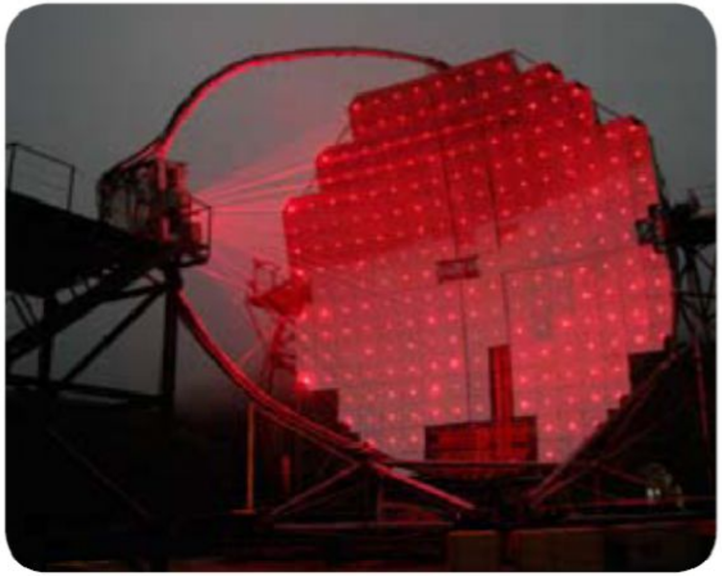
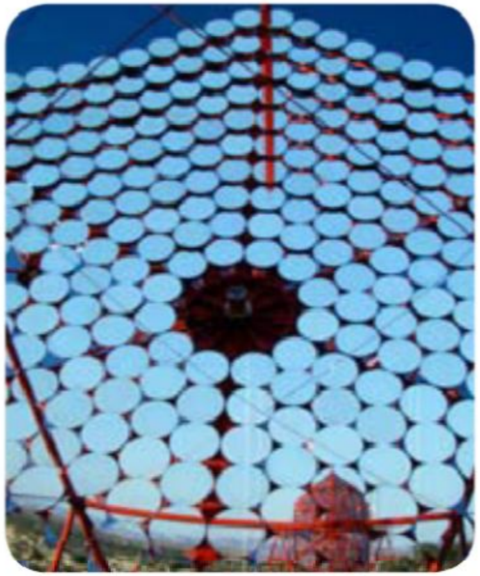



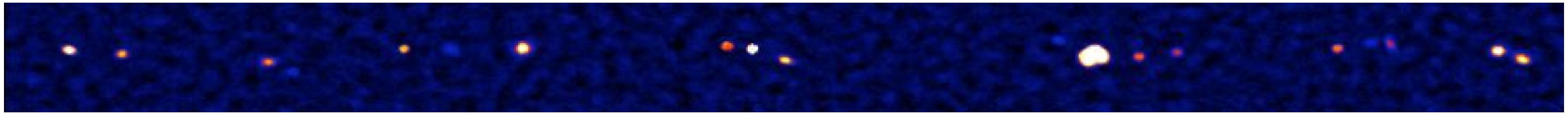
Observing the sky at Very High Energy Gamma-rays :

Current results and perspectives with CTA, the very large Cherenkov Telescope Array

H. Sol, LUTH, Observatoire de Paris (CTA collaboration)

4th International Sakharov Conference on Physics, Moscow, May 18-23, 2009

Outline



- Introduction : ubiquitous VHE gamma-ray emission and the high energy component of the universe
- Results from current IACT, Imaging Atmospheric Cherenkov Telescopes
- Some open fields to explore with the next generation of IACT
- A few words on IACT techniques
- The CTA project, Cherenkov Telescope Array

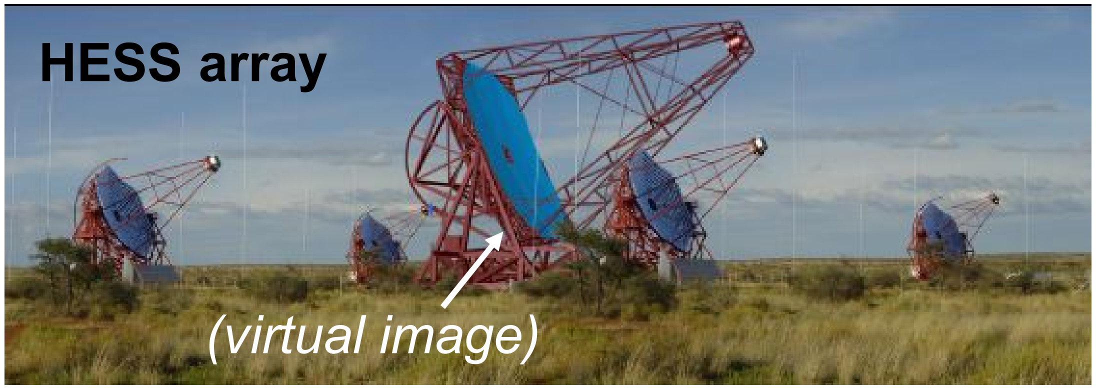
After pionnering works by Whipple, HEGRA, CAT …, present IACT are revealing our cosmos at V.H.E.

Soon improved performences towards lower energies :

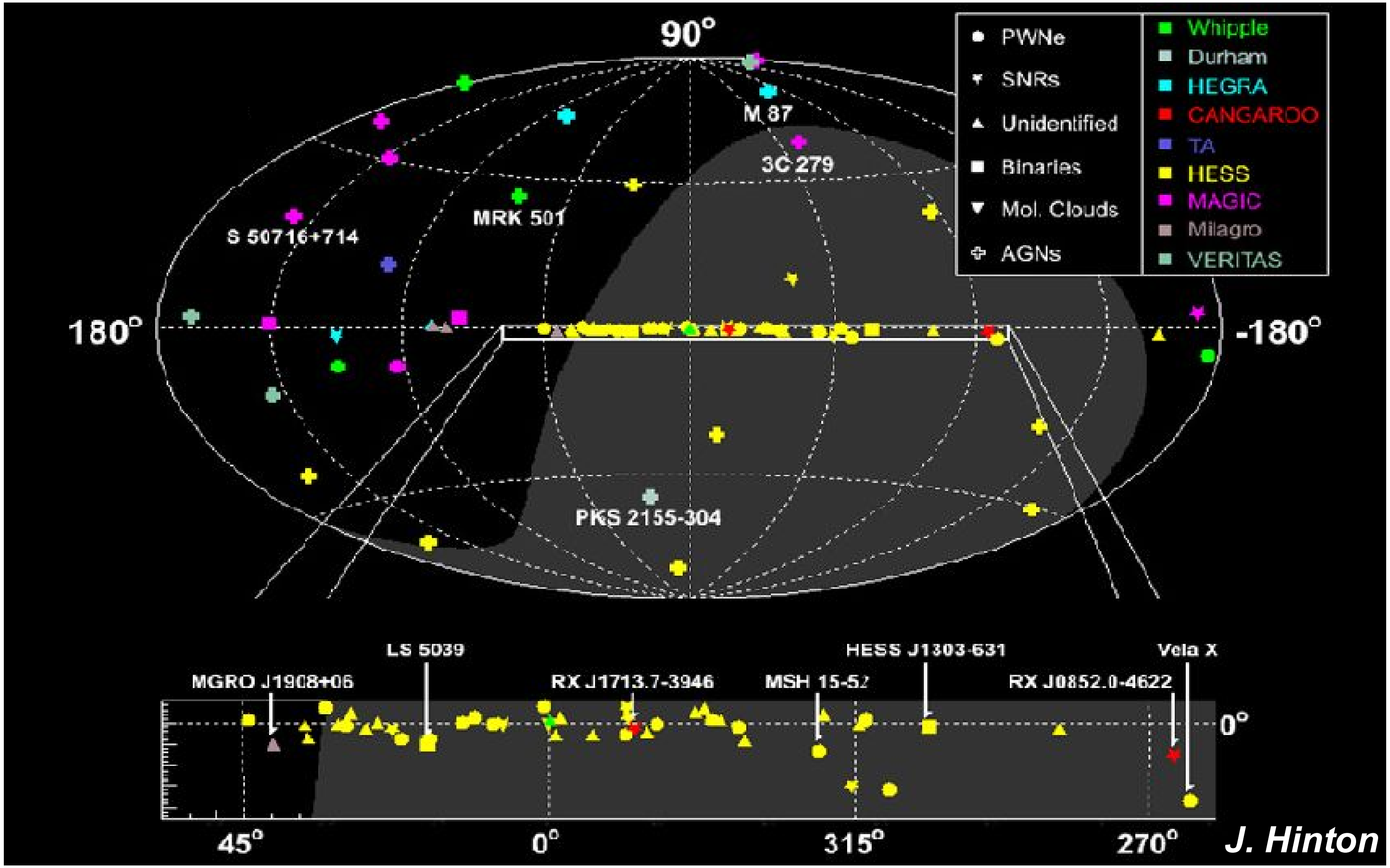
Extension of present IACT with MAGIC II and HESS II

MAGIC II : 2nd 17m tel
First data this spring.

HESS II : large 28m tel being added to the present HESS 1 array; under construction. First operations foreseen for 2010.



A large variety of TeV γ-ray sources …

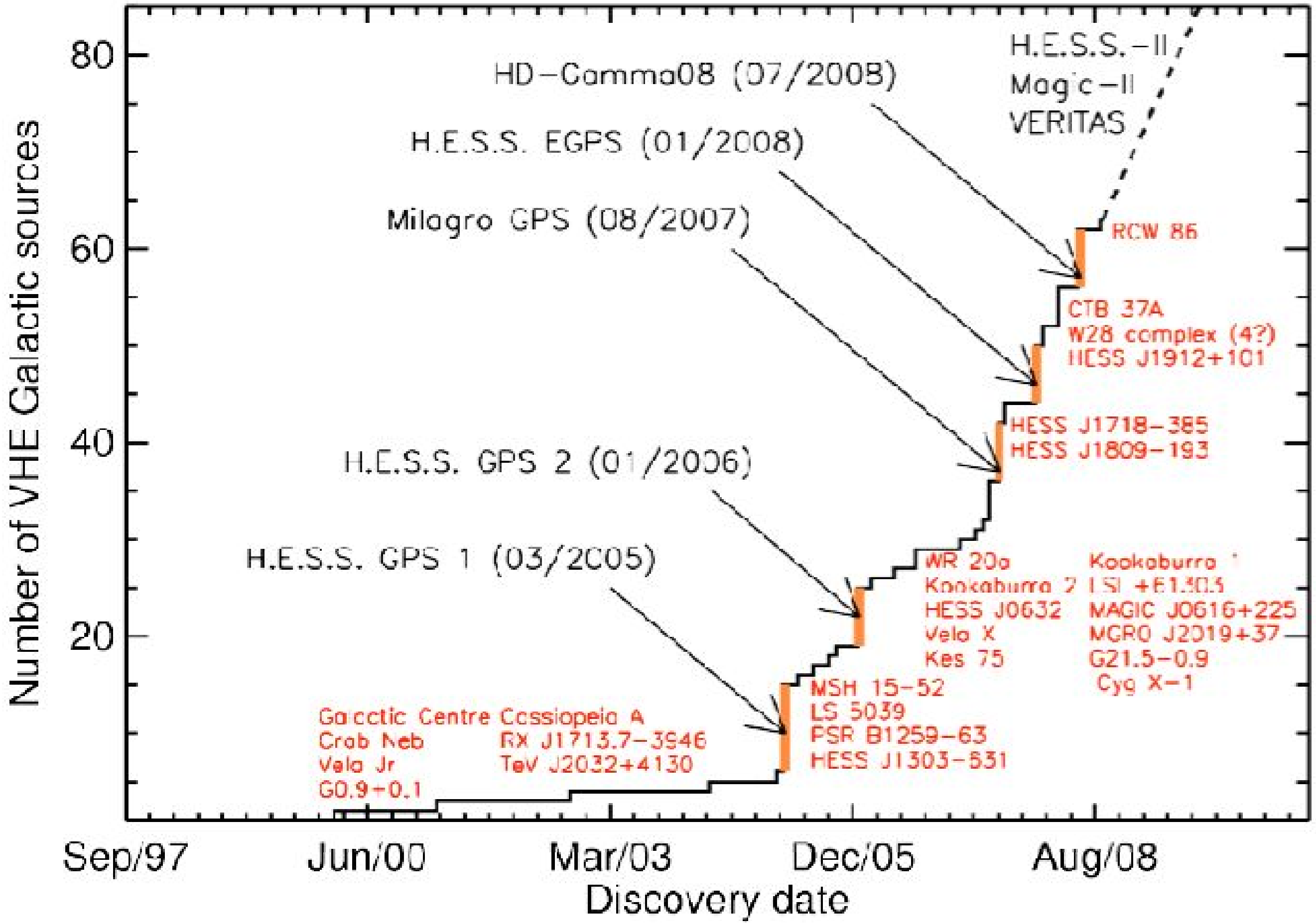


Towards a hundred confirmed TeV sources

Extragalactic space : Active Galactic Nuclei (>25)

Galactic plane : Pulsar Wind Nebulae (PWN), SNR, binaries, diffuse emission, clouds and stellar clusters, «dark accelerators», galactic center

A large variety of TeV γ-ray sources …



from M. Renaud

… but a limited number of VHE γ-rays emission mechanisms : 2 (+1)

- Leptonic scenarios : synchrotron and Inverse-Compton (IC) radiation of relativistic electrons (positrons)
  e + B → e + B + γ, in magnetic field B (also X-rays)
  e + γ_0 → e + γ, with $h\nu \sim \min[\gamma_e^2 h\nu_0, \gamma_e m_e c^2]$, IC on synchrotron emission (SSC) or on external photon field (EC)

- Hadronic scenarios : Interaction of energetic protons (CR) with local gas and radiation backgrounds
  p + p → N + N + $n_1(\pi^+ + \pi^-) + n_2\,\pi^0$ (N = p or n)
  p + γ → p + π^0, n + π^+, others (for $\gamma_p h\nu > m_\pi c^2$); or p + e^+ + e^- (for $\gamma_p h\nu > 2m_e c^2$)
  Then decay **π^0 → 2 γ produce VHE photons with $E_\gamma \sim E_\pi/2 \sim 10\%\ E_{p,i}$**
  + Decay pions → muons → *secondary electrons and neutrinos* (also X-rays)
  Alternatives : curvature and synchrotron radiation of VHE protons.

- (Annihilation of Dark Matter particles : predictions of supersymmetric theories, Kaluza-Klein scenarios → open questions to explore. No detection yet. A great challenge, but not yet granted !)

… but a limited number of VHE γ-rays emission mechanisms : 2 (+1)

- Leptonic scenarios : synchrotron and Inverse-Compton (IC) radiation of relativistic electrons (positrons)

  $e + B \rightarrow e + B + \gamma$, in magnetic field B (also X-rays)

  $e + \gamma_0 \rightarrow e + \gamma$, with $h\nu \sim \min [\gamma_e^2 h\nu_0, \gamma_e m_e c^2]$, IC on synchrotron emission (SSC) or on external photon field (EC)

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  $p + p \rightarrow N + N + n_1(\pi^+ + \pi^-) + n_2 \pi^0$ (N = p or n)

  $p + \gamma \rightarrow p + \pi^0, n + \pi^+$, others (for $\gamma_p h\nu > m_\pi c^2$); or $p + e^+ + e^-$ (for $\gamma_p h\nu > 2m_e c^2$)

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  + Decay pions → muons → *secondary electrons and neutrinos* (also X-rays)

  Alternatives : curvature and synchrotron radiation of VHE protons.

→ Reduces to one single need :
Efficient particle acceleration processes

« Universal particle acceleration »

- Acceleration was predicted from all nonuniform velocity fields in low density plasmas, where hydrodynamic power is converted into that of HE particles *(i.e. Katz, 1991 …)*
  → basically, everywhere in the cosmos
  → ubiquity of gamma-ray radiation

- Assumptions : (1) Fermi acceleration processes efficient in any astrophysical **flows with low enough density** (to avoid collisional losses)
  (2) Energy density in HE particles grows until it affects the flow and the acceleration

- Indeed, almost all VHE sources detected up to now have powerful outflows (or inflows). Except possibly passive sources (clouds).

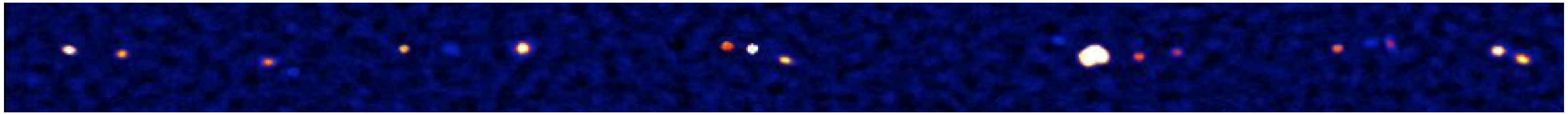
- **Fermi acceleration : 1st and 2nd order processes in shocks and turbulence → widely invoked to explain VHE cosmic sources**

- Alternatives : magnetic reconnection, direct electric forces, centrifugal force

High energetic particles : an important component of the universe

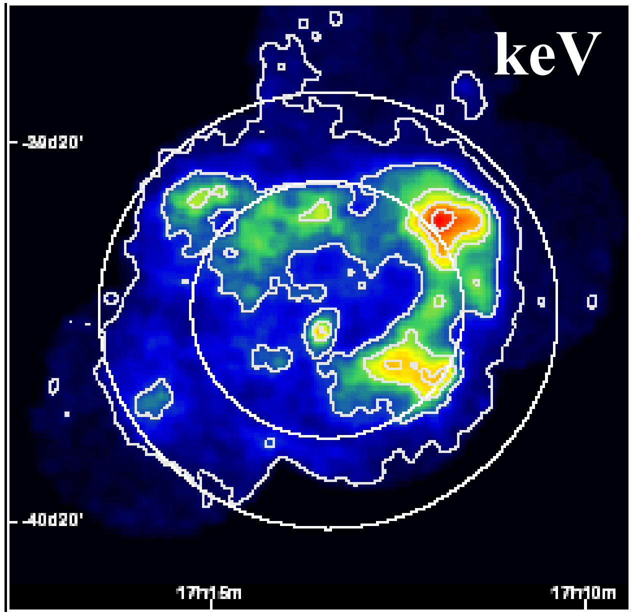
- HE particles are an intrinsic component of cosmic plasmas, together with thermal gas and electromagnetic fields
- Significant contribution of HE particles to total pressure and total energy budgets.
  In the interstellar medium , $w_{HE} \sim w_{gas} \sim w_B \sim w_{star\text{-}light}$
- Reveal the non-thermal universe, out of equilibrium processes, and extreme cosmic events.
- TeV astronomy offers at the moment a unique tool to directly probe the extreme high energy tail of HE particle populations, and extremes accelerators which produce them.

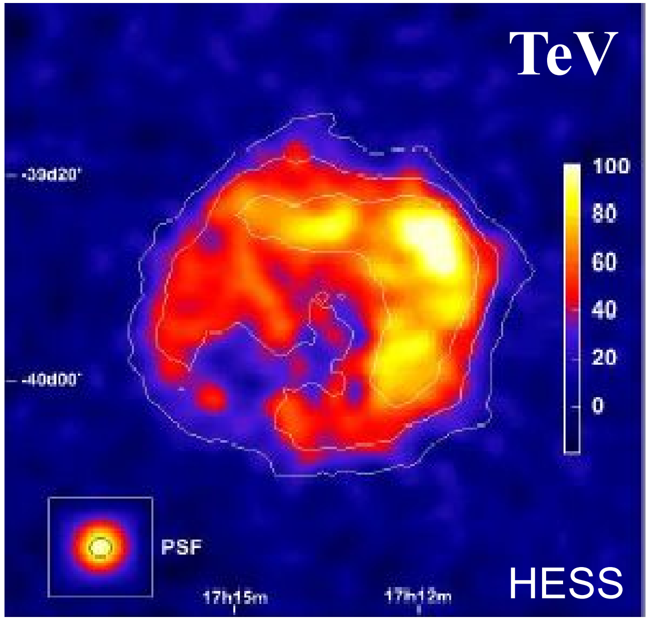
Some results from current IACT



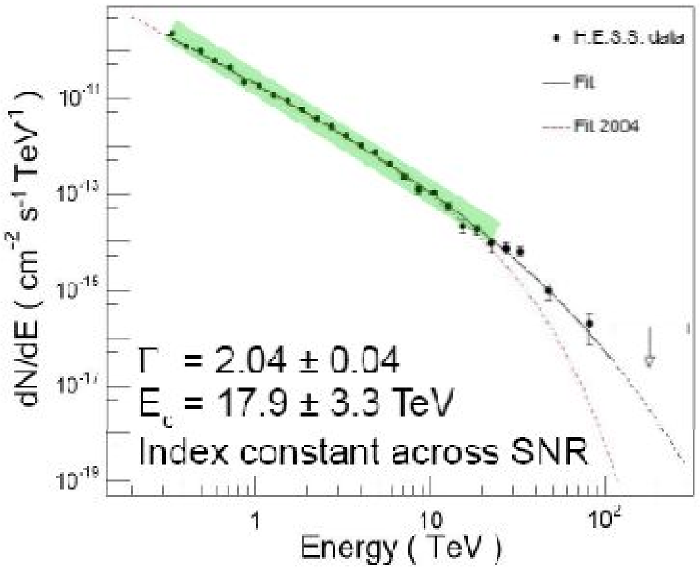
Our Galaxy : SNR, Pulsar Wind Nebulae, pulsars, binary systems, stellar clusters, galactic center and diffuse emission
Extragalactic space : Active galactic nuclei (blazars and radiogalaxies)

SuperNova Remnants ex : RXJ1713.7-3946





Shell-type SNR
D ~1.3 kpc
Complex V.H.E. morphology rather similar to X-ray map.

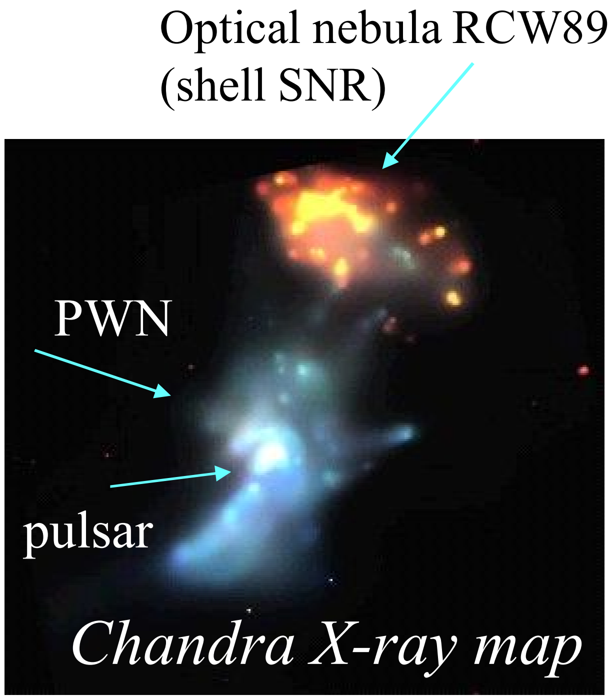


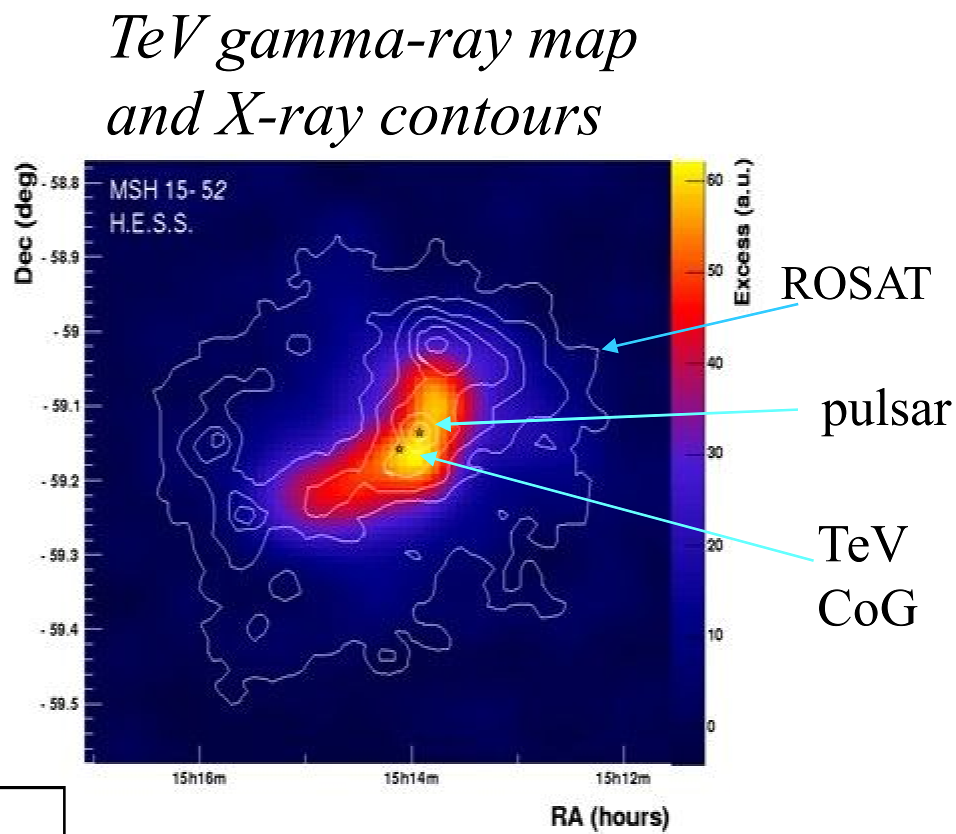
→ **Presence of particles with E> 100 TeV inside the SNR(s). Origine of galactic C.R.**

Origine of the VHE emission ?
Still an open question :
- Hadronic (amplified B, thinness of X-ray filaments)
- Leptonic (lack of thermal X-ray emission)

Pulsar wind nebulae, the largest VHE galactic population

Ex 1 : MSH 15-52



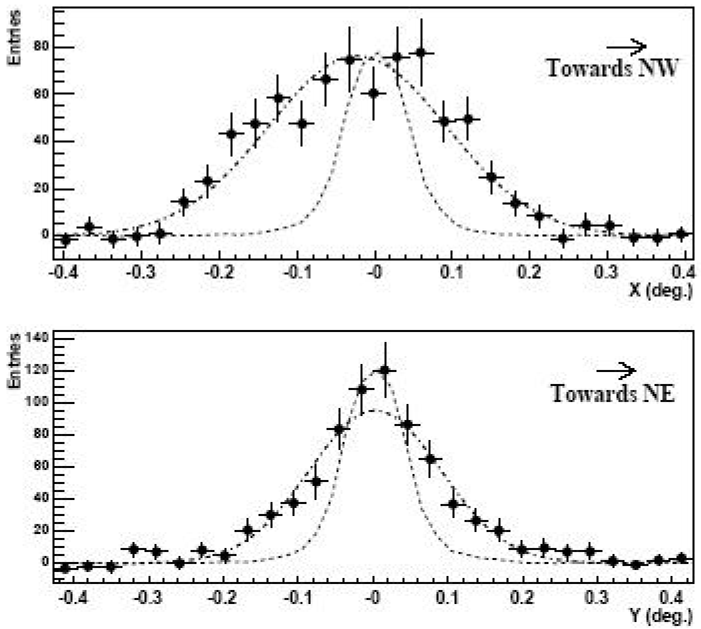


Central energetic pulsar B1509-58
Young PWN
Outflow at 0.2c (jet) along pulsar axis ?
Synchrotron X emission from accelerated e^-

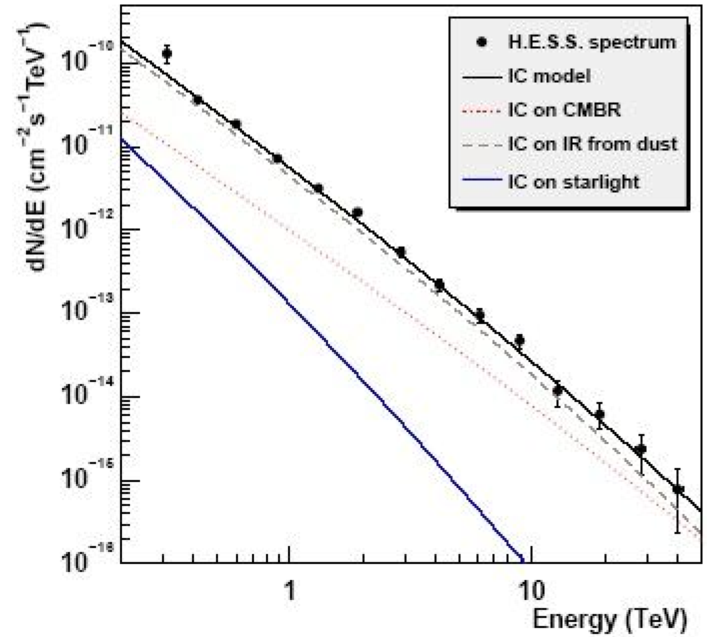
→ first image of a TeV extended 'jet', related to X-rays

MSH 15-52

VHE profiles



VHE spectrum



A clearly resolved structure :

•15’ extension along PWN axis

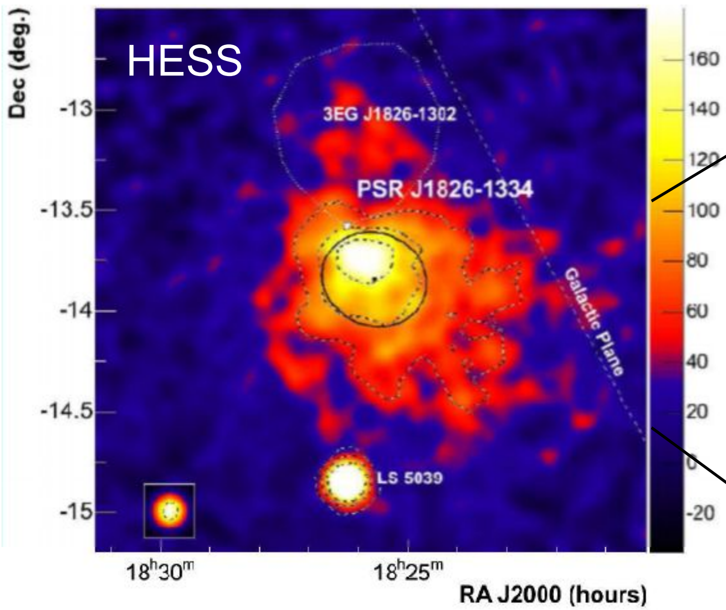
• 5’ extension transverse to axis

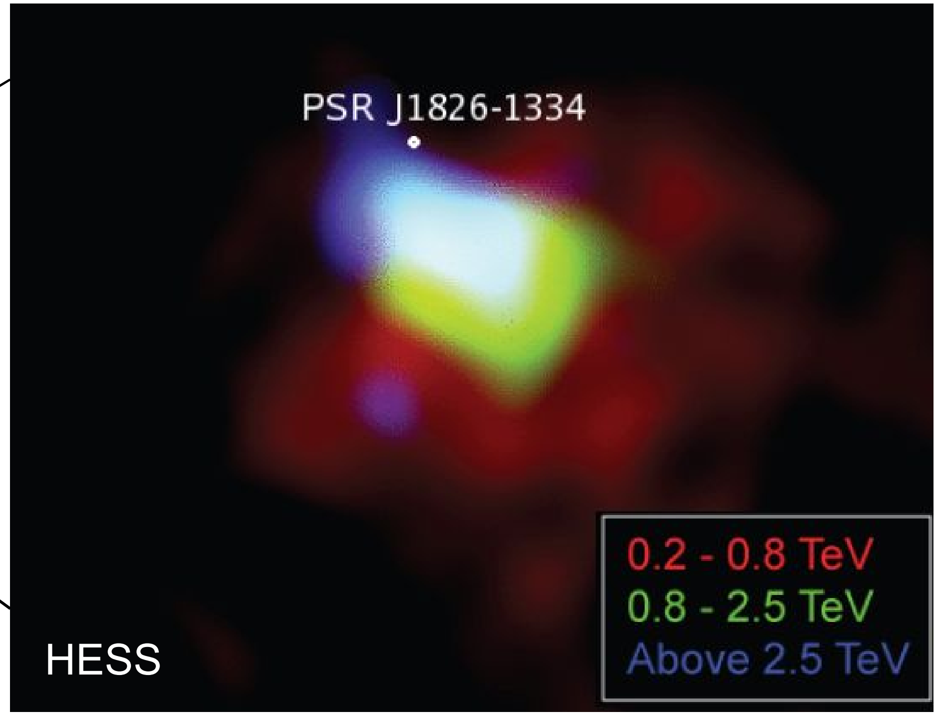
(shown : best gaussian fits and point-like source effect)

TeV spectrum = power-law with photon index ~ 2.3 up to 30 TeV. Good fit by Inverse Compton of relativistic e^- on IR from dust, CMB, and starlight in ***B ~ 17 μG***

Pulsar wind nebulae

Ex 2 : HESS J1825-137
evolved (offset) PWN, t ~ 21.4 kyr

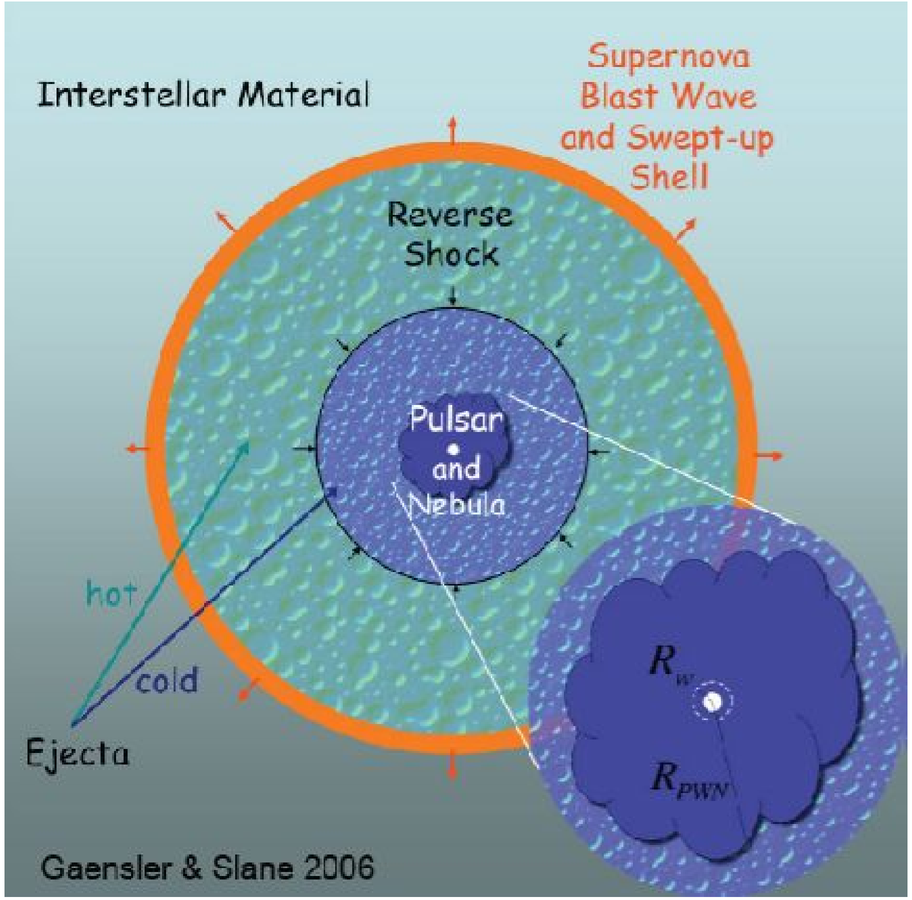




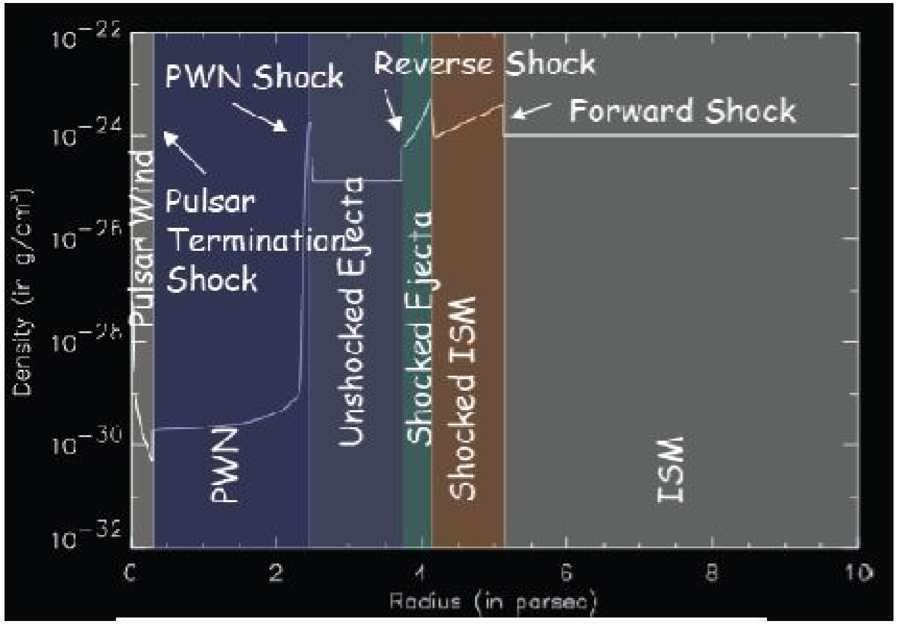
Observed spectral evolution with distance from pulsar → significant constraints. Favours leptonic scenario with radiative losses.

Detailed morphology → studies of particle transport, radiative losses …
Particle acceleration mechanisms
Fermi processes; contribution to CR?
Outer boundary conditions for physics of pulsar magnetospheres

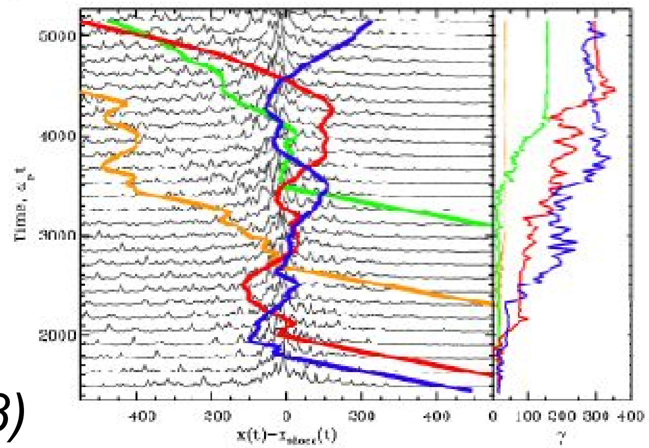
PWN : laboratories to study particle acceleration in shocks and turbulence



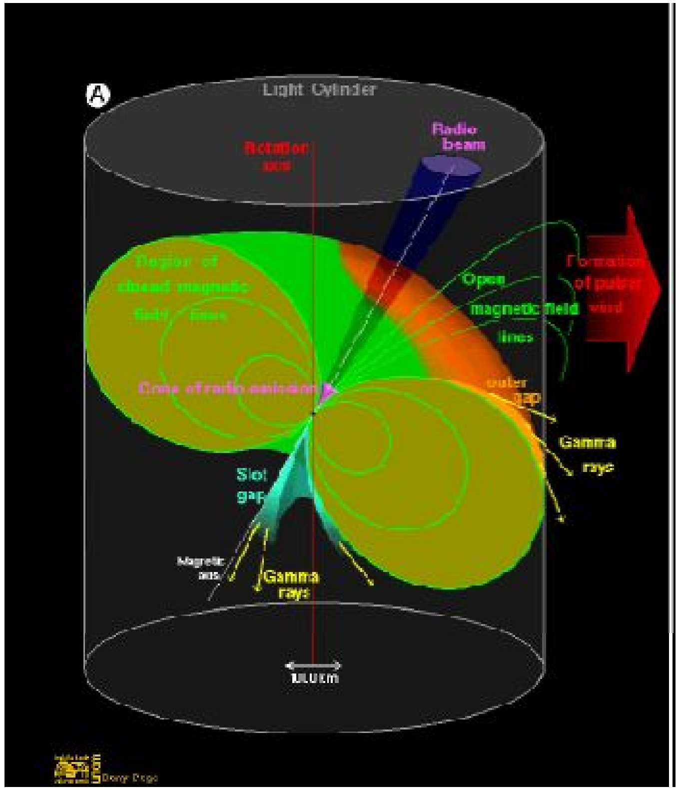
A complex shock pattern, with constrained boundary conditions



Acceleration at a relativistic shock : 1st observation of Fermi process in PIC simulations ? *(Spitkovsky, 2008)*



Pulsars

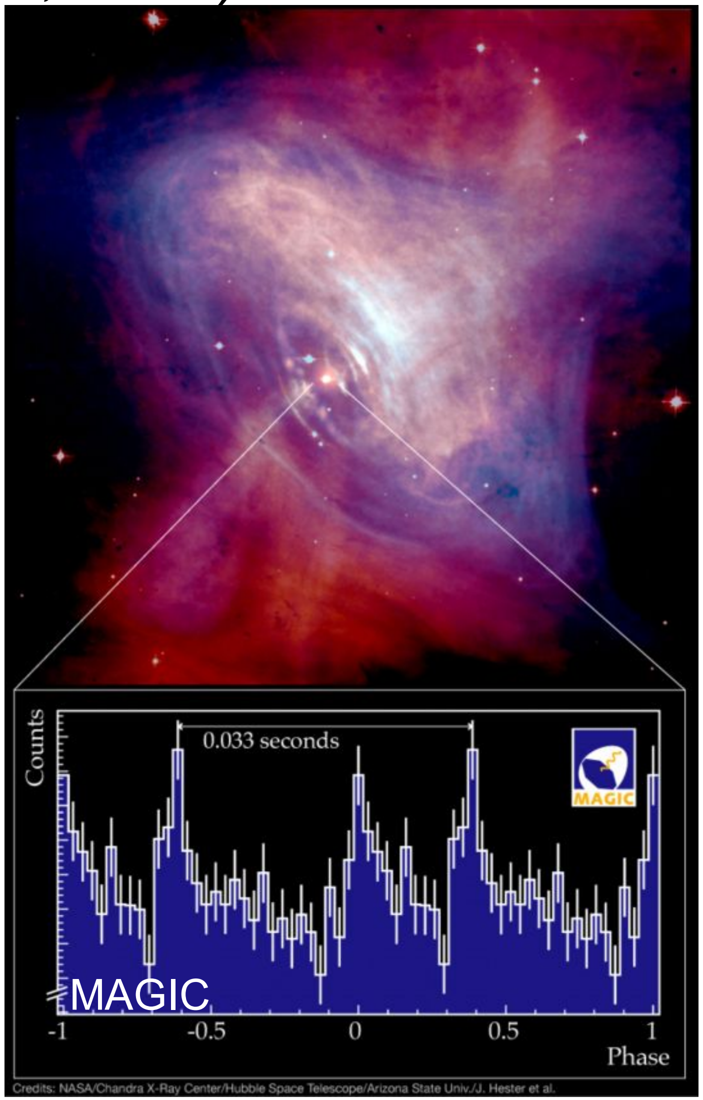


A new field to further study at VHE.

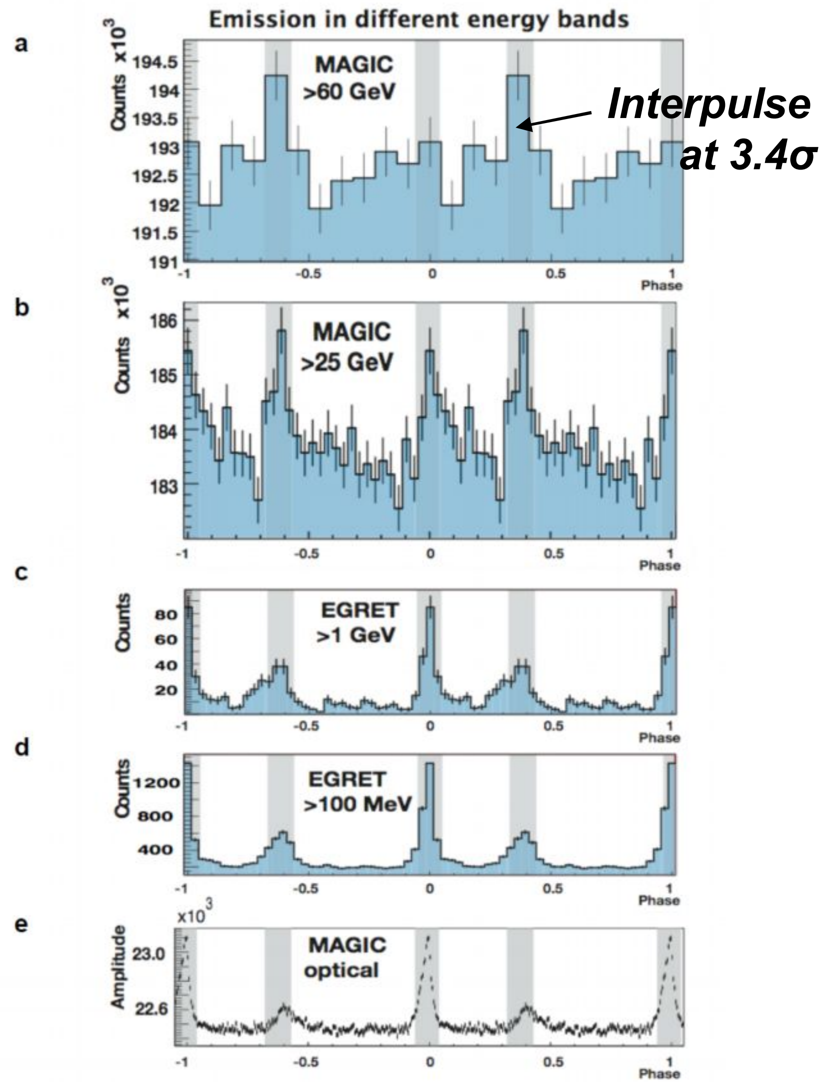
Search for pulsar cut-off, constrain acceleration and emission mechanisms, tests the various gap models, search for short timescale events (drift, glitches …)

Field to be explored with FERMI, MAGIC II and HESS II.
However, cut-off at higher E for ms-pulsars.

Very first detection of pulsed VHE (> 25 GeV) emission from a pulsar : the Crab pulsar → Steep turnover above 10 GeV, but relatively high cutoff energy in phase-averaged spectrum.
(Sciences , 2008)



Pulse in phase with EGRET



Such detection excludes polar cap scenarios for VHE gamma-rays.
Favors outer-gap models.
Challenges slot-gap models.

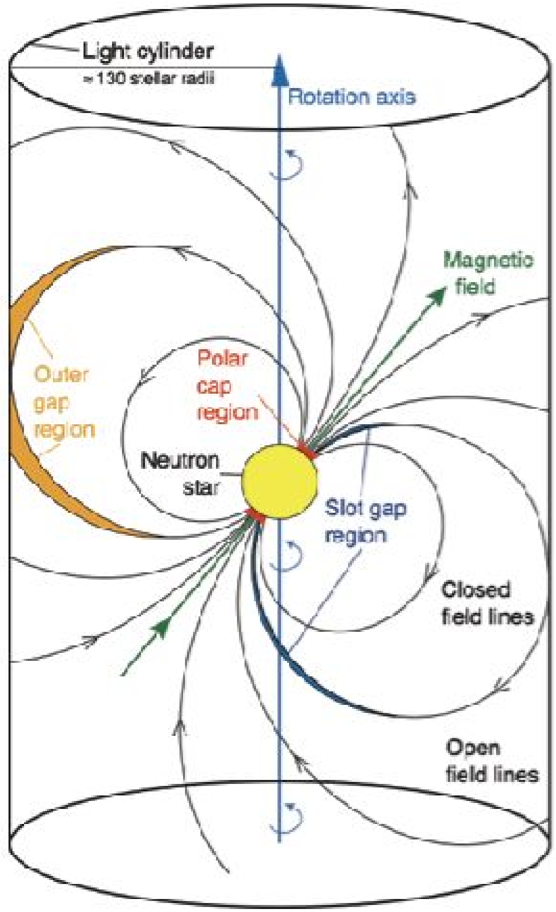
pair-creation cut-off energy

r, radial distance of VHE emitting zone

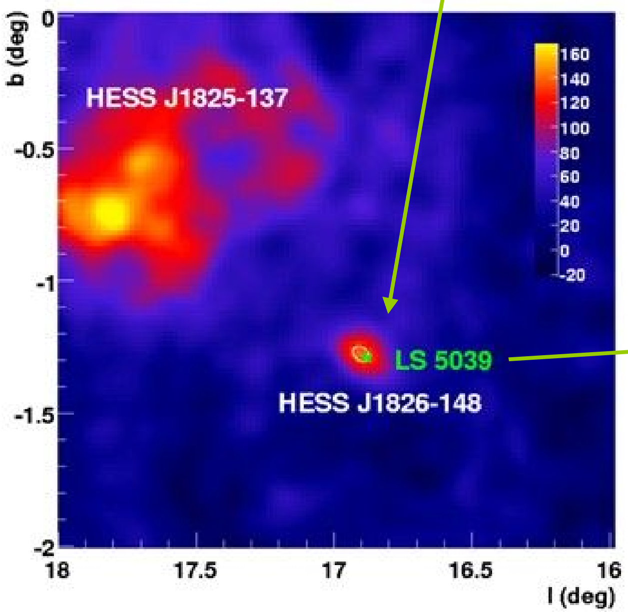
$$\varepsilon_{max} \approx 0.4 \sqrt{P \frac{r}{R_0}} \max\left\{1, \frac{0.1 B_{crit}}{B_0}\left(\frac{r}{R_0}\right)^3\right\} GeV$$

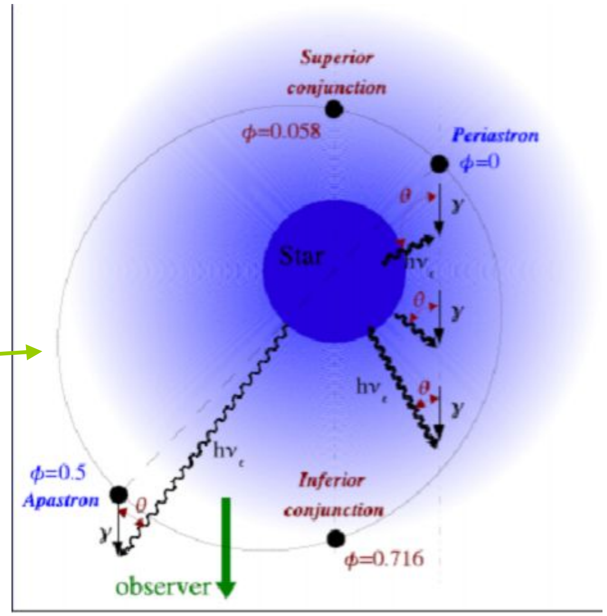
from Baring, 2004 : gamma-ray absorption by magnetic-pair production in rotating dipolar B

$B_0 = 8 \times 10^{12}$ G (Crab values)
$B_{crit} = 4.4 \times 10^{13}$ G (onset of quantum effects)
P = 0.033 s
$\varepsilon_{max} \sim 23$ GeV → r > 6 R_0, well above the neutron star surface.



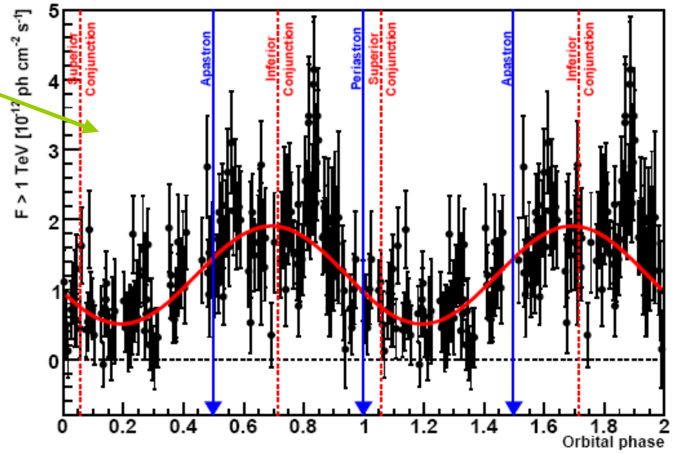
Binary systems :
the HMXRB *LS 5039, microquasar candidate*

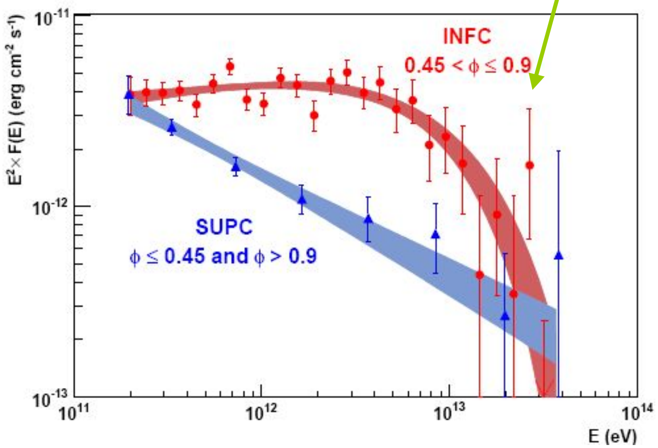




2 spectral states at TeV

VHE detection of the orbital period P_{orb} = 3.9 days

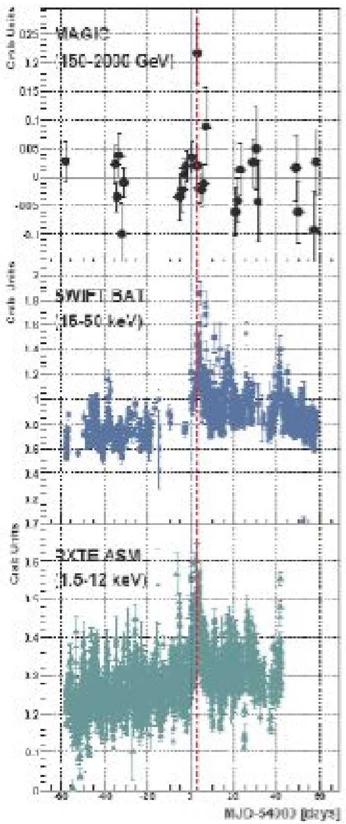


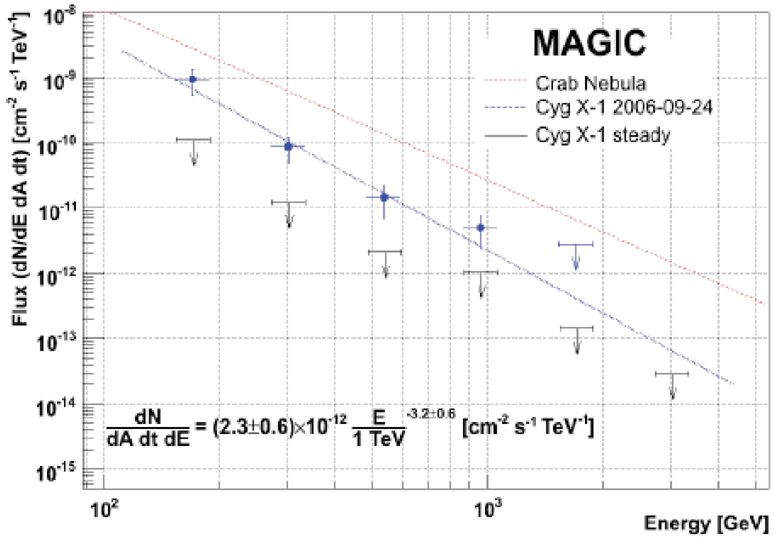


A well constrained system now with detailed modelling.

Cygnus X-1

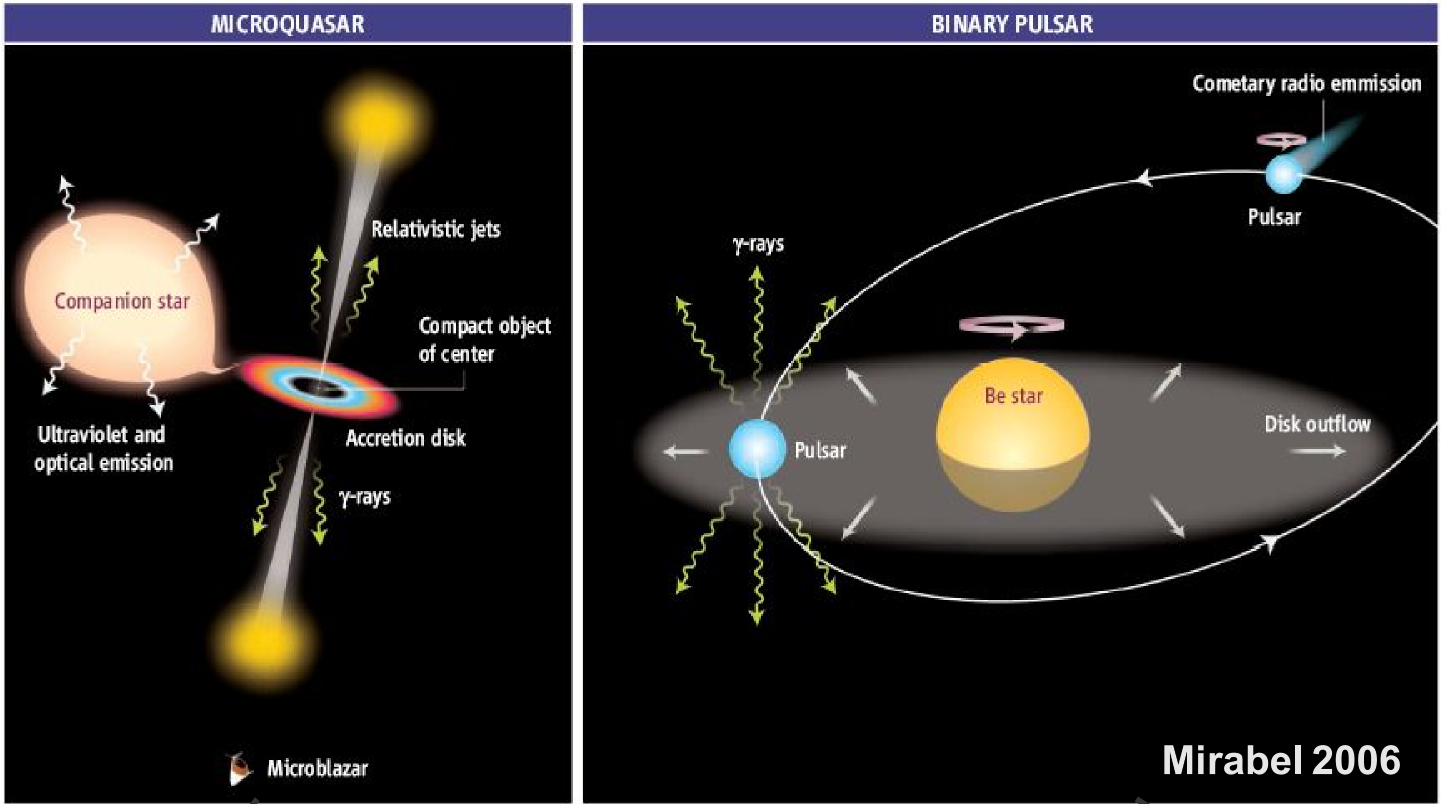
Best candidate for stellar BH (~ 21 M☼), among the brightest X-ray sources VHE flares coincident with X-ray flares seen by Swift/BAT, RXTE/ASM and INTEGRAL.





Gamma-ray Binaries

Jets versus pulsar winds scenarios



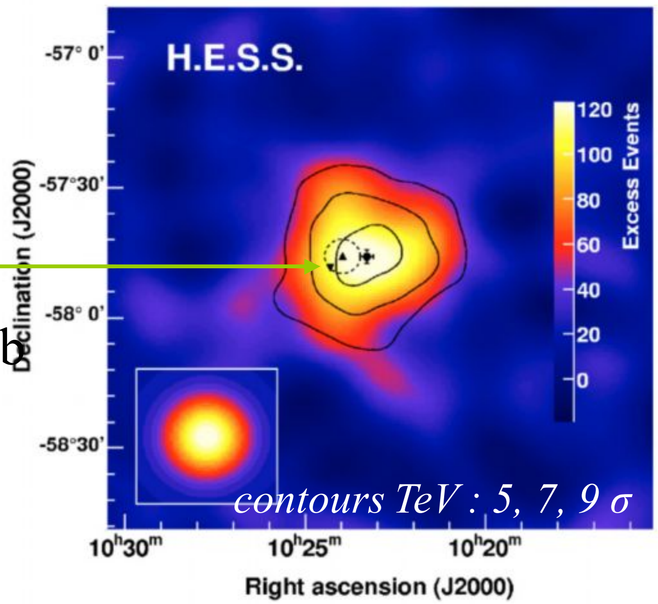
Particles (electrons or hadrons) are accelerated in a jet powered by accretion

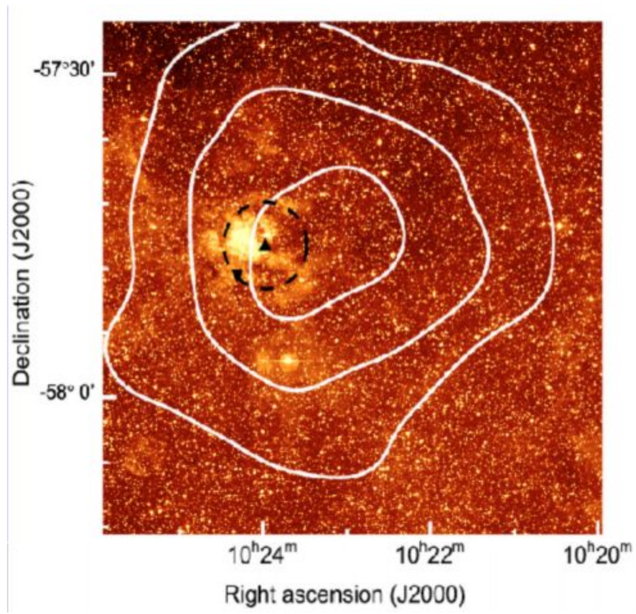
γ-rays produced in the shock where the wind of the young pulsar and the wind of the companion star collide

VHE gamma-rays from young stellar clusters

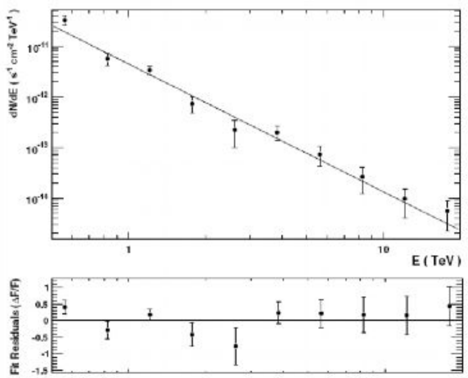
Westerlund 2

binary
WR 20a,
and WR 20b





TeV
contours
on B
image

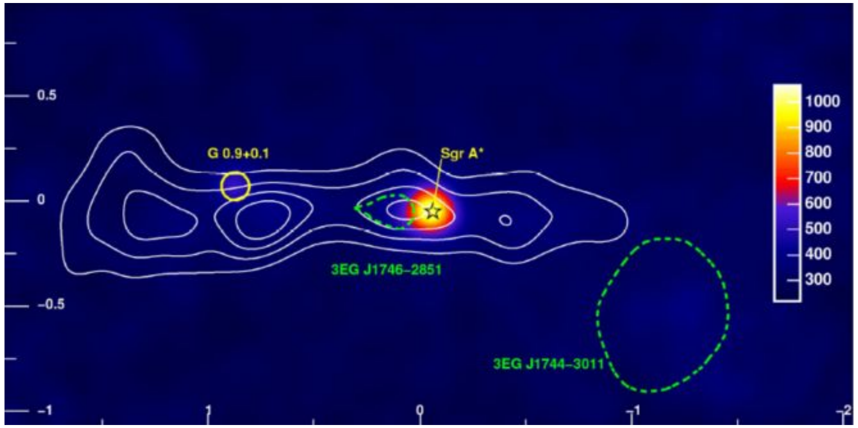


Possible origines of the TeV emission ?

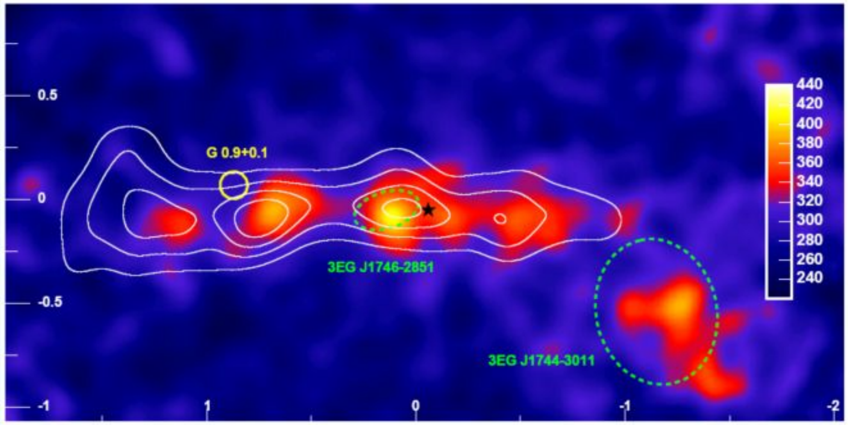
- Colliding winds in the supermassive system WR 20a
- Collective effect of stellar winds from hot and massive stars
- Acceleration in shock from a superbubble wind
- Supersonic winds / ISM interaction

→ requires further investigation with higher sensitivity and angular resolution.

The galactic center



2 bright TeV sources :
. J1745-290 (Sgr A* ?)
. G0.9+0.1
200 pc, resolution < 6'



Diffuse emission, after subtracting the 2 point sources : VHE fluxes + white contours of CS, a molecular tracer
→ clear correlation VHE-CS
(Nature, 2006)

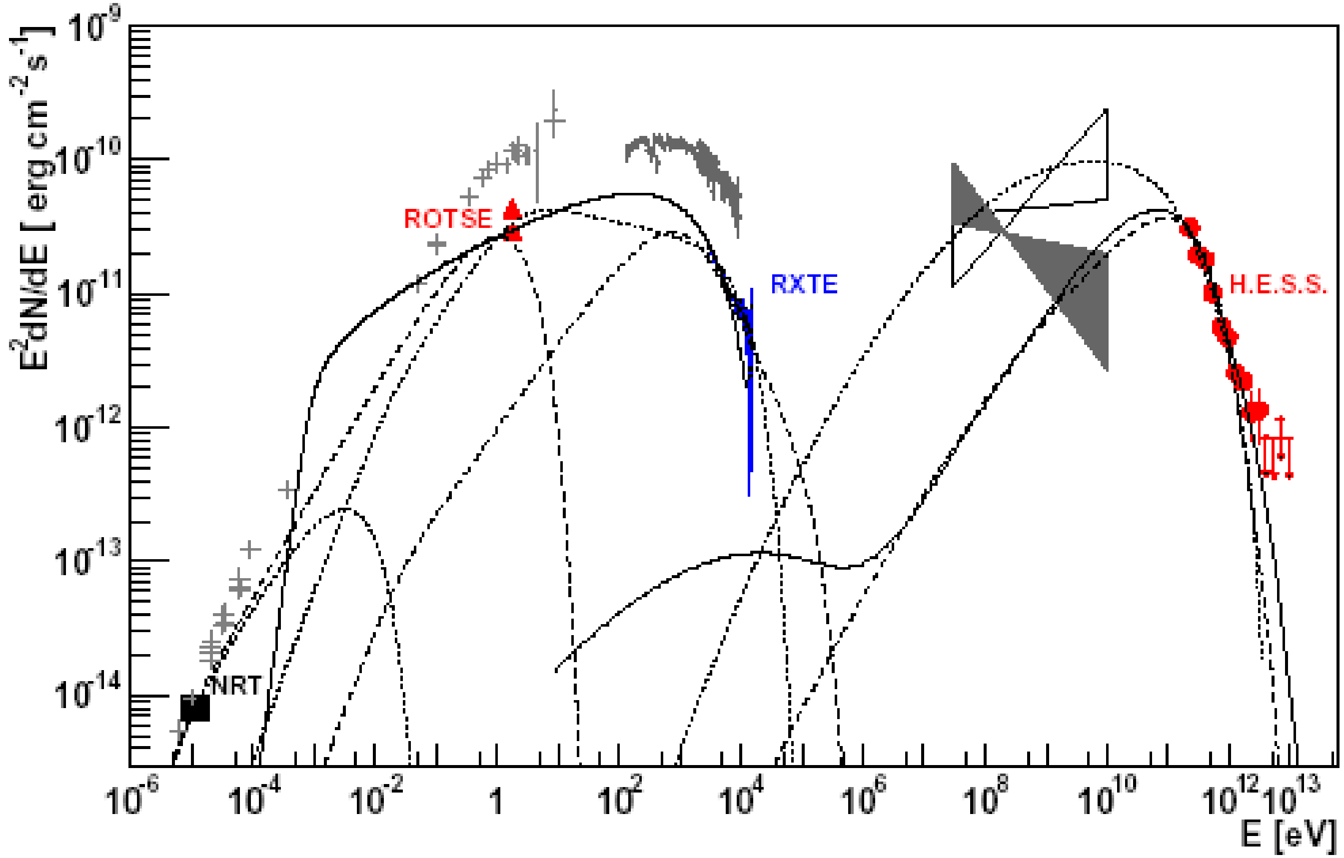
Observed TeV flux requires an energy density of cosmic rays > 3 times the one in the solar environment, and a harder spectrum

→ recent particle acceleration event, < 10 000 years,
near the Galactic Center (SNs or active BH).

Active Galactic Nuclei :

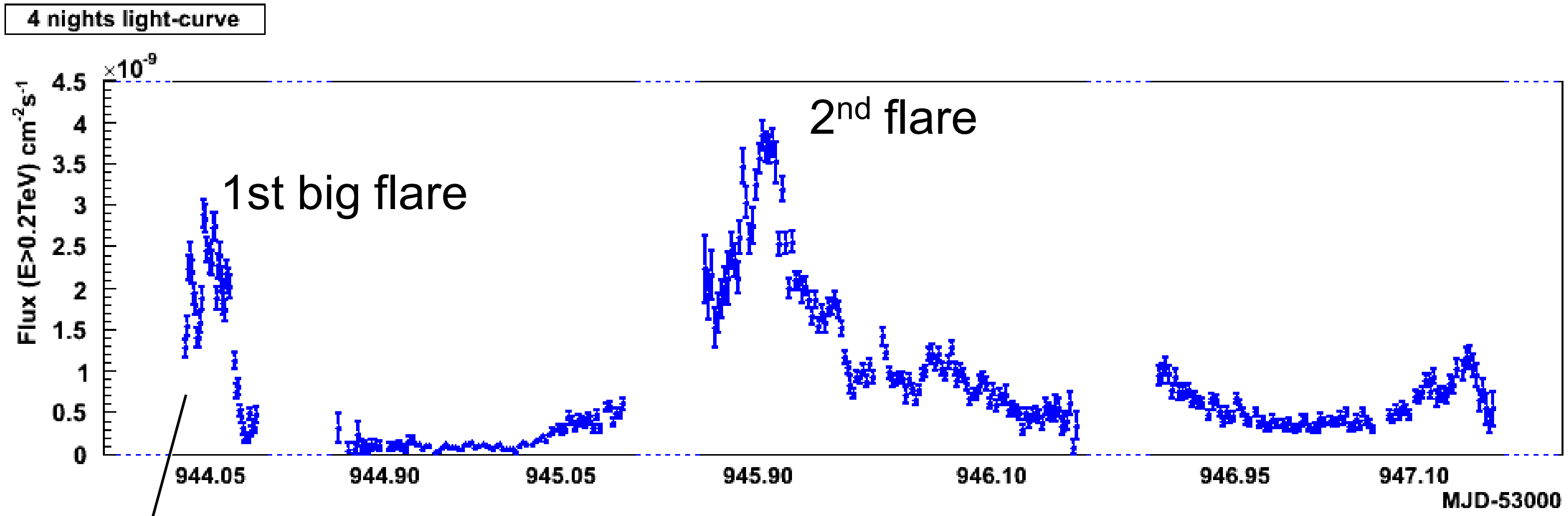
More than 20 **blazars** of the **HBL** type detected at VHE

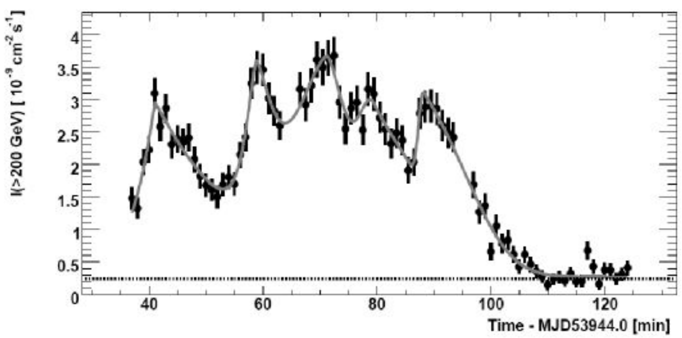
(HBL = high frequency peaked BL Lac)



Various hadronic and leptonic models can often fit present available spectra of HBL *ex : SED of PKS2155-304 in quiescent state*

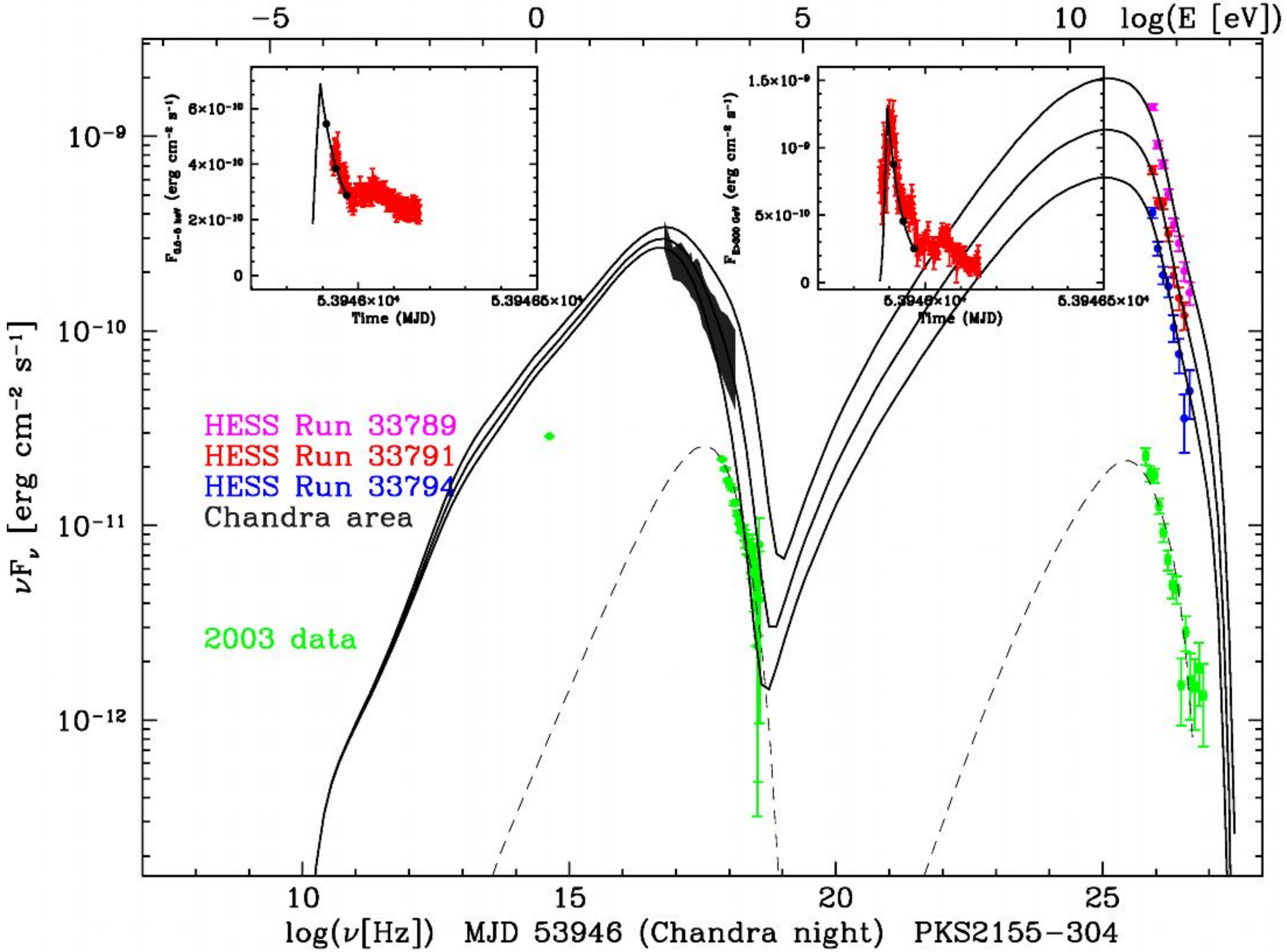
Probing highly variable events in TeV blazars





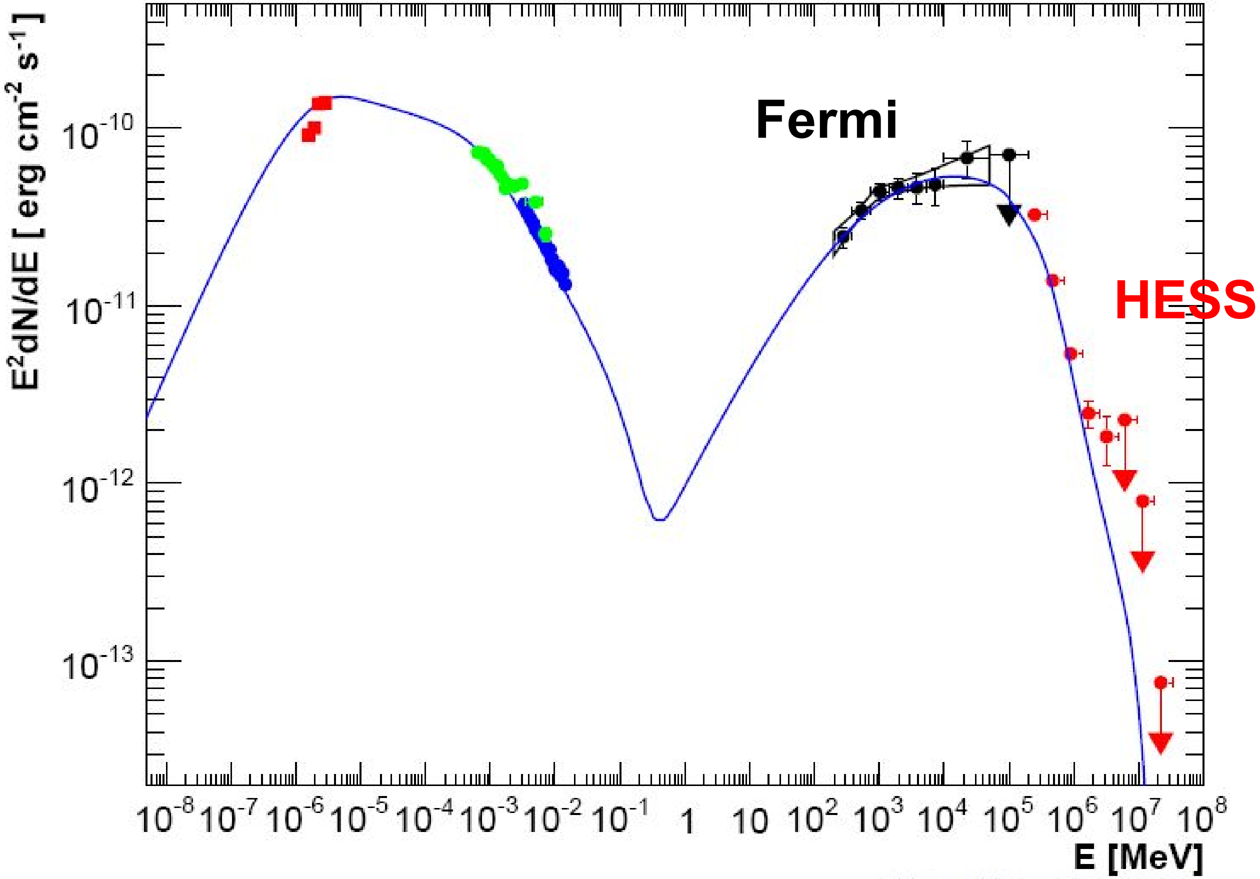
Monitoring an extraordinary active state of PKS 2155-304 in 2006, detected by HESS + multi-lambda campaign.

Down to minute time scale !
→ Emitting zone smaller than R_g or very high bulk Lorentz factor



Fit of the 2nd flare of PKS2155 by SSC time-dependent modeling : Reproduce light curves and spectra in X and gamma rays

PKS 2155 in 2008



New multi-lambda campaign in 2008, including HESS, Fermi, RXTE, SWIFT, ATOM

Complexity of correlation between various lambda :

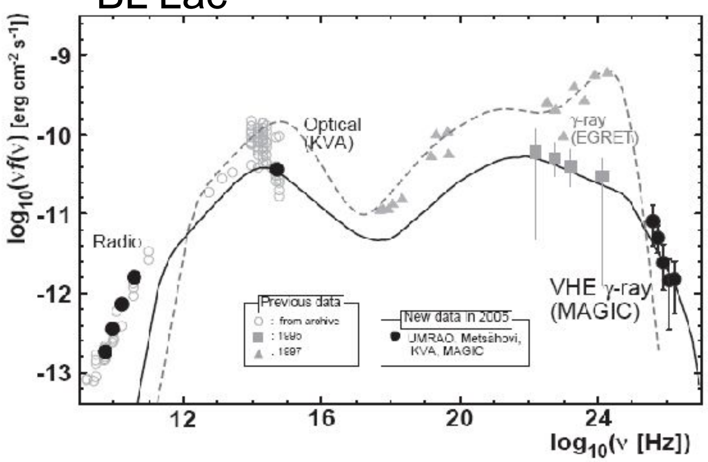
Simple SSC model can not explain all correlation properties.

Correlations appear different between active and low states.

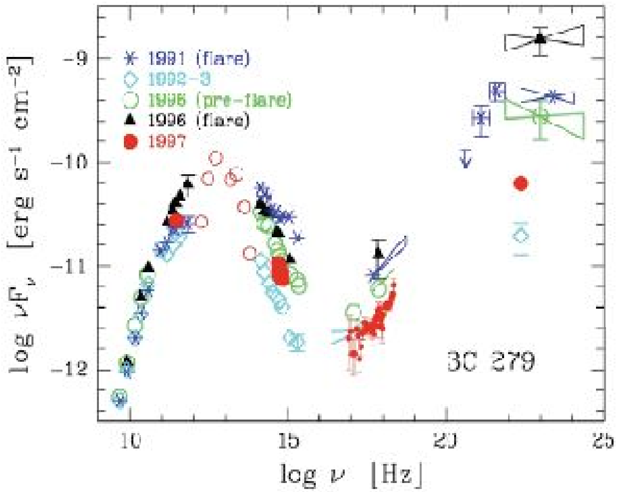
Active Galactic Nuclei :

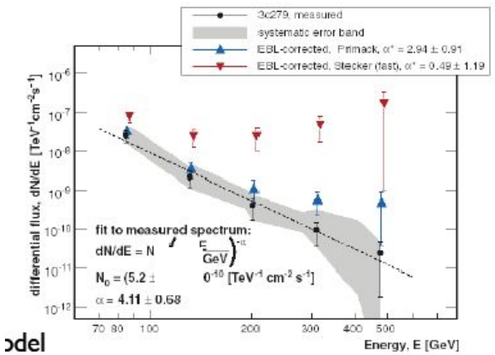
~ a few **blazars** of others BL Lac types (**LBL**, **IBL** and **FSRQ**) detected at TeV

BL Lac



High variability and broad band spectra
→ Stringent necessity of coordinated HE and multi-lambda monitoring to constrain SED and evolution.





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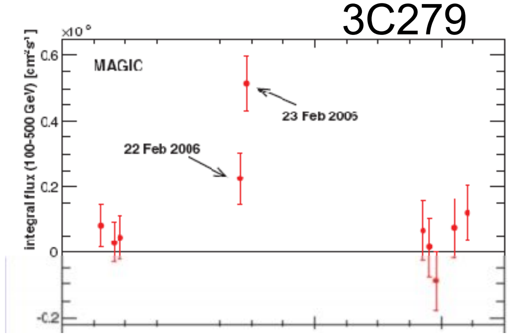
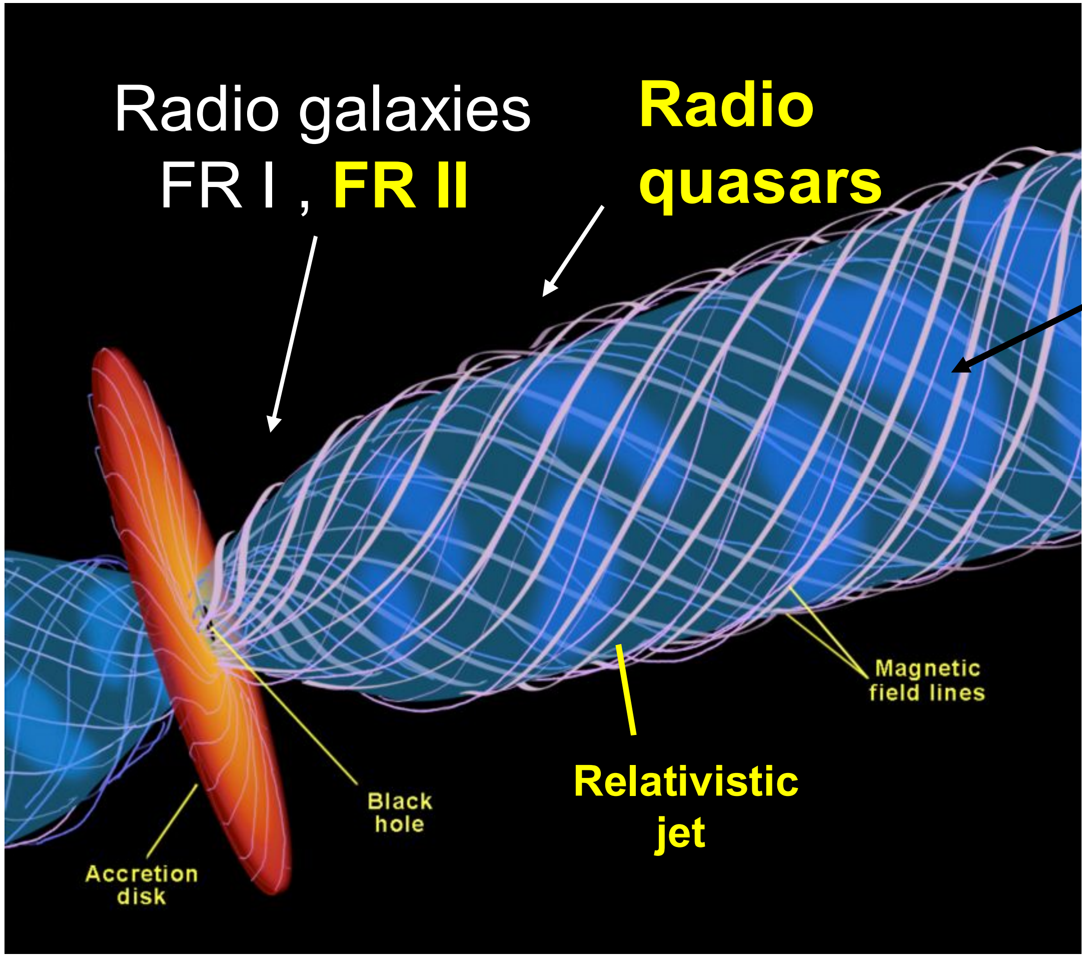


TeV emitting zone(s) : in a jet or outflow with relativistic bulk motion

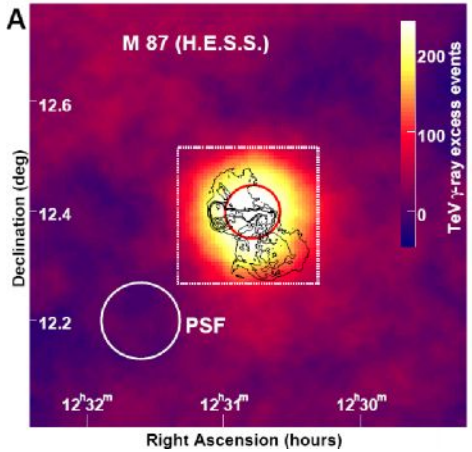


BL Lac
(HBL, LBL)
and FSRQ

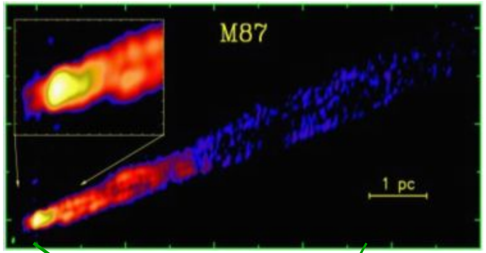
Strong relativitic boosting (~ factor δ^4) favours detection of blazars/BL Lac
However …

Active Galactic Nuclei :

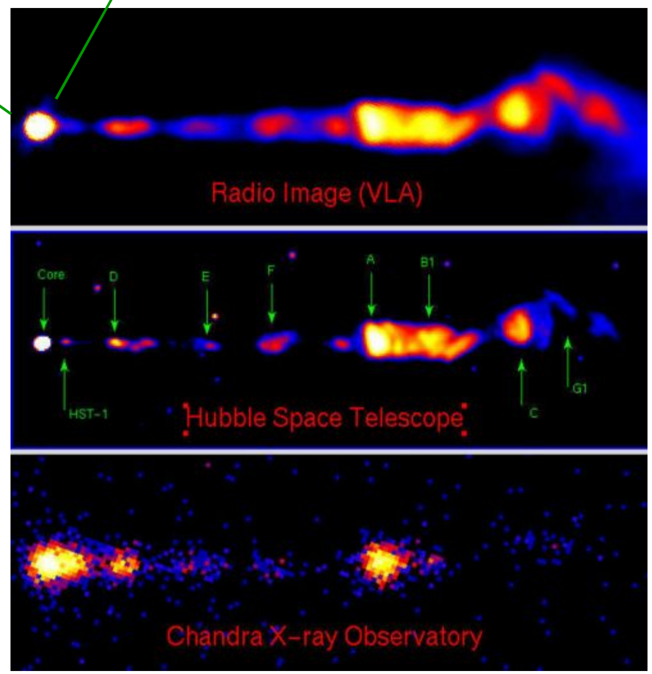
...two **radiogalaxies** now detected at TeV energies, M87 and Cen A



TeV



radio

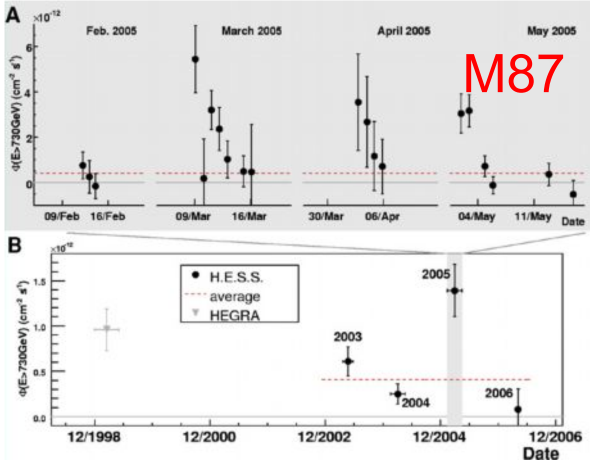


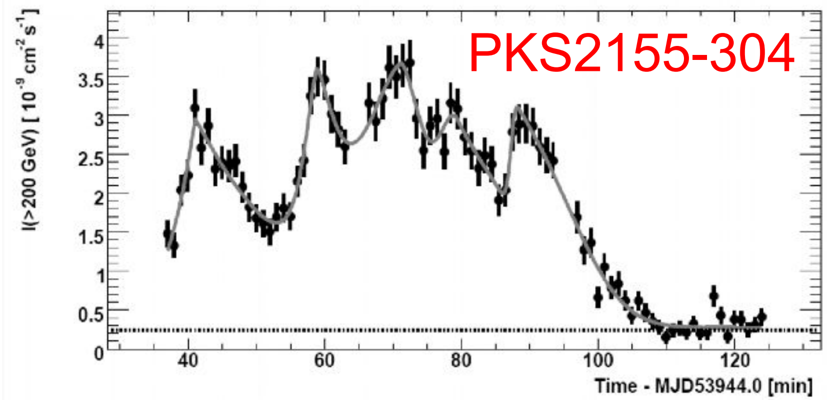
HST

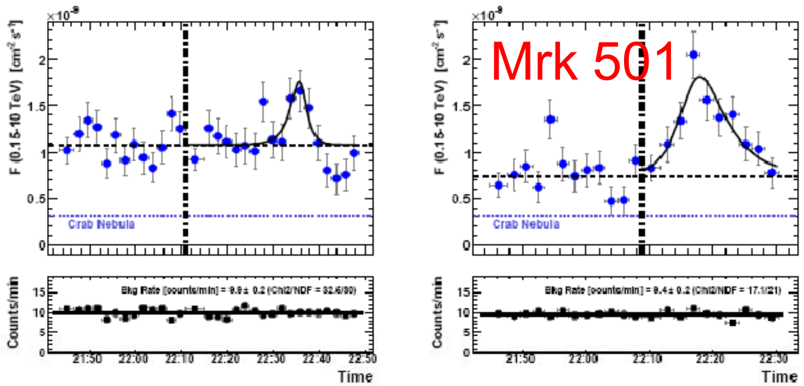
X

M87 : 3 possible TeV emitting zones

- The peculiar knot HST-1 at ~ 65 pc from the nucleus
- The inner VLBI jet
- The central core and the black hole environment







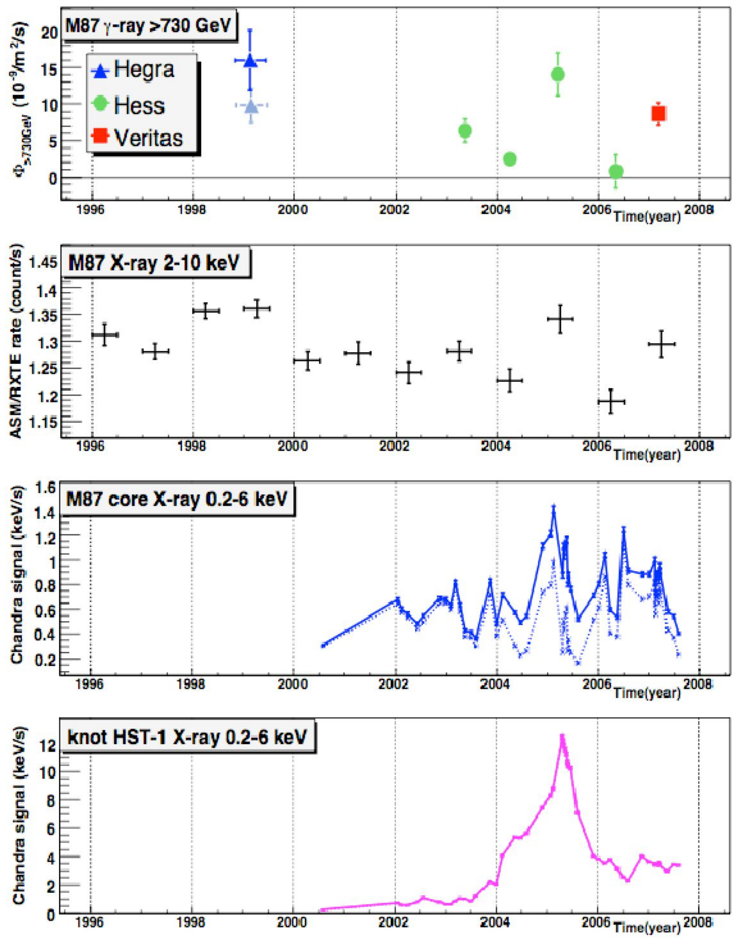
Size constraints from variability

- TeV variability of M87 requires very small emitting zone, of the order of a few r_g or even less (even for high δ) under causality argument, as for the BL Lac PKS2155-304 and Mrk501.
- Challenge to efficiently accelerate particles in such small zones (core around BH, or very inner jet).
- Study of close BH environment
- Possibly a mixture of hadronic and leptonic processes → requires further observationnal multi-lambda constraints.

M 87 : HST-1 versus core scenarios ?

X-ray light curve of HST-1 obtained by Chandra in 2008 does not follow the TeV one *(VERITAS)*

→ favours scenarios with TeV emission from inner jet or central core.



- Recent inner jet scenarios, adapted from standard TeV models for HBL but at larger viewing angles *(ex: Lenain et al, 2008)*

- New core scenarios, with particle acceleration in turbulent accretion disks or in rotating magnetosphere *(ex : Istomin, Sol, 2009)*

Exploring radiogalaxies at VHE

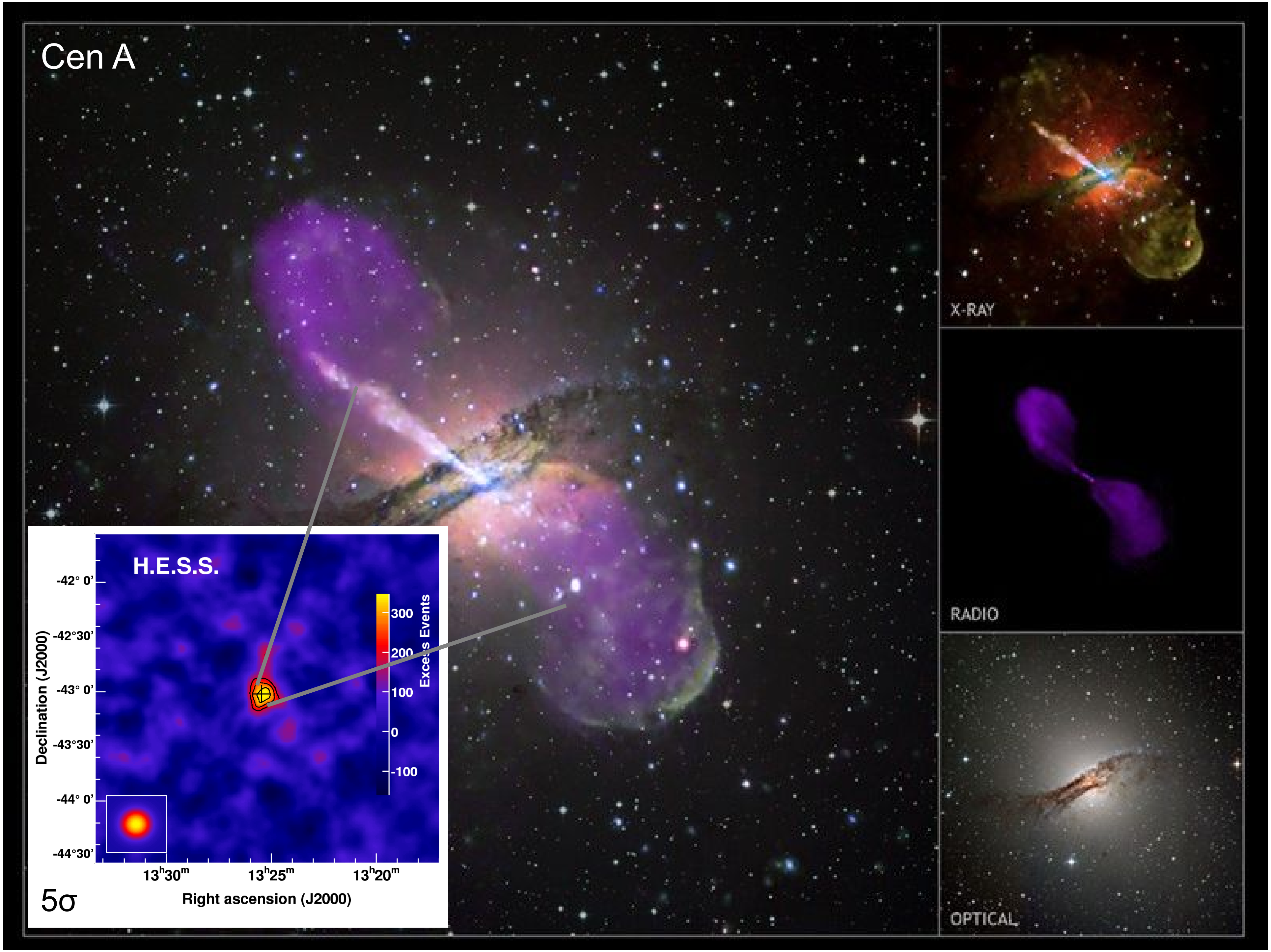
- Recent discovery of VHE emission from **Cen A** with HESS *(ApJ Letter, 2009)*

- Together with M87, ***establishes radio galaxies as a new class of VHE emitters***

- Three different types of AGN now detected at VHE (blazars, radiogalaxies, and weak AGN as Galactic Center)

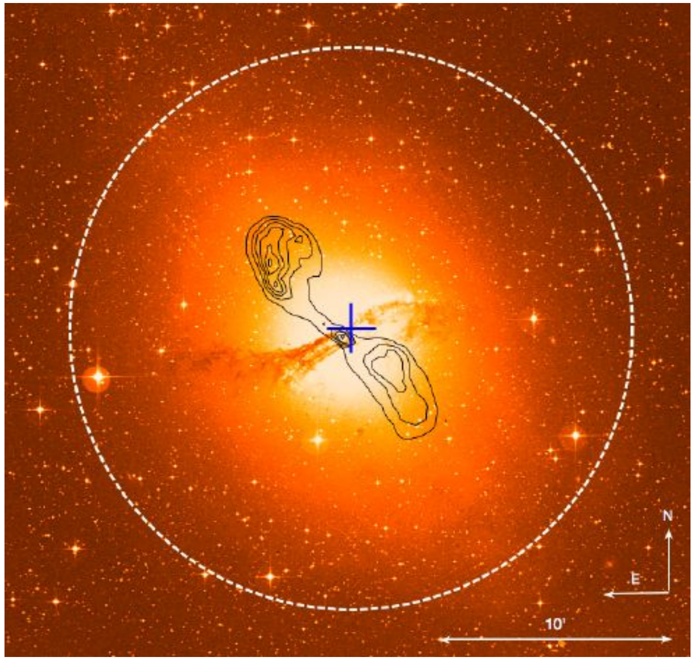
  → ***is VHE emission a general feature of AGN and SMBH ?***

Richness of the extragalactic space at VHE, to further explore with MAGIC II, HESS II and CTA



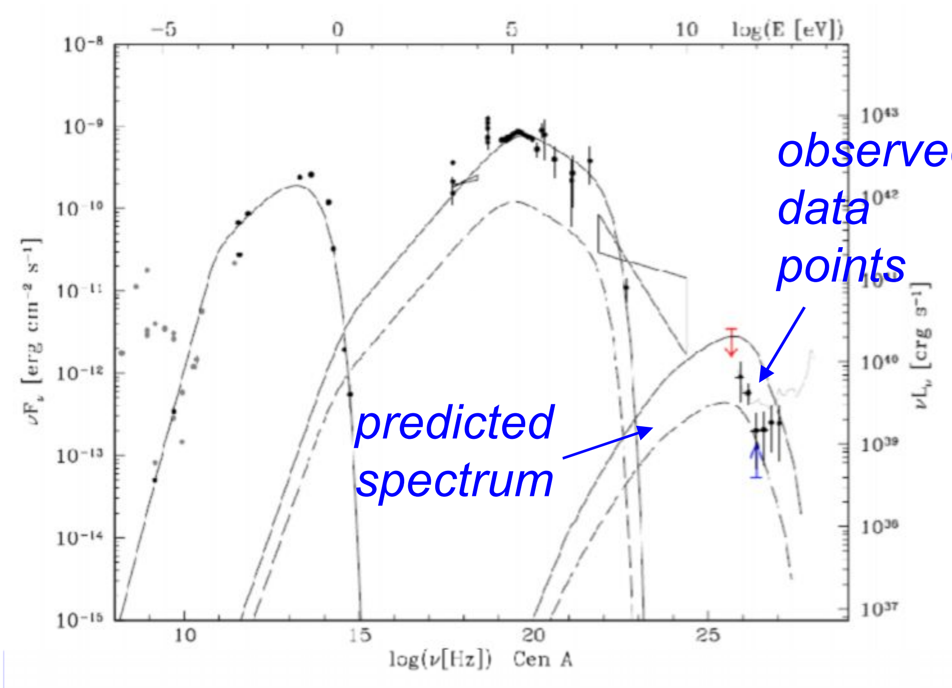
Cen A
H.E.S.S.
-42° 0'
-42°30'
-43° 0'
-43°30'
-44° 0'
-44°30'
Declination (J2000)
13h30m
13h25m
13h20m
Right ascension (J2000)
300
200
100
0
-100
Excess Events
5σ
X-RAY
RADIO
OPTICAL

Origin of the VHE emission ?
Compatible with radio core and inner kpc jets of Cen A



Possible VHE zones ?
- BH magnetosphere
- base of jets
- jets and inner lobes
- pair halo in host galaxy

Link to UHECR ?



SSC emission from jet formation zone (Lenain et al, 2008)

Further observing AGN at VHE

- TeV observations *disentangle non-thermal effects from thermal ones* possibly present at others wavelengths → provide a simplified view of the physics at the highest energies.

- Explore *variability at the shortest time scales*

  → jet physics, particle acceleration and radiation processes; search for VHE emission from large scale radio jets and hot spots

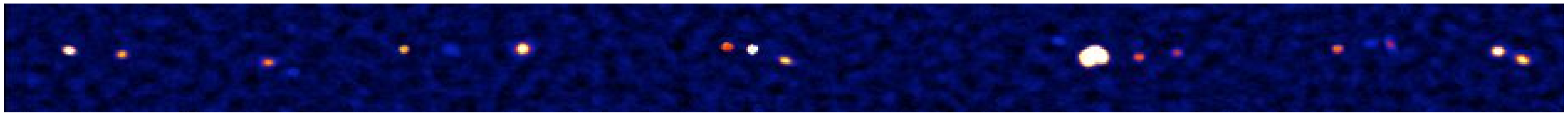
  → physics of supermassive Black Hole environnement; constraints on accretion physics

  → build a sample of sources at different redshifts, to check validity of Lorentz invariance (and analyze the Extragalactic Background Light in parallel).

- Gather samples of different AGN types to allow *statistical studies* for classification, unification schemes, AGN evolution. Check the 'blazar sequence', probe the quiescent states … Look for VHE emission from « dormant » BH or « dead » quasars (could provide evidences for missing SMBH) → Studies of *AGN and SMBH evolution*, AGN feedback and co-evolution with host-galaxies.

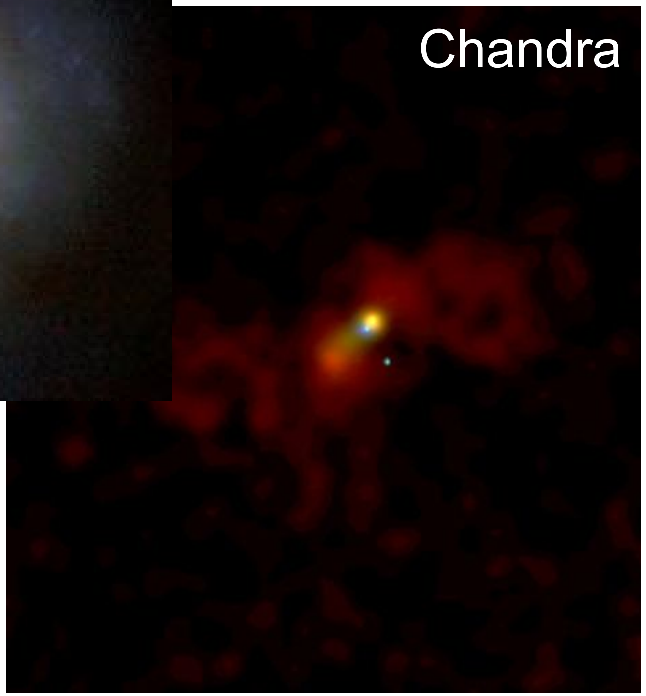
- **Importance of multi-messenger and multi-lambda analyses.**

Some open fields to explore
with the next generation of IACT

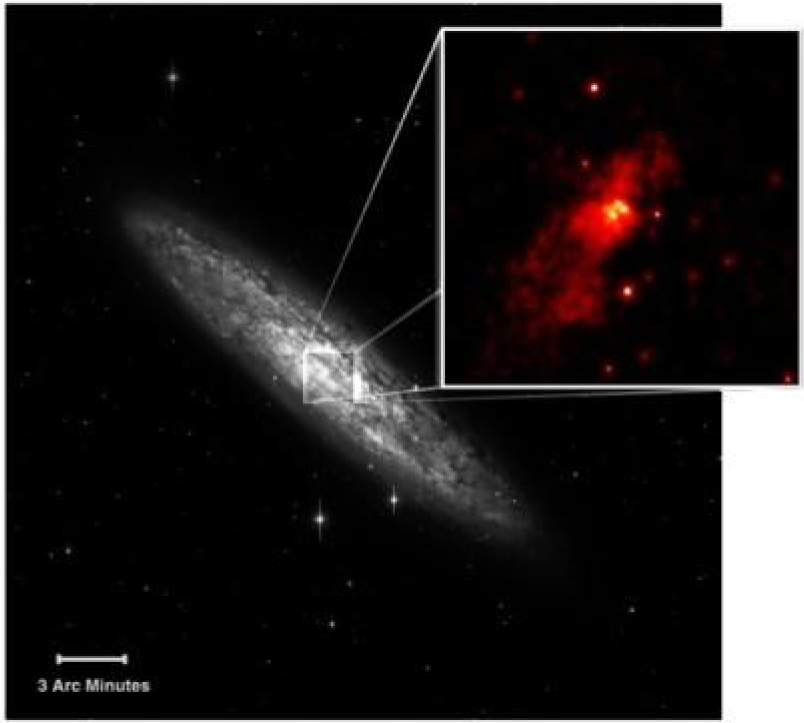


Starburst galaxies and ULIRG :

TeV detection still difficult although flux upper limits are approaching theoretical predictions



Collision,
star formation,
superwind …

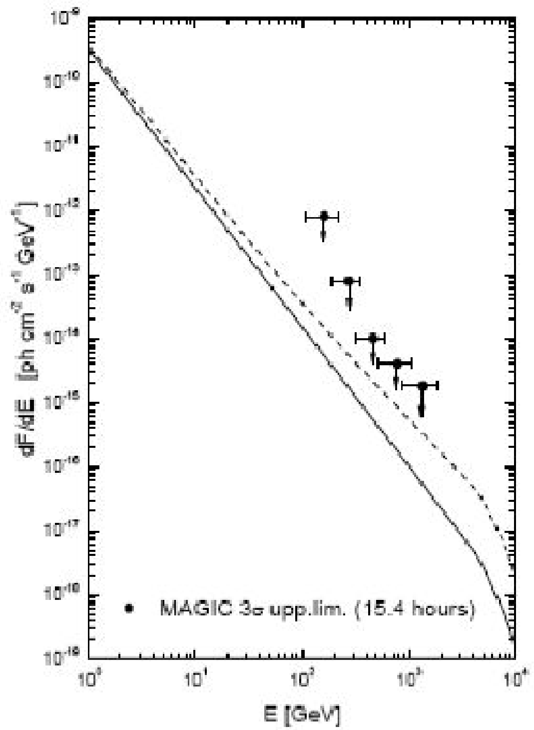


Arp 220 (ULIRG)

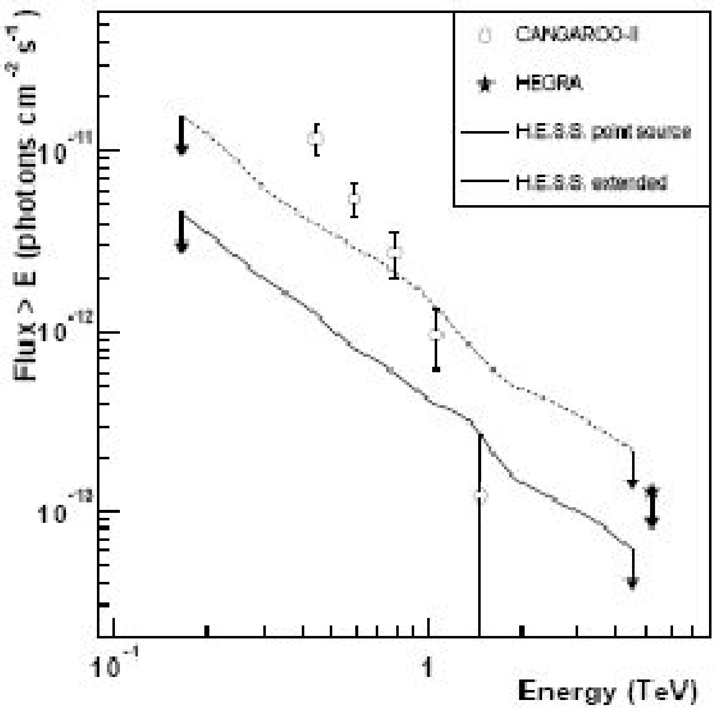
NGC 253

Starburst galaxies and ULIRG :

TeV detection still difficult although flux upper limits are approaching theoretical predictions



Arp 220 (ULIRG)



NGC 253

Clusters of galaxies :

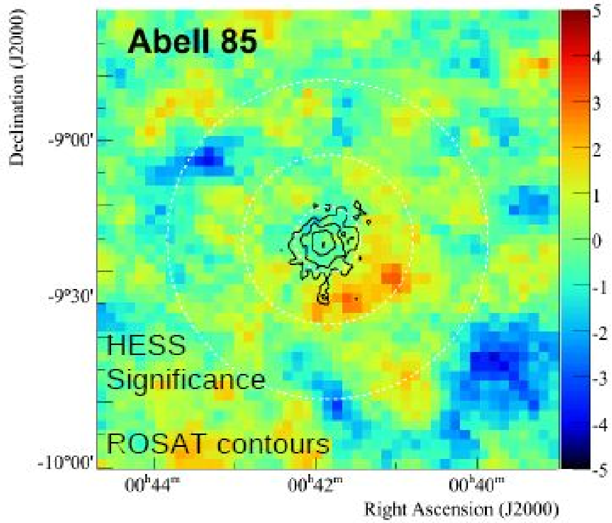
No VHE detection yet

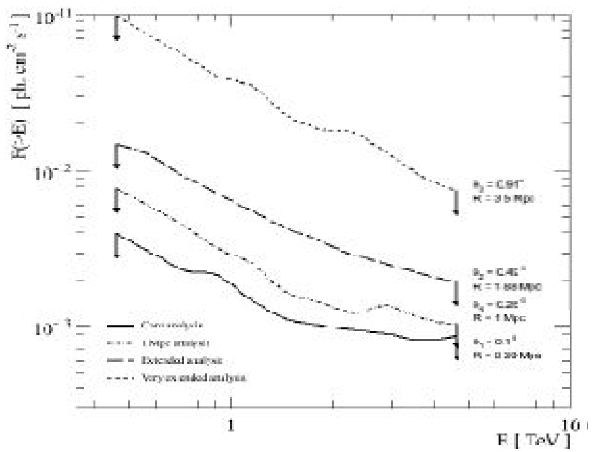
Non-detection of nearby clusters (A&A, 2009) provides upper limits on the total energy E_{CR} of hadronic Cosmic Rays :

In Abell 496 : E_{CR} < 51% of E_{th}

In Abell 85 : E_{CR} < 8 % of E_{th}

Close to theoretical models which predict E_{CR} ~ 10 % of E_{th} , thermal energy of the ICM.

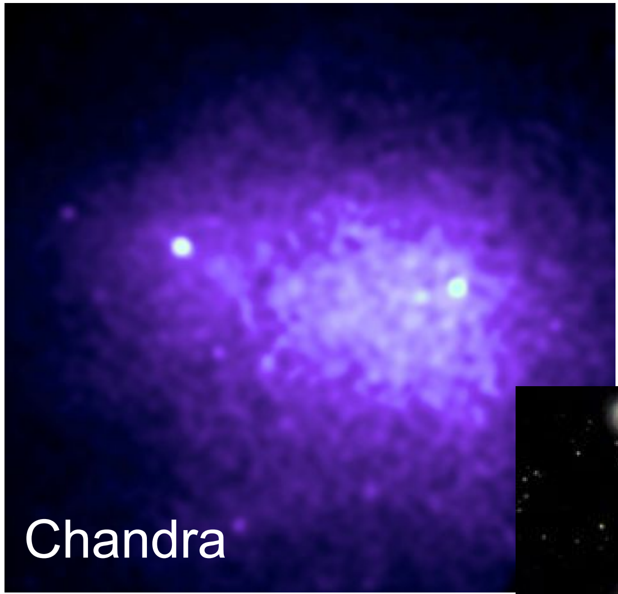


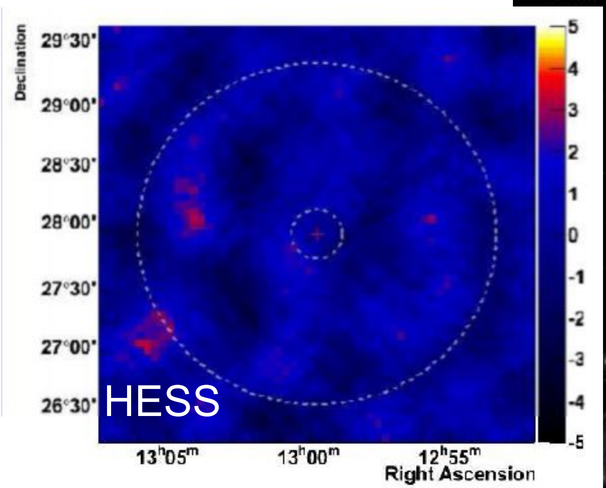


32.5 hours livetime

Detect galaxy clusters ?

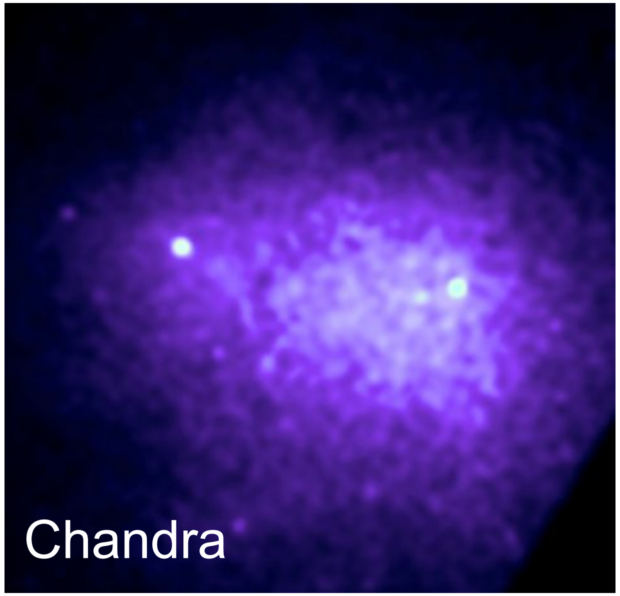
Coma cluster





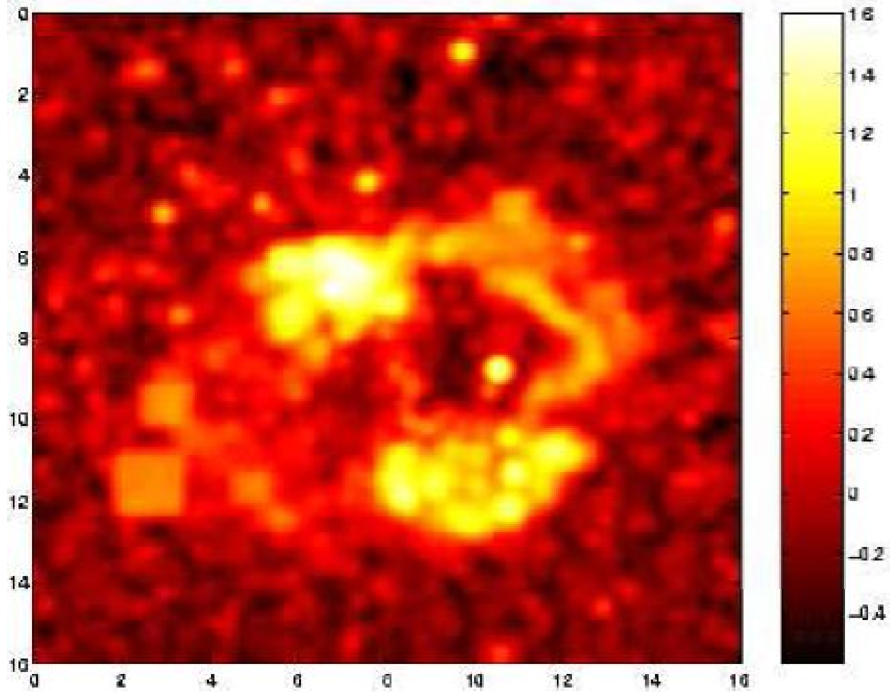
Detect galaxy clusters ?

Coma cluster



Several potential particle acceleration sites :
- Accretion and merger shocks
- SNR and galactic winds
- AGN outbursts
- Turbulence → re-acceleration

Expect VHE radiation from :
- IC of electrons on 3K CMB
- pp collisions (enhanced due to p confinement)



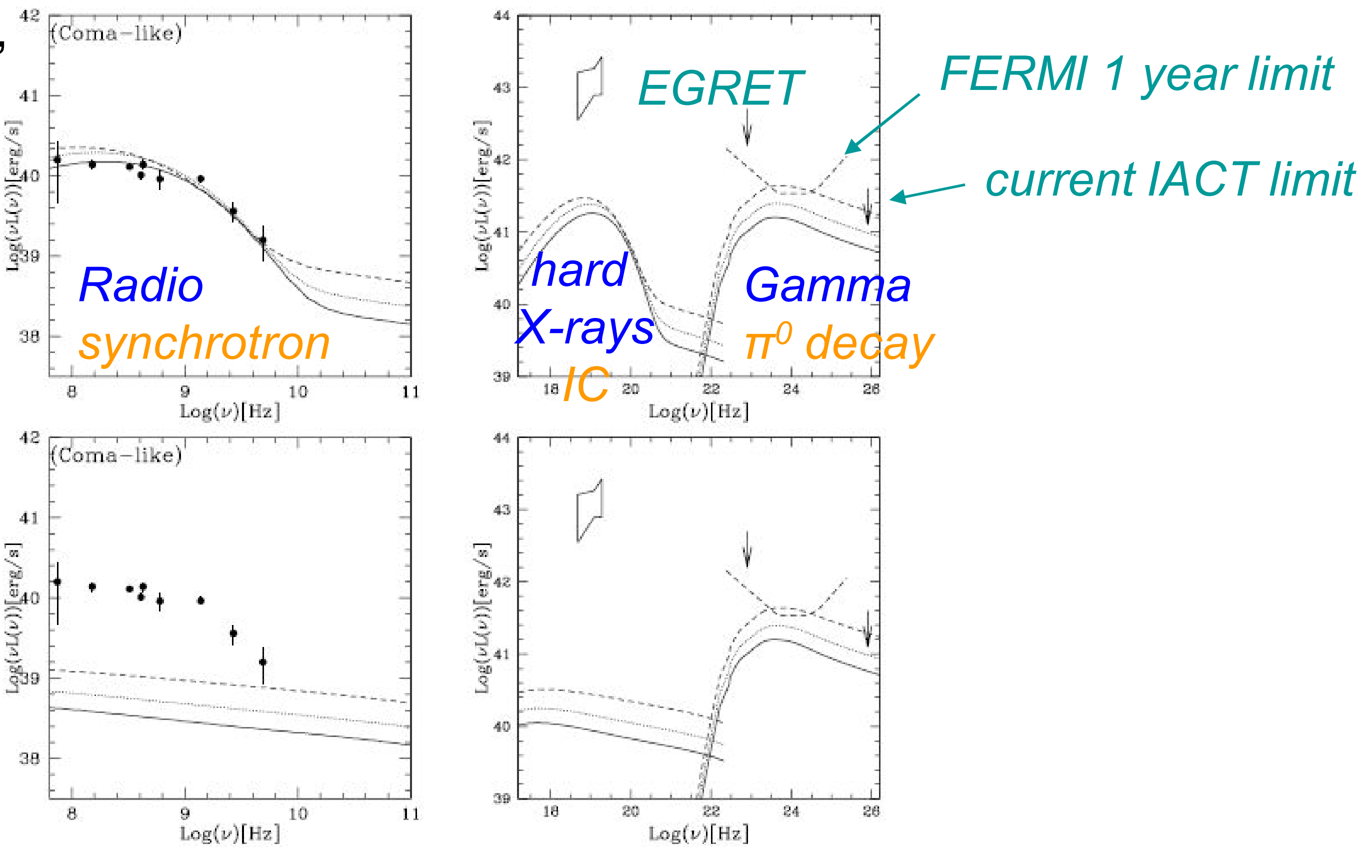
Simulated VHE emission from a nearby rich galaxy cluster, with 0.2° resolution, 16°x16°, IC process *(Keshet et al, 2003).* A 5-10 Mpc ring ~ cluster accretion shock?

Detect galaxy clusters at VHE

A project for the next generation of IACT ?

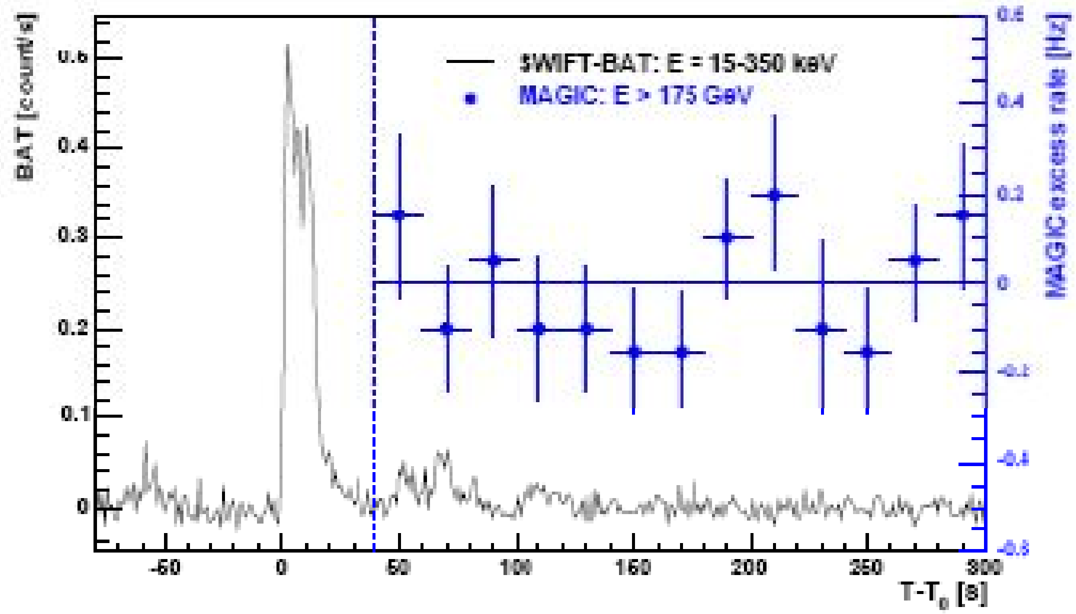
(2) : (1) + 'transient' emission due to reaccelerated electrons (0.5 Gyr after injection of turbulence)

(1) : long-term emission due to relativistic protons



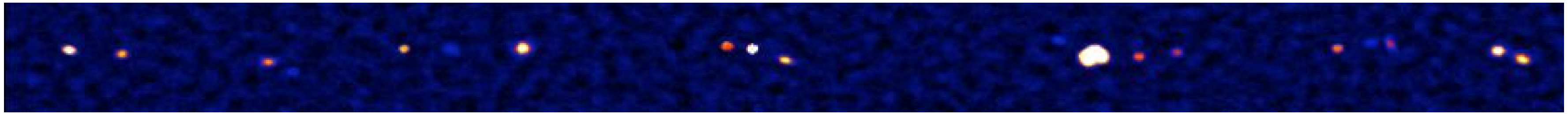
(Brunetti et al, 2008)

Gamma-ray bursts :
no signal detected yet above 80-200 GeV
despite very fast repositionning



Expected VHE fluxes should be within reach of next IACT generation
Difficulties : ToO requiring fast reaction + strong EBL absorption for high z bursts (and low z bursts are often short)

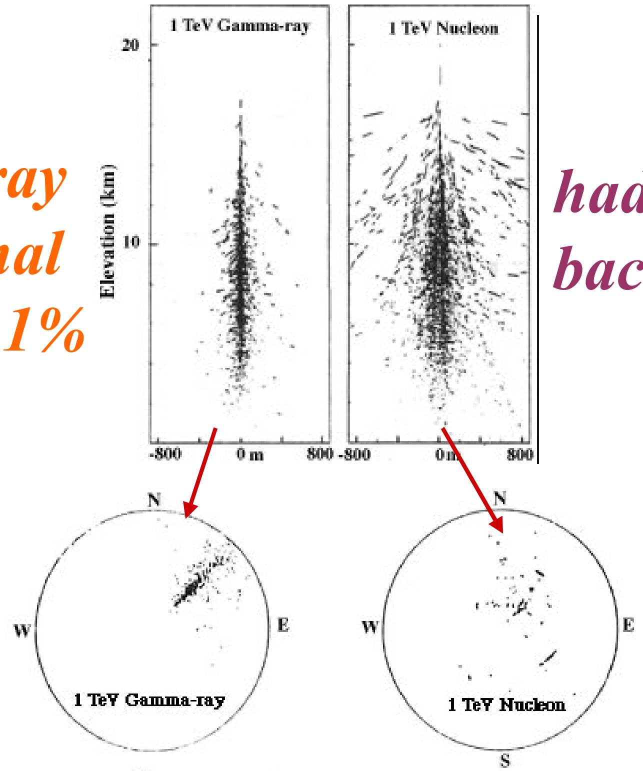
A few words on IACT techniques



IACT : detecting the flash of Cherenkov light from atmospheric showers

(1 TeV = 2.4 x 10^{26} Hz)

γ - ray signal < 0.1%



hadronic background

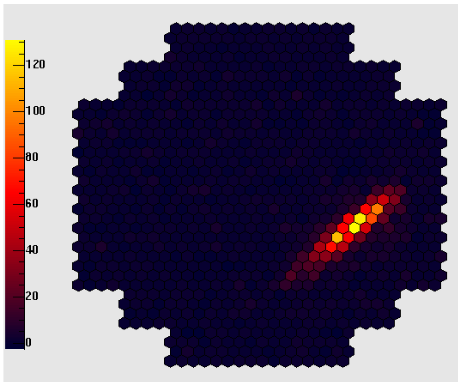
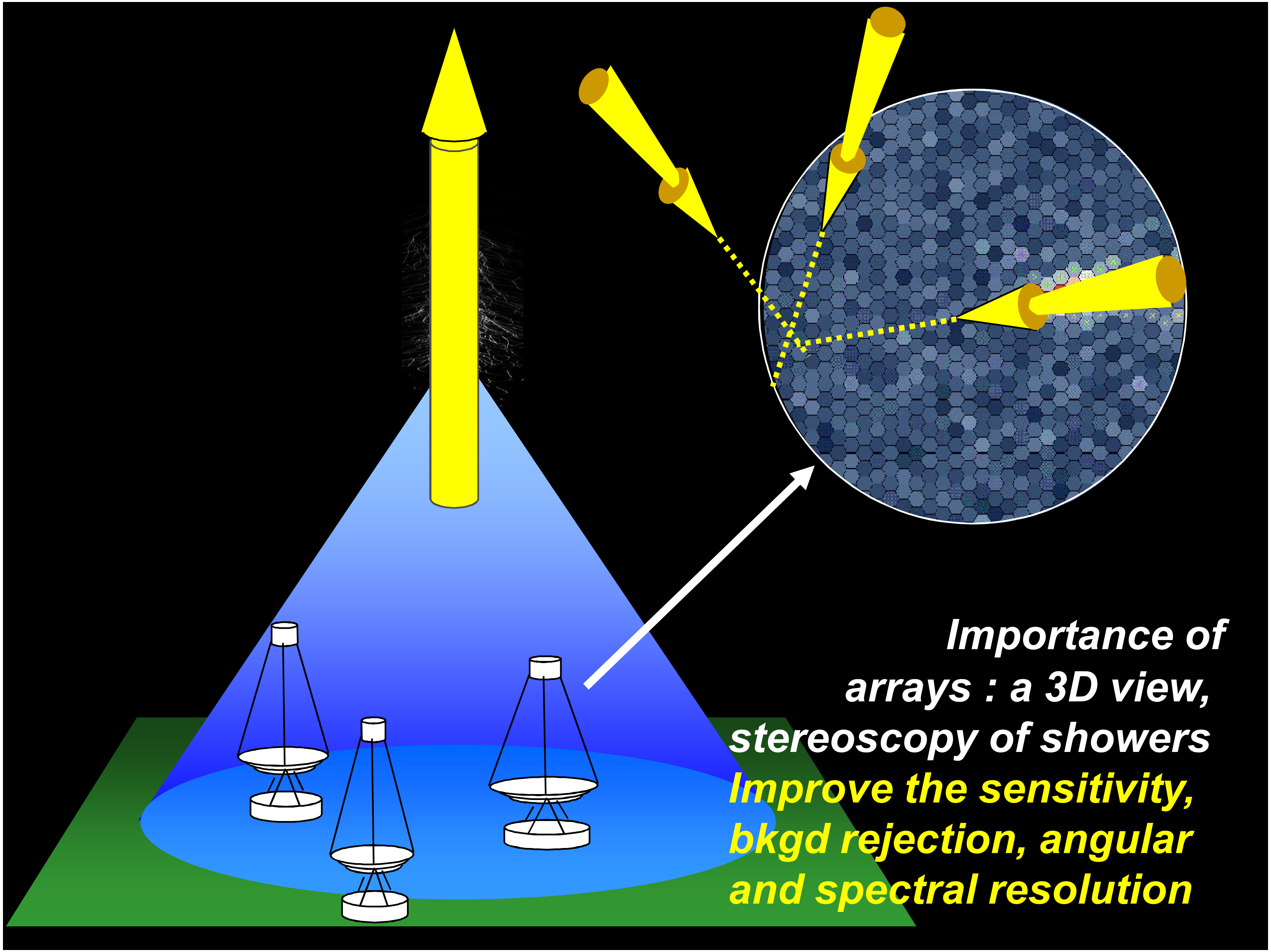


Image of an elmg shower

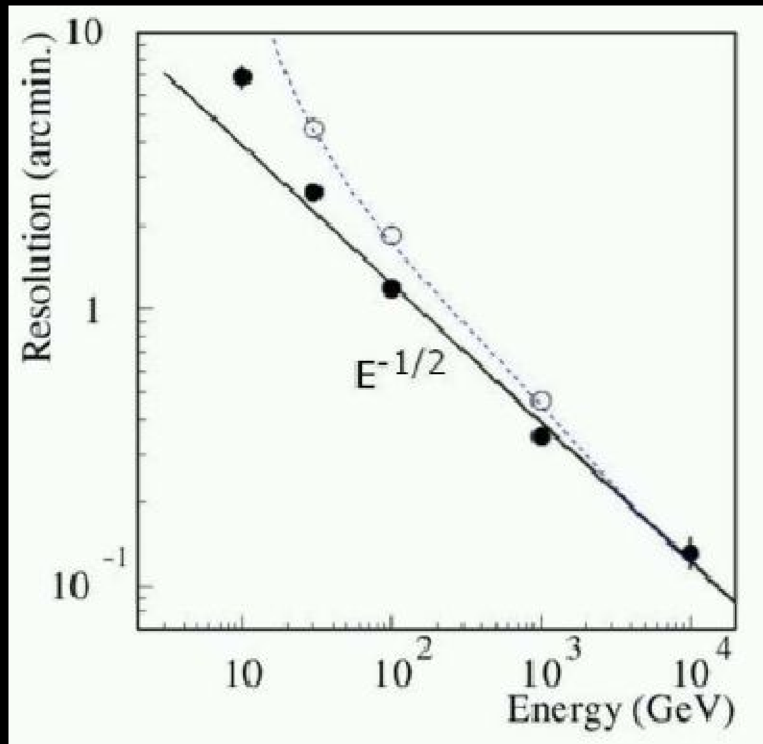
Analysis → properties of primary VHE gamma


Importance of arrays : a 3D view, stereoscopy of showers
Improve the sensitivity, bkgd rejection, angular and spectral resolution

Performance improvements of IACT arrays

IACT raised a wealth of new questions, opened fields to explore in physics, astrophysics, astroparticles, plasma physics … However ***fundamental limitations of the technique are not yet reached***

Angular resolution and background rejection can be improved, especially around TeV and above *(Hofmann, 2005)*



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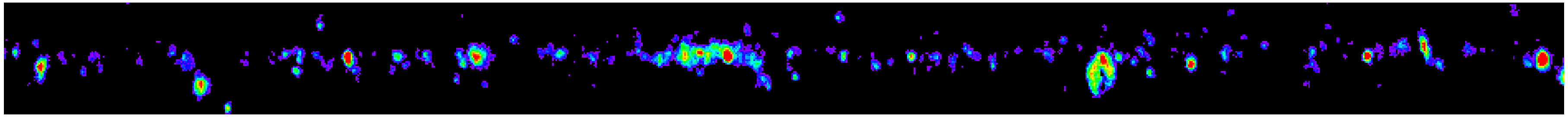
→

A strong motivation for the next generation of instruments, open facility for a large user community

The CTA project, Cherenkov Telescope Array

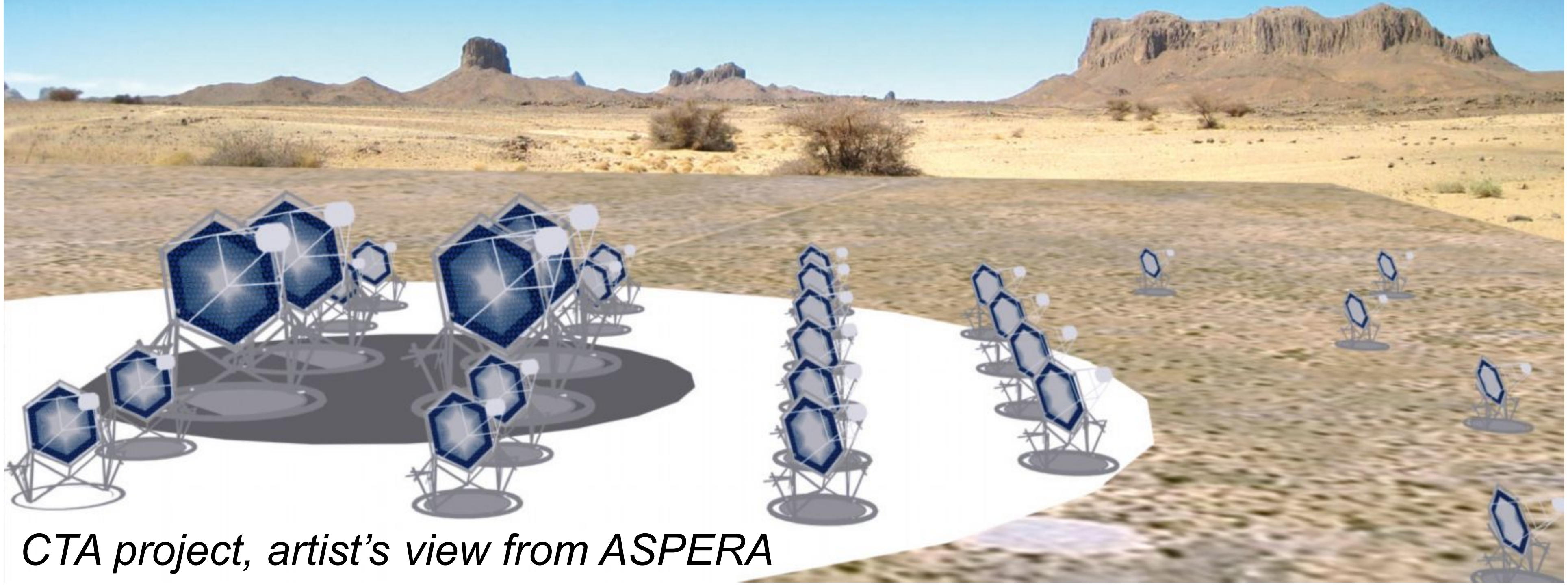


Performance goals for CTA

- Jump of factor 10 in sensitivity, down to **mCrab**
- Very large spectral coverage : **a few 10 GeV to above 100 TeV**
- Improved angular resolution down to **arc-minute range**
- Temporal resolution down to **sub-minute time scale**

→ a VHE timing explorer

- **Flexibility** of operations : deep field, monitoring, survey, alarms, ToO, full sky coverage, multi-lambda campaigns.



CTA project, artist's view from ASPERA

The CTA consortium

- > 50 institutes, > 14 countries (~ 300 scientists)
- Present partners : Germany, France, Spain, Italy, Poland, Ireland, UK, South-Africa, Armenia, Switzerland, Finland, Czech Republic, Netherlands, Namibia (+ Sweden)
- Expression of interest by Japan *(Jan. 2008; joining now).*
- Expressions of interest from Argentina, Denmark, Russia
- Some coordination with US scientists, who work on a project similar to CTA : AGIS, Advanced Gamma-ray Imaging System

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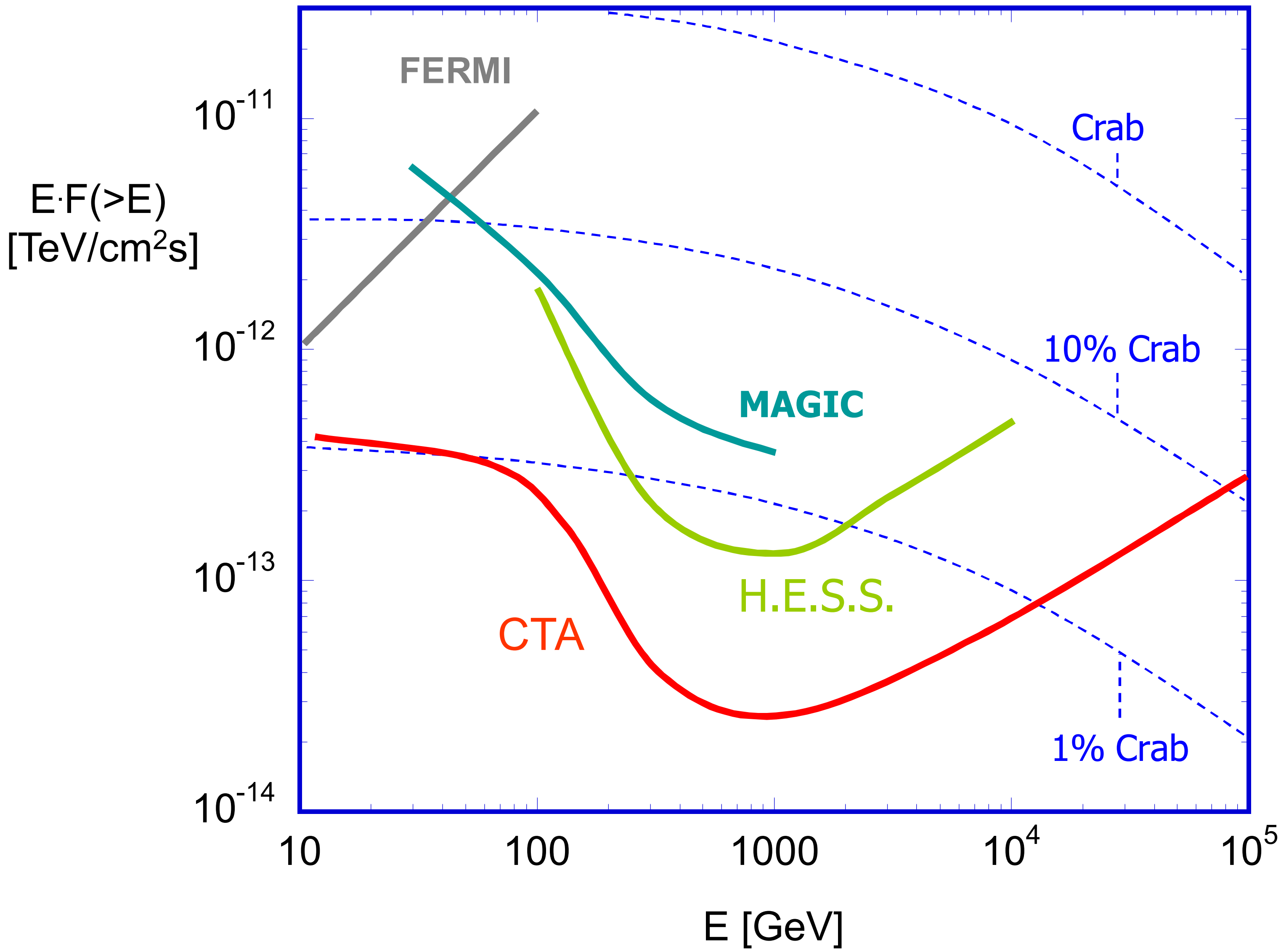
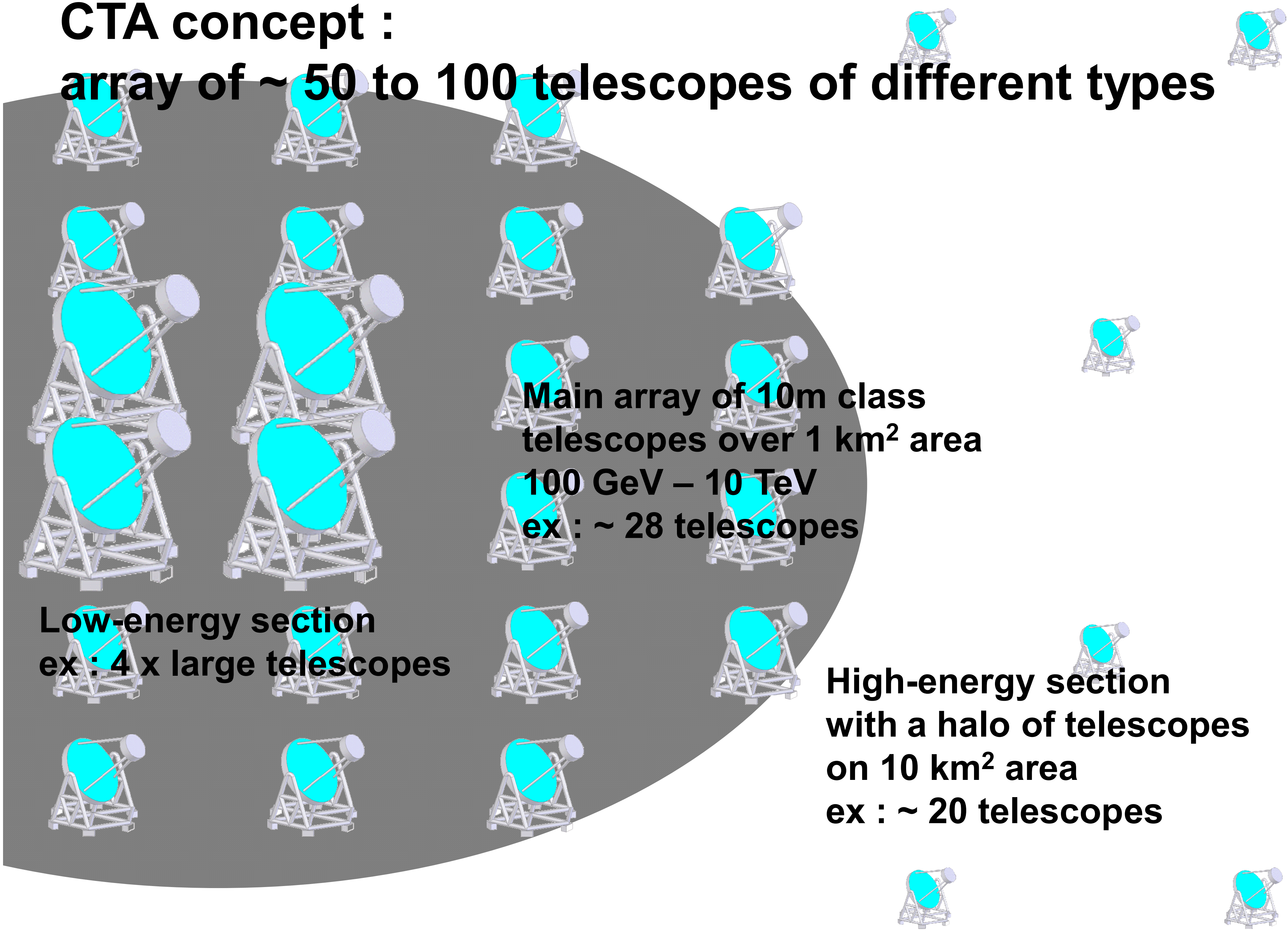
- Some coordination with US scientists, who work on a project similar to CTA : AGIS, Advanced Gamma-ray Imaging System
- Regular general CTA meetings since 2006 (Berlin 06, Paris 07, Barcelone 08, Padova 08, Cracow 09; next : Zurich Oct 09)
- Tasks distributed among « WorkPackages »

  (Science, Site, Simulations, Telescope and Mirrors, Camera with focal plane instrumentation and electronics, Data, Calibration and atmospheric monitoring, Observatory, Quality and risks).

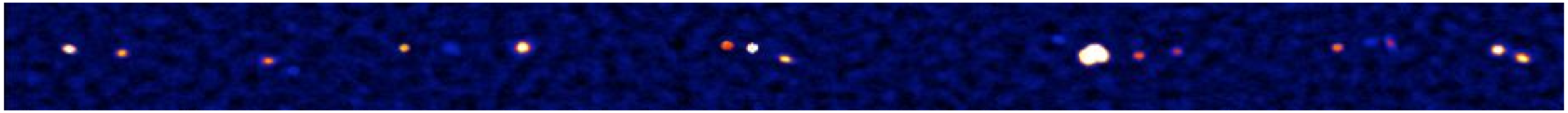
Goals for CTA sensitivity

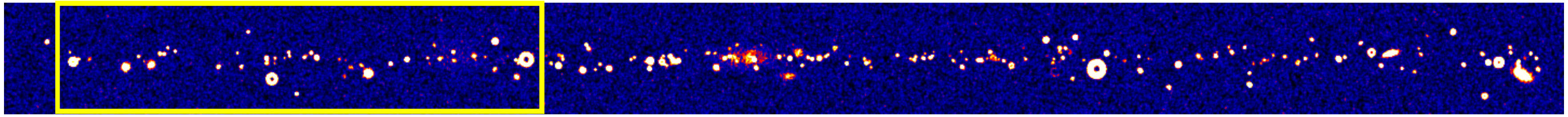


CTA concept :
array of ~ 50 to 100 telescopes of different types

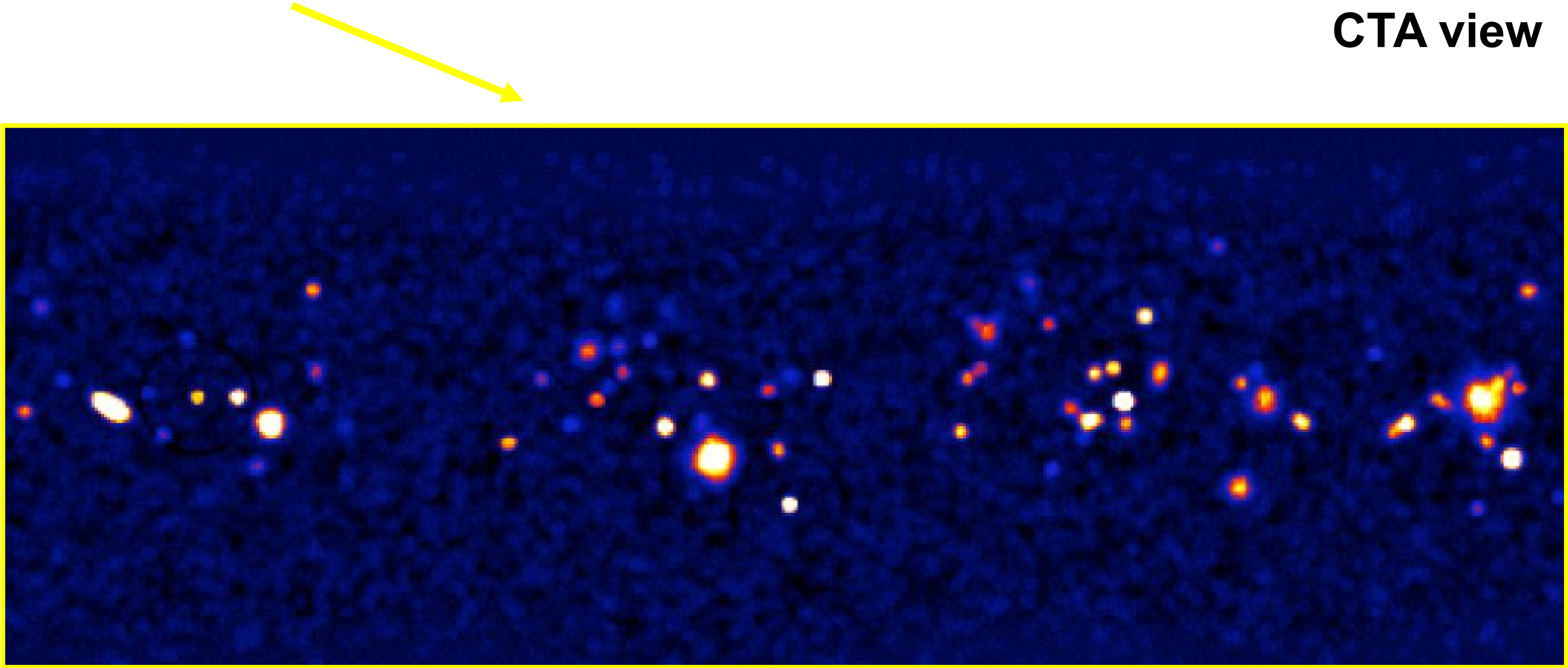


Galactic plane as seen by HESS





CTA view



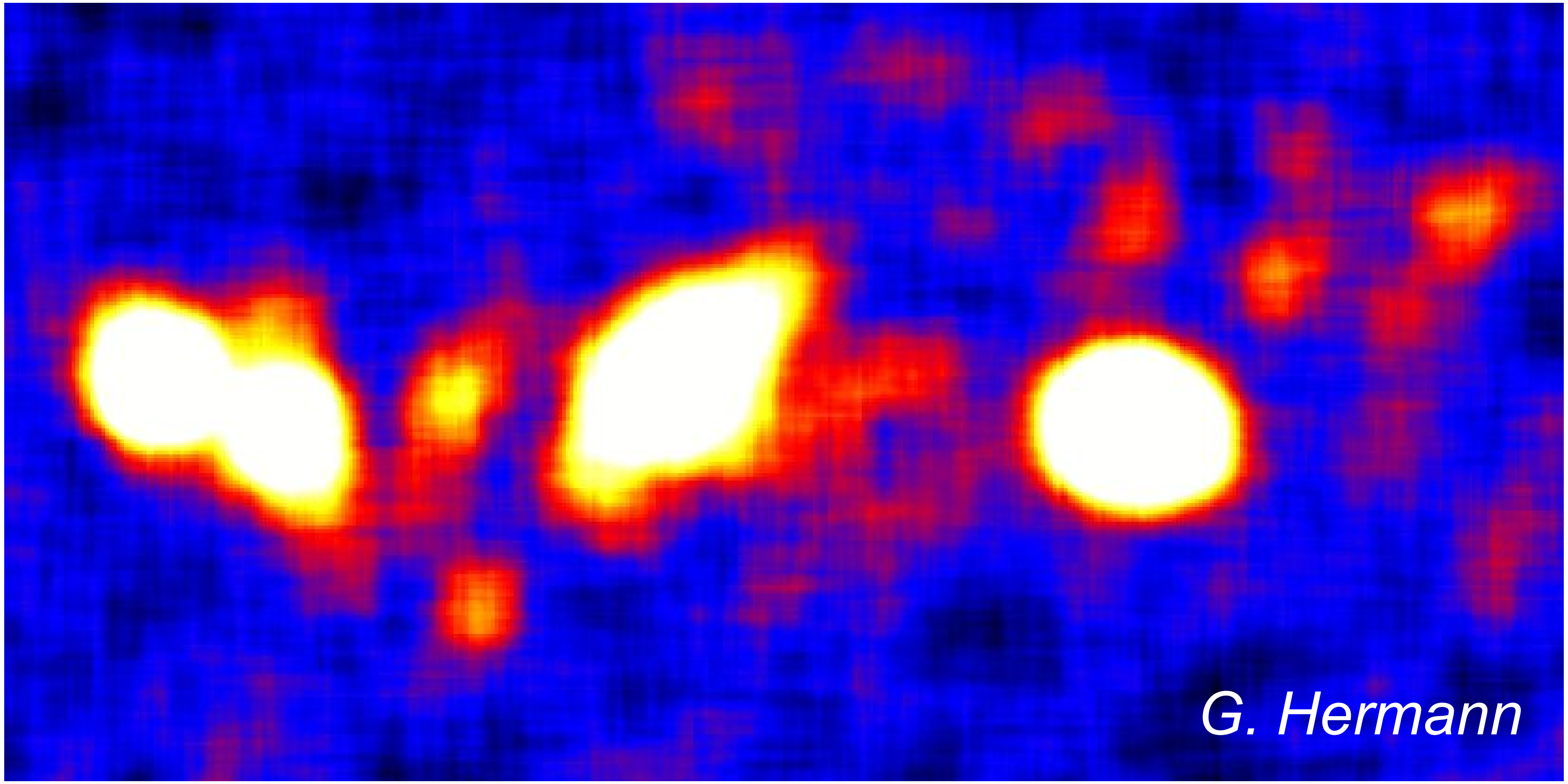
Simulations CTA/AGIS

Digel + Funk (Stanford) + Hinton (Leeds)

Improvement of angular resolution

(can be 2 orders of magnitude better with IACT at a few TeV than GLAST at 1 GeV)

Angular resolution of 0.2 degrees :

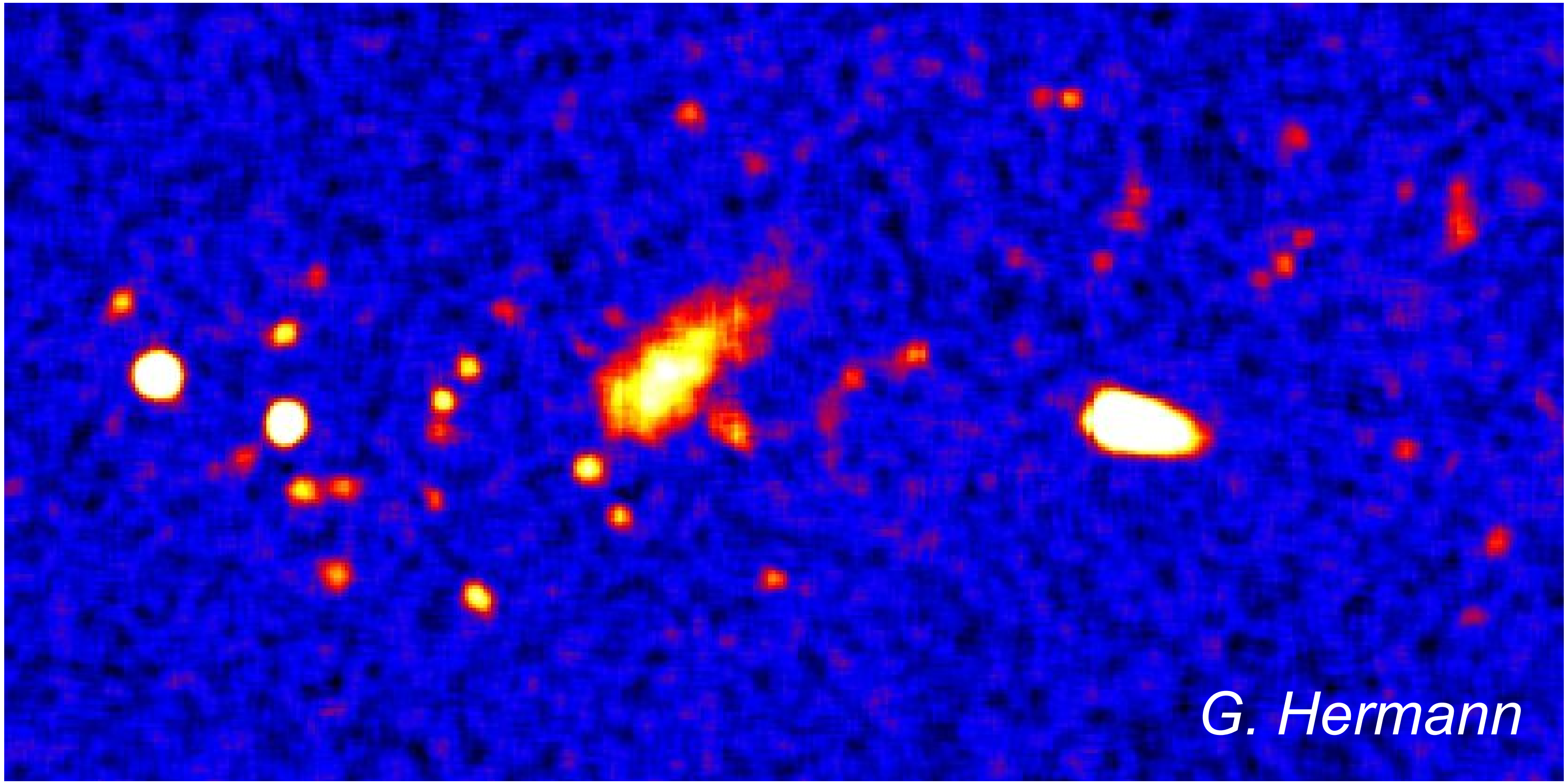


6 degrees FoV, > 50 GeV

Improvement of angular resolution

(can be 2 orders of magnitude better with IACT at a few TeV than GLAST at 1 GeV)

Angular resolution of 0.05 degrees :



6 degrees FoV, > 1 TeV

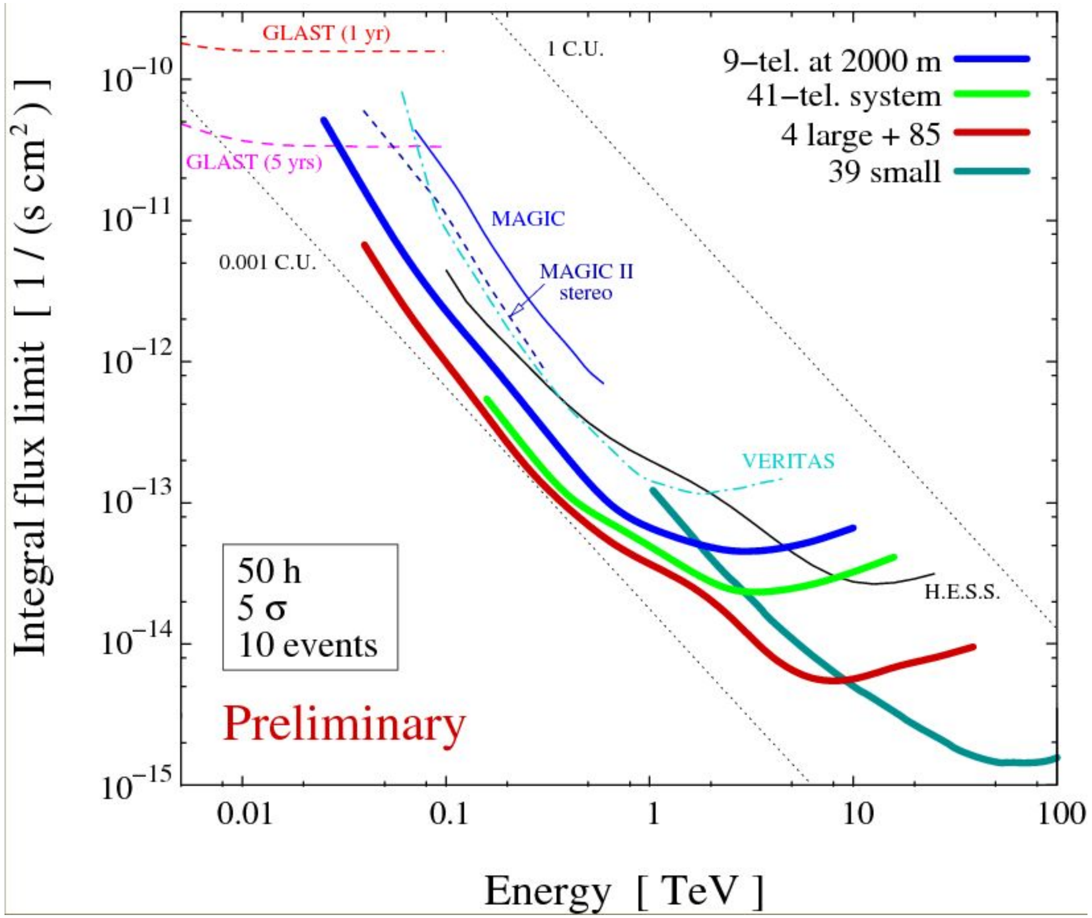
On-going Design Studies

- Aims : optimize the performances and reliability, lower the costs (150 M€ class project)
- Optimize the array layout : fine tuning of dish size, FoV, pixel size, spacing and arrangement
- Improve photo sensors and electronic signal recording
- Analyze array trigger schemes
- Optimize telescope structure, optics and mirrors
- Prototypes before large scale production
- Atmospheric monitoring and selection of 2 sites, S and N
- Develop tools to operate a user facility and provide data access

CTA will operate as an observatory open to all scientists. The project is now on ESFRI, ASPERA and ASTRONET roadmaps.

Complex optimization problem

ex : simulation of the sensitivity of various arrays



(K. Bernlohr, 2008)

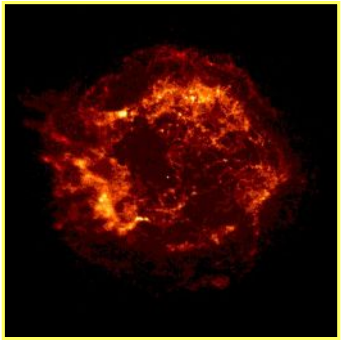
Time line

- Design Studies : up to 2009-2010
- Prototype construction : 2010-2011
- Array construction : 2012-2018
- Partial operations : starting from 2013
- Complete array : 2018

Should have rewarding overlaps with FERMI (2nd phase), and others large projects as AUGER, LOFAR, ALMA, JWST 2013+, E-ELT 2017+, SKA and pathfinders (2015/2019+), KM3NeT, IXO, LISA …

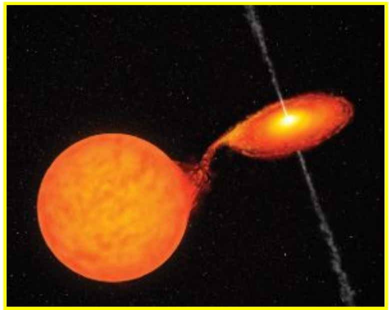
CTA sciences

Stars and galaxies

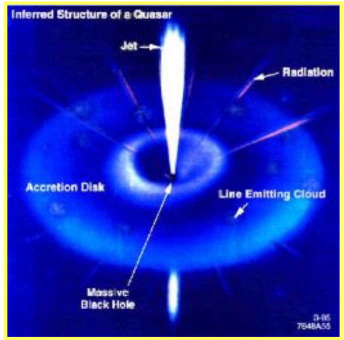


SNRs

Pulsars and PWN



Micro quasars and X-binaries



AGNs

GRBs

A garanteed scientific return

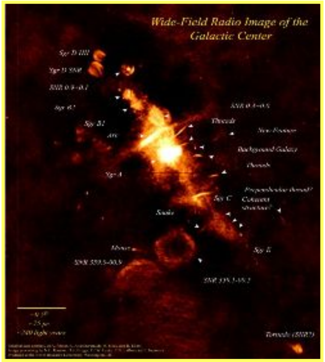
in several astrophysical fields

(compact objects, stellar physics, physics of ISM, galaxies)

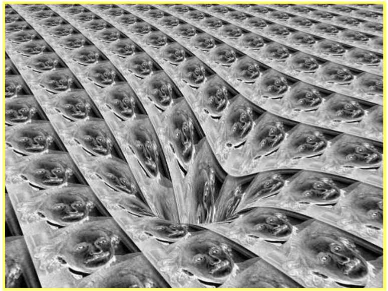
Towards thousand VHE sources.

CTA sciences

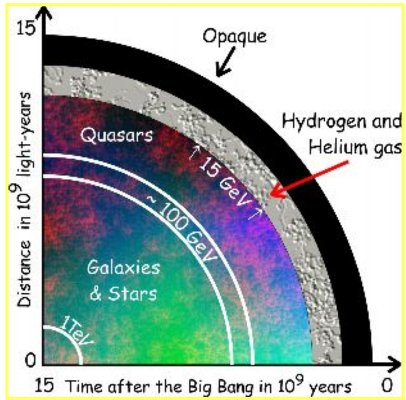
Cosmic Rays



Dark Matter



Space-time and relativity



Cosmology

High discovery potential

in fundamental physics

(physics of cosmic accelerators, non-photonic sources, dark matter, nature of non-identified VHE sources, black holes, check of validity of Lorentz invariance, EBL and formation of cosmic structures ‘stars and galaxies’)

CTA perspective :

Foresee significant return on plasma physics and acceleration processes, outflows and winds, Black Hole physics, evolution of AGN and SMBH, non-thermal emission from galaxy clusters ...

Interesting synergies with any future X-ray missions :

- The 2 spectral ranges can provide 2 different views of the same population of particles (leptonic scenarios with synchrotron X-rays and IC gamma-rays),
or on 2 related populations (hadronic scenarios with secondary electrons) → constrain parameters
- CTA avoids confusion with thermal radiation; X-rays can bring better angular resolution for imaging (and identifying)

Importance of coordinated multi-lambda monitoring, ToO ...


Acknowledgments to all CTA scientists.
Special thanks to W. Hofmann, M. Teshima,
M. Martinez, G. Hermann,
and CTA WorkPackage conveners.

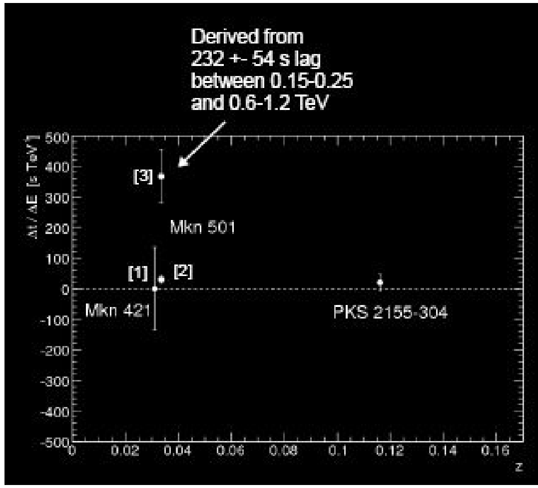
Several Quantum Gravity models have predicted energy dependence of the speed of light. General parametrization:

$$c' = c\left(1 \pm \xi \frac{E}{E_P} \pm \zeta^2 \frac{E^2}{E_P^2}\right)$$, with $E_P = 1.22 \times 10^{19}$ GeV

• VHE signal from PKS 2155-304 shows no energy dispersion. This yields the *most constraining limits* on speed of light modifications to date:

$\xi < 17.6$ *(Linear)*

$\zeta < 1.10 \times 10^{10}$ *(Quadratic)*

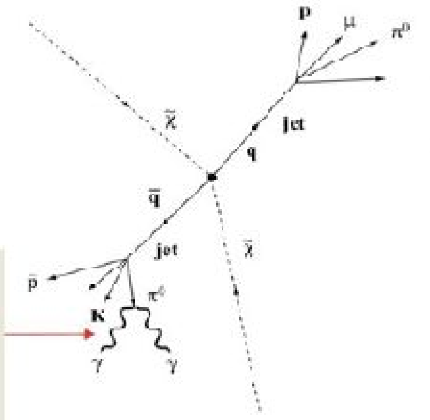


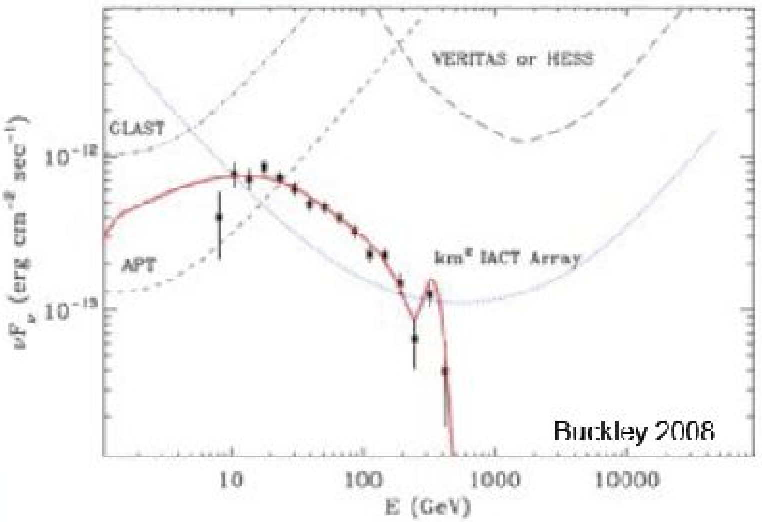
• To date three measurements at VHE → No trend with redshift

• Future measurements will allow conclusions on "delay cancellation"

From Buhler and Jacholkowska, HESS, 2008)

(iii) Search for Dark Matter Annihilation γ-Rays.



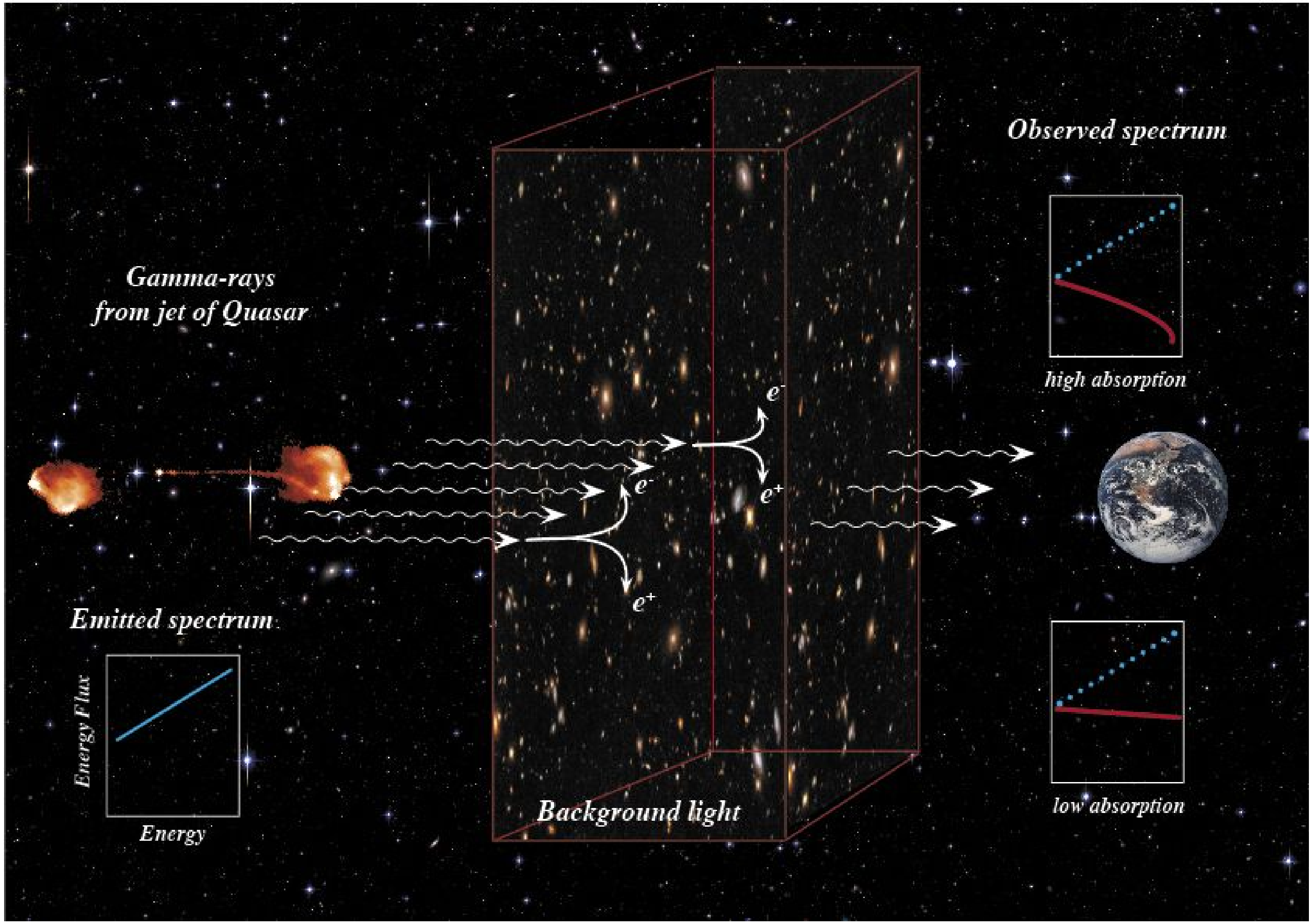


* M ~ 330 GeV; line to continuum contribut. 10^{-3} ; cross-section ~ 2 x 10^{-26} cm^3 s^{-1} ; b = 3

arXiv:0812.0793

Target energy range: 100 GeV-100 TeV.

Absorption of VHE gamma-rays by the IR diffuse extragalactic background



Propagation of γ-rays

dominant process for the γ absorption:

$$\gamma_{VHE}\gamma_{EBL} \rightarrow e^+e^-$$

$$\sigma(\beta) \sim \; 1.25 \cdot 10^{-25}(1-\beta^2)\cdot\left[2\beta(\beta^2-2)+(3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right]\,\mathrm{cm}^2$$

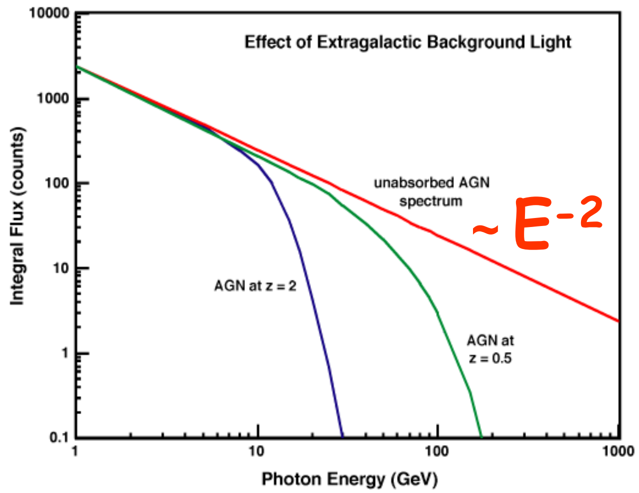
Heitler 1960

≈

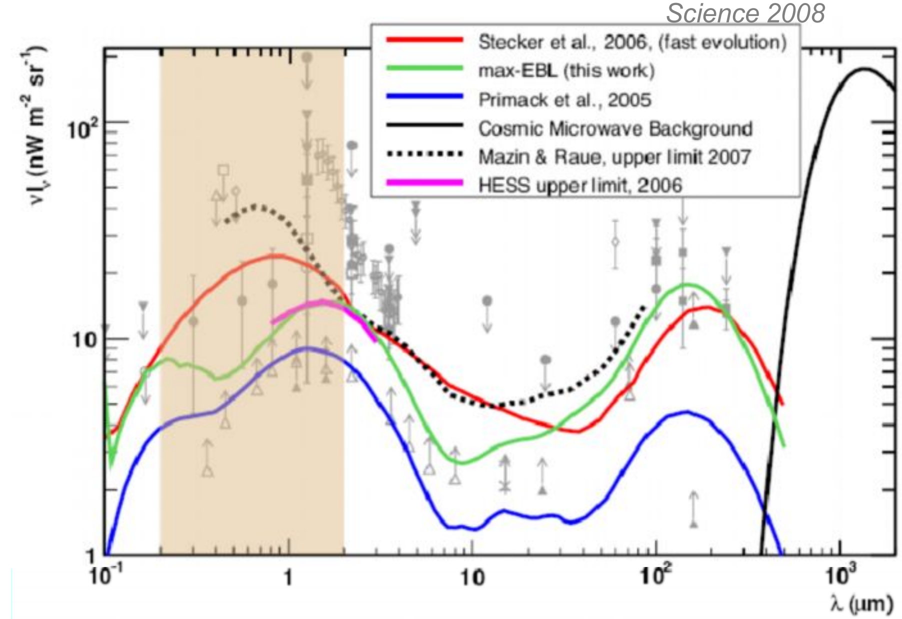
maximal for: $$\epsilon \simeq \frac{2m_e^2c^4}{E} \simeq \left(\frac{500\ \mathrm{GeV}}{E}\right)\mathrm{eV}$$

- For γ–rays, relevant background component is optical/infrared (EBL)
- different models for EBL: minimum density given by cosmology/star formation

Measured spectrum affected by attenuation in the EBL:



Science 2008



(De Lotto)

Attenuation of γ-rays

$$\Phi = \Phi_o e^{-\tau(E,z)}$$

γ-ray horizon:
$\tau(E,z) = 1$

Fazio & Stecker 1970

$$\tau(E,z) = \int_0^z dl(z) \int_{-1}^{1} d\mu \, \frac{1-\mu}{2} \int_{\epsilon_{thr}(E(z),\theta)}^{\infty} d\epsilon(z) \, n_\epsilon(\epsilon(z),z) \, \sigma(E(z),\epsilon(z),\theta)$$

where $\mu = \cos\theta$ is the cosine of the scattering angle. $l(z) = c \, dt(z)$ is the distance

$$\frac{dl}{dz} = \frac{c}{H_0} \frac{1}{(1+z)\left[(1+z)^2(\Omega_M z + 1) - \Omega_\Lambda z(z+2)\right]^{\frac{1}{2}}} \qquad ($$

where H_0 is the Hubble constant, Ω_M is the matter density and Ω_Λ is the cosmological const.