Scineghe 08, Padova, Oct 8-10, 2008

# Performance and Potential of Ground-Based Gamma-Ray Detectors

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# Ground Based Gamma-Ray observations

presently provide crucial window in the spectrum of cosmic E-M radiation

0.1 TeV and 100 TeV TeV gamma-ray Astronomy

with a potential for extension of the energy domain

- below 100 GeV down to < 10 GeV GeV gamma-ray Astronomy
- above 0.1 PeV up to > 1 PeV PeV gamma-ray Astronomy

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

# TeV gamma-ray astronomy

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

addresses diversity of topics related to the nonthermal Universe:
*acceleration, propagation and radiation of ultrarelativistic protons/nuclei and electrons*

generally under extreme physical conditions in environments characterized with
*huge gravitational, magnetic and electric fields, highly excied media, shock waves*

and very often associated with relativistic bulk motions linked, in particular, to
*jets in black holes (AGN, Microquasars, GRBs) and cold ultrarelativistic pulsar winds*

# Observational TeV gamma-ray astronomy - *a success story*

*over last several years the field has bee revolutionized*

before – *“astronomy“ with several sources and*
*advanced branch of Particle Astrophysics*

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

## major factors which made possible this success ?

many factors…

but basically thanks to the lucky combination of two independent circumstances

- ✓ effective acceleration of TeV/PeV particles on almost all astronomical scales often coupled with very favourable conditions for gamma-ray production

e.g. PWNe: almost 100% conversion of the pulsar rotational energy to multi-TeV electrons in an environement with very low magnetic field =>

*very effective IC scattering of electrons on 2.7K CMBR => TeV gamma-rays*

- ✓ great potential of the detection techniques:

*(1) broad-band coverage: 0.1-100 TeV (2) sensitivity: down to $10^{-13}$ erg/cm$^2$s,*
*(3) angular resolution: few arcmin; (4) all sky monitoring!*

presently: Ground Based Gamma Ray Astronomy

= TeV Gamma Ray Astronomy

with more than 80 detected G & EXG sources

and two well established detection techniques

*Imaging Atmospheric Cherenkov Telescope Arrays*

**(HESS, MAGIC, VERITAS… => CTA, AGIS, ….)**

*Water Cherenkov Detectors/High Altitude EAS Detectors*

**( MILAGRO, ARGO => HAWK)**

# TeV gamma-rays

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

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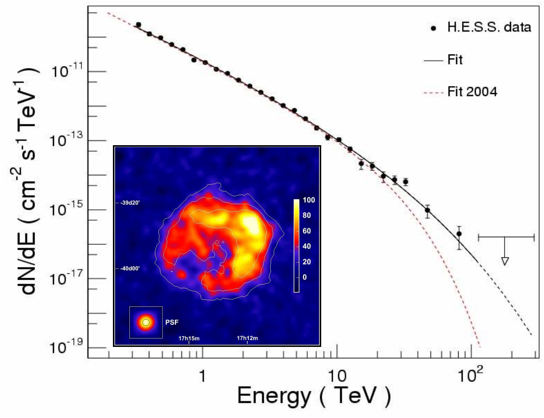


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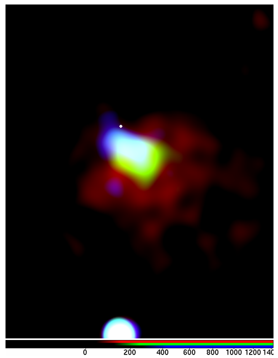

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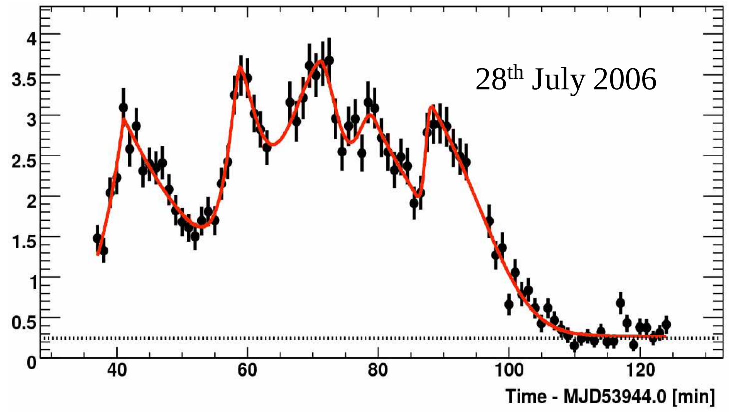



multi-functional tools: *spectrometry* *temporal studies* *morphology*

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

✓ transient phenomena: *$\mu$QSOs, AGN, GRBs, ...*

*Galactic Astronomy | Extragalactic Astronomy | Observational Cosmology*

*information about both relativistic electrons and hadrons*

# “hadronic gamma-rays” - with or without neutrinos

- synchrotron radiation of protons - pure electromagnetic process
  interaction of hadrons without production of neutrinos

- generally in hadronic interactions neutrinos and $\gamma$-rays are produced at same rates, and the $\gamma/\nu$ ratio could be << 1 because of absorption of gamma-rays… but in high density environments ($n > 10^{18}$ cm$^{-3}$ and/or $B>10^{6}$ G) production of TeV neutrinos is suppressed because charged mesons are cooled before they decay

- on the other hand, in compact objects muons and charged pions can be accelerated and thus significantly increase the energy and the flux of neutrinos, e.g. from GRBs

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**

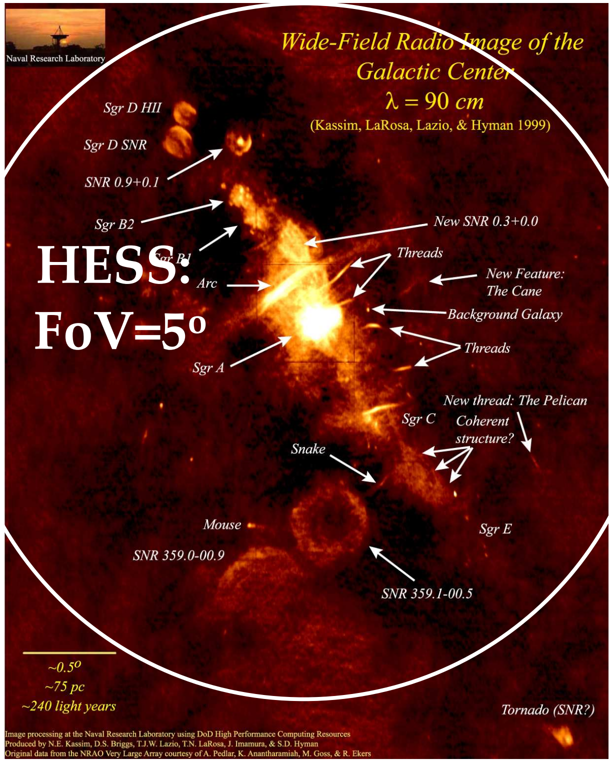
**Extragalactic objects**

- ✓ M87 - a radiogalaxy
- ✓ TeV Blazars – with redshift from 0.03 to 0.18 or even 0.5 ? (3C 279)

- ✓ and a large number of yet unidentified TeV sources …

VHE gamma-ray source populations

TeV gamma-rays from GC




GC – a unique site that harbors many interesting sources packed with un-usually high density around the most remarkable object $3x10^6$ Mo SBH – Sgr A*

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

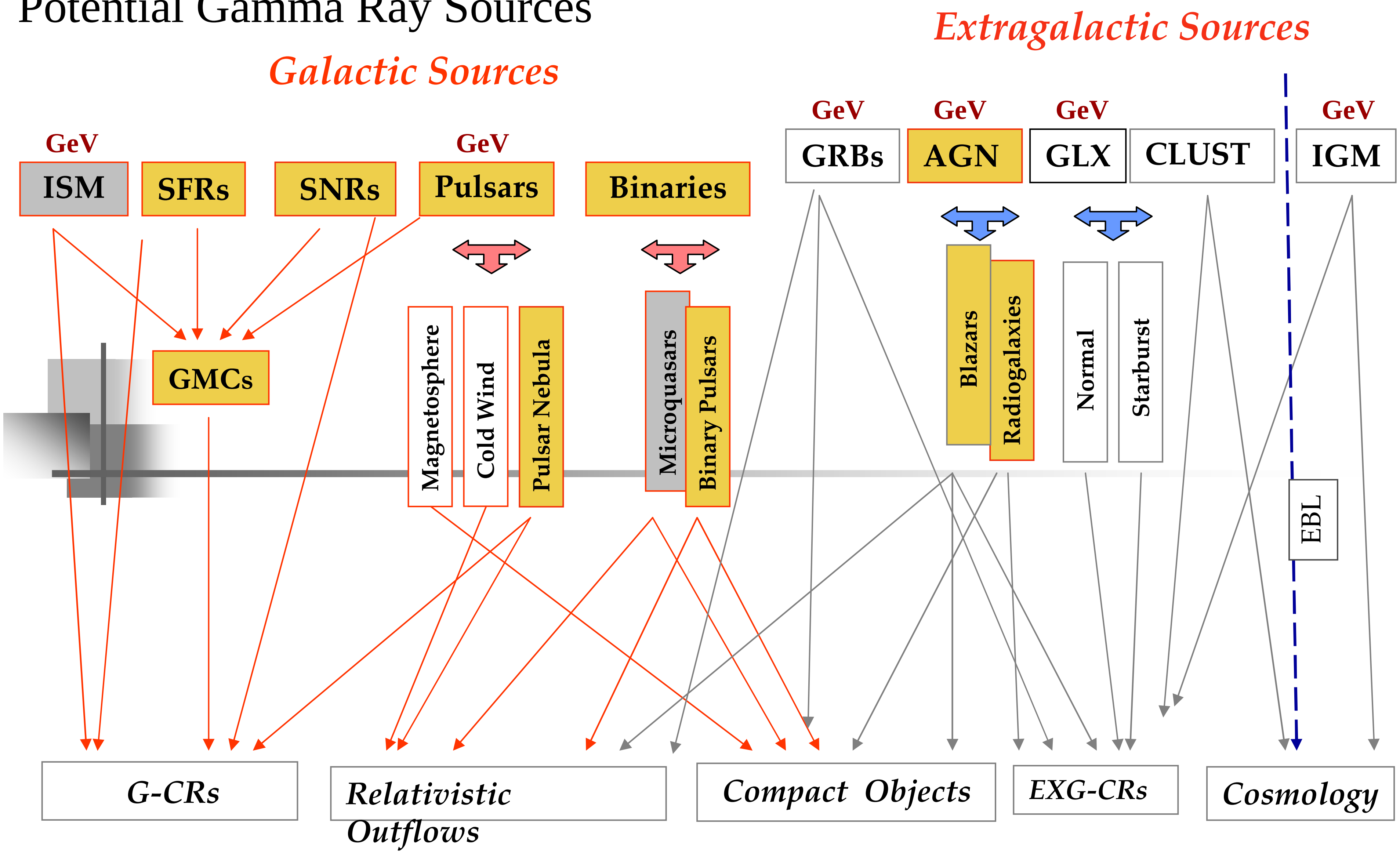
all of them are in the FoV an IACT, and can be simultaneously probed down to a flux level $10^{-13}$ erg/cm$^2$s and localized within << 1 arcmin

# major topical areas

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

.....

Potential Gamma Ray Sources




Major Scientific Topics

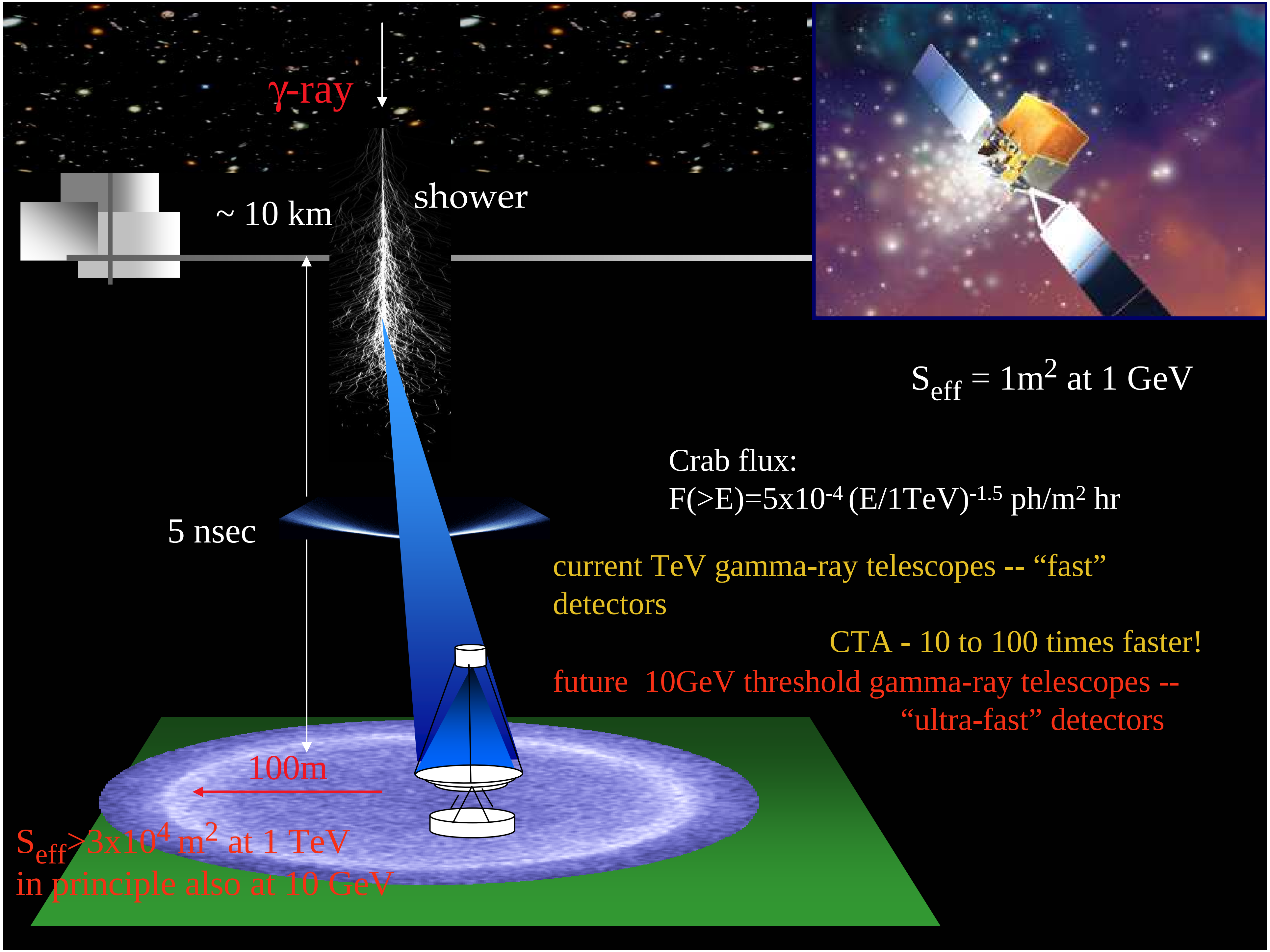
# two basic requirements to gamma-ray detectors

(1) in extreme accelerators the acceleration/radiation processes proceed on timescales comparable to the characteristic ("r/c") timescales => gamma-rays contain unique information about the location of the source and its dynamics (e.g. formation and termination of relativistic outflows) => one needs "fast" $\gamma$-ray detectors

(2) existence of a powerful accelerator is not yet sufficient for $\gamma$-ray production; it requires an additional component - a nearby dense gas or photon target field.

$\gamma$-rays from surrounding regions contain information about highest energy paricless which escape the accelerator and therefore cannot contribute to $\gamma$-ray production inside the accelerator itself => one needs large FoV and good angular and energy resolutions (morphology+spectrometry)

**IACT arrays and "dense" (low-threshold) EAS detectors satisfy both requirements!**

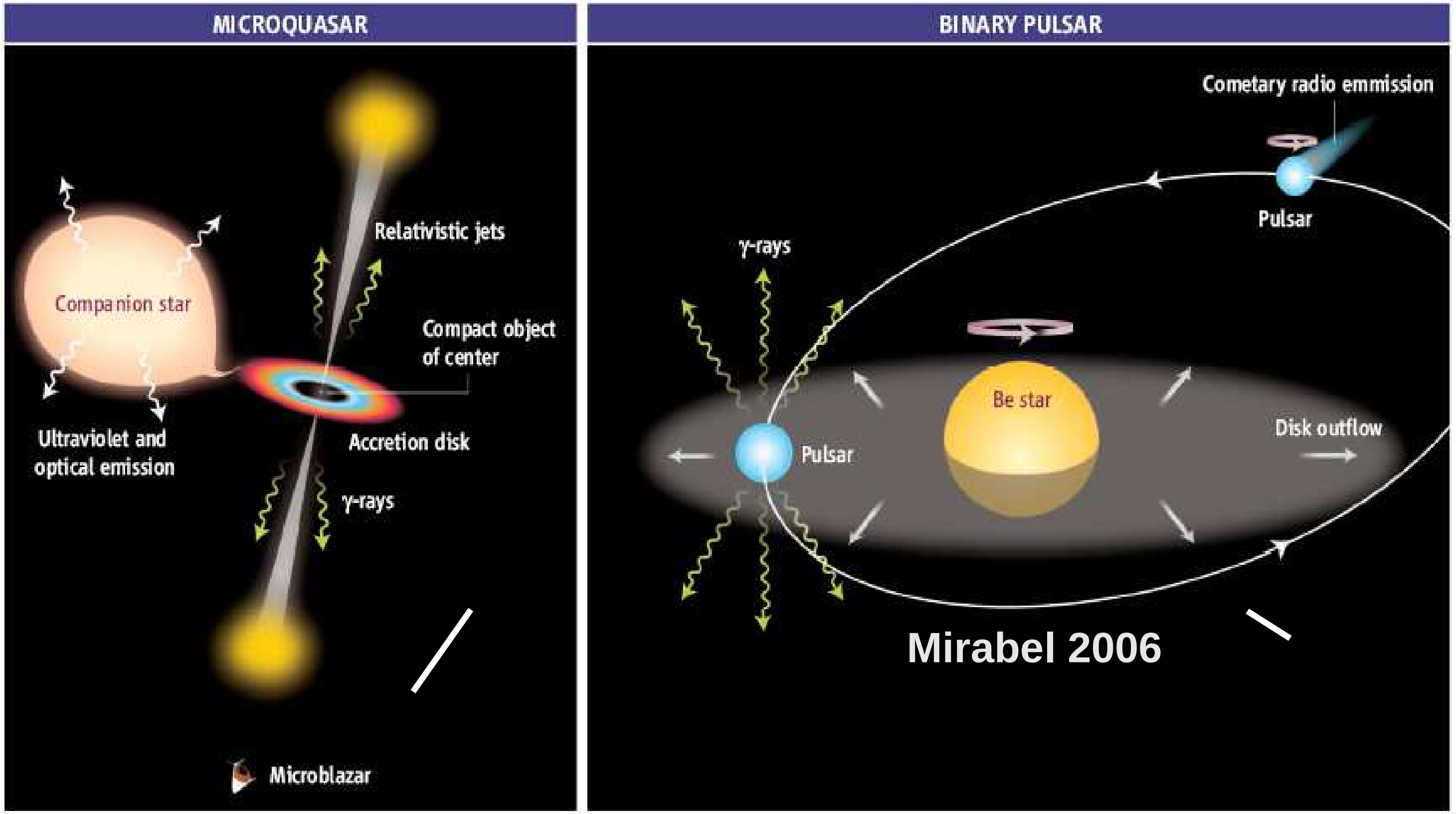

γ-ray
shower
~ 10 km
5 nsec
100m
$S_{eff}$ = $1m^2$ at 1 GeV
Crab flux:
$F(>E)=5x10^{-4} (E/1TeV)^{-1.5}$ ph/$m^2$ hr
current TeV gamma-ray telescopes -- “fast” detectors
CTA - 10 to 100 times faster!
future 10GeV threshold gamma-ray telescopes -- “ultra-fast” detectors
$S_{eff}>3x10^4$ $m^2$ at 1 TeV
in principle also at 10 GeV

# 1. Exploring extreme cosmic accelerators

*X-ray binary systems, blazars, GRBs, …*

an example

# Extreme accelerators in Binaries Systems



# PSR1259-63 - a unique high energy laboratory

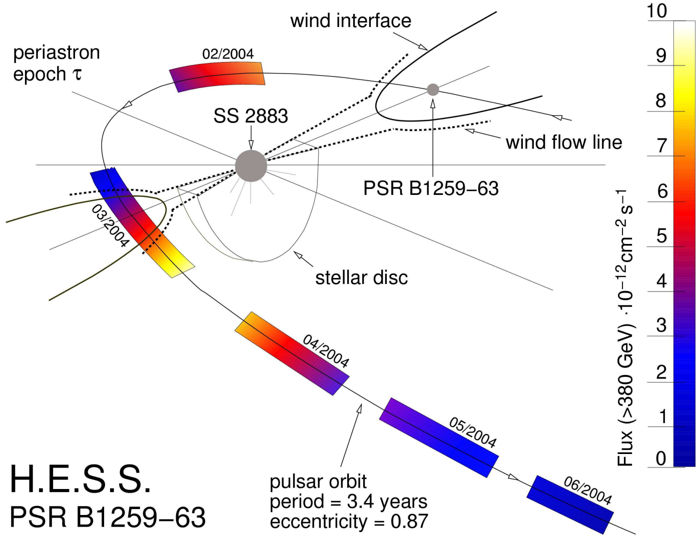
binary pulsars - a special case with strong effects associated with the optical star on both the dynamics of the pulsar wind and the radiation before and after its termination

the same 3 components - *Pulsar/Pulsar Wind/Synch.Nebula* - as in plerions but with characteristic radiation and dynamical timescales less than hours

both the cold ultrarelativistic wind and shocke-accelerated electrons are illuminated by optical radiation from the companion star
=> detectable IC gamma-ray emission

*on-line watch of creation/termination of the pulsar wind accompanied with formation of a shock and effective acceleration of electrons*

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

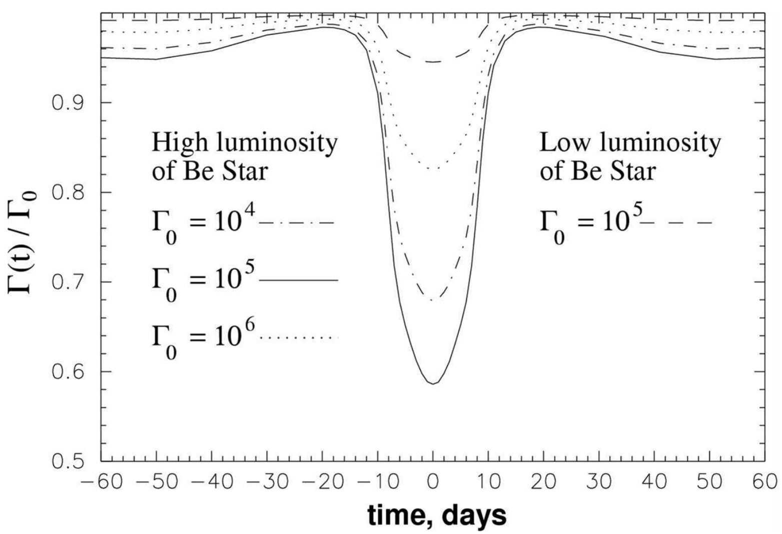


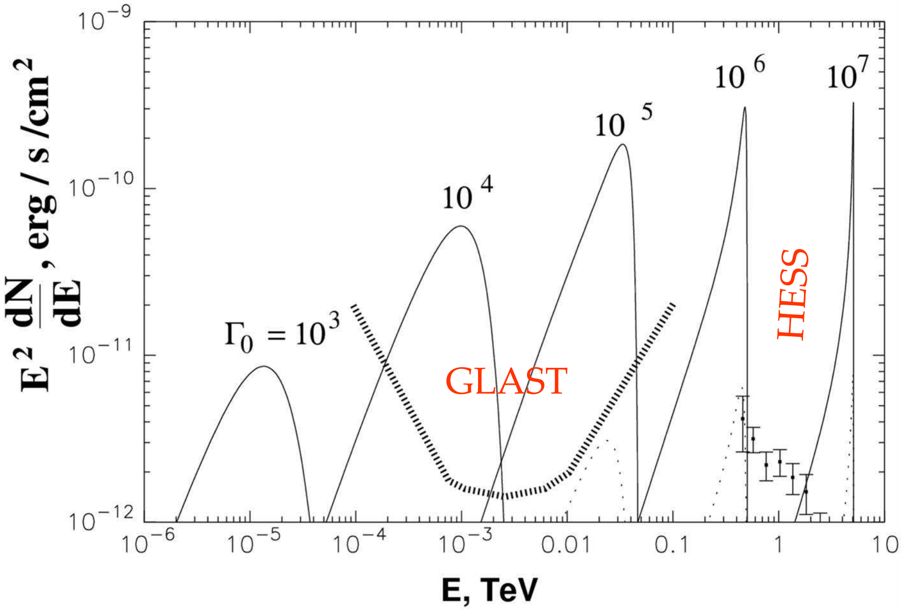

the target photon field is function of time, thus the only unknown parameter is B-field? easily/robustly predictable X and gamma-ray fluxes ?

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

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

## probing the "cold" pulsar wind Lorentz factor with comptonizied radiation



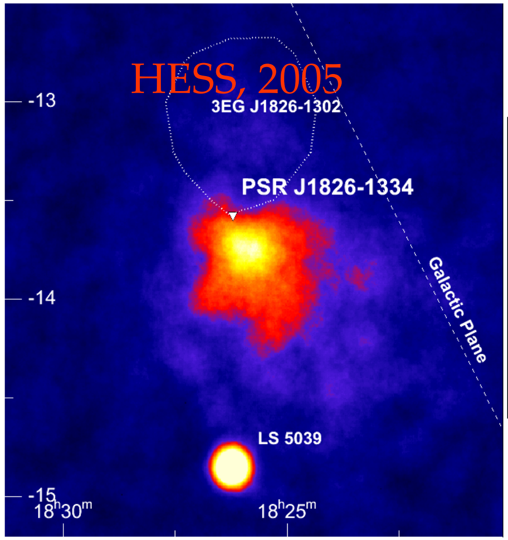



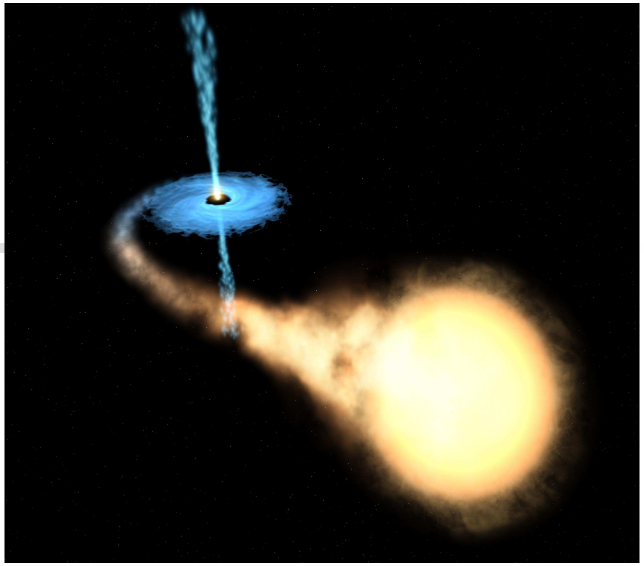

the effect is not negligible, but not sufficient to explain the lightcurve

Loretz factors exceeding $10^6$ are excluded

Khangulyan et al. 2008

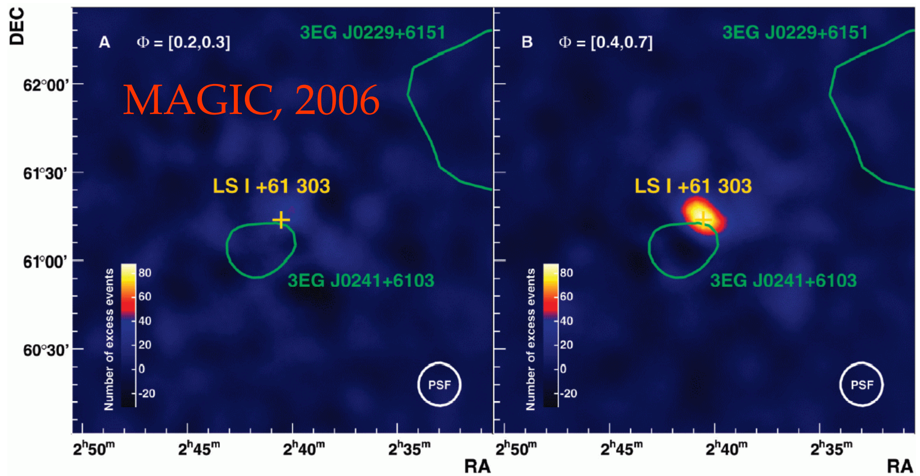
## TeV gamma rays from microquasars?



**microqusars or binary pulsars?**

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



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

scenarios? $\gamma$-ray production region within and outside the

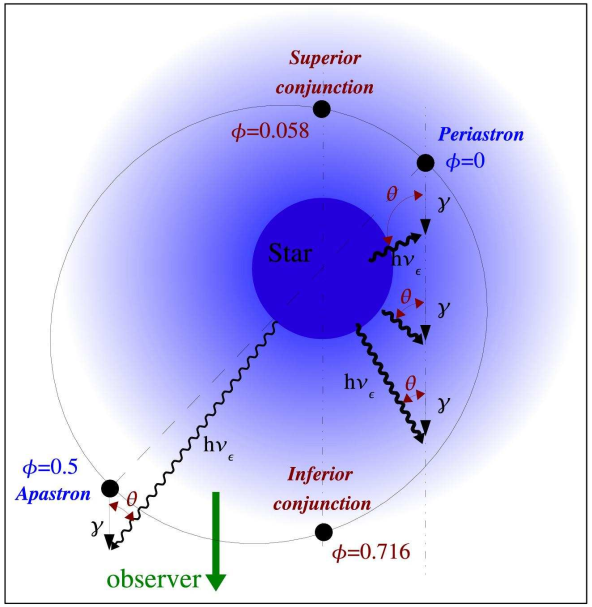
binary system cannot be excluded

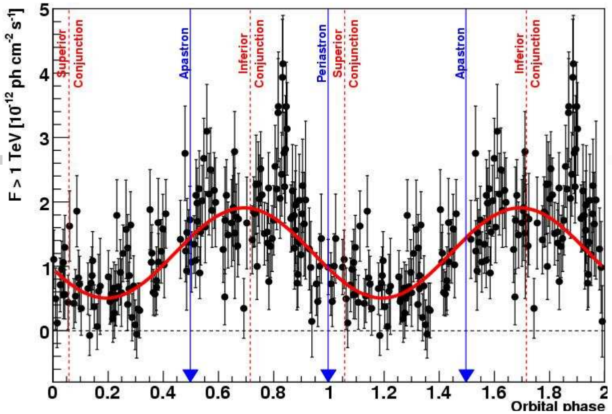
periodicity expected? yes — because of periodic variation of the geometry (interaction angle) and density of optical photons – as target photons for IC scattering and $\gamma\gamma$ absorption, as a regulator of the electron cut-off energy; also because of variation of the B-field, density of the ambient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

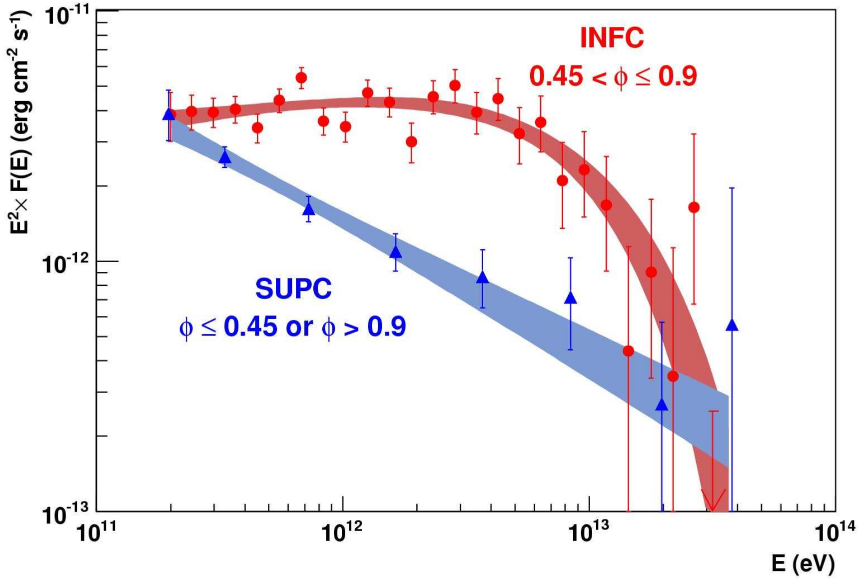
periodicity detected ! is everything OK ?

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

# LS 5039 as a perfect TeV clock and an extreme TeVatron

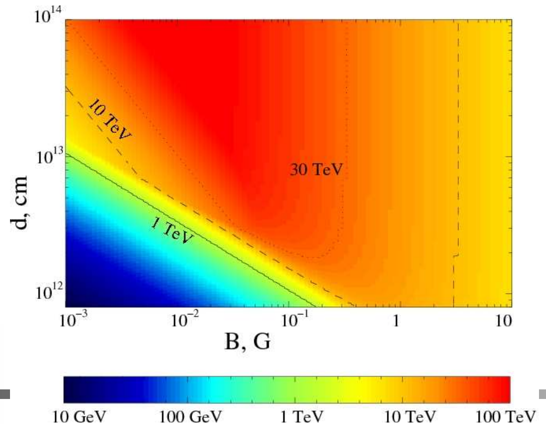


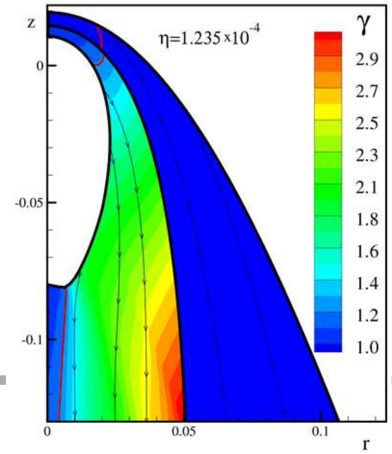



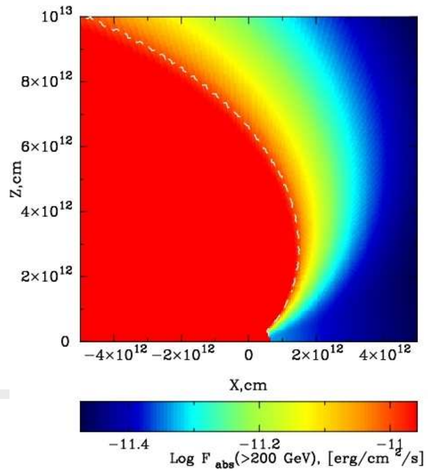




*close to inferior conjuction - maximum*
*close to superior conjuction – minimum*

one needs a factor of 3 or better sensitivity compared to HESS to detect signals within different phase of width 0.1 and measure energy spectra (phase dependent!)




- can electrons be accelerated to > 20 TeV in presence of radiation?
  *yes, but accelerator should not be located deep inside the binary system, and even at the edge of the system* $\eta < 10$

- does this excludes the model of "binary pulsar"
  *yes, unless the interaction of the pulsar and stellar winds create a relativistic bulk motion of the shocked material (it is quite possible)*

- can we explain the energy dependent modulation by $\gamma$–$\gamma$ absorption ?
  *yes, taking into account the anysotropic character of IC scattering ?*

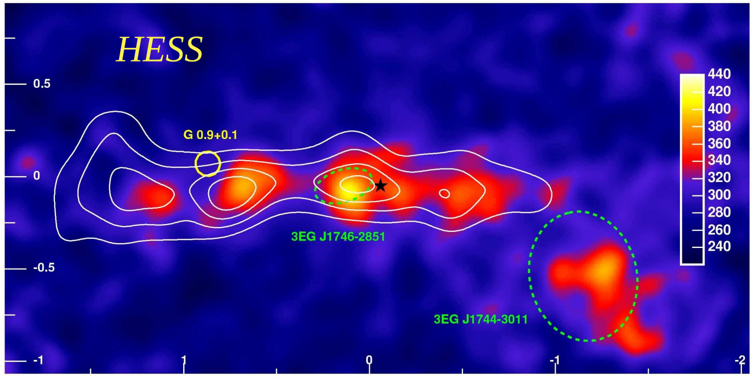
- can the gamma-ray producton region be located very deep inside the system
  *no, unless magnetic field is less than* $10(R/R_*)^{-1}$ G

# 2. searching for accelerators with VHE gamma-rays

*from  nearby regions surrounding the accelerator*

# searching for Galactic PeVatrons

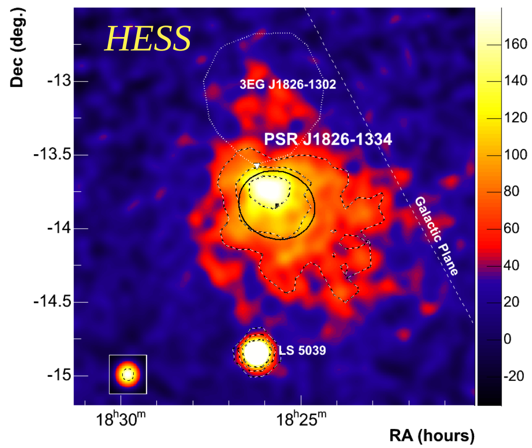
by detecting $\pi^0$-decay (pp) $\gamma$-rays from nearby GMCs




gamma-rays from GMCs in GC:

*do we see the "echo" of a CR flare of the central BH some $10^4$ (or so) years ago?*

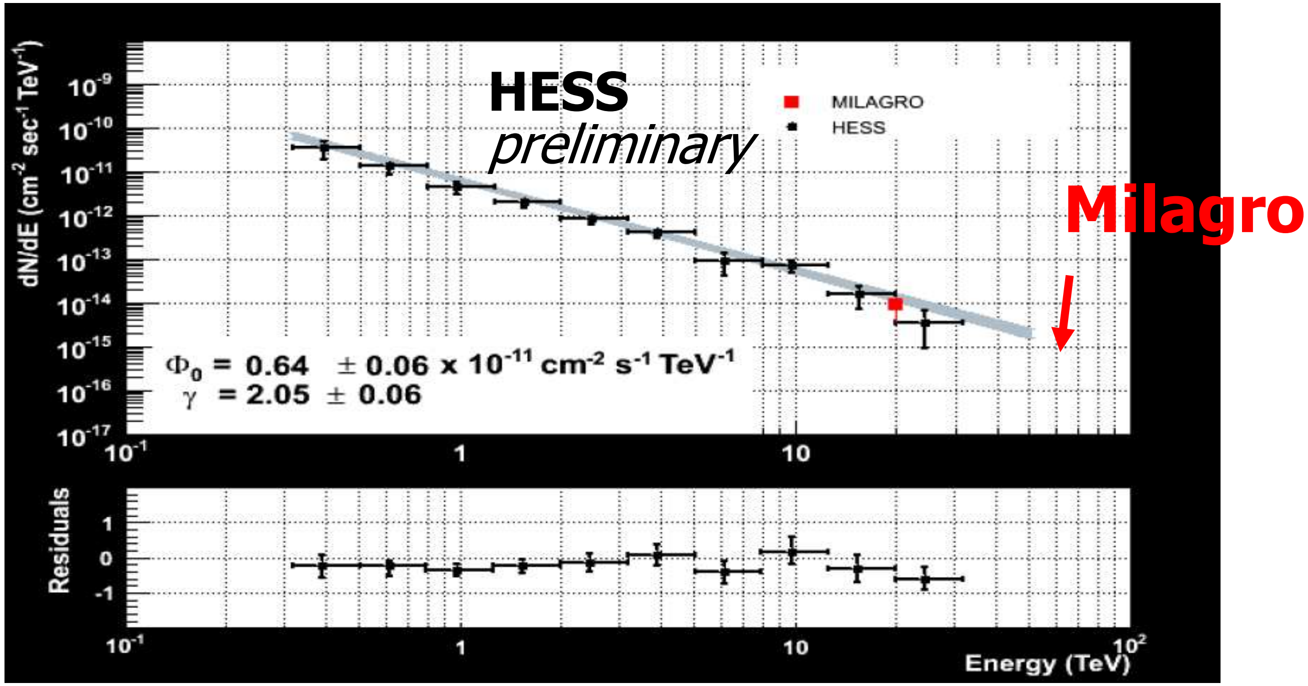
or IC $\gamma$-rays due to interactions of electrons with 2.7K CMBR




IC $\gamma$-halo around PSR J1826-1334:

*do we "see" directly the spectral and spatial distributions of electrons?*

# MGRO J1908+06 - a PeVatron?

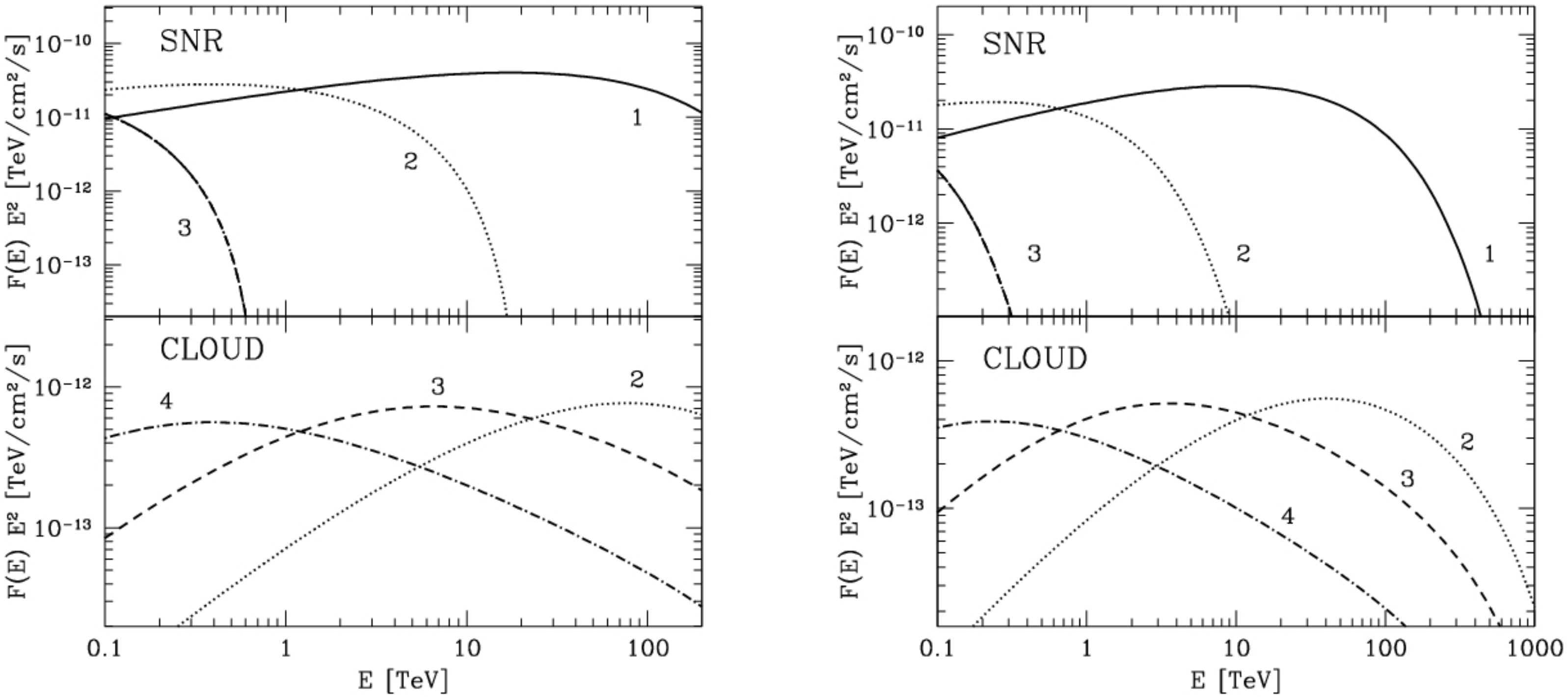


gamma-rays and neutrinos inside and outside of SNRs

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

d=1 kpc

gamma-rays  neutrinos

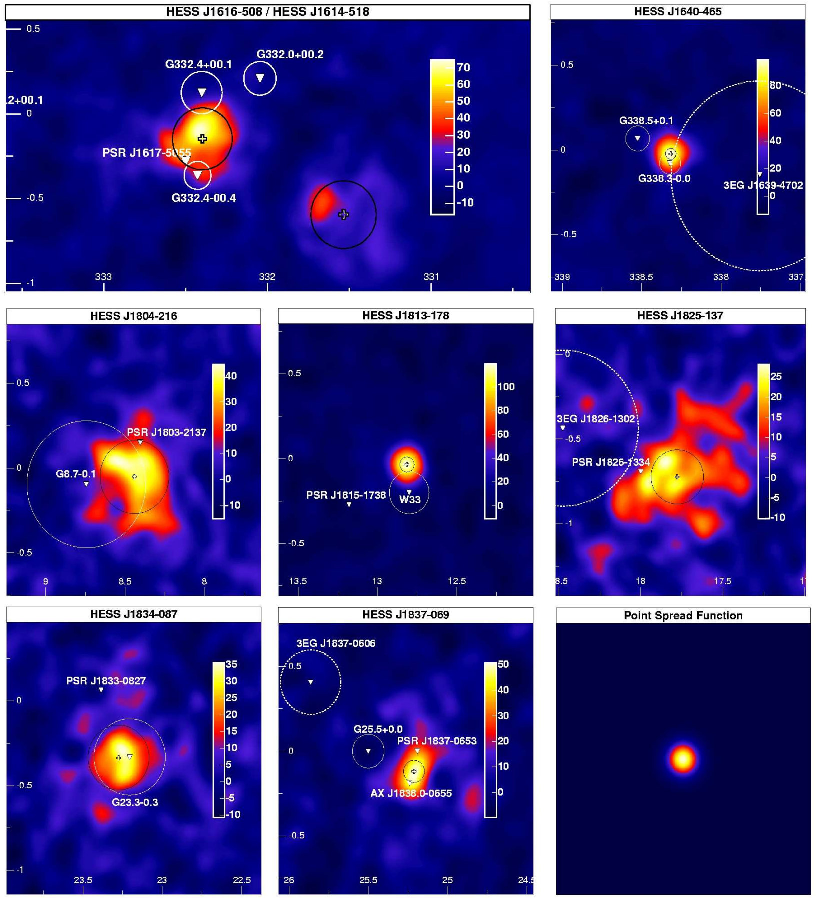



Gabici, FA 2007

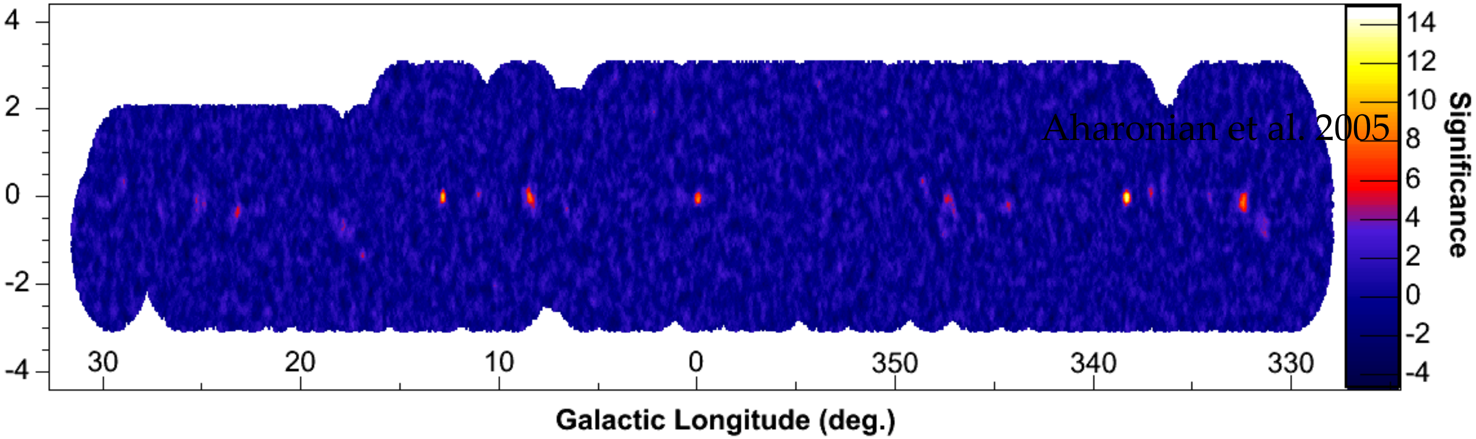
SNR:  $W_{51}=n_1=u_9=1$

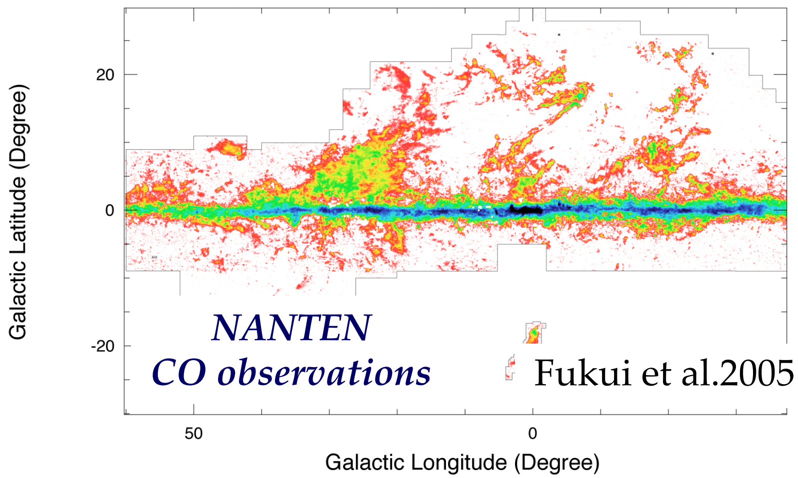
ISM:   $D(E)=3x10^{28}(E/10TeV)^{1/2}$ $cm^2/s$    GMC: $M=10^4$ $M_o$  d=100pc

# Zoo of  TeV galactic sources



# distribution of HESS sources HESS




**TeV and CO data:**
narrow distributions
in the Galactic Plane:

because of **GMCs** ?
**Star Formation Regions ?**

# morphology vs. energy spectrum

morphology pp: depends on spatial distributions of CR and gas: $n_H(r) \times Np(r)$
IC: depends only on spatial distribution of electrons: $N_e(r)$

energy spectra: depends on acceleration spectrum $Q(E)$, energy losses $dE/dt$, age of accelerator $t_o$, and character of propagation/diffusion coefficient $D(E)$

**pp:** generally energy spectrum independent of morphology, but for young objects energy spectrum could be harder at larger distances than near the accelerator, therefore angular size increases with energy

**IC:** very important are synchrotron energy losses; generally angular size decreases with energy

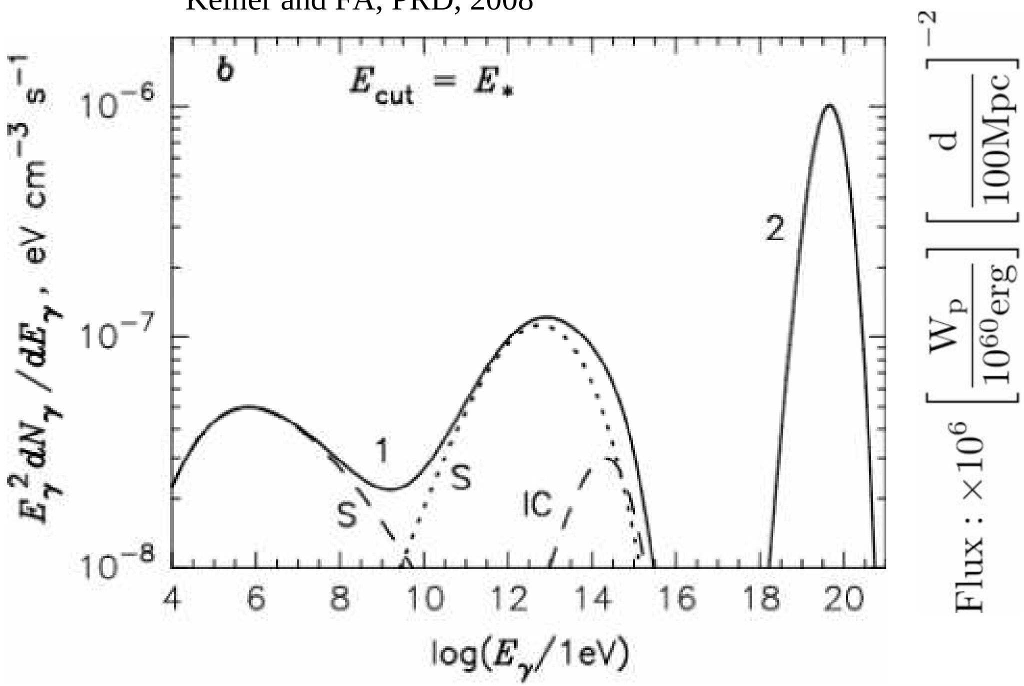
irregular shapes of $\gamma$-ray images : because of inhomogeneous distribution of gas (pp) or unisotropic propagation of cosmic rays (pp or IC)

# Extragalactic sources of UHECR

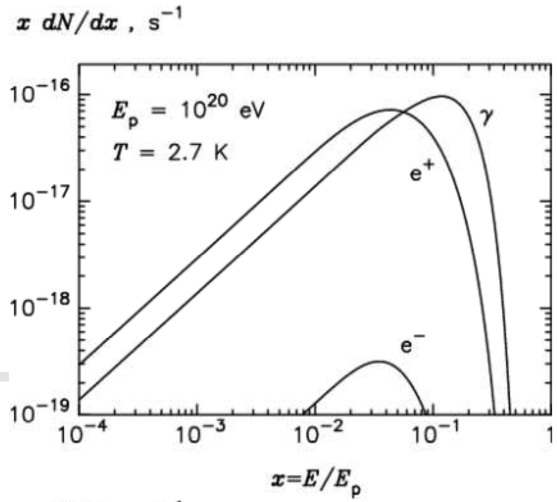
synchrotron γ-ray "halo" around a UHECR accelerator in strongly magneized region of IGM (e.g. an AGN within a galaxy cluster)

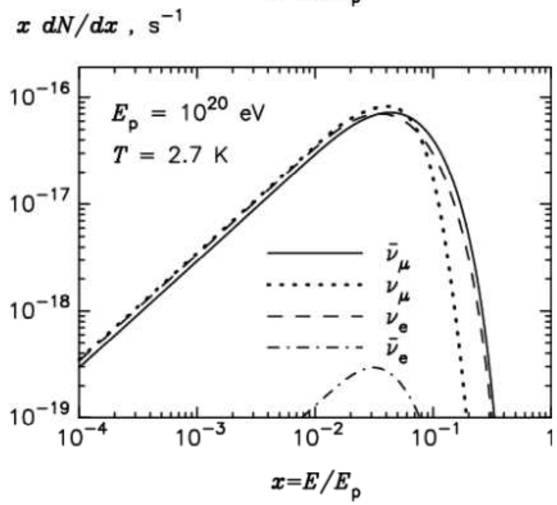
*gamma-radiation of secondary electrons* !

Kelner and FA, PRD, 2008




$$J(E_p) \propto E^{-2} \exp\left(-E_p/E_{cut}\right) \qquad w_p = 1 \ \mathrm{erg/cm^3}$$




synchrotron radiation of secondary electrons from Bethe-Heitler and photomeson production at interaction of CRs with 2.7K MBR in a medium with B=1 μG (e.g. Galaxy Clusters)

$E_* = 3\mathrm{x}10^{20}$ eV

secondary synchrotron gamma-rays produced wthin
> 10 Mpc region of IGM around a UHECR accelerator

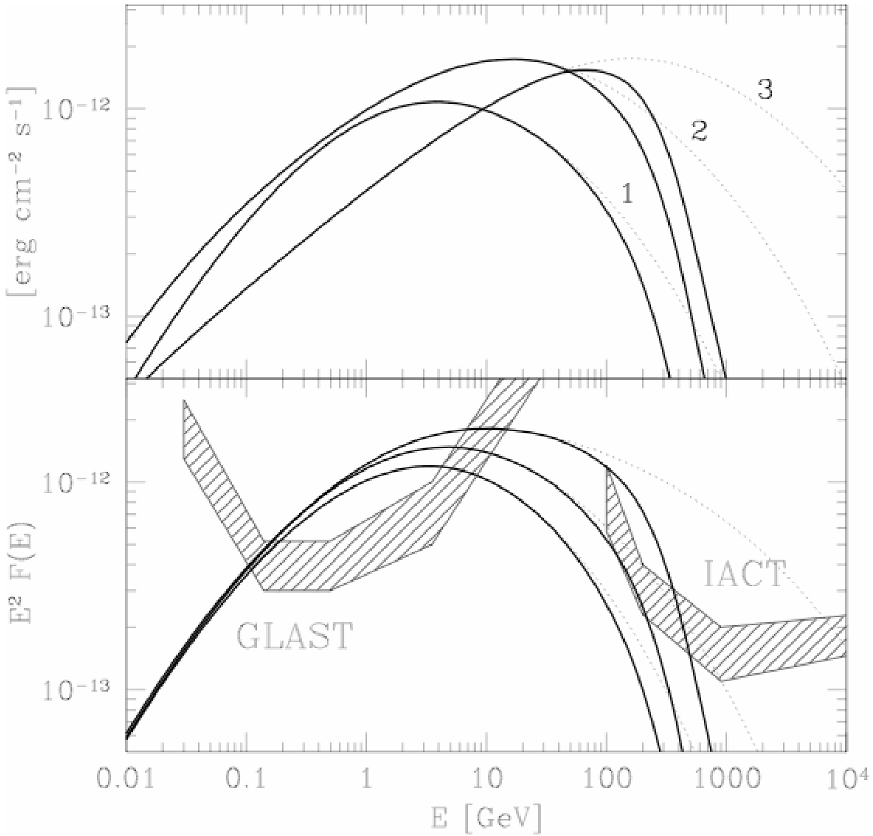
*non-variable but point-like gamma-rays source* !

photon spectra for a source at a distance of 1 Gpc in a 20 Mpc region of the IGM: power of UHECR source is $10^{46}$ erg/s (proton spectral index $\Gamma = 2$)

top: $E_{cut} = 10^{21}$ eV,
(1) B=0.5 nG, (2) 5 nG , (3) 50 nG

bottom: $E_{cut} = 5 \times 10^{20}$ , $10^{21}$, $5 \times 10^{21}$ eV
and B=1nG

dotted lines - intrinsic spectra,
solid lines - absorption in EBL




Gabici and FA, PRL 2005

# Future

- aim? sensitivity: $F_E$ => $10^{-14}$ erg/cm$^2$ s (around 1TeV)
- realization ? 1 to 10 km$^2$ scale 10m+ aperture IACT arrays
- timescales short (years) - no technological challenges
- price no cheap anymore: 100+ MEuro
- expectations guaranteed success - great results/discoveries

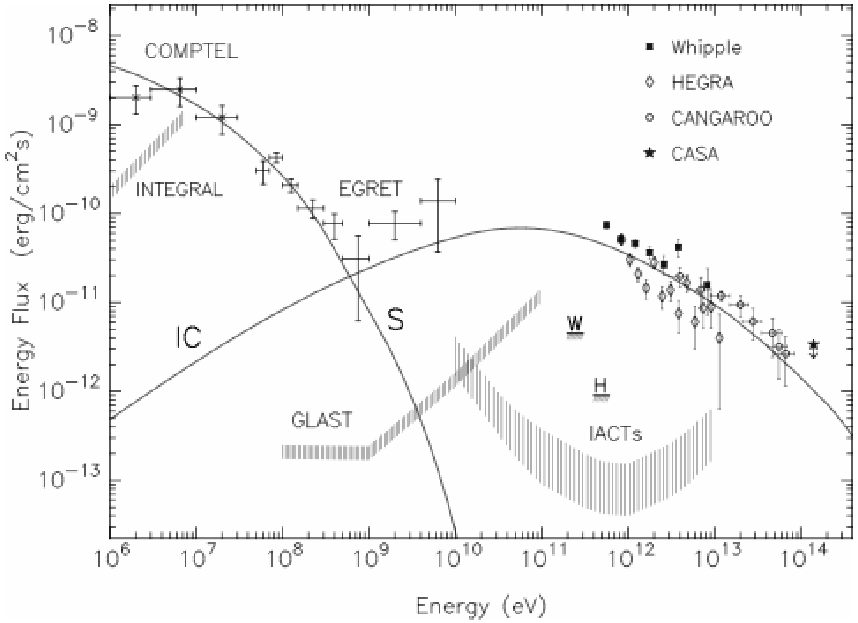
first priority? ”classical” 100 (30) GeV - 30 (100 ) TeV IACT arrays

next step (or parallel?): <10 GeV threshold IACT array

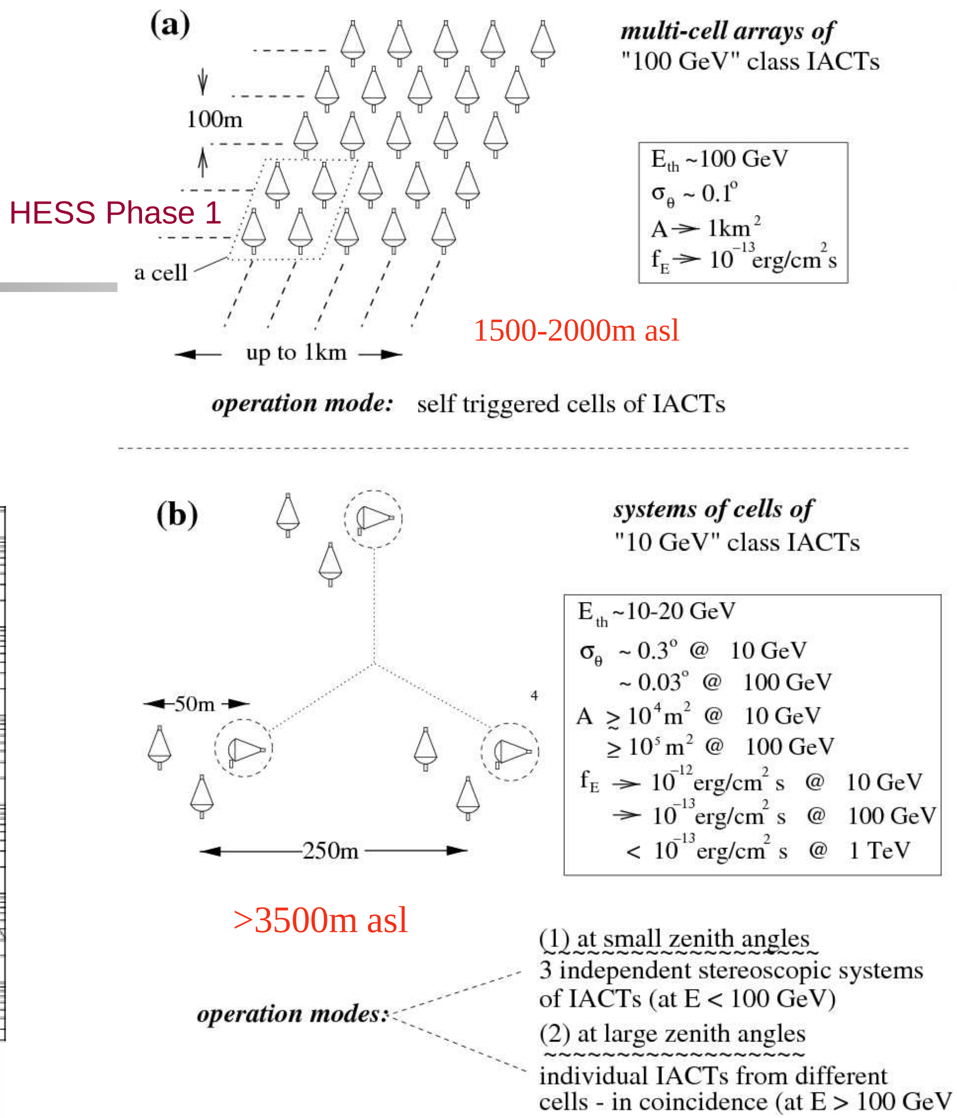
0.1-1 TeV threshold
all sky monitor: “HAWK” *(an analog of Fermi in VHE band with comparable angular and energy flux sensitivity)*

two possible designs
of IACT arrays =>

the slide shown first time in Padova in 1995 at the 4th “Towards a major …” Workshop but published 2years later, in: Aharonian 1997, LP97 (Hamburg)




**FUTURE GROUND-BASED GAMMA RAY DETECTORS**



# 5@5 - a GeV timing explorer

- Detector : **several 20 to 30m diameter IACTs to study the sky at energies from several GeV to several 100 GeV with unprecedented** ***photon and source statistics***

- Potential: **can detect "standard" EGRET sources with spectra extending beyond 5 GeV for exposure time from** ***1 sec to 10 minutes***

- Targets: **Gamma Ray Timing Explorer for study of nonthermal phenomena**
  ***AGN jets, Microquasars, GeV counterparts of GRBs, Pulsars ...***

5@5 is complementary to FERMI,
in fact due to small FoV needs very much FERMI
and ... FERMI *certainly* needs a 5@5 type instrument

**(1) The Magic detection of 25 GeV gamma-rays from the Crab pulsar demonstrated that a sub-10GeV threshold IACT array can be realized with advanced Cherenkov detectors**

**(2) GLAST detects >10 GeV gamma-rays from pulsars, AGN, GRBs**

a sub-10GeV threshold IACT array can be realized during the liftime of FERMI