UHE domain of gamma-ray astronomy:
specifics and major objectives

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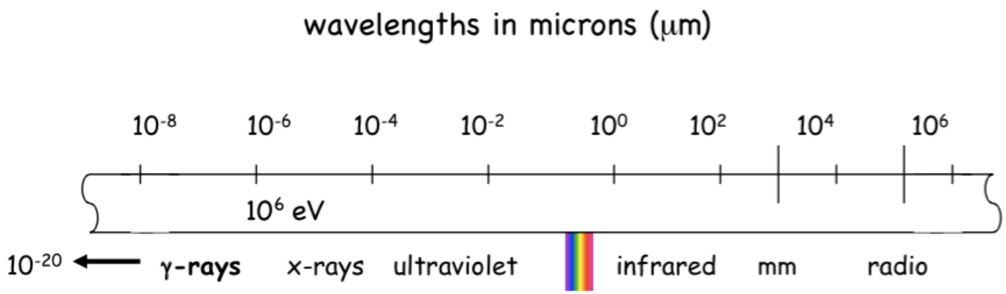
Neutrinos and Cosmic Rays in the Multi-Messenger Era, Dec 7-10, 2020

Gamma-rays: ‘the last window’ in the cosmic EM spectrum

UHE (PeV) gamma-rays: “last (?) window in the last window”



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

…

window is opened in MeV, GeV, TeV
we are at the threshold of PeV band

MeV-GeV-TeV-PeV Gamma Ray Astronomy

TeV gamma-ray astronomy - *a success story*

over last 2 decades the field has bee revolutionized

before "astronomy" with several sources
(a part of Cosmic Ray studies rather than Astronomy)

now truly astronomical discipline with characteristic key words:
SEDs, sky maps, lightcurves, surveys…

$>$ 250 G & EXG sources and $>$ 10 source populations

two well established detection techniques in the energy interval
between 0.1 TeV to 100 TeV

- IACT arrays HESS/VERITAS/Magic
- Particle arrays HAWK/ARGO/Tibet

major factors of the success?

several factors… but basically thanks to the combination of two:

- great potential of the detection technique (gamma/hadron separation)
  predicted … although with significant delay

- effective acceleration of multi-TeV particles on all astronomical scales coupled with favourable conditions for production of gamma-rays

  predicted…but the detection of >250 galactic and extragalactic sources representing more than 10 source populations was a big surprise

analogy with therm al X-rays:

as cosmic thermal plasmas are easily heated to keV temperatures: *almost everywhere*
electrons/protons can be easily accelerated to TeV energies: *almost everywhere!*

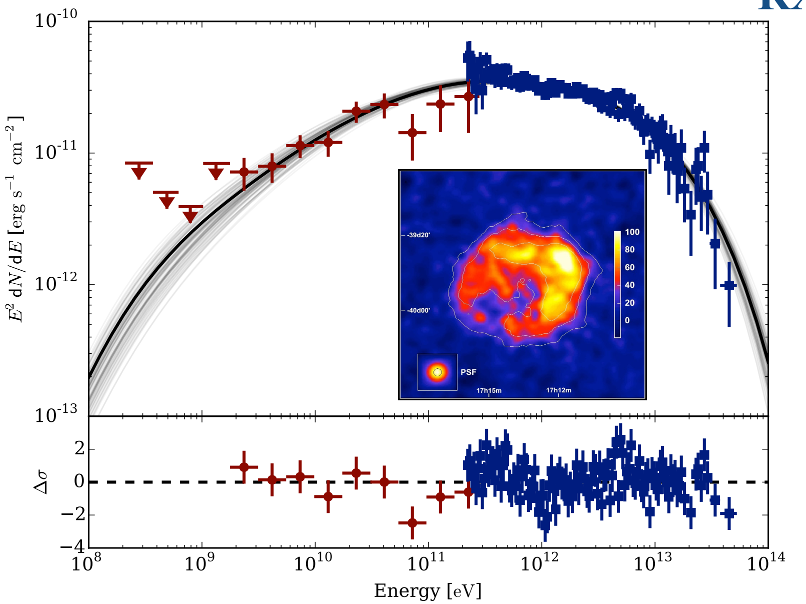
spectrometry - morphology

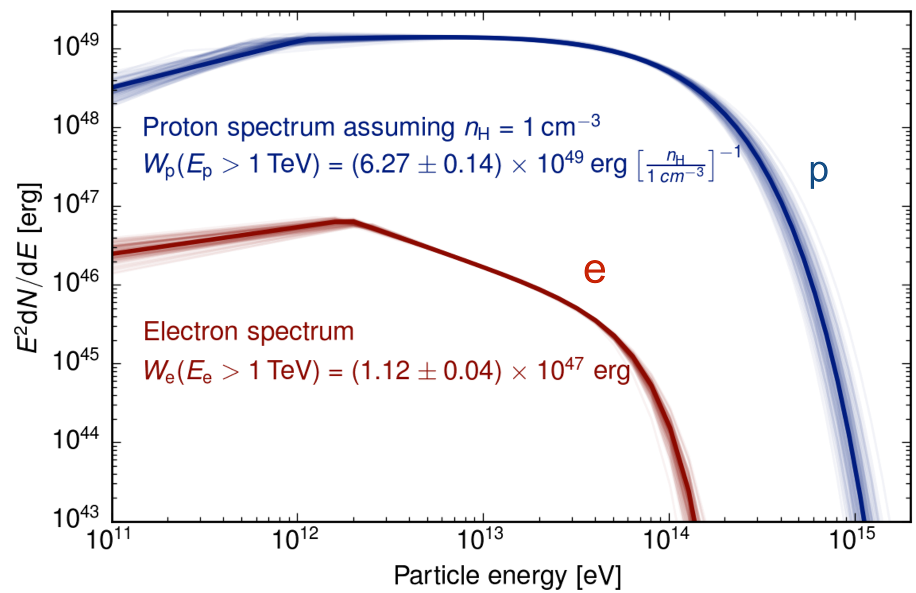
Probing the distributions of accelerated particles in SNRs

HESS measurements

RXJ 1713

derived spectra of e and p





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

should we expect similar success in UHE domain? Conditions:

- **detection technique ?** (1) ~10 km^2 arrays of multi-TeV (small) IACTs

  (2) LHAASO

- **UHE sources ?**

  acceleration of electrons and protons to PeV energies

  - not trivial but possible for galactic sources
  - easier for extragalactic objects but limited by the local Universe

  effective gamma-ray production?

  not trivial - fast escape of PeV particles, $t_{esc} \sim l/c << t_{cool}$

- **currently** a few candidates Crab, J1825, J1908 (Tibet, HAWK)

great expectations from LHAASO - stay tuned!

should we expect similar success in UHE domain?

detection technique:
same methods as in VHE band but dramatically increased detection areas

(1) IACT arrays

from observations of HESS/VERITAS/MAGIC >10 times larger collection area is needed; on the other hand energy threshold is not a critical issue

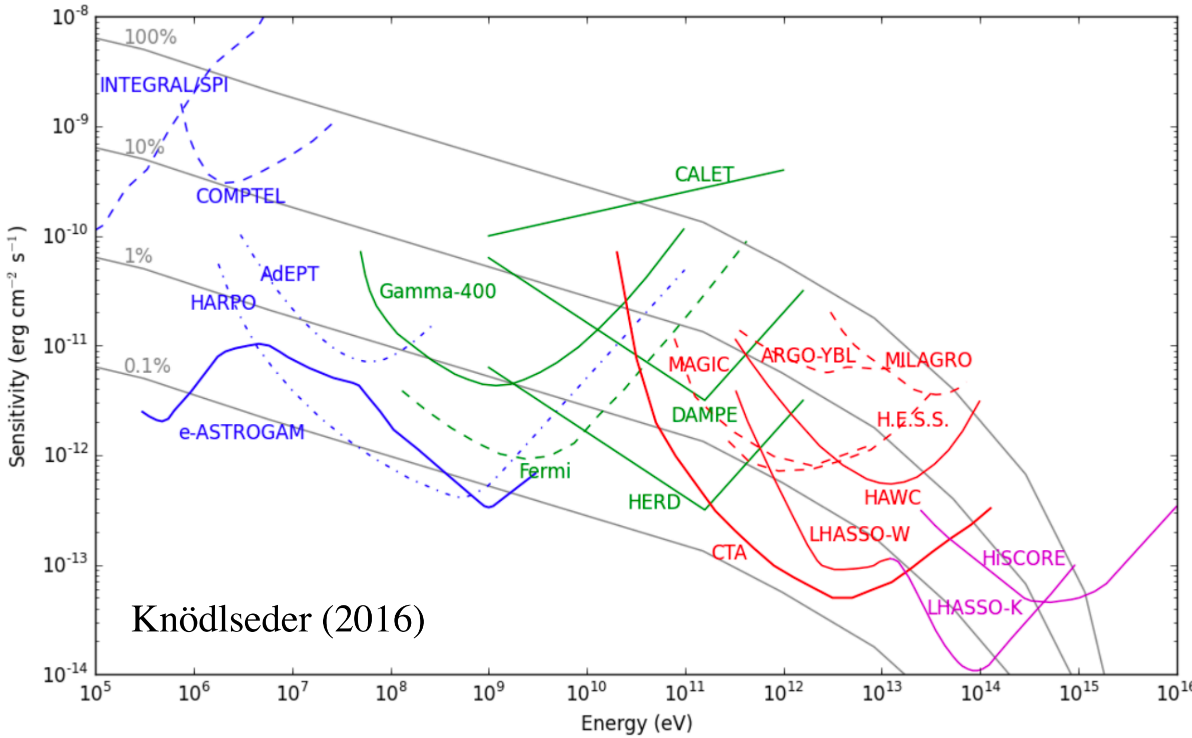
CT South; dedicated multi-TeV IACT arrays in both Hemispheres?

(2) LHAASO, SWGO, HiSCORE

LHAASO is almost completed !

jump from the 1st generation (Tibet, HAWK) to 3rd generation

TAIGA-HiSCORE - multi-PeV detector



LHAASO - most sensitive gamma-ray detector in the entire gamma-ray domain

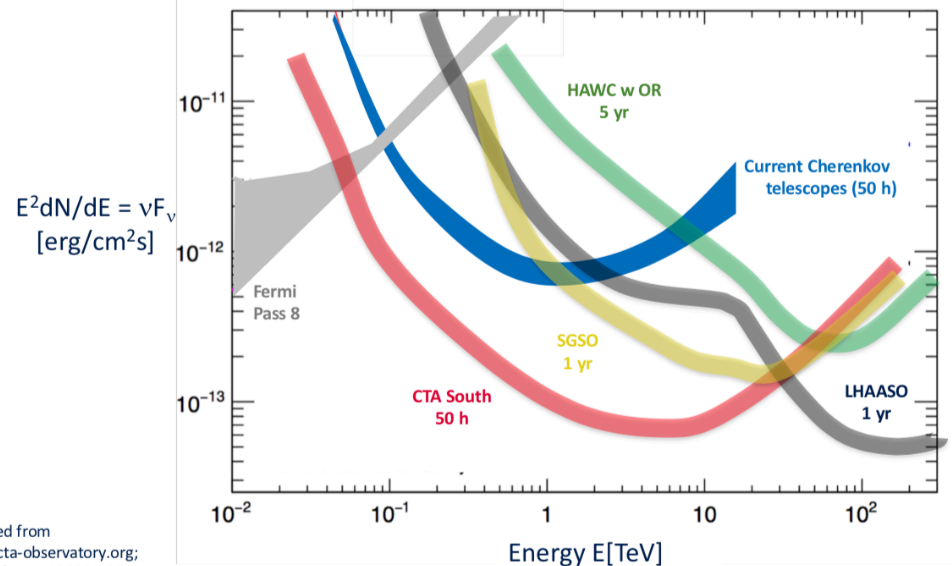
large FoV, good energy resolution, reasonable PSF!

do we need IACT arrays for >100 TeV studies?

- perhaps not critical anymore *for source discovery*
- but very useful for better *morphology* and *source identification*

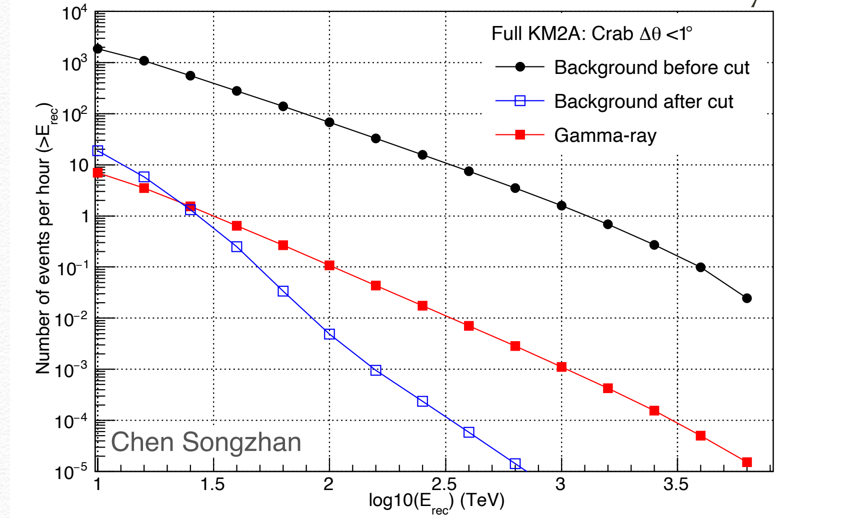
LHAASO - a PeVatron hunter

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



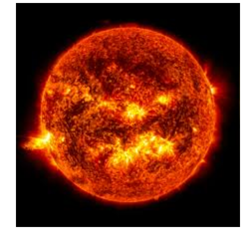
KM2A - PSF: 25′ at 20 TeV, 12′ at 100 TeV

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

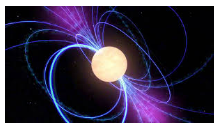
ideal performance to study diffuse emission of the galactic disk, Fermi Bubbles, …

PeVatrons?



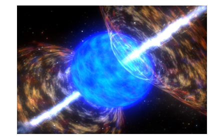
nonthermal processes in Universe proceed everywhere and on all astronomical scales:

Pulsars

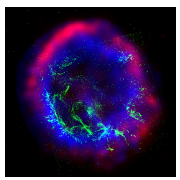


Binary Pulsars
Microquasars

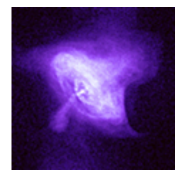
γ-ray Bursts



Supernova Remnants

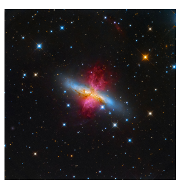


Pulsar Wind Nebulae

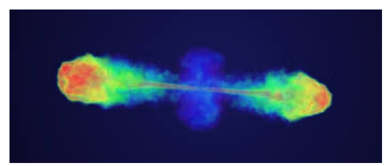


Massive Stars

Galaxies
Starburst Galaxies

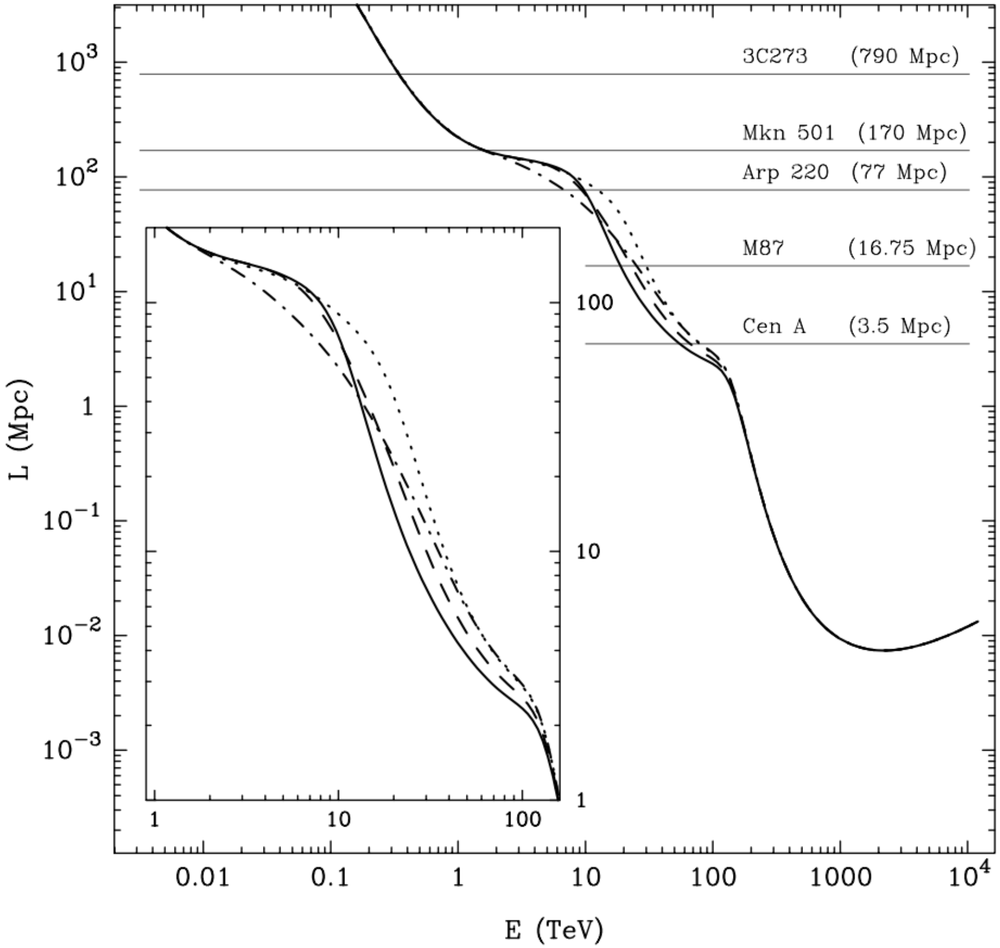


AGN Jets



GalaxyClusters

mean free path of gamma-rays in EBL+CMB



extragalactic sources at
multi-TeV and UHE energies

>10 TeV

- nearby blazers, Mkn 501,421,
- radiogalaxy M87,
- powerful SBGs like Arp220
- Clusters of Galaxies Coma, Perseus

E>100 TeV

- starburst galaxies M82, NGC 253

- nearby radiogalaxy Can A
- Wind (100kpc) Halo
- Fermi Bubbles

$E_\gamma \sim 10$ TeV d ~ 100 Mpc $E_\gamma \sim 100$ TeV d ~ several Mpc $E_\gamma \sim 1-10$ PeV d ~ 10 kpc

Extragalactic Source

do we expect acceleration of particles to PeV energies?

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

all above sources + two more possibilities

Galactic Wind Halo and SMBH in GC.

important to extent search beyond PeV!

Detectors: LHAASP HiSCORE still reasonable sensitivities
Gamma-ray production: low efficiency because of fast escape

Milky Way

do we expect acceleration of particles to PeV energies?

stellar sources - very difficult but possible, in particular,

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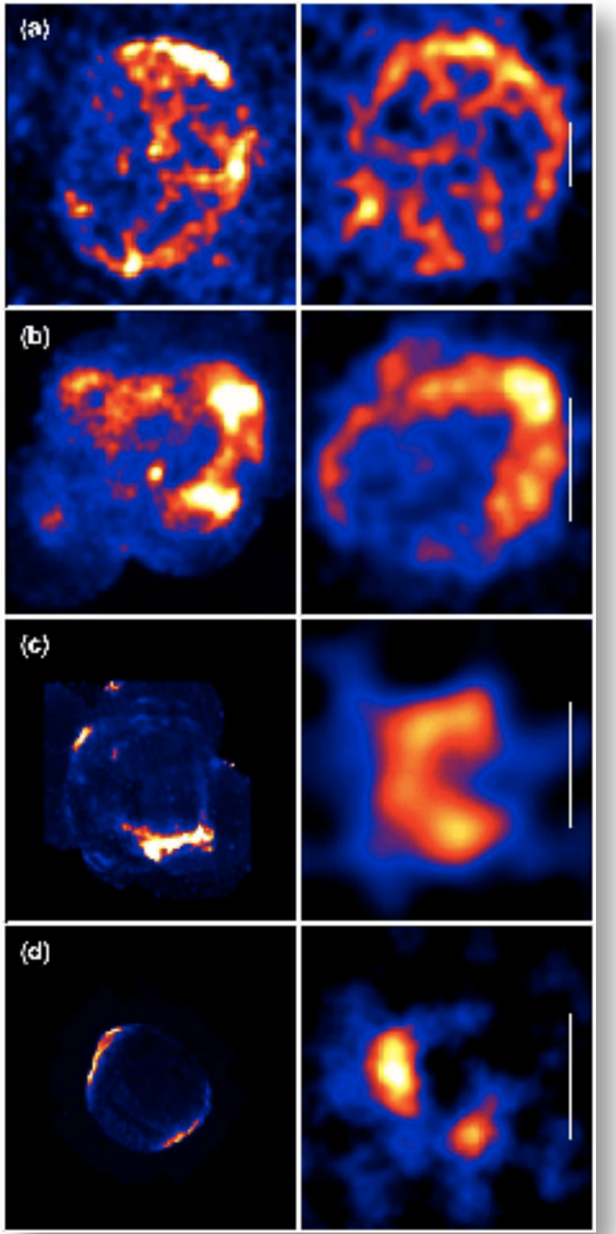
SNRs, Supper-Bubbles, Pulsars ?

Galactic Wind halo?

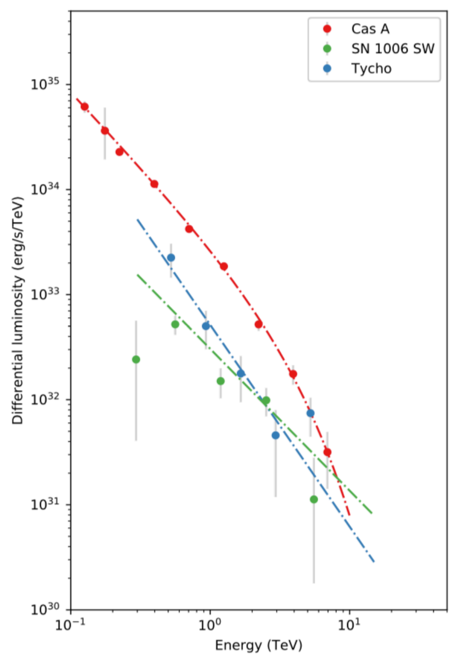
Fermi Bubbles?

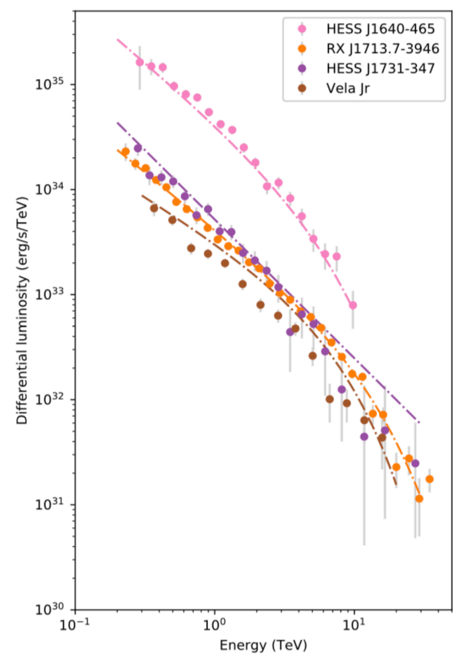
SMBH in the Galactic Center ?

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

second option:

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

?

two options

- large power-law index (> 2.3)

  it is more realistic than Γ=2 of the "standard" DSA? No (M. Malkov, T. Bell, …)

  constrains on the proton maximum energy from gamma-ray data?:

  probing Emax ~ 1 PeV - very difficult but possible for LHAASO

- "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

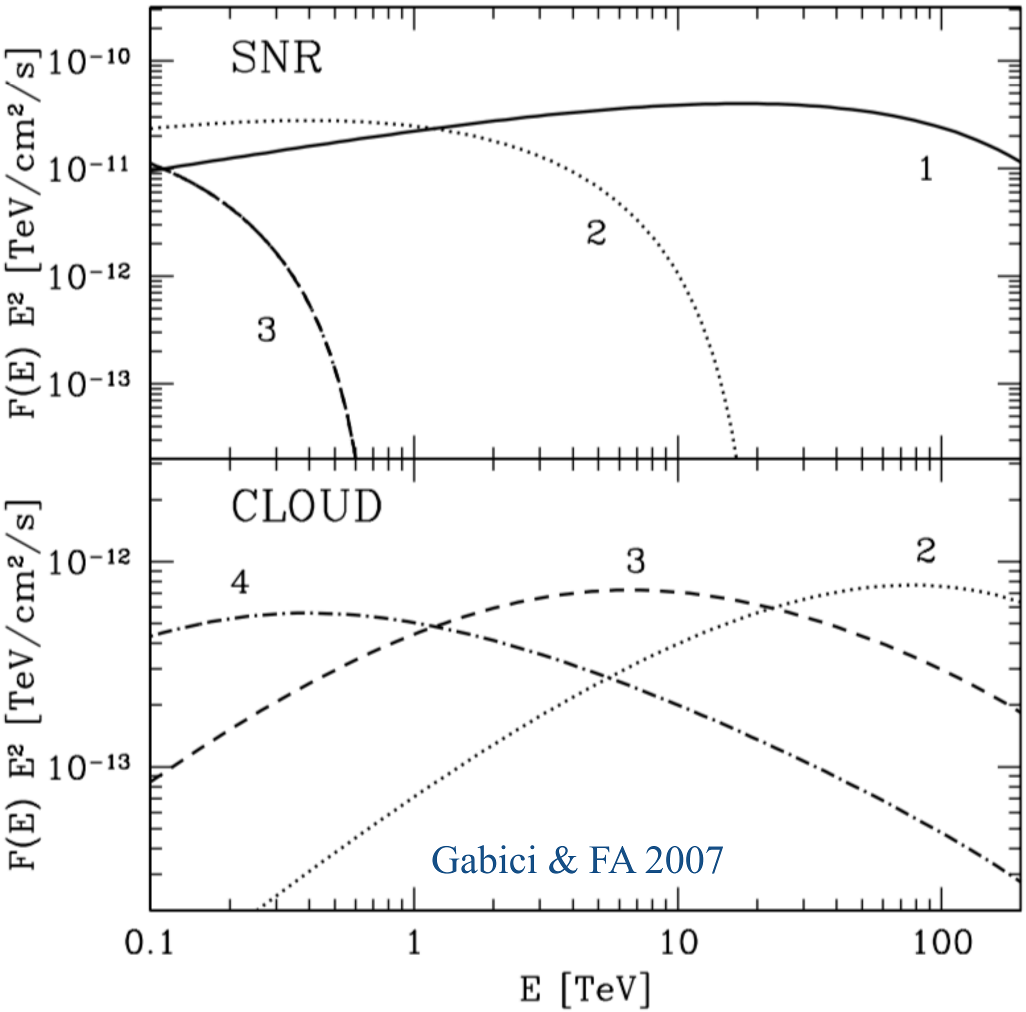
– protons of energy exceeding 100 TeV are accelerated and leave the shell at $T<1000$ yr or, more likely, <100 year, epochs

– 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



d=1 kpc

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

$M=10^4 Mo$

$D(E)=3x10^{29}(E/1PeV)^{0.5}\ cm^2/s$

1 - 400 yr; 2 - 2000 yr; 3 - 8000 yr; 4 - 32000 yr after the explosion

warning: don't be tricked by propagation effects!

transition from rectilinear to diffusive regime of propagation

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

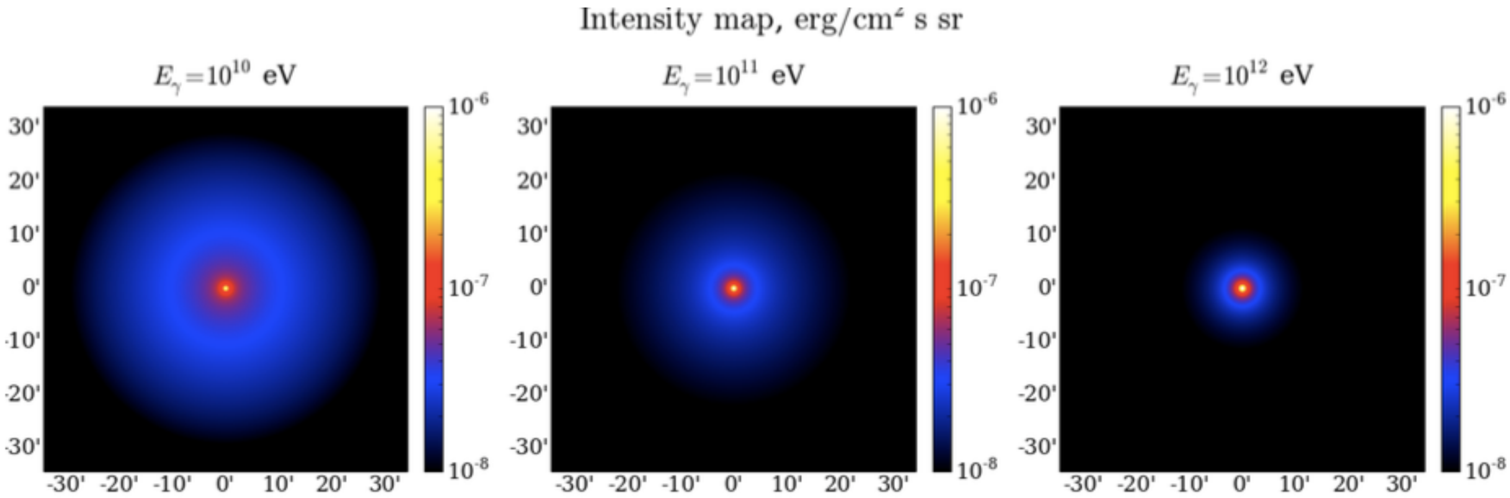
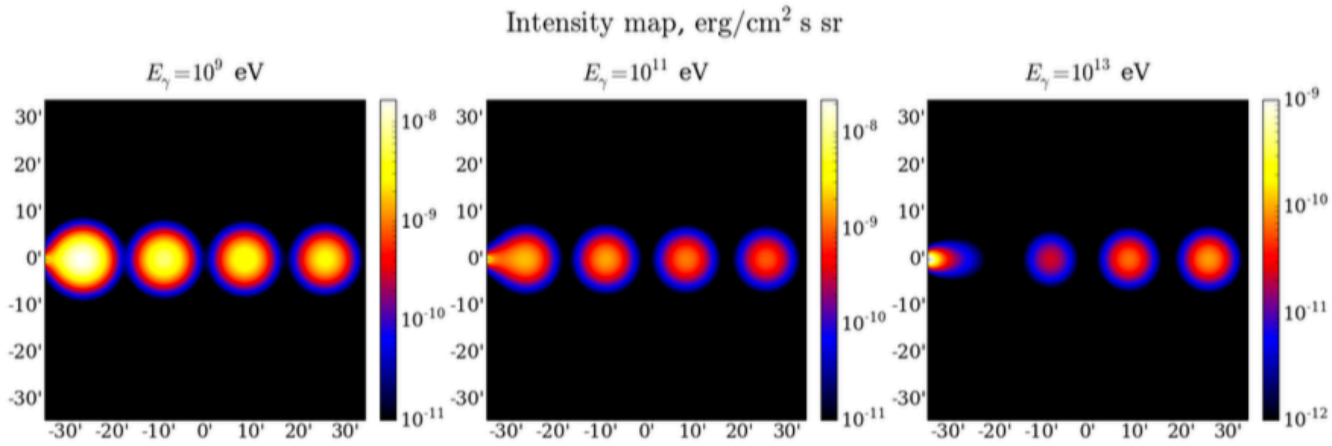


Figure 2: The intensity maps of gamma-ray emission at different energies. The spherical cloud with homogeneous density distribution is irradiated by the cosmic-ray source located in its centre. The gas density inside the accelerator is assumed very low, so the contribution of the accelerator to the gamma-ray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

Prosekin, Kelner, FA 2015

warning:

transition from rectilinear to diffusive regime of propagation

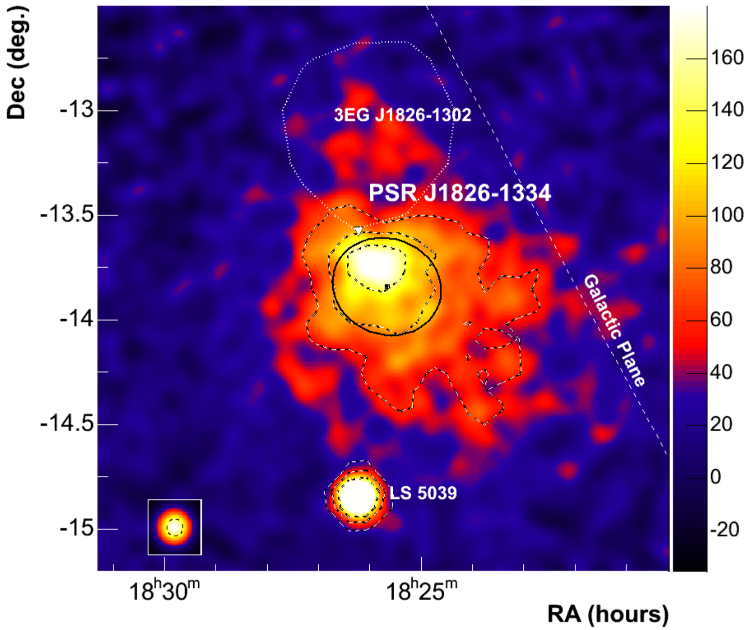


d=1 kpc

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

Prosekin, Kelner, FA 2015

PWNe: Electron PeVatrons and (absolute) Extreme Accelerators

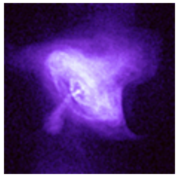


very effective gamma-ray emitter:
$\kappa = w_{2.7K}/w_B \approx 0.1(B/10\mu G)^{-2}$

IC: $e + 2.7K \rightarrow \gamma$

unambiguous determination of spatial (projection) and energy distribution of parent electrons

each gamma-ray photon detected by LHAASO above 100 TeV => electron of energy Ee and its position (x,y) determined with accuracies < 20 % and 3(d/1kpc) pc



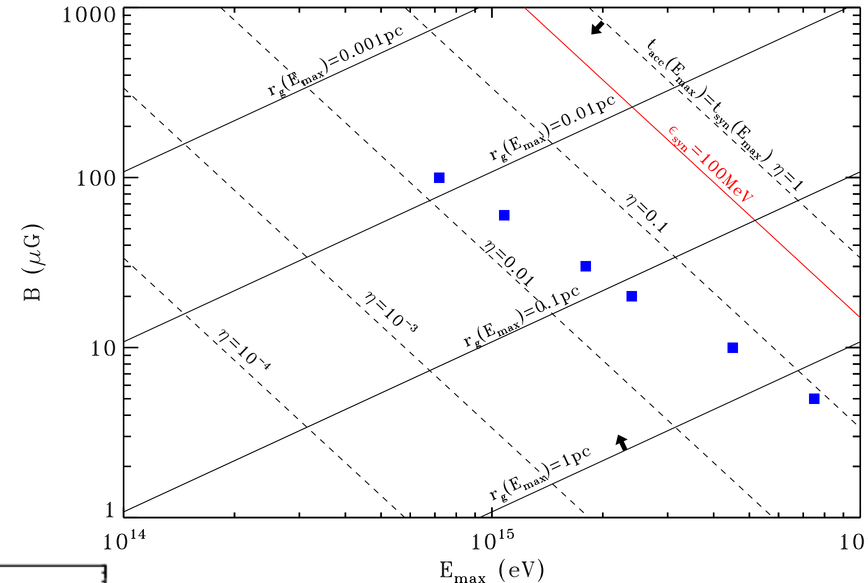
Crab pulsar/wind/nebula:

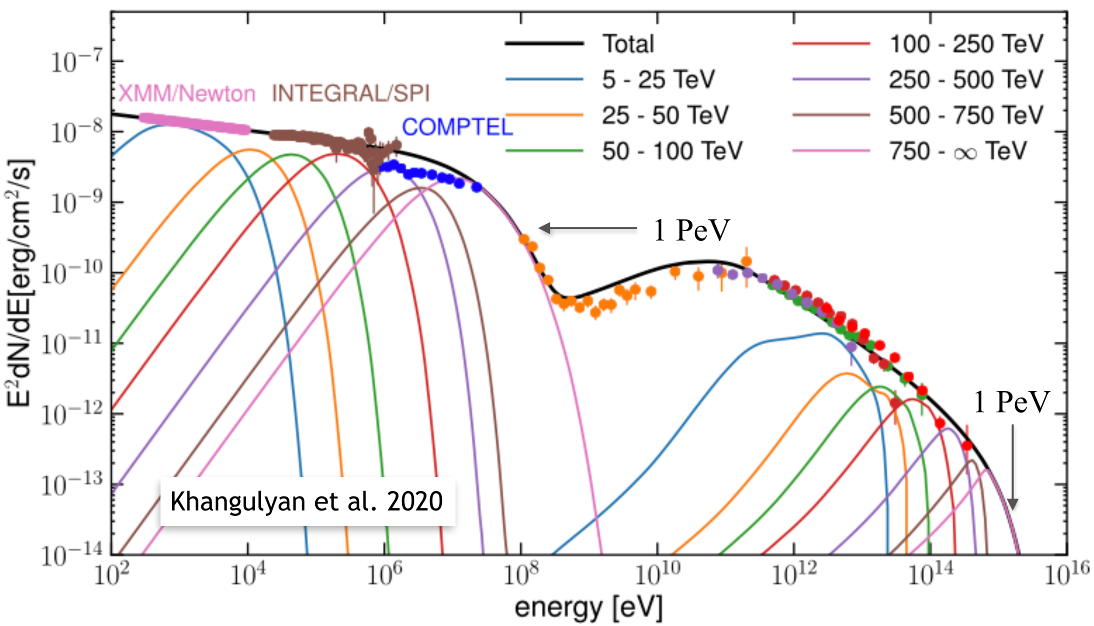
absolute extreme accelerator !

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

electron acceleration with 100 % efficiency

E_{max} versus B for fixed l η



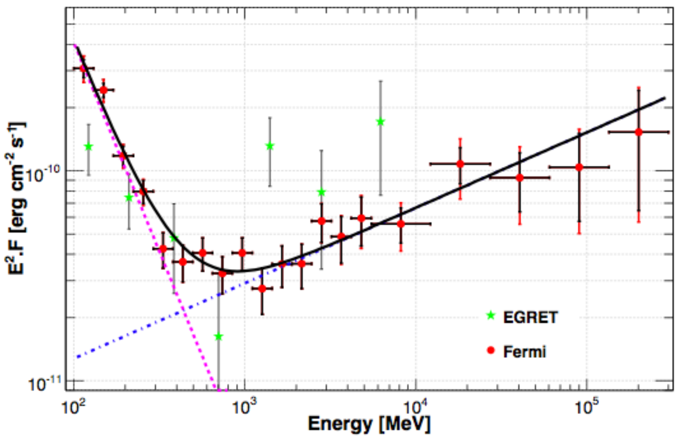


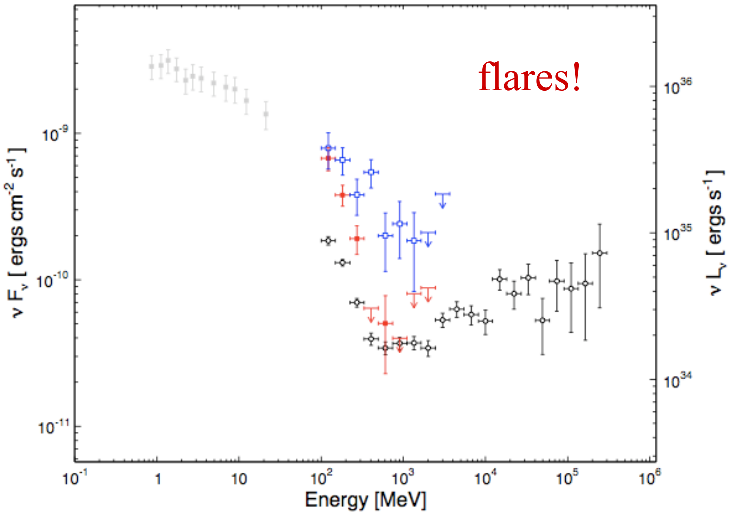
E_{max} from $l = r_g$ & $t_{acc} = t_{sy}$

e^+e^- are accelerated to >1 PeV (!)
acceleration rate be at the margin allowed by theory (ideal MHD)

$$t_{acc}^{-1} = \eta (r_g/c)^{-1};\ \eta \geq 1$$

Flares of Crab (Nebula) :





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

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

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

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

Extended Regions surrounding Clusters of Young Massive Stars sources of GeV and TeV 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

energy distributions?

very hard as hard as E^{-1} (Bykov et al.) but see Vieu et al. 2020

spatial distribution?

continuous CR injections of into ISM over $\sim 10^6$ yrsc => formation of $\sim 1/r$ radial distribution of CRs up to 100+ pc or (typically irregular) gamma-ray morphology

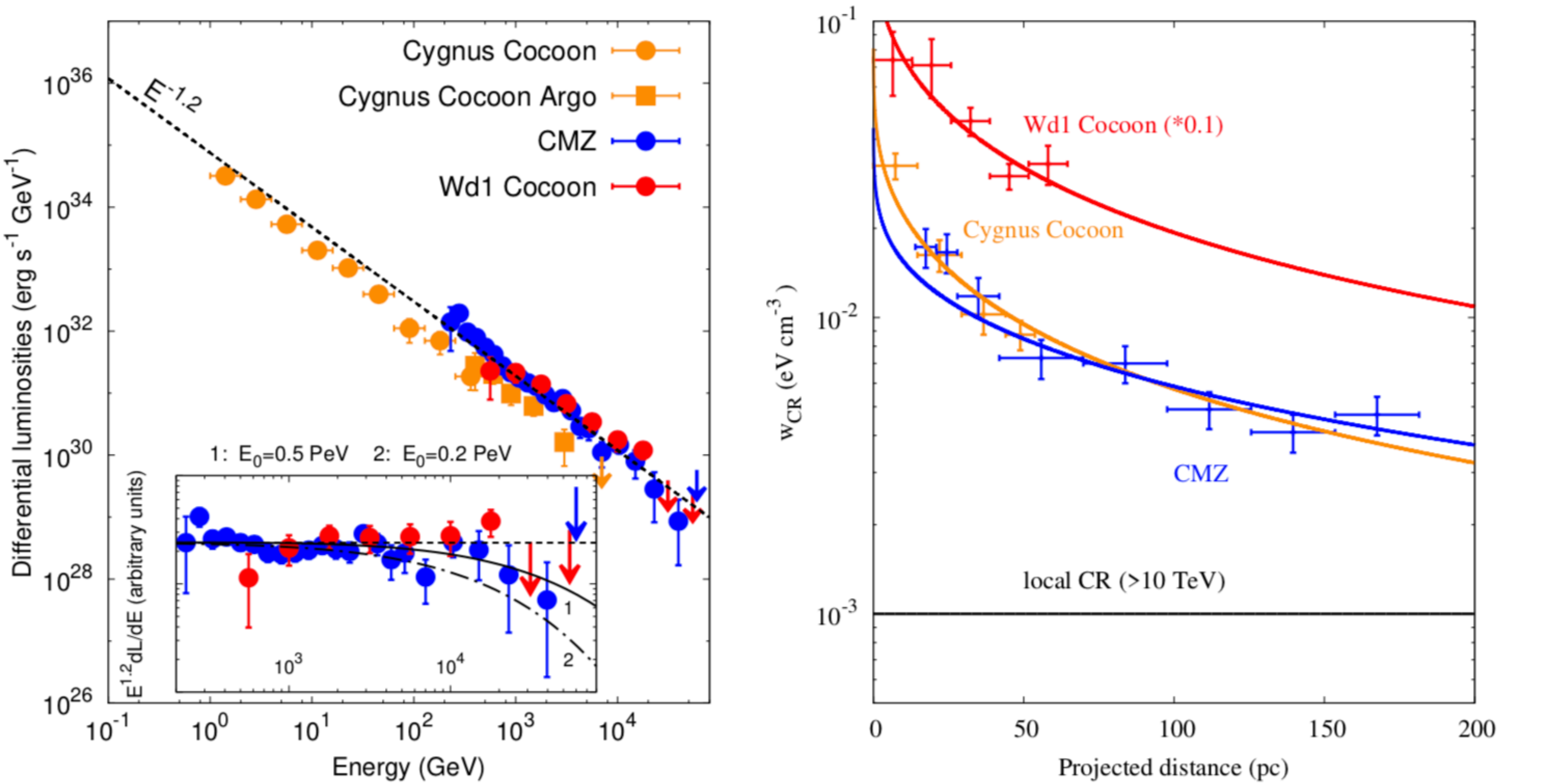
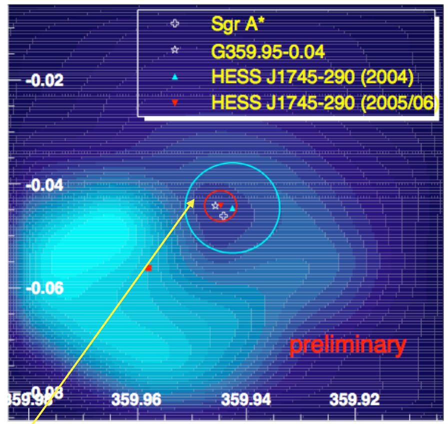


Figure 1: Gamma-ray luminosities and CR proton radial distributions in extended regions around the star clusters Cyg OB2 (Cygnus Cocoon) and Westerlund 1 (Wd 1 Cocoon), as well as in the Central Molecular Zone (CMZ) of the Galactic Centre assuming that CMZ is powered by CRs accelerated in *Arches*, *Quintuplet*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

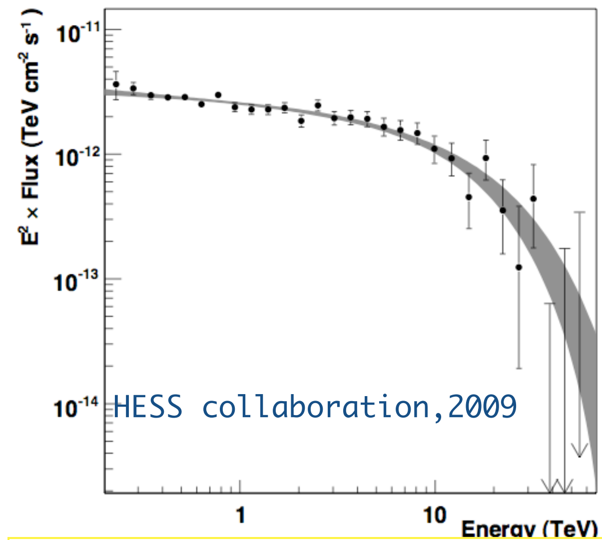
FA, Yang, Ona de Wilhelmi, 2018

TeV gamma-rays from GC

90 cm VLA radio image



Sgr A* or the central diffuse < 10pc region or a plerion?



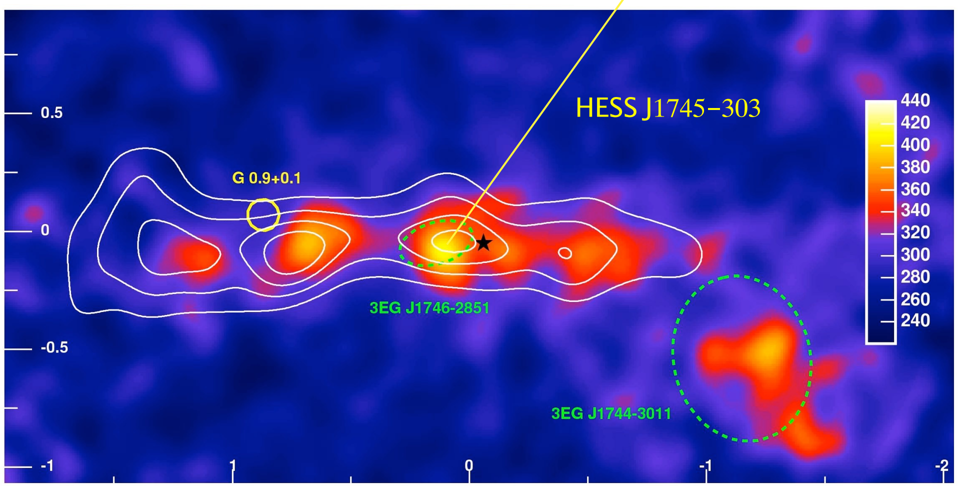
Energy spectrum:

$dN/dE = AE^{-\Gamma} \exp[(-E/E_{0)})^{\beta}]$

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

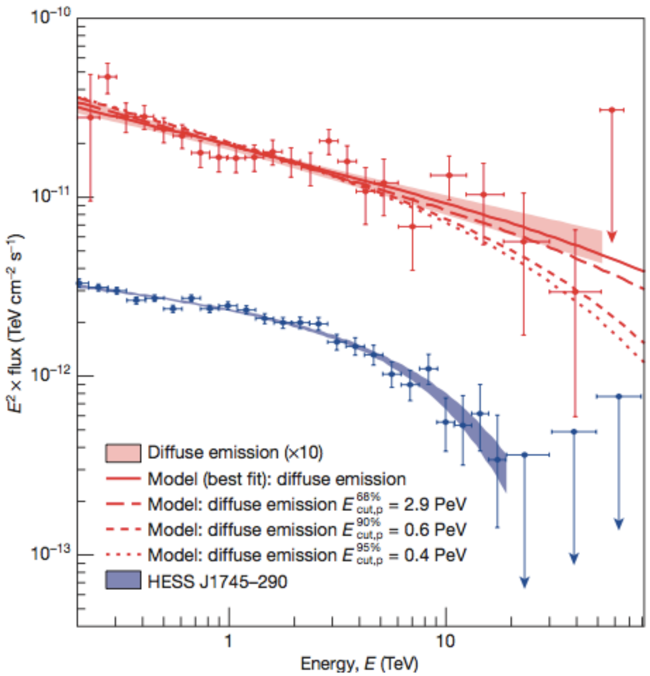
$\beta=1/2$ $\Gamma=1.9$ E0=4.0 TeV

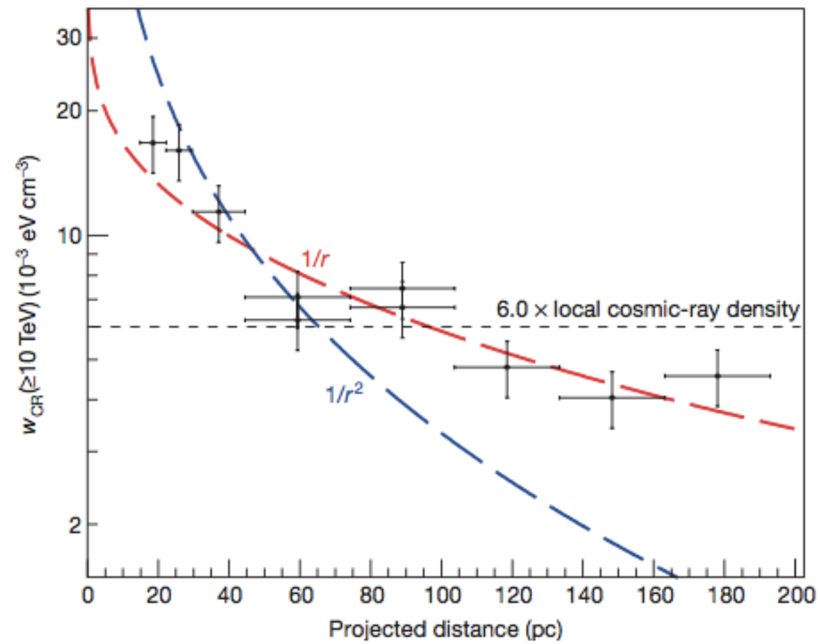
γ-ray emitting clouds



HESS collaboration,2006

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





no-cutoff in the gamma-ray spectrum up to **25 TeV**

=> *no-cutoff* in the proton spectrum up to ~ **1 PeV**

what do we expect?

1/r — continuous source

$1/r^2$ — wind or ballistic motion

constant — burst like source

derived: **1/r** distribution

=> continuous acceleration !

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?

UHE gamma-rays in the context of MWL Multi-Messenger studies

business as usual ?

R (21cm, GHz), mm (CO), O-FIR, X-ray, MeV/GeV/TeV, $\gamma -$ rays, **neutrinos**

specifics:

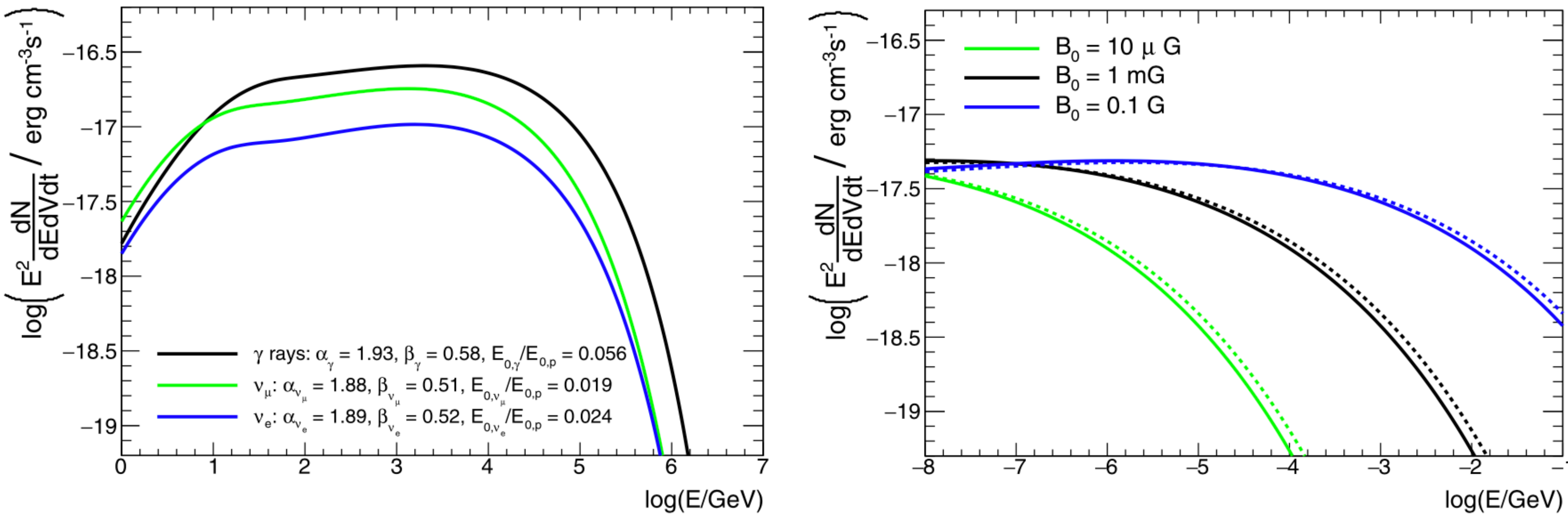
O-FIR ($1 - 100\ \mu$m) gamma-ray production $p + \gamma \rightarrow \pi^0 \rightarrow \gamma$
FIR ($\lambda \geq 100\ \mu$m) gamma-ray absorption $\gamma + \gamma \rightarrow e^{\pm}$

multi-TeV - PeV neutrinos - only UHE messengers beyond the Galaxy?

No! X to gamma rays from synchrotron radiation of secondary electrons

because of short cooling time of UHE electrons the component of radiation can be considered as prompt (simultaneously with primary gamma-rays and neutrinos

THE ASTROPHYSICAL JOURNAL, 903:61 (10pp), 2020 November 1 Celli, Aharonian, & Gabici



emissivity of gamma-rays, neutrinos and synchrotron radiation of secondary electrons from from pp interactions;

"classical" DSA set-up: $N(E) \propto E^{-2} e^{-E/E_0}$ $E_0 = 1\mathrm{PeV}$

normalisation $w_p(\geq 100\mathrm{GeV}) = 1\mathrm{erg/cm^3}$ $n = 1\mathrm{cm^{-3}}$

galactic neutrino sources detected by 1km³ scale detectors should appear in the future LHAASO source catalog as very bright UHE gamma-rays