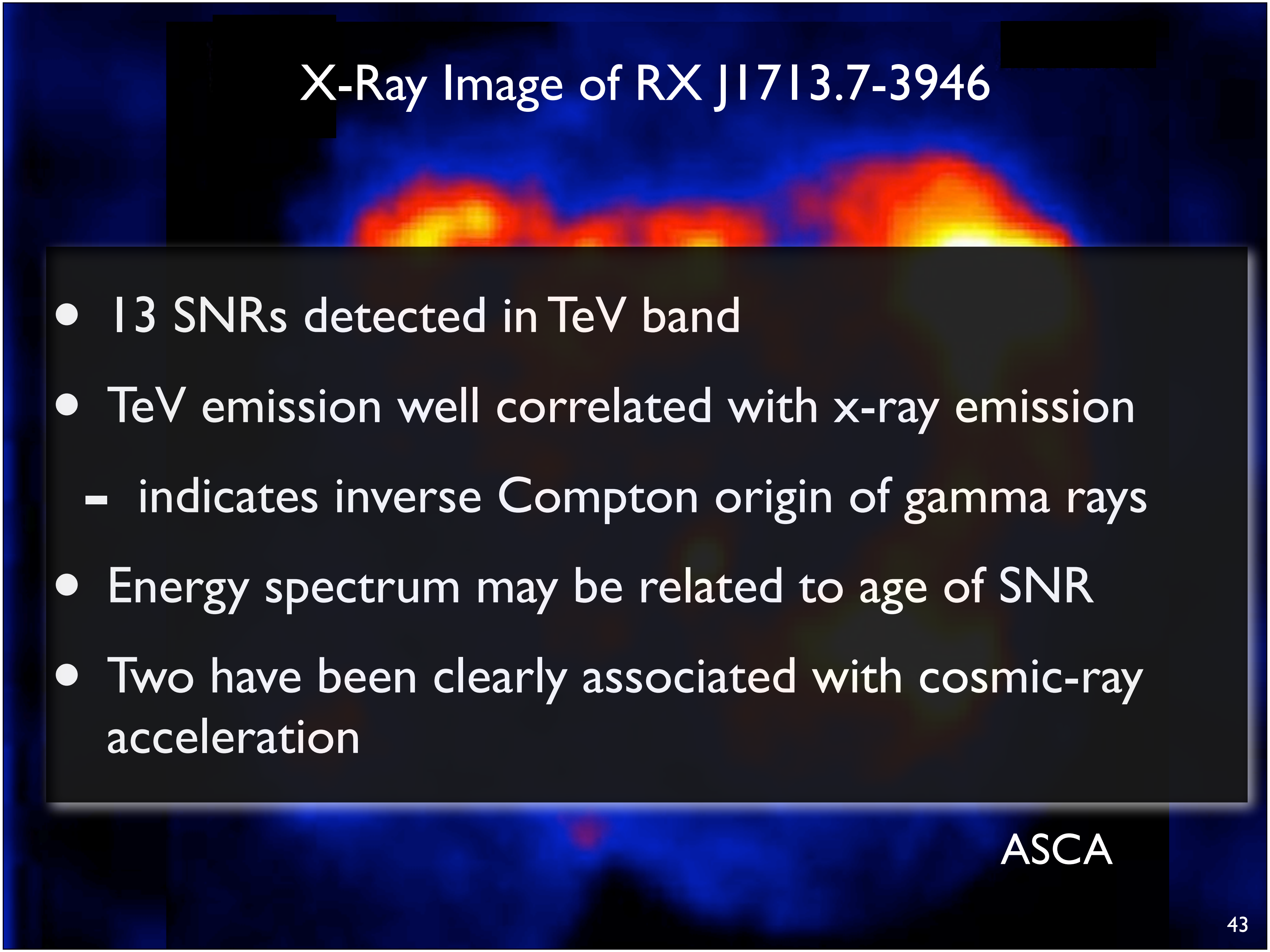
Cosmic-Ray Origins

- Steep spectrum $E^{-2.7}$
- Galactic energy loss of 10^{41} ergs/sec (from lifetime measurements)
- Supernova Remnants long suspected GCR source
  - Energy budget 10^{51} ergs/30 years = 10^{42} ergs/sec
  - Strong shocks yield $E^{-2.1}$ spectrum
  - Maximum energy ~10^{15} eV
- Direct proof has been elusive!

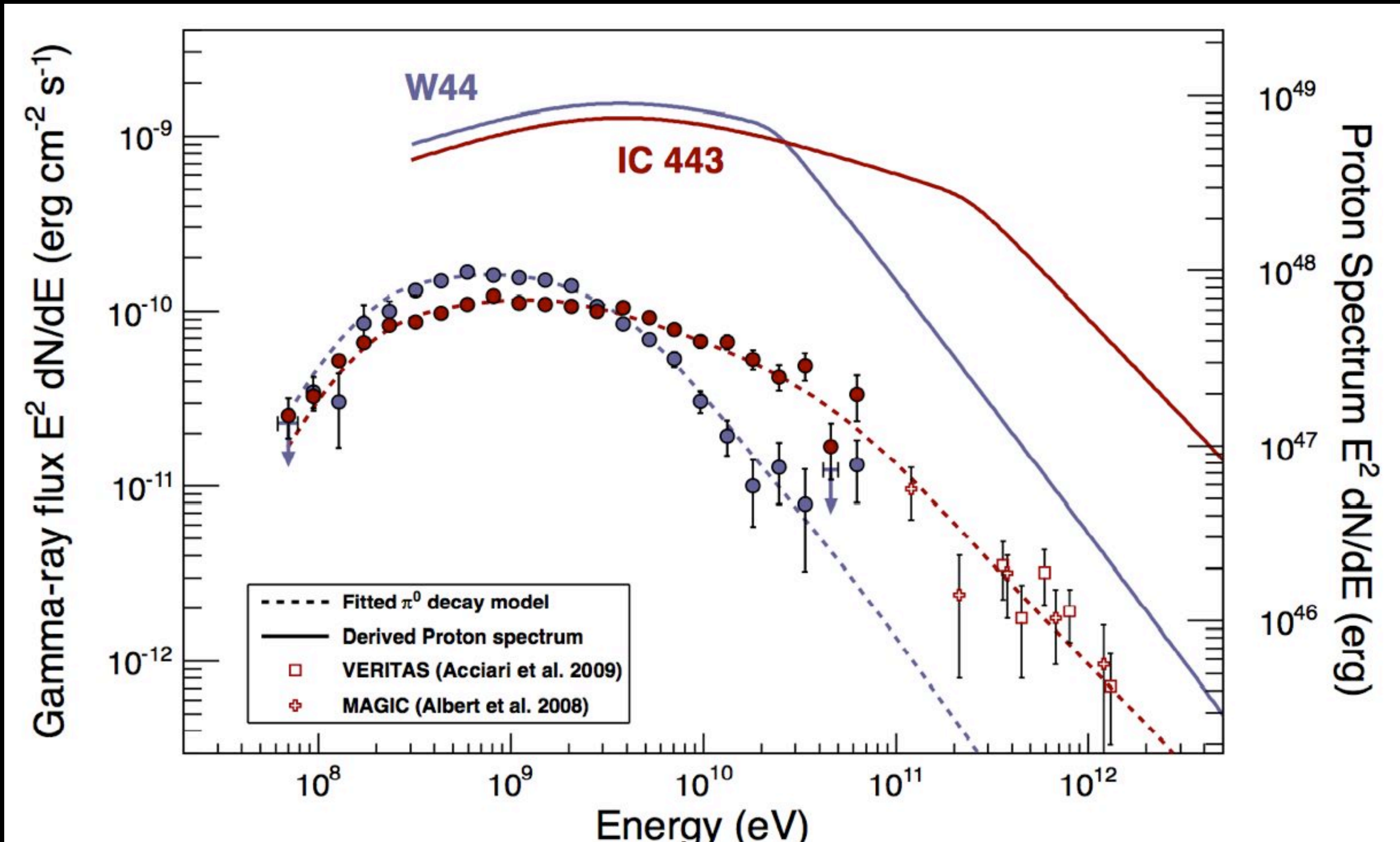


X-Ray Image of RX J1713.7-3946

- 13 SNRs detected in TeV band
- TeV emission well correlated with x-ray emission
  - indicates inverse Compton origin of gamma rays
- Energy spectrum may be related to age of SNR
- Two have been clearly associated with cosmic-ray acceleration



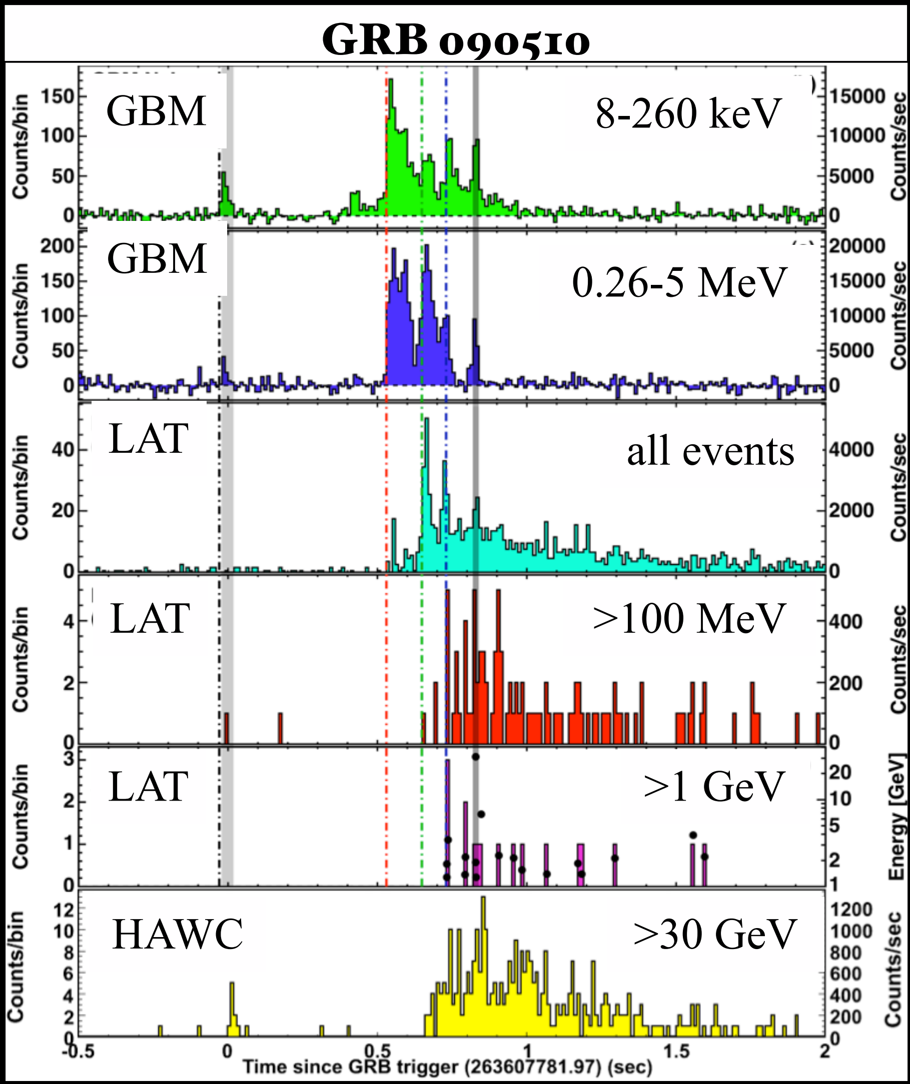
CR Proton Spectrum at SNR



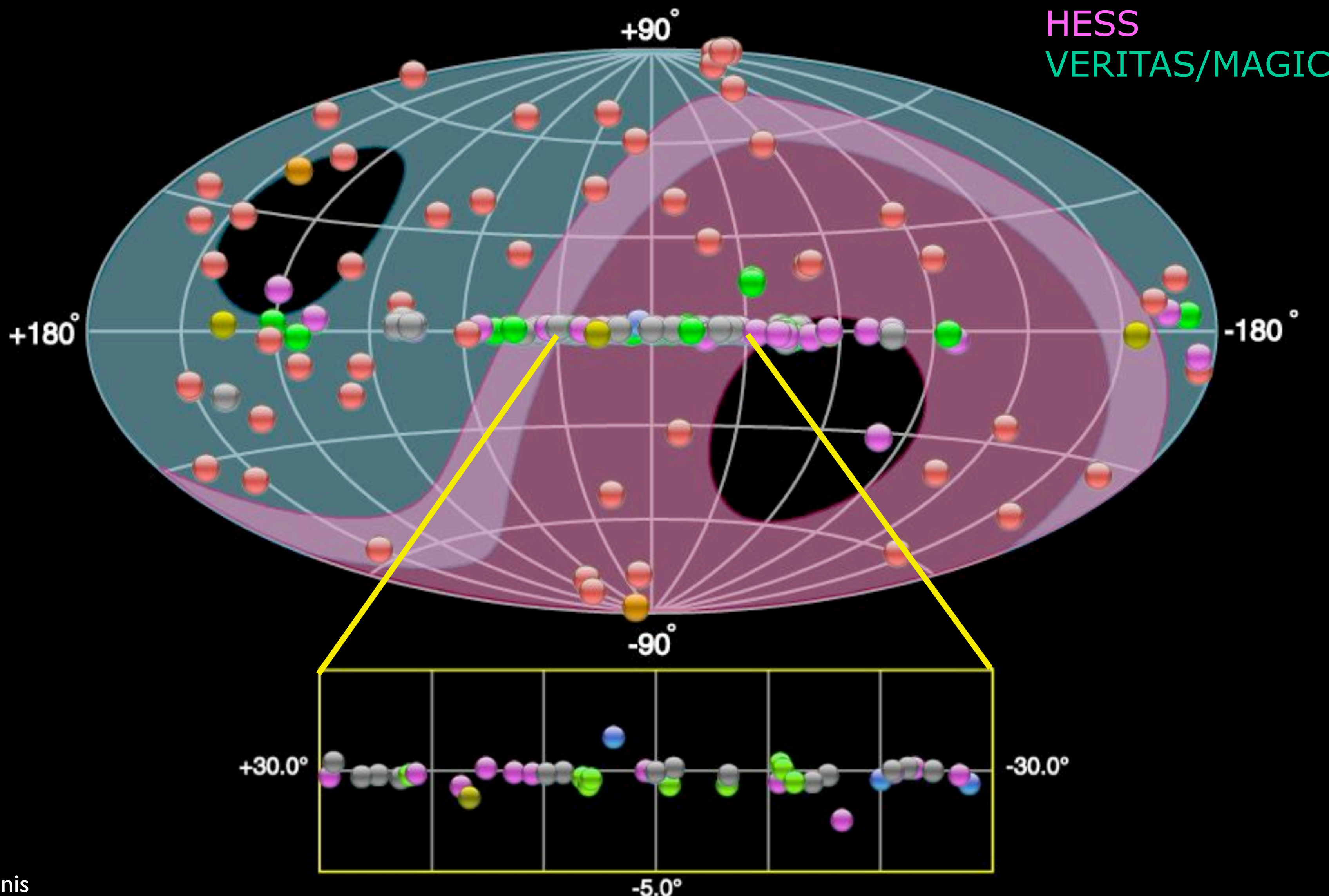
Ackermann, et al. Science v339 p807 2013

Gamma-Ray Bursts

- Fermi observation of GRB 090510 (z = 0.9)
- Simulated HAWC light curve assuming extension of spectrum with LAT index
  - EBL absorption included
- ~200 events expected above 30 GeV
- Detection (5σ) by HAWC if emission cuts off at 50 GeV
- HAWC more sensitive than LAT above 10 GeV for short GRBs
- Expect ~1.5 GRB/yr in HAWC (Taboada & Gilmore arXiv:1306.1127)

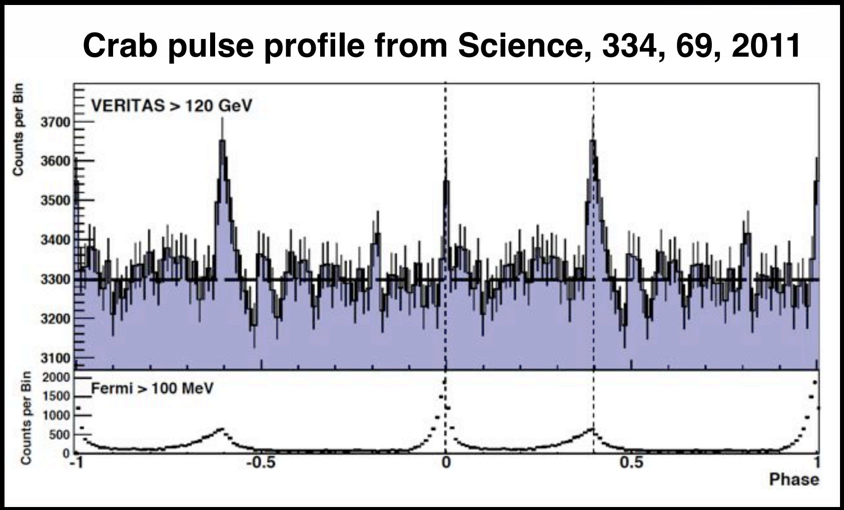


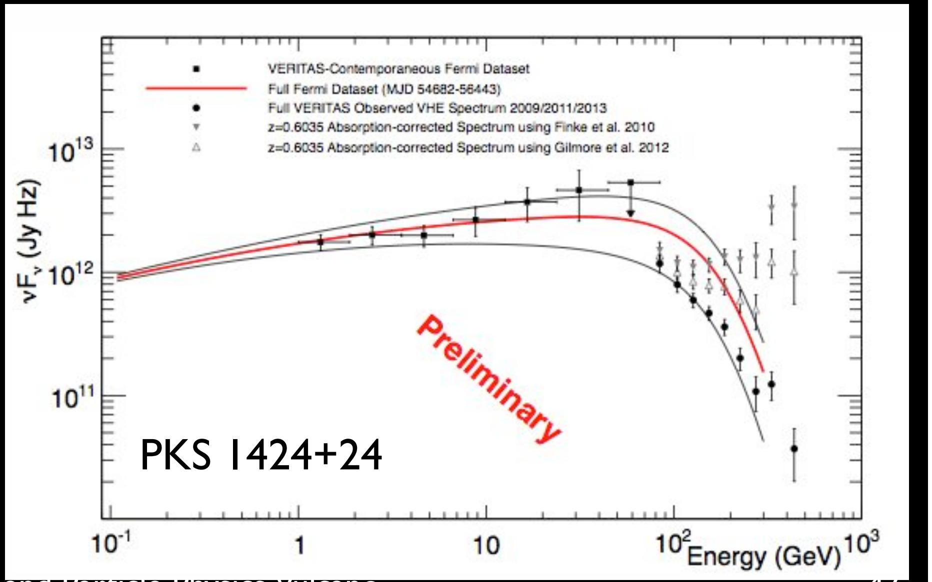
TeV Sky



VERITAS

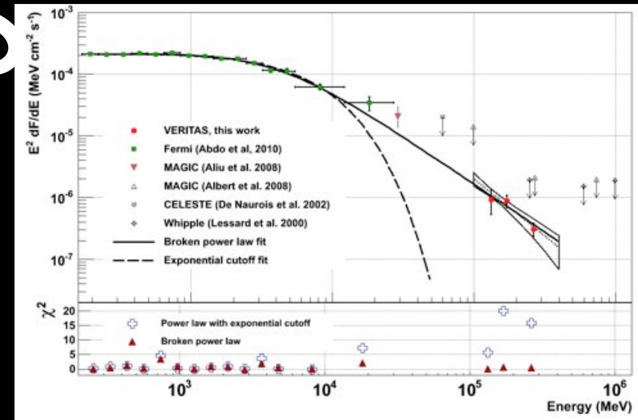
- AGN Campaign observed >130 AGN detected 27
- PKS 1424+24 most distant AGN detected at TeV energies (z>0.6)
- Crab Pulsar

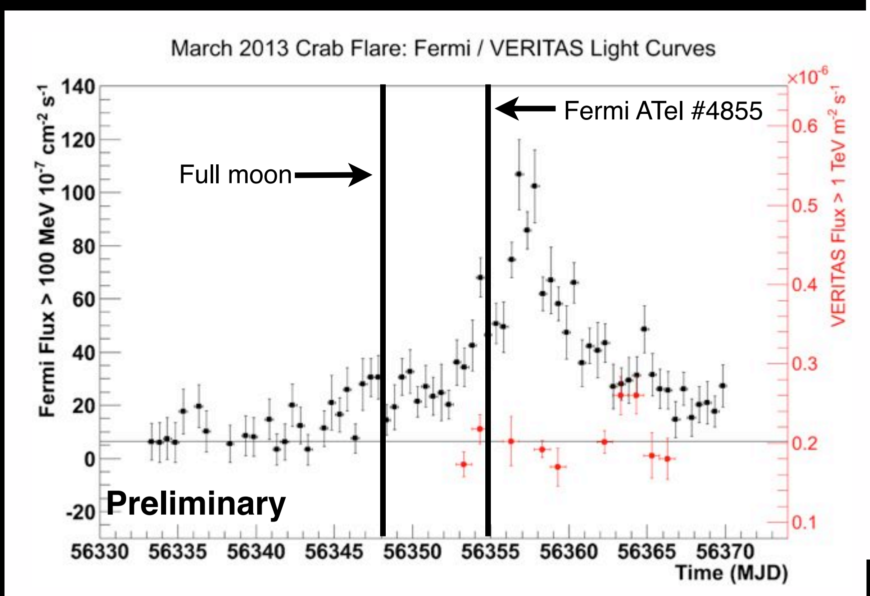


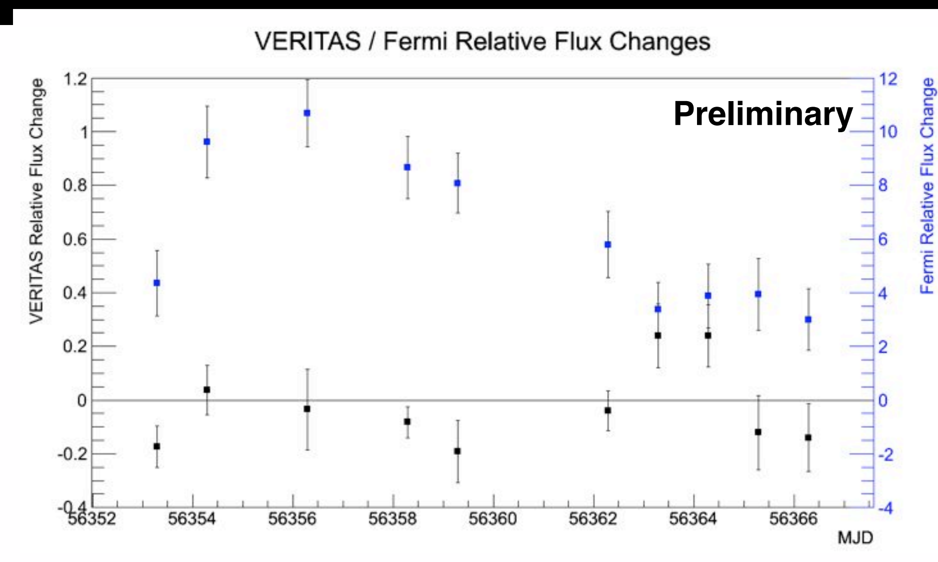


VERITAS

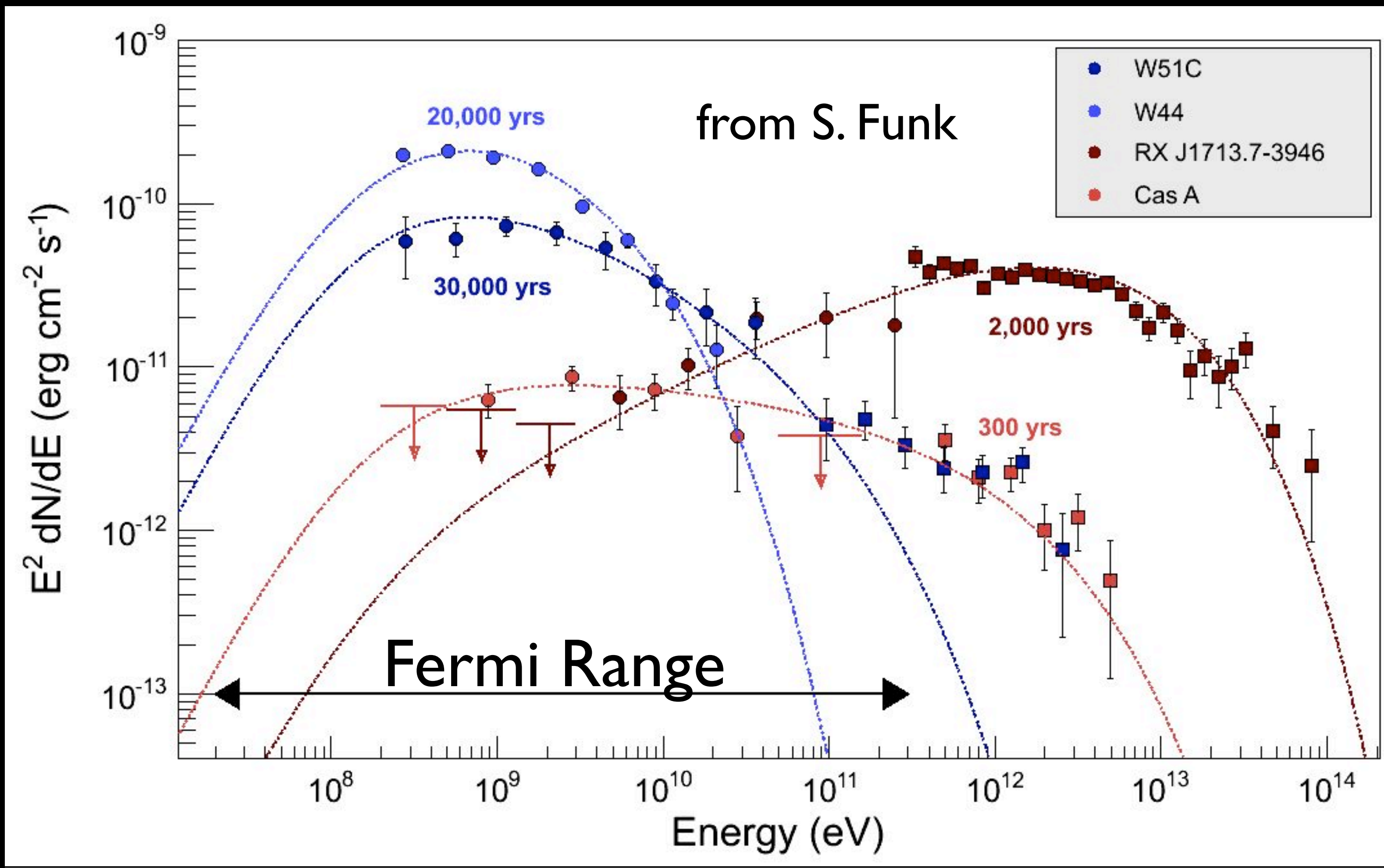
Crab Flares in GeV no flares in TeV



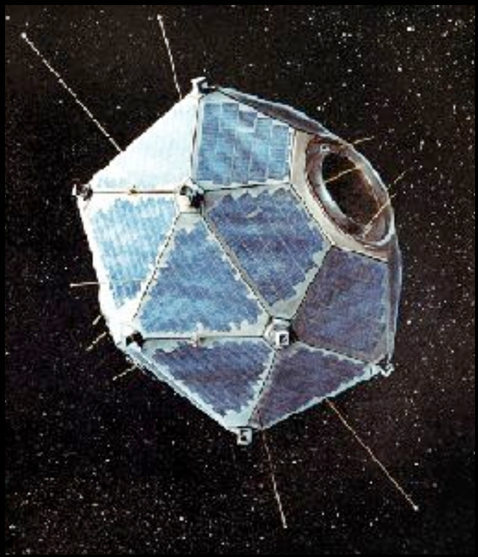




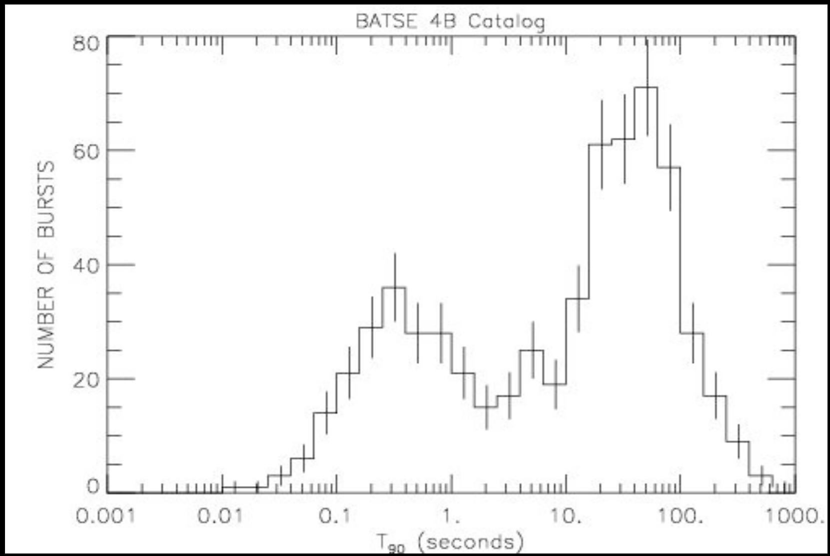
SN Remnant Evolution



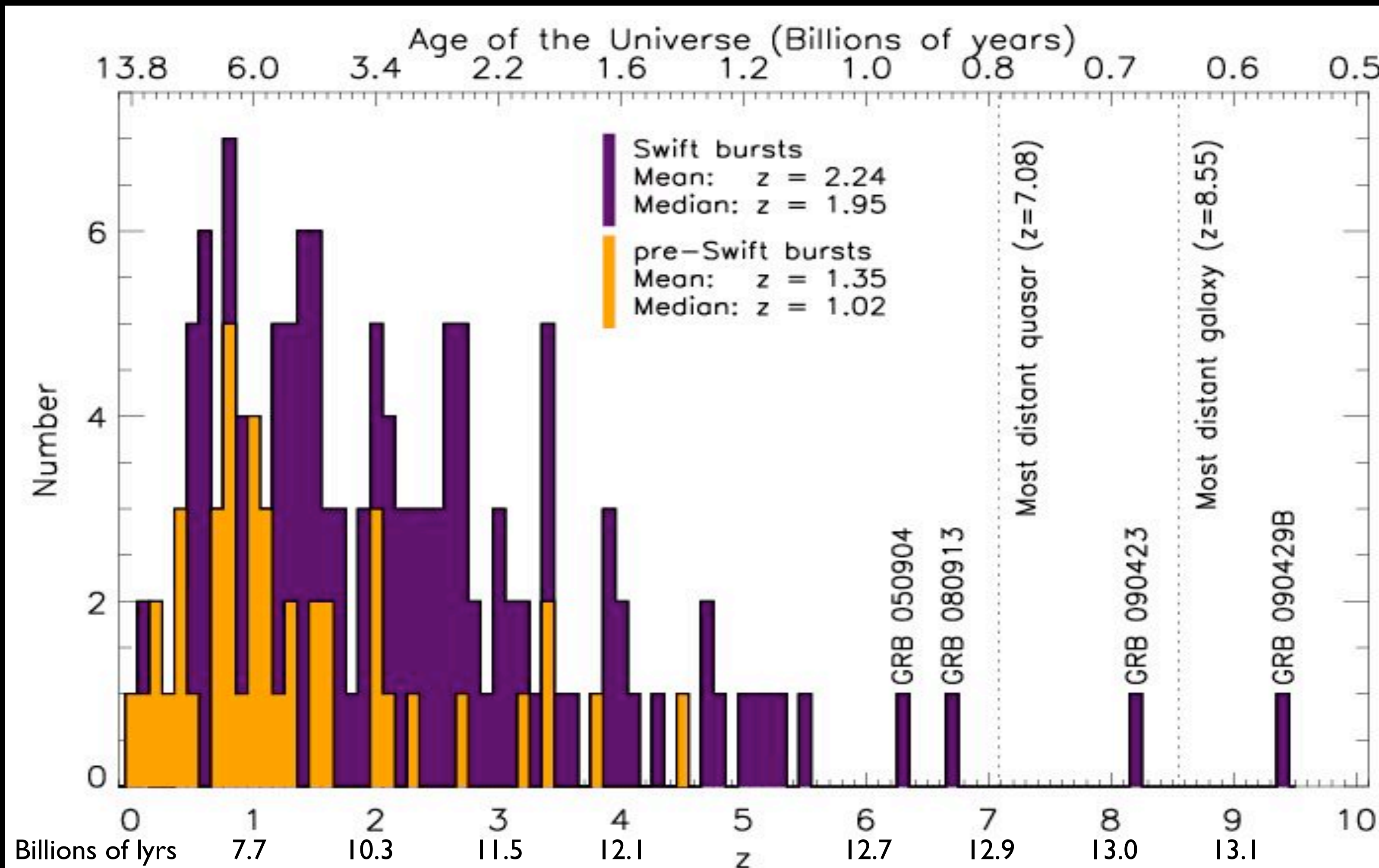
Gamma-Ray Bursts



- Discovered in 1960's - Vela satellite
- Most energetic events in the universe
- Detected to z~9.4
- ~10^{51} ergs released in gamma rays
- Emission highly collimated (1°-10°)
- Bi-modal duration distribution
  - short duration bursts <2 seconds (binary neutron star mergers)
  - long duration bursts >2 seconds (hypernovae - collapse of massive stars)



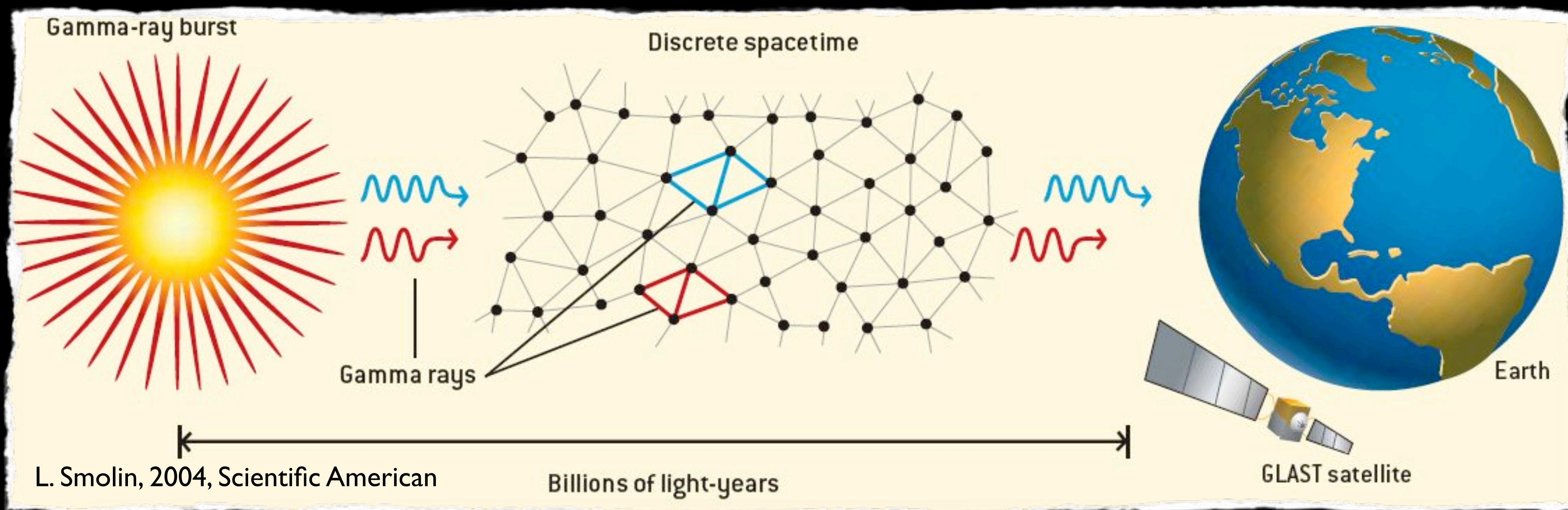
GRB Distances



P. Jakobsson http://www.raunvis.hi.is/~pja/GRBsample.html

Testing Lorentz Invariance

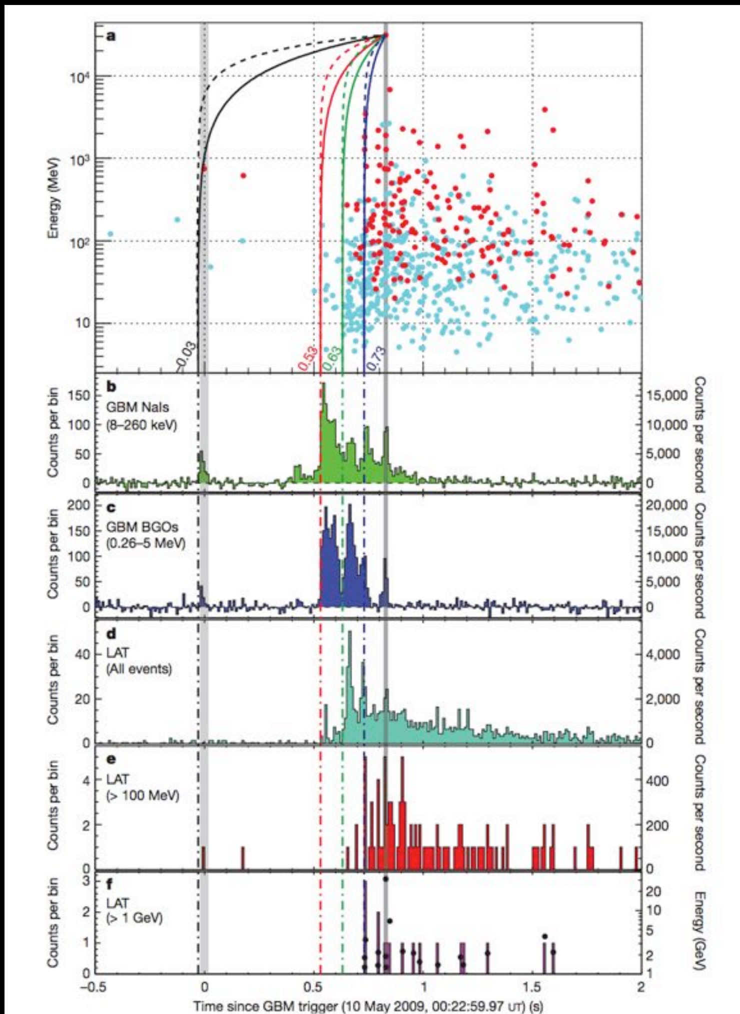
- Many theories of quantum gravity violate Lorentz invariance
- Can be manifest as an energy dependent speed of light
- Gamma ray bursts and AGN flares provide an excellent probe of LIV



L. Smolin, 2004, Scientific American

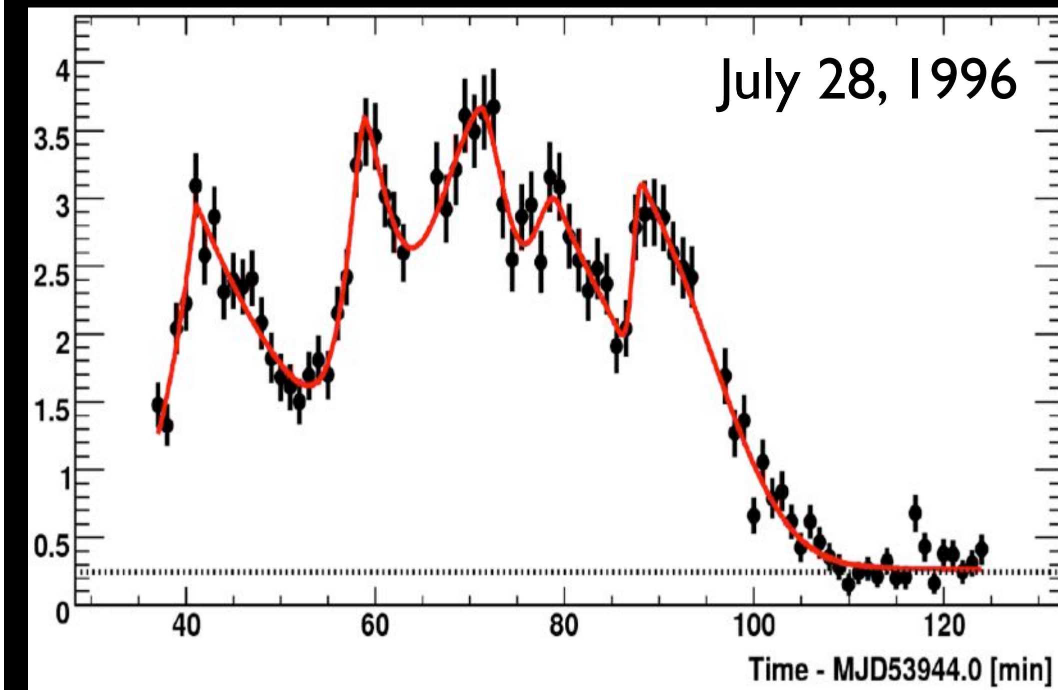
$$v_l \approx c\left(1 - \xi_1 \frac{E}{M_{QG}}\right) \qquad v_q \approx c\left(1 - \xi_2 \frac{E^2}{M_{QG}^2}\right)$$

GRB 090510
z=0.903 E_{max} = 31 GeV



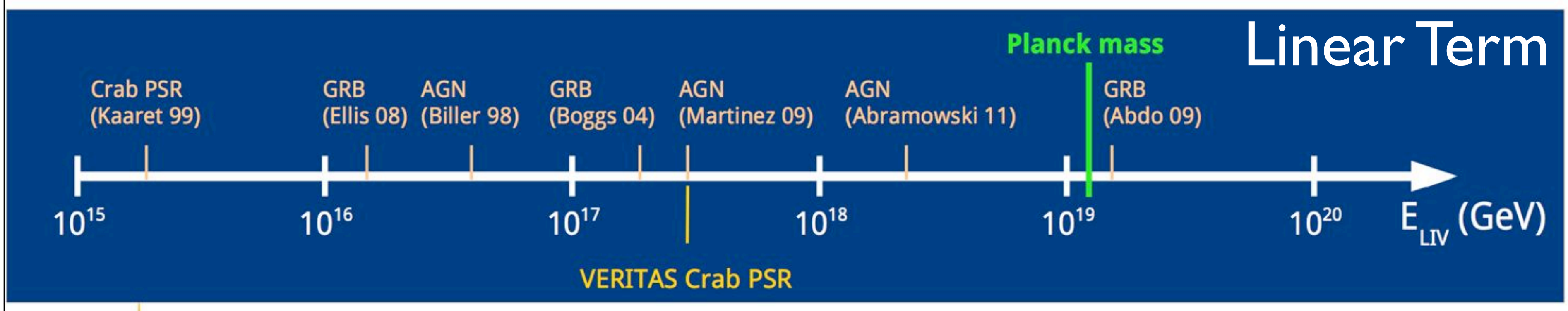
Fermi collaboration, Nature, 2009 v. 462 p331

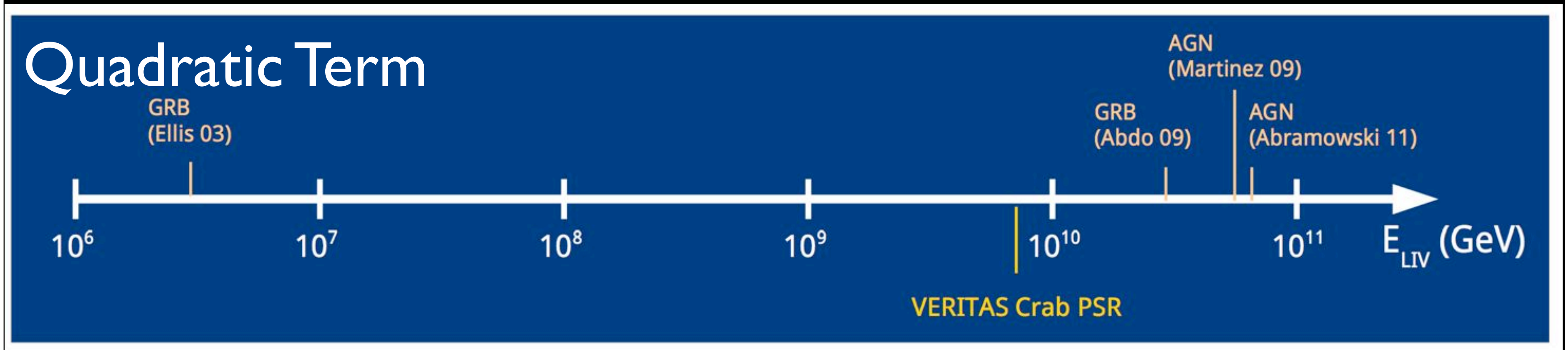
PKS 2155-304
z=0.116 Emax=2 TeV



H.E.S.S. Collaboration, Astroparticle Physics, 2011 v34 p738

Current Limits on LIV





from O. Nepomuk Snowmass

Lorentz Invariance Violation

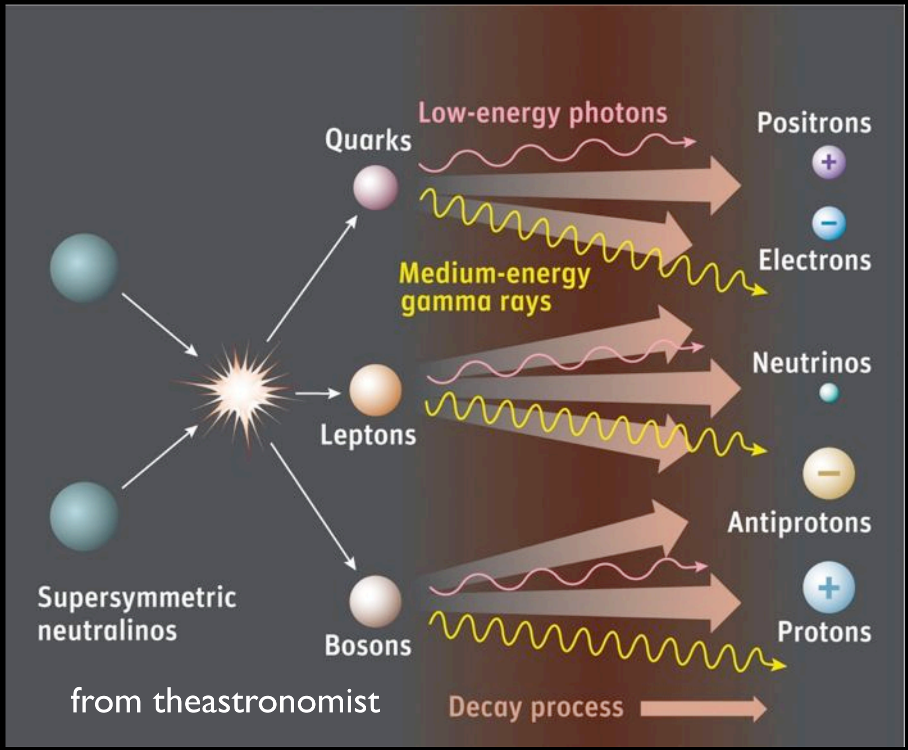
- Theories of quantum gravity typically define a minimum length scale, usually the Planck length, 1.6×10^{-33} cm (or 1.2×10^{19} GeV)
- This is a violation of Lorentz invariance
- LIV can lead to a vacuum dispersion relation - an energy dependent speed of light
- Gamma ray bursts and AGN flares provide an excellent probe of LIV

$$p^2c^2 = E^2\left(1 \pm \xi_1 \frac{E}{M_{QG}} \pm \xi_2 \left(\frac{E}{M_{QG}}\right)^2 + \ldots\right)$$

$$v_l \approx c\left(1 - \xi_1 \frac{E}{M_{QG}}\right) \qquad v_q \approx c\left(1 - \xi_2 \frac{E^2}{M_{QG}^2}\right)$$

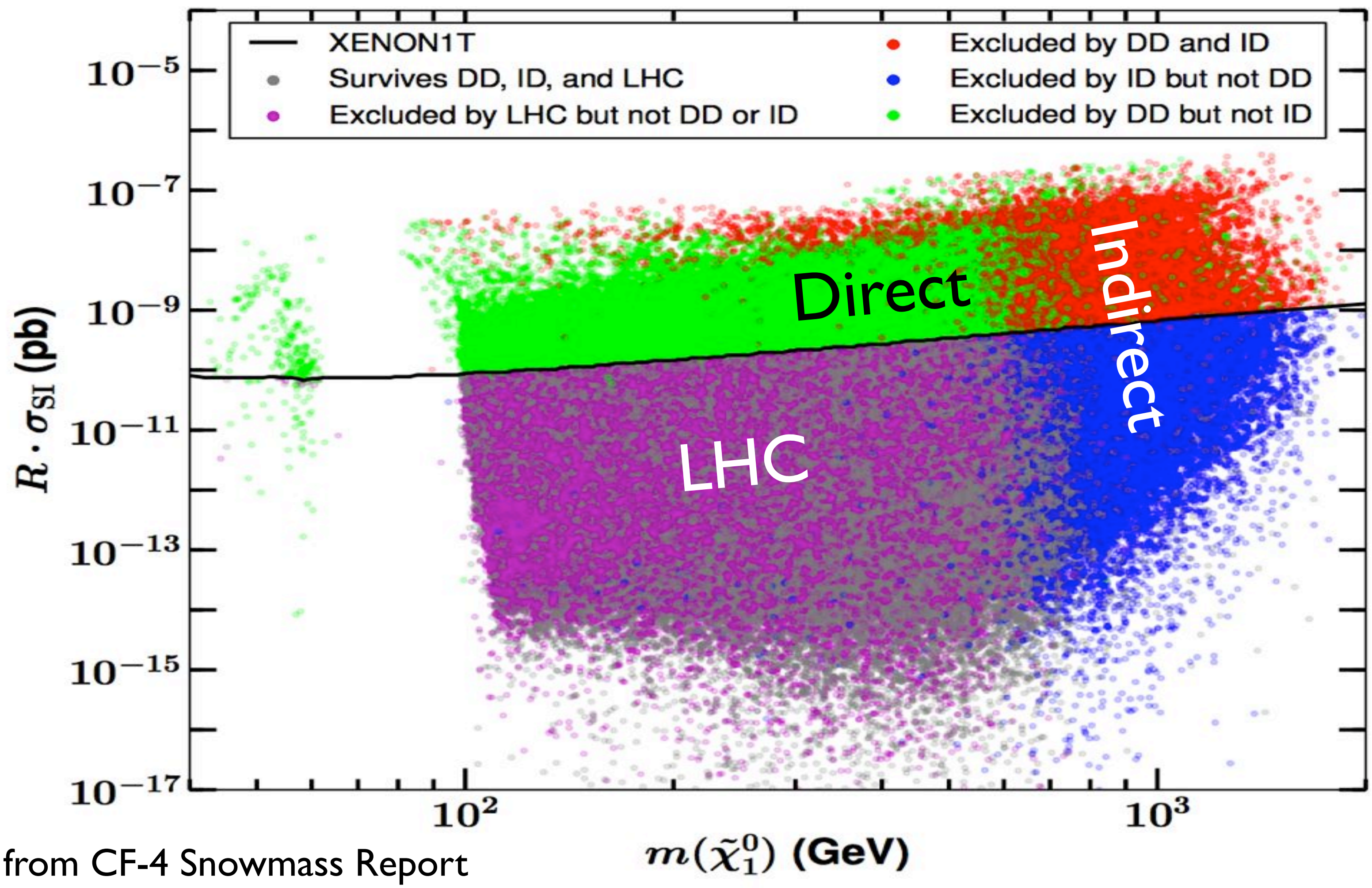
Indirect Dark Matter Detection

- Neutralino annihilation to quarks, leptons, and bosons (W,Z) yields gamma rays, neutrinos, and cosmic rays
- Search for gamma ray signal with DM energy spectrum in regions with no/low (or understood) astrophysical backgrounds
  - Galactic Center, dwarf spheroidals, Galaxy Clusters



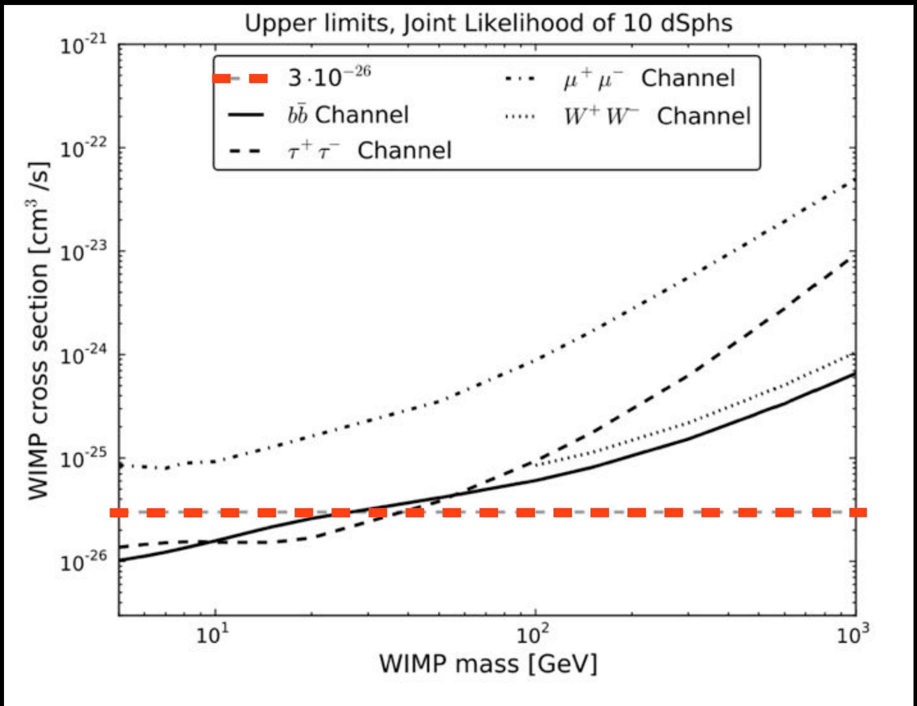
$$\frac{d\phi}{dEd\Omega} = \sum_i \frac{\langle \sigma v \rangle_i}{M_\chi^2} \frac{dN_{\gamma,i}}{dE} \int_{los} \rho^2(r)\, dl(\Psi)$$

DM Complementarity

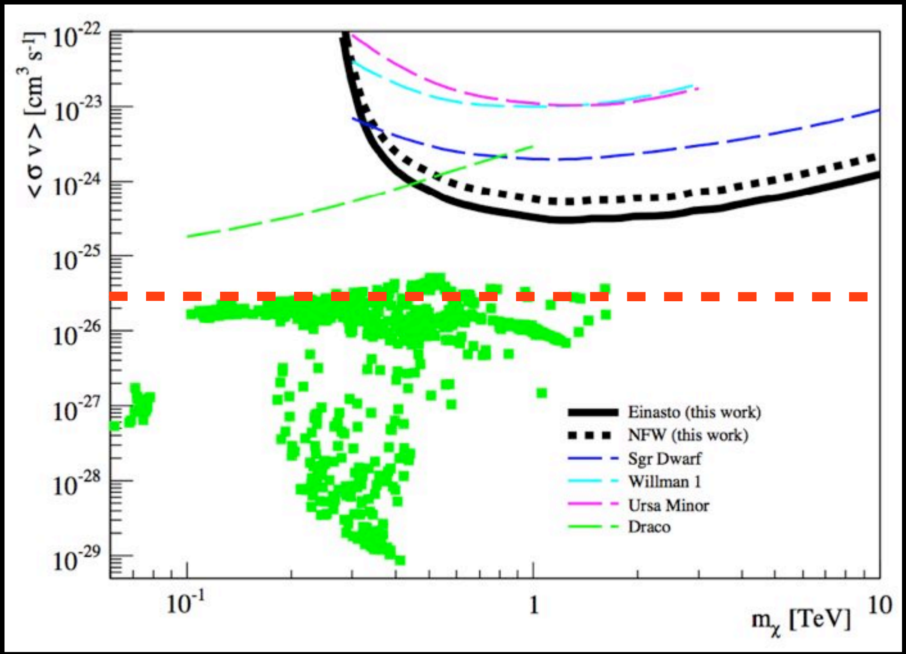


from CF-4 Snowmass Report

Indirect Limits

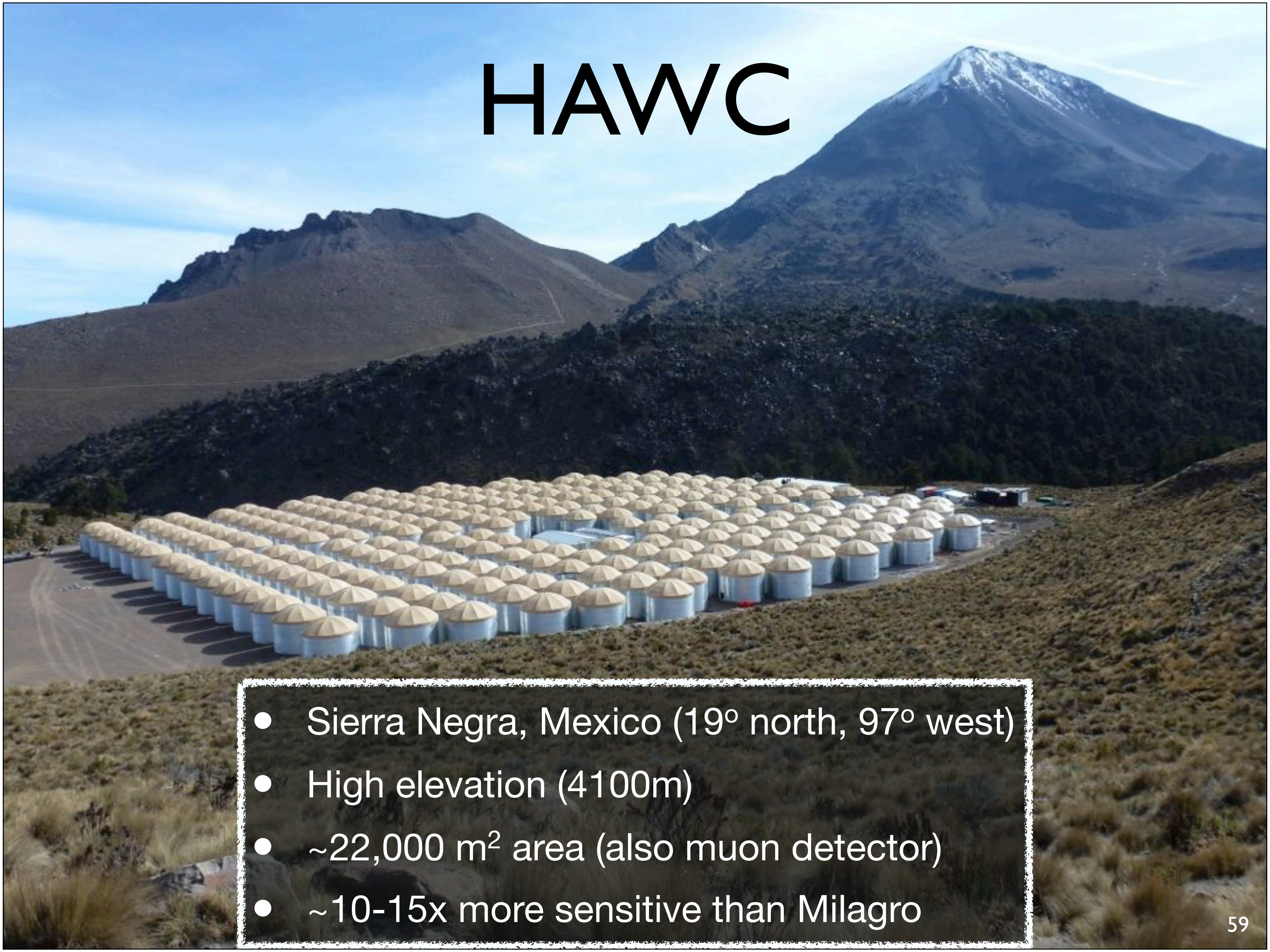


Fermi Collaboration PRL v107 p241302 2011



H.E.S.S. Collaboration PRL v106 p161301 2011

HAWC



- Sierra Negra, Mexico (19^{o} north, 97^{o} west)
- High elevation (4100m)
- ~22,000 m^2 area (also muon detector)
- ~10-15x more sensitive than Milagro

HAWC

- Sierra Negra, Mexico (19^{o} north, 97^{o} west)
- High elevation (4100m)
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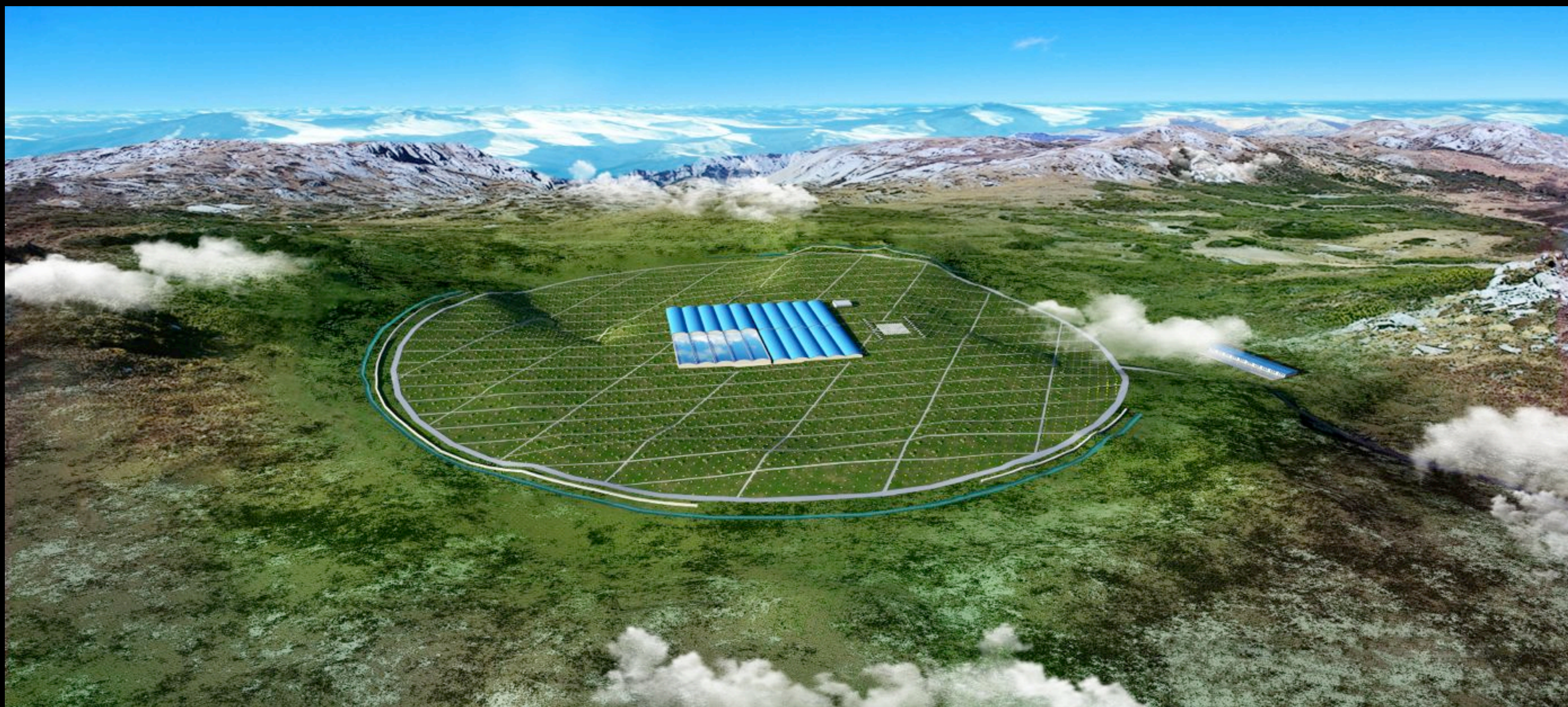
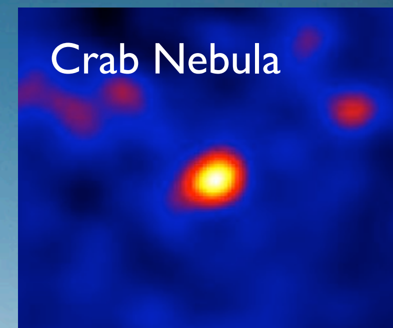
LHAASO

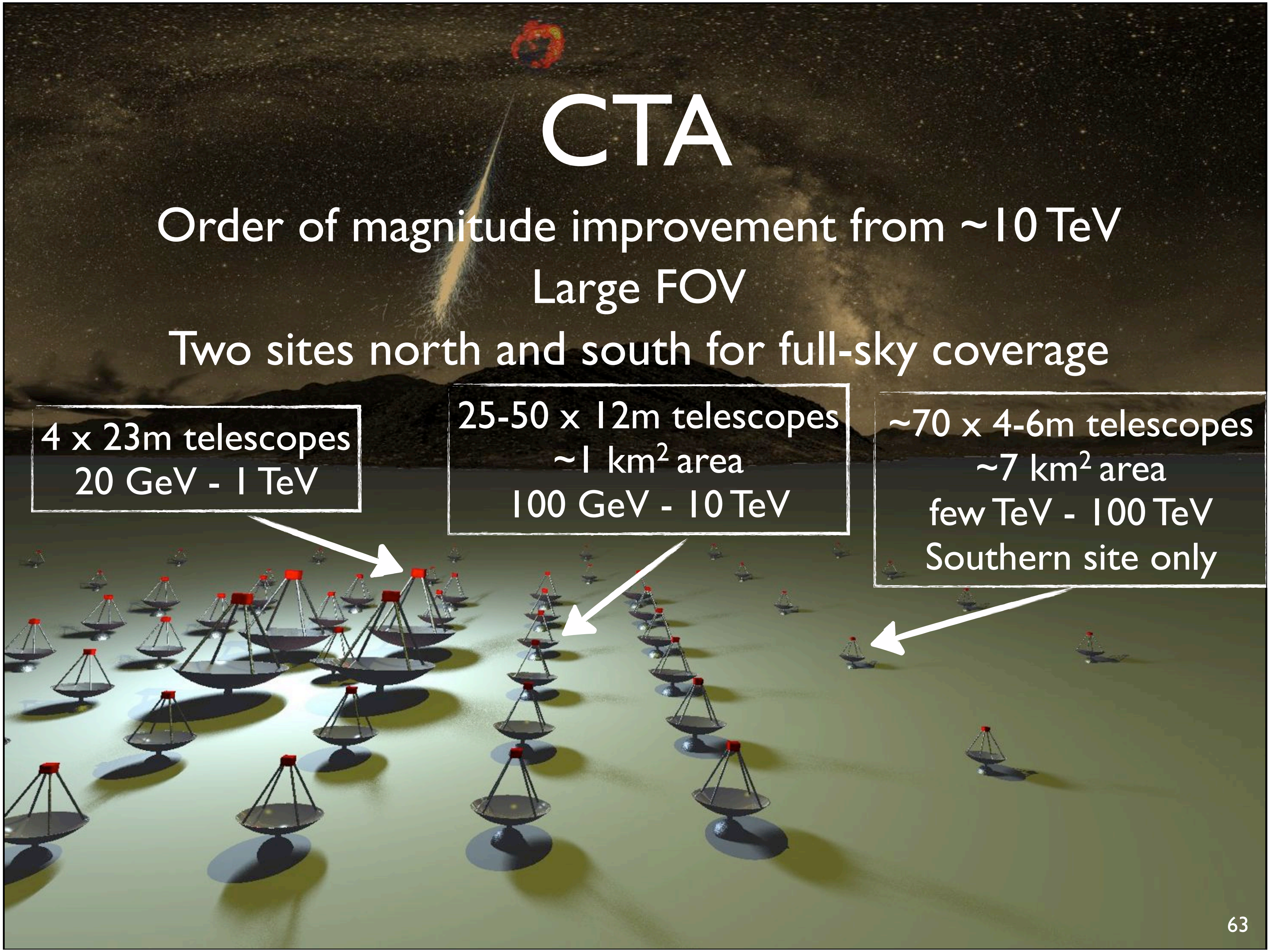


- 90,000 m^2 water Cherenkov detector (~5x HAWC)
- 1 km^2 scintillator array (5600 scintillators + 1200 μ detectors)
- Funding approved 2018 completion schedule
- 5-10x more sensitive than HAWC

H.E.S.S. II

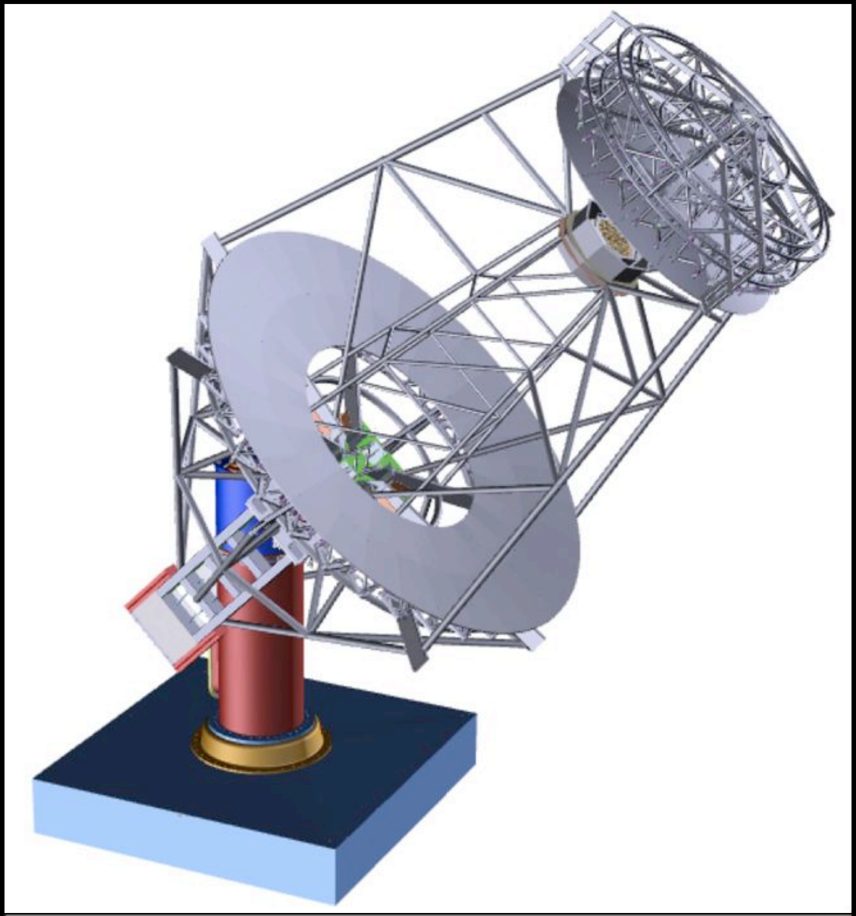
614 m^2 mirror area: ~30 GeV Threshold
36 m focal length
2048 PMT camera
3.2° field-of-view

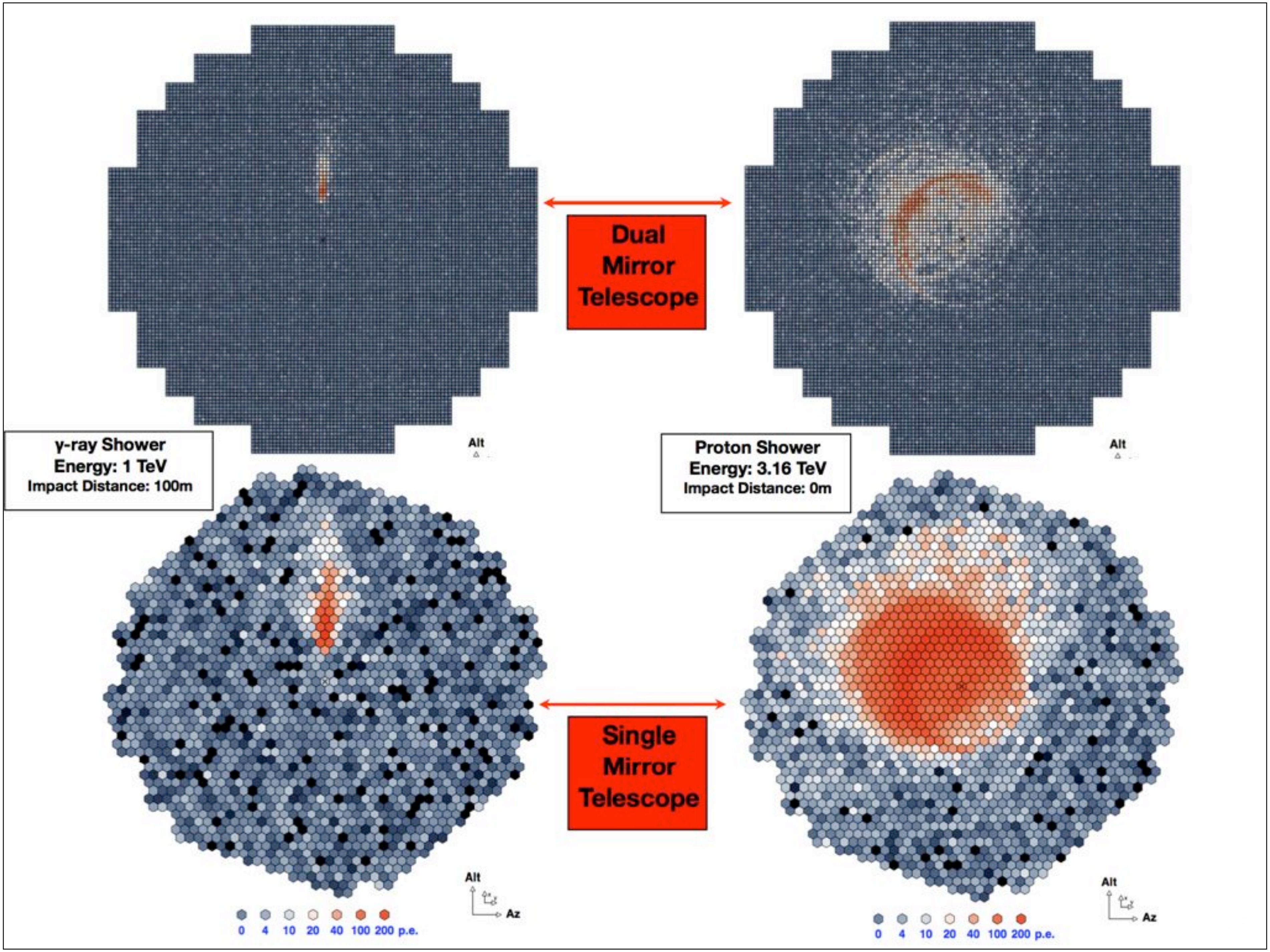



CTA
Order of magnitude improvement from ~10 TeV
Large FOV
Two sites north and south for full-sky coverage
4 x 23m telescopes
20 GeV - 1 TeV
25-50 x 12m telescopes
~1 km² area
100 GeV - 10 TeV
~70 x 4-6m telescopes
~7 km² area
few TeV - 100 TeV
Southern site only

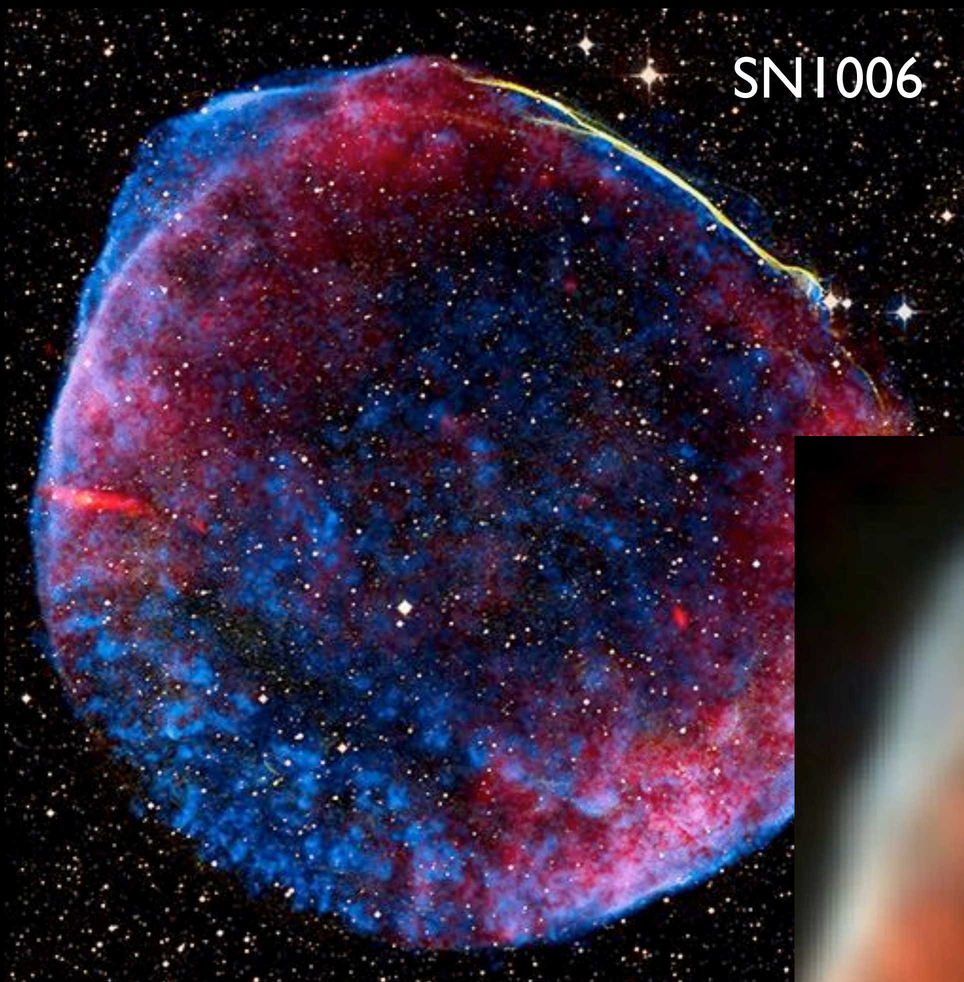
US Contribution

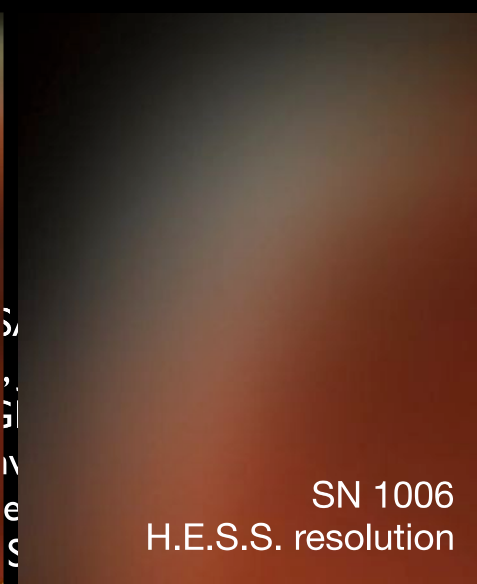
- ~25 mid-size telescopes
- Schwarzschild-Couder design (secondary optics)
  - small psf across large fov
  - small plate scale
  - advanced camera system (MAPMTs, SiPMs, etc.)
- 2-3 x improvement in sensitivity



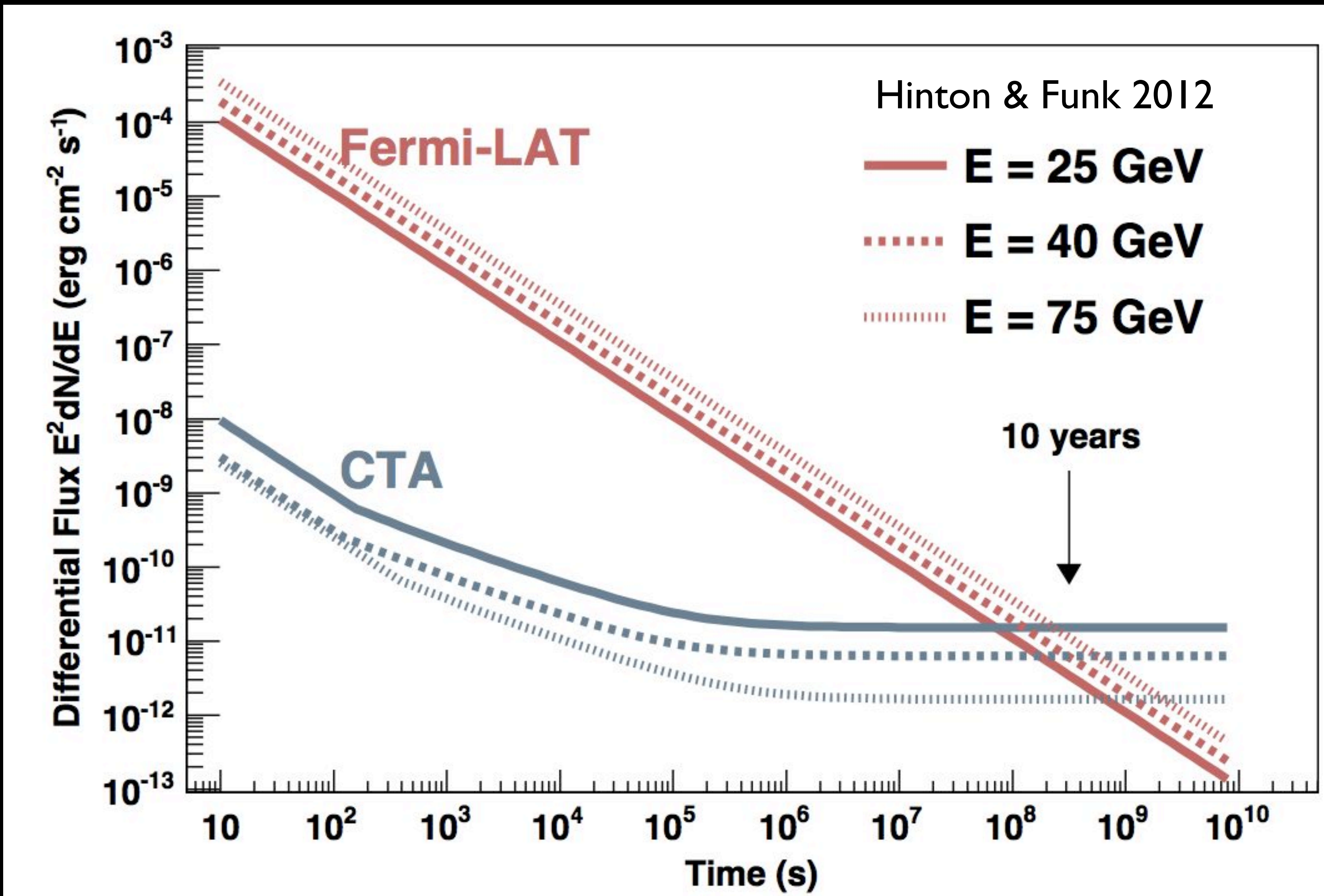

Dual Mirror Telescope
γ-ray Shower
Energy: 1 TeV
Impact Distance: 100m
Proton Shower
Energy: 3.16 TeV
Impact Distance: 0m
Single Mirror Telescope
Alt
Az
0 4 10 20 40 100 200 p.e.

Resolving Sources

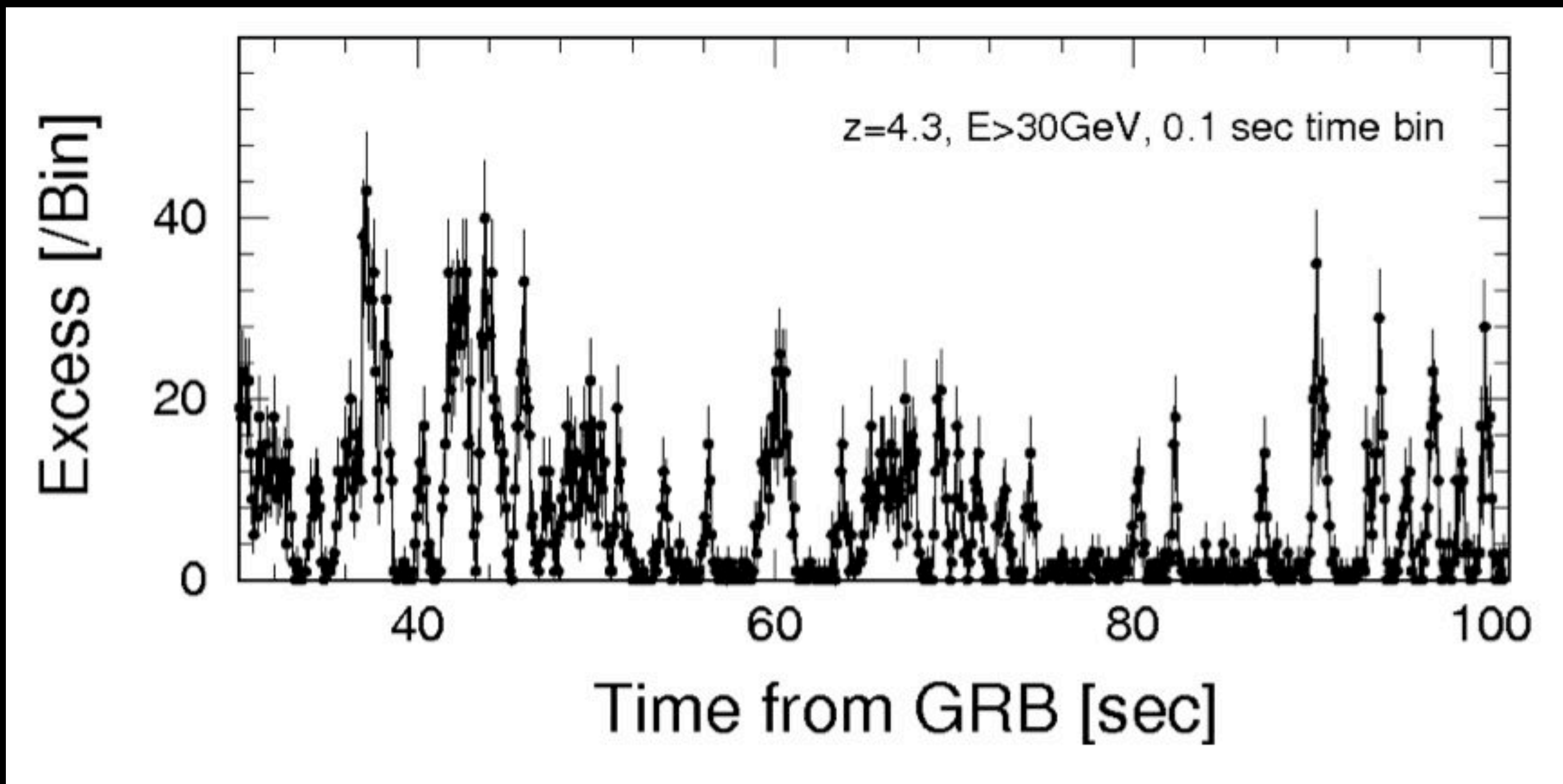




Transients: CTA vs. Fermi



Simulated Gamma-Ray Burst



Gamma-Ray Burst Science in the Era of Cherenkov Telescope Array
(Astroparticle Physics special issue article)
Susumu Inoue et al.

AGN Tip Sheet

- 57 detected at VHE energies
- Variability observed in:
  - Mrk 421 (z=0.03), Mrk 501 (z=0.03),
  - M87 (z=0.004),
  - PKS 2155-304 (z=0.116),
  - 1ES 1959+650 (z=0.048)
  - VER J0521+211 (z=0.108)
  - RBS 0723 (z=0.198)
  - 3C66A (z> 0.3347 and z<0.41)
  - W Comae (z=0.102)
  - BL Lac (AKA 1ES 2200+420) (z=0.069)
  - 1ES 1215+303 (z=0.13)
  - PKS 0301-243 (z=0.266) [2.5 sigma hint of variability]
  - PKS 2005-489 (z=0.071) [marginal variability]