

# Astroparticules et neutrinos

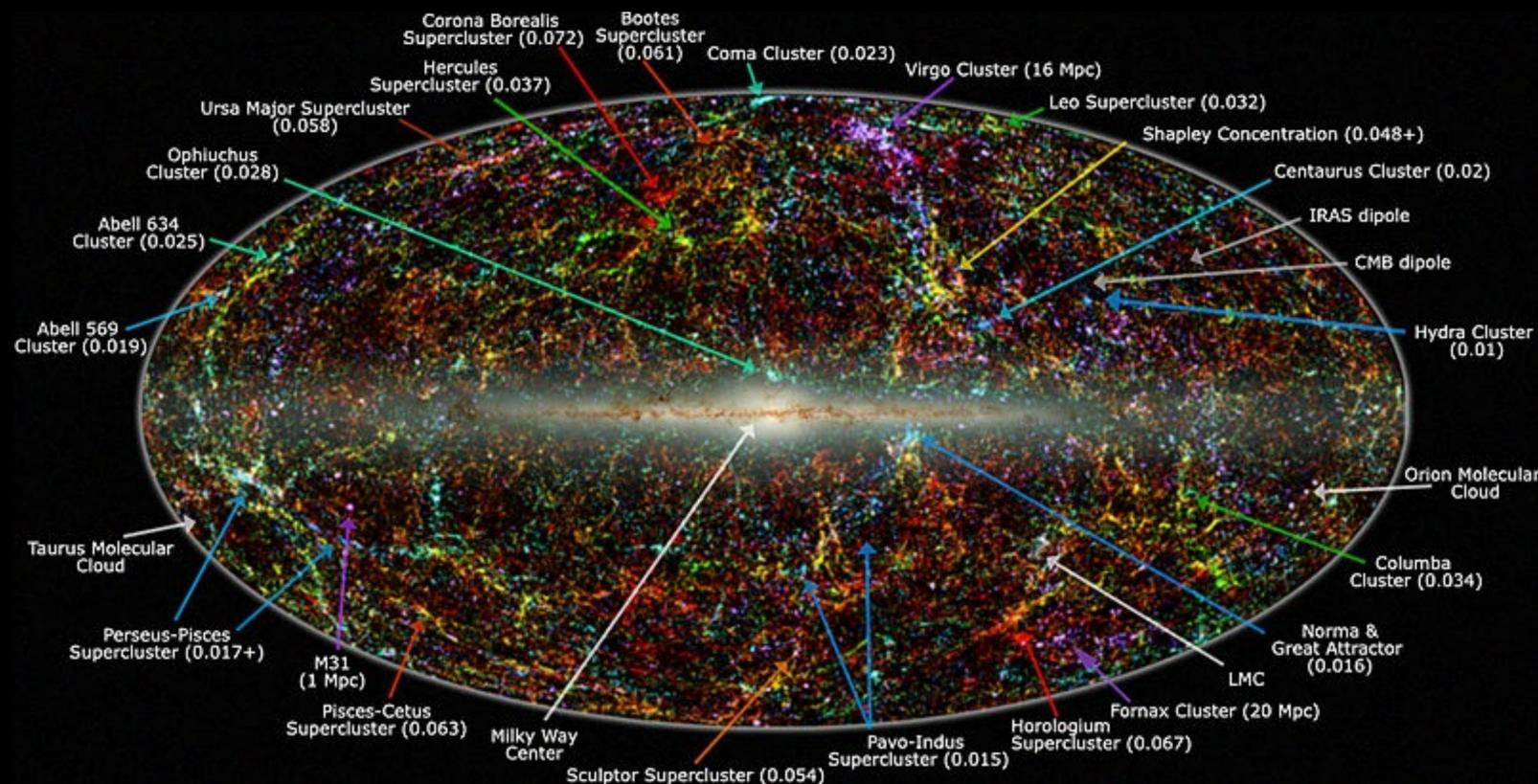
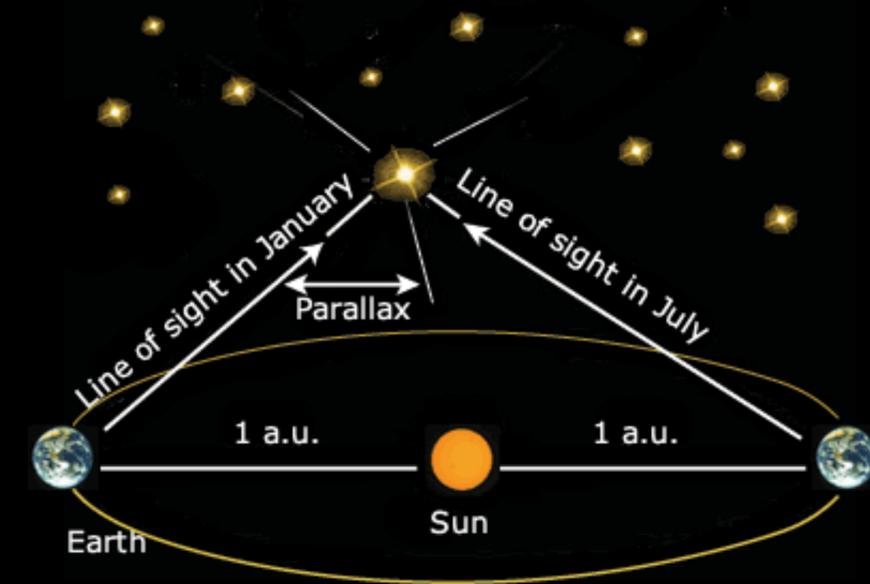
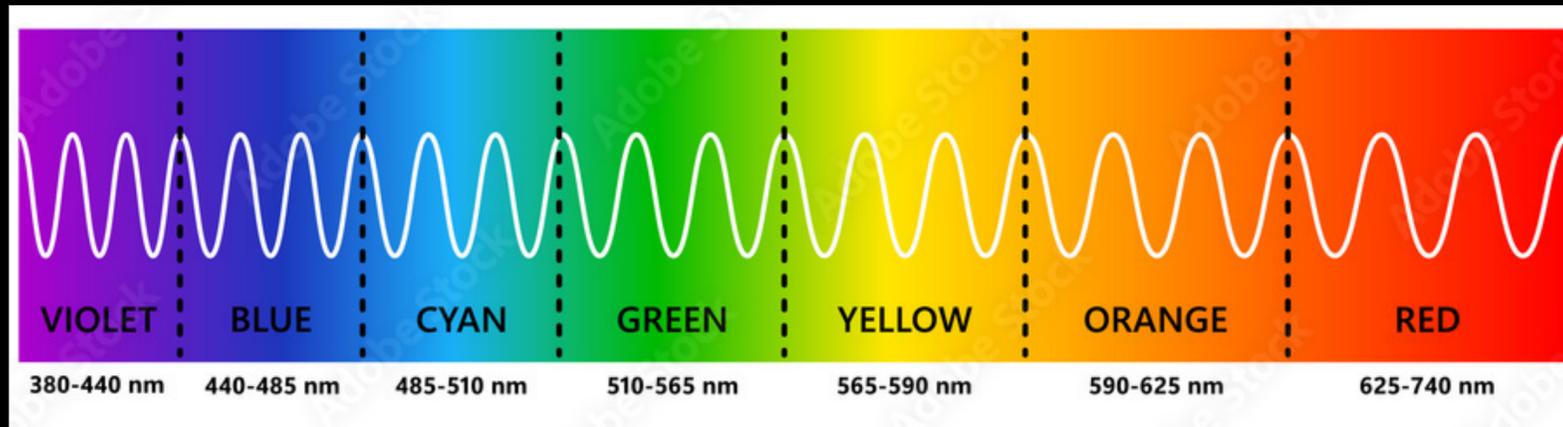
Les messagers du cosmos

Sonia El Hedri — Ecole "De la physique au détecteur" — 26/11/2024



# Observer le cosmos — Lumière visible

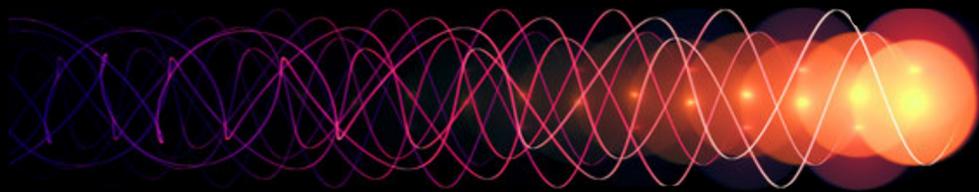
## Cartographeur l'Univers



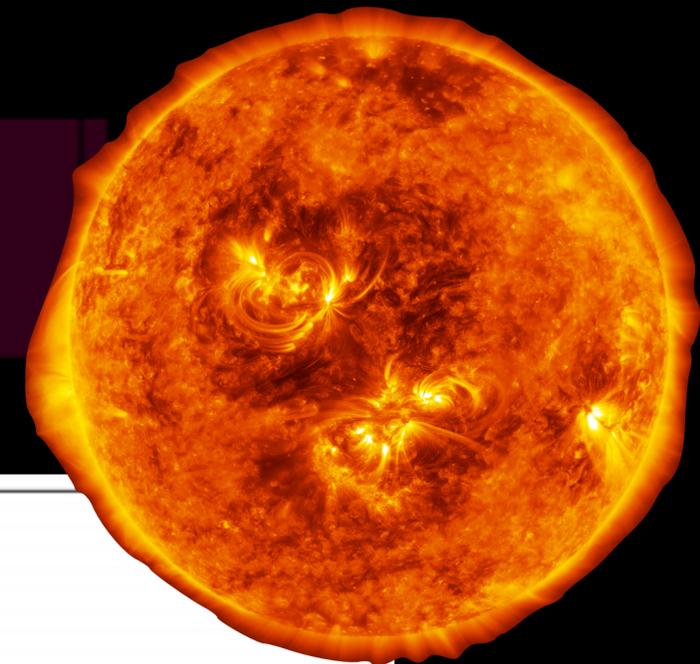
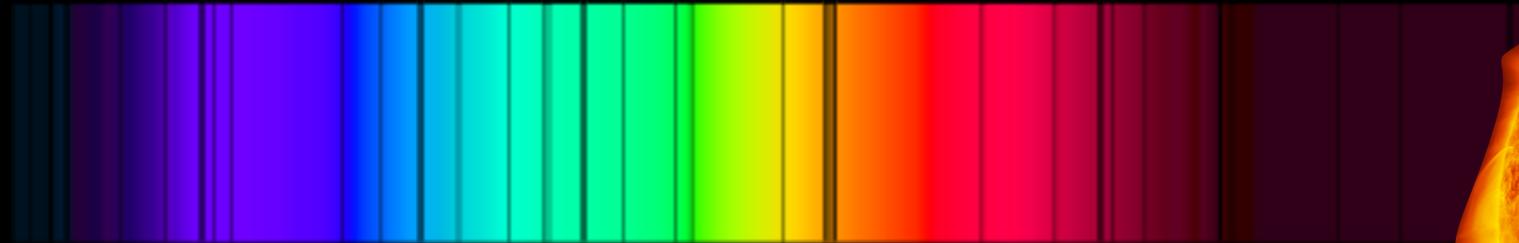
- **Positions et distances des étoiles:** parallaxe, chandelles standard, décalage vers le rouge

# Observer le cosmos — Lumière visible

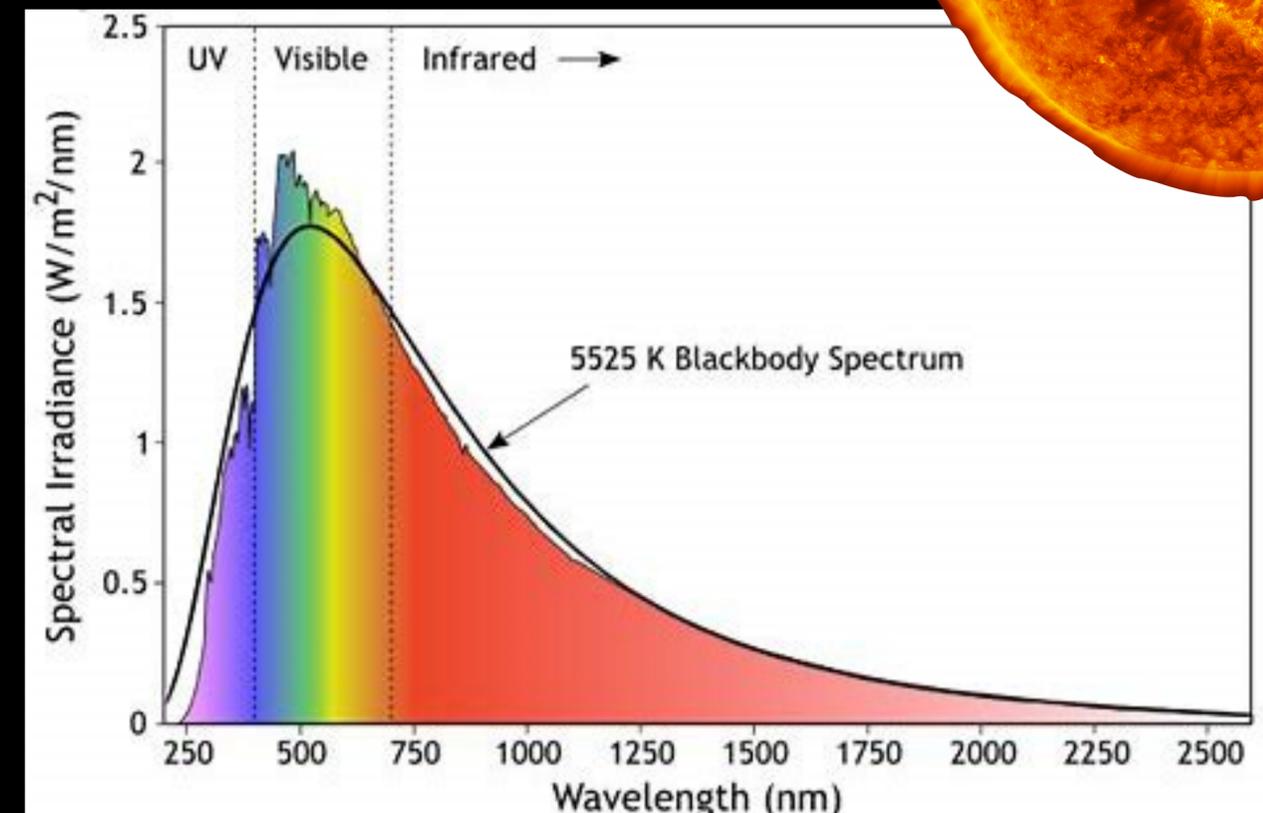
## Mécanique quantique: température et composition chimique



Fréquence  $\leftrightarrow$  Energie

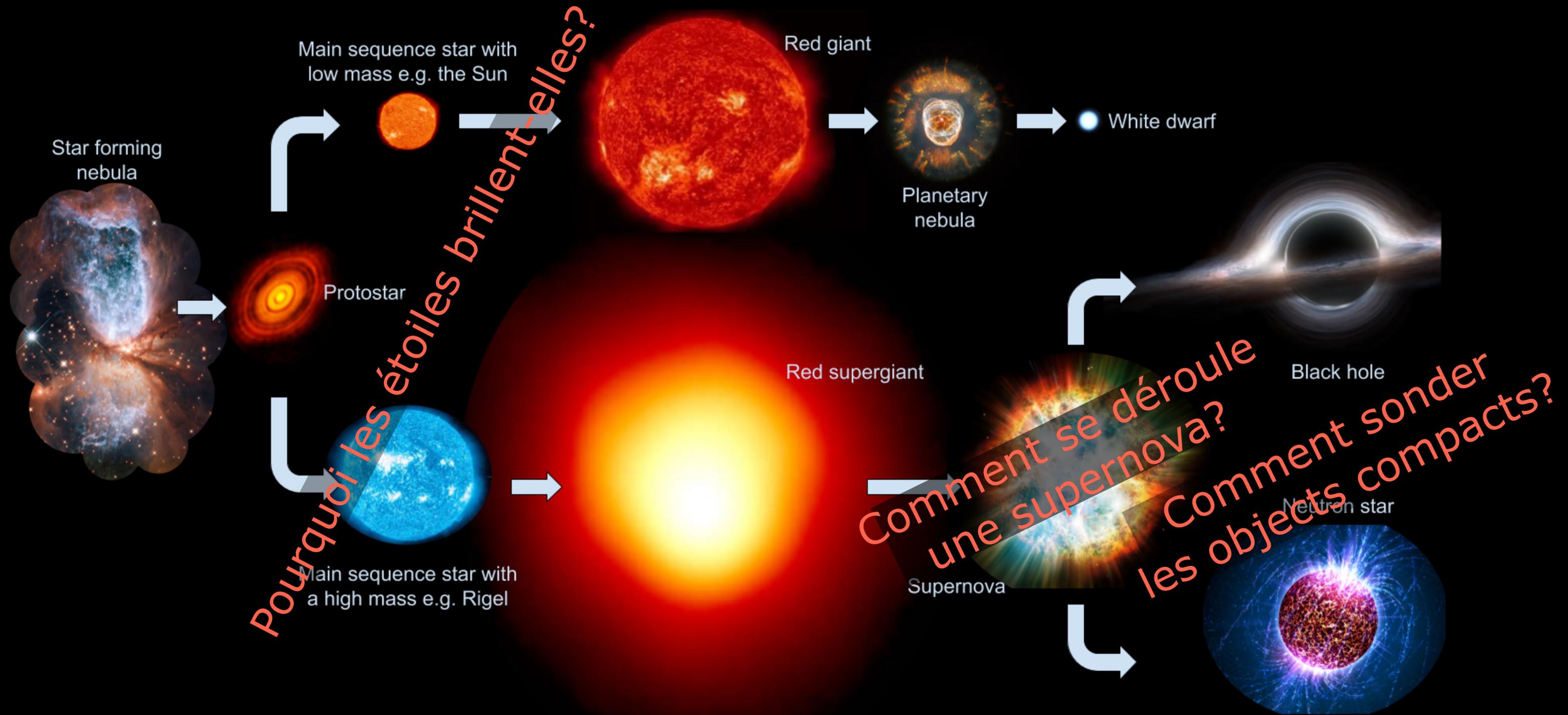


- Description particulière de la lumière: introduction du **photon**
- Spectres lumineux des objets  $\rightarrow$  température et composition chimique



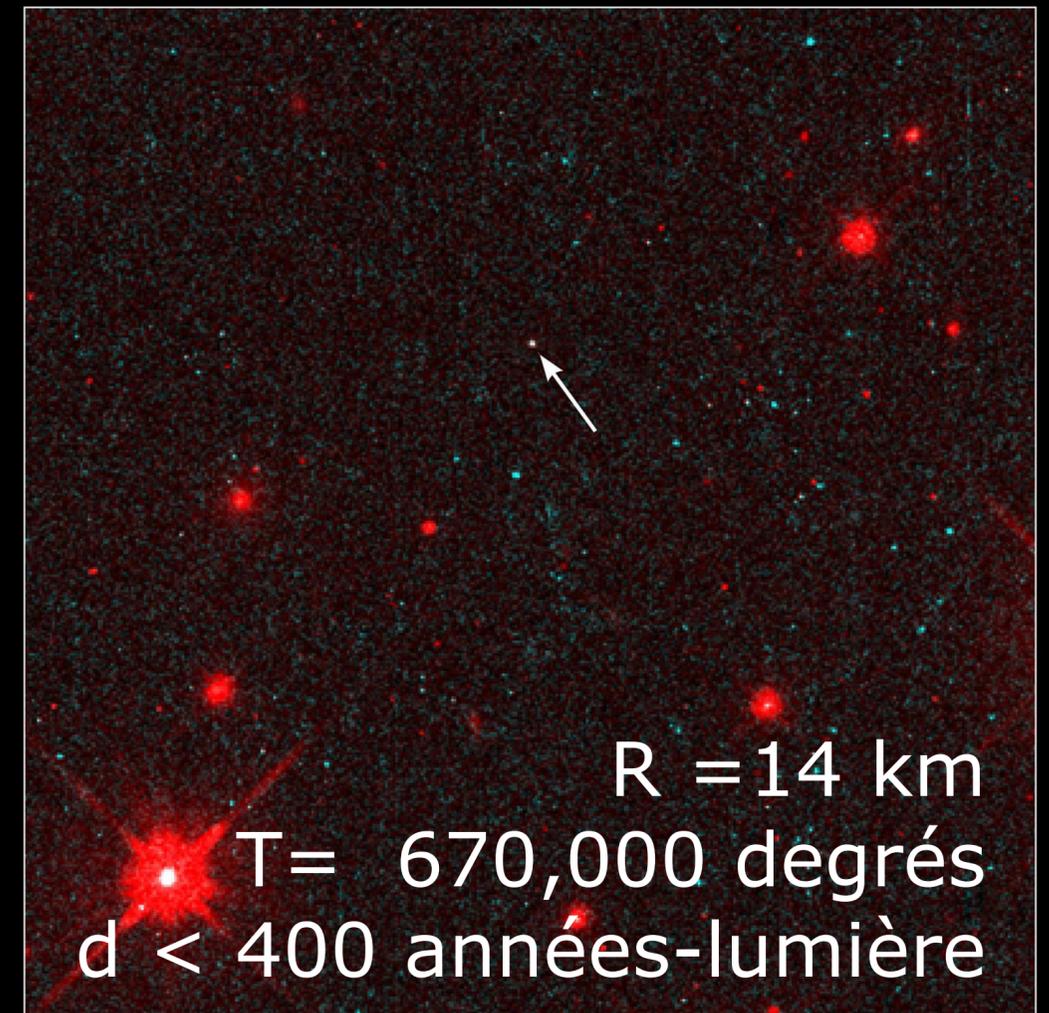
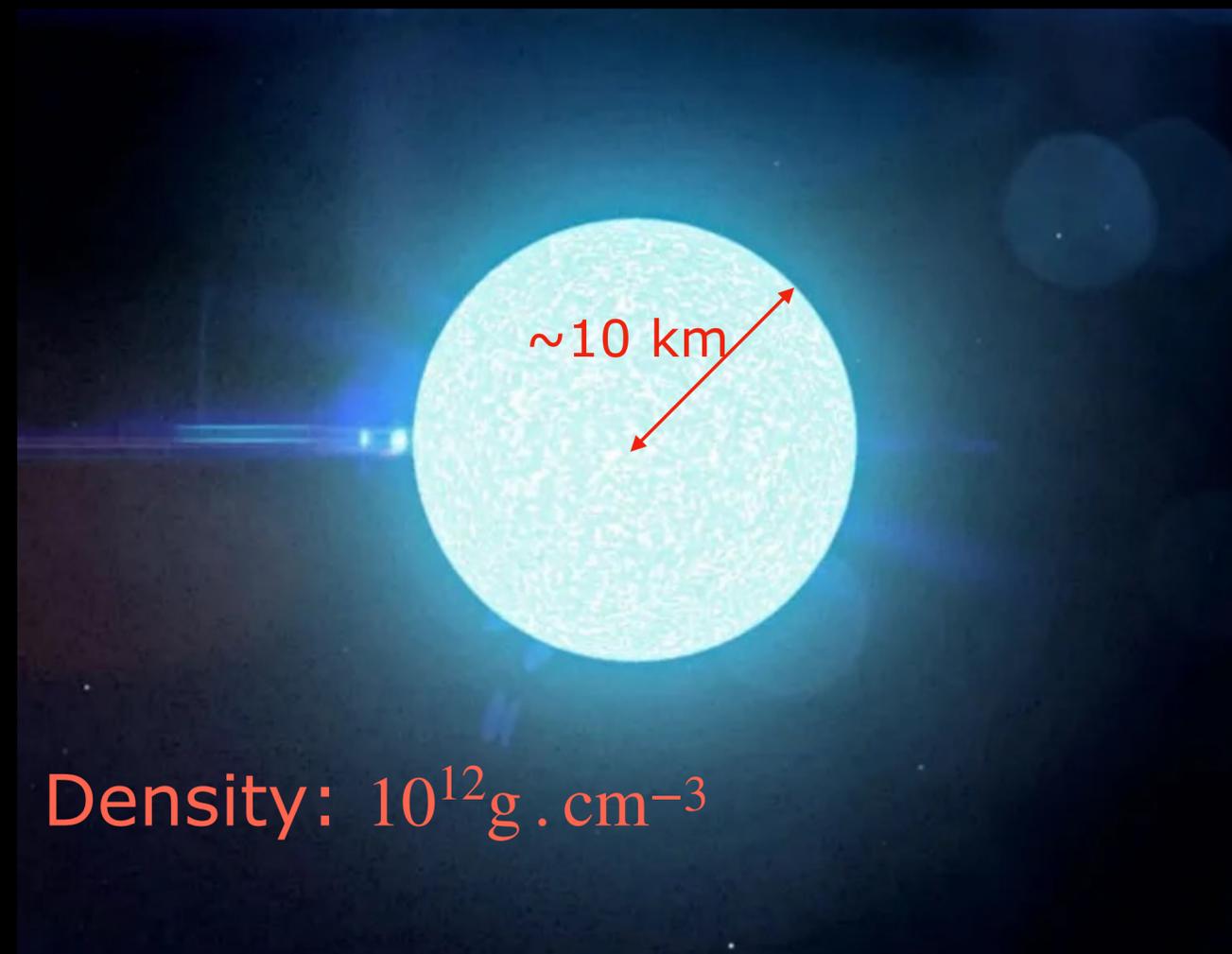
# Des questions en suspens...

## Vie et mort des étoiles



# Les objets compacts — Étoiles à neutrons

## Coeur effondré d'une étoile lourde



Isolated Neutron Star RX J185635-3754  
Hubble Space Telescope • WFPC2

PRC97-32 • ST ScI OPO • September 24, 1997  
F. Walter (State University of New York at Stony Brook) and NASA

- 1-2 solar masses: nucléons agglomérés
- Nouveaux états de la matière. Pulsars: champs magnétiques de  $10^4 - 10^{11} \text{ T}$

# Les objets compacts — Trous noirs

## Résidu de l'effondrement complet d'une étoile

Rayon de Schwartzchild  
(horizon):

$$R_s = 2 \frac{GM_{\text{BH}}}{c^2}$$

1 masse solaire  $\rightarrow R_s = 3$  km



1992

10 light days

Centre de la Voie lactée  
Sagittarius A\*

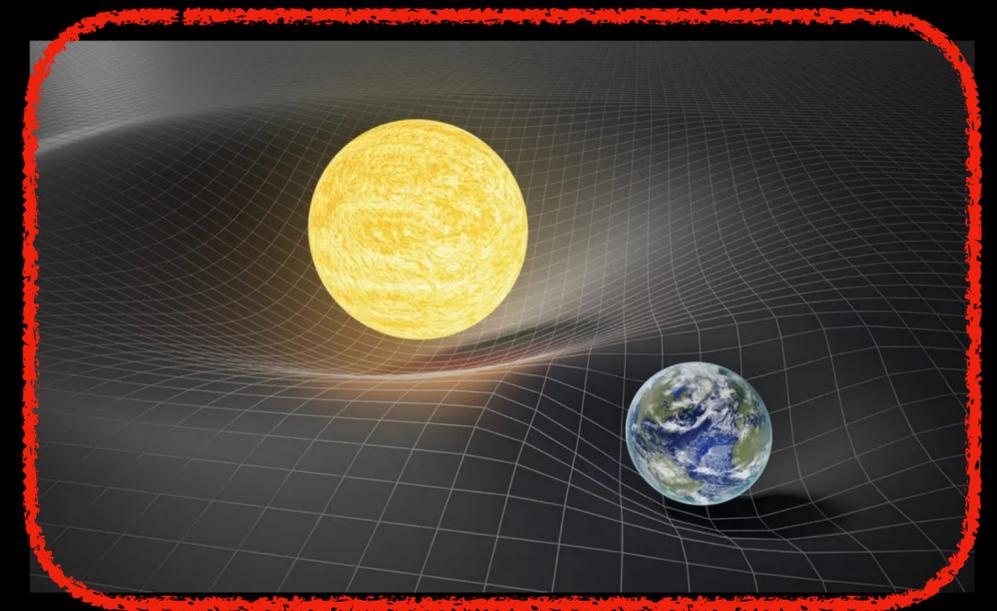
4.3M masses solaires

- Lumière piégée gravitationnellement  $\rightarrow$  objets cachés derrière un horizon
- Jusqu'à 100 milliards de masses solaires! Pourquoi une telle variation?

# Comment aller plus loin?

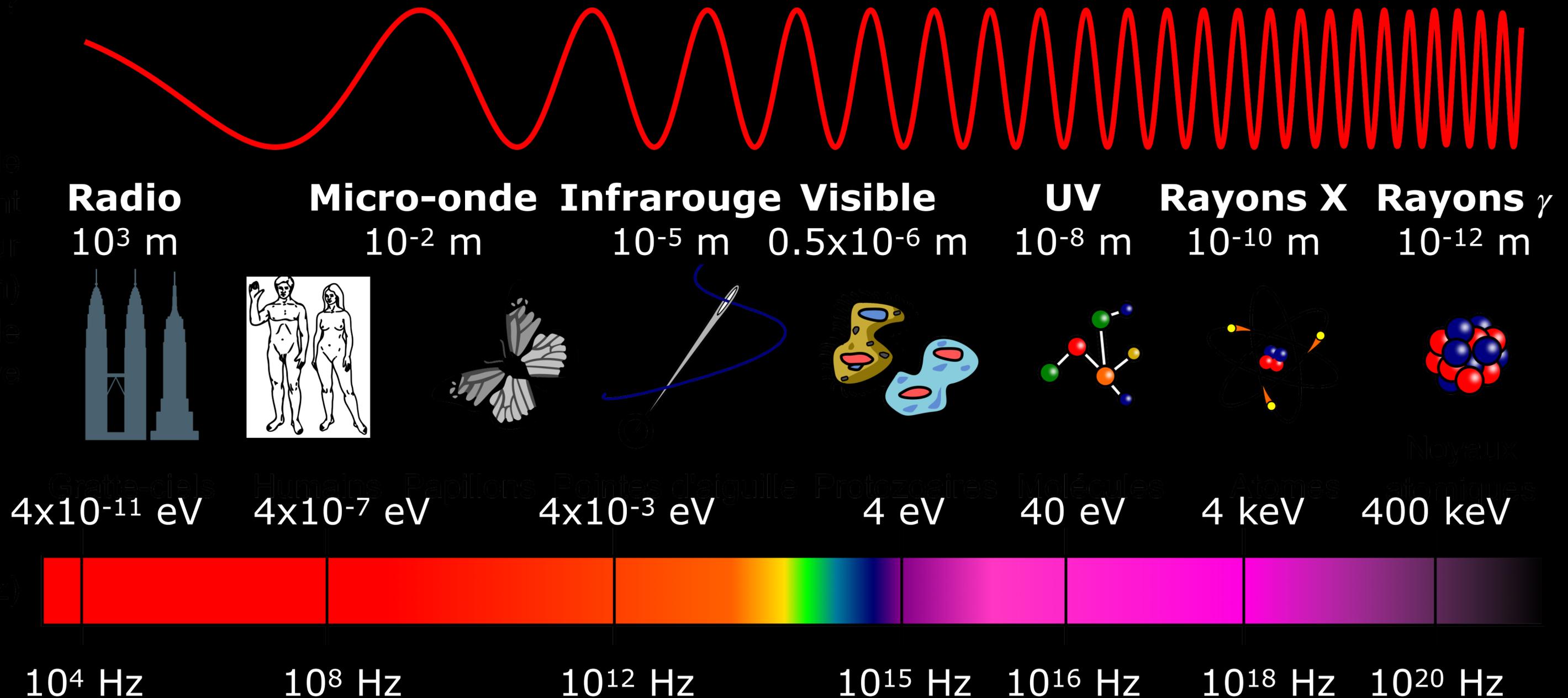
Utiliser les particules stables...et la gravité

	QUARKS			SCALAR BOSONS
mass	=2.2 MeV/c <sup>2</sup>	=1.28 GeV/c <sup>2</sup>	=173.1 GeV/c <sup>2</sup>	=124.97 GeV/c <sup>2</sup>
charg	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
sp	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon
	=4.7 MeV/c <sup>2</sup>	=96 MeV/c <sup>2</sup>	=4.18 GeV/c <sup>2</sup>	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>γ</b> photon
	=0.511 MeV/c <sup>2</sup>	=105.66 MeV/c <sup>2</sup>	=1.7768 GeV/c <sup>2</sup>	=91.19 GeV/c <sup>2</sup>
	-1	-1	-1	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>Z</b> Z boson
	<2.2 eV/c <sup>2</sup>	<0.17 MeV/c <sup>2</sup>	<18.2 MeV/c <sup>2</sup>	=80.39 GeV/c <sup>2</sup>
	0	0	0	±1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>W</b> W boson

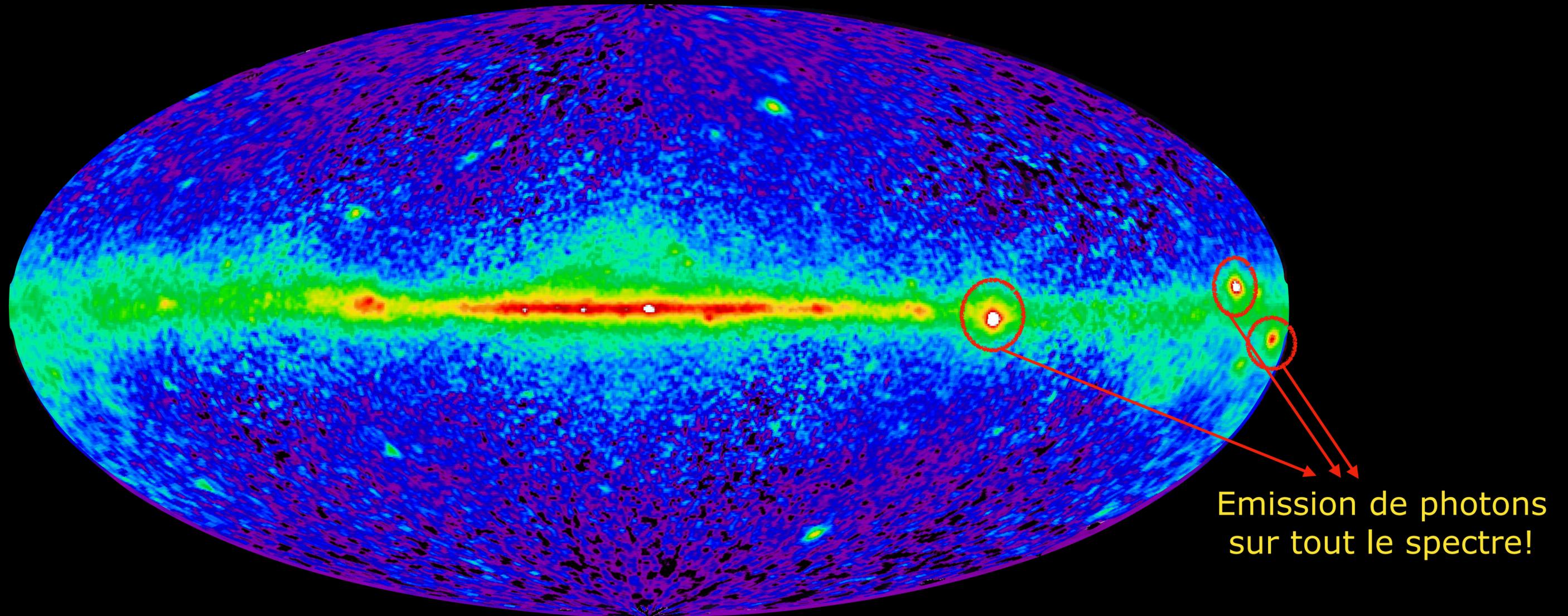
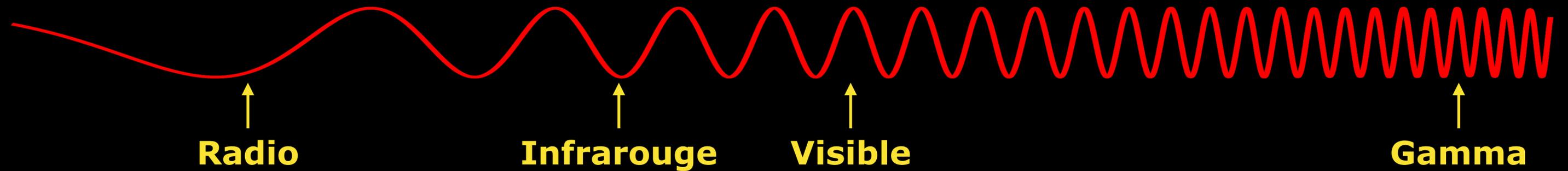


# Comment aller plus loin?

## Exploiter les longueurs d'ondes au-delà du visible



# La Voie Lactée en multi-longueurs d'ondes



# Astroparticules et neutrinos

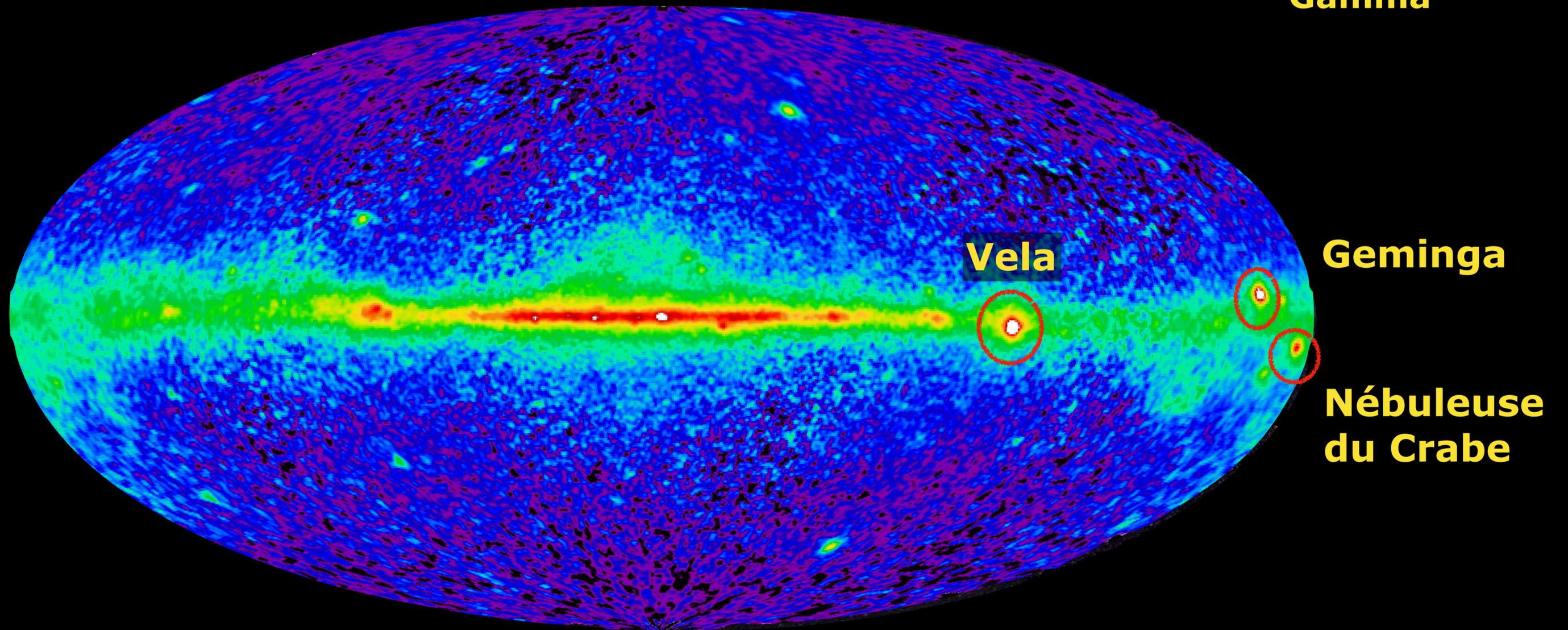
## Vue générale

- **Cours I-1:** Les accélérateurs de particules cosmiques
- **Cours I-2:** Les rayons cosmiques
- **Cours II:** Ondes gravitationnelles — Neutrinos de basse énergie
- **Cours III:** Neutrinos de haute énergie — Astrophysique multi-messenger

# Le mystère des sources gamma



↑  
**Gamma**



# Les rémanents de supernovae

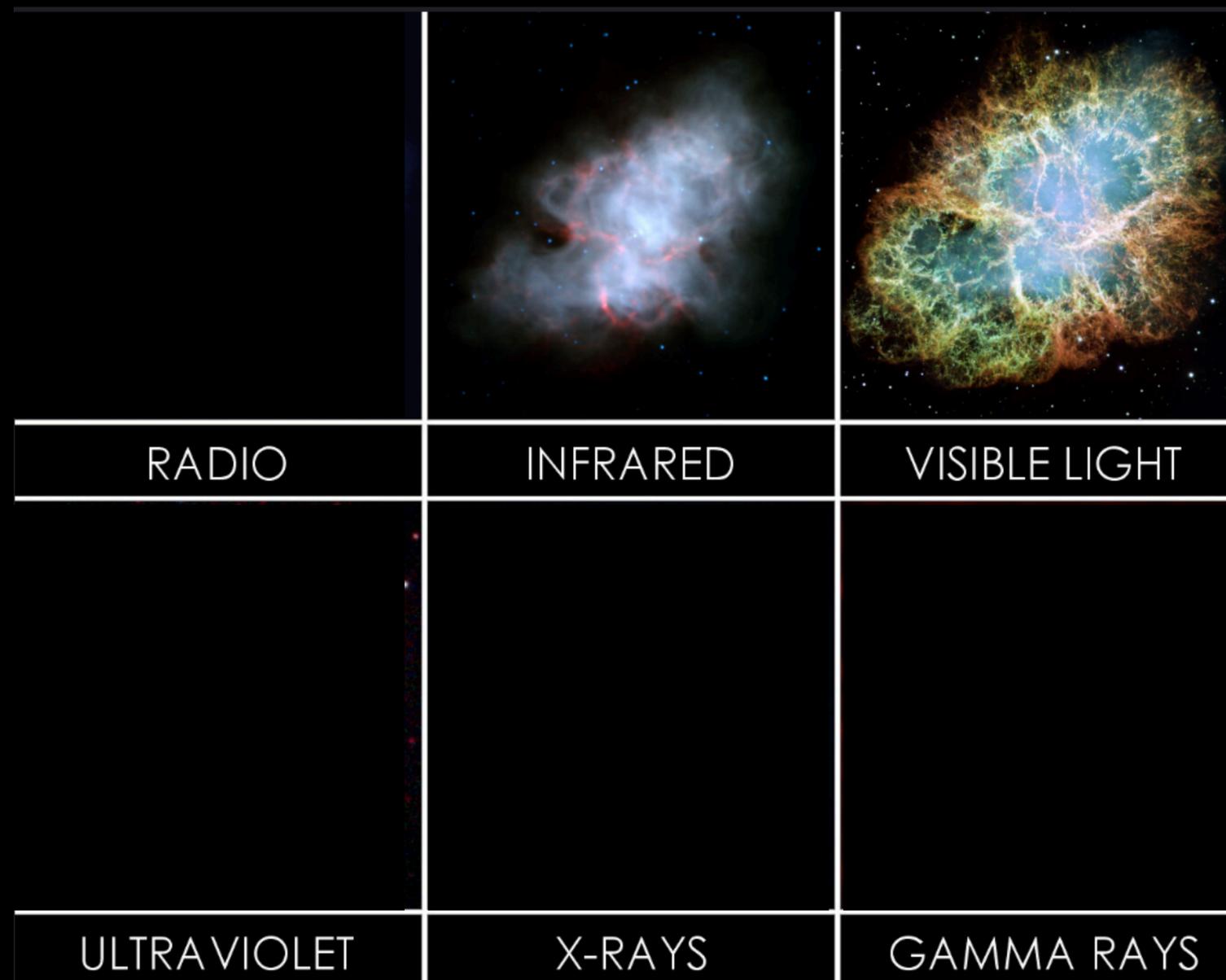
## Exemple: Nébuleuse du Crabe



Supernova observée in 1054

Relevée en Chine, Japon, Europe  
...et peut-être aussi par les Amérindiens

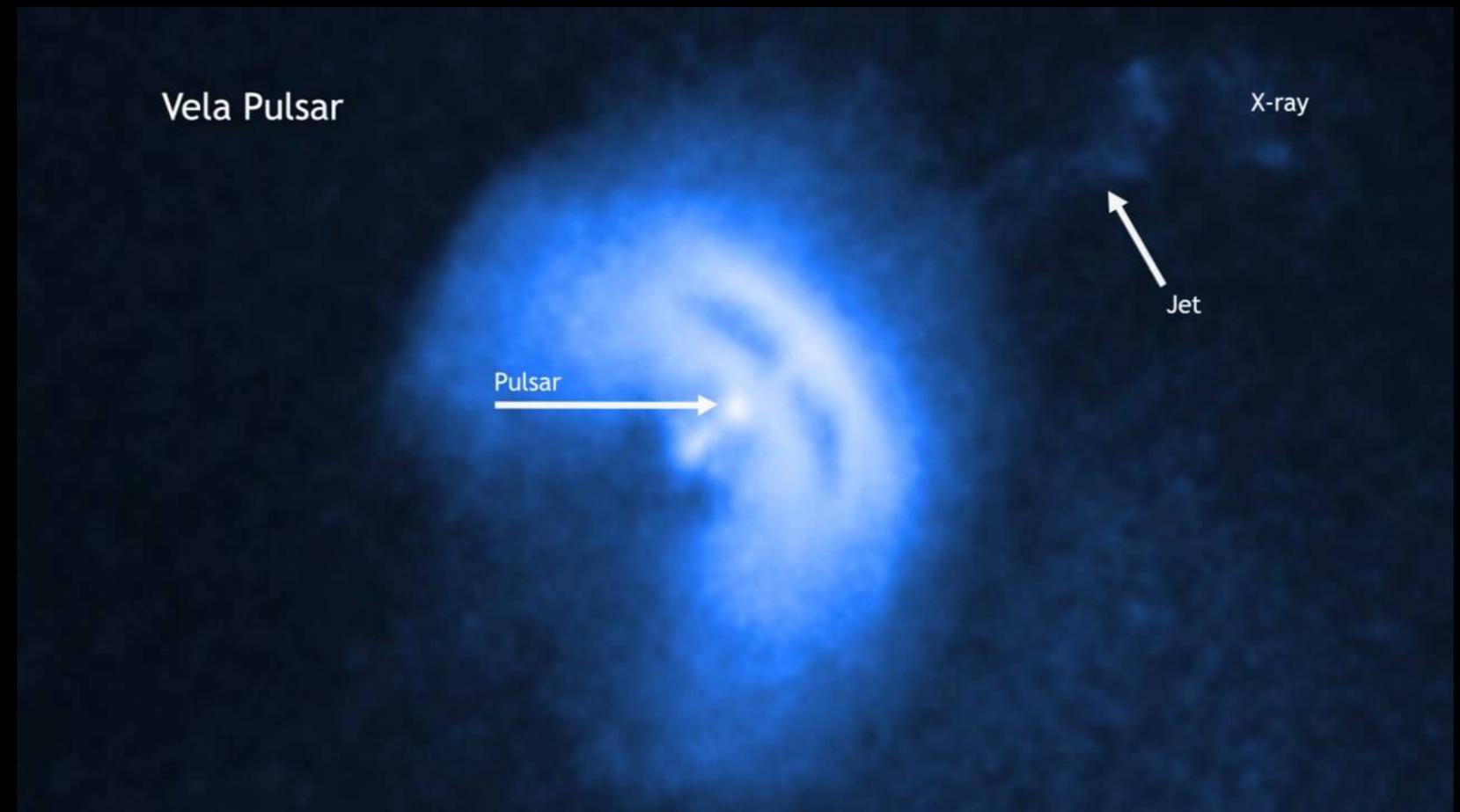
L'ondes de choc se propage toujours



# Les nébuleuses de pulsars

## Exemple: Vela X

- Distance: 100 années lumières
- Pulsar Vela: 25 km de diamètre  
11 rotations par seconde
- Disques/tores d'accrétion
- Jet de particules  $\sim 200\,000$  km/s

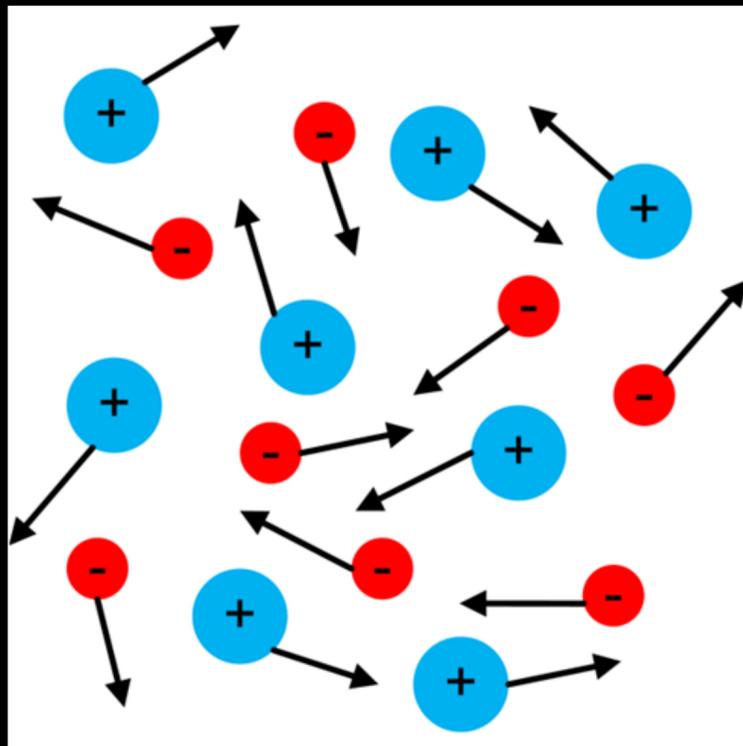


Télescope Chandra — Rayons X

# Ingrédients de base

## Plasma

Matière chaude ionisée



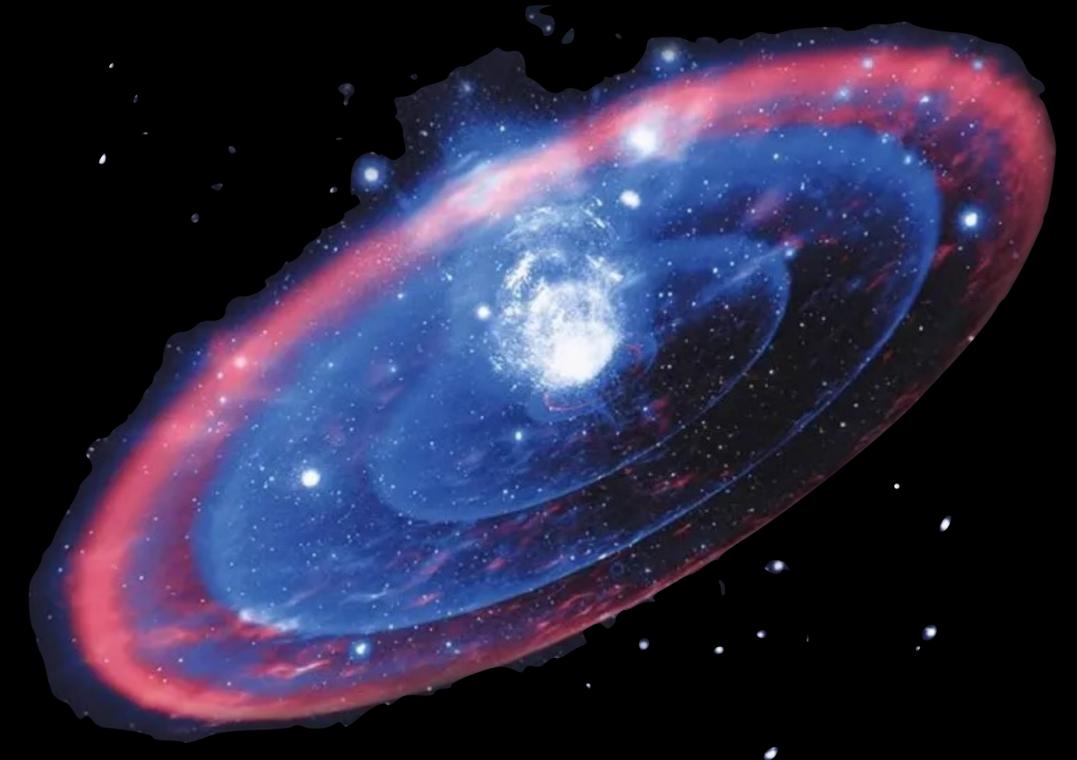
## Champs magnétiques

Transfert d'énergie/confinement



## Chocs

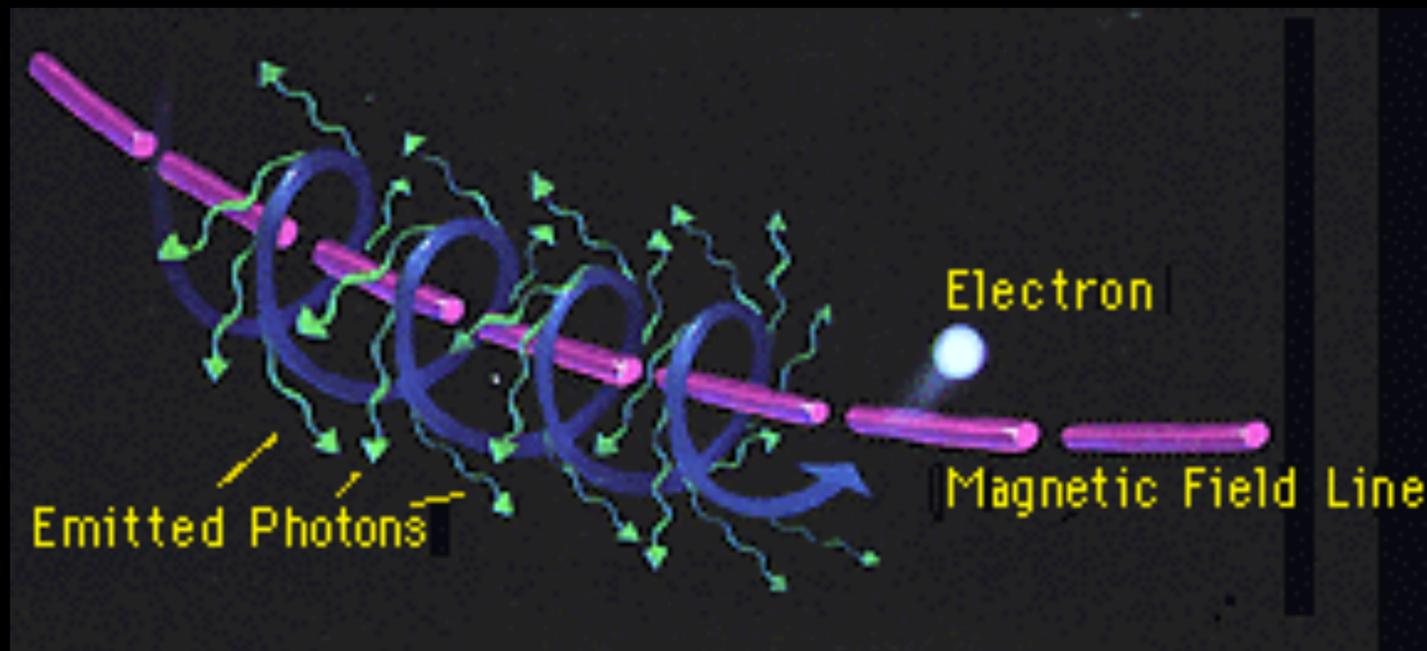
Onde de choc ou collisions



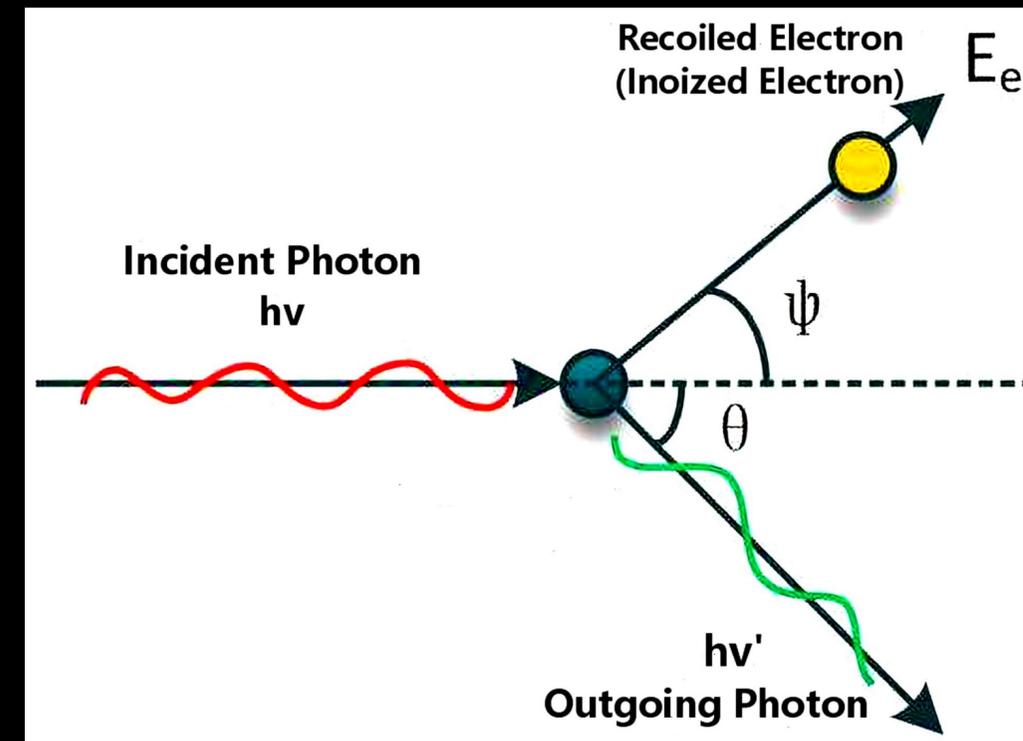
Accélération de particules chargées

# De l'accélération d'électrons aux photons

## Rayonnement synchrotron et diffusion de Compton

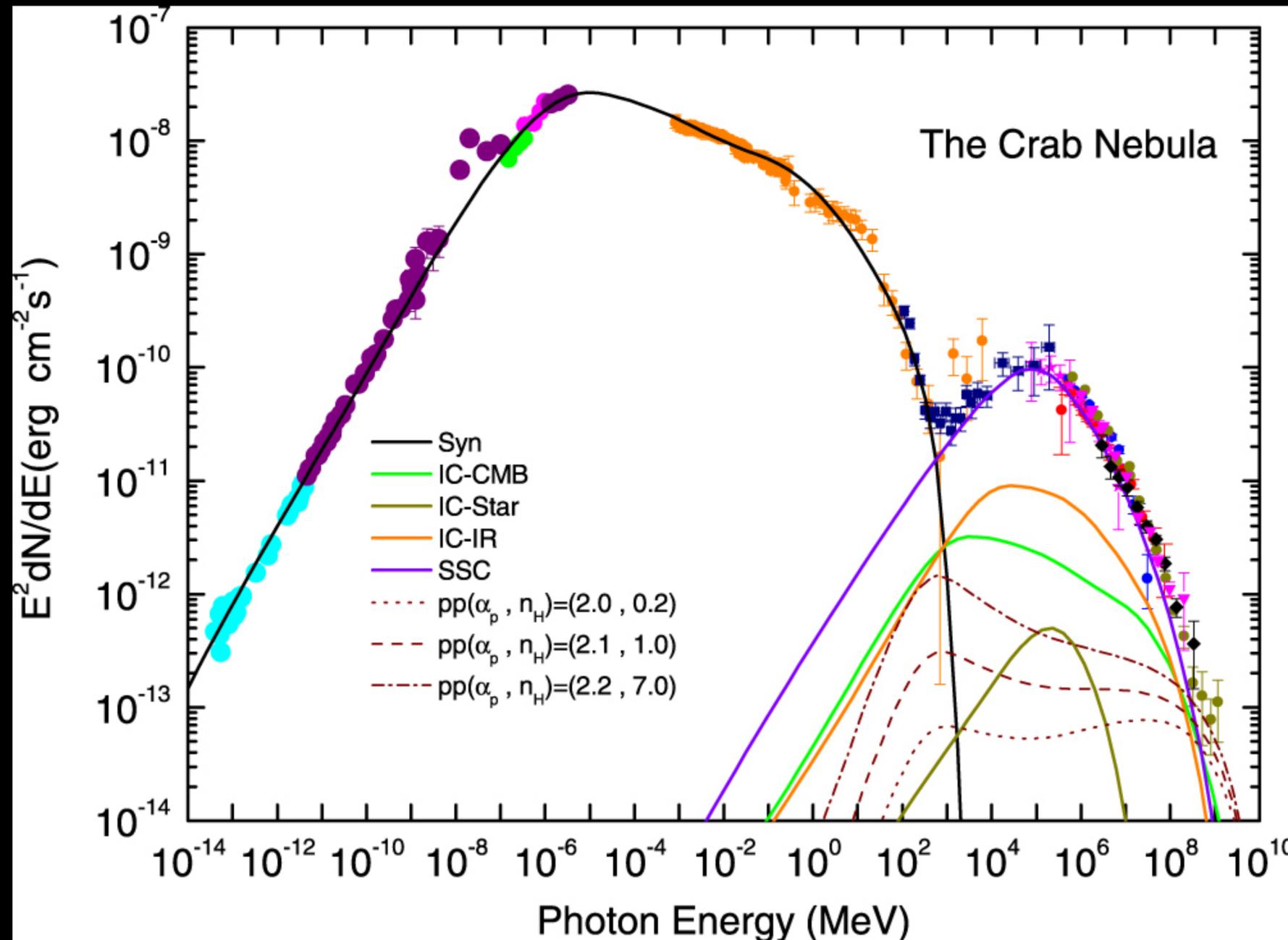


$$E_{\text{photon}} \propto \frac{heBE_e^2}{4\pi m_e^3 c^3}$$



**Compton inverse:** don d'énergie aux photons par les électrons

# Spectre de photons et modèles d'émission



- Spectre de photon bien fitté par **synchrotron + Compton inverse**
- Expérience LHAASO: observation de photons  $\sim 1$  PeV!

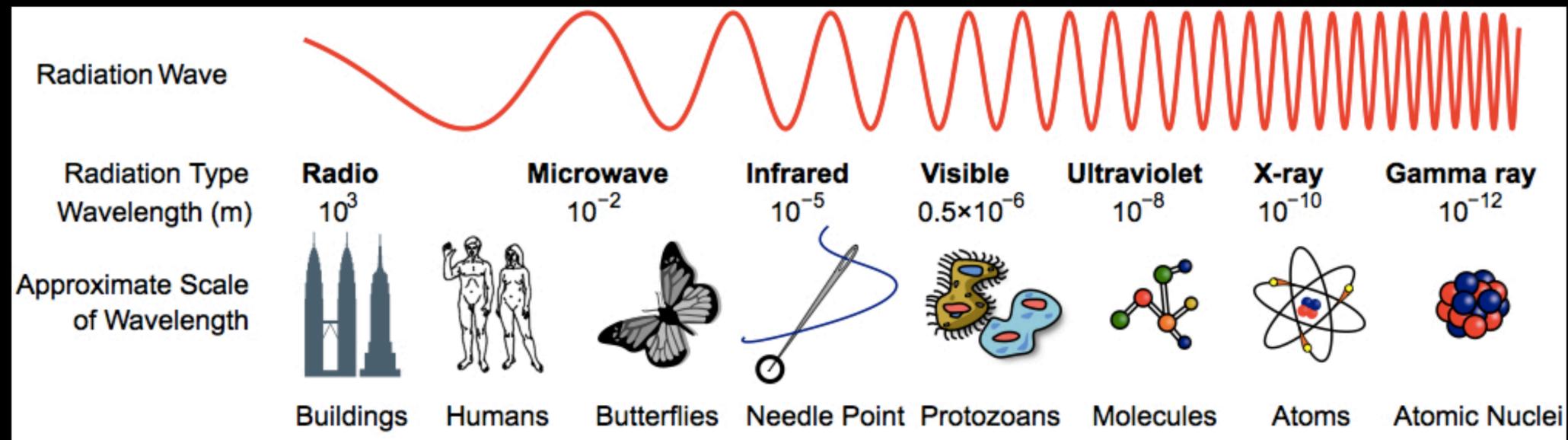
“The ultra-high-energy photons imply the presence of a PeV electron accelerator (a pevatron) in the nebula”

*Science, 2021*

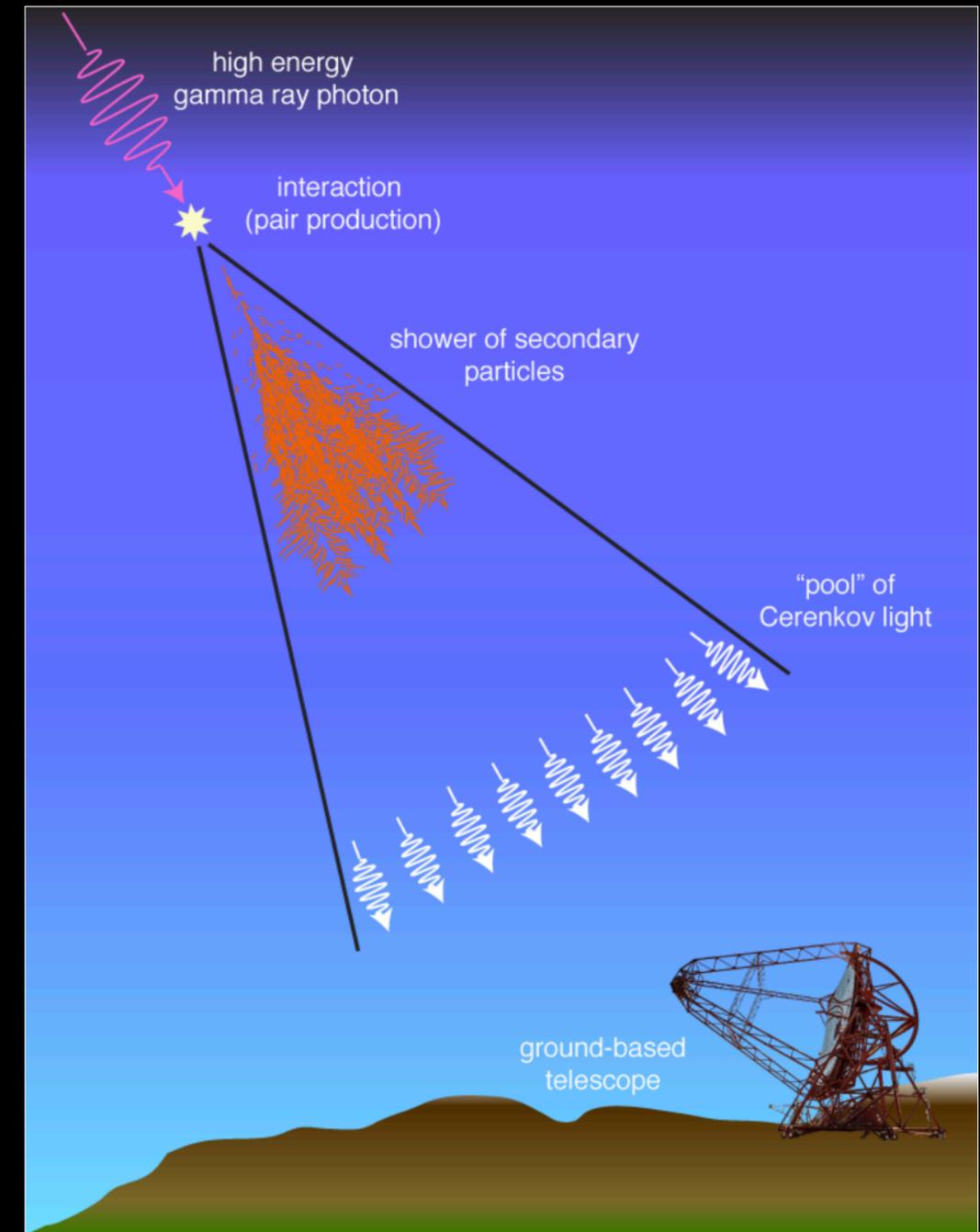
Si électrons  
5000 x le LEP!



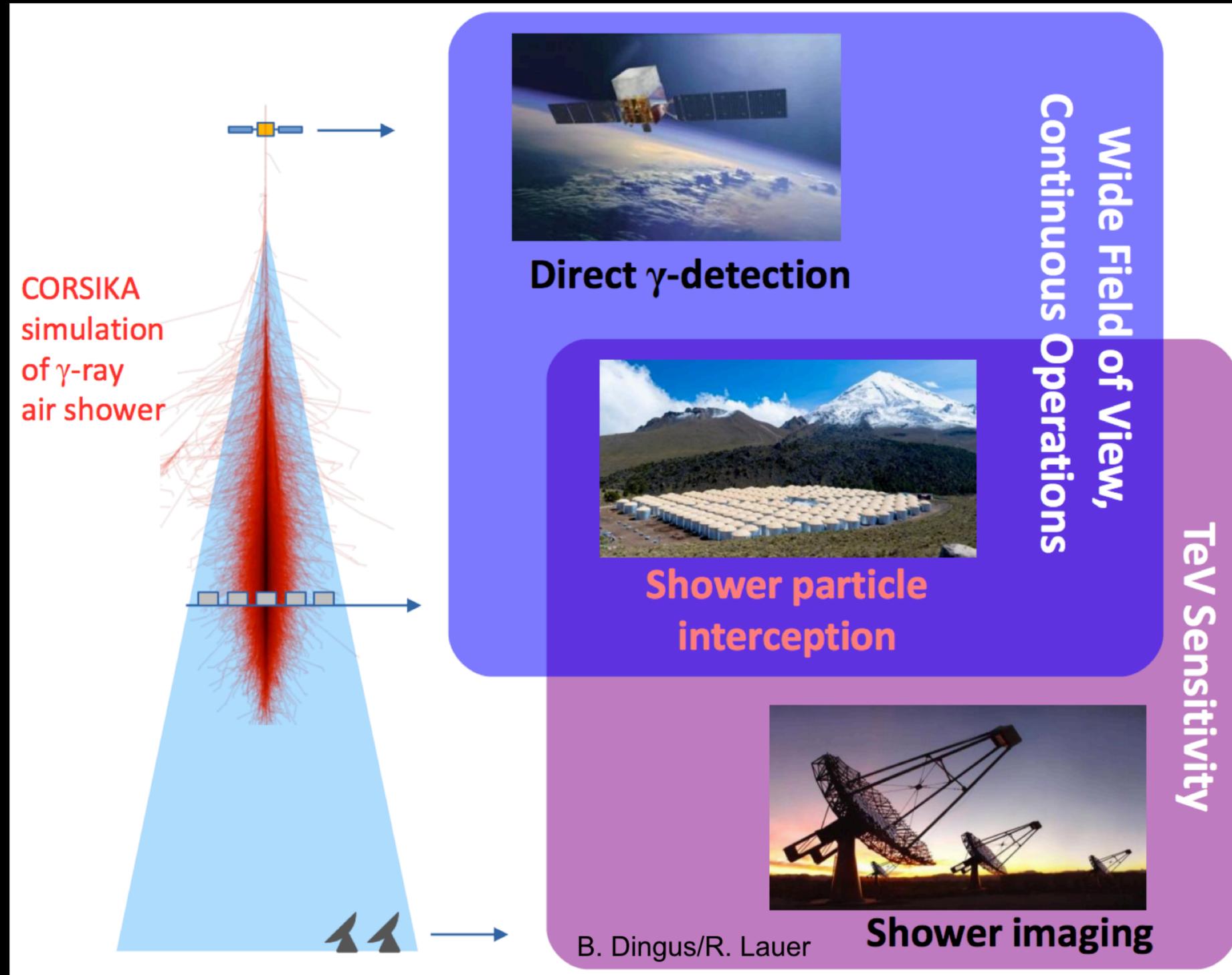
# Les rayons gamma



- Photons d'énergie supérieure à 100 keV
- Sur Terre: radioactivité
- Rayons gamma venant de l'espace: interactions avec l'atmosphère → gerbes de particules



# Observer les rayons gamma



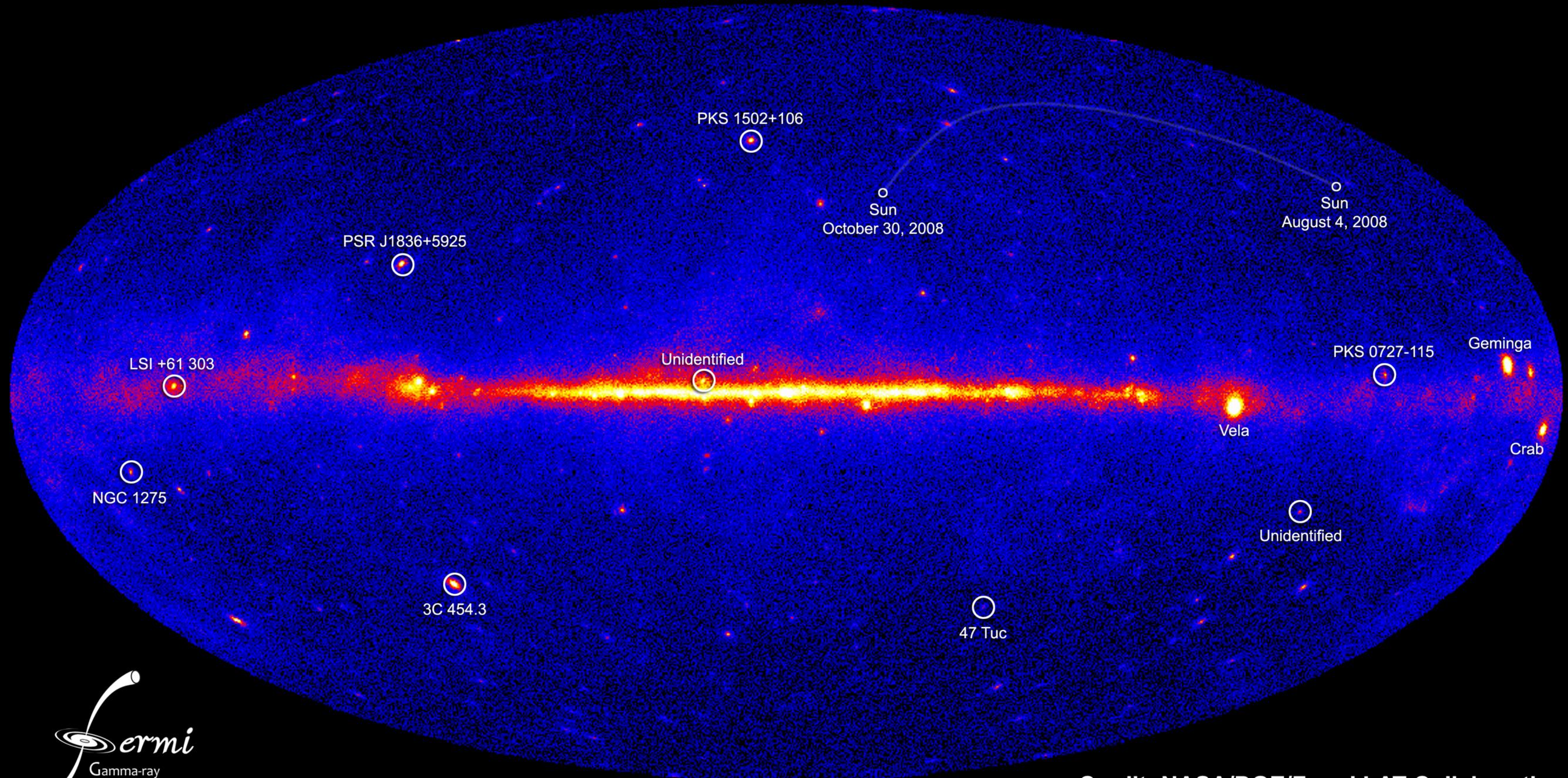
Télescope  
FERMI

LHAASO  
(Tibet)

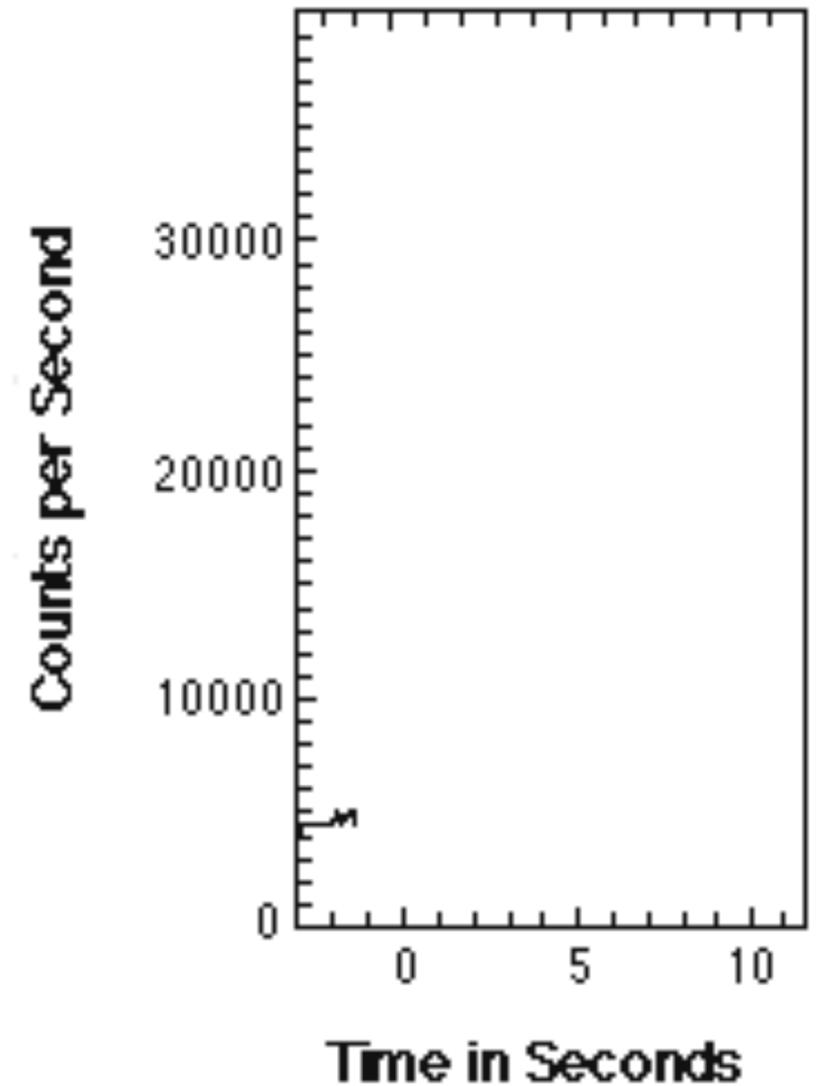
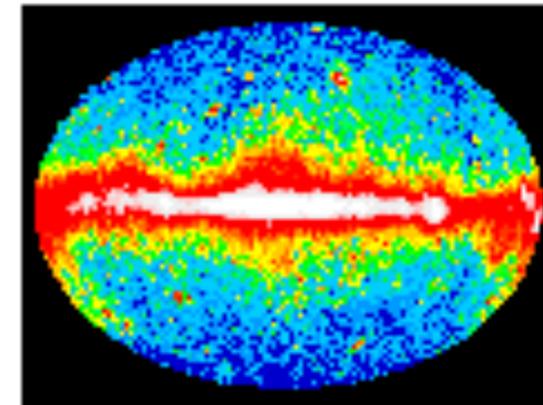
HESS  
(Namibie)  
MAGIC  
CTA

(La Palma, Chili)

# Le ciel en gamma



# Sources extragalactiques: premières observations

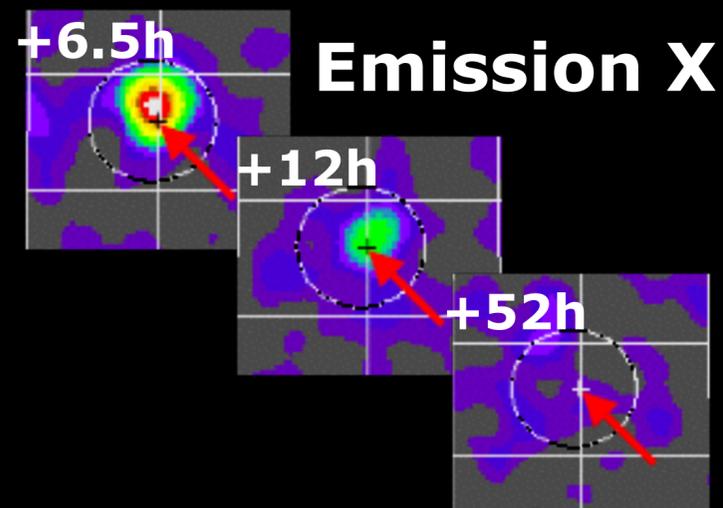
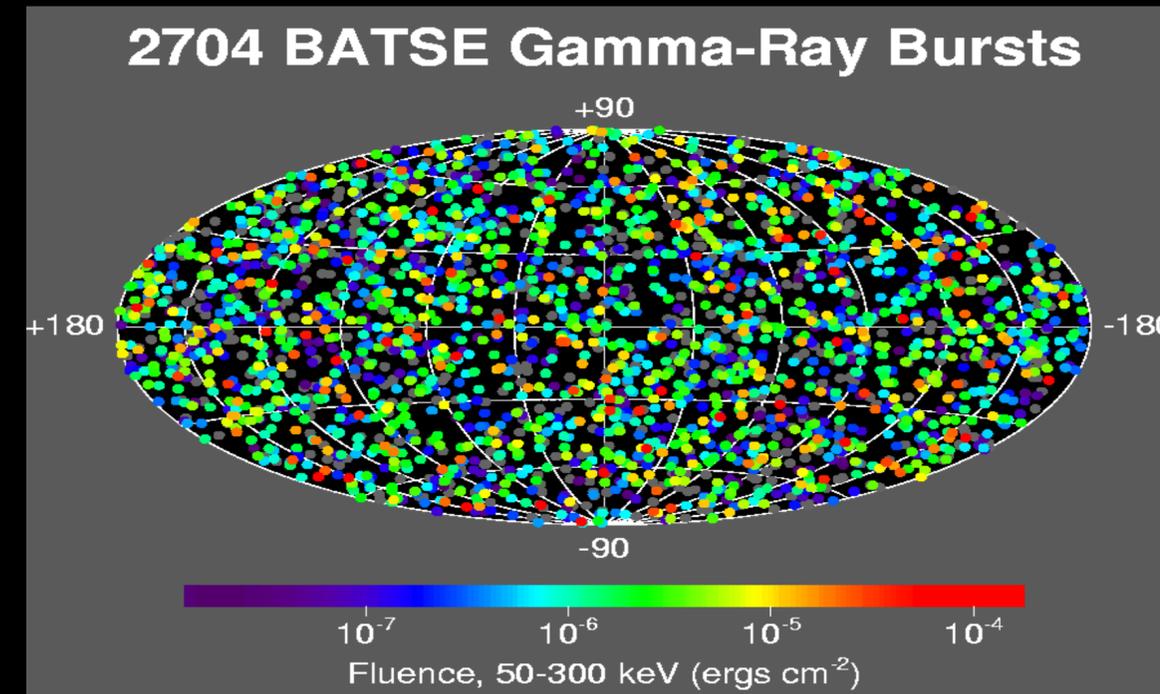


- 1967: 16 flash gamma vus par le satellite Vela. **Déclassification et publication en 73**
- Caractérisation par les télescopes C.G.R.O., BeppoSax, Swift

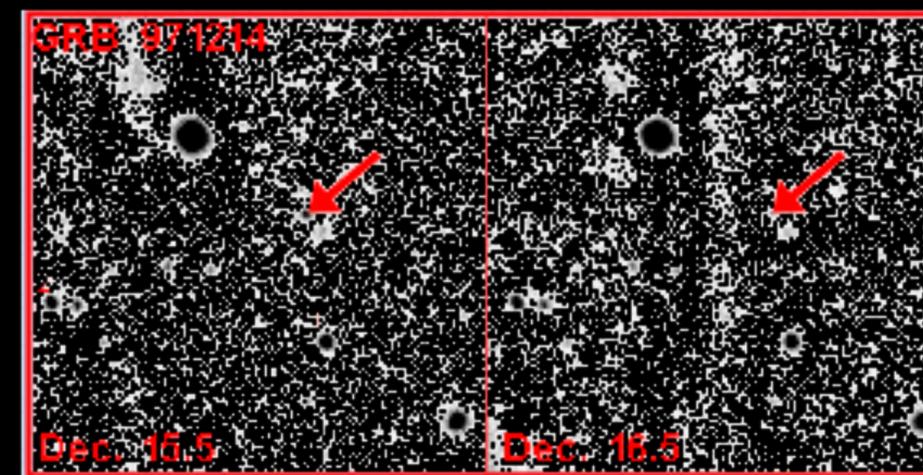
# Les sursauts gamma: étude

## Objets extragalactiques ( $z \sim 0.43$ à $6.3$ )

- Objets les plus brillants de l'Univers  
 $E \sim 10^{44} - 10^{47} \text{ J} \sim M_{\odot} c^2$   
Emission collimatée?
- Durée: 0.01s à quelques secondes  
 $\Delta L \sim 0.01c \sim 30,000 \text{ km} \ll \text{Soleil}$   
Objet compact?

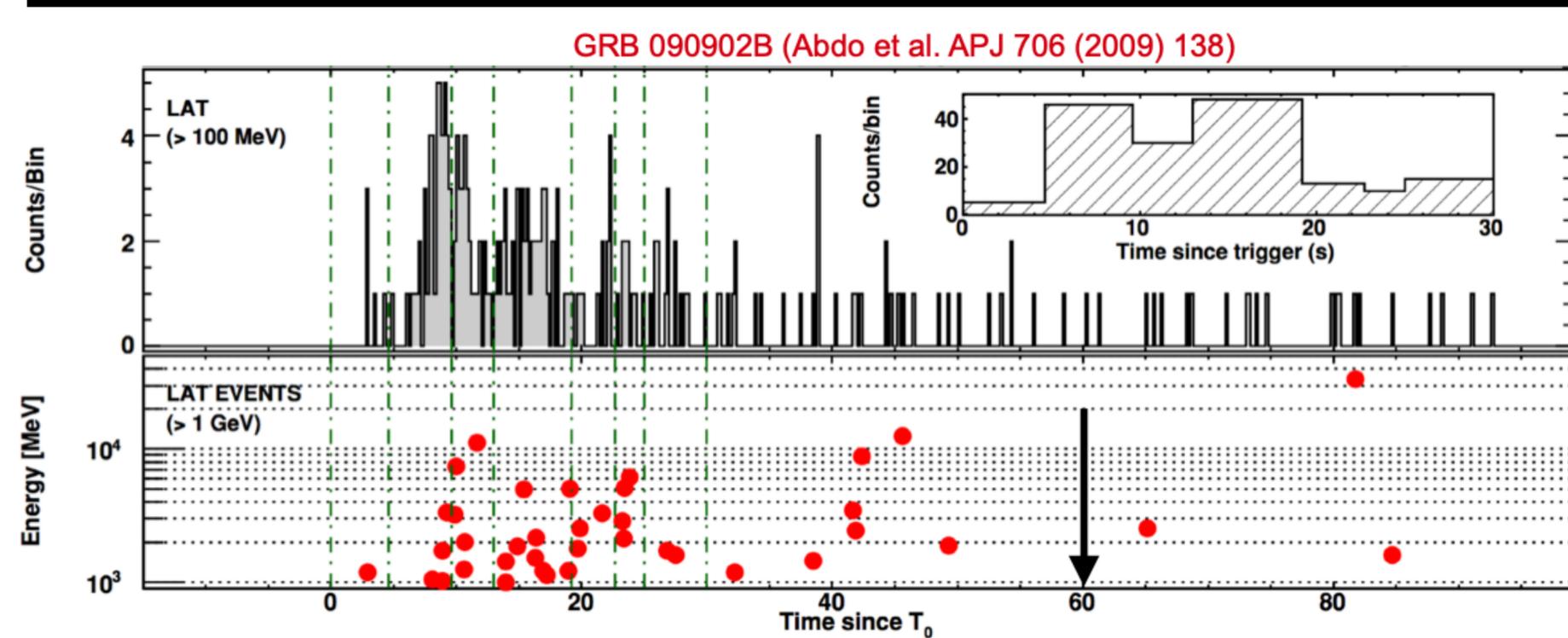
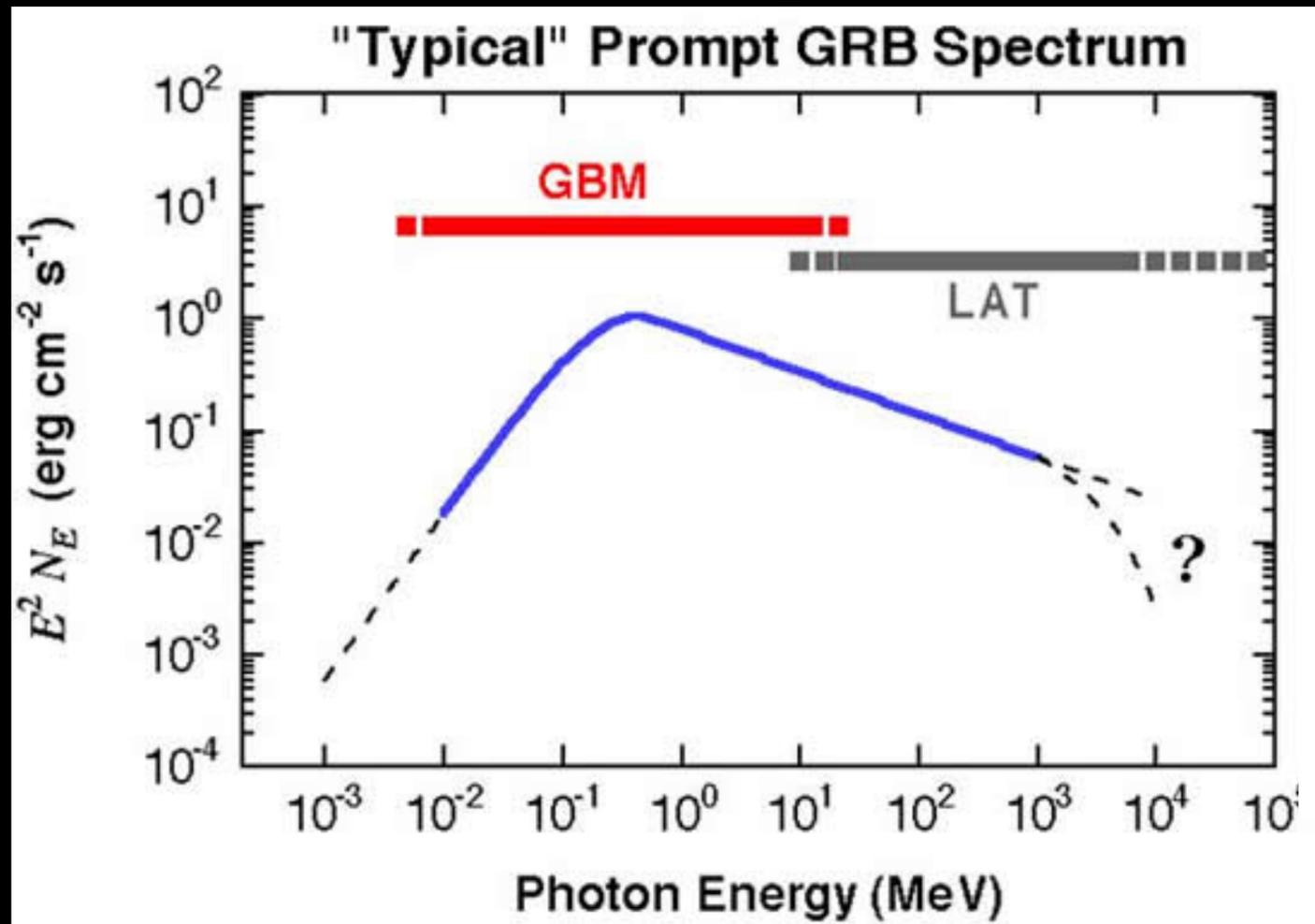
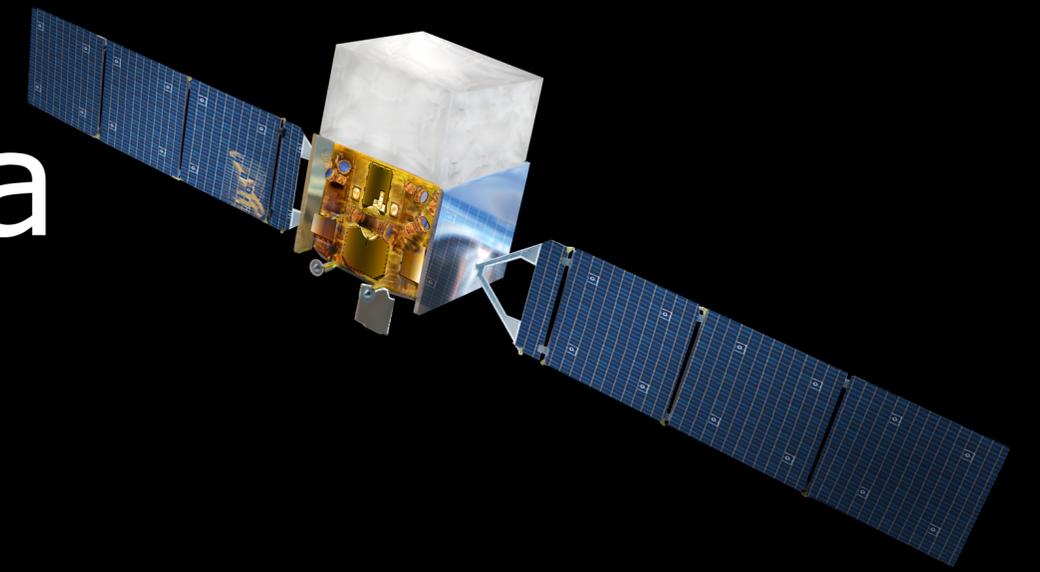


## Emission optique



# Energie des sursauts gamma

## Observations typiques – FERMI

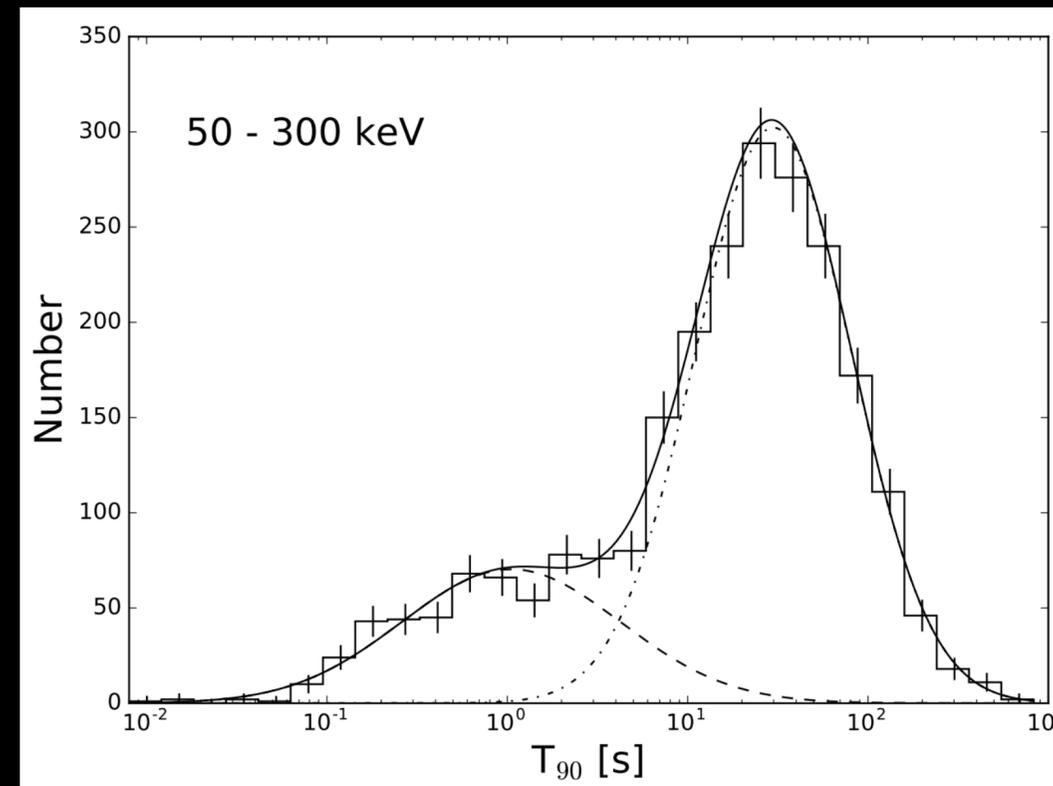


- Photons jusqu'au MeV en général
- Jusqu'au GeV dans quelques cas  
Hautes énergies même après 1 minute!

# Origine des sursauts gamma: hypothèses

## Sursauts courts

Fusion d'étoiles à neutrons

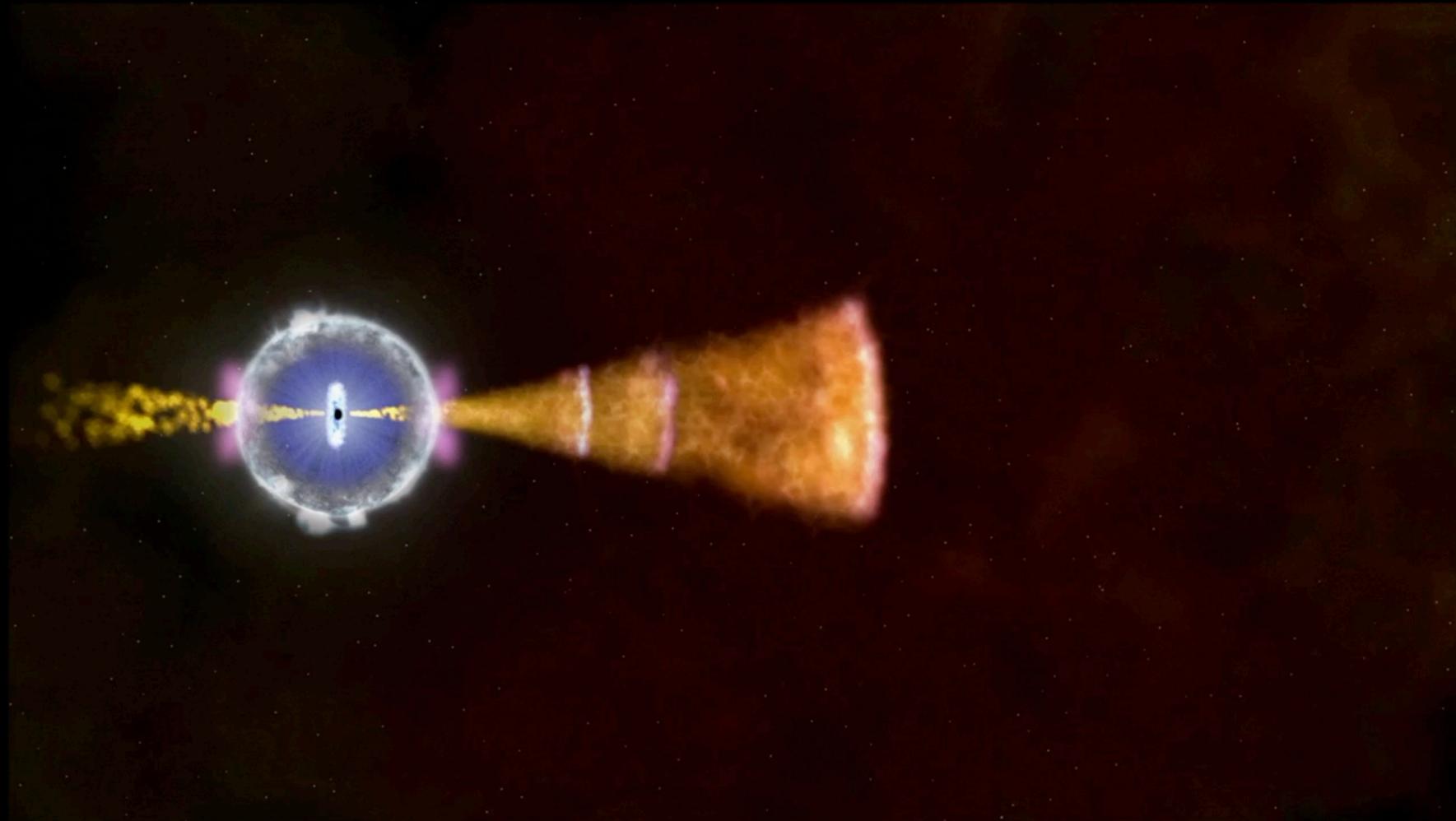


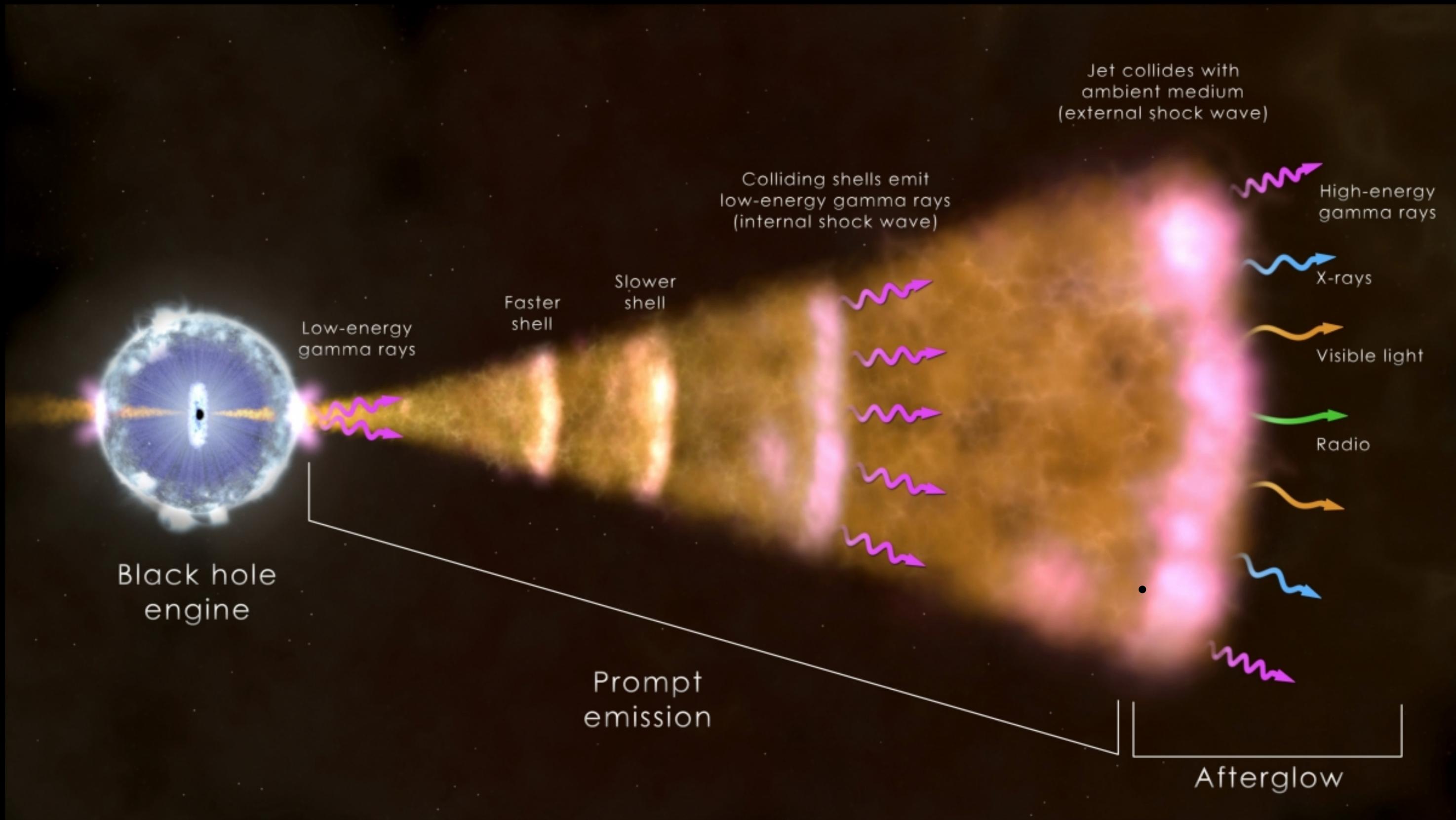
Sursauts longs  
Supernovae extrêmes



# Origine des rayons gamma — Hypothèse

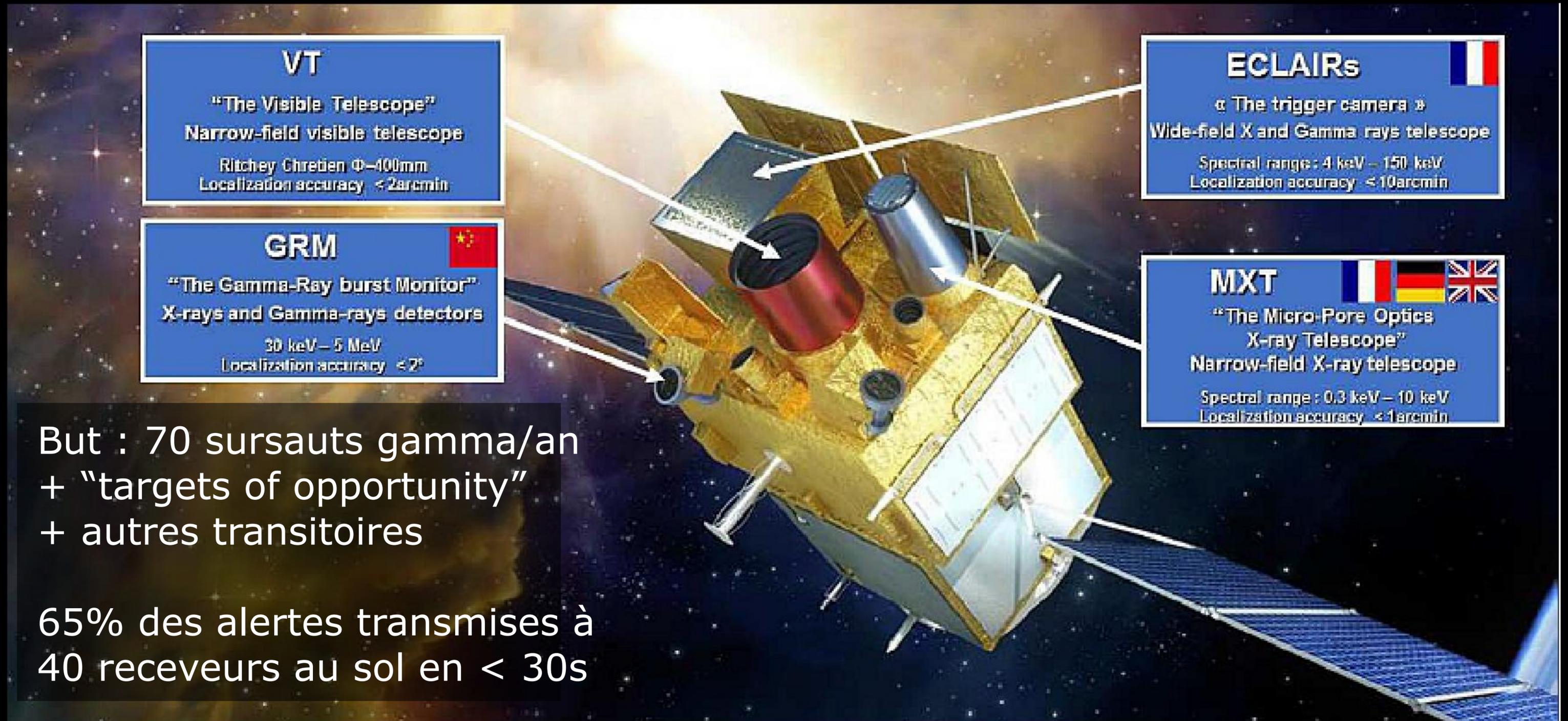
## Chocs internes et collisions du jet avec milieu externe





# Suivi de sursauts gamma: SVOM

## Space Variable Objects Monitor — Successeur de SWIFT



But : 70 sursauts gamma/an  
+ "targets of opportunity"  
+ autres transitoires

65% des alertes transmises à  
40 receveurs au sol en  $< 30\text{s}$

# Les sursauts gamma extrêmes

## Observations à très hautes énergies



**MAGIC (25 GeV – 30 TeV)**

La Palma  
2004/2009



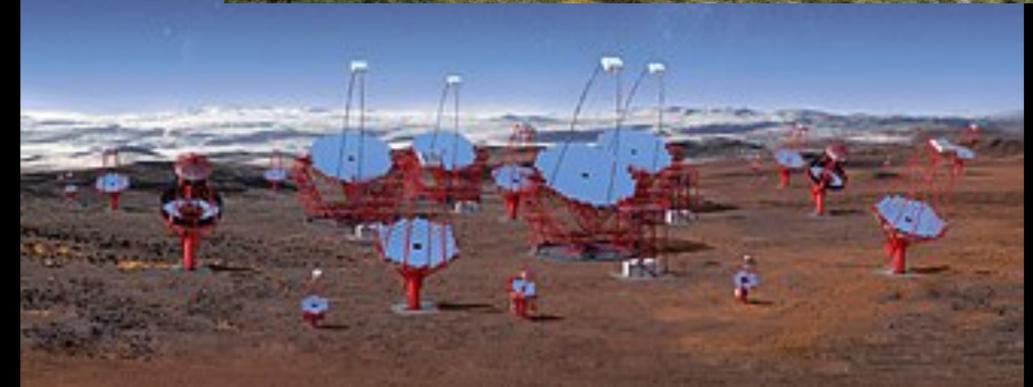
**HESS (0.03–100 TeV)**

Namibie  
2004



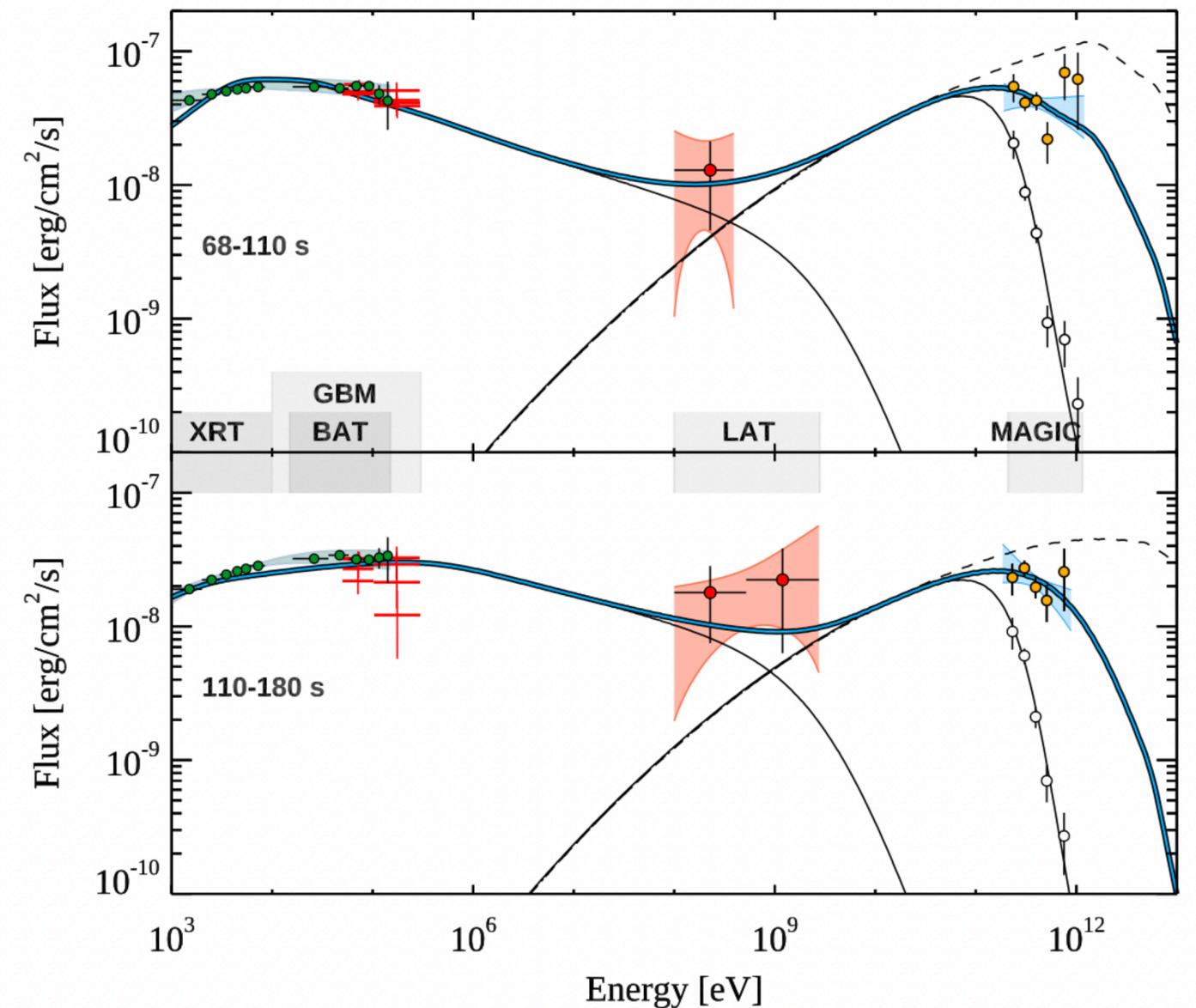
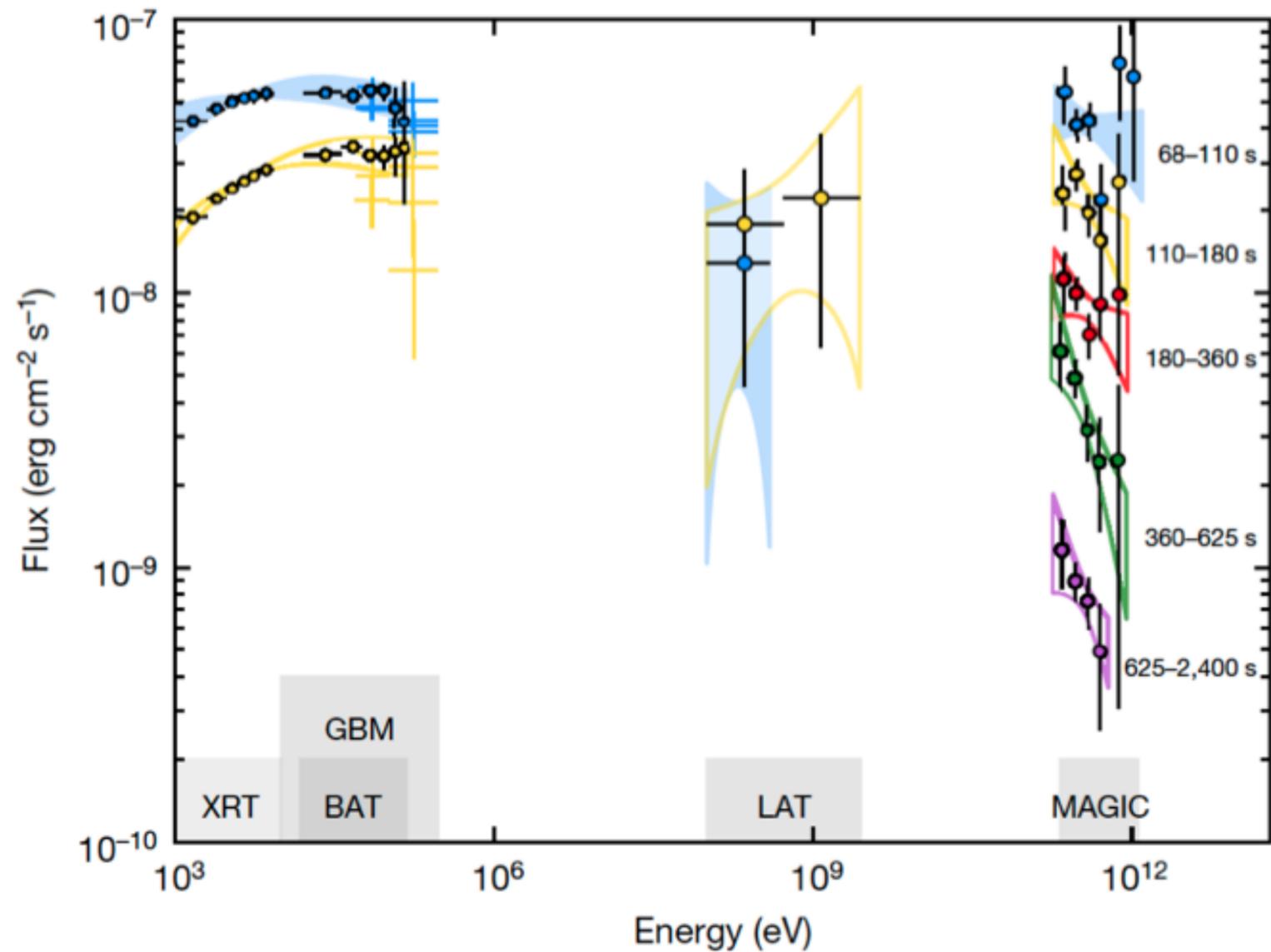
**CTA (0.02–300 TeV)**

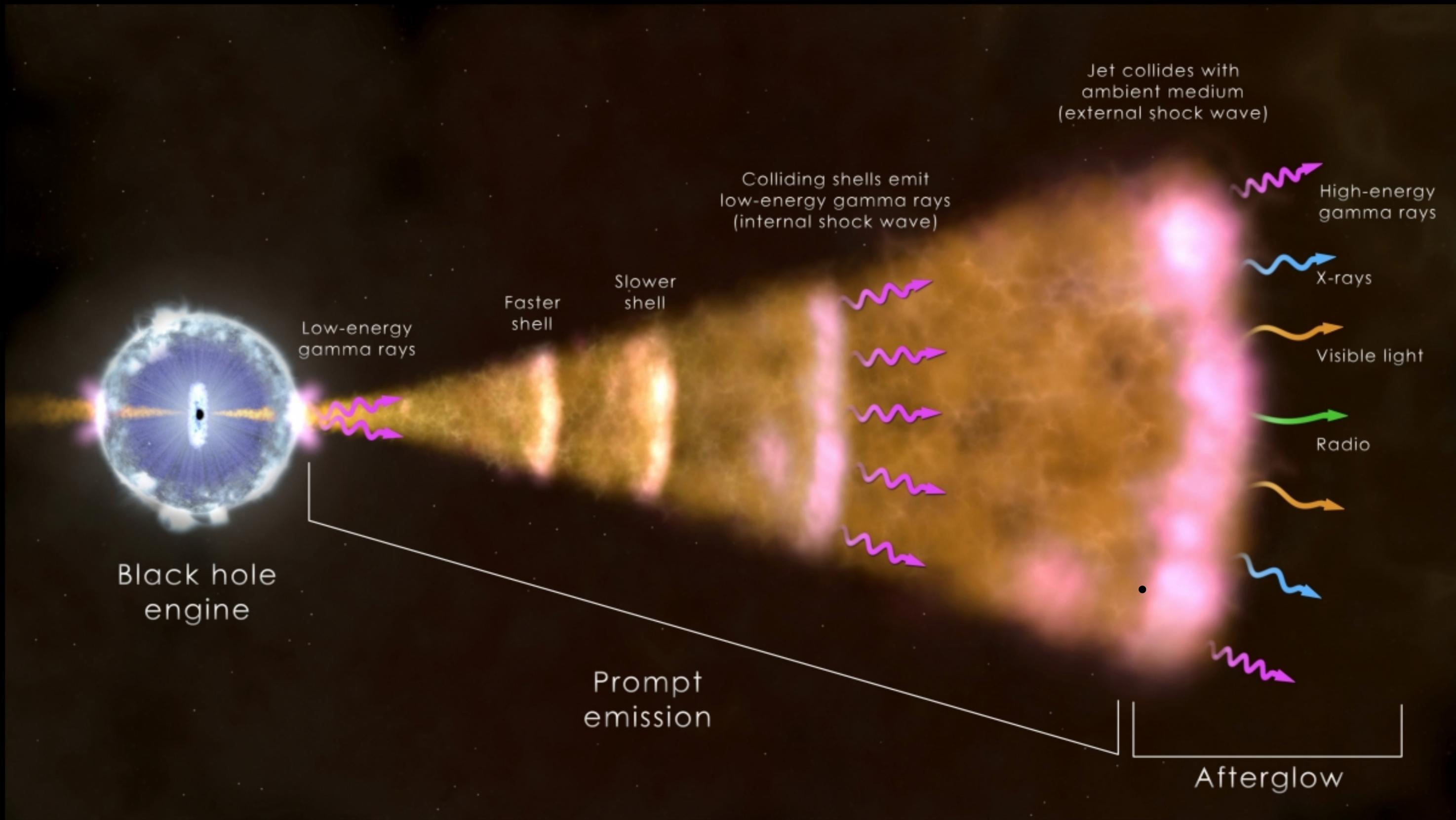
La Palma + Désert d'Atacama  
2025-?



# Accélération de particules et afterglow

## Sursauts gamma extrêmes – Exemple de GRB190114C





Black hole engine

Low-energy gamma rays

Faster shell

Slower shell

Colliding shells emit low-energy gamma rays (internal shock wave)

Jet collides with ambient medium (external shock wave)

High-energy gamma rays

X-rays

Visible light

Radio

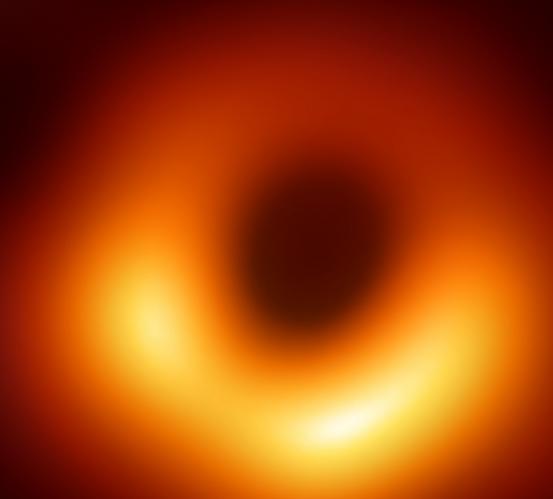
Prompt emission

Afterglow

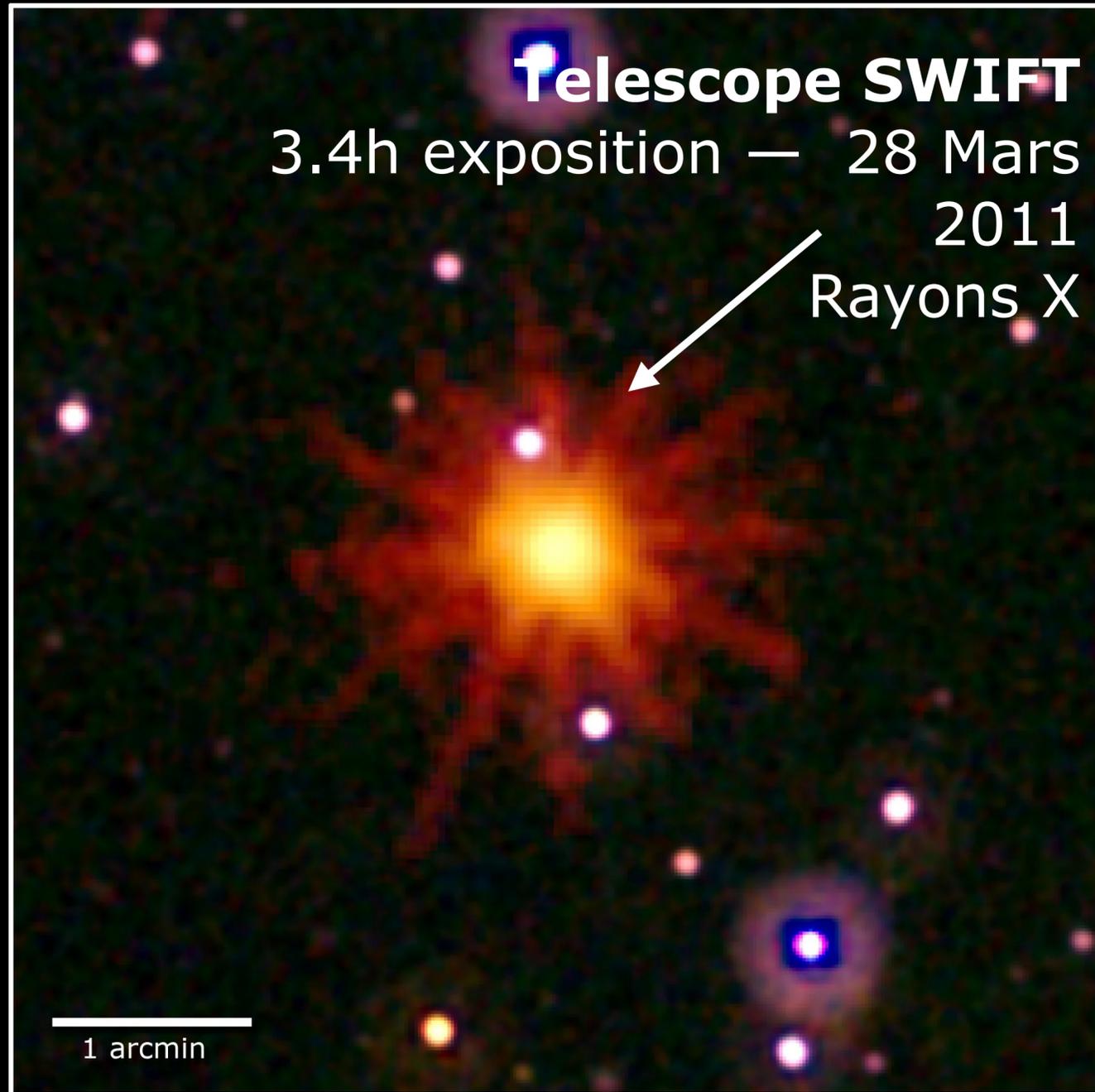
# Les accélérateurs de particules cosmiques



# Comment mange un trou noir?

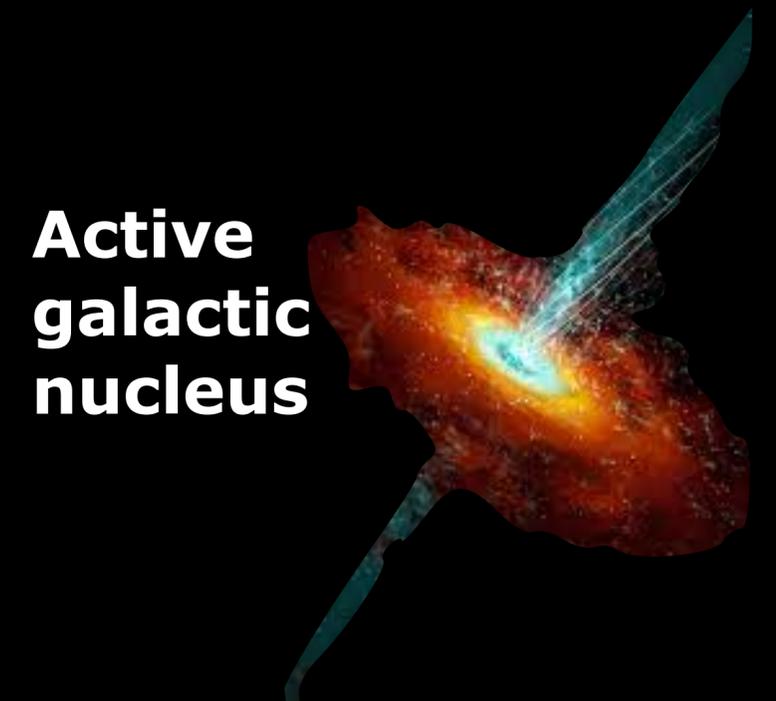
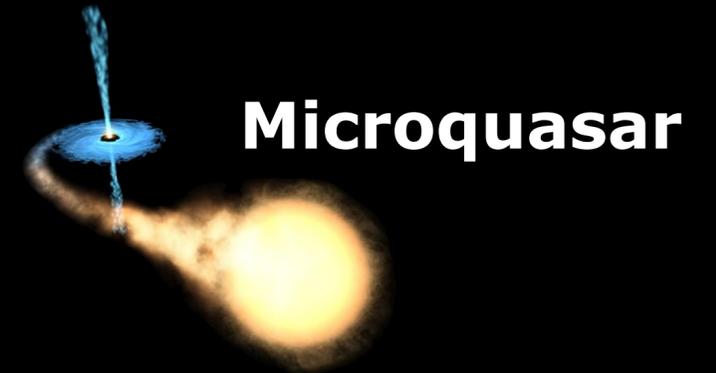


# Comment mange un trou noir



Swift J1644+57

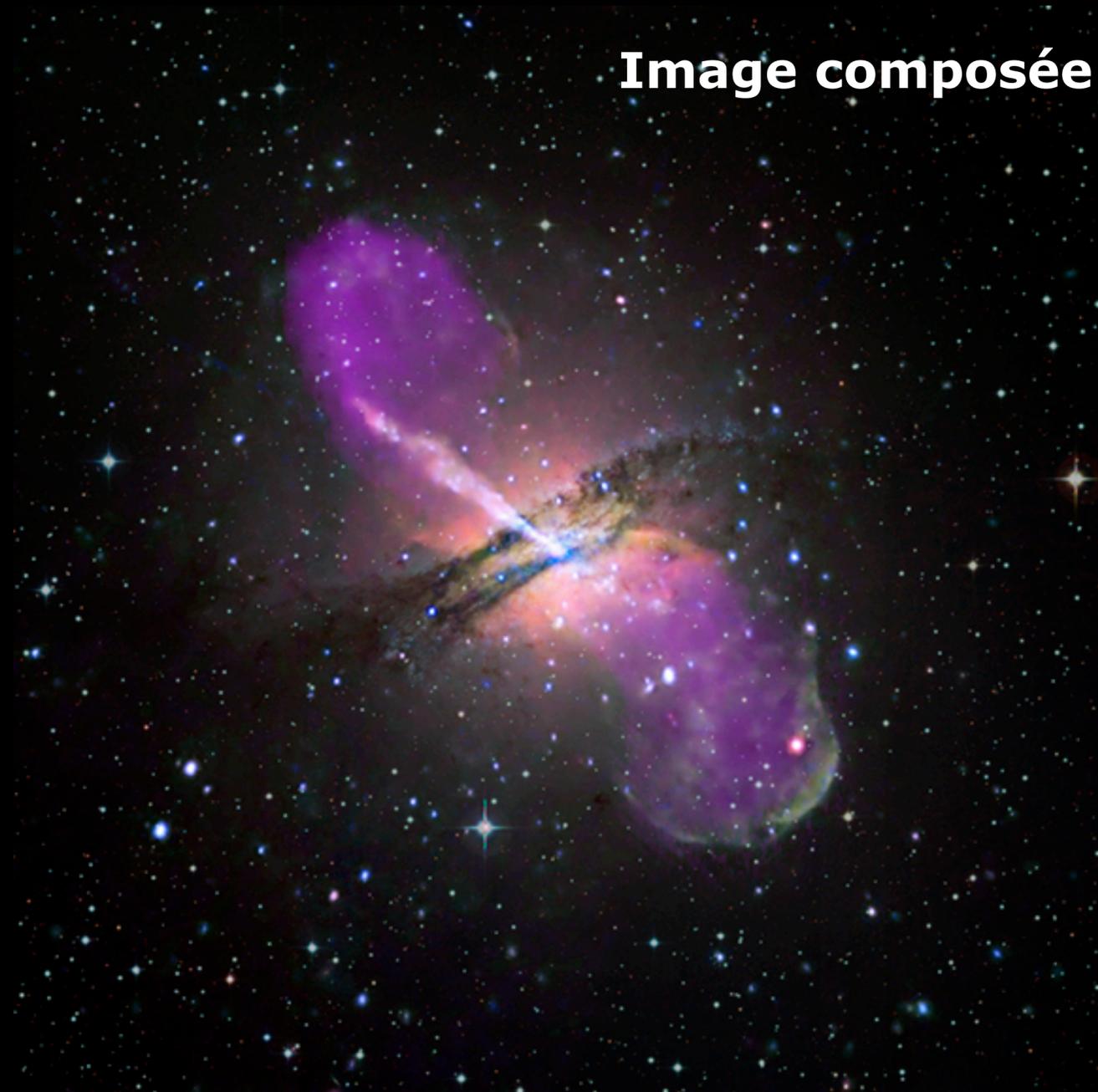
NASA/Swift/Stefan Immler



# Les noyaux actifs de galaxies (AGNs)

## La galaxie Centaurus A

Image composée



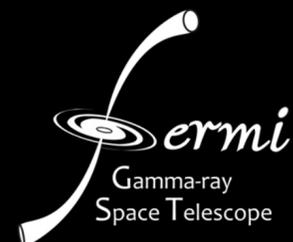
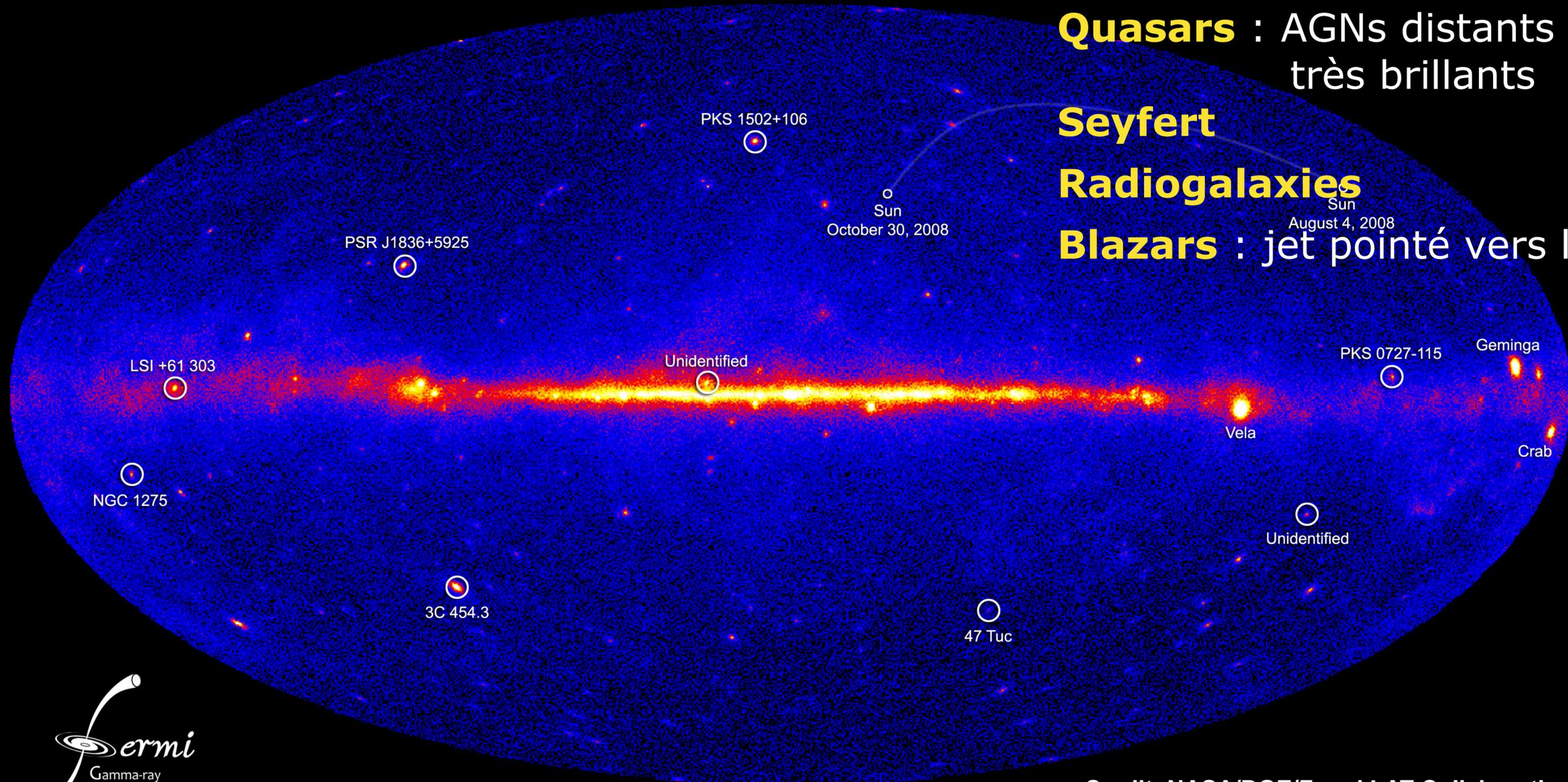
# Le ciel en gamma

Autres noms:

**Quasars** : AGNs distants très brillants

**Seyfert Radiogalaxies**

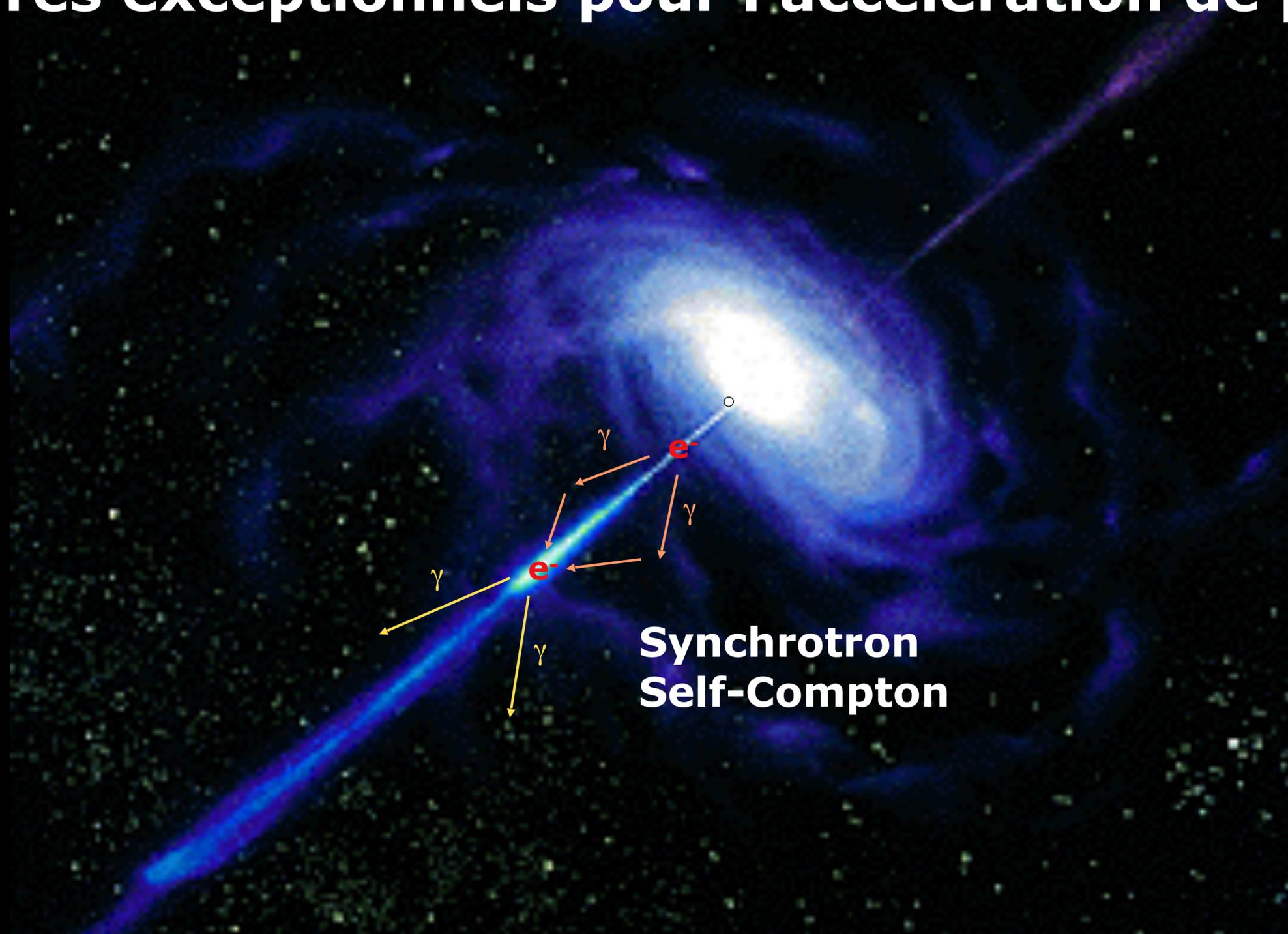
**Blazars** : jet pointé vers la Terre



Credit: NASA/DOE/Fermi LAT Collaboration

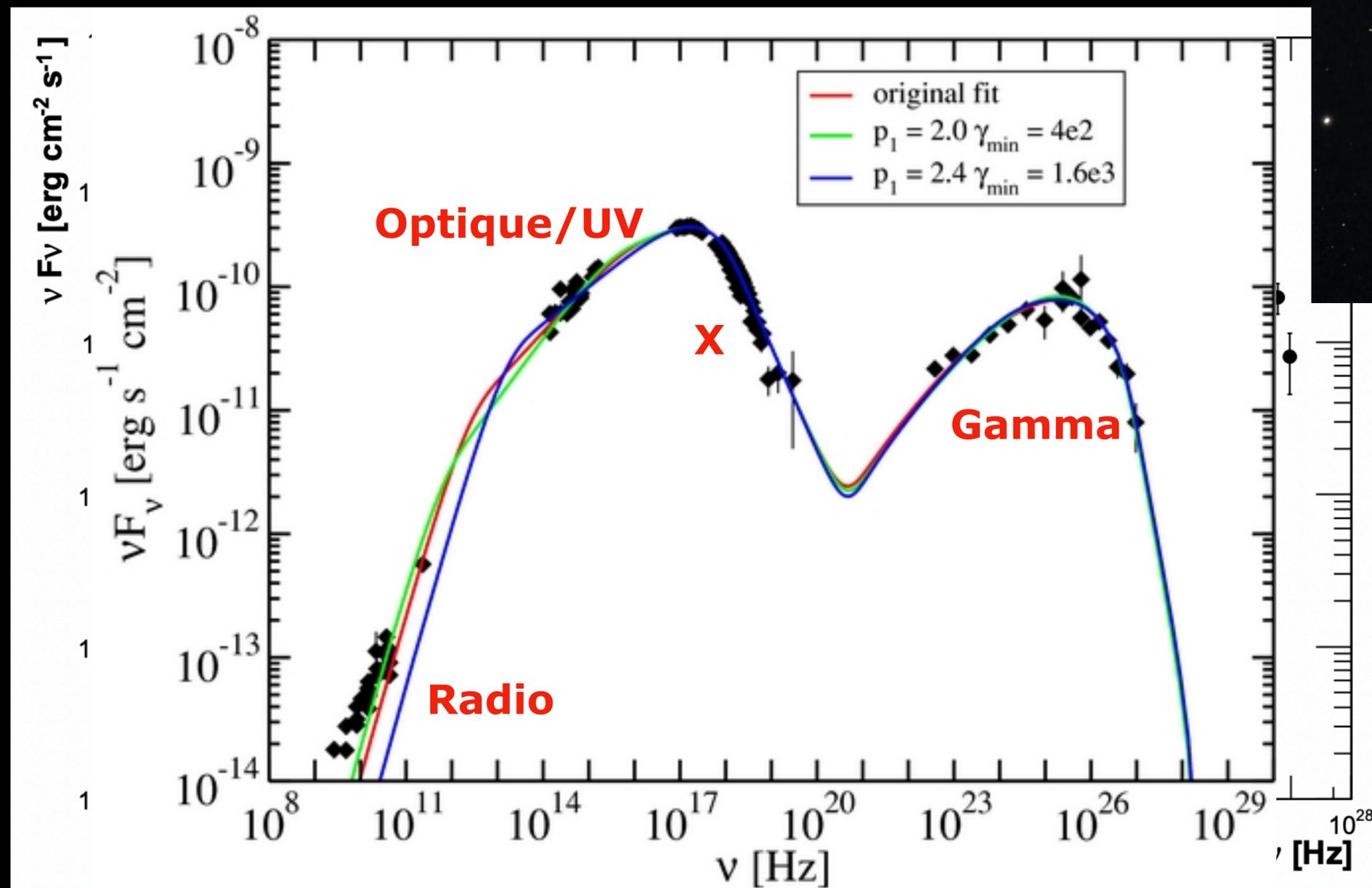
# Les blazars

Observatoires exceptionnels pour l'accélération de particules



# Blazars et accélération de particules

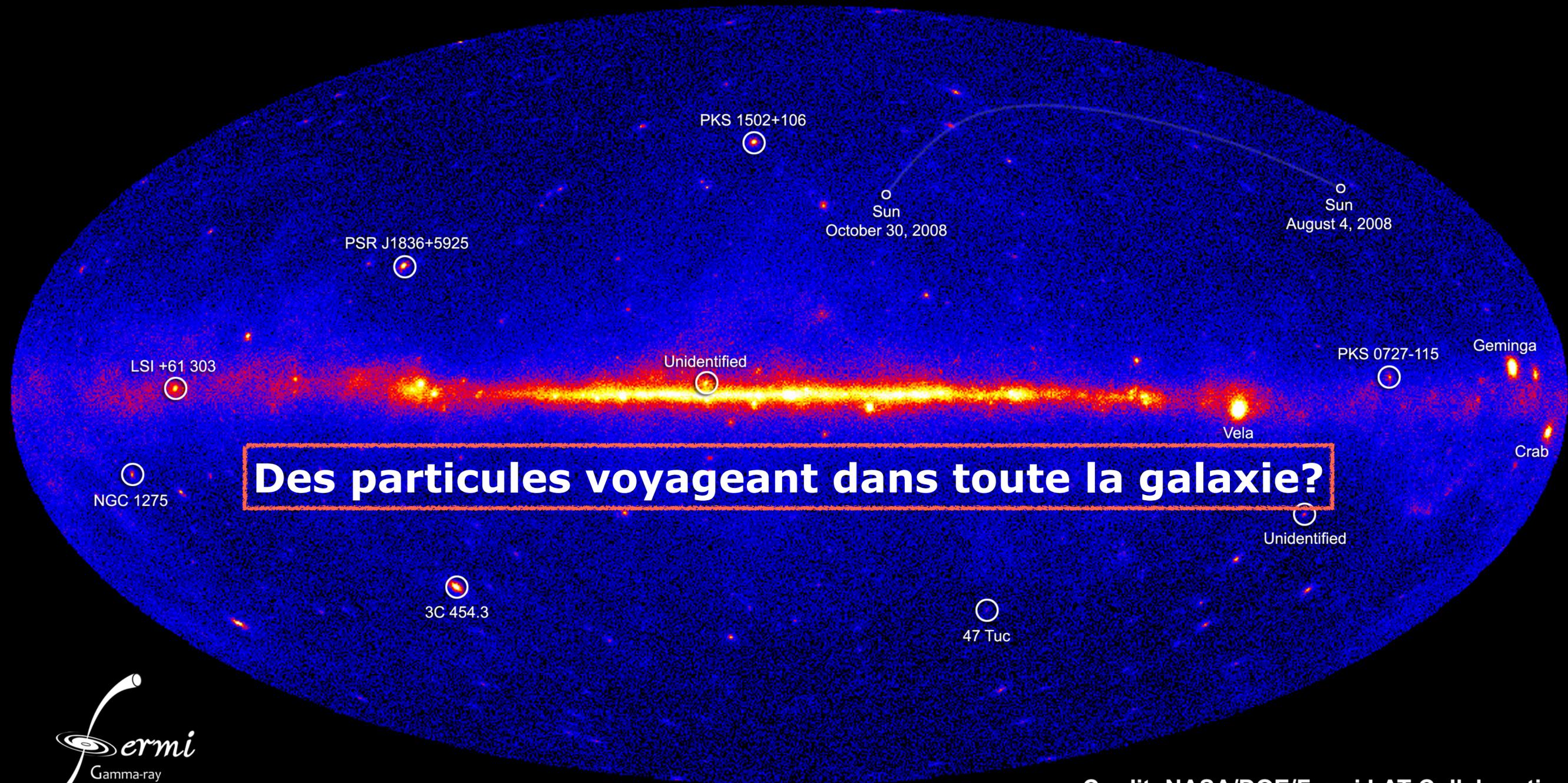
Exemple: Markarian 421 @ 122 Mpc



# Les accélérateurs de particules cosmiques



# Le ciel en gamma...que reste t'il?



# Astroparticules et neutrinos

- **Cours I-1:** Les accélérateurs de particules cosmiques
- **Cours I-2:** Les rayons cosmiques
- **Cours II:** Ondes gravitationnelles — Neutrinos de basse énergie
- **Cours III:** Neutrinos de haute énergie — Astrophysique multi-messenger

# Des particules dans l'air...

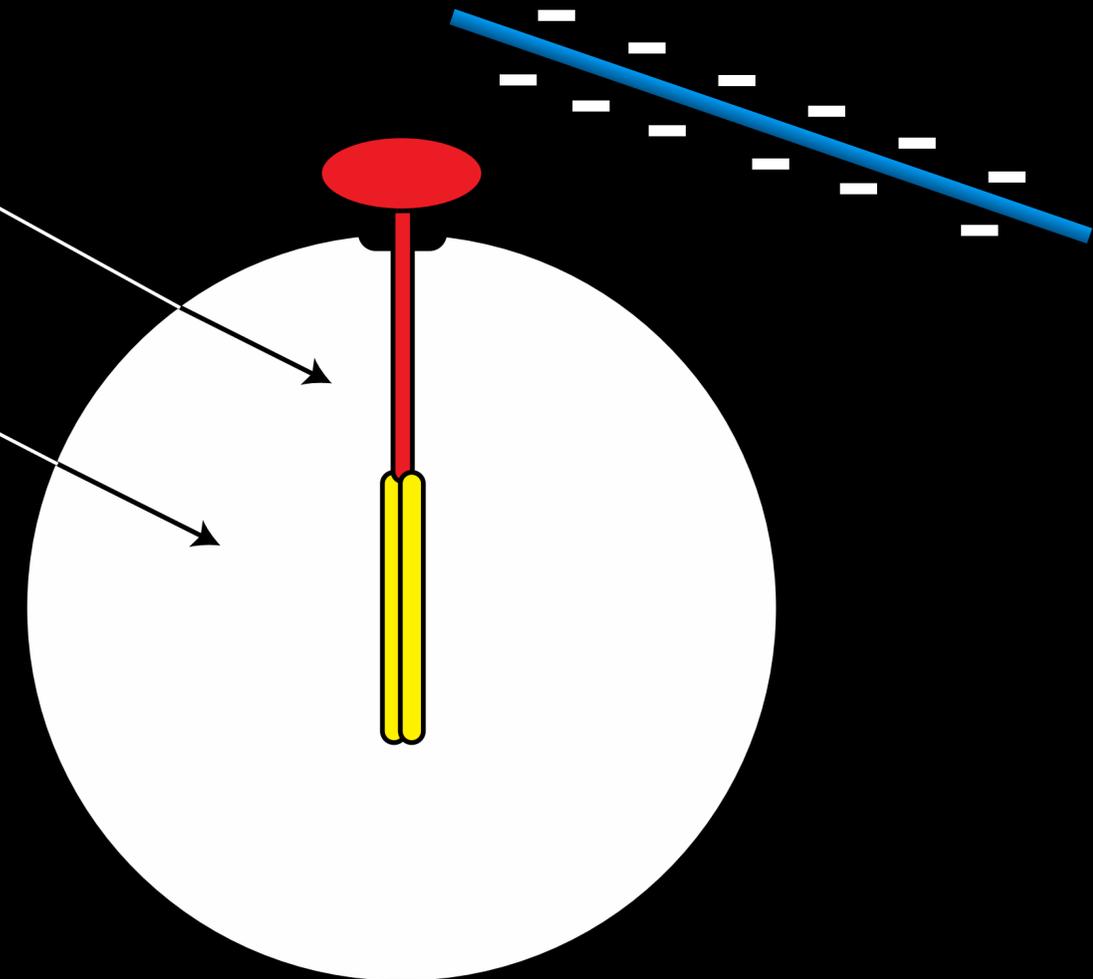
**1901: découverte d'un rayonnement ionisant**

## Electroscope



Barre métallique

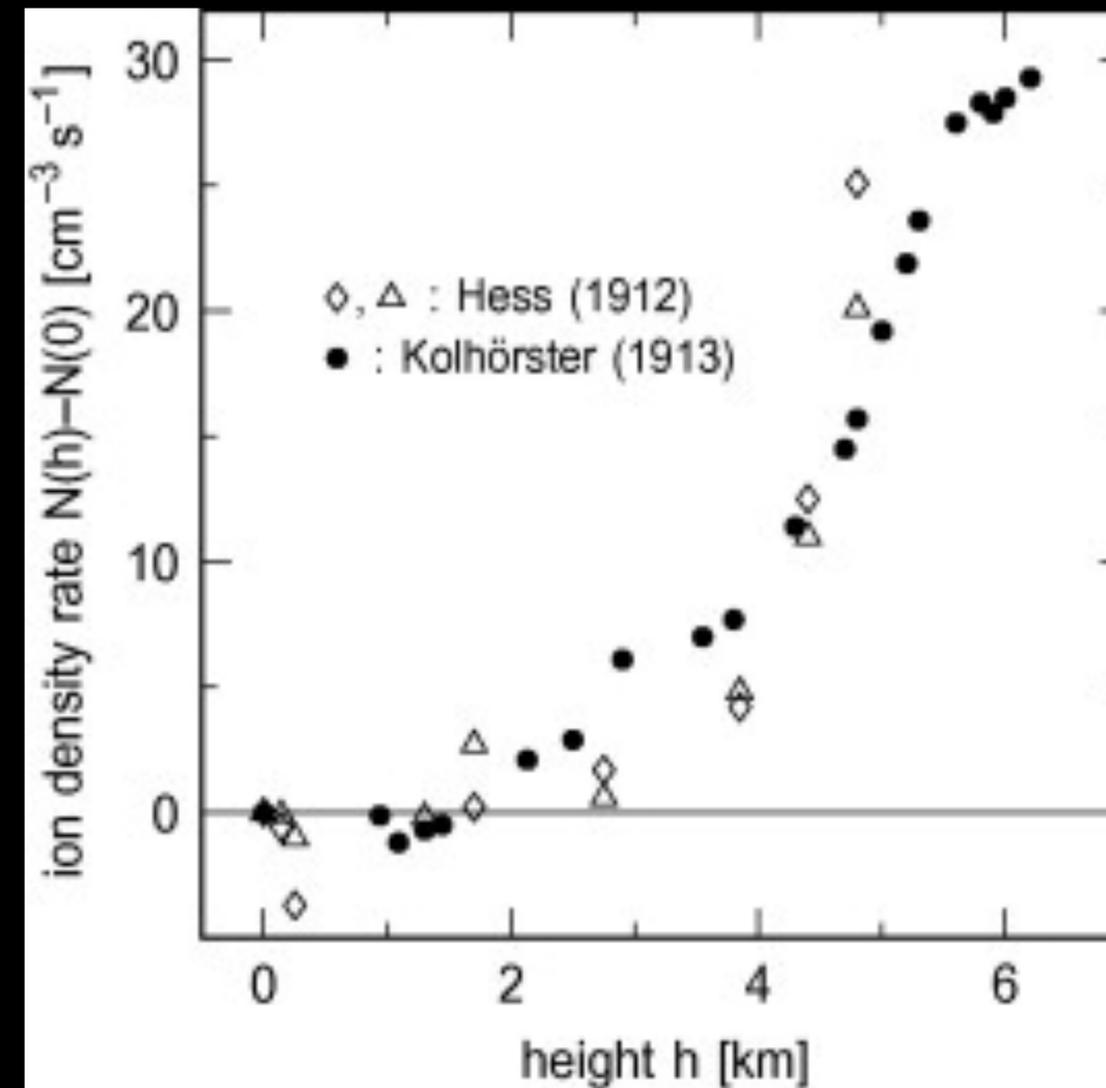
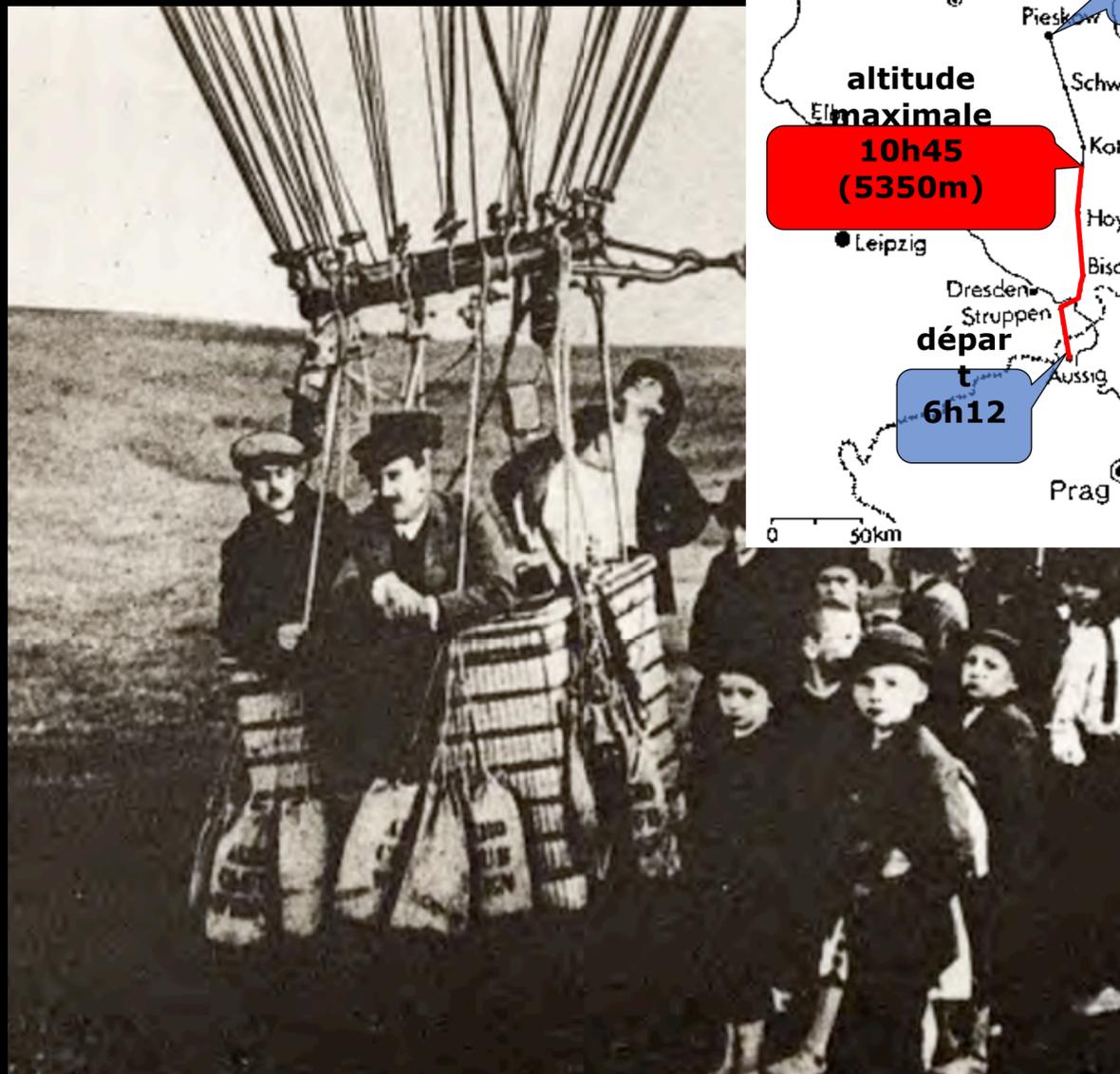
Feuille d'or



Radioactivité des roches?

# Un "rayonnement" venant de l'espace

1911-1913: 10 vols de Victor Hess



L'intensité augmente avec l'altitude

1912: mesure pendant une éclipse de Soleil → rayonnement extrasolaire!

# Rayonnement ou matière



**Millikan**

Rayons gamma  
Rayons cosmiques"



**Compton**

Particules chargées  
Electrons?

Two Nobel Prize Winners Expound Rival Theories of the Cosmic Ray

## NEW DATA CHALLENGE COSMIC RAY THEORY

Compton Reports Findings That Undermine Millikan Hypothesis Creation Is Still Going On.

VARYING INTENSITY SHOWN

Scientists

COVER A WIDE RANGE

California Physicist Reveals He Plans New Studies With Use of Balloons and Planes.

## ADDED DATA ON RAY DISPUTE MILLIKAN

Prof. Compton Lists Evidence of Tests in Peru as Upsetting the Light-Wave Theory.

FORCE RISES WITH ALTITUDE

Electronic Explanation of Cosmic Rays Also Held Confirmed by Variations With Latitude.

In the current number of the Physical Review Professor A. H. Compton summarizes the results of his South American studies of the cosmic rays and piles up more evidence to show that the rays are not light-waves, as Professor Robert A. Millikan supposes, but true electrons

## THE WEEK IN SCIENCE: THE DEBATE CONCERNING THE COSMIC RAYS

The Views Held by Millikan and Compton as They Affect Our Picture of the Universe—Comets That Strike the Earth—Explaining Why the Stars Shine

By WALDEMAR KAEMPFERT.

THE debate between Dr. Millikan and Compton that enlivened the meeting of the American Association for the Advancement of Science made it clear that physicists cannot yet claim to know what the cosmic rays are and whence they come. Dr. Millikan was far more positive in his assertions than Dr. Compton. Nothing is retracted from the views advanced by Millikan seven years ago. Indeed, he thinks his case is stronger than ever because of the work that he and Dr. Anderson of his laboratory have done since then. Probably physicists as a whole lean more to Compton's view that the rays are high-speed electrons, and that they originate either in outer space or on the fringe of our atmosphere, and this because physicists are naturally conservative.

space in the form of super-X-rays, he points out that we may look for an effect something like that which occurs in an X-ray tube.

X-rays are produced when fast electrons strike a target of metal. Similarly, high-speed electrons may simply set up super-X-rays by hitting atoms of air. Accordingly at lower altitudes we may find a mixture of both photons (super-penetrating X-rays) and electrons. That something like this can occur has actually been shown with the aid of X-rays by Dr. Gordon L. Locher, who also spoke of his experiments at Atlantic City. He made the discovery while he was experimenting with cosmic radiation.

prospector are bound to detect iron. Meteorites are almost pure metallic iron. Ore is a form of rust (oxide) and not nearly so responsive to electrical tests.

Why the Stars Shine.

IN order to explain why the stars have been radiating heat and light for billions of years, and will continue to do so for billions more, Sir James Jeans proposed his famous annihilation-of-matter theory. We are to imagine that under the terrific forces that prevail within a star, such as the sun, the protons and electrons of atoms are not simply destroyed, by which we mean converted into vapor or ashes,

are the same. "Hence it is just as proper to speak of a pound of heat as a pound of ice," explains Professor Russell. The excess mass becomes radiation. "A pound of heat is a large amount—large enough, in fact, to melt 30,000,000 tons of rock and turn it into white-hot lava."

In the coalescing of protons and electrons to form new atoms he finds the secret of starlight.

Professor Russell adopts the theory of Dr. Werner Heisenberg, propounded soon after the neutron was discovered and discussed in these columns, to explain this atom-building process. According to Heisenberg, atomic nuclei are built up of protons and neutrons. If a nucleus

are unsatisfactory. We stand amid a heap of speculations that have been demolished by mathematical analysis.

Kant and Laplace thought that the solar system was once a whirling mass of gas that cooled and contracted. Professors Chamberlin and Moulton gave us the tidal theory, since elaborated by Jeffries and Jeans, according to which a passing star pulled out of the sun streams of gas that congealed into the planets. Buffon and latterly Jeffries have tried to account for the solar system by supposing that there was a grazing collision between the sun and a star.

In all these speculations only me-

## MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

Clash of Rival Theorists Unfolds Drama to Session of Nation's Scientists.

THEIR DATA AT VARIANCE

Findings of His Ex-Pupil Thrust by Millikan as Cautious' Work.

## MILLIKAN'S DATA CONFIRM COMPTON

Results of Cosmic Ray Study at Panama Tend to Back Rival's Ideas.

RAY INTENSITY VARIES

Strength Is Greater at the Poles—Equatorial Tests Are Now Projected.

PASADENA, Cal., Feb. 4 (AP).—The stratosphere above equatorial regions of the earth should be the next scene of exploration in the quest of the secrets of the cosmic ray, Dr. Robert A. Millikan said here today.

Announcing that observations of his co-workers at Panama confirmed the earlier reports of Dr. Arthur H. Compton of Chicago that the rays from interstellar space showed latitude effects, Dr.

RUSSELL

## COSMIC RAY RIVALS TO MEET IN DEBATE

Clash of Millikan and Compton Theories to Form High Point at Scientific Convention.

4,500 TO ATTEND SESSIONS

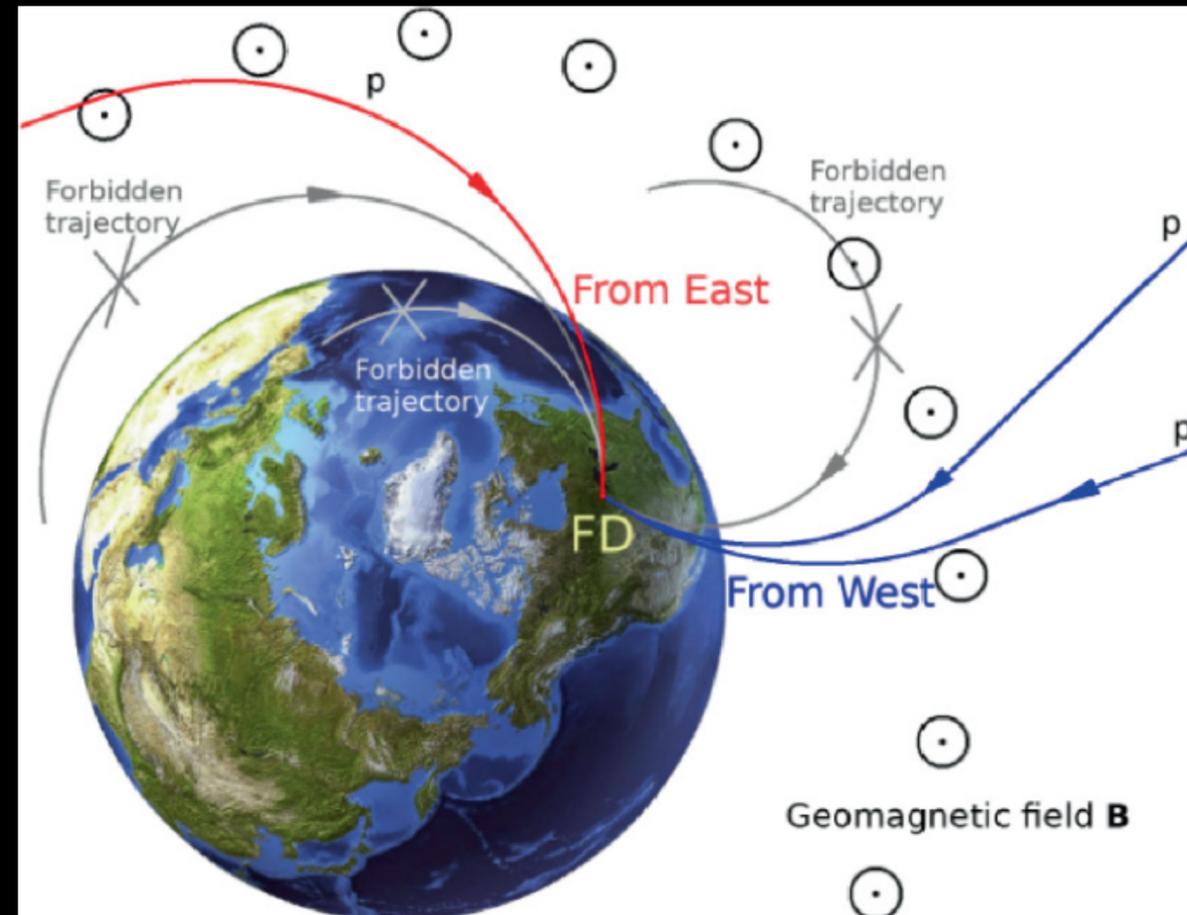
Atlantic City Meeting This Week to Hear 1,500 Papers—Gerard Swope to Speak on Unemployment.

Special to THE NEW YORK TIMES.

ATLANTIC CITY, Dec. 25.—The nature of cosmic rays, revolving around the specific question whether they enter the earth's atmosphere as electrically charged particles or as photons, will be the subject of debate between two of America's outstanding physicists at the annual meeting of the American Association for the Advancement of Science, which opens here Tuesday.

More than 4,500 scientists, laboratory workers and teachers of science will attend the meeting of the association and its affiliated scientific bodies.

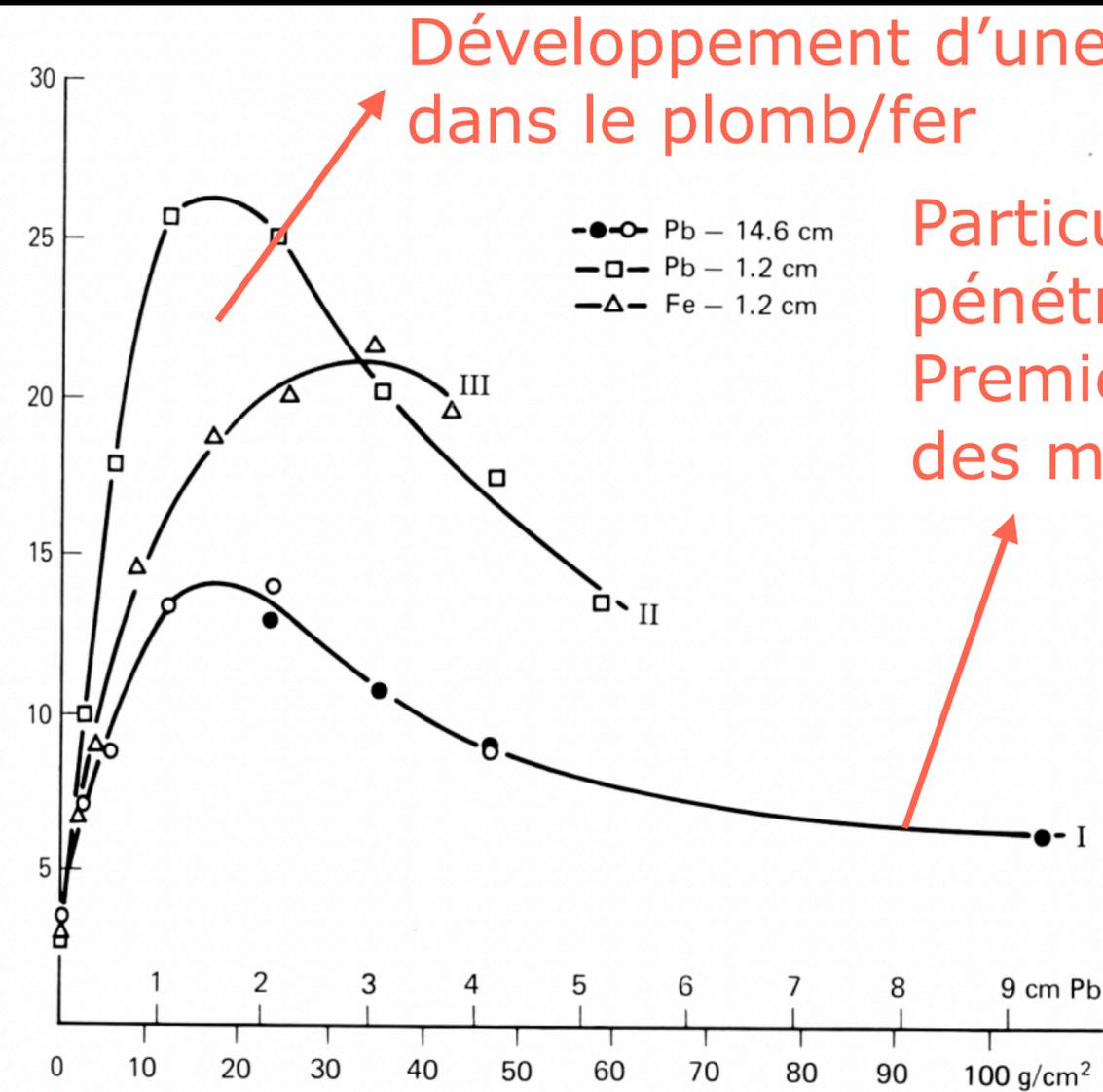
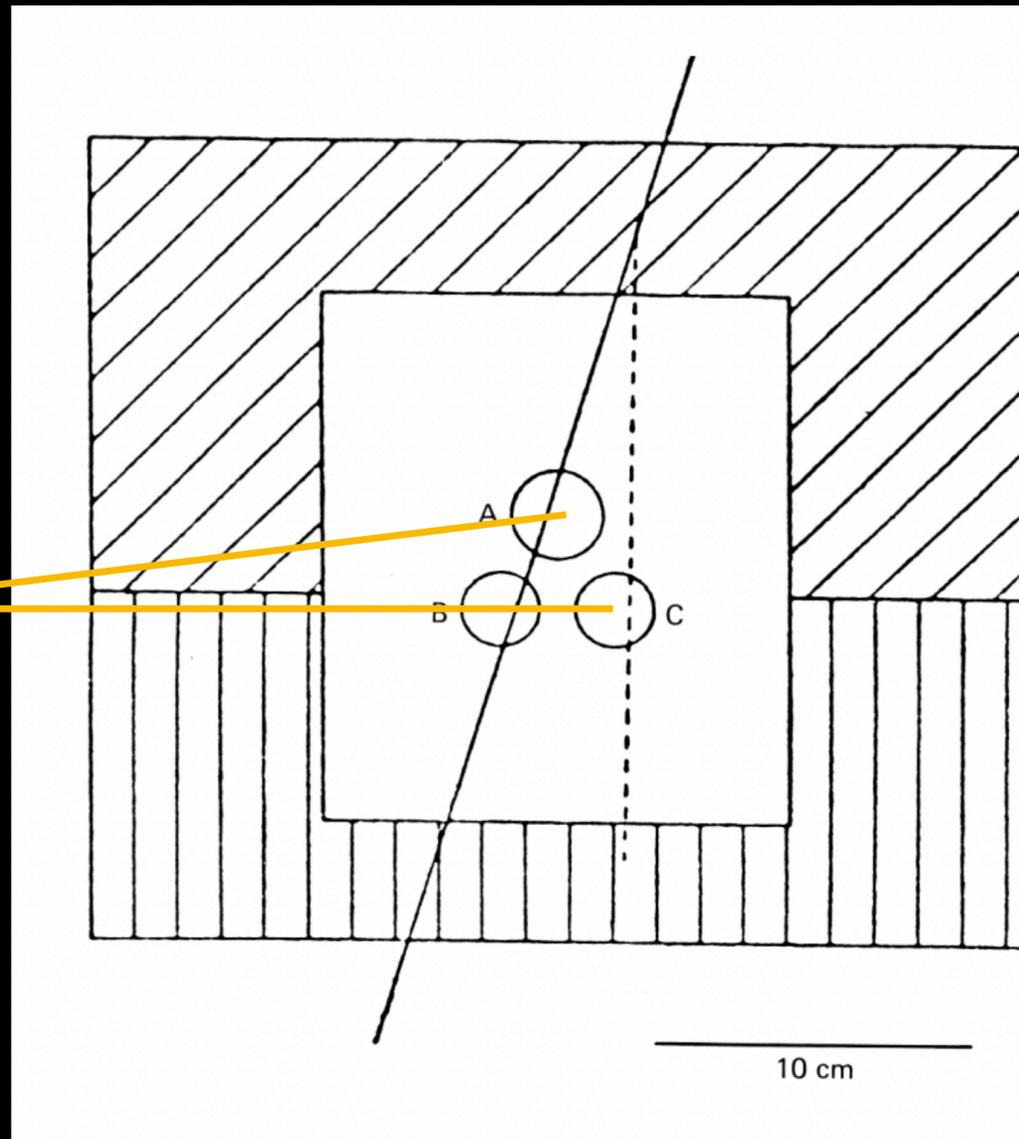
# Les "rayons cosmiques": des particules chargées



- 1932: expédition de Compton — Le rayonnement dépend de la latitude
- 1933: "effet est-ouest" observé par Rossi — Particules chargées positivement

# Rayons cosmiques et gerbes de particules

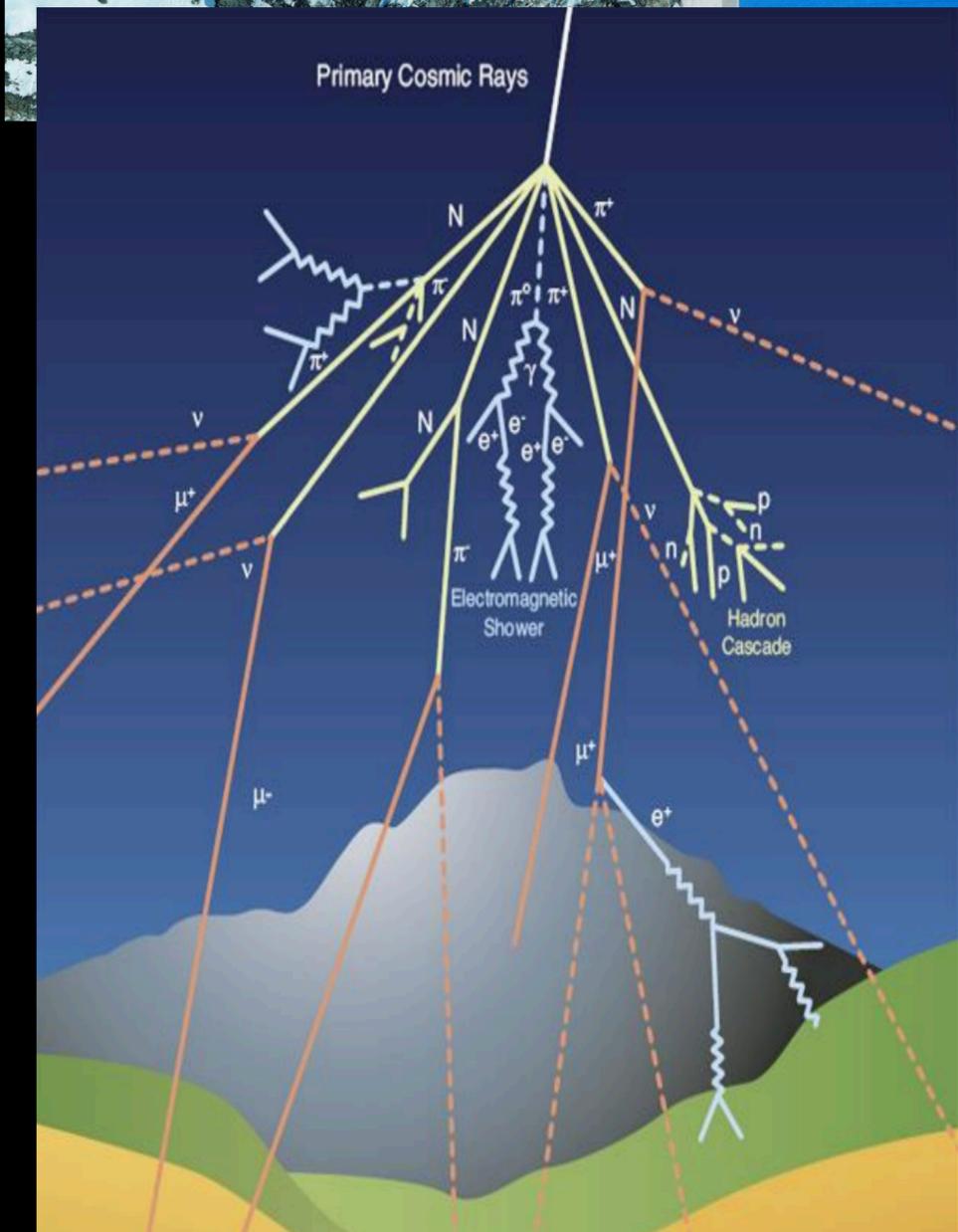
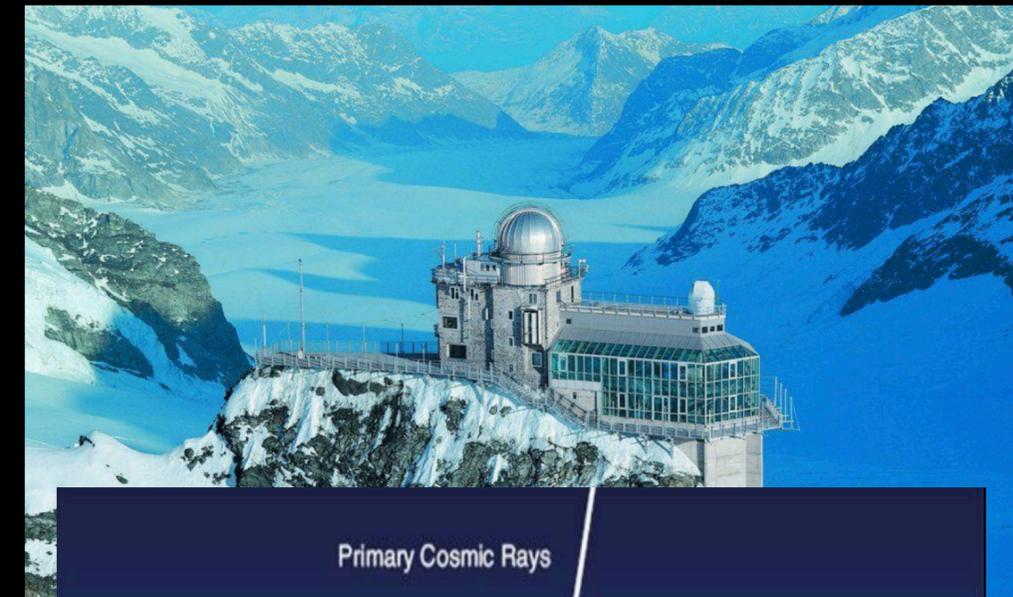
Compteurs  
Geiger  
(détection de  
coïncidences)



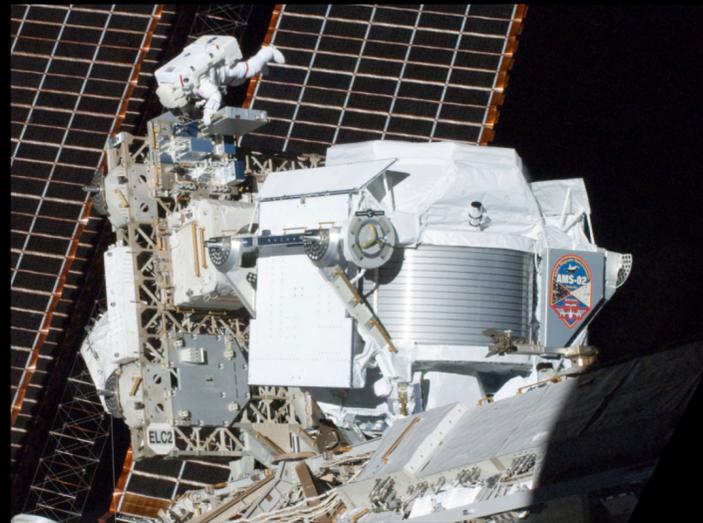
# Les gerbes atmosphériques

## Mesures à grande échelle

- Pierre Auger, 1939: mesures de coïncidences sur des détecteurs de plus en plus espacés, de 1 à 300m
- Découverte de **gerbes atmosphériques étendues**, énergie totale jusqu'à  $10^{15}$  eV
- Découverte de **nouvelles particules**: positron, muon, pion, kaon → **origine hadronique**
- Mot de la fin (Schein, 1940s): **89% de protons, ~11% noyaux, traces d'électrons, positrons et antiprotons**

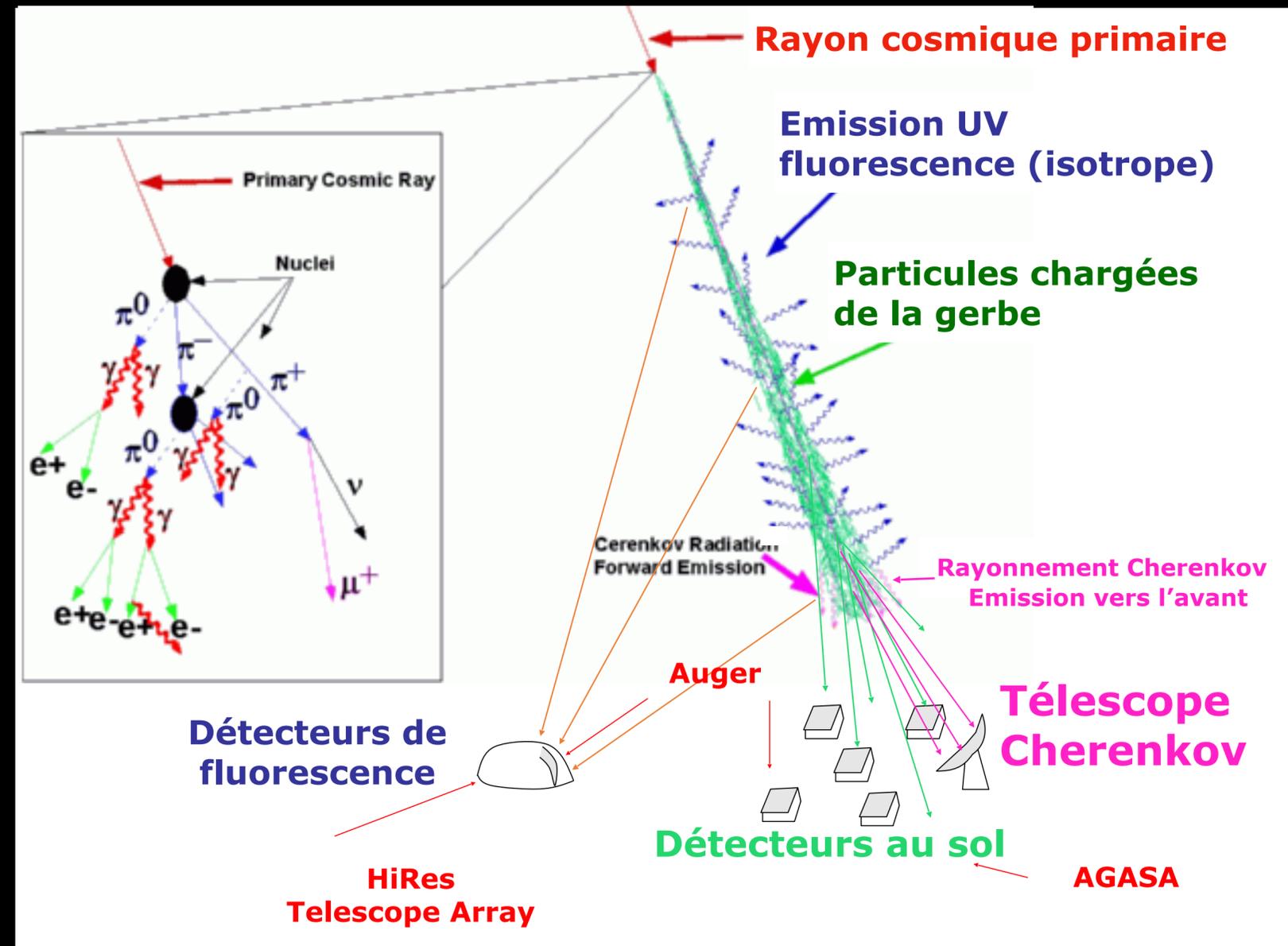


# Détection: principes généraux



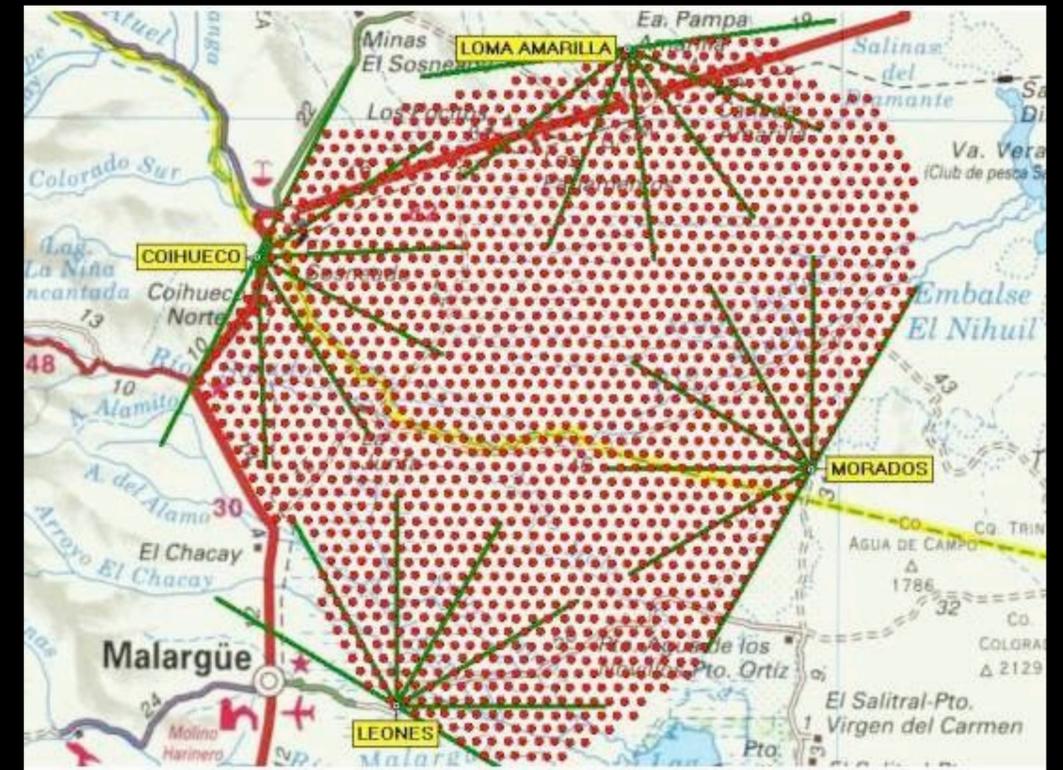
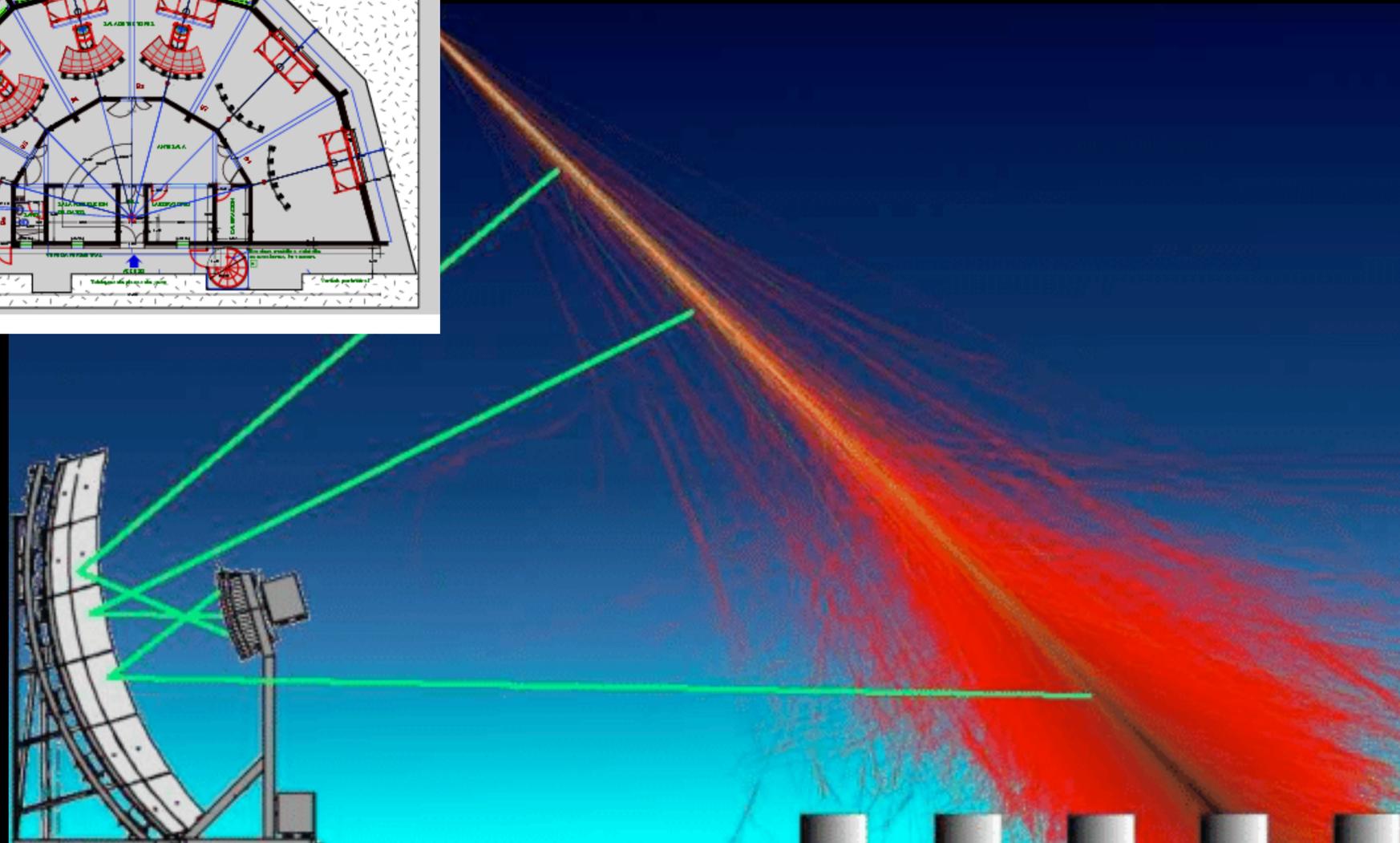
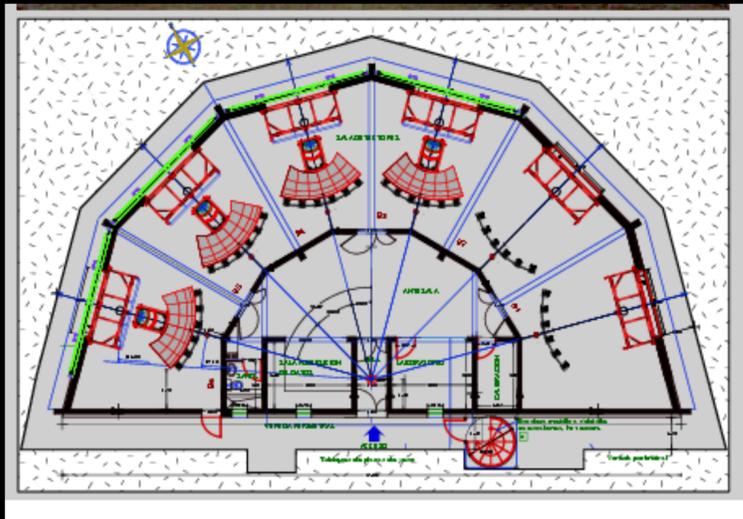
Détection des rayons cosmiques dans l'espace (AMS)

## Détection de la gerbe au sol



# L'expérience Pierre Auger Argentine, Pampa Amarilla, 26 km<sup>2</sup>

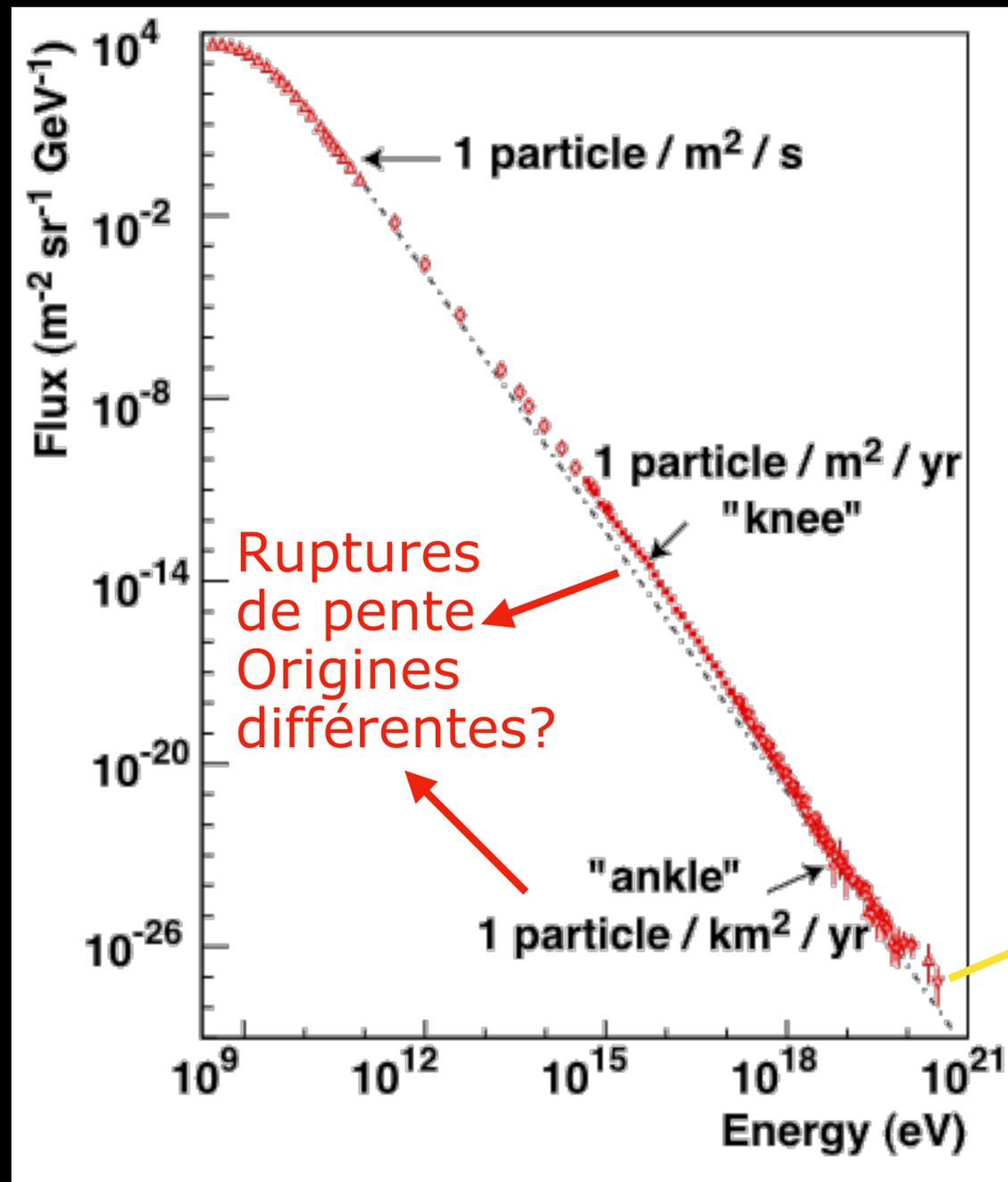
## Détection de fluorescence



## Détection de particules chargées



# Le spectre des rayons cosmiques



Ballons

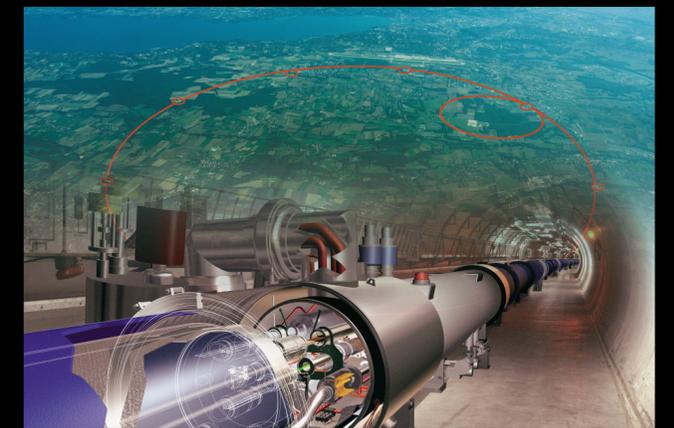
Satellites

Détecteurs au sol



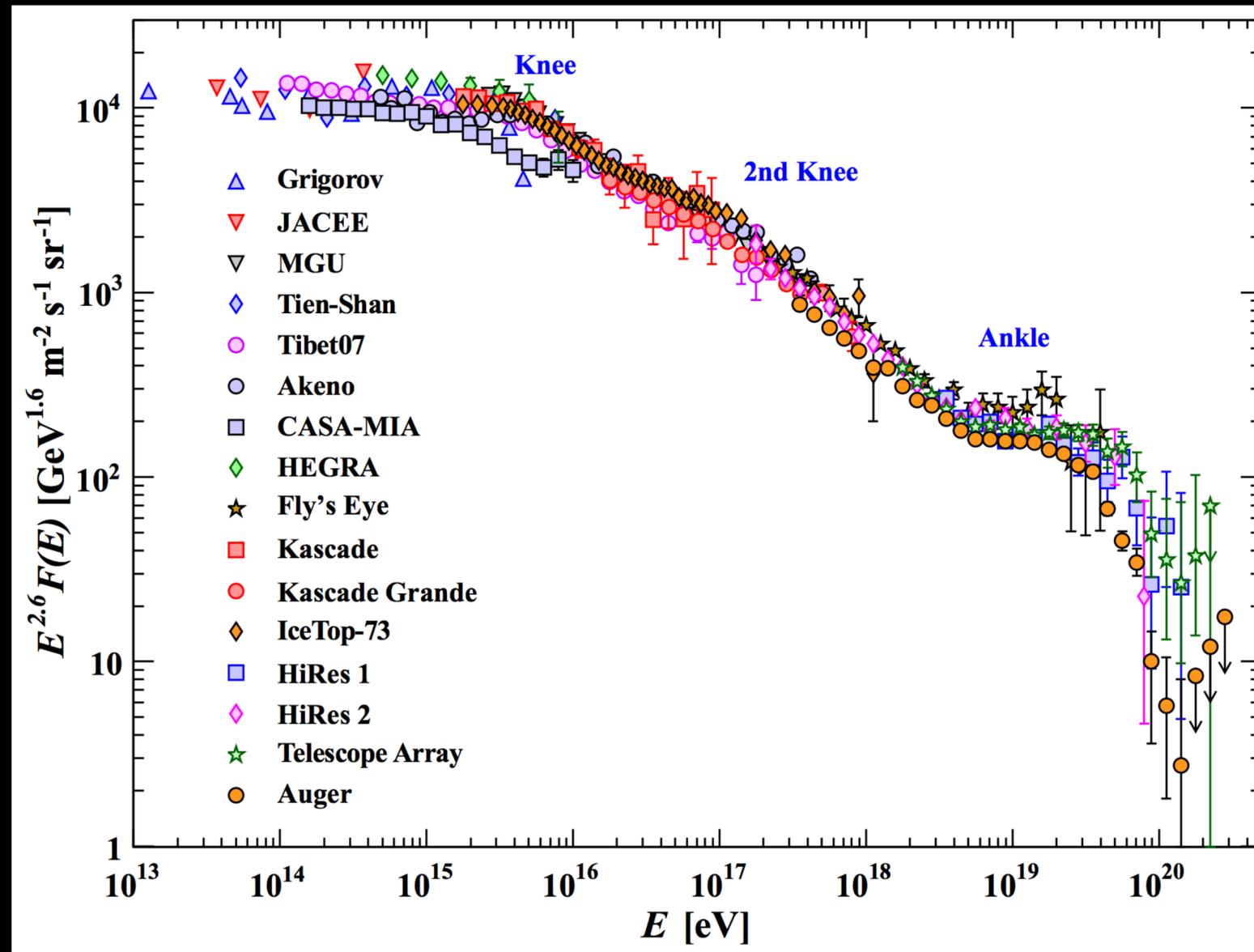
$3 \times 10^{20} \text{ eV} = 50 \text{ Joules!}$

30 millions x LHC

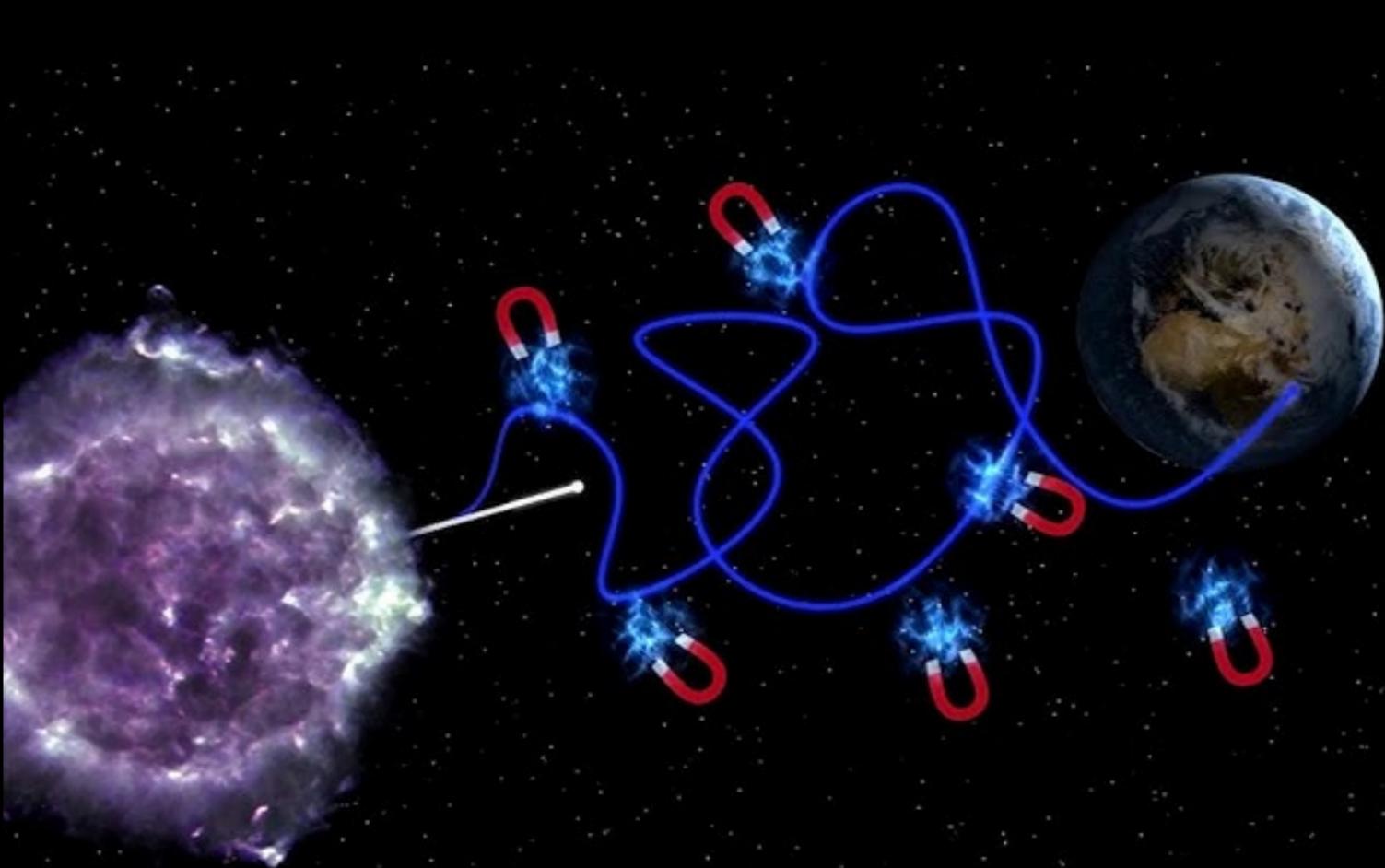


# Le spectre des rayons cosmiques

## Déviations par rapport à la loi de puissance



# Origine des rayons cosmiques?



- Déviation par les champs magnétiques  
→ perte du pointé
- Rayons cosmiques de **très haute énergie**: corrélation restante
- Auger,  $E \gtrsim 10^{19}$  eV: corrélations  
**Noyaux actifs de galaxies** ( $2.7\sigma$ , 2007)  
**Galaxies à forte formation d'étoiles**  
( $4\sigma$ , 2018)

A suivre...

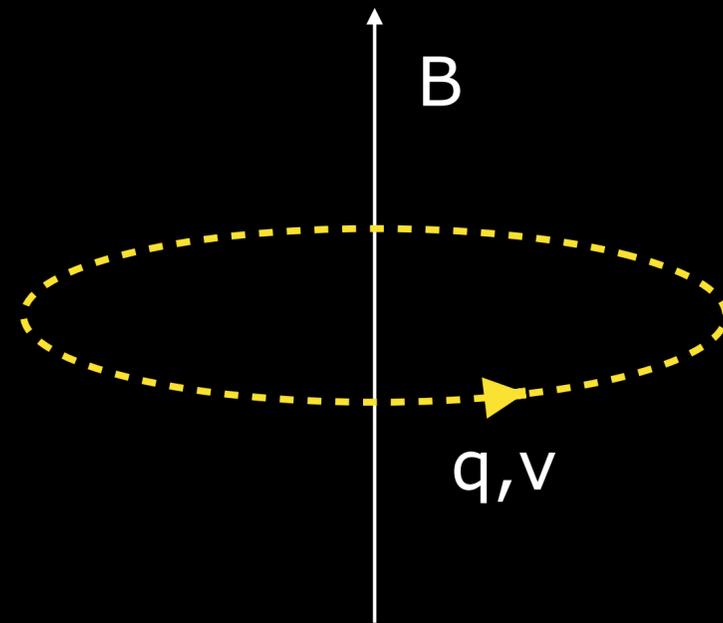
# Origine des rayons cosmiques?

## Candidats possibles

Rayon de Larmor

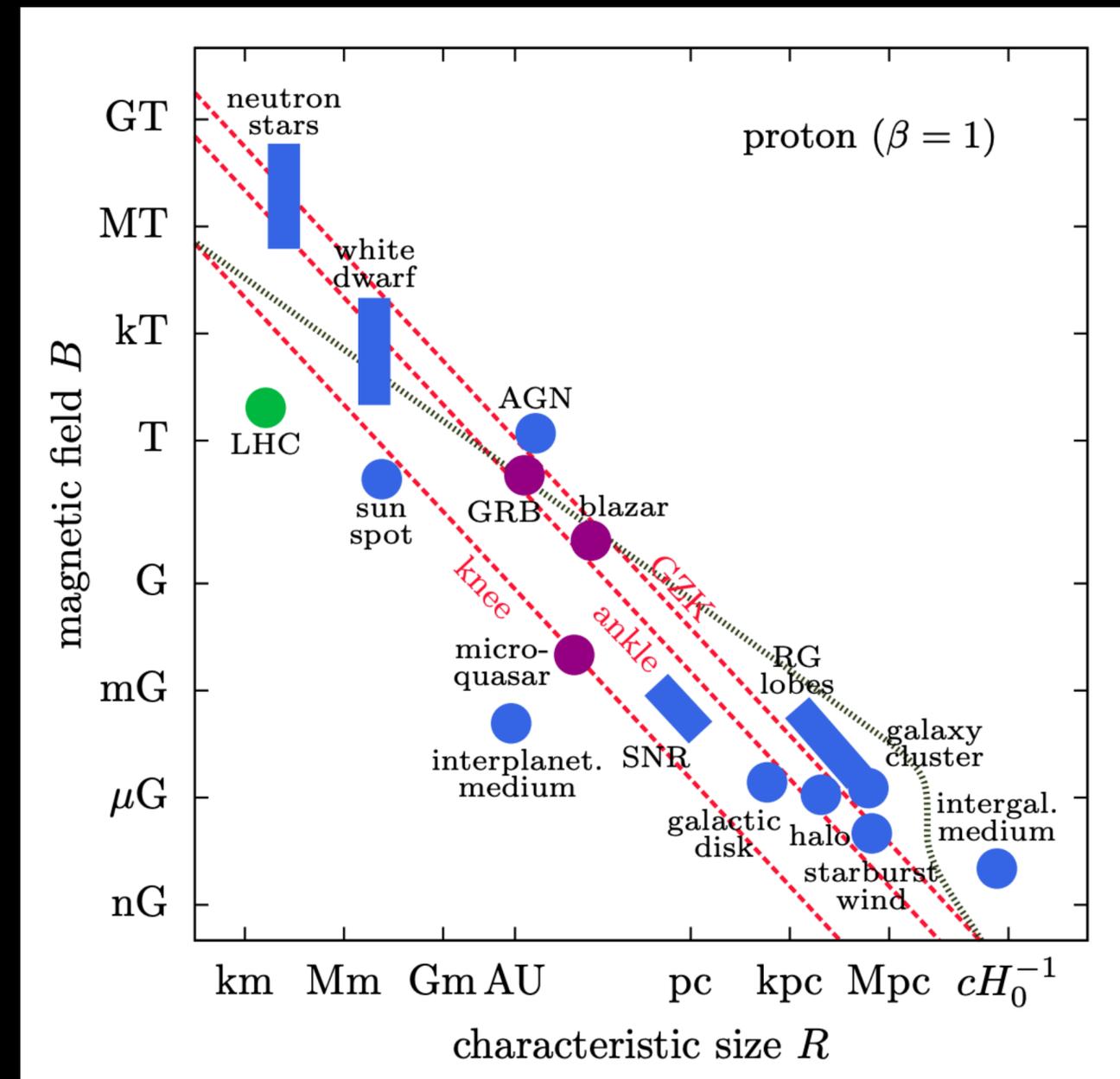
$$qv \times B = mv^2/R_L$$

$$qB = mv/R_L$$

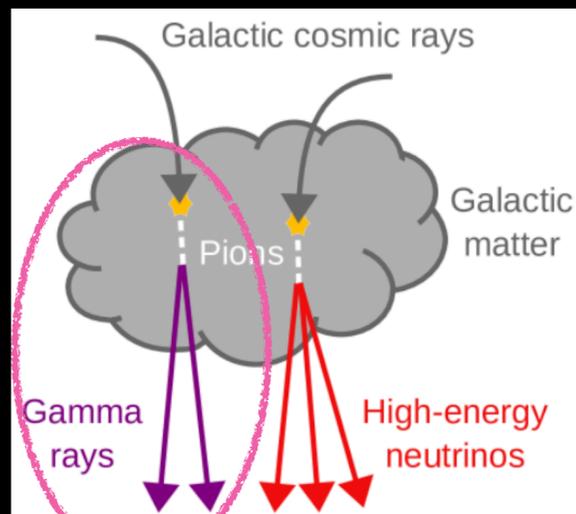


Limite ultra-relativiste:

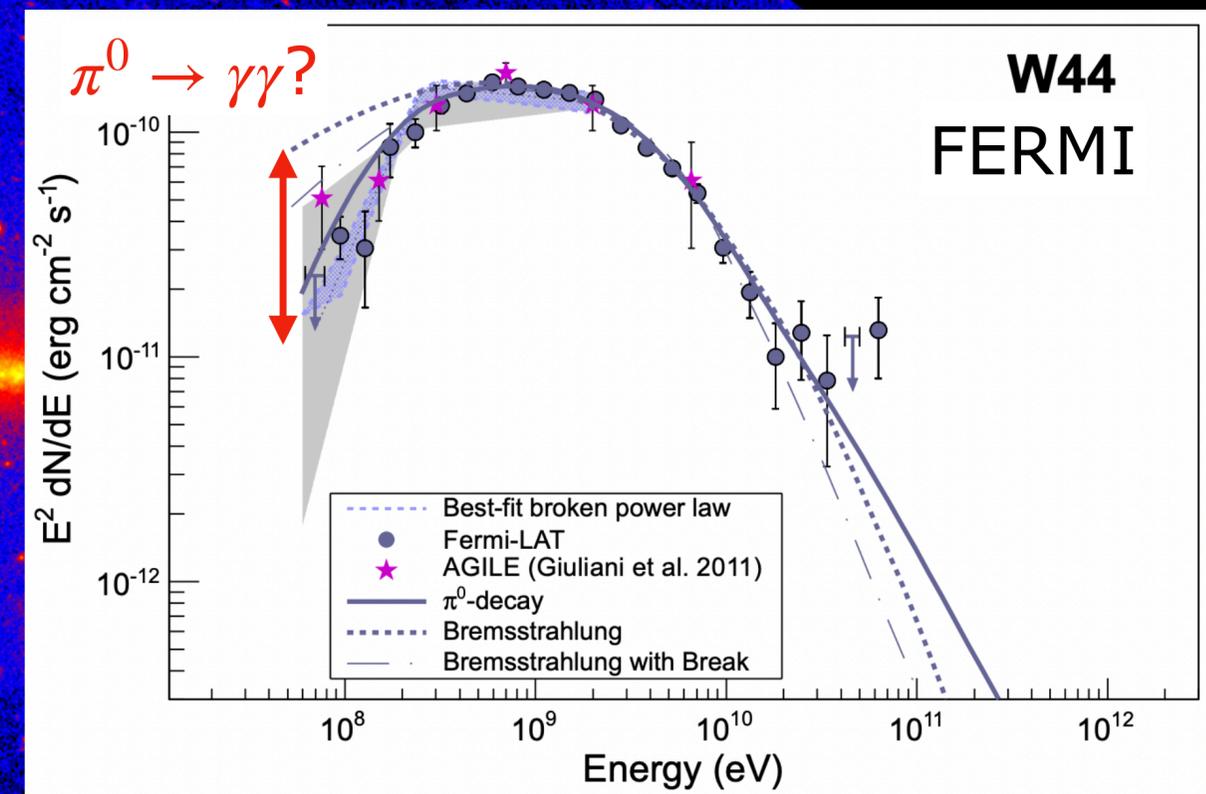
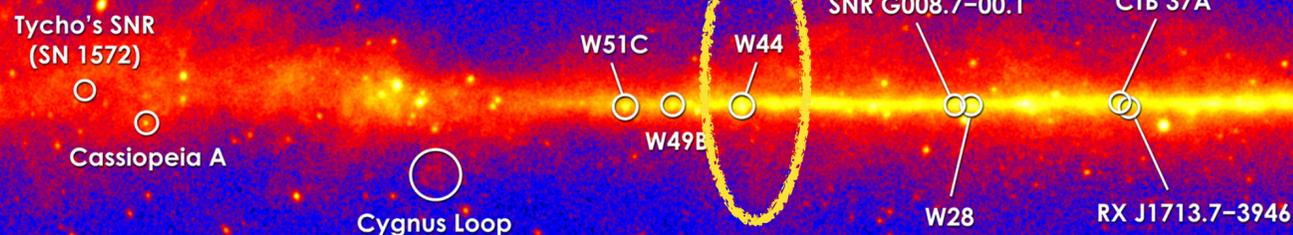
$$R_{\text{source}} \geq R_L = \frac{E}{qBc}$$



# Localiser les rayons cosmiques grâce aux gamma? Sources galactiques – Restes de supernovae?

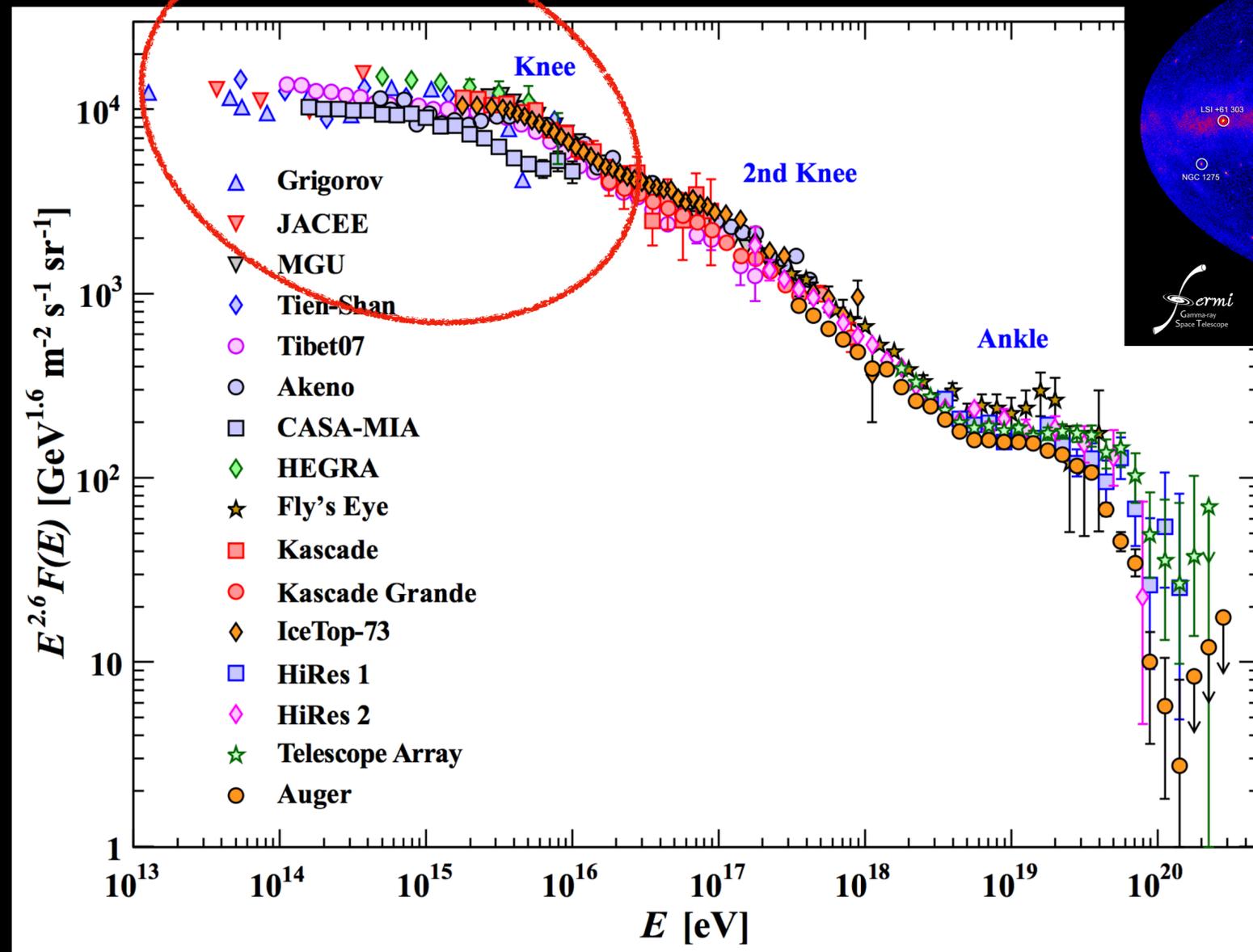


Ambiguïté  
sur le mécanisme  
de production

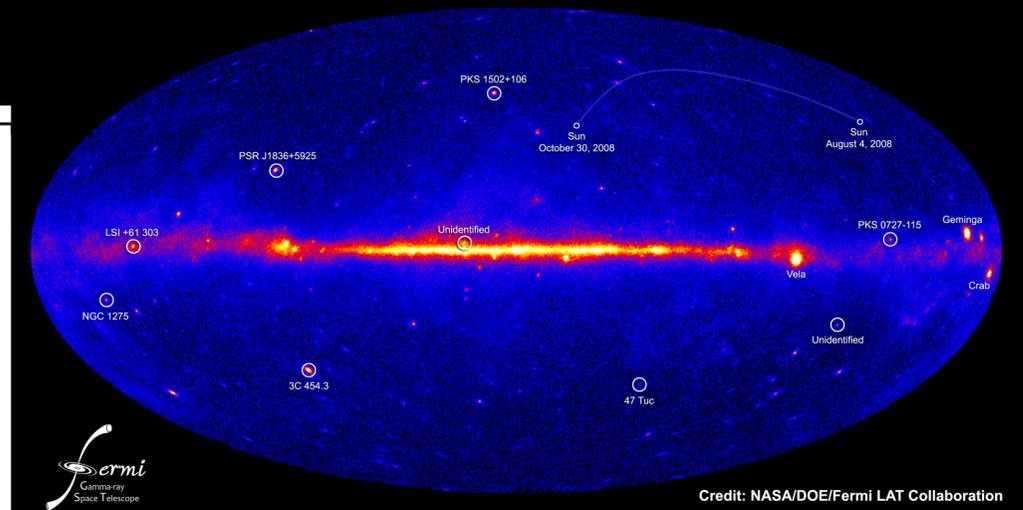


# Origine des rayons cosmiques

Origine galactique possible



NASA's Fermi telescope reveals best-ever view of the gamma-ray sky

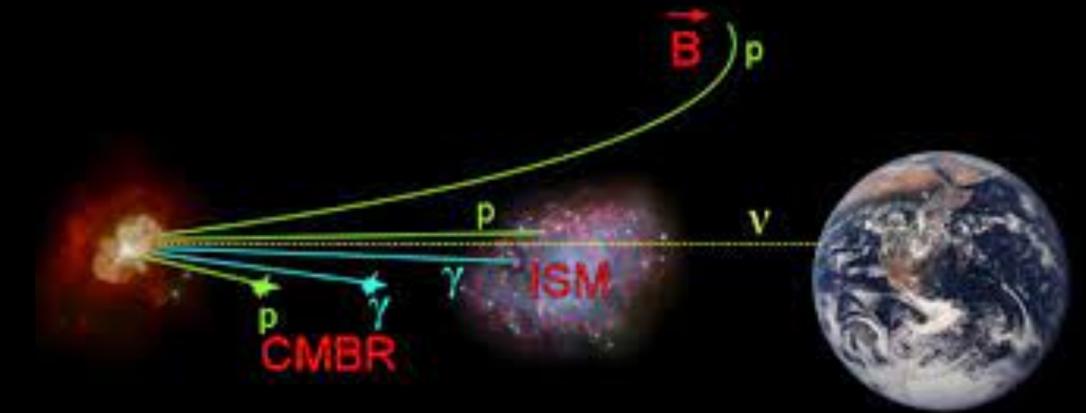
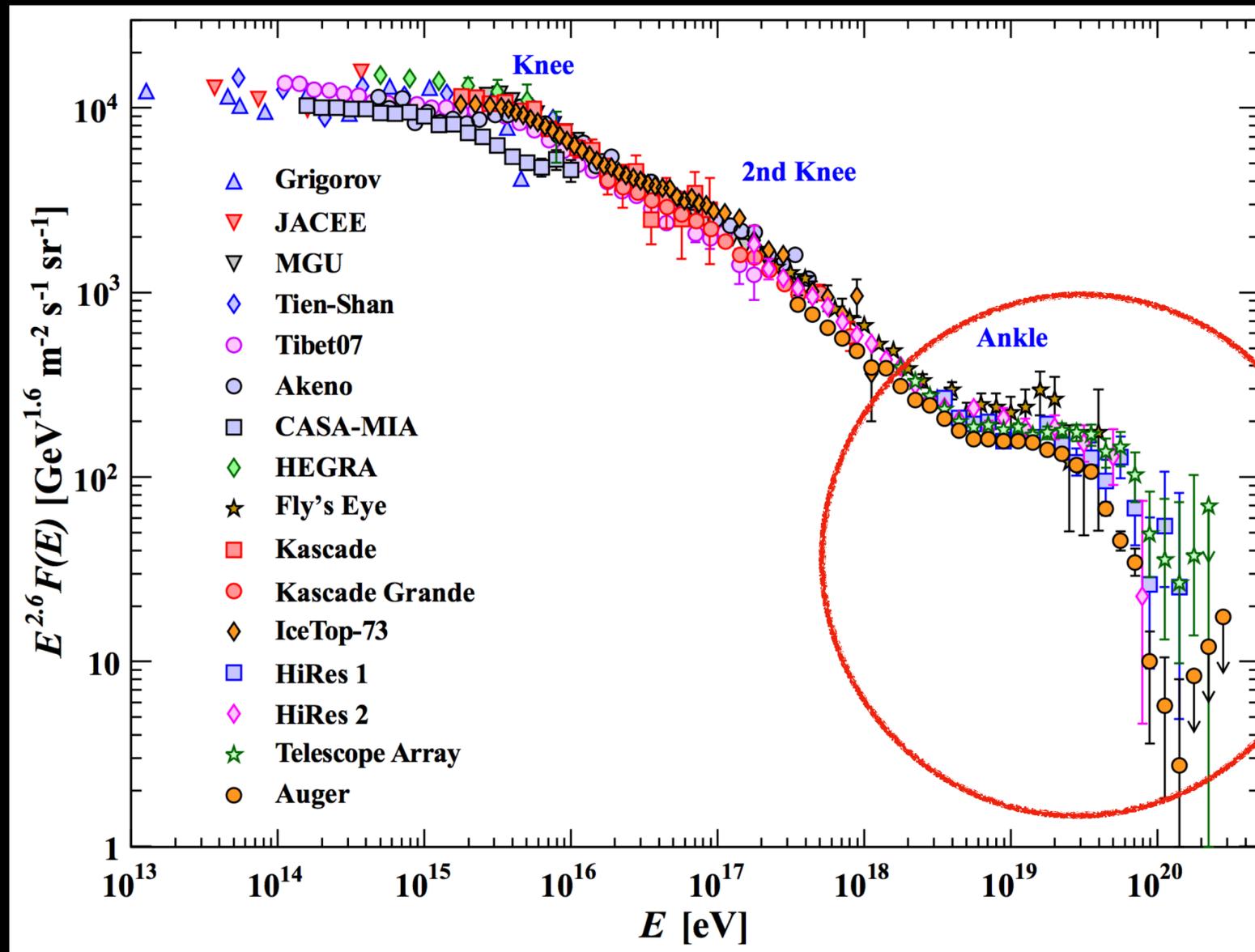


Credit: NASA/DOE/Fermi LAT Collaboration

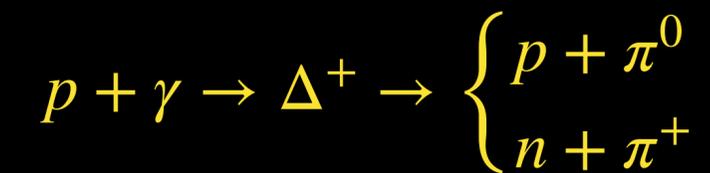
Origine extragalactique

# La fin du spectre

## Coupure GZK (Grinstein Zatsepin Kuzmin)



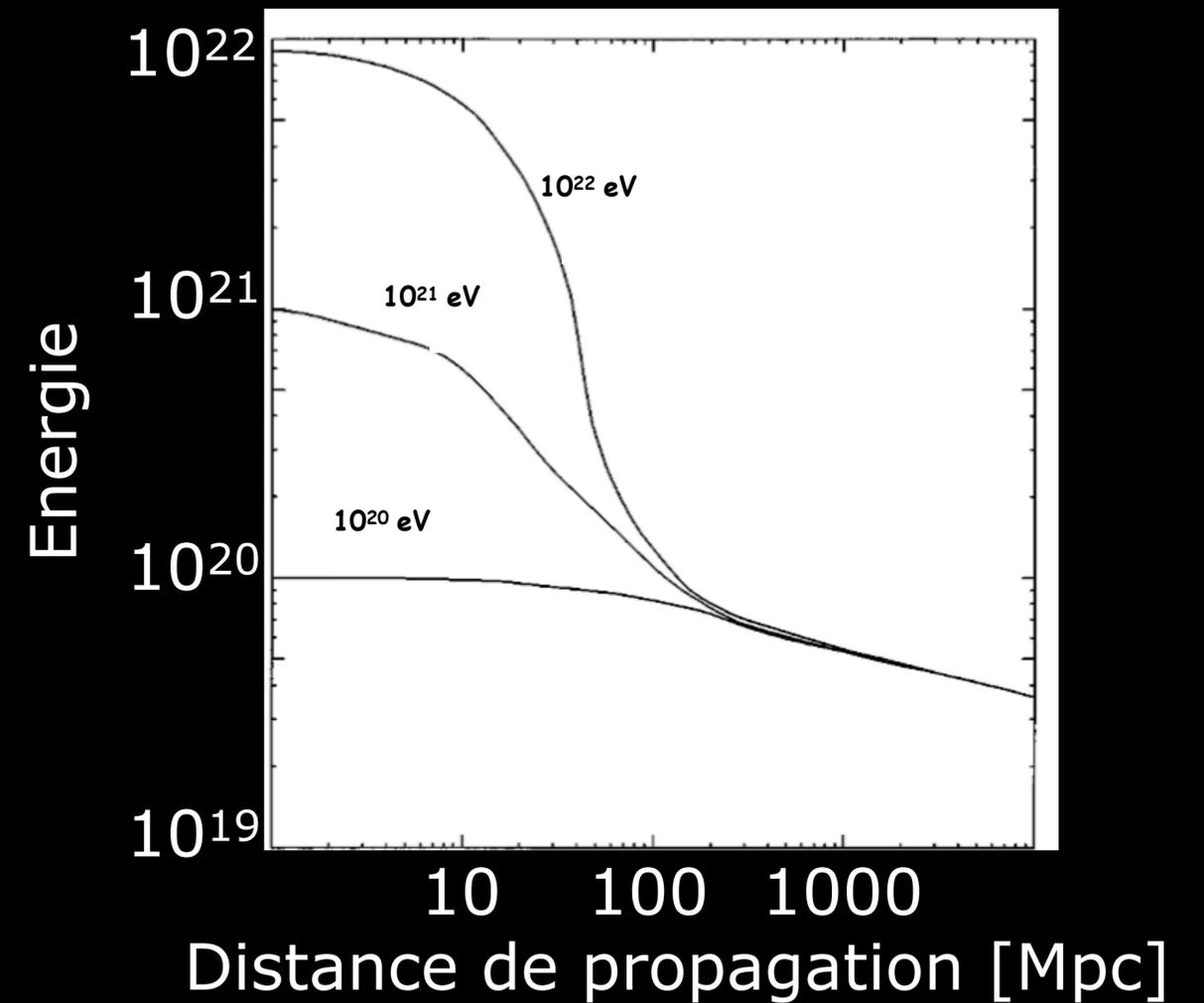
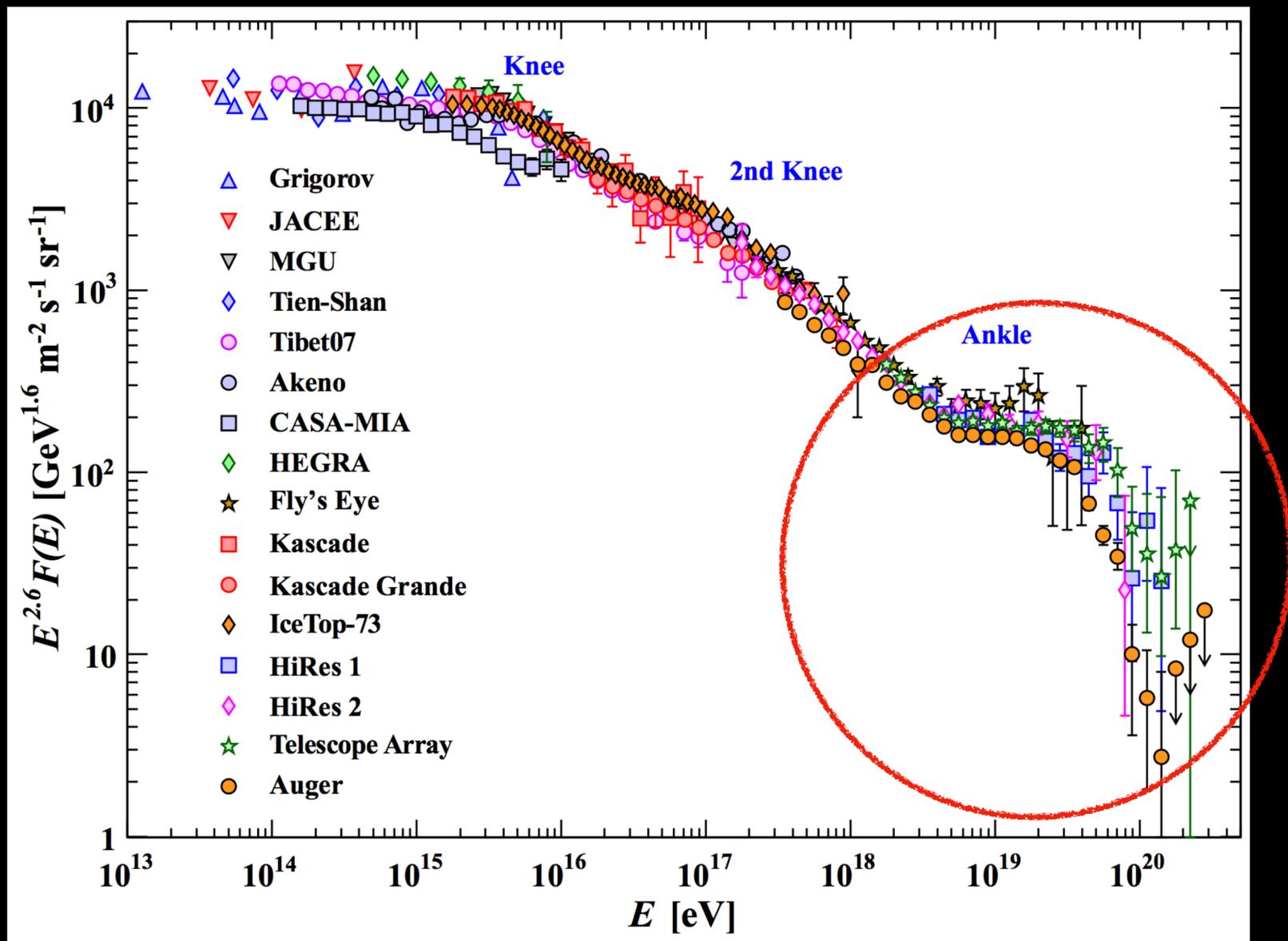
Absorption par le rayonnement de fond cosmologique



$$E \geq 5 \times 10^{19} \text{ eV}$$

# La fin du spectre

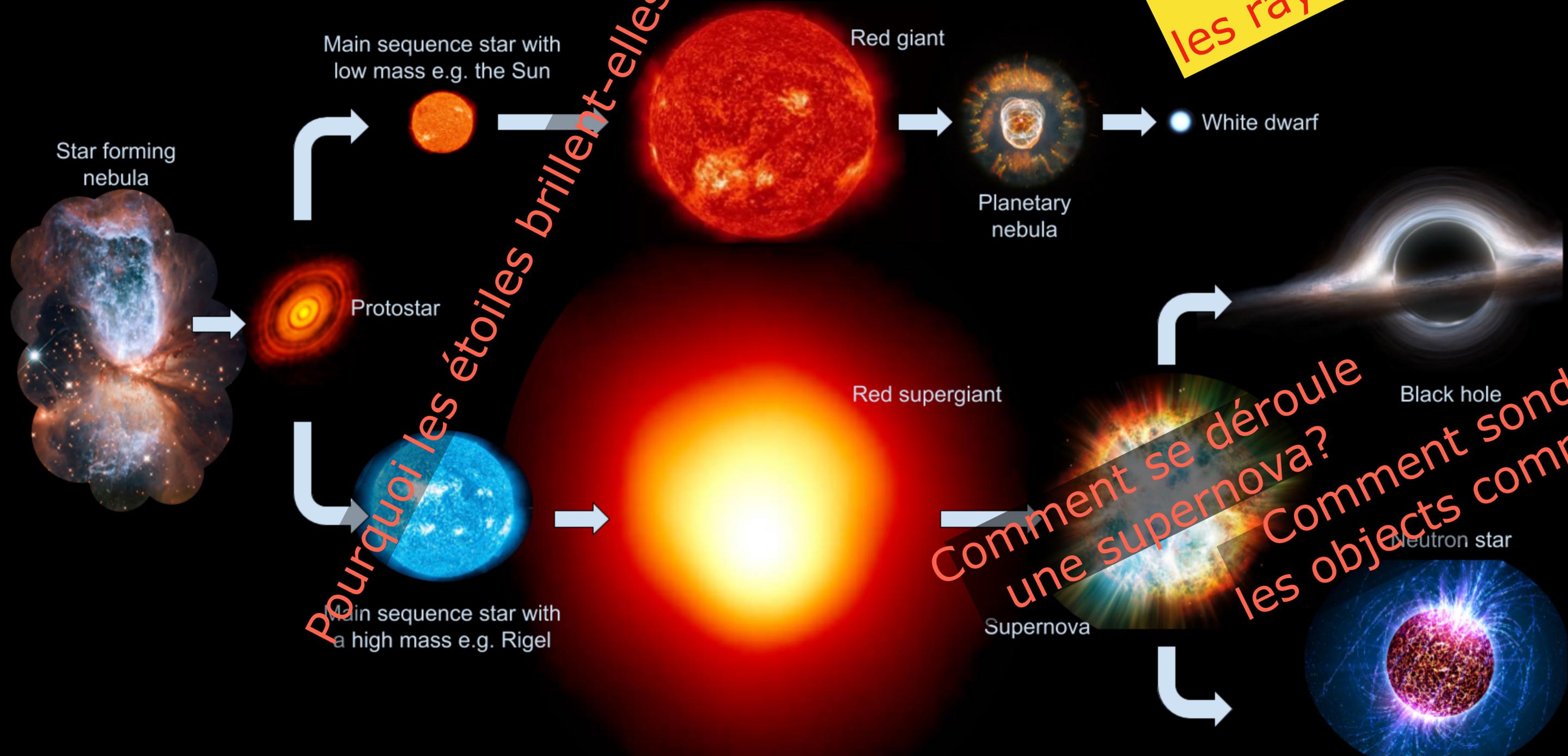
## Des rayons cosmiques lointains?



Propagation impossible sur des **distances cosmologiques (>100 Mpc)**

# Des questions en suspens... Vie et mort des étoiles...et au delà

D'où viennent  
les rayons cosmiques?



Pourquoi les étoiles brillent-elles?

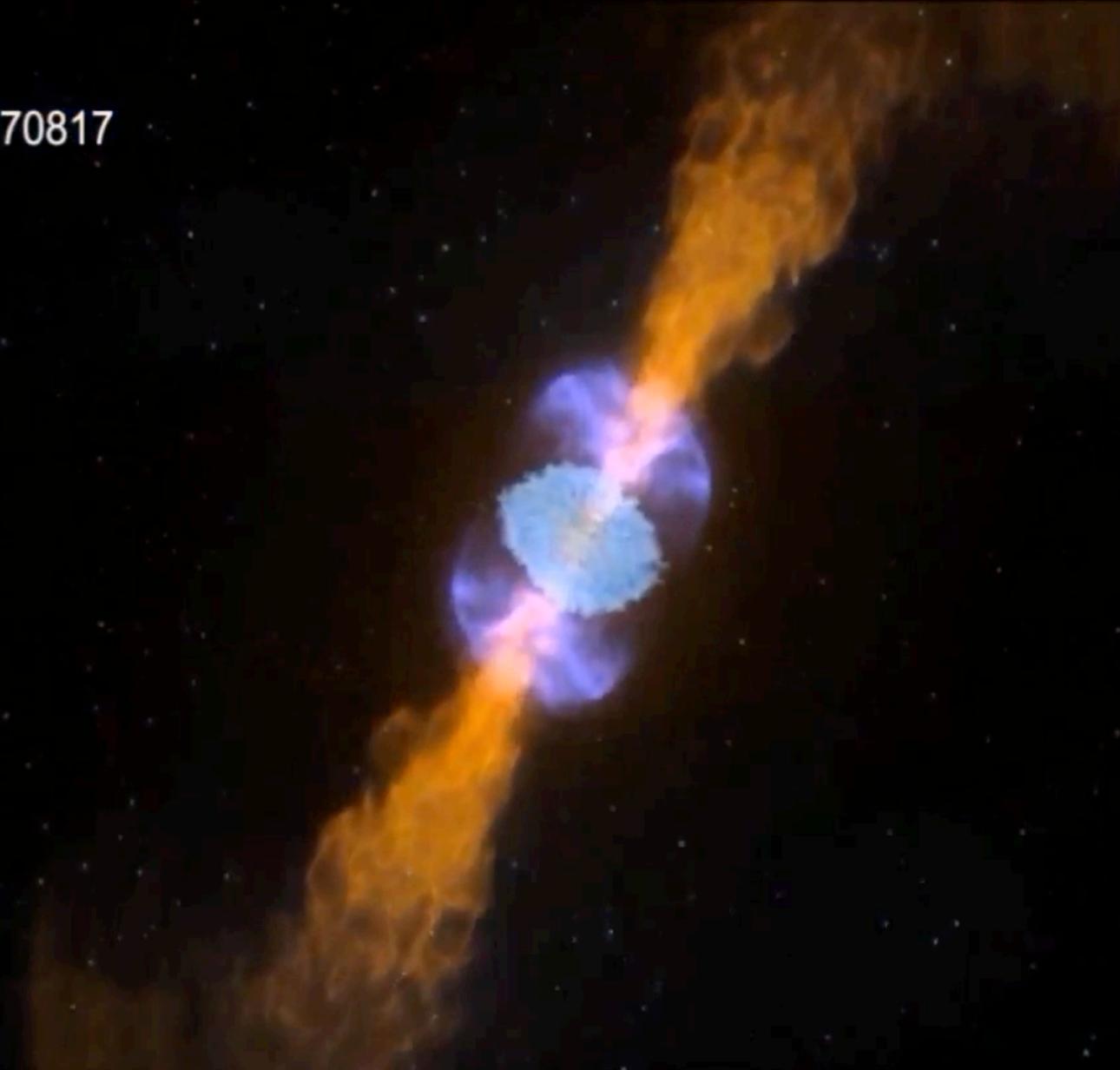
Comment se déroule  
une supernova?  
Comment sonder  
les objets compacts?

# Structure des sursauts gamma

## Hypothèse — Simulation

GW170817

Animation

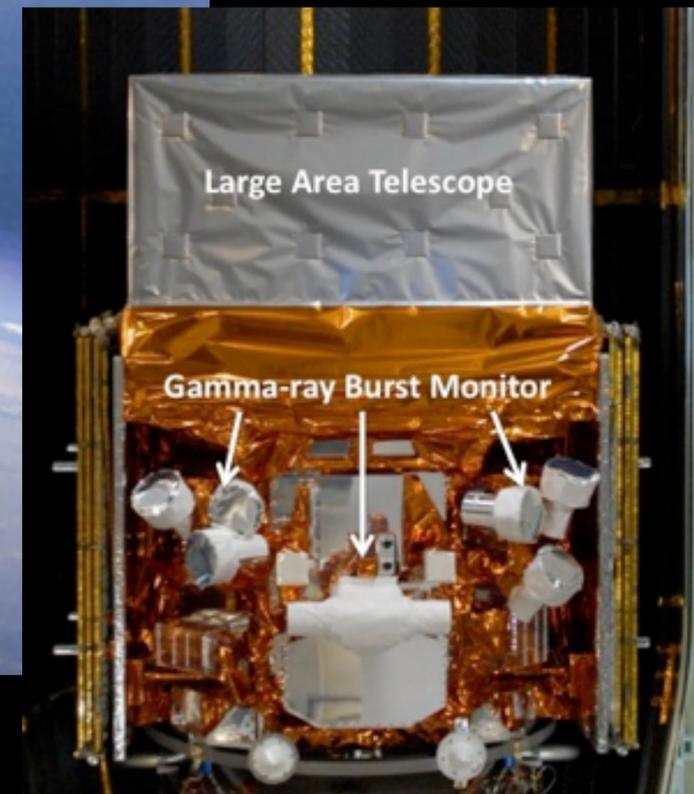


# Observation de sursauts gamma

## Télescope FERMI



Lancement en 2008  
2 orbites = 1 scan complet du ciel



**LAT (20 MeV - 300 GeV)**

**GBM (8keV - 40 MeV)**