Results from Imaging Cherenkov Telescopes

Gernot Maier

The high-energy gamma-ray sky

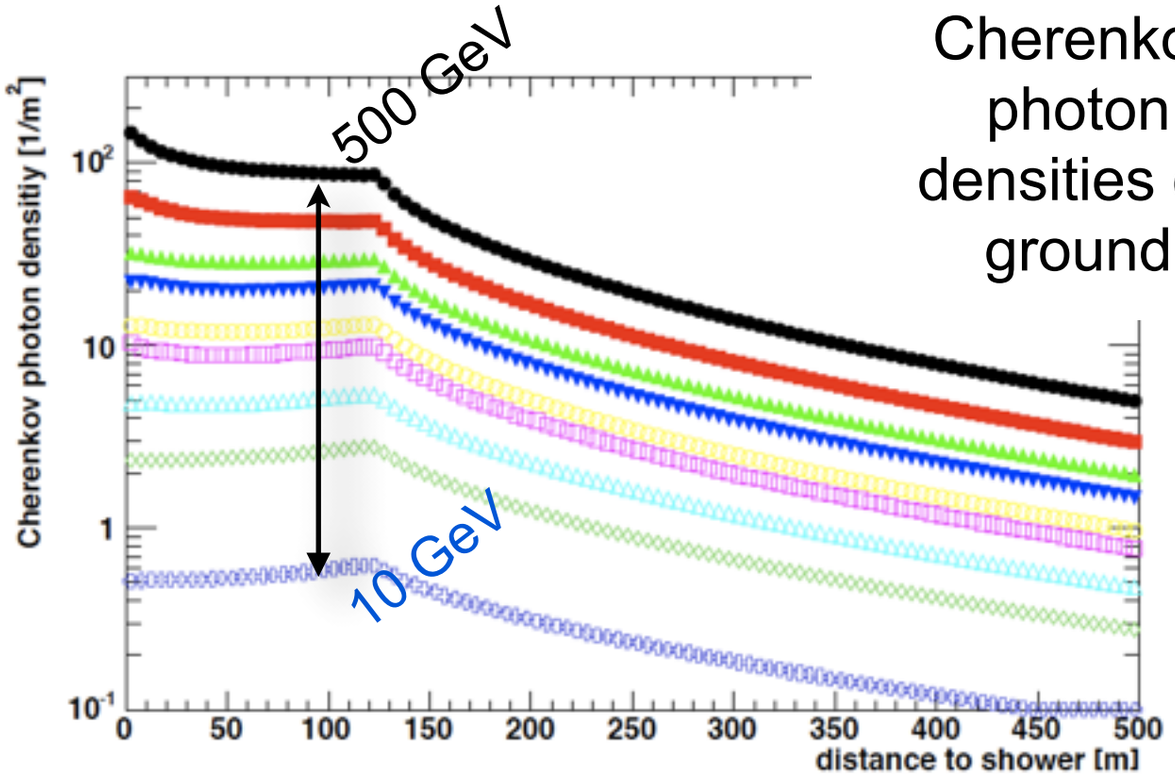
>2500 sources @ MeV-GeV
>500 sources >10 GeV
>150 sources >100 GeV

- Origin of cosmic rays
- Interaction of particle, matter, electromagnetic fields in astrophysical environments
- Detailed astrophysics of different source types
- Identification of dark matter
- Searches for physics beyond the standard model

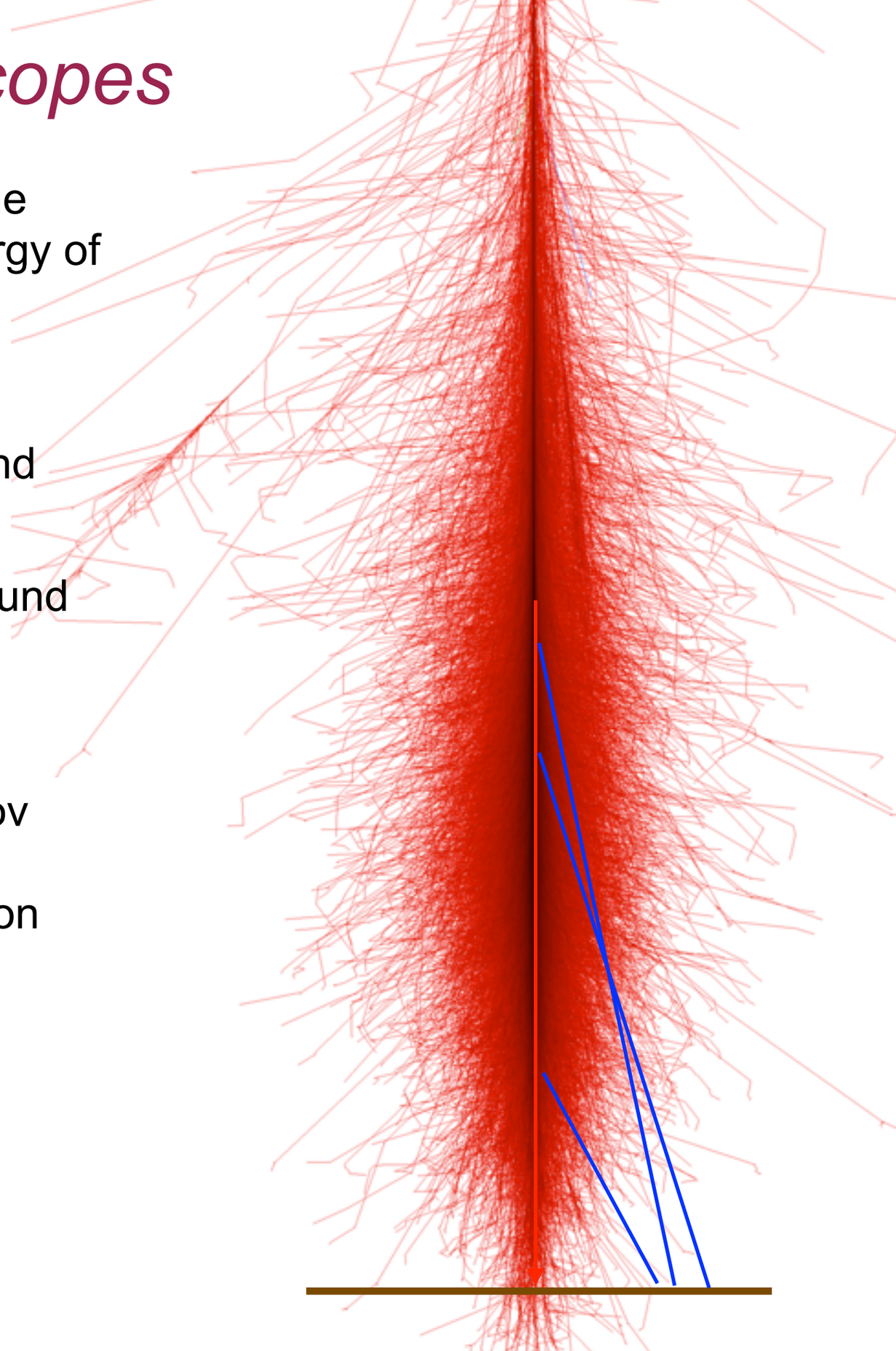
(c) F. Acero & H. Gast

Imaging Cherenkov Telescopes

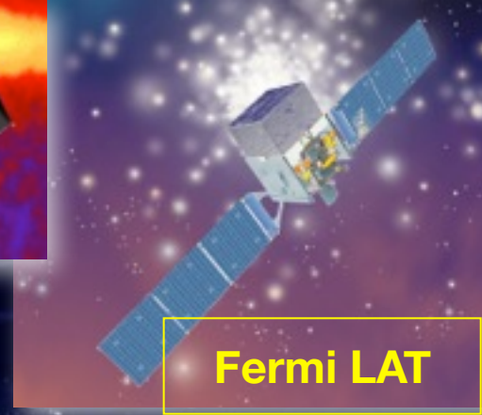
- measure the Cherenkov light emitted by the shower particles to infer direction and energy of incoming photon
- duty cycle: ~1000h/yr; field of view: 3-5^0
- excellent angular resolution (~0.03-0.1^0) and energy resolution (15-20%)
- large effective area (>10^5 m^2) and background rejection
- pointed observations and (limited) surveys



Cherenkov photon densities on ground



Gamma-ray observatories



Tibet -ASγ
ARGO-YBJ
LHAASO

FACT

HIGOR

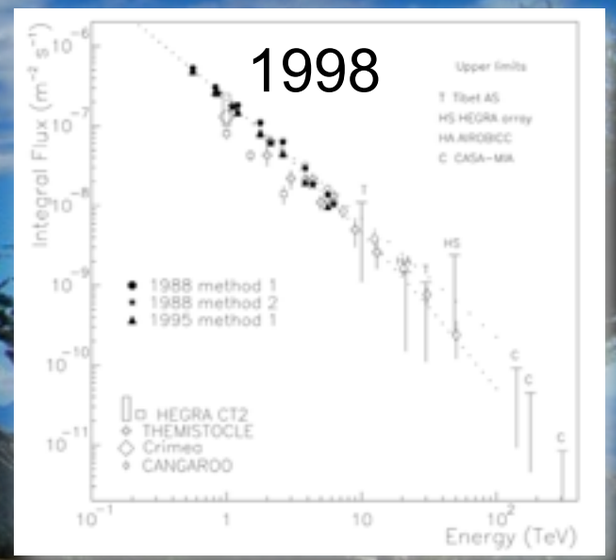
VERITAS

H.E.S.S.

space based: 20 MeV - 300 GeV
ground based: 25 GeV - 1 PeV

Whipple in 2013

- 10-m Gamma Ray Reflector operation started in 1968
- decommissioned last year
- discovery of first TeV source
- discovery of first extragalactic TeV source
- (positioner in good condition after 45 years!)



MAGIC

- La Palma; Spain
- two 17m telescopes with 50 GeV threshold
- upgrade of camera & readout in MAGIC I
- fast repositioning (<20s/180^0)

VERITAS

- southern Arizona
- array of four 12 m Imaging
- several upgrades: T1 move, mirror alignment, L2 trigger, PMTs
- new observation modes for increased temporal coverage
  - ~850 hours of normal operations
  - ~200 hours of moonlight operations (at nominal + reduced HV)
  - ~250 hours of bright moonlight observations with UV filters in front of the cameras

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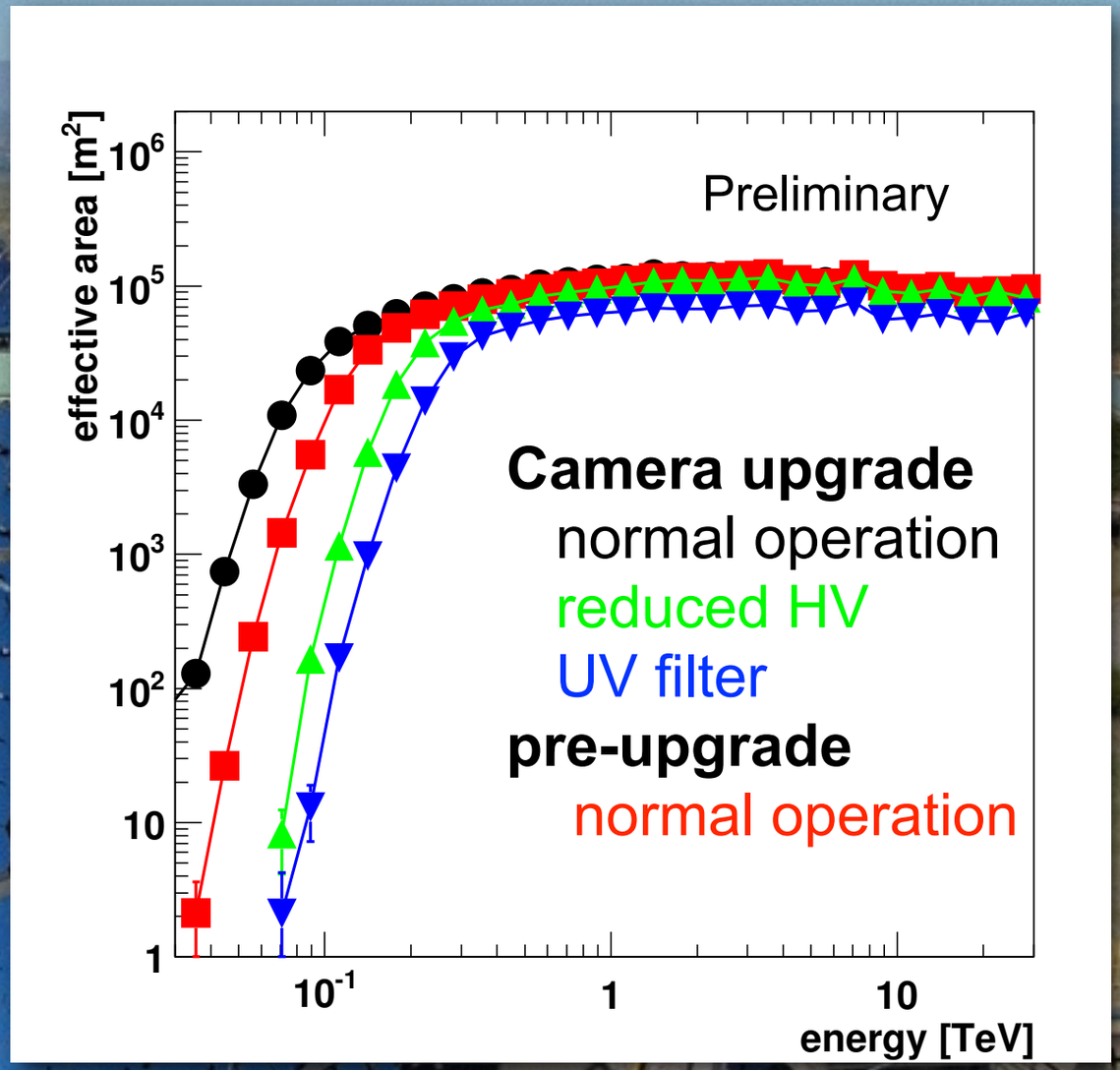

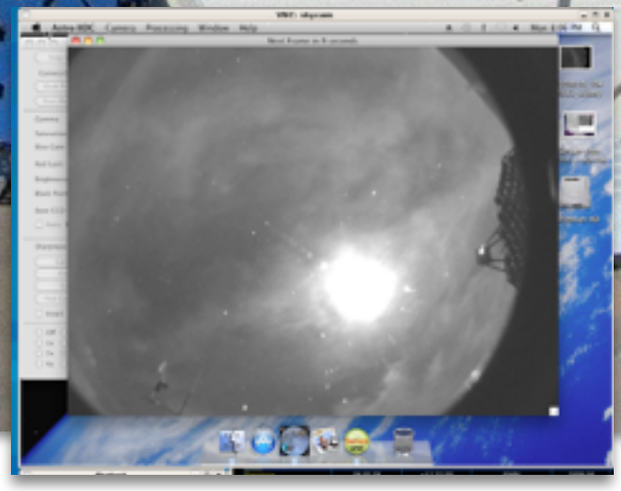

HESS

- Namibia
- array of four 12 m telescopes
- addition of a 28 m telescope
  - 614m^2 mirror area, 36m focal length
- 12 m telescope camera upgrades

H.E.S.S. collaboration

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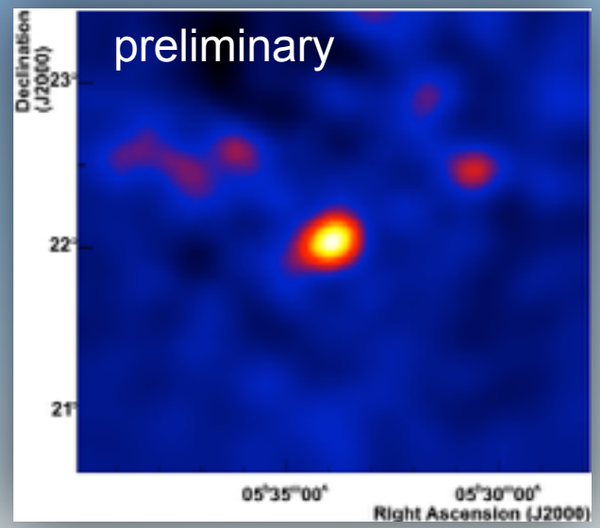
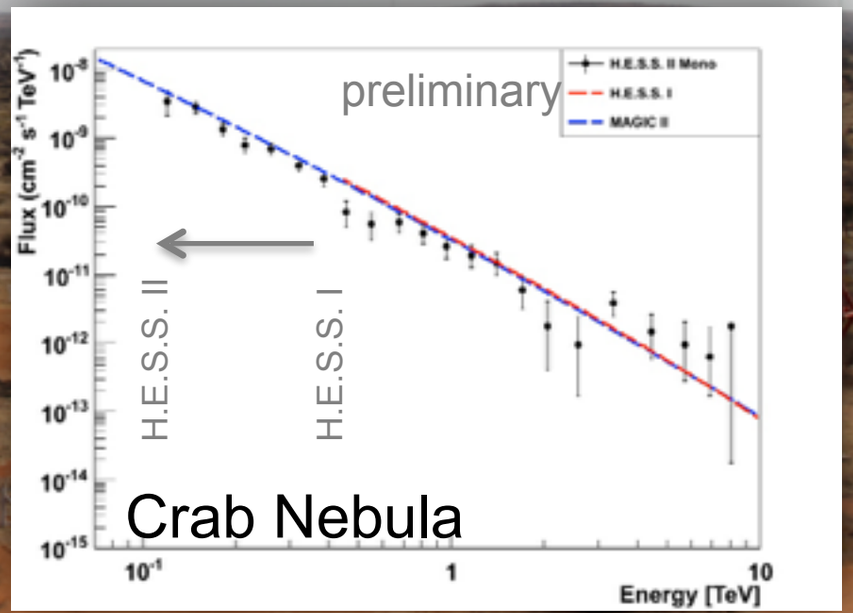
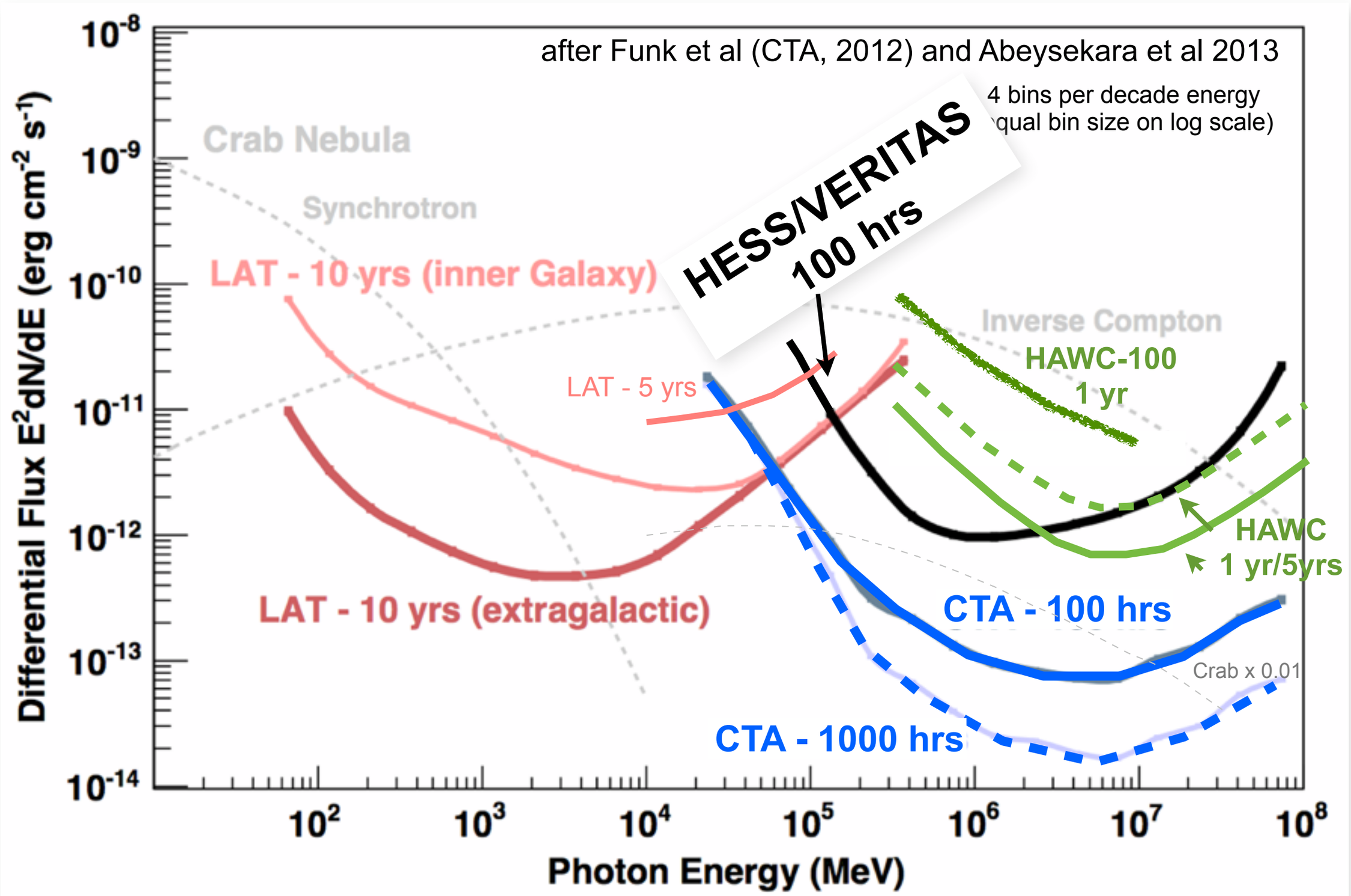




H.E.S.S. collaboration

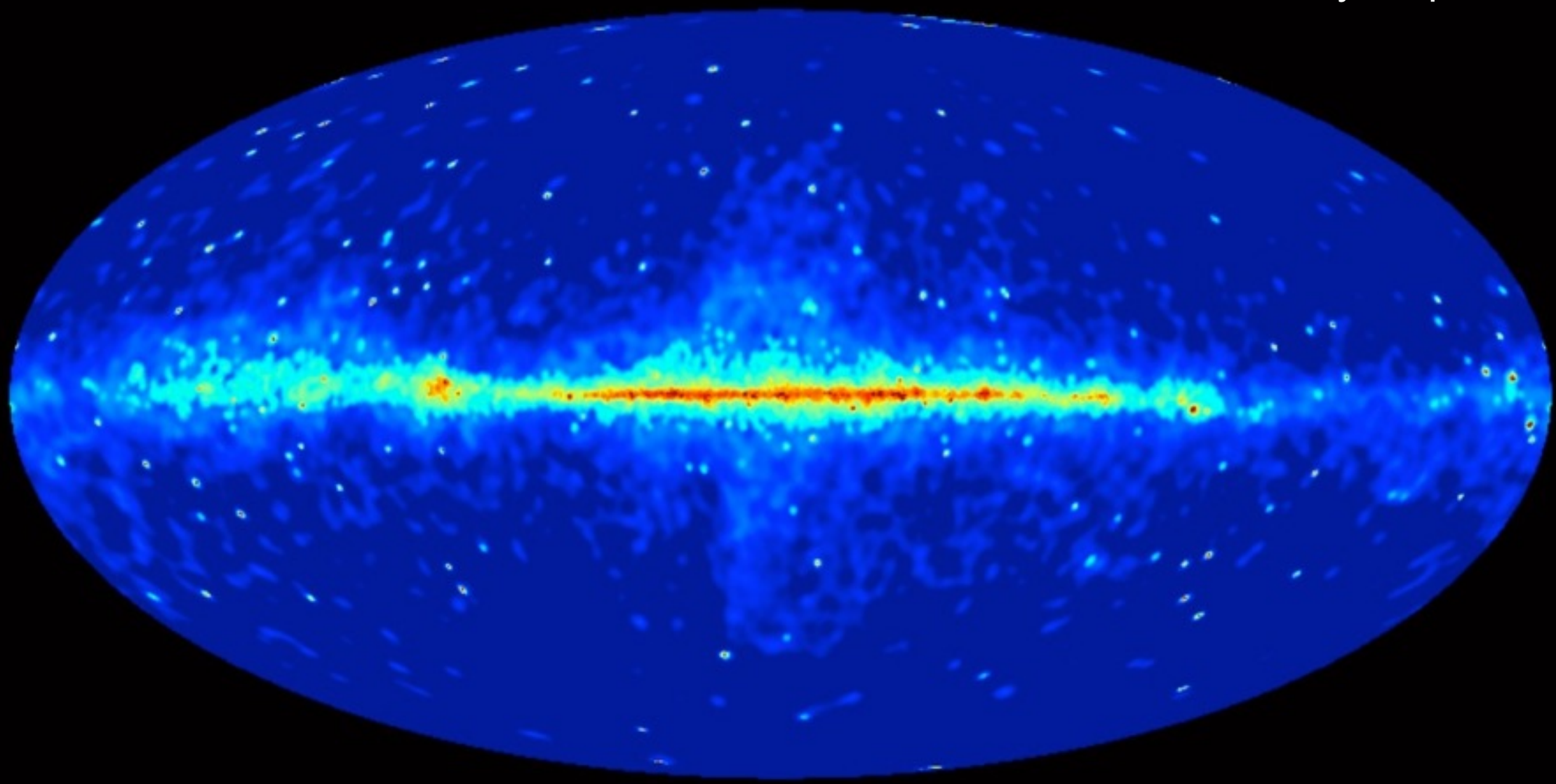
Differential Flux sensitivity



HAWC: 24/7 duty cycle; IACTS: 1200 hrs/year

The high-energy gamma-ray sky

Fermi LAT 3-years
sky map > 10 GeV

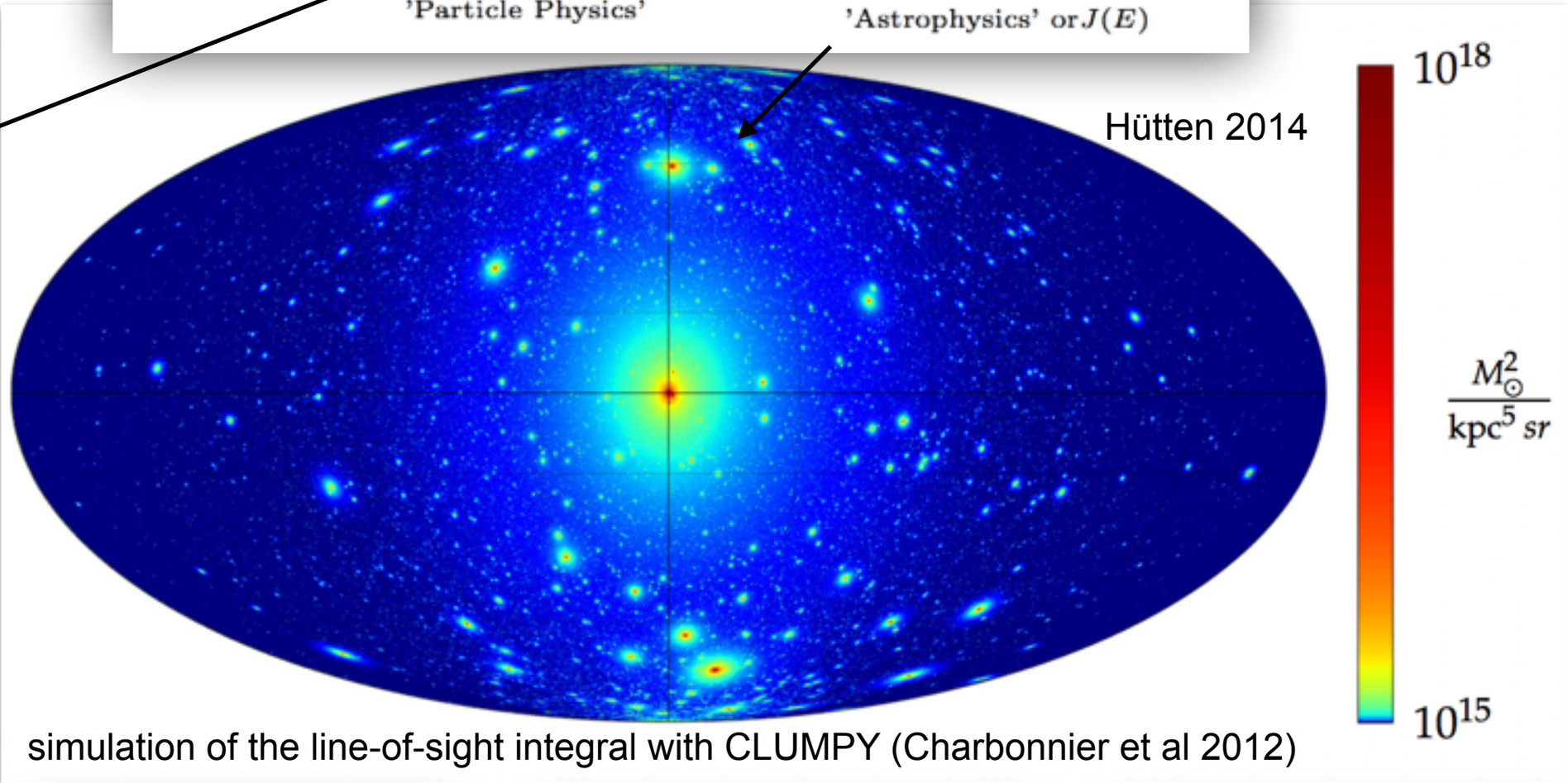


supernova remnants, pulsars, pulsar wind nebulae, binary systems, massive star clusters, starburst galaxies, active galactic nuclei (mostly blazars), gamma-ray bursts, nova, diffuse, dark matter, ...

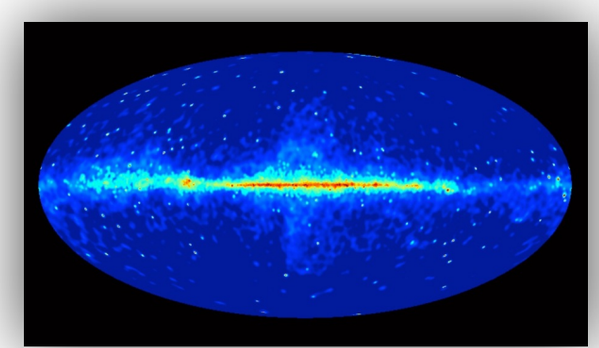
Dark Matter searches

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{dE}_\gamma} = \frac{1}{4\pi} \underbrace{\frac{<\sigma_{\mathrm{ann}} v>}{2\mathrm{m}^2_{\mathrm{WIMP}}} \sum_f \frac{\mathrm{dN}^f_\gamma}{\mathrm{dE}_\gamma} \mathrm{B}_f}_{\text{'Particle Physics'}} \times \underbrace{\int_{\Delta\Omega} \mathrm{d}\Omega' \int_{\mathrm{los}} \rho^2 r(l,\theta') \mathrm{d}l(r,\theta')}_{\text{'Astrophysics' or } J(E)}$$

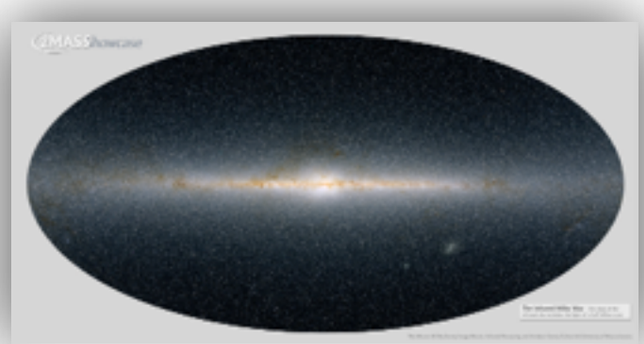
WIMPS
Axions
….



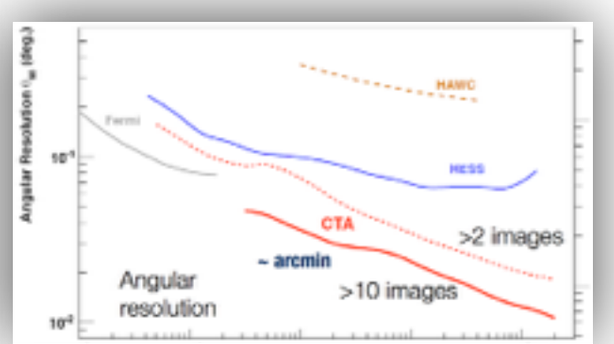
simulation of the line-of-sight integral with CLUMPY (Charbonnier et al 2012)



γ-background



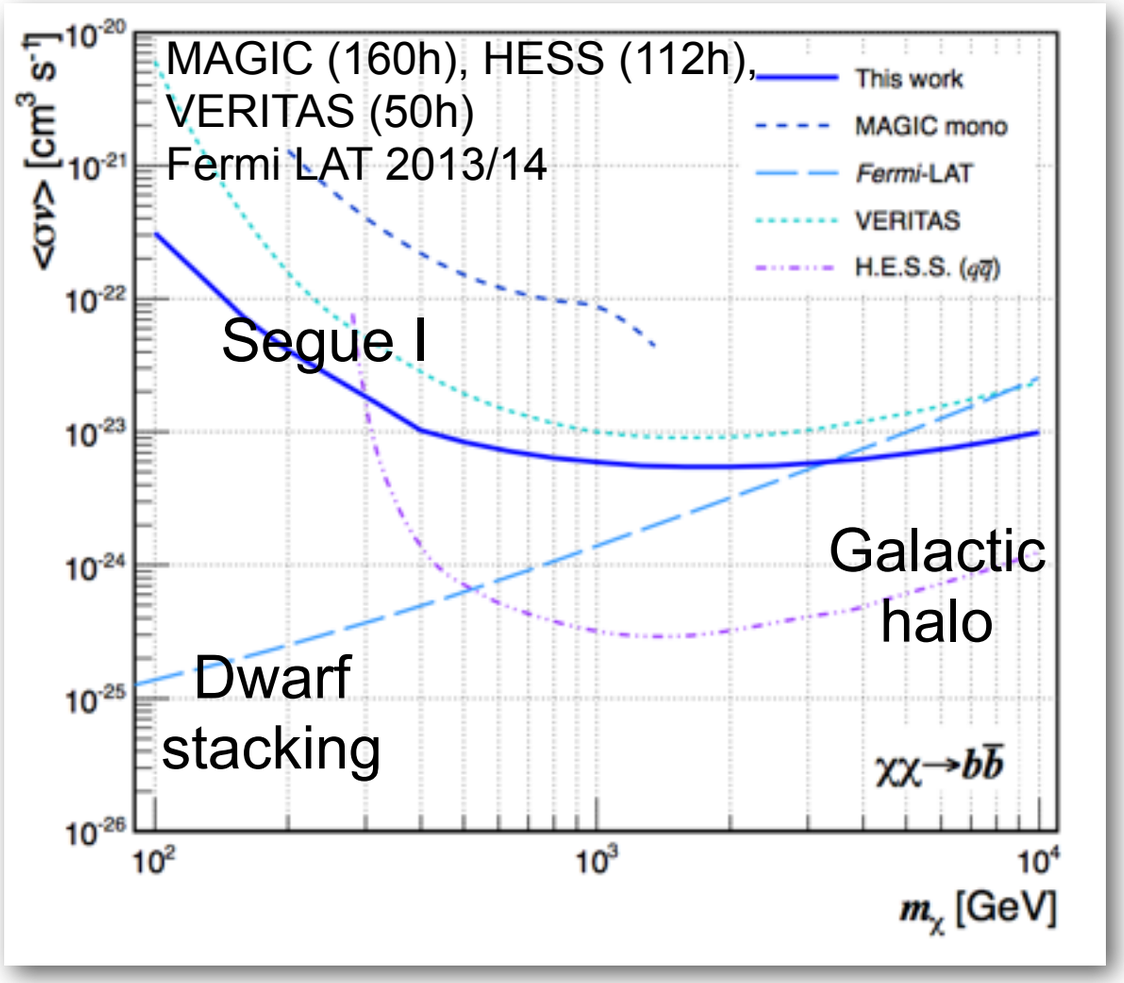
systematics - bright fields



instrument response

Dark matter searches

investigate overdense regions

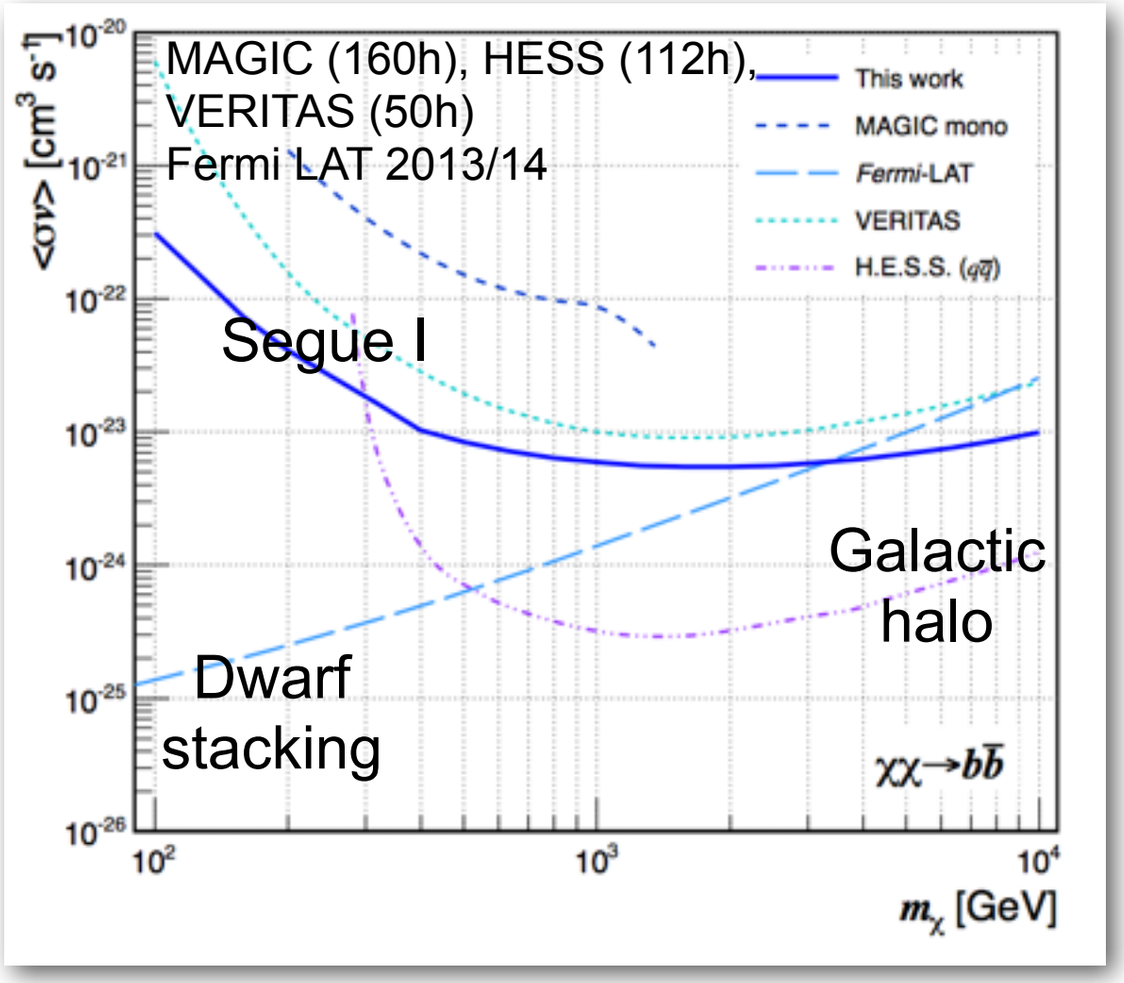


Upper limits for WIMP annihilation into $b\bar{b}$

Start hitting the sensitivity limit of the instruments for many dark-matter searches
+ systematic limits (dwarf J-factors, diffuse galactic emission)

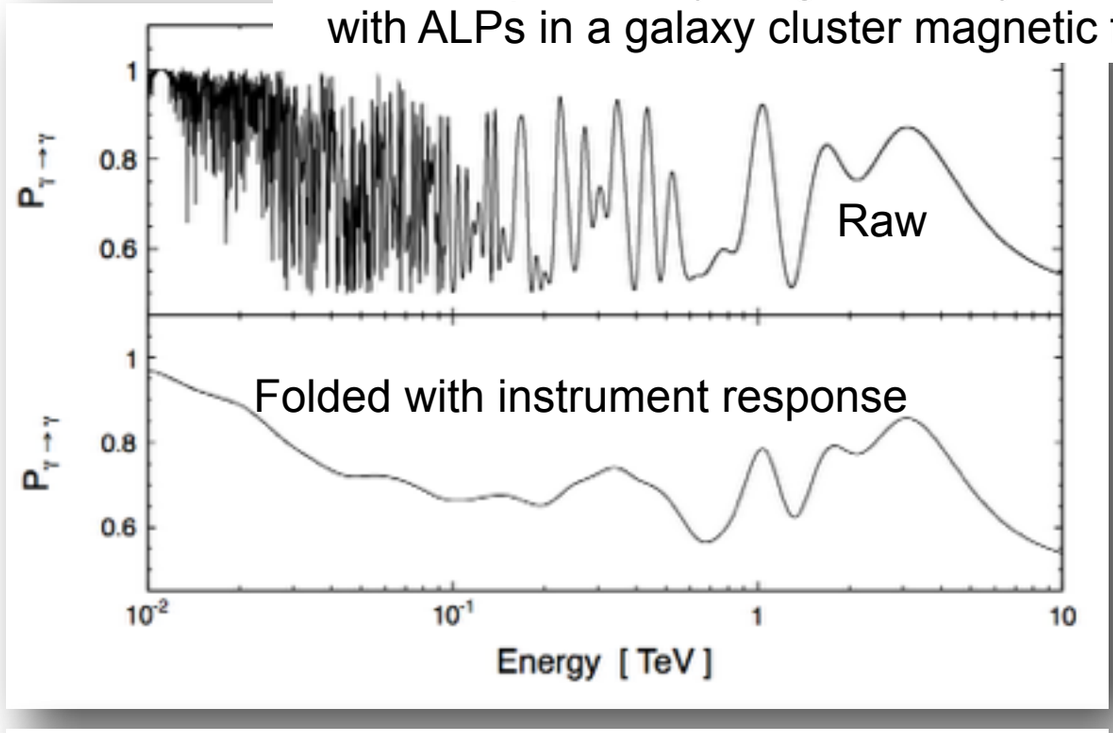
Dark matter searches

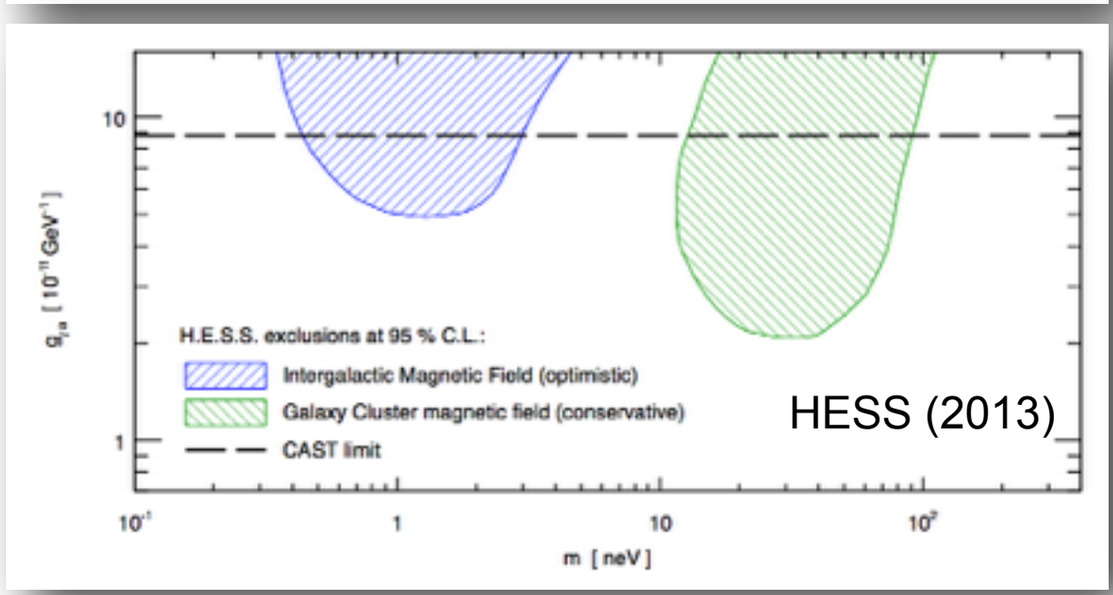
investigate overdense regions



Upper limits for WIMP annihilation into $b\bar{b}$

Survival probability for gamma rays mixing with ALPs in a galaxy cluster magnetic field



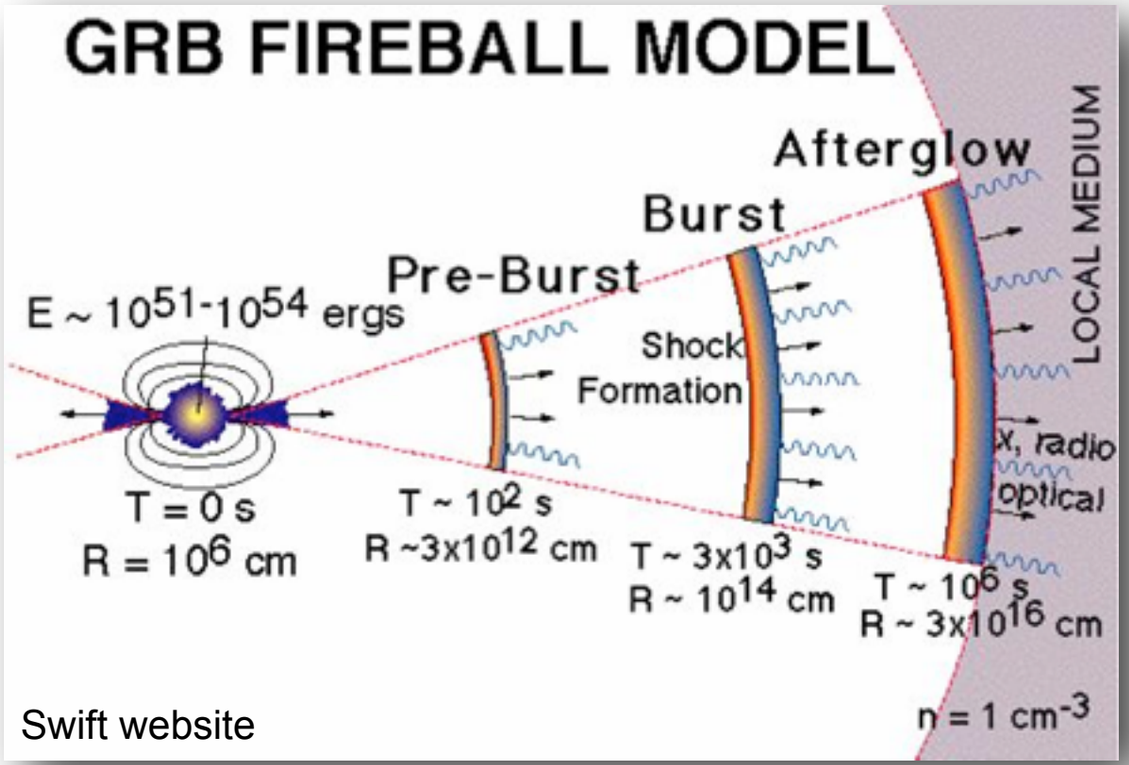


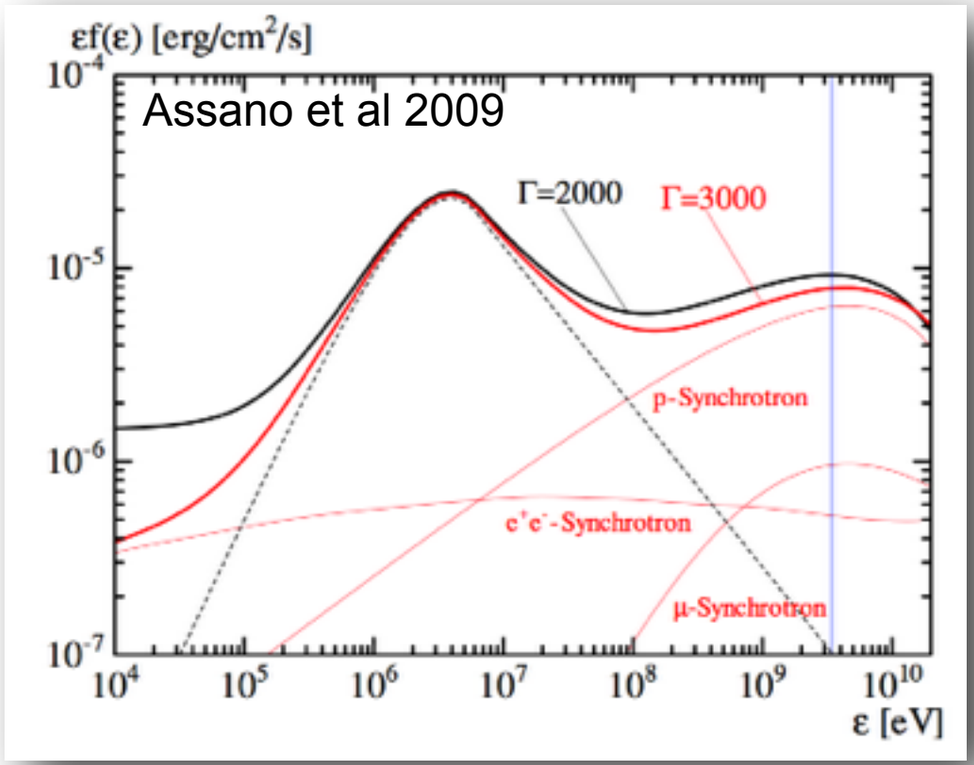
Axion-like particles search: coupling between photons and ALPs

Start hitting the sensitivity limit of the instruments for many dark-matter searches
+ systematic limits (dwarf J-factors, diffuse galactic emission)

Gamma-ray bursts

many unknowns in GRBs: nature of central engine, jet formation, particle acceleration, cosmological evolution, progenitors, …





Constrain the Lorentz factor of the outflow ('compactness'):

$$\Gamma_{\min} \lesssim (1+z)\frac{E_{\mathrm{ph,max}}}{m_e c^2} \approx 2000(1+z)\left(\frac{E_{\mathrm{ph,max}}}{1\mathrm{GeV}}\right).$$

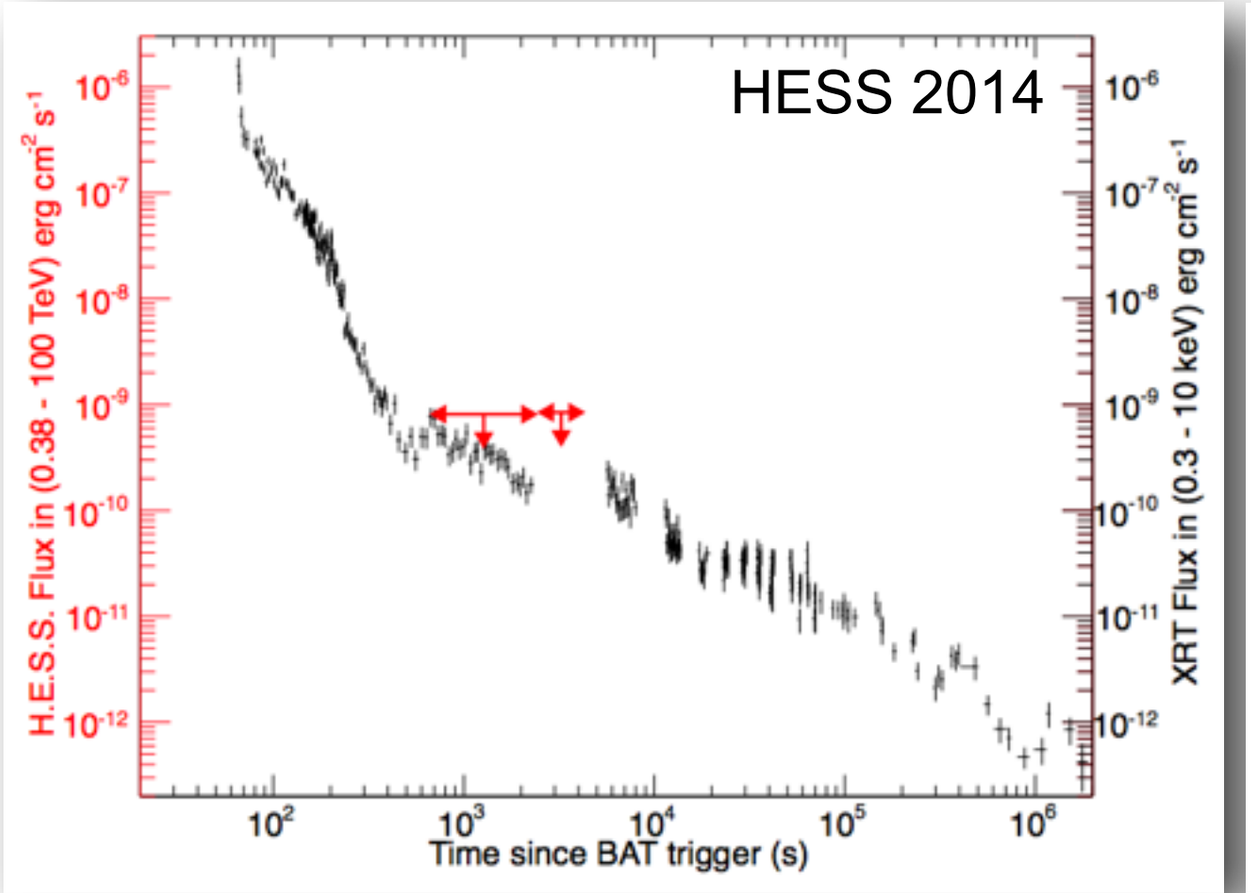
Are GRBs sources of ultra-high energy cosmic rays?

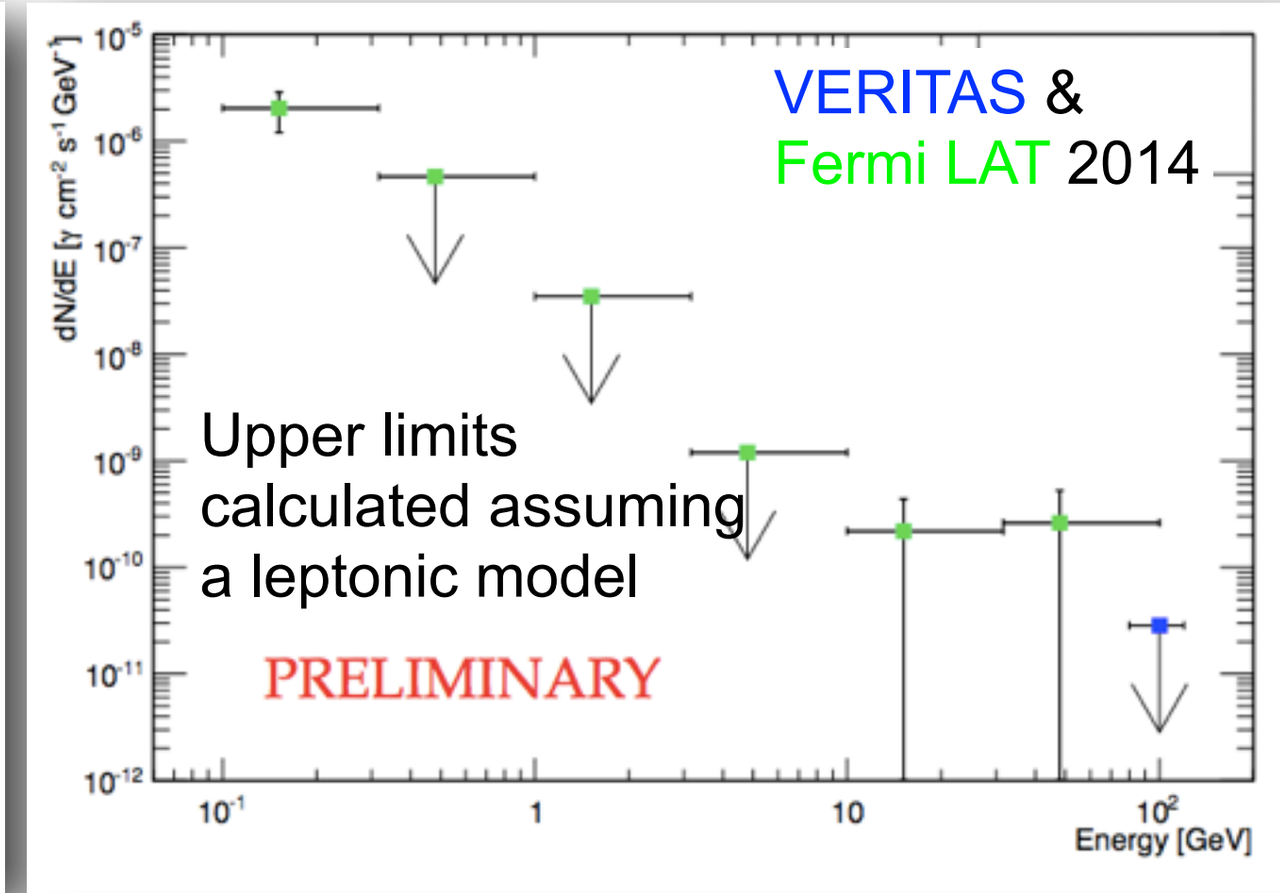
Temporal development crucial
(e.g. different time scale of leptonic and hadronic acceleration)

Gamma-ray bursts observations

GRB 100621A: one of the brightest X-ray sources ever detected by Swift (z=0.5)

The exceptional bright and nearby GRB 130427A (z=0.34): LAT photon at 95 GeV



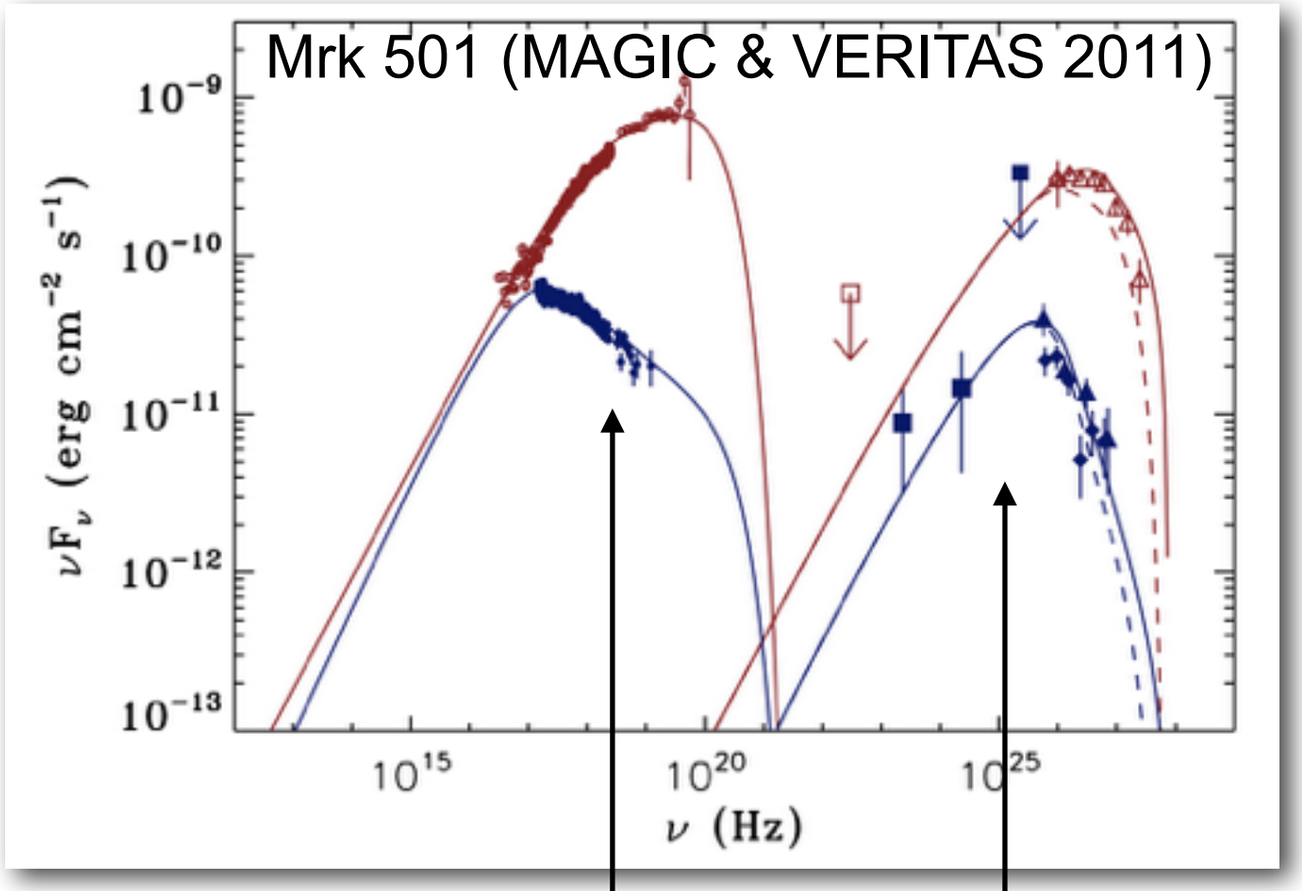


Fluence ratio X-ray/Gamma-ray >0.4
Constrains leptonic models, as X and Gamma-ray emission is closely connected

Probably best change until now to detect a GRB with a ground-based VHE instrument

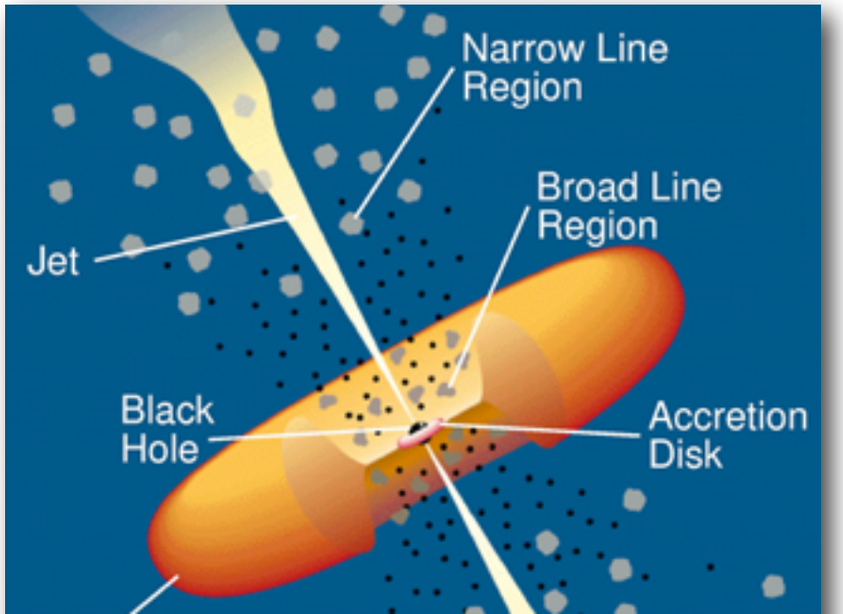
Active Galactic Nuclei

- among most energetic phenomena in the Universe
- powered by supermassive black hole (energy source is accretion on and/or rotation of BH)
- beamed non-thermal emission (geometrical selection)
- double peaked spectral energy distribution
- variability in every band and on every time scale tested

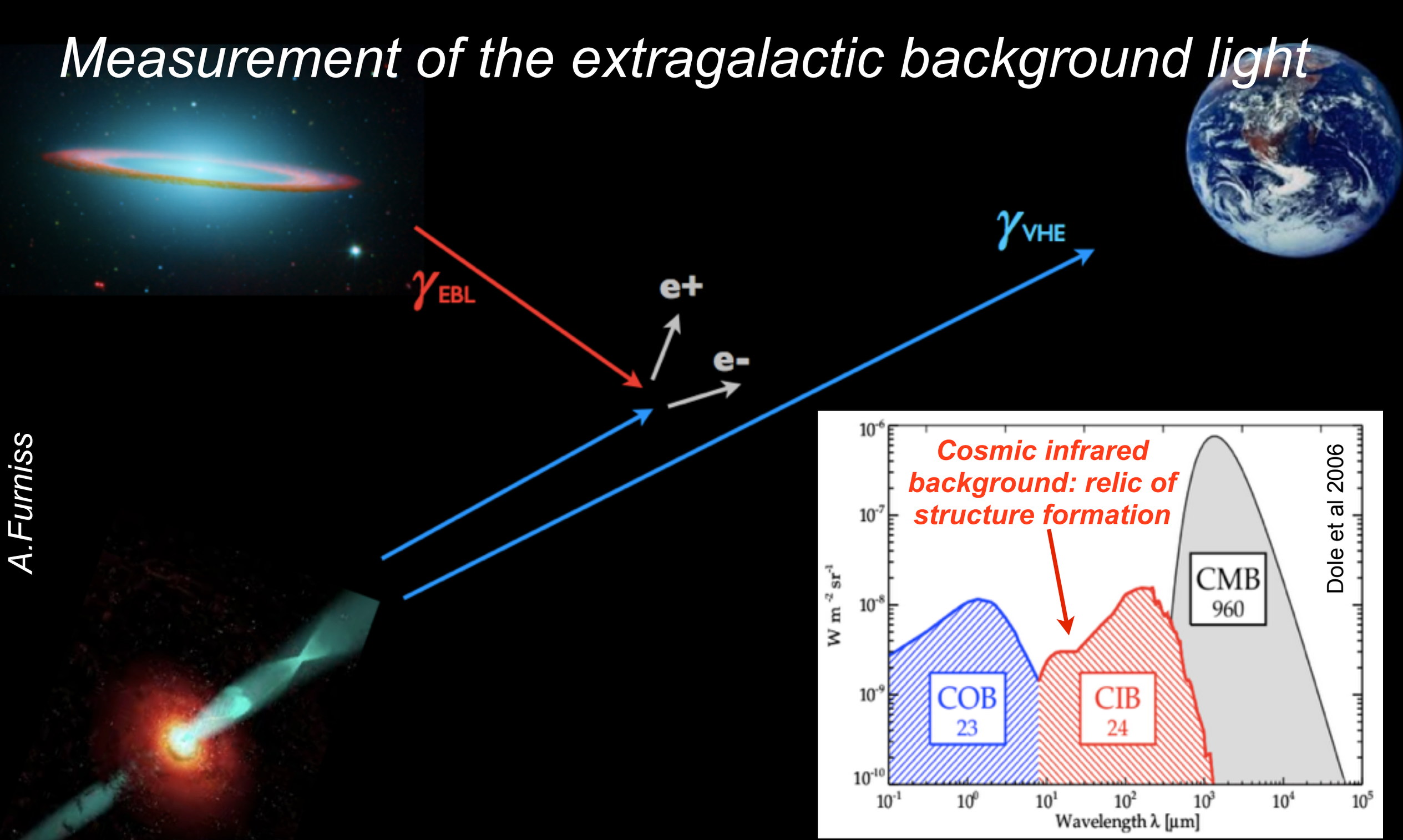


synchrotron radiation from leptons

Inverse Compton scattering and/or hadronic production



Measurement of the extragalactic background light



expect a unique redshift-dependent imprint on γ-ray spectra

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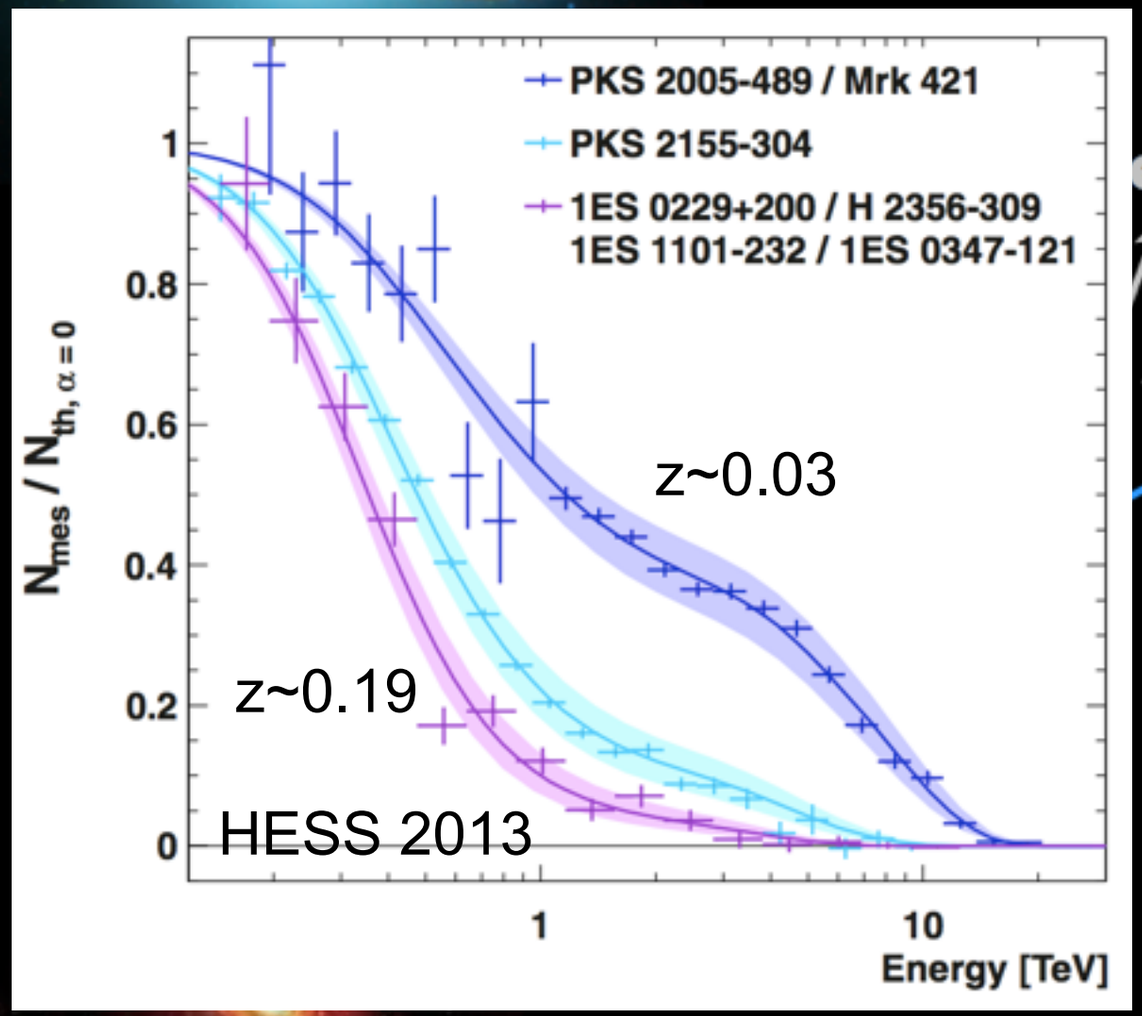
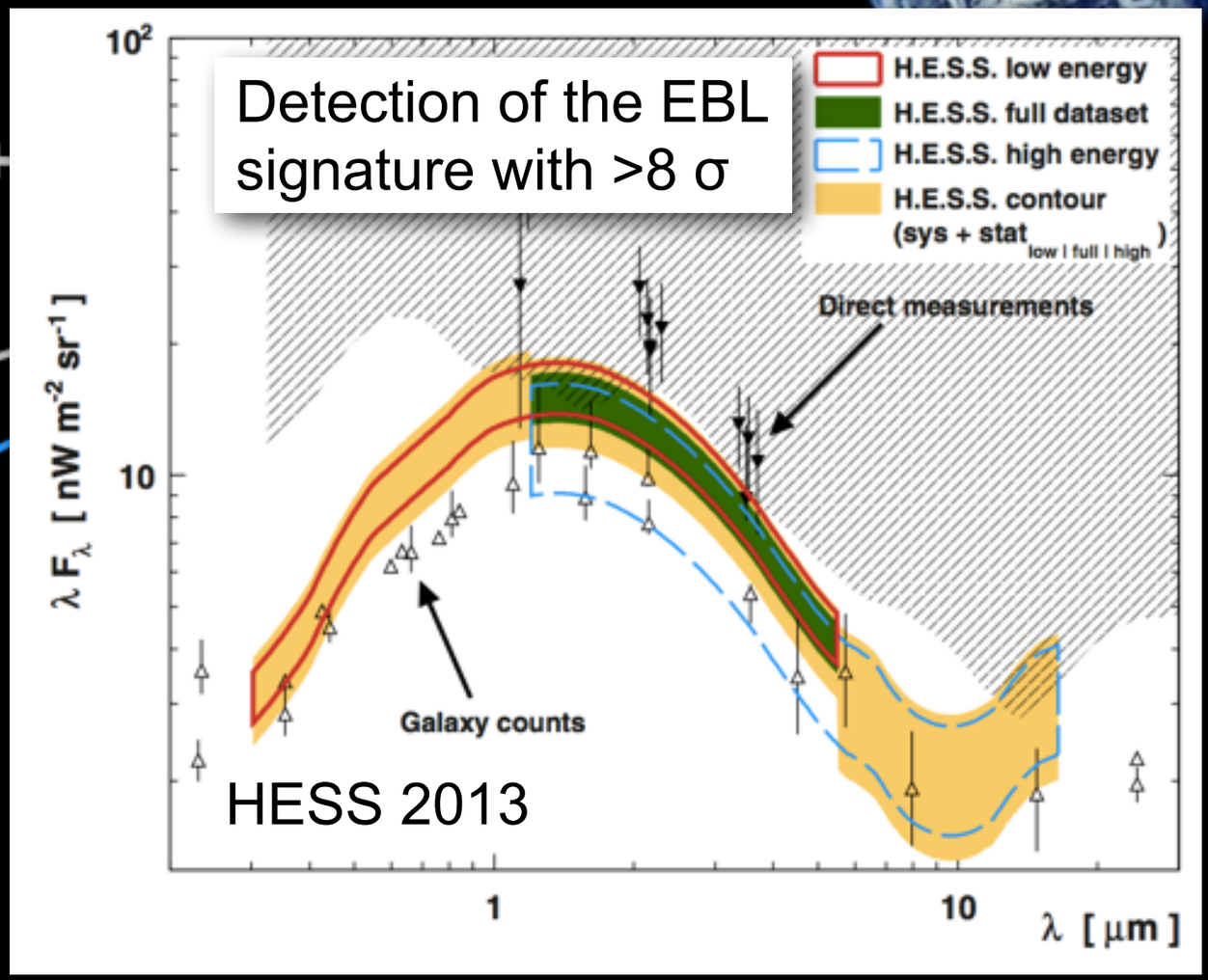
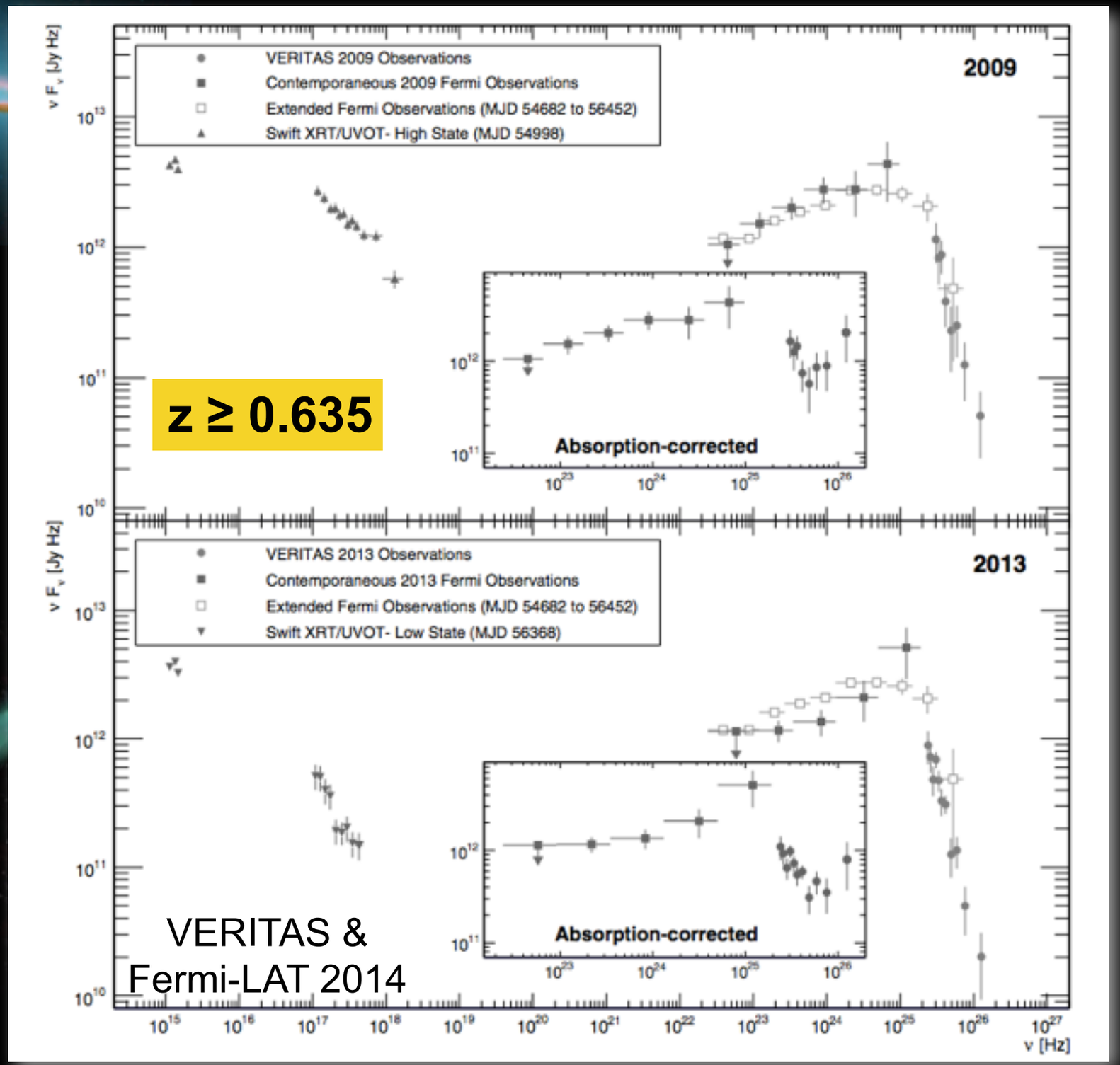




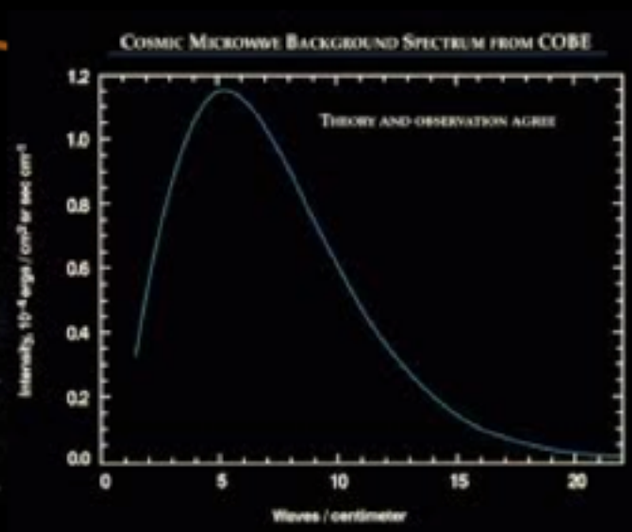
detection of redshift-dependent imprint on γ-ray spectra of bright blazars

Measurement of the extragalactic background light



PKS 1424+240
(see also MAGIC 2014)

Measurement of the extragalactic background light

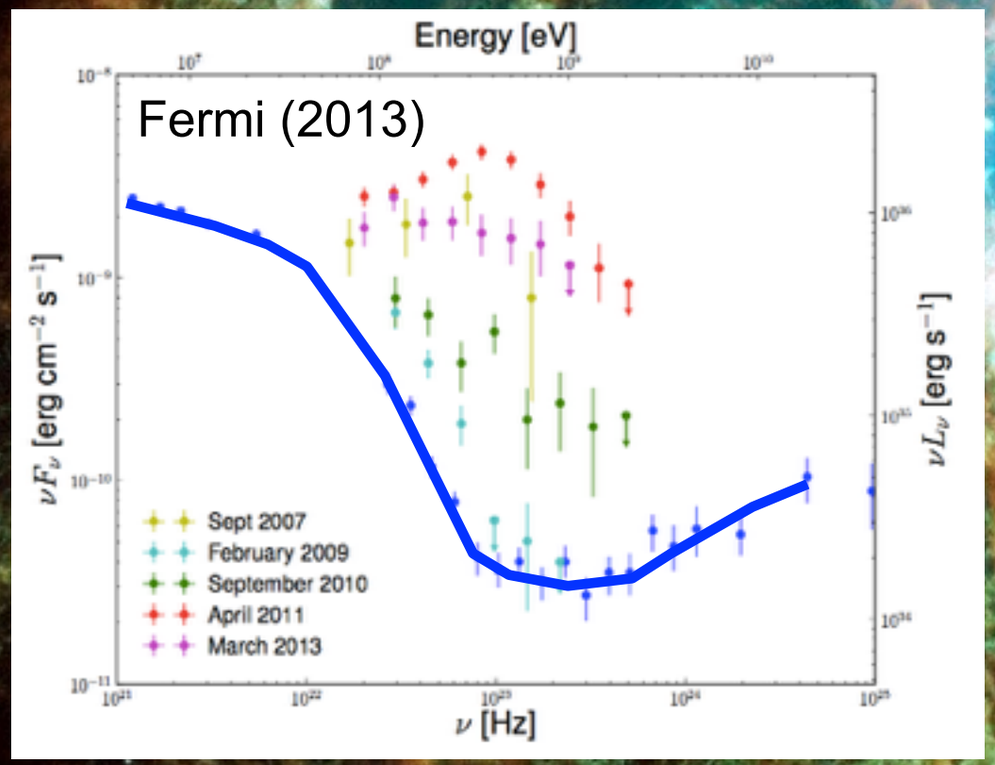


PKS 1424+240

A.Furniss

Variability of the Crab Nebula

- historically the standard candle in VHE astronomy
- LAT & Agile discovered variations of ~30 >100 MeV on 6 h time scales
- Flares appear at the end of the synchrotron component
- origin of flares not clear



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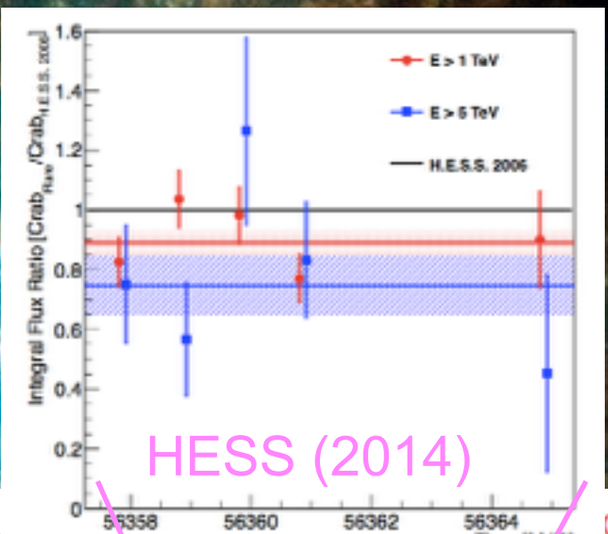
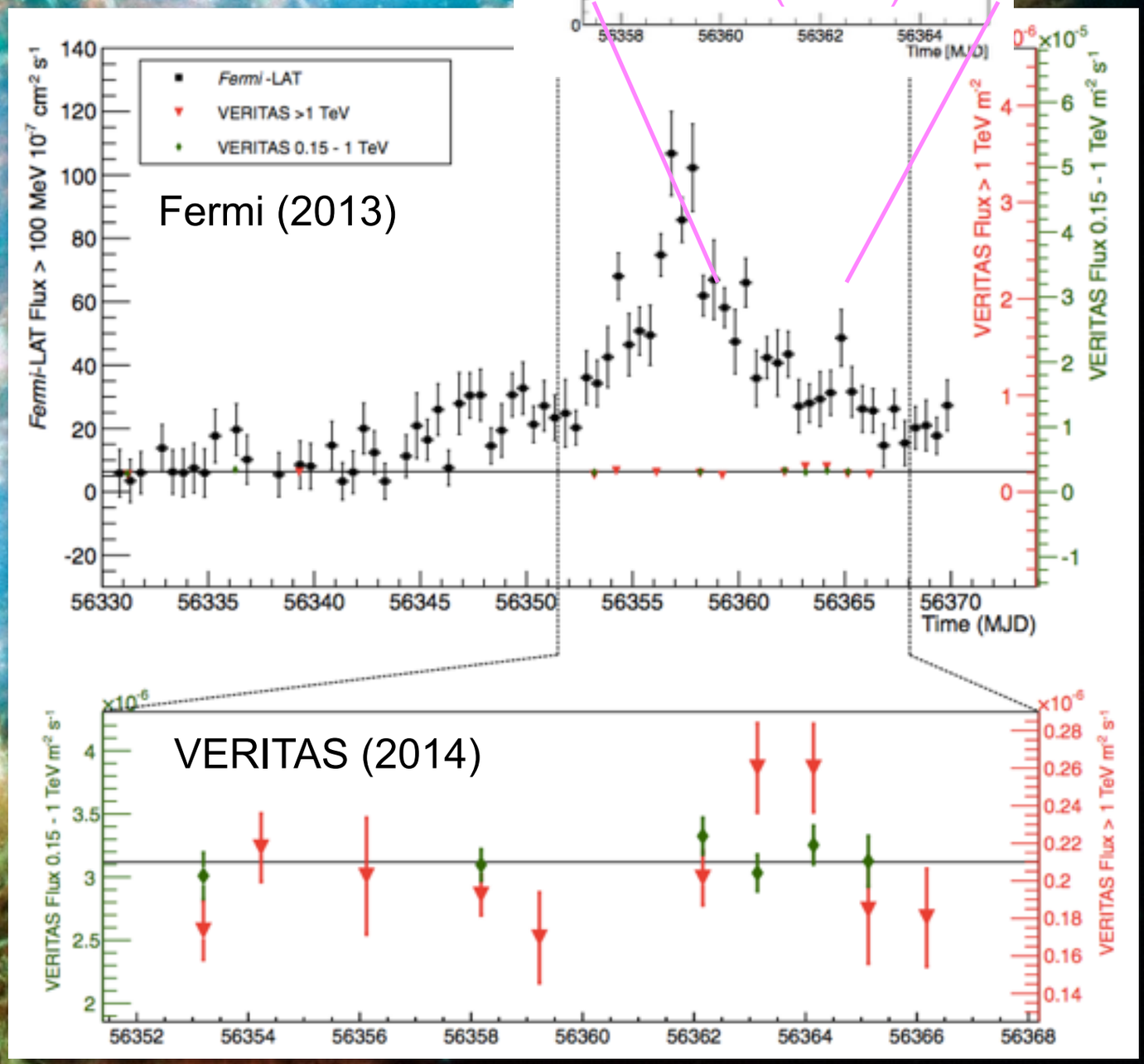
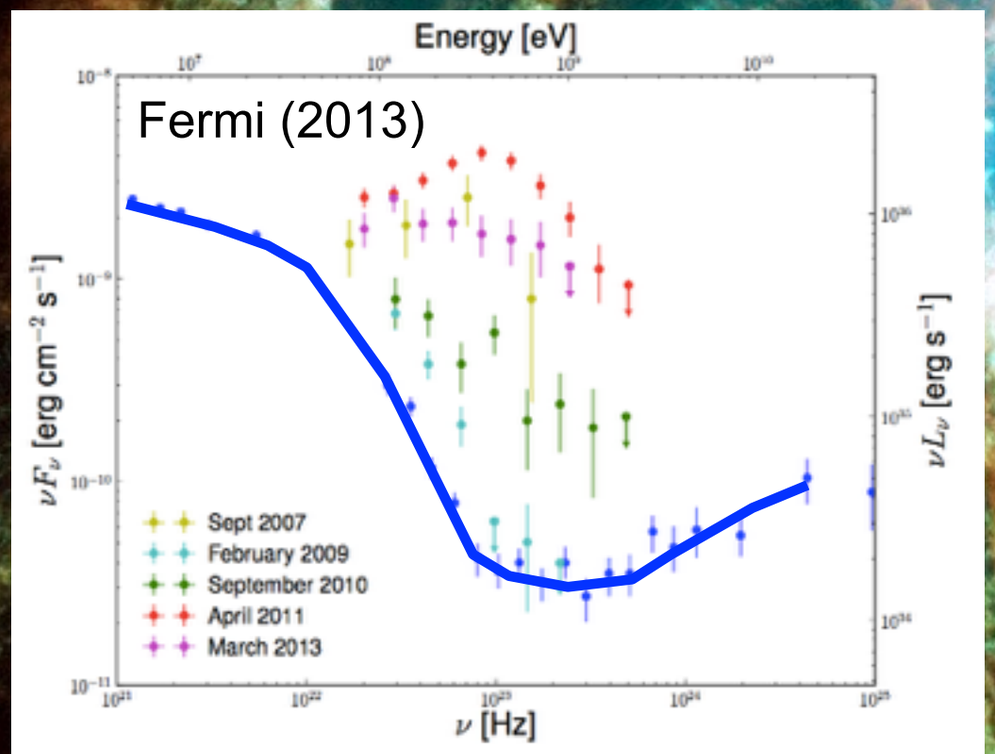


HESS (2014)

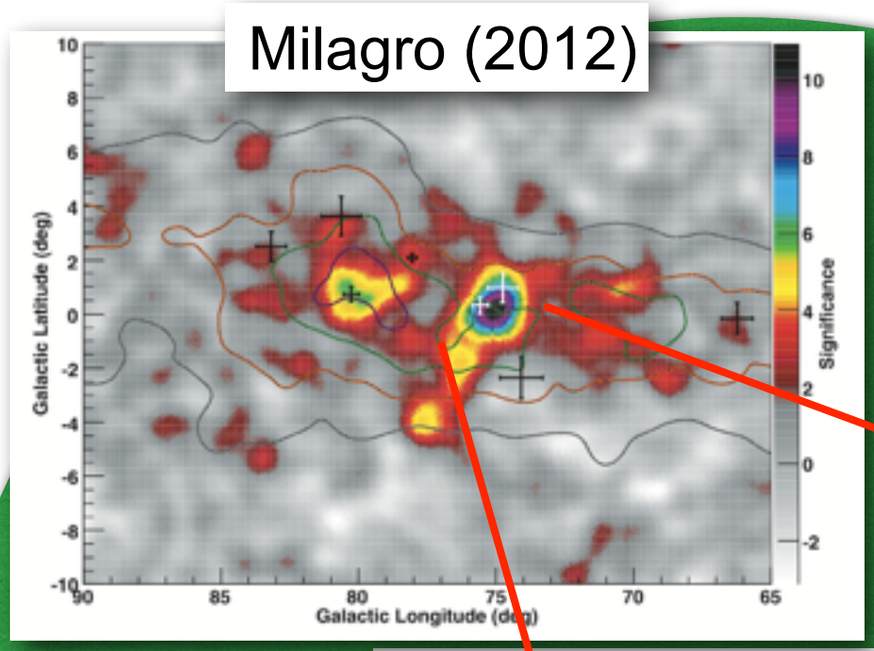


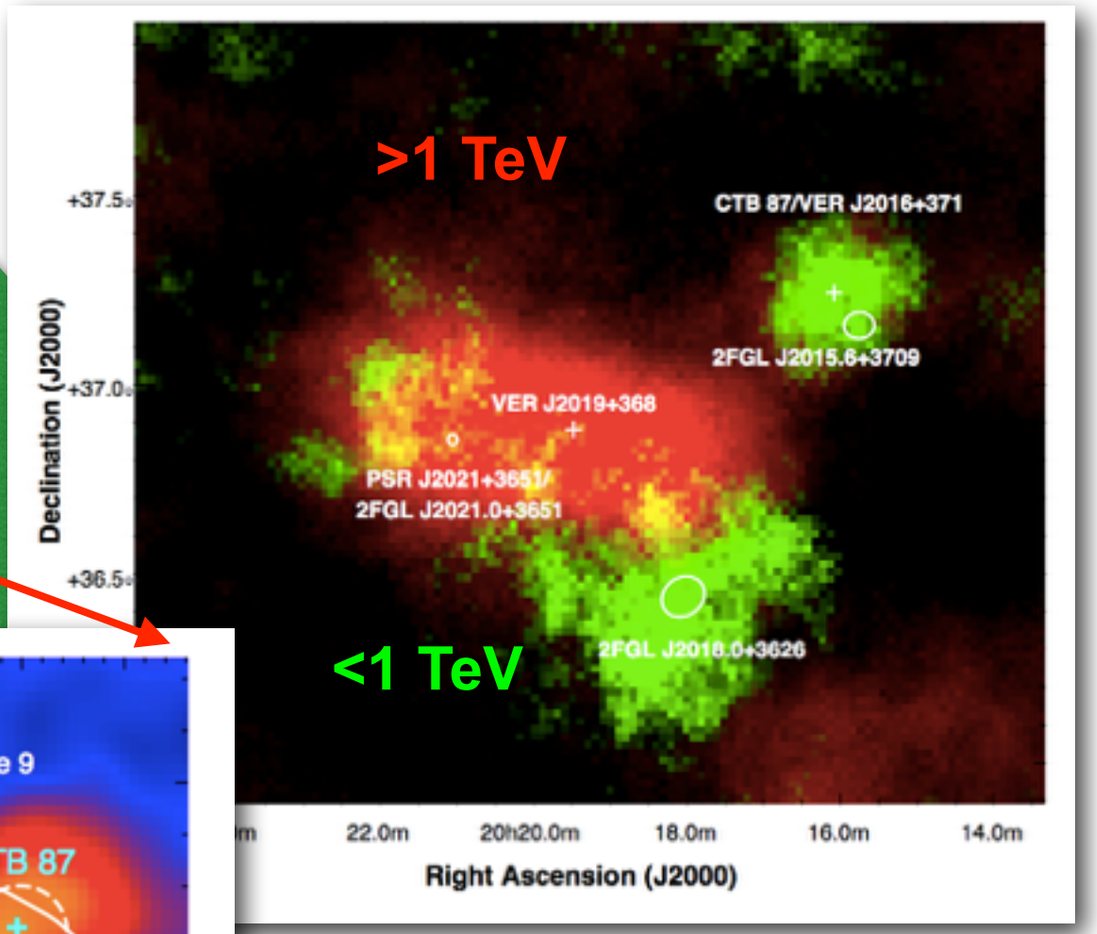
Fermi (2013)

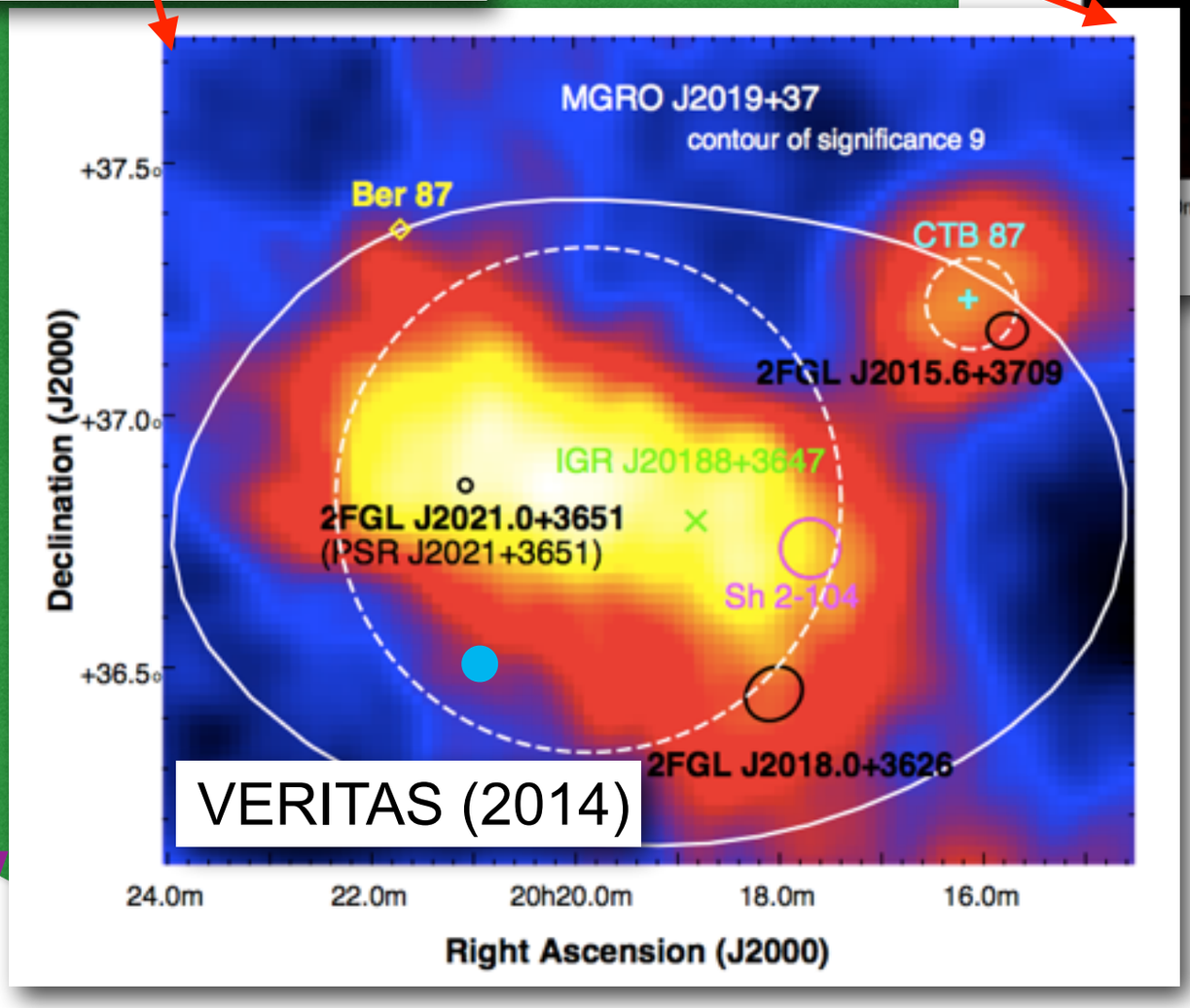


VERITAS (2014)

Milagro sources resolved







Milagro
0.6^0 @ 10 TeV

HAWC
0.15^0 @ 10 TeV

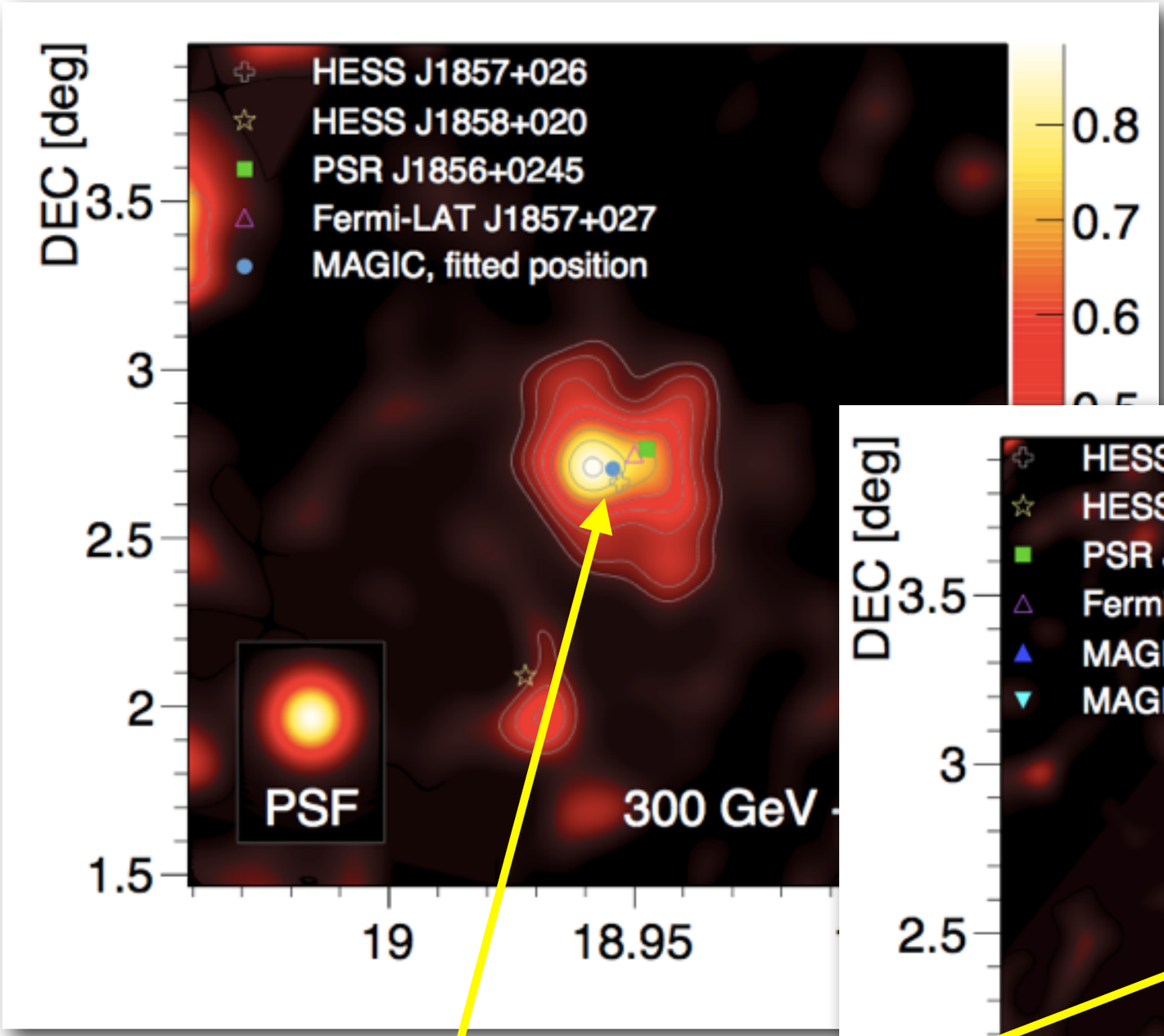
H.E.S.S./
MAGIC/
VERITAS
0.07^0 @ 1 TeV

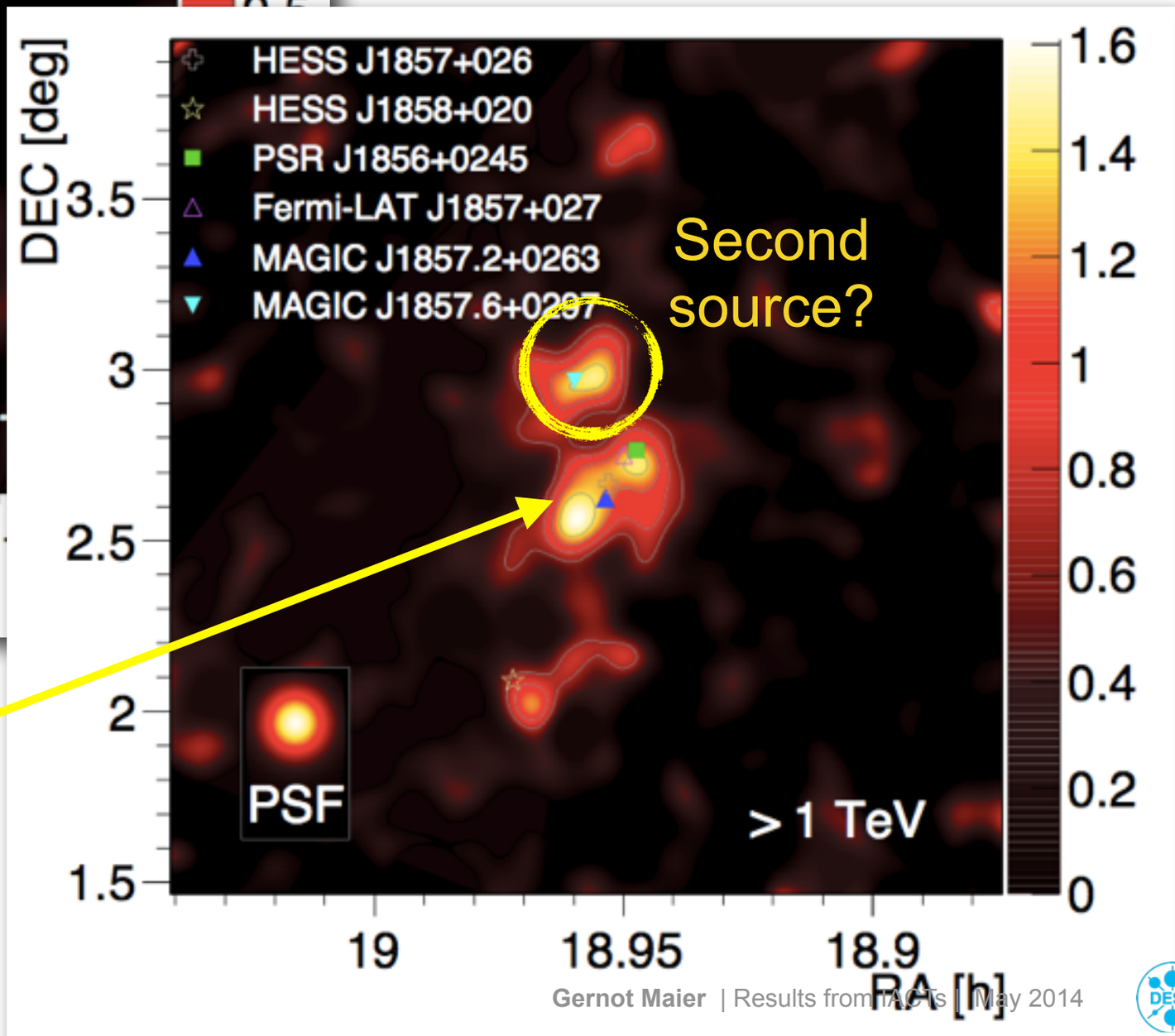
CTA
0.04^0 @ 1 TeV

(68% containment radii for angular resolution values)

Complex Morphologies in Pulsar Wind Nebulae

HESS J1857+026
HESS J1858+020
MAGIC J1857.2+0263
MAGIC J1857.6+0297
Fermi-LAT J1857+057

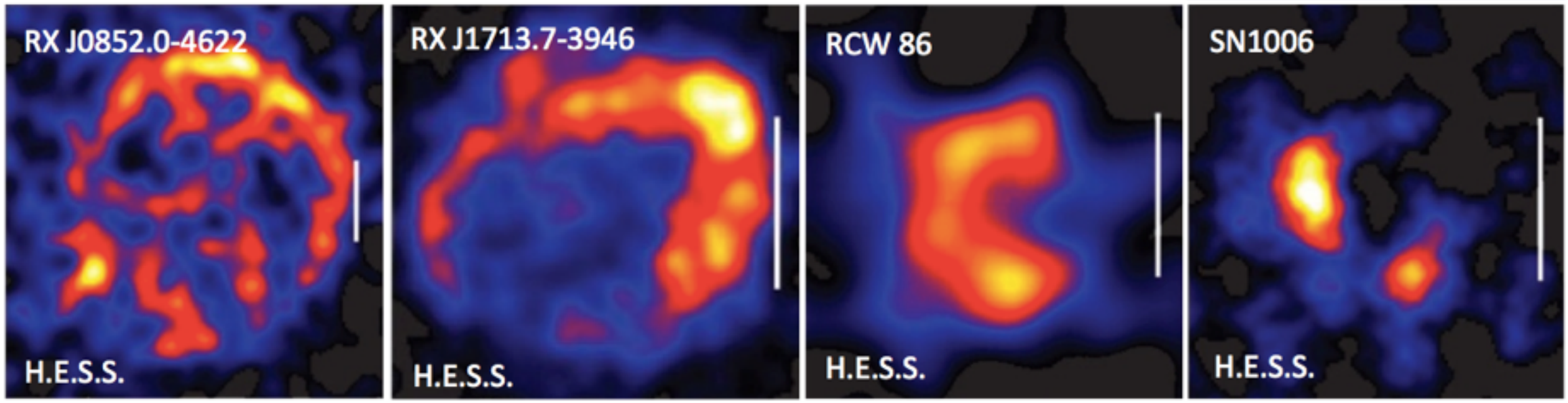


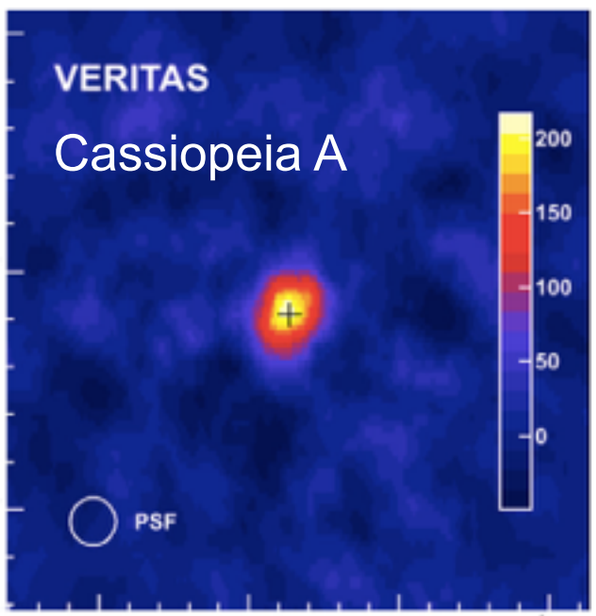


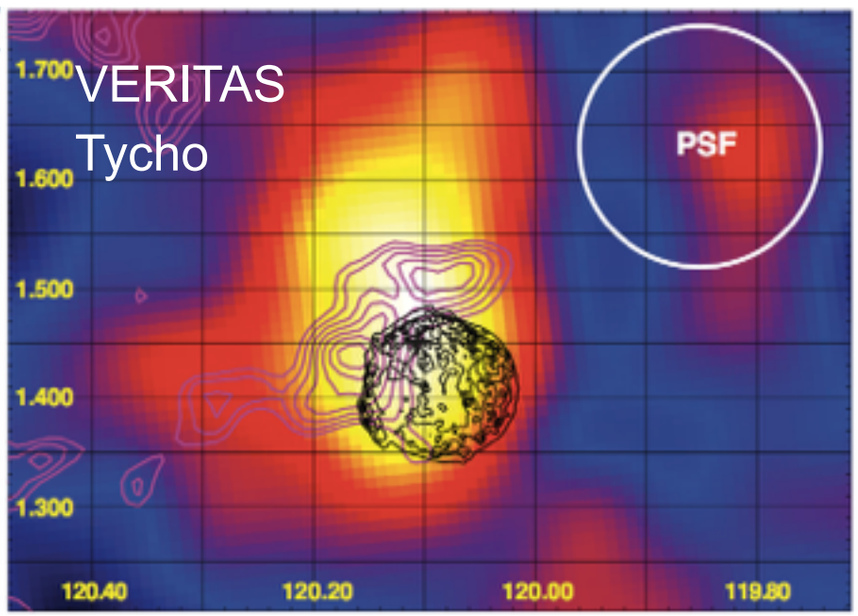
Leptonic emission from pulsar wind nebula?
(lower-energy electrons can diffuse further out of the nebula)

Particle acceleration in Supernova Remnants

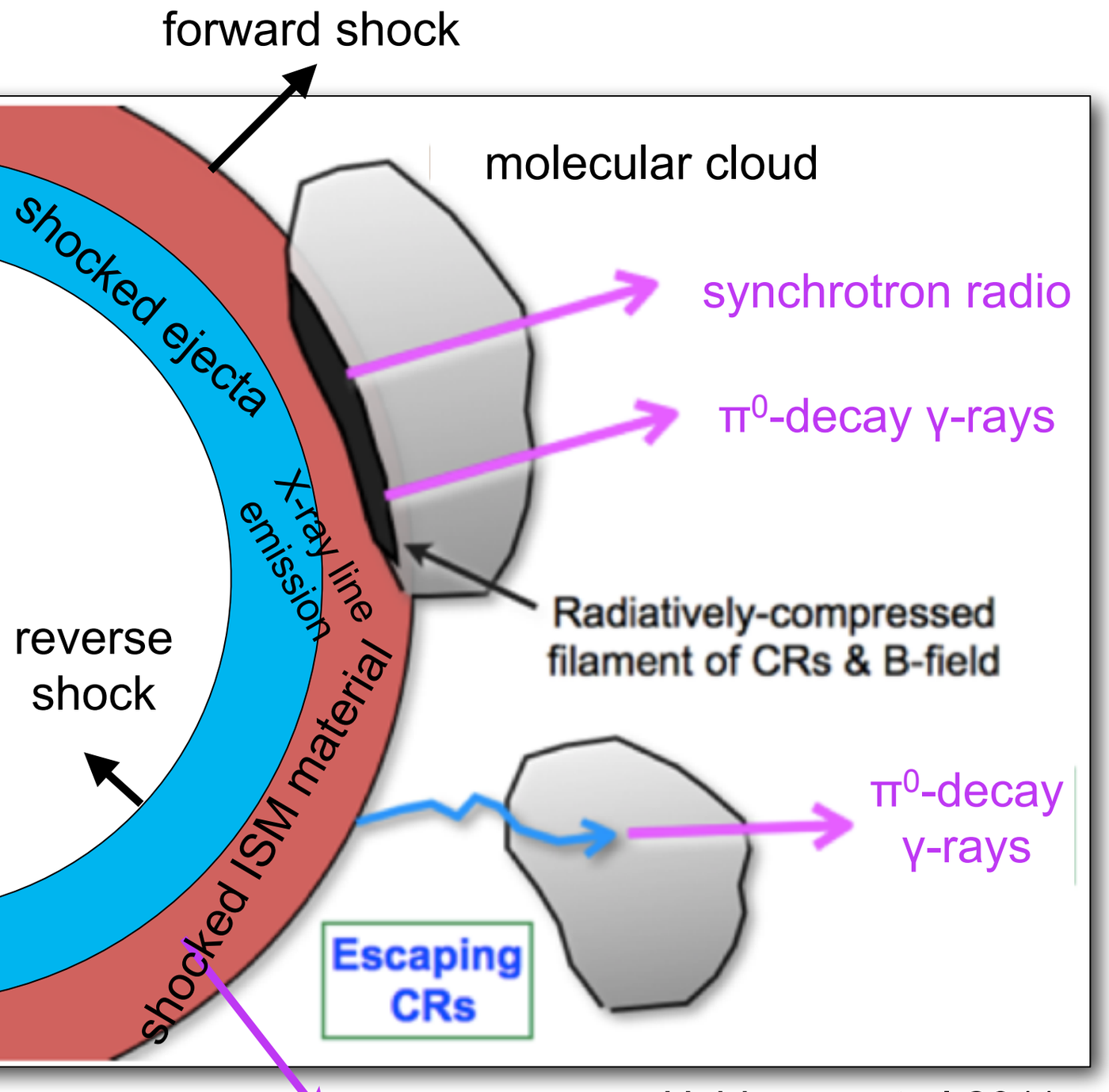
It is very hard to image a supernova remnant which does not accelerate







Particle acceleration in Supernova Remnants



Uchiyama et al 2011
Ellision et al 2014

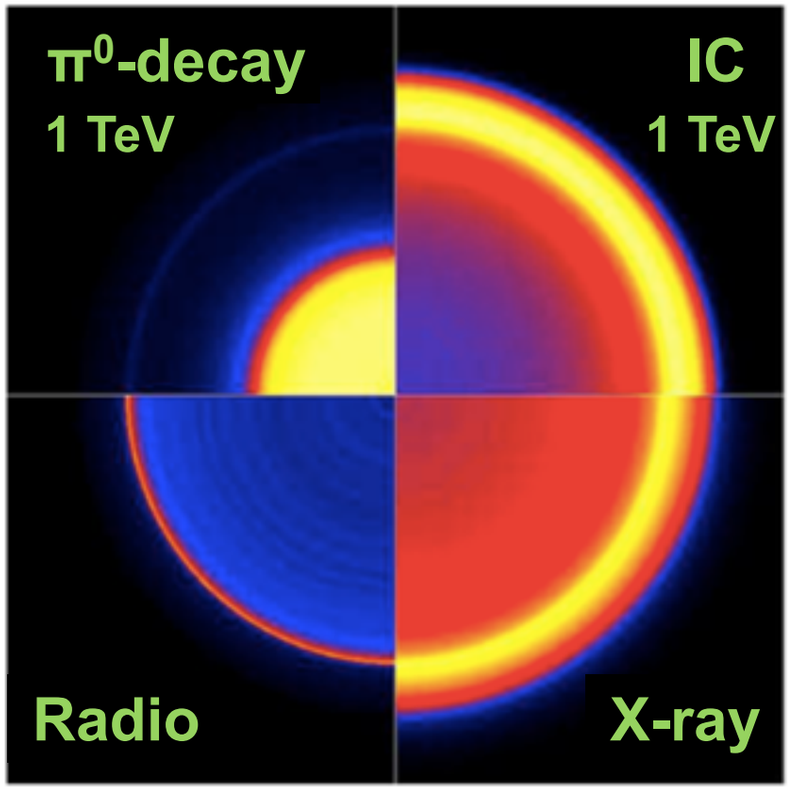
Amazingly complex models needed to explain broadband emission:

- hydrodynamic of evolving SNR ↕ feedback
- non-linear diffusive shock acceleration
- Non-equilibrium ionization for X-ray line emission at forward and reverse shocks
- ejecta composition
- magnetic field amplification
- electron and ion distributions from thermal to relativistic energies
- photon emission
- cosmic-ray propagation

Coupling of thermal and non-thermal emission

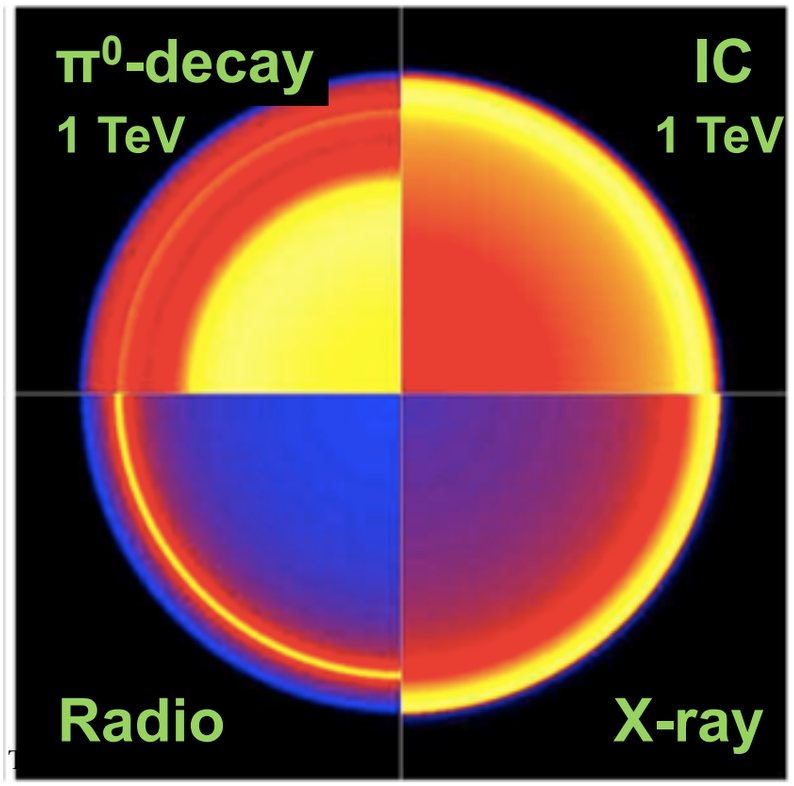
Young supernova remnants - modeling

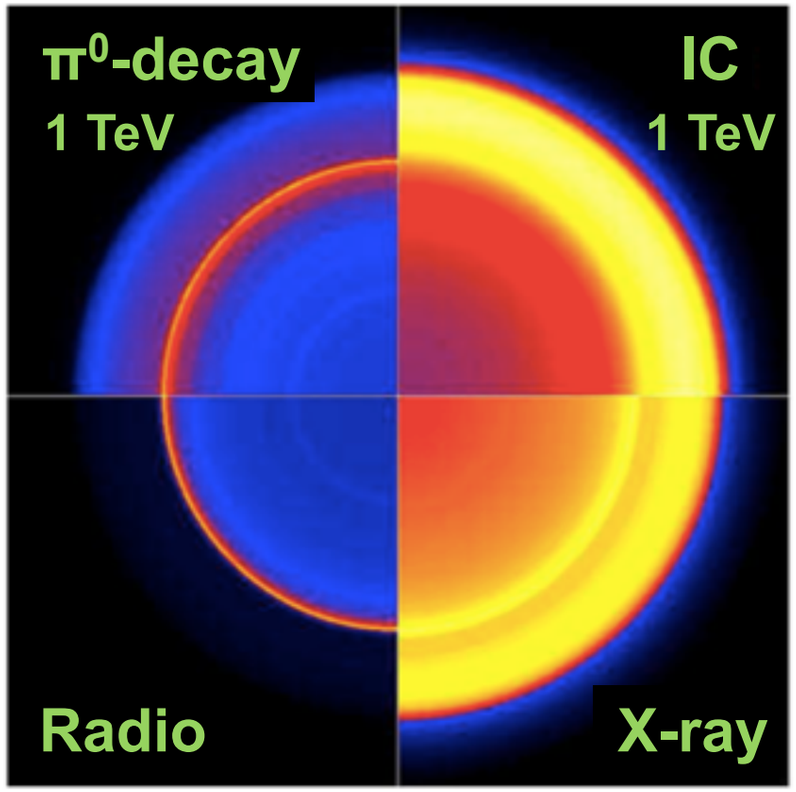
400 years



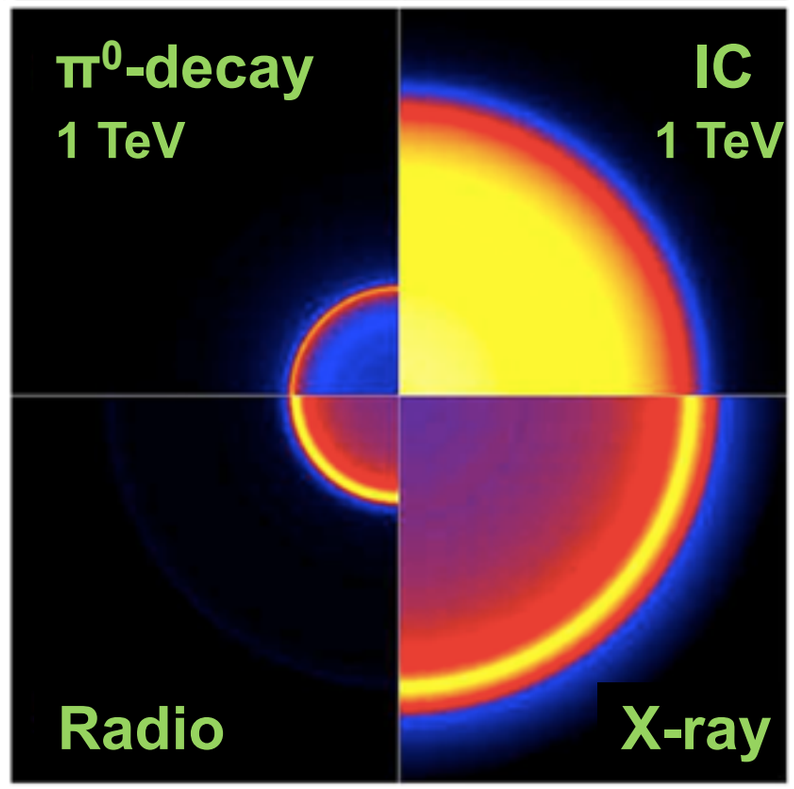
SNR Type Ic
(Wolf Rayet, fast, low density wind)

2000 years





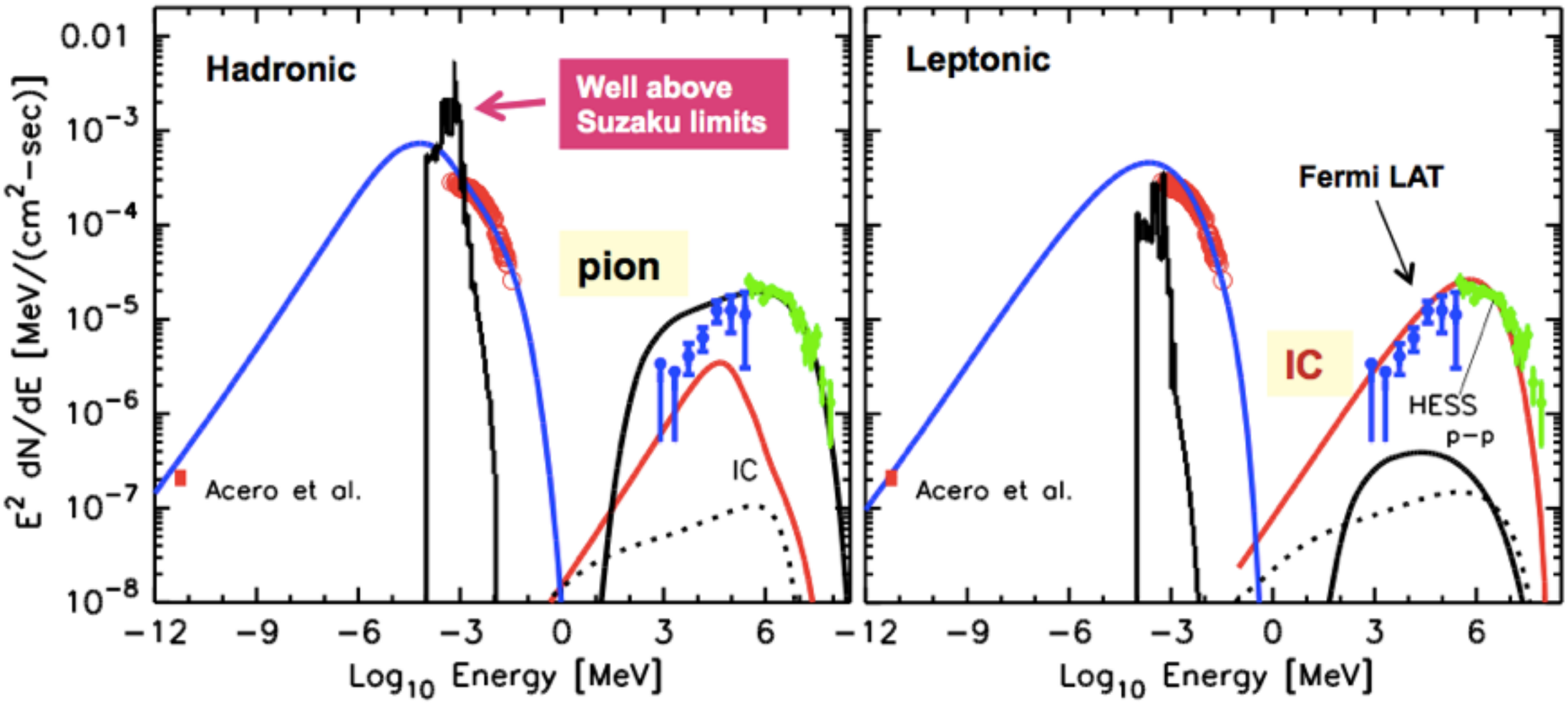
SNR Type IIb
(Red SG, slow, high density wind)



Telezhinsky et al (2013)

Supernova remnants - RXJ 1713.7-3946

Core-collapse or type Ia SNR?



Hadron model parameters:

→ $n_p = 0.2$ cm^{-3}

→ $e/p = K_{ep} = 5\ 10^{-4}$

$B_2 = 45$ µG

Lepton model parameters:

→ $n_p = 0.05$ cm^{-3}

→ $e/p = K_{ep} = 0.02$

$B_2 = 10$ µG

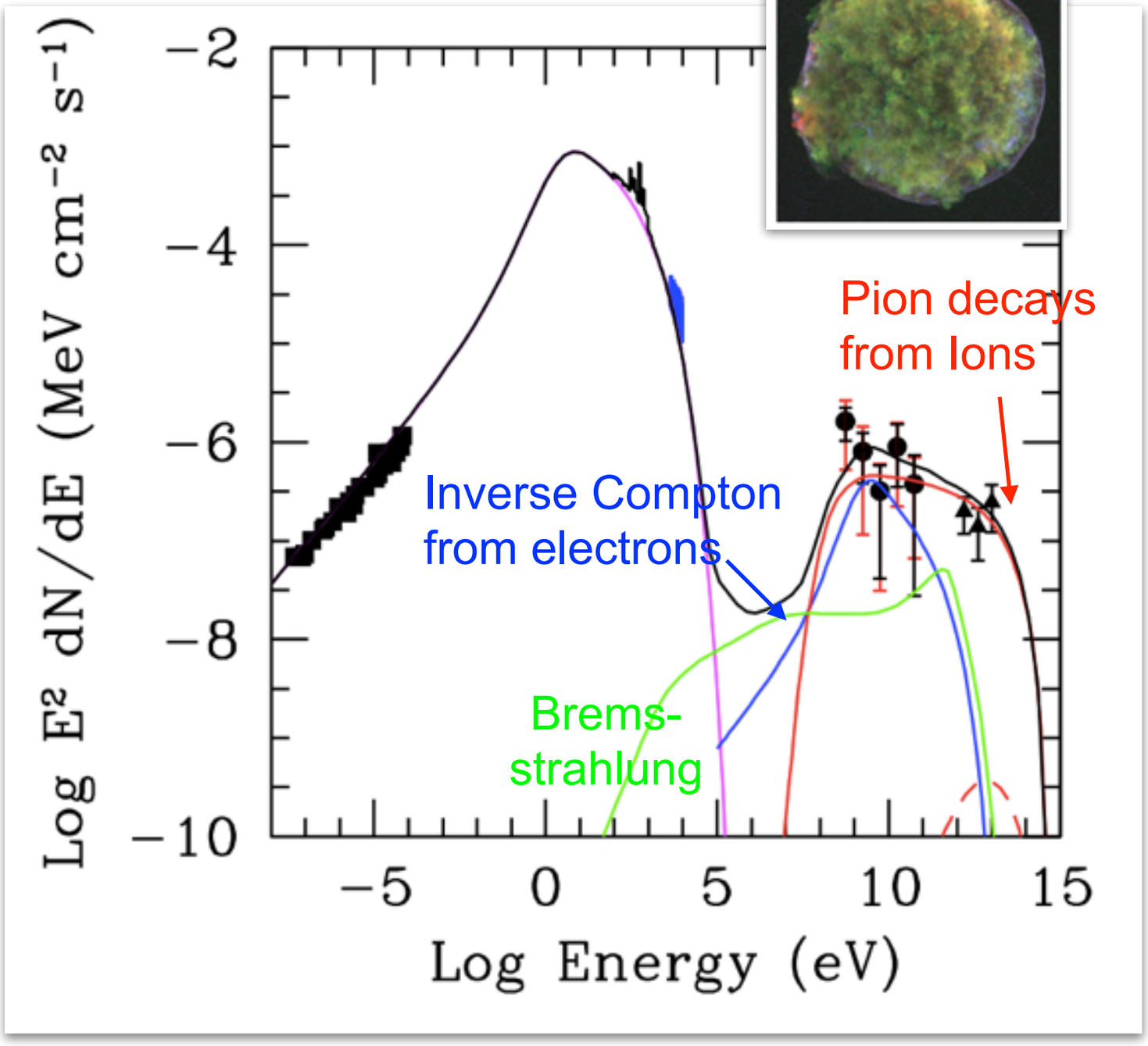
Uniform ISM model: Ellison, Patnaude, Slane & Raymond ApJ 2010

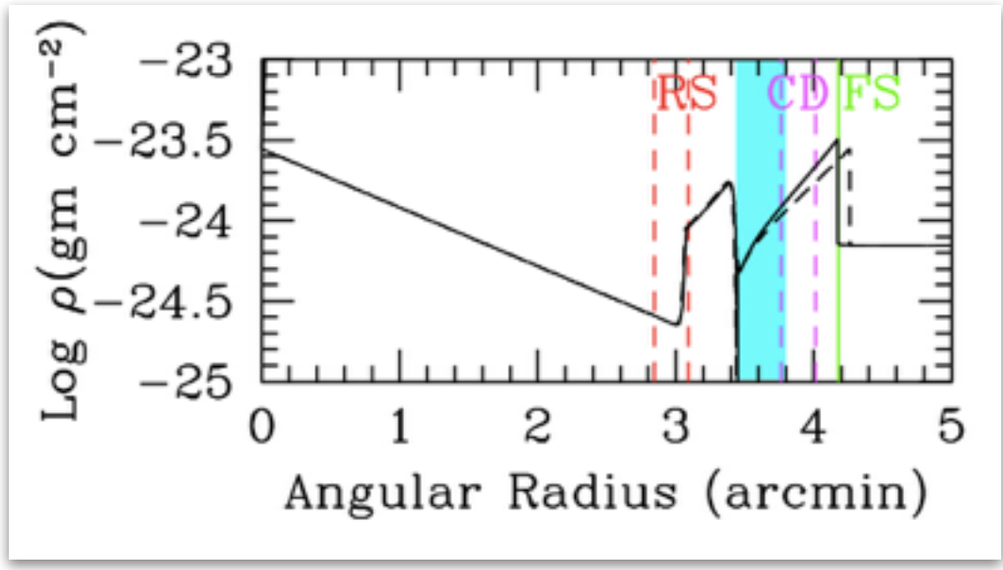
see also updated models in Lee et al 2012, Ellison et al 2012

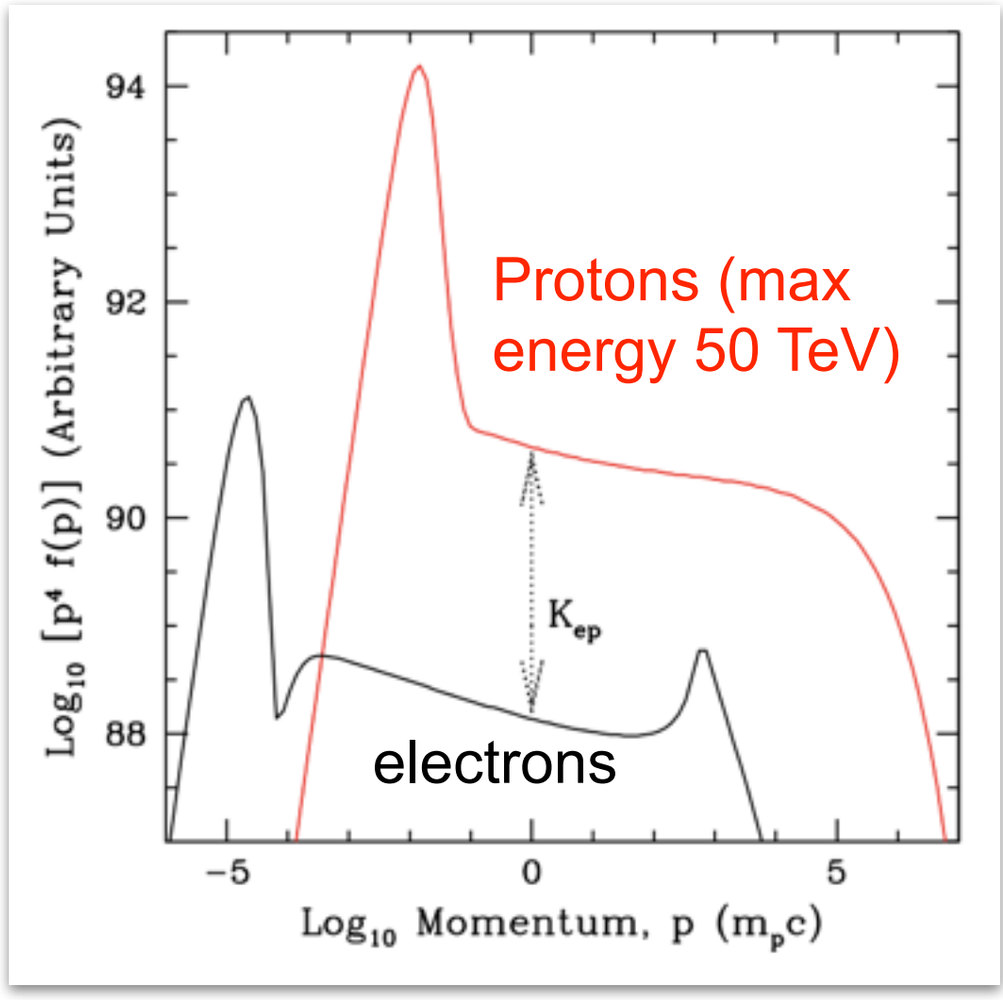
Even in IC dominated model: majority of CR energy (99%) is in ions

Supernova remnants - Tycho

Type Ia SNR; 1572





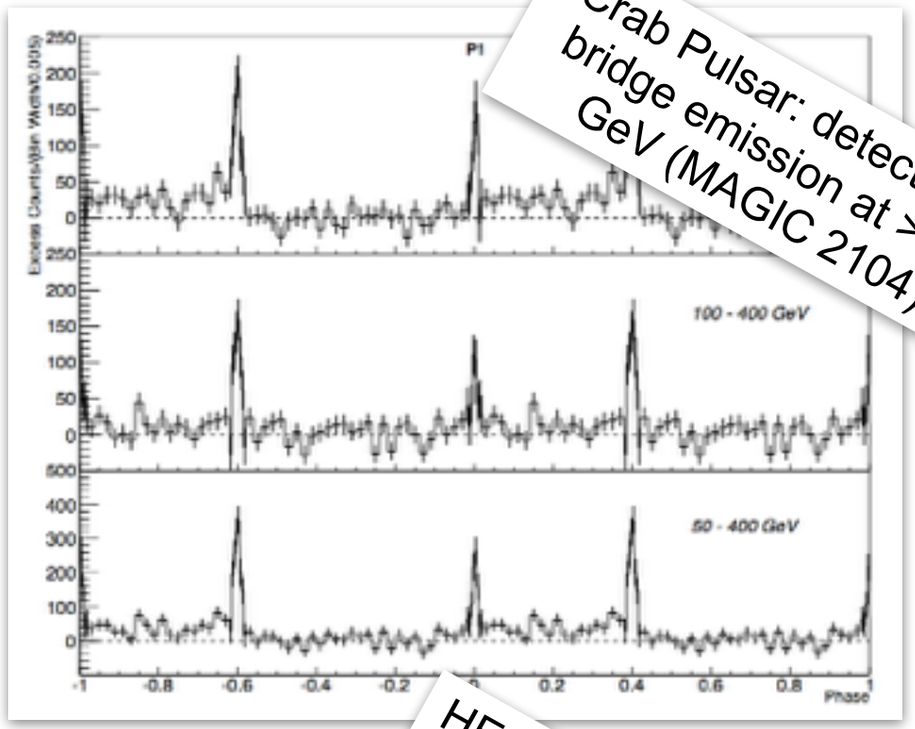


~16% of SNR kinetic energy is placed into relativistic particles

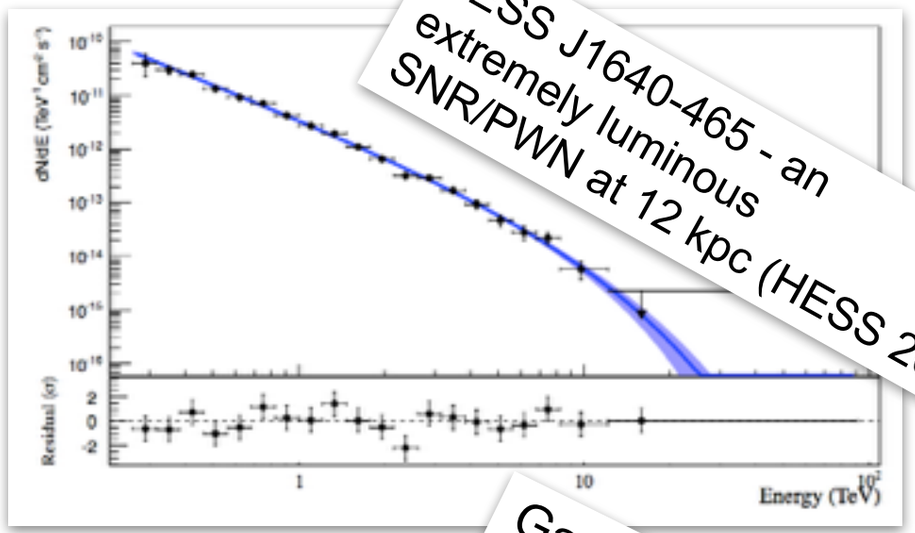
Slane et al 2014
(also Morlino & Caprioli (2012); Berezhko et al. (2013))

Conclusions

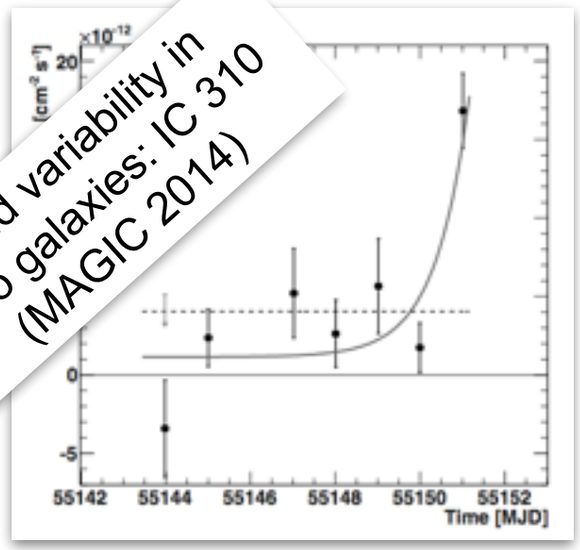
- astrophysics, cosmology and fundamental physics
  - origin of Cosmic Rays, black hole accelerators
  - dark matter particles, Lorentz invariance, …
- all major observatories (HESS, MAGIC, VERITAS with significant upgrades
  - close to 10,000 h of observations with each observatories
  - deep studies & sophisticated modeling
- large synergies with Fermi LAT, HAWC and other observatories
- CTA: 10x higher sensitivity…



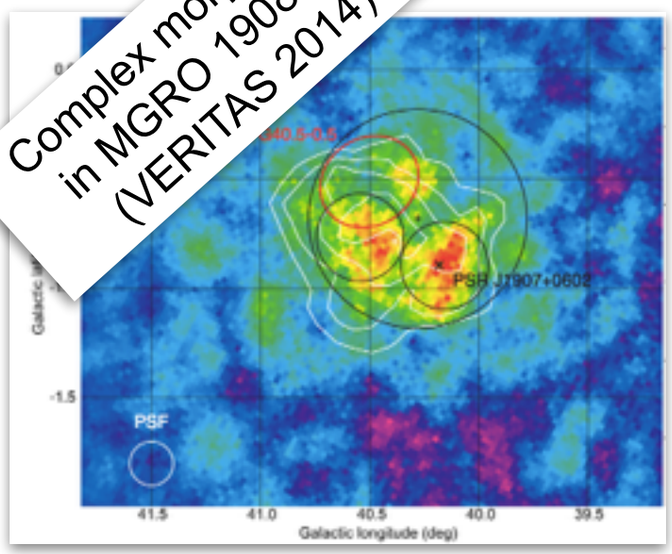
Crab Pulsar: detection of bridge emission at >100 GeV (MAGIC 2104)



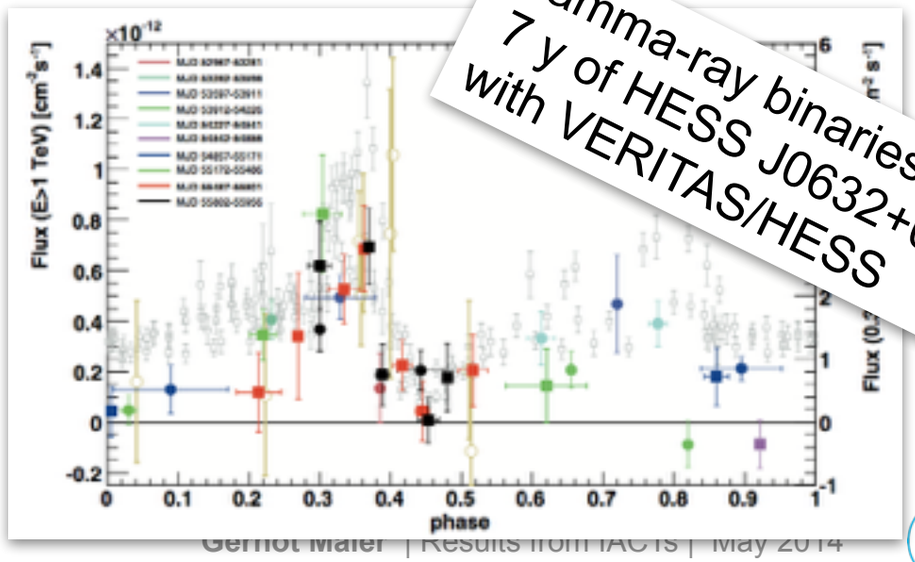
HESS J1640-465 - an extremely luminous SNR/PWN at 12 kpc (HESS 2014)



Rapid variability in radio galaxies: IC 310 (MAGIC 2014)



Complex morphology in MGRO 1908+06 (VERITAS 2014)



Gamma-ray binaries: 7 y of HESS J0632+057 with VERITAS/HESS

stop....

stop!!!!

The Cherenkov Telescope Array (CTA)

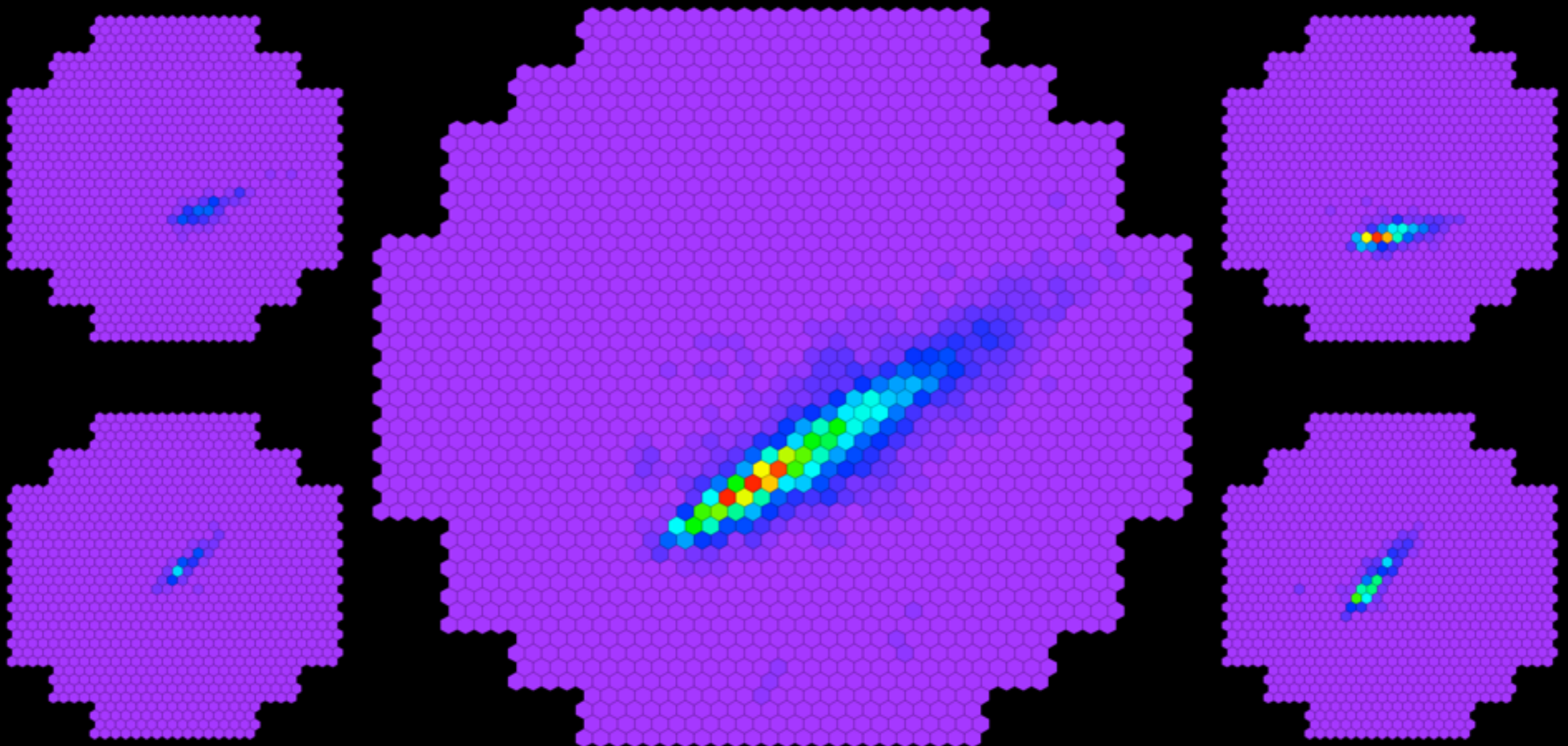
Prototypes: now; first science 2017; completion 2020

Array of >50 telescopes (3 telescope types)
20 GeV to >300 TeV energy range
factor 10 improvement in sensitivity
significantly improved angular resolution
two observatories: North and South
Collaboration of ~1000 scientist

See talk tomorrow

Imaging extensive air showers

A shower seen by H.E.S.S.



H.E.S.S. collaboration

Cosmic rays → Gamma rays

Cosmic rays
(p, He, .., Fe, $e^{\pm}$)

matter, magnetic,
photon fields

Cosmic rays → Gamma rays

Cosmic rays
(p, He, .., Fe, $e^{\pm}$)

matter, magnetic, photon fields

leptonic

inverse Compton scattering

Bremsstrahlung

hadronic

proton synchrotron

$p_{CR} + p \rightarrow p + \pi^{0/+/-} + ...$

$\hookrightarrow \gamma\gamma$

$p_{CR} + \gamma \rightarrow p + \pi^{0}$

$p_{CR} + \gamma \rightarrow p + \pi^{+/-}$

$\hookrightarrow \mu^{+/-}\nu$

$\hookrightarrow e^{+/-}...$

cascades/synchrotron

Cosmic rays → Gamma rays

Cosmic rays
(p, He, .., Fe, $e^{\pm}$)

matter, magnetic, photon fields

inverse Compton scattering

Bremsstrahlung

leptonic

top down: decay, annihilation

hadronic

proton synchrotron

$p_{CR} + p \rightarrow p + \pi^{0/+/-} + ...$

$\hookrightarrow \gamma\gamma$

$p_{CR} + \gamma \rightarrow p + \pi^{0}$

$p_{CR} + \gamma \rightarrow p + \pi^{+/-}$

$\hookrightarrow \mu^{+/-}\nu$

$\hookrightarrow e^{+/-}...$

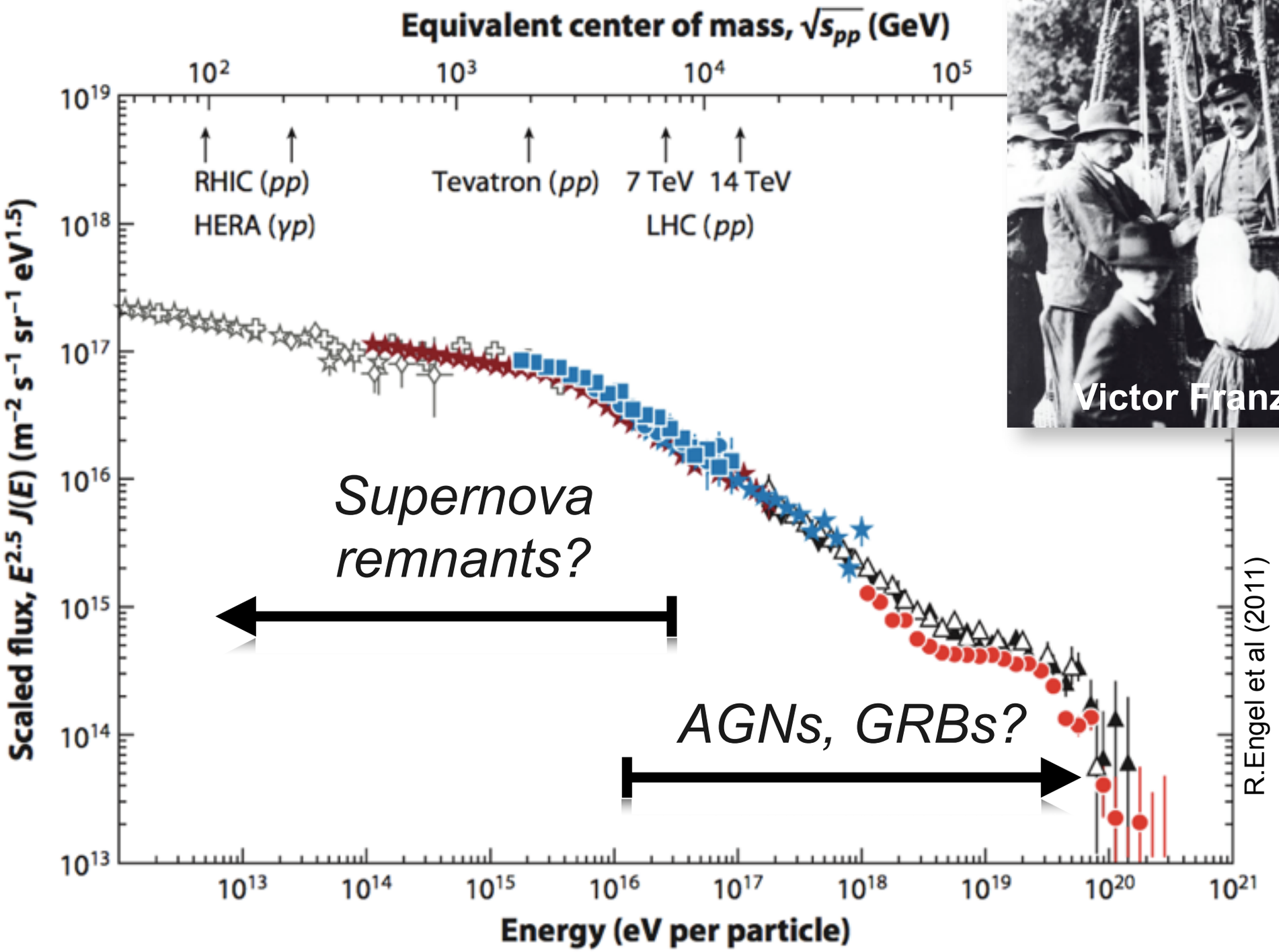
cascades/synchrotron

CTA midsize telescopes

full-scale mechanical prototype (Berlin)

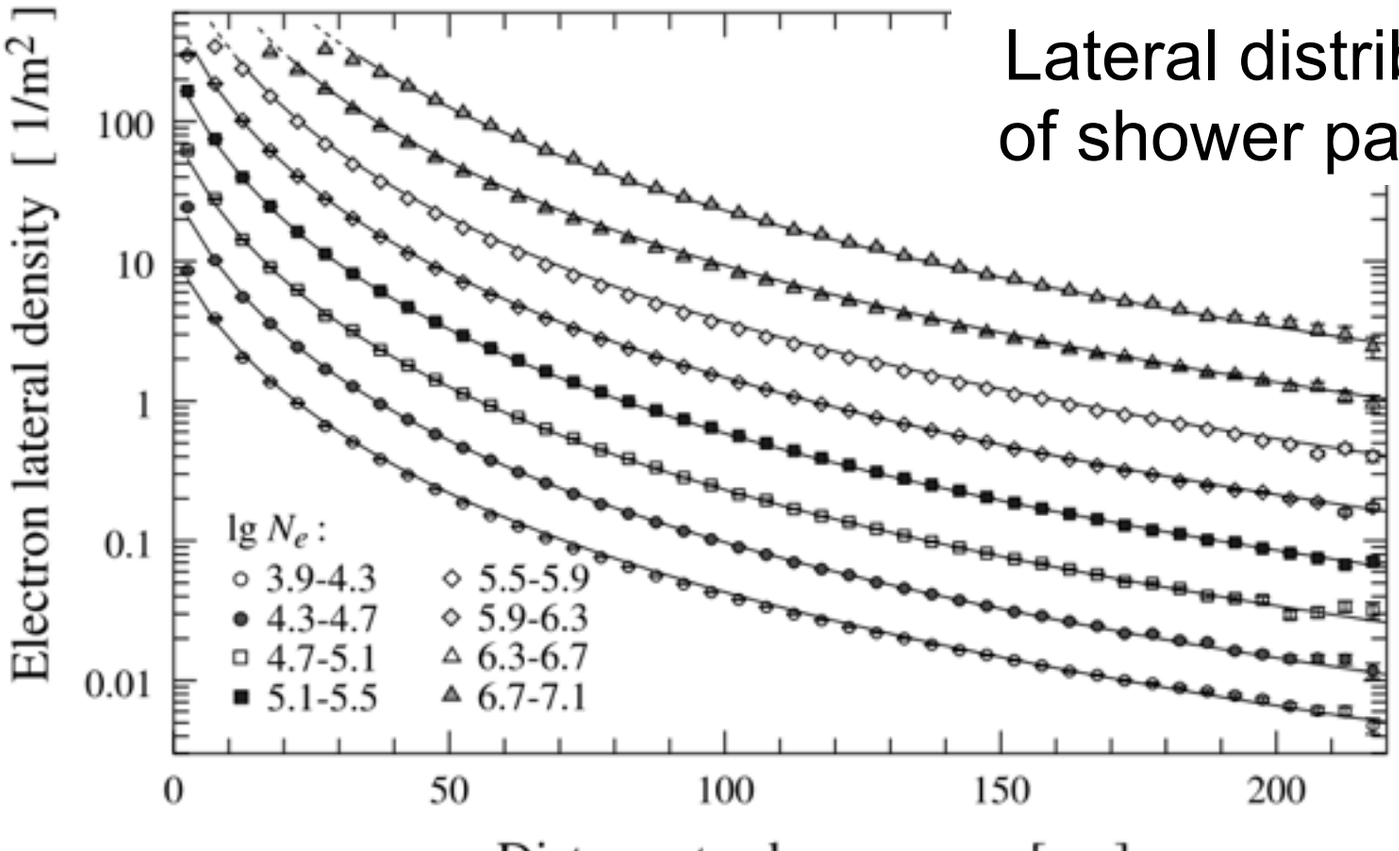
Dual-mirror telescope (prototype to be build in AZ)

How do cosmic rays gain their energy?
Where are they accelerated?

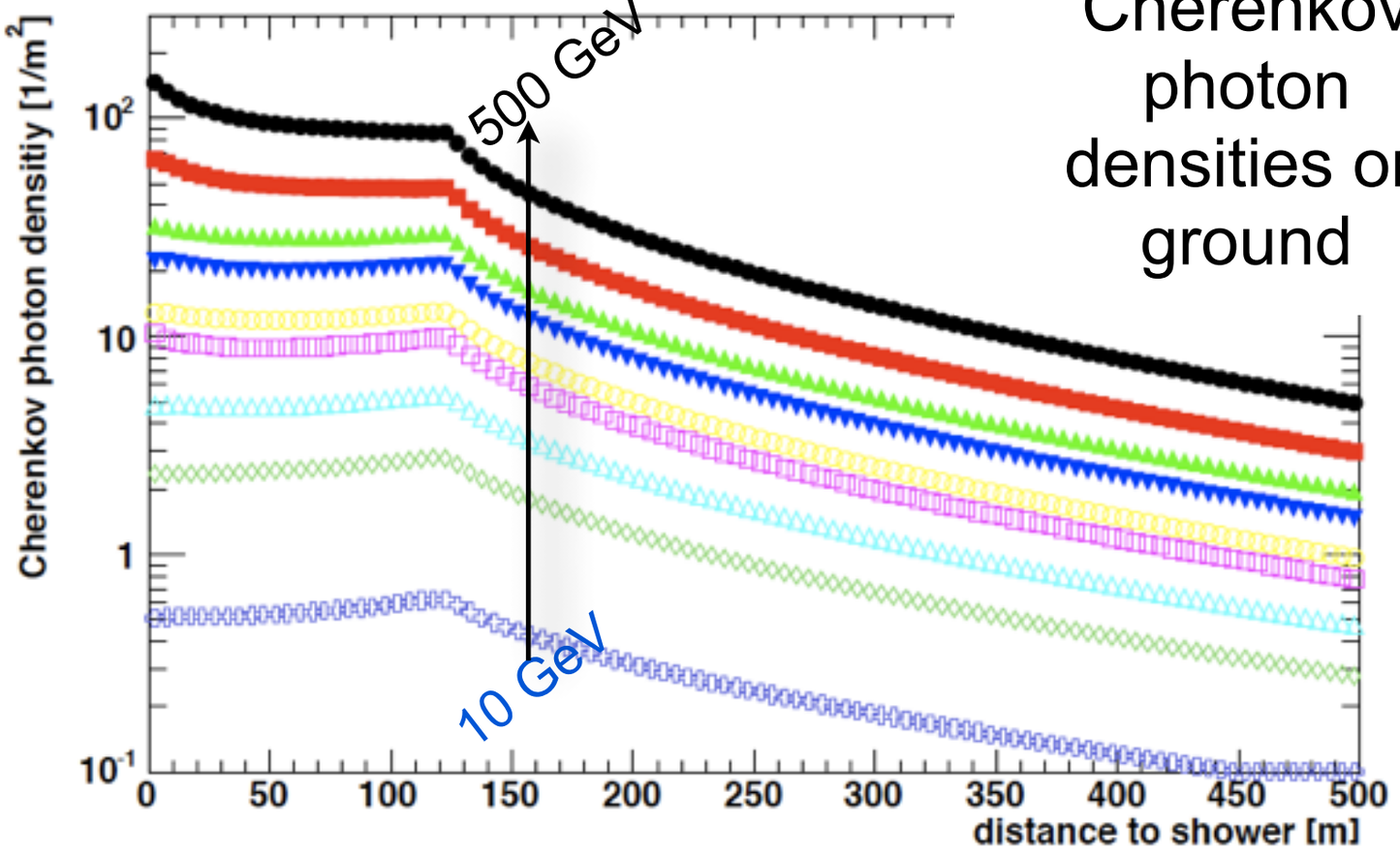


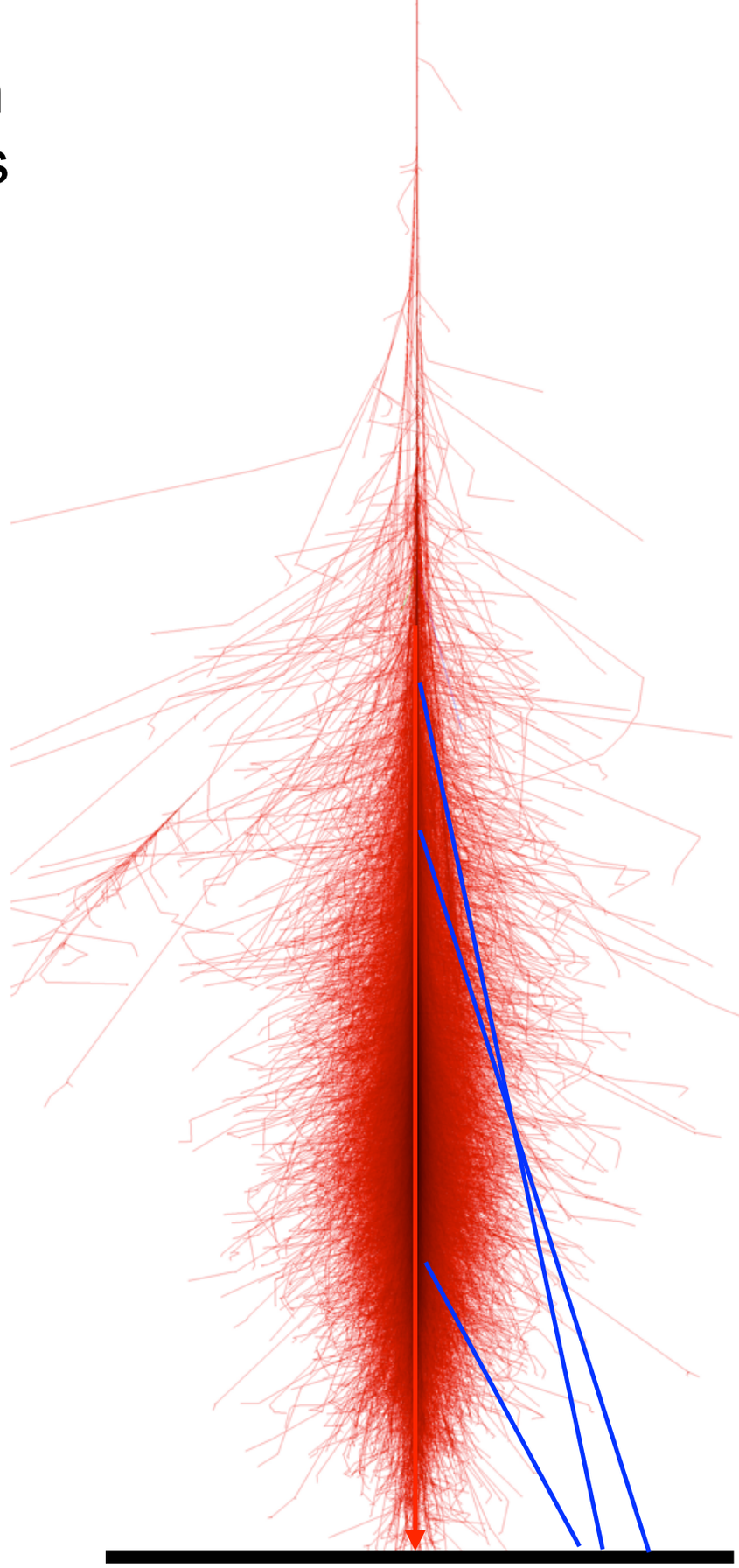
Victor Franz Hess

Lateral distribution of shower particles

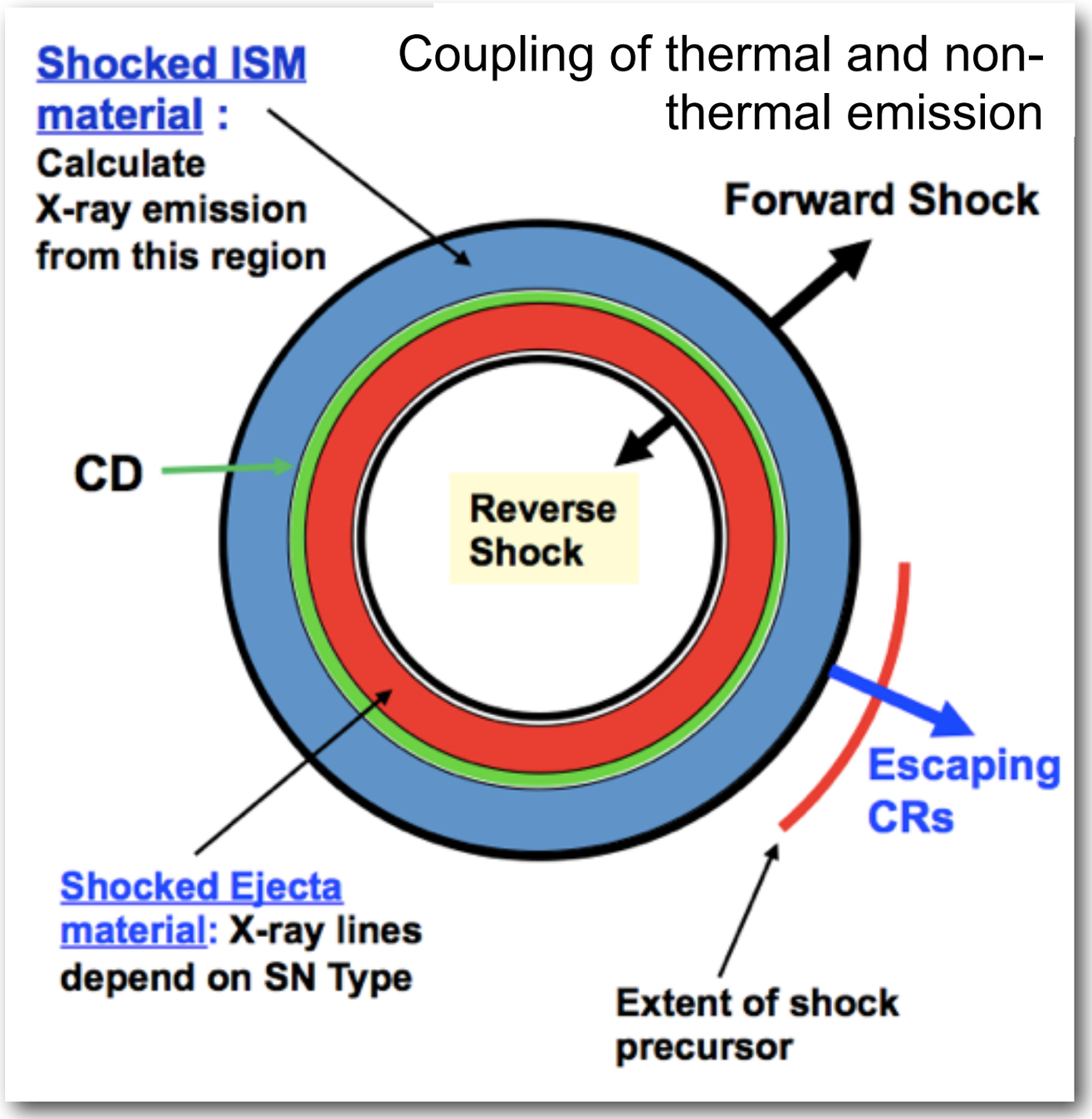


Cherenkov photon densities on ground





Particle acceleration in Supernova Remnants



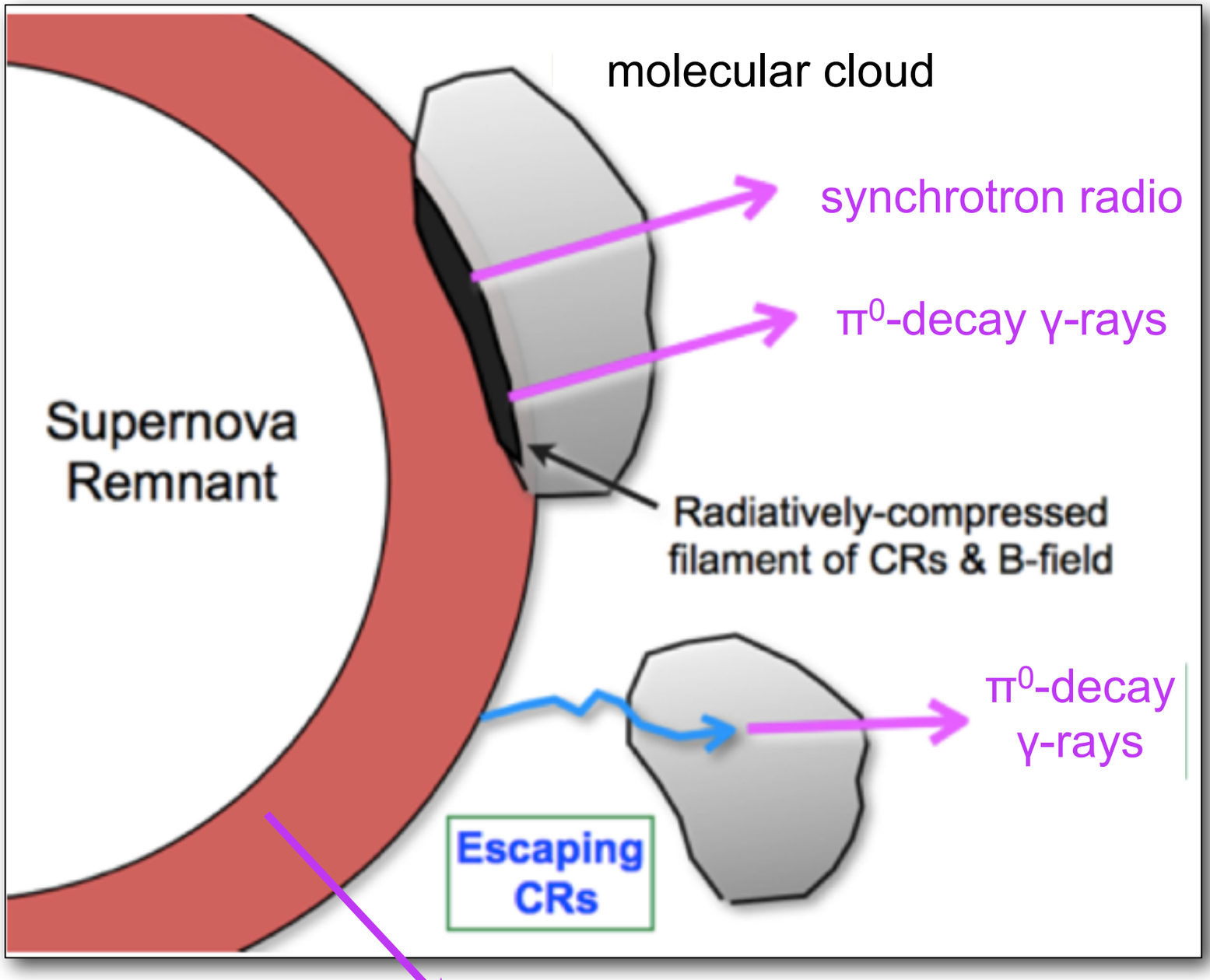
Don Ellison 2014

Amazingly complex models needed to explain broadband emission:

- hydrodynamic of evolving SNR
- non-linear diffusive shock acceleration
- Non-equilibrium ionization for X-ray line emission at forward and reverse shocks
- ejecta composition
- magnetic field amplification
- electron and ion distributions from thermal to relativistic energies
- photon emission
- cosmic-ray propagation

Particle acceleration in Supernova Remnants

It is very hard to image a supernova remnant which does not accelerate charged particles



Uchiyama et al 2011

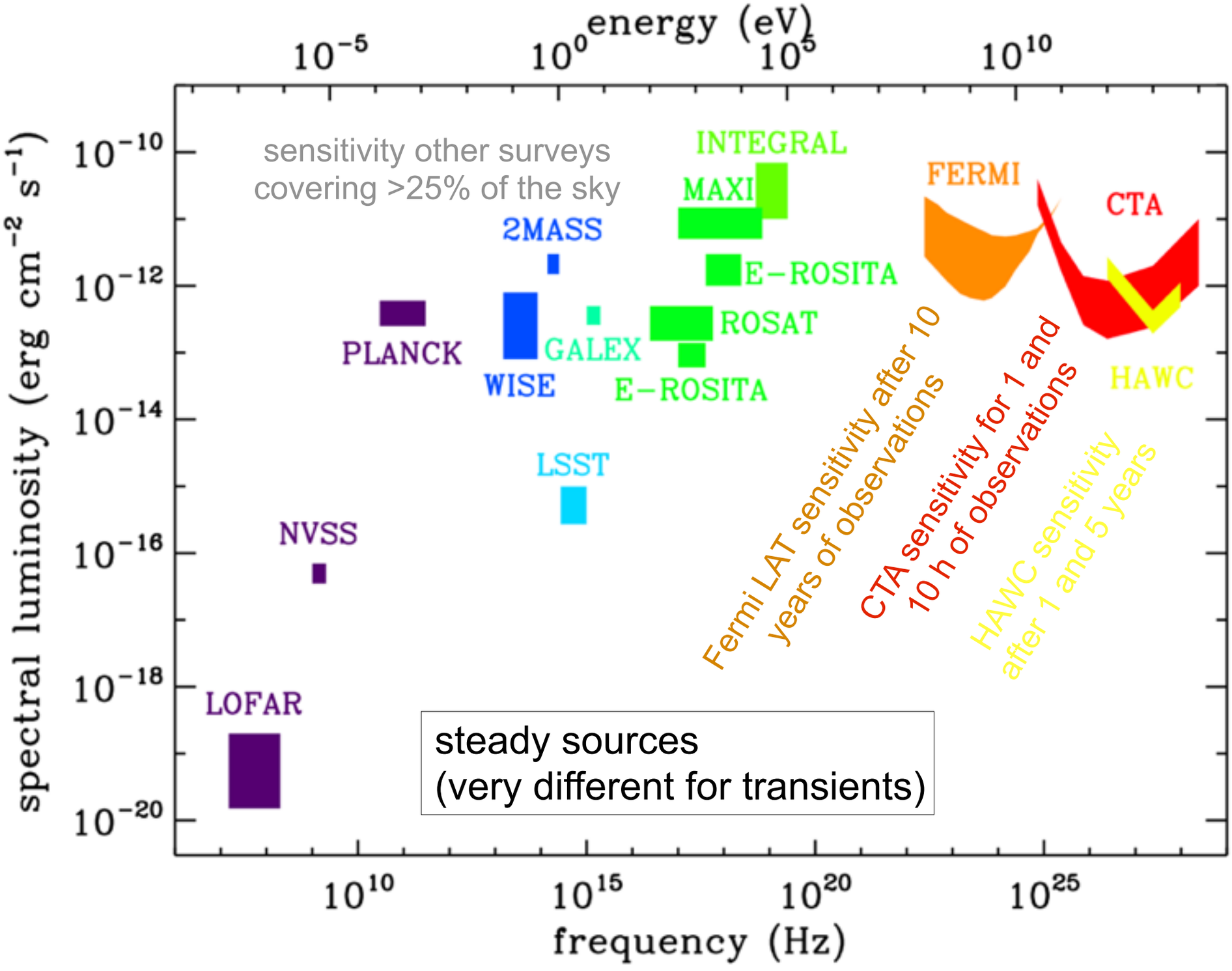
non-linear diffusive acceleration

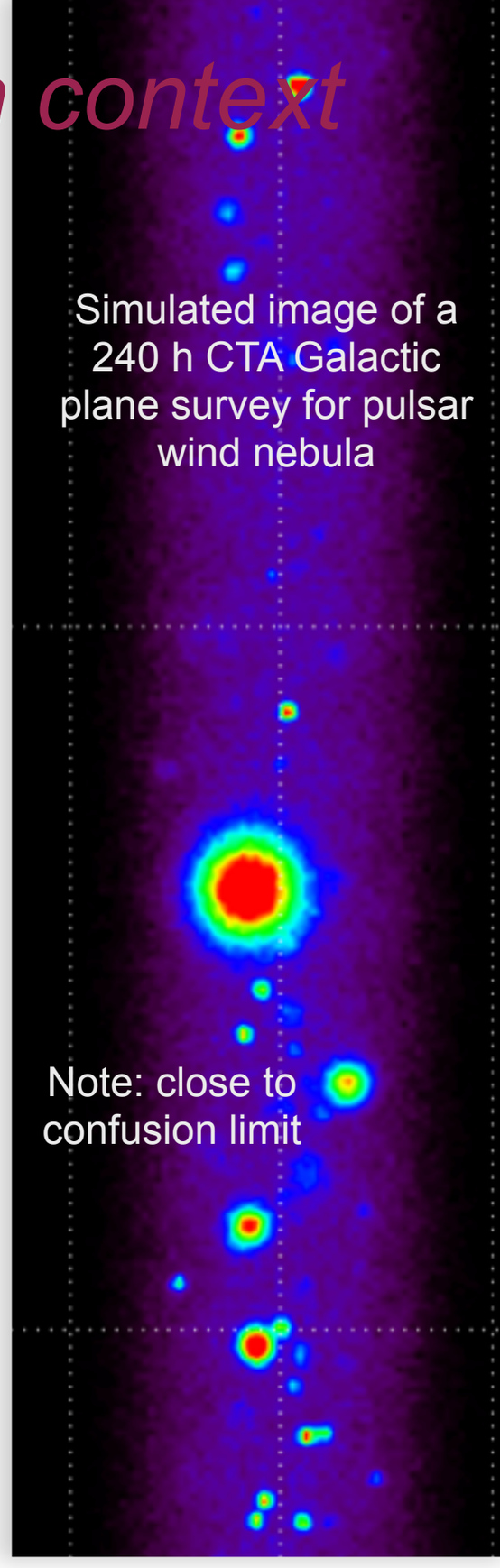
energetics (3-30% of shock energy is converted into particle energies)

Are SNRs efficient accelerators?

Can they accelerate particles up to and beyond

Survey sensitivity in the multi-wavelength context

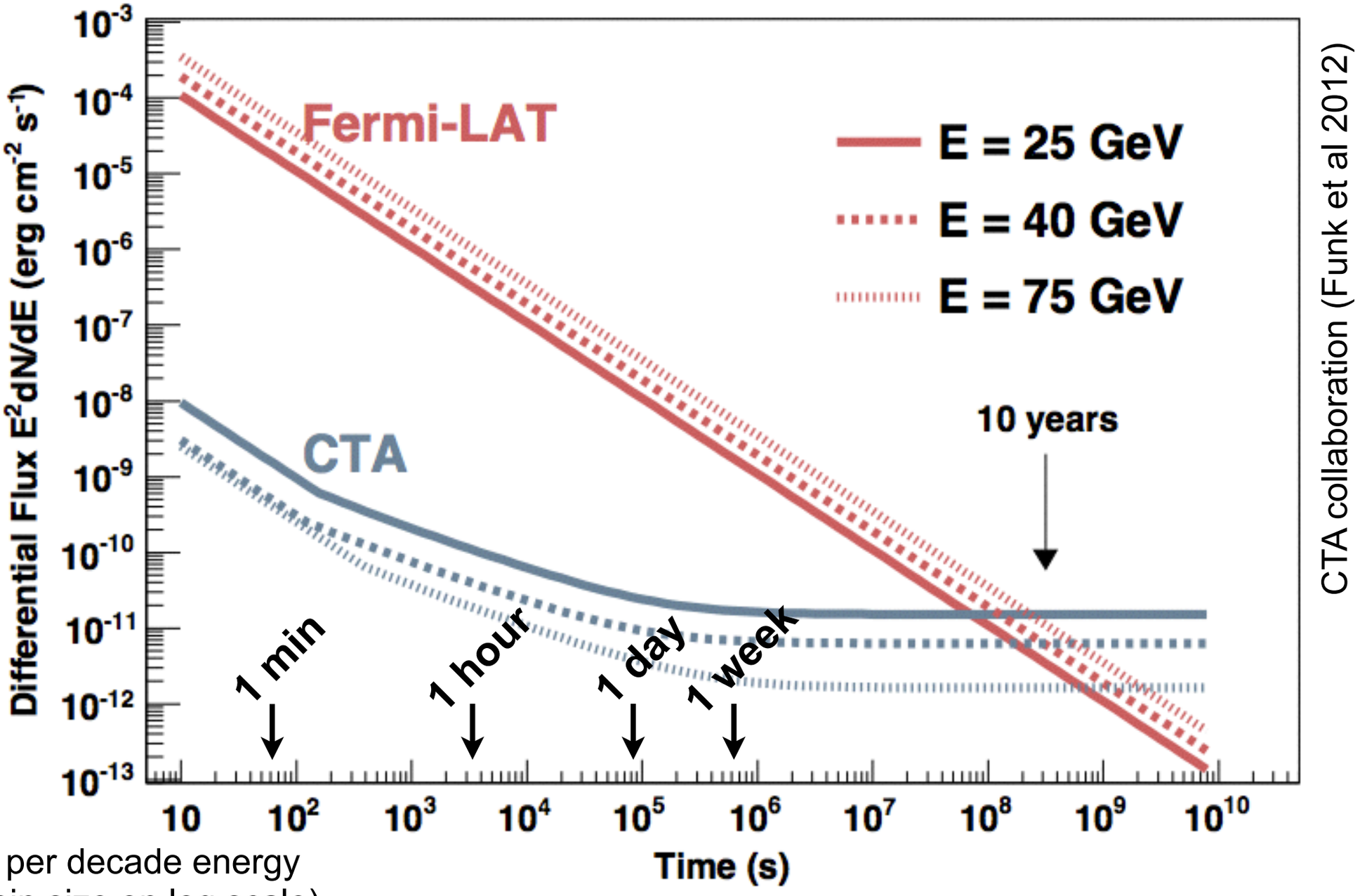




CTA (Dubus et al), astro-ph/12108.5686; 2012

Sensitivity to transients

effective areas: 1 m^2 (LAT) vs 10^4 m^2 (CTA at 40 GeV)

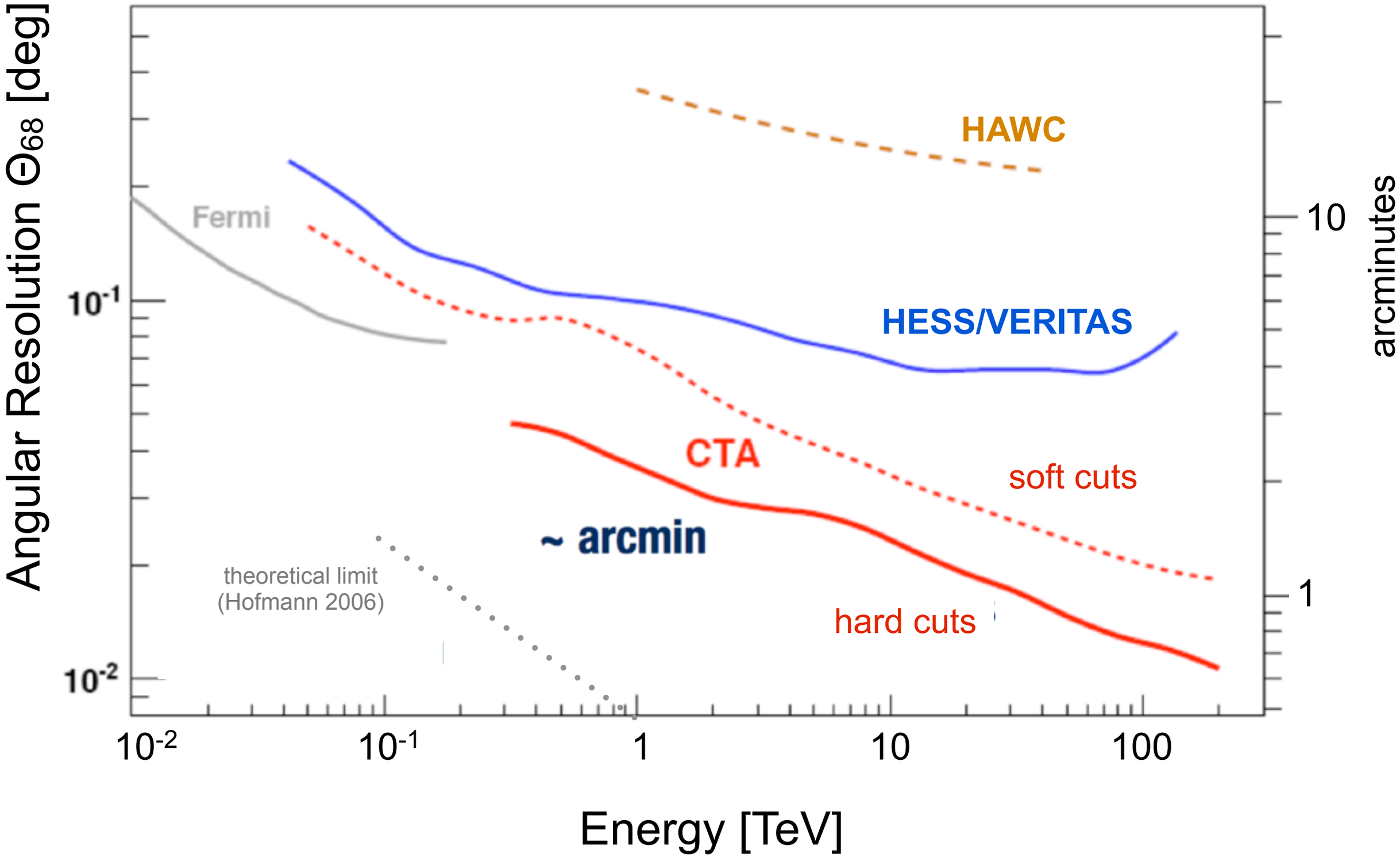


CTA collaboration (Funk et al 2012)

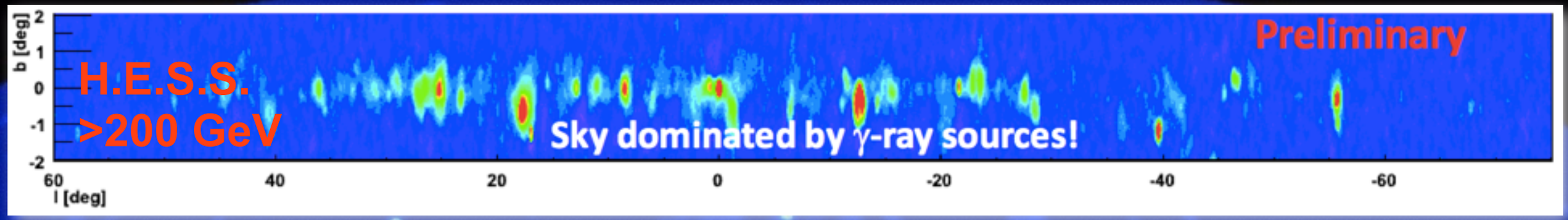
4 bins per decade energy
(equal bin size on log scale)

factor 1000 higher sensitivity of CTA for short (hours) transients

Angular resolution



The diffuse component



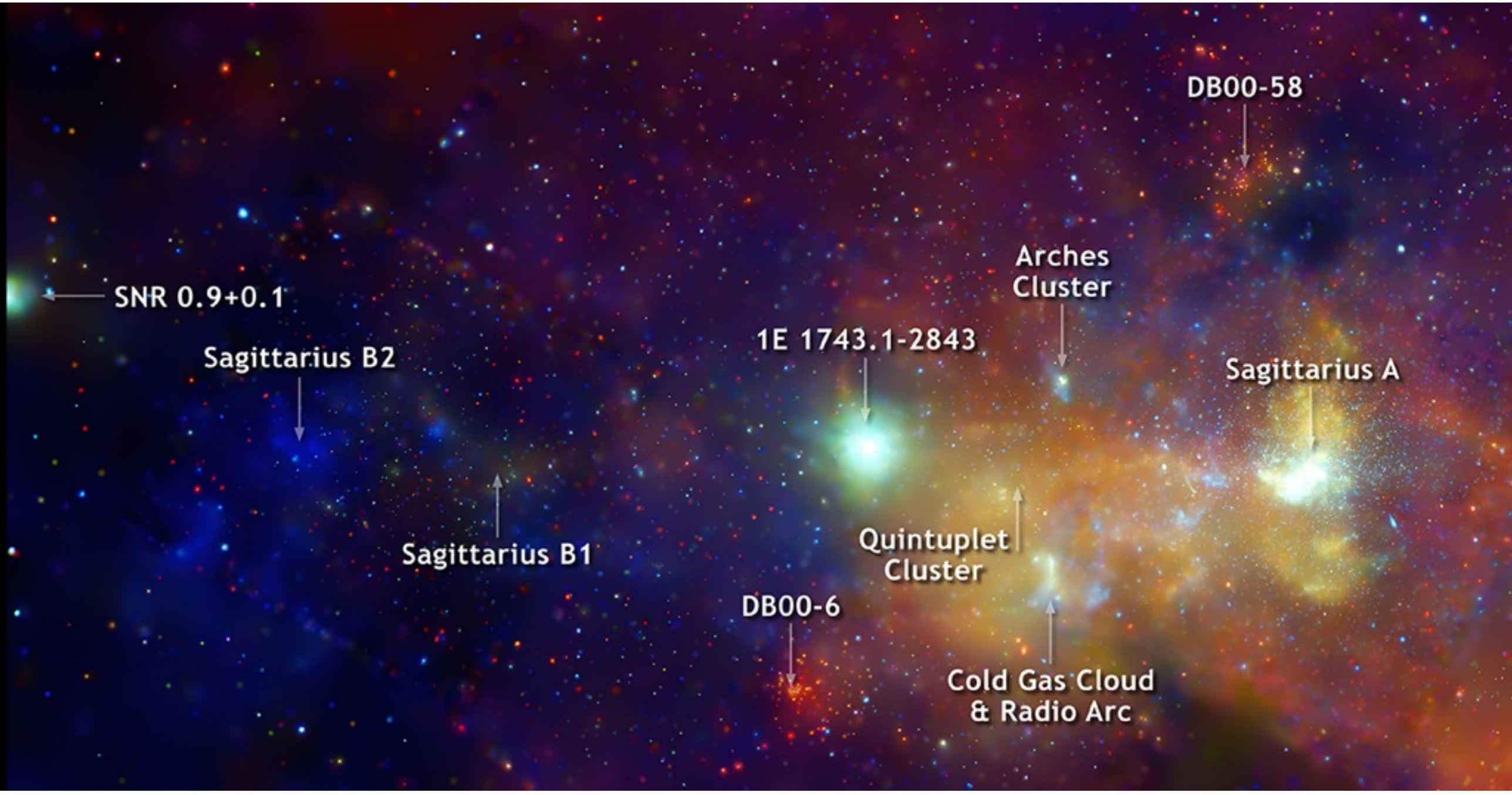
Egberts et al 2013

MeV-GeV sky dominated by diffuse background

Fermi LAT 3-years sky map > 10 GeV

Diffuse measurements:
- **cosmic ray content (p,e^-,...) and spatial distribution**
- **gas content**
- **CR diffusion in magnetic fields, convection, reacceleration**
- **unresolved sources**

The Galactic Centre



Band	Telescope
X-ray	Chandra ACIS
Optical	Hubble Space Telescope NICMOS
Infrared	Spitzer Space Telescope IRAC

The Galactic Centre

H.E.S.S. CTA

point-like gamma-ray source
+ diffuse component
(no extension as expected
for most DM models)

DB00-58

Arches
Cluster

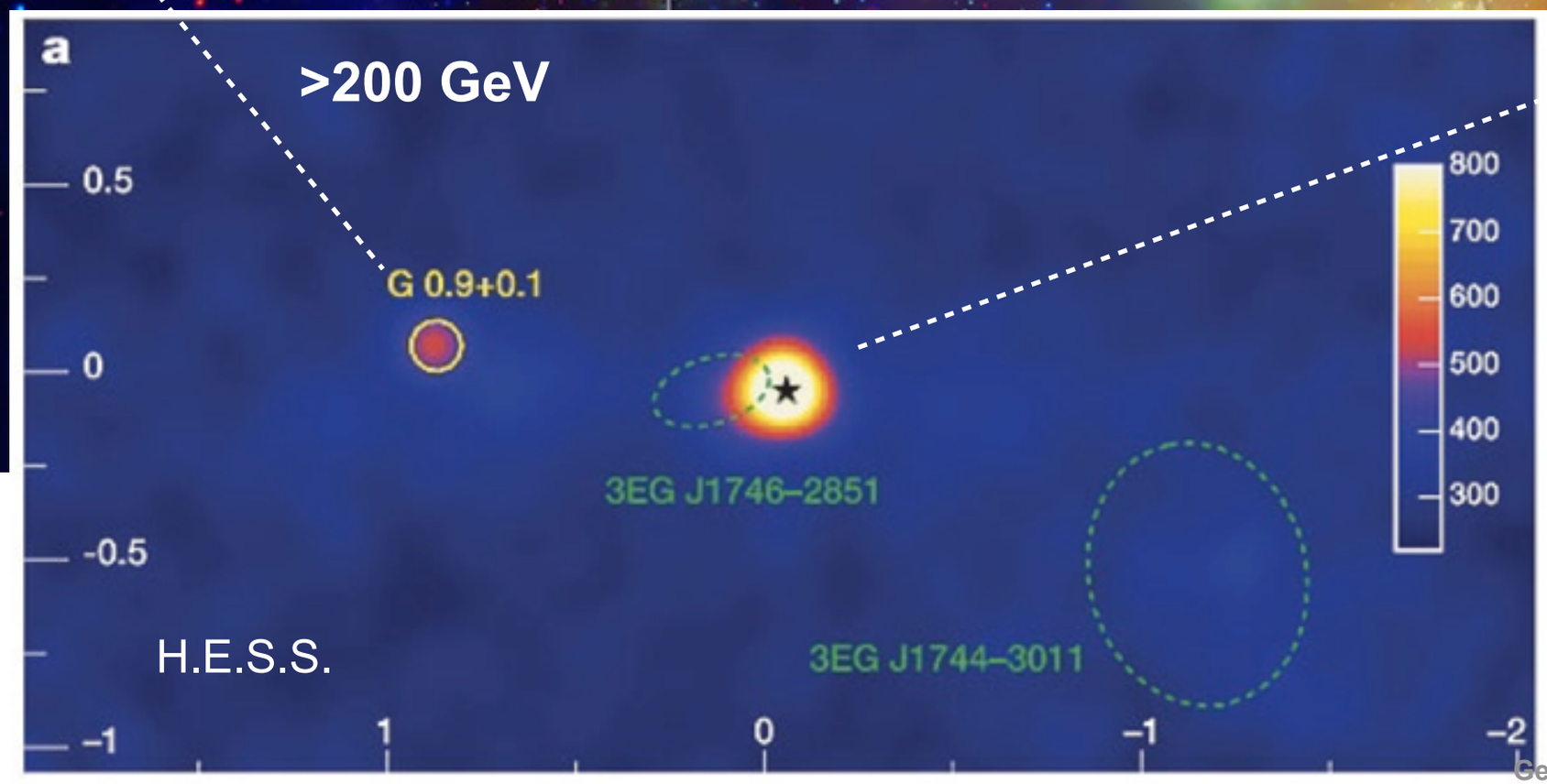
SNR 0.9+0.1

Sagittarius B2

1E 1743.1-2843

Sagittarius A

Cloud
Arc

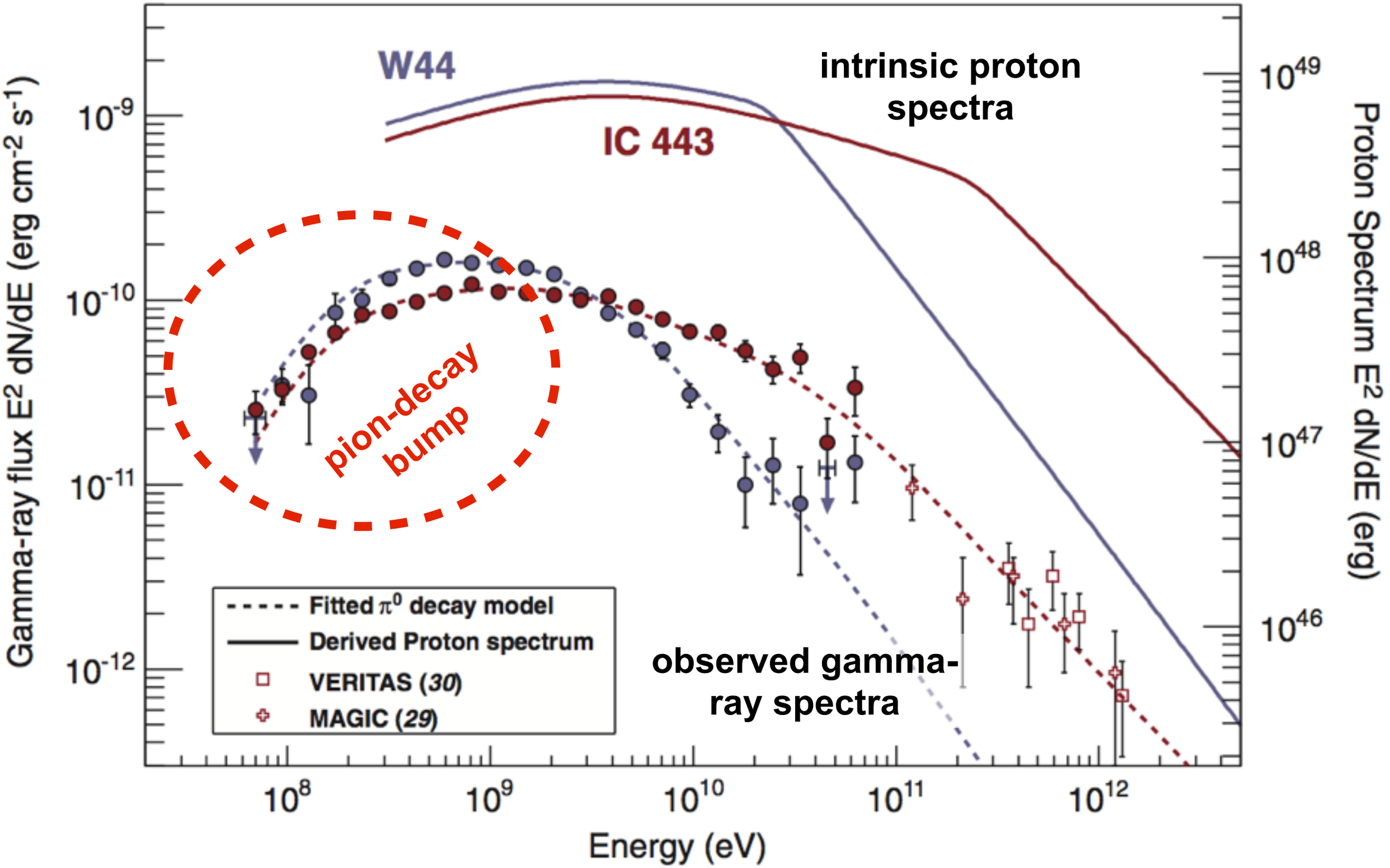


The Pion-Decay Signature

see also talk by S.Funk in yesterday's parallel session

π^0

E_γ



Fermi LAT collaboration 2013