Astroparticle Physics (3/3)

Nathalie PALANQUE-DELABROUILLE
CEA-Saclay

CERN Summer Student Lectures, August 2004

1) What is Astroparticle Physics ?
   Big Bang Nucleosynthesis
   Cosmic Microwave Background

2) Dark matter, dark energy

3) High energy astrophysics
   Cosmic rays
   Gamma rays
   Neutrino astronomy

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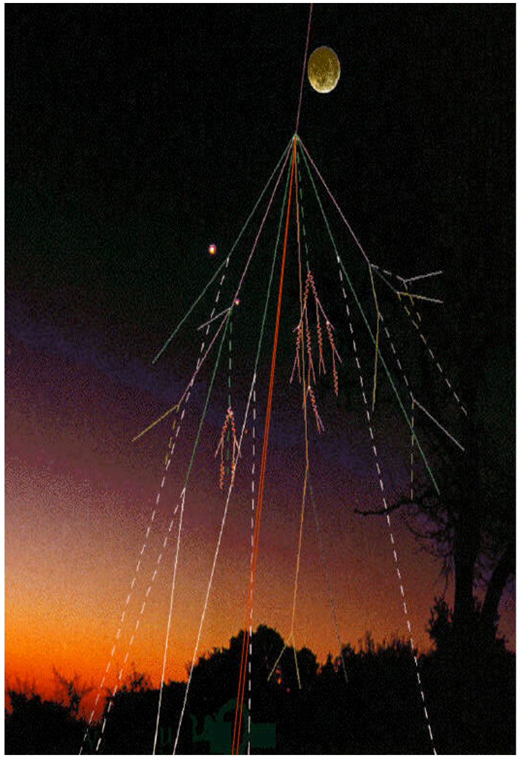


Brief history of Cosmic Ray detection

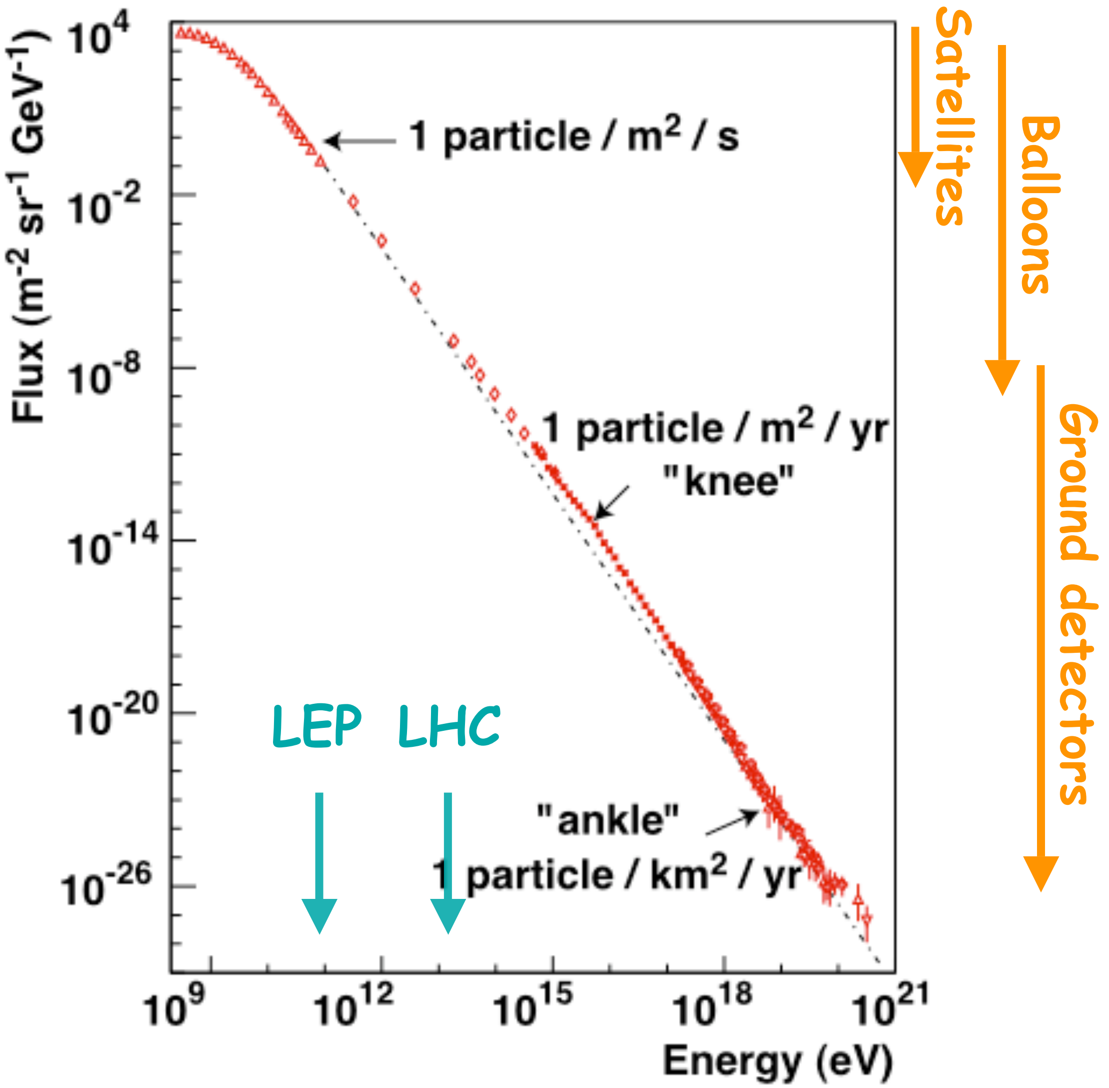
1912 Hess discovers cosmic rays

1925 Quasi-isotropy

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

1946 First air shower experiment

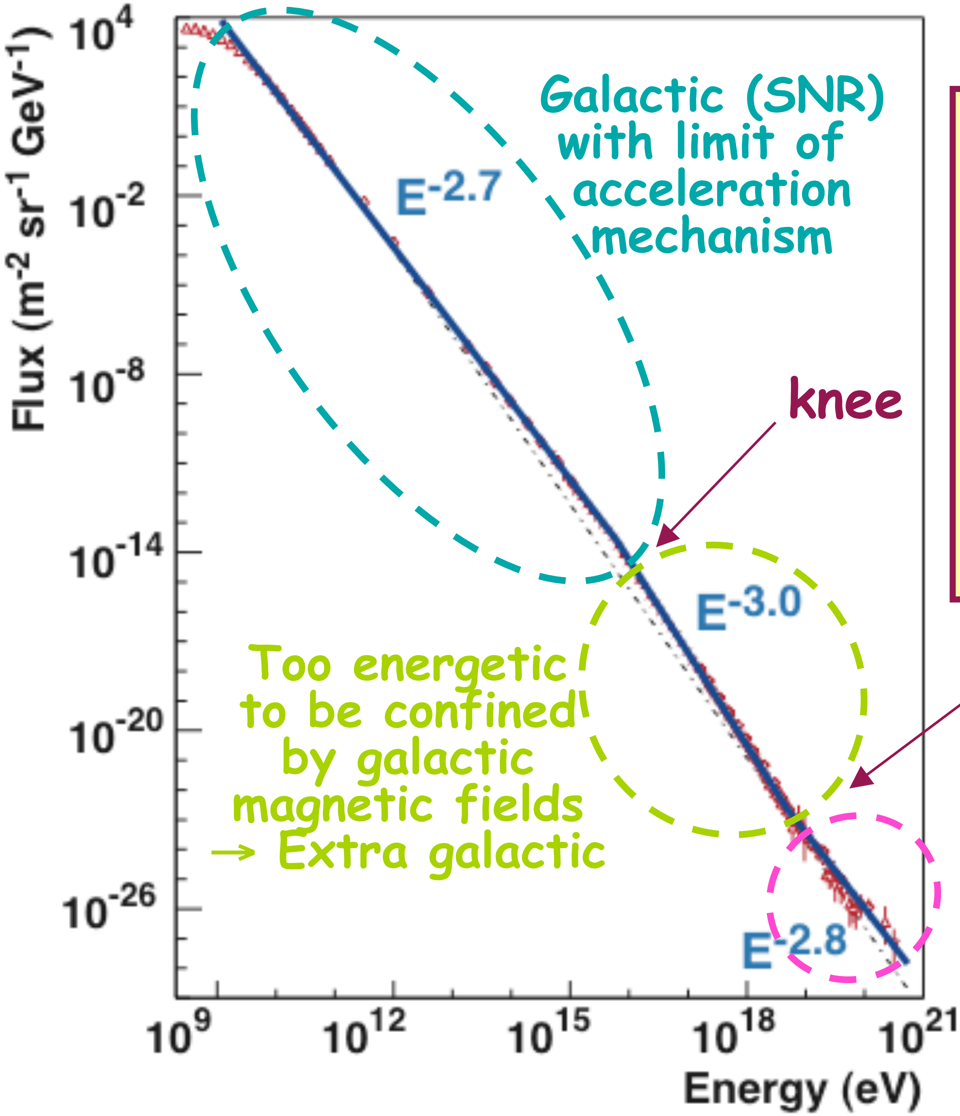
Energy spectrum



E<10^{14} eV
Flux high enough for detection of primary particle
(AMS on ISS)

E>10^{14} eV
Use atmosphere to create extensive air showers
(AGASA, Fly's eye)

Structure in cosmic ray spectrum



ankle

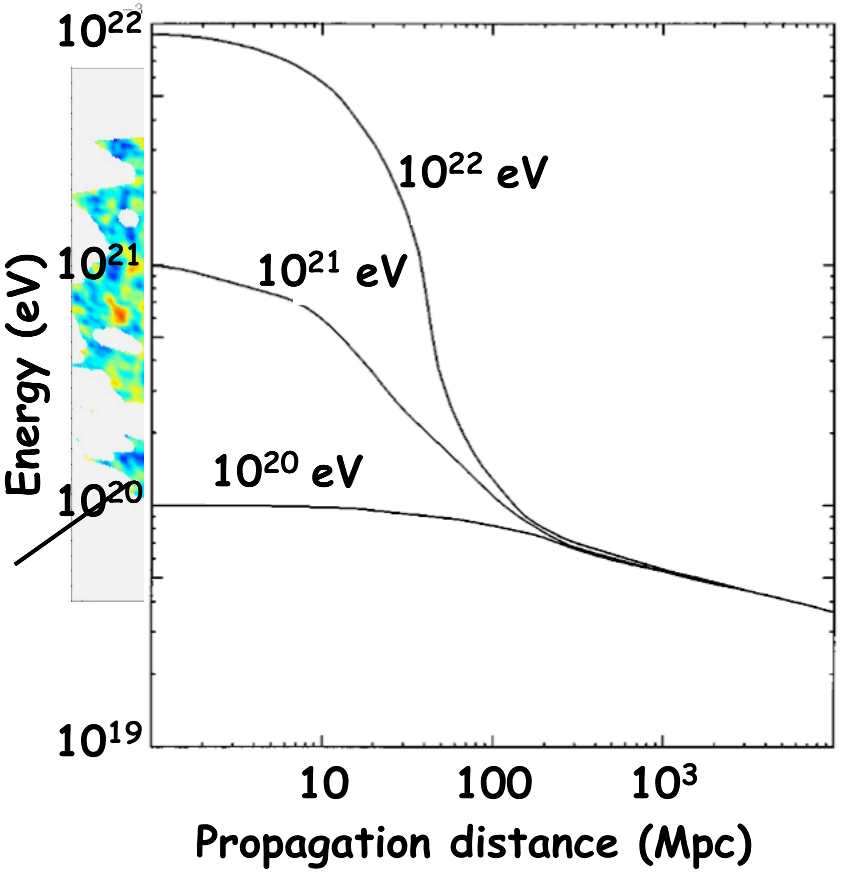
Complete mystery!

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

Source acceleration 2.0 — 2.2

Propagation ~ 0.6

GZK (Greisen Zatsepin Kuzmin) cut-off



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

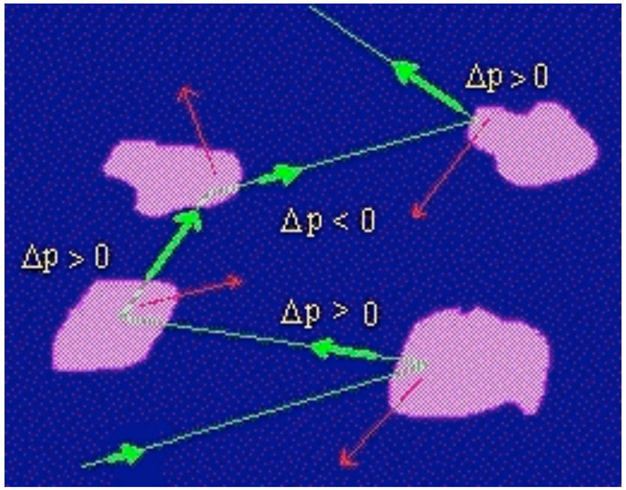
When process energetically allowed ($>5 \times 10^{19}$ eV), space becomes opaque to CR

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

(no known acceleration sites…)

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

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

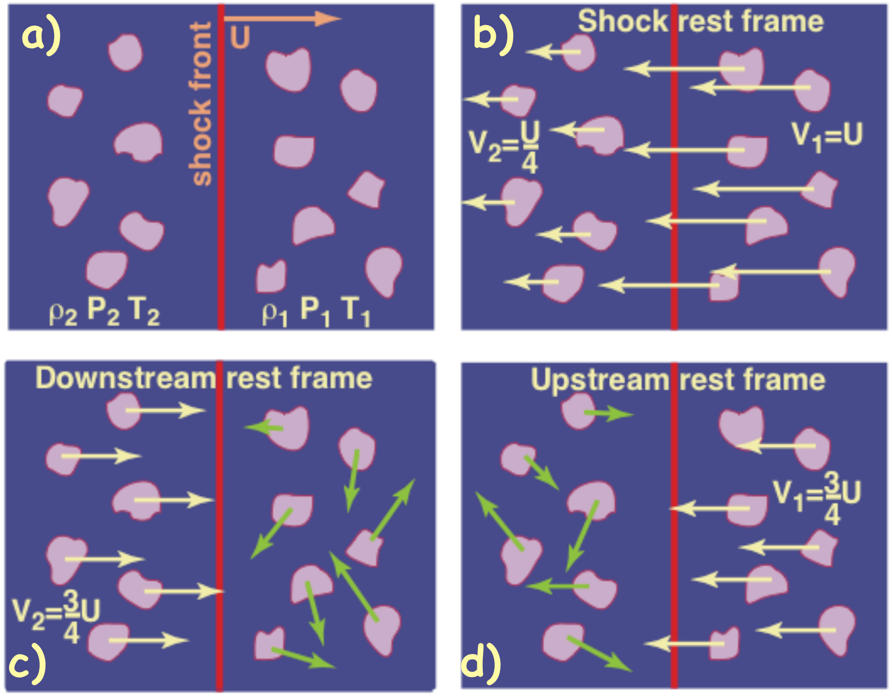
Slow and inefficient

" Second order "

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 $v_1/v_2 = 4$

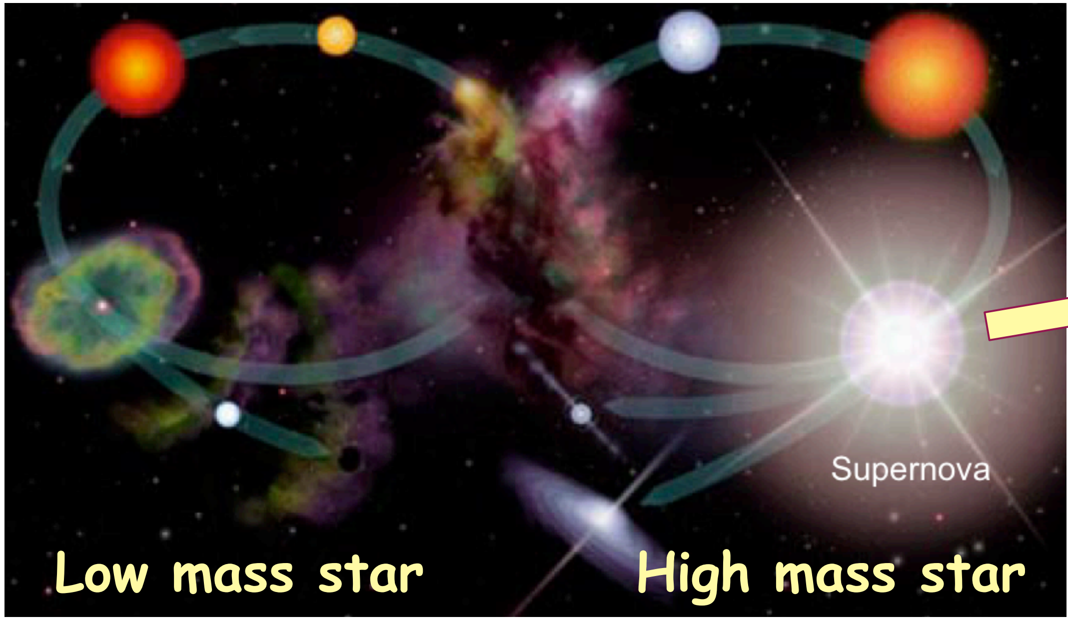
$\Rightarrow$ Rapid gain in energy as particles repeatedly cross shock front

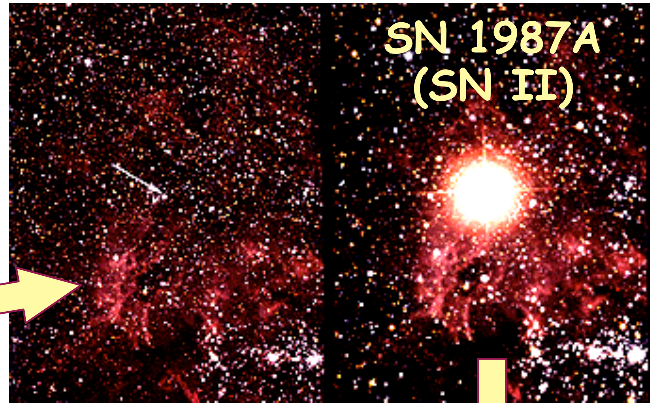
$\Delta E/E \;\alpha\; \beta\,(\sim 10^{-1})$ and E^{-2} spectrum

" First order "

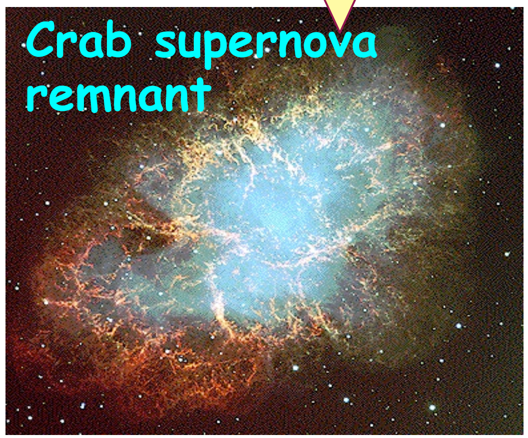
Powerful shocks?

→ Supernovae !



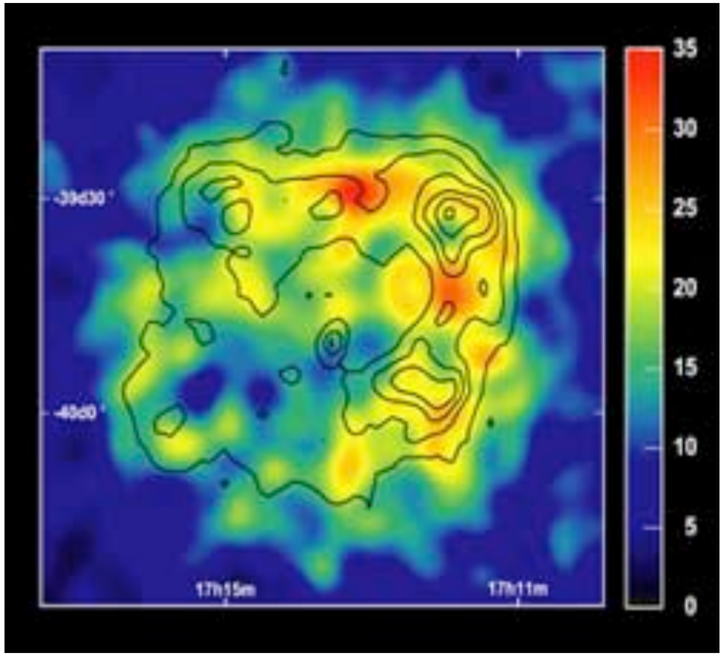


(too short) life and
(extremely violent) death
of massive stars



1 SN II / 50 years in our galaxy

HESS : first confirmation



HESS : gamma-ray color map
(E > 100 GeV)

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

Excellent overlap → confirmation of SN remnants
as particle accelerators

Energy limitation

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

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

(no energy losses)

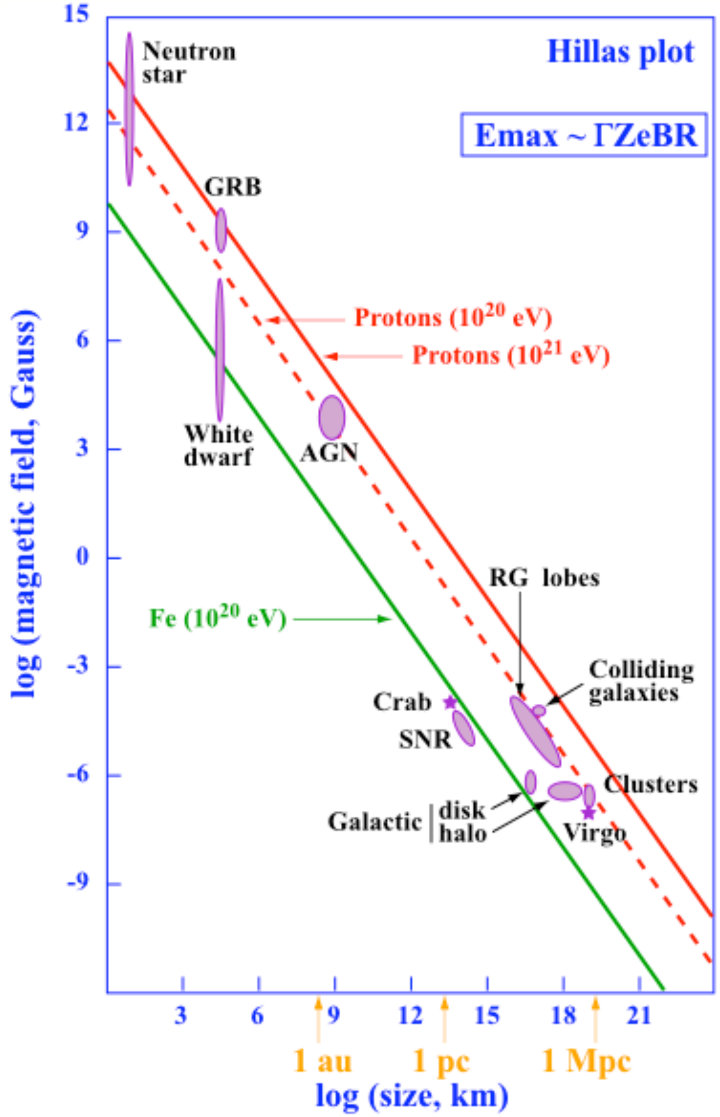
⇨ Need high B, large R

Supernova remnants :

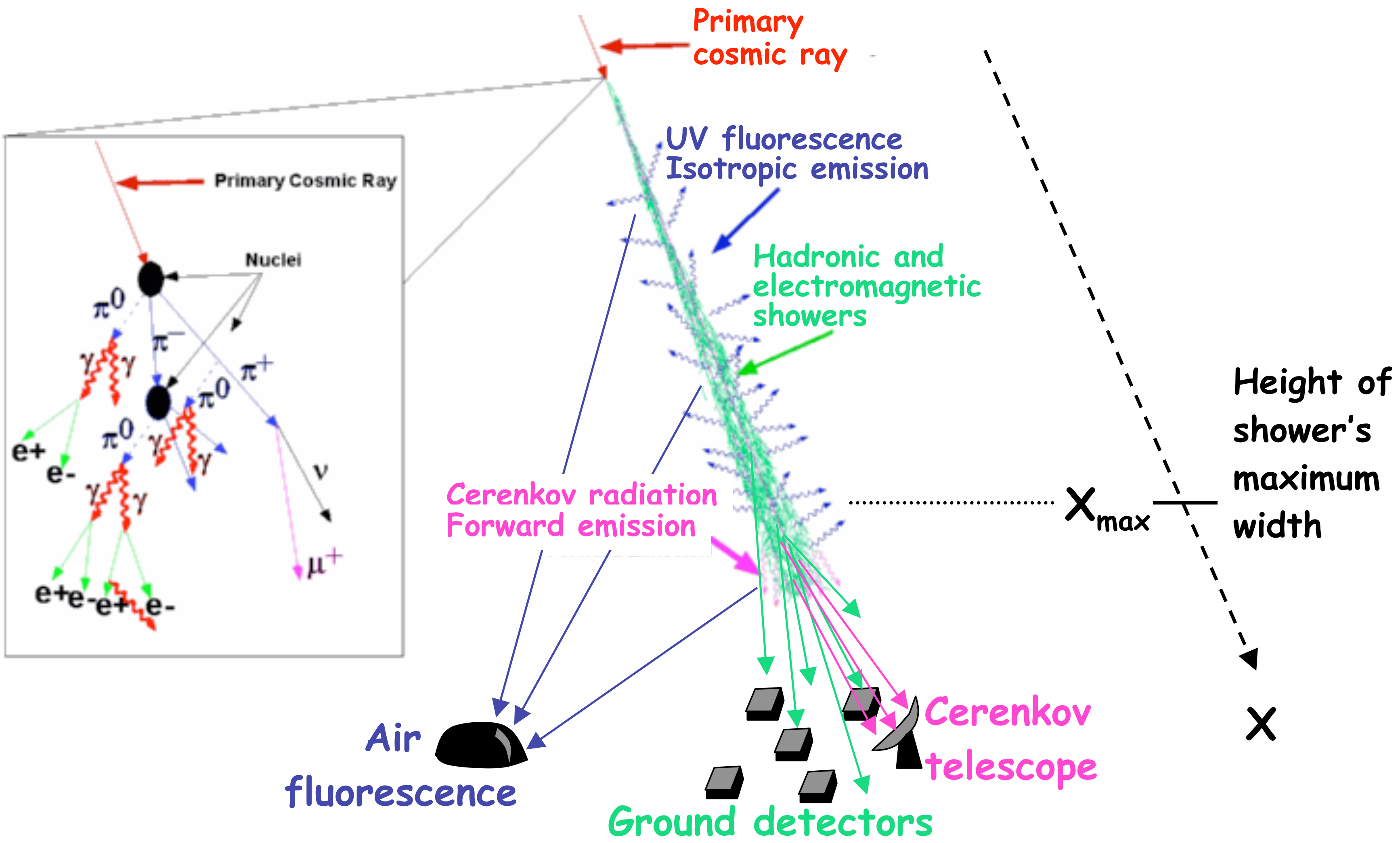
→ $E_{max} \sim 10^{15}$ eV (knee)

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

→ Relativistic motions (Γ)



Cosmic ray detectors

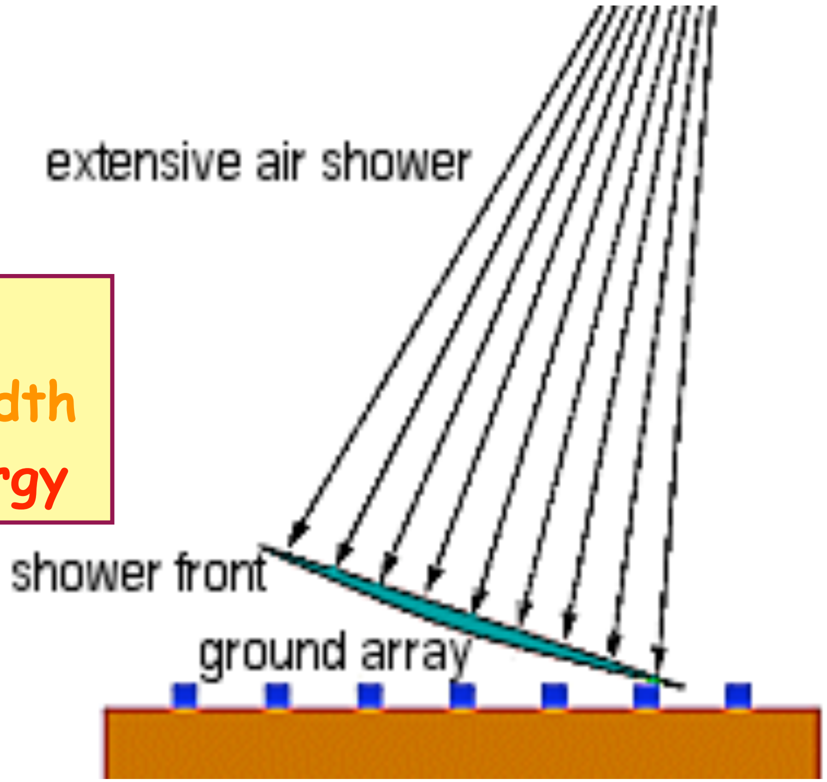


Counting particles: AGASA

Trajectory determined from arrival time of shower front on ground detectors

Cerenkov detectors measure height of shower maximum width (X_{max}) related to primary energy

130 km west of Tokio

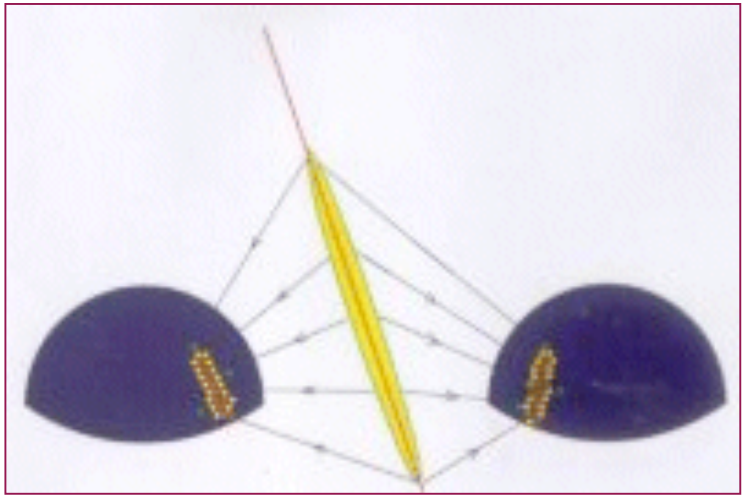


Air fluorescence: Fly's Eye

Spherical mirrors viewed by PMT's at the focal plane

Dual setup allows accurate trajectory reconstruction

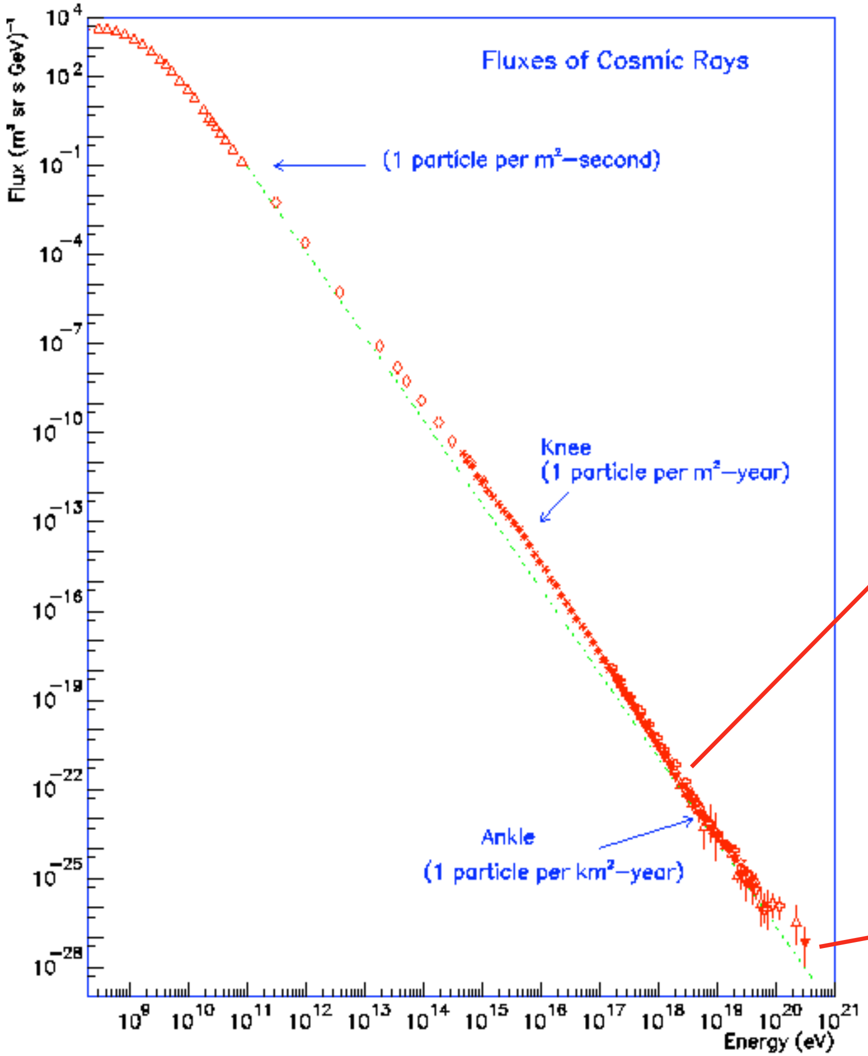
Amount of light (with $1/r^2$ correction for geometry)
→ shower profile
→ shower maximum X_{max}
→ primary energy



Can only operate on clear and moonless nights

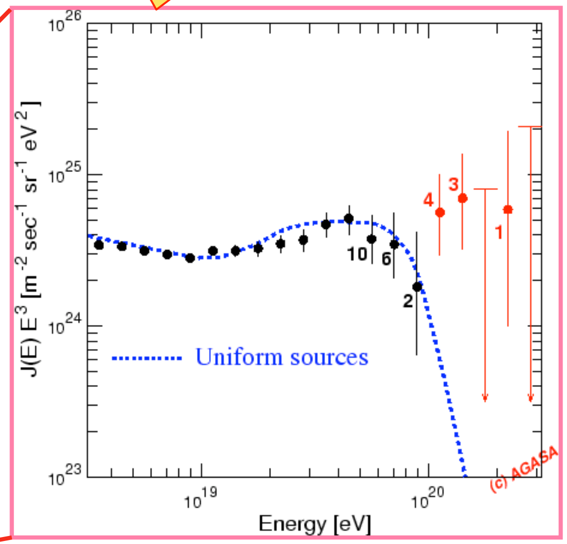
13 km apart in Utah desert

Ultra High Energy Cosmic Rays



AGASA: 17 events above $6x10^{19}$ eV
HiRes : 2 events (~ 20 expected)

cross calibration needed



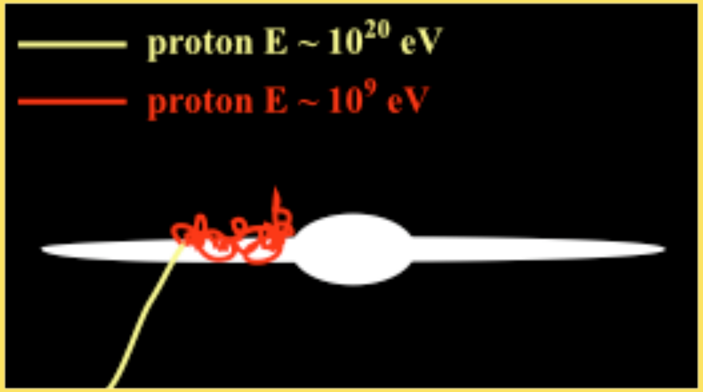
E_{max} = 3.2 10^{20} eV = 50 J !

Puzzling facts

Ultra high energy protons are
not confined in galaxy
+
Isotropy

⇩

Extra-galactic sources



Cosmological sources ⇨ No GZK cut-off ?

No counterpart (any wavelength) ⇨ Invisible source ?

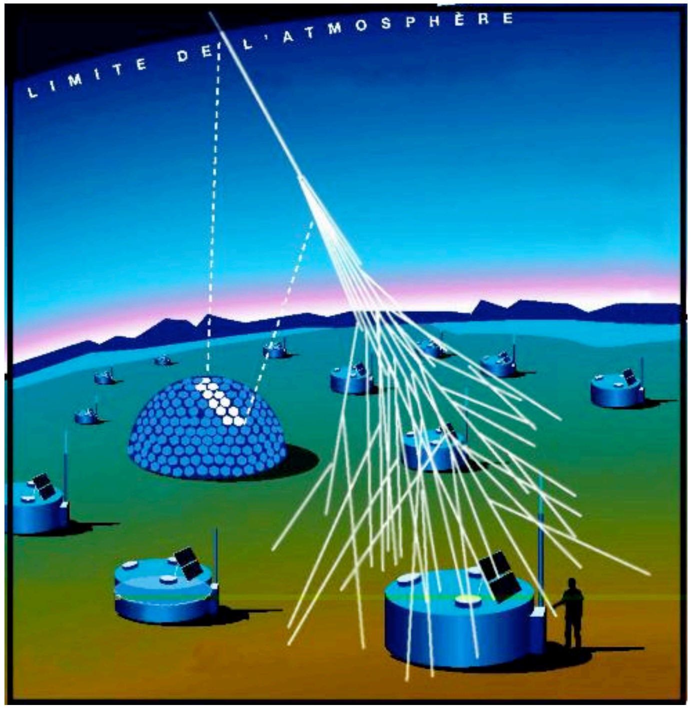
Possible suspects :
- Local GRB's
- Exotica
- …

Need more events

Future with AUGER and EUSO

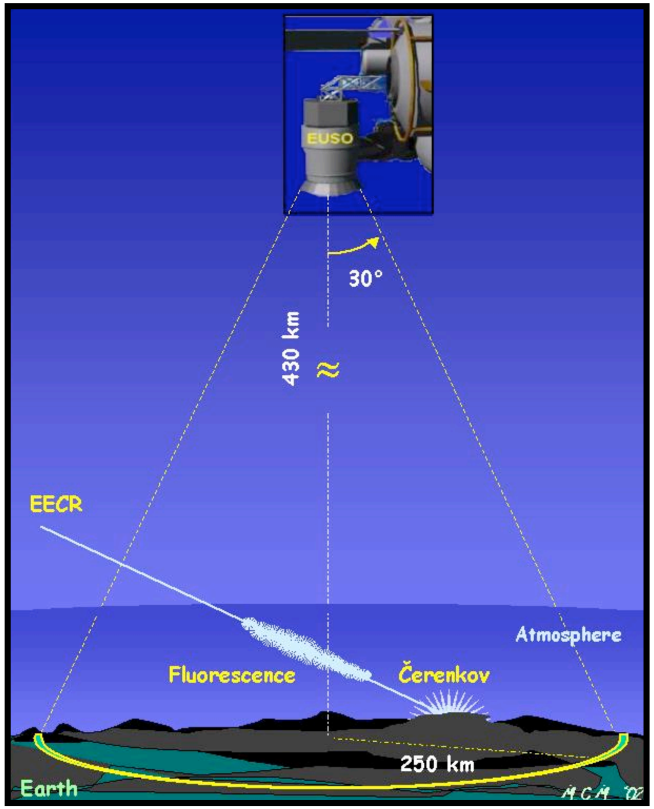
AUGER

Air fluorescence + ground arrays
2 sites (Argentina, USA):
1600 detectors + 4 telescopes, 3000 km^2
First results (though not all detectors)



EUSO

Air fluorescence from space
Expect 10^3 CR yr^{-1} above GZK
Launch: 2010 (for 3 years)



Lecture outline

1) What is Astroparticle Physics ?
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   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)

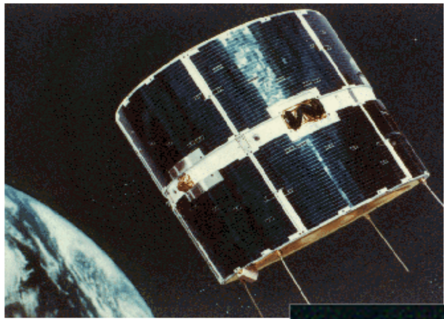
1967 First exhaustive review devoted to gamma-ray astronomy

1968 Detection of Galactic disk and Crab nebula

Gamma ray satellites

1972 SAS-2

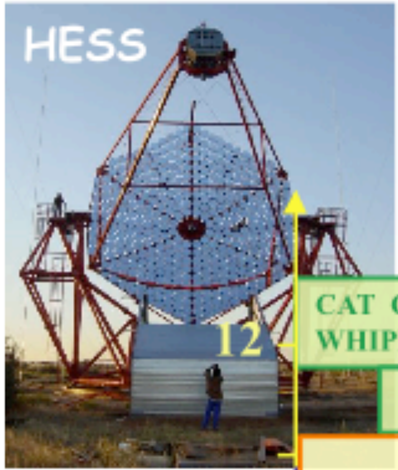
1975 COS-B
70 MeV - 5 GeV

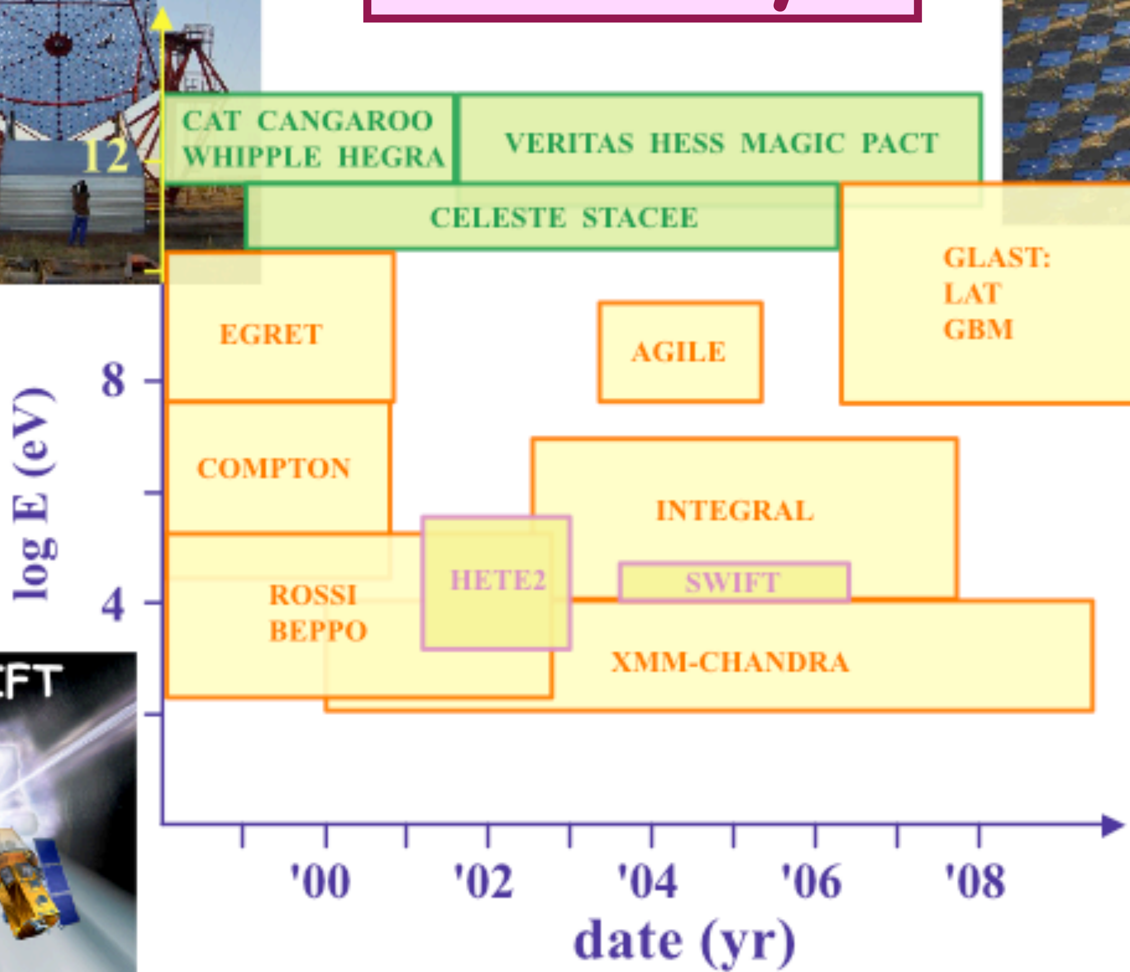


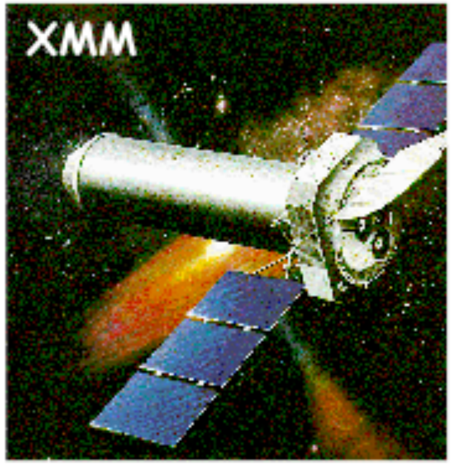
1991 G.R.O.-EGRET
50 MeV - 30 GeV

2006 GLAST
20 MeV - 300 GeV

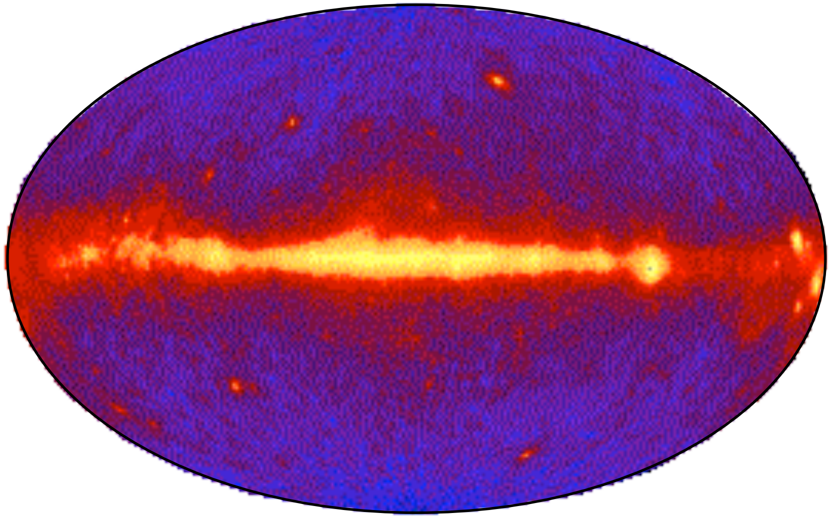
21st century



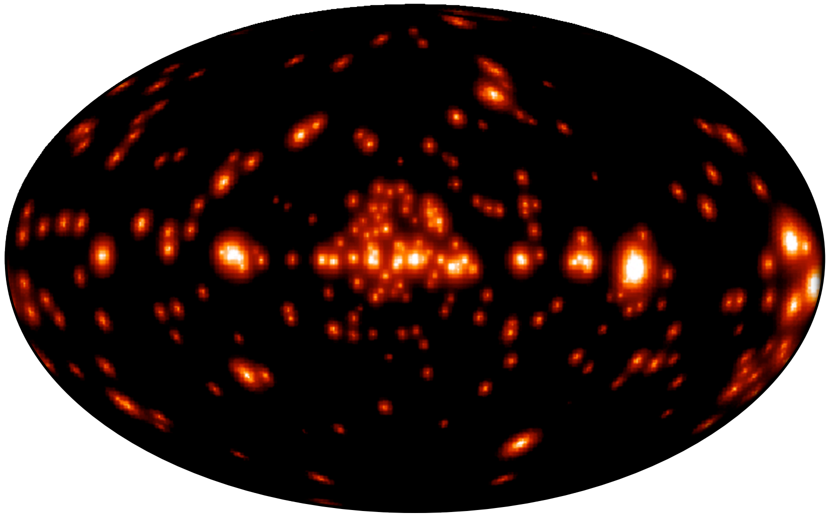




EGRET (E > 100 MeV)



Galactic diffuse interstellar emission from interaction with cosmic rays

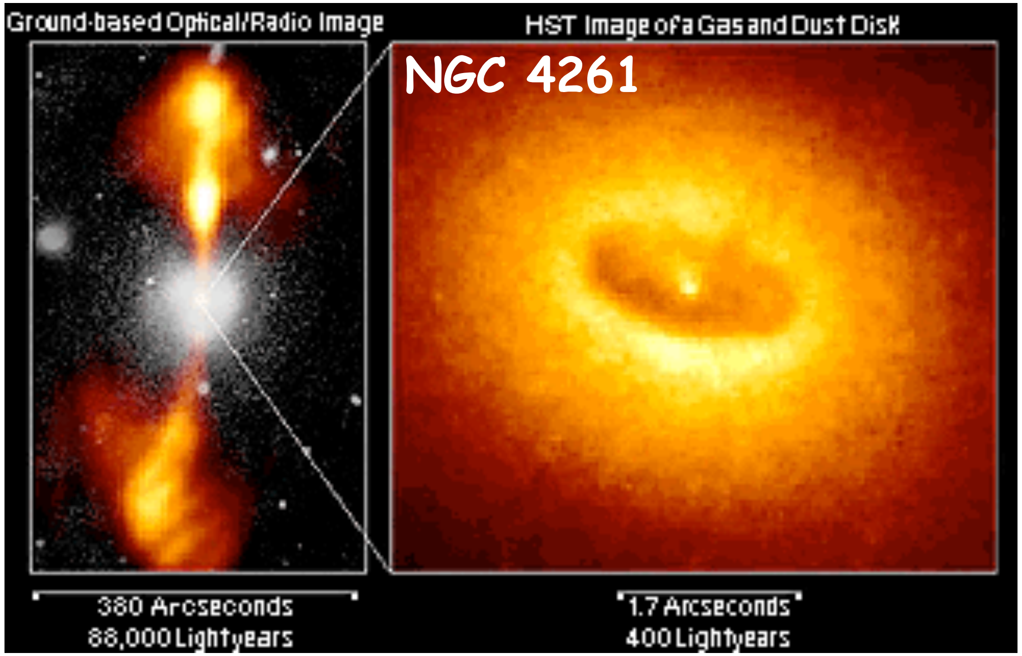


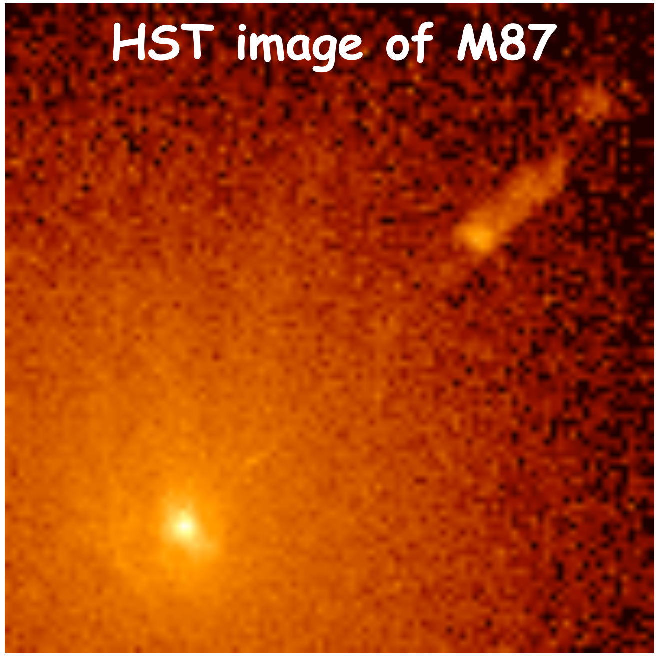
Point sources

- Jets from active galactic nuclei
- Galactic sources in star-forming sites : pulsars, binaries, supernova remnants …
- Unidentified sources (170/270)

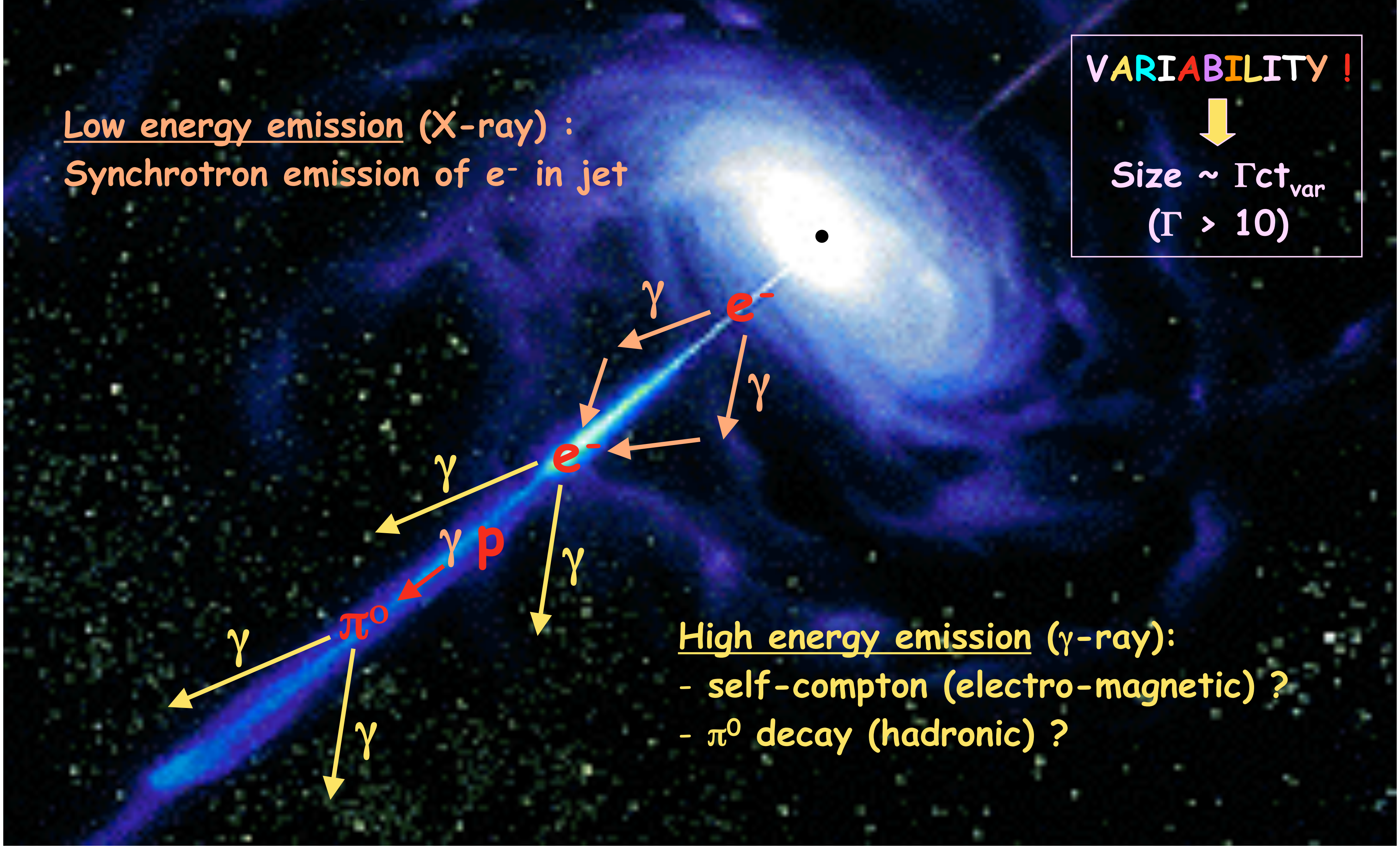
Active Galactic Nuclei

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

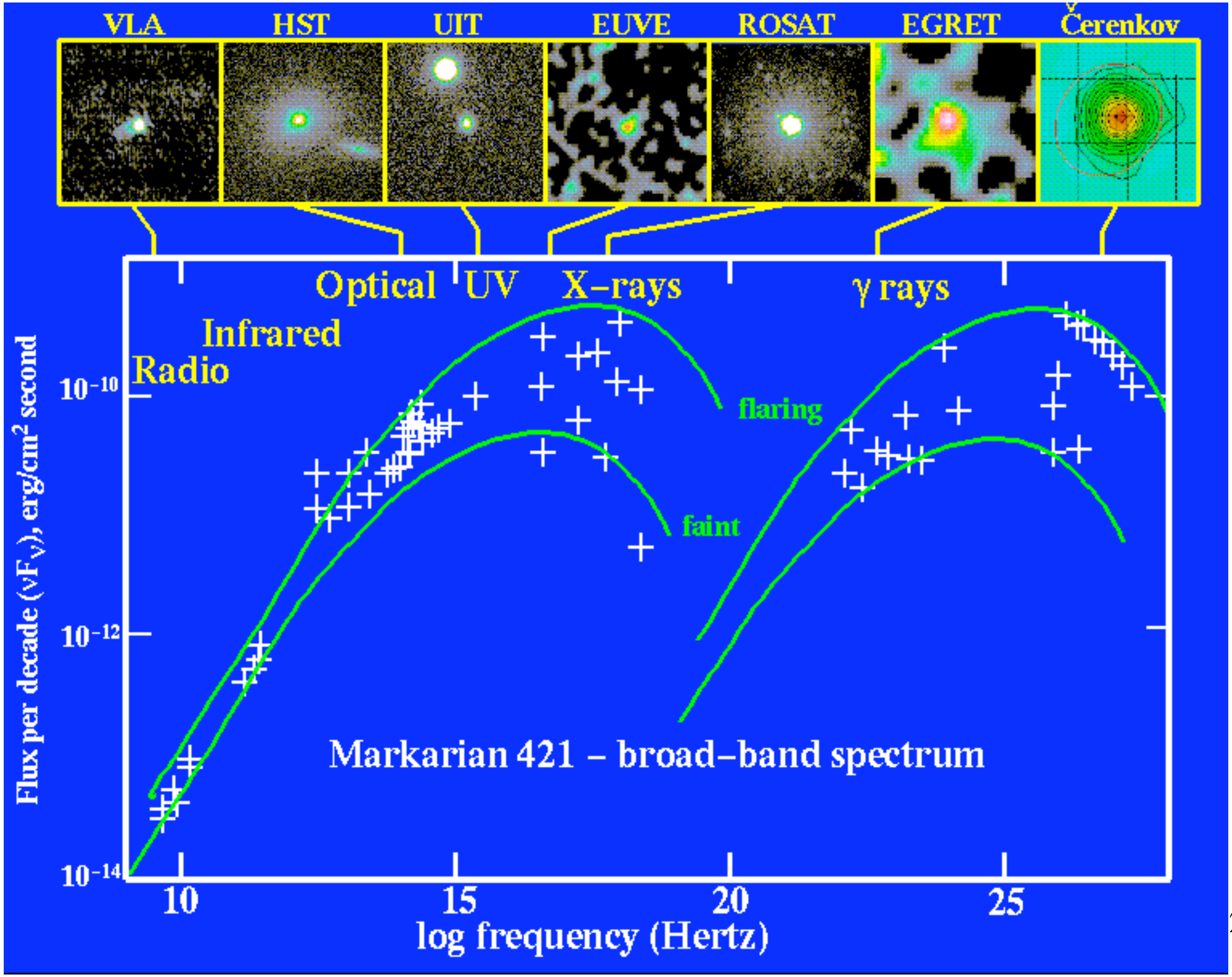


<u>Low energy emission</u> (X-ray) :
Synchrotron emission of e^- in jet

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

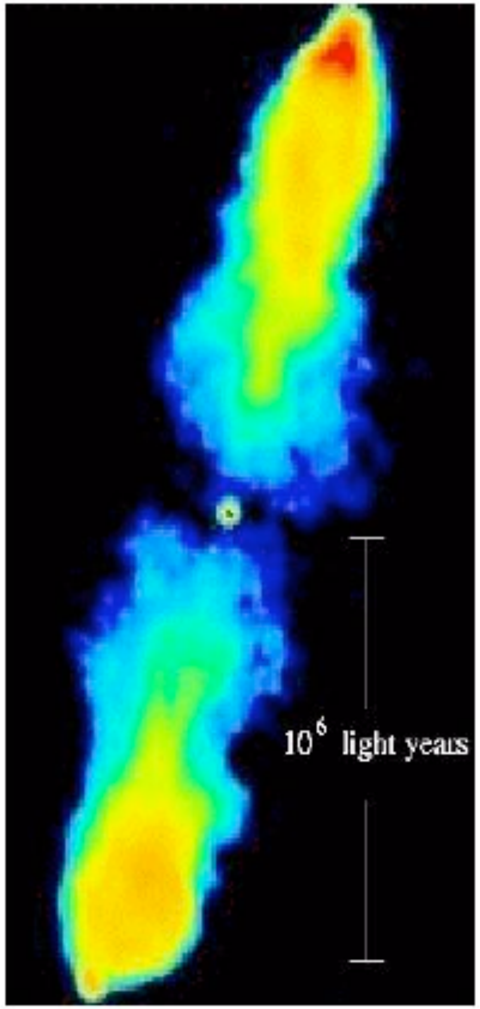
<u>High energy emission</u> (γ-ray):
- self-compton (electro-magnetic) ?
- π^0 decay (hadronic) ?

Markarian 421 : closest blazar

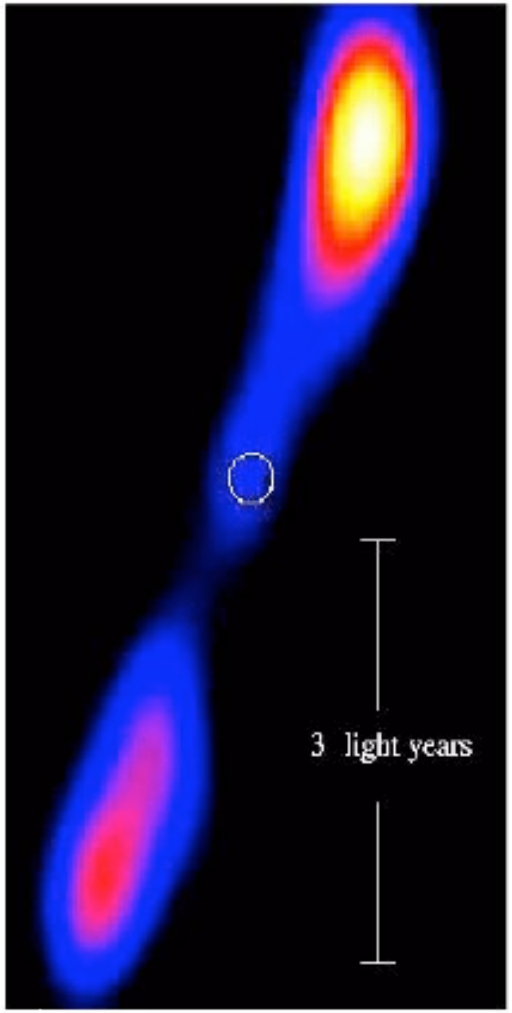


Quasars and Microquasars

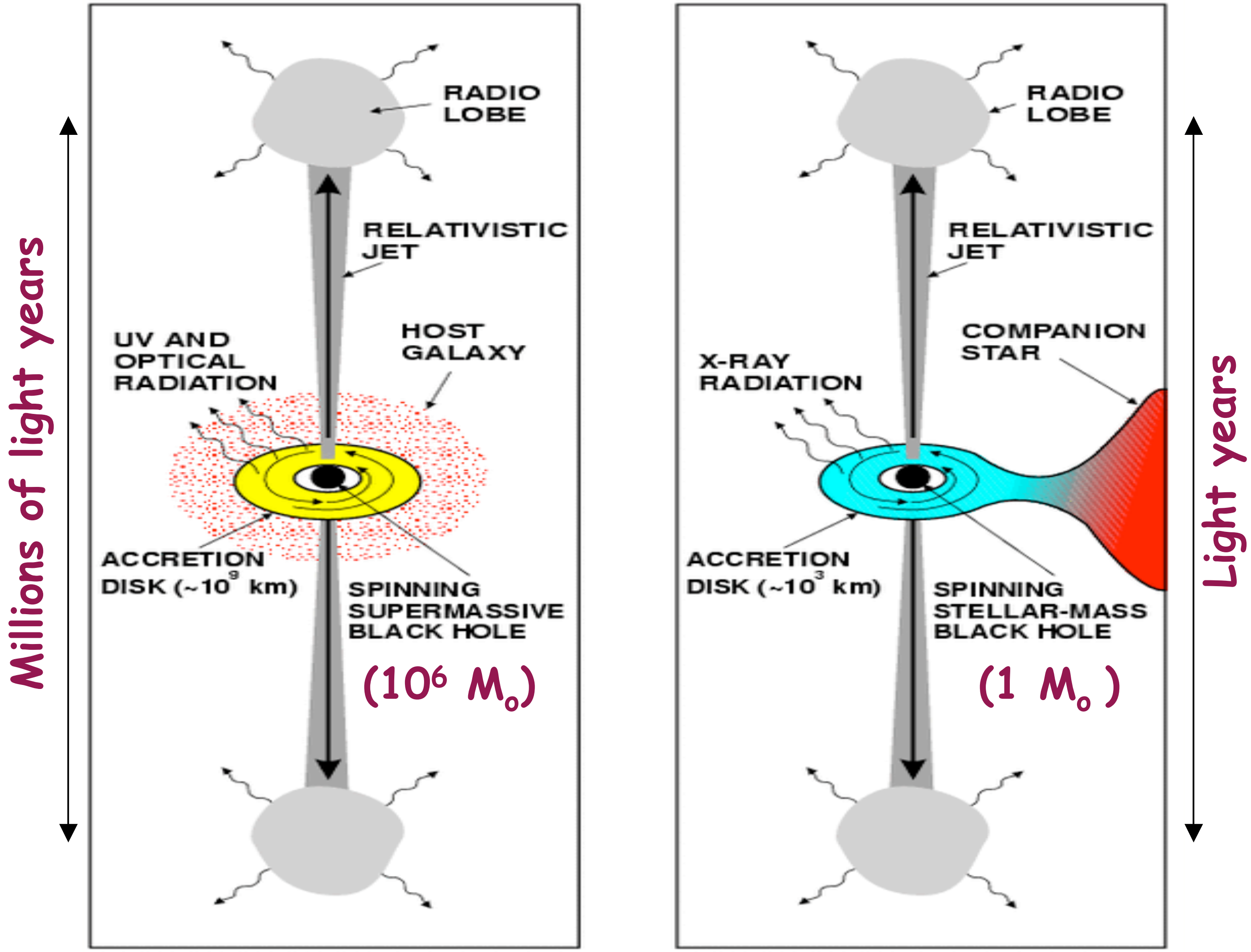
QUASAR 3C 223



MICROQUASAR 1E1740.7-2942



QUASAR   MICROQUASAR



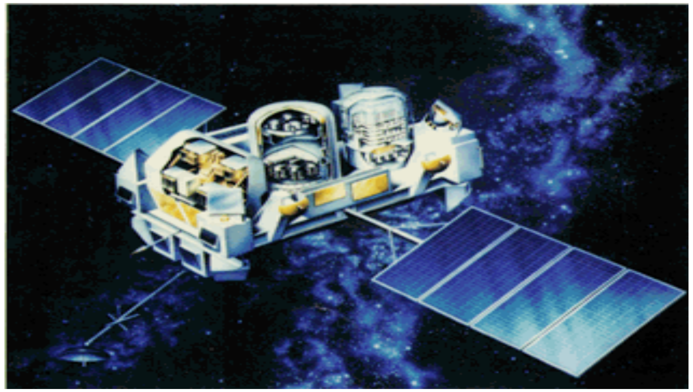
$R \alpha M_{BH}$ $T \alpha M_{BH}^{-1/4}$

Mirabel & Rodriguez

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, Δt from 10ms to 1000s

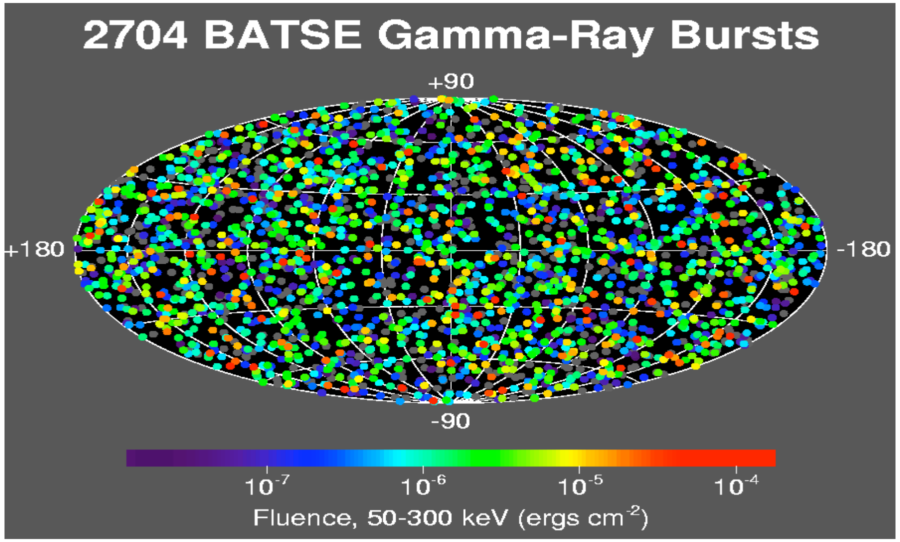
→ compact region, Lorentz boost (Γ ~100)

2005 (>2000 bursts) still very poorly understood …

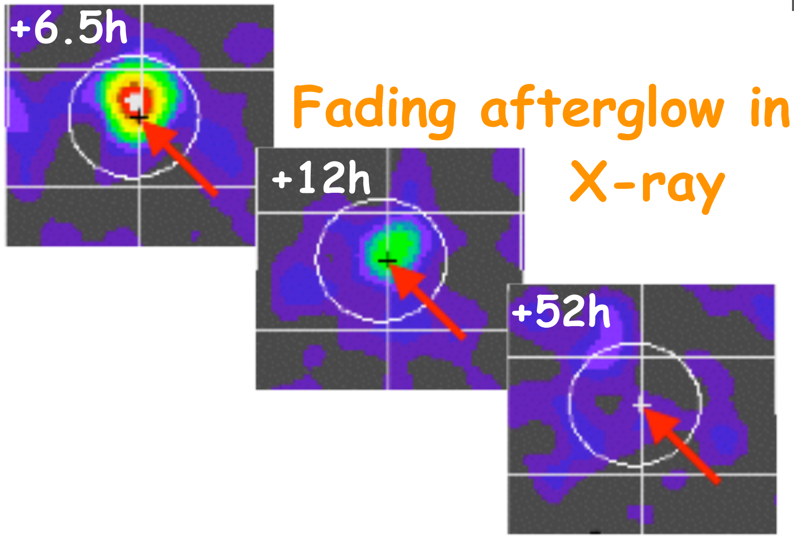
Burst location

Isotropy
+
Optical counterparts

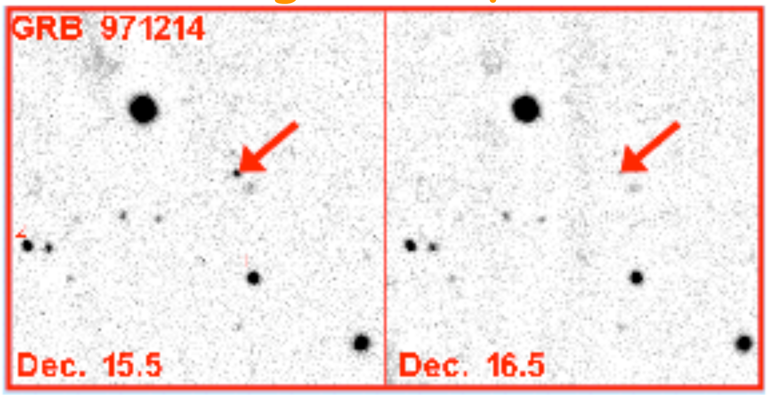
Cosmological phenomena!
(z = 0.43 to 4.50)



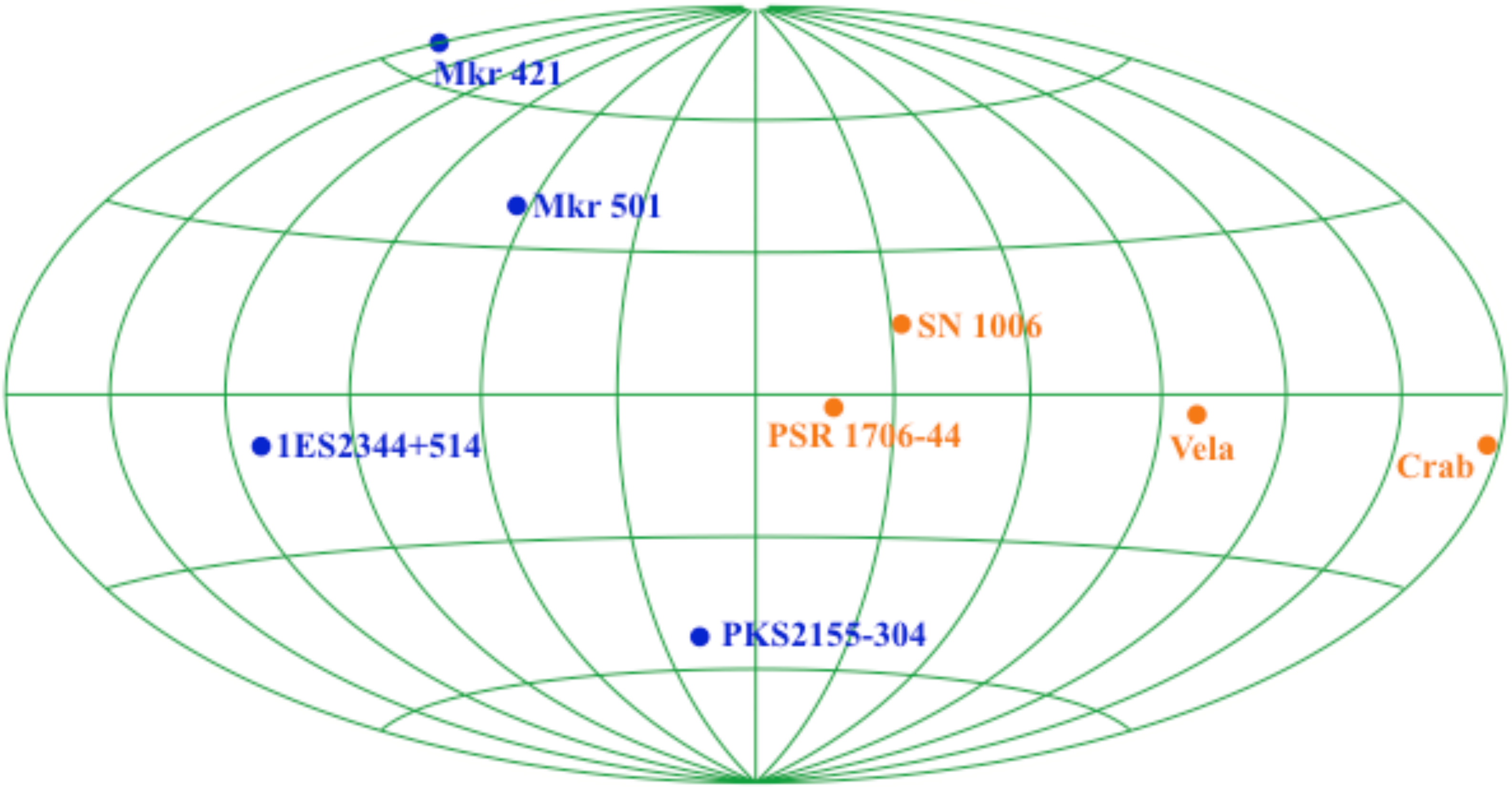
Fading afterglow in X-ray



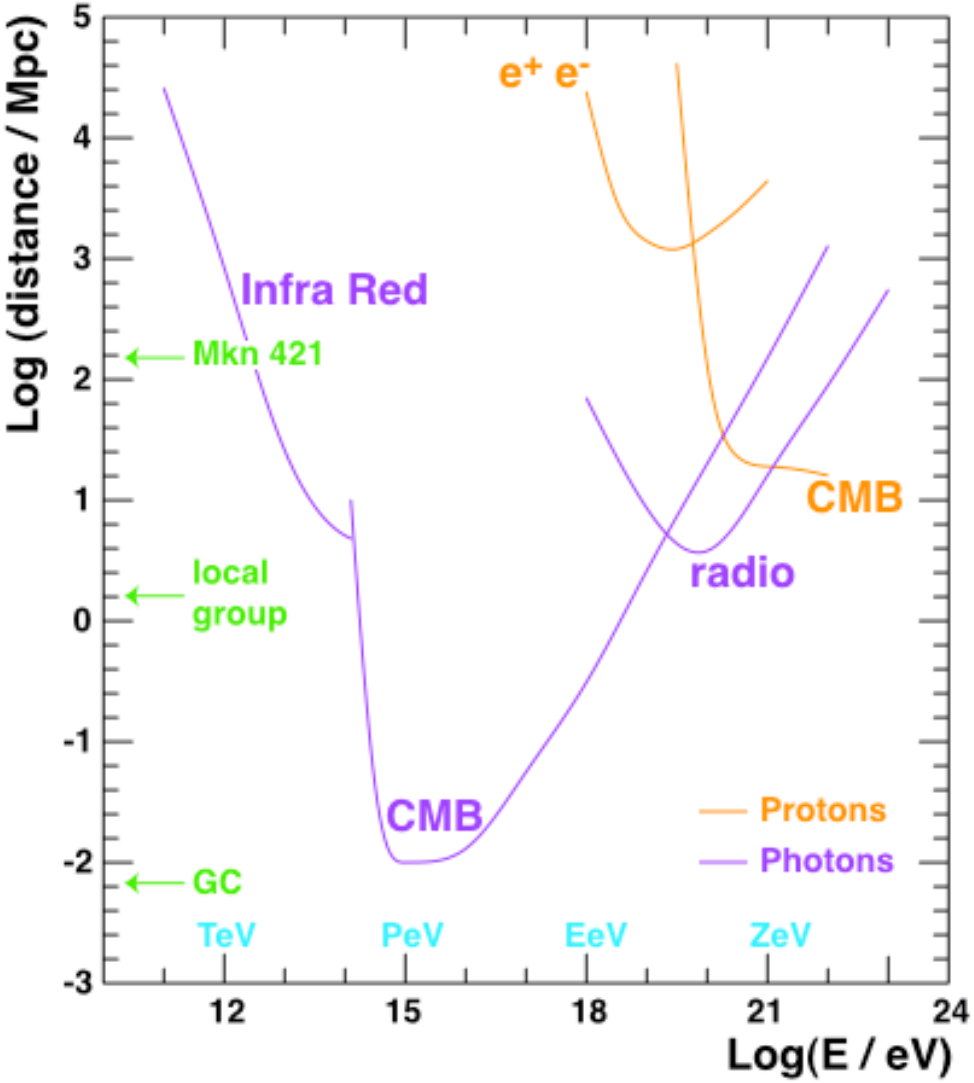
Afterglow in optical



TeV sky


Mkr 421
Mkr 501
SN 1006
1ES2344+514
PSR 1706-44
Vela
Crab
PKS2155-304

High energy cut-off !



GZK cutoff

Main explanation for lack of TeV sources

GZK cutoff for γ but not for UHECR ?

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Other messengers ?

Photons: absorbed (GZK)

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

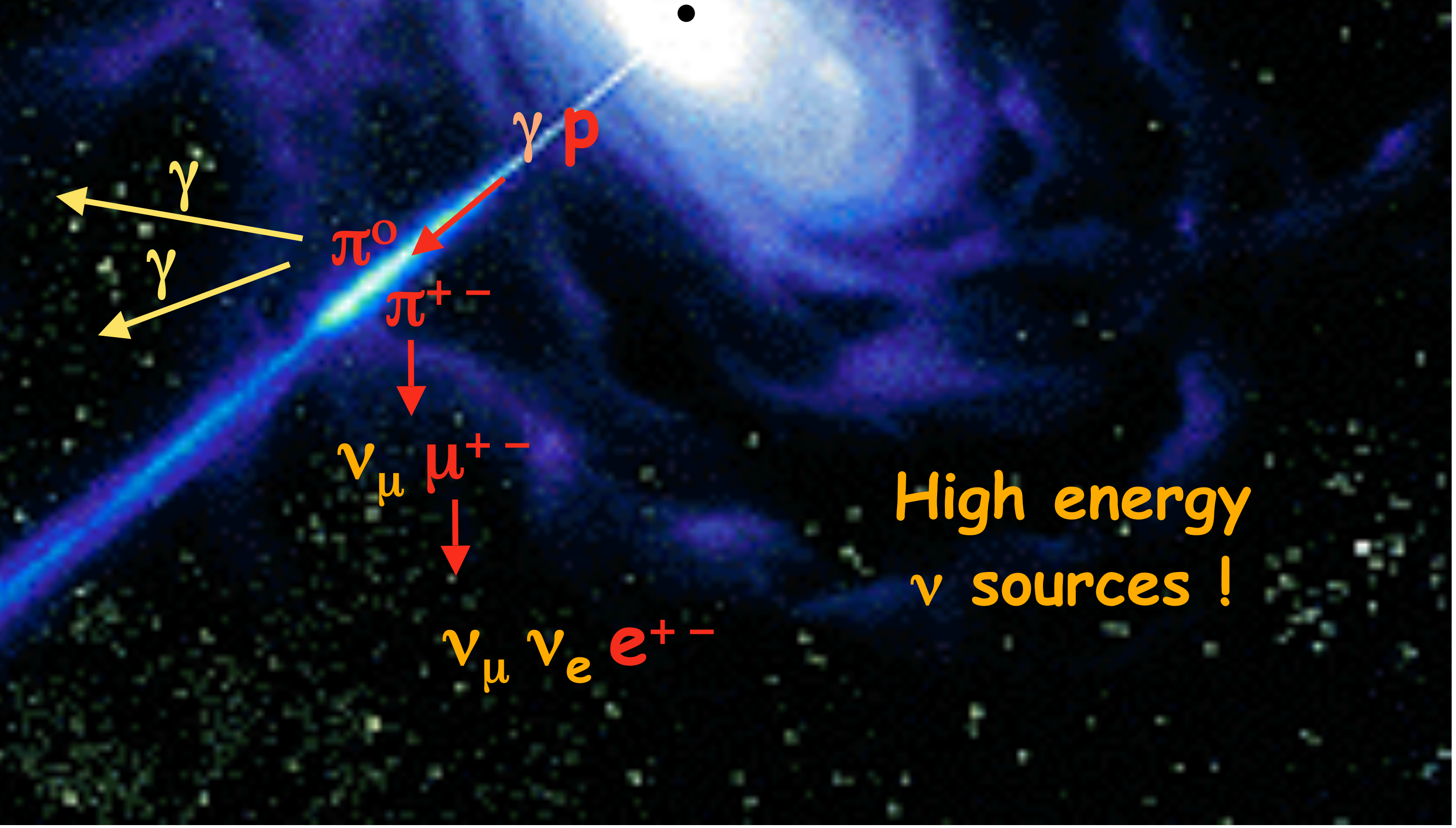
Protons: absorbed (GZK)
& deviated (E<10^{18} eV)

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

High energy sources

High energy emission (γ-ray):

- ~~self-compton (electro-magnetic) ?~~
- π^0 decay (hadronic) ?

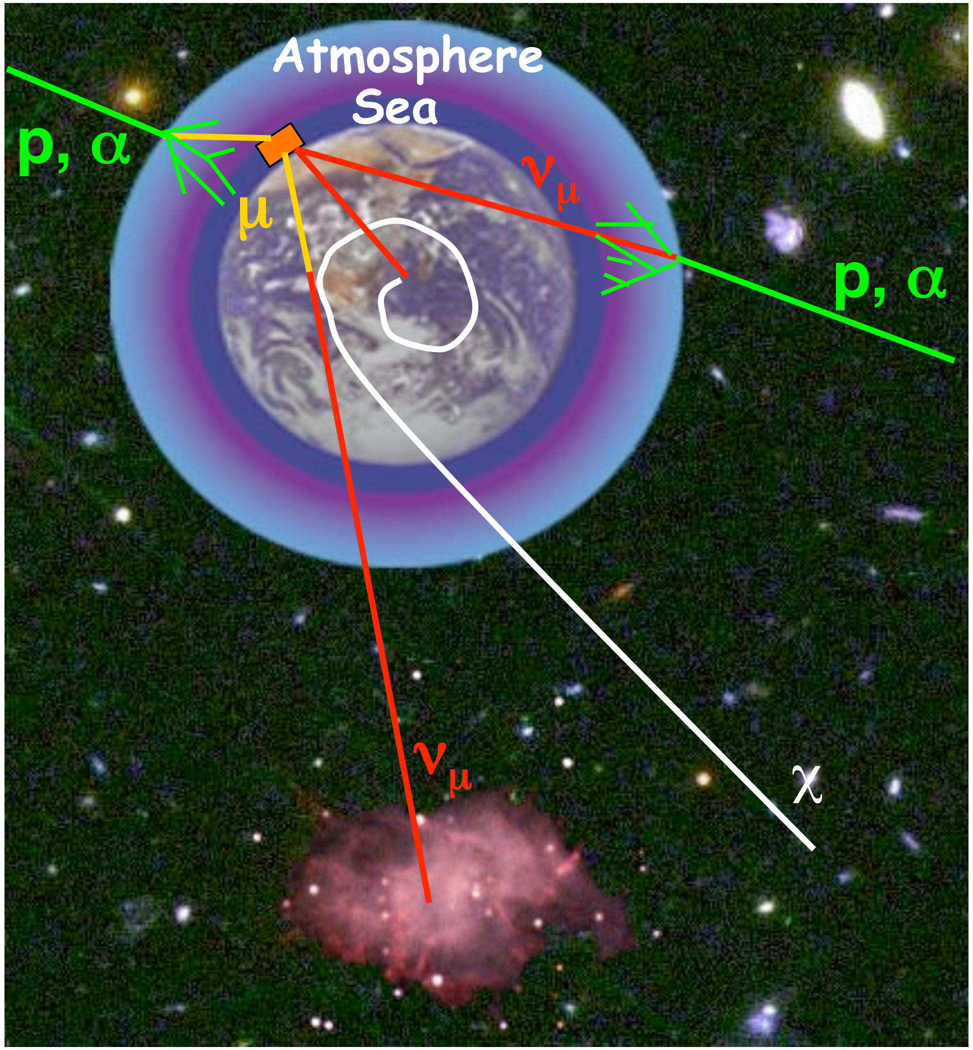


Experimental challenge

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

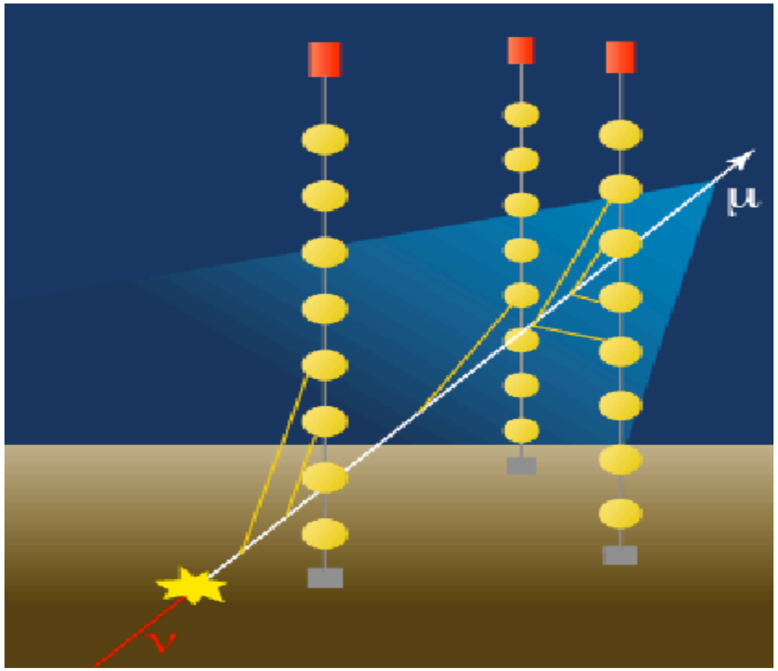
High background → Good shielding
(atmospheric μ & ν) (> 1000m water eq.)
Search for upgoing ν's

Detection principles



- Cosmic ν (> 1 TeV)
- $\chi\chi \rightarrow \nu$ (10-1000 GeV)
- Atm. ν (10-100 GeV)
- Atm. μ

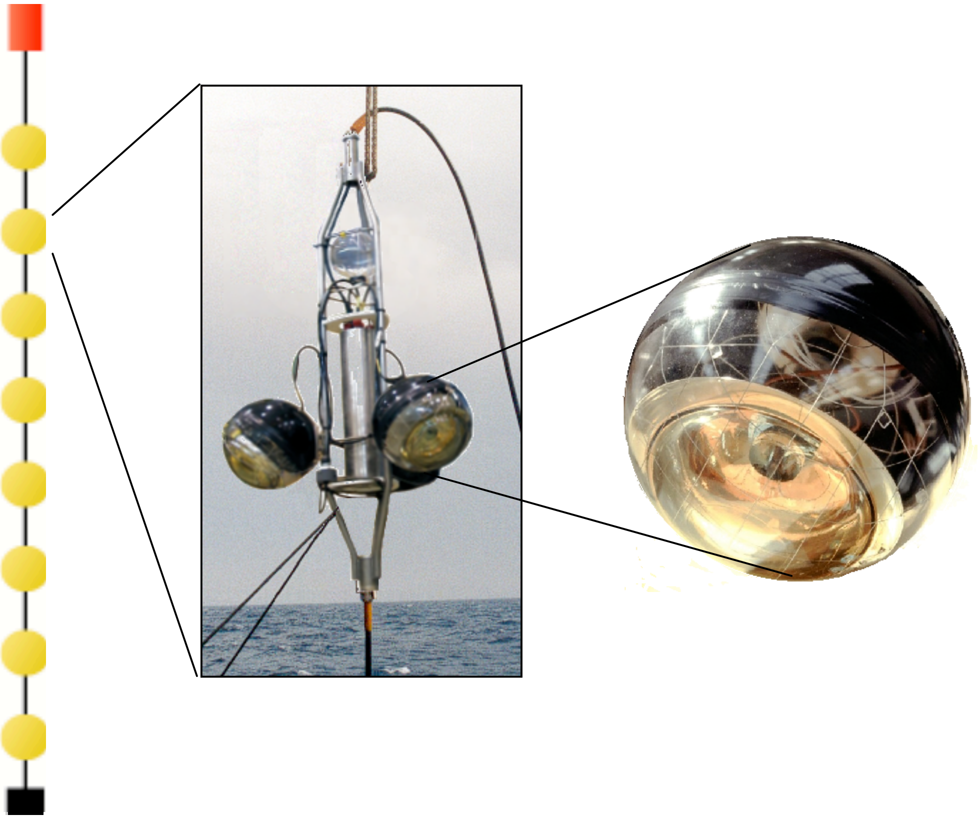
$\nu \rightarrow \mu \rightarrow$ Cerenkov light



HE neutrino experiments

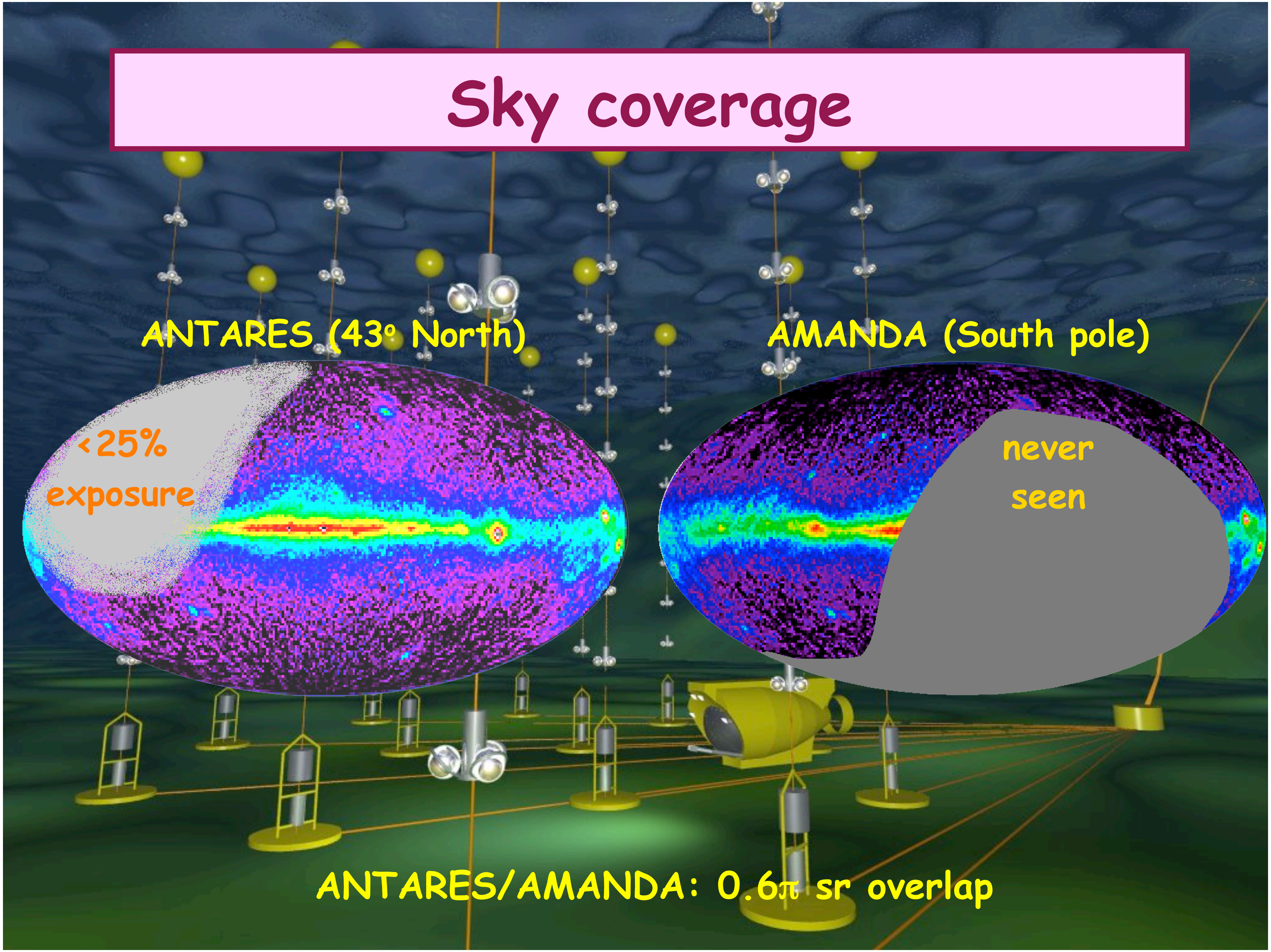
Detectors

Strings with optical modules (PMT in glass sphere)



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

Sky coverage



Conclusions

Cosmic Ray physics

- Existence or not of post GZK cut-off events ?

Gamma Ray physics

- Study of high energy sources (AGNs, blazars)
- GRB mystery

Neutrino physics

- Complementary to photon astrophysics
  (models confrontations)
- Indirect dark matter searches

New look on the Universe $\rightarrow$ room for unexpected discoveries