Exploring Nature's Extreme Accelerators with Gamma Rays

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Astro-Particle Physics

modern interdisciplinary research field at the interface of
astronomy, physics and cosmology

HE Astrophysics — X-, gamma-ray astronomies, cosmic rays
neutrino (but also also R,O, UV, …)

Relativistic Astrophysics — black holes, gravitational waves

HE Physics/ Cosmology — "non-accelerator particle physics"
Early Universe, Dark Matter, Dark Energy

both experiment/observations and theory

Golden Age of Astroparticle Physics

- ✓ traditionally is treated as a top priority research activity within the *Astronomy/Astrophysics Community*

- ✓ is strongly supported by the *Particle Physics Community* for different objective and subjective reasons:

subjective - it is not clear what can be done with accelerators after LHC;
in general, APP projects are dynamical and cost-effective;
can be realized by small groups on quite short timescales, …

objective - (huge) discovery potential *in fundamental (particle) physics*
("particle physics without accelerators")

Major Objectives of Astroparticle Physics

No 1: **Universe** - its content ("what is the Universe made of"), history/evolution; how (why) it was created? formation of large-scale structures, magnetic and radiation fields,…

good concepts/ideas - Big Bang, inflation, …
established facts: existence of Dark Matter (DM) and Dark Energy (DE), fluctuations of MBR

combined efforts of astronomers and (particle) physicists - to clarify missing "details" - e.g. *nature of DM* and *origin of DE*, or reason(s) of asymmetric creation of the Universe

HE astrophysicists are "*high-flyers*" (as well)

at first glance HE astrophysics community has more modest objectives; e.g. for them the study of *astrophysics and physics of black holes* is not "too boring" and they can discuss over and over "minor" issues like "which particles - e or p ? - produce γ-rays in Supernova Remnants"

but, in fact, HE astrophysicists also are "*high-flyers*" with a (the) major scientific objectives - study the "*Nonthermal Universe*". For example they try to understand the origin of Gamma-Ray Bursts - "mini Big Bangs" with a very attractive features (advantage) compared to Big Bang - we detect such explosions every day! These enormous events with energy release 10^{51}erg (or more) over seconds contain also huge cosmological information, e.g. about *First Stars*

High Energy Astrophysics

a (the) major objective: study of *<u>nonthermal</u>* phenomena in

most energetic and violent forms in the Universe

many research topics are related, in one way or another,
to exploration of Nature's perfectly designed machines:

Extreme Particle Accelerators

extreme physical conditions

- *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/interpretation of HE phenomena requires deep understanding of many disciplines of experimental and theoretical physics:

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

and (of course) Astronomy/Astrophysics

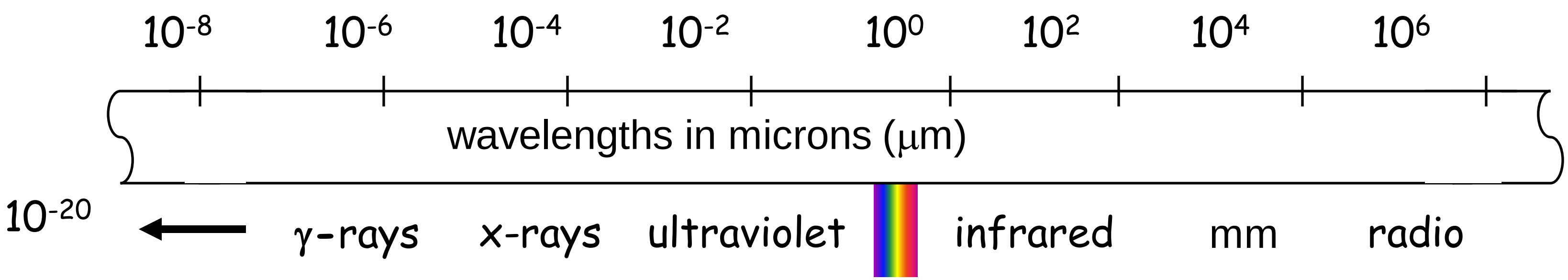
Gamma Ray Astronomy

a modern interdisciplinary research field at the interface of
astronomy, physics and cosmology

with the major objective: study of nonthermal phenomena
most energetic and violent forms in the Universe

many research topics are related, in one way or another, to exploration of Nature's perfectly designed machines:
Extreme Particle Accelerators

Gamma Ray Astronomy: *a part of multiwavelength astronomy*
but, at the same time, a discipline in its own right



- ‘Ground-based’: presently 3-decades from 0.1 to 100 TeV (TeV astronomy!)
  potentially: *significant extension down to 10 GeV and up to 1 PeV (5 decades*)

- Fermi/Agile: presently E: 3-decades: 0.1 to 100 GeV (GeV Astronomy!); t~10yr:
  broader coverage but not significantly beyond 100 GeV and below 100MeV

- **10-100 GeV** - very interesting perspectives very-low-energy threshold
  Chereknov Telescopes operating together with Fermi LAT as an all sky monitor

- **MeV astronomy** - hopeless or the next breakthrough ?

TeV gamma-ray astronomy - *a success story*

discovery of more than 150 TeV gamma-ray sources representing 10+ Galactic and Extragalactic sources populations - a remarkable achievement

=> significant impact on several areas of modern Astrophysics

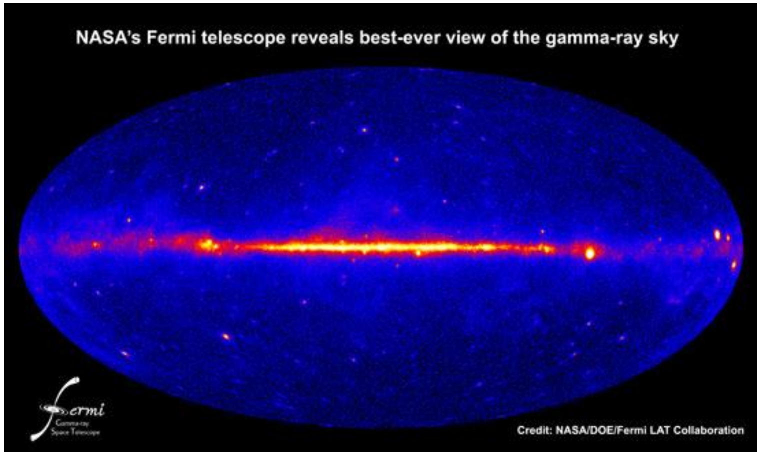
main factors which make possible this success? several factors… but basically thanks to the lucky combination of two:

- ✓ *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*


H.E.S.S.


MAGIC

another success story - *Fermi* Gamma-Ray Space Telescope



almost 2000 detected MeV/GeV sources representing >10 clearly identified source populations (before – only Pulsars and AGN), Diffuse Galactic and Extragalactic Backgrounds, Transients, …

space based γ-ray astronomy*:* a “planned“ success

future?   requires >10m^2 space platforms – not realistic

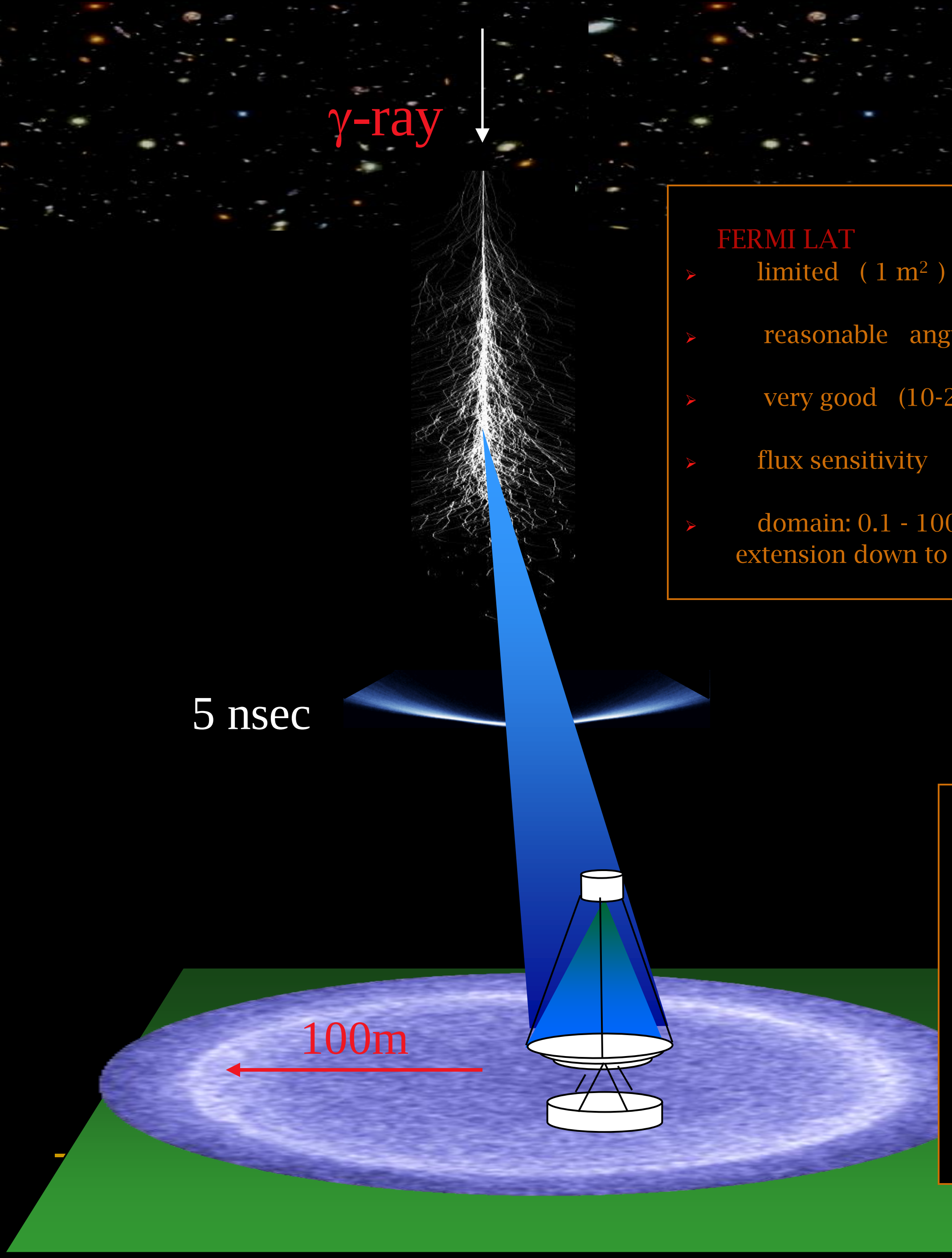
(at least for the foreseeable future)

more promising seems to be the “MeV“ (0.1-100) MeV regime

ground-based γ-ray astronomy*:*   a big surprise!

future? potential is not saturated => the range could be significantly extended – from 10 GeV to 100 TeV

foreseeable future - ground-based astronomy



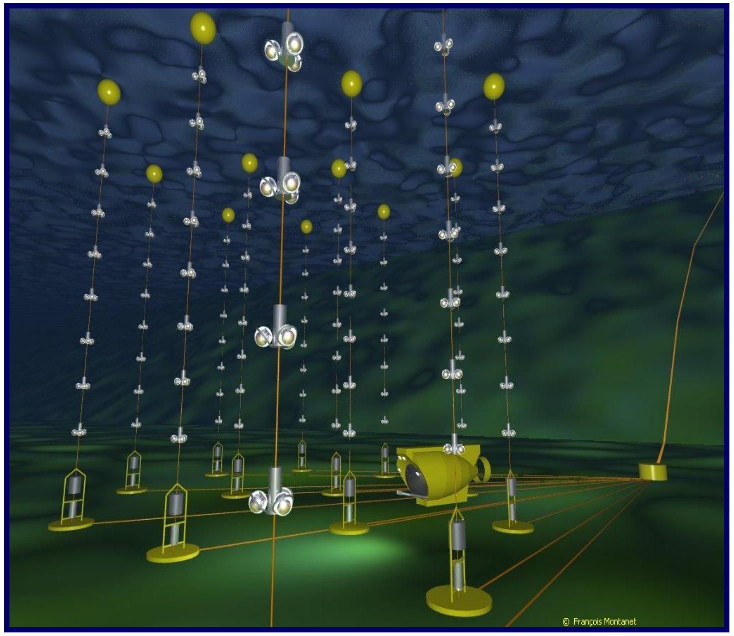
FERMI LAT

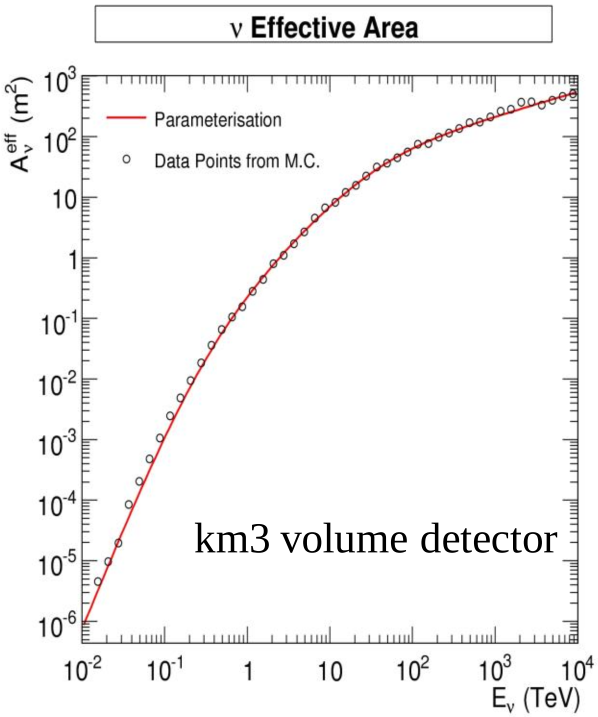
- limited (1 m^2) detection area
- reasonable angular resolution
- very good (10-205 %) energy resolution
- flux sensitivity => 10^{-12} erg/cm^2 s
- domain: 0.1 - 100 GeV with a potential of extension down to 20 MeV and up to 1TeV ?

IACT Arrays

- huge (>1km^2 or larger) detection area
- good (=> 1arcmin) angular resolution
- good (10-205 %) energy resolution
- flux sensitivity => 10^{-13} erg/cm^2 s
- domain: 0.1 - 100 TeV with a potential of extension down to 10GeV and up to 1PeV

neutrino telescopes





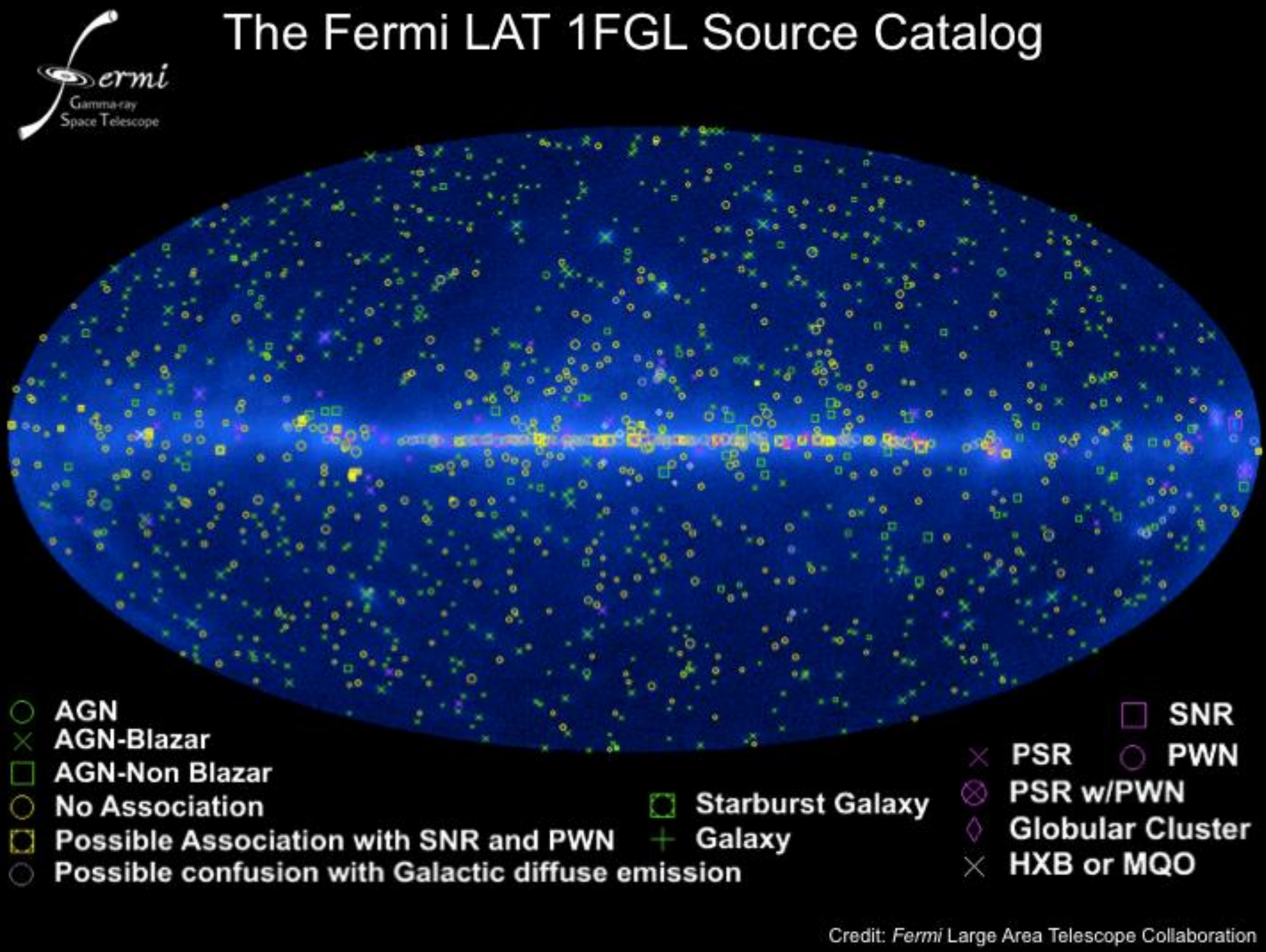
effective area: 0.3m^2 at 1 TeV
10m^2 at 10 TeV

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

detection areas of neutrino telescopes <<< detection areas of γ-ray detectors!
this fact should not be ignored, but should not be exaggerated either

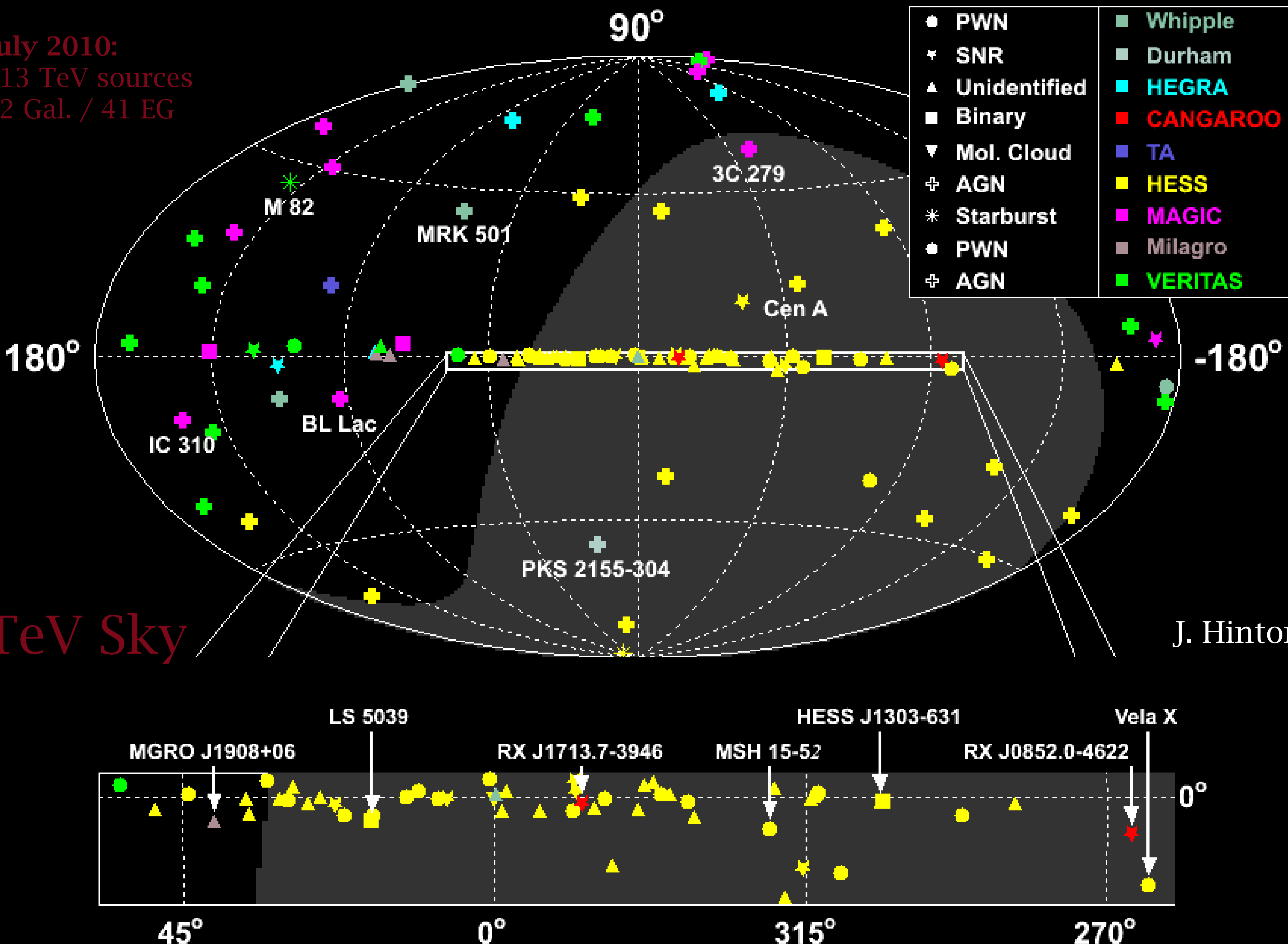
even after the recent detection of >30 TeV neutrinos of extraterrestrial origin

GeV Sky



The Fermi LAT 1FGL Source Catalog
Fermi
Gamma-ray Space Telescope
AGN
AGN-Blazar
AGN-Non Blazar
No Association
Possible Association with SNR and PWN
Possible confusion with Galactic diffuse emission
Starburst Galaxy
Galaxy
SNR
PSR
PWN
PSR w/PWN
Globular Cluster
HXB or MQO
Credit: Fermi Large Area Telescope Collaboration

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

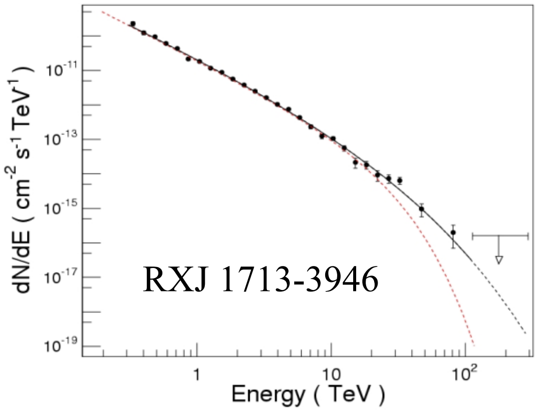


TeV Sky

J. Hinton

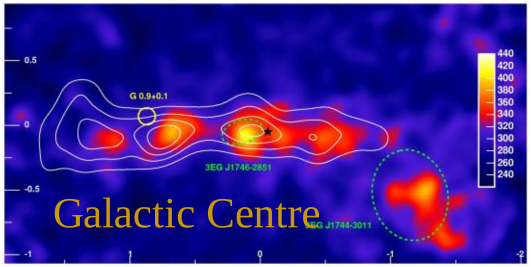
good performance => high quality data => solid basis for theoretical studies

spectrometry



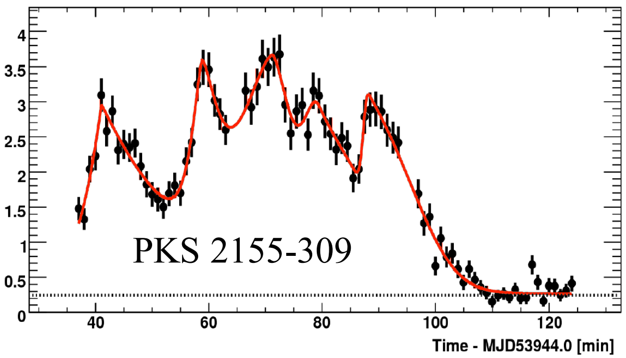
spectrum over 2+ decades

morphology



resolving sources within 1 degree

timing



variability on minute time-scales (10k photons per 1h)

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

extended sources: *from SNRs to Clusters of Galaxies*

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

Galactic Astronomy | Extragalactic Astronomy | Observational Cosmology

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

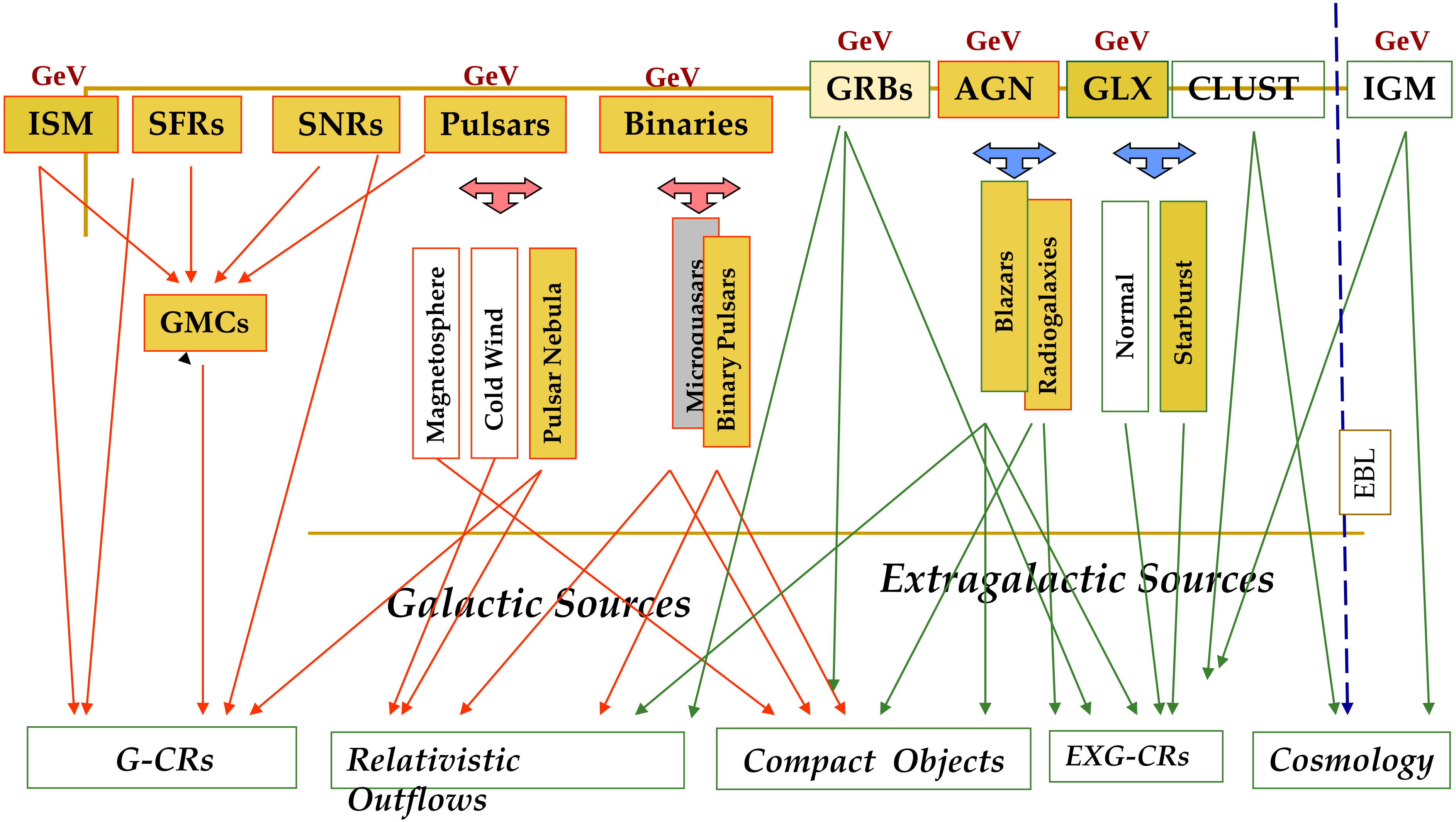
- ✓ M87, Cen A - radiogalaxy
- ✓ TeV Blazars – with redshift from 0.03 to 0.18
- ✓ NGC 253 and M82 - starburst galaxies

- ✓ 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



Major Scientific Topics

first lessons/conclusions from the VHE γ-ray/HESS observations:
Universe is full of Extreme Accelerators - TeVatrons and PeVatrons

machines where acceleration proceeds with efficiency close to 100%

(i) fraction of available energy converted to nonthermal particles

(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>

like cosmic plasmas which are easily heated to keV temperatures - *almost everywhere*, particles (electrons/protons) can be easily accelerated to 10+ TeV and beyond (*almost everywhere*!), especially in objects containing relativistic outflows -jets & winds

relativistic outflows (pulsar winds and AGN/BH jets) as extreme accelerators

distinct feature of relativistic outflows: effective particle acceleration at different stages of their development

close to the central engine

during propagation on larger scales,

at the jet (wind) termination

the theory of relativistic jets – very complex and not (yet) fully understood – all aspects (MHD, electrodynamics, shock waves, particle acceleration) contain many problems and uncertainties

maximim (theoretically possible) acceleration rate: ηqBc

or minimum acceleration time: $t_{min}=\eta^{-1}R_L/c$

η close to 1 – *extreme accelerators*

From the condition of $t_{acc}=t_{synch}$:

$h\nu_{max} = (9/4)\, \alpha_f^{-1}\, mc^2 \sim 150\, \eta^{-1}$ MeV for electrons *

$\sim 300\, \eta^{-1}$ GeV for protons

$\eta \sim 1$ – signature of extreme accelerators ?

high energy gamma-rays - best cariers of information about extreme accelerators

relativistic outflows – high energy gamma-ray emitters ("on" and "off" axis)

comment:

* DSA in SNRs: $\eta \sim 10(c/v)^2 \sim 10^5$ (in the Bohm regime) => $h\nu_0 \sim 1$keV for given shock speed young SNRs act as extreme accelerators!

topics to be briefly covered in this talk

(i) SNRs and Origin of Galactic Cosmic Rays

(ii) Pulsars – Pulsar Winds - Pulsar Wind Nebulae

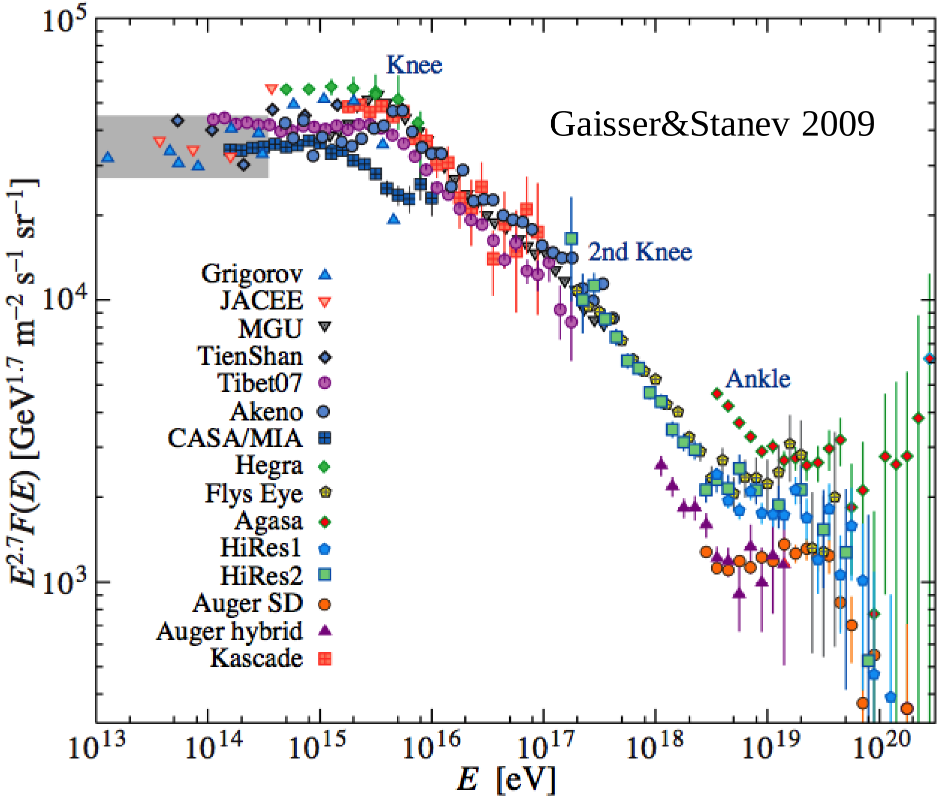
(iii) Blazars and EBL

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 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* Diffusive Shock Acceleration

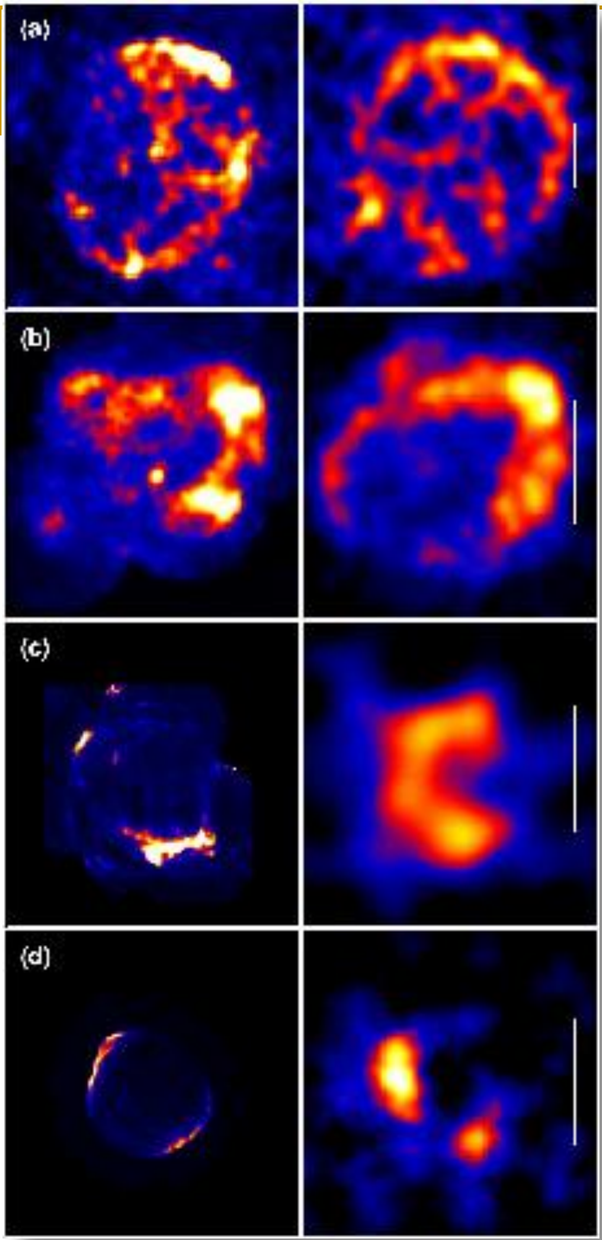
one of the key objectives of VHE γ-ray astronomy:
confirmation that SNRs operate as PeVatrons, and
provide the bulk of Galactic CRs up to $E \sim 10^{15}$ eV

other possible sources?

Pulsars/PWNe OB stars Binaries Galactic Center …

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

leptonic or hadronic?



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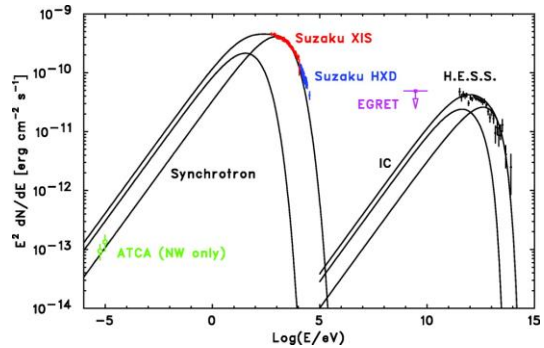
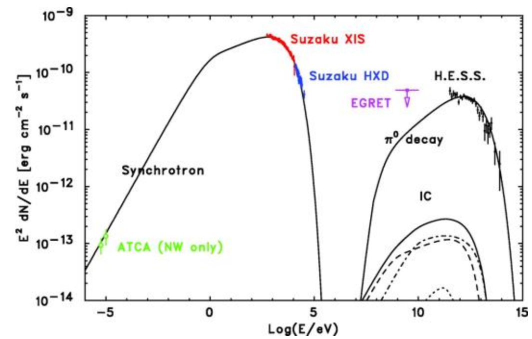




RXJ1713.7-4639

$e + 2.7K \Rightarrow \gamma$

$pp \Rightarrow \pi^o \Rightarrow 2\gamma$

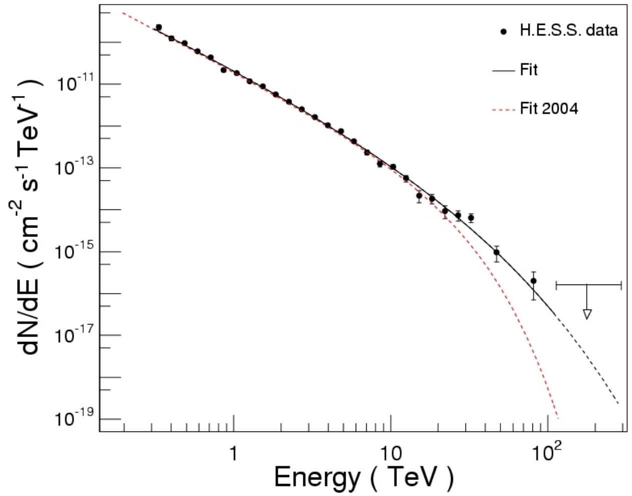
B=15μG
We ≈3 10^{47} erg

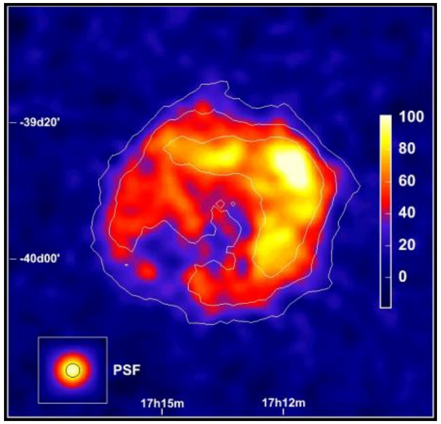
B=200μG
Wp ≈ $10^{50}(n/1cm^{-3})^{-1}$ erg

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

RXJ1713.7-4639

TeV γ-rays and shell type morphology:
acceleration of protons and/or electrons
in shell up to 100TeV (not much higher)





can be explained by **γ**-rays from pp $\to \pi^o \to 2\gamma$
HESS: $dN/dE = K\,E^{-\alpha}\,\exp[-(E/E_o)^{\beta}]$
$\alpha=2.0$ Eo=17.9 TeV $\beta=1$
$\alpha=1.79$ Eo=3.7 TeV $\beta=0.5$

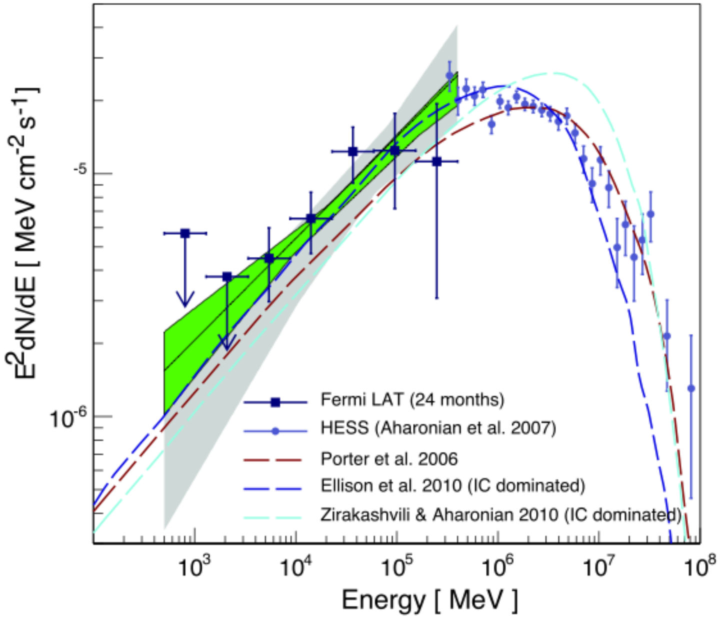
with just "right" energetics:
$W_p=10^{50}\,(n/1cm^{-3})^{-1}$ erg

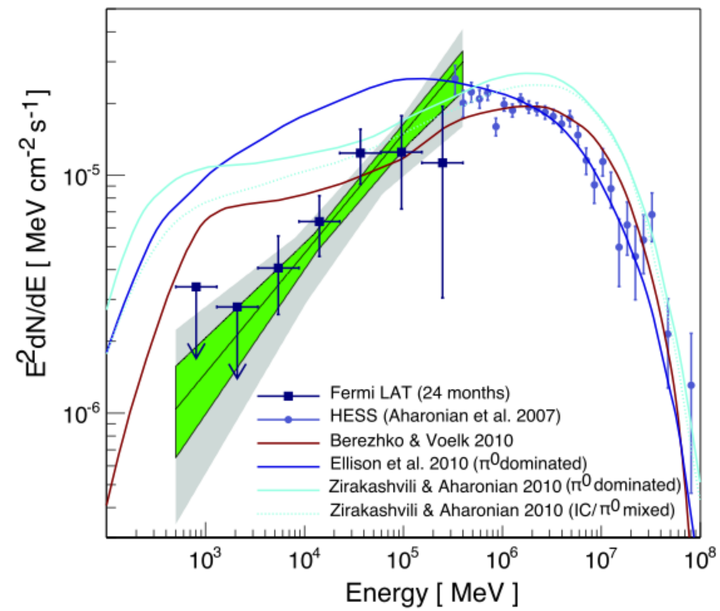
but IC models generally are more preferred… because of TeV-X correlations (?)

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

definite answer – detect neutrinos (very difficult)
more realistic approach – γ-ray: morphology with 1 arcmin resolution and spectrometry, especially above 10 TeV

Fermi: GeV data contradict hadronic origin of γ-rays ! (?)





leptonic models

hadronic models

Questions: (i) can we compare GeV and TeV fluxes within one-zone models?

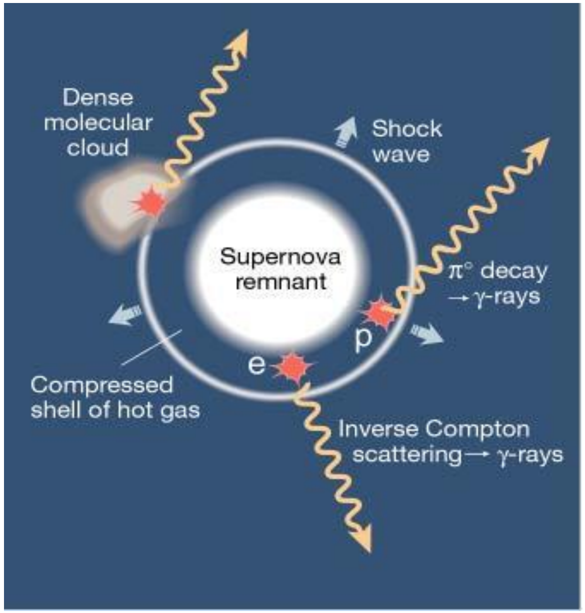
they could come from quite different regions

(ii) hard proton spectrum ?

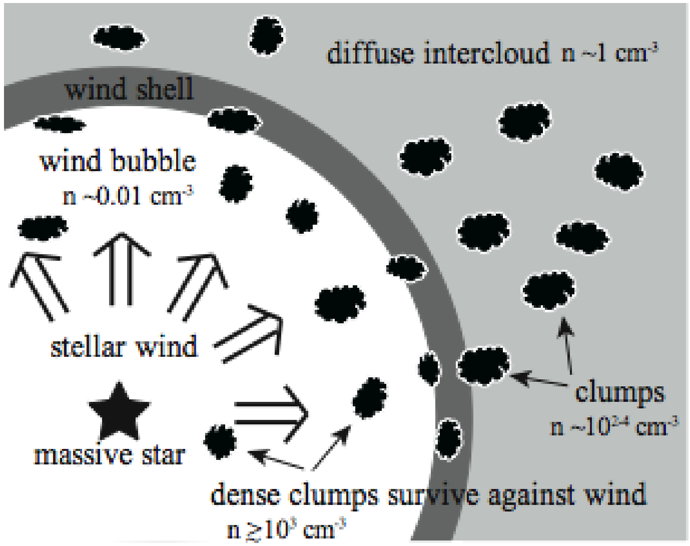
nonlinear theories do predict very hard spectra with α => 1.5

IC gamma-rays from (i) the entire shell with average small B-field and (ii) π^0 -decay gamma-rays from dense clouds/clumps inside the shell

(Zirakashvili & FA 2010)



Aharonian 2002, Nature **416**,797



Inoue et al. 2011, ApJ

Fermi LAT - important, but only neutrinos, ultra-high energy gamma-rays and hard synchrotron X-rays from secondary electrons can provide decisive conclusions propagation effects in clumps can, in principle, explain Fermi LAT – HESS spectral points from 1 GeV to 100 TeV (Gabici & F.A. 2014) and, possibly, also the lack of thermal X-ray emission

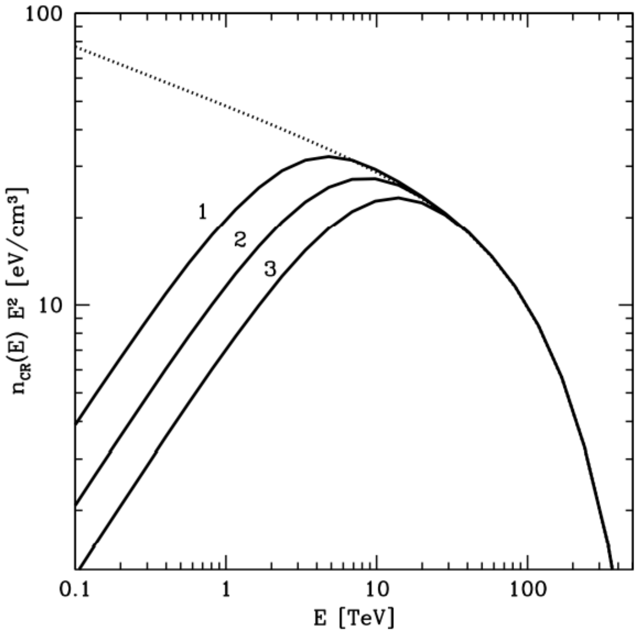


Figure 1. Spectrum of CRs in the SNR shell (dotted line) and inside a clump that entered the shock at $t_c = 1400$, 1500, and 1550 *yr* (solid line 1, 2, and 3 respectively).

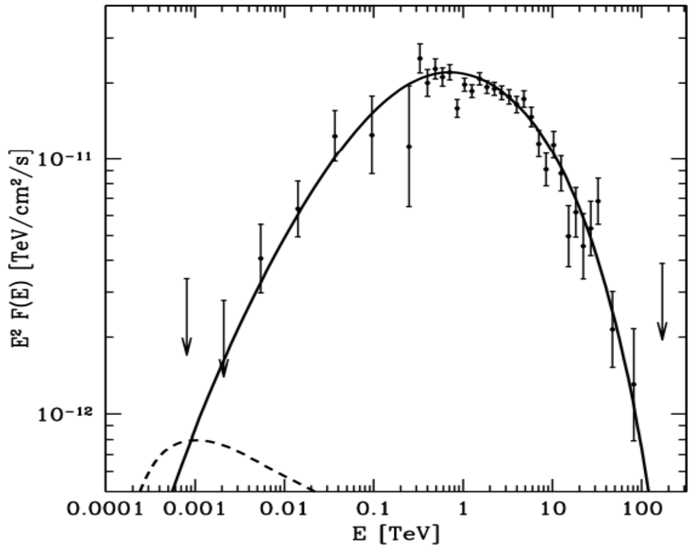
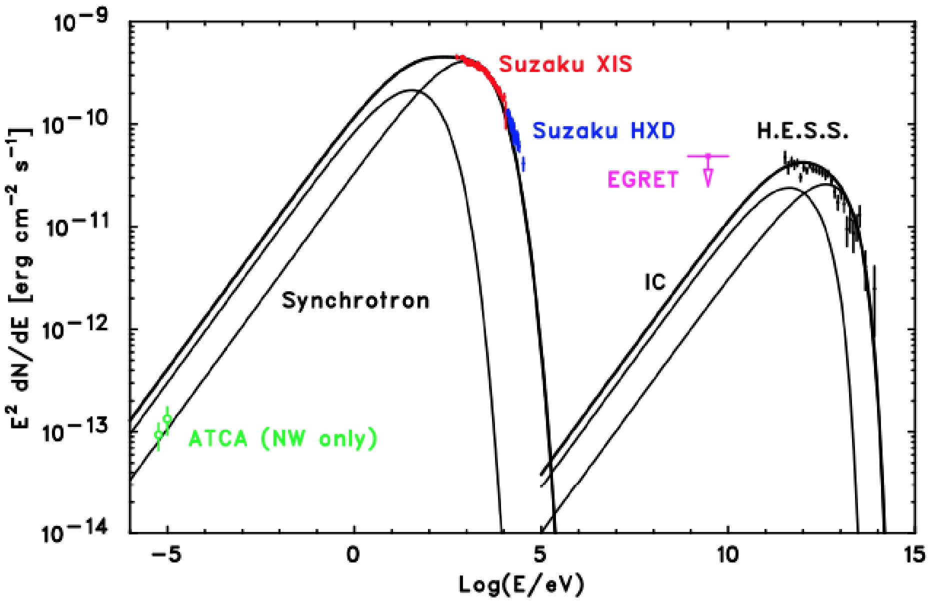


Figure 2. Gamma–rays from RX J1713.7-3946. The emission from the clumps is shown as a solid line, while the dashed line refers to the emission from the diffuse gas in the shell. Data points refer to *FERMI* and *HESS* observations.

!

Leptonic models – prediction of a maximum in SED above 1 TeV, while HESS data do not show any maximum down to 200 GeV

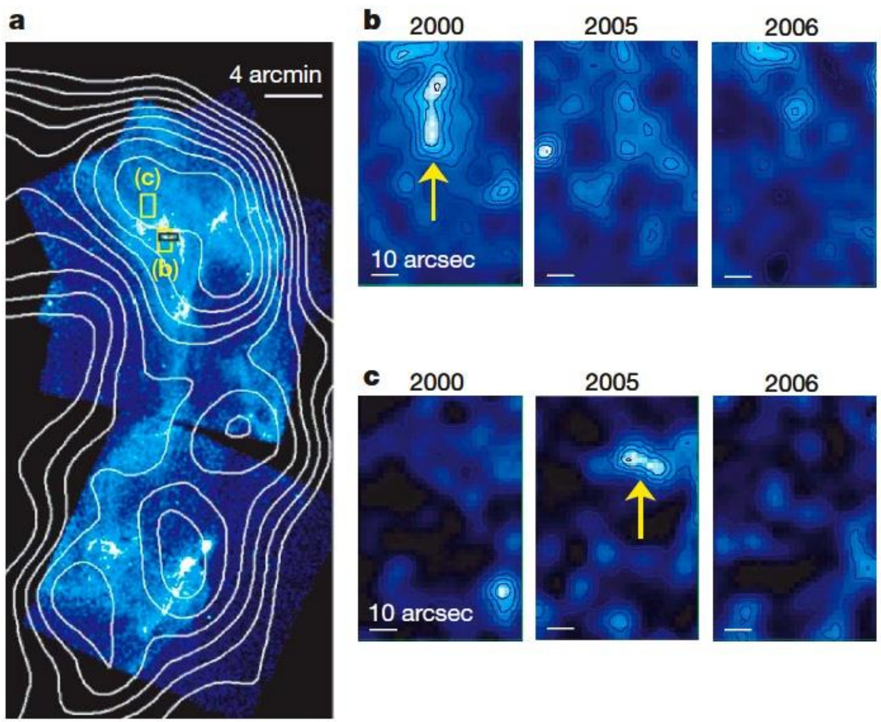
solutions? since B ~ 10μG to move the break in the gamma-ray spectrm to 200 GeV if t ~ 10^4 yr – not realistic; target optical field, w > 100 eV/cm^3 – not realistic; (3) second electron component below 20 GeV



detailed models of Zirakashvili, Berezhko, Amato, etc confirm this feature

Variability of X-rays on year timescales -

strong magnetic field and particle acceleration in real time



flux increase - particle acceleration

flux decrease - synchrotron cooling *)

both require B-field of order 100μG, at least in hot spots

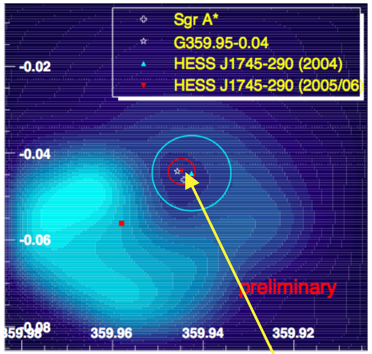
strong support of the idea of amplification of B-field by in strong nonlinear shocks through non-resonant streaming instability of charged energetic particles (T. Bell)

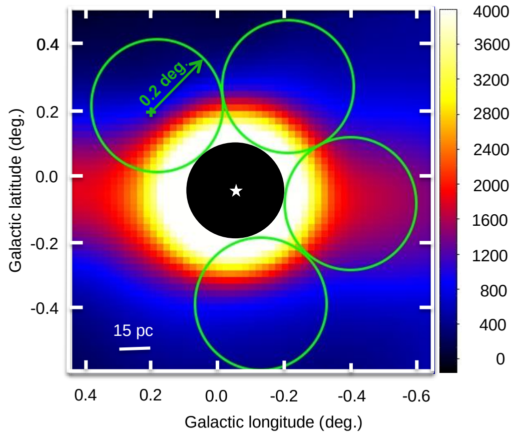
Uchiyama, Aharonian, Takahasi 2007, Nature **449**, 576

*) explanation by variation of B-field does't work as demonstrated for Cas A (Uciyama&FA, 2008)

Galactic Center

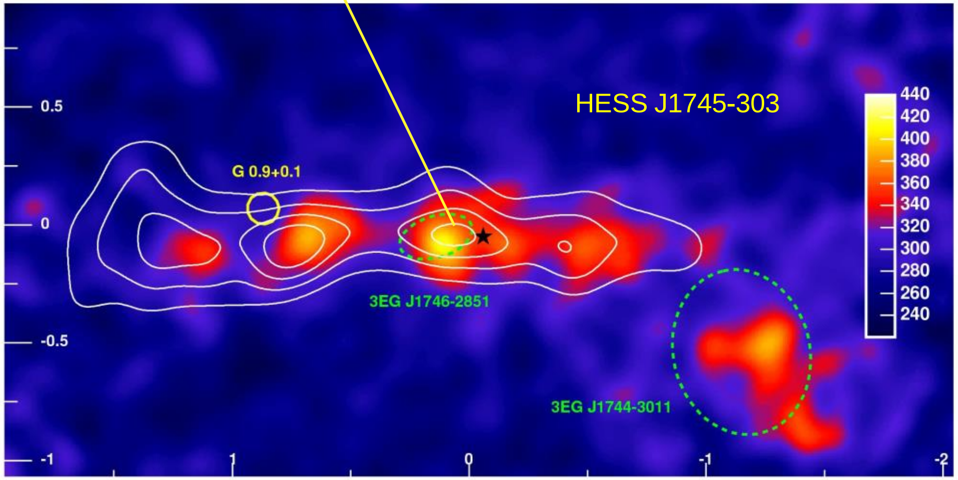
90 cm VLA radio image

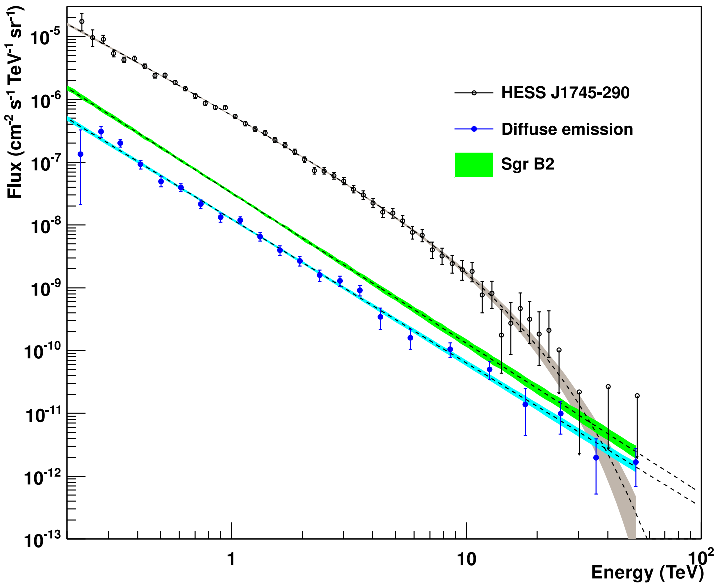




Cosmic Ray PeVatron in the Galactic Center with a power of 10^{39} erg/s ?

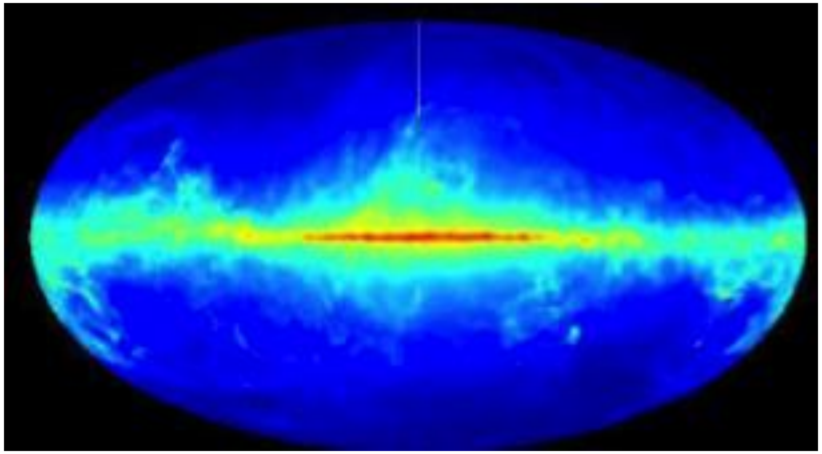
γ-ray emitting clouds

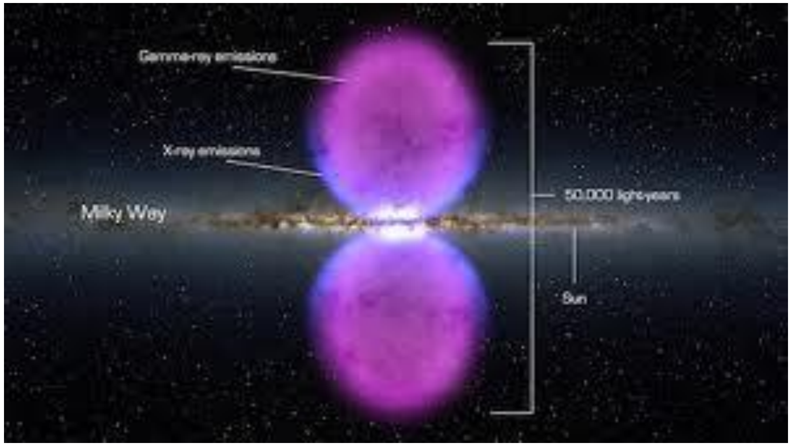


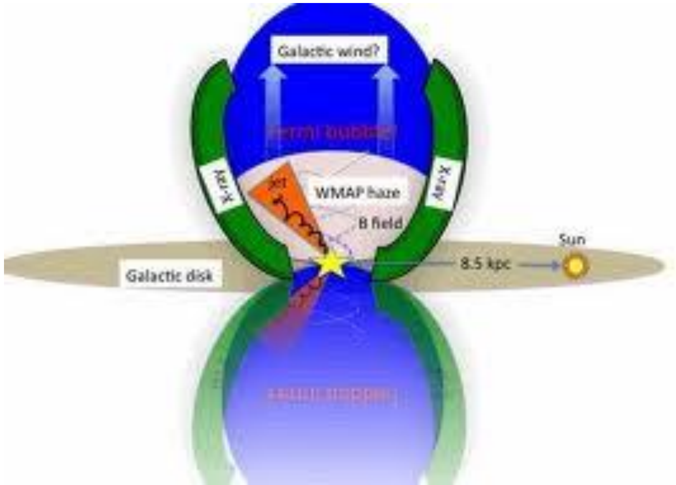


γ-rays from GMCs in GC: a result of an active phase in Sgr A* with acceleration of CRs some 10^4yr ago?

Fermi Bubbles !





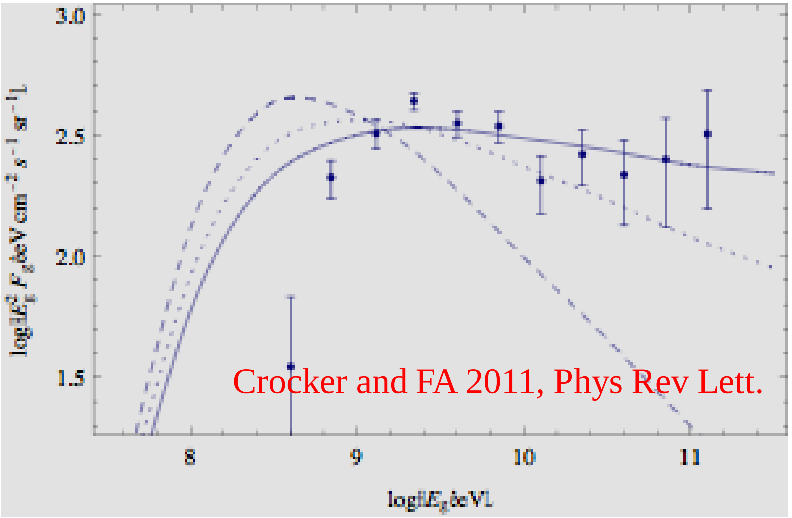


Finkbeiner and collaborators 2010

Fermi Bubbles - result of interactions of CRs produced in the GC and accumulated in R ~10 kpc regions over 10 Gyr comparable to the age of the Galaxy?
(Crocker&Aharonian PRL 2011)

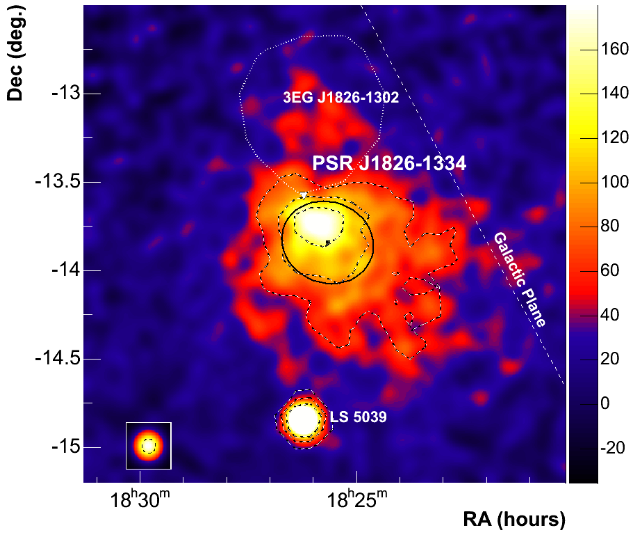
recent detection of diffuse flux of >30 TeV neutrinos by IceCube (Aarsen et al. 2013) as a result of the same interactions but on larger (100 kpc) scales?

(Taylor, Gabici, Aharonian, PRD 2014)

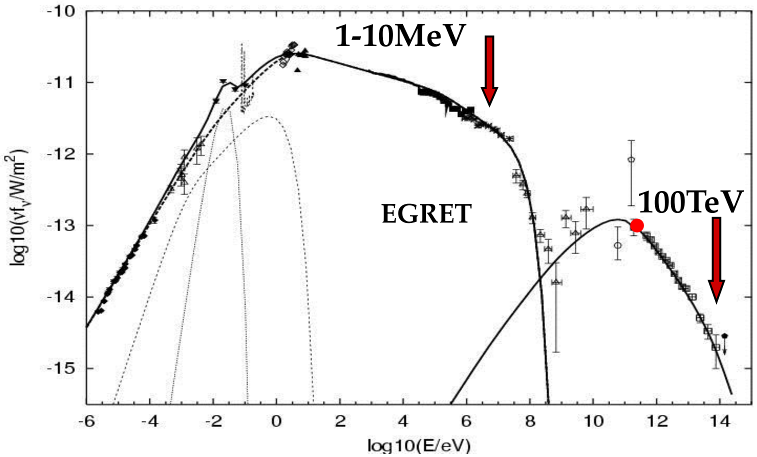


Pulsar Wind Nebulae:

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

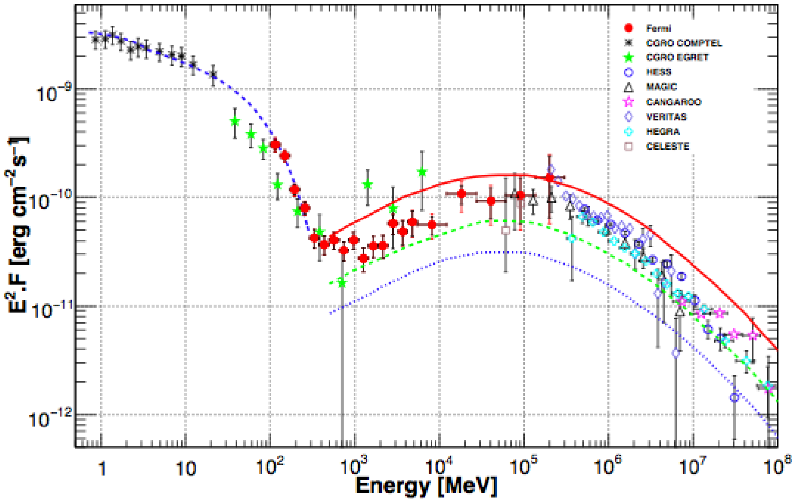
Crab Nebula – a powerful $L_e = 1/5 L_{rot} \sim 10^{38}$ erg/s
and extreme accelerator: Ee >> 100 TeV

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

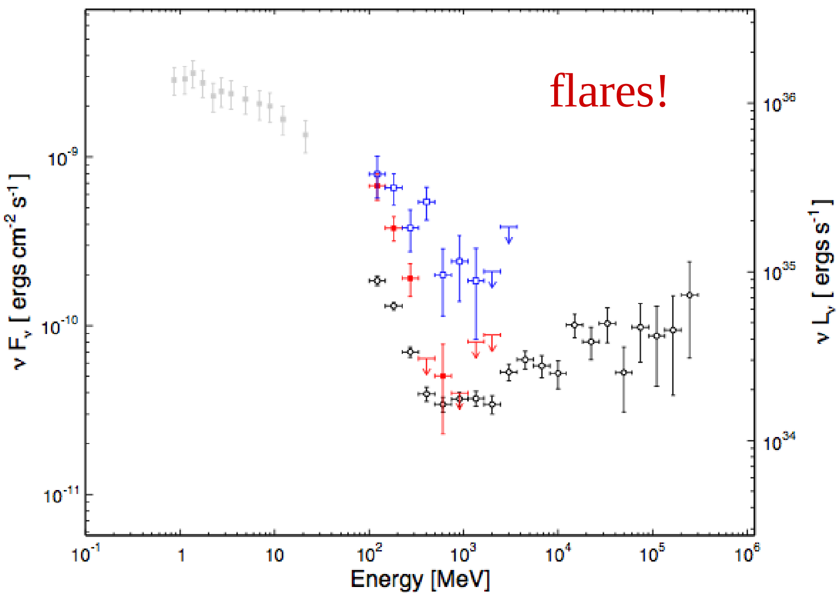
Cutoff at $h\nu_{cut}$ =10-20 MeV => $\eta \sim 10$ - acceleration at 10 % of the maximum rate
γ-rays: $E_\gamma \sim 50$ TeV (HEGRA, HESS) => $E_e > 200$ TeV
B-field ~100 mG => h ~ 10 - independent and more robust estimate
1 mG => $\eta \sim 1$?

Confirmed recently by the discovery of the „Crab Flares“ by Agile and Fermi satellites

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>

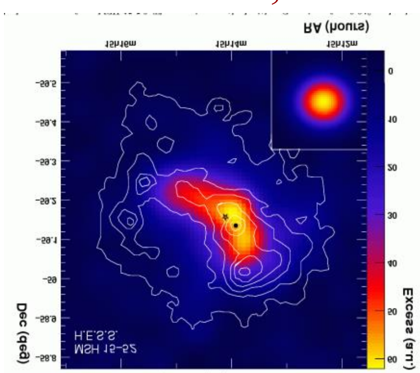
we do see TeV γ-rays from the Crab Nebula because of very large spin-down flux: $f_{rot}=L_{rot}/4\pi d^2=3\times10^{-7}$ erg/cm^2 s

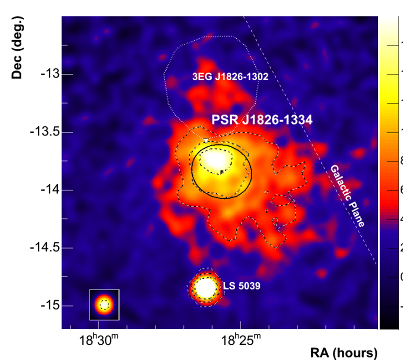
gamma-ray flux << "spin-down flux" *because of large B-field*

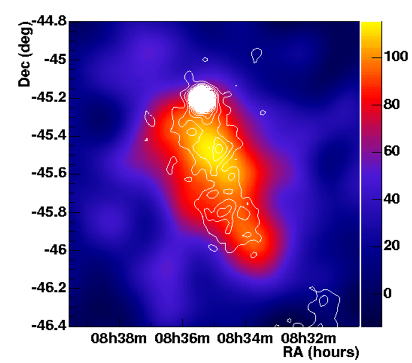
if the B-field is small (environments with small external gas presure)

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, ...



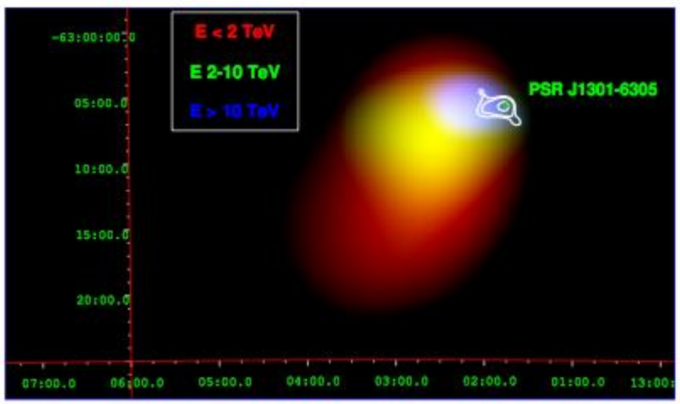


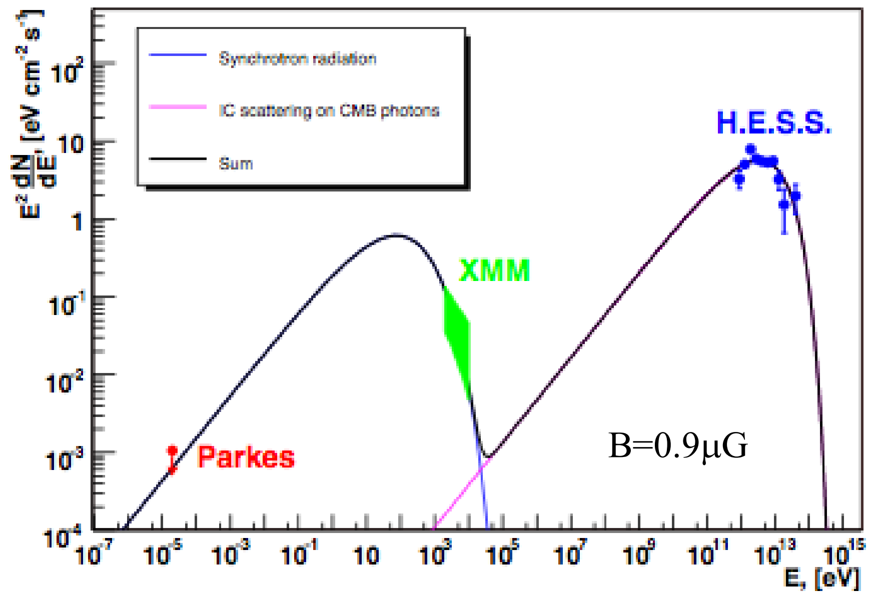


PWNe - *perfect electron accelerators and perfect γ-ray emitters!*

(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?



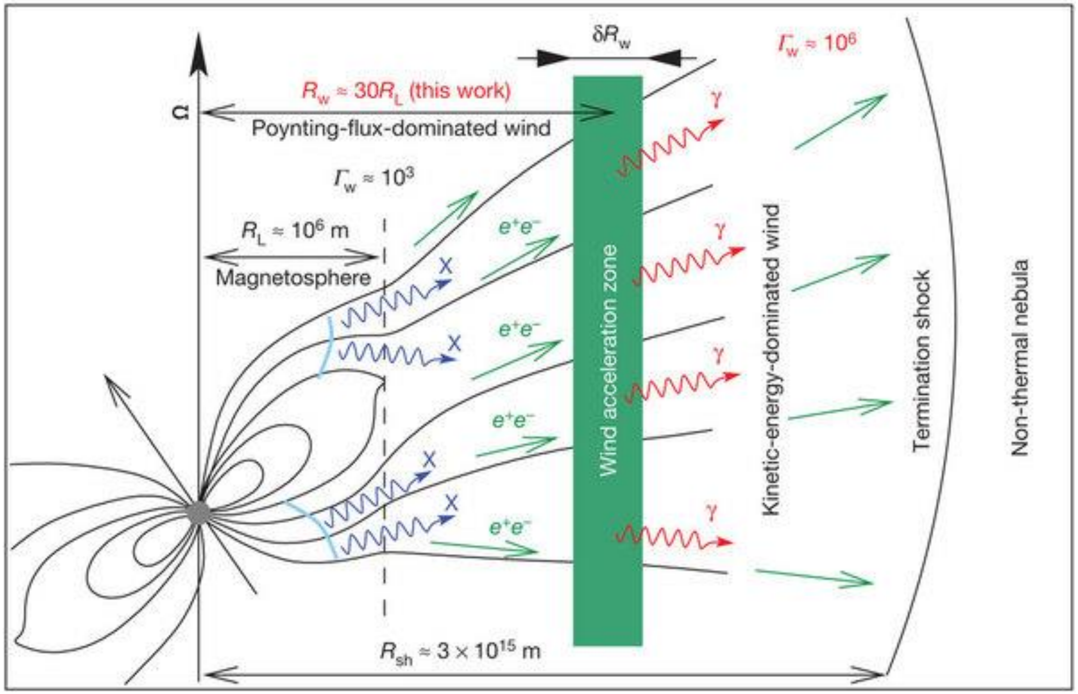


dramatic reduction of the angular size with energy:strong argument in favor of the IC origin of the γ-ray nebula

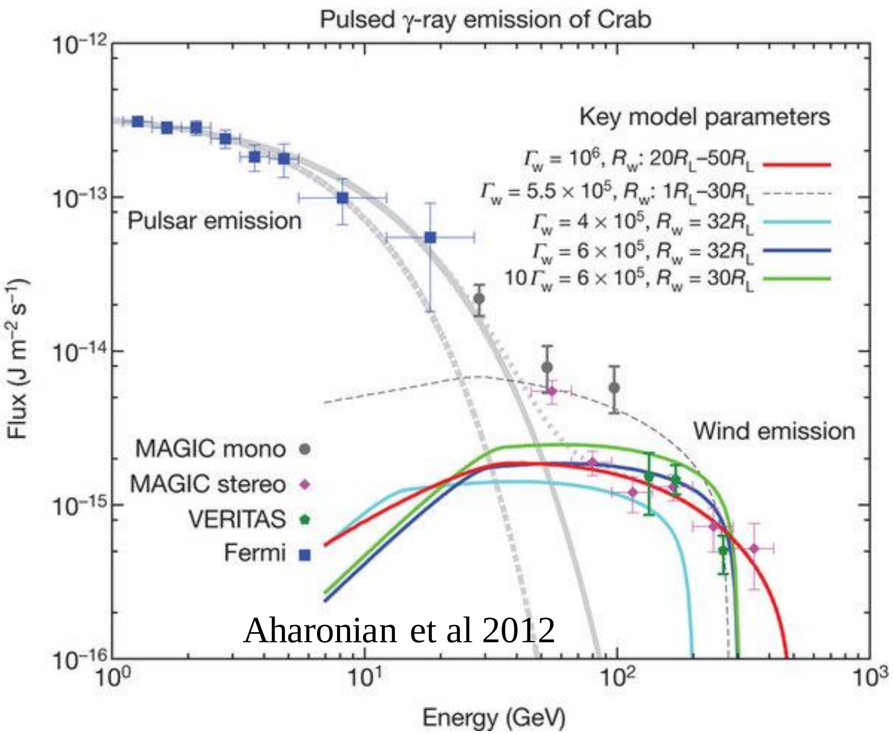
very small average B-field; for d=12.6kpc
L_γ/L_{SD} = 0.07; 3arcmin ~ 10 pc

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

pulsar–wind–nebula paradigm



Pulsed component extends to VHE energies!



where pulsed VHE signal is produced?

if in the *pulsar magnetosphere*, one should expect a cutoff at GeV energies otherwise we need to revise dramatically the magnetospheric models of gamma-ray emission

a more likely site of the pulsed VHE gamma-ray emission is the "cold" ultrarelativistic e+e- wind

✓ wind is accelerated at R~ $30R_L$ to bulk motion Lorentz factor Γ~0.5-1 x 10^6

Aharonian, Bogovalov, Khangulyan 2012, Nature **472**, 507

Particles in CRs with energy 10^{20} eV

the very fact of existence of such particles implies existence of

extragalactic extreme accelerator

the "Hillas condition" - $l > RL$ - a necessary but not sufficient condition…

(i) maximum acceleration rate allowed by classical electrodynamics

t-1=hqBc or c/RL with h ~ 1 and ~ $(v/c)^2$ in shock acceleration scenarios

(ii) B-field cannot be arbitrarily increased - the synchrotron and curvature radiation losses become a serious limiting factor, unless we assume…

perfect linear accelerators!

only a few options survive from the original Hillas ("l-B") plot:

$>10^9$ Mo BH magnetospheres, small and large-scale AGN jets, GRBs

acceleration sites of 10^{20} eV CRs ?

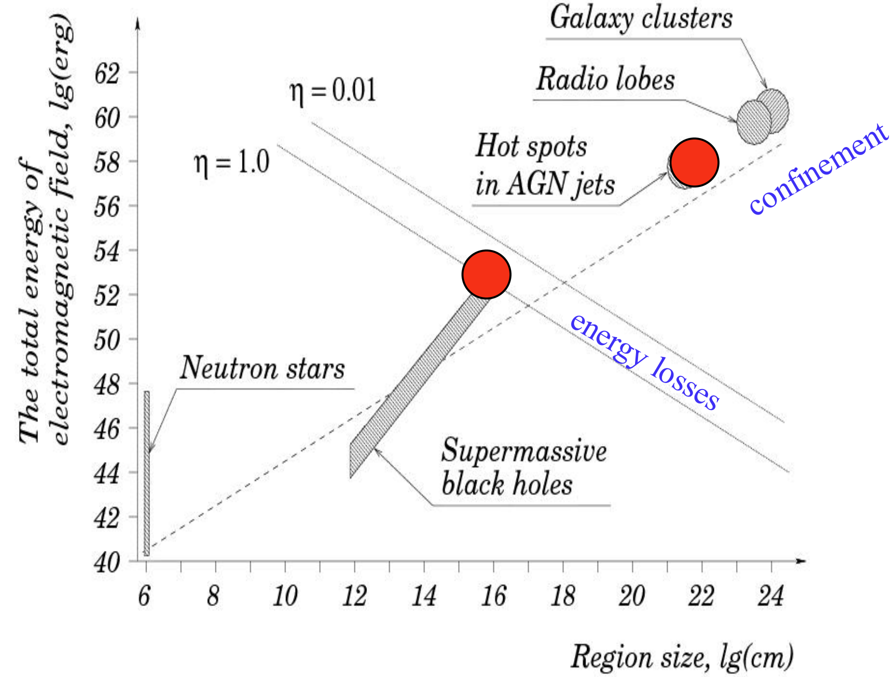
*Aharonian et al. 2002, Phys Rev D, **66**, id. 023005*

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

signatures of extreme accelerators?

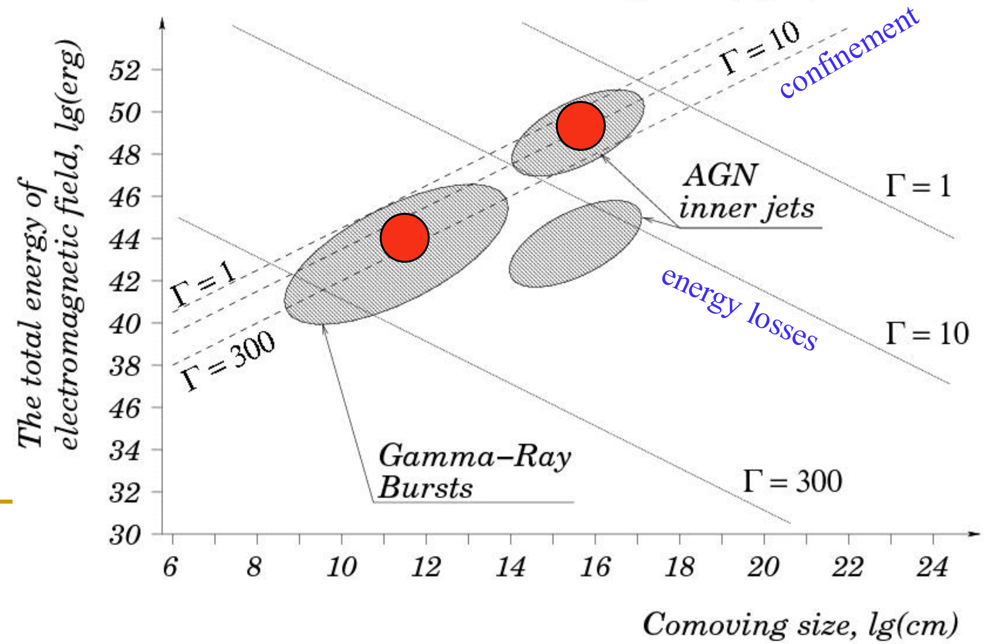
✓ $h\nu_{\rm cut} = \frac{9}{4}\alpha_{\rm f}^{-1}{\rm mc}^2\eta$:

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



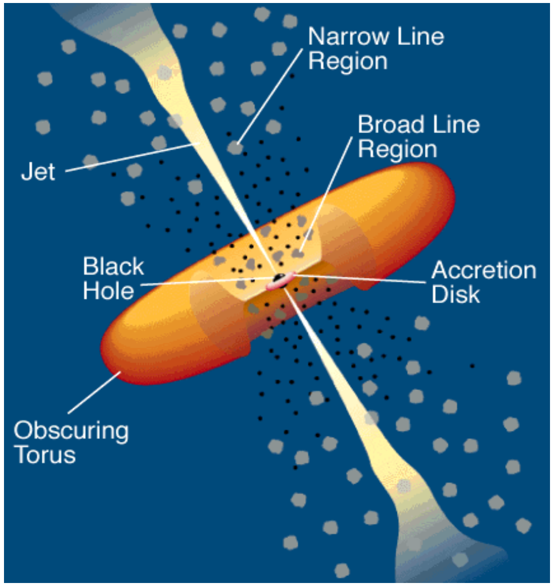
✓ neutrinos (through "converter" mechanism) production of neutrons (through pγ interactions) which travel without losses and at large distances convert again to protons => Γ^2 energy gain !

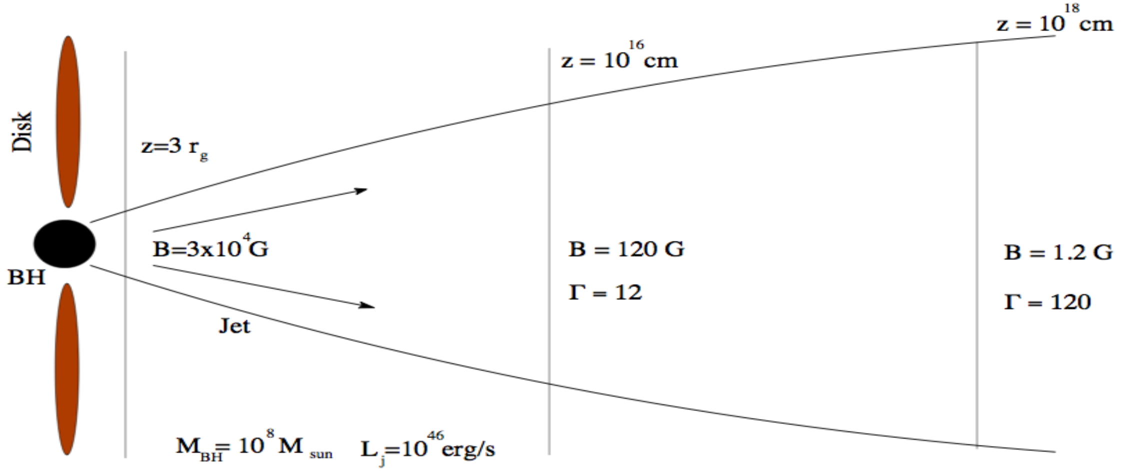
✓ observable off-axis radiation
radiation pattern can be much broader than $1/\Gamma$



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

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





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

TeV Blazars

before 2004:

detection of 6 TeV Blazars, extraordinary outbursts of Mkn 501 in 1999, variations on <1h timescales;

=> initiated huge interest in AGN and EBL communities

today:

more than three dozens TeV blazars; quite unexpectedly TeV **γ**-rays from distant blazars;

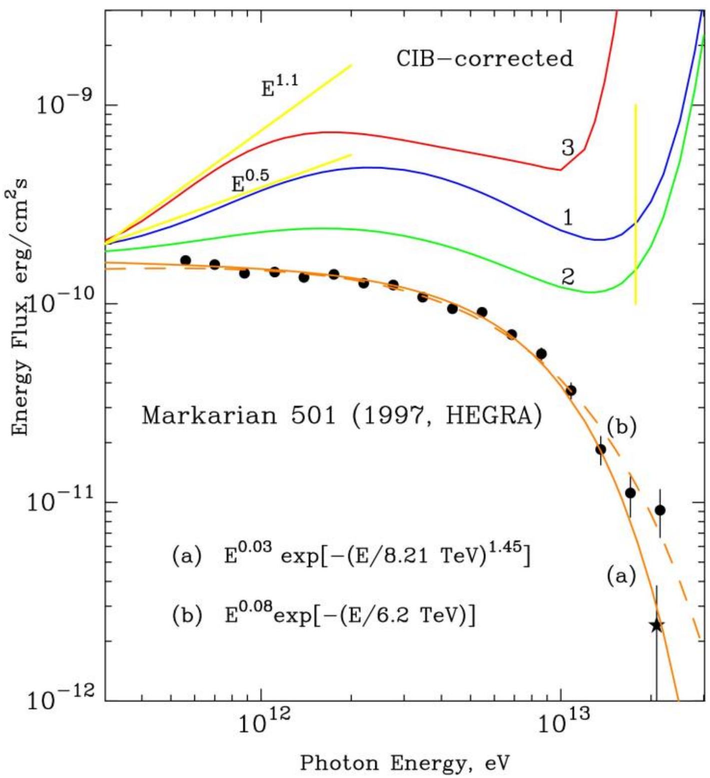
=> strong impact on both blazar physics and on the Diffuse Extragalactic Background (EBL) models

most exciting results - variability on minute timescales

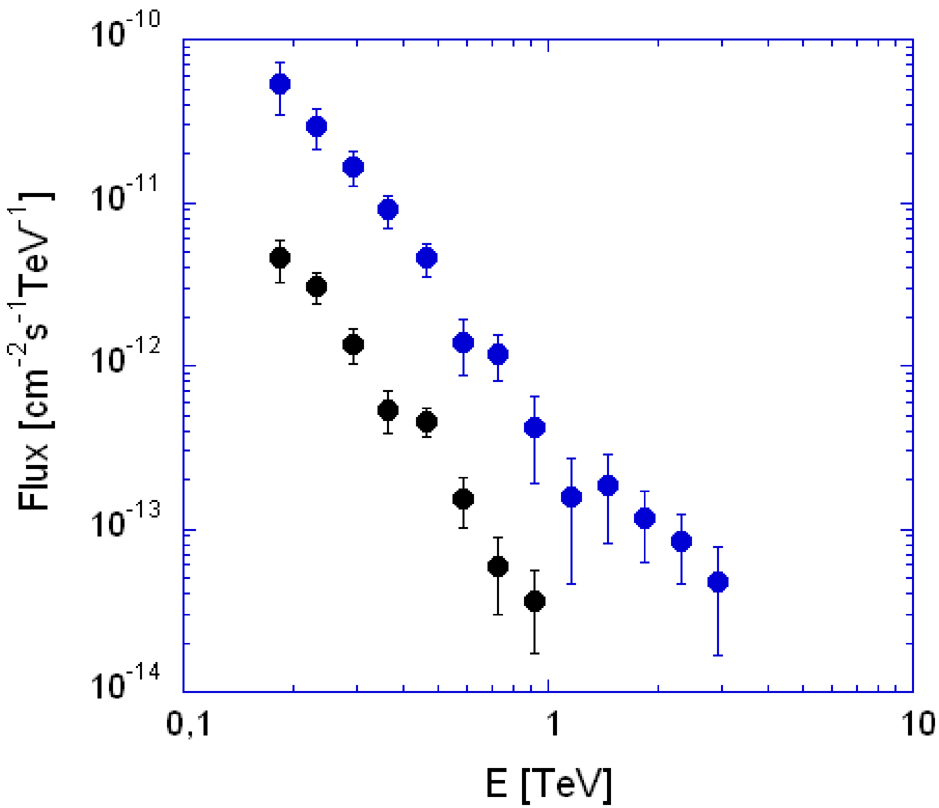
unusually hard gamma-ray spectra

Blazars and EBL: link through the energy-dependent absorption: $J_{obs}=J_o e^{\tau(E)}$

Mkn 501: z=0.031: "far infrared crisis", but with a happy end…



TeV blazars detected by HESS at z> 0.15 !

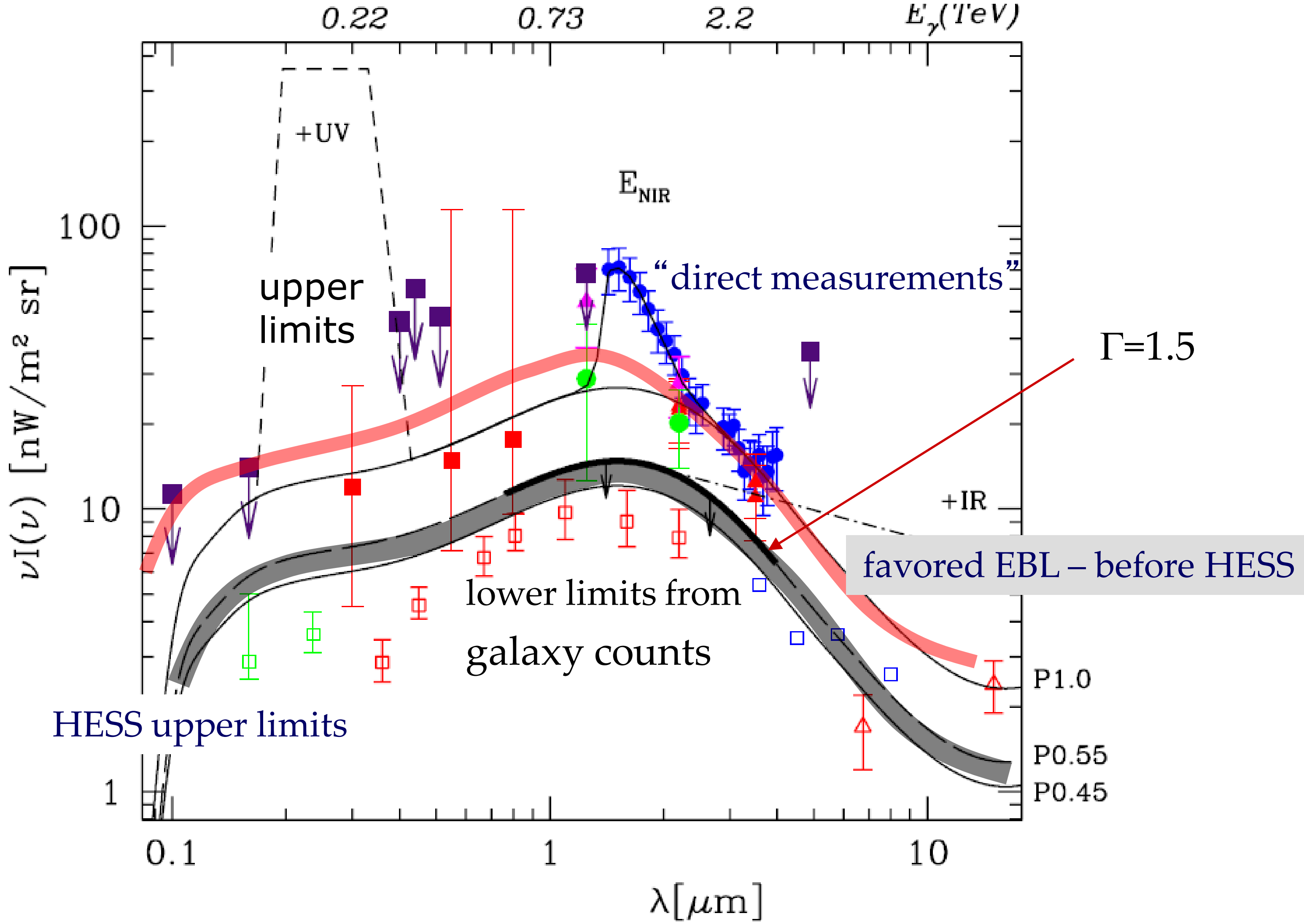


reported EBL flux at FIR have not been confirmed

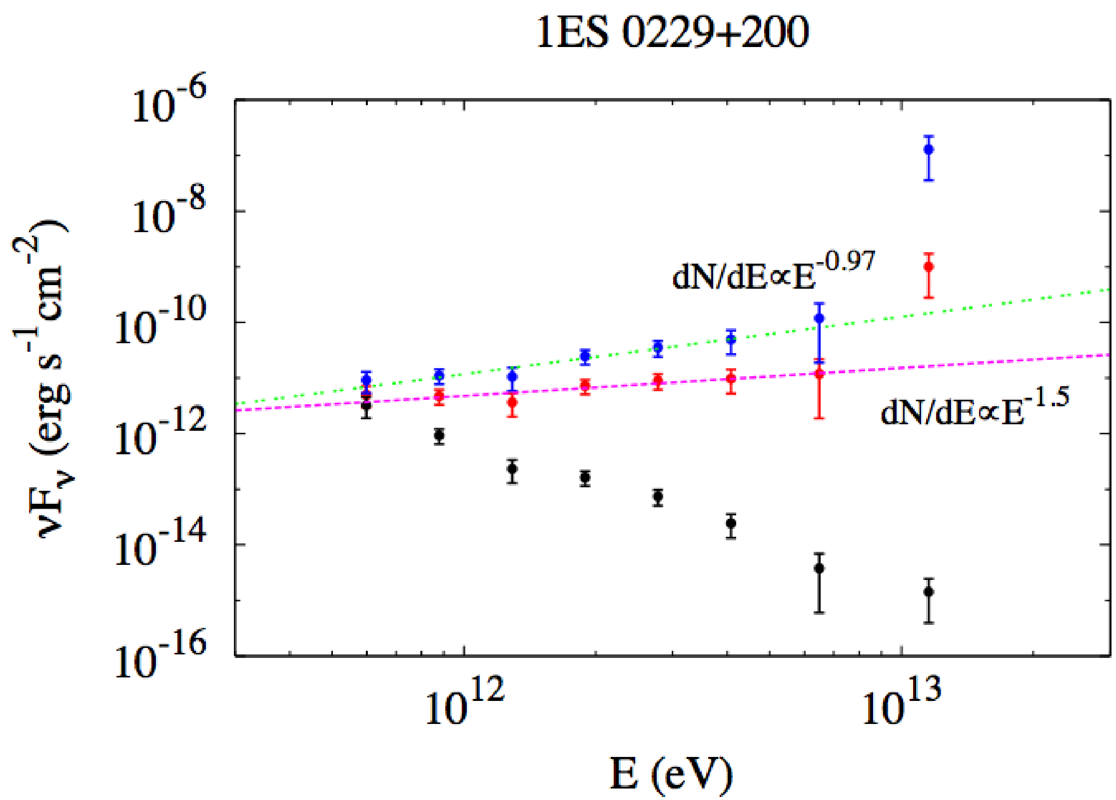
corrected for EBL absorption γ-ray spectrum not harder than $E^{-\Gamma}$ (Γ=1.5) ➔ **u.l. EBL**

HESS upper limits on EBL - good agreement with recent EBL studies

EBL (almost) resolved at NIR ?

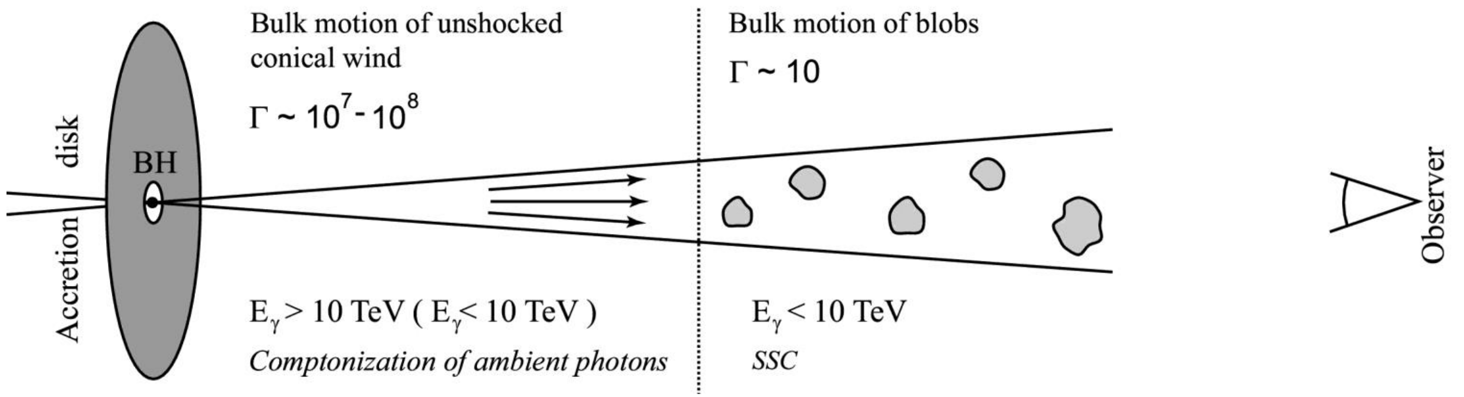


1ES 0229+200 - *a new "trouble-maker"*

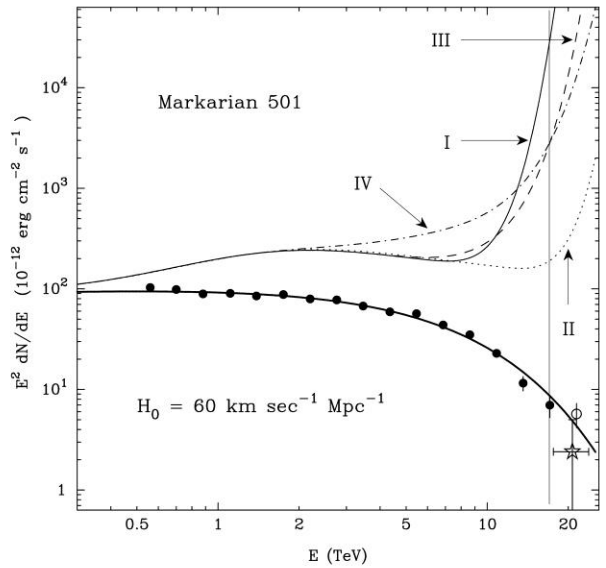


z= 0.14, but spectrum extends to >5 TeV ! Even slight deviation from the "standard" EBL => extremely hard spectrum with $\Gamma < 1$

Gamma Rays from a cold ultrarelativistic wind ?

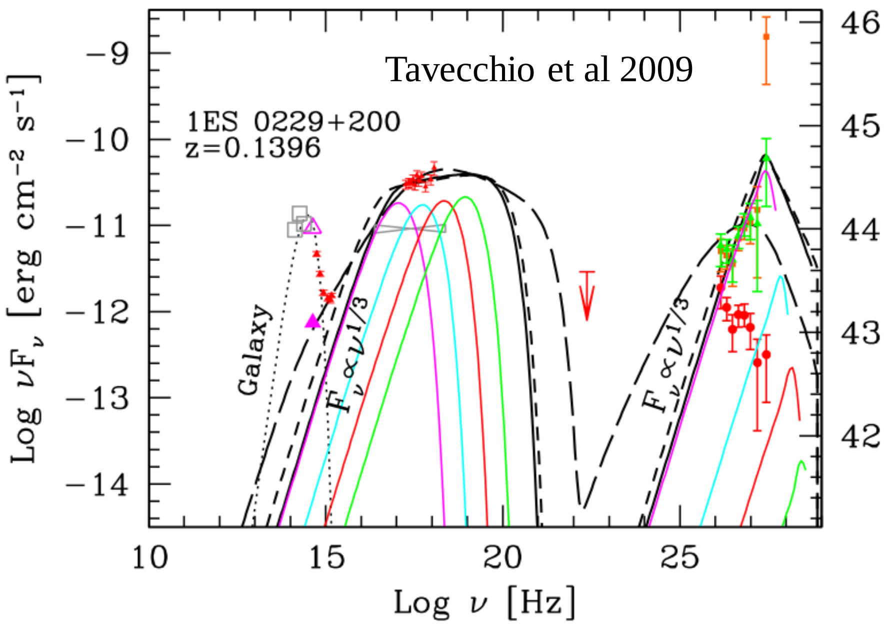


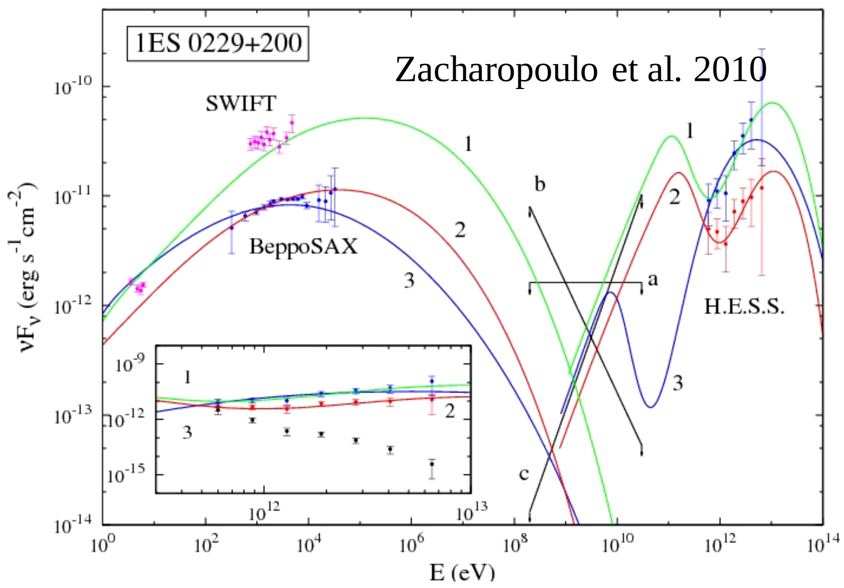
in fact not a very exotic scenario ...



explanation of extremely hard intrinsic spectrum of 1ES 0229+2000

two examples





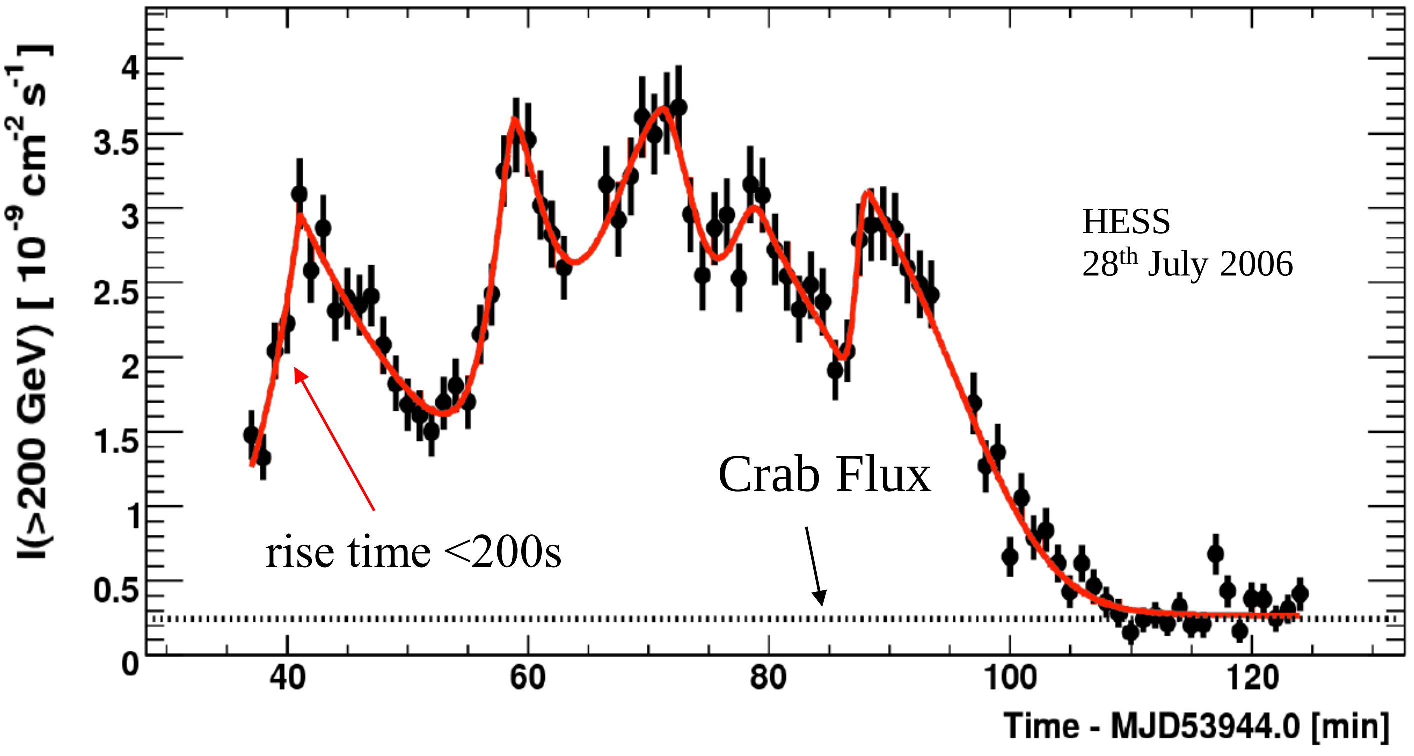
SSC with high "low-energy cutoff in electron distribution- no cooling"
B < 10^{-3} (?!) - orders of magnitude deviation from equipartition

internal γ–γ absorption: range of parameters:
R~10^{15}-10^{16} cm, T~10^4 K, δ~30, B~ 10-100G
proton synch. radiation as the only option ?

extremely small B-field

very large B-field

Spectacular flares of PKS2155-304



γ–ray lightcurve based on 10,000+ VHE photons detected during 1.5h contains unique information about the source

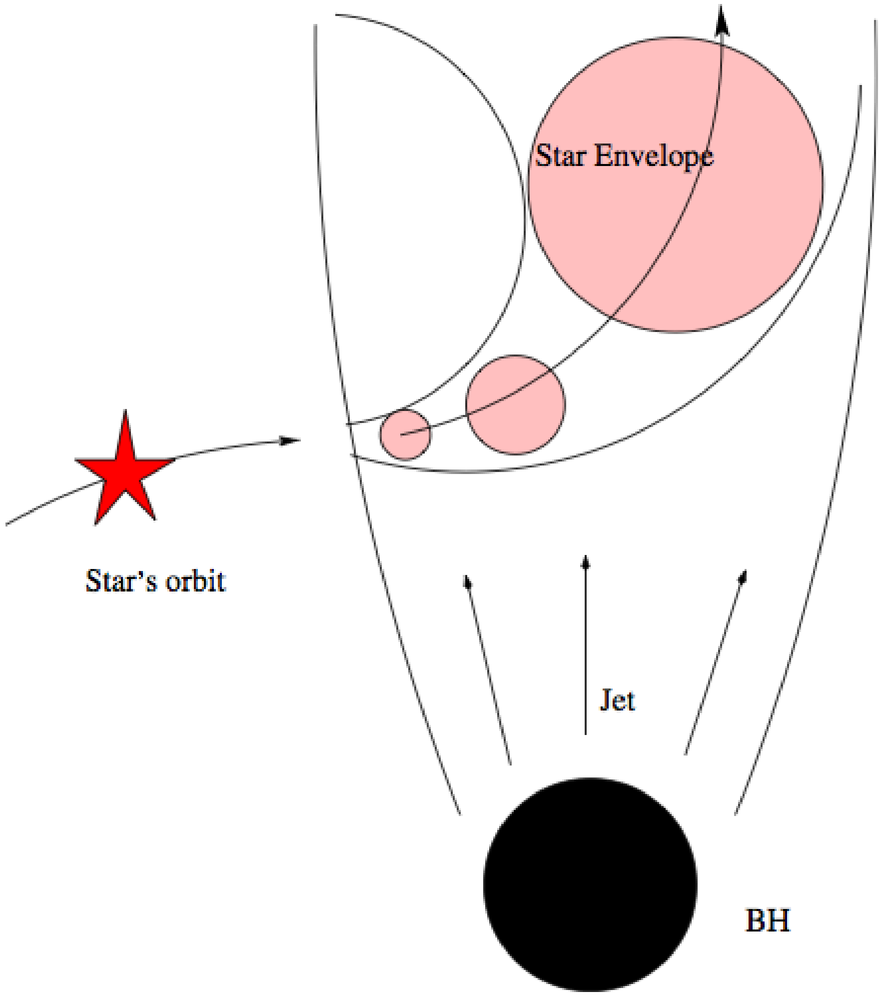
on the Doppler boosing and mass of BH in PKS2155-309

- a few min variability timescale => **$R = c\,\Delta t_{var}\,\delta j \sim 10^{13}\delta_j$ cm**; for a 10^9Mo BH with $3R_g \sim 10^{15}$ cm => $\delta j > 100$, i.e. close to the accretion disk (the base of the jet), the Lorenz factor of the jet $\Gamma > 50$ - but we don't expect such large values of Γ at the base

- **the (internal) shock scenario:** shock would develope at $R = Rg\,\Gamma^2$, i.e. minimum gamma-ray variability would be **$R_g/c = 10^4(M/10^9 Mo)$ sec**, despite the fact the γ-ray production region is located at $R_g \sim c\,t_{var}\,\Gamma^2$ (see e.g. Begelman, Fabian, Rees 2008); this is true for other scenarios with perturbation originating from the central BH

- thus for the observed time $t_{var} < 200$ s variability, the mass of BH cannot exceed significantly 10^7 Mo. 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; this can be realized e.g. in the scenario of formation of bubbles due to interactions of red giants with powerful jet


Star Envelope
Star's orbit
Jet
BH

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

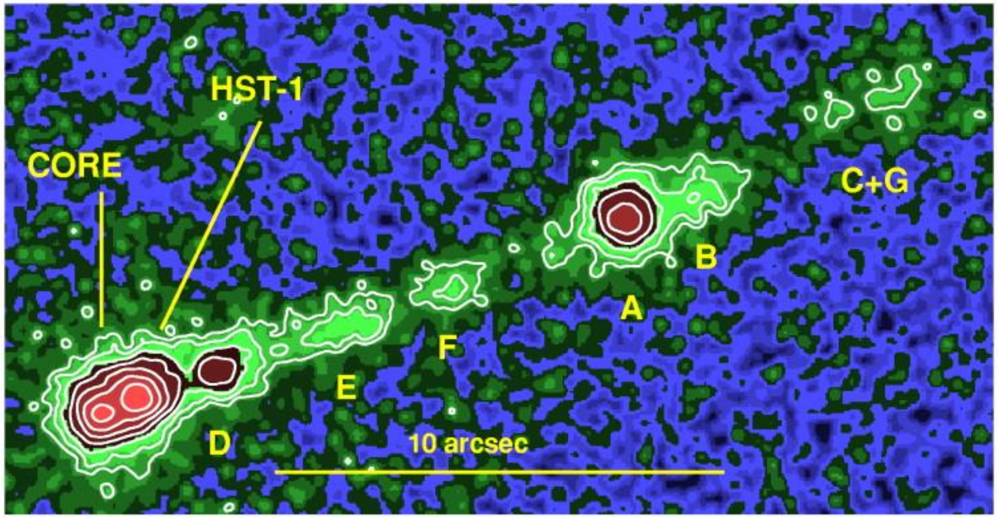
- Distance: ~16 Mpc

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

  => *not a blazar*!

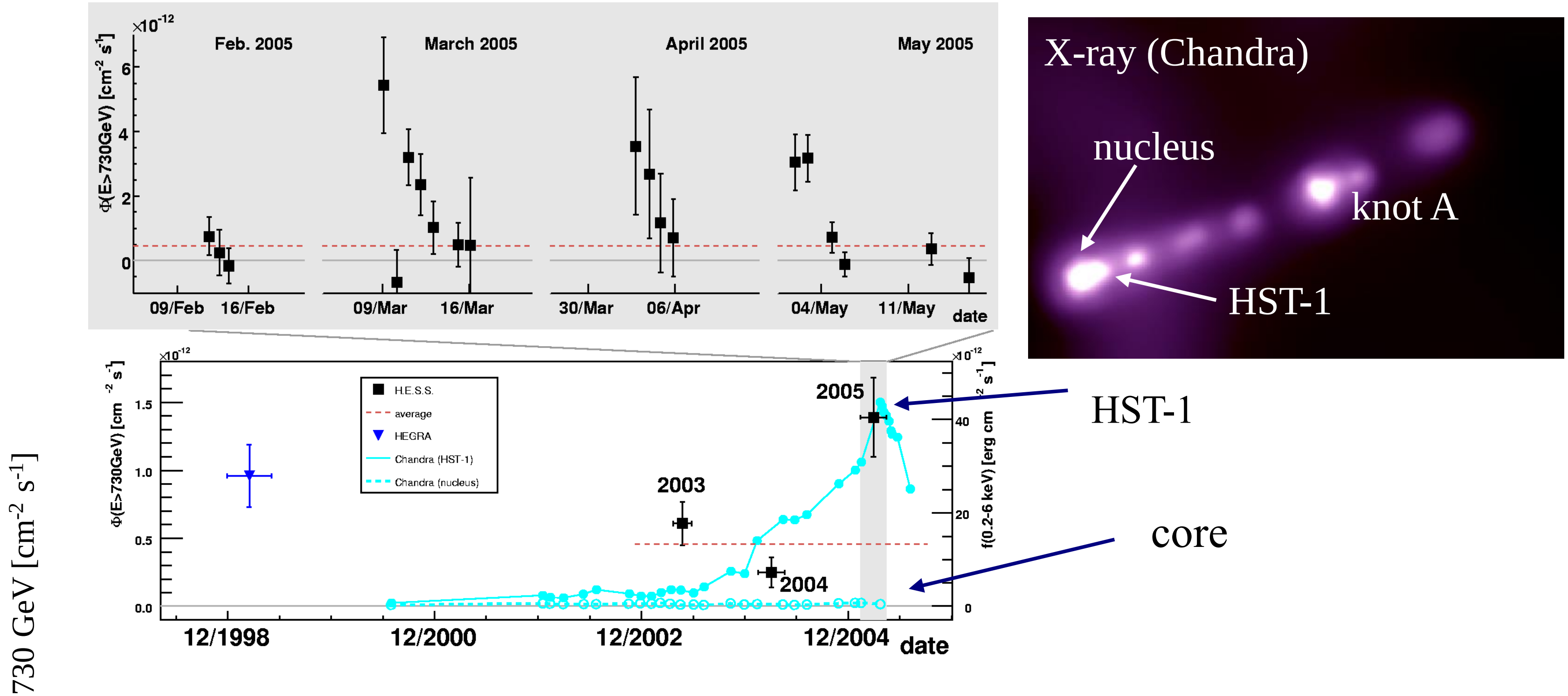
discovery (>4σ) of TeV γ-rays by HEGRA (1998) and confirmed recently by HESS/VERITAS, MAGIC

*) recently $6.4 \times 10^9\ M_o$ arXiv: 0906.1492 (2009)



M87: light curve and variabiliy

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

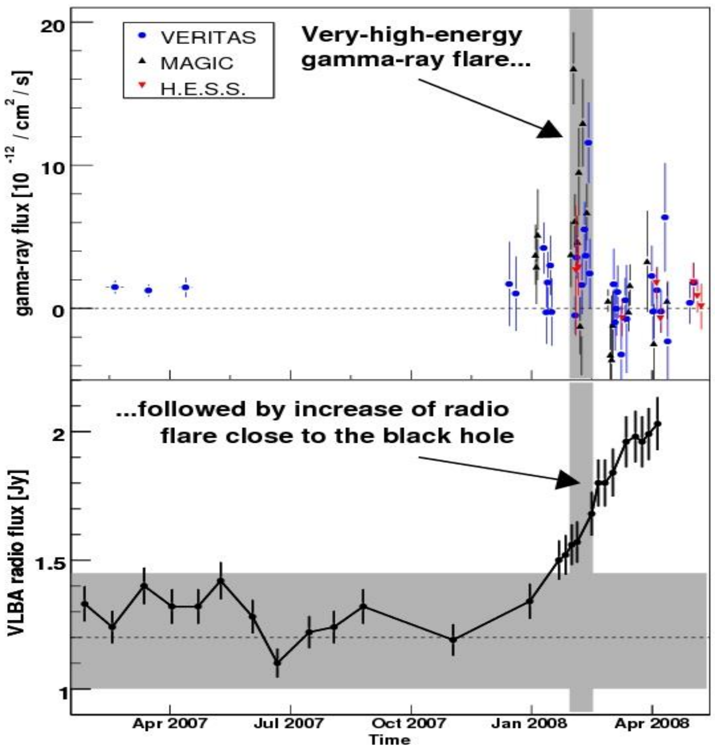


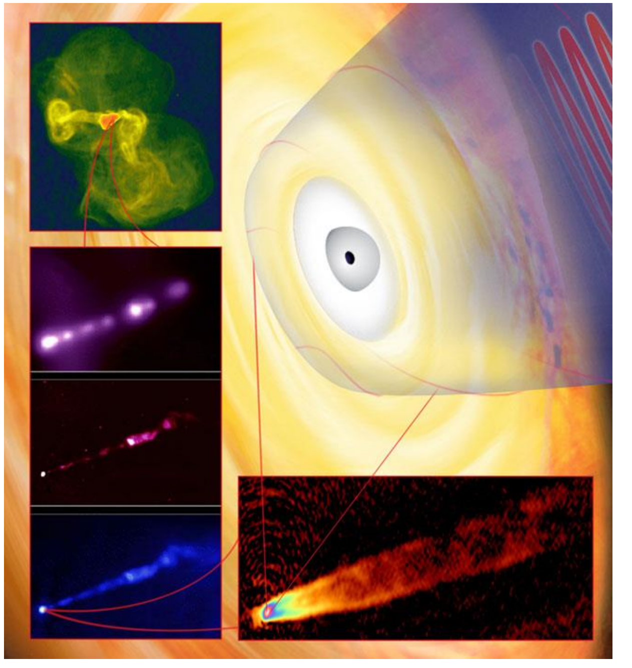
short-term variability on 1-2 day scales => emission region R ~ $5 \times 10^{15} \delta_j$ cm
=> production of gamma-rays very close to the 'event horizon' of BH?

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*

Conclusions:

- sources with relativistic outflows - Pulsar Wind Nebulae, Binary Systems and Blazars have greatly contributed to the HESS success

- IACT systems has significantly contributed to understanding of the physics and astrophysics of relativistic outflows in different astrophysical environments

deeper study of sources with relativistic outflows will be one of the highest priority objectives of science programs for the next generation IACT arrays

higher sensitivity	better angular resolution	broader energy coverage
10^{-14} erg/cm2 s	1-2 arcmin	10 GeV - 100 TeV

the next breakthrough? - detection of multi-GeV gamma-rays from GRBs !

a robust/reliable prediction: more than ten thousand 10-30 GeV photons (during the main event and/or afterglow) - **a huge discovery potential !**

Summary

- the recent success of observational γ-ray astronomy in high- and very-high energy regimes, together with extensive theoretical and phenomenological studies of non-thermal processes in the Universe, resulted in a deeper insight into a number of fundamental problems of high energy astrophysics (modern astrophysics, in general)

- these results introduced important corrections to our understanding of many relevant phenomena and revealed new features which in some cases require revisions of current theoretical paradigms or even demand formulations of new concepts

- the field is not "saturated". We can claim with a confidence that the performance of ground-based gamma-ray detectors can be dramatically improved, and it is going to happen in the (relatively) near future. At least in the case of one project – CTA – the plans are rather certain. This should result in a new breakthrough or perhaps even another revolution in several areas of the field

why next generation ground-based γ-ray instruments?

minimum detectable energy flux at 1TeV down to 10^{-14} erg/cm^{2}s

more sources and source populations: $L_{g,min} \sim 10^{30}\,(d/1kpc)^2$ erg/s

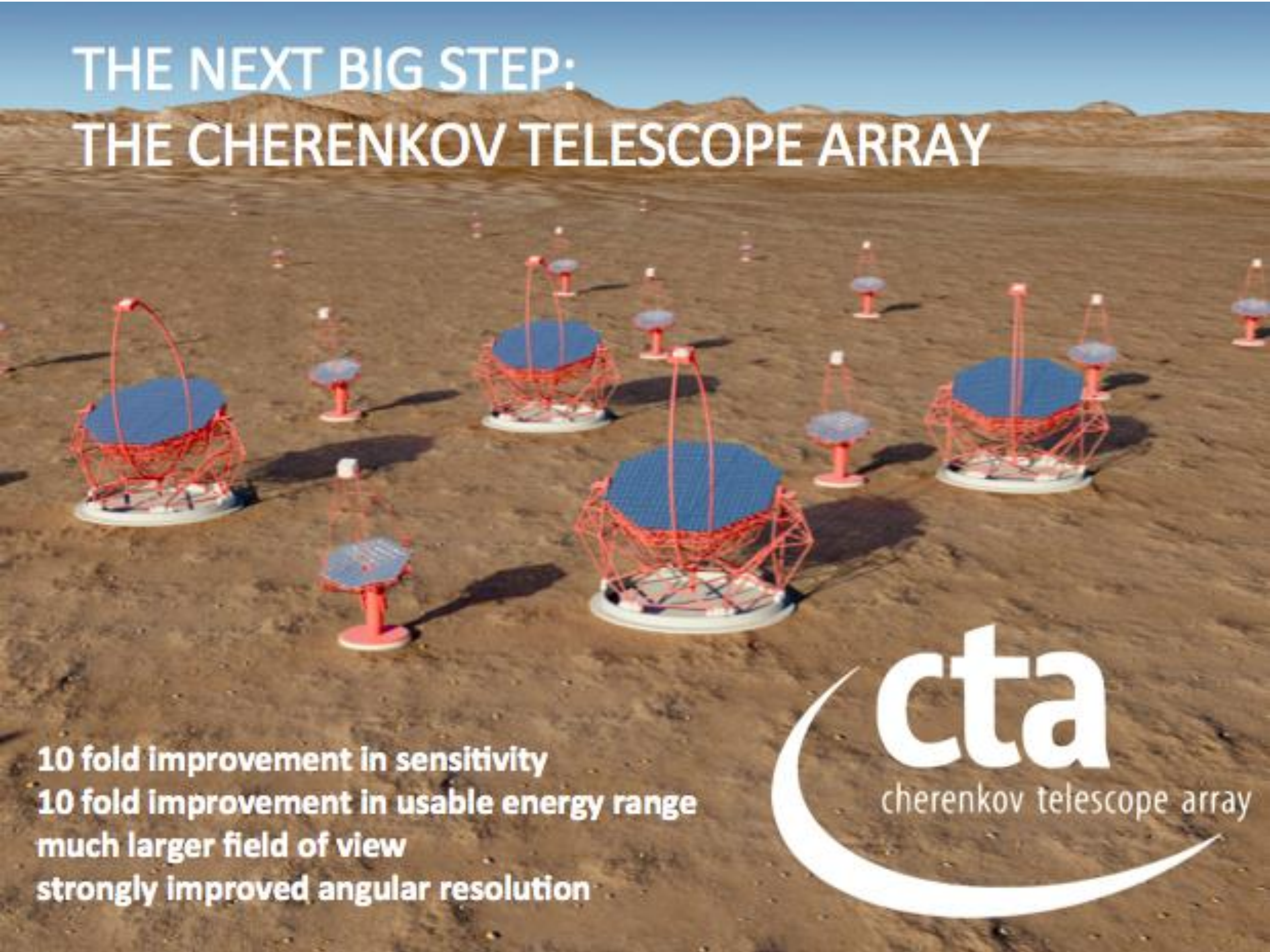
angular resolution down to 1-2 arcmin - *better morphology*

extension of the energy band

down to 10 GeV (timing explorer) | up to 100 TeV (search for PeVarton)

all sky monitoring

hunt for VHE transient events (HAWC)


THE NEXT BIG STEP:
THE CHERENKOV TELESCOPE ARRAY
10 fold improvement in sensitivity
10 fold improvement in usable energy range
much larger field of view
strongly improved angular resolution
cta
cherenkov telescope array