Galactic PeVatrons

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Ultrahigh-energy photons up to 1.4 petaelectronvolts

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

LHAASO Collaboration

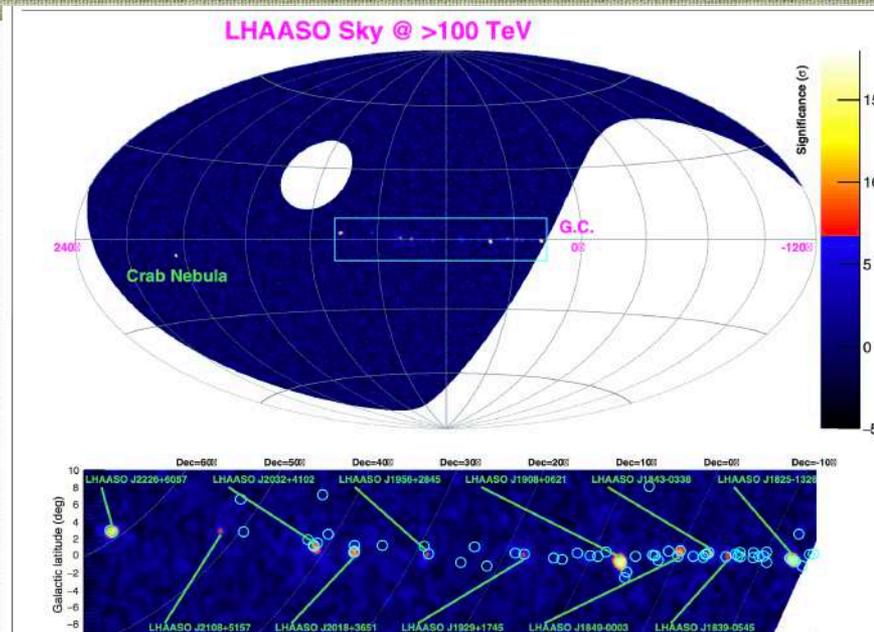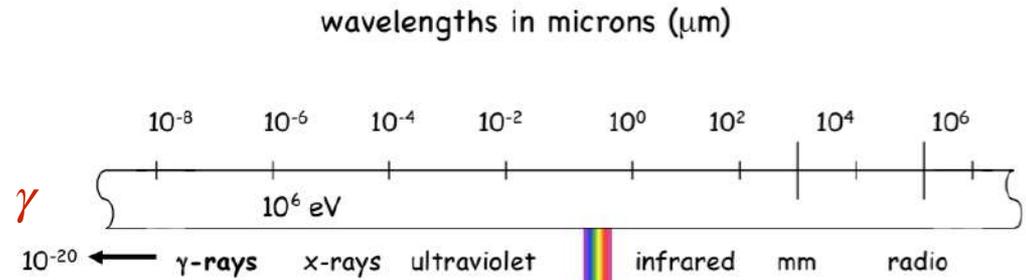first results/conclusions - many > UHE or PeV sources!

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.

Gamma-rays: 'the last window' in the cosmic EM spectrum

wavelengths in microns (μm)

| 10^{-8} | 10^{-6} | 10^{-4} | 10^{-2} | 10^{0} | 10^{2} | 10^{4} | 10^{6} |

PeV-TeV-GeV-MeV γ

10^{6} eV

10^{-20} ← γ-rays   x-rays   ultraviolet   infrared   mm   radio

LE   or MeV :   0.1 -100 MeV
HE   or GeV :   0.1 -100 GeV
VHE   or TeV :   0.1 -100 TeV
UHE   or PeV :   0.1 -100 PeV   new!

two revolutions in gamma-ray astronomy

2000s :   in TeV gamma-ray astronomy after the exploitation of full potential of
          Stereoscopic Imaging atmospheric Cherenkov telescope technique

2010s :   in GeV gamma-ray astronomy thanks to Fermi LAT and AGILE

we are at the threshold of the 3rd revolution - in PeV astronomy

VHE gamma-ray astronomy - *a success story*

Reasons?

(1) *great potential of the detection technique*

- very large collection area > 0.1 km^2,

- good gamma/hadron separation (10^{-2})

- very good angular and energy resolutions (several arcmin)

- 3+ decades energy coverage - tens of GeV to tens of TeV

- good energy resolution   ~ 15 %

- limited FoV (a few deg), limited exposure time (<100 h per year)

=> *morphology, timing, spetroscopy*

(2) *abundance of VHE sources*

Universe is full of TeVatrons !

=>   *250 of sources representing more than 10 source population*

LHAASO
Sichuan, China, 4410 m asl
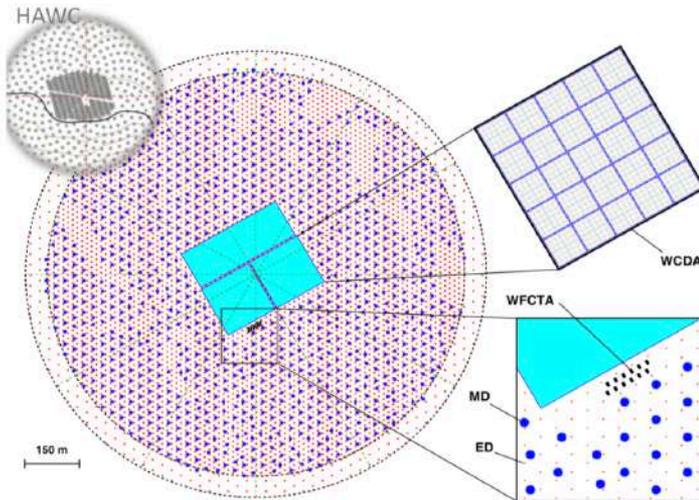
5195 Scintillators
- 1 m² each
- 15 m spacing

1171 Muon Detectors
- 36 m² each
- 30 m spacing

3000 Water
Cherenkov Cells
- 25 m² each

12 Wide Field
Cherenkov Telescopes

PeV Astronomy:

expect another success story?
very likely!

reasons?

great detection potential:

detection area   ~1 km2
γ/h separation   <10^{-4}
large FoV   ~1 ster
exposure time   ~2000 h/yr
good PSF   ~15 arcmin
energy resolution.   ~15%

many >100 TeV sources ! *

a big surprise !   Universe is full also of PeVatrons ?

* credit also to HAWC and Tibet

LHAASO - a PeVatron hunter
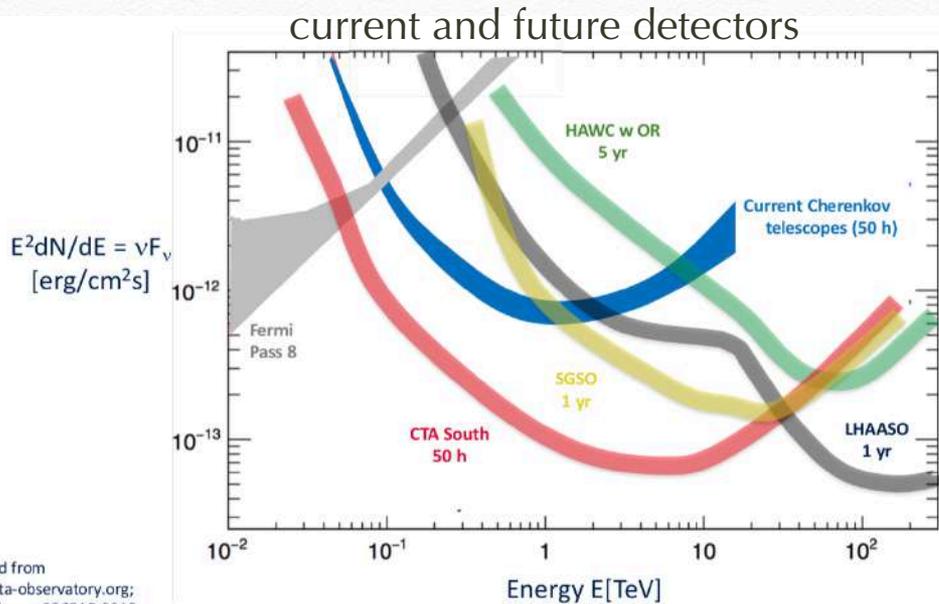
current and future detectors

detection rate of the full KM2A array

Chen Songzhan
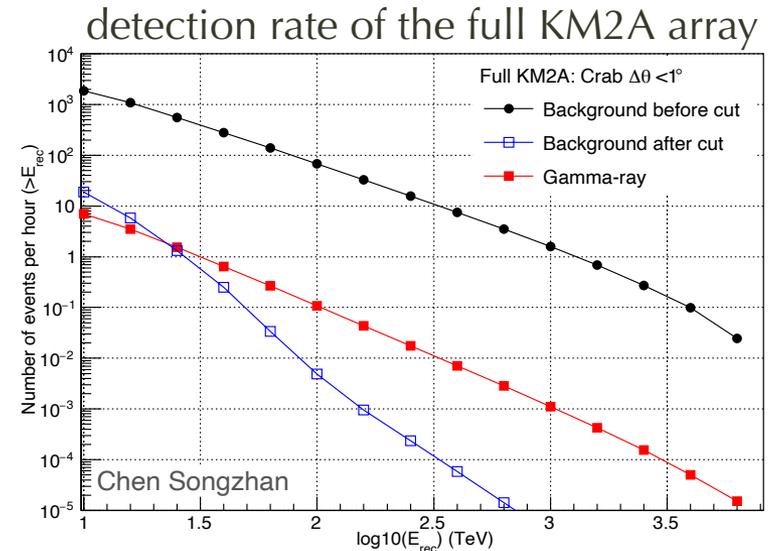
KM2A - PSF: 25′ at 20 TeV,   12′ at 100 TeV
KM2A - energy resolution better than 20%

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

ideal to study diffuse gamma-ray emission of the galactic disk, Fermi Bubbles
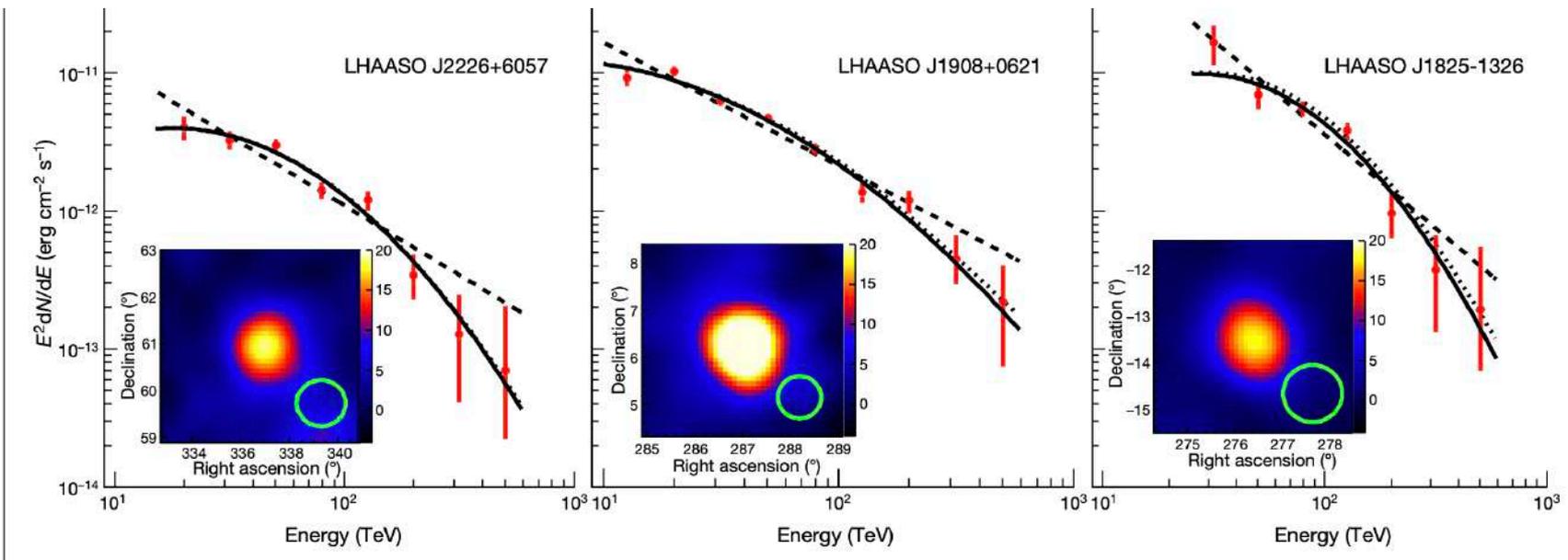
Extended Data Table 1 | Number of on-source events of energy >100 TeV, residual CR background events and corresponding exposure time for the 12 UHE sources

source	Number of on-source events	number of background events	exposure (hr)
LHAASO J0534+2202	67	5.5	2236.4
LHAASO J1825-1326	61	3.2	1149.3
LHAASO J1839-0545	26	4.2	1614.5
LHAASO J1843-0338	30	4.3	1715.4
LHAASO J1849-0003	36	4.8	1865.3
LHAASO J1908+0621	74	5.1	2058.0
LHAASO J1929+1745	29	5.8	2282.6
LHAASO J1956+2845	34	6.1	2461.5
LHAASO J2018+3651	42	6.3	2610.7
LHAASO J2032+4102	45	6.7	2648.2
LHAASO J2108+5157	30	6.4	2525.8
LHAASO J2226+6057	60	6.2	2401.3

$\gamma - \gamma$ absorption
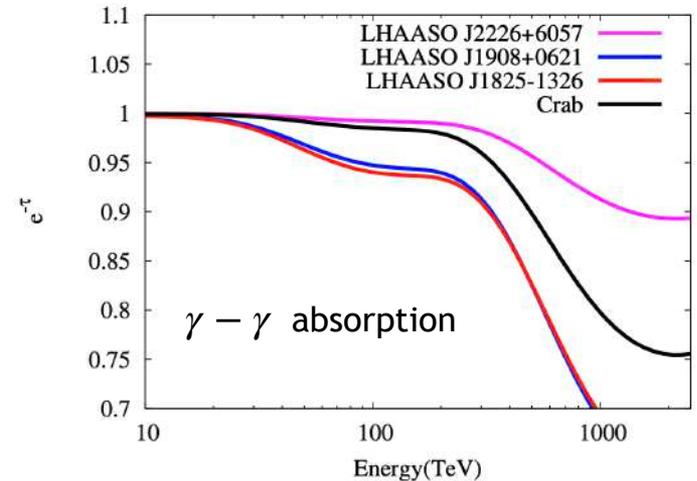
an example of a PeVatron
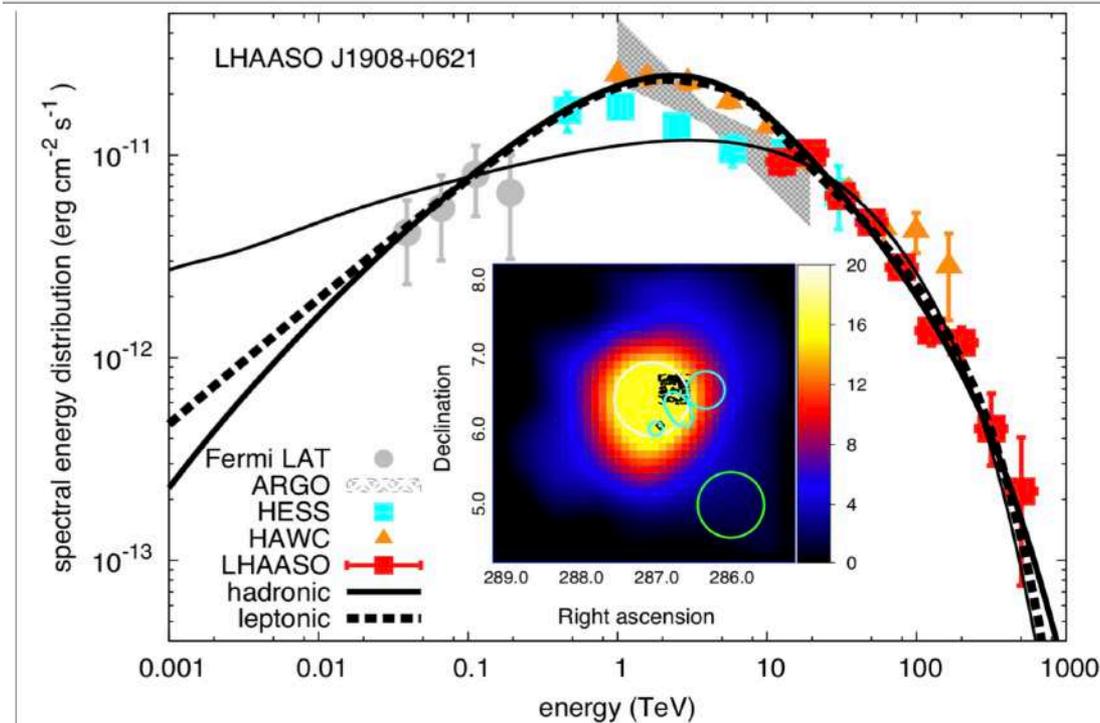
PH around PSR J1907+0602
or
SNR G40.5-0.5 + GMC
or
something else?

above 100 - steeper than E_γ^{-3} :

300 TeV photon requires

~ 1 PeV proton or electron

- - - IC electron spectrum: $dN/dE \propto E^{-1.75}\exp[-(E/800\text{TeV})^2]$
   6% of the spin-down luminosity of PSR J1907+0602. (2.4 kpc)

___ pp   proton spectrum: $dN/dE \propto E^{-1.85}\exp[-(E/380\text{TeV})]$

detectable neutrinos?

__ pp   proton spectrum: $dN/dE \propto E^{-1.2}$ $E \leq 25\text{TeV}$;
$\propto E^{-2.7}\exp[-(E/1.3\text{PeV})]$ $E \geq 25\text{TeV}$

Extended Data Table 2 | List of energetic astrophysical objects possibly associated with each LHAASO source

LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3^e	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3^f	$< 2^f$	—	HESS J1843-033, HESS J1844-030,
						2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7^g	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5^h	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4^i	$\sim 10 - 20^j$	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8}_{-0.7}\,^d$	$1.8 - 3.3^k$	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2^d	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7}_{-1.4}\,^l$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	$3.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08^o	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

- firmly identified - Crab (Nebula);
- no yang SNRs (Cas A, Tycho,…)
- middle-age SNRs ?
- PWNe and/or PHs
- Stellar clusters - W43, Cygnus Cocoon surrounding Cygnus OB
- - - - - -

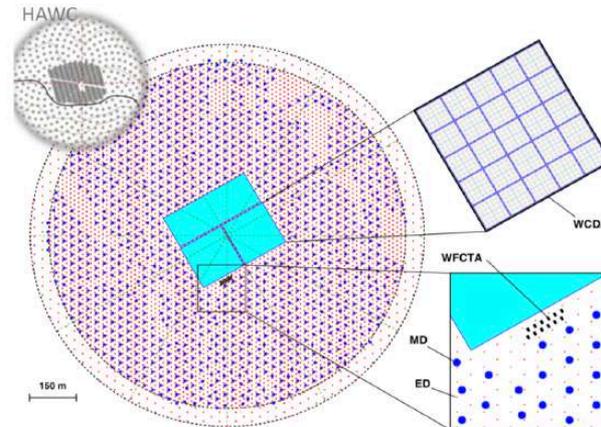# IACT Arrays and LHAASO
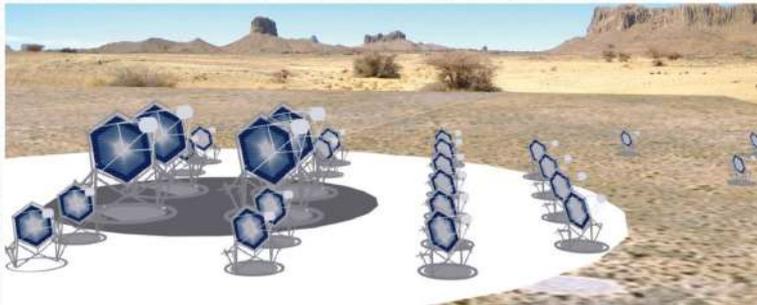
HESS, MAGIC, VERITAS,...

LHAASO does not reduce the significance of IACT arrays;
even for PeVatrons LHAASO needs very much IACTs

IACT arrays:
- 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

"… origin of cosmic rays remains a mystery…"
    a standard statement used in reviews/textbooks over many decades
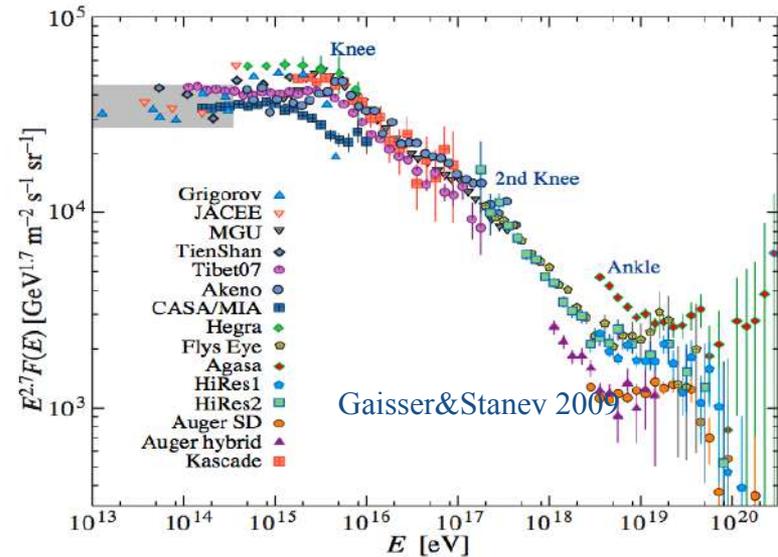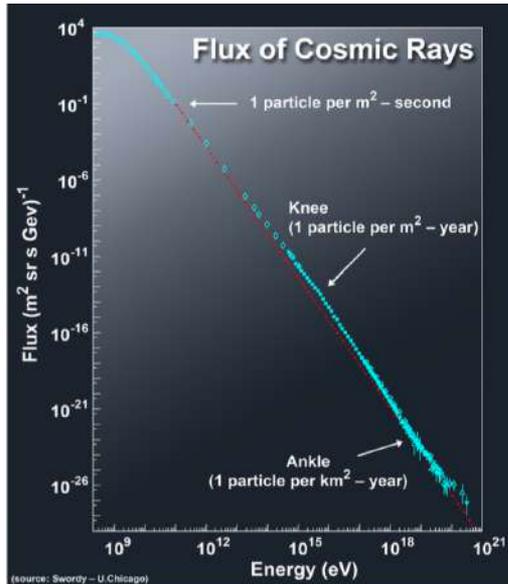
Figure 24.8: The all-particle spectrum from air shower measurements. The shaded area shows the range of the the direct cosmic ray spectrum measurements.

| below | 10^{15} eV | G | challenge : $> 10^{15}$ eV likely up to 10^{17} eV |

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

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

Proton PeVatrons in the Milky Way

definition of the term **"PeVatron"**
particle accelerators boosting energy of protons to the
PeV domain without a sharp cutoff/break up to 1 PeV

until recently:

(i)   featureless power-law spectrum up to the "knee" around 1 PeV
      has been interpreted as the dominance of a single CR component
         supported by a single source population

(ii) SNRs as the major contributors to GCRs until the "knee"   should
      operate as "PeVatrons" ... despite all theoretical challenges !

both convictions under question

CR proton spectrum

Lipari and Vernetto 2019
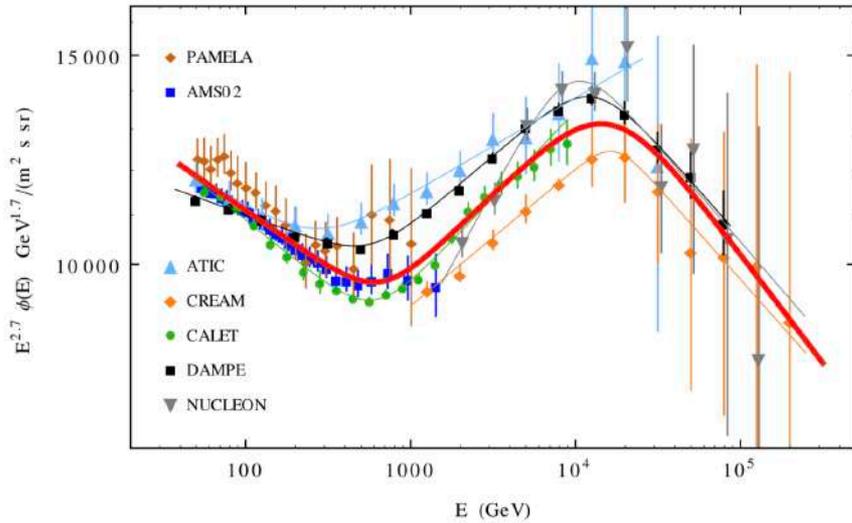
the spectrum is not single power-law; it contains (at least) two spectral features:

- hardening above a few 100 GeV
- steepening above 10 TeV
- hardening above 100 TeV ?

we do need PeVatrons ?

- **quasi-PeVatrons**
  up to 0.1 PeV and more

- **nominal - PeVatrons**
  up to 1 PeV

- or **super-PeVatrons**
  >10 PeV up to 100 PeV
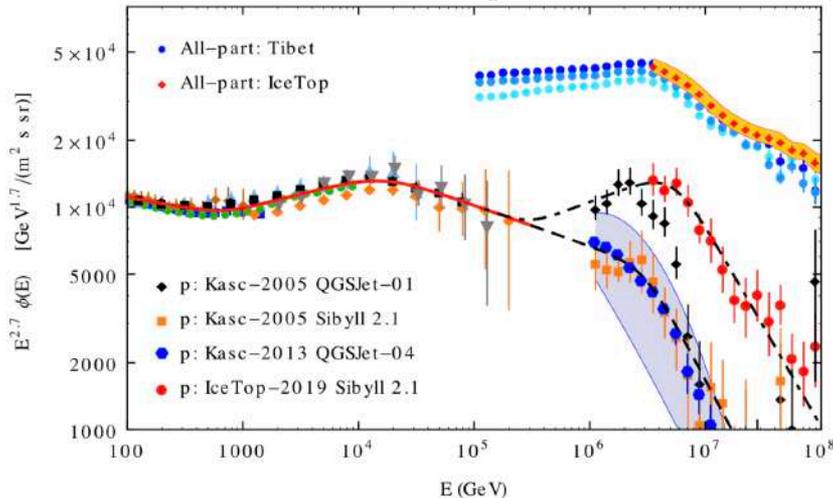
what does mean "Origin of Cosmic Rays" ?

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

CR factories can be identified only by neutral stable messengers:
photons and neutrinos (also neutrons with $E > 10^{14}(d/1pc)$ eV)

Relativistic Matter Factories
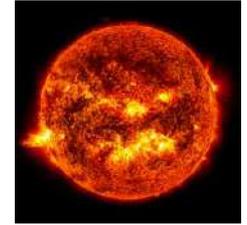
nonthermal processes in Universe proceed everywhere and on all astronomical scales:

Neutron Stars/Pulsars   Black Holes   γ-ray Bursts
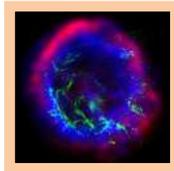
Supernova Remnants   Pulsar Wind Nebulae   Massive Stars

Starburst Galaxies   AGN Jets   GalaxyClusters
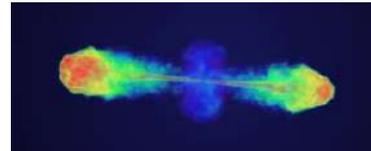
recent gamma-ray discoveries - a breakthrough in the field

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
- Clusters of Galaxies
- Radiogalaxies,
- AGN,
- GRBs

analogy with thermal 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/PeV 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:
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>

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

$\eta = 1$ - absolute extreme accelerator determined by ED and ideal MHD
combined with the Synchrotron energy lose rate

Crab Nebula and Sources of of 10^{20} eV Cosmic Rays are
Absolute Extreme Accelerators

1984
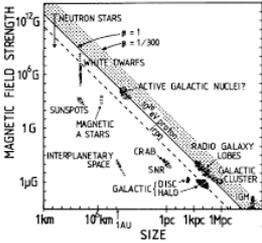
"Hillas plot" : $R_L \leq R$ $E_{20} \leq 10 R_{pc} B_G$

trivial and non-trivial implications

"Clearly, very few sites remain as possibilities:
either one wants highly condensed objects
with huge B or enormously extended object"
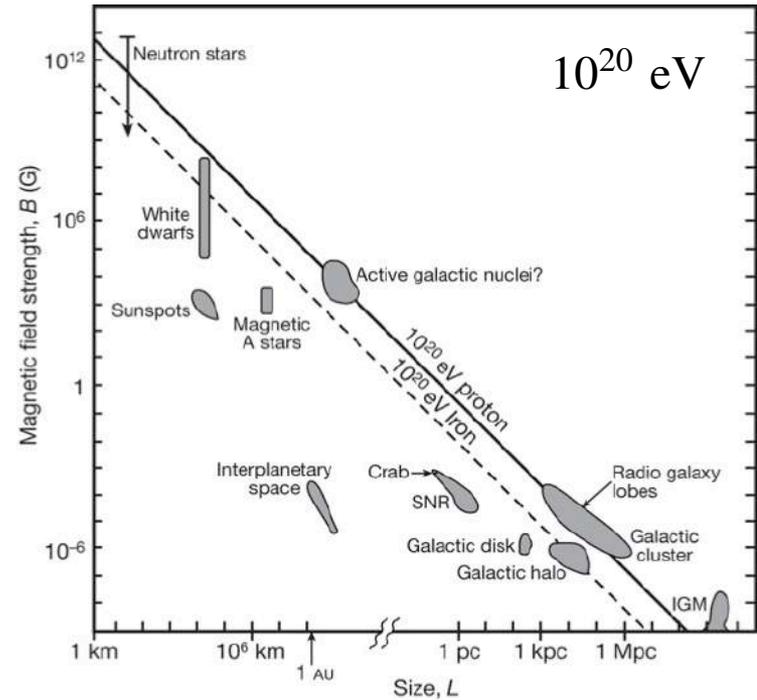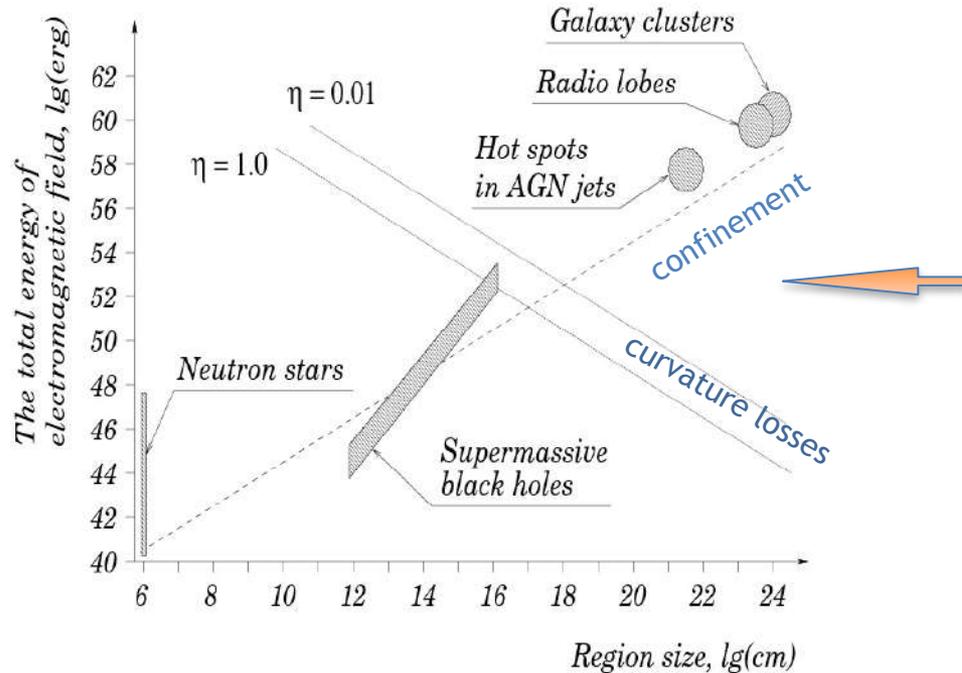
10^{20} eV

more conventional (synchrotron) losses:
B-field in "10^{20}eV factories" cannot exceed 1 G;
unless is moving with bulk motion Lorentz factor

$E_{20} \leq 2\eta^{1/2} B_G^{-1/2}$

$\Gamma \leq 30, \ B \leq 1$ kG

Crab pulsar/wind/nebula: *Absolute Extreme Accelerator*

Chandra

- conversion of the rotational energy of pulsar to non-thermal energy with efficiency ~50 %
- electron acceleration with 100 % efficiency

$h\nu_{max} \sim 100\eta$ MeV

HESS

LHAASO

max energy electrons:

$$E_{max} \approx 6\eta^{-1/2}(B/100\mu G)^{-1/2}$$

$$E_\gamma \approx 0.37(E_e/1 \text{ PeV})^{1.3} \text{ PeV}$$

$$\eta = E/B \leq 1$$
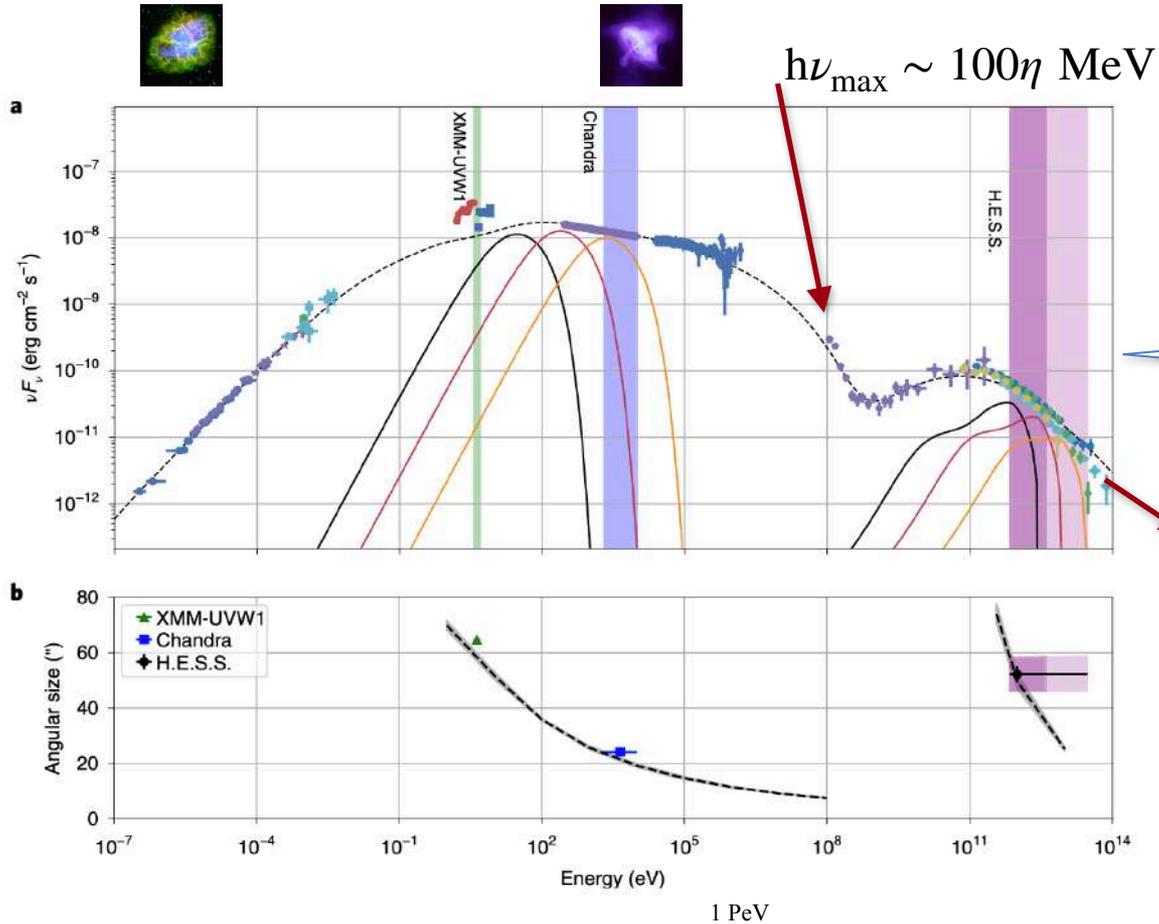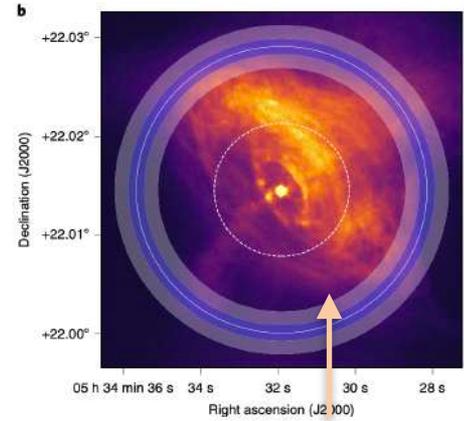
$$\eta = 1 \quad \text{extreme accelerator !}$$

1 PeV

$$h\nu \approx 9.3(E_\gamma/1 \text{ PeV})^{1.5}(B/100\mu G) \text{ MeV}$$

PeVatrons in our Galaxy?

Electron PeVatrons -   related to the pulsar winds in PWNe
                        with Crab Nebulae as a "special case"

Proton PeVatrons -   in young individual SNRs and Stellar Winds
                     with v > 0.01c, and provided B > 0.01 G

Galactic Center   magnetosphere of SMBH (Sgr A*)

$$E_{15} \sim eBR \approx 10^3 (B/10^4 \text{G})(\text{M}/3 \times 10^6 \text{M}_\odot)$$

relativistic (barionic) outflows
            wind in GC or the jet in SS 433, Cyg X-1, Cyg X-3, GRS 1915

Large Scale structures -   Superbubbles, Fermi Bubbles, …

Galactic Cosmic Rays

Cosmic Rays: primary component + secondary component

primary: directly accelerated p, A, e⁻, e⁺

secondary: A, γ, ν, e⁺, p̄   produced in
   interactions of primary CRs with ISM

secondary/primary fraction X =>   "grammage" Λ

=> confinement time T => diffusion coefficient $D(E) \propto E^{\delta}$

source - injection spectrum into ISM $S(E) \propto E^{-\alpha}$

CR spectrum in ISM - modulated $\Phi(E) \propto E^{-\Gamma}; \; \Gamma = \alpha + \delta$

Galactic Cosmic Rays: sources ?

SNRs as prime candidates - over decades the conviction has been based on
phenomenological arguments and theoretical meditations

❑   as early as 1933 W. Baade and Zwicky recognized the comparable energetics
characterizing SN explosions and CRs and envisaged a link between

$E_{SN} \sim 10^{51}$ erg, $R \sim 0.03$ yr^{-1}, $P_{SN} \sim 10^{42}$ erg/s $=>$ 10 % to CRs ?

❑   Diffusive Shock Acceleration theory applied to SNRs - viable mechanism
for acceleration of particles with hard E^{-2} type spectrum in young (< 3 kyr)
SNRs up to 1 PeV ? Difficult but in principle possible - amplification of
the magnetic field in upstream is a critical issue

❑   direct prove -   gamma-rays, neutrinos

Probing SNRs with gamma-rays

SNRs as the most likely sources

of galactic cosmic rays up to 1 PeV?

main hope is related to gamma-ray observations:

- detect VHE gamma-rays from SNRs
- demonstrate that they have hadronic origin
- demonstrate that proton spectra continue up to 1 PeV

Probing the distributions of accelerated particles in SNRs

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

HESS collaboration, 2018
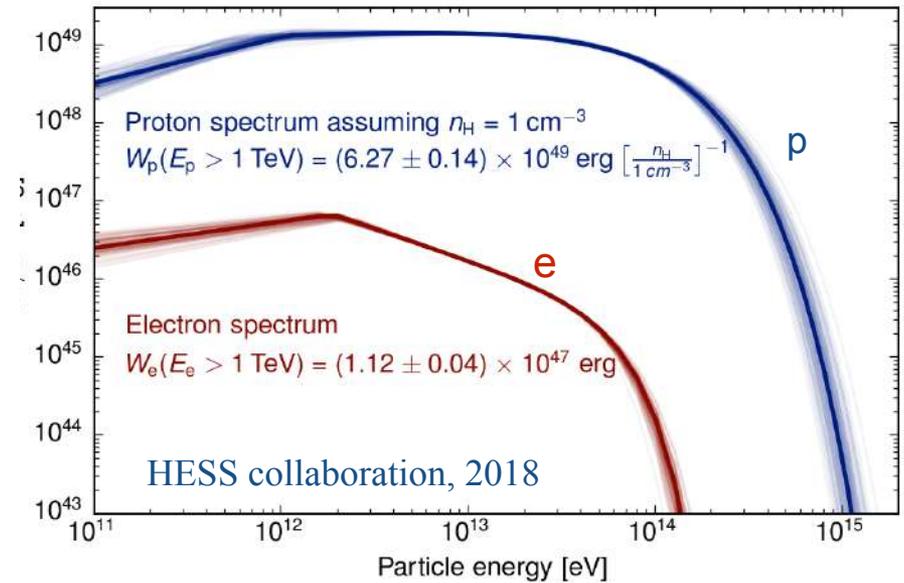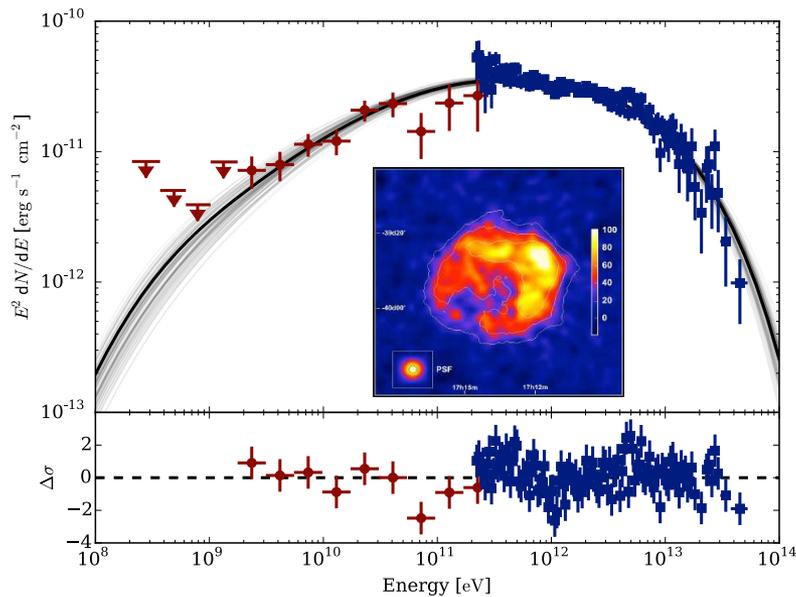
cutoff /break in the proton spectrum at 100 TeV

RXJ 1713.7-4639
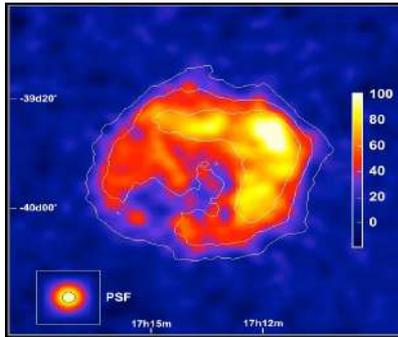
modeling of broad-band SEDs:

hadronic model

good spectral fit, reasonable radial profile, but …
(1) lack of thermal emission - possible explanation?
>70% energy is released in acceleration of protons!
(2) very high p/e ratio (10^4)

leptonic model

not perfect, but still acceptable, fits for spectral
and spatial distributions of IC gamma-rays;
suppressed thermal emission, comfortable p/e
ratio ($\sim 10^2$);small large-scale B-field ($\sim$ 10 μG)

both forward&reverse shock contribute to γ-rays
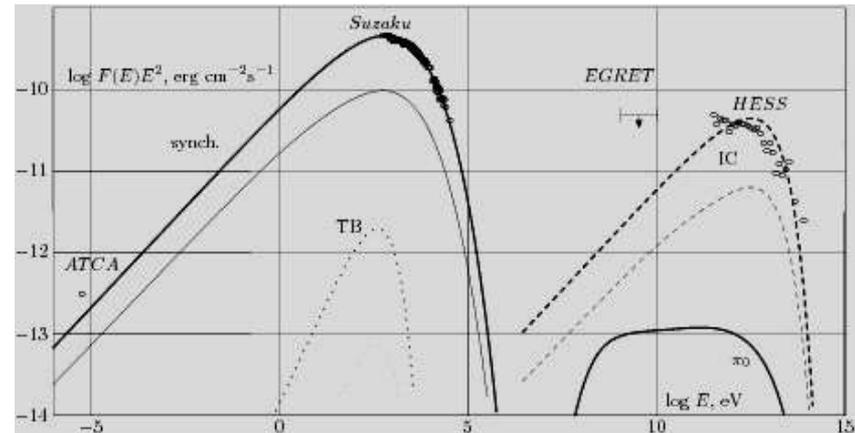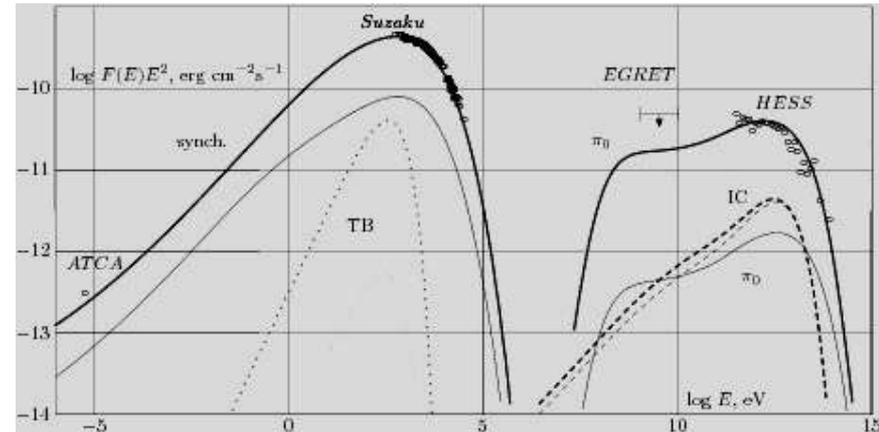
spectra of young SNRs above 1 TeV - steep with Γ= 2.3-2.6
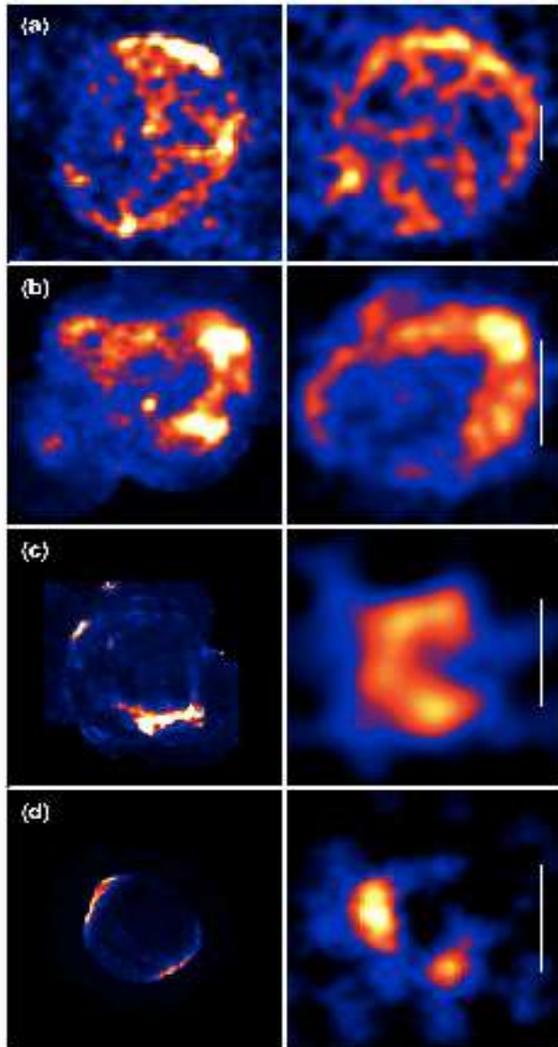
TeV gamma-rays from from >10 young SNRs:
support to the SNR origin of galactic CRs,
but it is not yet clear whether SNRs alone can
provide the CR flux up to the *knee* (~1 PeV)
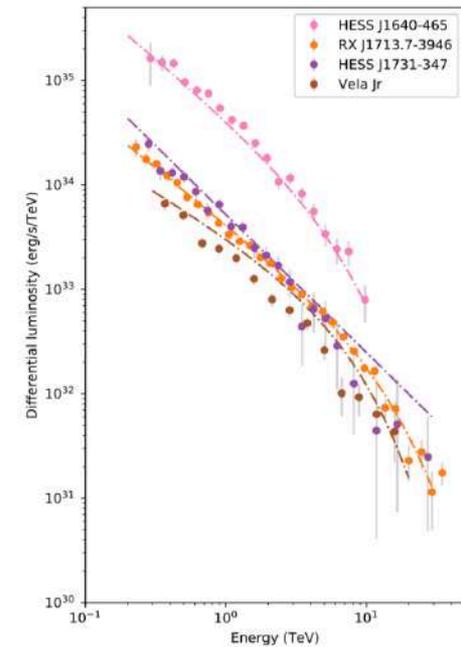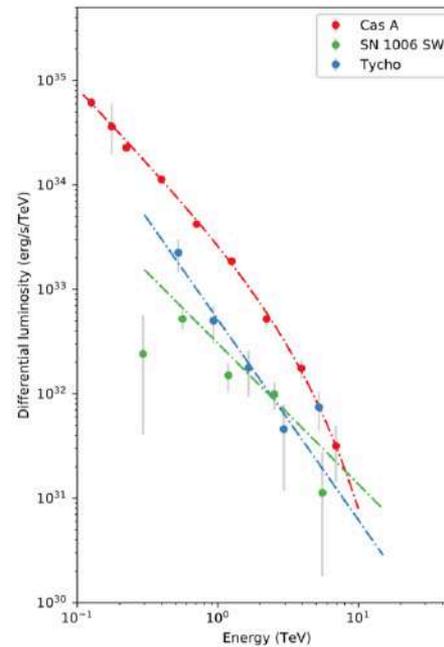
steep spectra or 'early' cutoffs ?

slope or intrinsic power-low index?

formally the spectra can be presented in the form:

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

with reasonable combination of E_0 and β, $\Gamma=2$ could be an option

price?

Eo < 10 TeV => Ep < 100 TeV is not a PeVatron

Eo > 10 TeV => Ep > 100 TeV and $\Gamma > 2.3$ can be a PeVatron

many reasons for deviation of the acceleration spectrum from E^{-2}

two options

- large power-law indices
  it is more realistic than Γ=2 of the "standard" DSA (M. Malkov, T. Bell, …)
  no constrains on the proton maximum energy from gamma-ray data:
       probing Emax ~ 1 PeV - very difficult

- "early cutoff"

  standard DSA but low-energy cutoff

  should we relax and accept that SNRs are main contributors to CRs but at TeV
  energies are overtaken by other source population ("PeVatrons") responsible for
  the knee region? (Laggage and Cesarsky 1983) ?

  or

relate it to the much early "PeVatron Phase" - first 10 to 100 years after
  the SN explosion (Bell+, Zirakashvili+) and the escape of highest energy
  (>1 PeV) particles from the remnant energy particles

  "large Γ or small Eo ?" - extension of observations to 100 TeV

searching for proton PeVatrons through their "echos":

multi-TeV radiation from dense clouds located outside the accelerator

– protons of energy exceeding 100 TeV are accelerated and leave the shell at T<1000 yr or, more likely, <100 year, epochs

– γ-rays above 100 TeV expected only from very young SNRs - the chance of their detection is small

– if (by chance) a massive gas cloud appears in the 100 pc vicinity of SNR, "delayed" γ-rays signals arise when run-away partices reach the cloud

– detection of such delayed emission of multi-TeV γ-rays allows indirect but robust identification of the SNR as a proton PeVatron

gamma-rays from SNR and nearby molecular cloud

isotropic escape

d=1 kpc

1 - 400 yr
2 - 2000 yr
3 - 8000 yr
4 - 32000 yr

Gabici and FA, 2007
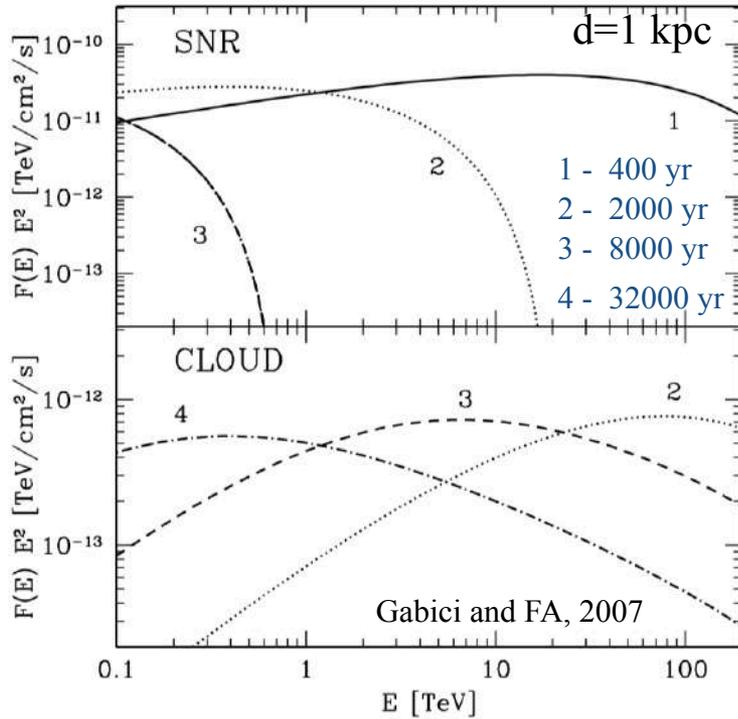
SNR:
$W=10^{51}$ erg
$n= 1$ cm^{-3}
$f(p)\sim p^{-4}$
$p_{max}=5$ PeV
$p_{max}\sim t^{-2.4}$

Cloud:
$R=100$ pc
$M=10^4 Mo$
$D(E)=3 \times 10^{29}(E/1PeV)^{0.5}$ cm^2/s

anisotropic escape - CR "clouds"

W44
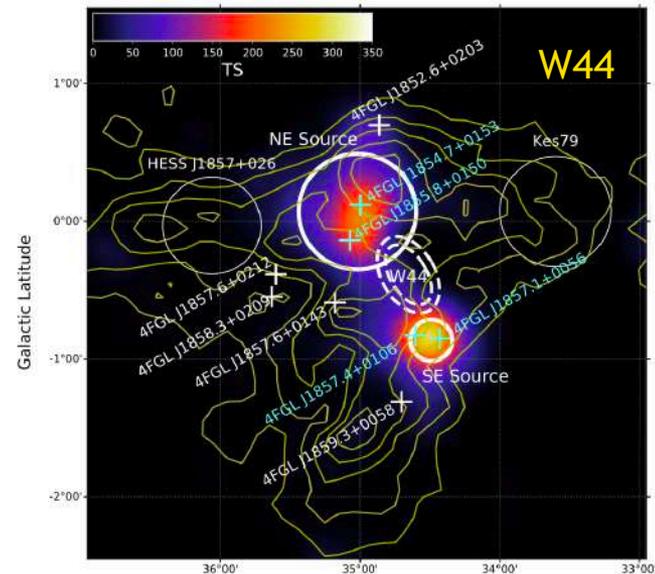
warning: don't be tricked by propagation effects!

transition from rectilinear to diffusive regime of propagation

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

Intensity map, erg/cm² s sr
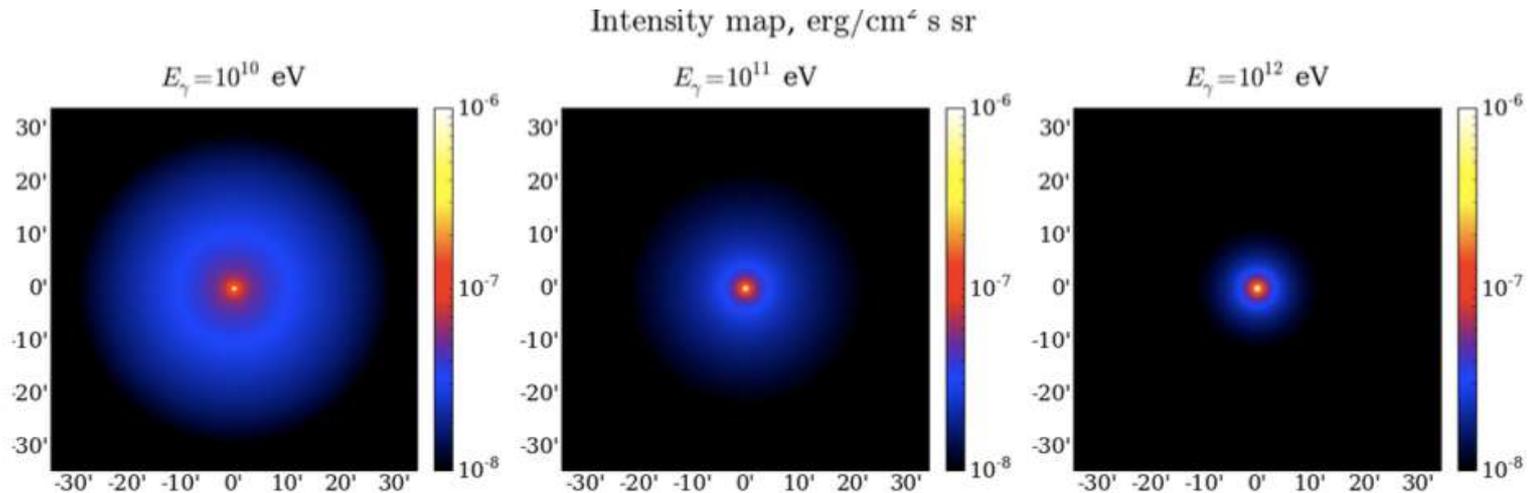
Figure 2: The intensity maps of gamma-ray emission at different energies. The spherical cloud with homogeneous density distribution is irradiated by the cosmic-ray source located in its centre. The gas density inside the accelerator is assumed very low, so the contribution of the accelerator to the gamma-ray 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 $\sim 1° \times 1°$ corresponds to the area $\sim 20 \times 20$ pc².

Prosekin, Kelner, FA 2015

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warning:

transition from rectilinear to diffusive regime of propagation

Intensity map, erg/cm^2 s sr
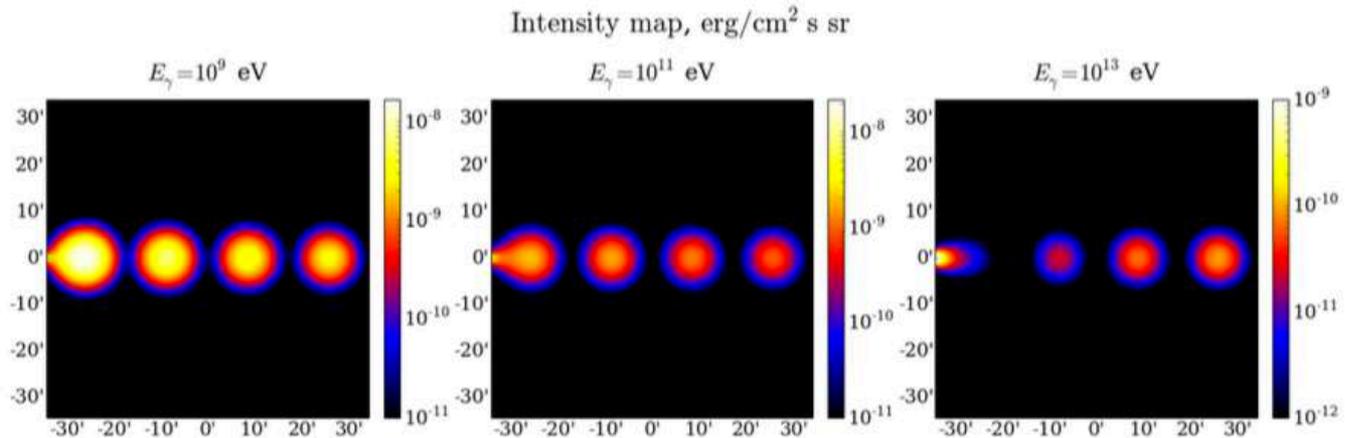
d=1 kpc

intensity map of gamma-rays at different energies from a group
of clouds located at different distances from the accelerator

Prosekin, Kelner, FA 2015

Small diffusion coefficient or correct treatment of diffusion ballistic motion

Occam's Razor principle - nominal diffusion coefficient

Recchia et al.

arXiv:2106.02275v1

Fig. 4.15 IC γ-ray fluxes expected within different detection angles from an electron accelerator located at a distance of 0.5 kpc. The injection rate of electrons is $Le = 3.5 \cdot 10^{36}$ erg/s. (a) (left) fast diffusion – power-law diffusion coefficient $D(E) = D_*(E/10\text{GeV})^{-\delta}$ with $D_* = 10^{27}$ cm^2/s and $\delta = 0.5$; steep spectrum of accelerated electrons with $\Gamma = 2.4$. (b) (right) slow diffusion – constant diffusion coefficient with $D_* = 10^{27}$ cm^2/s and $\delta = 0$; hard spectrum of accelerated electrons with $\Gamma = 2$.

ballistic motion does not imply very extended ource - just opposite…

300 TeV photon is produced by 1 PeV electron; over mean path of L~100 pc in ISM, the motion is ballistic - we should see a point like source!

with >300 TeV γ-rays we can localise/identify the Electron PeVatrons (PWNe) in Milky Way!

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Very young SNRs as PeVatrons?

G1.9+0.3 - youngest (100yr-old) known SNR in Galaxy
with the current shock speed v=14,000 km/s

$$h\nu_{\mathrm{max}} \approx 1(\mathrm{v_{sh}}/3000 \ \mathrm{km/s})^2 \ \mathrm{keV}$$

in the Bohm diffusion limit the peak should
be around 20 keV but is detected at at 1 keV
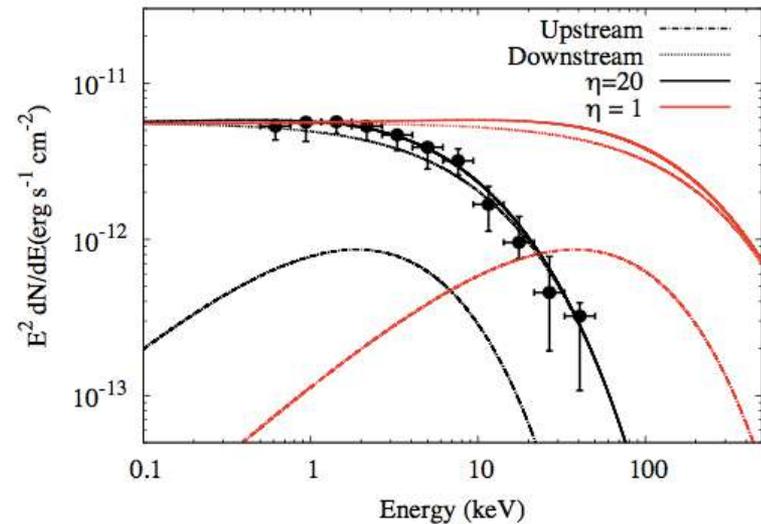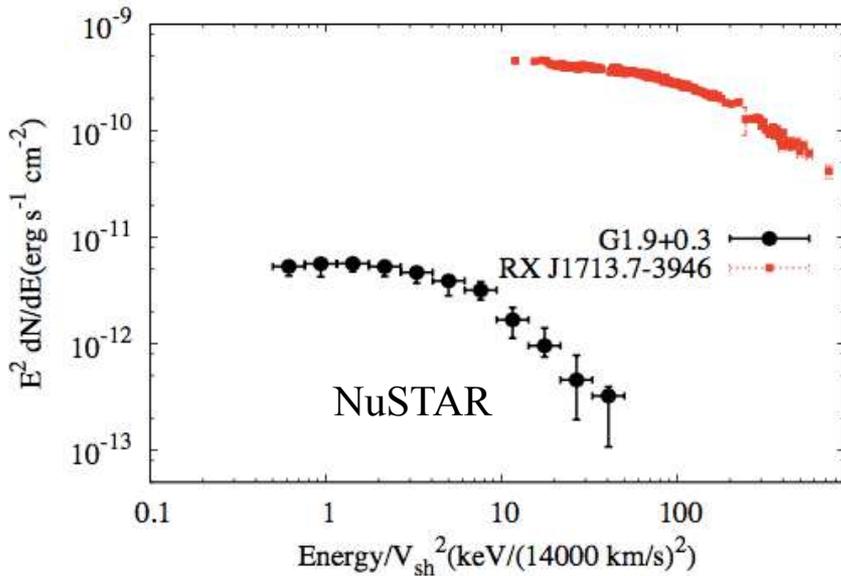
Presently G1.9+0.3 does not operate as a PeVatron!   35

PeVatrons and Super-PeVatrons in Milky Way

do we expect acceleration of particles to PeV energies and well beyond?

stellar sources - very difficult but possible, in particular,

Supernova Remnants, Stellar Clusters/Superbubbles (extreme accelerators)
Pulsar Wind Nebulae electron PeVatron   (absolute-extreme accelerators)

multi-PeV accelerators in our Galaxy?

extension of the cosmic ray spectrum well beyond 1 PeV =>
        super-PeVatrons should exist in the Milky Way

SNRs, Supper-Bubbles, Pulsars ?

Galactic Wind halo?

Fermi Bubbles?

SMBH in the Galactic Center ?

PeVatron(s) in the Galactic Center!

90 cm VLA radio image
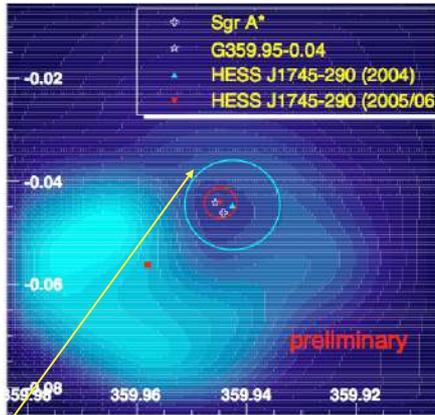
TeV gamma-rays
from Galactic Center
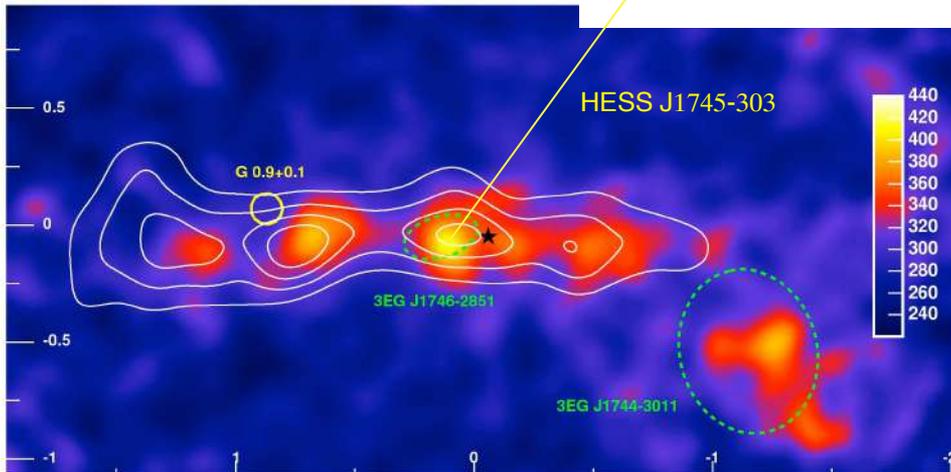
Sgr A* or the central diffuse
< 10pc region or a plerion?

γ-ray emitting clouds

HESS J1745-303

HESS collaboration,2006

HESS collaboration,2009
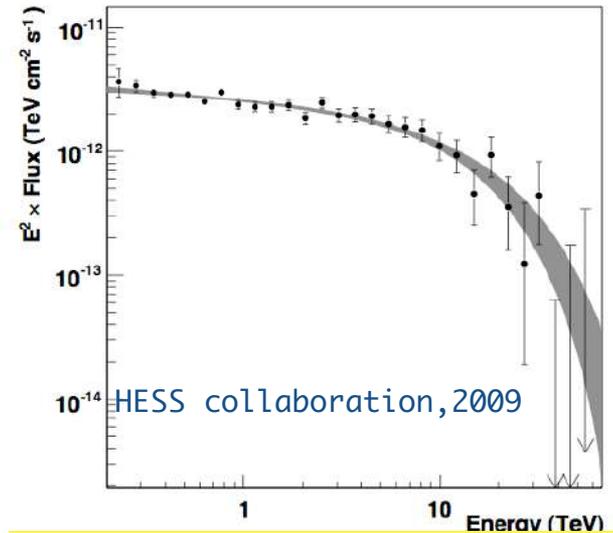
Energy spectrum:

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

$\beta=1$ $\Gamma=2.1$; $E_0=15.7$ TeV

$\beta=1/2$ $\Gamma=1.9$ $E0=4.0$ TeV
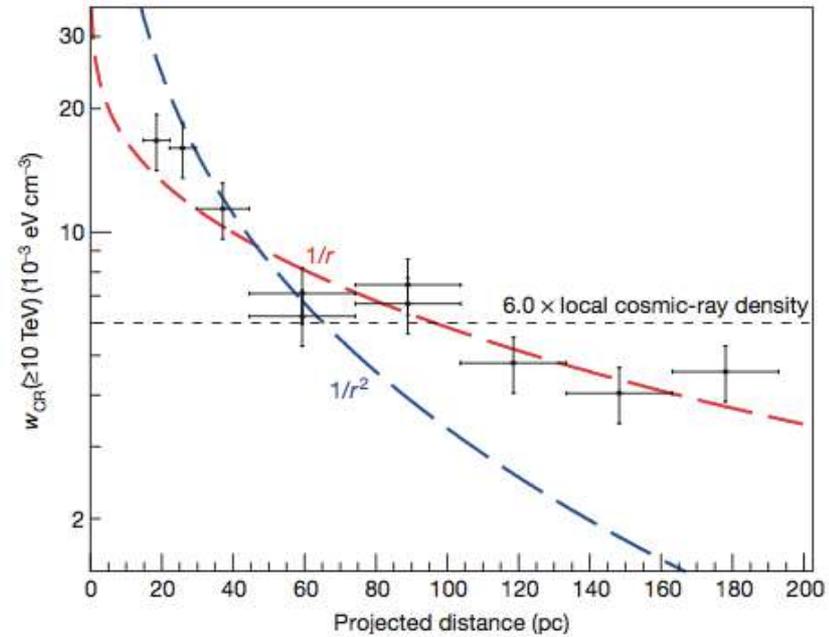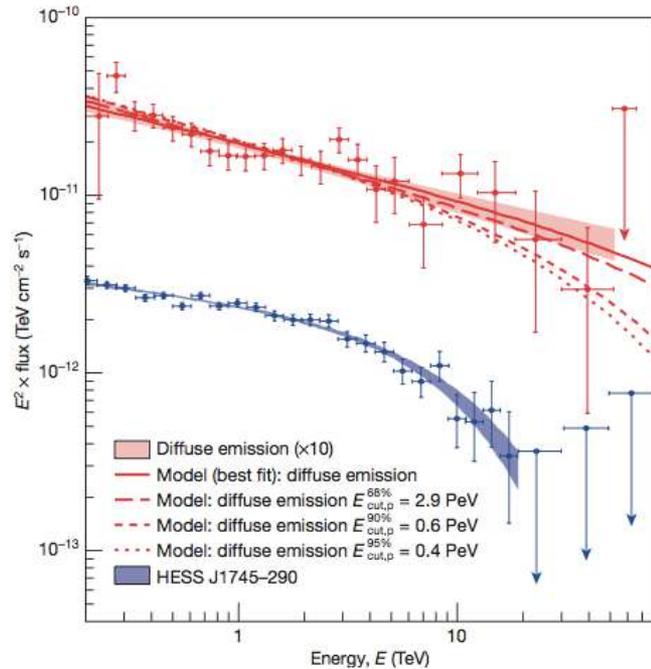
no-cutoff in the gamma-ray spectrum up to **25 TeV**
=> *no-cutoff* in the proton spectrum up to   ~ **1 PeV**

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 !**

implications?

❑ Galactic Center (GC) harbors a hadronic PeVatron within a few pc region around Sgr A* (a SMBH in GC)

❑ 1/r type distribution of the CR density implies (quasi)continuous regime of operation of the accelerator with a power 10^{38} erg/s (on timescales 1 to 10 kyr) - a non negligible fraction of the current accretion power

❑ this accelerator alone can account for most of the flux of Galactic CRs around the "knee" if its power over the last 10^6 years or so, has been maintained at average level of 10^{39} erg/s

❑ escape of particles into the Galactic halo and their subsequent interactions with the surrounding gas, can be responsible for the sub-PeV neutrinos recently reported by the IceCube collaboration

SMBH or young massive-star clusters?

CRs from GC responsible for Fermi Bubbles?
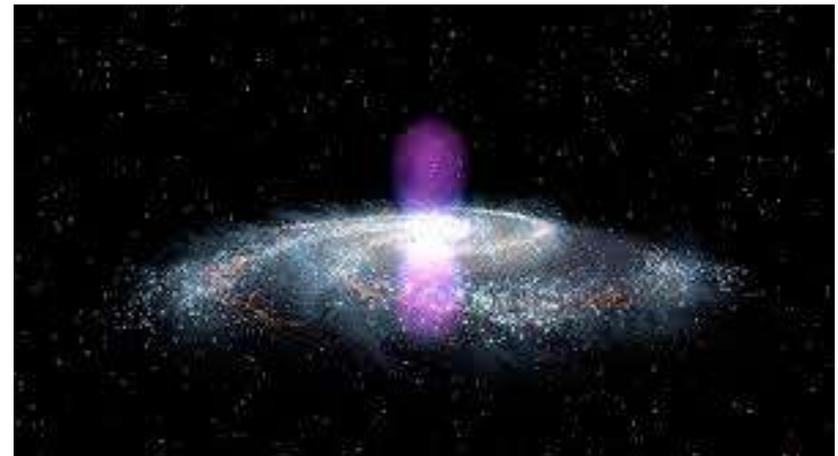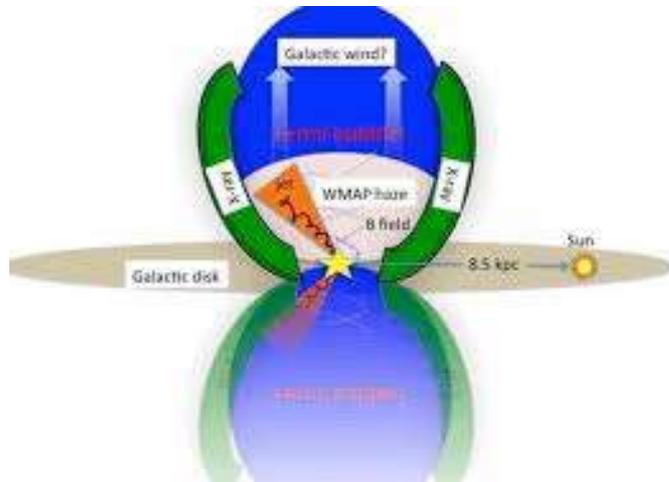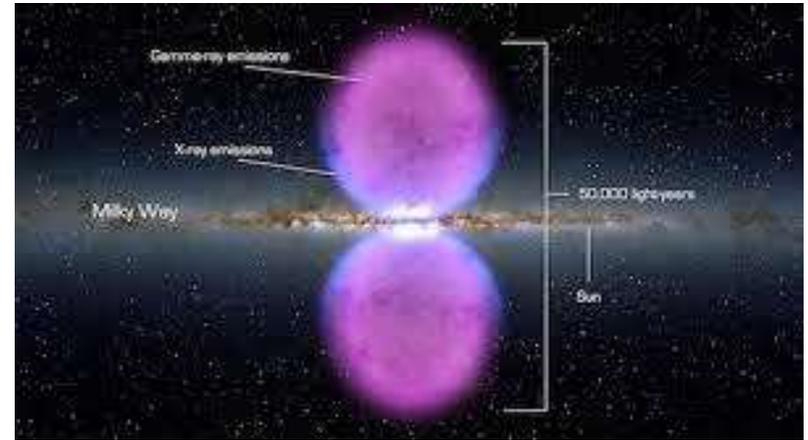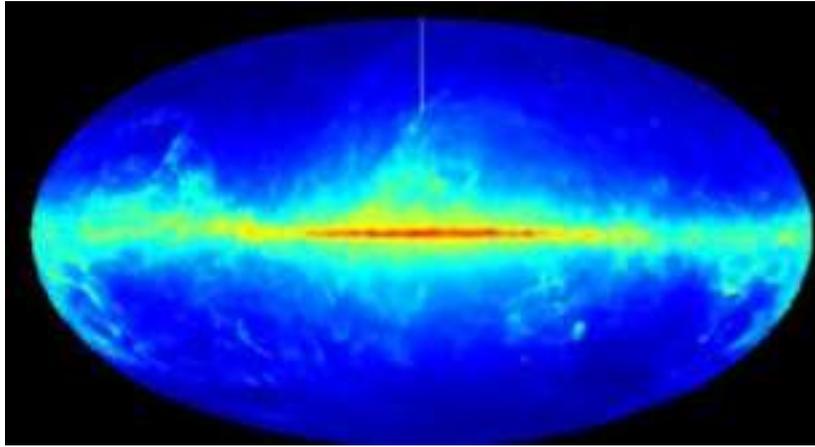
and "IceCube Neutrinos" from a larger >>10 kpc halo ?

Young Massive Stars as Cosmic Ray PeVatrons?

Extended Regions surrounding Clusters of Young Massive Stars
are sources sources of GeV, TeV and … PeV gamma-rays !

Westerlund 1, *Westerlund 2, 30 Dor C* (in LMC)

CygnusOB2, *Westerlund 2*, *NGC3603*

Arches, *Quintuplet* and *Nuclear* ultracompact clusters in GC

- collective power in stellar wind 10^{38} - 10^{39} erg/s

- typical speeds of stellar winds several times 1000 km/s

continuous injections of CRs into ISM over (2-5) x 10^6 yrs formation of ~ 1/r radial
distribution of CRs up to 200 pc; diffuse (typically irregular) gamma-ray morphology
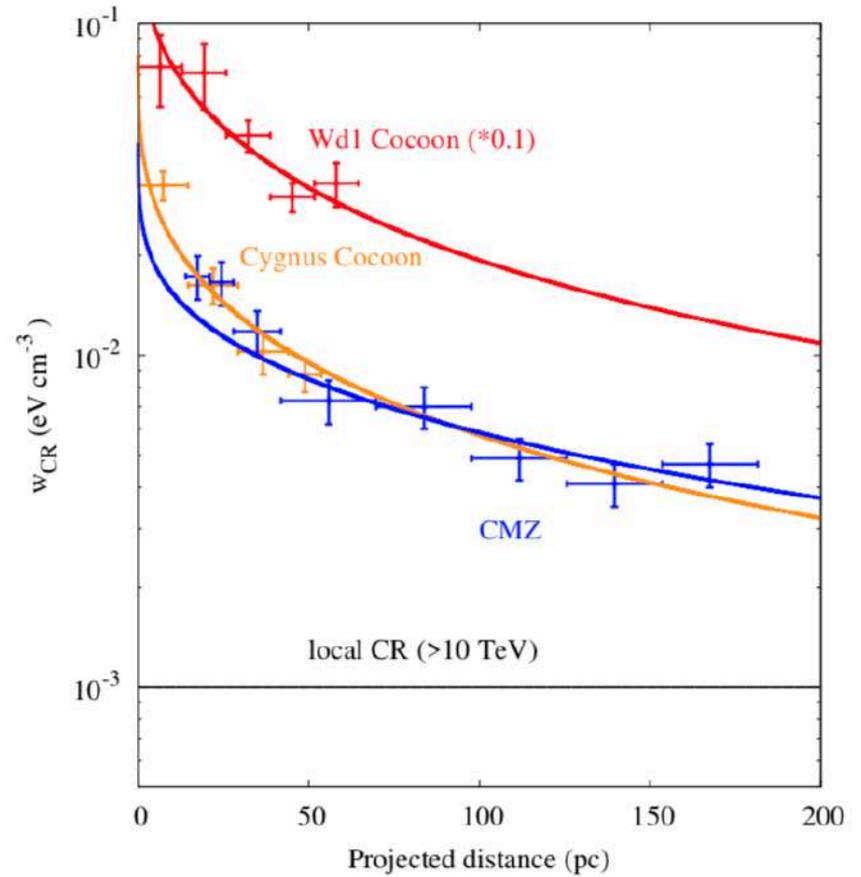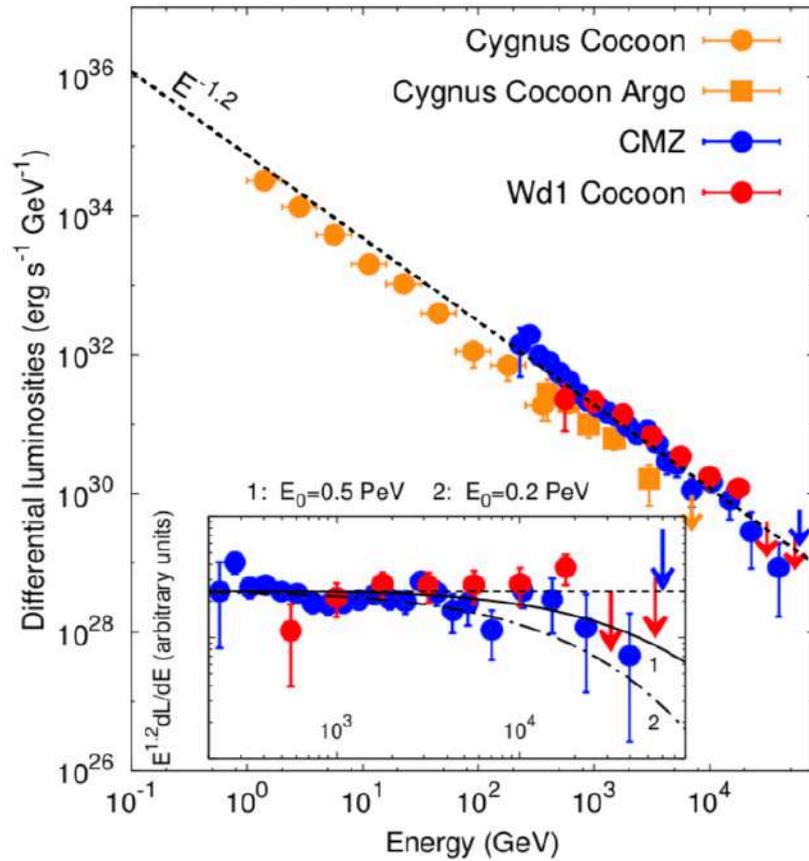
Figure 1: Gamma-ray luminosities and CR proton radial distributions in extended regions around the star clusters Cyg OB2 (Cygnus Cocoon) and Westerlund 1 (Wd 1 Cocoon), as well as in the Central Molecular Zone (CMZ) of the Galactic Centre assuming that CMZ is powered by CRs accelerated in *Arches*, *Quintuplet* and *Nuclear* clusters.

Total energy in CRs within the size of radius Ro

$$W_{\mathrm{p}} = 4\pi \int_0^{R_0} w(r) r^2 \, \mathrm{d}r \approx 2.7 \times 10^{47} (w_0/1 \text{ eV/cm}^3)(R_0/10 \text{ pc})^2 \text{ erg}$$

Size of emission region - depends on D and To

$$R_{\mathrm{D}} = 2\sqrt{T_0 D(E)} \approx 3.6 \times 10^3 (D_{30} T_6)^{1/2} \text{ pc}$$

Efficiency of conversion of the wind kinetic energy to CRs

$$f(\geq 10 \text{ TeV}) \approx 1 w_0 D_{30} L_{39}^{-1}$$

For $E^{-2.3}$ proton spectrum, f(>10TeV) does not significantly exceed 1%
the diffusion coefficient D_{30} cannot be larger than 0.01; $R_D \sim 300$ pc

LHAASO, CTA - measurements of D and consequently f

detection of >10 TeV hard spectrum gamma-rays from SS 433

HAWC - HESS/MAGIC upper limits

spectrum as flat as E^{-2} extending 20 TeV
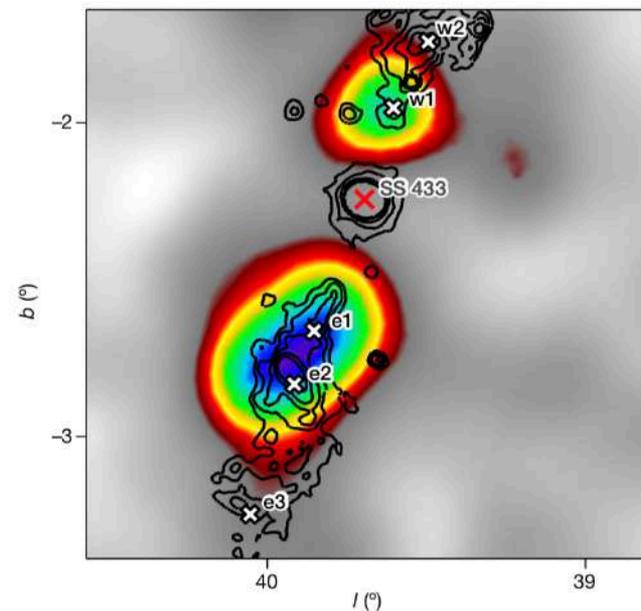
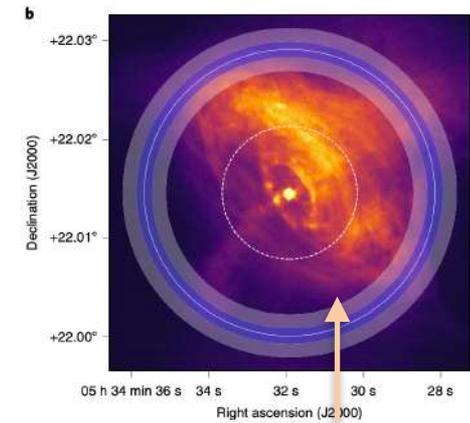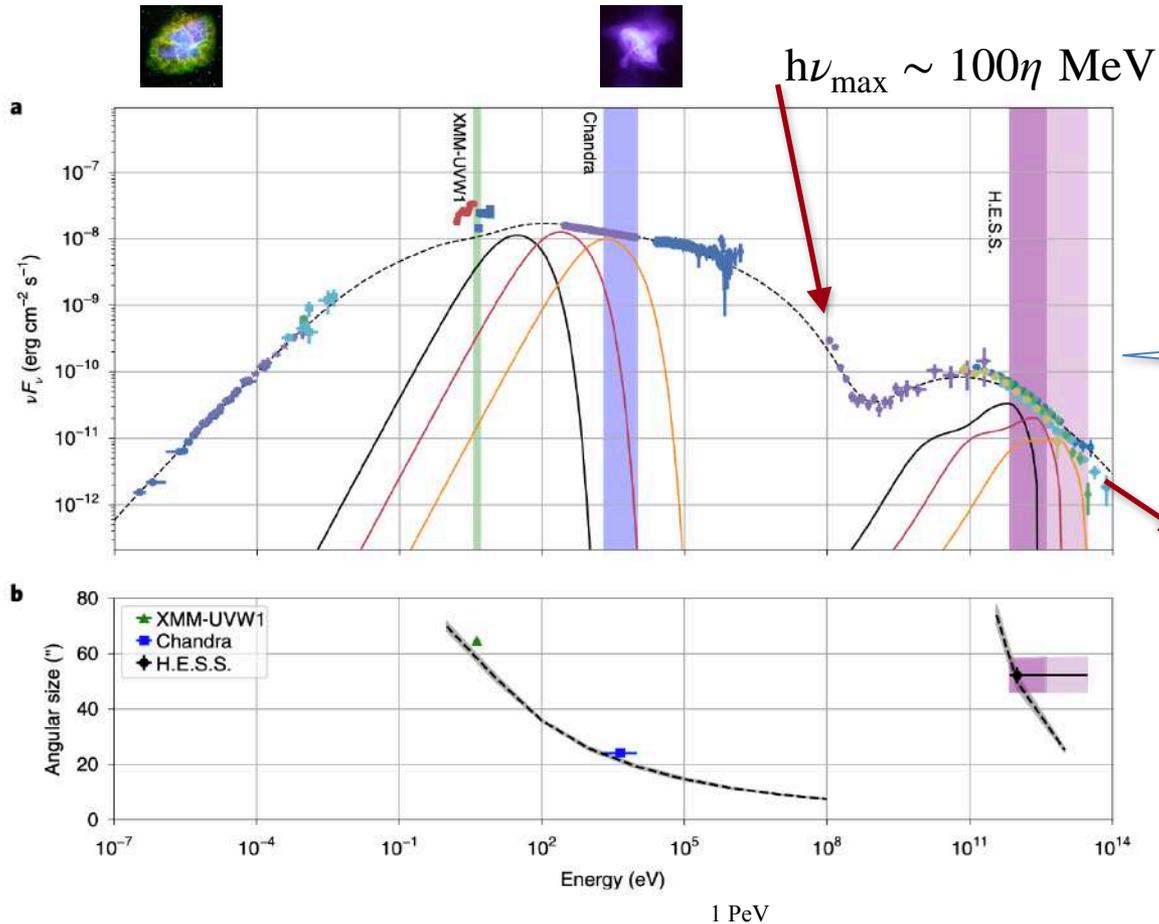- E^{-2} electron spectrum with Eo=2 PeV

- gas density - not sufficient?
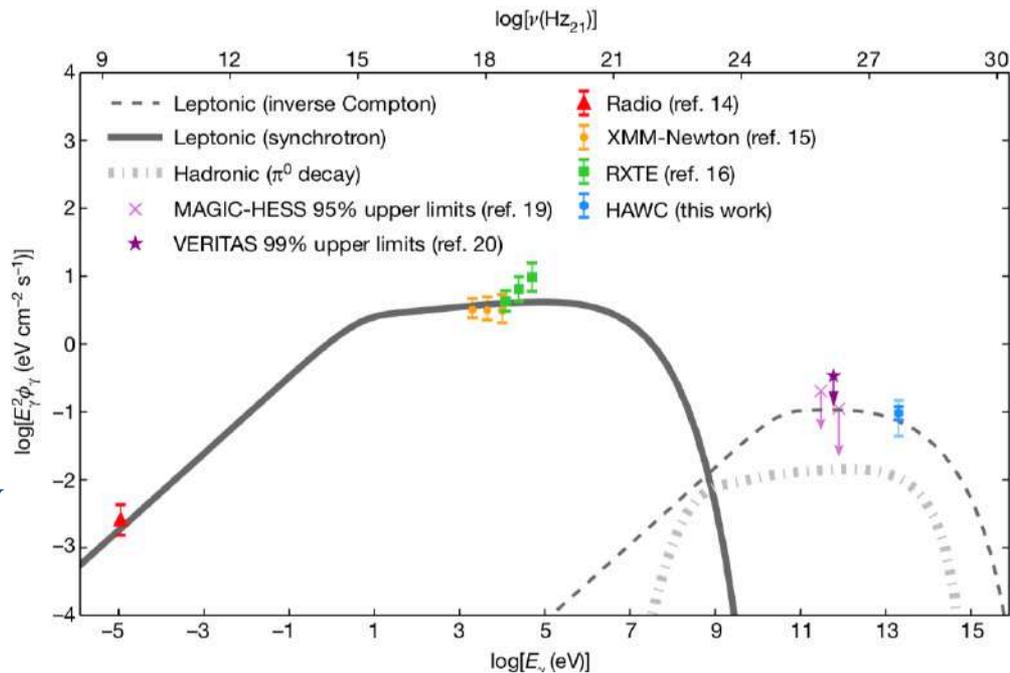
other Microquasars?

Cyg X-1, Cyg X-3, GRS 1915, …   good candidates for acceleration of protons $>>10^{15}$ eV

Crab pulsar/wind/nebula: *Absolute Extreme Accelerator*

Chandra

- conversion of the rotational energy of pulsar to non-thermal energy with efficiency ~50 %
- electron acceleration with 100 % efficiency

$$h\nu_{max} \sim 100\eta \text{ MeV}$$

HESS

LHAASO

max energy electrons:

$$E_{max} \approx 6\eta^{-1/2}(B/100\mu G)^{-1/2}$$

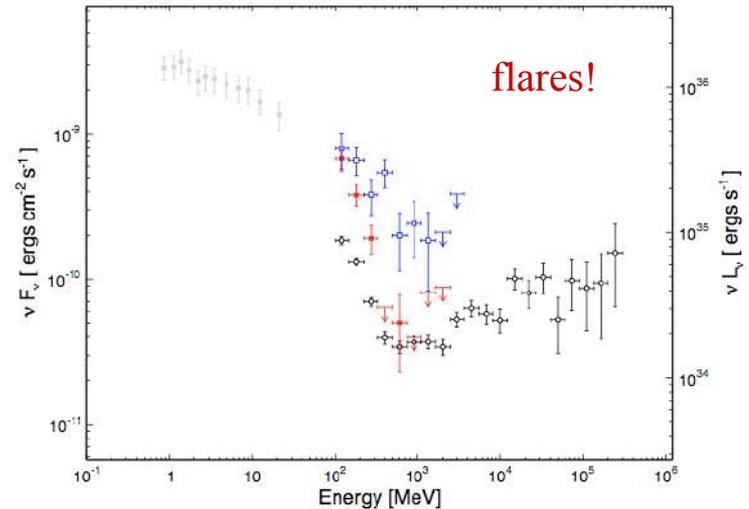$$E_\gamma \approx 0.37(E_e/1 \text{ PeV})^{1.3} \text{ PeV}$$

$$\eta = E/B \leq 1$$

$$\eta = 1 \quad \text{extreme accelerator !}$$

1 PeV

$$h\nu \approx 9.3(E_\gamma/1 \text{ PeV})^{1.5}(B/100\mu G) \text{ MeV}$$

Flares of Crab (Nebula) :
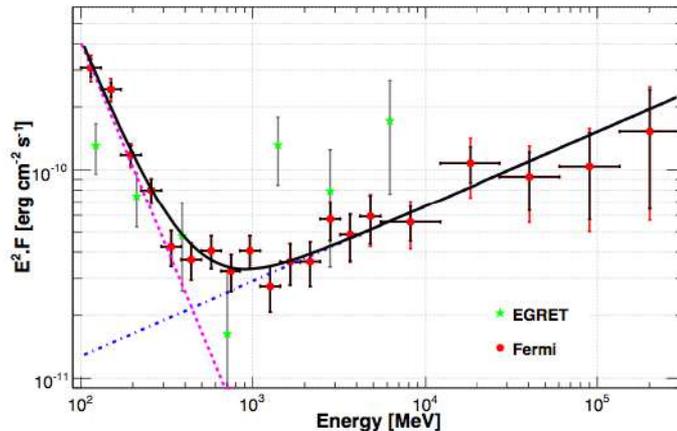
IC emission consistent with average
nebular B-field: B ~ 100μG-150μG

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.

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

efficiency of gamma-ray production

Crab is effective electron accelerator but not effective gamma-ray emitter

because of $B \geq 100\mu G, \ \kappa \sim 10^{-3}$

other ("standard") PWNe are effective accelerators/effective gamma-ray emitters
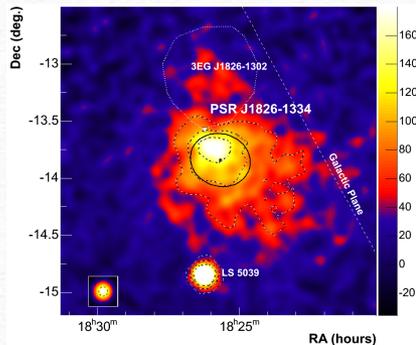
$t \geq t_{cool}, \ \kappa = t_{Sy}/t_{IC} \approx 1(B/3\mu G)^{-2}$

compensates smaller spin-down luminosities of "standard" PWNe
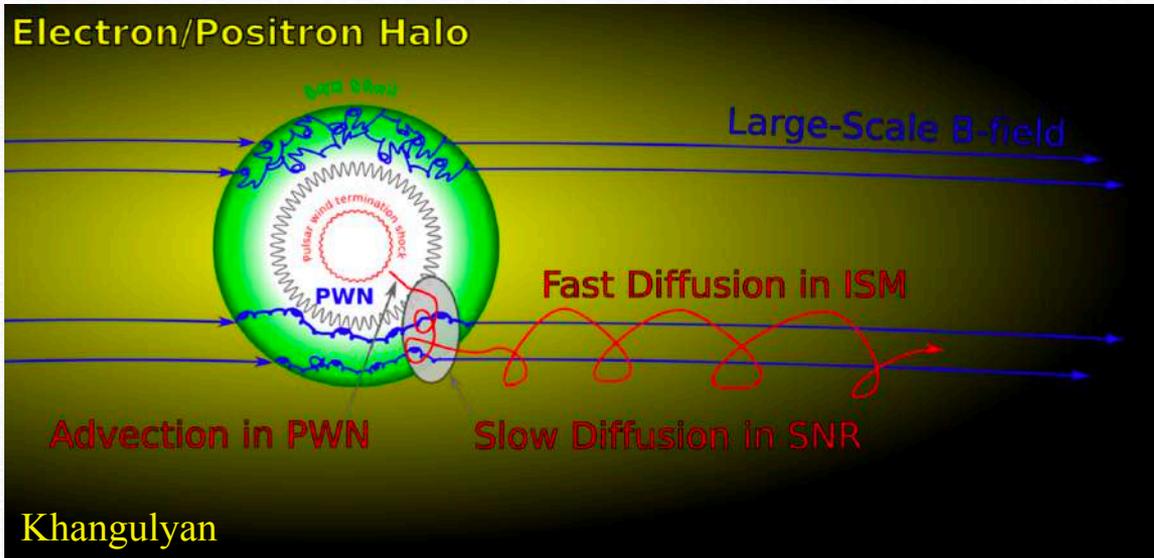
robust (assumption-free!) derivation of spatial and energy distribution of multi-TeV electrons
absolutely unique in astrophysics; great for development of models, theories, concepts

HESS standard PWNe:
 or PWNe (MHD structure) + Pulsar Halos (IC of electrons after they escape PWN)
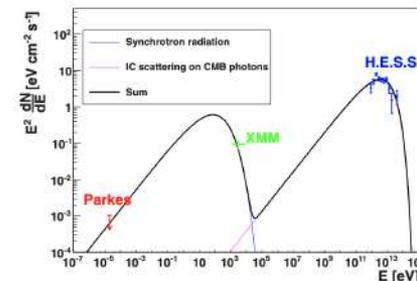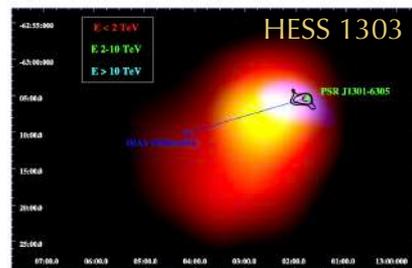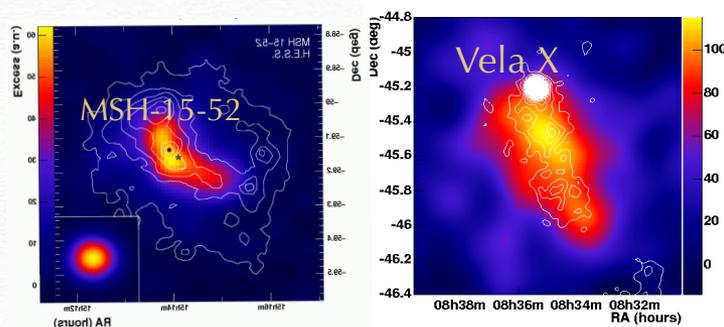
Energy dependent morphology
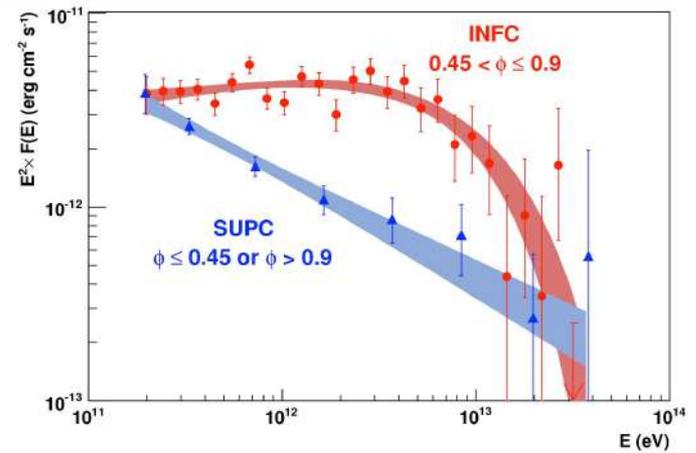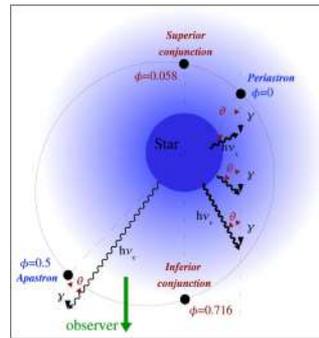very low B-field B $\sim 1.4\mu G$

PWNe - MHD structure

PHs - diffusively expanding
            cloud of electrons

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 add-
itional factors (adiabatic losses, modest Doppler boosting) also play a non-negligible role*
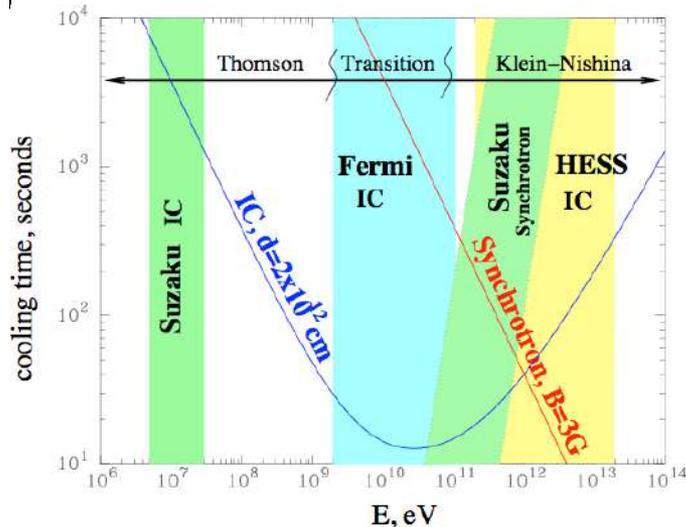
can electrons be accelerated to energies up to 20 TeV
in presence of dense radiation? *yes, but accelerator
should not be located deep inside binary system; even
at the edge of the system η > 0.1 =>* although the
origin of the compact object is not yet known (pulsar
or a BH) and we do not understand many details, it is clear
that this binary system works as an extreme accelerator

Summary:

The results reported in the Nature article reveal only the tip of the iceberg. In the coming years, we anticipate breakthrough discoveries by the LHAASO detectors that could dramatically change the current concepts about the most energetic and extreme phenomena in the non-thermal Universe in general, and about the Galactic PeVatrons, in particular.

stay tuned!