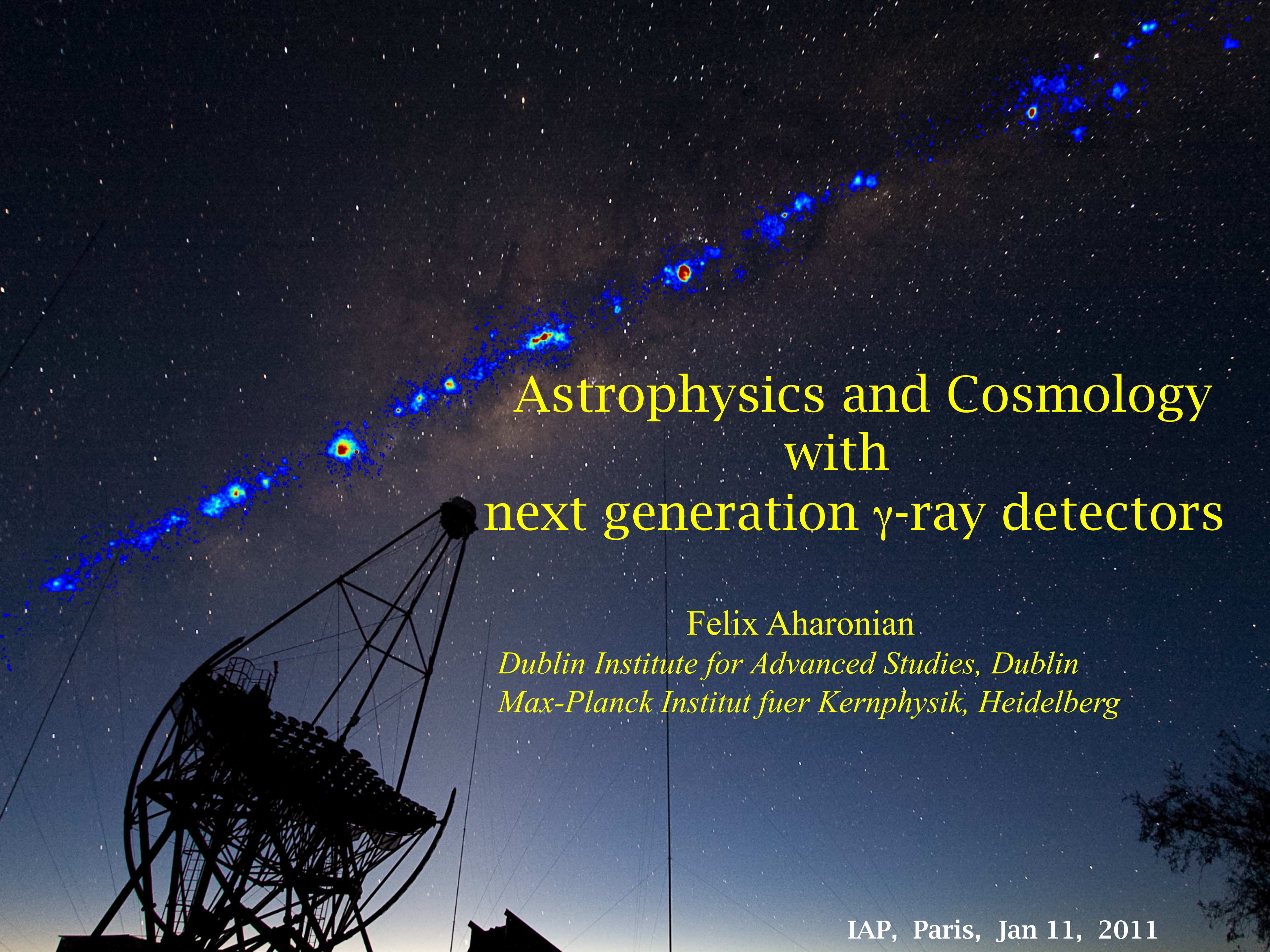

Astrophysics and Cosmology with next generation γ-ray detectors

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Max-Planck Institut fuer Kernphysik, Heidelberg

IAP, Paris, Jan 11, 2011

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 almost 150 reported VHE gamma-ray sources representing more than 10 Galactic & Extragalactic populations in the energy interval 0.1 TeV to 100 TeV

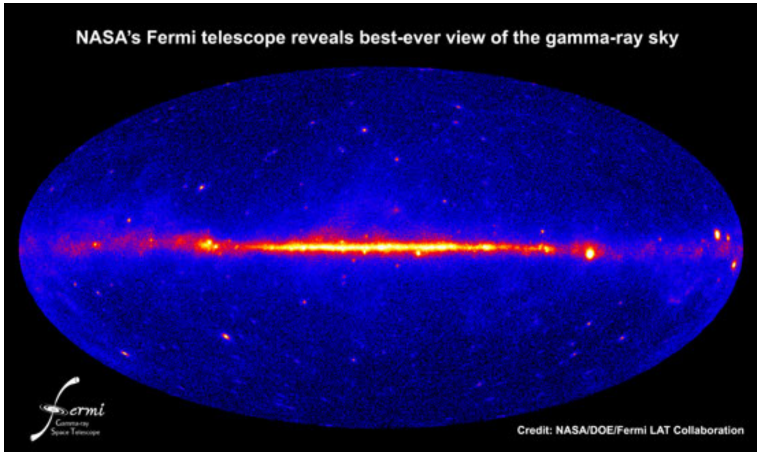
first surprises and conclusions from VHE gamma-ray observations:
protons/electrons are effectively accelerated to multi-TeV energies in diverse astronomical environments - almost in all nonthermal source populations

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


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

aim of this talk

what do we expect from the next generation of ground-based γ-ray detectors for the anticipated

collection area: up to 10 km^2

angular resolution: down to 1-2 arcmin

energy coverage: from 10 GeV to 100 TeV

field of view: 5 to 10 degree

flux sensitivity: down to 10^{-14} erg/cm^2s at 1TeV

Gamma-Ray Astronomy

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

High Energy Astrophysics: high energy processes in astrophysical environments

Relativistic Astrophysics: - acceleration of and radiation of relativistic particles (electrons/protons/nuclei) close to relativistic objects: *black holes, neutron stars/pulsars, SN explosions …* high energy phenomena in relativistic outflows: *pulsar winds, AGN and μQSO jets,…*

Cosmology gamma-rays as carriers of cosmological information: Extragalactic Background Light, Intergalactic Magnetic Fields, indirect search of Dark Matter,

Fundamental Physics: probing (or challenging) laws of basic physics, e.g. the Lorentz invariance

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

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 can be as large as 50 %

(ii) maximum energy achieved by individual particles

acceleration rate close to the maximum (theoretically) possible rate

sometimes efficiency can even "exceed" 100% ?

(due to relativistic and non-linear effects)

Golden age of VHE (ground-based) gamma-ray astronomy

(i) strongly support by (Astro) Particle Physics (APP) community, for several objective and subjective reasons:

objective - *perspectives of fundamental particle physics and cosmology*
subjective - *it is not clear what can be done with accelerators after LHC; VHE GA projects are dynamical and cost-effective; can be realized by relatively small groups on quite short timescales*, …

for Particle Physics Community APP was (first of all) "*Particle Physics Without accelerators*" but Particle physicists started to realize the potential and beauty of astrophysics – partly because of the recent great success of VHE GA

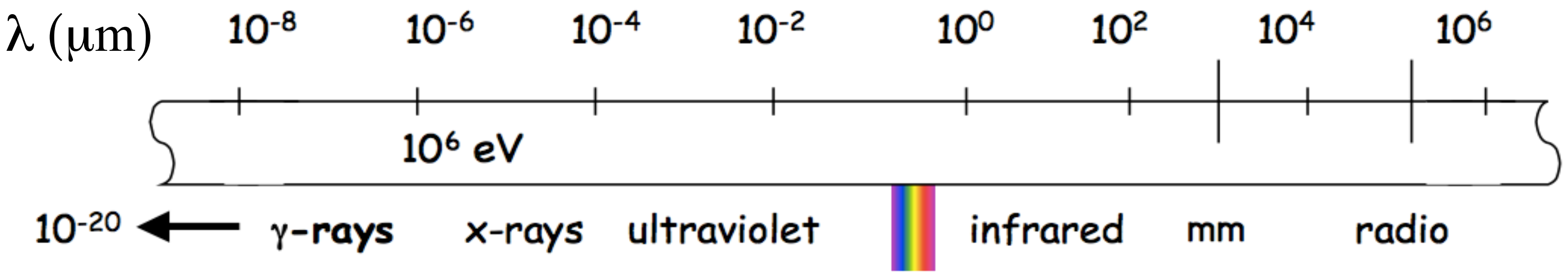
(ii) Astronomers finally accepted VHE GA as a branch of modern Astrophysics (in 2008 HESS appeared in the list of the top-ten most cited/influential astronomical telescopes - together with giants like Hubble, Chandra, VLT, etc.)

CTA - accepted as a very high rank project within the "Roadmaps" of both European Astroparticle and Astronomical Communities

Gamma-Ray Astronomy

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* …



γ-rays: photons with wavelengths less than 10^{-6} μm

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:

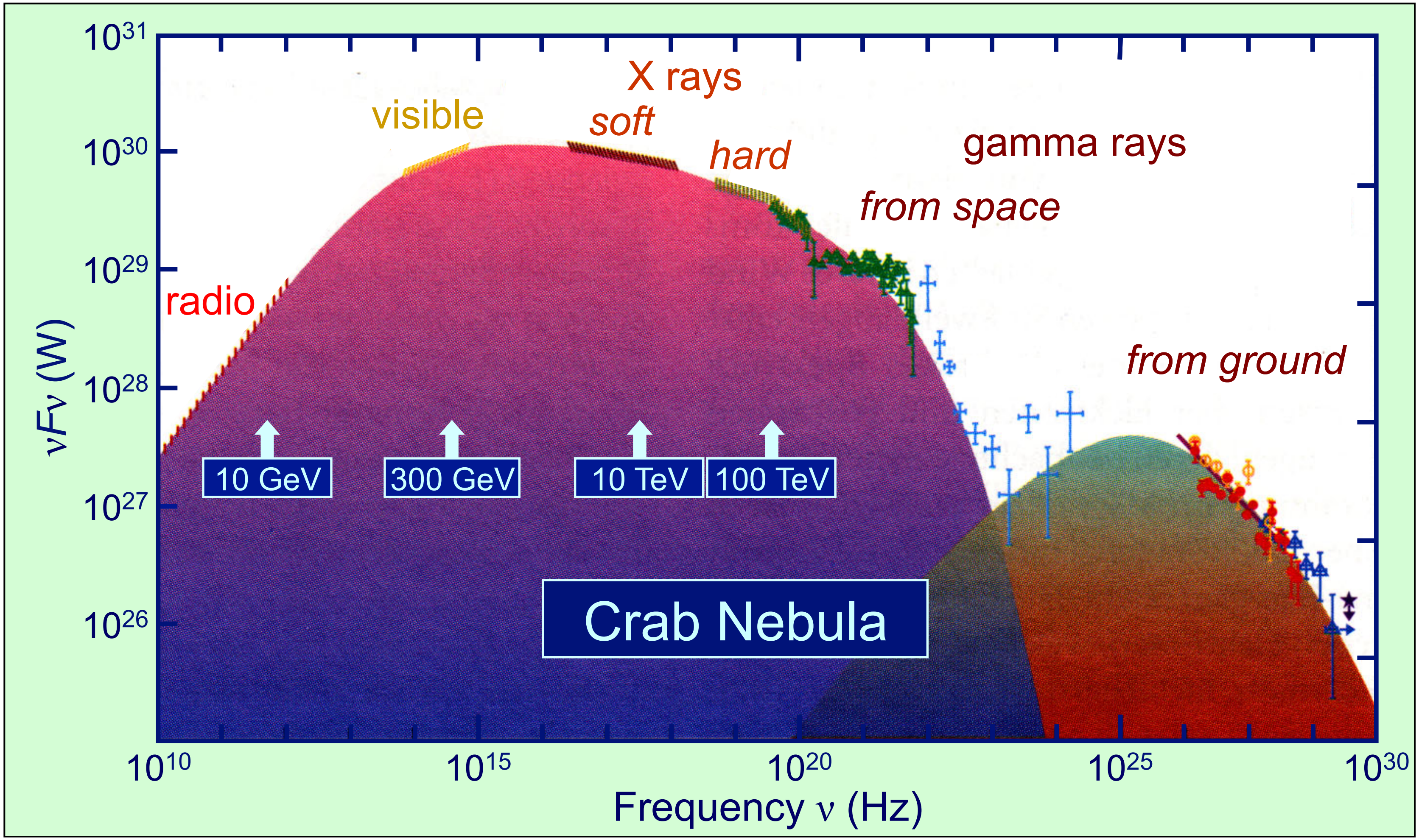
LE,HE *domain of space-based astronomy*

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

a non-thermal astrophysical object seen over 20 energy decades



R, mm, IR, O, UV,X

gamma-rays

why gamma-rays?

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

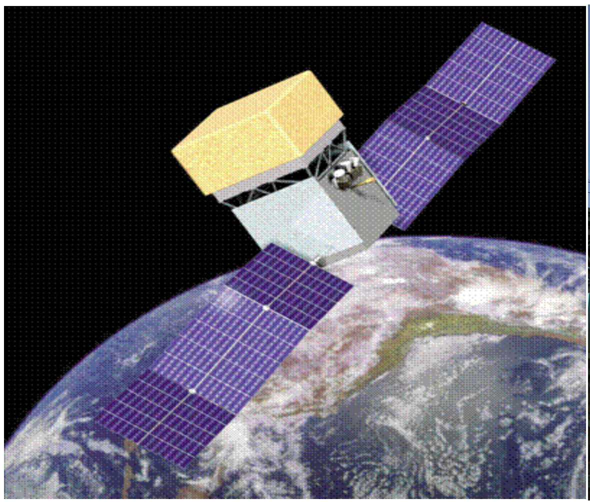
- ✓ are effectively produced
  in both electromagnetic and hadronic interactions
- ✓ penetrate (relatively) freely throughout
  intergalactic and galactic magnetic and photon-fields
- ✓ are effectively detected
  by space-based and ground-based detectors

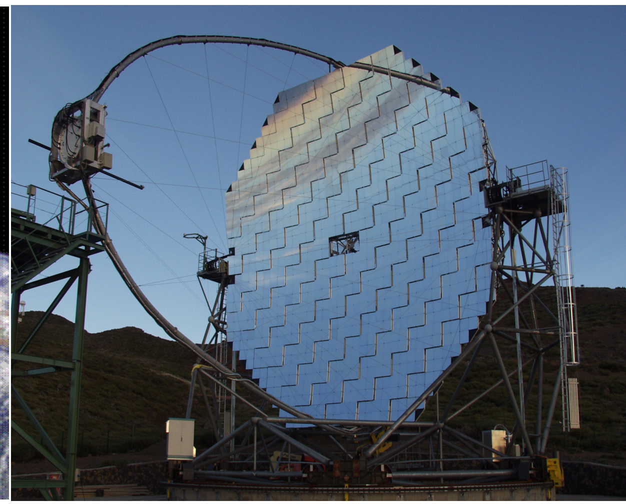
HE, VHE, and UHE Gamma-Ray Detectors

HE

VHE

UHE





direct

indirect

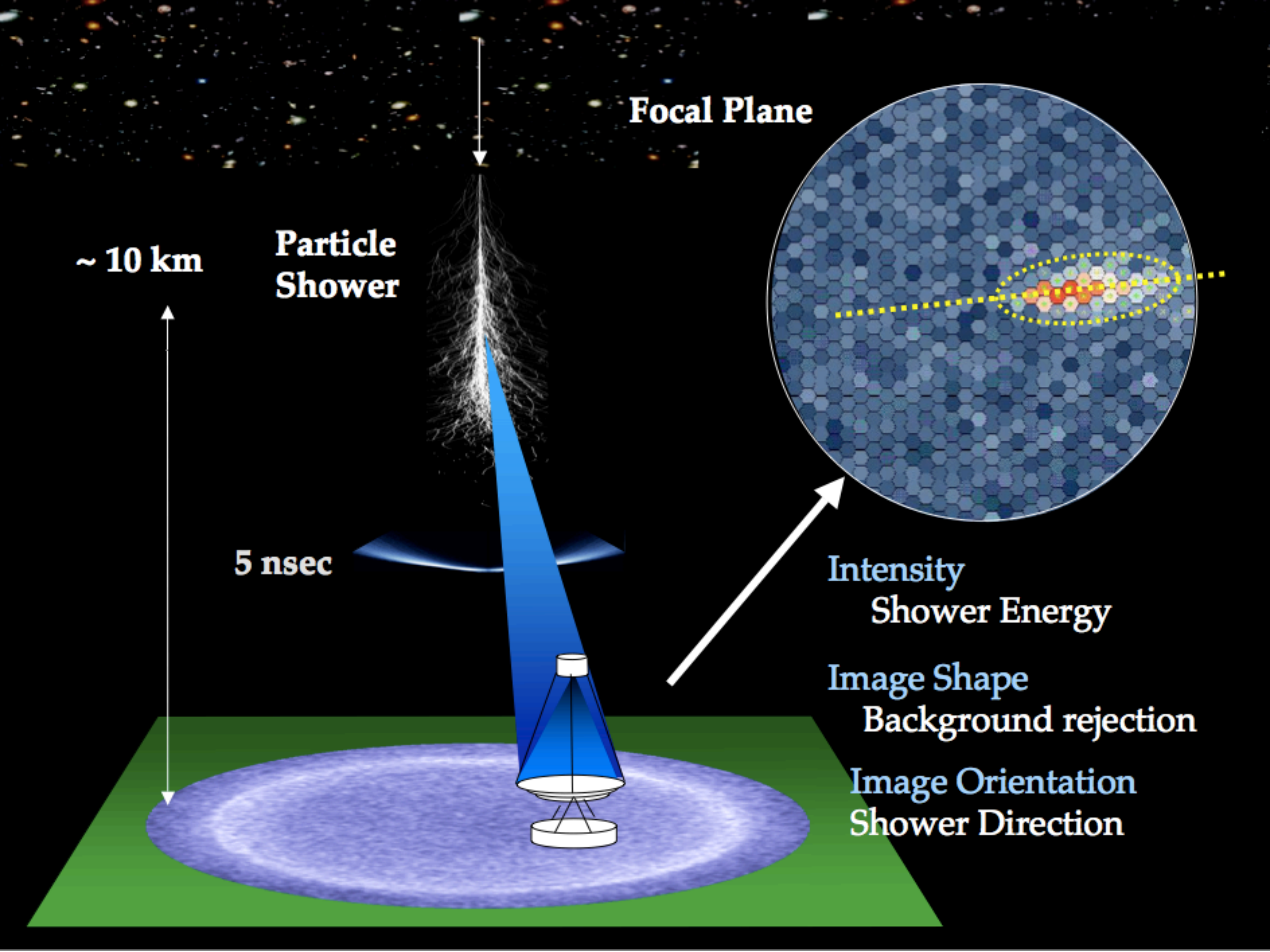
Cherenkov light

EAS particles

E < 100 GeV

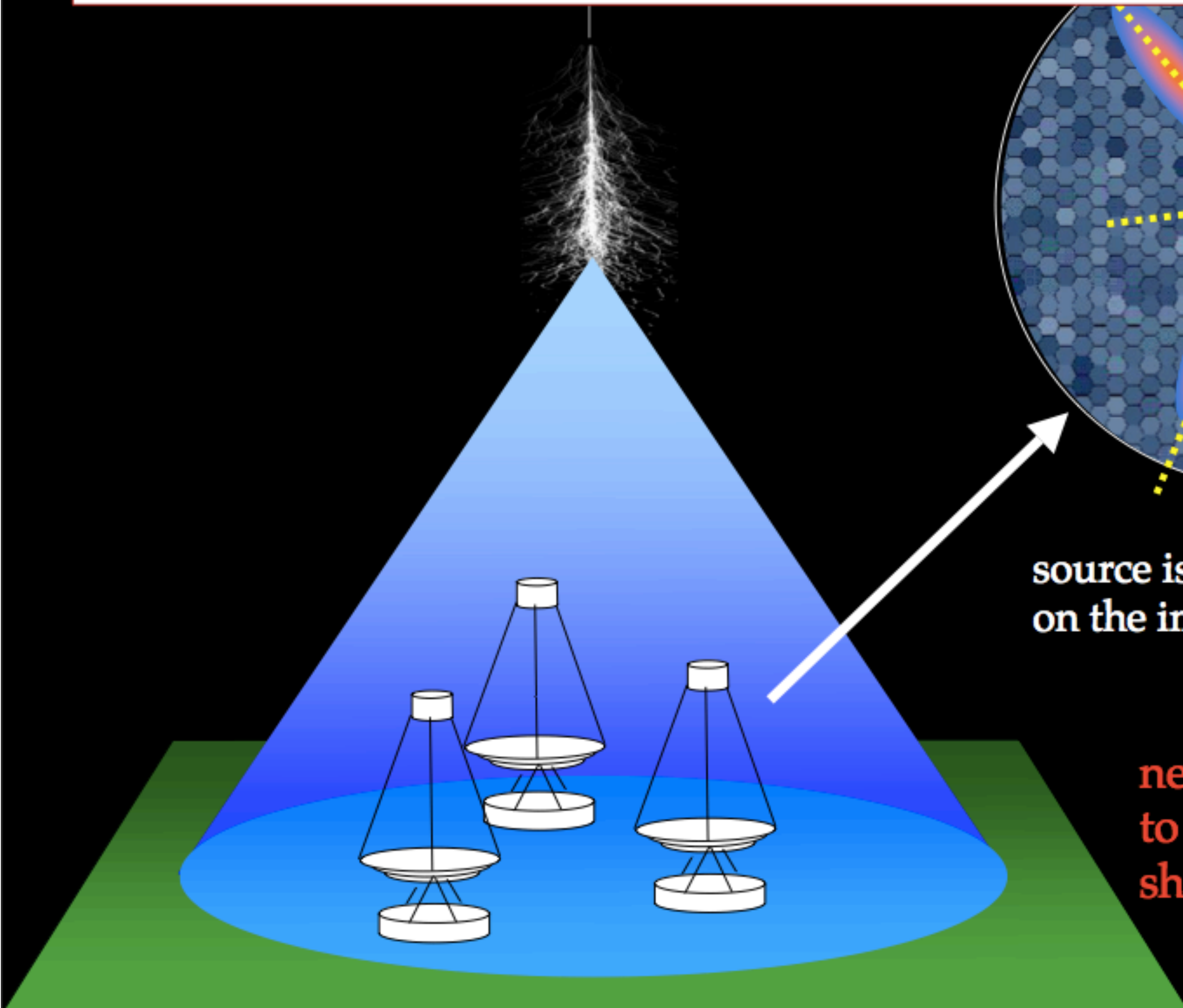
E > 10 GeV

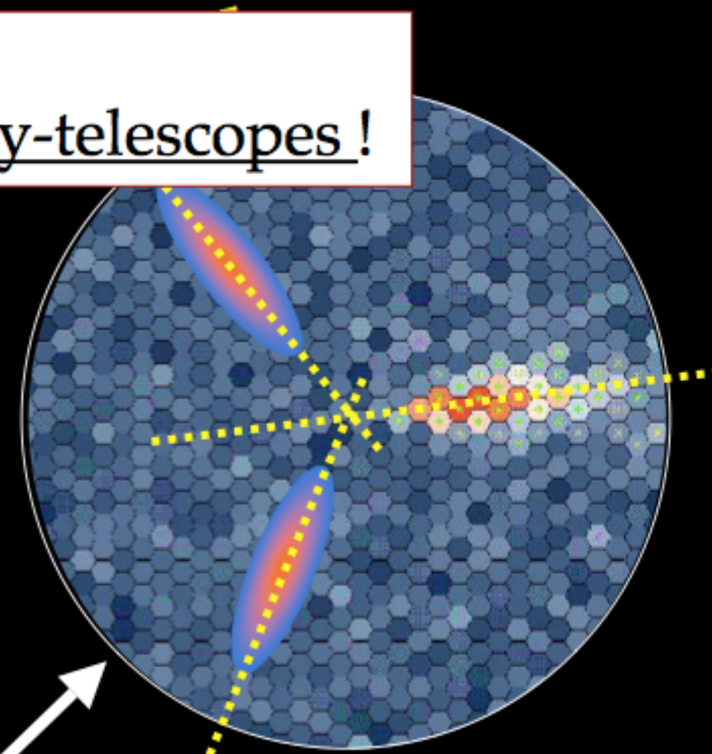
E > 100 GeV



Focal Plane
Particle Shower
~ 10 km
5 nsec
Intensity
Shower Energy
Image Shape
Background rejection
Image Orientation
Shower Direction

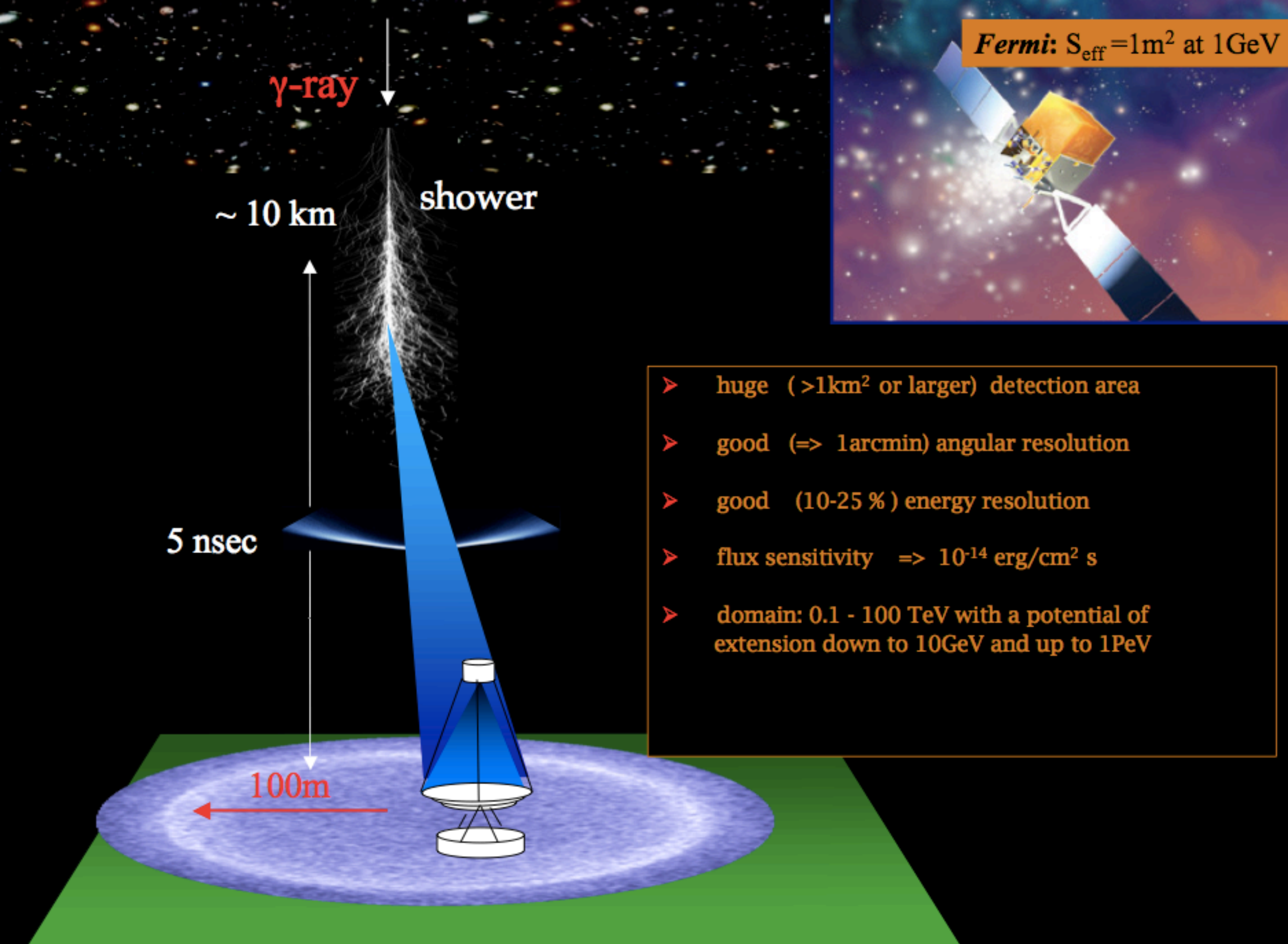
Stereoscopic IACT arrays as perfect <u>γ-ray-telescopes</u> !





source is located (somewhere) on the image axis ...

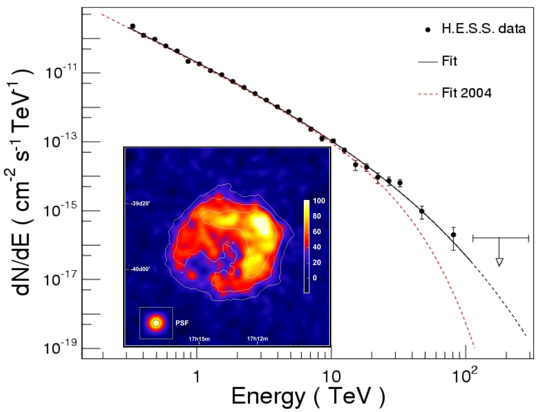
need several views to get unambiguous shower direction



γ-ray
shower
~ 10 km
5 nsec
100m
Fermi: S_{eff} =1m² at 1GeV
huge (>1km² or larger) detection area
good (=> 1arcmin) angular resolution
good (10-25 %) energy resolution
flux sensitivity => 10^{-14} erg/cm² s
domain: 0.1 - 100 TeV with a potential of extension down to 10GeV and up to 1PeV

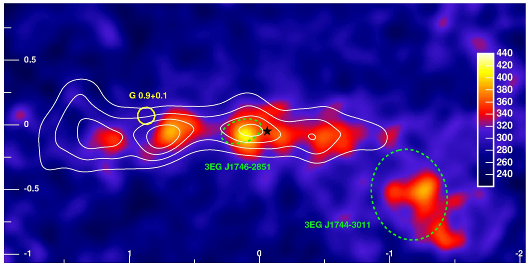
H.E.S.S. : good performance => high quality data

RXJ 1713.7-3946



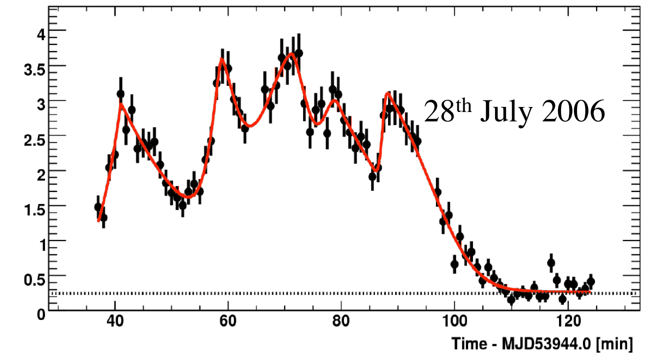
TeV image and energy spectrum of a SNR

Galactic Center



resolving GMCs in the Galactic Center 100pc region

PKS 2155-309



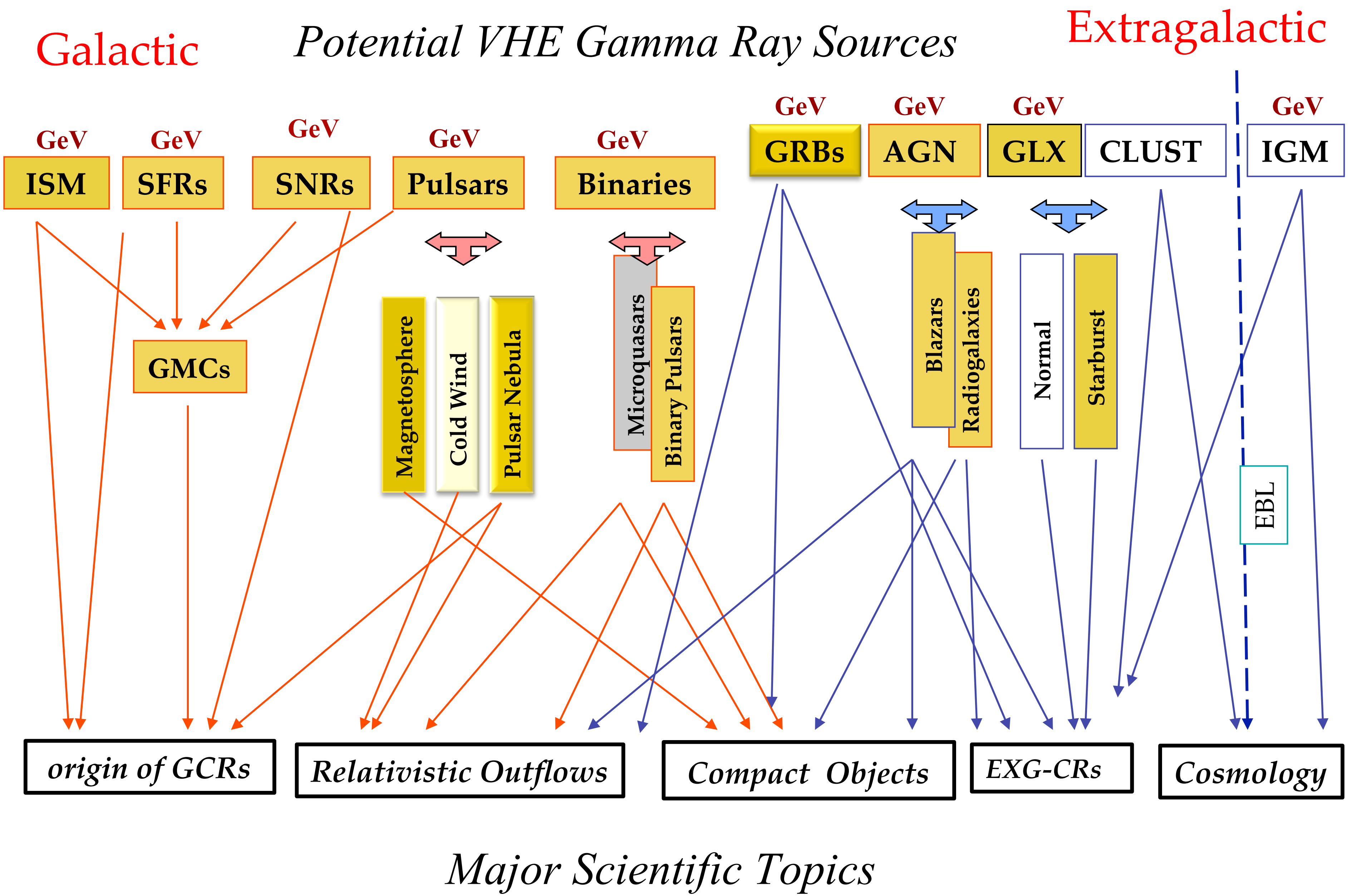
variability of TeV flux of a blazar on minute timescales

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


Galactic
Potential VHE Gamma Ray Sources
Extragalactic
GeV
ISM
GeV
SFRs
GeV
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
origin of GCRs
Relativistic Outflows
Compact Objects
EXG-CRs
Cosmology
Major Scientific Topics

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: $L_{\gamma,min} \sim 10^{30}\,(d/1kpc)^2$ erg/s

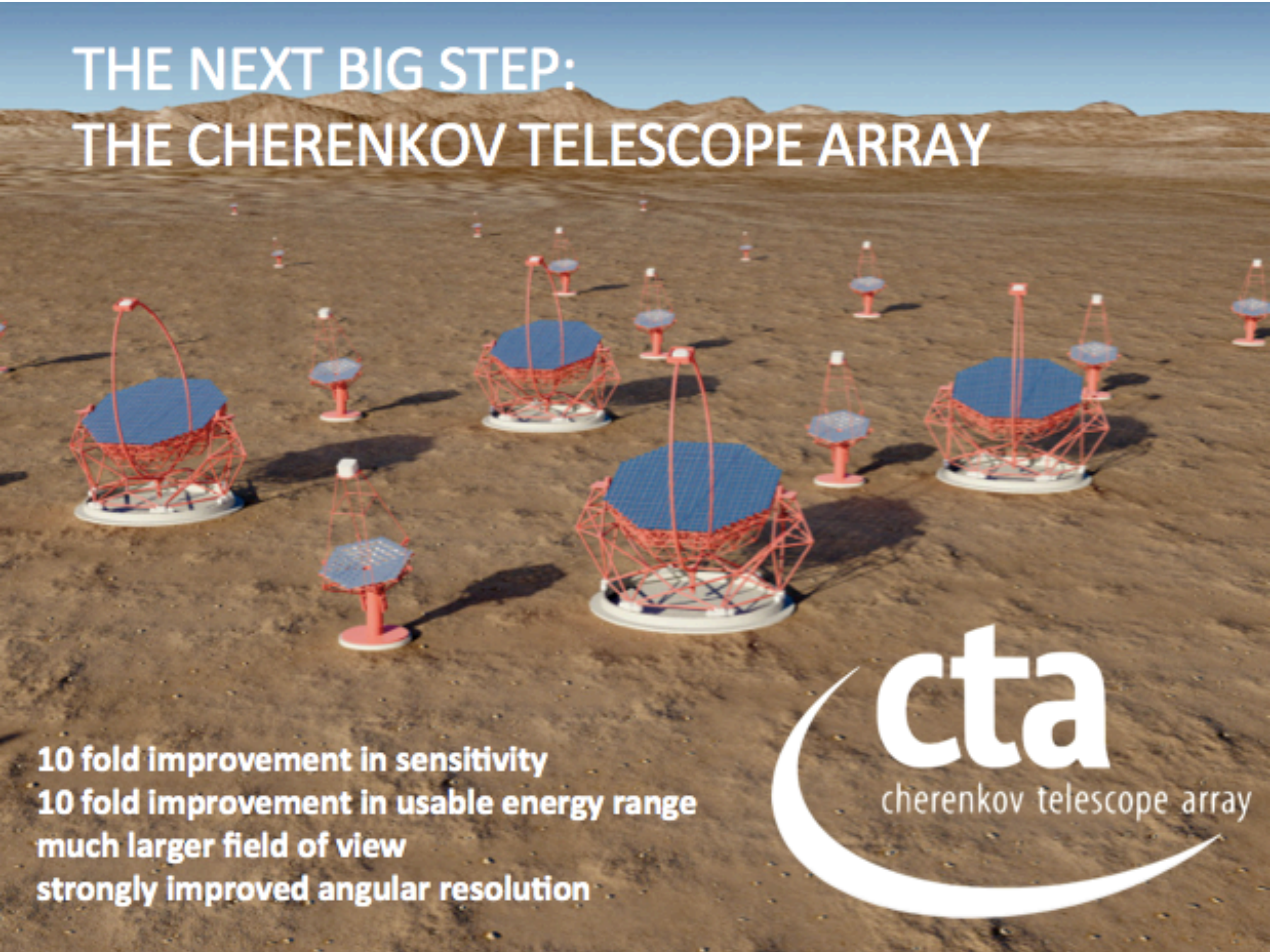
angular resolution down to 1-2 arcmin - *better morphology*

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

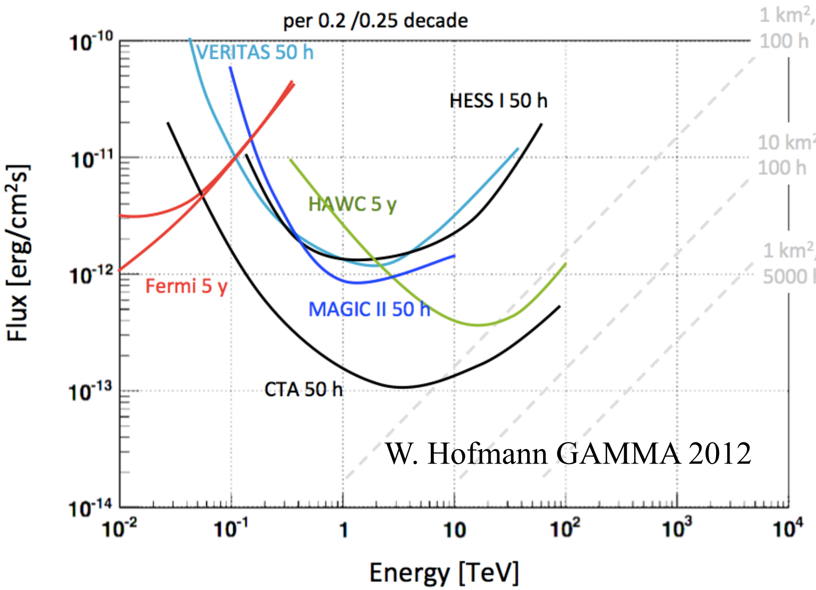


- 10 fold improvement in sensitivity
- 10 fold improvement in usable energy range
- much larger field of view
- strongly improved angular resolution

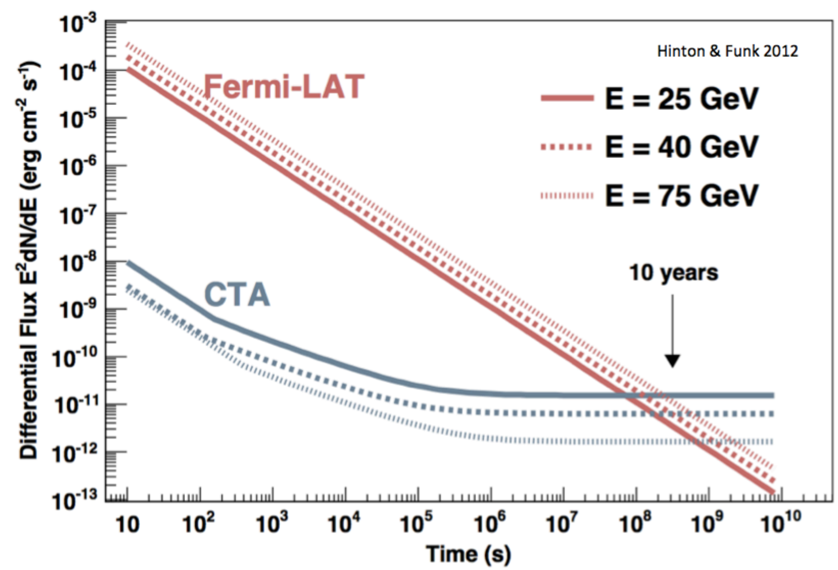

we already are there !

CTA – a powerful tool for exploration of the Nonthermal Universe

DIFFERENTIAL SENSITIVITY



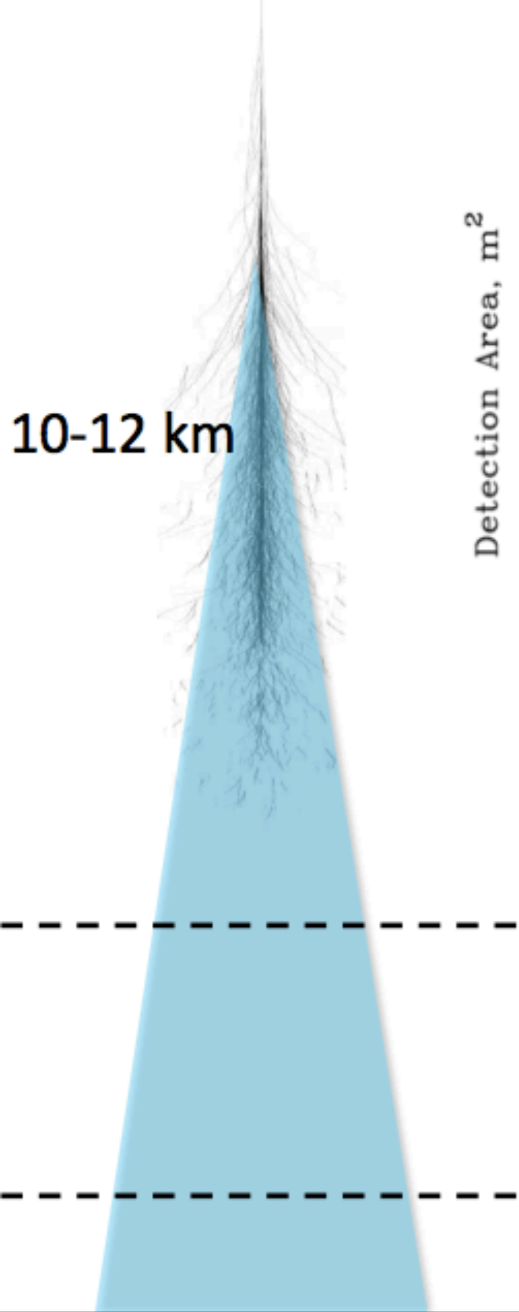
CTA VERSUS FERMI – TRANSIENT SOURCES

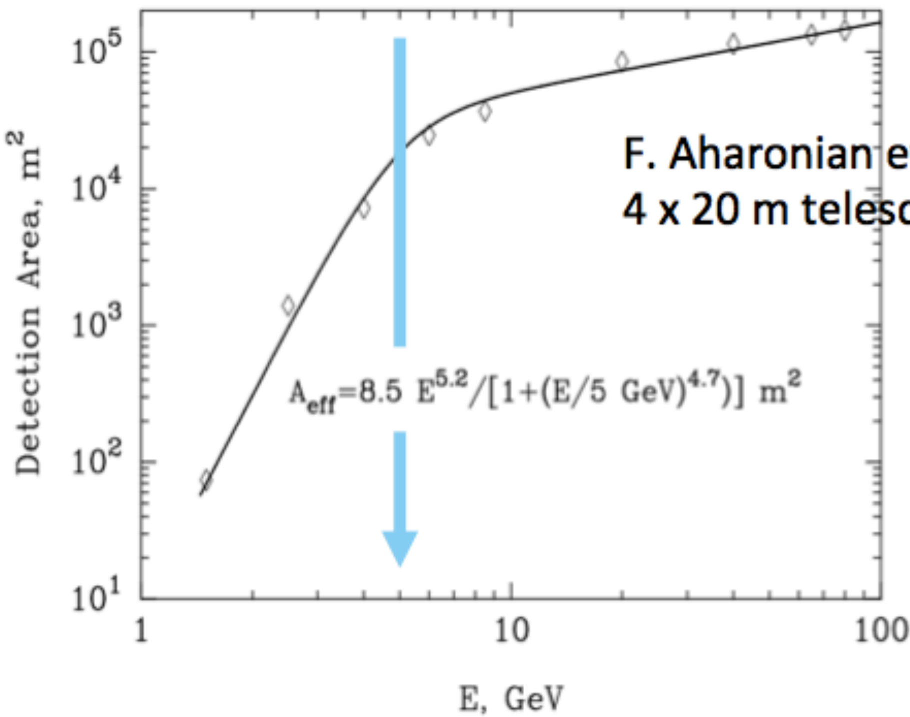


- detection of `nominal' (Fermi/AGILE) AGN for just 1min,
- detection of >10,000 gamma-rays from (Fermi LAT) GRBs with >10-GeV tails

but above several tens of GeV, the emission could be suppressed at tens of GeV
=> low threshold is critical (as low as 10 GeV is possible!)

HIGH-ALTITUDE CHERENKOV TELESCOPES





F. Aharonian et al., astro-ph/0006163
4 x 20 m telescopes @ 5000 m asl

higher light intensity (5000 m: x2)
➔lower threshold
smaller light pool area (5000 m: /2)

Reference height ~2000 m

W. Hofmann GAMMA 2012

topics to be covered in this talk

(i) SNRs and Origin of Galactic Cosmic Rays

(ii) Pulsars – Pulsar Winds - Pulsar Wind Nebulae

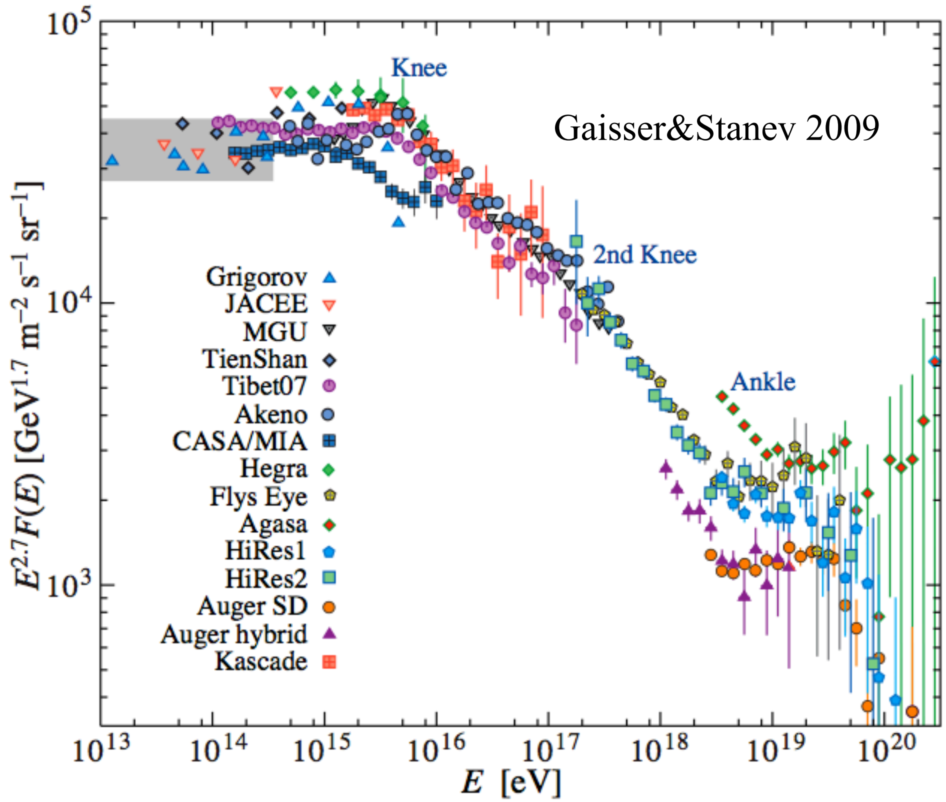
(iii) Blazars and EBL

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

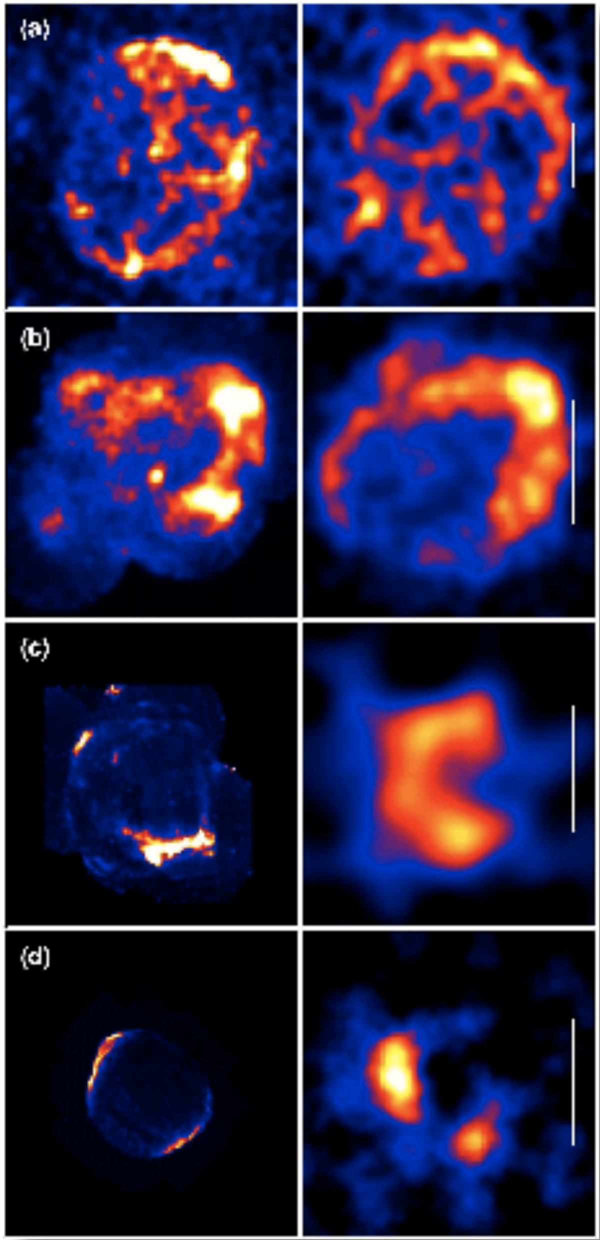
Supernova Remnants? two attractive features:

- ✓ *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?

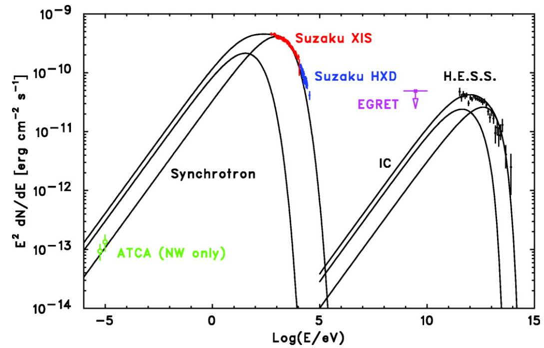
Pulsars/PWNe OB stars Binaries Galactic Center …

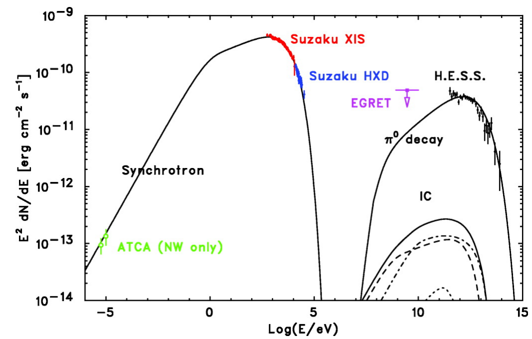


=>

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

leptonic or hadronic?





RXJ1713.7-4639

$e + 2.7K \Rightarrow \gamma$ $\qquad$ $pp \Rightarrow \pi^o \Rightarrow 2\gamma$

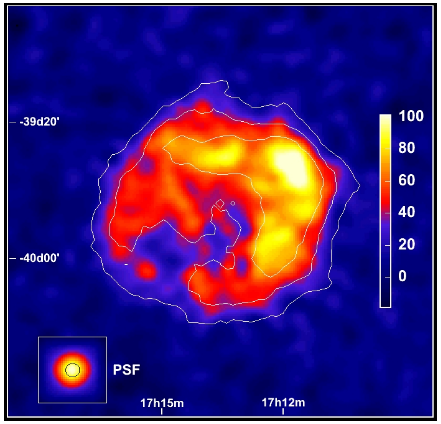
B=15μG
We ≈3 10^{47} erg

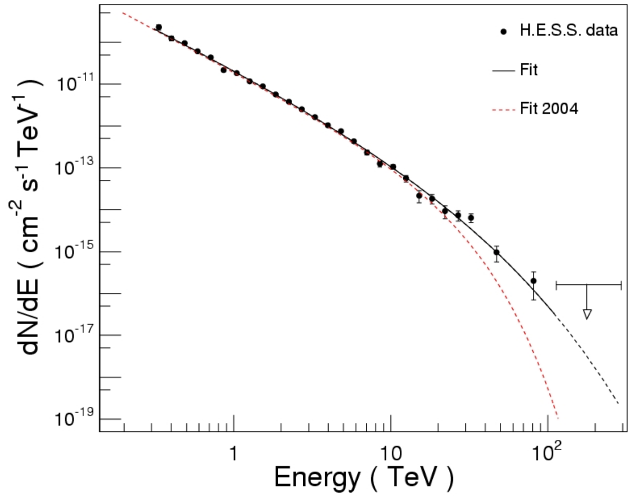
B=200μG
Wp ≈ $10^{50}(n/1cm^{-3})^{-1}$ erg

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

$\alpha=2.0$ Eo=17.9 TeV $\beta=1$

$\alpha=1.79$ Eo=3.7 TeV $\beta=0.5$

with just "right" energetics:

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

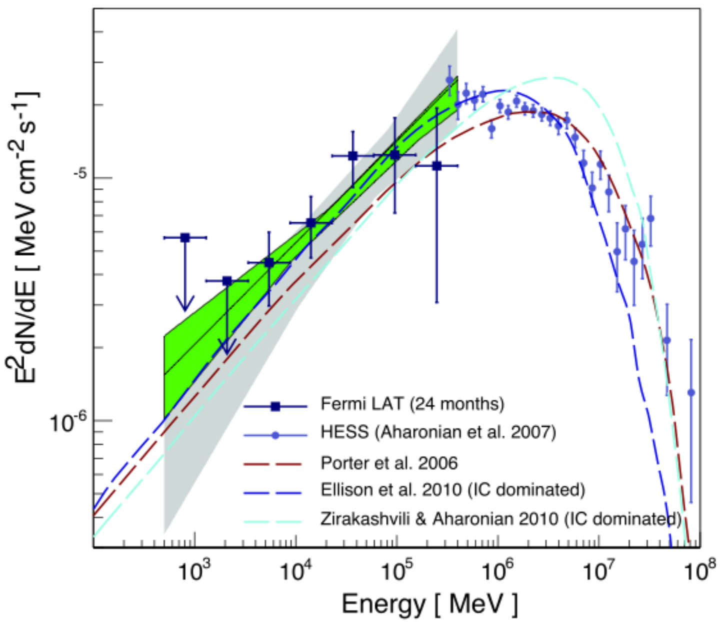
but IC models generally are more preferred… because of TeV-X correlations (?)

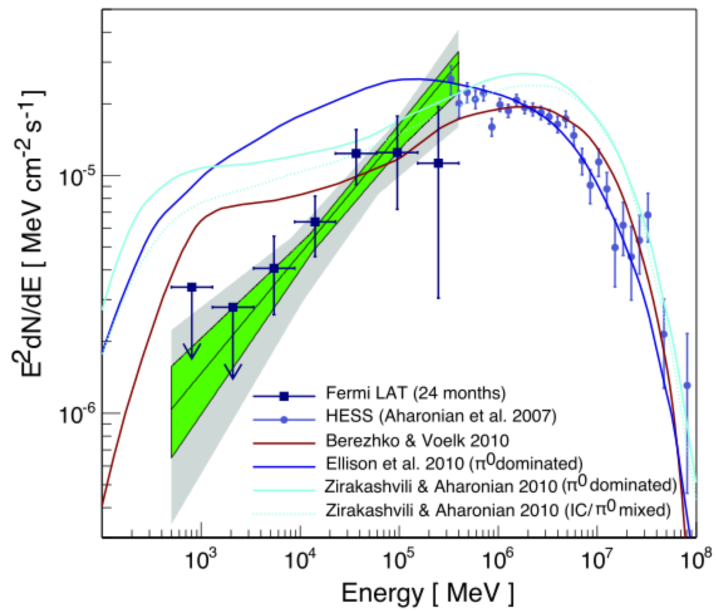
IC origin of γ-rays cannot indeed be excluded, but this is not a good argument

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

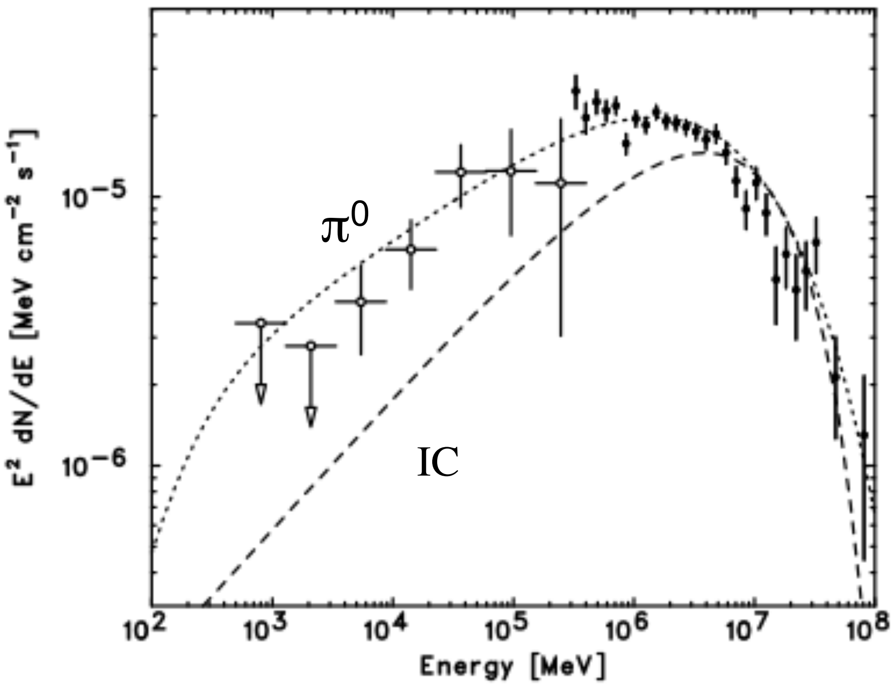
Questions: (i) can we compare GeV and TeV fluxes within one-zone models?

they could come from quite different regions

(ii) hard proton spectrum ?

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

GeV-TeV data can be explained by protons with spectral index α=1.8



data: HESS and Fermi LAT

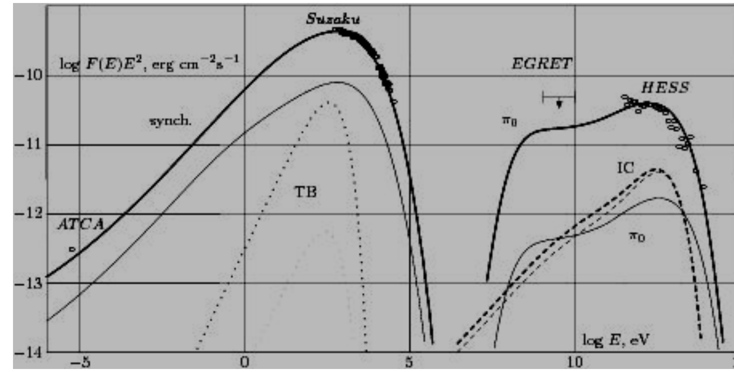
theoretical curves: Tanaka et al. 2008

proton spectrum: best fit spectrum from the HESS paper (2007)

extremely efficient DSA theory predicts α=1.5 (Malkov 1999) but Abdo et al. 2011 *argued that "...such a proton energy distribution is not observed in the current models of DSA (Ellison et al. 2010)"* (not a good argument)

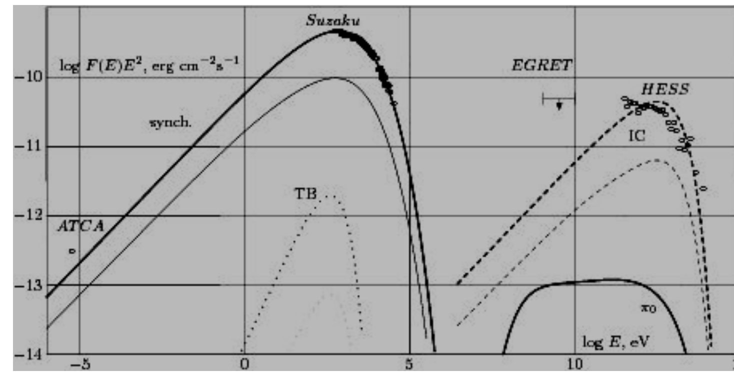
the story of the death of hadronic origin of γ-rays has been greatly exaggerated *broad-band SEDs*

hadronic model



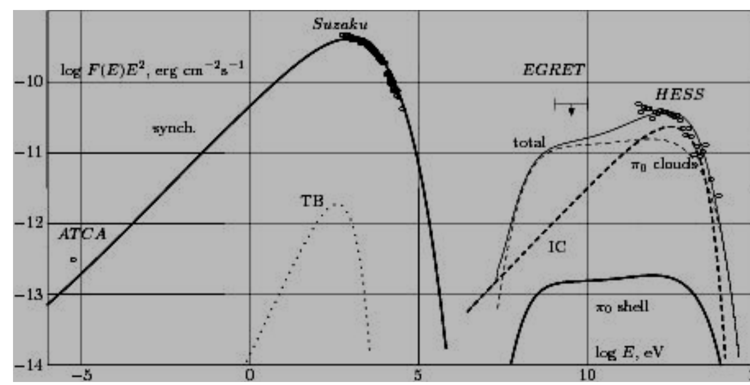
good spectral fit, reasonable radial profile, but …
(1) lack of thermal emission - possible explanation?
>70% energy is released in acceleration of protons!
(2) very high p/e ratio (10^4)

leptonic model



not perfect (but still acceptable) fits for spectral and spatial distributions of IC gamma-rays; suppressed thermal emission, comfortable p/e ratio (~10^2);small large-scale B-field (~ 10 μG)

"composite" model?



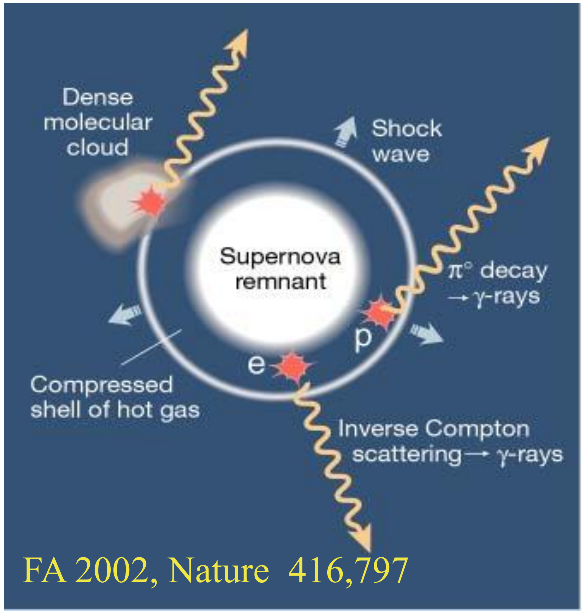
gamma-rays detected by Fermi?
very important… but not decisive

both forward and reverse shock contribute to γ-rays

Zirakashvili, FA 2010

the "composite" model

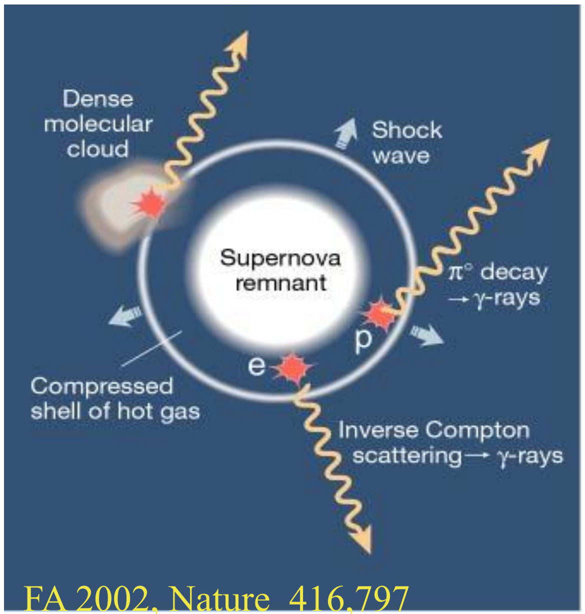
IC gamma-rays from (i) the entire shell with average small B-field and (ii) π^0-decay gamma-rays from dense clouds inside the shell

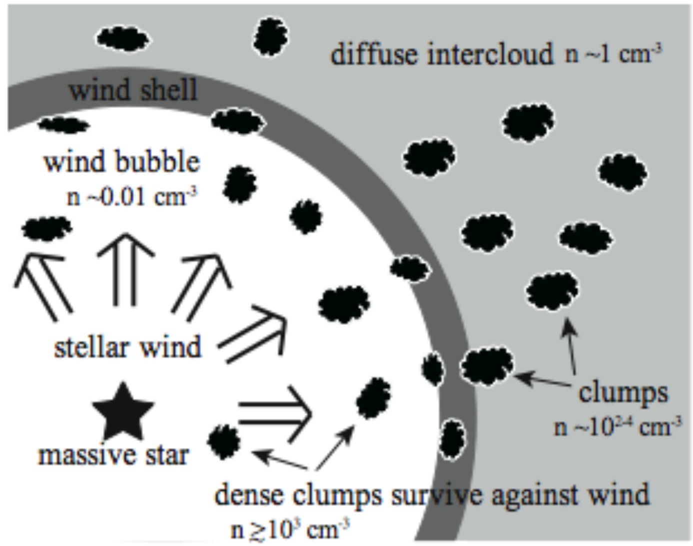


GeV gamma-rays can be suppressed because low energy protons cannot penetrate deep into dense clumps (Zirakashvili&FA 2010, Inoue et al. 2011)

Fermi LAT - important, but only neutrinos, ultra-high energy gamma-rays and hard synchrotron X-rays from secondary electrons can provide decisive conclusions *the "composite" model*

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





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

a serious problem…

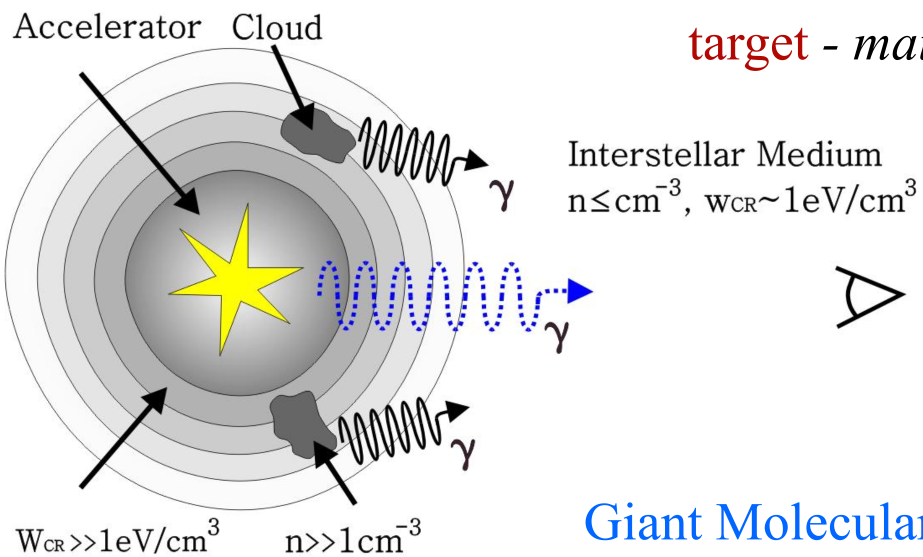
- “early cutofs” - in all SNRs Ecut < 100 TeV
  because of escape? do they contribute to the the region around the “knee”

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



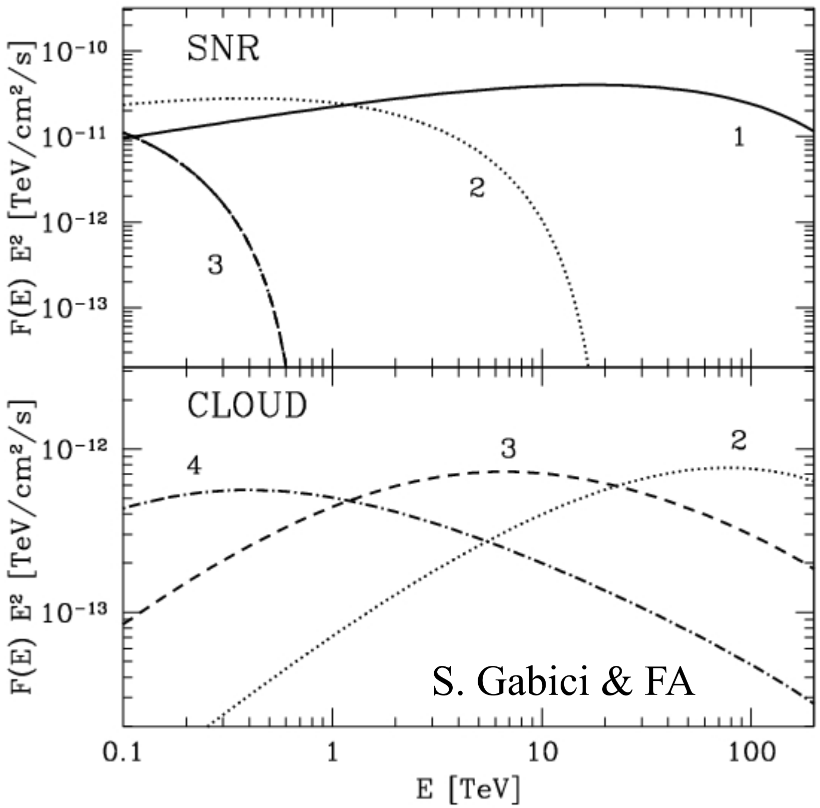
target - *matter, radiation, magnetic field*

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 inside and outside of SNRs

1 - 400yr, 2 – 2kyr, 3 – 8kyr, 4 – 32 kyr



young SNRs:

- *both GeV and TeV γ-rays from shells (TeV but not GeV from dense clumps)*
- *TeV, but not GeV from nearby clouds*

middle-aged SNRs:

- *only GeV γ-rays from shells (with or without clumps)*
- *both GeV and TeV γ-rays from clouds*

SNR: $W_{51}=n_1=u_9=1$ d=1 kpc

GMC: $M=10^4\ M_o$ d=100pc

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

CTA – an ideal instrument to study all scenarios

how to find the “missing PeV protons in SNRs?

highest energy particles, E > 100 TeV, are confined in the shell only during a few 100 years => most promising search for PeVatrons? multi-TeV γ-rays from dense gas clouds in the near neighborhood

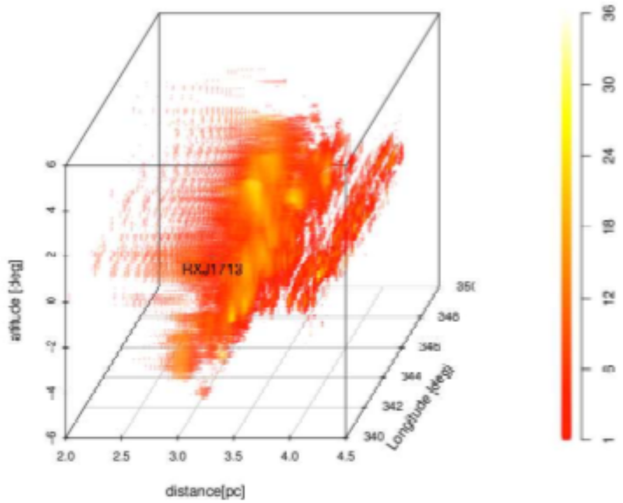
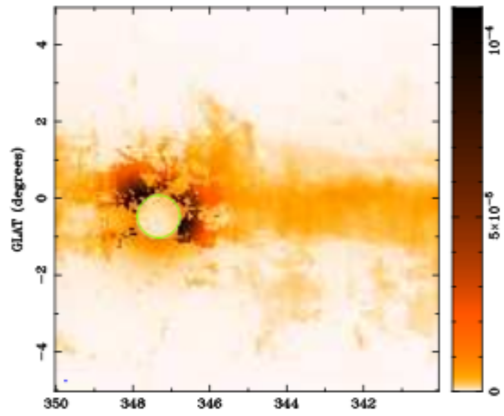


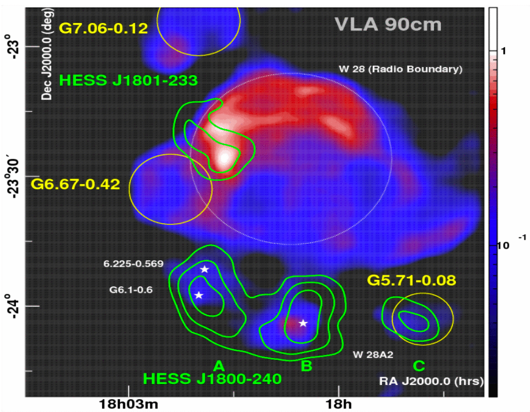
Fig. 1. The gas distribution in the region which spans Galactic longitude 340° < l < 350°, Galactic latitude −5° < b < 5° and heliocentric distance 50 pc < l_d < 30 kpc, as observed by the NANTEN and LAB surveys, expressed in protons cm^{-3}. The distance axis is logaritmic in base 10. A value for the gas density is given every 50 pc in distance, which is reflected in the apparent slicy structure for distances below 100 pc. For sake of clarity only densities above 1 protons cm^{-3} are shown. Also indicated the position of the historical SNR, RX J1713.7-3946.

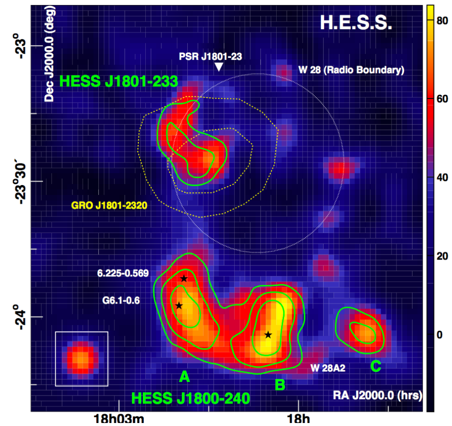


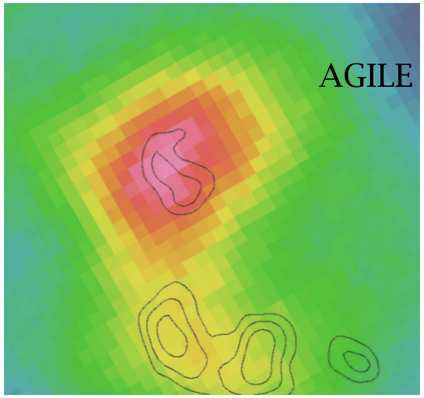
to detect gamma-ray from run-away protons just beyond the shell of young SNRs we need sensitive detectors for >10 TeV γ-rays with < 2 arcmin PSF

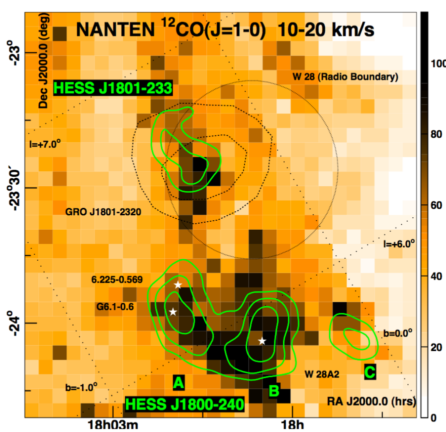
GeV and TeV gamma-ray sources around mid-age W28:

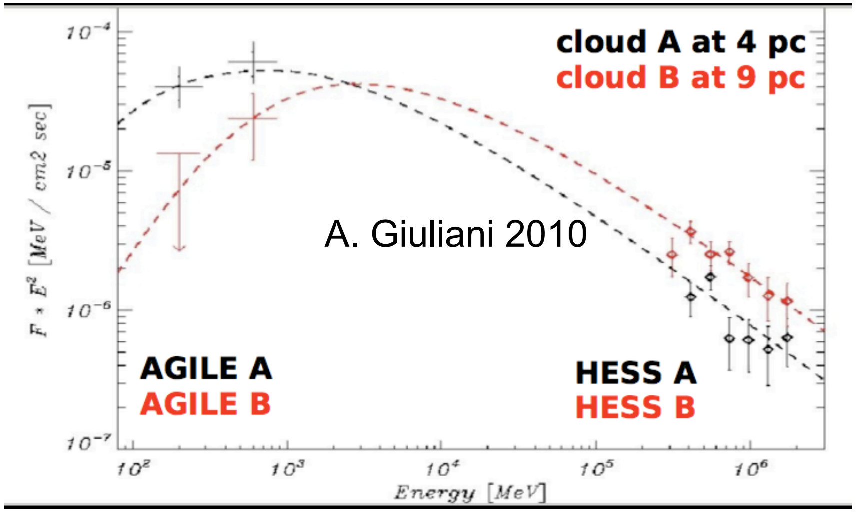
CRs from an old SNR interacting with nearby clouds?



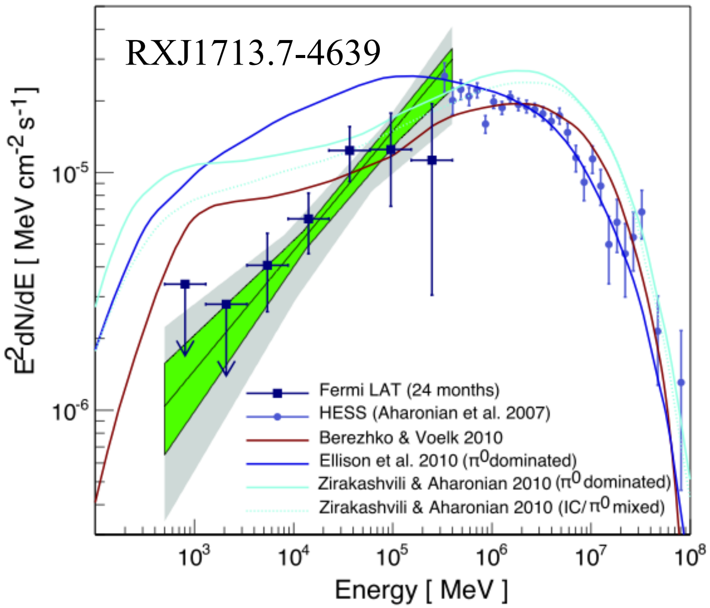


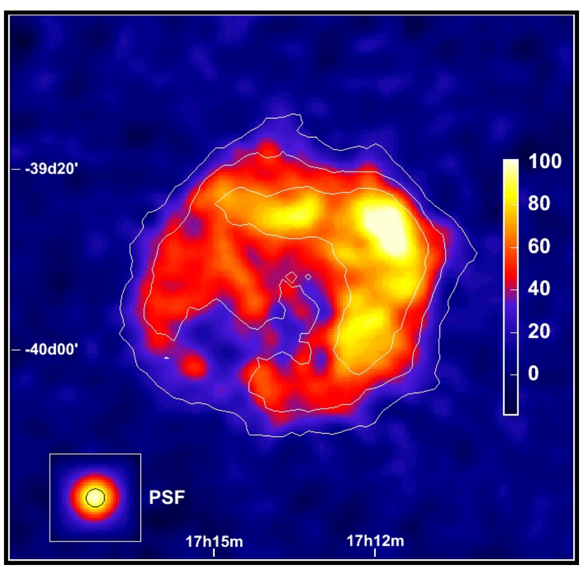




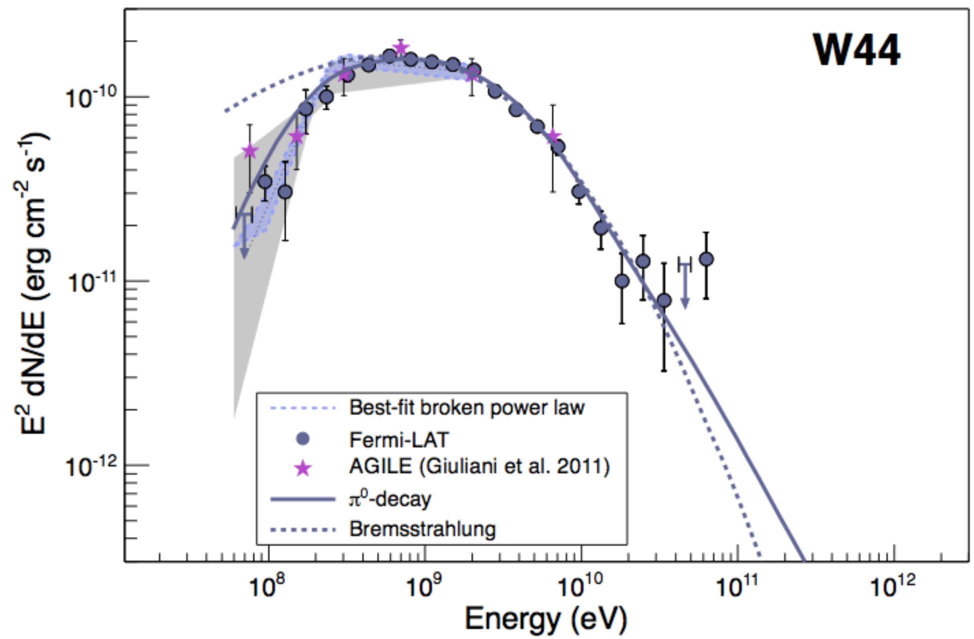


Clumps?





Clumps!



spectum can be explained only by γ-rays from pp ->π^o ->2γ , but the total γ-ray flux requires (n/40 cm^{-3}) (W_p/10^{50} erg) ~ 1,

n >>1cm^{-3}, gas density inside the shell is not sufficient => dense clumps inside the shell (clouds overtaken by the shell?)

``passive'' clouds as barometers of GCRs

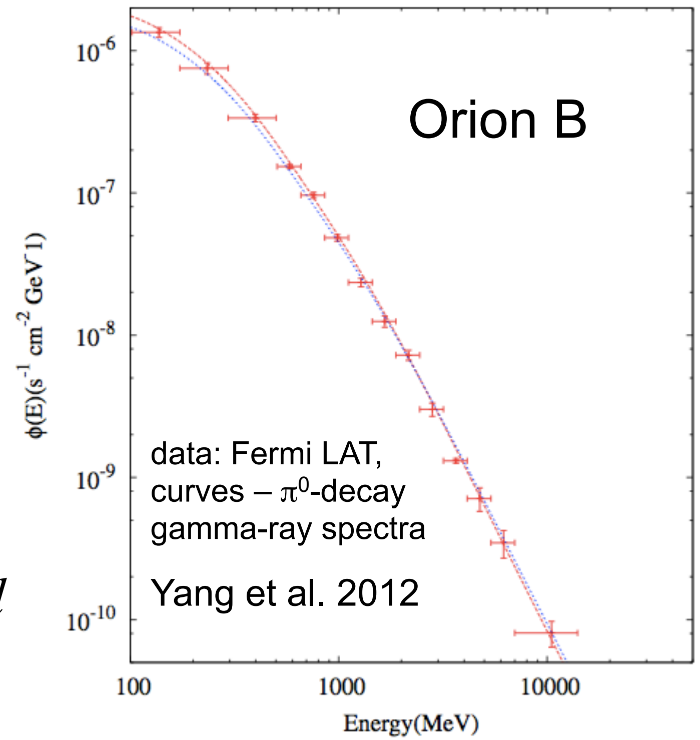
Fermi LAT data: 10-100 GeV:

$$\mathrm{dN/dE} \propto \mathrm{E}^{-\alpha} \text{ with } \alpha = 2.85 - 2.9$$

both the absolute flux and spectrum perfectly agree with direct measu- remnants of CR protons by Pamela

$$\mathrm{Q(E)} \propto \mathrm{E}^{-2.3} \text{ but not } \mathrm{E}^{-2}$$

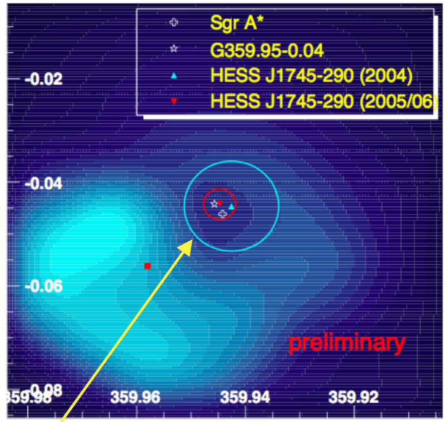
GCRs are homogeneously distributed in the local Galaxy within several 100 pc (!); the source spectra are steeper that anticipated



extension of observations to TeV energies? – current IACT arrrays are not sufficiently sensitive, but CTA should be able to detect the strongest ones

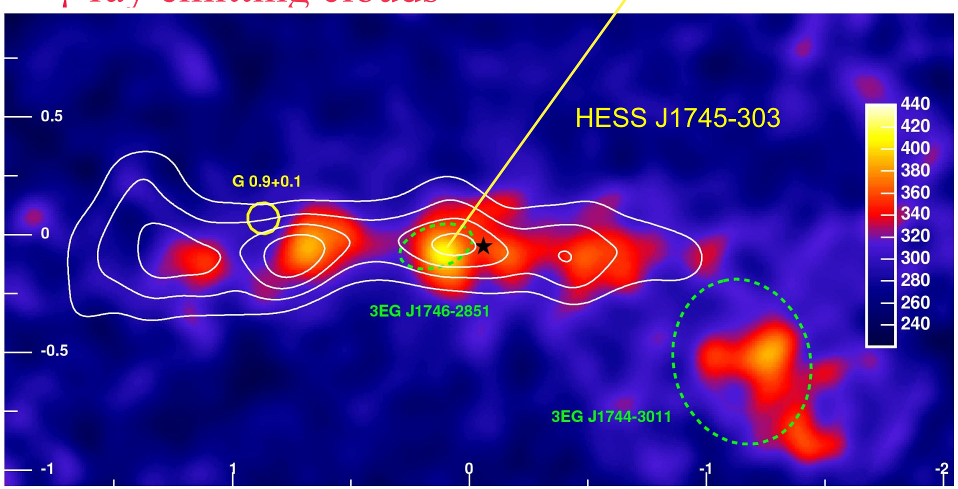
Galactic Center

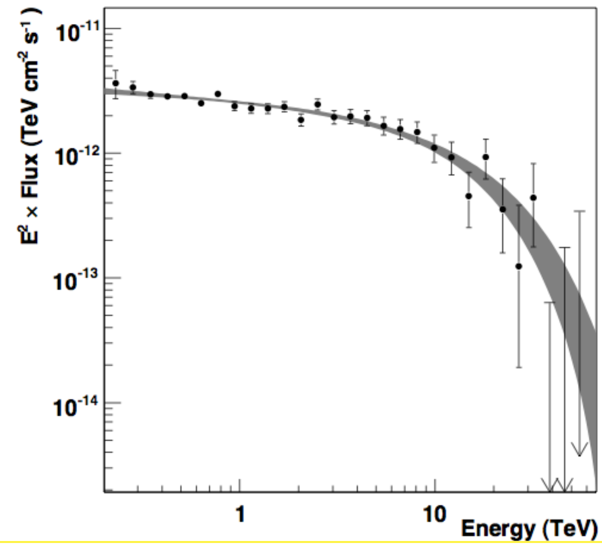
90 cm VLA radio image



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

γ-ray emitting clouds





Energy spectrum:

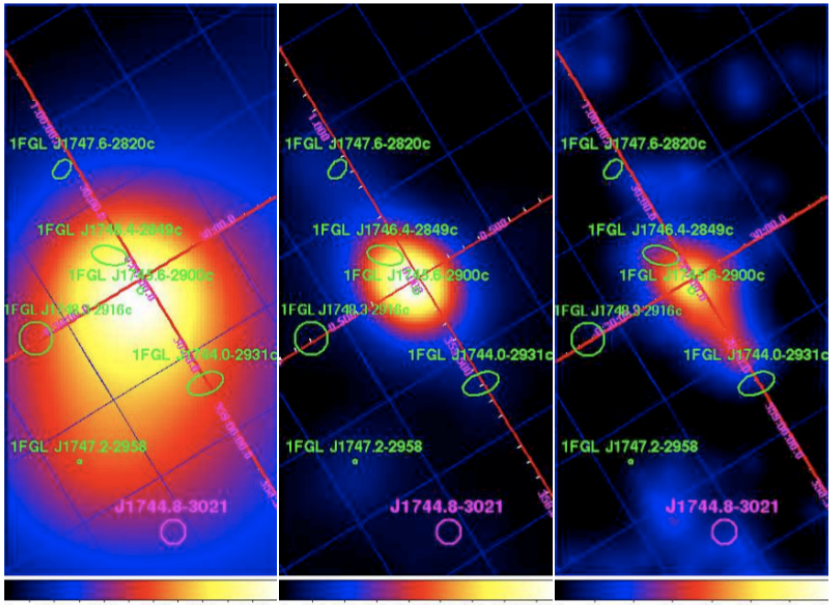
$dN/dE = AE^{-\Gamma} \exp[(-E/E_{0)})^{\beta}]$

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?

Galactic Center at high energies

0.3-3 GeV 3-30 GeV 30-300 GeV



$L_p \approx 10^{39}$ erg/s

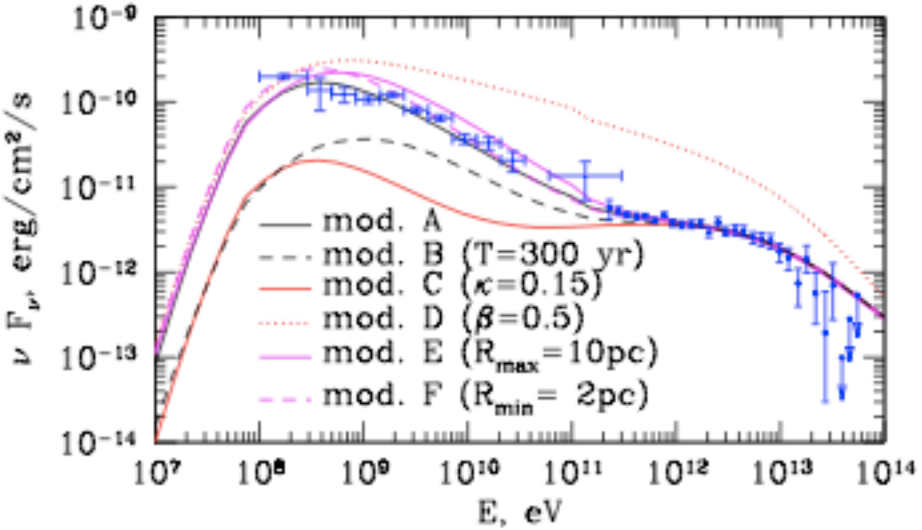
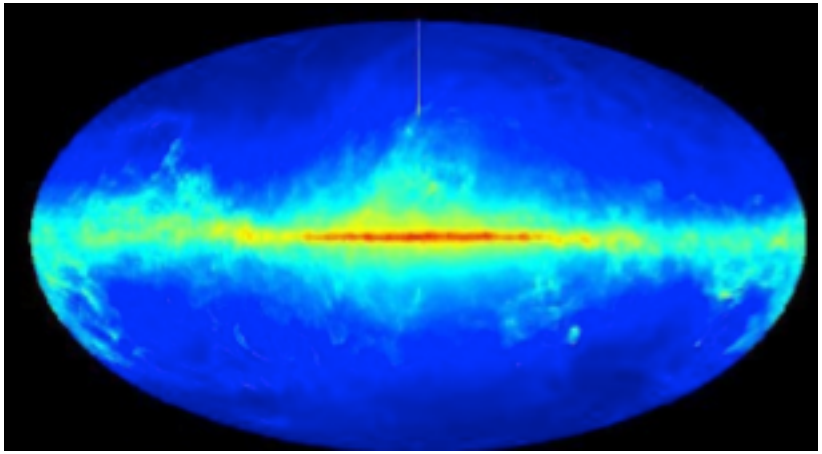
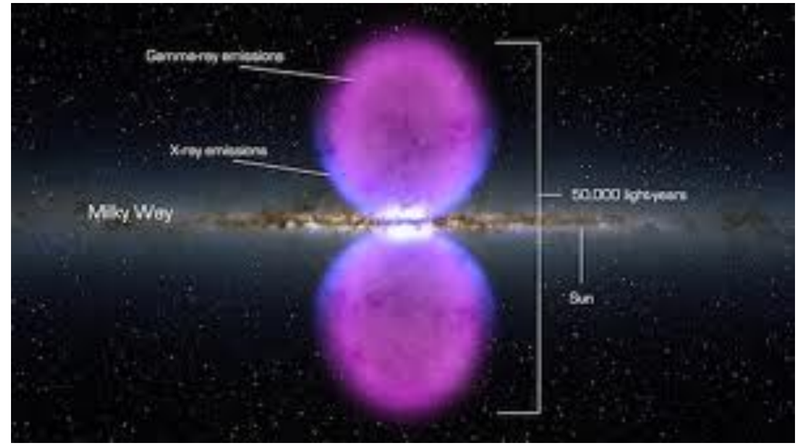


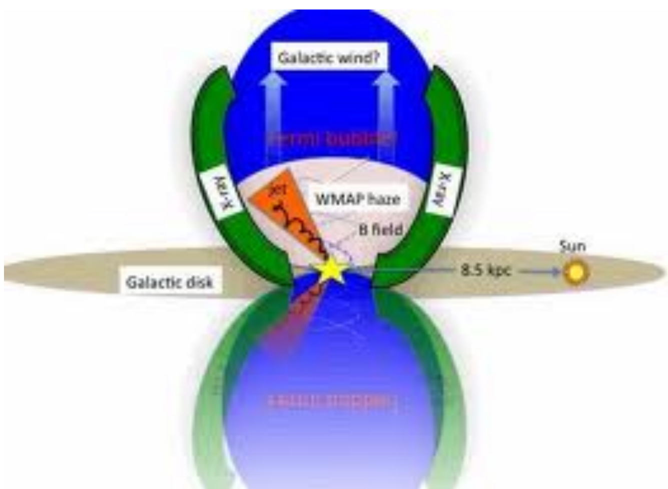
FIG. 5.— Spectral energy distribution of gamma-rays expected from a region filled with relativistic and non-relativistic protons within different assumptions concerning the injection, diffusion and the region geometry (see text for a discussion of parameters for each specific model). The data points have been derived from the Fermi and HESS data

Chernyakova et al 2010

Fermi Bubbles !







Finkbeiner and collaborators 2010

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

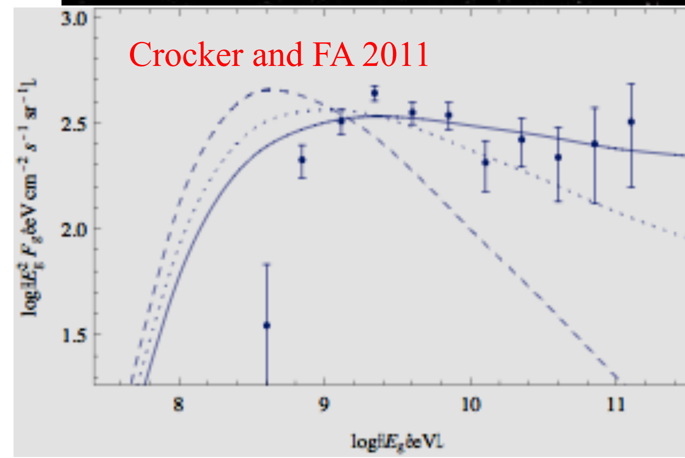
Size - because of slow diffusion in turbulent environment (10 times slower than in the Galactic Disk)

plasma density: $n \sim 0.01\ cm^{-3}$ timescale: $t_{pp} \sim 5$ Gyr $< t_{Galaxy}$

saturation (calorimetric) regime can explains:

generally homogeneous distribution of gamma-rays (local γ-ray production rate does not depend on density), unless possible gradients in the CR spatial distribution, e.g. due to propagation effects ; if the sharp edges tentatively found in the Fermi images is a real effect, they can be naturally explained by higher turbulence introduced by shocks => slower diffusion => accumulation of CRs close to the edges

modest requirements to CR rate : $L_p \sim 10^{39}$ erg/s



Fermi Bubbles as a ν-source ?
if γ-ray spectrum extends to 100 TeV, Km3NeT should be able to detect neutrinos

are FBs sites (reservoirs or accelerators) of Pe CRs? The answer can can be provided by γ-ray observation at multi-Tev energies, and CTA is the best hope!

Fermi Bubbles - alternative explanation:

IC scattering of electrons:

age: 10^7 yr, electron inj. rate 10^{38-39} erg/s

Problem: how transport E >1 TeV electrons to distances 10 kpc - in situ acceleration?

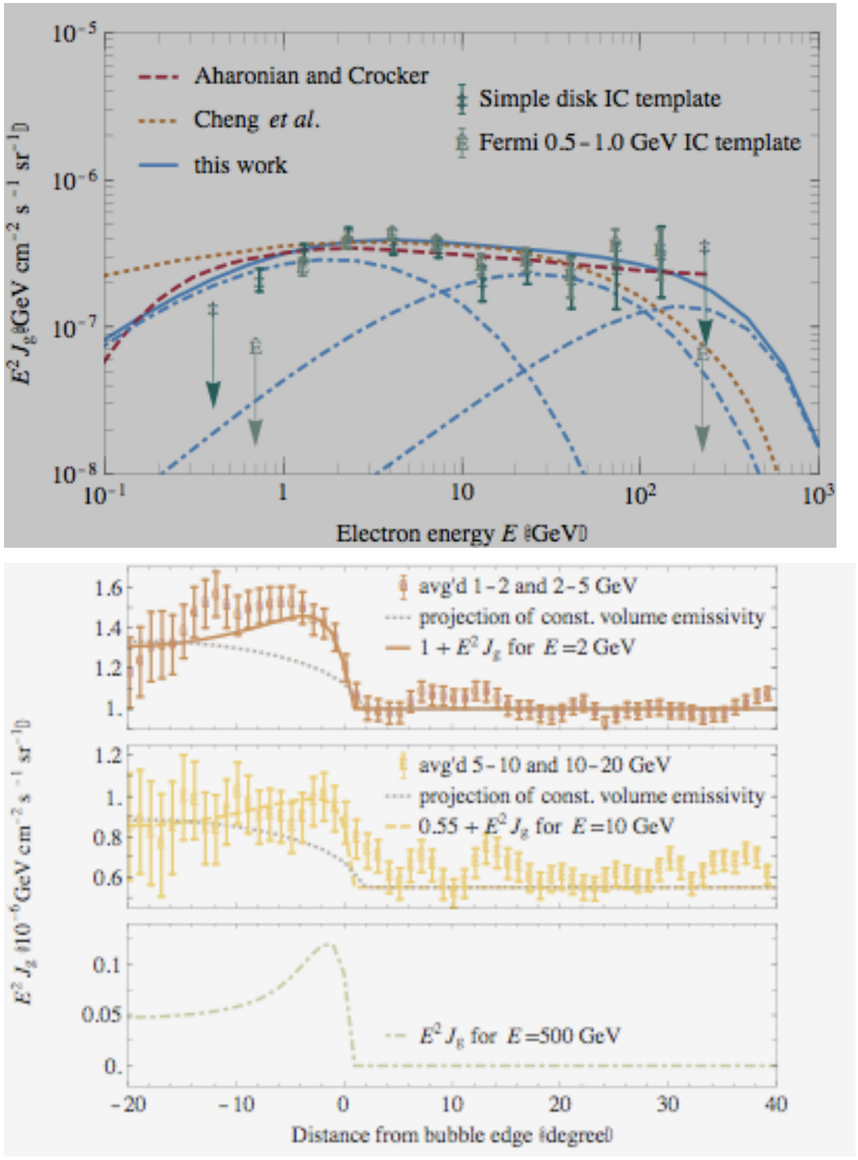
stochastic (2nd order Fermi) most viable option (Mertsch& Sarkar 2011)

shock fronts at Bubble edges (ROSAT) => higher turbulence - concentration of electrons close to the edges => sharp γ-ray edges

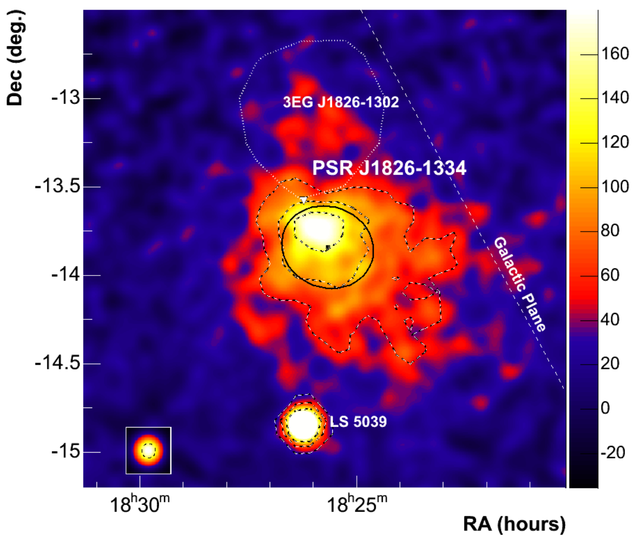
narrow electron distribution+limited E_{max}~1TeV only 2.7K MBR as a target cannot for IC explain the 1-100 GeV γ-radiation: galactic FIR/O target field helps to explain the average 1-100 GeV E^{-2} type flat gamma-ray spectrum

distinct feature of the model - much steeper energy spectra of gamma-rays at large heights compared to region close to the galactic plain.

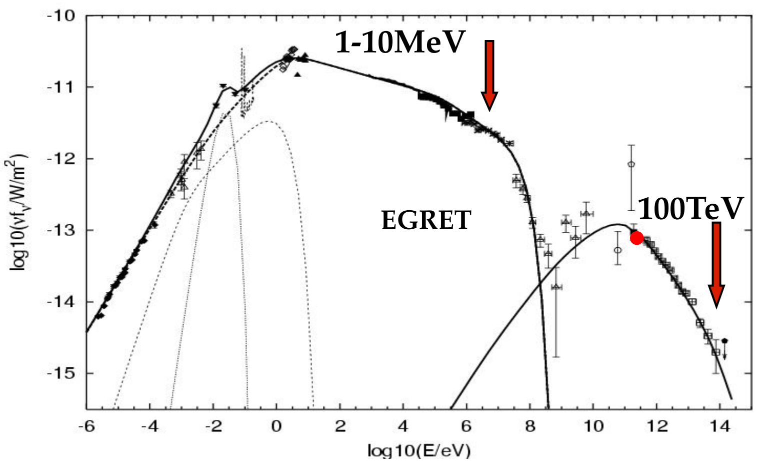
can be checked very soon …



Pulsar Wind Nebulae:
electron PeVatrons



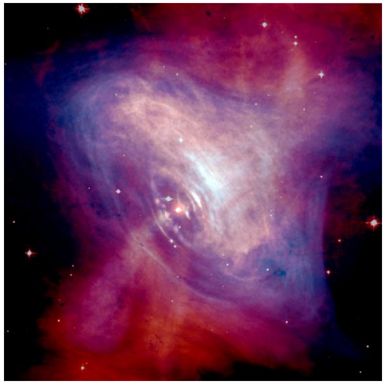
Crab Nebula – *a perfect electron PeVatron*



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

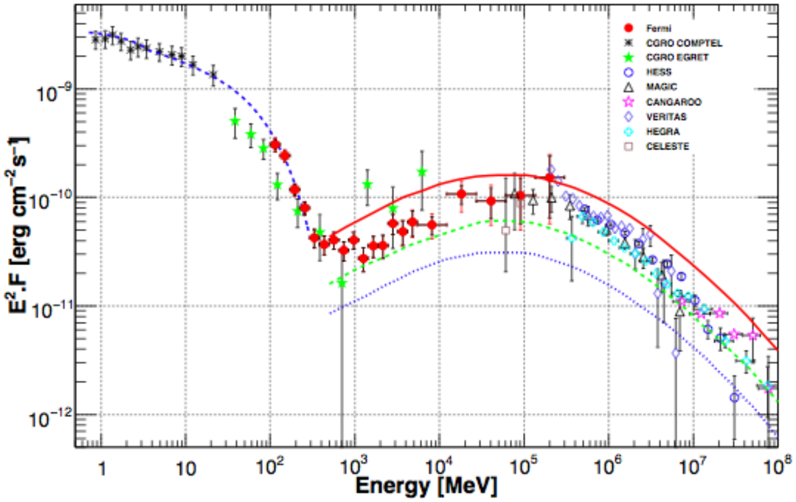


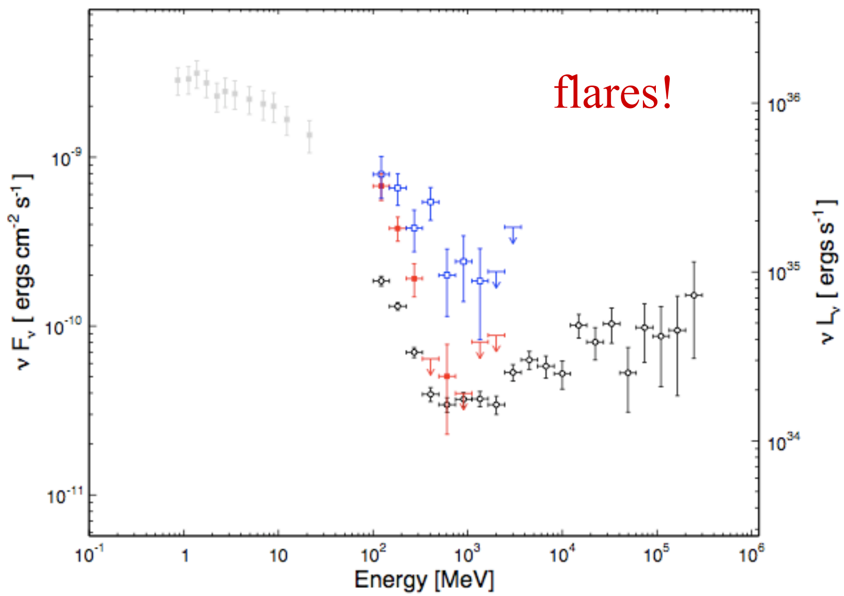
Crab Nebula – a powerful $L_e=1/5L_{rot} \sim 10^{38}$ erg/s
and extreme accelerator: Ee >> 100 TeV

$E_{max}=60\ (B/1G)^{-1/2}\ \eta^{-1/2}$ 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 => $\eta \sim 1$?

Crab Nebula - news from AGILEE and Fermi LAT :





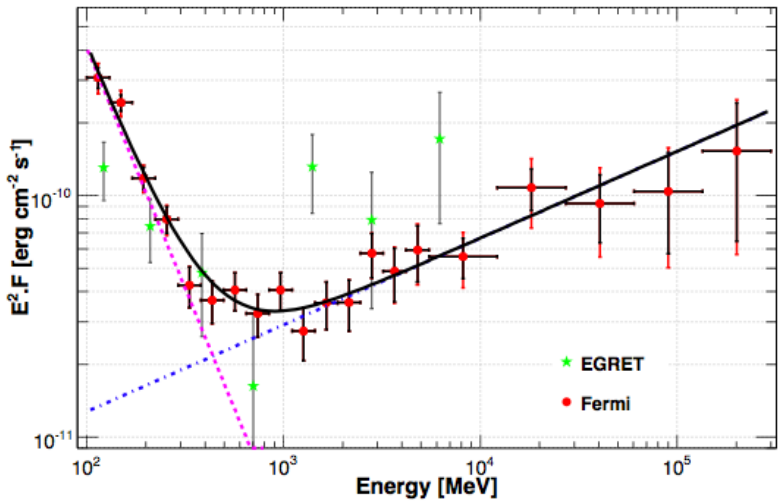
IC emission consistent with average nebular B-field: B ~ 100μG-150μG

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 - news from AGILEE and Fermi LAT :



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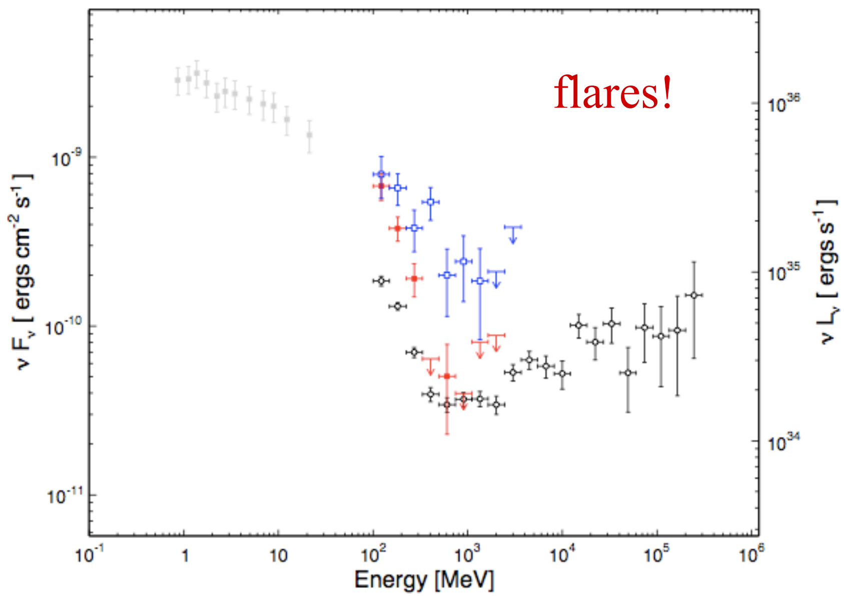

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<u>observations of 100TeV gamma-rays</u> - IC photons produced by electrons responsible for synchrotron flares - a key towards understanding of nature of MeV/GeV flares

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

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

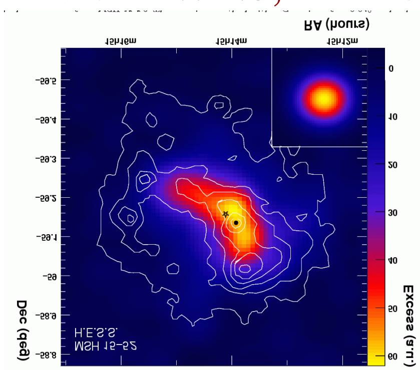
we do see TeV γ-rays from the Crab Nebula because of very large spin-down flux: $f_{rot}=L_{rot}/4\pi d^2=3x10^{-7}$ erg/cm^2 s

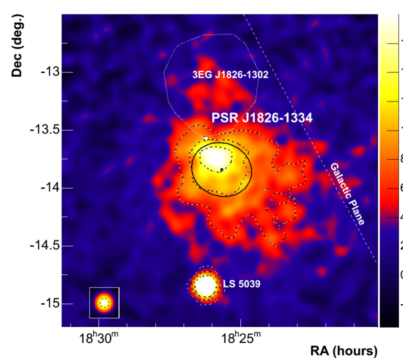
gamma-ray flux << "spin-down flux" *because of large B-field*

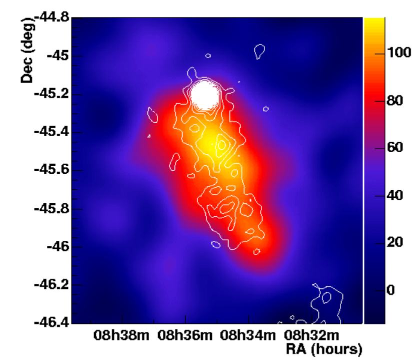
if the B-field is small (environments with small external gas presure)

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, ...



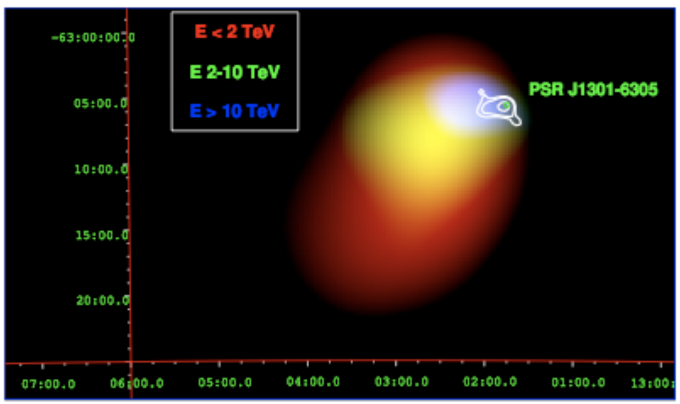




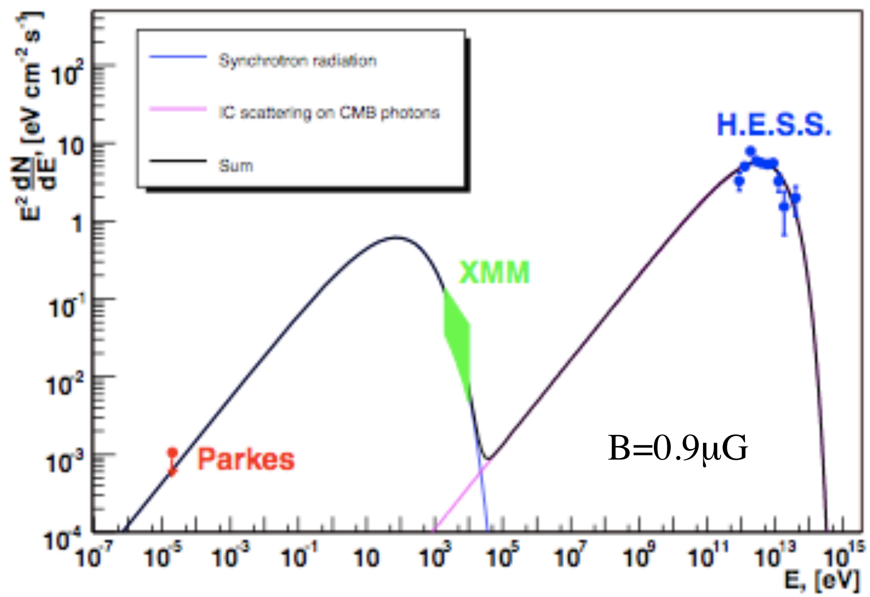
PWNe - *perfect electron accelerators and perfect γ-ray emitters!*

(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?



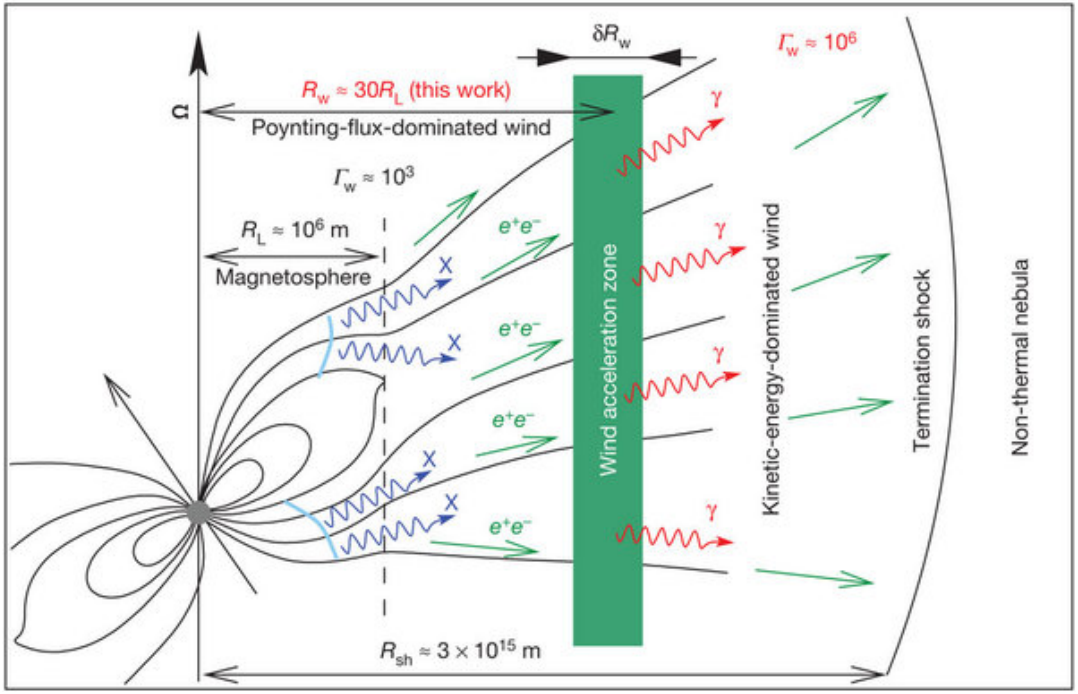
dramatic reduction of the angular size with energy:strong argument in favor of the IC origin of the γ-ray nebula



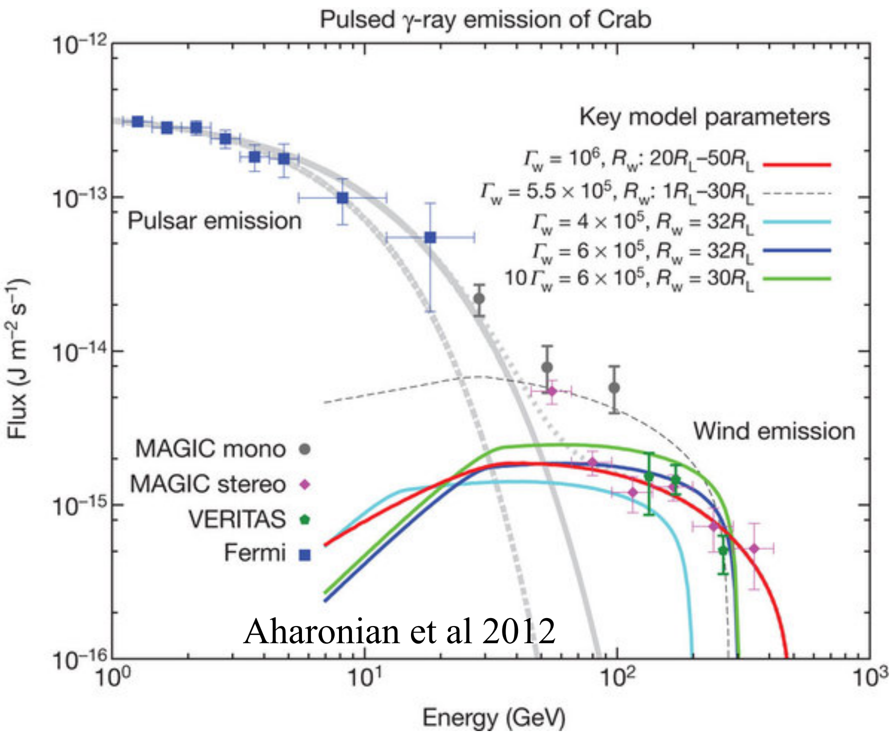
very small average B-field; for d=12.6kpc
$L_\gamma/L_{SD} = 0.07$; 3arcmin ~ 10 pc

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

pulsar–wind–nebula paradigm



Pulsed component extends to VHE energies!



where pulsed VHE signal is produced:

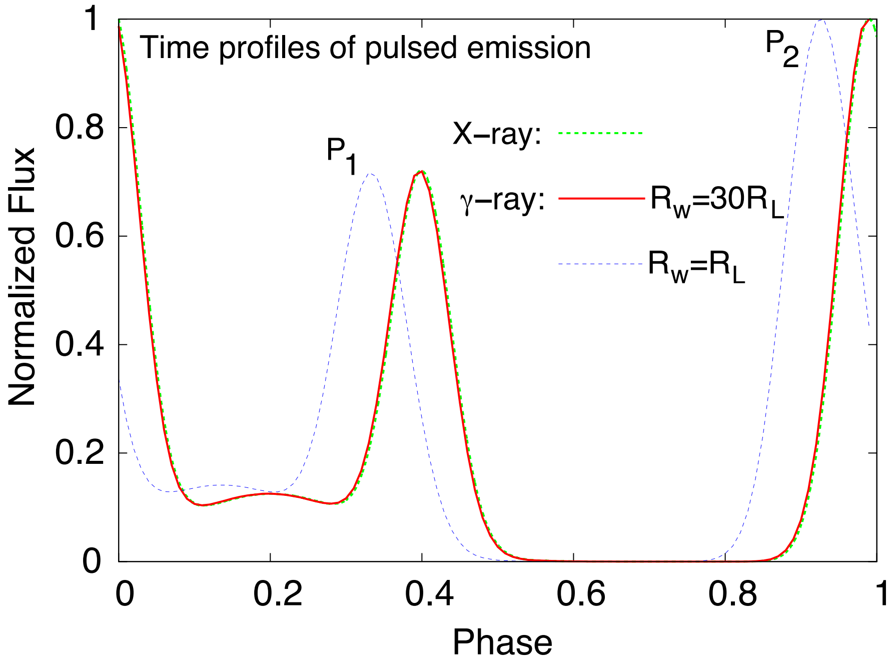
in the magnetosphere
or in the pulsar wind?

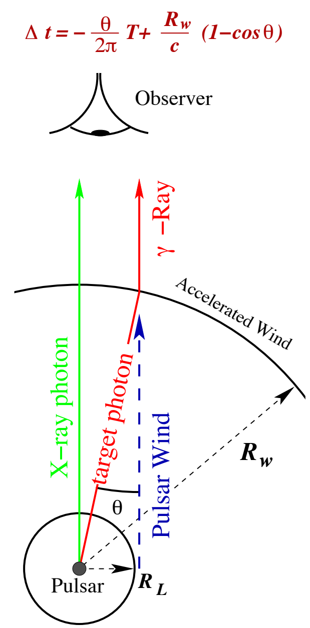
very low fluxes – for adequate spectrometry and lightcurve – we need more sensitive instruments between 10 GeV and 1000 GeV

if the VHE gamma-ray emission is due to the "cold" wind

- ✓ wind is accelerated at R~ $30R_L$ to bulk motion Lorentz factor Γ~0.5-1 x 10^6
- ✓ no need to revise dramatically the magnetospheric models of GeV emission

time structure of the periodic signal





TeV pulsed emission mimics the lightcurve of soft X-rays:

at $R_w >> R_L$, $\Delta t \approx T/4\pi\ (R_L/R_w)$, for $R_w=30R_L$, $\Delta t \sim 0.003T$

binary systems - unique high energy laboratories

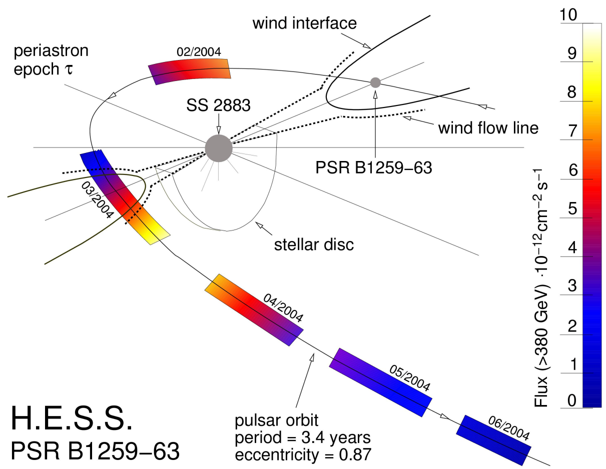
binary pulsars - a special case with strong effects associated with the optical star on both the dynamics of the pulsar wind and and the radiation before and after its termination

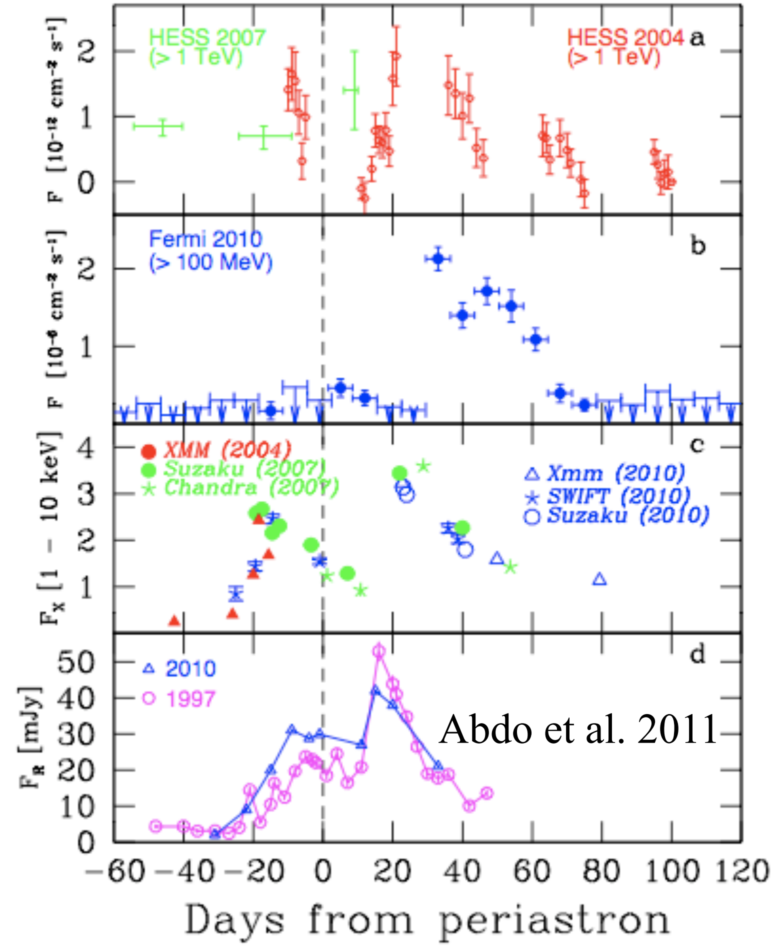
the same 3 components - *Pulsar/Pulsar Wind/Synch.Nebula* - as in PWNe both the electrons of the cold wind and shocke-accelerated electrons are illuminated by optical radiation from the companion star detectable IC γ-rays

"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;

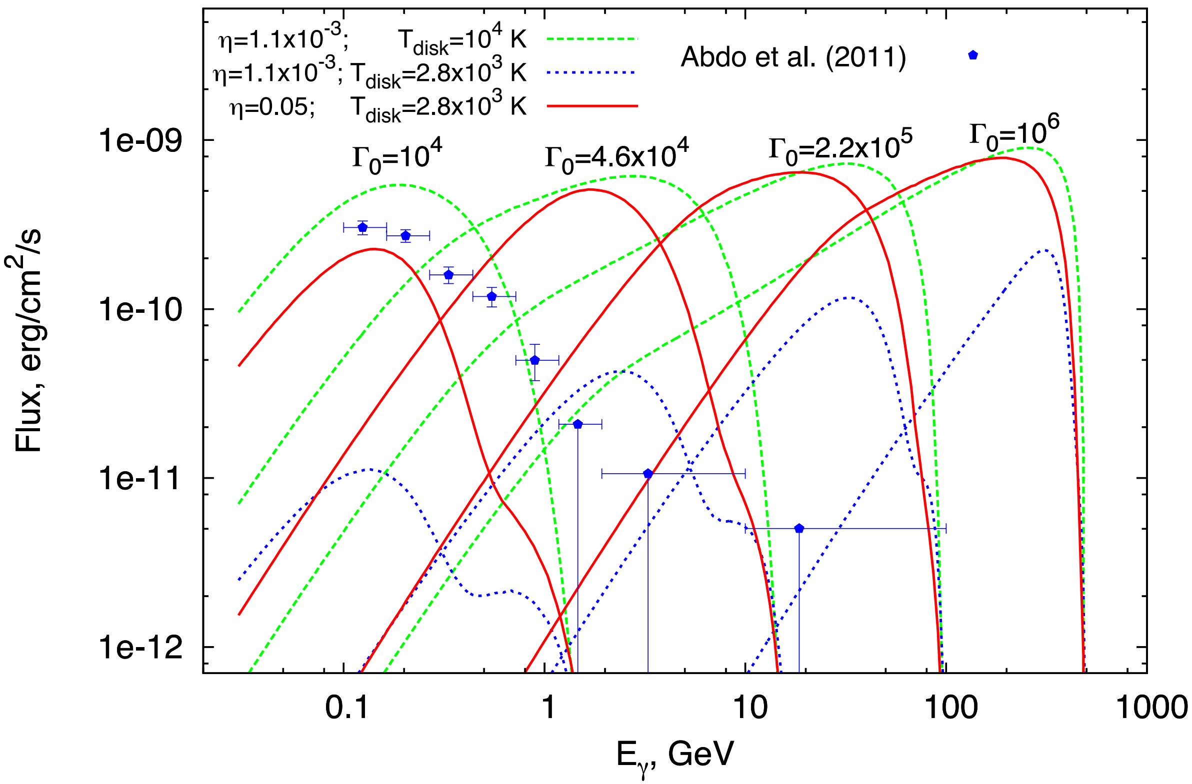
Several possible explanations, but many things uncertain and confusing.

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)

GeV Flare in PSR1259



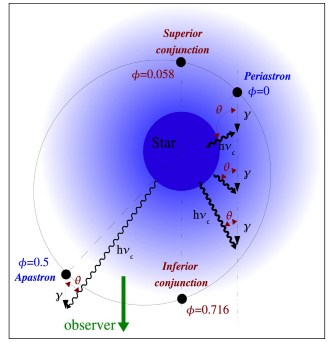
flare – Comptonization of the unshocked wind by IR of the disk just after the exit of the pulsar from the disk => $\Gamma \sim 10^4$

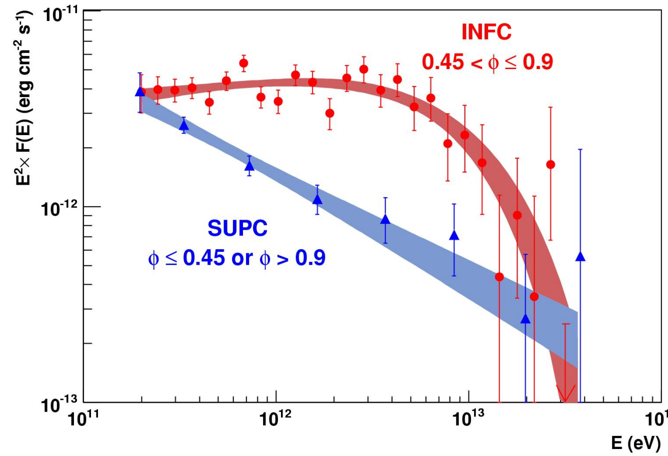
Khangulyan et al 2011

LS 5039

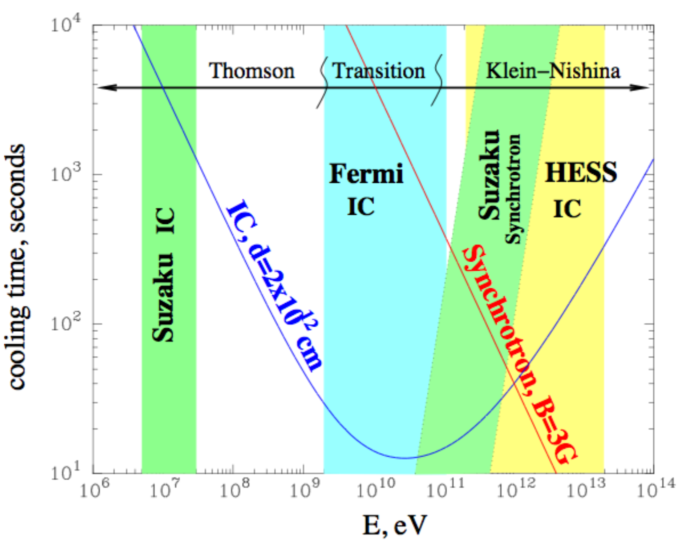
works as a perfect TeV clock
and an extreme accelerator

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



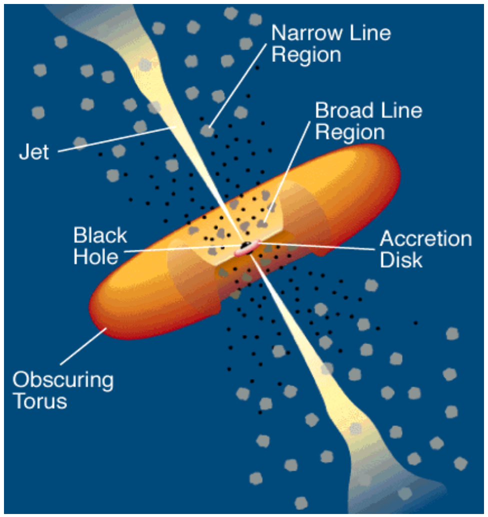


modulation of the gamma-ray signal? *a quite natural reason (because of $\gamma\!-\!\gamma$ absorption), but we see a different picture… anisotropic IC scattering? yes, but perhaps some additional factors (adiabatic losses, modest Doppler boosting) also play a non-negligible role*



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

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



GeV/TeV gamma-ray observations

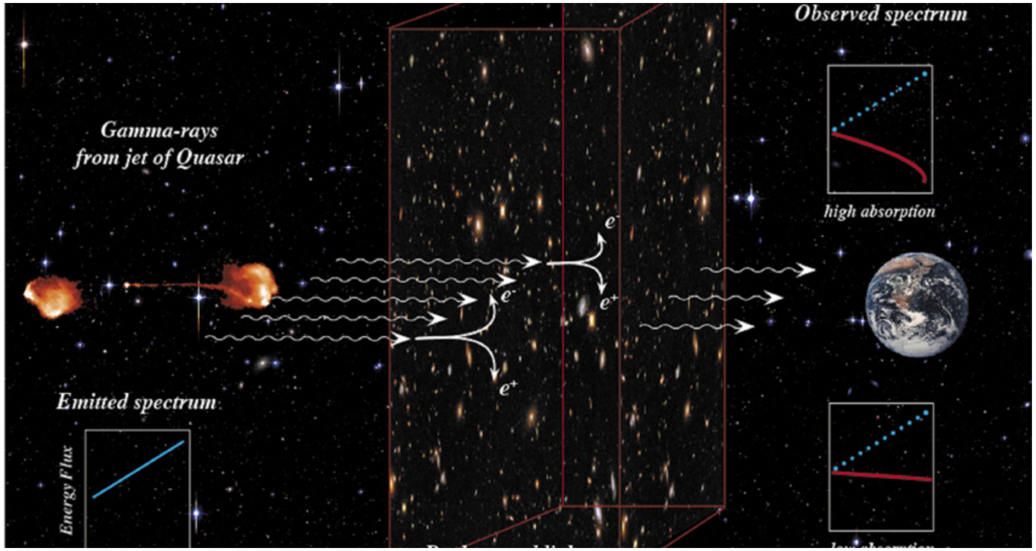
strong impact on

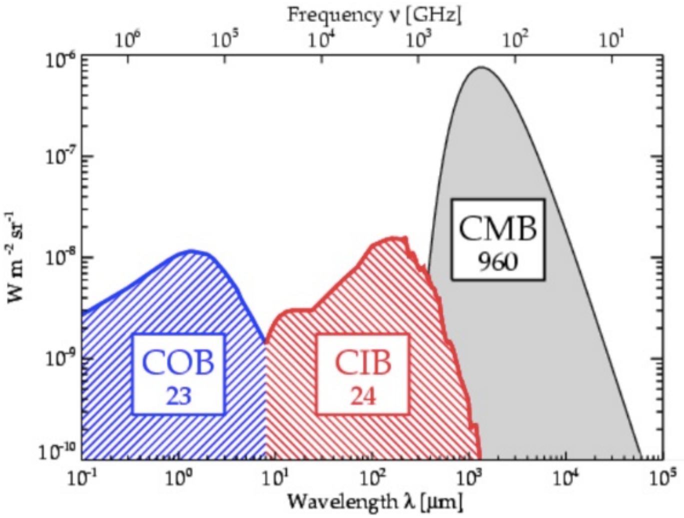
- Blazar physics and astrophysics
- Diffuse Extragalactic Background (EBL)
  Intergalactic Magnetic fields (IGMF)

most exciting results of recent years

- ultra short time variability (on min scales)
- Jet power exceeds Eddington luminosity
- extremely hard energy spectra
- VHE blazars up to z=0.5

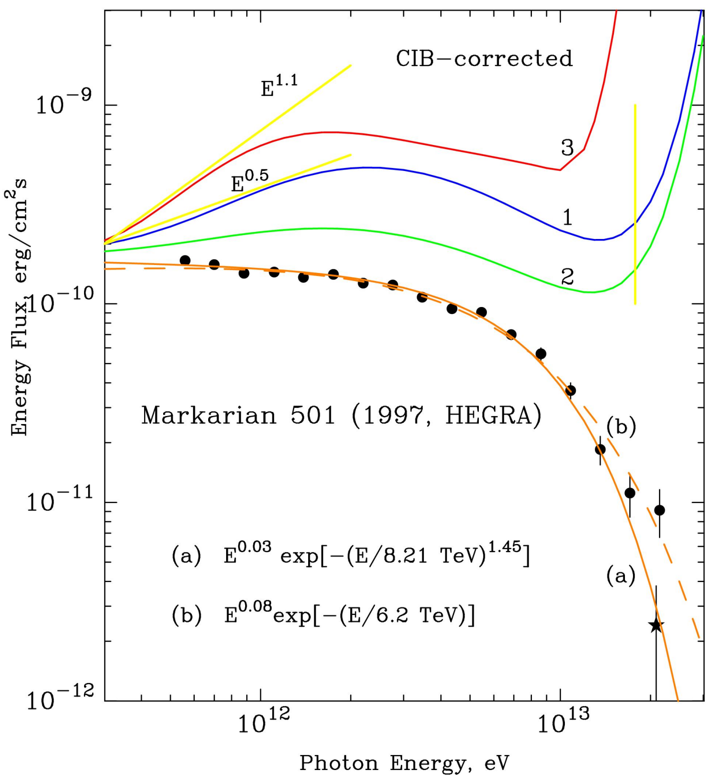
gamma-ray blazars and EBL





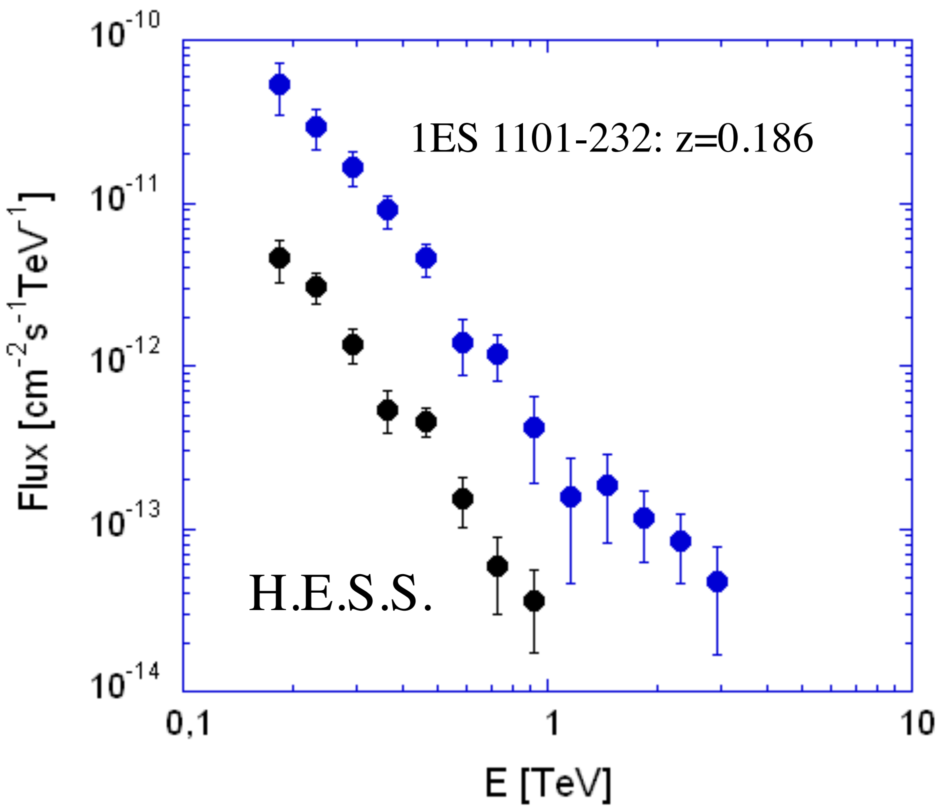
Blazars and EBL

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



reported EBL flux at FIR have not been confirmed

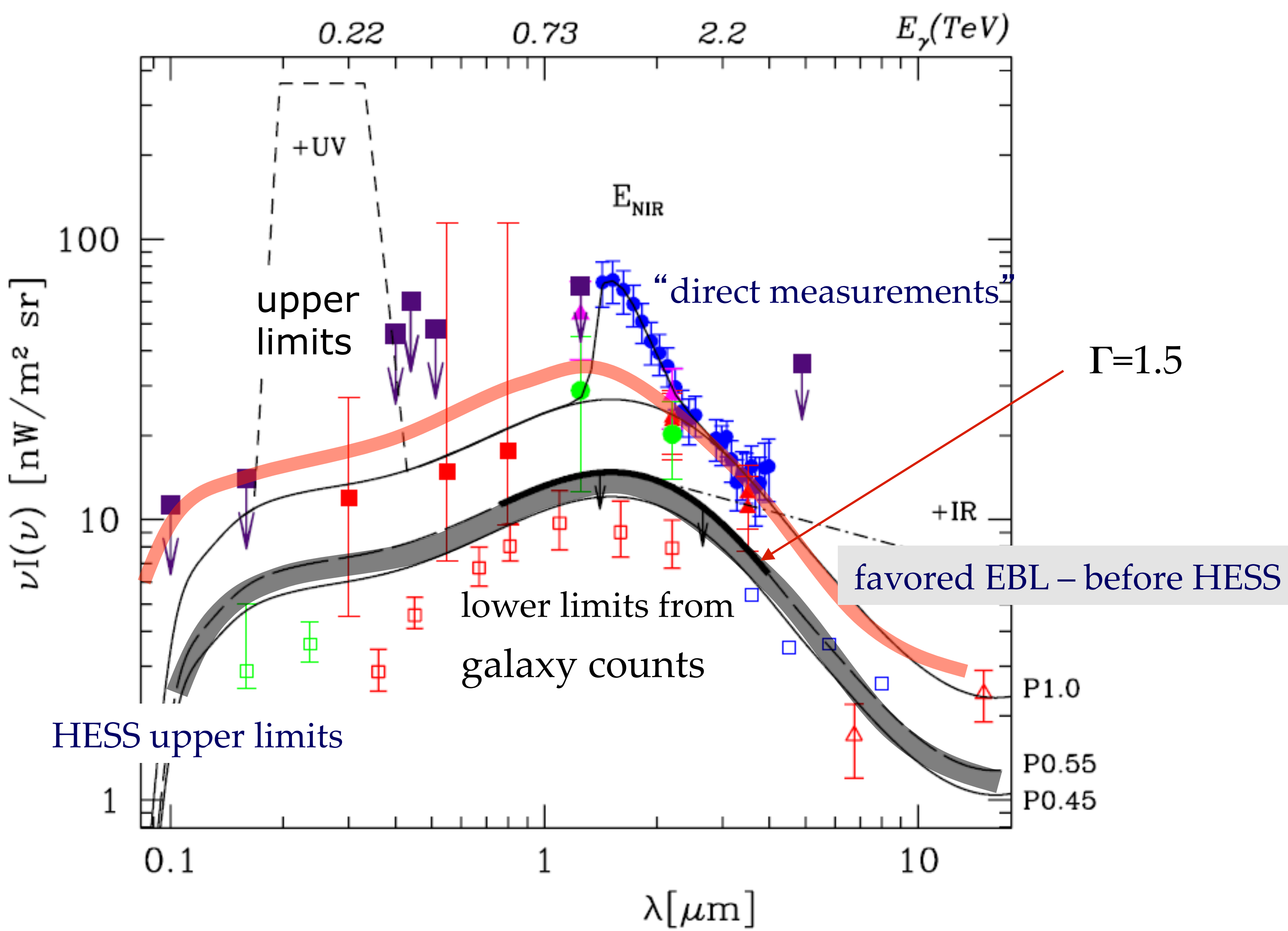
TeV blazars detected by HESS at z> 0.15 !



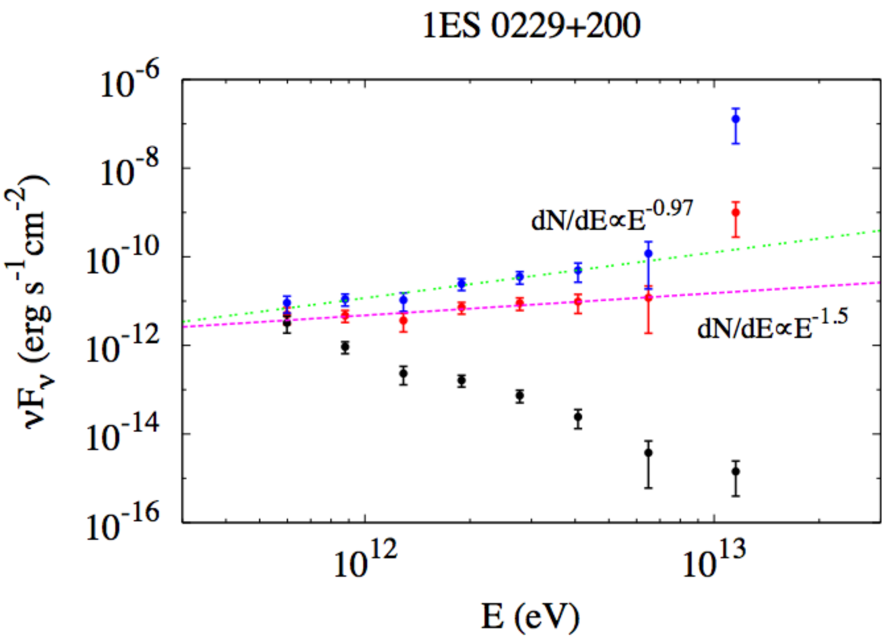
corrected for EBL absorption γ-ray spectrum not harder than $E^{-\Gamma}$ (Γ=1.5) => **u.l. EBL**

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

EBL (almost) resolved at NIR ?



new "trouble-makers"



possible explanations:

✓ very narrow electron distribution - no significant radiative energy losses =>

typically very small B-field: 0.001G

introduce adiabatic losses or assume stochastic (Fermi II type) acceleration with Maxwellian type distribution

✓ internal γ−γ absorption =>

very strong magnetic field, B >10 G

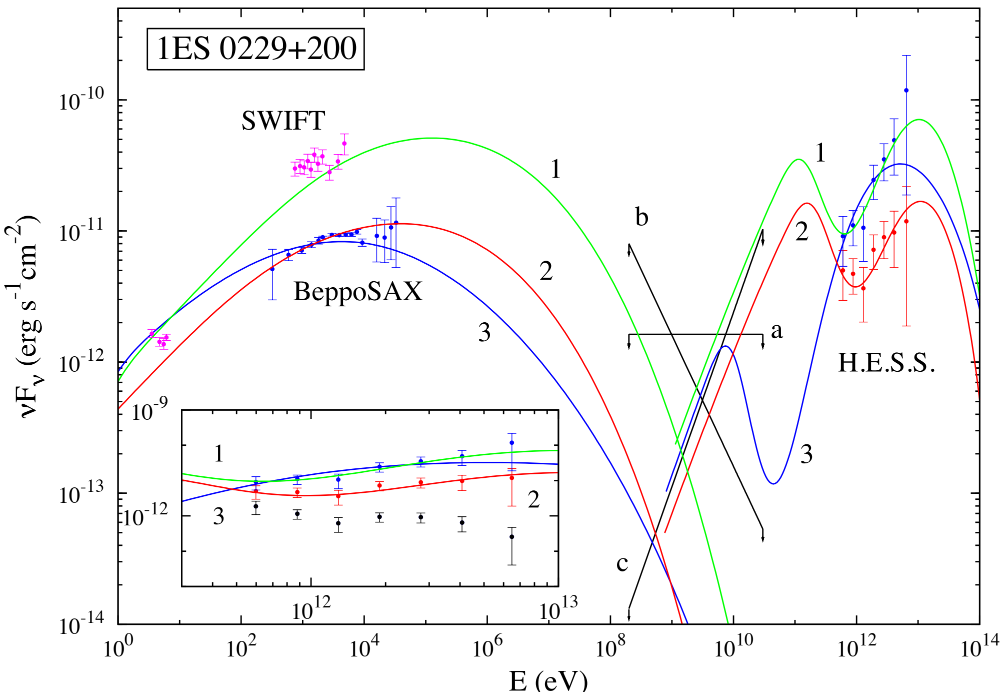
mechanism: proton synchrotron

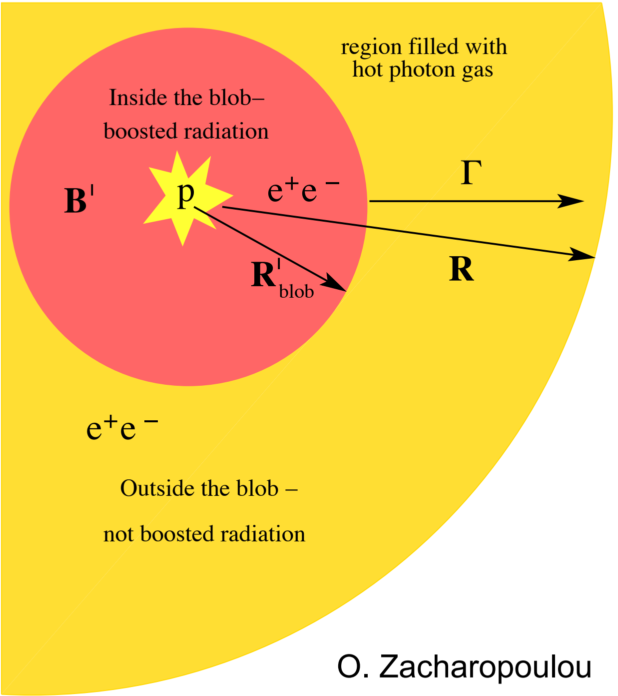
z= 0.14, but spectrum extends to >5 TeV !

even slight deviation from the "standard" EBL

=> extremely hard γ-ray spectra with Γ < 1

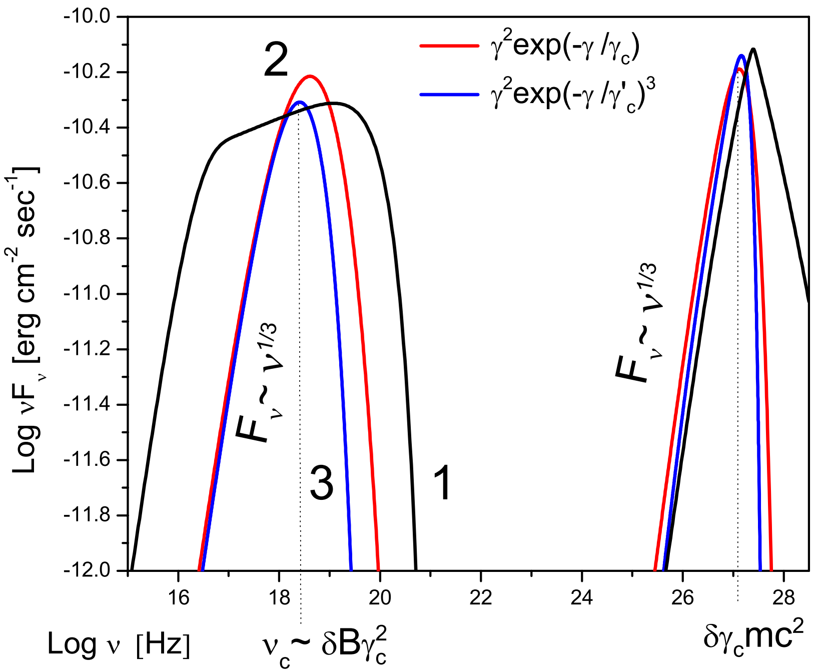
Proton synchrotron and internal γ−γ absorption

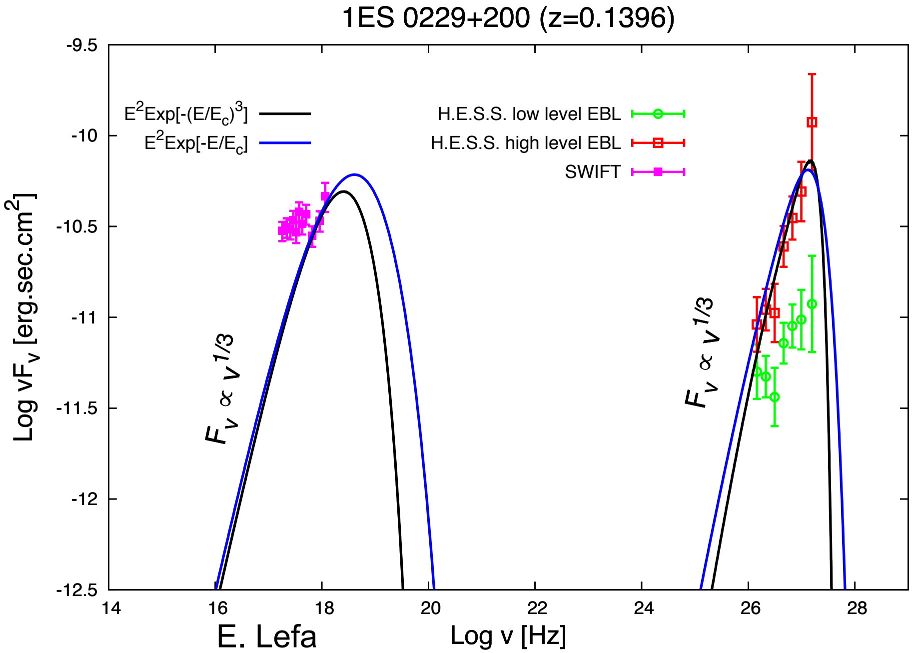




very strong magnetic field: B > 10 G !

Synchrotron Self Compton: narrow distribution of electrons



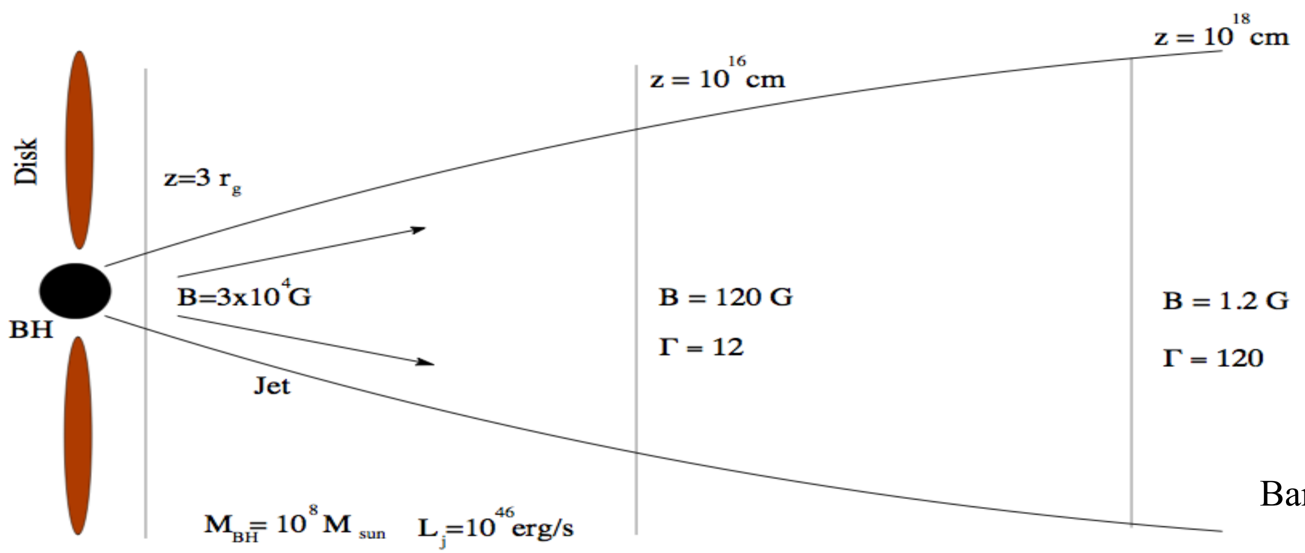


1. γ_{min}=5 10^5; γ_{max}=4$10^7$; B=0.4mG; δ=50
2. γ_c=1.5 10^5; B= 70mG; δ=33
3. γ_c=5.3 10^5; B=0.4mG; δ=33

small or very small B-field!

E.Lefa

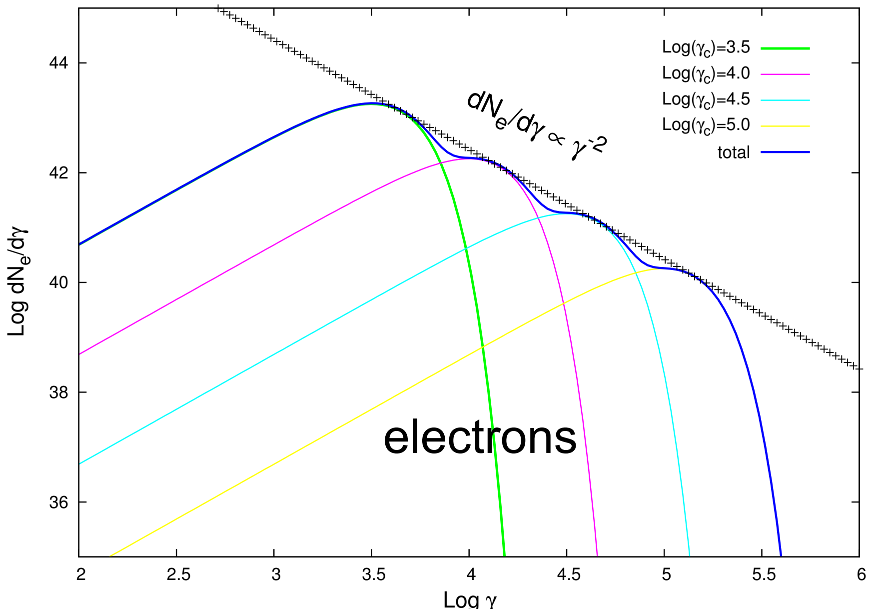
B-field: very large or very small?

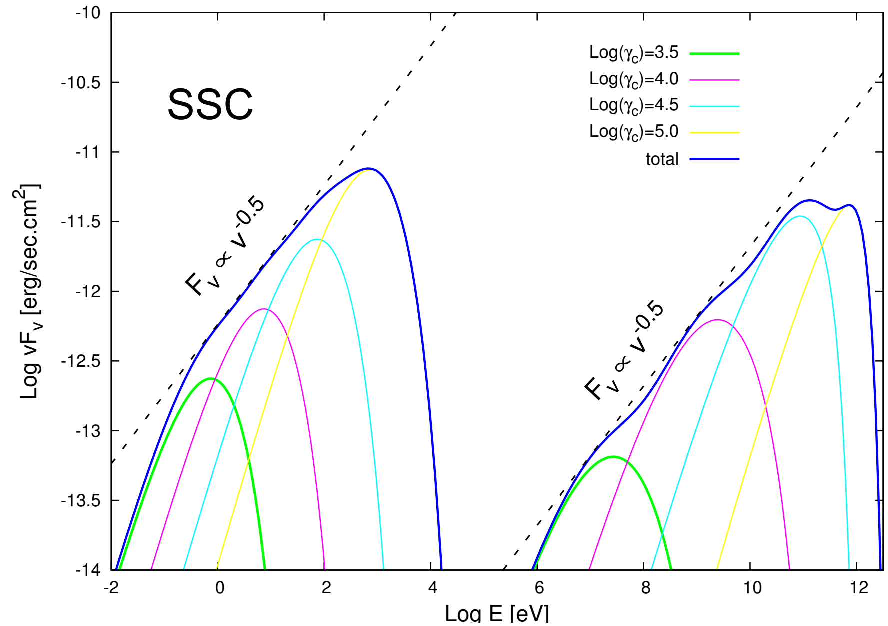


Barkov et al 2010

in powerful blazars at subparsec scales B-field cannot be smaller than 1G, a serious constraint for the simplified one-zone “leptonic models,

multi-zone (multi-blob) concept

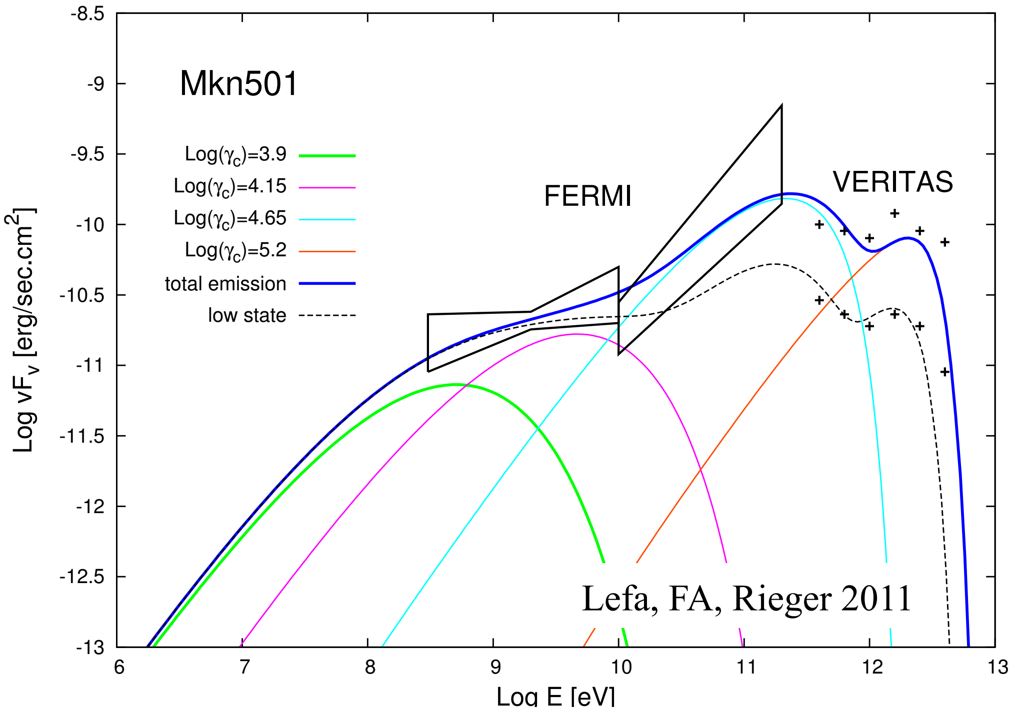




$$\frac{dN}{d\gamma} = A\gamma^2 \exp[-(\gamma/\gamma_0)^2] \qquad \mathrm{E_i} = 2\times 10^{44}\mathrm{erg},\ \mathrm{B} = 0.1\mathrm{G},\ \delta = 30,\ \mathrm{R} = 3\times 10^{14}\mathrm{cm}$$

depending on E_i and γ_{0i} => arbitrary total electron spectrum
for E_i=const, but different γ_0 and i >>1 almost ideal γ^{-2} spectrum

Very hard spectrum of Mkn 5011 during 2009 flare



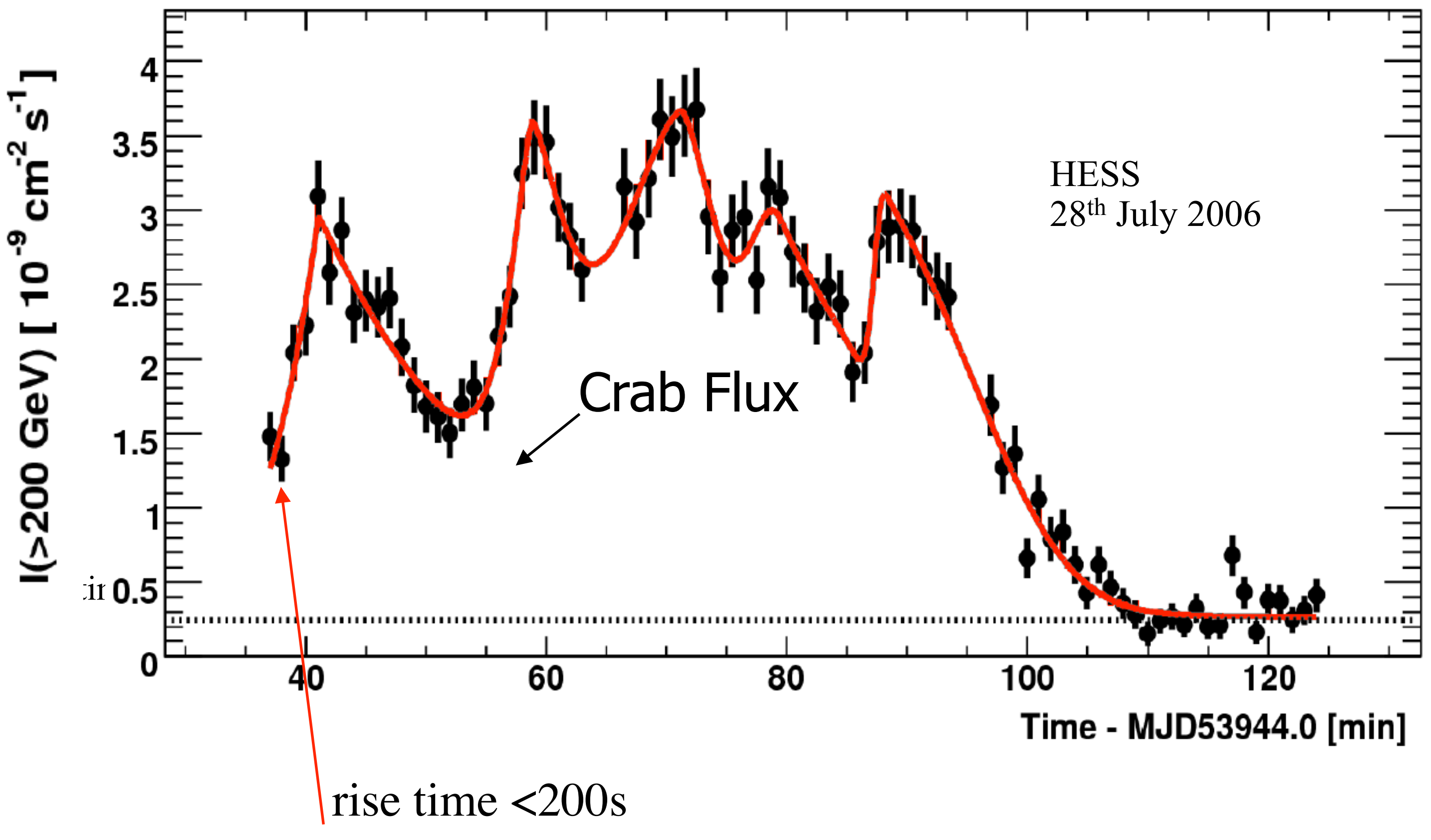
Fermi LAT: flat spectrum in a low state and very hard dN/dE ~E^{-1} type during 2009 flare (Abdo et al. 2010 and Neronov et al 2011)

can be explained by change δ=30 to 40 of two "hottest" blobs; B=0.1G, R=10^{14} cm

we can expect g-ray spectrum of arbitrary form; in flaring state as hard as E^{-1}

conclusions: do not try to get 'smooth' spectral fits, especially in low-states
do not overestimate the potential of "single-zone" models
do not overestimate the potential of γ-rays for derivation of EBL

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



on the Doppler boosting and mass of BH

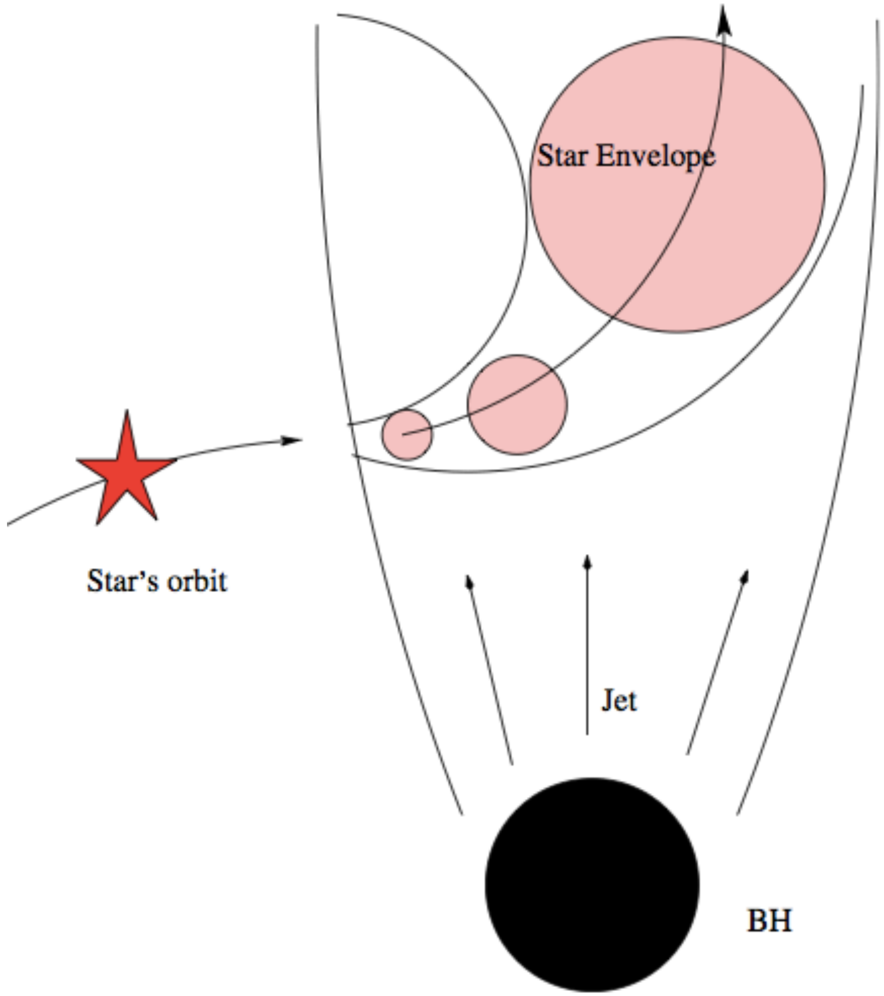
- several min variability timescale => $R = ct_{var}\delta_j \sim 10^{13}\delta_j$ cm for a 10^9Mo BH with $3R_g \sim 10^{15}$ cm => $\delta j > 100$, i.e. close to the accretion disk (the base of the jet), the Lorenz factor of the jet $\Gamma > 50$ - this hardly can be realized close to Rg!

- the (internal) shock scenario: shock would develop at $R = R_g \Gamma^2$, i.e. minimum γ-ray variability would be $R_g/c = 10^4 (M/10^9 Mo)$ sec, although the γ-ray production region is located at $R_g \sim ct_{var}\Gamma^2$ (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 coused 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 ?

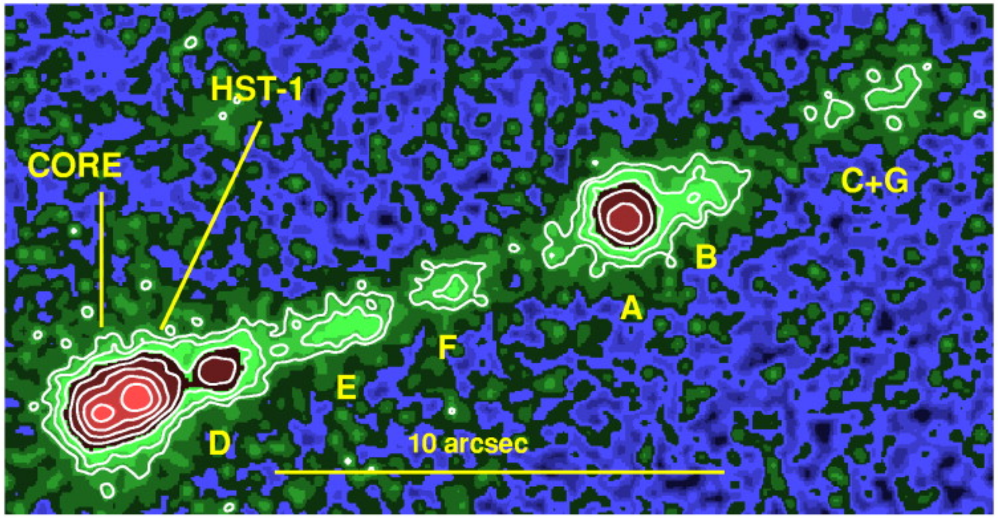
- Distance: ~16 Mpc

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

  => *not a blazar*!

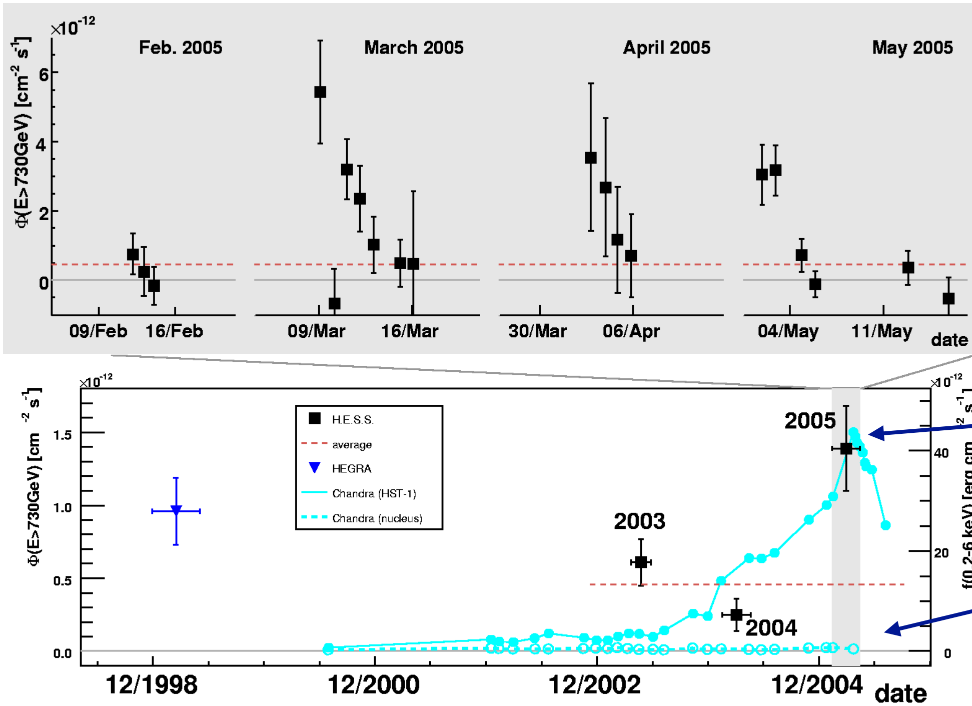
discovery (>4σ) of TeV γ-rays by HEGRA (1998) and confirmed recently by HESS/VERITAS, MAGIC

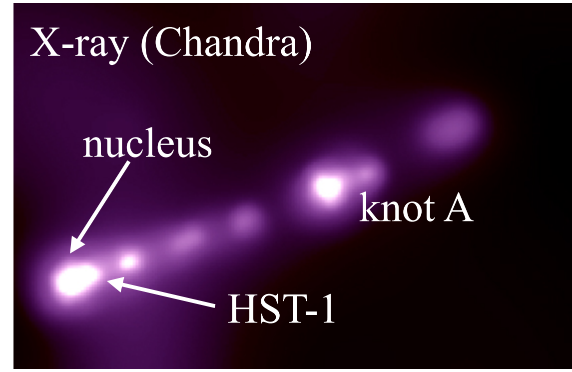
*) recently 6.4 x 10^9 M_o
arXiv: 0906.1492 (2009)



M87: light curve and variabiliy

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





HST-1

core

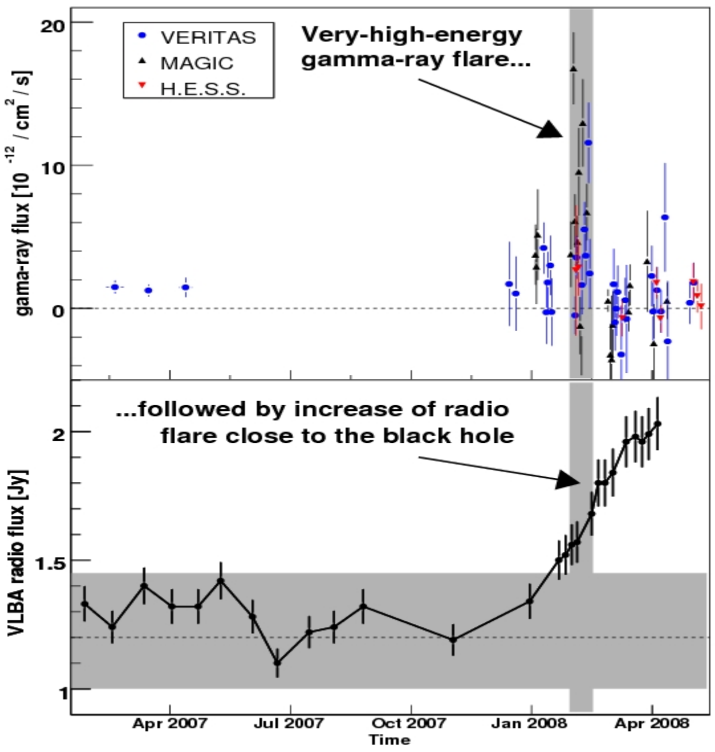
>730 GeV [cm^{-2} s^{-1}]

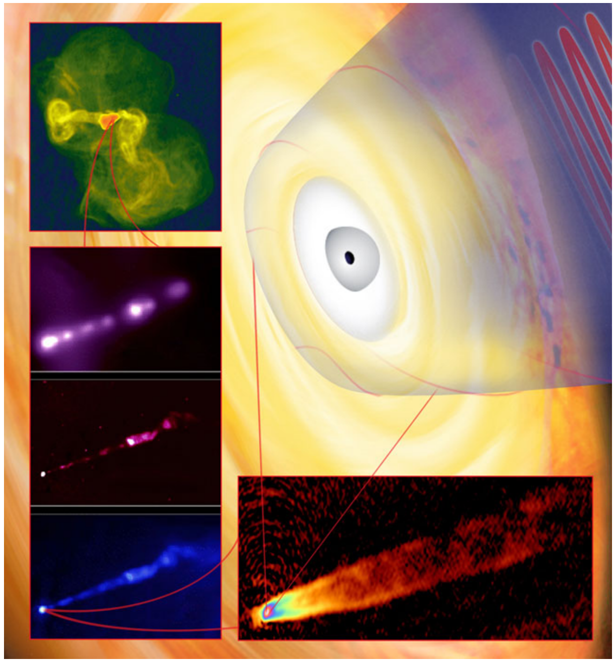
short-term variability on 1-2 day scales => emission region R ~ $5 \times 10^{15} \delta_j$ cm
=> production of gamma-rays very close to the 'event horizon' of BH?

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





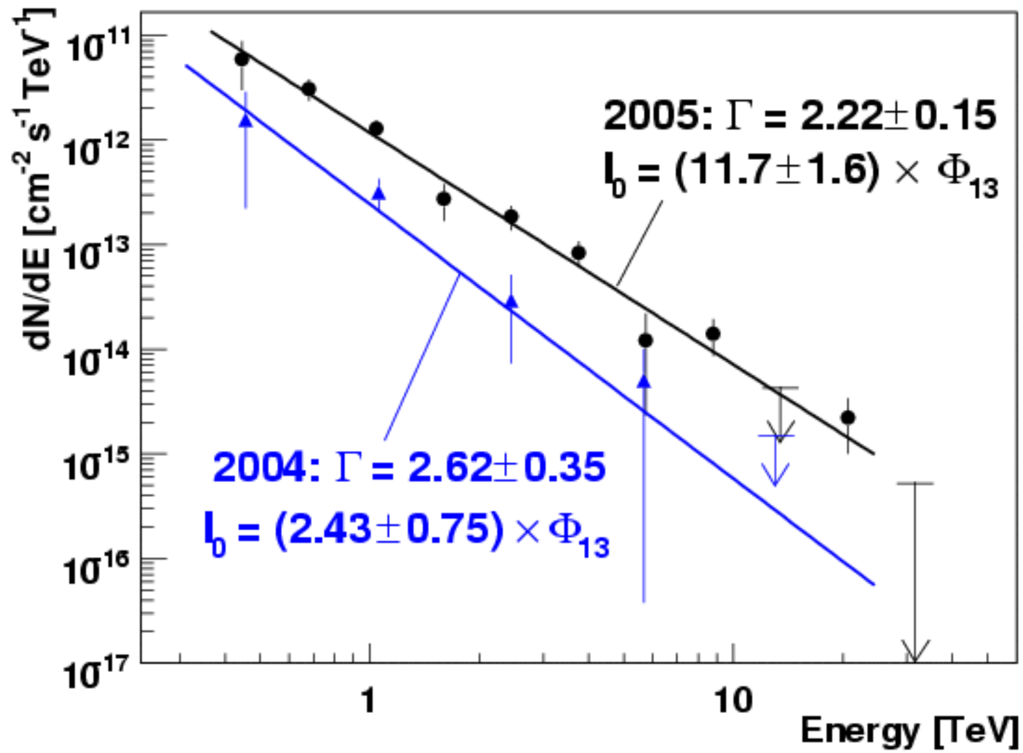
monitoring of the M87 inner jet with VLBA at 43 GHz (ang. res. 0.21x0.43 mas) revealed increase of the radio flux by 30 to 50% correlated wit the increase in TeV gamma-ray flux in Feb 2008

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

energy spectra

energy spectra for 2004 (~5σ)
and 2005 (~10σ)

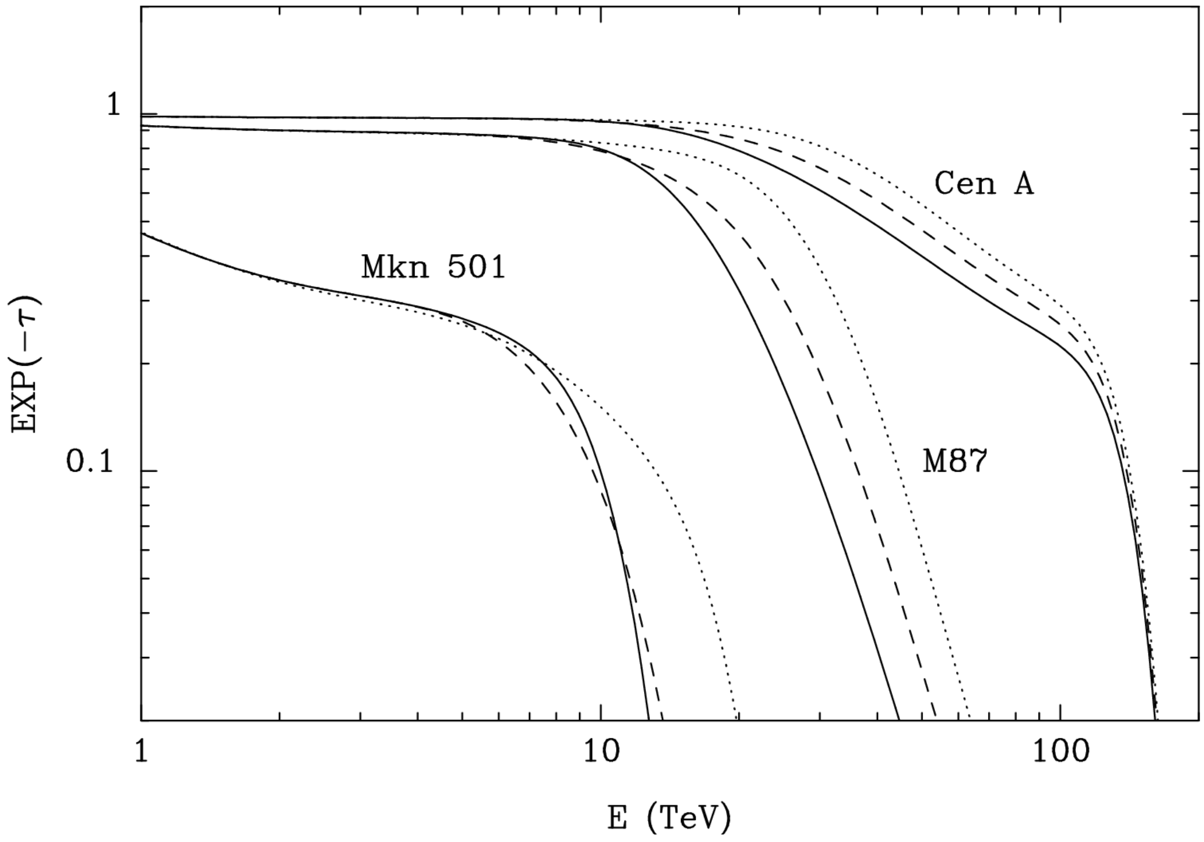
Differential spectra well described by power-laws:



$\Phi_{13} = 10^{-13}$ cm^{-2} s^{-1} TeV^{-1}

2004 vs. 2005:
Photon indices compatible, but different flux levels

Probing DEBRA at MIR /FIR with E_γ > 10 TeV γ-rays from nearby extragalactic sources (d < 100 Mpc)



we need more sensitive detectors up to 100 TeV!

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

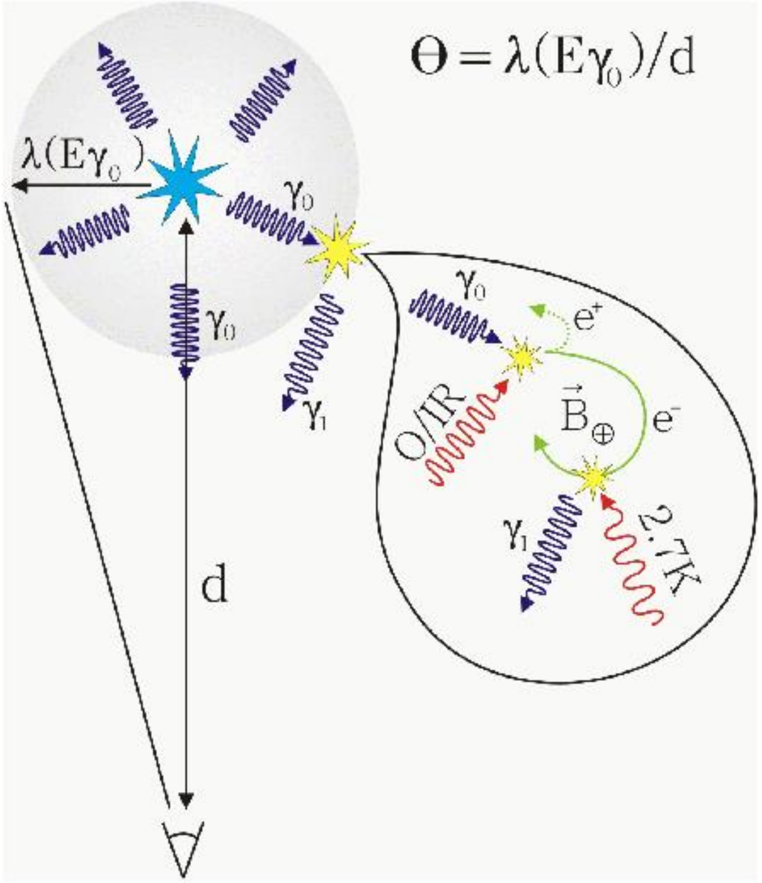
$$\lambda(E_{\gamma,0}) \sim d \times \Theta$$

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, 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 <u>unique</u> !

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

- objects with jets at large angles - <u>many more</u> γ-ray emitting AGN

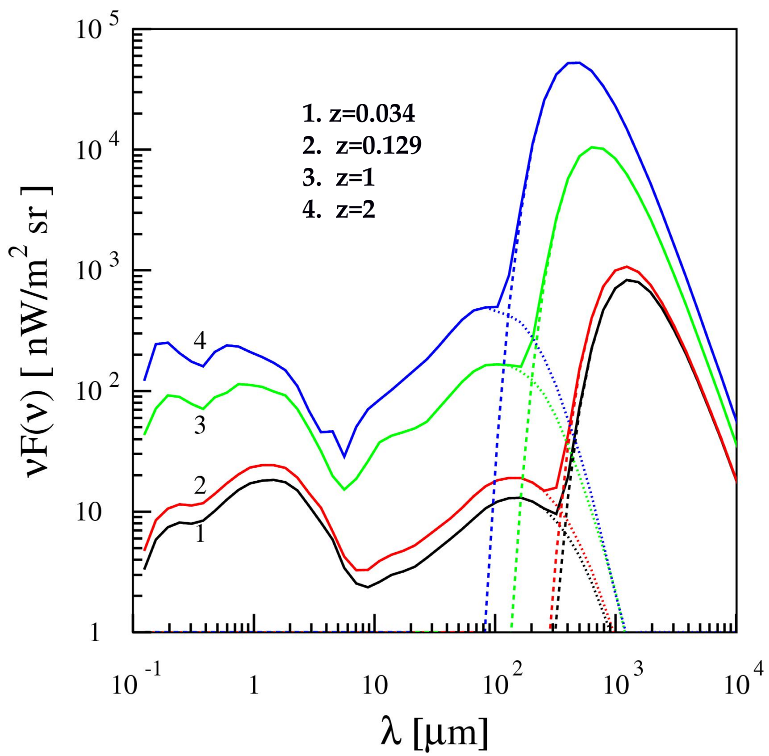
but the advantage of the large Doppler boosting of blazars disapeares: beam => isotropic source

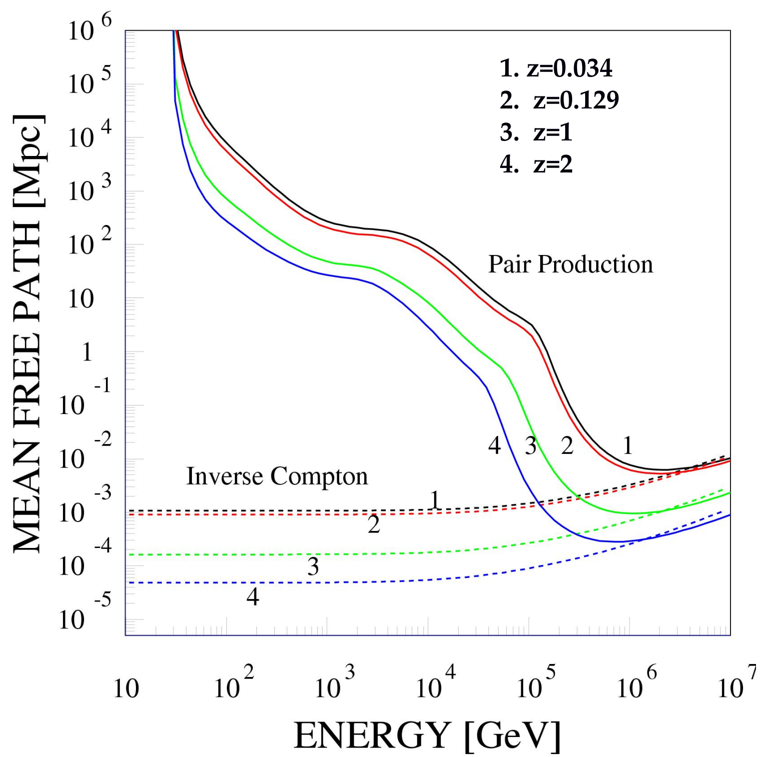
therefore very powerful central objects needed

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

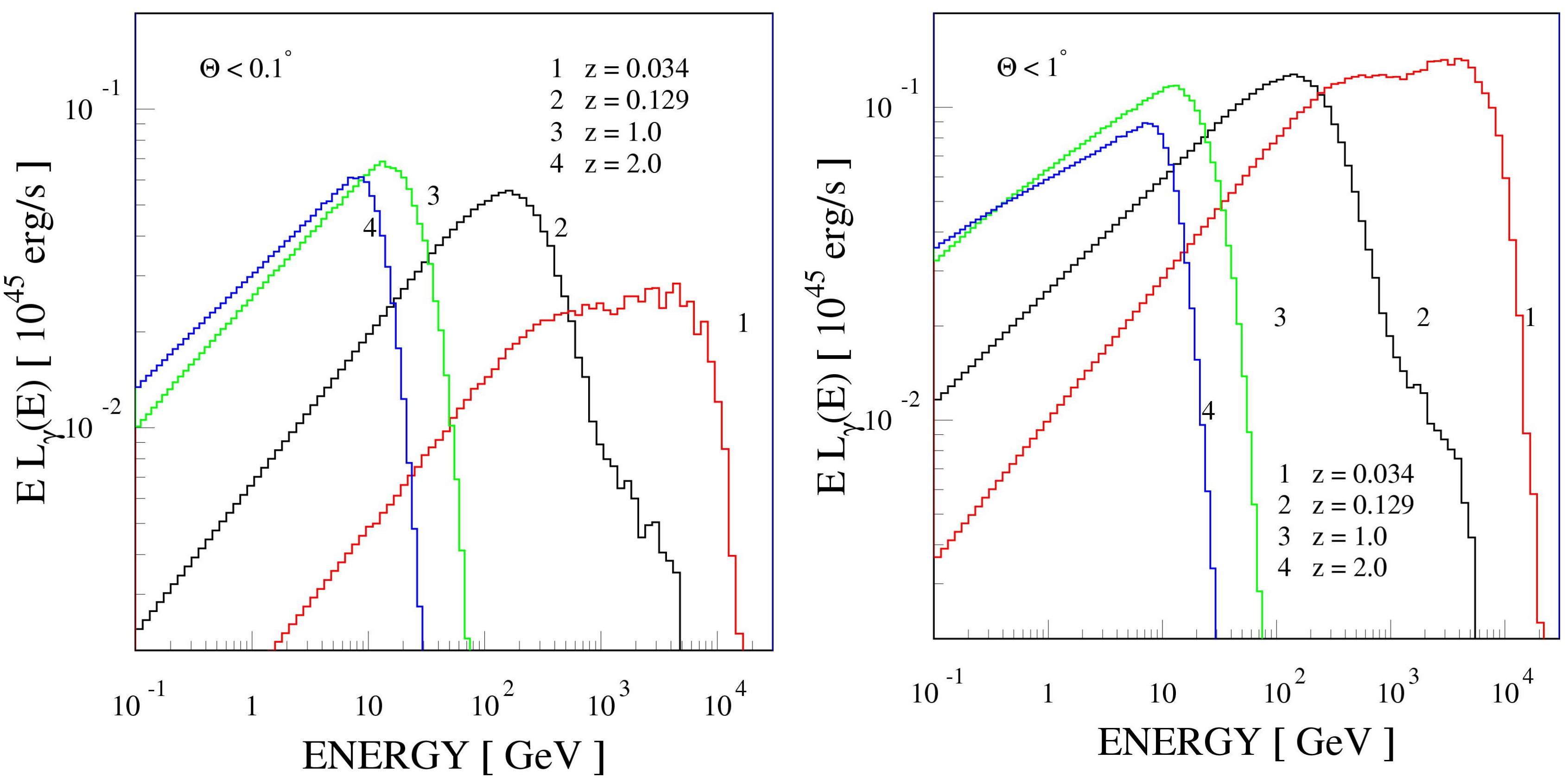
this requires low-energy threshold detectors

EBL at different z and corresponding mean freepaths





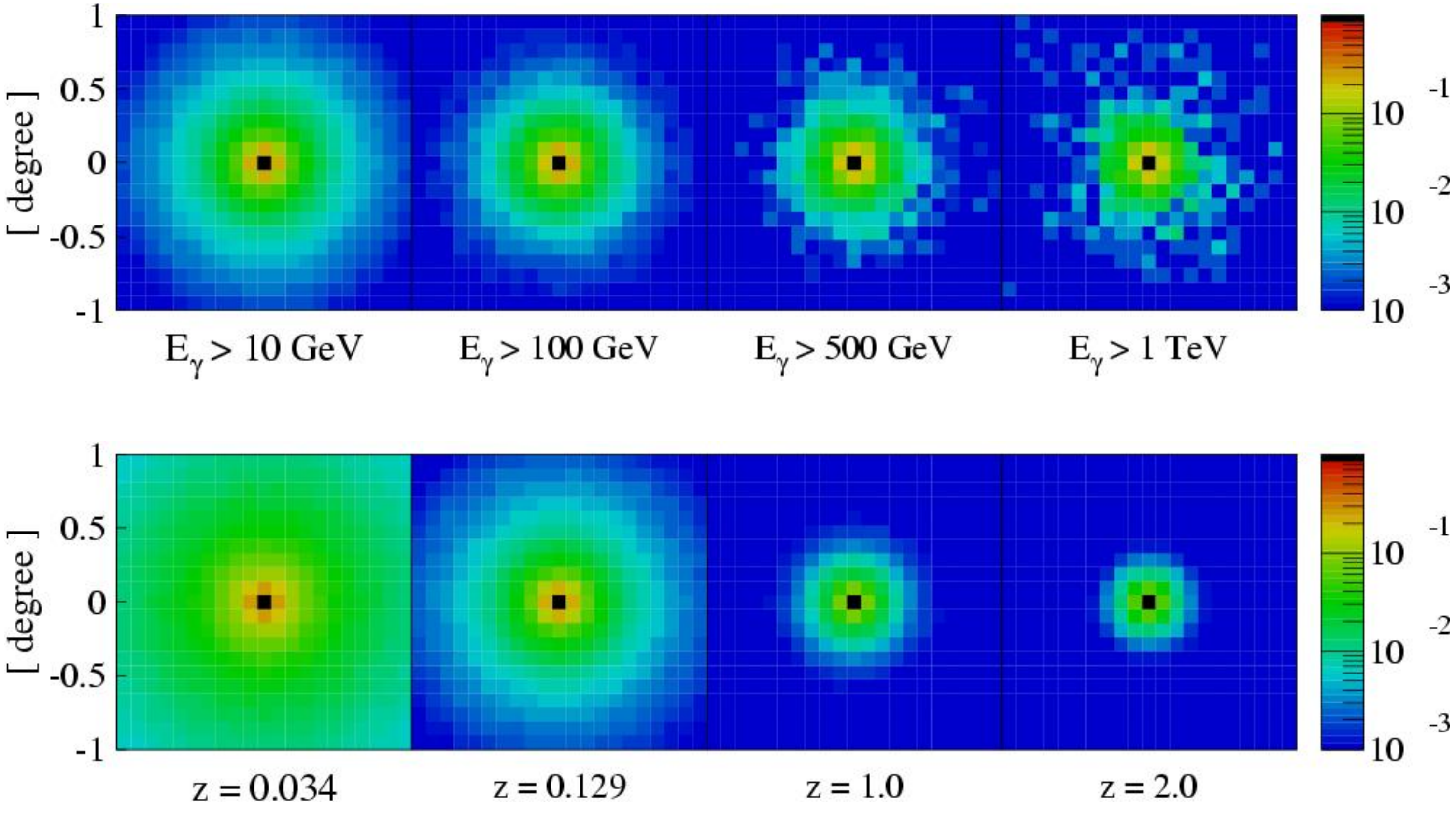
SEDs for different z within 0.1° and 1°



EBL model – Primack et al. 2000

$L_o = 10^{45}$ erg/s

Brightness distributions of Pair Halos



z=0.129

E=10 GeV

A. Eungwanichayapant, PhD thesis, Heidelberg, 2003

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