The violent universe

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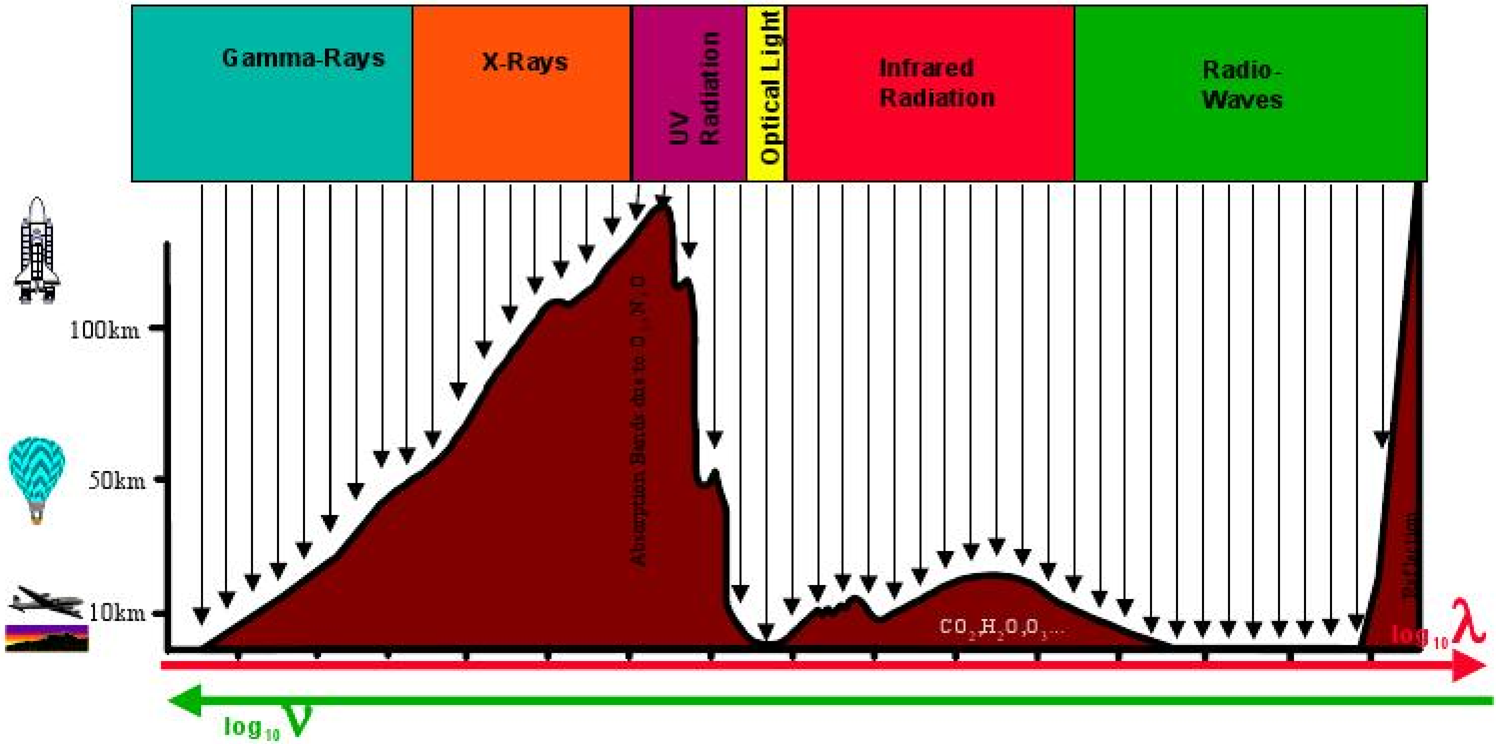
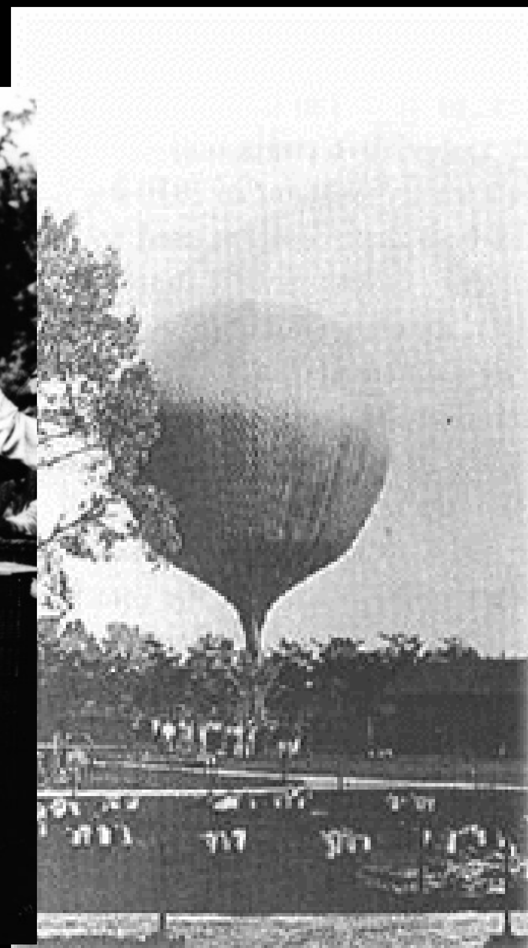
The spectrum of the electromagnetic radiation



- 'Windows' in Optical and Radio-Regime
- All Other Types Require Space-Based Observations

Cosmic Rays

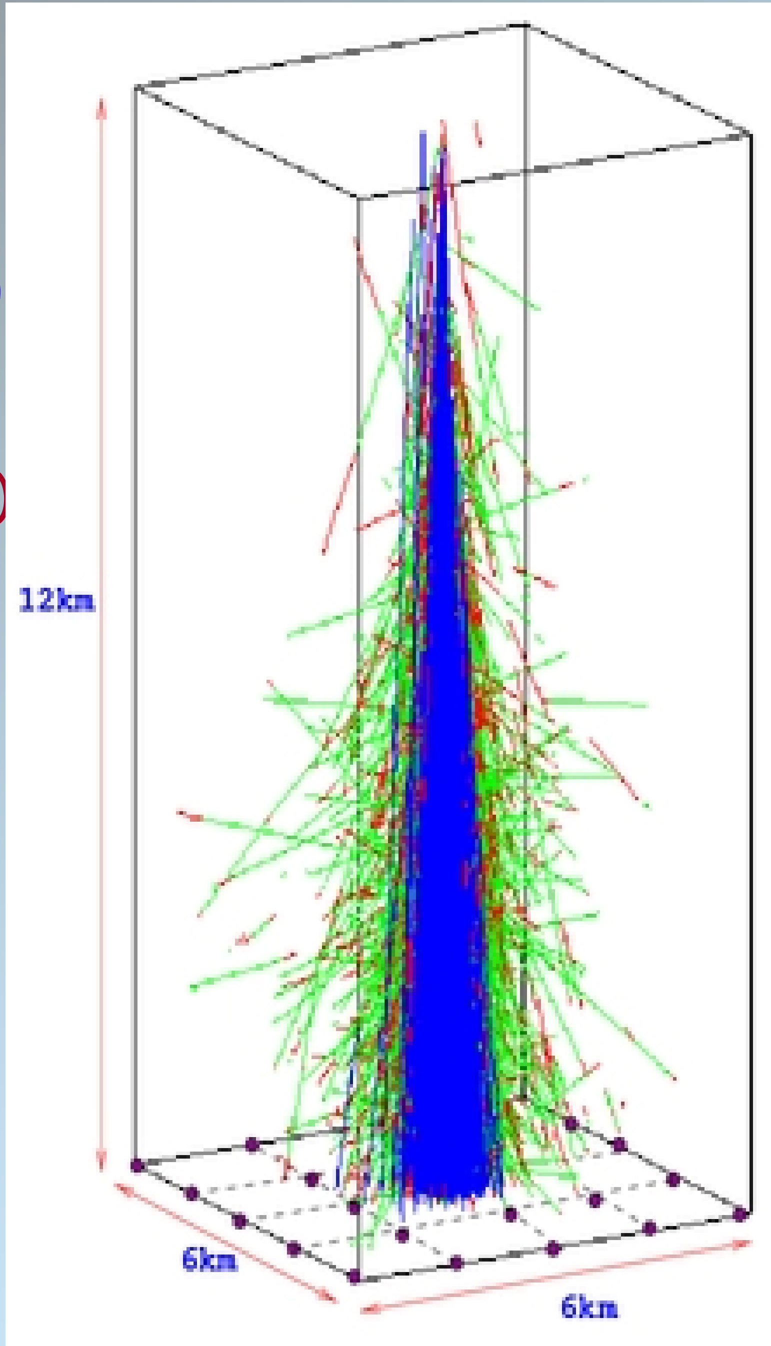


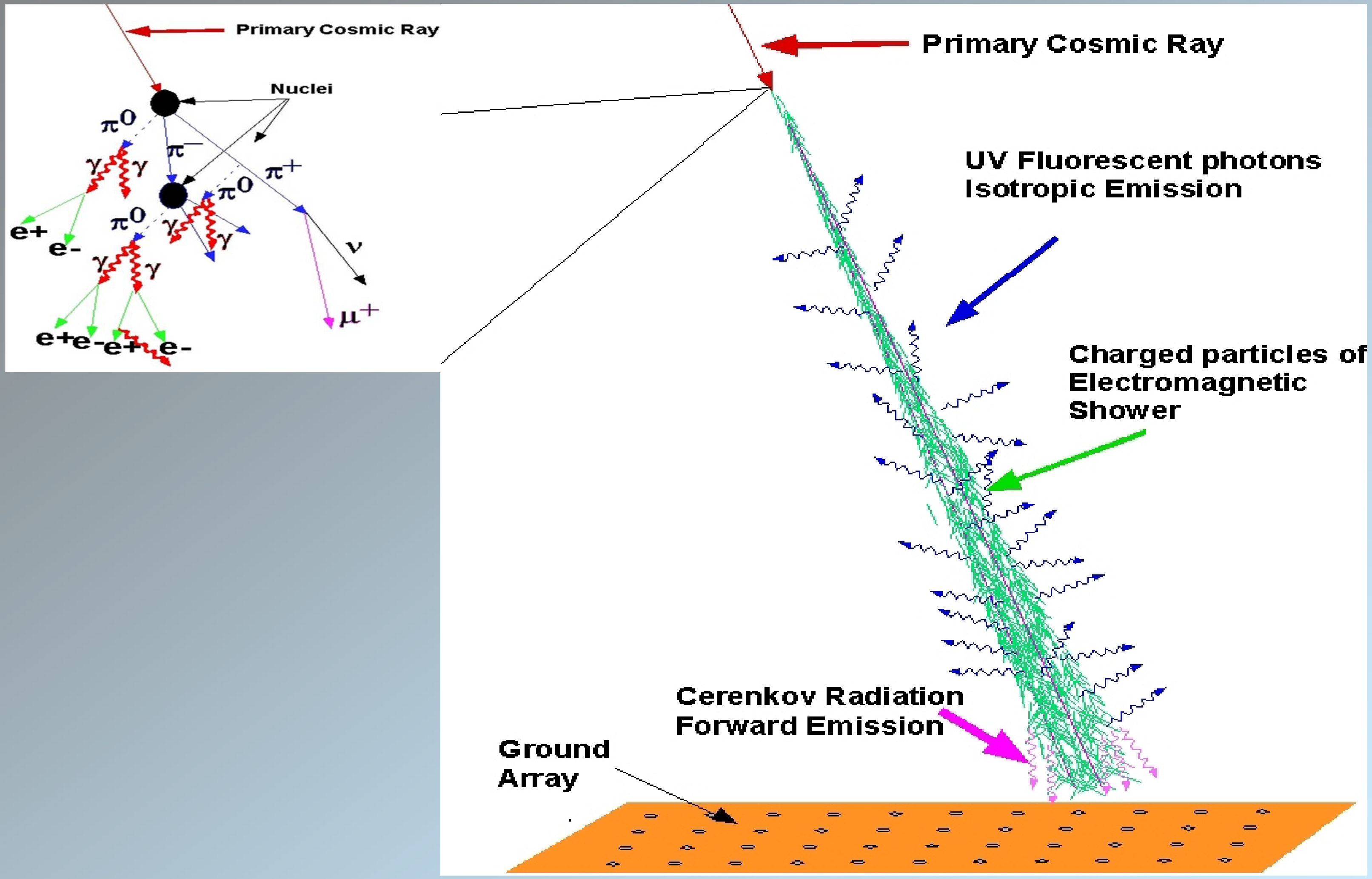
- *Cosmic Rays* are subatomic particles and radiation of *extra-terrestrial* origin.
- First discovered in 1912 by German scientist *Victor Hess*, measuring radiation levels aboard a balloon, up to 17,500 feet (*without oxygen!)*
- Hess found increased radiation levels at higher altitudes: named them *Cosmic Radiation*

- $<10^{14}$ eV (balloon experiments, satellites)

- $>10^{14}$ eV (Ground arrays, large telescopes)
  - -fluorescence light,
  - -cherenkov emission

- $>10^{18}$ eV (AGASA,Hires,Auger,Euso*)




Primary Cosmic Ray
Nuclei
π^0
π^-
π^+
γ
e+
e-
ν
μ^+
e+e-e+ e-
Primary Cosmic Ray
UV Fluorescent photons
Isotropic Emission
Charged particles of
Electromagnetic
Shower
Cerenkov Radiation
Forward Emission
Ground
Array

The observed cosmic ray spectrum

Key features

10 decades of energy – 30 decades of flux

$\sim E^{-2.7}$ 'knee' → 3×10^{15}eV

$\sim E^{-3.1}$ above the knee → $\sim 10^{16}$eV

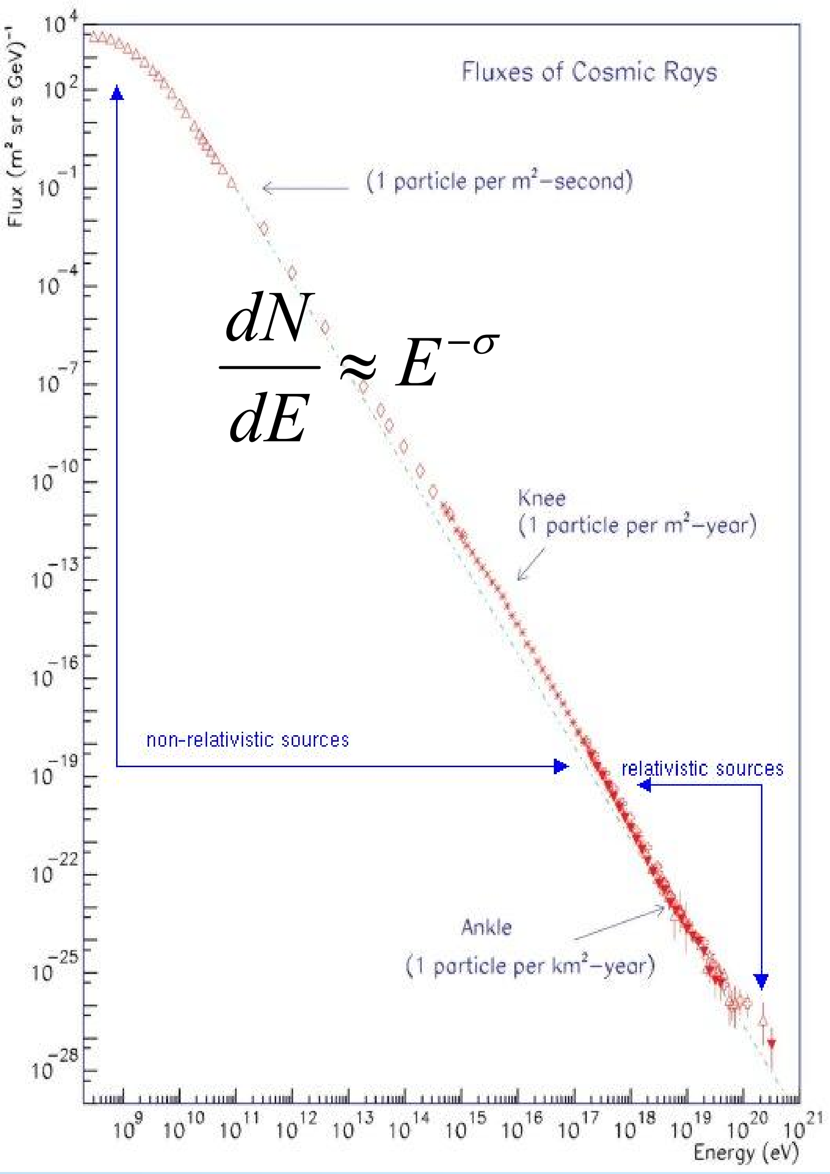
chemical transition 3×10^{18}eV

$\sim E^{-2.7}$ 'multi-ankle?' → $\sim 10^{18}$eV -10^{20}eV

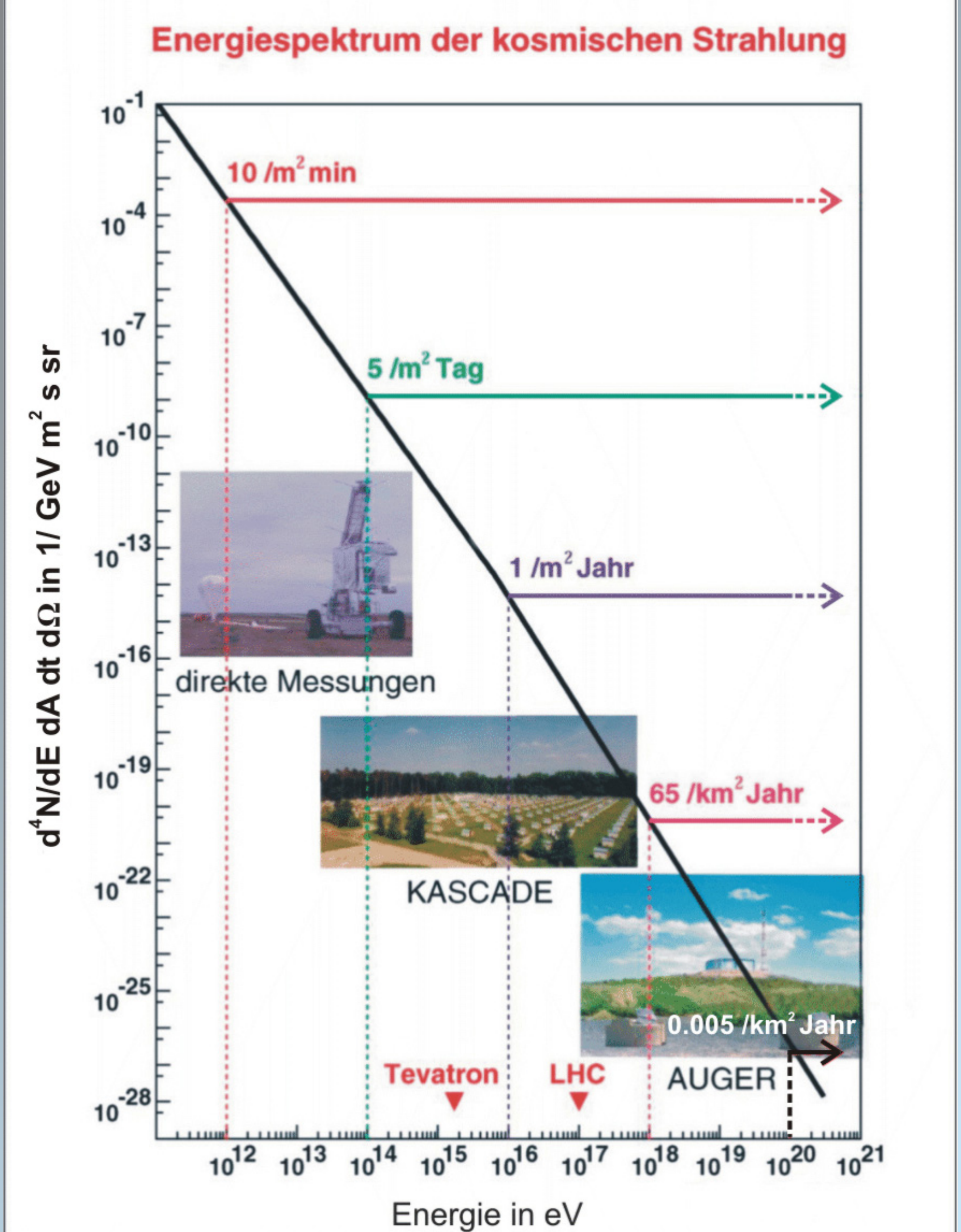
Transitions: 1) nature of CR accelerators

2) propagation

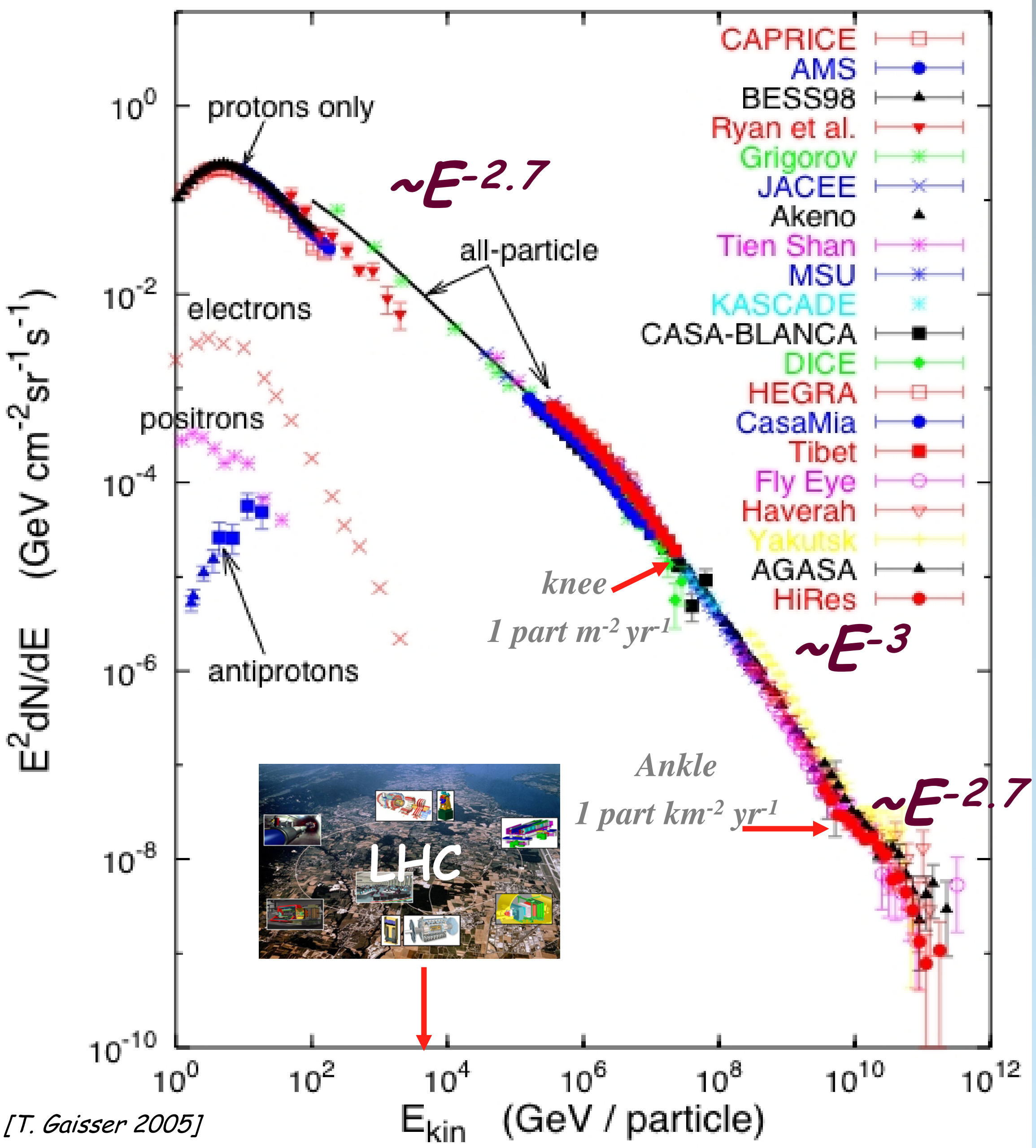
$>6\times10^{19}$ uncertainty (low flux, event st.)



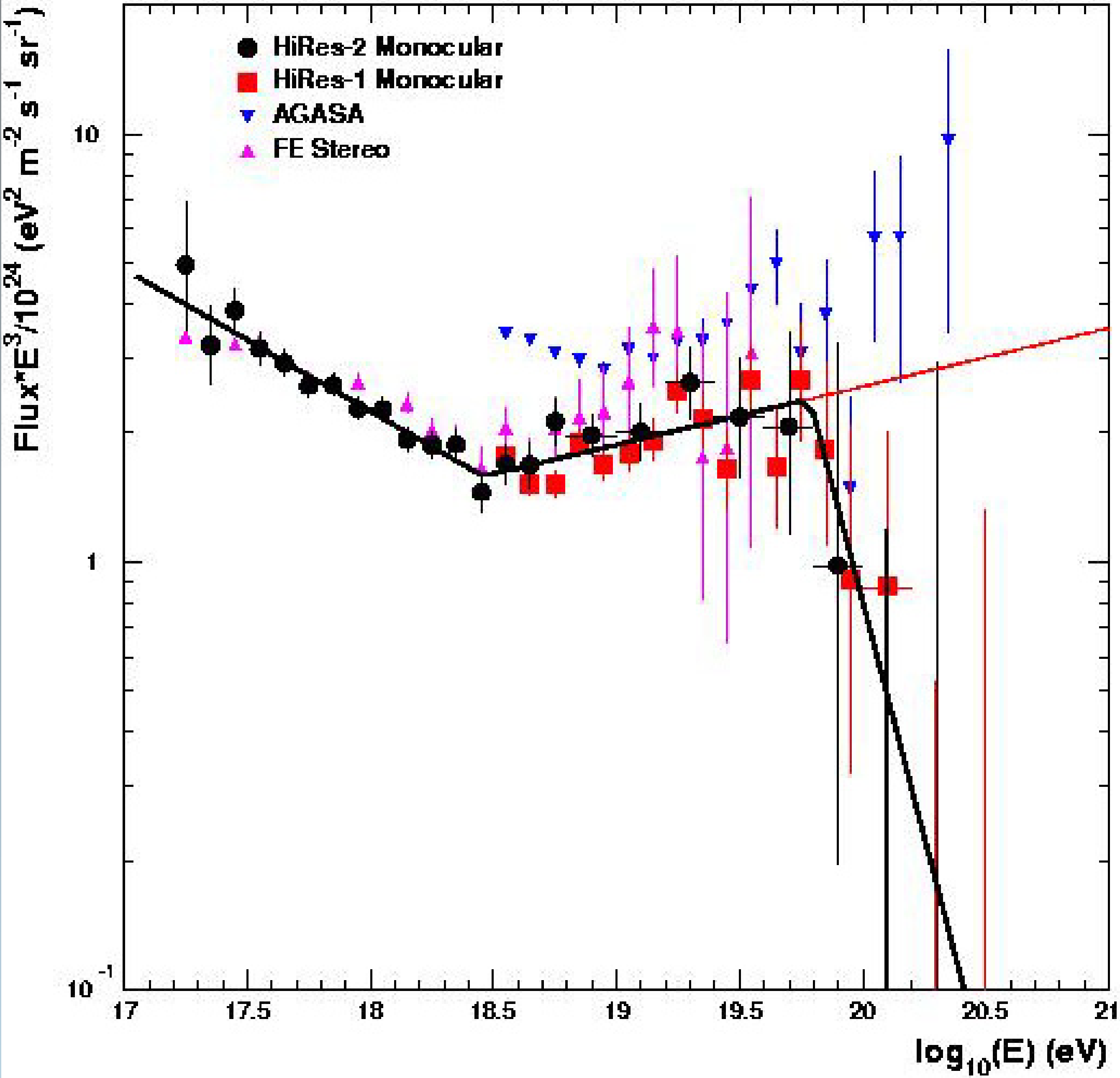
$$\frac{dN}{dE} \approx E^{-\sigma}$$


Energiespektrum der kosmischen Strahlung
10 /m² min
5 /m² Tag
1 /m² Jahr
65 /km² Jahr
0.005 /km² Jahr
direkte Messungen
KASCADE
AUGER
Tevatron
LHC
d⁴N/dE dA dt dΩ in 1/ GeV m² s sr
Energie in eV
10^-1
10^-4
10^-7
10^-10
10^-13
10^-16
10^-19
10^-22
10^-25
10^-28
10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20 10^21

Energies and rates of the cosmic-ray particles



…at the highest energies



The sources of cosmic rays

Galactic Vs Extragalactic
Non-relativistic Vs Relativistic

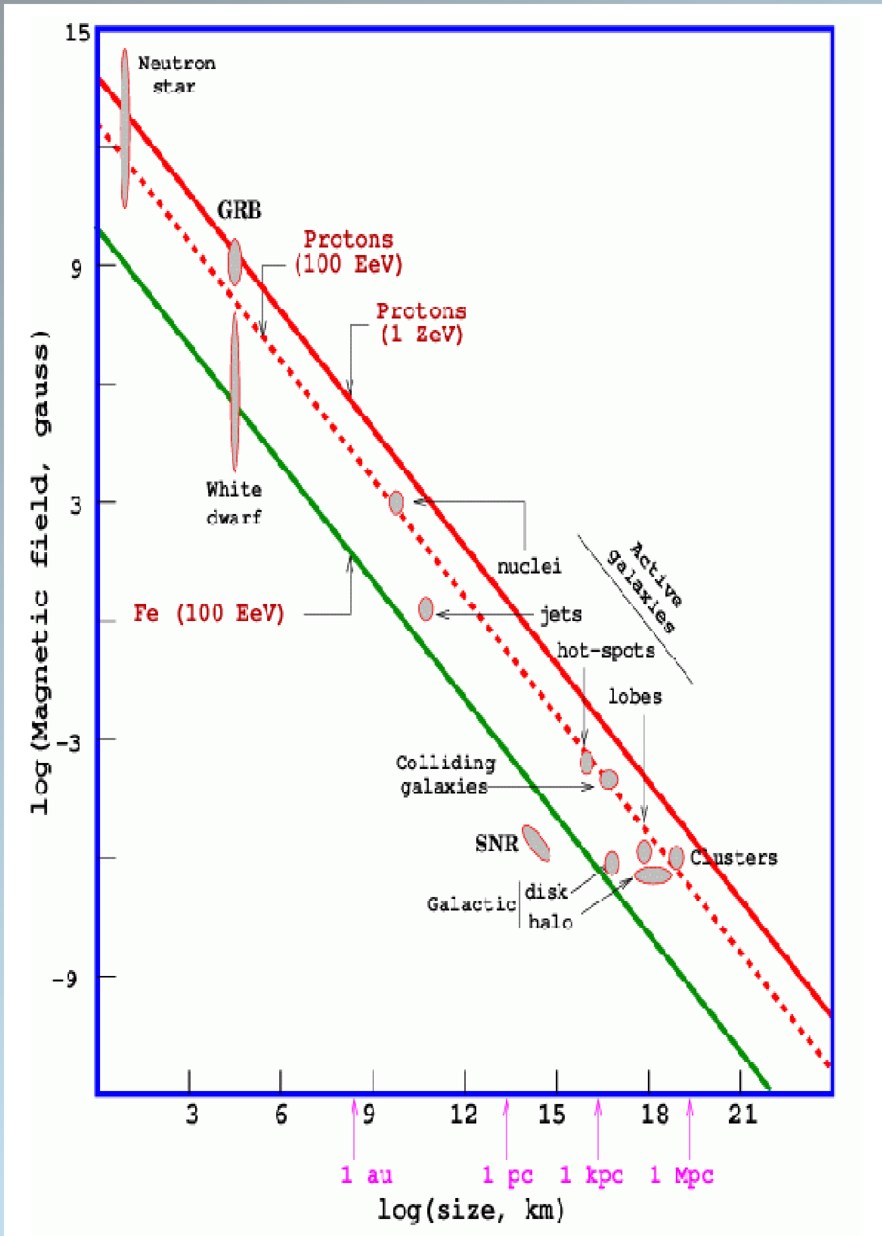
Requirements:

-*Dimension* of magnetic field sufficient to contain the accelerating particles.

-*Strong* fields with large-scale structure (astrophysical shocks)

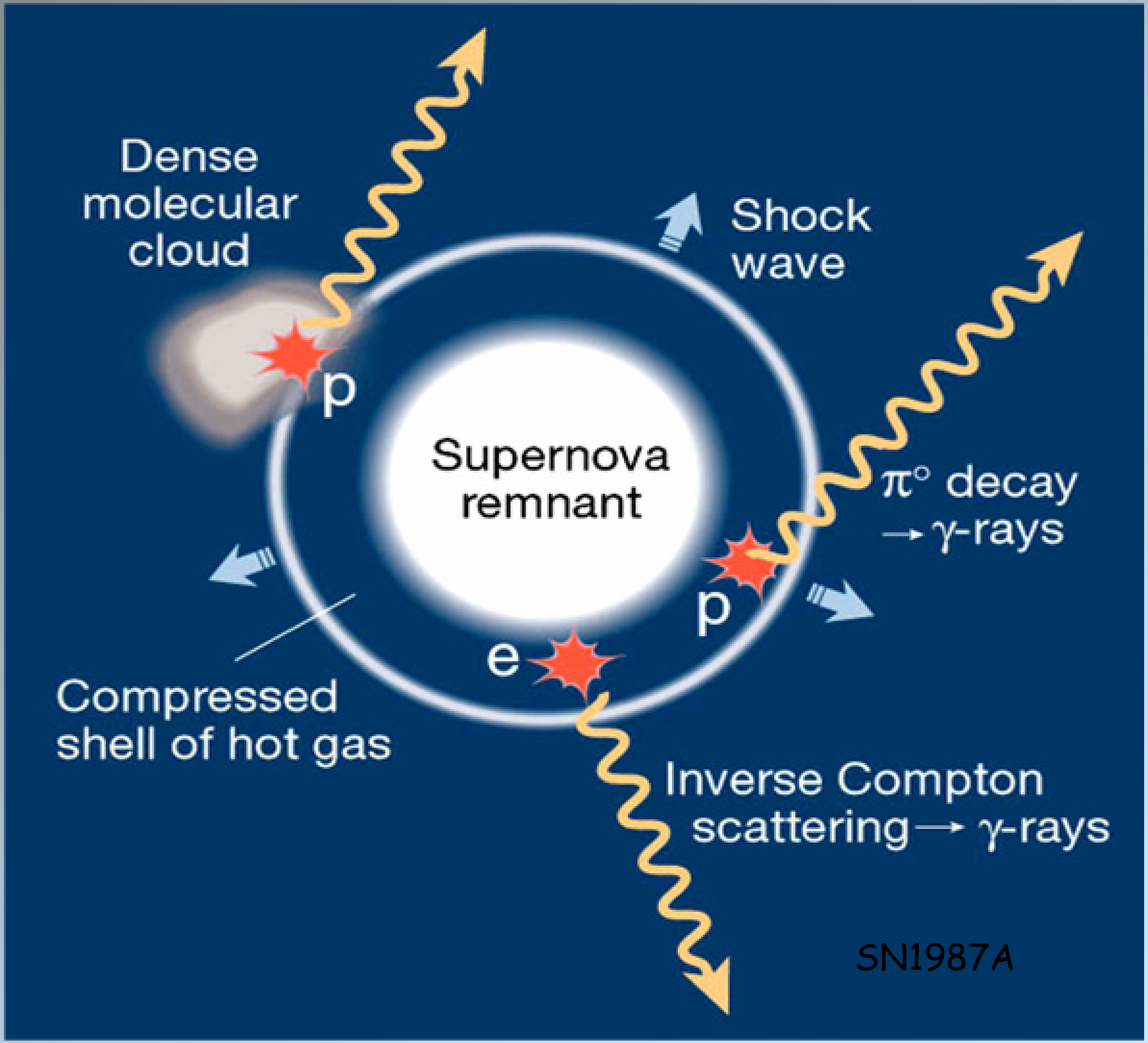
$$E_{max} = \beta \cdot Z\ (B/1\mu G)\ (R/1\ kpc)$$

ISM-SN: (Lagage&Cesarsky, 1983)
Wind-SN: (Biermann, 1993)
AGN radio-lobes: (Rachen&Biermann,1993)
AGN Jets or cocoon: (Norman et al.,1995)
GRB: (Meszaros&Rees, 1992,1994)
Neutron stars:(Bednarek&Protheroe,2002)
Pulsar wind shock: (Berezhko, 1994)

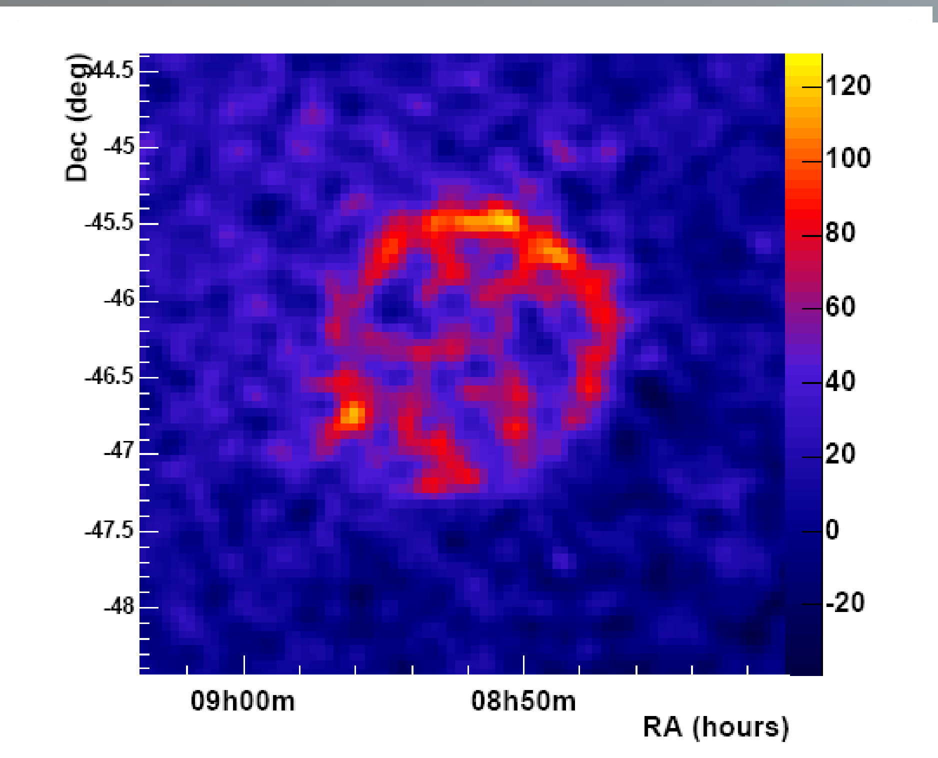


Hillas, 1984

Non-relativistic shocks in Supernovae

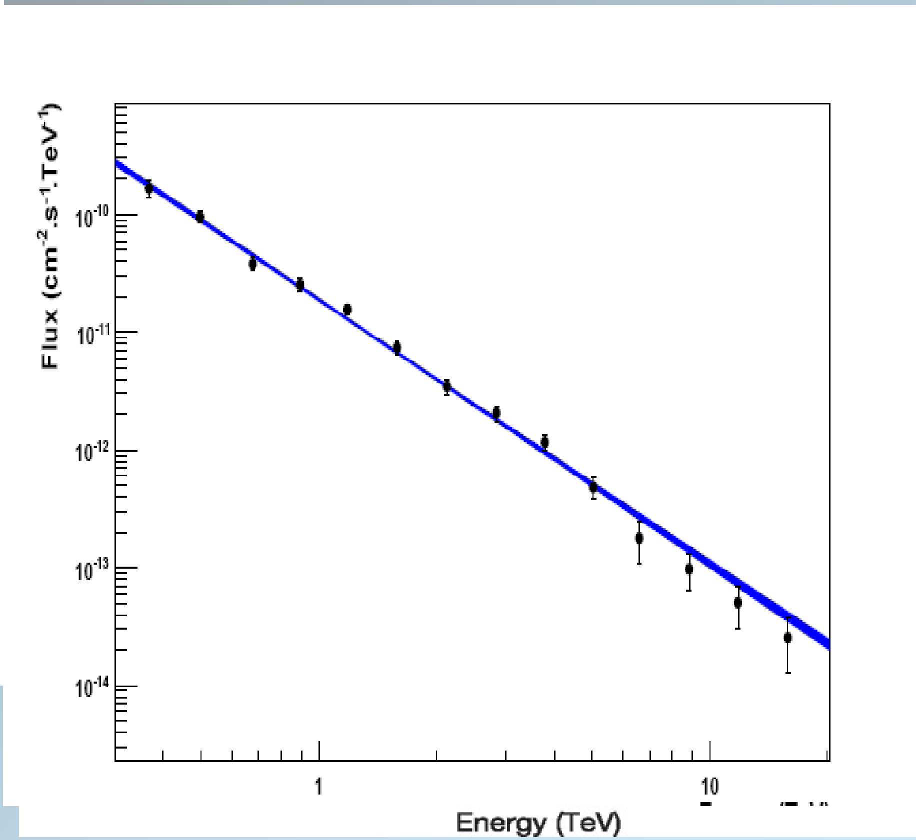


Hadronic acceleration…

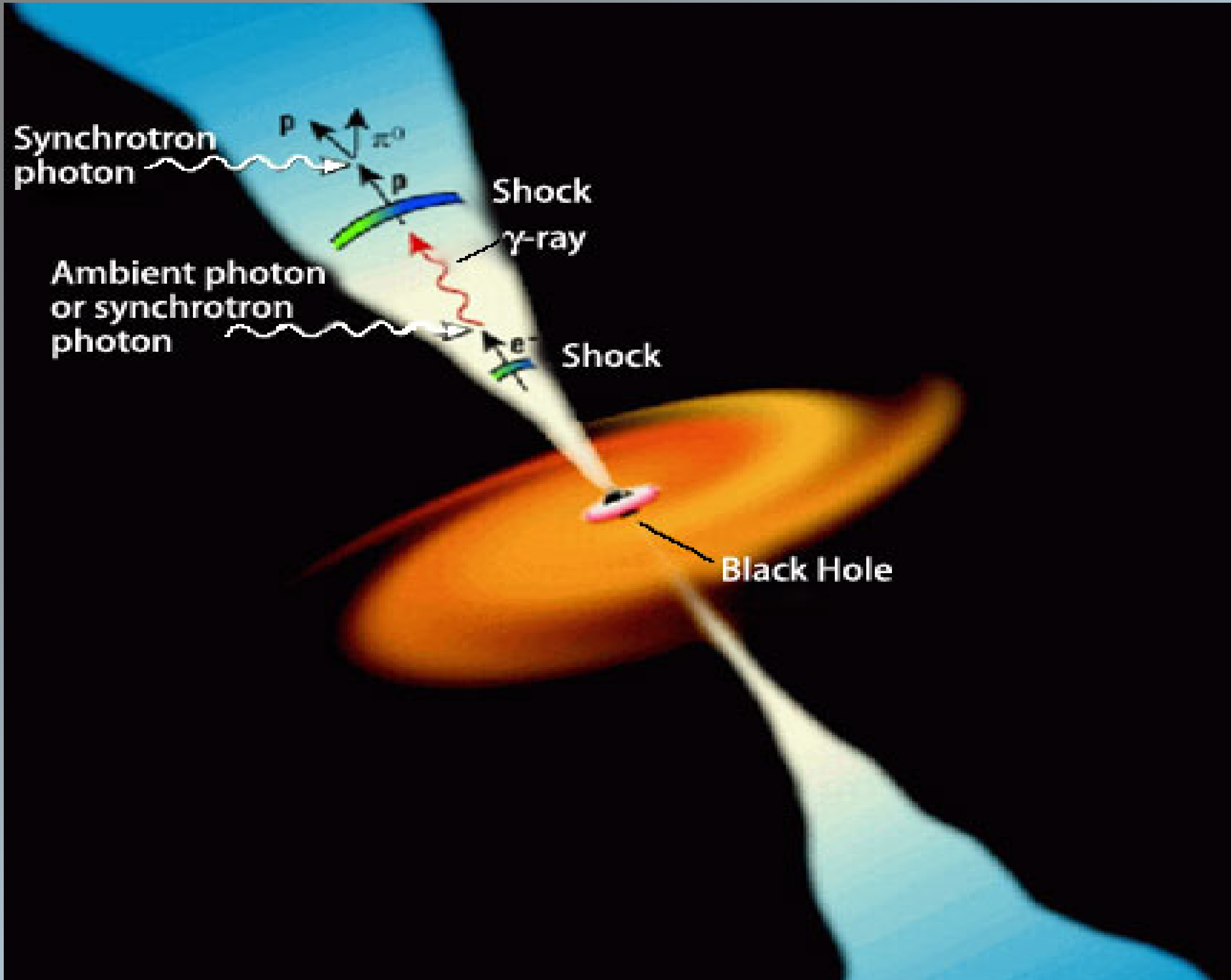


Gamma-ray image of the SNR RX J1713.7 (G347). Linear color scale is in units of counts.

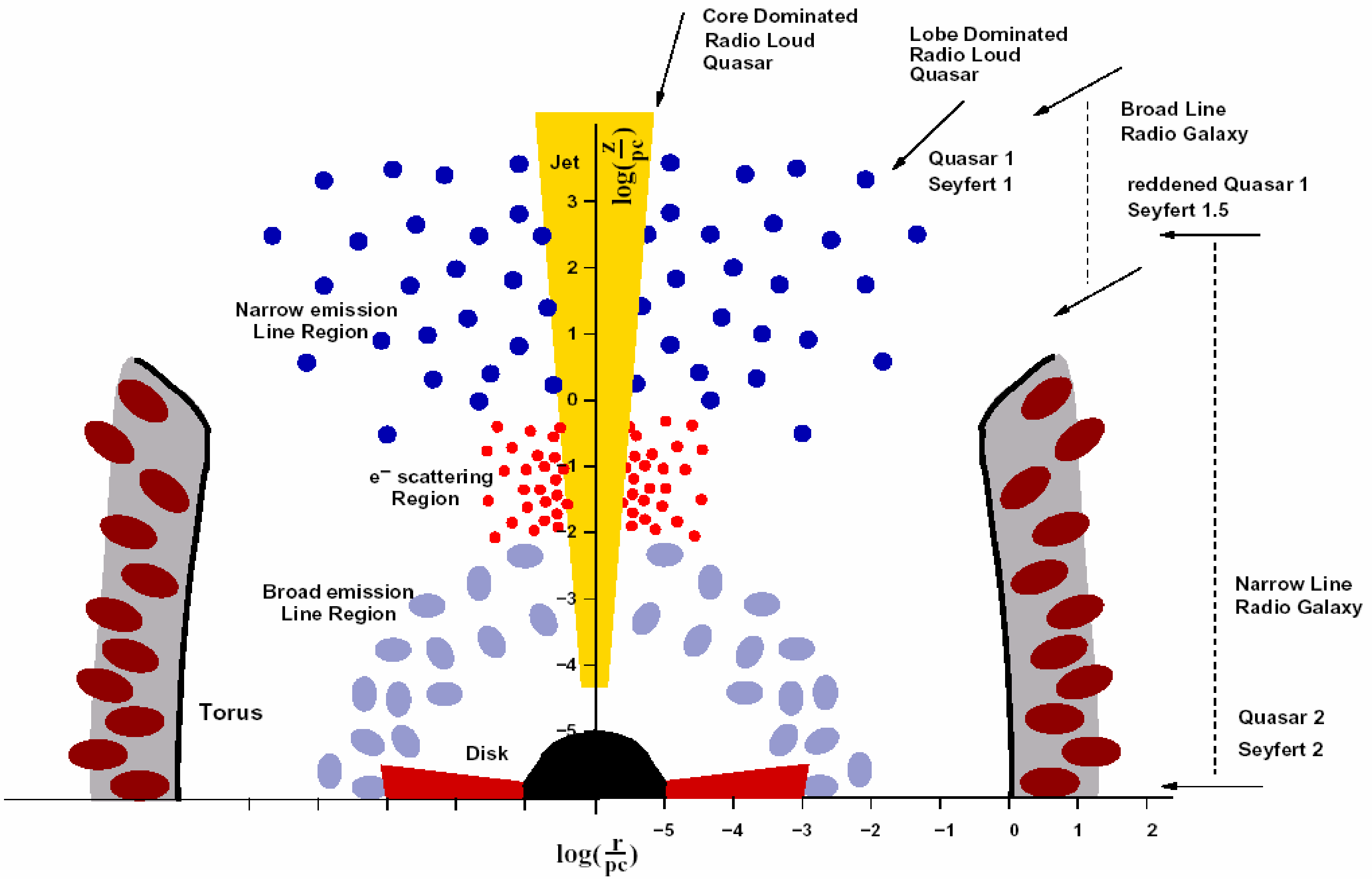
The superimposed (linearly spaced) black contour lines show the X-ray surface brightness as seen by ASCA in the 1–3 keV range.

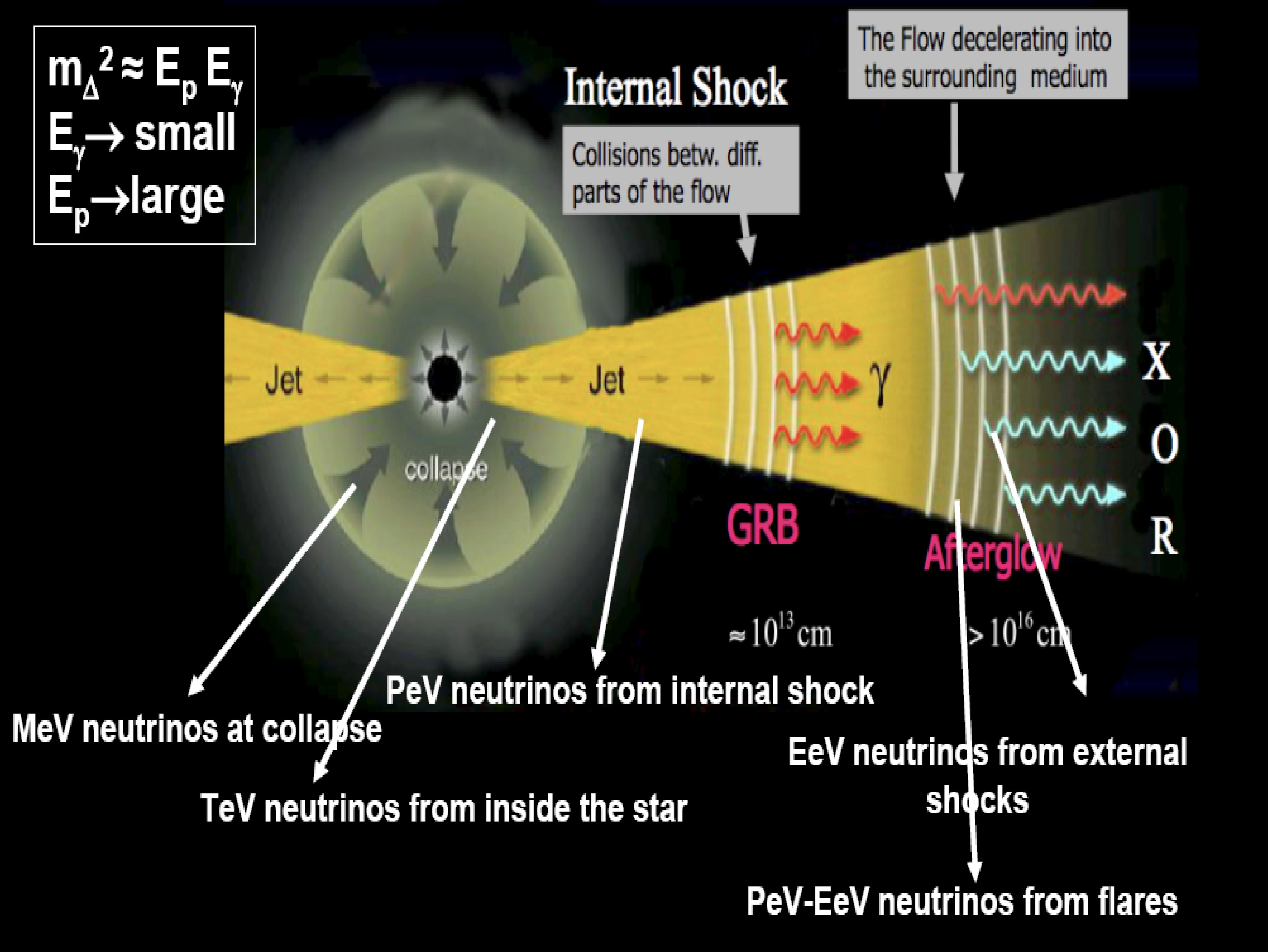


HESS collaboration: Aharonian et al *Nature* 2004, 432, 75 – 77


Synchrotron photon
p
π⁰
p
Shock
γ-ray
Ambient photon or synchrotron photon
e⁻
Shock
Black Hole

The unification model for all AGN





$m_\Delta^2 \approx E_p E_\gamma$
$E_\gamma \to$ small
$E_p \to$ large
Internal Shock
Collisions betw. diff. parts of the flow
The Flow decelerating into the surrounding medium
Jet
Jet
collapse
γ
X
O
R
GRB
Afterglow
$\approx 10^{13}$ cm
$> 10^{16}$ cm
PeV neutrinos from internal shock
MeV neutrinos at collapse
TeV neutrinos from inside the star
EeV neutrinos from external shocks
PeV-EeV neutrinos from flares

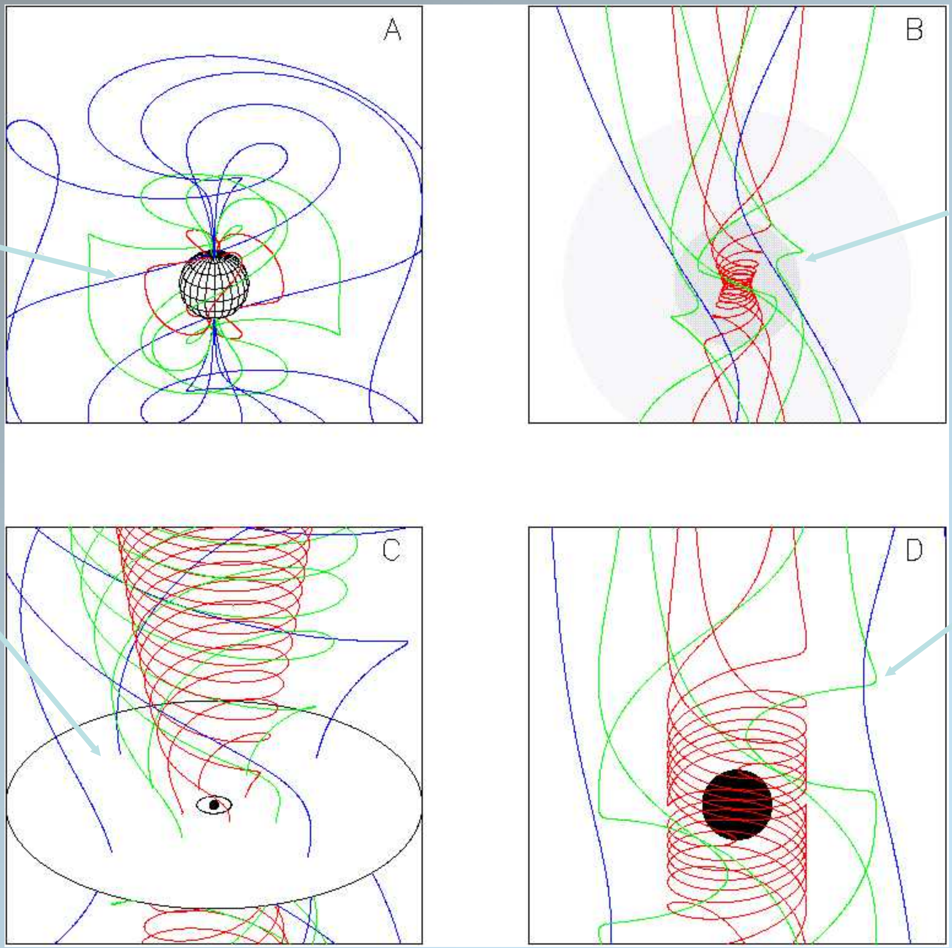
Remark 1:

-Presently, a good explanation/hypothesis is that *all relativistic jets* are created by *similar* MHD/electrodynamic processes

-The basic configuration of differential rotation and twisted magnetic field accelerating a collimated wind can be achieved in all relativistic jet objects

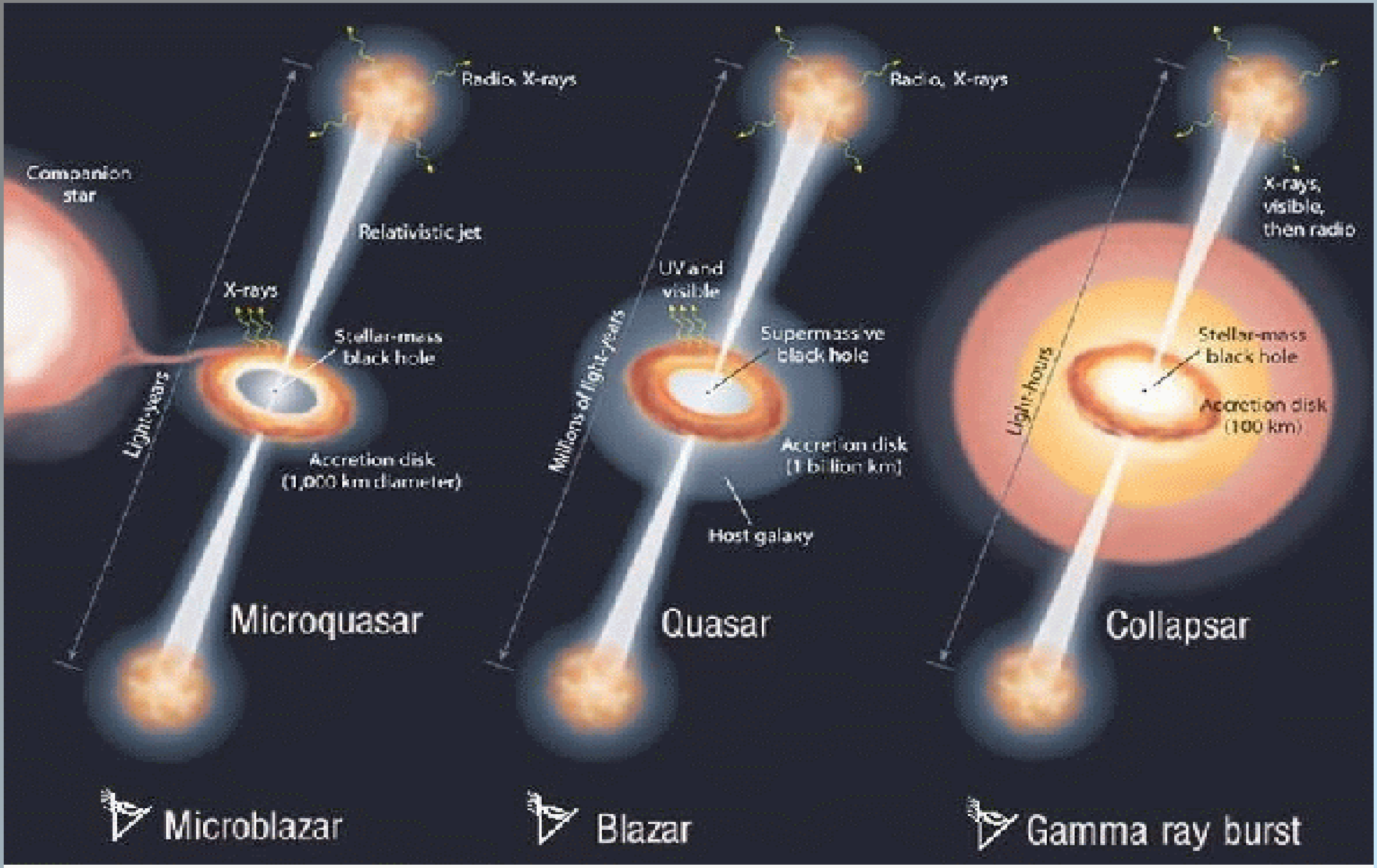
Pulsar magnetosphere, beyond the light cylinder

Collapsing, magnetized supernova core



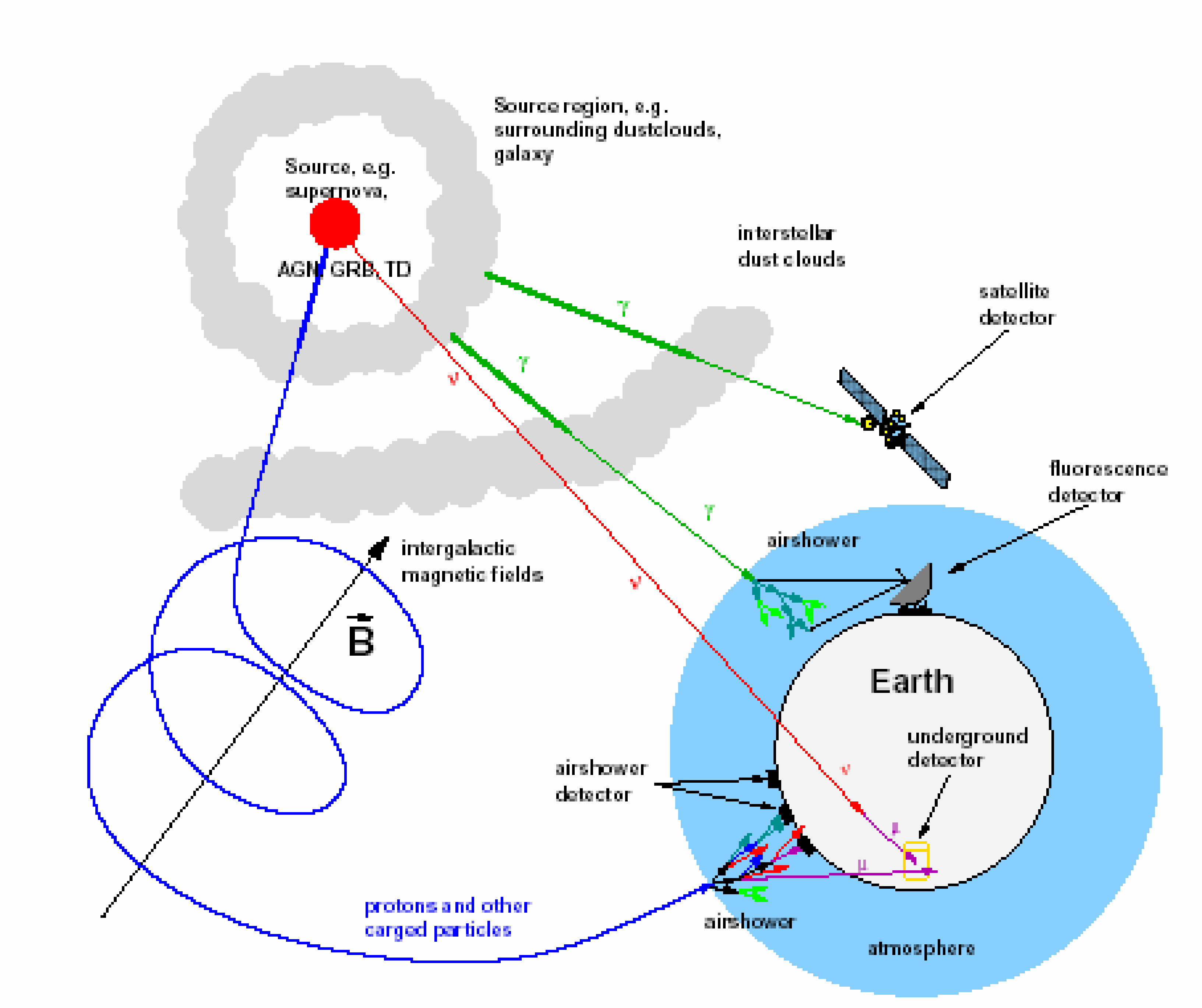
Magnetized accretion disks around neutron stars and black holes

Magnetospheres of Kerr black holes, with differentially-rotating metric



Remark2 : A *universal mechanism* seems to be responsible for astrophysical objects

Associating Cosmic Rays with the 'Cosmic Messengers'


Source region, e.g.
surrounding dustclouds,
galaxy
Source, e.g.
supernova,
AGN, GRB, TD
interstellar
dust clouds
satellite
detector
fluorescence
detector
γ
γ
γ
ν
ν
ν
airshower
intergalactic
magnetic fields
B
Earth
underground
detector
airshower
detector
μ
μ
protons and other
carged particles
airshower
atmosphere

W.Wagner 05

Neutrino emission

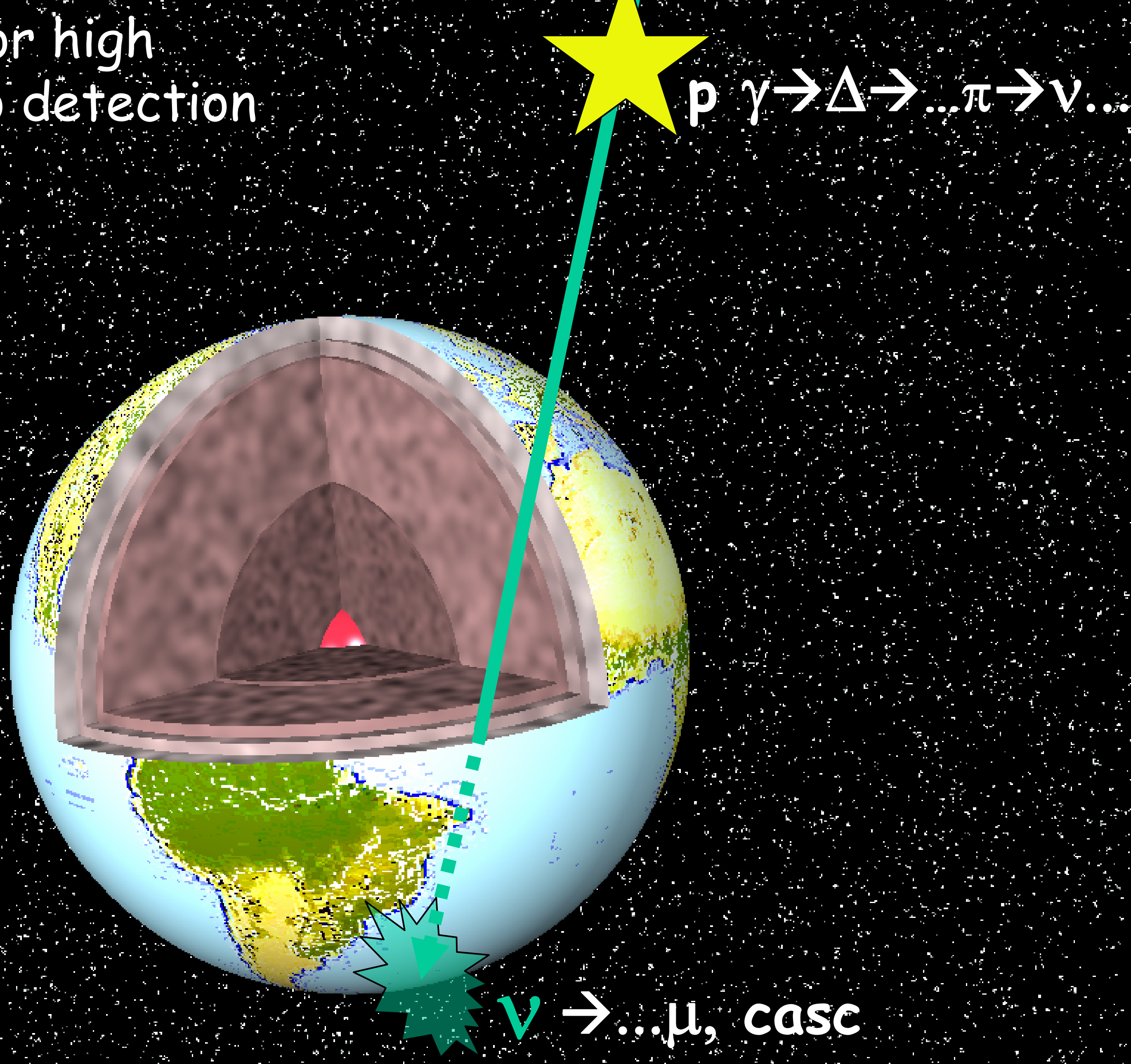
$p + p \rightarrow p\, n\, \pi^+$
$n + p \rightarrow p\, p\, \pi^-$
$p + \gamma \rightarrow p\, \pi^-$

$\pi^+ \rightarrow \mu^+ \nu_m \rightarrow e^+ \nu_e\ \nu_m$
$\pi^- \rightarrow \mu^- \nu_m \rightarrow e^- \nu_m$

High energy neutrinos from extragalactic neutrino sources:
AGN (Protheroe, 1997)
GRBs (Meszaros et al. 2004)

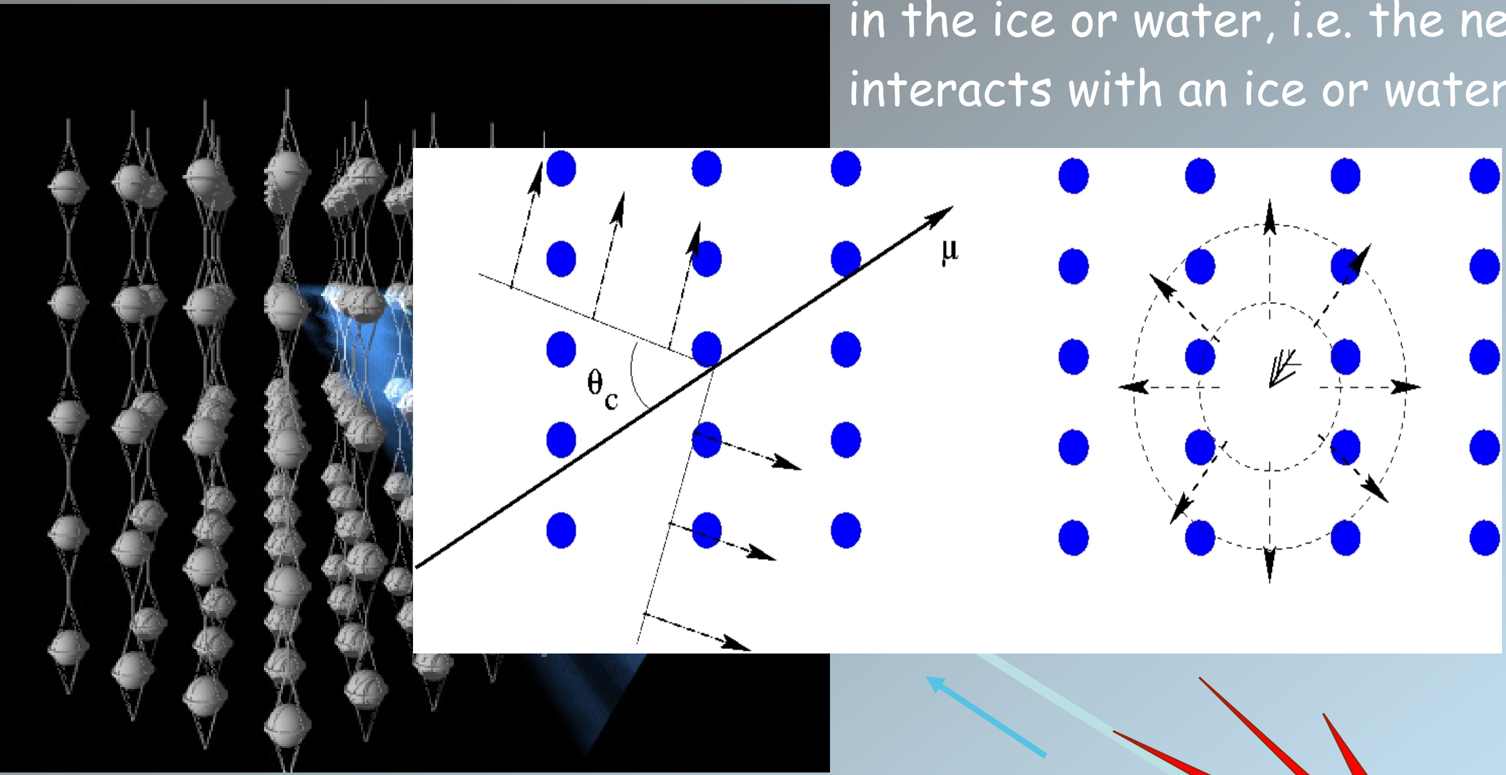
Detectability: High energy neutrino telescopes (eg: IceCube, Baikal, Antares, Nestor, etc)

The principle for high energy neutrino detection



Neutrino detectors

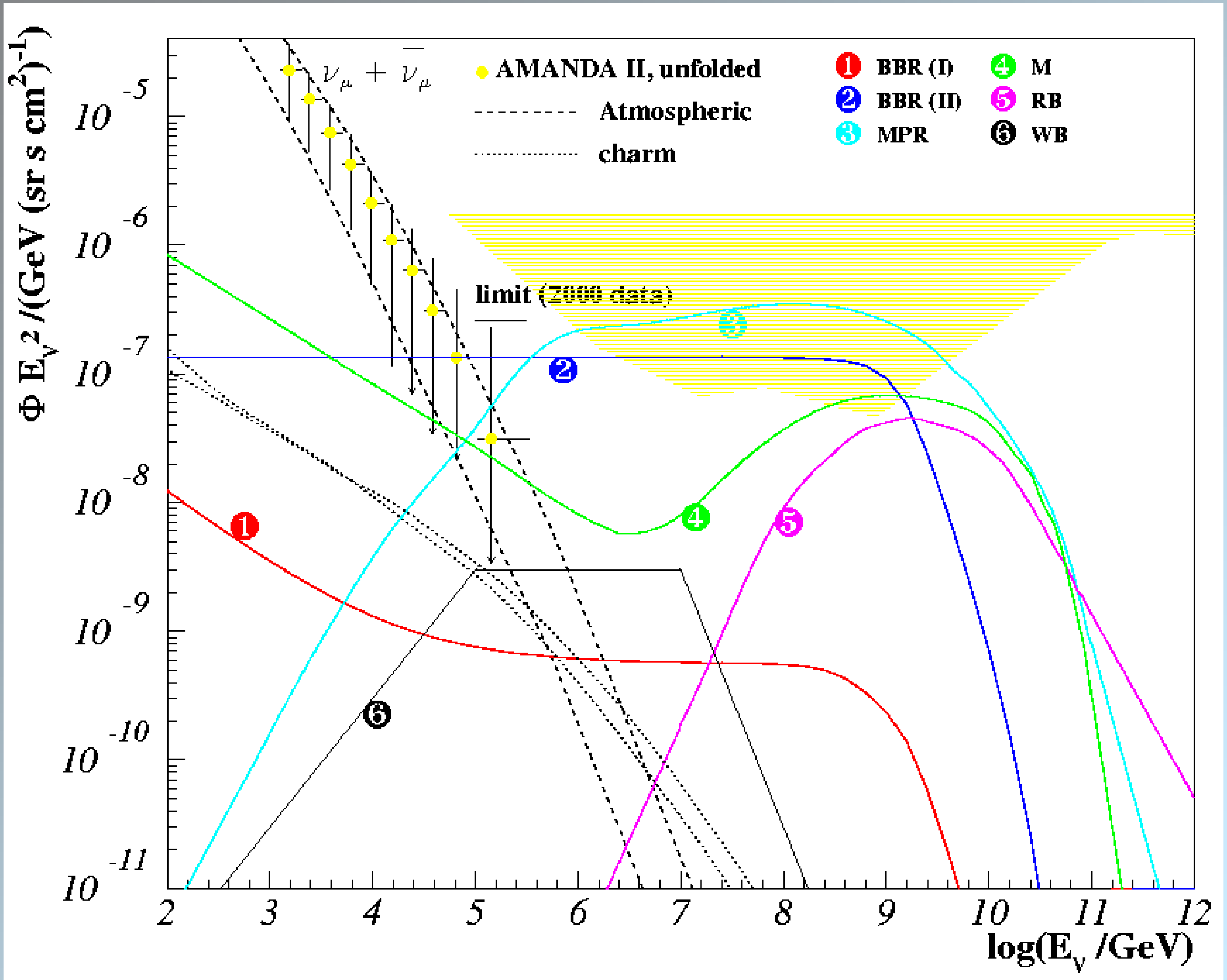
- infrequently, a cosmic neutrino is captured in the ice or water, i.e. the neutrino interacts with an ice or water nucleus



(electron,tau)

- the muon radiates blue light in its wake
- optical sensors capture (and map) the light

Many prediction models…

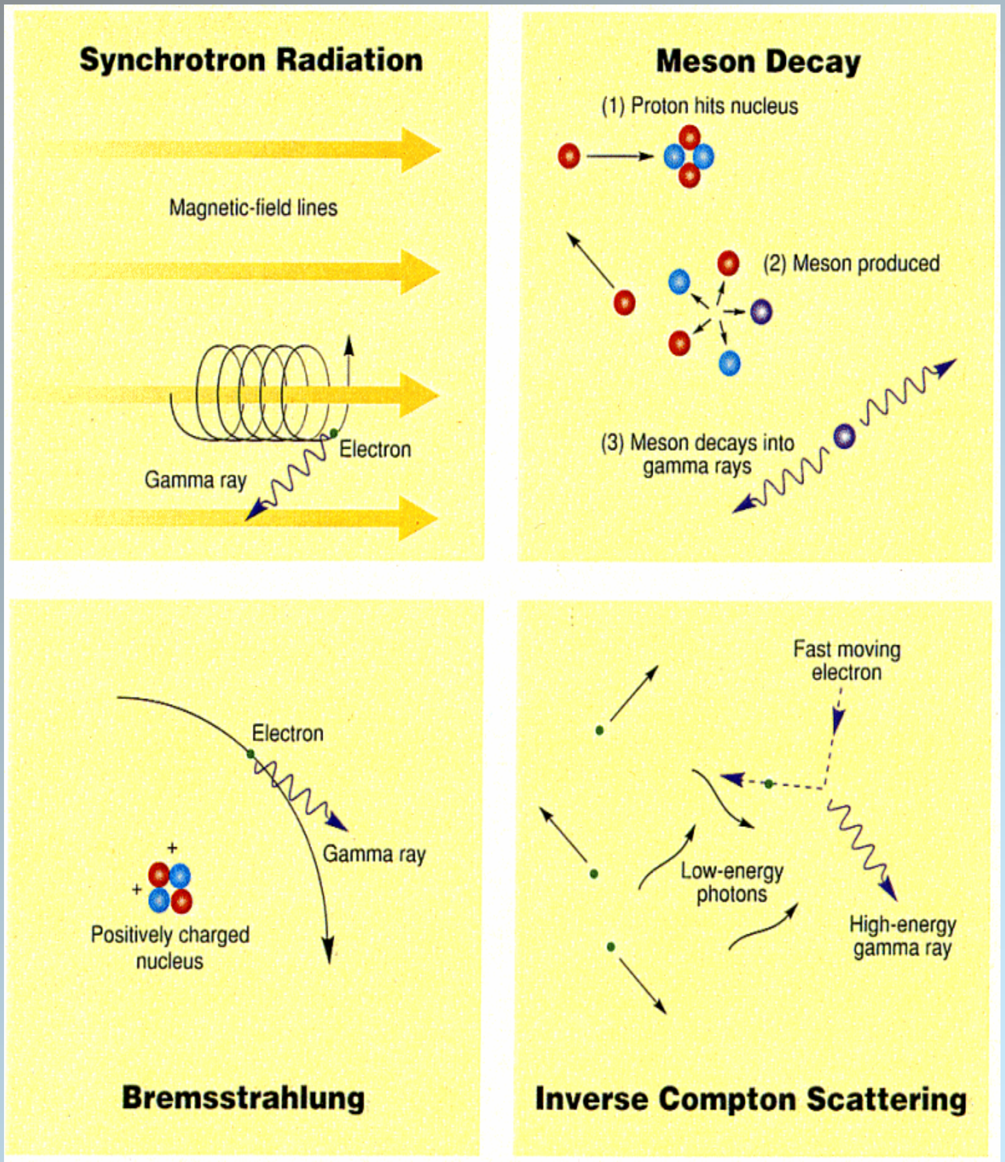


Gamma ray emission

$e^{\pm} + B$

"leptonic"

$e^{\pm}$ + matter



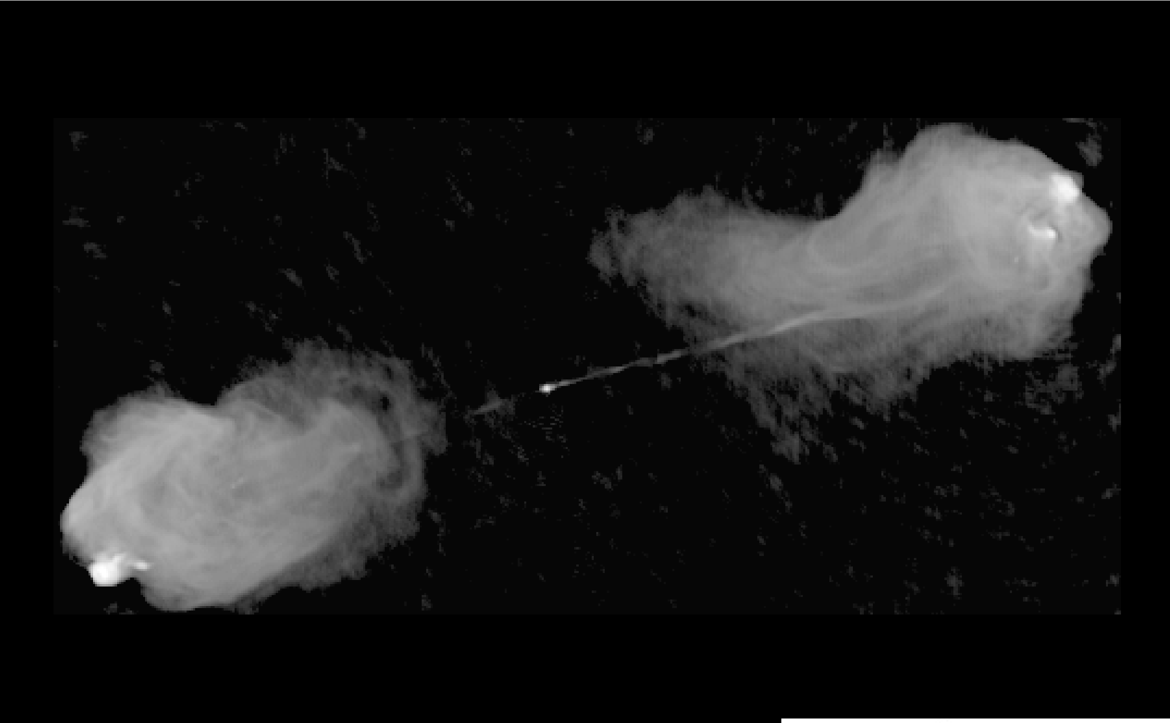
"hadronic"

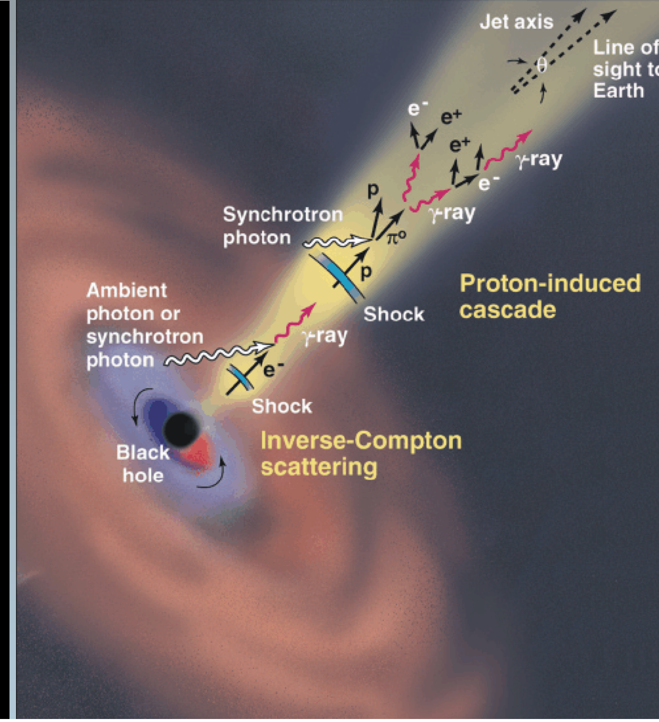
p + matter

p + p

$p + \gamma$

$e^{\pm} + h\nu$



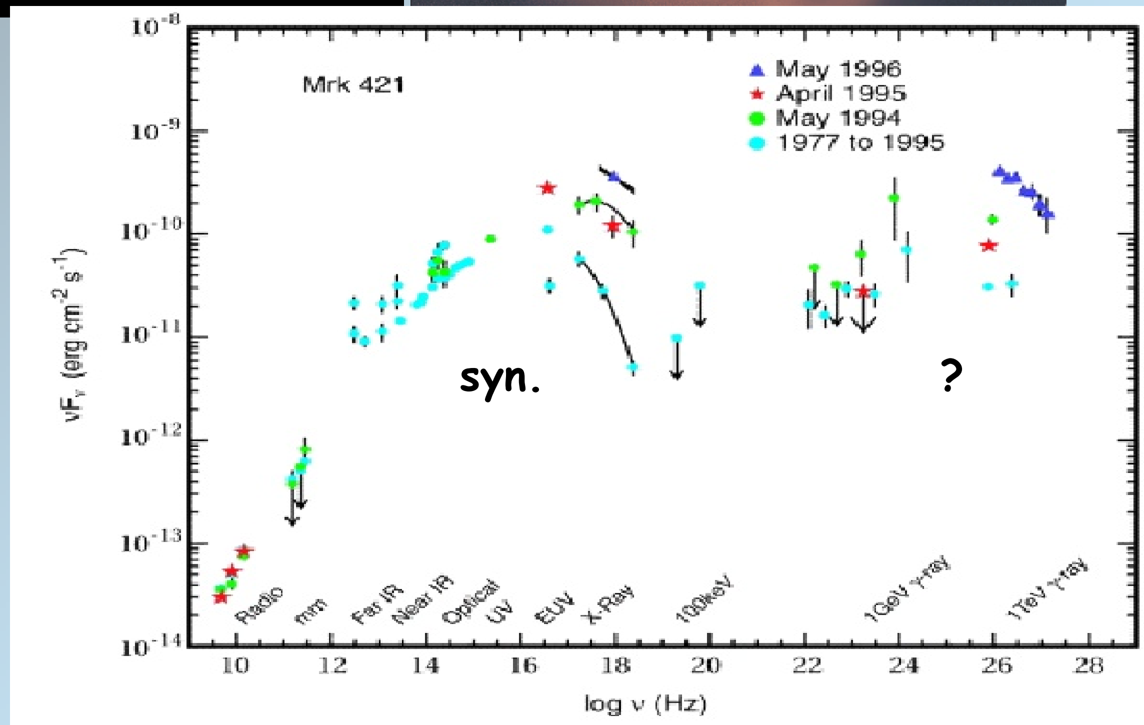


"leptonic" models

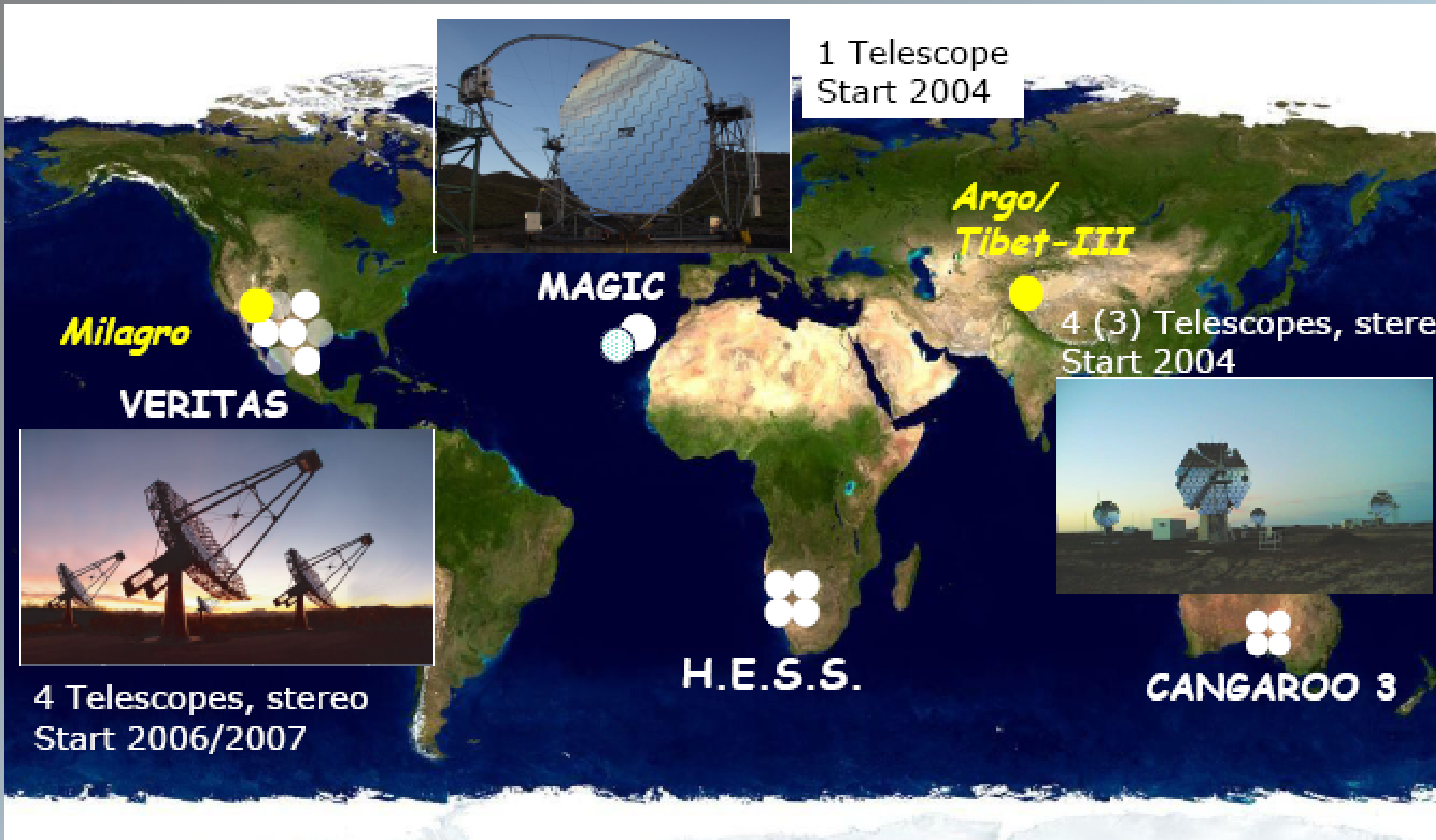
$e^+ e^-$ Jets

"hadronic" models

e^- p Jets

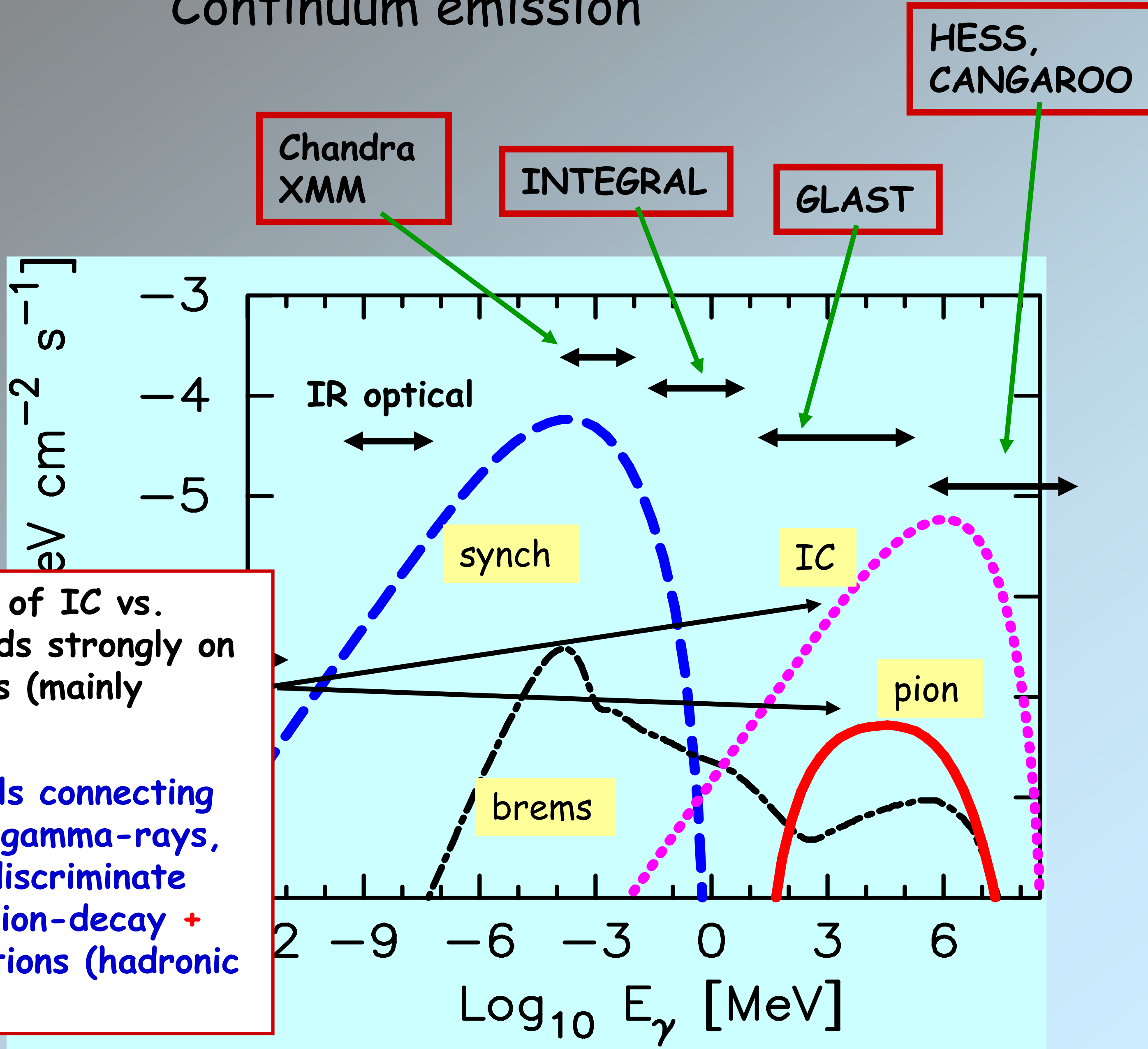


Gamma-ray telescopes



Ground based

Continuum emission



Relative intensity of IC vs. pion-decay depends strongly on ambient conditions (mainly density).

Broad-band models connecting Radio – X-rays – gamma-rays, in principle, can discriminate between IC and pion-decay + Neutrino observations (hadronic nature)

Key question: what is the “driving force” responsible for the very high energy of the ‘primary’ cosmic rays and the consequent emitted radiation ?

Key answer: Fermi *shock* acceleration mechanism

Fermi acceleration mechanism

- Second order Fermi acceleration (Fermi, 1949,1954)

 - @ magnetic clouds

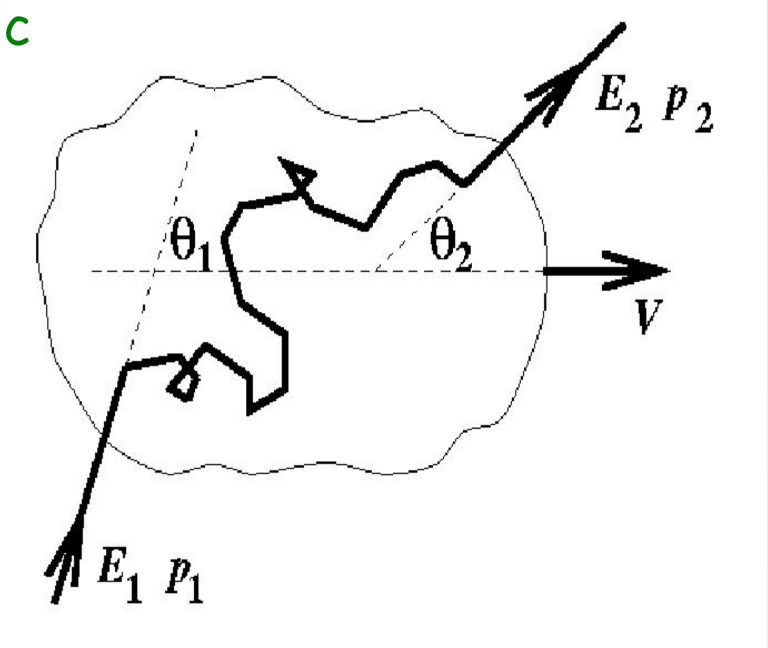
- First order Fermi acceleration -diffusive acceleration- (Krymskii, 1977; Bell, 1978a,b; Blandford&Ostriker, 1978; Axford et al. 1978)

 - @ plasma shocks

Transfer of the macroscopic kinetic energy of moving magnetized plasma to individual charged particles → non- thermal distribution

Second order Fermi acceleration

- *Observer's frame:*
 Particles are reflected by 'magnetic mirrors' associated with irregularities in the galactic magnetic field. → *Net energy gain.*



- *Cloud frame:*
  1) No change in energy
     (colissionless scattering, elastic)
  2) Cosmic ray's direction randomised

- If particles *remain* in the acceleration region for τ → power law distribution :

$$N(E) \propto E^{-s}$$

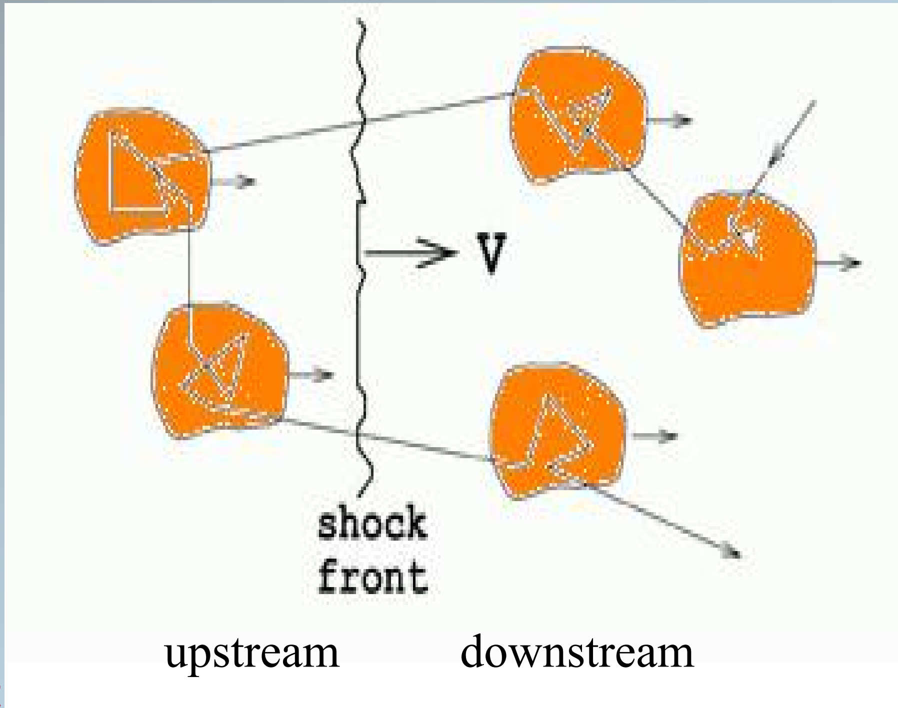
$$s=1+1/\alpha\tau \quad \text{and} \quad \alpha \propto (V/c)^2$$

The average energy gain per collision:

$$\langle \Delta E/E \rangle = (V/c)^2$$

First order Fermi acceleration

1970's modification of general theory: Particles undergo a process on crossing a *shock* from upstream to downstream and back again (*Supernovae shocks*)

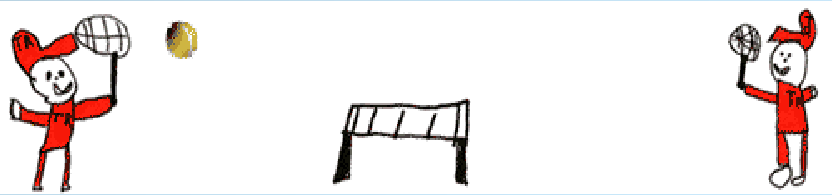


Power-law distribution depends only on compression ratio, r :

$$N(E) \propto E^{-s}$$

$$s=(r+2)/(r-1), \quad r=V_1/V_2=(\gamma+1)/(\gamma-1)$$

for mono-atomic gas $\gamma=5/3 \rightarrow r=4 \rightarrow E^{-2}$



The average energy gain per collision:

$$\langle \Delta E/E \rangle = V/c$$

Note: Only for non-relativistic shocks…

Shock waves 'jump conditions'

$$\rho_2 v_2 = \rho_1 v_1$$ mass

$$p_2 + \rho_2 v_2^2 = p_1 + \rho_1 v_1^2$$ momentum

$$\rho_2 v_2 (v_2^2/2 + p_2/\rho_2 + e_2) = \rho_1 v_1 (v_1^2/2 + p_1/\rho_1 + e_1)$$

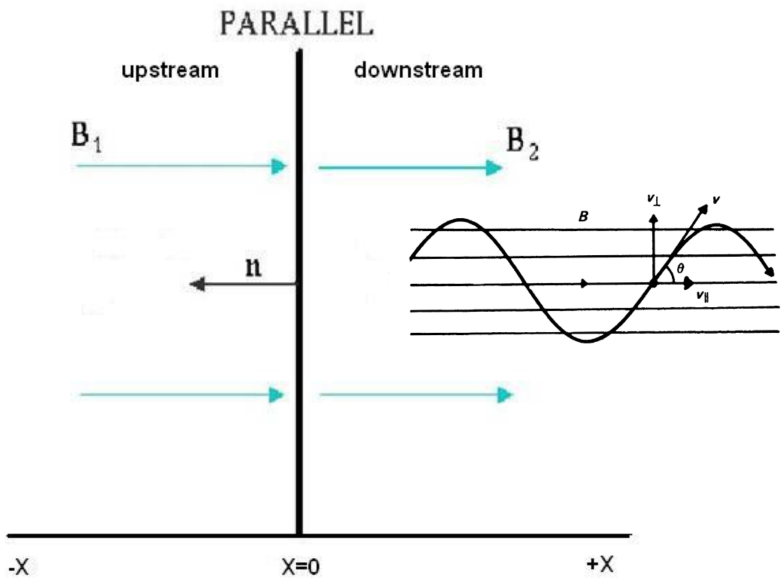
energy

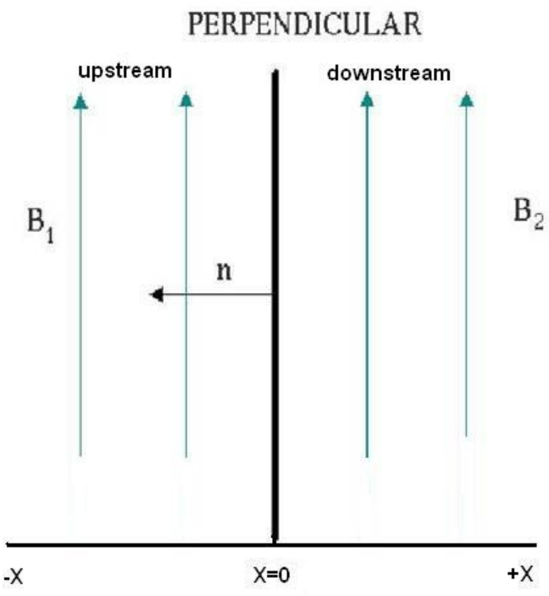
$$\frac{v_2}{v_1} = \frac{\gamma + M_1^{-2} \pm (1 - M_1^{-2})}{\gamma + 1}$$

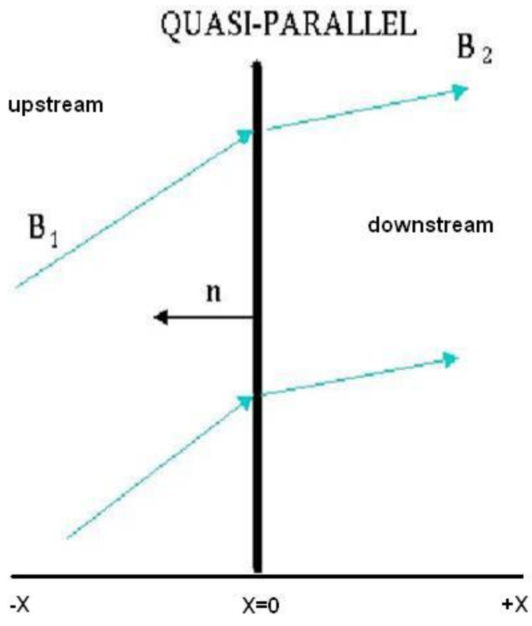
$$\frac{p_2}{p_1} = \frac{2\gamma M_1^2 - (\gamma - 1)}{\gamma + 1}$$

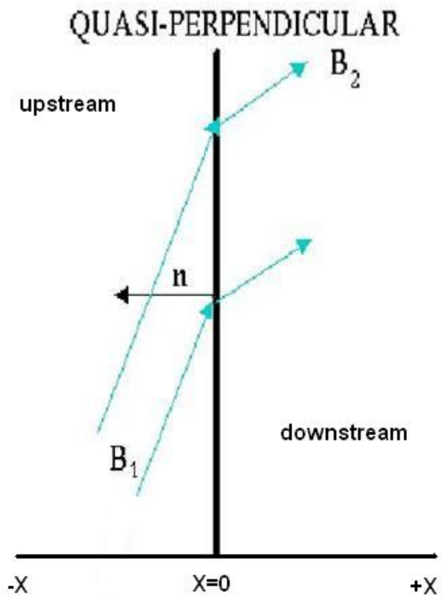
$$\frac{\rho_2}{\rho_1} = \frac{\gamma + 1}{\gamma - 1 + 2M_1^{-2}}$$

$$\frac{T_2}{T_1} = \frac{[2\gamma M_1^2 - (\gamma - 1)][\gamma - 1 + 2M_1^{-2}]}{(\gamma + 1)^2}$$

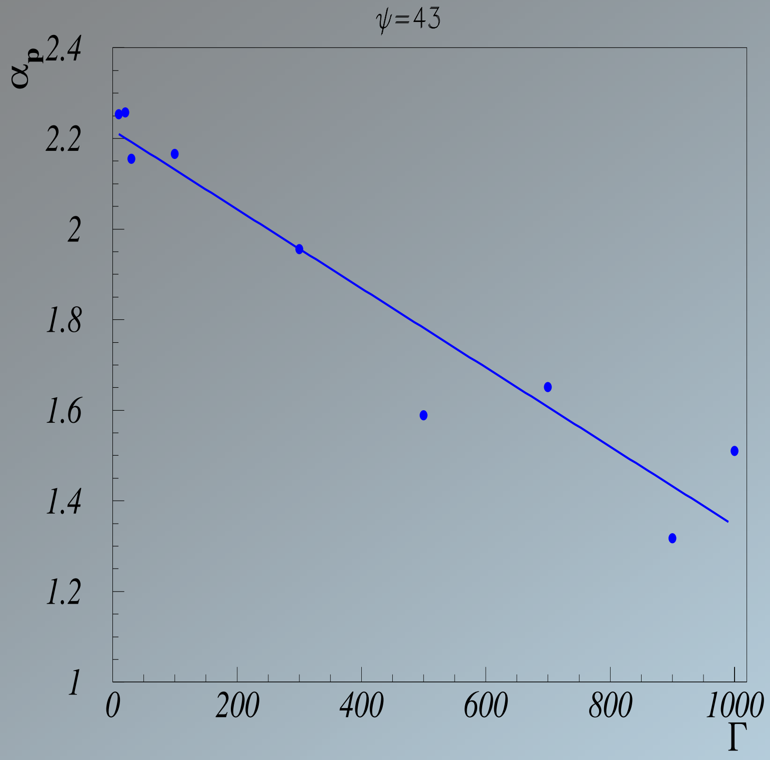

PARALLEL
upstream
downstream
B1
B2
n
B
v⊥
v
θ
v∥
-X
X=0
+X

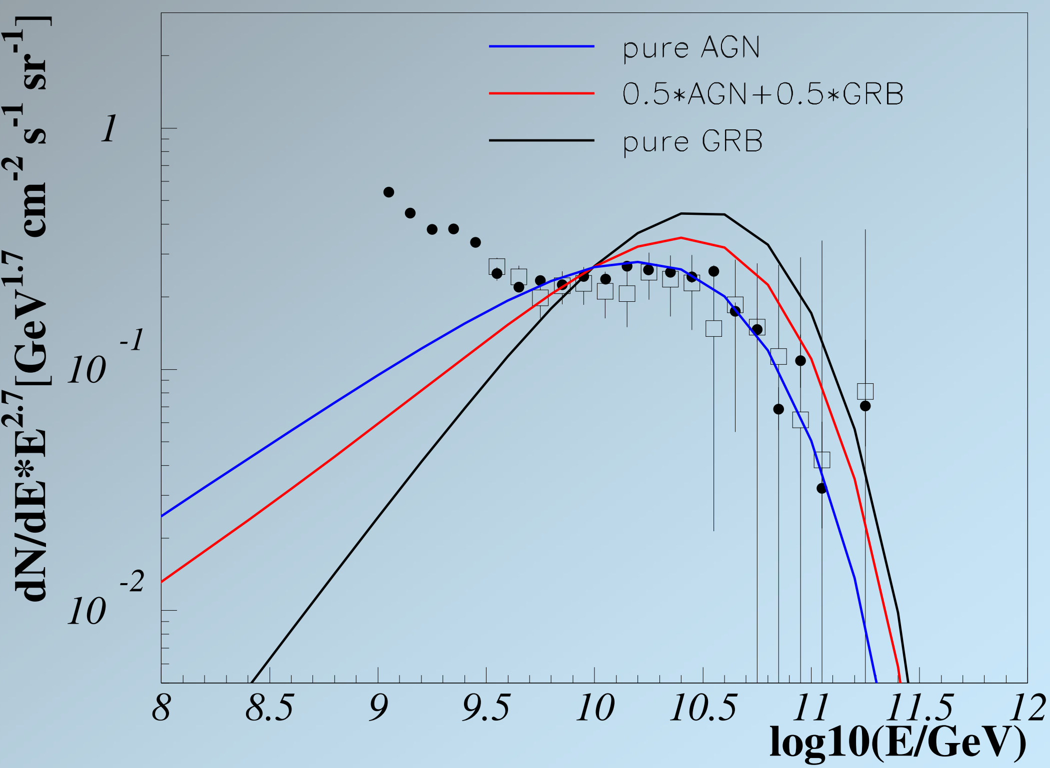

PERPENDICULAR
upstream
downstream
B1
B2
n
-X
X=0
+X


QUASI-PARALLEL
B 2
upstream
B 1
downstream
n
-X
X=0
+X


QUASI-PERPENDICULAR
B 2
upstream
n
downstream
B 1
-X
X=0
+X

Simulation studies, the primary' accelerated particles and the diffuse spectrum

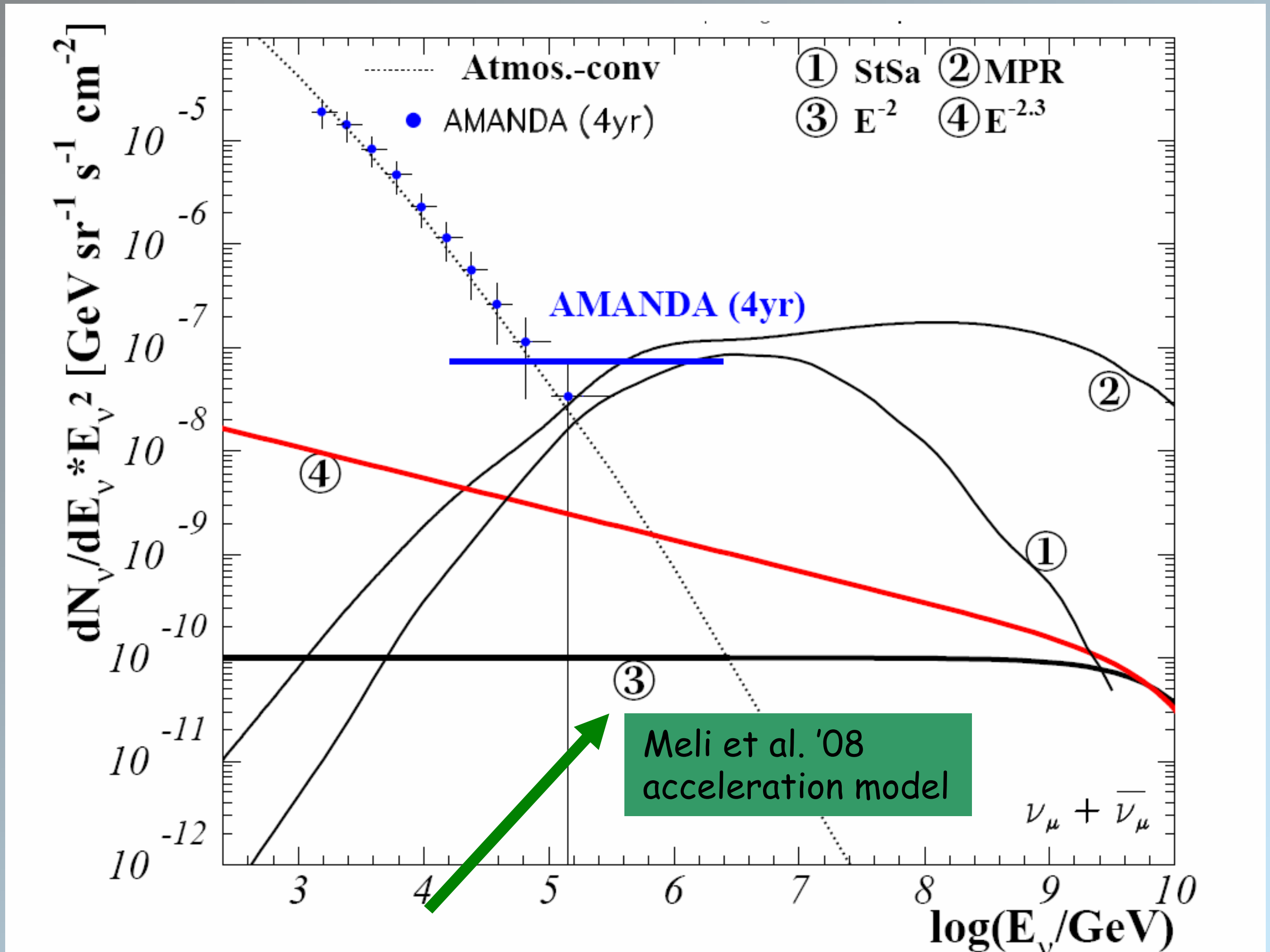




UHECR proton acceleration applicable to AGN and GRBs

Meli et al. (2007, 2008)

…and then neutrino fluxes

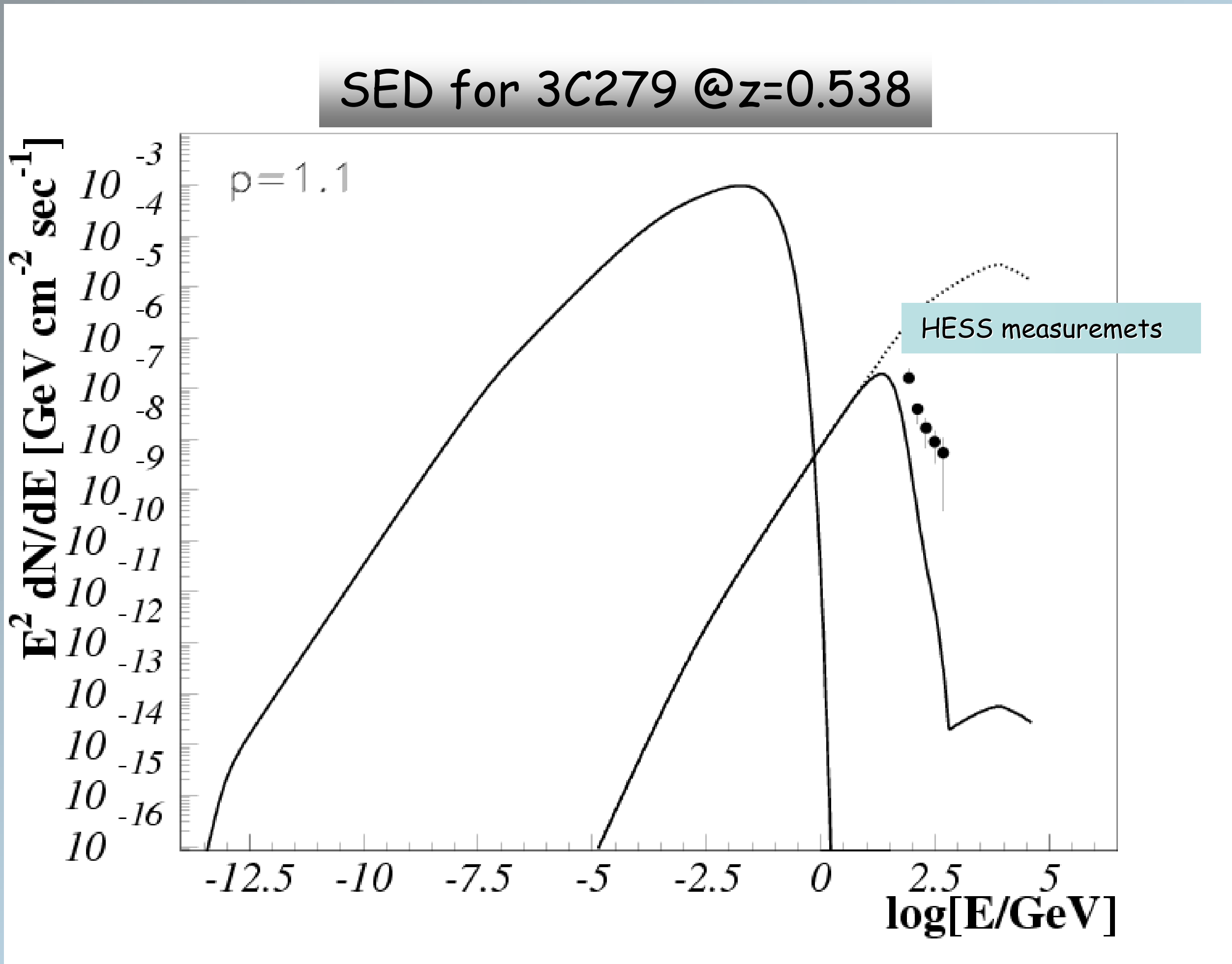


Becker&Biermann 08

diffuse neutrino flux prediction from UHECR correlation

…and consequent continuum radiation

An example "toy" for a leptonic scenario (one -zone SSC model), by altering the primary electron spectral index



A final thought

The understanding of the very high radiation events, using cosmic-ray, neutrino and gamma-ray observations, will eventually bring us closer to a profound understanding of Cosmos…


Thank you