Ground-Based Gamma-Ray Astrophysics

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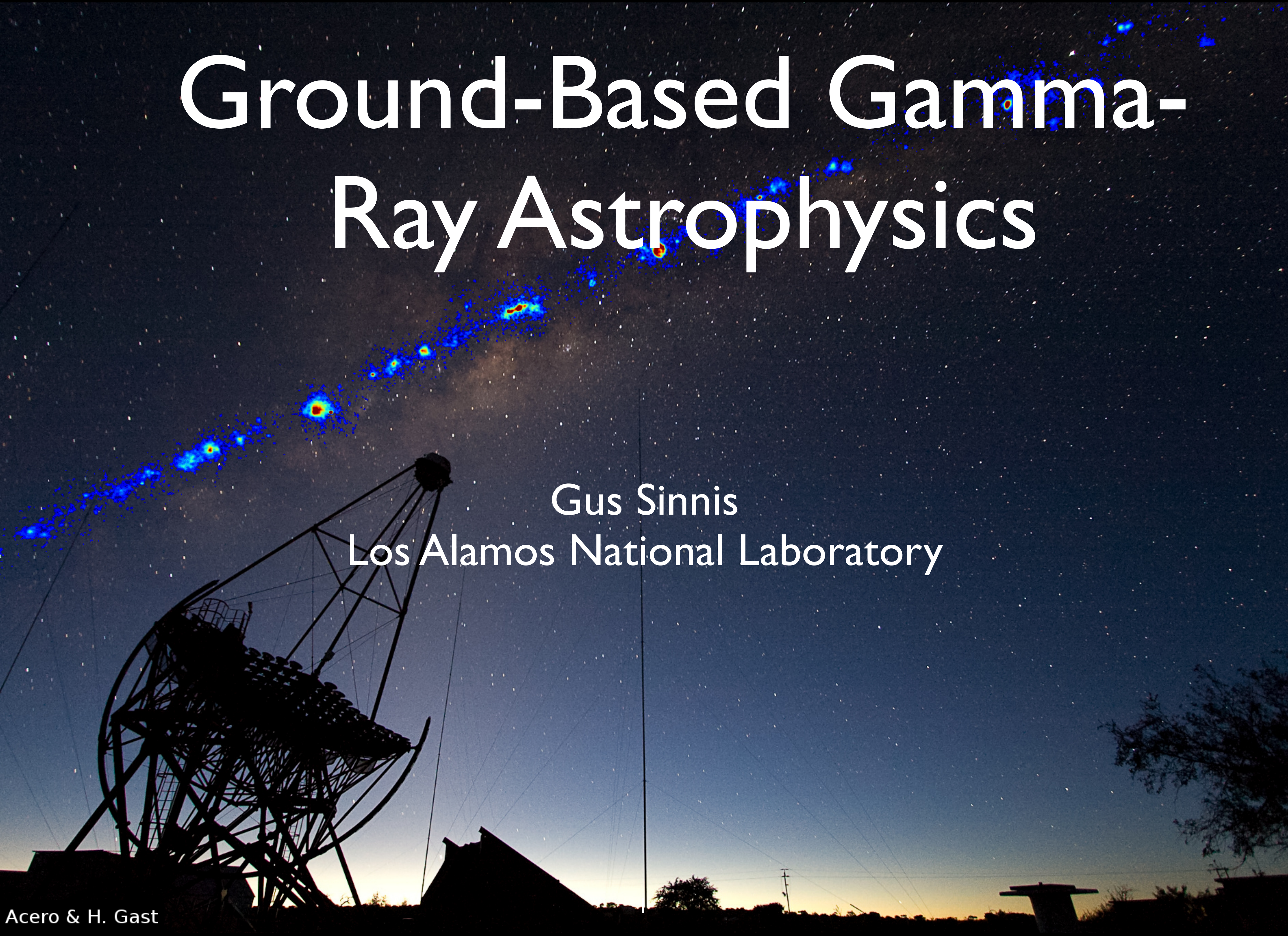


Goals of VHE Astrophysics

- Cosmic Particle Acceleration
  - Origin of cosmic rays
  - Understand astrophysical jets and extreme environments
  - VHE Pulsar emission
- Cosmology
  - Measure the extragalactic background light
- 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
  - Astrophysical backgrounds

Gamma Ray Telescopes

<u>Atmospheric Cherenkov Telescopes</u>
H.E.S.S./VERITAS/MAGIC

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

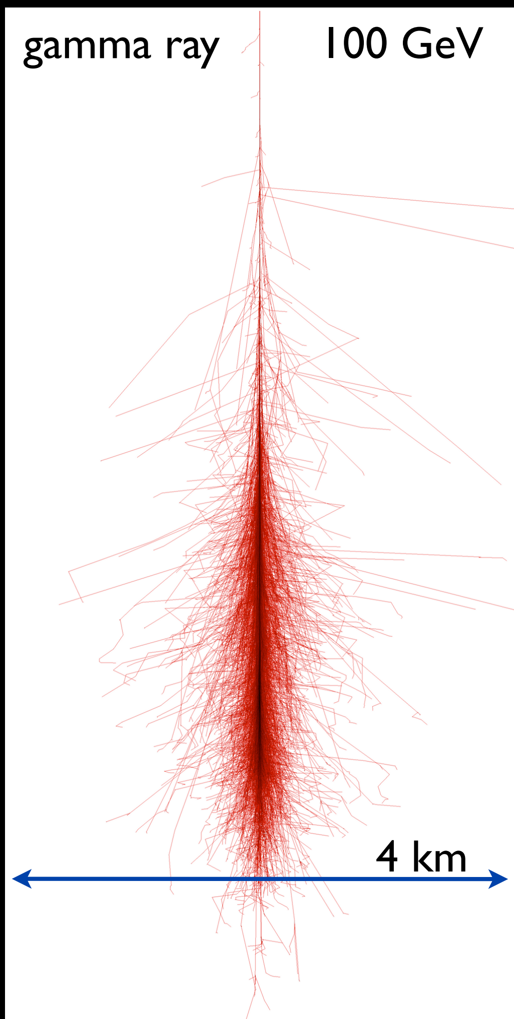
Study known sources
Deep surveys of limited regions
Source morphology (SNRs)
Fast transients (AGN flares)

<u>EAS Arrays</u>
Milagro/Tibet/ARGO

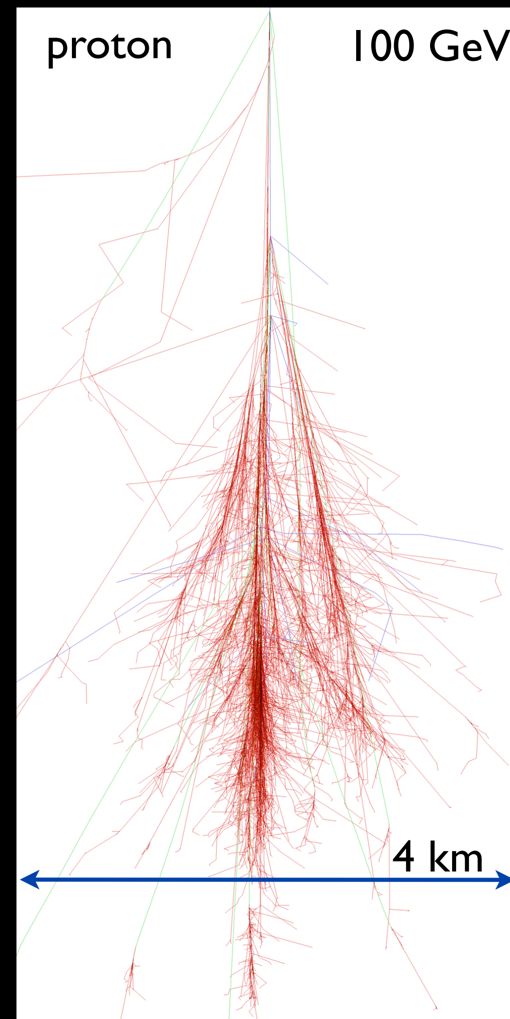
100 GeV - 100 TeV
Large Area
Good background rejection
Large Aperture & Duty Cycle

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

Extensive Air Showers

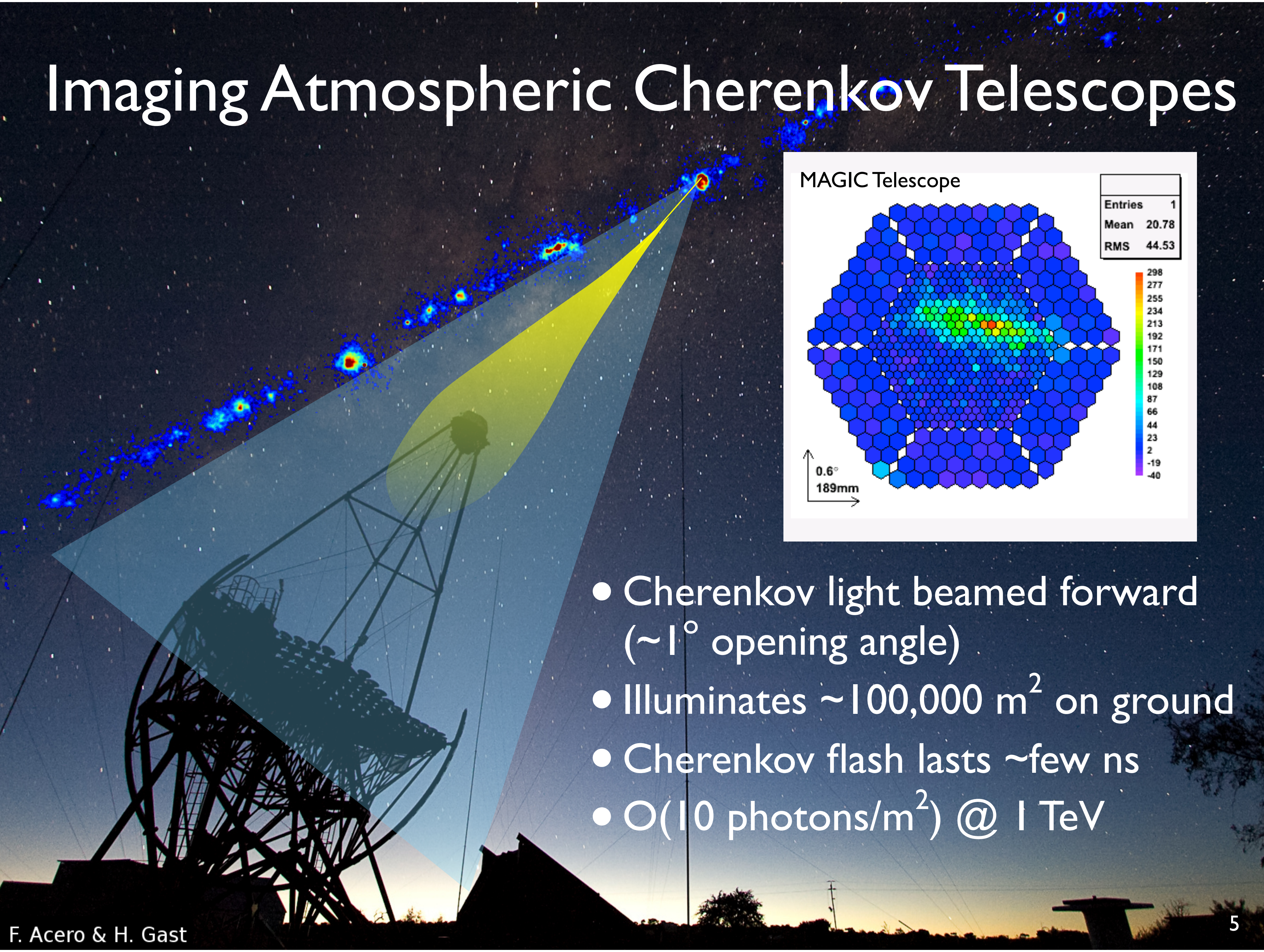


- γ showers almost purely e-m and relatively compact
- Hadronic showers contain muons (~30/TeV)
- Both have core of energetic particles
- Ground-based VHE telescopes must distinguish protons from photons



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

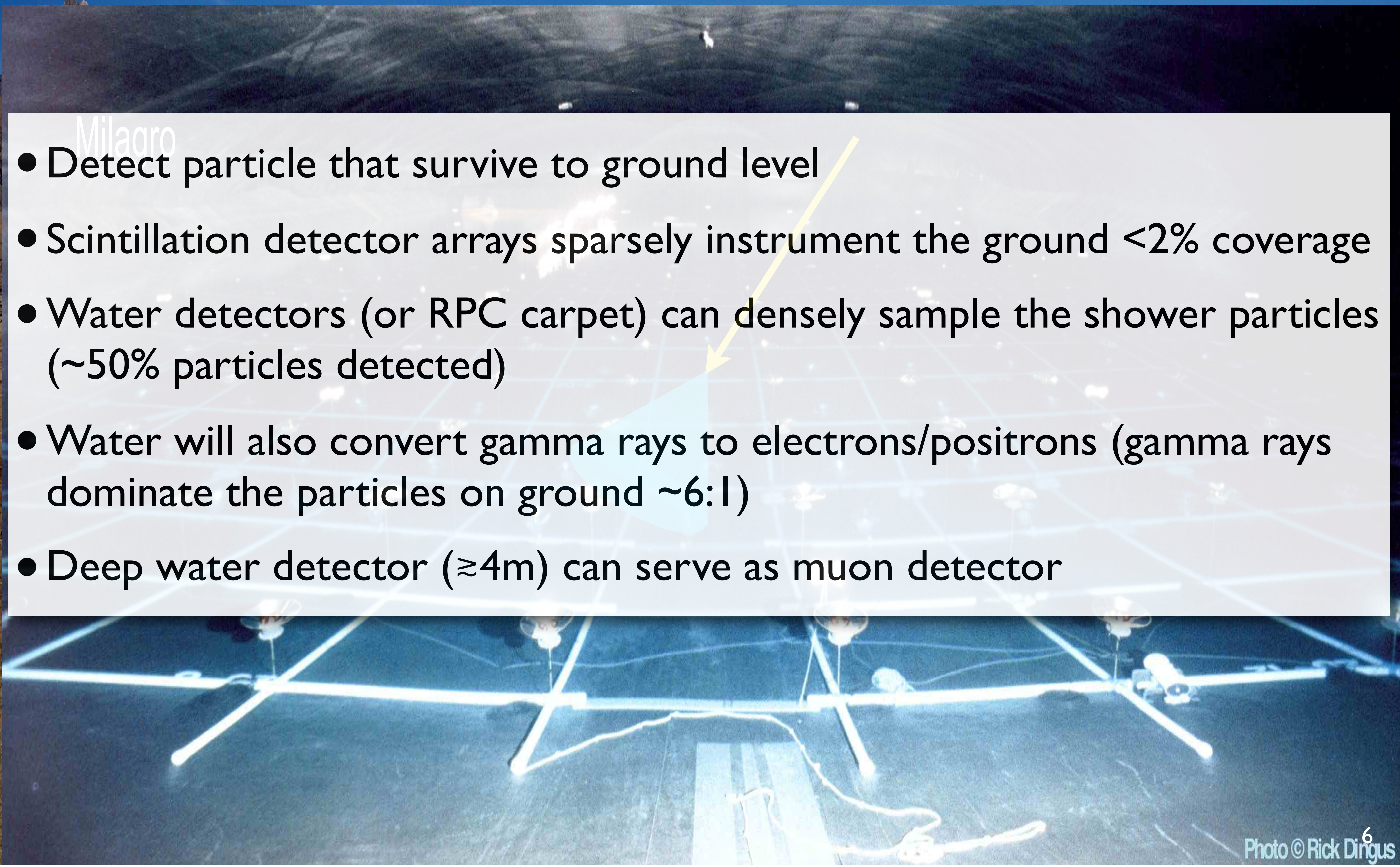
Imaging Atmospheric Cherenkov Telescopes



- 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

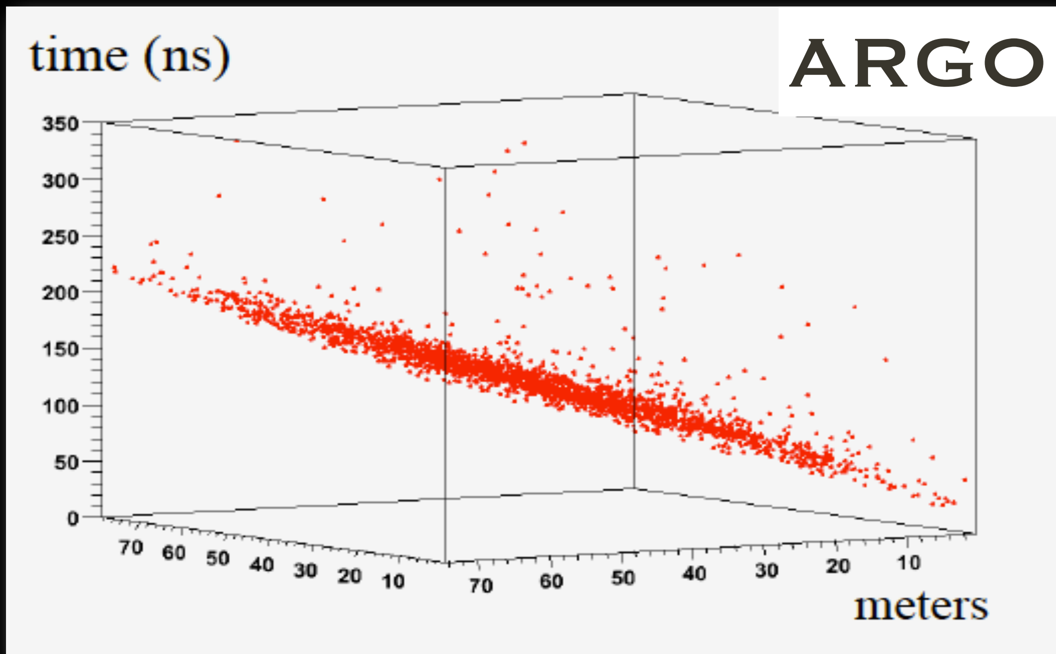
F. Acero & H. Gast

Extensive Air Shower Arrays

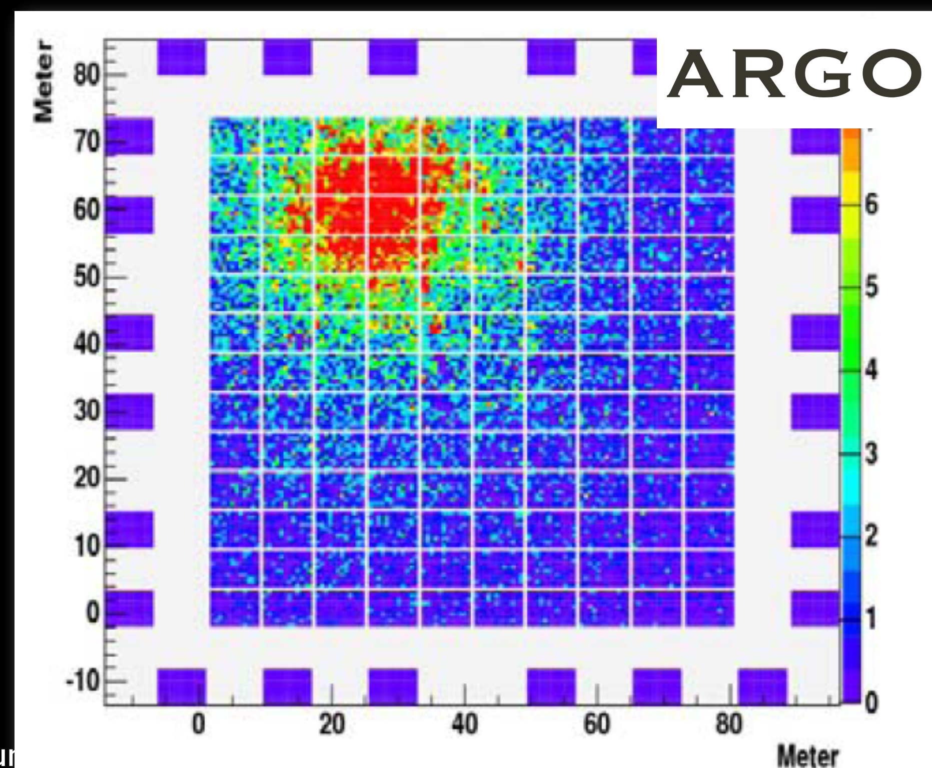


- Detect particle that survive to ground level
- Scintillation detector arrays sparsely instrument the ground <2% coverage
- Water detectors (or RPC carpet) can densely sample the shower particles (~50% particles detected)
- Water will also convert gamma rays to electrons/positrons (gamma rays dominate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

Angular and Energy Reconstruction



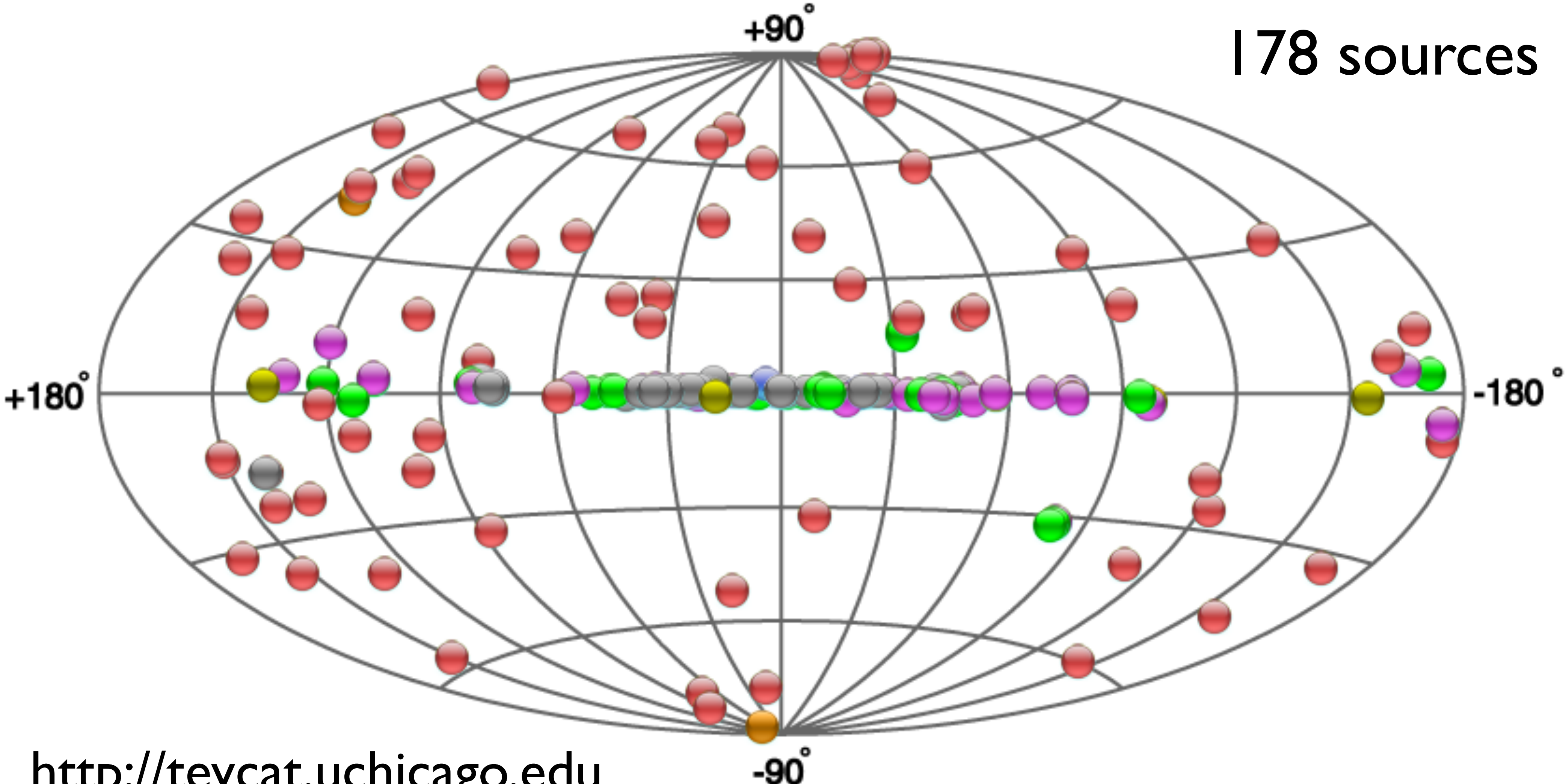
Direction via timing
(~ns timing yields 0.2°-1° resolution)



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

VHE Instruments

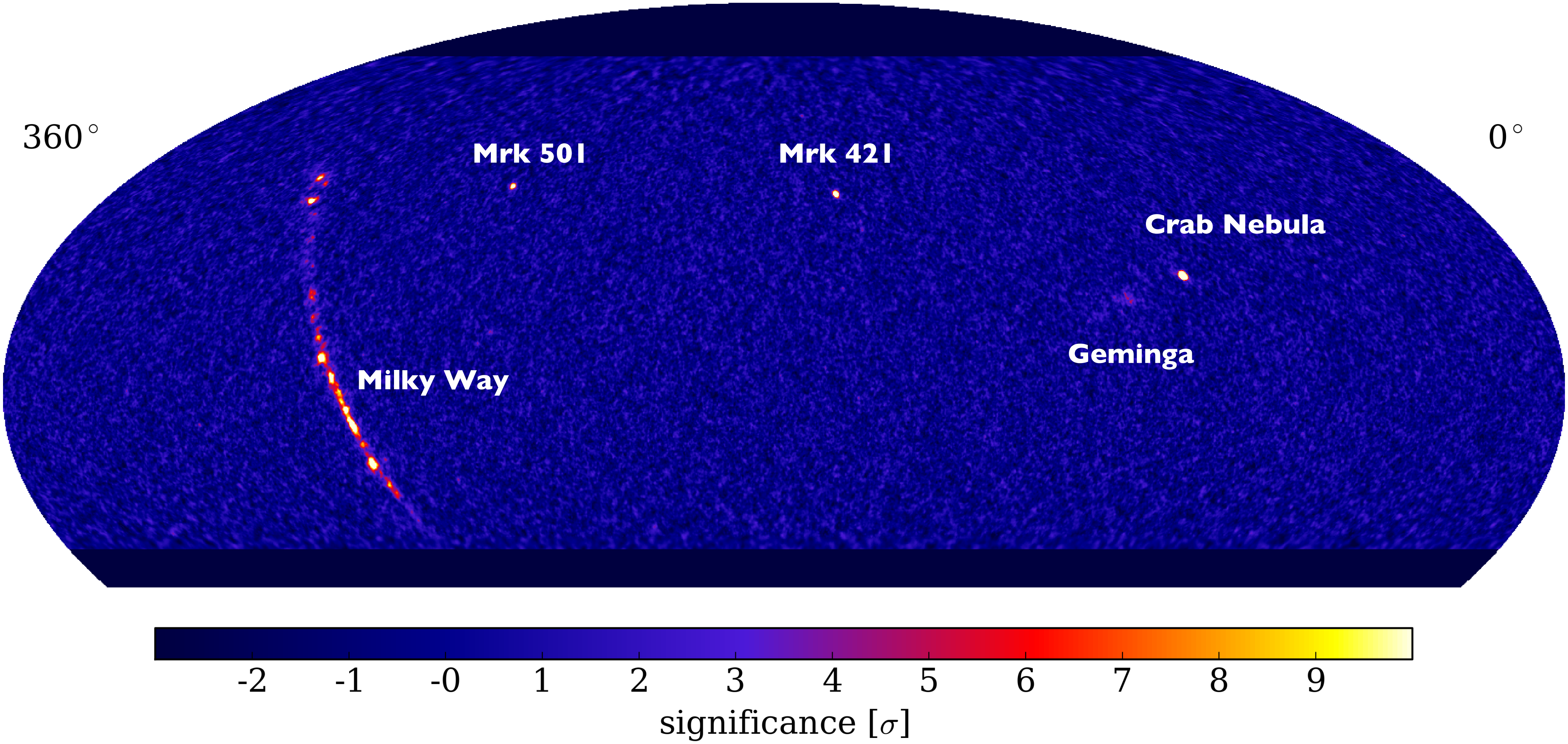
VHE Sky



178 sources

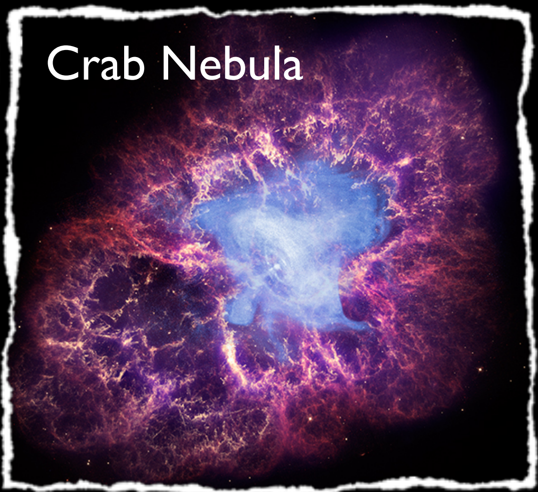
http://tevcat.uchicago.edu

HAWC View of the Sky



Galactic Gamma-Ray Sources

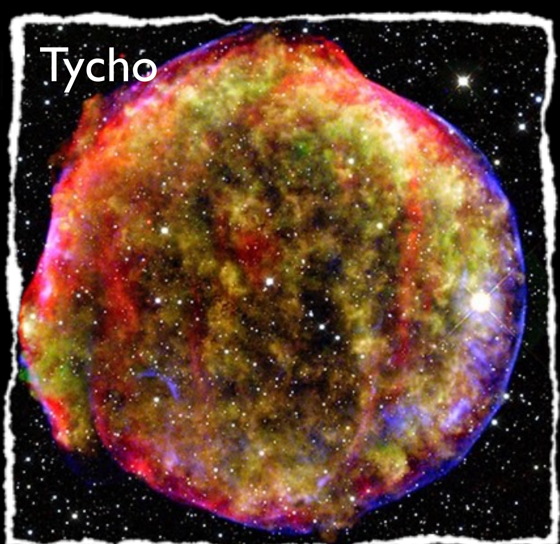
PWN



Globular Clusters

36 PWN (2 pulsars)
35 UNID
13 SN Shell
10 SNR/Mol. Cloud
6 binaries
4 massive star clusters
2 Star Forming Regions
1 Globular Cluster

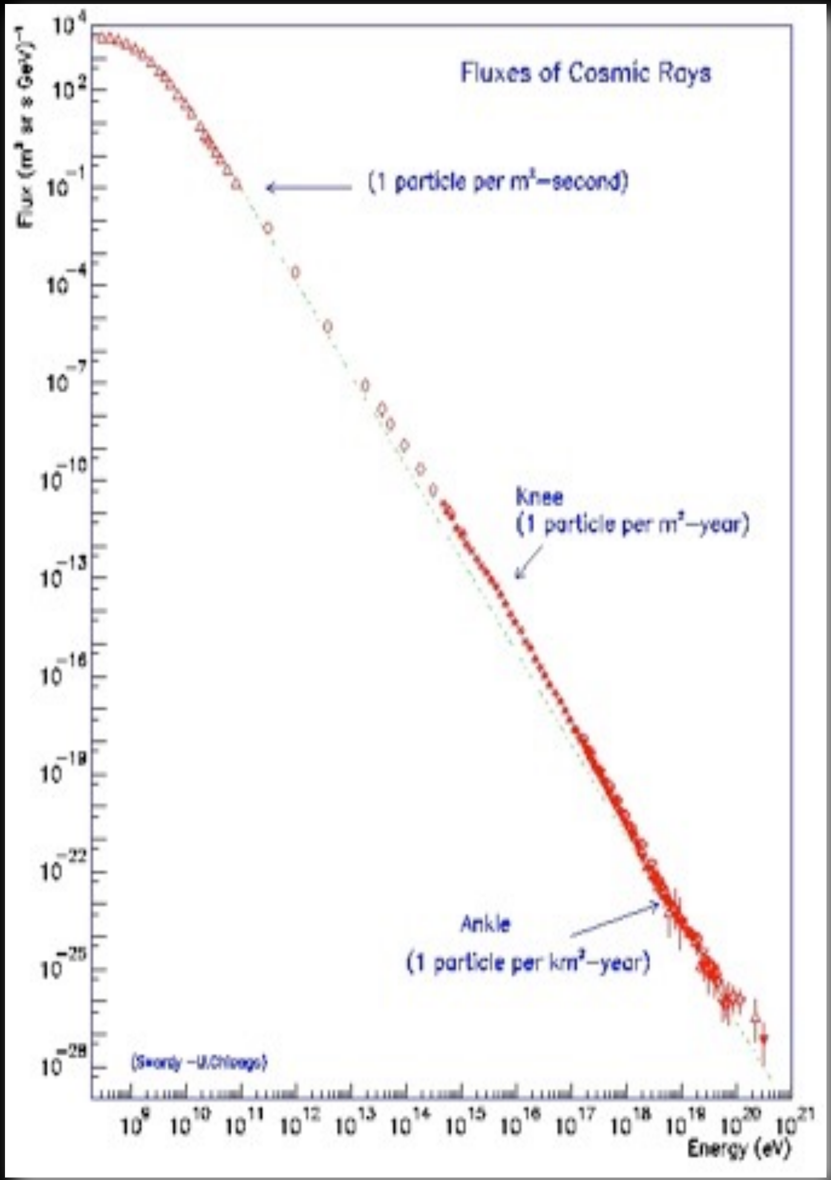
SNR



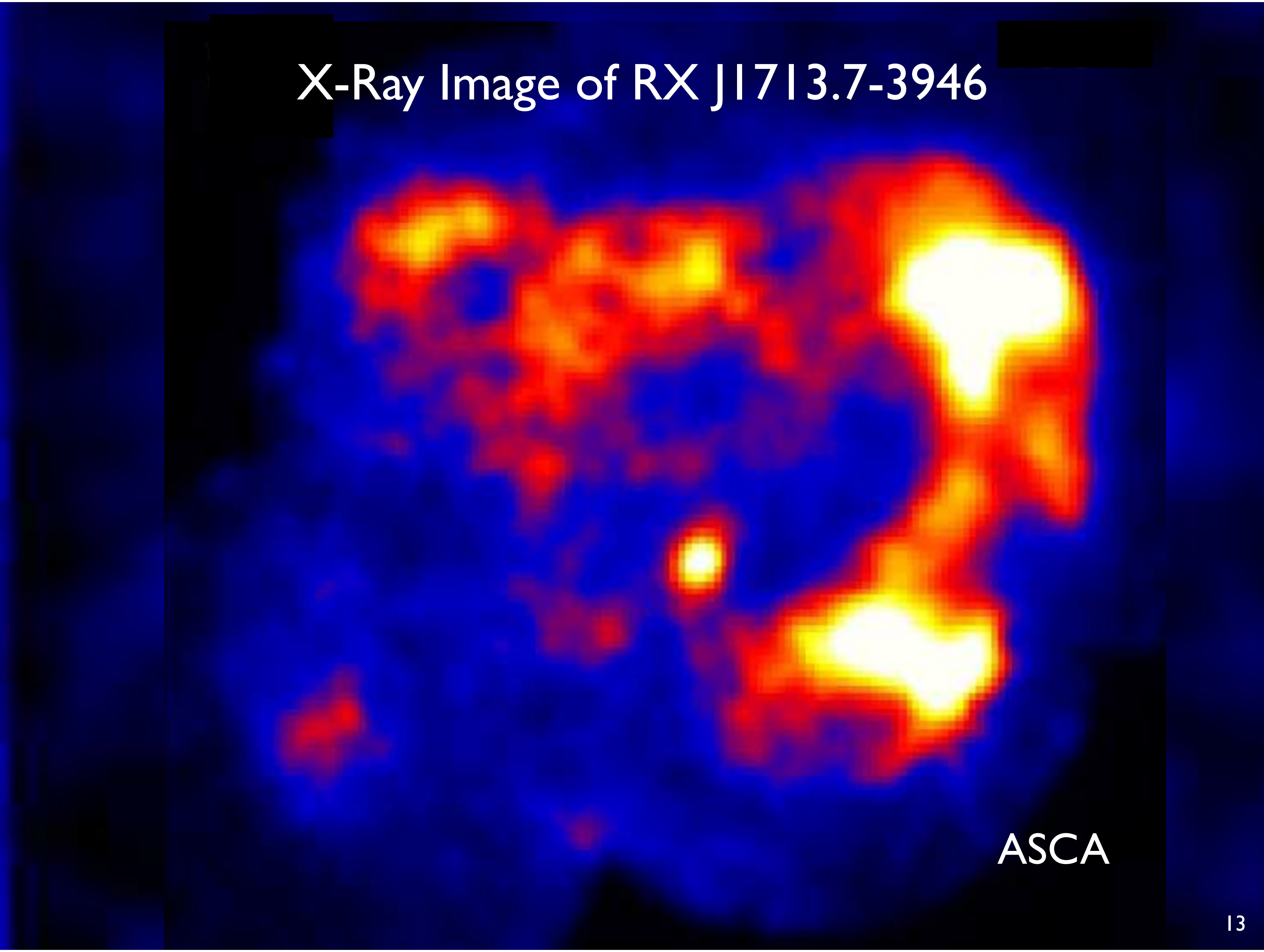
SNR/Molecular Clouds

Cosmic-Ray Origins

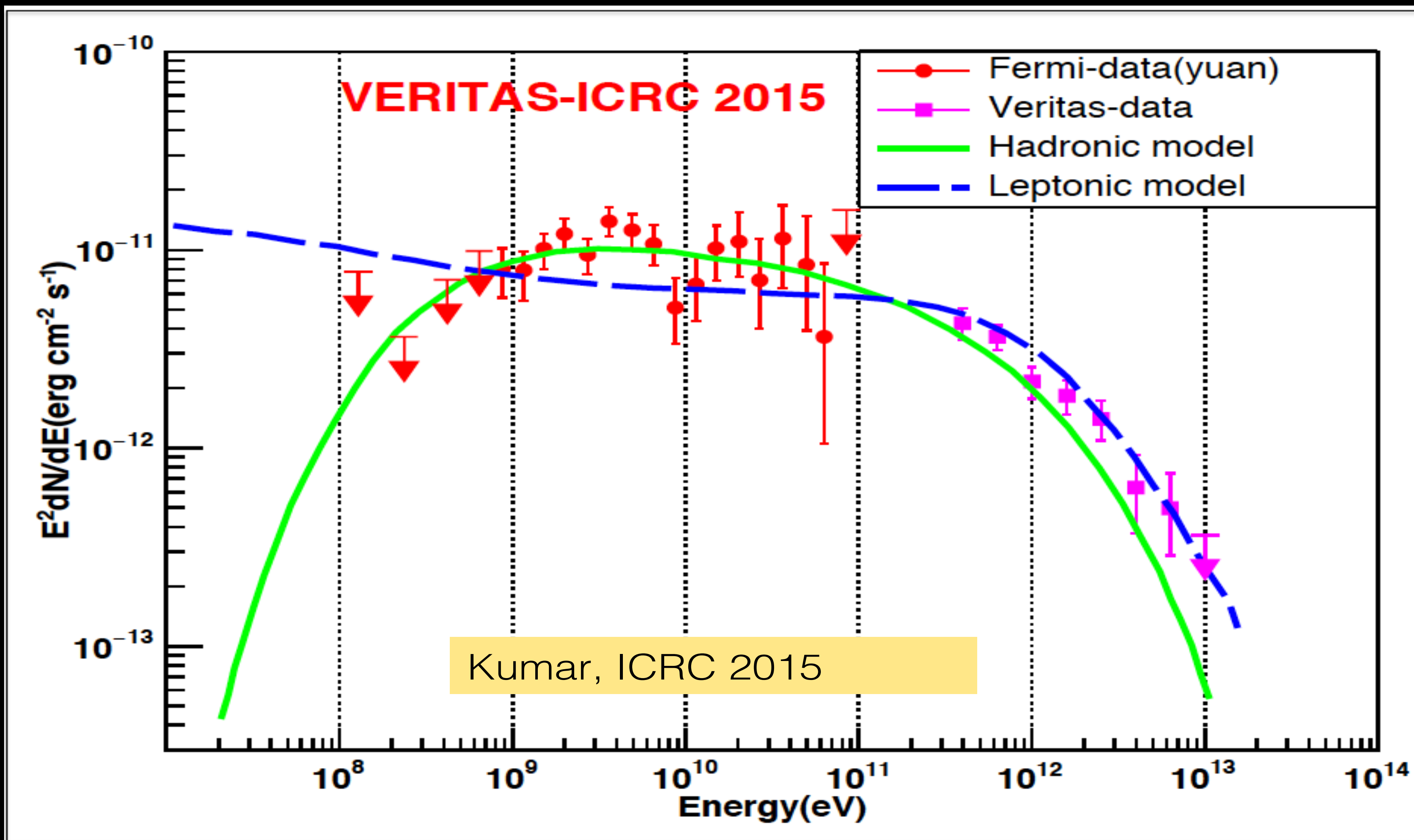
- Steep spectrum $E^{-2.7}$
- Galactic energy loss of 10^{41} ergs/sec (from lifetime measurements)
- Supernovae long suspected GCR source
  - Energy budget 10^{51} ergs/30 years = 10^{42} ergs/sec
  - Strong shocks yield $E^{-2.1}$ spectrum
  - Maximum energy ~10^{16} eV
- Direct proof has been elusive!



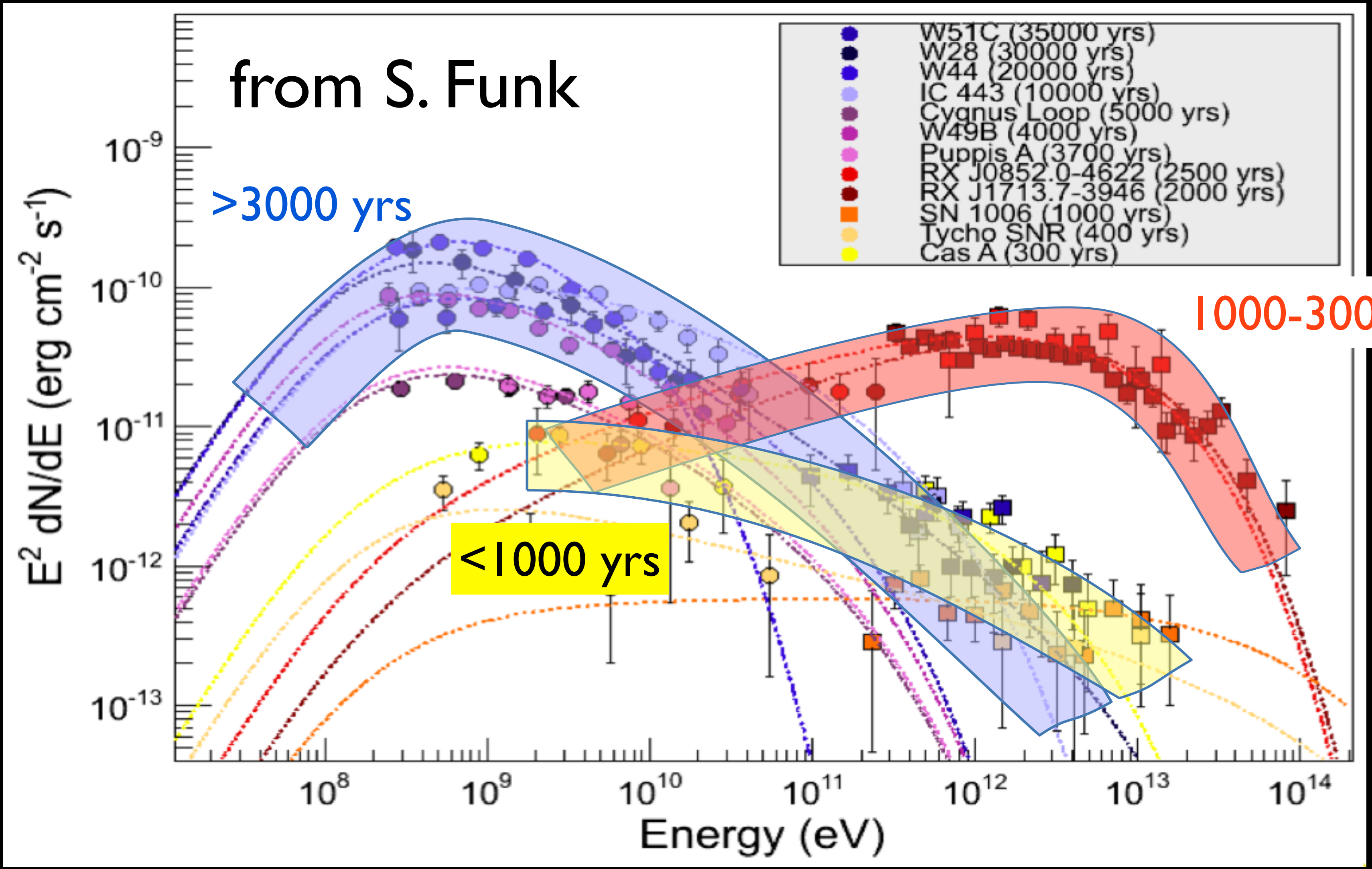
X-Ray Image of RX J1713.7-3946



Cassiopea A (300 yrs)



SN Remnant Evolution



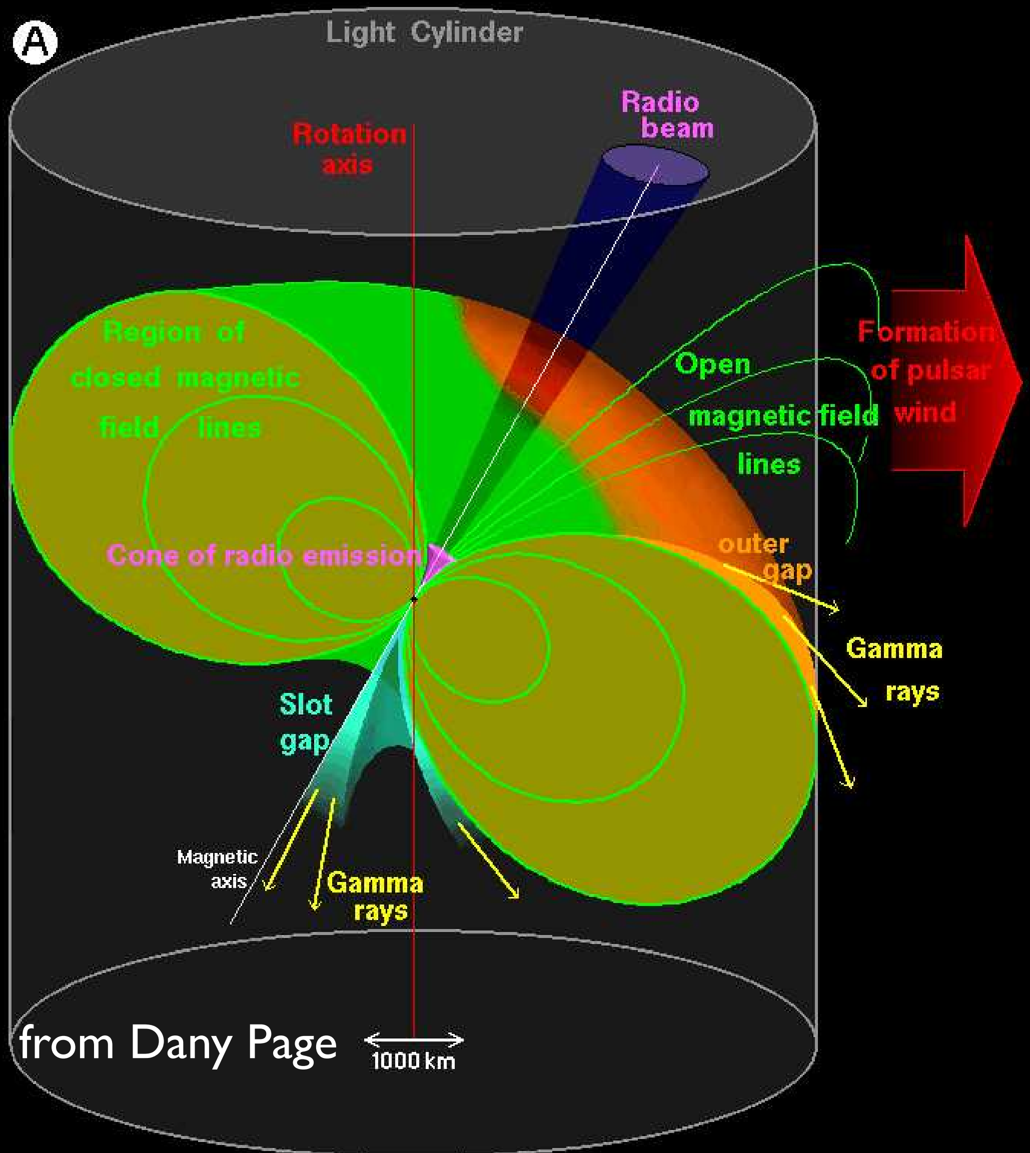
SNR and Cosmic Rays

- SNRs are complicated objects:
  - Age, environment, progenitor, magnetic fields all may play a role
- Likely leptonic and hadronic acceleration
- Need multi-wavelength observations to understand:
  - particle energy distributions
  - X-ray - TeV correlation
  - broadband energy spectrum
- No evidence for PeV energies
- Higher spatial and energy resolution needed - CTA

Pulsars and Their Nebulae

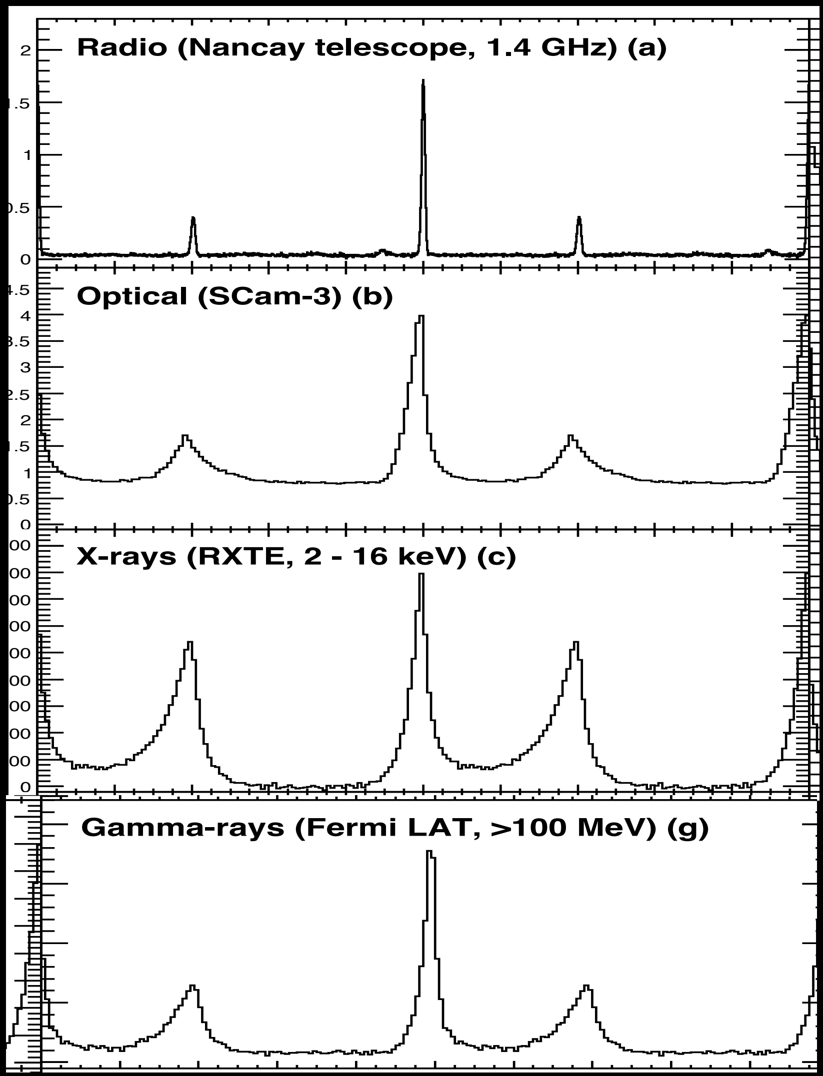
- PWN are most common Galactic source of TeV gamma rays
- PWN are powered by their pulsars
- Nebulae trap high-energy electrons/positrons
- Eventually release electrons/positrons into the ISM
- Potential background for dark matter searches
- Understanding particle diffusion critical

VHE Emission from Pulsars

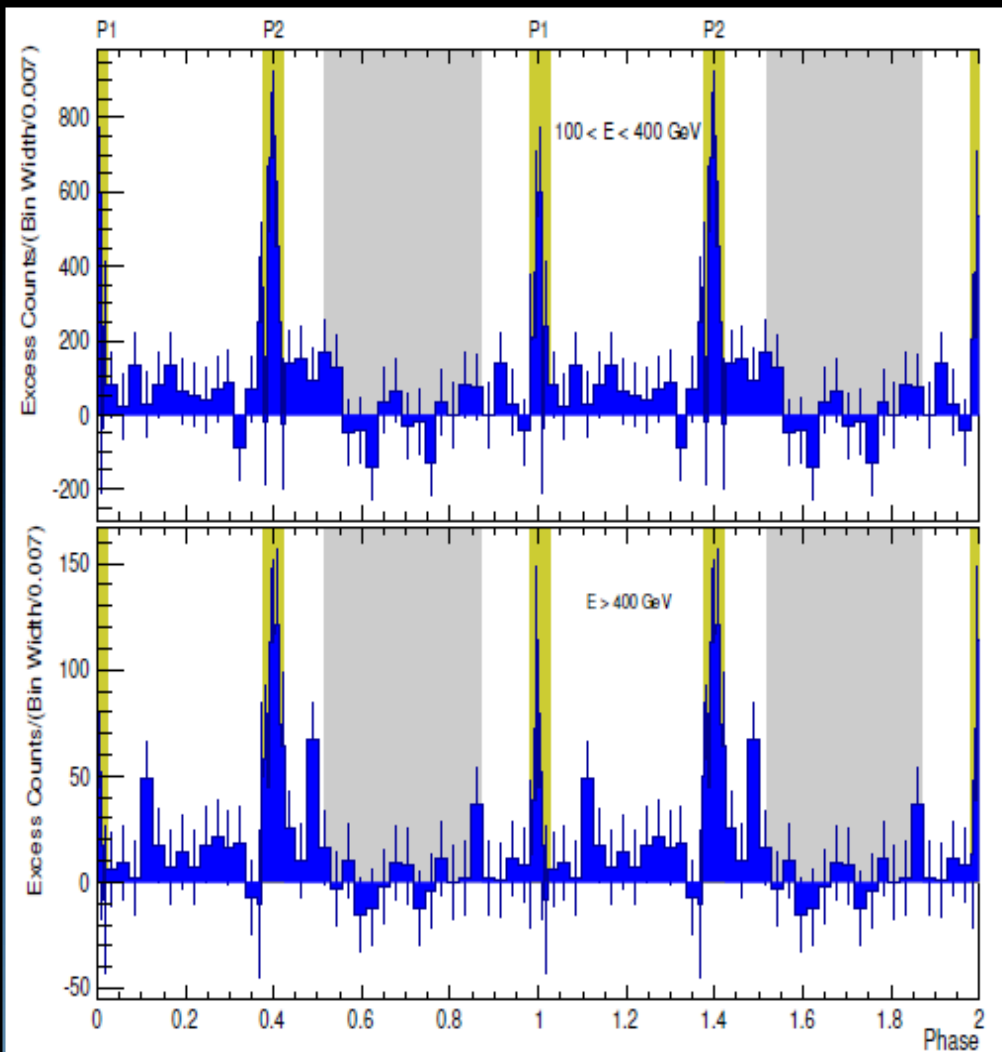


from Dany Page

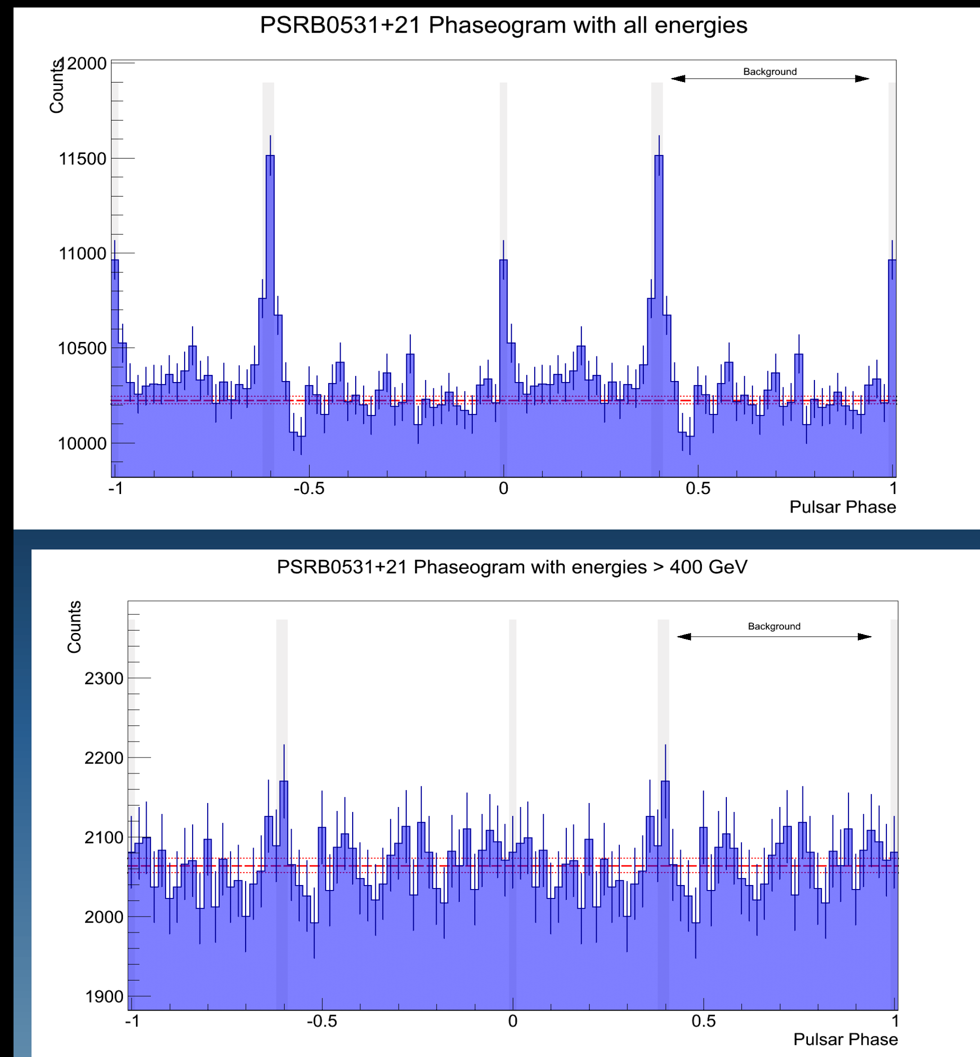
Crab Pulsar



Crab Pulsar >400 GeV Emission

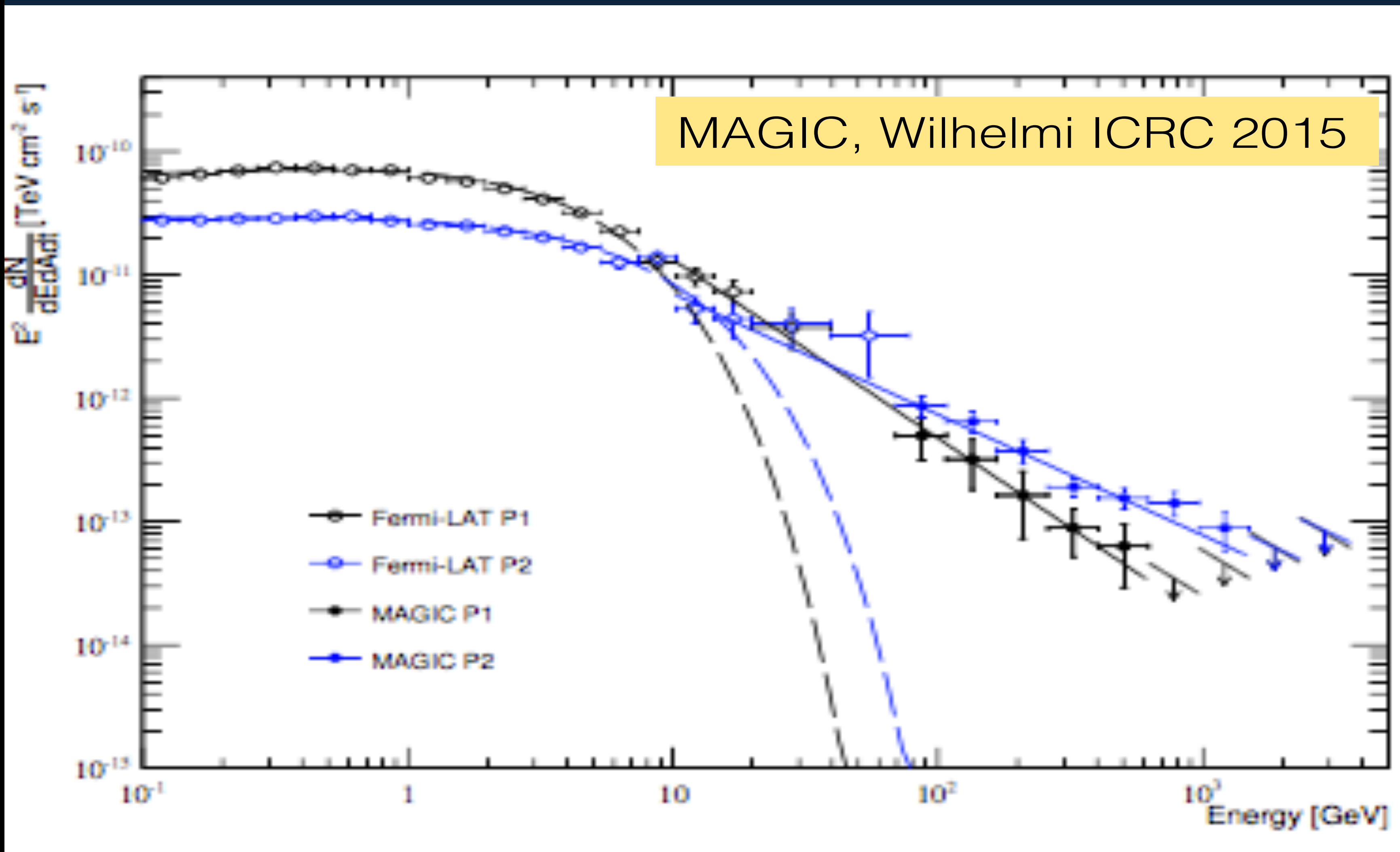


MAGIC



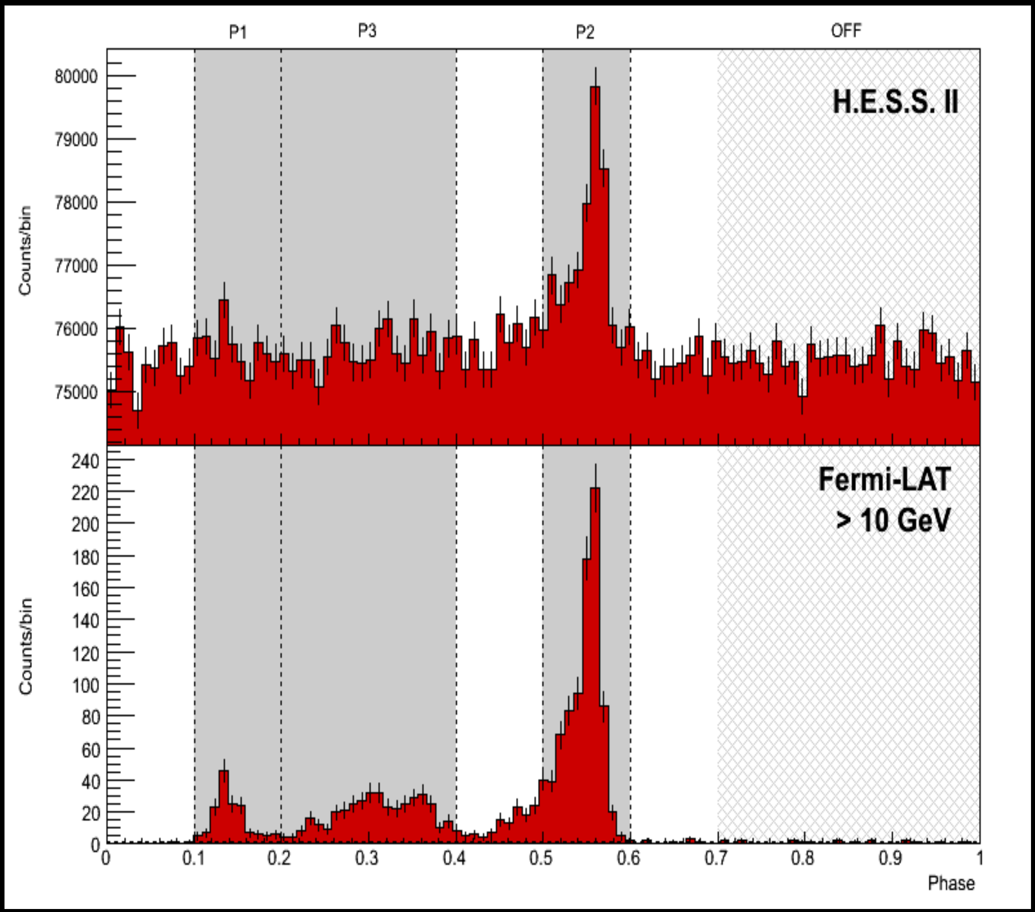
VERITAS

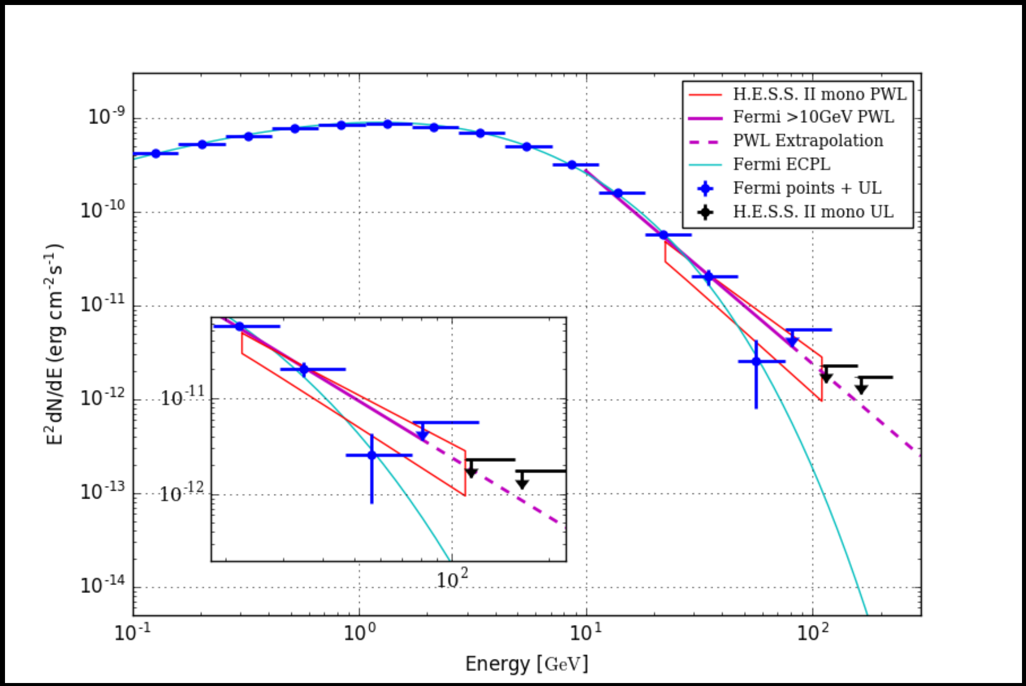
Crab Pulsar VHE Spectrum



VHE emission challenges Pulsar models

Vela Pulsar: H.E.S.S. II

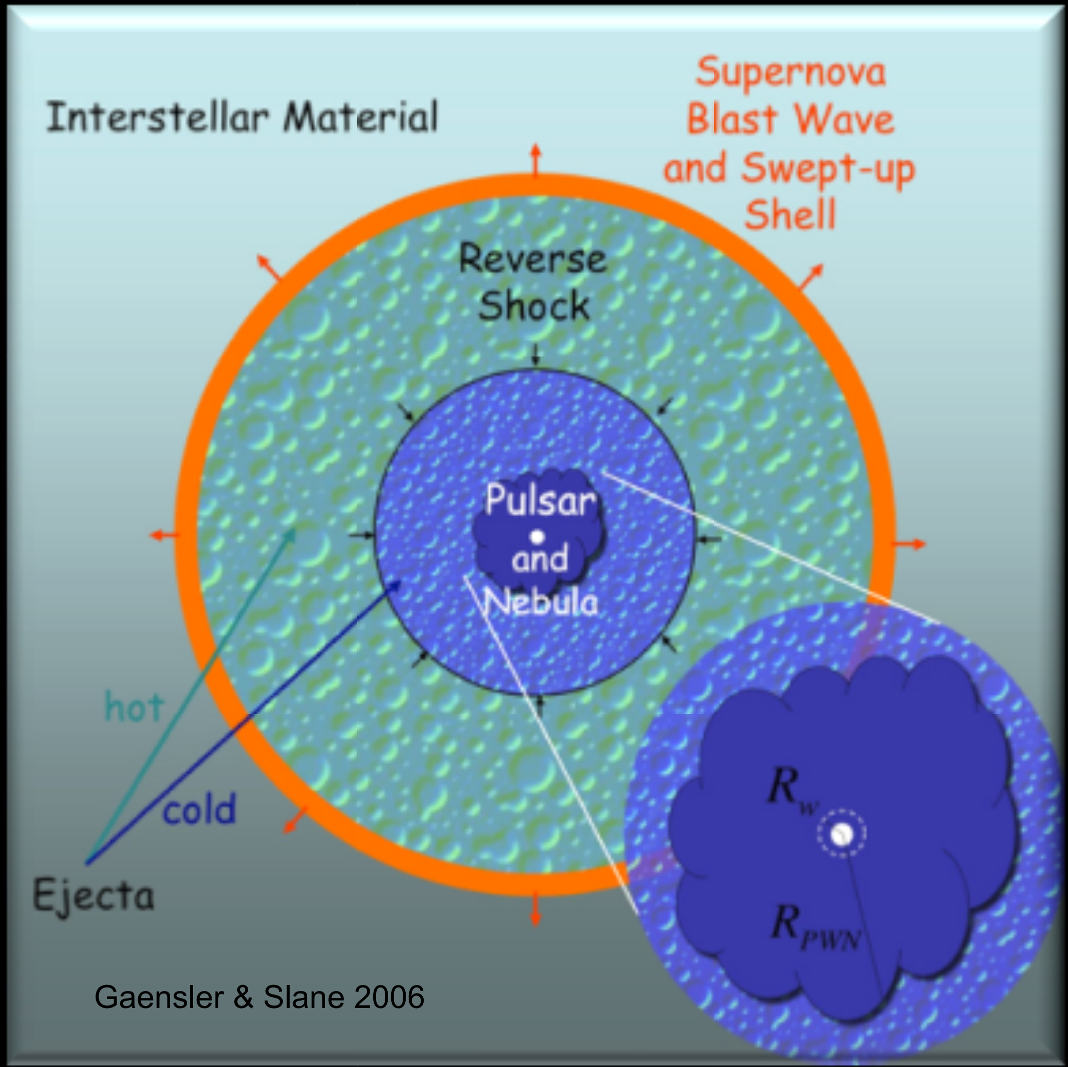




- H.E.S.S. measurement at 10 GeV!
- Spectrum consistent with Fermi
- No evidence of hard component

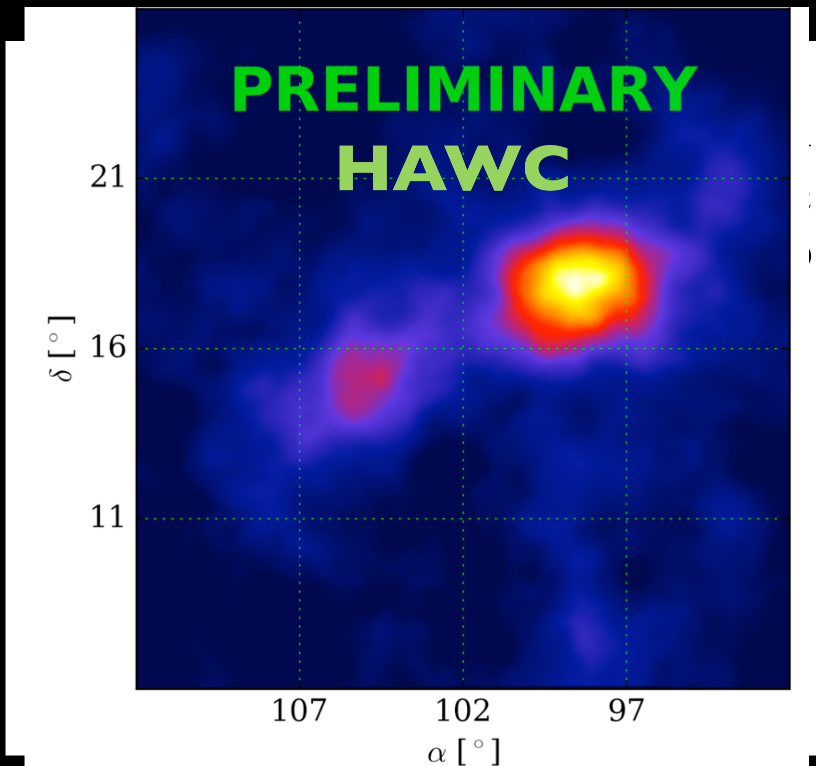
Pulsar Wind Nebulae

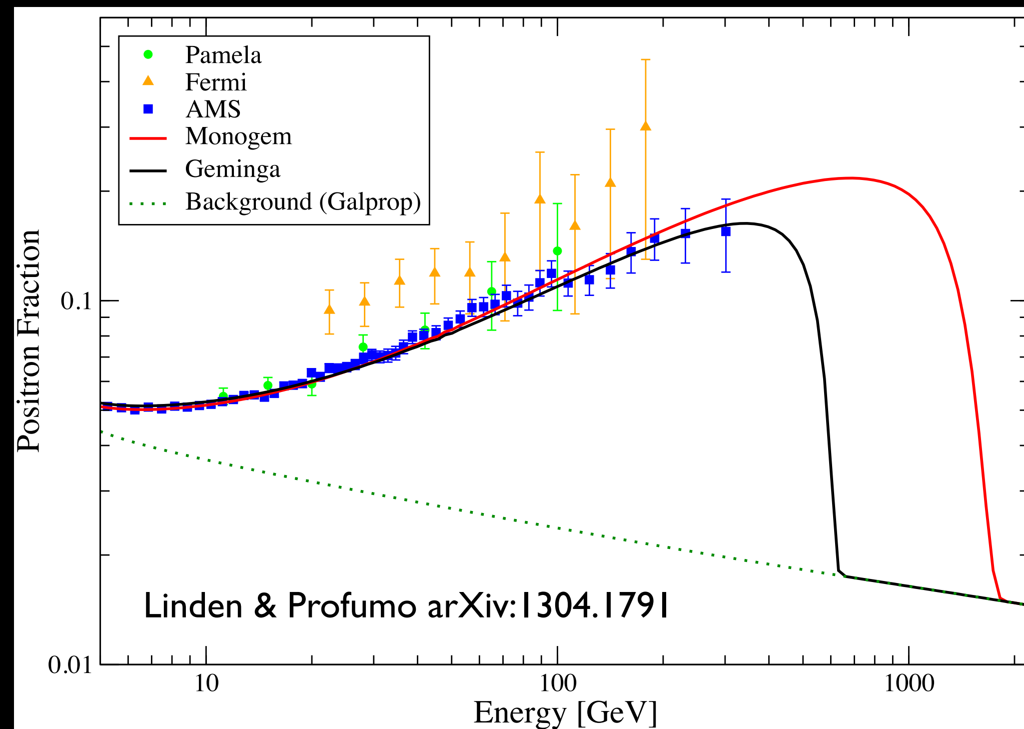
- Rapidly spinning neutron star powers a cold relativistic electron-positron wind
- Wind termination shock accelerates e^+e^-
- Inverse Compton reactions lead to production of VHE gamma rays
- Over time nebula expands, magnetic field weakens, and e^+e^- are released into the ISM



Gaensler & Slane 2006

PWN: Positron Generators

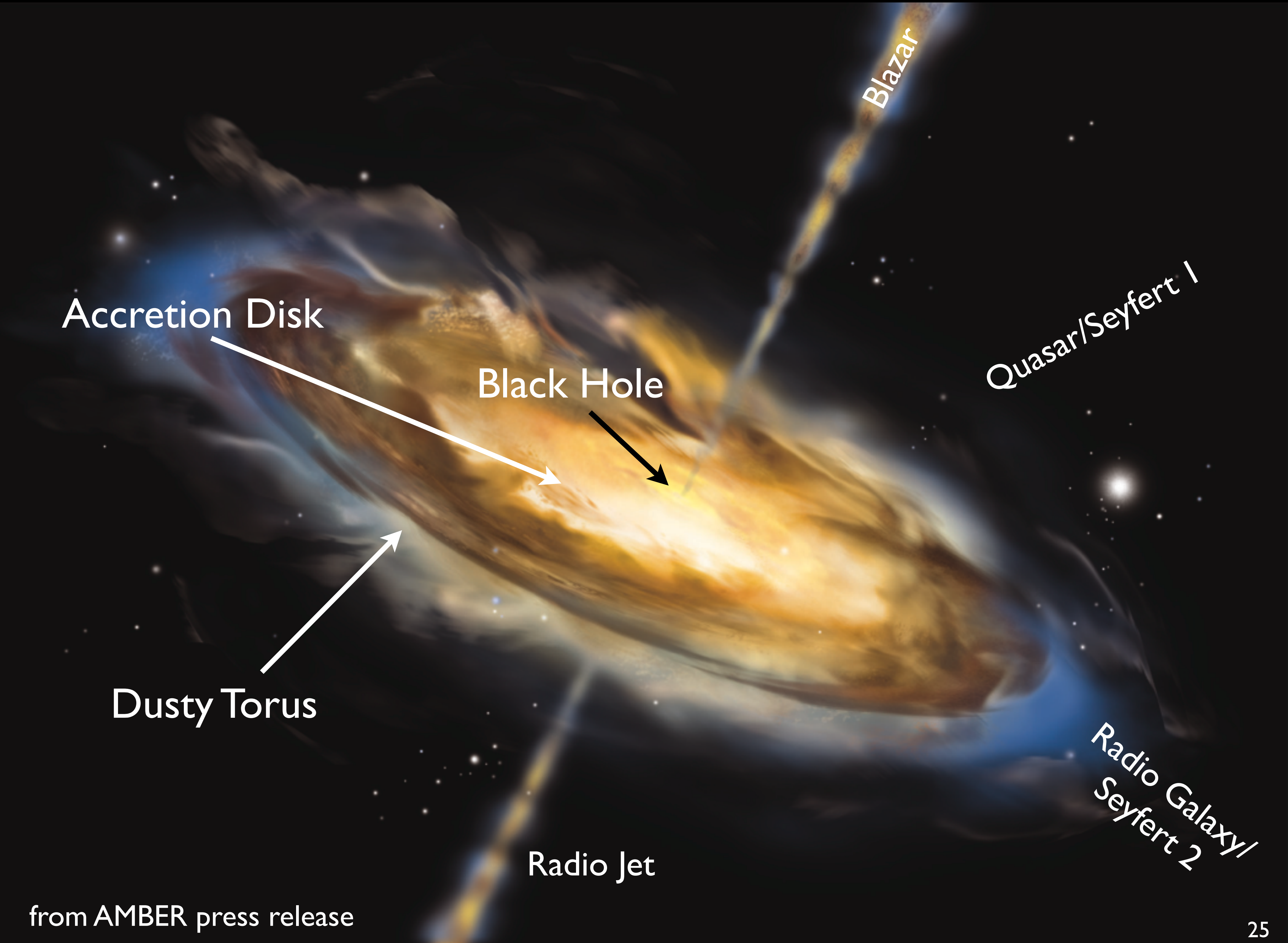




- Geminga (~300,000 yrs at ~200 pc) and Monogem (100,000 yrs at ~300 pc) are good candidates
- Milagro detected (HAWC confirmed) an extended gamma ray source (3°) coincident with the Geminga pulsar (~10^{32} ergs/sec) at ~20 TeV. Most likely seeing the PWN.
- Understanding diffusion important for understanding role of PWN in local positron flux

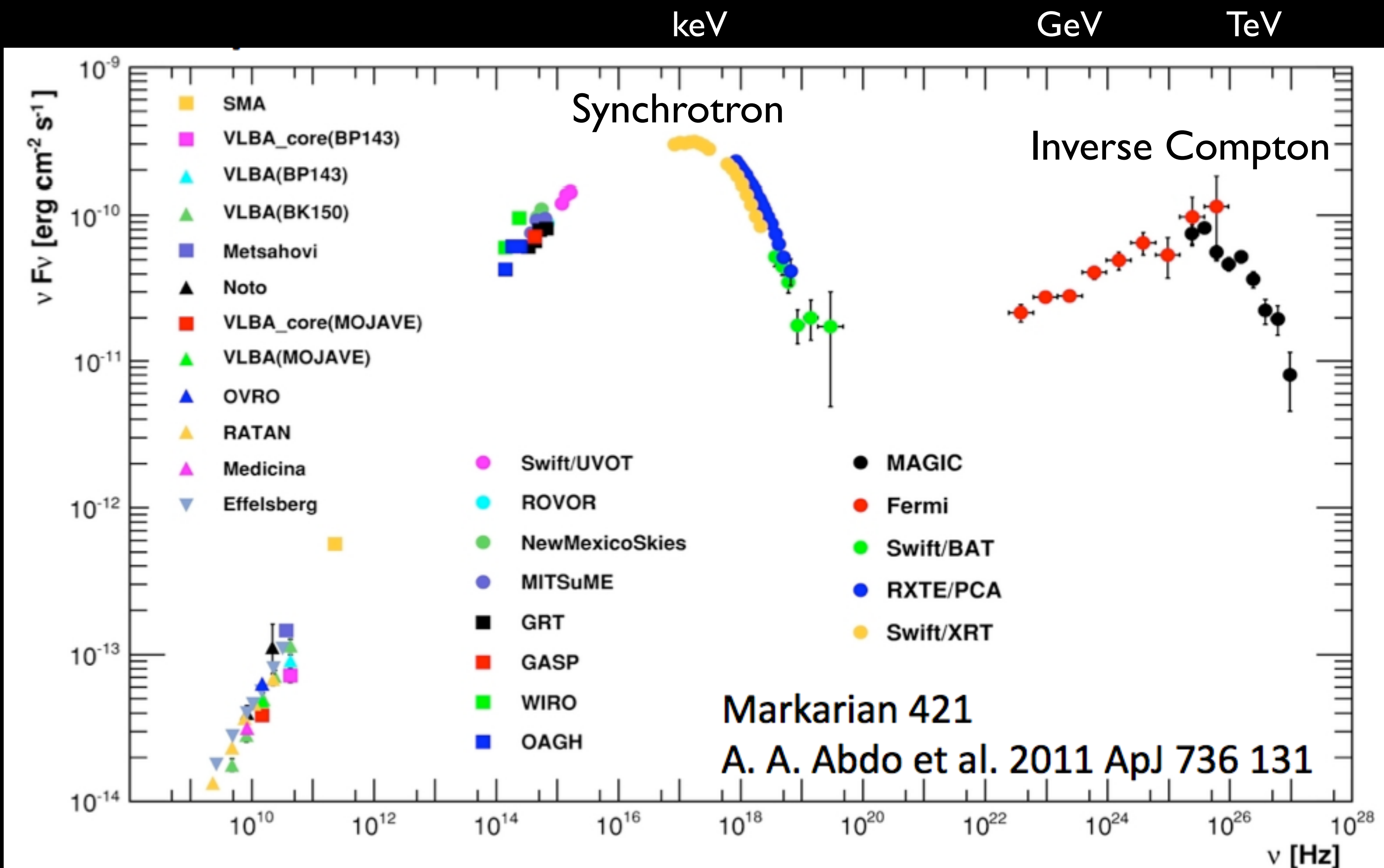
Extragalactic Gamma Rays

- Active Galaxies (67 detected in VHE band)
  - Extragalactic Background Light
  - Primordial Magnetic Fields
  - Axion-like Particle Searches
  - Lorentz Invariance Violation
- Gamma Ray Bursts (not yet detected from ground)
  - Lorentz Invariance Violation

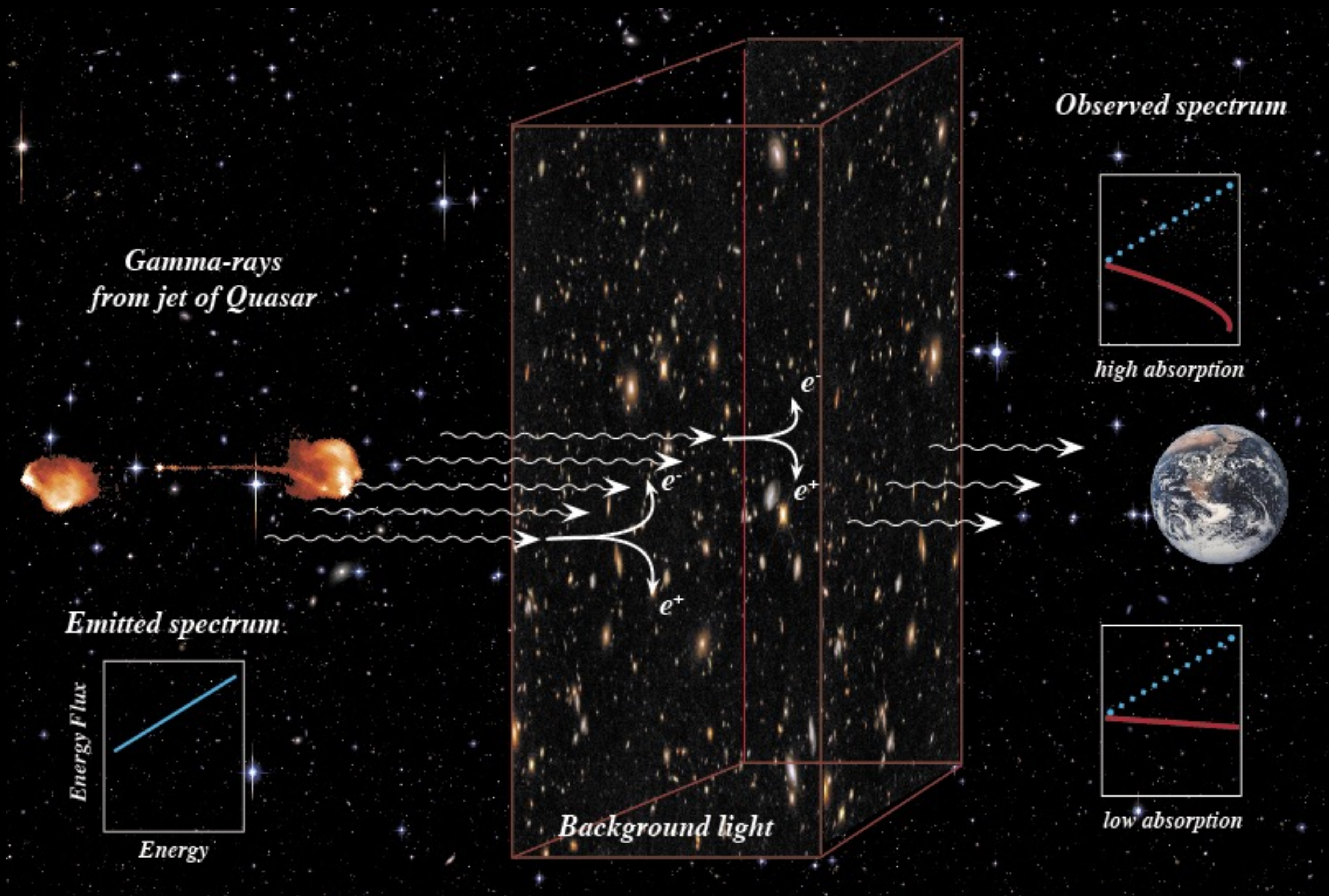


from AMBER press release

AGN Spectral Energy Distribution



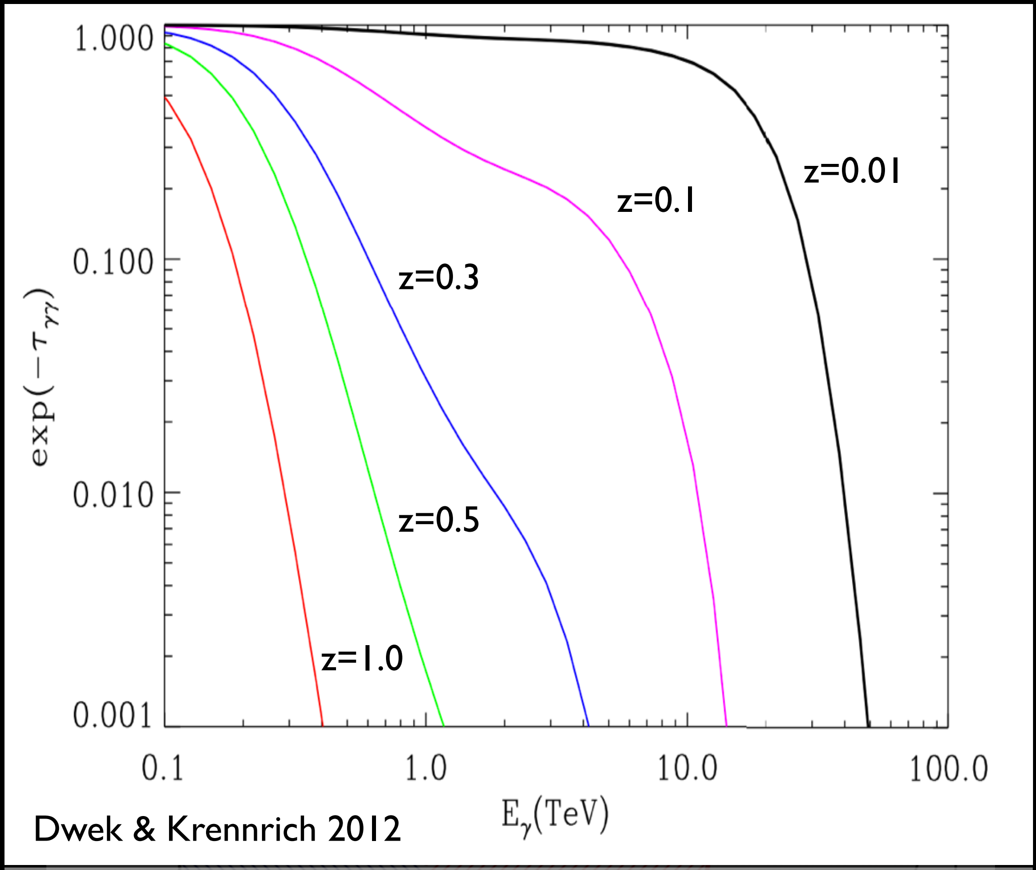
Extragalactic Background Light



from CTA and MPI

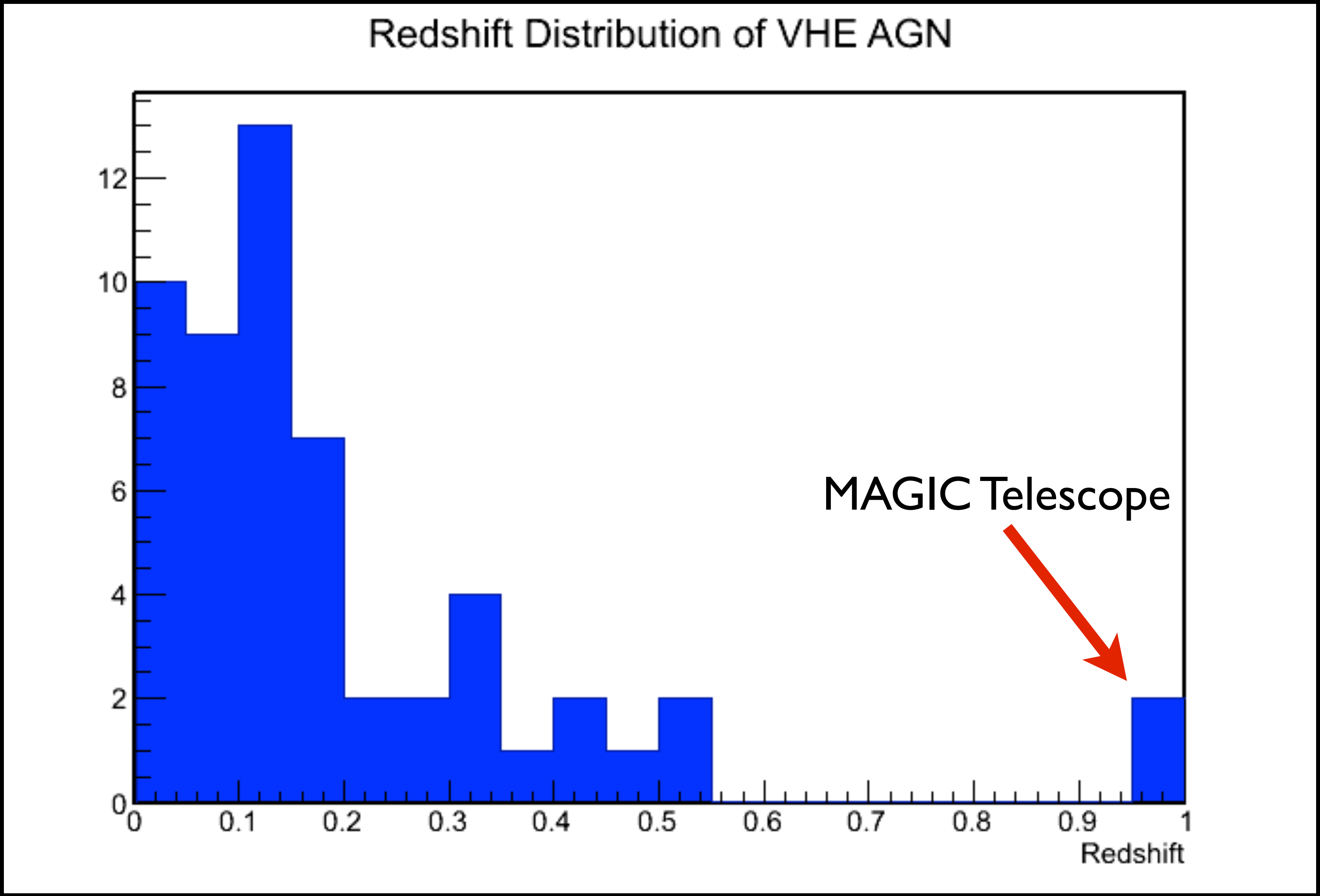
The EBL

- 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

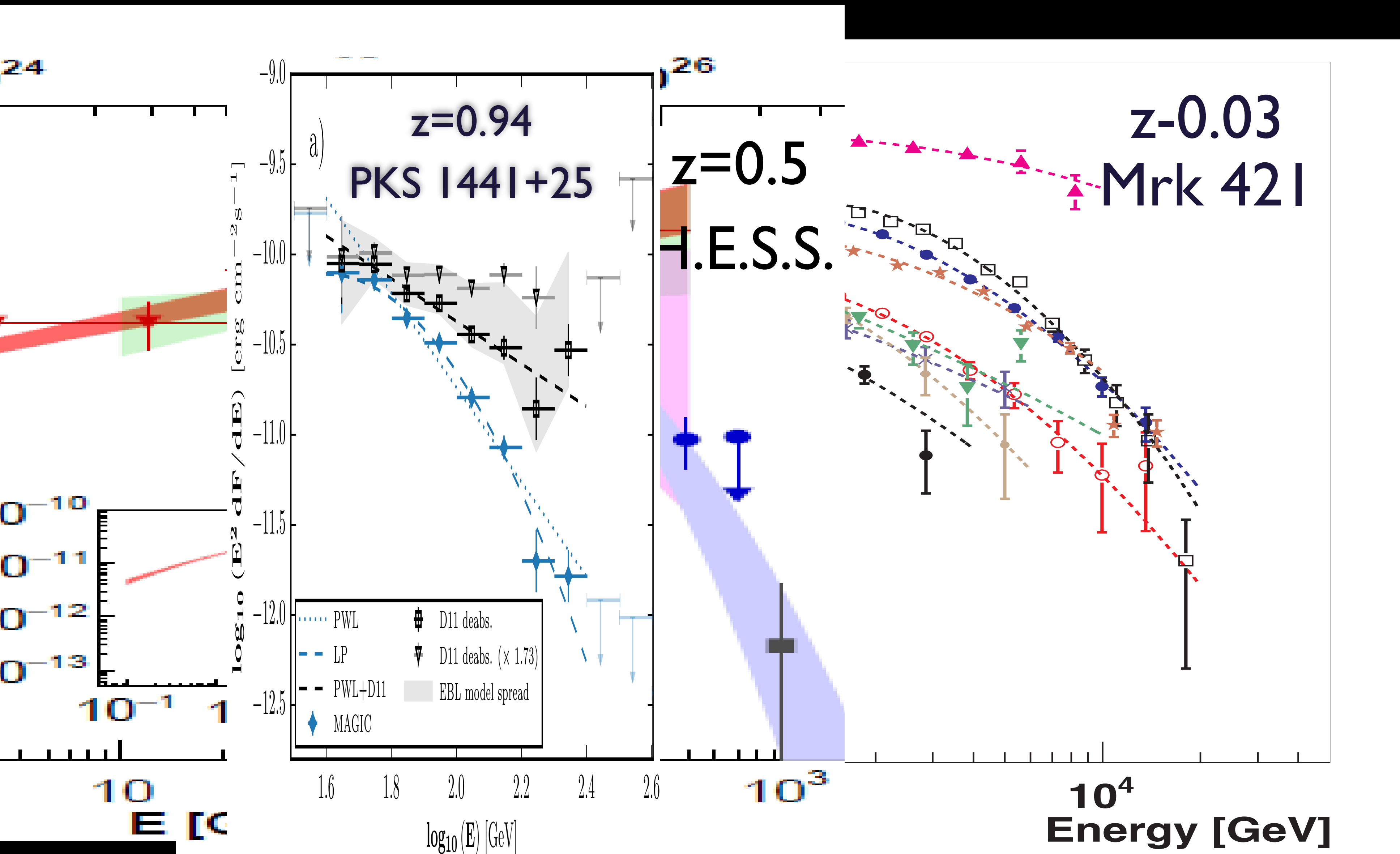


Dwek & Krennrich 2012

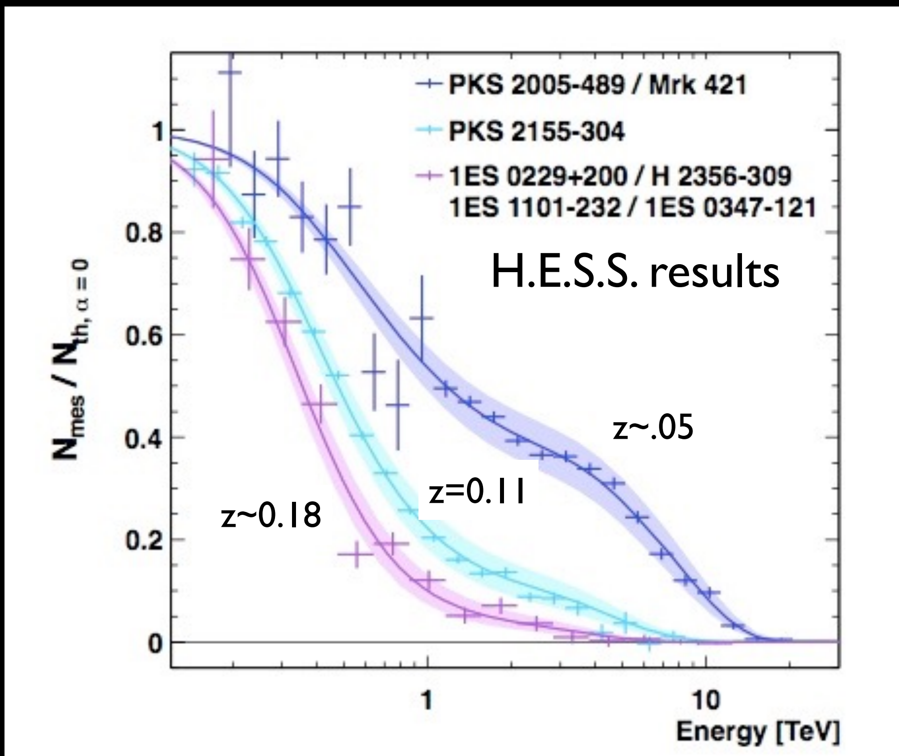
Redshift of TeV AGN

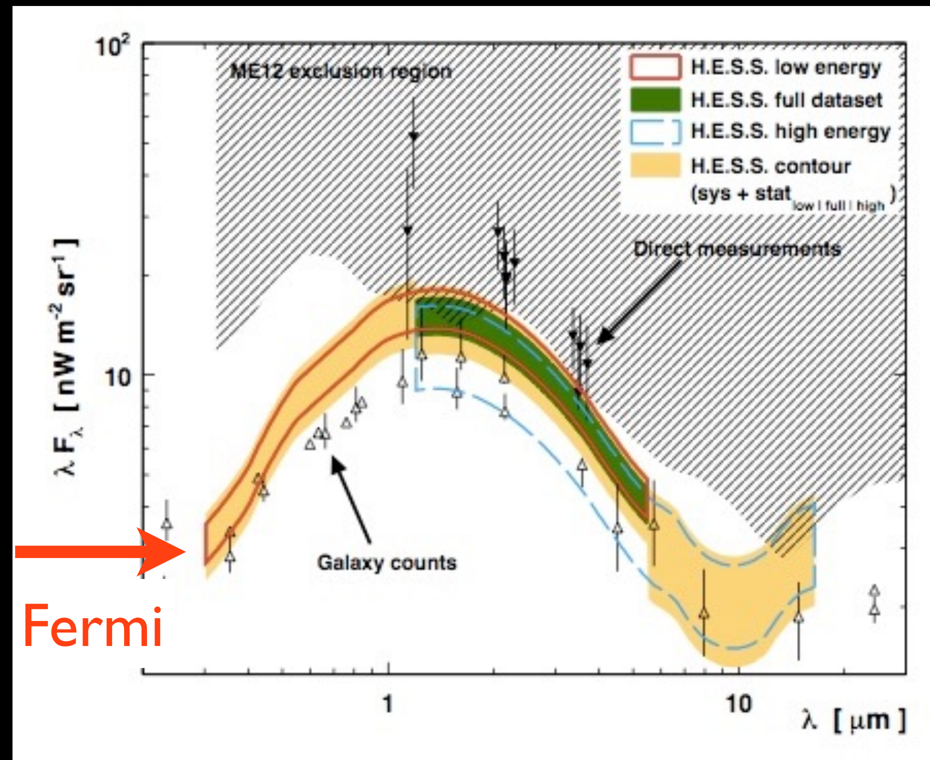


Redshift and Spectrum



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 Challenges

- Pulsar emission - is Crab only VHE pulsar? How is VHE emission generated?
- PWN - can they explain the local positron flux?
- What role do environment, age, and progenitor play in the acceleration of cosmic rays/electrons in SNR?
- Where are the cosmic Bevatrons?
- How do AGN jets generate multi-TeV gamma rays?
- Do gamma-ray bursts emit TeV gamma rays?
- What are the sources of the IceCube neutrinos?
- Do gravitational wave sources emit VHE gamma rays?
- How well can we constrain the EBL? (Exclude ALPs)
- Was there a primordial magnetic field?
- What is the nature of the dark matter?

Thanks To

Reshmi Mukherjee, Jamie Holder, Mathieu de Naurois, Razmik Mirzoyan