Ground-based Gamma Ray Astronomy: Status and Future

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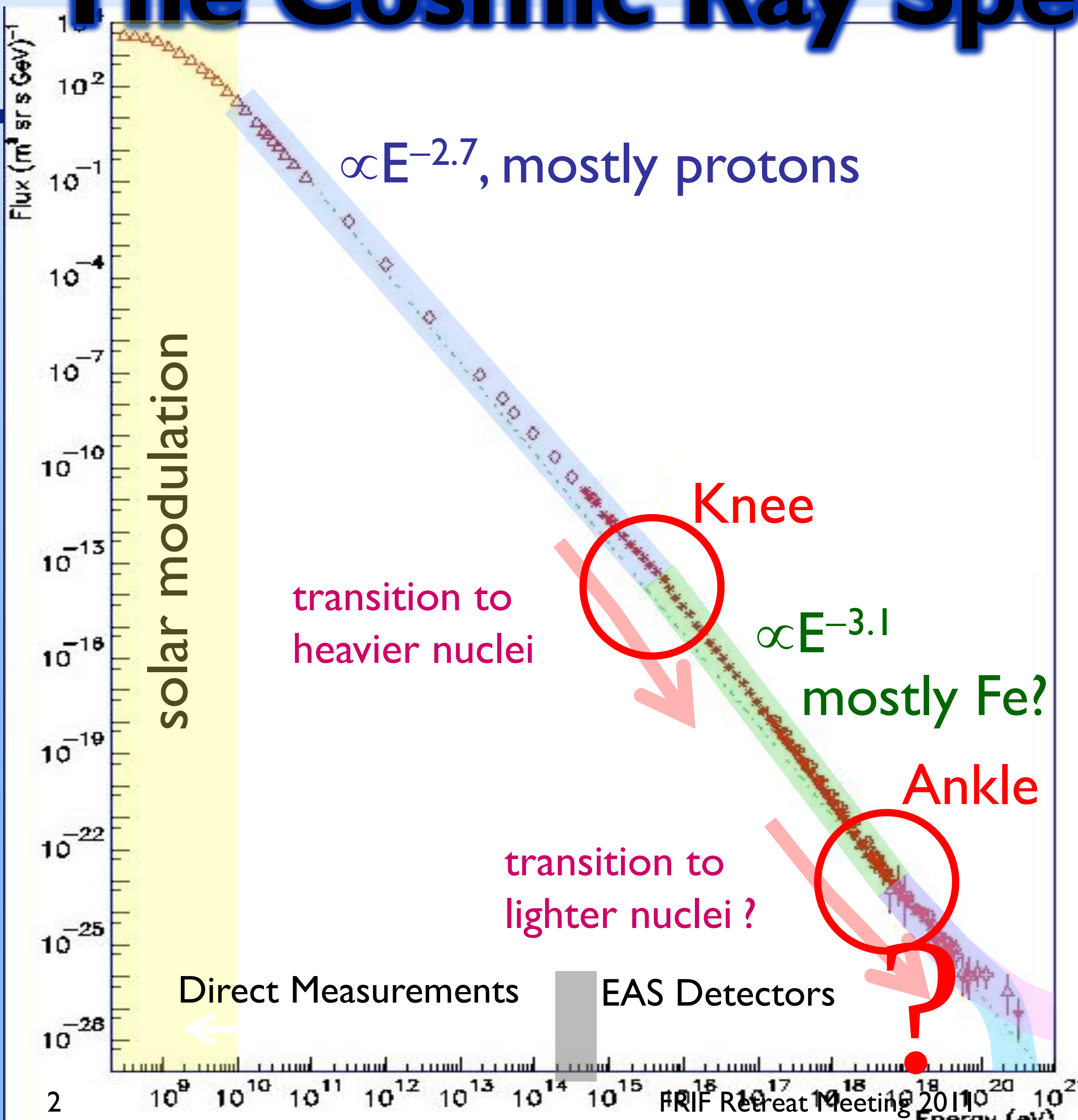
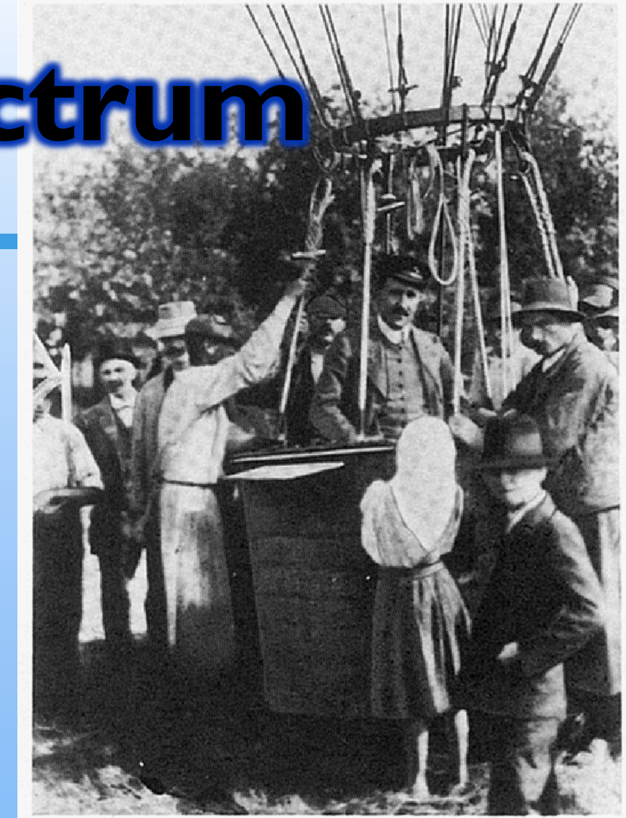
LPNHE/UPMC

An experimentalist point of view

The Cosmic Ray Spectrum





Discovery Balloon Flight
Victor Hess, 1912

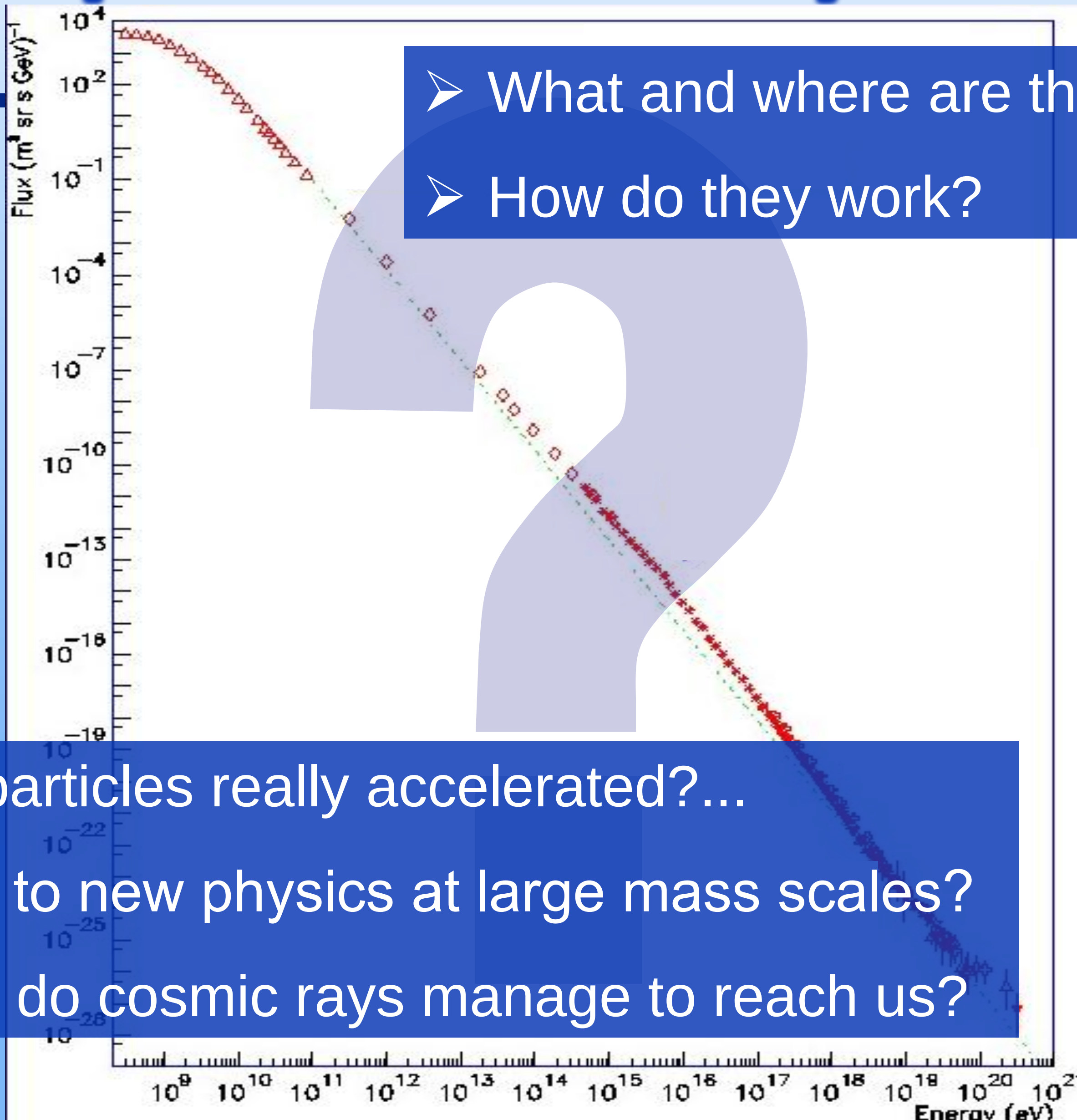
Power Laws

⬍

Shock Acceleration

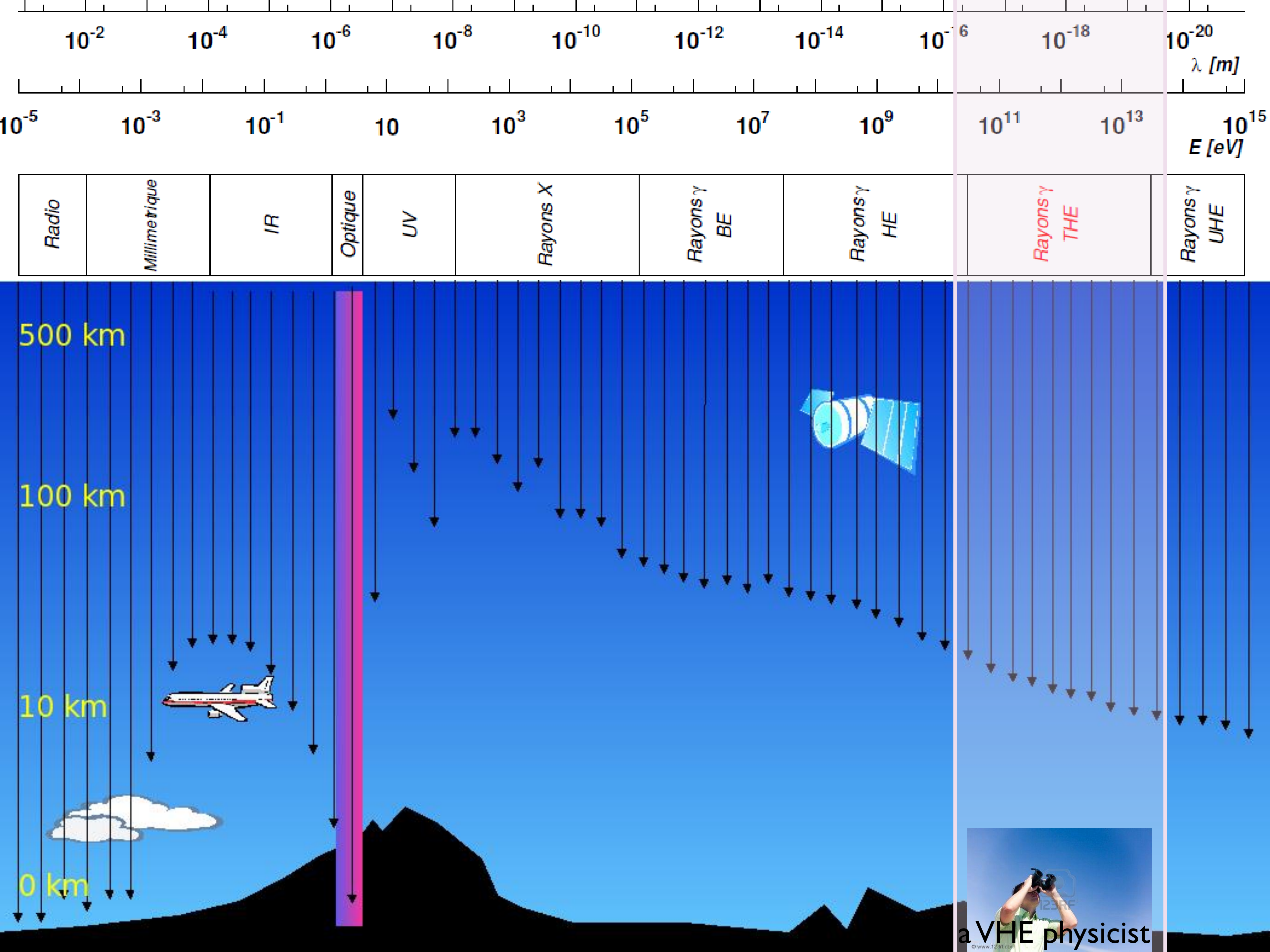
predicts $F_{Source} \propto E^{-2}$

Open question after 98 years



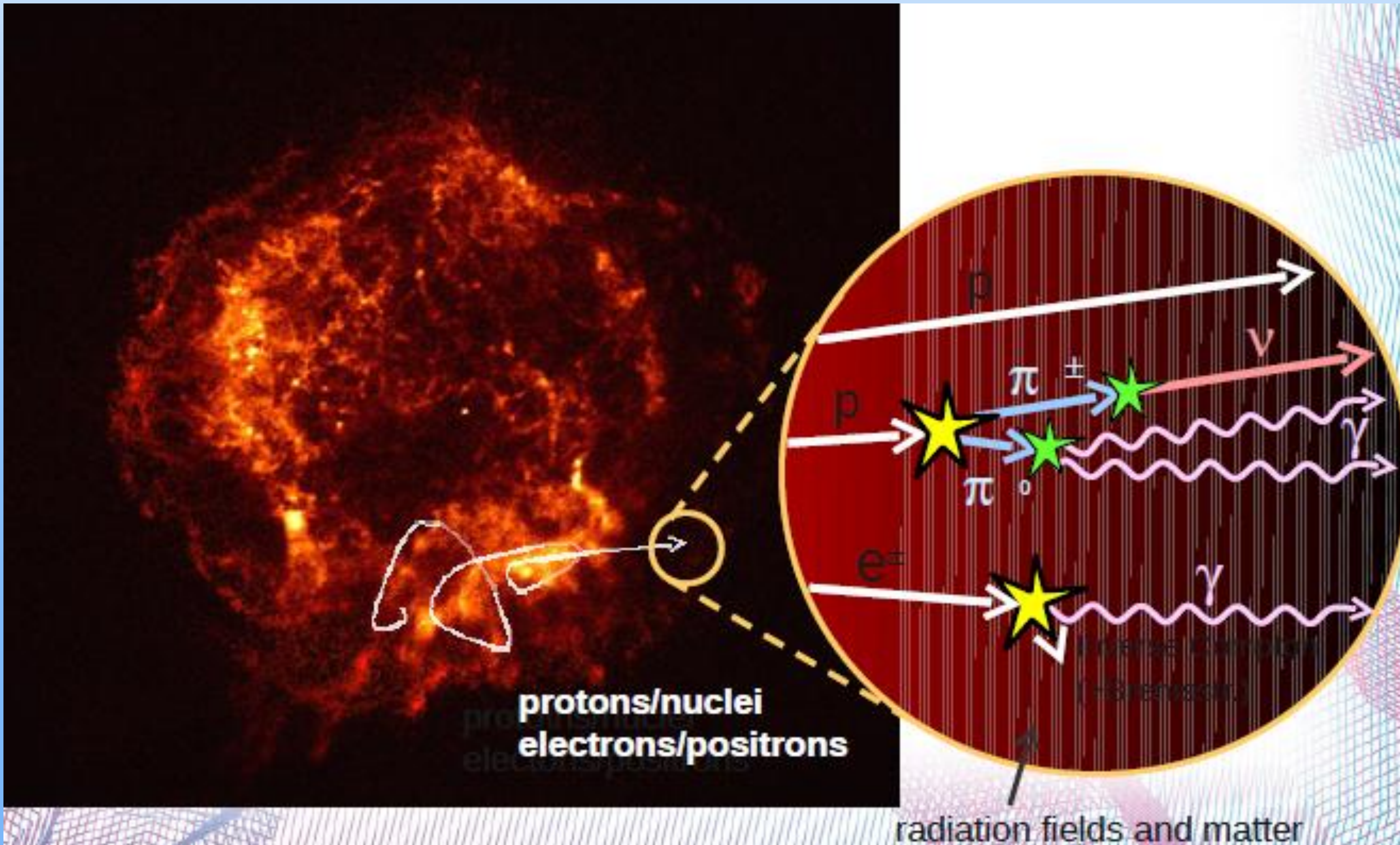
- What and where are the sources?
- How do they work?

- Are the particles really accelerated?...
- …or due to new physics at large mass scales?
- And how do cosmic rays manage to reach us?

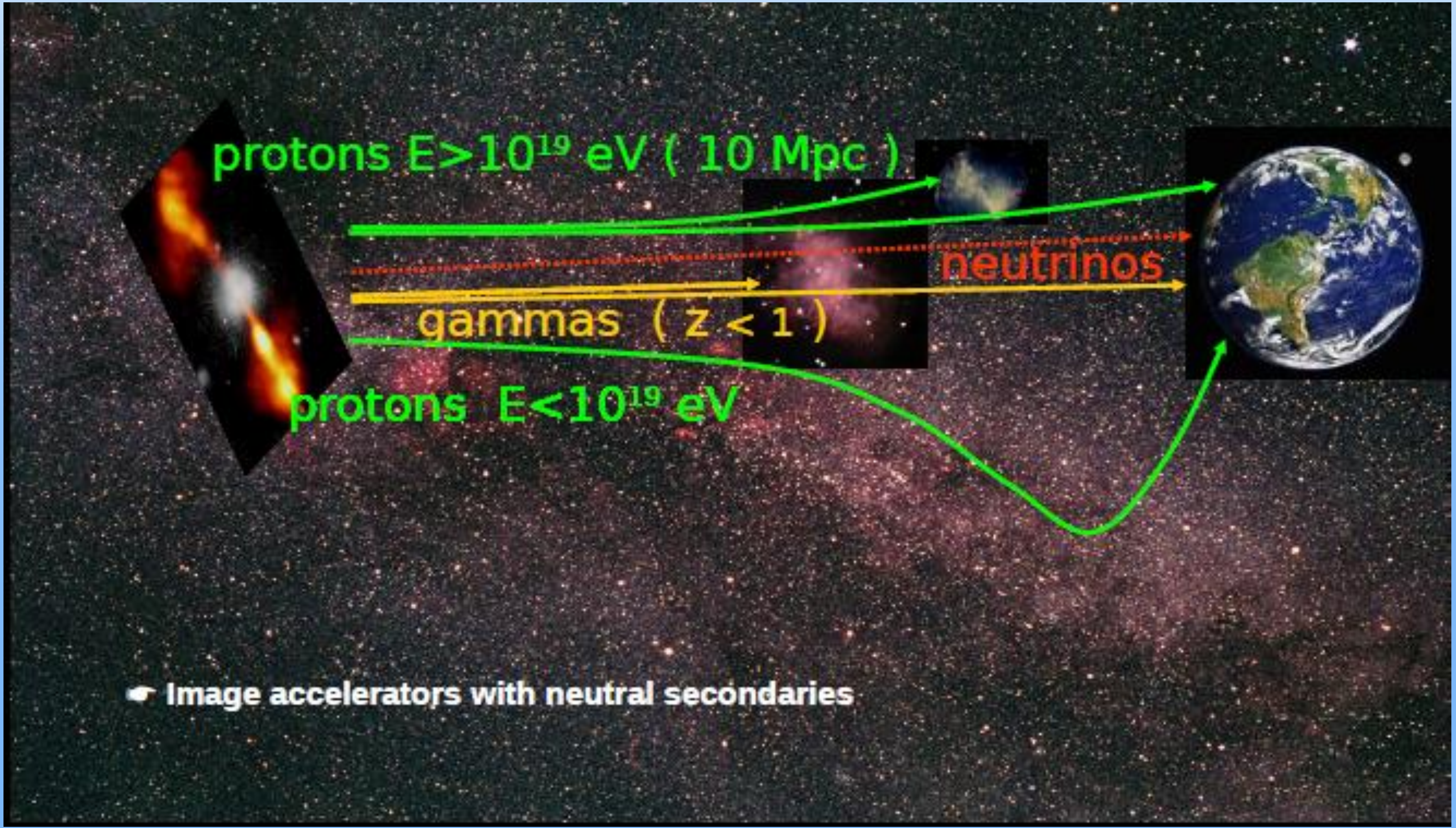


10-2
10-4
10-6
10-8
10-10
10-12
10-14
10-16
10-18
10-20
λ [m]
10-5
10-3
10-1
10
10^3
10^5
10^7
10^9
10^11
10^13
10^15
E [eV]
Radio
Millimetrique
IR
Optique
UV
Rayons X
Rayons γ BE
Rayons γ HE
Rayons γ THE
Rayons γ UHE
500 km
100 km
10 km
0 km
a VHE physicist

Gamma Production in Cosmic Accelerator



Probing the Nonthermal Universe

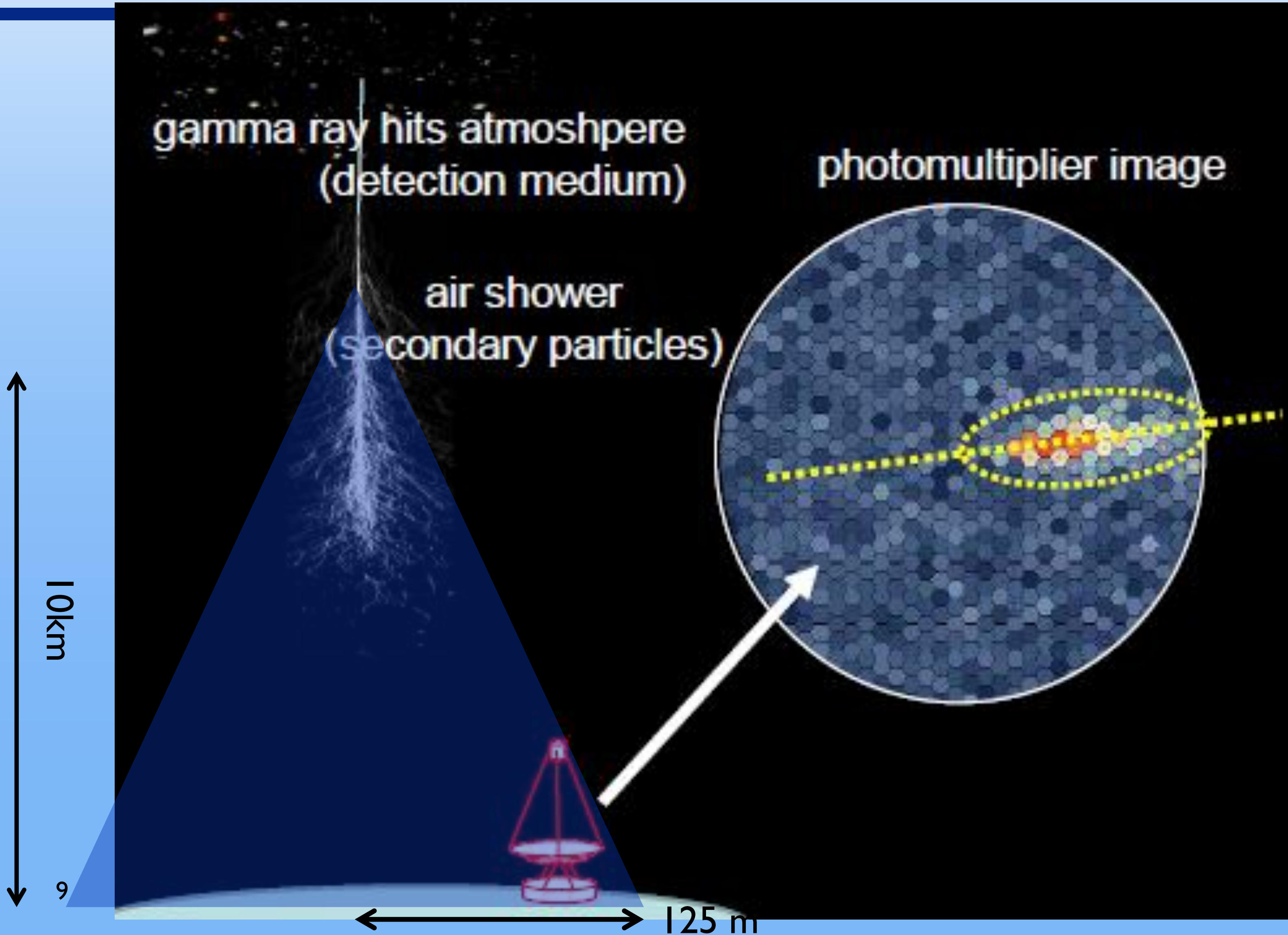


VHE Astronomy (vocabulary)

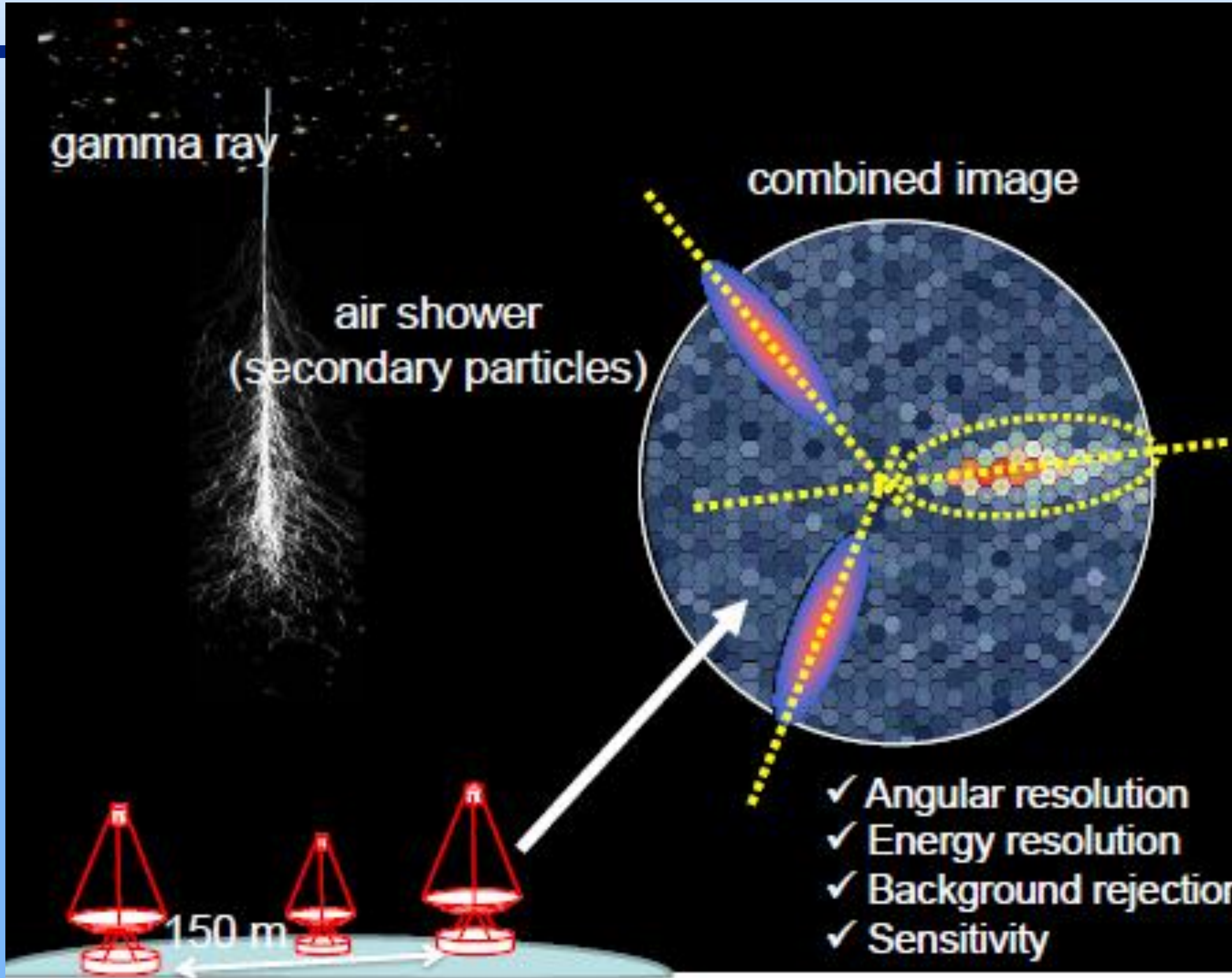
Why are these sources so important ?

- Astrophysics
  - Probing the highest energy physical processes occurring in different objects (SNRs, …)
  - Origin of cosmic rays
- Astroparticle Physics
  - Indirect search for dark matter
  - Search for energy dependence of the speed of light break of "Lorentz invariance"
- Cosmology
  - Indirect measure of the Extragalactic Background light: help us to understand star formation history

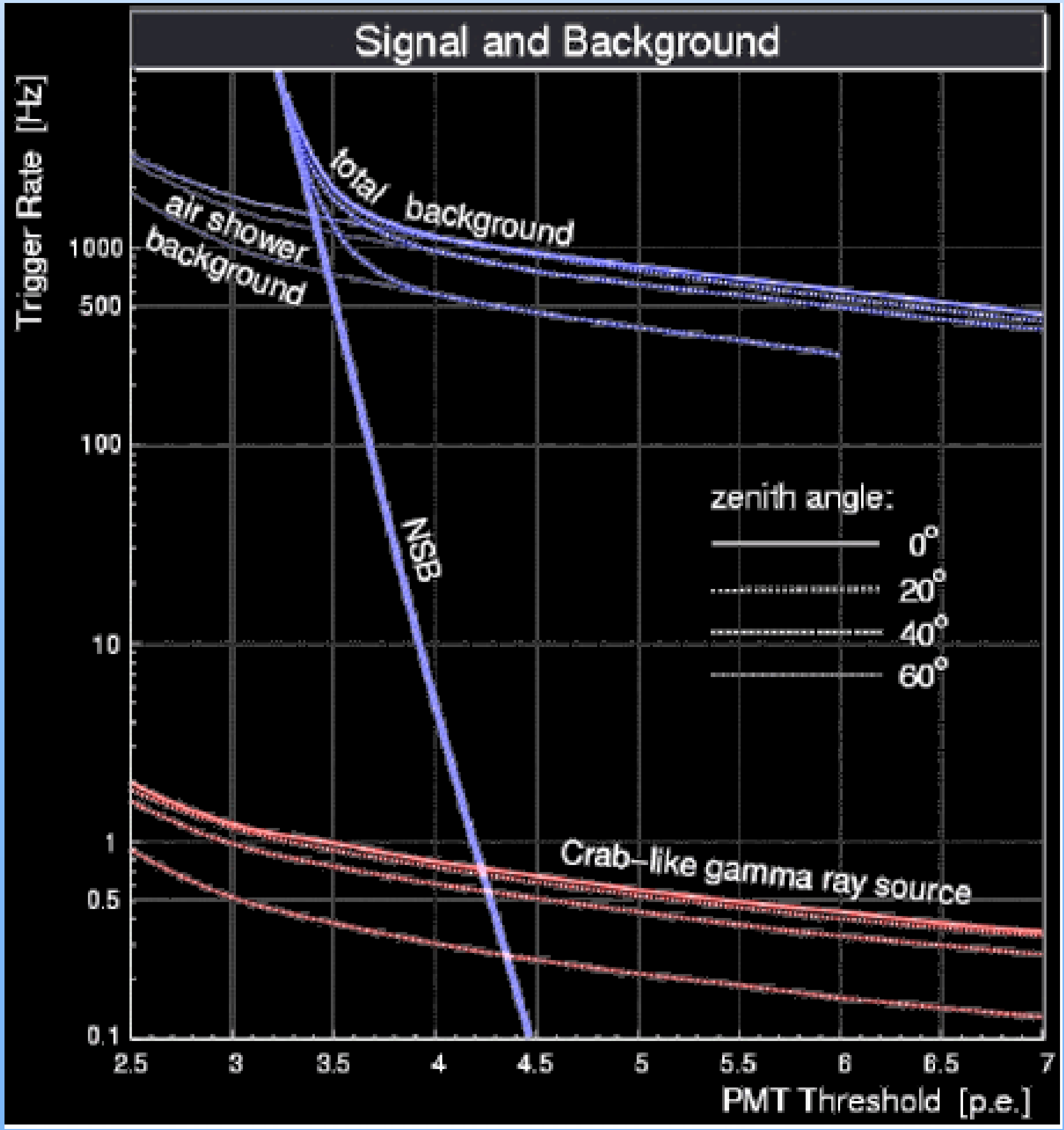
The Cerenkov Technique



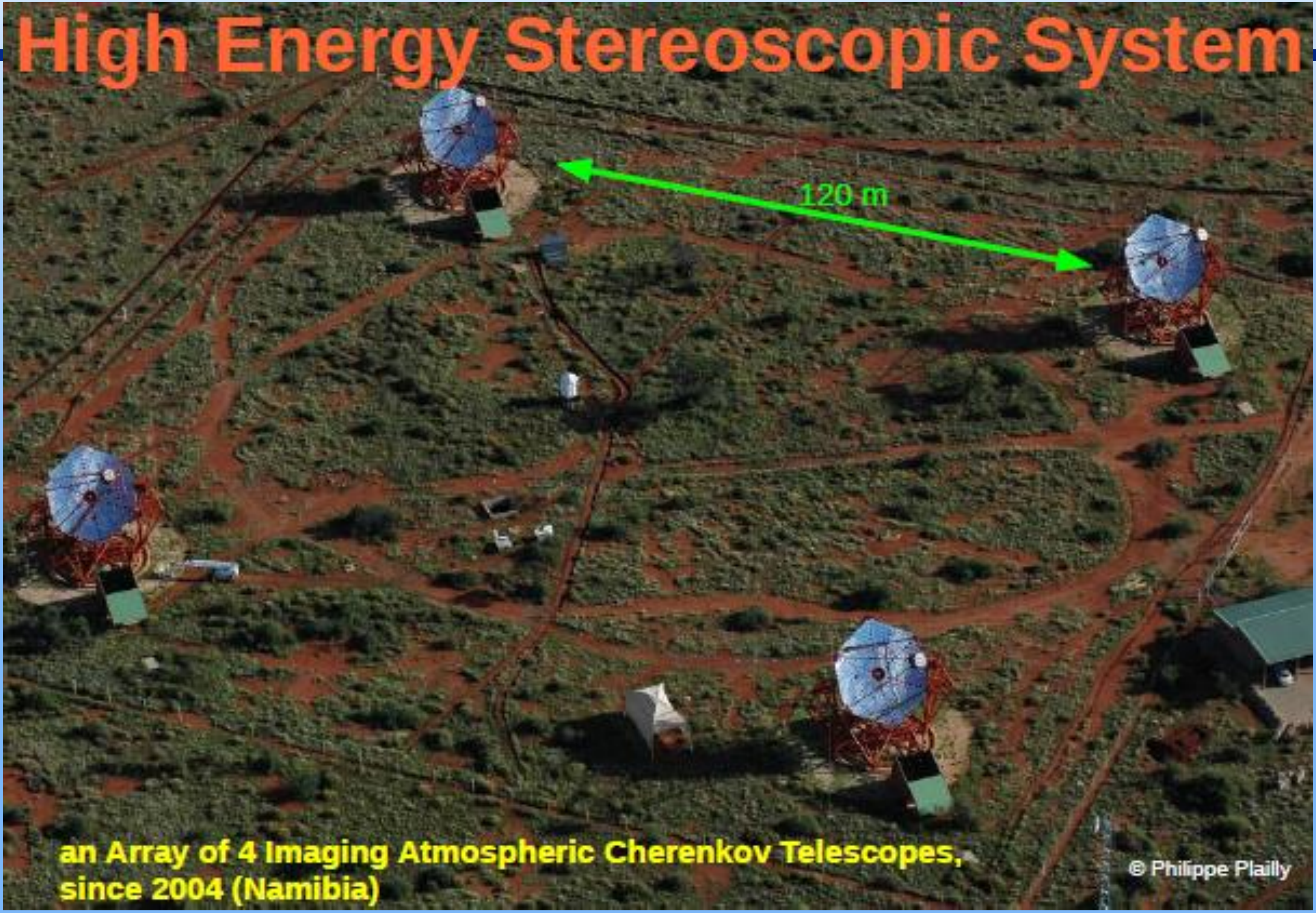
The Cerenkov Technique with Stereoscopy



Signal and Background

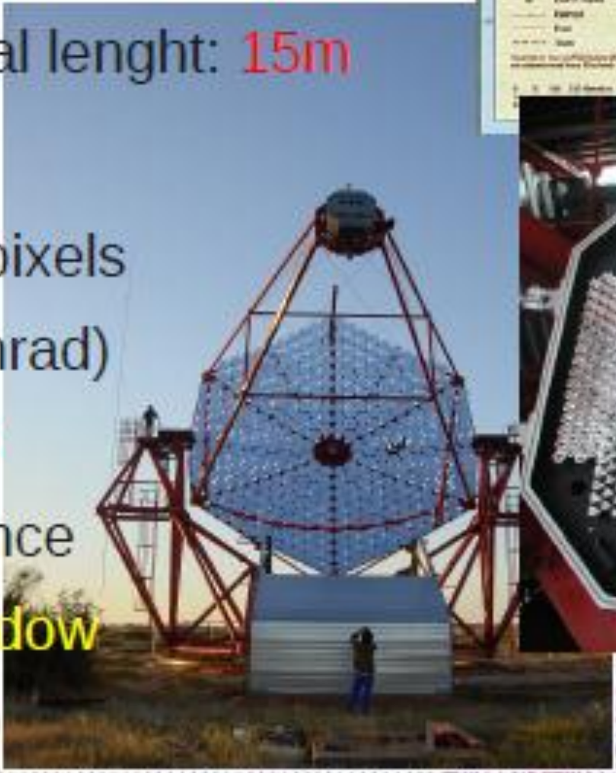


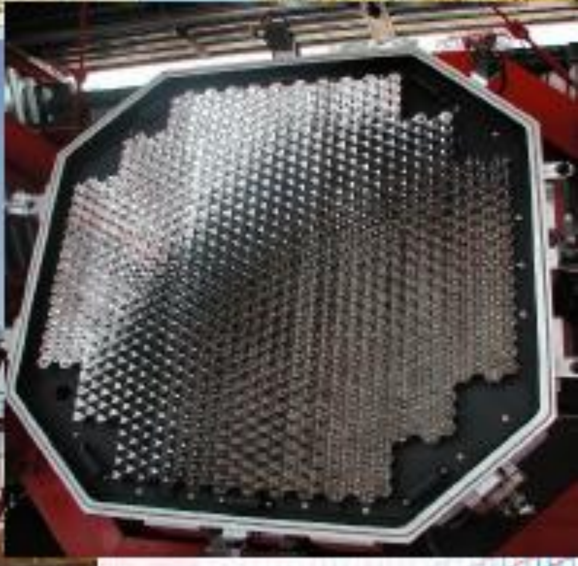
H.E.S.S.


High Energy Stereoscopic System
120 m
an Array of 4 Imaging Atmospheric Cherenkov Telescopes,
since 2004 (Namibia)
© Philippe Plailly

H.E.S.S. (phase I) Characteristics

- Four-Telescope network
  - Sited in Namibia: 23°S, 15°E, 1800 m altitude
  - Telescope separation: 120m
- Telescope Structures
  - Mirror dishes : 4 x 107 m^2
  - Diameter: 12 m, Focal lenght: 15m
- Cameras
  - 960 phoyomultiplier pixels
  - Pixels of 0.16° (2.8 mrad)
  - Wide field of view: 5°
  - Fast trigger coincidence
  - 16 ns integration window
- Threshold : ~ 100 GeV



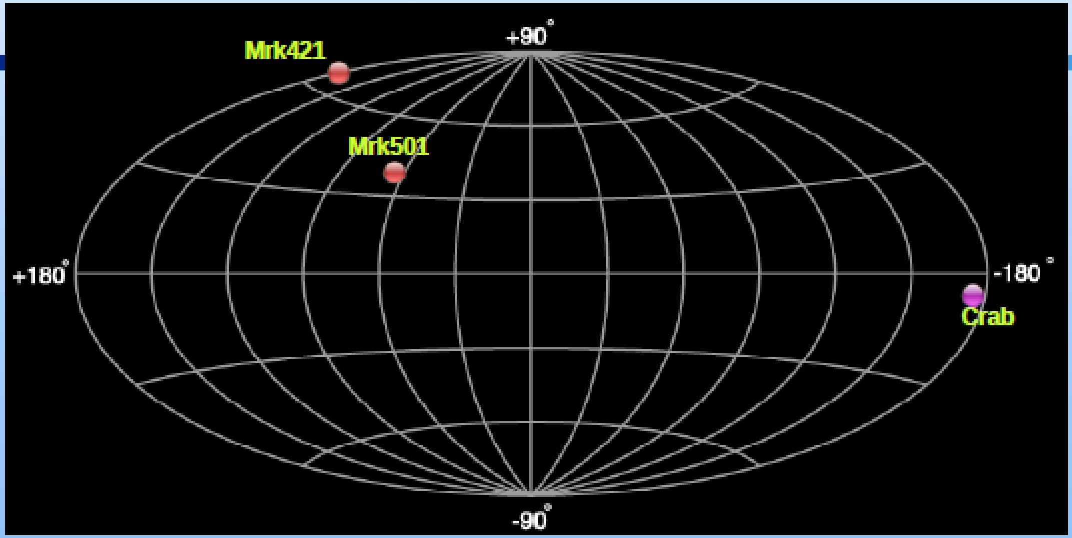


System Parameters

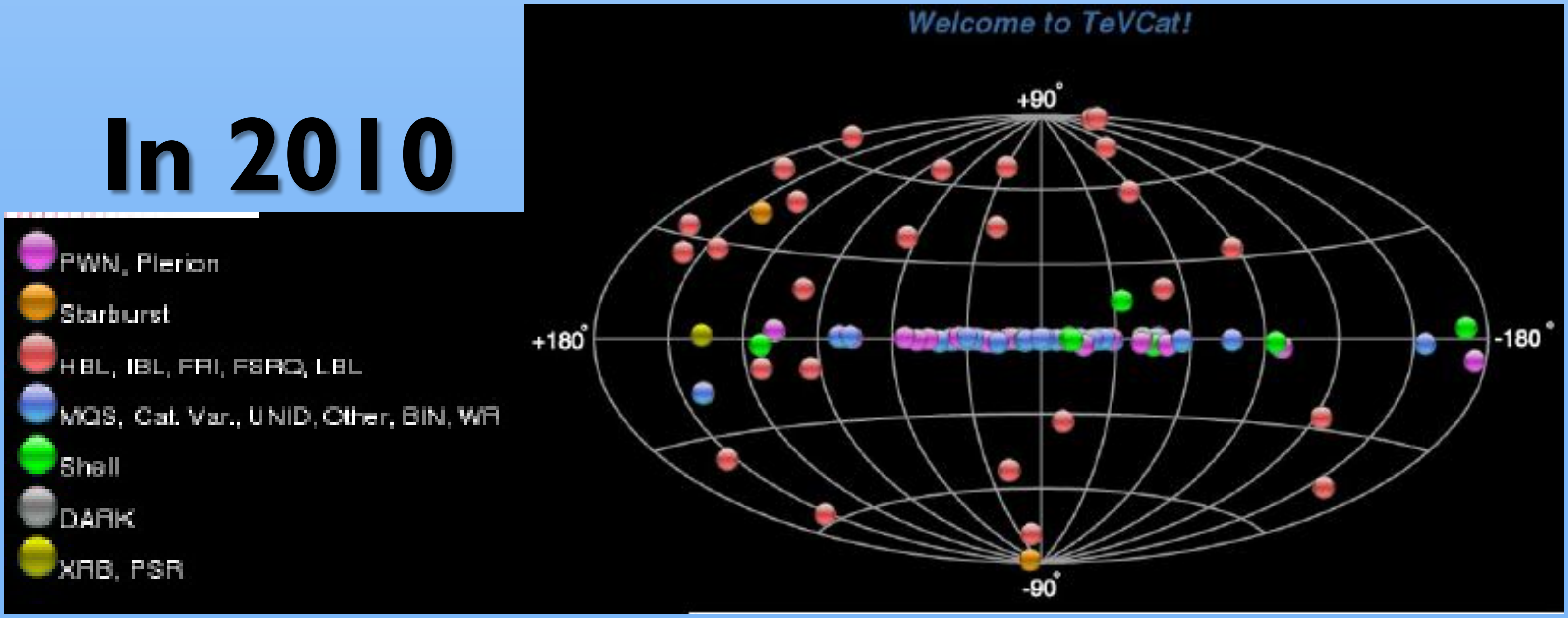
- Energy Threshold 100 GeV
- Energy Resolution ~15%
- Angular Resolution 0.05°-0.1°
- Pointing Accuracy ~ 10 arcsec
- Signal Rate ~55γ/min (Crab like)
- Background Rate 400 Hz
- Sensitivity:
  - 1 Crab in 30 sec
  - 0.01 Crab in 50h

(All at Zenith) and 1 Crab = Crab Nebula Flux = 2.3 10^{-11} cm^{-2} s^{-1} (>1 TeV)

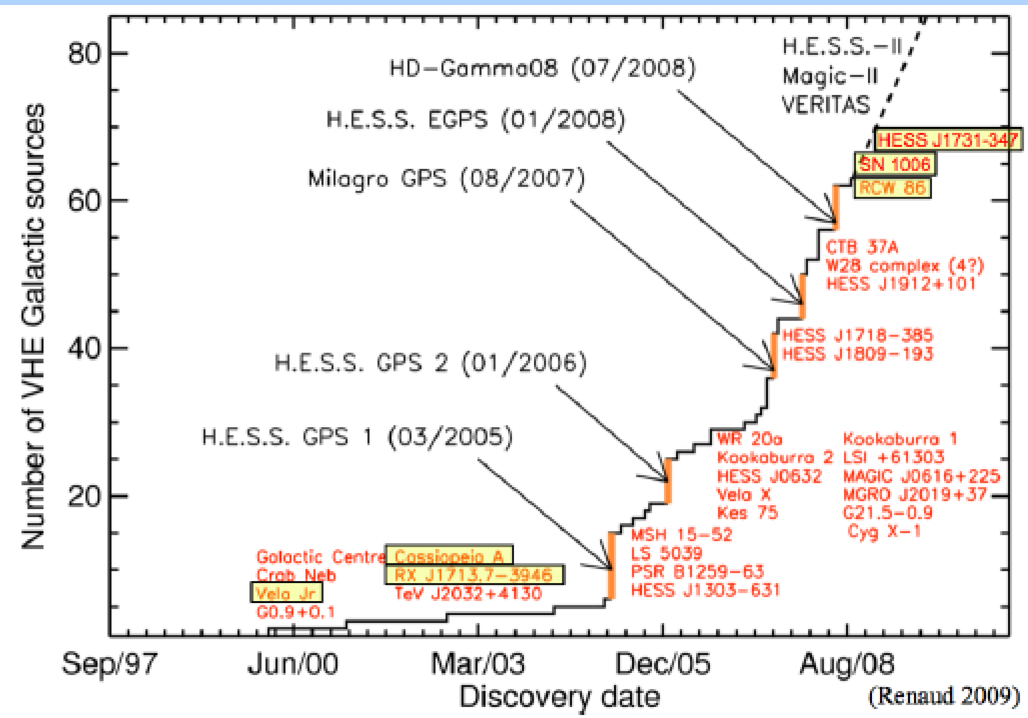
VHE sky in 1996 and in 2010



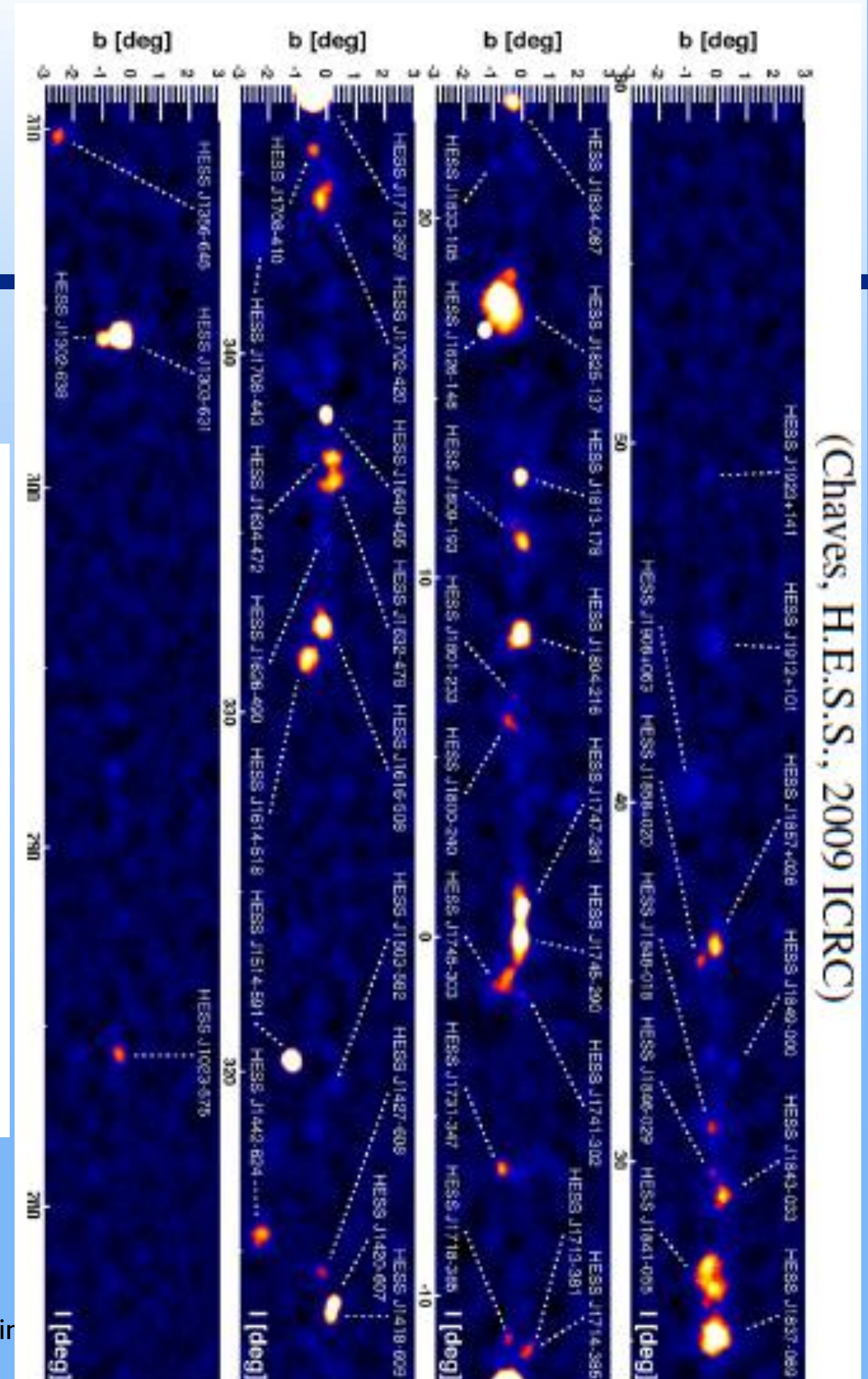
In 2010



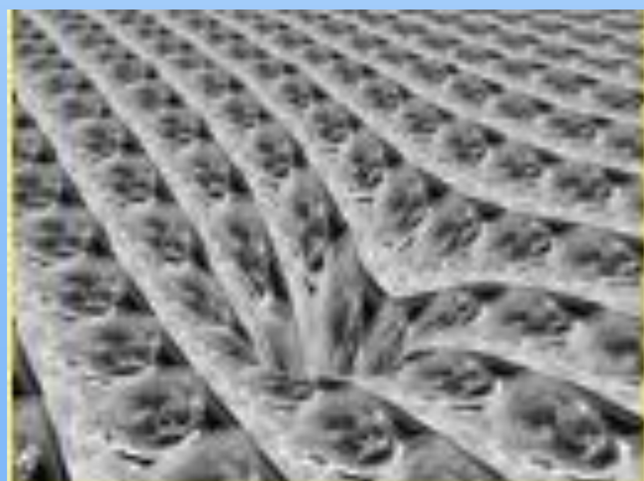
Galactic sources



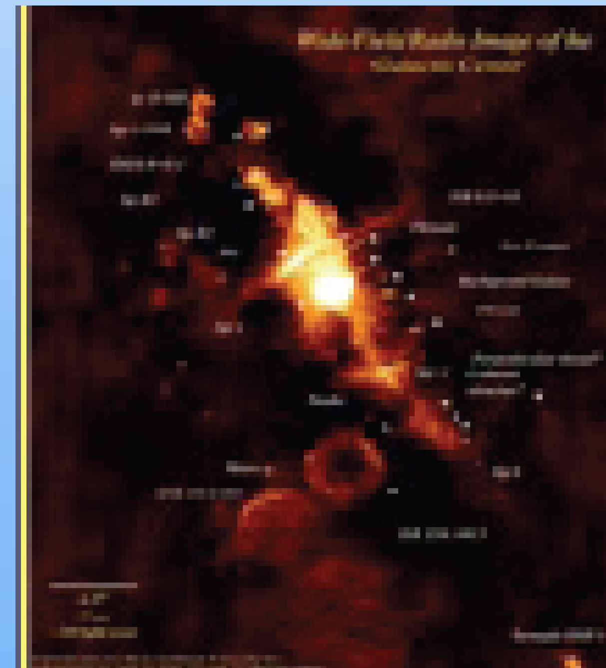
(Renaud 2009)


(Chaves, H.E.S.S., 2009 ICRC)

LPNHE activities



Space-time & Relativity

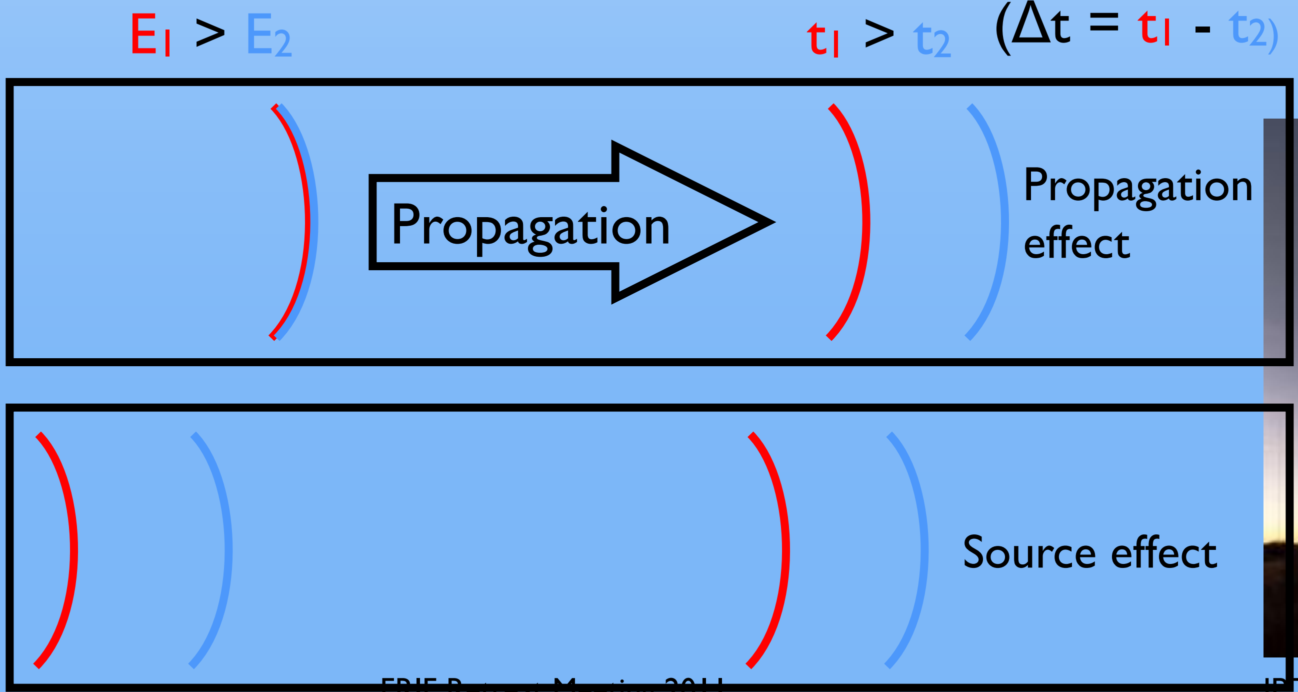


Dark Matter

Limits on Quantum Gravity energy scale

- Some models predict a violation of Lorentz invariance (LIV): the speed of photons depends on their energy

$$c' = c\left(1 \pm \xi \frac{E}{E_\mathrm{P}} \pm \zeta^2 \frac{E^2}{E_\mathrm{P}^2}\right)$$



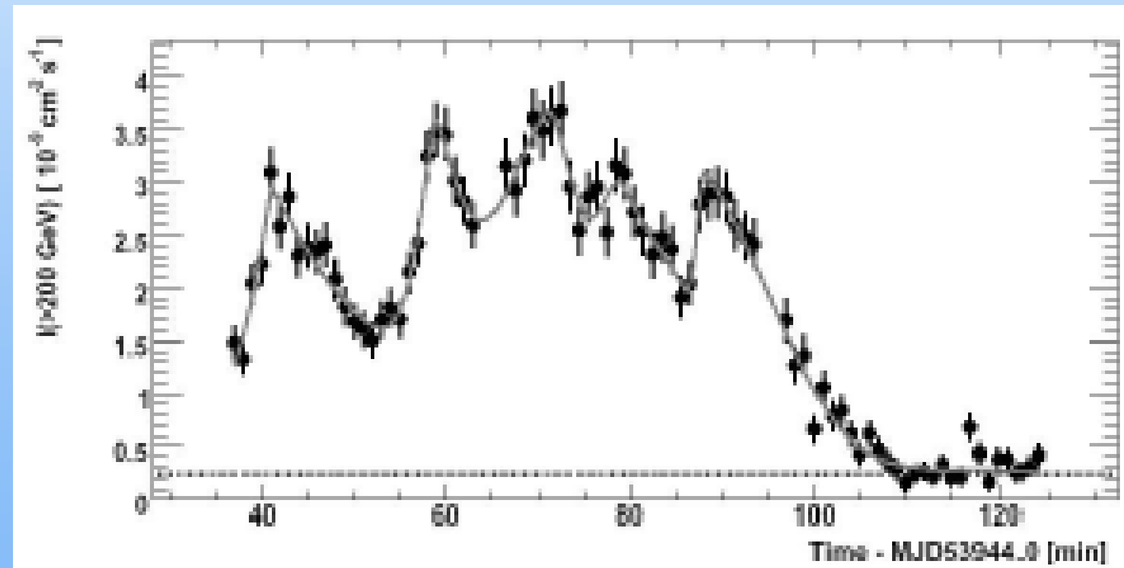
Testing LIV

- If two photons are emitted at the same time, they detected at different times:

$$\frac{\Delta t}{\Delta E} \approx \frac{\xi}{E_{\rm P} H_0} \int_0^z dz' \frac{(1+z')}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

- Increased with redshift
- Need of variable and distant sources: GRBs, AGNs

PKS 2155-304 in 2006 and LIV



- Extremely bright flares
- *2 in ~ 3min
- No differences (time-lags) between light-curves in different energy ranges was found:

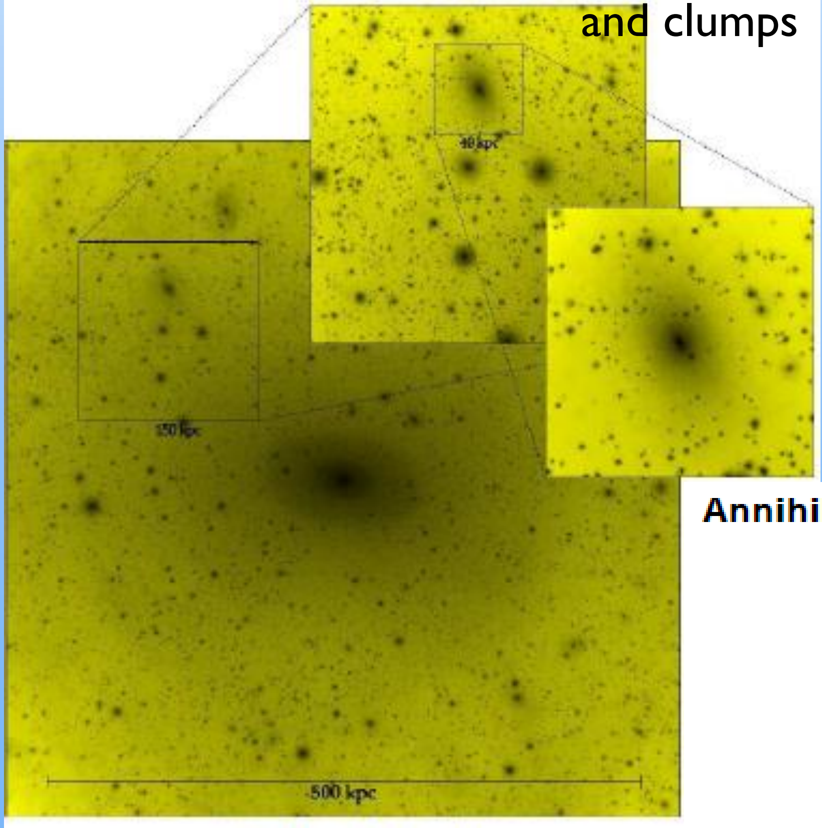
  $M^{l}_{QG} > 2.1\text{x}10^{18}$ GeV ($\xi < 5.7$)

  $M^{q}_{QG} > 0.6\text{x}10^{11}$ GeV ($\zeta < 3.6\text{x}10^{16}$)

arXiv:1101.3650

Dark Matter annihilation

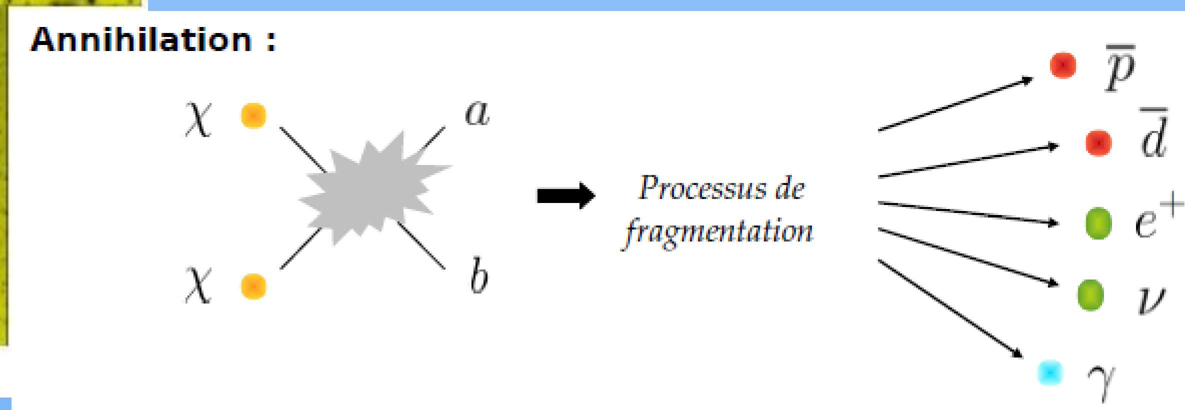
N-Body simulation : hierarchic structures and clumps



Kuhlen et al, 2008

Proprieties :

- $\sigma v \approx 10^{-26}$ cm^{3}s^{-1} (thermal decoupling)
- M ≈ 1 GeV – 120 TeV

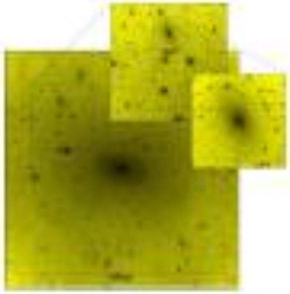


Where ?

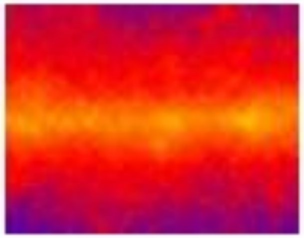
- Galaxies cluster (far !)

- Galactic Centre (Astrophysics sources)

- Dwarf Spheroidal Galaxy

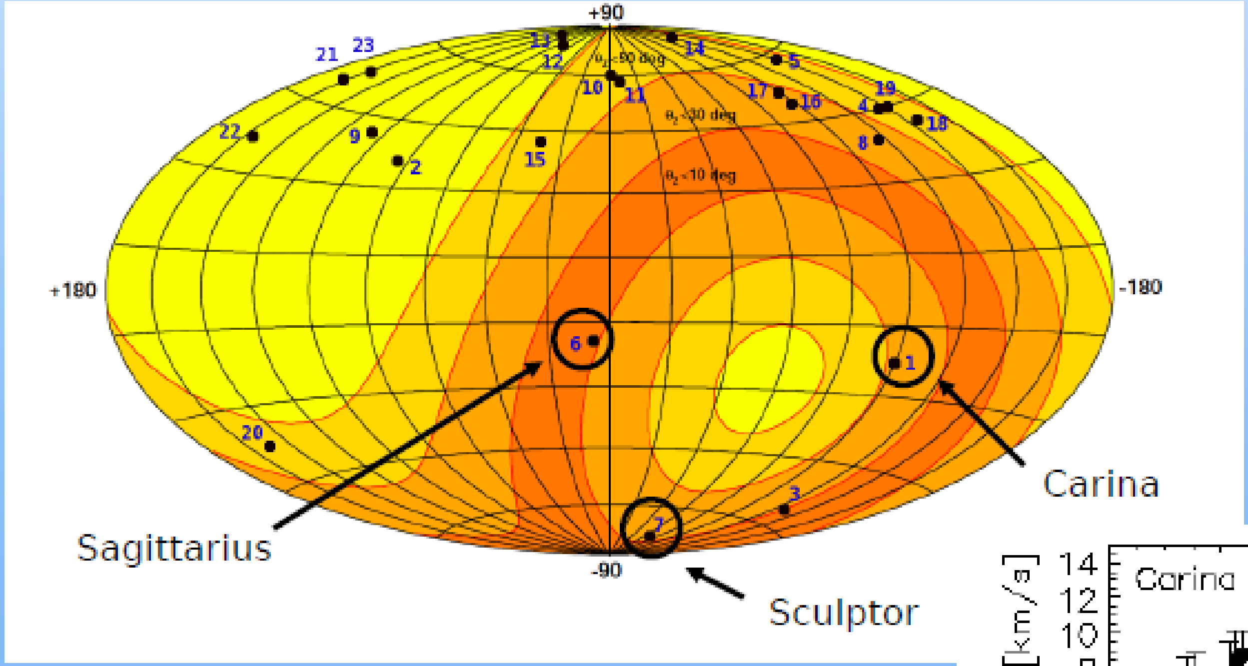


- Clumps (plenty of but where ?)

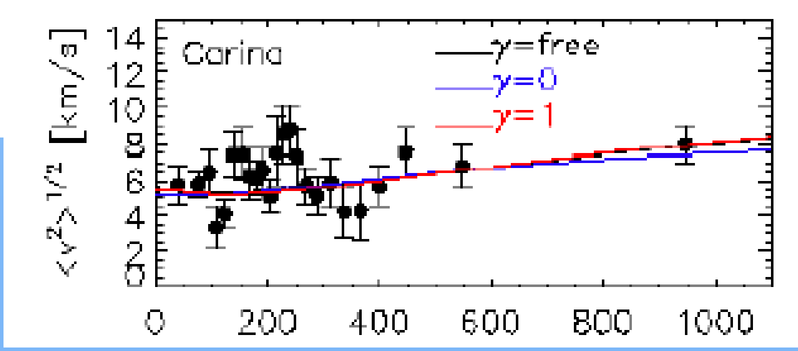


- Diffuse emission (How ?)

Dwarf spheroidal Galaxies

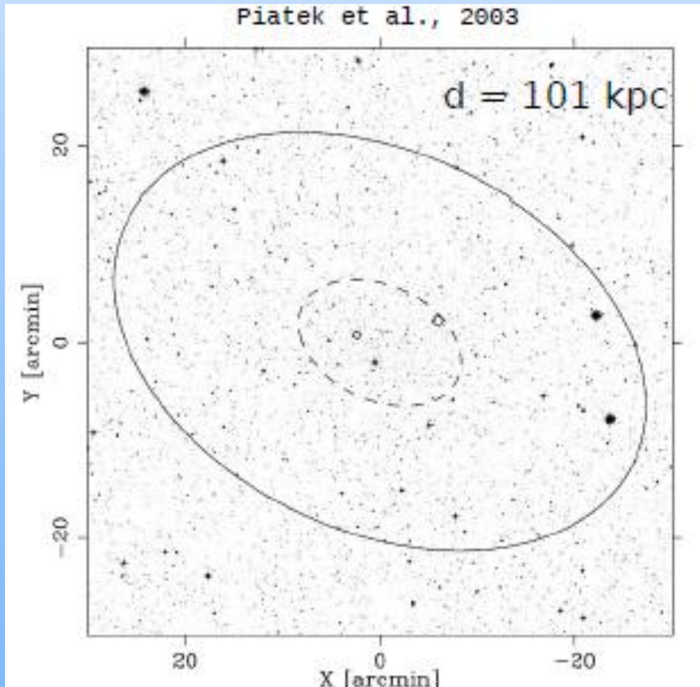


$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{\frac{\beta-\gamma}{\alpha}}}$$



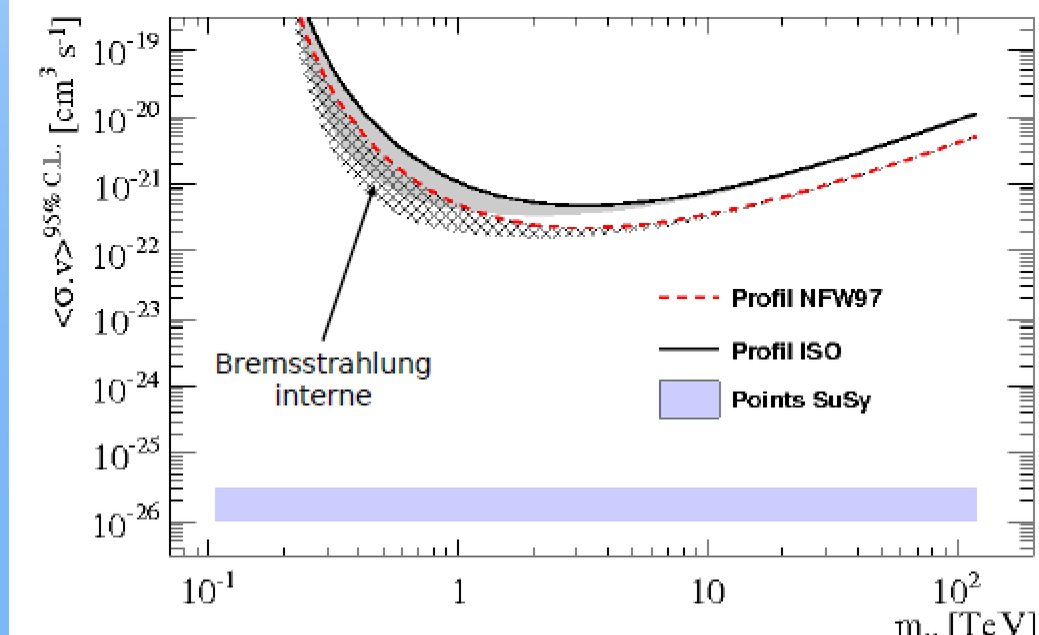
Walker et al., 2007

Dwarf Spheroidal Galaxy Carina



Density profile :

- NFW97 : $r_s = 0{,}54$ kpc
  $\rho_s = 4{,}63 \cdot 10^7\ M_\odot kpc^{-3}$
  Walker et al., 2007
- ISO : $r_s = 0{,}22$ kpc
  $\rho_s = 1{,}36 \cdot 10^8\ M_\odot kpc^{-3}$
  Wilkinson et al., 2006



H.E.S.S. Collaboration, soumis à Astroparticle Physics

arXiv:1012.5602


So what next???

H.E.S.S. Phase II

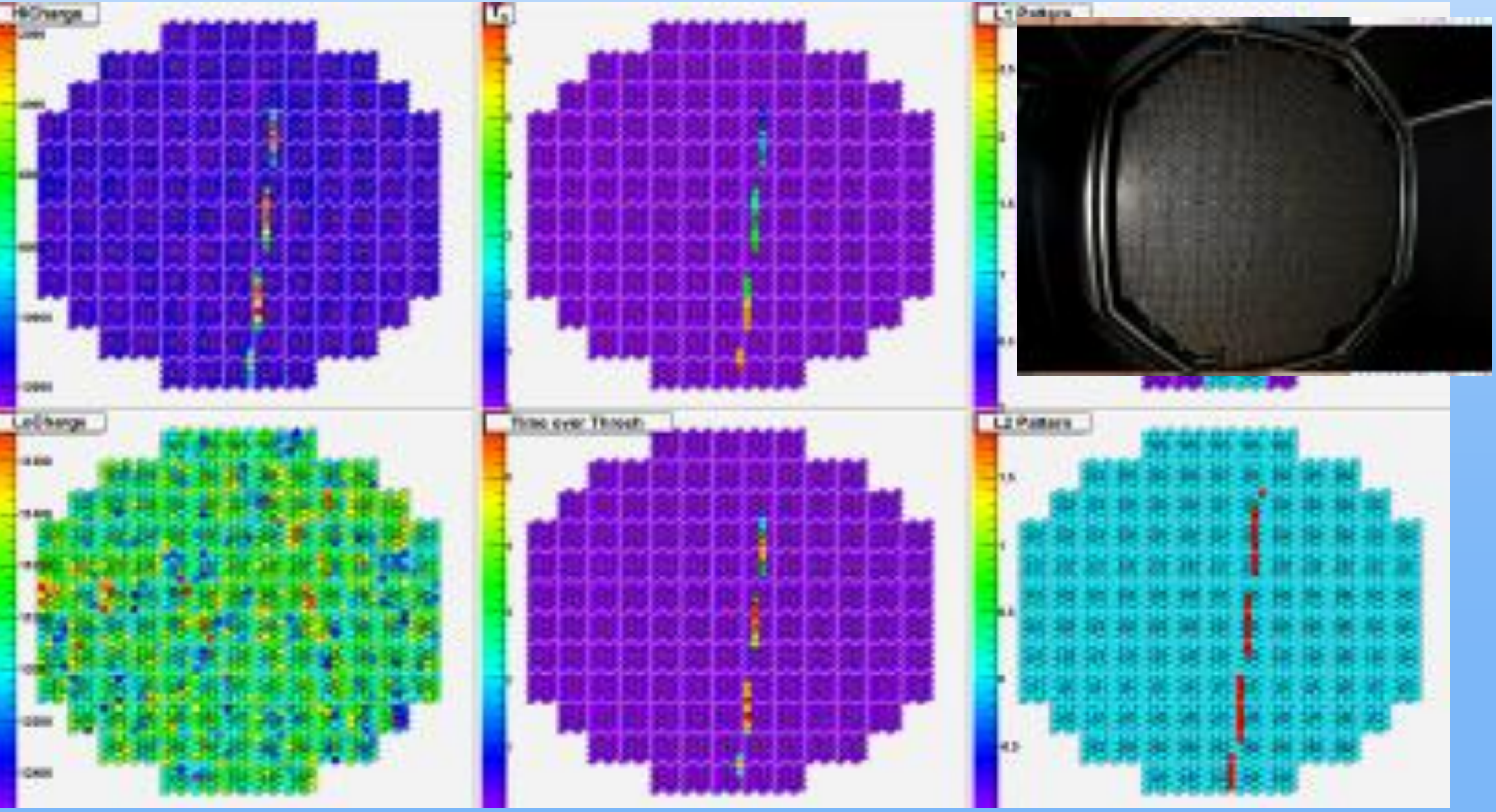
- Mirror 600 m2 (6* H.E.S.S. I)
- Expected energy threshold 10-20 GeV
- First light in mid-2012 (Prob. 99,99%)

Under construction

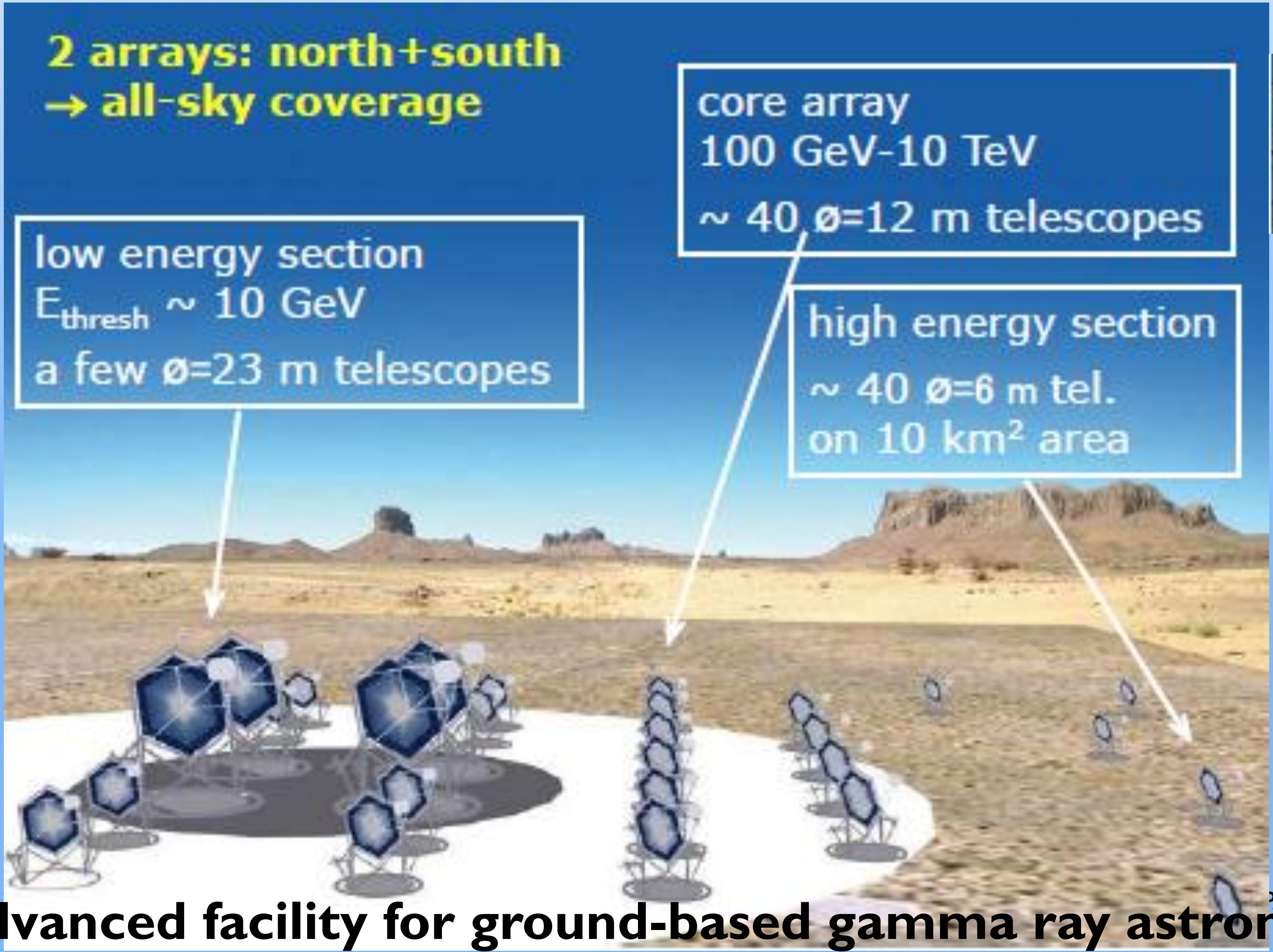
- 5 000 Tonnes
- Hauteur ~ 50 m
- Focale 35 m
- Miroir parabolique ~ 600 m^2
- Structure en acier

H.E.S.S.-2 au LPNHE

THE LPNHE camera
with LLR, IRFU, LAPP, LPTA, ...

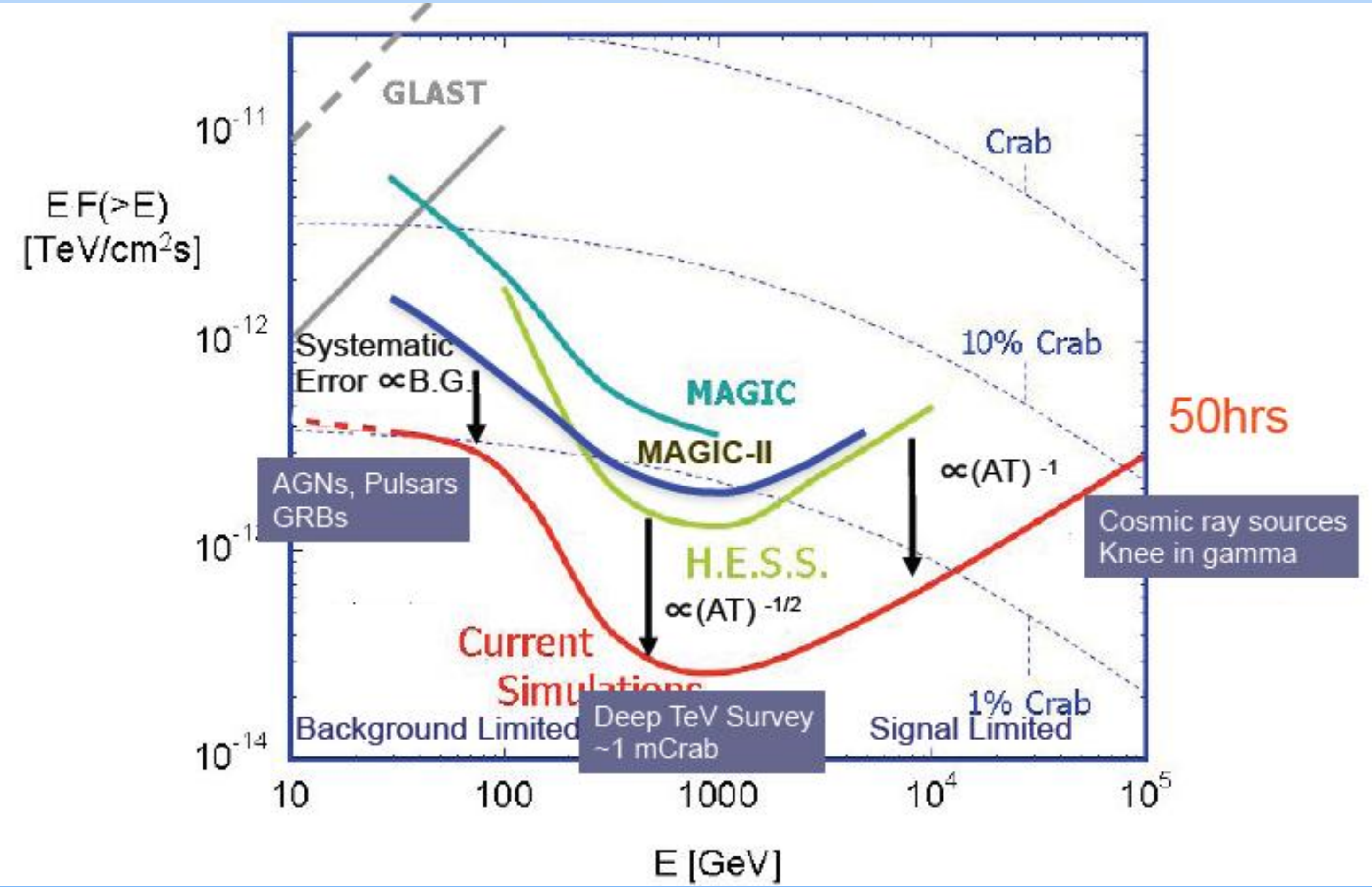


A plan of a future IACT experiment

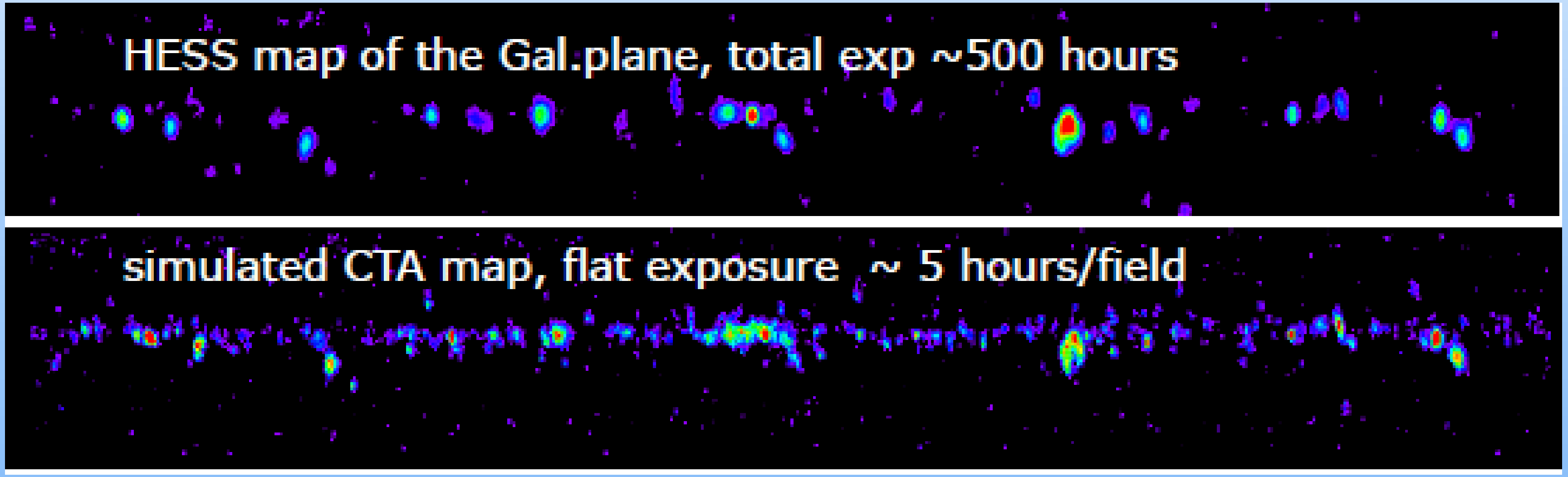


an advanced facility for ground-based gamma ray astronomy

Expected Sensitivity



Expectations for Galactic Plane Survey



- Assumptions
  - *2 improvement in hadron rejection
  - *2 gain in angular resolution
  - *10 gain in effective area

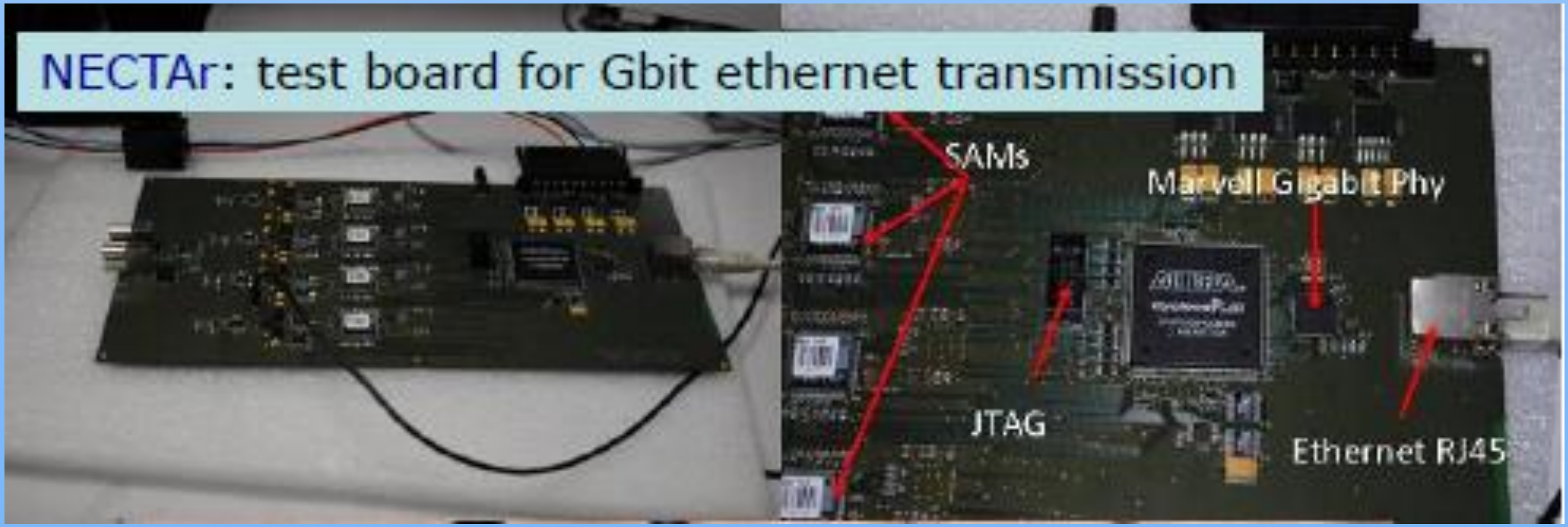
… there are 'a few' challenges

- Factor of 10 in sensitivity with factor of 10 in funding
- Find an optimized array layout , that has the required performance
- Optimize designs for effective production and for stability and high reliability
    - O(50-100) telescopes
    - O(10.000)m^2 mirror area
    - O(70)m^2 photo sensitive area
    - O(100.000) electronic channels
    - O(100)M€funds

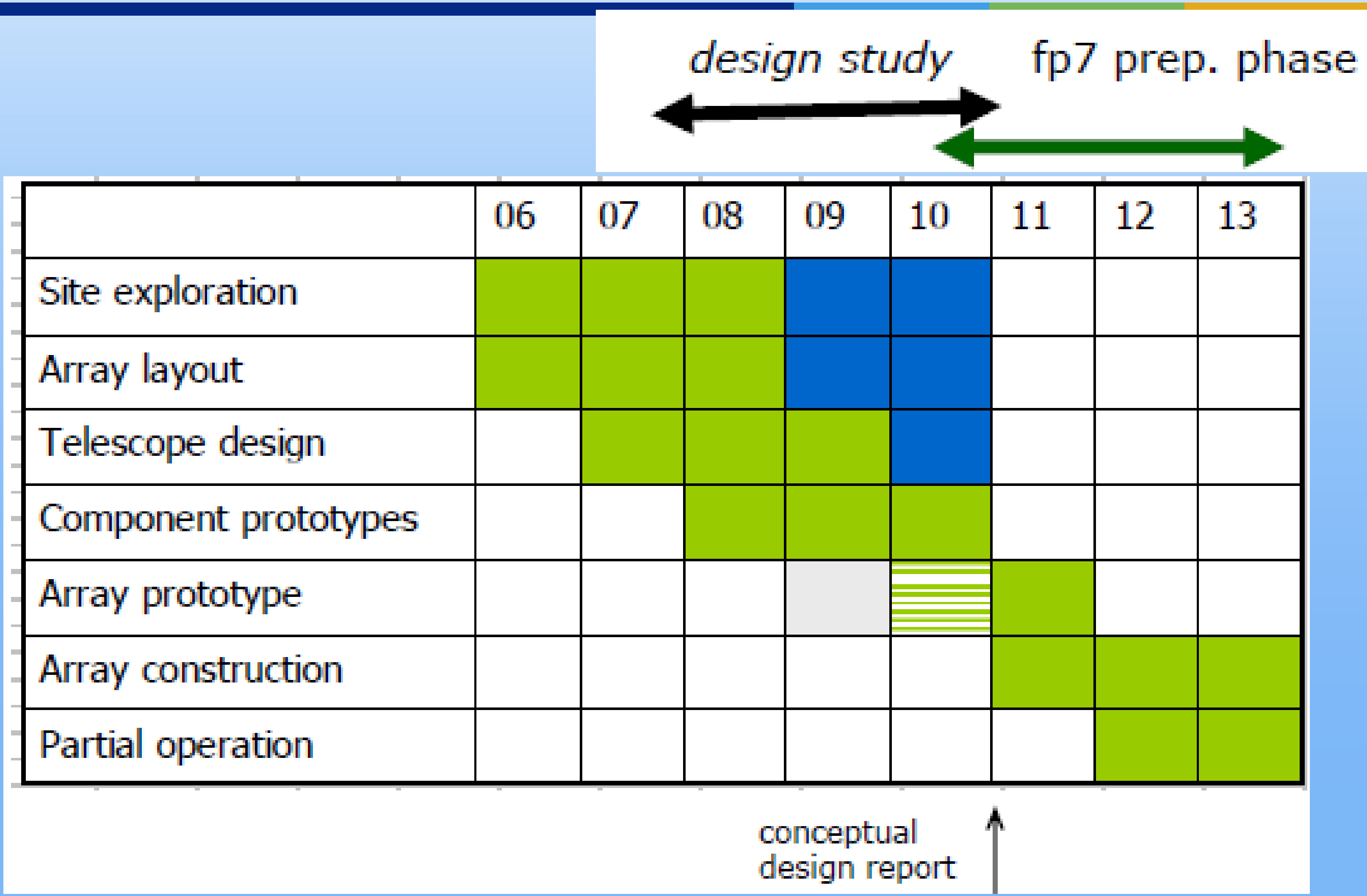
Signal Readout and Camera Trigger

Different options exist :

- neCTAr proposition (LPNHE, IRFU Saclay, LPTA, Univ. Barcelona)
  - analogue memories (1 GHz sampling)+ADC



Timeline for CTA

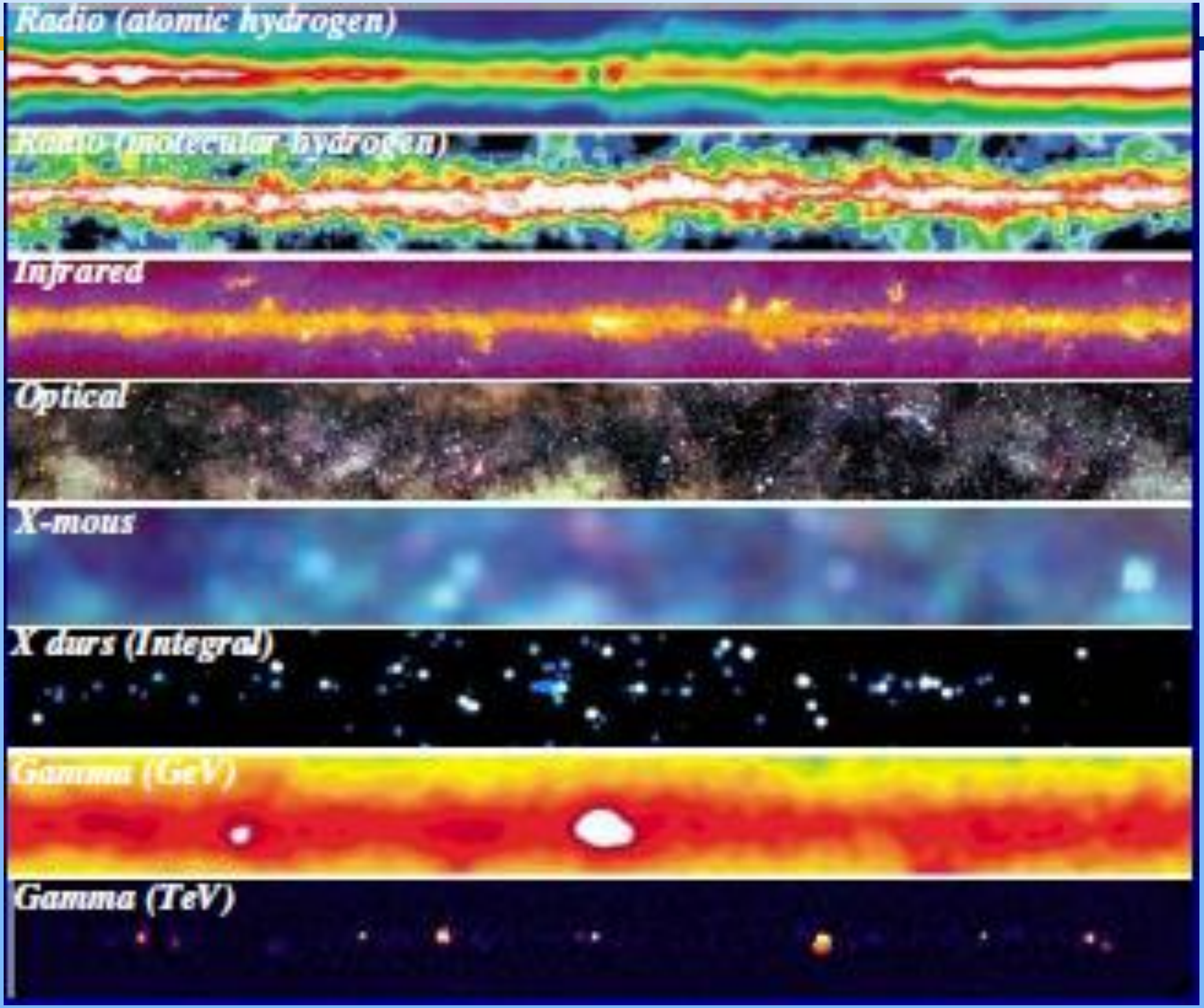


. . . a little optimistic ??

Conclusions

- VHE astronomy is a well-established field of astronomy: spectrum, images, light curves
- One can do cosmology, astroparticle physics with VHE detectors
- MAGIC-II, H.E.S.S.-II, VERITAS, CTA (future)
- Number VHE sources is approaching 100
- Galactic sources include PWN, SNR, helps our understanding of the origin of cosmic rays
- Extragalactic sources include AGN and radio galaxies (and starburst galaxies), GRBs are yet to be detected
- Still waiting for detection on Globular clusters, Dwarf galaxies, ...

The Galactic Plane



The LIV Method

→ Event by event approach

- Method used by Lamon *et al.* for INTEGRAL and by Martinez and Errando for MAGIC
- We use the following form for the probability density function:

$$P(t,E) = N \int_0^{\infty} A(E_S)\,\Gamma(E_S)\,G(E-E_S,\sigma(E_S))\,F_S(t-\tau E_S)\,dE_S$$

- where $\Gamma(E_S)$ is the emitted spectrum, $G(E-E_S, \sigma(E_S))$ is the smearing function in energy, $A(E_S)$ is the acceptance of H.E.S.S. and F_S is the emission time distribution at the source
- The likelihood function is then given by the product

$$L = \prod_i P_i(t,E)$$

- over all photons in the studied sample
- The maximum of the likelihood gives the time-lag τ_l (τ_q) in s/TeV (s/TeV^2)

Flux de rayons gamma

$$\frac{d\phi^{tot}}{dE_\gamma}(E_\gamma,\psi,\Delta\Omega)=\frac{d\phi^{pp}}{dE_\gamma}(E_\gamma)\times\phi^{astro}(\psi,\Delta\Omega)$$

Physique des particules

$$\frac{d\Phi^{pp}}{dE_\gamma}(E_\gamma)=\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{dN_\gamma}{dE_\gamma}$$

Distribution spatiale

$$\Phi^{astro}(\psi,\Delta\Omega)=\int_{\Delta\Omega}d\Omega\int_{los}dl\,\rho^2(l,\psi)$$