IceCube

Neutrino Astrophysics

Teresa Montaruli
University of Wisconsin - Madison and University of Bari Italy
tmontaruli@icecube.wisc.edu

The real voyage is not to travel to new landscapes,
but to see with new eyes. . .

Marcel Proust

Lectures contents

Lecture 1

- Introduction to neutrino astronomy
- connections with cosmic rays and gamma-astronomy
- calculation of neutrino fluxes from gamma fluxes
- candidate sources: galactic sources
- UHECR and Auger

Lecture 2

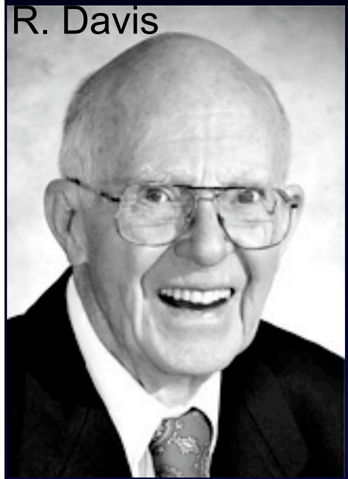
- Extra-galactic sources: AGNs and GRBs
- Calculation of rates
- Detection Technique
- Main Parameters of Detectors
- Existing detectors

Lecture 3

- Event topologies and reconstructions
- Example of analyses
- Point-source analysis and current results
- Atmospheric neutrino analysis
- Current physics results
- SN collapse

The Birth of Neutrino Astronomy

Neutrinos from thermonuclear reactions in the Sun



$$4p \rightarrow {}^{4}\mathrm{He} + 2e^{+} + 2\nu_e$$

~6 x 10^{10} ν cm^{-2} s^{-1}

E_ν ~ 0.1 – 20 MeV

~ 10 s bursts of 10 MeV νs from stellar collapse

Nobel Prize in Physics 2002

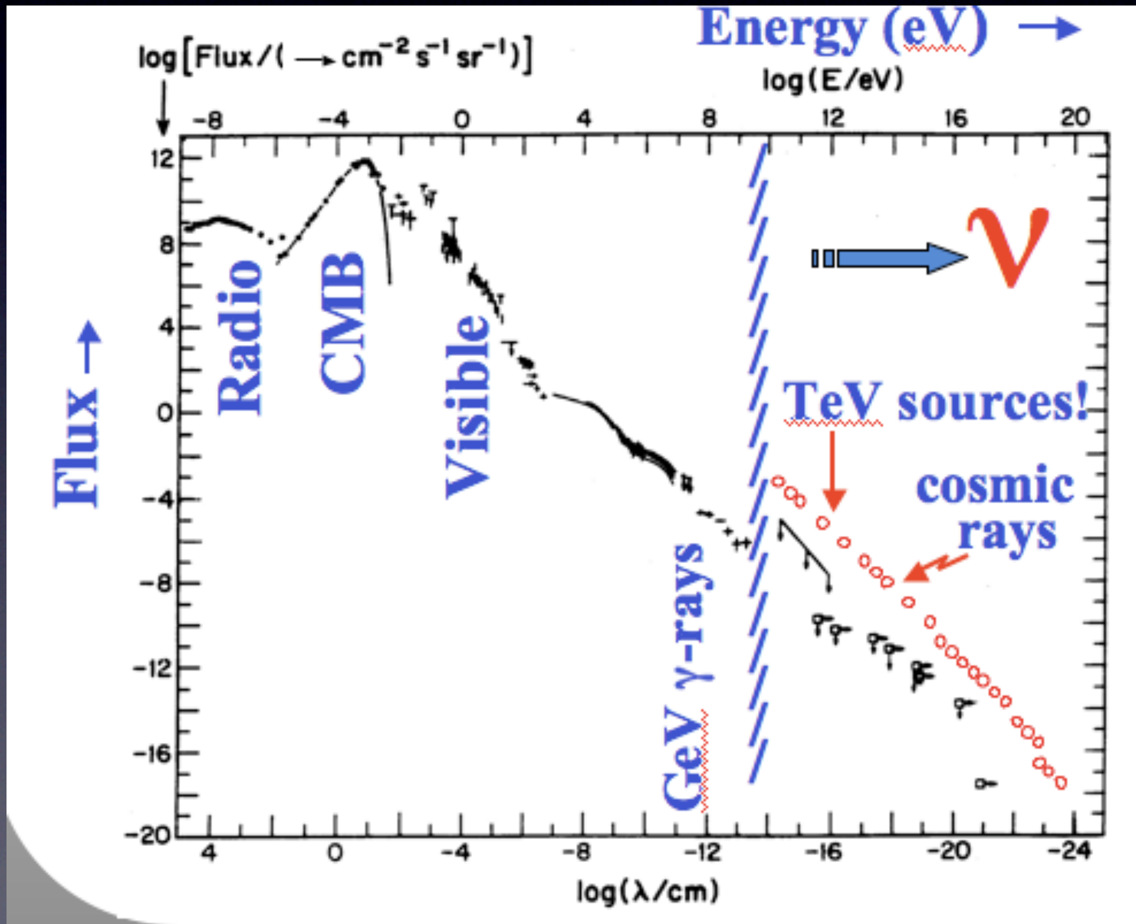
Neutronization

Thermalization:

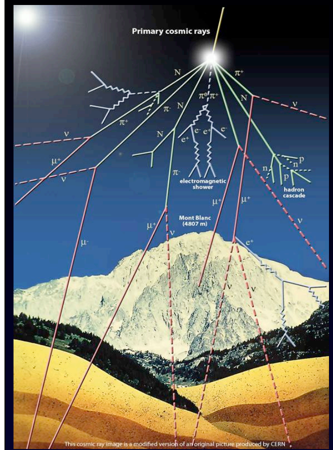
$$e^- + p \rightarrow n + \nu_e$$

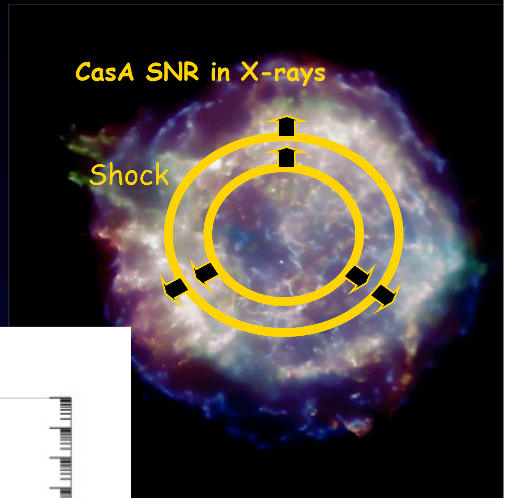
$$e^- + e^+ \rightarrow \bar{\nu} + \nu$$

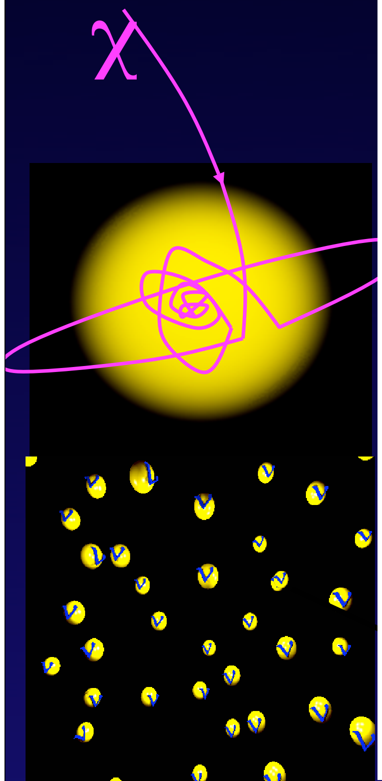
CRs and Neutrinos

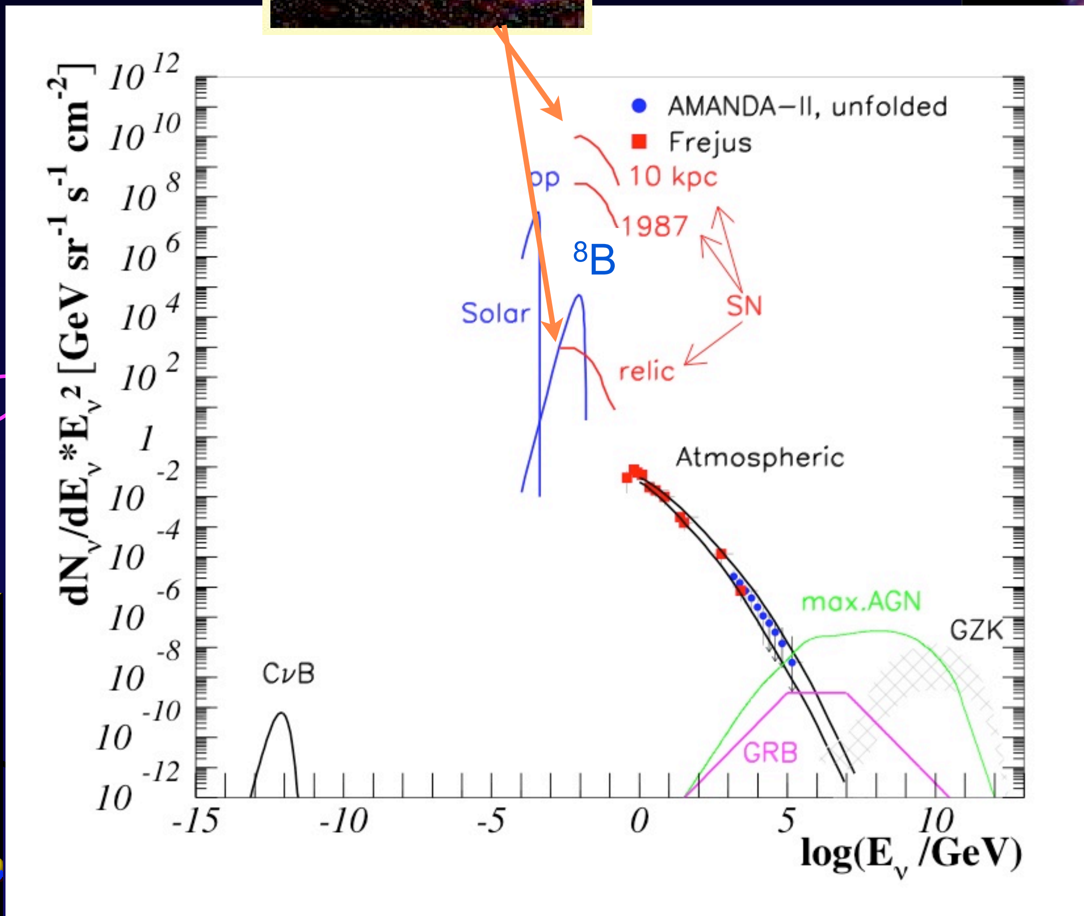


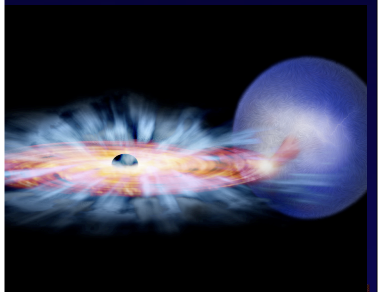
Neutrino Fluxes











Messengers of the universe

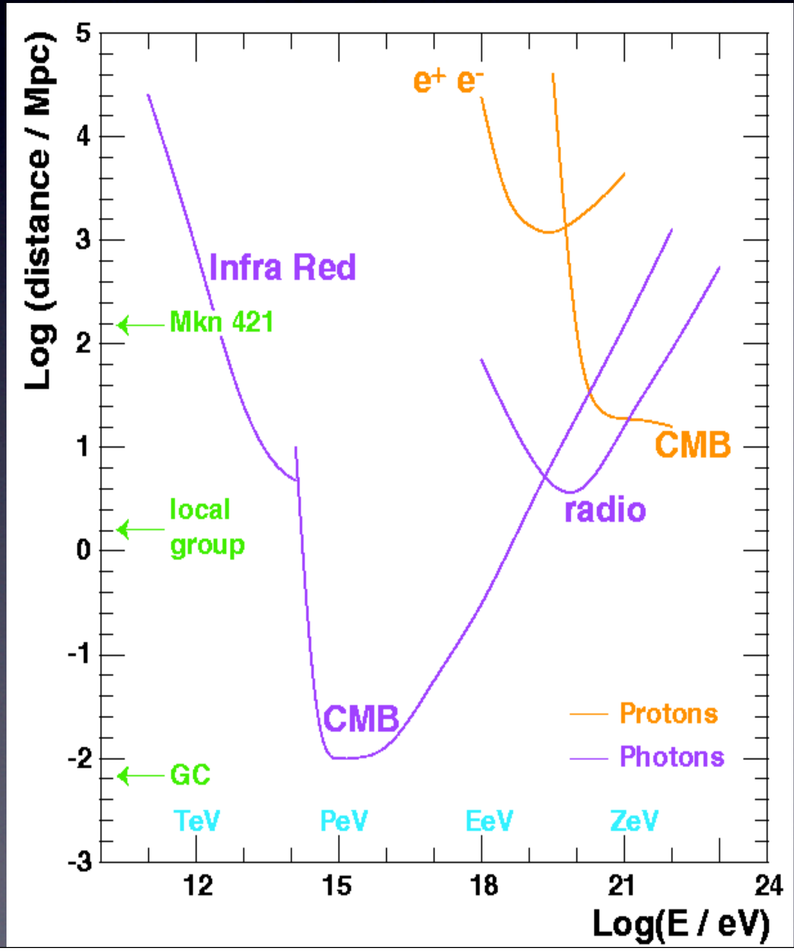
absorption		cut-off	mean free path
γ-rays:	$\gamma + \gamma_{2.7k}$	$>10^{14}$eV	10 Mpc
proton:	$p + \gamma_{2.7k} \rightarrow \pi^0 + X$	$>5.10^{19}$eV	50 Mpc
neutrinos:	$\nu + \nu_{1.95K} \rightarrow Z+X$	$>4.10^{22}$eV	(40 Gpc)

1pc = 3.26 ly = 3.1 10^{13} km

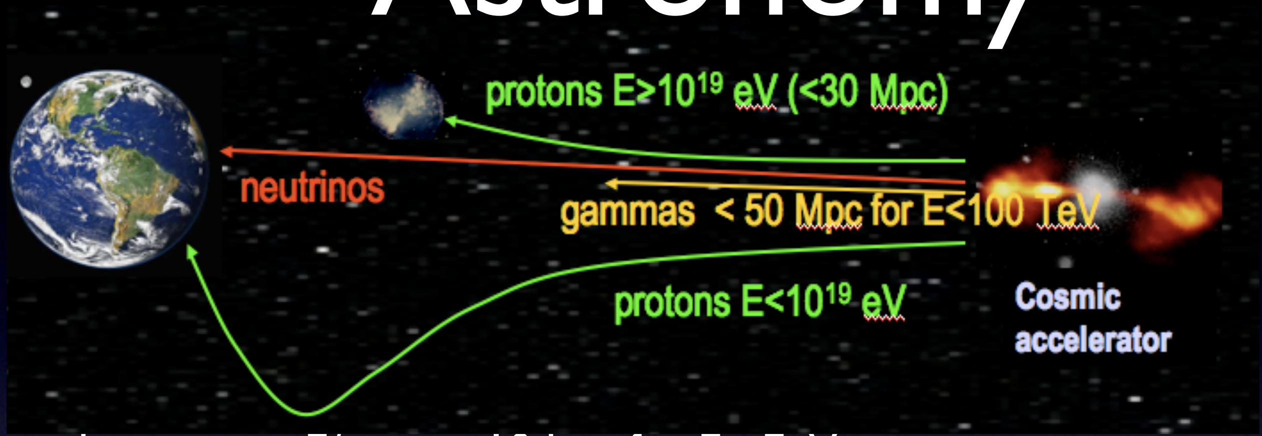
1 Mpc ~ 3.1x 10^{24} cm

p and gamma astronomy have not access to the entire Universe

Particles are messengers if the point back to sources (neutral or UHE)



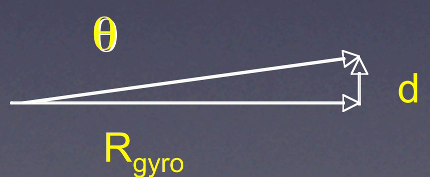
Astronomy

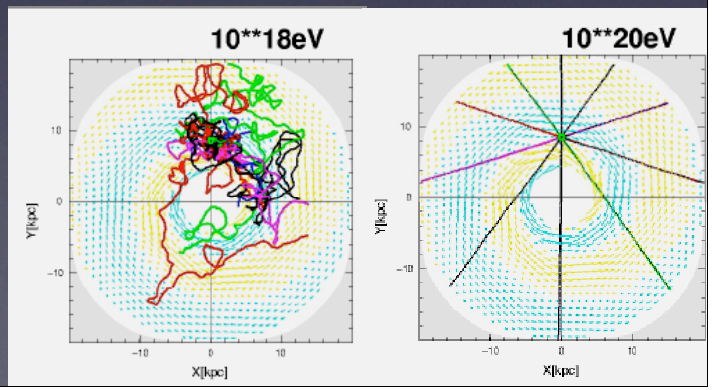


•Neutrons: decay γct = E/m ct ≈ 10 kpc for E ~EeV

•Photons: currently provide most information on the Universe but they are reprocessed in sources and interact during propagation with extra-galactic backgounds.
For E > 500 GeV they do not survive the journey from the Galactic Centre
•Protons: directions scrambled by the galactic and intergalactic magnetic fields

$$\vartheta \cong \frac{d}{R_{gyro}} = \frac{dB}{E} \Rightarrow \frac{\vartheta}{0.1°} = \frac{\left[\frac{d}{1Mpc}\right]\left[\frac{B}{1nG}\right]}{\left[\frac{E}{3\times 10^{20} eV}\right]}$$

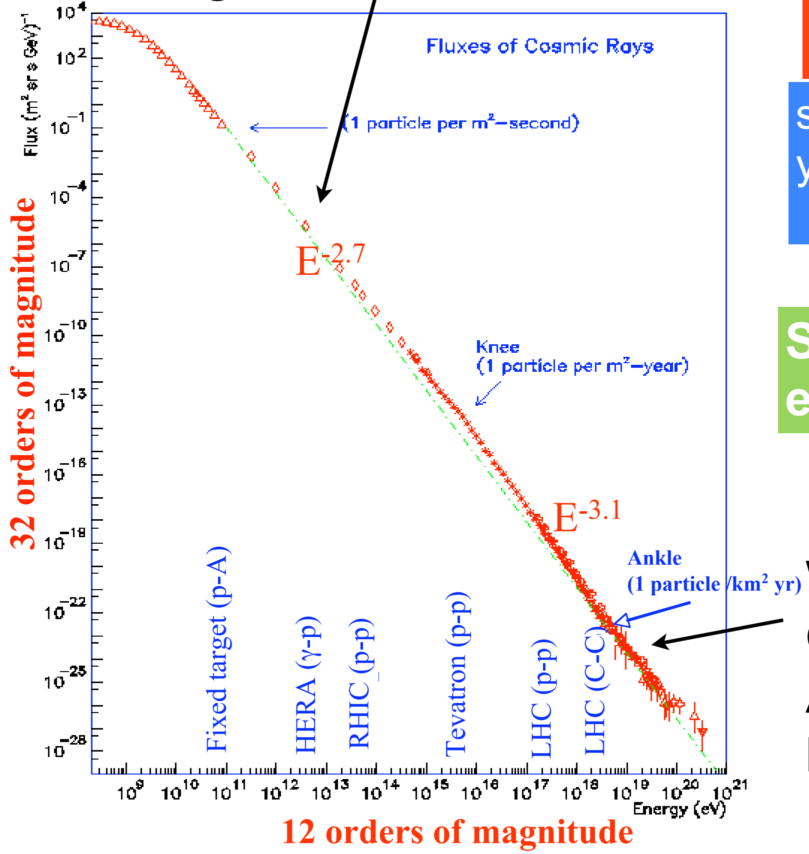




Cosmic Rays

1 TeV = 1.6 erg
1 EeV = 0.16 Joule

galactic



Below the knee (galactic CRs):

observed energy density of galactic CR: ~ 10^{-12} erg/cm^3

supernova remnants: 10^{50} ergs every 30 years
~10^{-12} erg/cm^3

SNRs provide the environment and energy to explain the galactic CRs!

Who are the sources of the highest energy CRs?
A 320 EeV CR has 50 J (energy of a tennis ball!)

The knee

- Acceleration cutoff E_{max}~ZBL~Z x100 TeV (SNR), change in acceleration mechanisms

- A-dependent knee (cannonball model) not preferred respect to Z (Kascade)
- Rigidity dependent cutoff due to confinement of CRs in the galaxy
- Change in interaction properties (eg. onset of a channel where energy goes into unseen

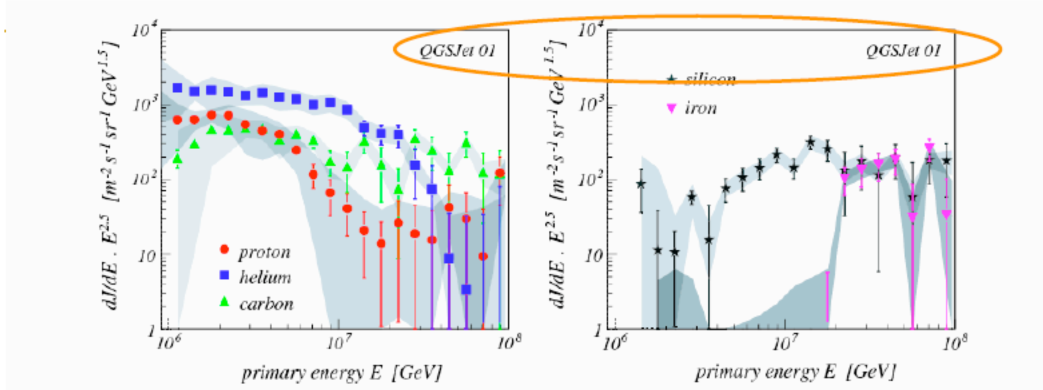


Fig. 14. Unfolded energy spectra for H, He, C (left panel) and Si, Fe (right panel) based on QGSJet simulations. The shaded bands are an estimate of the systematic uncertainties due to the used parameterizations and the applied unfolding method (Gold algorithm).

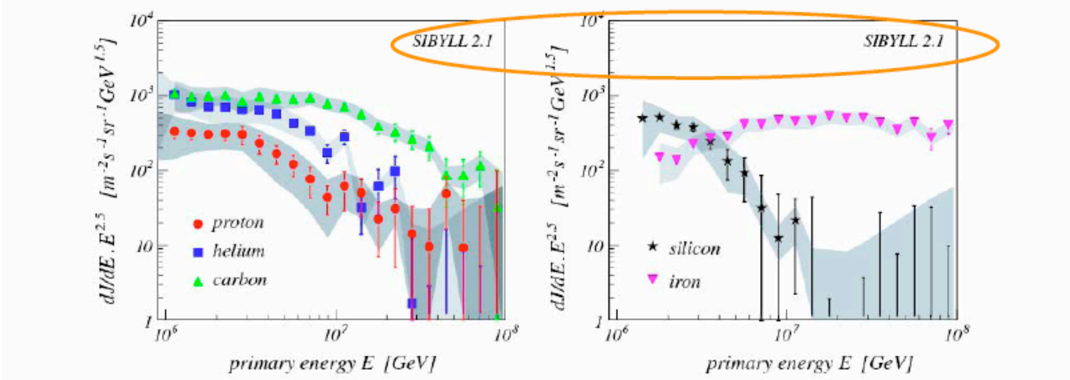
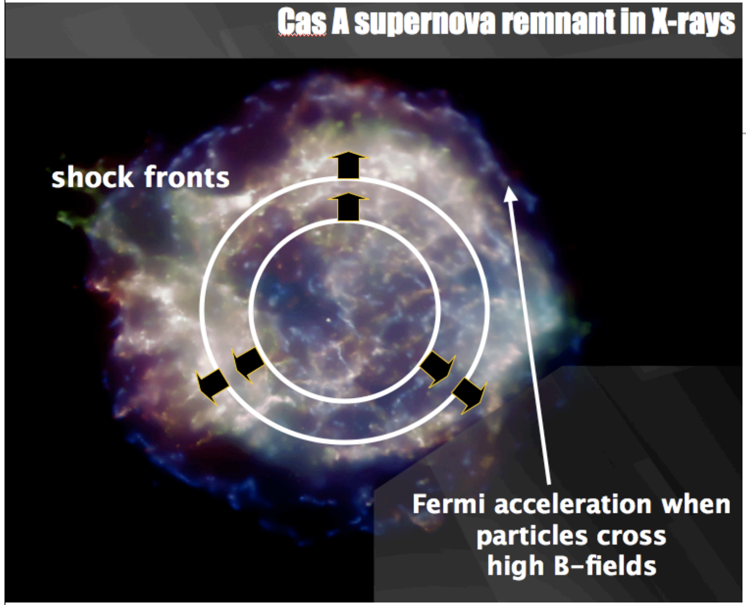


Fig. 15. Unfolded energy spectra for H, He, C (left panel) and Si, Fe (right panel) based on SIBYLL simulations. The shaded bands are estimates of the systematic uncertainties due to the used parameterizations and the applied unfolding method (Gold algorithm).

Observed knee for p at about 4000 TeV
Z dependent knee favored by data
Depends on interaction models

Supernova remnants and shock acceleration



In 1st order Fermi particles are efficiently accelerated since energy increases on both directions across shock

- conserve m,E,p across the shock front
- Energy gain crossing shock in either direction

A shock is a transition layer where the velocity field of the fluid suddenly decreases

Continuity equation (conservation of mass across shock): $\rho_1 v_1 = \rho_2 v_2$

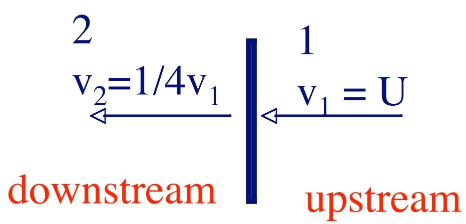
For ionized gas R= compression ratio = $\rho_2/\rho_1 = v_1/v_2 = 4$

4 gas theory

Increase of energy for particle crossing the shock front in both directions: $\Delta E/E \sim U/c$

1nd order in the velocity of the shock

Shock rest frame

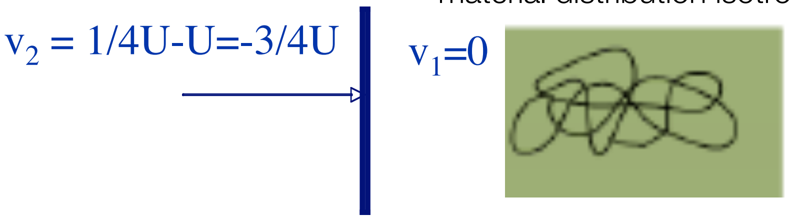


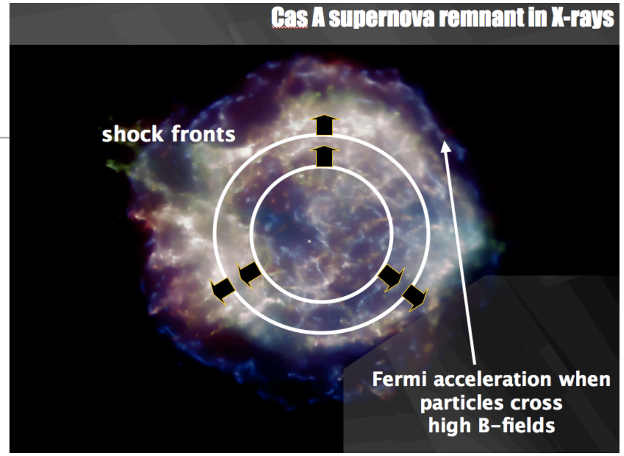
Shock front at rest: upstream gas flows into shock with velocity v_1 = U and leaves the shock with smaller velocity v_2 = U/4

Supernova remnants and shock acceleration

Upstream material rest frame

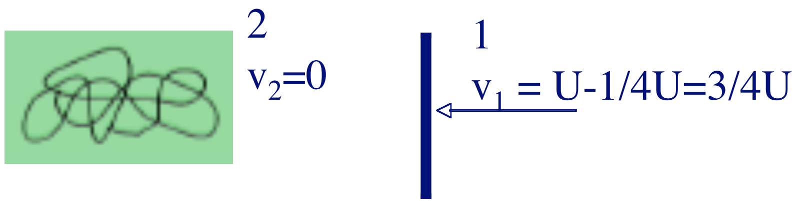
material distribution isotropic





Let's consider the particles upstream with the front. Here the particle distribution is isotropic. The shock advances through the medium at velocity U, but the gas behind the shock travels at velocity 3/4U relative to the upstream gas.
When a high energy particle crosses the shock front, it obtains a small increase in the energy of the order of
$\Delta E/E \sim U/c$

Downstream material frame



Let us consider the opposite process of a particle diffusing from behind the shock (downstream) to the upstream region. The velocity distribution of particles is isotropic downstream the shock and when they cross the shock front they encounter gas moving towards the shock front with the velocity 3/4U.
The particle undergoes exactly the same process of receiving a small increase in the energy on crossing the shock from downstream to upstream. So every time the particle crosses the shock it receives an increase of energy and the increment is the same in both directions

Increase of energy for particle crossing the shock front in both directions: $\Delta E/E \sim U/c$

Spectrum from 1st Fermi acceleration

Total flux of particles that cross the shock

$$\Phi_+ = \frac{1}{4\pi}\int d\Omega\, \Phi_i \cos\theta = \frac{\rho c}{4}$$

ρ = density of particles.
Flux of particles that cannot cross again the shock $\rho v_1 = \rho U$
So the fraction of particles lost is $(\rho U)/(1/4\rho c) \sim U/c$

- $(E-E_0)/E_0 \sim U/c \Rightarrow \beta = E/E_0 = 1+U/c$
- For U<<c (non relativistic shock) $\ln\beta = \ln(1+U/c) \sim U/c$
- Average particles lost across the shock ~ U/c
- Probability remains in acceleration region and will cross the shock again: $P \sim 1-U/c \Rightarrow \ln(1+P) \sim -U/c$ (U<<c)
- $\ln P/\ln\beta \sim -1$

integral spectral index

- After k collisions:

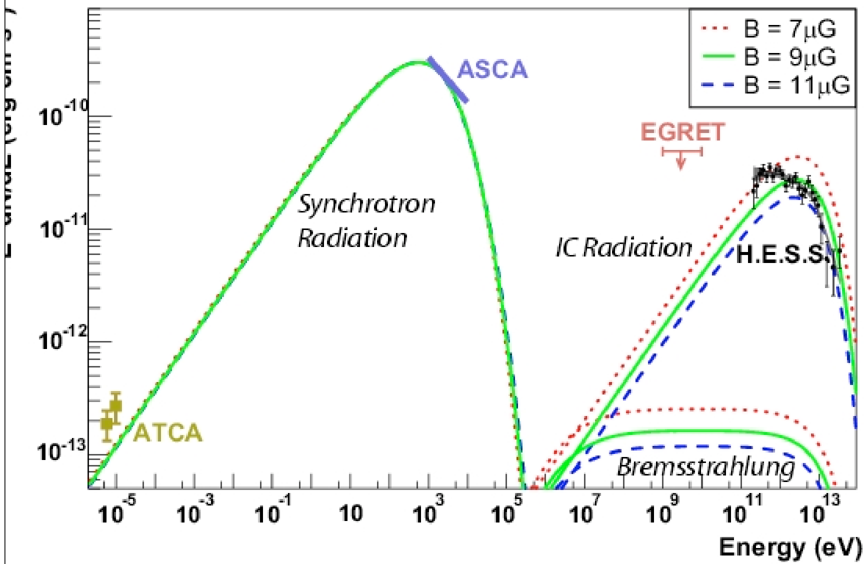
$$\left.\begin{aligned} \frac{E}{E_0} = \beta^k \Rightarrow k\ln\beta = \ln\frac{E}{E_0} \\ \frac{N}{N_0} = P^k \Rightarrow k\ln P = \ln\frac{N}{N_0} \end{aligned}\right\} \Rightarrow k = \frac{\ln\frac{E}{E_0}}{\ln\beta} = \frac{\ln\frac{N}{N_0}}{\ln P} \Rightarrow$$

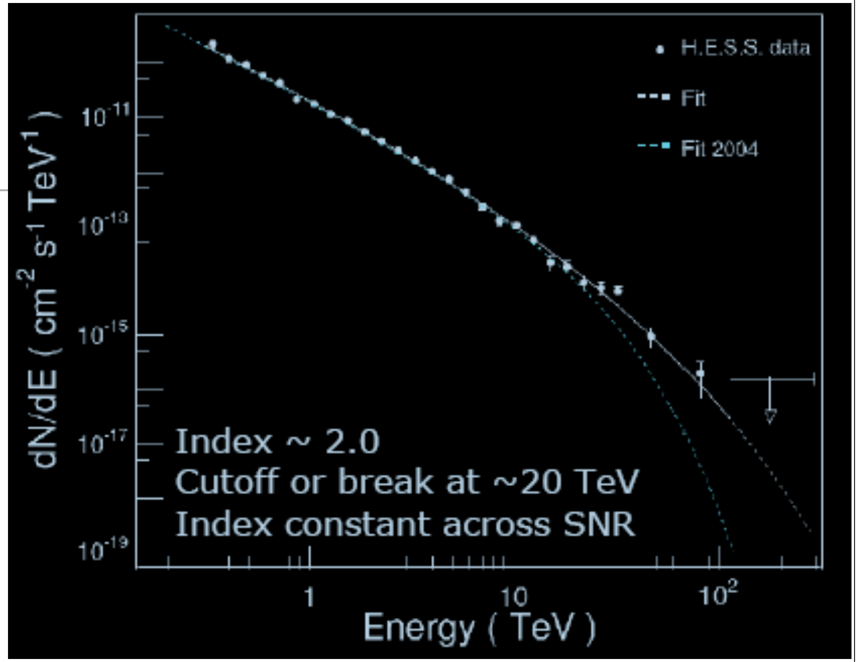
$$\ln\frac{N}{N_0} = \frac{\ln P}{\ln\beta}\times\ln\frac{E}{E_0} = \ln\left(\frac{E}{E_0}\right)^{\ln P/\ln\beta} \Rightarrow \frac{N}{N_0} = \left(\frac{E}{E_0}\right)^{\ln P/\ln\beta}$$

$$\text{differentiating } dN \propto E^{\ln P/\ln\beta - 1}dE \Rightarrow \boxed{\frac{dN}{dE} \propto E^{-2}}$$

RX J1713.7-39.46

IC model: B-field cannot exceed 10 μG and ...
does not provide good spectral fit





Electrons emit synchrotron radiation. Relativistic electrons make Inverse Compton scattering on ambient photons that are seen then at higher energies.

$$e^{\pm} + \gamma_{\text{basse énergie}} \longrightarrow e^{\pm} + \gamma_{\text{TeV}}$$

- Particles up to >100 TeV
- If hadrons
  primary energy >200 TeV
- If leptons
  primary energy >100 TeV (KN)

$$E_e^{max} = 2{,}3\,.10^4 \, \frac{v_1}{c} \left(\frac{B}{1\,G} \right)^{-\frac{1}{2}} \text{GeV}$$

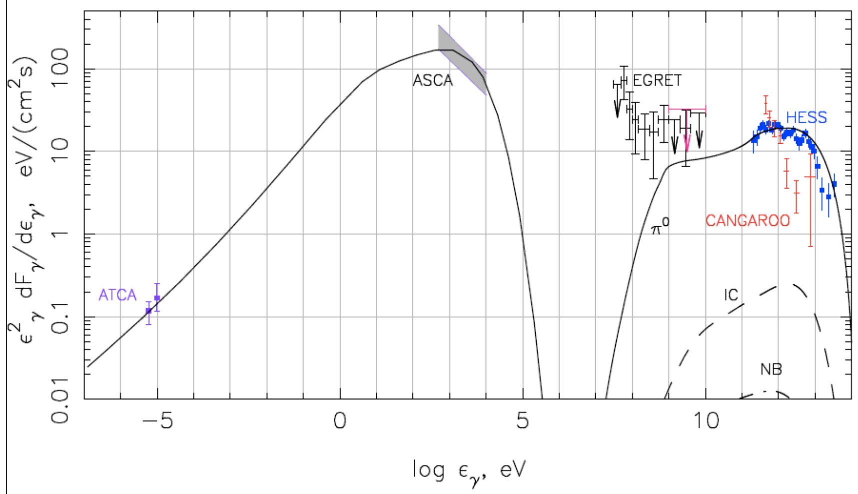
v_1=velocity of particle upstream shock

B ~ 10 μG et $v_1 \sim 10^8$ cm·s^{-1} 2,2.10^5 GeV

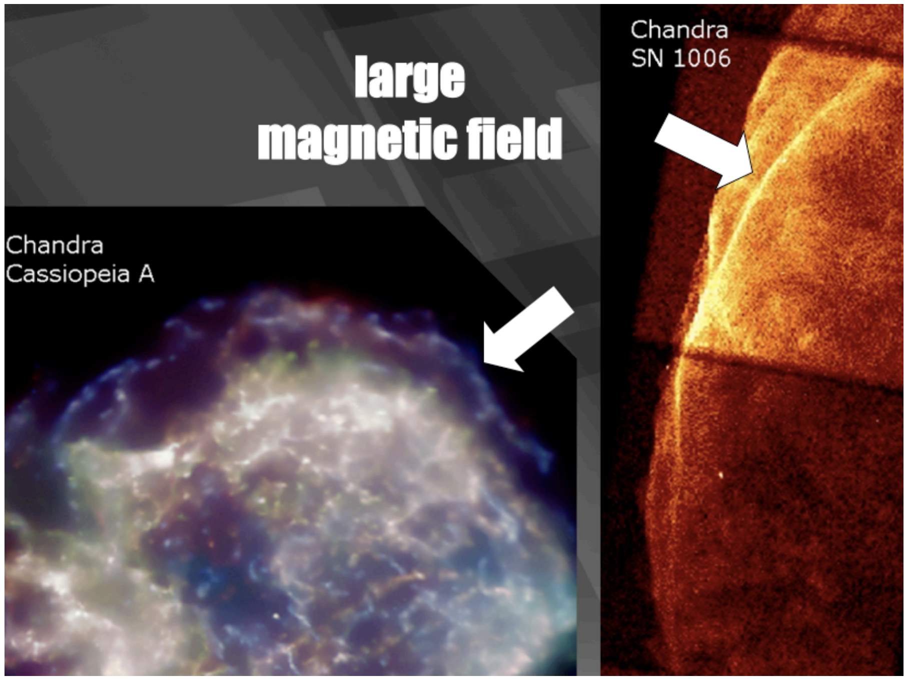
For high B-fields synch losses dominate over IC losses. Large $E_{e,max}$ (> 100 TeV) can be achieved only for B ≤ 10 μG

Hadrons in SNRs?

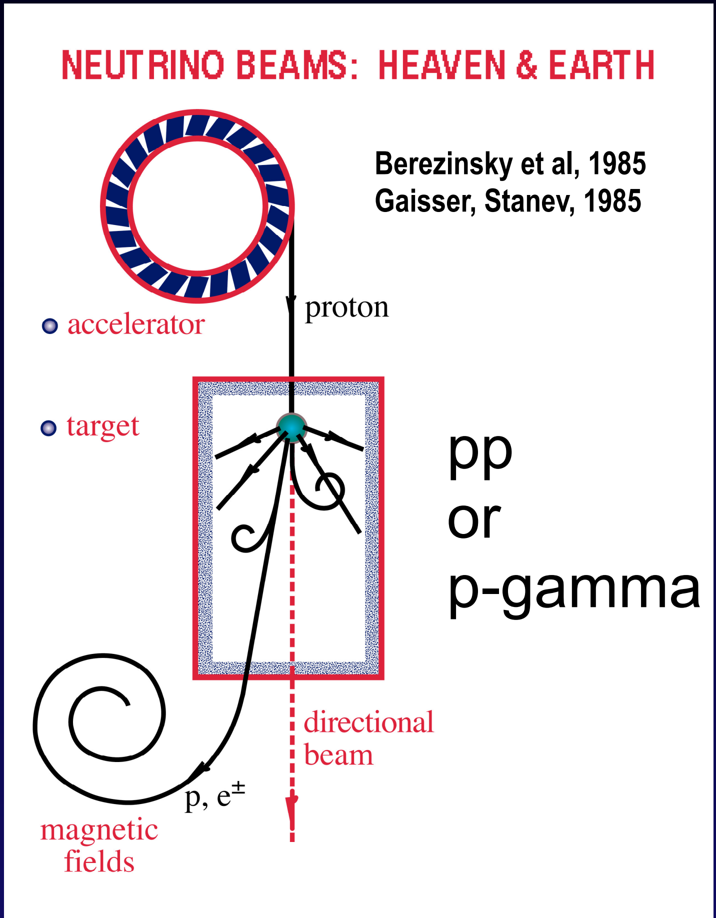
SED of RX J1713.7-3946
Berezhko, Volks ICRC2007
B-field required for fit is 126μG for pion production. In models with magnetic field amplification the energy at which SNR accelerate can be as high as Z x 10^3 TeV at early stages of SNR evolutions.

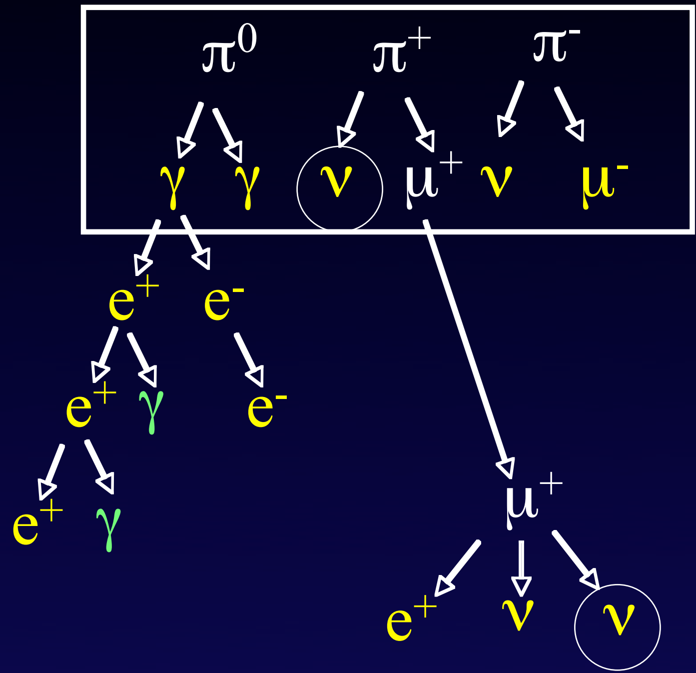


High resolution X-ray observations of SNR rims: brightness profiles connected to intensity of B-fields ~100μG



The generic source of neutrinos





Connection with gamma
Same order of magnitude for neutrino flux and gamma flux if no attenuation of gammas

Reminder on reaction thresholds

CM frame

m_t, p_t $\longrightarrow$ $\longleftarrow$ m_p, p_p

$$t + p \to M_1 + M_2 + \ldots + M_f$$

$$\sqrt{s} = \sum_f M_f = \sqrt{E_{tot}^2 - \vec{p}_{tot}^{\,2}}$$

$$E_{cm} = \sqrt{s}$$

energy of projectile available to
produce particles at rest in final state:

Lab frame (m_t at rest)

m_t $\circ$ $\longleftarrow$ m_p, p_p

$$E_{tot} = m_t + m_p + E_{k,p}$$

$$\vec{p}_{tot} = \vec{p}_p$$

True in any
ref frame

$$E_{tot} = E_k + m = \sqrt{\vec{p}^{\,2} + m^2}$$

$$E_k^2 + m^2 + 2mE_k = \vec{p}^{\,2} + m^2$$

$$\Rightarrow \quad E_{k,p}^2 = \vec{p}_p^{\,2} - 2m_p E_{k,p}$$

$$\left(\sum_f M_f\right)^2 = E_{tot}^2 - \vec{p}_{tot}^{\,2} = (m_t + m_p + E_{k,p})^2 - \vec{p}_p^{\,2} = (m_t + m_p)^2 + E_{k,p}^2 + 2(m_t + m_p)E_{k,p} - \vec{p}_p^{\,2} =$$

$$= (m_t + m_p)^2 + \vec{p}_p^{\,2} - 2m_p E_{k,p} + 2(m_t + m_p)E_{k,p} - \vec{p}_p^{\,2} = (m_t + m_p)^2 - 2m_p E_{k,p} + 2(m_t + m_p)E_{k,p} =$$

$$= (m_t + m_p)^2 + 2m_t E_{k,p} \Rightarrow E_{k,p} = \frac{(m_t + m_p)^2 - \left(\sum_f M_f\right)^2}{2m_t}$$

Alvarez-Muniz and Halzen ApJ 576 (2002)

The photon ⇔ neutrino connection

pp interactions

$$p + A \rightarrow \pi^0 + \pi^+ + \pi^-$$

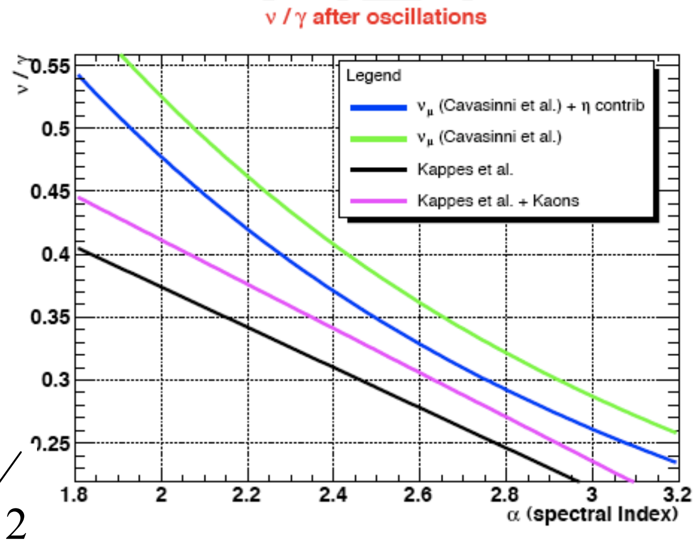
pions share p energy

$$\gamma\gamma \qquad \mu\nu_\mu$$

2 photons with: $E_\gamma \approx E_\pi/2 \approx E_p/6$ $\qquad e + 2\nu_\mu + \nu_e$

For each gamma 2 muon neutrinos with: $E_\nu \approx E_\pi/4 \approx E_p/12$

Hence energy in photons and gammas is the same:

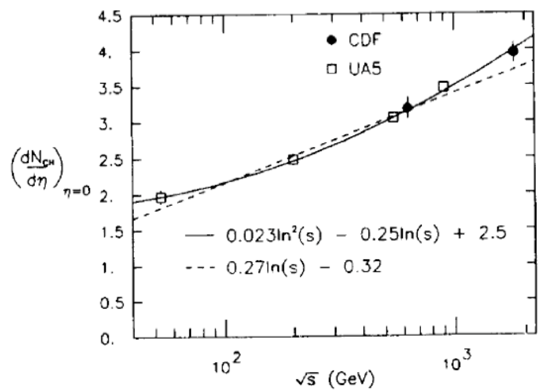


After oscillations: ν_μ/γ ~0.5

$$\int_{E_\gamma^{\min}}^{E_\gamma^{\max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} dE_\gamma = K \int_{E_\nu^{\min}}^{E_\nu^{\max}} E_\nu \frac{dN_\nu}{dE_\nu} dE_\nu,$$

K~0.5

particle multiplicity in pp



$$E_p^{\max} = 6E_\gamma^{\max}, \quad E_\nu^{\max} = \frac{1}{12}E_p^{\max},$$

$$p + p \rightarrow p + p + \pi^0$$

$$E_p^{\min} = \Gamma \frac{(2m_p + m_\pi)^2 - 2m_p^2}{2m_p} \simeq \Gamma \times 1.23\ \text{GeV}$$

$$p + p \rightarrow p + n + \pi^+$$

Minimum proton energy fixed by threshold for π production (Γ =E/m is the Lorentz factor of the p jet respect to the observer)

The photon $\Leftrightarrow$ neutrino connection

pγ interactions

$$1)\, p + \gamma \rightarrow \Delta^+ \rightarrow p\pi^0$$
$$2)\, p + \gamma \rightarrow \Delta^+ \rightarrow n\pi^+$$

BR = 2/3
BR = 1/3

E of gammas in lab (p at rest)

$$E_{k,p} = \frac{\left(\sum_f M_f\right)^2 - (m_t + m_p)^2}{2m_t} = \frac{(m_N + m_\pi)^2 - m_p^2}{2m_p} \sim 150 \text{ MeV}$$

$$E_\gamma = \gamma_p \varepsilon_\gamma = 150\text{MeV}$$

Energy of gammas p rest frame

Energy of gammas in CM

$$E_{p,thr} = \gamma_p m_p = 150\,MeV \times m_p / \varepsilon_\gamma = \left(\frac{1MeV}{\varepsilon_\gamma}\right) \times 150\,GeV$$

2 gammas with 2/3 x 0.1 E_p = 4/3 x 0.1 E_p
2 muon neutrinos (if muon decays) with 1/3 x 0.1E_p/2 = 1/3 x 0.1 E_p

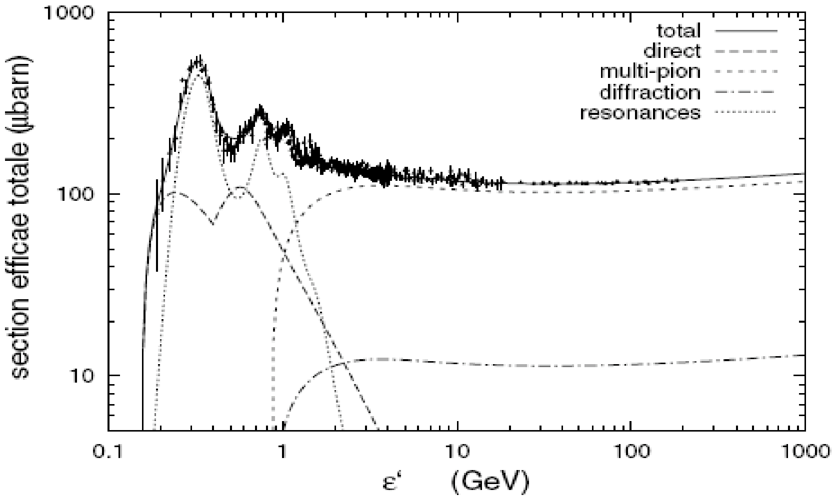
$$E_\gamma = \frac{E_p < x_{p\rightarrow\pi} >}{2} = 10\% E_p$$

$$E_\nu = \frac{E_p < x_{p\rightarrow\pi} >}{4} = 5\% E_p$$

$$< x_{p\rightarrow\pi} > \approx 0.2$$

$$\int_{E_{\gamma\,\min}}^{E_{\gamma\,\max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} dE_\gamma = K \int_{E_{\nu\,\min}}^{E_{\nu\,\max}} E_\nu \frac{dN_\nu}{dE_\nu} dE_\nu$$

K = 2 after oscillations are accounted for



Halzen and Hooper, astro-ph/0502449

Current scenario

Giunti

- The relation between flavor states and mass ones containes a 3 x 3 matrix V = U A, A relevant only if neutrino is Majorana and U = MNSP matrix

B. Pontecorvo, Sov. Phys. JETP **7**, 172 (1958) [Zh. Eksp. Teor. Fiz. **34**, 247 (1957)].
Z. Maki, M. Nakagawa and S. Sakata, Prog. Theor. Phys. **28** 870 (1962)

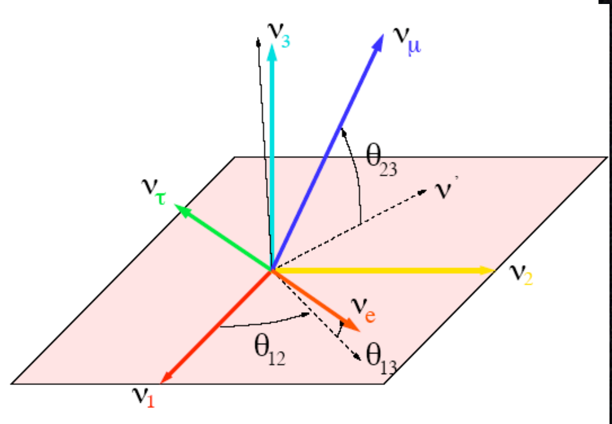
$$A = \begin{pmatrix} e^{i\alpha} & 0 & 0 \\ 0 & e^{i\beta} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

solar U_{e1}, U_{e2} $\leftrightarrow \theta_{12}$ CHOOZ U_{e3} $\leftrightarrow \theta_{13}$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

atmospheric U_{e3} $\leftrightarrow \theta_{13}$ $U_{\mu 3}$,$U_{\tau 3}$ $\leftrightarrow$ θ_{23}

$s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$

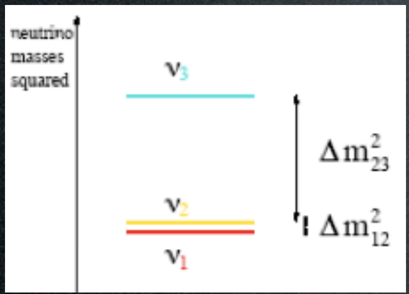


Neutrino scenario depends on 3 angles $(\theta_{12}, \theta_{23}$ and $\theta_{13})$, 2 square mass differences $(\Delta m^2_{12}$ and $\Delta m^2_{23})$ and a CP violation phase δ

Astrophysical neutrino oscillations

$$P(\nu_\alpha \to \nu_\beta) = \sum_i |U_{\alpha,i}|^2 |U_{\beta,i}|^2 + 2\sum_{i<j} U_{\alpha,i}U_{\beta,i}U_{\alpha,j}U_{\beta,j}\cos\left(\frac{\Delta m^2_{ij} L}{2E}\right).$$

$$\Delta m^2_{31} \sim \Delta m^2_{32} \gg \Delta m^2_{21}$$



$2\text{x}10^{-3}$ eV^2 atmospheric

$7\text{x}10^{-5}$ eV^2 solar

$\vartheta_{13} = 0$

$$\varphi \sim 3\cdot 10^8 \left(\frac{\Delta m^2}{8\cdot 10^{-5}\ \text{eV}^2}\right)\left(\frac{\text{L}}{1\ \text{kpc}}\right)\left(\frac{10\ \text{TeV}}{E_\nu}\right)$$

For astrophysical source @1 kpc emitting νs of 10 TeV:
COSφ averages to zero since the extension of sources about 1 pc and distance 1 kpc so L known with precision 1/1000 not 1/10^8

$$P(\nu_\alpha \to \nu_\beta) = \sum_i |U_{\alpha,i}|^2 |U_{\beta,i}|^2$$

$\nu_\alpha \backslash \nu_\beta$	ν_e	ν_μ	ν_τ
ν_e	60%	20%	20%
ν_μ	20%	40%	40%
ν_τ	20%	40%	40%

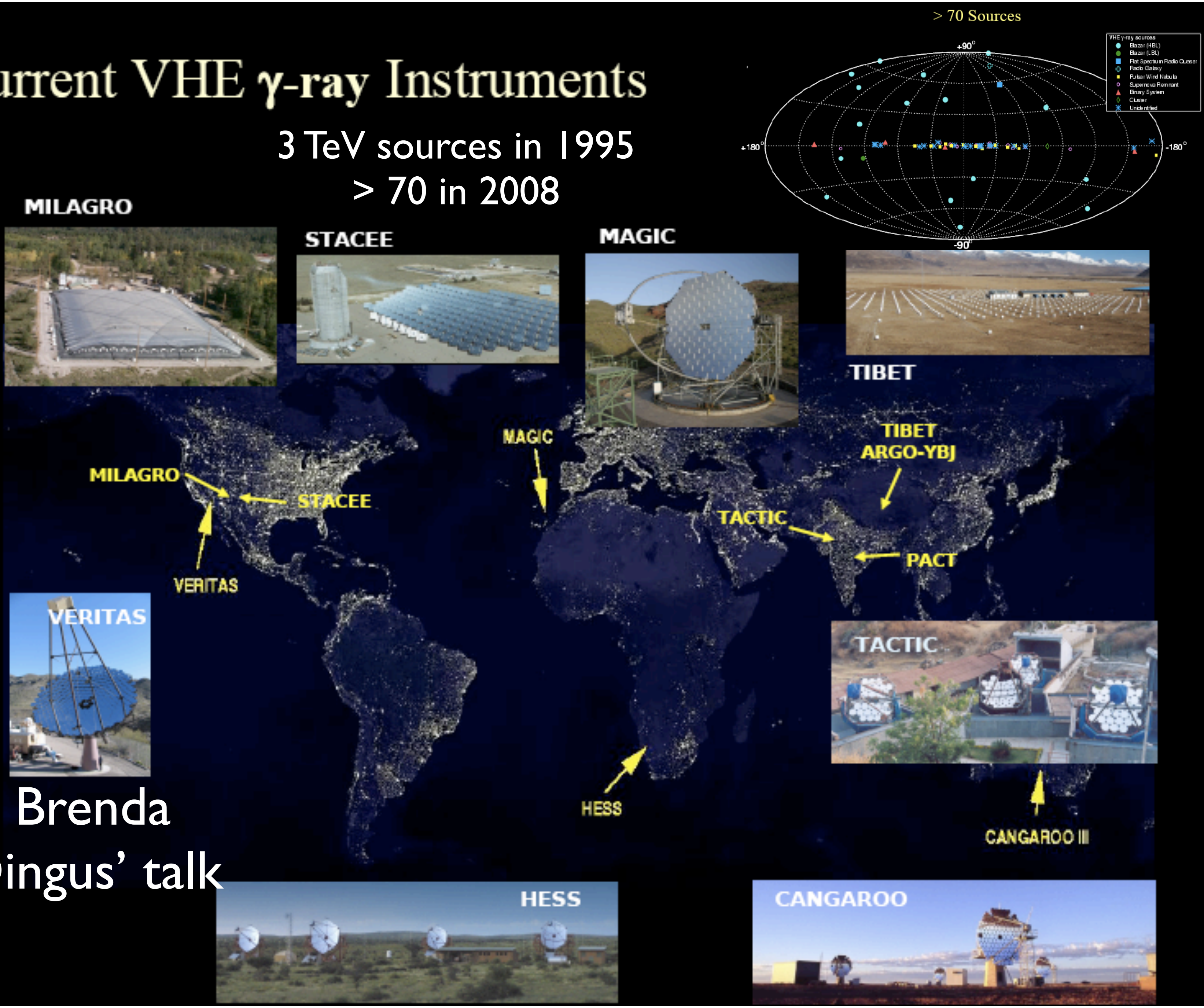
$$P(\nu_e \to \nu_e) = \sum_i |U_{ei}|^2 |U_{ei}|^2 = |U_{e1}|^4 + |U_{e2}|^4 + |U_{e3}|^4 = 0.82^4 + 0.57^4 + 0 = 0.56$$

$$P(\nu_e \to \nu_\mu) = \sum_i |U_{ei}|^2 |U_{\mu i}|^2 = |U_{e1}|^2|U_{\mu 1}|^2 + |U_{e2}|^2|U_{\mu 2}|^2 + |U_{e3}|^2|U_{\mu 1}|^2 = 0.82^2\cdot 0.4^2 + 0.57^2\cdot 0.58^2 + 0 = 0.22$$

$$P(\nu_e \to \nu_\tau) = \sum_i |U_{ei}|^2 |U_{\tau i}|^2 = |U_{e1}|^2|U_{\tau 1}|^2 + |U_{e2}|^2|U_{\tau 2}|^2 + |U_{e3}|^2|U_{\tau 1}|^2 = 0.82^2\cdot 0.4^2 + 0.57^2\cdot 0.58^2 + 0 = 0.22$$

Current VHE γ-ray Instruments

3 TeV sources in 1995
> 70 in 2008



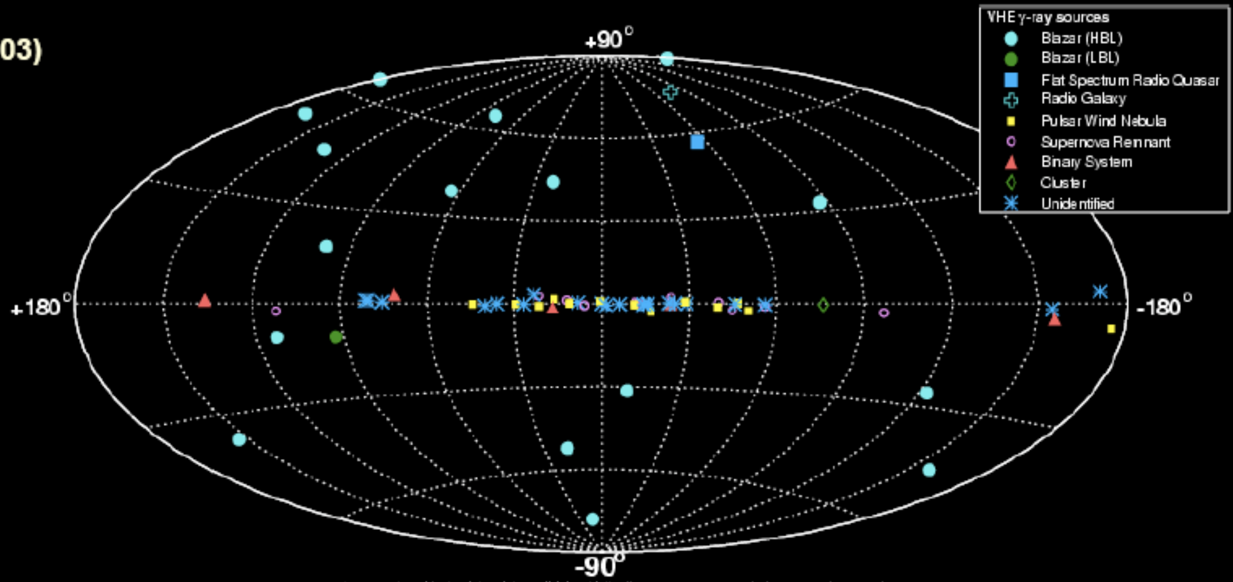
Brenda Dingus' talk

TeV Sky 2008

GALACTIC :

- Young Shell type Supernova Remnants
- Older and/or Interacting SNRs
- Composite SNRs
- Pulsar Wind Nebulae (PWN)
- Binary Systems (LS 5039, LSI +61 303)
- Variable PWN in binary
- Open Stellar Clusters
- Galactic Center
- Galactic diffuse emission
- Unidentified sources ...

> 70 Sources



2007-09-15 - Up-to-date plot available at http://www.mppmu.mpg.de/~rwagner/sources/

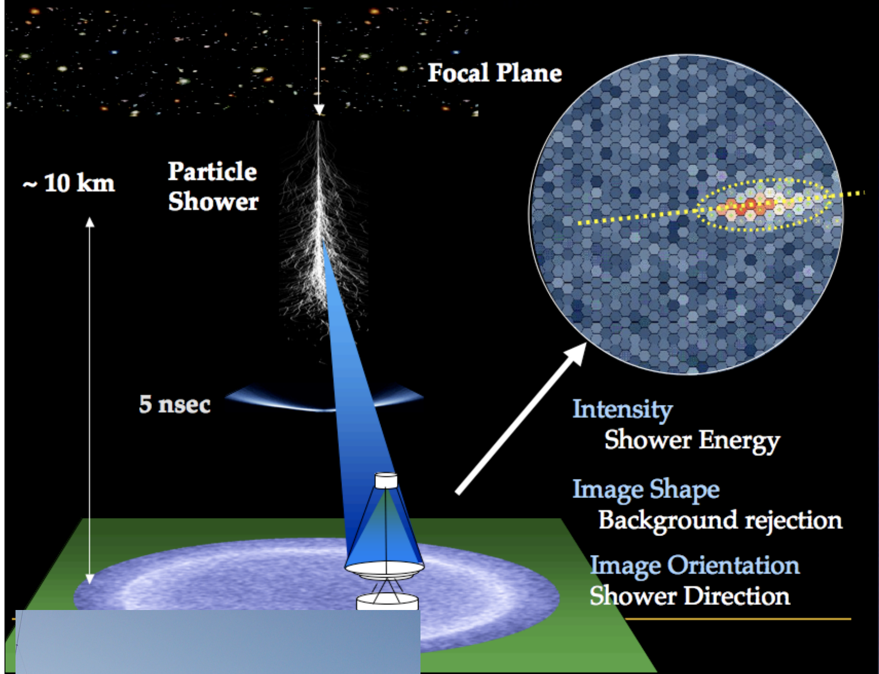
EXTRAGALACTIC :

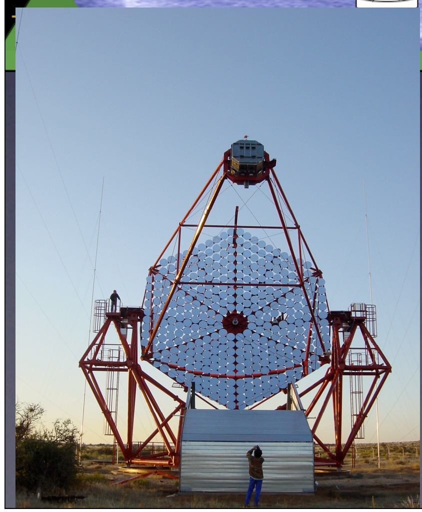
- Blazars
- Radiogalaxies (FRII: M87+?)
- Flat Spectrum Radio Quasars (3C 273, recent)
- Extragalactique Background Light (EBL)
- Multiwave-length campains
- Starburst Galaxies (UL)
- GRBs (UL)
- ...

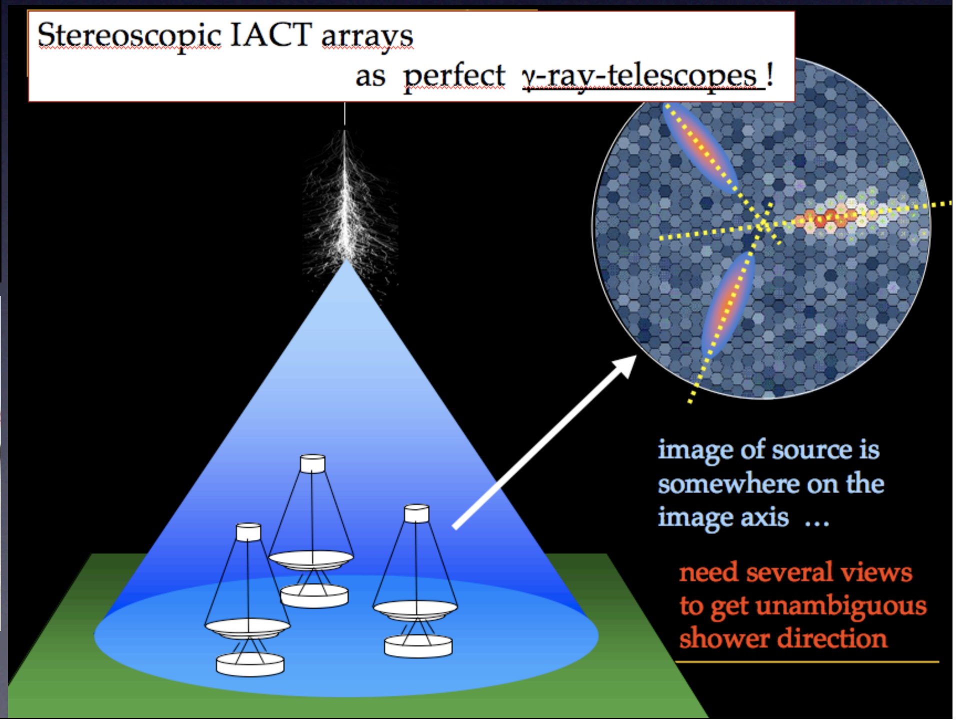
www.tevcat.uchicago.edu

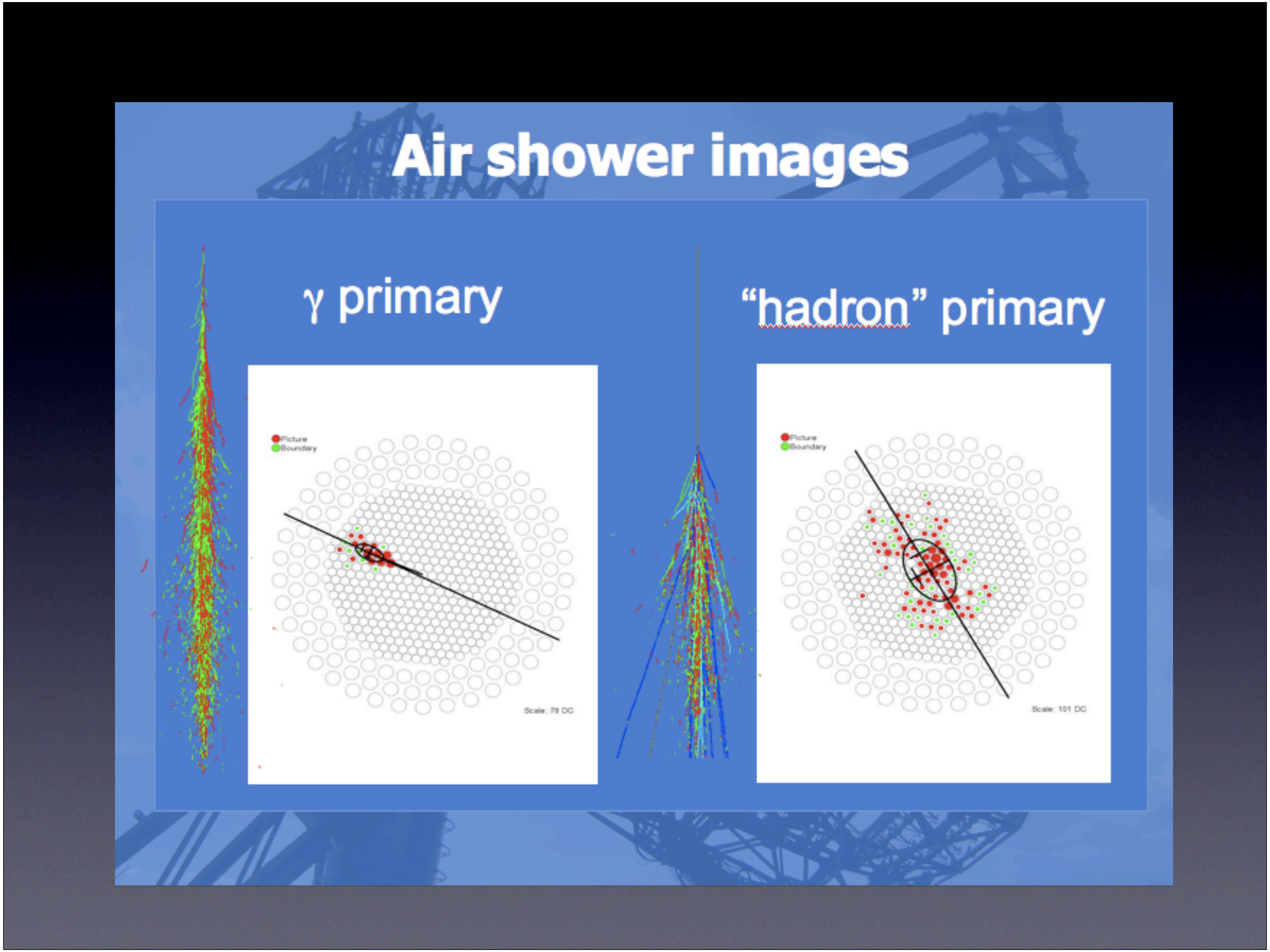
Detection technique of IACT

1Crab = 3 x 10^{-11} erg/cm^{2}s
=1.9 x 10^{-11} TeV/cm^{2}s (100 GeV-10 TeV)
1 TeV = 1.6 erg



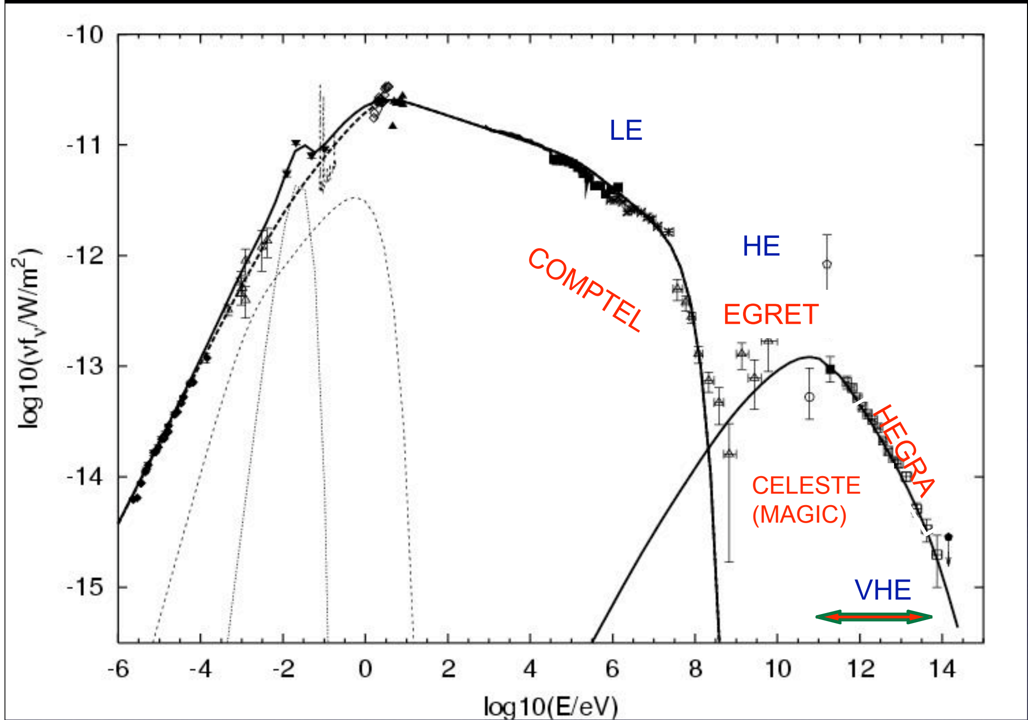


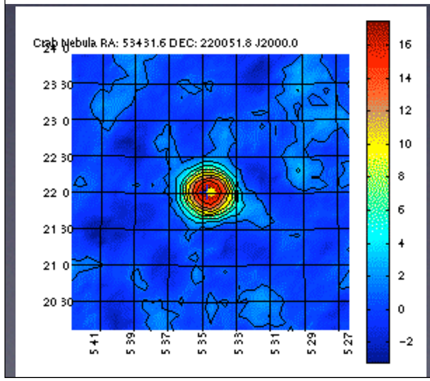




Air shower images
γ primary
"hadron" primary
Picture
Boundary
Scale: 78 DC
Picture
Boundary
Scale: 101 DC

Standard Candle: Crab





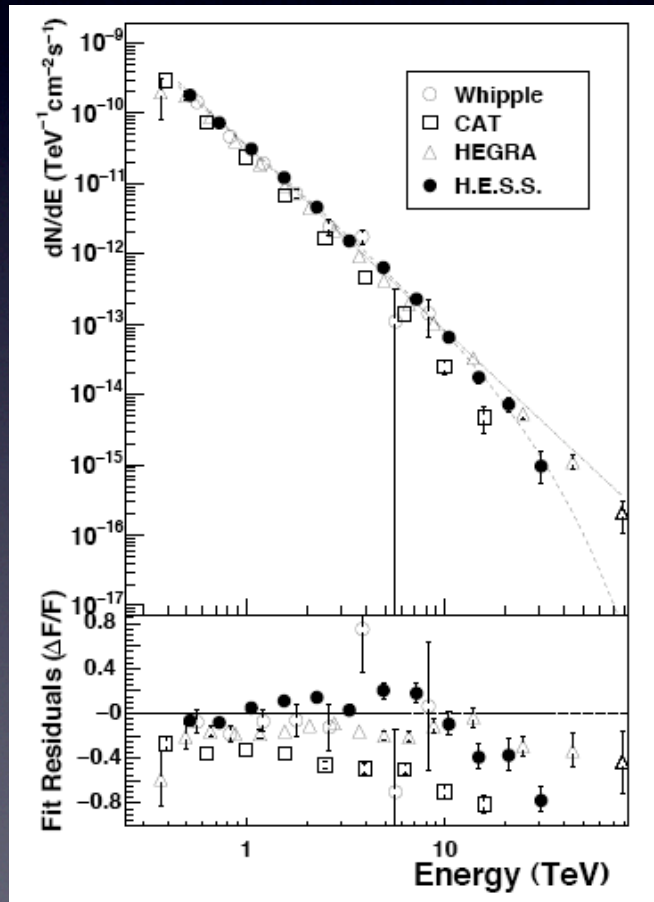
HESS 2006

cut-off at 14.3 ±2.1stat ± 2.8sysTeV

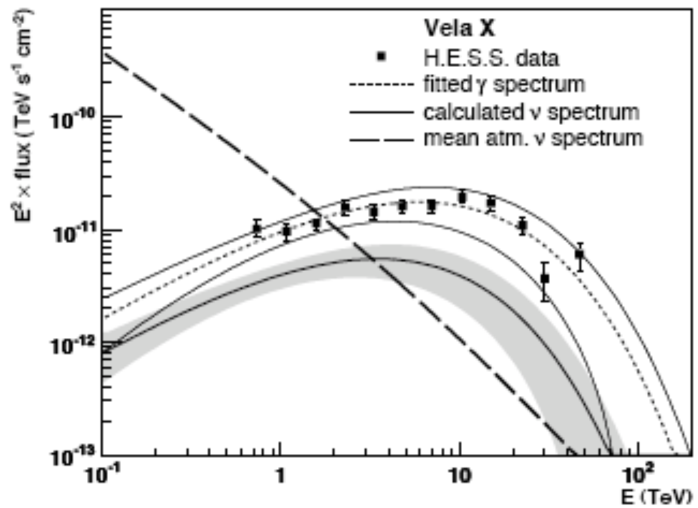
spectral index = 2.39 ± 0.03stat ±0.09sys

flux > 1 TeV

2.26 ± 0.08stat ± 0.45sys x 10^{-11} cm^{-2} s^{-1}



Neutrino fluxes from SNRs



a SNR at d = 1 kpc transfers W = 10^{50} erg
to cosmic rays interacting with molecular clouds
with density n = 1 cm^{-3}

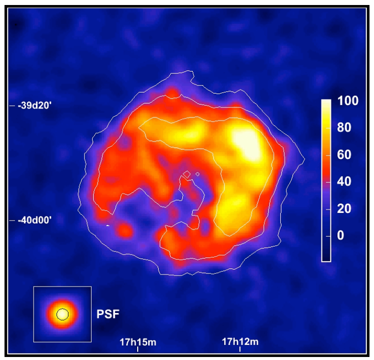
$$E\frac{dN_\gamma}{dE}(>1\,TeV) =$$

$$= 10^{-11} \sim 10^{-12}\,\frac{photons}{cm^2 s}\,\frac{W}{10^{50}\,erg}\,\frac{n}{1\,cm^3}\left(\frac{d}{1\,kpc}\right)^{-2}$$

km^3 detector
5 yr

$$\frac{dN_\nu}{dt} = \int dE_\nu\, A_\nu^{\rm eff}\,\frac{dN_\nu}{dE_\nu}$$

$$\boxed{\frac{dN_\nu}{dE_\nu} = A_\nu \cdot E_\nu^{-\alpha_\nu} \cdot \exp\left(-\frac{E_\nu}{E_{\max}}\right)}$$



cut-off in gamma may be due to absorption not only acceleration mechanism

Kappes et al, astro-ph/0607286
pp - interactions