Hard X-rays as distinct features of PeVatrons+

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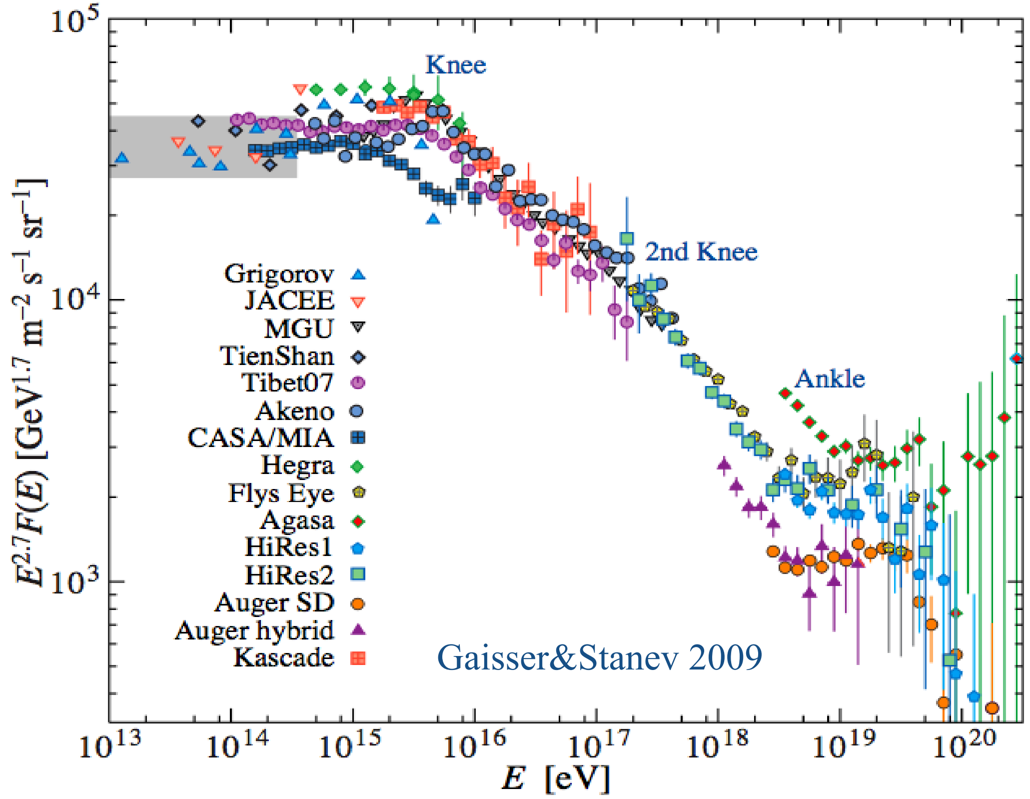
a standard (for many decades, statement)
"origin of cosmic rays still is a mystery"

what do we know about CRs ?

before the knee -   galactic

after the ankle -   extragalactic

between knee and ankle ?



all particle spectrum of Cosmic Rays

what does imply "Origin of Cosmic Rays" ?

the term "Cosmic Rays" itself has two meanings

- *locally detected nonthermal/relativistic particles - "local fog"*
  => information about the contributors to the "local fog"

- *relativistic particles anywhere - the 4th substance of the visible Universe (after the matter, radiation and magnetic fields)*
  => information about the "4th substance"

for the origin of the locally detected Cosmic Rays

the problem is somewhat exaggerated; perhaps it should not be characterized as a “mystery” but rather as an annoying “uncertainty” regarding the *major contributors* (astrophysical sources) to the *local fog*

moreover, it is not clear what should be done to solve the problem since they cannot be identified by means of detection of Cosmic Ray:

even an ideal EHE CR detector cannot tell us more about the origin (sources) of 10^{20} eV particles than the simple “Hillas plot”

CR measurements could be infinitely improved which would initiate new ideas and concepts but the origin of the “local fog” never could be ultimately solved

the very fact of existence of Cosmic Rays tells us a lot

- we know that ultra-relativistic particles represent an equally important (in addition to matter, radiation and B-fields), substance of the visible Universe

- CRs play crucial role in many (not necessarily, nonthermal) phenomena (ionization/chemistry, star formation, etc.)

- **there are factories of ultra-relativistic particles (protons and nuclei) in our Galaxy - up to at least 10^{15} eV and in the Universe up to 10^{20} eV**

but we do not know the main contributors to the "local fog"

is it a big deal? Perhaps, but it is not (in my view) a fundamental issue

HE & VHE gamma-ray observations of recent years revealed 10+ classes of effective Galactic and Extragalactic particle accelerators, some of them are feasible contributors to the "local fog"

a big puzzle - the very fact of existence of PeVatrons and EeVatrons

Measurements tell us that there should be factories of relativistic particles

in our Galaxy - up to at least 10^{15} eV - PeVatrons and

in the Universe - up to at least 10^{20} eV - EeVatrons

Theory tells us that it is almost impossible to have such accelerators unless we accept that we deal with machines operating at efficiency close to the theoretical limits set by classical electrodynamics

a major objectives of astronomy/astrophysics and astroparticle physics: to reveal and study these mysterious objects using multiwavelength and multi-messenger approaches - **CRs, neutrinos, gamma-rays, X-rays**

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

necessary but not sufficient; it implies:

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

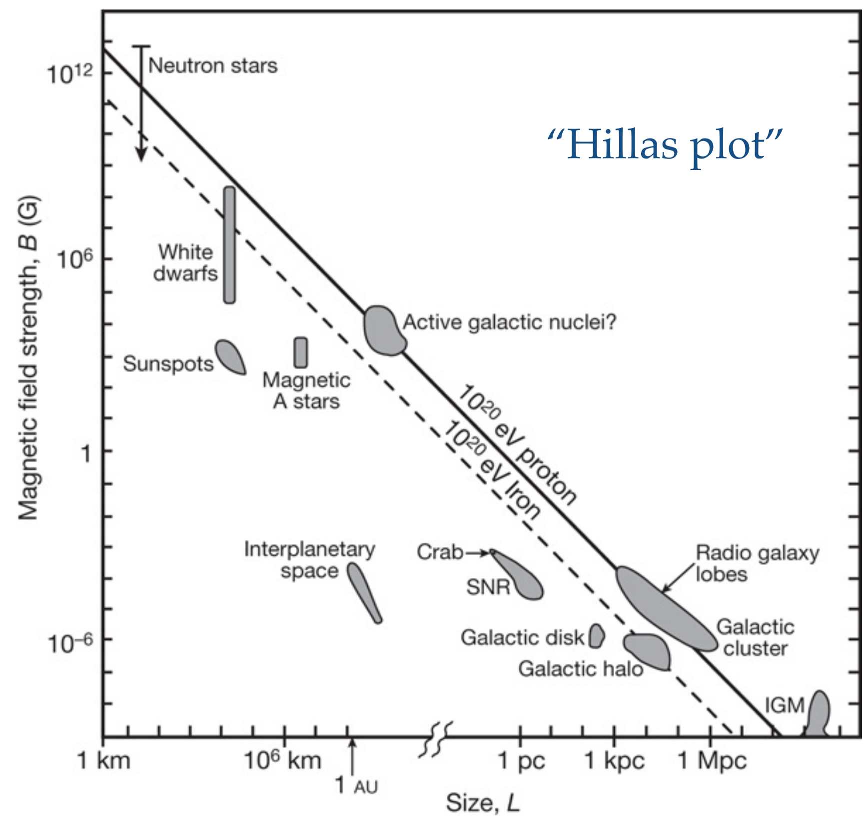
acceleration in fact is slower:

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

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

(2) no energy losses

synchrotron/curvature losses in compact objects become severe limiting factor



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

Particle Acceleration in Galaxy Clusters

Several ingredients for effective acceleration to highest energies

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

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

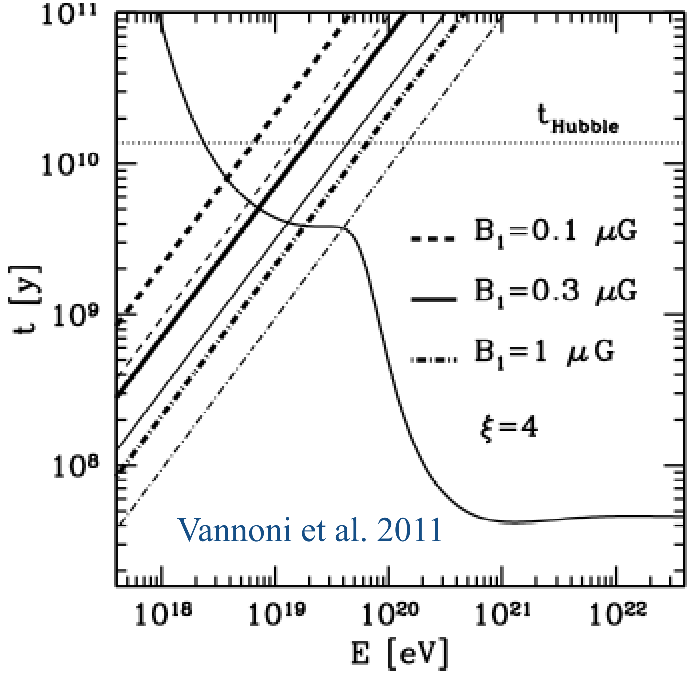


Fig. 1. Acceleration and energy loss time scales as a function of the proton energy. The acceleration time scales are obtained for the values of the upstream magnetic field B_1 reported in figure and a downstream magnetic field $B_2 = 4B_1$. The thick lines correspond to a shock velocity of 2000 km/s,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

acceleration sites of 10^{20} eV CRs ?

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

signatures of extreme accelerators?

✓ synchrotron self-regulated cutoff:

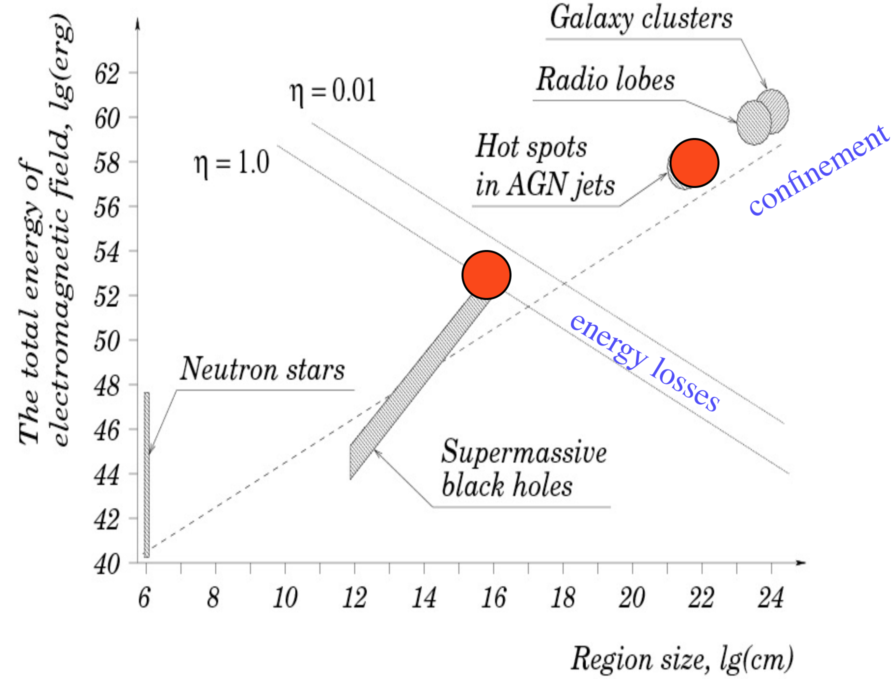
$$h\nu_{cut} = \frac{9}{4}\alpha_f^{-1} mc^2 \eta :$$

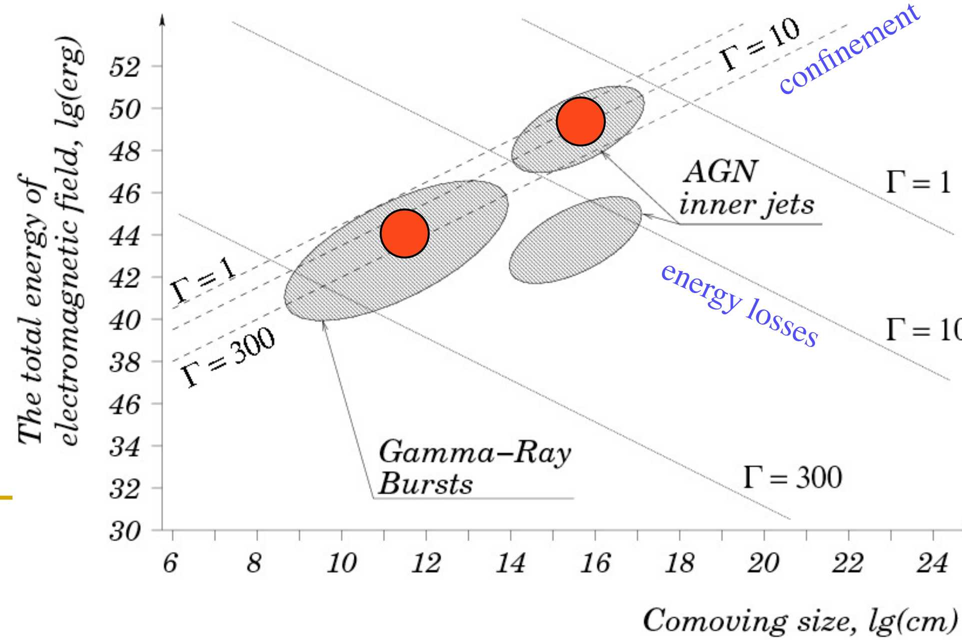
$\simeq$ 300GeV proton synchrotron
$\simeq$ 150MeV electron synchrotron

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

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

✓ observable off-axis radiation
radiation pattern can be much broader than $1/\Gamma$





questions beyond the origin of CRs - physics of Extreme Accelerators (MHD, electrodynamics, plasma physics…

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 and AGN it can be as large as 50%

(ii) maximum possible energy achieved by individual particles

the very fact of existence of 10^{20}eV CRs

also the Crab flares in >100 MeV photons

Cosmic Ray Astrophysics with CRs?

an attempt to extract information from the "smell" (energy spectrum and chemical composition of CRs) of a "soup" (isotropic CRs flux) cooked from different ingredients over huge $T > 10^7$ (10^{10})*yr timescales…*

it is not a surprise that origin of main contributors
to the locally measured CR flux is yet a mystery!

the contributors of CRs can be revealed by astronomical means

astronomical messengers

should be neutral & stable:

photons and neutrinos satisfy fully to these conditions*

partly also ultra-high energy neutrons and protons …

neutrons: $d < (E_n/m_n c^2)\, c_{\ 0} \;\Rightarrow\; E_n > 10^{17} (d/1\ \text{kpc})$ eV
galactic astronomy with $E > 10^{17}$ eV neutrons

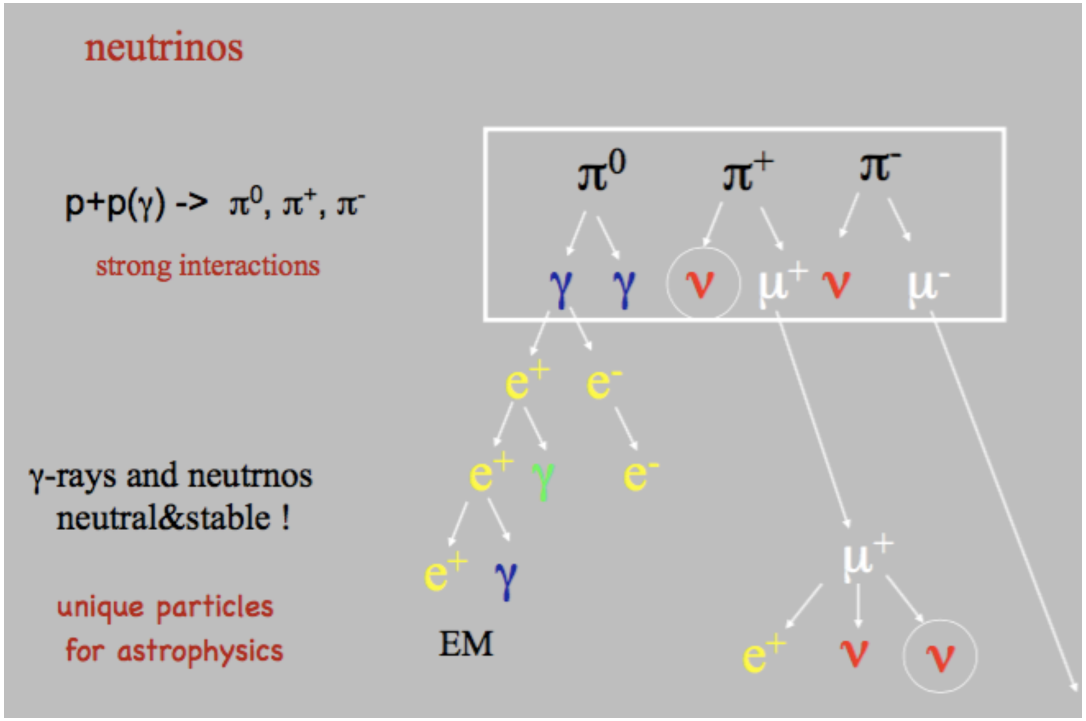
protons: if $E > 10^{20}$ for IGMF $B < 10^{-12}$ G eV
extragalactic astronomy with $E > 10^{20}$ eV protons

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

secondary electrons - three channels of production

1. charged pion production

$\pi^{\pm}$



2. Bethe-Heitler pair production $p + \gamma \rightarrow e^+e^-$

3. photon-photon pair production $\gamma + \gamma \rightarrow e^+e^-$

hard X-rays as the 4th messengers

arguments?

- unavoidable secondary PeV+ electrons from charged π - meson decays (produced both in *pp* and *p*-γ interactions) and from Bethe-Heitler pairs

- low background (almost no competing radiation mechanisms (thermal plasmas hardly are heated to electron temperatures well beyond 10 keV; synchrotron peak of primary electrons typically does not exceed 10 keV; Inverse Compton components are not effective for producing X-rays

- shallow spectra in the cutoff region

- perfect detector performance:

PSF	20 (10?) arcsec
energy resolution	few percent
flux sensitivity	10^{-14} erg/cm^2 s

hard X-rays

recognized and broadly used

synchrotron X-rays of *directly accelerated* electrons - messengers complementary to VHE gamma-rays for probing Cosmic TeVatrons: SNRs, Pulsar Wind Nebulae, gamma-ray loud binaries, AGN/blazars…

not yet fully acknowledged and realized

synchrotron (hard) X-rays from *secondary* electrons - messengers unique (more than "complementary" to gamma rays and neutrinos) for probing Cosmic PeVatrons and EeVatrons (suspected and yet-unknown) *gamma-ray astronomy*

versus

neutrino astronomy

presently: VHE gamma-ray astronomy - a truly *observational* discipline

Why VHE gamma-rays?

are effectively produced in E-M and hadronic interactions
are effectively detected by space- and ground-based instruments

one of the highest priorities of new generation detectors > 10 TeV photons

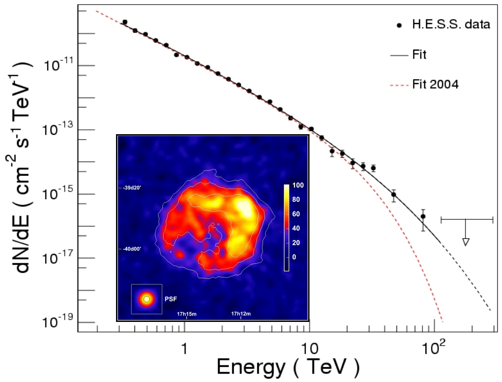
but… these gamma-rays are very fragile, especially at >> 10 TeV
(effectively interact with radiation and magnetic fields)

information arrives after significant distortion, often - sources are opaque:
>100 TeV - only galactic; >1 PeV - no chance to survive also in ISM

100 TeV - 1 PeV energy band - is a big challenge…
but this is the most important energy interval to study PeVatrons!

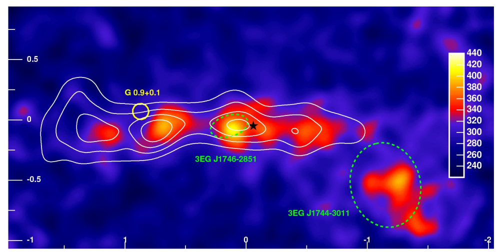
good performance/high quality data => modeling/theory

RXJ 1713.7-3946



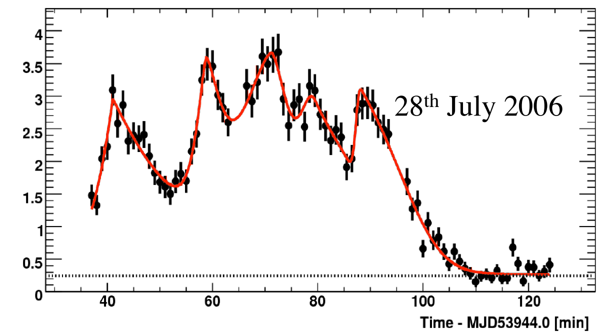
TeV image and energy spectrum of a SNR

Galactic Center



resolving GMCs in the Galactic Center 100pc region

PKS 2155-309



variability of TeV flux of a blazar on minute timescales

multi-functional tools: *spectrometry* *temporal studies* *morphology*

✓ extended sources: *from SNRs to Clusters of Galaxies*

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

Galactic Astronomy | Extragalactic Astronomy | Observational Cosmology

VHE neutrino astronomy -- presently "astronomy" *without sources*

are effectively produced in hadronic interactions

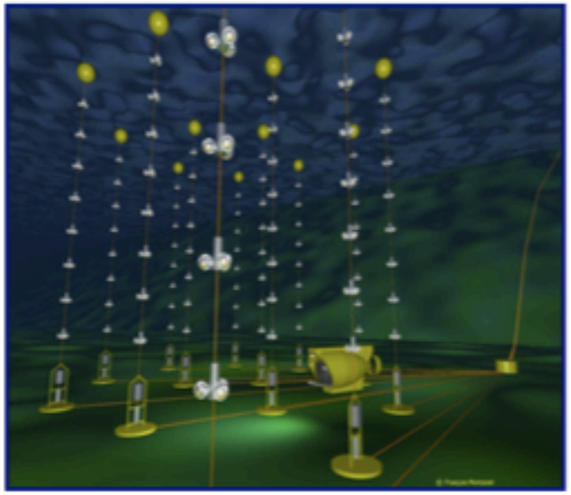
do not interact with matter, radiation and magnetic fields:

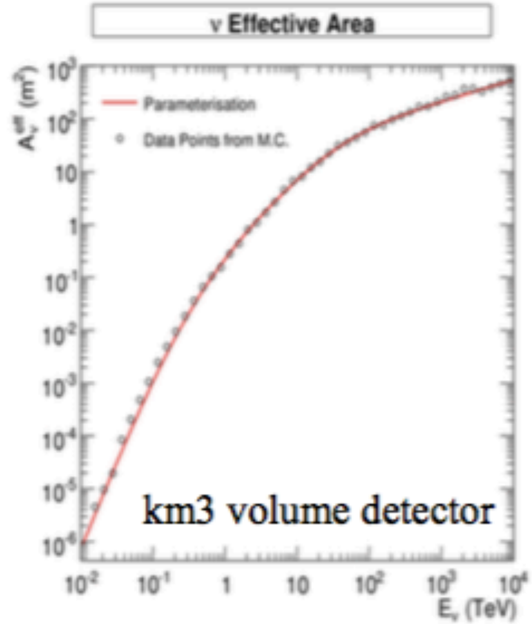
(1) information without distortion; (2) "hidden accelerators" possible

but... difficult to detect -- even "1km^3 volume" class detectors have limited performance

IceCube/KM3NET: "right" energy band 10 TeV - 1 PeV, but not very impressive sensitivity...

neutrino telescopes





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

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

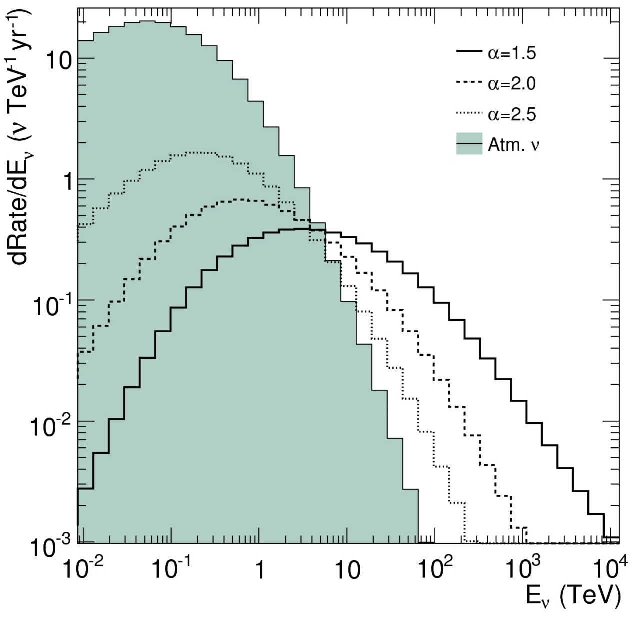
compare with detection areas of gamma-ray detectors:

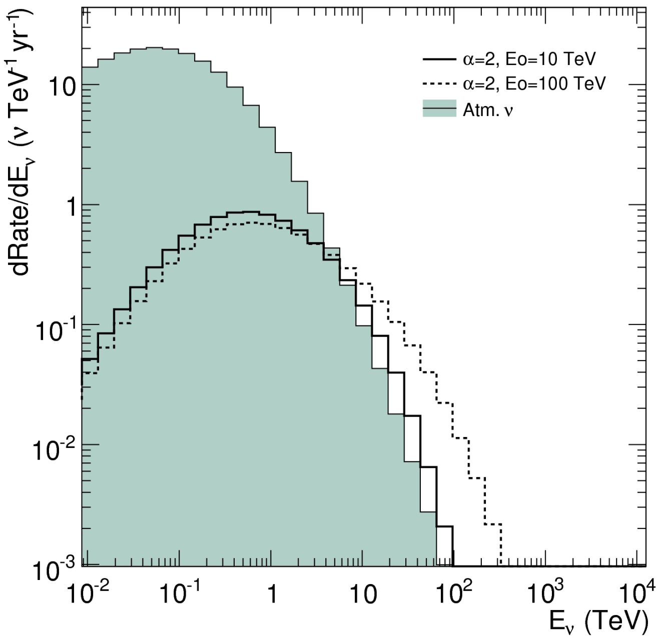
Fermi - 1m^2 but at GeV energies, ground-based >10^{4}m^2 at same energies neutrino astronomy - perfect for search for PeVatrons, but has limited potential of km^3 class detectors

effectively >10 TeV neutrinos; a few events pr year

$$J(E_\nu) = AE_\nu^{-\alpha} \quad \text{with} \quad J(>1\text{TeV}) = 10^{-11}\ \nu/\text{cm}^2\text{s}$$ approx 1 Crab

1 km3 volume neutrino detector





recommendation?

optimize/build neutrino detectors for >10 (100) TeV range ?

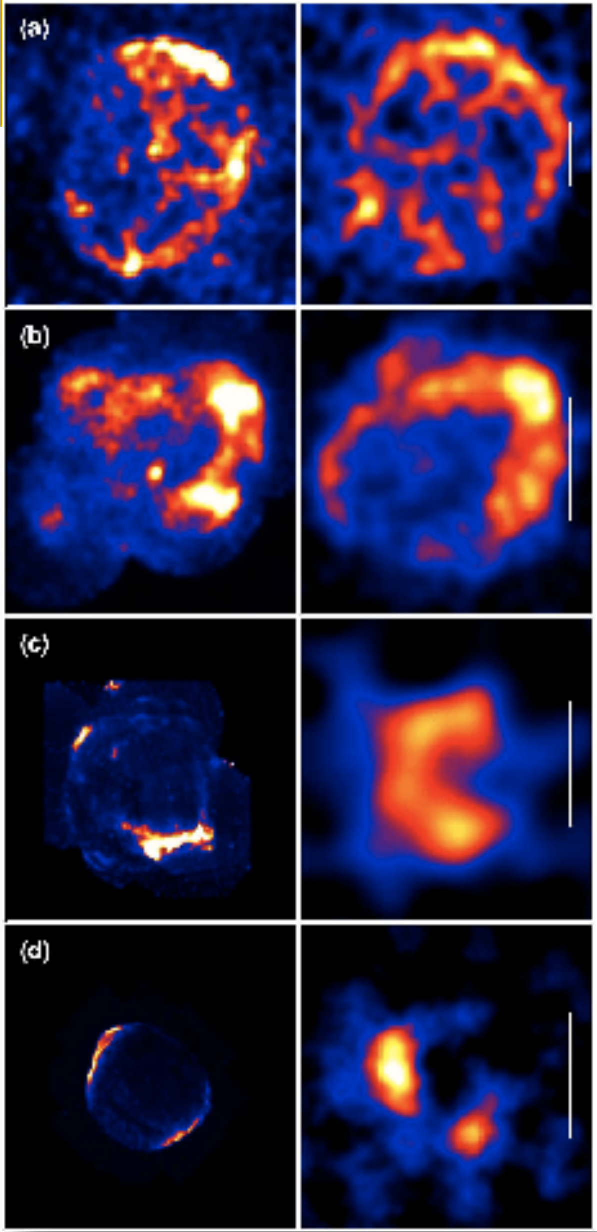
hard X-rays as alternative messengers for exploring Cosmic PeVatrons+ ?

SNRs and Galactic Cosmic Rays

SNRs as the most likely sources
of galactic cosmic rays? If so they should be PeVatrons

main hope is related to gamma-ray observations:

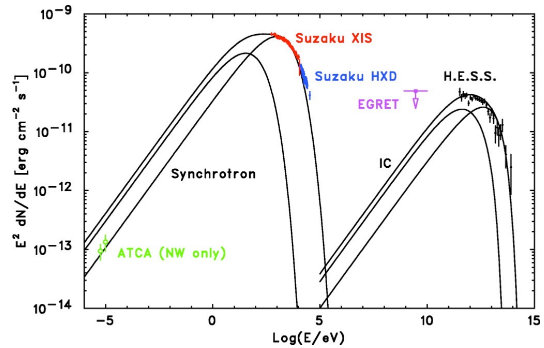
- detect VHE gamma-rays from SNRs
- demonstrate that they have hadronic origin
- demonstrate that proton spectra continue up to 1 PeV

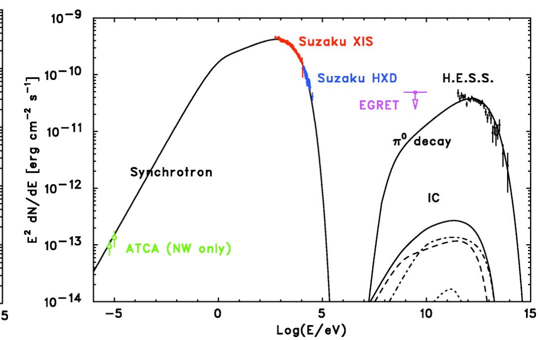


=>

acceleration of protons and/or electrons in SNR shells to energies up to 100TeV

leptonic or hadronic?





RXJ1713.7-4639

inverse Compton scattering of electrons on 2.7K CMBR

B=15μG

We ≈3.4 10^{47} erg/cm^3

γ-rays from pp -> π^o -> 2γ

$dN/dE = A\, E^{-\alpha} \exp(-E/Eo)$

with α=1.7, Eo ≈ 25 TeV,

B=200μG

Wp ≈2 $10^{50}(n/1cm^{-3})^{-1}$erg/cm^3

unfortunately we cannot give preference to hadronic or leptonic models - both have attractive features but also serious problems

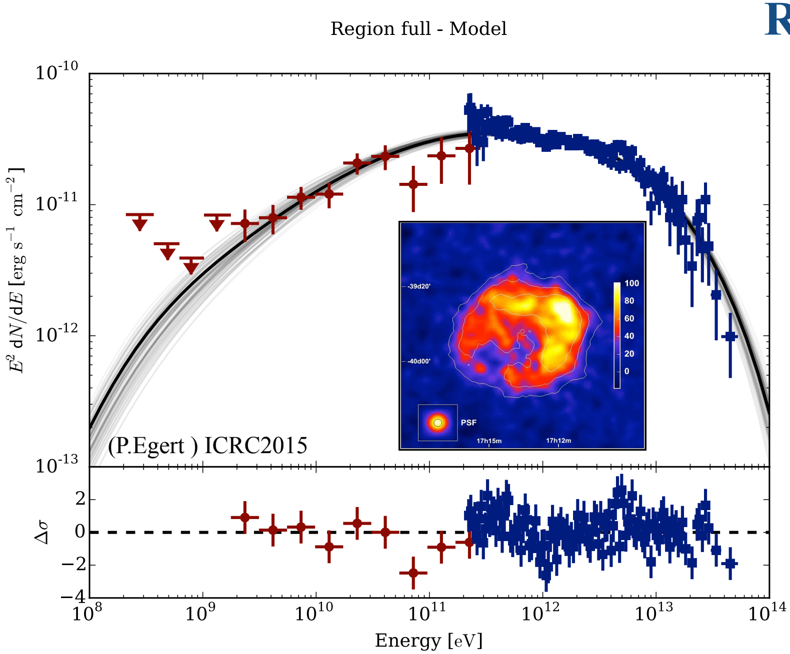
solution? detection of more sources, broader energy coverage, and search for neutrinos

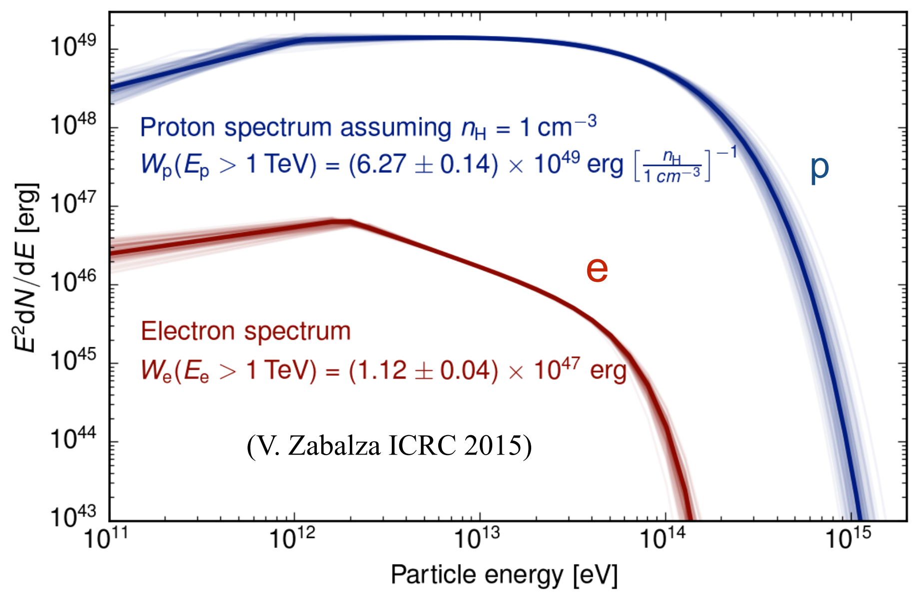
Probing the distributions of accelerated particles in SNRs

HESS measurements

derived spectra of e and p

RXJ 1713





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

simplest test for a SNR operating as PeVatron?

power-law gamma-ray spectra extending up to 100 TeV !

(1) can be only of hadronic origin and

(2) spectrum of parent protons should extend up to 1 PeV

detection of 10-1000 TeV neutrinos? - complementary but not crucial

so far a rather disappointing outcome:

so far a rather disappointing outcome…

"early cutofs" Ecut < 100 TeV in the spectra of all SNRs!

should we relax and accept that SNRs are the main contributors to GCRs but until 10-100 TeV, and that there should be other sources (PeVatron responsible for the knee around 1 PeV ?

perhaps, but we should explore other possibilities as well,
in particular the role of the **escape**

HESS: it seems there is a component beyond the shell in RXJ1713; if so it would be important to measure the gamma-ray (and the secondary hard synchrotron X-ray) spectra related to the escaping protons
For decisive conclusions we need a better PSF compared to HES

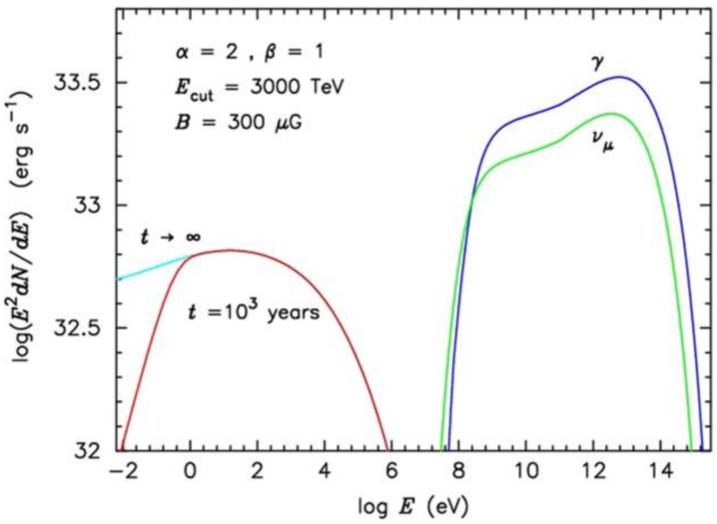
a Galactic PeVatron: E~10^{15}eV

three channels of information about cosmic PeVatrons:

10-1000 TeV gamma-rays

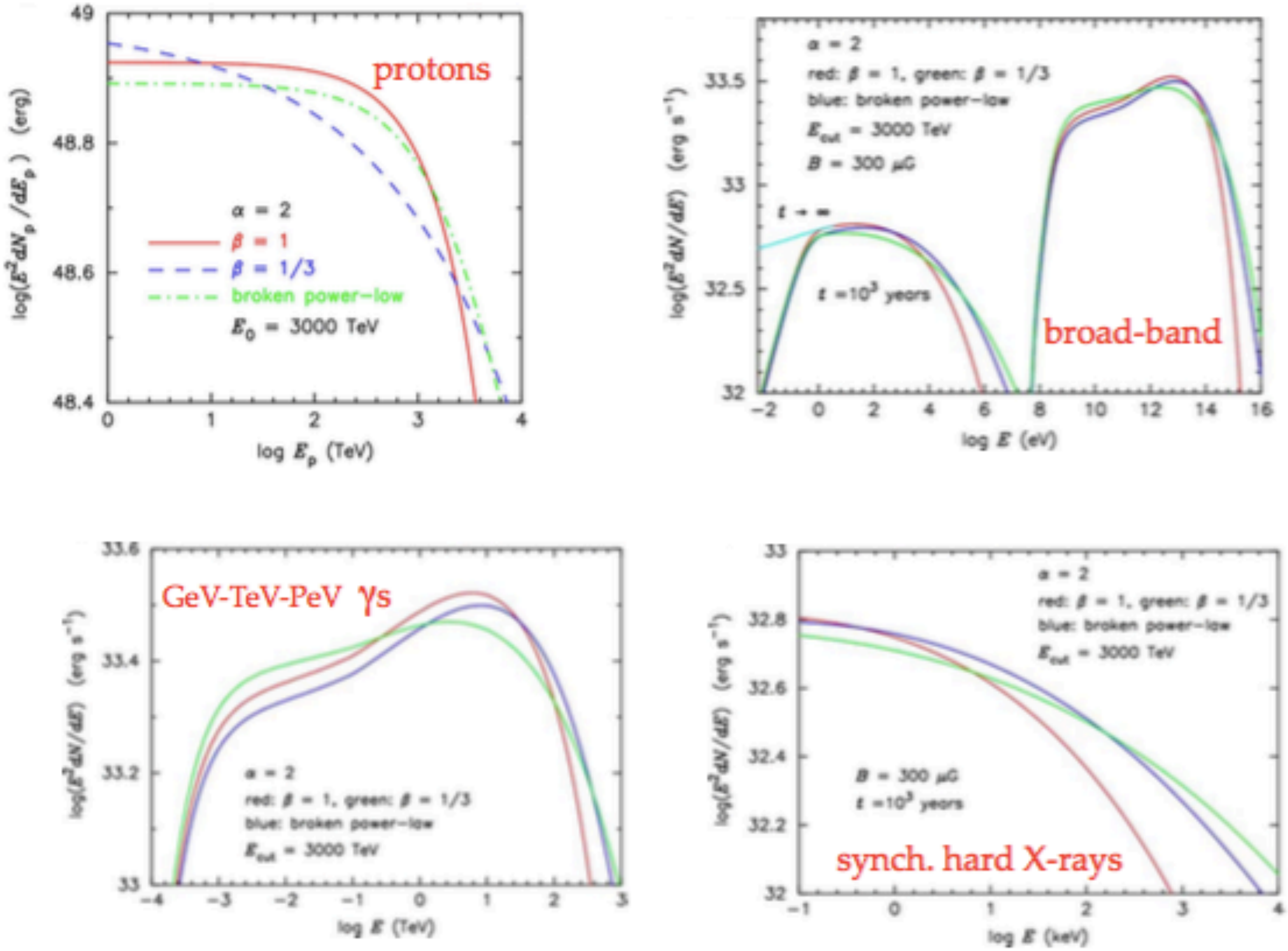
10-1000 TeV neutrinos

10 -100 keV hard X-rays



- γ-rays: difficult, but possible with future “10km²“ area multi-TeV IACT arrays
- neutrinos: marginally detectable by IceCube, Km3NeT - don’t expect spectrometry, morphology; uniqueness - unambiguous signatute!
- “prompt“ synchrotron X-rays: smooth spectrum a very promising channel - quality!

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

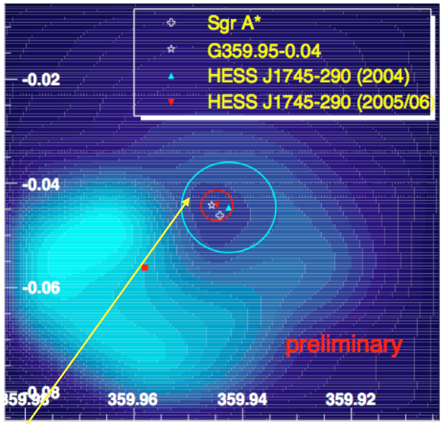


broad-band emision initiated by pp interactiosn : Wp=10^{50} erg, n=$1cm^{-3}$

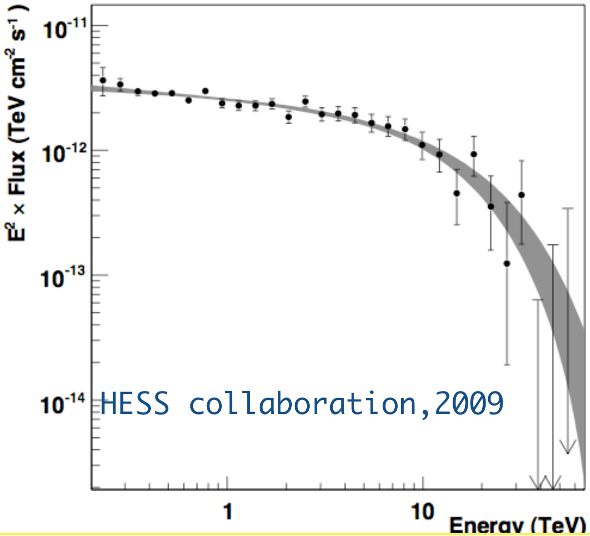
a PeVatron in the Galactic Center!

TeV gamma-rays from GC

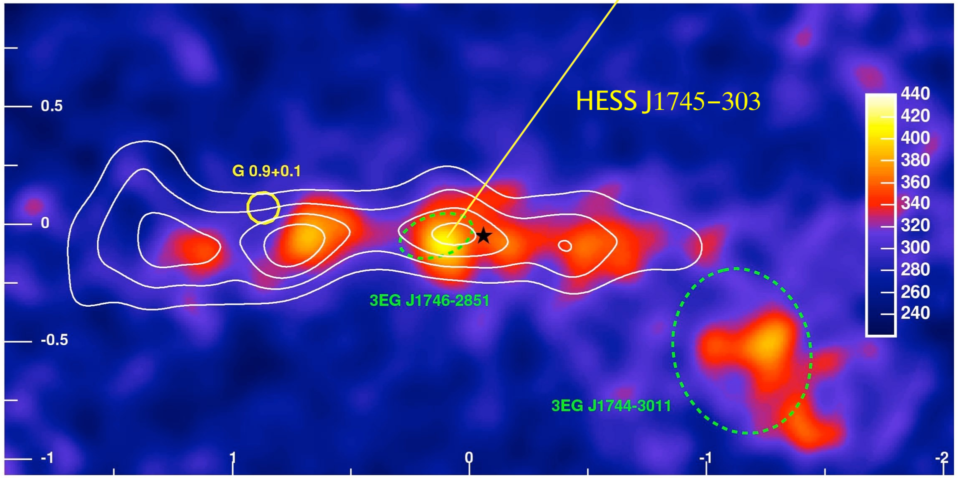
90 cm VLA radio image



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



γ-ray emitting clouds



HESS collaboration,2006

Energy spectrum:

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

β=1 Γ=2.1; E_0=15.7 TeV

β=1/2 Γ=1.9 E0=4.0 TeV

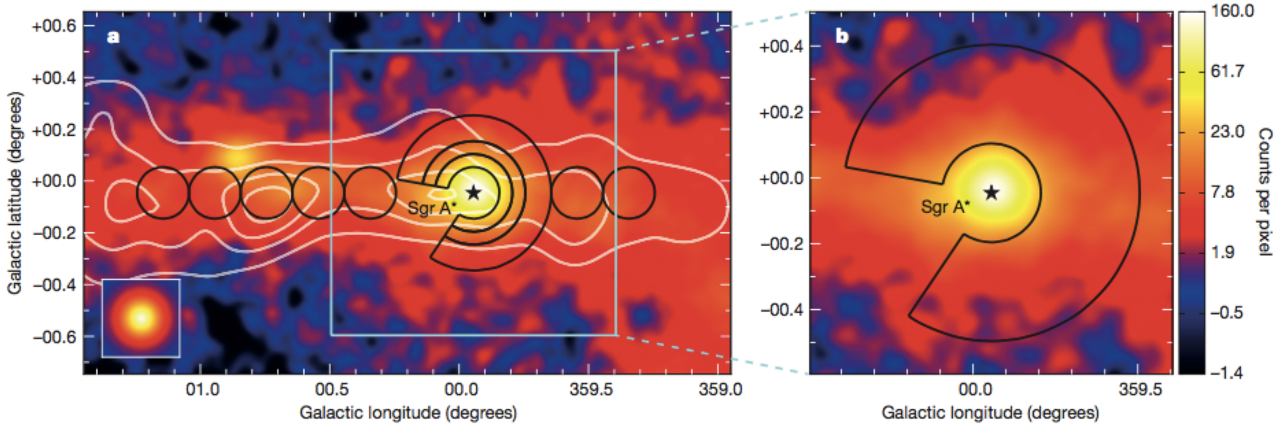
New - HESS collaboration

a proton PeVatron - a machine accelerating particles up to 10^{15} eV and beyond presently operates in R<10 pc region of the Galactic Center with acceleration rate of protons above energy 10TeV at level 10^{37-38} erg/s

this conclusion is based on spectroscopic and morphological studies of diffuse VHE gamma-ray component in so-called ~200 pc radius Central Molecular Zone (CMZ) of the GC

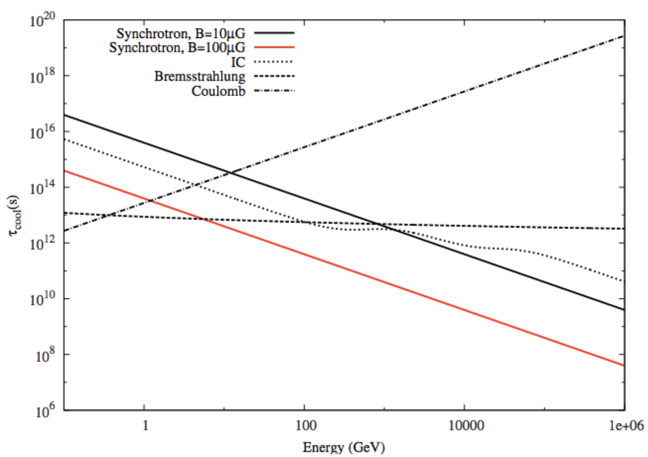
- for the first time, a gamma-ray spectrum is registered that continues without a cutoff or a break up to 20-30 TeV (most likely, 50 TeV)

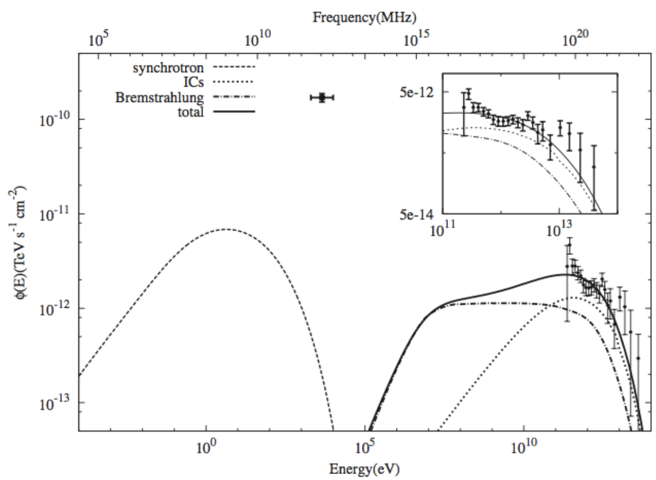
- for the first time, the density profile of parent protons is derived based on analysis of spatial distributions of VHE gamma-rays and the gas in GC



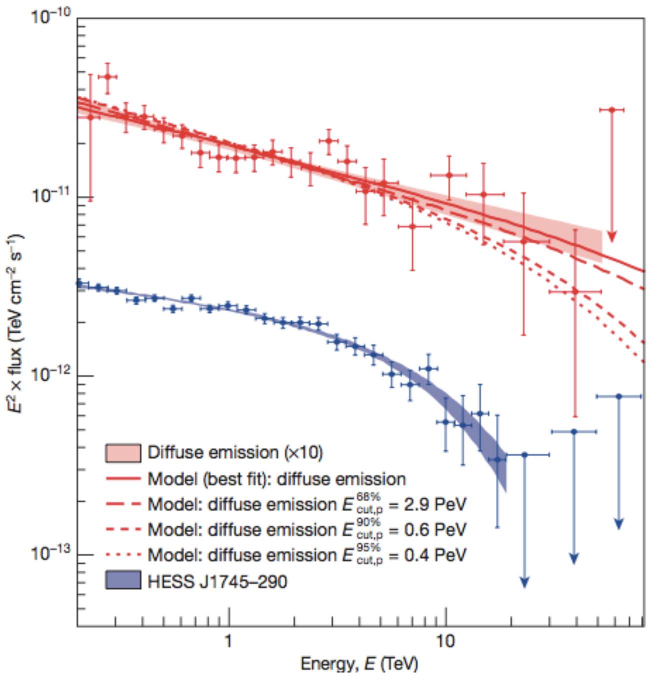
gamma-rays are of hadronic (pp) origin:

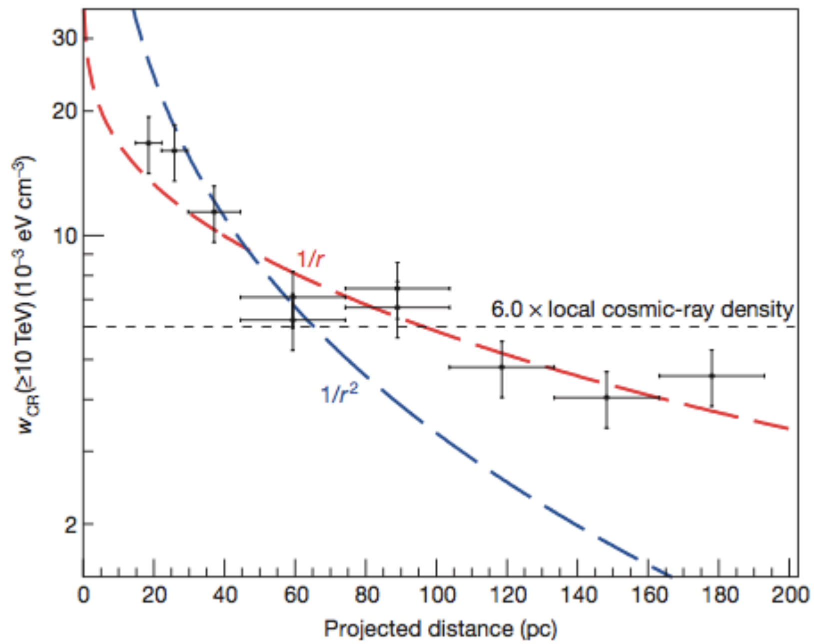
- gamma-ray brightness correlates with gas density (but not linearly!)
- mean free paths of 100 TeV gamma-rays cannot exceed a few pc
- because of cooling of electrons the IC spectrum breaks below 10TeV





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 !

Conclusions:

- 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

- the expected >10 TeV neutrino flux is within the range of sensitivity of a several km^3 volume neutrino detector

a PeVatron or a EeVatron ?

Can we exclude that the CR source in the GC accelerates particles to energies well beyond 1 PeV, e.g. up to EeV energies (1EeV=10^{18} eV) ?

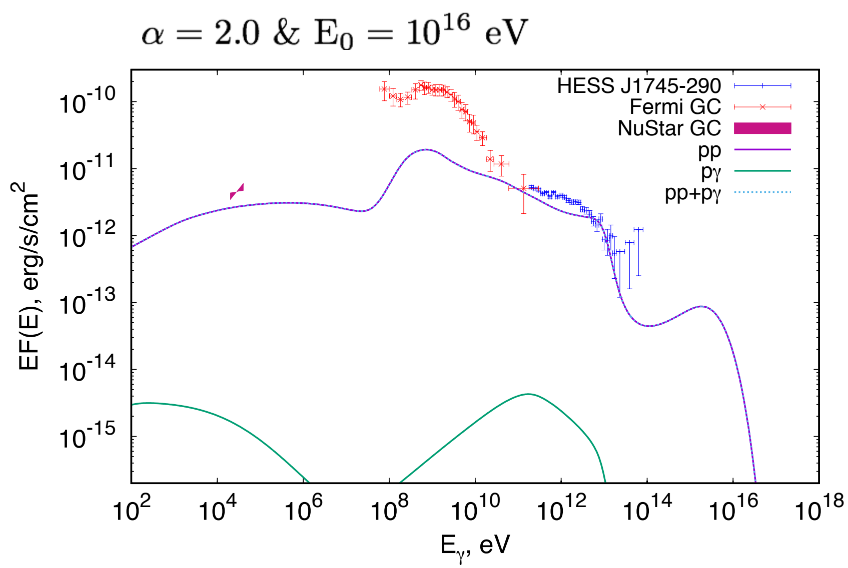
who can tell us**?**

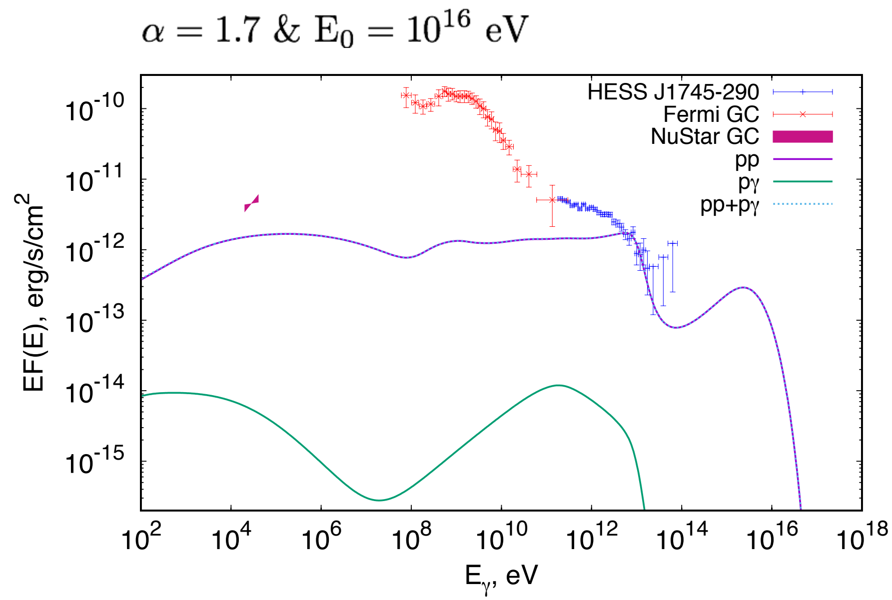
100 TeV - 10 PeV gamma-rays? severe absorption in the far IR (> 100 micron dust) emission

100 TeV - 10 PeV neutrinos? opportunity/challenge… ideally, one needs >>1 km3 scale detector

10 keV -100 keV X-rays ? NuStar, Hitomi , future hard X-ray imagers

X-rays from a few pc region of the GC - secondary synchrotron?





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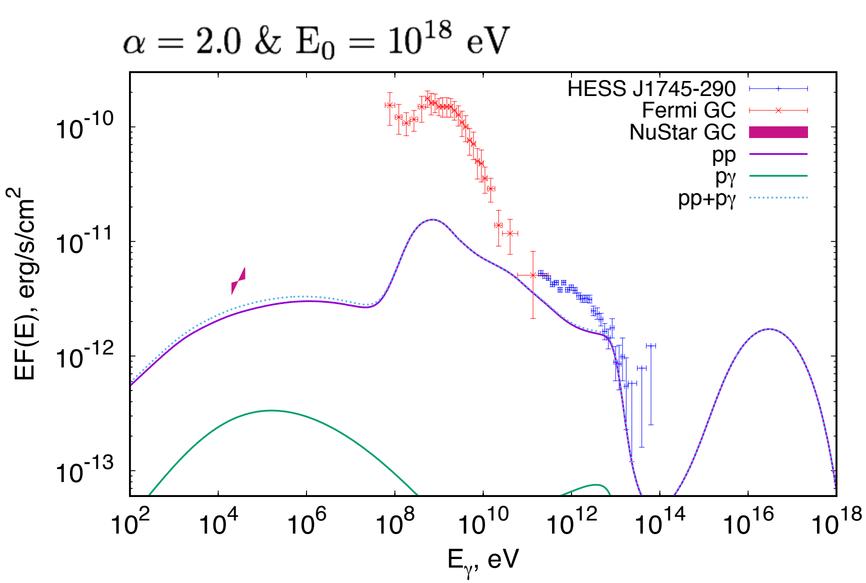

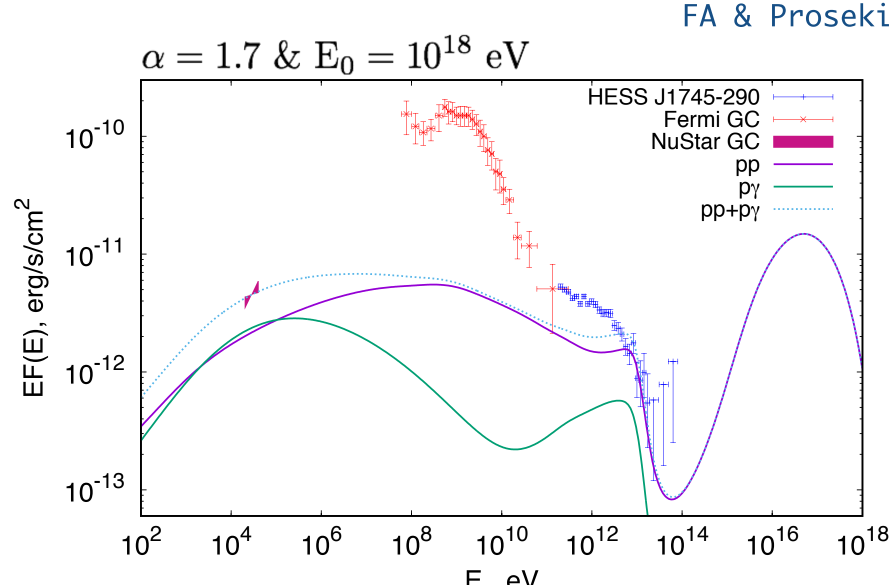

n=100 cm^{-3}; NIR-FIR - as measured from a few pc region

X-ray flux from a compact (~1 acrimin) hard X-ray source can be contributed also by >10 PeV protons interacting with the CMZ gas*

- gas density > 10^3 cm^{-3}; IR density << than in the <10 pc region
  => pp interactions strongly dominate over p-IR interaction

- diffuse X-rays from CMZ too high to be explained by synchrotron radiation of secondary electrons from pp interactions

*) the compact diffuse hard X-ray source detected by NuSTAR can be explained by secondary electrons produced in the CMZ - the angular size of the X-ray image of ~1 arcim is a result of (almost) rectilinear propagation of >10 TeV protons, but not the CMZ's size . This can be realized for a diffusion coefficient in CMZ (~200 pc) region if $D=Do(E/10\ GeV)^{-0.5}$ with $Do \sim 10^{27}$ cm^2/s (smaller than in the Gal. Disk)

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the angular size of the X-ray image could be much smaller than the angular size o gamma-rays although both components are produced in the same CMZ region!

TeV gammas from CMZ are explained by <1 PeV protons, while X-rays from the central (< 10 pc) region are explained by >100 PeV protons provided that <1 PeV protons are propagating in the diffusion regime while > 100 PeV protons in a (quasi)ballistic regime

X-ray source could be point-like or compact if the acceleration spectrum is E^{-s}, with s< 1.8, and diffusion coefficient D=Do(E/10 GeV)^-0.5 with Do~ 10^{27} cm2/s

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

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

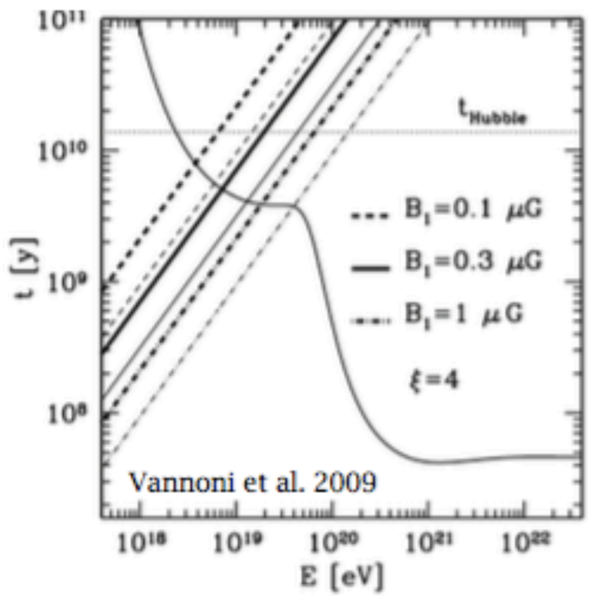


Fig. 1. Acceleration and energy loss time scales as a function of the proton energy. The acceleration time scales are obtained for the values of the upstream magnetic field B_1 reported in figure and a downstream magnetic field $B_2 = 4B_1$. The thick lines correspond to a shock velocity of 2000 km/s,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

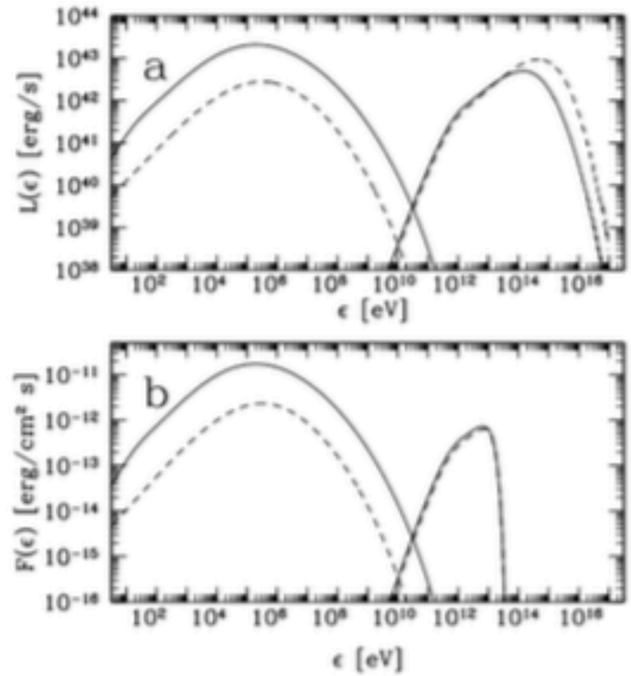


Fig. 13. a) Broadband radiation spectra produced at the source by the electron distributions in Fig. 12**b**, downstream (solid line) and upstream (dashed line). **b)** Energy flux at the observer location, after absorption in the EBL, for a source distance of 100 Mpc. 20

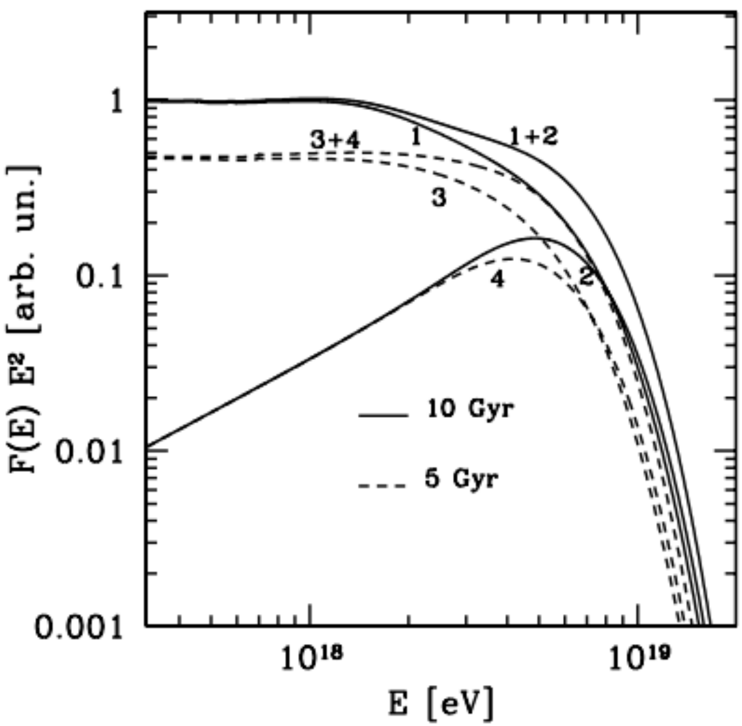


Fig. 3. Spatially integrated spectra for the proton distributions in Fig. 2 for an accelerator age of 10 Gyr (solid lines) and 5 Gyr (dashed lines). The lines 1 and 3 represent the downstream contributions, 2 and 4 the upstream ones, and 1+2 and 3+4 the sum of each pair.

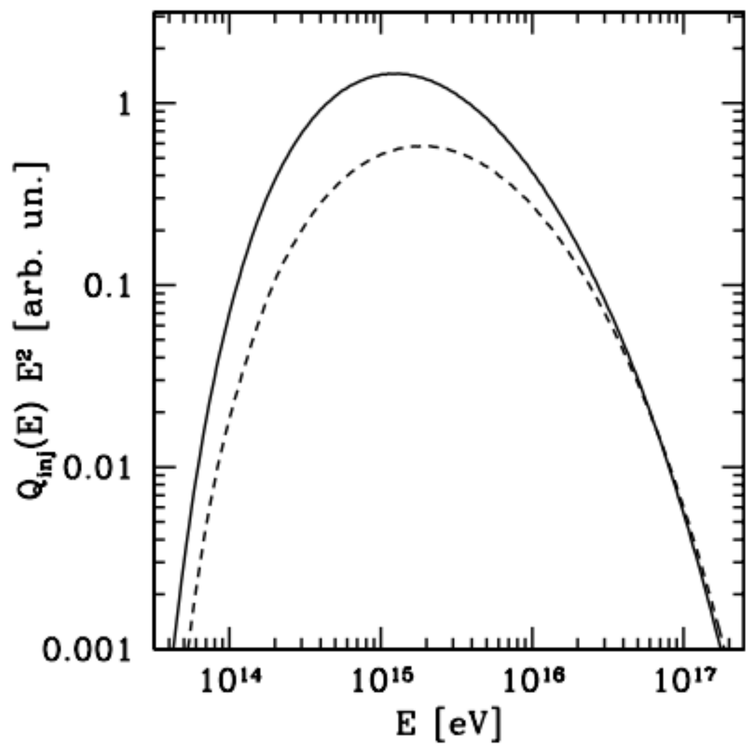
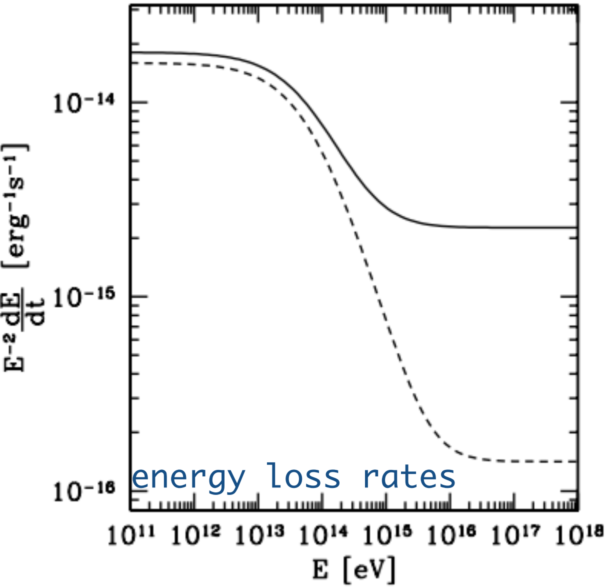
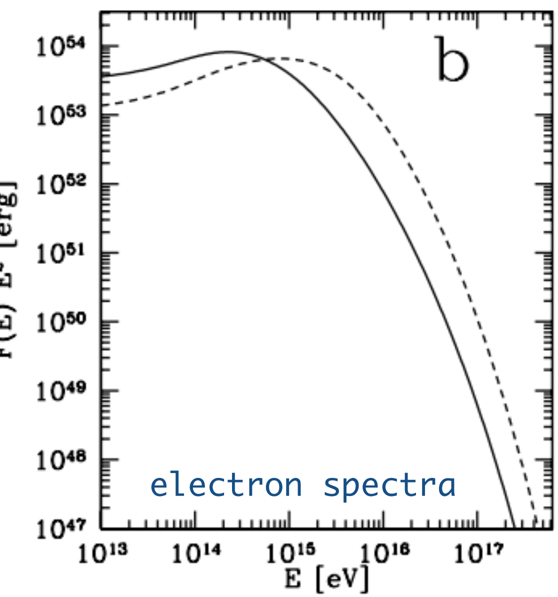
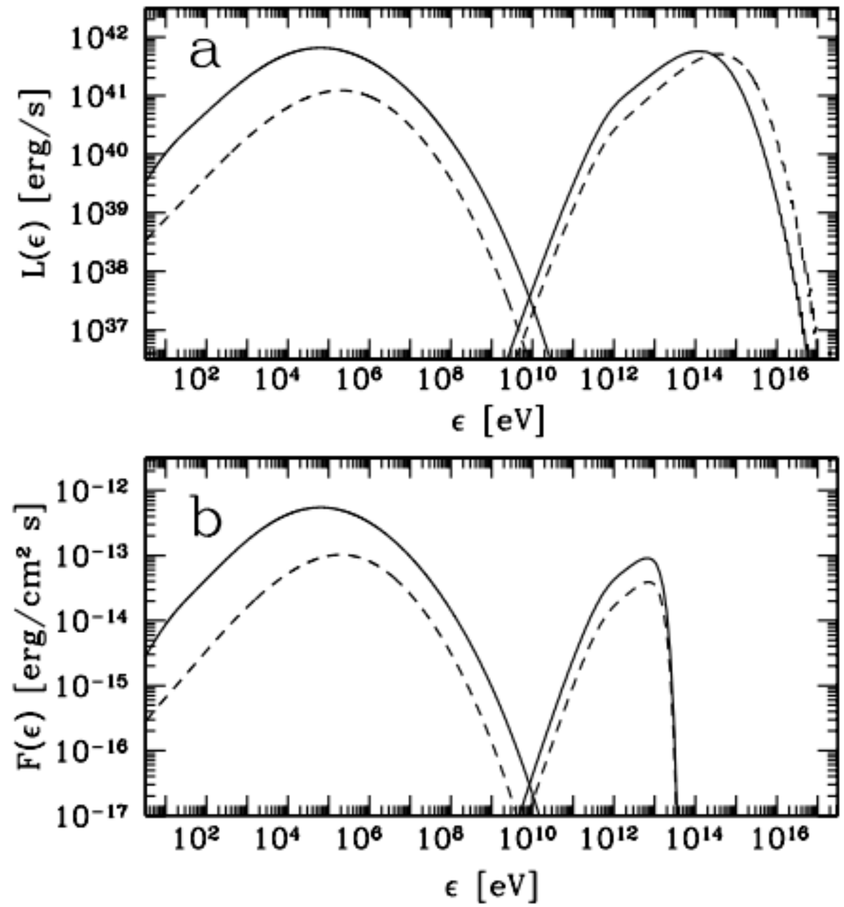


Fig. 4. Production spectra of pairs. Solid line: downstream spectrum an accelerator age of 5 Gyr; dashed line: upstream spectrum.







while the crucial >30 TeV gamma-rays disappear, synchrotron hard X-rays/soft-gamma-rays remain the only carriers of information about EeV protons; and, apparently, no way to detect neutrinos…

Summary

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

TeV gamma-rays: effectively produced/detected, although it is not an easy task to identify the "hadronic" origin. Great expectations from CTA!

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

TeV/PeV/EeV neutrinos: difficult to detect

alternatives? - *hard X-rays of secondary electrons*

future hard X-ray imager with PSF < 10 arcsec and $F_{min} < 10^{-14}$ erg/cm^{2}s

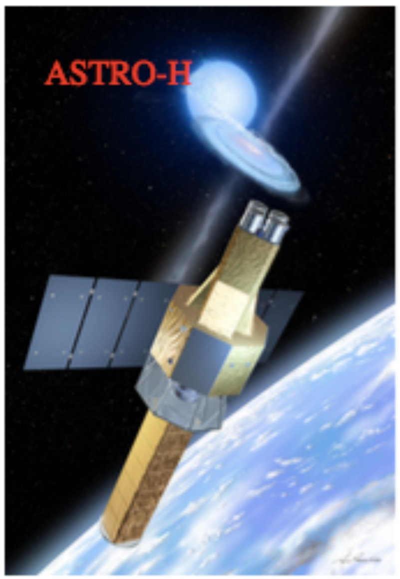
Probing hadrons with secondary hard X-rays

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

Energy Band: 3 - 80 keV
Angular resolution : 58" (HPD), 18" (FWHM)
Energy Resolution: 0.4 keV at 6 keV, 0.9 keV at 60 keV (FWHM)



- X-ray imaging and spectroscopy in the hard X-ray band
- angular resolution one arcmin (10")
- Minimum detectable energy flux down to 10^{-14} erg/cm^{2}s !