The TeV Universe:
VHE γ-ray source populations

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Gamma-Ray Astronomy

a branch of astrophysics/astroparticle-physics for study of the sky in MeV, GeV, TeV (and more energetic) photons

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

'the last window' *in the spectrum of cosmic E-M radiation* …

the last E-M window ... 15+ decades:

LE	or	MeV :	0.1 -100 MeV	(0.1 -10 + 10 -100)
HE	or	GeV :	0.1 -100 GeV	(0.1 -10 + 10 -100)
VHE	or	TeV :	0.1 -100 TeV	(0.1 -10 + 10 -100)
UHE	or	PeV :	0.1 -100 PeV	(*only hadronic*)
EHE	or	EeV :	0.1 -100 EeV	(*unavoidable because of GZK*)

low bound - nuclear gamma-rays, upper bound - highest energy cosmic rays

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

LE,HE — *domain of space-based astronomy*
VHE, ... — *domain of ground-based astronomy*

potentially 'Ground-based γ-ray astronomy' can cover five decades (from 10 GeV to 1 PeV) , but presently it implies 'TeV γ-ray astronomy'

1MeV=10^6 eV, 1GeV=10^9 eV, 1TeV=10^{12} eV, 1PeV=10^{15} eV 1EeV=10^{18} eV

why gamma-rays?

gamma-rays – unique carriers of information about high energy processes in the Universe

- ✓ are effectively produced
  in both electromagnetic and hadronic interactions
- ✓ penetrate (relatively) freely throughout
  intergalactic and galactic magnetic and photon-fields
- ✓ are effectively detected
  by space-based and ground-based detectors

extreme physical conditions...

generally the phenomena relevant to HEA generally proceed under extreme physical conditions in environments characterized with

- *huge gravitational, magnetic and electric fields,*
- *very dense background radiation,*
- *relativistic bulk motions (black-hole jets and pulsar winds)*
- *shock waves, highly excited (turbulent) media, etc.*

any coherent description and interpretation of phenomena related to high energy cosmic gamma-rays requires knowledge and deep understanding of many disciplines of experimental and theoretical physics, including

nuclear and particle physics,
quantum and classical electrodynamics,
special and general relativity,
plasma physics, (magneto) hydrodynamics, etc.

and (of course) Astronomy/Astrophysics

TeV gamma-ray astronomy - a success story

over last several years the field has bee revolutionized

before – “astronomy“ with several sources
(Astroparticle Physics rather than Astronomy)

now – a truly astronomical discipline with characteristic key words:
energy spectra, images, lightcurves, surveys...

with tens (=>100) detected G & EXG sources
and two well established detection techniques
in the energy interval between 0.1 TeV to 100 TeV

the major factors which make possible this success ?

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

- ✓ *great potential of the detection technique*
- ✓ *effective acceleration of TeV/PeV particles on all astronomical scales (coupled with favourable conditions for production of gamma-rays)*

detectors of high energy gamma-rays

"direct" detection of LE/HE gamma-rays - possible from space, but can be effective below 10 (100?) GeV

"indirect" detection of VHE gamma-rays - possible from ground, but is effective above 100 (10?) GeV

recently: Fermi LAT - detection of gamma-rays up to 100 GeV
MAGIC - detection of gamma-rays down to 100 GeV

very good agreement of measured fluxes around 100 GeV !

Ground Based Gamma-Ray Astronomy

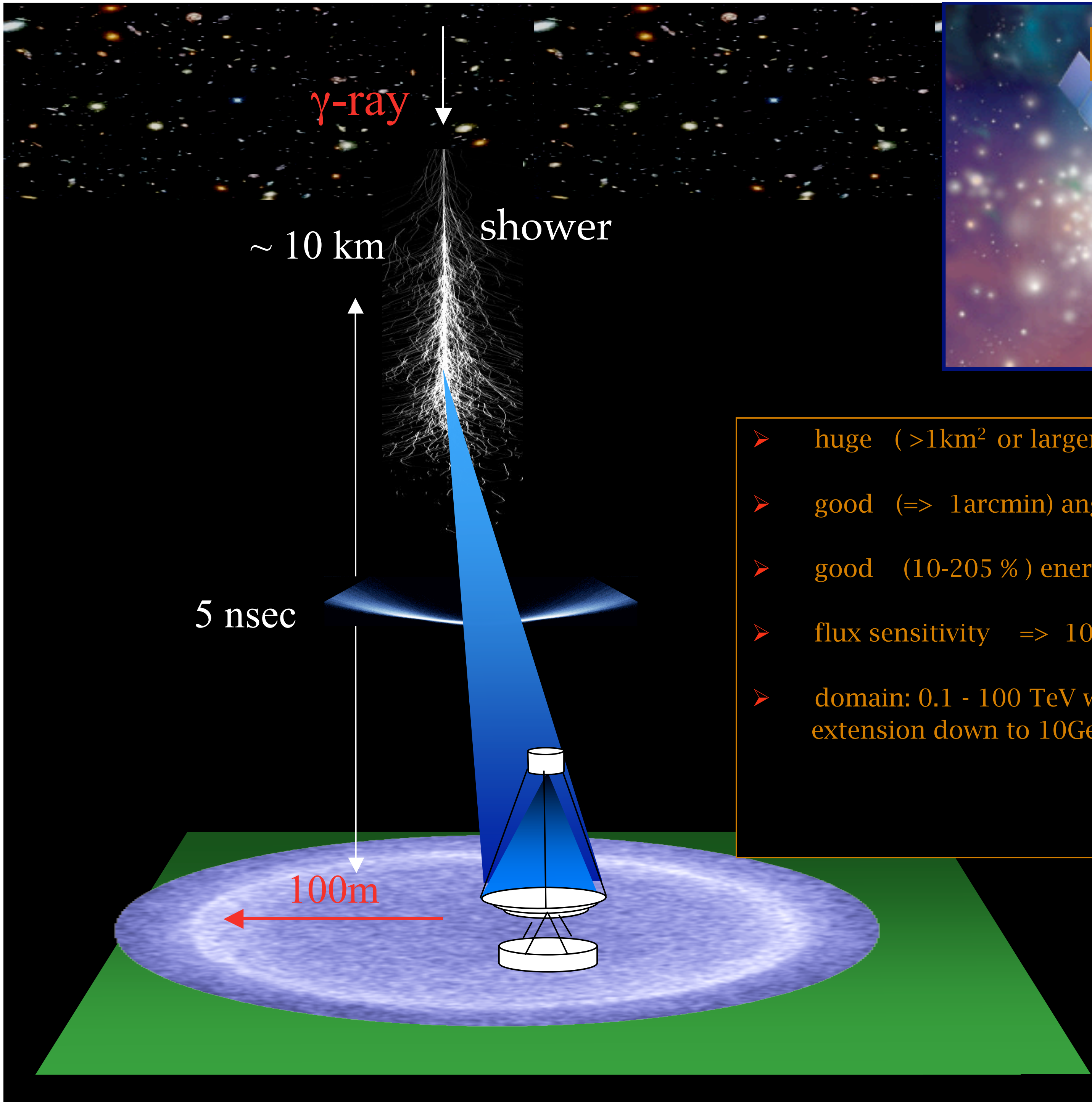
presently provides the VHE window in the spectrum of cosmic E-M radiation

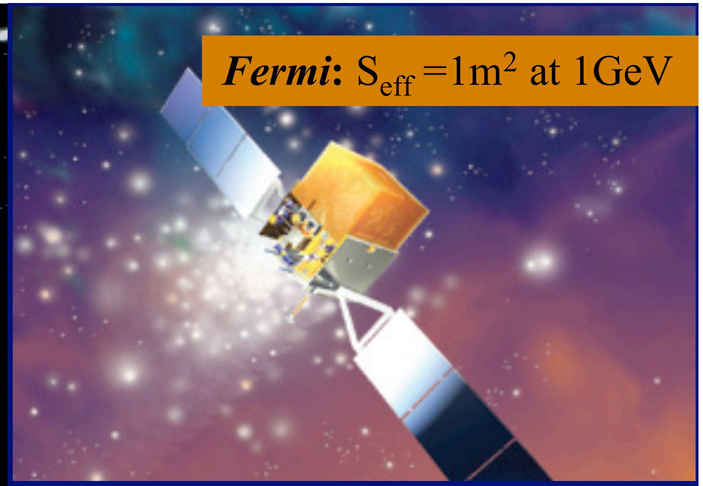
0.1 TeV and 100 TeV => TeV (VHE) gamma-ray Astronomy *)

with a potential for extension of the energy domain

- below 100 GeV down to 10 GeV: GeV (HE) gamma-ray Astronomy
- above 0.1 PeV up to 1 PeV: PeV (UHE) gamma-ray Astronomy

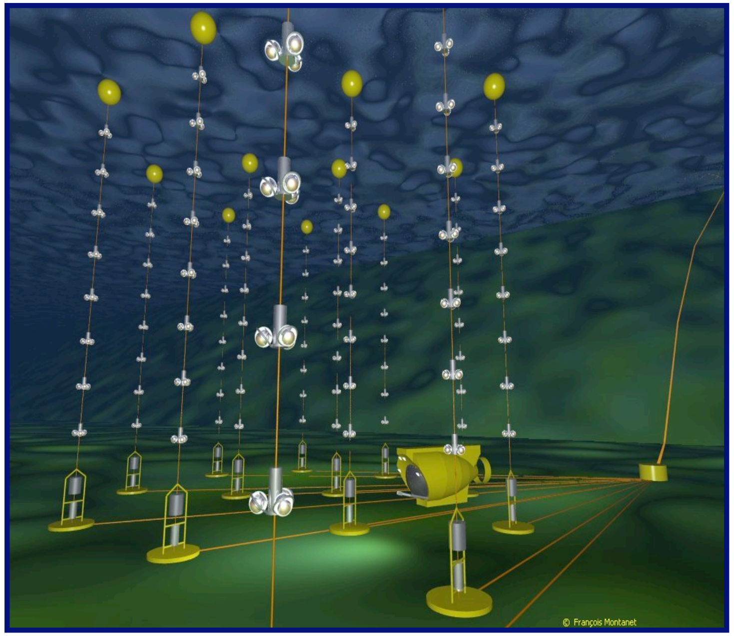
in foreseeable future (hopefully) => GeV-TeV-PeV astronomy

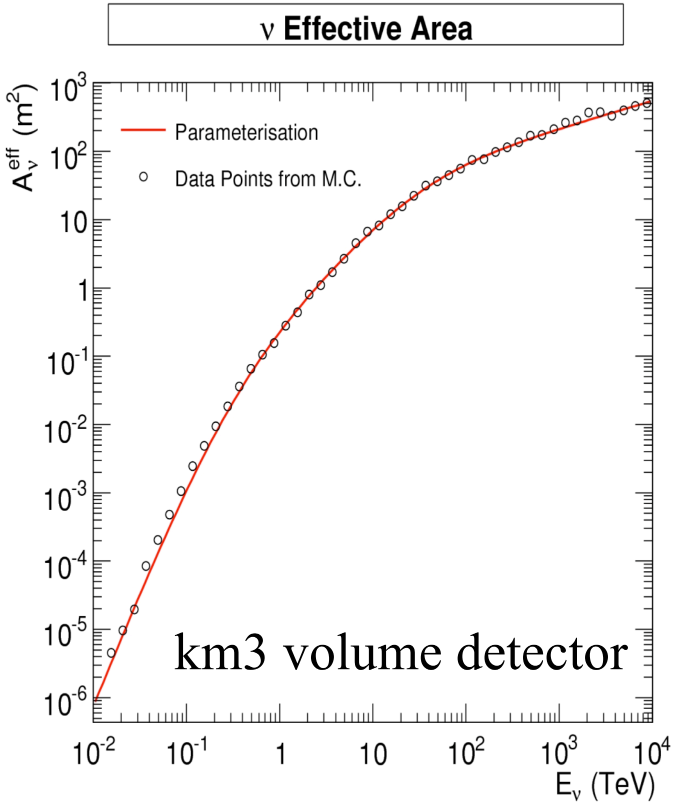




- huge (>1km^2 or larger) detection area
- good (=> 1arcmin) angular resolution
- good (10-205 %) energy resolution
- flux sensitivity => 10^{-14} erg/cm^2 s
- domain: 0.1 - 100 TeV with a potential of extension down to 10GeV and up to 1PeV

neutrino telescopes





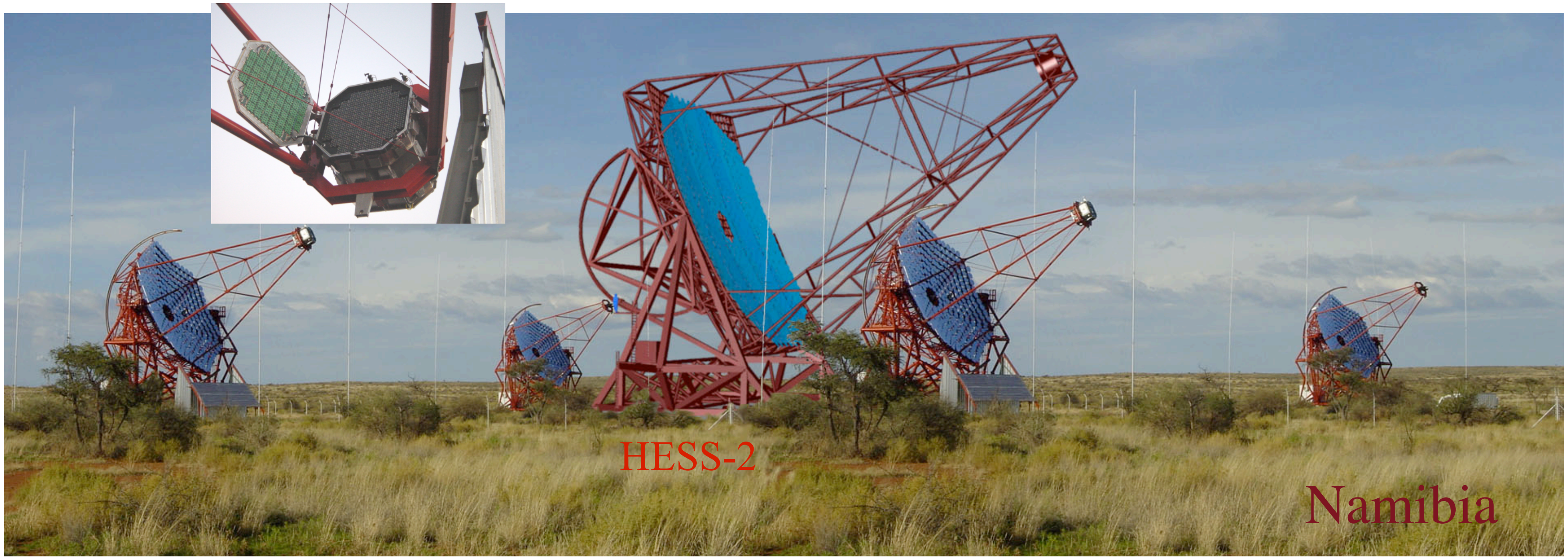
effective area: 0.3m^2 at 1 TeV
10m^2 at 10 TeV

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

neutrino telescpes -- "slow" detectors

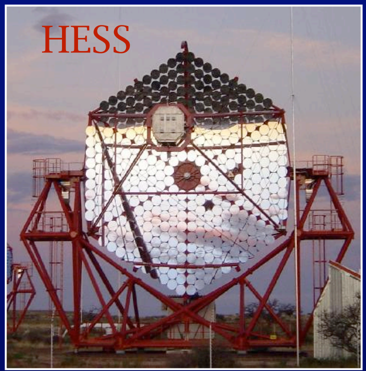
nevertheless first (major) discoveries are expected from burst type phenomena like blazar flares or GRBs

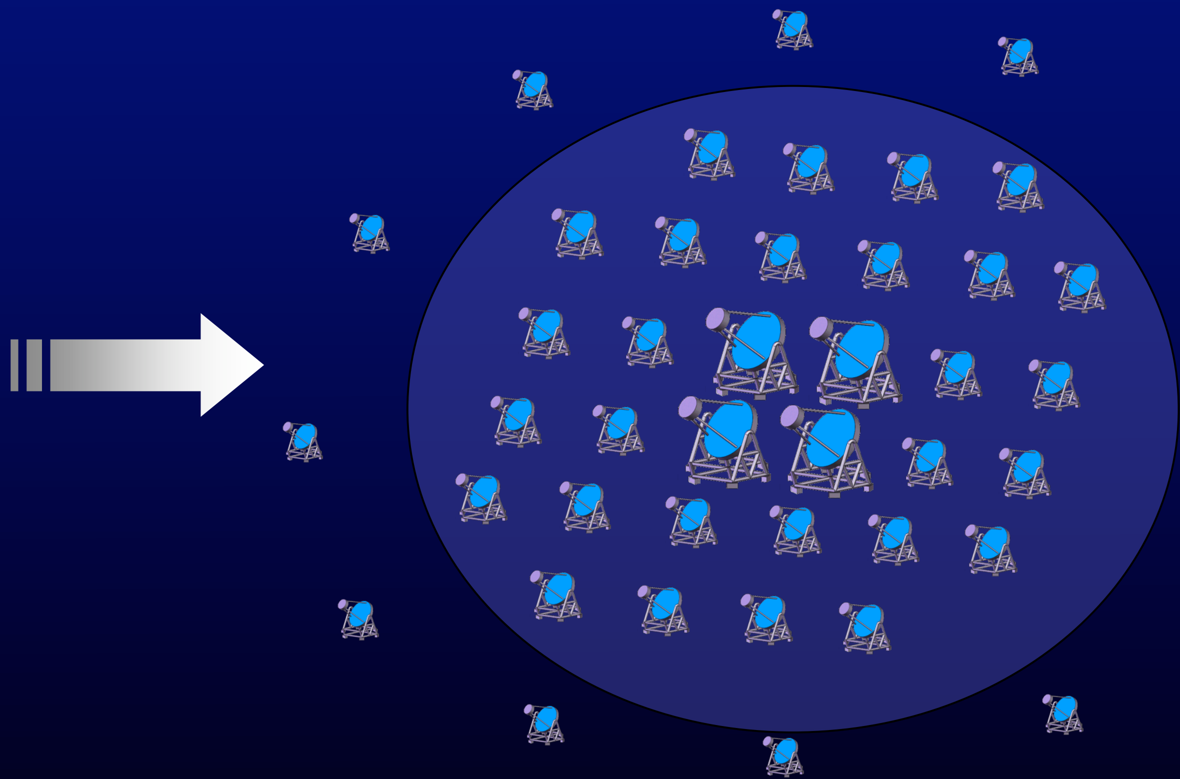
H.E.S.S. - High Energy Stereoscopic System



one of the current 3 (HESS, MAGIC, VERITAS) major IACT arrays 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, AGIS…

Future

- aim? sensitivity: F_E => 10^{-14} erg/cm^2 s (around 1TeV)
- realization ? 1 to 10 km^2 scale 10m+ aperture IACT arrays
- timescales short (years) - no technological challenges
- price no cheap anymore, but still reasonable
- three energy regimes with different objectives and goals

✓ "classical" 0.1 TeV - 30 TeV - *more sources/population studies*

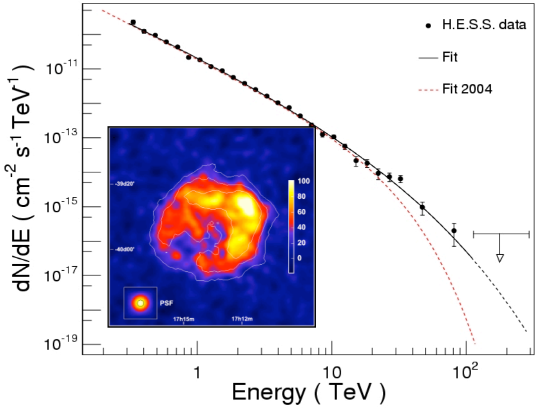
✓ a few GeV -100 GeV - *powerful timing explorer*

✓ 3- TeV -300 TeV - searching for PeVatrons

0.1-1 TeV threshold
all sky monitor: "HAWK" *(an analog of Fermi in VHE band with comparable angular and energy flux sensitivity)*

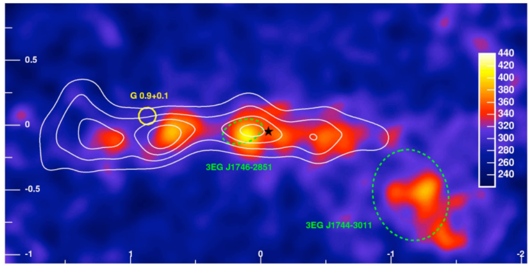
good performance => high quality data => solid basis for theoretical studies

RXJ 1713.7-3946



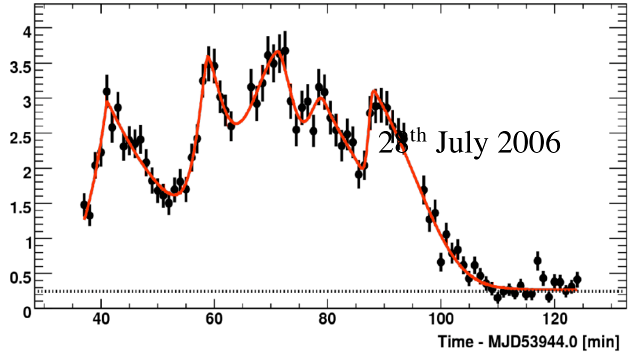
TeV image and energy spectrum of a SNR

Galactic Center



resolving GMCs in the Galactic Center 100pc region

PKS 2155-309



variability of TeV flux of a blazar on minute timescales

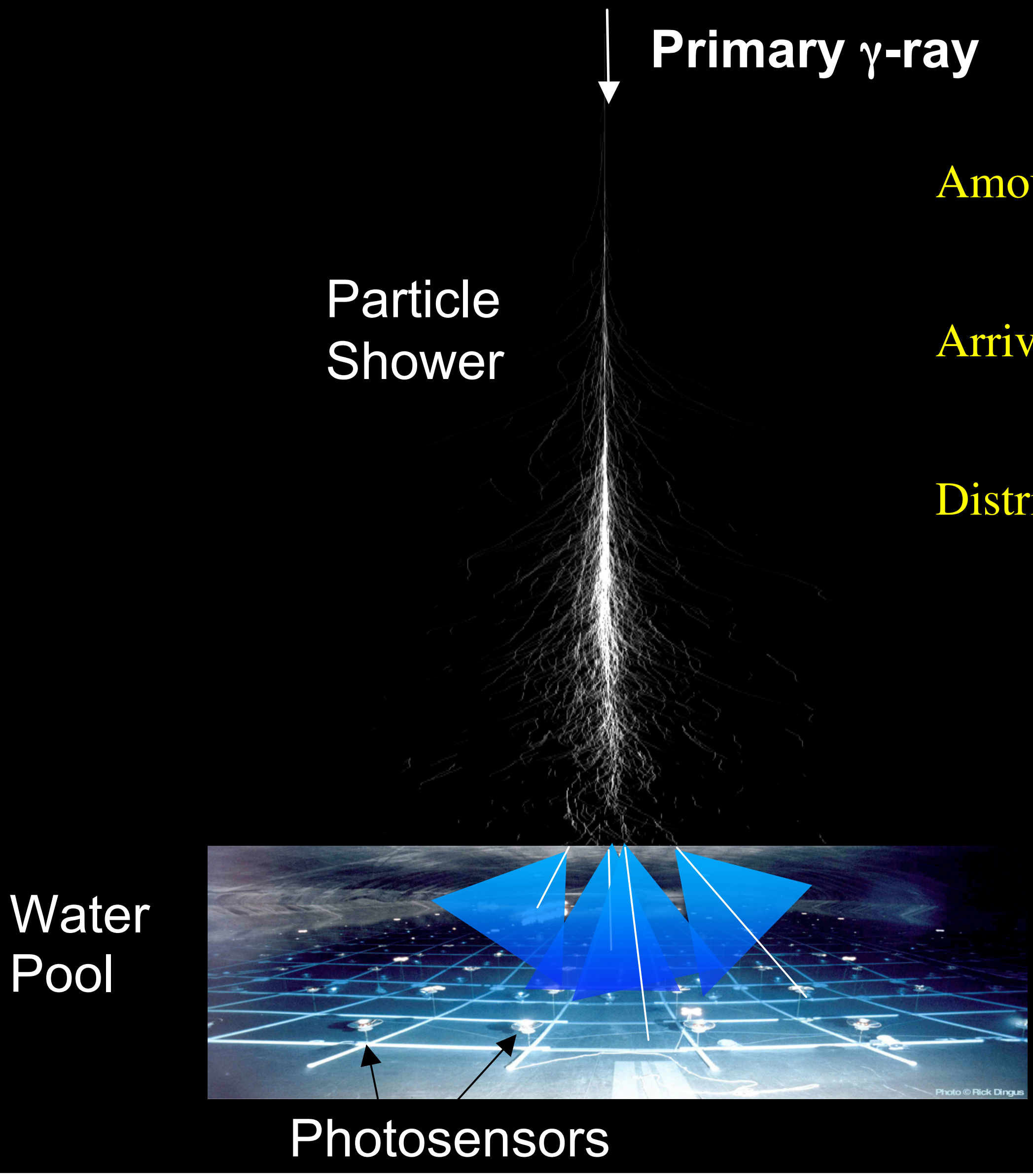
multi-functional tools: *spectrometry* *temporal studies* *morphology*

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

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

Galactic Astronomy | Extragalactic Astronomy | Observational Cosmology

Shower particle Technique



Amount of Cherenkov in detector
=> Shower Energy

Arrival times at photosensors
=> Shower Direction

Distribution of particles on ground
=> background rejection

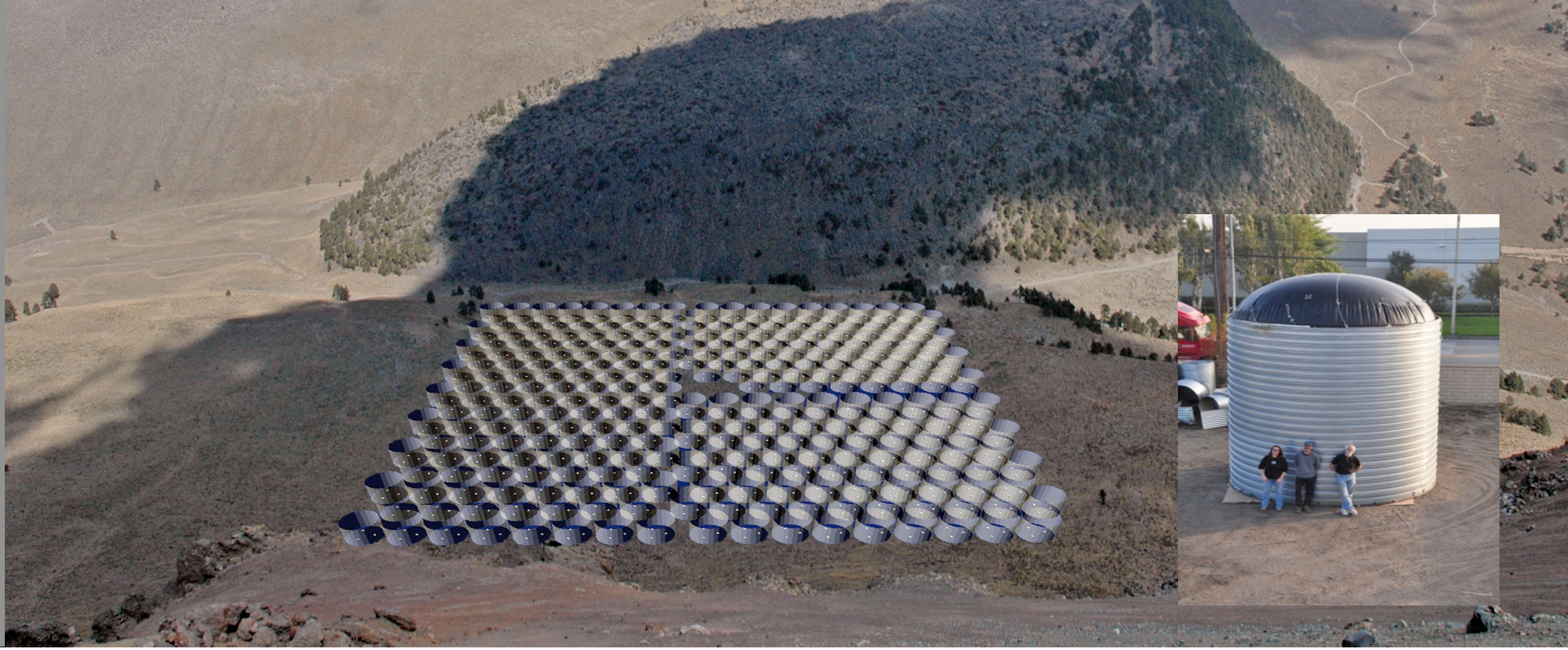
- Larger fluctuations
- Higher altitude is better

MILAGRO
(and ARGO)

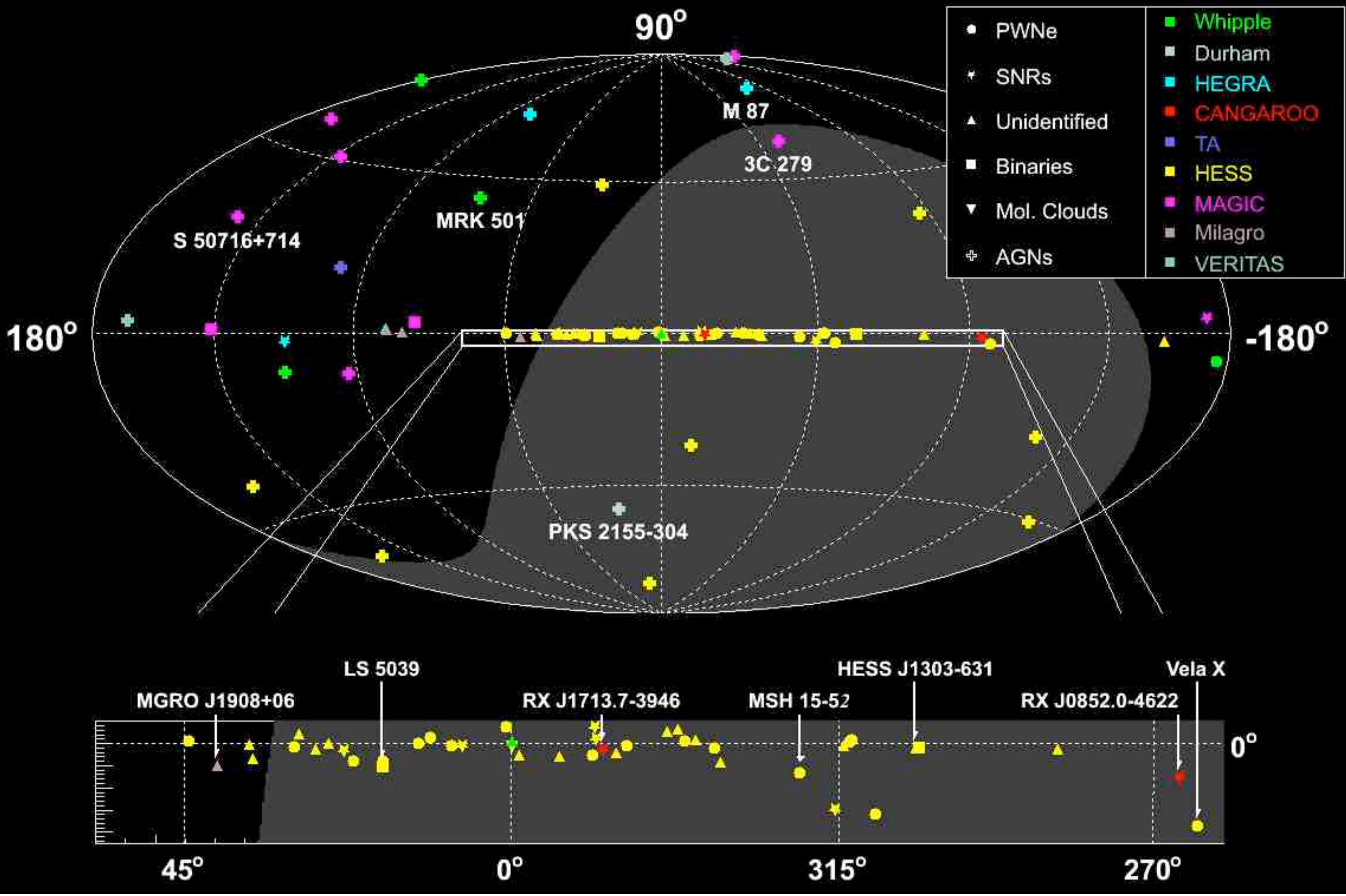
from Milagro to HAWC - bigger and higher:
to reduce energy threshold and increase sensitivity

HAWC: High Altitude Water Cherenkov

all sky monitor with flux sensitivity 10^{-12} erg/cm^2 s
similar to *Fermi LAT* but in the TeV energy domain



The Fascinating TeV Sky



first lesson from recent observations: Universe is full of *Extreme Accelerators* - TeVatrons and PeVatrons

machines where acceleration proceeds with efficiency close to 100%

efficiency ?

(i) fraction of available energy converted to nonthermal particles

in PWNe and perhaps also in SNRs, *can be as large as 50 %*

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

acceleration rate close to the maximum (theoretically) possible rate : $t_{acc} \sim r_L/c$

sometimes efficiency can "exceed" 100% (!) e.g. at CR acceleration in SNRs
in Bohm diffusion regime with amplification of B-field by CRs ($E_{max=} \sim B\,(v/c)^2$)
this effect provides the extension of the spectrum of Galactic CRs to at least 1 PeV

"> 100% efficiency" because of nonlinear effects:

acceleration of particles creates better conditions for their further acceleration

VHE gamma-ray observations:

"Universe is full of extreme accelerators on all astronomical scales"

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

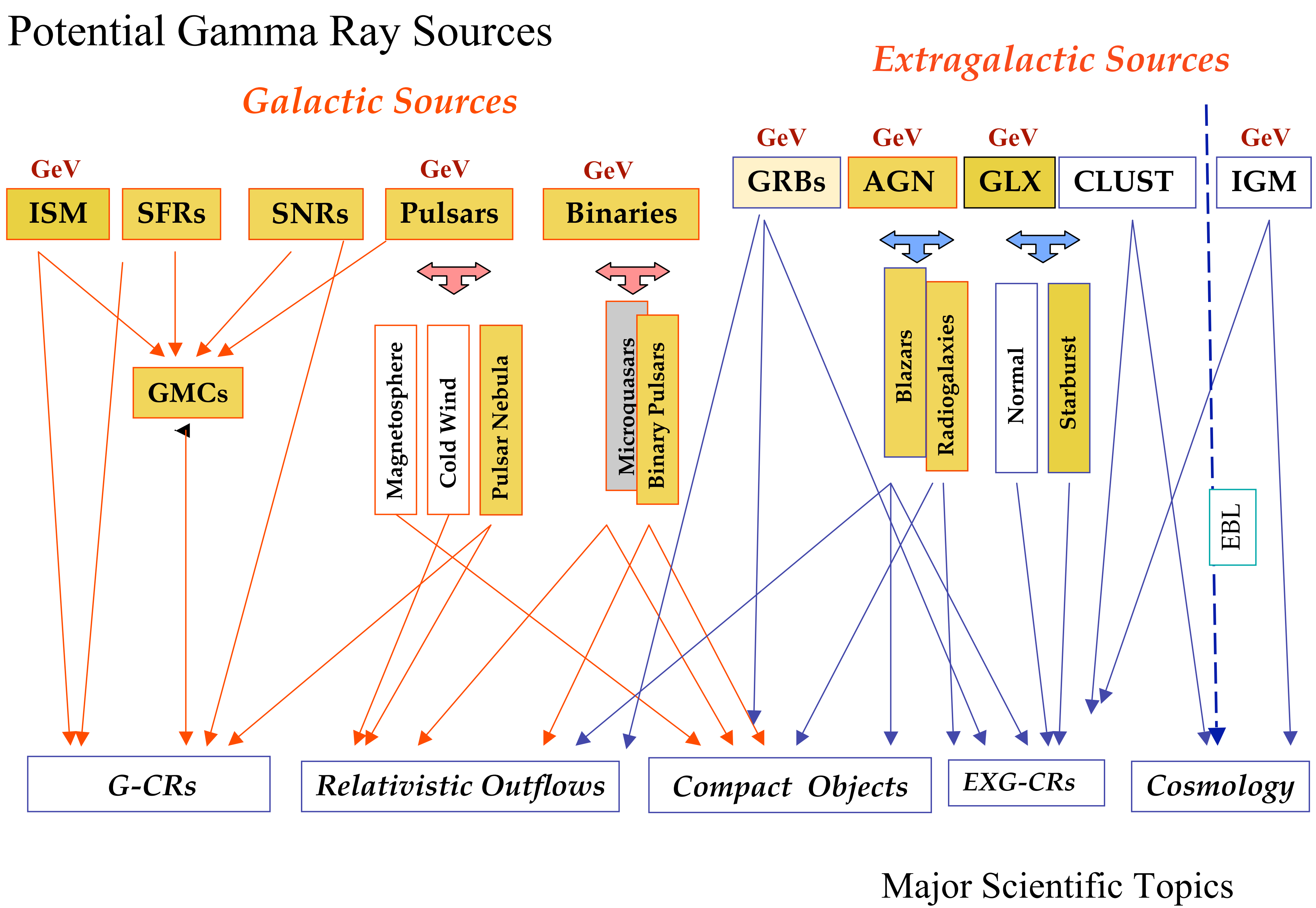
Extragalactic objects

- ✓ M87, Cen A - 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 …

VHE gamma-ray source populations

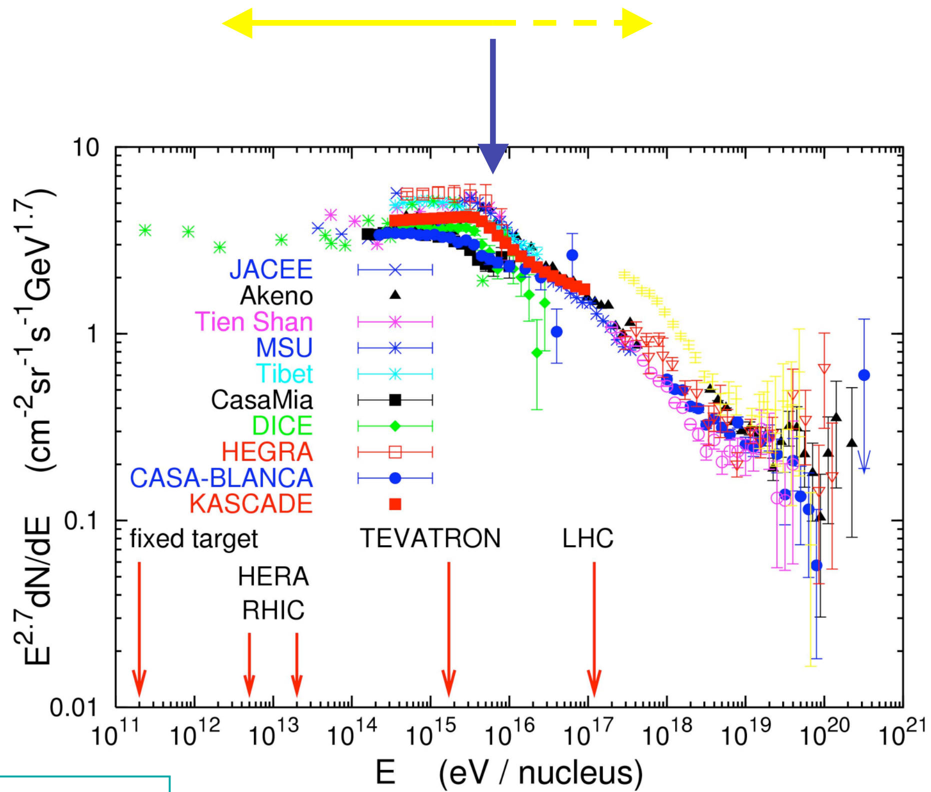

Potential Gamma Ray Sources
Galactic Sources
Extragalactic Sources
GeV
ISM
SFRs
SNRs
GeV
Pulsars
GeV
Binaries
GeV
GRBs
GeV
AGN
GeV
GLX
CLUST
GeV
IGM
GMCs
Magnetosphere
Cold Wind
Pulsar Nebula
Microquasars
Binary Pulsars
Blazars
Radiogalaxies
Normal
Starburst
EBL
G-CRs
Relativistic Outflows
Compact Objects
EXG-CRs
Cosmology
Major Scientific Topics

major topical areas

- origin of galactic and exttragalactic cosmic rays
- physics and astrophysics of relativistic outflows (jets and winds)
- high energy processes at extreme conditions (e.g. close to BHs)
- cosmological issues - Dark Matter, Extragalactic Background Light (EBL)

…..

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



Gaisser 2001

One of the highest priorities of TeV astronomy:
experimental tests/demonstration that young SNRs operate as PeVatrons, and provide the bulk of the flux of Galactic CRs up to 10^{15} eV

Pulsars/Plerions ?

OB, W-R Stars ?

Microquasars ?

Galactic Center ?

. . .

* the source population responsible for the bulk of GCRs are PeVatrons ?

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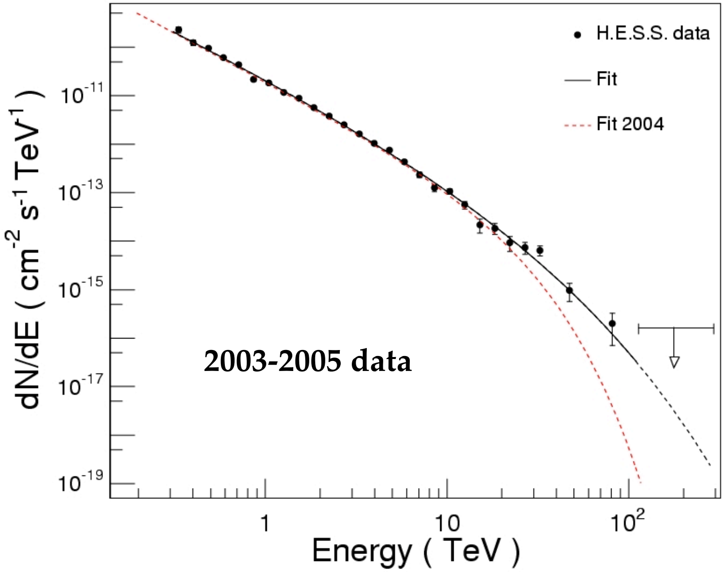
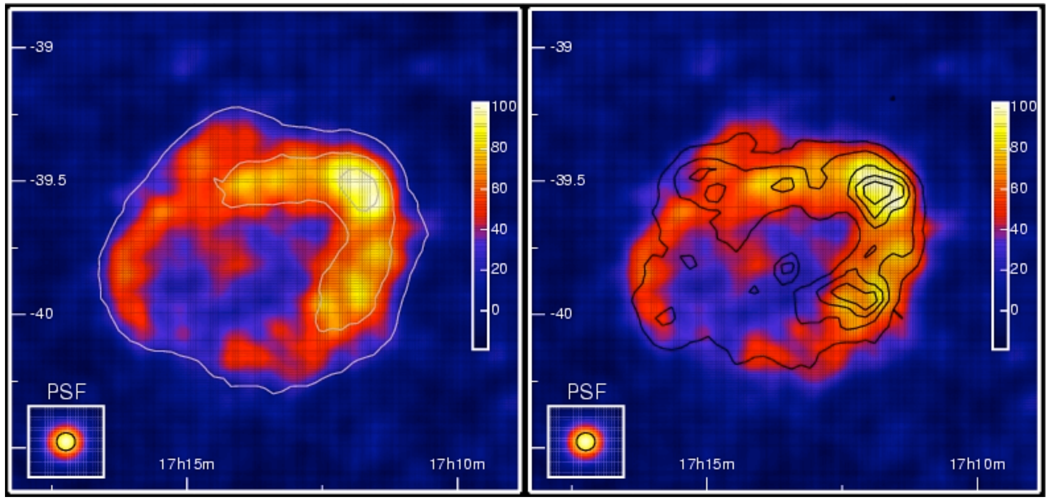




TeV γ-ray image - shell type morphology:
shock acceleration of p or e in the shell
To energies exceeding 100TeV

γ-rays from pp $\to \pi^o \Rightarrow 2\gamma$?

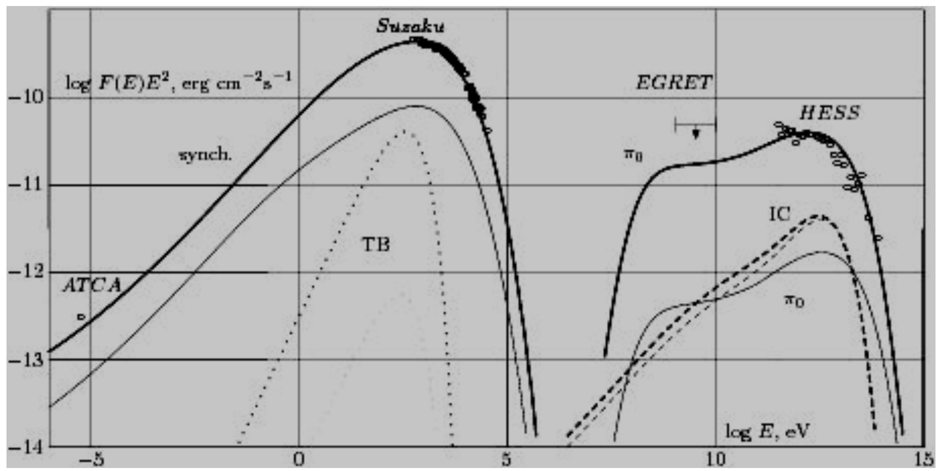
$$\alpha_p \sim 2 \text{ and } E_0 \sim 100 \text{ TeV}$$

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

but IC canot be immediately excluded…

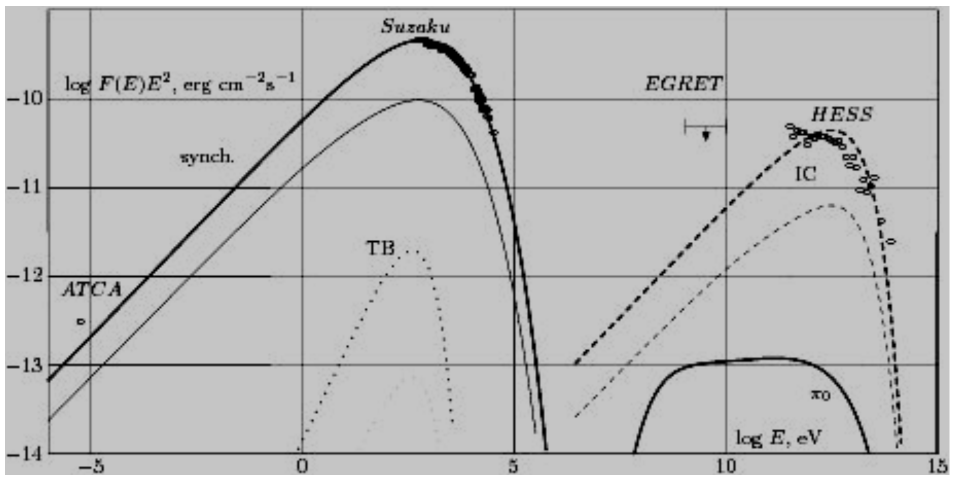
self-consistent (nonlinear) consideration of
SNR including forward and reverse shocks

hadronic model



$Wp > 5\ 10^{50}$ erg, $p/e > 10^4$
good spectral fit

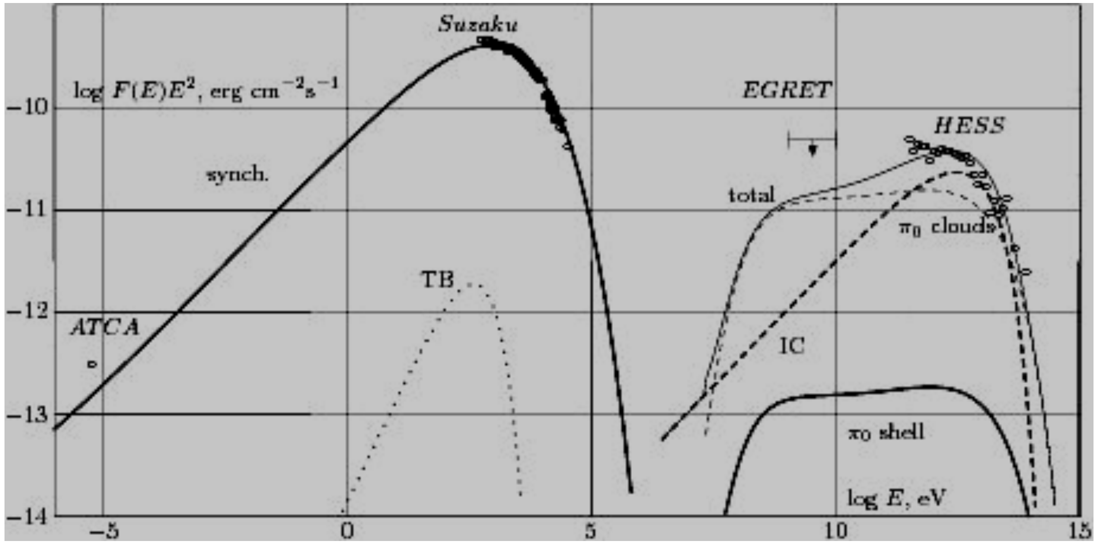
leptonic model



$Wp < 10^{50}$ erg, $p/e \sim 100$
bad spectral fit

Zirakashvili, FA, 2009

"composite" model - dense clouds in a very low density shell?



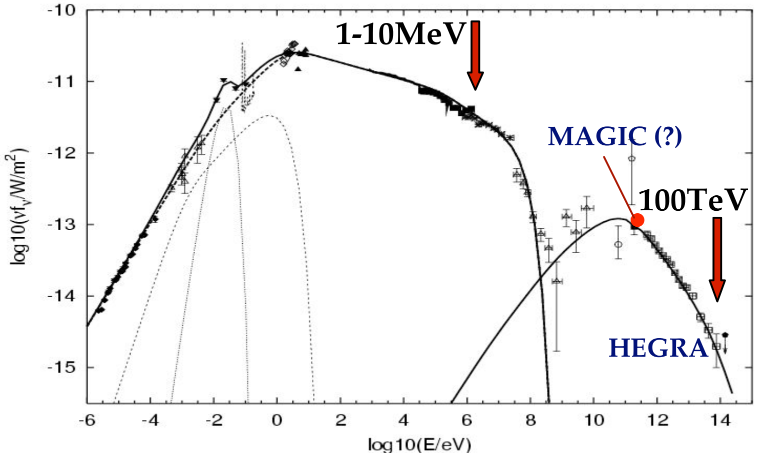
Zirakashvili, FA, 2009

gamma-radiation between 100 GeV and 10 TeV is dominated by IC
but at low, E< 10 GeV, and ultra-high, E>10 TeV, energies γ-rays are contributed mainly from pp interactions produced in dense condensations

has all advantages of leptonic and hadronic models...

recent results from AGILE and Fermi LAT support this scenario ?!
correlations of GeV and >10TeV gamma-rays with CO maps ?

Crab Nebula – a perfect PeVatron of electrons (and protons ?)



Standard MHD theory

cold ultrarelativistc pulsar wind terminates by a reverse shock resulting in acceleration with an unprecedented rate: $t_{acc} = \eta r_L/c$, $\eta < 100$ *)

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

Crab Nebula – a very powerful $W = L_{rot} = 5\times10^{38}$ erg/s

and extreme accelerator: Ee > 1000 TeV

$E_{max} = 60\ (B/1G)^{-1/2}\ \eta^{-1/2}$ TeV and $h\nu_{cut} = (0.7\text{-}2)\ \alpha_f^{-1} mc^2\ \eta^{-1} = 50\text{-}150\ \eta^{-1}$ MeV

$\eta = 1$ – minimum value allowed by classical electrodynamics
Crab: $h\nu_{cut}$ = 10MeV: acceleration at 1 to 10 % of the maximum rate (η=10-100)

maximum energy of electrons: E_γ=100 TeV => E_e > 100 (1000) TeV → B=0.1-1 mG
– very close the value independently derived from the MHD treatment of the wind

* for comparison, in shell type SNRs DSA theory gives $\eta = 10(c/v)^2 = 10^4\text{-}10^5$

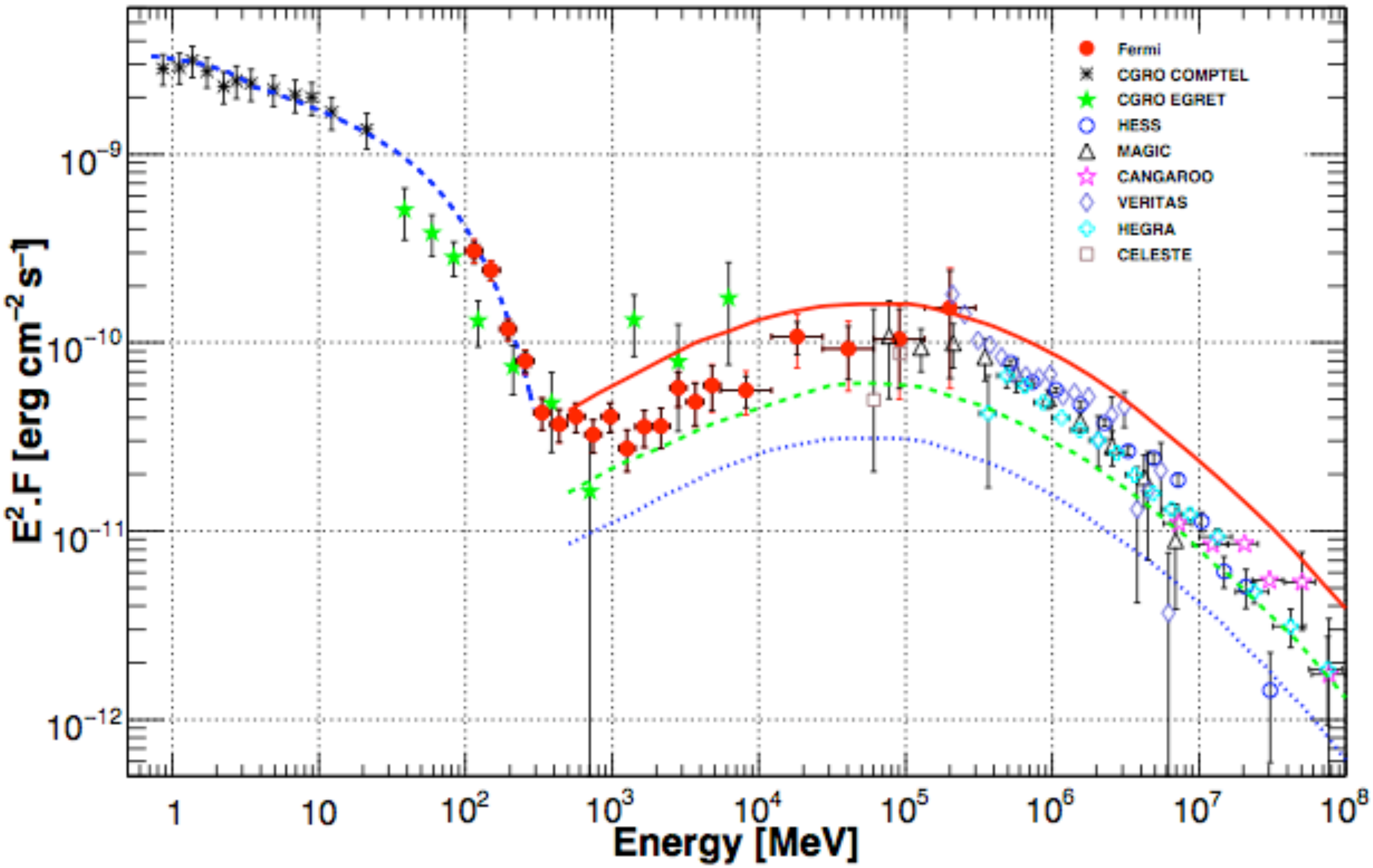
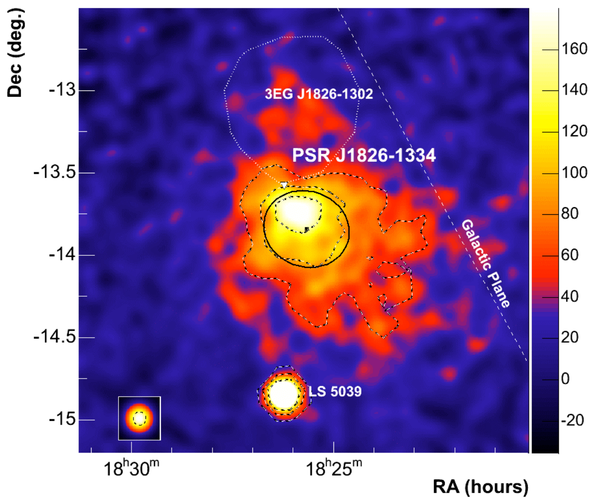
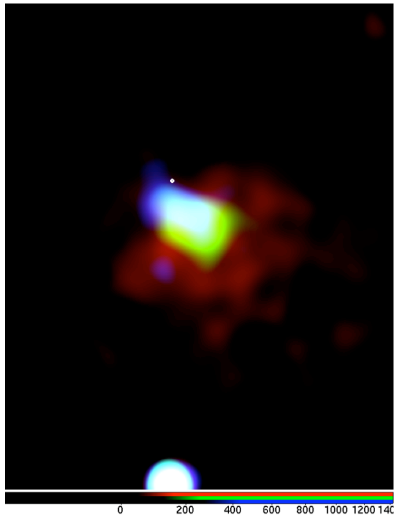


FIG. 9.— The spectral energy distribution of the Crab Nebula from soft to very high energy γ-rays. The fit of the synchrotron component, using COMPTEL nd LAT data (blue dashed line), is overlaid. The predicted inverse Compton spectra from Atoyan and Aharonian (1996) are overlaid for three different values of he mean magnetic field: 100 μG (solid red line), 200 μG (dashed green line) and the canonical equipartition field of the Crab Nebula 300 μG (dotted blue line). eferences: CGRO COMPTEL and EGRET: Kuiper et al. (2001); MAGIC: Albert et al. (2008); HESS: Aharonian et al. (2006); CANGAROO: Tanimori et al. 1997); VERITAS: Celik (2007); **HEGRA: Aharonian et al. (2004); CELESTE: Smith et al. (2006)**

results from *Fermi* LAT - confirmation of IC origin of TeV emission!

another TeV PWN:
HESS J1825/PSR J1826





energy-dependen image !

red – below 0.8 TeV
yellow – 0.8TeV -2.5 TeV
blue – above 2.5 TeV

Pulsar's period: 110 ms, age: 21.4 kyr,
distance: 3.9 +/- 0.4 kpc

<u>Luminosities</u>:

spin-down: $L_{rot}= 3 \times 10^{36}$ erg/s
X: 1-10 keV $Lx=3 \times 10^{33}$ erg/s (< 5 arcmin)
γ: 0.2-40TeV $L_{\gamma}=3 \times 10^{35}$ erg/s (< 1 degree)

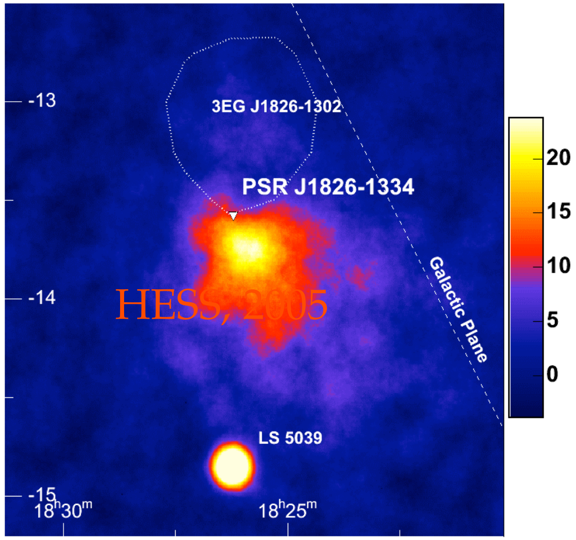
the γ-ray luminosity is comparable to the TeV luminosity of the Crab Nebula, while the spindown luminosity is two orders of magnitude less ! Implications ?

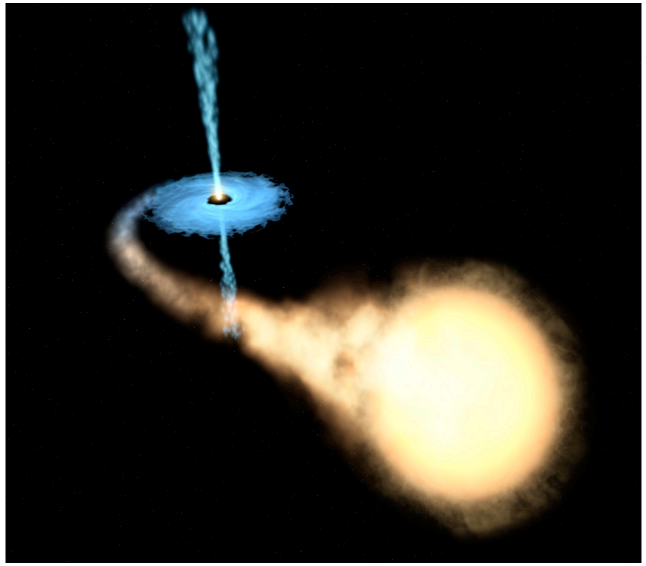
(a) magnetic field should be significantly less than 10μG (<1 μG?)

but even for $L_e=L_{rot}$ this condition alone is not sufficient to achieve 10 % γ-ray production efficiency (Compton cooling time of electrons on 2.7K CMBR exceeds the sotce age)

(b) the spin-down luminosity in the past was much higher (very low B-field)

gamma-rays from binary systems

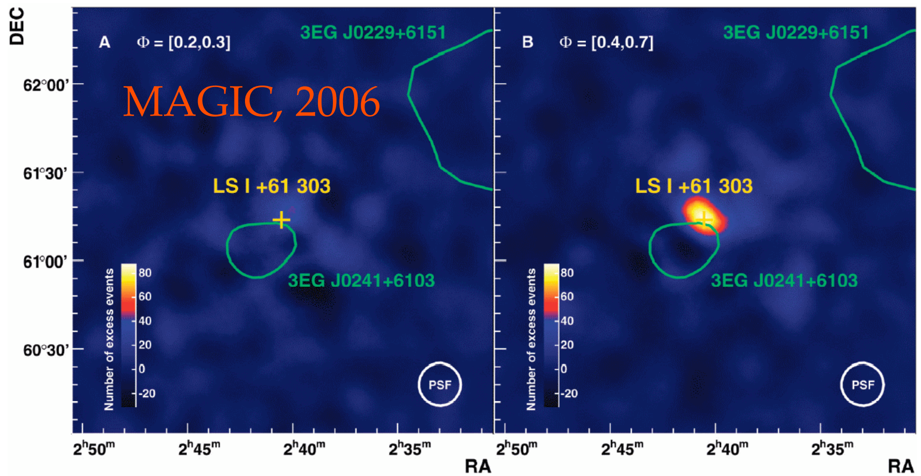




microqusars or binary pulsars?

PSR1259 - binary pulsar (TeV)
Cyg X-3 - microquasar (GeV)

independent of the answer – particle acceleration is linked to (sub) relativistic outflows



LS5039 and LS I +61 303 as TeV gamma-ray emitters

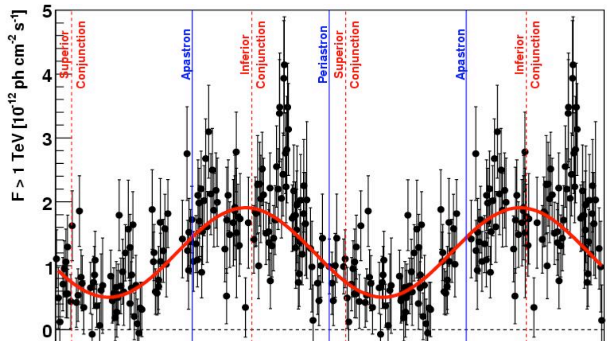
<u>scenarios?</u> γ-ray production region within and outside the binary system cannot be excluded

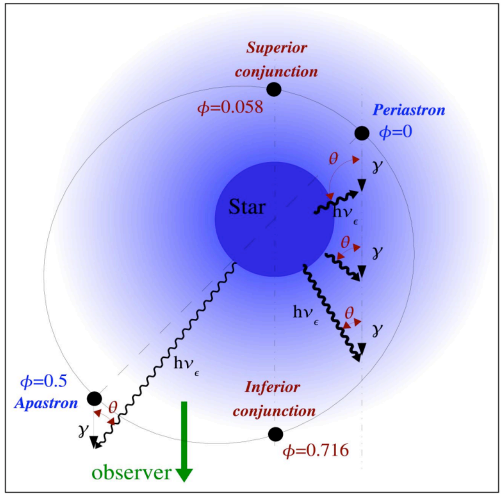
<u>periodicity expected?</u> yes — because of periodic variation of the geometry (interaction angle) and density of optical photons – as target photons for IC scattering and $\gamma\gamma$ absorption, as a regulator of the electron cut-off energy; also because of variation of the B-field, density of the ambient plasma (stellar wind), ...

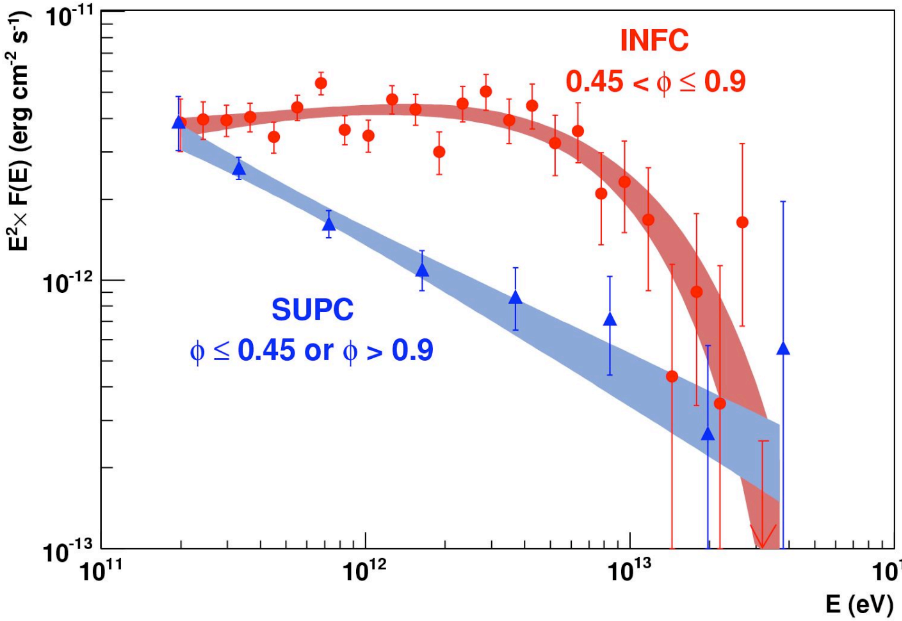
periodicity detected ! is everything OK ?

may be OK, but a lot of problems and puzzles with interpretation of the data …

LS 5039 as a perfect TeV clock
and an extreme TeVatron







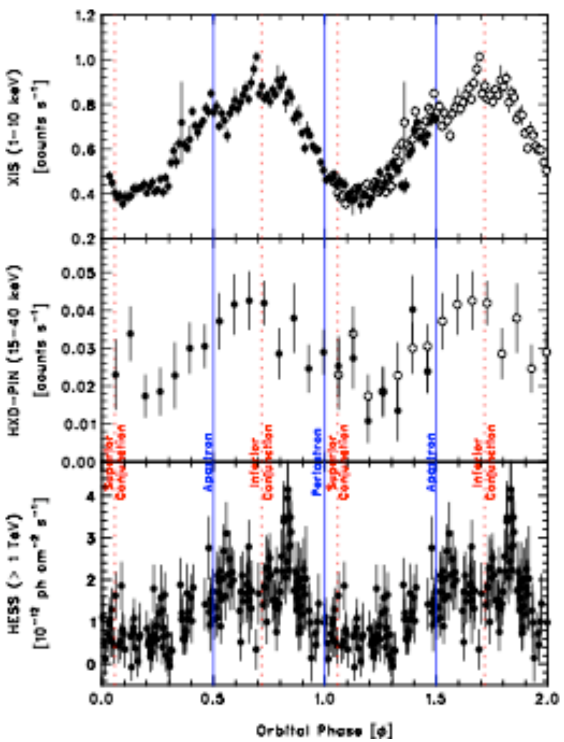
close to inferior conjuction - maximum
close to superior conjuction – minimum

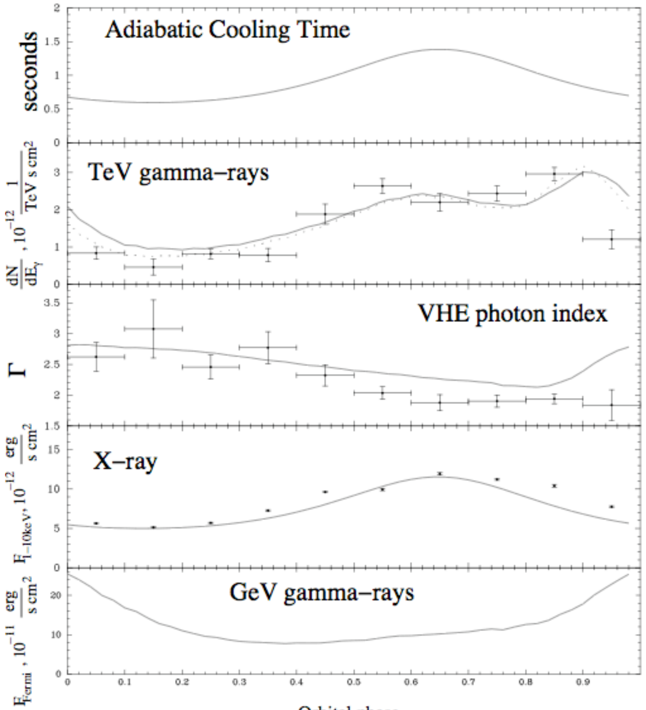
modulation of the gamma-ray signal?
a quite natural reason (because of γ–γ absorption), but we see a different picture…
anisotropic IC scattering? yes, but not only …

modulated X-ray signal:
explanation?

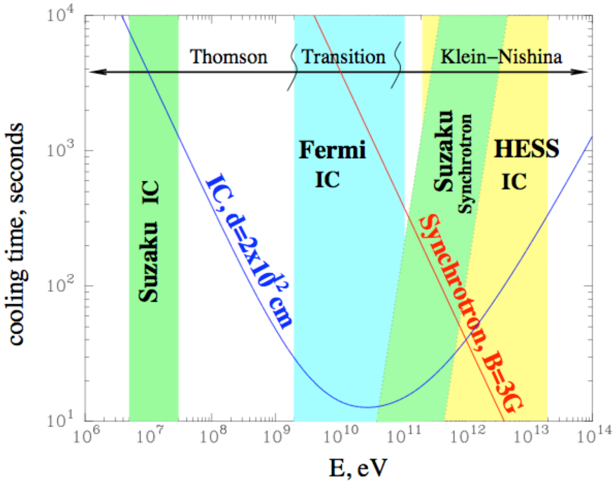
adiabatic loses

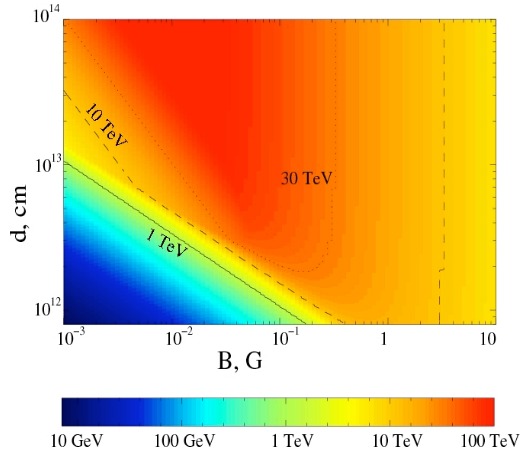
Takahashi et al. 2009

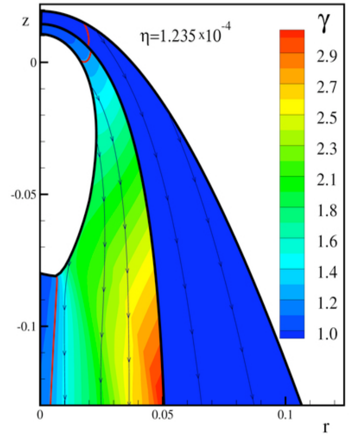




recent detection of GeV gamma-rays by Fermi LAT and AGILE
should help to understand better the origin of the compact object







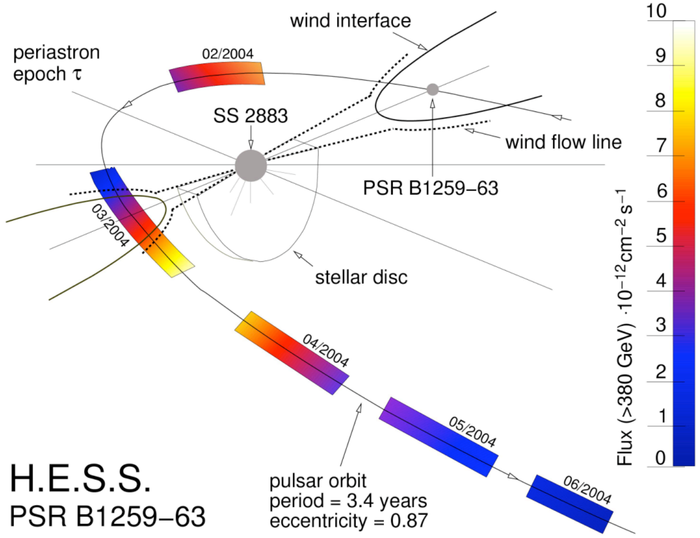
- ❑ can electrons be accelerated to > 20 TeV in presence of radiation?

  yes, but accelerator should not be located deep inside the binary system, and even at the edge of the system $\eta < 10$

- ❑ does this excludes the model of “binary pulsar”

  yes, unless the interaction of the pulsar and stellar winds create a relativistic bulk motion of the shocked material (it is quite possible)

PSR 1259-63: a binary containing
(i) pulsar!
(ii) Be-star - no significant gg absorption



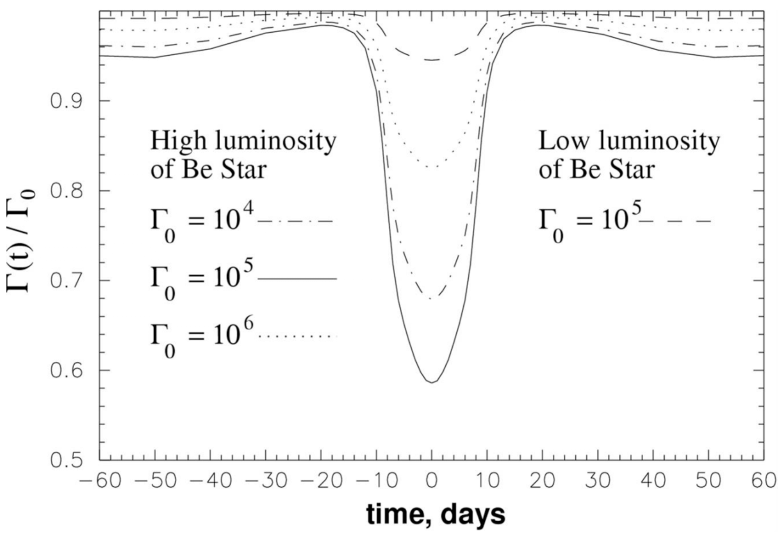
HESS: detection of TeV gamma-rays from PSR1259-63 several days before the periastron and 3 weeks after the peristron

the target photon density is a strict function of time, thus the only unknown parameter is B-field? Predictable X and gamma-ray fluxes ?

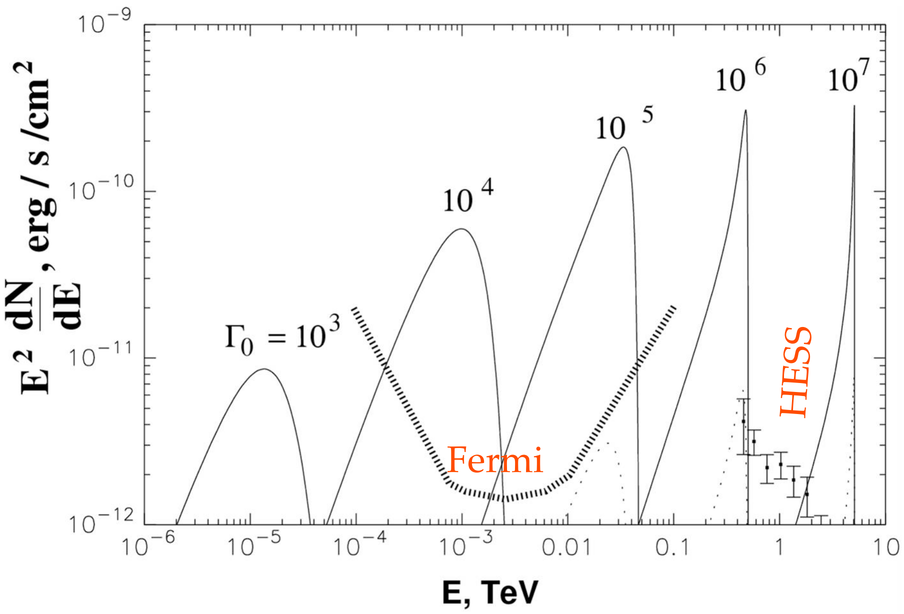
unfortunately more unknown parameters - adiabatic losses, Doppler boosting, etc.
One needs deep theoretical (especially MHD) studies to understand this source

time evolution of fluxes and energy spectra of X- and gamm-rays contain unique information about the shock dynamics, electron acceleration, B(r), plus … a unique probe of the Lorentz factor of the cold pulsar wind

Probing the wind Lorentz factor with comptonizied radiation

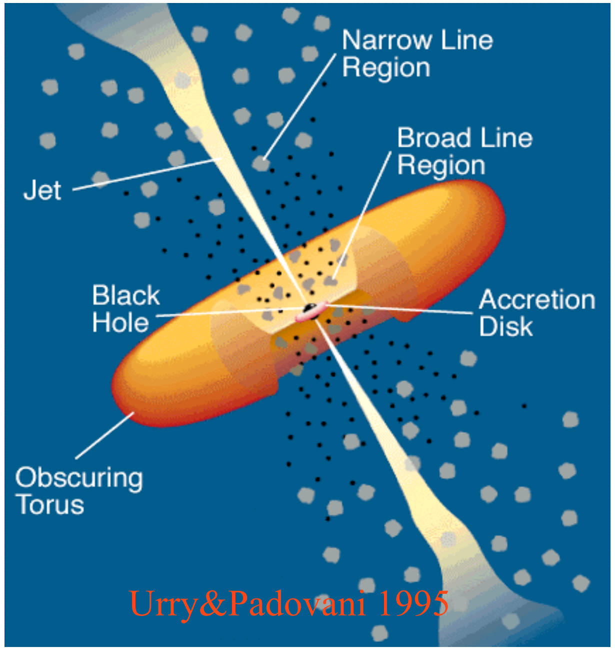


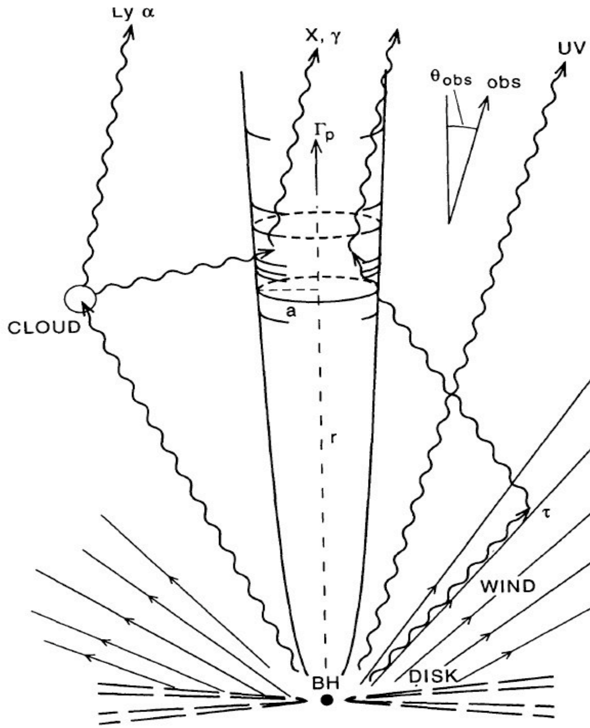
the effect is not negligible, but not sufficient to explain the lightcurve



Loretz factors exceeding 10^6 are excluded

Blazars - sub-class of AGN dominated by nonthermal/variable broad band (from R to γ) adiation produced in relativistic jets close to the line of sight, with massive Black Holes as central engines





Sikora 1994

FIG. 2.—Geometry of the source. The radiating region, denoted by short cylinder of dimension a, moves along the jet with pattern Lorentz factor Γ_p. Underlying flow moves with Lorentz factor Γ, which may be different.

γ-rays from >100 Mpc sources - detectable because of the Doppler boosting

TeV emission from 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 X-rays: 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
  very slow process: $t_{pp} \sim 10^{15} (n/1 cm^{-3})^{-1} sec$

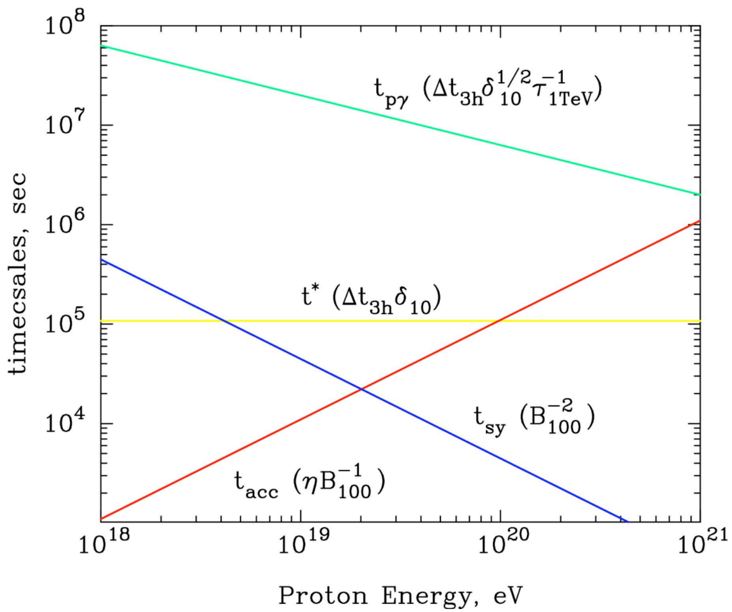
- protons interacting with photon fields
  low efficiency + severe absorption of TeV γ-rays

- proton synchrotron
  very large magnetic field B=100 G + accelaration rate c/r_g
  "extreme accelerator" (of EHE CRs) Poynting flux dominated flow

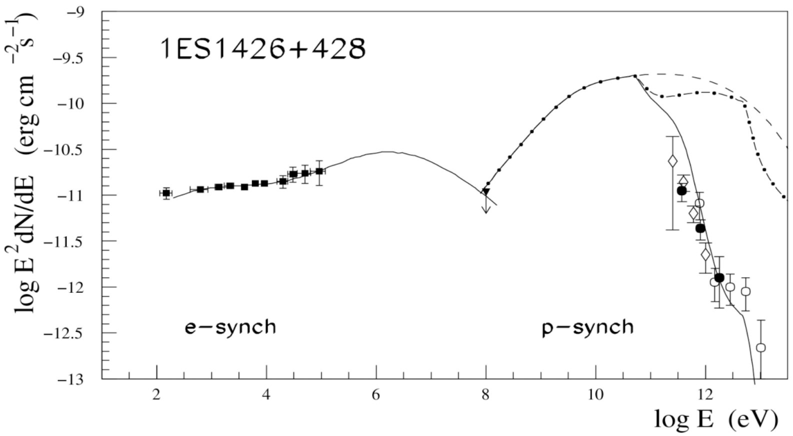
variability can be explained by nonradiative losses in expense of increase of total energetics, but as long as Doppler factors can be very large (up to 100), this is not a dramatic issue : $L \propto \delta^4$

Synchrotron radiation of an extreme proton accelerator

cooling and acceleration times of protons



FA 2004



synchrotron radiation of protons:
a viable radiation mechanism

E_{max} =300 η^{-1} δj GeV
requires extreme accelerators: $\eta \sim 1$

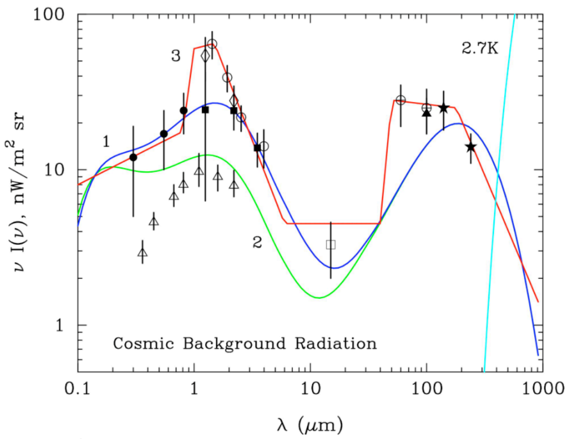
E_{cut}=90 (B/100G)(Ep/10^{19} eV)^2 GeV

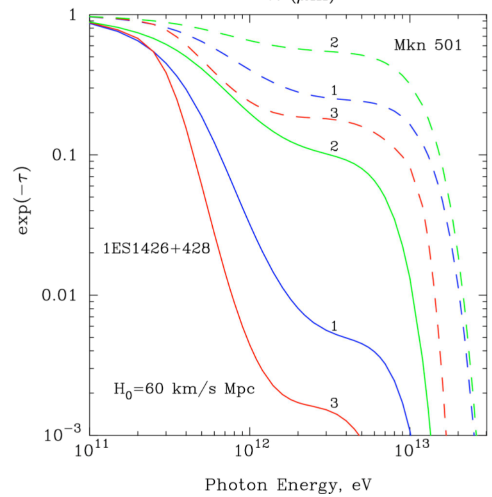
t_{synch}=4.5x10^4(B/100G)$^{-2}$ (E/10^{19} eV)$^{-1}$ s

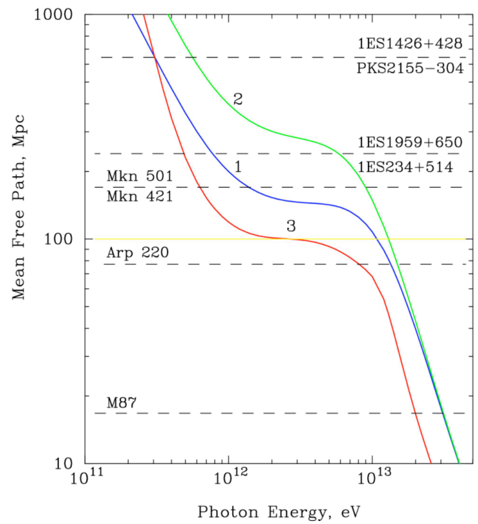
t_{acc}=1.1x10^4 (E/10^{19}) (B/100G)$^{-1}$ s

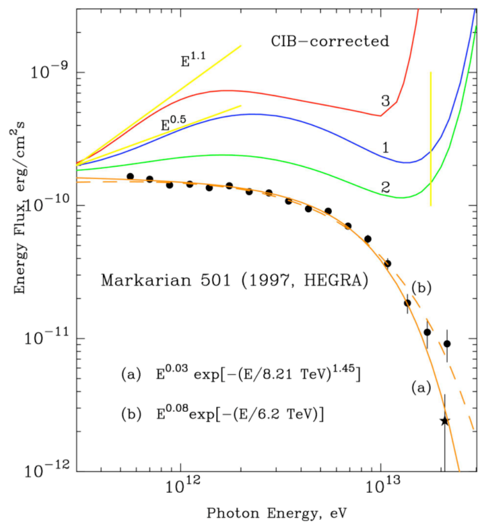
in TeV blazars the synchrotron radiation of protons is much more effective cooling process compared to photomeson reactions => no high energy neutrinos

integalactic absorption of gamma-rays

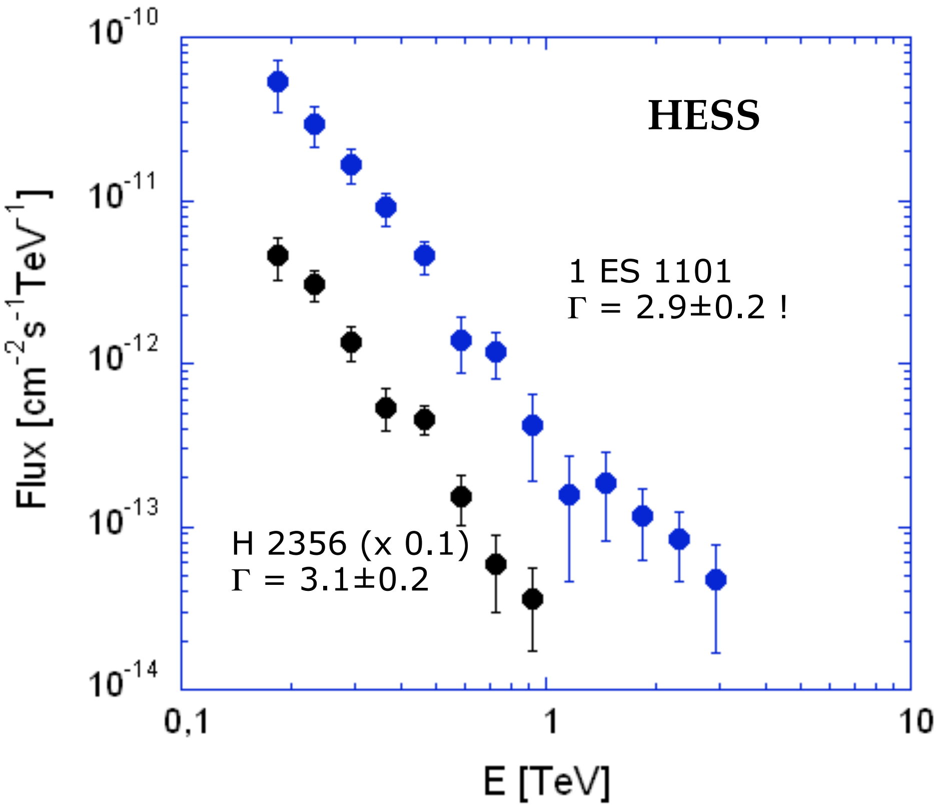








new blazars detected at large z:
HESS/MAGIC at z> 0.15 !

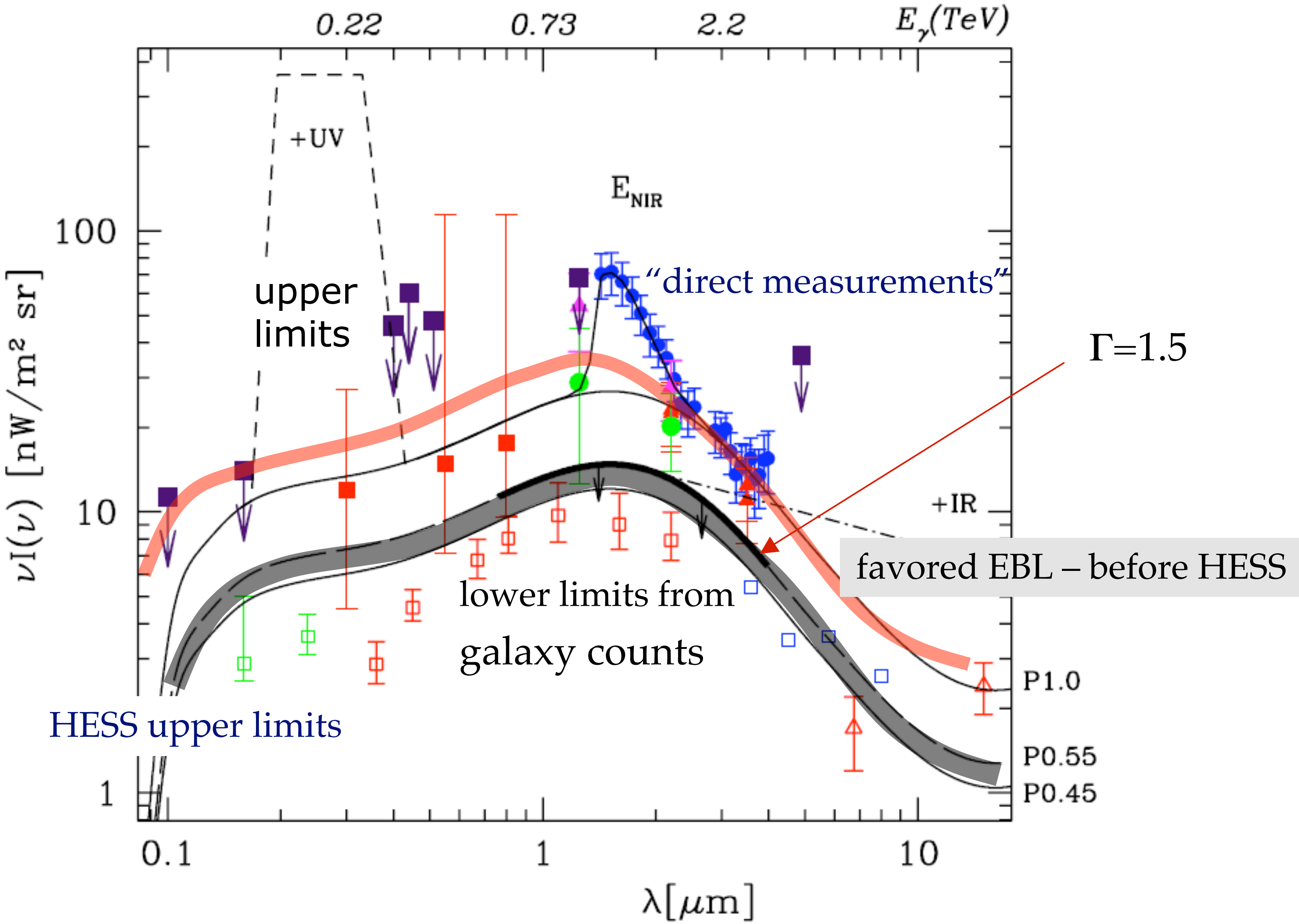


condition: corrected for IG absorption γ-ray spectrum not harder than $E^{-\Gamma}$ ($\Gamma=1.5$)

➔ **upper limit on EBL**

HESS – upper limits on EBL at O/NIR:

EBL (almost) resolved at NIR ?



two options:

claim that EBL is "detected" between O/NIR and MIR

or

propose ***extreme*** hypotheses, e.g.

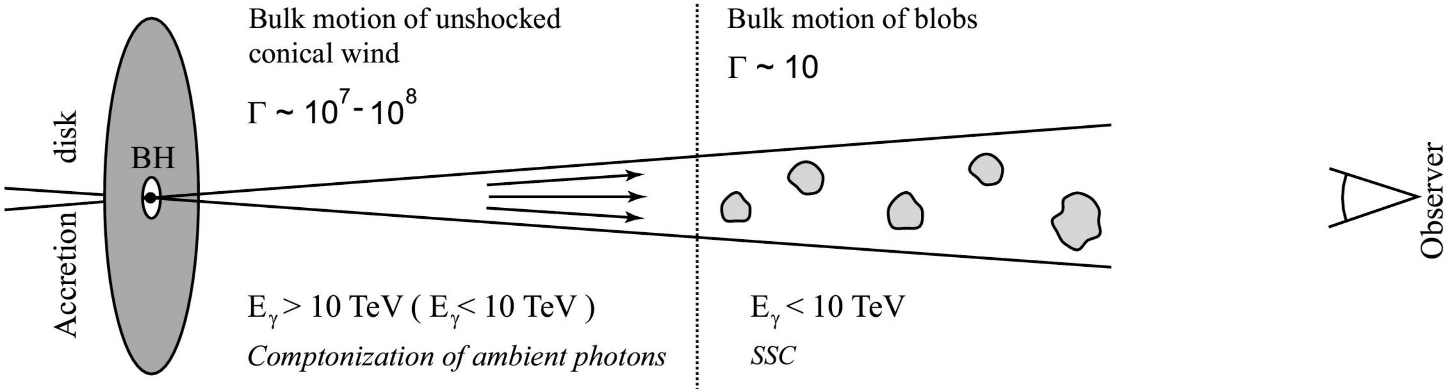
violation of Lorentz invariance, non-cosmological origin of z ...

or

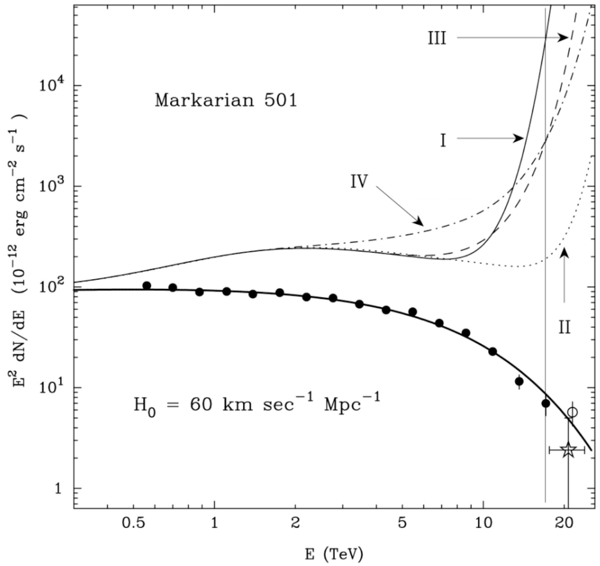
propose ***less dramatic (more reasonable)*** ideas, e.g.

- very specific spectrum of electrons and no cooling ➔ $\nu F\nu \sim E_\gamma^{1.33}$
- TeV emission from blazars due to comptonization of cold relativistic winds with bulk Lorentz factor $\Gamma > 10^6$
- internal gamma-ray absorption

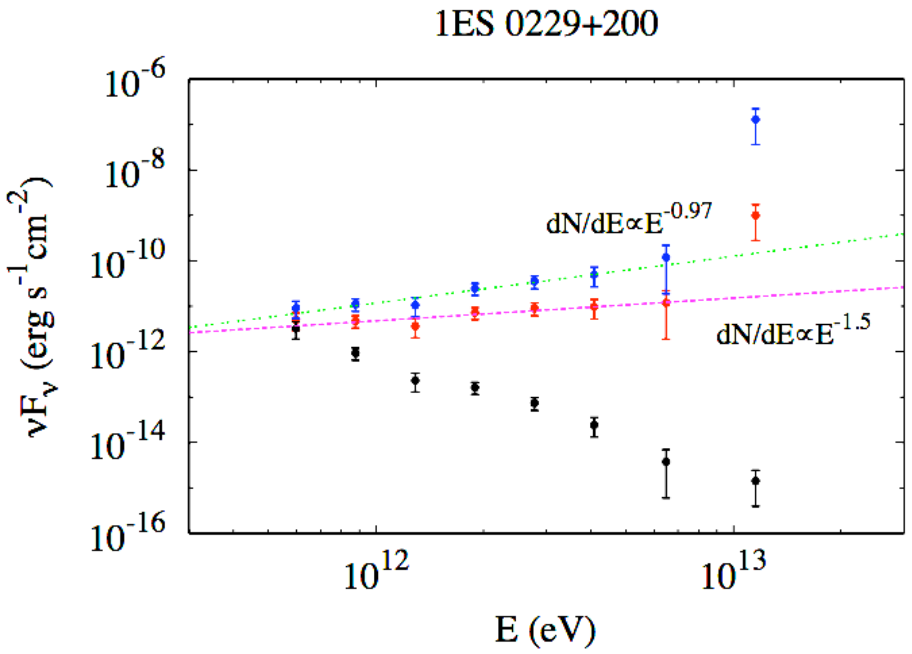
Gamma Rays from a cold ultrarelativistic wind ?



in fact not a very exotic scenario ...

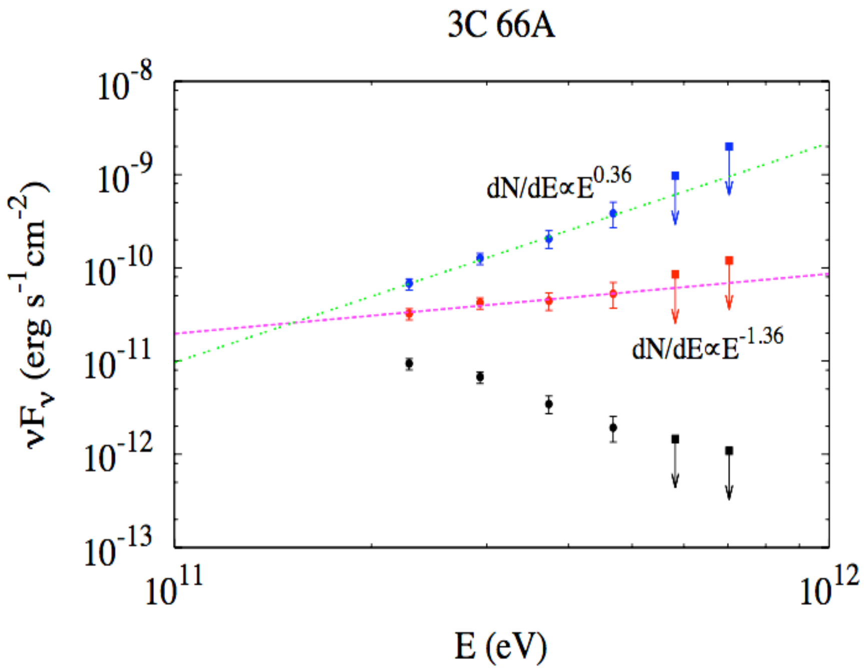


new "trouble-makers"

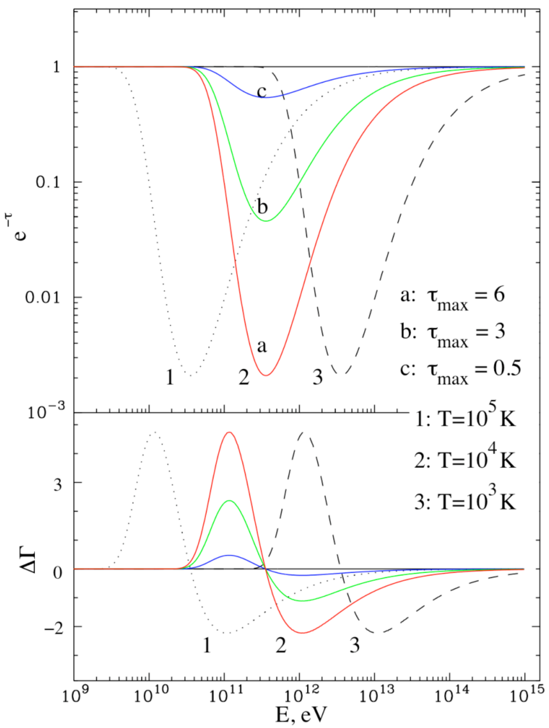


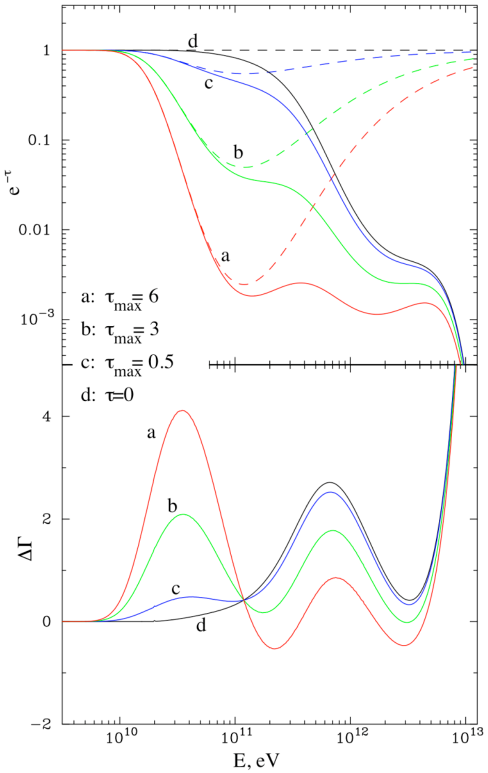
1ES 0229+200: z= 0.14, but spectrum extends to >5 TeV ! (HESS collaboration) !

3C 66A z=0.44 ! (VERTAS collaboration)

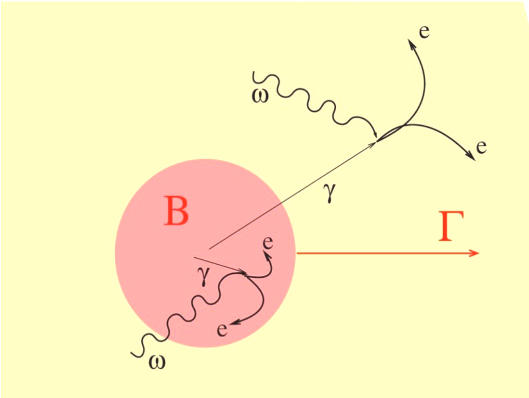


internal gamma-gamma absorption



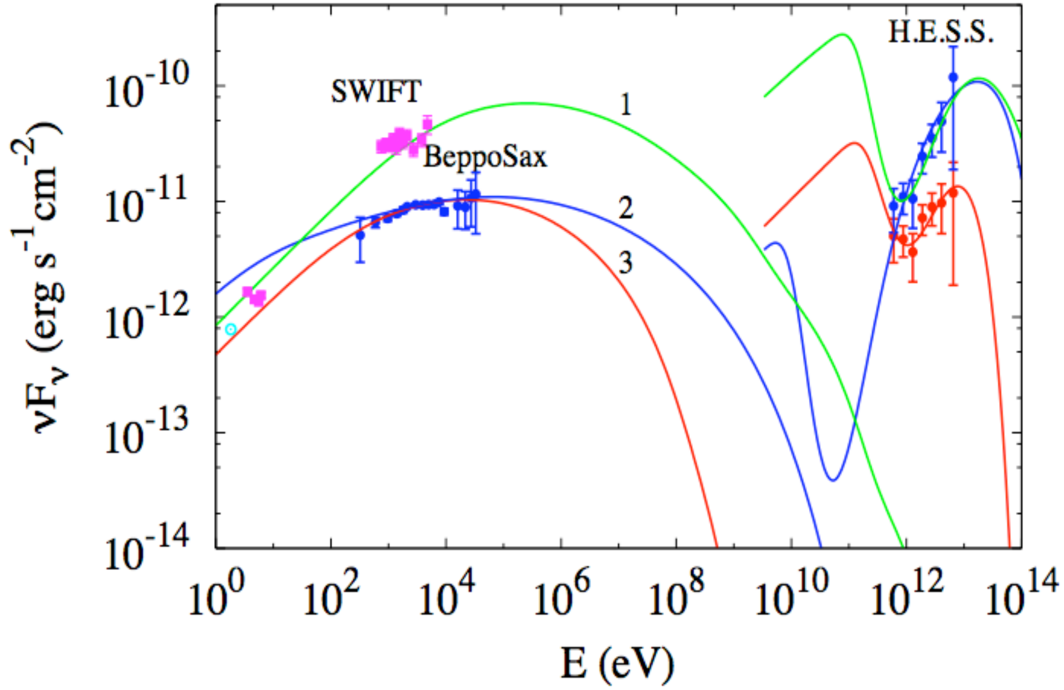


can make the intrinsic spectrum arbitrary hard without any real problem from the point of view of energetics, given that it can be compensated by large Doppler factor, $\delta j > 30$



Model: *internal γ–γ absorption inside and outside the blob*

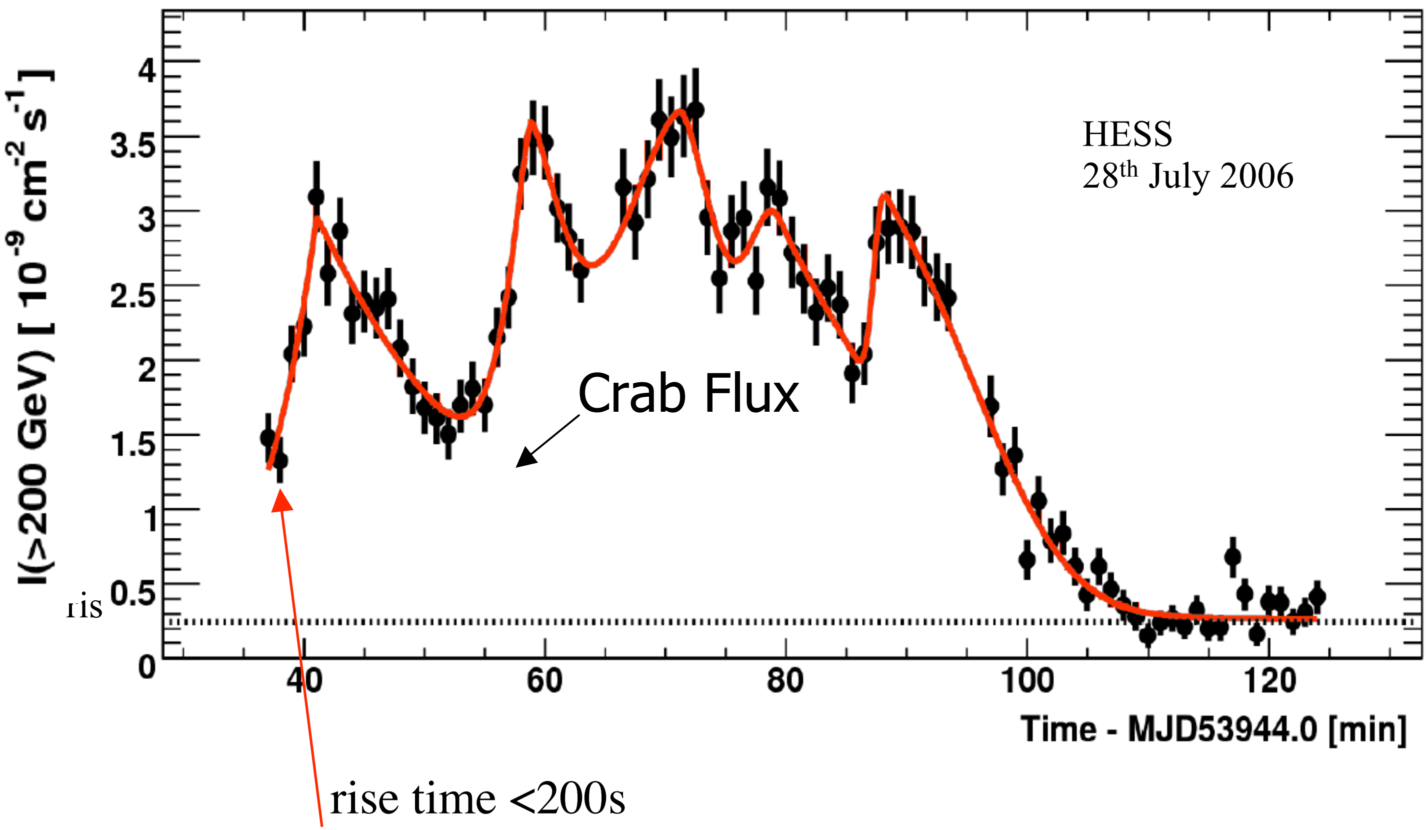
1ES 0229+200



assuming optical depth $\tau_{\gamma\gamma} \sim$ 3-7, $\Gamma \sim 10$, one can explain not only gamma-ray spectra (after) correction for intergalactic absorption), but also the synchrotron emission by secondary e^+e^-

short TeV flares of PKS2155-304 on min-timescales

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 $\Gamma > 100$



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

- Distance: ~16 Mpc

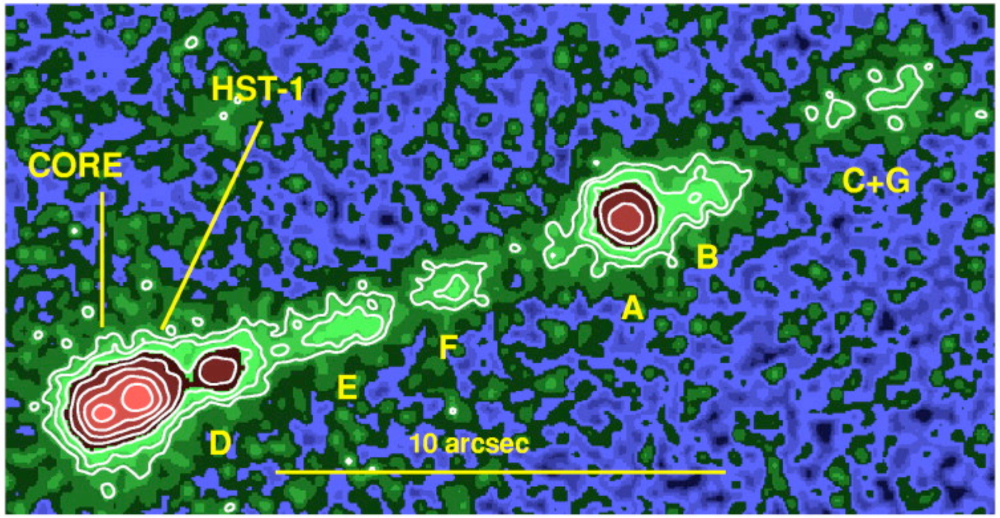
- central BH: 3×10^9 M_O *)
- Jet angle: ~30°

  => *not a blazar*!

discovery (>4σ) of TeV γ-rays by HEGRA (1998) and confirmed recently by HESS/VERITAS, MAGIC

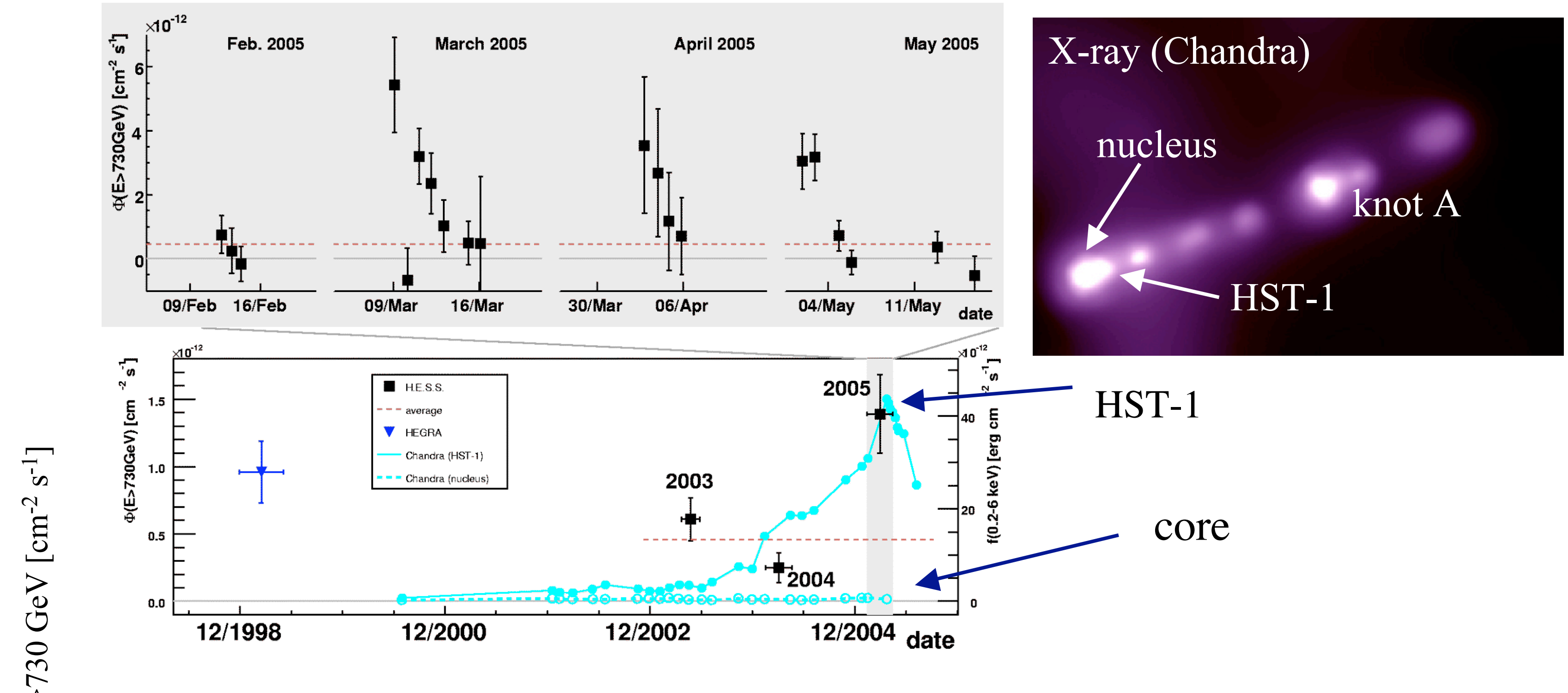
*) recently 6.4 x 10^9 M_o

arXiv: 0906.1492 (2009)



M87: light curve and variabiliy

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



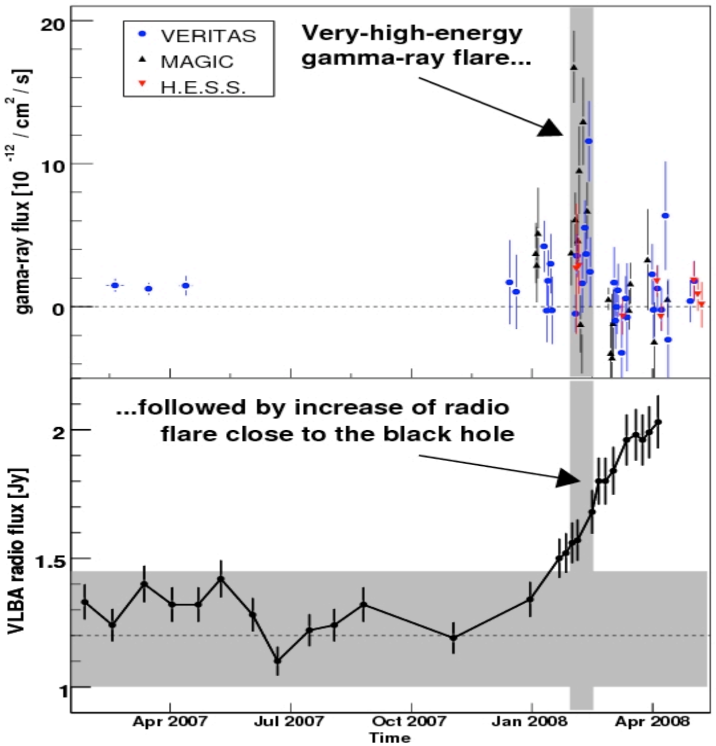
short-term variability on 1-2 day scales => emission region R ~ 5x10^{15}δj cm

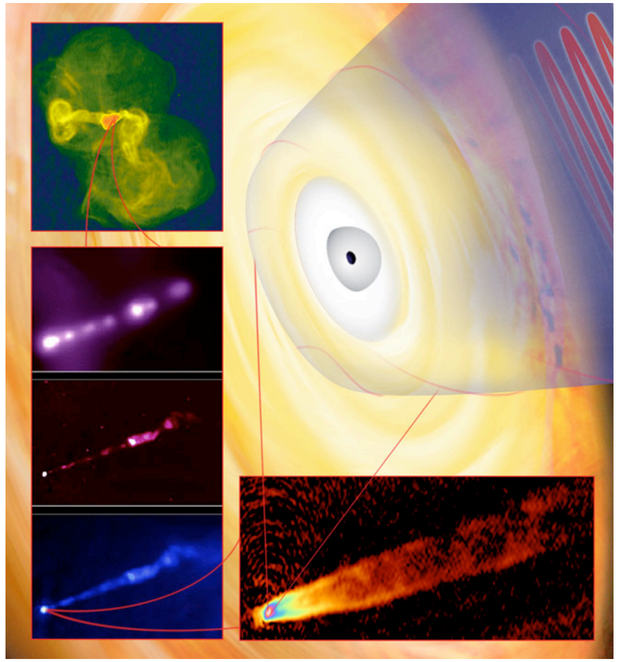
=> production of gamma-rays very close to the 'event horizon' of BH?

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

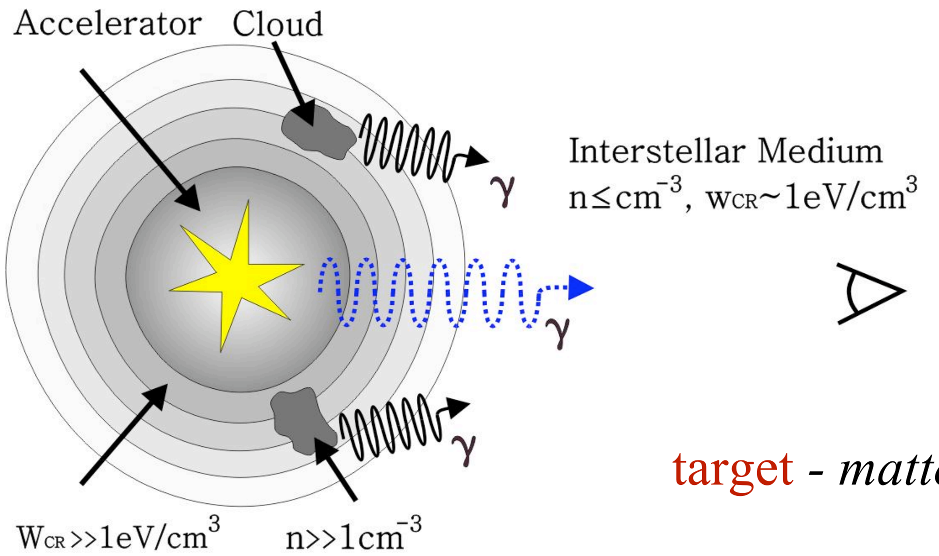
conclusion? *TeV gamma-rays are produced in the jet collimation region within 50 Rs around BH*

Unidentified (yet) TeV Gamma Sources:

why so many?

<u>*gamma-ray production:*</u> particle accelerator + target

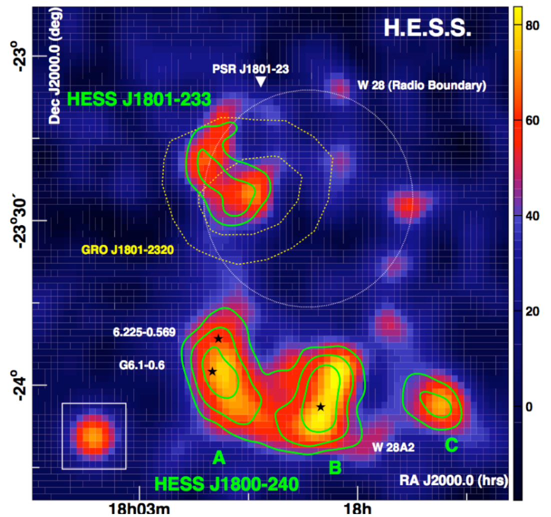
existence of a powerful particle accelerator by itself is not sufficient for γ-radiation; an additional component – a dense target - is required

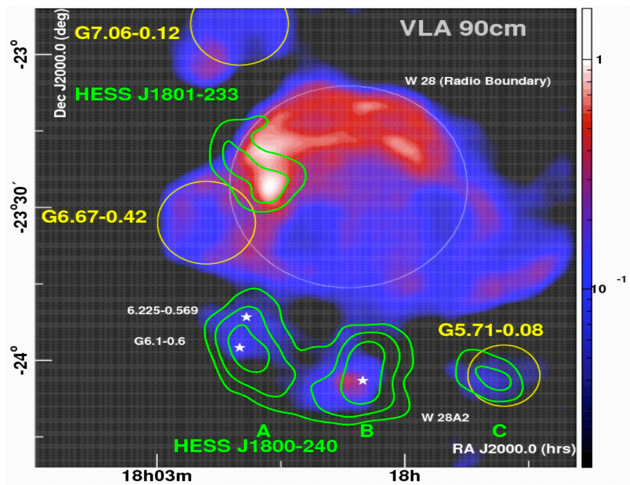


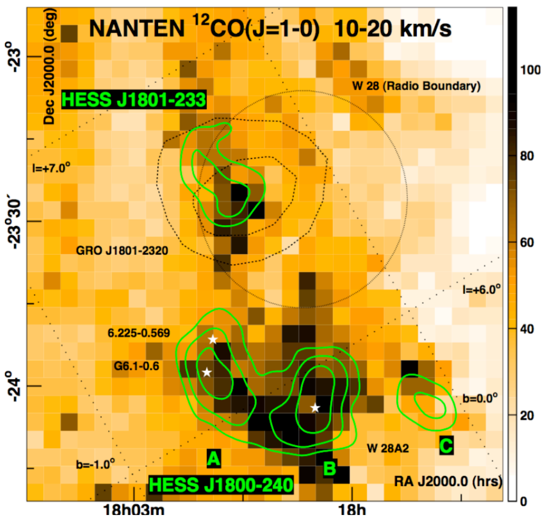
target - *matter, radiation, magnetic field*

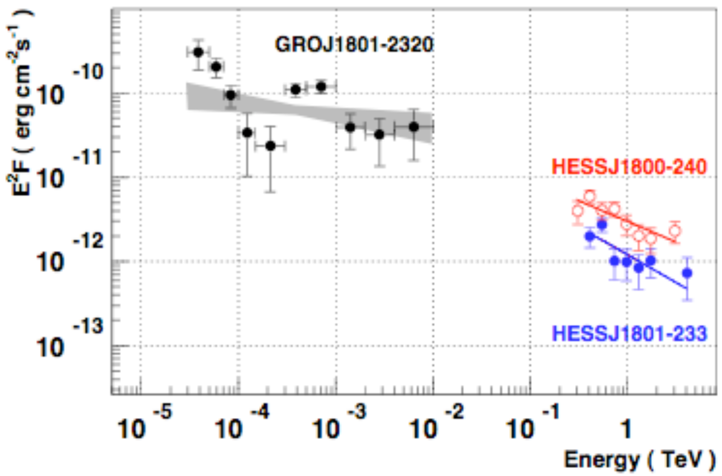
any gamma-ray emitter coincides with the target, but not necessarily with the "primary" source/particle-accelerator

1. TeV gamma-ray sources around W28: CRs from an old SNR interacting with nearby clouds?





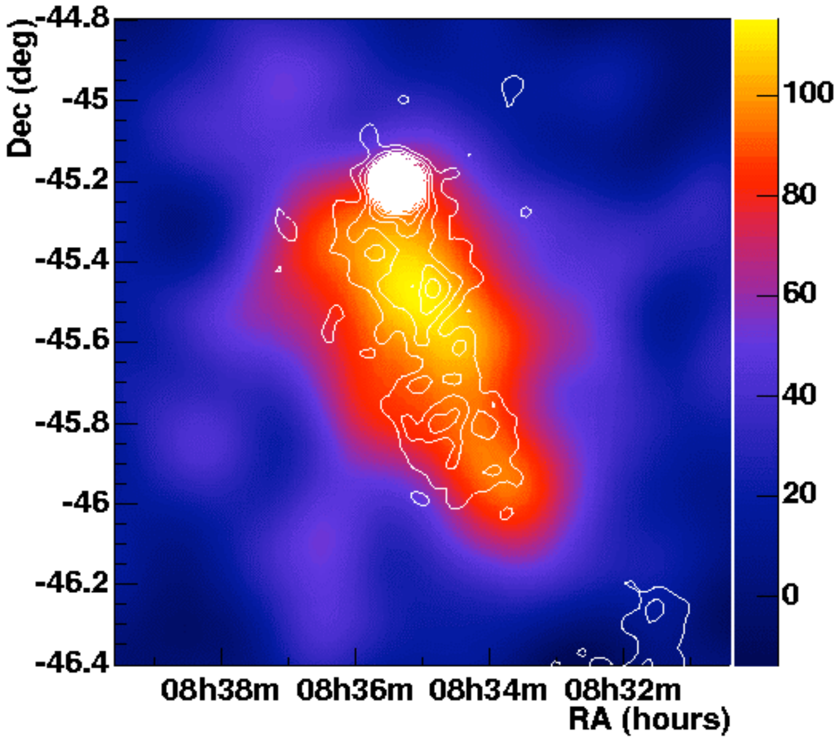


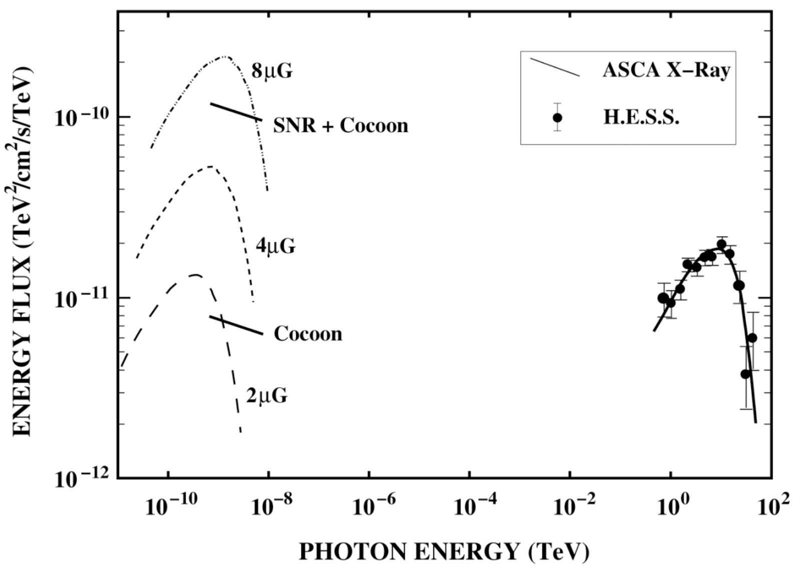


2. HESS J0835-456 (Vela X):

a PWN (plerion)

gamma-rays are produced due to IC scattering of multi-TeV electrons on 2.7 K, X-rays - due to synchrotron radiation of same electrons

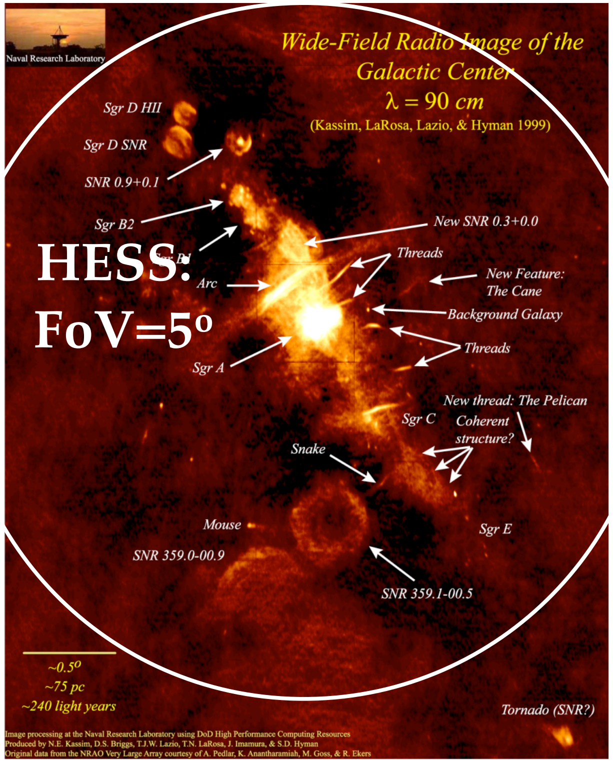




since 2.7 K MBR is the main target field, TeV images reflect spatial distributions of electrons Ne(E,x,y); coupled with synchrotron X-rays, TeV images allow measurements of B(x,y)

3.

TeV gamma-rays from GC



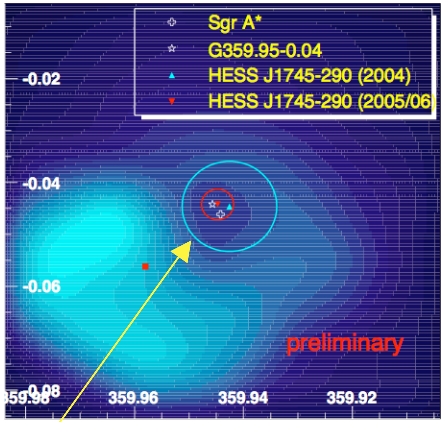
GC – a unique site that harbors many interesting sources packed with unusually high density around the most remarkable object 3×10^6 Mo SBH – Sgr A*

*many of them are potential γ-ray emitters - Shell Type SNRs Plerions, Giant Molecular Clouds Sgr A * itself, Dark Matter …*

all of them are in the FoV an IACT, and can be simultaneously probed down to a flux level 10^{-13} erg/cm^{2}s and localized within << 1 arcmin

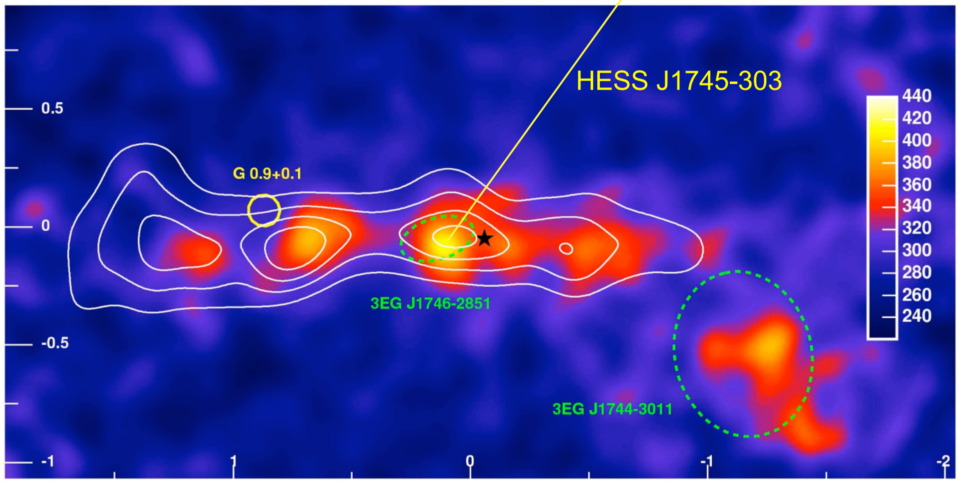
Galactic Center

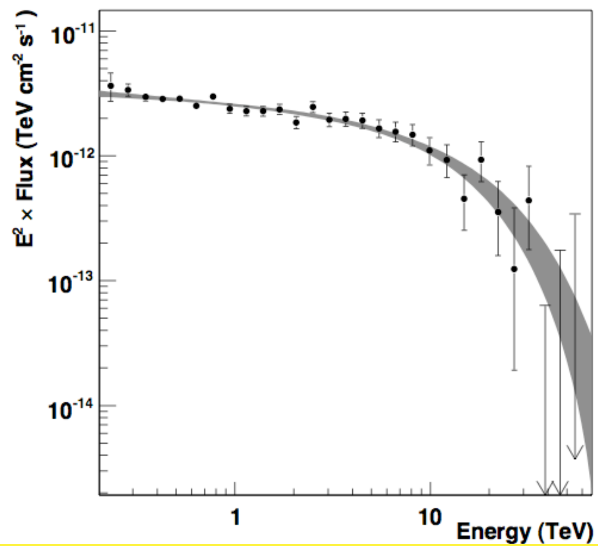
90 cm VLA radio image



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

γ-ray emitting clouds





Energy spectrum:

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

$\beta=1$ $\Gamma=2.1$; $E_0=15.7$ TeV
$\beta=1/2$ $\Gamma=1.9$ E0=4.0 TeV

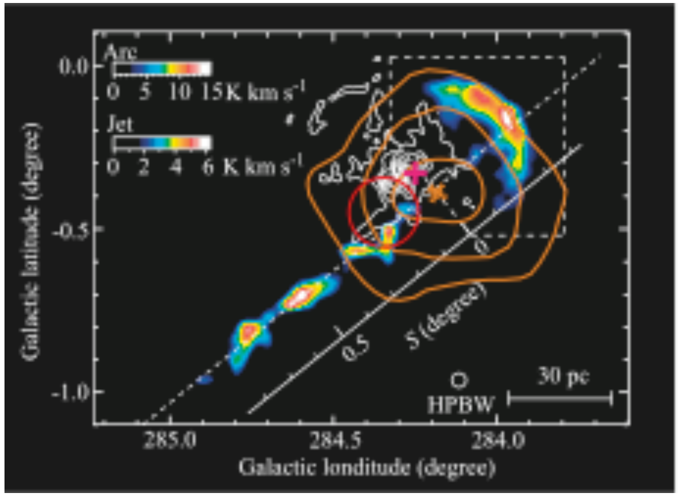
γ-rays from GMCs in GC: a result of an active phase in Sgr A* with acceleration of CRs some 10^4yr ago?

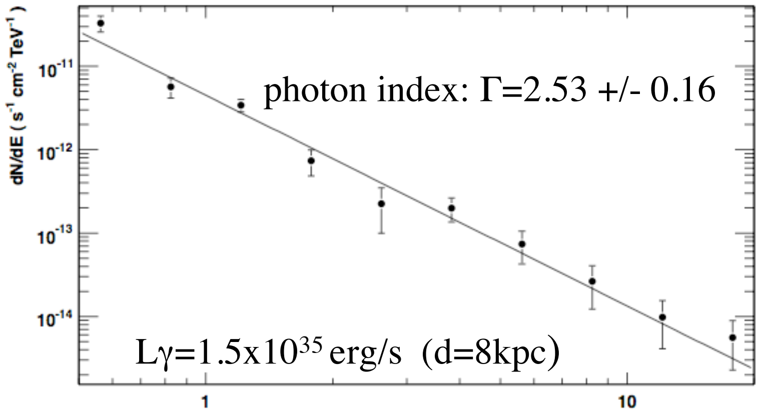
4. *an unidentified source*

Westerlund-2: a rich young star cluster

gamma-ray source? - *colliding stellar winds, supernova shocks, PWN*

electrons, protons, nuclei, …





NANTEN 2:

"jet" and "arc" in CO
anisotropic SN explosion
(a hypernova remnant?)

HESS:

IC ? a steep electron spectrum; α>4
or a cutoff; modest energetics
L_X (1-10keV) < 5 10^{34} erg/s

Protons? $W_p=10^{50}$ $(n\ /1cm^{-3})^{-1}$ erg
a SN? provided flattening below 1TeV
steep spectrum - old source?

origin of the TeV source - *an old proton source/remnant of a SN explosion*

5. Pair Halos

TeV Gamma-rays from distant extragalactic sources, d > 100 Mpc interact effectively with Extragalactic Background Radiation (EBL; (0.1-100 mm)

when a gamma-ray is absorbed its energy is not lost !
absorption in EBL leads to E-M cascades suppoorted by

- Inverse Compton scattering on 2.7 K CMBR photons
- photon-photon pair production on EBL photons

if the intergalactic field is sufficiently strong, $B > 10^{-11}$ G,
the cascade e^+e^- pairs are promptly isotropised

➡ formation of extended structures – Pair Halos

how it works ?

energy of primary gamma-ray

$$E_{\gamma,0} \simeq 10(E_\gamma/100\text{GeV})^{1/2}\ \text{TeV}$$

mean free path of parent photons

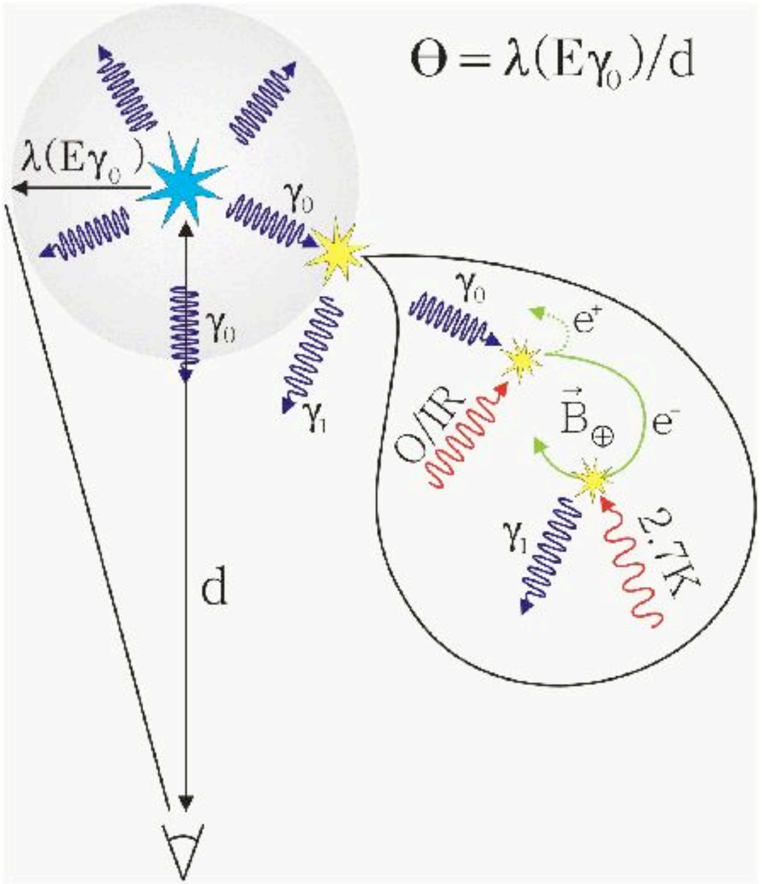
$$\lambda(E_{\gamma,0}) \sim d \times \Theta$$

information about EBL flux at

$$\lambda \simeq 10(E_\gamma/100\text{GeV})^{1/2}\ \mu\text{m}$$

gamma-radiation of pair halos can be recognized by its distinct variation in spectrum and intensity with angle Θ and depends rather weakly (!) on the features of the central VHE source

two observables – angular and energy distributions allow to disentangle two variables $u_{EBL}(\lambda, z)$ and $d\ (H_0)$!



Pair Halos as Cosmological Candles

- informationabout EBL density at fixed cosmological epochs given by the redshift of the central source unique !

- estimate of the total energy release of AGN during the active phase

- objects with jets at large angles - many more γ-ray emitting AGN

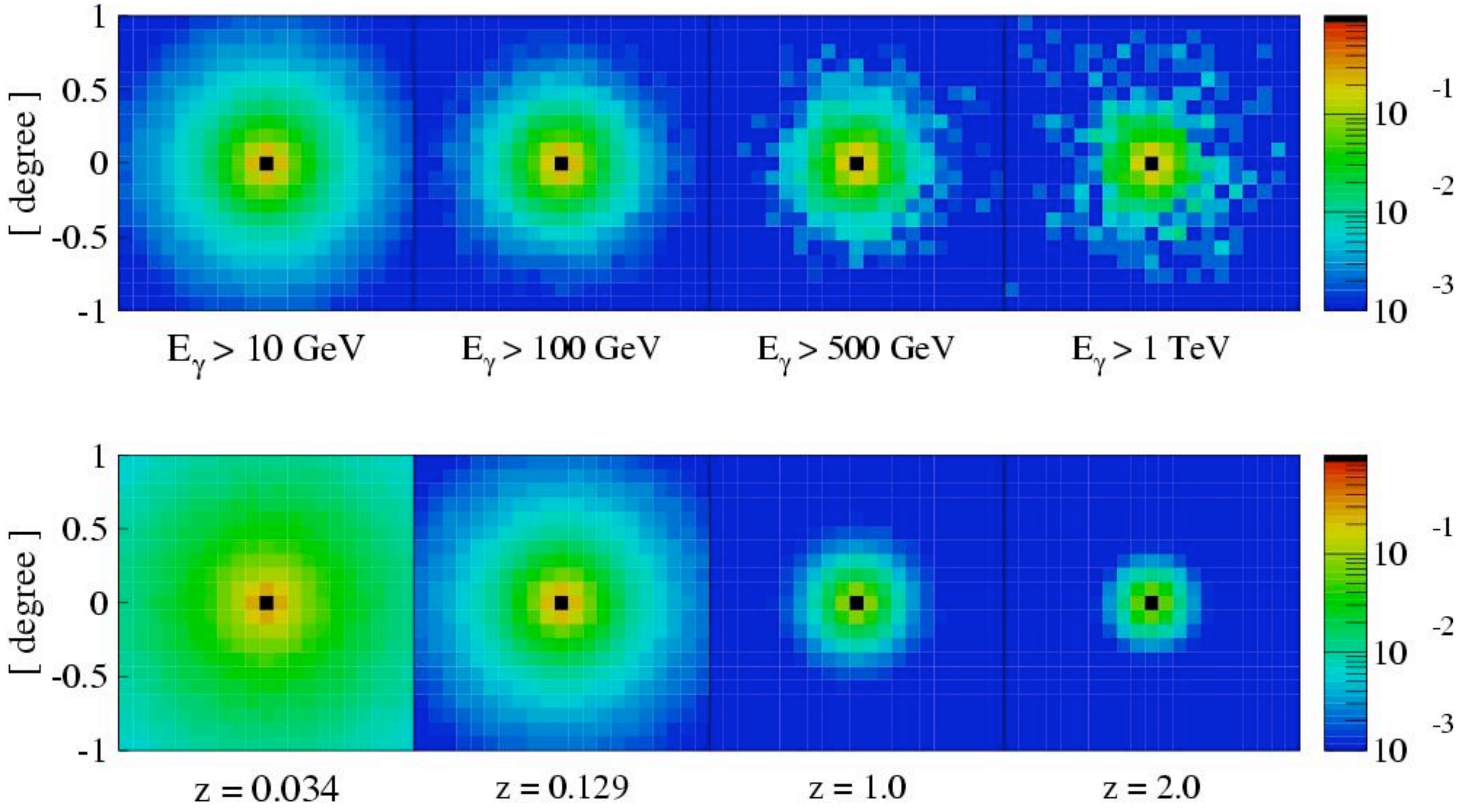
but the advantage of the large Doppler boosting of blazars disapeares: beam ⇨ isotropic source

therefore very powerful central objects needed

QSOs and Radiogalaxies (sources of EHE CRS ?) as better candidates for Pair Halos

this requires low-energy threshold detectors

Brightness distributions of Pair Halos



z=0.129

E=10 GeV