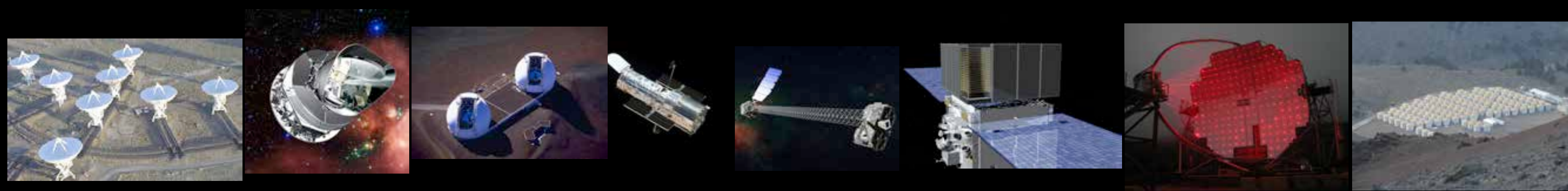
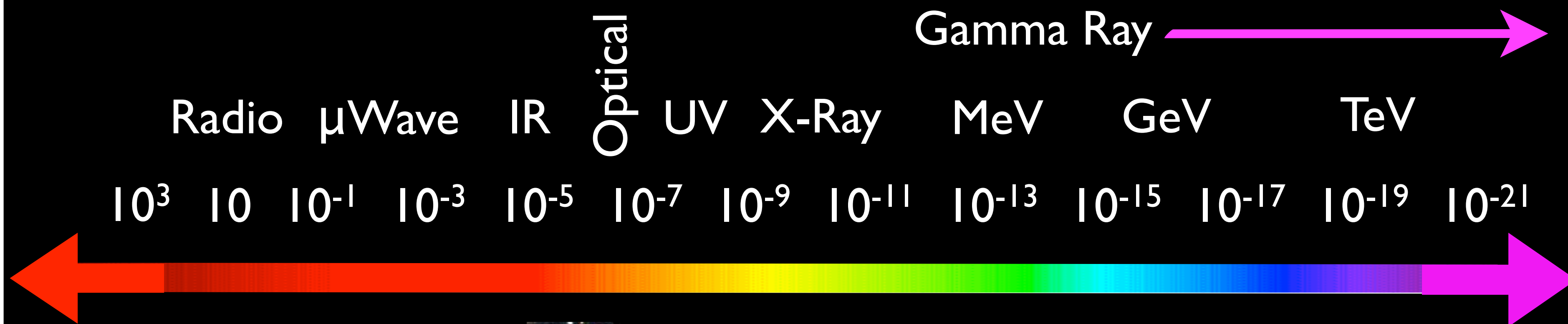
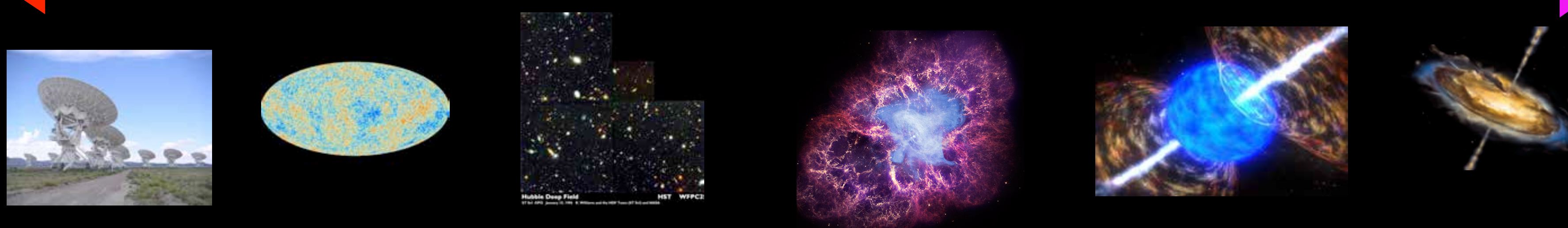
TeV Astrophysics with HAWC

Gus Sinnis
Los Alamos 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)
    - Direct detection of Q-Balls
  - 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

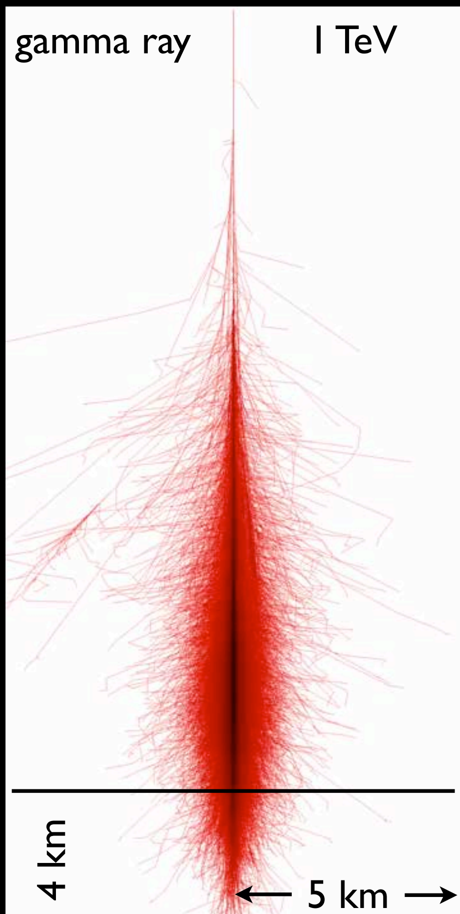
Study known sources
Deep surveys of limited regions
Source morphology (SNRs)
Fast transients (AGN flares)

EAS Arrays
Milagro/Tibet/ARGO

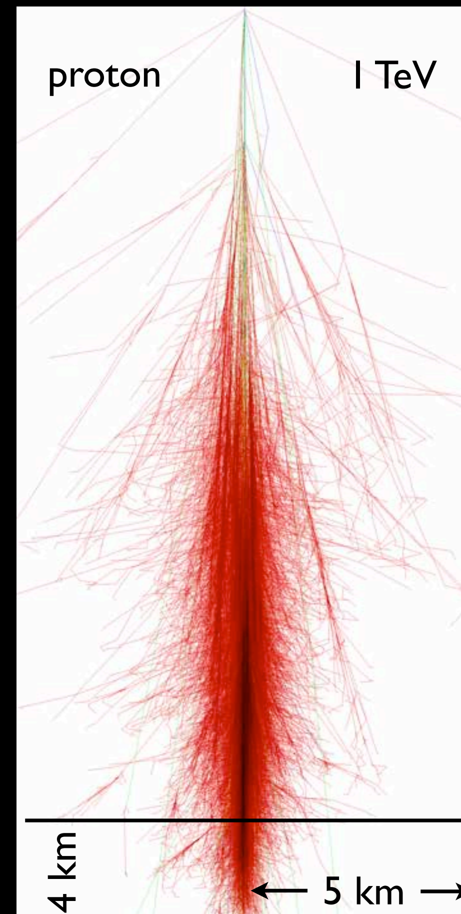
100 GeV - 100 TeV
Large Area
Good background rejection
Large Aperture & Duty Cycle

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

Extensive Air Showers

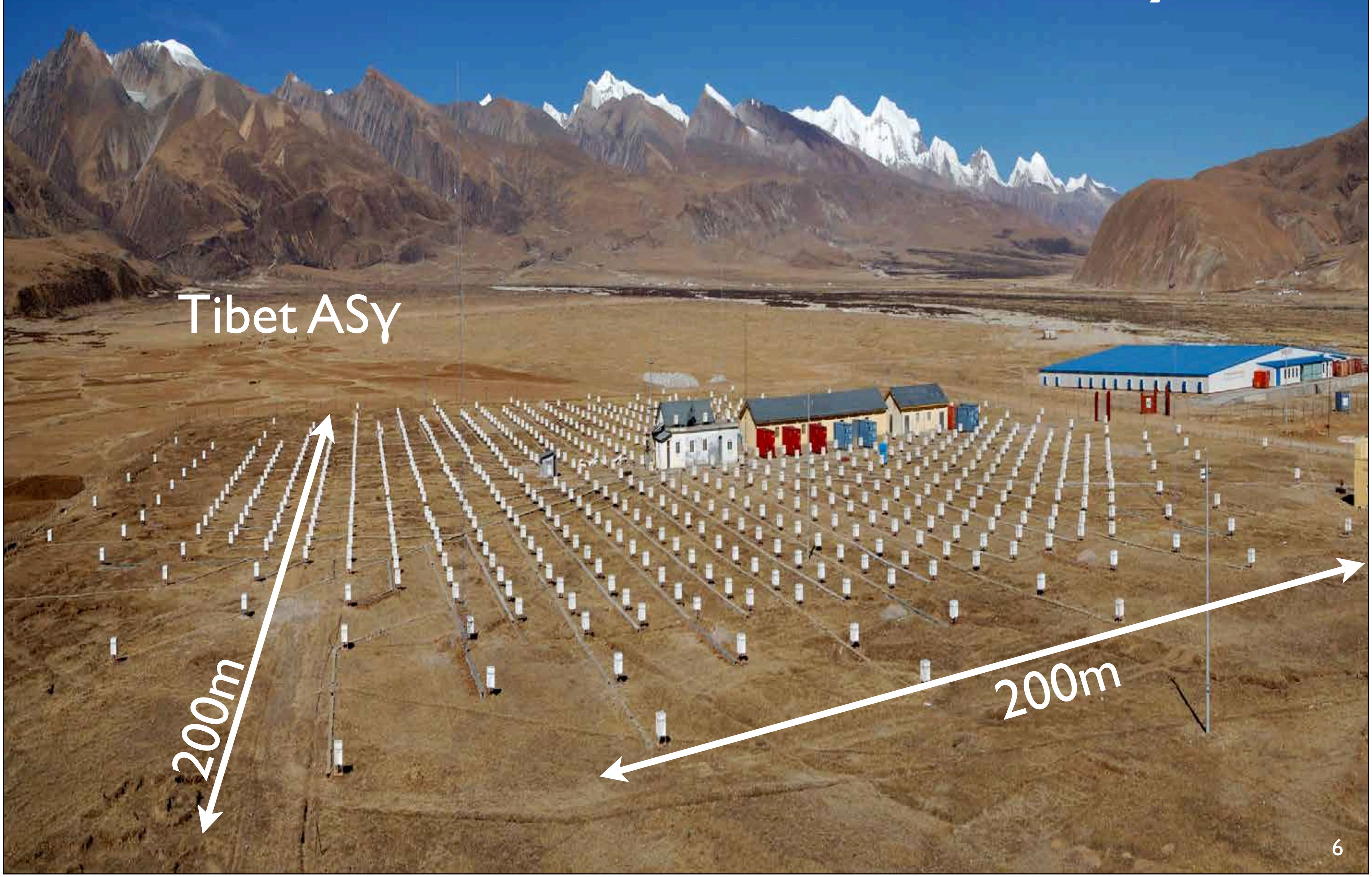


- γ showers almost purely e-m and relatively compact
- Hadronic showers contain muons (~30/TeV)
- Both have core of energetic particles
- Ground-based VHE telescopes must distinguish protons from photons

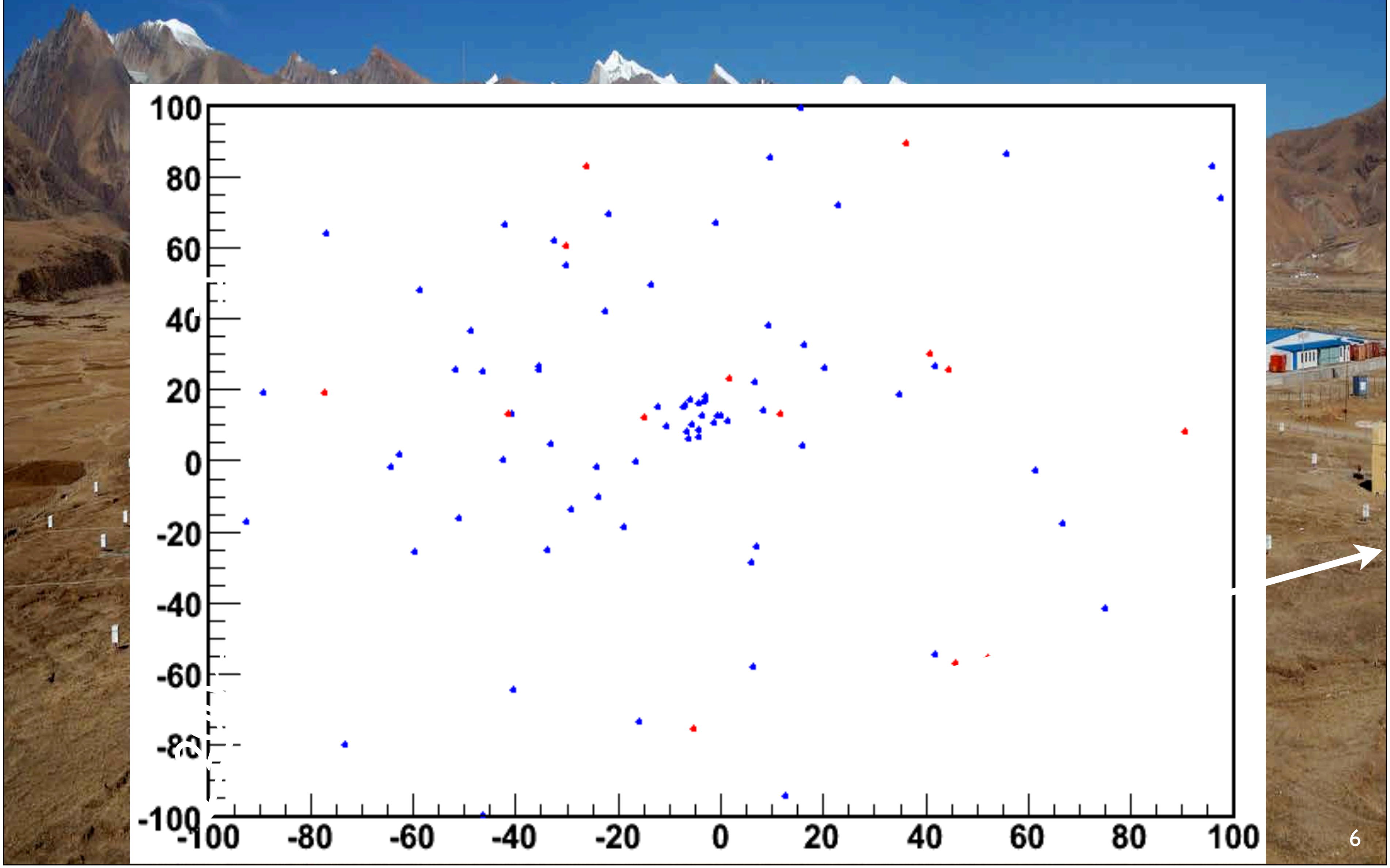


F. Schmidt, "CORSIKA Shower Images", http://www.ast.leeds.ac.uk/~fs/showerimages.html

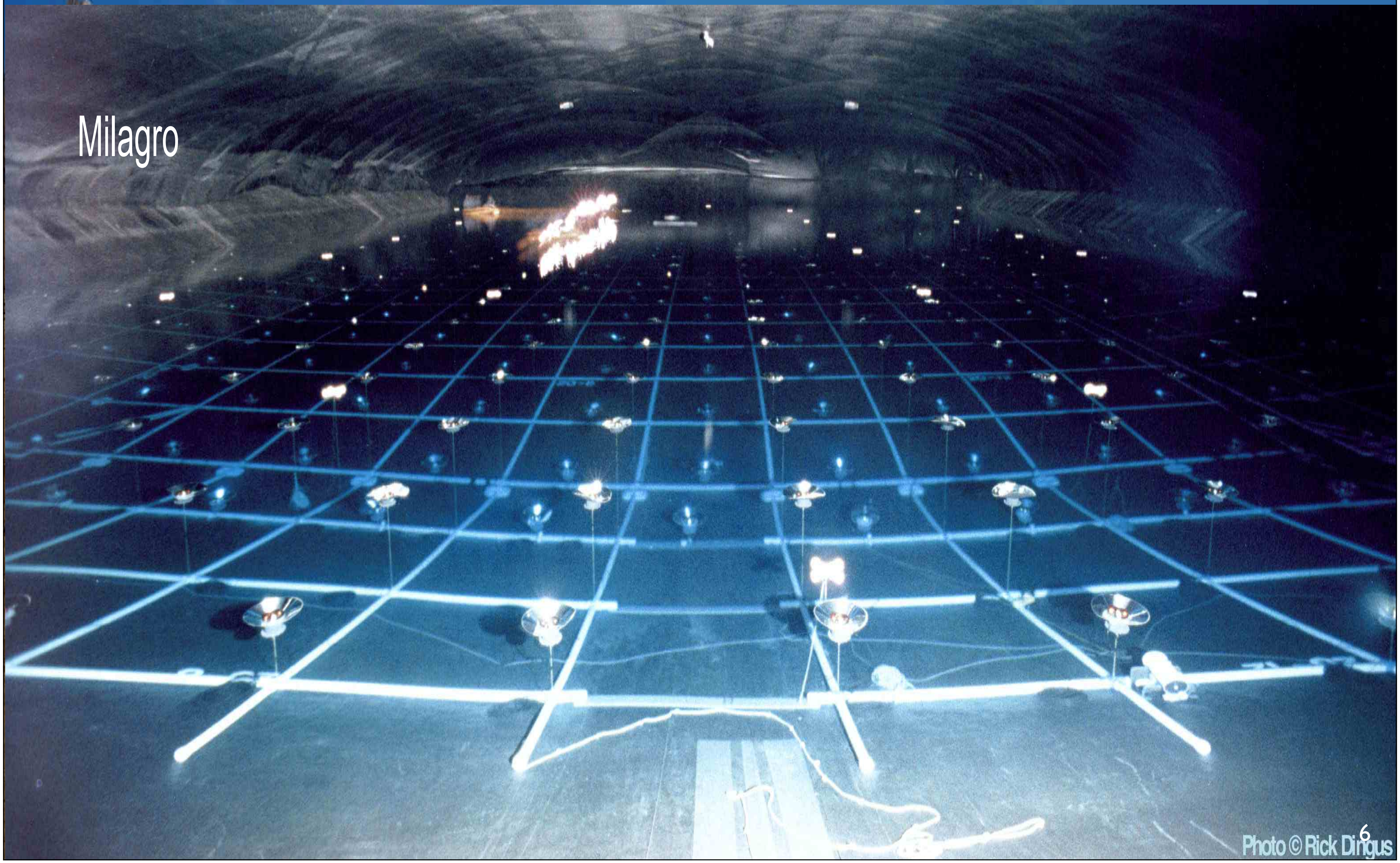
Extensive Air Shower Arrays



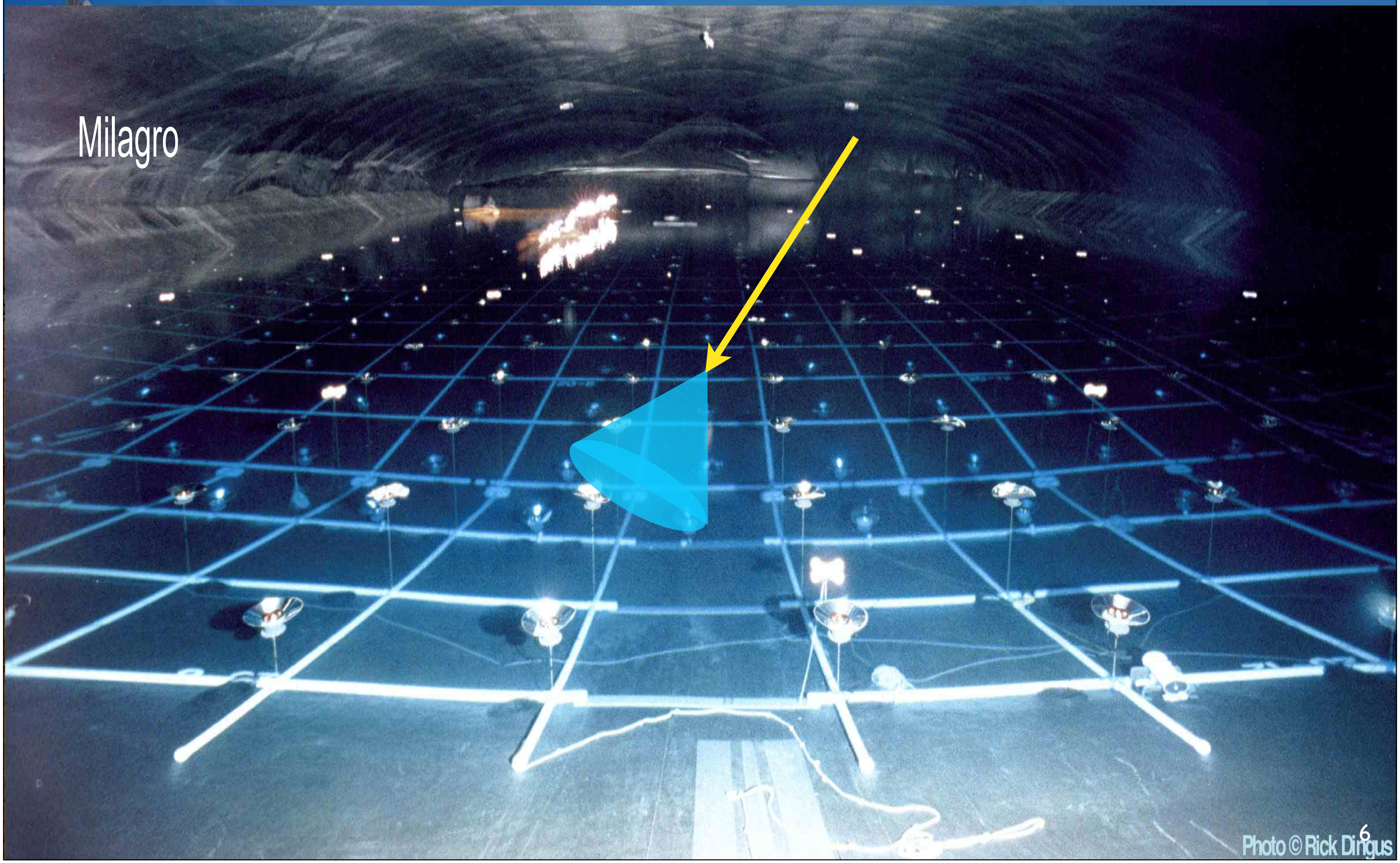
Extensive Air Shower Arrays



Extensive Air Shower Arrays

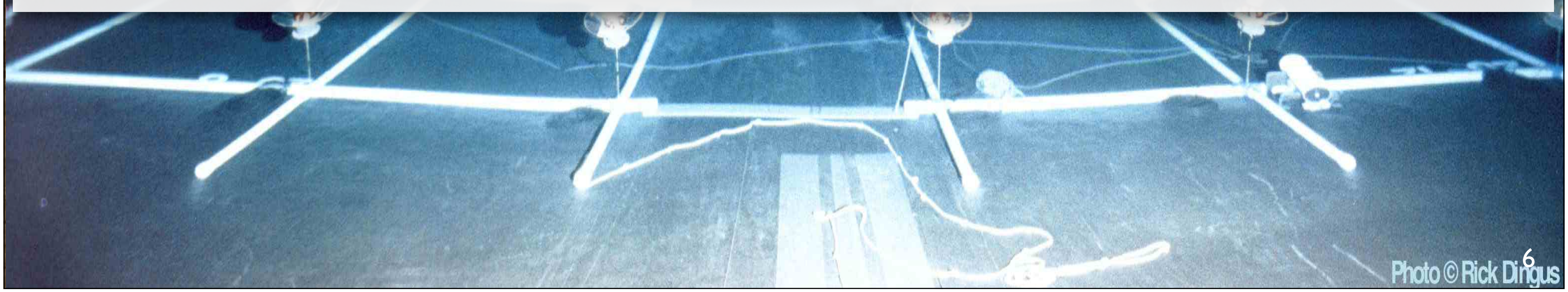


Extensive Air Shower Arrays

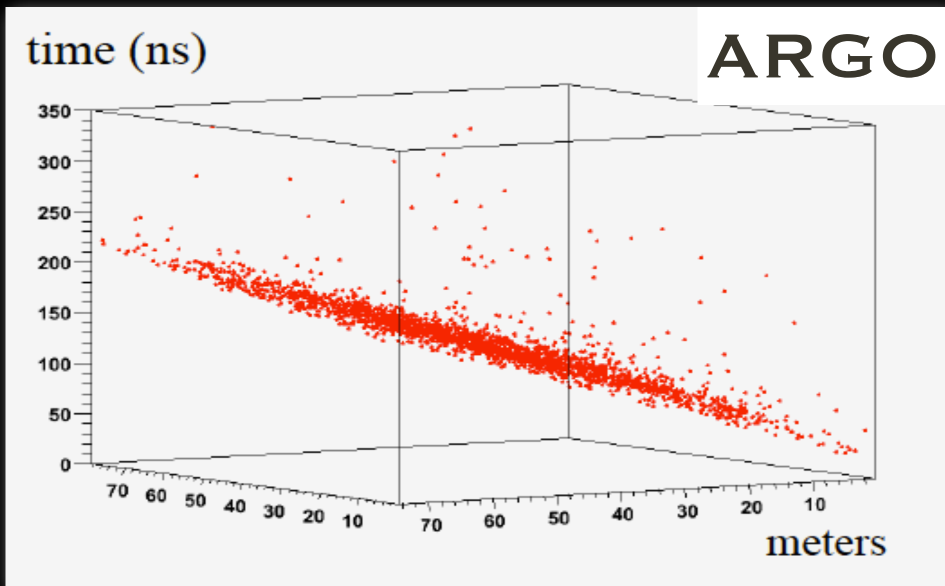


Extensive Air Shower Arrays

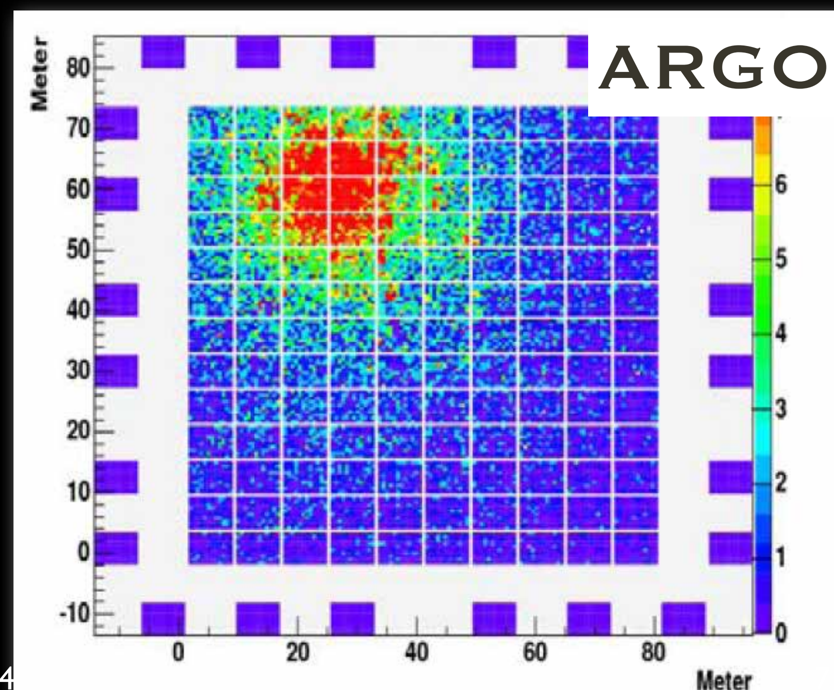
- Detect particle that survive to ground level
- Scintillation detector arrays sparsely instrument the ground <2% coverage
- Water detectors (or RPC carpet) can densely sample the shower particles (~50% particles detected)
- Water will also convert gamma rays to electrons/positrons (gamma rays dominate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



Angular and Energy Reconstruction

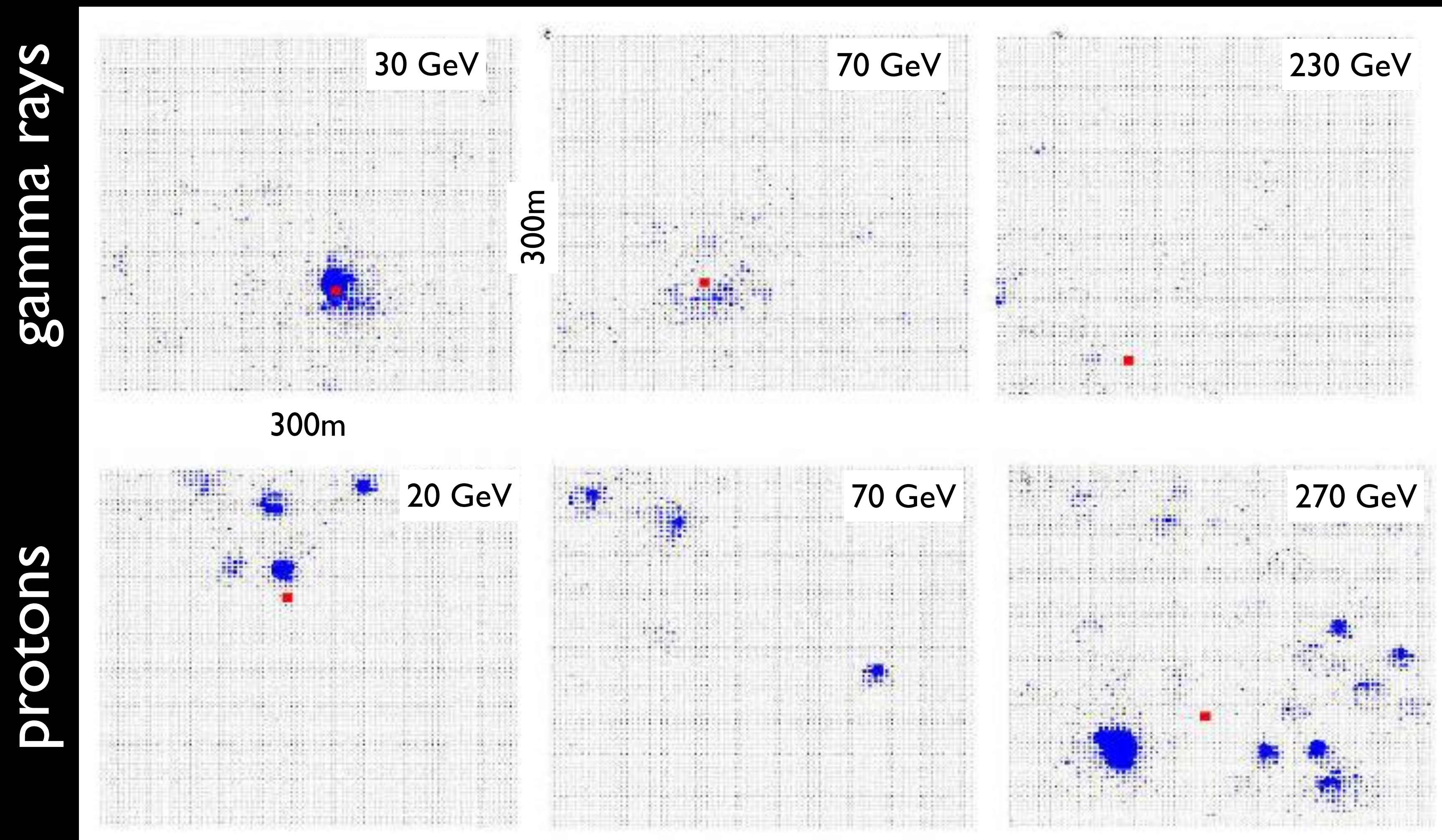


Direction via timing
(~ns timing yields 0.2°-1° resolution)



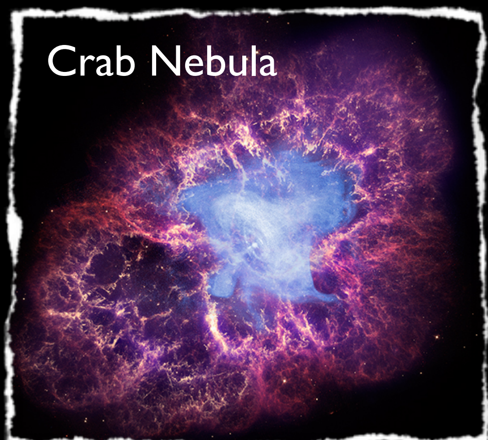
Primary energy via energy at ground
(shower fluctuations dominate resolution ~40%)

Background Rejection

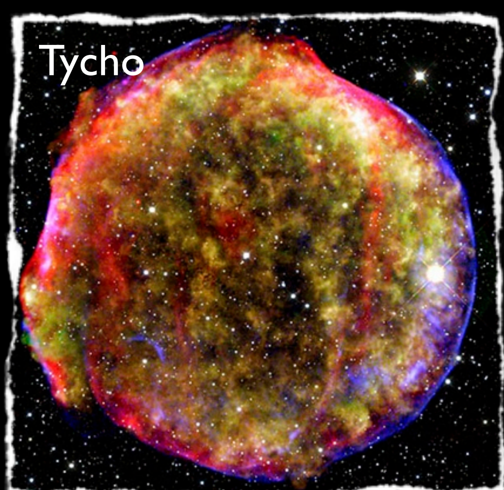


Galactic Gamma-Ray Sources

PWN

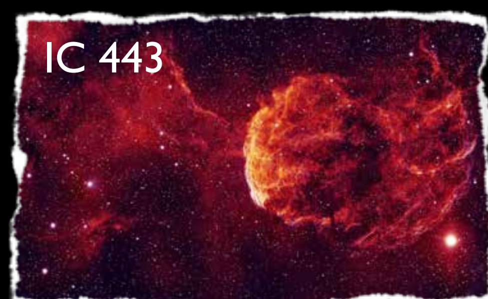


SNR



Globular Clusters

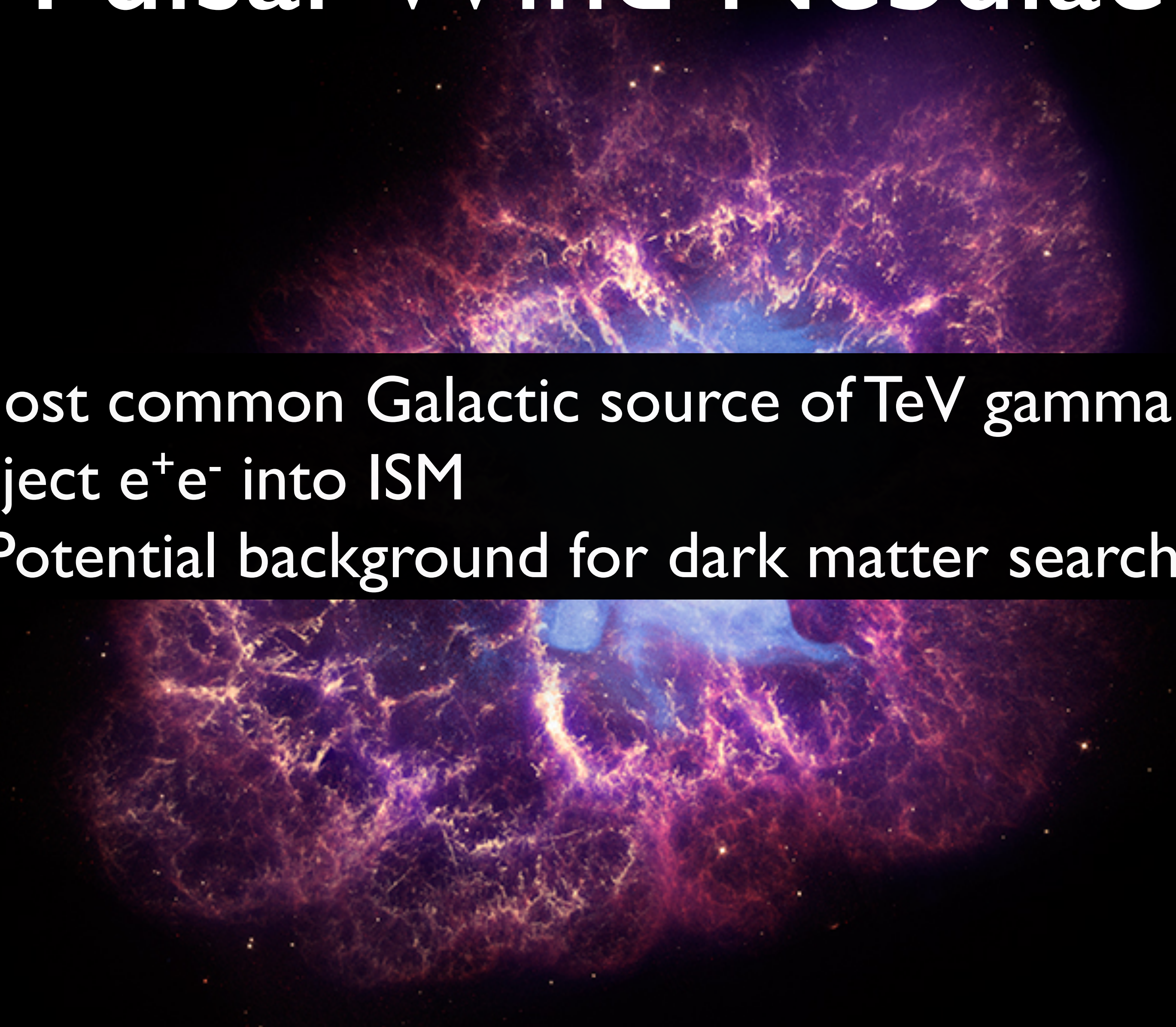
SNR/Molecular Clouds



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

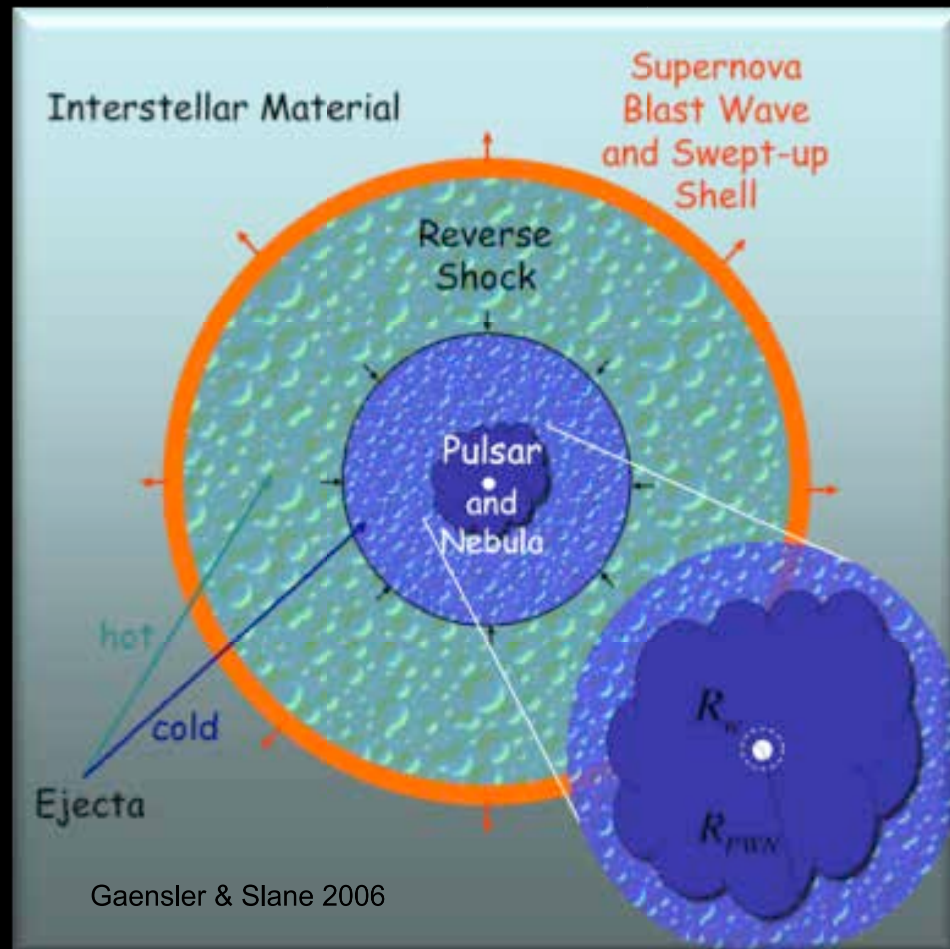
Pulsar Wind Nebulae



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

Pulsar Wind Nebulae

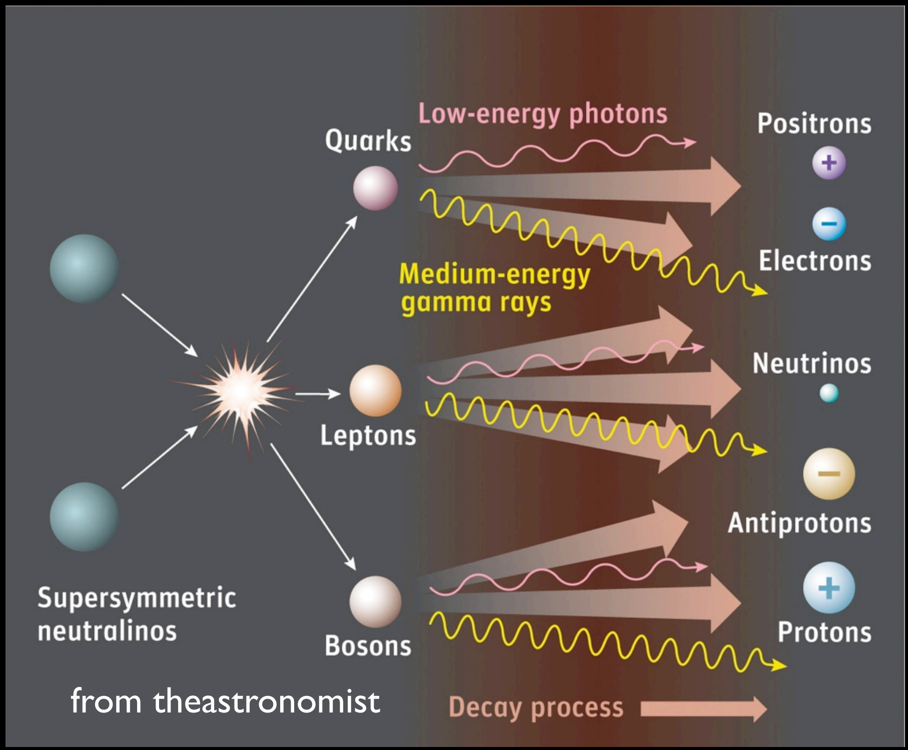
- Rapidly spinning neutron star powers a cold relativistic electron-positron wind
- Wind termination shock accelerates e^+e^-
- Inverse Compton reactions lead to production of VHE gamma rays
- Over time nebula expands, magnetic field weakens, and e^+e^- are released into the ISM



Gaensler & Slane 2006

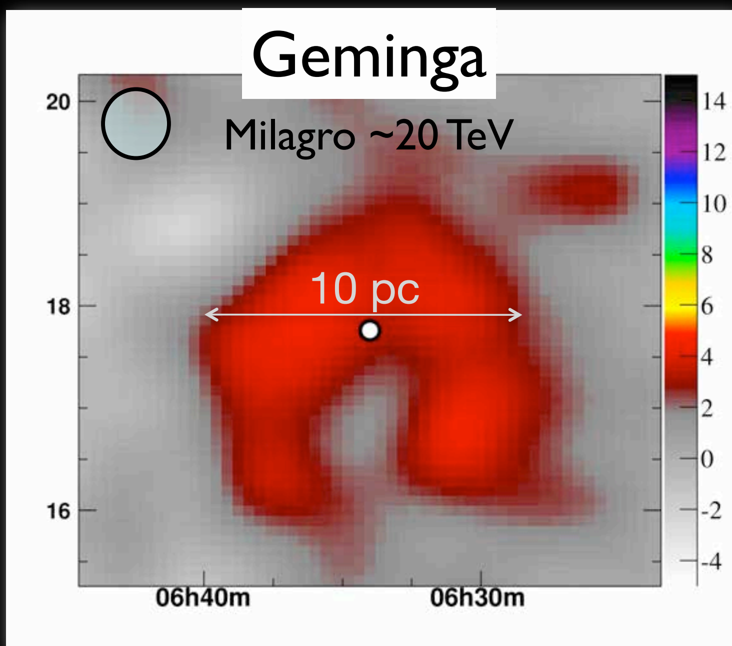
Indirect Dark Matter Detection

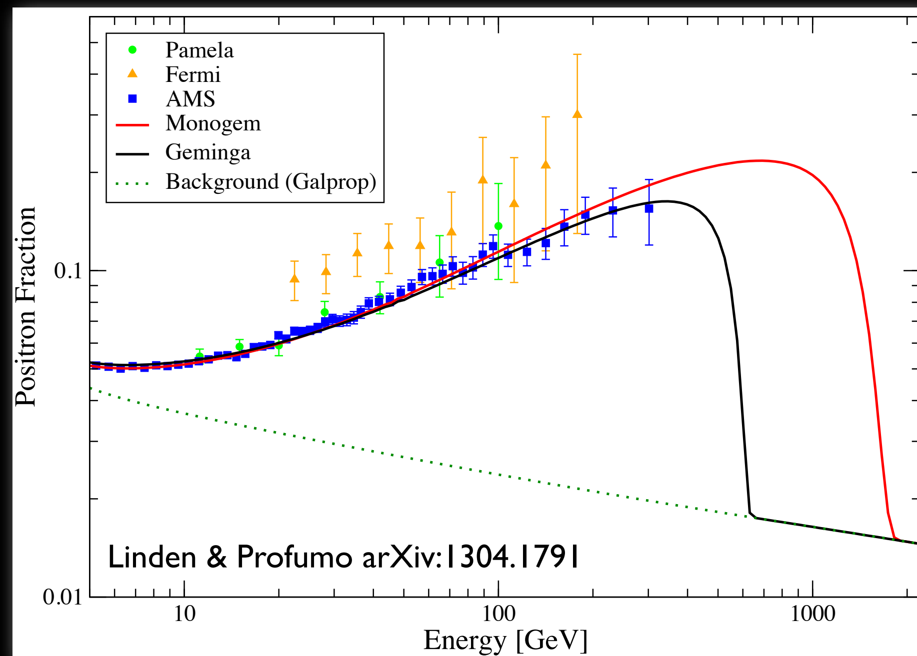
- Neutralino annihilation to quarks, leptons, and bosons (W, Z) yields gamma rays, neutrinos, and cosmic rays (positrons)
- Search for gamma ray signal with DM energy spectrum in regions with large M/L and no/low (or understood) astrophysical backgrounds
  - Dwarf spheroidal galaxies, Galaxy Clusters, Galactic Center, Andromeda



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

PWN: Positron Generators

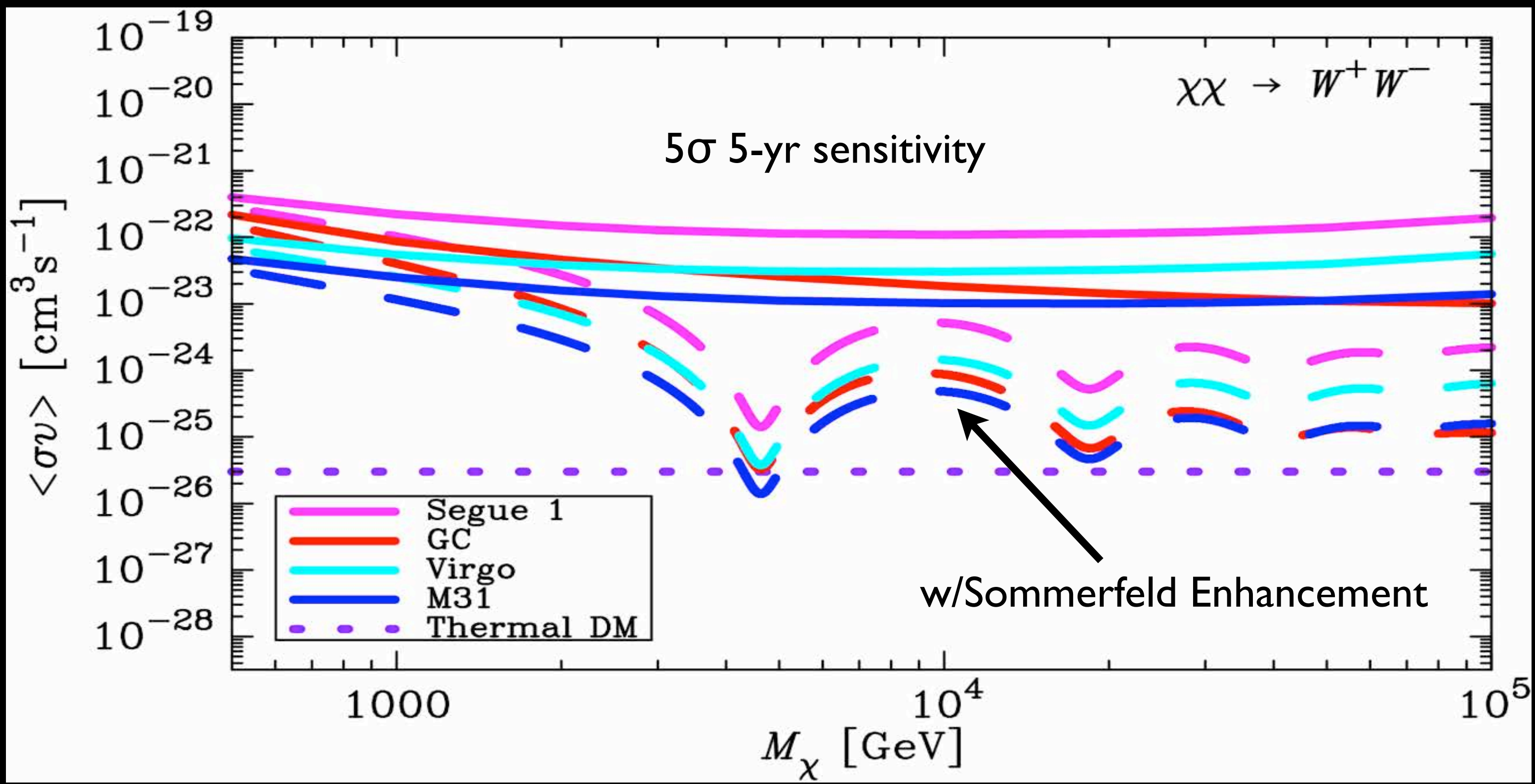


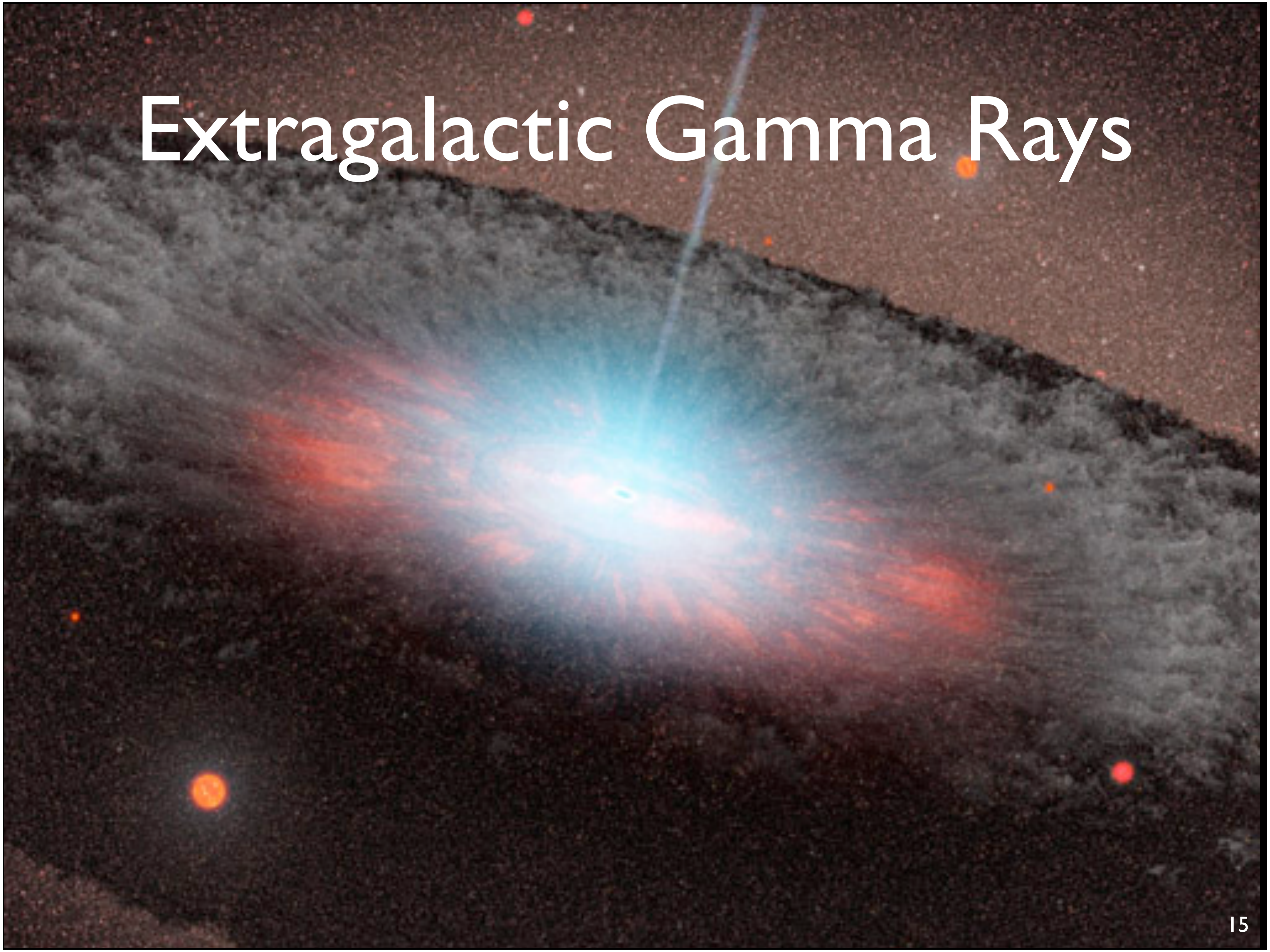


- Geminga (~300,000 yrs at ~200 pc) and Monogem (100,000 yrs at ~300 pc) are good candidates
- Milagro detected an extended gamma ray source (3°) coincident with the Geminga pulsar (~10^{32} ergs/sec) at ~20 TeV. Most likely seeing the PWN
- HAWC will detect Geminga at ~50σ - measure energy spectrum and map the region to understand electron diffusion

HAWC DM Sensitivity

HAWC has sensitivity to TeV mass DM
We can search for undiscovered high M/L satellites

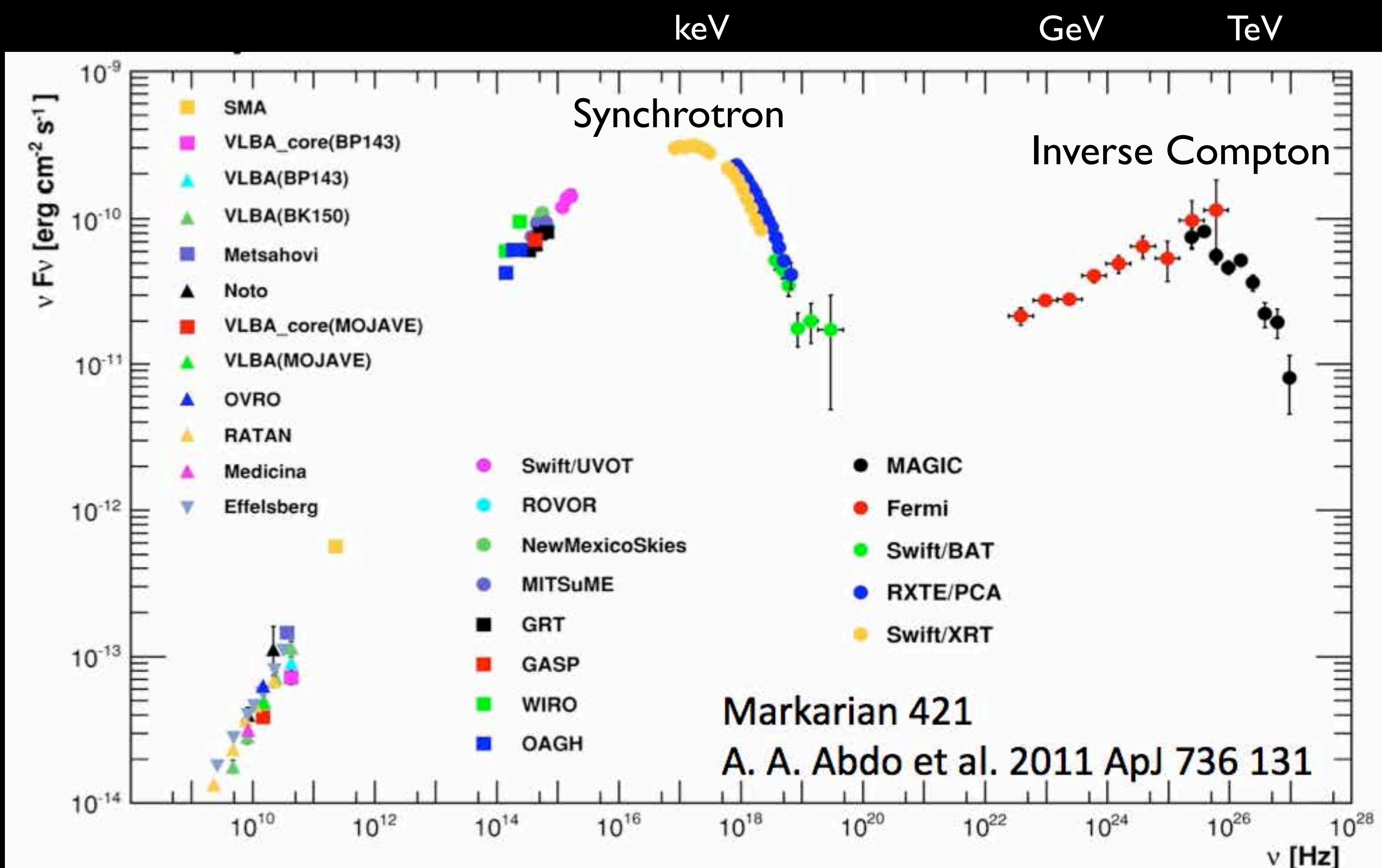



Extragalactic Gamma Rays

Extragalactic Gamma Rays

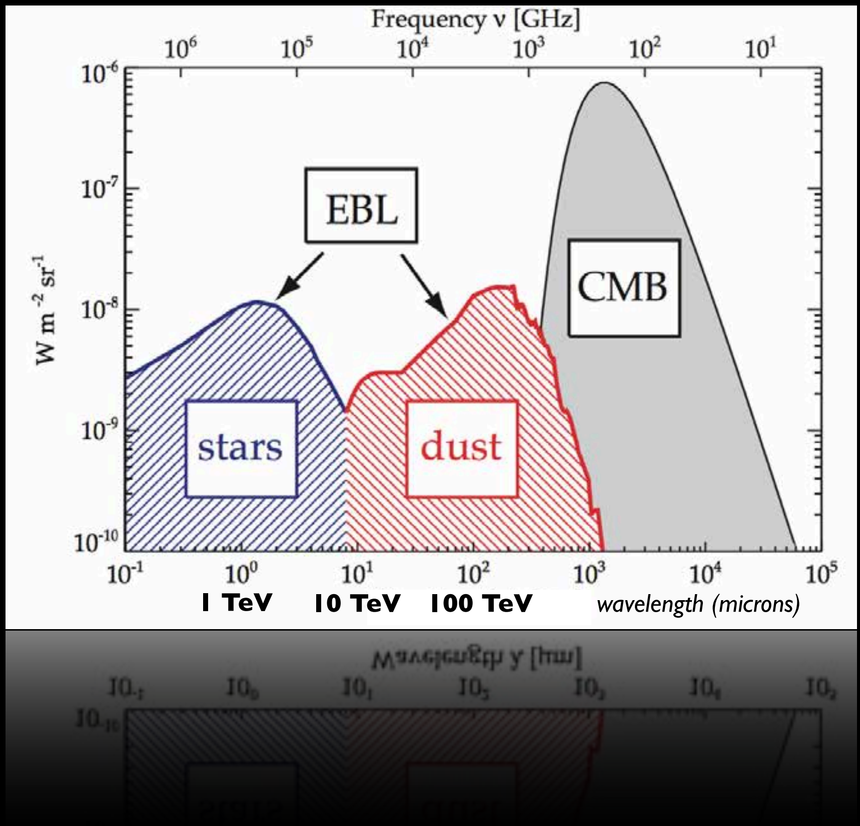
- Active Galaxies (57 detected in VHE band)
- Gamma Ray Bursts (not yet detected from ground)
  - Extragalactic Background Light
  - Primordial Magnetic Fields
  - Axion-like Particle Searches
  - Lorentz Invariance Violation

AGN Spectral Energy Distribution



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



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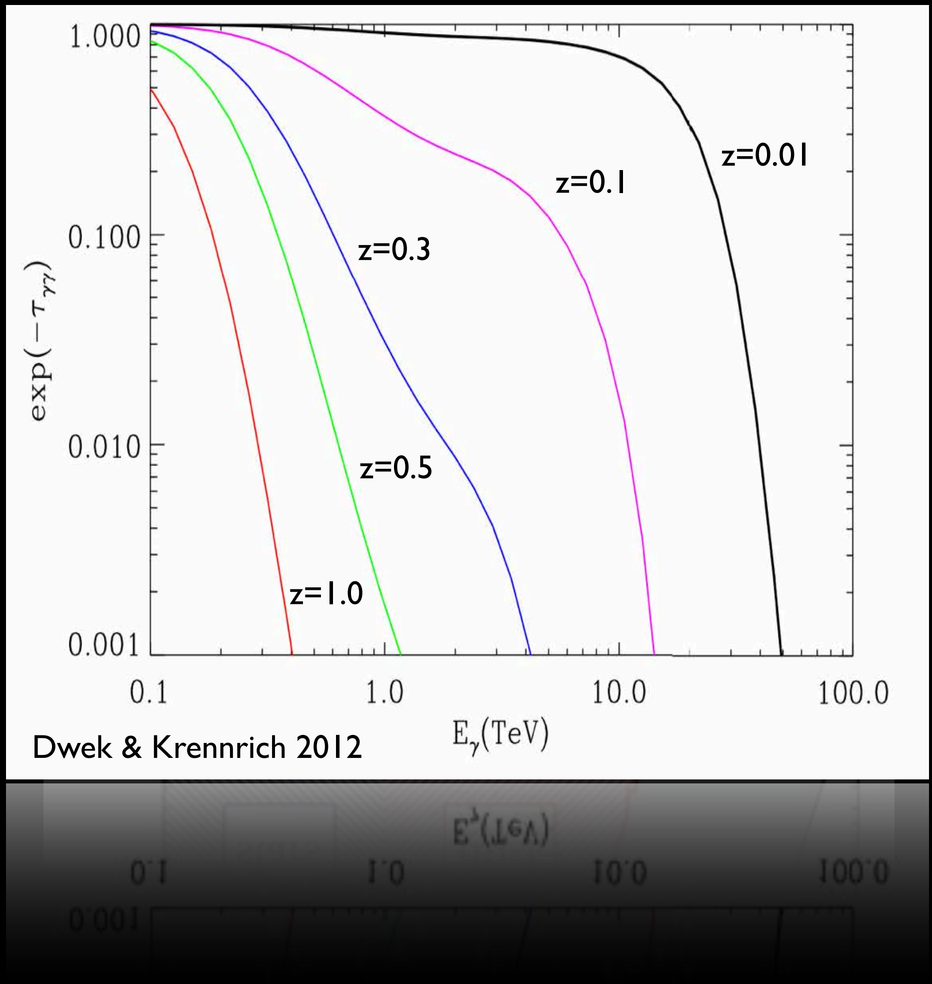
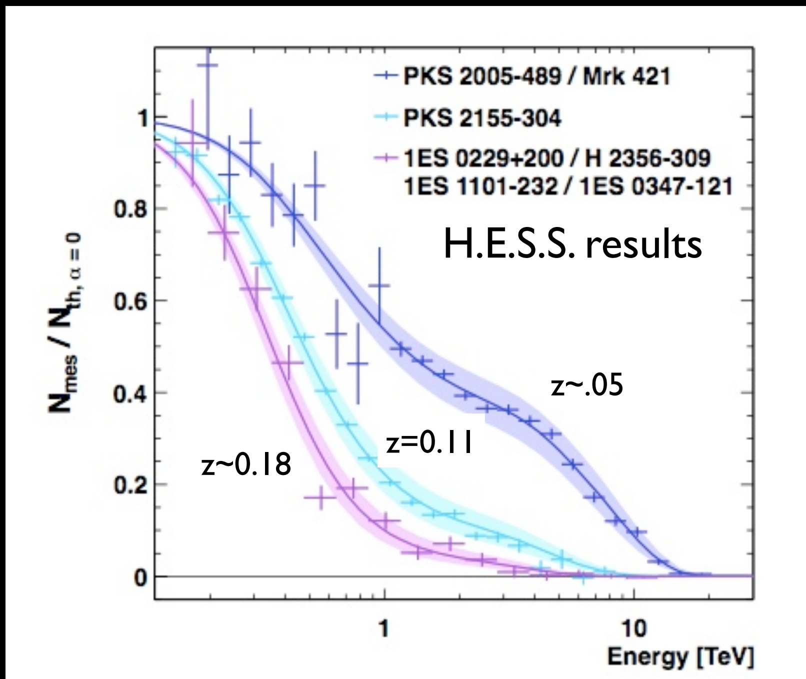
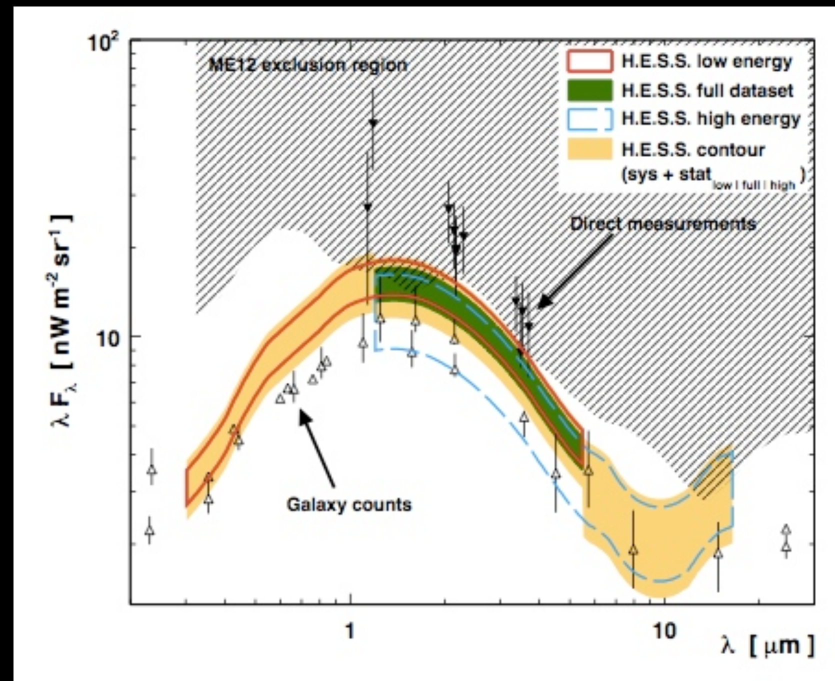


EBL Measurements



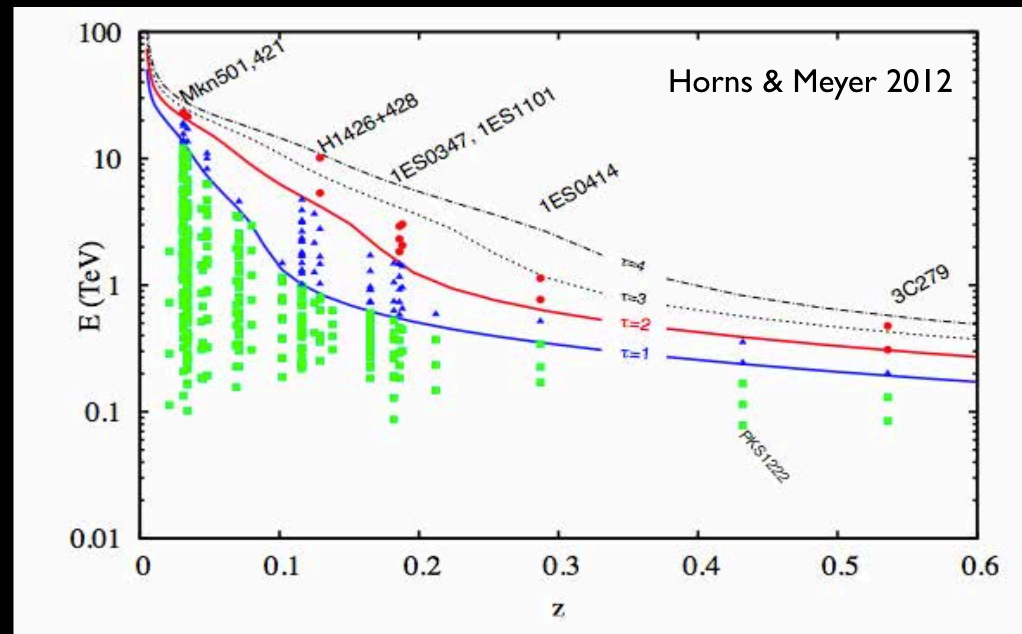


- H.E.S.S. has measured the EBL from 2~1-10 microns
- Fermi has measured the EBL below 0.2 micron (3±1 nW m^{-2} sr^{-1} at z=1)
- These values are close to the lower bounds set by Galaxy counts
- Large star formation rates at the end of the cosmic dark ages excluded

Some Tension at High Opacity

$$\Phi_{int}(E) = \phi_{obs}(E)e^{\tau(E,z)}$$

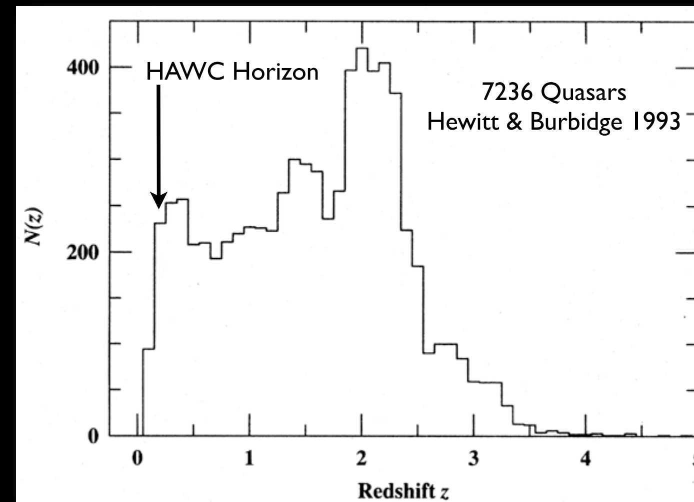
- Fit spectra in optically thin regime (τ<1)
- Test sample τ>2
- Observe ~4σ hardening of intrinsic spectra in optically thick regime

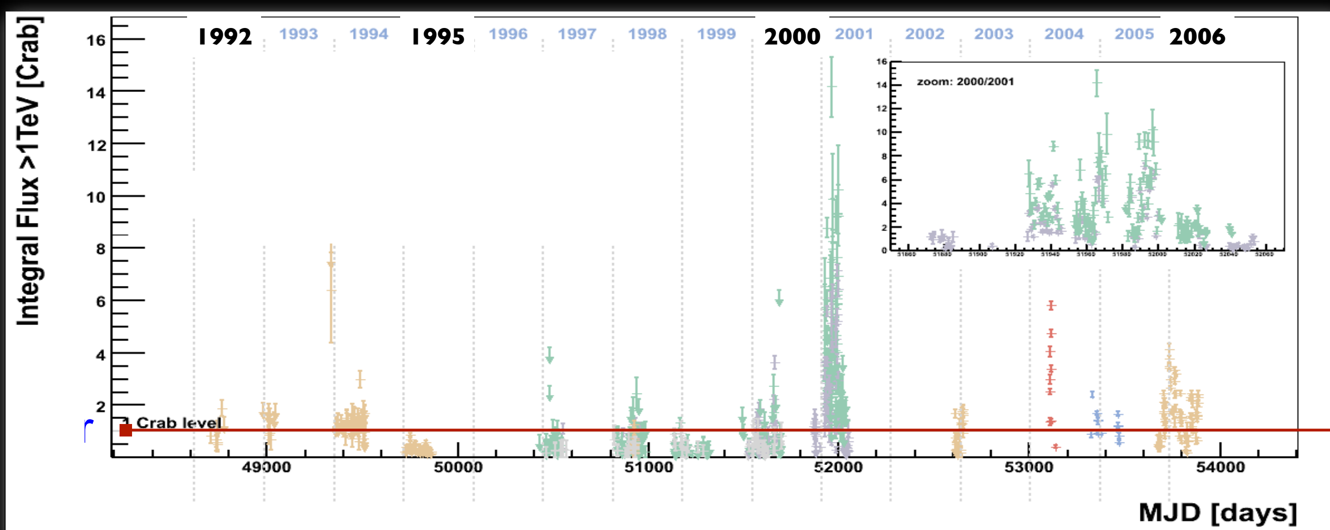


- Possible explanations
  - Cascades from UHECR (if AGN are UHECR sources)
  - Evidence of photon/ALP mixing (~neV axion-like particle)
- Need to increase AGN sample size
- Need to search for VHE transients from distant sources (z>0.1)

AGN Transients

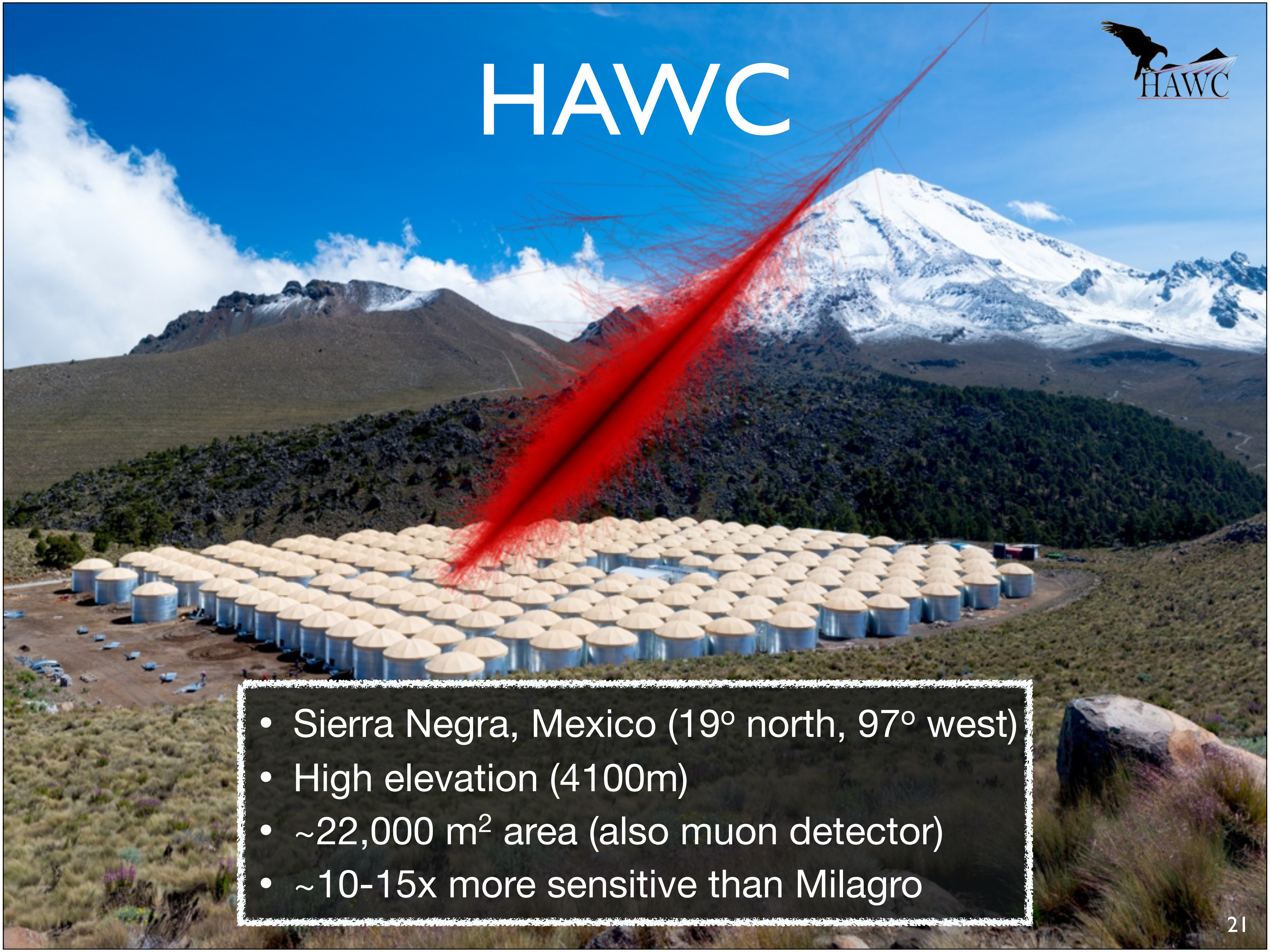
- HAWC will monitor all AGN in our field-of-view every day (8 sr)
- Search for high redshift transient emission
  - probe EBL absorption anomalies
- Alert other observatories of flaring activity
  - search for inter galactic magnetic fields





HAWC 1-day sensitivity

HAWC



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

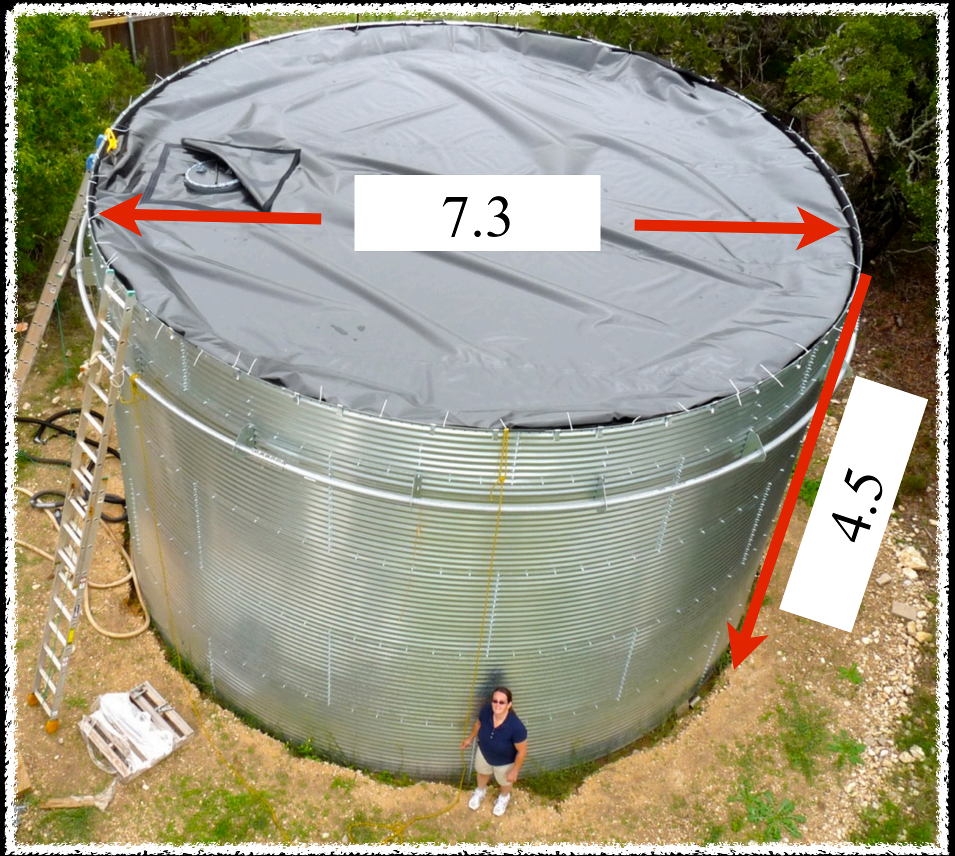
HAWC Collaboration

Los Alamos National Laboratory
University of Utah
George Mason University
University of New Mexico
Georgia Institute of Technology
UC Santa Cruz
University of Maryland
Univ. of California, Irvine
University of New Hampshire
Michigan Technological University
University of Alabama
University of Wisconsin
Michigan State University
Penn State University
NASA/Goddard
Colorado State University

Instituto Nacional de Astrofísica Óptica y Electrónica (INAOE)
Universidad Nacional Autónoma de México (UNAM)
Benemérita Universidad Autónoma
Universidad Autónoma de Chiapas
Universidad Autónoma del Estado de Hidalgo
Universidad de Guadalajara
Universidad Michoacana de San Nicolás de Hidalgo
Centro de Investigacion y de Estudios Avanzados
Universidad de Guanajuato

HAWC Design

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



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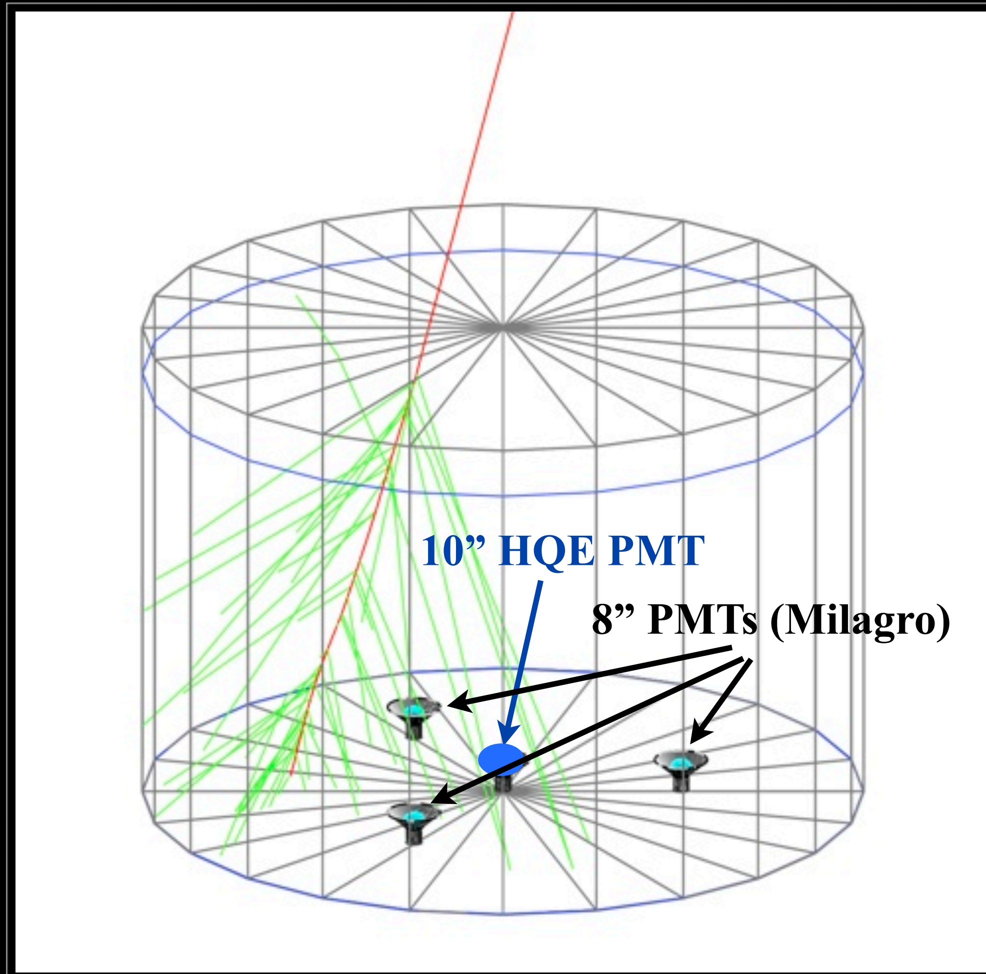
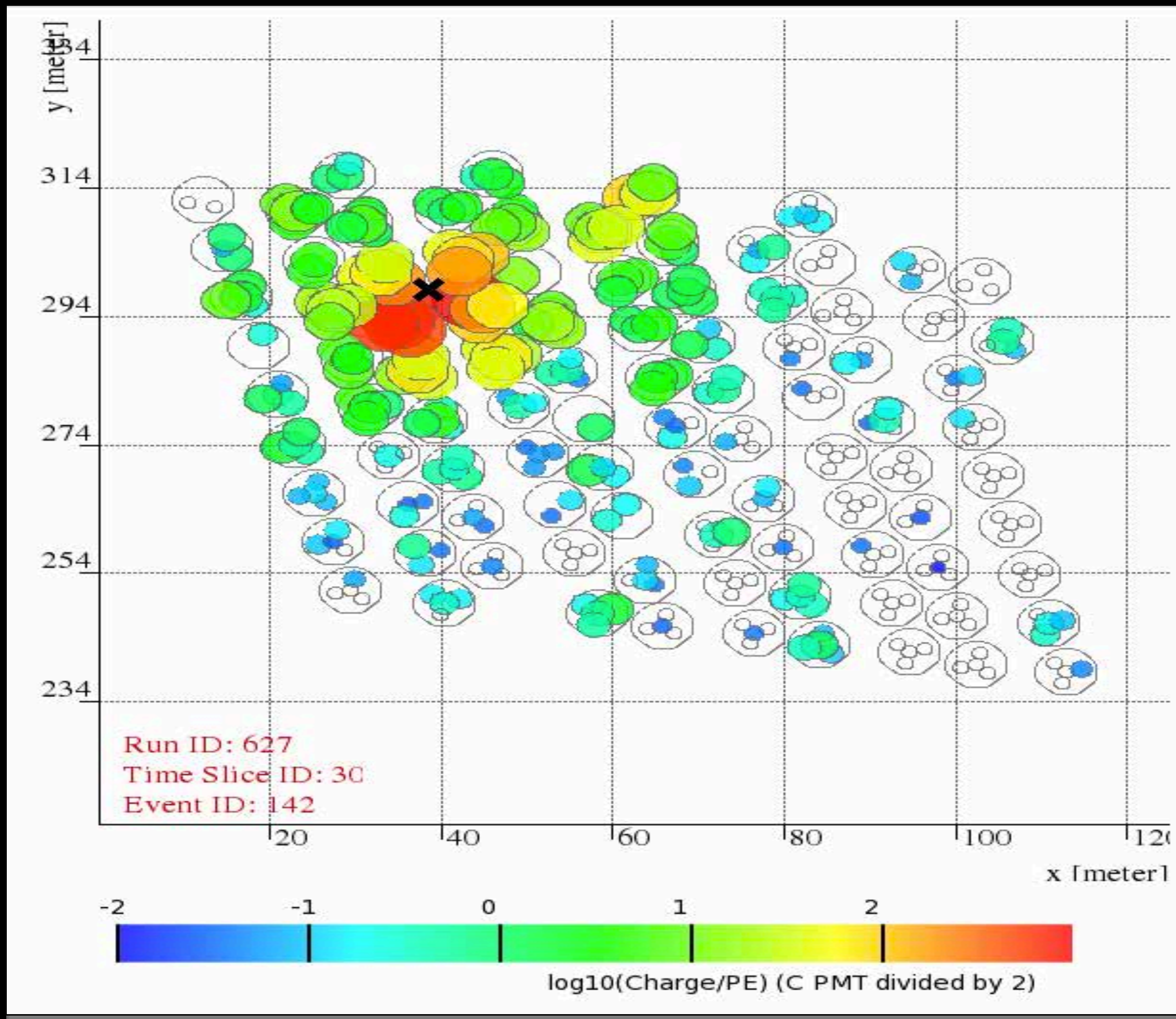
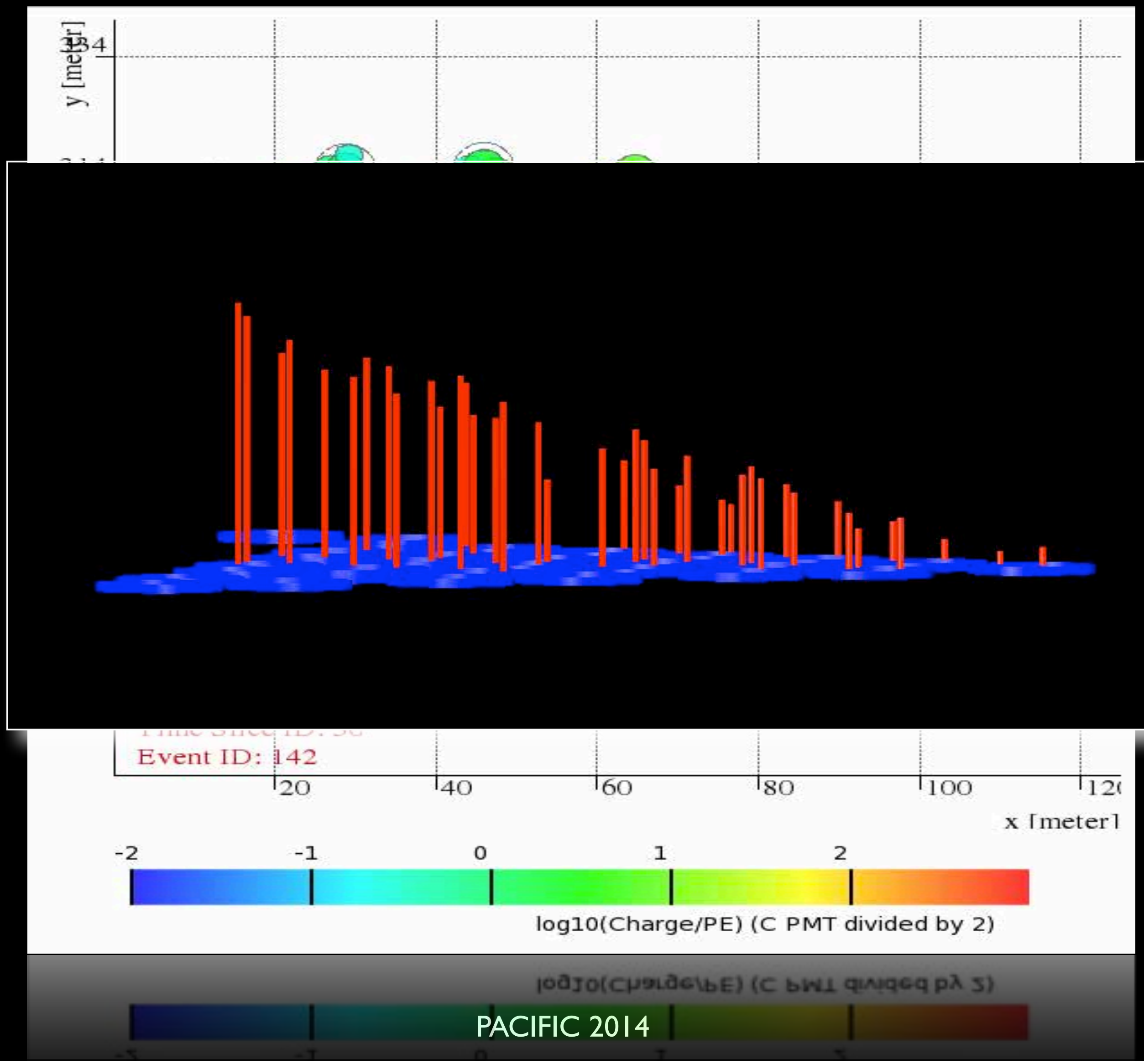


HAWC Event


y [meter]
334
314
294
274
254
234
Run ID: 627
Time Slice ID: 30
Event ID: 142
20
40
60
80
100
x [meter]
-2
-1
0
1
2
log10(Charge/PE) (C PMT divided by 2)

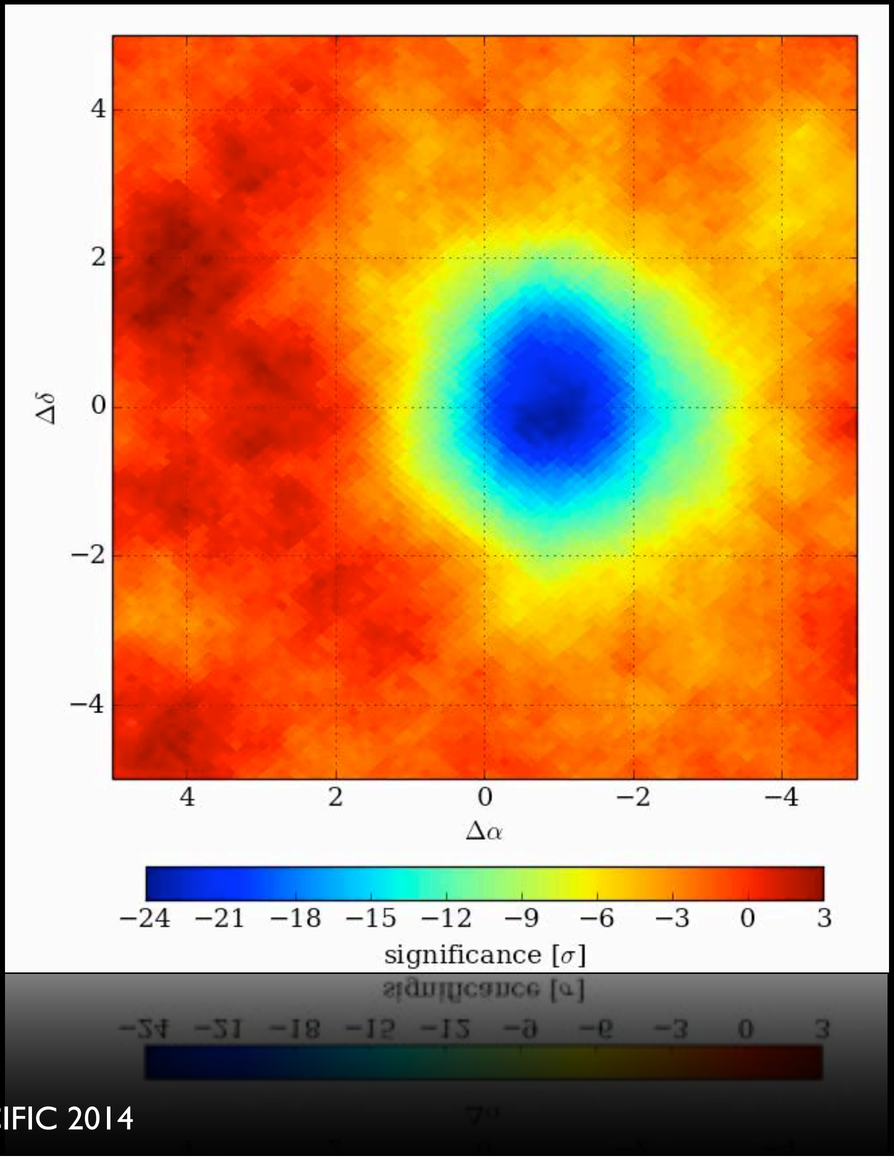
HAWC Event



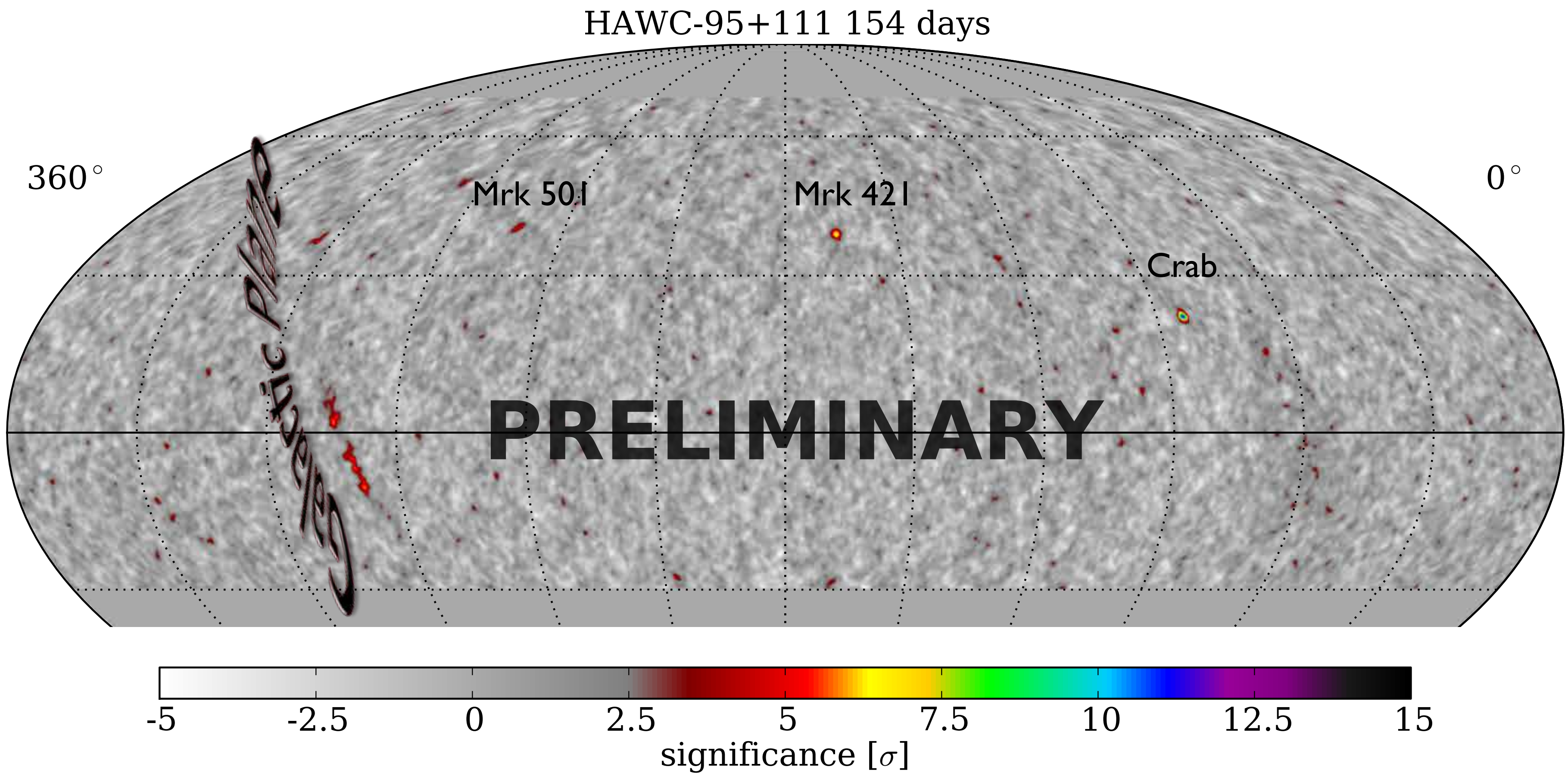
y [meter]
Event ID: 142
20
40
60
80
100
x [meter]
-2
-1
0
1
2
log10(Charge/PE) (C PMT divided by 2)

Moon Shadow

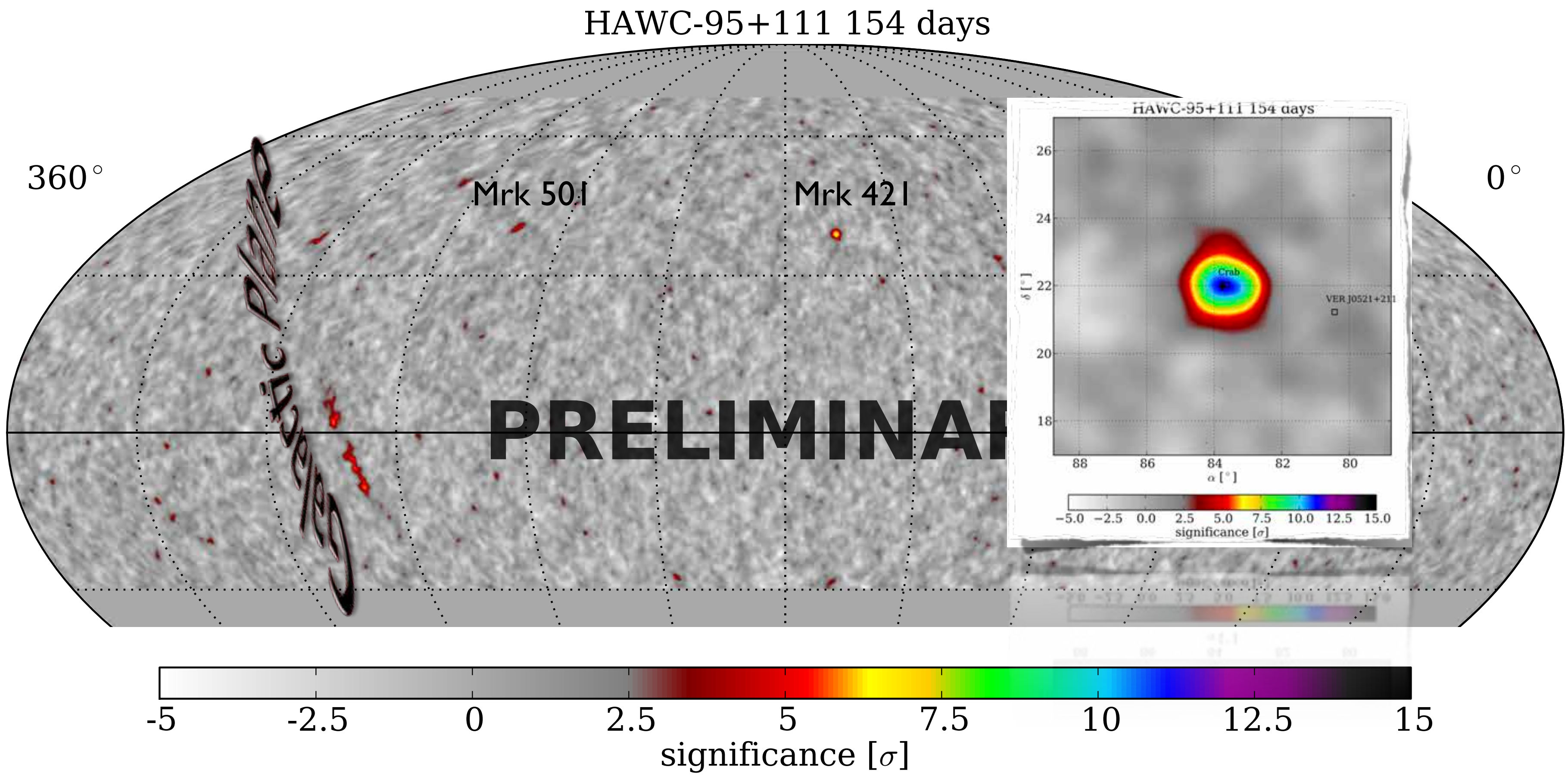
- Moon blocks cosmic rays
- Good calibration source
  - angular resolution
  - energy scale (earth as magnetic spectrometer)
- Simulation predicts E_{med} ~ 1.6 TeV (protons)
- Expect 1° deflection for 1.6 TeV protons
- Observe 1.04° ± 0.11°



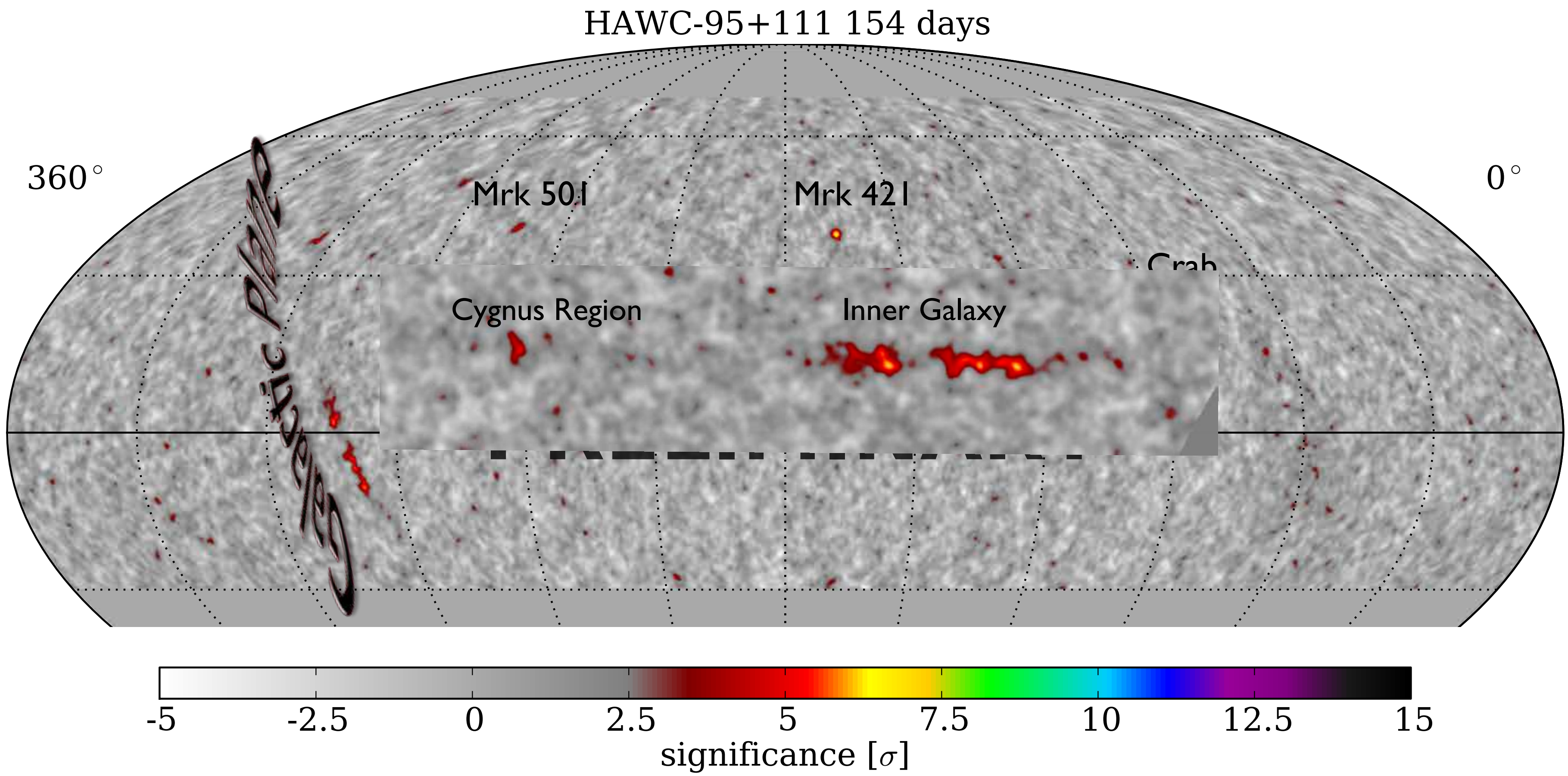
HAWC-111 Sky


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

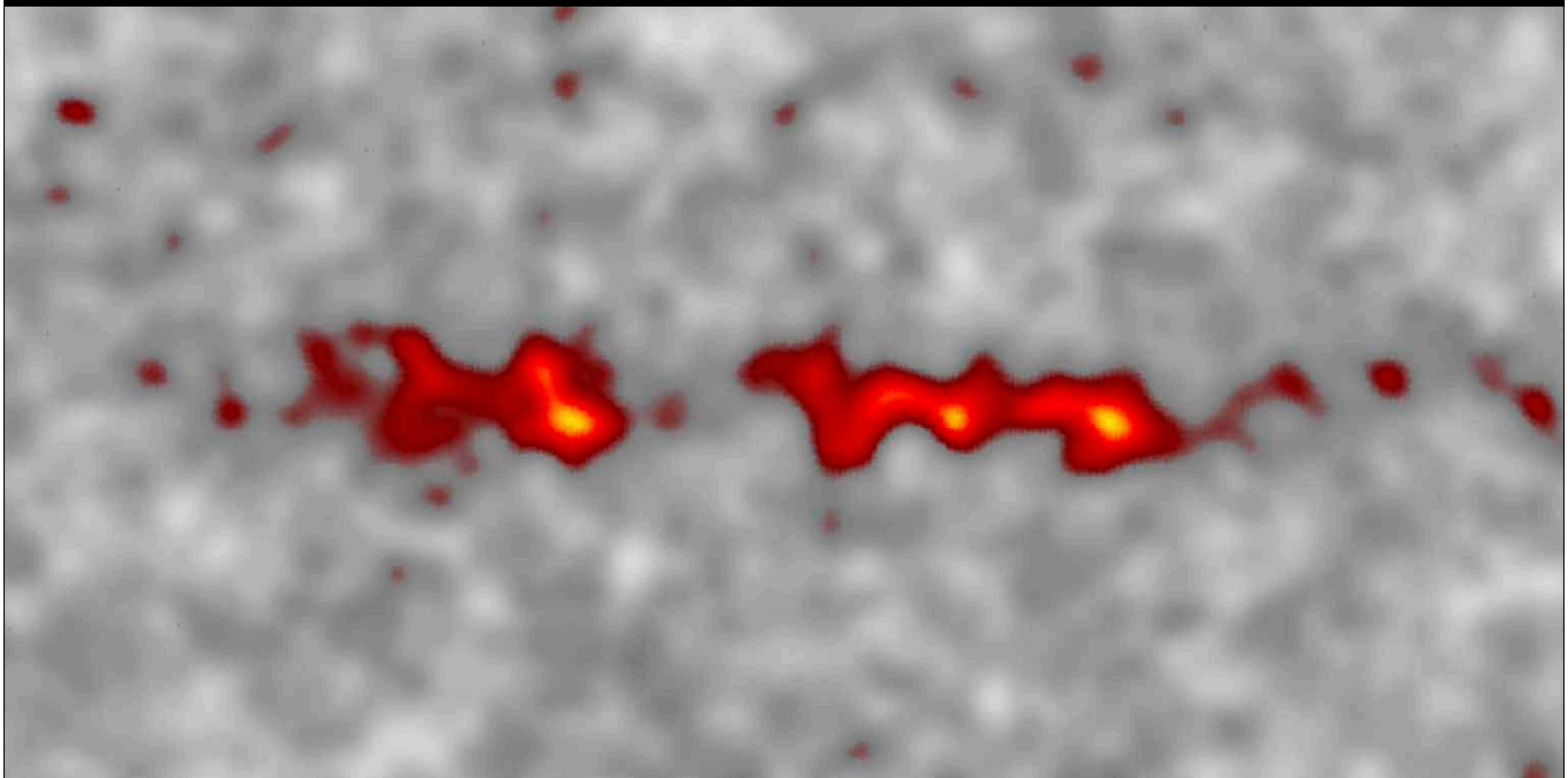
HAWC-111 Sky


HAWC-95+111 154 days
360°
0°
Mrk 501
Mrk 421
Galactic Plane
PRELIMINARY
HAWC-95+111 154 days
Crab
VER J0521+211
-5
-2.5
0
2.5
5
7.5
10
12.5
15
significance [σ]

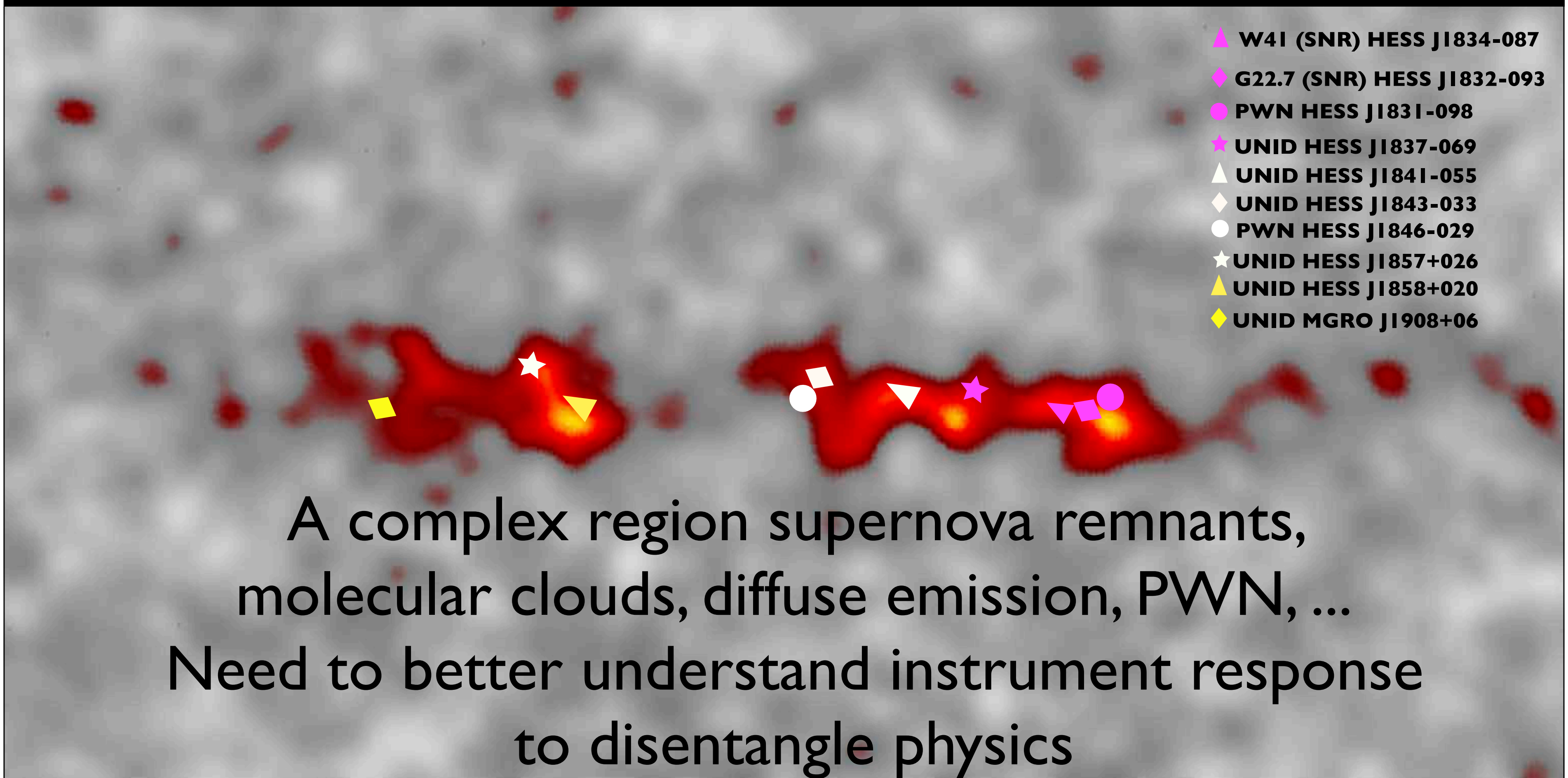
HAWC-111 Sky


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

The Inner Galaxy



The Inner Galaxy



A complex region supernova remnants, molecular clouds, diffuse emission, PWN, ...
Need to better understand instrument response to disentangle physics

Summary

- 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, & Lorentz invariance violation
- HAWC is now operating with 111 tanks (~5x more sensitive than Milagro/ARGO)
- Already seeing objects undetected by Milagro
- Complete in March 2015 (300 tanks)
- Sky survey (~8 sr) in the TeV regime to 30 mCrab