# Astroparticle Physics (3/3)

Nathalie PALANQUE-DELABROUILLE
CEA-Saclay

CERN Summer Student Lectures, August 2009

1) What is Astroparticle Physics ?
   - Cosmic Microwave Background
   - Dark energy

2) Dark matter

3) High energy astrophysics
   - Cosmic rays
   - Gamma rays
   - Neutrino astronomy

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   Cosmic rays
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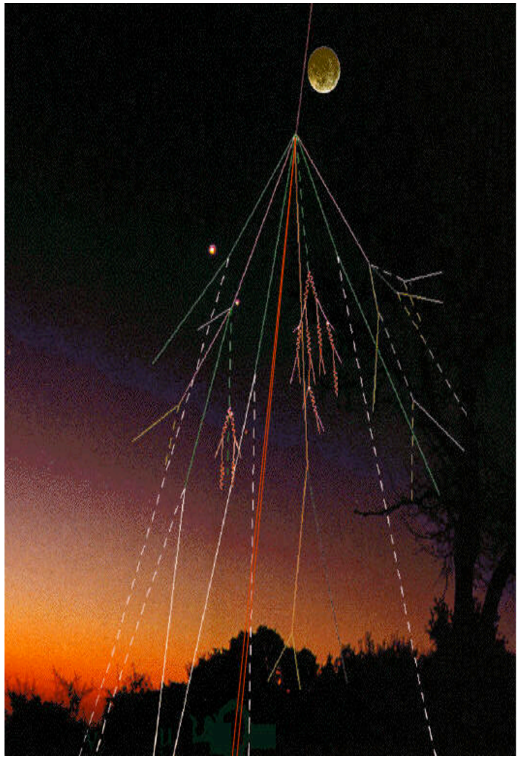
   Neutrino astronomy



# Brief history of Cosmic Ray detection

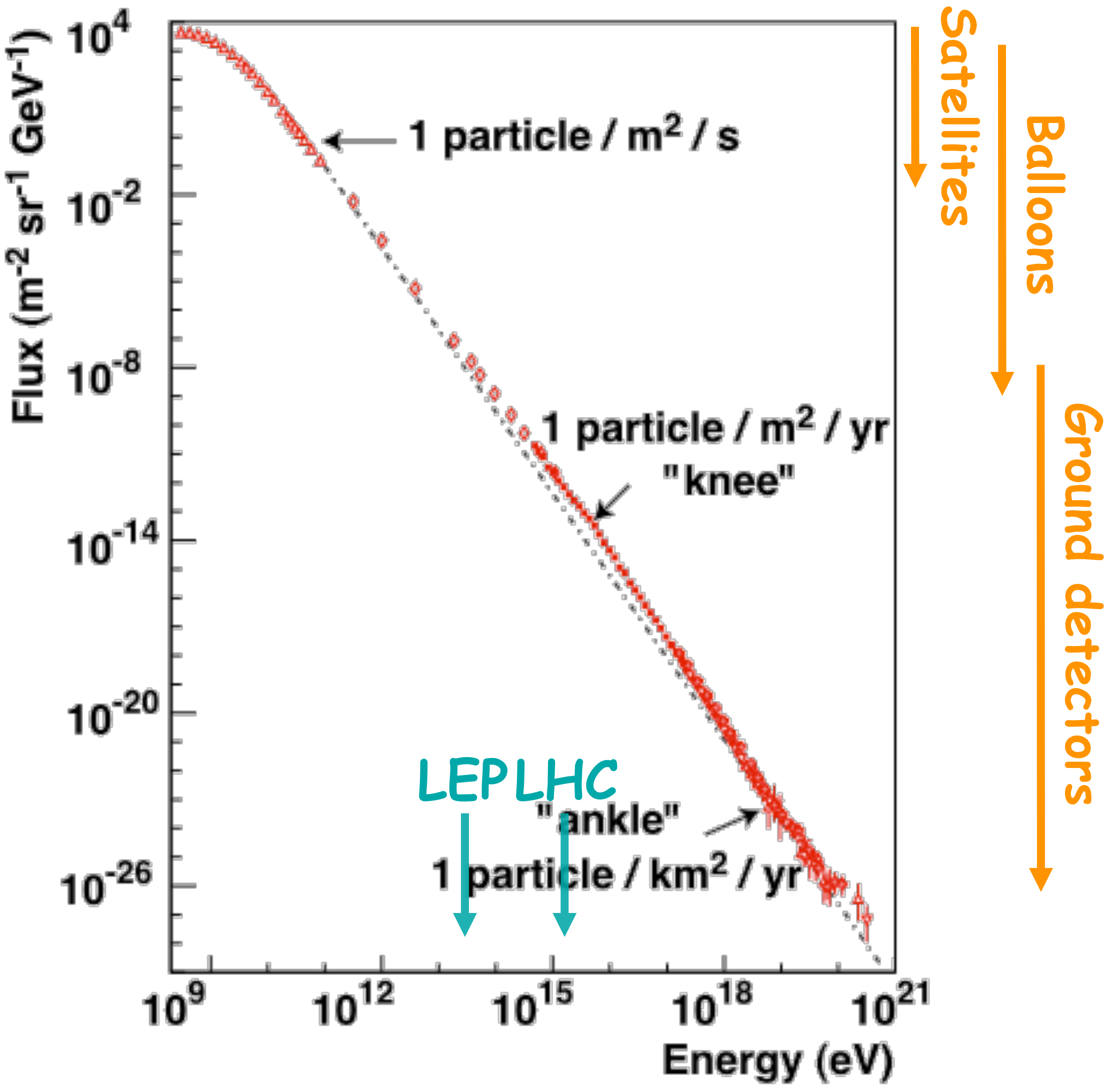
1912 Hess discovers cosmic rays

1925 Quasi-isotropy

1938 Auger discovered extensive air showers ($E = 10^{15}$ eV!)

1946 First air shower experiment

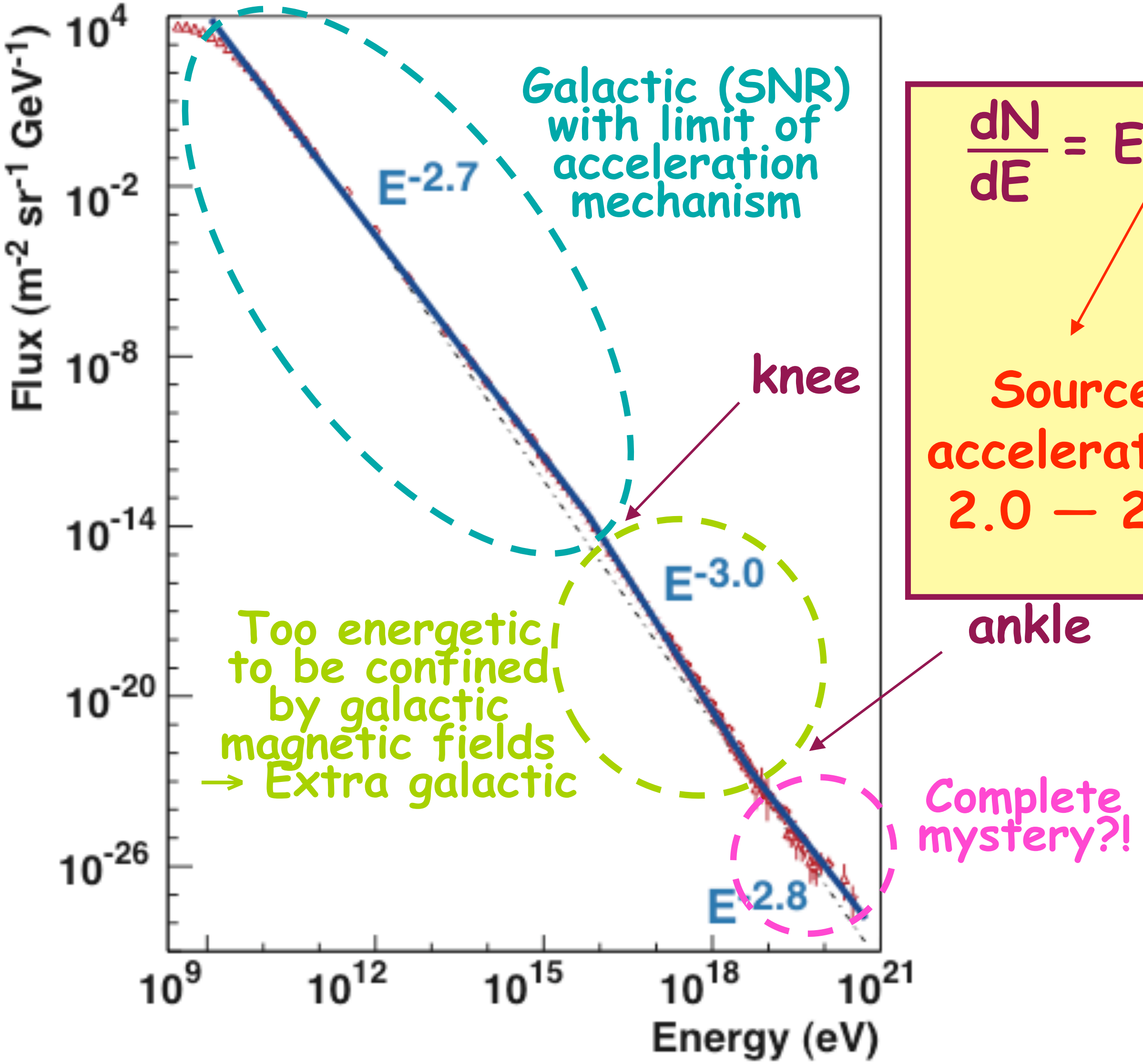
# Cosmic ray energy spectrum




$E<10^{14}$ eV
High flux : detection of primary particle (AMS on ISS)

$E>10^{14}$ eV
Atmosphere → extensive air showers (AGASA, Fly's eye Auger)

# Structure in cosmic ray spectrum



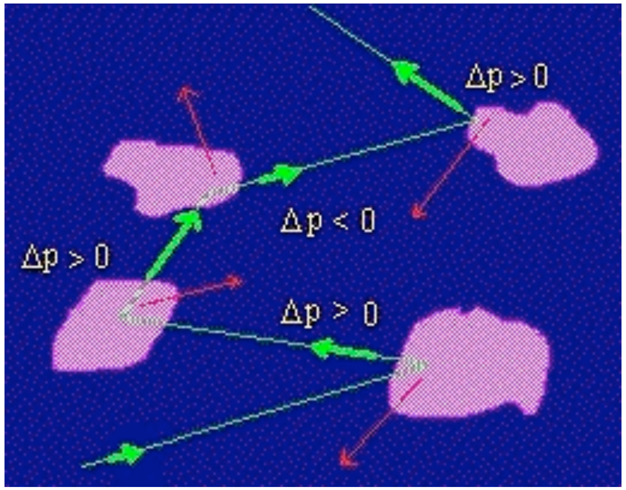

$\frac{dN}{dE} = E^{-\alpha}$ above 10 GeV

Source acceleration
2.0 – 2.2

Propagation (confinement)
~ 0.6

# Acceleration mechanisms

## 1949 : Fermi acceleration




**Stochastic acceleration of particles**
**on magnetic inhomogeneities**

**Head-on collisions ⇒ Energy gain**
**Tail-end collisions ⇒ Energy loss**
**On average, head-on more probable**
**⇒ Energy gain over many collisions**

$\Delta E/E \propto \beta^2 \qquad \beta = v/c \sim 10^{-4}$

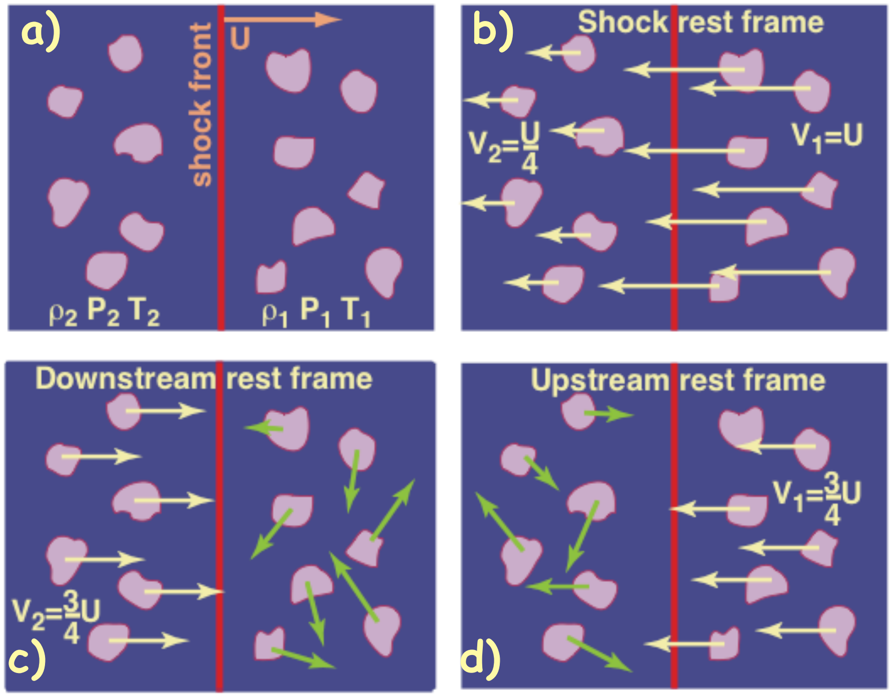
**" Second order "**

**Slow and inefficient**

# First order Fermi acceleration

<u>1970's : First order Fermi acceleration</u>

Acceleration in strong shock waves




Conservation of nb of particles :

$$\rho_1 v_1 = \rho_2 v_2$$

Strong shock : $\rho_2/\rho_1 = (\gamma+1)/(\gamma-1)$

Fully ionized plasma ($\Leftrightarrow$ ideal gas)

$\gamma = 5/3$ and $v_1/v_2 = 4$

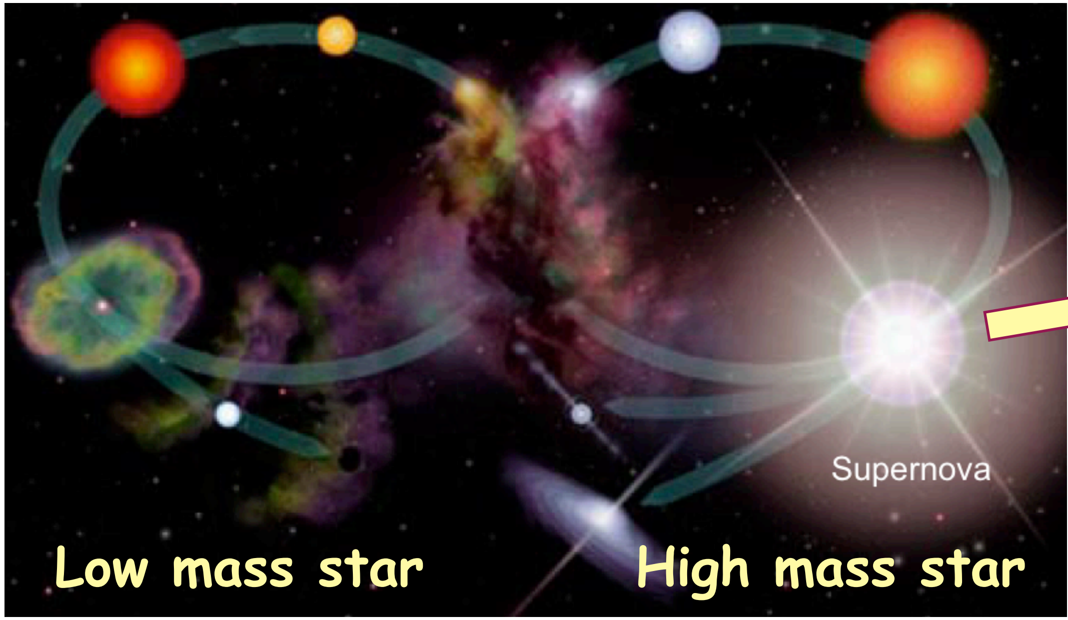
$\Rightarrow$ Rapid gain in energy as particles repeatedly cross shock front

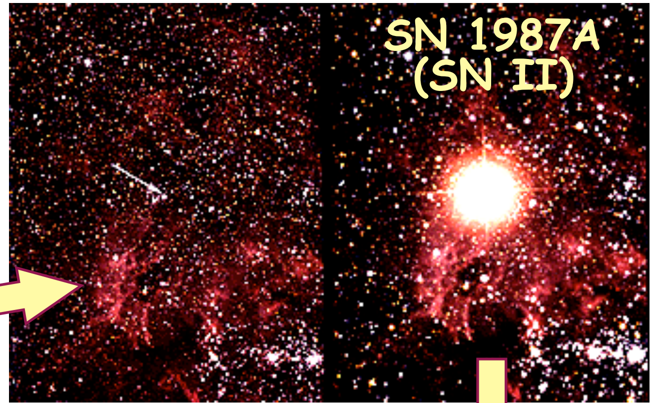
$\Delta E/E \propto \beta$ ($\sim 10^{-1}$) and $E^{-2}$ spectrum

" First order "

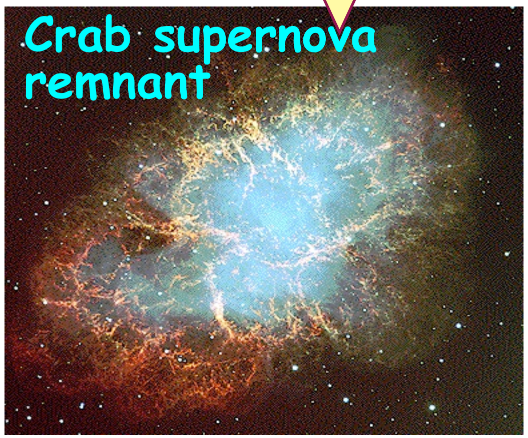
# Powerful shocks?

## Supernovae !



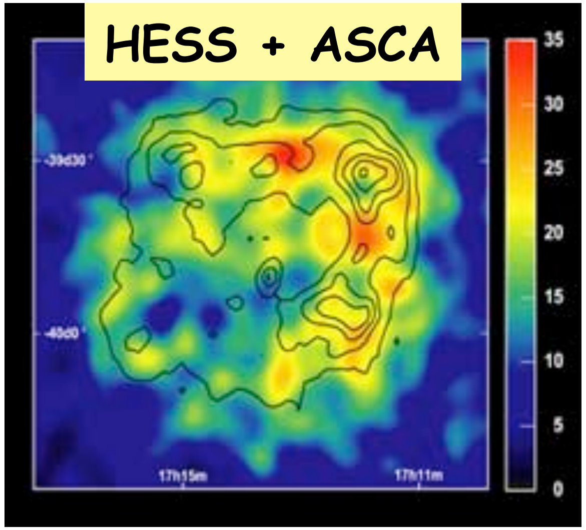




(too short) life and
(extremely violent) death
of massive stars

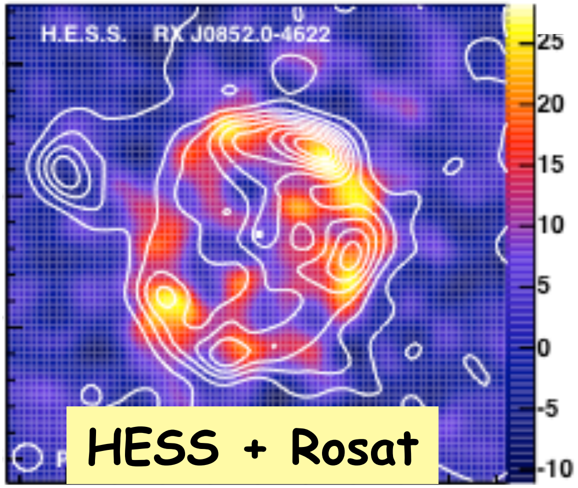



1 SN II / 50 years in our galaxy

# HESS : first confirmation




F. Aharonian et al., 2004 Nature 432, 75




F. Aharonian et al., 2005 A&A 437, L7

HESS : gamma-ray color map
(E ~1 TeV)

ASCA / ROSAT : X-ray contours
(E ~ 1 keV)

Excellent overlap →
confirmation of SN remnants
as multi TeV particle accelerators

# Energy limitation

Natural limit : containment of particles in acceleration (shock) region

$E_{max} \sim Z\ e\ B\ R\ c$

(no energy losses)

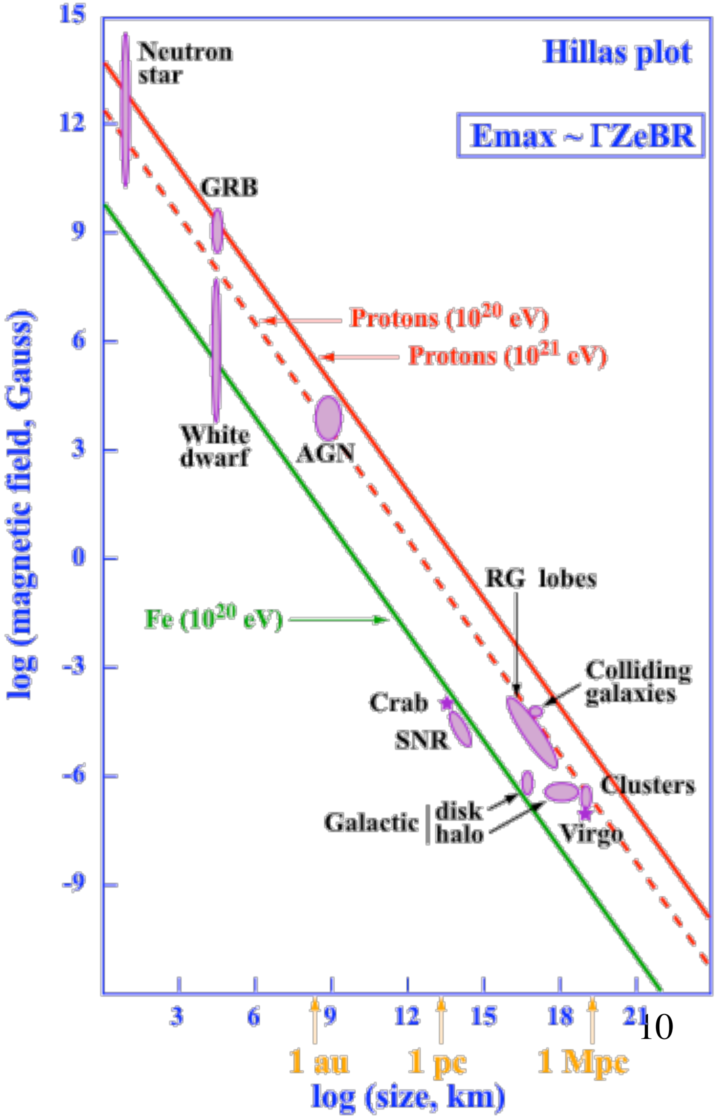
⇨ Need high B, large R

Supernova remnants :

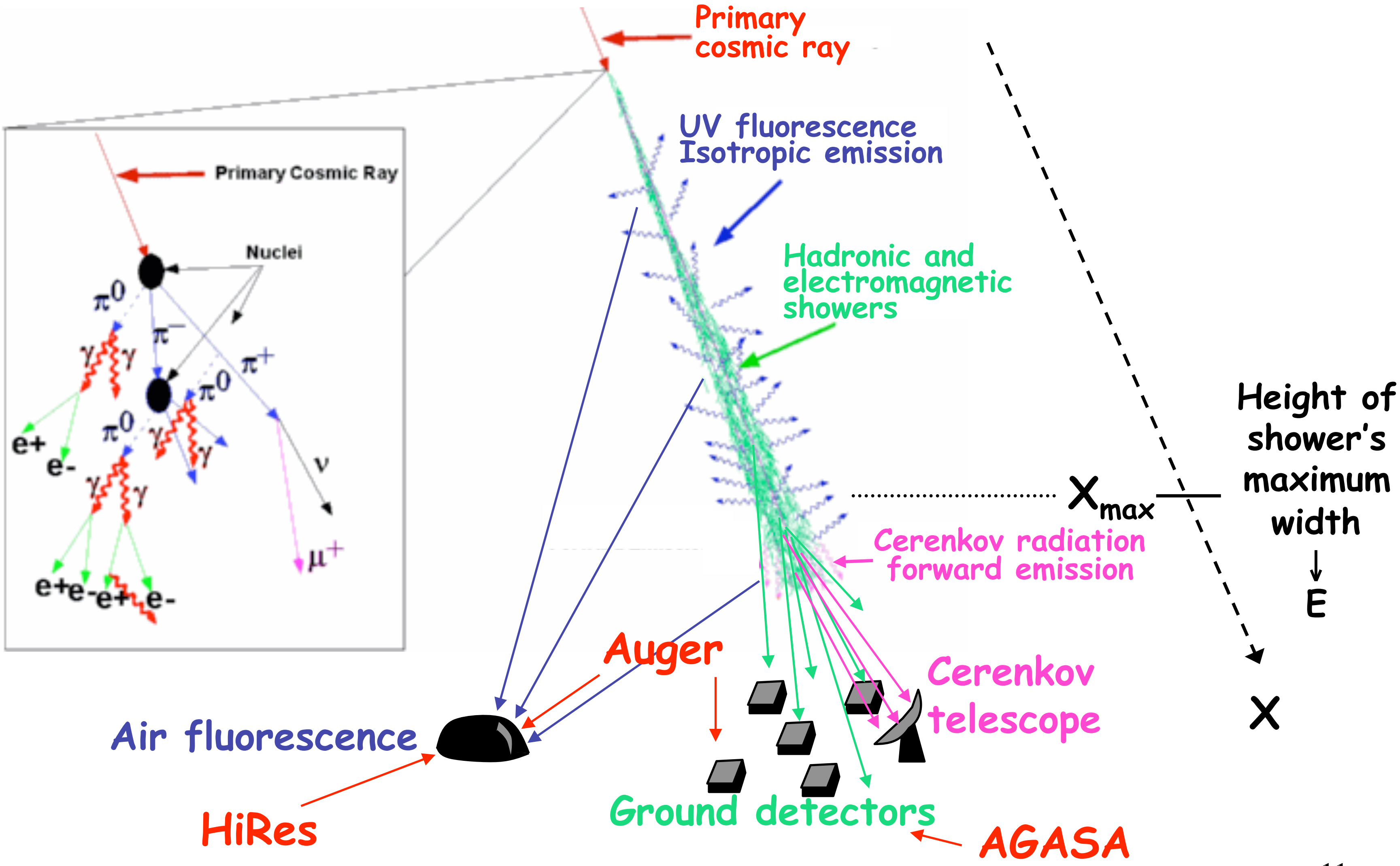
→ $E_{max} \sim 10^{15}$ eV (knee)

Cosmic rays in $10^{15}$ - $10^{20}$ eV region ?

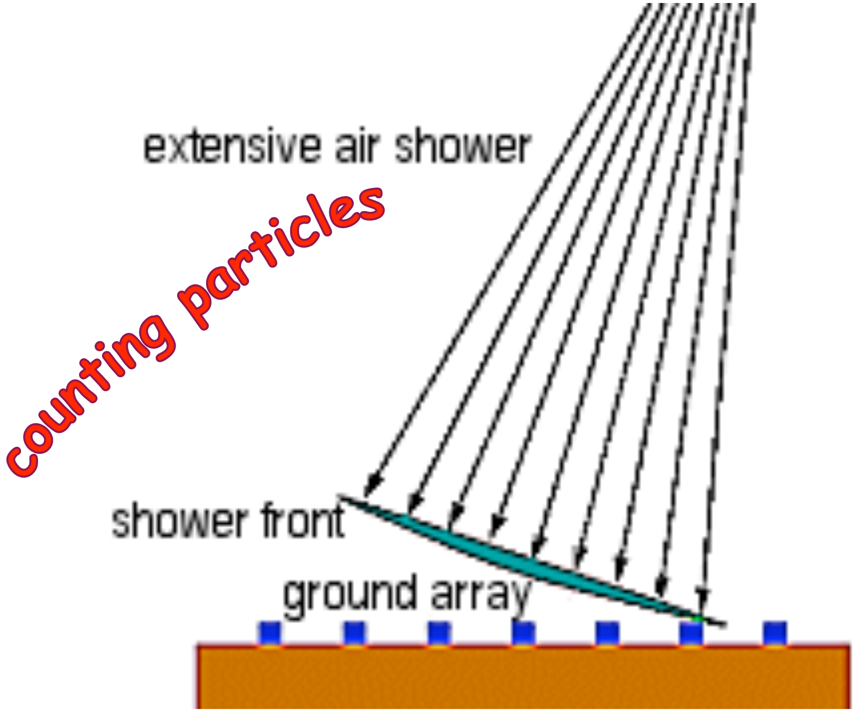
→ Relativistic motions ($\Gamma$)



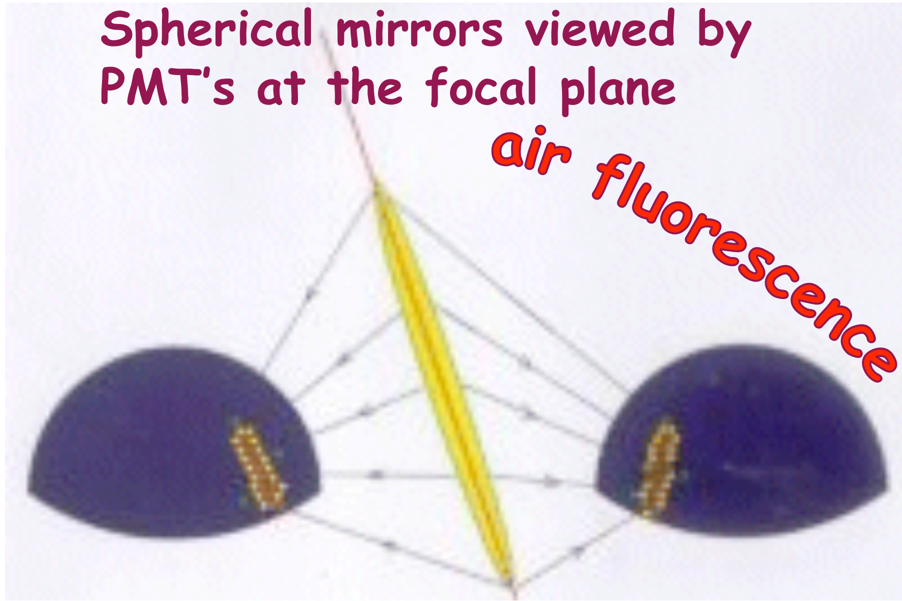
# Cosmic ray detectors



# Detection techniques



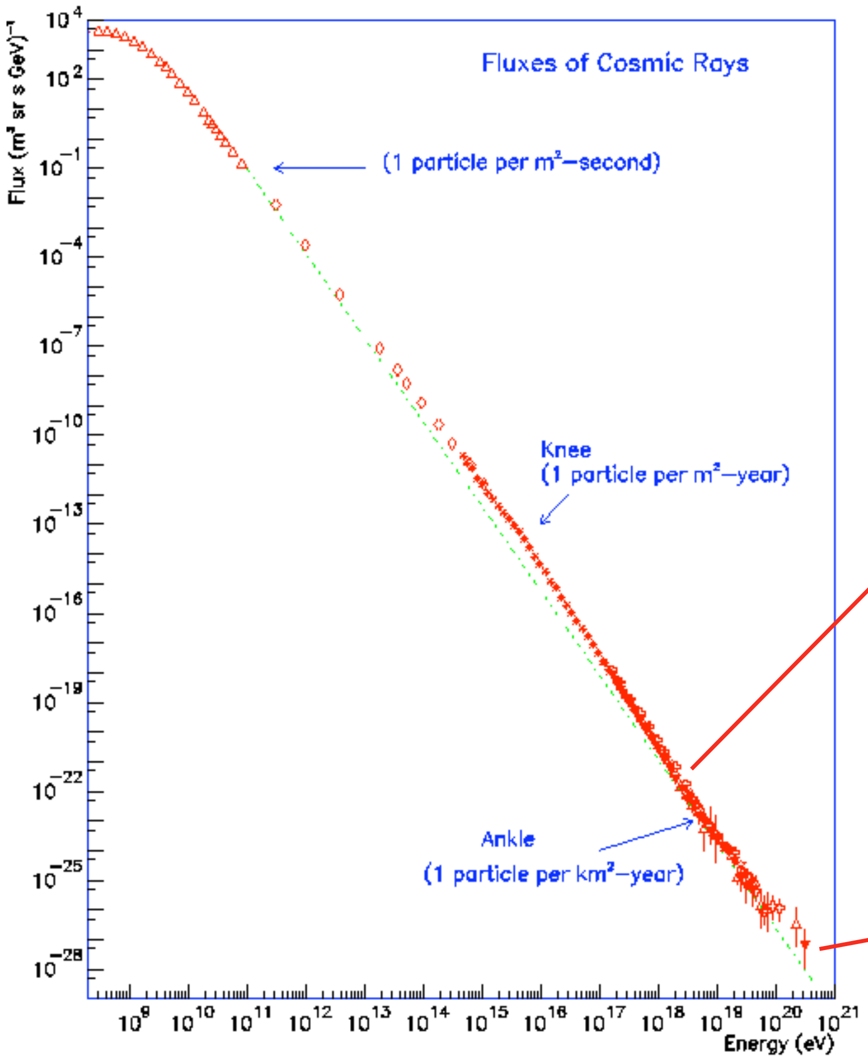

Trajectory determined from arrival time of shower front on ground detectors




(clear & moonless nights)

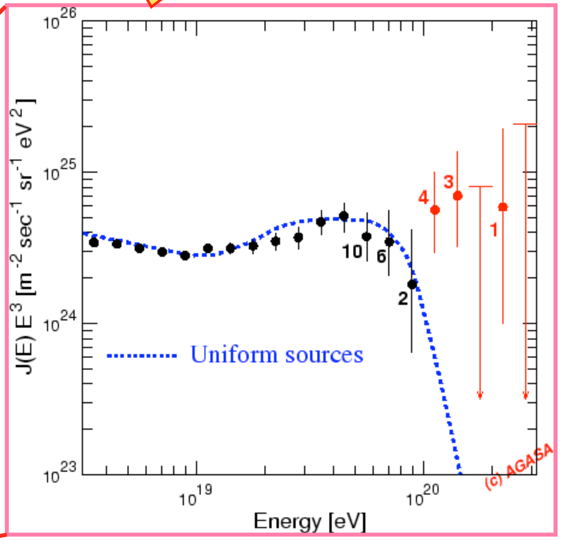
Trajectory from geometry, good accuracy thanks to dual setup

# Ultra High Energy Cosmic Rays



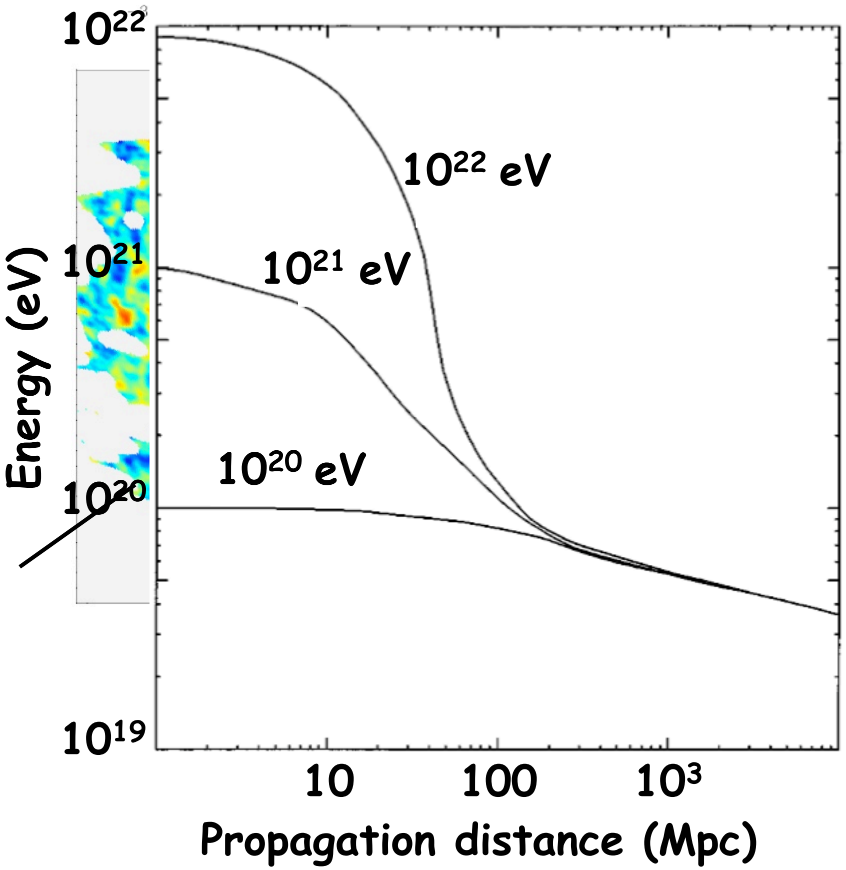

AGASA: 17 events above $5 \times 10^{19}$ eV
HiRes : 2 events (~ 20 expected)

cross calibration needed




$E_{max} = 3.2 \; 10^{20}$ eV = 50 J !

# GZK (Greisen Zatsepin Kuzmin) cut-off




$$p + \gamma_{CMB} \rightarrow \Delta^+ \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

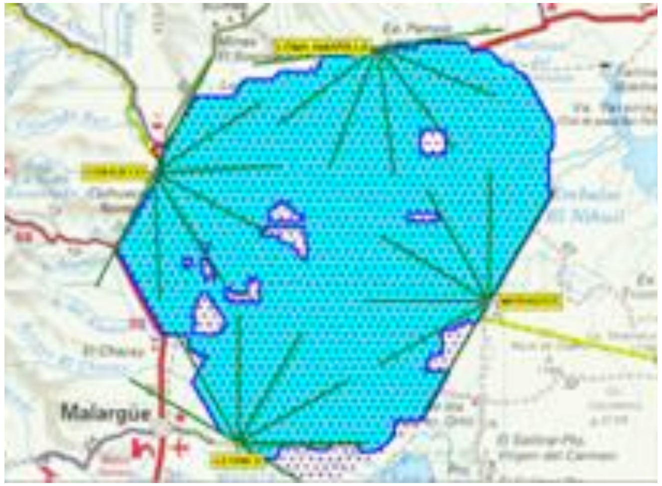
When process energetically allowed (>$5\times10^{19}$ eV), space becomes opaque to CR

Sources with $E > E_{GZK}$ must be at d<100 Mpc (local cluster)

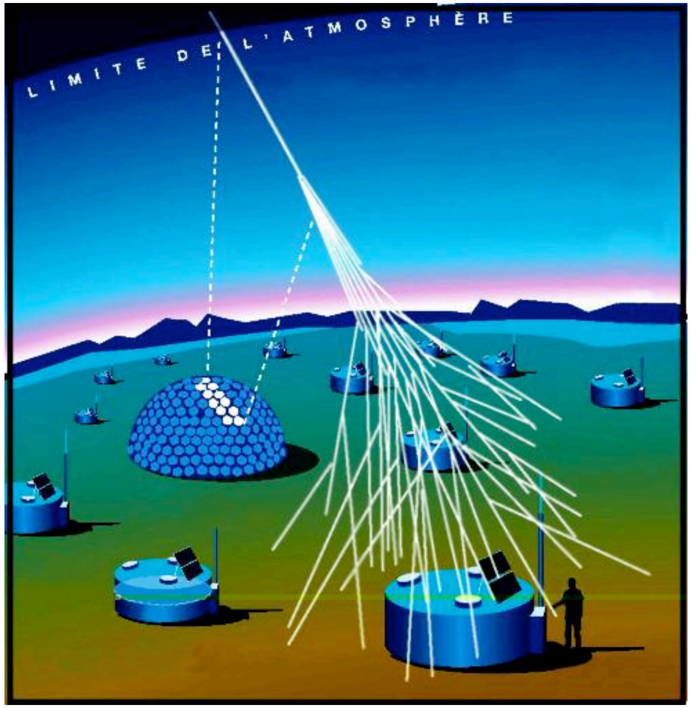
(very few known acceleration sites…)

# AUGER

Air fluorescence + ground arrays
2 sites (Argentina, USA):
1600 ground detectors
+ 4 air fluorescence telescopes
Over 3000 km$^2$

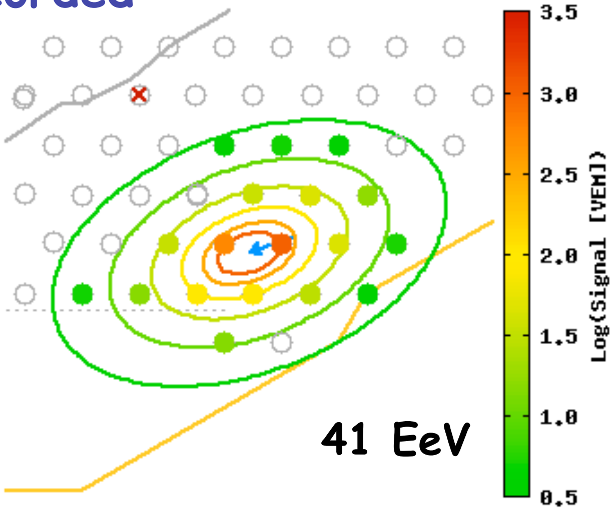



June 2008




Auger South
- ~ completed
- >1 million events recorded
- $E_{max}$= 1.8 $10^{20}$ eV

Auger North?
- improved statistics
  (local supercluster)
- test of isotropy



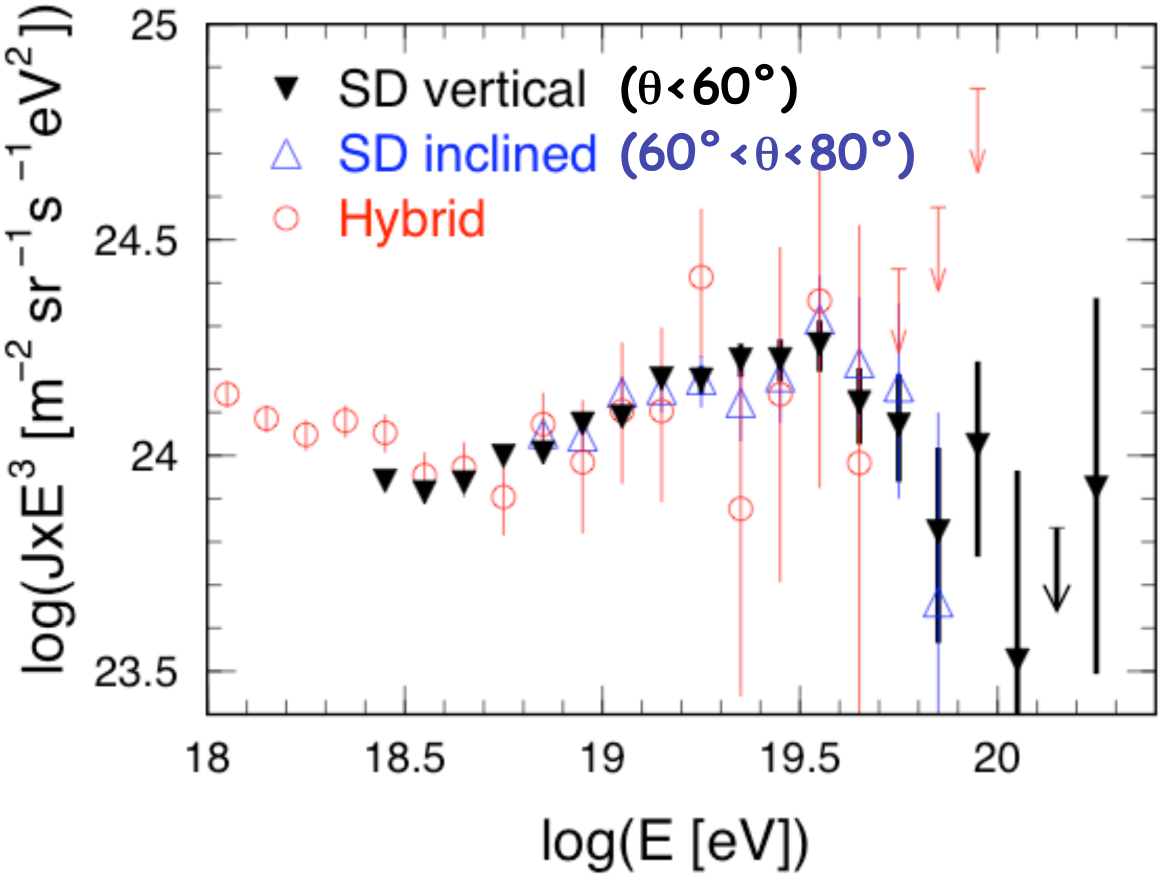
# AUGER - spectrum

UHE end of spectrum

3 samples

All agree with
presence of
GZK cut-off

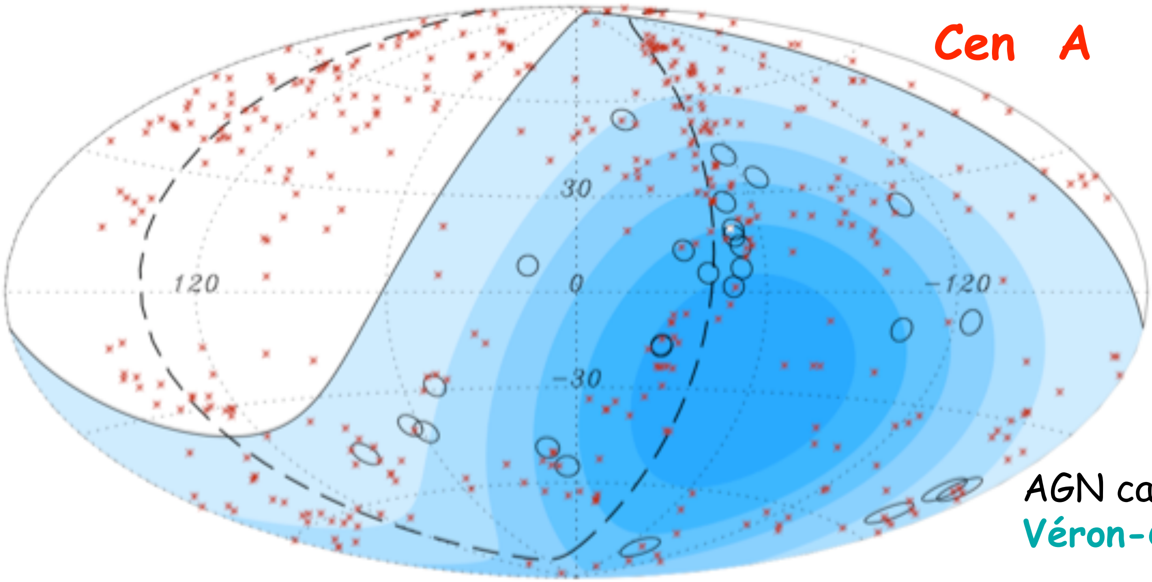
(flat spectrum
above 4 $10^{19}$
excluded at $6\sigma$)






Abraham et al., arXiv:0806.4302v1 [astro-ph]

# AUGER - origin of UHECR




Cen A

Good angular resolution (<1°)
⇒ Study of anisotropies

⬭ Events E > 57 EeV
✗ AGNs d < 71 Mpc

AGN catalog:
Véron-Céty and Véron, A&A 2006, 455 773

| | Number E > 57EeV | Number correlated within 3° | Expected if isotropy |
|---|---|---|---|
| Total sample | 27 | 20 | 5.6 |
| Excluding galactic plane | 21 | 19 | 5.0 |

**First evidence for a correlation of UHECR with astronomical sources**

Abraham et al., arXiv:0712.2843v2 [astro-ph]

# Lecture outline

1) What is Astroparticle Physics ?
   Big Bang Nucleosynthesis
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3) High energy astrophysics
   Cosmic rays
   Gamma rays
   Neutrino astronomy

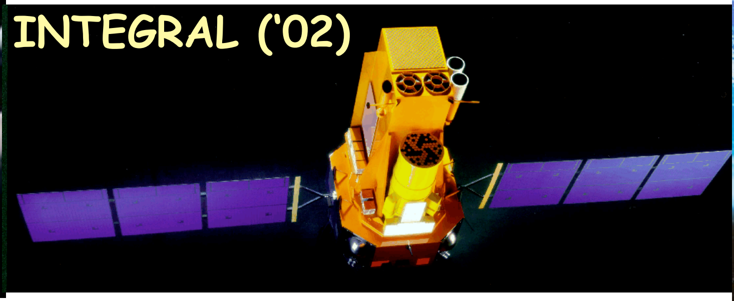
# Gamma ray astronomy

Cosmic accelerators → high energy protons (cosmic rays)
deviated by B up to $10^{18}$ eV
→ high energy photons (gamma rays)
point back to source!

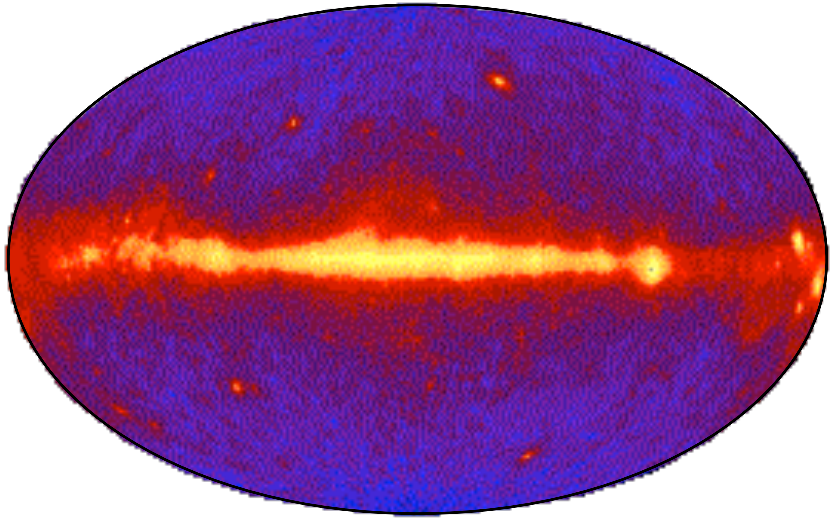
1952 Prediction of HE gamma-ray emission of Galactic disk

1958 First detection of cosmic gamma rays (solar flare)

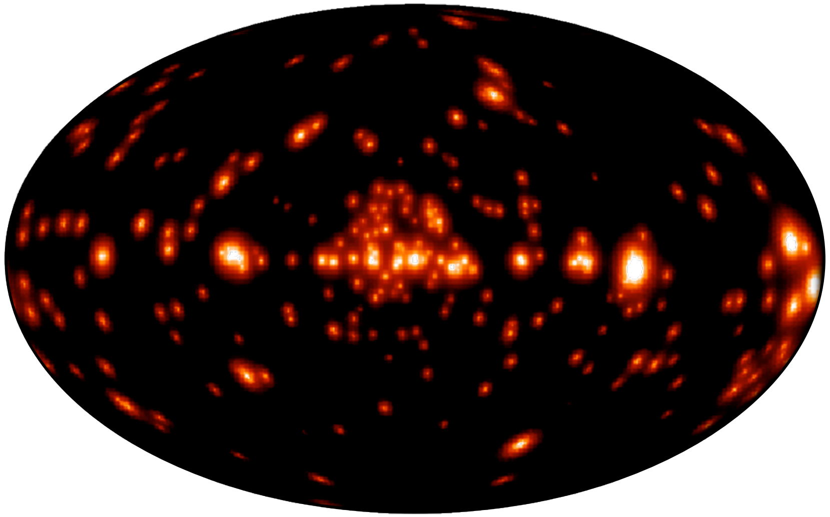
1968 Detection of Galactic disk and Crab nebula
Still no EXTRA-galactic gamma ray


# EGRET (E > 100 MeV)



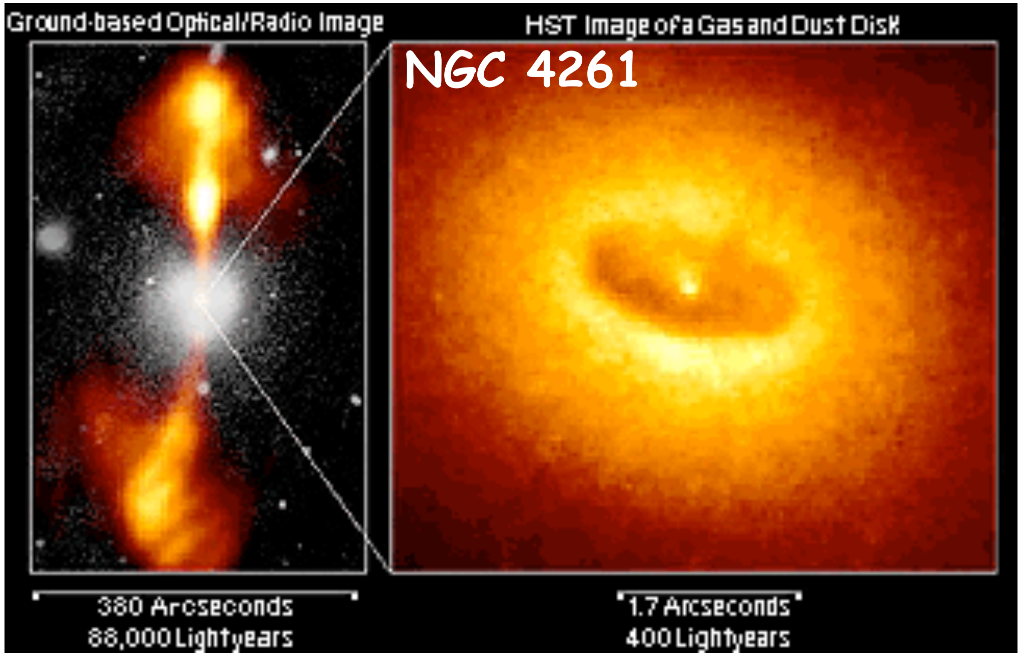
Galactic diffuse interstellar emission from interaction with cosmic rays



Point sources
- Jets from active galactic nuclei
- Galactic sources (pulsars, binaries, supernova remnants ...)
- Unidentified sources (170/270)

# Active Galactic Nuclei

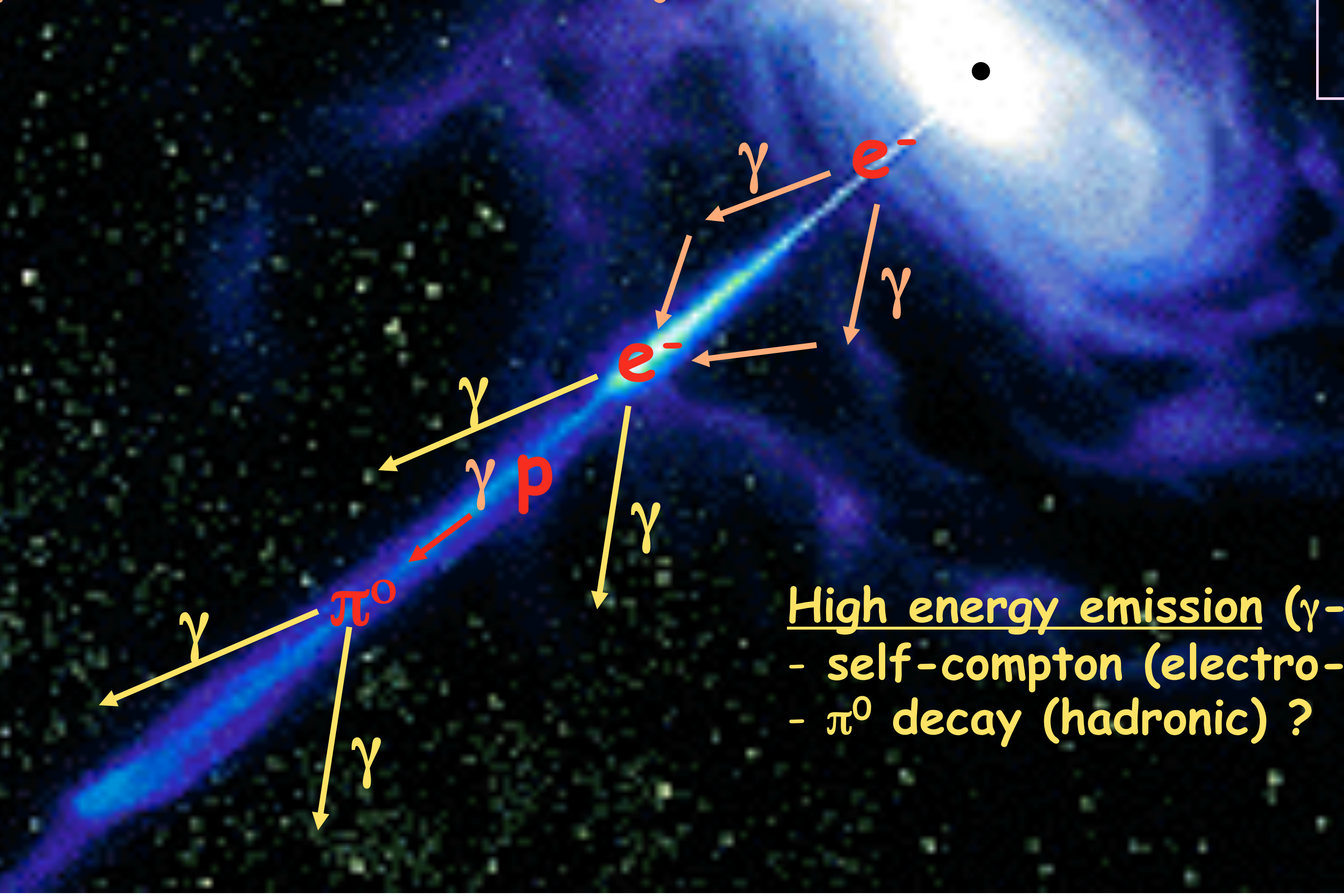
AGN : galaxy with $10^8$ - $10^9$ $M_o$ central black hole
10% - radio jets (relativistic ejection of plasma)
1% - blazars (all EGRET AGNs !)




# Blazars

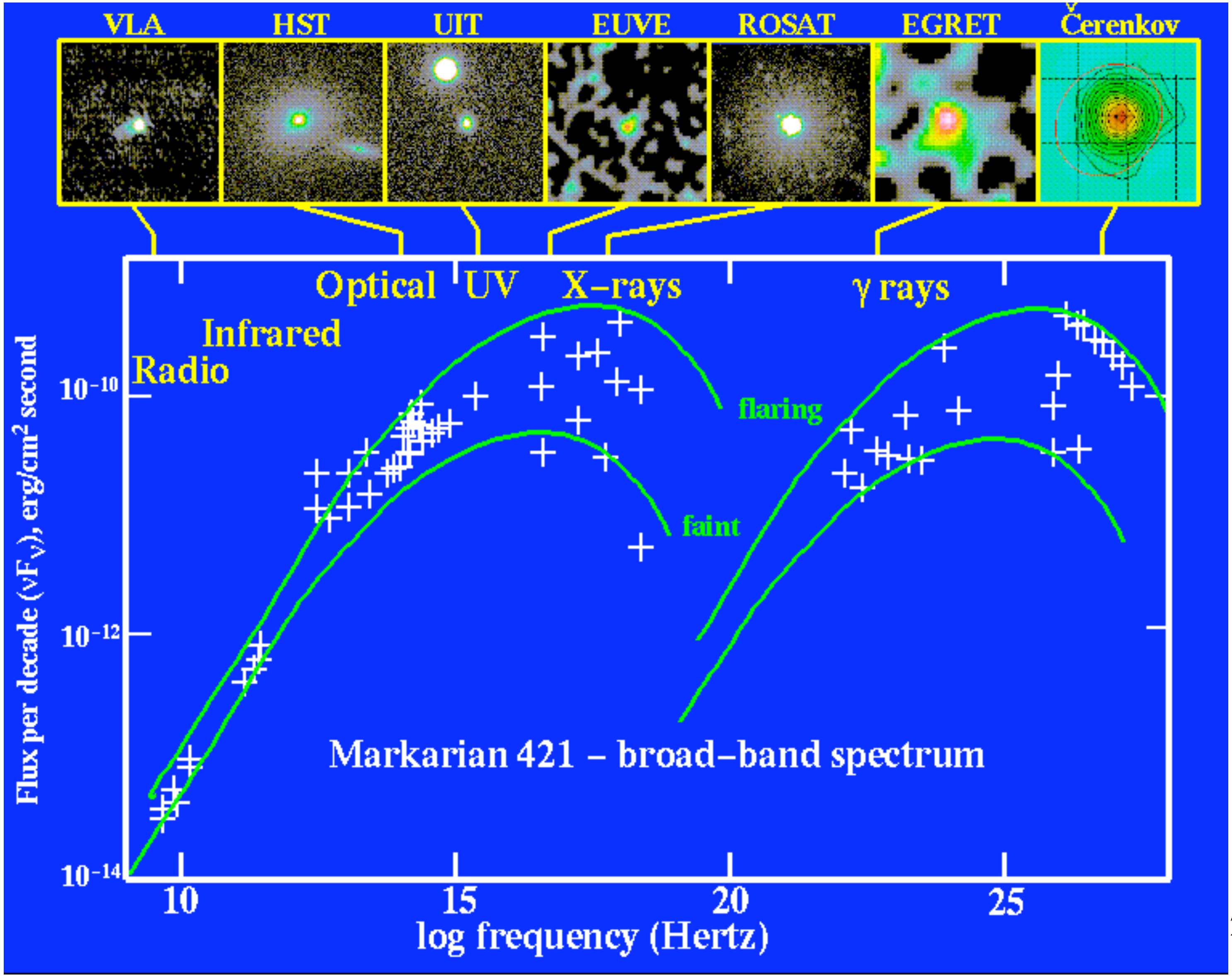
Low energy emission (X-ray) :
Synchrotron emission of $e^-$ in jet

VARIABILITY !
⇓
Size ~ $\Gamma c t_{var}$
($\Gamma$ > 10)



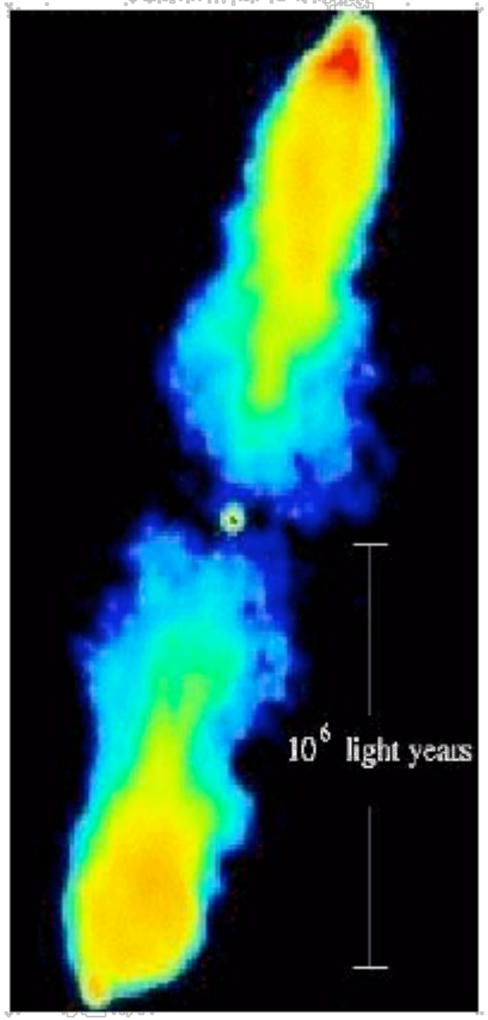

High energy emission ($\gamma$-ray):
- self-compton (electro-magnetic) ?
- $\pi^0$ decay (hadronic) ?

# Markarian 421 : closest blazar

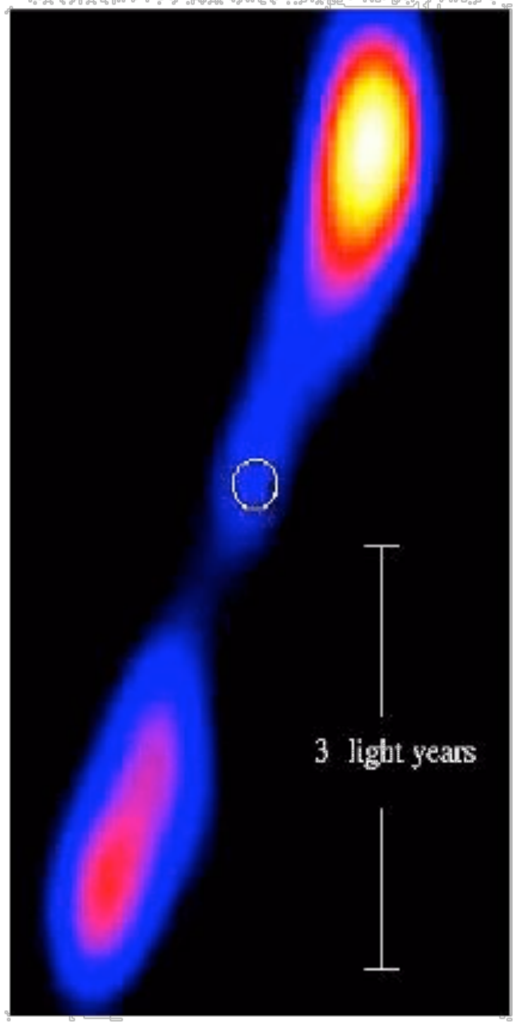


# Quasars and Microquasars

QUASAR 3C 223

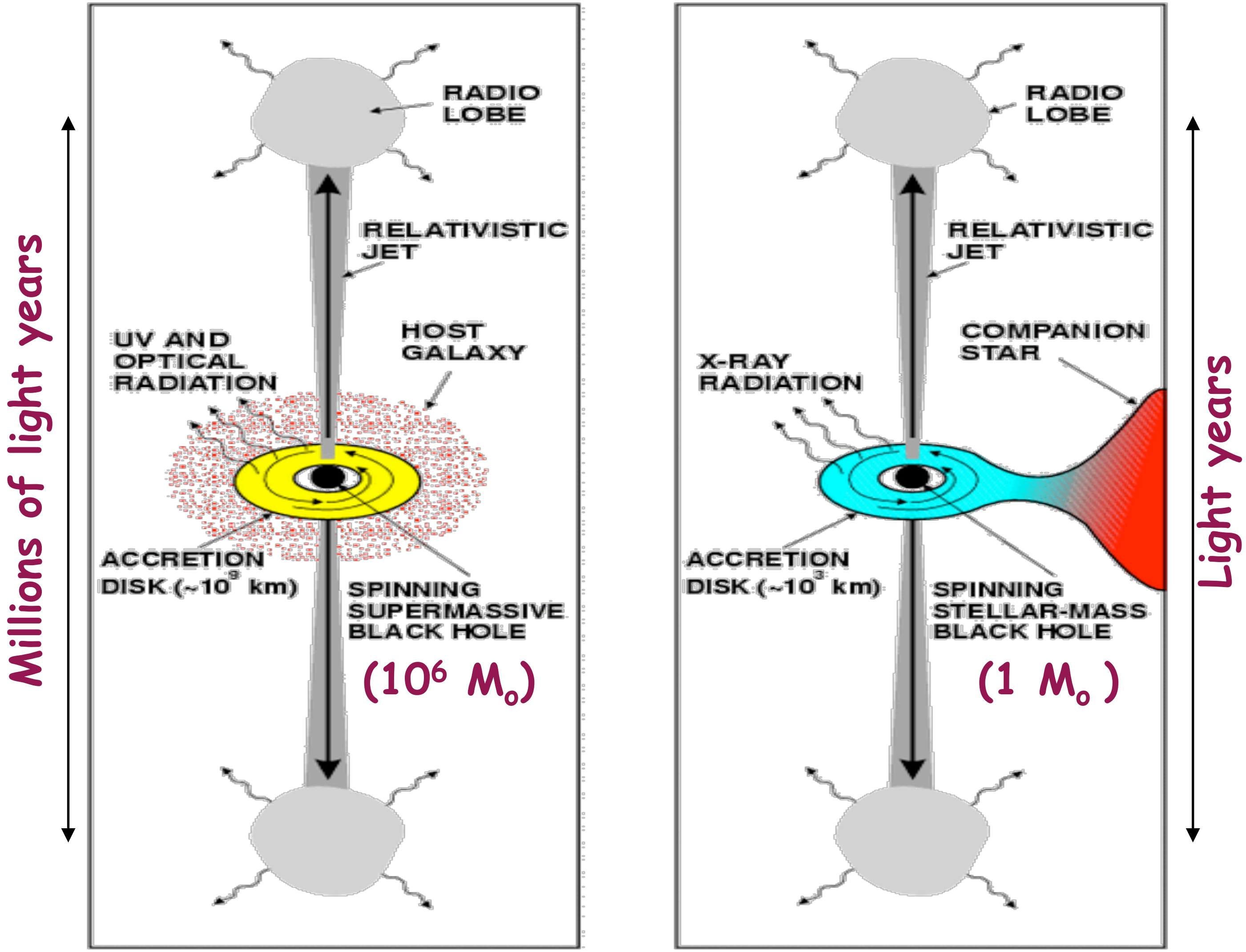



MICROQUASAR 1E1740.7-2942



## QUASAR

## MICROQUASAR

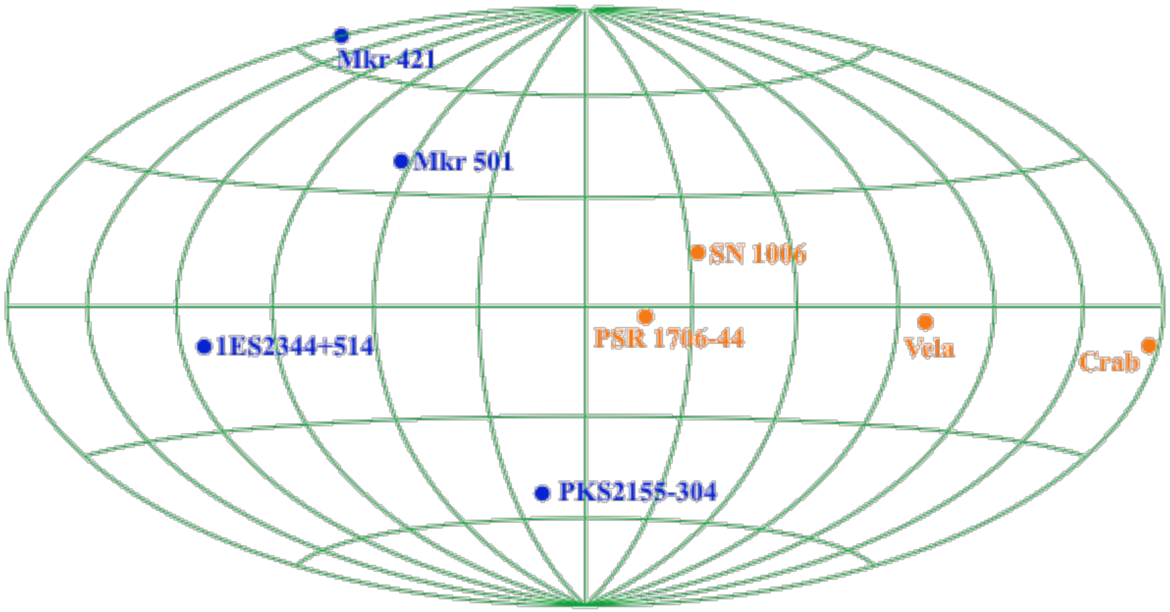



$R \propto M_{BH}$ $\quad$ $T \propto M_{BH}^{-1/4}$

Mirabel & Rodriguez

# TeV sky

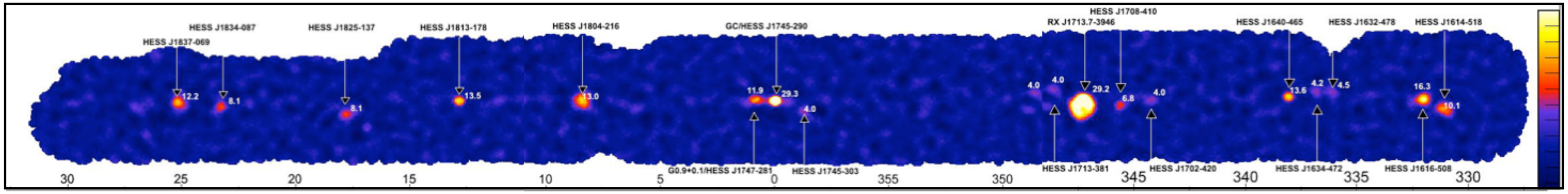
2003



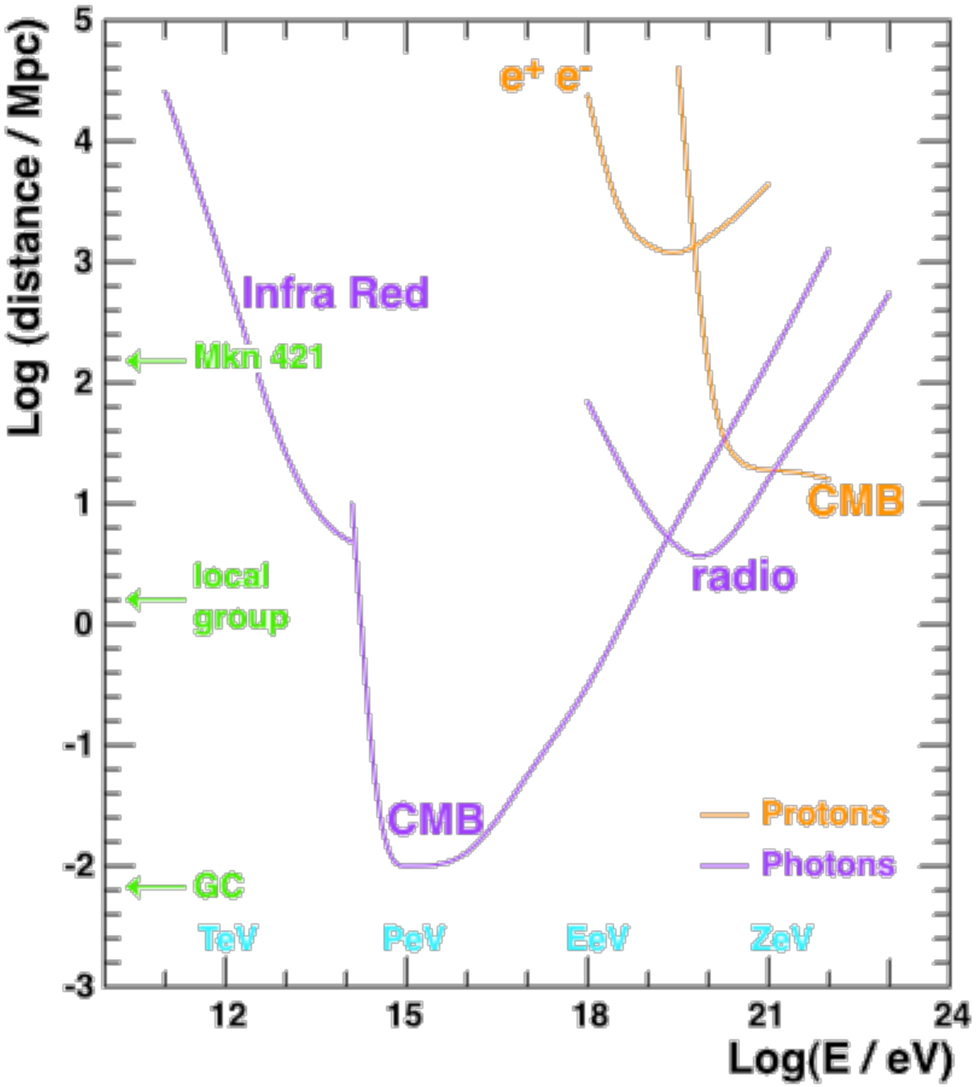

2005

HESS:
Survey of galactic plane

14 new sources (+ 3 already known ones):
- SNRs, X-ray binaries, pulsars
- 3 with no counterpart at any $\lambda$



# Gamma horizon

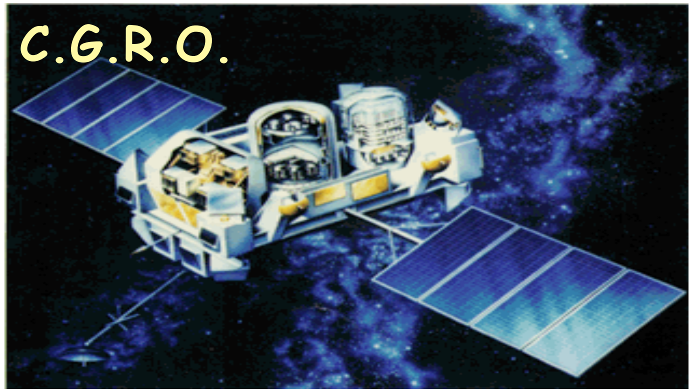



GZK cutoff
Main explanation for lack of TeV sources

# Gamma ray bursts (GRB)

1967 Chance discovery of prompt emission by VELA (16 events), published in 1973

1991 Observation with the satellites C.G.R.O (EGRET, BATSE…) & BeppoSAX

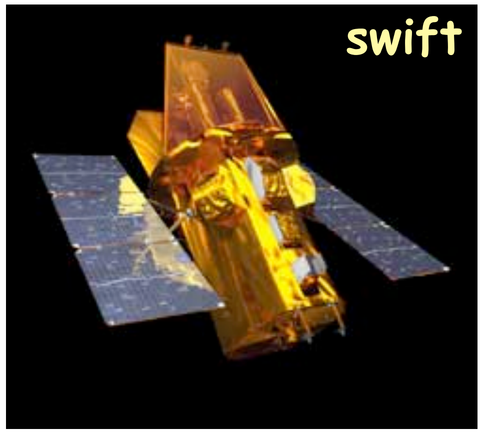



brightest objects in the universe, emitting mostly at high E

⟶ emission collimated ?

wide variety of time profiles, $\Delta t$ from 10ms to 1000s

⟶ compact region, Lorentz boost ($\Gamma$ ~100)

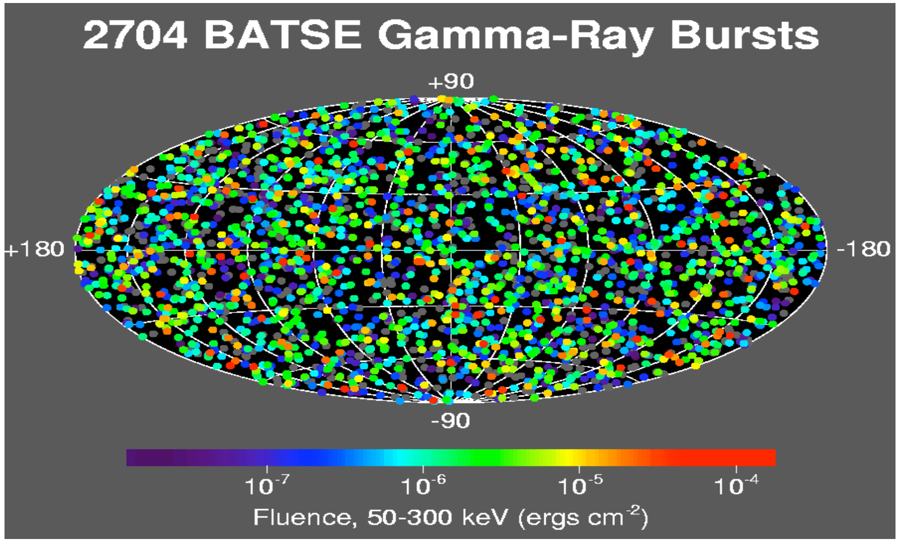


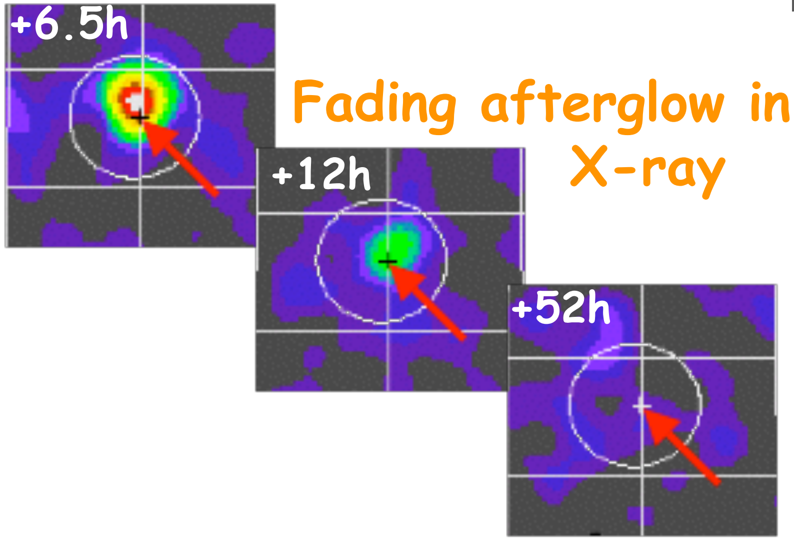

2009 (>3000 bursts) still very poorly understood …

# Burst location

Isotropy
+
Optical counterparts

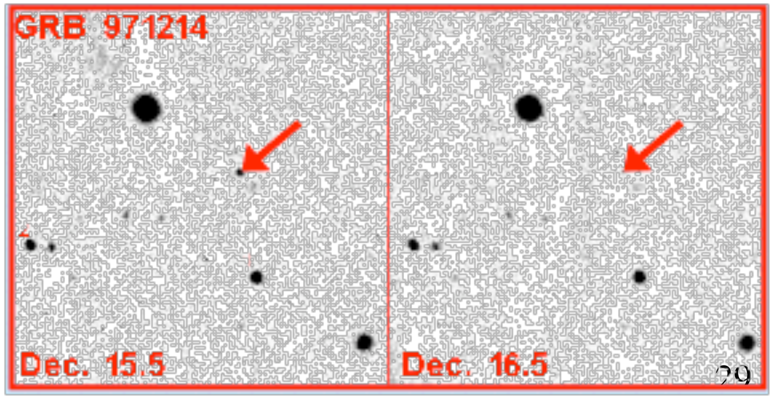
Cosmological phenomena!
(z = 0.43 to 6.3)




Fading afterglow in X-ray

Afterglow in optical



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# Other messengers ?

Photons: absorbed (GZK)

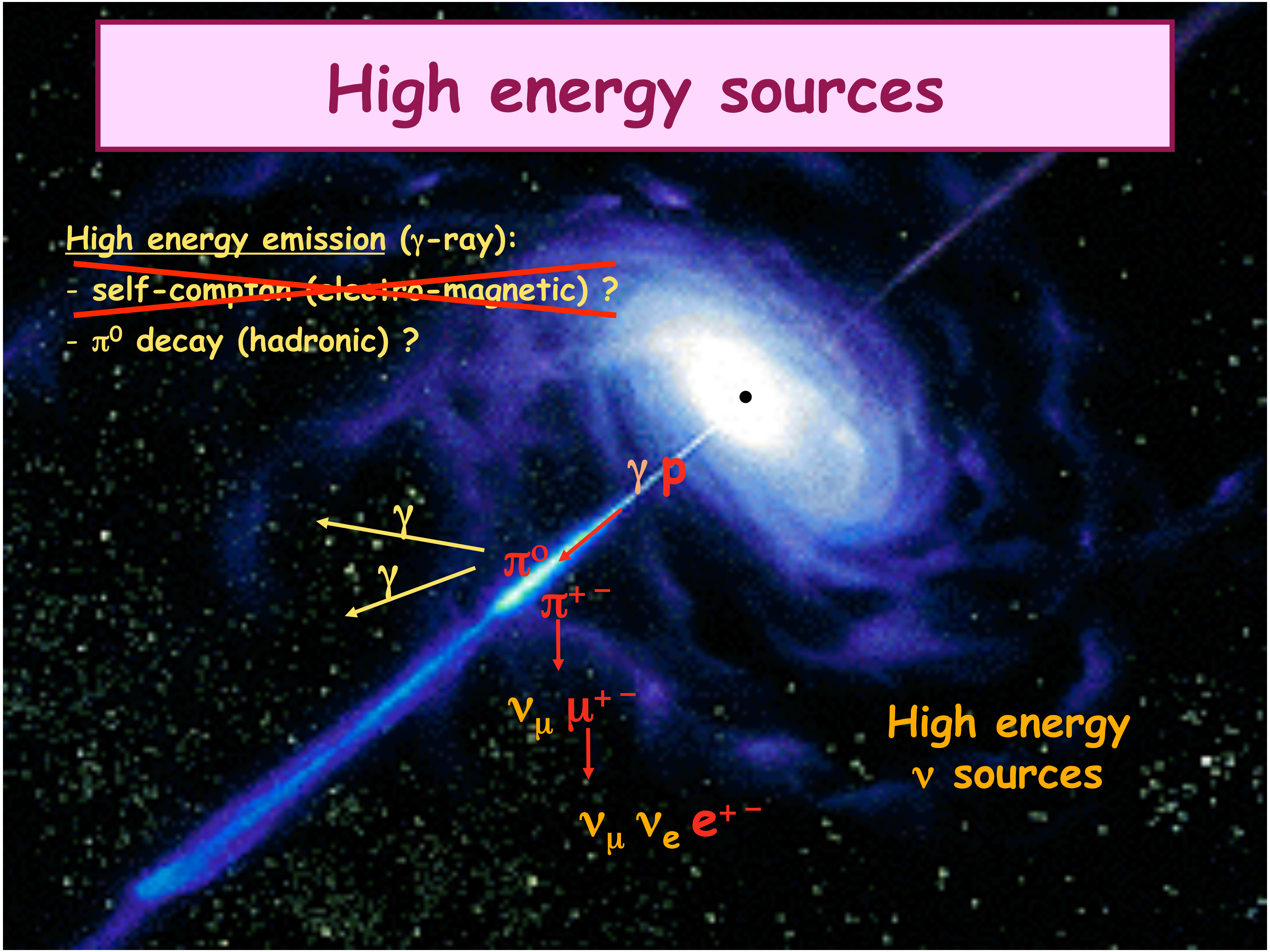
Neutrons: $\tau \sim 15$ mn
$d_{max}$=10 kpc ($E=10^{18}$ eV)

Protons: absorbed (GZK)
& deviated ($E<10^{18}$ eV)

Neutrinos: no charge, "no" interaction with matter nor radiation

**Ideal probes of:**
dense regions,
sources on cosmological scales,
acceleration processes

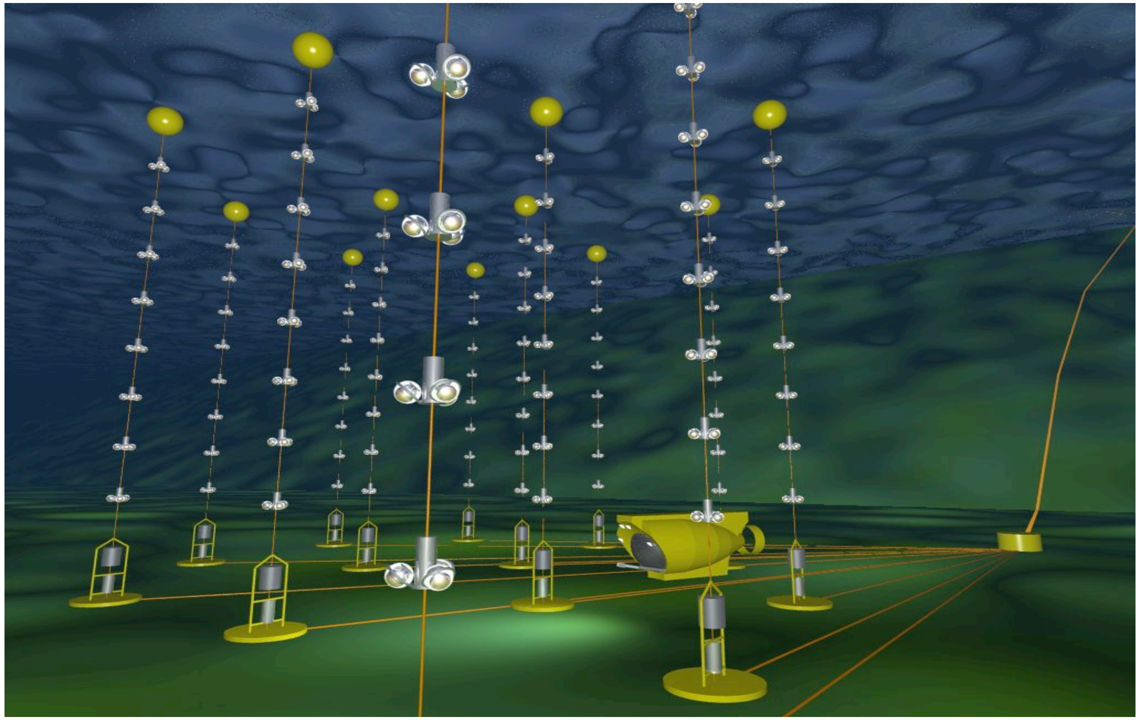
# High energy sources

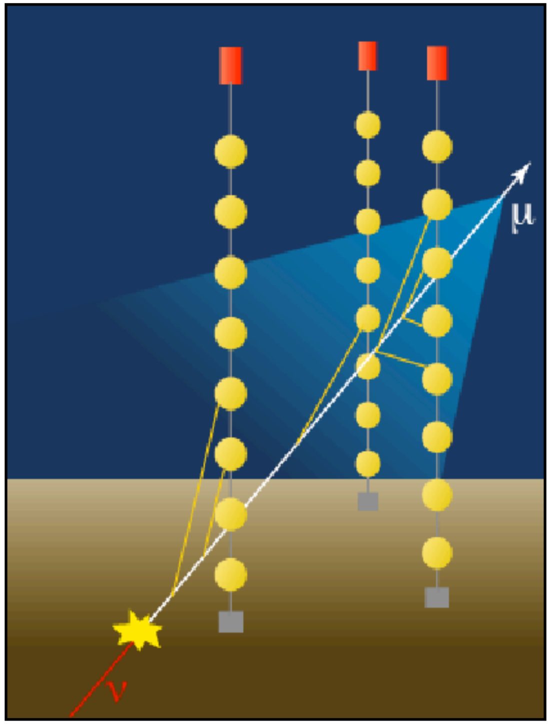


# Experimental challenge

Low fluxes @ high E → Large volume
Low cross-sections → (lake, sea, polar ice)

High background (atmospheric $\mu$) → Good shielding (> 1000m water eq.)

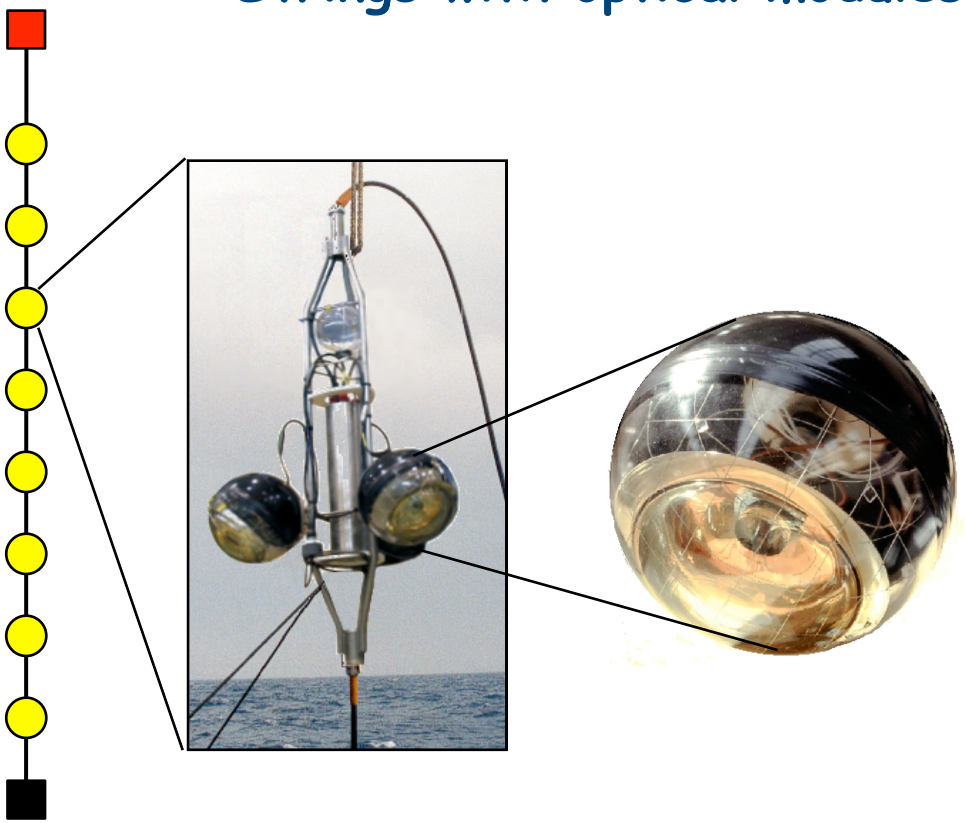





$\nu \rightarrow \mu \rightarrow$ Cerenkov light

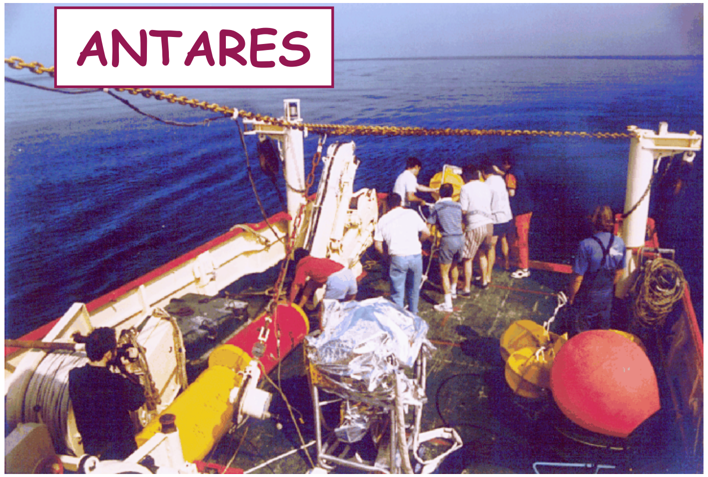
# Detectors

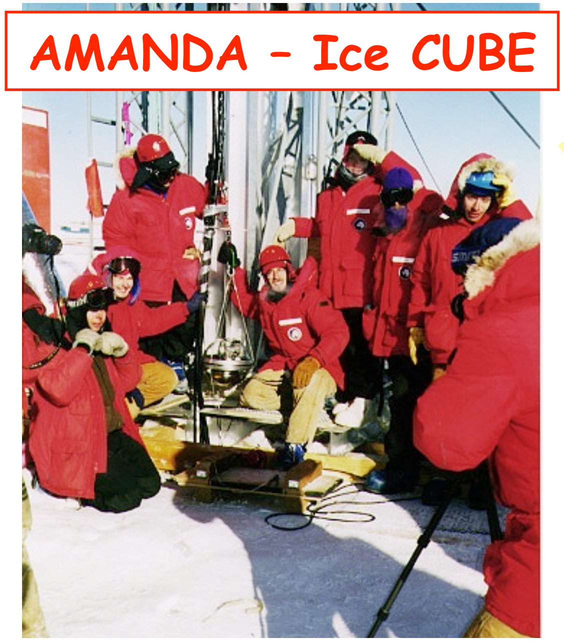
Strings with optical modules (PMT in glass sphere)



- $d_{OM-OM}$: E threshold
- # of OM: E resolution
- $d_{string-string}$: effective volume, E limit

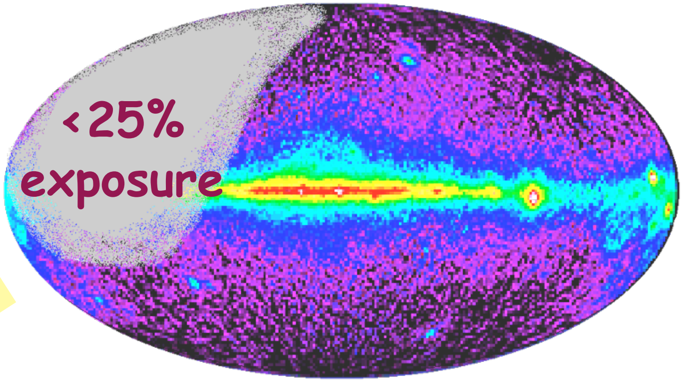
# HE neutrino experiments




Better angular resolution (~0.2°)

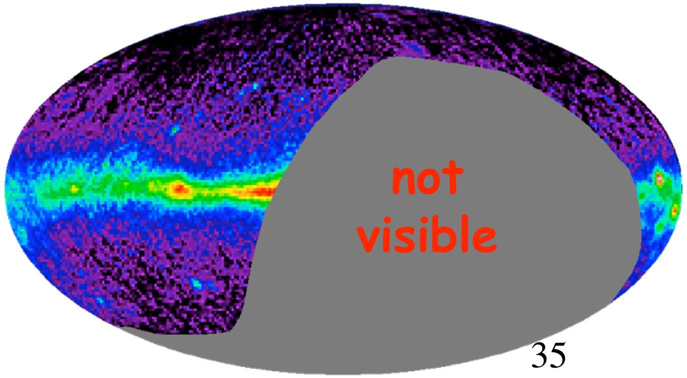
ANTARES (43° North)
deployment ended 2008




ANTARES/AMANDA
0.6$\pi$ sr overlap

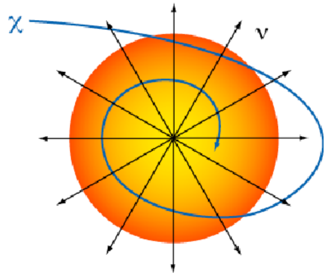
Better sensitivity (less absorption)

AMANDA (South pole)
taking data

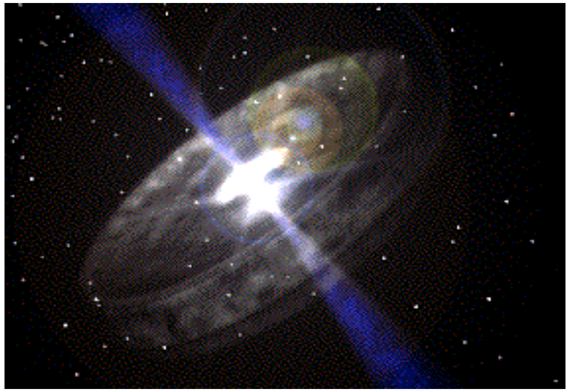


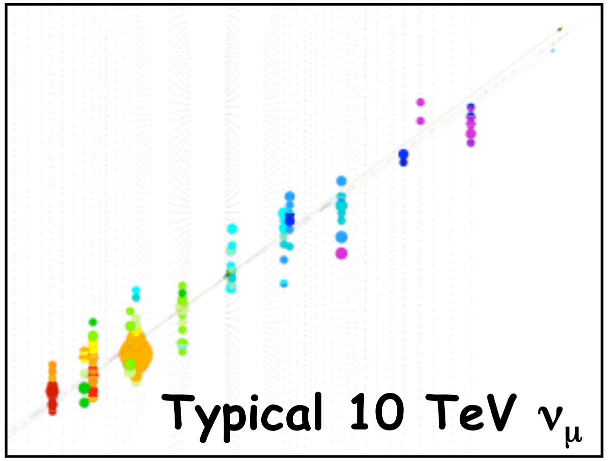
# Science reach

**Medium Energy (10 GeV - 1 TeV):**
- Dark matter searches from dense regions (neutralino concentration & annihilation)
- $\nu$ from supernovae




**High Energy (> 1 TeV):**
- $\nu$ from (extra-)galactic sources (cf. gamma rays)
- PeV & EeV $\nu$
- $\nu_\tau$ detection





# Status & future of $\nu$ astronomy

**ANTARES, AMANDA**: 0,1 km$^2$ arrays
Allow assessment of under-ice, under-water $\nu$ telescopes
Possible observation of diffuse neutrino fluxes (from AGN)
(current limits from AMANDA reaching predictions for some models)
No point sources so far

**Actual $\nu$ astronomy (point sources) requires 1 km$^3$**

**IceCube**: 80 1-km long strings over ~1 km$^2$
July 2009: 40 lines in operation (completion 2011)

**KM3**: design study in FP7 through network KM3Net
Joint study from ANTARES, NESTOR, NEMO

# Conclusions

**Cosmic Ray**

- UHECR source study (correlation with known objects)
- AUGER

**Gamma Ray**

- Study of high energy sources (AGNs, blazars)
- GRB mystery
- Indirect dark matter searches
- Fermi, HESS, CTA

**Neutrino**

- Complementary to photon astrophysics (model confrontations)
- Indirect dark matter searches
- AMANDA, ANTARES, Ice CUBE, KM3