Exploring Nature's Extreme Accelerators with High Energy Gamma-rays

Felix Aharonian

Dublin Institute for Advanced Studies, Dublin

Max-Planck Institut f. Kernphysik, Heidelberg

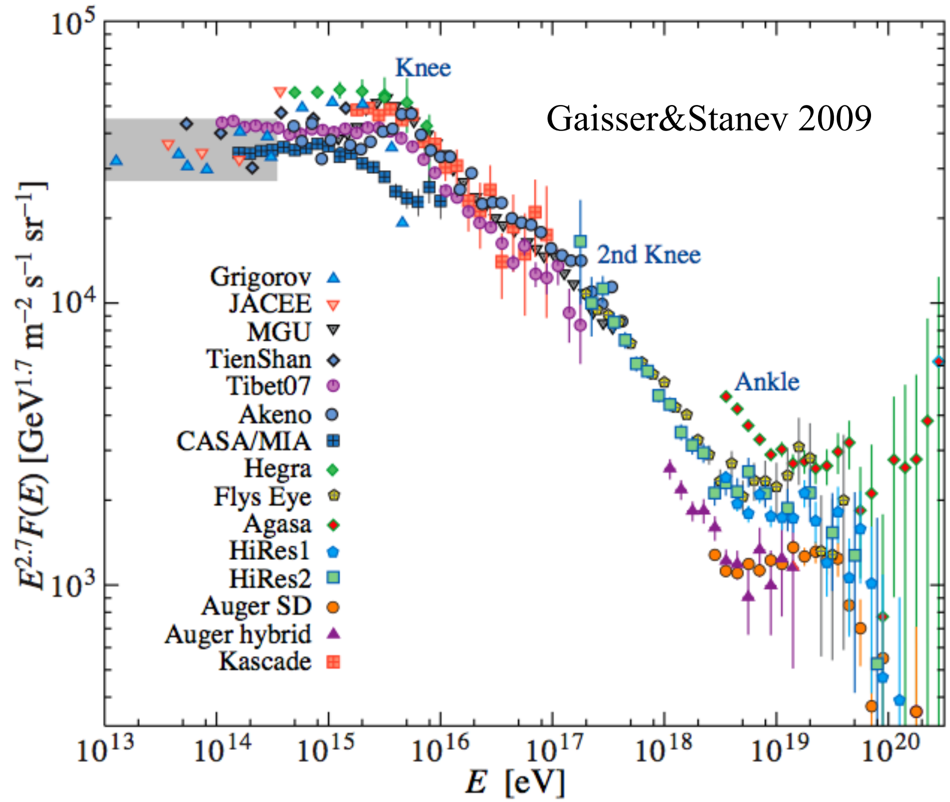
Florianopolis, USFC, March 11, 2016

Origin of Cosmic rays - "after 100yr of the discovery still a mystery"

energy range: 10^9 to 10^{20} eV

what do we know about CRs:

- before the knee - galactic
- after the ankle - extragalactc
- between knee and ankle ?



all particle cosmic ray spectrum

Galactic Cosmic Rays:

basic facts:

energy density: ~ 1eV/cm^3 ; age: ~ 10^7 yrs,

production rate: (0.3-1) x 10^{41} erg/s, source spectrum: hard Q(E) ~ E^{-2}

sources ?

✓ SNRs: protons up to 10^{15} eV – in principle possible by strong shocks but provided that the magnetic field is enhanced by at least an order of magnetude by CRs (Bell 2004). In any case so far we do not have evidence of SNRs operating as CR PeVatrons…

✓collective stellar winds and SNR shocks in clusters and associations of massive stars (e.g. Cesarsky and Montmerle 1982, Bykov & Toptygyn 2001)

✓other potential sources? Galactic Center (Sgr A*)? "GRB remnants", pulsars?

one cannot exclude that the observed CR flux up to 10^{15}eV is significantly contributed (or even dominated) by a single (or a few) local sources (e.g. Erlykin&Wolfendale 2010), i.e. we see a "local fog"; this is the case of TeV electrons (e.g. Aharonian et al 1995)

Extragalactic Cosmic Rays

EXG origin of CRs? certainly above 10^{19} eV or perhaps even avove 10^{17} eV;

at lower energies? problematic: $t \sim R^2/D$; for any reasonable diffusion coefficient, the propagation time from multi-Mpc distances exceeds Hubble time $\sim 10^{10}$ yr

actually, because of interactions with 2.7 K MBR, the highest energy (10^{20}eV) CRs also represent a "local fog" (nearby universe): R ~ 100 Mpc or less:

"GZK cutoff" is not a cosmological effect!

paradoxically only particles of $E < 10^{18}$ eV can (in principle) carry cosmological information- in the case of extremely weak intergalactic magnetic fields $<10^{-15}$ G

sources ?

go to the "Hillas Plot", but don't be mislead - viable options are quite limited -

it implies acceleration of particles at maximum possible rate: $t_{acc} \sim c/R_L$.

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 $t_{acc}=R_L/c=E/eBc$

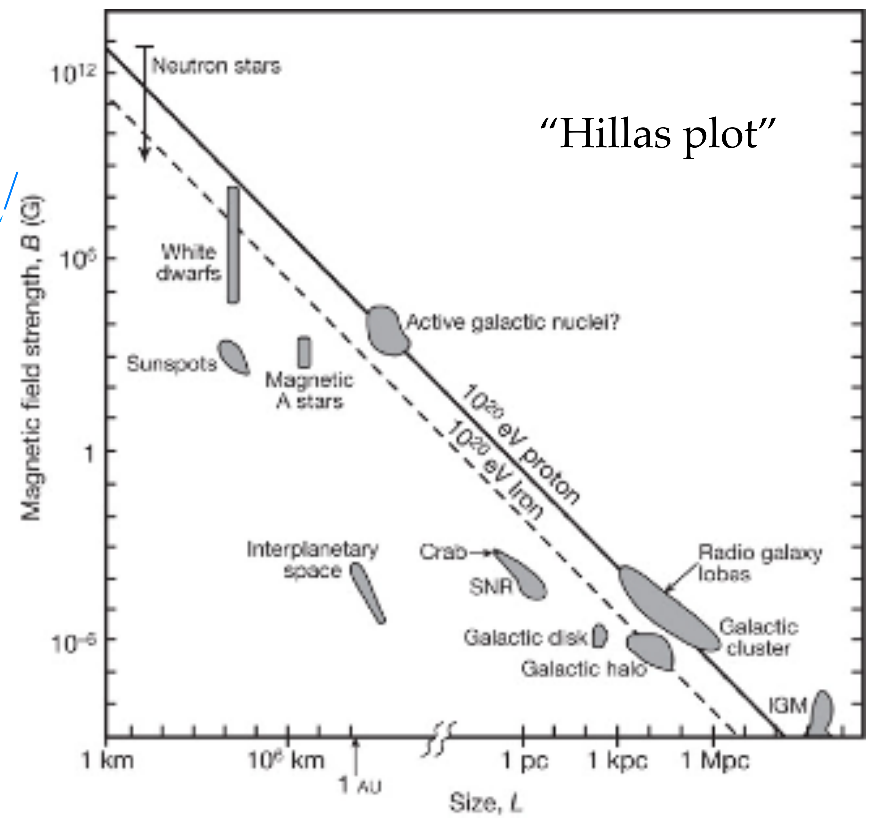
acceleration in fact is slower:

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

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

Two major issues related to Cosmic Rays

origin of 10^{15} eV CRs

Galactic!

SNRs – likely but

mechanisms – DSA ?

origin of 10^{20} eV CRs

Extragalactic!

AGN and GRBs

mechanism - relativistic shocks?

10^{18} eV – less attention,

more uncertainties

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 ($T > 10^7$ yr) timescales…

it is not a big surprise that the origin of CRs is yet a mystery!

origin of CRs can be revealed only by *astronomical means;*
the astronomical messengers should be *neutral & stable*:*

gamma-rays and neutrinos, but partly also neutrons

$d < (E_n/m_n c^2)\, c\, t_o \;\Rightarrow\; E_n > 10^{17}(d/1\text{ kpc})\text{ eV}$

do satisfy fully to these conditions;

*astronomy with protons?: only for $E \sim 10^{20}$ eV if IGMF $B < 10^{-11}$ G

why gamma-rays?

gamma-rays are unique carriers of astrophysical/cosmological information about nonthermal phenomena in many galactic and extragalactic sources

✓ are effectively produced in E-M and hadronic interactions
(“*good*” but also “*bad*”)

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

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

=> often information arrives after significant distortion

VHE gamma-ray astronomy - *a success story*

over last several years the field has bee revolutionized

before – "astronomy with several sources"

(an activity related to *Astroparticle Physics rather than Astronomy*)

now – a truly astronomical discipline with characteristic key words:

energy spectra, images, lightcurves, surveys...

with more than 100 reported gamma-ray sources representing more than 10 Galactic & Extragalactic populations in the energy interval 0.1 TeV to 100 TeV

first conclusions from VHE gamma-ray observations:

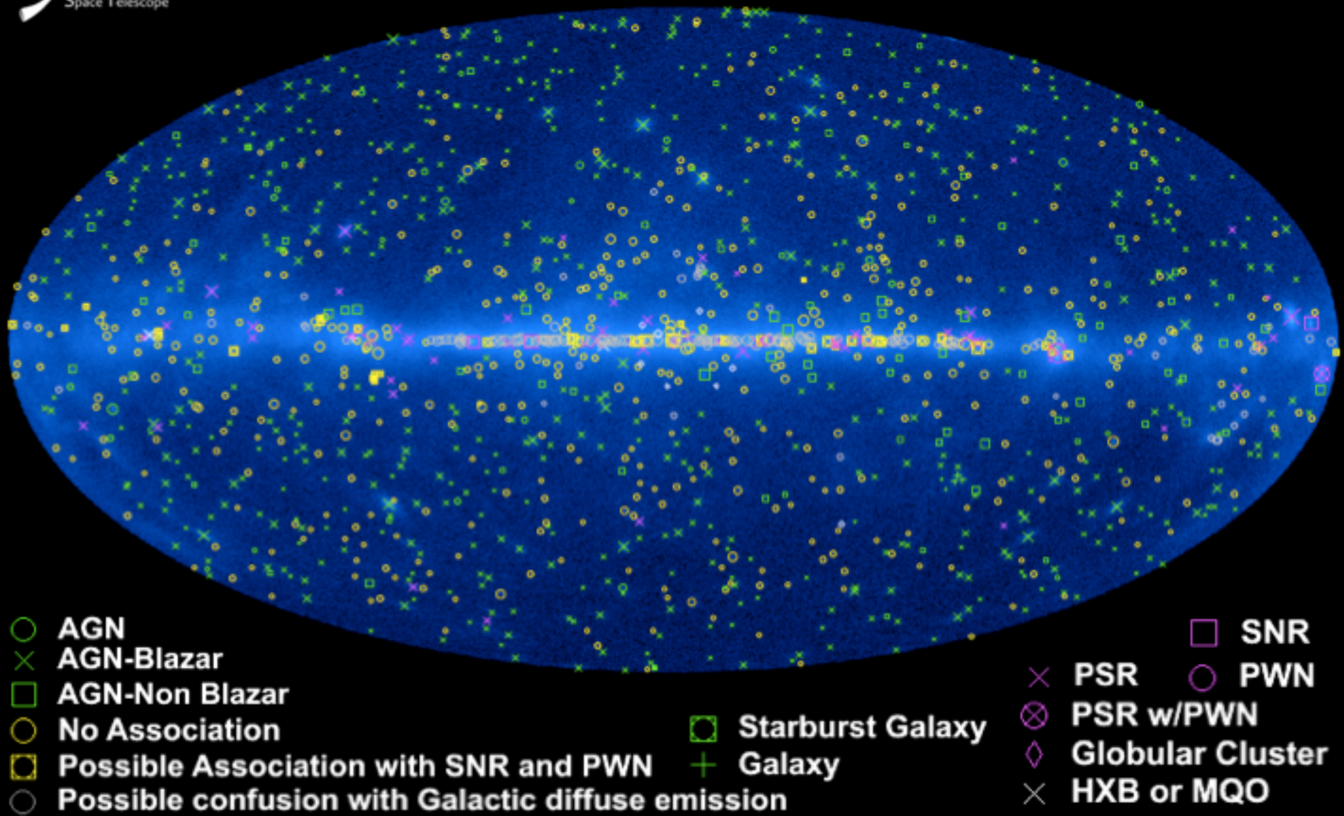
Universe is full of Extreme Accelerators - TeVatrons (and PeVatrons ?)

Clear views concerning future: CTA, LATTES?

Fermi LAT: good sensitivity, reasonable angular resolution, large FoV

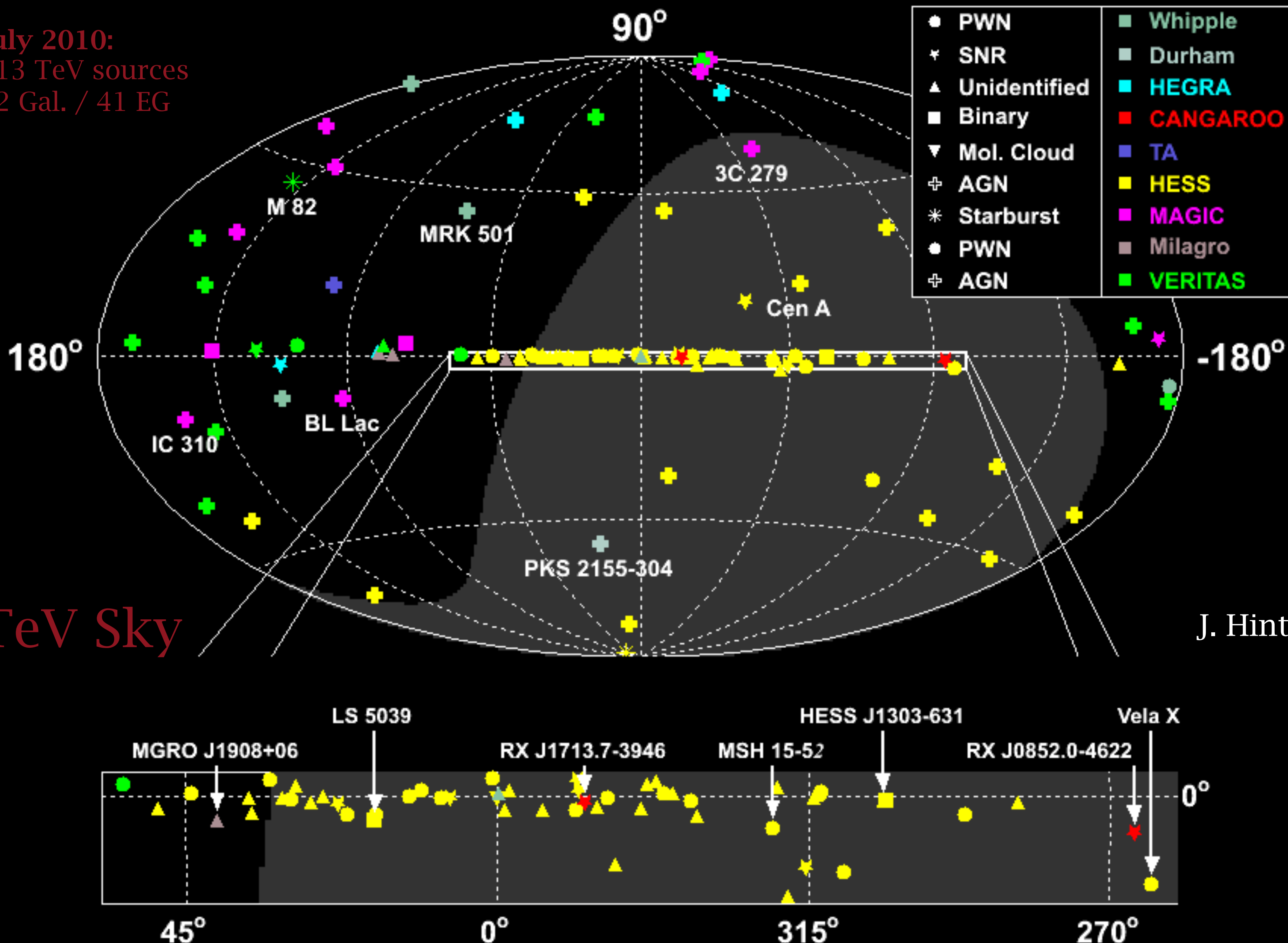
thousand of sources - diffuse structures - monitoring transient GeV phenomena

Continuous watch of the GeV Sky



Credit: *Fermi* Large Area Telescope Collaboration

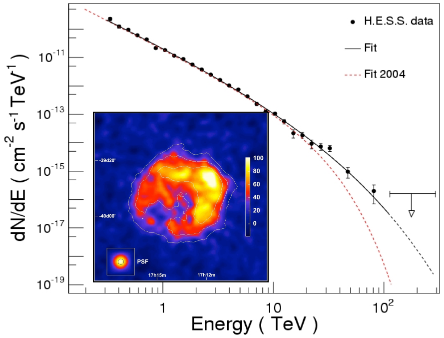
July 2010:
113 TeV sources
72 Gal. / 41 EG



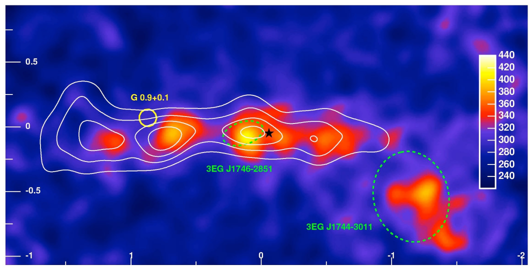
TeV Sky

J. Hinton

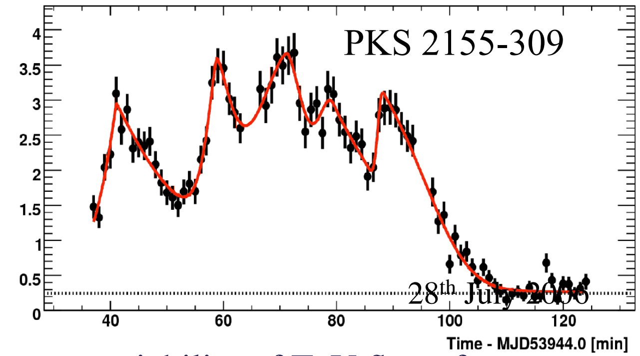
IACTs : good performance* => high quality data



TeV image and energy spectrum of a SNR



resolving GMCs in the Galactic Center 100pc region



variability of TeV flux of a blazar on minute timescales

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

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

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

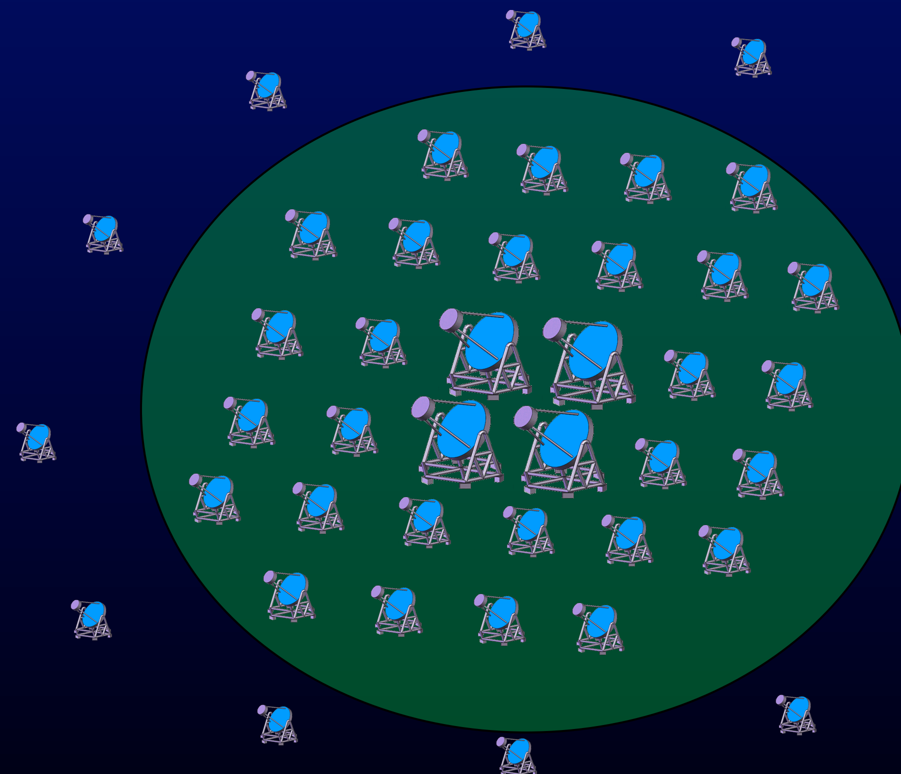
Galactic Astronomy | Extragalactic Astronomy | Observational Cosmology

E: 0.1-100TeV, $\Delta E/E \sim 15\text{-}20\%$, $F_{min} \sim 3\ 10^{-13}$ erg/cm^{2}s, $\delta\phi \sim$ a few arcmin, $L_{min} \sim 3\times10^{30}$ erg/s $(d/1\text{kpc})^2$


H.E.S.S.

towards next generation IACT Arrays:

- ✓ an order of magnitude better sensitivity
- ✓ broader energy coverage: 10^{10} to 10^{15} eV



from HESS/MAGIC/VERITAS to CTA…

VHE gamma-ray source populations

Extended Galactic Objects

- ✓ Shell Type SNRs
- ✓ Giant Molecular Clouds
- ✓ Star formation regions
- ✓ Pulsar Wind Nebulae

Compact Galactic Sources

- ✓ Binary pulsar PRB 1259-63
- ✓ LS5039, LSI 61 303 – microquasars?
- ✓ Cyg X-1 ? (a BH candidate)

Galactic Center

Extragalactic objects

- ✓ M87, Cen A - radiogalaxy
- ✓ TeV Blazars – with redshift from 0.03 to 0.18
- ✓ NGC 253 and M82 - starburst galaxies
- ✓ GRBs (Fermi LAT; photons of tens of GeVs at $z > 1$)

and a large number of yet unidentified TeV sources …

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 and AGN <u>can be as large as 50 %</u>

(ii) maximum (theoretically) possible energy achieved by individual particles

acceleration rate close to the <u>maximum (theoretically) possible rate</u>

sometimes efficiency can even "exceed" 100% ?

(no violation of conservation laws - but due to relativistic and non-linear effects)

<u>analogy with X-ray Astronomy:</u>
as cosmic plasmas are easily heated up to keV temperatures - almost everywhere, particles (electrons and protons) can be easily accelerated to TeV energies - almost everywhere, especially in objects containing relativistic outflows -jets & winds

acceleration sites of 10^{20} eV CRs ?

*Aharonian et al. 2002, Phys Rev D, **66**, id. 023005*

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

signatures of extreme accelerators?

✓ synchrotron self-regulated cutoff:

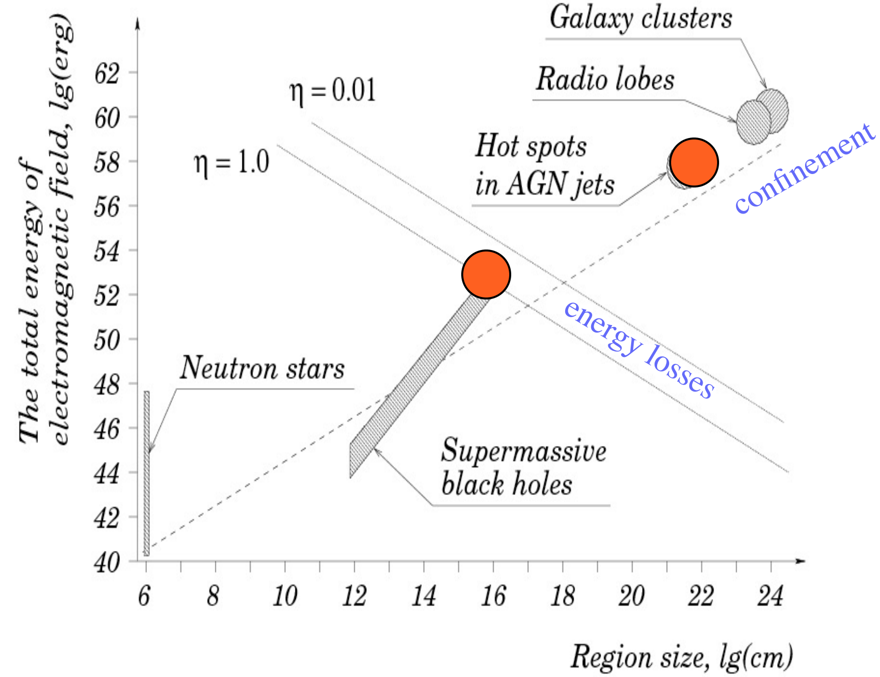
$$h\nu_{\rm cut} = \frac{9}{4}\alpha_f^{-1} mc^2 \eta :$$

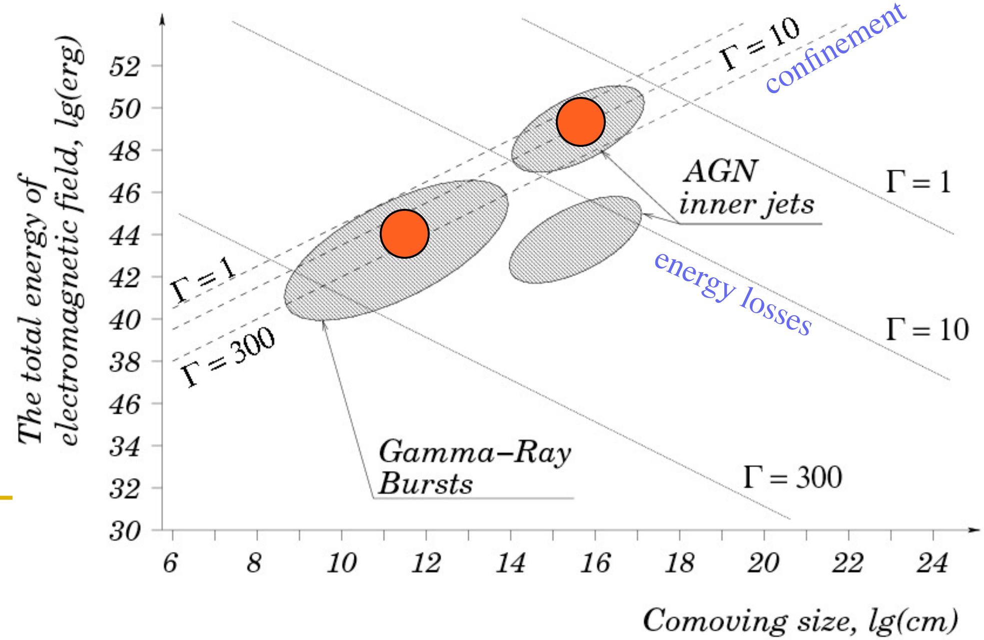
$\simeq 300\mathrm{GeV}$ proton synchrotron
$\simeq 150\mathrm{MeV}$ electron synchrotron

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! (Deerishev et al. 2003)

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



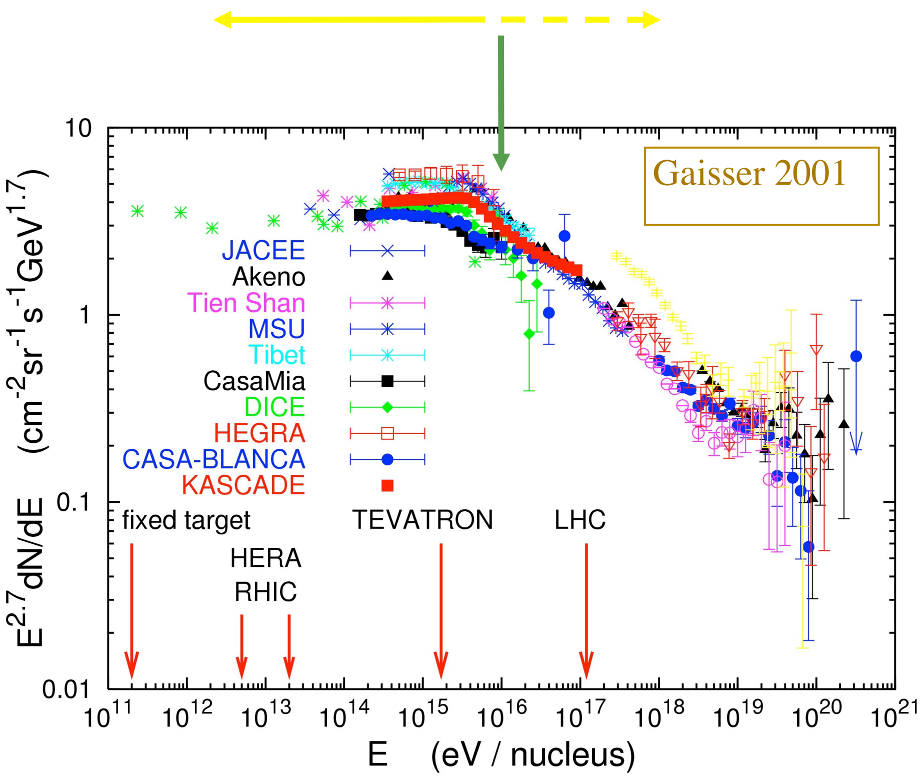


*) in nonrelativistic shocks $\eta \approx 0.1(v_{\rm shock}/c)^2$

SNRs as the most likely sources
of galactic cosmic rays?

Galactic TeVatrons and PeVatrons - particle accelerators responsible for cosmic rays up to the “knee” around 1 PeV

Supernova Remnants?



two attractive features:

- ✓ *available energy:* $W_{CR} \sim 0.1 E_{SN}$
- ✓ *effective mechanism* (DSA)

one of the key objectives of the high energy gamma-ray astronomy: confirmation that SNRs operate as PeVatrons, and can provide the bulk of Galactic CRs up to $E \sim 10^{15}$ eV

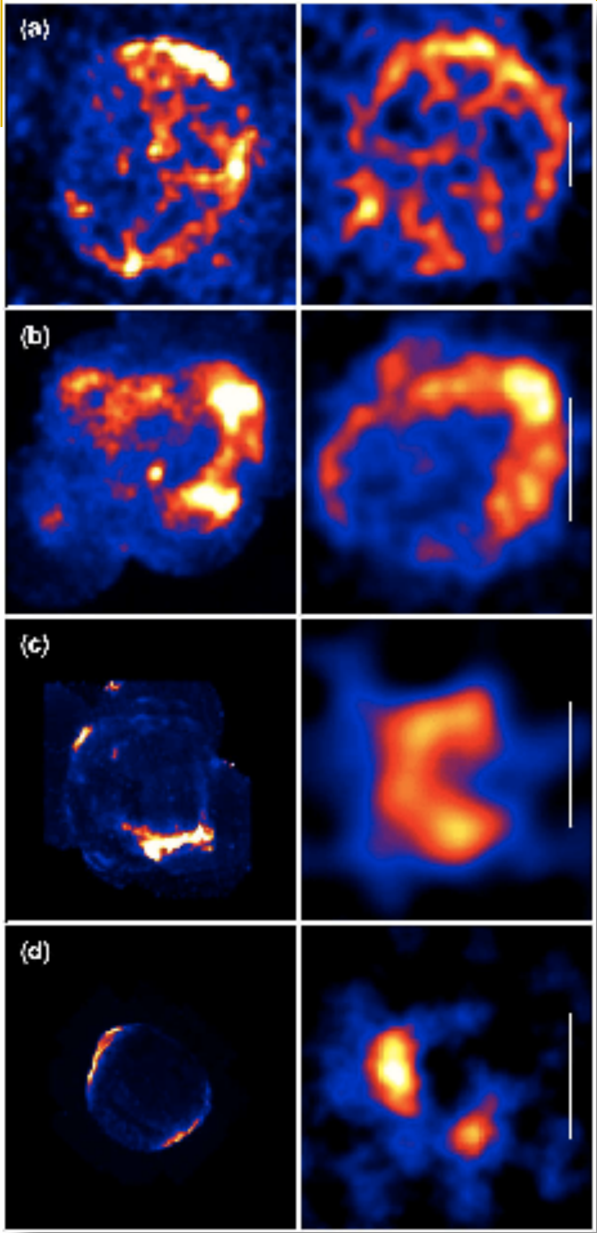
other possible sources?

Pulsars/Plerions

OB, W-R Stars

“microquasars”

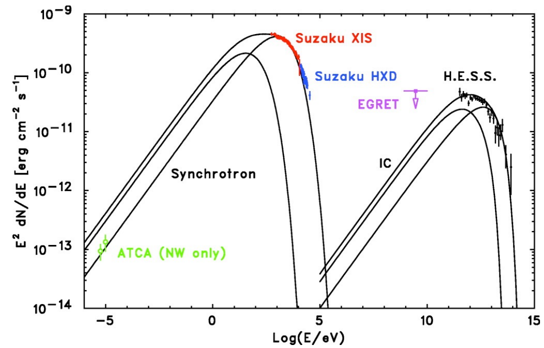
Galactic Center

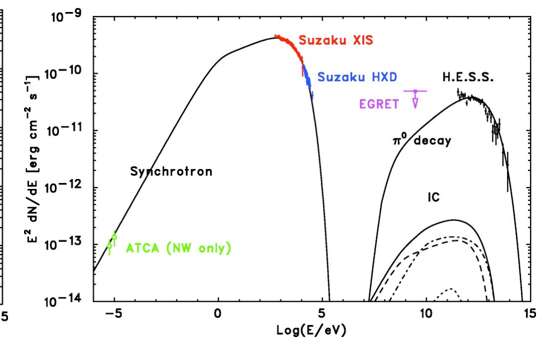


=>

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

$B=15\mu G$

$We \approx 3.4\ 10^{47}$ erg/cm^3

γ-rays from pp ->π^o ->2γ

$dN/dE=A\ E^{-\alpha} \exp(-E/Eo)$
with $\alpha=1.7$, $Eo \approx 25$ TeV,
$B=200\mu G$

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

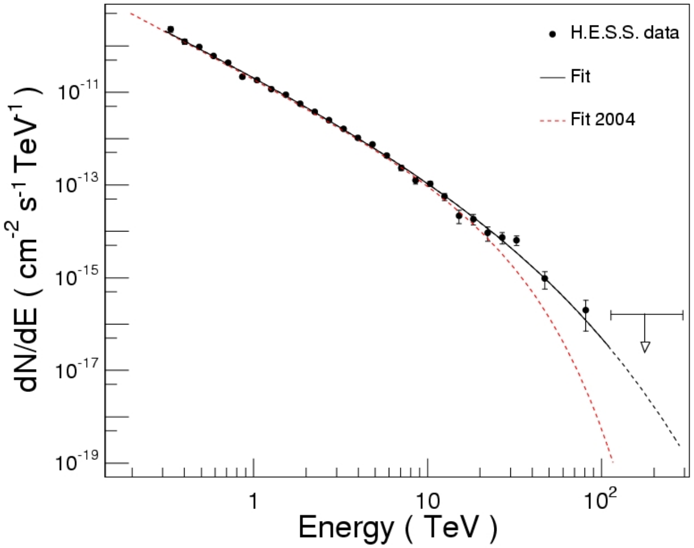
unfortunately we cannot give preference to hadronic or leptonic models - both have

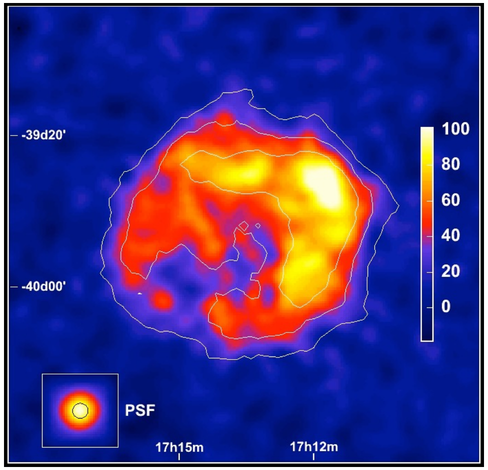
attractive eatures but also serious problems

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

RXJ1713.7-4639

TeV γ-rays and shell type morphology: acceleration of p or e in the shell to energies exceeding 100TeV





can be explained by γ-rays from pp $\to \pi^0 \to 2\gamma$

HESS: $dN/dE = K\, E^{-\alpha} \exp[-(E/E_o)^{\beta}]$

α=2.0 Eo=17.9 TeV β=1

α=1.79 Eo=3.7 TeV β=0.5

with just "right" energetics:
$W_p = 10^{50}\,(n/1\mathrm{cm}^{-3})^{-1}$ erg/cm^3

(e.g. Berezhko et al, Blasi et al 2007+)

but IC models generally are more preferred… because of TeV-X correlations (?)

IC origin of γ−rays cannot indeed excluded, but this is not a good argument

real problems related to hadronic models:

- lack of thermal emission in RXJ 1713.7-3946

  almost all available energy goes to particle acceleration? (Drury et al 2010)

- p/e ratio > 10^3 - cosmic rays p/e ~ 100

  in Cas A p/e in principle could be 100, but could be also less than 10

- "early cutofs" - in all SNRs Ecut < 100 TeV

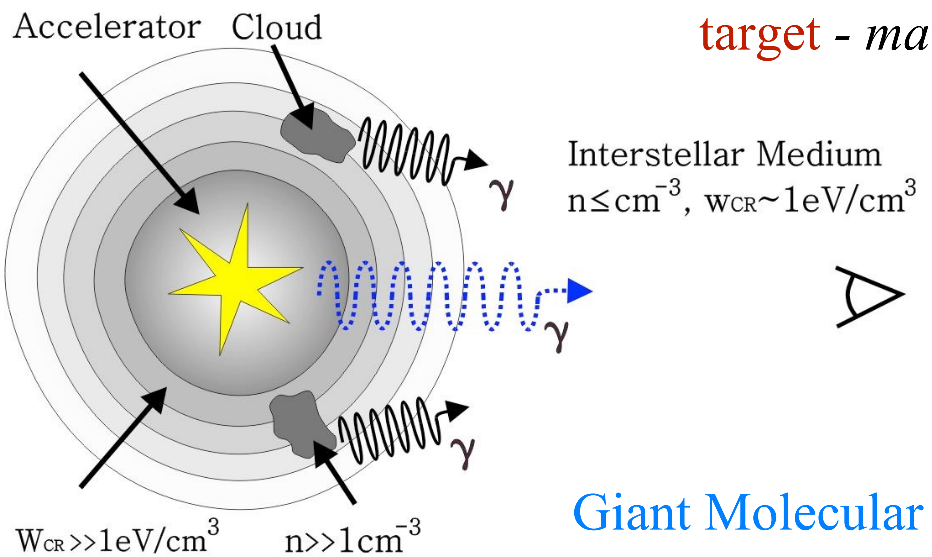
  because of escape? do they contribute to the the region around the "knee"

paradoxical conclusion: from the point of view of the SNR paradigm of CRs
leptonic (but not hadronic!) models of gamma-rays are more comfortable

=> there are protons in SNRS with spectra up to 1 PeV but ….
we do not "see" them because of the low density ambient gas

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*

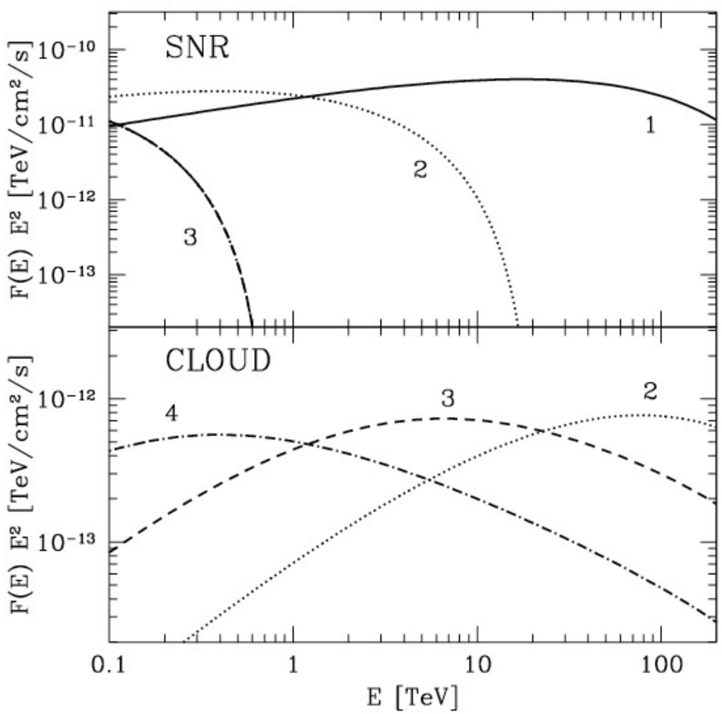
Giant Molecular Clouds as barometers of CRs

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

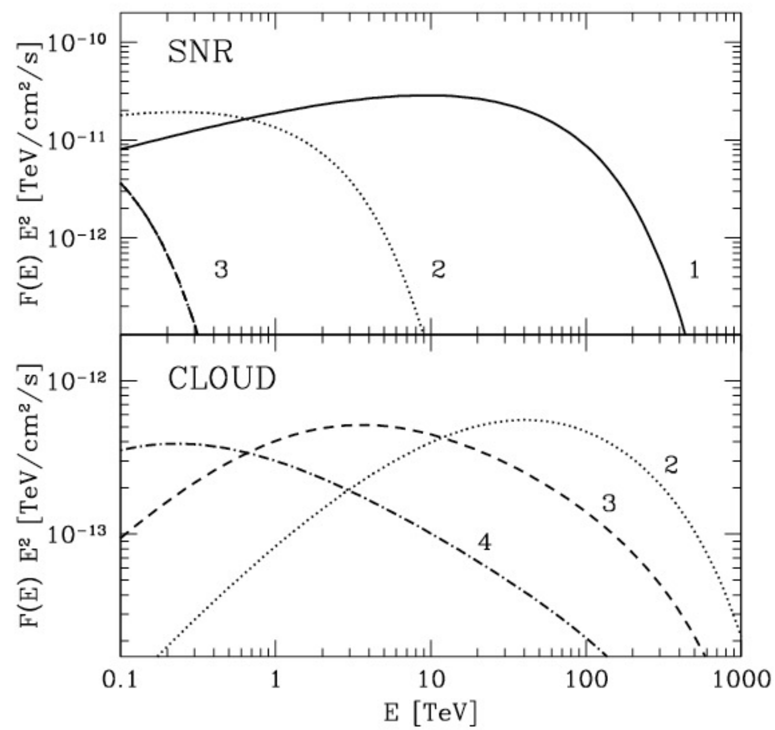
Gamma-rays and neutrinos inside and outside of SNRs

1 - 400yr, 2 - 2000yr, 3 - 8000yr, 4 - 32,000 yr

gamma-rays



neutrinos



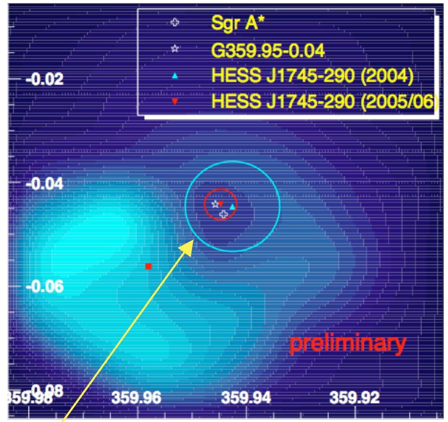
SNR: $W_{51}=n_1=u_9=1$ d=1 kpc GMC: $M=10^4\ M_o$ d=100pc

ISM: $D(E)=3\times10^{26}(E/10\mathrm{TeV})^{1/2}\ \mathrm{cm}^2/\mathrm{s}$

S. Gabici & FA

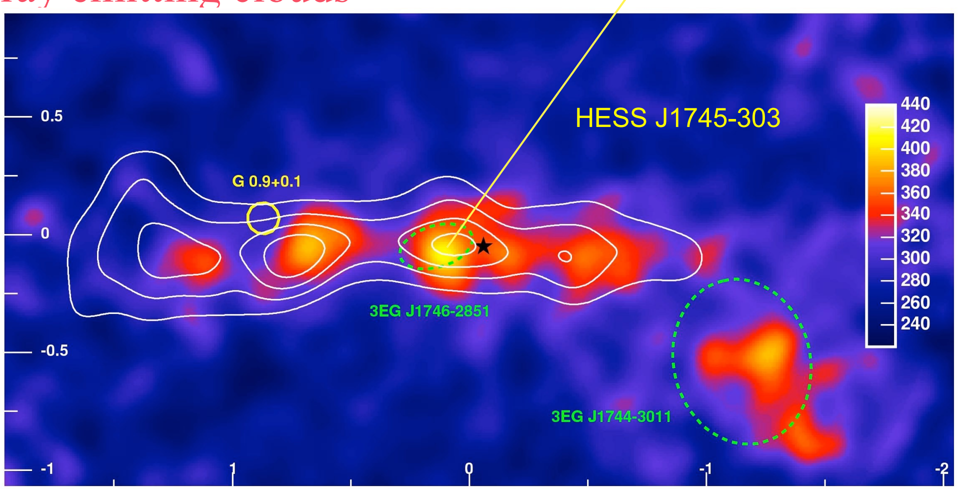
Galactic Center

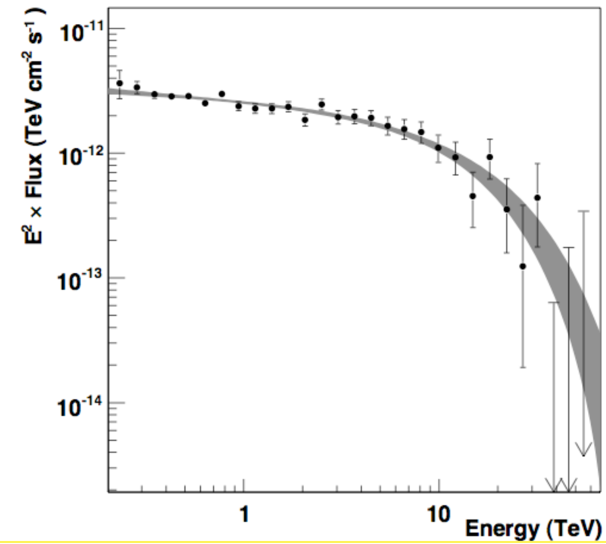
90 cm VLA radio image



Sgr A* or the central diffuse < 10pc region or a plerion? [no indication for variation]

γ-ray emitting clouds





Energy spectrum:

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

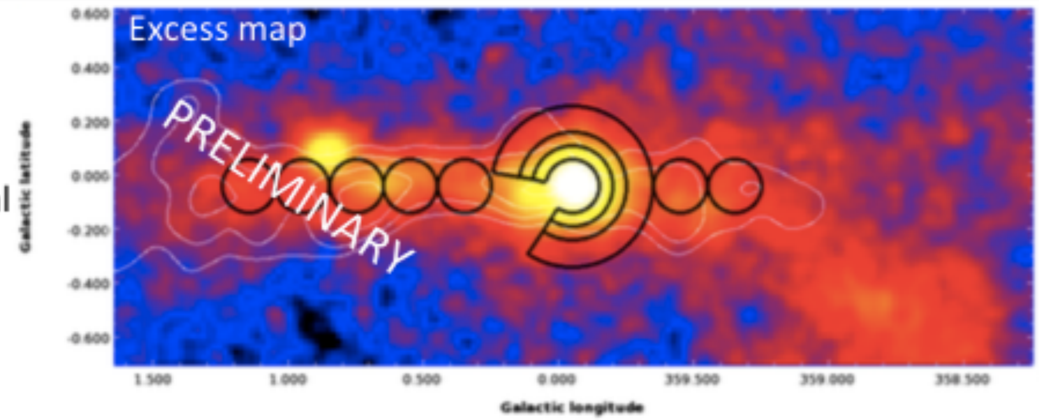
β=1	Γ=2.1; E_0=15.7 TeV
β=1/2	Γ=1.9 E0=4.0 TeV

γ-rays from GMCs in GC: a result of an active phase in Sgr A* with acceleration of CRs some 10^4yr ago?

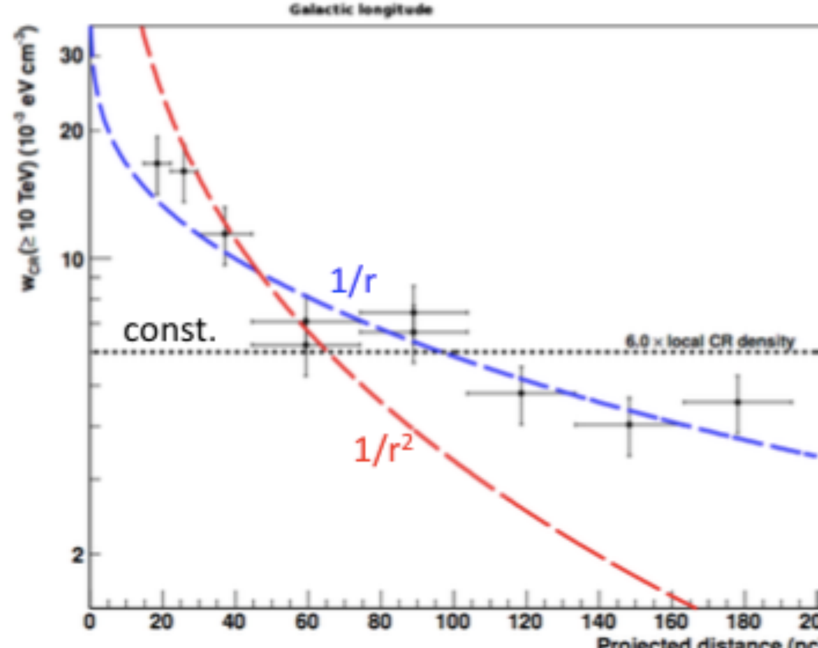
new!

Cosmic-ray density distribution

- Correlation with molecular clouds => pp interaction target mass (M)
- Gamma-ray luminosity (L) in several regions
- => CR density ∝ L/M



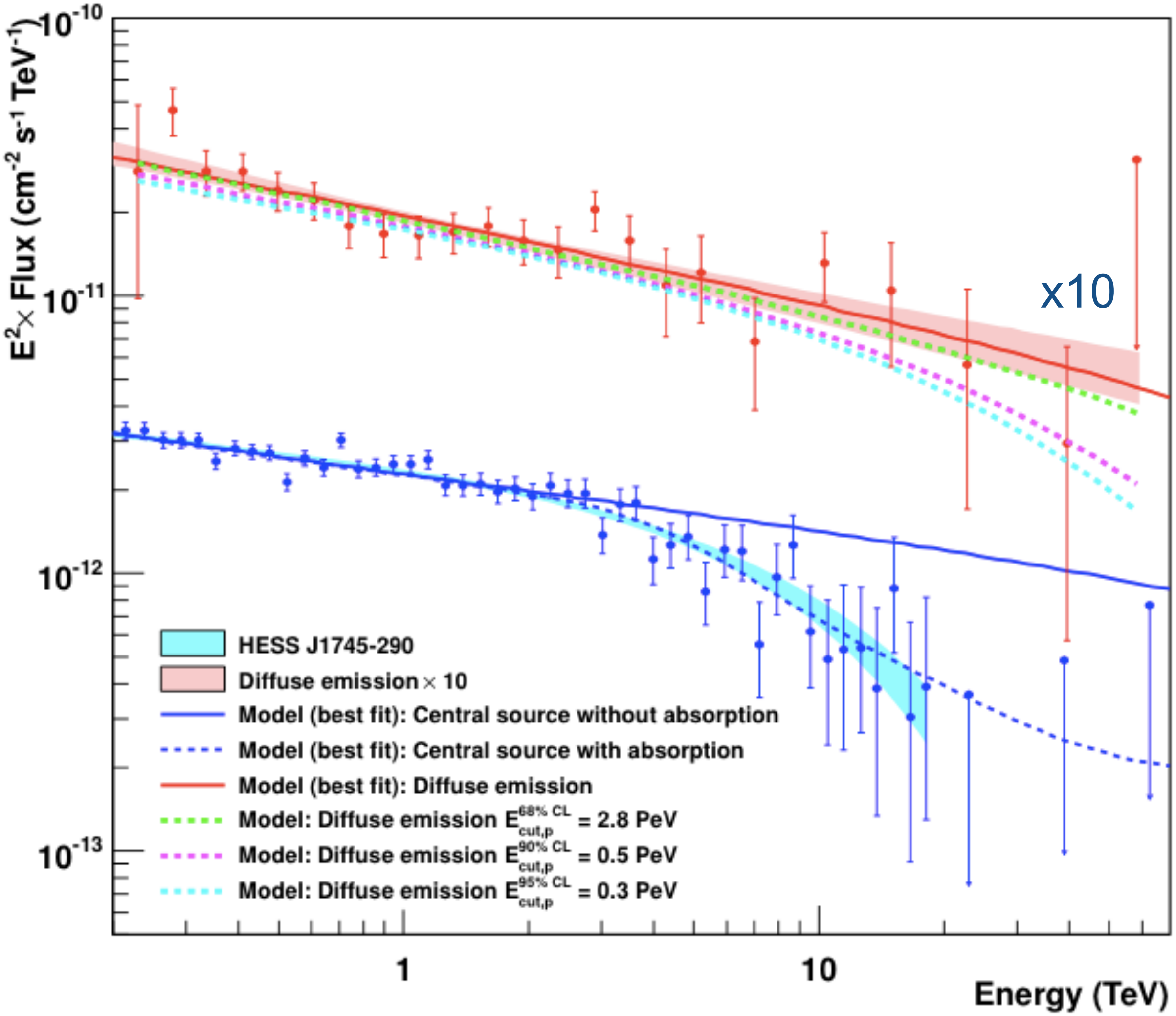
CR density radial distributions:
- Homogeneous => Impulsive injection of CRs and diffusive propagation
- 1/r2 => Wind-driven propagation
- 1/r => continuous injection and diffusive propagation



Central accelerator located within 10 pc and injecting CRs continuously for > 1 kyrs

new!

GC: the central source and the diffuse emission of CMZ

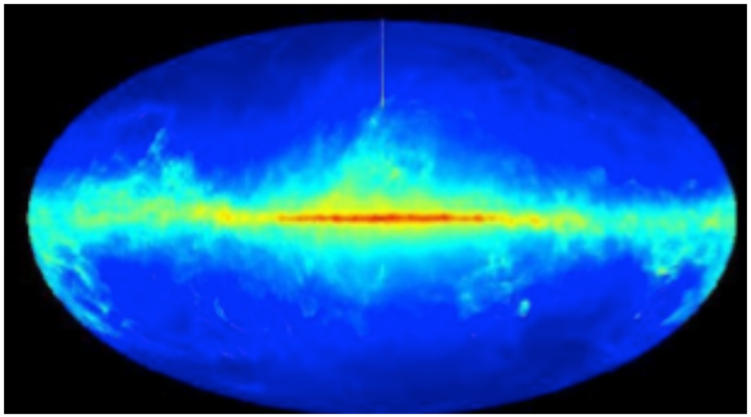


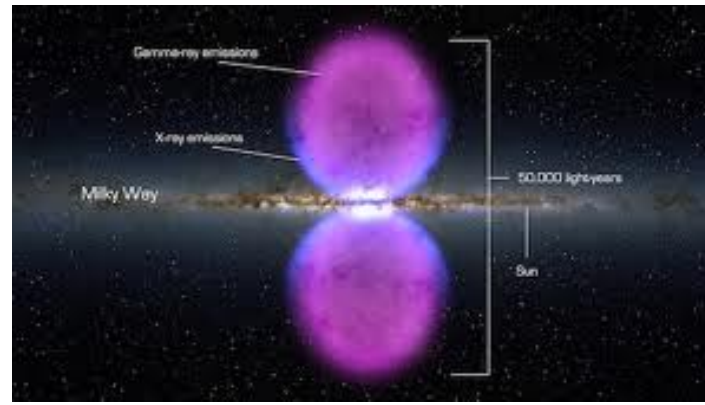
Conclusions:

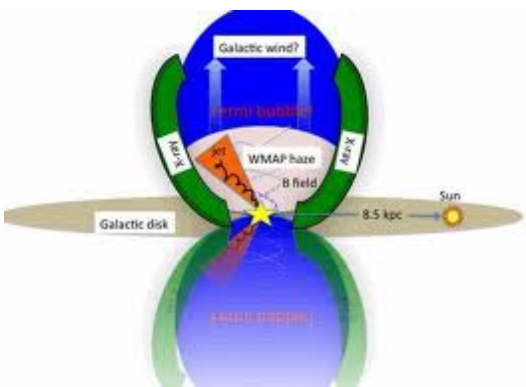
- Galactic Center (GC) harbors a hadronic PeVatron within a few pc region around Sgr A* a suspected SMBH
- 1/r type distribution of the CR density implies (quasi)continuous regime of operation of the accelerator with a power 10^{38} erg/s (on timescales 1 to 10 kyr) - a non negligible fraction of the 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 volumee neutrino detector
- perfect target for CTA - to search for the variability of the central source, to measure the spectrum of diffuse (CMZ) gamma-rays up to 100 TeV and beyond

one of the most important discoveries of *FERMI* LAT:

Fermi Bubbles!



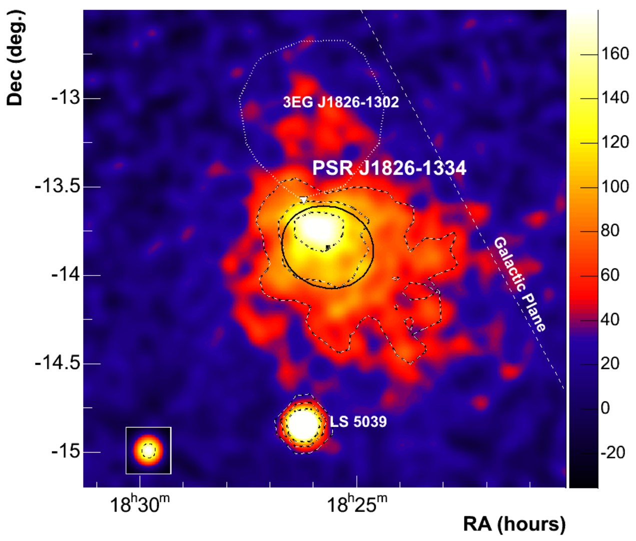




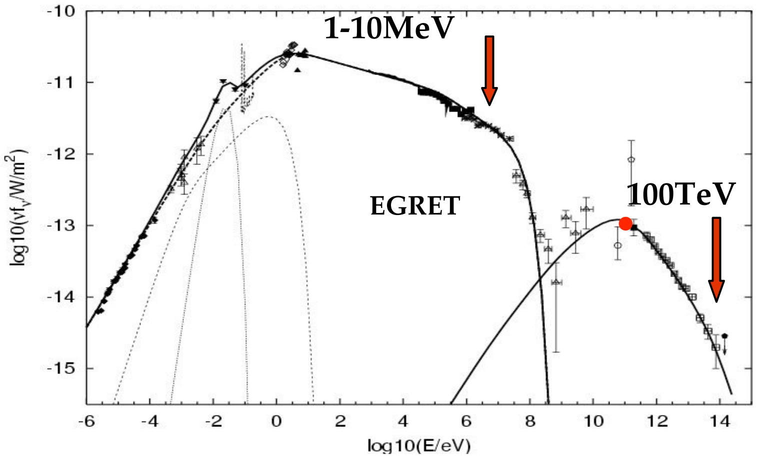
Finkbeiner and collaborators 2010

should be a link, in one way or another, to the Galactic Center

Pulsar Wind Nebulae:
electron PeVatrons



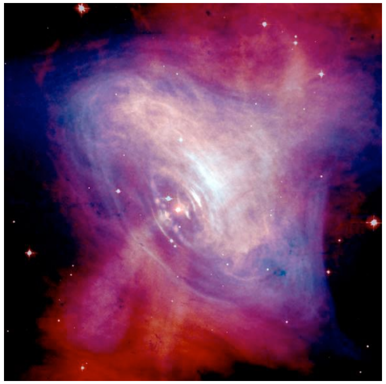
Crab Nebula – *a perfect electron PeVatron*



standard MHD theory (Kennel&Coroniti)

cold ultrarelativistc pulsar wind terminates by reverse shock resulting in acceleration of multi-TeV electrons

synchrotron radiation => nonthermal optical/X nebula
Inverse Compton => high energy gamma-ray nebula

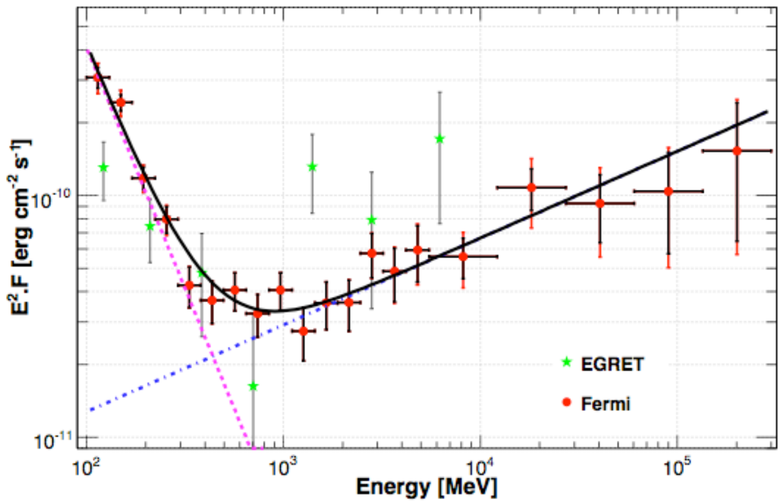


Crab Nebula – a powerful L_e=1/5L_{rot} ~ 10^{38} erg/s
and extreme accelerator: Ee >> 100 TeV

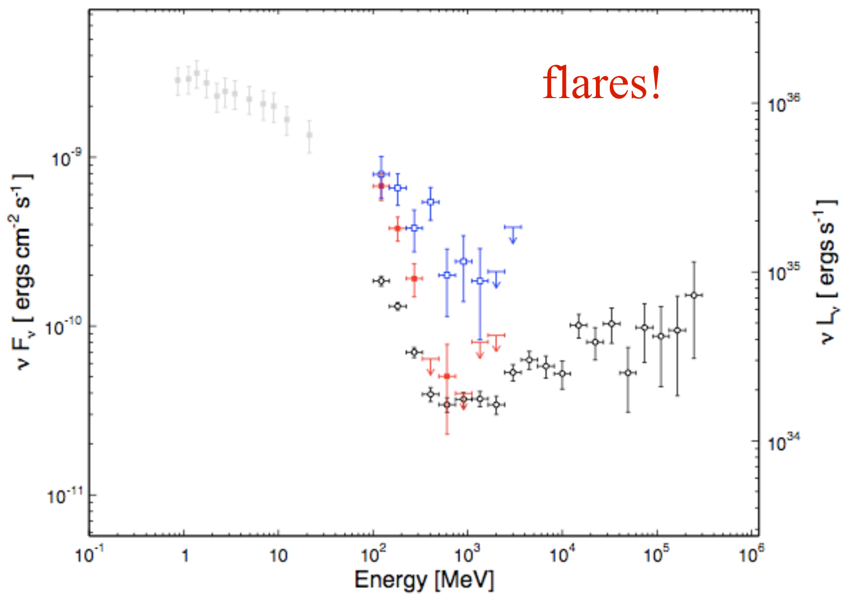
E_{max}=60 $(B/1G)^{-1/2}$ $\eta^{-1/2}$ TeV and $h\nu_{cut}$ ~150η^{-1} MeV

Cutoff at $h\nu_{cut}$ =10-20 MeV => η ~10 - acceleration at 10 % of the maximum rate
γ-rays: E_γ ~ 50 TeV (HEGRA, HESS) => E_e > 200 TeV
B-field ~100 mG => h ~ 10 - independent and more robust estimate
1 mG => η ~ 1 ?

Crab Nebula - news from AGILEE and Fermi LAT :



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.

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

Crab Nebula is a very <u>effective accelerator</u>

but <u>not an effective IC γ-ray emitter</u>

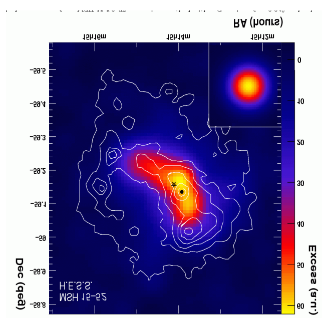
we do see TeV γ-rays from the Crab Nebula because of very large spin-down flux: $f_{rot}=L_{rot}/4\pi d^2=3\times10^{-7}$ erg/cm^2 s

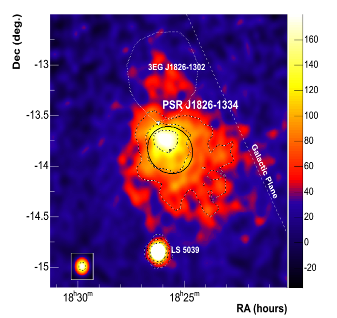
gamma-ray flux << “spin-down flux“ *because of large B-field*

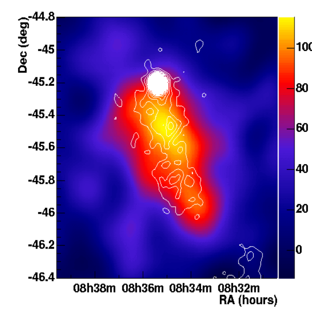
if the B-field is small (environments with small external gas presure)

higher γ-ray efficiency ➡ detectable γ-ray fluxes from other plerions

HESS confirms this prediction – many (20+) candidates associated with PWNe; firm detections - MSH 15-52, PSR 1825, Vela X, ...



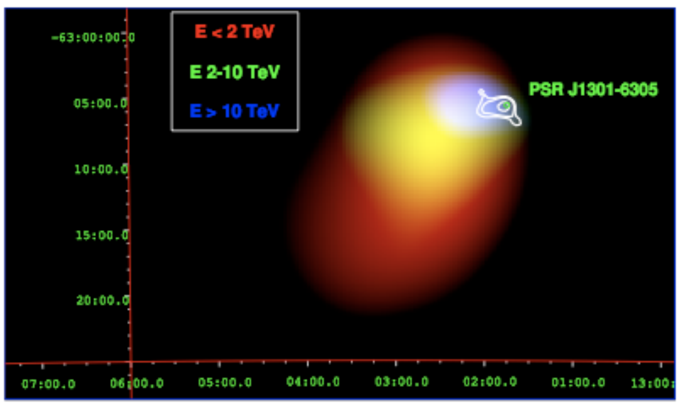


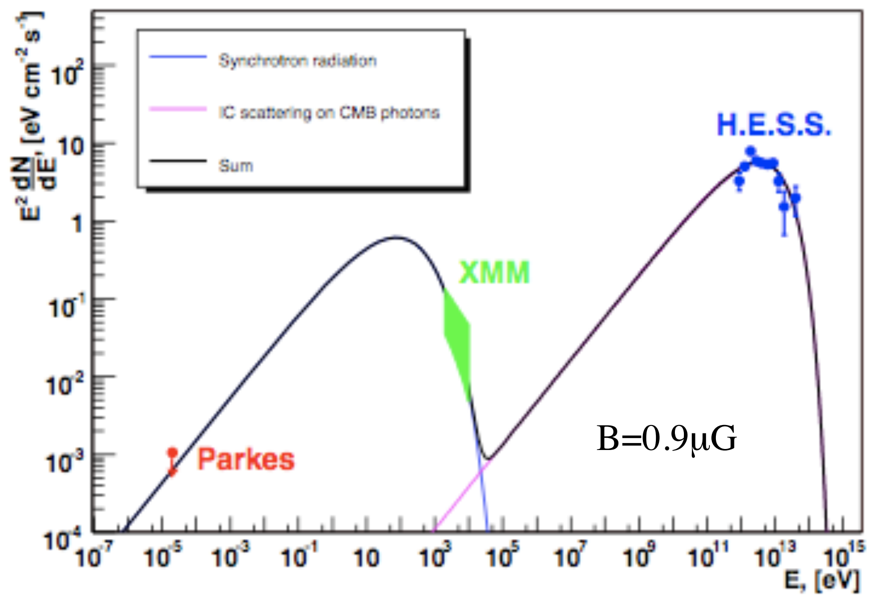


PWNe - *perfect electron accelerators and perfect γ-ray emitters!*

(1) rot. energy => (2) Poynting flux => (3) cold ultrarelativistic wind =>
(4) termination of the wind/acceleration of electrons => gamma-radiation:
efficiency at each stage >50% !

HESS J 13030-62 = PSR J1301-6305?





dramatic reduction of the angular size with energy:strong argument in favor of the IC origin of the γ-ray nebula

very small average B-field; for d=12.6kpc
$L_\gamma/L_{SD} = 0.07$; 3arcmin ~ 10 pc

because of small B-field we see "relic" electrons produced at early epochs of the pulsar

binary systems - unique high energy laboratories

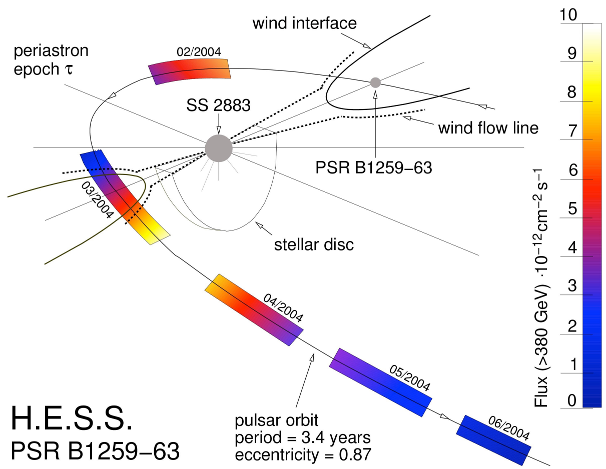
binary pulsars - a special case with strong effects associated with the optical star on both the dynamics of the pulsar wind and and the radiation before and after its termination

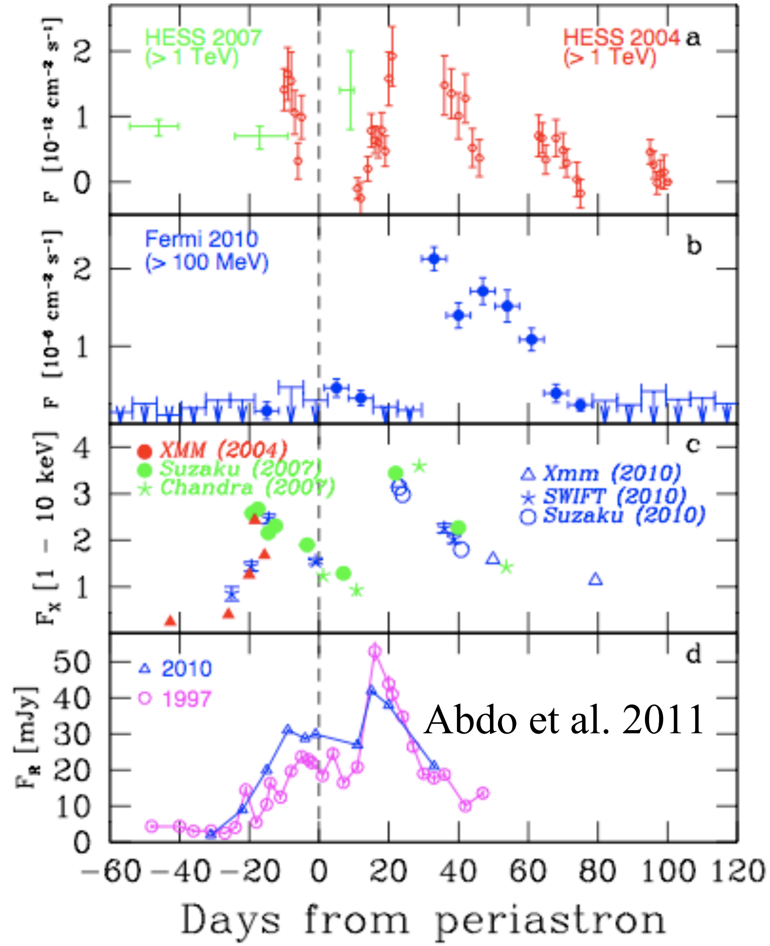
the same 3 components - *Pulsar/Pulsar Wind/Synch.Nebula* - as in PWNe both the electrons of the cold wind and shocke-accelerated electrons are illuminated by optical radiation from the companion star detectable IC γ-rays

''on-line watch'' of the MHD processes of creation and termination of the ultrarelativistic pulsar wind, as well as particle acceleration by relativistic shock waves, through spectral and temporal studies of γ-ray emission

(characteristic timescales 1 h or shorter !)

the target photon field is function of time, thus the only unknown parameter is B-field => predictable gamma-ray emission?





HESS: detection of γ-rays at < 0.1Crab level - tendency of minimum flux close to periastron;

Several possible explanations, but many things uncertain and confusing.

Special expectations/hopes from Fermi related to the periastron passage in Dec 2010

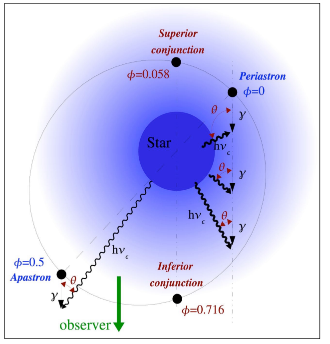
Fermi LAT - weak signal faround periastron, but flares after 1 month!

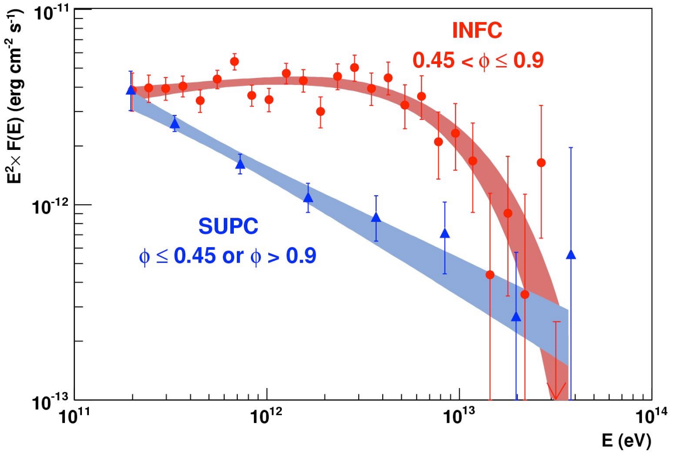
IC emission of unshocked wind with Lorentz factor 10^4 ? (Khangulyan et al 2011)

LS 5039

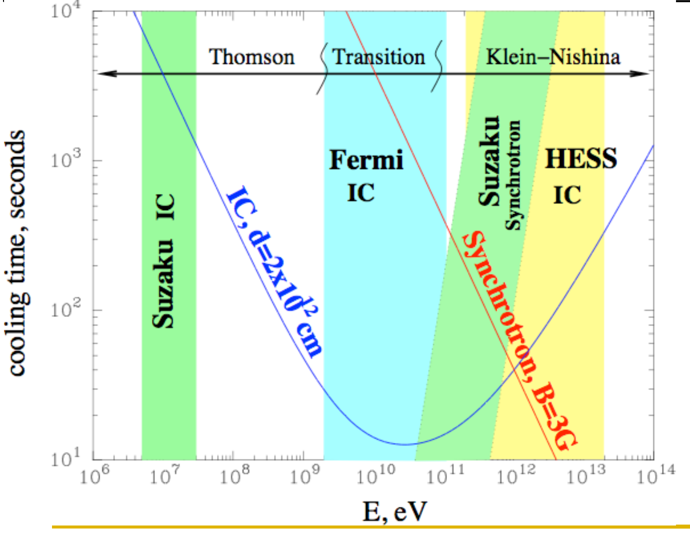
works as a perfect TeV clock
and an extreme accelerator

close to inferior conjuction - maximum
close to superior conjuction – minimum

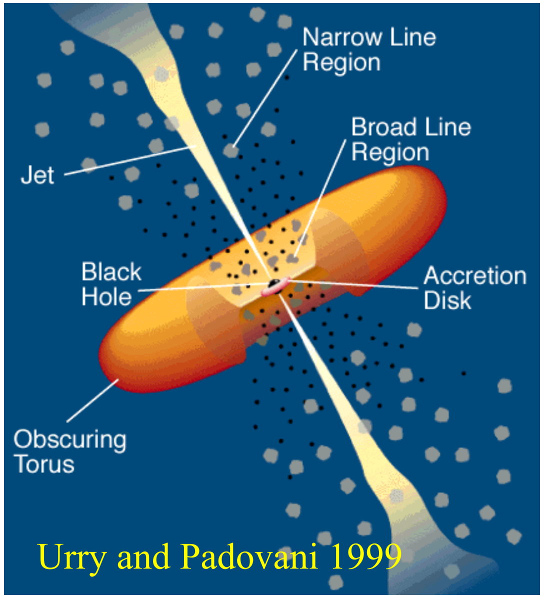




modulation of the gamma-ray signal? *a quite natural reason (because of γ−γ absorption), but we see a different picture… anisotropic IC scattering? yes, but perhaps some additional factors (adiabatic losses, modest Doppler boosting) also play a non-negligible role*



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* $\eta < 10$ => *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 *sites* *acceleration* *radiation*



(sub) relativistic shocks
convertor mechanism
stochastic (Fermi II)
magnetic reconnection,
……..

Inverse Compton
electron synchrotron
Proton synchrotron
photomeson processes
(and subsequent cascades)
γ-γ pair production

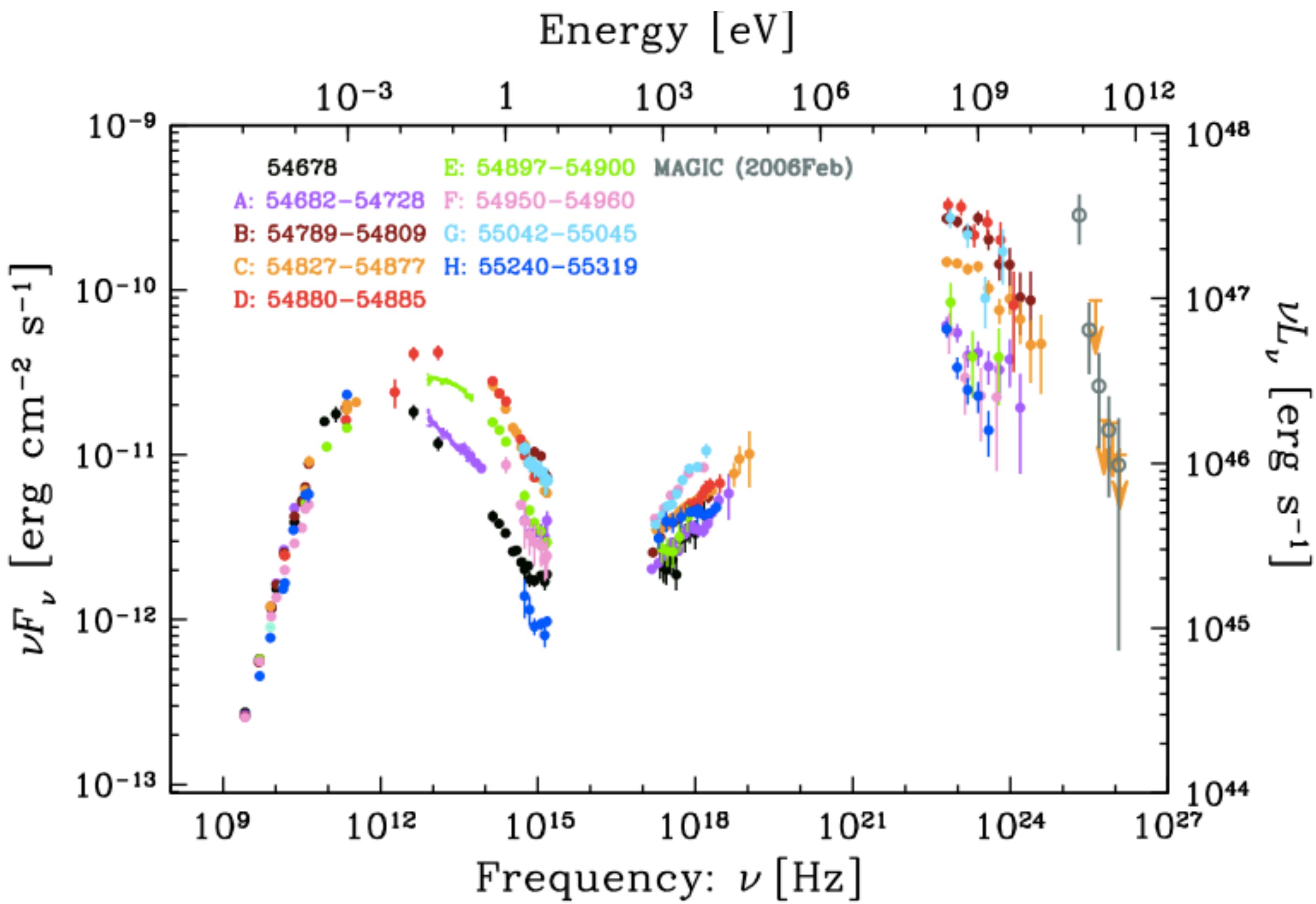
plus very complex *magnetohydrodynamics*

BH magnetosphere
sub-parsec jet
pc-scale jet
multi-pc jet
multi-kpc lobes

gamma-ray images of AGN – not possible, the only information through energy spectra and variability

$\Rightarrow$ broad range of possible realization (scenarios)

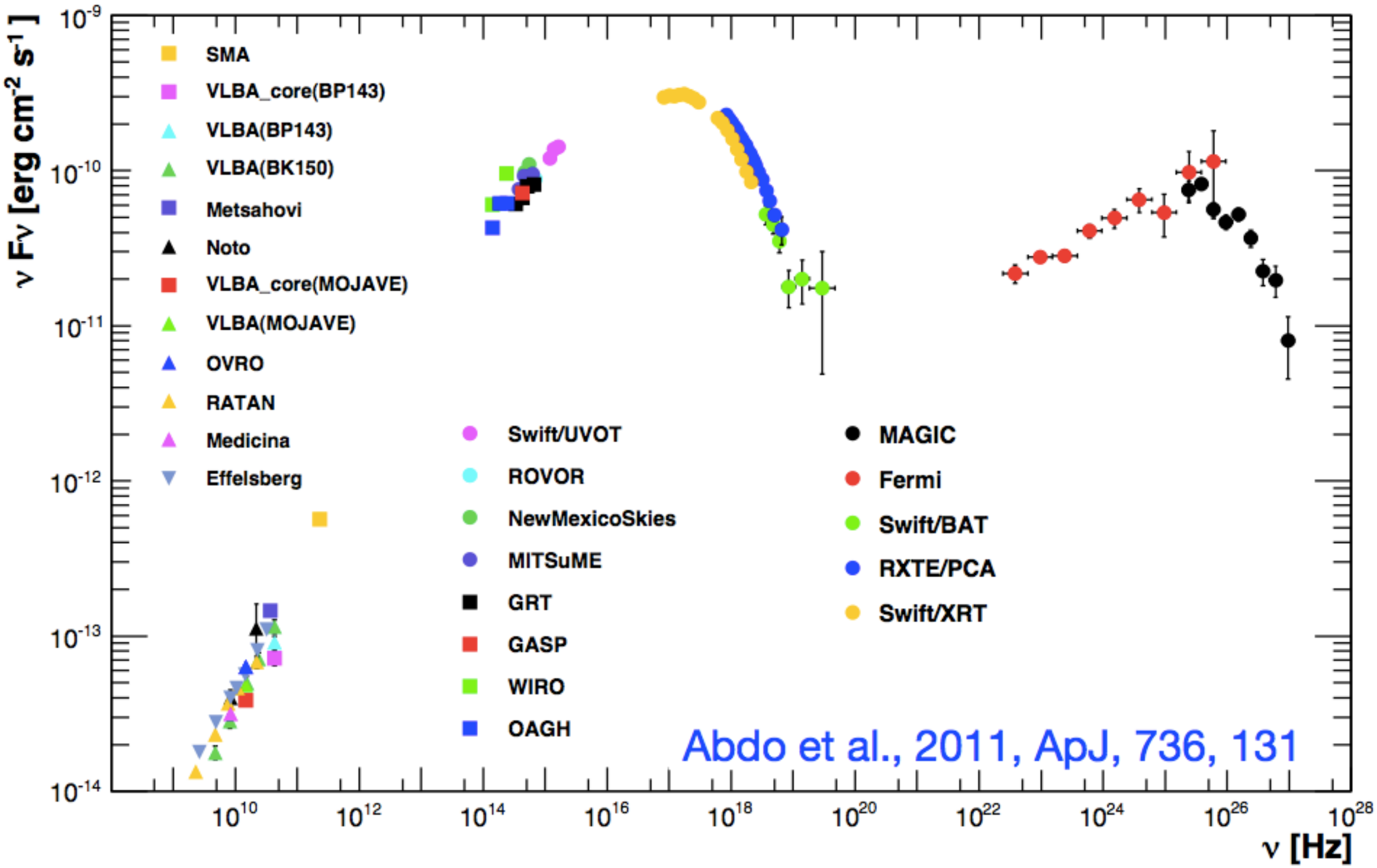
SED of 3C 279 – a classical GeV blazar



$L_\gamma/L_S > 10$ | Synchrotron peak at mm & MIR | X-rays of IC origin | variability - days

TeV emission?

a typical TeV blazar: Mkn 421



When we deal with AGN we should remember that

generally the acceleration and radiation processes proceed under extreme physical conditions in environments characterized with

huge gravitational, magnetic and electric fields (in the cores)
very dense background radiation
relativistic bulk motions (black-hole jets with δ **> 10**
shock waves, highly excited (turbulent) media, etc.

in γ-ray emitting AGN everything should proceed with an extreme efficiency:

conversion of the gravitationl, thermal, bulk motion, electromagnetic forms of energy to nonthermal relativistic particles, i.e. effective acceleration of GeV/TeV/PeV/EeV particles coupled with favourable conditions for production of gamma-rays

SMBH and relativistic Doppler boosting – not sufficient:

AGN - extremely effective particle accelerators and effective emitters

Gamma-ray emission of Blazars

large Doppler factors: make more comfortable the interpretation of variability timescales (larger source size, and longer acceleration and radiation times), reduces (by orders of magnitude) the energy requirements, allow escape of GeV and TeV γ-rays ($\tau_{\gamma\gamma} \sim \delta_j^6$)

uniqueness: Only TeV radiation tells us unambigiously that particles are accelerated to high energies (one needs at least a TeV electron to produce a TeV photon) in the jets with Doppler factors > 10 otherwise gamma-rays Cannot escape the source due to severe internal photon-photon pair production

combined with synchrotron: derivation of several basic parameters like B-field, total energy budget in accelerated particles, thus to develope a quanititative theory of MHD, particle acceleration and radiation in relativistic jets, although yet with many conditions, assumptions, caveats...

Hadronic vs. Electronic models of TeV Blazars

SSC or external Compton – *currently most favoured models*:

- easy to accelerate electrons to TeV energies
- easy to produce synchrotron and IC gamma-rays

recent results require more sophisticated leptonic models

Hadronic Models:

- protons interacting with ambient plasma — neutrinos

  very slow process:

  unlikely

- protons interacting with photon fields — neutrinos*

  low efficiency + severe absorption of TeV γ-rays

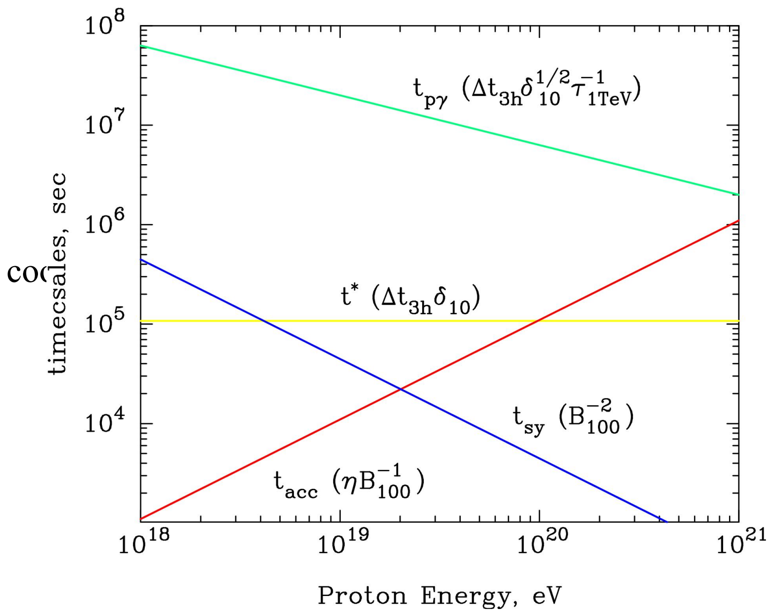
- proton synchrotron — no neutrinos

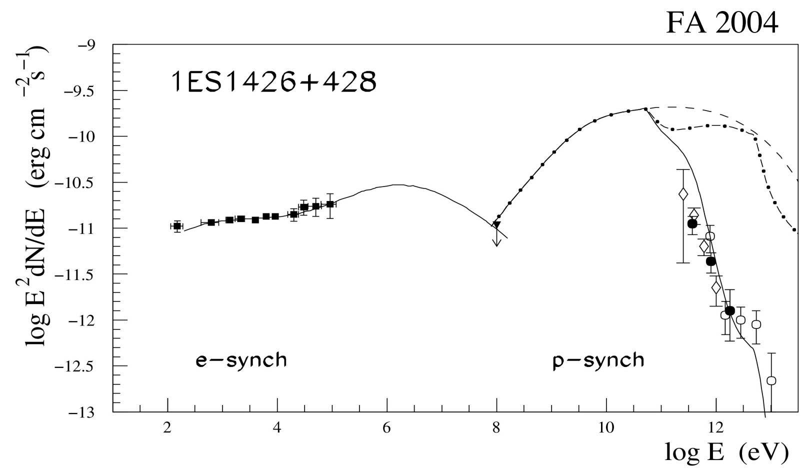
  very large magnetic field B=100 G + accelaration rate c/r_g

"extreme accelerator" (of EHE CRs) Poynting flux dominated flow

*detectable neutrinos from EGRET AGN but not from TeV blazars

Synchrotron radiation of an extreme proton accelerator





E_{cut}=90 (B/100G)(Ep/10^{19} eV)^2 GeV

t_{synch}=4.5x10^4(B/100G)$^{-2}$ (E/10^{19} eV)$^{-1}$ s

t_{acc}=1.1x10^4 (E/10^{19}) (B/100G)$^{-1}$ s

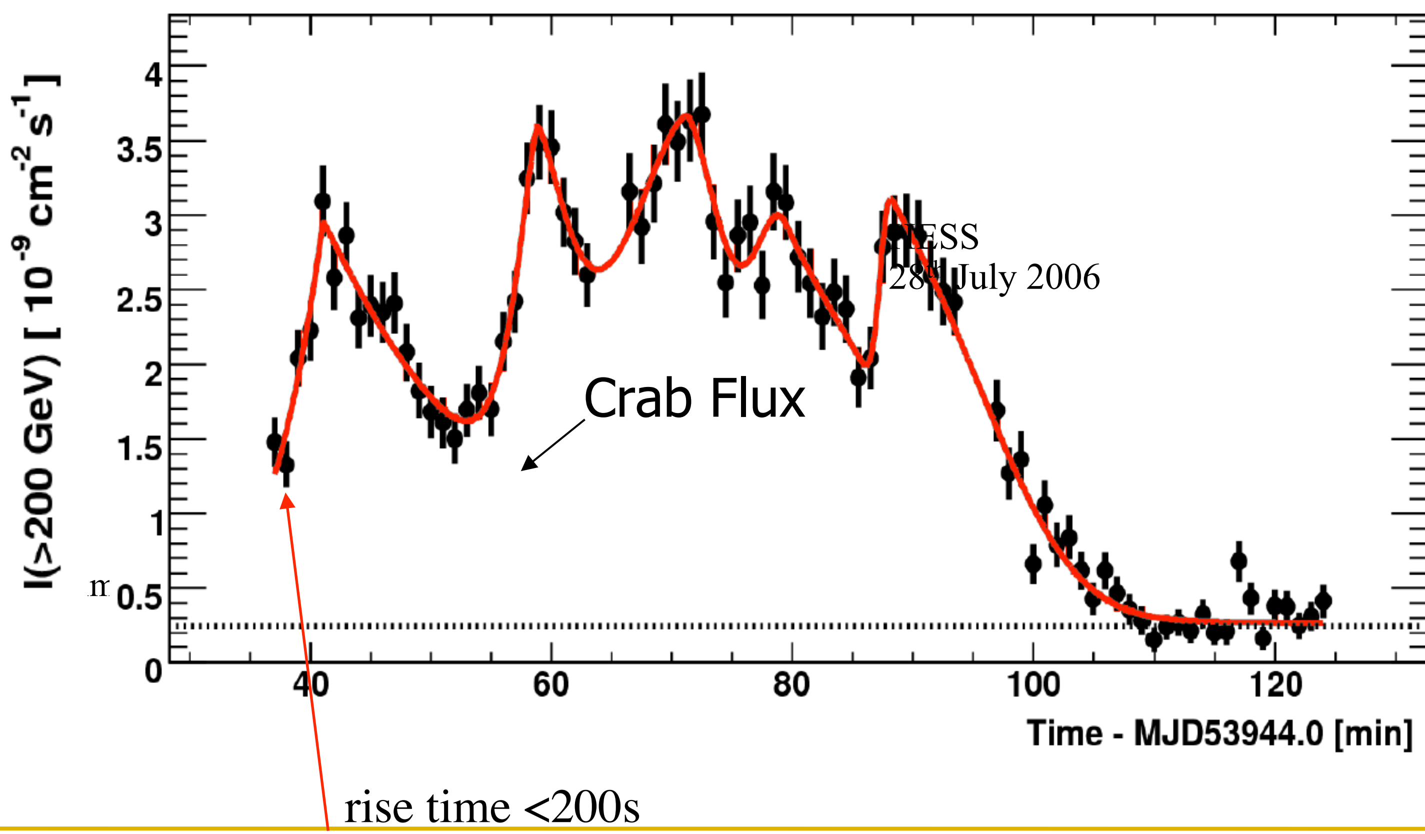
synchrotron radiation of protons: a viable radiation mechanism

E_{max} =300 η^{-1} δj GeV
requires extreme accelerators: η ~ 1

most exciting results of recent years

- ultra short time variability (on min scales)
- Jet powers could exceed Eddington luminosity
- extremely hard energy spectra

several min (200s) variabiliry timescale => $R=c\ \Delta t_{var}\ \delta_j=10^{14}\delta_{10}$ cm for a 10^9Mo BH with 3Rg = 10^{15} cm => $\delta j > 100$, i.e. close to the accretion disk (the base of the jet), the bulk motion $\Gamma > 100$

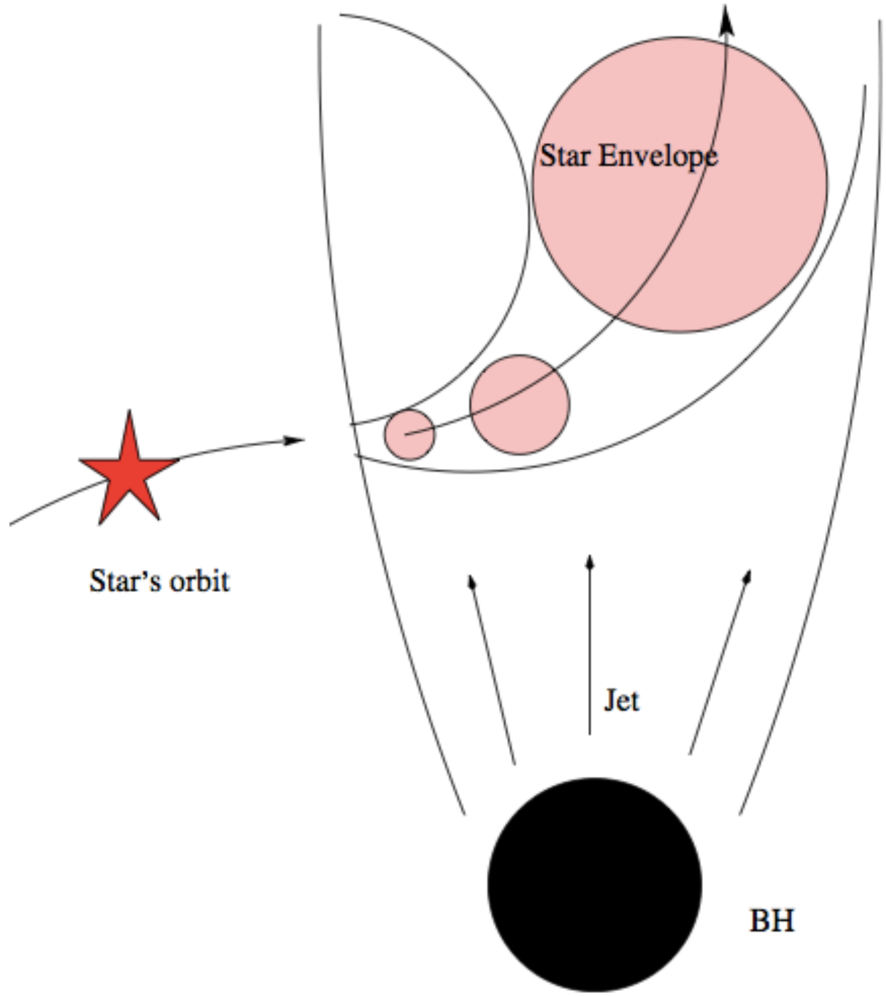


rise time <200s

on the Doppler boosting and mass of BH in PKS2155-309

- several min variability timescale => $R = ct_{var}\delta_j \sim 10^{13}\delta_j$ cm for a 10^9Mo BH with 3Rg ~ 10^{15} cm => $\delta j > 100$, i.e. close to the accretion disk (the base of the jet), the Lorenz factor of the jet $\Gamma > 50$ - this hardly can be realized close to Rg!
- the (internal) shock scenario: shock would develop at $R = Rg\,\Gamma^2$, i.e. minimum γ-ray variability would be $R_g/c = 10^4(M/10^9Mo)$ sec, although the γ-ray production region is located at $R \sim ct_{var}\Gamma^2$ (e.g. Chelotti, Fabian, Rees 1998) - this is true for any other scenario with a "signal-pertubaution" originating from the central BH
- thus for the observed $t_{var} < 200$ s, the mass of BH cannot significantly exceed 10^7Mo. On the other hand the "BH mass–host galaxy bulge luminosity" relation for PKS2155-304 gives $M > 10^9$Mo.

Solution? perturbations are cased by external sources, e.g. by magnetized condensations ("blobs") that do not have direct links to the central BH; do we deal with the scenario "star crosses the relativistic e^+e^- jet" ?


Star Envelope
Star's orbit
Jet
BH

M 87 – evidence for production of TeV gamma-rays close to BH ?

- Distance: ~16 Mpc
- central BH: $3\times10^9\ M_O$ *)
- Jet angle: ~30°

  => *not a blazar*!

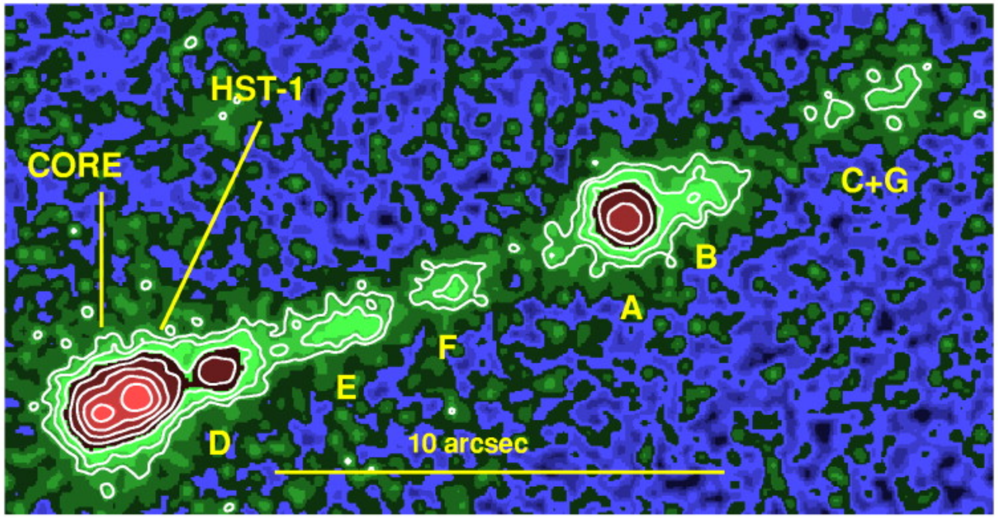
discovery (>4σ) of TeV γ-rays

by HEGRA (1998) and confirmed

recently by HESS/VERITAS, MAGIC

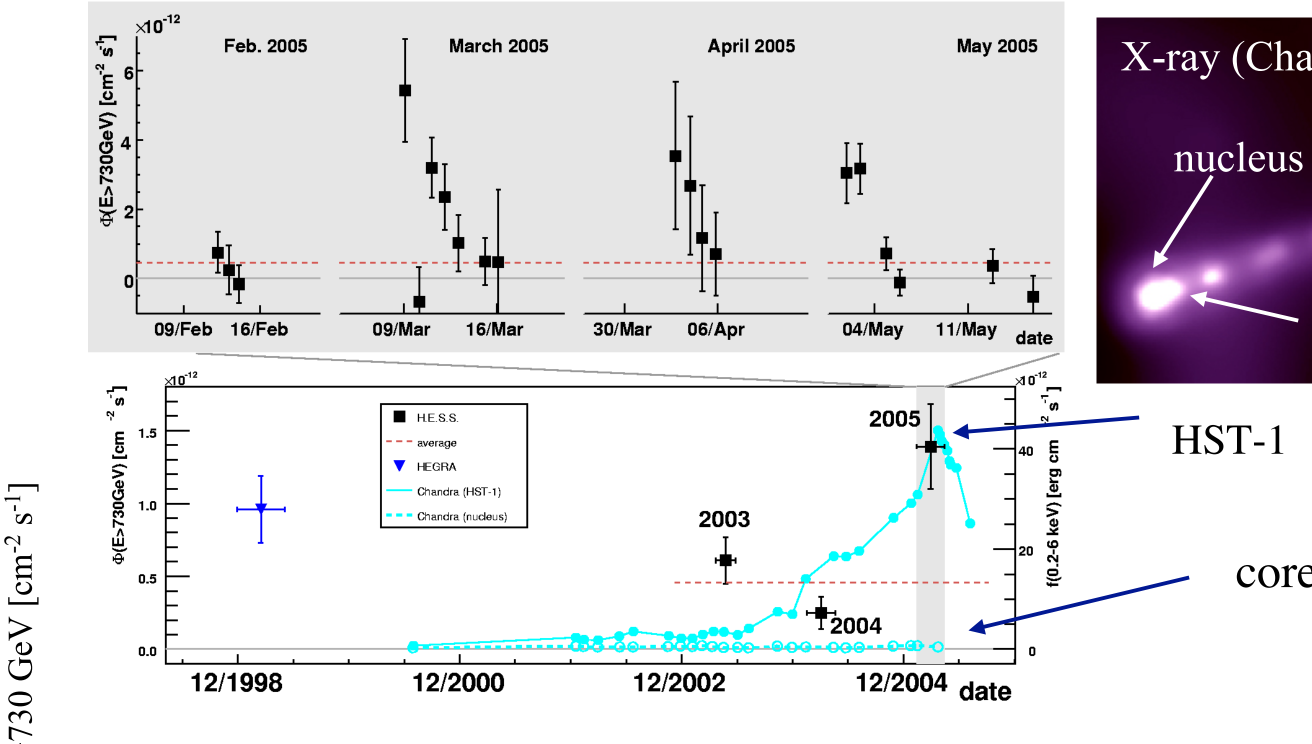
*) recently 6.4 x $10^9\ M_o$

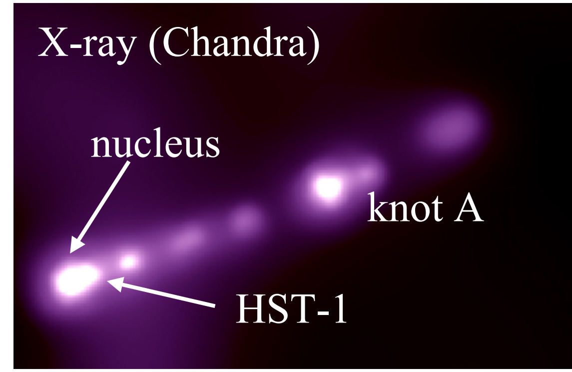
arXiv: 0906.1492 (2009)



M87: light curve and variabiliy

HESS Collaboration 2006, Science, **314**,1427



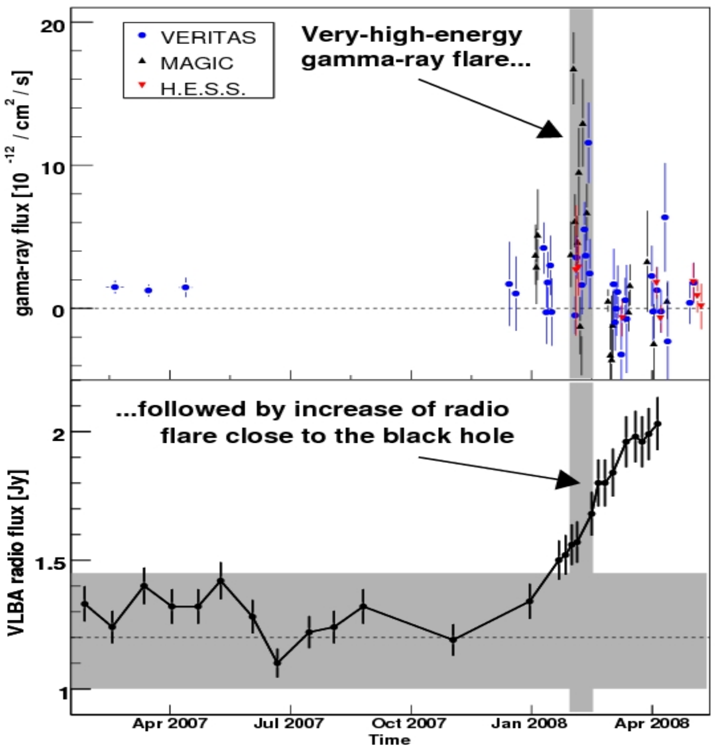


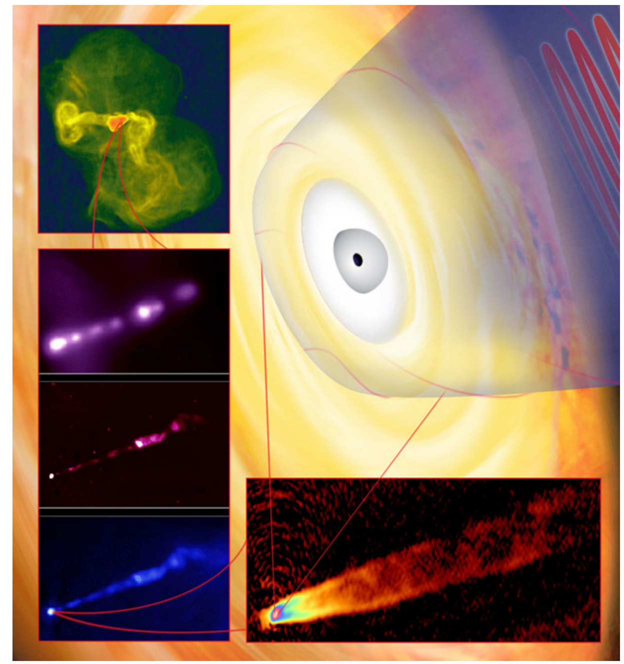
short-term variability on 1-2 day scales => emission region R ~ $5 \times 10^{15} \delta_j$ cm
=> production of gamma-rays very close to the 'event horizon' of BH?

because of very low luminosity of the core in O/IR: TeV gamma-rays can escape the production region

$L_{IR} \approx 10^{-8} L_{Edd}$

New! NRAO and VERITAS/MAGIC/HESS: *Science, July 2, 2009*
Simultaneous TeV and radio observations allow localization of gamma-ray production region within 50 R_s





monitoring of the M87 inner jet with VLBA at 43 GHz (ang. res. 0.21x0.43 mas) revealed increase of the radio flux by 30 to 50% correlated wit the increase in TeV gamma-ray flux in Feb 2008

conclusion? *TeV gamma-rays are produced in the jet collimation region within 50 Rs around BH*

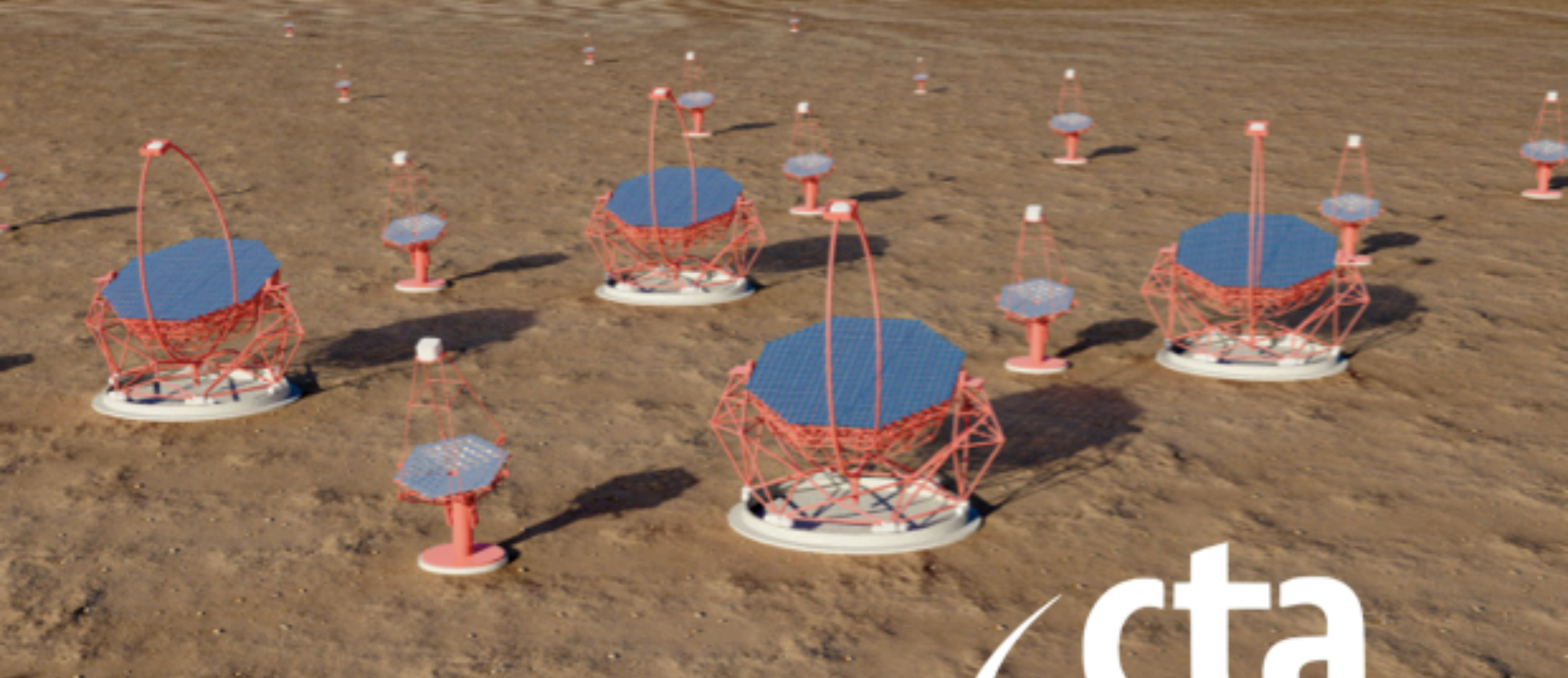
Summary:

- VHE gamma-rays are perfect carriers of information about sites and processes of particle acceleration on both galactic and extragalactic scales

- the contribution to the field of CR studies with the current ground-based detectors HESS/MAGIC/VERITAS is substantial, unique and impressive

- CR related studies will be one of the highest priority tasks for the new generation of ground-based detectors – Cherenkov Telescope Array (CTA) and large FoV high altitude air shower detectors (super-HAWC, LATTES?)

THE NEXT BIG STEP:
THE CHERENKOV TELESCOPE ARRAY



cta
cherenkov telescope array

- 10 fold improvement in sensitivity
- 10 fold improvement in usable energy range
- much larger field of view
- strongly improved angular resolution