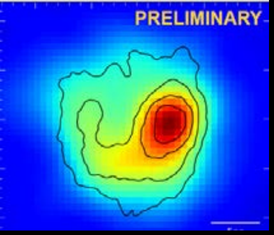
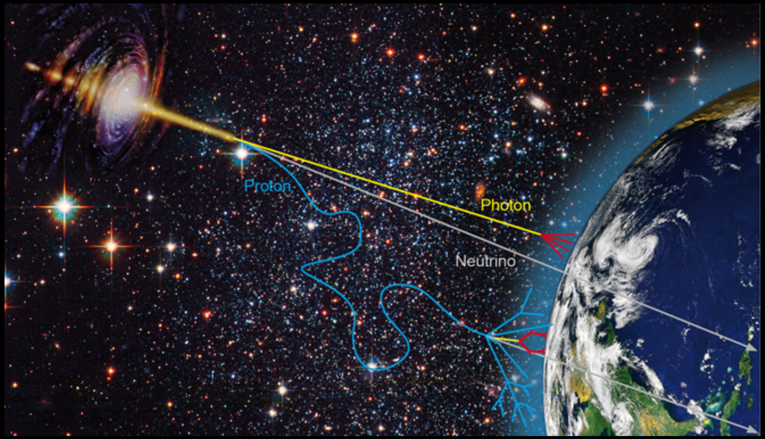
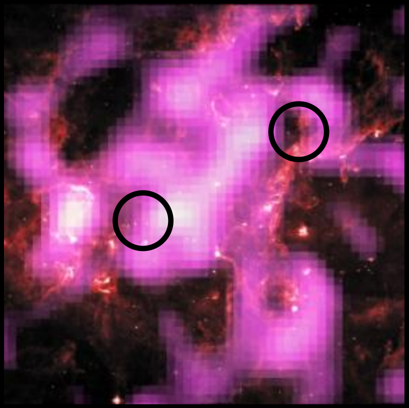


GeV and TeV gamma rays in the era of multi-messenger synergy





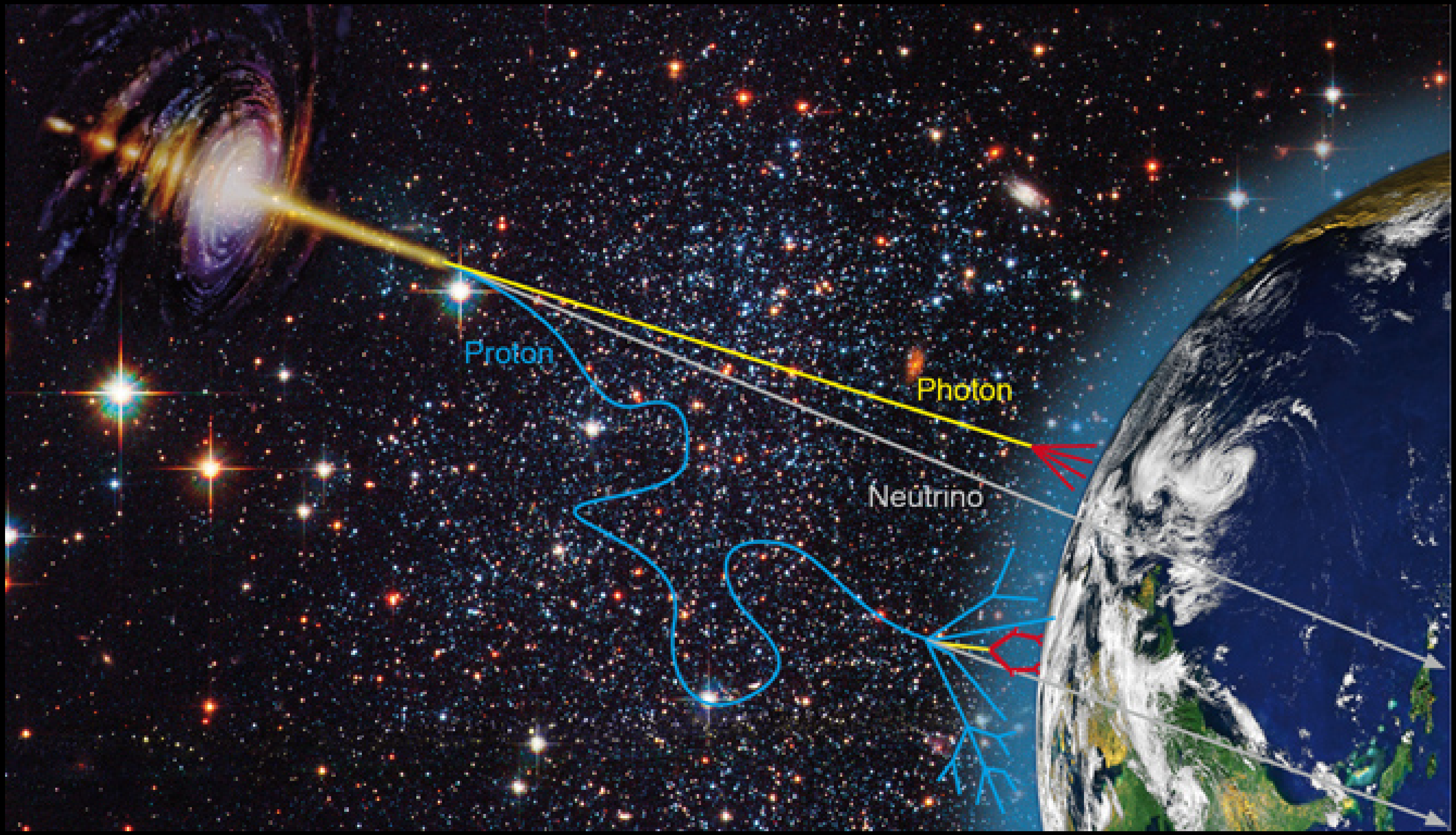
Amanda Weinstein
(for the VERITAS collaboration)
Iowa State University

Overview

- Why more than one messenger?
- How do we squeeze the most out of multi-messenger (multi-instrument) data?
- What we are doing now
- What we can do better in the future

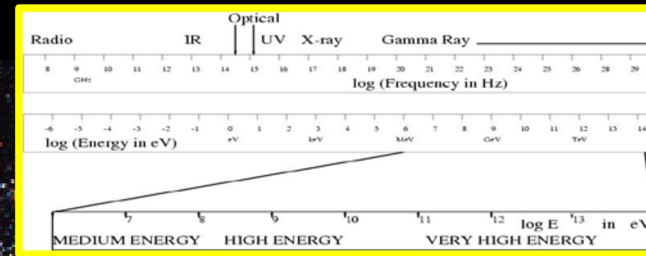
Multi-messenger synergy

- Different messengers provide complementary probes of the same physics

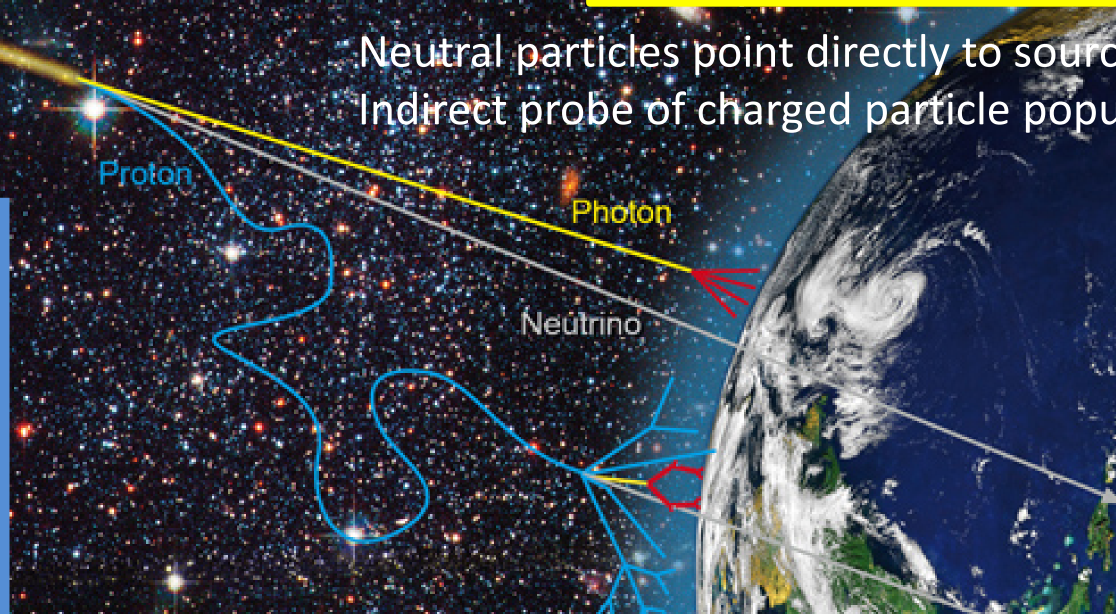


Multi-messenger synergy

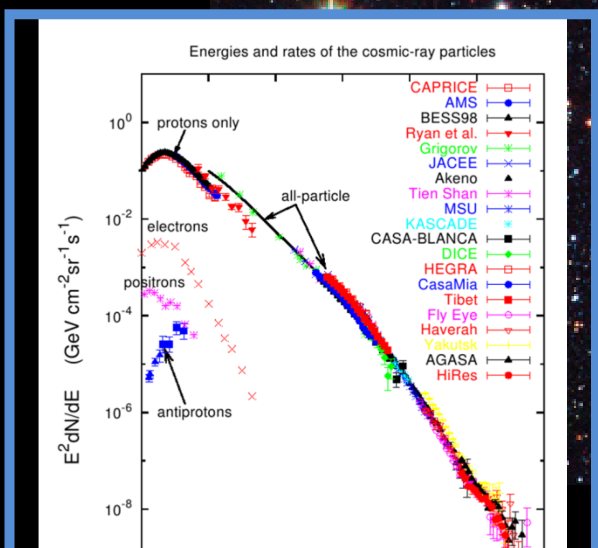
- Different messengers provide complementary probes of the same physics



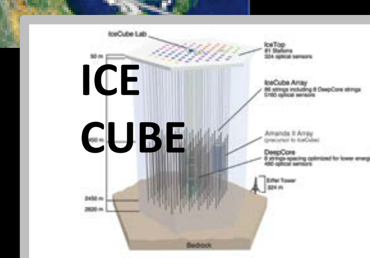
Charged particles directly probe cosmic-ray composition
Sources difficult to resolve



Neutral particles point directly to sources
Indirect probe of charged particle population



AMS-02



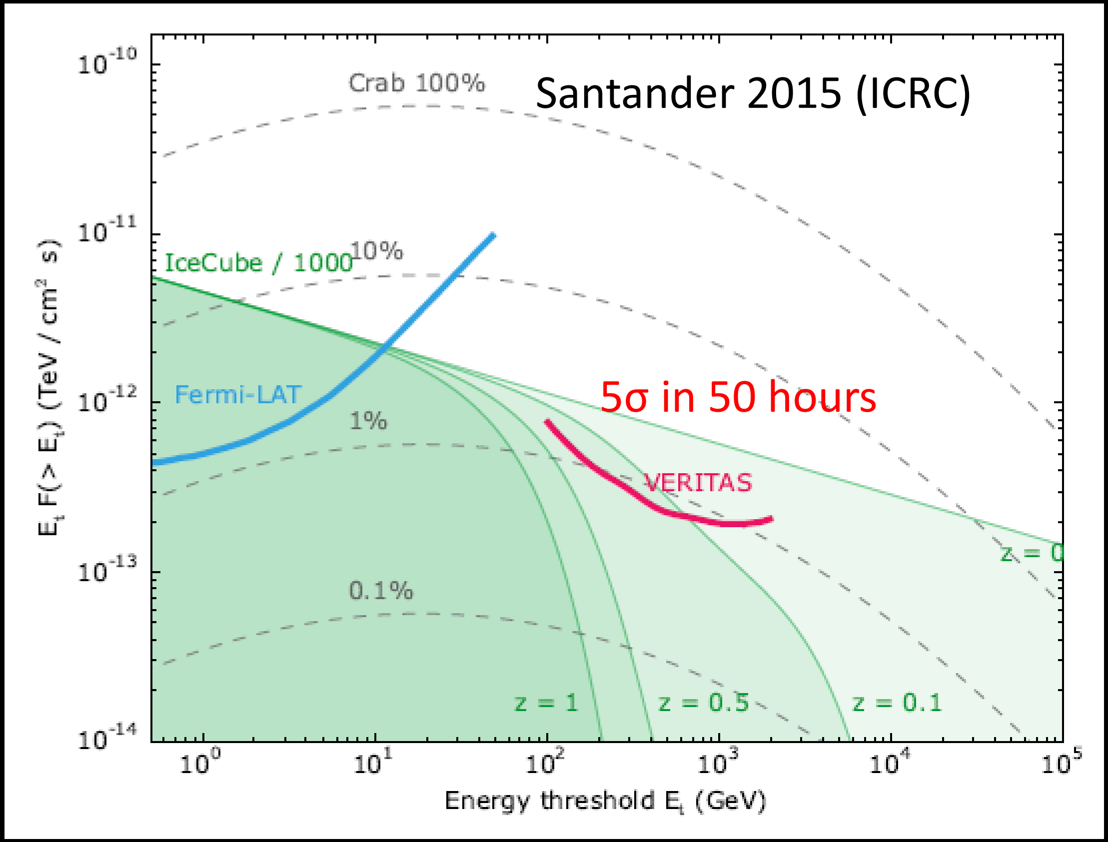
Multi-messenger synergy

- Alerts and follow-ups
  - AMON, SNEWS

- Correlation studies

Zhou et al. (2015)

Astrophysical neutrino follow-up

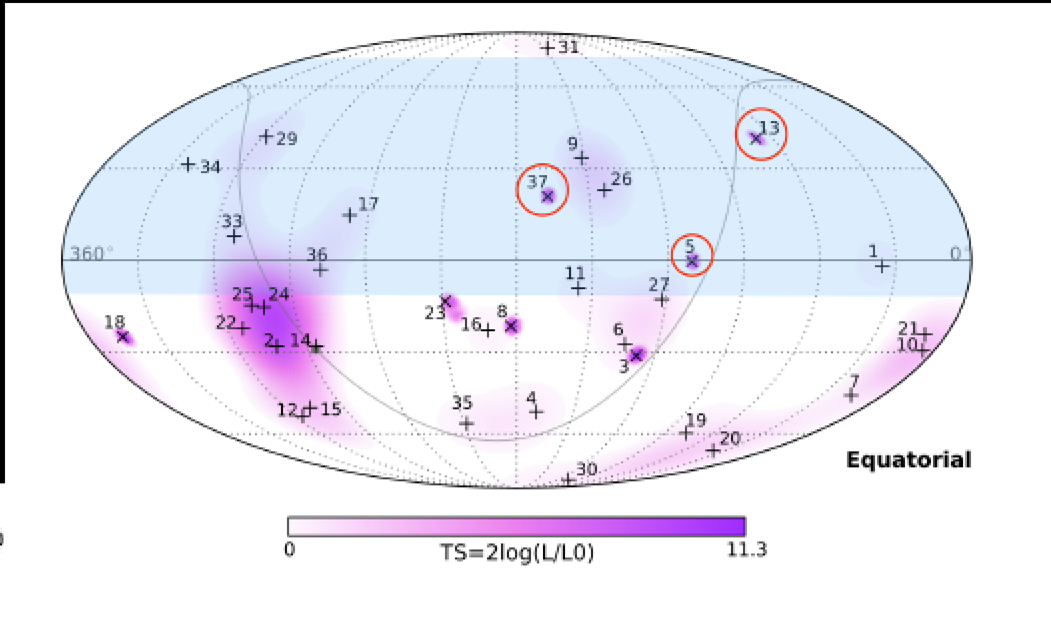


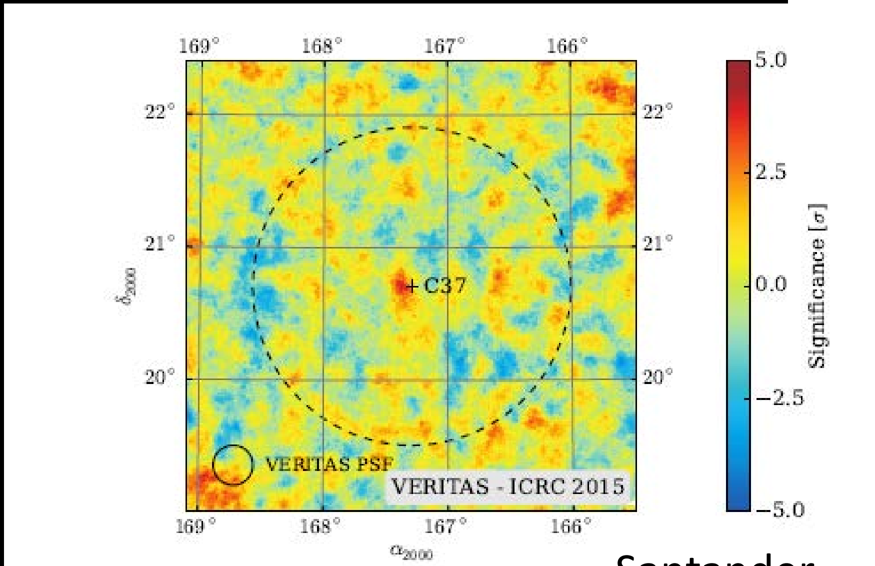
Ice Cube flux corrected for EBL absorption using Francheschini et al. (2008)

Focus on muon neutrino events: (better than 1 degree angular resolution so localized to within VERITAS f.ov.)

Astrophysical neutrino follow-up

- 3 contained events + 20 “uncontained” events through cooperative agreement
- 3 observed last season: C5, C13, C37
- All upper limits (largest excess, C37, ~2σ after trials)

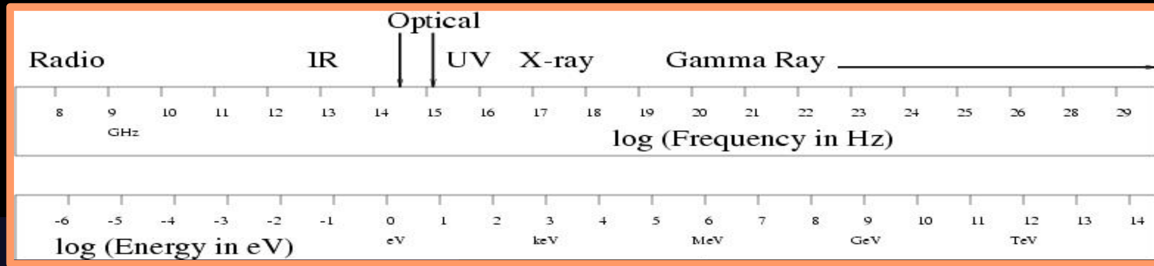


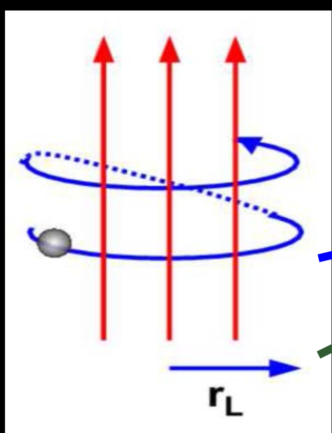


Santander

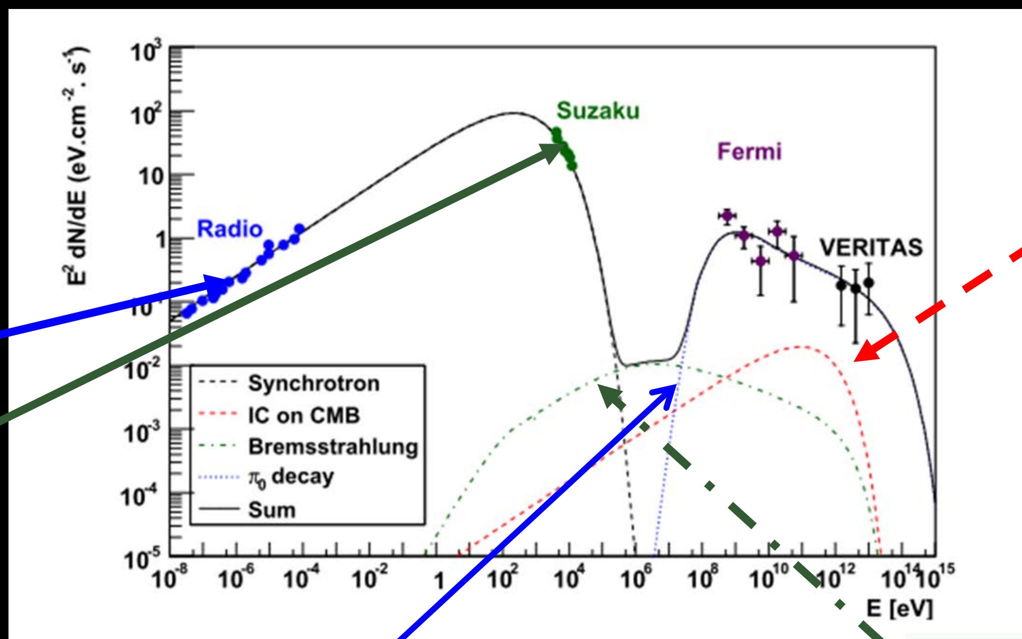
- Ongoing effort (bring in Fermi-LAT data as well)
- Uses bright moonlight as well as dark time

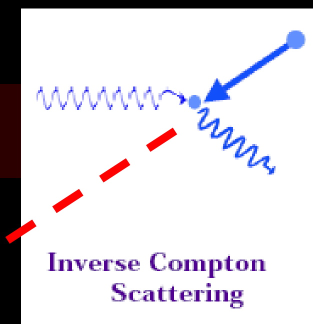
Multi-wavelength synergy

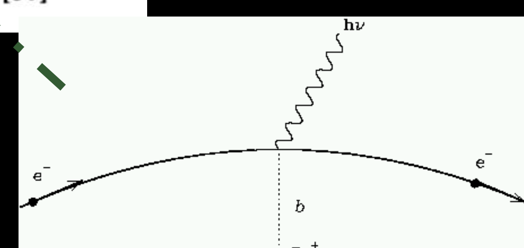




Synchrotron

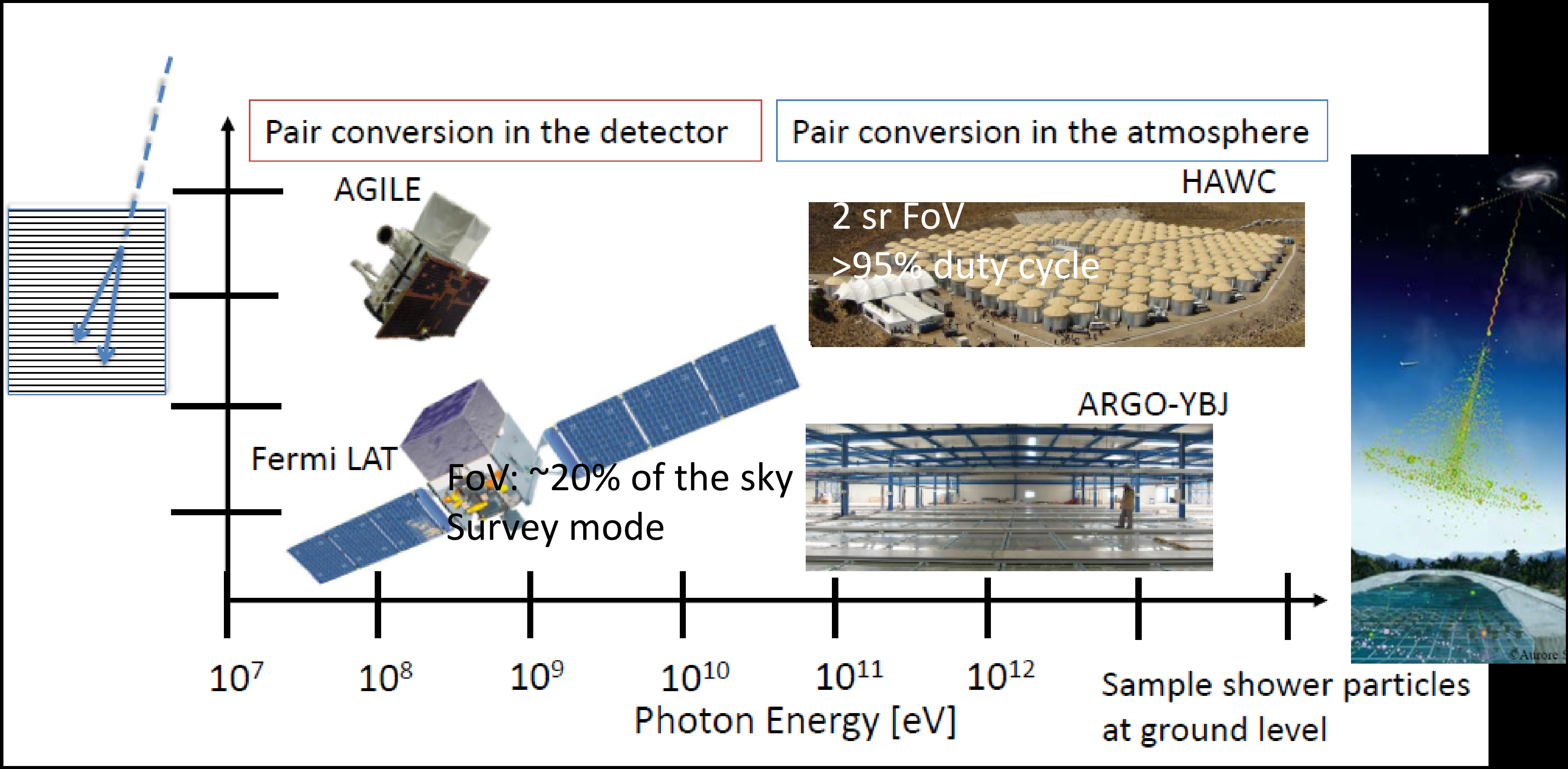




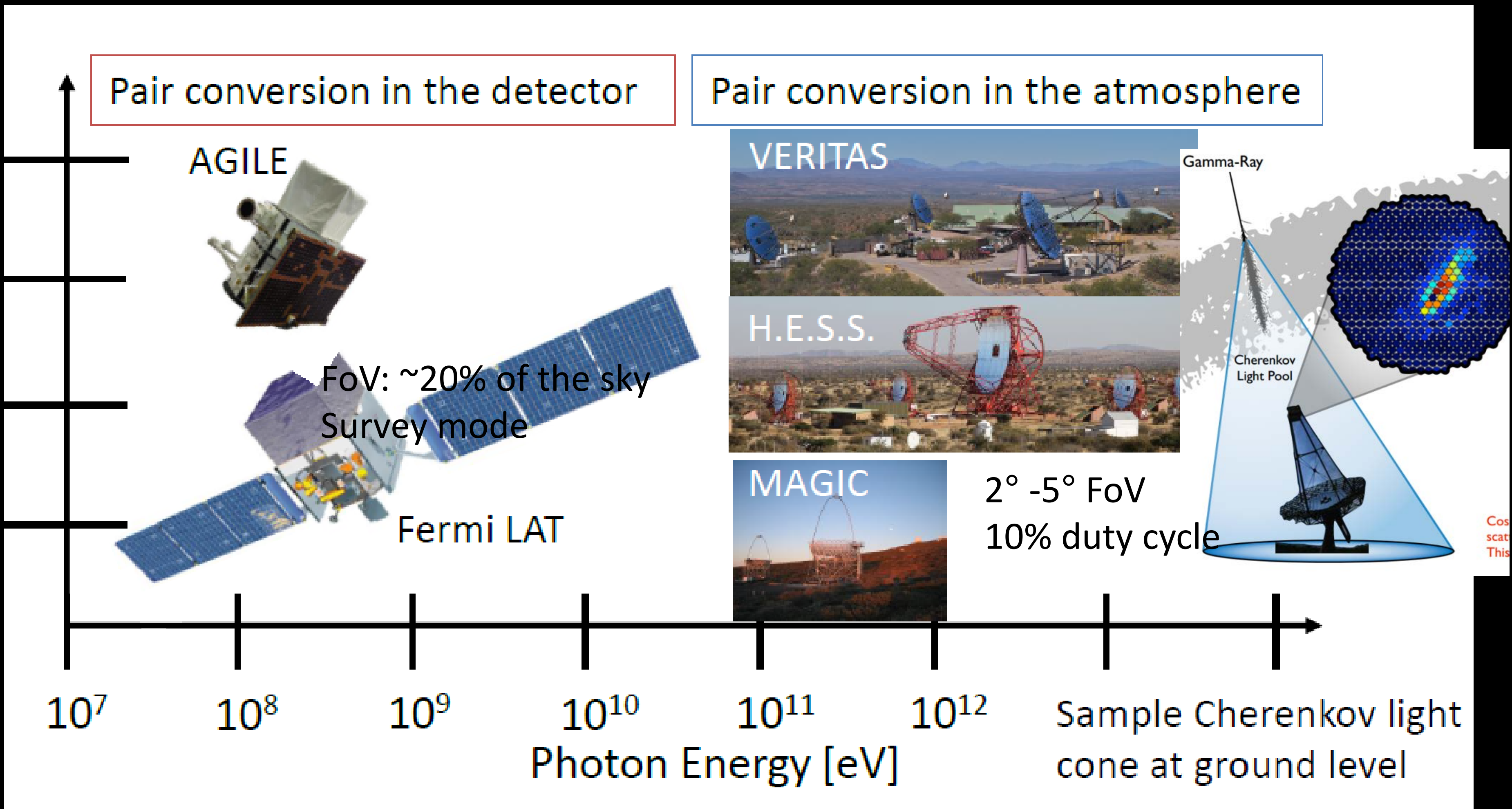


p^++target material $\rightarrow \pi^0 \rightarrow \gamma\gamma$

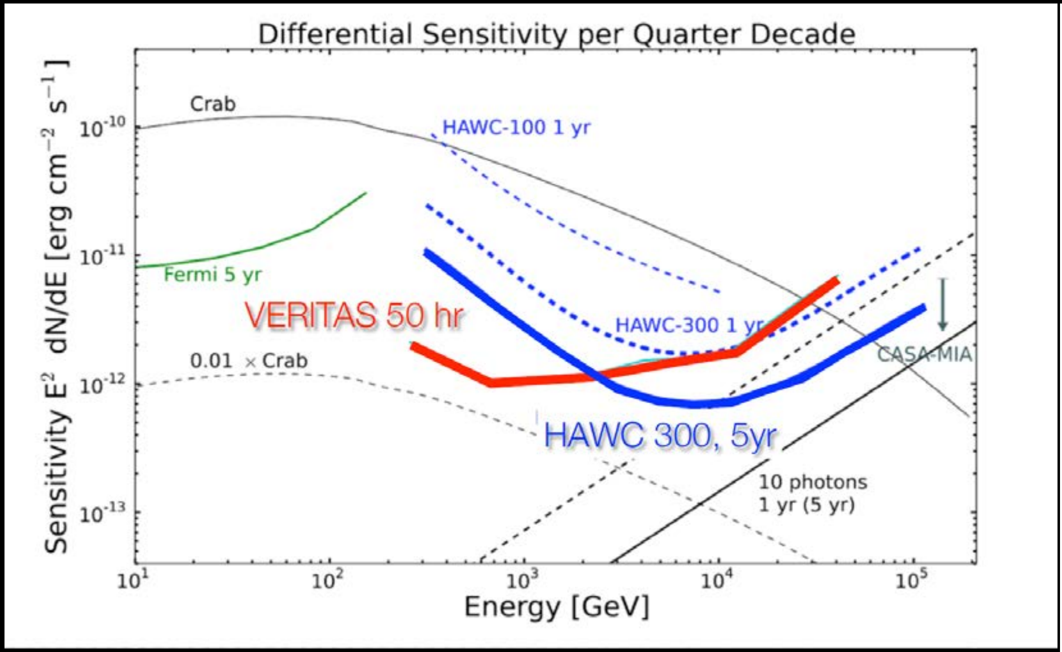
Gamma-ray Detectors I

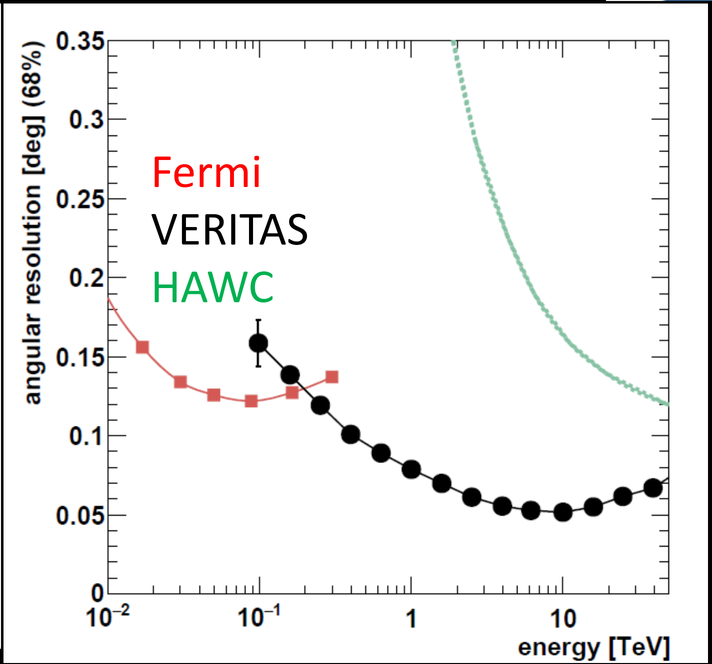


Gamma-ray Detectors II



Multi-instrument analysis

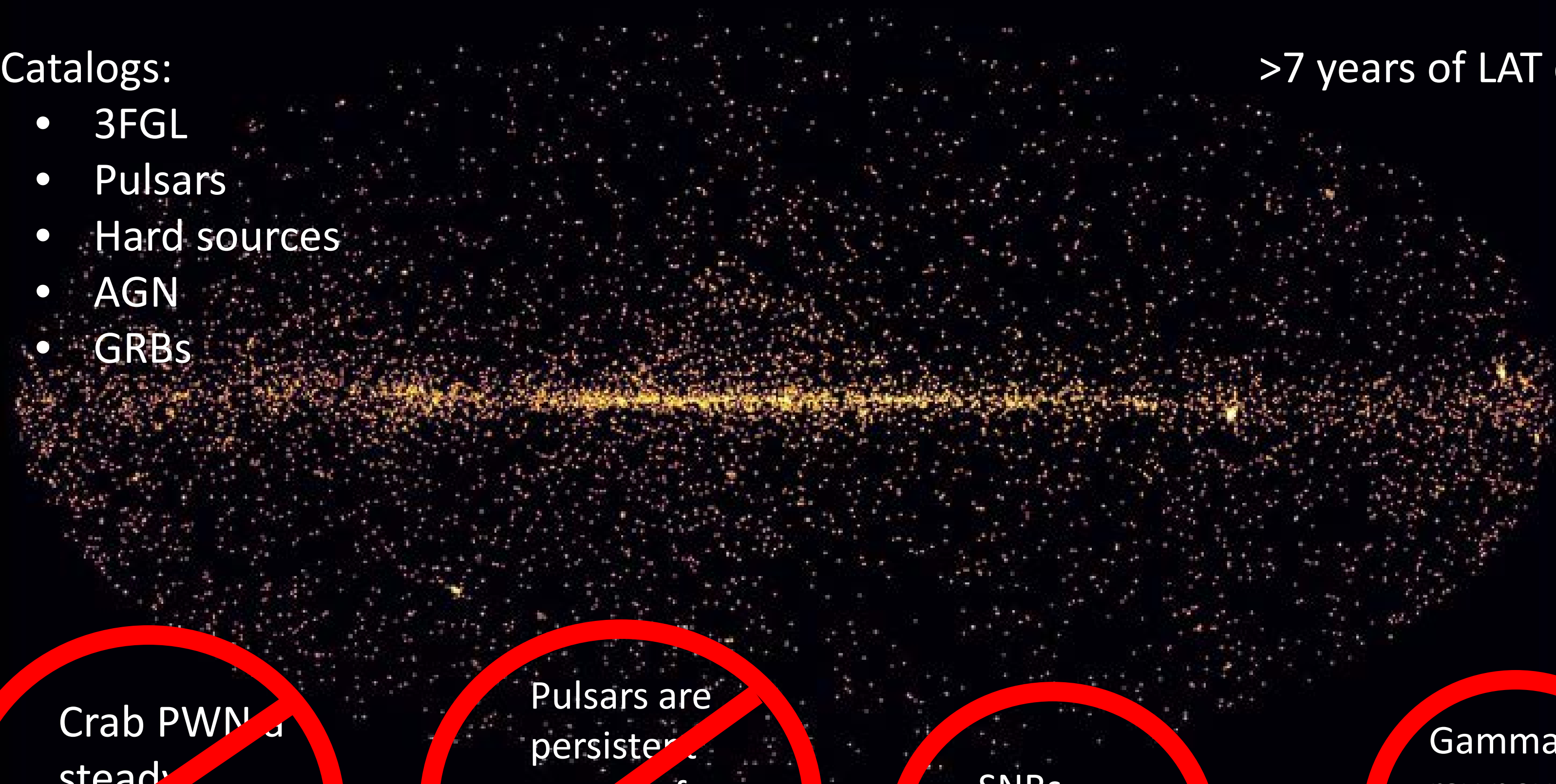




- Full suite of gamma-ray data = multi-messenger problem in microcosm
- How do we best combine data from instruments with different sensitivities, performance parameters?

WHAT ARE WE LEARNING FROM THE GAMMA-RAY SKY?

Gamma-ray satellite view



- Catalogs:
  - 3FGL
  - Pulsars
  - Hard sources
  - AGN
  - GRBs

>7 years of LAT data

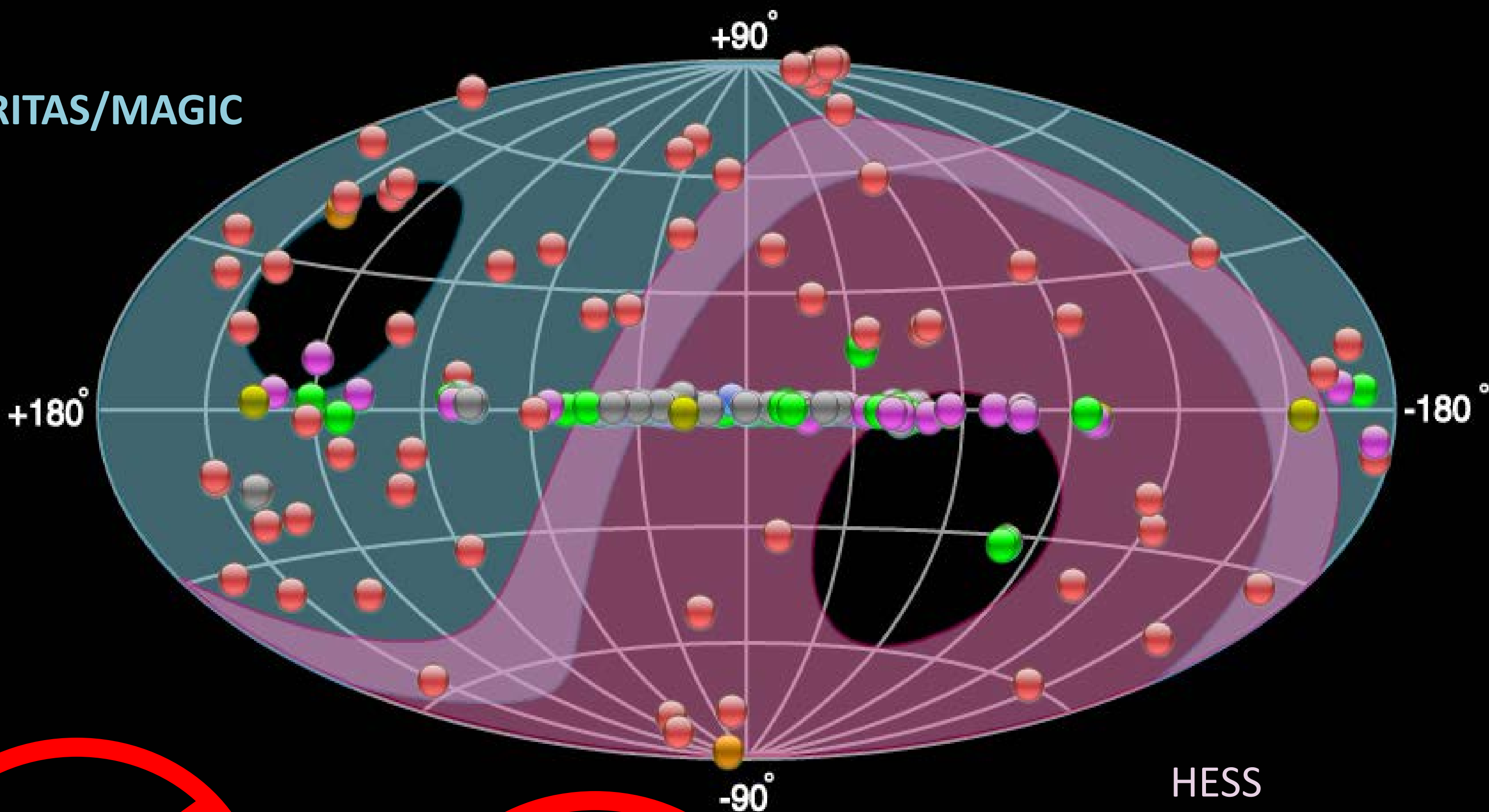
~~Crab PWN a steady gamma-ray source~~

~~Pulsars are persistent source of gamma-ray emission~~

SNRs accelerate protons

Gamma-ray novae Fermi bubbles

IACT view

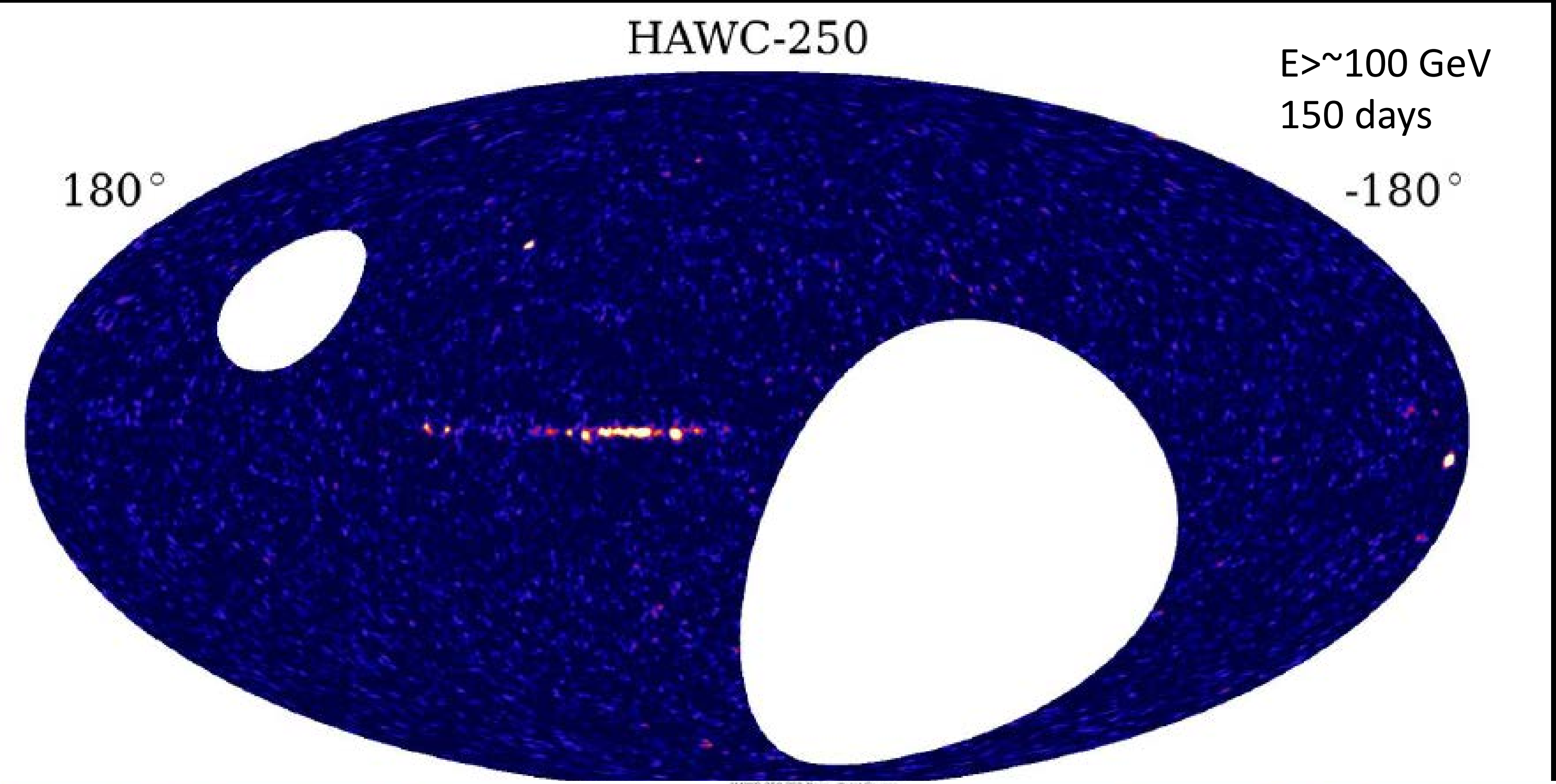


Pulsars don't pulse at high energies

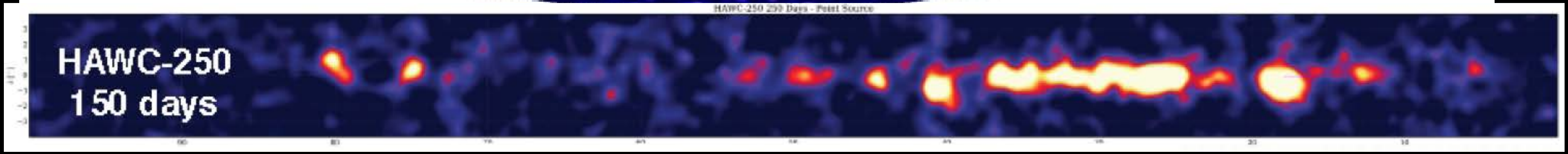
Starburst galaxies
Superbubbles

- >170 sources

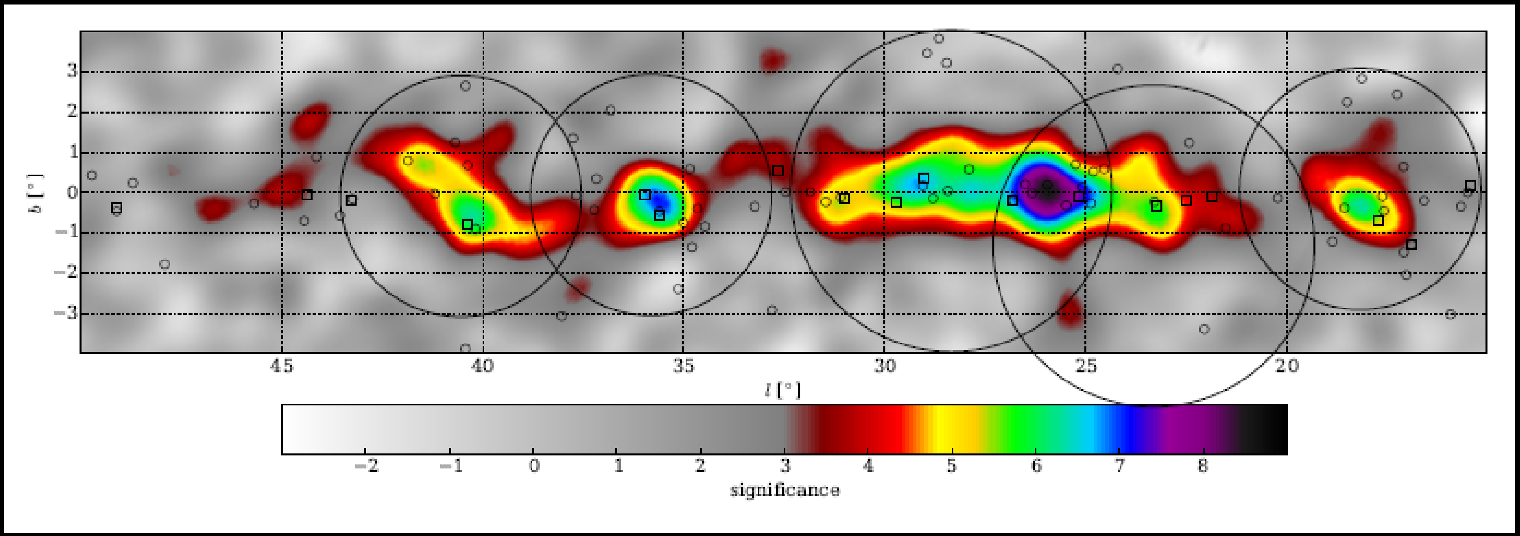
Water Cherenkov view



E>~100 GeV
150 days



Multi-instrument analysis: correlations



Inner galaxy: 283 days of HAWC 111 data

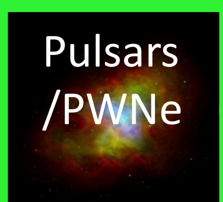
Small circles: 3FGL sources

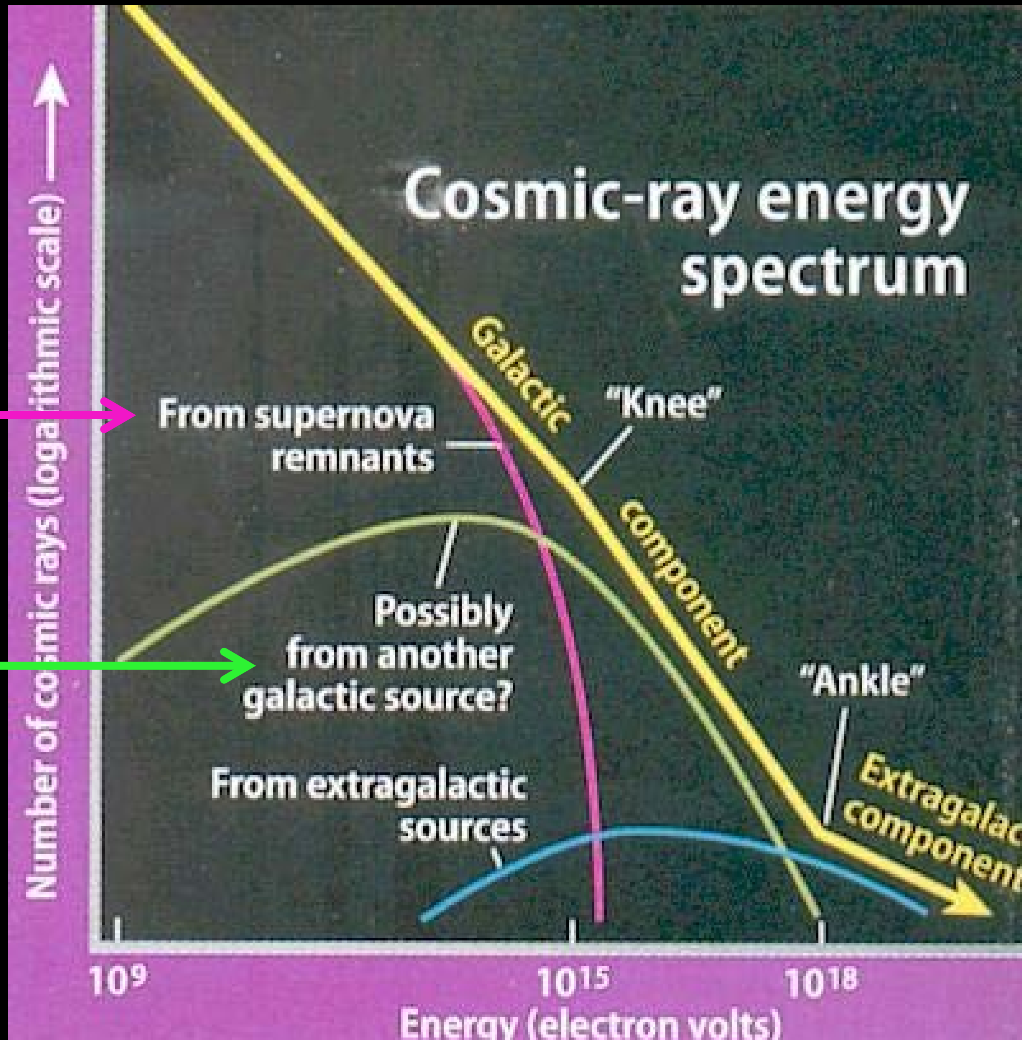
Open squares: TevCaT

GALACTIC CR ACCELERATORS AND MULTI-INSTRUMENT SYNERGY

CR Accelerators: What and Where?

Superbubbles!



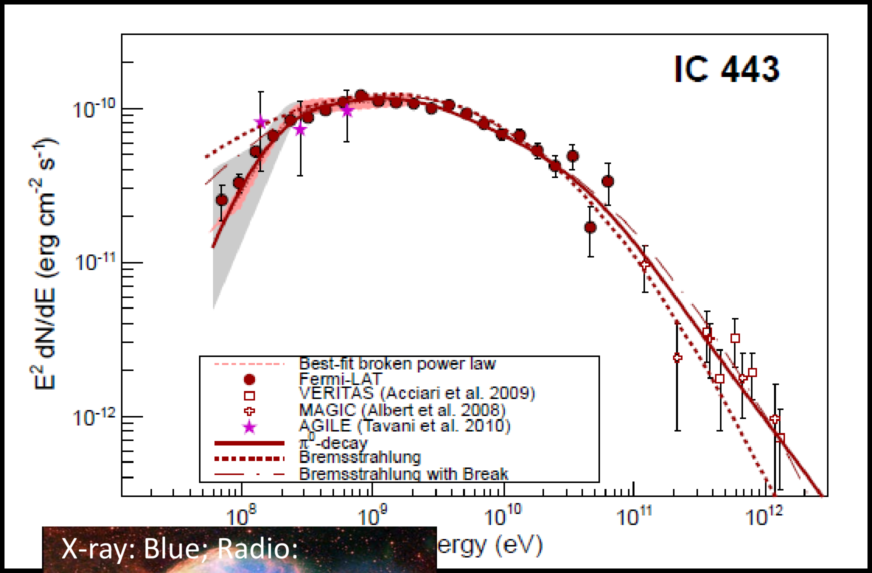


Gamma ray bursts

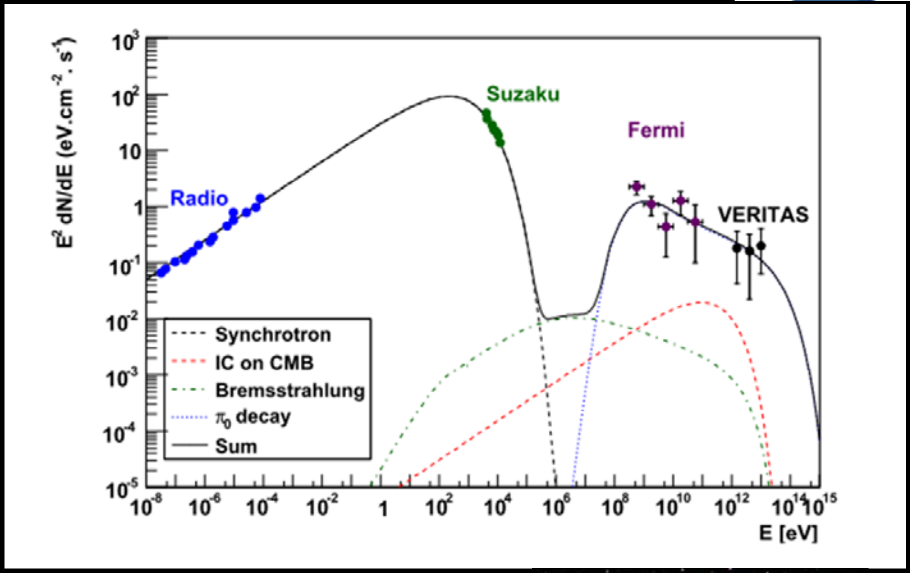
Contribute electrons and hadrons (e.g. protons, He, Fe..)

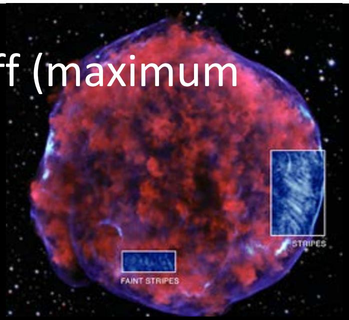
- Draw on Galactic CR examples

SNRs Are Cosmic Ray Accelerators



IC443 and the "pion decay bump"

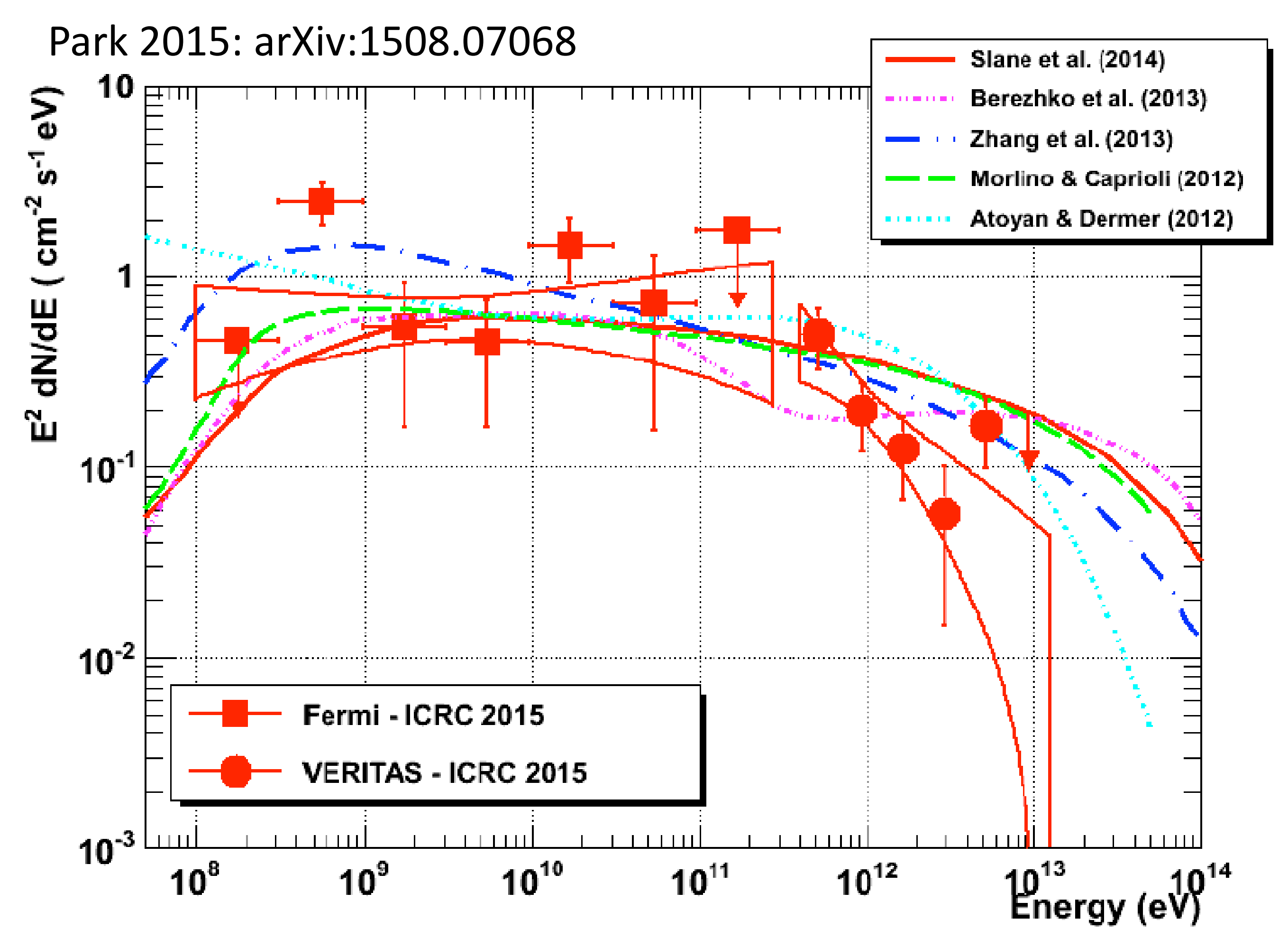




Tycho: hunting the cutoff (maximum proton energy)

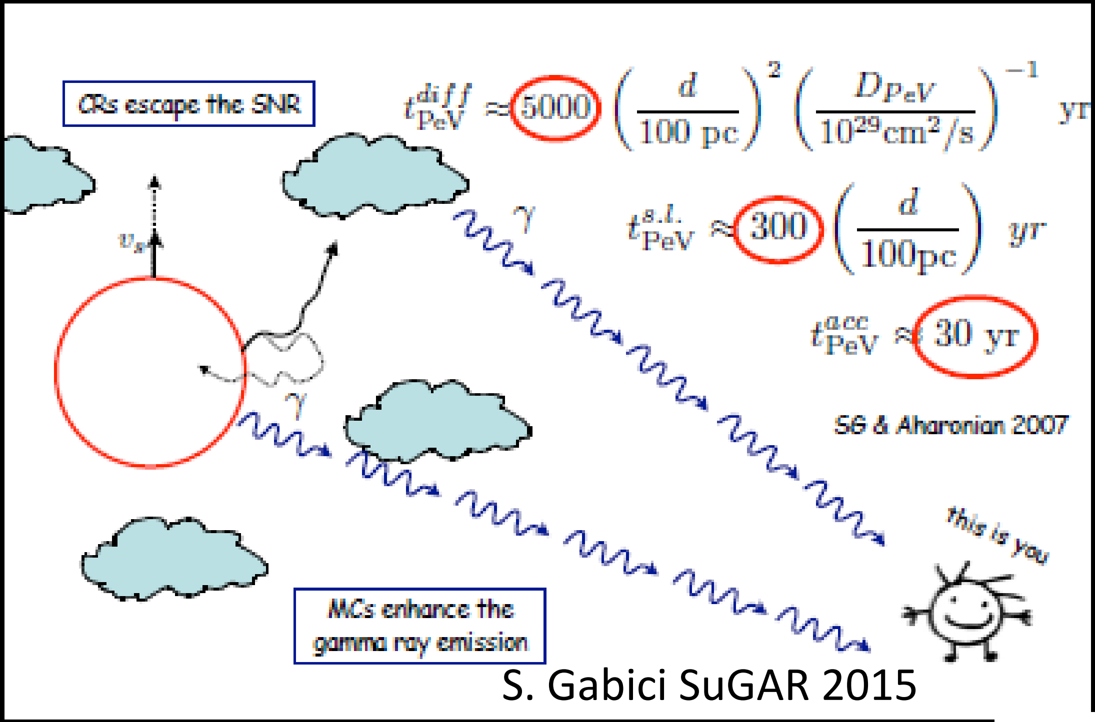
- New results on IC443 further illustrate multi-instrument synergy

Updates on Tycho



- Updated spectrum from deeper VERITAS observations softer, broadband SED in tension with models

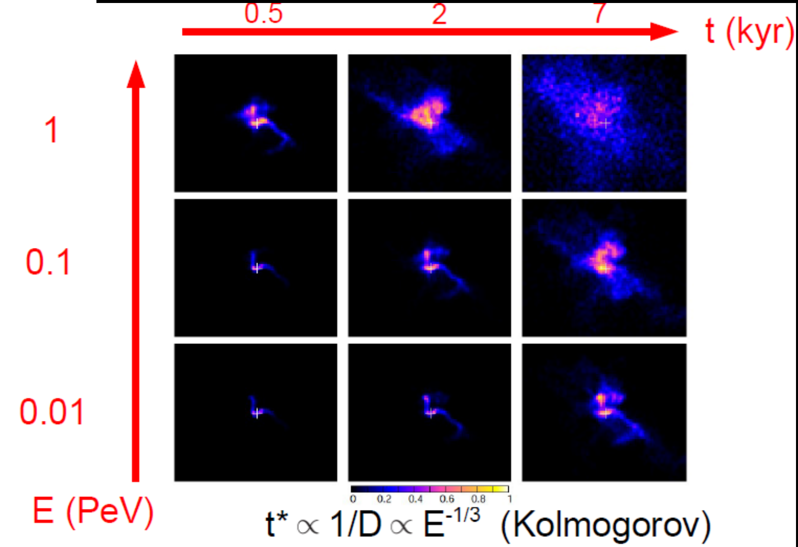
CR Escape Signatures



S. Gabici SuGAR 2015

- Alternative to capturing PeVatrons
  - Highest CR energies reached very early on
  - SNR = PeVatron at ~50 years (P. Blasi)

G. Giacinti SuGAR 2015



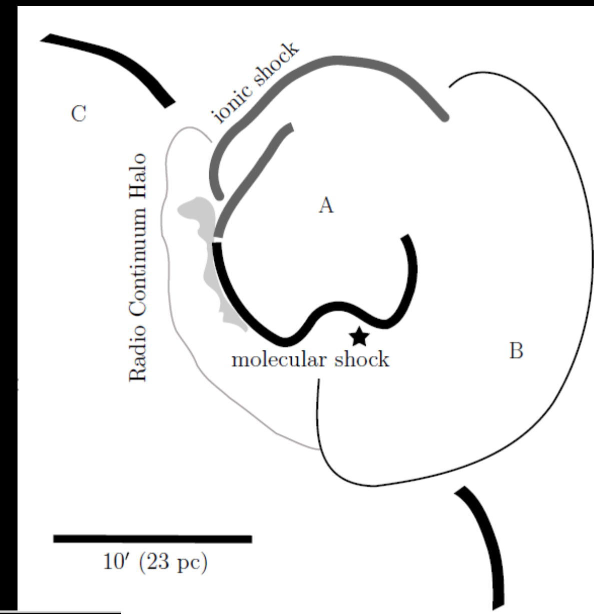
- Catch them “outside the barn door”
  - Molecular clouds
  - Diffuse and offset signatures (anisotropic diffusion)

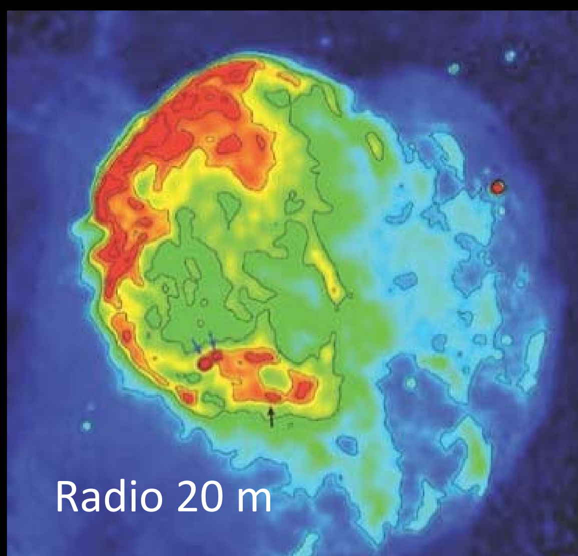
Resolving IC443

- Evolved (radiative) SNR interacting with a molecular cloud
- Conventional approach informative

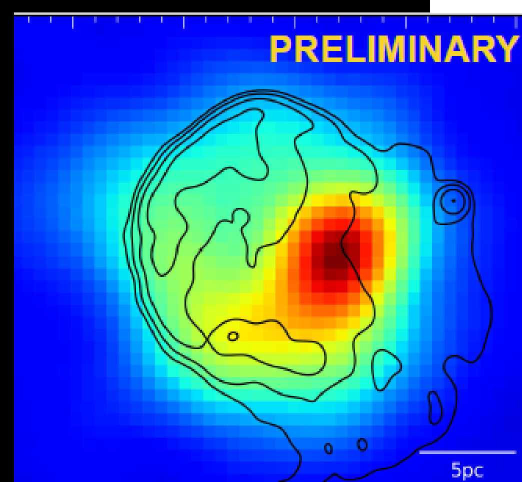
WISE 3-color IR image (shocked dust)

Lee et al. 2008 cartoon





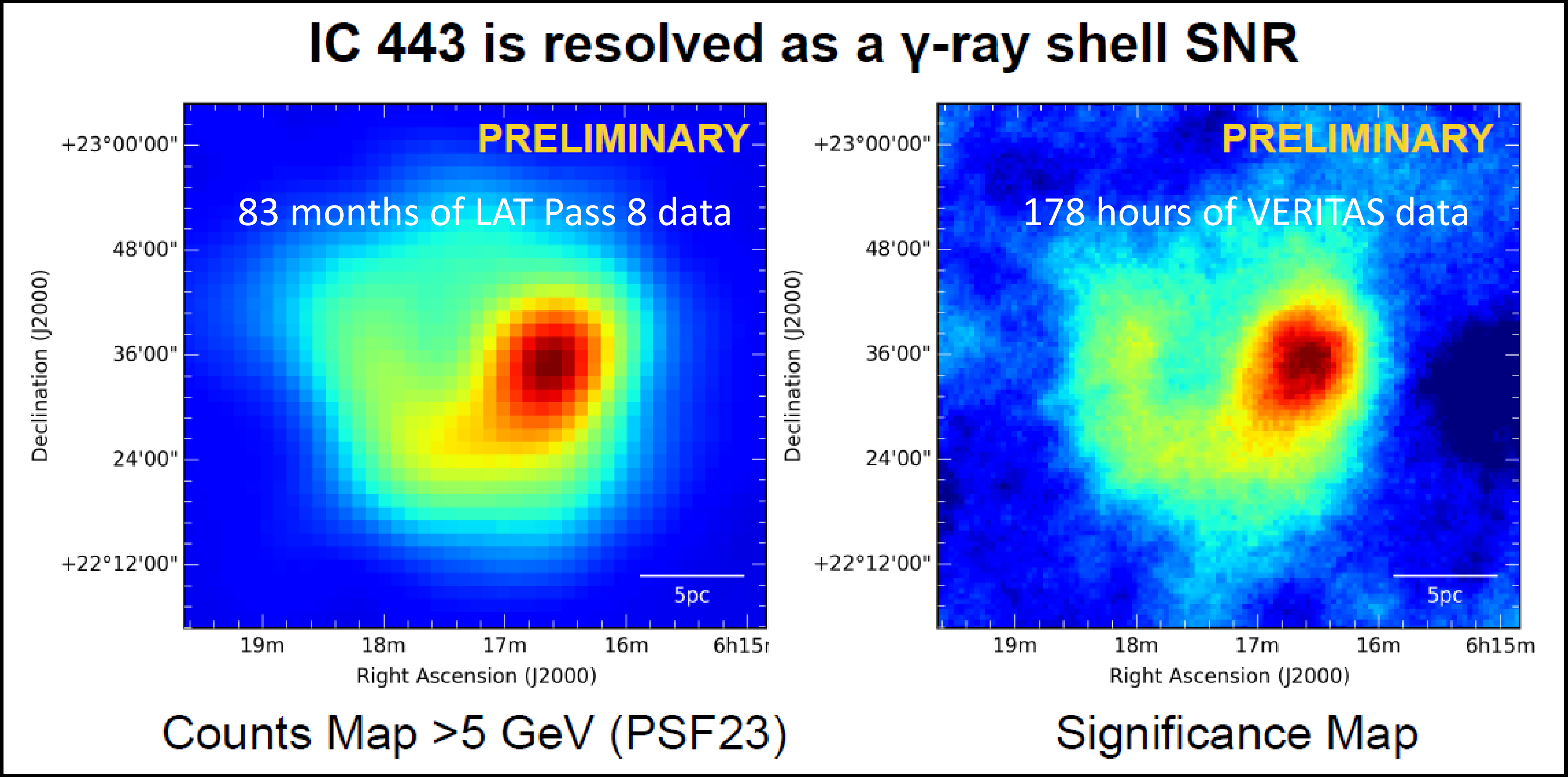
Radio 20 m



Fermi-LAT > 5 GeV counts map

IC443: A deeper γ-ray view

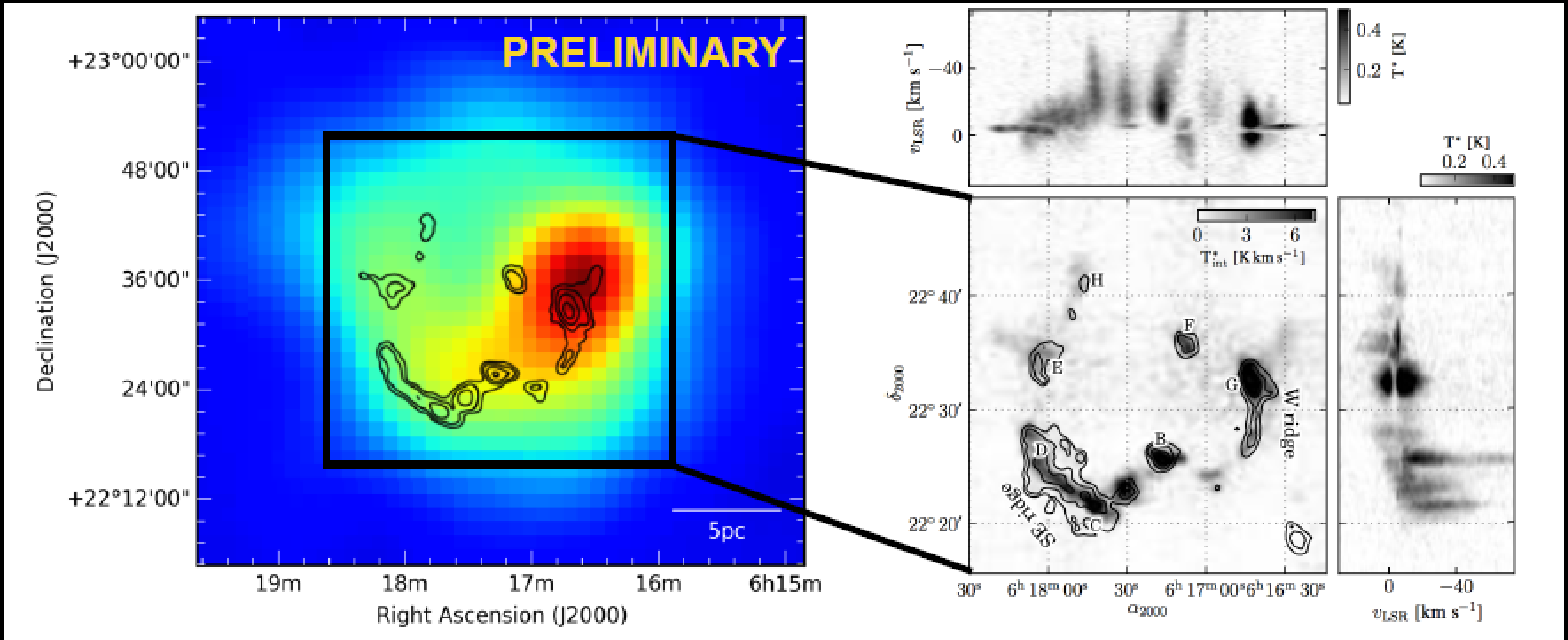
- Resolve gamma-ray emission zones on 5 pc scale
- Strikingly stable morphology from > 5 GeV



(J. Hewitt, T.B. Humensky)

Comparing morphologies

- GeV/TeV gamma-rays seem to trace distribution of **shocked** gas in IC443

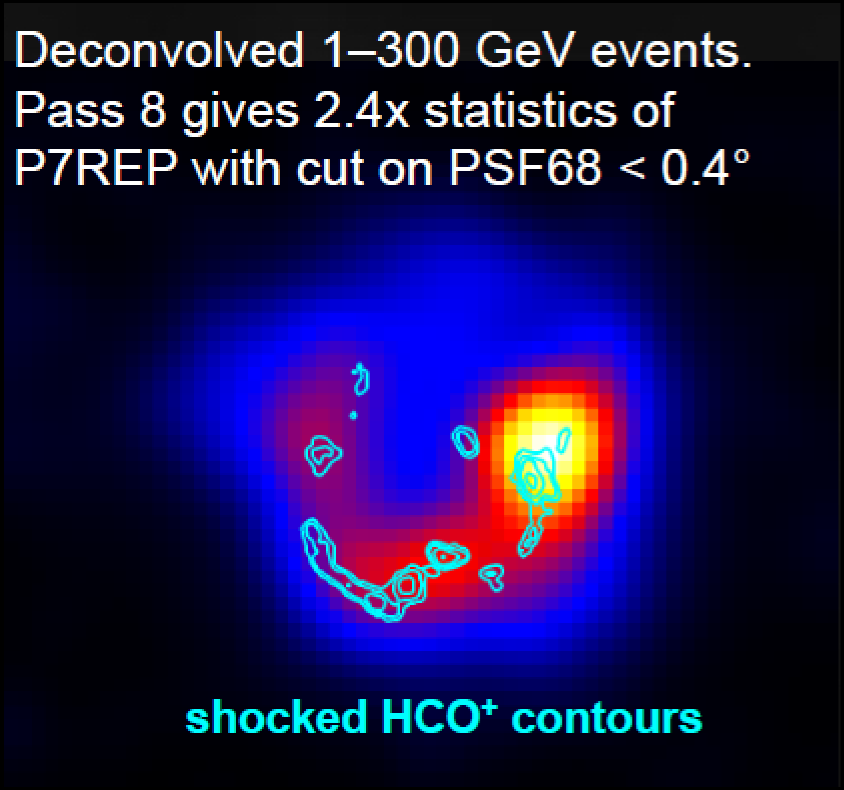


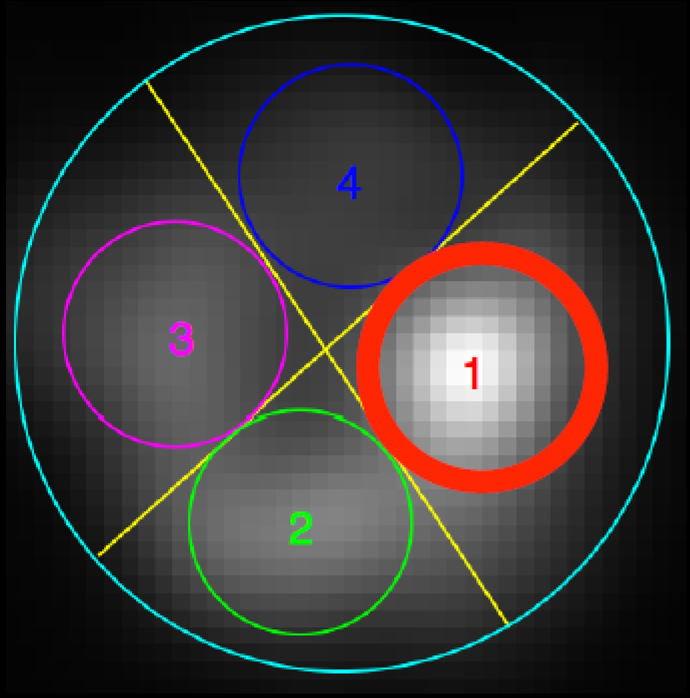
Counts Map >5 GeV (PSF23)

~10^4 M_{sun} of shocked gas along southern ridge (Lee, et al. 2008)

Isolating regions of the SNR

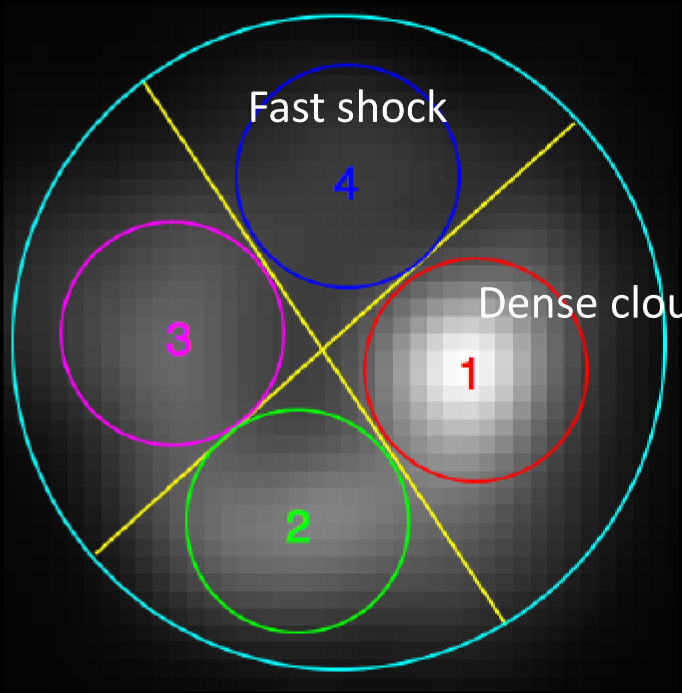
- Use deconvolved LAT image as extended spatial template to isolate/select emission regions to study:

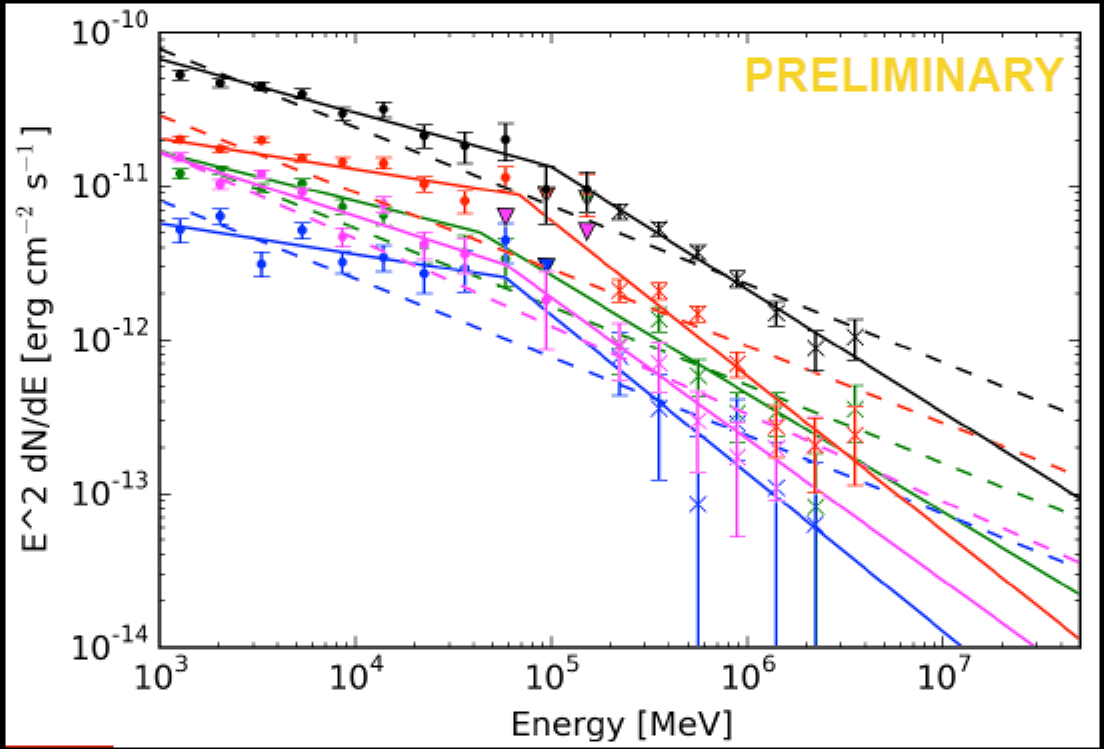




Comparing regions

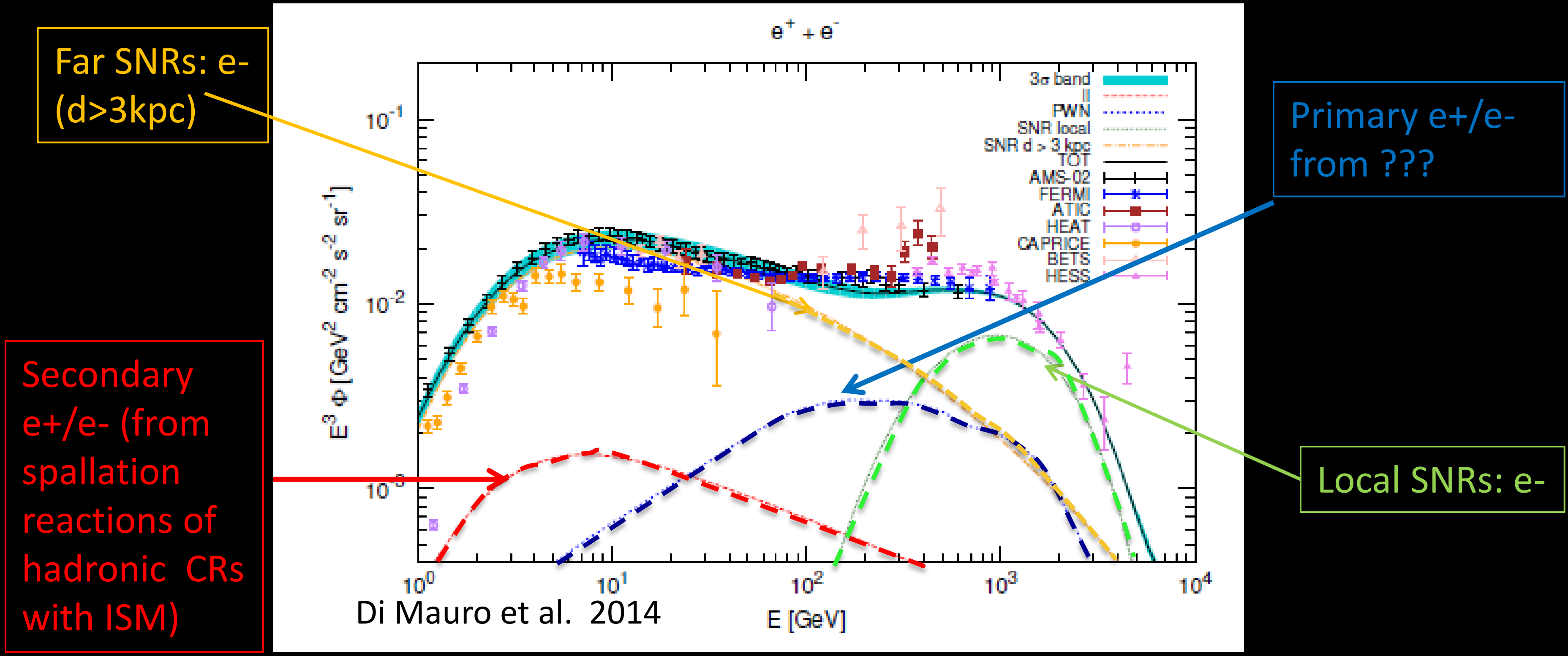
- Broken PL fits for all regions :Γ_1~2.3, Γ_1~2.9, break energy ~ 60 GeV





- Strong differences in environment but no clear differences in spectral shape!
- Order of magnitude variation in intensity but TeV/GeV integral flux ratios consistent within errors.
- Conventional approach can already tell us a great deal.

Contributions to the local e+/e- spectrum

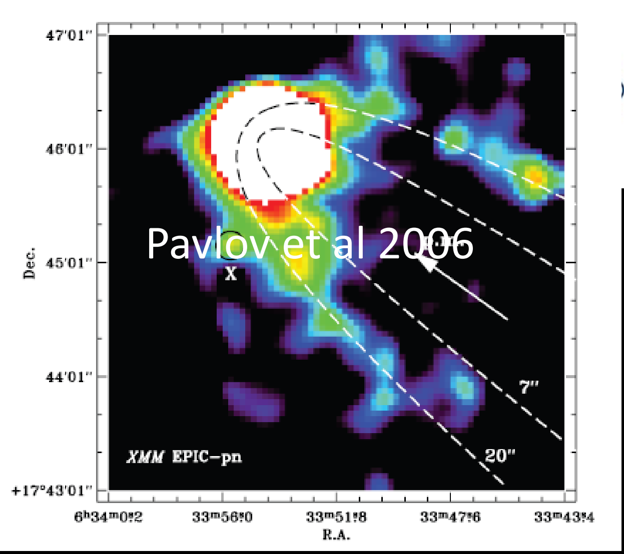


Di Mauro et al. JCAP 2014 (04) 06

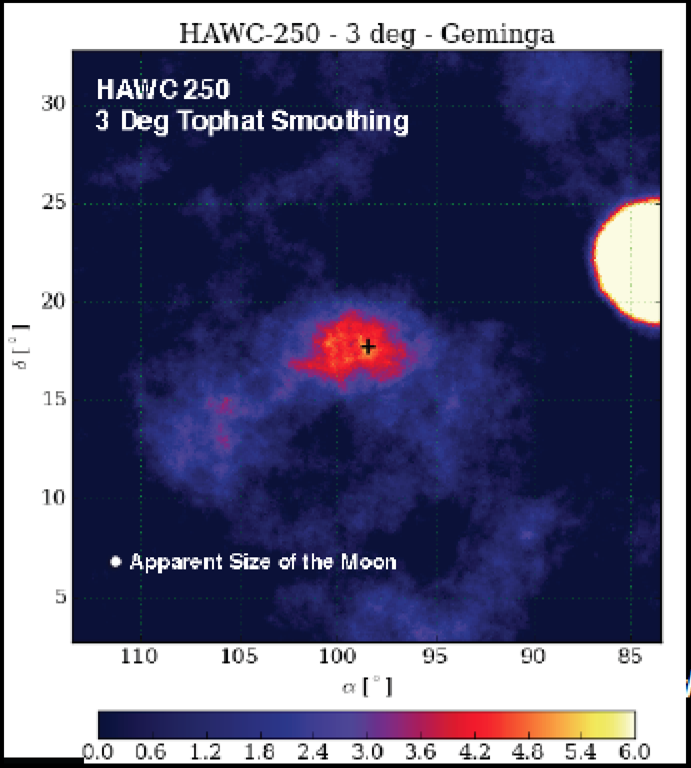
- Dark matter? (disfavored)
- Pulsars (a population, or one to a few local)
- Re-acceleration in SNR

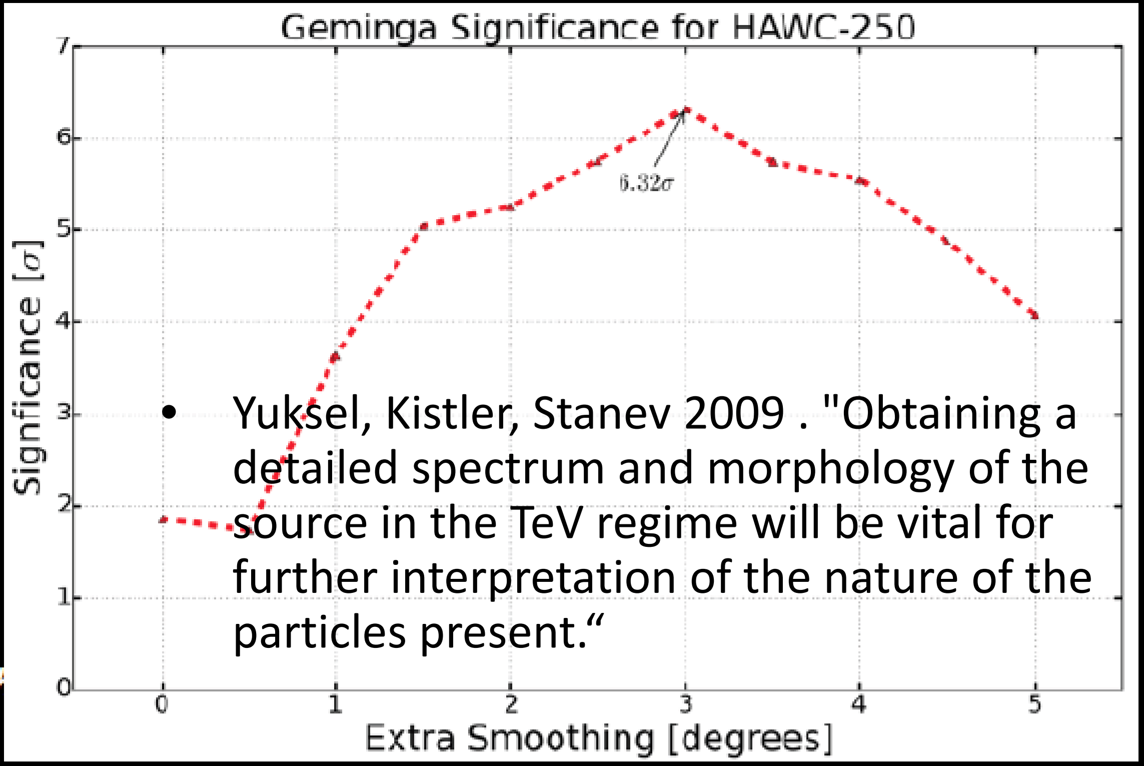
Geminga

- Well known, 340 kyr-old X-ray and gamma-ray pulsar with a compact X-ray PWN and a huge gamma-ray halo.
- First detected by Milagro, now confirmed at greater extension (!) by HAWC



Pavlov et al 2006

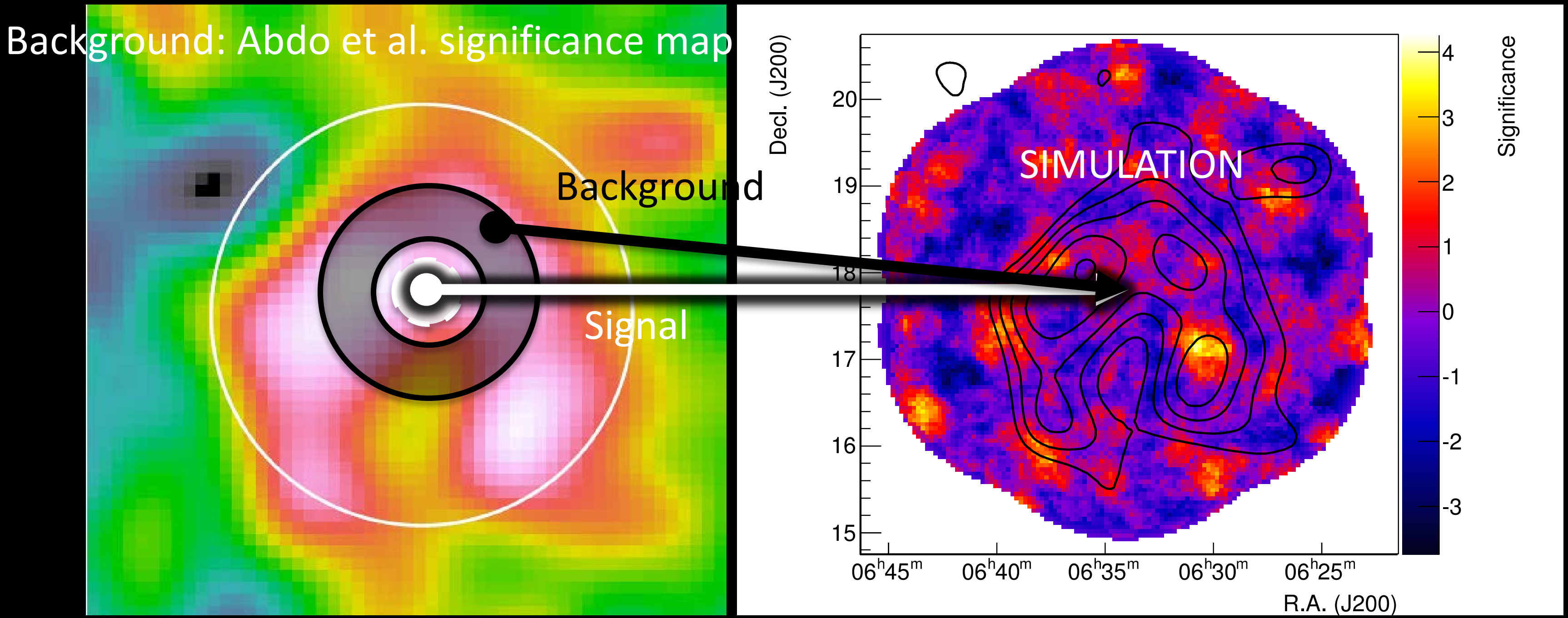




- Yuksel, Kistler, Stanev 2009 . "Obtaining a detailed spectrum and morphology of the source in the TeV regime will be vital for further interpretation of the nature of the particles present.“

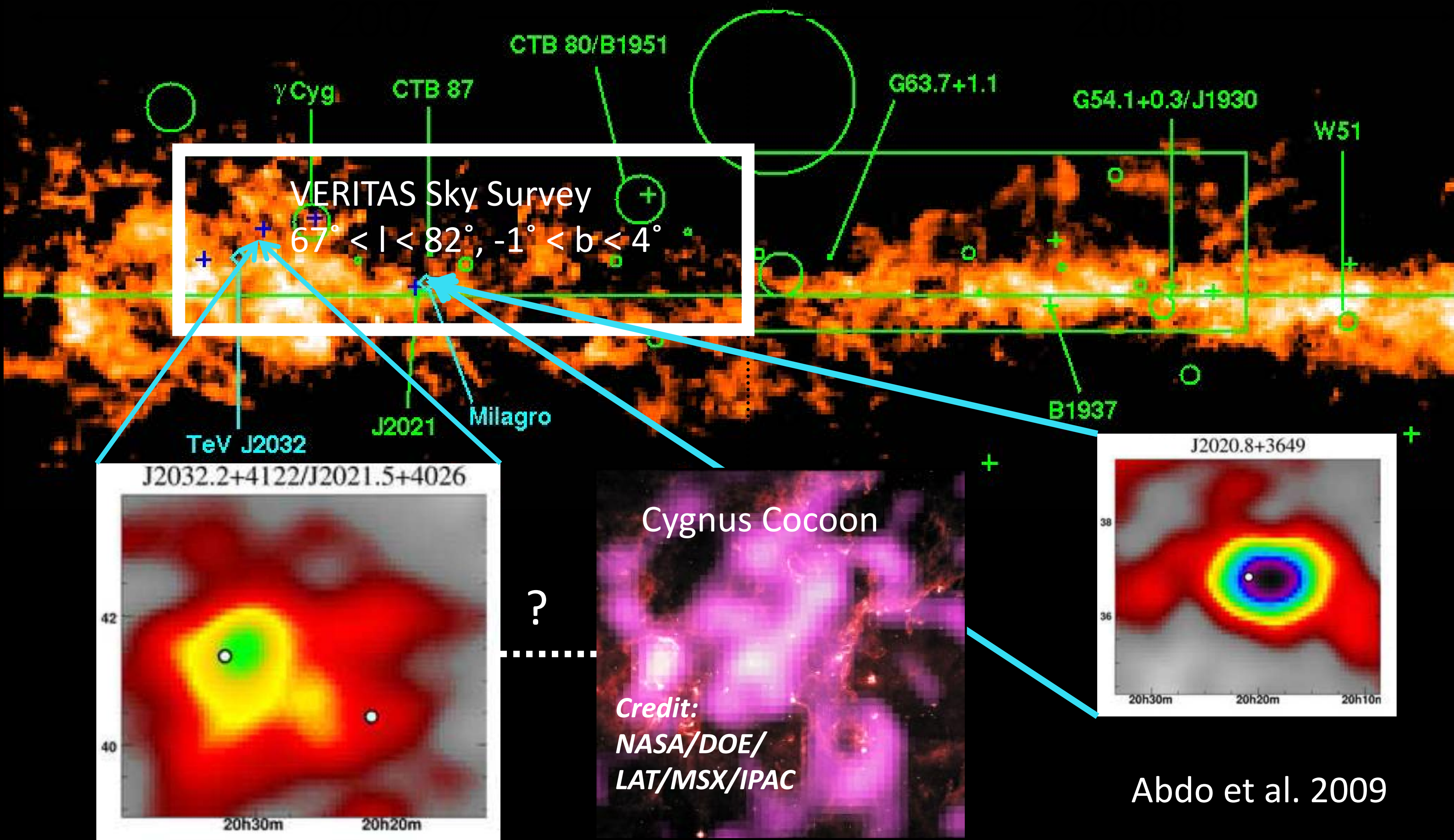
The Challenge

- Yesterday upon a stair I met a man who wasn't there. He wasn't there again today, I wish, I wish he'd go away." --- *Antigonish*, Hughes Mearns
- How do we handle a source comparable to / greater than the VERITAS field of view?



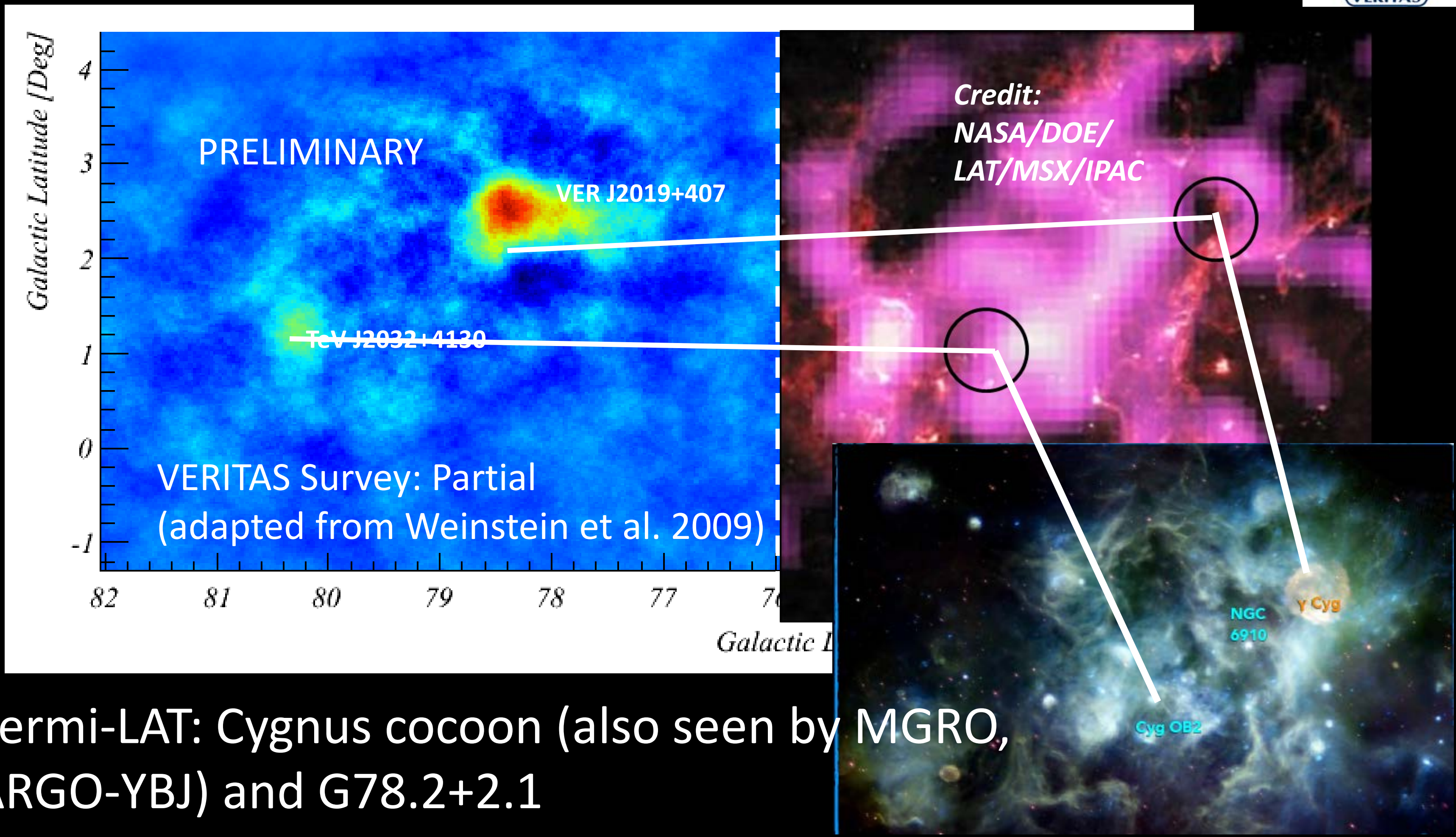
Analysis technique can make a difference.

Gamma-rays in Cygnus



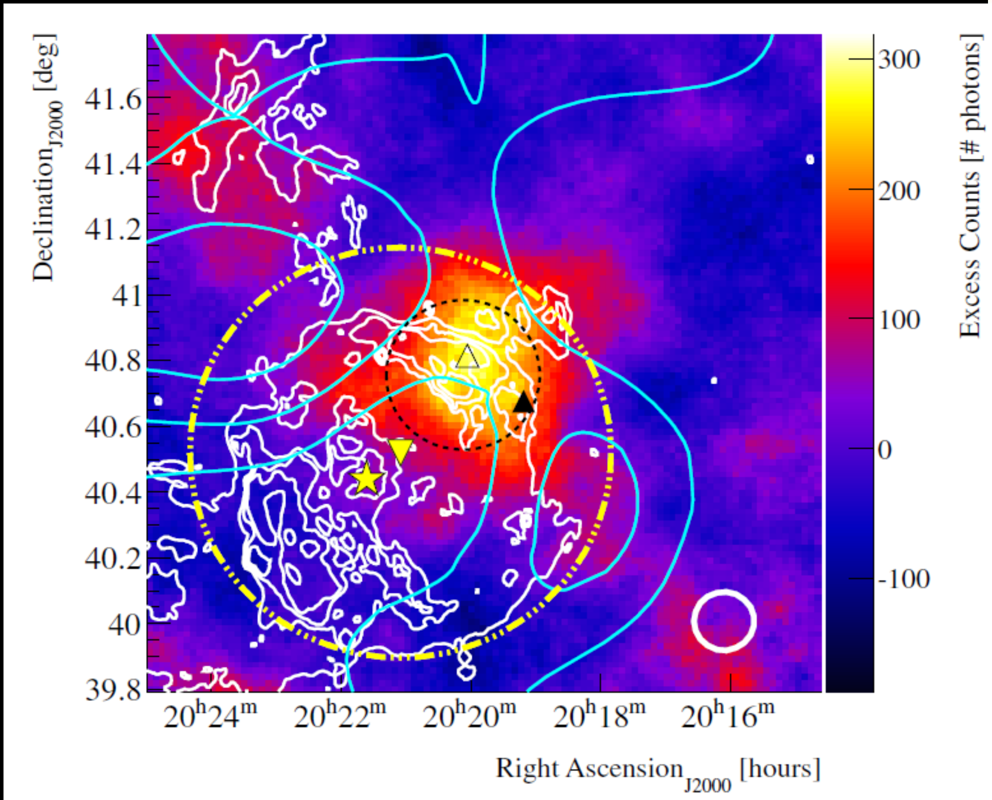
Abdo et al. 2009

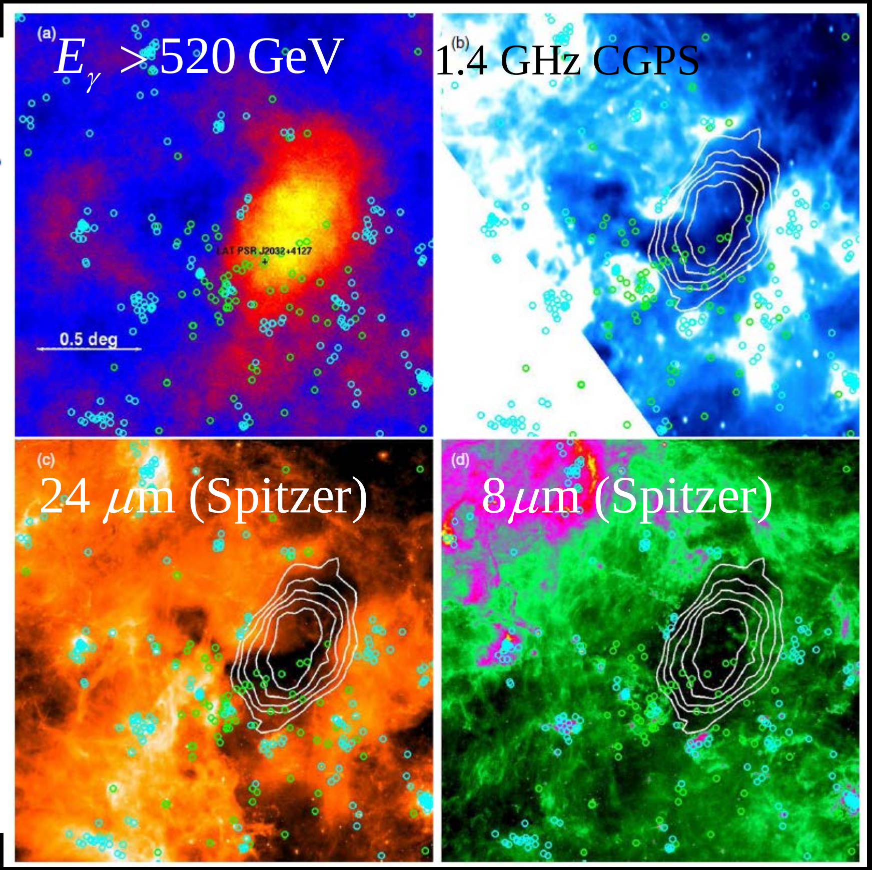
Cygnus Cocoon and Environs



- Fermi-LAT: Cygnus cocoon (also seen by MGRO, ARGO-YBJ) and G78.2+2.1
- VERITAS : VER J2019+407 and TeV J2032+4130

VER J2019 +407 and TeV 2032

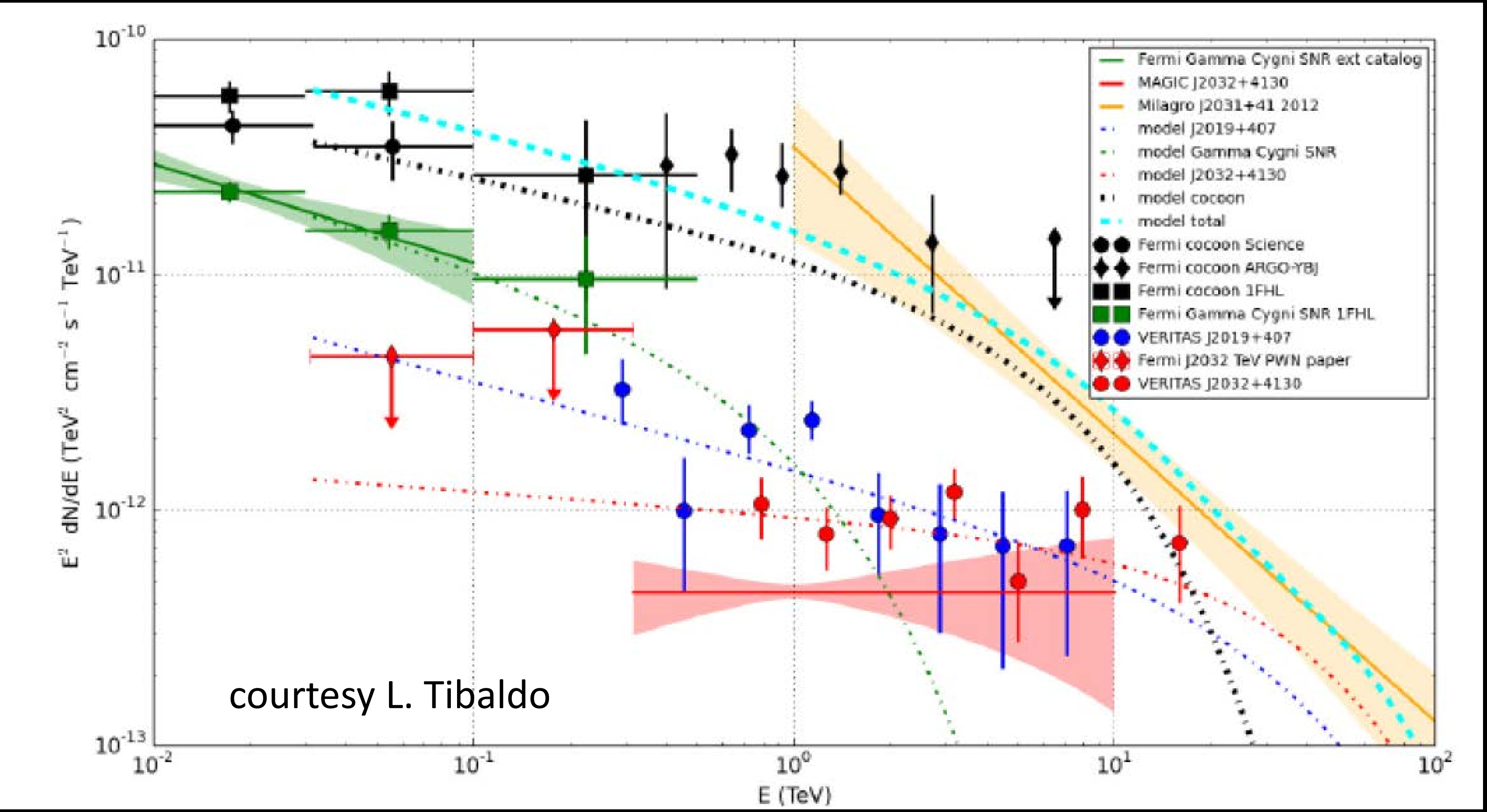




- Emission from remnant or line of sight PWN?

TeV data argues for a PWN. GeV gamma rays, etc. indicate pulsar part of a binary system.

Disentangling the Cocoon



- ARGO corrects spectrum using IACT fluxes
- IACT resolution has a key role to play

Maximum likelihood model (MLM)

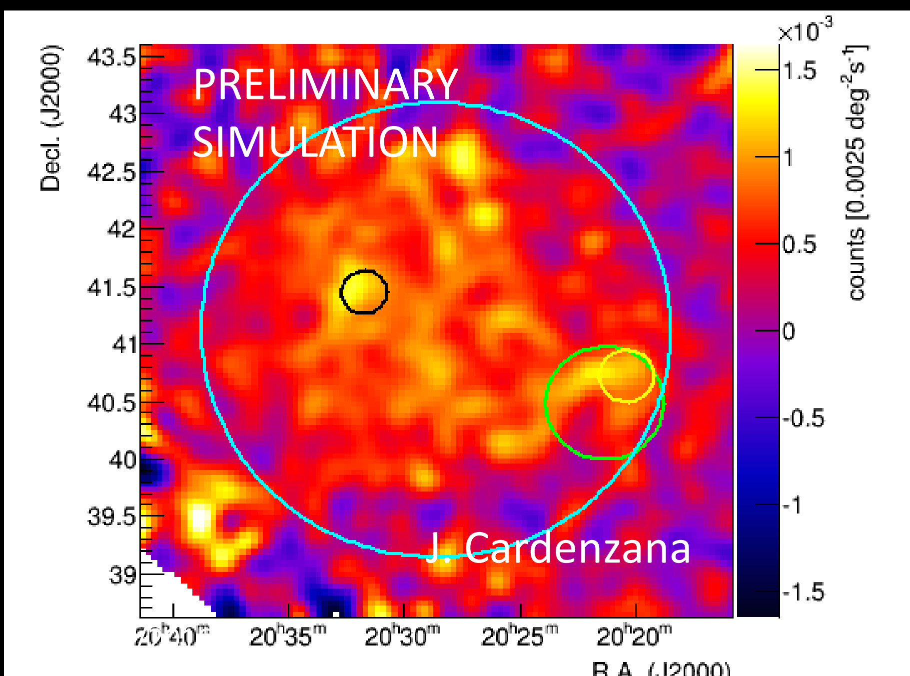
Fit models of signal and background
Incorporate gamma-hadron discriminating quantity into fit
Far more sensitive to highly extended sources

TeV J2032+4130
VER J2019+407
Cocoon (2°Gaussian)
Gamma Cygni

Toy model simulation of observations in the Cygnus region between 500GeV-1TeV.

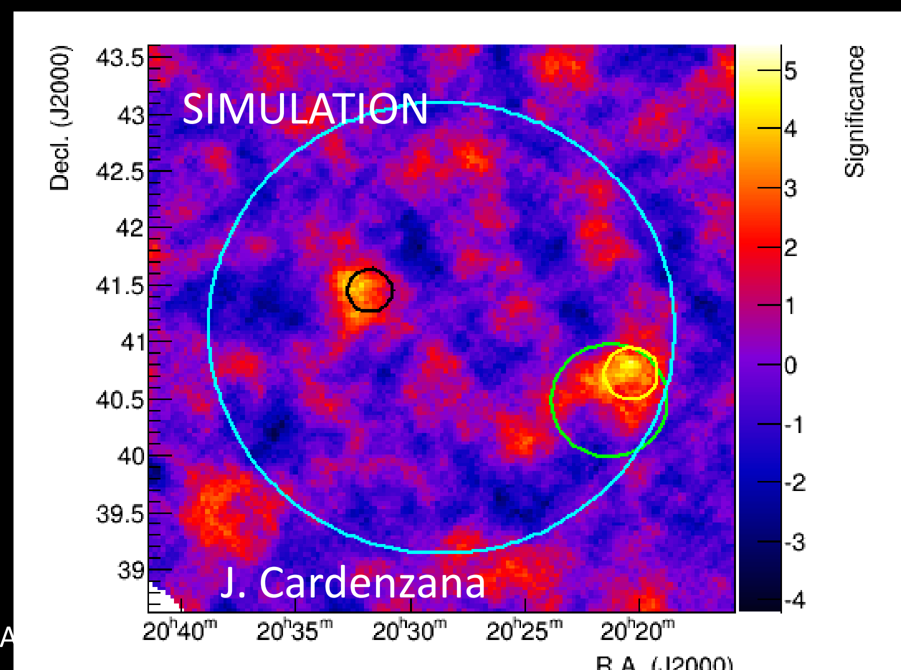
MLM

Shows evidence of extended emission



RBM

No evidence of extended emission



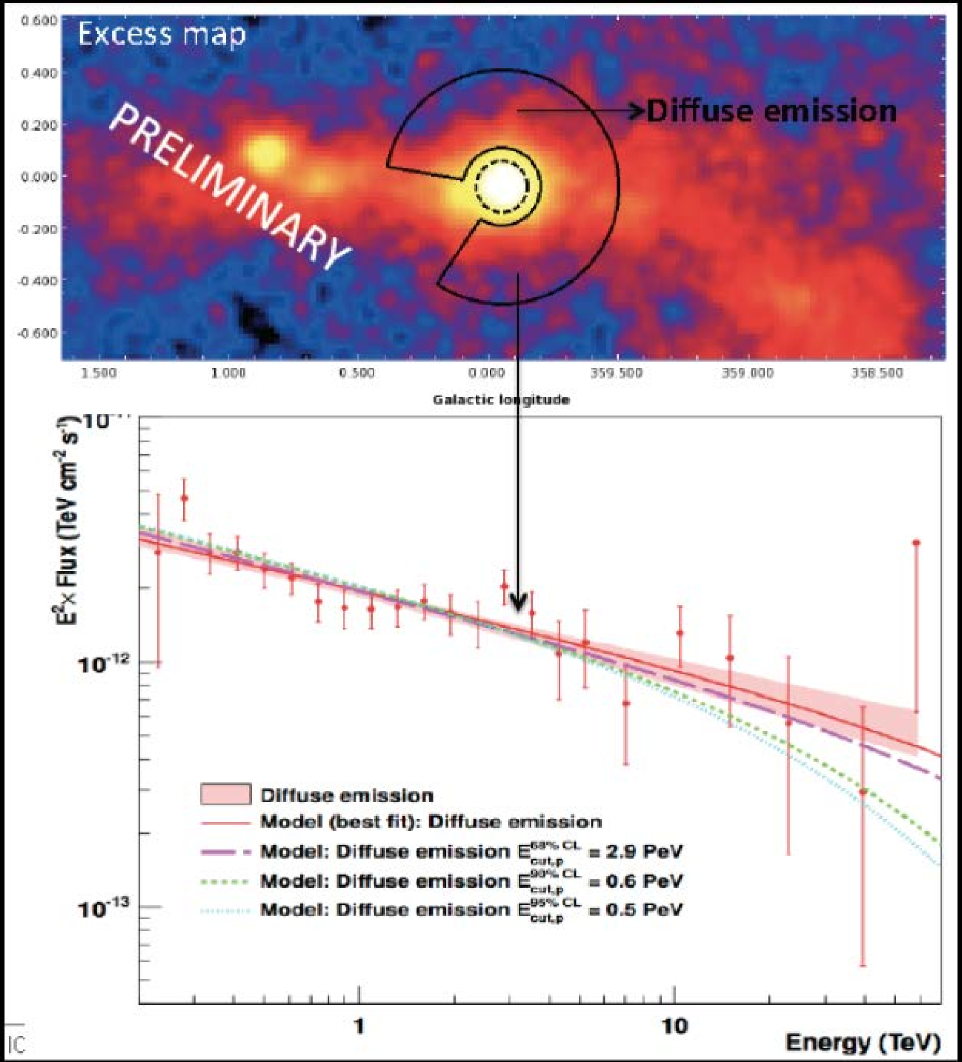
Key Advantages of MLM

- We fit a model to the entire extended or diffuse source
  - **Higher Sensitivity:** Signal/background ratio for any category controlled by flux of **full source** (or fraction of source in field of view).*
  - **Reduced Trials Factors:** Test coarse grid of extended source model positions rather than checking at many (correlated) points within the extended source.
- **Powerful diagnostic tools** to address systematic errors from modeling
- Handles **multiple overlapping sources**
  - Can test assumptions
- **Natural extension** to **multi-instrument datasets** (Fermi, HAWC)

Disentangling components II

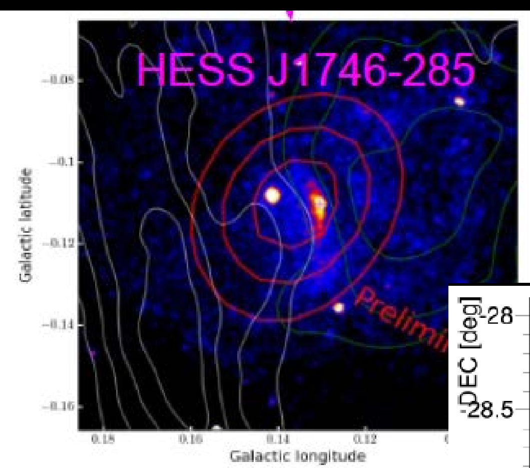
- From 250 hr H.E.S.S. observation of the Galactic Center.
- ~1/2 of GC ridge emission is distributed like dense gas tracers over a projected distance of 140 pc.
- Remainder: no correlation (unresolved sources, diffuse gas?)
- Additional feature in central 30 pc with radial gradient
  - Argued for diffuse emission from protons from central black hole -> 1 PeV protons = PeVatron?

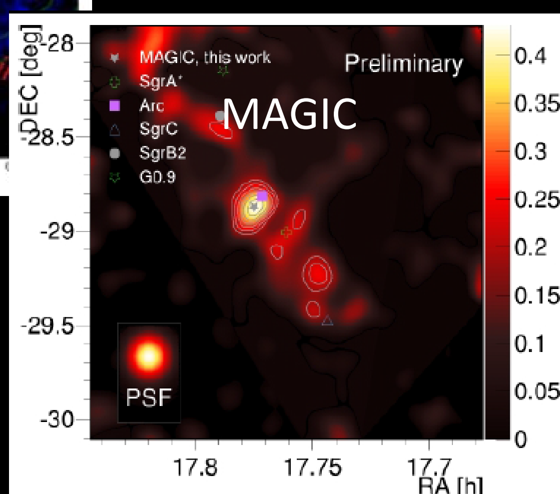
- Note: use of 2D maximum likelihood approach to test phenomenological models of signal

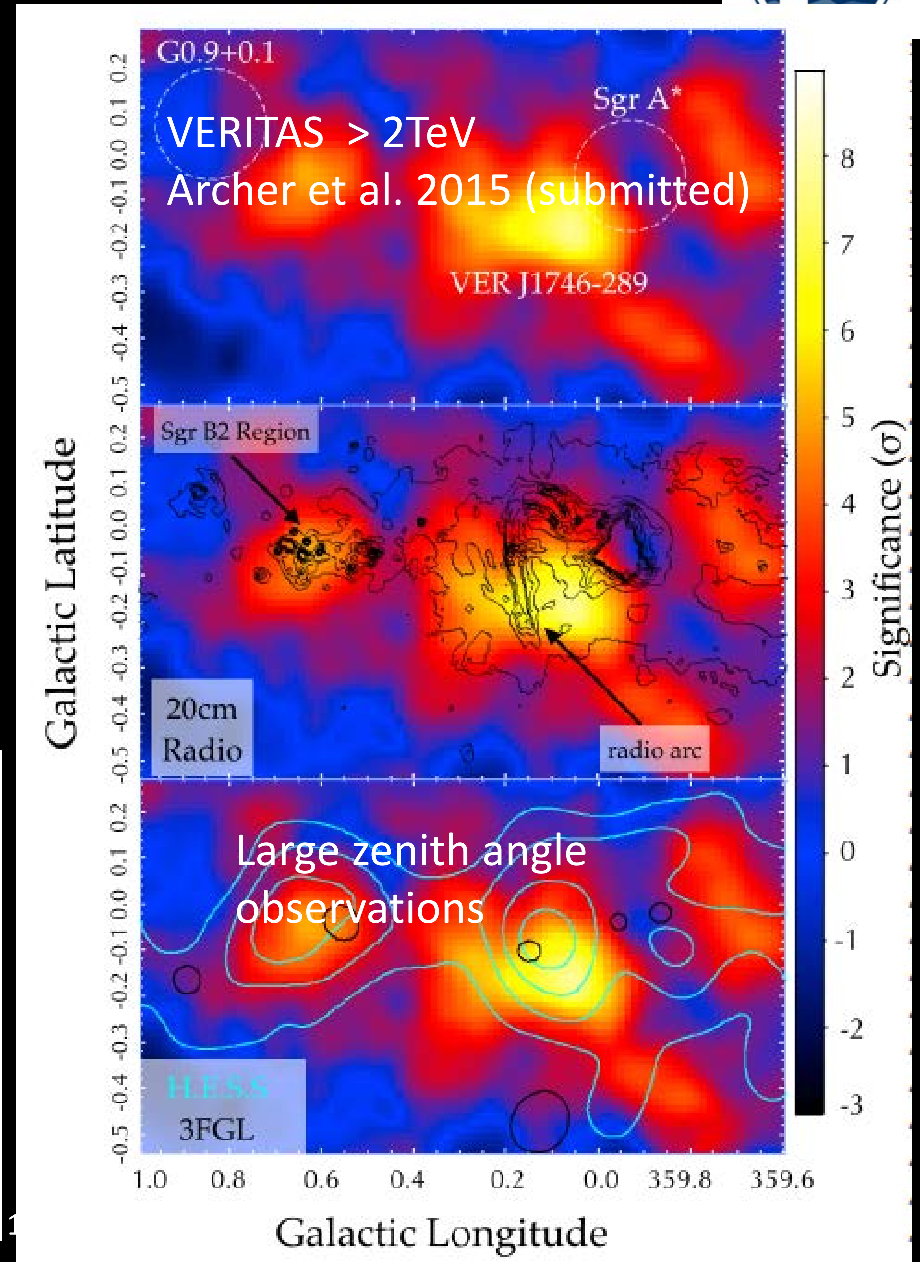


Views of the Galactic Center

- Multiple deep observation campaigns by IACT observatories (HESS, VERITAS, MAGIC) coupled with Fermi-LAT view
  - Detection of new source coincident with Radio Arc (HESS J1746-285)

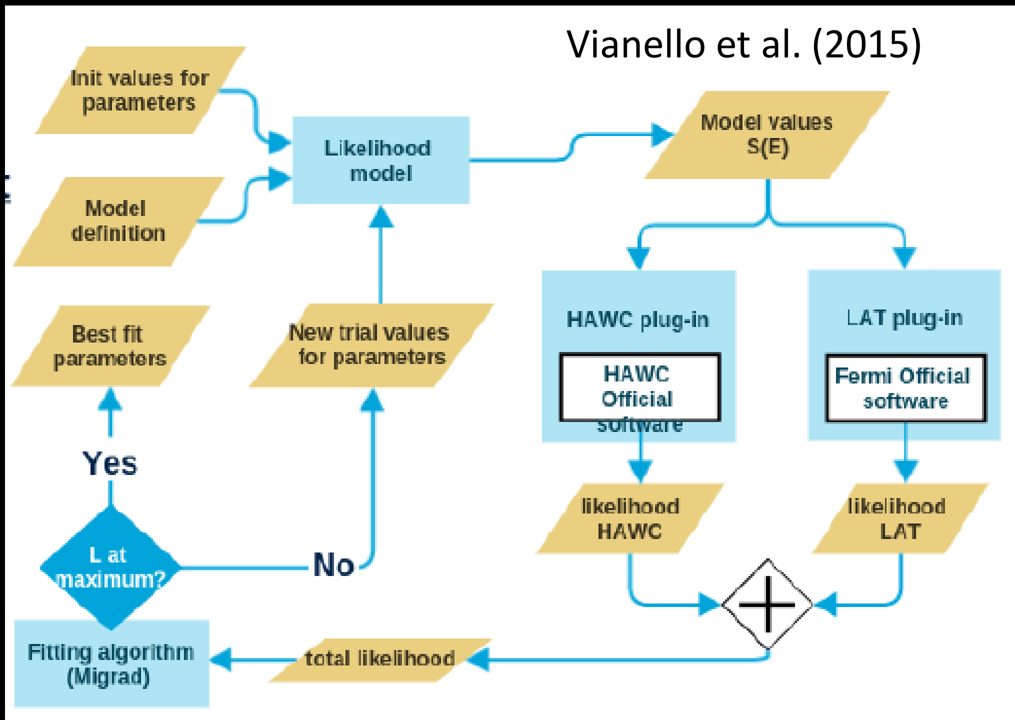




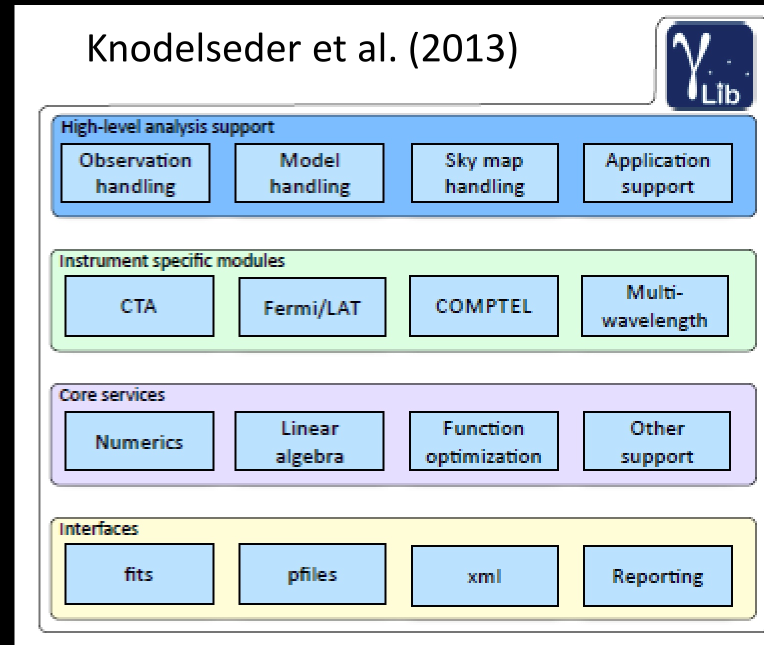


Multi-instrument frameworks

3ML plugin framework



GammaLib (common framework)



- Fermi, HAWC already have maximum likelihoods
- IACTs are developing likelihoods (HESS/CTA 2D, VERITAS 3D)
- Multi-wavelength compatibility (e.g. forward folding in X-rays)
- Common frameworks/scaffolding under development

Conclusions

- Gamma-ray astronomy above 300 MeV has evolved dramatically over the past decade and a half
  - New views of known gamma-ray sources
  - New classes of gamma-ray sources
  - Higher-resolution, wider-field sky surveys and increasingly large source catalogs
- Gamma-ray astronomy also at a watershed period with strong coverage from 300 MeV to 100 TeV
  - We are developing more effective ways to combine and use this rich multi-instrument dataset
- Other messengers can
  - Guide current and future gamma-ray observations
  - In the future: we incorporate other messengers in the same simultaneous data analysis framework we use for gamma rays?