The Future of Research on Cosmic Gamma Rays, Los Cancajos, Aug 26-29 July 2015

Scientific tasks of ground-based gamma ray detectors in different energy bands

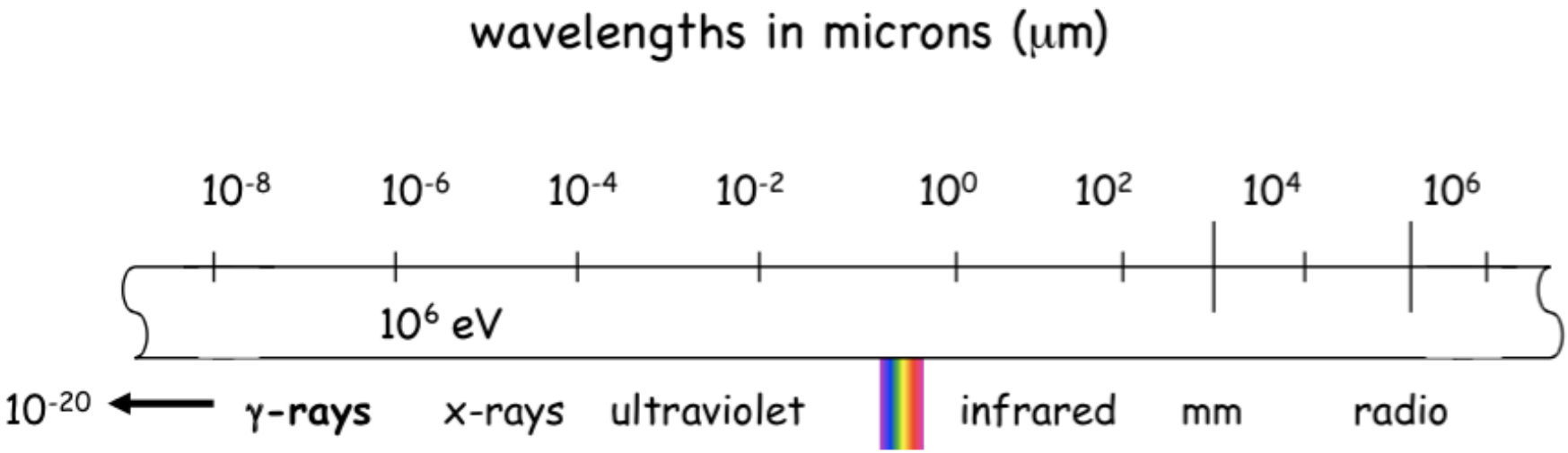
Felix Aharonian

DIAS/Dublin & MPIK/Heidelberg

Gamma Ray Astronomy

provides crucial window in the cosmic E-M spectrum for exploration of non-thermal phenomena in the Universe in most energetic and violent forms

'the last window' in the cosmic EM spectrum covers 8+ decades



LE or MeV : 0.1 -100 MeV (0.1 -10 + 10 -100)
HE or GeV : 0.1 -100 GeV (0.1 -10 + 10 -100)
VHE or TeV : 0.1 -100 TeV (0.1 -10 + 10 -100)
UHE or PeV : 0.1 -100 PeV (*only hadronic*)
EHE or EeV : 0.1 -100 EeV (*unavoidable because of GZK*)

low bound - nuclear gamma-rays, upper bound - highest energy cosmic rays

the window is opened in MeV, GeV, and TeV bands:

LE,HE *domain of space-based astronomy*
VHE, ... *domain of ground-based astronomy*

potentially 'Ground-based γ-ray astronomy' can cover five decades (from 10 GeV to 1 PeV) , but presently it implies 'TeV γ-ray astronomy'

$1\text{MeV}=10^{6}\,\text{eV},\ 1\text{GeV}=10^{9}\,\text{eV},\ 1\text{TeV}=10^{12}\,\text{eV},\ 1\text{PeV}=10^{15}\,\text{eV}\ 1\text{EeV}=10^{18}\,\text{eV}$

VHE gamma-ray astronomy - *a success story*

"over last 10 years the field has bee revolutionized…"

before – *"astronomy with several sources"*
(Astroparticle Physics rather than Astronomy)

now – a "*truly astronomical discipline*" with characteristic key words: energy spectra, images, lightcurves, surveys...

> 150 reported VHE emitters representing >10 source populations

first conclusions from VHE gamma-ray observations

- Universe is full of Extreme Accelerators - *TeVatrons (and PeVatrons ?)*

- unique carriers of information about astronomical environments on all scales - from *Black Hole horizons* to *radiation and B-fields of IGM*

the strength and uniqueness

- unique for specific topics e.g. for the solution of
  Origin of Galactic an Extragalactic Cosmic Rays

- may provide key insight into a number of principal issues e.g.
  paradigm of *"Pulsar/Pulsar-Wind/Pulsar-Wind-Nebula"*
  physics and astrophysics of Supermassive Black Holes

- contribution to fundamental physics, e.g. *violation of Lorentz invariance,* search for *Dark Matter*, or less exotic issues, like *Relativistic MHD* "experiments" (e.g. in PWNe and AGN)

- established detection technique - *IACT arrays* - for adequate *spectrometry, morphology, timing, surveys*, with a clear plan for next steps (in the foreseeable future - CTA)

IACT arrays - high performance and great potential

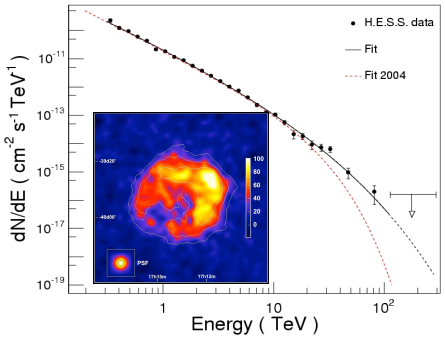
- huge detection areas, potentially >> 1 km^2
  => huge photon statistics coupled with
- good (~10 to 20%) energy resolution and
- good angular resolution (down to 1-2 arcmin)
- relatively large FoV (5 to 10 degree)

=> spectrometry, morphology, timing, surveys

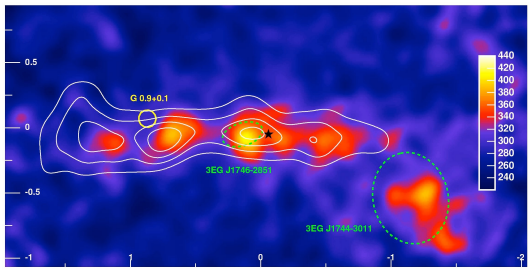
- sensitivity for point-like sources down to 10^{-14} erg/cm^2s
  (impressive by standards of modern astronomical instruments!)

- energy coverage from 10 GeV to 1 PeV (5 decades!)
  using the same technique ! (unique in astronomy)

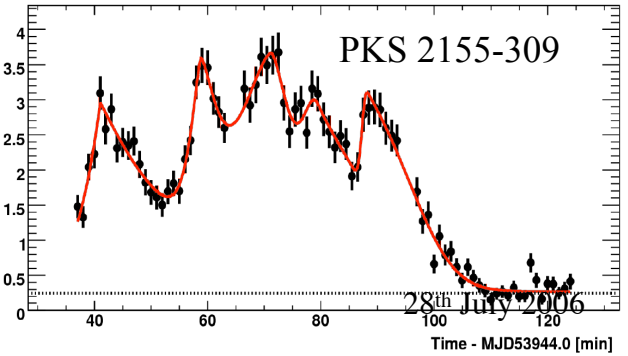
IACT Arrays : nice performance



TeV image and energy spectrum of a SNR



resolving GMCs in the CMZ 200pc region of Galactic Center



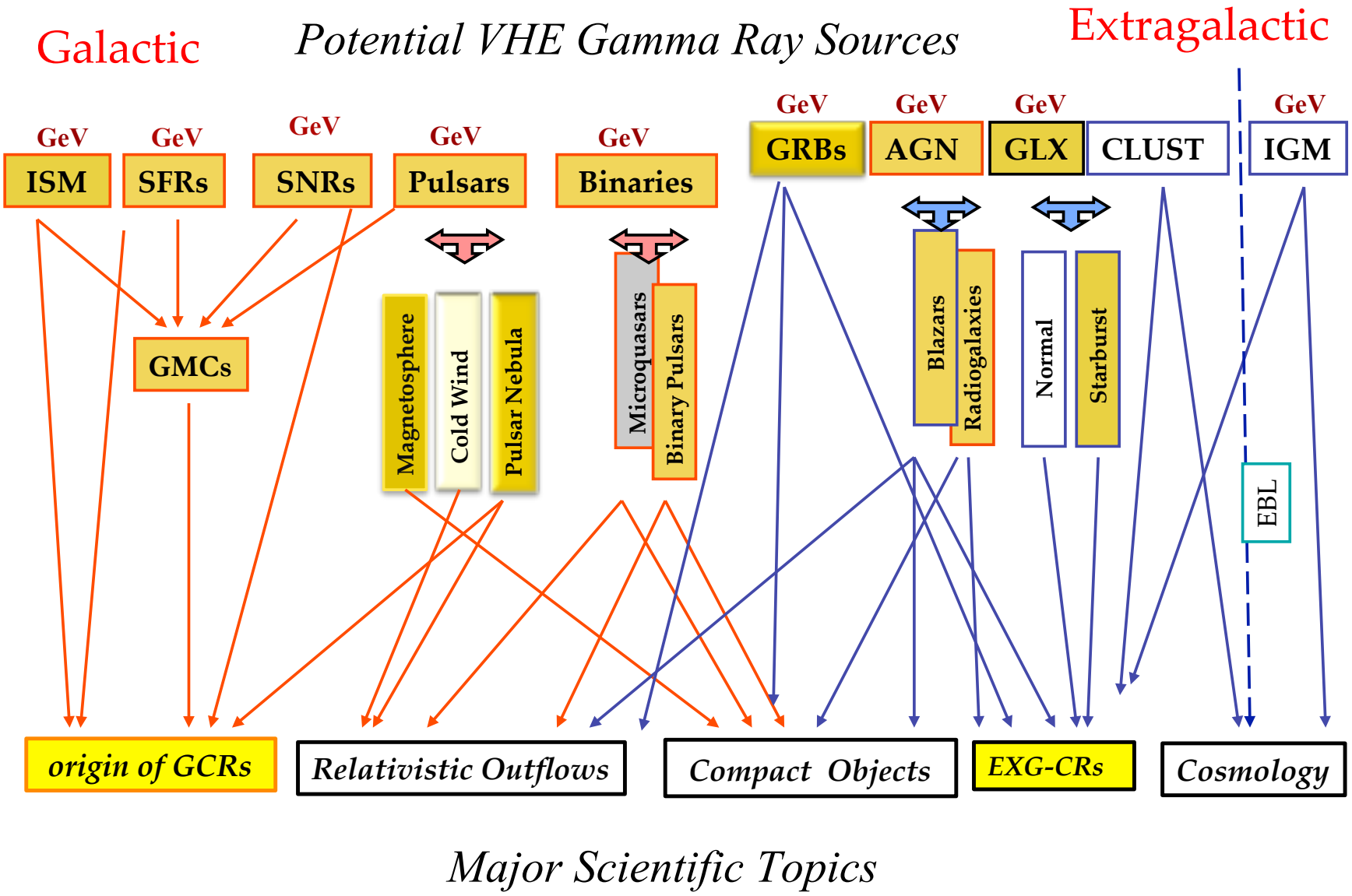
variability of TeV flux of a blazar on minute timescales

multi-functional tools: *spectrometry / temporal studies / morphology / surveys*

✓ extended sources: *from SNRs to Clusters of Galaxies*

✓ transient phenomena *μQSOs, AGN, GRBs, ...*

Galactic Astronomy | Extragalactic Astronomy | Observational Cosmology


Galactic
Potential VHE Gamma Ray Sources
Extragalactic
GeV
ISM
GeV
SFRs
GeV
SNRs
GeV
Pulsars
GeV
Binaries
GeV
GRBs
GeV
AGN
GeV
GLX
CLUST
GeV
IGM
GMCs
Magnetosphere
Cold Wind
Pulsar Nebula
Microquasars
Binary Pulsars
Blazars
Radiogalaxies
Normal
Starburst
EBL
origin of GCRs
Relativistic Outflows
Compact Objects
EXG-CRs
Cosmology
Major Scientific Topics

VHE gamma-ray source populations

Galactic Objects

- ✓ Shell Type SNRs
- ✓ Giant Molecular Clouds
- ✓ Star formation regions

- ✓ Pulsar Wind Nebulae
- ✓ Pulsar magnetospheres
- ✓ Pulsar unshocked winds (?)
- ✓ Binary pulsars (PRB 1259-63, also LS5039, LSI 61 303… ?)
- ✓ Accreting BHs/Microquasars? (Cyg X-1 ?)

Galactic Center

Extragalactic objects

- ✓ *S*tarburst galaxies (NGC 253 and M82)
- ✓ Radiogalaxies (M87, Cen A, NGC 1275) -
- ✓ TeV Blazars – with redshift from 0.03 to ~1
- ✓ GRBs (Fermi LAT; photons of tens of GeVs at $z > 1$)

Four Energy Regimes

- very low or **multi-GeV**: < 30 GeV (down to 3 GeV)
- low or **sub-TeV**: 30 GeV - 300+ GeV
- high or **TeV** : 300- GeV - 30+ TeV
- very-high or **sub-PeV** > 30 TeV **(**up to 3 PeV**)**

(subjectively) chosen from the requirements of
(i) detection specifics and (ii) principal scientific issues

each energy interval requires a specific configuration of IACTs but each configuration covers at least two decades

TeV Regime: "10^{-14} erg/cm^2 sensitivity arrays"

- energy coverage: 0.1 to 100 TeV but best performance: 0.3-30 TeV
- 10^{-14} erg/cm^2 sensitivity for point like (<1 arcmin) sources in the energy is impressive even for standards of most advanced branches of astronomy; it should allow us to probe the TeV emitters at level

  G: 10^{30}(d/1 kpc)^2 erg/sec or EXG: 10^{42}(d/1Gpc)^2 erg/s (EXG)

- for moderately extended (0.1 to 1 deg) sources the resolution will be 1-2 orders of magnitude worse; yet it would be better than the sensitivities of all current X-ray satellites Chandra, XMM, Suzaku)
- detection of thousands of new sources - population studies
- spectroscopy/morphology/timing of 10mCrab TeV emitters

sub-TeV (<0.3 TeV) & multi-**GeV** (< 30 GeV)

sub-TeV:

- **new source populations with cutoff energy Eo <100 GeV**

  μQSOs, z>1 blazars; >10^4 yr old SNRs, unidentified Fermi LAT sources, …

- **great help for understanding the origin of "TeV" sources**

  broader energy coverage - better spectrometry (all sources)

  and new component (pulsars, binaries, PWNe, Blazars, …

  smaller timescales - better variability studies (Blazars, binaries)

  energy-dependent propagation - diffusion/convection/ballistic (SNRs/GMCs)

multi-GeV:

takes advantage of high fluxes at GeV energies and huge collection areas provided by the Cherenkov light pool => perfect (best) time-explorer

– key insight into the physics of GRBs, AGN (up to z~5), μQSOs , …

– new transient events and phenomena

sub-PeV (>30 TeV)

sub-PeV:

better/broader energy coverage in the cutoff regions above 10 TeV

better understanding of TeV sources, e.g. the energy spectra
of most of VHE sources can be presented in the form

$$\frac{dN}{dE} \propto E^{-\alpha} \exp[-(E/E_0)^{\beta}]$$

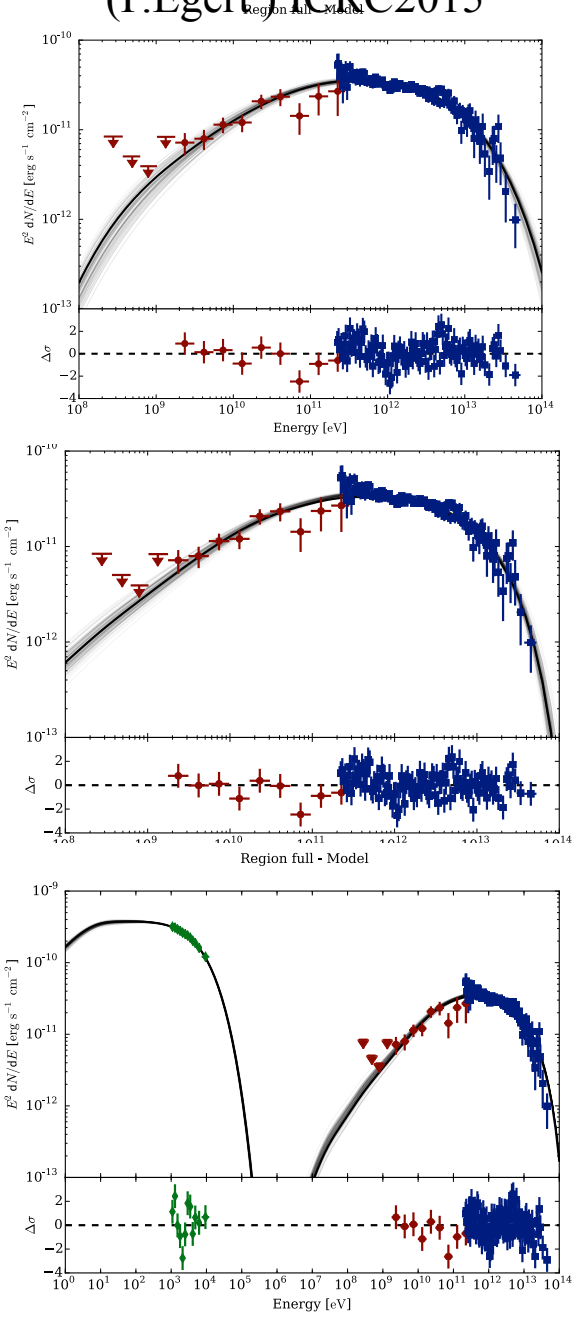
the same data can be fitted with different combinations (α, β, E_0)

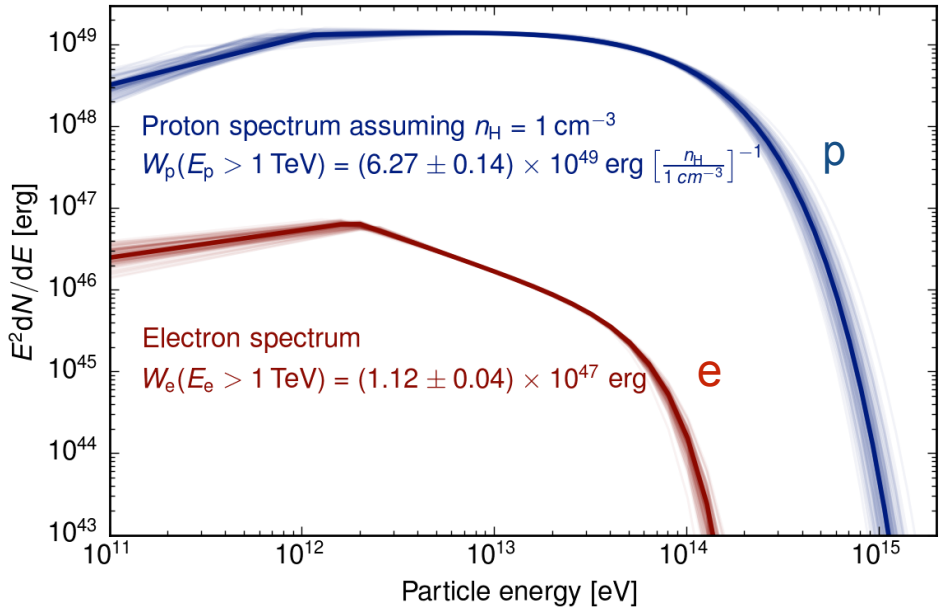
=> misleading conclusions and interpretation of these parameters
(photon index, the energy and the shape of the cutoff)

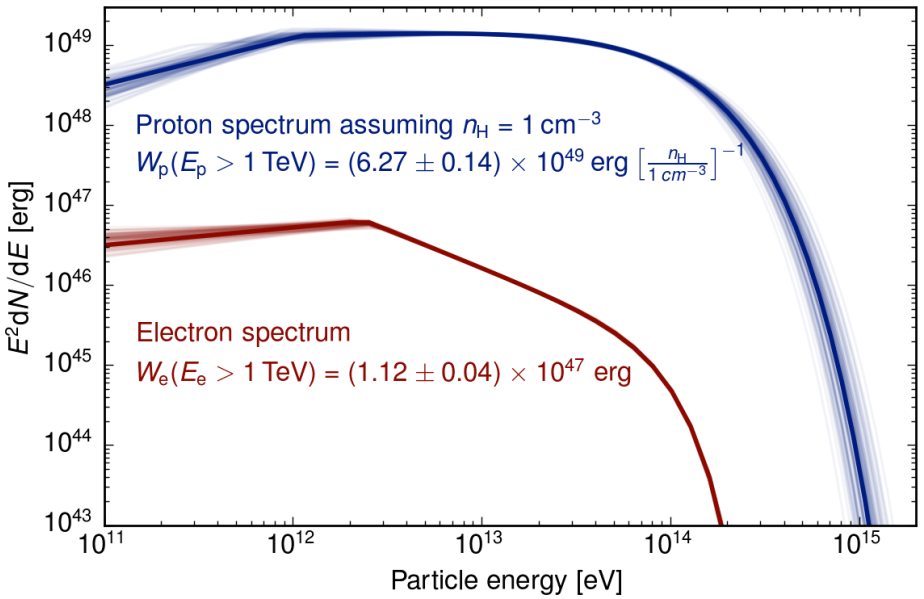
HESS new results
(P.Egert.) ICRC2015

RXJ 1713

model-independent spectra of p and e
(V. Zabalza ICRC 2015)







Realization?

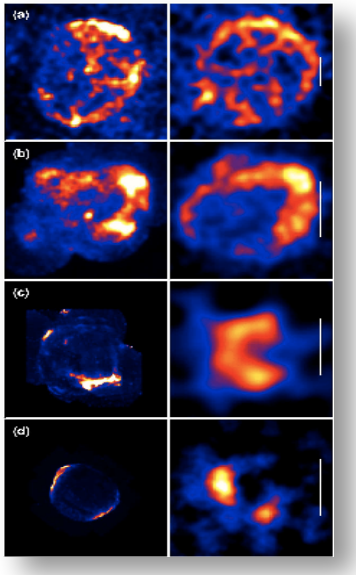
- **TeV:** arrays of tens of 10m diameter class and ~5deg FoV ACTs; separation ~ 100m (original HESS proposal or the CTA MST sub-array)
  range: > 100 GeV to be optimized between 300 GeV to 30 TeV

- **sub-TeV**: a few 20m class ~3-4 deg FoV ACTs (separation 50-100m)
  range: > 30 GeV to be optimized between 30-300 GeV
  (unless operates as an independent array)

- **sub-PeV**: tens of 3-5m class & 6-8 deg FoV ACTs (separation ~300m)
  range: > 1 TeV to be optimized for 30 to 300 TeV
  (unless operates as an independent array)

- **multi-GeV**: 25m class ACTs located (preferably) at 5km a.s.l.
  range: > to be optimized between 3 (10) -30 (100) GeV

Galactic Sources



Supernova Remnants sub-TeV,**TeV,**sub-PeV

- *status*

great achievements - detection of important young shell-type SNRs but the main question "whether SNRs are main contributors to GCRs?" does not yet have clear answer.

- *what do we expect from CTA*? - the answer to the above question ! (?)

- significant increase of number of gamma-ray emitting SNRs - because of improved sensitivity at TeV energies and the reduction of the energy threshold

- improvement of morphology (at TeV energies) - detection of clumps inside shells, detection of gamma-rays from escaping protons (and electrons?)

- spectrum from 30 GeV to 100 TeV: adequate information to identify the radiation mechanism(s), to derive the spectra of parent particles in and outside the remnant, to measure their energy spectra (especially in the cutoff region), arrive at conclusions regarding the acceleration spectrum, escape, energetics.

Galactic Sources

- SFRs, super bubbles, clusters of massive young stars …
  stellar winds colliding with each other or SNR shocks,
  acceleration of particles by multi shocks, etc…
  30 Dor C (very powerful !) Westerlund (PeVatron candidate?)

  complimentary or instead of (individual) SNRs as factories
  where GCRs are produced ? sub-TeV/**TeV**/sub-PeV

- GMCs - using as "barometers" for mapping CR distributions
  - to probe the "sea" of CRs in different parts of Galaxy
  - to discover old ("dead") accelerators;
  - to study propagation character of CRs in the vicinity of sources; measuring the diffusion coefficient; exploring the transition from rectilinear to diffusion regime **sub-TeV,TeV,sub-PeV**

transition from rectilinear to diffusive regime of propagation

Aloisio, Berezinsky, Gazizov 2009, Prosekin, Kelner, FA 2015

$$f(r,\mu) = \frac{Q}{4\pi c}\left(\frac{1}{r^2} + \frac{c}{rD}\right)\frac{1}{2\pi Z}\exp\left(-\frac{3D(1-\mu)}{rc}\right)$$

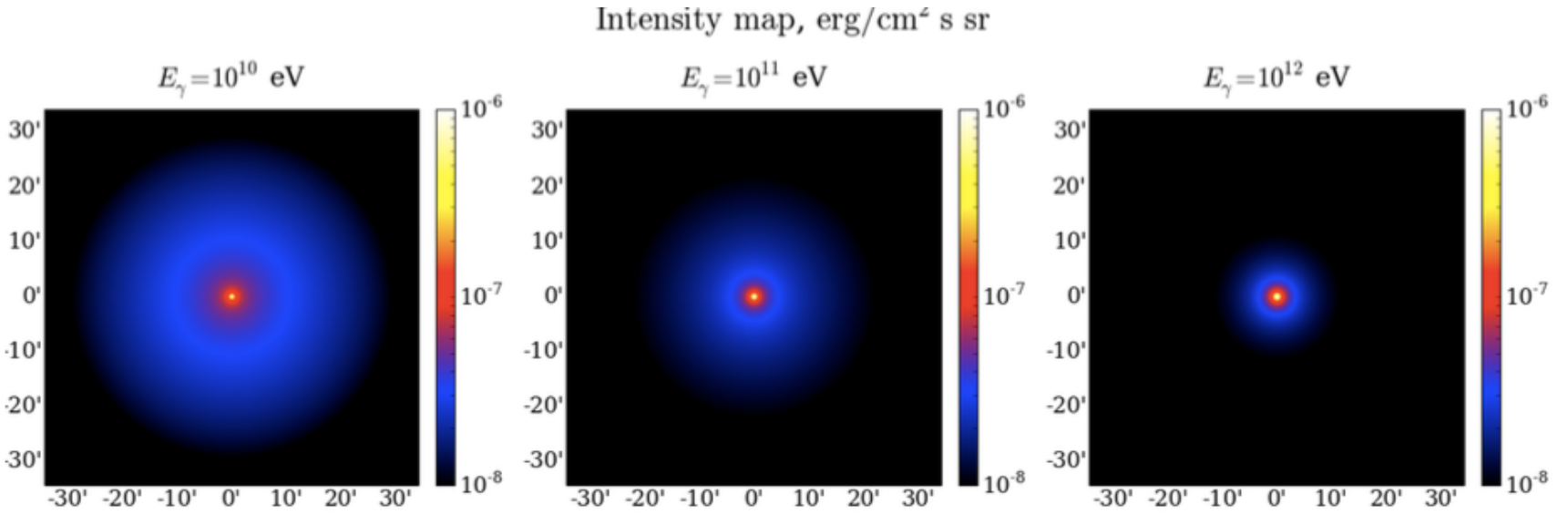
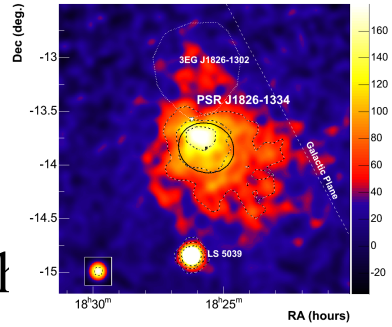


Figure 2: The intensity maps of gamma-ray emission at different energies. The spherical cloud with homogeneous density distribution is irradiated by the cosmic-ray source located in its centre. The gas density inside the accelerator is assumed very low, so the contribution of the accelerator to the gamma-ray emission is negligible. The maps are produced for the case of small diffusion coefficient (for details, see the text). For the distance to the source $d = 1$ kpc, the region of $\sim 1^\circ \times 1^\circ$ corresponds to the area $\sim 20 \times 20$ pc^2.

Prosekin et al. 2015

Galactic Sources

- **PWNe** - spatial and energy distribution of electrons without any assumption (unique in astrophysics), spatial distribution of the average B-field by adding theX-ray results, turbulence of tl field, size of the regions filled by electrons, propagation of electrons (transition from PWN to ISM), sub-TeV, **TeV**, sub-PeV

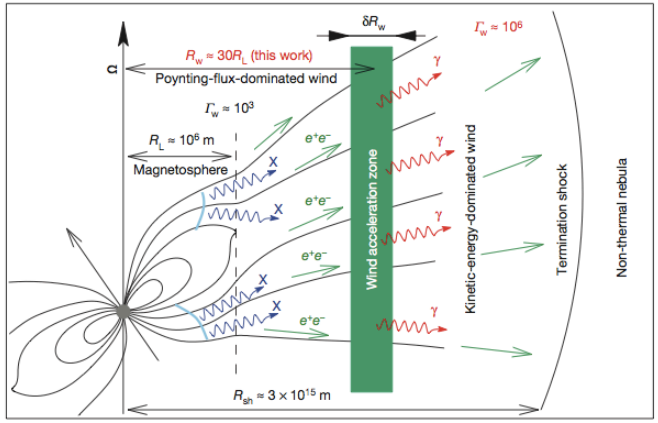


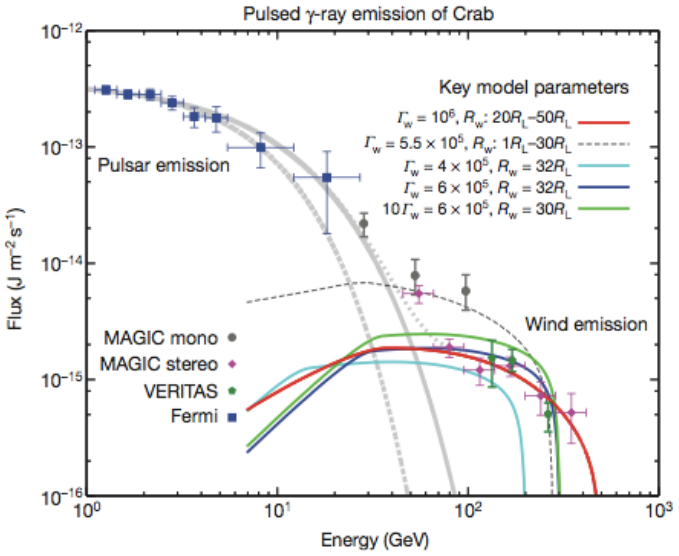
- **Pulsars/Pilsar-Winds:** pulsed TeV emission - magnetospheres or cold winds? **sub-TeV**, TeV

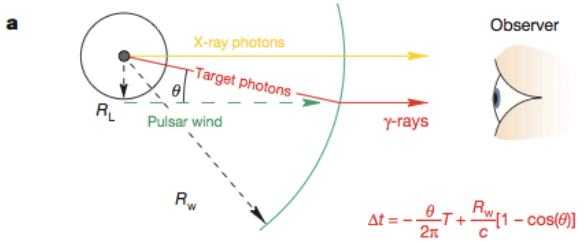
- **Binary Pulsars** - termination of pulsar winds, formation of relativistic shocks, acceleration of electrons in *on-line* regime, study the sites and mechanisms of acceleration

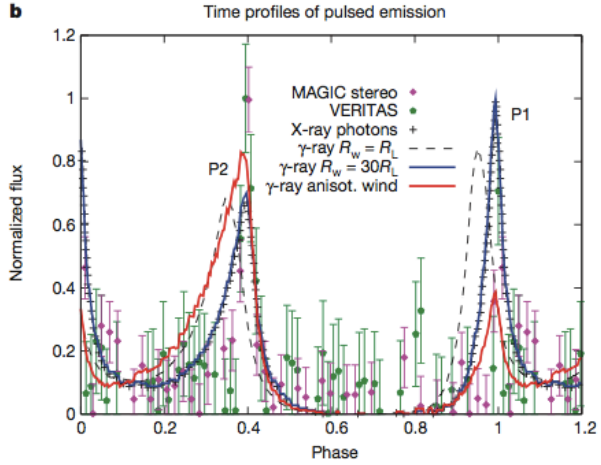
sub-TeV, TeV,sub-PeV

Pulsed VHE gamma-rays from the Crab – Comptonization of the cold ultrarelativistic pulsar wind?









$\Gamma \sim 10^6$; R ~ 30 L

Galactic Sources

Black-Holes in our Galaxy

- Microquasars - jets in stellar mass BHs ?
  Cyg X-1, Cyg X-3, GRS 1915, SS 433 **sub-TeV,** TeV

- Galactic Center

- detailed morphology and energy spectrum of CMZ **TeV**
- connections with Fermi Bubbles TeV, sub-PeV **TeV, sub-PeV**

– search for flares in Sgr A* **sub-TeV**

ultimate aim - identification of the central PeVatron

outcome => contribution to physics of SMBH and Origin of GCRs

Extra Galactic Sources

- Starburst Galaxies - so far NGC 253 and M82 have been detected both at GeV and TeV energies with very high proton-to gamma conversion factor > 0.1 (almost "calorimetric"), hard spectra

next step: detailed spectral measurements up to 100 TeV, angular distribution up to 1 deg (to map >10kpc halos), search for VHE emission from most powerful representatives - Arp 220, Mkn 279

topics: origin of CRs, EBL at MIR-FIR sub-TeV,**TeV,**sub-PeV

- nearby AGN - so far M87 (variability on timescales of days, Cen A (central source and radiolobes at GeV energies)

next steps: detailed spectral/spatial distributions, timing
topics: BH physics, jets, EBL at MIR-FIR **TeV**/sub-PeV

ExtraGalactic Sources

- Clusters of Galaxies **TeV**

so far - no detections at GeV and TeV, but there is little doubt (?) that gamma-rays will appear at some level because of pp, IC and "p -2.7K + IC of Bethe-Heitler electrons" interactions

reasons for optimism? accretion shocks with $v > 1000$ km/s

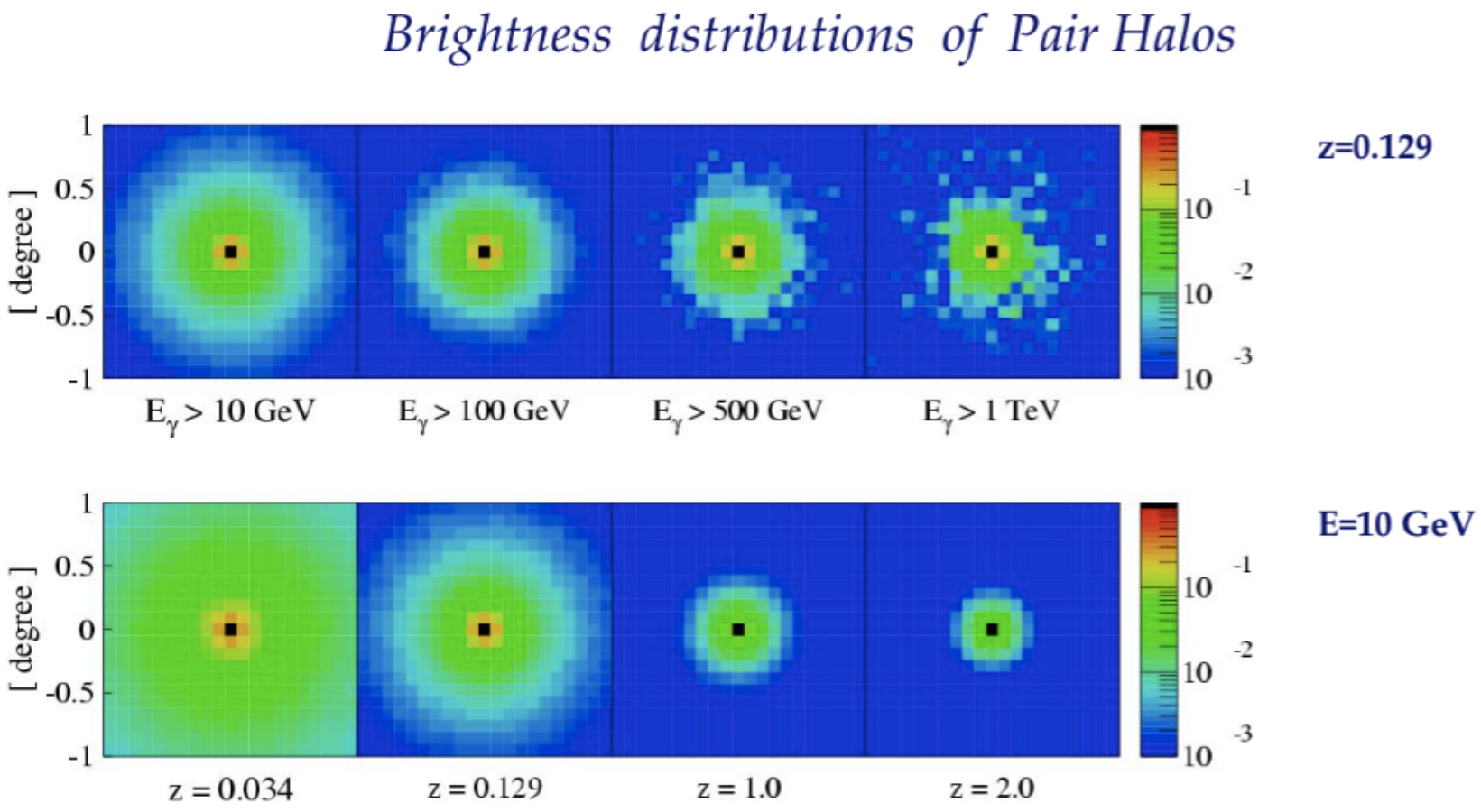
objects: Clusters of Galaxies - Coma, Perseus A, …

topics: large-scale cosmological structures in the context of nonthermal phenomena, B-fields, accretion shocks, …

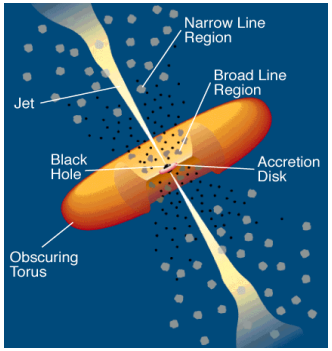
- Large scale structures of different origin

Radio lobes of powerful radiogalaxies; Synchrotron Halos of secondary electrons; Giant e^+e^- pair Halos around AGN; photon beams broadened in the very week B-fields of IGMFs **sub-TeV /TeV**

Giant Pair Halos as perfect Cosmological Candles



Blazars - sub-class of AGN dominated by nonthermal/variable broad band (from R to γ) radiation produced in relativistic jets close to the line of sight, with massive Black Holes as central engines



GeV/TeV gamma-ray observations

strong impact on

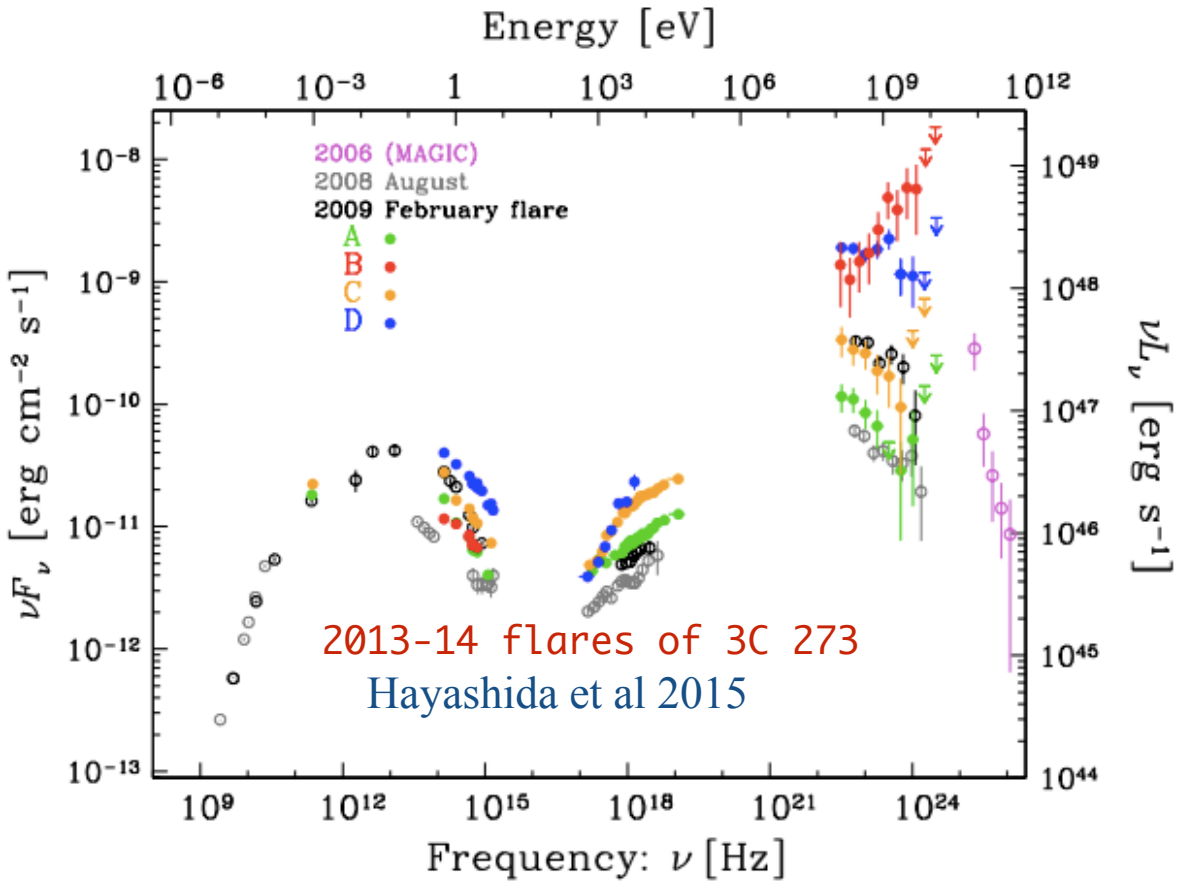
- Blazar physics and astrophysics
- Diffuse Extragalactic Background (EBL)
  Intergalactic Magnetic fields (IGMF)

most exciting results of recent years

- ultra short time variability (on min scales)
- Jet power exceeds Eddington luminosity
- extremely hard (harder than E-1.5) energy spectra
- VHE blazars up to z~1! (MAGIC)

next steps - population studies from z=0.01 to 3
study of SEDs during flares from 30GeV to 30TeV
structures in lightcurves (on down to second scales)

topics: BHs, jets (relativistic MHD and shocks), particle acceleration, EHE CRs, B-fields, EBL, IGMFs, …



Leptonic model: LB/Lj < 10-4, electron power-law index p=1 !
hadronic (photo-meson processes) model: not realistic
proton synchrotron - can explain the GeV gamma-ray peak?

variability $t \sim 7\ 10^3$ sec vs $t_{bh} \sim (3\text{-}8)\ 10^3$ sec !

Summary:

future of ground-based gamma-ray astronomy? *very bright* !

- solid predictions (based on the current data and theory)
- exciting expectations which can dramatically change our present understanding of the nonthermal Universe
- very good prospects for next generation instruments (CTA and beyond)