Astroparticle physics:
Very High Energy Gamma-ray Astronomy

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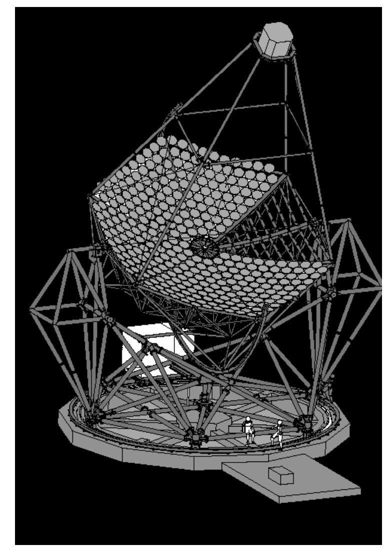
GraSPA2013

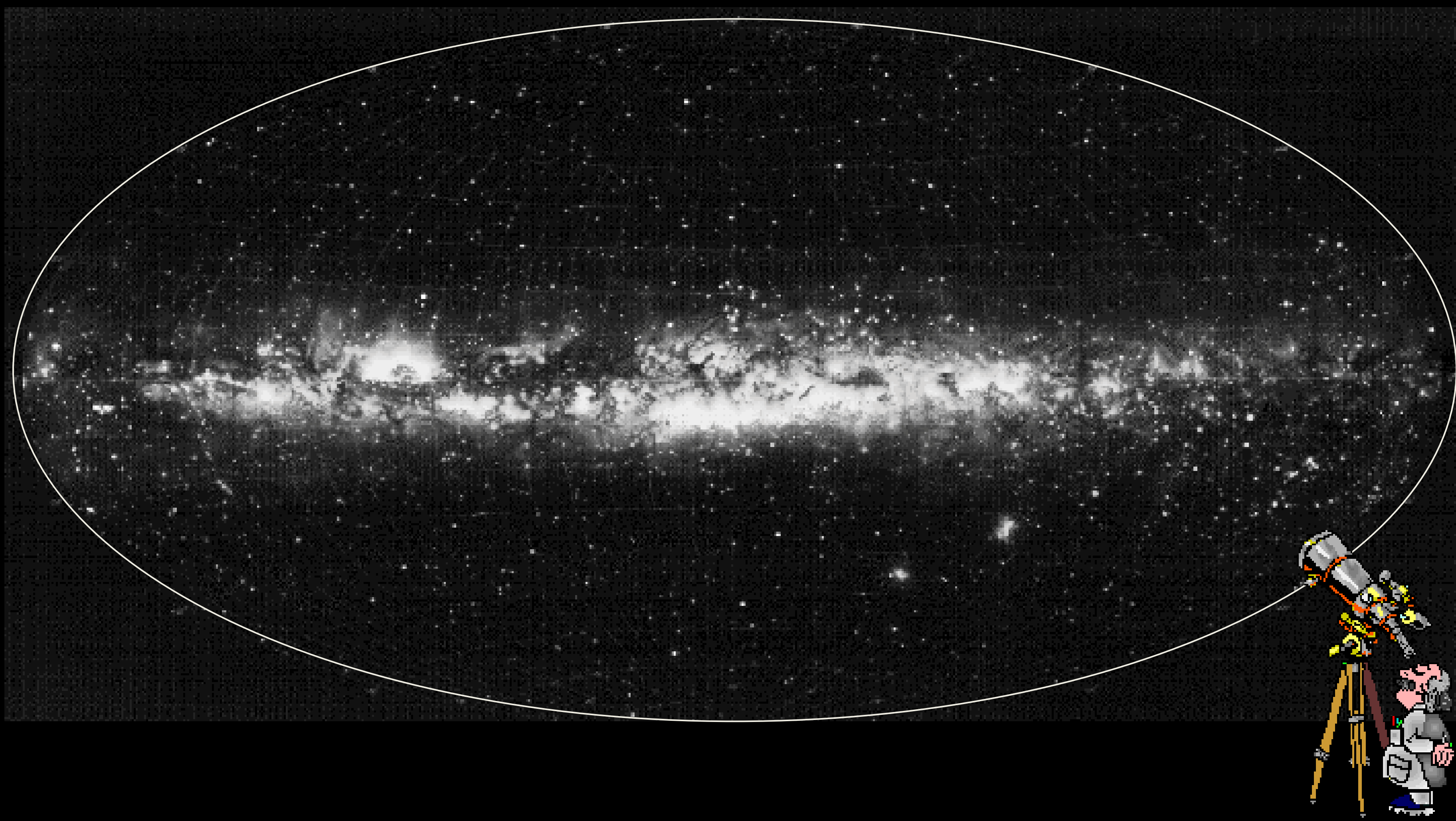
OUTLINE

- The non-thermal Universe and the high energy gamma rays.
- The Cherenkov telescopes.
- Astroparticle physics with gamma-rays:
  Astrophysics,
  Cosmology and
  Fundamental physics.



Radio Infrared **Visible light** X rays Gamma rays

(eV)



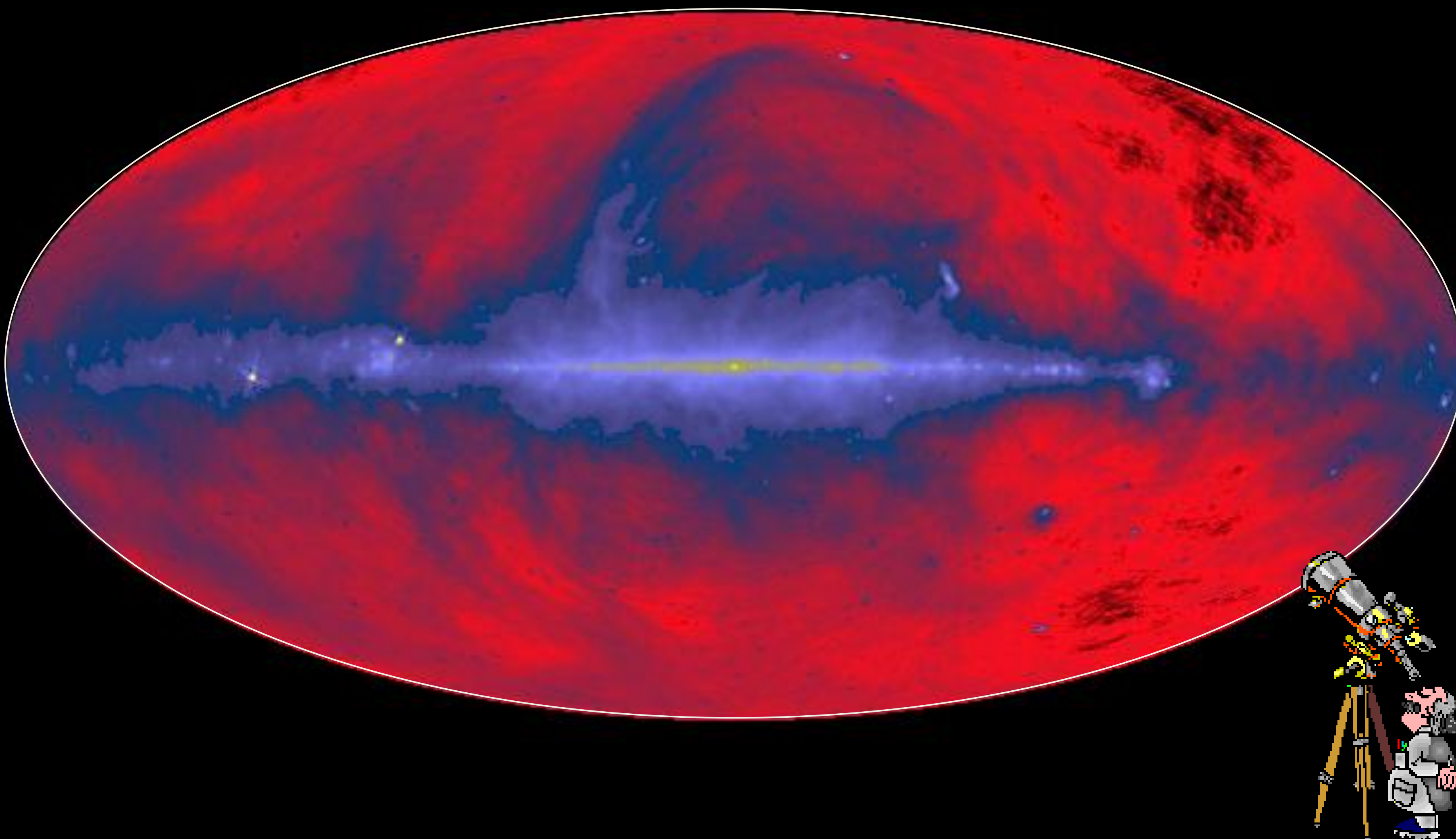
Radio
(10^{-6} eV)

Infrared

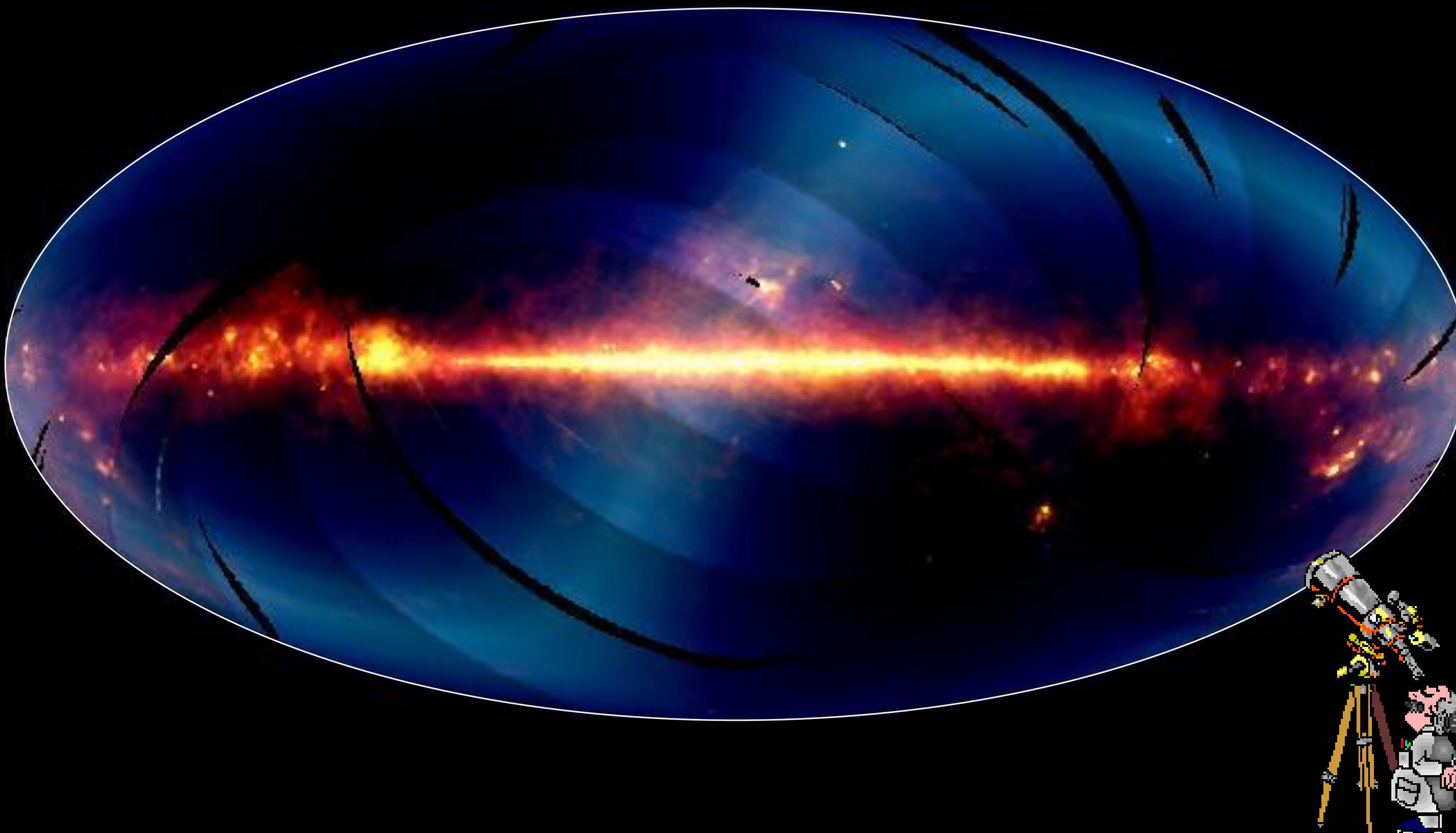
Visible light

X rays

Gamma rays



Radio | Infrared (10^{-2} eV) | Visible light | X rays | Gamma rays



Radio

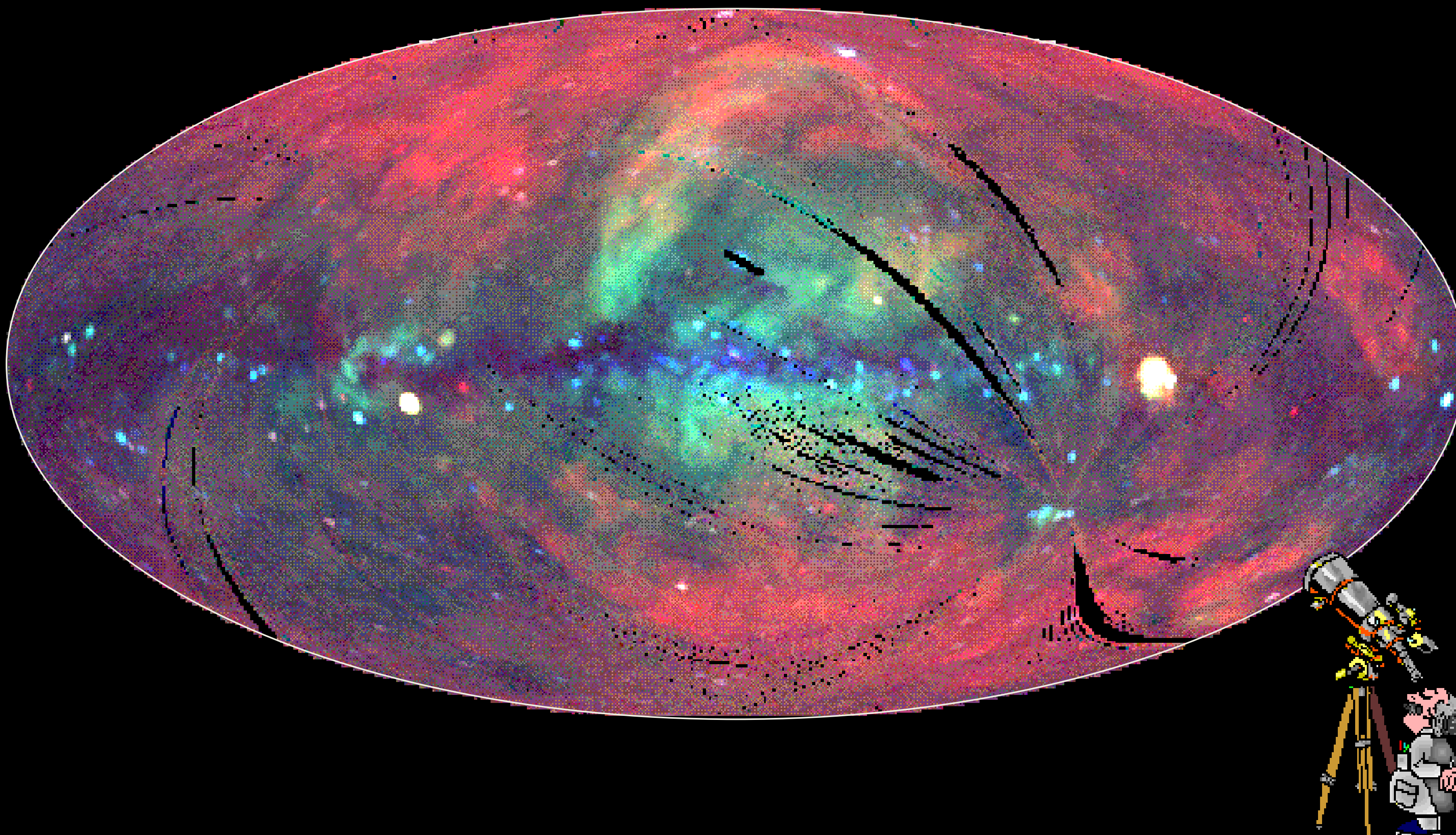
Infrared

Visible light

X rays

(10^3 eV)

Gamma rays



Cosmic radiation and non-thermal universe

- Cosmic Rays (CR) have non-thermal origin: their spectra do not show any « characteristic temperature » and a thermal emission mechanism to their energies does not exist.

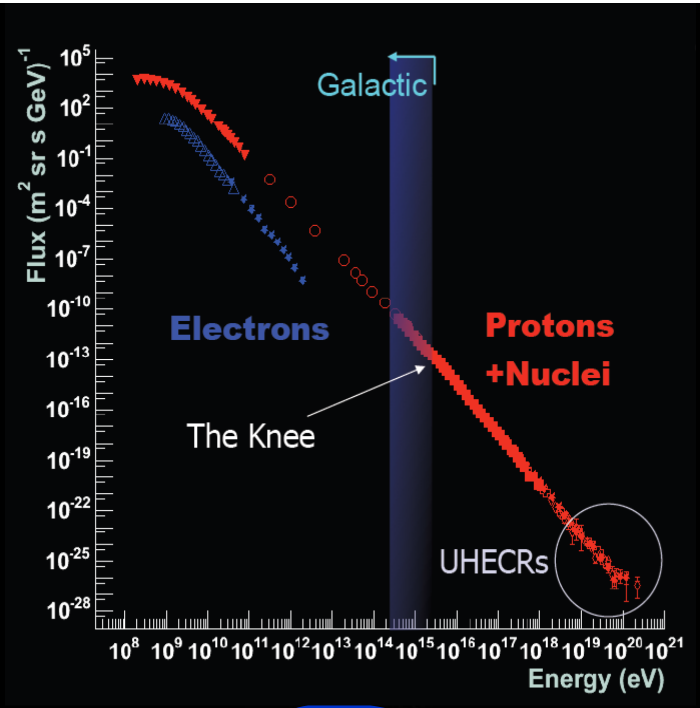
- Our Galaxy is filled up of ultra-relativistic particles:

  - energy density ~ 1eV/cm^3
    (~ e. d. of stars light, intergalactic magnetique fields , kinetid e.d. of interstellar gas)

  - 99% protons + nuclei

  - of galactic origin at least up to ~ 10^{15} eV

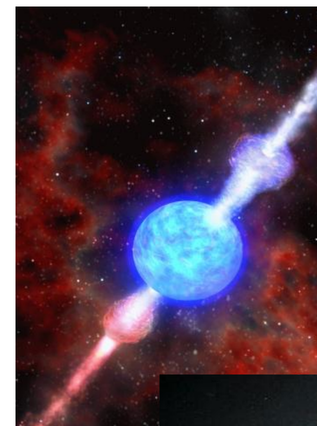
  - charged CR are diffused by B (B_{IS}~ 3 μG)
    (directional information lost)



- The images of the CR accelerators are achieved by neutral (secondary) particles: ➔ **Gammas** and Neutrinos (**Astronomy)**

Gamma rays and the non-thermal universe

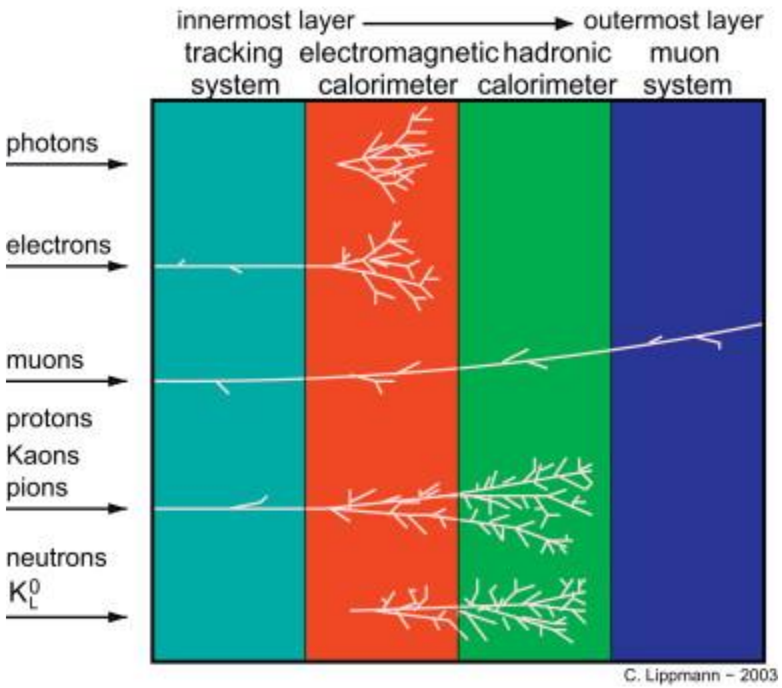
- The cosmic rays origin in our Galaxy is still one of the major open questions in astrophysics:
  High-energy gamma-ray astronomy provides an experimental approach for a better understanding of acceleration, propagation and interaction mechanisms.



- High-energy gamma-ray astronomy gives access to the most energetic non-thermal phenomena in place in the observed sources and generally studied by complex theories (e.g. magneto -hydrodynamic).

- In particular the VHE photons are privileged probes for a large series of astrophysical systems.

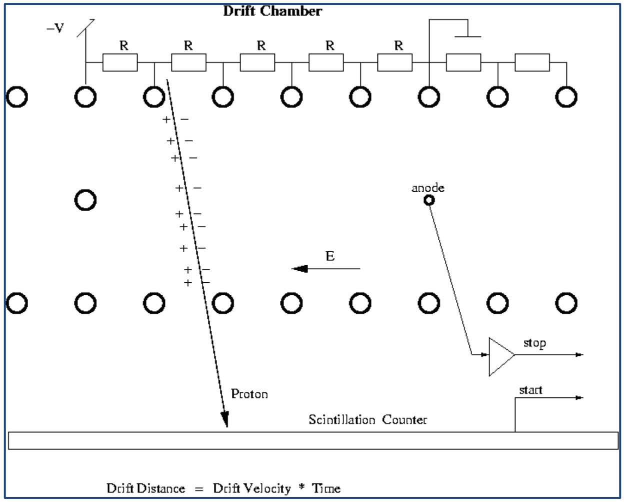
New detection methods, new wavelengths

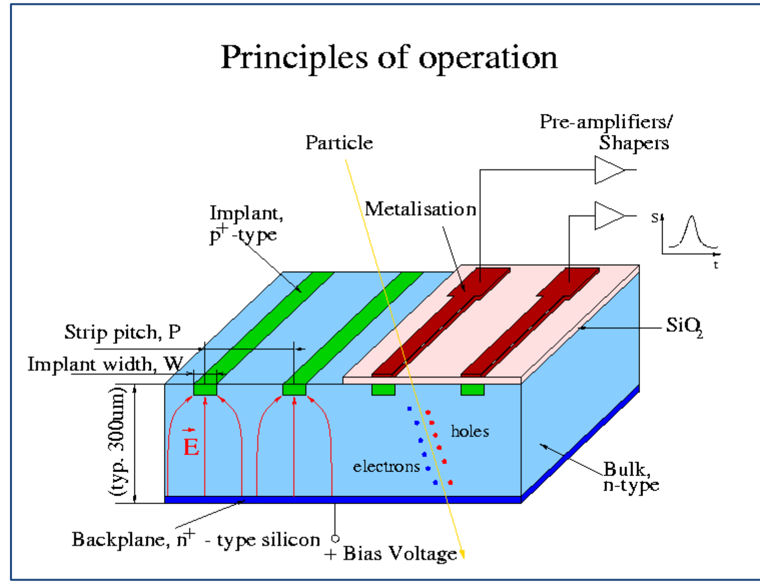


In particle physics detector: **calorimeter** measuring the energy of particles through their particle shower
Calorimeters are segmented transversely to provide information about the direction of the particles, as well as the energy deposited,

… longitudinal segmentation can provide the identity of the particle based on the shape of the shower.

New detection methods, new wavelengths

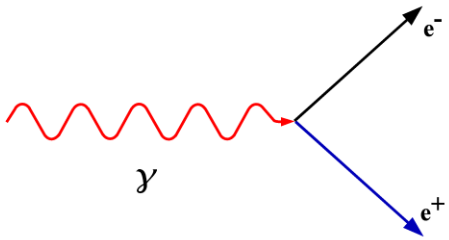




From **spark chamber** to …
drift chamber for measuring the space coordinates of the trajectory of a charged particle. Detecting the ionization electrons produced in the gas and measuring their drift times and arrival positions on sensitive electrodes.

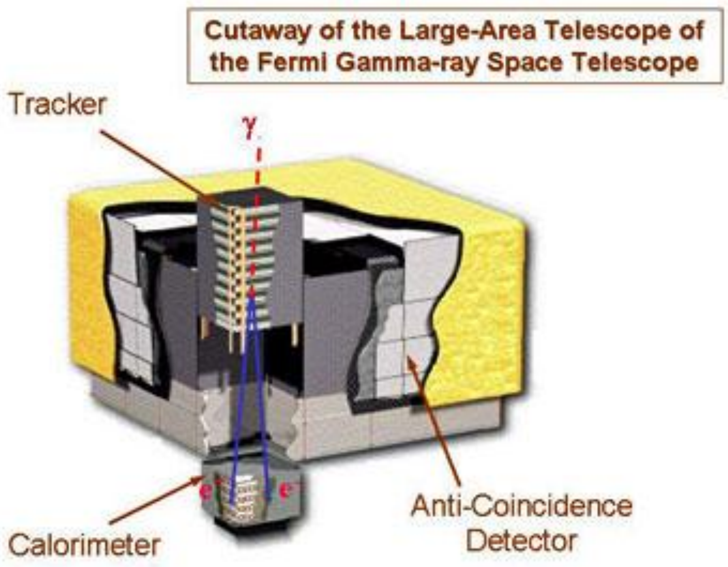
… to **Silicon particle detectors:**
doped narrow strips of silicon turned into diodes. As charged particles pass through these strips, they cause small ionization currents that can be detected and measured. Silicon detectors have a much higher resolution in tracking charged particles than older technologies such as gas chambers..

New detection methods, new wavelengths



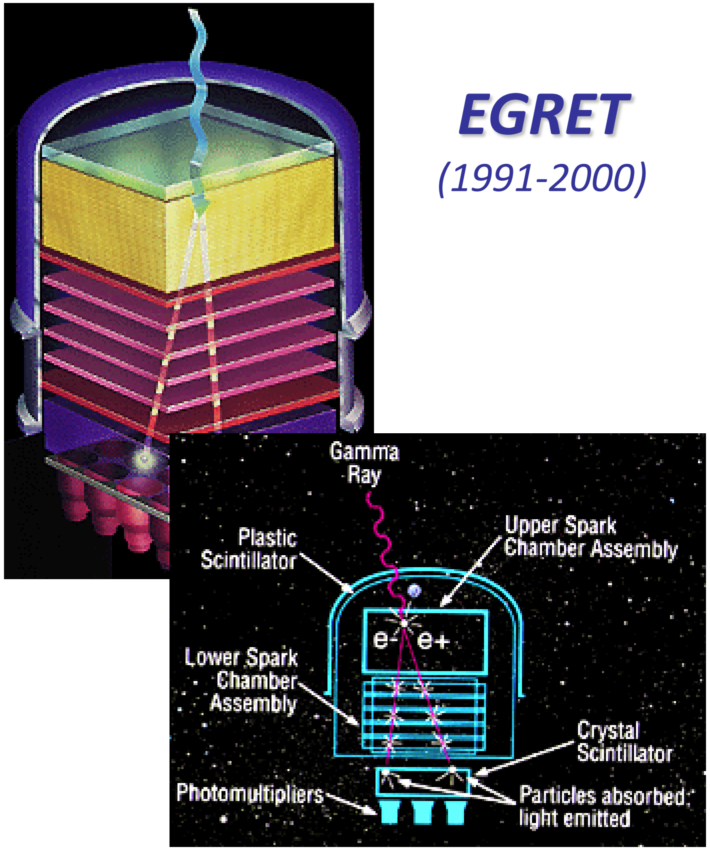
FERMI

(2008-..)



EGRET

(1991-2000)

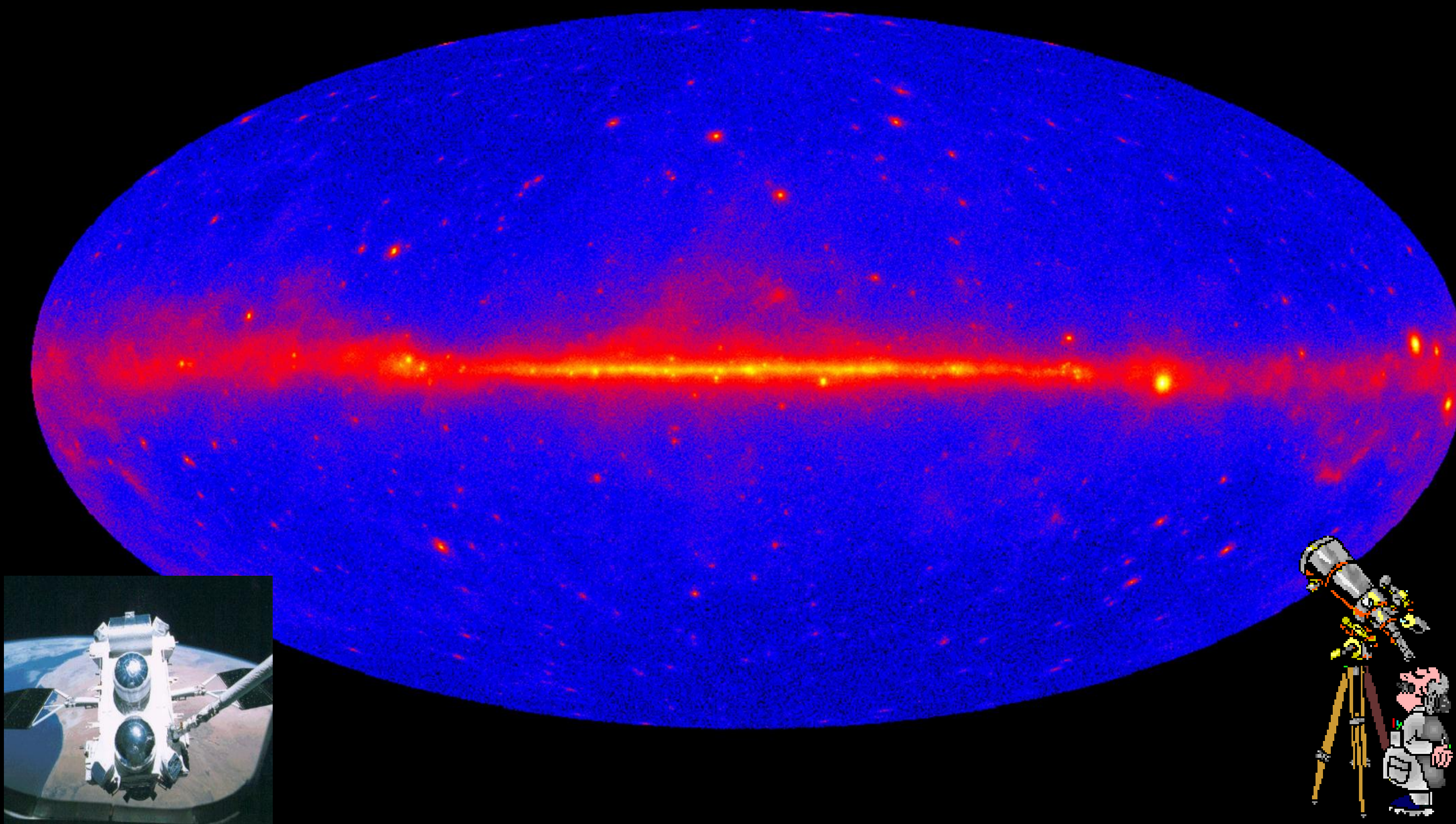


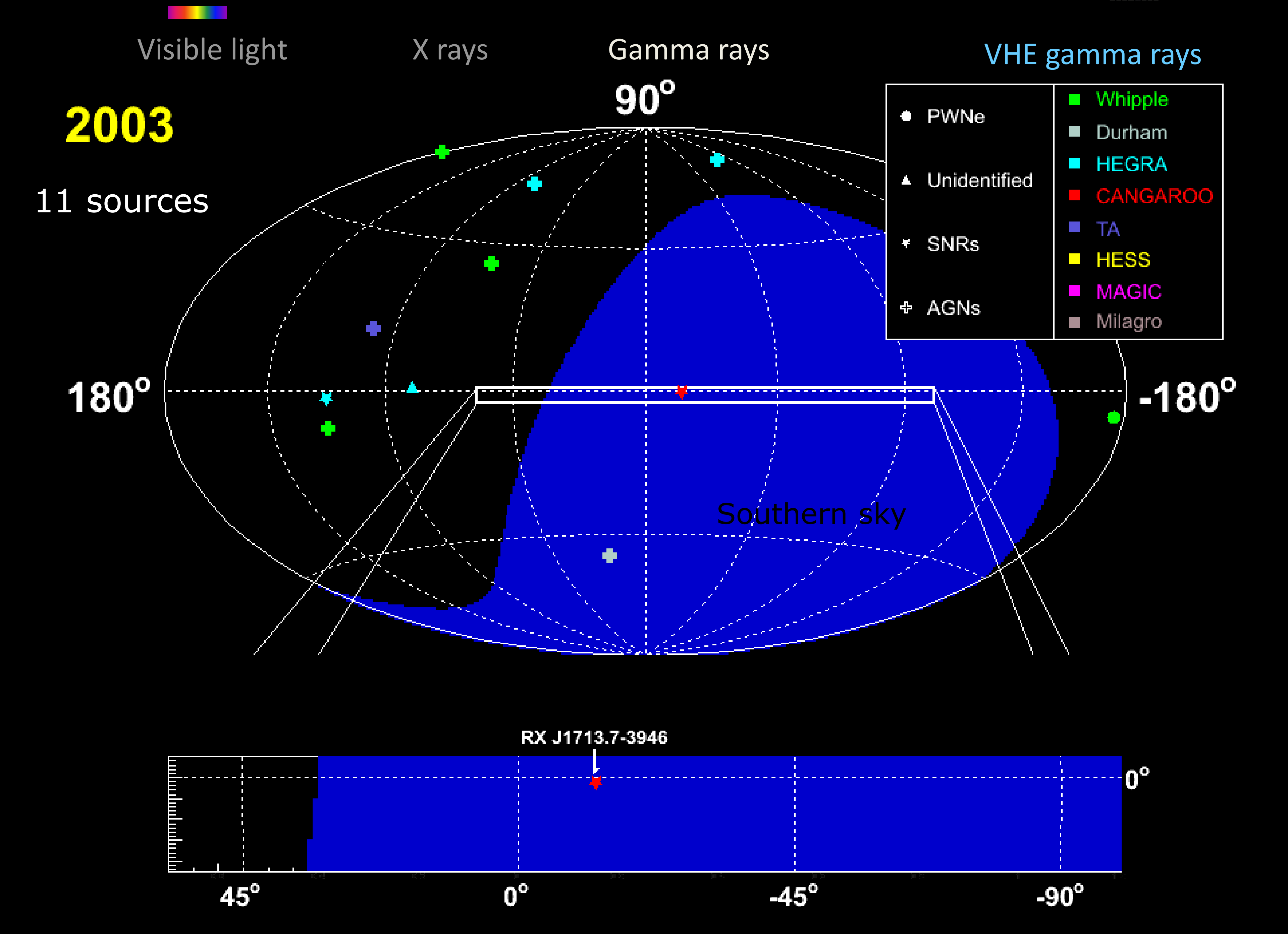
- Larger FoV (2.4 sr): sky covered in 3 hours
- Angular resolution ×3 better than EGRET
- Large effective area (1 m2) (×5 better than EGRET)
- Energy → 300 GeV (10 GeV for EGRET)

Radio | Infrared | Visible light | X rays | Gamma rays

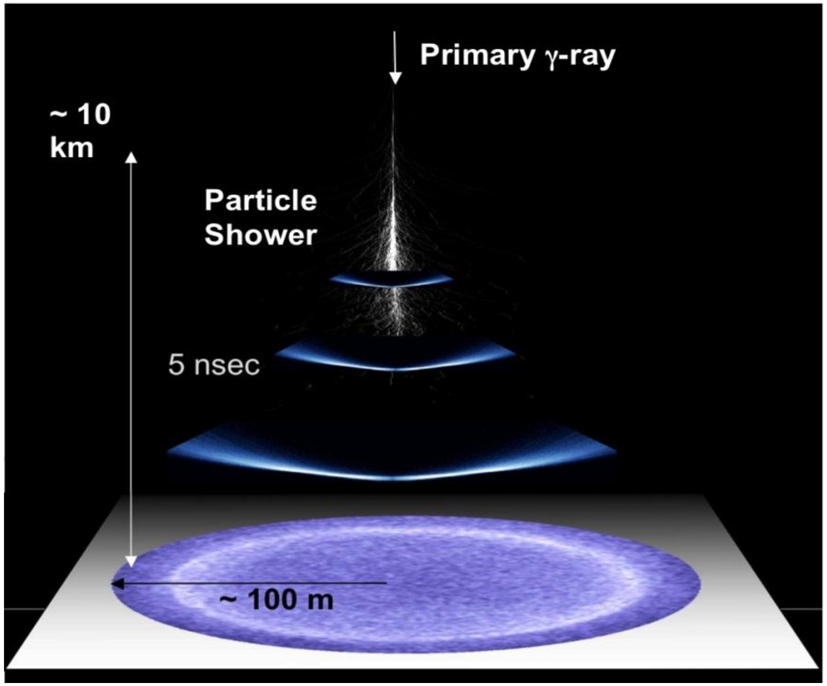
(10^{9} eV) VHE

(10^{12} eV)

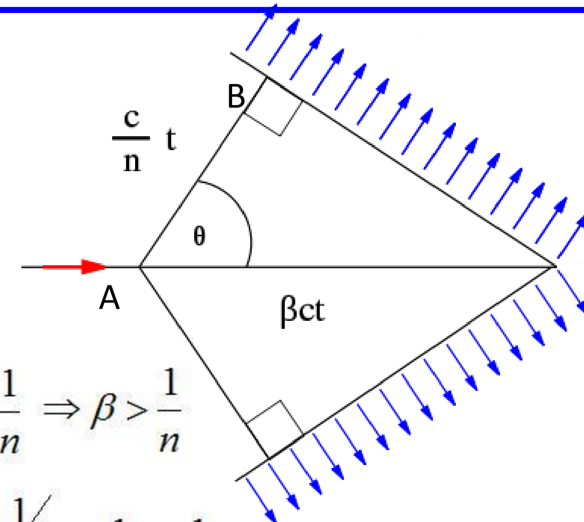



Visible light
X rays
Gamma rays
VHE gamma rays
2003
11 sources
90°
180°
-180°
PWNe
Unidentified
SNRs
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
Southern sky
RX J1713.7-3946
0°
45°
0°
-45°
-90°

New detection methods for VHE γ : Cherenkov radiation



Cherenkov Effect

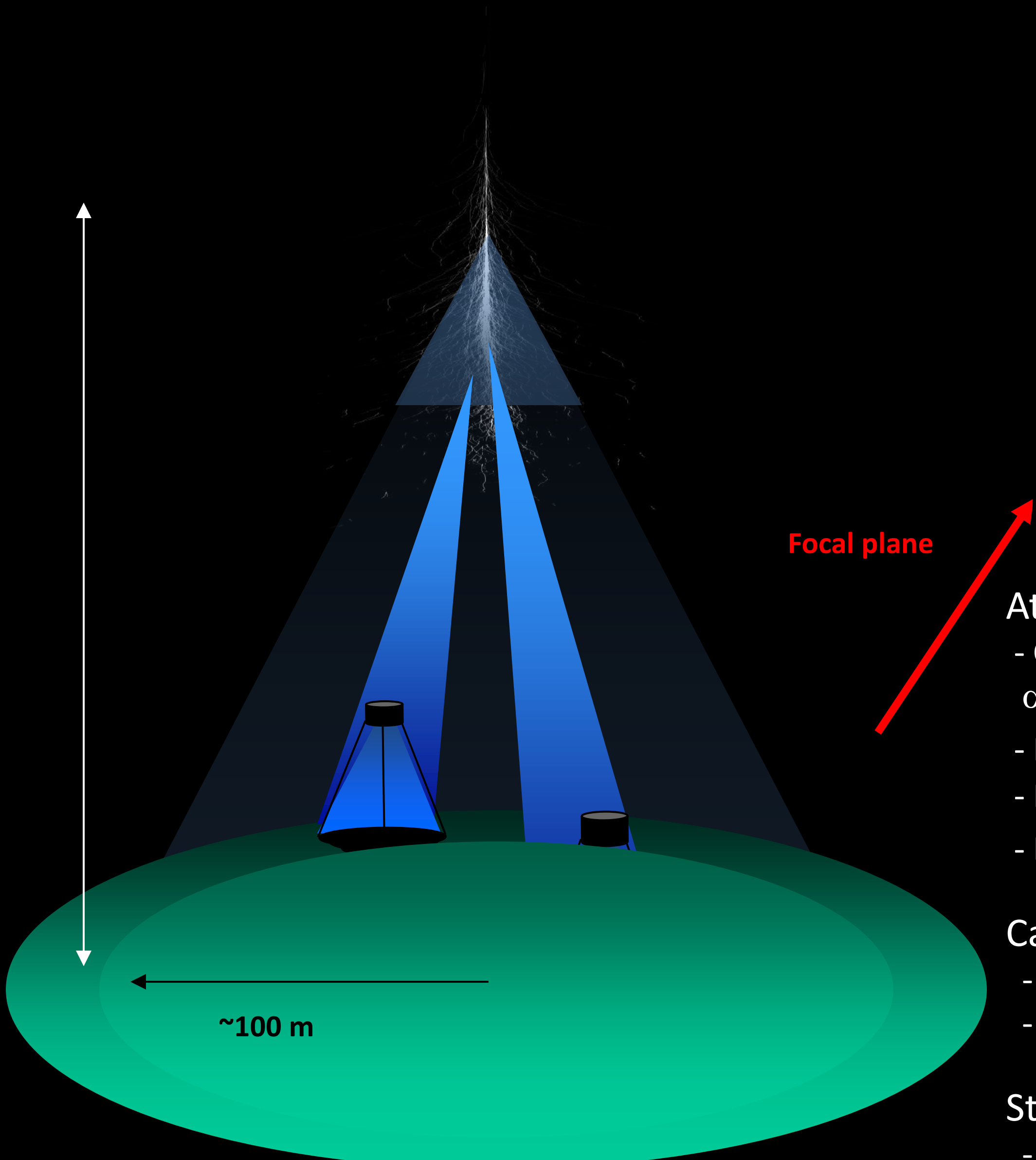


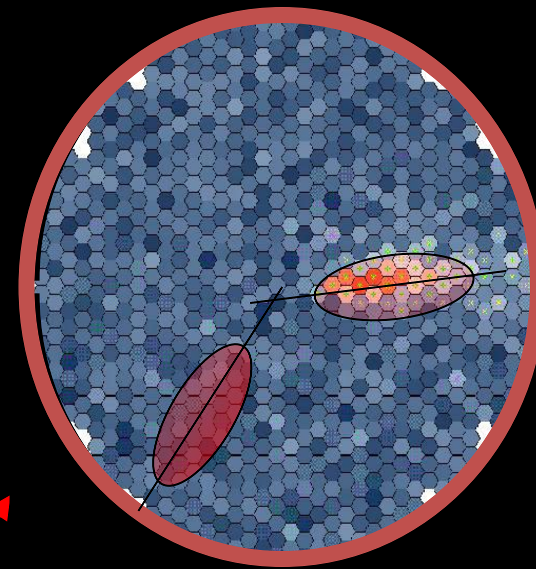
$$v > \frac{c}{n} \Rightarrow \frac{v}{c} > \frac{1}{n} \Rightarrow \beta > \frac{1}{n}$$

$$\cos\theta = \frac{AB}{AC} = \frac{1/n}{\beta} = \frac{1}{n\beta} = \frac{1}{n}$$

Cherenkov radiation is emitted when a charged particle (such as an electron) passes through a dielectric medium at a speed greater than the phase velocity of light in that medium. The charged particles polarize the molecules of that medium, which then turn back rapidly to their ground state, emitting radiation in the process.

New detection methods for VHE γ : Cherenkov radiation



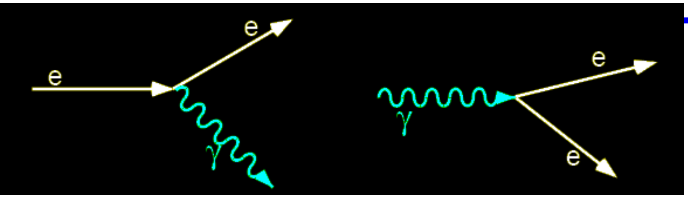


Atmospheric shower Développement:
- Cherenkov light cone:
  α=arccos(1/nβ); α=1^{o} at 10 km
- Flash of blue light lasting 5 ns
- Pool surface of 100 m radius
- Ligth ~ atm. path ~E_0

Camera images analysis:
- Energy and direction of the shower
- Proton background rejection

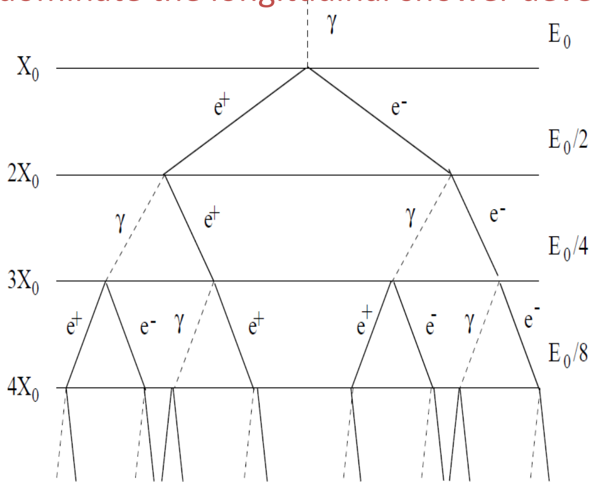
Stereoscopy:
- Improving angular resolution and bg. rej.

The atmospheric shower



Heitler Model:

Bremsstrahlung and pair-production dominate the longitudinal shower development

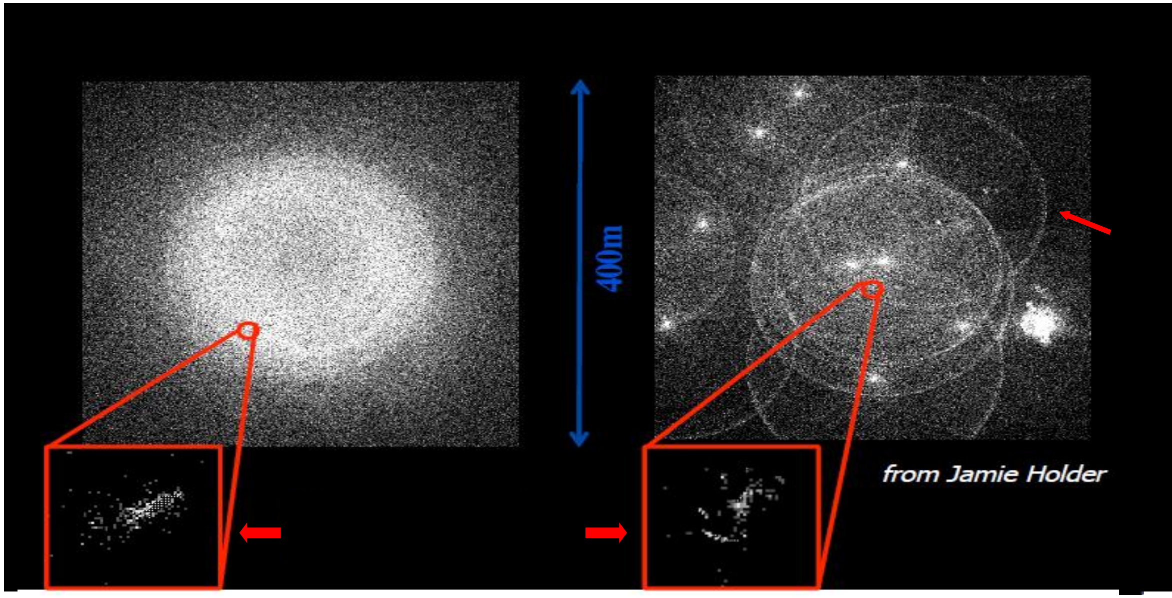


The atmosphere as a calorimeter:

- 1000 gr/cm^2 thick
- $\rho = \rho_0\, e^{-h/h0}$, h_0 ~ 8 km

The electromagnetic shower:

- X_0 ~ 40 gr/cm^2 , λ_{pair} ~ X_0
- First interaction @ ~20 km
- Maximum shower evolution @ ~ 10 km (for a 1 TeV photon)
- X_{MAX} ~ log(E_0)
- The number of electrons at the maximum of the shower is proportional to the gamma primary energy

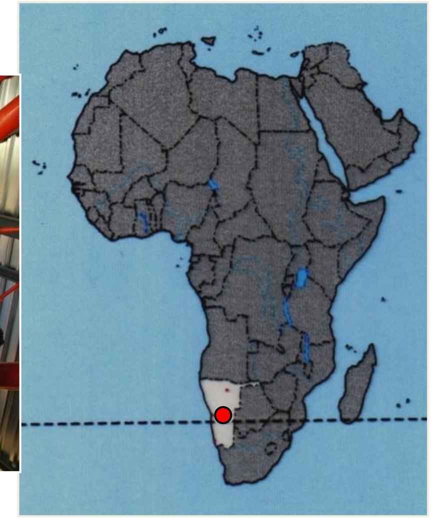


Shower morphology (and imaging):

- Gamma-showers more compact
- Proton-showers more disrupted and sub-structured

H.E.S.S.: High Energy Stereoscopic System

System of 5 télescopes on the Khomas island, in Namibia (1800 m)
(4 t. in operation since 2004):



- 13 m diametre mirror (*dish*): 107 m^2
- 15 m focal distance
- Camera with 960 pixels of 0.16^o
- Good gamma-hadron discrimination
  (rejet factor ≈ 10000 for pointlike surces)

- Sensitivity within 100 GeV – 100 TeV
  (Crab nebula detected in 30 s and 1% du Crabe en 25 h)

- Moon-free observations: ~1000 h / an
- 15% energy resolution

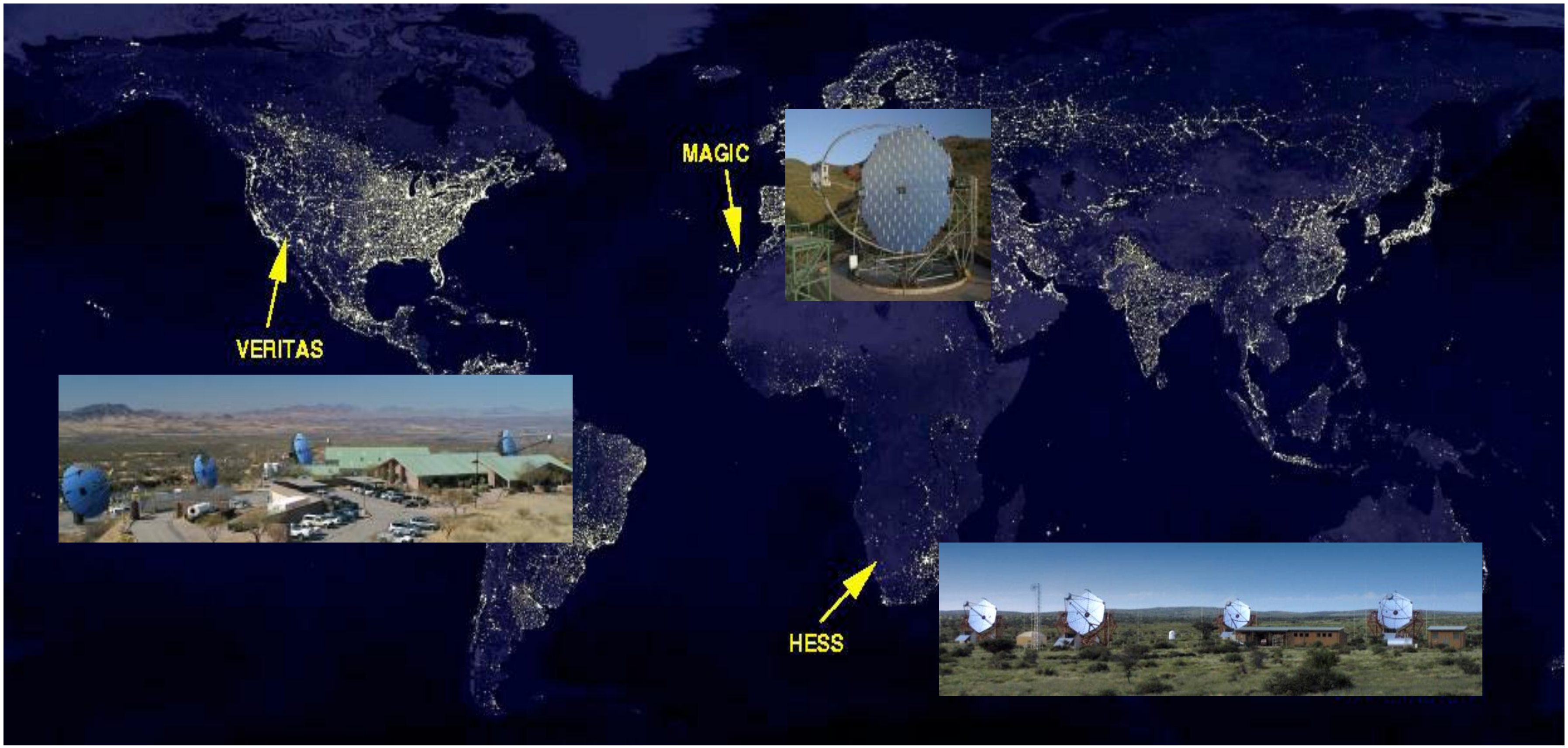
- 4' - 6‘ angular resolution **… but limited FoV** (5° diametre → sources need to e followed up

$$E_{\rm seuil} \propto \sqrt{\frac{\Omega \Delta t \phi_{\rm nsb}}{A\epsilon}}$$

HESS 2 (5th telescope since 2013) :
- 2048 pixels (0.07^o)
- 3.5^o (f.o.v.)
- 30 m *dish*
- **Lower energy threshold**

The main VHE IACT

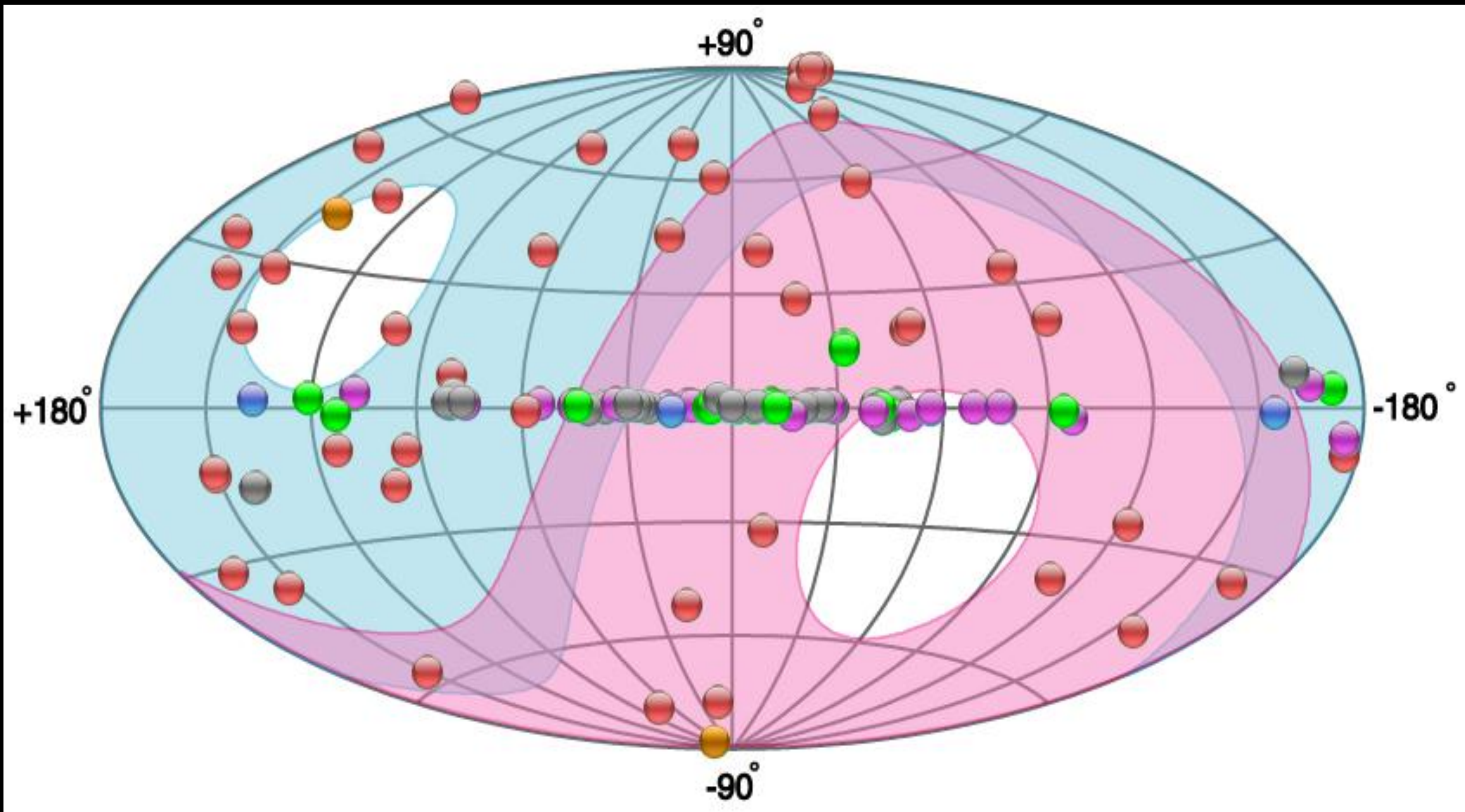
The current (succesful) generation of Imaging Atmospheric Cherenkov Telescopes

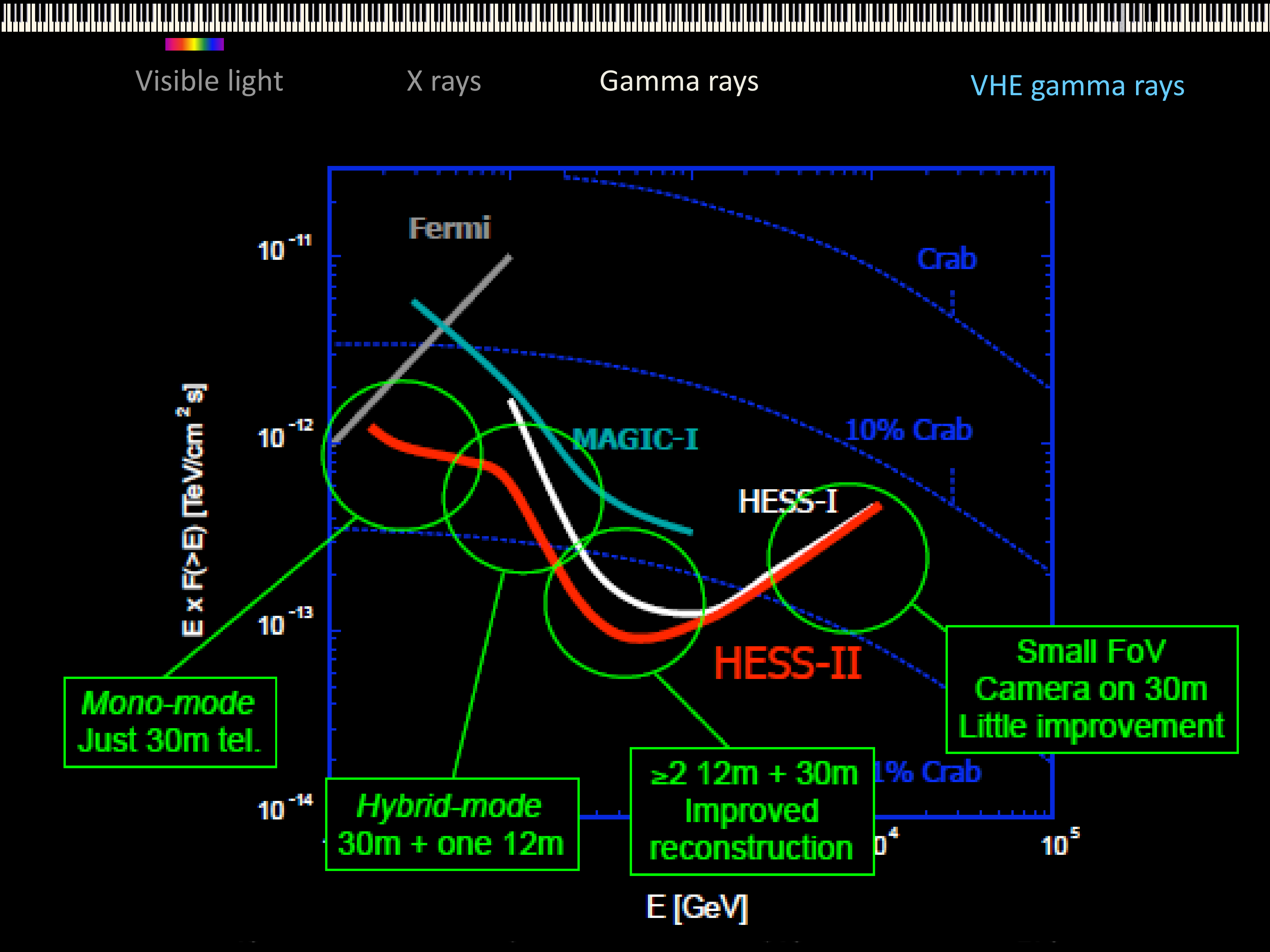


- A mature discipline
- Towards a new wavelength astronomy in the next decade

Visible light X rays Gamma rays VHE gamma rays

> 100 VHE sources

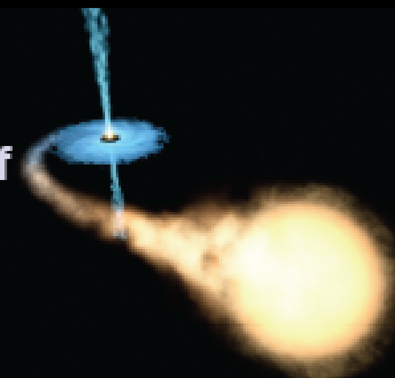




Visible light
X rays
Gamma rays
VHE gamma rays
Fermi
Crab
MAGIC-I
10% Crab
HESS-I
HESS-II
1% Crab
Mono-mode
Just 30m tel.
Hybrid-mode
30m + one 12m
≥2 12m + 30m
Improved
reconstruction
Small FoV
Camera on 30m
Little improvement
E x F(>E) [TeV/cm² s]
E [GeV]

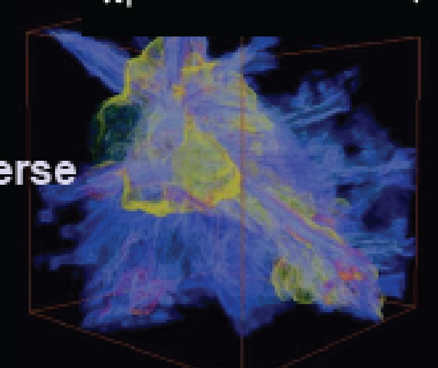
What we can learn using VHE Gamma rays?

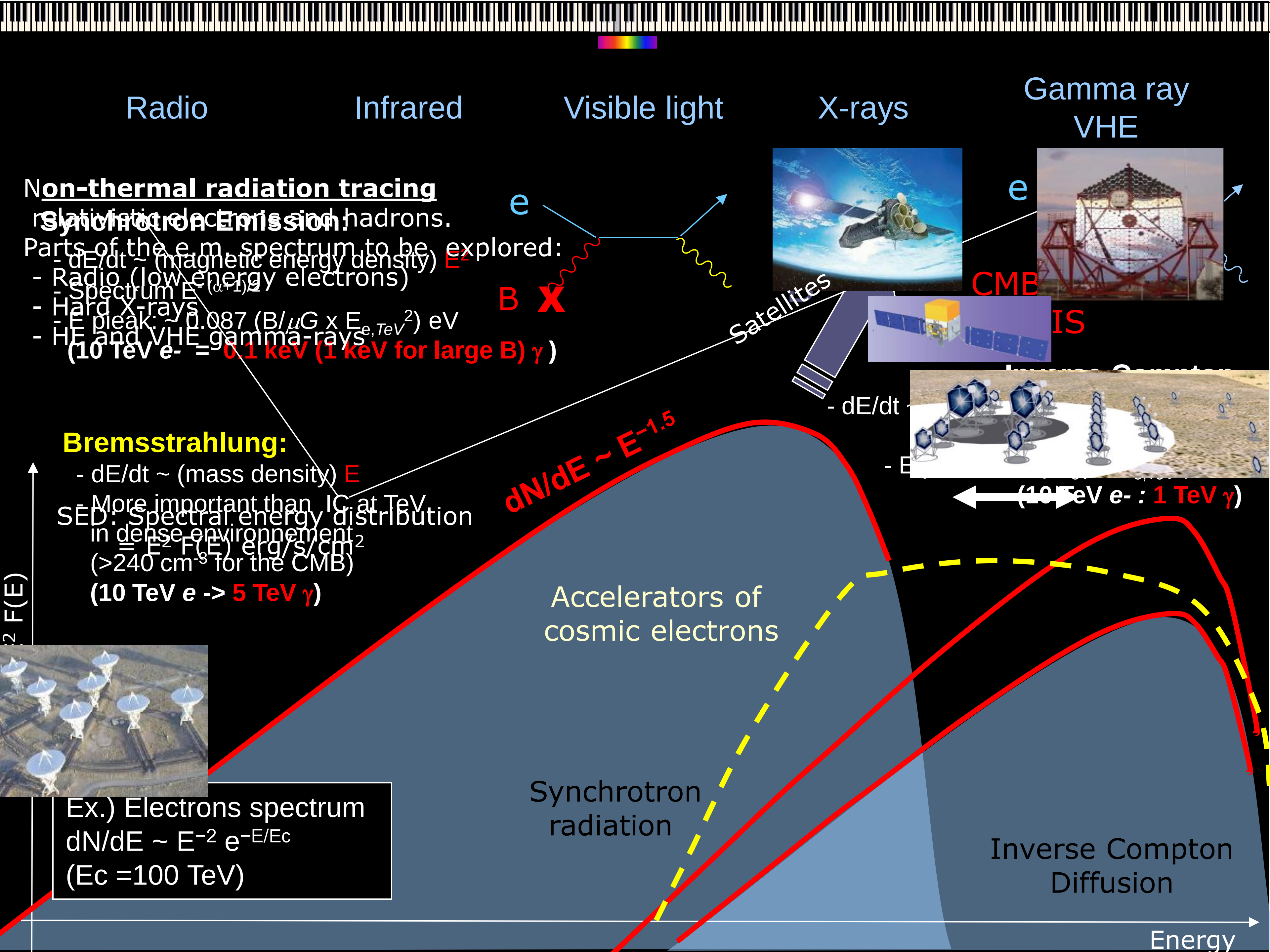
- High energy astrophysics
  - Acceleration, propagation and energy losses of ultra-relativistic particles in astrophysical environments
    - Specific question:
      - Where are the "cosmic rays" accelerated?

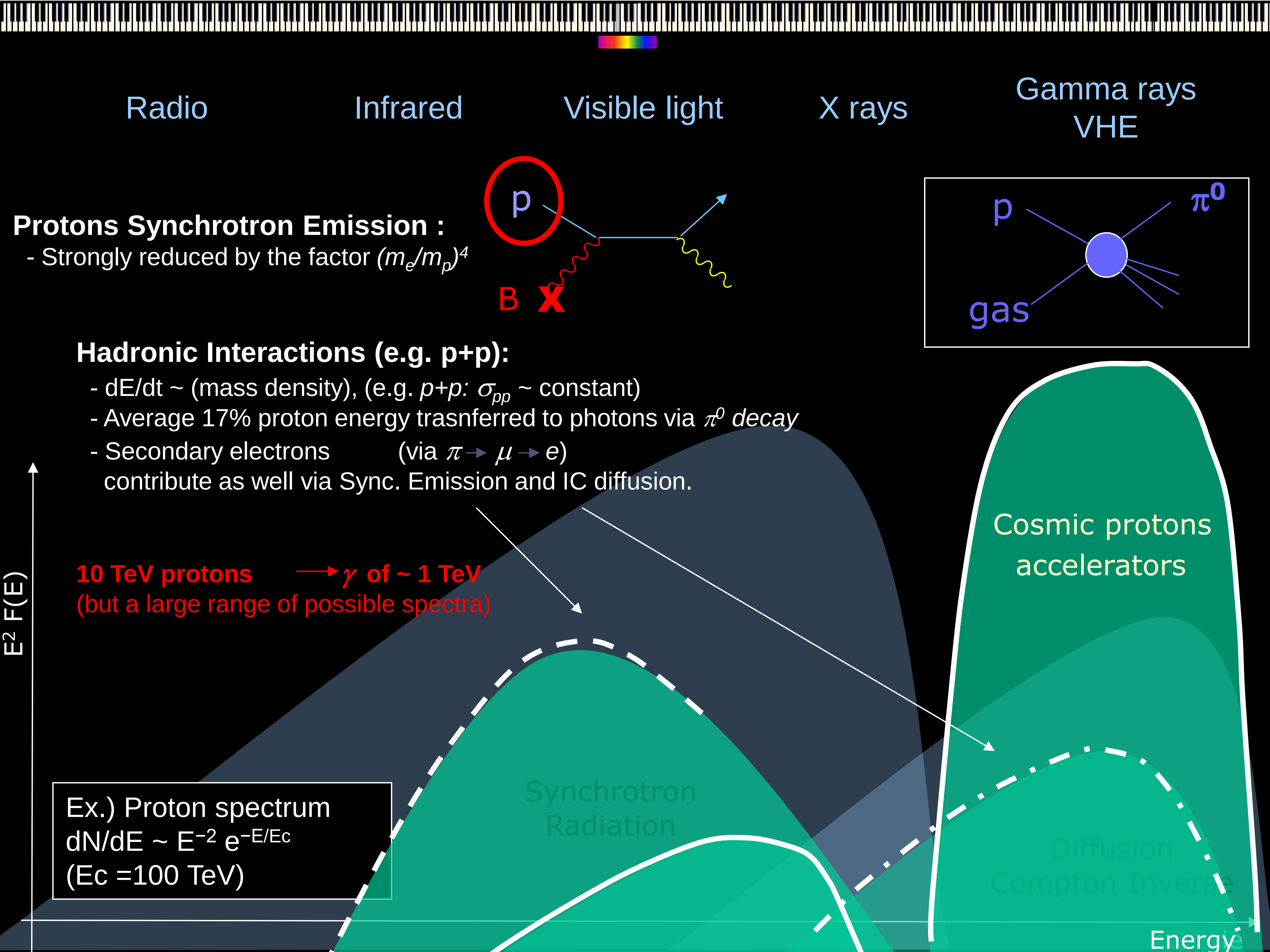


- Astroparticle Physics
  - Indirect search for Dark Matter
  - Search for energy dependence of the speed of light

- Cosmology
  - Indirect measurement of the Extragalactic Background light
    - Probing the star formation history of the universe
  - Non-thermal content of galaxy clusters




Radio
Infrared
Visible light
X-rays
Gamma ray
VHE
Non-thermal radiation tracing
relativistic electrons and hadrons.
Parts of the e.m. spectrum to be explored:
- Radio (low energy electrons)
- Hard X-rays
- HE and VHE gamma-rays
Synchrotron Emission:
- dE/dt ~ (magnetic energy density) E²
- Spectrum E^-(α+1)/2
- E peak: ~ 0.087 (B/μG x E_e,TeV²) eV
(10 TeV e- = 0.1 keV (1 keV for large B) γ)
e
B
CMB
IS
Satellites
- dE/dt
(10 TeV e- : 1 TeV γ)
Bremsstrahlung:
- dE/dt ~ (mass density) E
- More important than IC at TeV
in dense environnement
(>240 cm⁻³ for the CMB)
(10 TeV e -> 5 TeV γ)
SED: Spectral energy distribution
= E² F(E) erg/s/cm²
dN/dE ~ E^-1.5
Accelerators of
cosmic electrons
Synchrotron
radiation
Inverse Compton
Diffusion
Ex.) Electrons spectrum
dN/dE ~ E^-2 e^-E/Ec
(Ec =100 TeV)
E² F(E)
Energy



Radio
Infrared
Visible light
X rays
Gamma rays VHE
p
B
p
π⁰
gas
Protons Synchrotron Emission :
- Strongly reduced by the factor $(m_e/m_p)^4$
Hadronic Interactions (e.g. p+p):
- dE/dt ~ (mass density), (e.g. $p+p$: σ_{pp} ~ constant)
- Average 17% proton energy trasnferred to photons via π^0 decay
- Secondary electrons (via $\pi \to \mu \to e$)
contribute as well via Sync. Emission and IC diffusion.
10 TeV protons → γ of ~ 1 TeV
(but a large range of possible spectra)
Cosmic protons accelerators
E² F(E)
Synchrotron Radiation
Diffusion Compton Inverse
Ex.) Proton spectrum
$dN/dE \sim E^{-2}\, e^{-E/Ec}$
(Ec =100 TeV)
Energy

What we can learn using VHE Gamma rays?

In general it is expected :

<u>To see the sites of high energy particle production!</u>

- Either bottom up (acceleration) or top down (decay)

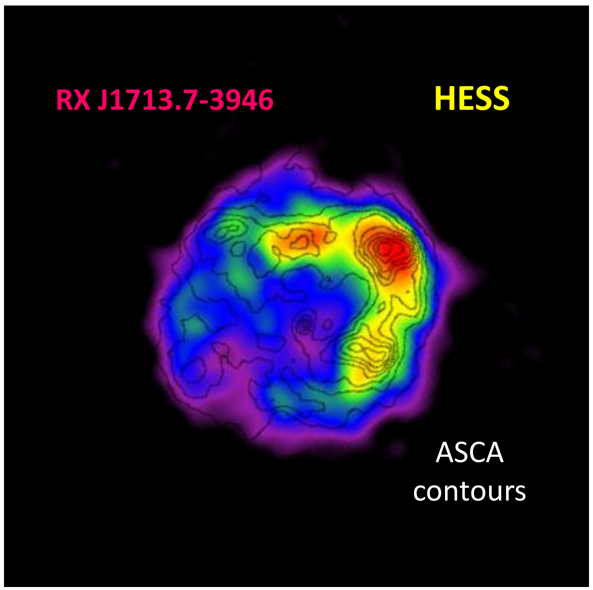
- **Proton** accelerators to produce TeV **π^0-decay gamma-rays –** correlated with the distribution of target material (gas) and not much radiation at lower energies
  - Must be many in our galaxy to explain local cosmic ray flux up to the “knee” at 1 PeV

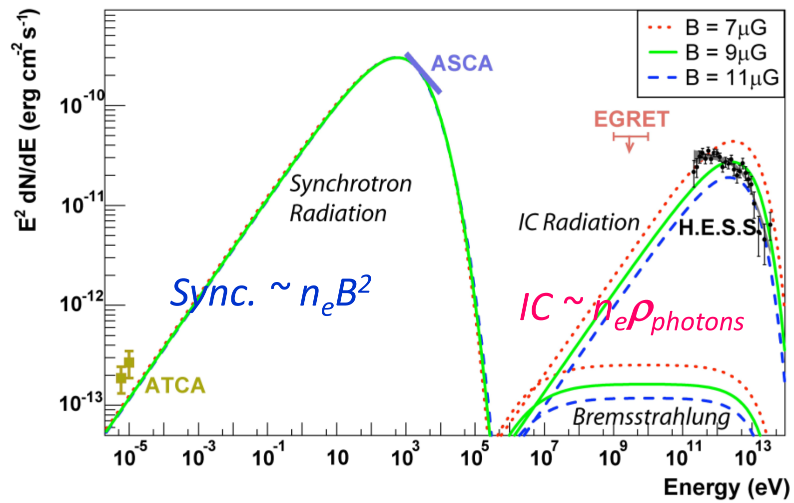
- **Electron** accelerators to produce TeV IC and keV X-ray synchrotron emission
  - Must be some to explain local CR electrons
  - Would expect co-acceleration with protons
    - But much more rapid (factor ~100) energy losses

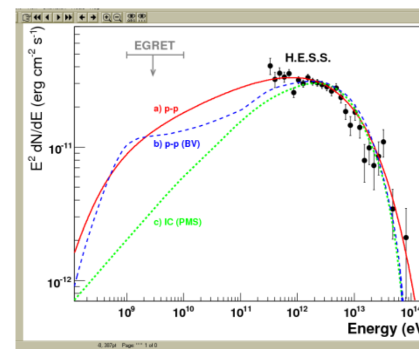
<u>So what do we actually see???</u>

Supernova Remnants (SNR)

SNR best candidates for acceleration of the bulk of the galactic cosmic rays
Well established mechanism (diffusive shock acceleration)
Energetics are OK (10% kinetic energy into cosmic-rays)
Non-thermal X-rays from young (less than ~1000 year old) supernova remnants:







- First TeV γ-ray SNR
- Age: 1000 ans
- Distance ~ 1 kpc.

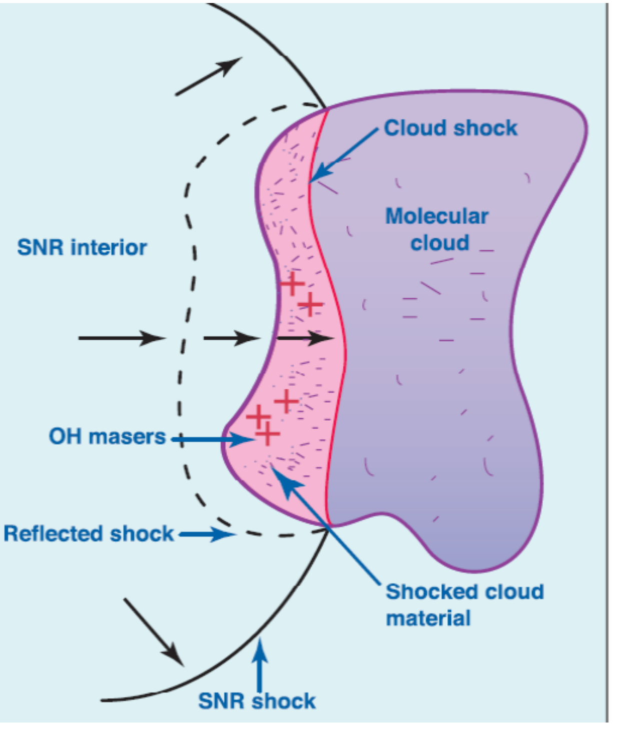
- HESS -TeV IC interpretation of the SED requires low B fields (+protons)
- Spectral shape (+ protons)
- Strong morphological correlation keV/TeV (+electrons)

Actually: $\Phi_X \sim 10\ \Phi_\gamma$ implies $U_{mag} \sim 10\ U_{rad}$
But for U_{rad} of CMBR: $B = 3\mu G \times sqrt(10) = 10\ \mu G$
B too weak?
Hypothesis: « Magnetic field amplification » -> $100\ \mu G$
and dense matter (+protons)

Supernova Remnants (SNR)

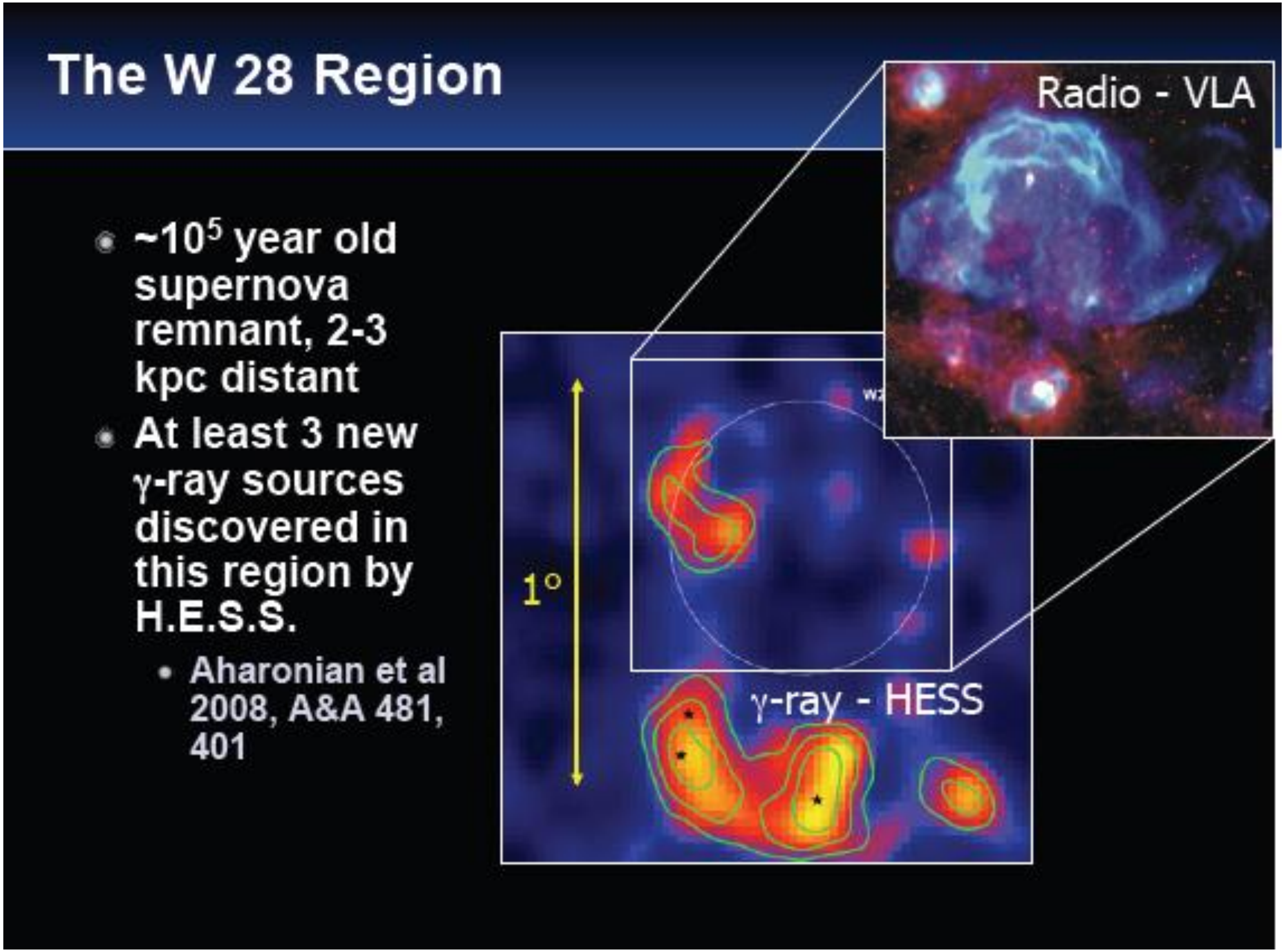
Another approach towards demonstrating CR acceleration in SNRs is to look for dense molecular clouds adjacent to, or interacting with, an SNR.

In clouds, interactions of accelerated protons and nuclei will give rise to an enhanced gamma-ray flux proportional to the cloud's mass whereas IC radiation from electrons is not enhanced.

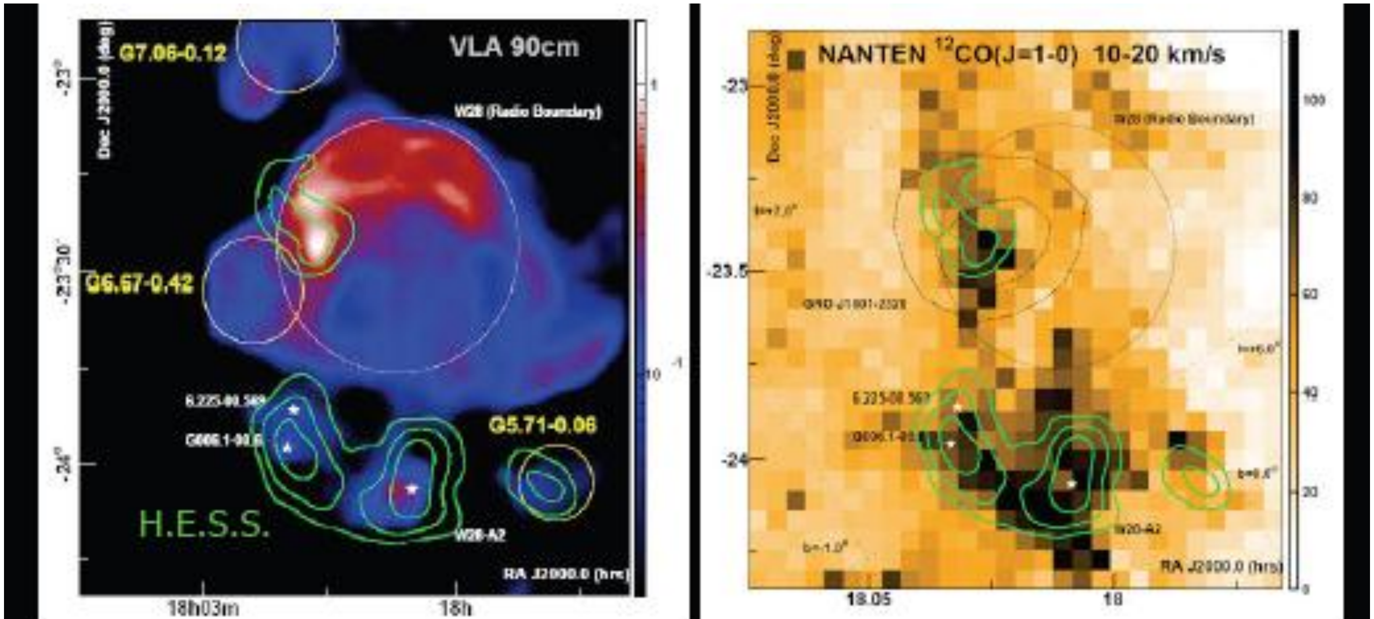


W28 a candidate system: an old remnant which has most likely released most of its CRs.

Supernova Remnants (SNR)



Supernova Remnants (SNR): W28



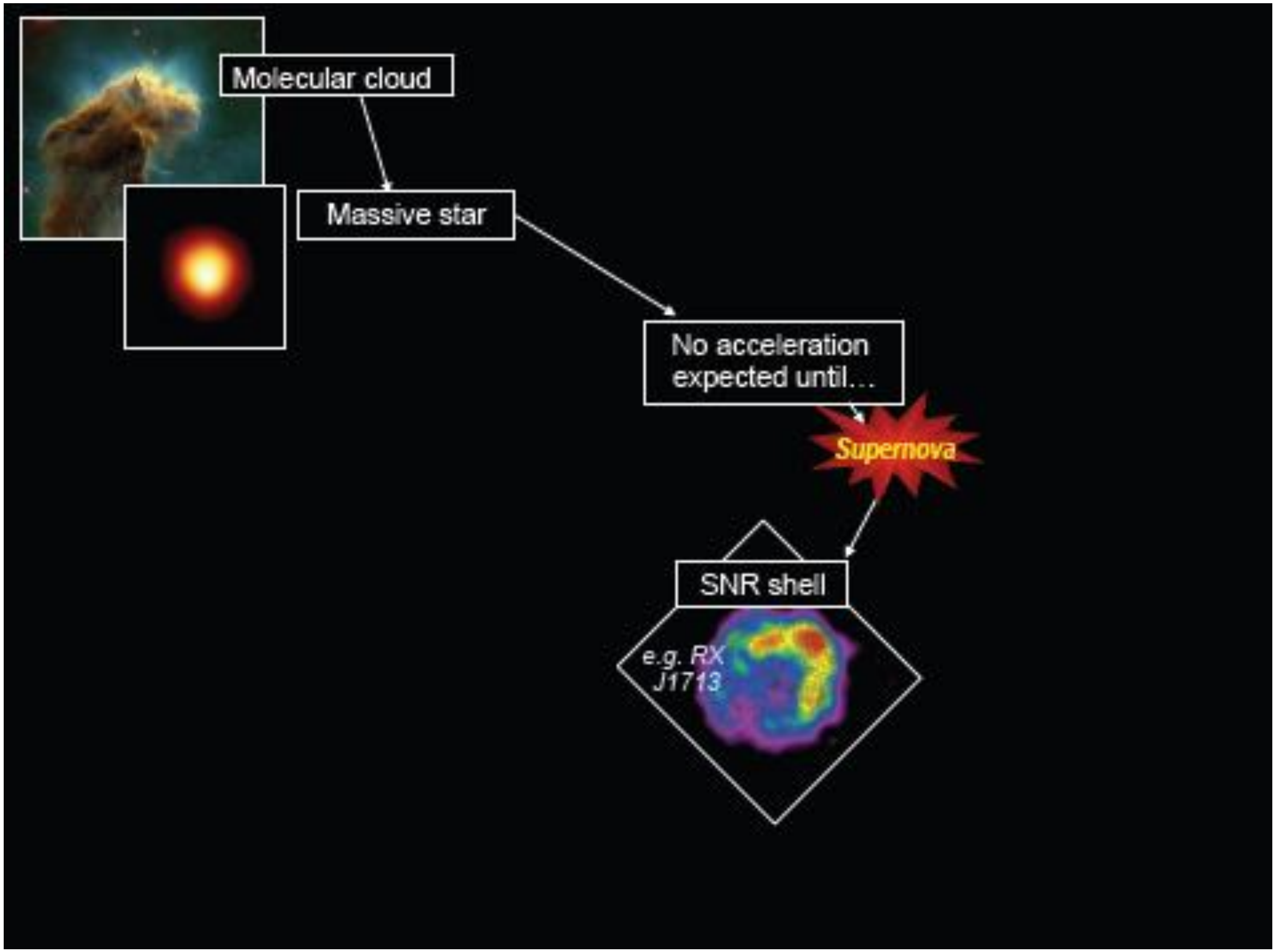
- Partial radio correlation, Good correlation with *CO*
- γ-ray flux follows target material

  → *looks like hadronic CRs interacting with gas*

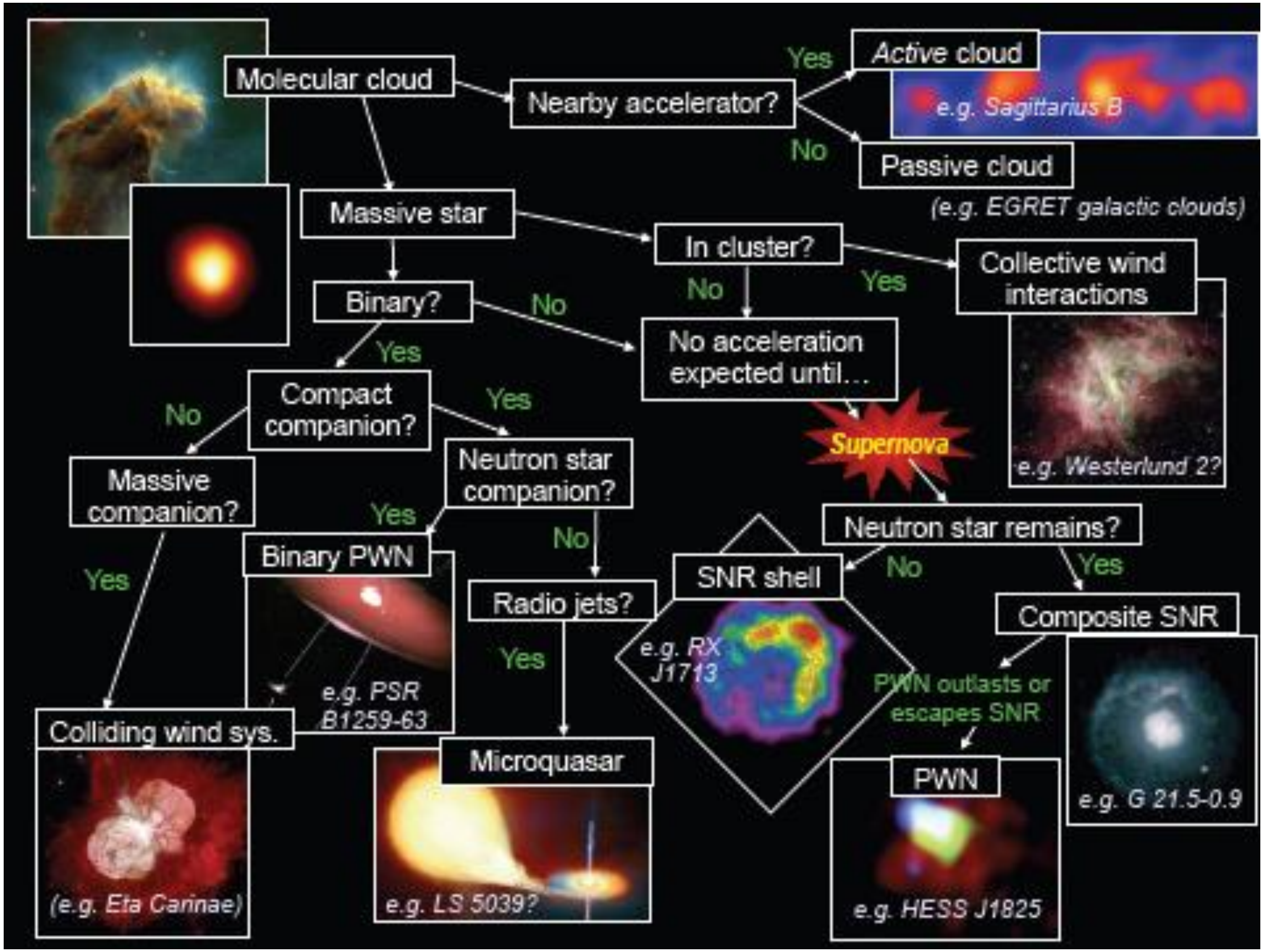
  $$pp \rightarrow \pi^0 \rightarrow \gamma\gamma$$

The clouds masses imply a CR flux which is 10 to 30 times the flux near Earth, a plausible value given the proximity of the remnant.

TeV to probe a wide range of astrophysical systems

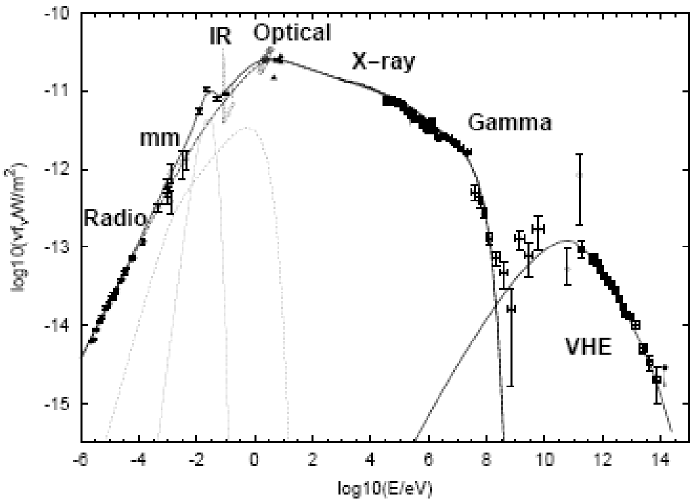


TeV to probe a wide range of astrophysical systems



Pulsar Wind Nebulae (e.g. « Crab »)

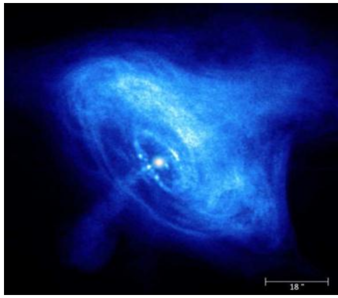
Crab nebula SED:



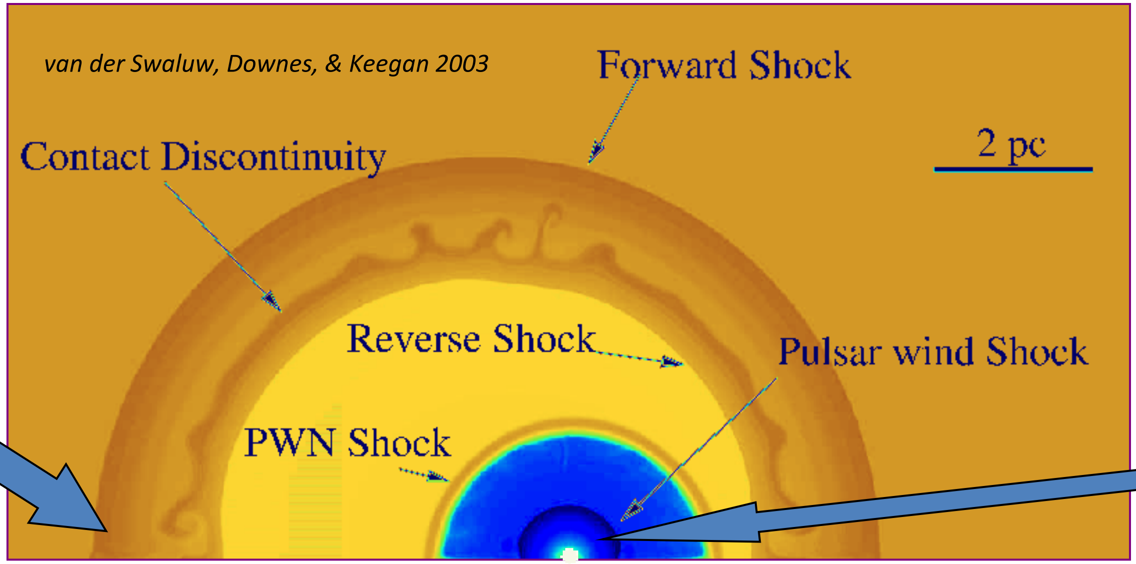
1) From Radio to low energy gamma (MeV) = synchrotron radiation by electrons accelerated by the nebula;
2) VHE = Inverse Compton of same electrons over synchrotron photons ("Synchrotron-Self Compton").

PWN

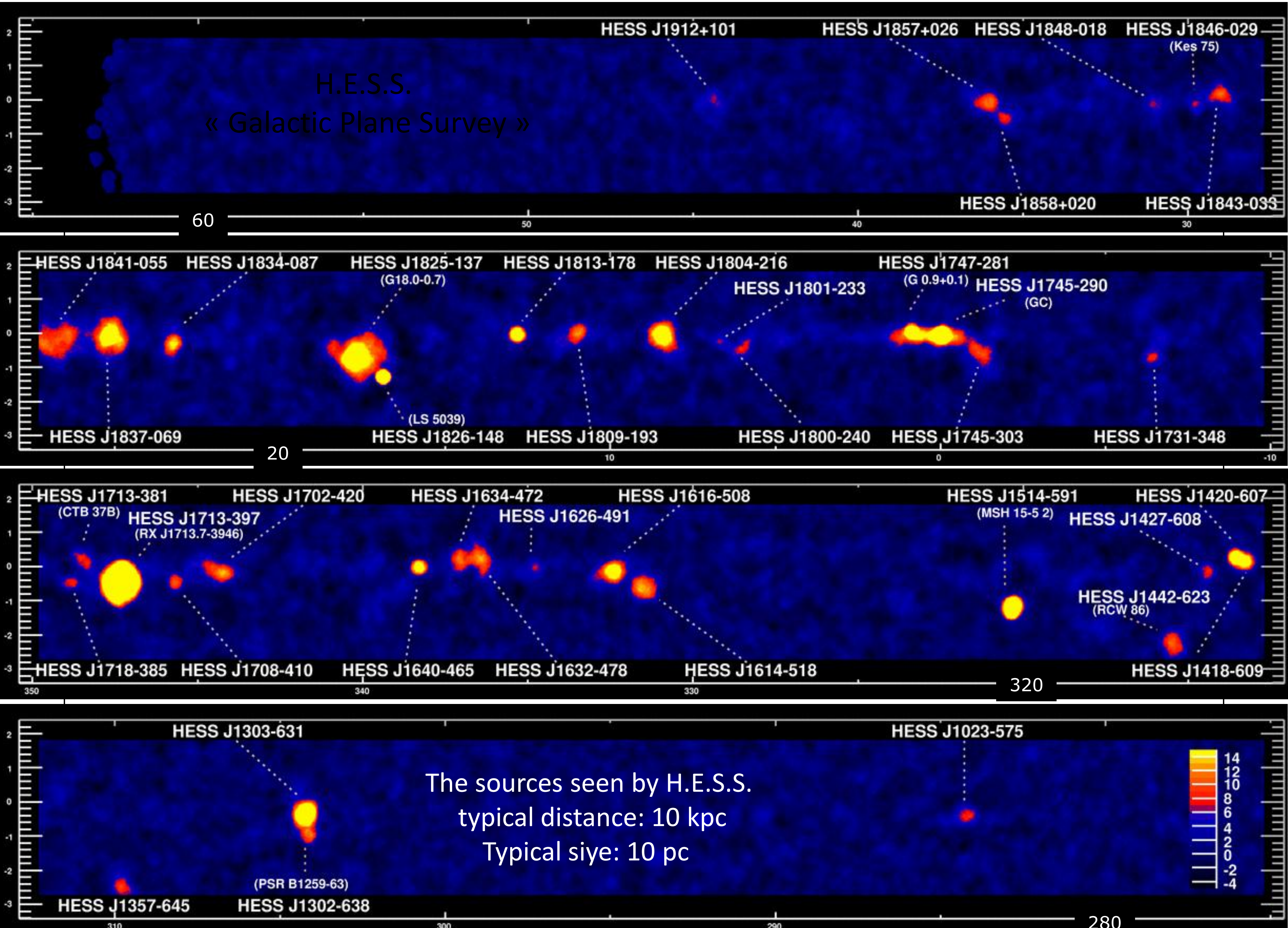
The Pulsar emitting e+e- wind which creates a shock wave accelerating further the electrons.

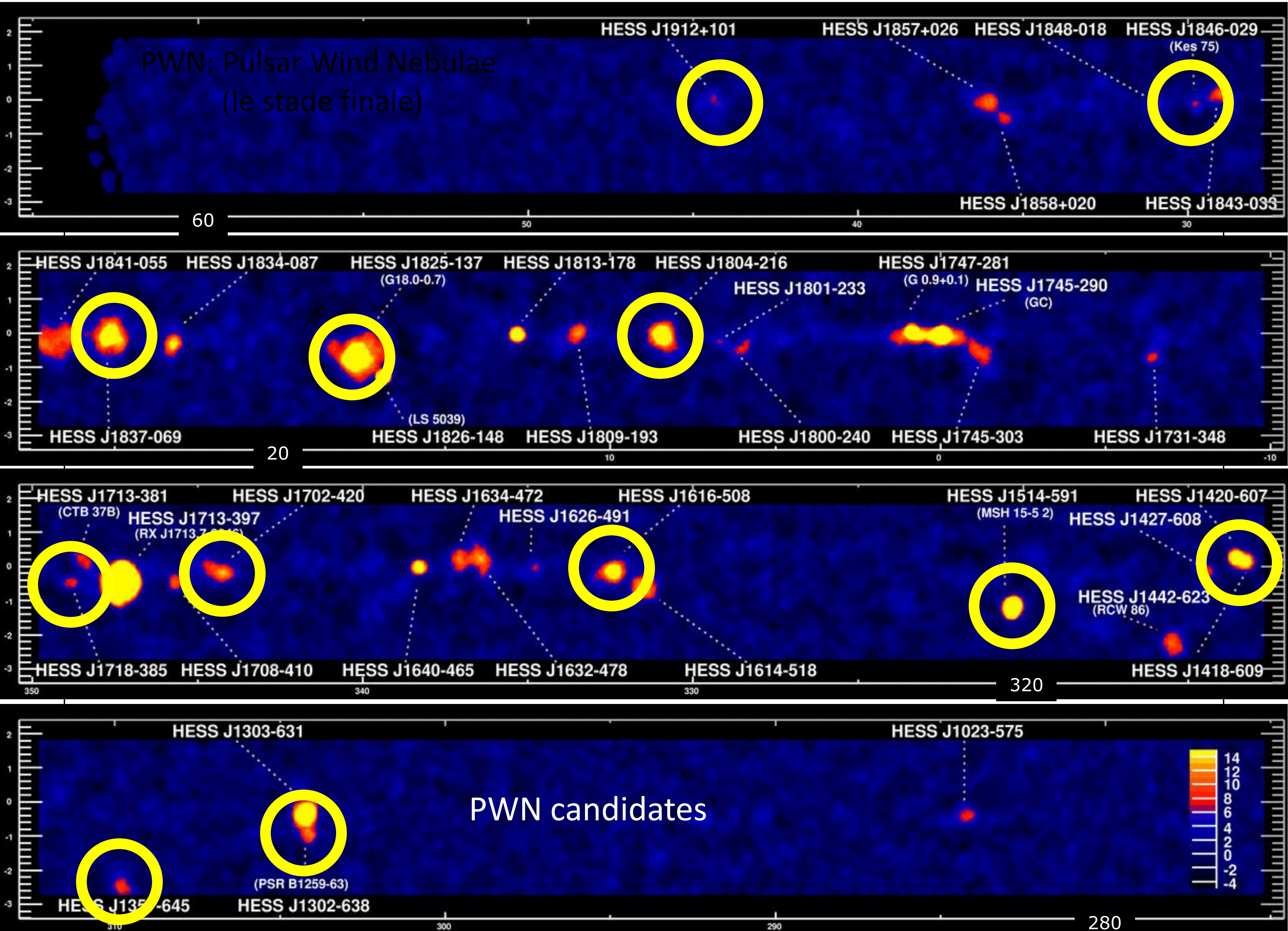


The SN shock accelerates particles during $O(10^4)$ ans.



Pulsar supporting the PWN over a lifetime of $O(10^5)$ years.

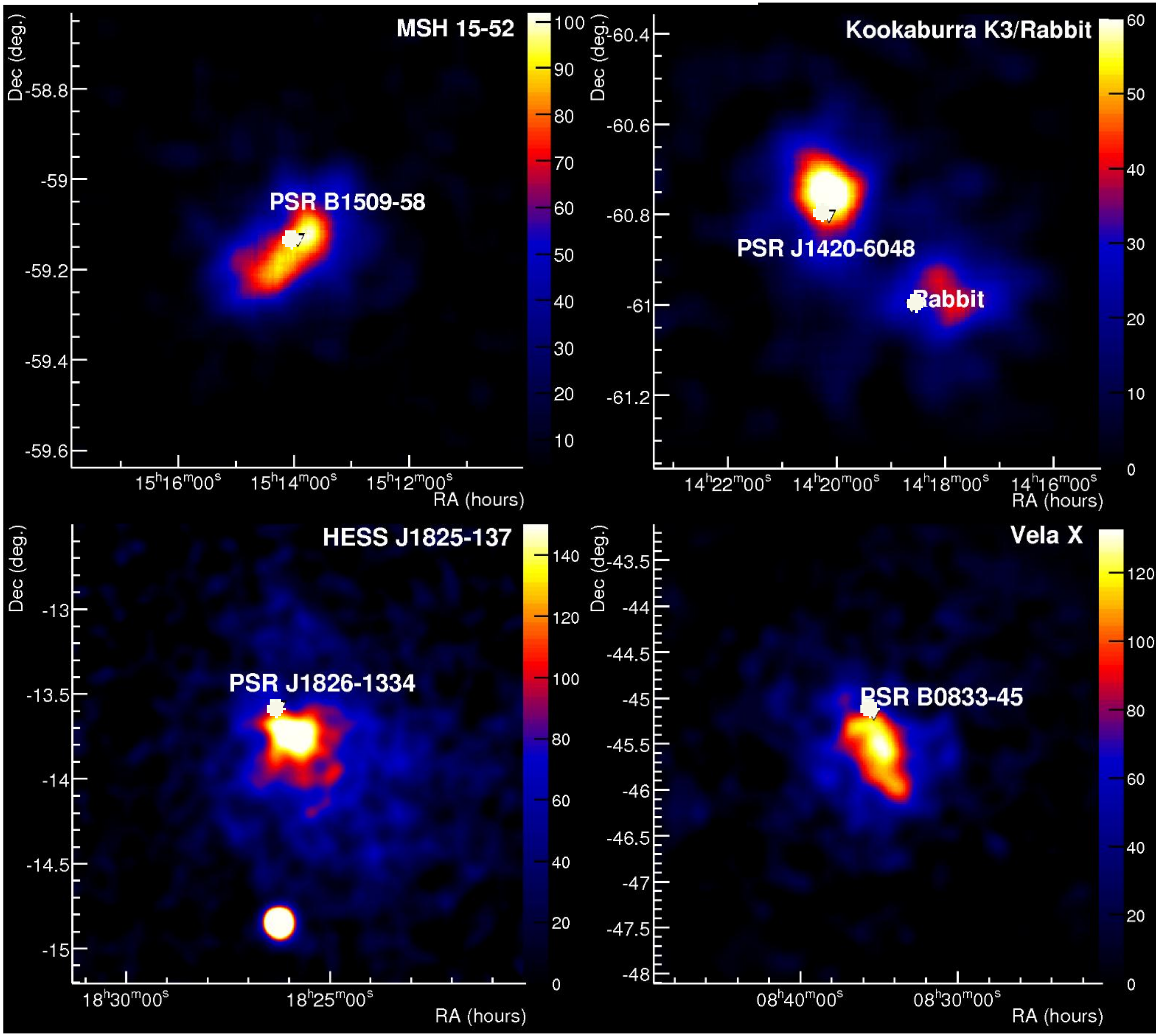

H.E.S.S.
« Galactic Plane Survey »
HESS J1912+101
HESS J1857+026
HESS J1848-018
HESS J1846-029
(Kes 75)
HESS J1858+020
HESS J1843-033
60
HESS J1841-055
HESS J1834-087
HESS J1825-137
(G18.0-0.7)
HESS J1813-178
HESS J1804-216
HESS J1801-233
HESS J1747-281
(G 0.9+0.1)
HESS J1745-290
(GC)
(LS 5039)
HESS J1837-069
HESS J1826-148
HESS J1809-193
HESS J1800-240
HESS J1745-303
HESS J1731-348
20
HESS J1713-381
(CTB 37B)
HESS J1713-397
(RX J1713.7-3946)
HESS J1702-420
HESS J1634-472
HESS J1626-491
HESS J1616-508
HESS J1514-591
(MSH 15-5 2)
HESS J1427-608
HESS J1420-607
HESS J1442-623
(RCW 86)
HESS J1718-385
HESS J1708-410
HESS J1640-465
HESS J1632-478
HESS J1614-518
HESS J1418-609
320
HESS J1303-631
HESS J1023-575
The sources seen by H.E.S.S.
typical distance: 10 kpc
Typical siye: 10 pc
(PSR B1259-63)
HESS J1357-645
HESS J1302-638
280
14
12
10
8
6
4
2
0
-2
-4



GraSPA 2013

G.Lamanna

Pulsar Wind Nebulae



γ-ray PWN are:

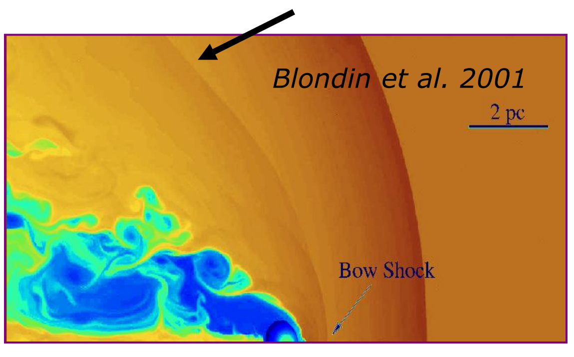
- Extended (10 pc)
- Close but offset from pulsars
- O(1%) spin-down luminosity in gamma rays
- In some cases: energy dependance of morphology due to the e^+e^- injection from the magnetosphere into teh nebula wind

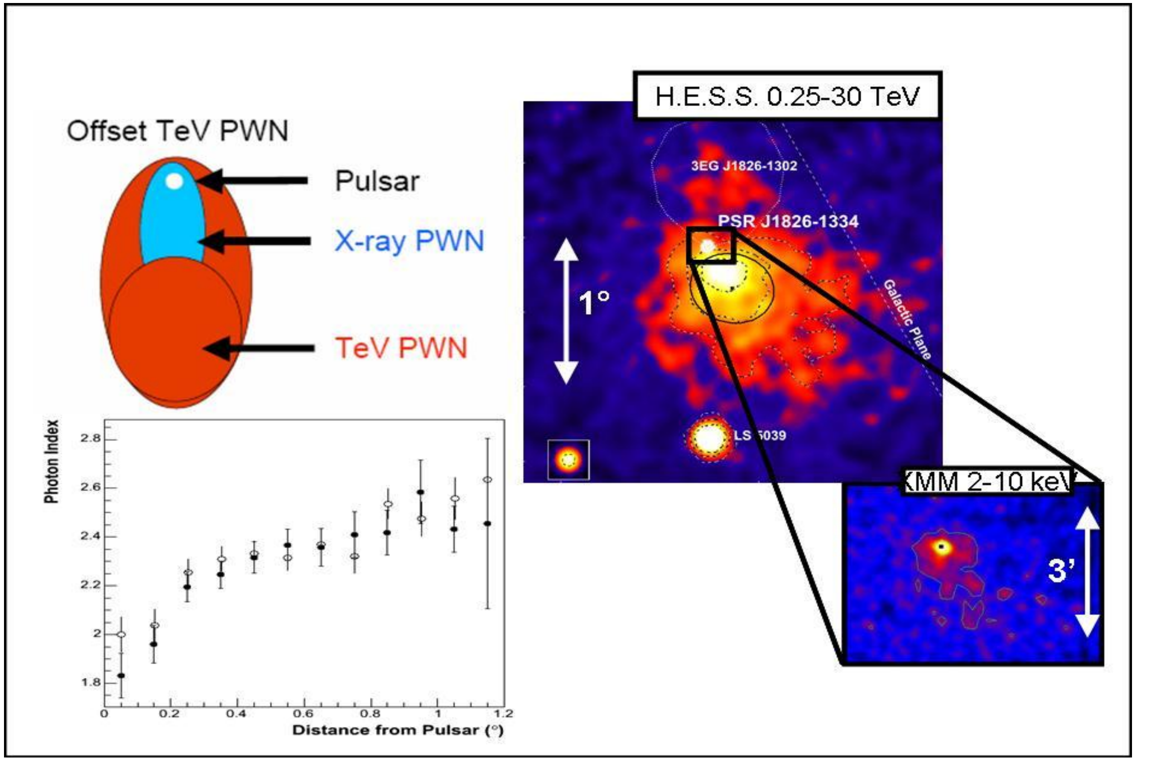
Pulsar Wind Nebulae

HESS J1825-137

- Evidence of cooling of e- (gamma spectra and X-ray size) : evolutionary reasons– « cooling-time » (Synch. vs IC)

- Molecular cloud responsible for the nebula offset. (confirmed by hydrodynamic simulations)

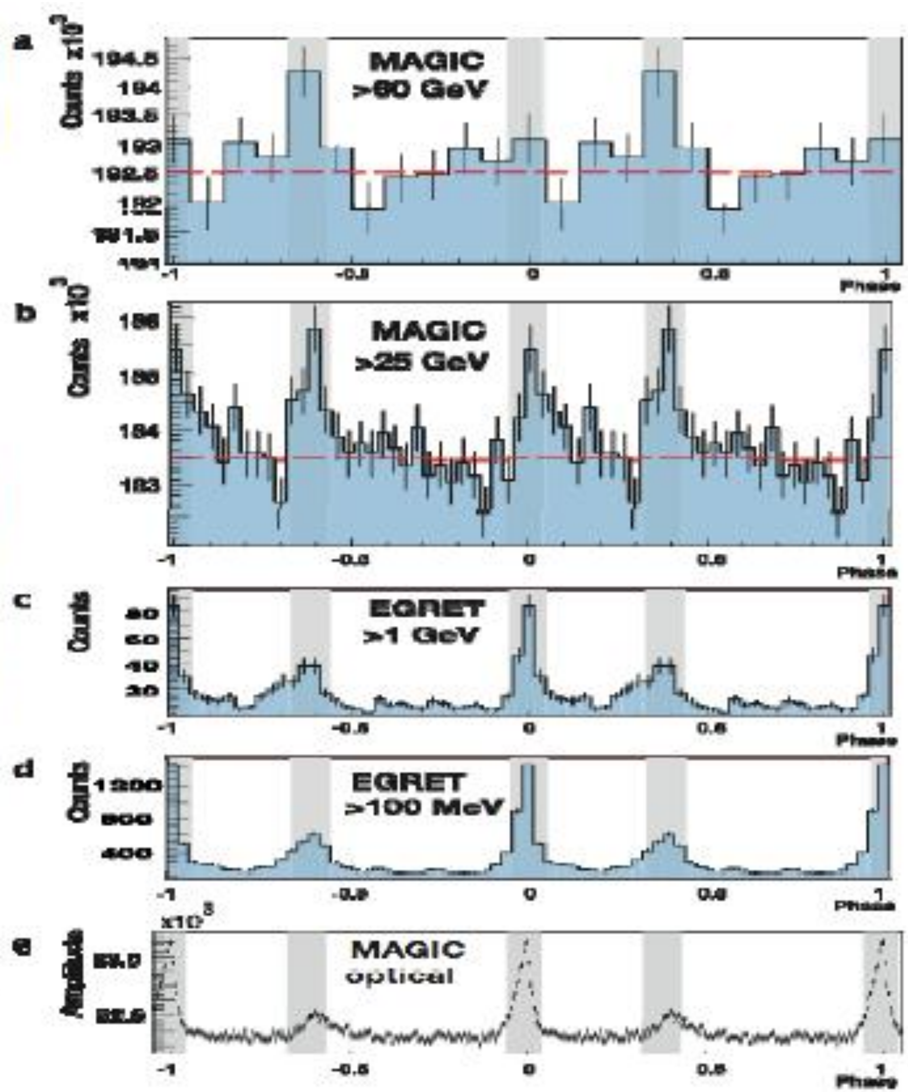




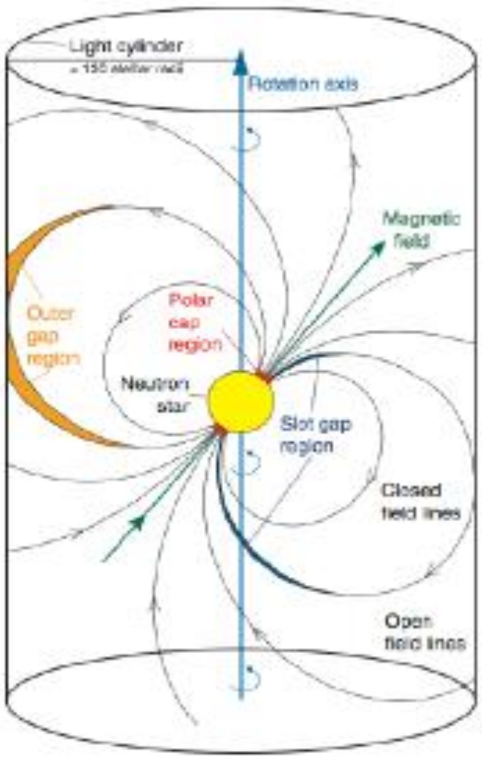
Pulsar

First ground-based detection of pulsed emission from a pulsar

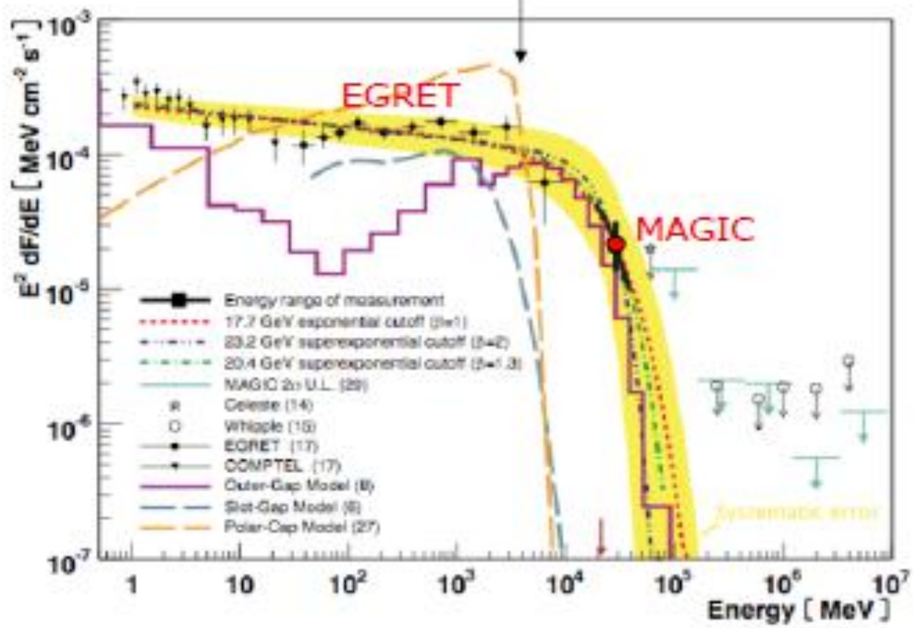
MAGIC, Science 322, 2008
using special low-energy trigger



Origin of pulsed emission: outer gap

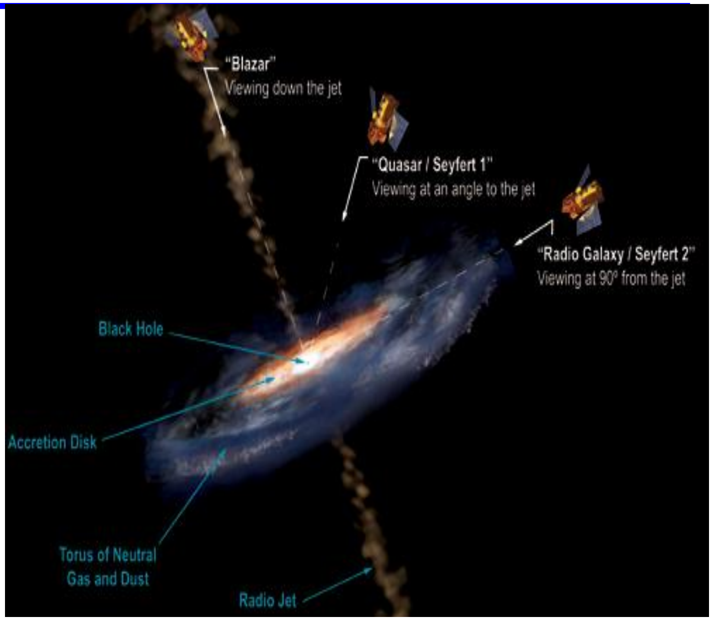


Emission from polar cap
and slot gap cut off around
10 GeV due to pair production



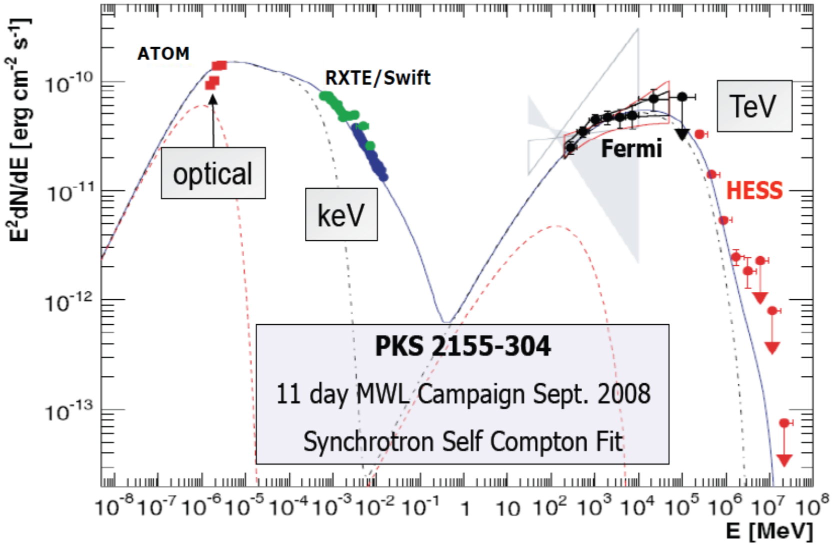
- More than 30 extragalactic VHE γ-rays sources

- Same object: AGN
  - A supermassive central black hole-> accretion of matter producing relativistic jets (mechanism under investigations and observed under different angles from the Earth
  - Acceleration of CR within the jets (Internal Shock? Leptonic or hadronic?)

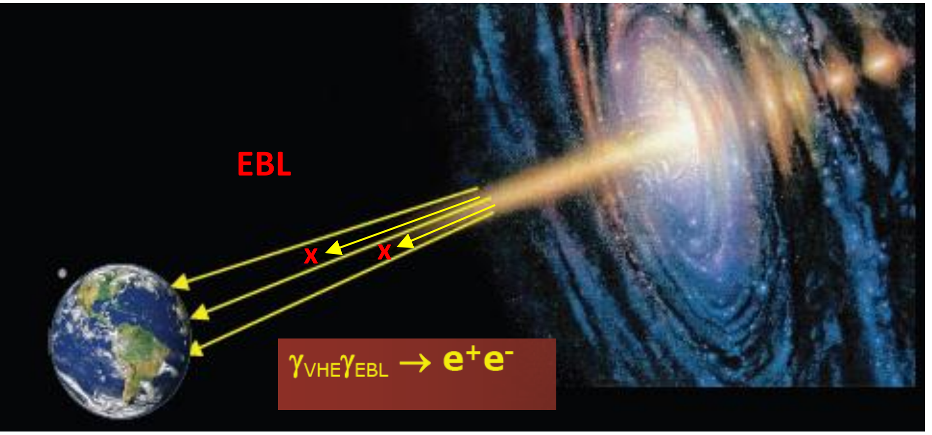


- Radiogalaxies:
  - Jets et lobes detected in radio, e.g. Cen A et M 87.

- More than 25 Blazars (BL Lacs, HBLs, LBLs etc.)
  - Jets aligned with the line of sight
  - SED: large emission range (radio-TeV) and double peaked spectra: Synchr. + IC
  - Strongly variable in X and at TeV: flares [...]



The gamma ray propagation : AGN and cosmology



Spectra of AGN (VHE) : power law but curved as a function of energy and distance (Γ >> with z >>):

- The most distant ones must be brighter to be observed

- H.E. γ absorbed by IR (via pair production e^+e^-) of the « extragalactic background light » (EBL)

EBL: link between the history of the galaxies and the H.E. astrophysics.

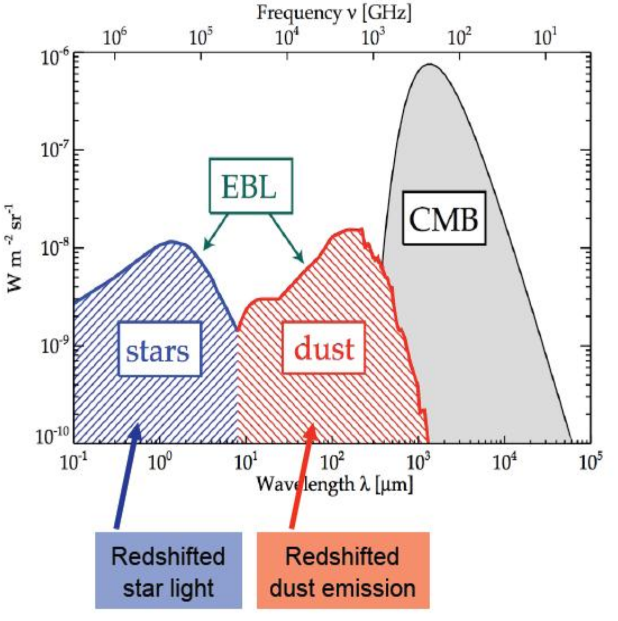
EBL Theoretical definition:

- « extragalactic background diffused light»: light emitted by all objects in the Universe along its history (stars, galaxies, quasars...) filling up the extragalactic space as an ocean of photons.

  (~ 1/20 of the CMB energy inn UV, visible and IR.)

EBL observational definition :

- All the light beyond our galaxy (z=0 background)

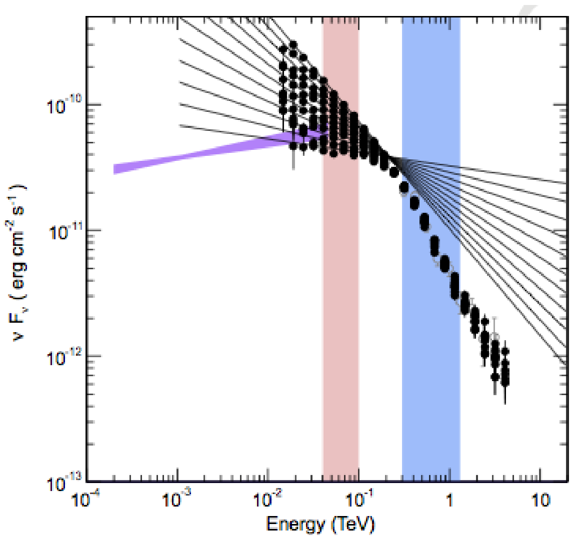


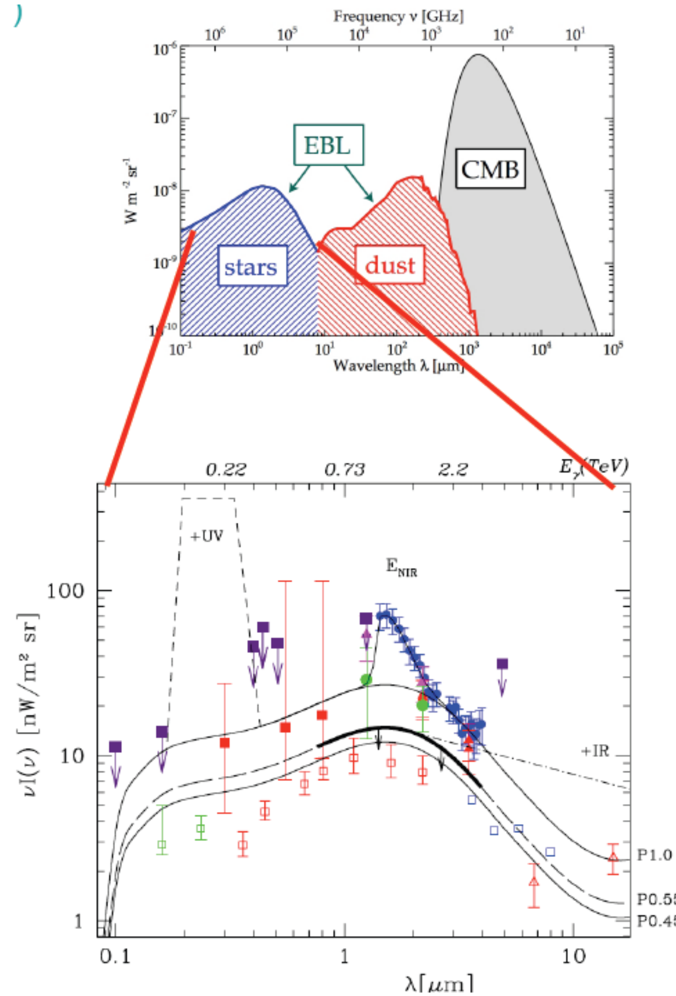
« Extragalactic Background Light (EBL) »: measuring its SED

Motivations:

- Photon archeology
- Testing star forming regions , galaxies formation evolution and cosmological evolution models

-> *indirect measurement by (GeV-TeV) AGN spectra*



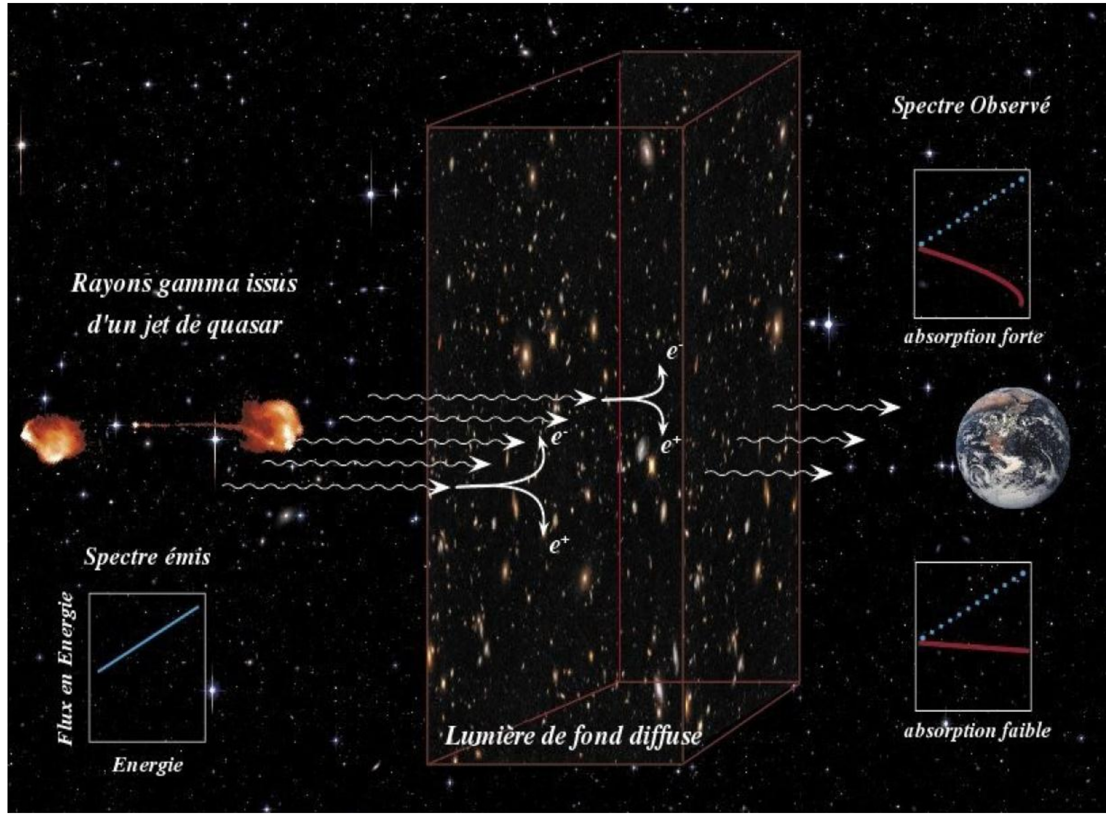


- HESS upper limit at 0.8 μm - 3.5 μm
- Models constraints and measurements excluded.
- EBL less opaque (close to the lower limit as from « *galaxy count* »)

EBL, atténuation et « Optical depth »

$\Phi_{obs}(E)=\Phi_{intr}(E) * e^{-\tau(E,z)}$

$\Phi_{obs}(E)$: Observed spectrum
$\Phi_{intr}(E)$: Emitted spectrum
τ : Attenuation coefficient
(τ =1:« optical depth »)

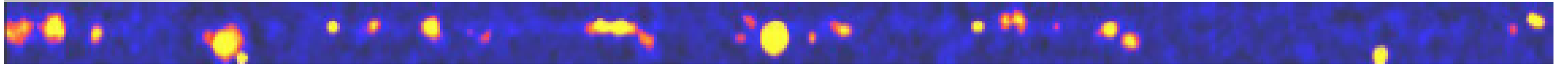


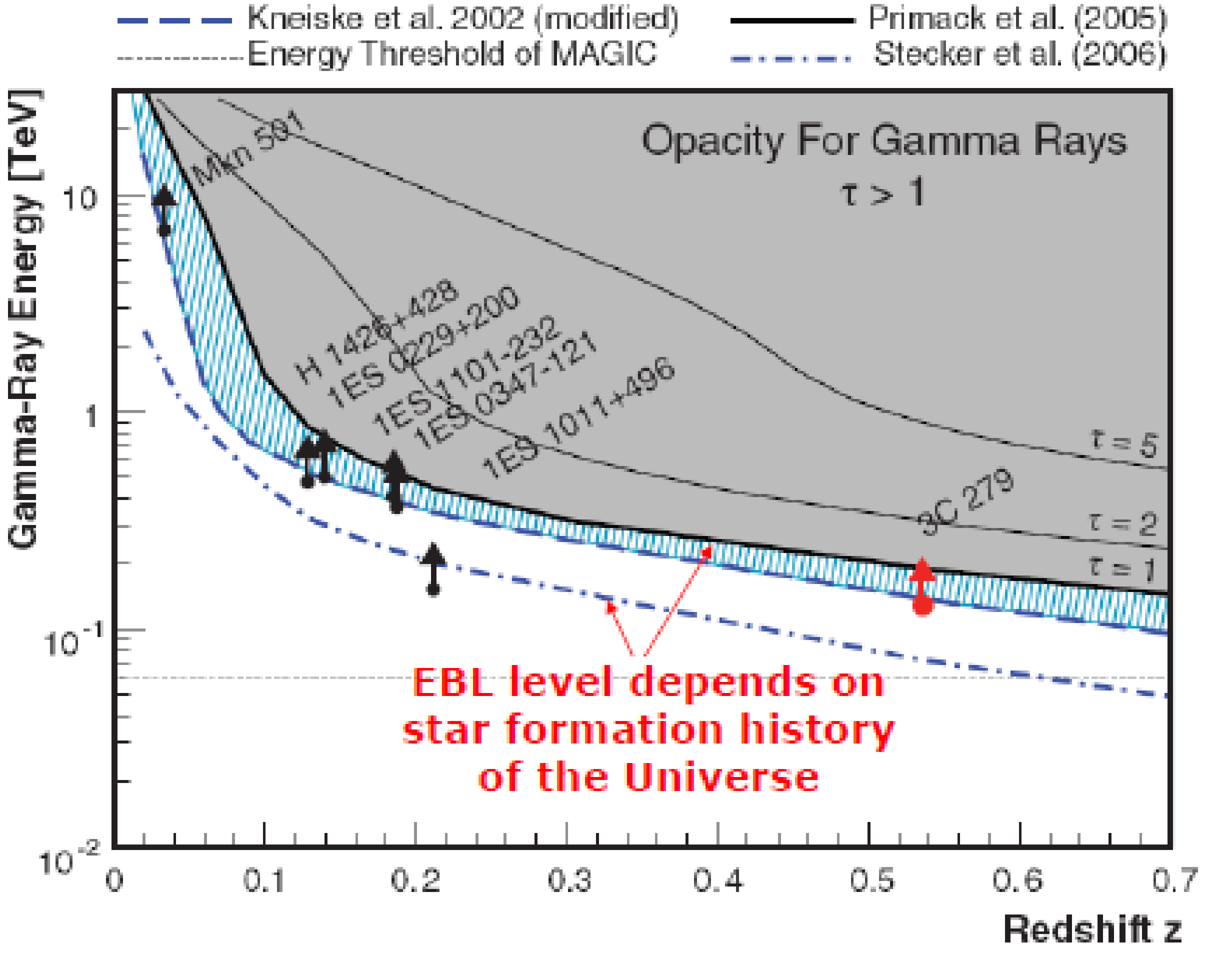
$$\tau(E_o, z_s) = \int_0^{z_s} dz \frac{dl}{dz} \int_{-1}^{1} d(cos\theta)(1 - cos\theta) \int_{\epsilon_{th}}^{\infty} d\epsilon n(\epsilon, z)\sigma(E, \epsilon, \theta)$$

Threshold condition: $E\epsilon(1 - cos\theta) \geq 2(m_e c^2)^2$

Gamma-ray horizon due to pair production

target: Extragalactic Background Light (EBL)





MAGIC Science 320 (2008)

Relevant EBL range: 1-10 µm

- Some quantum gravity models predict deviations from Einstein's postulate that the speed of light is constant, i.e.:

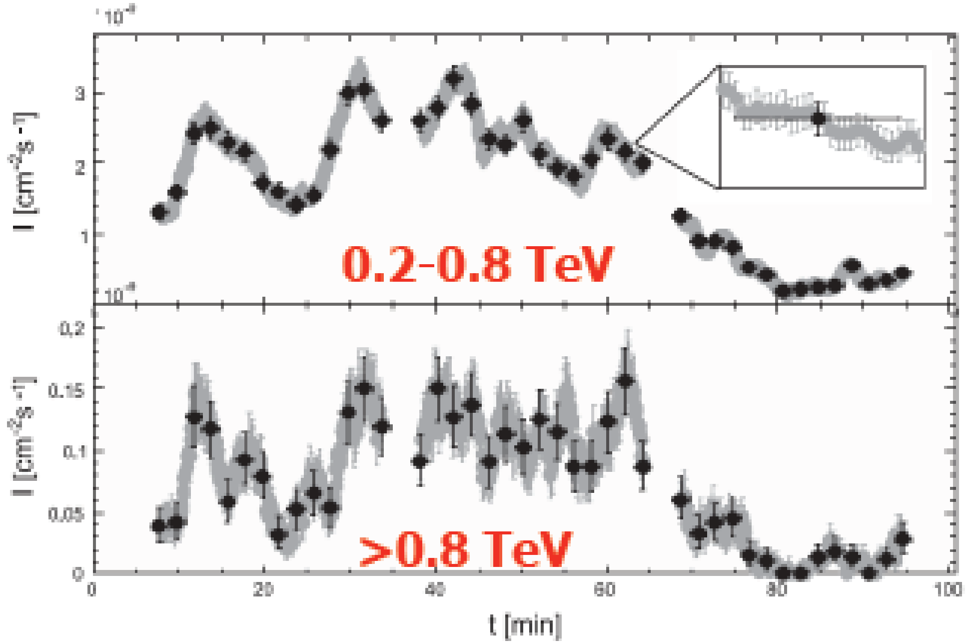
$$c' = c\left(1 \pm \frac{E}{k \cdot M_p} + ..\right) \quad , M_p \approx 1.2 \times 10^{19}\, GeV \,, k \approx 1$$

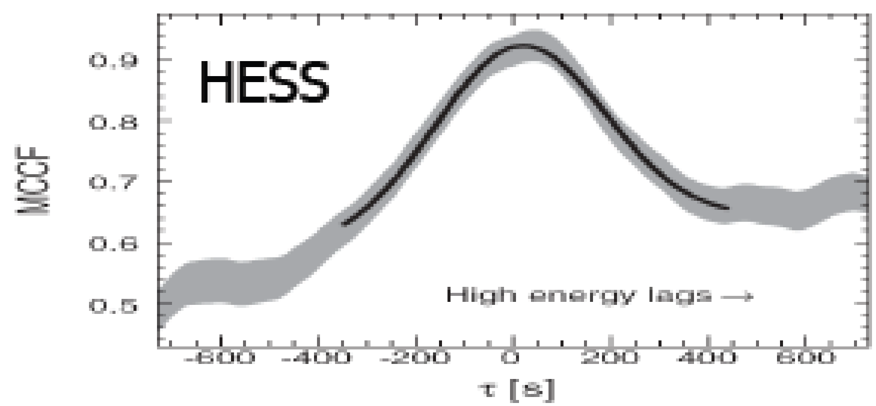
- Which would lead to a time delay between photons of different energies:

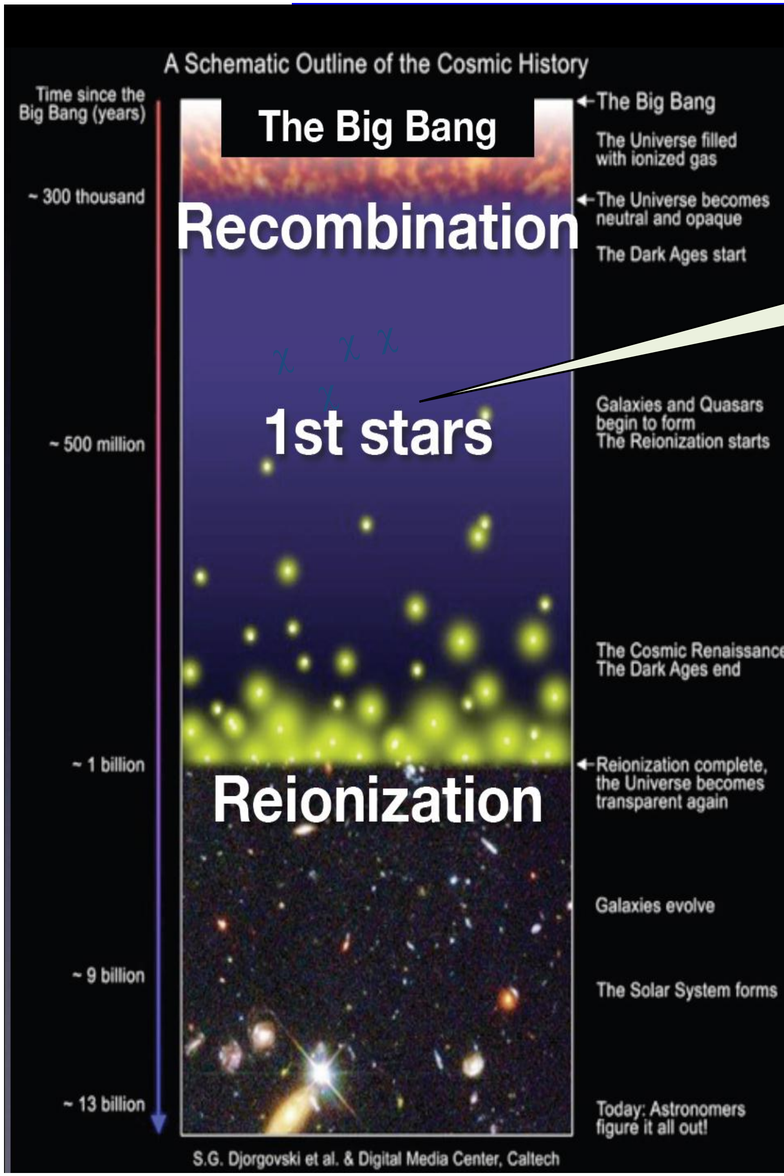
$$\Delta t_{QG} = L\left(\frac{1}{c_2} - \frac{1}{c_1}\right) \approx \frac{\Delta E}{k \cdot M_p} \frac{L}{c}$$

- To detect this effect we need high energy photons, huge distances and short timescales…

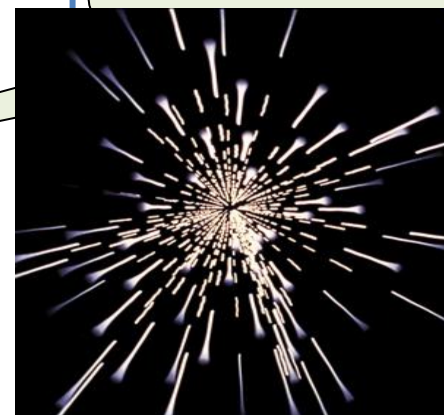
- A 2.5σ time lag seen by MAGIC for Mrk 501 butween high and low energy photons
  - *k* ~ 3%
  - Albert et al 2008 PRD
  - Quantum gravity effect?
- But not seen for 3x more distant PKS 2155-303 with more statistics
  - Time dispersion <100 seconds after 1 billion years of travel time!!!
  - *k* > 6%
  - Aharonian et al 2008 PRL
- For more sensitive instruments with wider energy ranges, the limits on *k* will approach 100% (the Planck scale!)

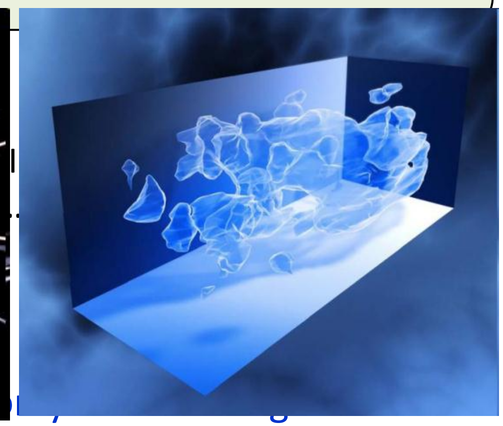




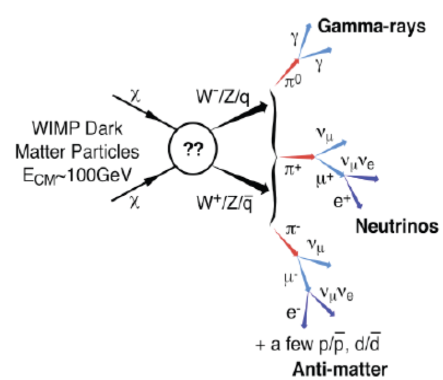


Cold Dark Matter χ is needed to explain structures formation





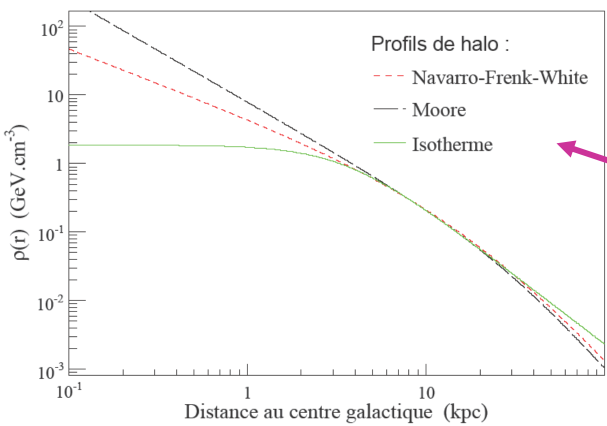
For the presence and nature of WIMPs



Indirect search for Dark Matter

$$\Phi_\gamma(E) \cong \frac{dN_\gamma}{dE\, dS\, dt\, d\Omega} = \frac{1}{4\pi}\frac{<\sigma v>}{m_\chi^2} \frac{dN_\gamma}{dE}(E) <J>$$

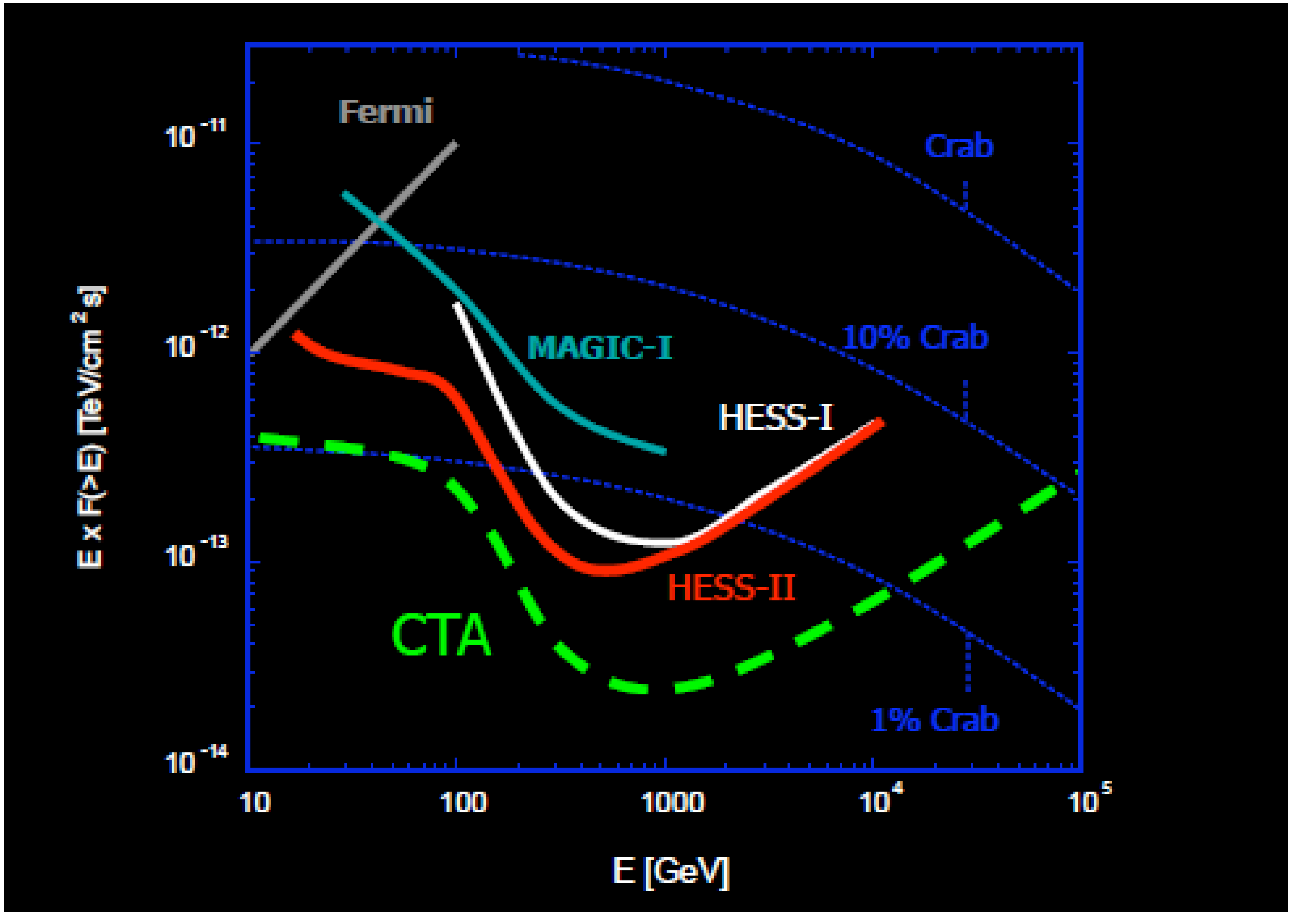
New Physics | Particle Physics | Astrophysics



$$<J> = \int \frac{1}{2\delta_{stst}} \rho^2(\vec{r})\, ds\, d\Omega$$

$$\rho(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1+(r_\odot/a)^\alpha}{1+(r/a)^\alpha}\right]^{\frac{\beta-\gamma}{\alpha}}$$

The future: Cherekov Telescope Array (CTA)



CONCLUSIONS