# Very high energy neutrinos and high energy cross-sections

**Irina Mocioiu**

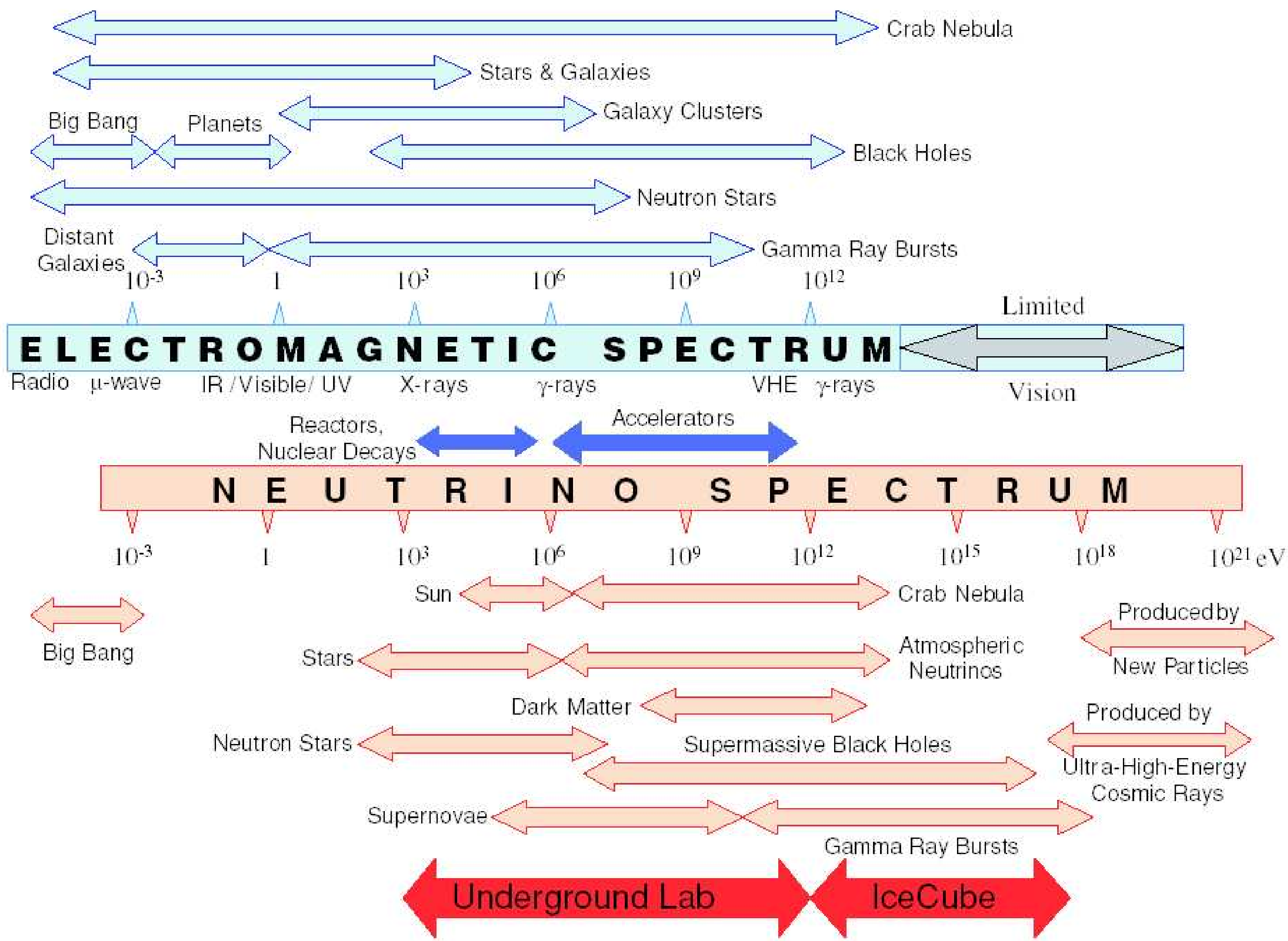
University of Arizona

**Argonne Theory Institute**, May 28, 2004

# Neutrinos

- Neutrino masses and oscillations: confirmed evidence of physics beyond the (old) Standard Model
- Unique probe of extreme environments
- Can probe scales from $10^{-33}$ to $10^{28}$ cm
- Energies between $10^{-3}$ eV and $10^{23}$ eV
- Play major role in particle physics, astrophysics and cosmology

Neutrino Facilities Assessment Committee, 2002



## Cross-sections

- in the Standard Model

  QCD

  - understood in some regime (perturbative), to some order
  - Parton Distribution Functions – extracted from data
  - large uncertainties
  - predictions of "backgrounds" in colliders rely on extrapolations - larger uncertainties

$\rightarrow$ measurements + higher order calculations

  - new measurement: new regime

- beyond the Standard Model

  ...

## Outline

- Very High Energy Neutrinos
- Small x QCD
- High Energy Cross-Sections from Neutrino Measurements

  (preliminary)

## Very high energy neutrinos

- energy much higher than available in colliders
- point back to sources $\Rightarrow$ neutrino astronomy
- 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

# Sources

Guaranteed

Highly speculative

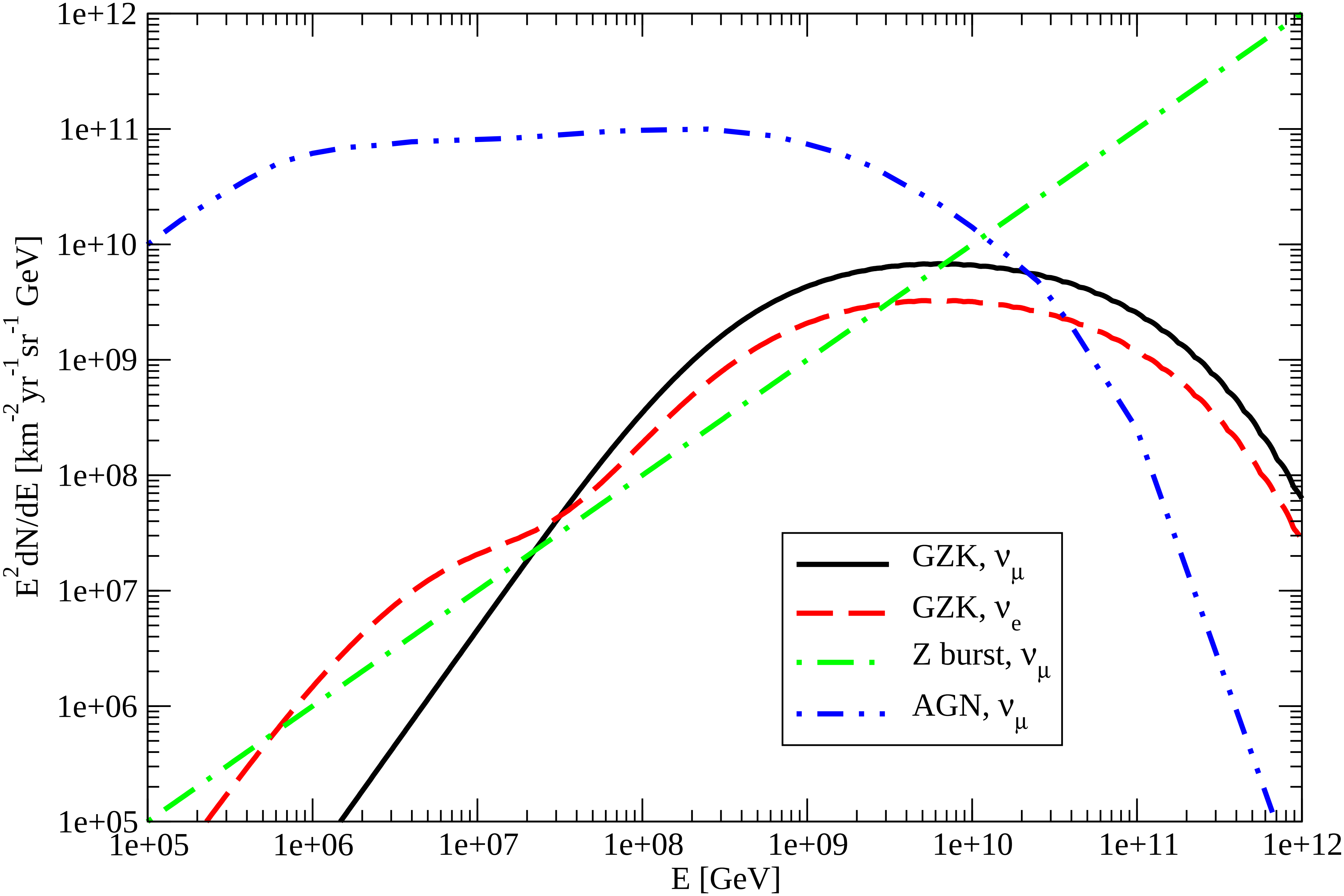
- "GZK" neutrinos:

$$p + \gamma \rightarrow ... \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\downarrow$$

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

- Gamma Ray Bursts
- Active Galactic Nuclei
- Z burst
- Topological Defects
- ...



1e+12
1e+11
1e+10
1e+09
1e+08
1e+07
1e+06
1e+05
1e+05
1e+06
1e+07
1e+08
1e+09
1e+10
1e+11
1e+12
E [GeV]
$E^2 dN/dE$ [$km^{-2} yr^{-1} sr^{-1}$ GeV]
GZK, $\nu_\mu$
GZK, $\nu_e$
Z burst, $\nu_\mu$
AGN, $\nu_\mu$

# 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, OWL: air showers (space)

- ...

# Neutrino flavors

- source: mostly $\pi$ decays $\Rightarrow \nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$
- propagation toward Earth:

  – neutrino oscillations over long distance

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

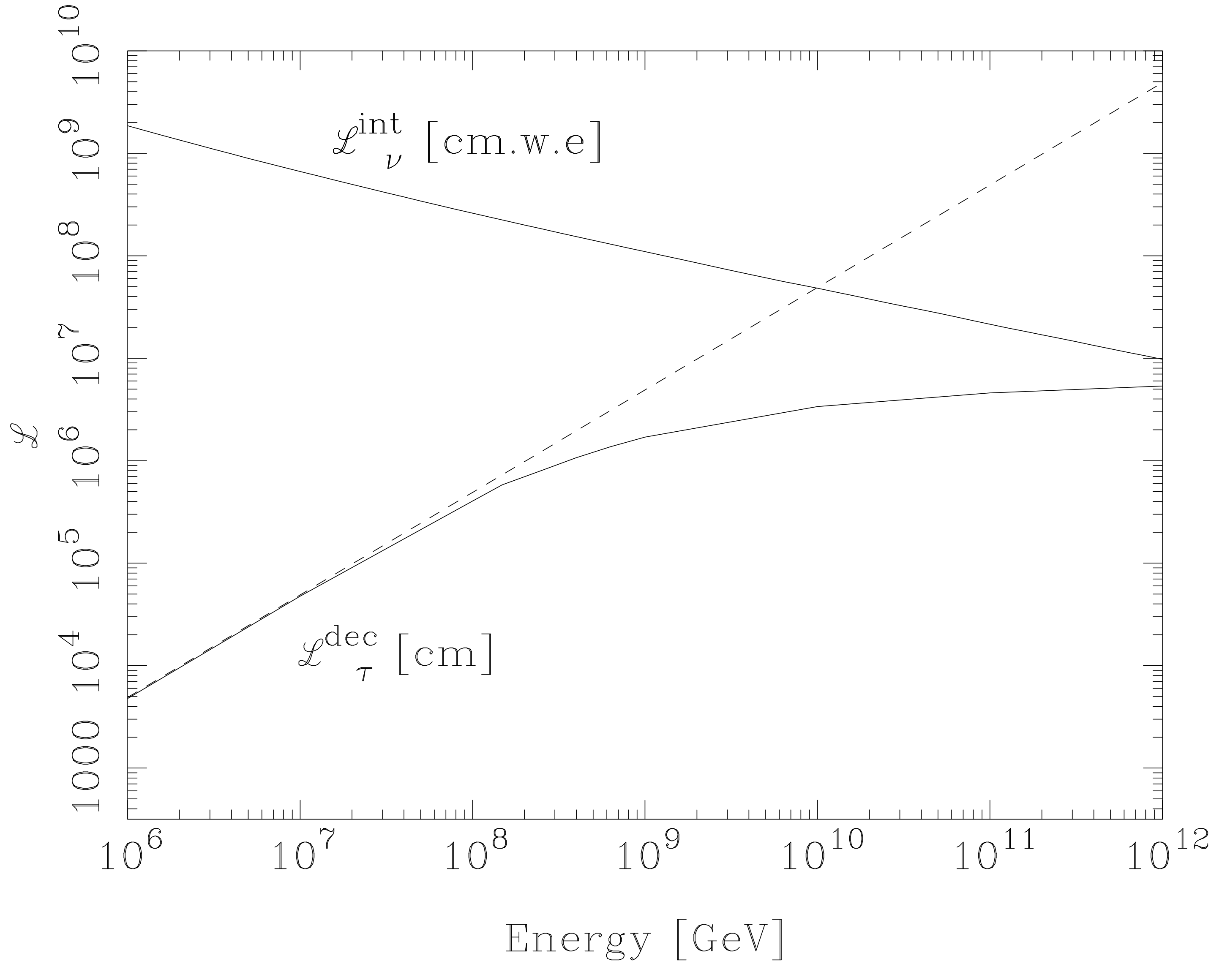
  – $\nu_\mu$ and $\nu_\tau$ maximally mixed

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

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

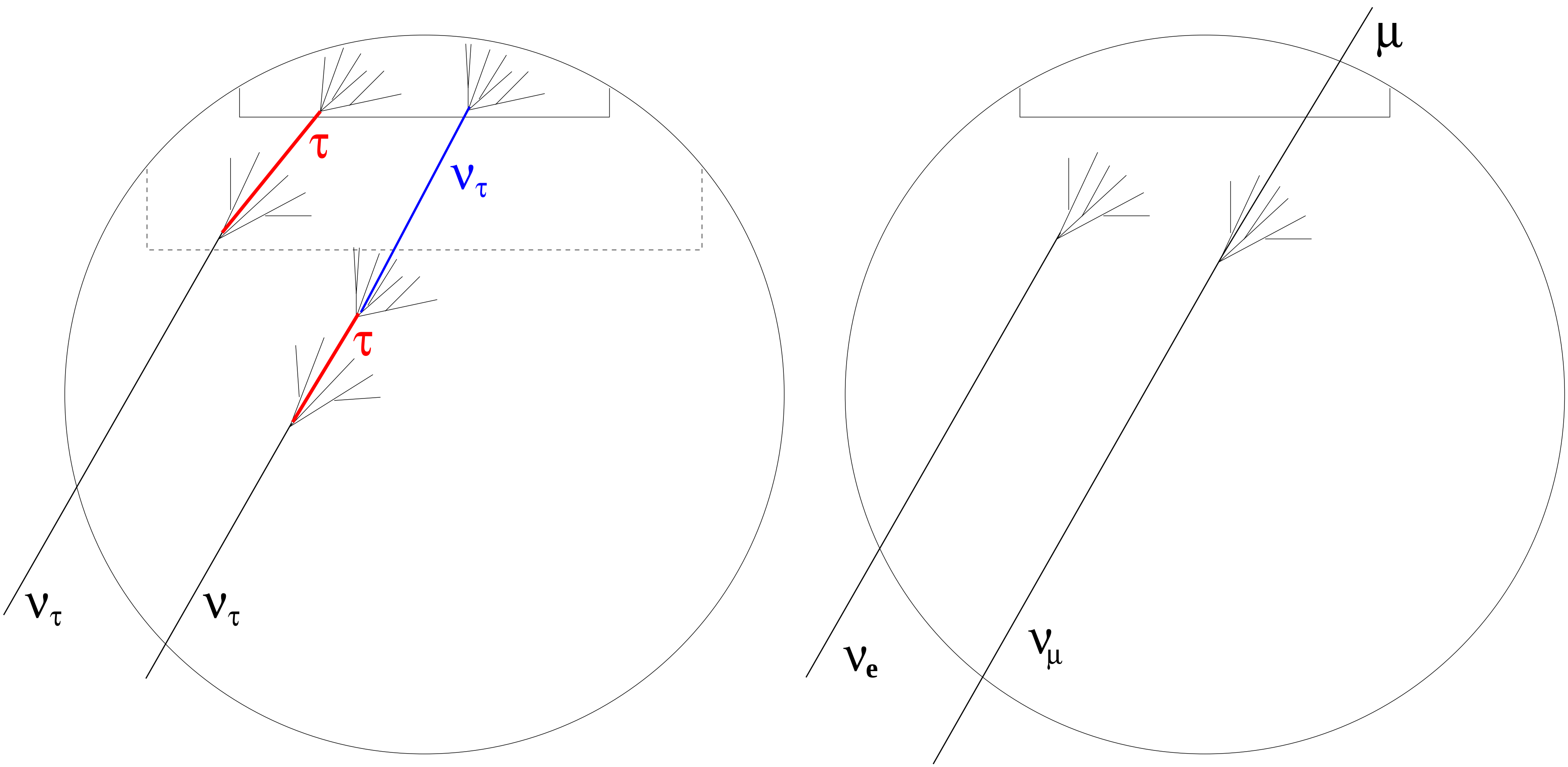
$$F_{\nu_\mu} = F_{\nu_\tau} = \frac{1}{2}(F^0_{\nu_\mu} + F^0_{\nu_\tau}) + \frac{1}{8}\sin^2 2\theta_{12}(2F^0_{\nu_e} - F^0_{\nu_\mu} - F^0_{\nu_\tau})$$

e.g. GZK neutrinos (J. Jones, I. M., M.H. Reno, I. Sarcevic)



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

**Use $\nu_\tau$:**
- gain volume
- lose energy
- flavor composition important



## Propagation through the Earth/ice

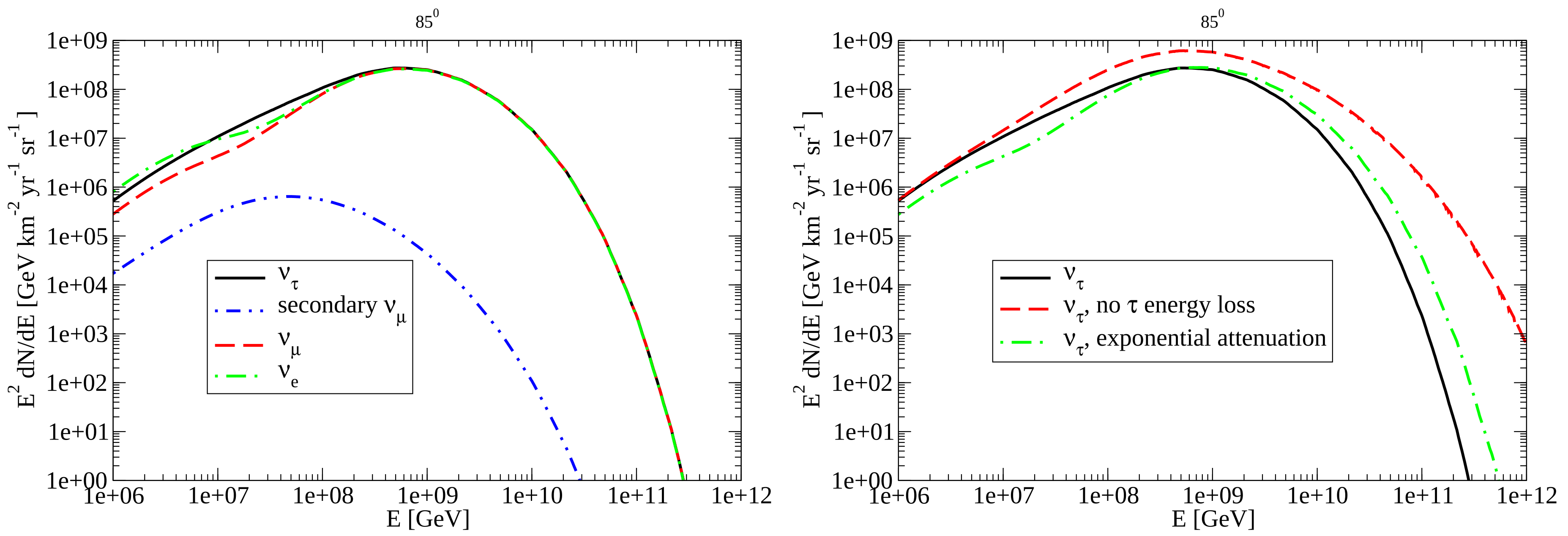
- $\nu$ attenuation due to charged (CC) and neutral current (NC) interactions
- NC return of $\nu$
- regeneration of $\nu$ from $\tau$ decay

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

- $\tau$ decay
- CC production of $\tau$

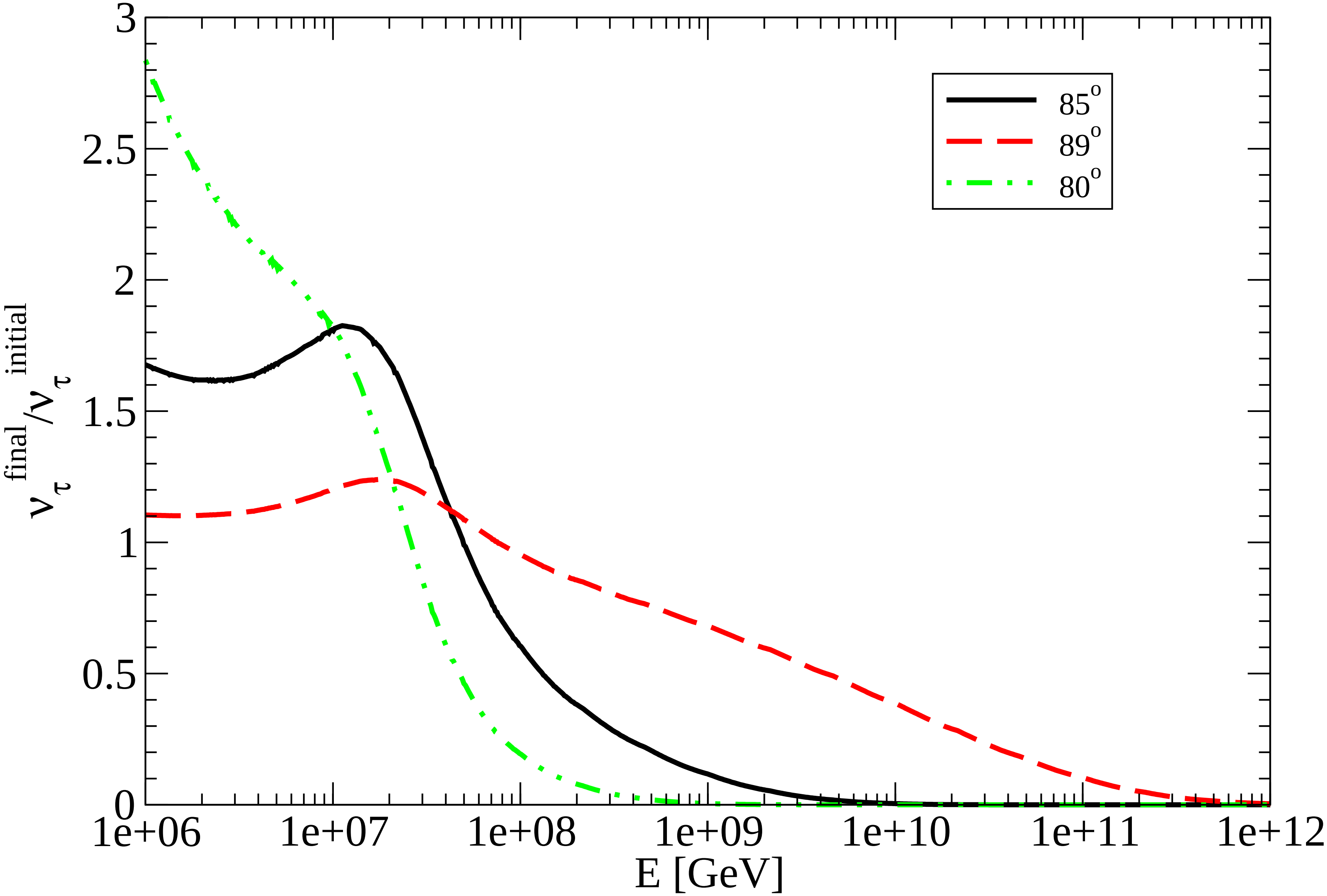
$$\frac{\partial F_\tau(E,X)}{\partial X} = N_A\int_E^\infty dE_y F_{\nu_\tau}(E_y,X)\frac{d\sigma^{CC}}{dE}(E_y,E) - \frac{F_\tau(E,X)}{\lambda_\tau^{dec}(E,X,\theta)}$$

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



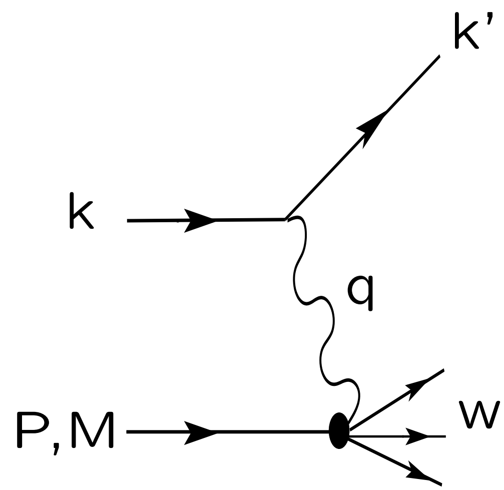

GZK

J. Jones, I.M., M. H. Reno, I. Sarcevic




J. Jones, I.M., M. H. Reno, I. Sarcevic

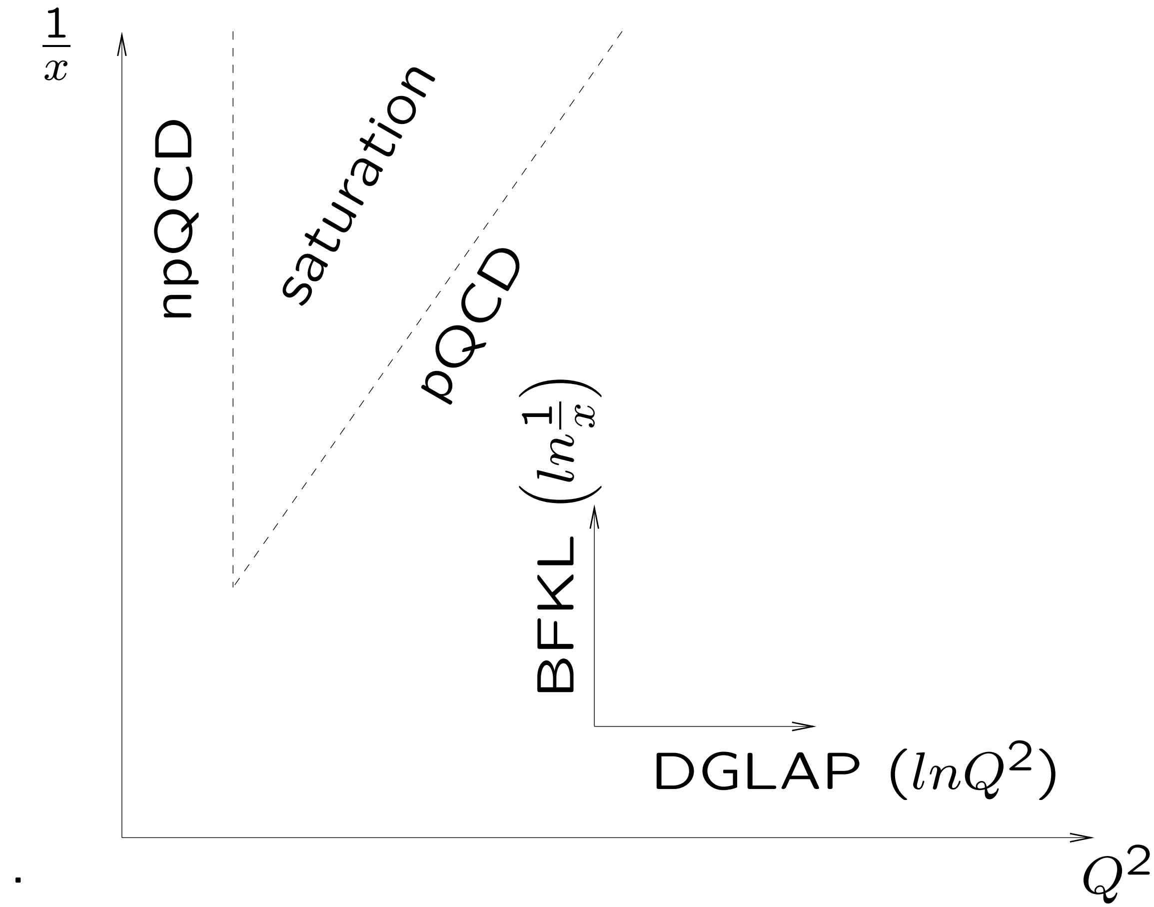
# Deep Inelastic Scattering




$$Q^2 = -q^2$$

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

$$y = \frac{P \cdot q}{P \cdot k} = \frac{E - E'}{E}$$




$\nu$N DIS: large $Q^2$ ($\sim M_W^2$)

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

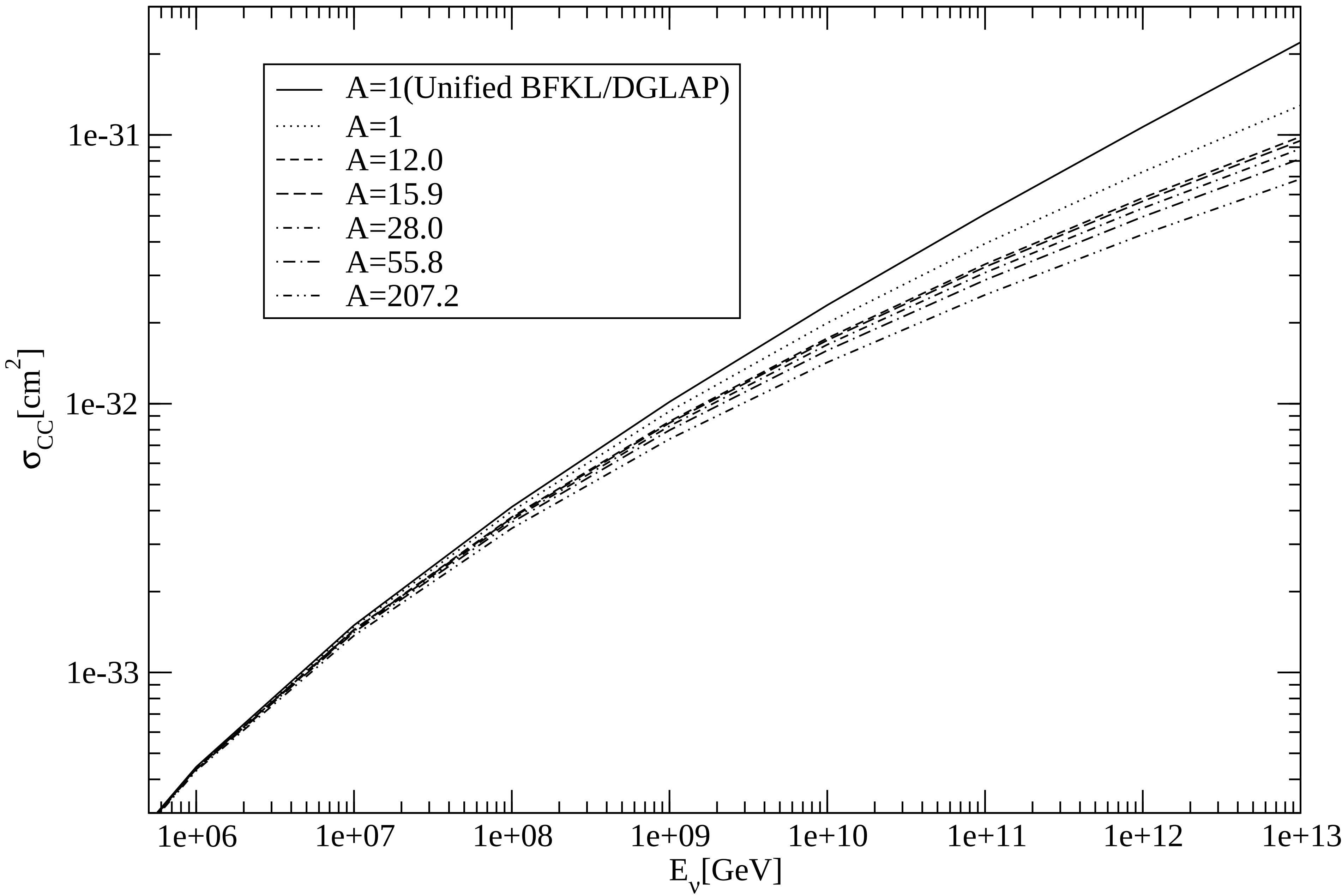
$$\sigma_{\nu,\bar{\nu}}(E) = \int_{Q^2_{min}}^{s} dQ^2 \int_{Q^2/s}^{1} dx \frac{1}{xs} \frac{\partial^2 \sigma_{\nu,\bar{\nu}}}{\partial x \partial y}$$

$$y = \frac{Q^2}{xs}$$

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

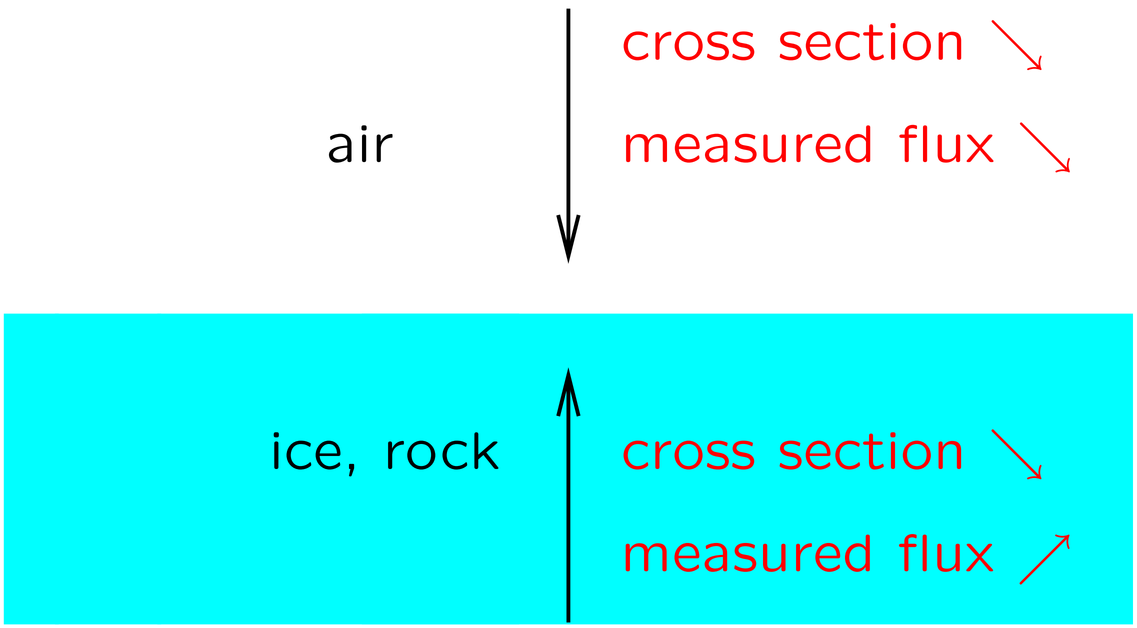
$$\left[ \frac{1 + (1-y)^2}{2} F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \pm y \left( 1 - \frac{y}{2} \right) x F_3(x, Q^2) \right]$$

(LO)

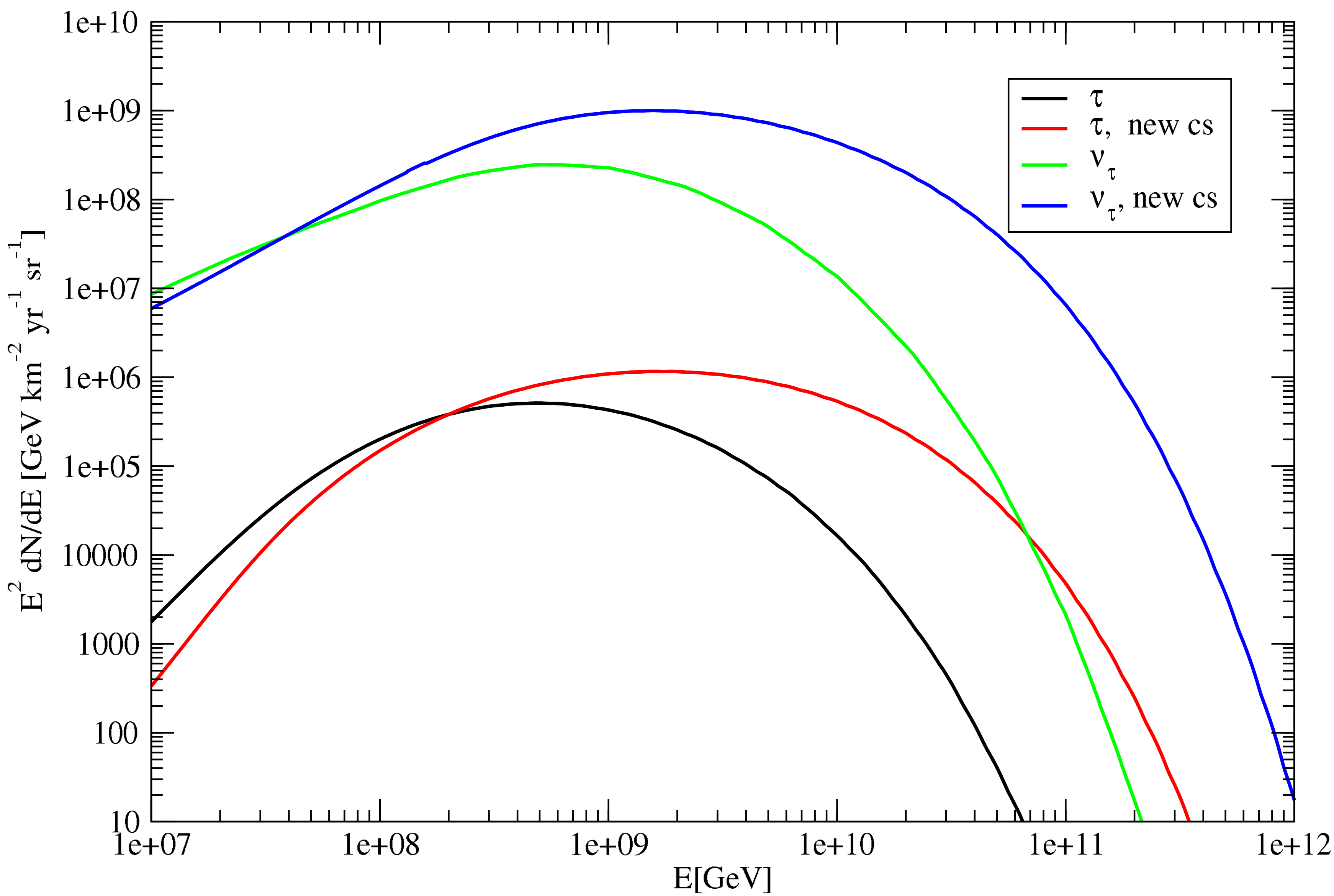



Kutak,Kwiecinski

## Measuring cross-sections




- asymmetries very sensitive to cross-sections
- Pierre Auger + ANITA + IceCube: angular + energy distriution




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

## Observables: showers in ice

- Electromagnetic showers:

  Tau decay: $\tau \rightarrow e + \bar{\nu}_e + \nu_\tau$

  $\nu_e$ CC interactions: $\nu_e + N \rightarrow e + X$

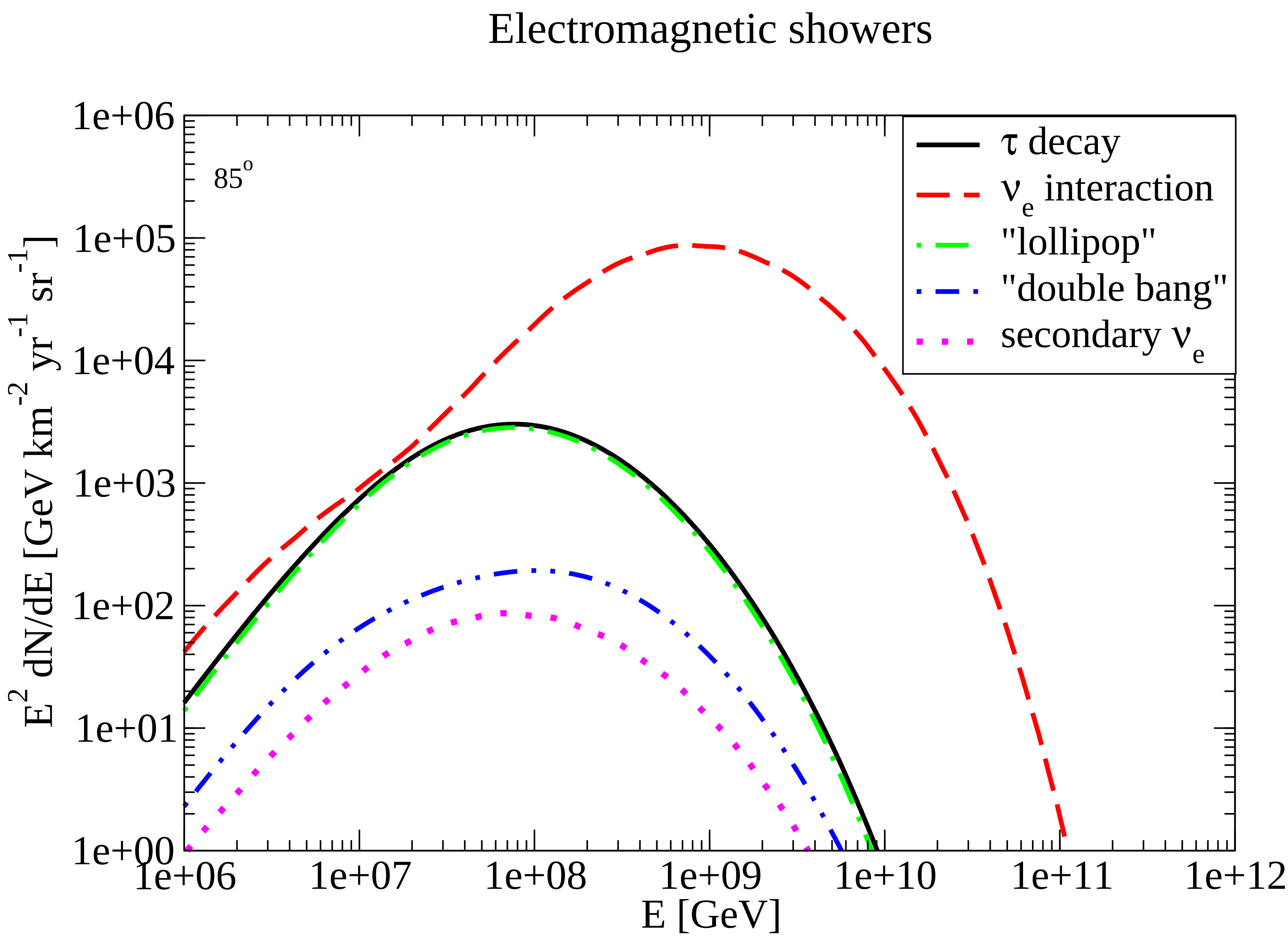
- Hadronic showers

  Tau decay: $\tau \rightarrow \nu_\tau + X$

  $\nu_\tau$ NC interactions: $\nu_\tau + N \rightarrow \nu_\tau + X$

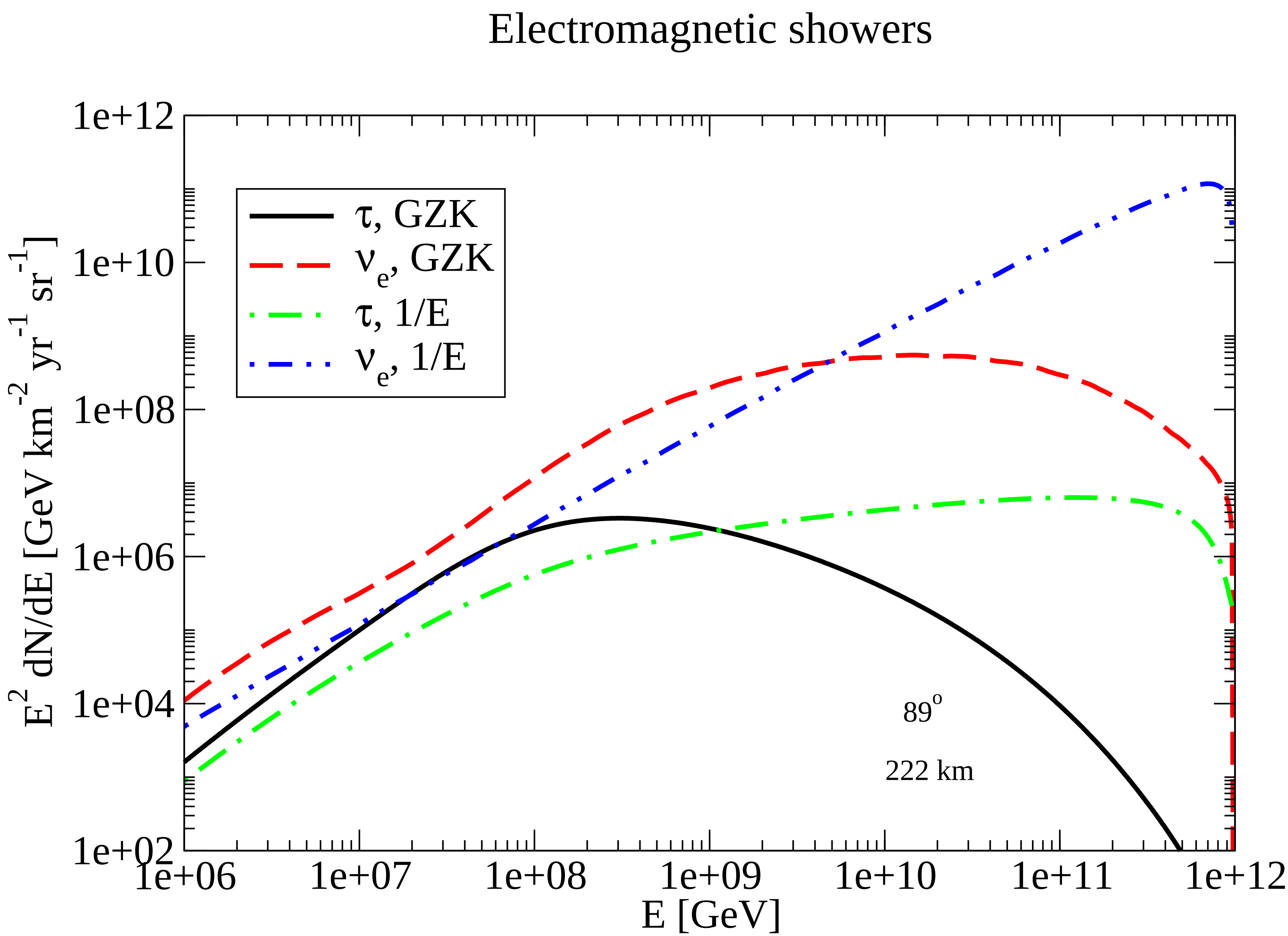
  $\nu_\tau$ CC interactions: $\nu_\tau + N \rightarrow \tau + X$

  $\nu_{e,\mu}$ NC and CC interactions



Electromagnetic showers
85°
τ decay
ν_e interaction
"lollipop"
"double bang"
secondary ν_e
E^2 dN/dE [GeV km^-2 yr^-1 sr^-1]
E [GeV]
1e+00
1e+01
1e+02
1e+03
1e+04
1e+05
1e+06
1e+07
1e+08
1e+09
1e+10
1e+11
1e+12


GZK


Electromagnetic showers
τ, GZK
ν_e, GZK
τ, 1/E
ν_e, 1/E
89°
222 km
E [GeV]
E^2 dN/dE [GeV km^-2 yr^-1 sr^-1]
1e+02
1e+04
1e+06
1e+08
1e+10
1e+12
1e+06
1e+07
1e+08
1e+09
1e+10
1e+11
1e+12

GZK

# Very High Energy Neutrinos

- tau energy loss very important at high energies
- NC important at high energy
- surface trajectories dominate at high energies
- deeper trajectories have significant contributions at energies between $\sim 10^6 - 10^8$ GeV, due to regeneration effects
- for large volume detectors the enhancement occurs in a broader energy range and peaks at higher energy
- regeneration smaller for fluxes which are steep at high energy
- good sensitivity to cross sections
- with combination of observables can distinguish particle physics from astrophysics effects

## Very High Energy Neutrinos

- probe particle physics, astrophysics, cosmology
- probe new energy and density regimes
- correlated with cosmic rays, gamma rays, etc.
- need many observables and detailed computations
- just beginning: A LOT of data to come

Opening new windows can lead to discoveries