

# les sources de rayons gamma

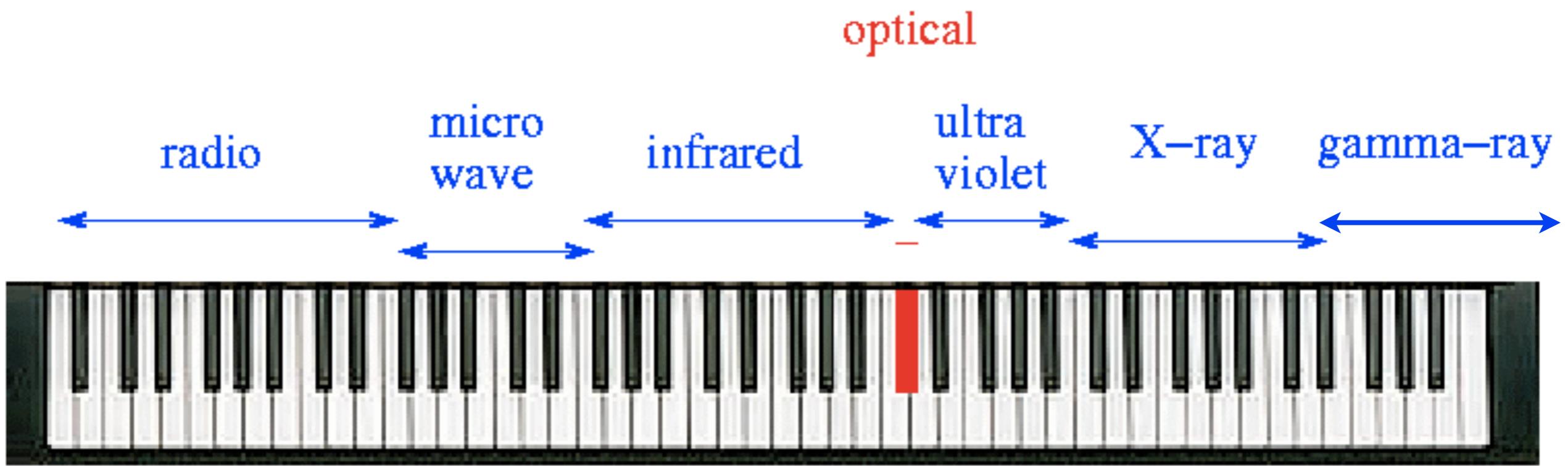
Cyril Trichard

LLR / École Polytechnique



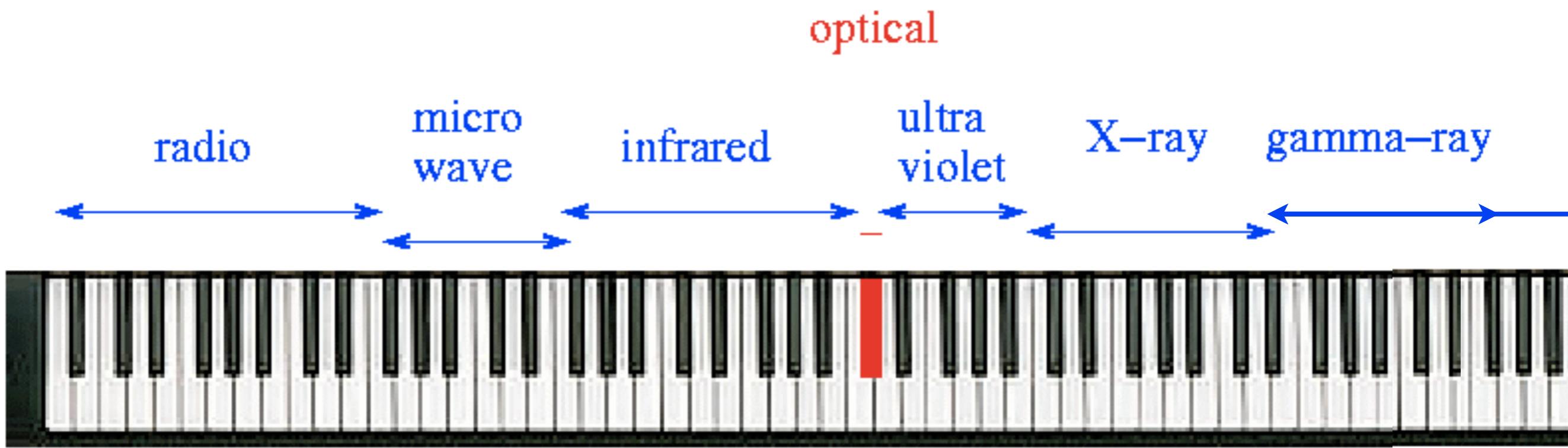
UN RAPPEL

# G'est quoi un rayon gamma?



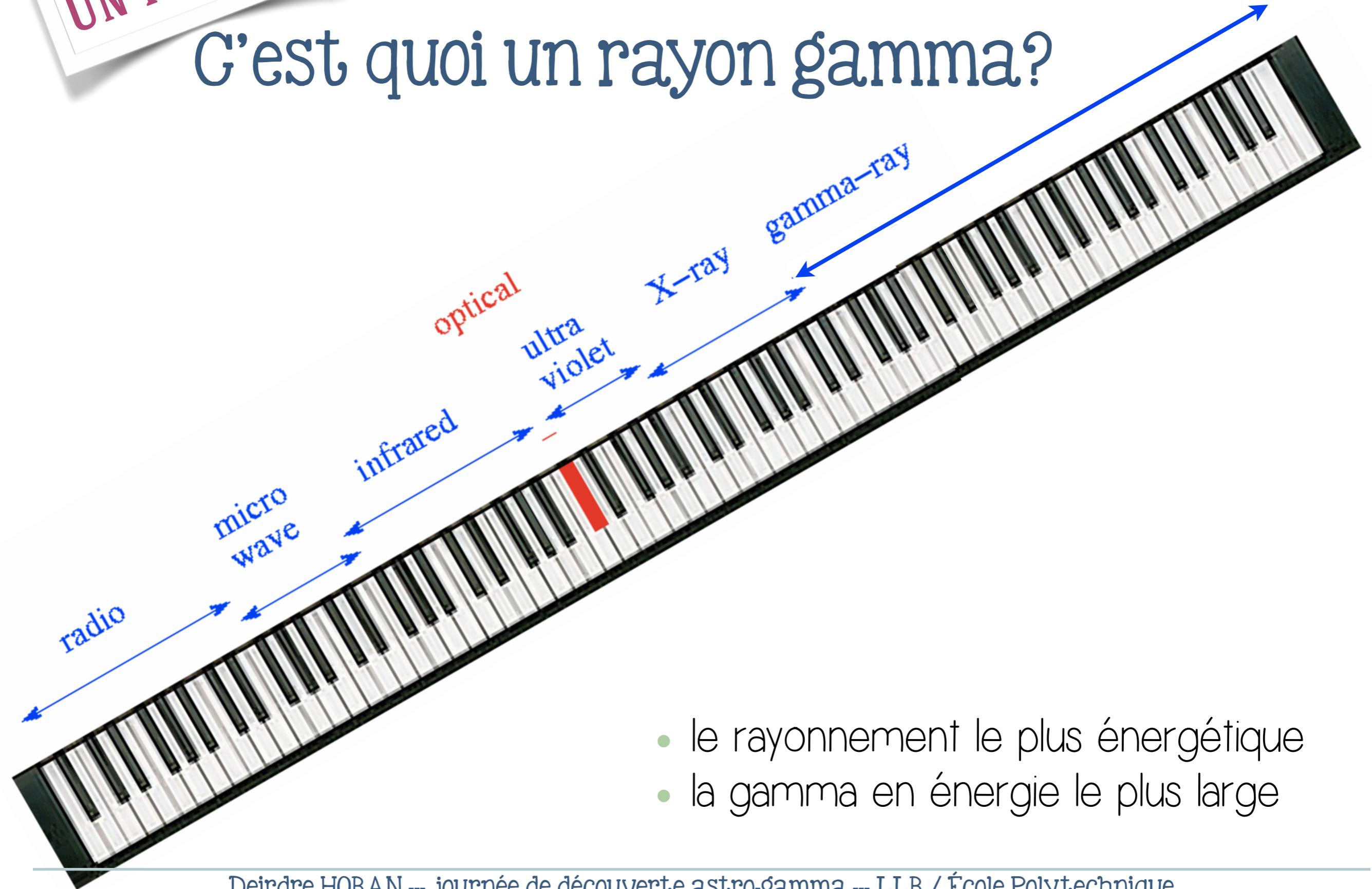
UN RAPPEL

# G'est quoi un rayon gamma?



UN RAPPEL

# G'est quoi un rayon gamma?



- le rayonnement le plus énergétique
- la gamma en énergie le plus large

# L'Astrophysique gamma – pourquoi?

le rayonnement le plus énergétique (il prend un tiers du spectre)



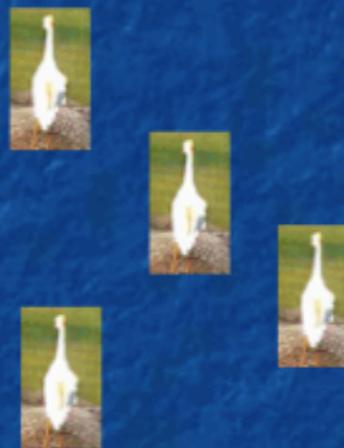
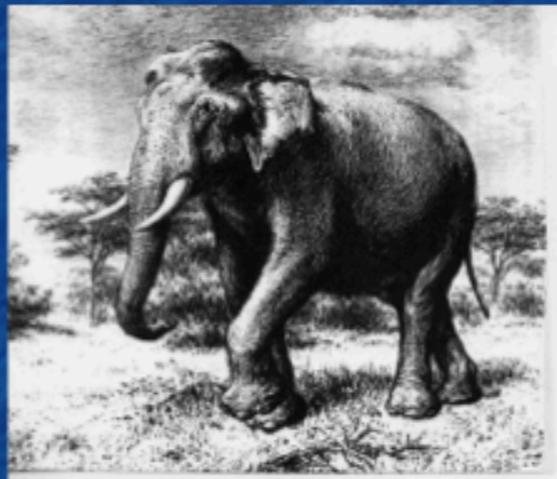
Trevor WEEKES  
(1940 - 2014)

One of founders of VHE  
gamma-ray astronomy

Trevor Weekes (Fermi Summer School 2012)

## Why study TeV Gamma rays?

Why do we study elephants when  
birds are easier to find and more plentiful?



TeV gamma-rays, like elephants, are bigger,  
more difficult to produce, and stretch the  
the production models to their limits!

June, 2012

VHE Gamma-ray Astronomy 101

# L'Astrophysique gamma – pourquoi?

+ intéressantes?

Les rayons gamma proviennent des régions les plus ~~violent~~ de l'univers

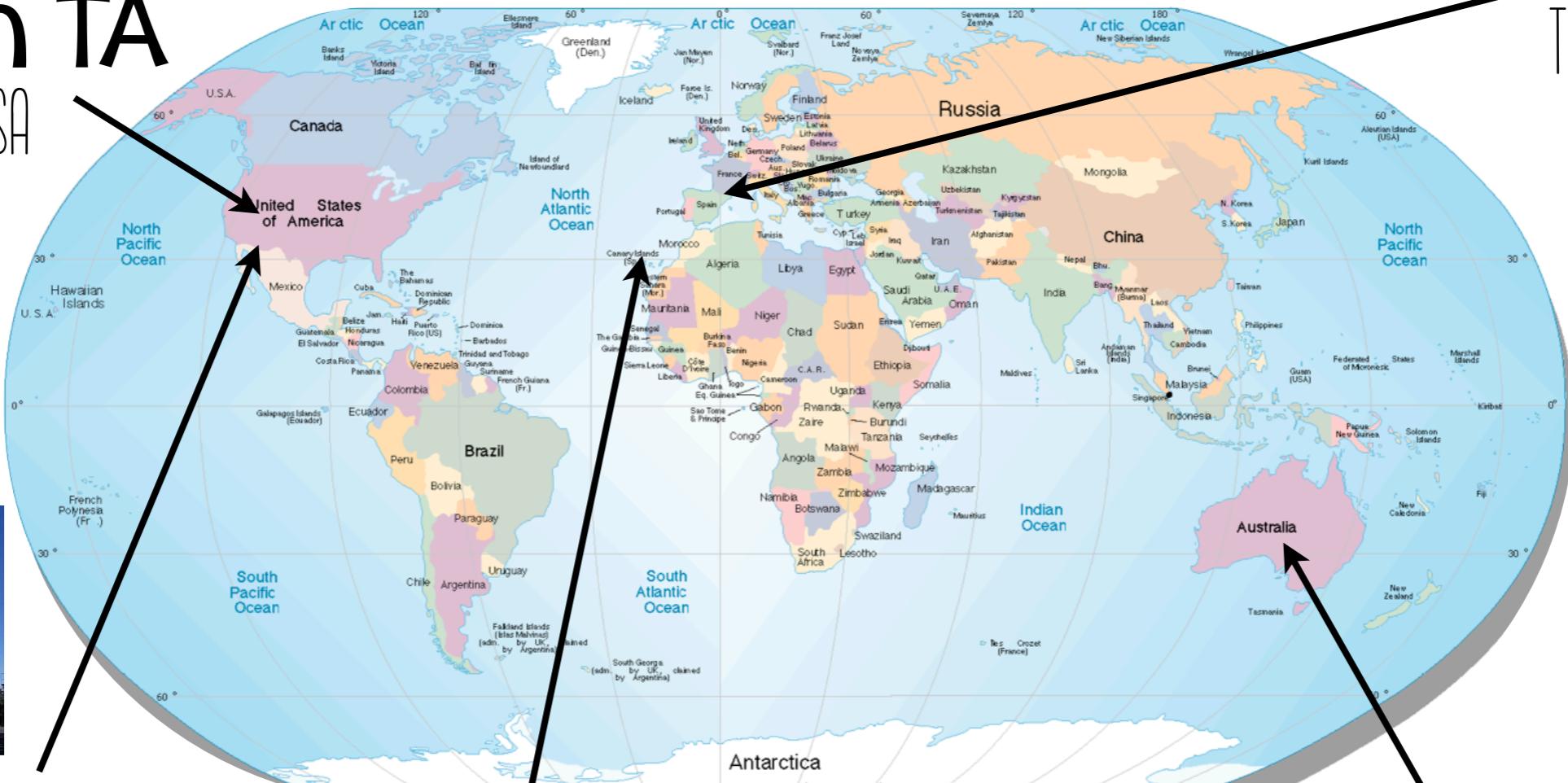


# “Deuxième génération” télescopes:

1989 - ~2003

Seven TA

Utah, USA



Whipple

Arizona, USA

HEGRA

La Palma, Canary Islands



CAT  
Themis, France



CANGAROO

Woomera, Australia

# l'Astrophysique gamma - la connexion irlandaise

## LA PREMIÈRE SOURCE DES HAUTES ÉNERGIES (1989):



... détectée par  
Whipple en 1989  
(après de  
nombreuses  
années de  
développement du  
technique)



... confirmée  
prochainement  
par CAT et  
HEGRA

## LA NEBEULEUSE DE CRABE: THE CRAB NEBULA

# La Nébuleuse de Crabe:

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**1054 AD: OBSERVATIONS DES ANASAZI INDIANS**

# La Nébuleuse de Crabe:

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Le reste de supernova était détecté en 1844 par Lord Rosse - un homme Irlandais. Son assistant a produit un "sketch" de nébuleuse qu'ils ont vue et cela rasssemblait à la griffe d'un crabe - donc ils l'ont appelé "**The Crab Nebula**" ...

# La Nébuleuse de Crabe:

---



mais ... je me demande si ils avaient eu un meilleur télescope ...

# La Nébuleuse de Crabe:

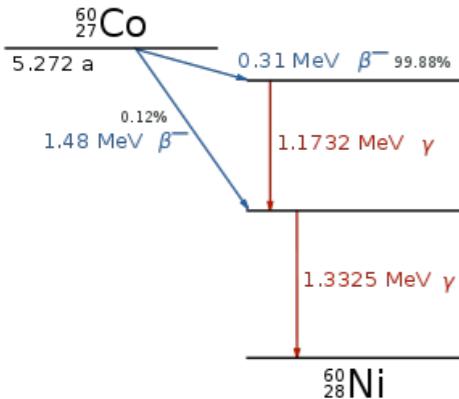


mais ... je me demande si ils avaient eu un meilleur télescope ...

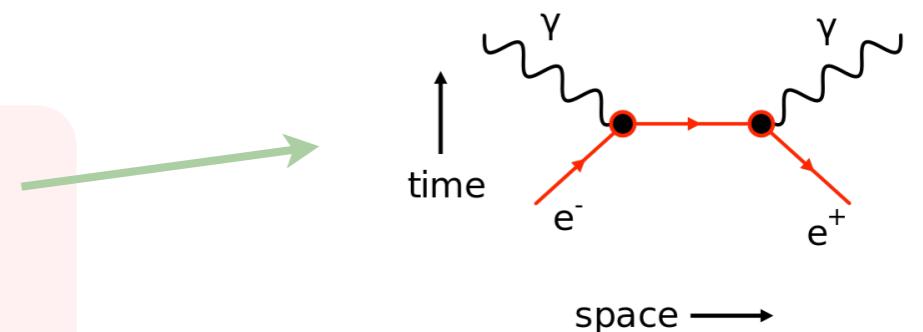
# Comment produire les rayons gamma?

## Nuclear & Non-nuclear

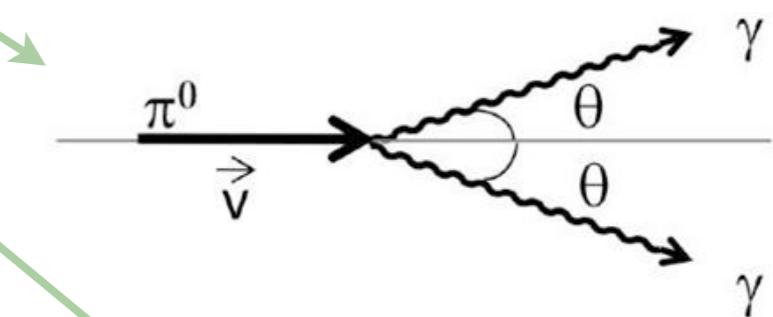
- nuclear decay



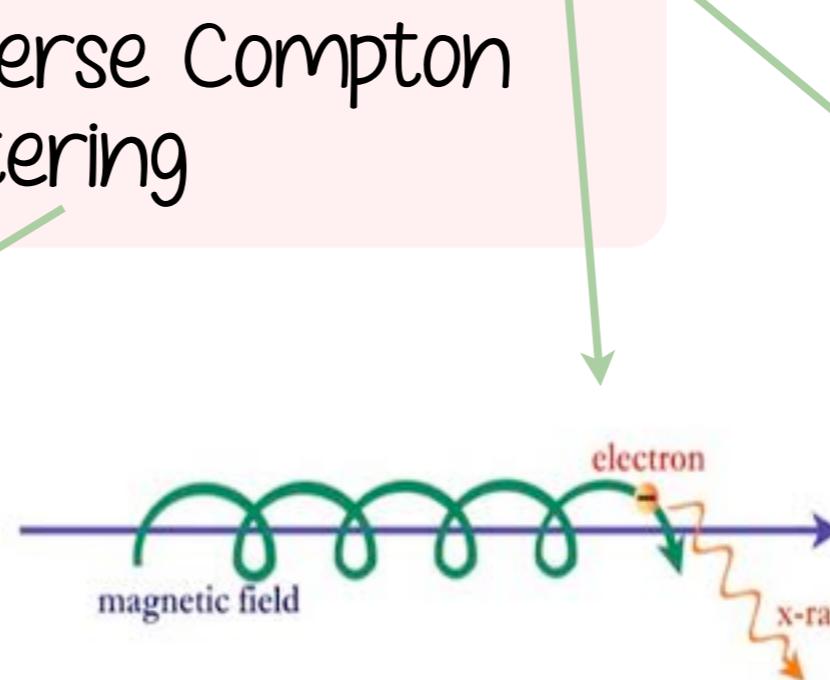
- electron-positron annihilation



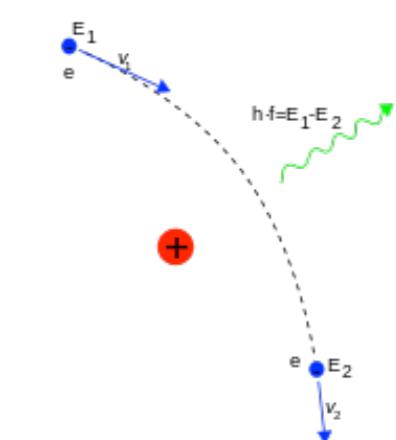
- neutral pion decay



- bremsstrahlung / synchrotron



- inverse Compton scattering



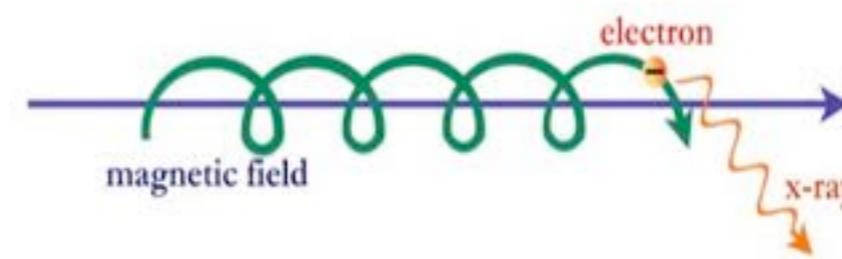
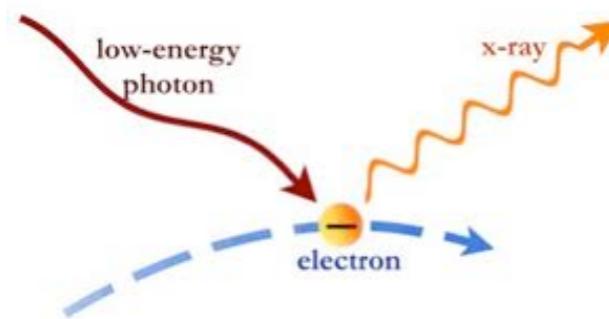
# Comment produire les rayons gamma?

## L'idée centrale:

il faut un moyen **d'accélérer** des particules chargées - dans une source astrophysique - puis c'est eux qui permettent la production des rayons gamma

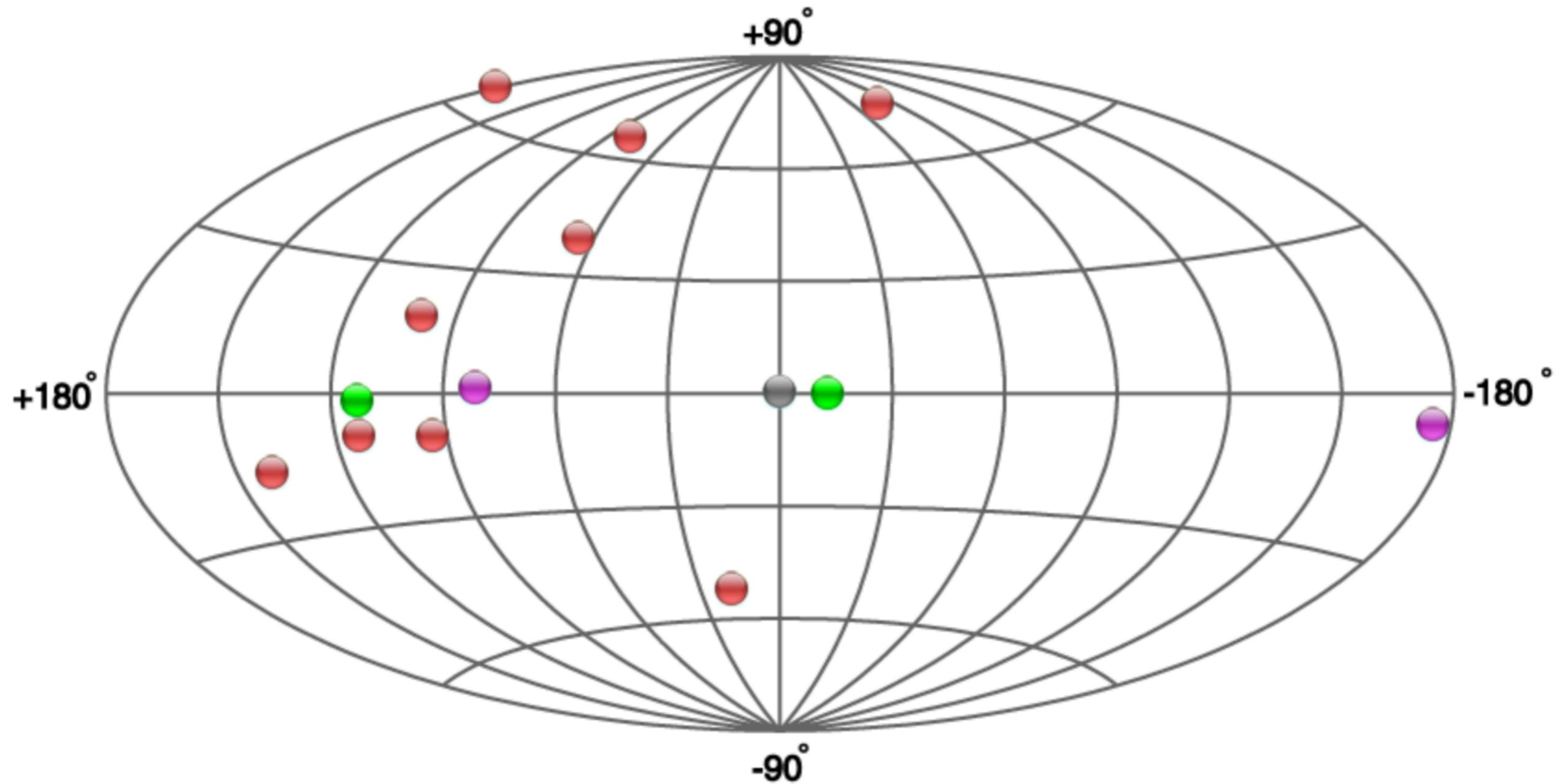
champ magnétique  
choque

$e^- e^+$   
 $p$



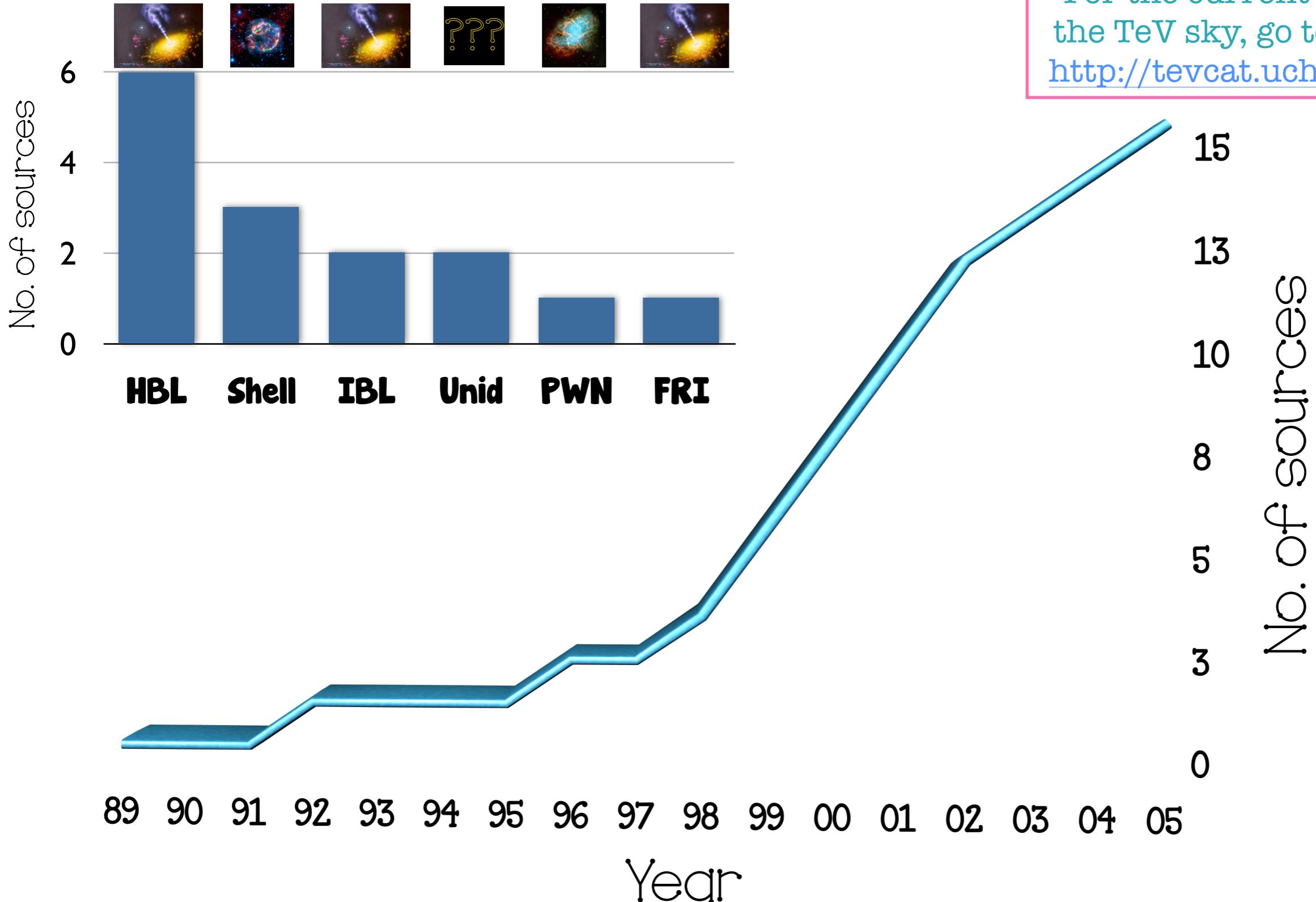
... et comme ça, on peut étudier et (mieux) comprendre les mécanismes d'accélération

# État du ciel aux hautes énergies: 2005 (avant 3ème gén)

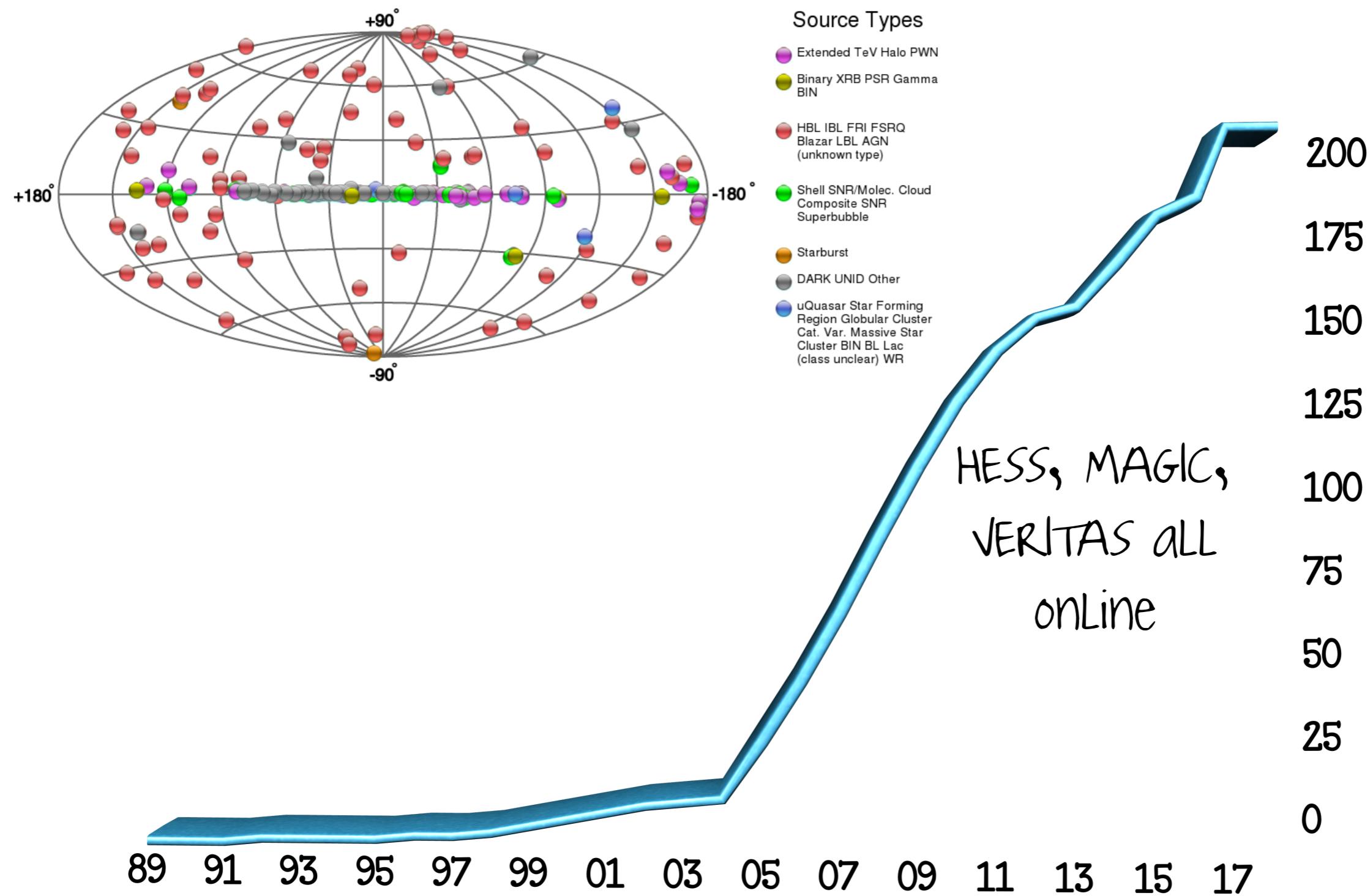


à la fin de ma thèse - nous avions 15 sources de hautes énergies (pas grâce à moi!!) - le 3ème génération était prête à démarrer

# État du ciel aux hautes énergies: 2005 (avant 3ème gén)



# Etat du ciel au TeV aujourd'hui:



Au moment de rédaction de cet exposé: on a 210 sources aux TeV

## Et maintenant?

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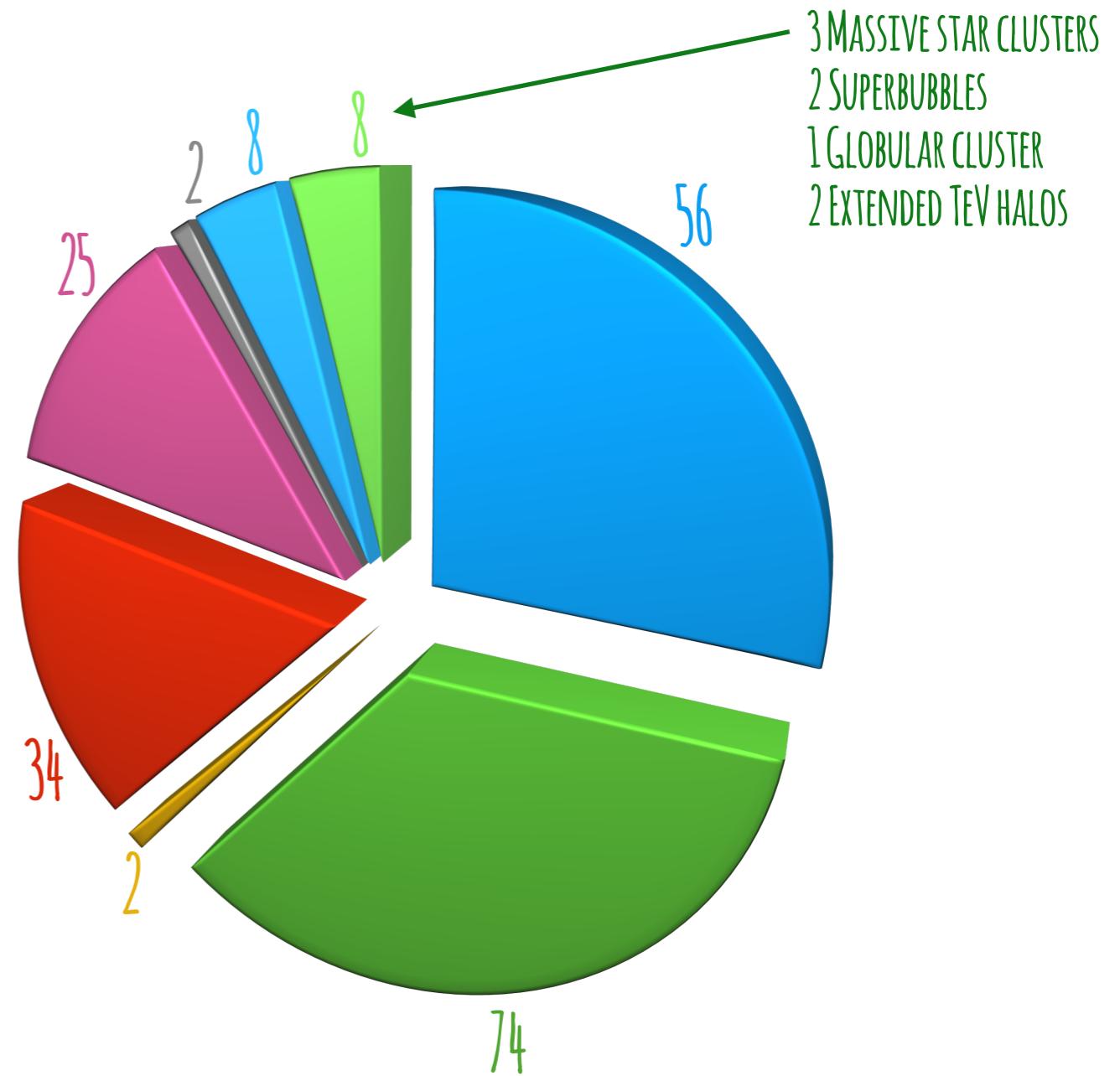
Maintenant chaque nouvelle source n'est pas  
"une grande nouvelle"  
et on est vraiment dans l'ère de  
faire des études détaillées  
des sources de rayons gamma

# Quelles sont les sources de rayons gamma?



# Quelles sont les sources de rayons gamma?

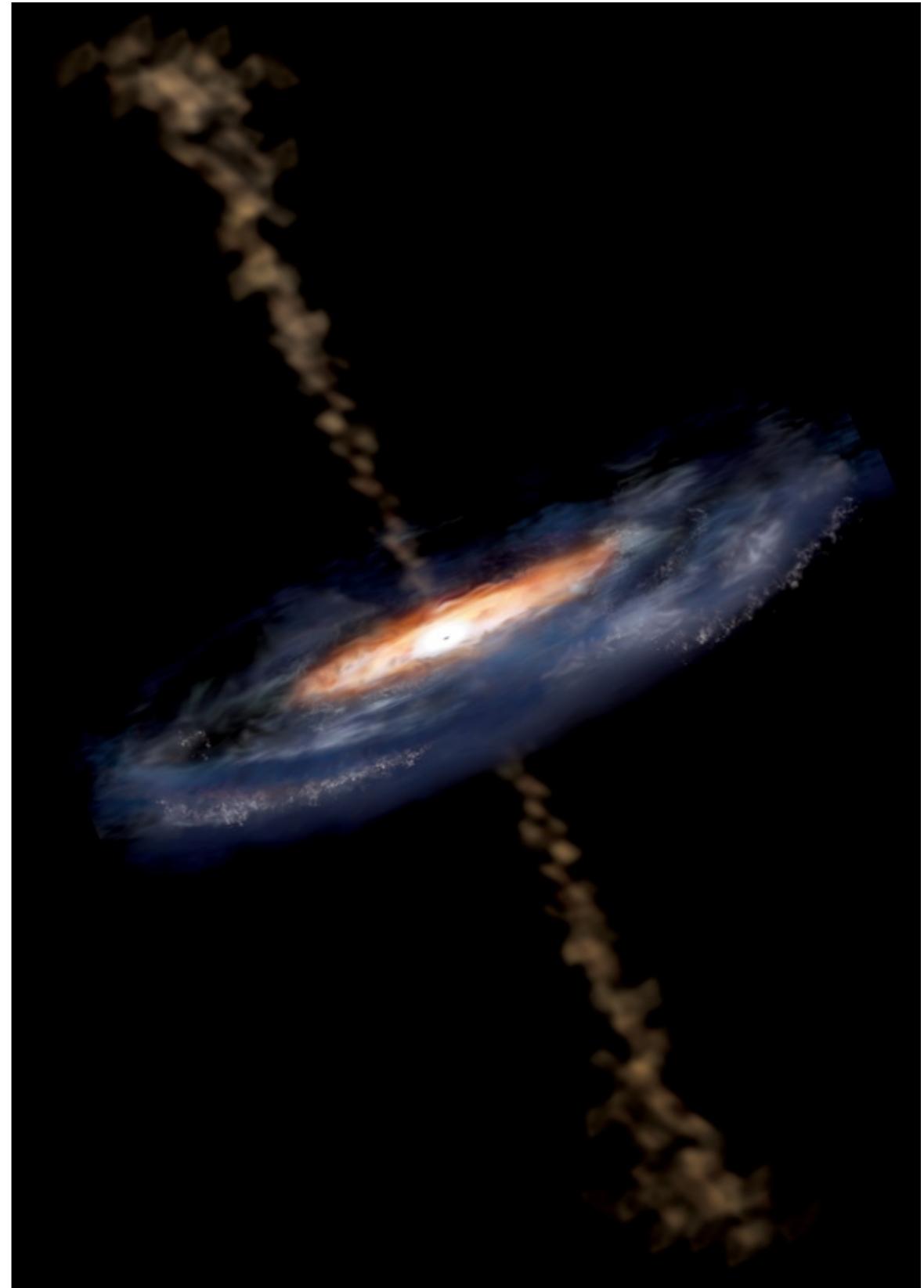
- NON-IDENTIFIÉS
- NOYAUX ACTIFS DE GALAXIES
- GALAXIES À FLAMBÉES D'ÉTOILES
- NÉBULEUSES DE PULSARS
- VESTIGES DE SUPERNOVAE
- PULSARS
- BINARIES
- "AUTRE"



# Les Noyaux Actifs de Galaxies (NAGS)

## CARACTÉRISTIQUES

- \* le noyau central est plus lumineux que le reste de la galaxie
- ils émettent à travers le spectre entier:  
radio ... keV ... MeV ... TeV  
→ non thermique
- mass:  $10^8 M_{\text{soleil}}$
- jets relativistiques ... mouvement superluminal

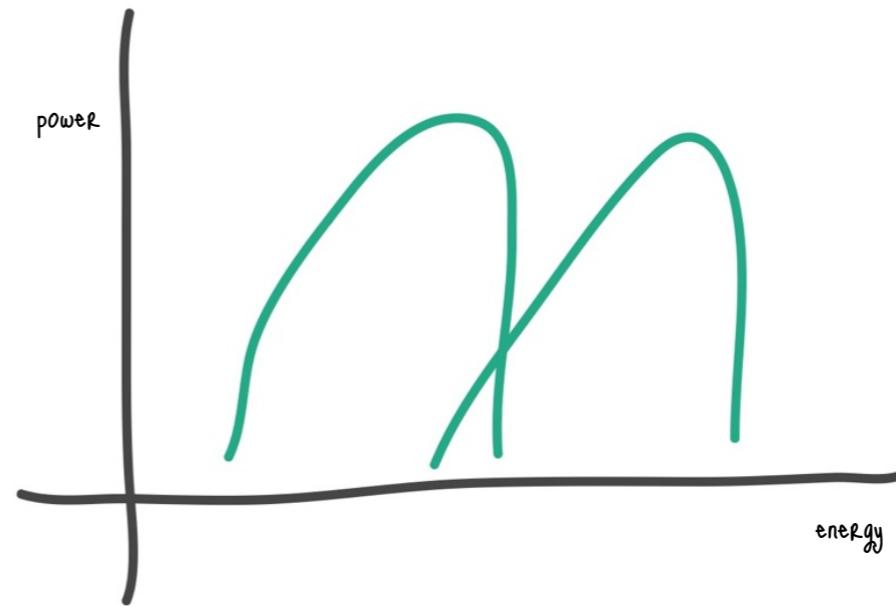


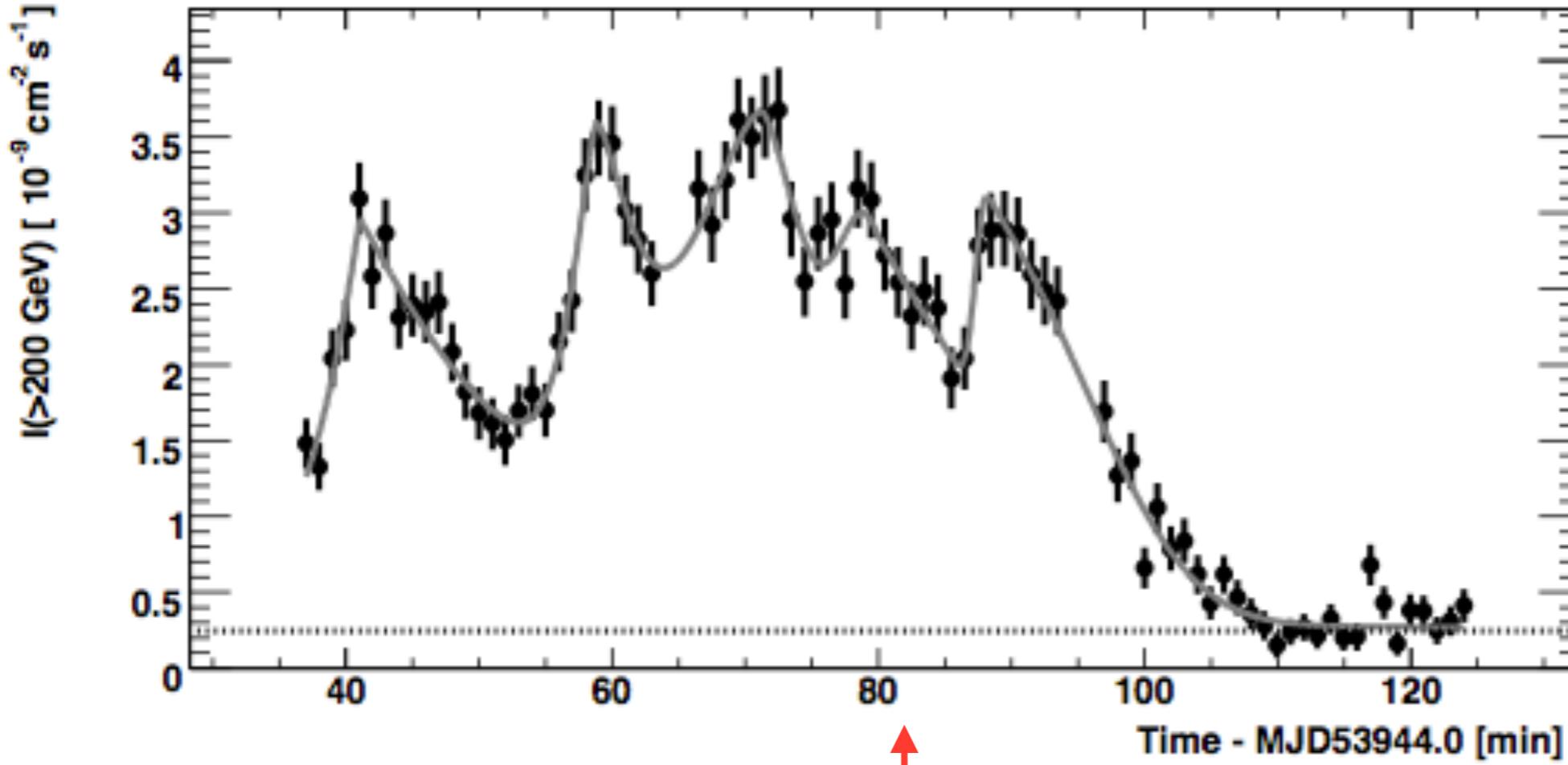
# Les Blazars



## CHARACTERISTIQUES

- \* <5% des NAGs
  - le jet point “vers” nous
  - émission très variable
  - spectral energy distribution





AHARONIAN ET AL. (2007), APJ, 730, L8



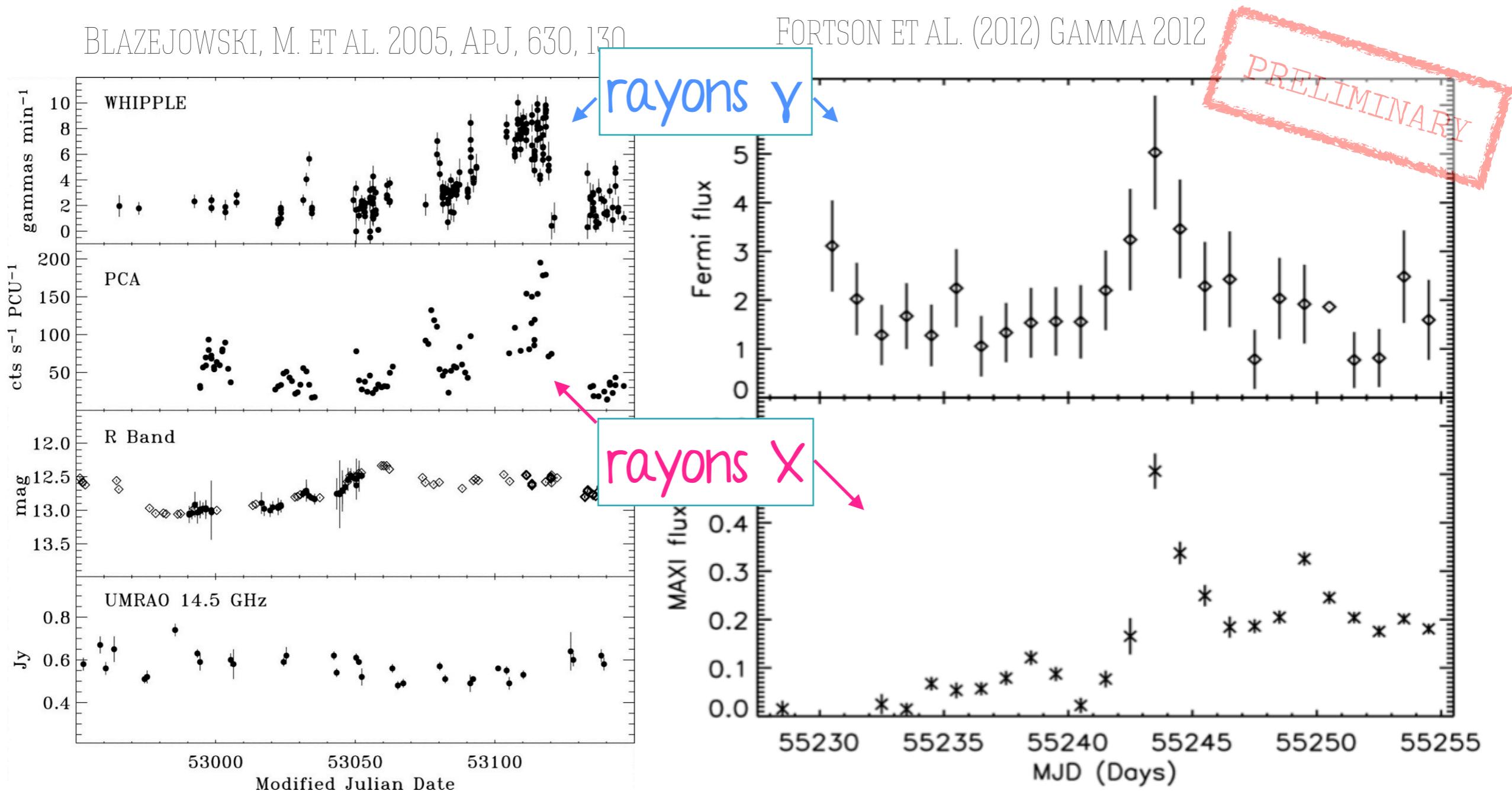
**distance: milliards  
d'années-lumière**

**PKS 2155-304**  
**1-minute time bins**  
**BH mass:  $\sim 10^9 M_{\odot}$**

# Les Blazars

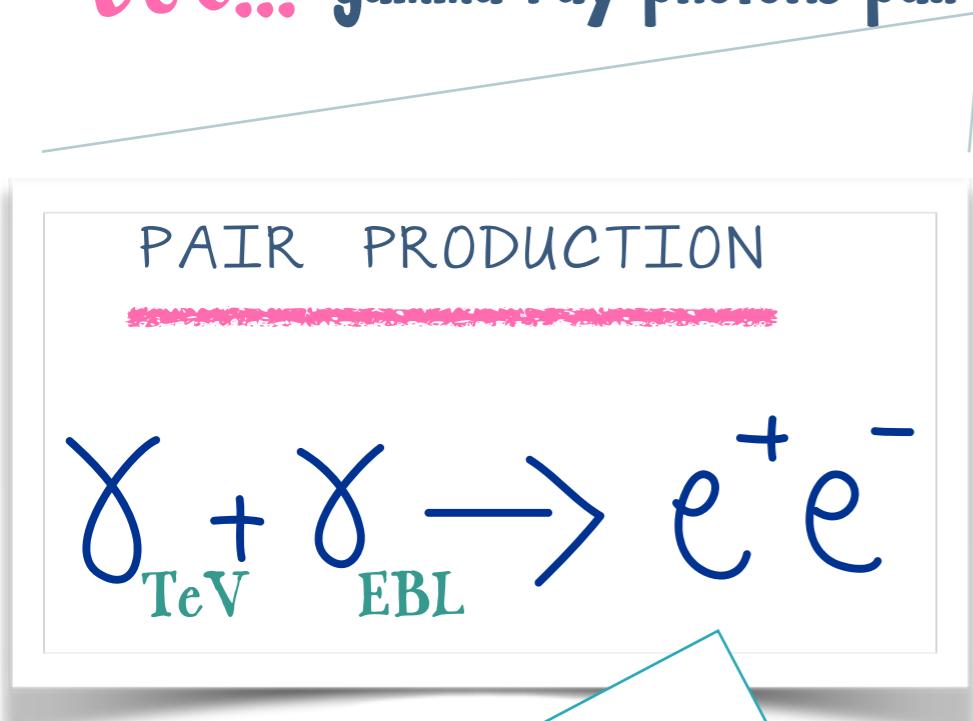
## Les modèles de l'émission des blazars

- leptonic models provide good fits to many blazars
- **X-ray and gamma-ray emission often correlated - a fact naturally explained by SSC models**

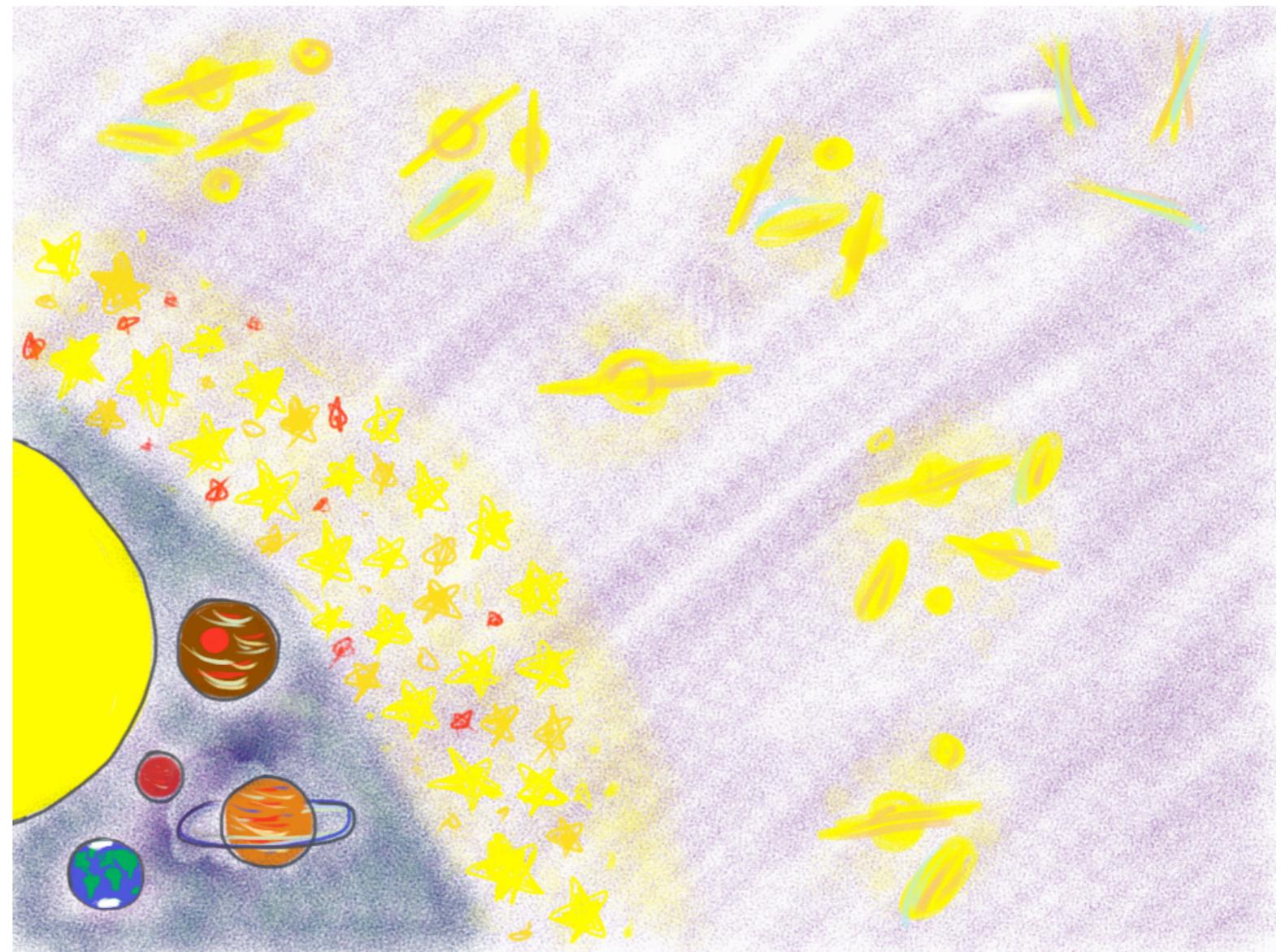


# Cosmology - Extragalactic Background Light

- The extragalactic background light is the **second largest energy reservoir** in the universe (after the cosmic microwave background radiation field)
- It comprises the **accumulated emission from stars and dust** that have lived at all ages of the universe
- It occupies the region of the spectrum from **IR** through **optical** to the **UV** ( $\sim 0.1 - 1000 \mu\text{m}$ )
- Because of the strong foreground emissions from our solar system and galaxy - it's difficult to measure directly  
**but... gamma-ray photons pair produce with the EBL photons and therefore get absorbed!**

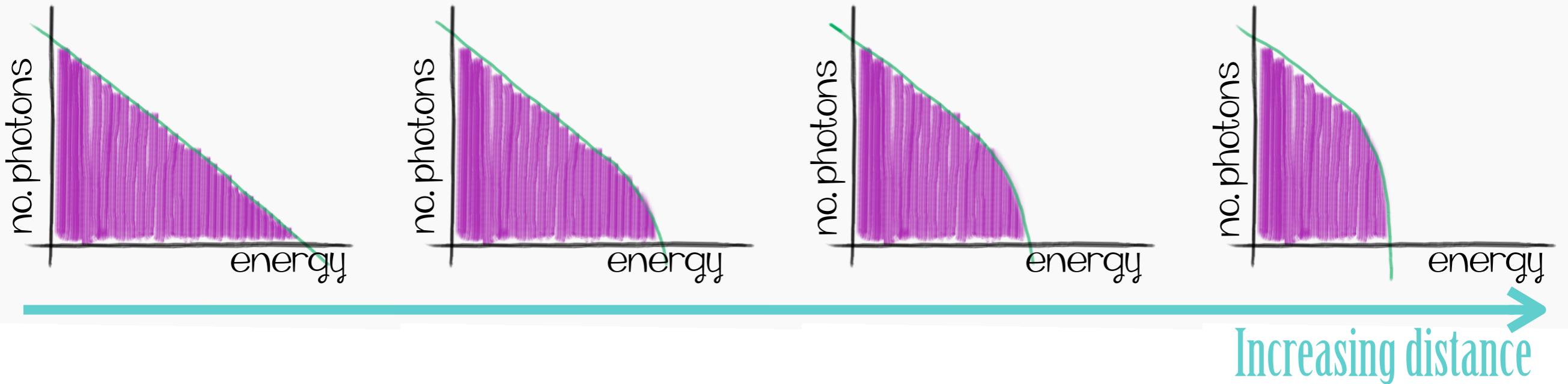


for gamma rays with  $E > \sim 200 \text{ GeV}$

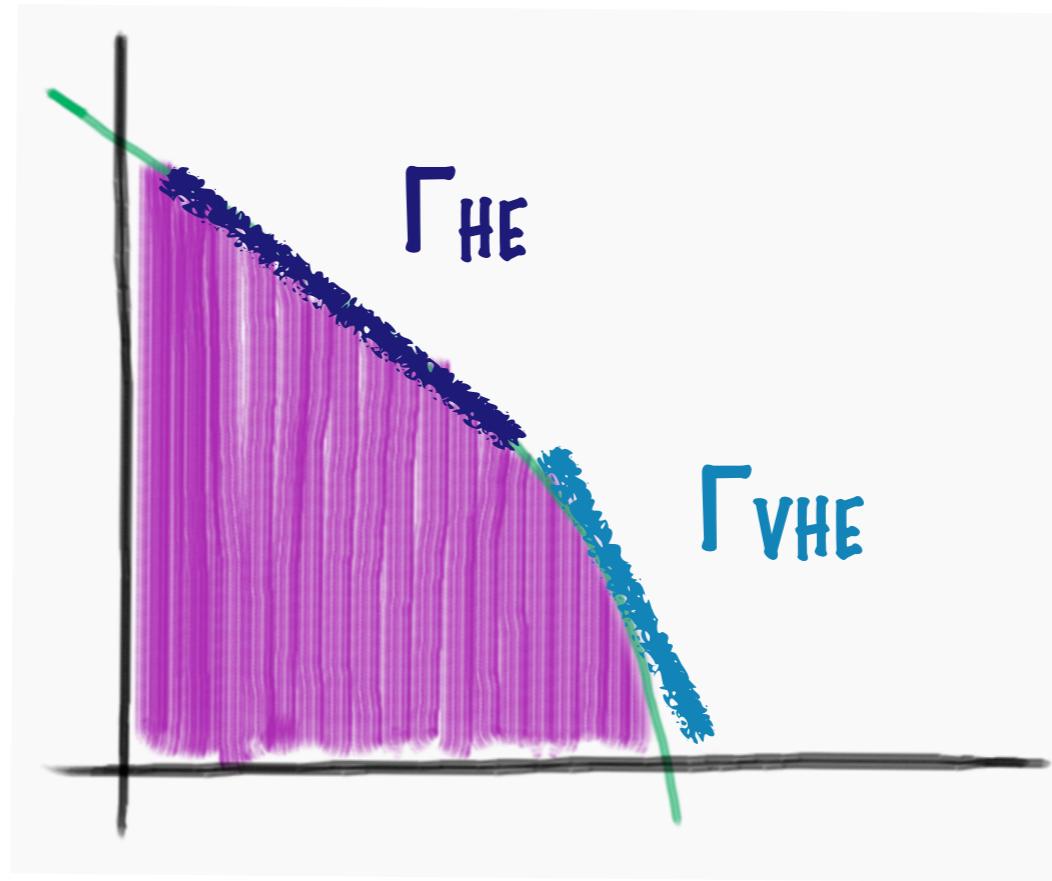


# Cosmology - Extragalactic Background Light

Gamma-ray photons pair produce with the EBL photons and therefore get absorbed!

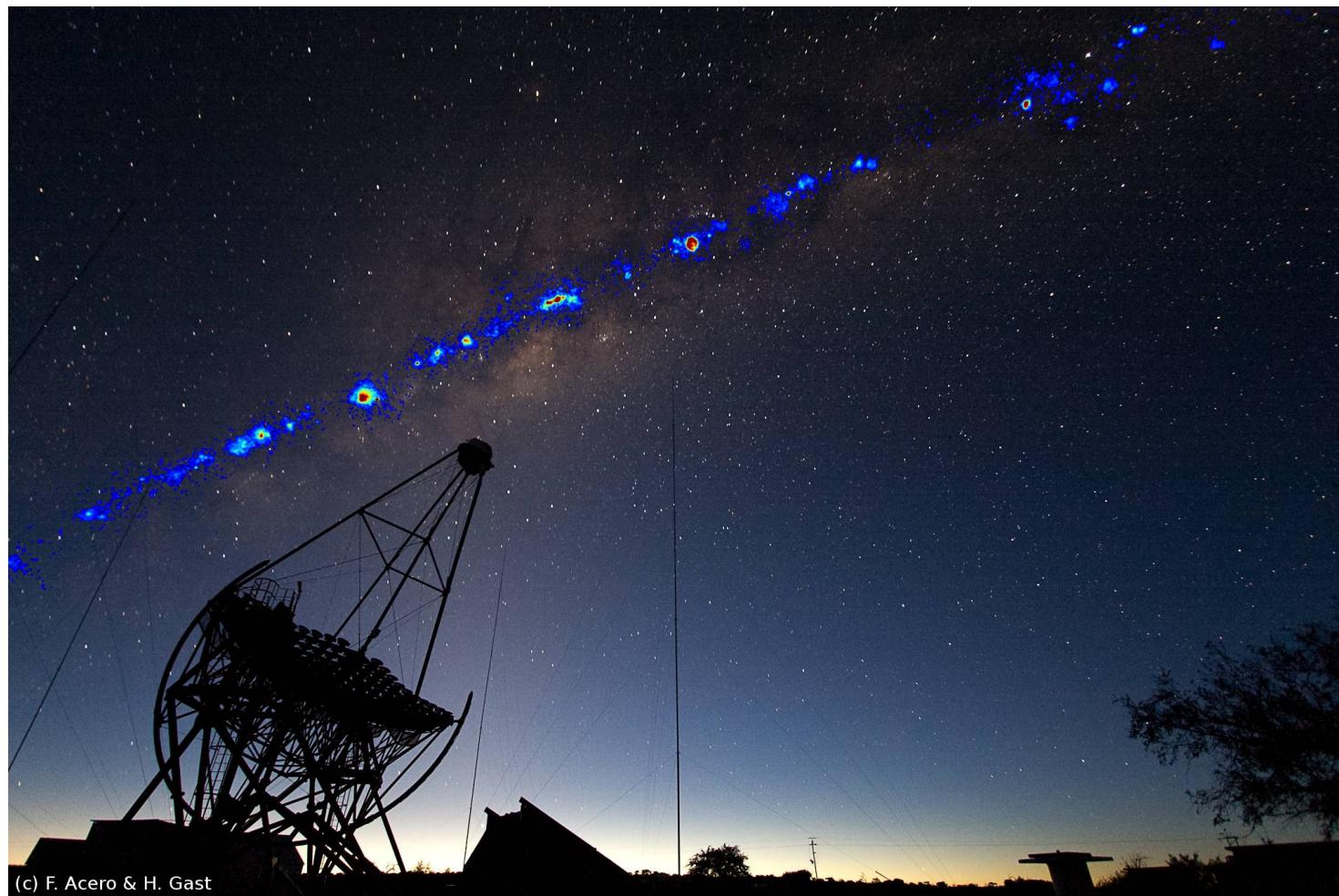


The further away the object we detect, the more its TeV photons are absorbed by the EBL - this results in a break in the spectrum



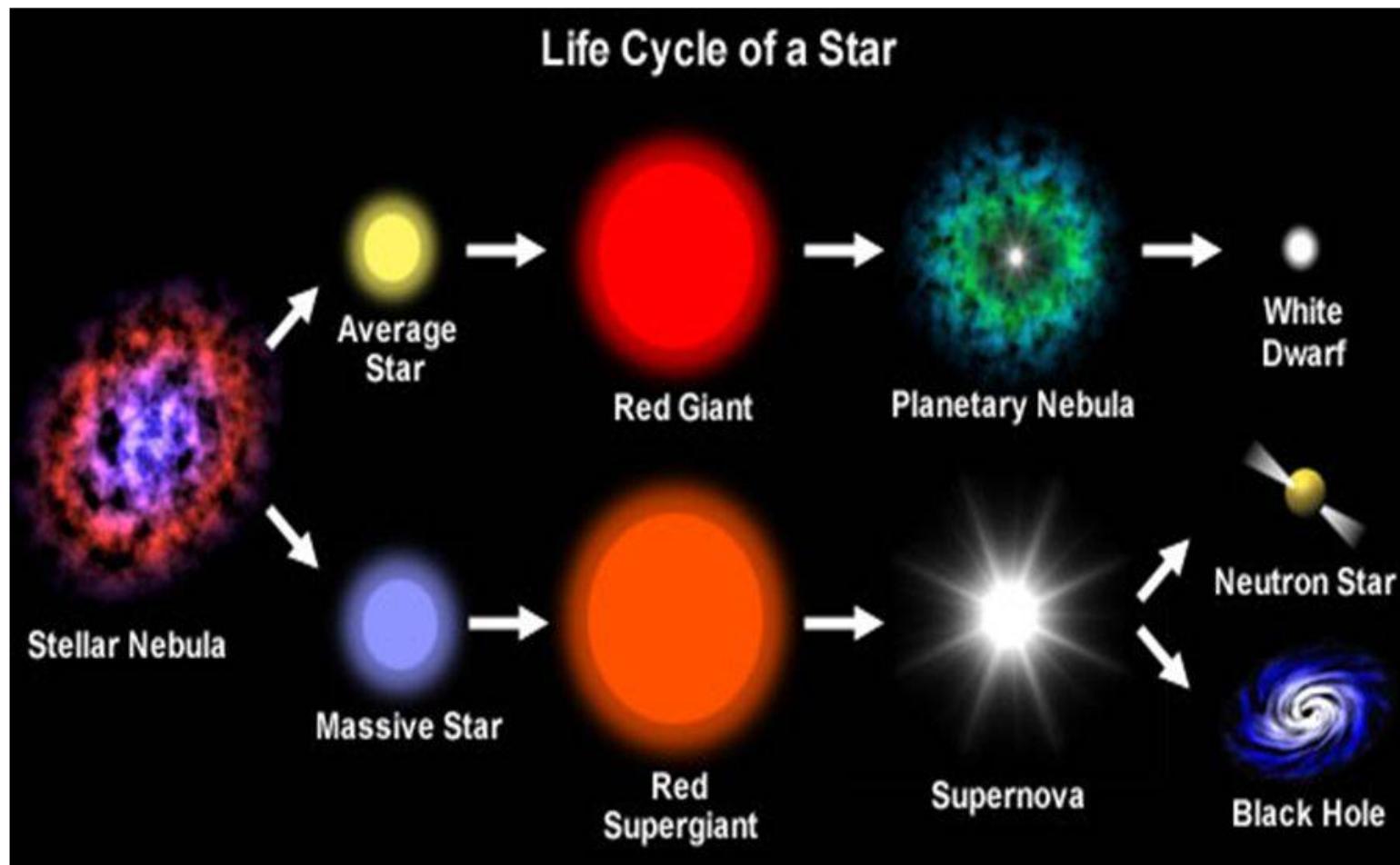
# Plan Galactique vu par HESS

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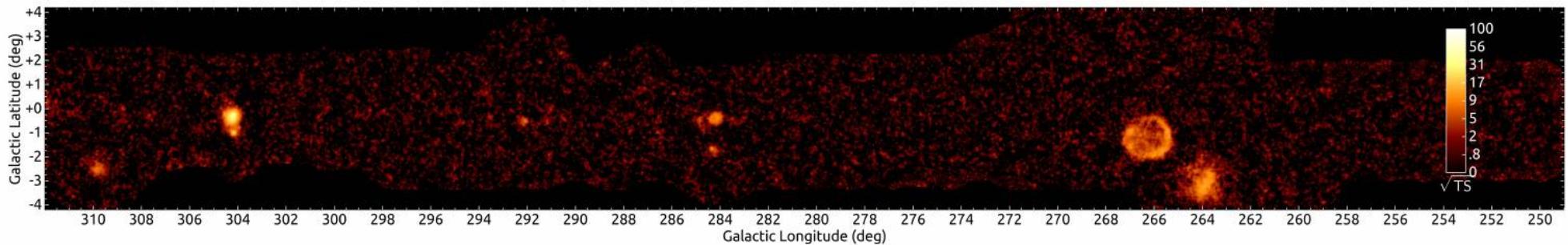
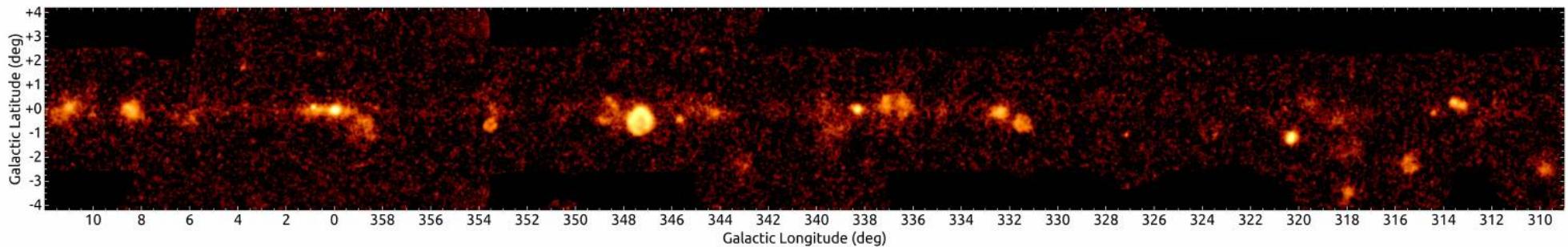
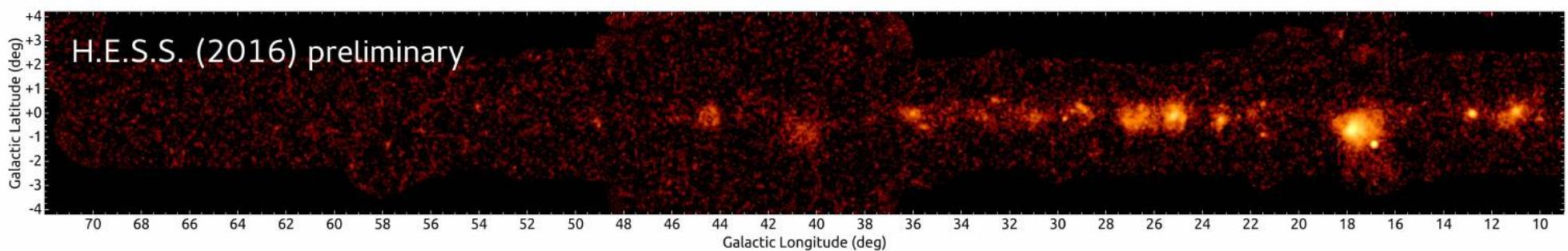
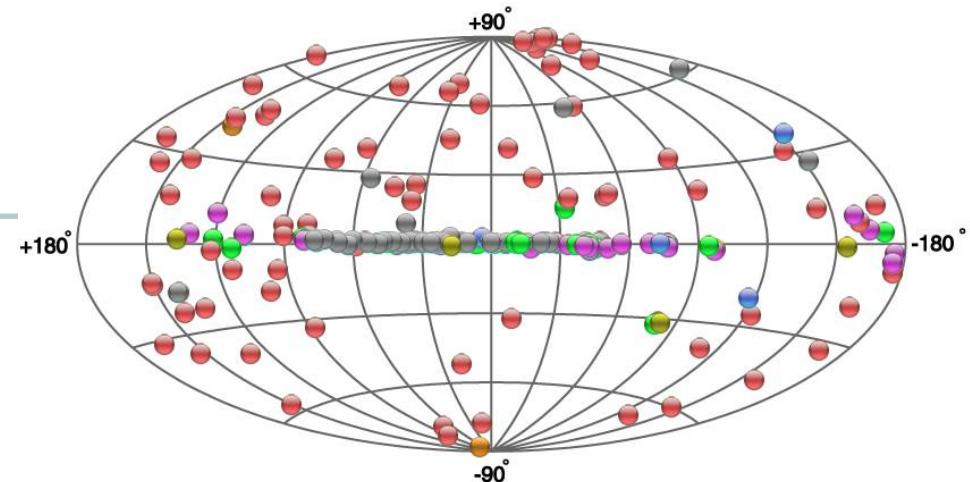


(c) F. Acero & H. Gast

# Star Lifecycle



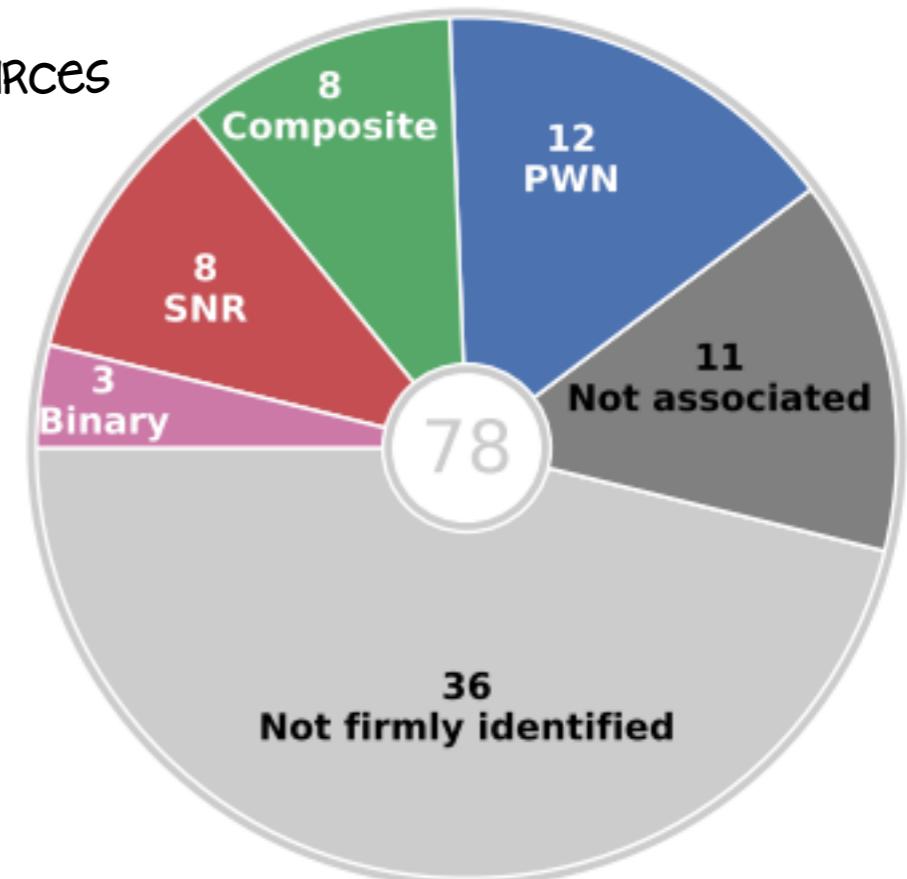
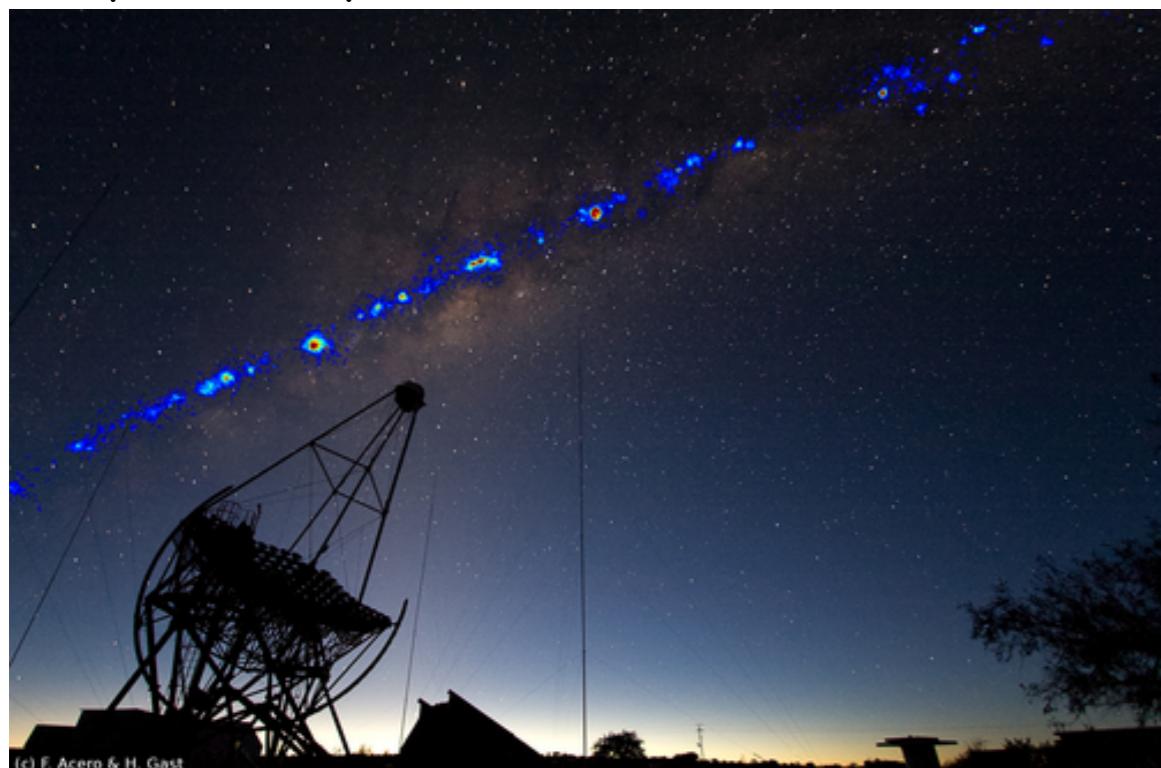
# Plan Galactique vu par HESS



# Galactic Physics: H.E.S.S. Galactic Plane Survey

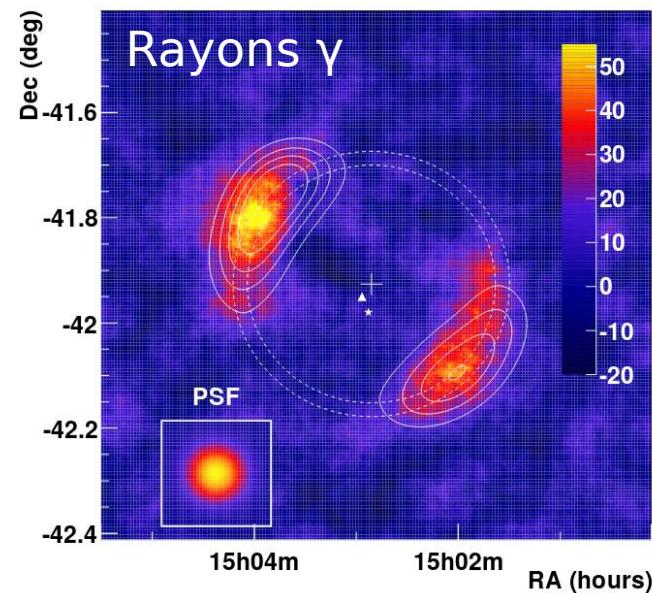
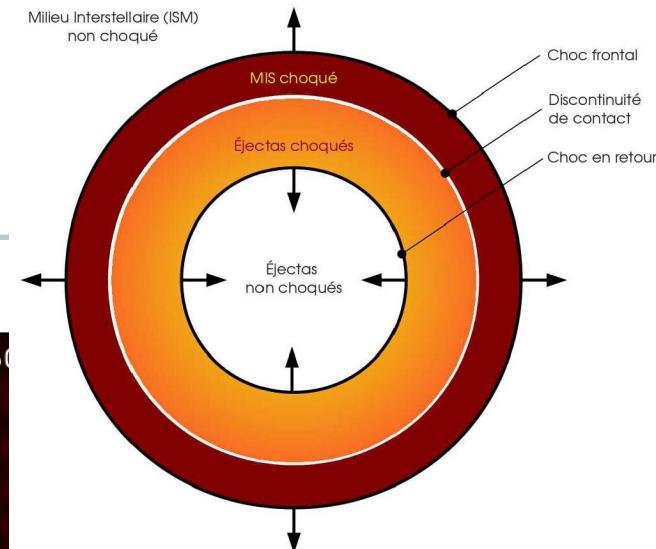
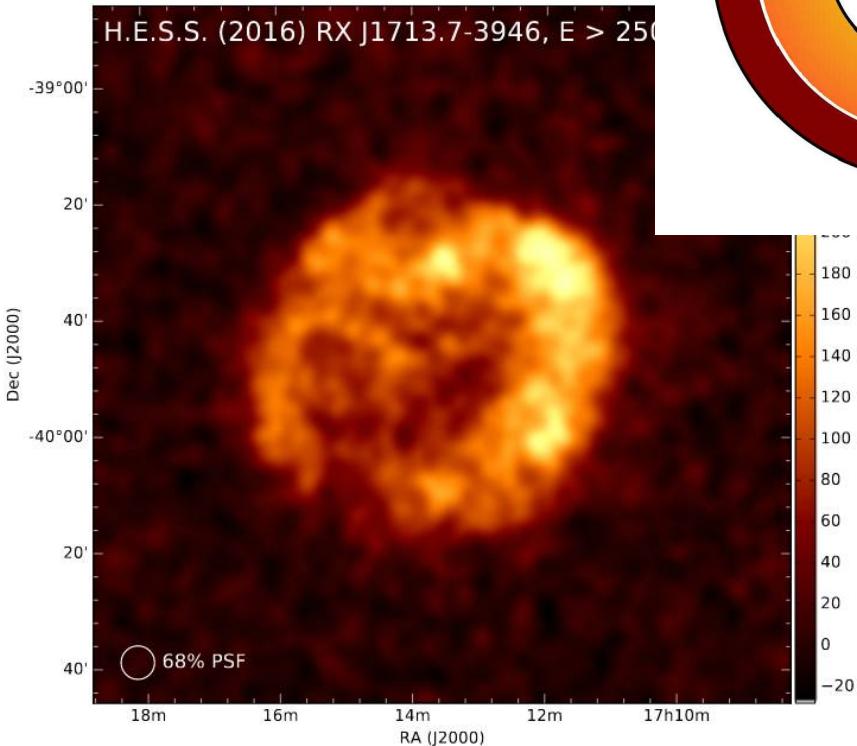
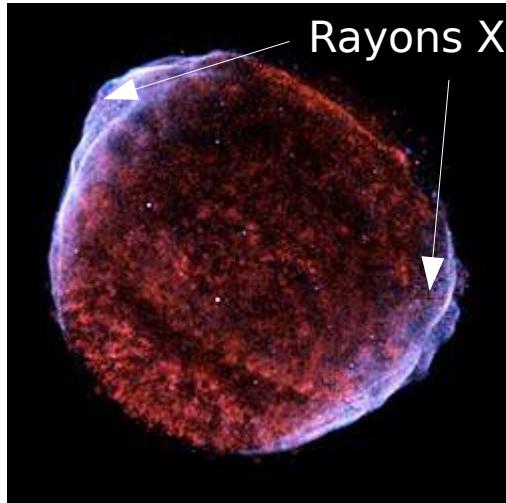
2018: "HESS Galactic Plane Survey" est sorti:

- première publication 2005 (14 sources) ... maintenant **78** sources



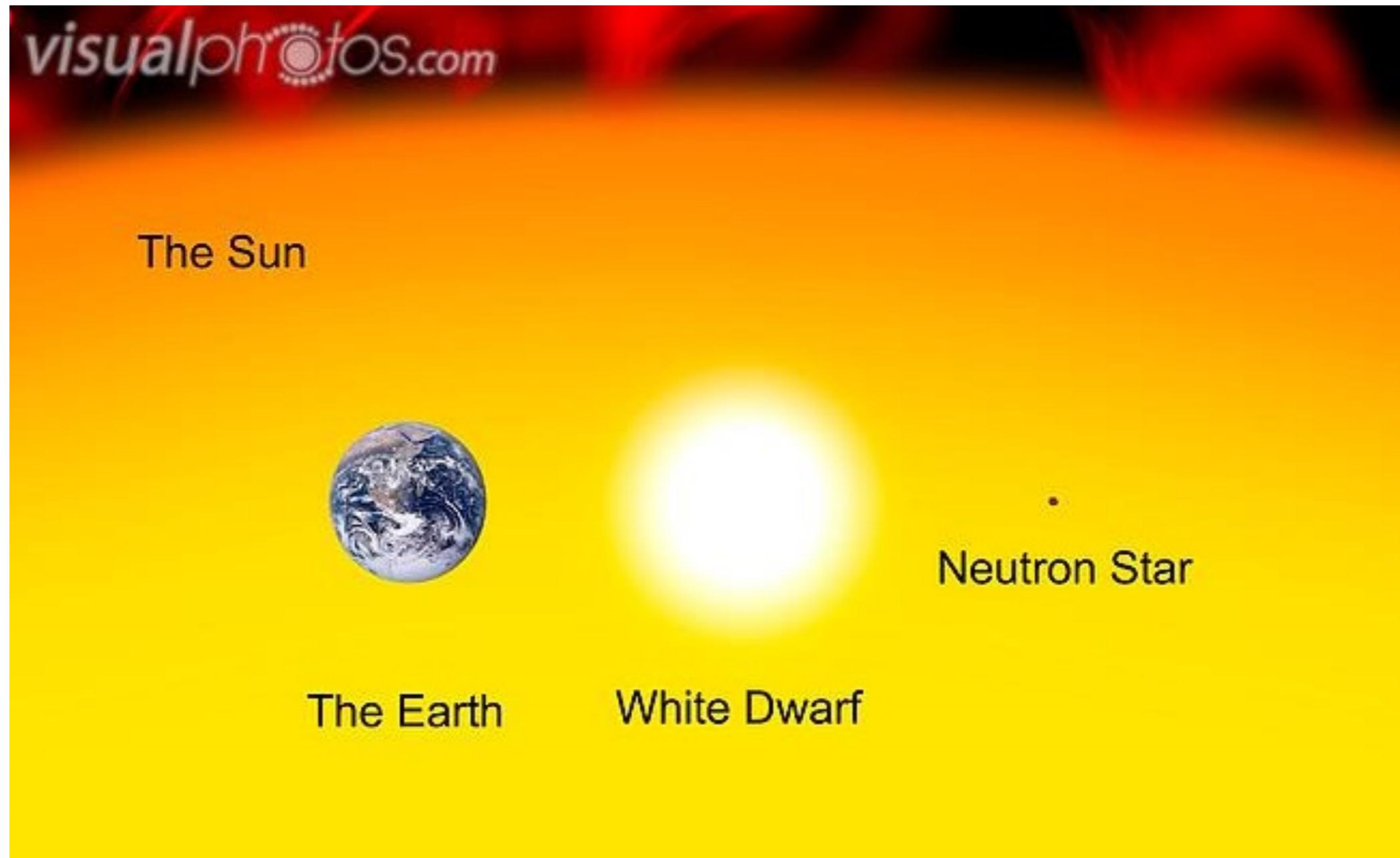
<https://www.mpi-hd.mpg.de/hfm/HESS/hgps/>

# Vestiges de supernova

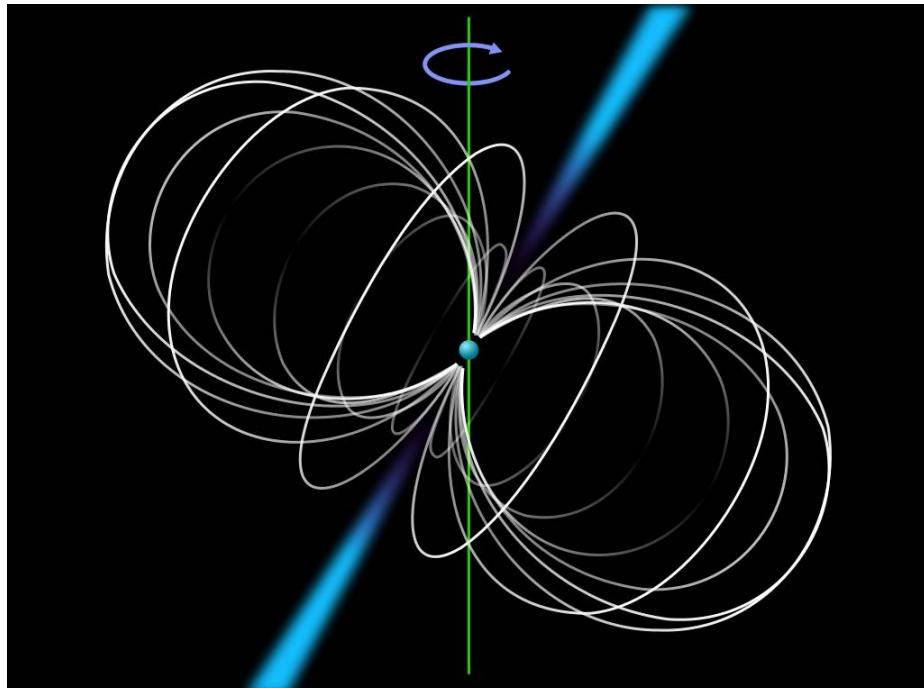


- Morphologie dépend du milieu environnant
- Acceleration de particules au niveau de l'onde de choc
- Permet de tester l'hypothèse de l'origine des rayons cosmiques

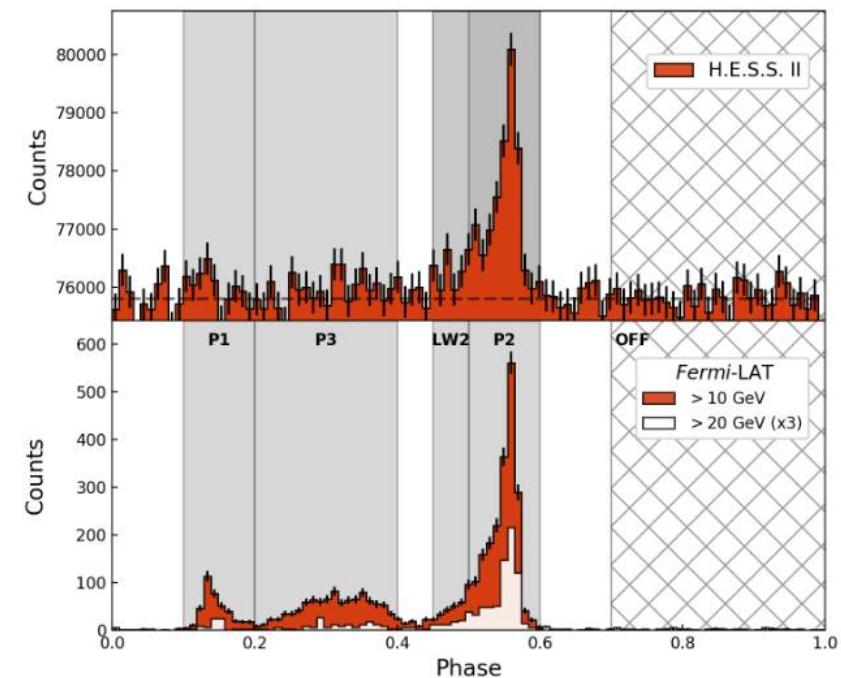
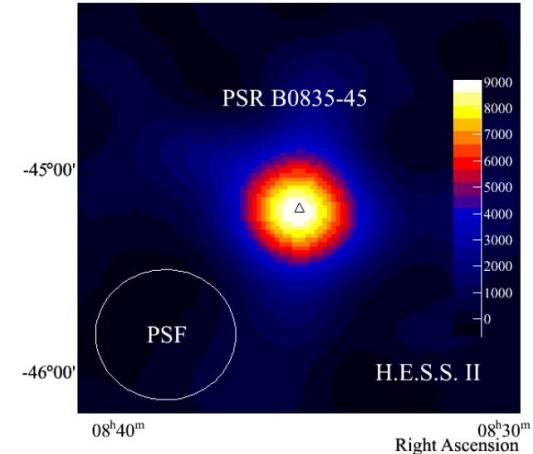
# Des étoiles à neutrons



# Les Pulsars

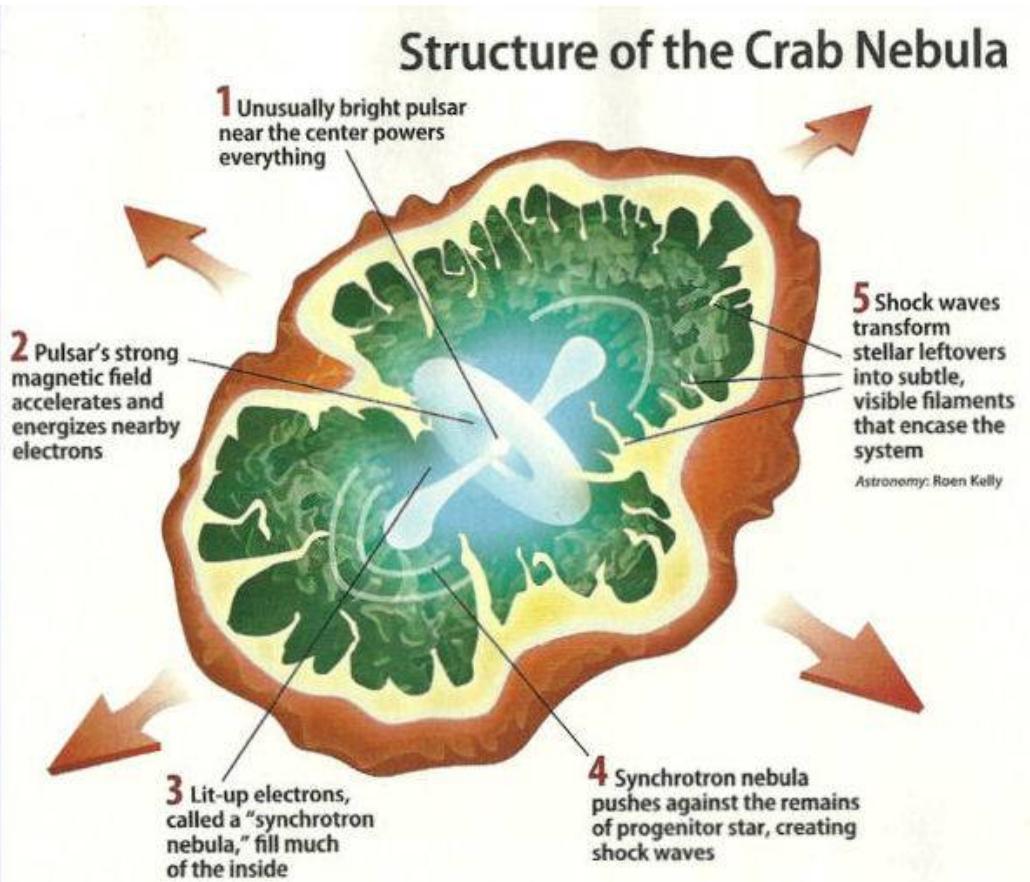
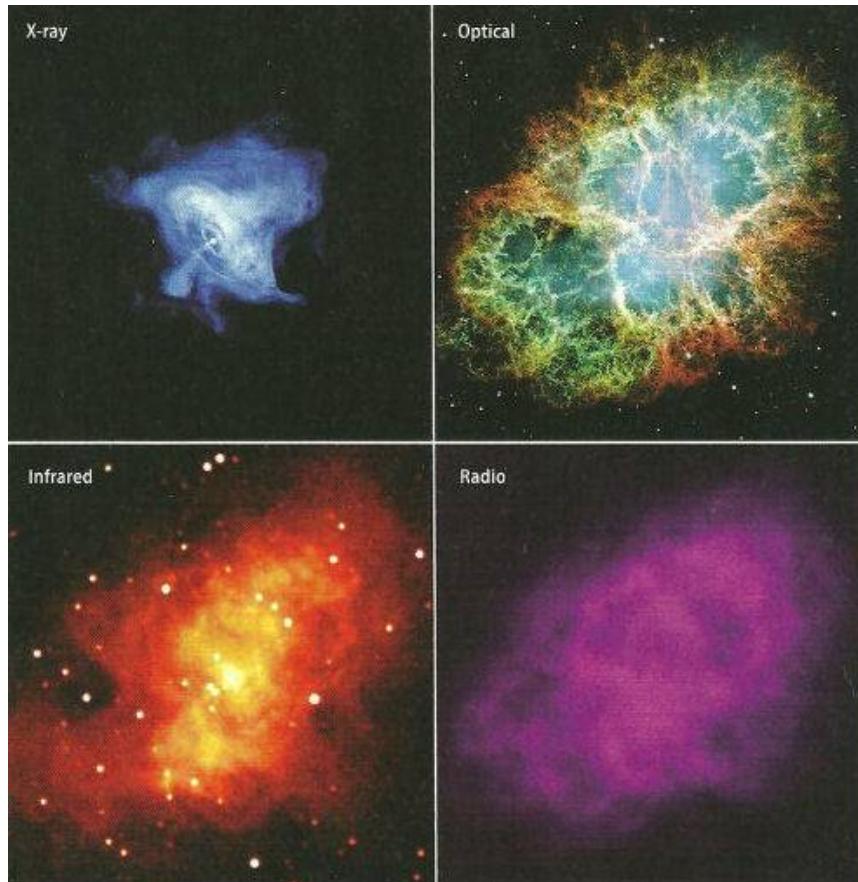


- Emission pulsée au TeV
- Physique proche du pulsar

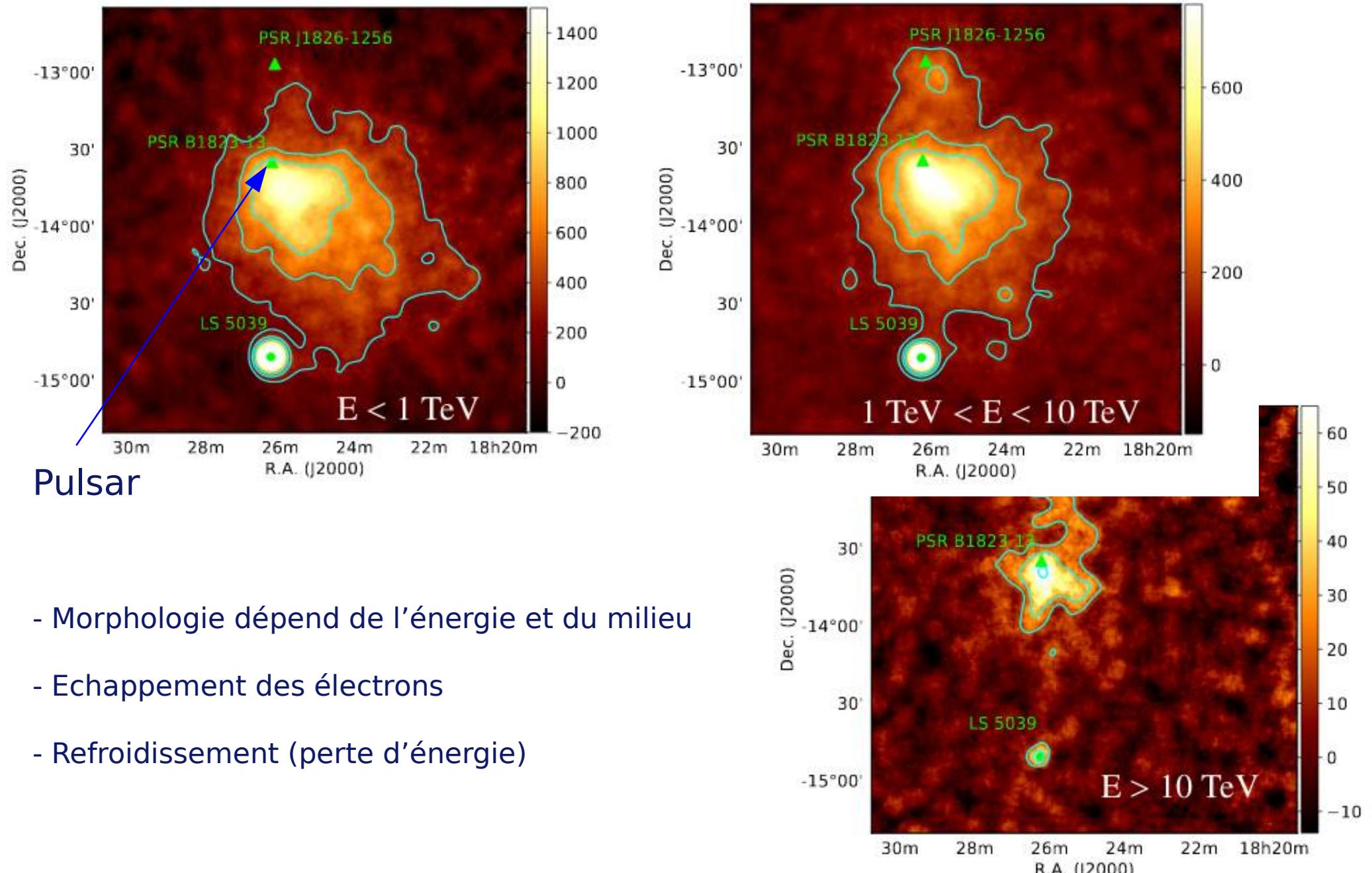


# Nébuleuse à vent de pulsar (PWN)

<https://universe-review.ca/F08-star14.htm>



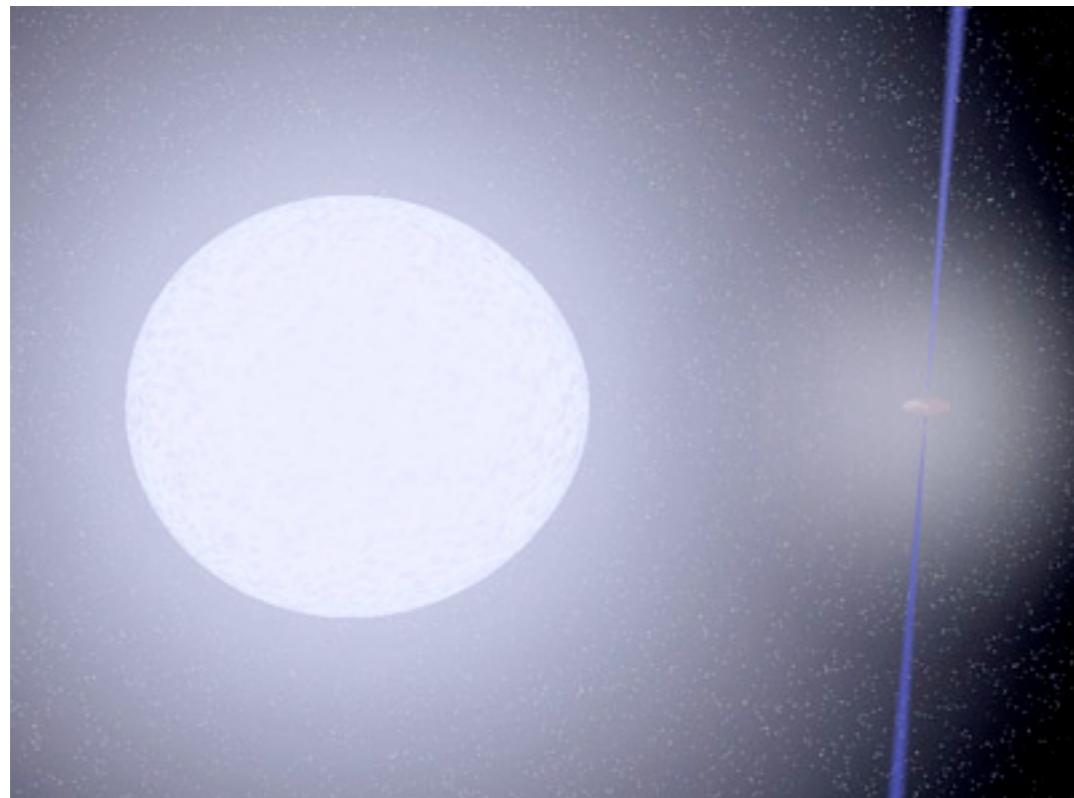
# Nébuleuse à vent de pulsar (PWN)



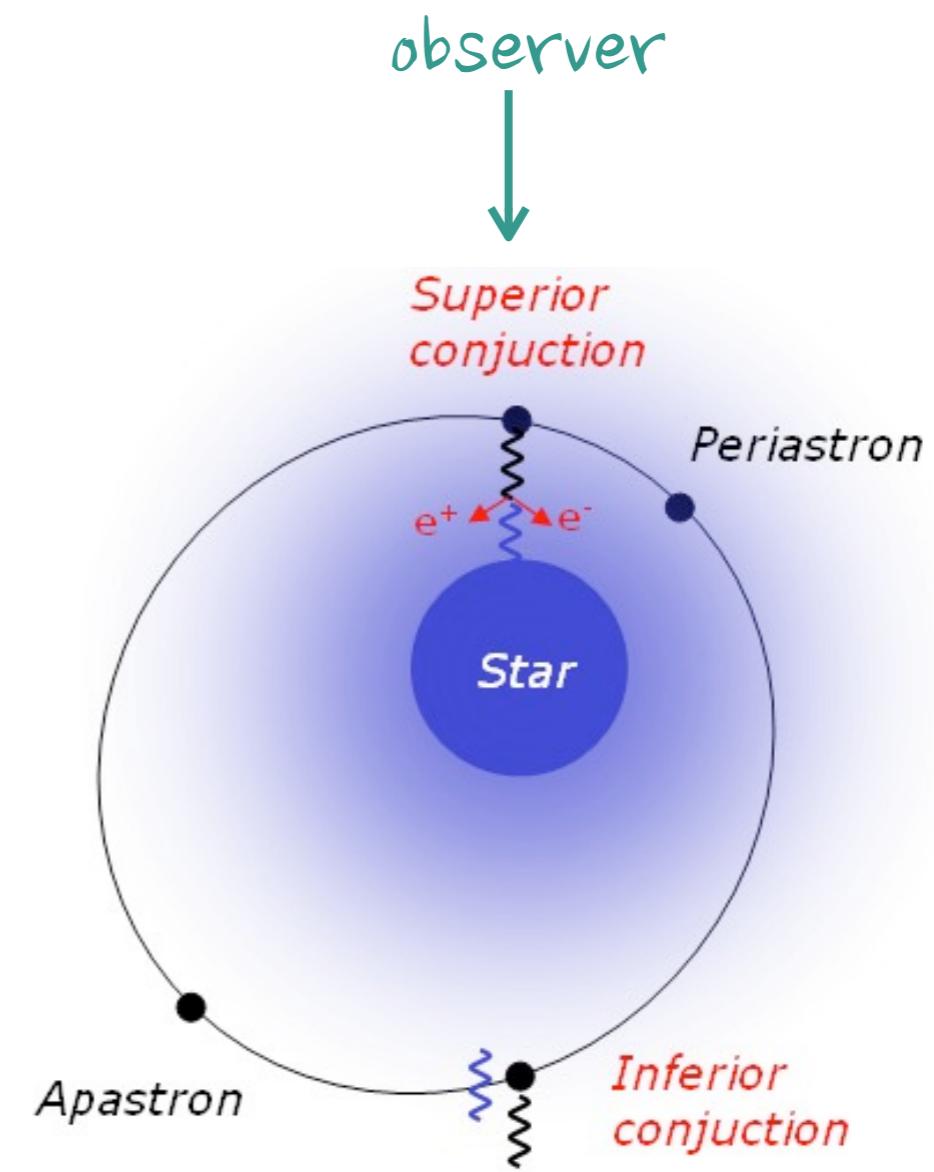
# Les binaires

LS 5039: the first gamma-ray binary detected - now there are 8 gamma-ray binaries

- orbital period  $3.902 \pm 0.005$  days
- consists of a compact object (pulsar?) orbiting a massive star
- gamma-ray emission is variable but cyclic



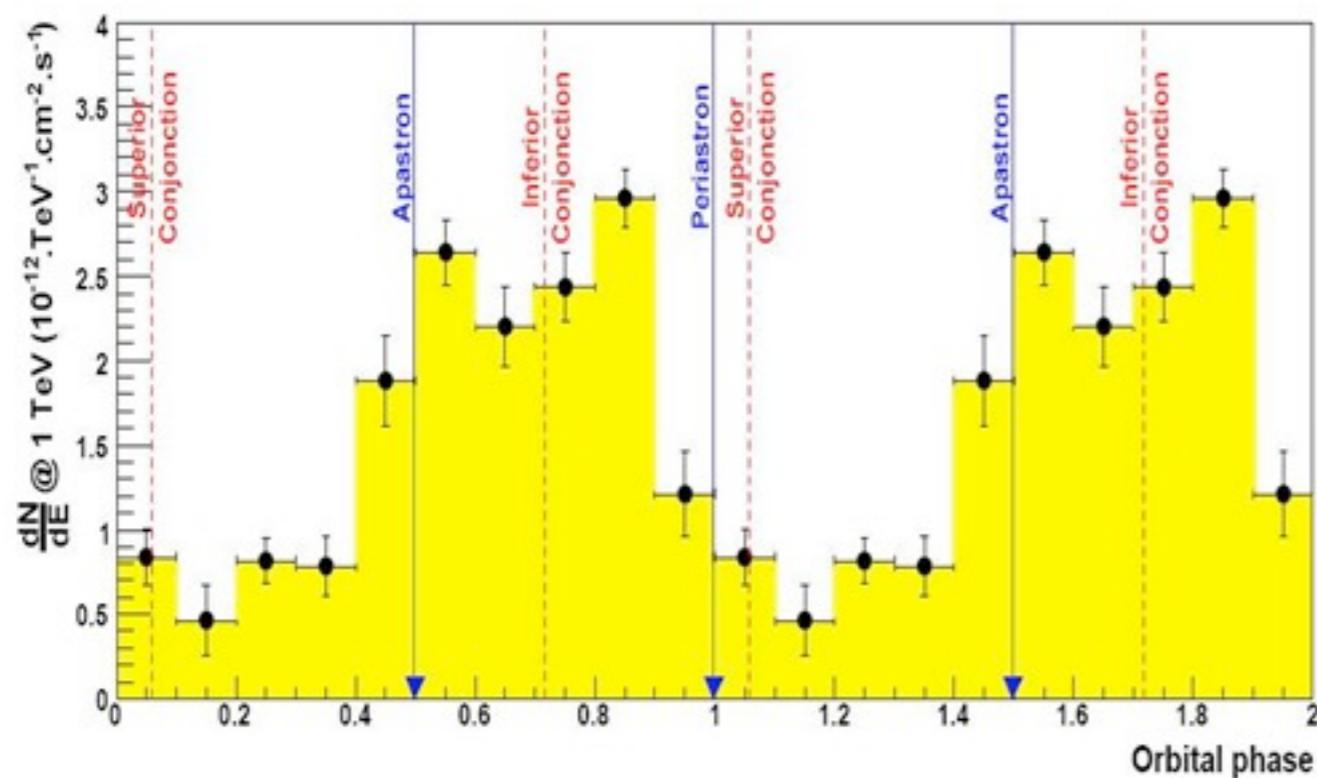
sometimes called microquasars



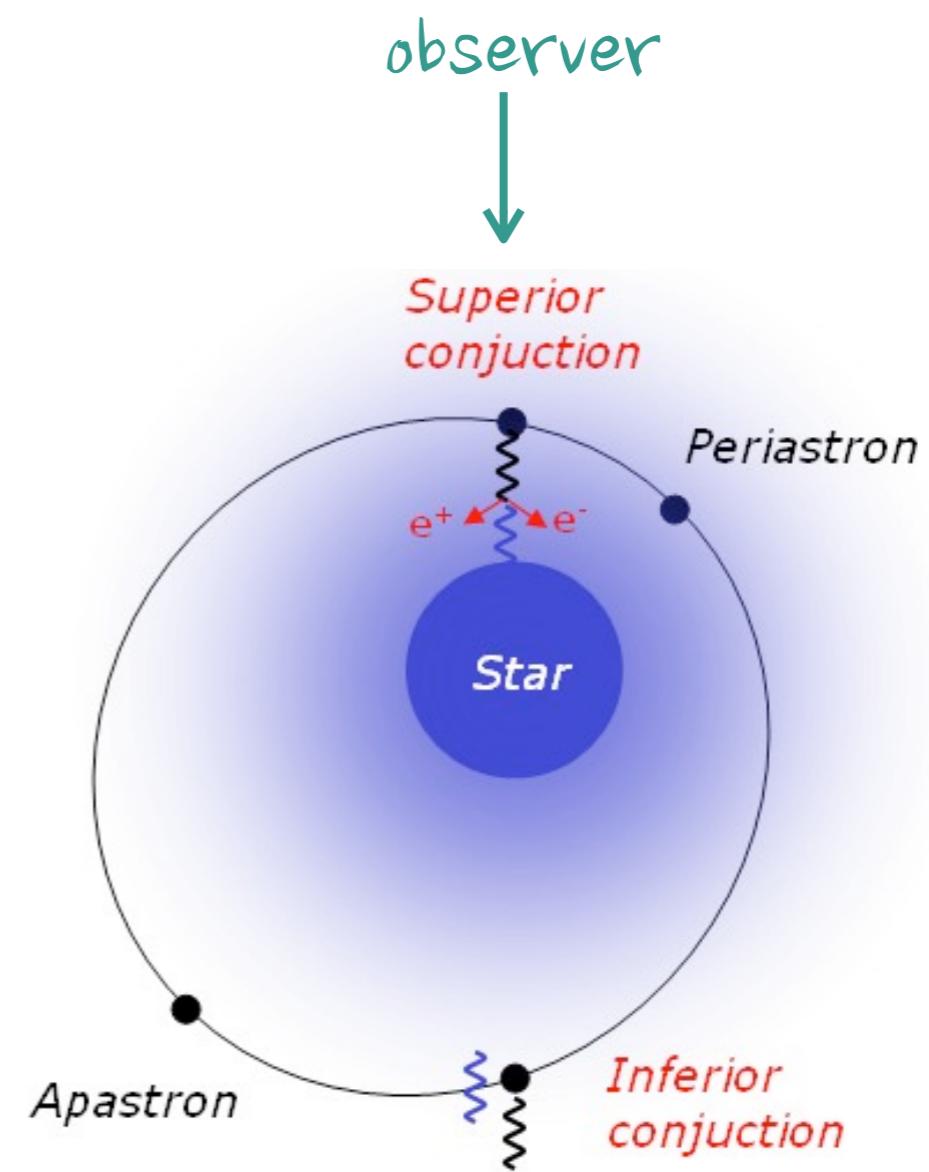
# Galactic Physics: Binary systems

LS 5039: the first gamma-ray binary detected - now there are 6 gamma-ray binaries

- orbital period  $3.902 \pm 0.005$  days
- consists of a compact object (pulsar?) orbiting a massive star
- gamma-ray emission is variable but cyclic



periodicity of signal established  
(2006)





THE ASTROPHYSICAL JOURNAL, 342: 379–395, 1989 July 1  
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## OBSERVATION OF TeV GAMMA RAYS FROM THE CRAB NEBULA USING THE ATMOSPHERIC CERENKOV IMAGING TECHNIQUE

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Received 1988 August 1; accepted 1988 December 9

### ABSTRACT

The Whipple Observatory 10 m reflector, operating as a 37 pixel camera, has been used to observe the Crab Nebula in TeV gamma rays. By selecting gamma-ray images based on their predicted properties, more than 98% of the background is rejected; a detection is reported at the  $9.0\sigma$  level, corresponding to a flux of  $1.8 \times 10^{-11}$  photons  $\text{cm}^2 \text{s}^{-1}$  above 0.7 TeV (with a factor of 1.5 uncertainty in both flux and energy). Less than 25% of the observed flux is pulsed at the period of PSR 0531. There is no evidence for variability on time scales from months to years. Although continuum emission from the pulsar cannot be ruled out, it seems more likely that the observed flux comes from the hard Compton synchrotron spectrum of the nebula.

*Subject headings:* gamma rays: general — nebulae: Crab Nebula — pulsars — radiation mechanisms

### I. INTRODUCTION

The observation of polarization in the radio, optical, and X-ray emission from the Crab Nebula is usually taken as confirmation of the synchrotron origin of the radiation and is a strong indication of the presence in the nebula of a reservoir of relativistic electrons with energies up to 1 TeV. The presence of the radio pulsar, PSR 0531, near the center of the nebula provides a source for the on-going injection of relativistic electrons into this reservoir. The collision of the synchrotron-radiating electrons with synchrotron-radiated photons within the nebula inevitably results in a hard photon spectrum (at some level) that extends from the X-ray into the gamma-ray energy range; the shape of the spectrum mirrors that of the soft photon spectrum but with greatly reduced intensity. The Compton synchrotron model of the nebula was first developed by Gould (1965) and was refined by Rieke and Weekes (1969) and by Grindlay and Hoffmann (1971). A strong flux of gamma rays was predicted with maximum luminosity in the 0.1–1.0 TeV energy range. The gamma-ray flux level depends on the strength of the nebular magnetic field, which is a free parameter in the model and is little constrained by observations at other wavelengths. However, based on equipartition arguments, it is estimated to be  $\sim 10^{-3}$  G.

The observation of a flux of 0.14 TeV gamma rays from the Crab Nebula was reported by the Smithsonian group using the atmospheric Cerenkov technique (Fazio *et al.* 1972); based on observations that spanned 3 years, this detection was still only at the  $3\sigma$  level. This demonstrates both the weakness of the source and the lack of sensitivity of the technique. The detection of TeV gamma rays from the Crab Nebula is a confirmation of the Compton synchrotron model and gives a direct measure of the magnetic field. This measurement, which was conservatively interpreted as an upper limit, implies an average magnetic field of  $3 \times 10^{-4}$  G, or a radially symmetric ( $1/r$ ) field with  $B_0 = 1 \times 10^{-3}$  G at a distance of 0.1 pc from the pulsar (Grindlay 1976).

<sup>1</sup> Harvard-Smithsonian Center for Astrophysics.

<sup>2</sup> St. Patrick's College, Maynooth.

<sup>3</sup> University College, Dublin.

<sup>4</sup> University of Leeds.

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Subsequent to the discovery of PSR 0531 in the nebula, TeV gamma-ray observations concentrated on the pulsar because greater sensitivity could be achieved by the assumption of synchronization of the gamma-ray emission with the periodic radio emission. Several detections were reported at very high energies (Grindlay 1972; Jennings *et al.* 1974; Grindlay, Helmken, and Weekes 1976; Porter *et al.* 1976; Erickson, Fickle, and Lamb 1976; Vishwanath 1982; Vishwanath *et al.* 1985; Gupta *et al.* 1977; Gibson *et al.* 1982b; Dowthwaite *et al.* 1984; Turner *et al.* 1985; Bhat *et al.* 1986), but the statistical significance was not high, and upper limits were also presented which appeared to be in conflict with the reported fluxes (Helmken *et al.* 1973; Vishwanath *et al.* 1986; Bhat *et al.* 1987). At energies above 1 TeV there were also reports of emission from the direction of the Crab (Mukanov 1983; Boone *et al.* 1984; Dzikowski *et al.* 1981; Kirov *et al.* 1985), but, because of the limited angular resolution and the absence of accurate timekeeping, it was not possible to identify the source of the observed signal with the nebula or the pulsar. Again there may be conflicting upper limits (Craig *et al.* 1981; Watson 1985). At 100 MeV energies (which are accessible to study by spark chambers on satellites), both a pulsed and steady component were detected (Kniffen *et al.* 1977; Hermsen *et al.* 1977; Clear *et al.* 1987); at 1 GeV the strength of the unpulsed component (which might originate in the nebula or near the pulsar) is 0.25 times that of the pulsed flux.

Using a refined version of the atmospheric Cerenkov technique, we here report the detection of gamma rays above 0.7 TeV from the Crab Nebula at a high level of statistical significance; over the epoch 1986–1988 we find no evidence for variability, and the observed flux is in agreement with that reported previously in 1969–1972 and in an earlier observation utilizing this same technique in 1983–5 (Cawley *et al.* 1985a; Gibbs 1987). The observed gamma-ray flux is only 0.2% of the cosmic-ray background. A periodic analysis using the known radio period of the pulsar indicates that less than 25% of the observed signal is pulsed. The detection of such a weak flux from a steady (nonpulsed) source with a significance of 9 standard deviations ( $\sigma$ ) is a milestone in the development of ground-based gamma-ray astronomy. It demonstrates the power of using atmospheric Cerenkov shower imaging to distinguish gamma-ray-initiated air showers from those gener-



## Observations of the Crab nebula with HESS

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### ABSTRACT

**Context.** The Crab nebula was observed with the HESS stereoscopic Cherenkov-telescope array between October 2003 and January 2005 for a total of 22.9 h (after data quality selection). This period of time partly overlapped with the commissioning phase of the experiment; observations were made with three operational telescopes in late 2003 and with the complete 4 telescope array in January–February 2004 and October 2004–January 2005.

**Aims.** Observations of the Crab nebula are discussed and used as an example to detail the flux and spectral analysis procedures of HESS. The results are used to evaluate the systematic uncertainties in HESS flux measurements.

**Methods.** The Crab nebula data are analysed using standard HESS analysis procedures, which are described in detail. The flux and spectrum of  $\gamma$ -rays from the source are calculated on run-by-run and monthly time-scales, and a correction is applied for long-term variations in the detector sensitivity. Comparisons of the measured flux and spectrum over the observation period, along with the results from a number of different analysis procedures are used to estimate systematic uncertainties in the measurements.

**Results.** The data, taken at a range of zenith angles between 45° and 65°, show a clear signal with over 7500 excess events. The energy spectrum is found to follow a power law with an exponential cutoff, with photon index  $\Gamma = 2.39 \pm 0.03_{\text{stat}}$  and cutoff energy  $E_c = (14.3 \pm 2.1_{\text{stat}}) \text{ TeV}$  between 440 GeV and 40 TeV. The observed integral flux above 1 TeV is  $(2.26 \pm 0.08_{\text{stat}}) \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$ . The estimated systematic error on the flux measurement is estimated to be 20%, while the estimated systematic error on the spectral slope is 0.1.

**Key words.** gamma rays: observations – ISM: individual objects: Crab nebula – ISM: supernova remnants

### 1. Introduction

The Crab supernova remnant (SNR) is an exceptionally well studied object, with extensive observations of the system existing across the entire accessible spectrum. At a distance of 2000 parsecs, with an age of 950 years, it is a prototypical centre-filled SNR, or plerion, as defined by Weiler & Panagia (1980). Within the supernova remnant lies the Crab pulsar, with a rotational period of 33 ms and a spin-down luminosity of  $L = 5 \times 10^{38} \text{ erg s}^{-1}$ . This energy source powers a surrounding synchrotron nebula, and polarization measurements exist from radio to hard X-ray wavelengths (Wilson 1972), indicating the non-thermal origin of the radiation detected. The total energy available from the pulsar to power the system is of the order

of  $10^{49} \text{ erg}$ . This is believed to be the power source for production of very high energy (VHE)  $\gamma$ -rays.

The rotational energy of the pulsar is thought to be mostly carried away by a relativistic wind of electrons and positrons. Interaction of this wind with the surrounding medium causes a standing termination shock wave (Rees & Gunn 1974; Kennel & Coroniti 1984). Electron acceleration may be due to a Fermi-type process (Achterberg et al. 2001) or to driven reconnection of the alternating magnetic field at this termination shock (Coroniti 1990; Michel 1994). The interaction of accelerated electrons with ambient photon fields (in this case mostly synchrotron photons) can produce VHE  $\gamma$ -rays via the inverse Compton process.

The Crab nebula was discovered at VHE energies in 1989 (Weekes et al. 1989) and emission has been confirmed by a



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Merci beaucoup  
de  
votre attention

# Astroparticle / Exotic Physics - Dark Matter Searches

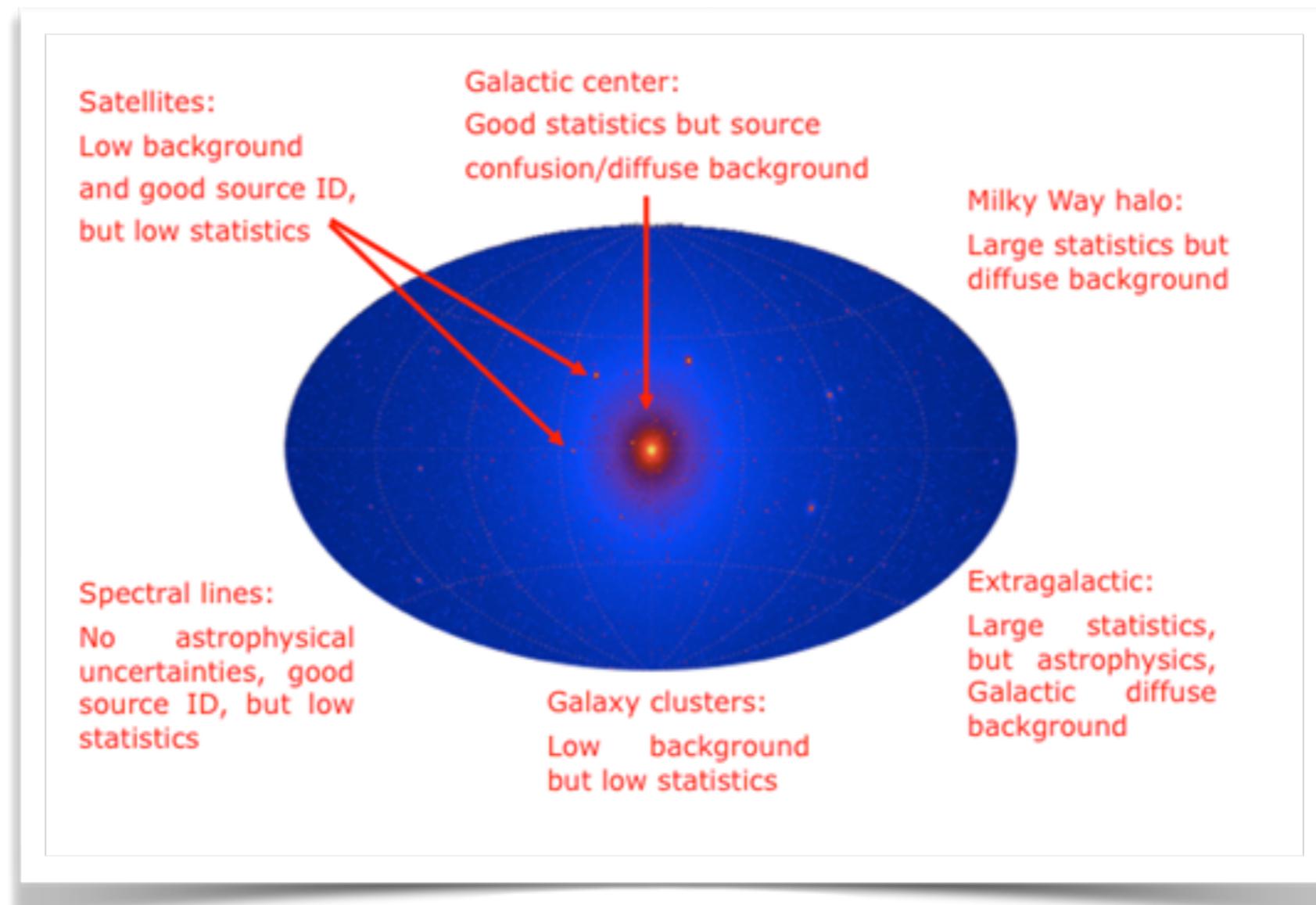
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# Astroparticle / Exotic Physics - Dark Matter Searches

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- We know that there was a large amount of dark matter in the early universe
- \* We see it in the BAO - it comprises ~27% of the total energy budget of the universe
- We see it astrophysically today e.g. galaxy rotation curves
  - We know that there has to be some particle associated with it and that that particle must be stable enough to have survived since the early universe
    - i.e. it doesn't interact (much) with normal matter
  - ♦ One possibility is the WIMP - it is its own antiparticle (only interacts weakly)
  - ★ When this annihilates with itself, it produces gamma rays
- It clusters in dense astrophysical environments

# Astroparticle / Exotic Physics - Dark Matter Searches



[HTTP://KIPAC-WEB.STANFORD.EDU/RESEARCH/FGST](http://KIPAC-WEB.STANFORD.EDU/RESEARCH/FGST)

# Astroparticle / Exotic Physics - Lorentz Invariance

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# Astroparticle / Exotic Physics - Lorentz Invariance

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- The assumption of Lorentz Invariance is one of the **founding principles** of Modern physics
- Certain theories that attempt to provide a unified model of quantum gravity predict that the vacuum could have an **effective refractive index**
- Thus photons with **different energies** would travel at **different velocities** becoming more pronounced as we approach the Planck Energy ( $10^{19}$  GeV)

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To search for the signature of **Lorentz Invariance Violation**, our test sources should have the following properties:

- emit at the highest energies (effect of vacuum dispersion more pronounced)
- lie at a very large distance from us (time delay will be larger)
- exhibit rapid variability (or only emit over a very short time period) so that we “know” (assume) photons were all emitted at the same time

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Constraints so far have come from the **NON** detection of differences in the arrival times of photons from distant gamma-ray bursts

# Astroparticle / Exotic Physics - Lorentz Invariance

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Next-generation TeV instruments, such as the  
Cherenkov Telescope Array (CTA)

will enable us to observe many sources and source classes  
as a function of redshift with high statistics so that we can  
disentangle the effects of  
dispersion internal to a paritcular source or source class  
and  
dispersion due to vacuum birefringence