Gamma Ray Observations

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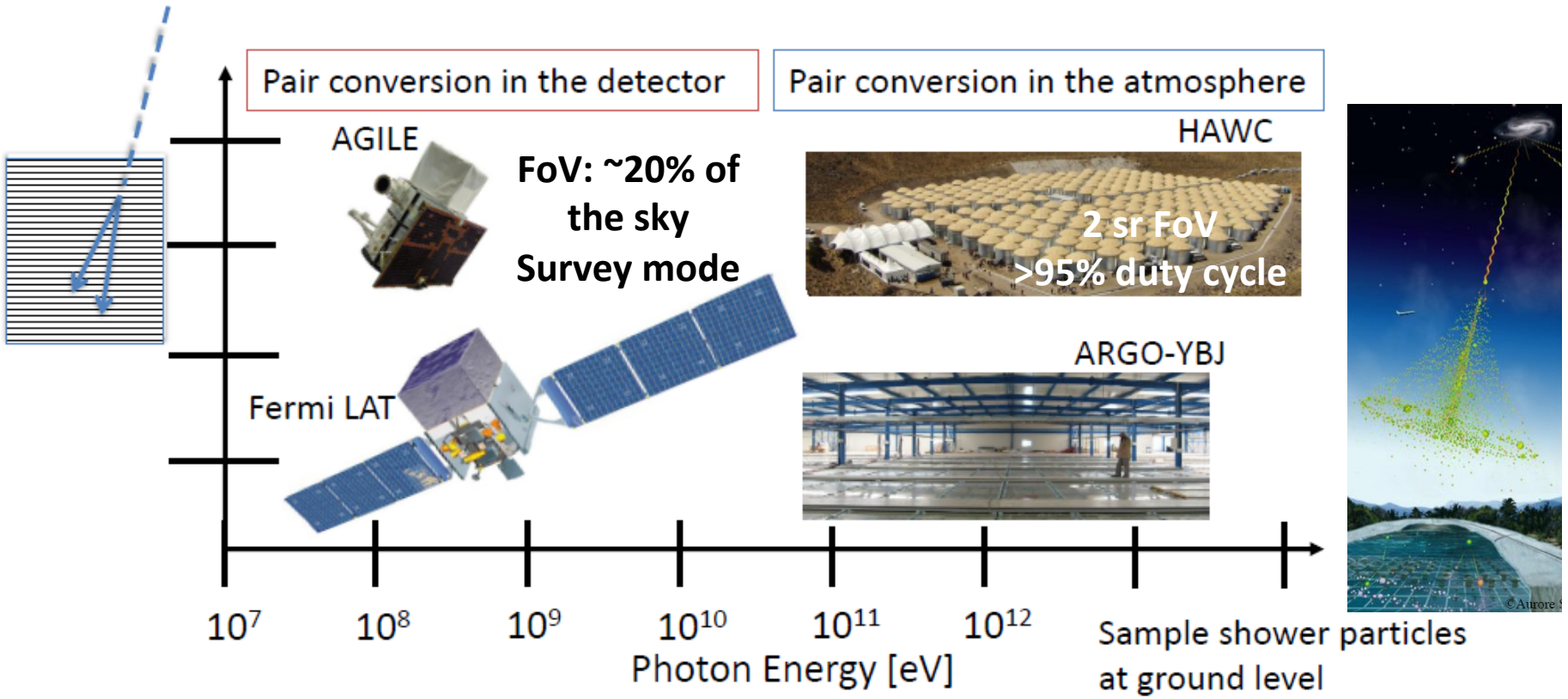
Outline

- The Current Players
- Surveying the GeV/TeV Sky
- Unraveling the Sources of Galactic Cosmic Rays
- Measuring the Diffuse Extragalactic Background Light
- Looking Ahead: CTA
- Conclusions

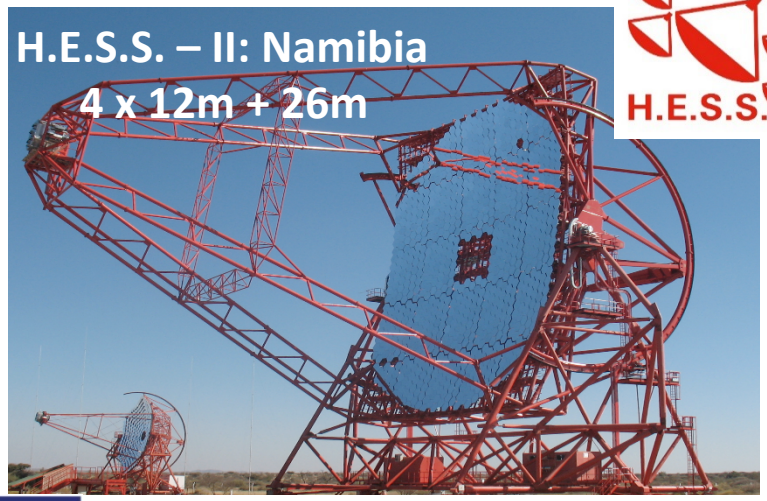
- (and more left out:)
- Pulsar Surprises
  - Crab pulsar flares (reconnection?), transitional pulsars, VHE pulsed emission, variable pulsars
  - Gamma Ray Bursts
  - Diffuse gamma-ray emission
  - Gamma-ray follow-up of IceCube neutrinos
  - Notable Absences: Clusters, GRBs, dSph's

Gamma-Ray Instruments: Wide Field

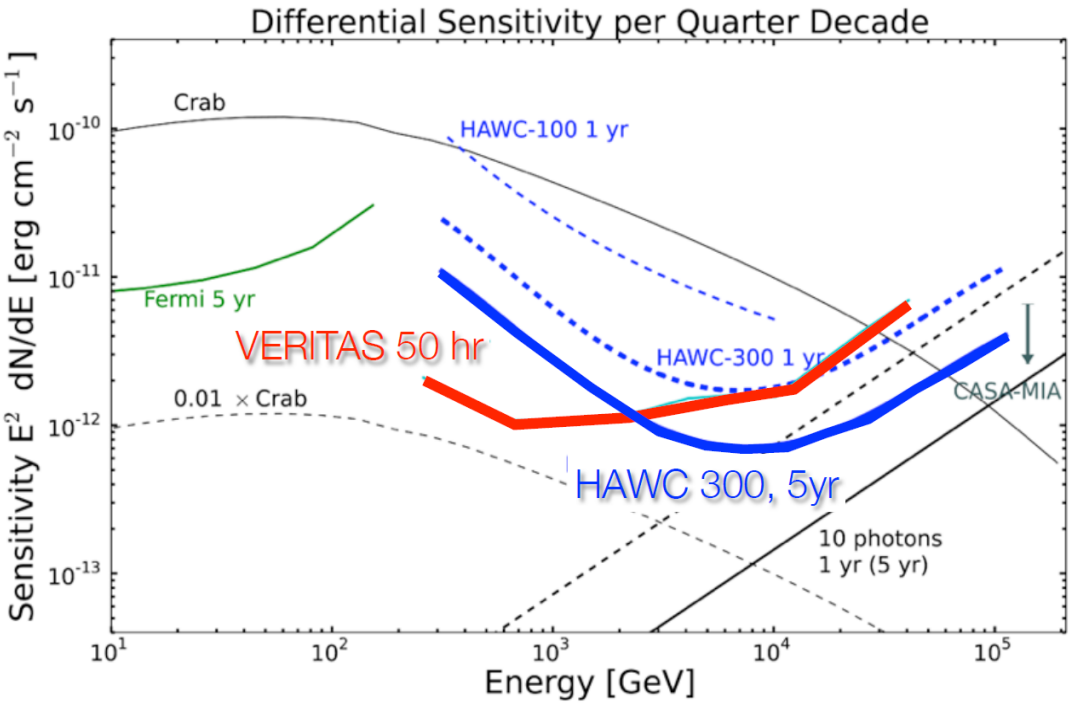


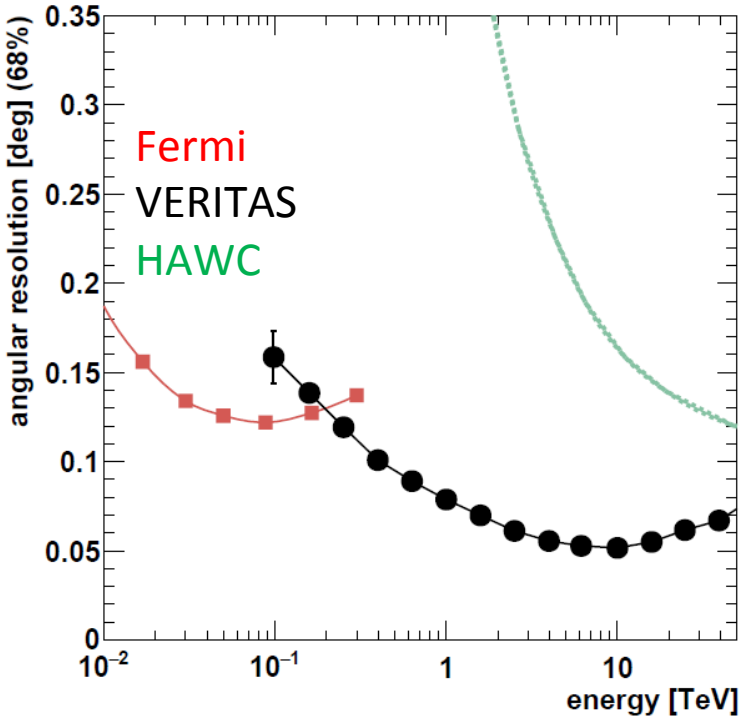
Gamma-Ray Instruments: Imaging

- Typical performance characteristics:
  - < 100 GeV - > 30 TeV
  - Angular resolution < 0.1° above 1 TeV
  - Energy resolution ~ 15%



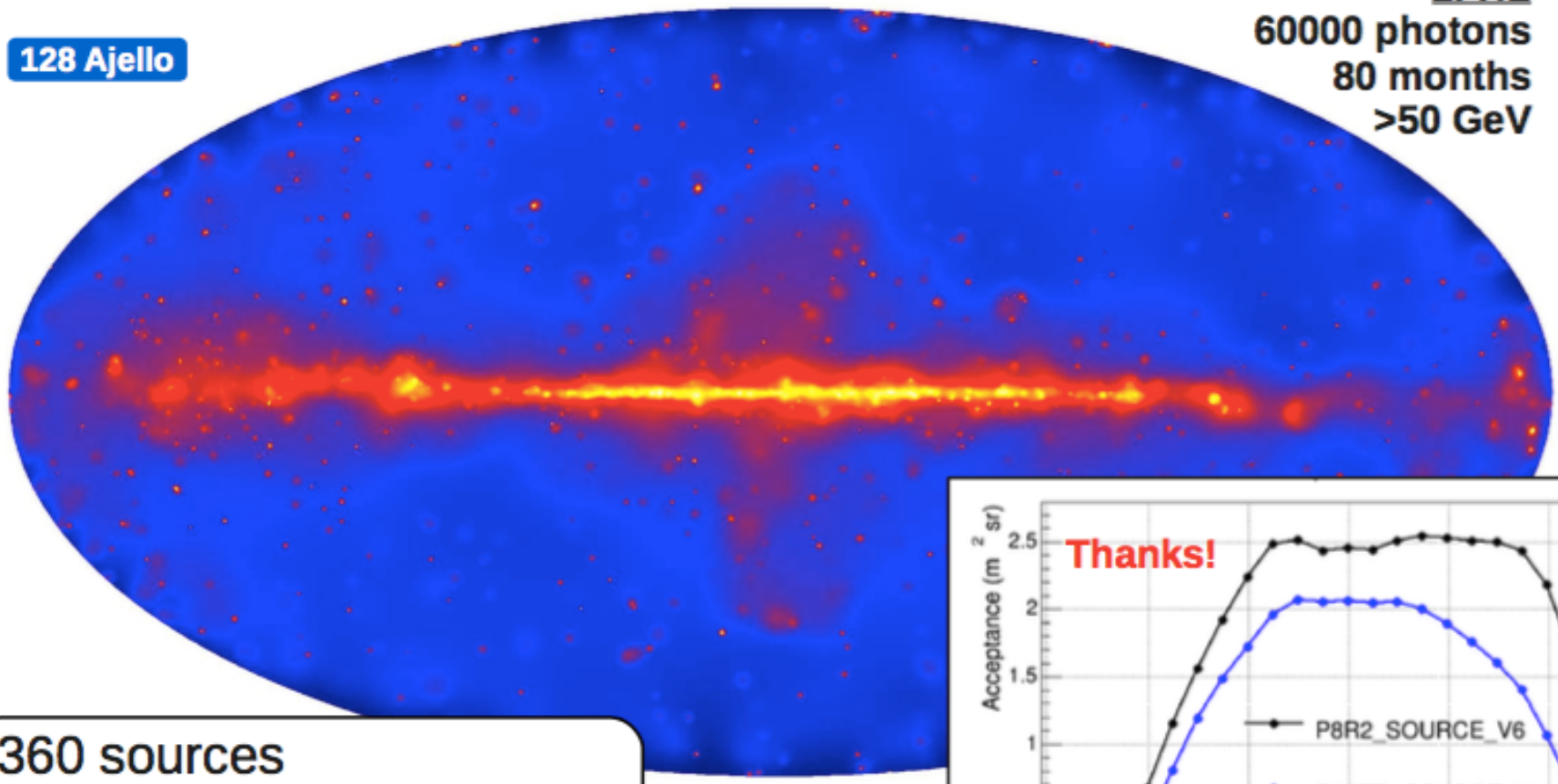
Sensitivity and Performance





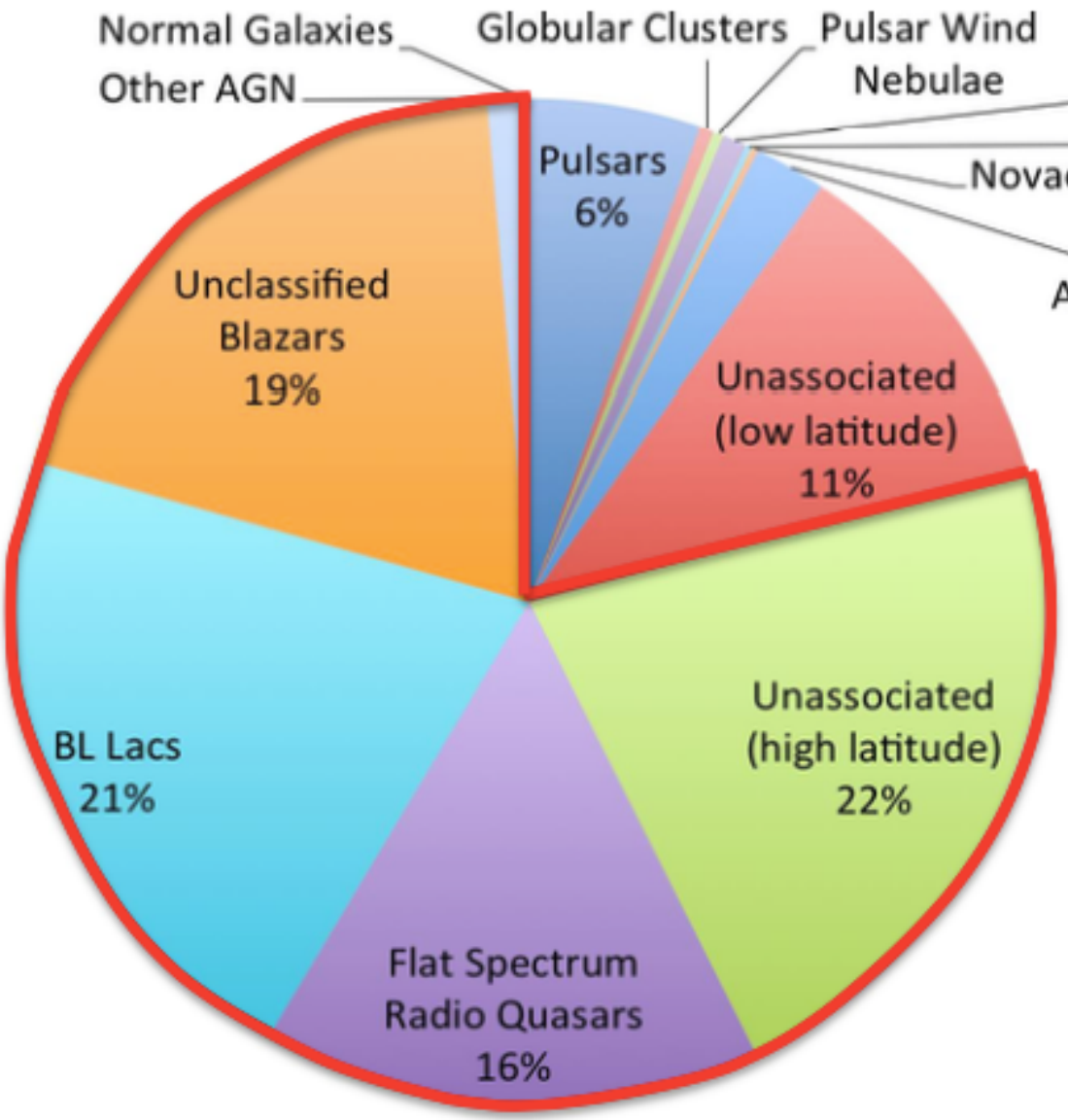
Surveying the GeV/TeV Sky

GeV Sky – Above 50 GeV



360 sources
78 detected also by IACTs
57 new sources

GeV Sky – 3FGL – Above 100 MeV



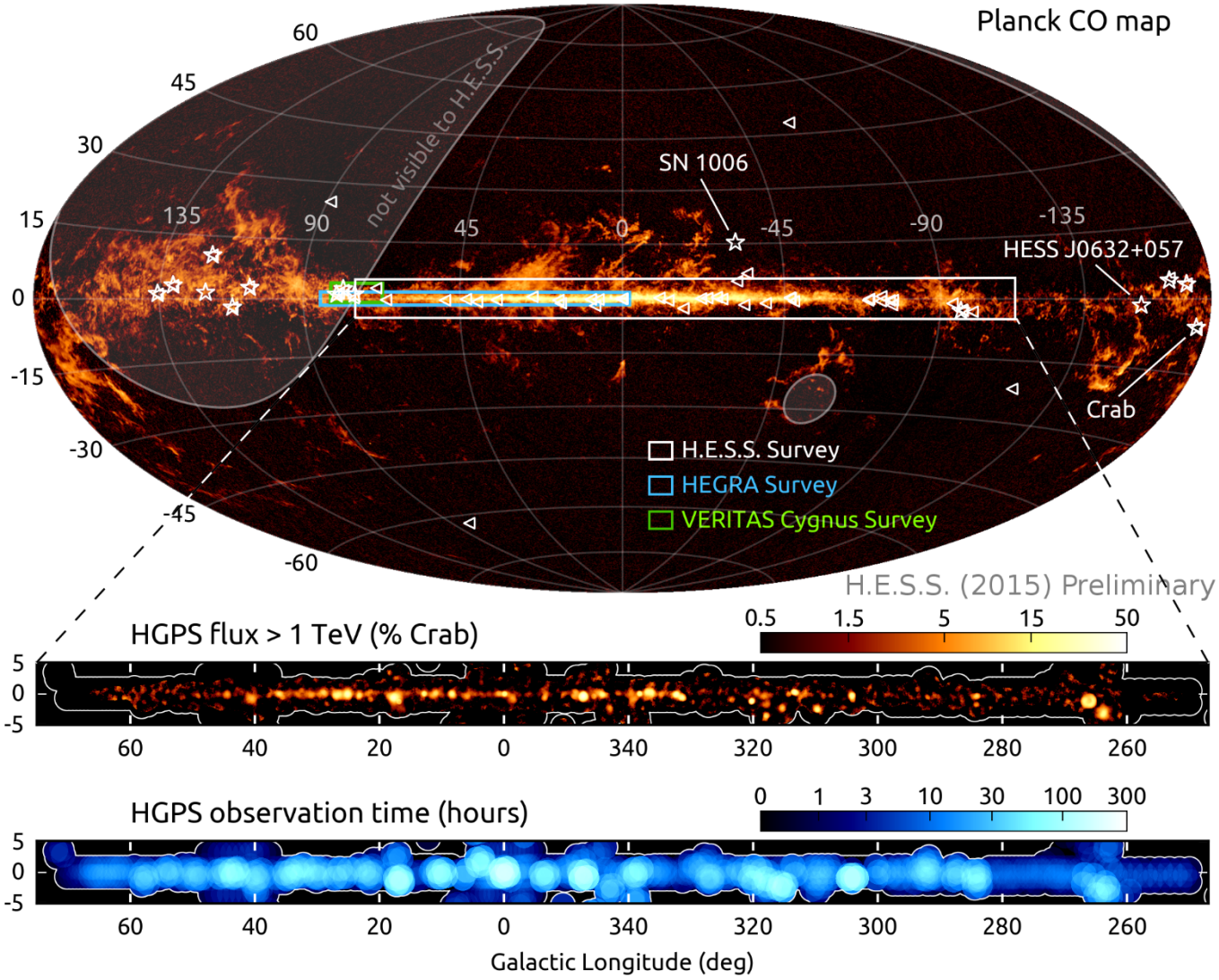
Liz Hays, ICRC 2015

>3033 sources
>100 MeV

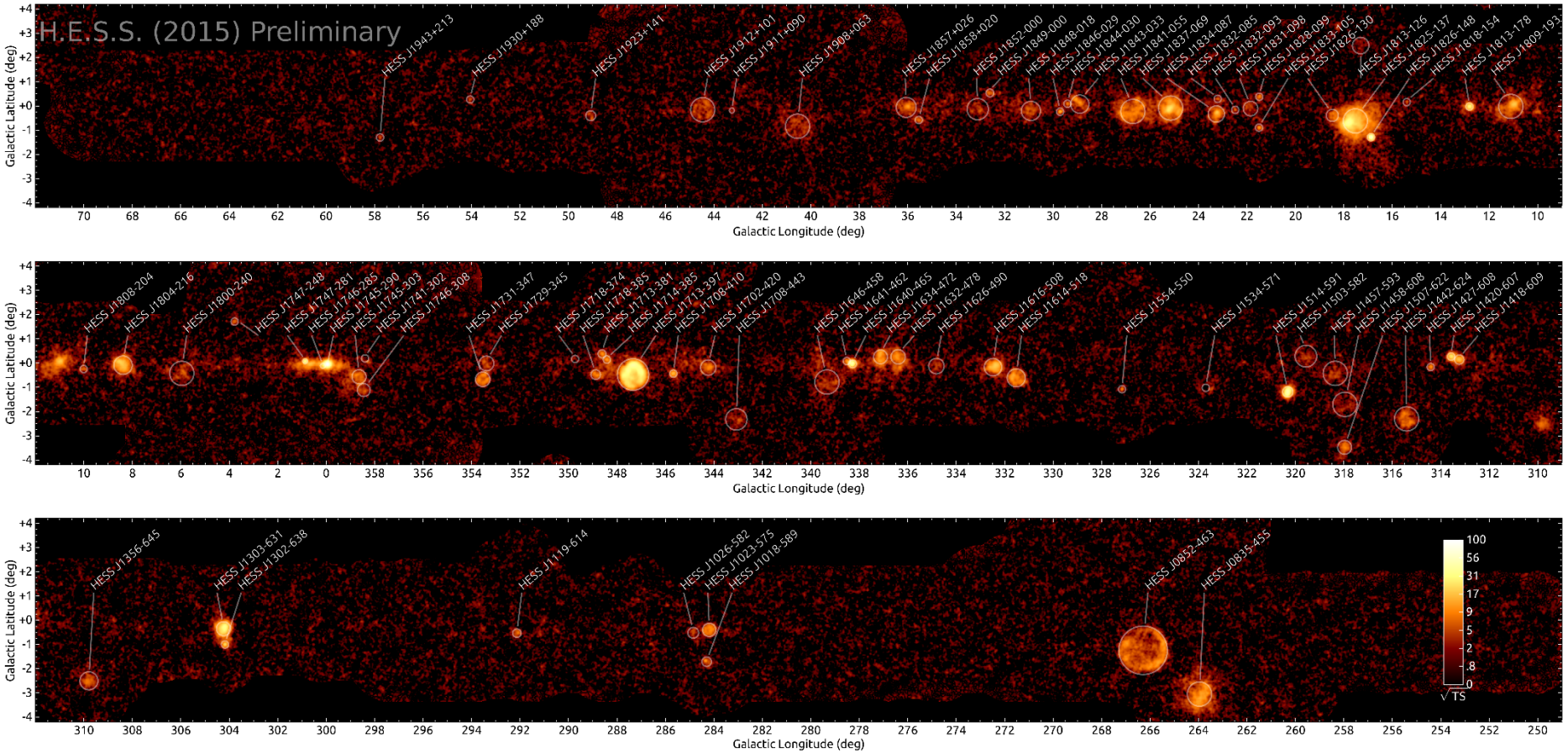
Based on 3FGL

H.E.S.S. Legacy Survey

- Major HESS project
- Data collected 2004 – 2013
- 2673 h after quality selection
- l in [-110°, 70°]
- b in [-5°, 5°]
- Inhomogeneous exposure (sources of particular interest)

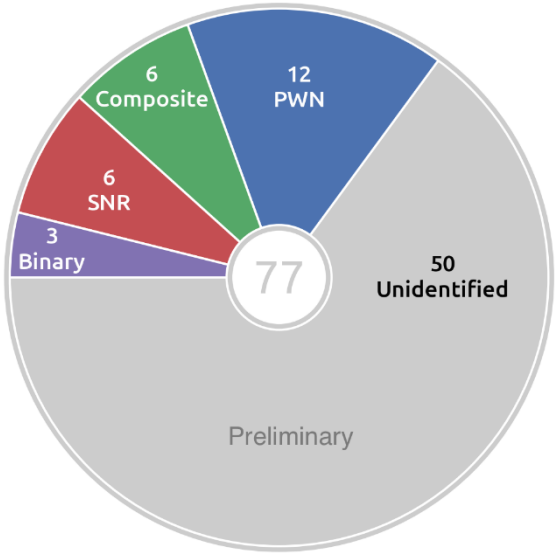


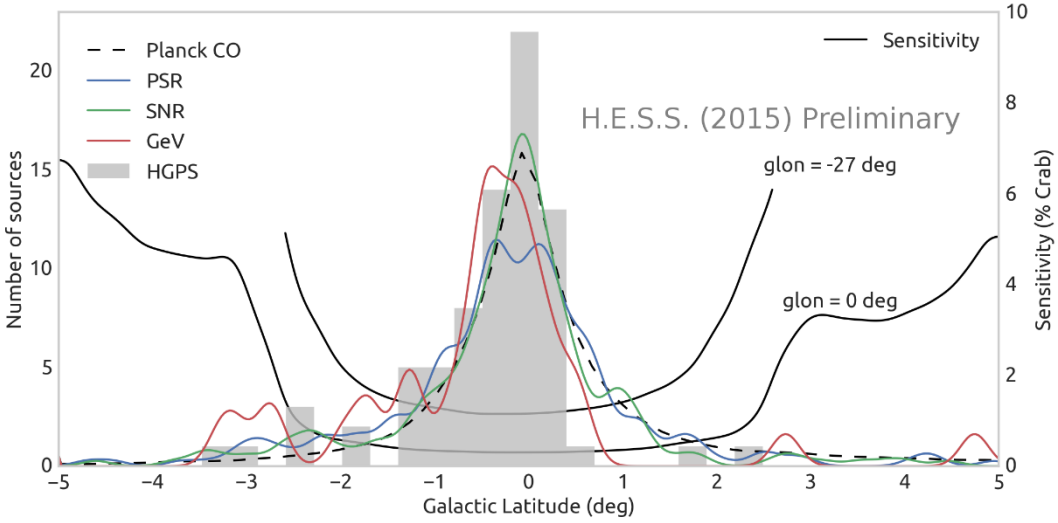
H.E.S.S. Legacy Survey – TS Map



H.E.S.S. Legacy Survey

- "Final" HESS catalog of survey sources
  - Data collected 2004 – 2013
  - 2673 h after quality selection
  - Significance and flux maps
  - Automatic pipeline for source extraction
  - Likelihood fit : Gaussian components plus diffuse background



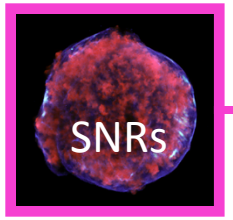


- 64 VHE sources + 13 complex sources (e.g. shell SNR) excluded from pipeline

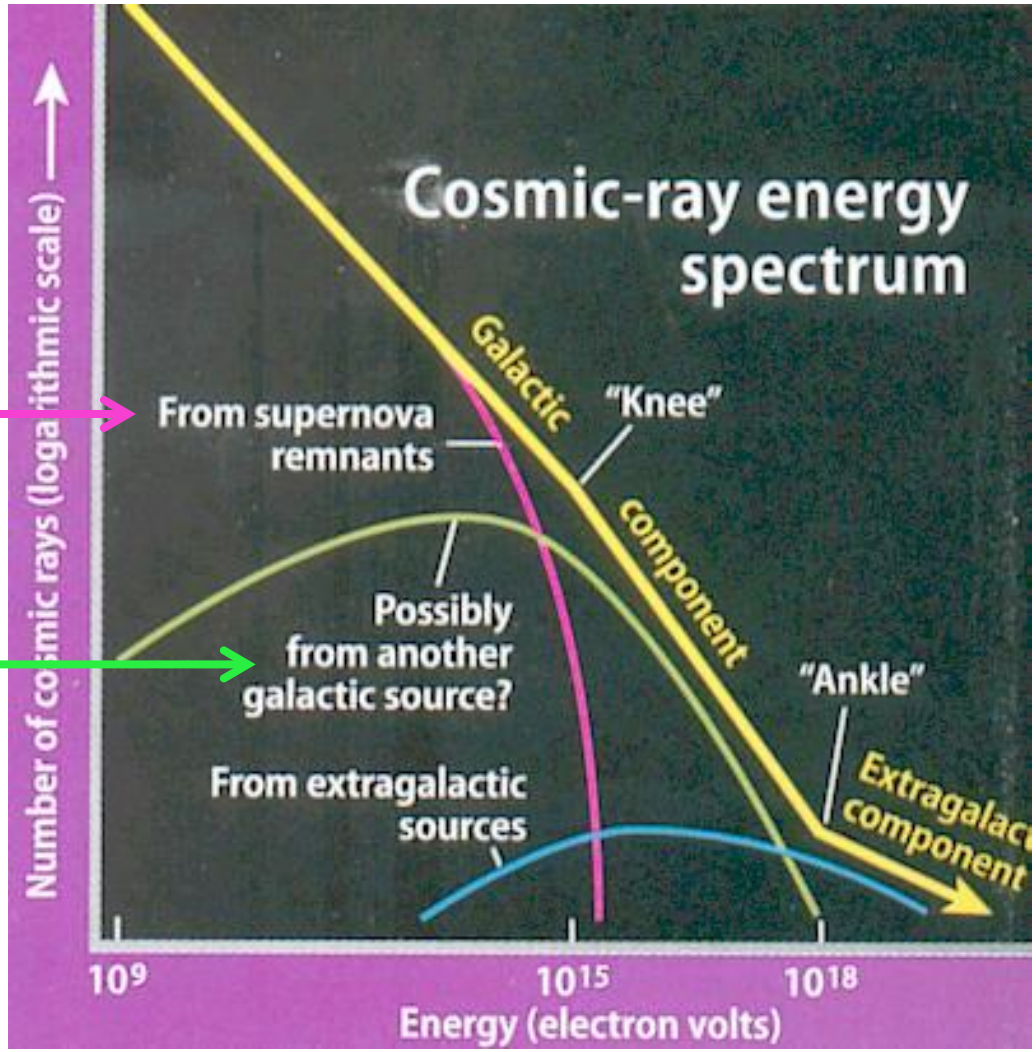
Unraveling the Sources of Galactic Cosmic Rays

Cosmic Ray Accelerators: What? Where?

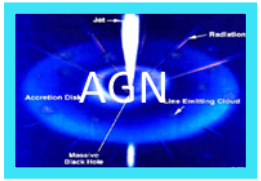
Superbubbles!



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

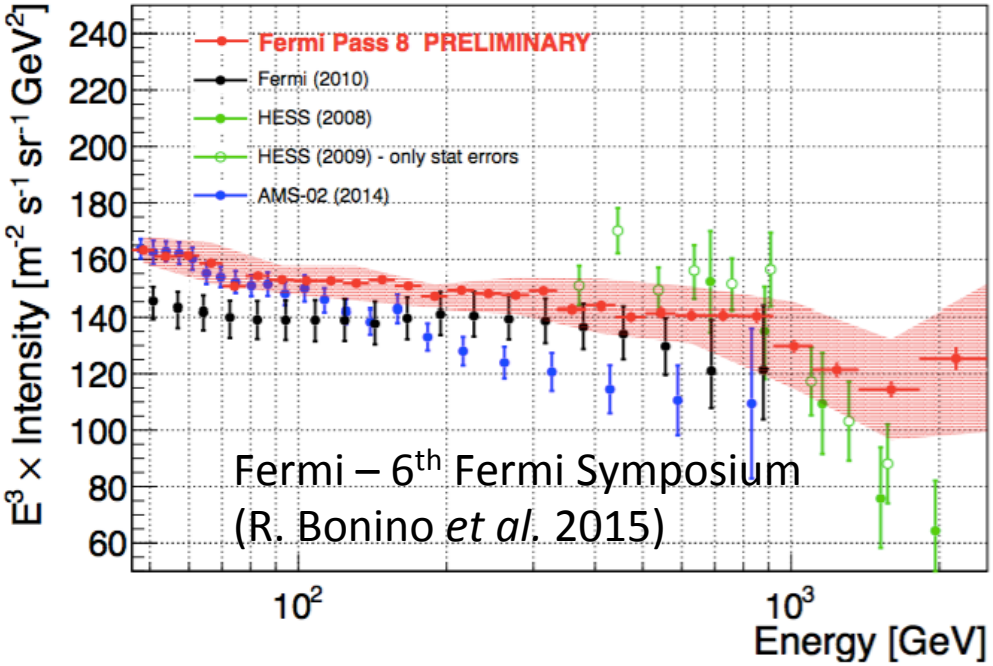


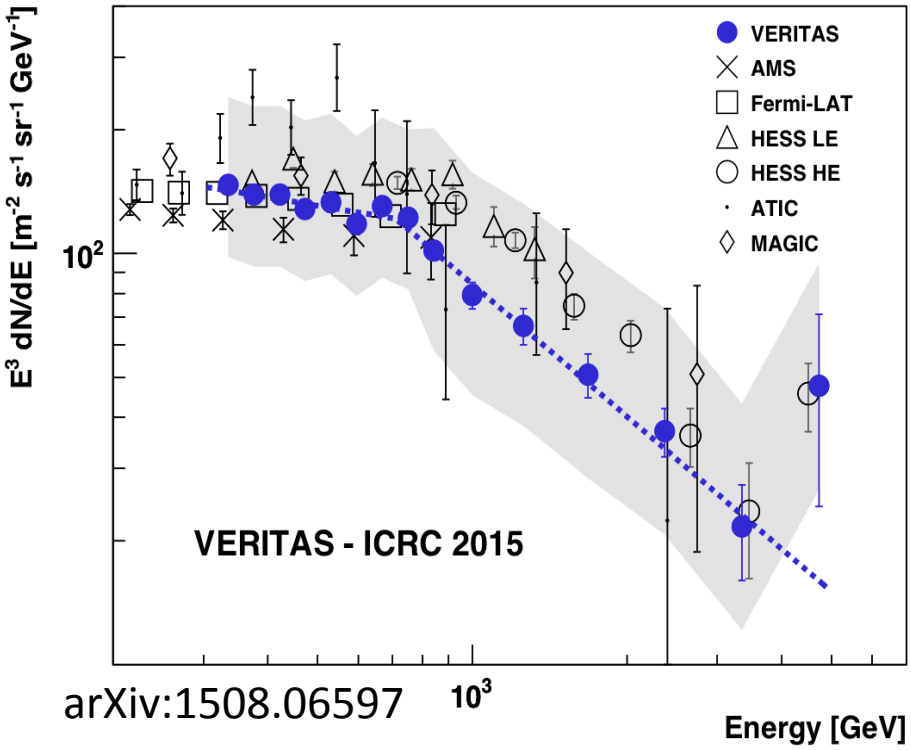
Gamma ray bursts



Cosmic Ray Electrons

Cosmic-ray electrons at TeV energies are a direct probe of nearby (~1kpc) accelerators



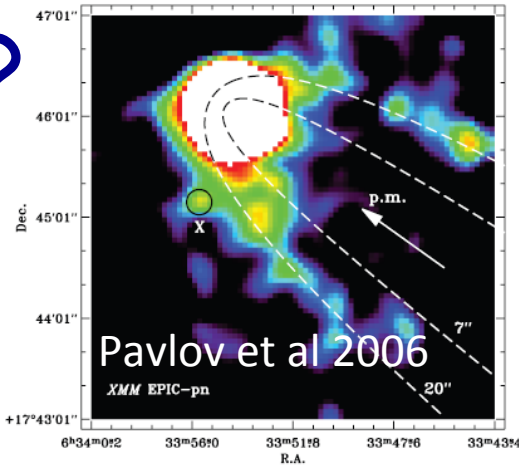


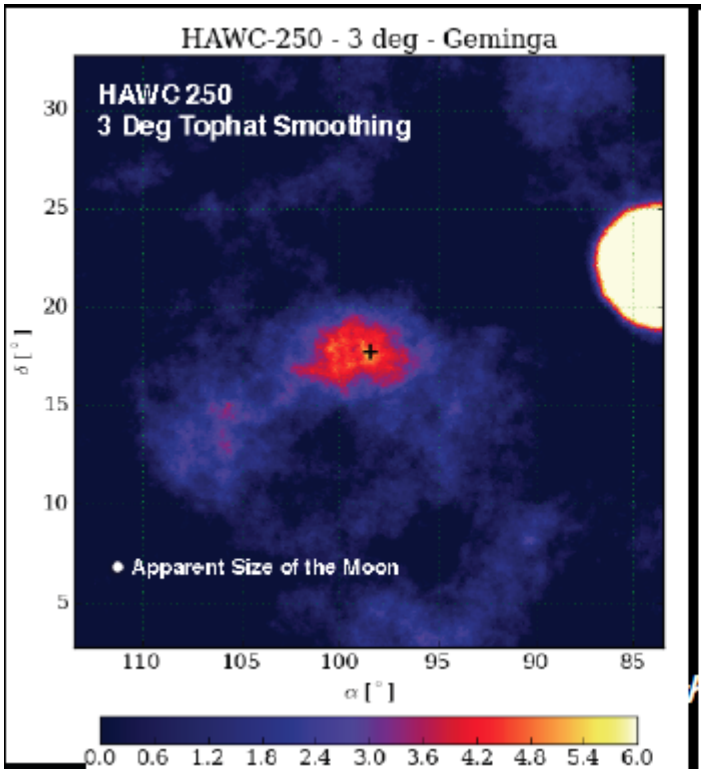
- VERITAS spectrum agrees qualitatively with other experiments within systematic uncertainty
  - Break at 710 ± 40 GeV
  - Index below (above) break of $-3.2 \pm 0.1_{STAT}$ $(-4.1 \pm 0.1_{STAT})$

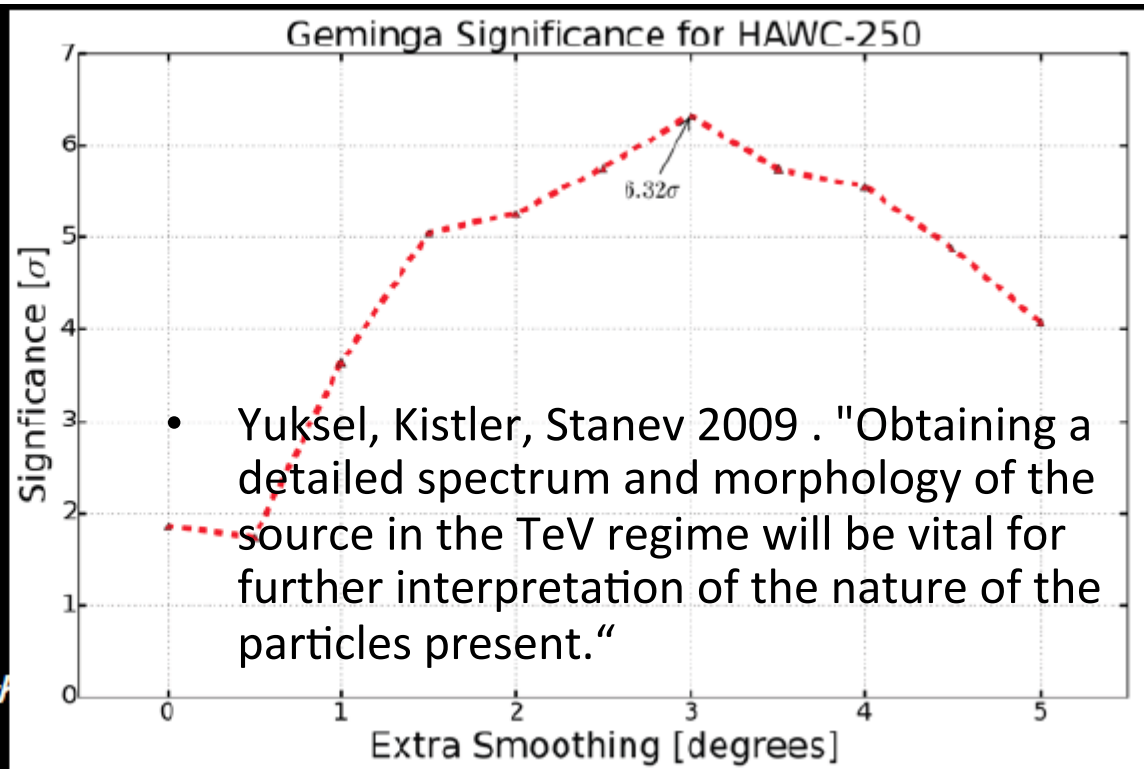
- Confirms evidence of at least one nearby CR electron emitter
- Second high-statistics measurement of a break below ~1 TeV

Geminga – A Nearby $e^{\pm}$ Source?

- 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 by HAWC.



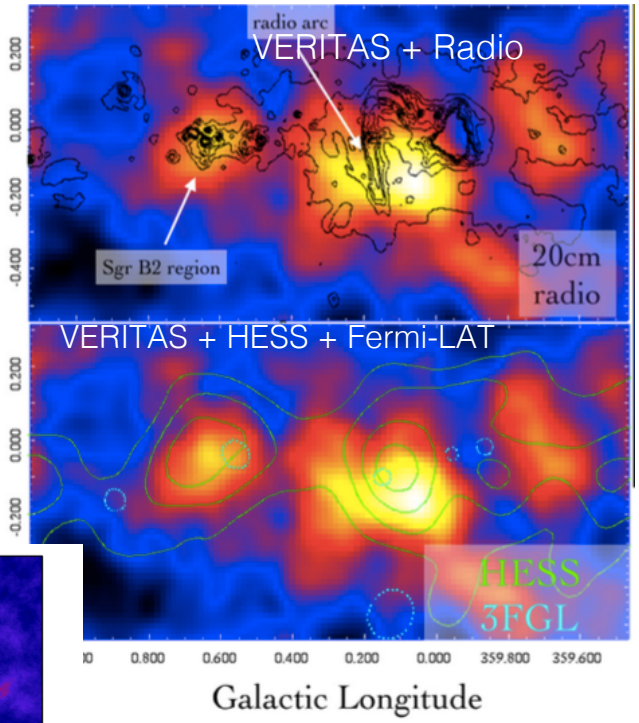


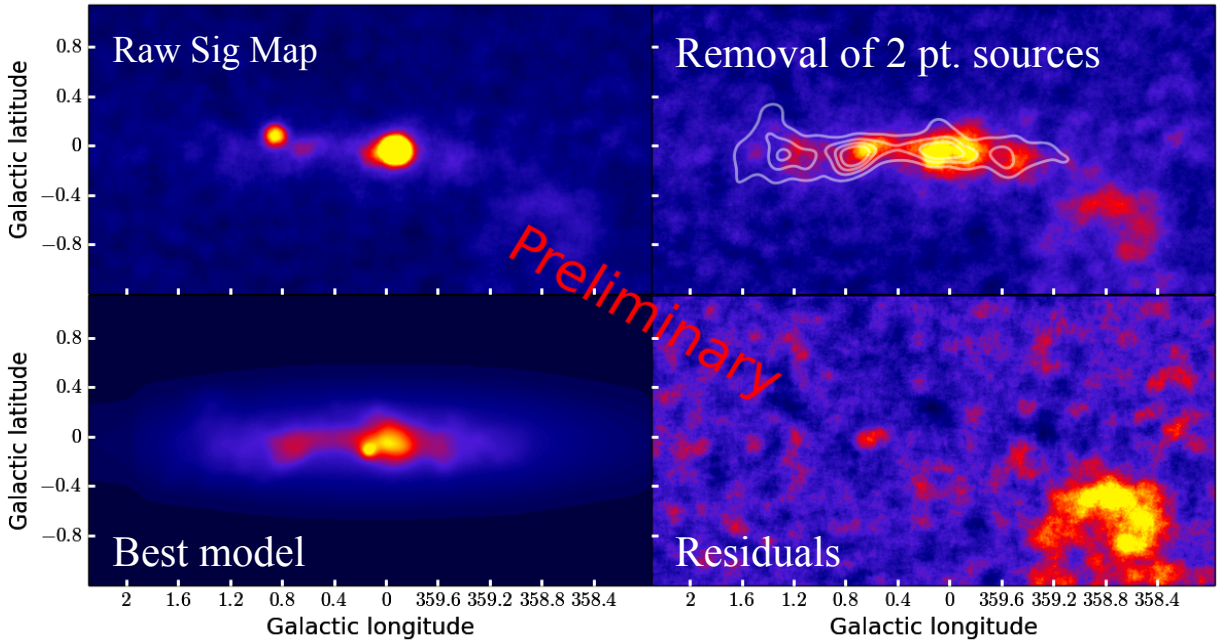


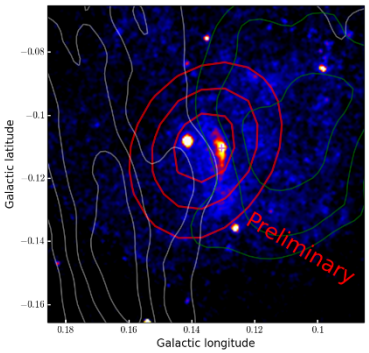
- Yuksel, Kistler, Stanev 2009 . "Obtaining a detailed spectrum and morphology of the source in the TeV regime will be vital for further interpretation of the nature of the particles present."

Galactic Center

- Complex morphology
  - VERITAS: correlation with radio, 3FGL & HESS
  - MAGIC observations at high zenith angle
  - HESS: Deep observation (250h) + Max. Likelihood
    - Diffuse emission (interaction of CRs with Molecular clouds)
    - Detection of Arc Source (HESS J1746-285) above CMZ contribution (likely PWN)

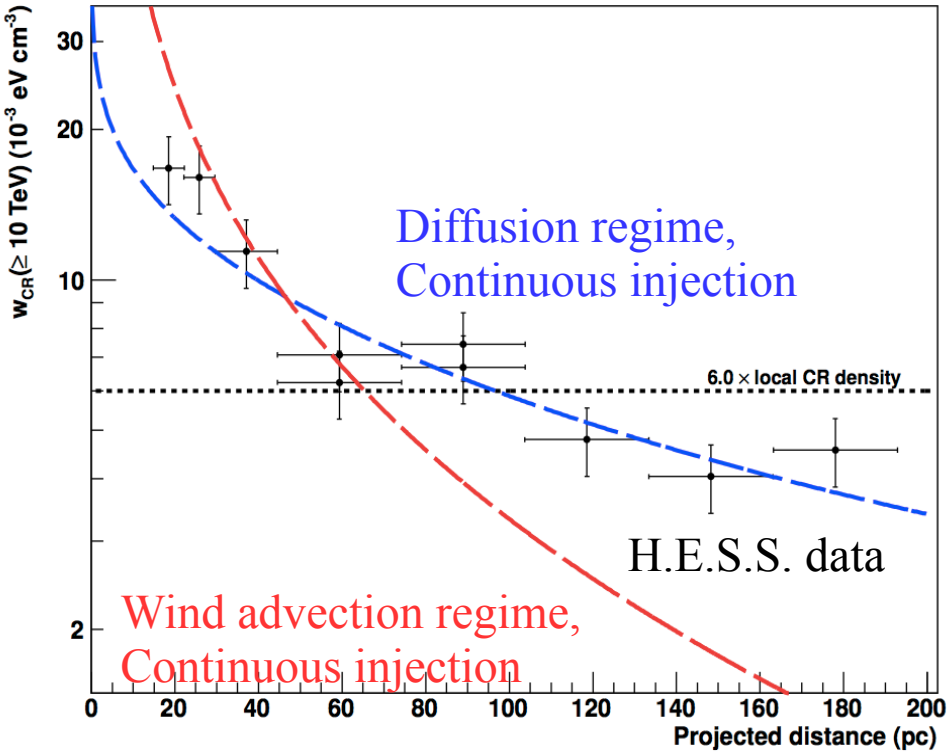


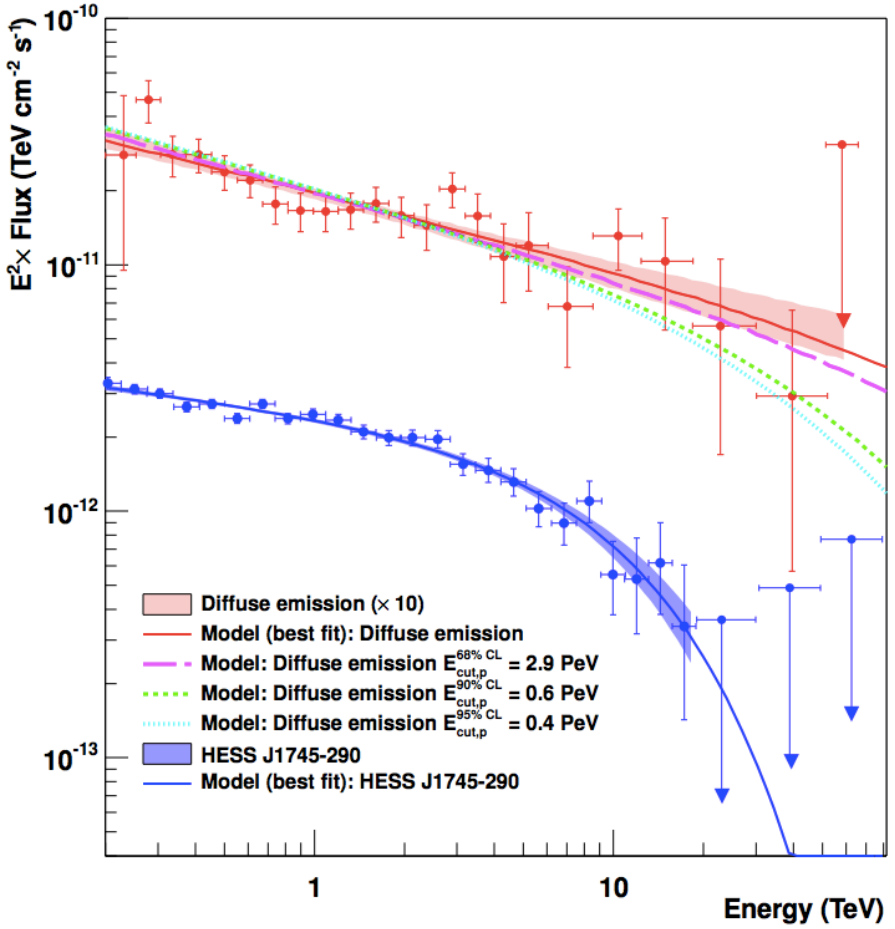




Galactic Center with H.E.S.S.

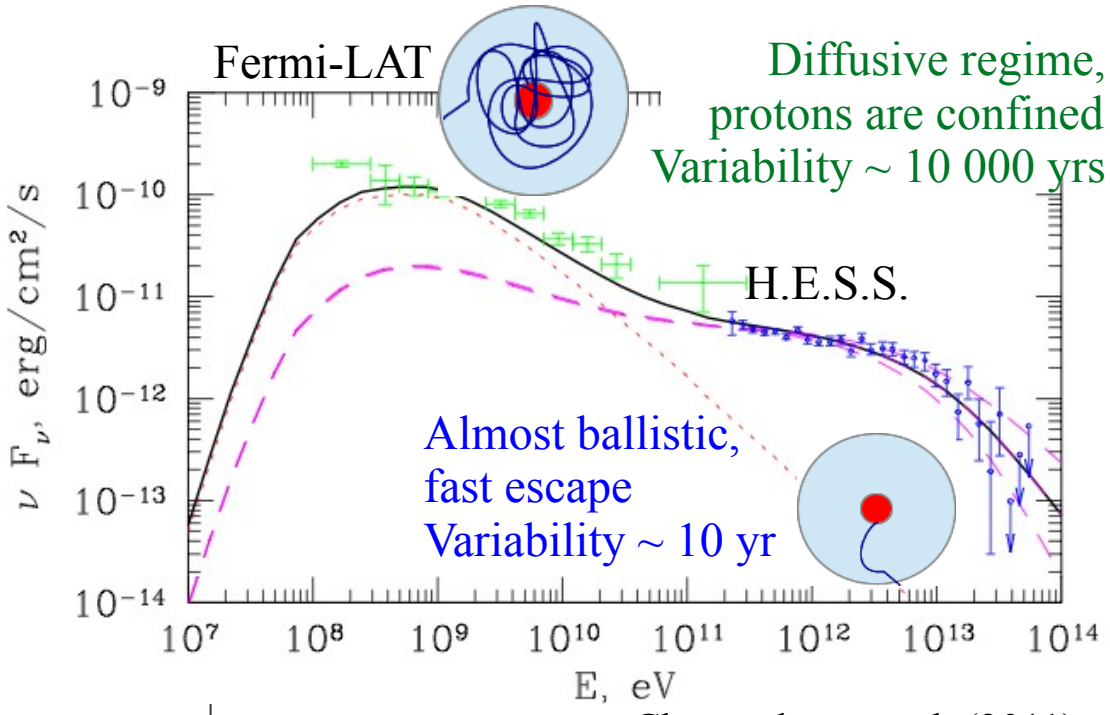
- Central source: cut-off @ 10 TeV
- Diffuse emission shows no cut-off well > 10 TeV
- Emission likely due to propagation of protons accelerated around central black hole and diffusing away (projected radial distribution matches)
- Parent proton population up to 1 PeV (2.9 PeV @ 68% CL)



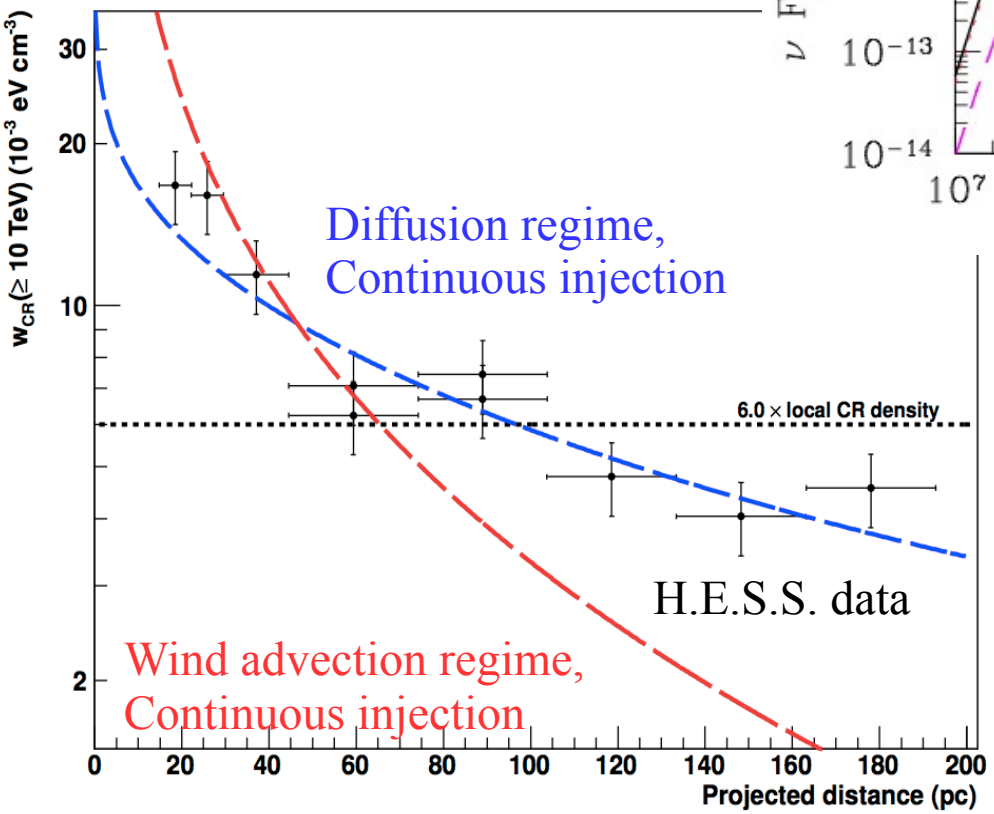


Cosmic Rays Diffusing Away from GC

Projected radial density of CRs indicates diffusion regime



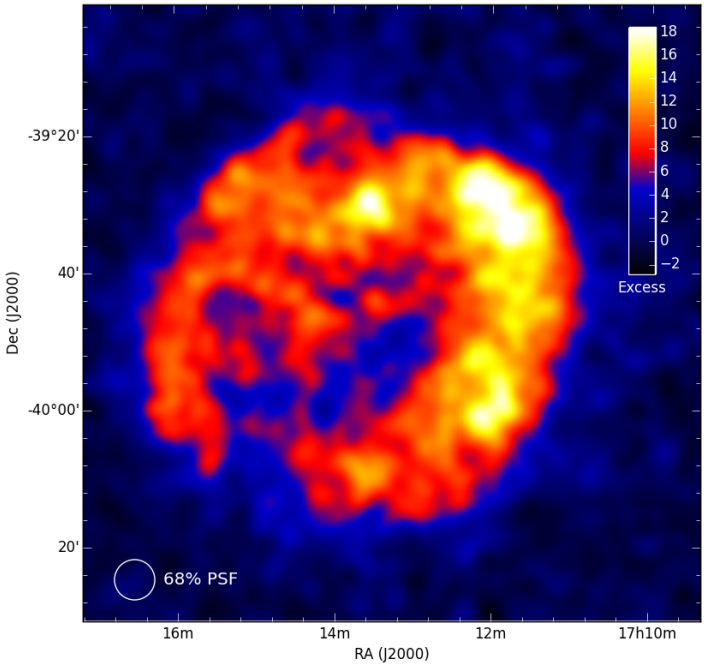
Chernyakova et al. (2011)

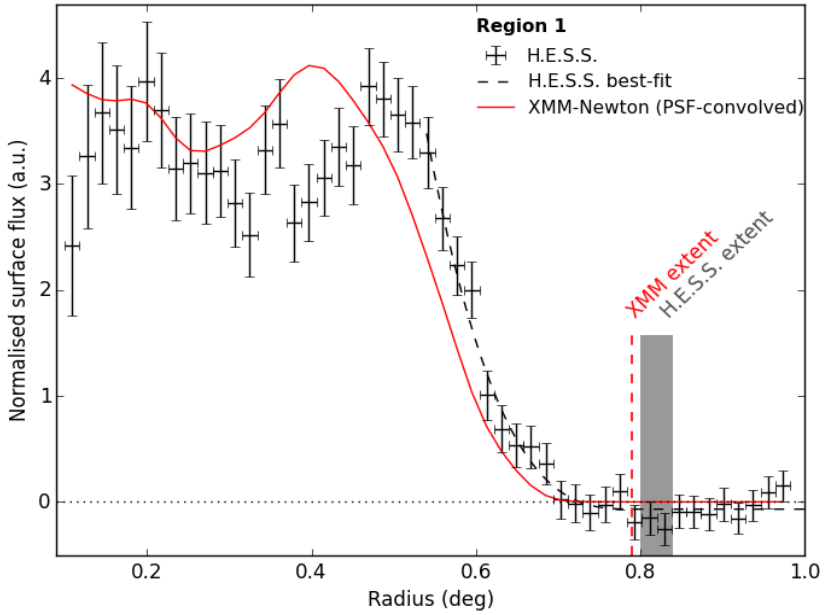


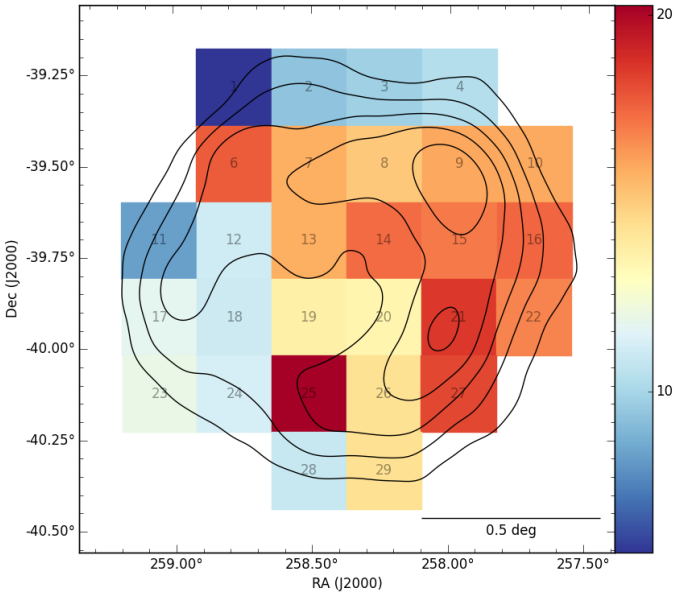
Spectro-Imaging of RX J1713-3946

10 years of H.E.S.S. data

- Factor 2 improvement in statistics
- Spatially resolved spectra
- Difference in X/γ radial profiles: Particle escape and/or B field geometry
- VHE astronomy can probe acceleration regions!



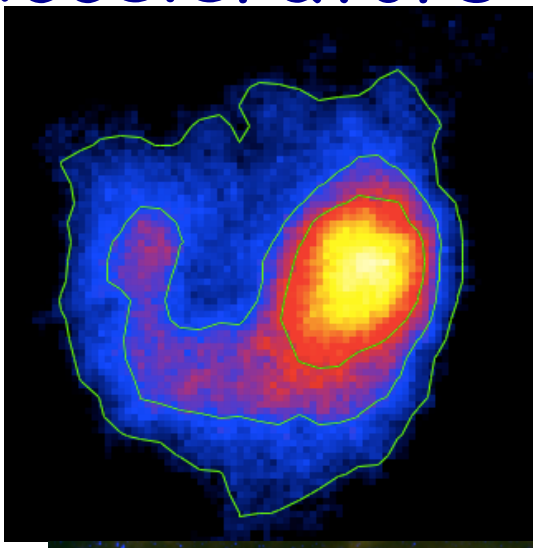


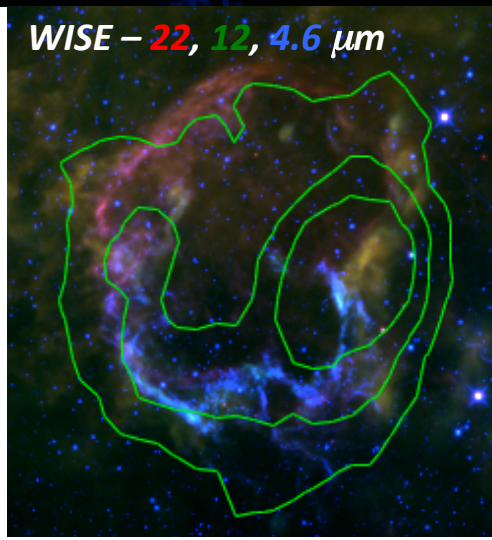


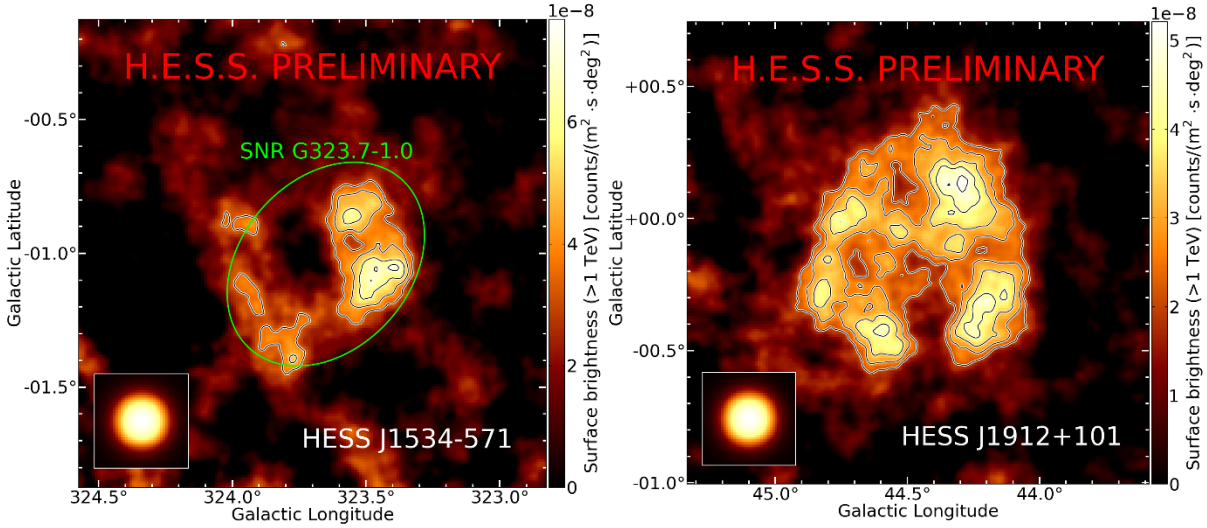
B Field Map

SNRs: More Shells & Hadronic Accelerators

- IC 443 shell resolved by VERITAS
  - Spectra from different regions probe the environmental dependence of cosmic-ray diffusion
  - Evidence for hadronic acceleration in old SNRs
- New shell-type SNRs resolved by HESS
  - HESS J1534-471 & HESS J1912+101
  - Shell identification (RCW 86)

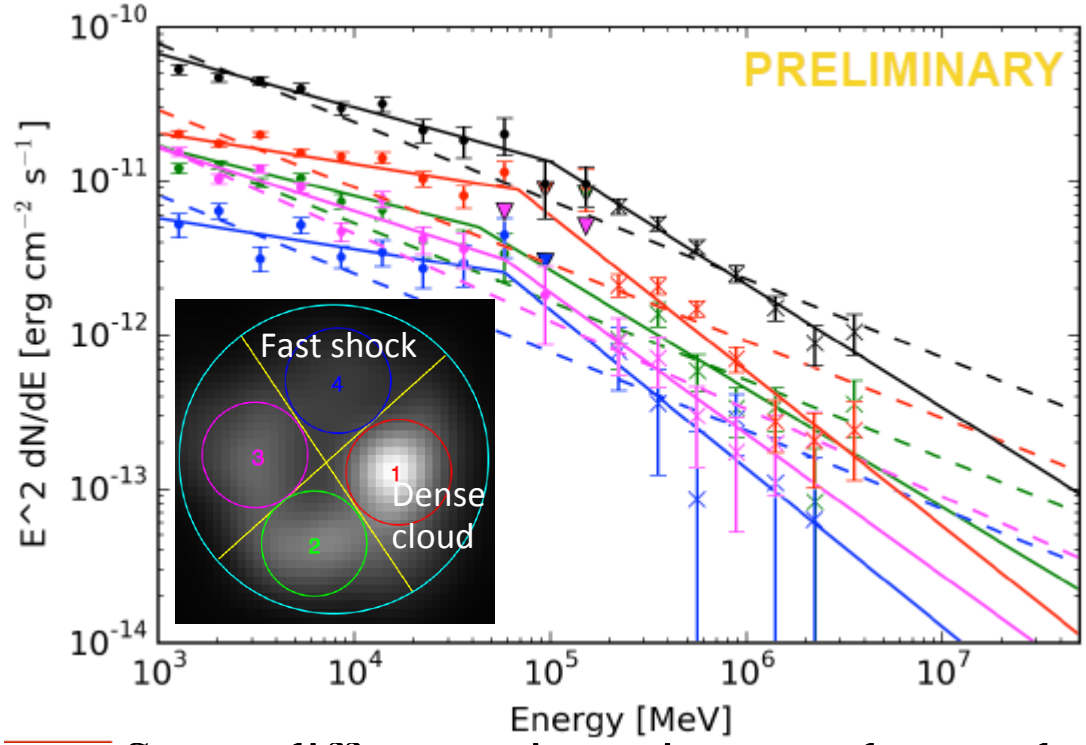


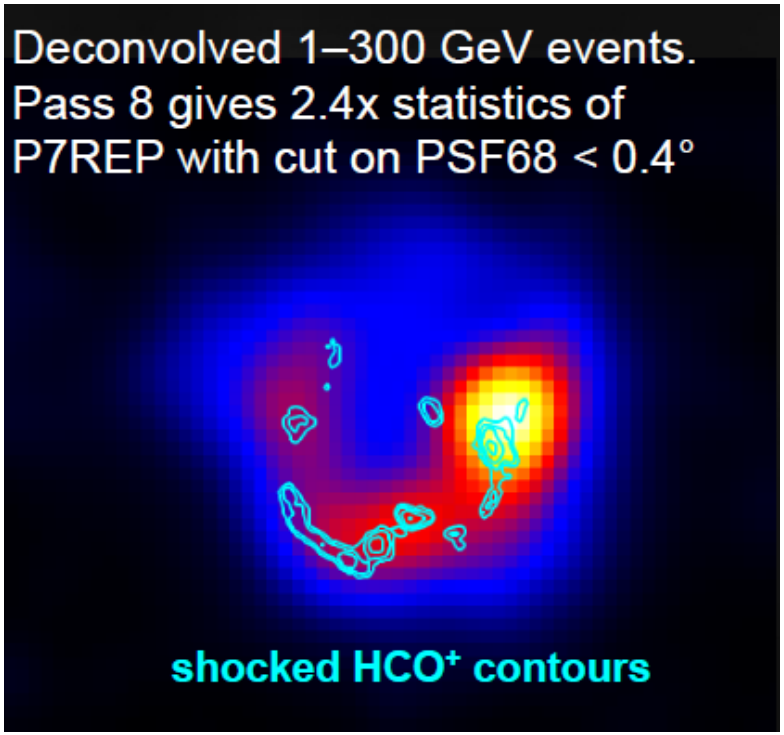




IC 443: Spatially Resolved Spectra

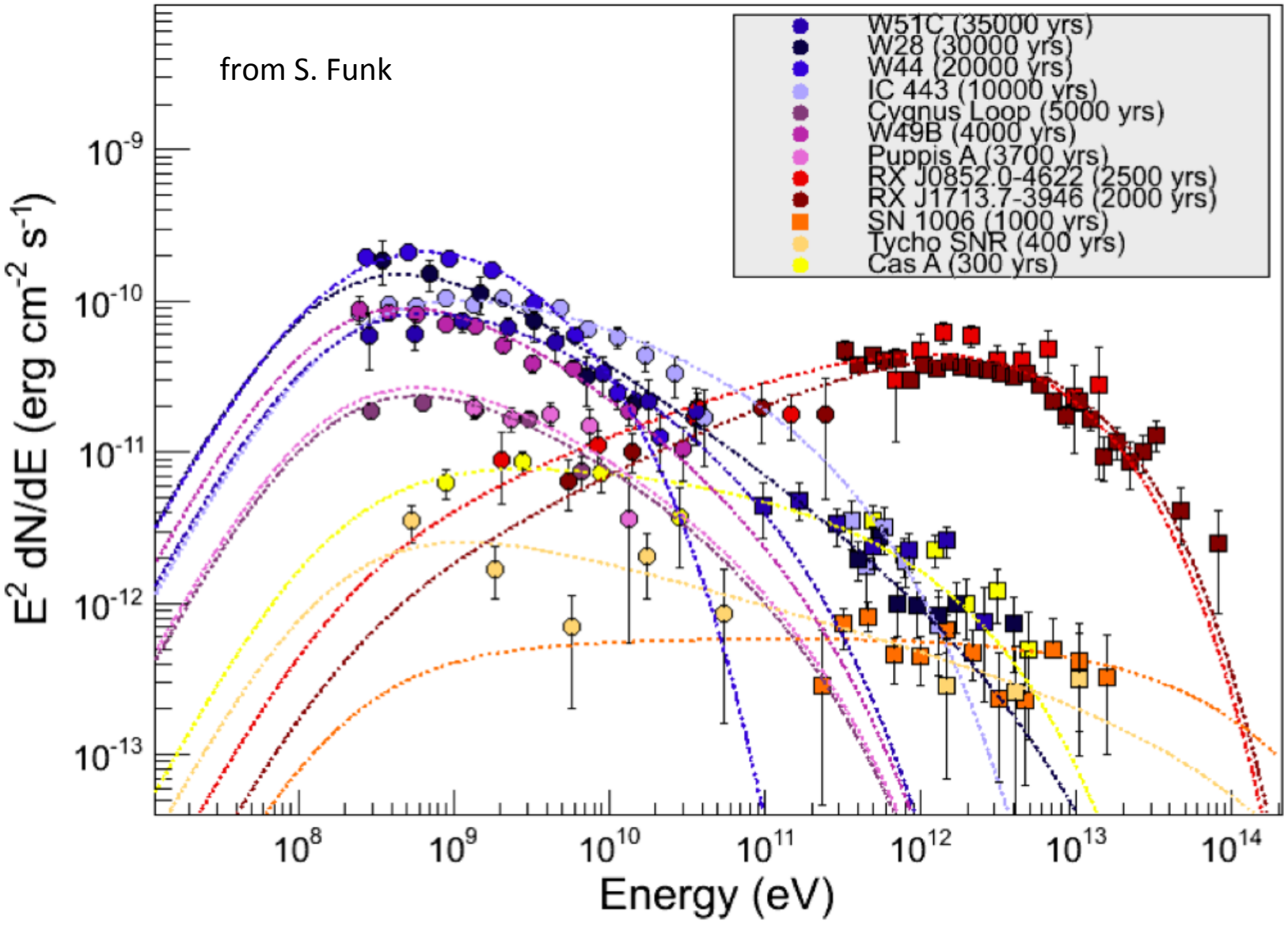
- Broken PL fits for all regions :Γ_1~2.3, Γ_1~2.9, break energy ~ 60 GeV





- 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.

Growing Sample: Evolution of SNRs



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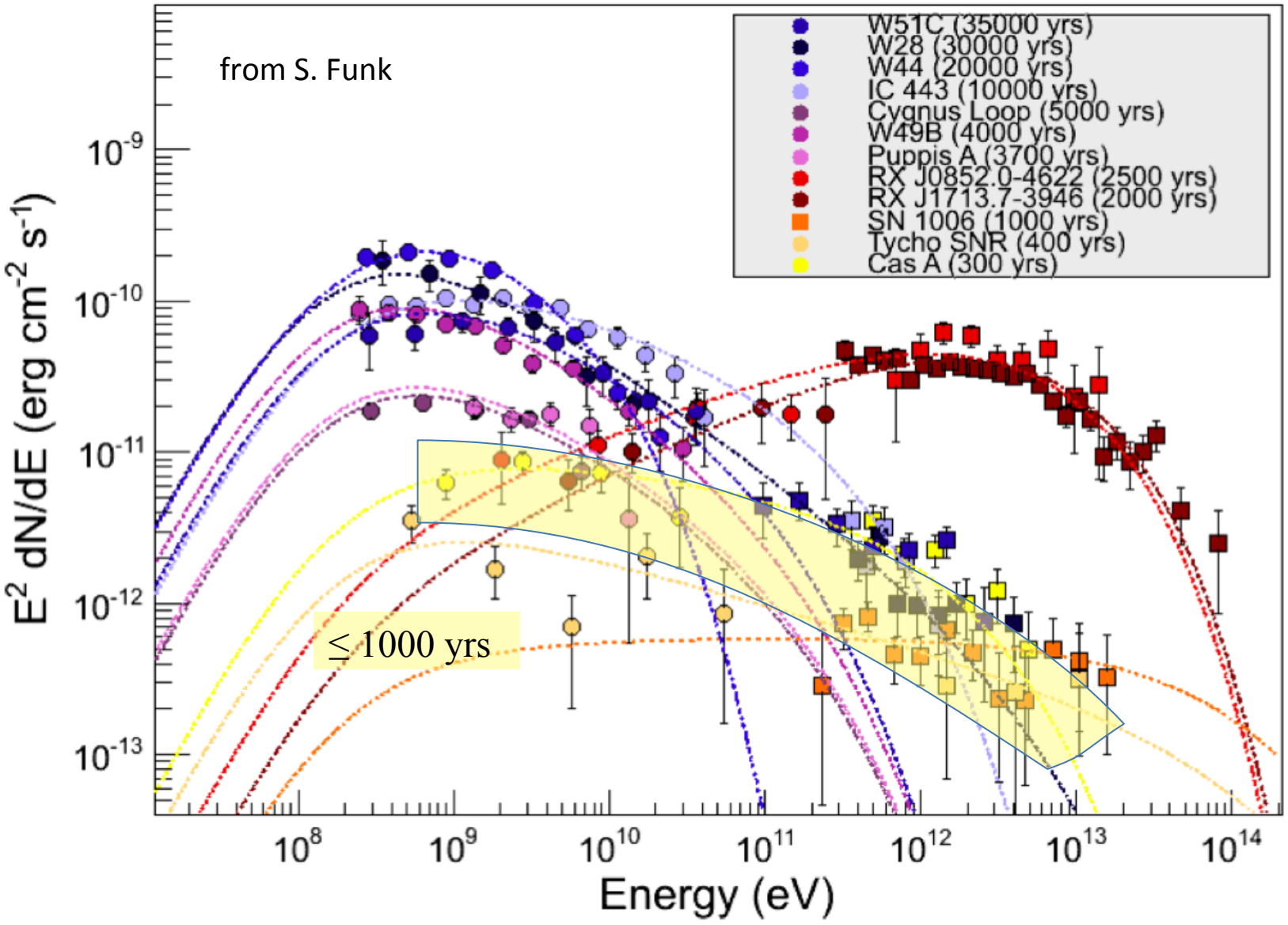

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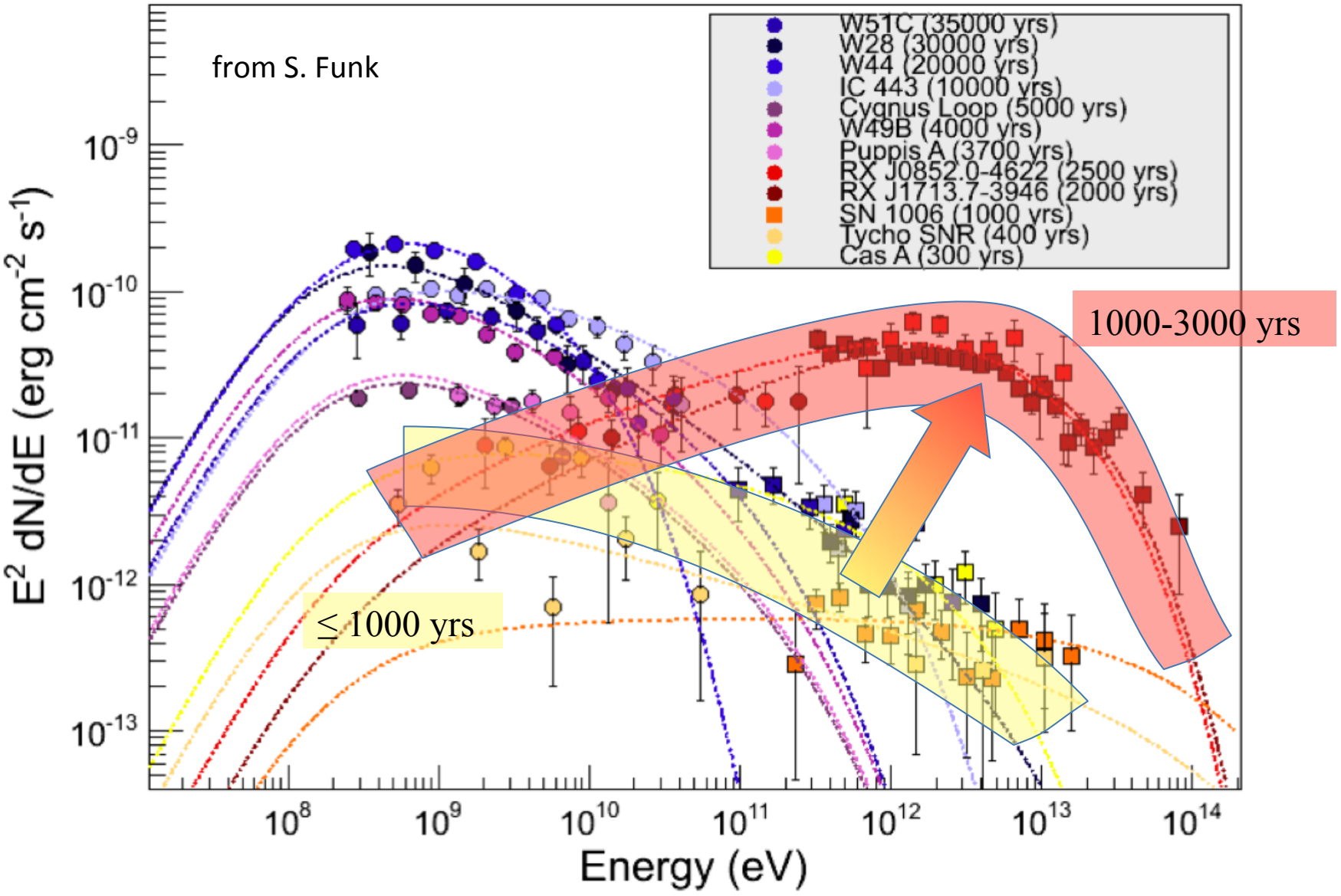

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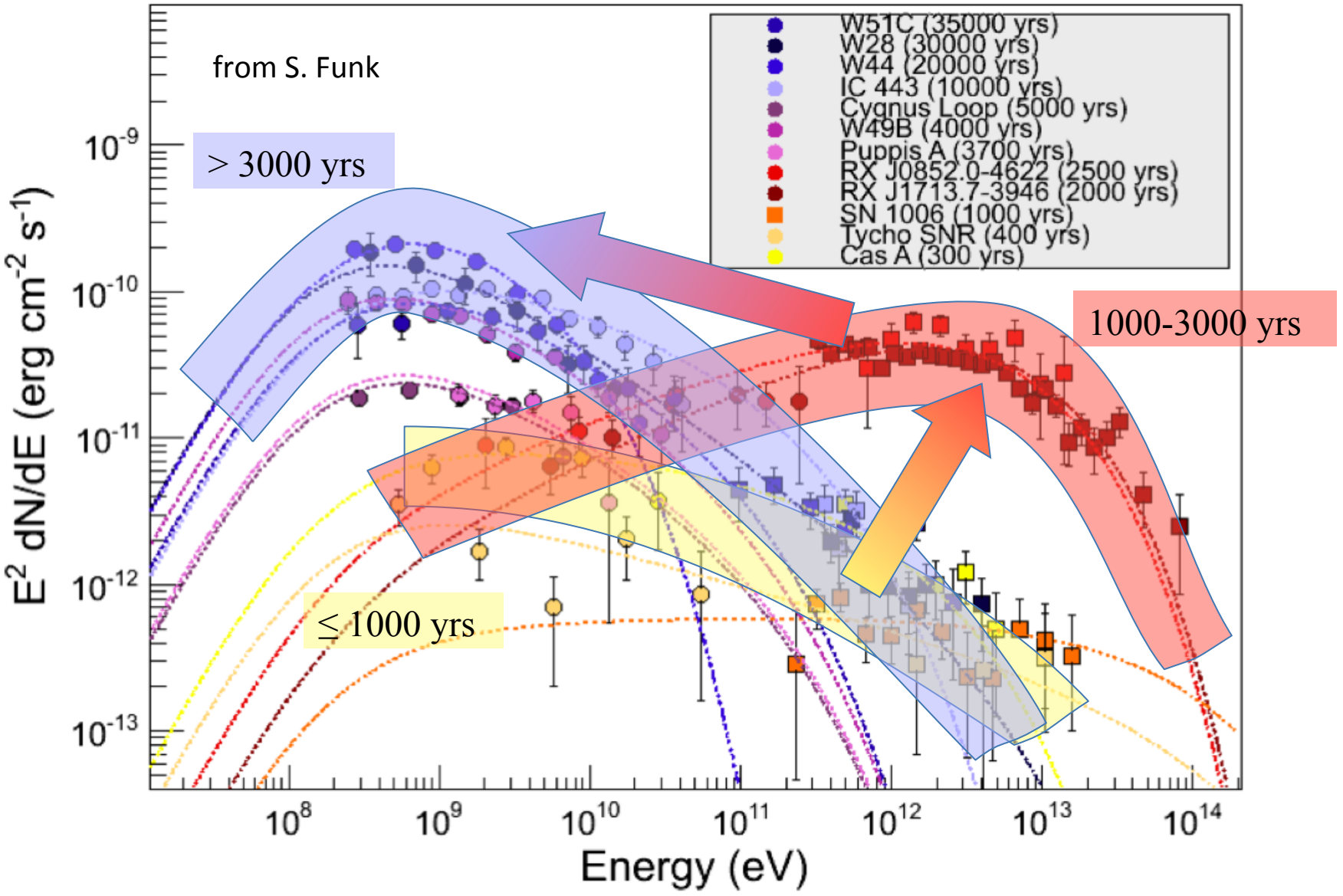
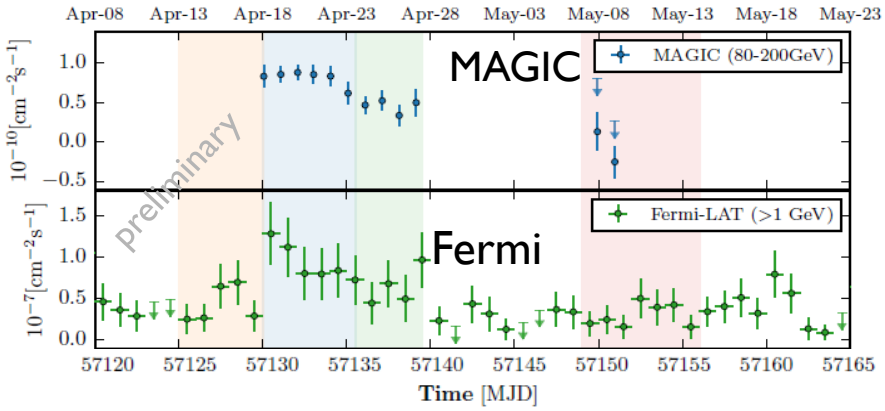
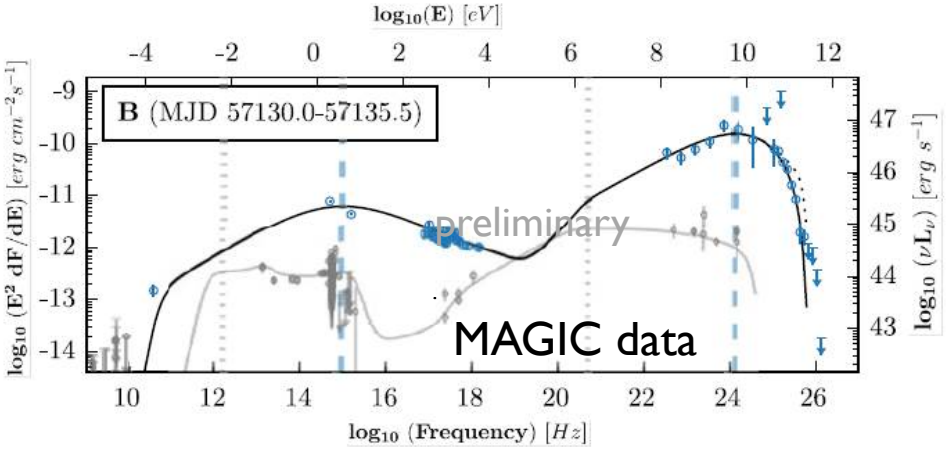


Diffuse Extragalactic Light

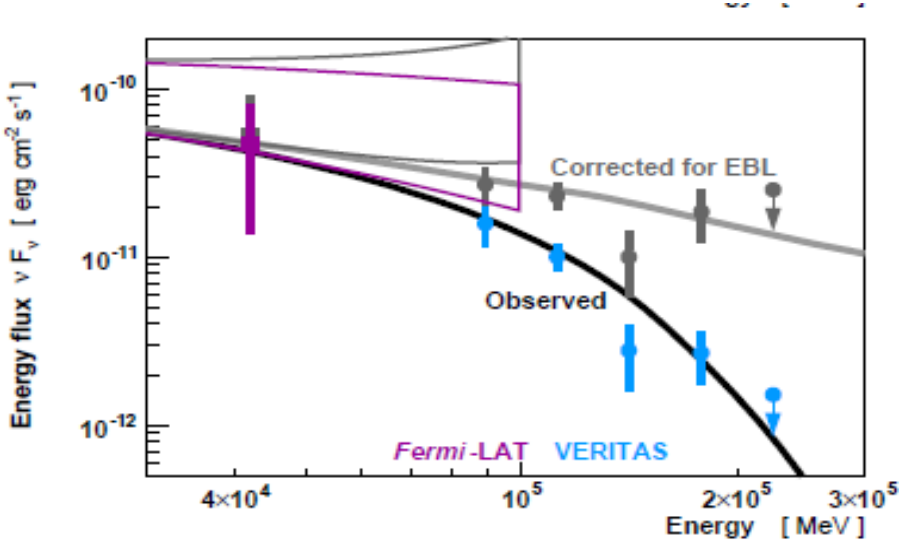
… and more from beyond the Galaxy

A quasar half a Universe away: PKS 1441+25 @ z = 0.939 !





- FSRQ @ z = 0.939
- MAGIC detection @ 25 σ
- VERITAS Confirmation
  - Up to 200 GeV
  - ~400 GeV accounting for z!
- Stringent constraints on the EBL < 1 μm from a single source



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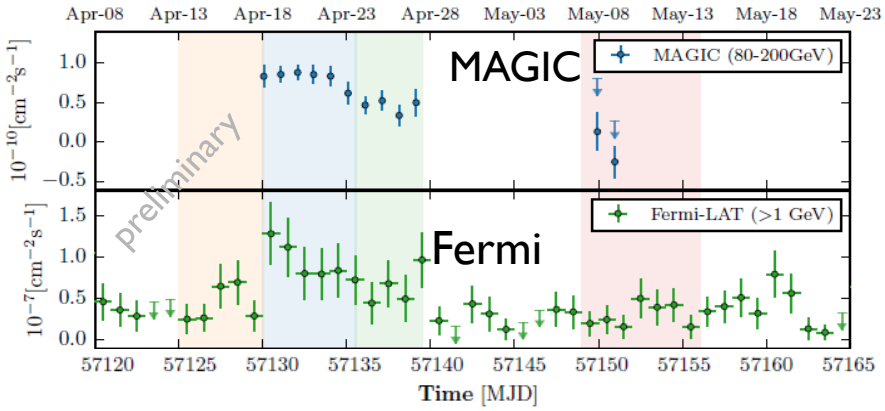
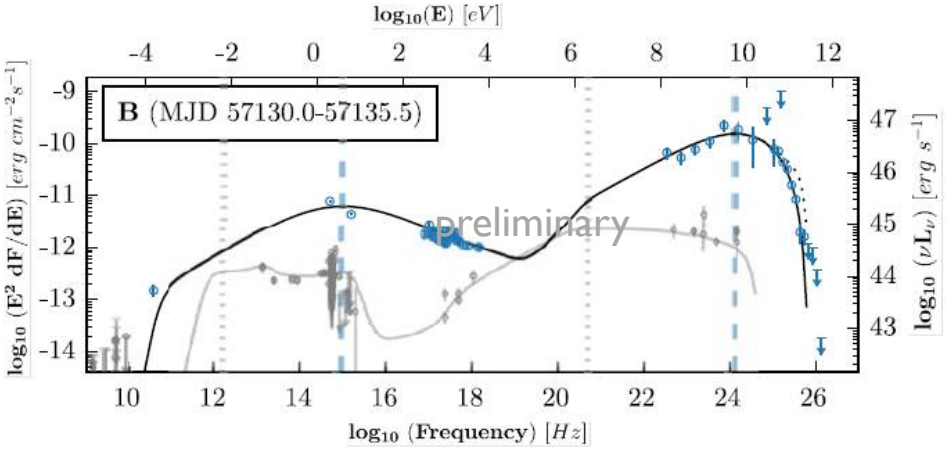
MAGIC: Ahnen et al. 2015





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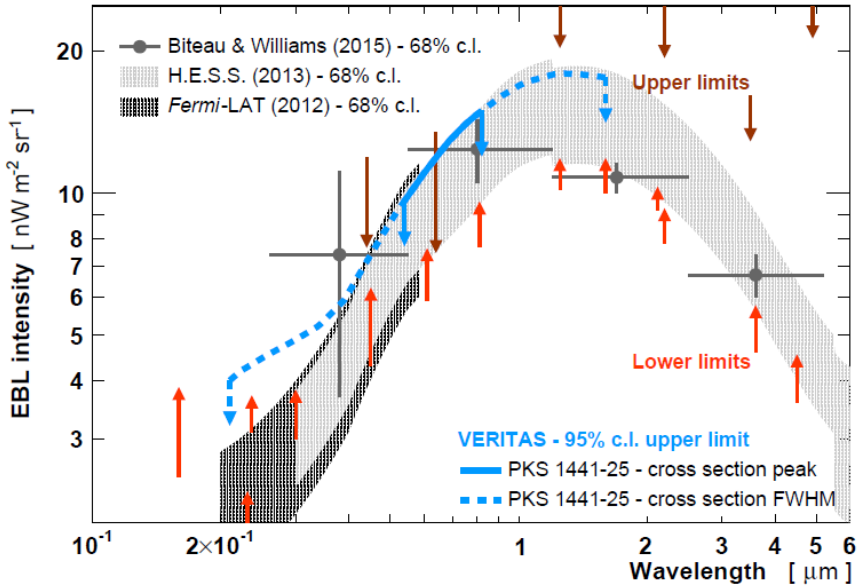
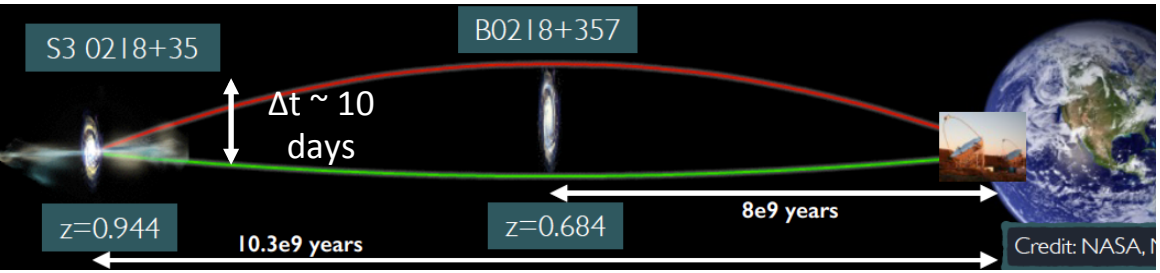
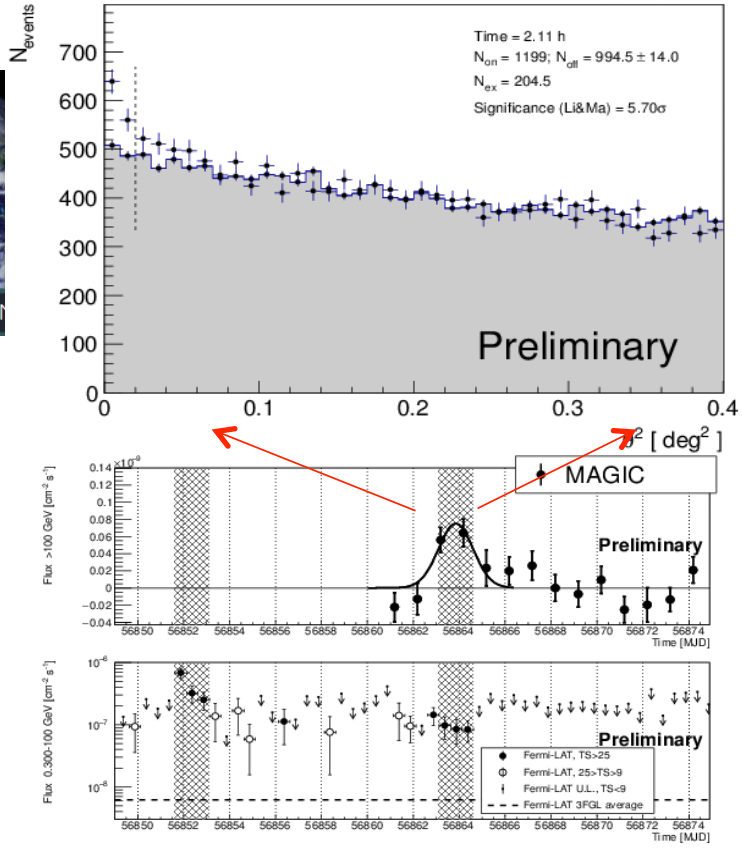


VERITAS: Abeysekara et al. 2015

QSO B0218+357: 1st VHE Gravitationally lensed blazar (@ z = 0.944 !)

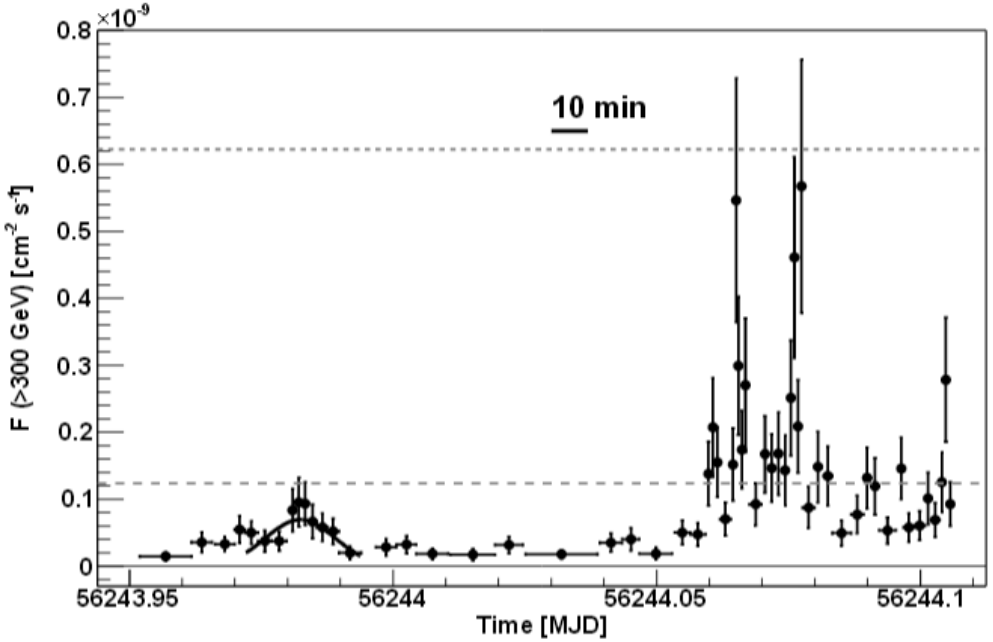


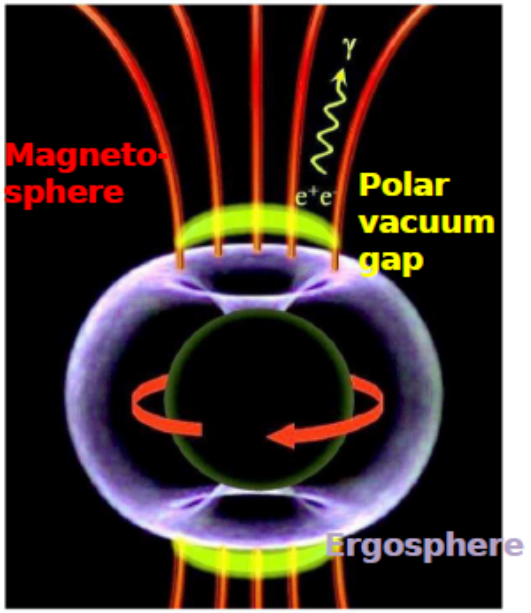


- ~11.5d delay between the direct & lensed components (Fermi – 2012)
- Observations with MAGIC performed during the 2nd flare: detection of sub-TeV lensed emission
  - much more prominent emission than by Fermi
  - VHE emission from z~1 is strongly attenuated above ~100 GeV
  - GeV + sub-TeV observations can put constraints on the EBL models at $z \leq 0.94$

Black Hole "Lightning": IC 310 - MAGIC

- Viewing angle $10° \leq \theta \leq 20°$ (EVN Image)
  - Not blazar, no strong Doppler Boost
- TeV Variability < 4min (MAGIC)
  - Emission region constrained to < $0.2R_G$
- Huge optical depth for γ-γ pair production due to small Doppler boost
  → inconsistent with shock-in-jet model
- Magnetospheric model similar to pulsar models (e.g. Levinson & Rieger, 2011)
  - Acceleration of particles close to black hole in vacuum gaps
  - hard γ-ray spectrum due to electromagnetic cascading

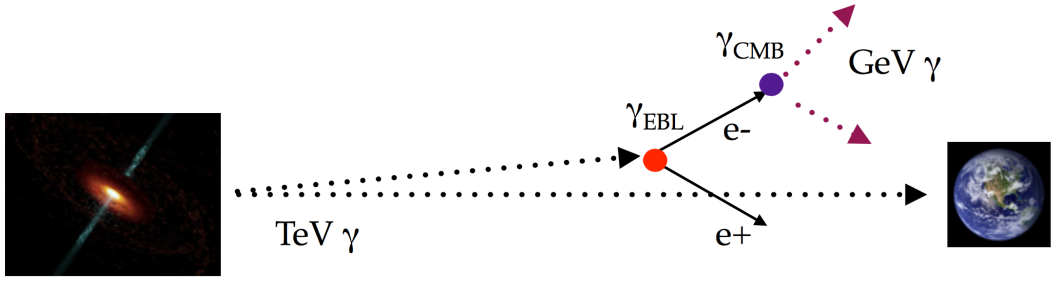


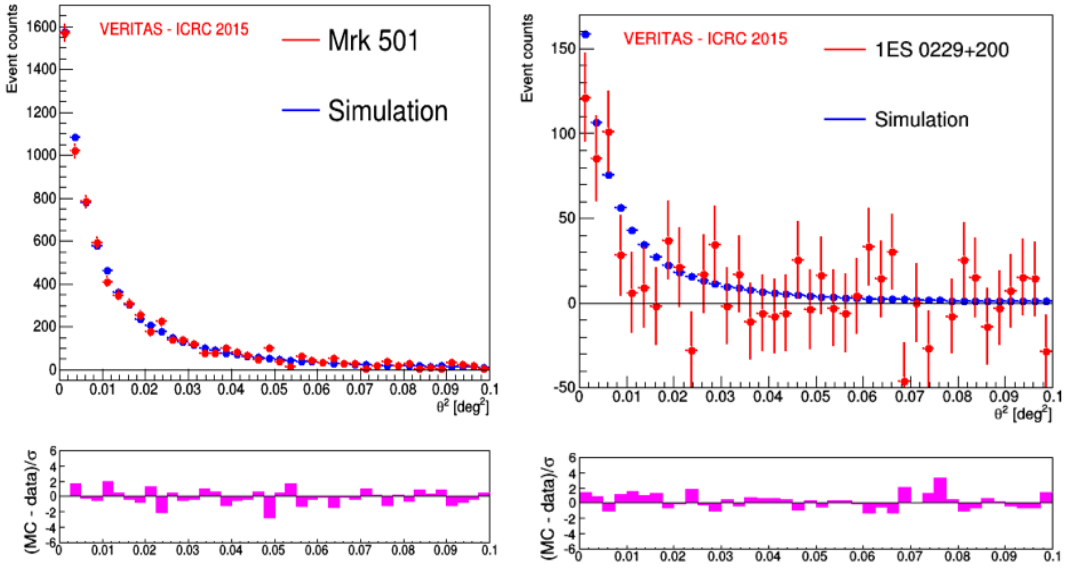


Limits on Intergalactic Magnetic Field - VERITAS

Unambiguous detection of IGMF remains elusive - important to understand large scale structure formation and to understand the propagation of cosmic rays in cosmic voids

Search for IGMF-broadened cascade emission in VHE blazars





Pueschel et al. 2015

- EBL produces e^+e^- pair, secondary particles are bent by the IGMF
- **No extension seen in the angular distribution in 7 blazars**
- Flux limits set for model independent case:

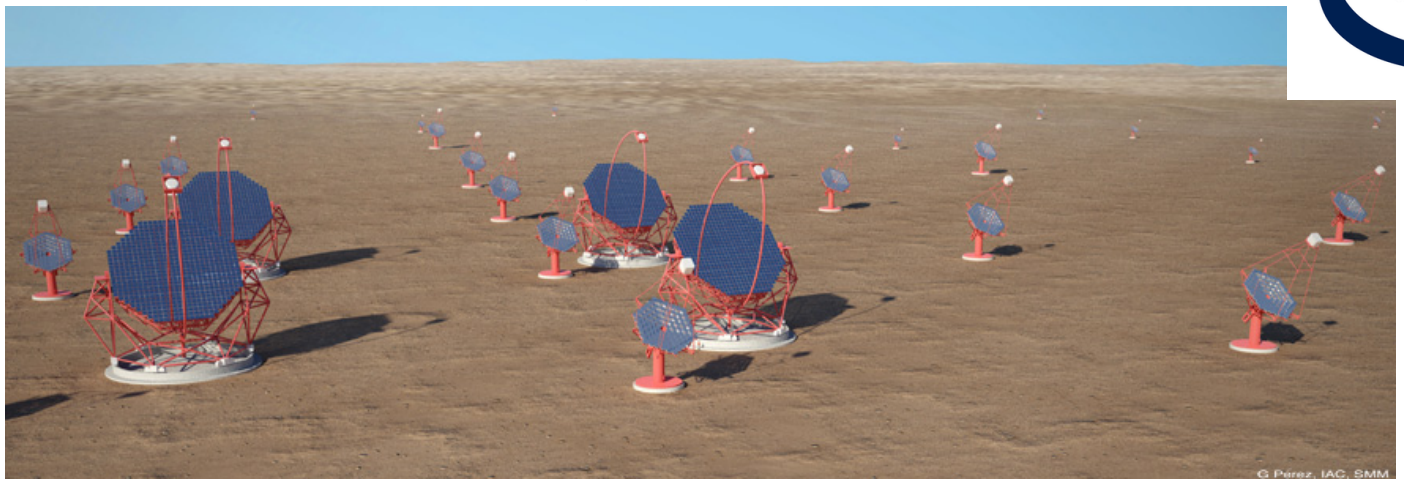
  (0.17-2.69) x 10^{-12} $cm^{-1}TeV^{-1}s^{-1}$
- Limits on IGMF magnitude set for model-dependent extended emission by comparing to simulated blazars and using 3D semi-analytical code

  (5-10) x 10^{-15} G ruled out @ 95% CL

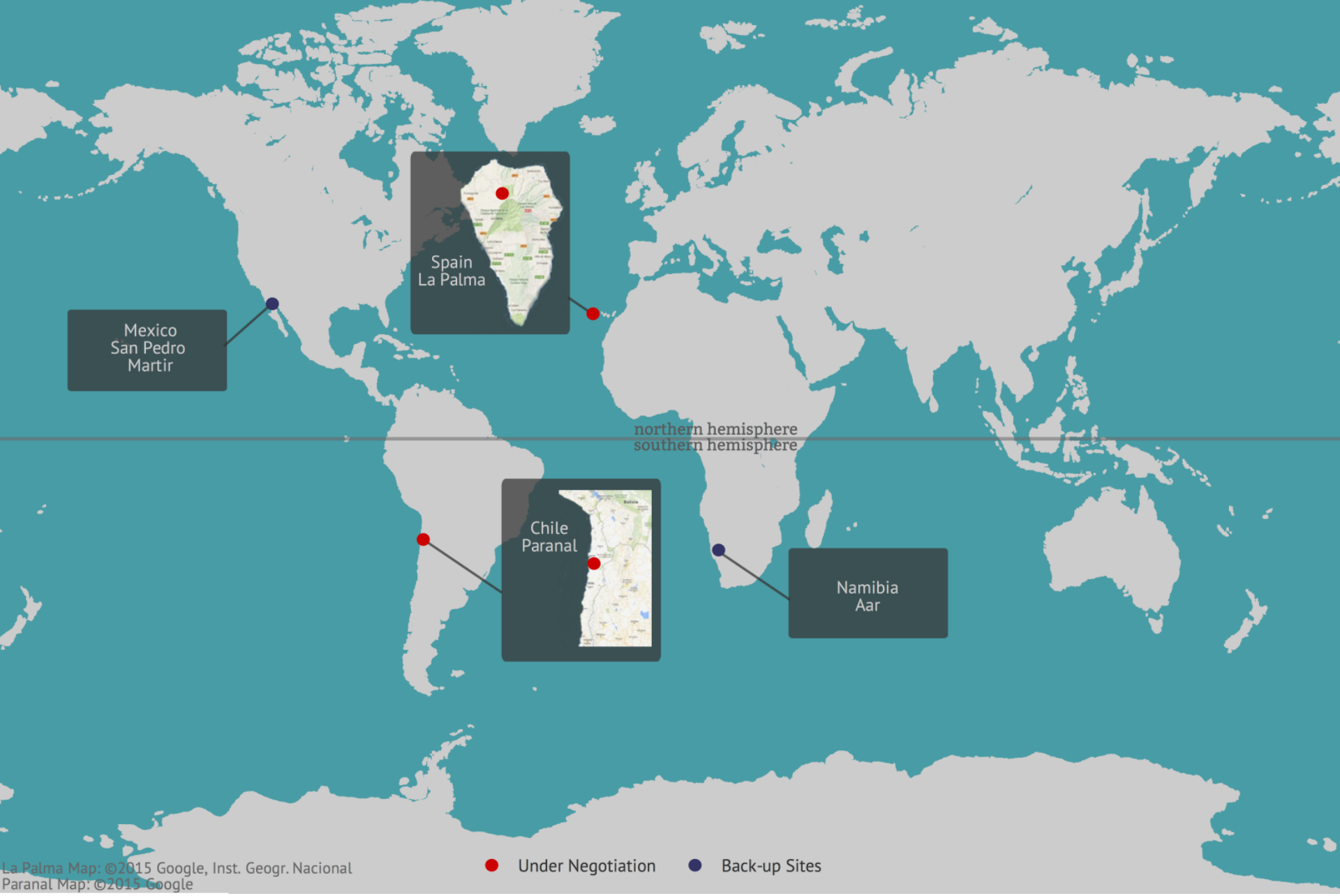
Looking Ahead: Cherenkov Telescope Array

(also new satellites: CALET, DAMPE)

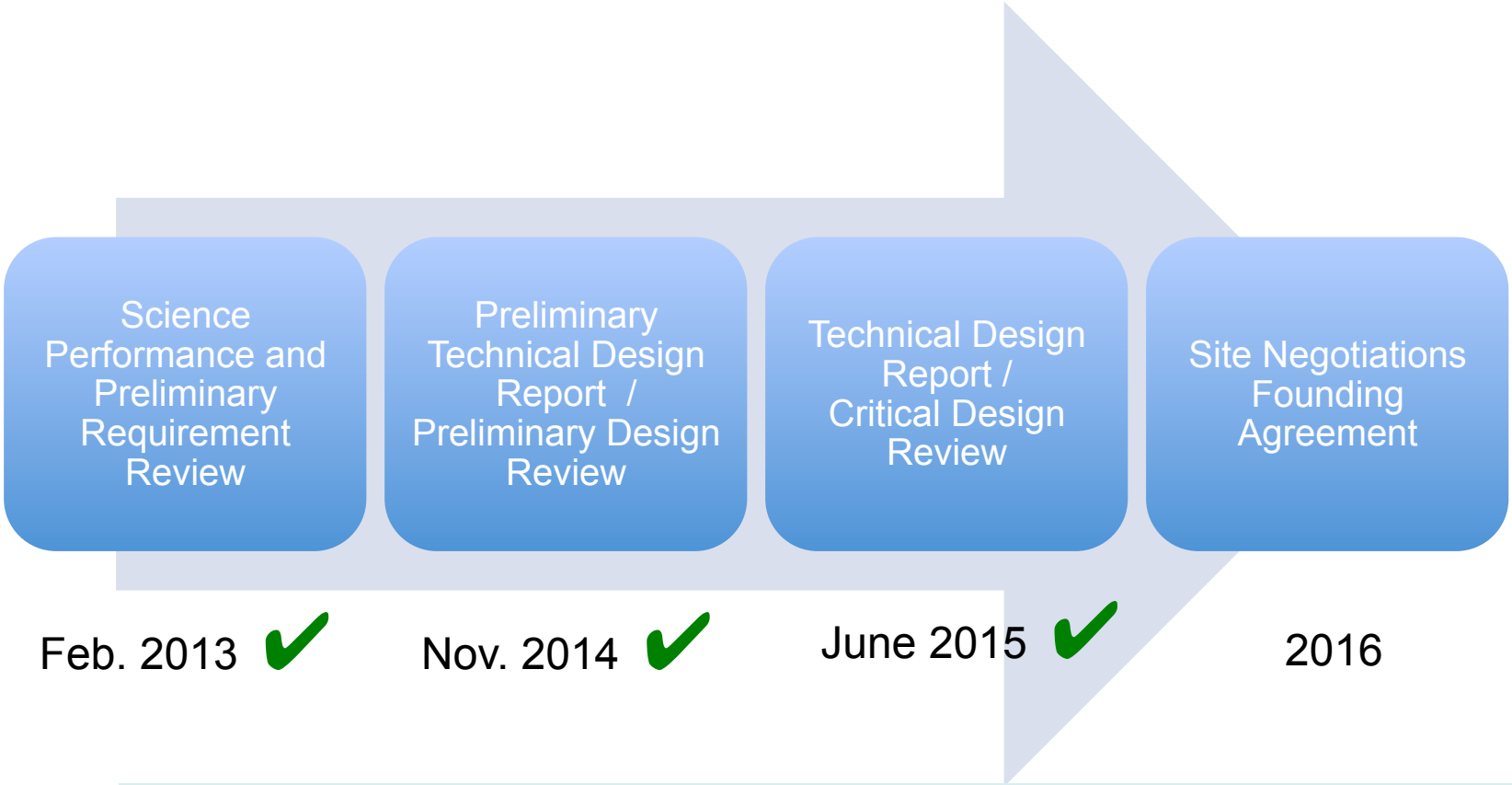
The CTA Concept ("Baseline")



- Arrays in both hemispheres for full sky coverage
  - ESO, Paranal, Chile in the south; ORM, La Palma, Spain in the north
- 4 large (23 m) telescopes (LSTs) in the center — threshold of 30 GeV
- Southern array adds:
  - 25 medium (9-12 m) telescopes (MSTs) — 100 GeV – 10 TeV energy coverage
  - 70 small (~4 m) telescopes (SSTs) covering >3 km^2 — expand collection area >10 TeV for Galactic sources
- Northern array adds 15 MSTs (no SSTs)
- Construction to begin as early as late 2016, continue through ~2023


Spain
La Palma
Mexico
San Pedro
Martir
northern hemisphere
southern hemisphere
Chile
Paranal
Namibia
Aar
Under Negotiation
Back-up Sites
La Palma Map: ©2015 Google, Inst. Geogr. Nacional
Paranal Map: ©2015 Google

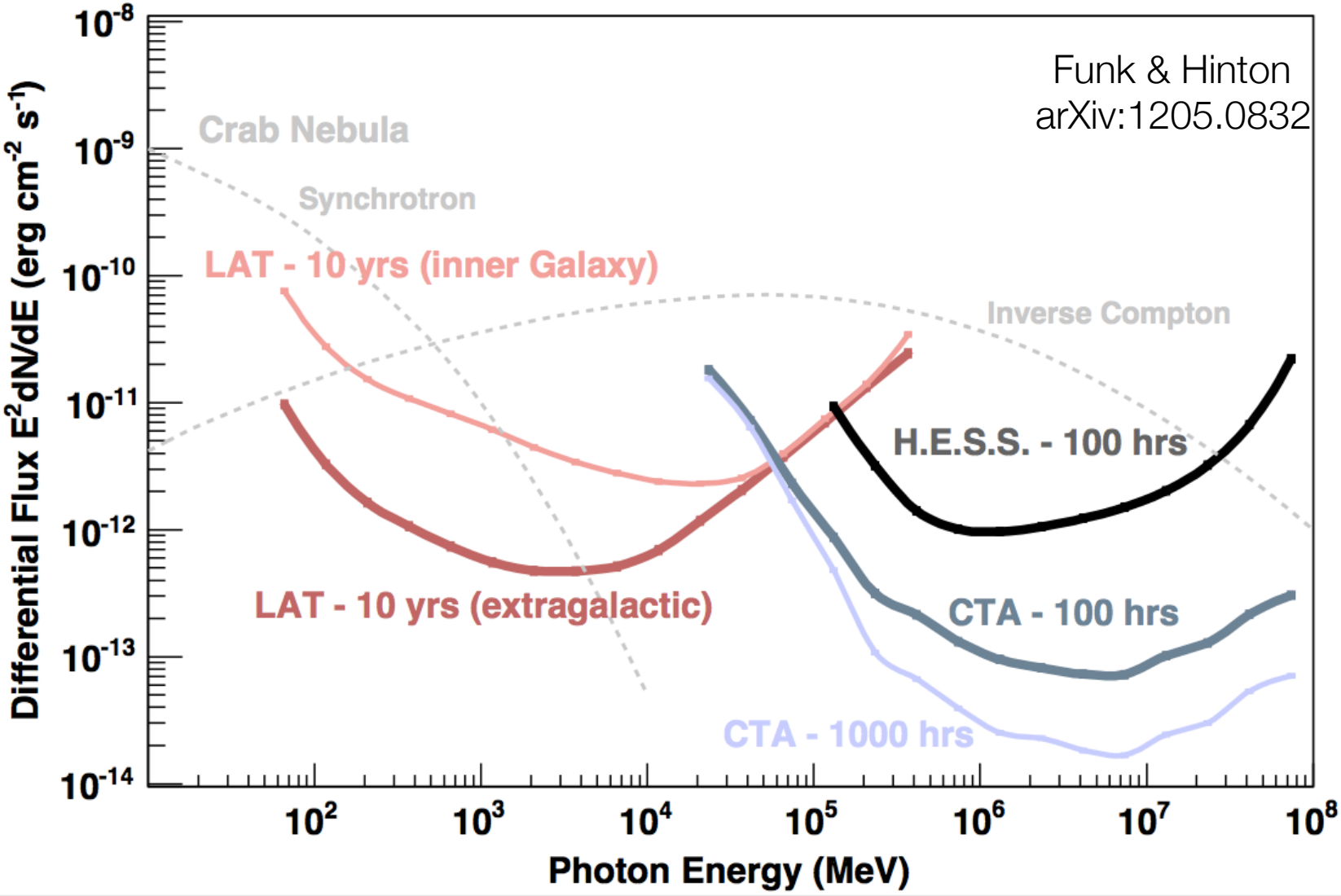
Steps Towards Approval



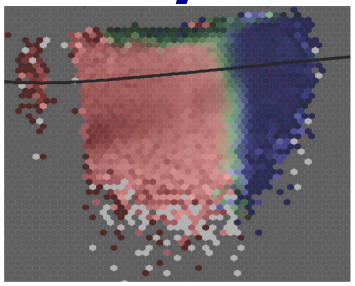
CDR carried out in June 2015 by
Science and Technical Advisory Committee (STAC) – Chair. R. Blandford

2016-2017: Site negotiations, founding agreement,
pre-production reviews, initial site construction

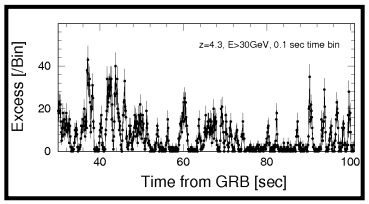
CTA Flux Sensitivity – Steady Point Sources



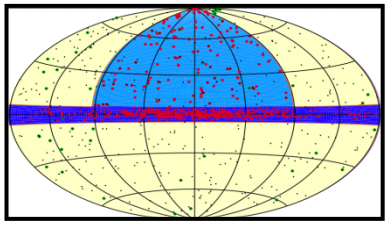
Key Science Projects



Dark Matter Programme

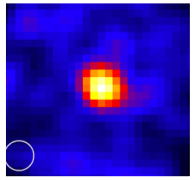


Transients



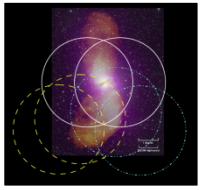
ExGal Survey

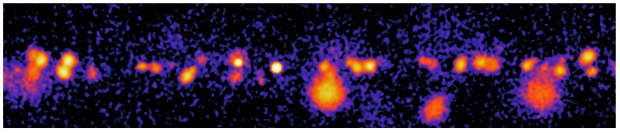
Galaxy Clusters



Star Forming Systems

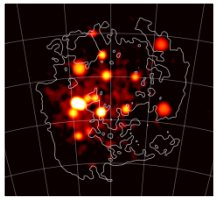
AGN



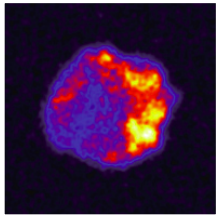


Galactic Plane Survey

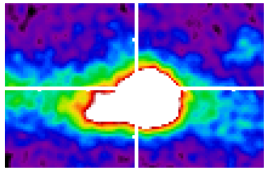
LMC Survey



PeVatrons



Galactic Centre



Galactic

Extragalactic

cta
cherenkov telescope array

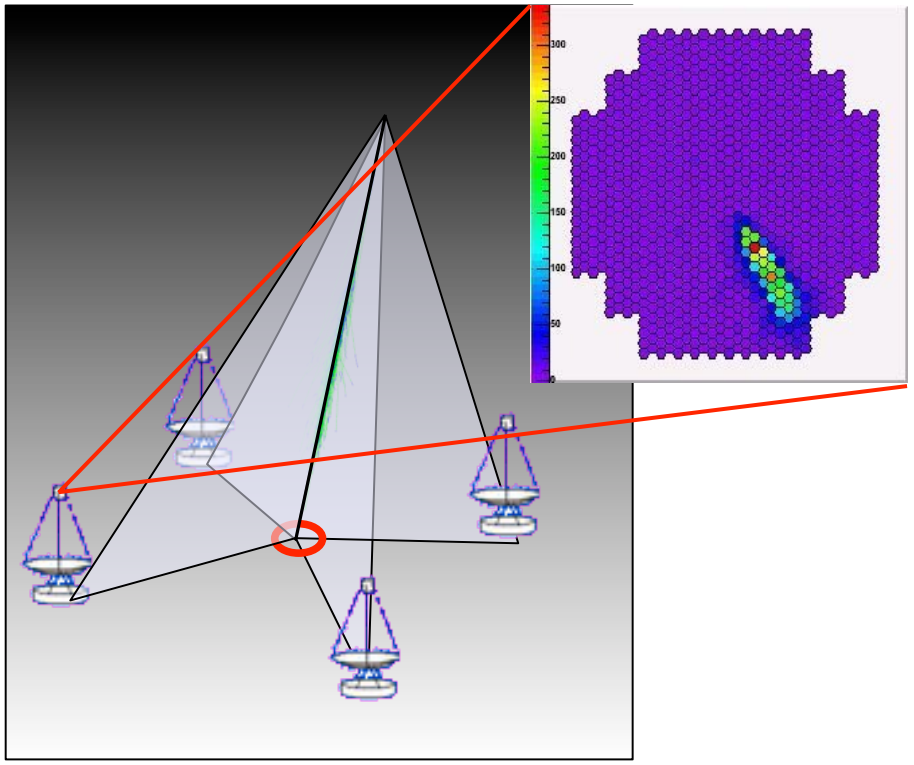
Conclusions

- Current-generation instruments still going strong
- CTA on the horizon…

Additional Material

Imaging Air Cherenkov Technique in Brief

- Shower develop in the atmosphere
- Ultra relativistic $e^{\pm}$ emit Cherenkov light ~10km above ground
- Fast camera (1 ns) image the shower
- Stereoscopy greatly improves reconstruction and identification of particles

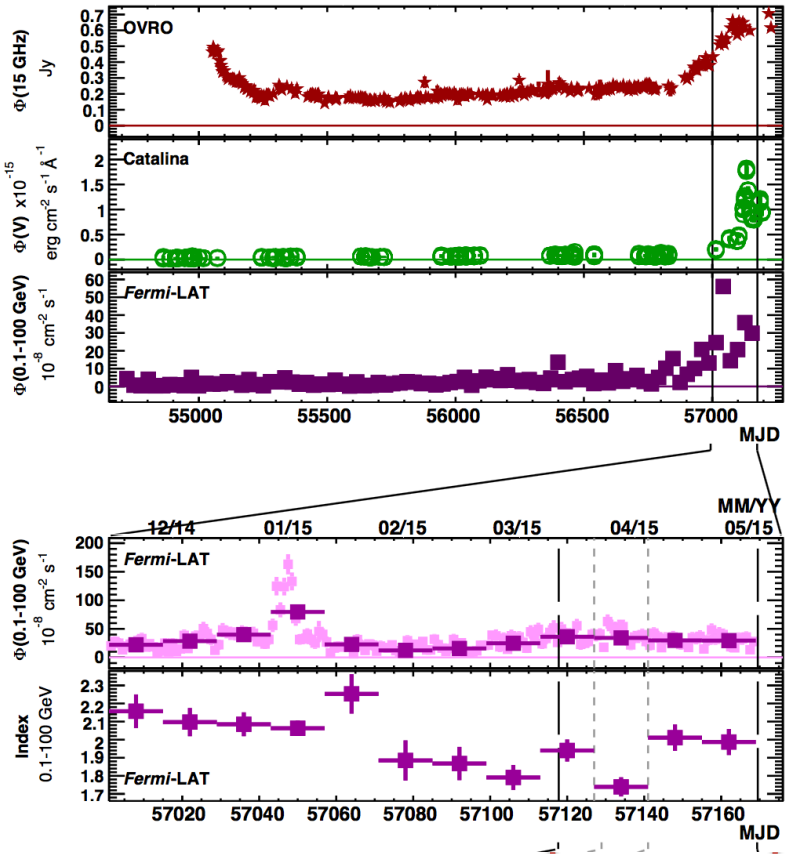


MAGIC

~160 astro-physicists from 10 countries

Bulgaria, Croatia, Finland, Germany, India, Italy, Japan, Poland, Spain, Switzerland

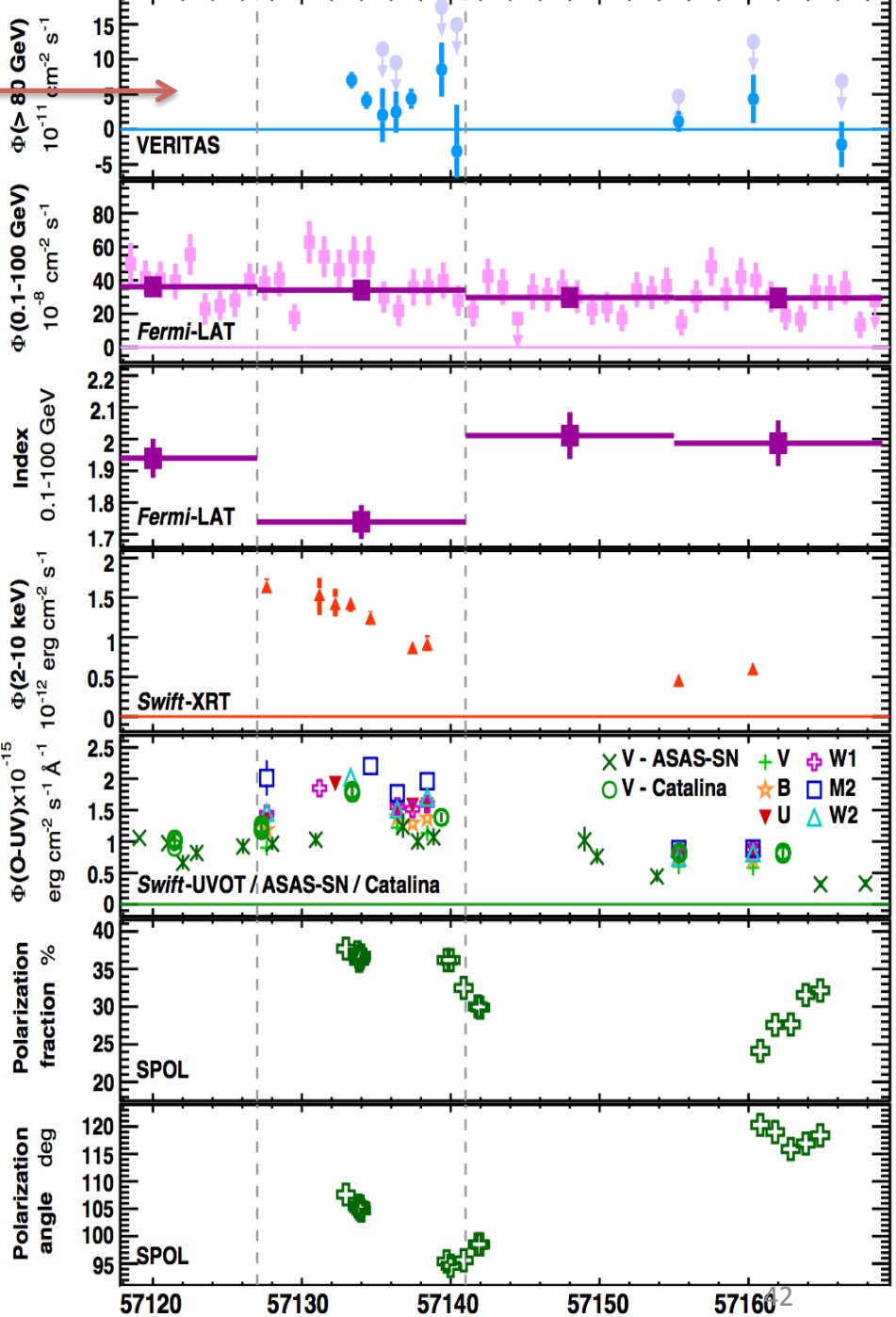
- 2 x 236 m^2 mirror, F = 17m
- M1 - M2 distance: 85m
- $E_{threshold}$ (trigger): ~ 50 GeV
- $E_{threshold}$ *Sum-Trigger:* ~35 GeV
- $\Delta E/E$: (15-20) %
- $\Delta\theta/\theta$: (0.05-0.1)°
- Sensitivity: ~ 0.6% Crab/50h
- Light-weight, only ~70 T
- Re-positioning: ~180°/25s
- Analog signal transmission by using 162m optical fibres
- ~2.5ns FWHM pulses
- Digitization: 1.64 GS/s DRS4
- ~ 1 TB/(telescope & night)



PKS 1441+25: MWL

- Radio, optical, Fermi-LAT correlation (no delay) supports single, large-scale emission region
- VERITAS detection is contemporaneous with period of high polarization & enhanced MWL emission
- Variability time scale (X-ray) < 2 weeks

Emitting region far from SMBH (10^3 R_g)



VERITAS Collaboration et al – submitted

Cosmic Ray Electrons with VERITAS

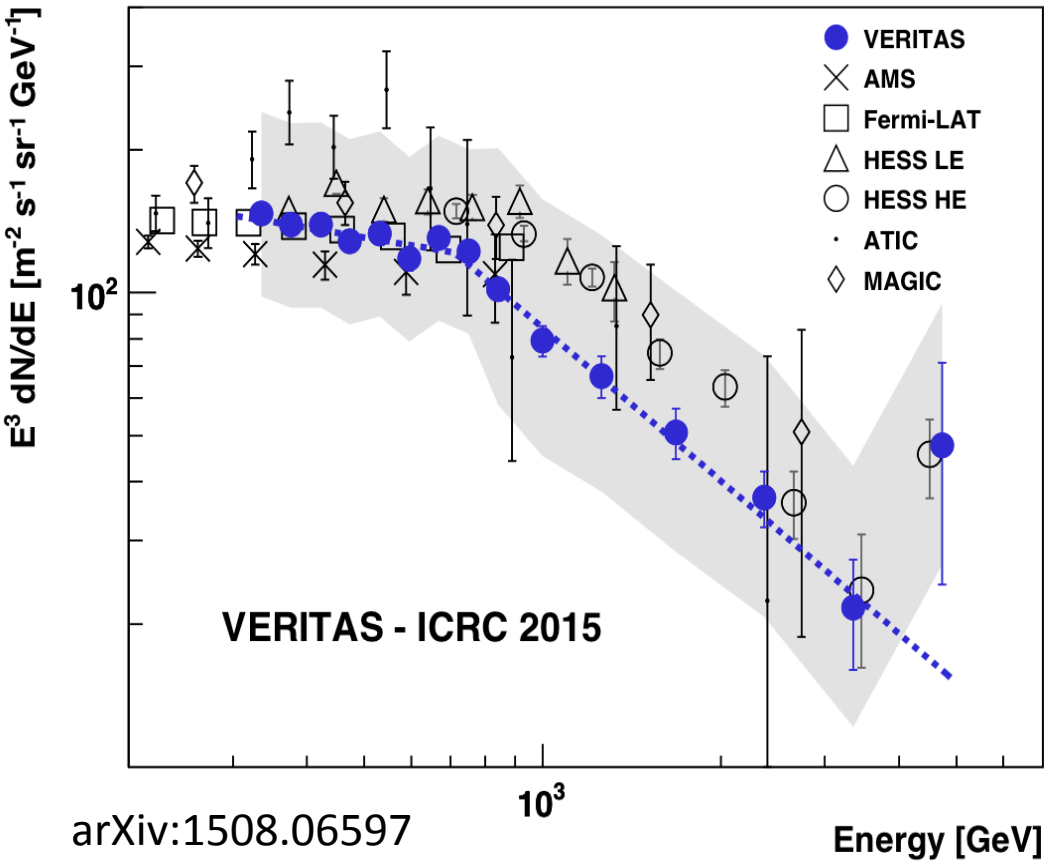
Cosmic-ray electrons at TeV energies are a direct probe of nearby (~1kpc) accelerators

296 hours of data between 2009 and 2012

- Electron-like events selected by Boosted Decision Trees and extended likelihood fitting
- Spectrum agrees qualitatively with other experiments within systematic uncertainty
  - Break at 710 ± 40 GeV
  - Index below (above) break of

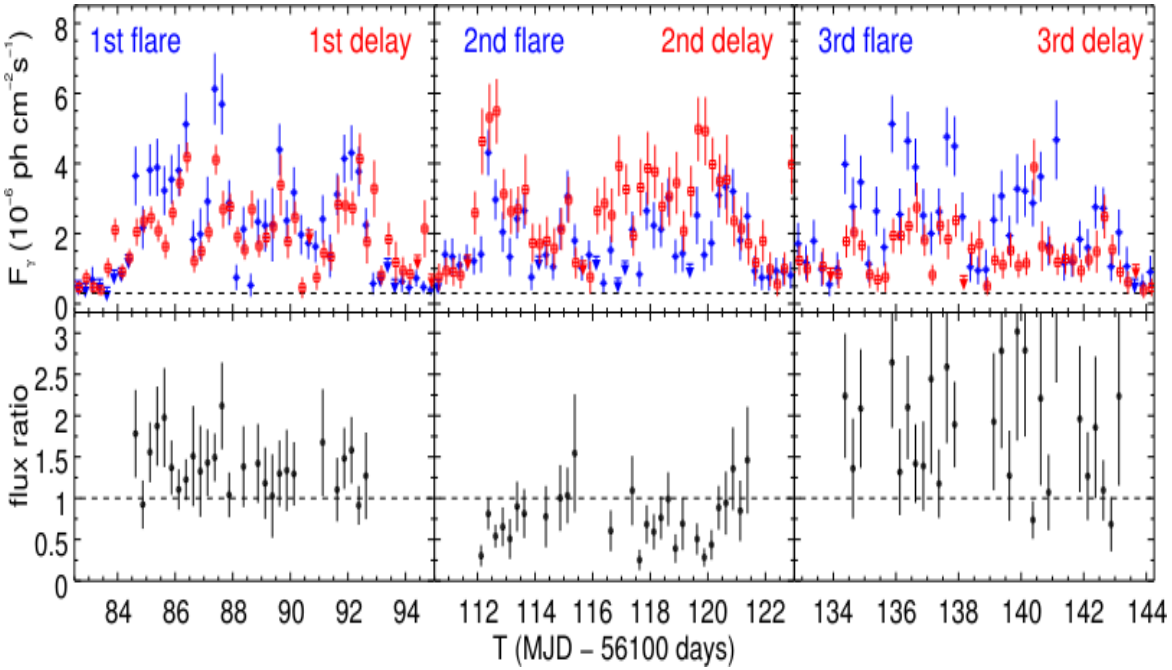
$-3.2 \pm 0.1_{STAT}$

$(-4.1 \pm 0.1_{STAT})$



- Confirms evidence of at least one nearby CR electron emitter
- Second high-statistics measurement of a break below ~1 TeV

Delay from Fermi



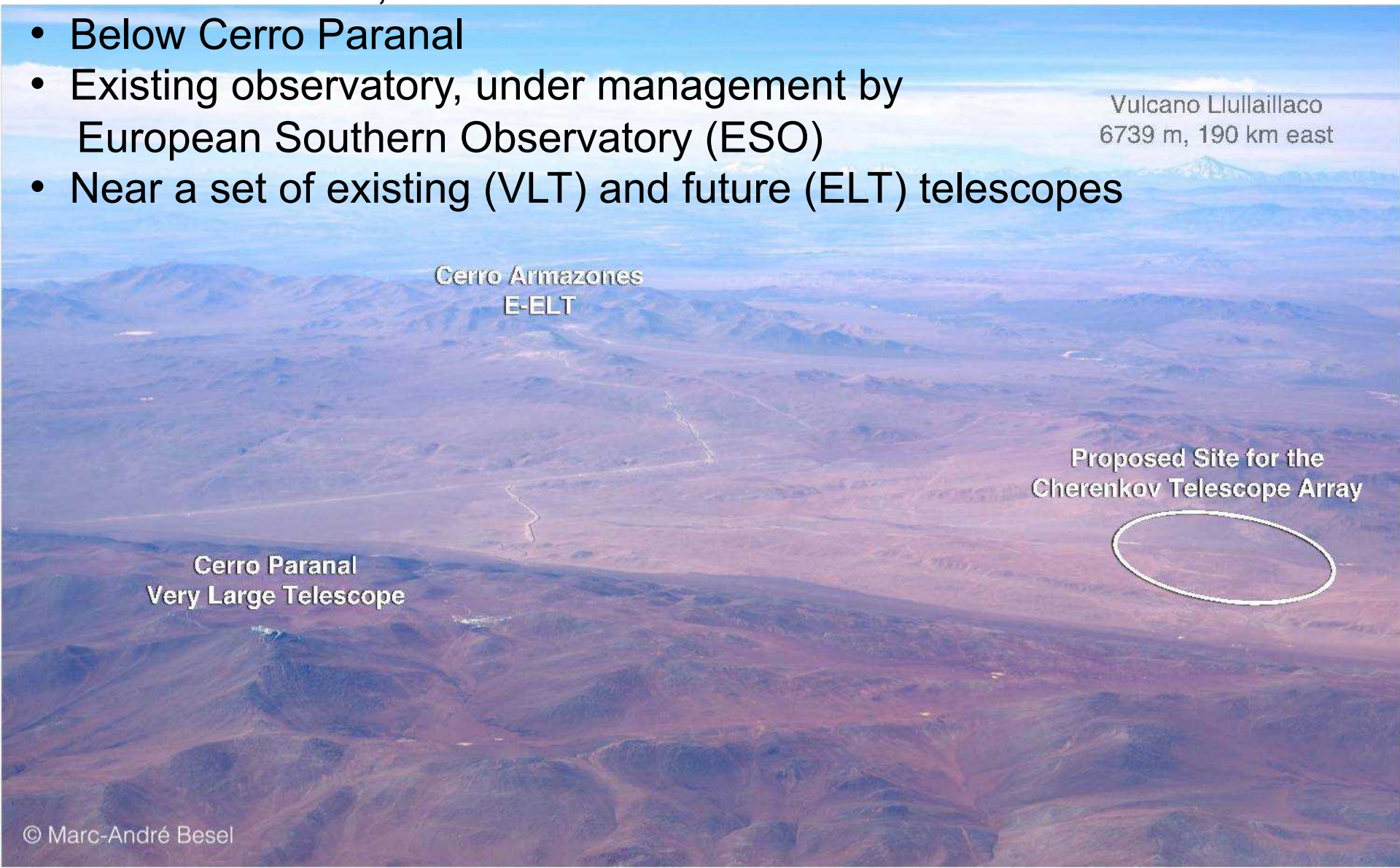
Cheung et al., ApJ 782, L14 (2014)

LA PALMA

- Canary Islands, Spain
- Observatorio del Roque de los Muchachos
- Existing observatory, under management by Instituto de Astrofisica de Canarias (IAC)
- Site of LST prototype & existing MAGIC telescopes

ESO/PARANAL

- Atacama Desert, Chile
- Below Cerro Paranal
- Existing observatory, under management by European Southern Observatory (ESO)
- Near a set of existing (VLT) and future (ELT) telescopes



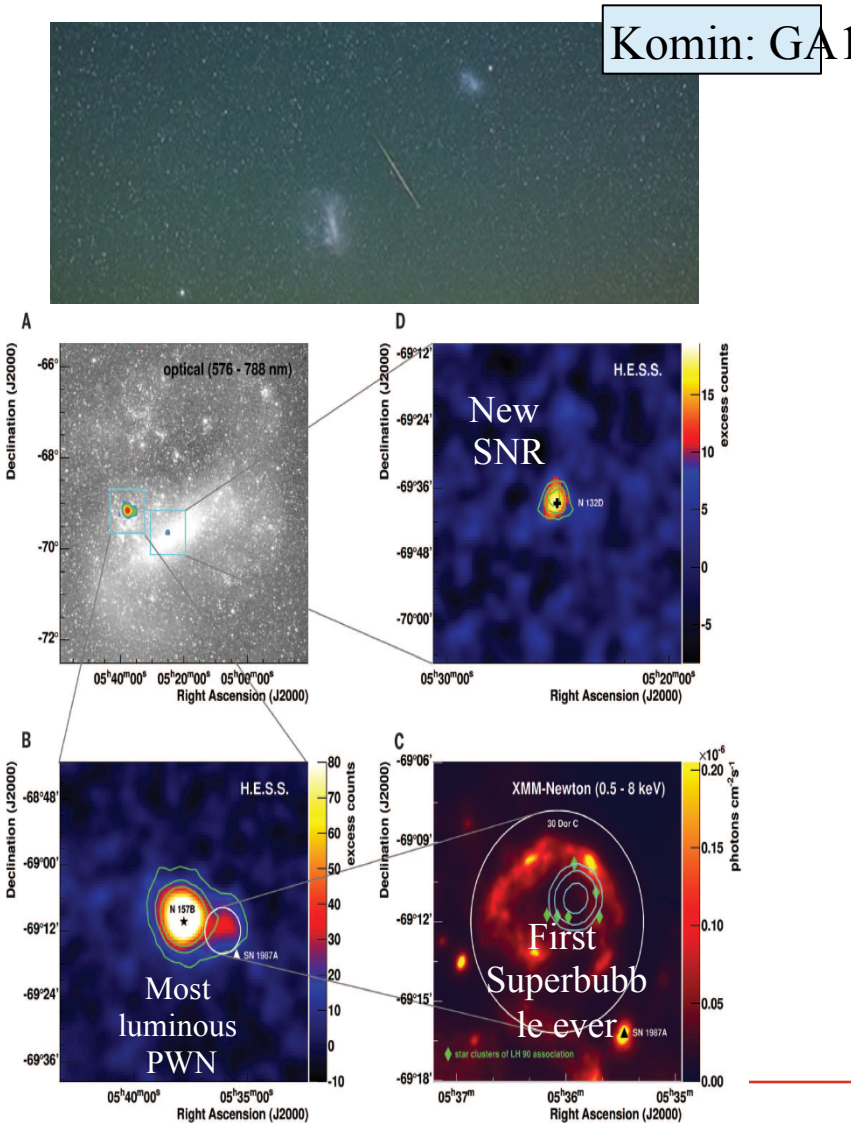
Extreme objects in the LMC

- First glimpse of the LMC population of (stellar-type) particle accelerators
- Extreme environment:
  - Large CR density
  - Large IR

  → Very efficient radiation mechanisms
- First TeV superbubble
  - Possible sources of UHECRs

First extragalactic Stellar Sources

First Superbubble

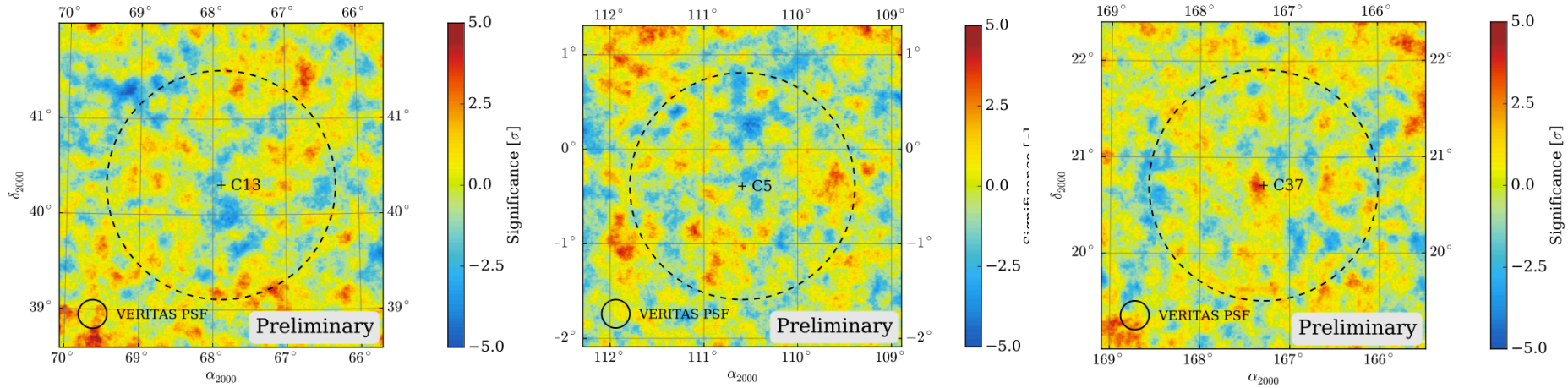


H.E.S.S. MAGIC VERITAS

Follow-up of IceCube Events

IceCube discovery of astrophysical flux of high-energy neutrinos provides evidence of sites of cosmic ray generation… however, no significant neutrino point sources seen yet (isotropic)

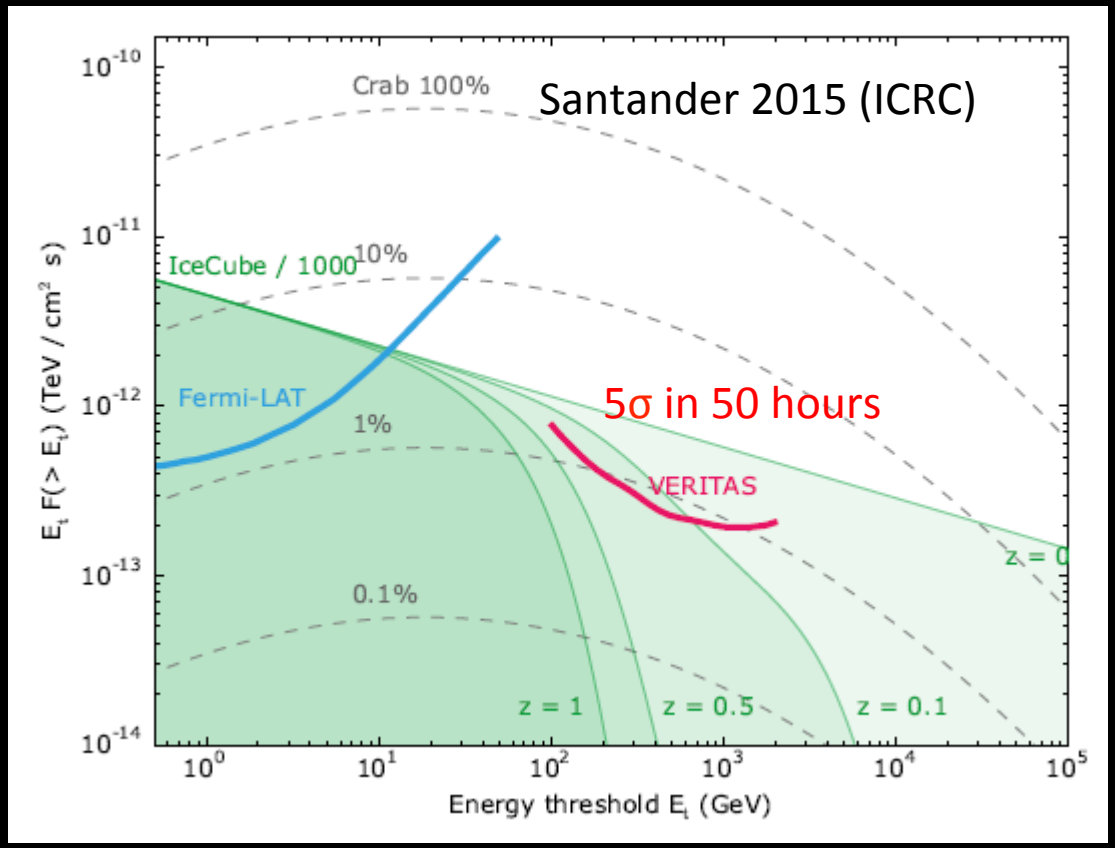
arXiv:1509.00517



- Observations of 22 IceCube ν_μ-induced muon-track events for a total of 40 hours
  - muon-track events have good localization, ~1 degree angular uncertainty
  - 3 positions publicly released, 19 shared by a mutual agreement

No significant signals seen: flux upper limits for each of the positions found in the range of ~2-10% Crab Nebula flux

Astrophysical neutrino follow-up

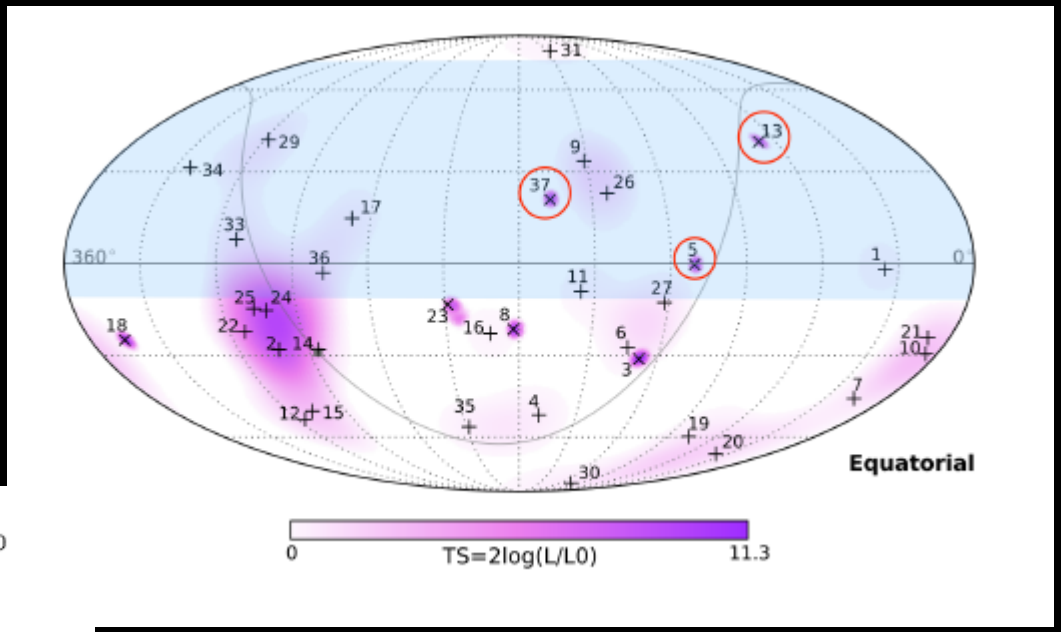


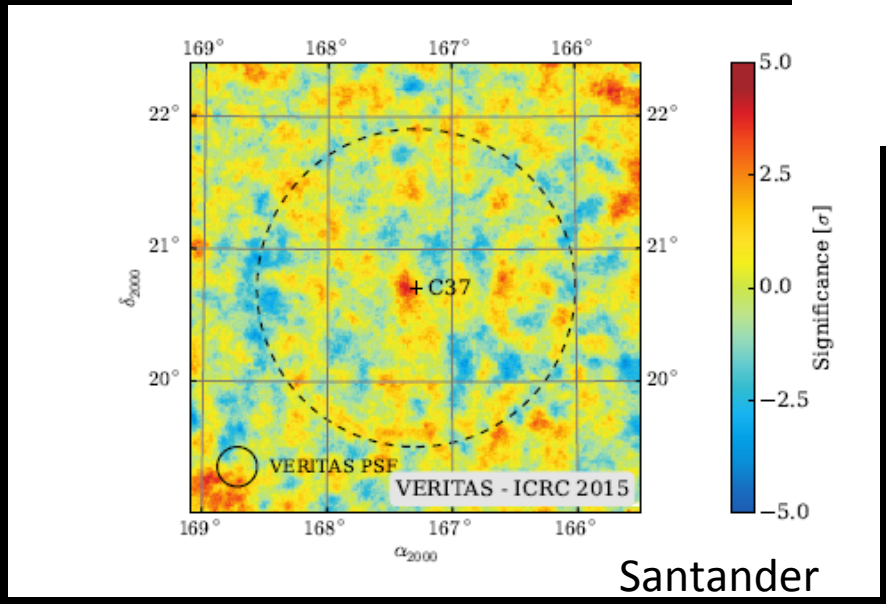
Ice Cube flux corrected for EBL absorption using Francheschini et al. (2008)

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)





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