The Roma International Conference on Astroparticle Physics 2022 (RICAP2022)

Multi-messenger signals from PeVatrons

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PeVatrons

Cosmic Ray Factories accelerating protons and electrons to PeV energies

Why PeVatrons?

1. main contributors to highest energy Galactic CRs
2. physics of perfectly designed by Nature Cosmic Accelerators

Messengers

direct **multi-TeV and PeV gamma-rays and neutrinos**

very important - synchrotron (X/γ) of primary and **secondary electrons**
- MeV-TeV γ-rays, non thermal radio (MHz and GHz)
- Radio (21 cm and 2.6 mm) and FIR - gas distribution
- target photons (especially, mm and FIR)

important - all other wavelengths of cosmic EM emission

exciting - gravitational waves (if GRBs accelerate PeV particles) carriers of information about Cosmic Rays

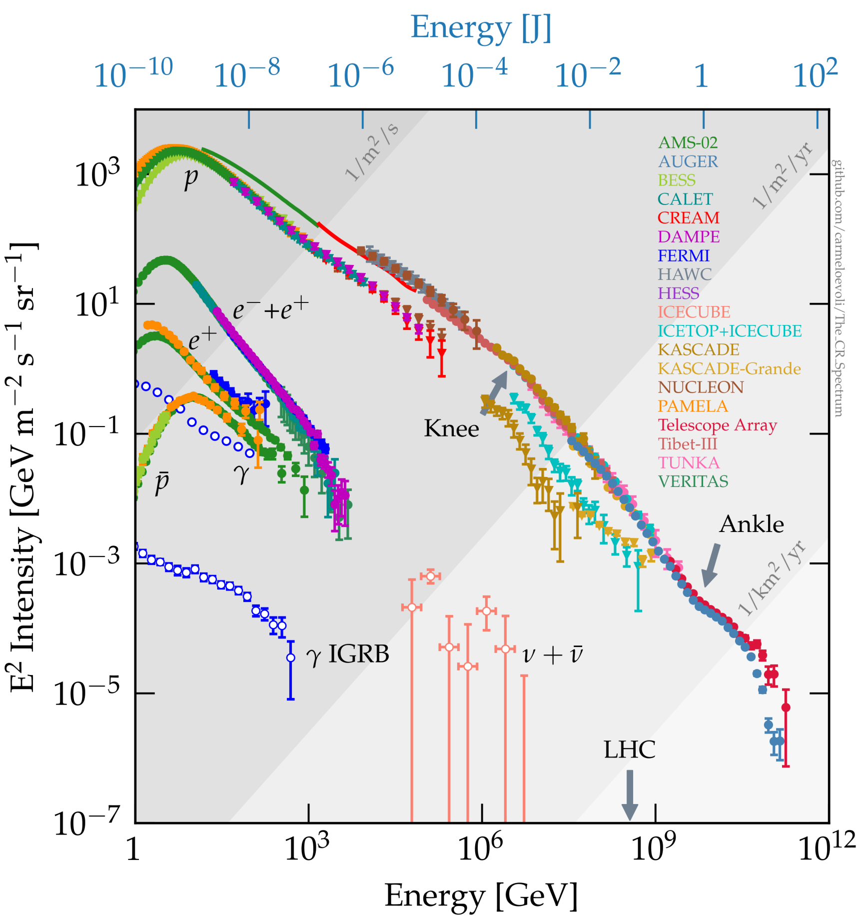
- ✓ *photons (radio, IR, O, UV, X-rays, gamma-rays)*
- ✓ *neutrinos*
- ✓ *cosmic rays*
- ✓ *gravitational waves* - a challenge

multi-wavelength and multi-messenger astronomy

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

PeVatrons and the Century-Old-Mystery

PeVatrons - sites of production of highest energy galactic CRs and contributors to the knee region of spectrum of locally measured CRs



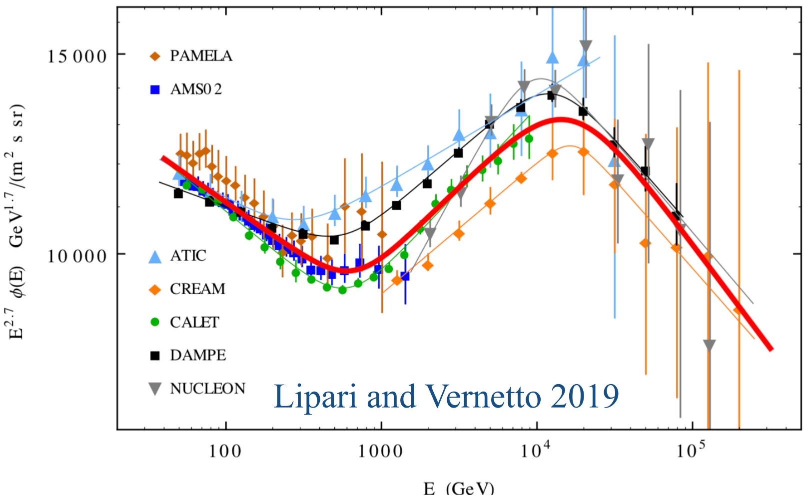
"mystery" perhaps is an exaggeration - we know a lot about CRs. But indeed the nature of CR sources accelerating particles out of 1 PeV is not established

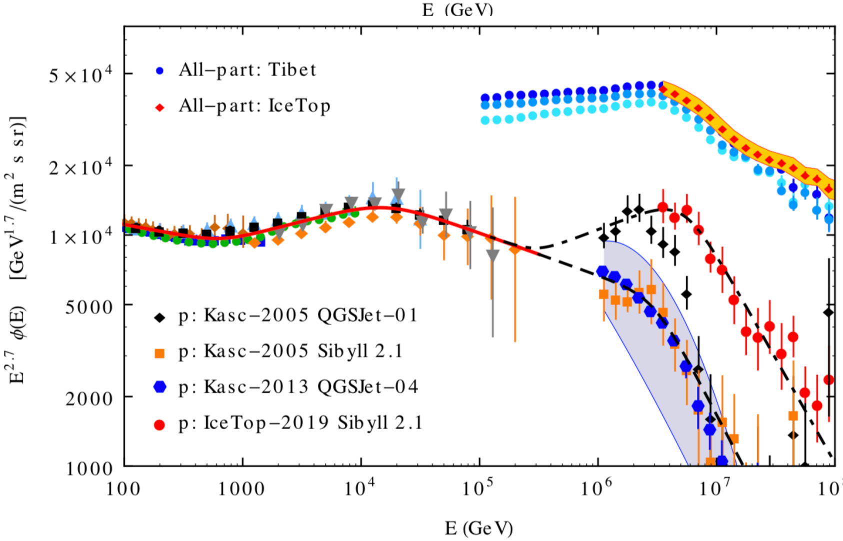
in our Galaxy, it is very difficult to produce particles up to 1PeV and beyond - only few type of 'stellar objects' can potentially accelerate particles to PeV energies.

Physics/Astrophysics of Galactic PeVatrons is a fast developing discipline in its own right

structures in HE GCR spectrum: contributions by two or more source populations?

CR proton spectrum





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 ?

do we need PeVatrons ?

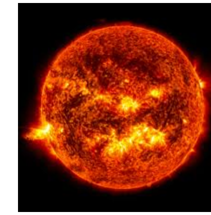
- **quasi-PeVatrons**
  up to 0.1 PeV and more

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

- **super-PeVatrons (of Galactic origin?)**
  >10 PeV up to 100 PeV

Relativistic Matter Factories

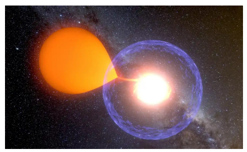
revealed by gamma-rays



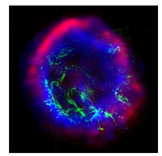
nonthermal processes in Universe proceed everywhere and on all astronomical scales:

G

Stars



Novae

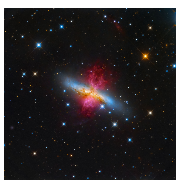


SNRs

Microquasars

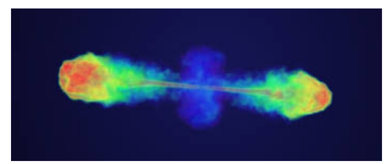
Neutron Stars*

EXG

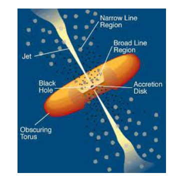


Galaxies

Galaxy Clusters

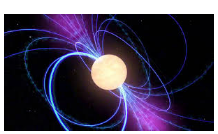


Large Scale Jets of AG

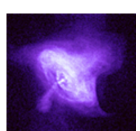


Blazars

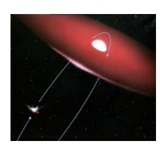
* accelerators associated with Neutron Stars



Pulsars



Pulsar Wind Nebula



Binary pulsars

(BNS mergers)

(short) GRBs

Gamma-ray sources at TeV and PeV energies

over the last two decades - discovery of hundreds of VHE (TeV) γ-ray sources
remarkable achievement of nonthermal astrophysics

=> Universe is full of TeVatrons

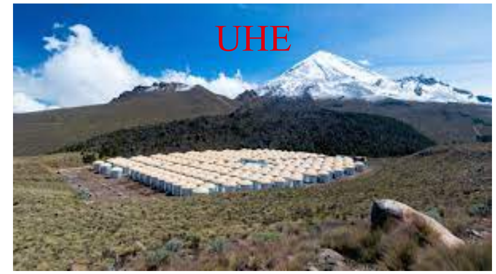
the surprise continues ...

over the last 1-2 years - discovery of many UHE (PeV) γ-ray sources

=> the Galaxy is full of PeVatrons

particles are accelerated in different environments and on all astronomical scales (almost everywhere!) at incredibly *high acceleration rates* and energy *conversion efficiencies* gamma-rays - carriers of information about cosmic accelerators

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



‘last window’ covers 10 decades: from 10^5 to 10^{15} eV

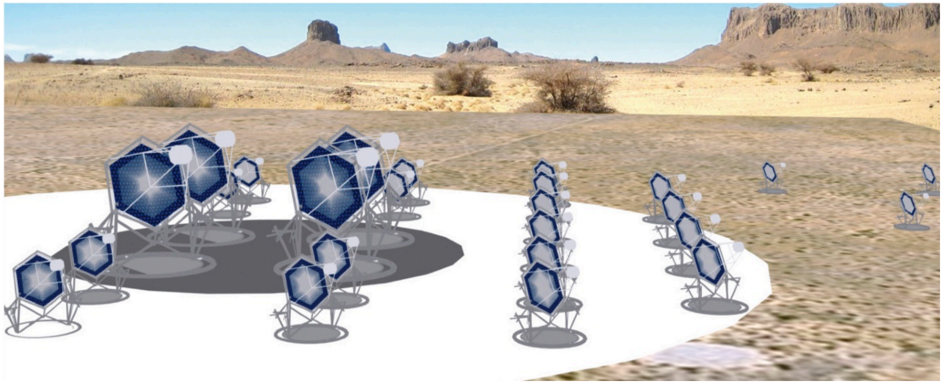
LE	or	MeV :	0.1 -100 MeV
HE	or	GeV :	0.1 -100 GeV
VHE	or	TeV :	0.1 -100 TeV
UHE	or	PeV :	0.1 -100 PeV

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

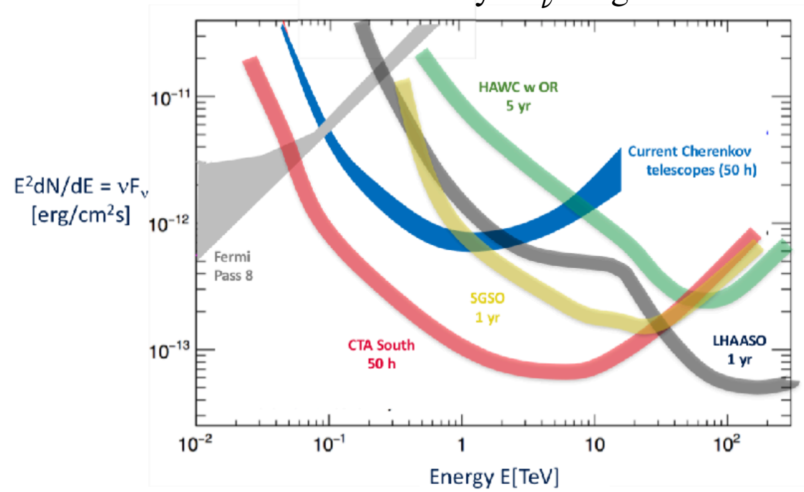
LE, HE — *domain of space-based astronomy*

VHE, UHE — *domain of ground-based astronomy*

CTA South

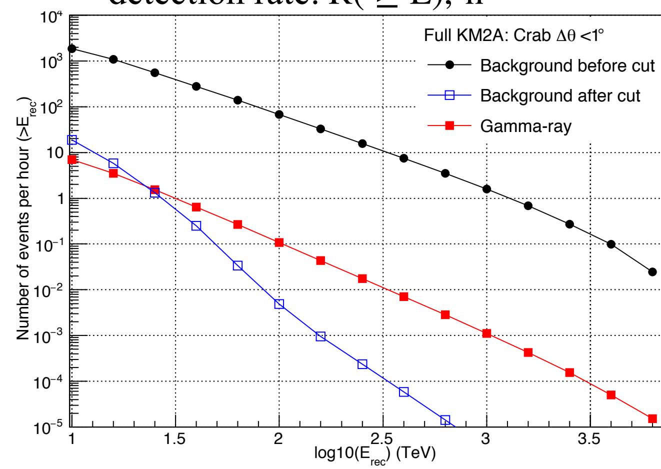


flux sensitivity νF_ν : erg/cm^{2}s

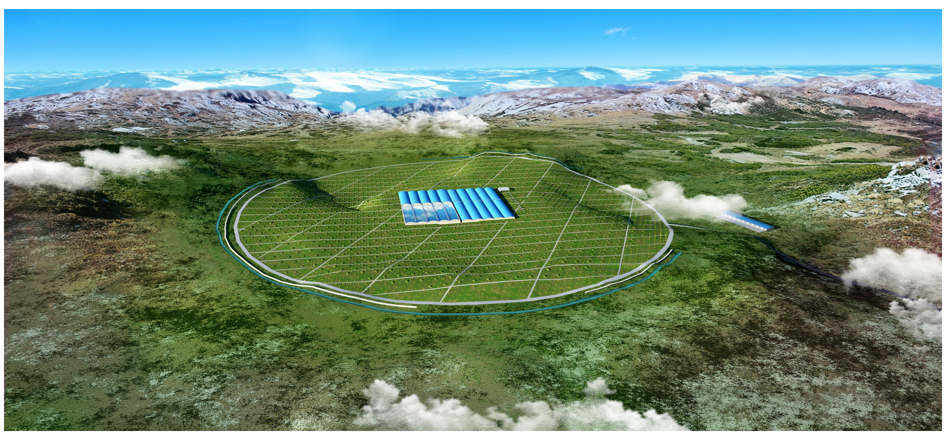


LHAASO: completed (July 2021)

detection rate: R($\geq$ E), h^{-1}



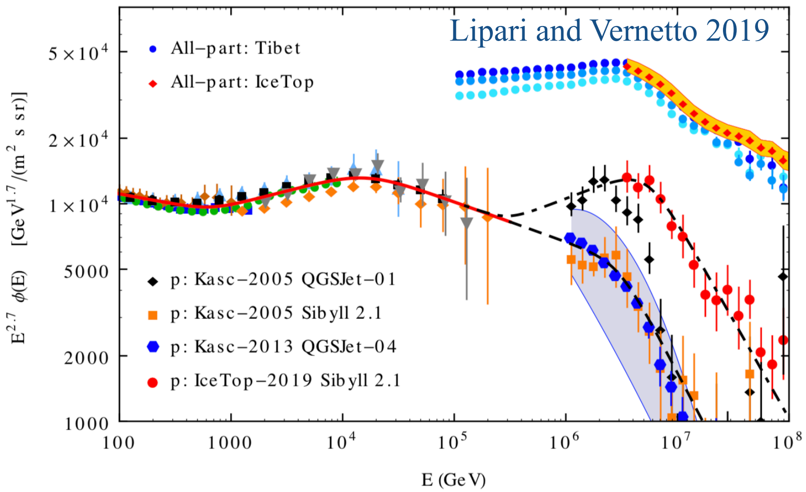
for PeVatron studies - **SST array** is the most relevant/crucial facility, LST and MSTs - are important for understanding of their nature



LHAASO-**KM2A** - ideal for hunting of PeVatrons

Southern Hemisphere - **CTA & SWGO** - very important for Galactic Center region

Northern Hemisphere - **LHAASO & ASTRI** - great results are anticipated in coming years



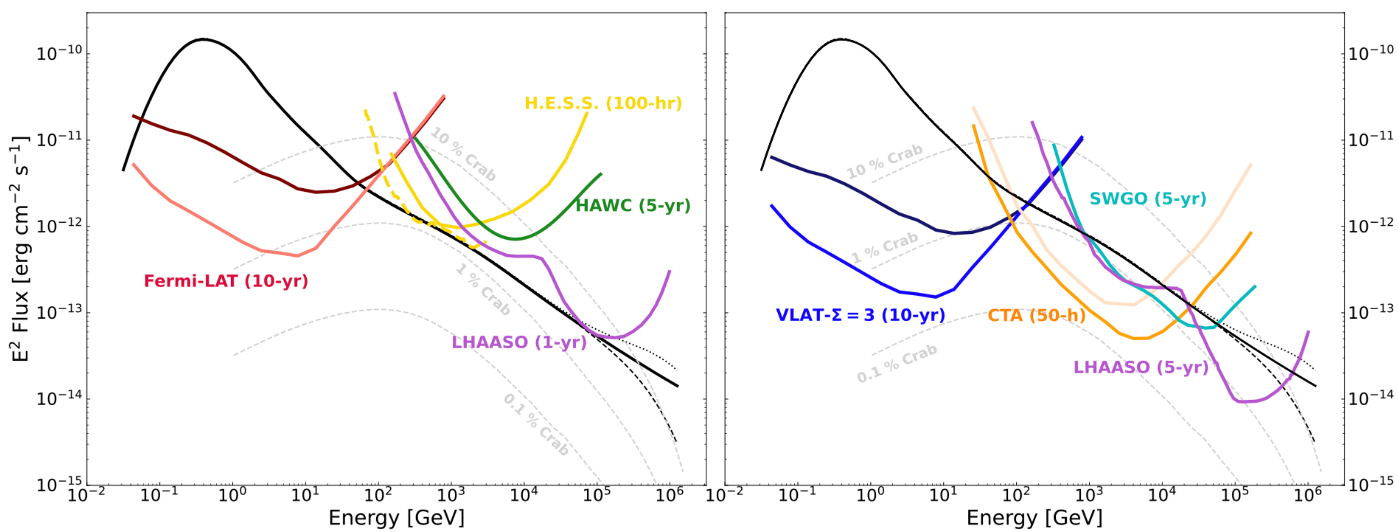
Probing CR density in the Galaxy

large uncertainty in CR spectrum and composition above 100 TeV

a solution - diffuse gamma-rays >10 TeV detectable by LHAASO provided that

$w_{GCR} \sim w_{local}$

probing CRs density in different parts of Galaxy using massive gas complexes



normalised to

$M_5/d_{kpc}^2 = 1$

$M = M/10^5 M_\odot$

$d_{kpc} = d/1\text{kpc}$

$w_{CR} = w_{local}$

Hunting PeVatrons: if $w_{CR} \geq 10 w_{local}$ - even modest ($M \sim 10^4 M_\odot$) clouds can reveal powerful (active or "dead") PeVatrons by detecting surrounding extended γ-ray structures

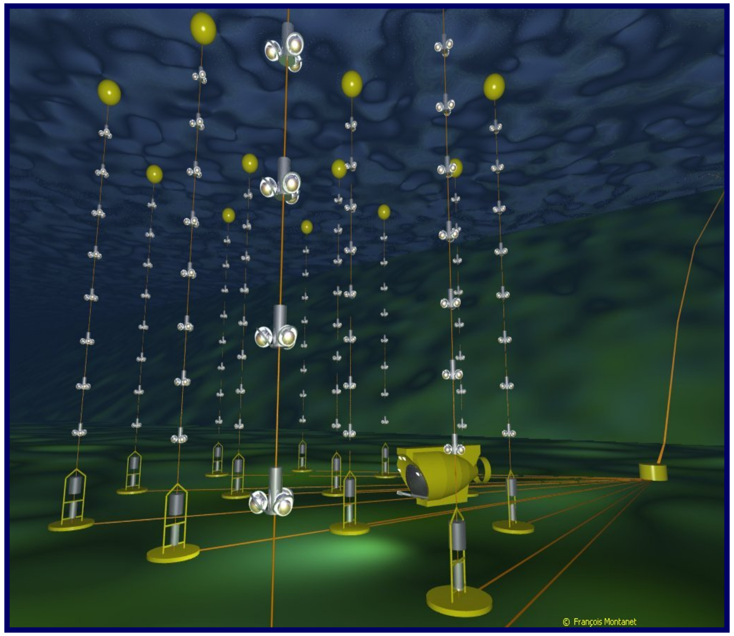
Neutrinos

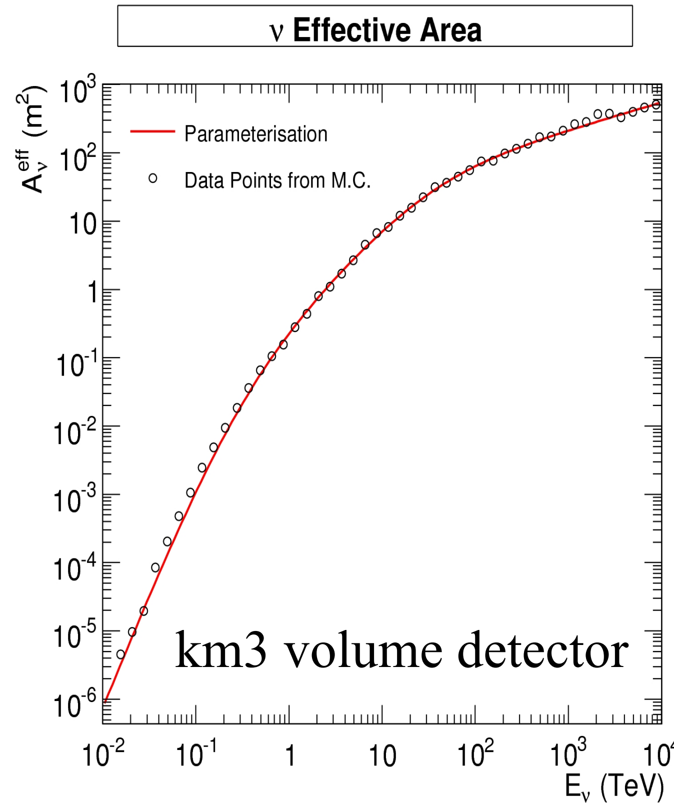
- unique for identification of the hadronic PeVatrons!
- can reveal "hidden" (not transparent for gamma-rays accelerators
- carry spectral information without distortion

unfortunately even huge "1km^3 volume" class detectors have limited performance

IceCube collaboration has reported detection of tens of TeV to PeV neutrinos but, except for 1-2 possible events, they are not (yet) associated with astronomical sources

neutrino telescopes





effective area: < $1m^2$ at 1 TeV

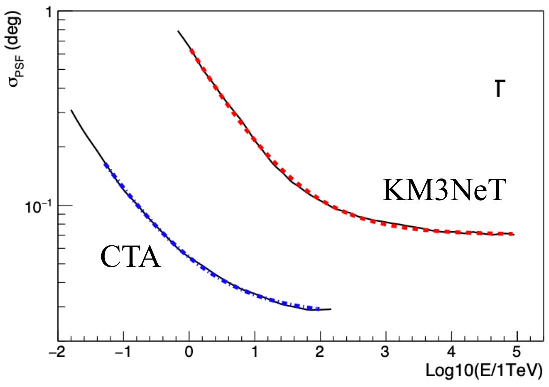
~ $10m^2$ at 10 TeV

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

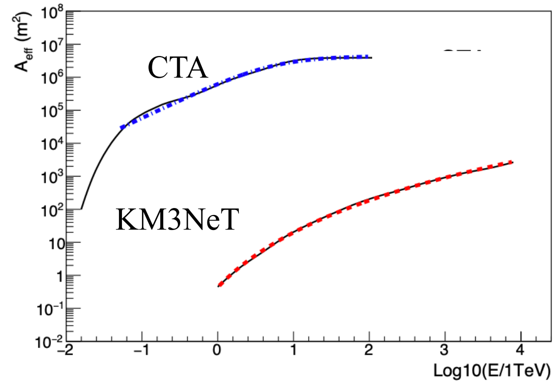
compare with detection areas of gamma-ray detectors:
Fermi - $1m^2$ but at GeV energies, ground-based >10^5 m^2 at same energies,
sounds quite pessimistic, however…

Performance CTA vs KM3NeT

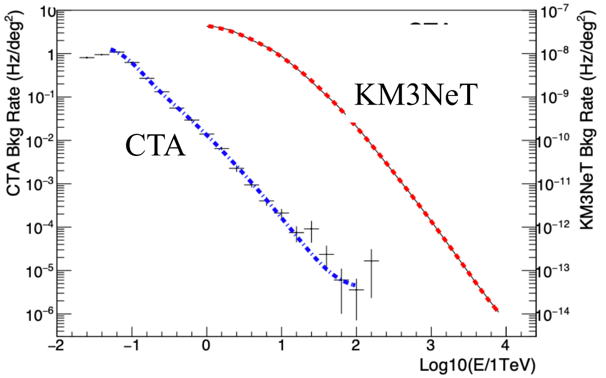
PSF



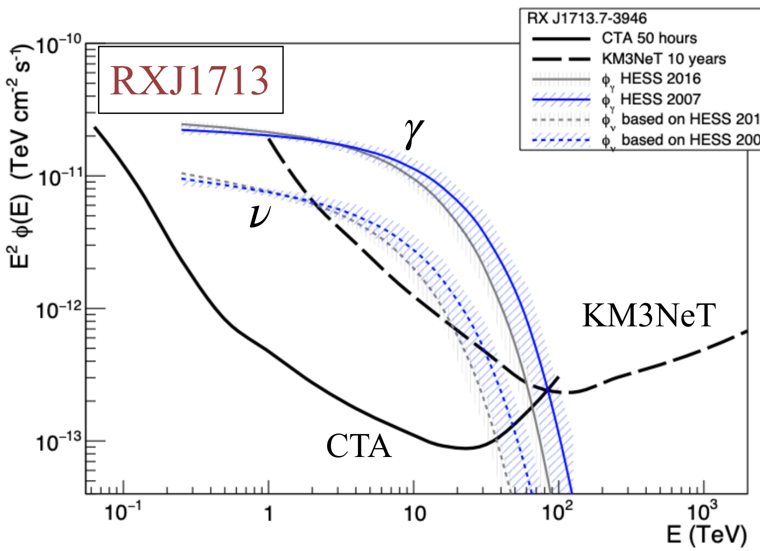
Detection Area

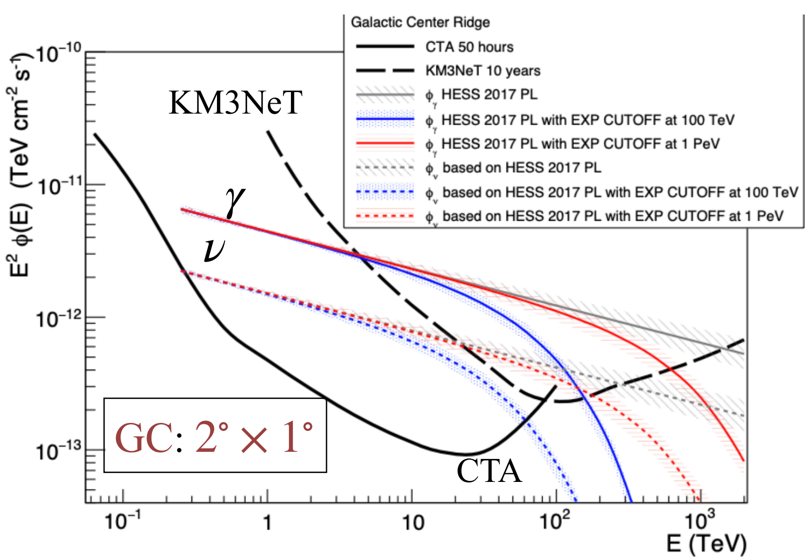


Background Rate



minimum detectable flux (sensitivity) - extended sources





Ambrogi, Celli, FA 2018

multi-TeV, PeV, EeV - gamma rays and neutrinos: direct carriers information about hadronic colliders

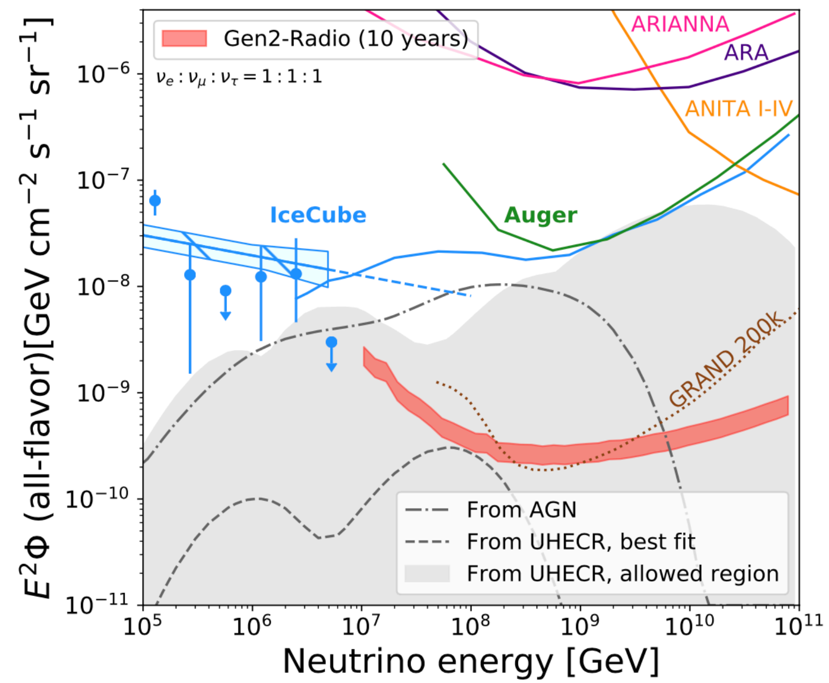
(multi) TeV γ-rays: effectively are detected by IACT arrays, => perfect morphology and spectrometry but the identification of the "hadronic" origin requires substantial efforts

> 0.1 PeV γ-rays: detected effectively by LHAASO-KM2A scale detectors;
modest performance for morphology (PSF ~ 0.2-0.3 deg);
good statistics above 0.1 PeV (100s detected photons)
limited but not-negligible statistics above 1 PeV (>10)

TeV/PeV/EeV neutrinos:

difficult to detect, but recent developments give optimism for detection of TeV-PeV and in future hopefully also multi-PeV neutrinos from PeVatrons and Super-PeVatrons

alternatives? - synchrotron X- and γ-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

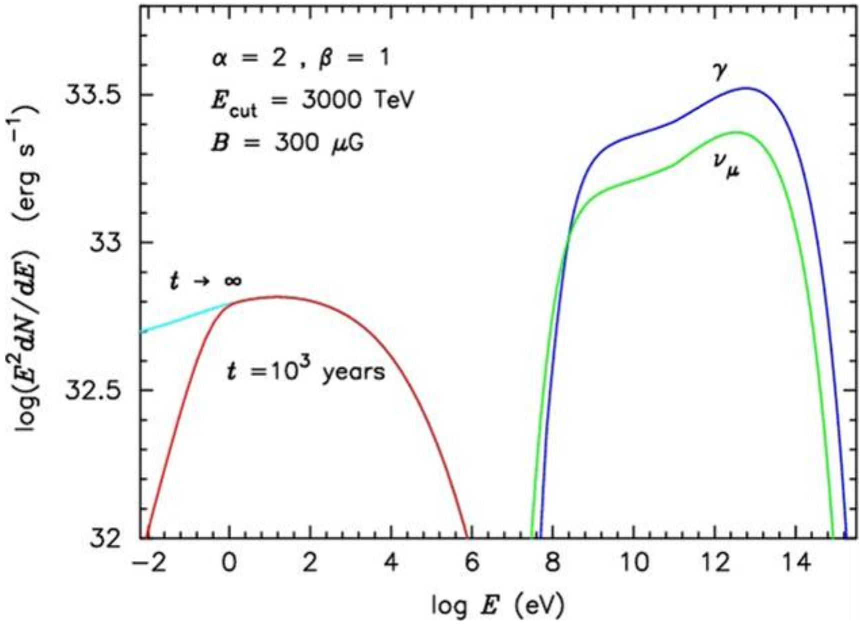
why hard X-rays/low energy gamma-rays?

- ✓ 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: $E \sim 10^{15}$ 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 - already demonstrated by IACTs and LHAASO
- neutrinos: marginally detectable by IceCube, Km3NeT - don't expect spectrometry, morphology, but unique - unambiguous signature of hadrons!
- "prompt" synchrotron X rays: $t_{synch} \approx 15(B/100\mu G)^{-3/2}(\epsilon/10\mathrm{keV})^{-1/2}$ yr

smooth spectrum in the cutoff region $\sim \varepsilon^{-(\alpha/2+1)} \exp[-(\varepsilon/\varepsilon_0)^{1/5}]$

very important channel - high quality morphology and spectrometry;
low background: thermal bremsstrahlung $h\nu_{max} \sim kT \leq 10$keV
synch. of primary electrons $h\nu_{max} \sim 1\,(v/3000\mathrm{km/s})^2$ keV

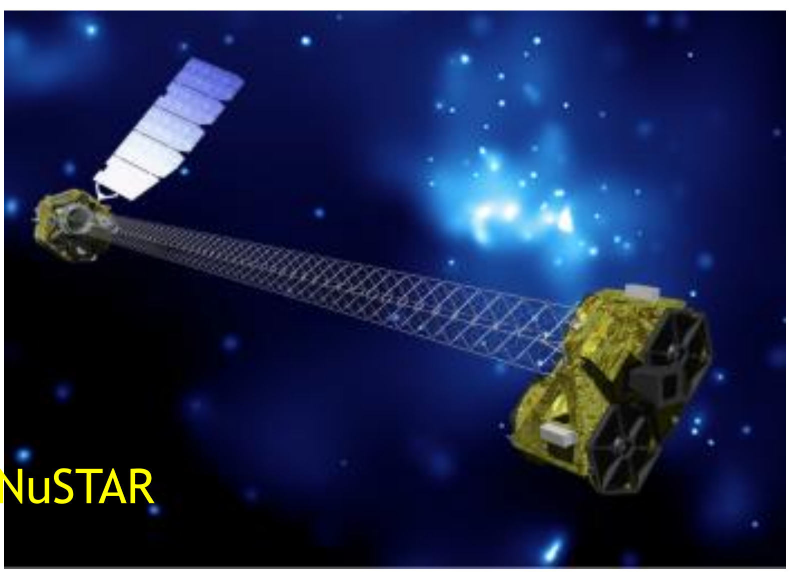
Probing hadrons with secondary hard X-rays

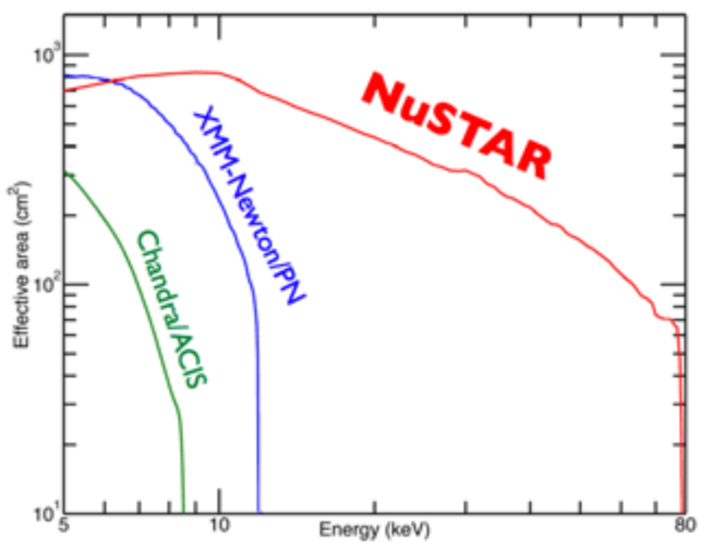
complementary to gamma-ray and neutrino telescopes

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 !

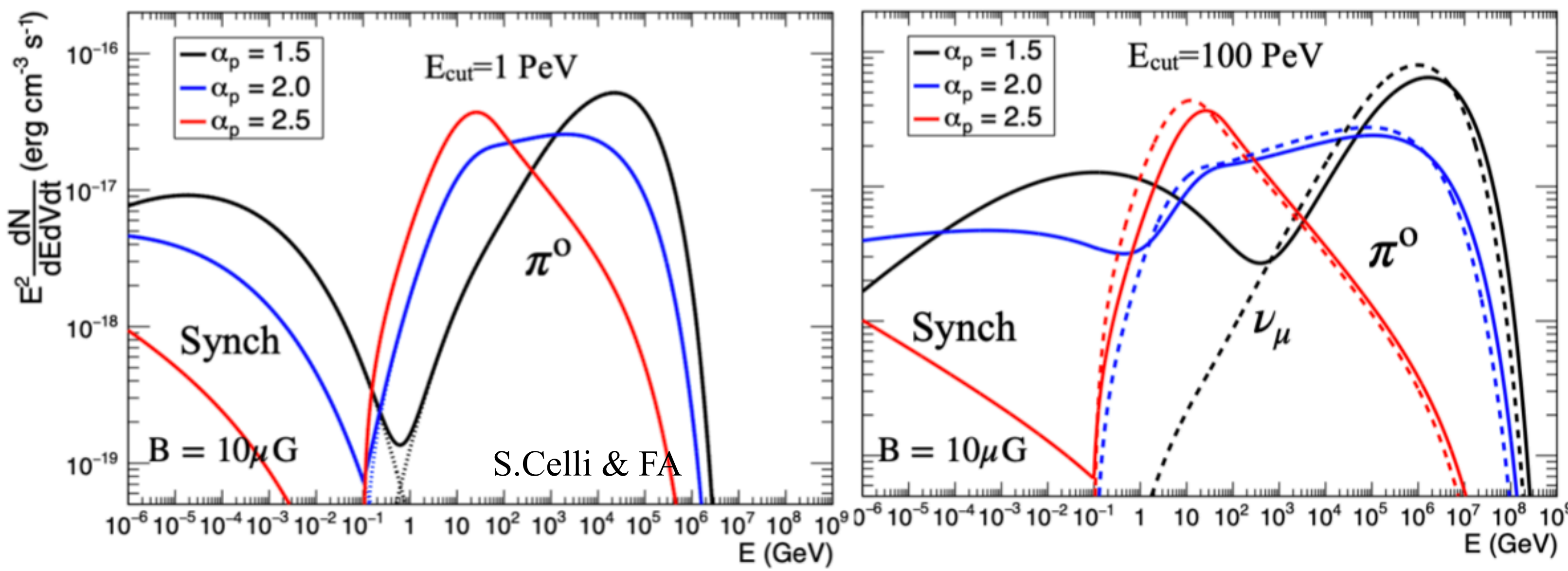




SuperPeVatrons: $E_{p,cut} \gg 1\,\mathrm{PeV}$

$pp \rightarrow \pi^{\pm} \rightarrow e^{\pm} + B \rightarrow \gamma \qquad \epsilon_{max} \simeq 2\,(B/10\mu G)(E/100\,\mathrm{PeV})^2\,\mathrm{GeV}$

radiation extends to GeV energies - searching for SuperPeVatrons with the next generation GeV gamma-ray and 2nd Generation multi-PeV neutrino detectors?



$dN/dE \propto E^{-\alpha_p} \exp - (E/E_{cut})$, $w_p(\geq 100\,\mathrm{GeV}) = 1\,\mathrm{erg/cm^3}$ $\quad n = 1\,\mathrm{cm^{-3}}$ $\quad B = 10\mu G$

$F(10\,\mathrm{keV})/F(100\,\mathrm{TeV}) \sim 0.1 - 1$; strongest LHAASO sources $F(100\,\mathrm{TeV}) \approx 10^{-12}\,\mathrm{erg/cm^2s}$

eROSITA can help to localise and identify extended LHAASO sources !

PeVatrons and "MeV to TeV" gamma-rays

Direct and <u>most relevant</u> messengers of PeVatrons are multi-TeV γ-rays: $E_\gamma \gg 10$TeV

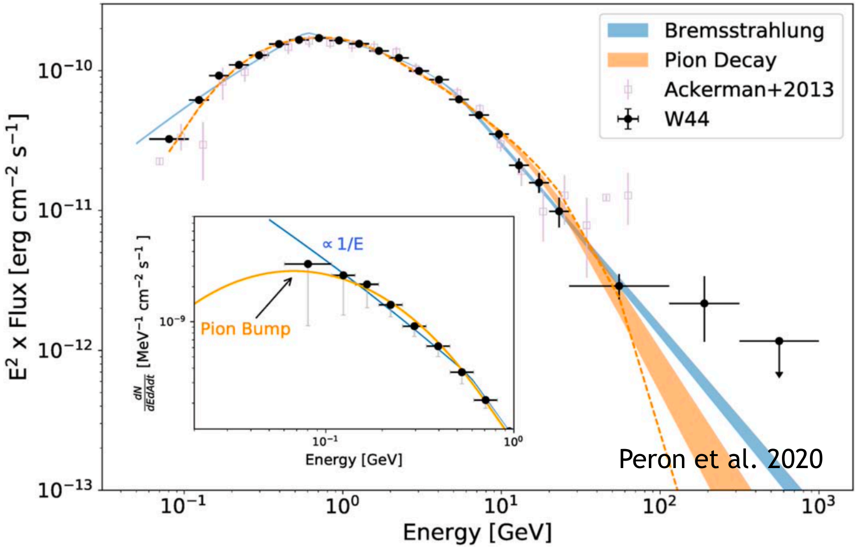
However, lower energy photons cannot be ignored when extracting information about the acceleration, propagation and radiation processes inside and outside accelerators

example:

'π^0 bump' - an indicator of hadronic origin of parent particles

a unique channel of information!

detection of the 'π^0 bump' from a mid-age SNR

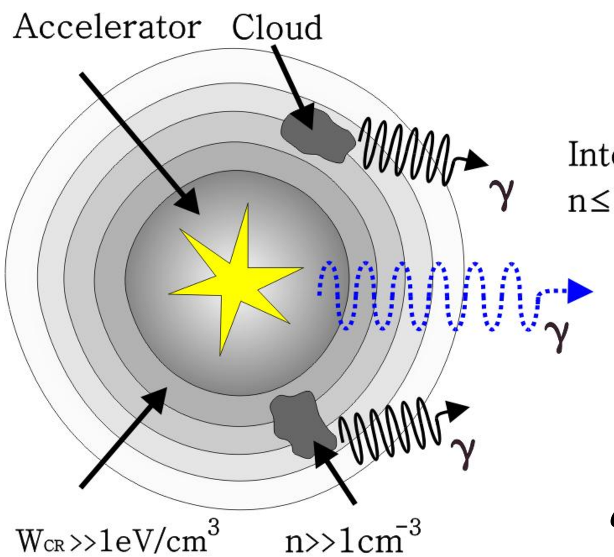


very important but it concerns only GeV protons - the conclusion cannot be extended to higher (E > 10 GeV) energy parent particles

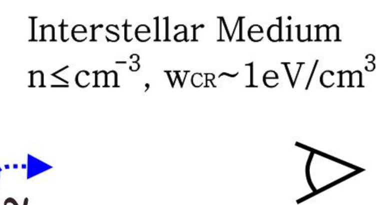
in PeVatron studies, low energy gamma-rays should not be ignored but they should not be overestimated either - it can lead to misleading conclusions

gamma-ray production: particle 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*



Giant Molecular Clouds as barometers of CRs

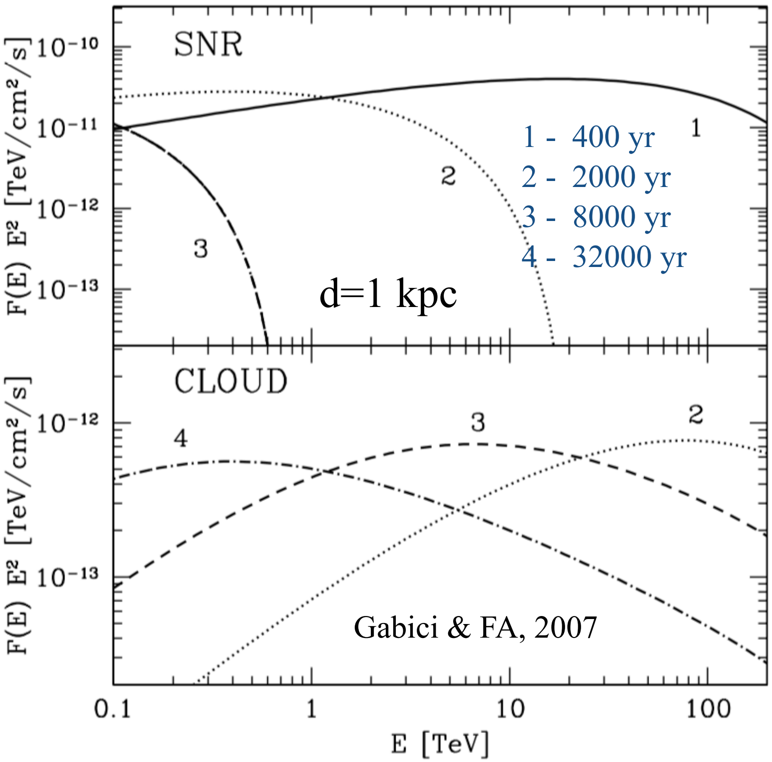
any gamma-ray emitter coincides with the target, but not necessarily with the "primary" source/particle-accelerator

"passive" GMCs - level of the sea of GCRs

"active" GMCs – nearby accelerators – history, escape, propagation, etc…

“smoking gun” from dense environments in <100 pc vicinities of mid-age SNRs

Time-evolution of gamma-radiation inside and outside of a SNR PeVatron



SNR: $W=10^{51}$ erg $n= 1$ cm^{-3}

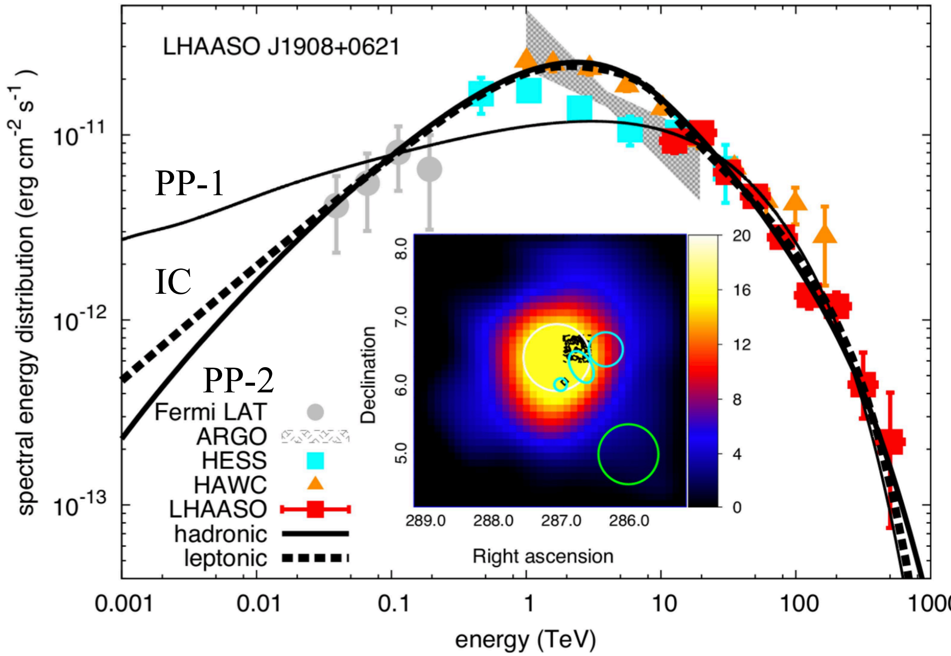
$f(p) \sim p^{-4}$ $p_{max}=5$ PeV

$p_{max} \sim t^{-2.4}$

Cloud: $R=100$ pc, $M=10^4 M_o$

$D(E)=3 \times 10^{29} (E/1PeV)^{0.5}$ cm^2/s

SNR G40.5-0.5 + GMC ?



— PP-1: $dN/dE \propto E^{-1.85} \exp[-(E/380TeV)]$

— PP-2: $dN/dE \propto E^{-1.2}$ $E \leq 25TeV$;

$\propto E^{-2.7} \exp[-(E/1.3PeV)]$ above 25 TeV

Galactic PeVatrons:

status and expectations for the near future

(brief overeview)

Status:

- SNRs

After decades of recognition as the major CR production sites, SNRs are still considered the primary sources of Galactic CRs, but we are less confident about their contribution to the *knee* (PeV) region. The deep γ-ray probes of SNRs by LHAASO will provide a decisive verdict on their ability to perform as PeVatrons.

alternative CR PeVatrons?

- Massive stellar clusters and related superbubbles
  - stellar winds - several 1000 km/s - comparable to young SNR shocks
  - 10^{41} erg/s only a factor of 2 less than the mechanical power of SN

- Galactic Center

Supermassive Black Hole (Sgr A*), M~ 5 x 10^6 solar masses can formally provide a power as large as 10^{43} erg/s (assuming 10 % acceleration efficiency)

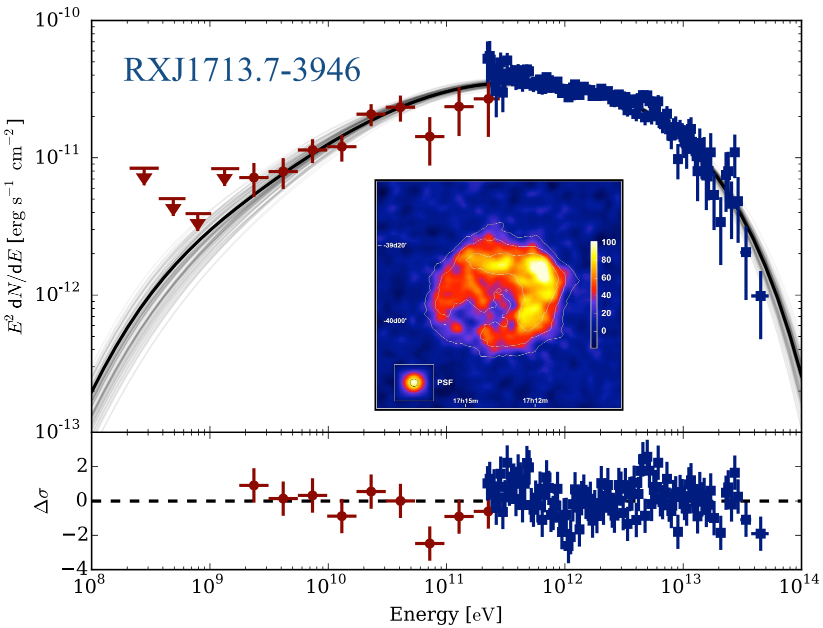
- Pulsars/Pulsar Wind Nebulae

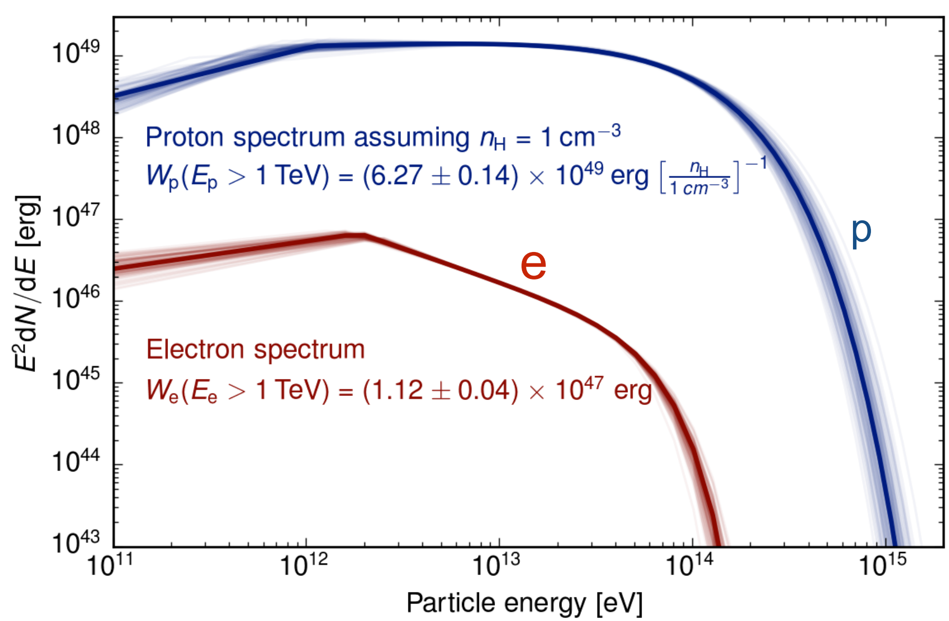
prolific accelerators of electrons/positrons; potential contributors to PeV protons

SNRs historically recognized/proposed/claimed to be
major contributors to Galactic Cosmic Rays

detection of TeV γ-rays from more than a dozen of young SNRs - great achievement and support of the SNR paradigm of Galactic CRs, but yet no evidence that they operate as hadronic PeVatrons - break or a cutoff at energies below 10 TeV

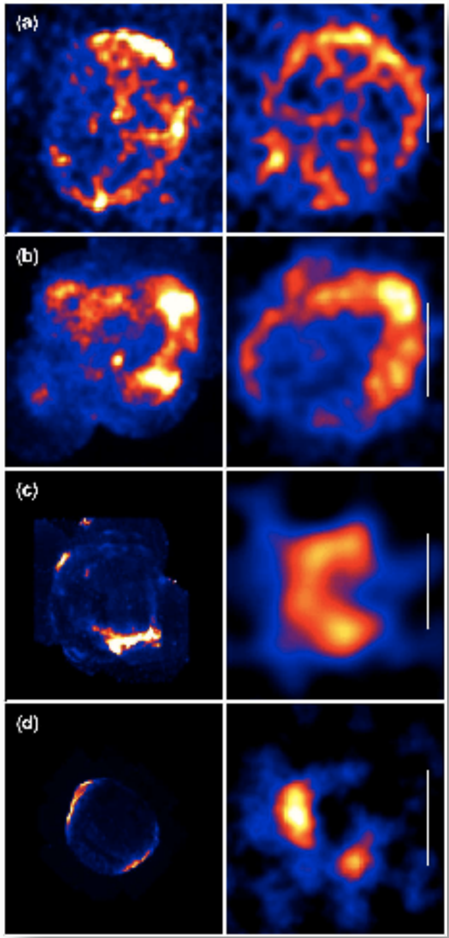
Fermi+HESS measurements → electron and proton spectra



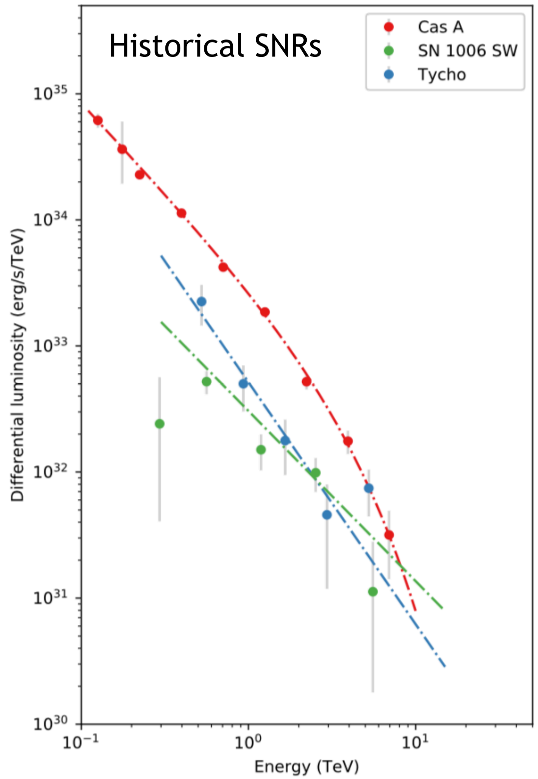


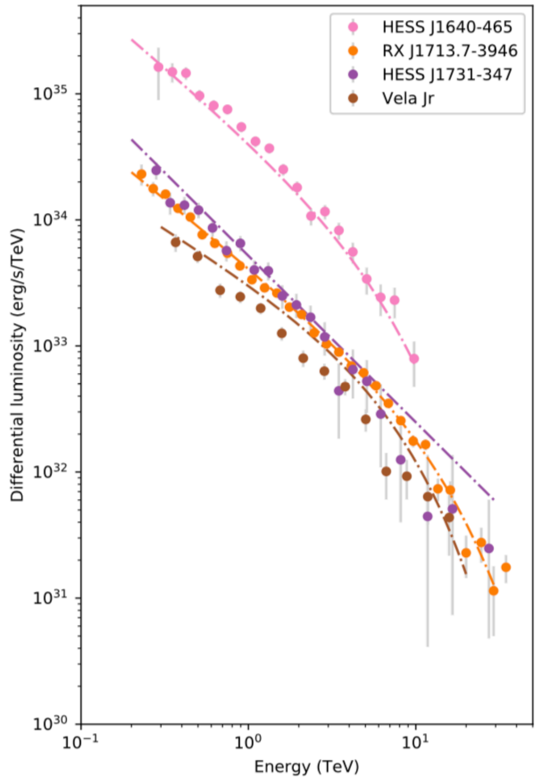
cutoff or break in the proton spectrum at 100 TeV ?

spectra of young SNRs above 1 TeV - steep with Γ= 2.3-2.6



TeV photons from from >10 young SNRs: support SNR paradigm of galactic CRs, but it is not yet clear whether SNRs can provide the CR flux up to the *knee* (~1 PeV)





steep spectra or 'early' cutoffs ? The studies should be extended to 100

LHAASO (and CTA ?) is able to answer to this question

slope or intrinsic power-low index?

formally the γ-ray spectra
can be presented in the form: $dN/dE \propto E^{-\Gamma} \exp[-(E/E_0)^{\beta}]$

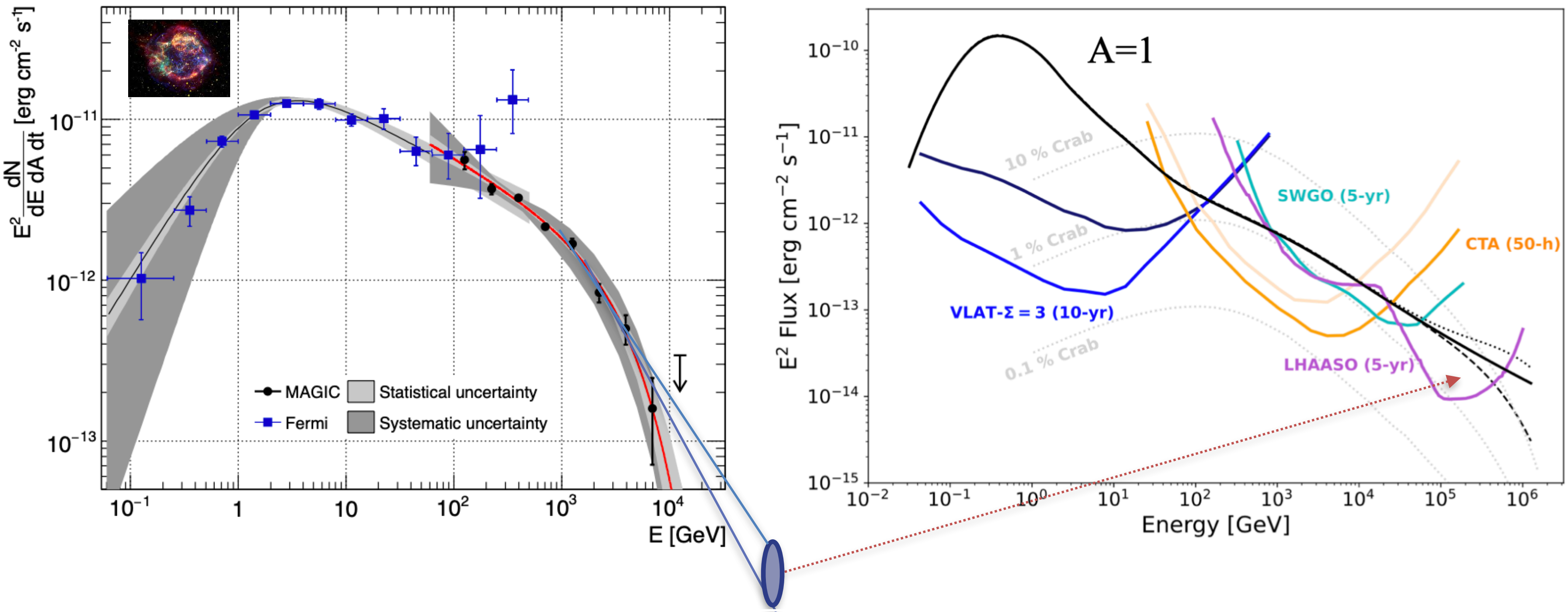
with reasonable combination of E_0 and β, $\Gamma=2$ could be an option

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

Cas A, a benchmark SNR-PeVatron candidate?



$dN/dE \propto E^{-3} \rightarrow F_E \sim 10^{-14}$ erg/cm^{2}s at $E_\gamma \sim 100$ TeV at the margin of sensitivity of LHAASO

no detection - acceleration at very early epochs (< 10 yr) because CRs already left the remnant ?

even moving ballistically R~100 pc (angular size $\sim 2^0$) but the γ-ray image would be a point like;

for "slow diffusion" R < 10 pc, angular size comparable with PSF of LHAASO

=> LHAASO upper limit (or detection) of 100 TeV γ-rays - at the level of 10^{-14} erg/cm^{2}s

decisive "PeVatron test" independent of the acceleration epoch

Stellar Clusters as factories of Galactic Cosmic Rays up to 1 PeV ?

Cesarsky and Montmerle 1983; A. Bykov - since 1990s, R. Lingenfelter - since 2000s
recent reviews: R. Lingenfelter 2018, A. Bykov et al 2020, T. Vieu 2021 (PhD thesis)

massive stars produced at the collapse of GMCs form compact groups consisting of tens of massive (O, WR type) stars and remain linked during their life (1-10 Myr)

SWs and SN explosions => *superbubbles* filled with turbulent plasma shocks
=> particle acceleration by interacting SWs, termination shocks in the vicinity of stars or in superbubbles

collective power in stellar winds 10^{38} - 10^{39} erg/s; speeds 3×10^3 km/s

at PeV energies - conditions can be more favourable than in individual SNRs

other motivations:

- ^{22}Ne/^{20}Ne ratio
- gamma-rays from a number of YMCs from GeV to TeV (and PeV ?)

Stellar Clusters operate as PeVatrons ?

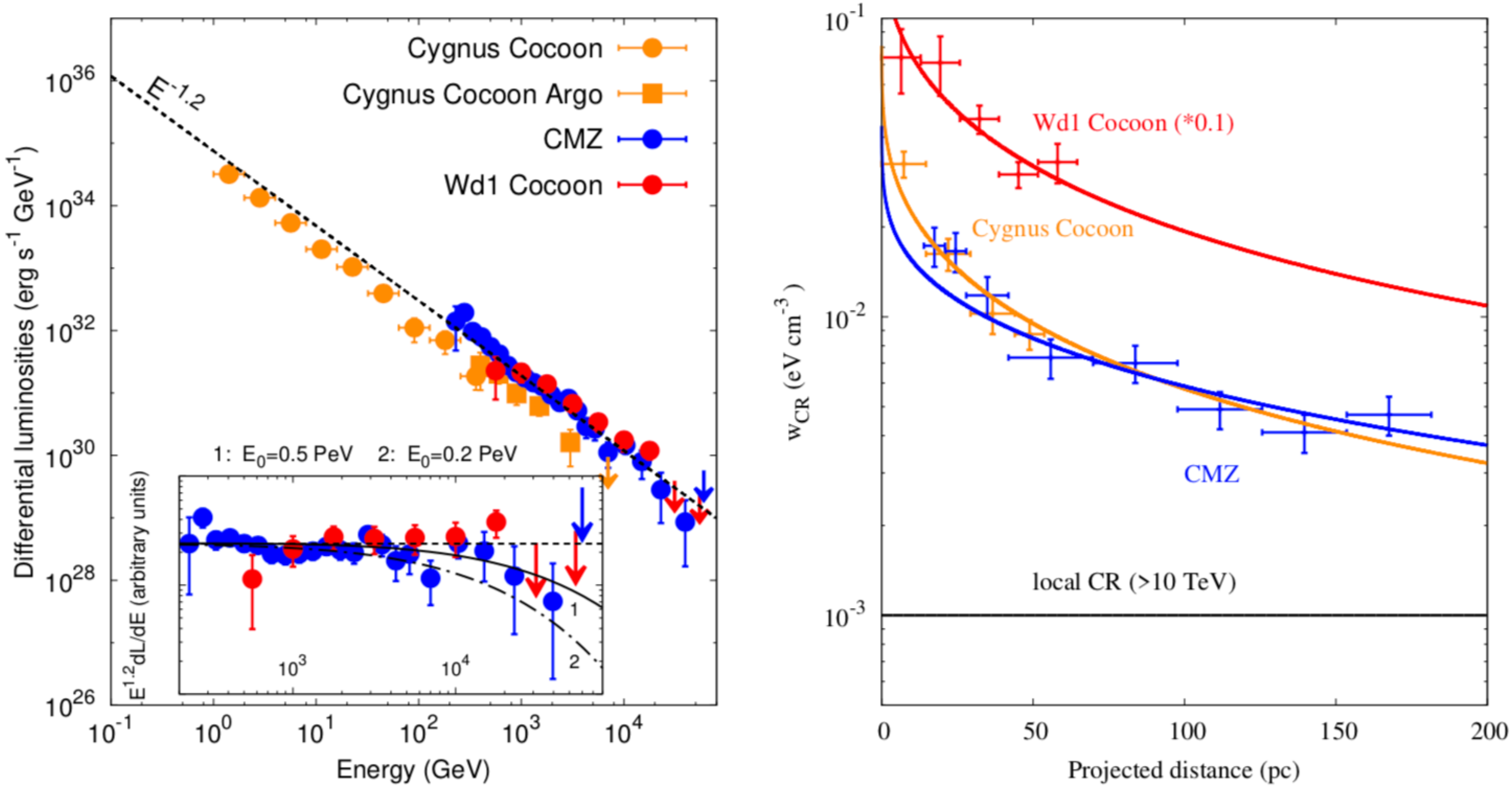


Figure 1: Gamma-ray luminosities and CR proton radial distributions in extended regions around the star clusters Cyg OB2 (Cygnus Cocoon) and Westerlund 1 (Wd 1 Cocoon), as well as in the Central Molecular Zone (CMZ) of the Galactic Centre assuming that CMZ is powered by CRs accelerated in *Arches*, *Quintuplet*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

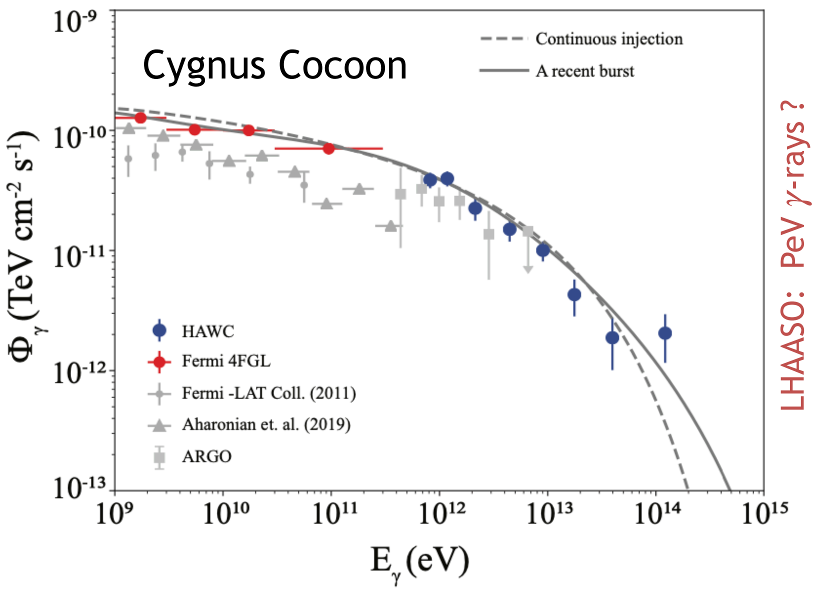
FA, Yang, Ona de Wilhelmi, 2018

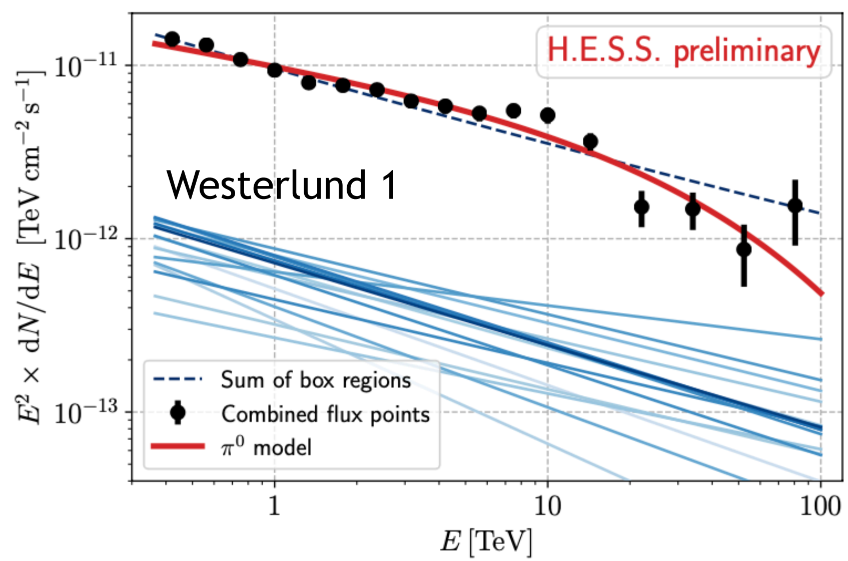
Extended Regions surrounding Clusters of Young Massive Stars
are sources of GeV, TeV and … PeV gamma-rays !

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

CygnusOB2, *W43*, *NGC3603*

Arches, *Quintuplet* and *Nuclear* ultracompact clusters





Origin of TeV/PeV γ-rays ? hadronic! (?)

IC (almost) excluded - only PWNe can accelerate electrons >> 100 TeV - γ-ray morphology

Detection is possible only if >100 TeV CRs propagate much slower than in the ISM

Total energy in CRs within the size of radius Ro

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

Size of emission region - depends on D and To

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

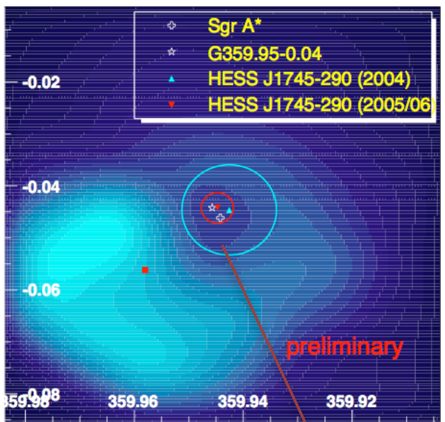
Efficiency of conversion of the wind kinetic energy to CRs

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

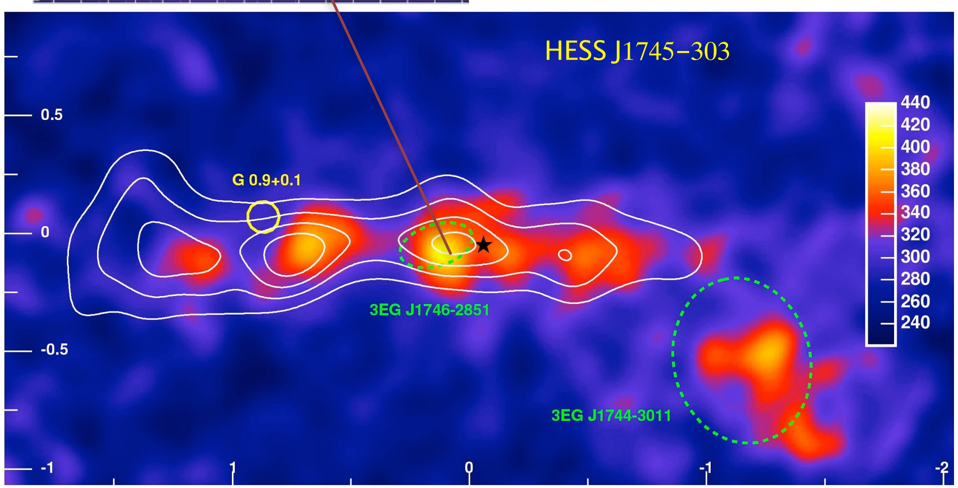
For $E^{-2.3}$ proton spectrum, f(>10TeV) does not significantly exceed 1%
the diffusion coefficient D_{30} cannot be larger than 0.01; $R_D \sim 300$ pc

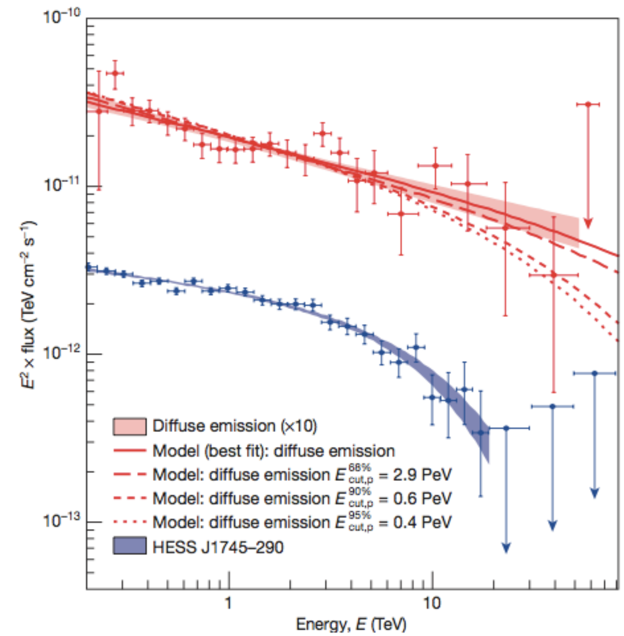
CTA - unique measurements of D and consequently f

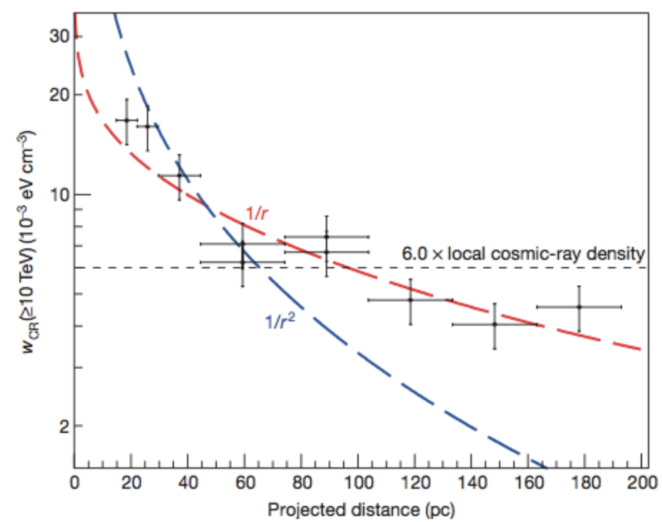
PeVatron(s) in the Galactic Center!



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 ?

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

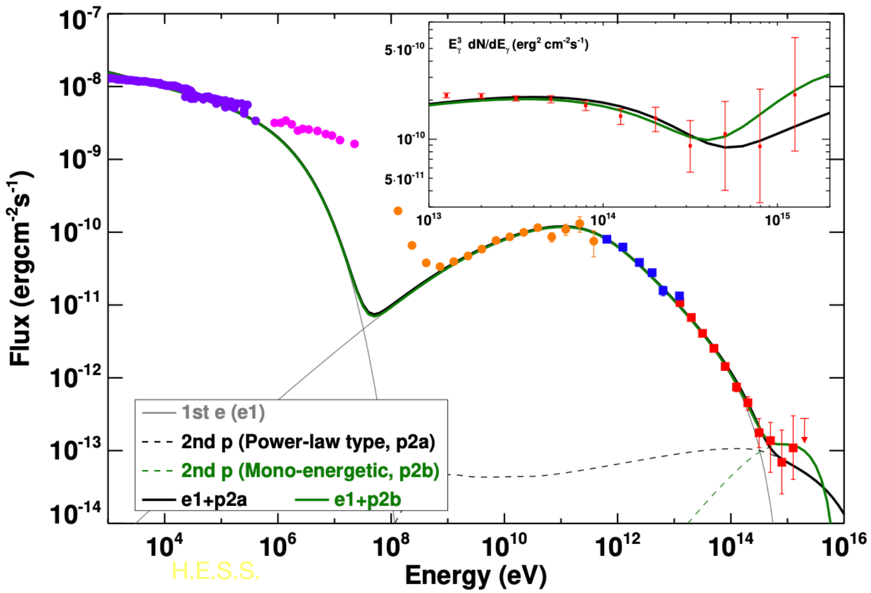
- escape of particles into the Galactic halo and their subsequent interactions with the surrounding gas, can be responsible for the sub-PeV neutrinos recently reported by the IceCube collaboration

SMBH or young massive-star clusters?

Detection of > 1 PeV photons from Crab by LHAASO

mechanism: Inverse Compton on 2.7 K CMBR: direct relation $E_e \simeq 2.15(E_\gamma/1\,\mathrm{PeV})^{0.77}$ PeV

$E_\gamma = 1.1\,\mathrm{PeV} \rightarrow E_e \simeq 2.5\,\mathrm{PeV}$



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

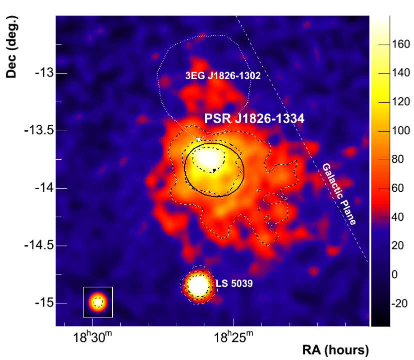
$\eta = 0.14(B/100\mu G)(E_\gamma/1\,\mathrm{PeV})^{1.54}$

$E_\gamma \geq 1.1\,\mathrm{PeV} \rightarrow \eta \geq 0.16$

for comparison, in SNRs: $\eta \sim 10^{-4}$

Crab: pulsar/wind/nebula: Extreme Accelerator
- conversion of the rotational energy of pulsar to non-thermal energy with efficiency ~50 %
- acceleration rate close to maxim possible

or PeV gamma-rays of hadronic origin?



Crab Nebula: **effective electron accelerator** but **not effective γ-ray emitter**:

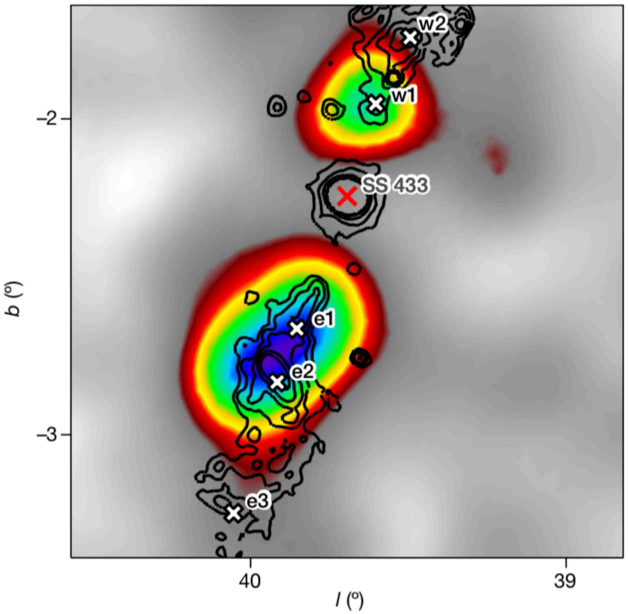
γ-ray efficiency: $\kappa = t_{Sy}/t_{IC} \approx 1(B/3\mu G)^{-2}$; because of $B \simeq 100\,\mu G$, $\kappa \sim 10^{-3}$

"standard" PWNe ($B \sim$ a few μG) are **effective accelerators/effective emitters** :

large $\kappa \sim 1$ in most of PWNe compensates smaller pulsars' spin-down luminosities

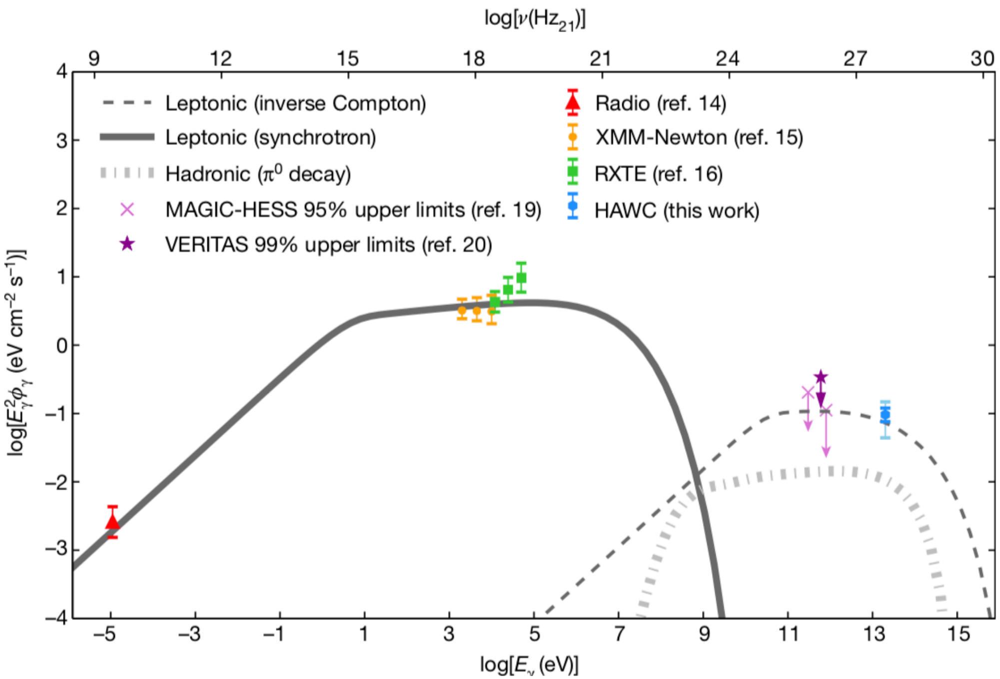
Pulsars/PWNe - sources of hadronic CRs

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?

Summary:

Over the last two decades, we have seen two revolutions in γ-ray astronomy with exciting discoveries of thousands (GeV) and hundreds (TeV) sources. Presently we are witnessing a new revolution - this time at PeV energies.

LHAASO (on-going) observations, combined with the current IACT arrays (HESS, MAGIC, VERITAS) and especially with forthcoming ASTRI array, in NH and later SWGO & CTA in SH promise breakthrough in the identification of PeVatrons contributing to the Galactic Cosmic Rays in the "knee" region.

Multi-TeV/PeV neutrinos are crucial for the firm identification of hadronic PeVatrons. Synchrotron radiation of secondary ('pp') electrons provide complementary information (with better sensitivity and angular resolution!).

Next Step - hunting Super-PeVatrons with multi-PeV (EeV) neutrinos and photons (and neutrons) as well as GeV-TeV γ-rays of secondary ('pp') electrons ?