Neutrinos in Particle Astrophysics

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Penn State

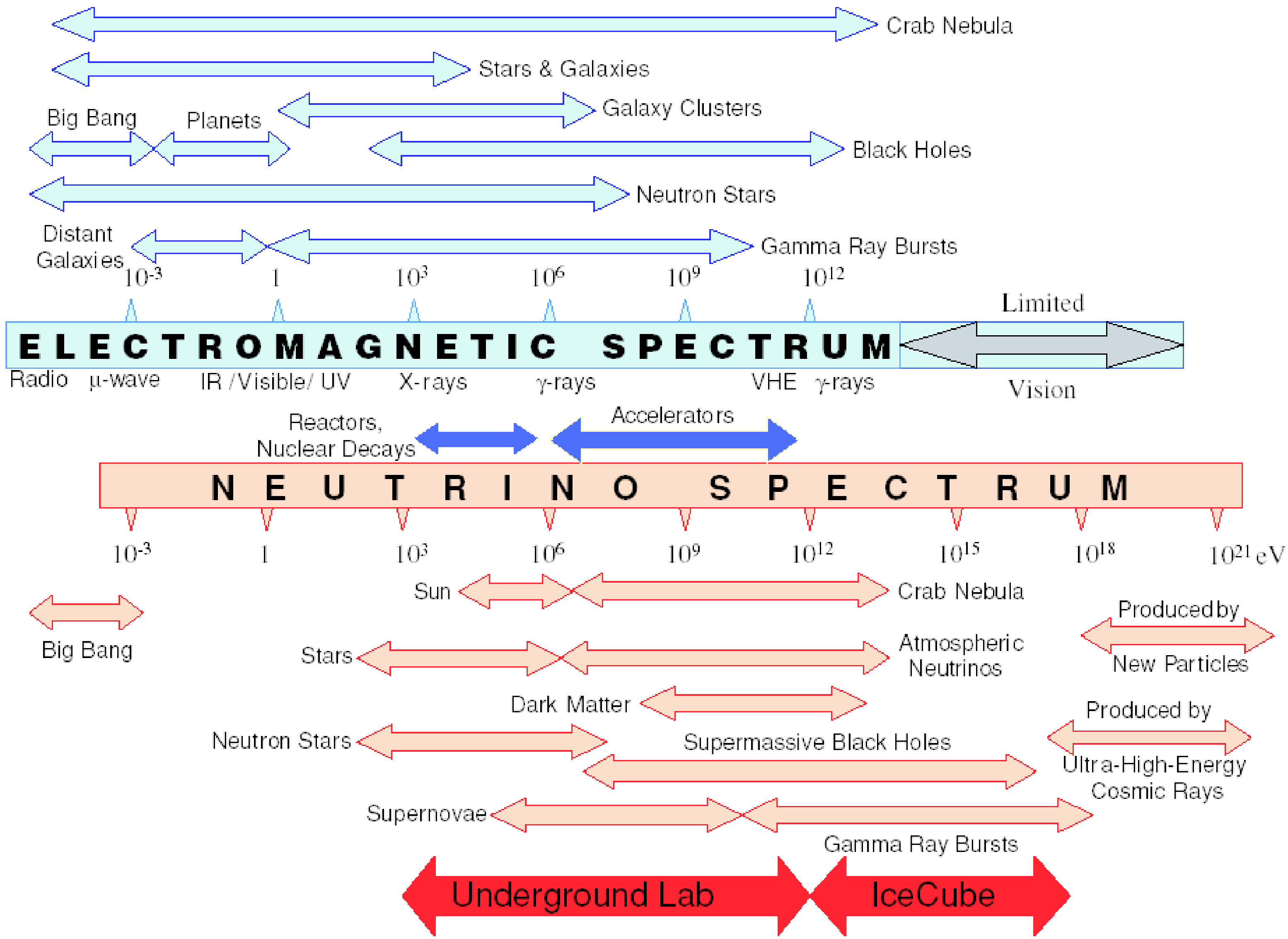
YITP at 40, May 3, 2007

YITP: 1998-2002 Neutrino oscillations... with Robert Shrock

Neutrinos

- Neutrino masses and oscillations
  - confirmed evidence of physics beyond the Standard Model
  - key importance for physics beyond the Standard Model
- Unique probe of extreme environments
- Can probe scales from 10^{-33} to 10^{28} cm
- Play major role in particle physics, astrophysics and cosmology

Neutrino Facilities Assessment Committee, 2002



Very high energy neutrinos

- escape from extreme environments
- test mechanism powering sources
- test astrophysical processes of acceleration of hadrons
- correlations with cosmic rays, gamma rays
- additional information - complementary to other sources

new window into physics, astrophysics, cosmology

Very high energy neutrinos

- detection: first events/sources - big breakthrough
- next step: what does it all mean?
- identify sources
- identify production mechanism at the source/understand source
- look for new particles/new physics: energies higher than colliders
- find something unexpected
- particle physics/particle astrophysics: how to tell them apart?
  like (worse) solar neutrino problem - fast forward?

Sources

Guaranteed

- "GZK" neutrinos:

$$\begin{array}{lll} p + \gamma \rightarrow \ldots \rightarrow \pi^+ \rightarrow & \mu^+ & + \nu_\mu \\ & \downarrow & \\ & e^+ & + \bar{\nu}_\mu + \nu_e \end{array}$$

- Gamma Ray Bursts

- Active Galactic Nuclei

- Topological Defects

- Decay of Super-Massive Particles

Highly speculative

...

Experiments

- AMANDA/ICECUBE : Cerenkov light in ice (South Pole)

- ANTARES, NESTOR: Cerenkov light in water (Mediterranean)

- RICE: radio Cerenkov in ice (South Pole)

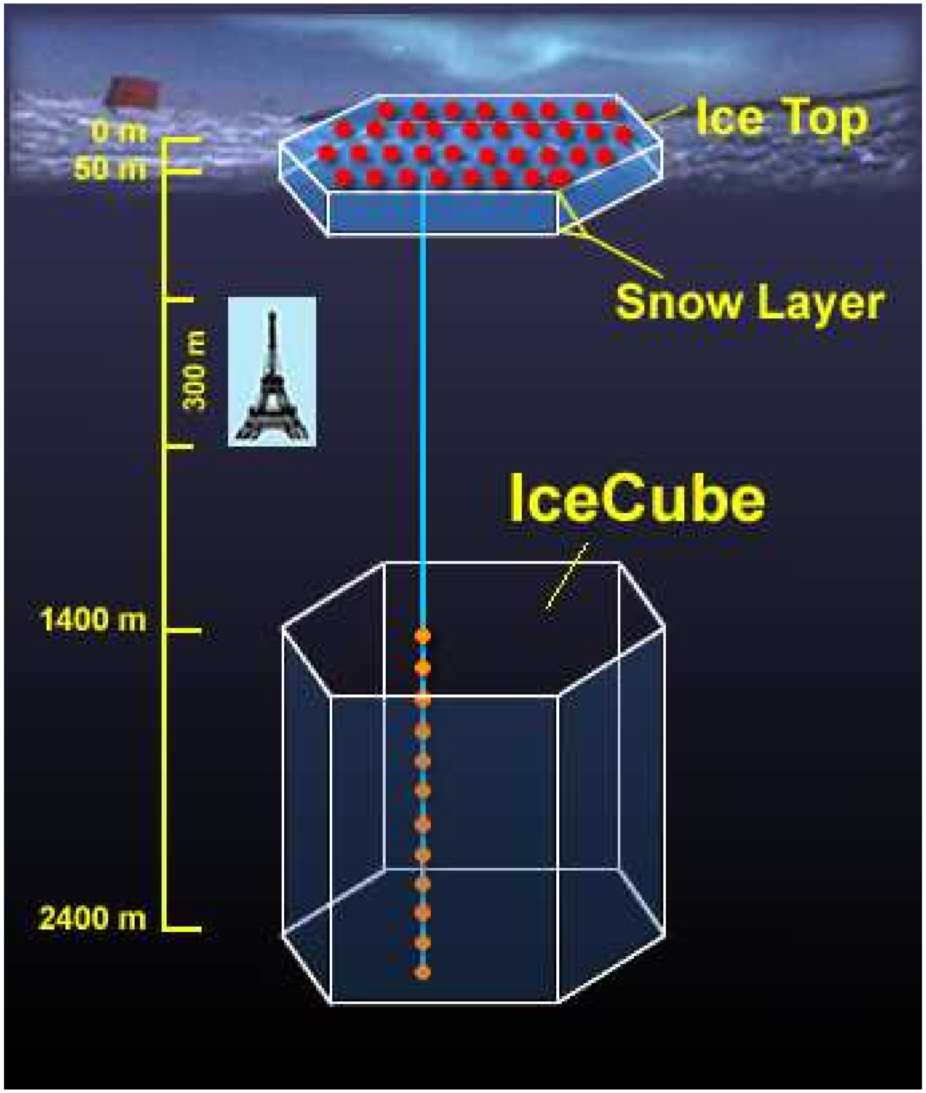
- ANITA: radio Cerenkov from ice (balloon at South Pole)

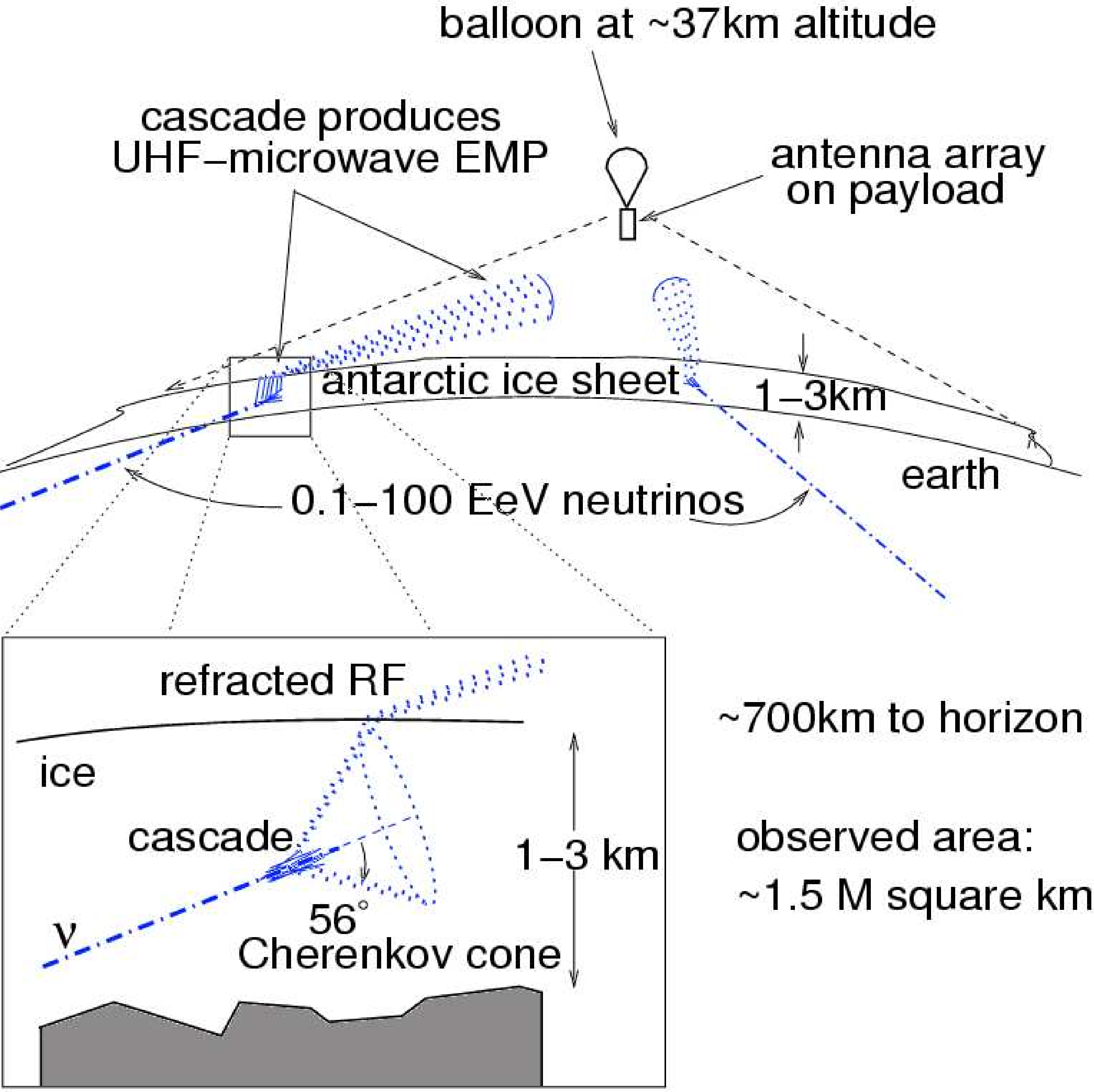
- PIERRE AUGER: air showers (Argentina,...)

- EUSO: air showers (space)

- ...

Detectors





balloon at ~37km altitude
cascade produces
UHF−microwave EMP
antenna array
on payload
antarctic ice sheet
1−3km
earth
0.1−100 EeV neutrinos
refracted RF
ice
cascade
56°
ν
Cherenkov cone
1−3 km
~700km to horizon
observed area:
~1.5 M square km


LIMITE DE L'ATMOSPHÈRE

Sources

- flavor composition

  - e.g. mostly π decays

$$\begin{array}{l} \pi^+ \longrightarrow \mu^+ + \nu_\mu \\ \qquad\quad\ \downarrow \\ \qquad\quad\ e^+ + \bar{\nu}_\mu + \nu_e \end{array}$$

$$\Rightarrow \nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$$

- energy distribution

- normalization

- correlations with photons, protons, etc.

- Source distribution: point back to source - neutrino astronomy

Sources

Not always $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

- neutron decay, etc. (e.g. GZK neutrinos)

- energy dependent flavour ratios

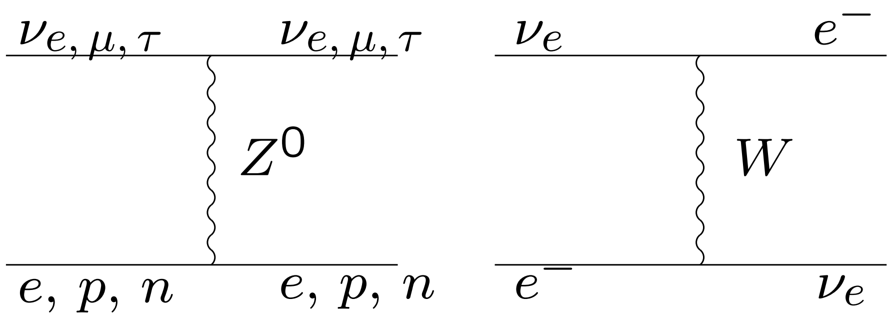
  - energy thresholds

  - energy losses

  - matter effects

Matter effects in sources

Neutrino Oscillations in Matter



- Add effective potential: $V_N = -\frac{G_F}{\sqrt{2}} N_n$, $V_C = \sqrt{2} G_F N_e$
  change signs for $\bar{\nu}$

$$i \frac{d}{dX} \nu_W = \left(\frac{1}{2E} M_W^2 + V \right) \nu_W, \quad V = \begin{pmatrix} V_C + V_N & 0 \\ 0 & V_N \end{pmatrix}$$

$$M_W^2 \rightarrow \begin{pmatrix} -\frac{\Delta m_{ji}^2}{4E} \cos 2\theta + \frac{V_C}{2} & \frac{\Delta m_{ji}^2}{4E} \sin 2\theta \\ \frac{\Delta m_{ji}^2}{4E} \sin 2\theta & \frac{\Delta m_{ji}^2}{4E} \cos 2\theta - \frac{V_C}{2} \end{pmatrix}$$

Constant density

- **resonance:** $\Delta m^2_{ji} \cos 2\theta = 2EV_R$

- Effective Δm^2

$$\Delta m^2_m = [(\Delta m^2 \cos 2\theta - 2EV)^2 + (\Delta m^2 \sin 2\theta)^2]^{1/2}$$

- Effective mixing

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\cos^2 2\theta (1 - V/V_R) + \sin^2 2\theta}$$

- Transition probability

$$P(\nu_e \to \nu_x) = \sin^2 2\theta_m \sin^2 \frac{\Delta m^2_m L}{4E}$$

Most sources: density too low, not enough column density
$\rightarrow$ matter effects negligible

Some sources: can reach resonance $\Rightarrow$ significant matter effects

e.g: neutrinos produced in jets of supernovae
S. Razzaque, P. Meszaros, E. Waxman, Mod.Phys.Lett.A20:2351,2005

$$n_e = 2 \times 10^{22} \left(\frac{6 \times 10^{10}}{r} \right) \text{cm}^{-3}$$

$$\frac{dN}{dE} \sim \frac{1}{E^3}, \;\; 10\text{GeV} < E < 300\text{GeV}$$

$$\frac{dN}{dE} \sim \frac{1}{E^4}, \;\; 300\text{GeV} < E < 300\text{TeV}$$

• π decay $1:2:0$ modified at the source
$+$ long distance vacuum oscillations $+$ Earth matter effects
$\rightarrow$ non-standard energy dependent flavour compositions

O. Mena, I. M., S. Razzaque

Propagation Through Space

Neutrino Oscillations over long distances

- ν_μ and ν_τ maximally mixed:

$$F^0_{\nu_e} : F^0_{\nu_\mu} : F^0_{\nu_\tau} = 1 : 2 : 0 \Rightarrow \nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$$

- sometimes $F^0_{\nu_e} : F^0_{\nu_\mu} : F^0_{\nu_\tau} \neq 1 : 2 : 0$ $\Rightarrow$Three flavour mixing relevant

$$\begin{aligned} F_{\nu_e} &= F^0_{\nu_e} - \frac{1}{4}\sin^2 2\theta_{12}(2F^0_{\nu_e} - F^0_{\nu_\mu} - F^0_{\nu_\tau}) \\ F_{\nu_\mu} &= F_{\nu_\tau} = \frac{1}{2}(F^0_{\nu_\mu} + F^0_{\nu_\tau}) + \frac{1}{8}\sin^2 2\theta_{12}(2F^0_{\nu_e} - F^0_{\nu_\mu} - F^0_{\nu_\tau}) \end{aligned}$$

J. Jones, I.M, M. H. Reno, I. Sarcevic, Phys.Rev.D69:033004,2004

- much smaller effects from deviation from maximal atmospheric mixing, θ_{13}, CP violation

Propagation Through Space

Non-Standard Neutrino Properties

- neutrino decay
  - see flavour composition of lowest mass state
  - energy dependence

- additional interactions
  - decoherence: quantum gravity

all change flavour composition

Propagation Through Air/Ice/Rock

- interaction cross-sections

  - in the Standard Model

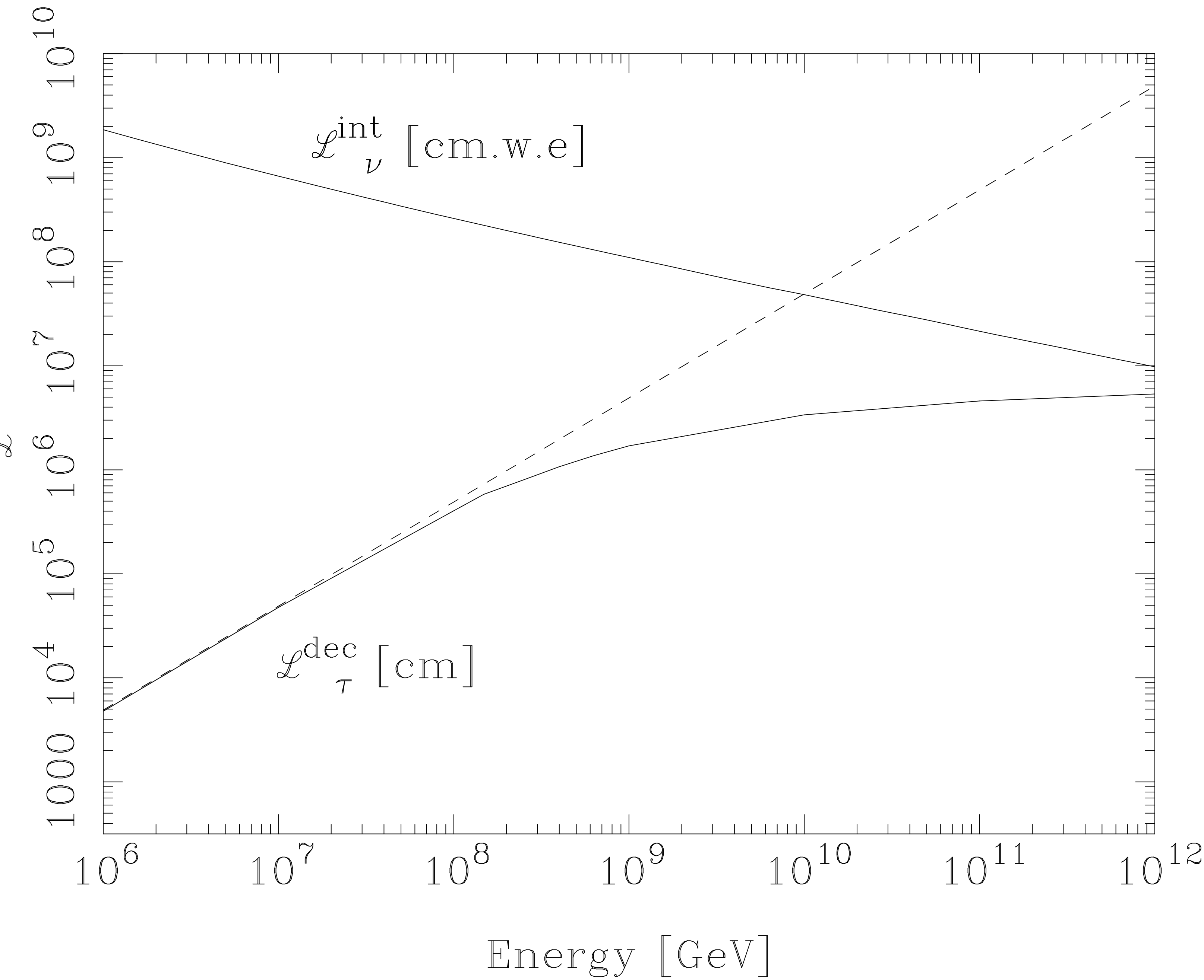
  Parton Distribution Functions extrapolations at high energies

  - beyond the Standard Model

- energy losses

- flavour composition

- other new physics

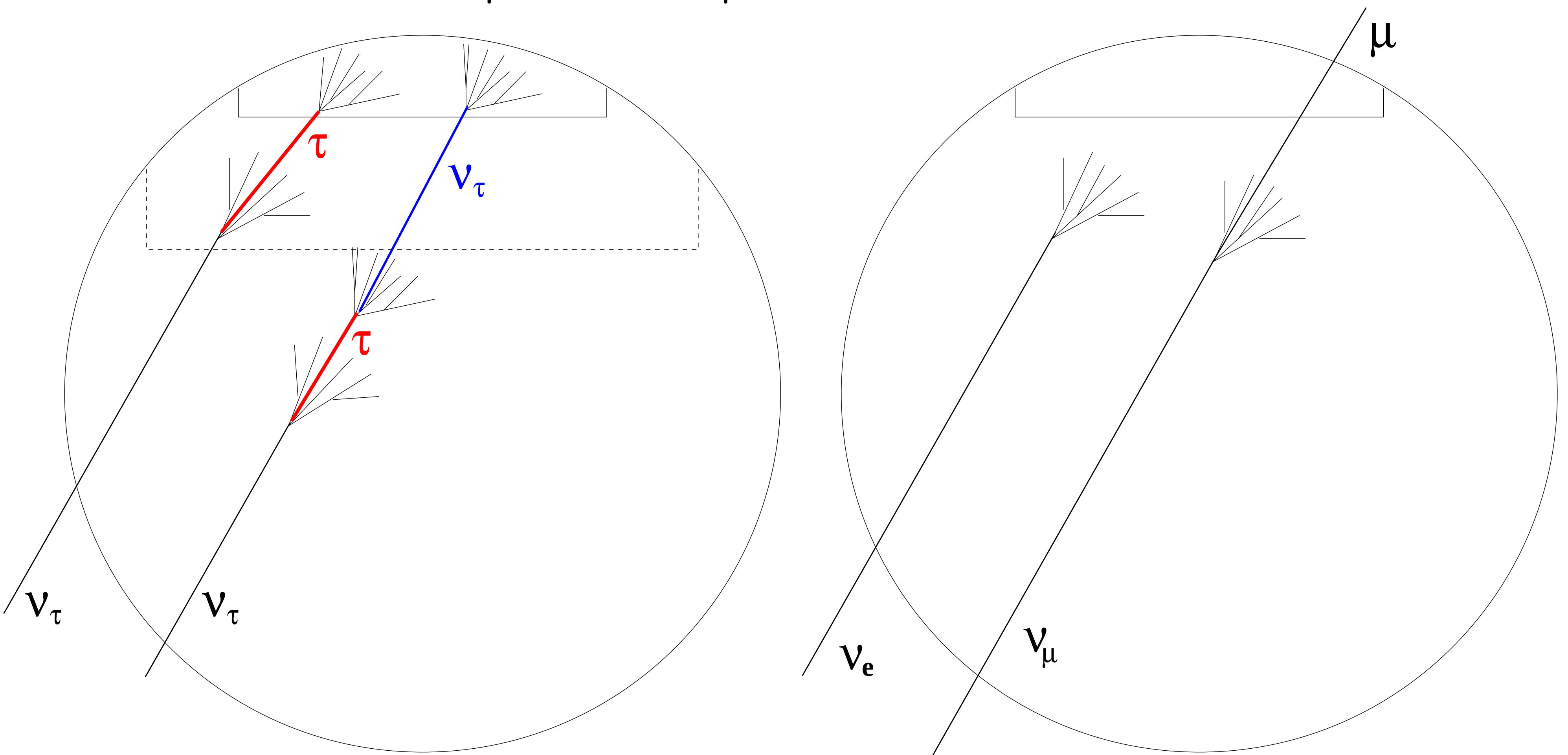


$\mathscr{L}^{\rm int}_{\nu}$ [cm.w.e]
$\mathscr{L}^{\rm dec}_{\tau}$ [cm]
$\mathscr{L}$
Energy [GeV]
1000
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}

Propagation Through Air/Ice/Rock

Above ~ 40 TeV Earth opaque to neutrinos

- Downward/horizontal
- Use ν_τ:
  - gain volume
  - lose energy
  - flavour composition important



Propagation Through Air/Ice/Rock

- ν attenuation due to charged (CC) and neutral current (NC) interactions
- NC return of ν
- regeneration of ν from τ decay and CC interactions

$$\frac{\partial F_{\nu_\tau}(E,X)}{\partial X} = -N_A\sigma^t(E)F_{\nu_\tau}(E,X) + N_A\int_E^\infty dE_y F_{\nu_\tau}(E_y,X)\frac{d\sigma^{NC}}{dE}(E_y,E) + \int_E^\infty dE_y \frac{F_\tau(E,X)}{\lambda_\tau^{dec}}\frac{dn}{dE}(E_y,E) + \tau CC$$

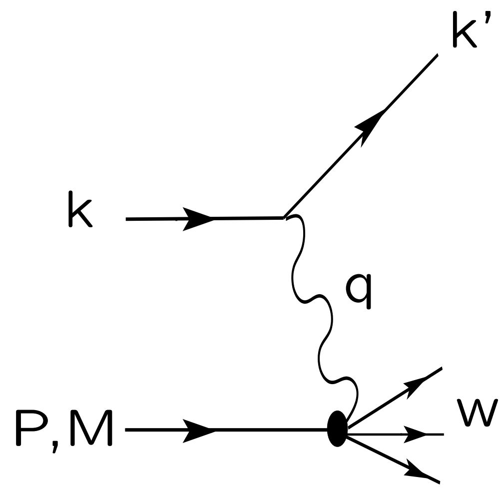
- τ decay, τ CC interactions
- CC production of τ

$$\frac{\partial F_\tau(E,X)}{\partial X} = -\frac{F_\tau(E,X)}{\lambda_\tau^{dec}(E,X,\theta)} + N_A\int_E^\infty dE_y F_{\nu_\tau}(E_y,X)\frac{d\sigma^{CC}}{dE}(E_y,E) - \tau CC$$

- τ energy loss

$$-\frac{dE_\tau}{dX} = \alpha_\tau + \beta_\tau E_\tau$$

Deep Inelastic Scattering

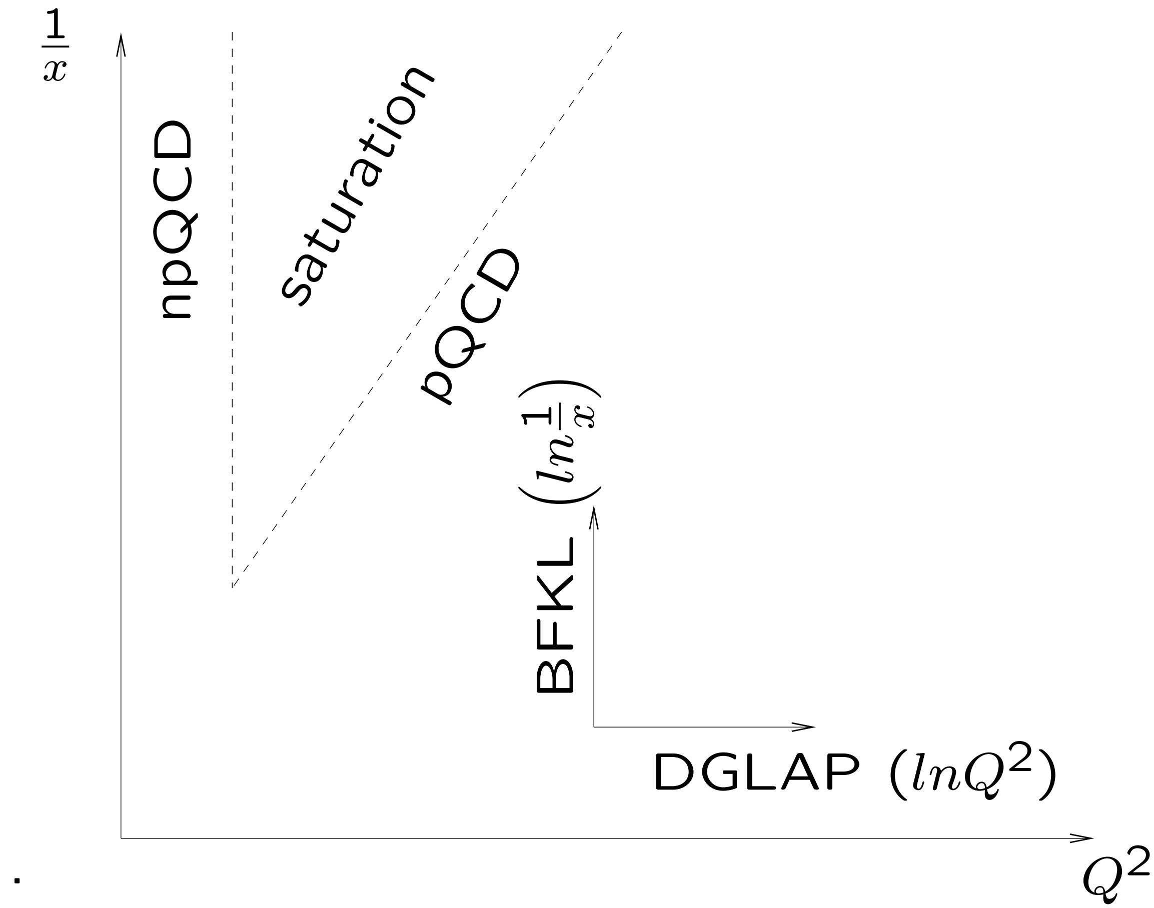


$$Q^2 = -q^2,\ x = \frac{Q^2}{2P\cdot q} = \frac{Q^2}{2M(E-E')},\ y = \frac{P\cdot q}{P\cdot k} = \frac{E-E'}{E} = \frac{Q^2}{xs}$$

$$\sigma_{\nu,\bar{\nu}}(E) = \int_{Q^2_{min}}^{s} dQ^2 \int_{Q^2/s}^{1} dx \frac{1}{xs} \frac{\partial^2 \sigma_{\nu,\bar{\nu}}}{\partial x \partial y}$$

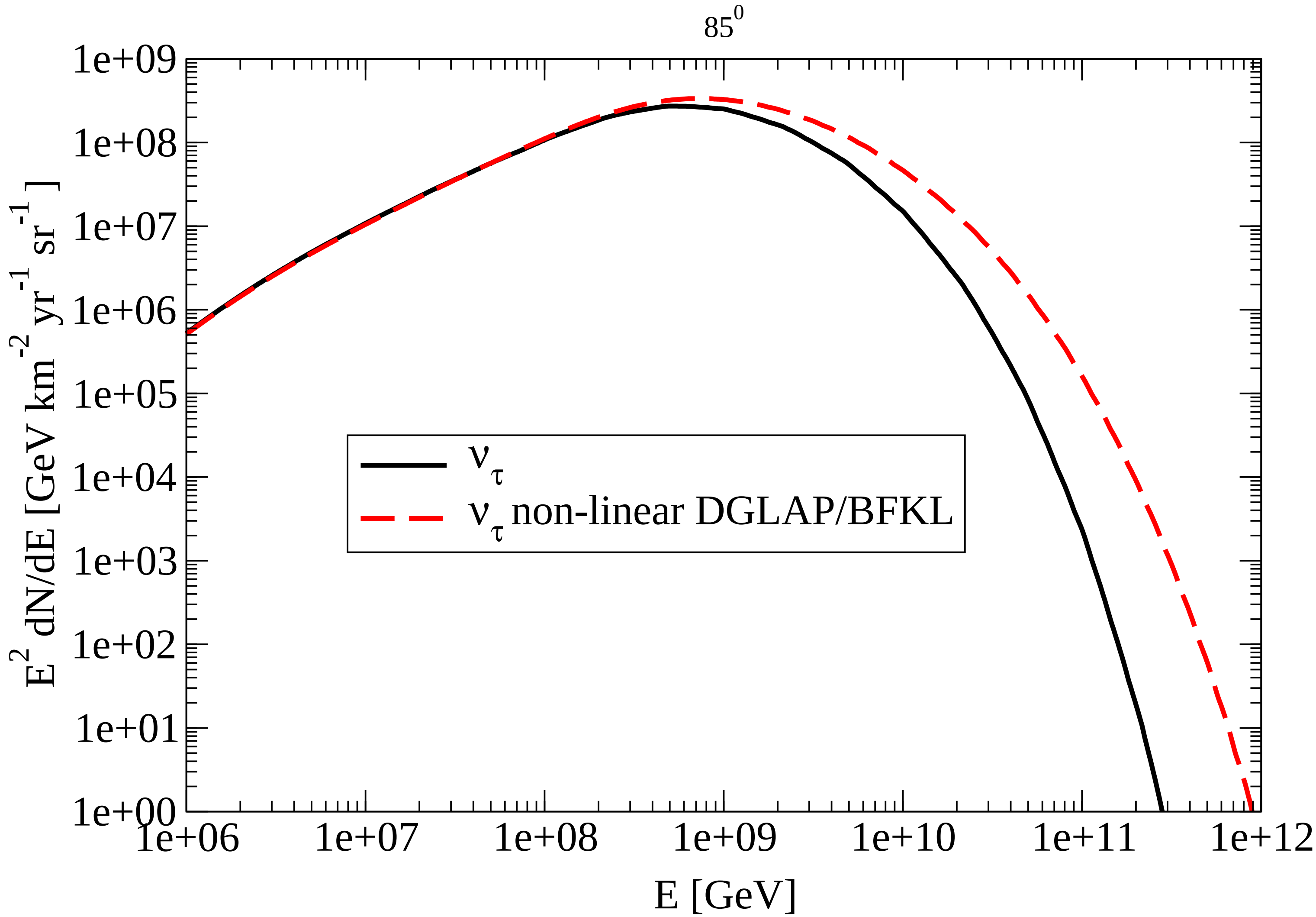
$$\frac{\partial^2 \sigma_{\nu,\bar{\nu}}}{\partial x \partial y} = \frac{G_F^2 M E}{2\pi} \left(\frac{M_i^2}{Q^2 + M_i^2} \right)^2 \times$$

$$\left[\left(1 + (1-y)^2\right) F_2(x,Q^2) - y^2 F_L(x,Q^2) \pm y\,(2-y)\, x F_3(x,Q^2) \right]$$



νN DIS: large Q^2 ($\sim M_W^2$)

small x ($\sim 10^{-4} - 10^{-8}$)



GZK neutrinos

I.M., M.H. Reno, I. Sarcevic, A. Stasto

Propagation Through Air/Ice/Rock

- energy losses large, especially at high energies
  maximum τ reach ~ 50 km
  uncertainties also large at high energy

- neutral current effects large at energies above $10^8 - 10^9$ GeV

- cross-section uncertainties $\sim 20 - 30\%$ below 10^8 GeV

- cross-section/fluxes could be very different above $10^8 - 10^9$ GeV
  within SM

- at "low" energy: neutrino oscillations - small, but non-zero

Beyond the Standard Model

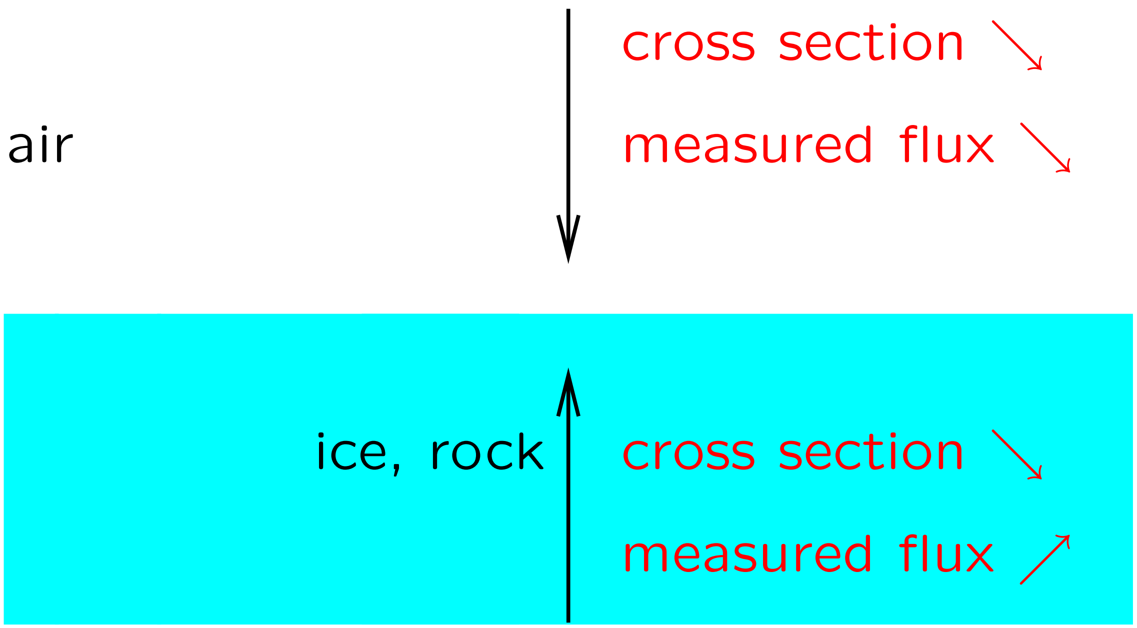
- new interactions: $\sigma = \sigma_{SM} + \sigma_{new}$
  low sale gravity, etc.
  increase absorption for upward events

- Lorentz invariance and CPT violation
  atmospheric neutrino oscillations
  L or LE instead of L/E - dominate oscillations at high energies

- new particles
  e.g. SUSY:
  - neutralinos
  - sleptons: gauge mediation SUSY breaking , super-WIMPs
  - R-parity violating models

- ...

Measuring cross-sections



- asymmetries very sensitive to cross-sections
- angular distribution

Specific Signatures

- flavour composition:

  - electromagnetic showers vs. hadronic showers vs. tracks

  - ν_τ double bang + lollipop: unique signatures

- competing effects:

  - high rates in detectors: large interaction rate

  - less absorption: small interaction rates

Very High Energy Neutrinos

- seeing very high energy neutrinos: **ESSENTIAL**
- counting very high energy neutrinos: first step
- need more! $\longrightarrow$ more work!
  - angular distributions
  - energy distributions
  - flavour composition
  - better detector techniques
  - more smart tricks, unique signatures, etc.
  - very good simulations
  - correlations with other observables: photons, protons, etc.
- find right observable and combination of observables
- can distinguish particle physics from astrophysics effects
- learn about both!

The unexpected

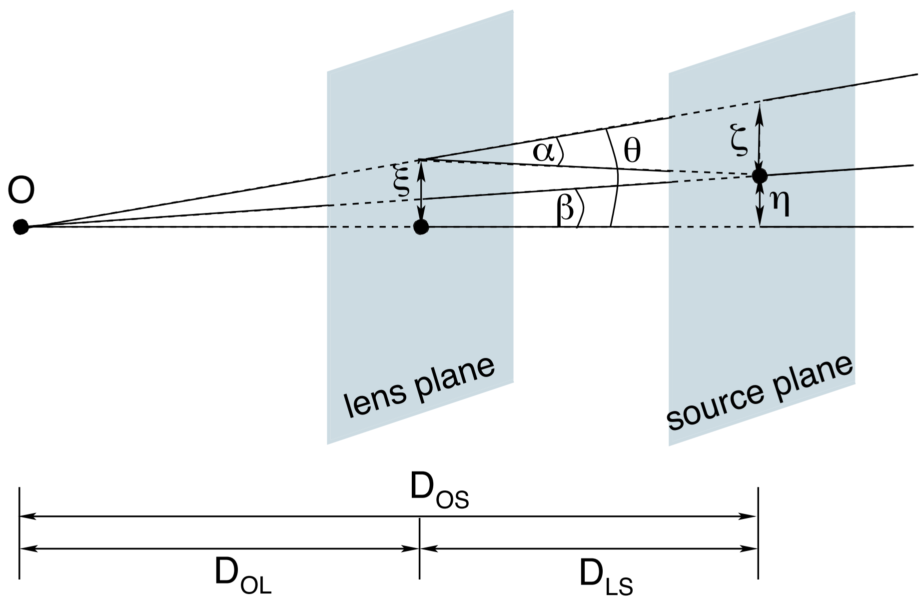
Neutrino Gravitational Lensing

Photons $\longrightarrow$ neutrinos:

Strong lensing: impossible to achieve required angular resolution

Weak lensing: need huge number of sources

Microlensing: apparent magnification



$$\mu = \frac{d\Omega}{d\Omega_0} = \frac{\beta^2 + 2\theta_E^2}{\beta\sqrt{\beta^2 + 4\theta_E^2}}$$

$$\theta_E = \sqrt{\frac{2\mathcal{R}D_{LS}}{D_{OS}D_{OL}}} = \sqrt{\frac{2\mathcal{R}}{D_{OL}}\frac{x}{1+x}}$$

Supernovae: ideal sources

- large numbers of neutrinos
- total luminosity known within factor of 3 or better
- for SN perfectly aligned with galactic center black hole and Earth:

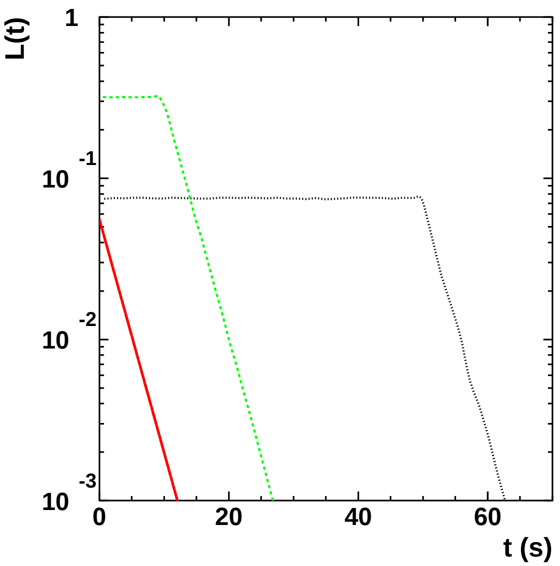
$$\mu \sim 2 \times 10^{11}!$$

Probability for perfect alignment: very small

Not so perfect alignment: higher probability

Magnifications of ~ 100 very interesting

Time spread



O. Mena, I.M., C. Quigg