DIAS
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Gamma Ray Astrophysics

Felix Aharonian

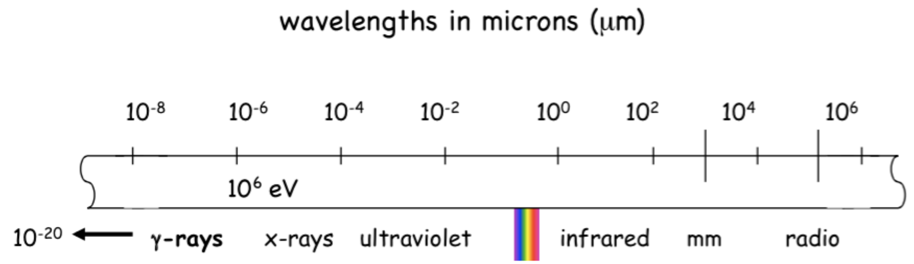
XVIII International Workshop on Neutrino Telescopes

Venice, March 18-22, 2019

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)

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

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

Ground Based Gamma Ray Astronomy

presently

provides the VHE window in the spectrum of cosmic E-M radiation

0.1 TeV and 100 TeV => TeV (VHE) γ-ray Astronomy

with a great potential for extension of the energy domain

below 100 GeV down to 10 (1) GeV: multi-GeV (HE) Astronomy

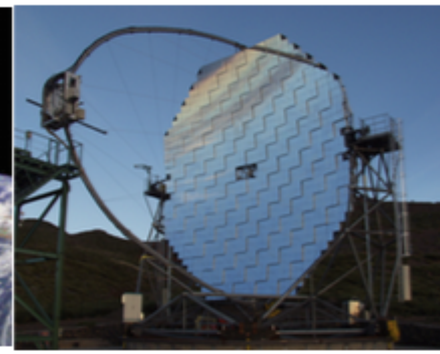
above 0.1 PeV: PeV (UHE) Astronomy

in foreseeable future (hopefully) => **GeV-TeV-PeV astronomy**

HE, VHE, and UHE Gamma-Ray Detectors

HE

VHE



UHE

future ?

(multi) GeV energies
detection area $\sim 10 m^2$
not realistic ?

1–100 MeV range
1m2 is sufficient
PSF should be 1^o
realistic !

CTA – great improvement

beyond CTA ?

1 GeV telescope?

10 to 100 km^2
multi–TeV array ?

LHAASO

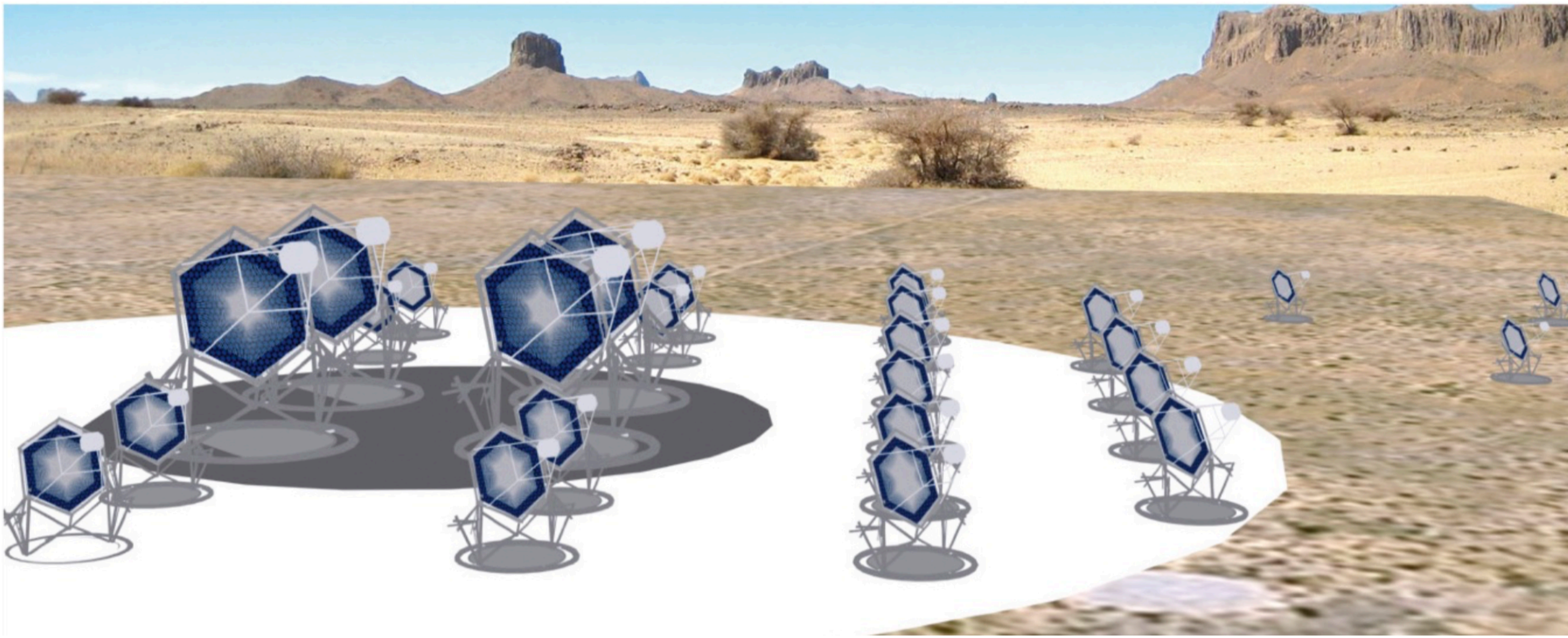
on going

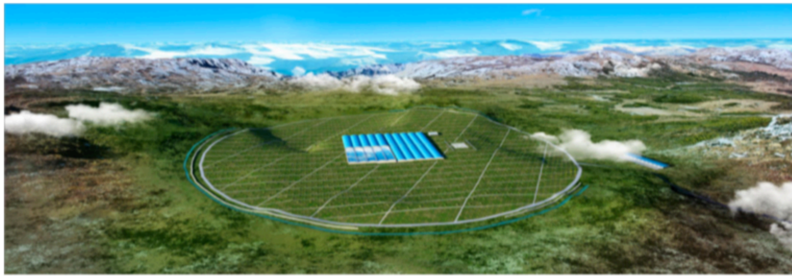
SGSO

very likely

Next Generation Detectors

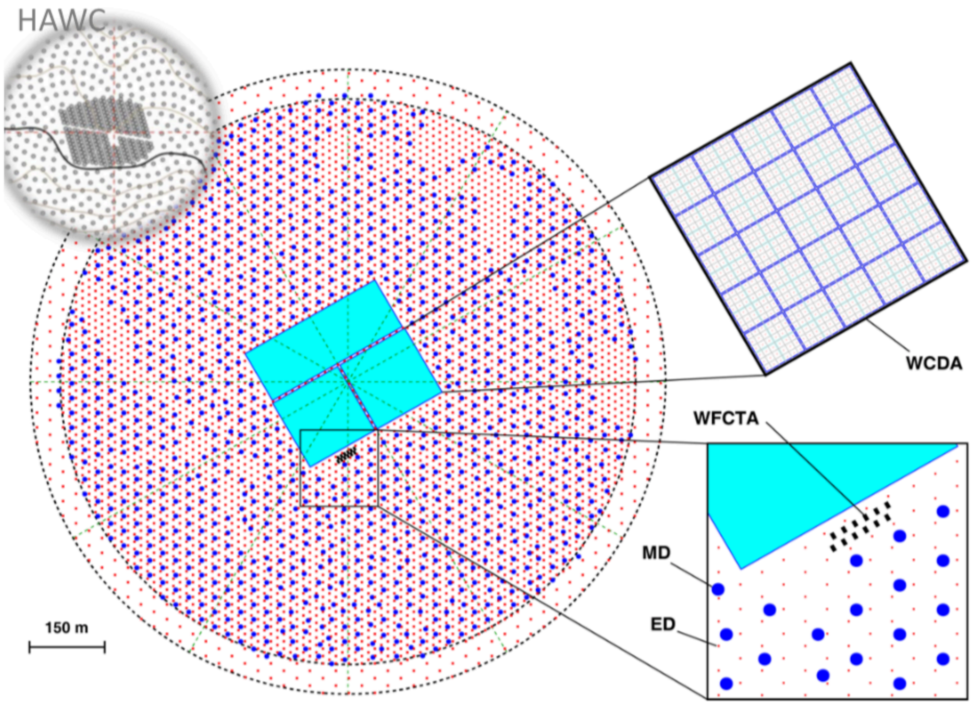
CTA - Cherenkov Telescope Array





LHAASO

Sichuan, China, 4410 m asl

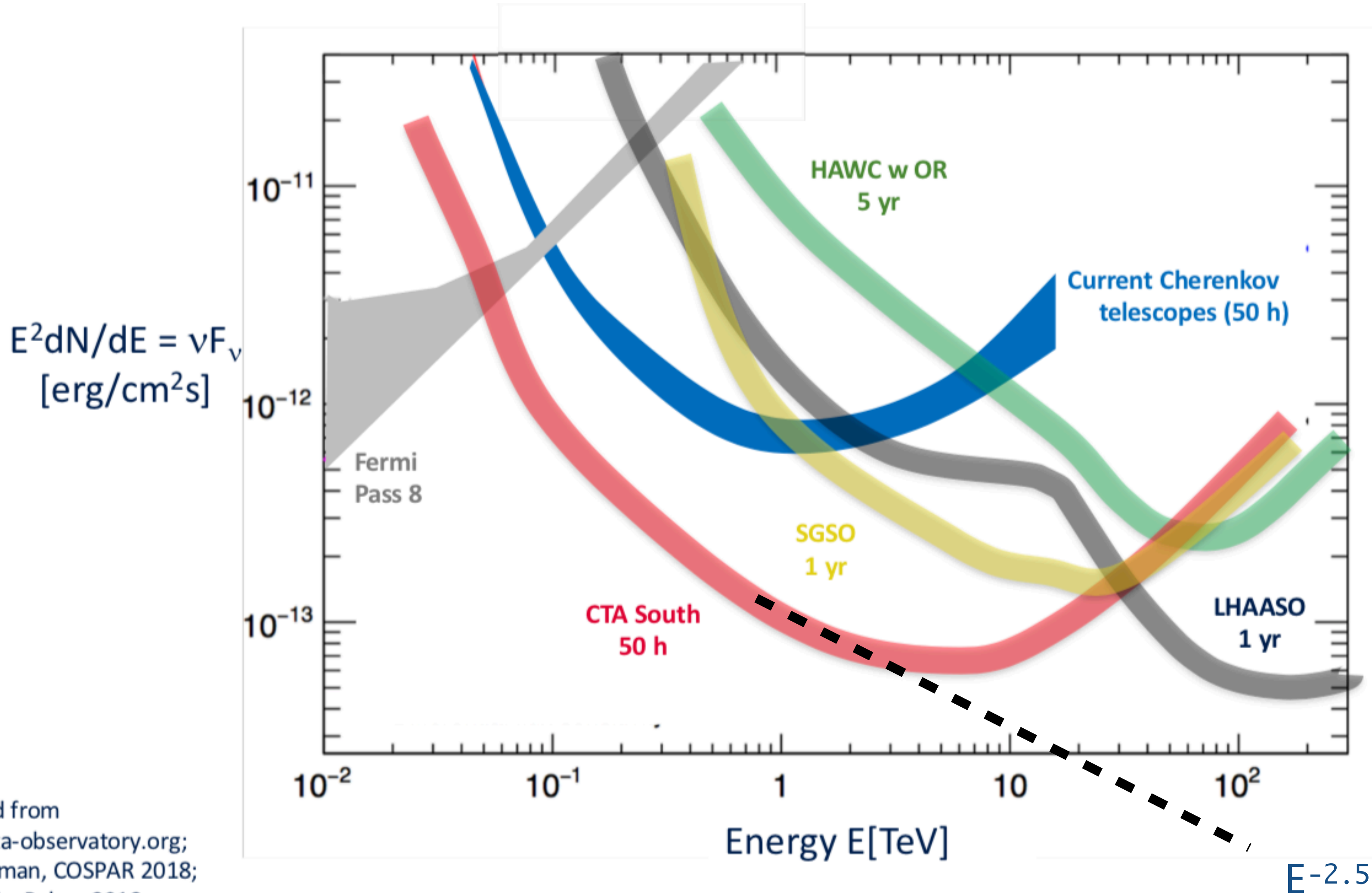


5195 Scintillators
- 1 m^2 each
- 15 m spacing

1171 Muon Detectors
- 36 m^2 each
- 30 m spacing

3000 Water Cherenkov Cells
- 25 m^2 each

12 Wide Field Cherenkov Telescopes



adapted from
www.cta-observatory.org;
J. Goodman, COSPAR 2018;
Z. Cao, La Palma 2018

IACT arrays - high performance and great potential

- huge detection areas, potentially >> 1 km; photon statistics !
- 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^{2}s
  (impressive by standards of modern astronomical instruments!)

- energy coverage from 1 GeV to 1 PeV (6 decades!)

multi-functional tools:

✓ extended sources: from SNRs to Clusters of Galaxies

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

Galactic Astronomy | Extragalactic Astronomy | Observational Cosmology

Beyond CTA?

Substantial improvement of sensitivity at TeV energies ?
very difficult: intrinsic limit on PSF ~ 1-2 arcmin plus operation in background dominated regime => Fmin ~ $1/N^{1/2}$

- potential for significant improvement of sensitivity above 10 TeV

  PeV astrophysics

- Reduction of the energy threshold down to 1 GeV

  GeV astrophysics

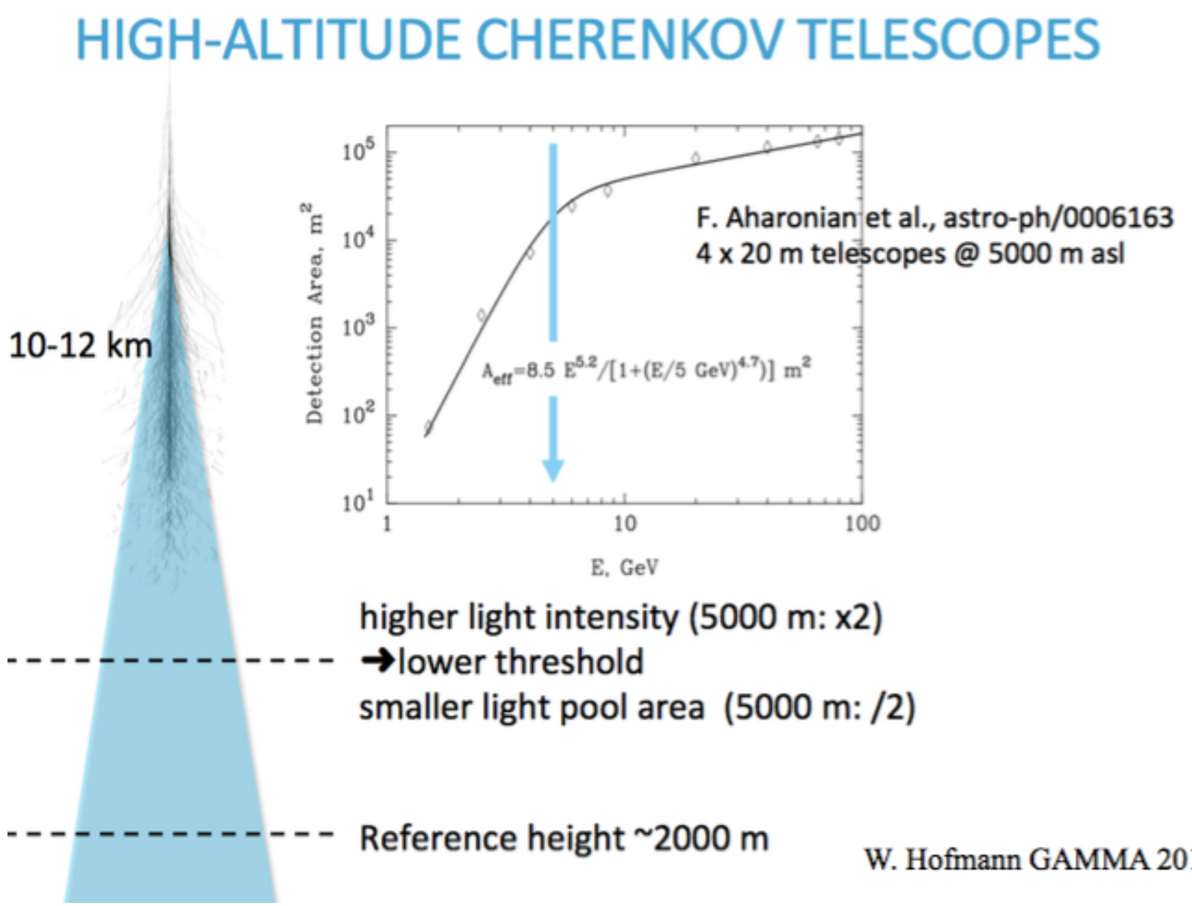
PeV astrophysics

significant improvement of sensitivity above 10 TeV with >> 10 km^2 arrays with arrays IACTs located at large (300m or so) distances

TenTen approach - 10km^2 at 10 TeV

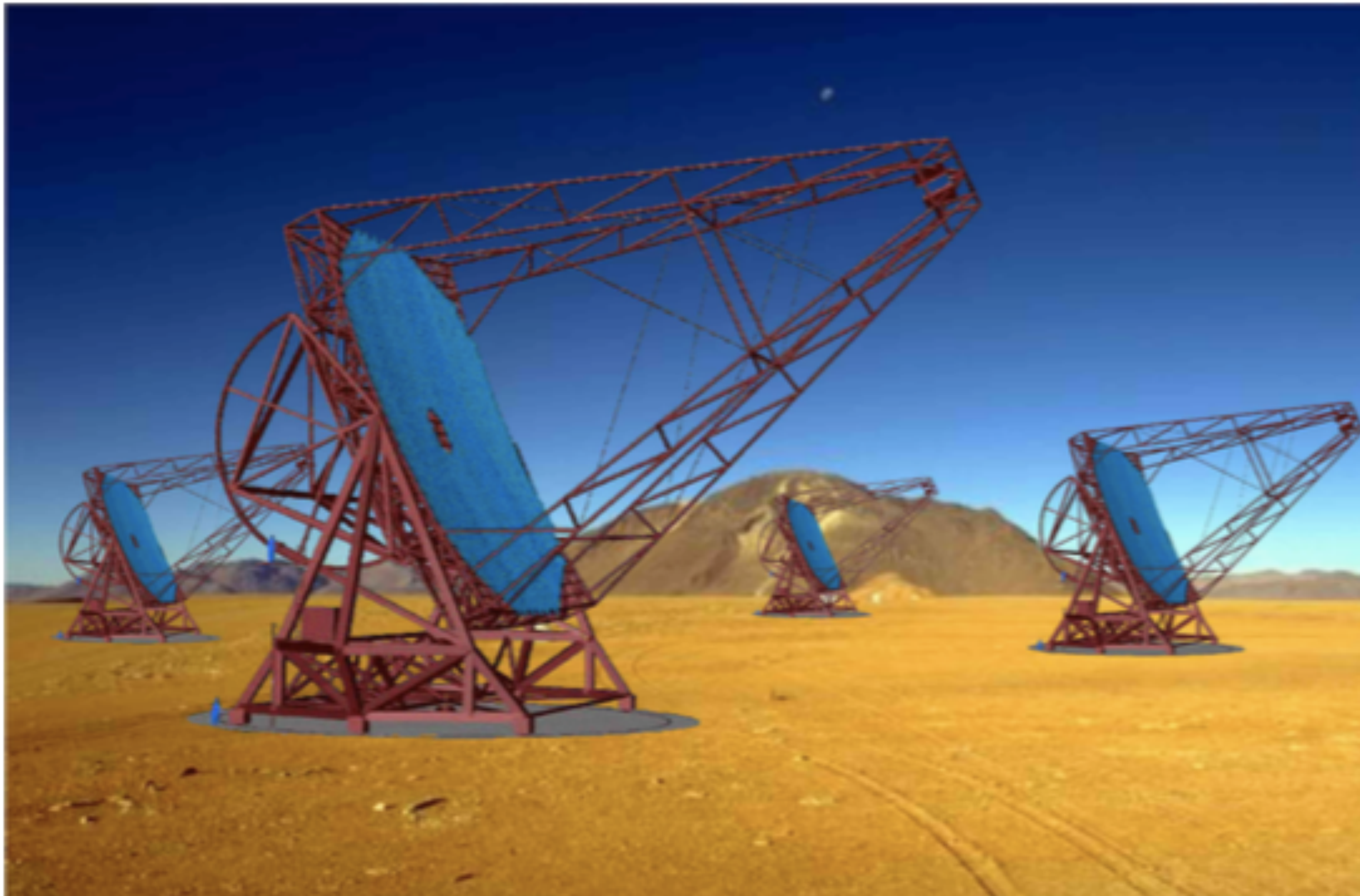
- Galactic Sources: SNR, PWNe, GC, YSCs, …
- Nearby Extragalactic Sources: Sources in LMC,
  SNe
  M82, NGC253, Arp 220,
  Cen A, M87, Cygnus A, M82,
  Mkn 501/Mkn 421
  Coma, Perseus
- Cosmology: EBL at FIR

Detecting GeV gamma-rays



W. Hofmann GAMMA 2012

5@5 – a Gamma Ray Timing Explorer



5@5 - a GeV timing explorer

- **Detector :** several 15 to 25m diameter IACTs to study the sky at energies from several GeV to several 100 GeV with unprecedented *photon and source statistics*
- **Potential:** can detect EGRET/Fermi sources with spectra extending beyond 5 GeV for exposure time from *1 sec to 10 minutes*
- **Targets:** Gamma Ray Timing Explorer for study of nonthermal phenomena: *AGN, Microquasars, GRBs,, Pulsars ...*

5@5 is complementary to GLAST
in fact due to small FoV needs very much GLAST
and ... GLAST certainly needs a 5@5 type instrument

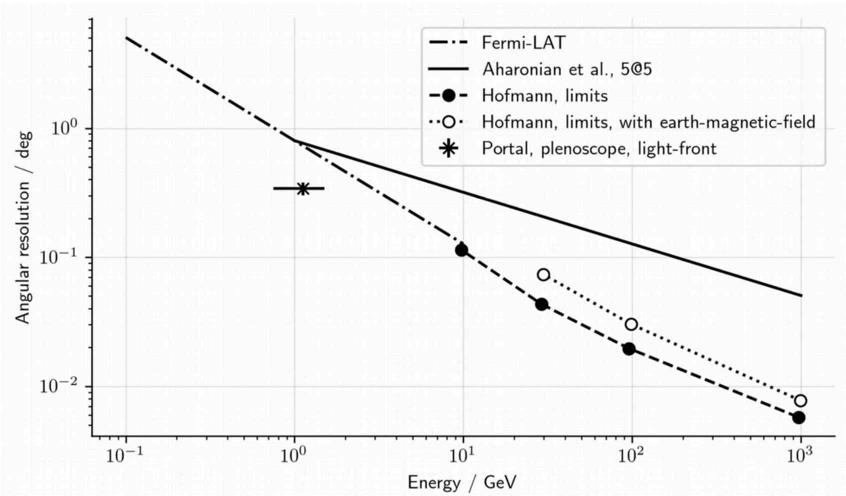
"The rapid development and successful operation of 5@5 during the lifetime of GLAST would represent a major observational coup"

Gamma Ray Group Summary Report, Snowmass "The future of particle Physics" (astro-ph/0201160)

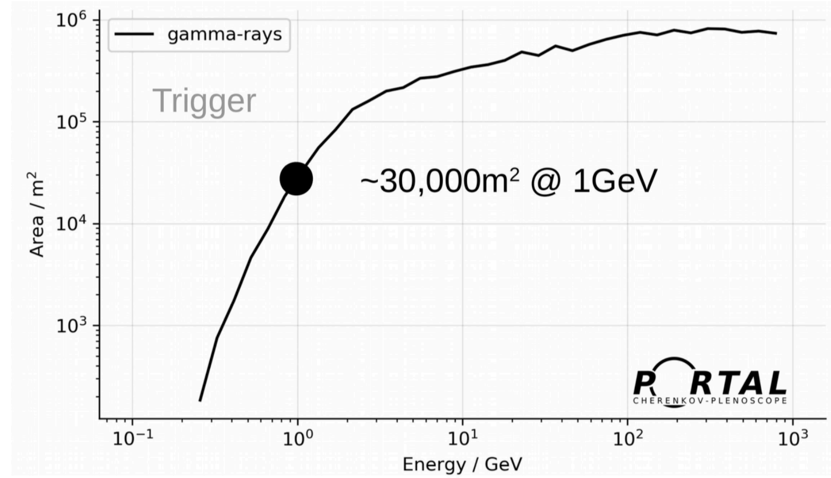
As Felix Aharonian phrased it: “...The scientific reward of a ground based approach in GeV gamma-ray-astronomy will be enormous…”

We can now ask him whether he still thinks so today.

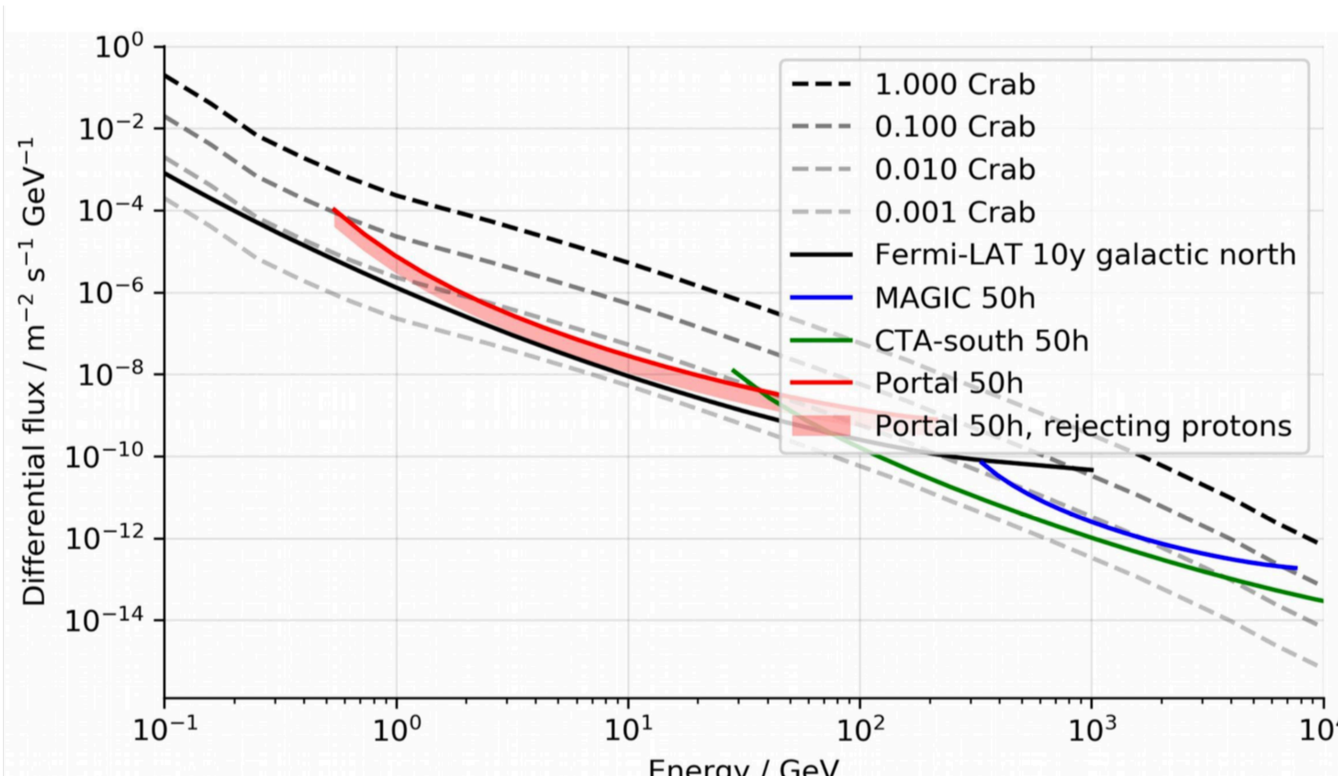
70m diameter Cherenkov telescope



Fermi-LAT
Aharonian et al., 5@5
Hofmann, limits
Hofmann, limits, with earth-magnetic-field
Portal, plenoscope, light-front
Angular resolution / deg
Energy / GeV



gamma-rays
Trigger
~30,000m² @ 1GeV
Area / m²
Energy / GeV
CHERENKOV-PLENOSCOPE



1.000 Crab
0.100 Crab
0.010 Crab
0.001 Crab
Fermi-LAT 10y galactic north
MAGIC 50h
CTA-south 50h
Portal 50h
Portal 50h, rejecting protons
Differential flux / m⁻² s⁻¹ GeV⁻¹
Energy / GeV

Status

after several decades of struggles and controversial claims ground-based gamma-ray astronomy finally became a truly observational discipline - a part of modern astrophysics with

250+ reported sources representing
10+ source populations

two established detection techniques:

- Imaging Atmospheric Cherenkov Telescope Arrays
- Low-threshold EAS arrays/Water Cherenkov Detectors

strength and uniqueness

- unique for specific topics e.g. for the solution of

  Origin of Galactic and 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*
  - less exotic issues, like *Relativistic MHD* (e.g. in PWNe and AGN)

Major topics

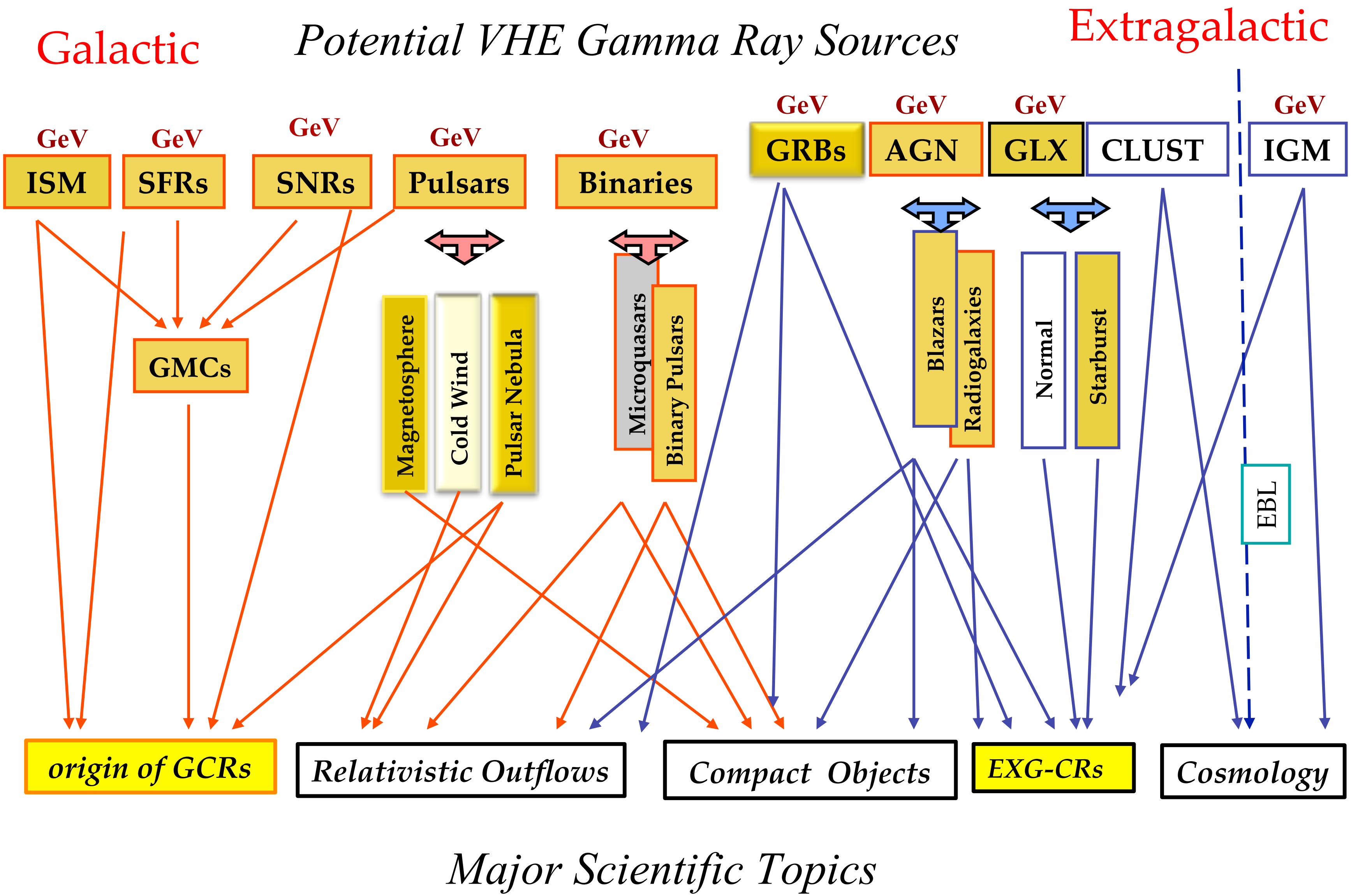
- origin of Galactic and Extragalactic Cosmic Rays

- physics and astrophysics of relativistic outflows (jets and winds)

- high energy processes at extreme conditions (e.g. close to BHs)

- cosmological issues - Dark Matter, Large Scale Structures., etc.

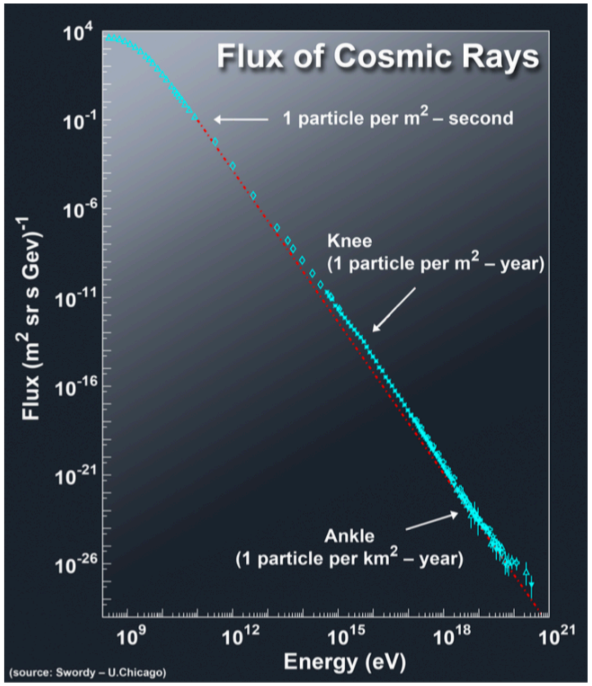
. . .

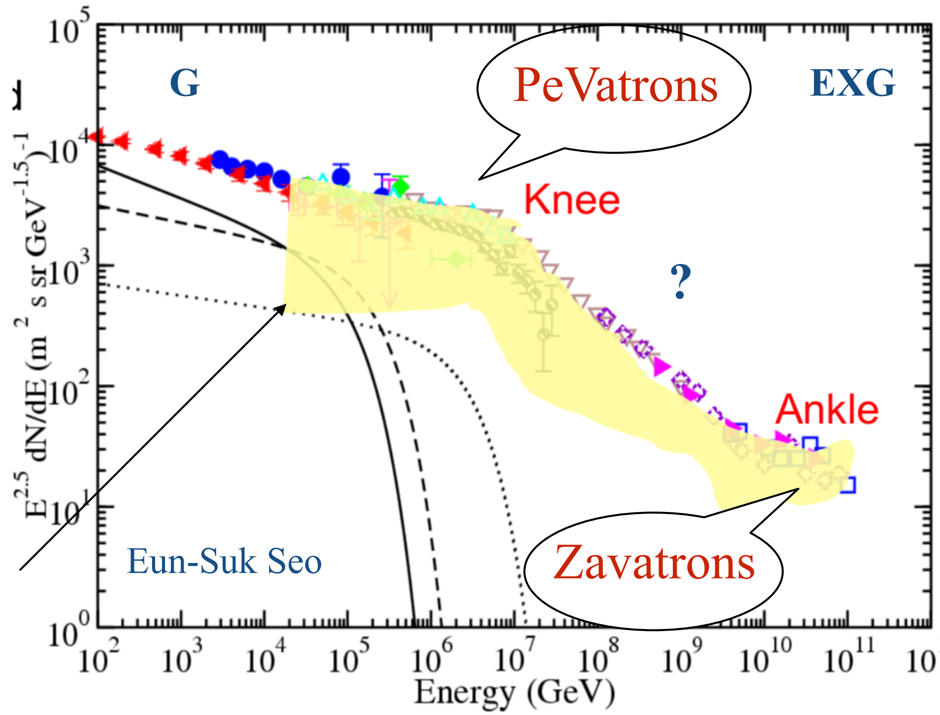


Galactic
Potential VHE Gamma Ray Sources
Extragalactic
GeV
ISM
GeV
SFRs
GeV
SNRs
GeV
Pulsars
GeV
Binaries
GeV
GRBs
GeV
AGN
GeV
GLX
CLUST
GeV
IGM
GMCs
Magnetosphere
Cold Wind
Pulsar Nebula
Microquasars
Binary Pulsars
Blazars
Radiogalaxies
Normal
Starburst
EBL
origin of GCRs
Relativistic Outflows
Compact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

"Origin of cosmic rays remains a mystery…"

a standard statement used in reviews/textbooks over many decades





below 10¹⁵ eV - G
beyond 10¹⁸ eV - EXG
between 10¹⁵-10¹⁸ eV ?

PeVatrons and Zevatrons
are extreme Accelerators

what does mean "Origin of Cosmic Rays" ?

term "Cosmic Rays" itself has two meanings:

- locally detected nonthermal/relativistic particles - a "local fog"
- the "4th substance" of the visible Universe (after the matter, radiation and magnetic fields) - a *more fundamental issue*

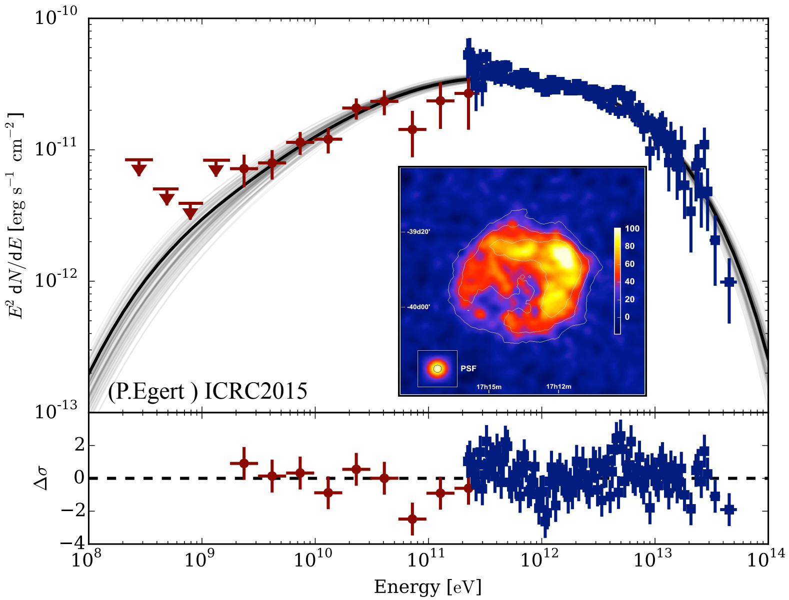
"origin of CRs" generally is reduced to the identification of the major contributors (SNRs, pulsars, GC, etc.) to the 'local fog'

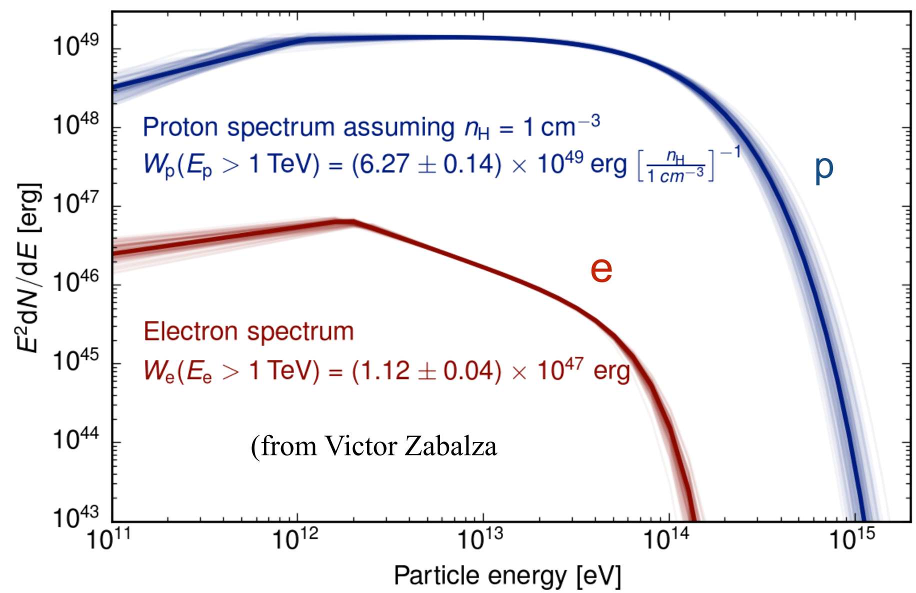
this issue principally cannot be addressed by observations of charged CRs

sources can be identified only by neutral stable messengers:
gamma-rays and neutrinos

Probing the distributions of accelerated particles in SNRs

HESS measurements **RXJ 1713** derived spectra of e and p





CTA can do much better; extension of measurements to >100 TeV
a few arcimin (sub-pc) structures
particles beyond the shell

hundreds of GeV and/or TeV gamma-ray emitters have been discovered representing 10+ source populations:

- SNRs, Stellar Clusters, GMCs
- Pulsars, PWNe
- Binaries (Binary Pulsars, Microquasars)
- Galaxies, Starburst Galaxies,
- Radiogalaxies,
- AGN, GRBs

analogy with X-rays:
as cosmic plasmas are easily heated up to keV temperatures - almost everywhere, particles (electrons and protons/nuclei) can be easily accelerated to TeV energies - almost everywhere!

not all of them contribute to local CR flux but all are

Particle Accelerators - *factories* of relativistic matter

questions beyond the origin of local CRs , for example
the physics of Extreme Accelerators

machines where acceleration proceeds with efficiency close to 100%

(i) fraction of available energy converted to nonthermal particles

in PWNe and perhaps also in SNRs <u>*can be as large as 50 %*</u>

(ii) maximum possible energy achieved by individual particles

acceleration rate close to the <u>*maximum (theoretically) possible rate*</u>

sometimes efficiency can even "exceed" 100% ?

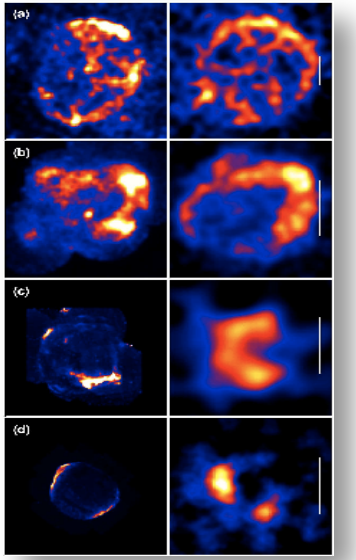
(no violation of conservation laws - but due to relativistic and non-linear effects)

Galactic Sources:

Major contributors to Galactic Cosmic Rays

- SNRs $\dot{\mathrm{W}} \approx 10^{42} \mathrm{erg/s}$
- Stellar Winds $\dot{\mathrm{W}} \approx 10^{42} \mathrm{erg/s}$
- SMBH in GC potentially up to $\dot{\mathrm{W}} \approx 10^{44} \mathrm{erg/s}$
- Pulsars. ??? certainly electrons and positrons; also hadrons

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



- *status*

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*?

- 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.

- detection of >30 TeV γ-rays from steep-spectra SNRs, e.g. Cas A or SN 1006

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 1 (PeVatron candidate?)

complimentary or instead of SNRs as GCR factories
sub-TeV/**TeV**/sub-PeV

PeVatrons: "young stars versus dead stars"

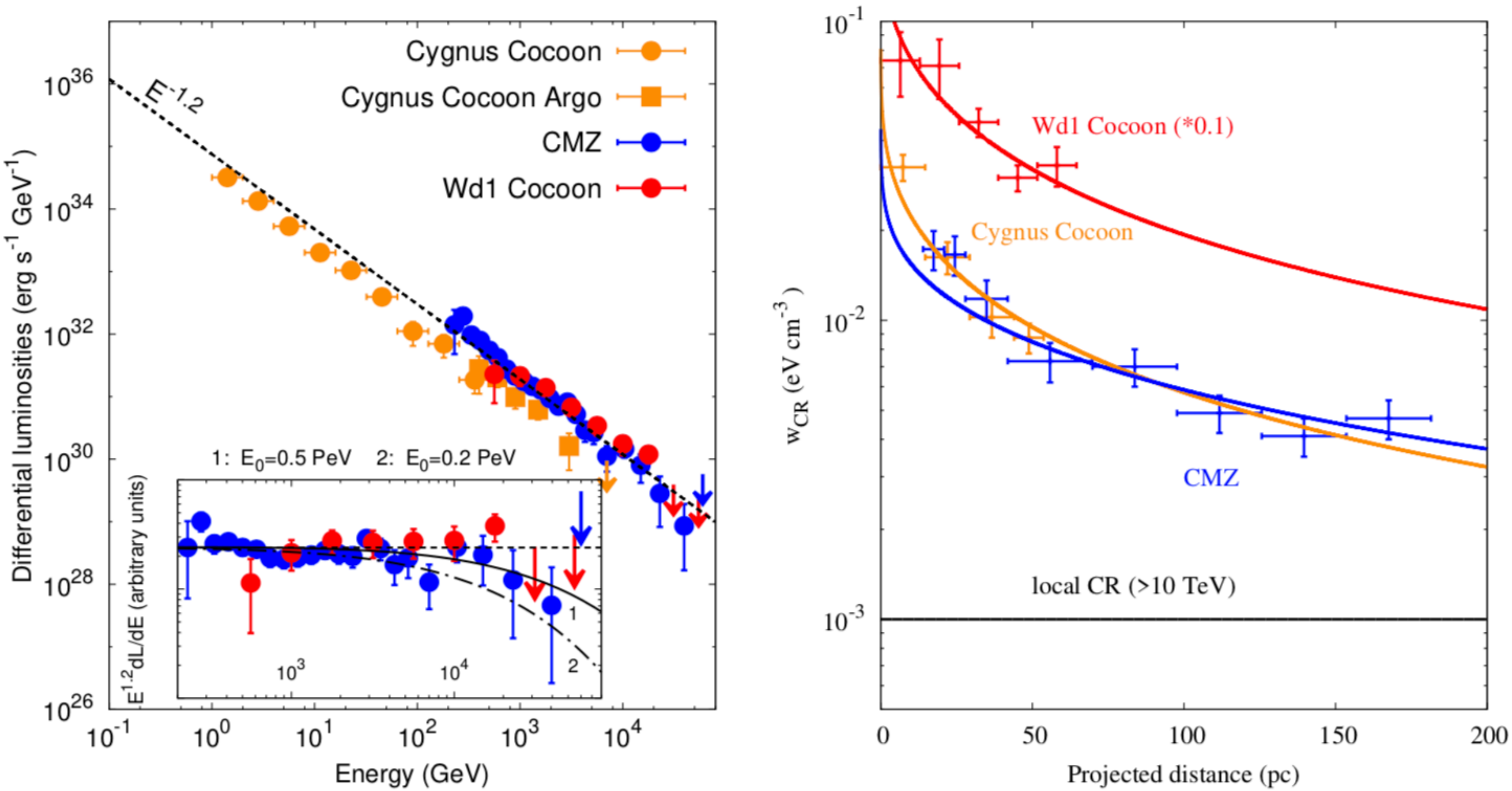


Figure 1: Gamma-ray luminosities and CR proton radial distributions in extended regions around the star clusters Cyg OB2 (Cygnus Cocoon) and Westerlund 1 (Wd 1 Cocoon), as well as in the Central Molecular Zone (CMZ) of the Galactic Centre assuming that CMZ is powered by CRs accelerated in *Arches*, *Quintuplet* and *Nuclear* clusters.

FA, Yang, Ona de Wilhelmi, 2018

Searching for PeVatrons

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 or a local slope ?
- the shape of the cutoff

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**

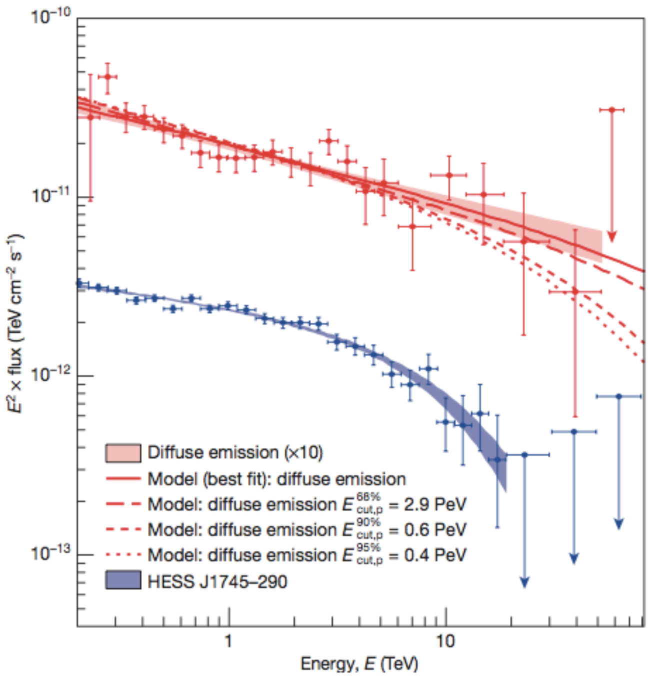
– connections with Fermi Bubbles TeV, sub-PeV **TeV, sub-PeV**

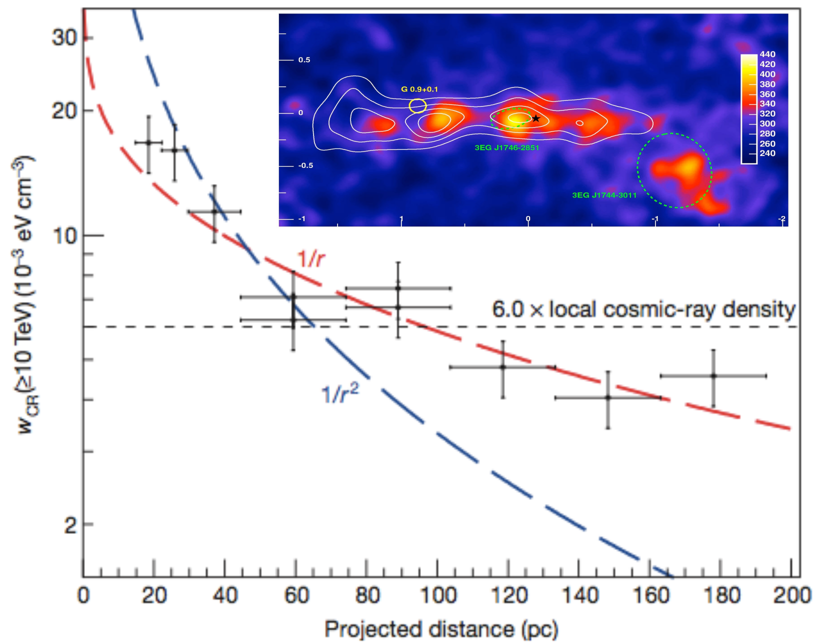
– search for flares in Sgr A* **sub-TeV**

ultimate aim - identification of the central PeVatron

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

PeVatron located within R<10 pc and operating continuously over > 10^3 yr





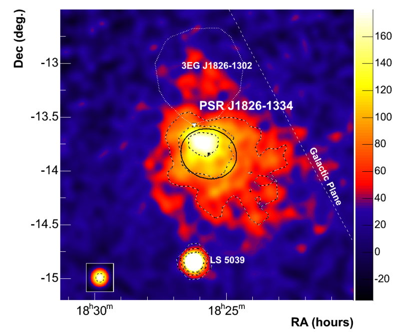
no-cutoff in the gamma-ray spectrum up to **25 TeV**
=> *no-cutoff* in the proton spectrum up to ~ **1 PeV**

what do we expect?

1/r continuous source
$1/r^2$ wind or ballistic motion
constant burst like source

derived: **1/r** distribution
=> continuous acceleration !

Galactic Sources

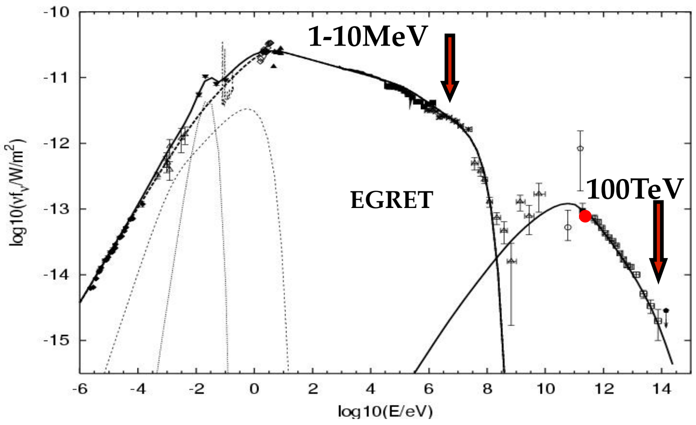


- **PWNe** - spatial and energy distribution of electrons without any assumption (unique in astrophysics), spatial distribution of the average B-field by adding the X-ray results, turbulence of the magnetic field, size of the regions filled by electrons, propagation of electrons (transition from PWN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

- **Pulsars/Pulsar-Winds:** pulsed TeV emission - magnetospheres or cold winds?

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

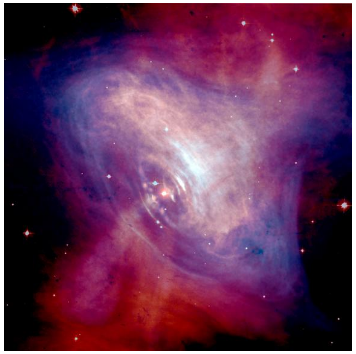
Crab Nebula – *a perfect electron PeVatron*



standard MHD theory (Kennel&Coroniti)

cold ultrarelativistc pulsar wind terminates by reverse shock resulting in acceleration of multi-TeV electrons

synchrotron radiation => nonthermal optical/X nebula
Inverse Compton => high energy gamma-ray nebula

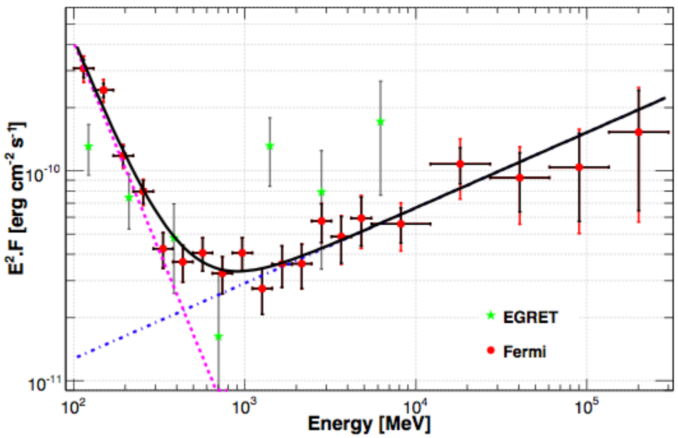


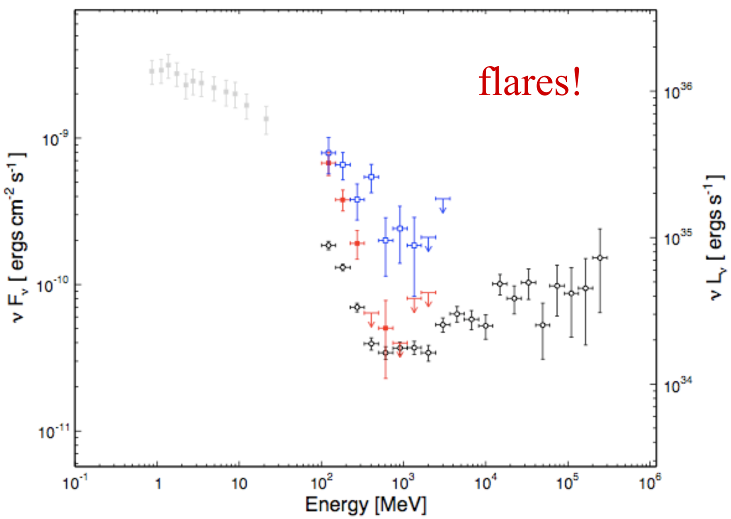
Crab Nebula – a powerful $L_e=1/5L_{rot} \sim 10^{38}$ erg/s
and extreme accelerator: Ee >> 100 TeV

$E_{max}=60\ (B/1G)^{-1/2}\ \eta^{-1/2}$ TeV and $h\nu_{cut} \sim 150\eta^{-1}$ MeV

Cutoff at $h\nu_{cut} > 10$ => $\eta < 10$ - acceleration at 10 % of the maximum rate
γ-rays: $E_\gamma \sim 50$ TeV (HEGRA, HESS) => $E_e > 200$ TeV
B-field ~100 mG => $\eta \sim 10$ - independent and more robust estimate
1 mG => $\eta \sim 1$?

Flares of Crab (Nebula) :





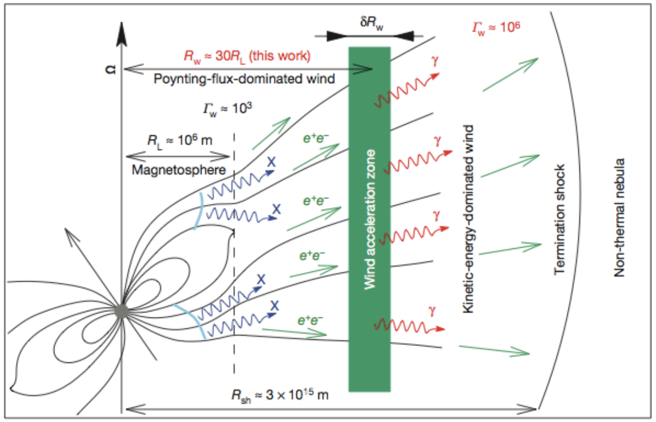
IC emission consistent with average nebular B-field: B ~ 100μG-150μG

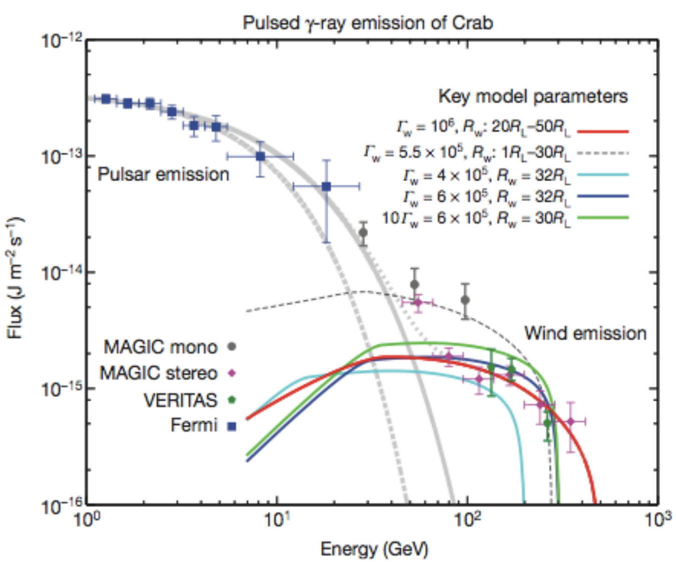
seems to be in agreements with the standard PWN picture, but … MeV/GeV flares!!

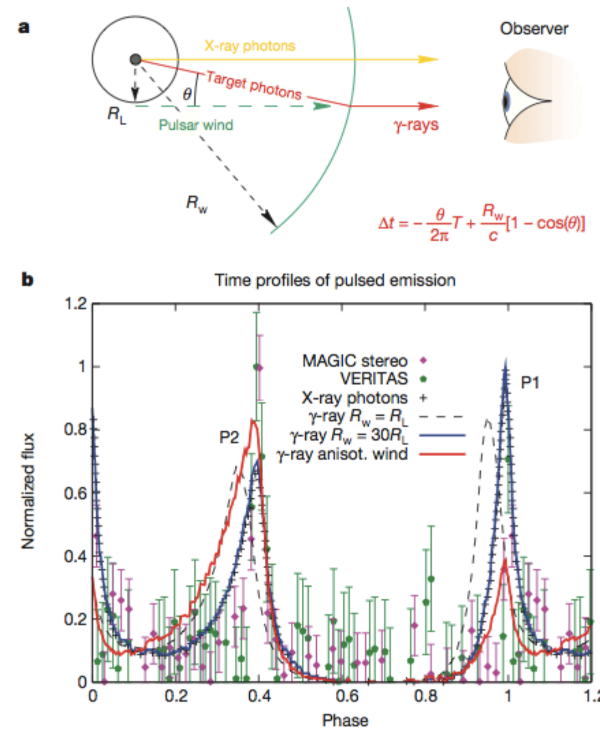
although the reported flares perhaps can be explained within the standard picture - no simple answers to several principal questions - extension to GeV energies, B>1mG, etc.

<u>observations of 100TeV gamma-rays</u> - IC photons produced by electrons responsible for synchrotron flares - a key towards understanding of the nature of MeV/GeV flares

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







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

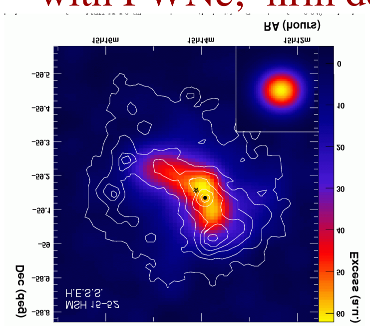
Crab Nebula is a very effective accelerator
but not an effective IC γ-ray emitter

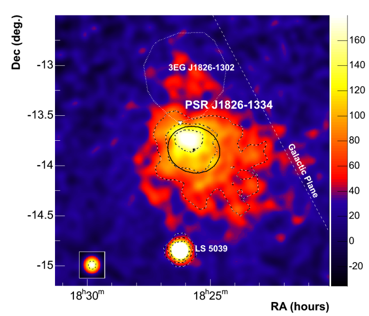
we do see TeV γ-rays from the Crab Nebula because of very large spin-down flux: $f_{rot}=L_{rot}/4\pi d^2=3x10^{-7}$ erg/cm^2 s

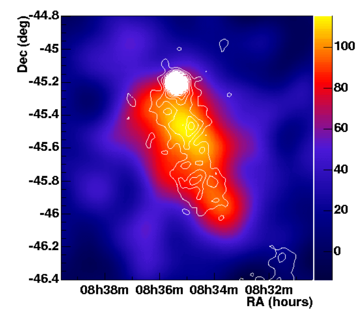
gamma-ray flux << "spin-down flux" *because of large B-field*

if the B-field is small (environments with small external gas presure)

higher γ-ray efficiency ➡ detectable γ-ray fluxes from other plerions
HESS confirms this prediction – many (20+) candidates associated with PWNe; firm detections - MSH 15-52, PSR 1825, Vela X, ... N157B!







binary systems - unique high energy laboratories

binary pulsars - a special case with strong effects associated with the optical star on both the dynamics of the pulsar wind and and the radiation before and after its termination

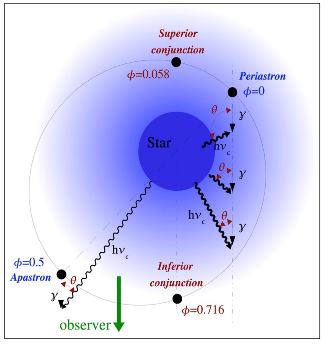
the same 3 components - *Pulsar/Pulsar Wind/Synch.Nebula* - as in PWNe both the electrons of the cold wind and shocke-accelerated electrons are illu-minated by optical radiation from the companion star detectable IC γ-rays

"on-line watch" of the MHD processes of creation and termination of the ultrarelativistic pulsar wind, as well as particle acceleration by relativistic shock waves, through spectral and temporal studies of γ-ray emission

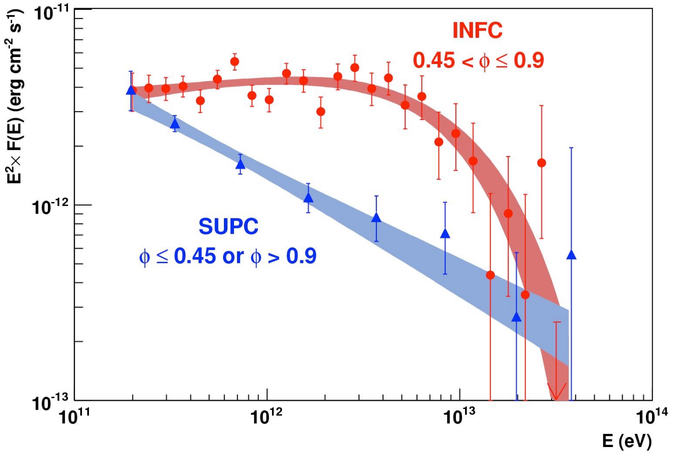
(characteristic timescales 1 h or shorter !)

the target photon field is function of time, thus the only unknown parameter is B-field => predictable gamma-ray emission?

LS 5039

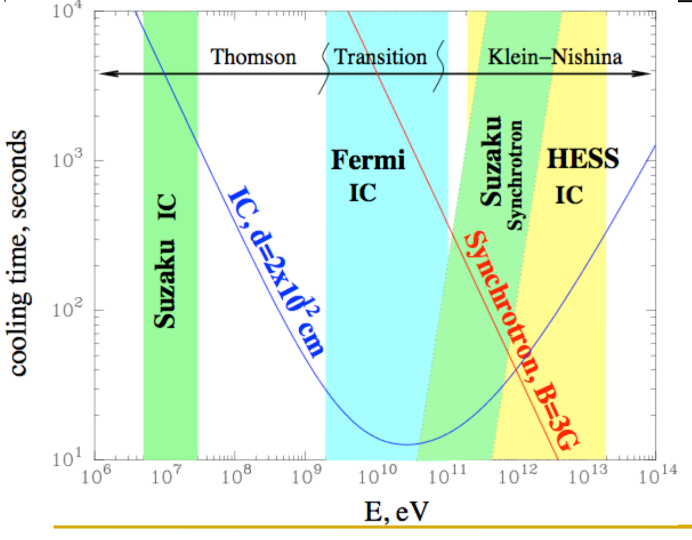


works as a perfect TeV clock
and an extreme accelerator



close to inferior conjuction - maximum
close to superior conjuction – minimum

modulation of the gamma-ray signal? *a quite natural reason (because of γ–γ absorption), but we see a different picture… anisotropic IC scattering? yes, but perhaps some additional factors (adiabatic losses, modest Doppler boosting) also play a non-negligible role*



can electrons be accelerated to energies up to 20 TeV in presence of dense radiation? *yes, but accelerator should not be located deep inside binary system; even at the edge of the system η < 10 => although* the origin of the compact object is not yet known (pulsar or a BH) and we do not understand many details, it is clear that this binary system works as an extreme accelerator

Extragalactic Sources

Extragalactic Sources

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

Extragalactic 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

ExtraGalactic Sources

- Clusters of Galaxies

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

Particle Acceleration in Galaxy Clusters

Several ingredients for effective acceleration to highest energies

- ✓ formation of strong accretion shocks
- ✓ magnetic field of order 0.1-1 μG
- ✓ shock velocity - few 1000 km/s
- ✓ acceleration time ~ Hubble time

but protons cannot be acceleratedto beyond 10^{19} eV (Kang et al., Vannoni et al) because of (Bethe-Heitler) pair production

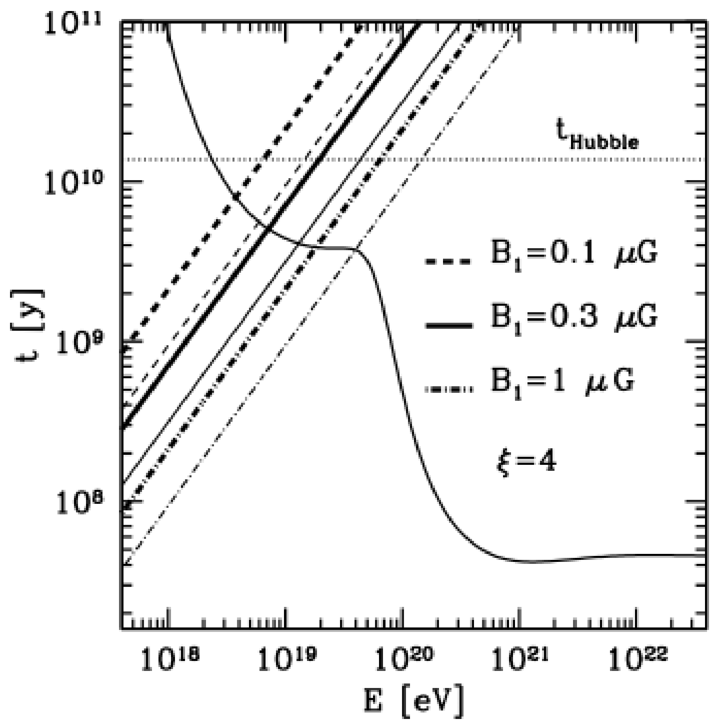
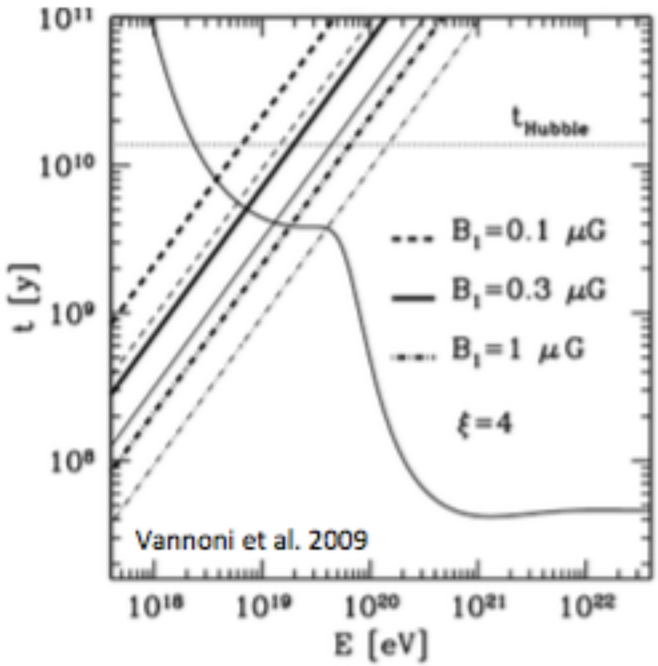


Fig. 1. Acceleration and energy loss time scales as a function of the proton energy. The acceleration time scales are obtained for the values of the upstream magnetic field B_1 reported in figure and a downstream magnetic field $B_2 = 4B_1$. The thick lines correspond to a shock velocity of 2000 km/s, the thin lines to a velocity of 3000 km/s. As an horizontal dotted line we report the estimated age of the Universe, for comparison.

Vannoni et al. 2009

Clusters of Galaxies accelerating protons to 10^{18}eV

DSA acceleration of protons=> interactions of protons with 2.7K CMBR
=> e^+e^- pair production => Synchrotron and IC of secondary electrons



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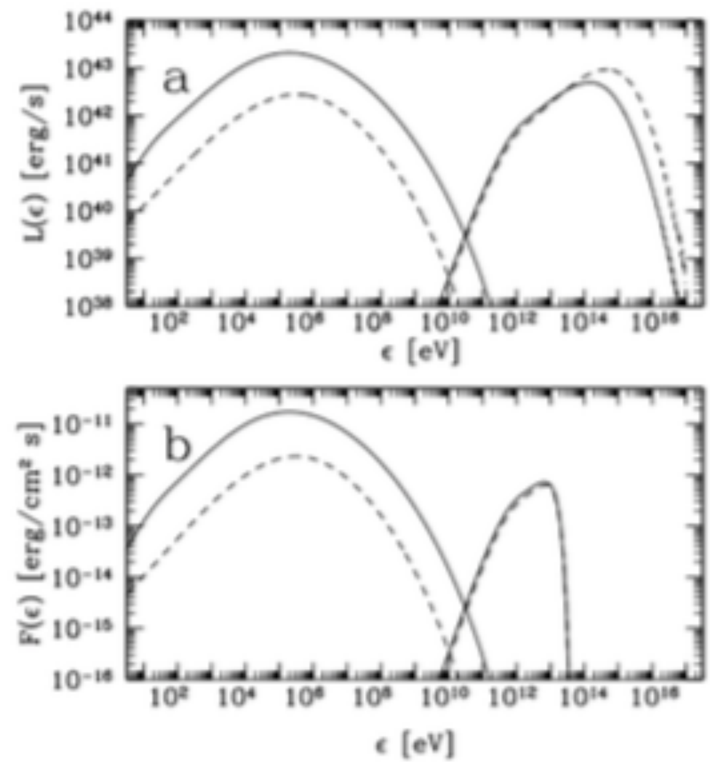


Fig. 13. a) Broadband radiation spectra produced at the source by the electron distributions in Fig. 12**b**, downstream (solid line) and upstream (dashed line). **b)** Energy flux at the observer location, after absorption in the EBL, for a source distance of 100 Mpc.

Extragalactic Sources and Highest Energy Cosmic Rays

potential sites of 10^{20} eV cosmic rays based on the condition:
source size > Larmor radious: $(R/1pc)(B/1G) > 0.1\ (E/10^{20}eV)$:

necessary but not sufficient; it implies:

(1) minimum acceleration time $t_{acc}=R_L/c=E/eBc$

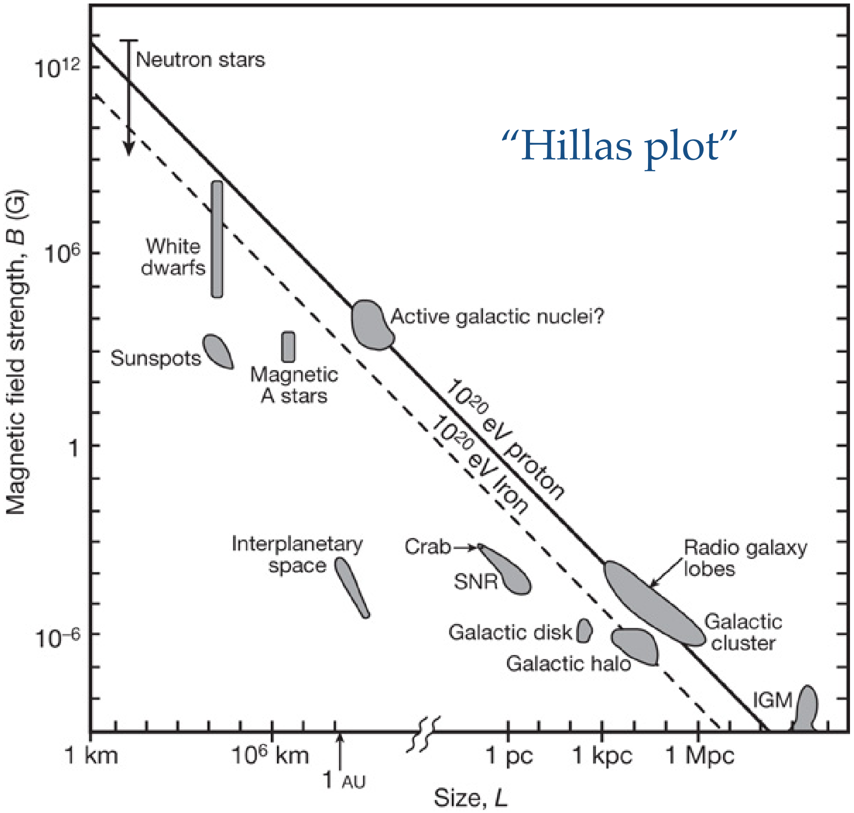
acceleration in fact is slower:

$t_{acc}=(1\text{-}10)\eta\ R_L/c\ (c/v)^2$

with $\eta>1$ and shock/bulk-motion speed $v<c$ ($\eta=1$ - Bohm diffusion)

(2) no energy losses

synchrotron/curvature losses in compact objects become severe limiting factor



PM Bauleo & JR Martino Nature 458, 847-851 (2009

acceleration sites of 10^{20} eV CRs ?

$$t_{\rm acc} = \frac{R_L}{c}\eta^{-1}$$

signatures of extreme accelerators?

✓ synchrotron self-regulated cutoff:

$$h\nu_{\rm cut} = \frac{9}{4}\alpha_f^{-1} mc^2 \eta :$$

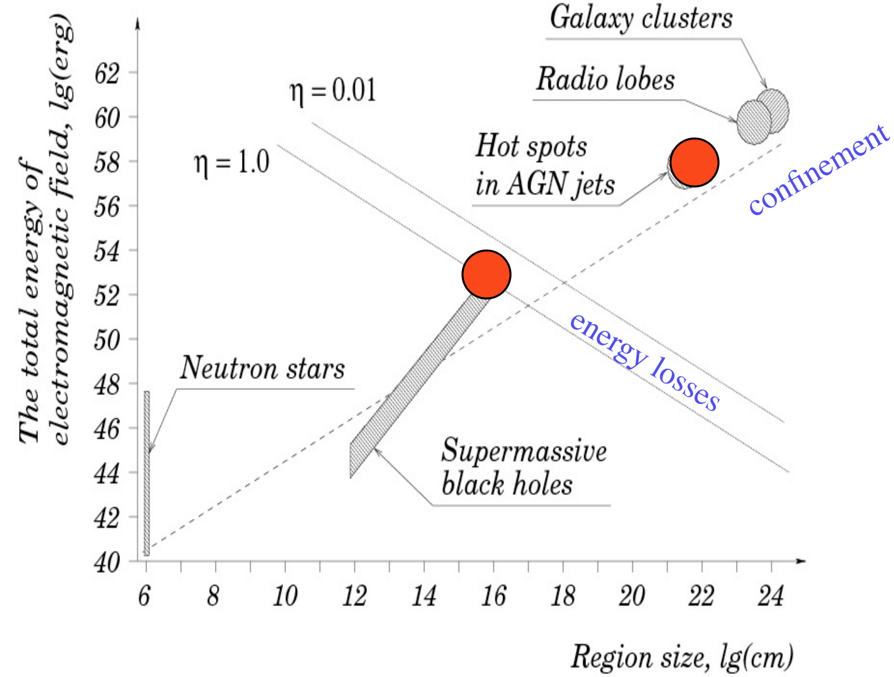
$\simeq$ 300GeV proton synchrotron
$\simeq$ 150MeV electron synchrotron

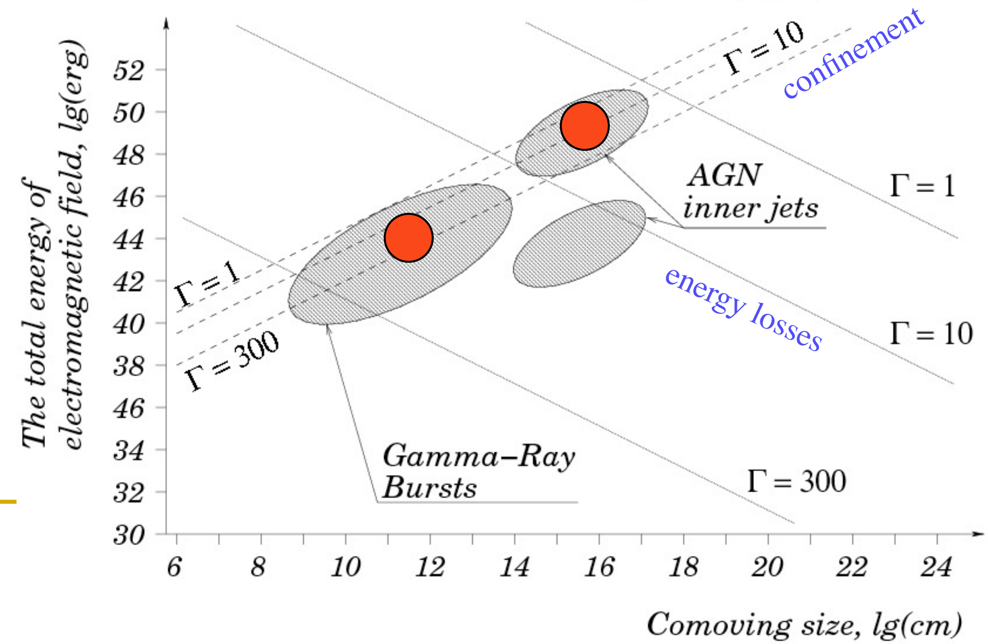
a viable "hadronic" model applicable for TeV γ-ray blazars if B ~ 100 G or so

✓ neutrinos (through "converter" mechanism) production of neutrons (through pγ interactions) which travel without losses and at large distances convert again to protons => Γ^2 energy gain! (Deerishev et al. 2003)

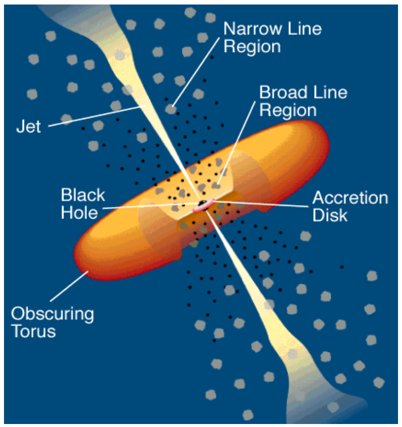
✓ observable off-axis radiation radiation pattern can be much broader than 1/Γ

*) in nonrelativistic shocks $\eta \approx 0.1(v_{\rm shock}/c)^2$





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!

"leptonic" versus "hadronic" models of TeV Blazars

leptonic (Inverse Compton) models: SSC or external IC

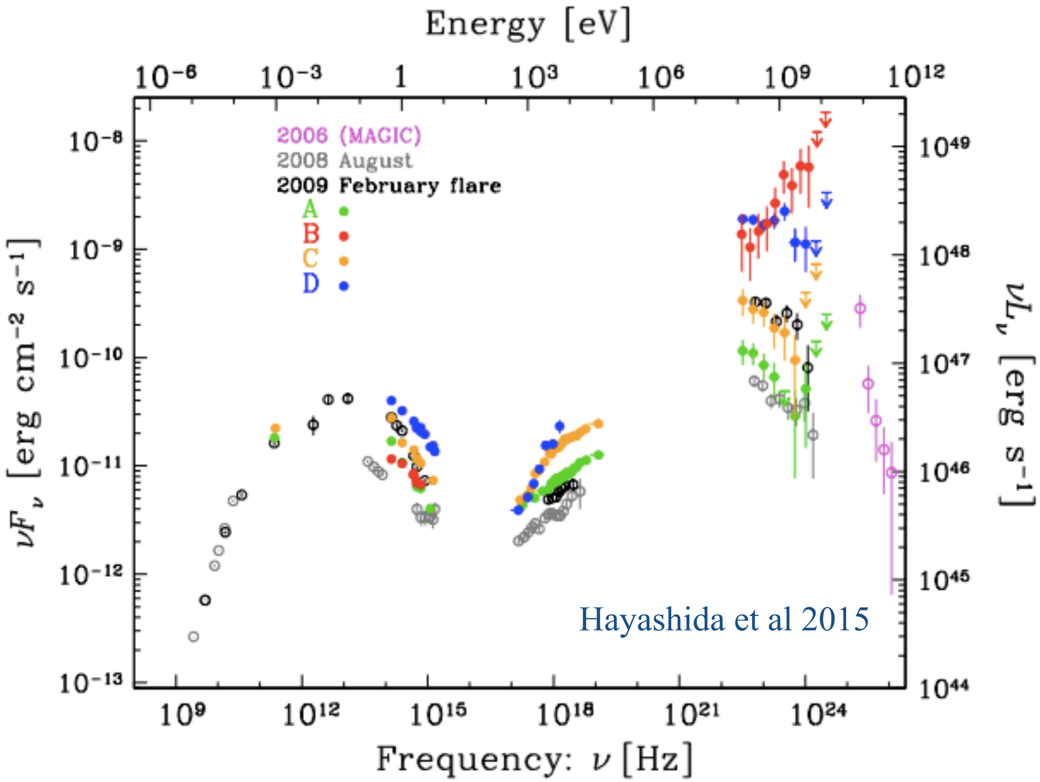
attractive: easy to accelerate electrons to TeV energies; easy to produce IC γ-rays

problems: B-field very small - 1-10 mG (in the inner parts of the jet): $W_e \gg W_B$

hadronic models

- interactions with matter ("pp") - *very slow process*
- interactions with photons ("pγ") - *low efficiency & severe γγ absorption*
- interactions with B-field (synchrotron) - (very?) large B-field, $W_B \gg W_p$
  & max. acceleration rate ~ R_L/c

can be realized only in the extreme accelerators (sources of 10^{20}eV CRs)



2013-14 flares of 3C 273:

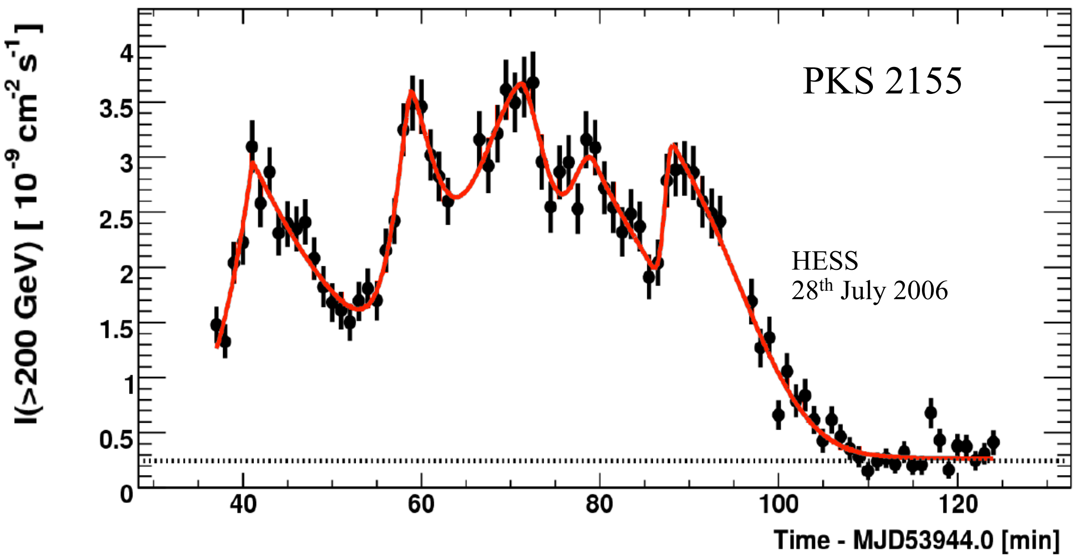
$\Delta t \sim 2$ hours
Lapp ~ 10^{49} erg/s
unusually hard spectra

"leptonic versus hadronic" - of course it's important to clarify

but now we face more serious challenges (for all models):

1. ultrafast variability ~ Rg/c
2. jet power > Eddington luminosity

Light curve of PKS 2155-304 during 2006 July flare
variability timescale $\Delta t \sim 3$ min: $L < c\Delta t \sim 6\ 10^{12}$cm!



it is convenient to express the variability through

$$\Delta t = R_g/c \sim 10\ (M/10^8 M_o)\ \text{min}$$

$R_g = GM_{BH}/c2 = 1.5\ 10^{13} M_8$ cm is gravitation radius of Kerr BH

how the ultrafast ("sub-horizon") flares can be explained?

1. γ-rays are produced in (parts of) BH magnetospheres?

   perhaps in M87, but certainly not for distant blazers

2. obviously one needs yo invoke relativistic effects, and the perturbations in the jets responsible for flares should have external origin (not directly linked to central black hole)

   two possibilities are under discussion:

   - "jet in jet"

   - "star - jet interactions"

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, LHAASO, SGSO and (hopefully) beyond