Neutrino Astronomy

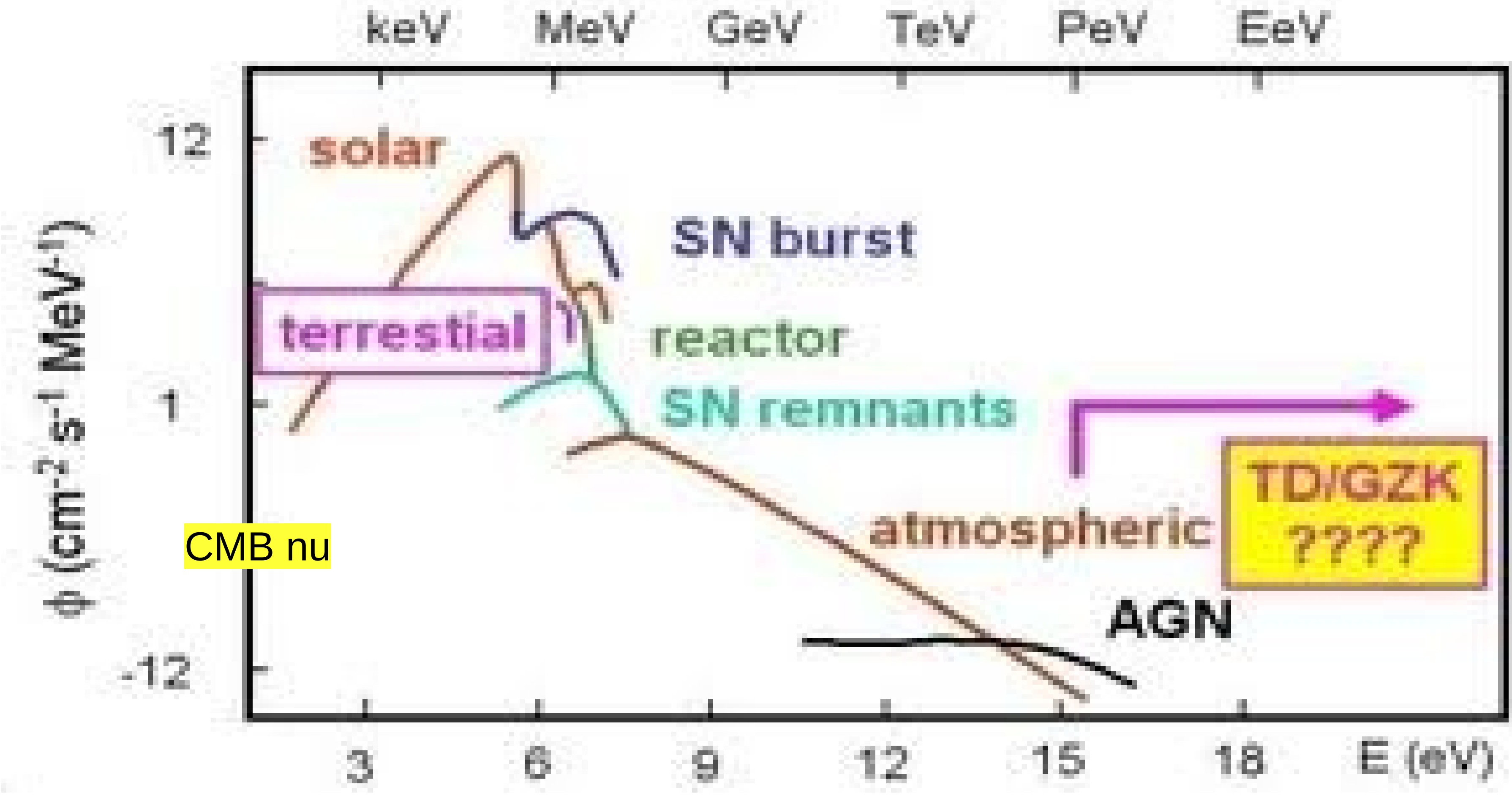
- + Neutrinos penetrate the whole Universe
- + Neutrinos point back to the source
- + Neutrinos are produced at the sources of the cosmic rays
- + Neutrinos are not reprocessed at the sources
- + Neutrinos expected from dark matter particle annihilation

- - Low expected flux of extragalactic neutrinos
- - Small cross section
- => - Needs gigantic detector volumes
- Backgrounds: Atmospheric Neutrinos, Atmospheric Muons, Prompt charm decays

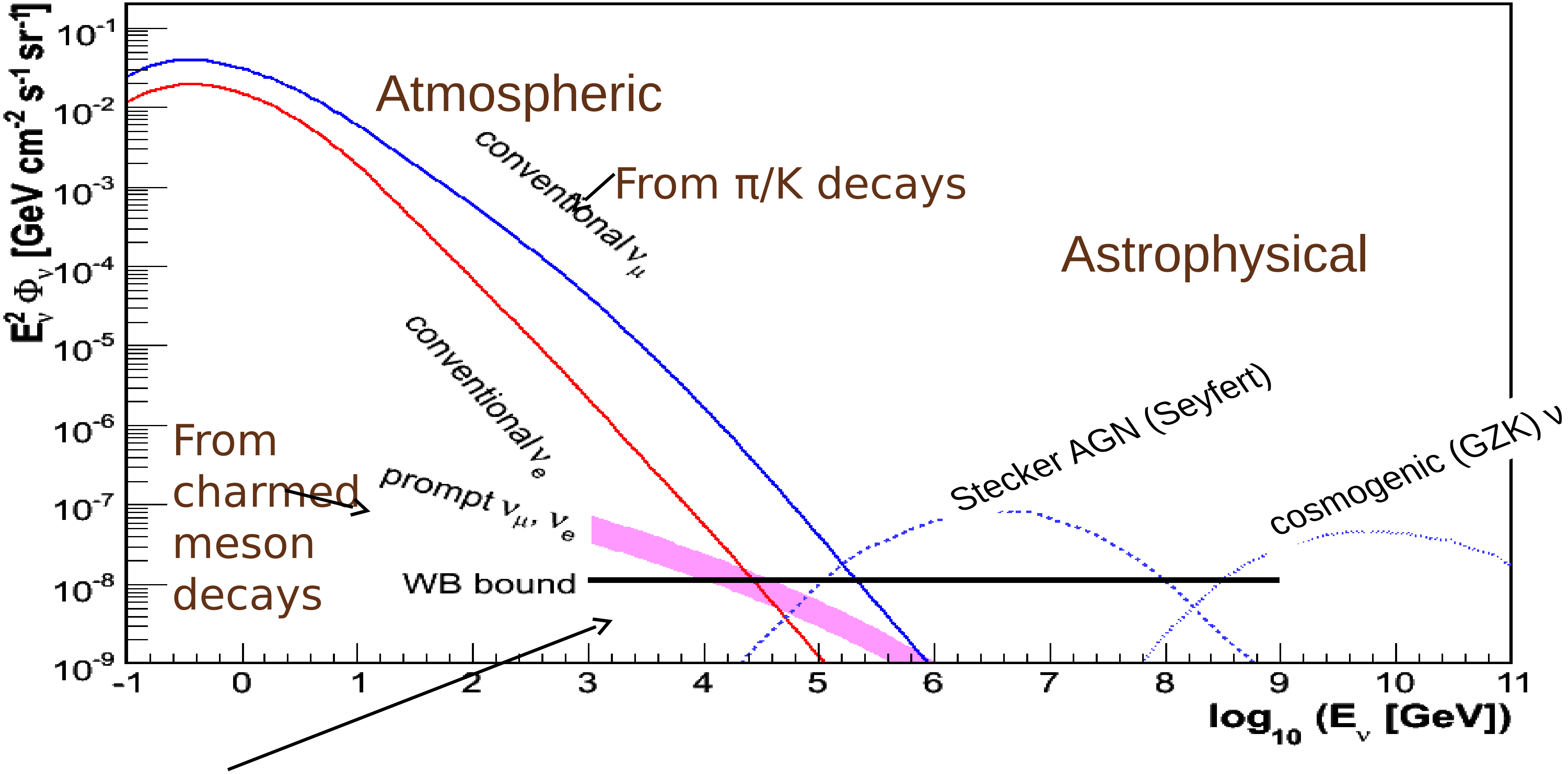
Sources of neutrinos

- “Low energy” - Big Bang Neutrinos (BBN), 300 per cubic centimeter, 13 billion years old. E~.001 eV
- “Medium energy” - Solar neutrinos, 60 billion per thumb per second.
  - On average, only one will be stopped by biomass per lifetime.
    - Aside: ^{40}K neutrinos in salt=>each person emits 200 million neutrinos per day
- “High energy” - Supernova neutrinos, 10^{15} eV, $1/m^2/sec$
- “Ultra-High energy **neutrinos**” – 10^{20} eV - blazar/GRB/topological defect neutrinos: $1/km^2/year$

What does the expected Neutrino flux look like?

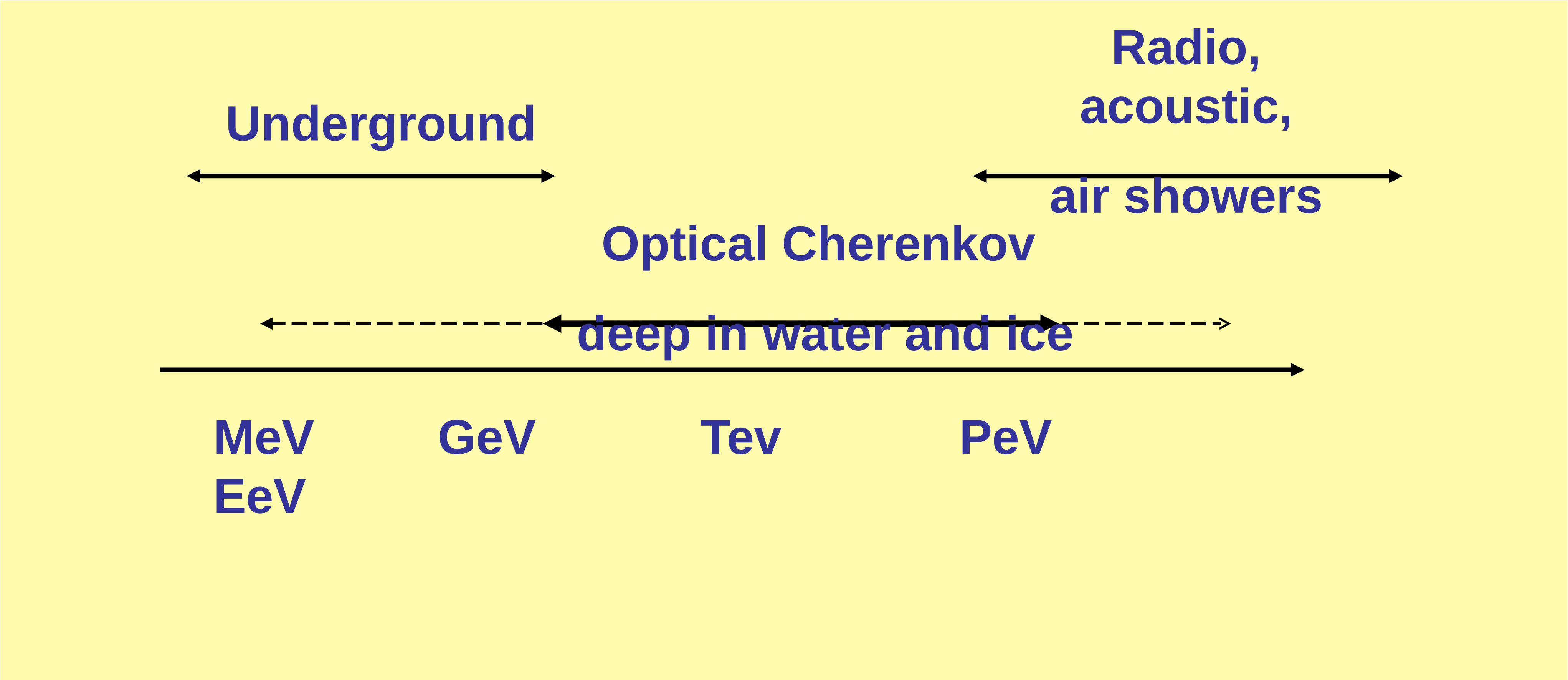


Neutrino Fluxes at Earth: expectations



Waxman-Bahcall upper “bound” for neutrinos derived from CR flux

Different energy range for detectors



If neutrons can escape:
Source of cosmic rays

Neutrinos produced in ratio $(\nu_e:\nu_\mu:\nu_\tau)=(1:2:0)$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$p + \gamma_{\rm CMB} \rightarrow \Delta^+ \rightarrow$$ Cosmogenic neutrinos

$$\pi^+ \rightarrow \mu^+ + \nu_\mu ,$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Delta resonance approximation:

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

π^+/π^0 determines ratio between neutrinos and gamma-rays

$$\pi^0 \rightarrow \gamma + \gamma$$

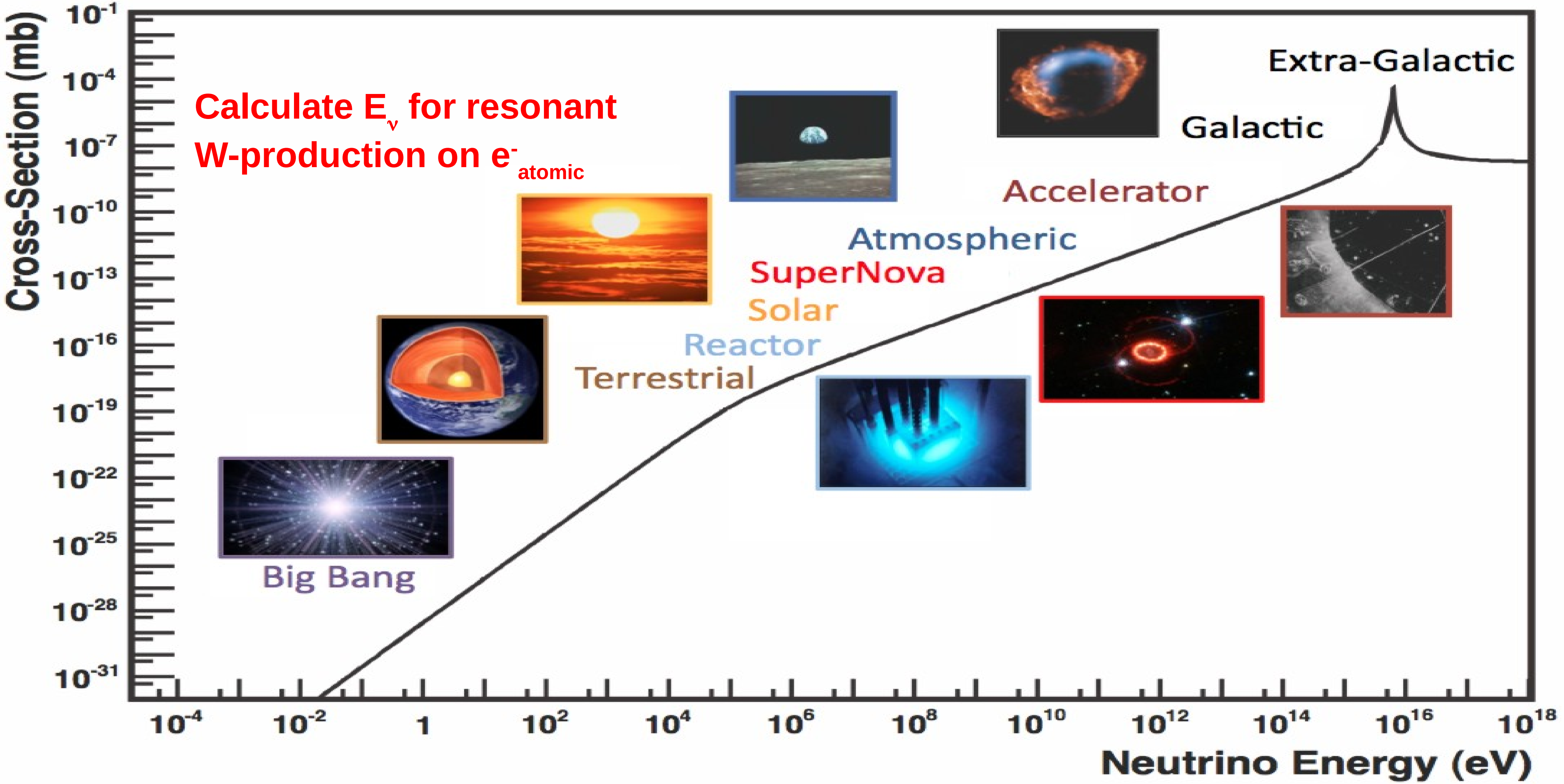
Cosmic messengers

High energetic gamma-rays;
might cascade down to lower E

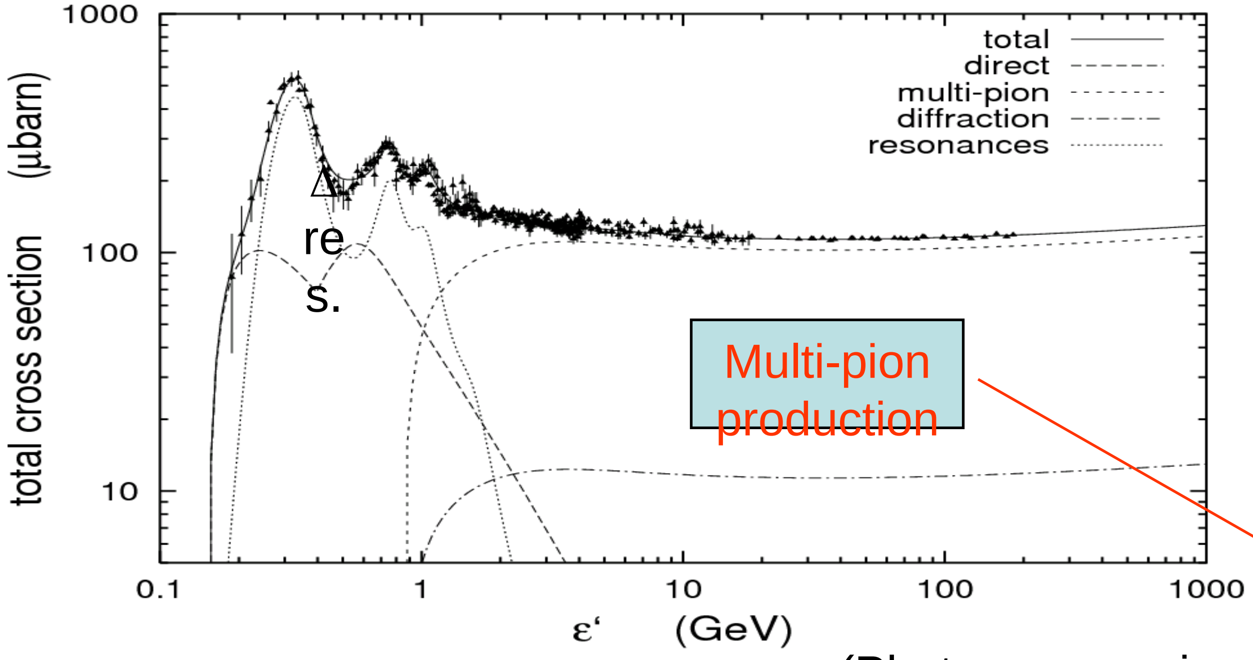
Photohadronic features

For detection rates, must fold in Neutrino Cross-Section (note Glashow resonance)

Calculate E_ν for resonant W-production on e^-_{atomic}



Photohadronics (more realistic)



Multi-pion production

(Photon energy in nucleon rest frame)

Resonant production, direct production

Different characteristics (energy loss of protons; energy dep. cross sec.)

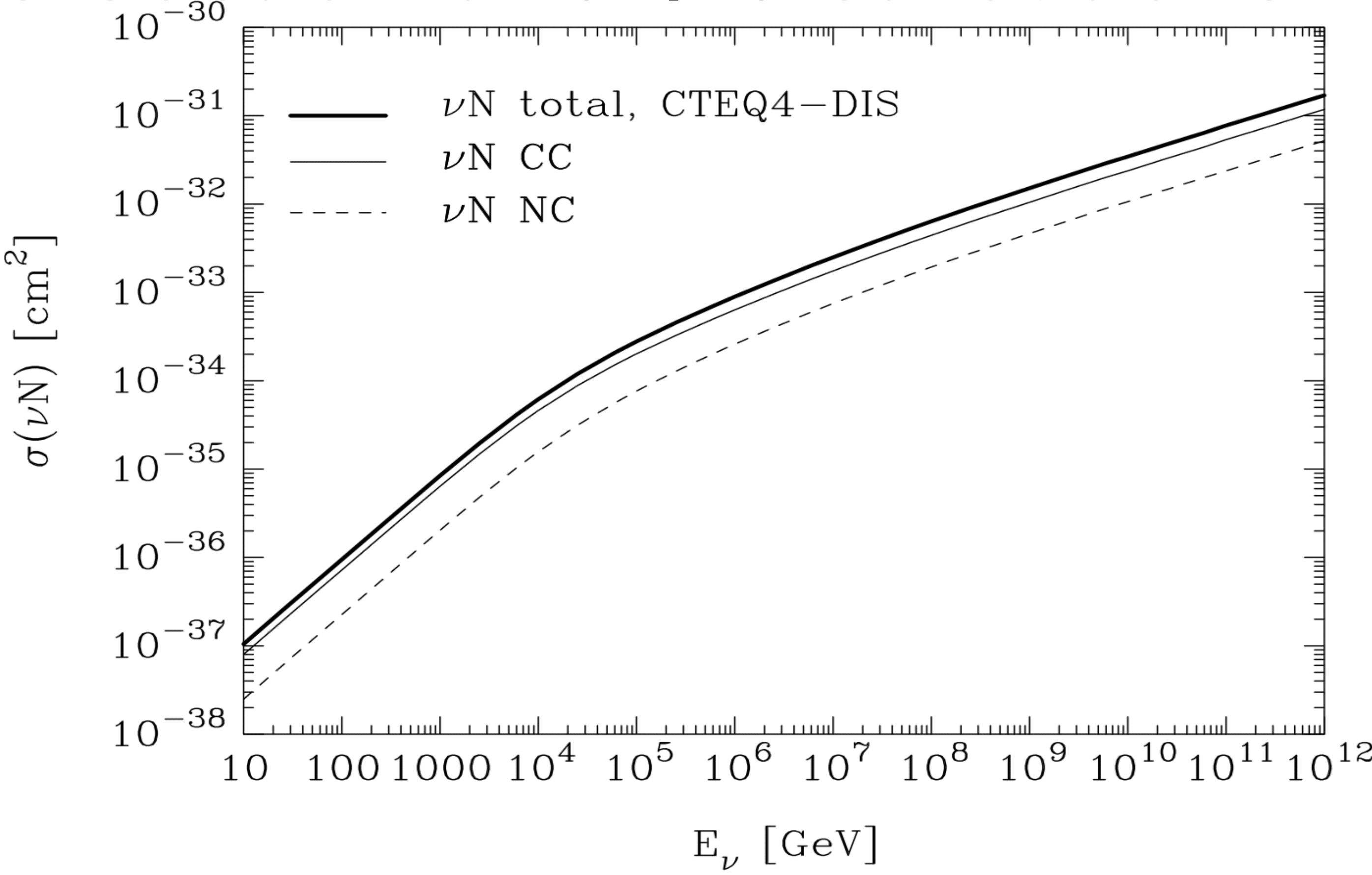
(Mücke, Rachen, Engel, Protheroe, Stanev, 2008; **SOPHIA**)

Neutrino cross-section and ν-distributions

For $E_\nu < 10^4$ GeV the x-section rises linearly with the energy

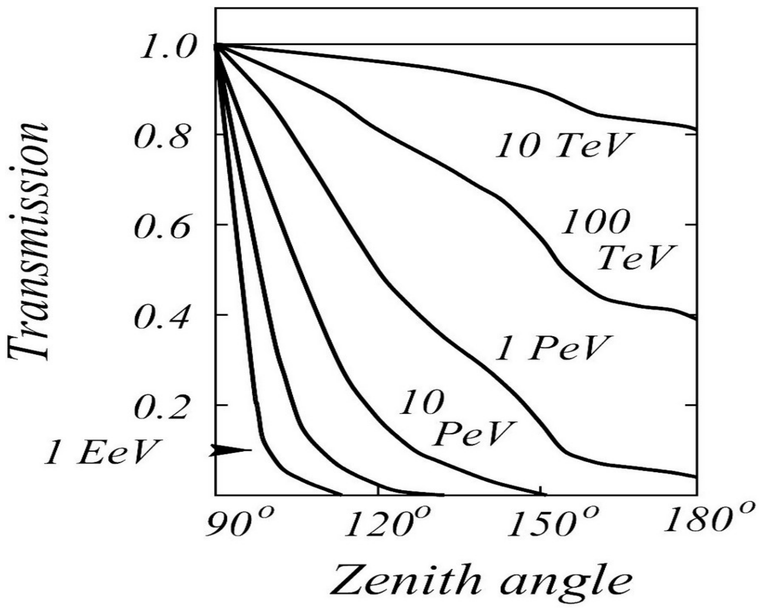
For $E_\nu > 10^4$ GeV (due to the W-boson propagator:

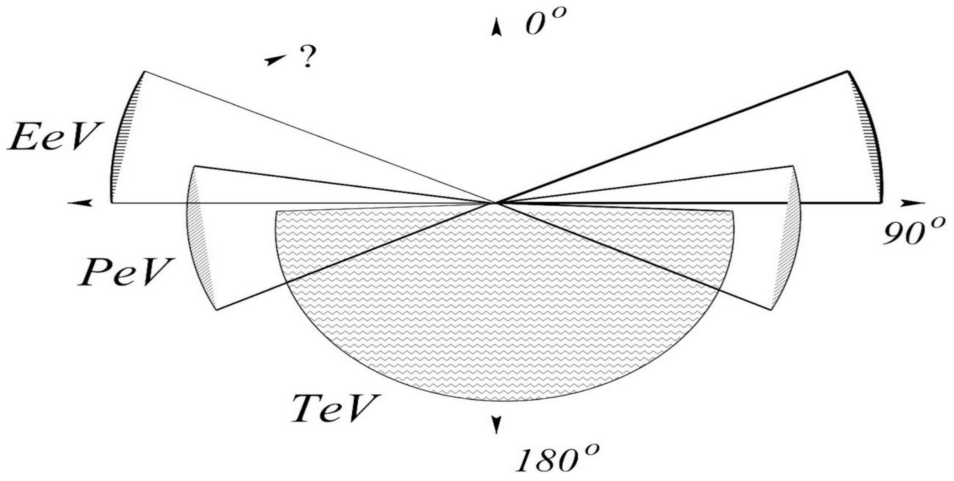
$$\sigma_{tot}(\nu N) = 7.84 \times 10^{-36} cm^2 \left(\frac{E_\nu}{1GeV}\right)^{0.363}$$



Cross-section measured up to 300 GeV. Up to about 10 TeV based on structure functions from HERA. Above different extrapolations.

Shadowing effect of the Earth



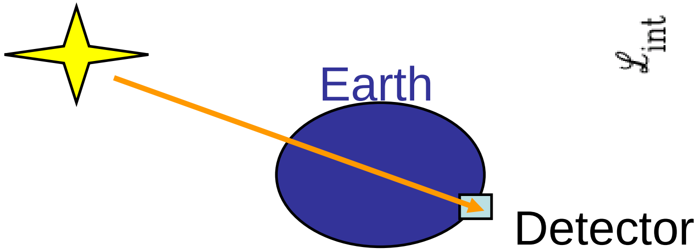


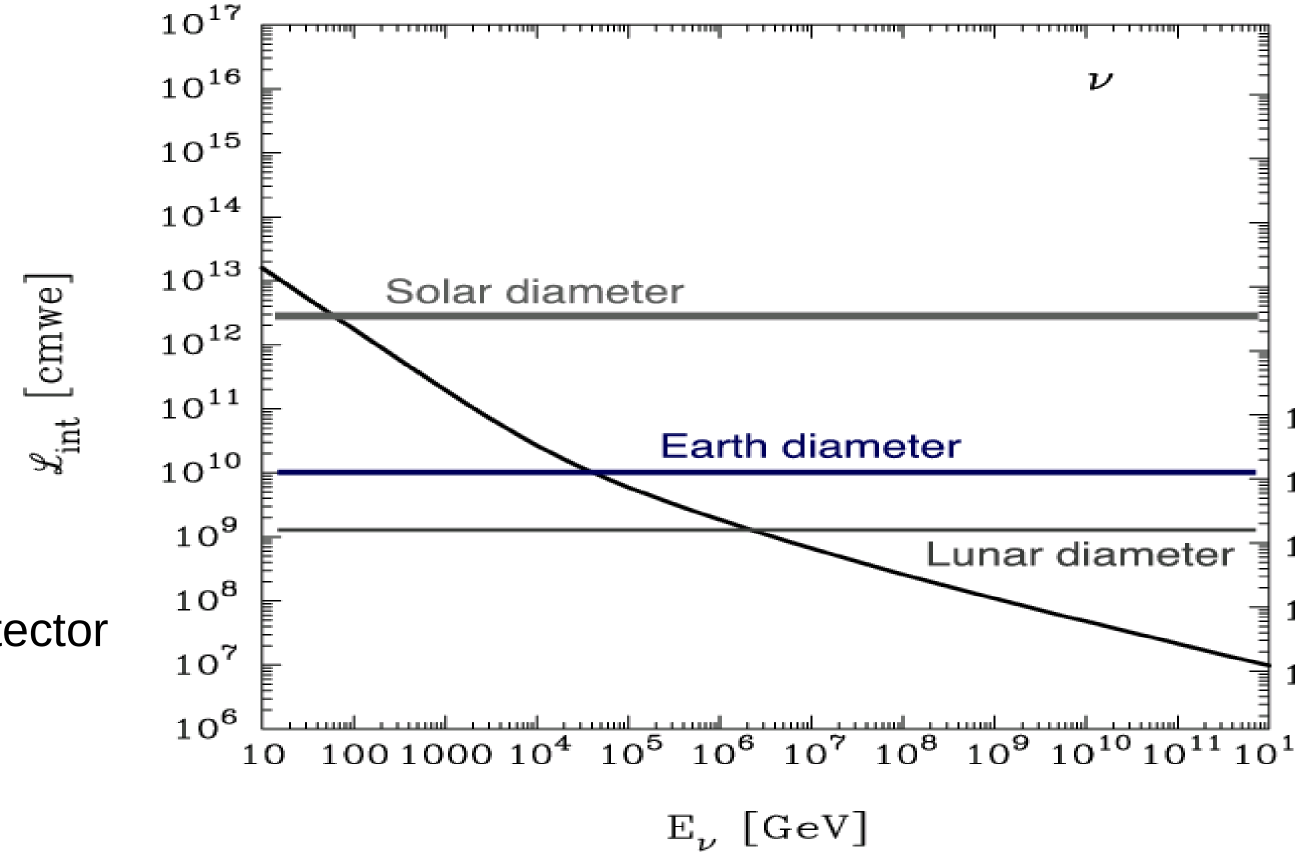
PeV acceptance around horizon

EeV acceptance above horizon

Earth attenuation

- High energy neutrinos interact in the Earth:





- However: Tau neutrino regeneration through ν_τ ⇨ τ ⇨ (17%) $\mu + \nu_\mu + \nu_\tau$

Earth is opaque to neutrinos above 1 PeV!

Neutrino propagation (vacuum)

- Key assumption: Incoherent propagation of neutrinos

$$P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

(see Pakvasa review, arXiv:0803.1701, and references therein)

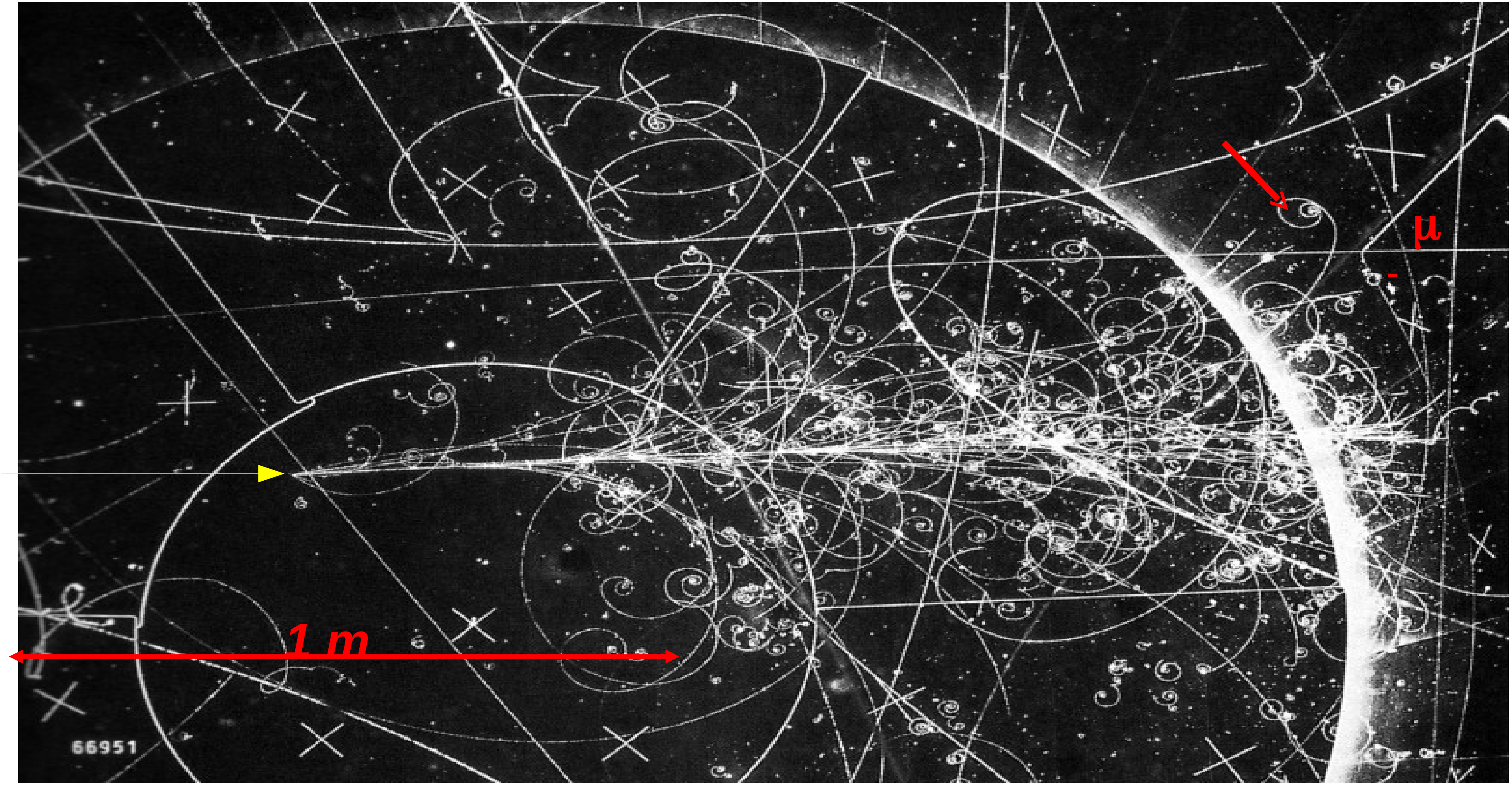
- Flavor mixing:
- Example: For $\theta_{13}=0$, $\theta_{23}=\pi/4$:

(In principle, sensitive to Re exp(-i δ) ~ cosδ)

$$\begin{pmatrix} \nu_e^{source} \\ \nu_\mu^{source} \\ \nu_\tau^{source} \end{pmatrix} = \begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} \longrightarrow \begin{pmatrix} \nu_e^{Earth} \\ \nu_\mu^{Earth} \\ \nu_\tau^{Earth} \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

(Bruno Pontecorvo)

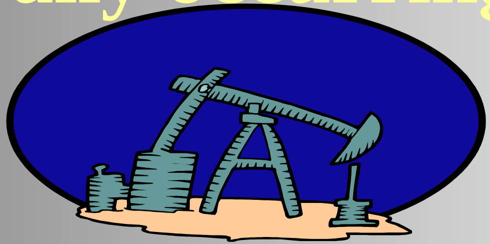
275 GeV ν_μ BEBC (Big European Bubble Chamber) event



Possible BIG targets (naturally occurring)

•Moon Rock

•Sea Water



•Oil deposit

Askaryan, 1962

•Salt Dome

•ICECAP:

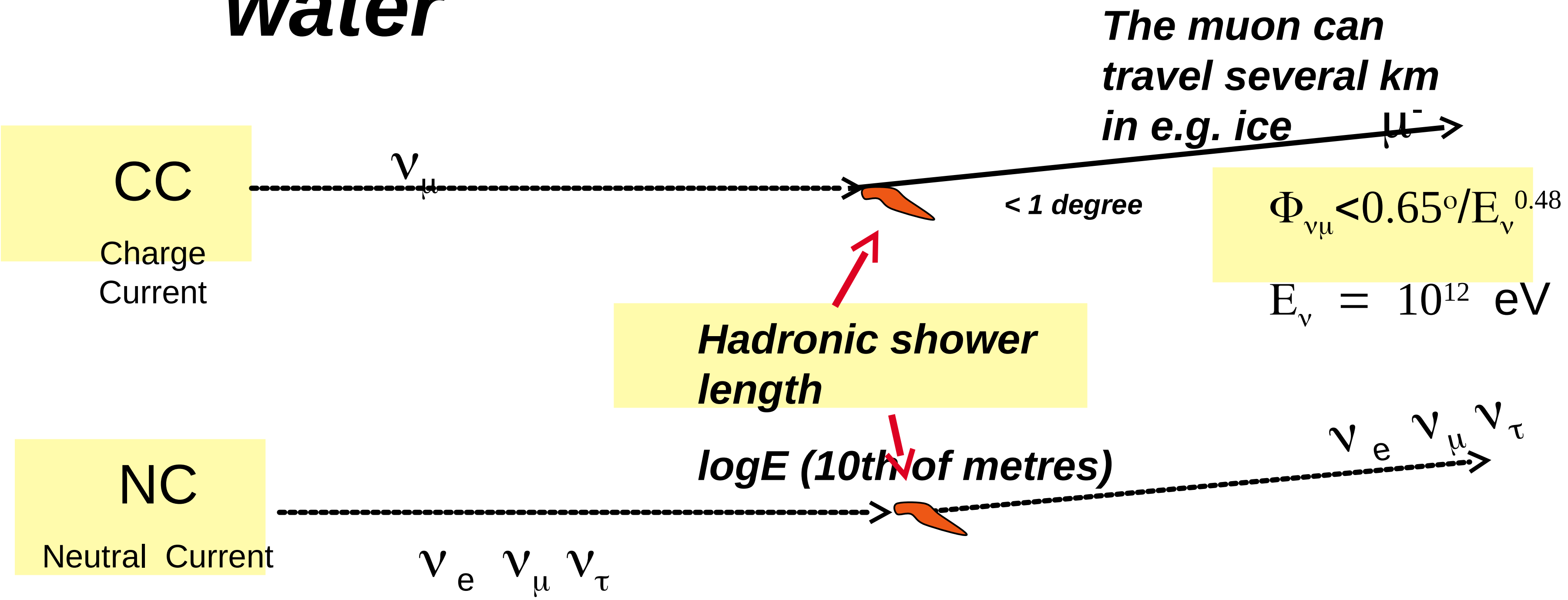
2 miles thick, surface area of USA

(+15K ff miles per trip)

Markov & Zheleznkyh (INR, Moscow) propose using Antarctic Icecap as neutrino target (1986)

Neutrino detectors: 1: the moon

Neutrino interactions in ice and water

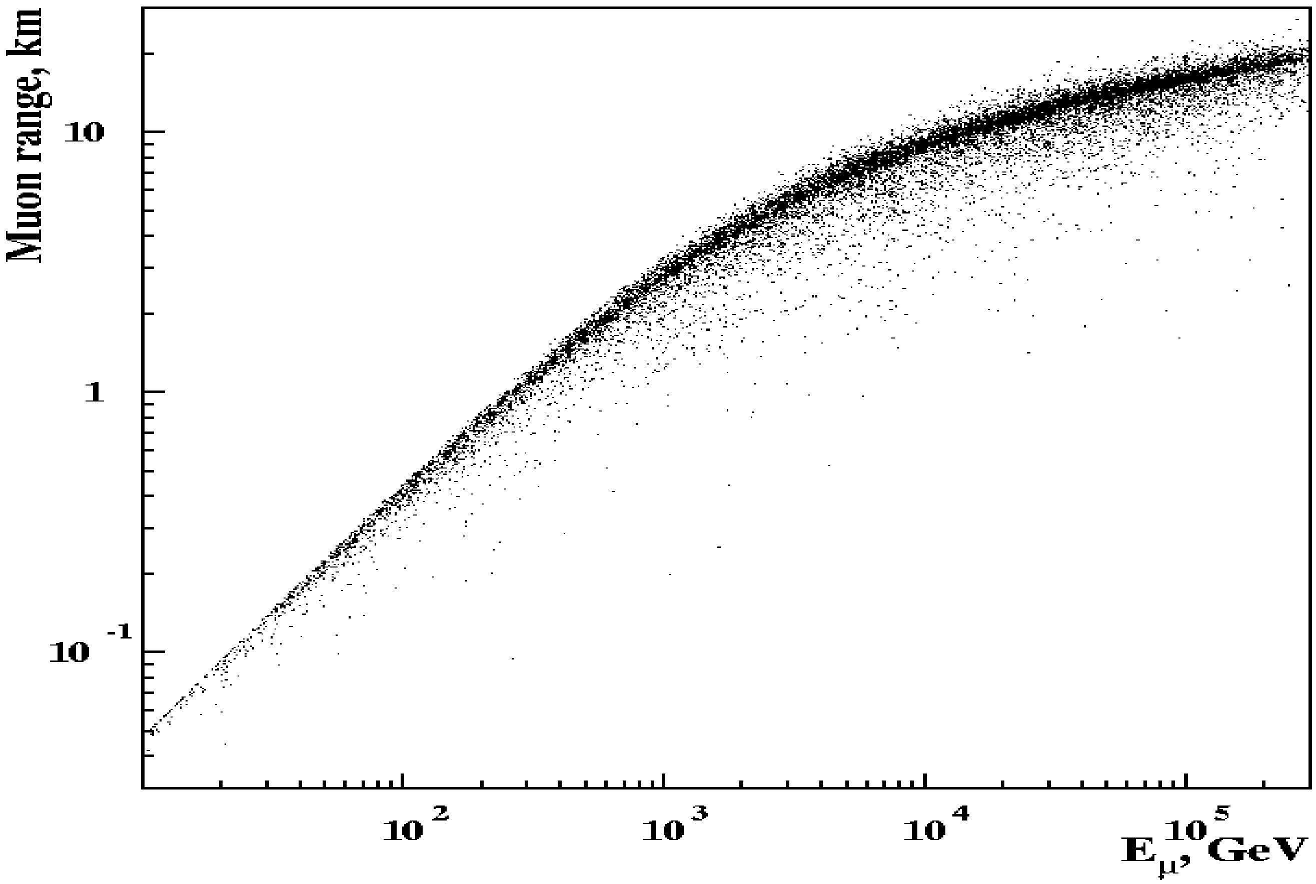


Detector Design Considerations: Muon range in ice

The muon starts to lose energy above 500 GeV to pair production, bremstrahlung

The muon will be dressed up by many e^+ /e^-.

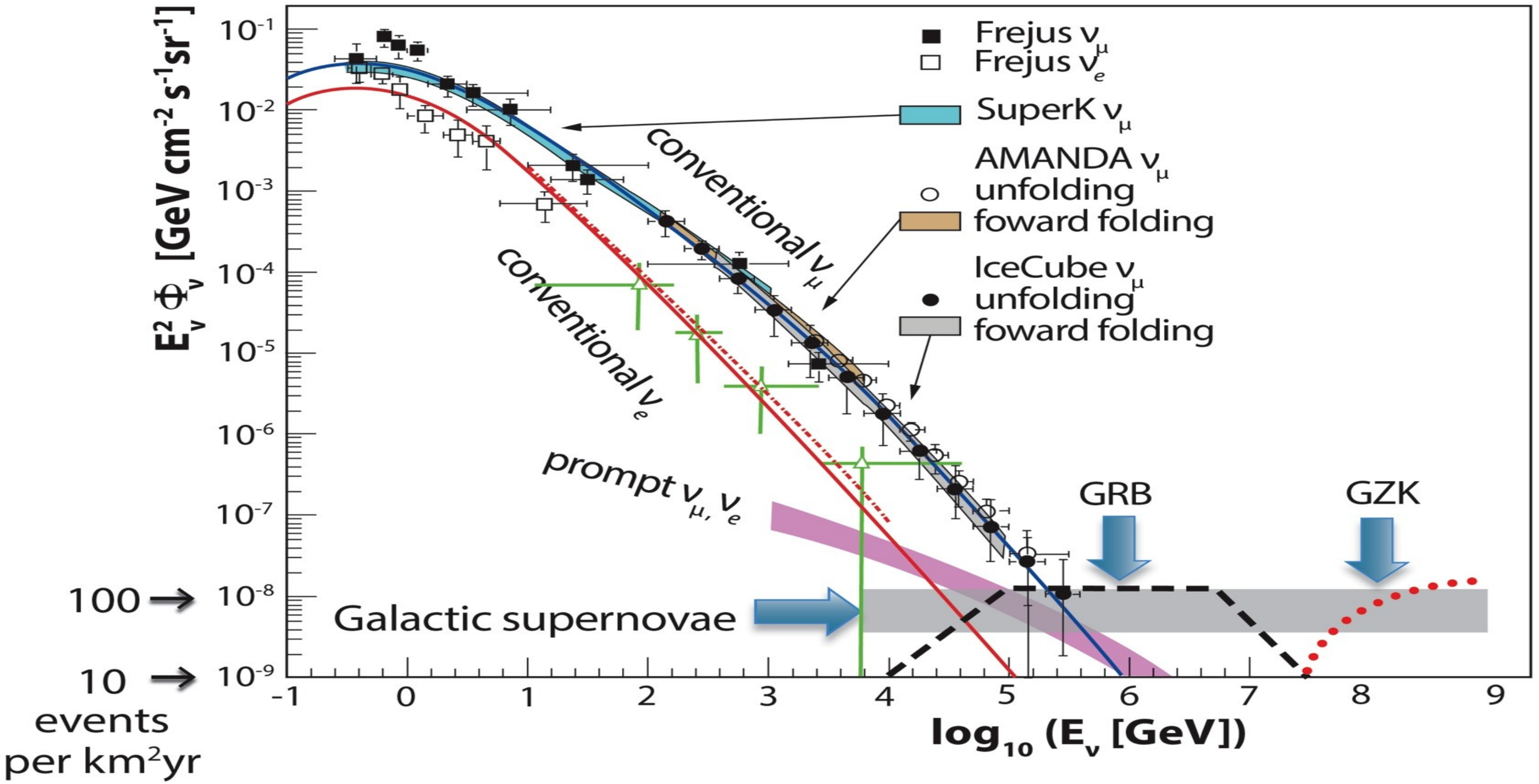
More Cherenkov light!



Muon propagator: MMC , Chirkin, D. 27th ICRC, HE 220, Hamburg 2001

- •Sample spectrum
  - (IceCube)
- •cosmic neutrinos: energy > 60 TeV

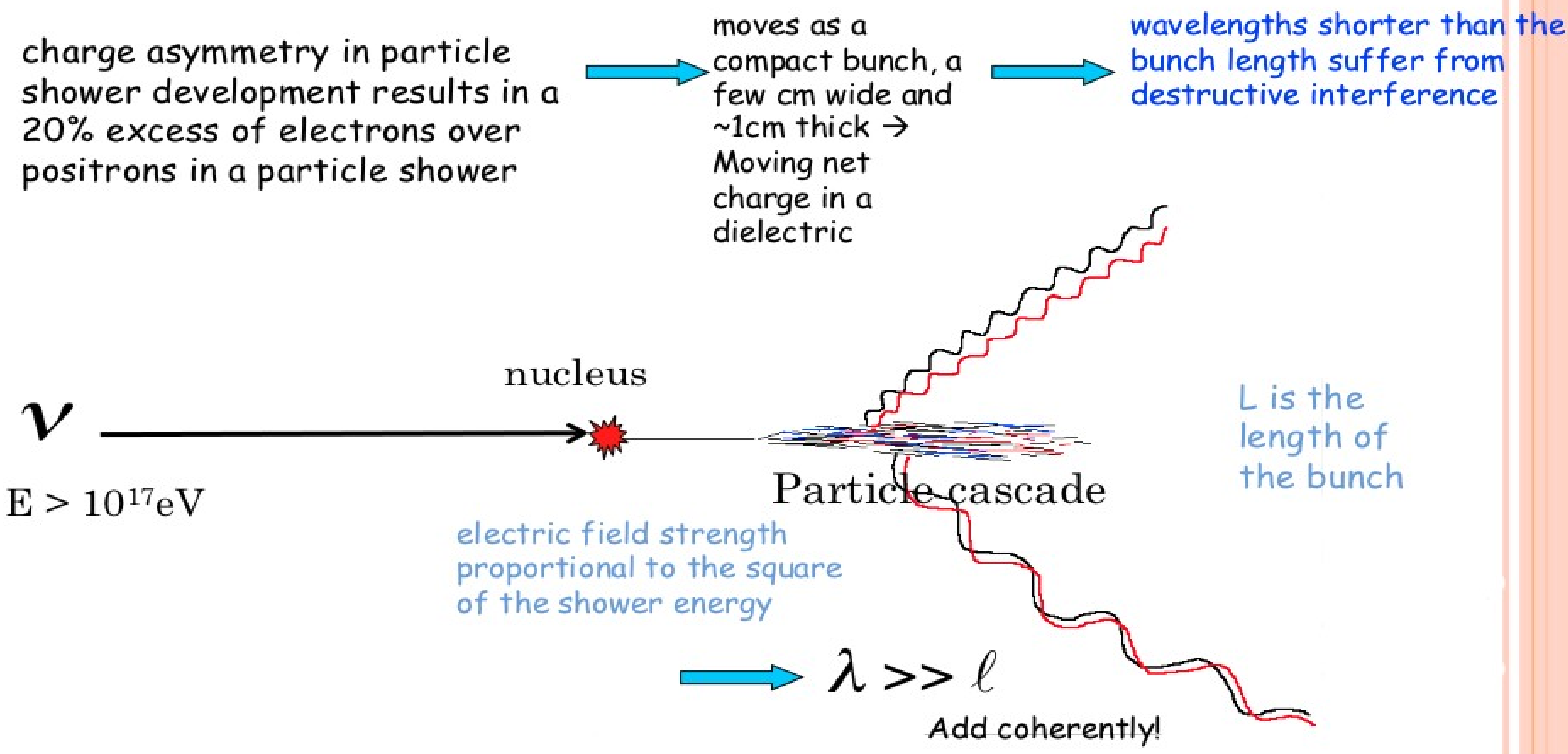
- atmospheric background: 1~2 events per year



$$\Phi_\nu \equiv \frac{dN}{dE} \approx \frac{1}{E^2}$$

atmospheric ⇧ cosmic

Radio Coherence (also in-air)



Caution: LPM: electron-showers

- Consider successive scatterings of electron off target nuclei
  - Electron momentum p
  - Momentum transfer b/w nucleus and incident e^-: q
  - Each scattering gives a photon of momentum k
  - $q=p_i-(p_f+k)\sim\mathrm{sqrt}(E^2-m^2)-\mathrm{sqrt}([E-k]^2-m^2)-k$
    - $\sim k/2\gamma^2$
  - =>as γ increases, q decreases (billiard balls)
  - BUT, as q decreases, the uncertainty principle requires that the interaction zone (L_f) increases
  - If L_f>atomic separation, no longer independent interactions and interference effects mitigate σ