Astroparticle Physics (3/3)

Nathalie PALANQUE-DELABROUILLE
CEA-Saclay

CERN Summer Student Lectures, August 2006

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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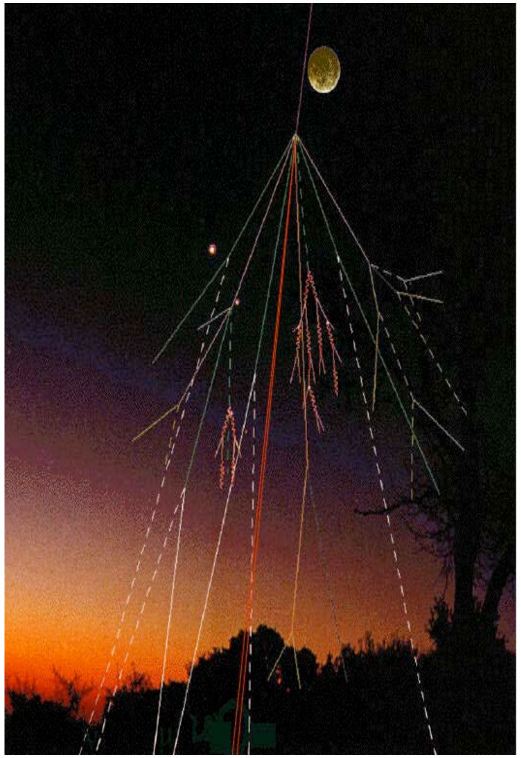


Brief history of Cosmic Ray detection

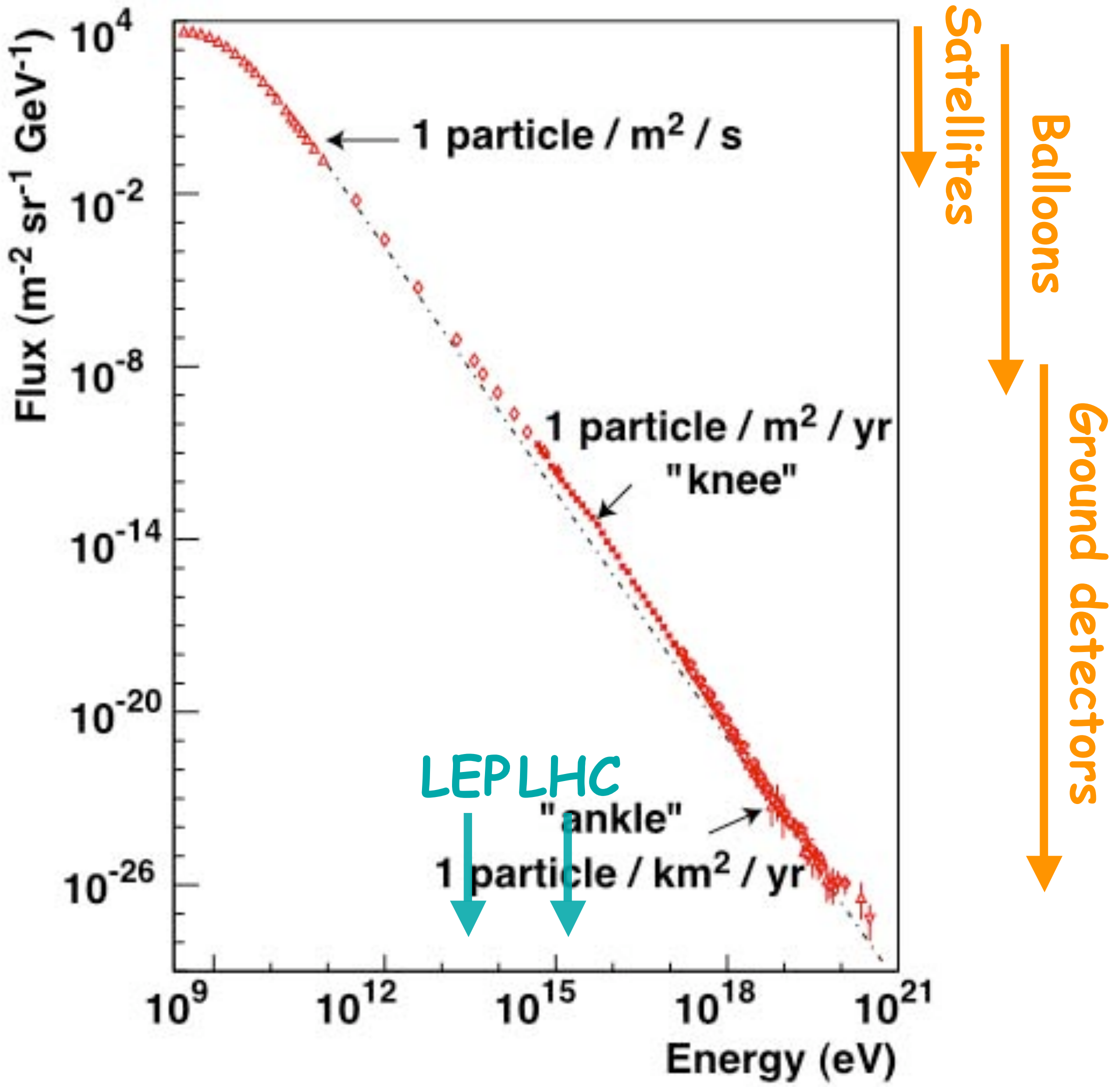
1912 Hess discovers cosmic rays

1925 Quasi-isotropy

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

1946 First air shower experiment

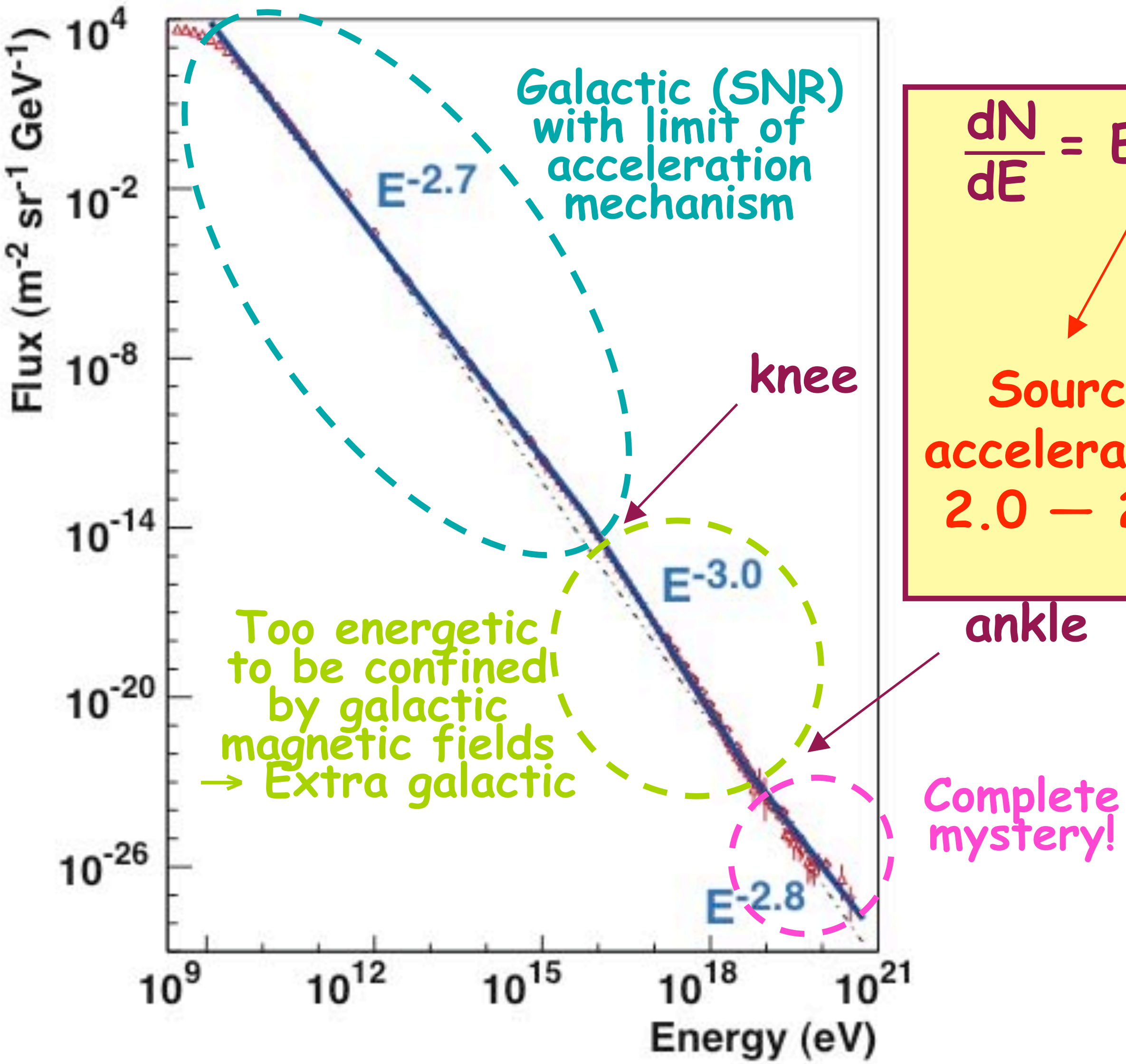
Energy spectrum



$E<10^{14}$ eV
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



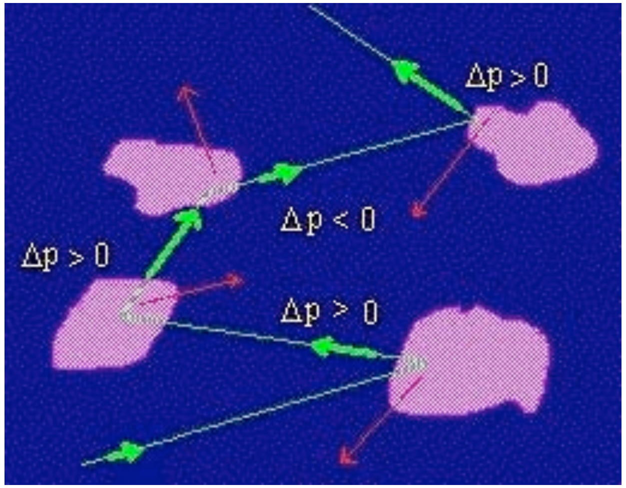
$$\frac{dN}{dE} = E^{-\alpha}$$ above 10 GeV

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

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

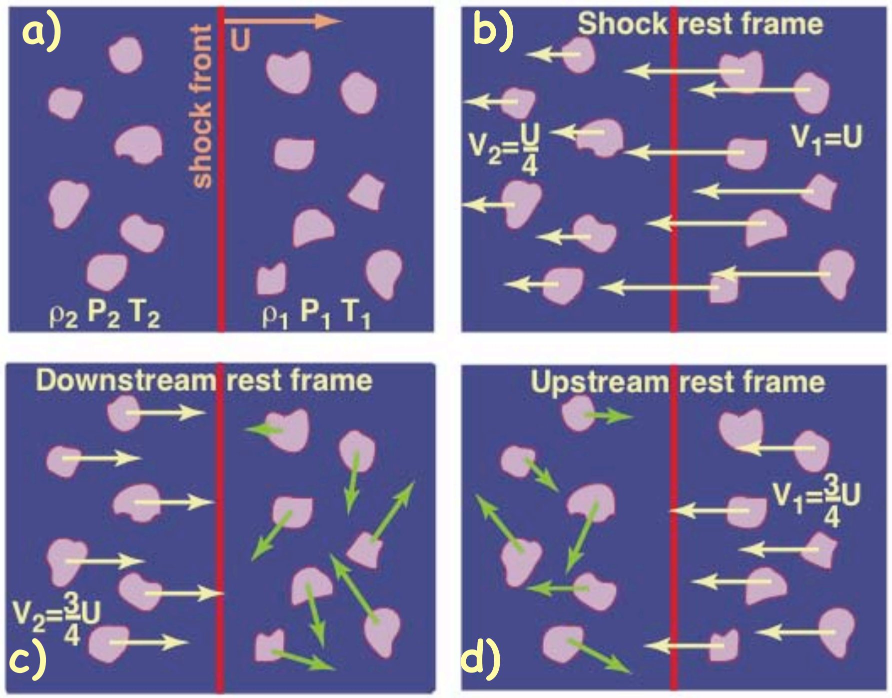
Slow and inefficient

" Second order "

First order Fermi acceleration

1970's : First order Fermi acceleration

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 $v_1/v_2 = 4$

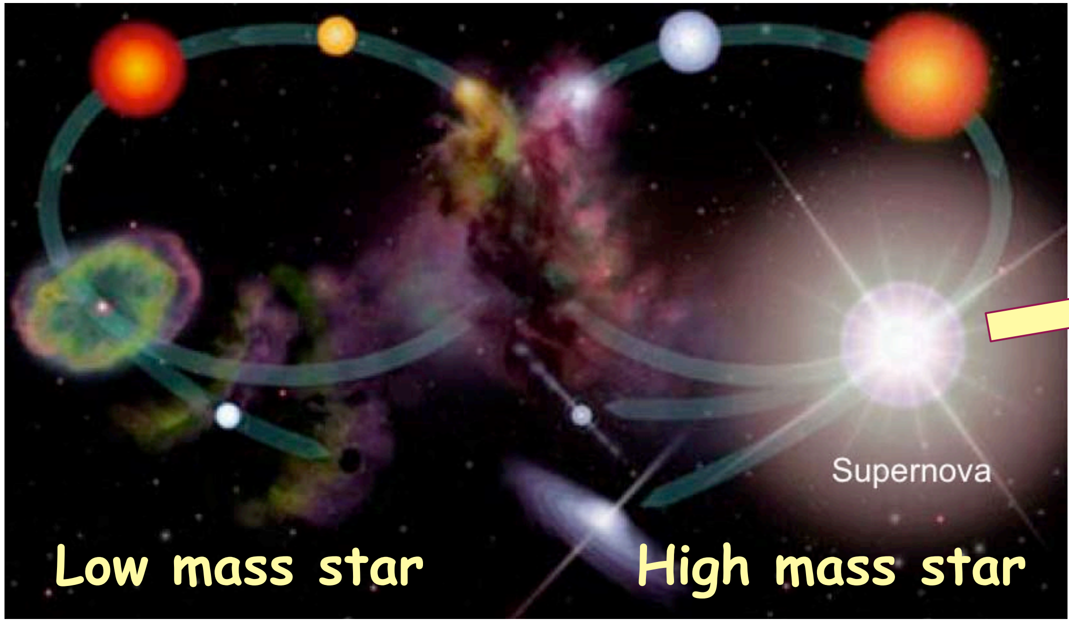
$\Rightarrow$ Rapid gain in energy as particles repeatedly cross shock front

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

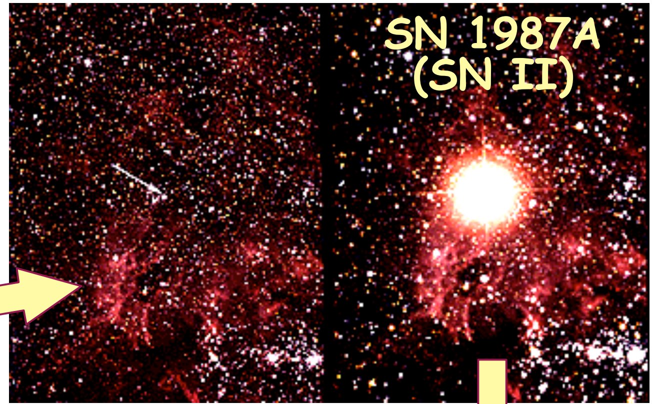
" First order "

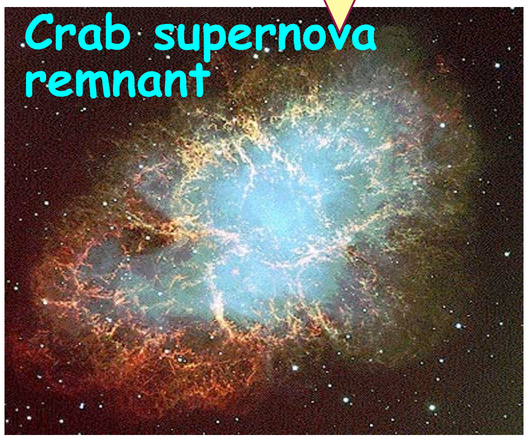
Powerful shocks?

Supernovae !



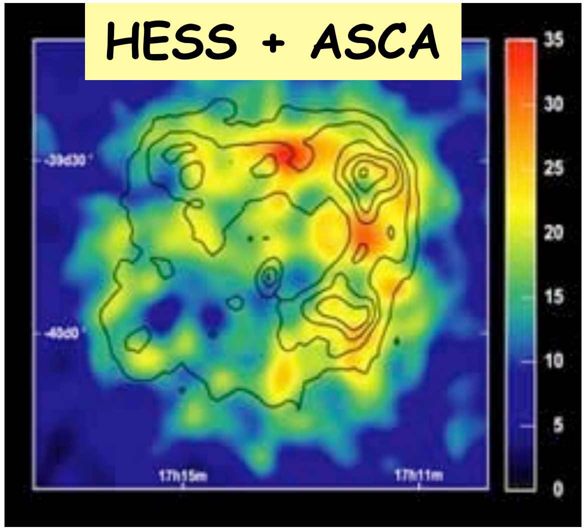
(too short) life and
(extremely violent) death
of massive stars

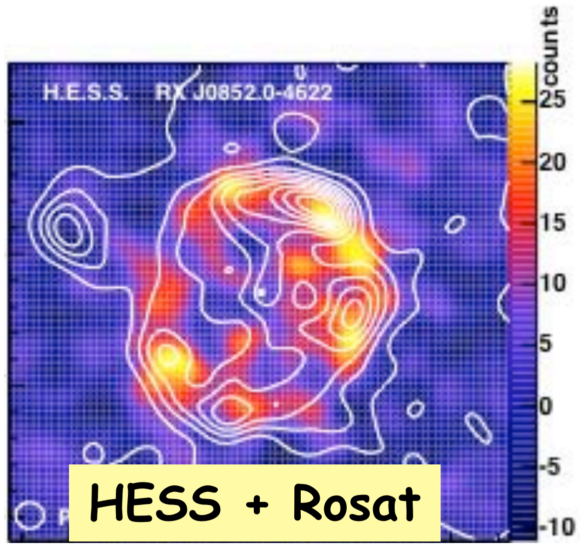




1 SN II / 50 years in our galaxy

HESS : first confirmation





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

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

Excellent overlap →
confirmation of SN remnants
as particle accelerators

ROSAT : radio contours

Energy limitation

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

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

(no energy losses)

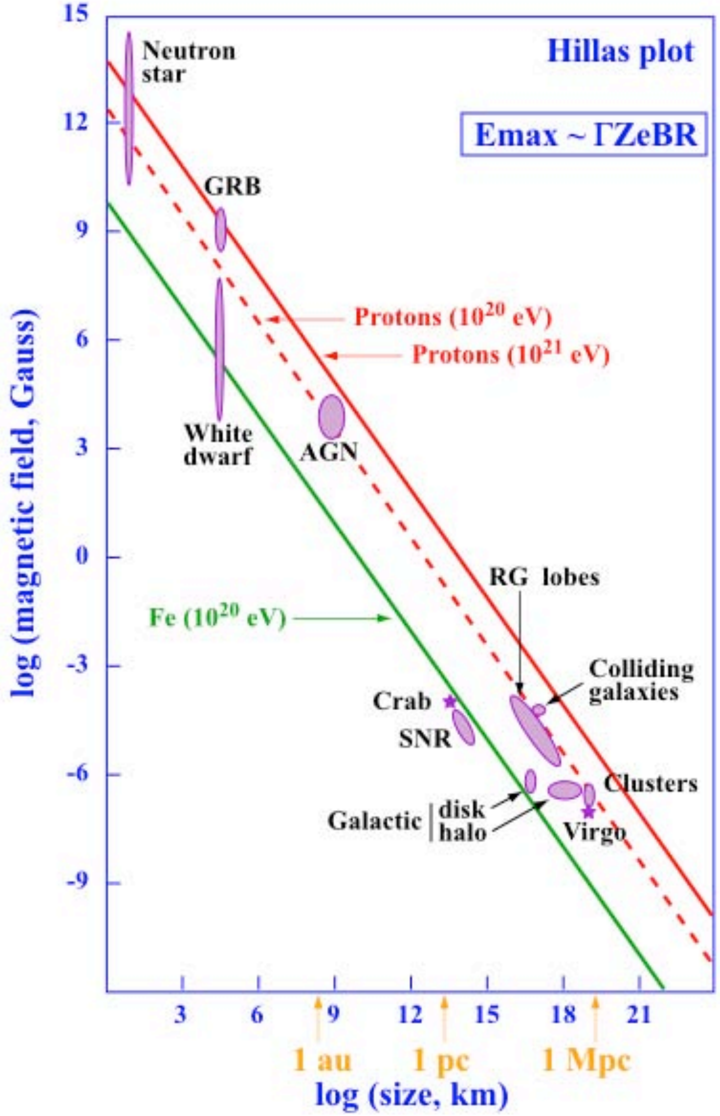
⇨ Need high B, large R

Supernova remnants :

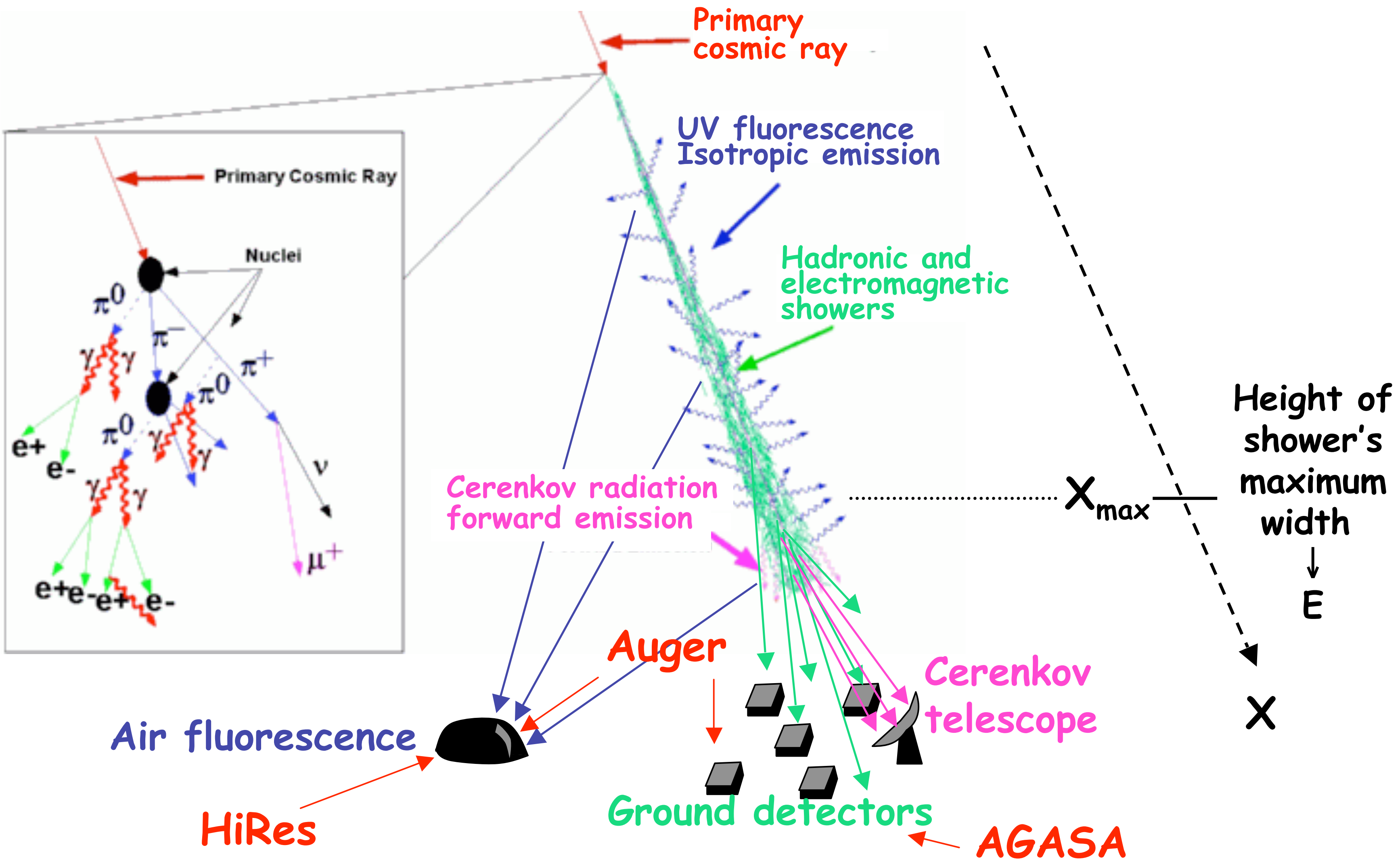
→ $E_{max} \sim 10^{15}$ eV (knee)

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

→ Relativistic motions (Γ)



Cosmic ray detectors

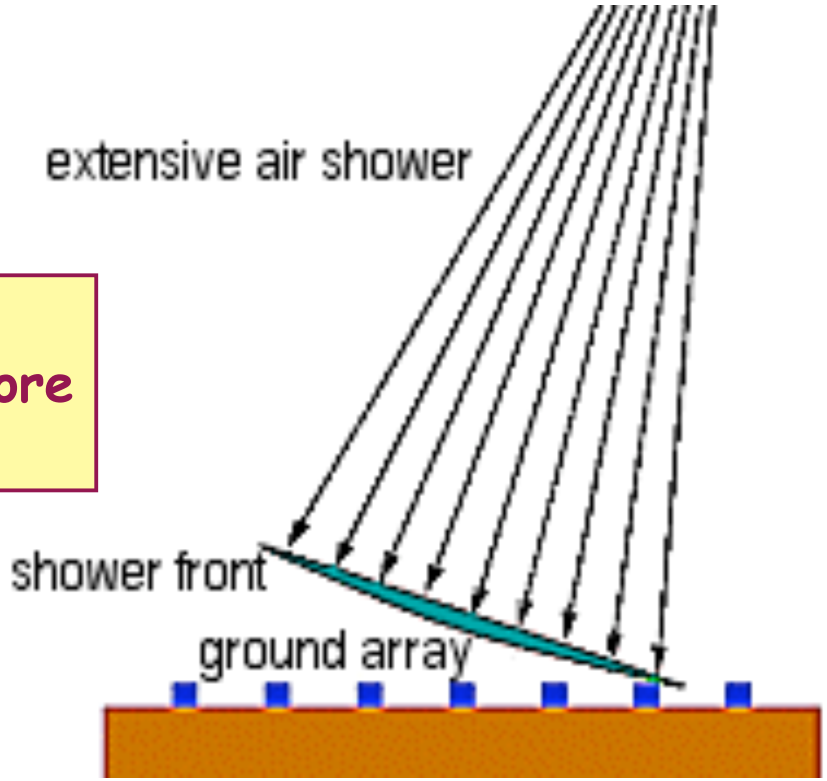


Counting particles: AGASA

Trajectory determined from arrival time of shower front on ground detectors

Density of light at a fixed distance from shower core related to primary energy

130 km west of Tokio

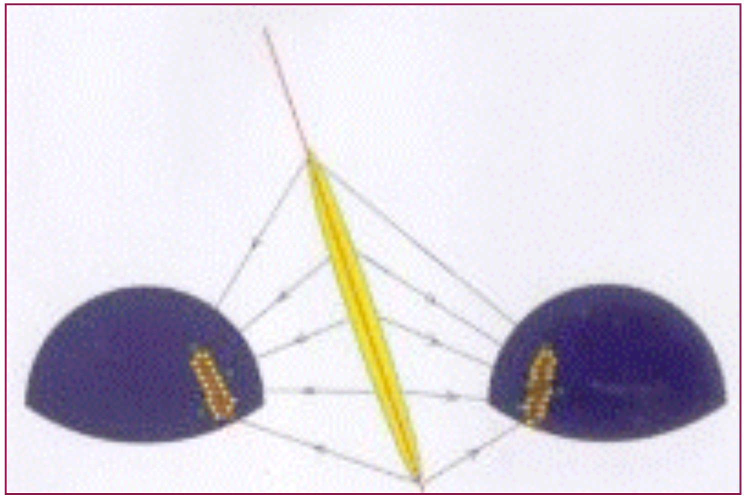


Air fluorescence: Fly's Eye

Spherical mirrors viewed by PMT's at the focal plane

Dual setup allows accurate trajectory reconstruction

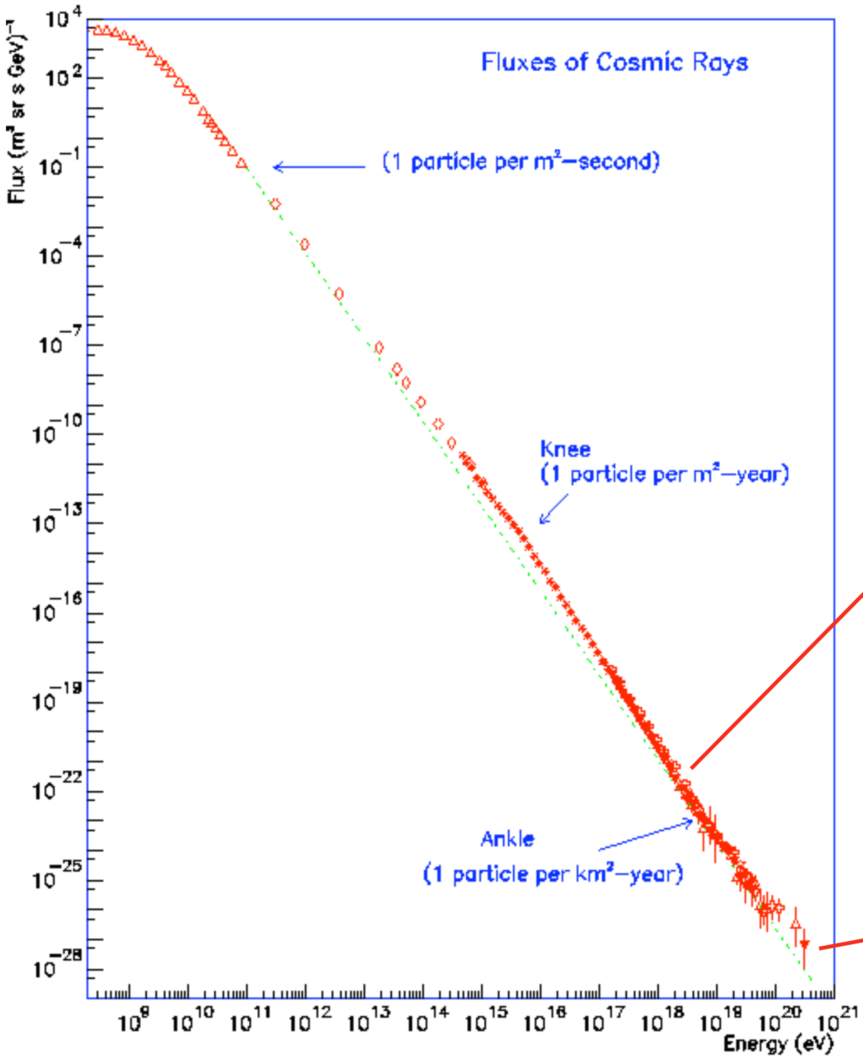
Amount of light (with $1/r^2$ correction for geometry)
→ shower profile
→ shower maximum X_{max}
→ primary energy



Can only operate on clear and moonless nights

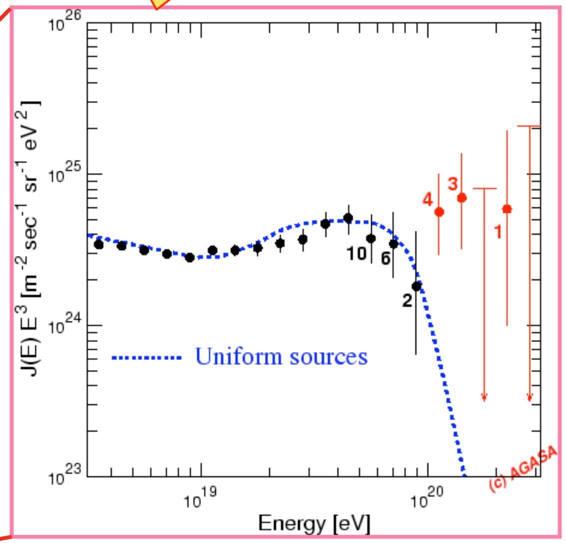
13 km apart in Utah desert

Ultra High Energy Cosmic Rays



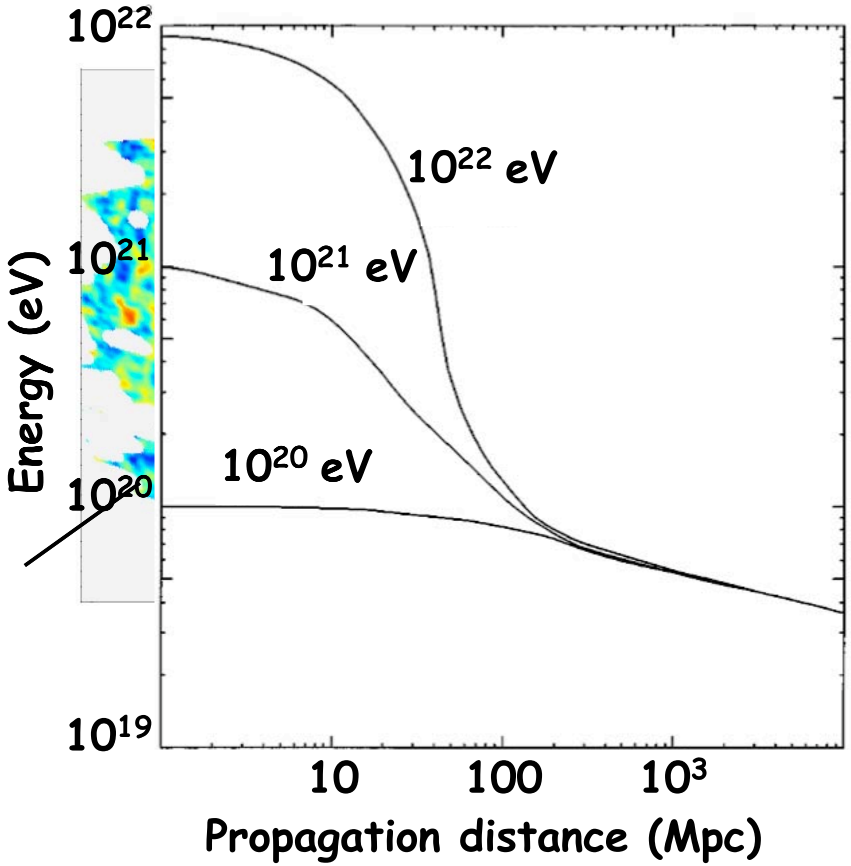
AGASA: 17 events above $6x10^{19}$ eV
HiRes : 2 events (~ 20 expected)

cross calibration needed



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

GZK (Greisen Zatsepin Kuzmin) cut-off



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

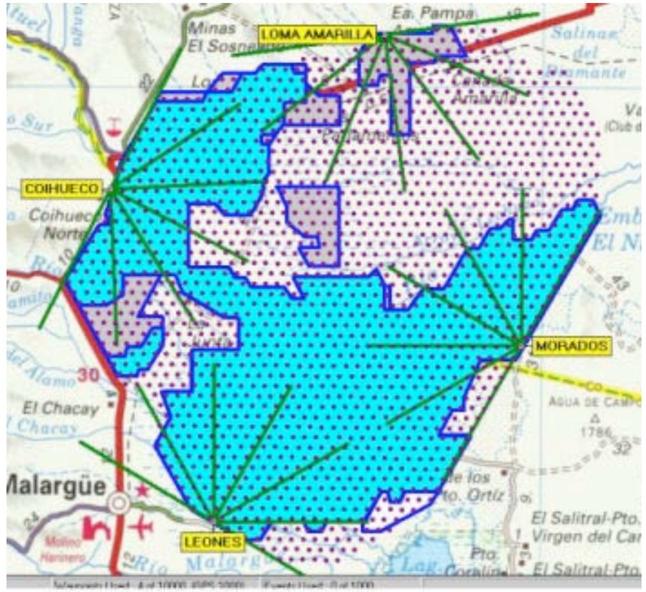
When process energetically allowed (>5×10^{19} eV), space becomes opaque to CR

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

(no known acceleration sites…)

AUGER

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



Auger South
- 3 fluorescence stations (out of 4)
- 60% of ground detectors
- E_{max} = 86 EeV (one at 140 EeV but not selected by cuts)

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

So far, neither confirms nor excludes past-GZK evts

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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!

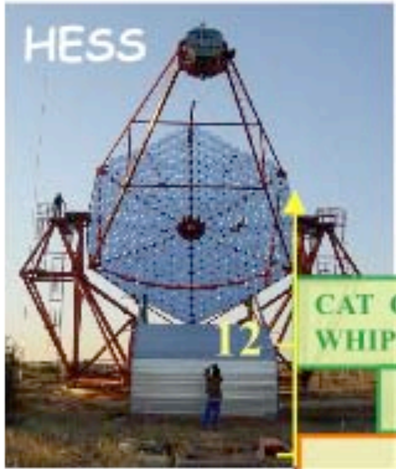
1952 Prediction of HE gamma-ray emission of Galactic disk

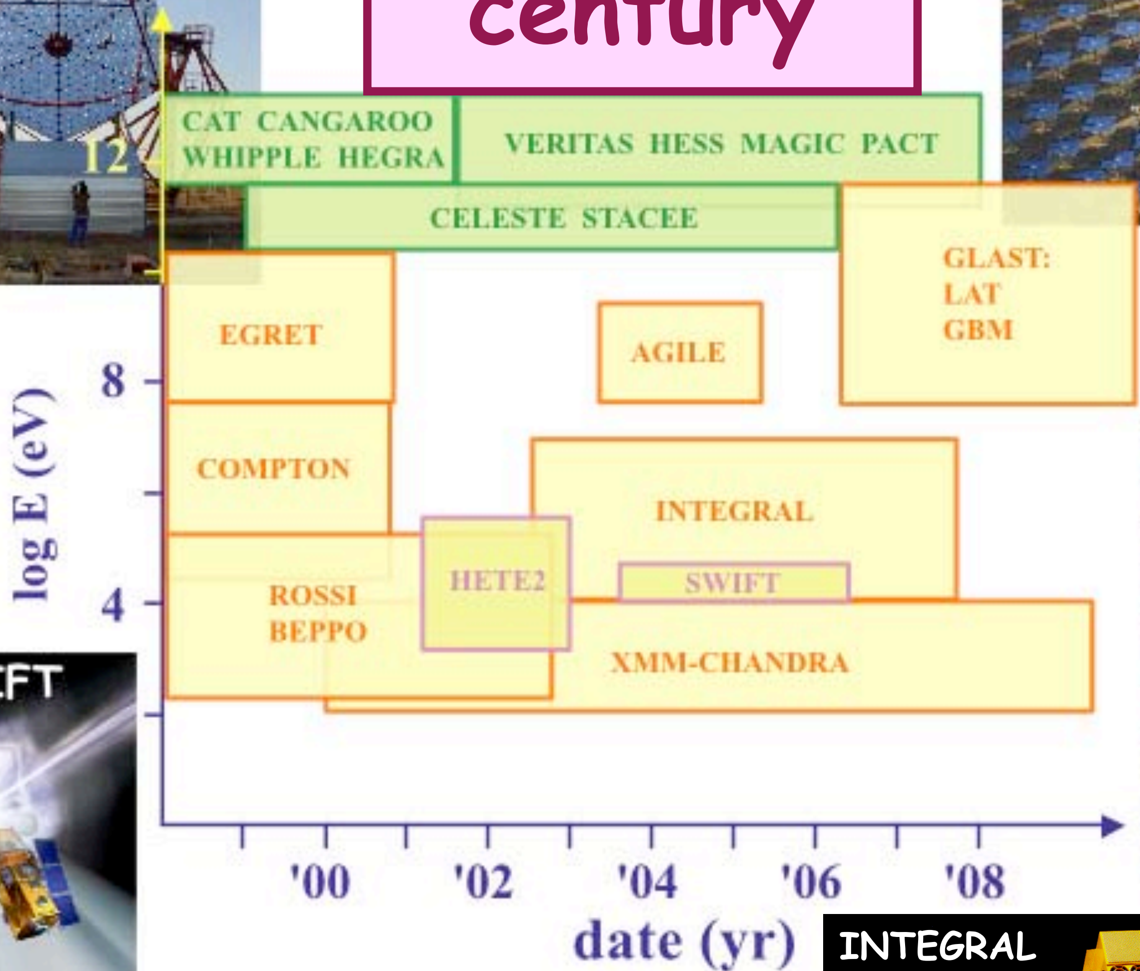
1958 First detection of cosmic gamma rays (solar flare)

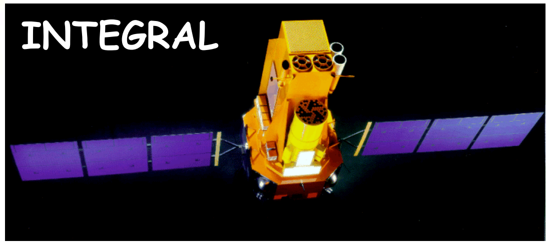
1967 First exhaustive review devoted to gamma-ray astronomy

1968 Detection of Galactic disk and Crab nebula

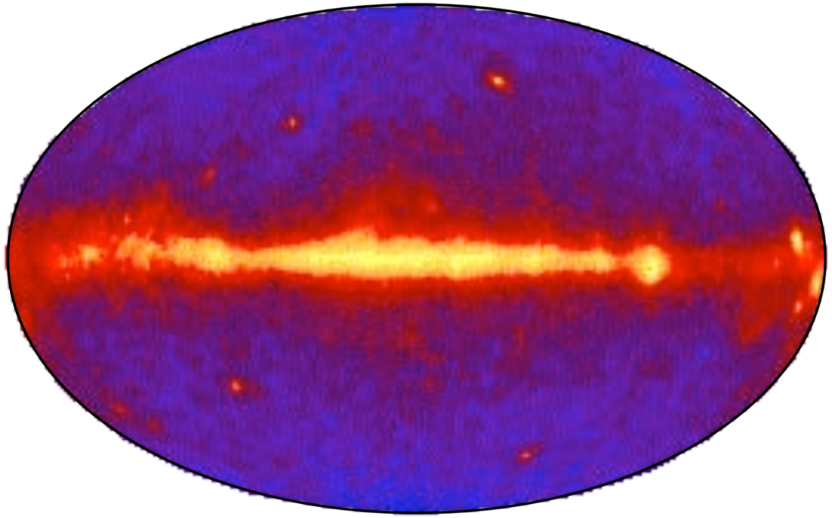
21st century



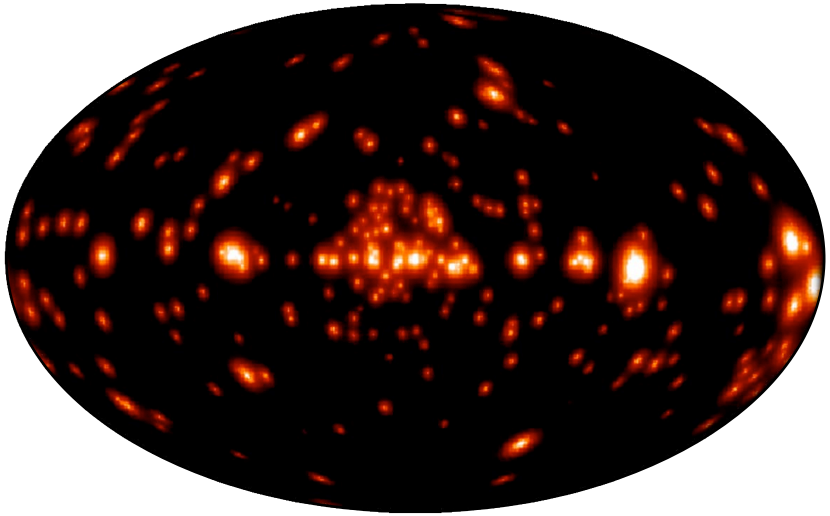




EGRET (E > 100 MeV)



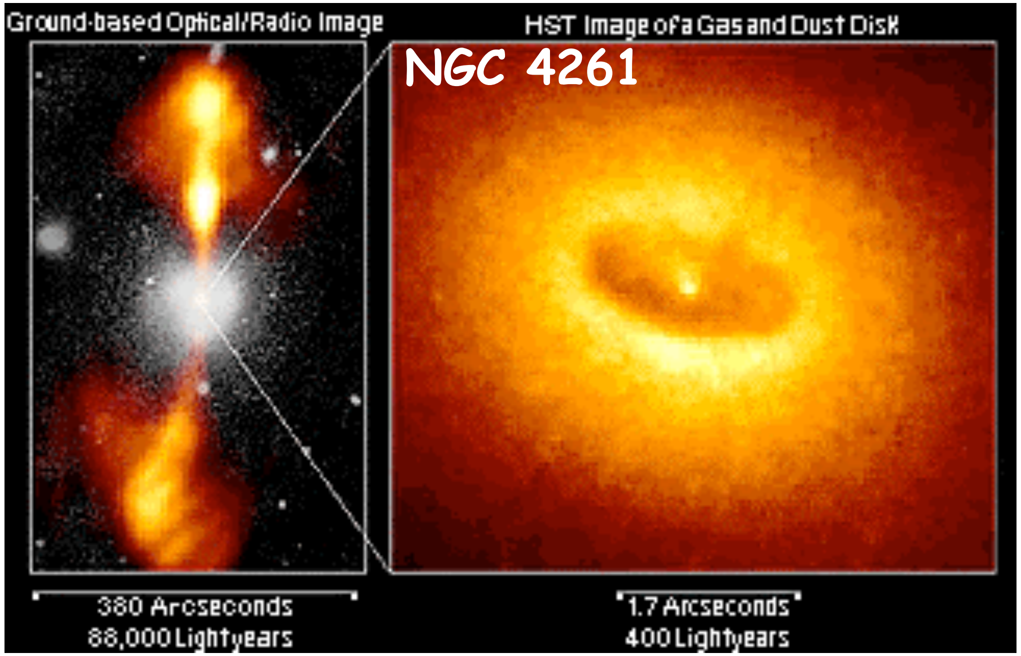
Galactic <u>diffuse interstellar emission</u> from interaction with cosmic rays



<u>Point sources</u>
- 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 !)

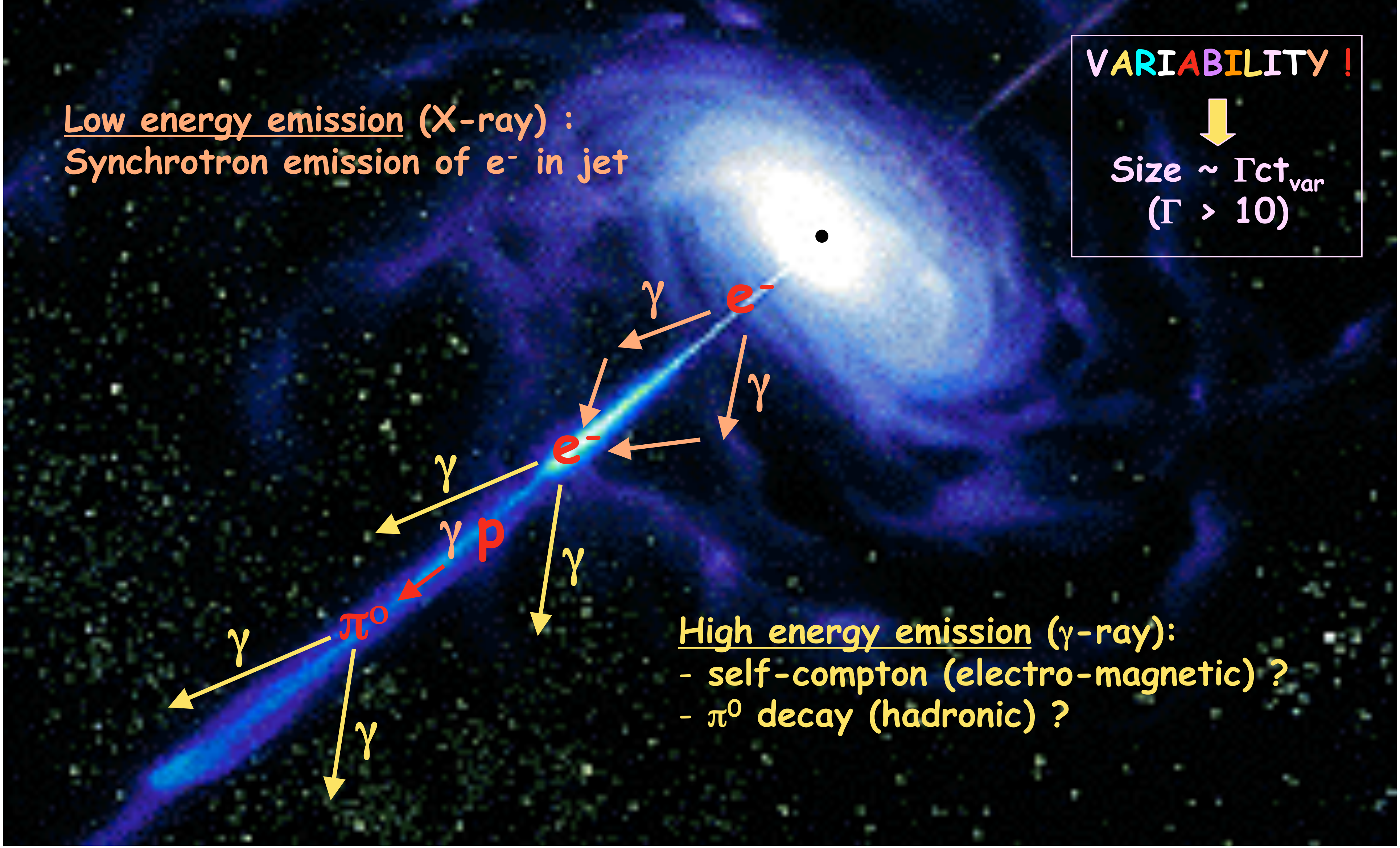


Blazars

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

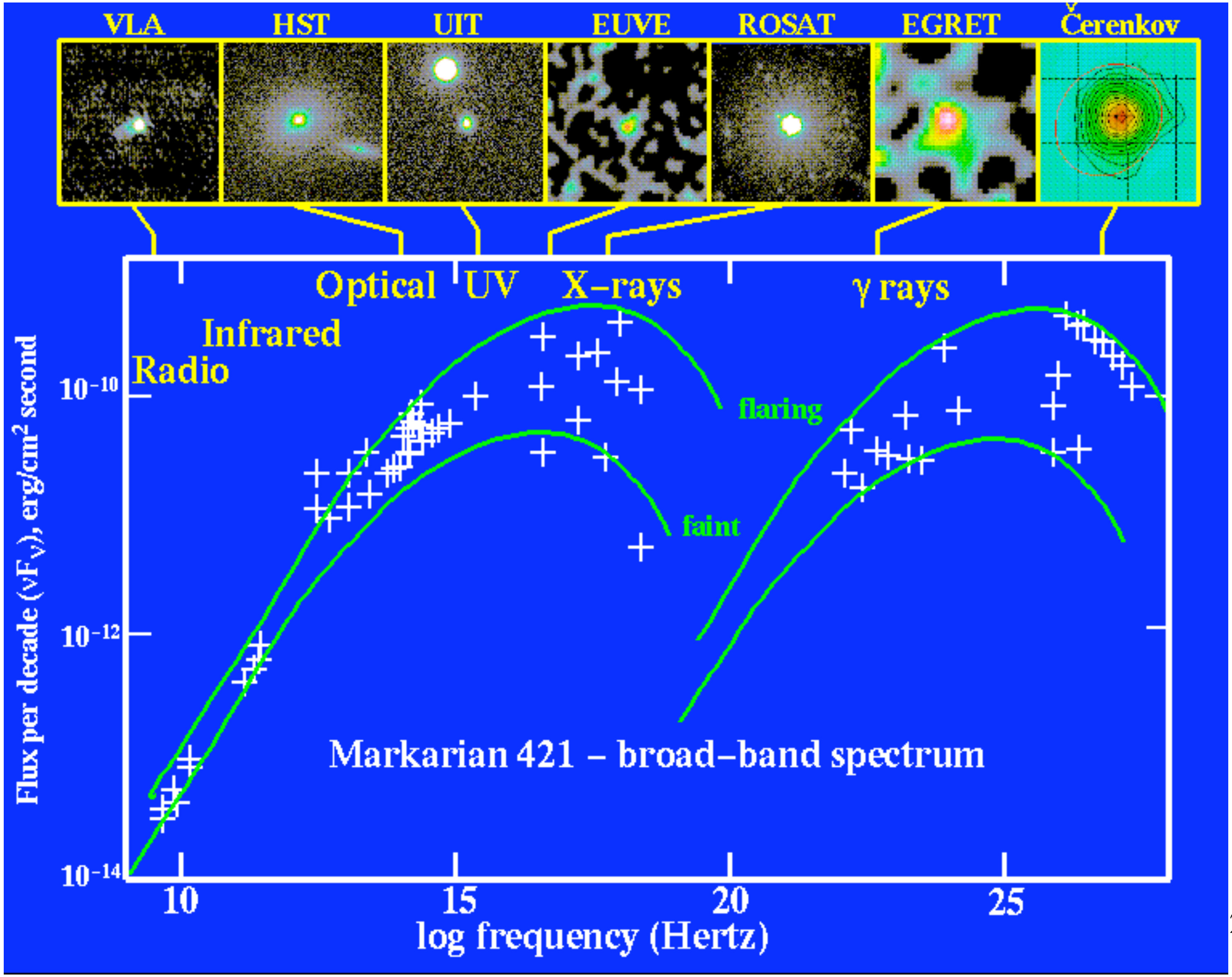
VARIABILITY !

Size ~ $\Gamma c t_{var}$
(Γ > 10)



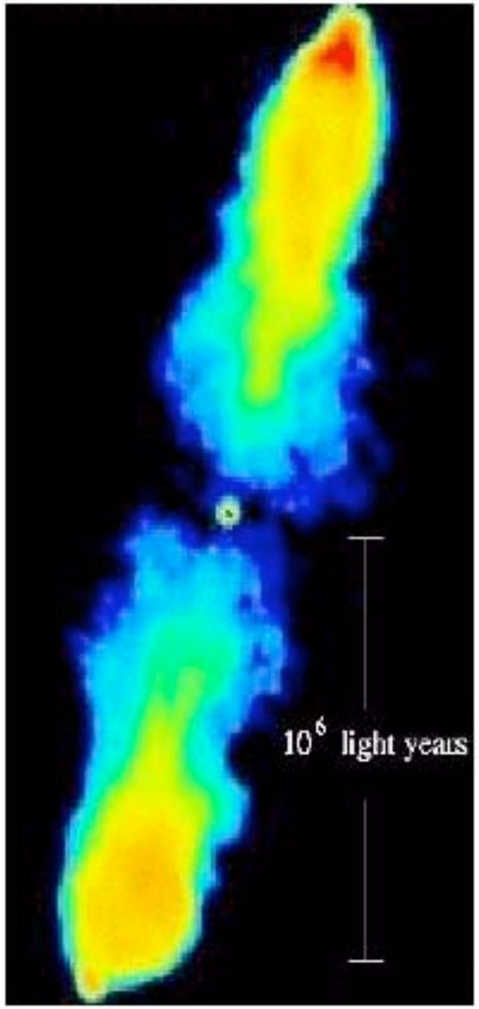
High energy emission (γ-ray):
- self-compton (electro-magnetic) ?
- π^0 decay (hadronic) ?

Markarian 421 : closest blazar

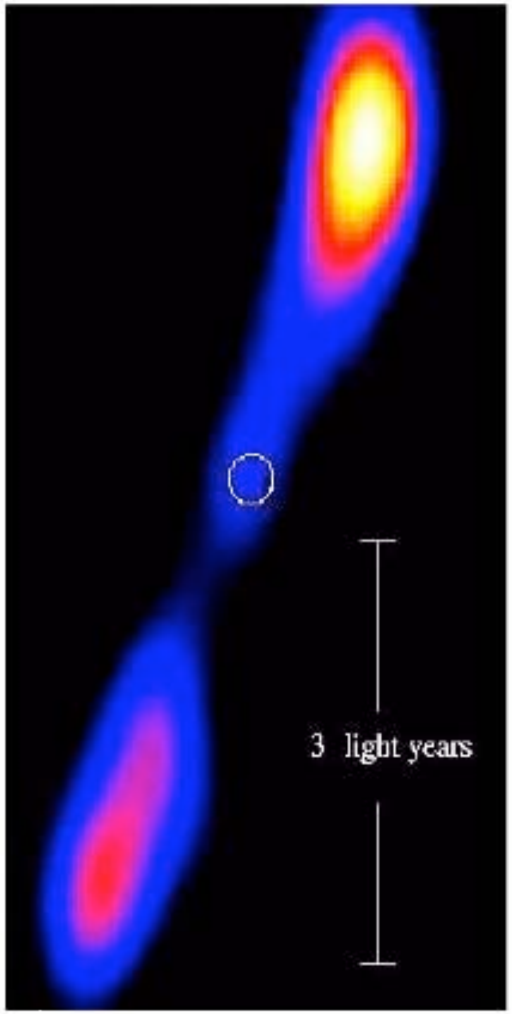


Quasars and Microquasars

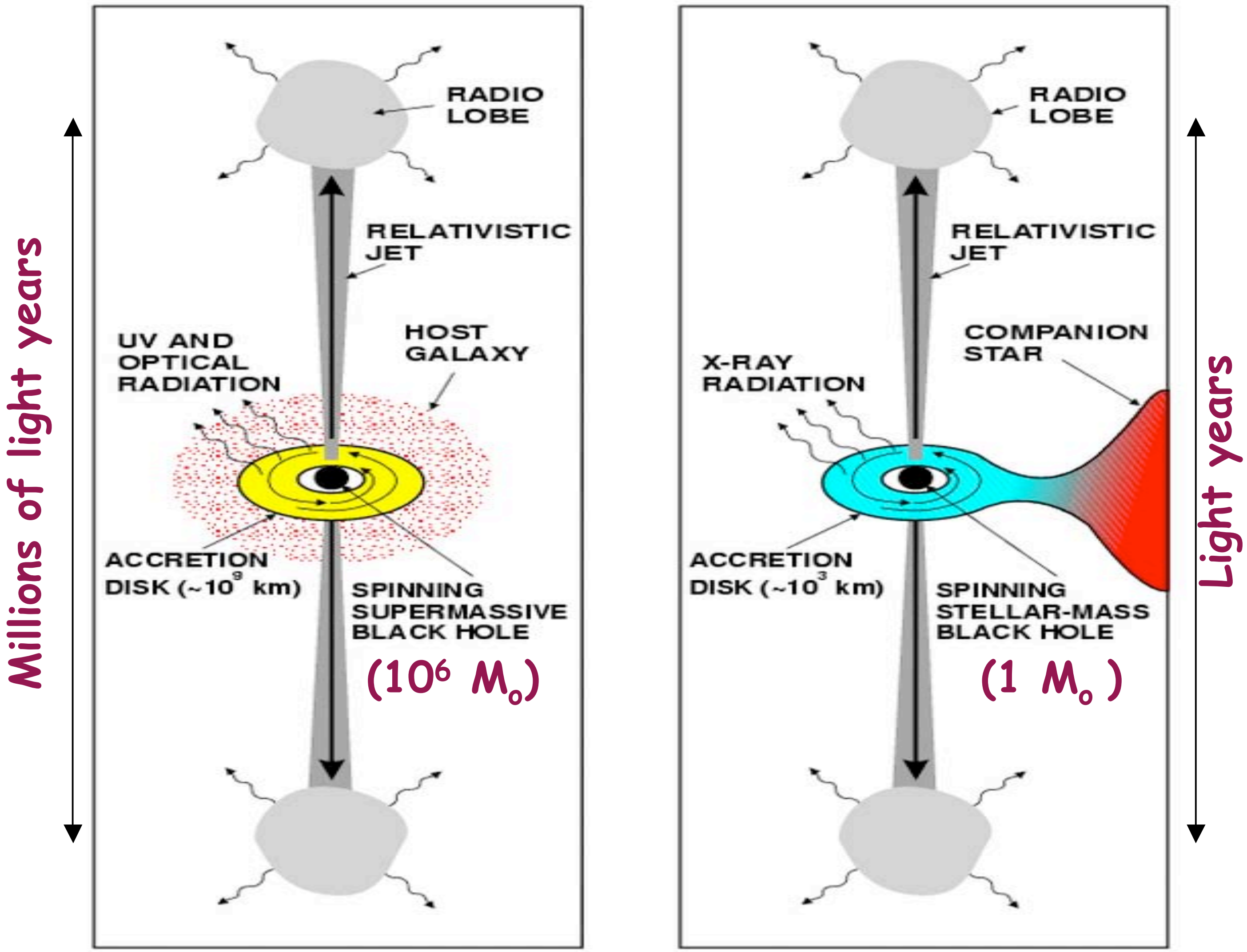
QUASAR 3C 223



MICROQUASAR 1E1740.7-2942



QUASAR   MICROQUASAR



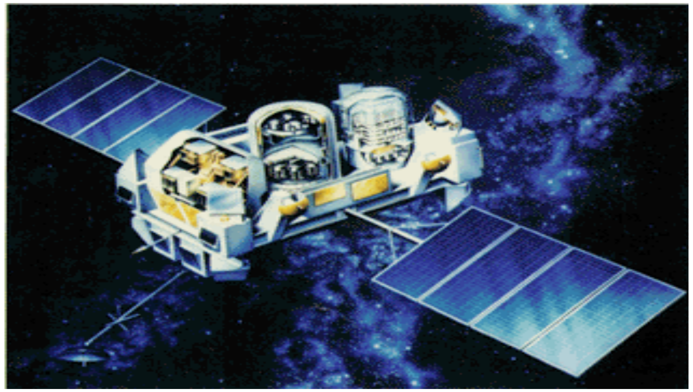
$R \propto M_{BH}$ $T \propto M_{BH}^{-1/4}$

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

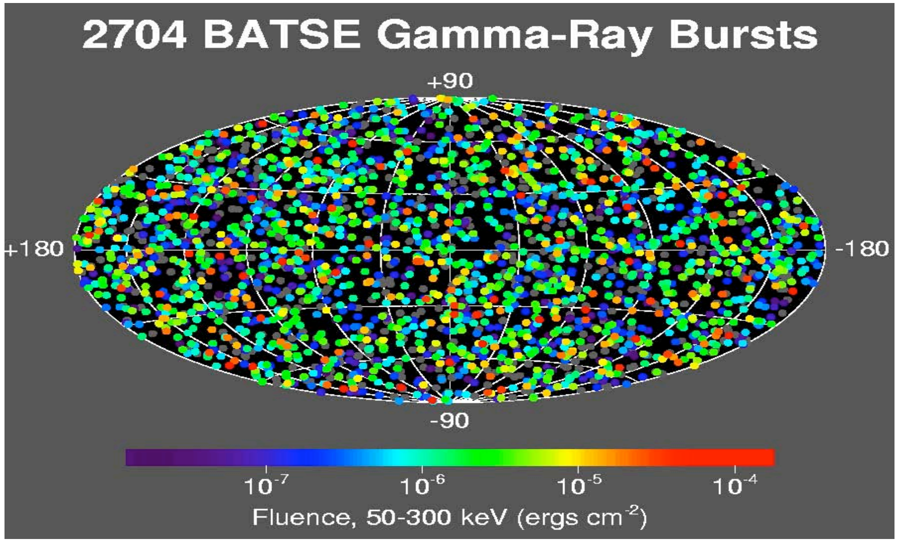
→ compact region, Lorentz boost (Γ ~100)

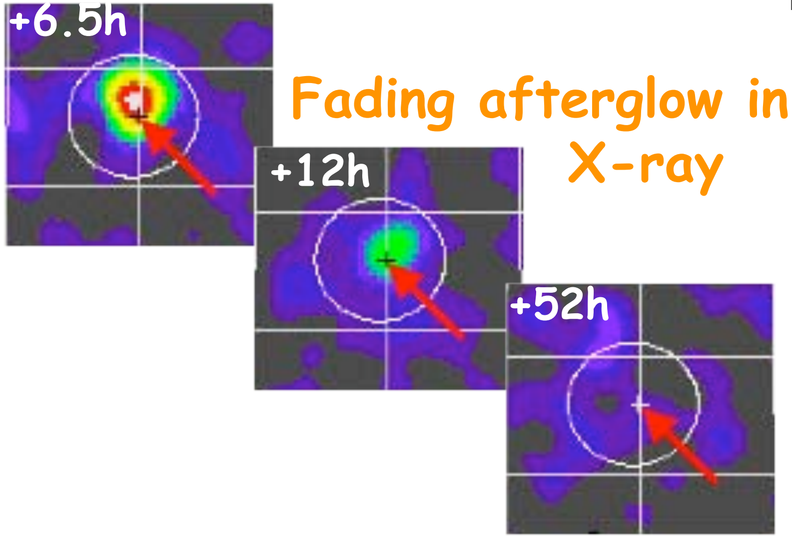
2005 (>2000 bursts) still very poorly understood …

Burst location

Isotropy
+
Optical counterparts

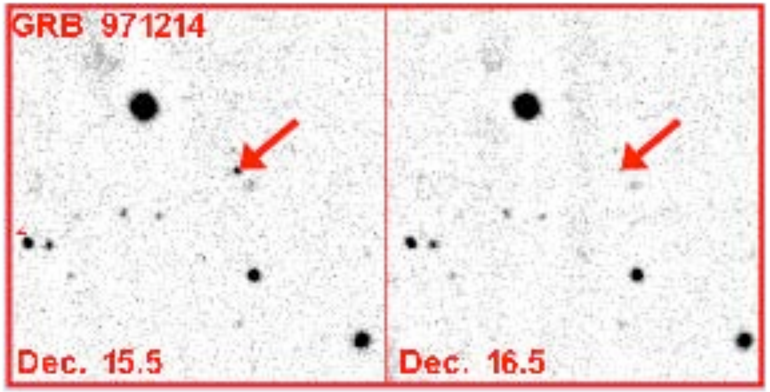
Cosmological phenomena!
(z = 0.43 to 6.3)





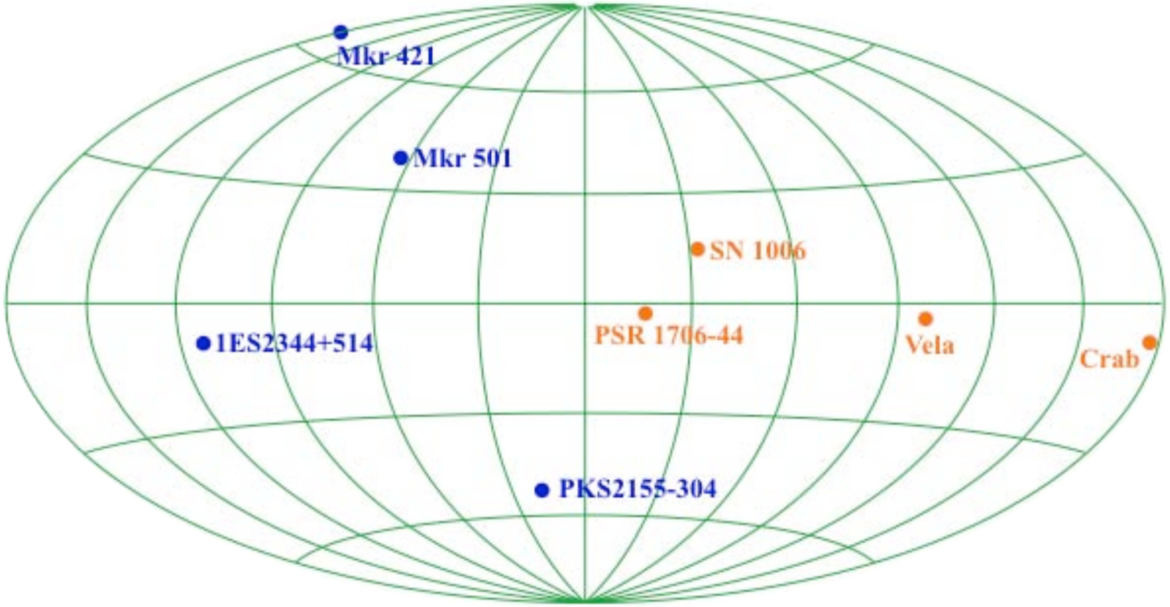
Fading afterglow in X-ray

Afterglow in optical



TeV sky

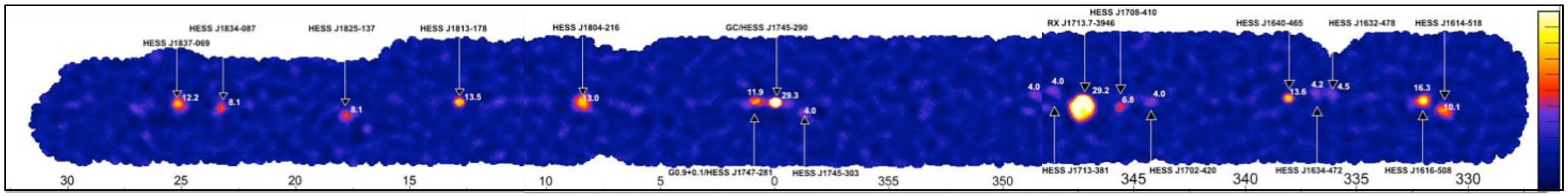
2003



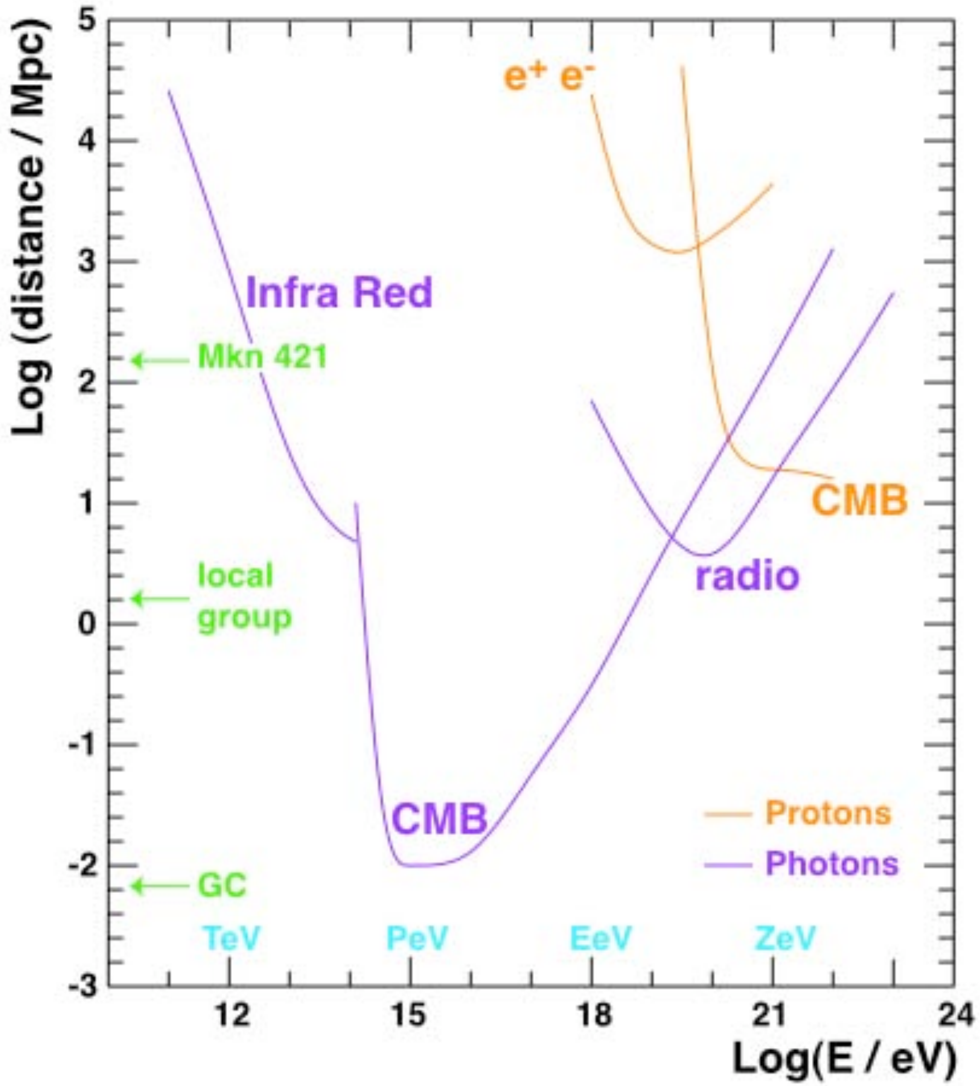
2005

HESS:
Survey of galactic plane

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



Gamma horizon



GZK cutoff

Main explanation for lack of TeV sources

Lecture outline

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   Gamma rays
   Neutrino astronomy

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)

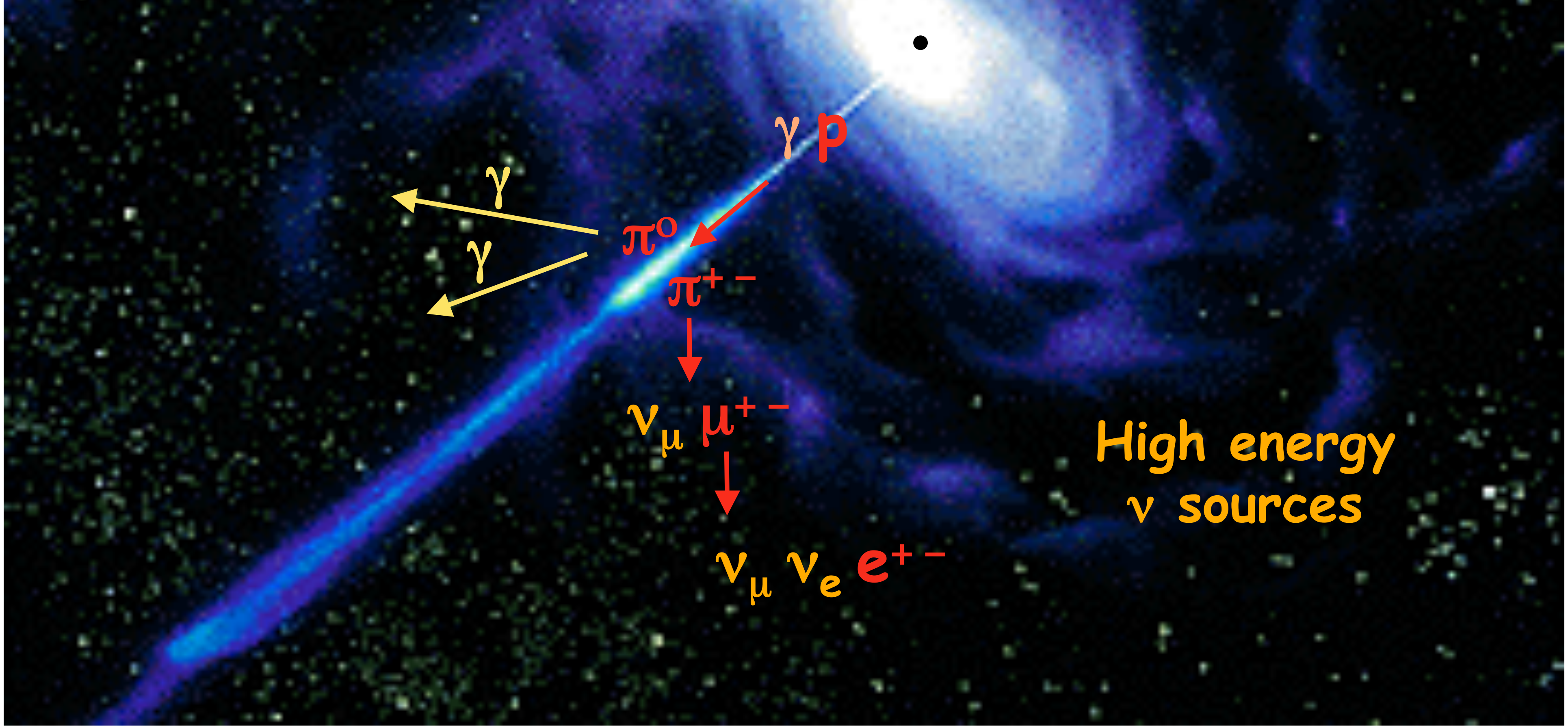
Neutrinos: no charge, "no" interaction with matter nor radiation

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

High energy sources

<u>High energy emission</u> (γ-ray):

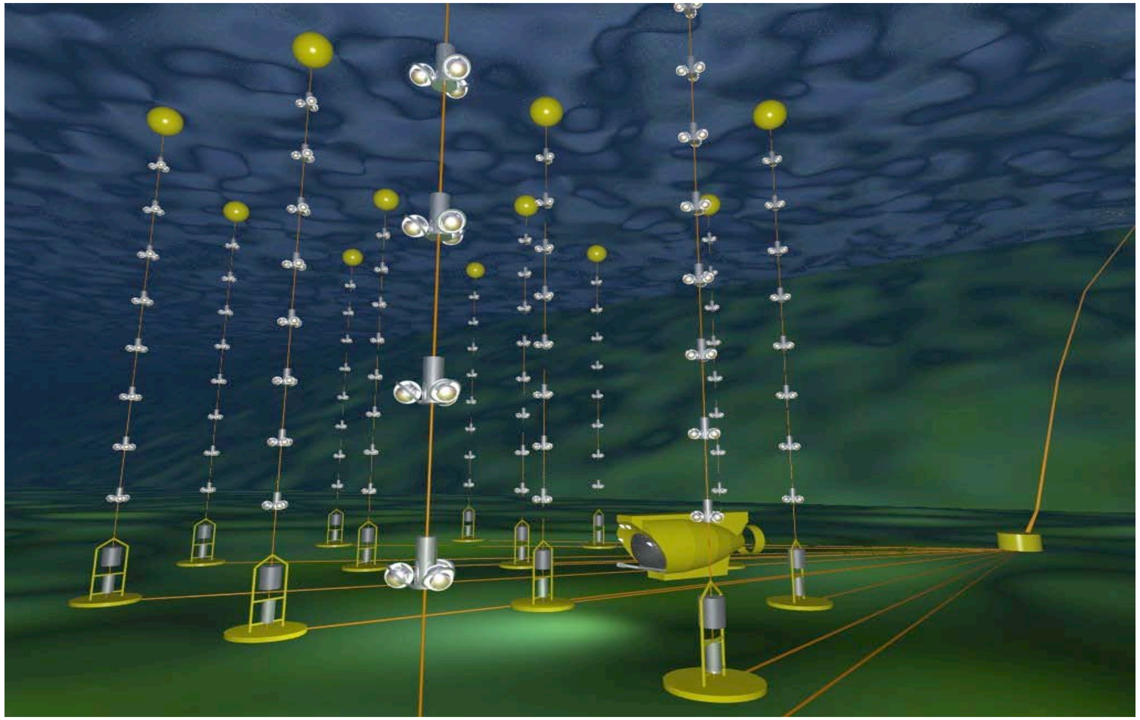
- ~~self-compton (electro-magnetic)~~ ?
- π^0 decay (hadronic) ?

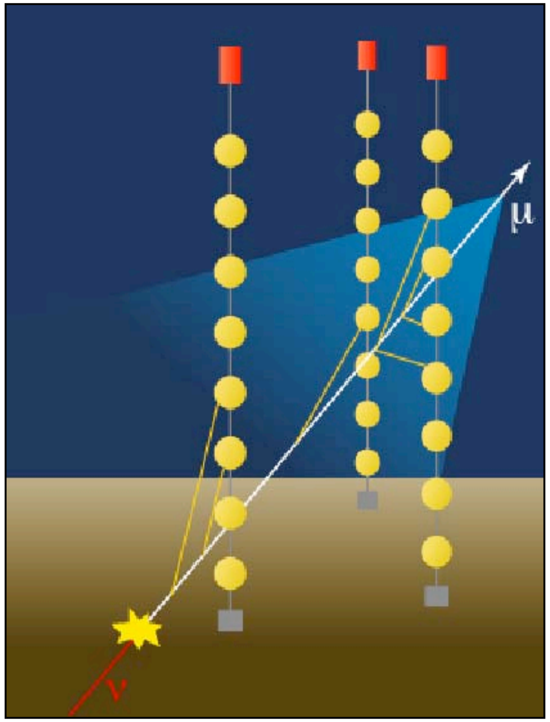


Experimental challenge

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

High background (atmospheric μ) → **Good shielding** (> 1000m water eq.)

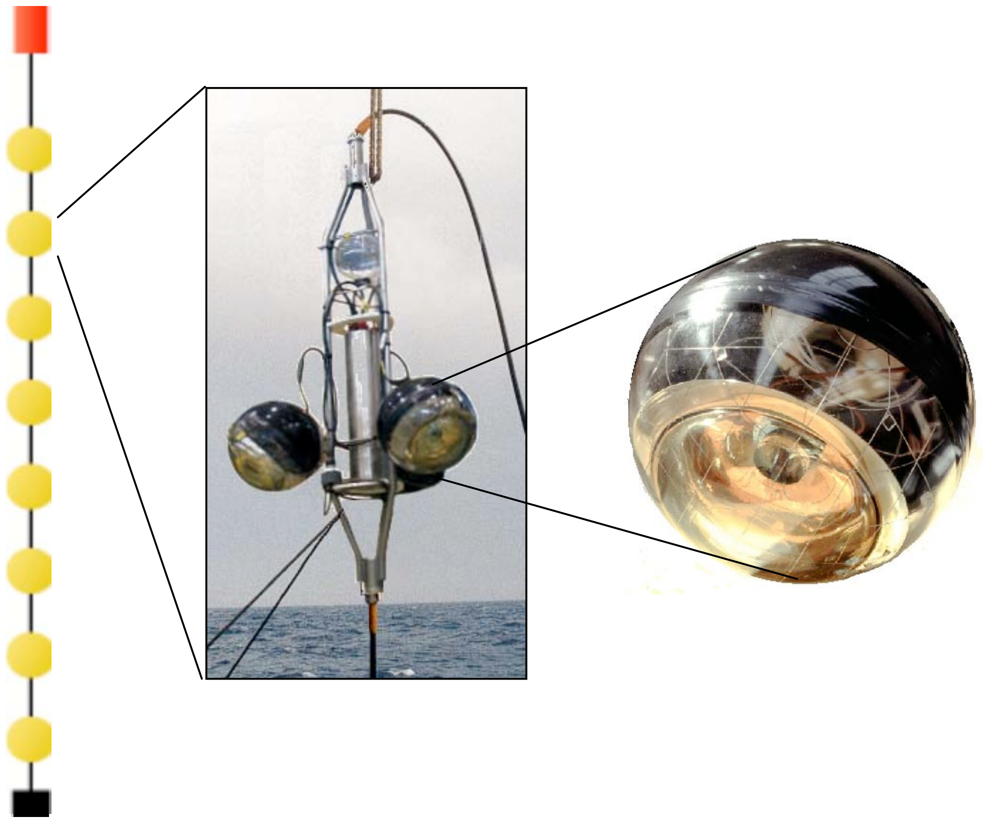




$\nu \rightarrow \mu \rightarrow$ Cerenkov light

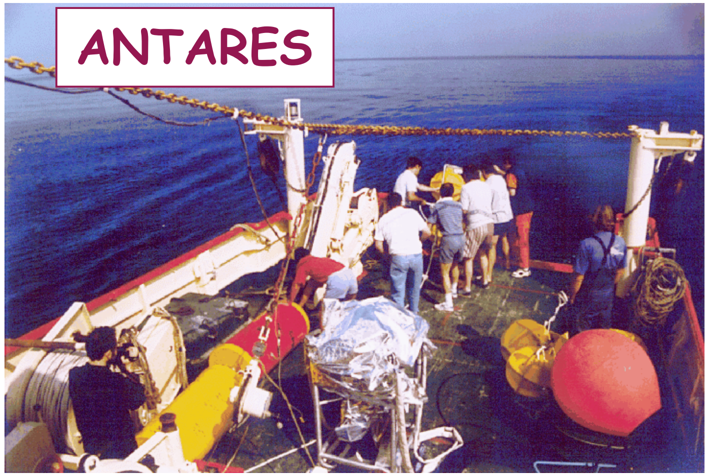
Detectors

Strings with optical modules (PMT in glass sphere)



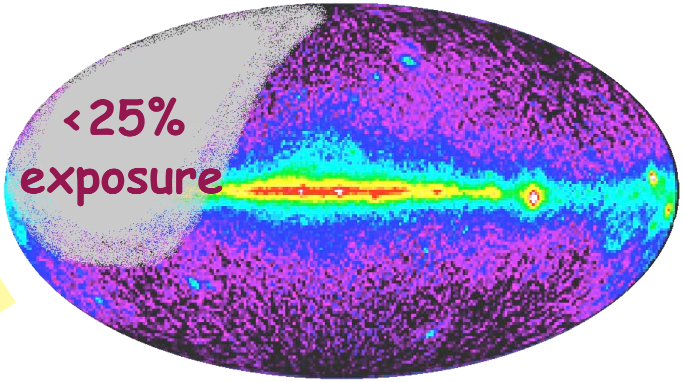
- d_{OM-OM}: E threshold
- # of OM: E resolution
- $d_{string-string}$: effective volume, E limit

HE neutrino experiments

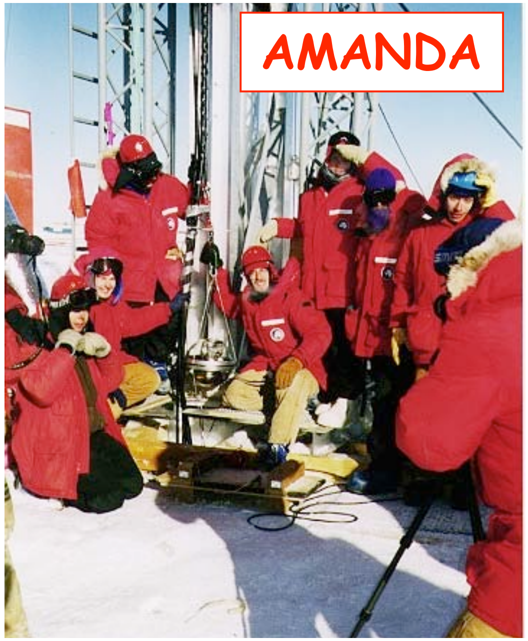


Better
angular
resolution
(~0.2°)

ANTARES (43° North)
deployment by end 2007

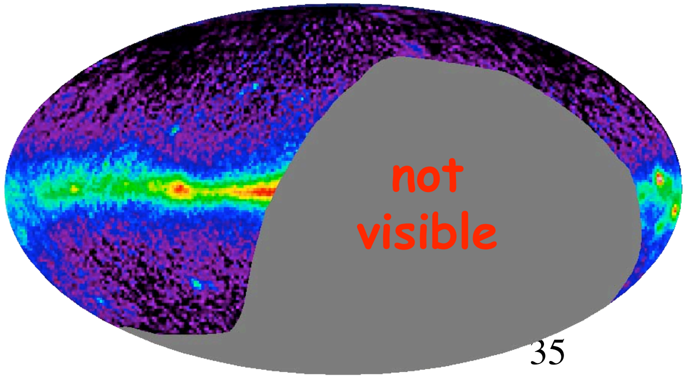


ANTARES/AMANDA
0.6π sr overlap



AMANDA (South pole)
taking data

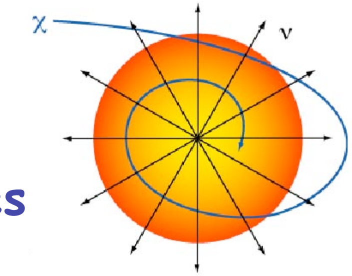
Better
sensitivity
(less absorption)



Science reach

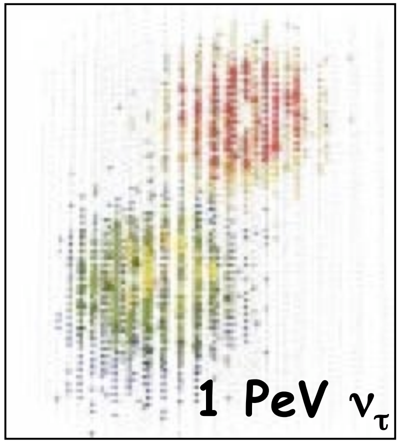
Medium Energy (10 GeV - 1 TeV):

- Dark matter searches from dense regions (neutralino concentration & annihilation)
  AMANDA: reaching the level of direct searches
- ν from supernovae



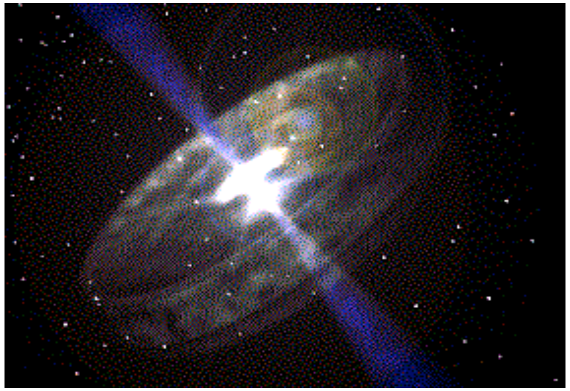
High Energy (> 1 TeV):

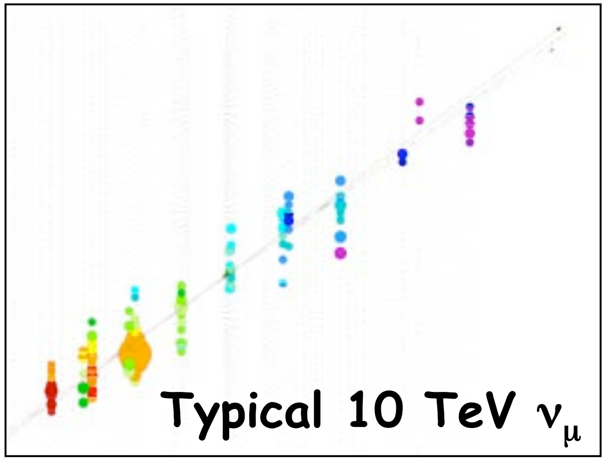
- ν from (extra-)galactic sources (cf. gamma rays)
- PeV & EeV ν
- ν_τ detection



1 PeV ν_τ

Double-bang signature





Typical 10 TeV ν_μ

Status & future of ν astronomy

ANTARES, AMANDA: 0,1 km2 arrays
Allow assessment of under-ice, under-water ν telescopes
Possible observation of diffuse neutrino fluxes (from AGN)
(current limits from AMANDA reaching predictions from some models)
No point sources so far

Actual ν astronomy (point sources) requires 1 km^3

IceCube: 80 1-km long strings over ~1 km^2
January 2006: 6 lines deployed

KM3: design study in FP6 through network KM3Net
Joint study from ANTARES, NESTOR, NEMO

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
- Indirect dark matter searches

Neutrino physics

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