International School of Physics ”Enrico Fermi” - Varenna 2022

Foundations of Cosmic Ray Astrophysics

High Energy Cosmic Rays and Gamma Radiation

Lecture 1. Introduction to gamma-ray astronomy

Villa Monastero Varenna, June 25, 2022

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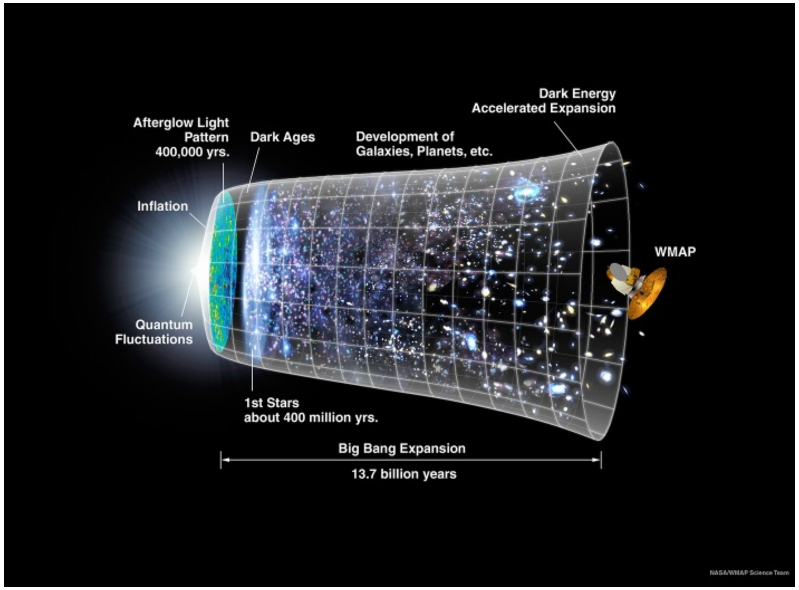
Astro-Particle Physics

modern interdisciplinary research field at the interface of
astronomy, physics and cosmology

HE Astrophysics	**gamma-ray astronomy** together with X, R, IR, O, UV astronomies and neutrino, GW astronomies
Cosmic Rays	“astronomy” with charged particles electrons, protons, nuclei, (secondary) antiparticles
HE Physics/ Cosmology	“non-accelerator particle physics” Early Universe, Dark Matter, Dark Energy

Universe as a high energy phenomenon



in the framework of "Big Bang Theory"

- the "Universe" itself is a high energy phenomenon
- its birth was an incredibly energetic event
- quite a long time it was "hot soup" consisting of relativistic ($E > mc^2$) particles and radiation; 2.7 K MBR ($\sim 10^{-3}$ eV) as remnant of that "soup"

now it is cold but contains *Cosmic Ray Factories* - particle accelerators producing the 4th substance - after *matter, radiation and magnetic fields* - of the visible Universe

Relativistic Plasma ("Cosmic Rays")

pressure (energy density) in Cosmic Rays in many objects can be comparable or even exceed the pressure contributed by the thermal gas, turbulent motion, radiation, B-fields carriers of information about High Energy phenomena

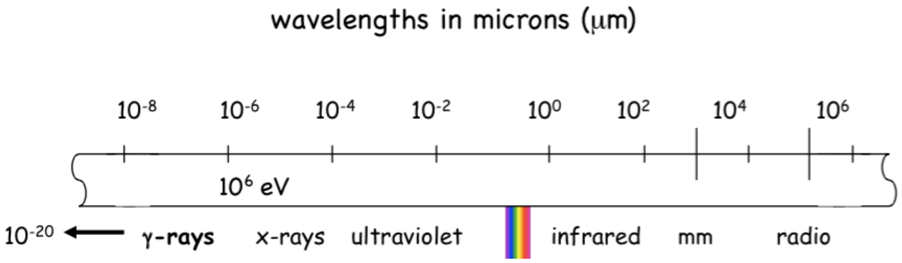
- ✓ *photons (radio, IR, O, UV, X-rays, gamma-rays)*
- ✓ *neutrinos*
- ✓ *cosmic rays*
- ✓ *gravitational waves*

multi-wavelength and multi-messenger astronomy

gamma rays as (the) key messengers of information about CR factories

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' covers 10 decades: from 10^5 to 10^{15} eV



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
UHE	or	PeV :	0.1 –100 TeV	(0.1 –10 + 1

new!

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

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

Gamma-Ray Detectors:

some general comments on the potential and perspectives

future?

HE: detection area > 10m^2:

- *improvement of sensitivity*
- *VHE range: >>100 GeV*
- *transient phenomena:*
  AGN, GRBs,

prospects: ???

LE: 1m^2 detectors - OK!
γ-ray line astronomy,
extreme synchr. sources
transients - AGN, GRBs

prospects: good
COSI, eASTROGAM, **GRAMS**

Sub-TeV (down to 30 GeV)
Multi-TeV (up to 100 TeV)
Multi-GeV (down to 3 GeV)

- *Cosmic Rays*
- *Relativistic Outflows -*
  GRBs AGN, μQSOs, PWs
- *Cosmology*

prospects: bright - CTA

> 100 TeV ASTRI

multi-GeV ?
very-high altitude very-large
aperture (30m class) IACTs

LHAASO: *"detector from*
future operating now"

breakthrough results - tip of
the iceberg
operational next 10-20 years

WCDA: 100 GeV - 100 TeV
KM2A : 10 TeV - 3 PeV
WFCTA: 0.1- 100 PeV (CRs)
6m IACT array - 0.1-300 TeV

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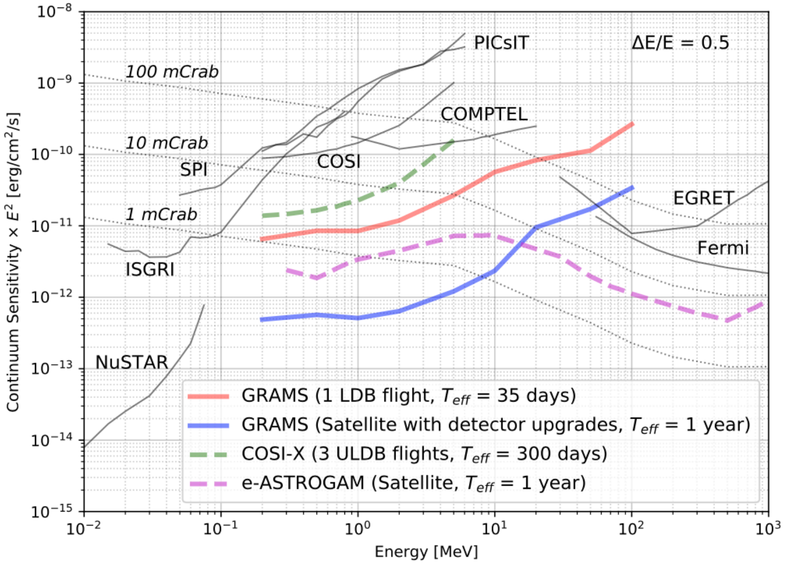
SGWO - super -"HAWC"
in 5 years?

Tunka-HiScore (Baikal) ???

Space-based LE and HE gamma-ray detectors



potential of proposed detectors ?

significant (GeV) and huge (MeV) improvements

objectives? many ('standard' list)

breakthroughs? for sure, at MeV energies

- position of the e-synchrotron peak in extreme accelerators (AGN, GRBs, Crab flares …
  $h\nu_{max} = 9/4\alpha^{-1} m_e c^2 \eta \approx 160\eta$ MeV
- for CR studies? 1-1000 MeV gamma-rays:
  shape of the "π^0 bump"
  unique information about
  < 100 MeV CRs (e and p)

GRAMS's sensitivity to important MeV lines

Sensitivity [ph/cm^2/s]	GRAMS Balloon (Satellite)	SPI/INTEGRAL	Improvement Factor
e^+ (511 keV)	2.9×10^{-6} (6.3×10^{-7})	5.0×10^{-5}	~15 (~80)
^{126}Sn (666/695 keV)	2.1×10^{-6} (4.2×10^{-7})	~2×10^{-5}	~10 (~50)
^{56}Co (847 keV)	1.4×10^{-6} (2.7×10^{-7})	~2×10^{-5}	~15 (~75)
^{44}Ti (1157 keV)	1.0×10^{-6} (1.9×10^{-7})	~2×10^{-5}	~20 (~110)
^{60}Fe (1173 keV)	1.0×10^{-6} (1.9×10^{-7})	~2×10^{-5}	~20 (~110)
^{60}Fe (1333 keV)	9.1×10^{-7} (1.7×10^{-7})	~2×10^{-5}	~20 (~120)
^{26}Al (1809 keV)	7.2×10^{-7} (1.3×10^{-7})	2.5×10^{-5}	~35 (~190)
^{2}H (2223 keV)	6.4×10^{-7} (1.1×10^{-7})	~2×10^{-5}	~30 (~180)
^{12}C* (4438 keV)	4.9×10^{-7} (7.3×10^{-8})	~1×10^{-5}	~20 (~140)

gamma-ray line astronomy!

$$\frac{\Delta E_s}{E} \simeq \frac{1\%}{\sqrt{E\,(\mathrm{MeV})/2.5}}$$

annihilation line 511 keV
deuterium line: 2.2 MeV
nuclear gamma-ray lines

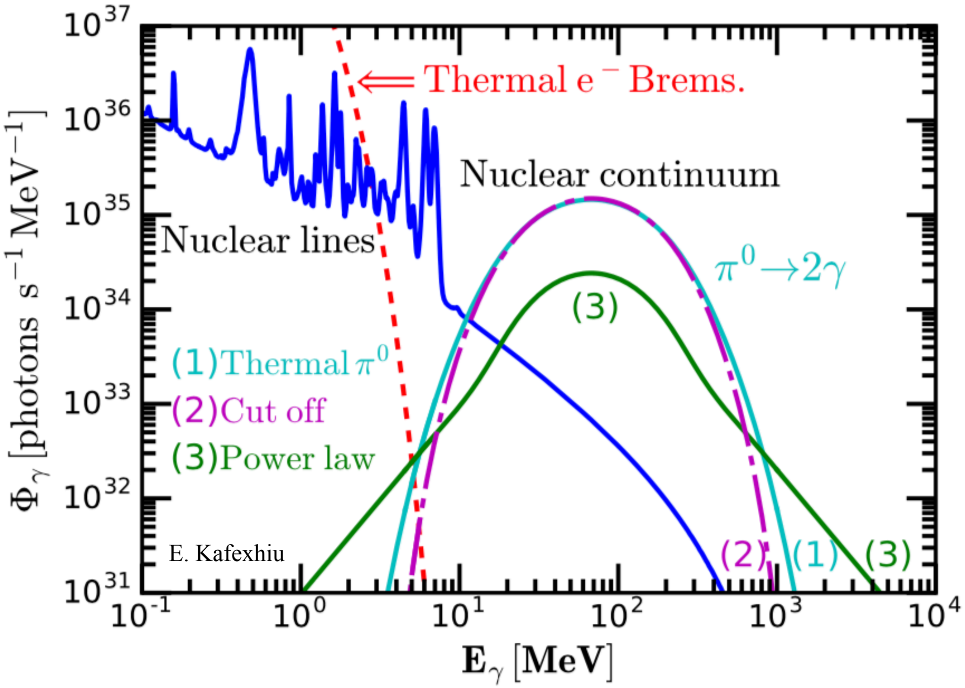
objectives? many, e.g.

- measuring temperature of two-temperature
- plasmas around accreting black holes

for CR studies? suprathermal/subrelativistic protons and nuclei - unique for understanding the role of ionisation in star formation, the energy balance in ISM,…

Gamma-ray emission of hot two-temperature thermal plasma formed at accretion of gas onto a 10 solar masses black hole

microquasar



unique measure of the ion temperature in the accretion flow close to the gravitational radius

radiation efficiency - less than 10^{-4} (fraction of the Eddington luminosity)
but could be higher in the case of acceleration in accretion flows

Revolutions with Ground Based Gamma Ray Detectors: GeV-TeV-PeV

- Imaging Atmospheric Cherenkov (IACT) Telescope Arrays
- Particle Detector (EAS) Arrays

IACT Arrays

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

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

with a potential for extension

down to 10 (1 ?) GeV: => (multi) GeV (HE) γ-ray Astronomy

High-altitude EAS Arrays

from (sub) TeV to (multi) PeV

‘Multi-GeV’ ‘TeV’ and ‘multi-TeV’ IACT arrays

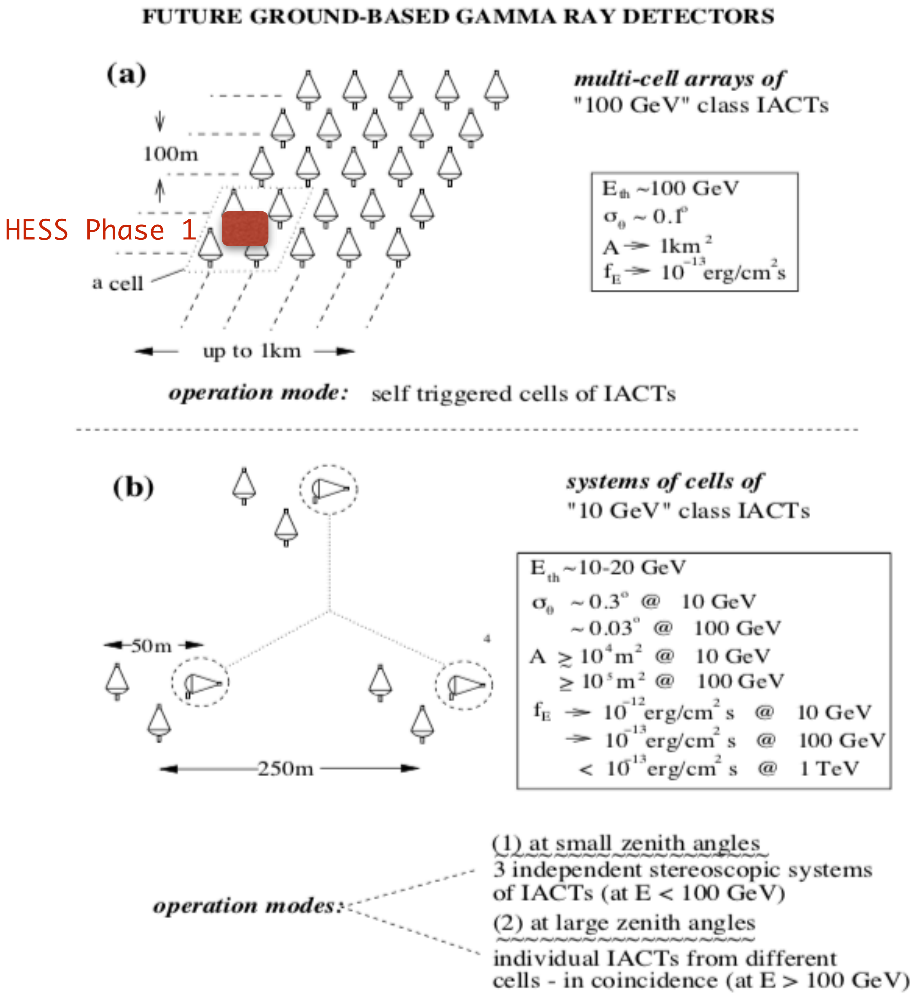
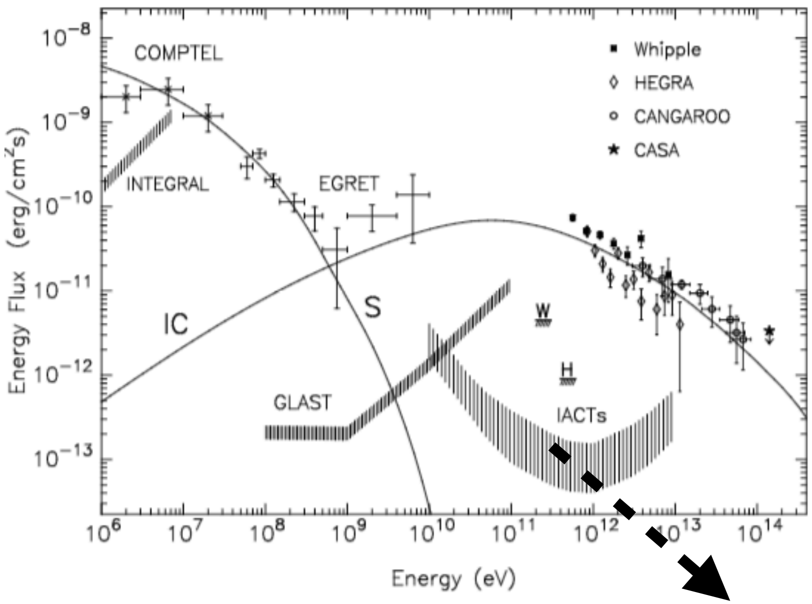


Figure 8: Two versions of future stereoscopic IACT arrays

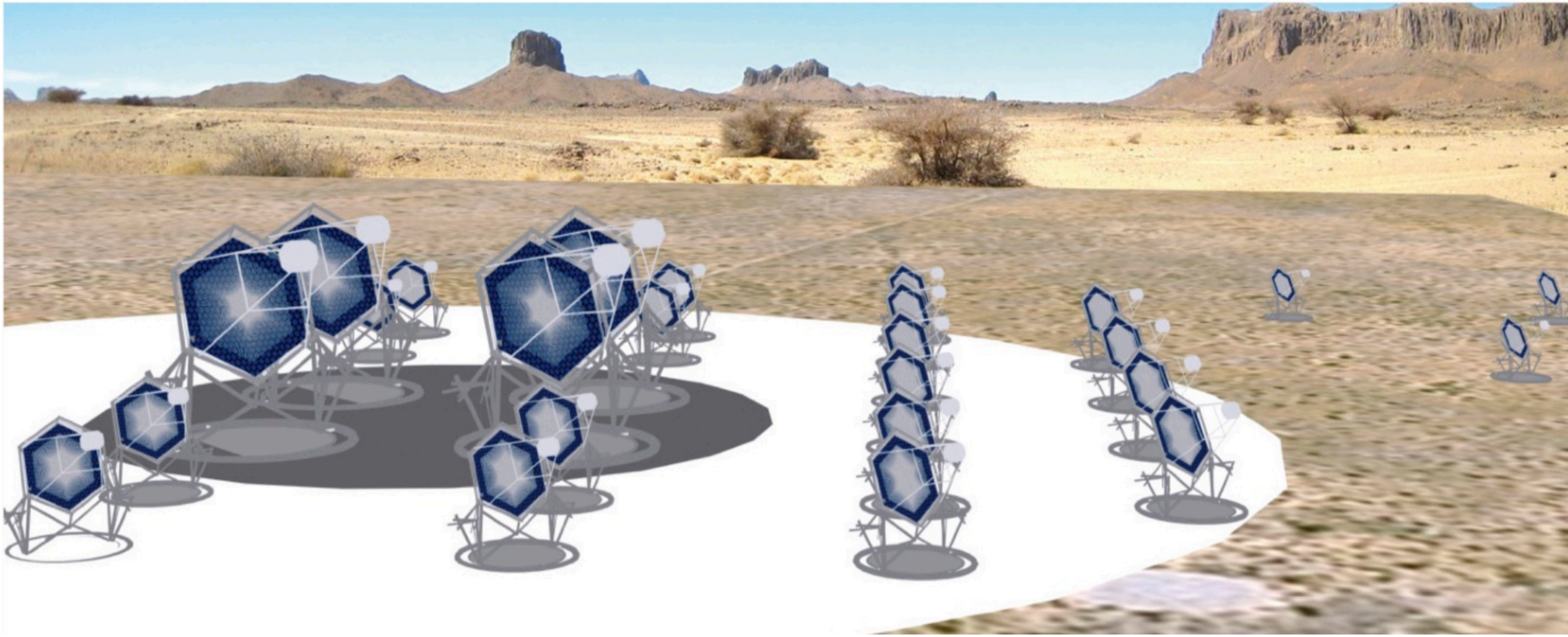


multi-TeV - concept ‘TenTen’
10 TeV threshold 10 km² coverage
FA et al 2000

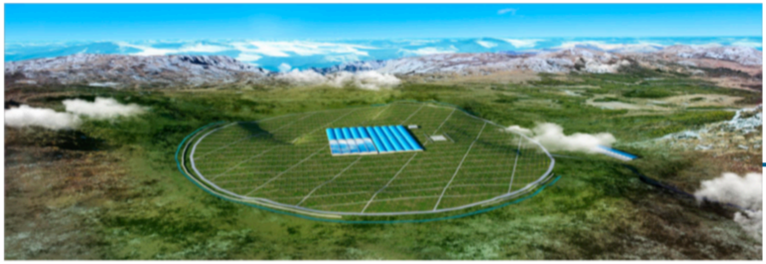
multi-GeV - concept ‘5@5’
5 GeV threshold at 5 km
FA et al 2001

FA 1997, LP97, Hamburg

CTA - Cherenkov Telescope Array

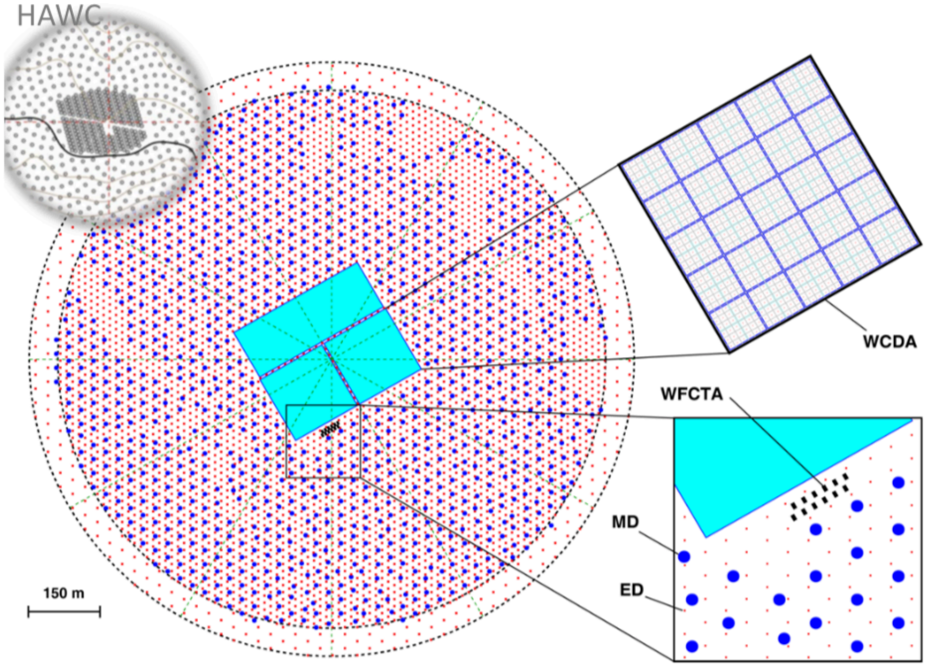


LHAAS0 - a PeVatron hunter



LHAASO

Sichuan, China, 4410 m asl



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

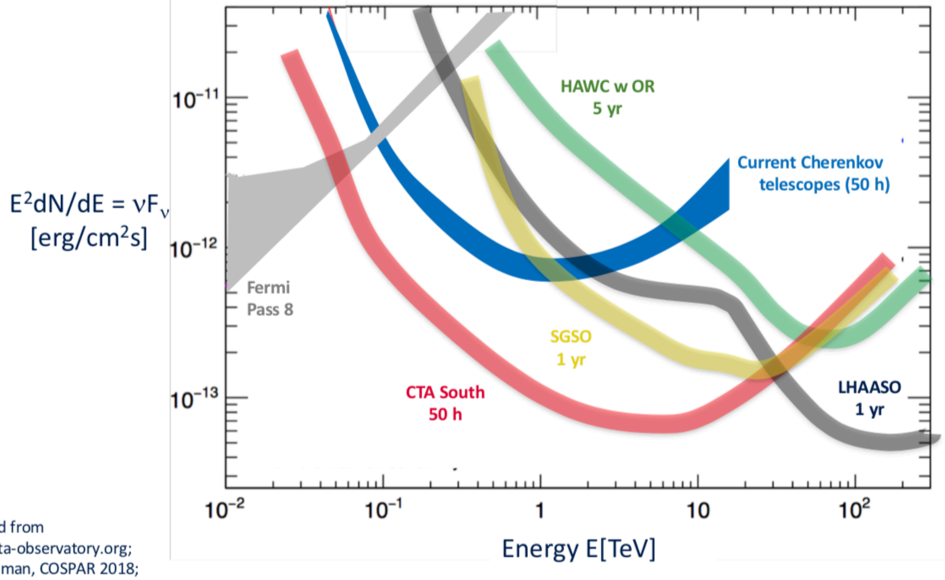
1171 Muon Detectors
- 36 m^2 each
- 30 m spacing

3000 Water Cherenkov Cells
- 25 m^2 each

12 Wide Field Cherenkov Telescopes

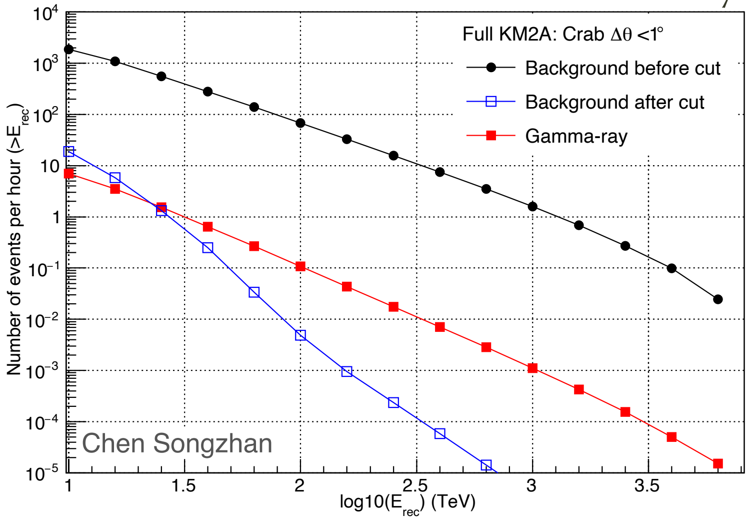
IACTs and LHAASO

sensitivities of current and future detectors



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

detection rate of the full KM2A array



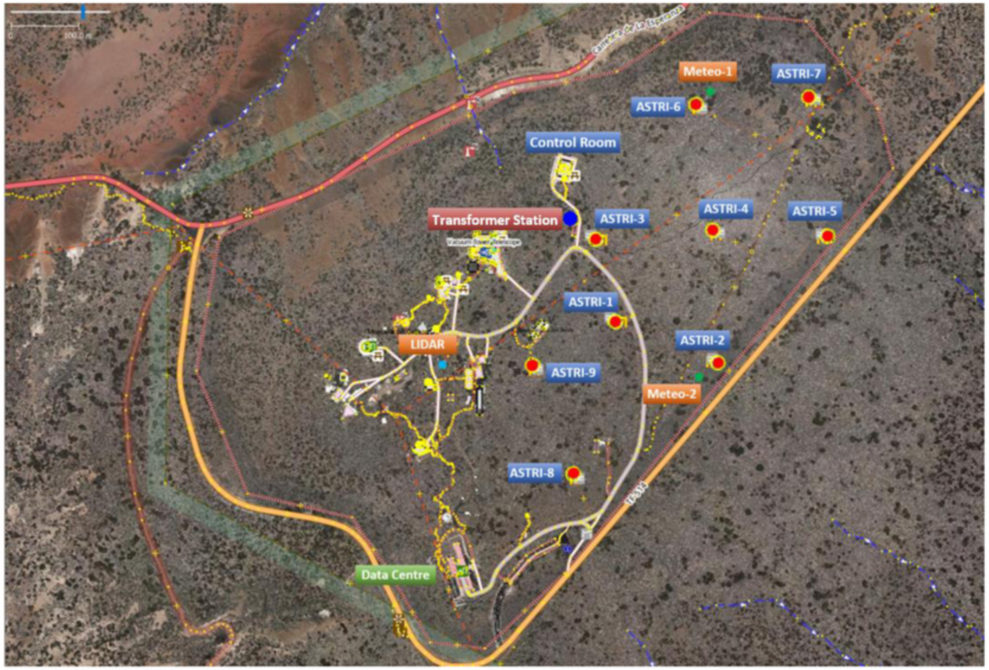
CTA - PSF: 2′-3′ from 100 GeV to 100 TeV
energy resolution 10-0%
sensitivity - best between 1-10 TeV
$(\sim 3 \times 10^{-14}\,\mathrm{erg/cm^2 s})$

KM2A - PSF: 25′ at 20 TeV, 12′ at 100 TeV
energy resolution better than 20%
sensitivity => $10^{-14}\,\mathrm{erg/cm^2 s}$

extremely “fast” detectors
very good potion statistics for sources > 0.1 Crab
very good for spectrometry, morphology, timing

background-free detection of extended 1deg sources of >100 TeV gamma-rays of strength 0.1 Crab by KM2A with a rate 1 ph/100 h
very good for diffuse/extended sources

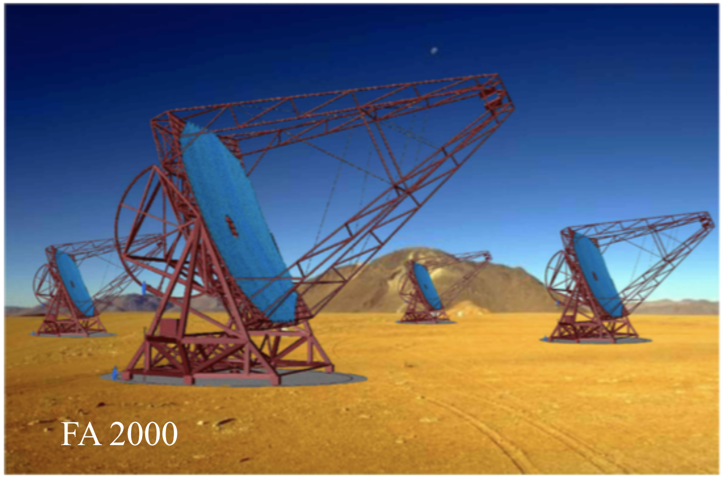
LHAASO has modest angular resolution - its combination with a complementary IACT array operating in UHE domain, would be critical for identification of extended gamma ray sources and localisation of particle accelerators inside (or nearby)n these sources



ASTRI with 9 deg FoV IACTs is arriving - very timely!

GeV Cherenkov Detectors?

5@5 – a Gamma Ray Timing Explorer



70m diameter Cherenkov telescope


ETH zürich The 2018 HILLAS SYMPOSIUM

One GeV, One Second
Gamma-Ray-Timing-Explorer

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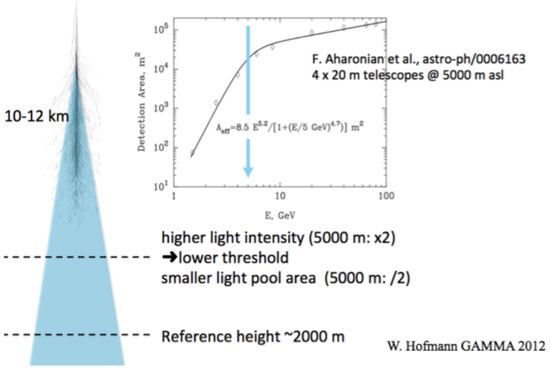
Institute for Particle Physics and Astrophysics
in collaboration with
Department of Civil, Environmental and Geomatic Engineering

HIGH-ALTITUDE CHERENKOV TELESCOPES

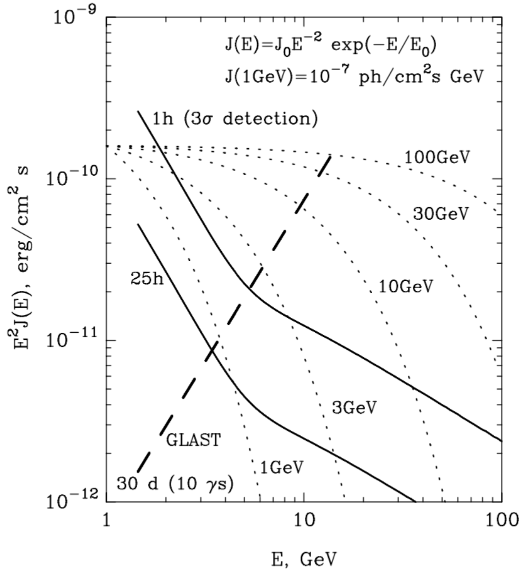


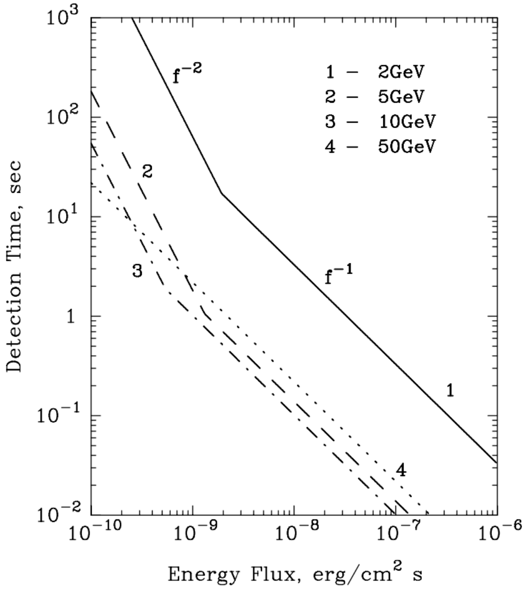
F. Aharonian et al., astro-ph/0006163
4 x 20 m telescopes @ 5000 m asl

higher light intensity (5000 m: x2)
➔lower threshold
smaller light pool area (5000 m: /2)

Reference height ~2000 m

W. Hofmann GAMMA 2012





Pulsars, Crab Flares, Microquasars, AGN flares, GRBs, FRBs, …

IACT arrays - high performance and great potential

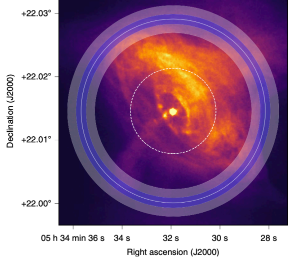
- ☐ huge detection areas, potentially >> 1 km^2
  => huge photon statistics coupled with
- ☐ good (~10 to 20%) energy resolution and
- ☐ good angular resolution (down to 2 arcmin)
- ☐ relatively large FoV (5 to 10 degree)

=> spectrometry, morphology, timing, surveys

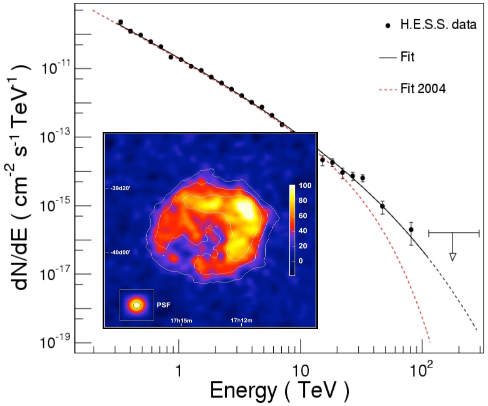
- ☐ sensitivity for point-like sources down to 10^{-14} erg/cm^2s
  (impressive by standards of modern astronomical instruments!)

- ☐ energy coverage from 1 GeV to 1 PeV (6 decades!)
  using the same technique ! (unique in astronomy/physics)

Results from current ACT Arrays

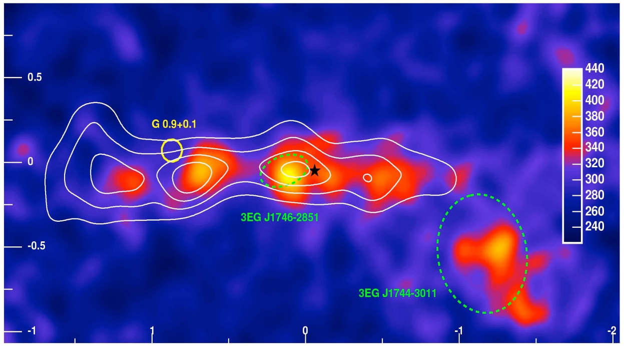


spectrometry



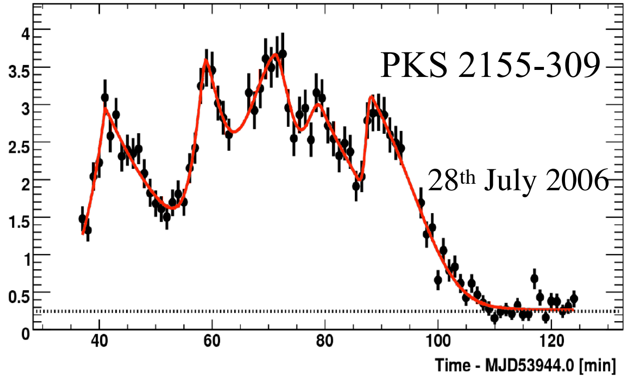
TeV image and energy spectrum of a SNR

morphology



resolving GMCs in the CMZ
200pc region of Galactic Center

timing



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

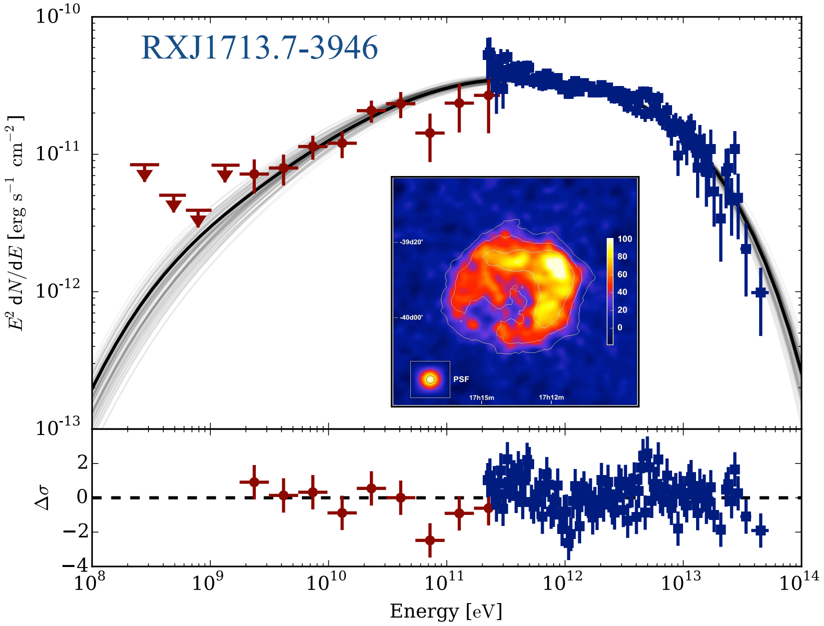
✓ transient phenomena μQSOs, AGN, GRBs, ...

Galactic Astronomy | Extragalactic Astronomy | Observational Cosmology

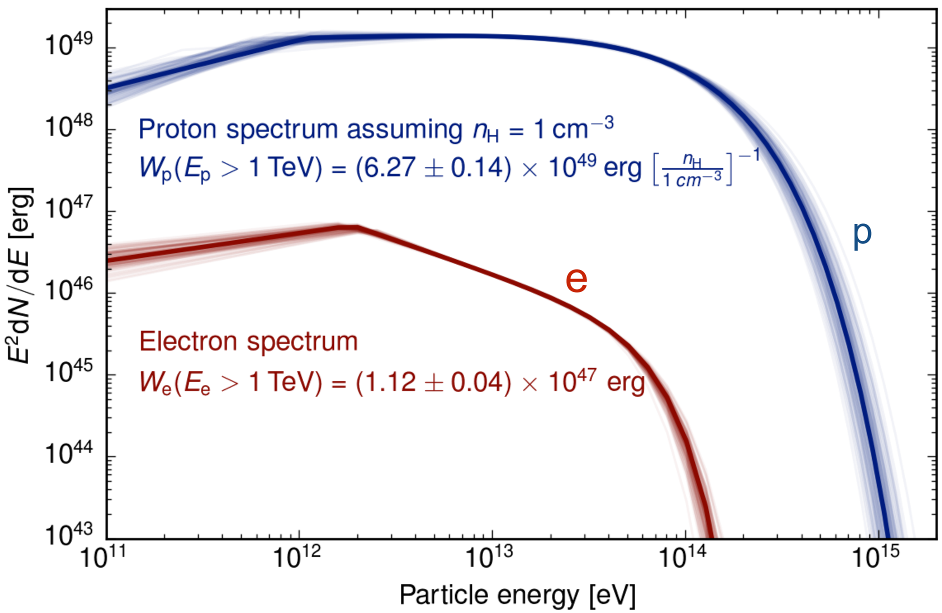
Spectrometry

Probing the distributions of accelerated particles in SNRs

Fermi+HESS measurements



electron and proton spectra

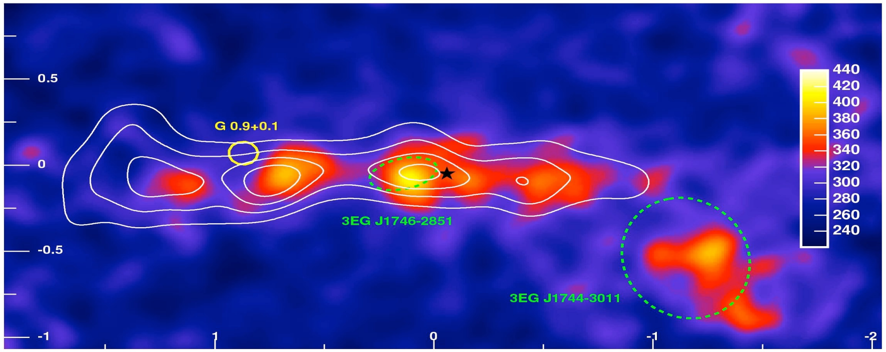


cutoff or break in the proton spectrum at 100 TeV ?

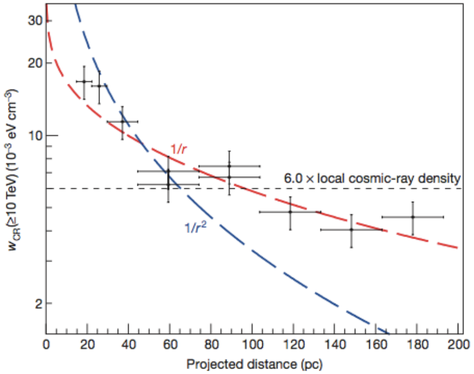
Morphology

PeVatron(s) in the Galactic Center!

CMZ in TeV gamma-rays



radial distribution of protons



continuous injection of protons into CMZ up to ~1/2 PeV : a PeVatron(s) within 10 pc of GC

SMBC in GC (Sgr A*) operating as a PeVatron ?
or particles are accelerated in the Arches, Quintuplet, Nuclear ultra-compact YMCs ?

CTA: better morphology and search for variability at TeV energies

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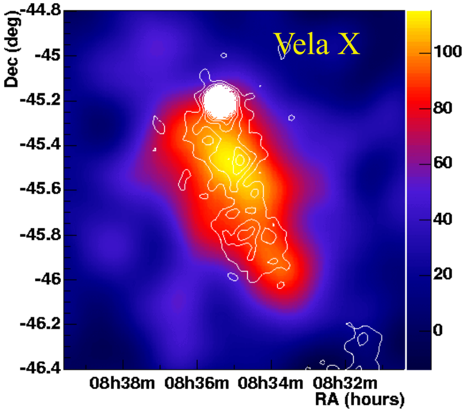
TeV gamma-ray map



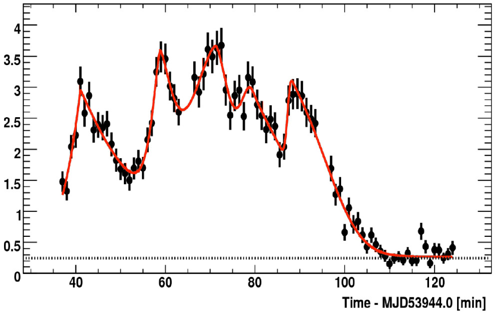
Vela X - Pulsar Wind Nebula produced by the Vela Pulsar
TeV γ-rays (most likely) of IC origin: $e + 2.7\,\mathrm{K}\ \mathrm{MBR} \rightarrow \gamma$

γ-ray distribution represents the spatial (2D) distribution of multi-TeV electrons!

=> the character of propagation of electrons - convection or diffusion?

Timing

1. AGN superfast flares



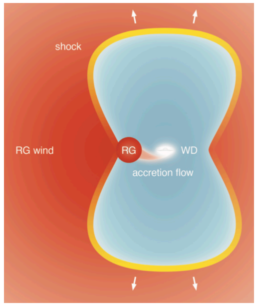
variability on timescales of

$$t \sim R_g/c = 10^4 \approx (M/10^9\,M_\odot)\ \mathrm{s}$$

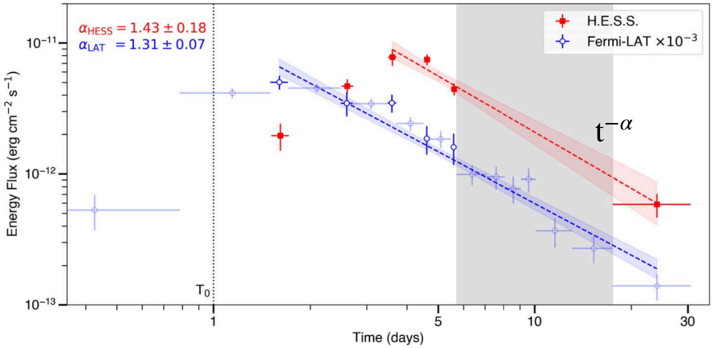
probing the environment close to the event horizon

in particular acceleration and cooling rates

2. explosion in RS Ophiuchi



WD accretes material from RG and trigger thermo-nuclear explosions driving shocks (v~ 5000 km/s)

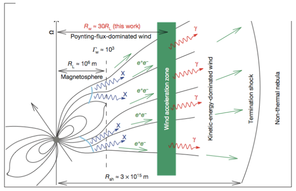


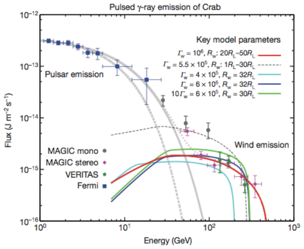
on-line "watch" of acceleration

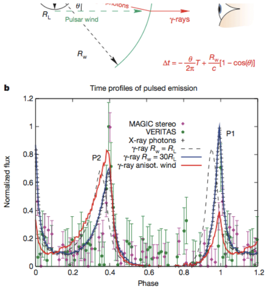
GeV flux peaks at $T_0 + 2$ day; TeV flux peak is delayed by another two days

determination of the accelerate rate!

3. Pulsed TeV emission from the Crab (and Vela)







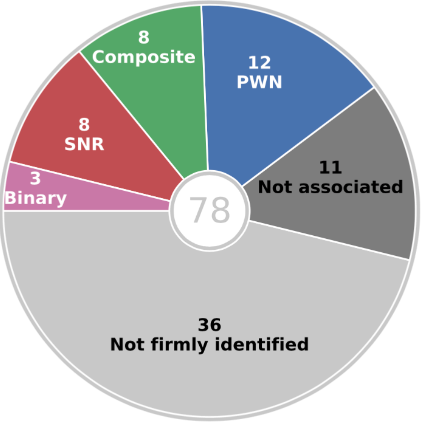
$\Gamma \sim 10^6$; $R \sim 30$ L

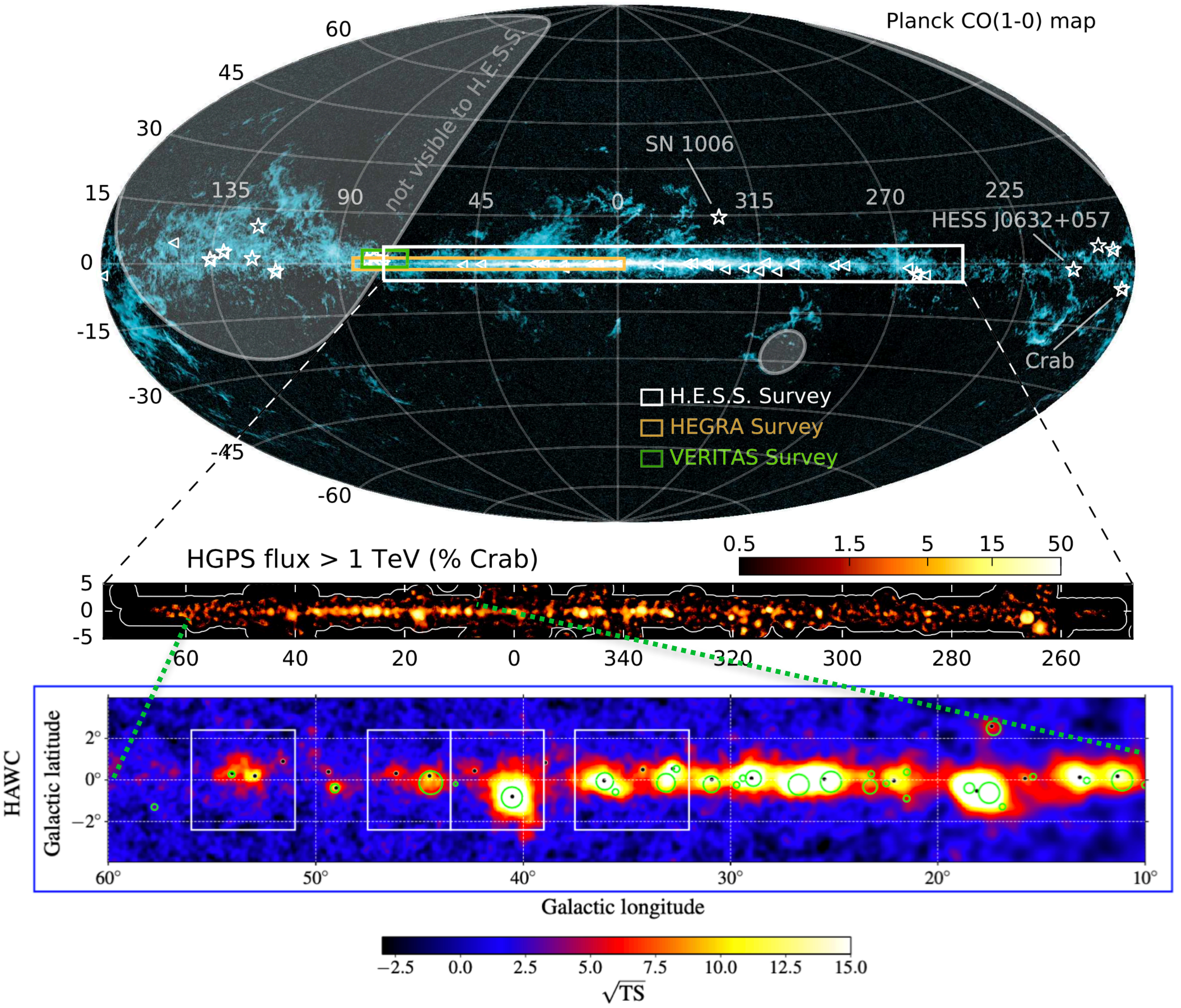
IC emission of the "dark pulsar wind" ?

Determination of the site of formation of the pulsar wind (Acceleration of the wind)

Surveys

despite small FoV IACT arrays can perform effective surveys





Galactic Plane is full of TeVatrons!

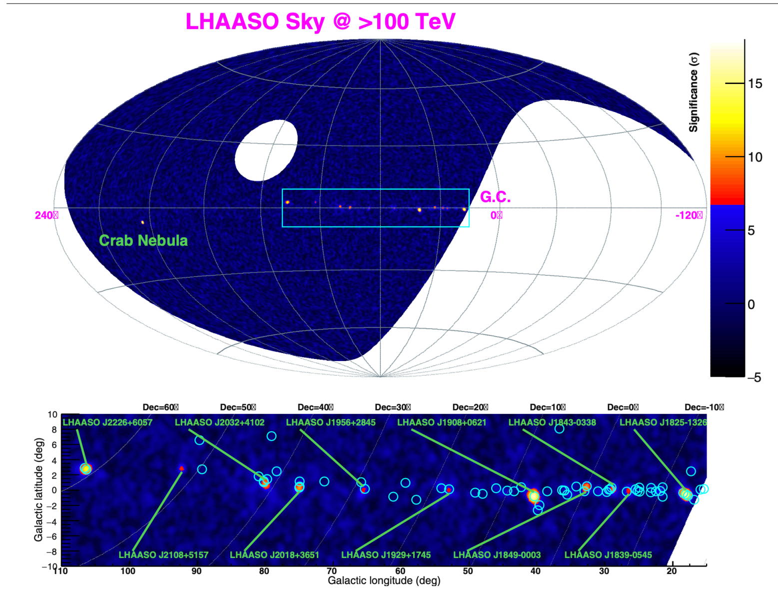
HAWC - sources with spectra up to 100 TeV!

Ultrahigh-energy photons up to 1.4 petaelectronvolts

from 12 γ-ray Galactic sources (Nature, June 3rd 2021)

LHAASO Collaboration

first results/conclusions - many > UHE or PeV sources!



Extended Data Fig. 4 | LHAASO sky map at energies above 100 TeV. The circles indicate the positions of known very-high-energy γ-ray sources.

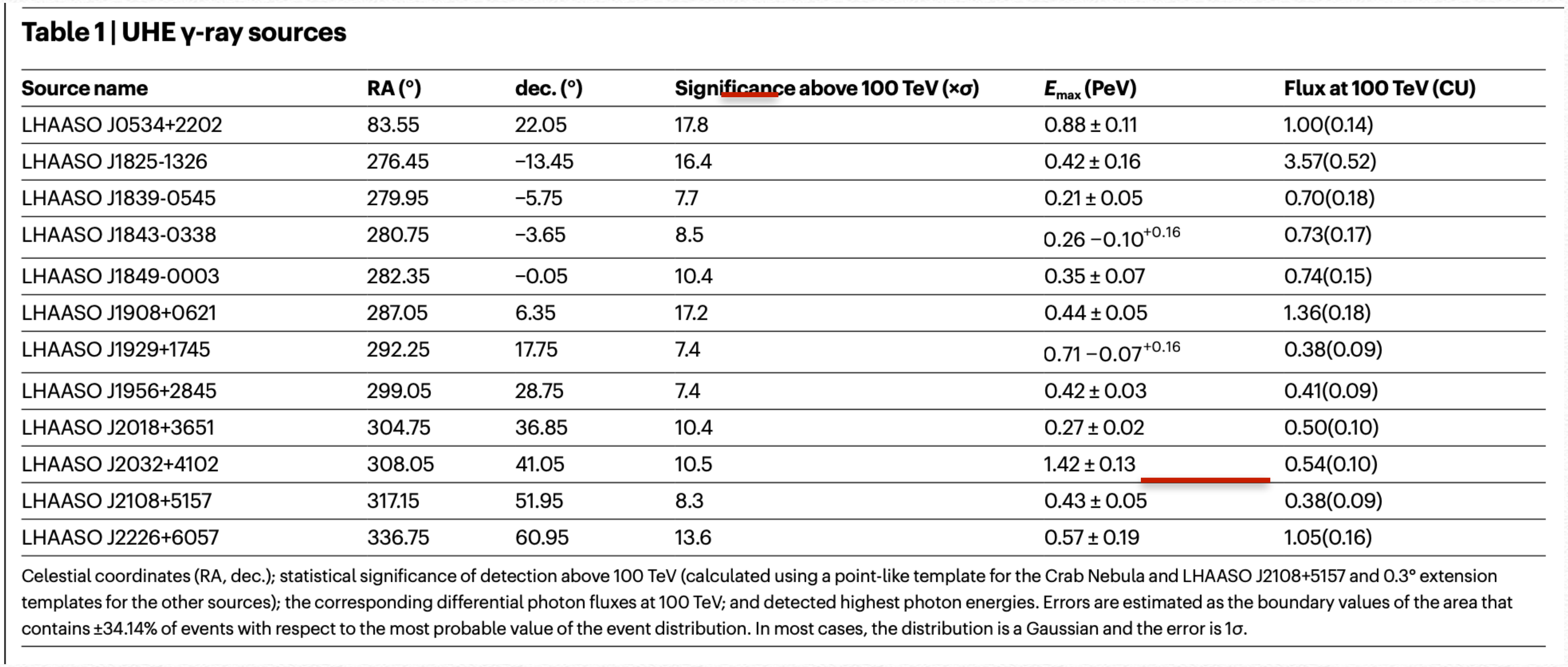
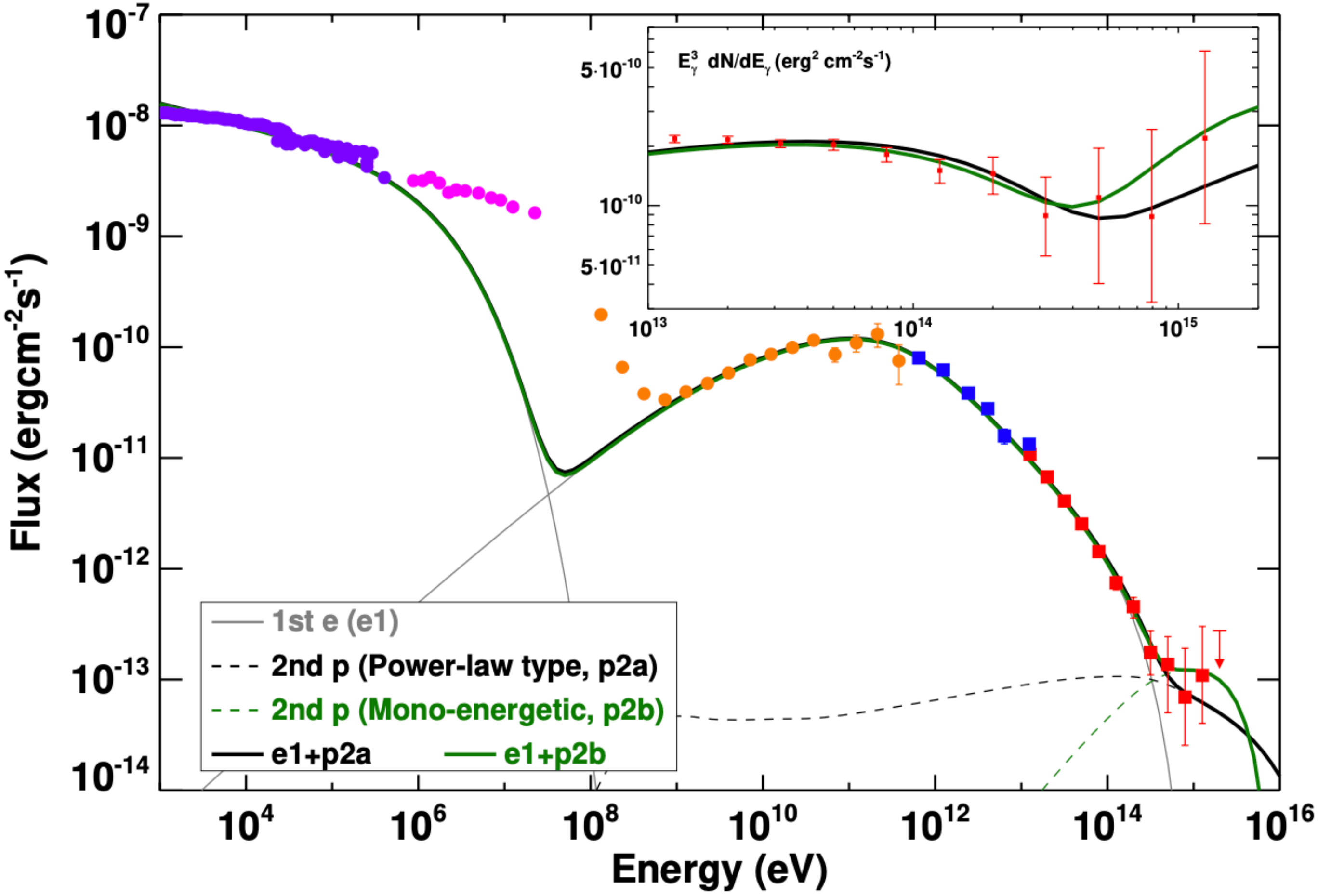


Table 1 | UHE γ-ray sources

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26 -0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 -0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

Celestial coordinates (RA, dec.); statistical significance of detection above 100 TeV (calculated using a point-like template for the Crab Nebula and LHAASO J2108+5157 and 0.3° extension templates for the other sources); the corresponding differential photon fluxes at 100 TeV; and detected highest photon energies. Errors are estimated as the boundary values of the area that contains ±34.14% of events with respect to the most probable value of the event distribution. In most cases, the distribution is a Gaussian and the error is 1σ.

Crab Nebula: extension of the gamma-ray spectrum beyond 1 PeV



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

Gamma-ray sources at TeV and PeV energies

discovery of hundreds TeV γ-ray sources over the last two decades, representing more than a dozen source populations, was a remarkable achievement of High Energy Astrophysics and Astroparticle Physics

=> universe is full of TeVatrons
factories accelerating particles to TeV energies (1TeV = 10^{12}eV)

surprise outcome:

particles are accelerated in different environments and on different scales at incredibly high acceleration rates and energy conversion efficiencies

surprise continues ...

over the last 1-2 years - discovery of many UHE (PeV) γ-ray sources in Milky Way (PeV = 10^{15}eV)

=> the Galaxy is full of PeVatrons

hundreds of GeV and/or TeV gamma-ray emitters have been discovered representing 13+ source populations:

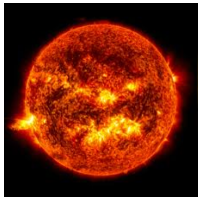
- SNRs, Stellar Clusters, GMCs
- Pulsars, Pulsar Winds (?) PWNe , Pulsar Halos (?)
- Binaries (Binary Pulsars, Novae, Microquasars)
- Galaxies, Starburst Galaxies,
- Radiogalaxies,
- AGN,
- GRBs

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 and even PeV energies - almost everywhere!

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

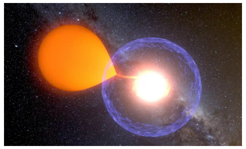
Particle Accelerators - *factories* of relativistic matter

Relativistic Matter Factories

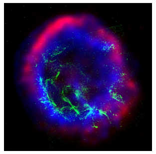


processes of particle acceleration and radiation proceed effectively throughout Universe - *everywhere* and on *all* astronomical scales:

Stars



Novae



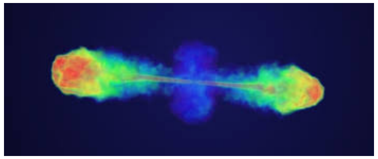
SNRs

Microquasars

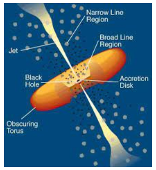
Neutron Stars*

Galaxies

Galaxy Clusters

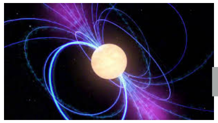


Large Scale Jets of AG



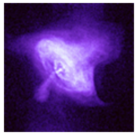
Blazars

* accelerators associated with Neutron Stars

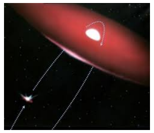


Pulsars

wind

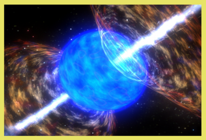


Pulsar Wind Nebula



Binary pulsars

(BNS mergers) ⇨



(short) GRBs

Major topics

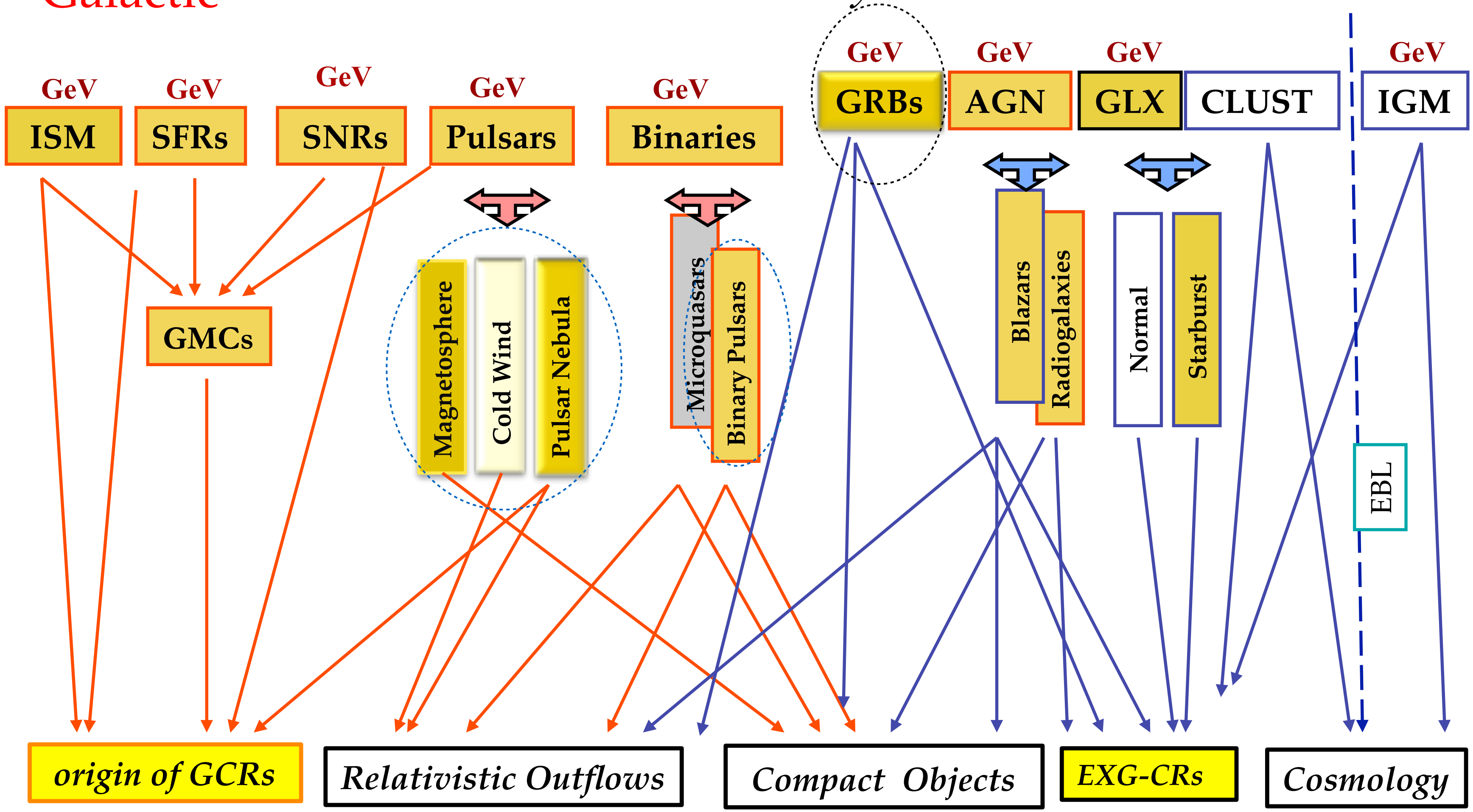
- origin of Galactic and Extragalactic Cosmic Rays
- physics and astrophysics of relativistic outflows (jets and winds)
- high energy processes at extreme conditions (e.g. close to BHs)
- cosmological issues - Dark Matter, Large Scale Structures., etc.

. . .

Galactic

Potential VHE Gamma Ray Sources

Extragalactic



GeV GeV GeV GeV GeV

ISM **SFRs** **SNRs** **Pulsars** **Binaries**

GMCs

Magnetosphere **Cold Wind** **Pulsar Nebula**

Microquasars **Binary Pulsars**

GeV GeV GeV GeV

GRBs **AGN** **GLX** **CLUST** **IGM**

Blazars **Radiogalaxies**

Normal **Starburst**

EBL

origin of GCRs

Relativistic Outflows

Compact Objects

EXG-CRs

Cosmology

Major Scientific Topics

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

  relativistic outflows - pulsar winds, Microquasars, AGN jets

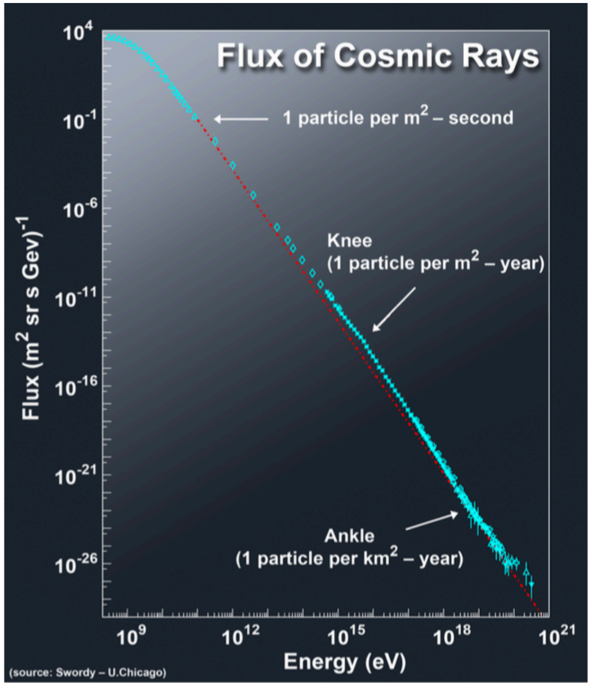
- ❑ contribution to fundamental physics, e.g.

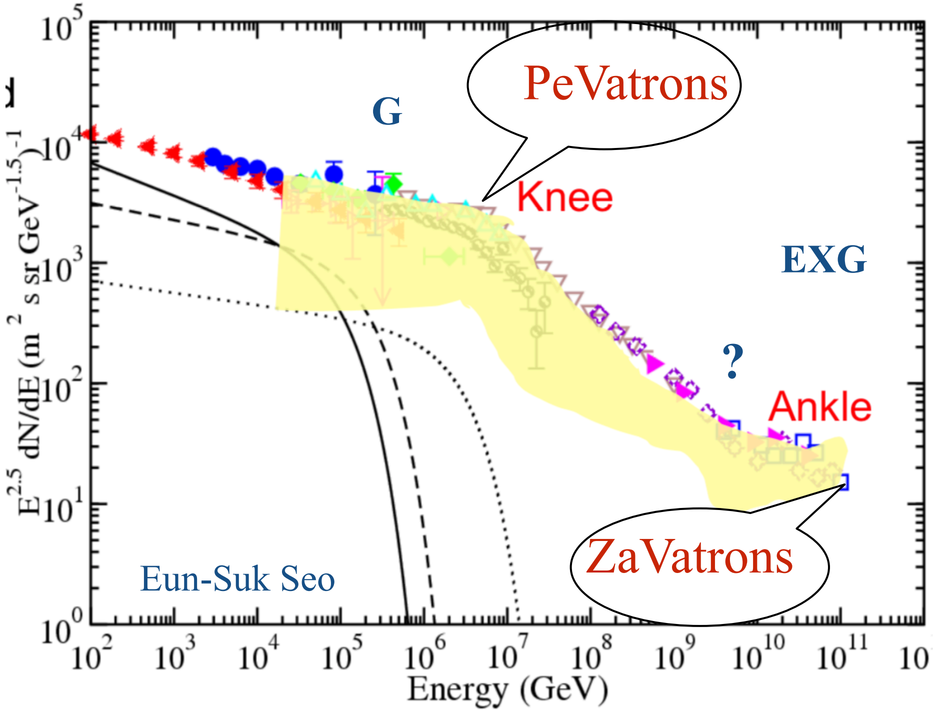
  \- *violation of Lorentz invariance,* search for *Dark Matter*

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

"Origin of cosmic rays remains a mystery…"

a standard statement used in reviews/textbooks over many decades





below 10^{15} eV - G challenge : $> 10^{15}$ eV

beyond 10^{18} eV - EXG challenge: $> 10^{20}$ eV

between 10^{15}-10^{18} eV transition ???

“Origin of Cosmic Rays” ?

Origin of CRs generally is reduced to the identification of major contributors (SNRs, pulsars, GC, etc.) to the locally measured Cosmic Rays

however, 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*

questions beyond the origin of local CRs:
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 *can be as large as 50 %*

(ii) maximum possible energy achieved by individual particles
acceleration rate close to the maximum (theoretically) possible rate

acceleration rate: $\dot{E} = e\mathcal{E}c = \eta eBc; \quad \eta = \mathcal{E}/B \leq 1$

$\eta \rightarrow 1$ - absolute extreme accelerator determined by ED and ideal MHD

combined with the Synchrotron energy lose rate => E_{max}

radiation signature: synch. peak at $h\nu = \frac{9}{4}\eta^{-1}mc^2/\alpha$ $(\alpha = 1/137$, m - particle mass)

for electrons: ≈ 0.15 GeV for protons: ≈ 0.3 TeV

Crab Nebula and Sources of of 10^{20} eV Cosmic Rays are Extreme Accelerators obviously, many reported gamma-ray sources require not only effective accelerators but also effective gamma-ray emitters

γ-ray production efficiency? $\kappa = \frac{t_{dyn}}{t_{rad}}$ $L_\gamma = \kappa \dot{W}_{cr}$

cooling time of the given gamma-ray production process is shorter than

(1) timescales of radiative and non-radiative (e.g. adiabatic) losses
(2) intrinsic dynamical (source age, acceleration time, particle escape time)

Note: high efficiency is an important but not sufficient/decisive condition for a gamma-ray sources to be detected. The detectability depends also on

- ✓ power and distance to the source (~ W/d^2)
- ✓ beaming factor, e.g. Doppler boosting (~ δ^4)
- ✓ Sensitivity of the instrument in the given energy domian

$$W_{cr} = L_\gamma t_{rad}\,; \quad \dot{W}_{cr} = \kappa^{-1} L_\gamma \ \ (L_\gamma = 4\pi d^2 F_\gamma)$$

be careful with the interpretation of W_{cr} and $\dot{W}_{cr}$: we could miss γ-ray emission from extended emission regions because of the reduced brightness where κ could be different - typically, much smaller

quick estimates of γ-ray fluxes and spectra

this can be done, in many cases with a surprisingly good accuracy, using cooling times (for energy fluxes)

$$F_\gamma = W_{p(e)}/4\pi d^2 t_{cool}$$

and δ-functional approximation (for energy spectra) using the relation

$$<E_\gamma>=f(E_{p(e)})$$

but be careful with δ-functional approximations …

this may lead to quite wrong results

two examples

often for particle (electron or proton) spectrum is assumed a convenient power-law with exponential cutoff spectrum, in a general form:

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

the cutoff region - *more important than any other energy region* - can be derived from the spectrum of radiation, e.g.

- ☐ synchrotron radiation: $\varepsilon^{-(\alpha+1)/2} \exp[-(\varepsilon/\varepsilon_0)^{\beta'}]$

  δ-functional approximation: $\beta' = \beta/2$ ($\varepsilon \sim E^2$), precise $\beta' = \beta/(\beta+2)$

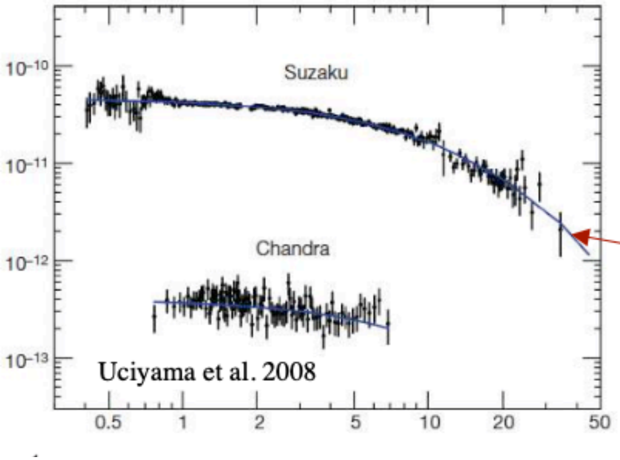
  $\beta=1 \Rightarrow \beta'=1/3$ but not 1/2; $\beta=2 \Rightarrow \beta'=1/2$ but not 1/4

- ☐ $p+p \to \pi^0 \to \gamma$: $\varepsilon^{-\alpha'} \exp[-(\varepsilon/\varepsilon_0)^{\beta'}]$

  δ-functional approximation: $\alpha' = \alpha$, $\beta' = \beta$ ($\varepsilon \sim 1/10E$)

  precise $\alpha' \sim \alpha$ $(+\Delta\alpha \sim 0.1$ for $\beta = 2$ $\beta^* \sim 0.5$ but not 1

SNR RXJ1713.7-3946



Uciyama et al. 2008

energy spectrum of synchrotron radiation of electrons in the framework of DSA (Zirakashvili&FA 07)

$$J_\nu \propto \nu^{-1}[1+0.46(\nu/\nu_0)^{0.6}]^{11/4.8}\exp[-(\nu/\nu_0)^{1/2}]$$

$$h\nu_0 \approx 1(v/3000\mathrm{km/s})^2\eta^{-1}\ \mathrm{keV}$$

$h\nu_0$=0.55 keV

strong support for acceleration in Bohm diffusion regime ($\eta \sim 1$) - from postion of synchrotron cutoff given that the shock speed v < 4000 km/s *(Chandra)*

an example: diffusive shock acceleration of electrons

in the Bohm diffusion regime; losses dominated by synchrotron radiation

$$N(E) \propto E^{-2}[1+0.523(E/E_0)^{9/4}]^2\exp[-(E/E_0)^2] \quad (*)$$

E_0 *almost coincides with the value derived from* $t_{acc} = t_{synch}$

the spectrum of synchrotron radiation at the shock front

$$J_\nu \propto \nu^{-1}[1+0.46(\nu/\nu_0)^{0.6}]^{11/4.8}\exp[-(\nu/\nu_0)^{1/2}]$$

$$h\nu_0 = 1(v/3000\ \mathrm{km/s})^2\eta^{-1}\ \mathrm{keV}$$

- electron spectrum derived from Suzaku data
- DSA prediction
- “standard $E^{-3}\exp(-E/E_0)$ type elec. spectrum

two errors combined - (i) exponential cutoff in the spectrum of accelerated electrons and (ii) δ-functional approximation for synch. radiation compensate each other and give (accidentally!) relatively correct behavior in the cutoff region

few examples of efficient/inefficient γ-ray emitters related to cosmic rays

inefficient!

Nonthermal X-ray Bremsstrahlung

at first glance quite attractive (“*why should I invoke multi-TeV electrons to produce X-rays when can I use keV electrons to produce keV X photons?”)* in fact only less than 10^{-5} fraction of the kinetic energy of electrons (protons) is released in X-rays; 99.99…% goes to the ionization and heating of the gas

$$L_e > 10^5 L_X = 10^{37} (f_X/10^{-12} \text{ erg/s}) (d/1\text{kpc})^2 \text{ erg/s}$$

the same is true for gamma-ray line emission due to excitation of nuclei by sub-relativistic protons - both mechanisms “work” during Solar flares, otherwise it typically leads to unreasonably high requirements for production rate of sub-relativistic electrons - this makes the extremely interesting issues like detection of gamma-ray lines, in particular from ISM, SNRs, GMCs, etc (information about the sub-relativistic CRs !) observationally very difficult

$pp \to \pi^0 \to 2\gamma$

not very efficient

no competing dissipation mechanisms - in "calorimetric scenarios": $L_\gamma \sim L_p/3$
but the process itself is not very fast/relatively slow: $t_\pi \sim 10^{15}\,(n/1\,cm^{-3})^{-1}$ s
usually the source age or particle escape is a big issue !

SNRs: typical density: $n \sim 1\,cm^{-3}$, magnetic field $B \sim 100\,\mu G$, size $R \sim 3$ pc assuming Bohm diffusion, $D(E) = r_L c/3 = 10^{25} (E_p/10\,TeV)^{-1}\ cm^2/s$, escape time of protons which produce 1 TeV gamma-rays: $t_{esc} \sim R^2/D \sim 10^{13}\ s \sim 0.01 t_\pi$

Galaxies - $n \sim 0.1 - 1\,cm^{-3} => t_{pp\to\pi^o} \sim 10^{7-8}$ yr;
confinement time $10^5 - 10^7$ yr => efficiency 0.1-100 %

Galaxy Clusters: densities $n \sim 10^{-3}$ s, size R>1Mpc - full confinement!
$t_\pi < 10^{18}\,(n/1\,cm^{-3})^{-1}$ s - comparable to the age (Hubble time) !

γBinaries: protons accelerated by the compact object and interacting with the dense stellar disk of companion: $n \sim 10^{13}\ cm^{-3}$; the cooling time could be shorter than escape time => potentially effective production of gamma-rays and νs

higher efficiencies at MeV/GeV energies because of problem of confinement

Synchrotron radiation

very efficient

especially in extreme particle accelerators where acceleration proceeds at the maximum (theoretically possible) rate and the further acceleration is limited by synchrotron losses

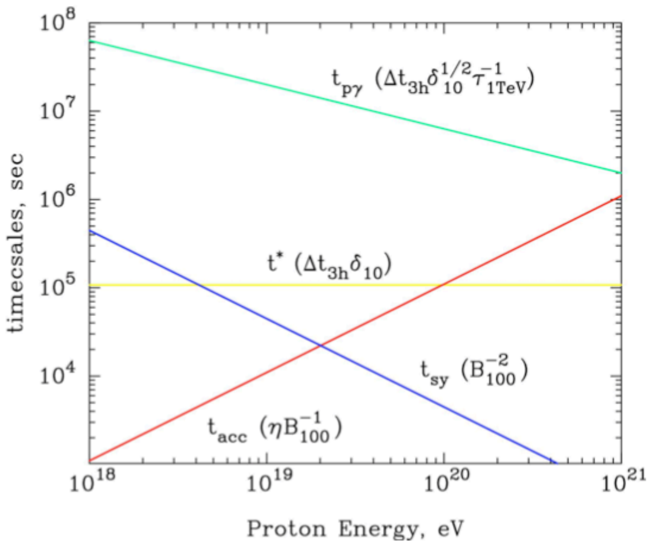
$$t_{\rm acc} = \frac{R_L}{c}\eta^{-1}$$ => self regulated cutoff

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

$\simeq$ 300GeV proton synchrotron

$\simeq$ 150MeV electron synchrotron

proton-synchrotron is effective in compact objects with large B-fields (when $t_{\rm coo} < R/c$)



$t_{\rm synch}=4.5{\rm x}10^4({\rm B}/100{\rm G})^{-2}\ ({\rm E}/10^{19}\ {\rm eV})^{-1}$ s

$t_{\rm acc}=1.1{\rm x}10^4\ ({\rm E}/10^{19})\ ({\rm B}/100{\rm G})^{-1}$ s

$E_{\rm max} \sim B^{-1/2}$, but $h\nu_{\rm cut}$ - independent of B

$t(h\nu_{\rm cut})=2.4{\rm x}10^4\ ({\rm B}/100{\rm G})^{-3/2}\ \eta^{1/2}$ s $< R/c$

$B > 100(R/10^{15}{\rm cm})^{-2/3}\ \eta^{1/3}$ G

Synchrotron radiation

very efficient

do we have evidence for signatures of extreme accelerators?

electron synchrotron - most likely in the spectrum of the Crab Nebulae
protons synchrotron - in some blazers, GRBs ?

factors reducing the maximum energies of the synchrotron cutoff?
radiative losses in the case of electrons-synchrotron (e.g. in binaries)
not sufficiently strong B-fields in the case of proton-synchrotron (in extended sources)

electron synchrotron efficiency could be close 100% even in non-extreme accelerators although the radiation at lower (typically X-ray) energies, e.g. in young SNRs

IC: eγ -> e+γ'

very efficient

- ✓ compact objects - binaries, AGN… -
  very effective with some exceptions

- ✓ PWNe with very small B-field: $L_{IC} = (w_{MBR}/w_B)\dot{W}_e = (B/3\mu G)^{-2}\dot{W}_e \sim \dot{W}_e$ if B <3mG; thanks to very effective (relativistic shock?) acceleration
  electrons still can be accelerated to 100 TeV or beyond

- ✓ Clusters of Galaxies - despite small B-field (~ 1μG) and limited shock speed (~ 2000 km/s), thanks to the large size and age of these cosmological structures, protons can be accelerated to 1018-1019 eV, produce secondary (Bethe-Heilter) pairs at interactions with 2.7K CMBR, and the secondary electrons can produce effective IC gamma-rays upscattering 2.7K CMBR

- ✓ many other realisations and … tricks related e.g. to Klein-Nishina scattering regime

often is accompanied with photon-photon pair-production

some more comments

On the power-law distribution of accelerated particles:

Generally it is typically considered as the intrinsic feature of accelerated particles - but it is an overstatement. For example, whe when interpreting γ-ray spectra sometimes we need a Maxwellian distribution. It does not mean, however, that we see the emission of thermal plasma. Some specific ("stochastic" or Fermi II type) mechanisms of particle acceleration can lead to a Maxwellian type distributions. Also, the hard particle spectra derived from the gamma-ray observations could be the result of propagation but not acceleration

Sources of nonthermal emission - *do not necessarily coincide with accelerators*

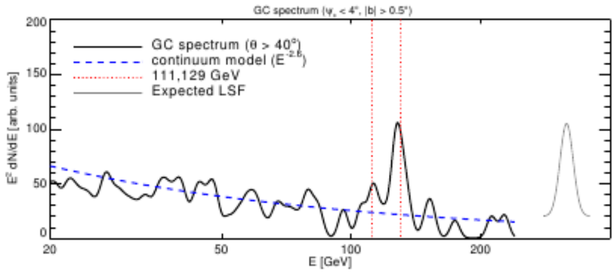
nonthermal emission is a result of interaction of a beam of relativistic particles with a target (gas, B-field, photons), therefore the emission source (= target) should not be identified with the accelerator.

Dark Matter as "smoking gun " ? - *often invoked to explain unusual/irregular features revealed by observations but in most cases unnecessary exaggeration*

such strong claims in the context of one of the most fundamental objectives of modern physics and astrophysics require a careful judgment through the "Occam's razor" principle, i.e. exploration of other more conventional (and natural) interpretations

an example

narrow GeV/TeV gamma-ray lines: astrophysical or DM origin

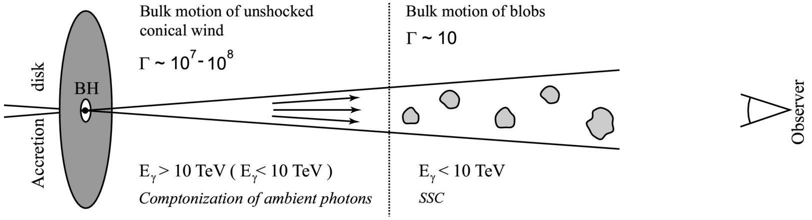


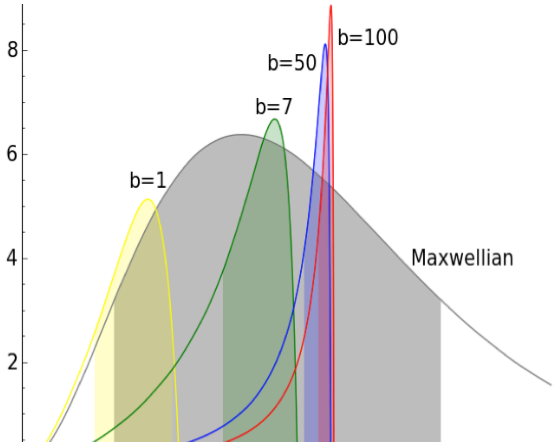
~100 GeV gamma-ray line detected by Fermi LAT? *

cosmological interpretation - **DM as the only option?**

No! can be interpreted as Inverse Compton scattering of monoenergetic electrons and cold ultra relativistic (e.g.) pulsar winds in the deep Klein-Nishina regime

often confusion between acceleration of bulk motion and particle acceleration !





* later not confirmed

why gamma-rays?

gamma-rays – unique carriers of information about high energy processes and phenomena in the Universe

- ✓ are effectively produced
  in both electromagnetic and hadronic interactions

- ✓ penetrate (relatively) freely throughout
  intergalactic and galactic magnetic and photon-fields

- ✓ are effectively detected
  by space-based and ground-based detectors

links to many disciplines of physics and astrophysics

a coherent description and interpretation of high energy phenomena requires deep knowledge of many areas of modern physics and astronomy and physics:

- ✓ special and general relativity
- ✓ quantum and classical electrodynamics
- ✓ atomic and molecular physics
- ✓ nuclear and particle physics
- ✓ plasma physics
- ✓ magneto(hydrodynamics)
- ✓ galactic and extragalactic astronomy

…

extreme physical conditions

generally the phenomena relevant to HEA generally proceed under extreme physical conditions in environments characterized with

- ➢ *huge gravitational, magnetic and electric fields,*
- ➢ *very dense background radiation,*
- ➢ *relativistic bulk motions (black-hole jets and pulsar winds)*
- ➢ *shock waves, highly excited (turbulent) media, etc.*

therefore some processes of gamma-ray production and absorption can proceed quite differently compared to the laboratory experiments

radiation and absorption processes

any interpretation of an astronomical observation requires

- ✓ *unambiguous identification of radiation mechanisms*
- ✓ *good knowledge of radiation and absorption processes*

gamma-ray production and absorption processes: *several but well studied*

interactions with matter

E-M: VHE

bremsstrahlung: $e\,N(e) \Rightarrow e'\,\gamma\;N(e)$ * $E\gamma \sim 1/2E_e$

pair production $\gamma\,N(e) \Rightarrow e^+e^-\;N(e)$ *

e+e- annihilation $e^+e^- \Rightarrow \gamma\,\gamma$ (511 keV line)

Strong/week: $pp\,(A) \Rightarrow \pi, K, \Lambda, \ldots$ ** $E\gamma \sim 1/10E_p$

$\pi, K, \Lambda \Rightarrow \gamma, \nu, e, \mu$

$\mu \Rightarrow \nu$

also in the low energy region

Nuclear: $p\;A \Rightarrow A^* \Rightarrow A'\,\gamma, n$

$n\,p \Rightarrow D\,\gamma$ (2.2 MeV line)

interactions with radiation and B-fields

Radiation field **VHE**

E-M:

inverse Compton: $e\,\gamma\,(B) \Rightarrow e'\,\gamma$ **

$\gamma\gamma$ pair production $\gamma\,\gamma\,(B) \Rightarrow e^+e^-$ **

$E_\gamma \sim \varepsilon(E_e/mc^2)^2$ (T) to $\sim E_e$ (KN)

Strong / week

$p\,\gamma \Rightarrow \pi, K, \Lambda, \ldots$ *

$\pi, K, \Lambda \Rightarrow \gamma, \nu, e, \mu$

$\mu \Rightarrow \nu$

$E_\gamma \sim 1/10 E_p$

$A\,\gamma \Rightarrow A^* \Rightarrow A'\,\gamma$ *

$E_\gamma \sim 1/1000A\ E_p$

B-field

synchrotron $e\,(p)\,B \Rightarrow \gamma$ *

pair production $\gamma\,B \Rightarrow e^+e^-$ *

$E_\gamma \sim B E_e^2$; $h\nu_{max} \sim \alpha^{-1} mc^2$

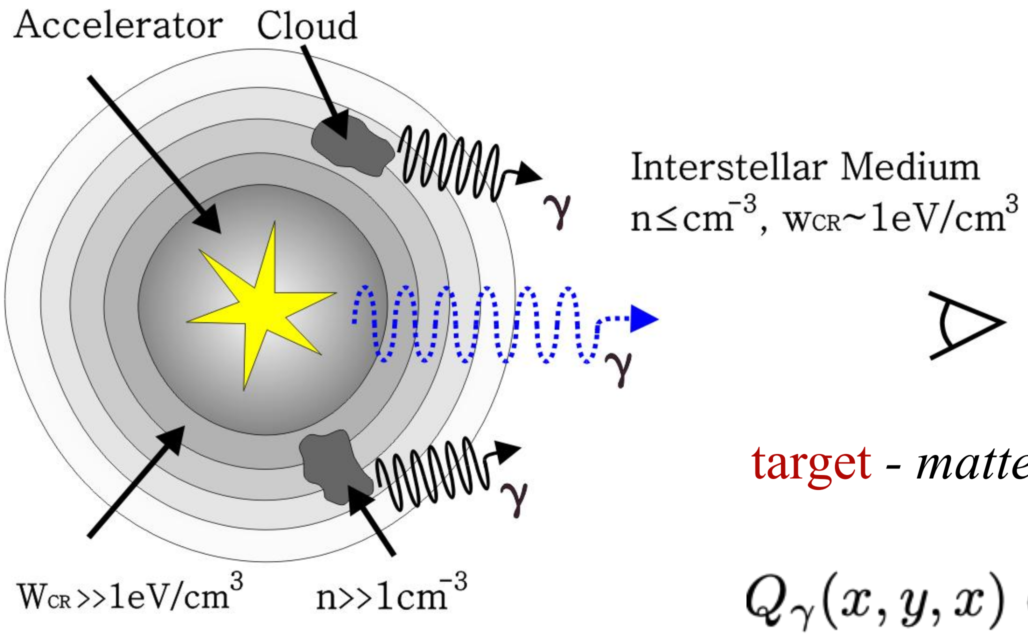
** - very important!

* - important!

specifics of cosmic gamma-ray studies

gamma-ray production: accelerator+target

existence of a powerful particle accelerator by itself is not sufficient for γ-radiation; an additional component – a dense target - is required

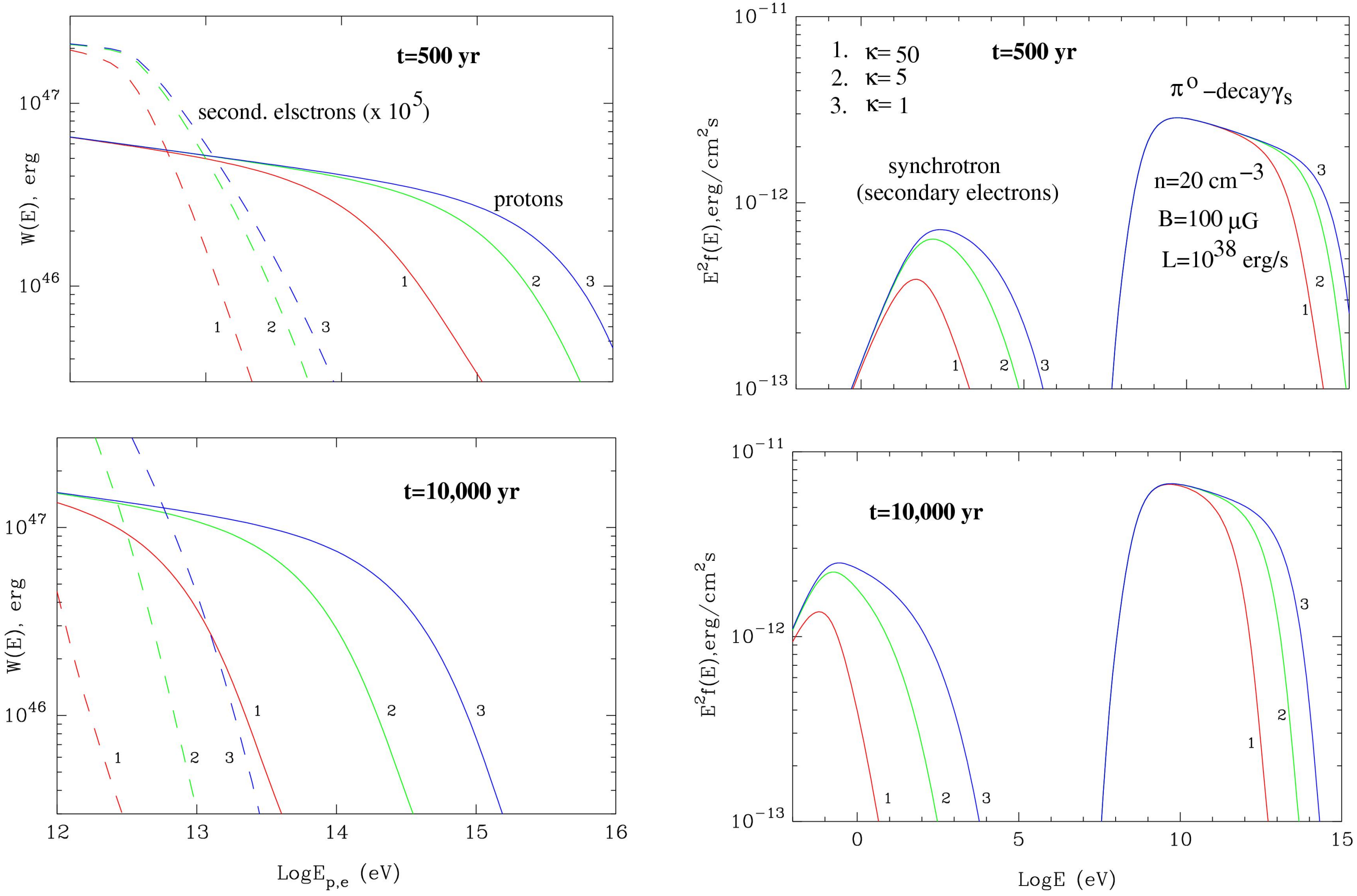


target - *matter, radiation, magnetic field*

$$Q_\gamma(x,y,x) \propto w_{\rm cr}(x,y,z) \times n(x,y,z)$$

any gamma-ray emitter coincides with the target, but not necessarily with the "primary" source/particle-accelerator

older source – steeper γ-ray spectrum

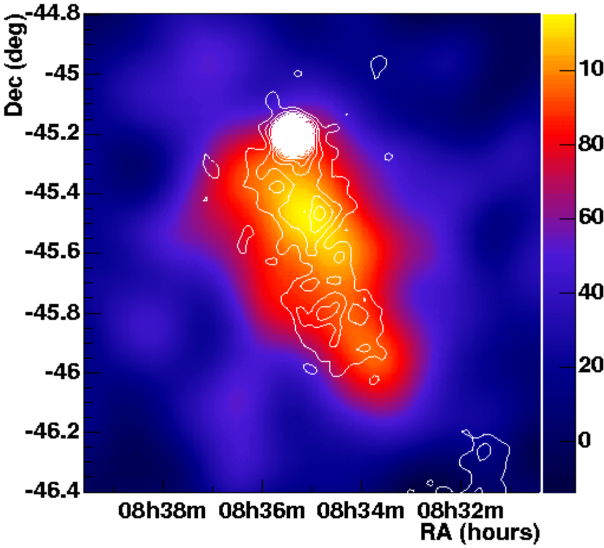


t_{esc}=4x10^5(E/1 TeV) $^{-1}\kappa^{-1}$ yr (R=1pc); κ=1 – Bohm Difussion

Qp = k $E^{-2.1}$ exp(-E/1PeV) Lp=10^{38}(1+t/1kyr) $^{-1}$ erg/s

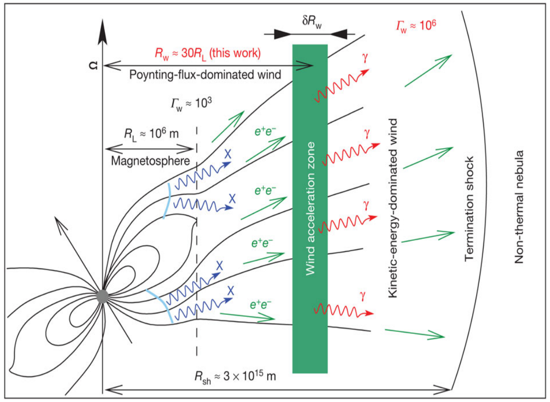
Inverse Compton gamma-rays from the cold wind and the synchrotron nebula

nebula

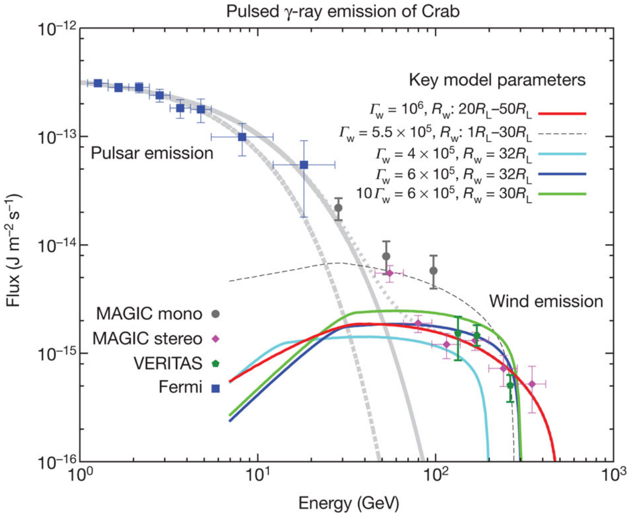


2.7 K MBR is the main target field; TeV images reflect spatial distributions of electrons Ne(E,x,y); coupled with synchrotron X-rays, this allow measurements of B(x,y)

pulsar



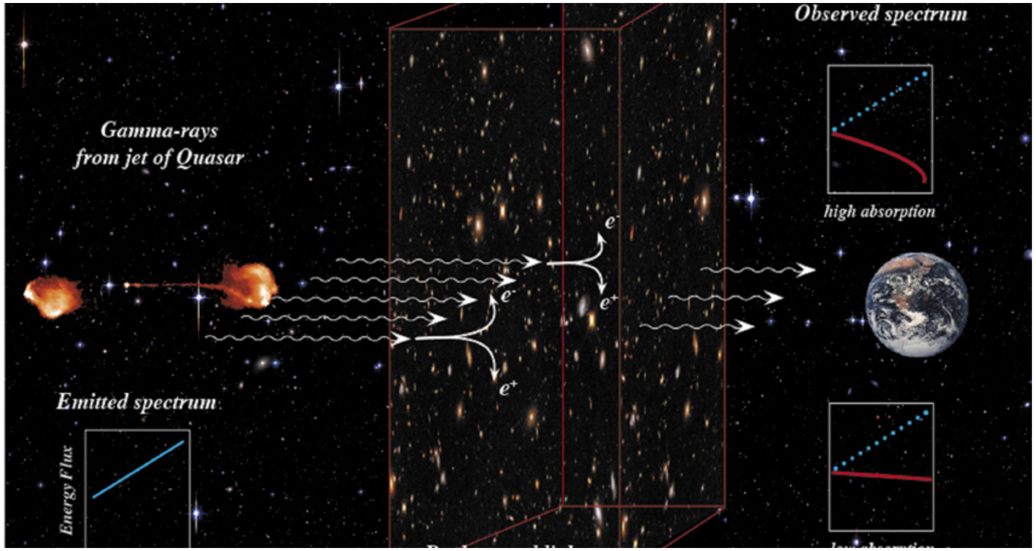
pulsar wind?

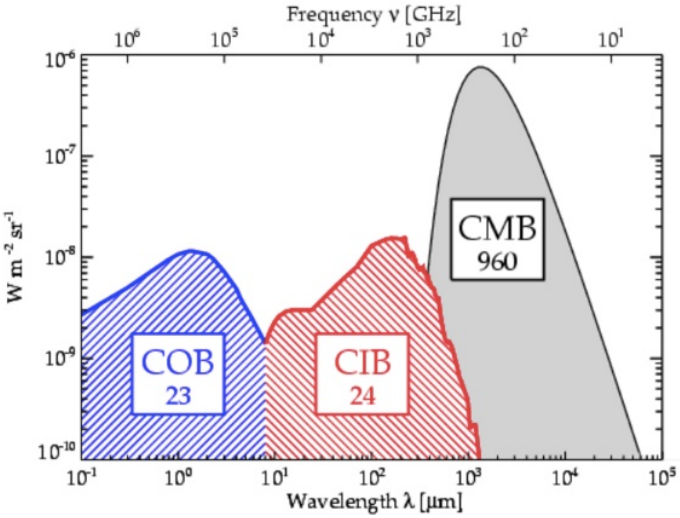


gamma-rays detected from the “invisible” wind or from the pulsar magnetosphere?

Absorption of Gamma-Rays in the Intergalactic Medium

γγ -> e+e- as a major gamma ray absorption mechanism





γ-ray horizon

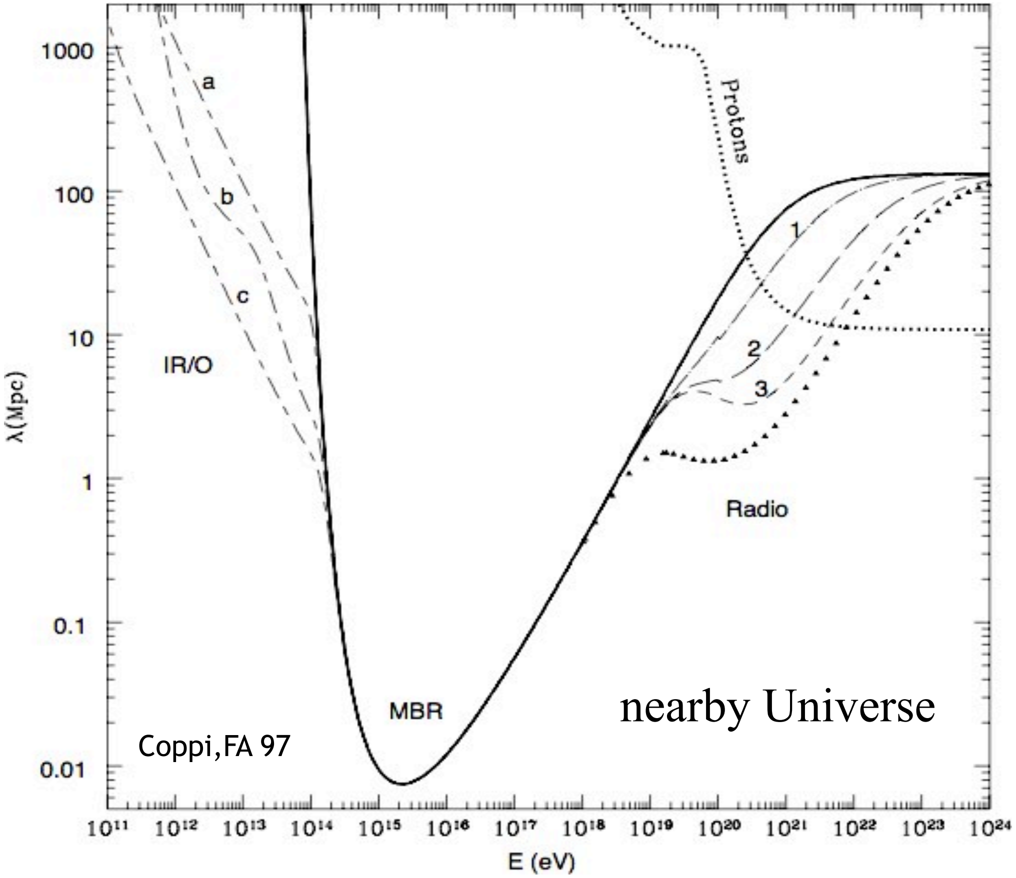
EHE (EeV) gamma-rays interact with
Radio emission:1-10MHz: 1Mpc<d<10Mpc

UHE (PeV) gamma-rays interact effectively
with 2.7K MBR: ~1mm 10kpc <d< 1Mpc

VHE (TeV) gamma-rays interact effectively
with EBL: 0.1-100 μm 100Mpc<d<1Gpc

Universe is (almost) transparent for <10 GeV
gamma-rays, z>3

mean free path of cosmic gamma-rays



nearby Universe

Coppi,FA 97

Other astronomical messengers

other astronomical messengers?

astronomical messengers should be neutral & stable:

photons and neutrinos satisfy fully to these conditions*

partly also ultra-high energy neutrons and protons …

neutrons: $d < (E_n/m_n c^2)\, c\, \tau_0 \Rightarrow E_n > 10^{17}(d/1\ \mathrm{kpc})$ eV
galactic astronomy with $E>10^{17}$ eV neutrons

protons: $\phi \sim 1^o$ if $E > 10^{20}$ for IGMF $B < 10^{-9}$G eV
extragalactic astronomy with $E>10^{20}$ eV protons

*) not only gamma-rays but also X-rays from both primary (directly accelerated) and secondary ($\pi^{+/-}$ decay) electrons

presently: TeV γ-ray astronomy -- a truly astronomical (*observational)* discipline

why TeV γ-rays ?

TeV γ-rays - *unique carriers of astrophysical/cosmological information about non-thermal phenomena in many galactic and extragalactic sources*

✓ are effectively produced in E-M and hadronic interactions ("good and bad")

✓ are effectively detected by space- and ground-based instruments

but… are fragile - effectively interact with matter, radiation and B-fields

(1) information arrives after significant distortion, (2) often - sources are opaque

presently: TeV neutrino astronomy - “astronomy” without sources*)

why TeV neutrinos ?

TeV neutrinos - unique carriers of astrophysical/cosmological information about non-thermal phenomena in galactic and extragalactic nonthermal sources

✓ are effectively produced in hadronic interactions (“good and bad”)

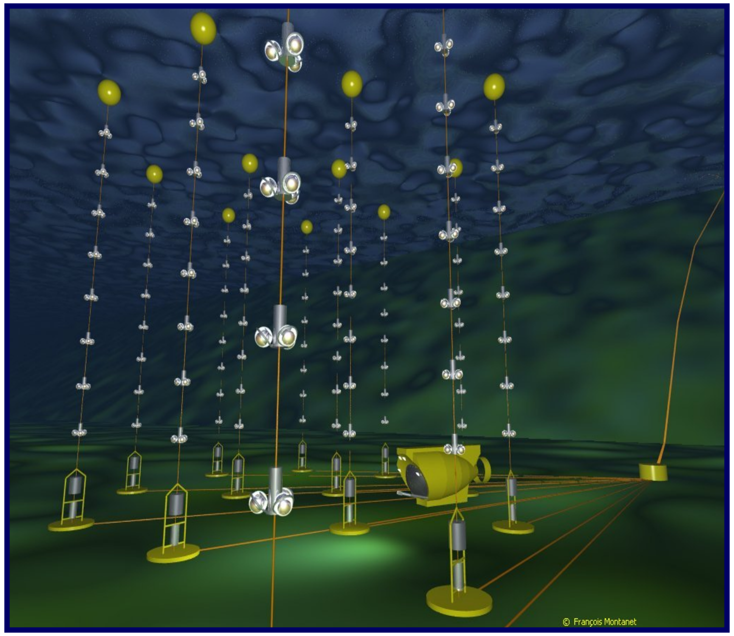
✓ do not interact with matter, radiation and magnetic fields:

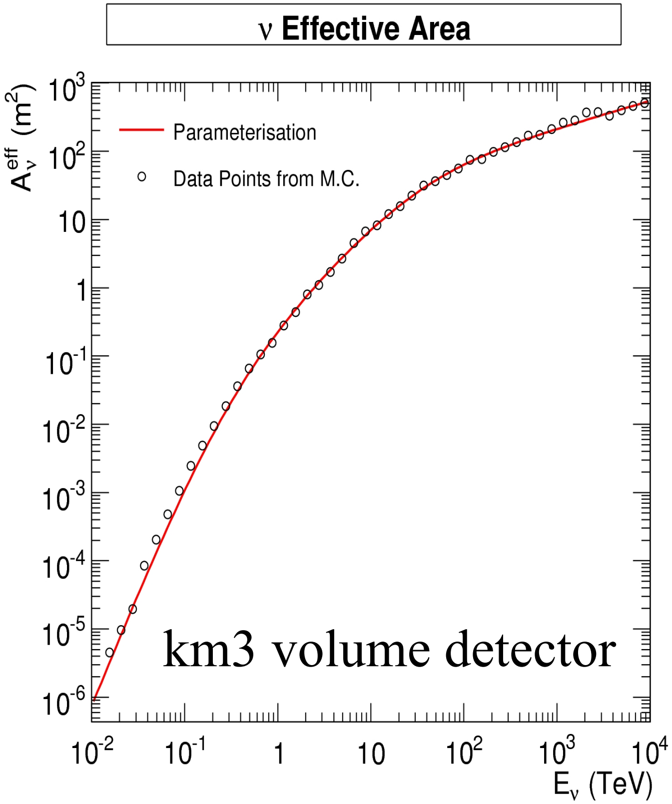
(1) information without distortion; (2) “hidden accelerators”

but… cannot be effectively detected - even huge “1km^3 volume” class detectors have limited performance

*) Ice Cube has detected tens of neutrino events of non-atmospheric origin but not yet firmly identified sources

neutrino telescopes





effective area: 0.3m^2 at 1 TeV
10m^2 at 10 TeV

=> several events from a "1Crab" source per 1year

compare with detection areas of gamma-ray detectors:

Fermi - 1m^2 but at GeV energies, ground-based >10^{4}m^2 at same energies

Potential multi-TeV neutrino sources

TeV gamma-ray sources as potential TeV neutrino sources?

yes, if γ-rays of hadronic (*pp* or *p*γ) origin

Detectable (by km^3 class) neutrino detectors ?

yes, if TeV γ-ray flux exceeds 2×10^{-11} ph/cm^2 s (~1 Crab)

(so far Crab Nebula, Vela X and and two SNRs)

or weaker sources if γ-rays are severely absorbed

(e.g. mQSOs LS 5039 and LS I +61 301, blazars!?)

some critical remarks concerning both gamma-rays and neutrinos

TeV, PeV, EeV - gamma rays and neutrinos: carriers of information about hadronic colliders, but

TeV γ-rays: effectively produced/detected, but it is not an easy task to identify the “hadronic” origin

PeV/EeV γ-rays: (i) difficult to detect (limited detection areas)
(ii) fragile (absorption in radiation and B-fields)

TeV/PeV/EeV neutrinos: difficult to detect

alternatives? - hard X-rays of secondary electrons!

hard X-rays - “hadronic” messengers?

the idea:

synchrotron radiation of secondary multi-100 TeV electrons produced at interactions of protons with ambient gas or radiation fields

- ➢ (1) p p (γ) => π, K, Λ, (2) π, K, Λ => γ, ν, e, μ (3) e B => X
- ➢ (1) p γ => e+ e- (2) e B => X

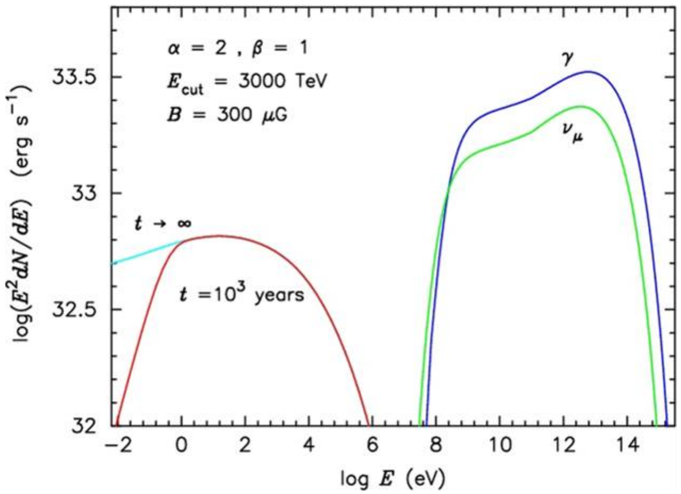
why hard X-rays/low energy gamma-rays?

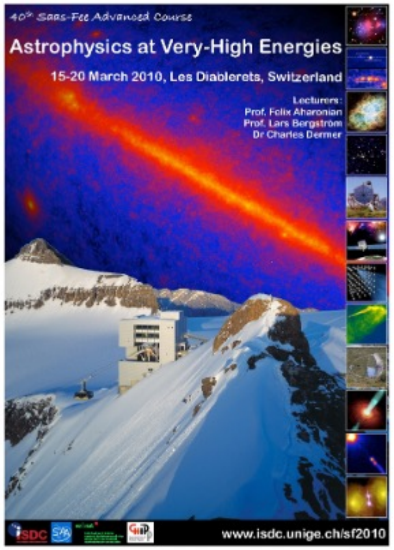
- ✓ radiation often peaks in the hard X-ray band
- ✓ not many competing production mechanisms
- ✓ no absorption in radiation and magnetic fields
- ✓ good sensitivity/good spectrometry/good morphology

Detecting Galactic PeVatrons: E~10^{15}eV

three channels of information
about cosmic PeVatrons:

10-1000 TeV gamma-rays
10-1000 TeV neutrinos
10 -100 keV hard X-rays





- ➢ γ-rays: difficult, but possible with future “10km²“ area multi-TeV IACT arrays*

- ➢ neutrinos: marginally detectable by IceCube, Km3NeT - don’t expect spectrometry, morphology; uniqueness - unambiguous signatute!

- ➢ “prompt“ synchrotron X-rays: smooth spectrum
a very promising channel - quality!

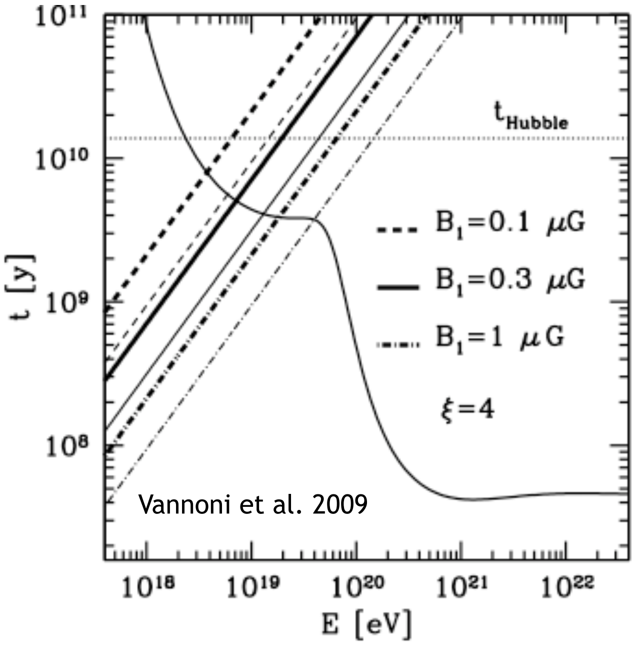
$$\sim \varepsilon^{-(\alpha/2+1)} \exp[-(\varepsilon/\varepsilon_0)^{1/5}]$$

*) done but with LHAASO

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



Vannoni et al. 2009

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.

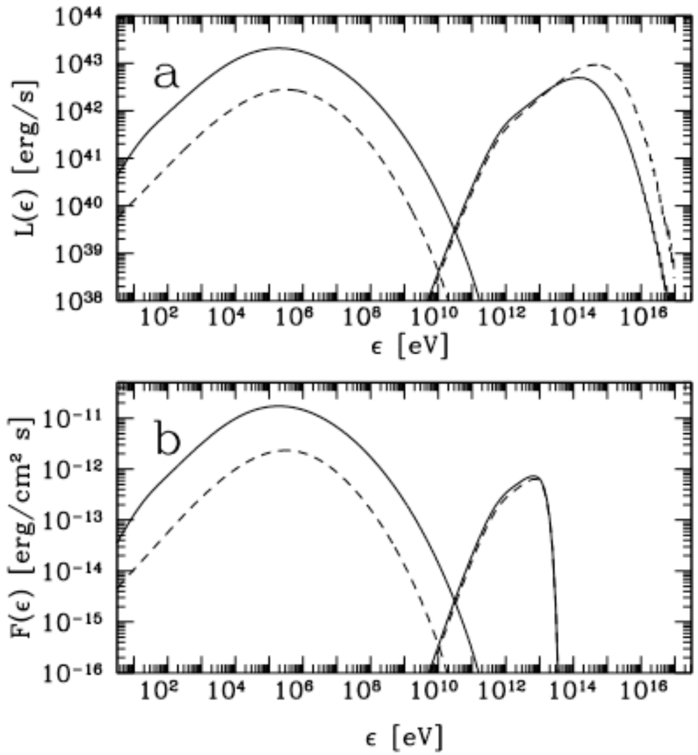


Fig. 13. a) Broadband radiation spectra produced at the source by the electron distributions in Fig. 12**b**, downstream (solid line) and upstream (dashed line). **b)** Energy flux at the observer location, after absorption in the EBL, for a source distance of 100 Mpc.

Probing hadrons with secondary hard X-rays

complementary to gamma-ray and neutrino telescopes

advantage - (a) comparable or better performance
(b) compensates lack of neutrinos and gamma-rays at “right energies”

disadvantage - ambiguity of origin of X-rays

- X-ray imaging and spectroscopy (up to 60 keV) ang. resolution 20”
- minimum detectable energy flux down to 10^{-14} erg/cm^{2}s !