NEUTRINO PHYSICS WORKING GROUP (WG3)

HIGHLIGHTS A

Manimala Mitra and Poonam Mehta

Institute of Physics, Bhubaneswar and
Jawaharlal Nehru University, New Delhi

Sources

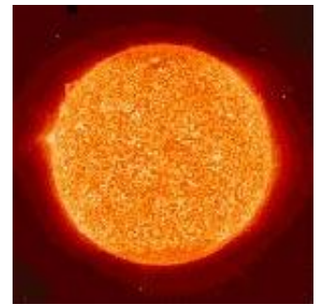
1 eV = 1.6×10^{-19} Joules

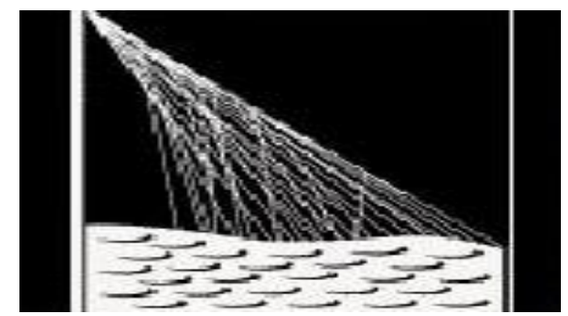
1 TeV = $1.6 \times 10^{-19} \times 10^{12}$ Joules = 1.6×10^{-7} Joules

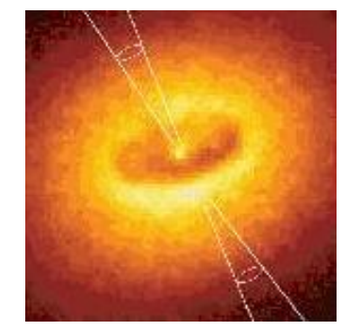
$1/2\ m\ v^2 = 1.6 \times 10^{-7}$ Joules, $m = 2 \times 10^{-6}$ kg therefore v = 0.4 m/s = 1.4 kph

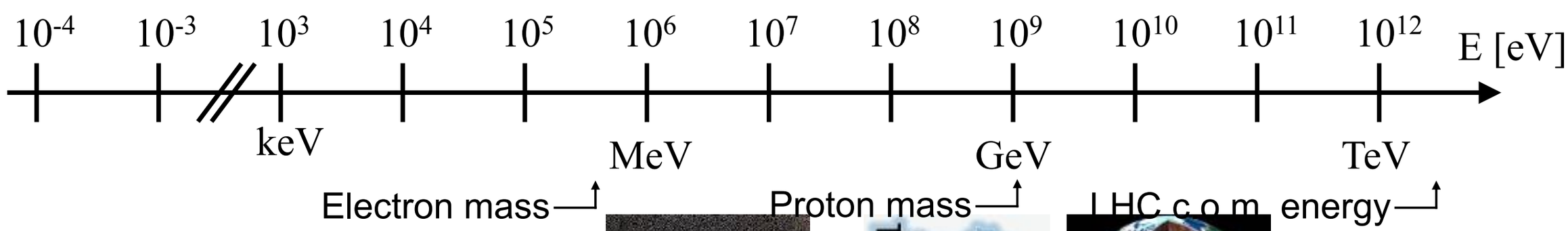
TeV : Energy of a flying mosquito!

Natural sources

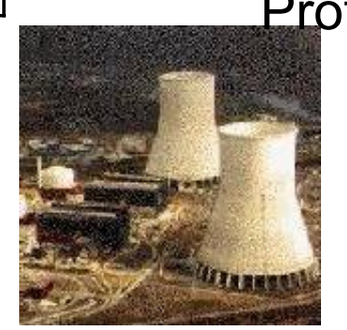


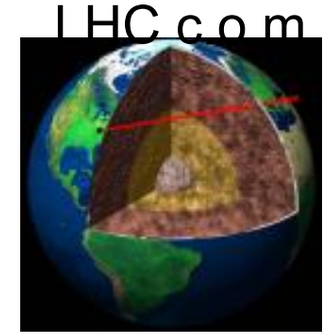






Man-made sources



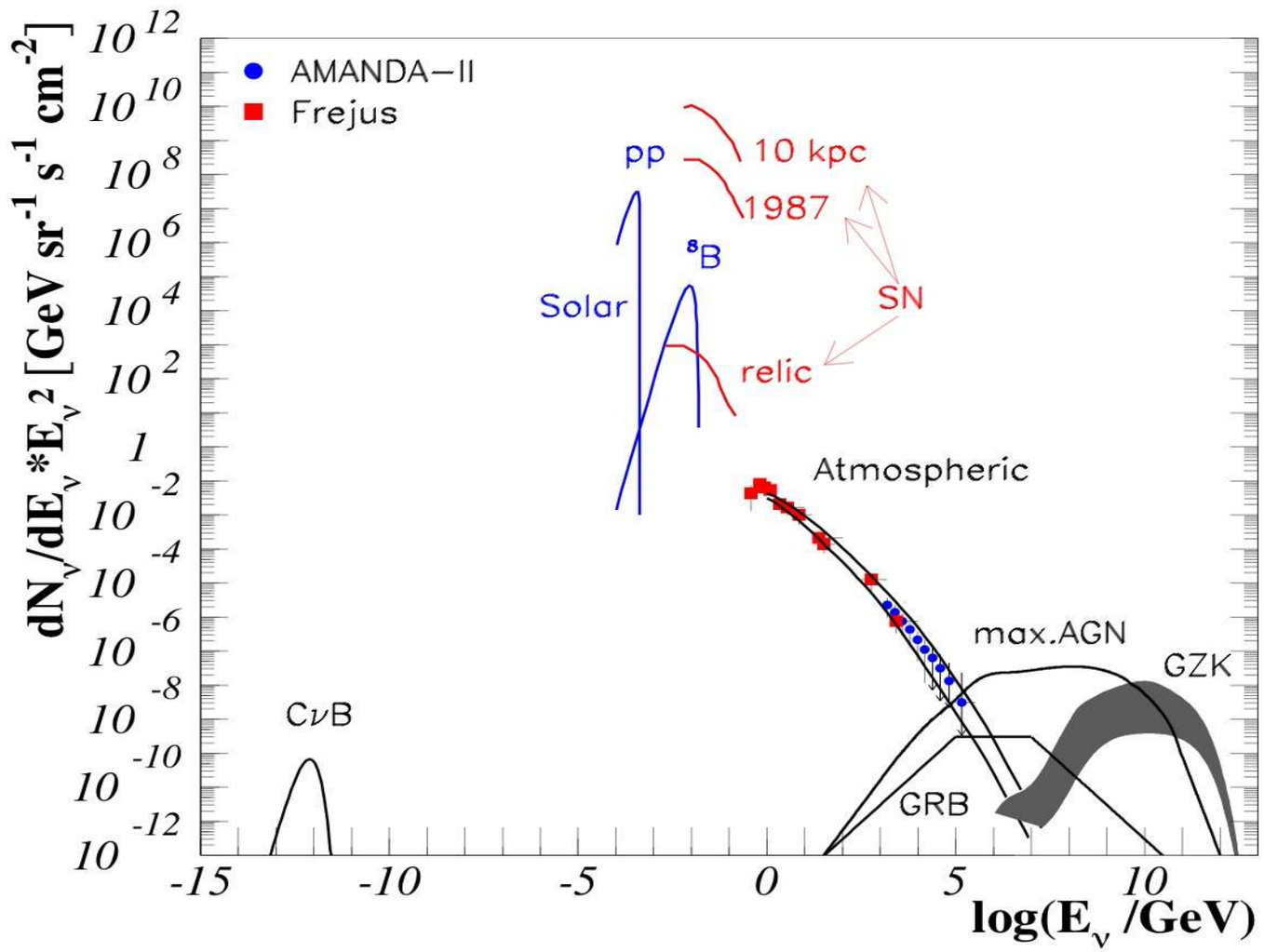


Spectrum of natural neutrinos

- Sub-eV: Cosmological
- MeV: Sun, SN
- MeV-GeV: Atmospheric
- TeV: Astrophysical
- EeV: GZK neutrinos

$$p + \gamma_{CMB} \rightarrow \pi^+ + n$$

$$E_{th} \simeq 5 \times 10^{19}\ eV$$



Ref: Greisen, PRL16, 748 (1966); Zatsepin and Kuzmin, ZhETF Pisma4, 114 (1966)

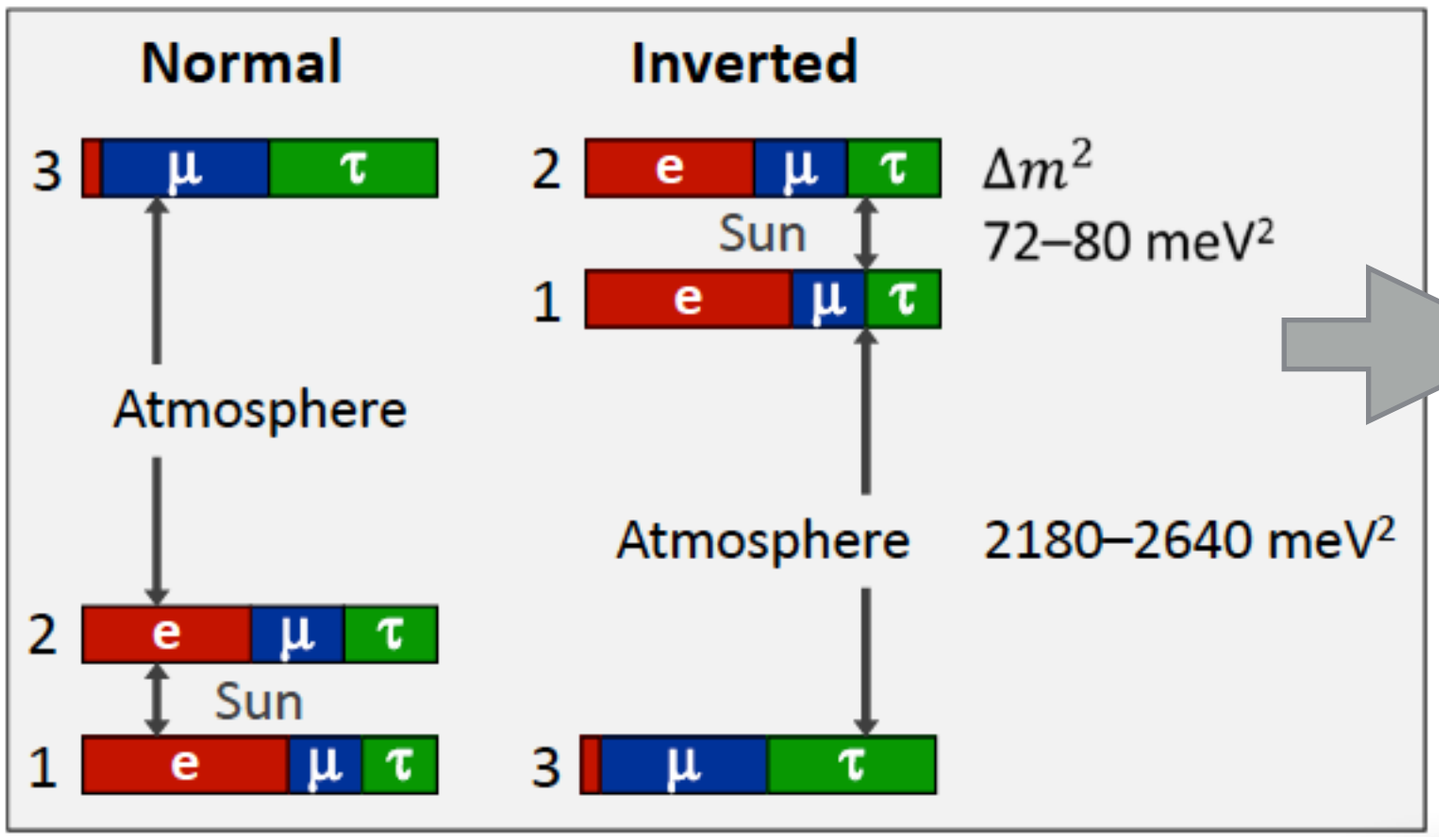
- Note : The 14 TeV cm energy at LHC implies a 0.1 EeV proton in the lab frame

$$E_{cm} = \sqrt{2 m_p E_{lab}}$$

Three flavour parameters

Three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ (Euler angles for 3D rotation), $c_{ij} = \cos\theta_{ij}$, a CP-violating "Dirac phase" δ, and two "Majorana phases" α_2 and α_3

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\substack{39^\circ < \theta_{23} < 53^\circ \\ \text{Atmospheric/LBL-Beams}}} \underbrace{\begin{pmatrix}c_{13} & 0 & e^{-i\delta}s_{13}\\ 0 & 1 & 0\\ -e^{i\delta}s_{13} & 0 & c_{13}\end{pmatrix}}_{\substack{7^\circ < \theta_{13} < 11^\circ \\ \text{Reactor}}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\substack{33^\circ < \theta_{12} < 37^\circ \\ \text{Solar/KamLAND}}} \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\frac{\alpha_2}{2}} & 0\\ 0 & 0 & e^{i\frac{\alpha_3}{2}}\end{pmatrix}}_{\substack{\text{Relevant for} \\ 0\nu2\beta \text{ decay}}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



Issues :

Improve precision

Mass ordering

Octant of θ_{23}

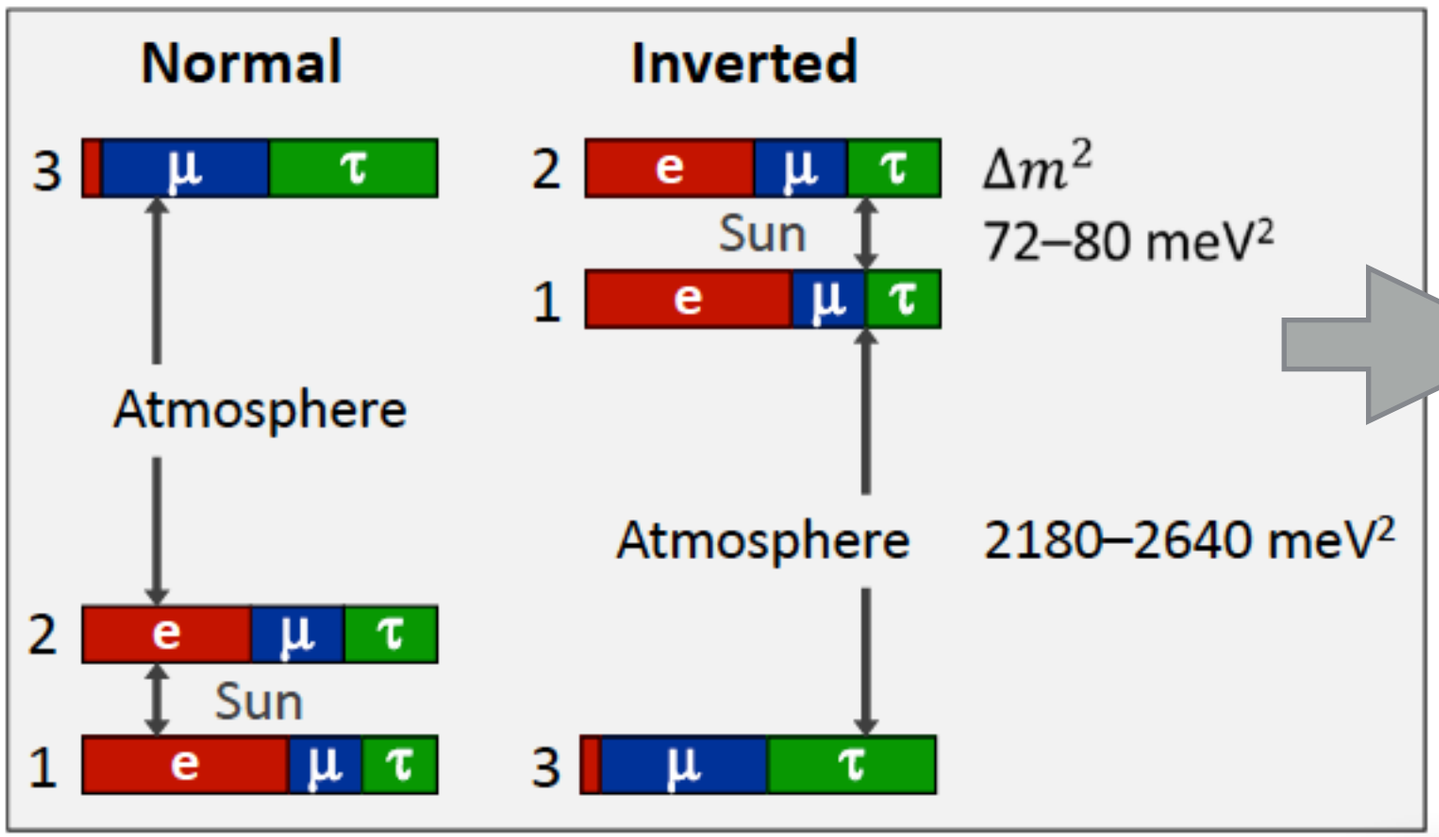
Dirac CP phase

Absolute neutrino mass

Three flavour parameters

Three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ (Euler angles for 3D rotation), $c_{ij} = \cos\theta_{ij}$, a CP-violating "Dirac phase" δ, and two "Majorana phases" α_2 and α_3

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\substack{39^\circ < \theta_{23} < 53^\circ \\ \text{Atmospheric/LBL-Beams}}} \underbrace{\begin{pmatrix}c_{13} & 0 & e^{-i\delta}s_{13}\\ 0 & 1 & 0\\ -e^{i\delta}s_{13} & 0 & c_{13}\end{pmatrix}}_{\substack{7^\circ < \theta_{13} < 11^\circ \\ \text{Reactor}}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\substack{33^\circ < \theta_{12} < 37^\circ \\ \text{Solar/KamLAND}}} \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\frac{\alpha_2}{2}} & 0\\ 0 & 0 & e^{i\frac{\alpha_3}{2}}\end{pmatrix}}_{\substack{\text{Relevant for} \\ 0\nu2\beta \text{ decay}}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



Issues :
Improve precision
Mass ordering
Octant of θ_{23}
Dirac CP phase
Absolute neutrino mass

PLENARY : Sanjib Agarwalla

Pattern of mixing

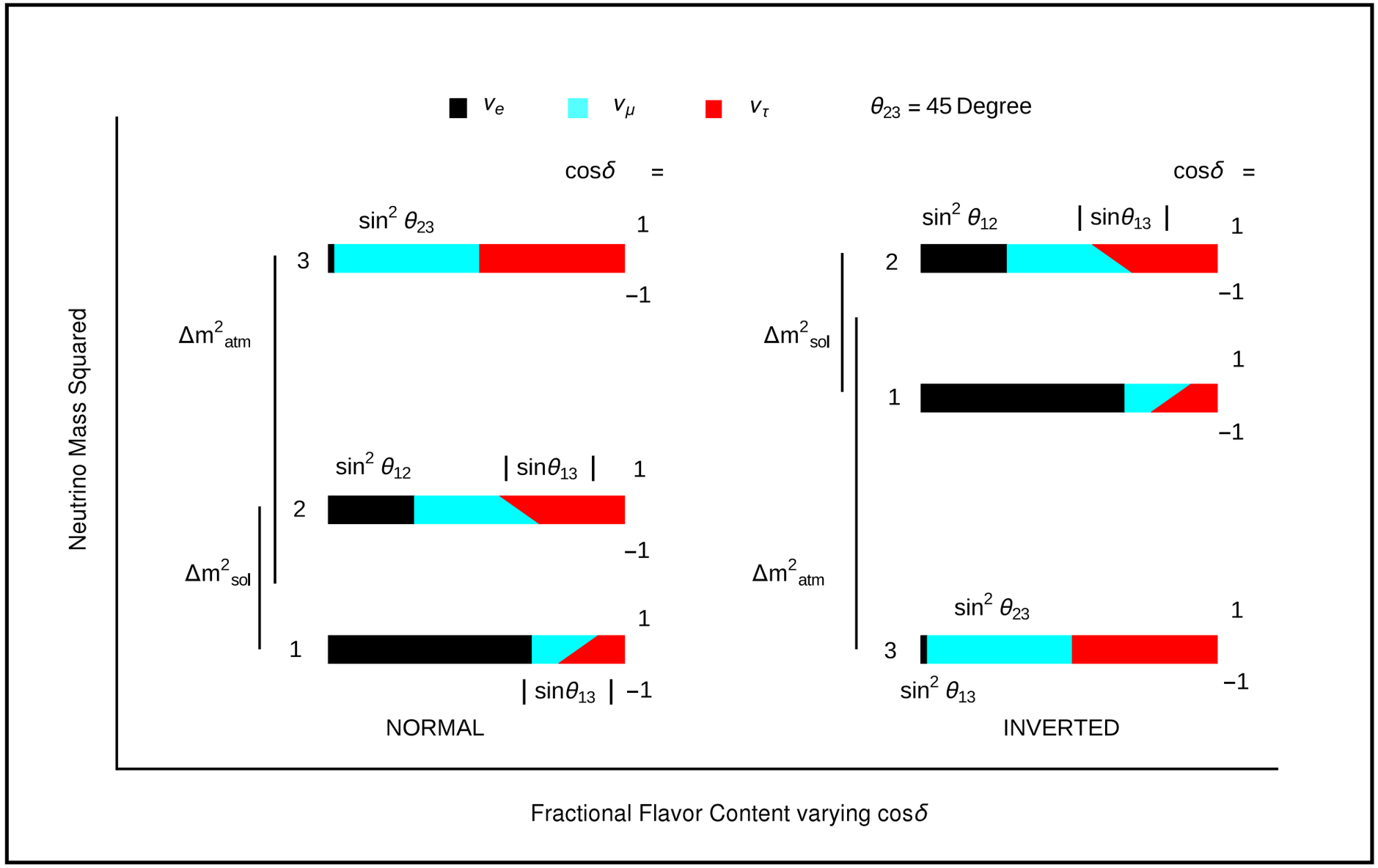
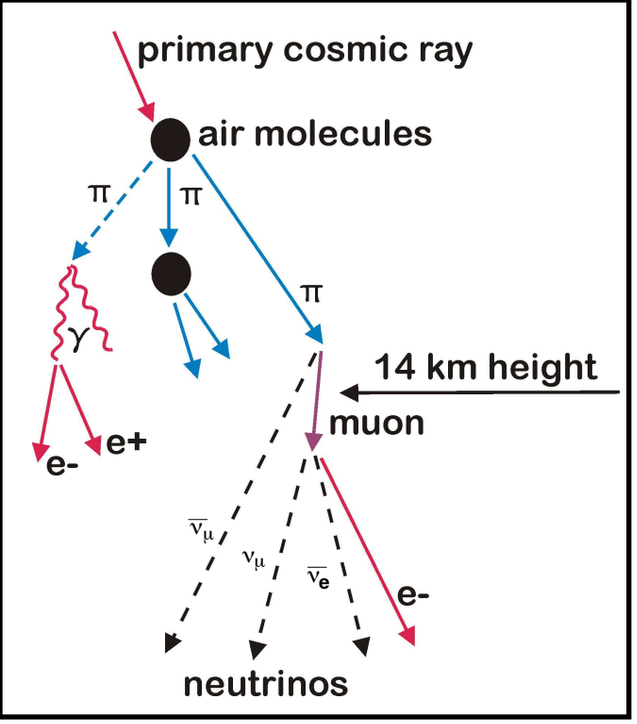
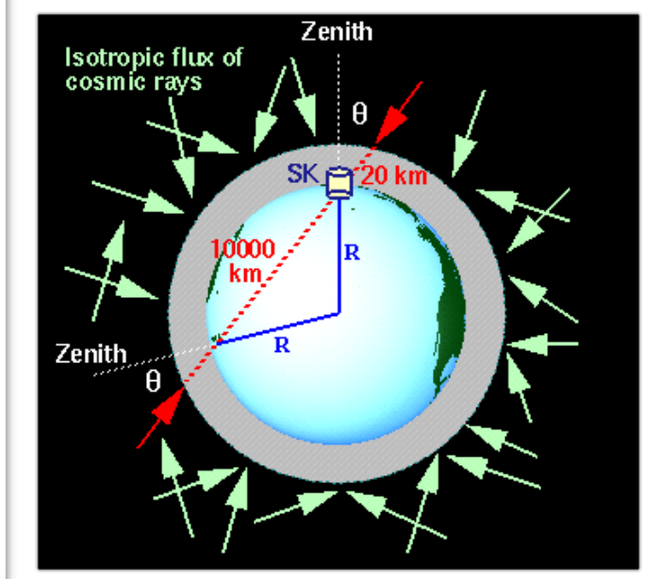


Image Credit : Jogesh Rout

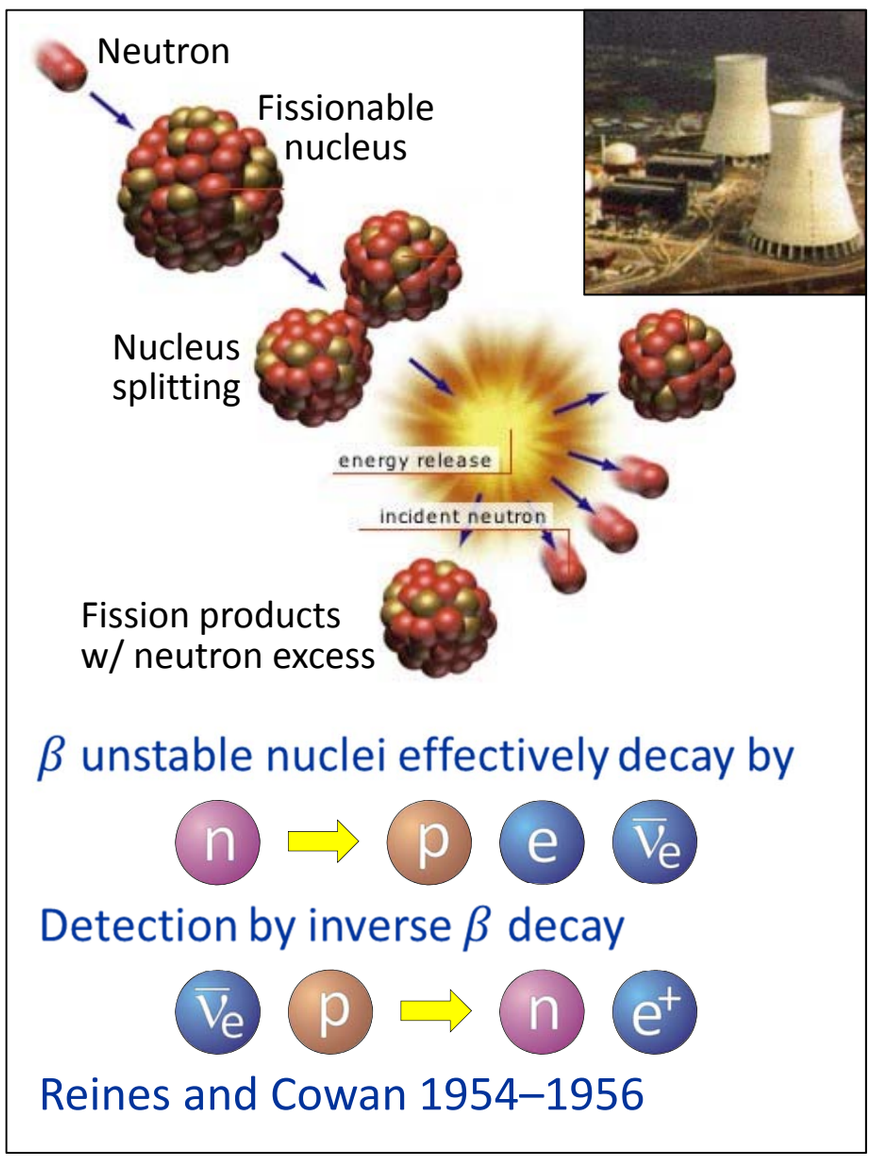
Standard and new physics





- **ATMOSPHERIC NEUTRINOS (16)**
  - D. Indumathi (overview)
  - Lakshmi S Mohan (parameter estimation), Moon Moon Devi (sterile nus), Amina Khatun (new physics and ICAL)

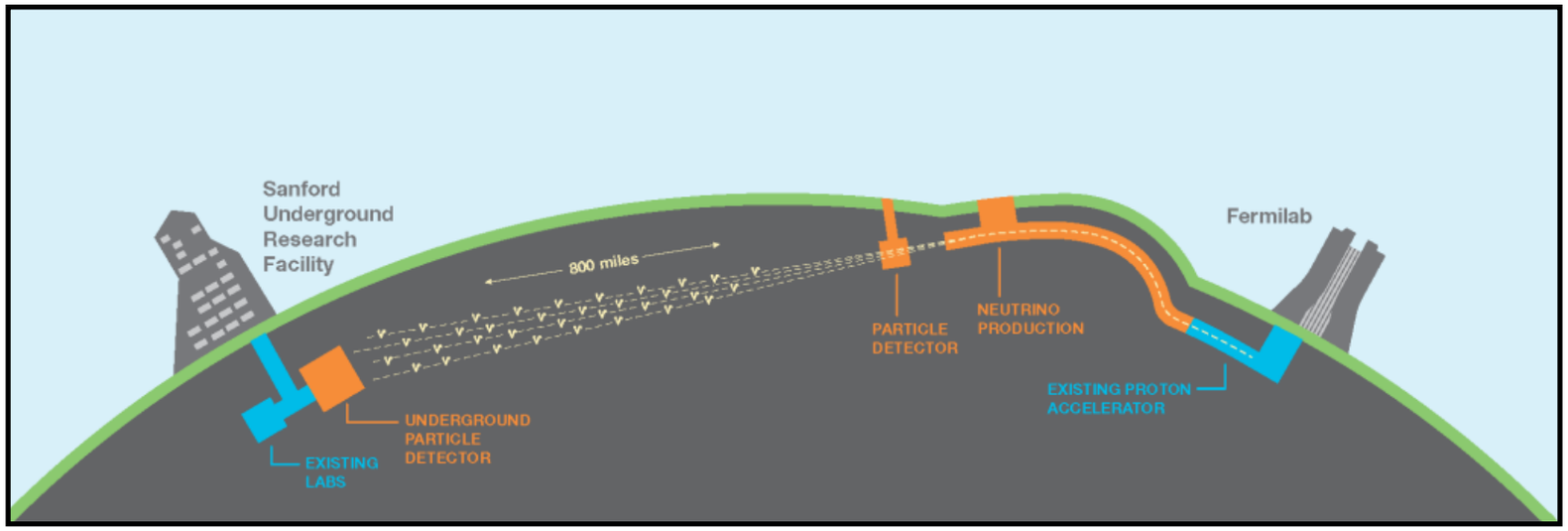
$$\pi^+ \to \mu^+ + \nu_\mu \qquad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$



- **REACTOR NEUTRINOS (16)**
  - Sushant Raut (overview)

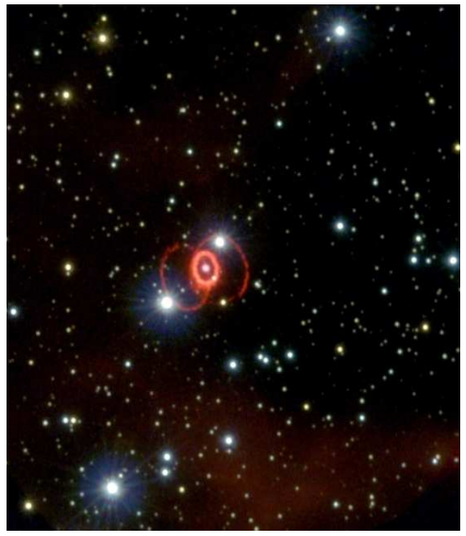
Standard and new physics

- **ACCELERATOR NEUTRINOS (21)**
  - Sandhya Choubey (long baseline neutrinos)
    - Rathin Adhikari (Non standard interactions),
    - Sabya Sachi Chatterjee (Sterile neutrinos),
    - Suprabh Prakash (Neutral Currents),
    - K N Deepthi (sensitivity studies at future experiments)
    - Samiran Roy (Short baseline neutrino experiments)



Astroparticle physics with neutrinos

- **SUPERNOVA NEUTRINOS (21)**
  - Amol Dighe (overview of supernova neutrinos)
    - Manibrata Sen (new physics + supernova neutrinos)

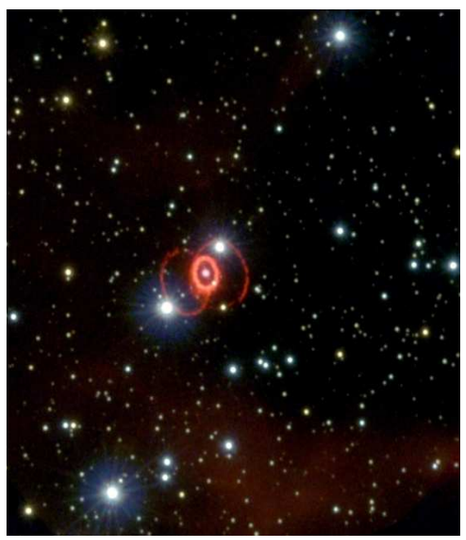


(Hubble image)

- **COSMOLOGICAL NEUTRINOS (15)**
  - Arindam Mazumdar (neutrino cosmology)

Astroparticle physics with neutrinos

- **SUPERNOVA NEUTRINOS (21)**
  - Amol Dighe (overview of supernova neutrinos)
    - Manibrata Sen (new physics + supernova neutrinos)



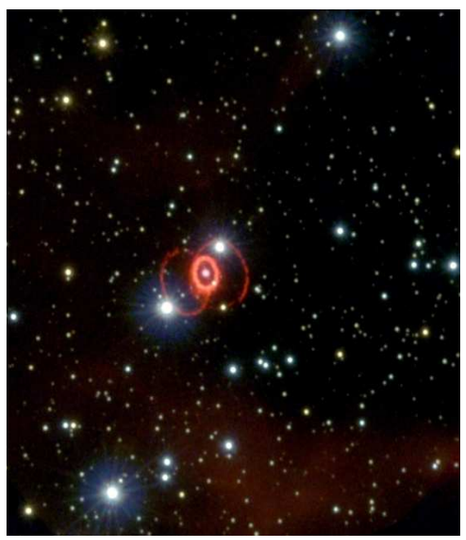
(Hubble image)

JOINT SESSION WITH WG V

- **COSMOLOGICAL NEUTRINOS (15)**
  - Arindam Mazumdar (neutrino cosmology)

Astroparticle physics with neutrinos

- **SUPERNOVA NEUTRINOS (21)**
  - Amol Dighe (overview of supernova neutrinos)
    - Manibrata Sen (new physics + supernova neutrinos)



(Hubble image)

JOINT SESSION WITH WG V

- **COSMOLOGICAL NEUTRINOS (15)**
  - Arindam Mazumdar (neutrino cosmology)

JOINT SESSION WITH WG V

Relic neutrino background

- Lies at the lowest energy end of the neutrino spectrum
- Temperature :

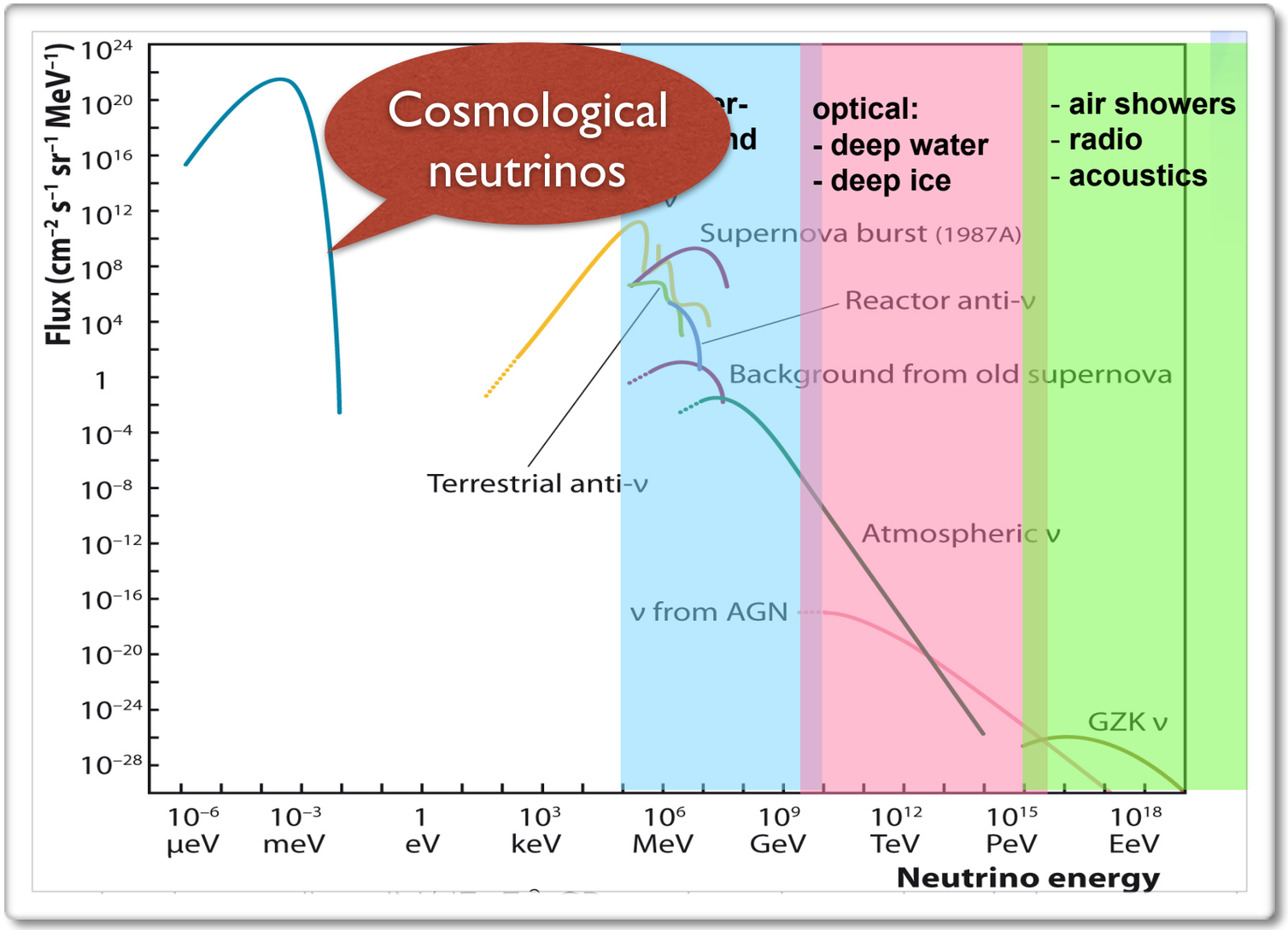
$$T_{\nu,0} = \left(\frac{4}{11}\right)^{1/3} T_{CMB,0} = 1.95\ K$$

- Number density per flavour :

$$n_{\nu,0} = \frac{6}{4}\frac{\zeta(3)}{\pi^2} T_{\nu,0}^3 = 112\ cm^{-3}$$

- Energy density per flavour :

$$\Omega_\nu h^2 = \frac{m_\nu}{93\ eV}$$



http://hep.bu.edu/~superk/atmnu/zenith-geom-small.gif

Relic neutrino background

- Lies at the lowest energy end of the neutrino spectrum
- Temperature :

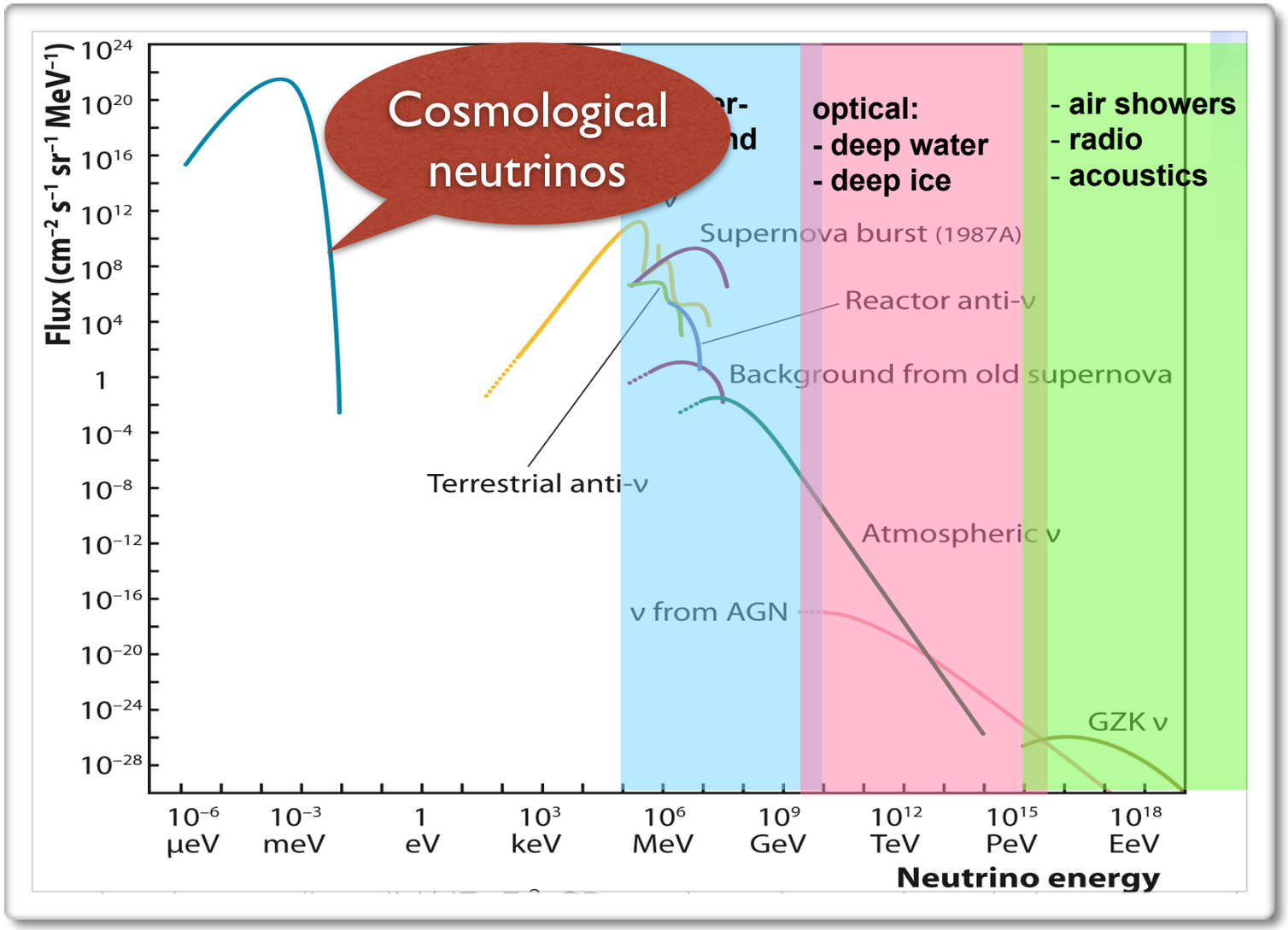
$$T_{\nu,0} = \left(\frac{4}{11}\right)^{1/3} T_{CMB,0} = 1.95\ K$$

- Number density per flavour :

$$n_{\nu,0} = \frac{6}{4}\frac{\zeta(3)}{\pi^2} T_{\nu,0}^3 = 112\ cm^{-3}$$

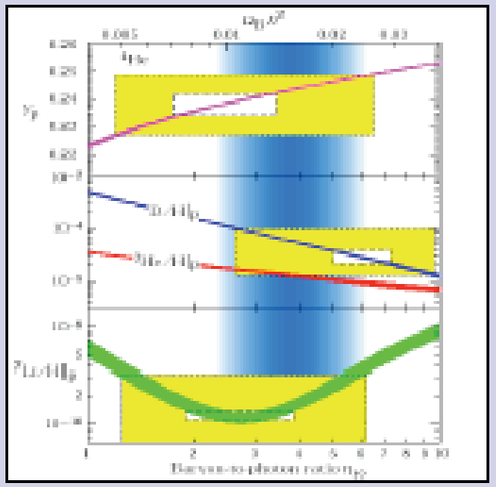
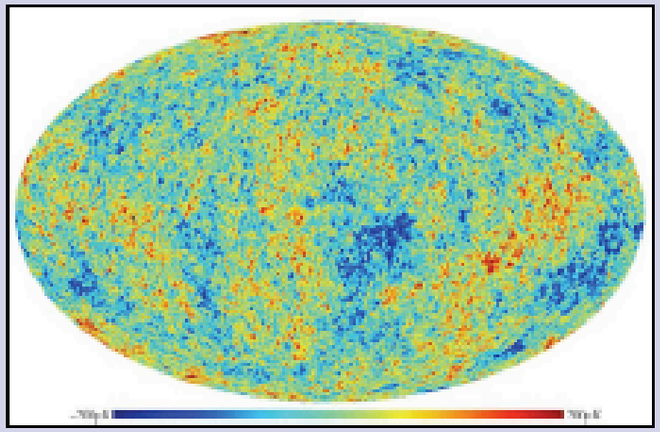
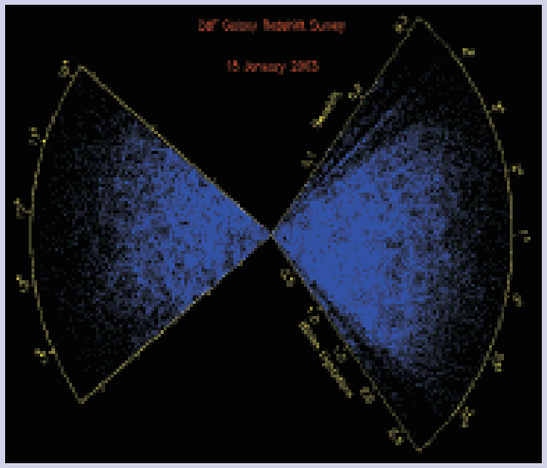
- Energy density per flavour :

$$\Omega_\nu h^2 = \frac{m_\nu}{93\ eV}$$

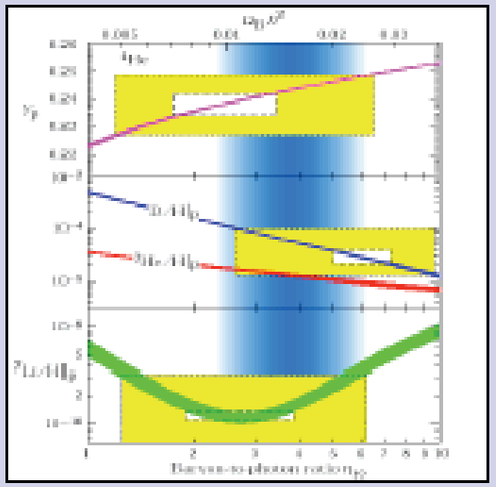
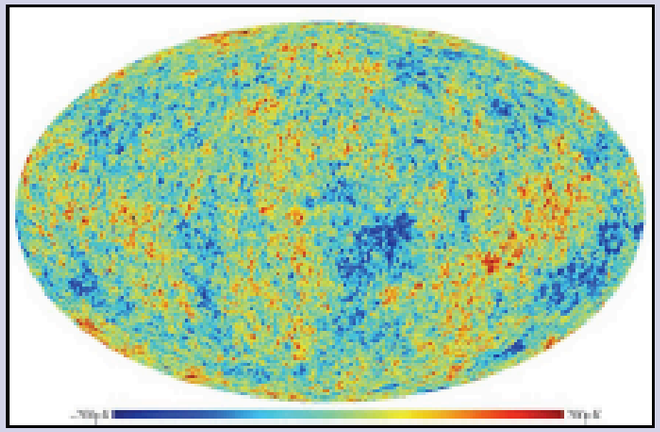
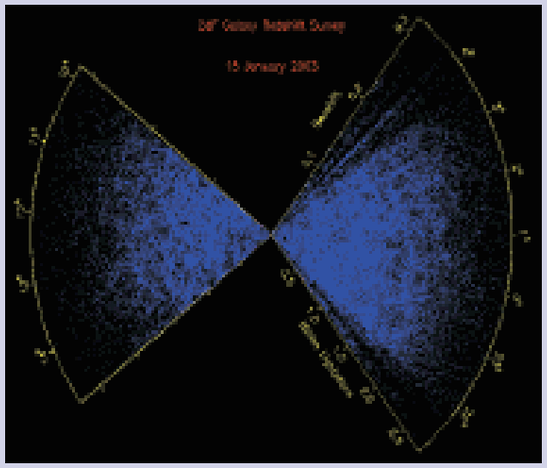


http://hep.bu.edu/~superk/atmnu/zenith-geom-small.gif

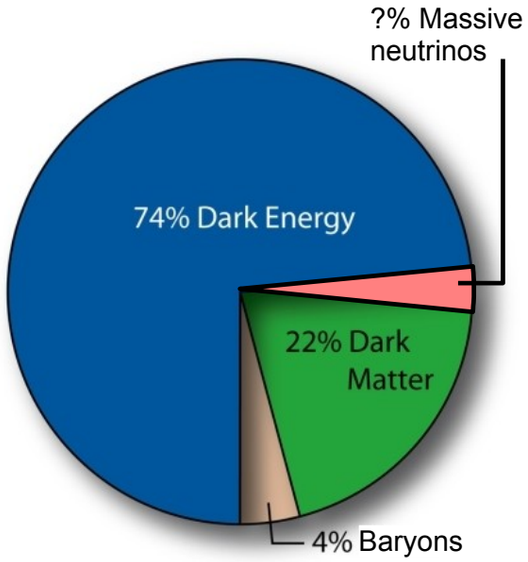
Impact of relic neutrinos on several cosmological epochs

		
Primordial Nucleosynthesis BBN	Cosmic Microwave Background CMB	Formation of Large Scale Structures LSS
T ~ MeV	T < eV	
ν_e vs $\nu_{\mu,\tau}$ N_{eff}	No flavour sensitivity	N_{eff} & m_ν

Impact of relic neutrinos on several cosmological epochs

		
Primordial Nucleosynthesis BBN	Cosmic Microwave Background CMB	Formation of Large Scale Structures LSS
T ~ MeV	T < eV	
ν_e vs $\nu_{\mu,\tau}$ N_{eff}	No flavour sensitivity	N_{eff} & m_ν

Neutrino mass : present limits



- Oscillation experiments : a **lower limit**

$$\min \sum m_\nu = 0.05 \text{ eV}$$
$$\min \Omega_\nu = 0.1\%$$

- Tritium beta decay experiment : an **upper limit**

$$m_e = \left(\sum_i |U_{ei}|^2 m_i^2 \right)^{1/2} < 2.2 \text{ eV}$$

$$\max \sum m_\nu = 7 \text{ eV}$$
$$\max \Omega_\nu = 12\%$$

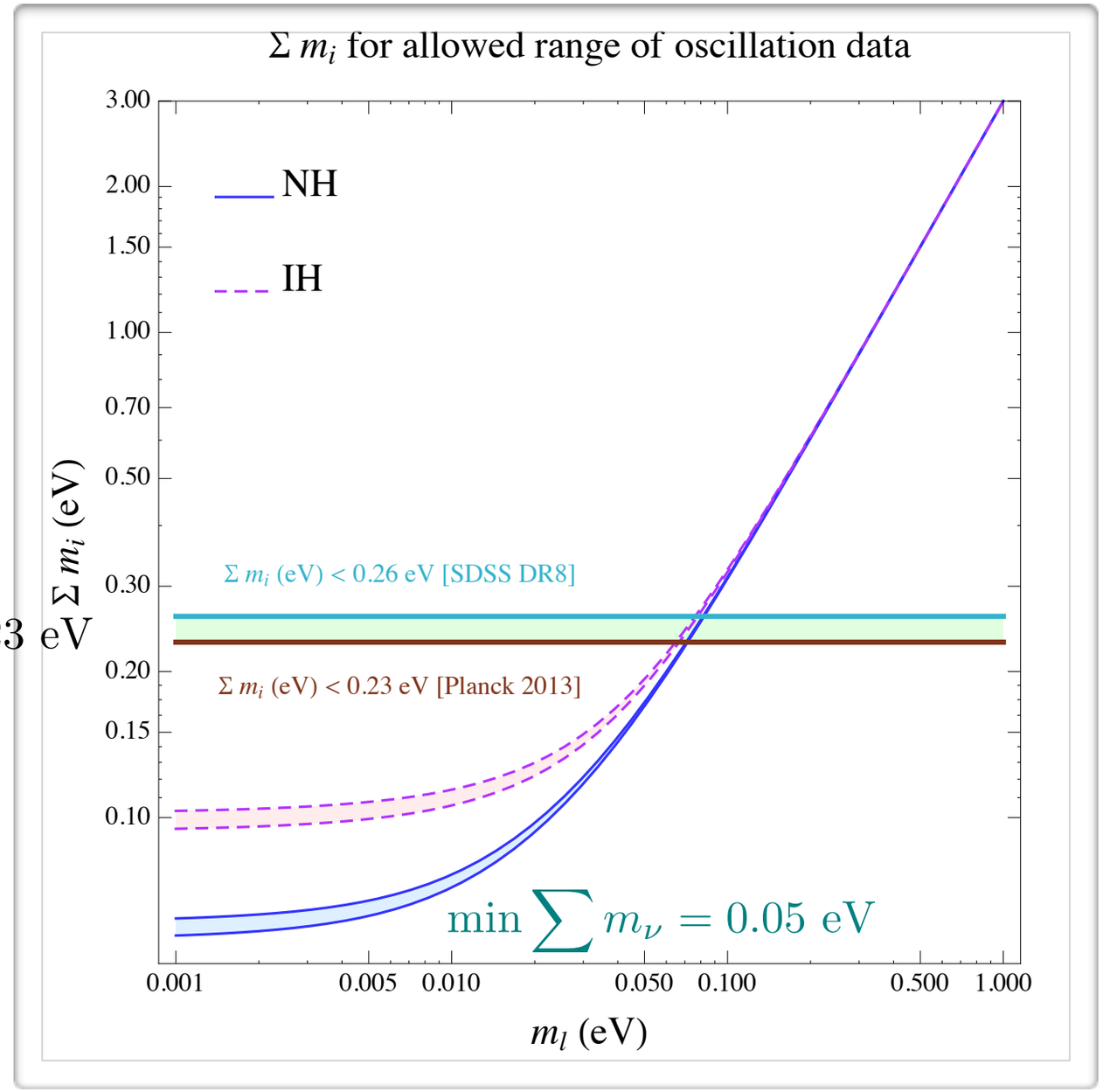
- **Cosmology : upper limit**

$$\sum m_\nu < 0.23 \text{ eV}$$

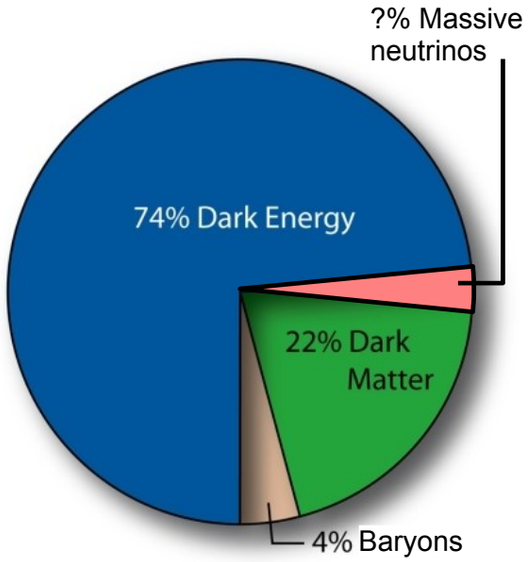
$$\Omega_\nu = \frac{\rho_\nu}{\rho_c} = \frac{\sum_i m_i}{93\ h^2\ eV}$$

$$\rho_\nu = m_\nu n_\nu$$

model-dependent



Neutrino mass : present limits



- Oscillation experiments : a **lower limit**

$$\min \sum m_\nu = 0.05 \text{ eV}$$
$$\min \Omega_\nu = 0.1\%$$

- Tritium beta decay experiment : an **upper limit**

$$m_e = \left(\sum_i |U_{ei}|^2 m_i^2 \right)^{1/2} < 2.2 \text{ eV}$$

$$\max \sum m_\nu = 7 \text{ eV}$$
$$\max \Omega_\nu = 12\%$$

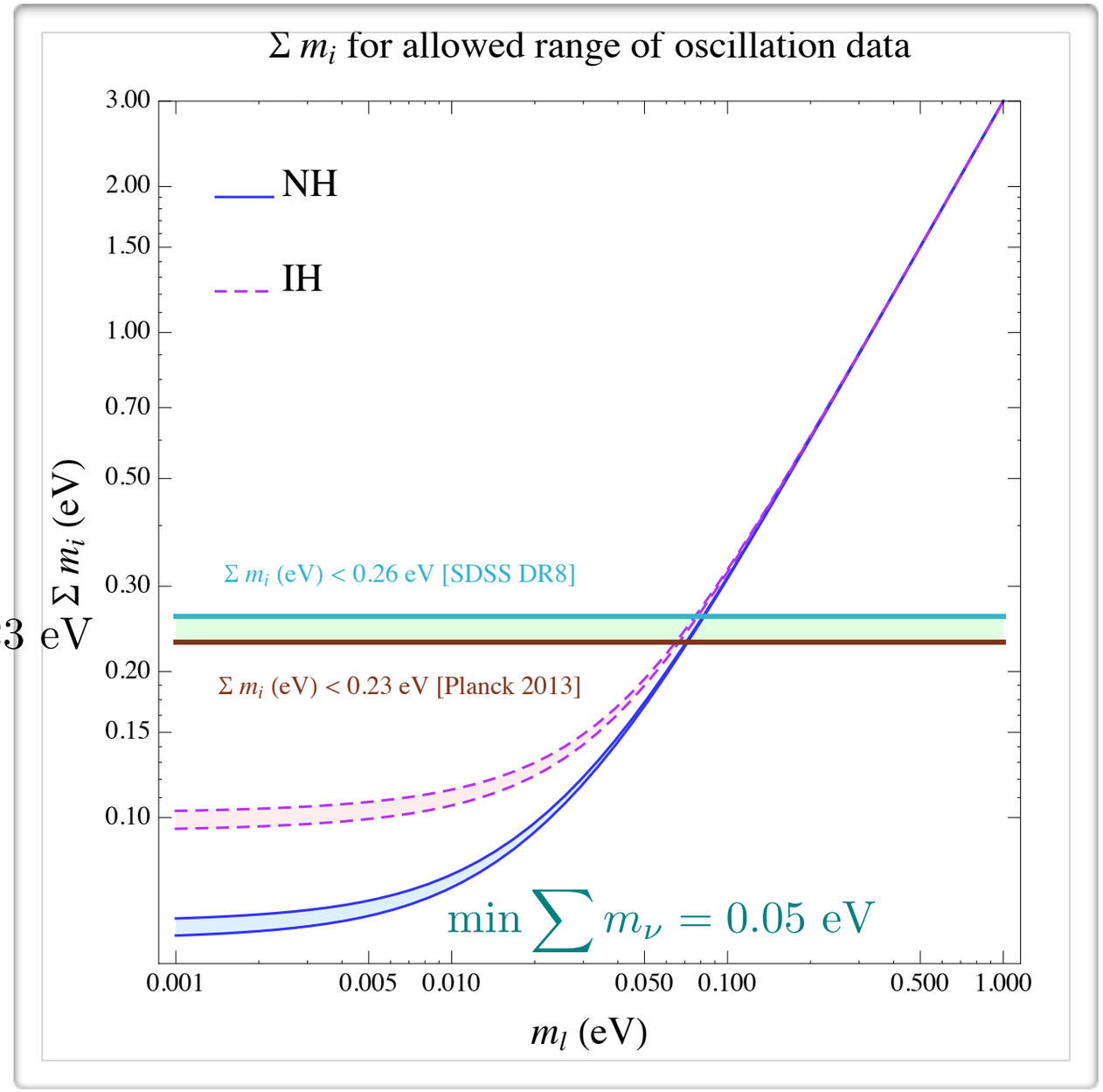
- **Cosmology : upper limit**

$$\sum m_\nu < 0.23 \text{ eV}$$

$$\Omega_\nu = \frac{\rho_\nu}{\rho_c} = \frac{\sum_i m_i}{93\ h^2\ eV}$$

$$\rho_\nu = m_\nu n_\nu$$

model-dependent



Mass hierarchy determination

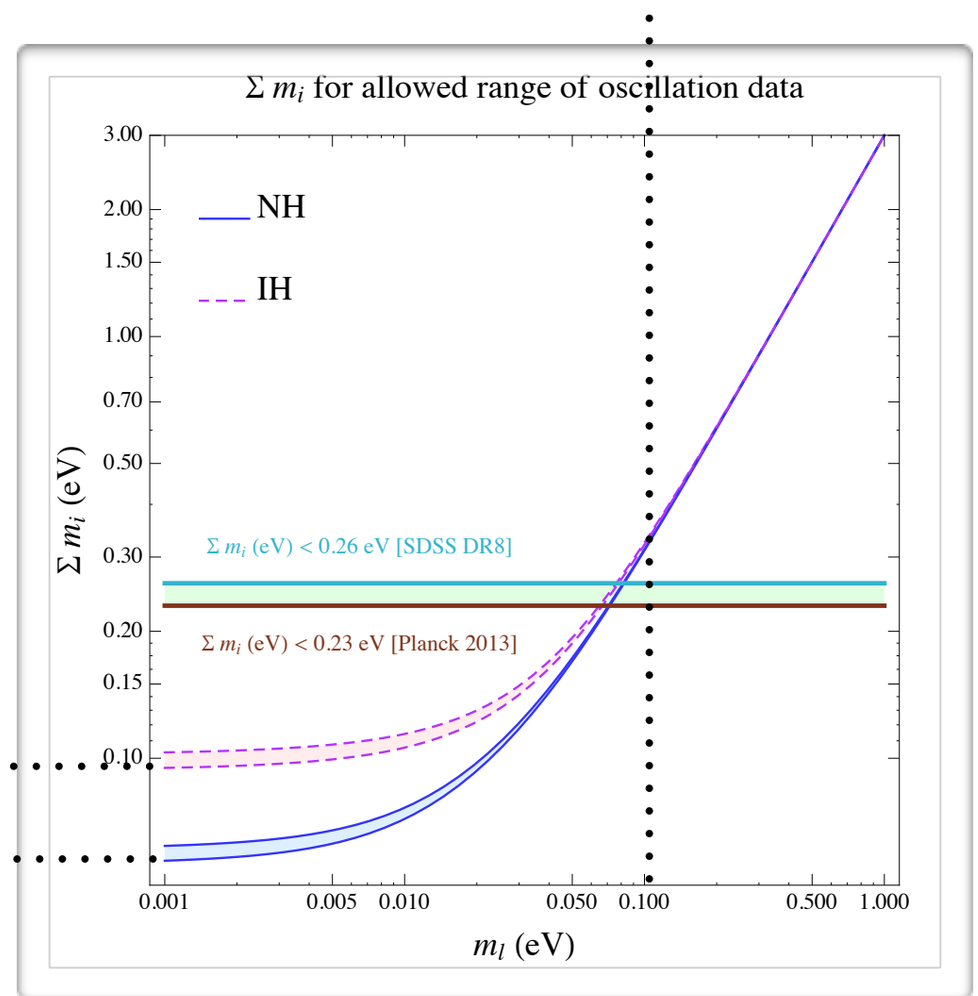
1. Normal hierarchy (NH) : sign of $\Delta m^2_{31} > 0$ or $m_3^2 > m_2^2 > m_1^2$

$$
\begin{aligned}
m_1 &= m_l; \quad m_2 = \sqrt{m_l^2 + \Delta m^2_{21}}; \quad m_3 = \sqrt{m_l^2 + \Delta m^2_{31}} \ . \\
\sum m_i &= m_l + \sqrt{m_l^2 + \Delta m^2_{21}} + \sqrt{m_l^2 + \Delta m^2_{31}}
\end{aligned}
$$

2. Inverted hierarchy (IH) : sign of $\Delta m^2_{31} < 0$ or $m_2^2 > m_1^2 > m_3^2$

$$
\begin{aligned}
m_1 &= \sqrt{m_l^2 - \Delta m^2_{31}} = \sqrt{m_l^2 - \Delta m^2_{32} - \Delta m^2_{21}}; \\
m_2 &= \sqrt{m_l^2 + \Delta m^2_{21} - \Delta m^2_{31}} = \sqrt{m_l^2 - \Delta m^2_{32}}; \\
m_3 &= m_l \ . \\
\sum m_i &= \sqrt{m_l^2 - \Delta m^2_{32} - \Delta m^2_{21}} + \sqrt{m_l^2 - \Delta m^2_{32}} + m_l
\end{aligned}
$$

- May be possible with cosmological probes and can be competitive with oscillation expts.



lightest neutrino state

- Meaningful if mass of lightest state is small

Mass hierarchy determination

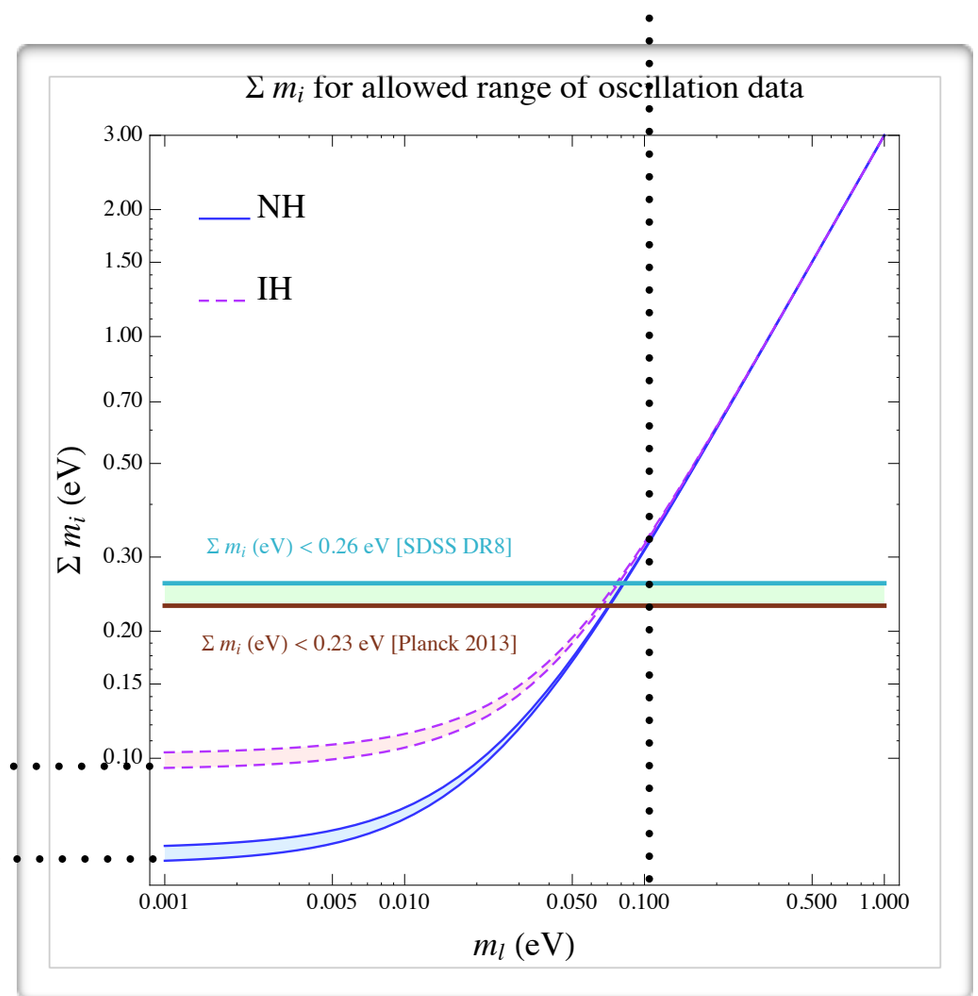
1. Normal hierarchy (NH) : sign of $\Delta m^2_{31} > 0$ or $m_3^2 > m_2^2 > m_1^2$

$$
\begin{aligned}
m_1 &= m_l; \quad m_2 = \sqrt{m_l^2 + \Delta m^2_{21}}; \quad m_3 = \sqrt{m_l^2 + \Delta m^2_{31}} \ . \\
\sum m_i &= m_l + \sqrt{m_l^2 + \Delta m^2_{21}} + \sqrt{m_l^2 + \Delta m^2_{31}}
\end{aligned}
$$

2. Inverted hierarchy (IH) : sign of $\Delta m^2_{31} < 0$ or $m_2^2 > m_1^2 > m_3^2$

$$
\begin{aligned}
m_1 &= \sqrt{m_l^2 - \Delta m^2_{31}} = \sqrt{m_l^2 - \Delta m^2_{32} - \Delta m^2_{21}}; \\
m_2 &= \sqrt{m_l^2 + \Delta m^2_{21} - \Delta m^2_{31}} = \sqrt{m_l^2 - \Delta m^2_{32}}; \\
m_3 &= m_l \ . \\
\sum m_i &= \sqrt{m_l^2 - \Delta m^2_{32} - \Delta m^2_{21}} + \sqrt{m_l^2 - \Delta m^2_{32}} + m_l
\end{aligned}
$$

- May be possible with cosmological probes and can be competitive with oscillation expts.

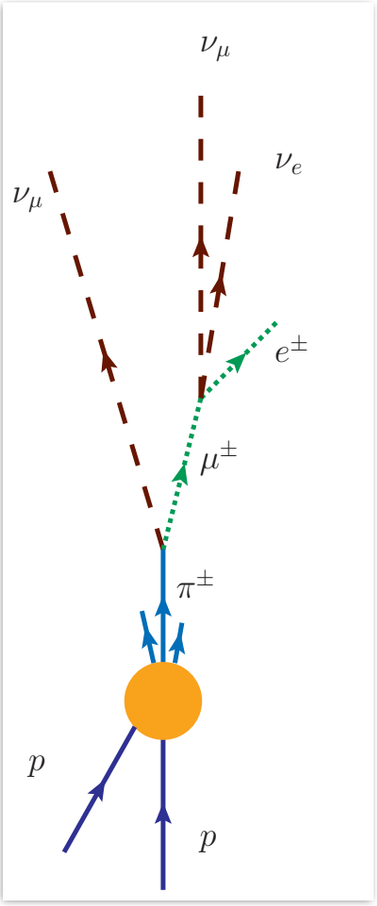


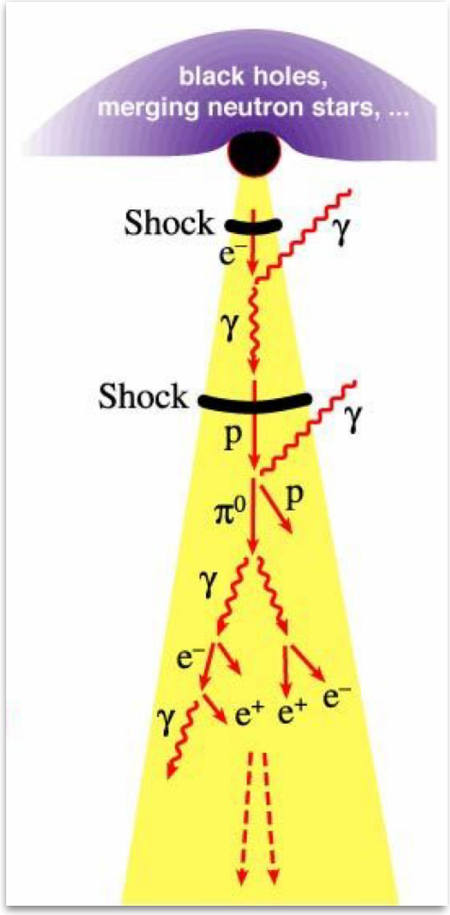
lightest neutrino state

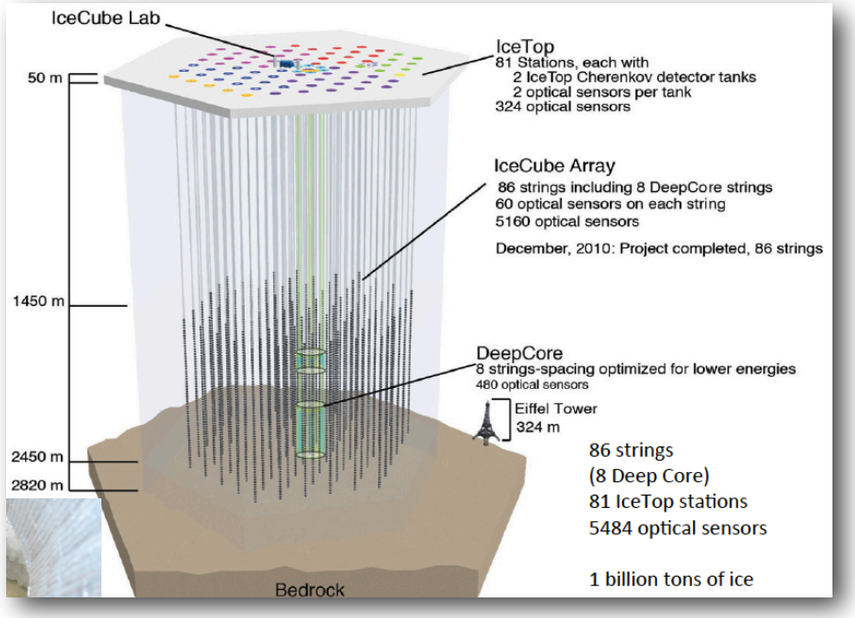
- Meaningful if mass of lightest state is small

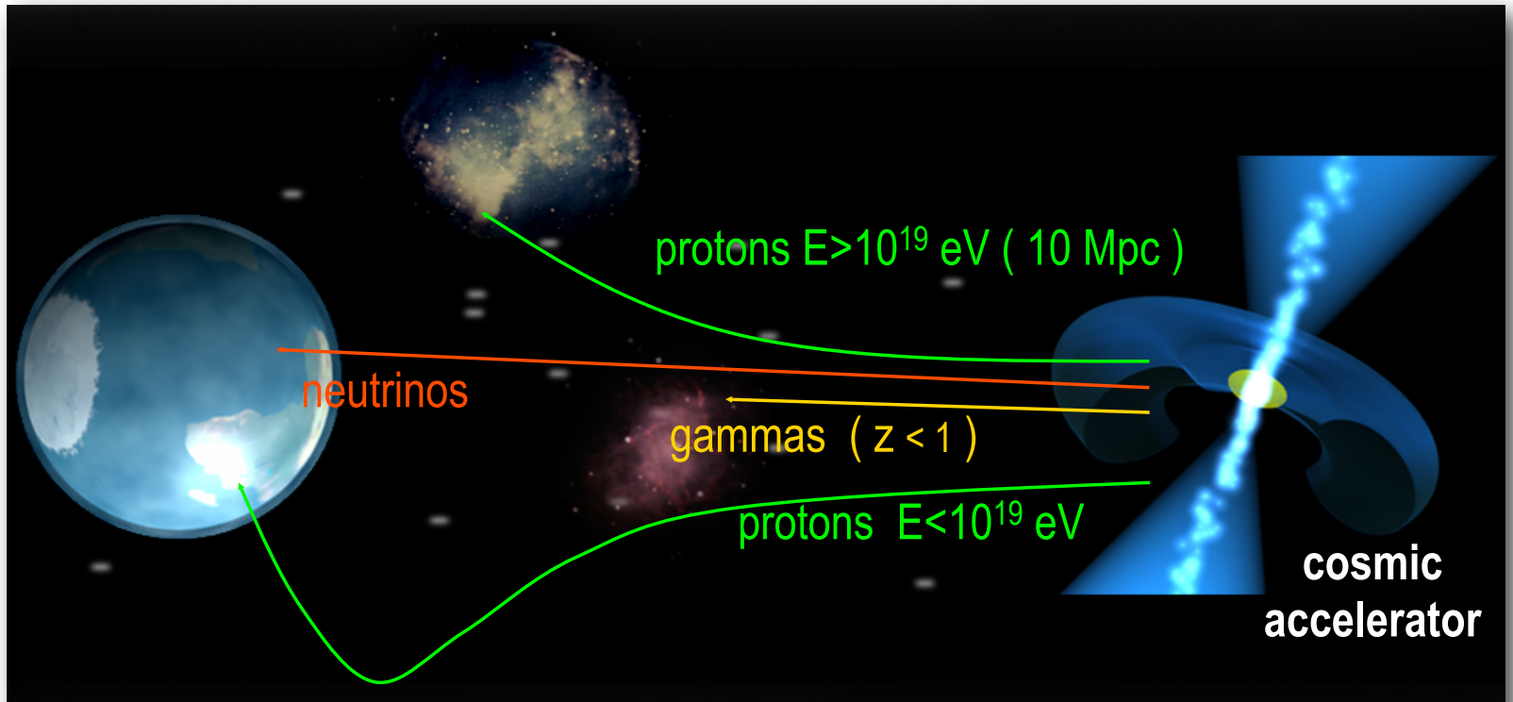
Astroparticle physics with neutrinos

- <u>ASTROPHYSICAL NEUTRINOS</u>
  - Raj Gandhi (anomalies and future directions) (17)
  - Debanjan Bose (multimessenger approach) (15)
    - Aritra Gupta (Dark Matter + IceCube) (17)
    - Ujjal Kumar Dey (BSM physics + IceCube) (22)



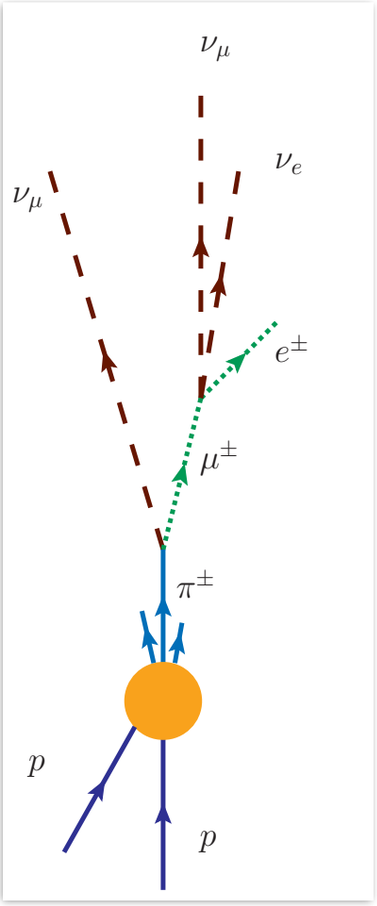


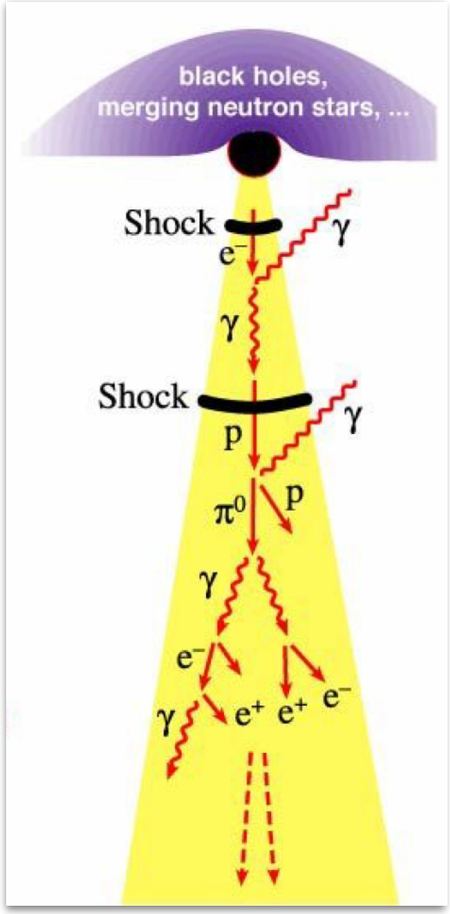


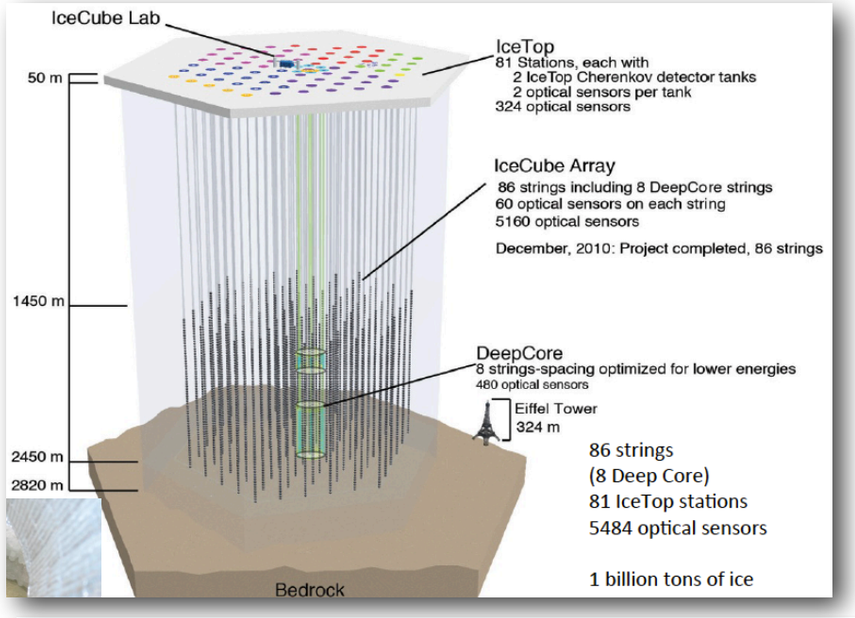


Astroparticle physics with neutrinos

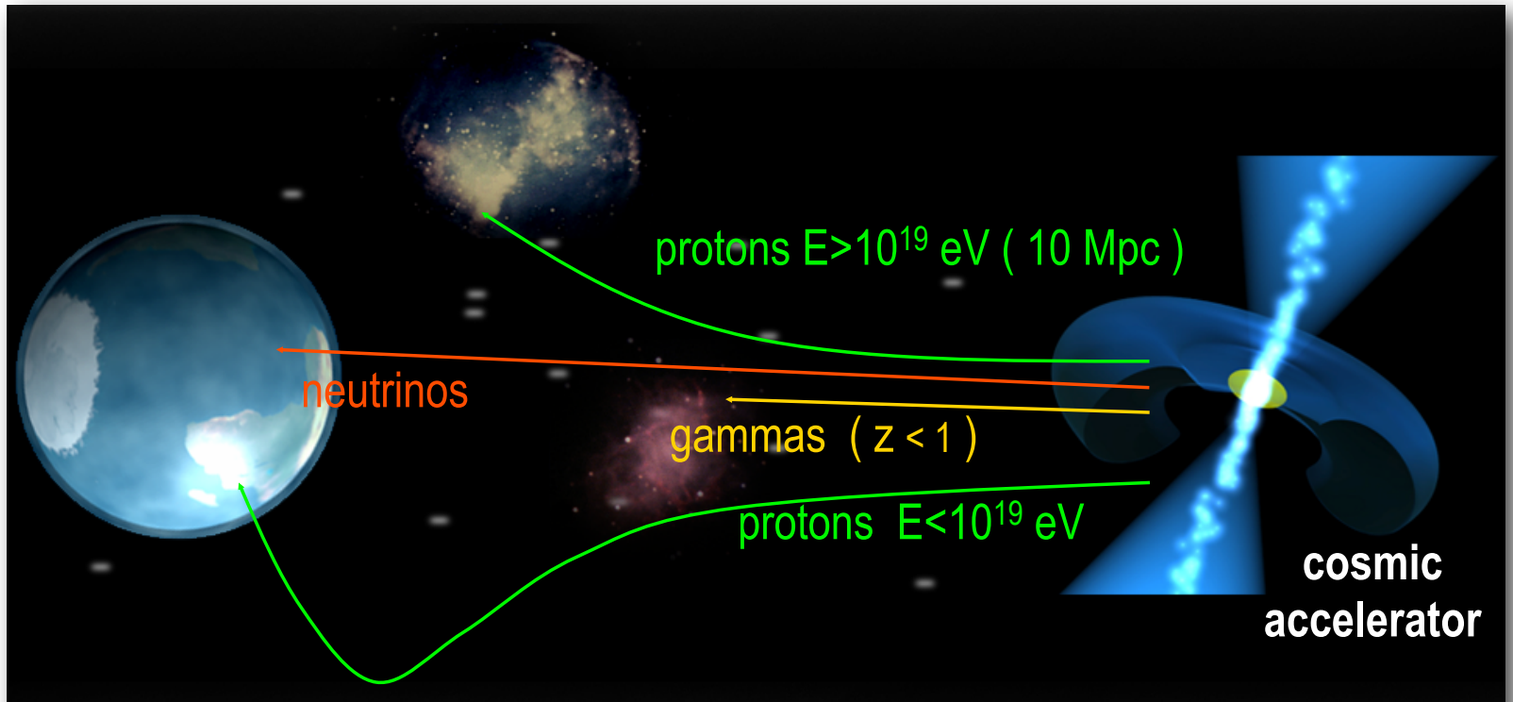
- **ASTROPHYSICAL NEUTRINOS**
  - Raj Gandhi (anomalies and future directions) (17)
  - Debanjan Bose (multimessenger approach) (15)
    - Aritra Gupta (Dark Matter + IceCube) (17)
    - Ujjal Kumar Dey (BSM physics + IceCube) (22)



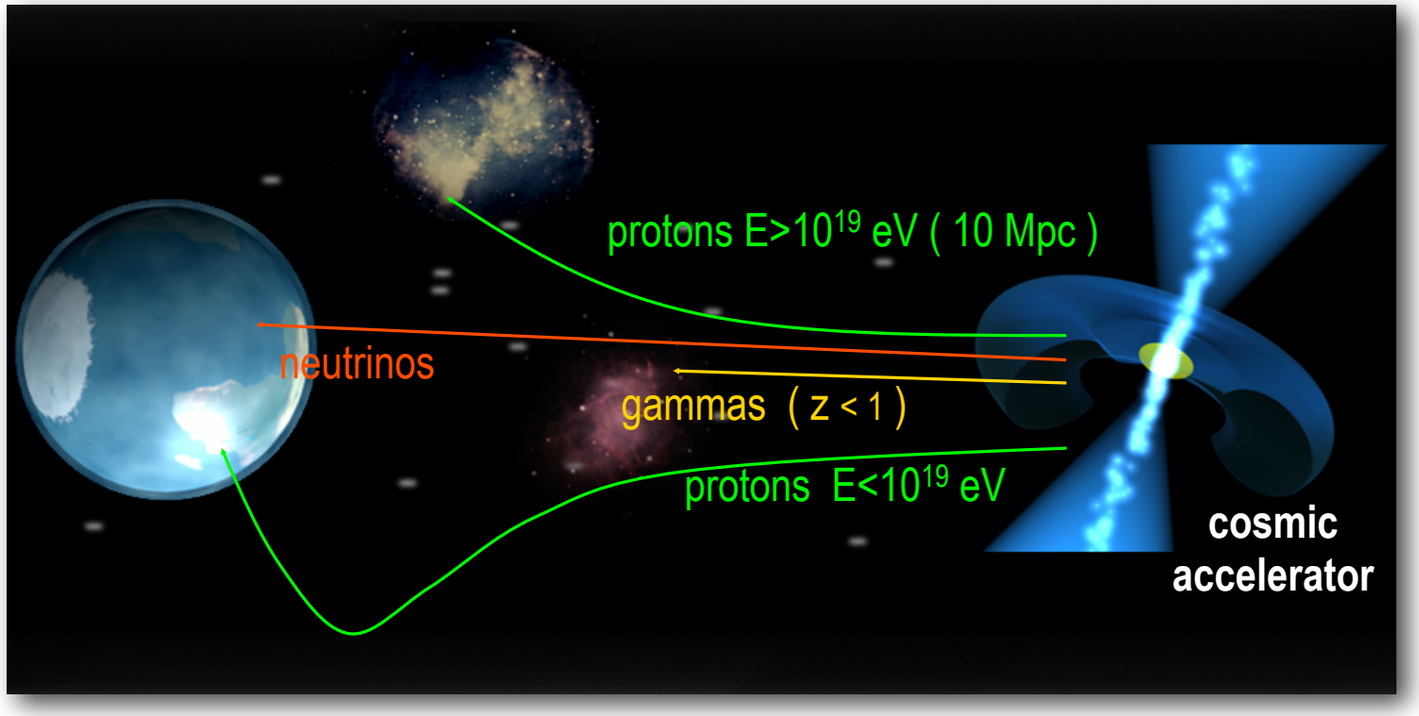




JOINT SESSION WITH WG V



Cosmic accelerators



Ref: Montaruli, talk at SSI 2010

$\gamma + \gamma_{2.7K}$

$$l_\gamma = \frac{1}{\sigma_{p-\gamma_{2.7K}} \times n_\gamma} \sim \frac{1}{5 \times 10^{-28} cm^2 \times 400 cm^{-3}} = 10 Mpc$$

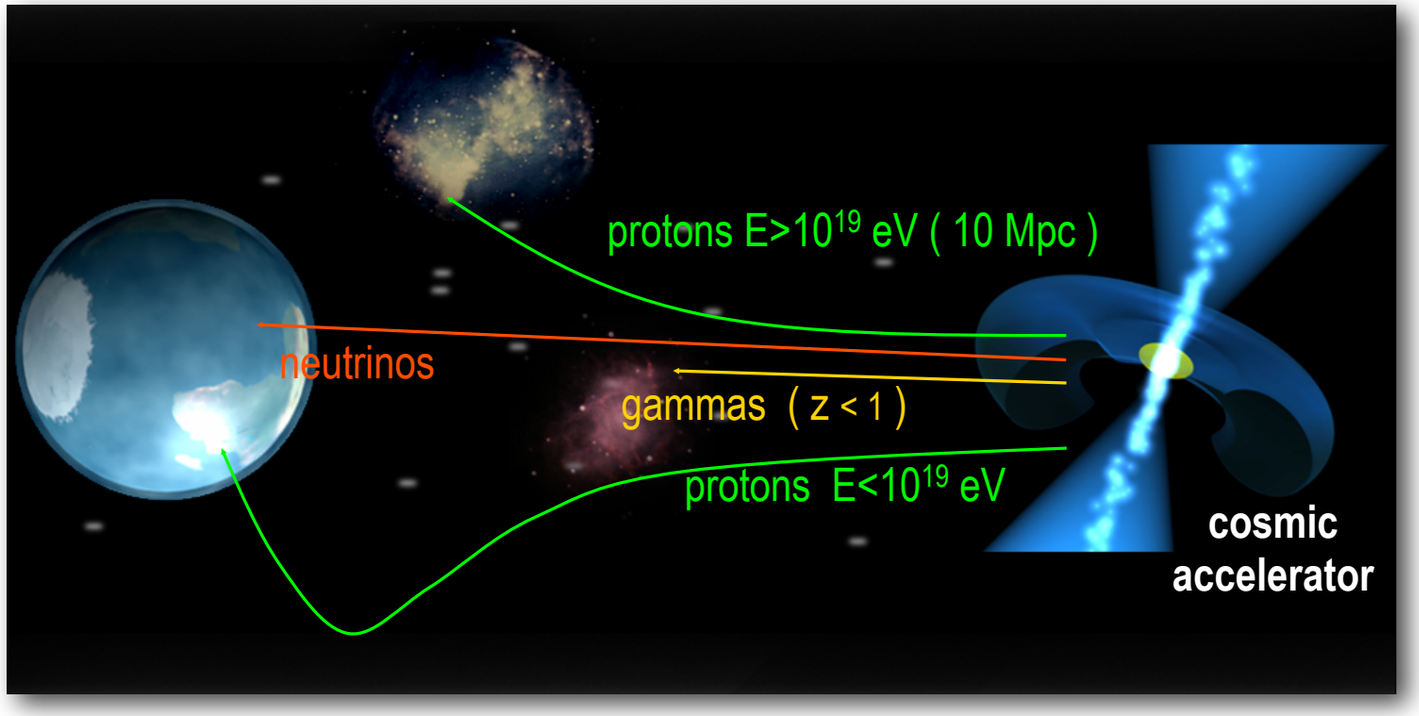
$\nu + \nu_{1.95K} \rightarrow Z + X$

$$l_\nu = \frac{1}{\sigma_{res} \times n} = \frac{1}{5 \times 10^{-31} cm^2 \times 112 cm^{-3}} = 6 Gpc$$

Neutrinos : can reliably lead to the discovery of such point sources

$1pc = 3.1 \times 10^{13}\ km$

Cosmic accelerators



Ref: Montaruli, talk at SSI 2010

- protons/nuclei: deflected by magnetic fields, absorbed on radiation (GZK)
- photons: absorbed on radiation/dust; reprocessed at source
- neutrinos: neither absorbed nor bent, straight path from source

$\gamma + \gamma_{2.7K}$

$$l_\gamma = \frac{1}{\sigma_{p-\gamma_{2.7K}} \times n_\gamma} \sim \frac{1}{5 \times 10^{-28} cm^2 \times 400 cm^{-3}} = 10 Mpc$$

$\nu + \nu_{1.95K} \rightarrow Z + X$

$$l_\nu = \frac{1}{\sigma_{res} \times n} = \frac{1}{5 \times 10^{-31} cm^2 \times 112 cm^{-3}} = 6 Gpc$$

Neutrinos : can reliably lead to the discovery of such point sources

$1pc = 3.1 \times 10^{13}\ km$

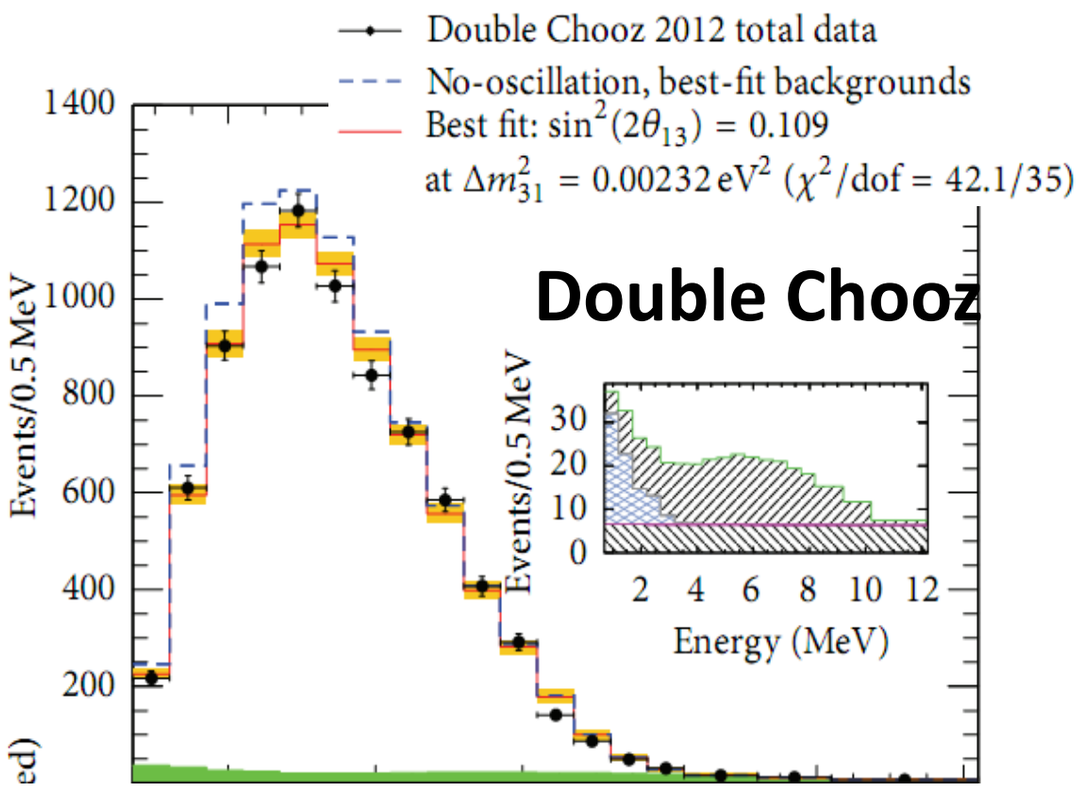
Some other topics...

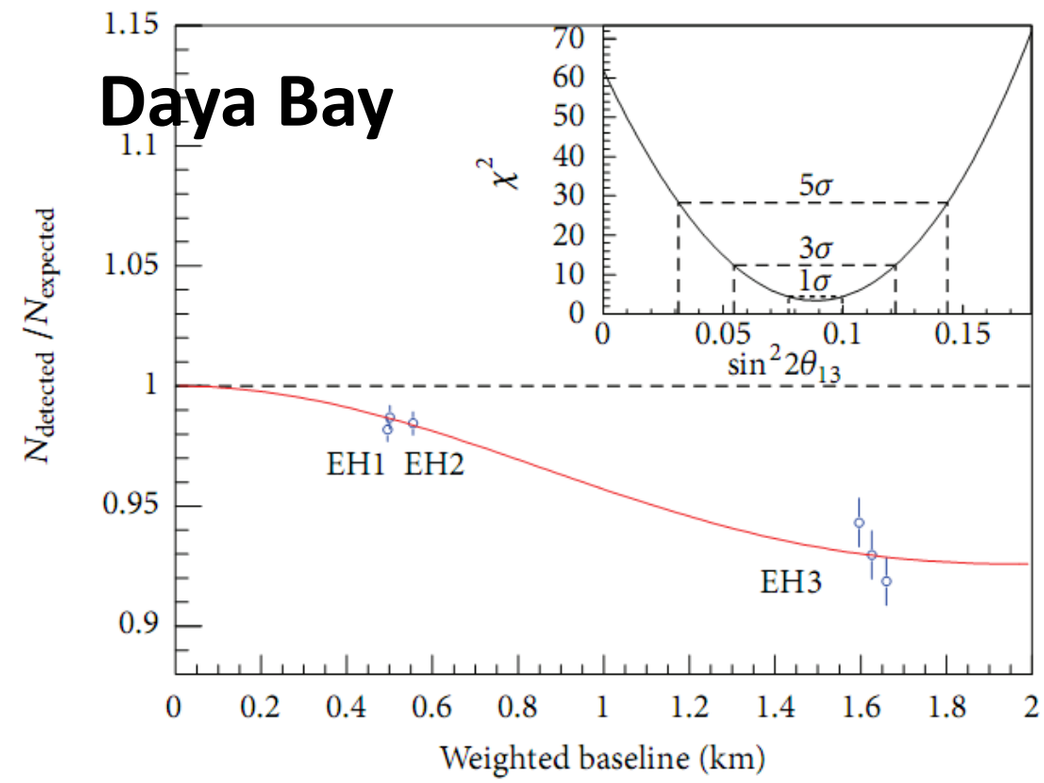
- **Legget-Garg inequalities and neutrino oscillations (21)**
  - Ashutosh Alok

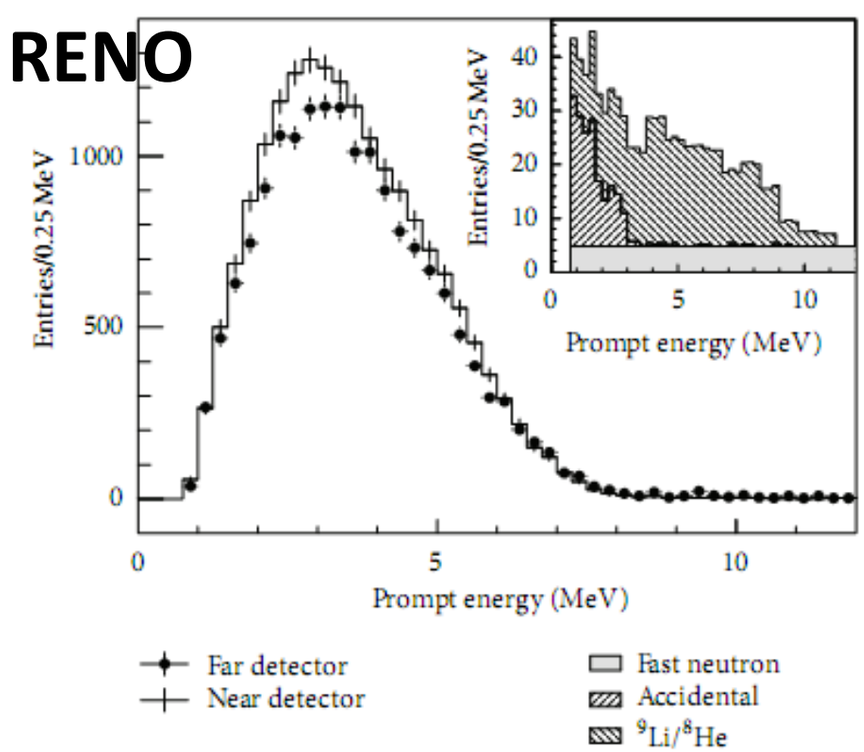
- **Quantum decoherence and neutrino oscillations (21)**
  - Poonam Mehta

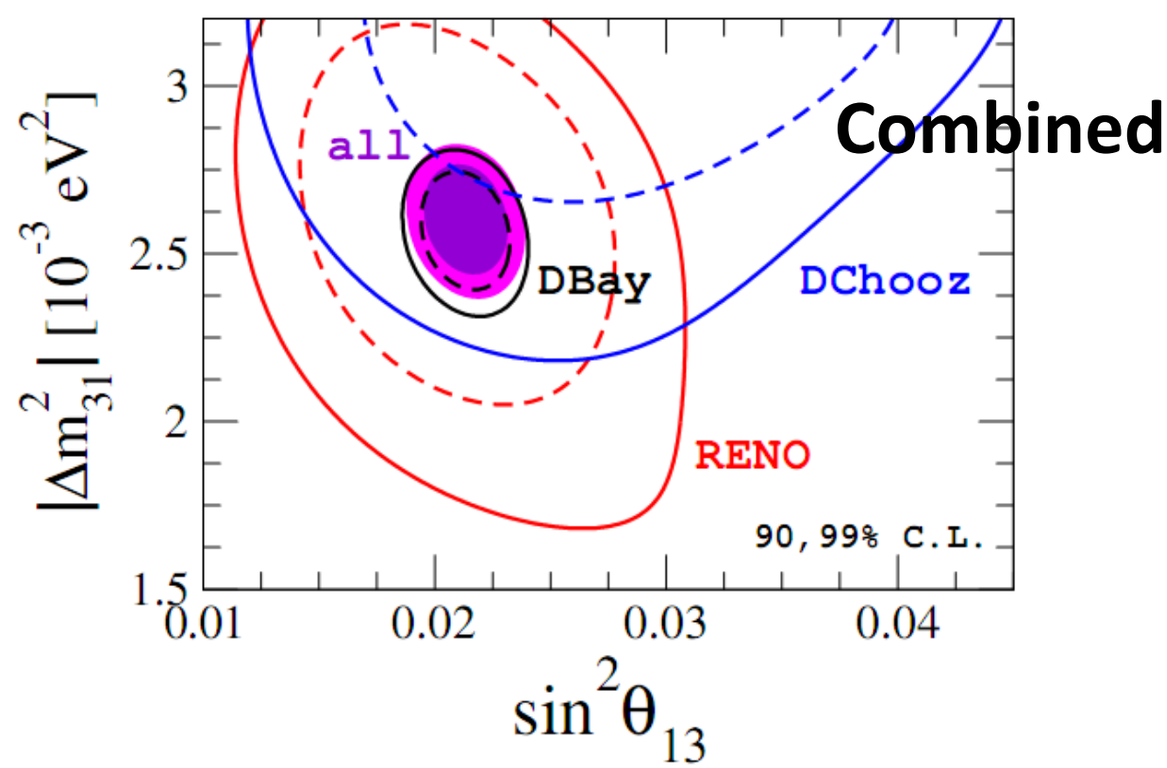
Some slides...

Reactor neutrinos

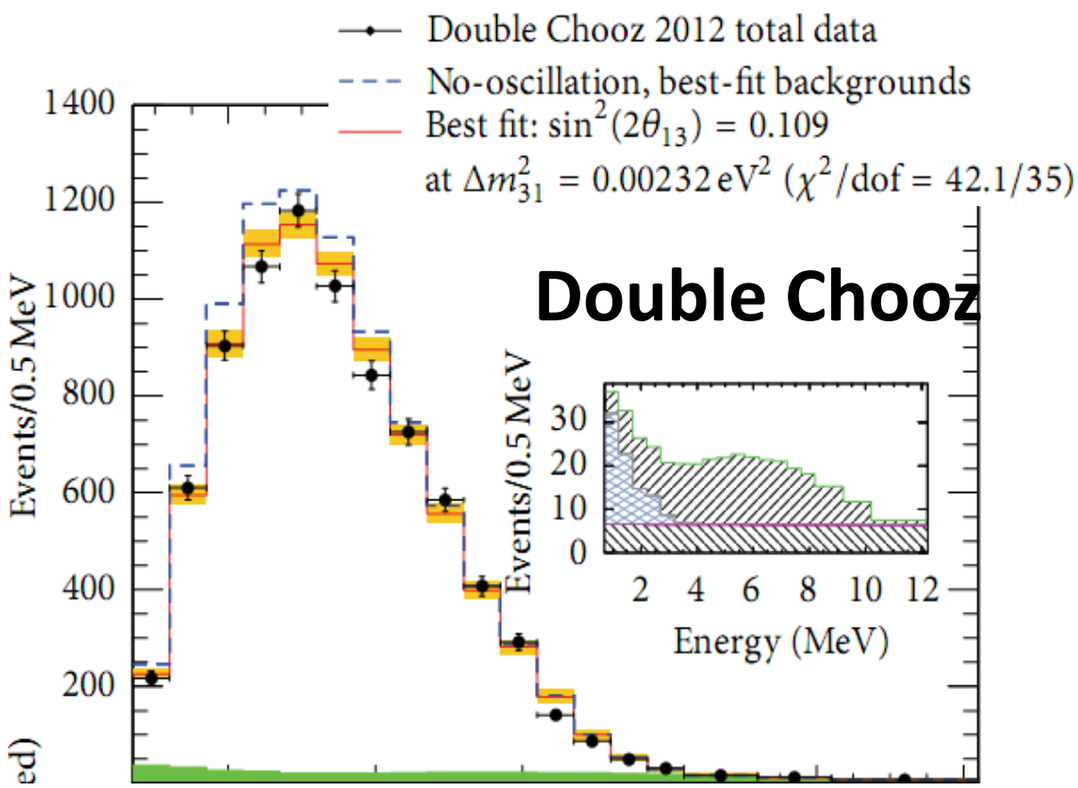


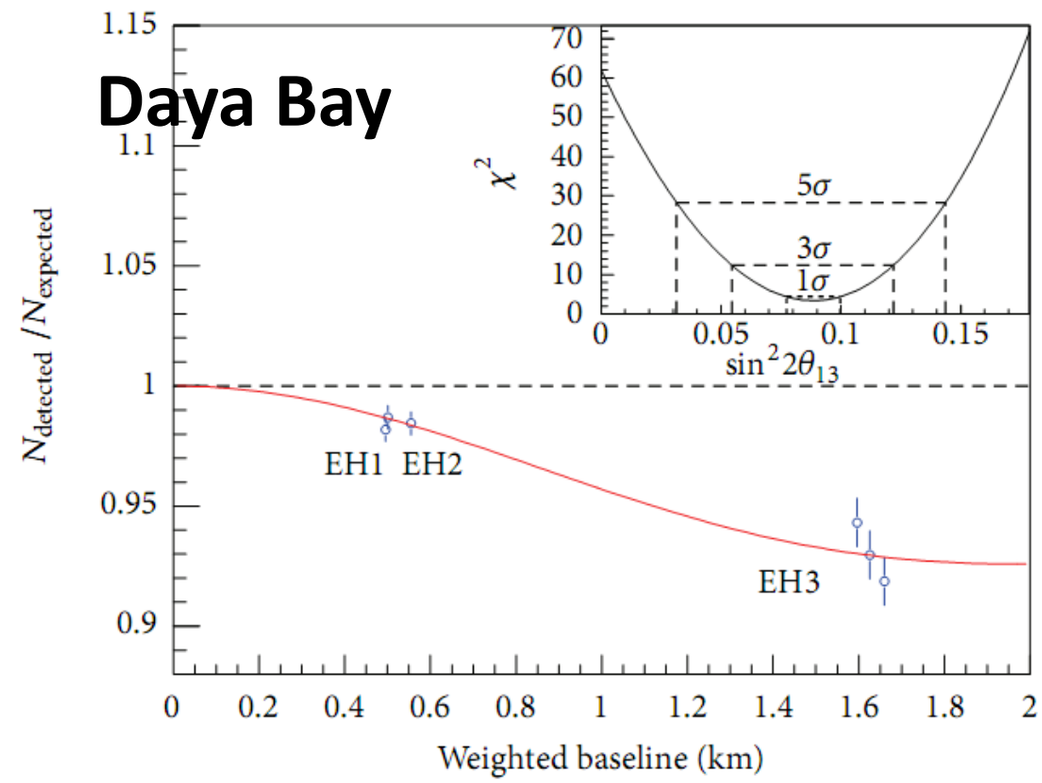


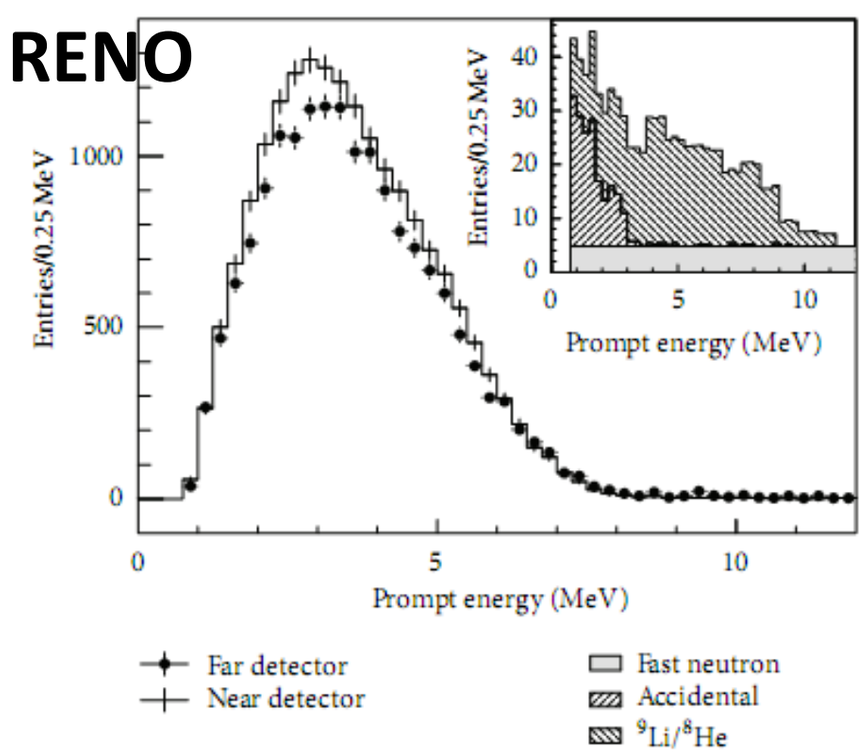


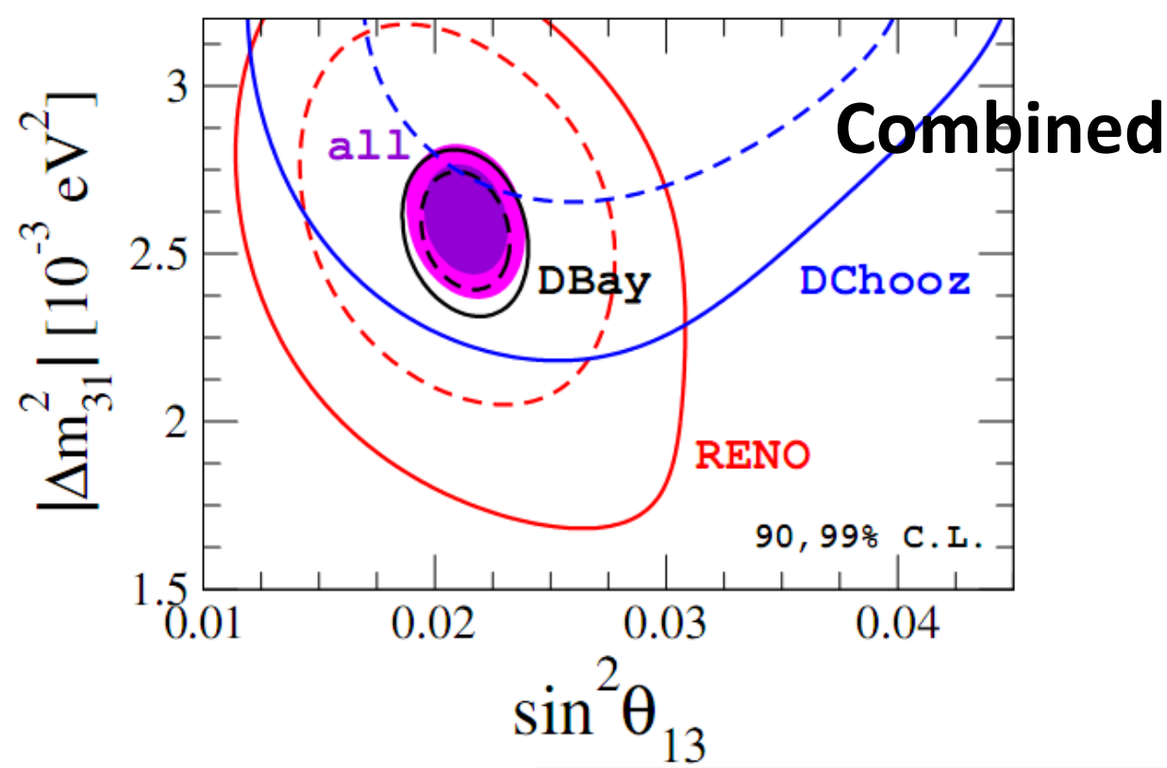


Reactor neutrinos

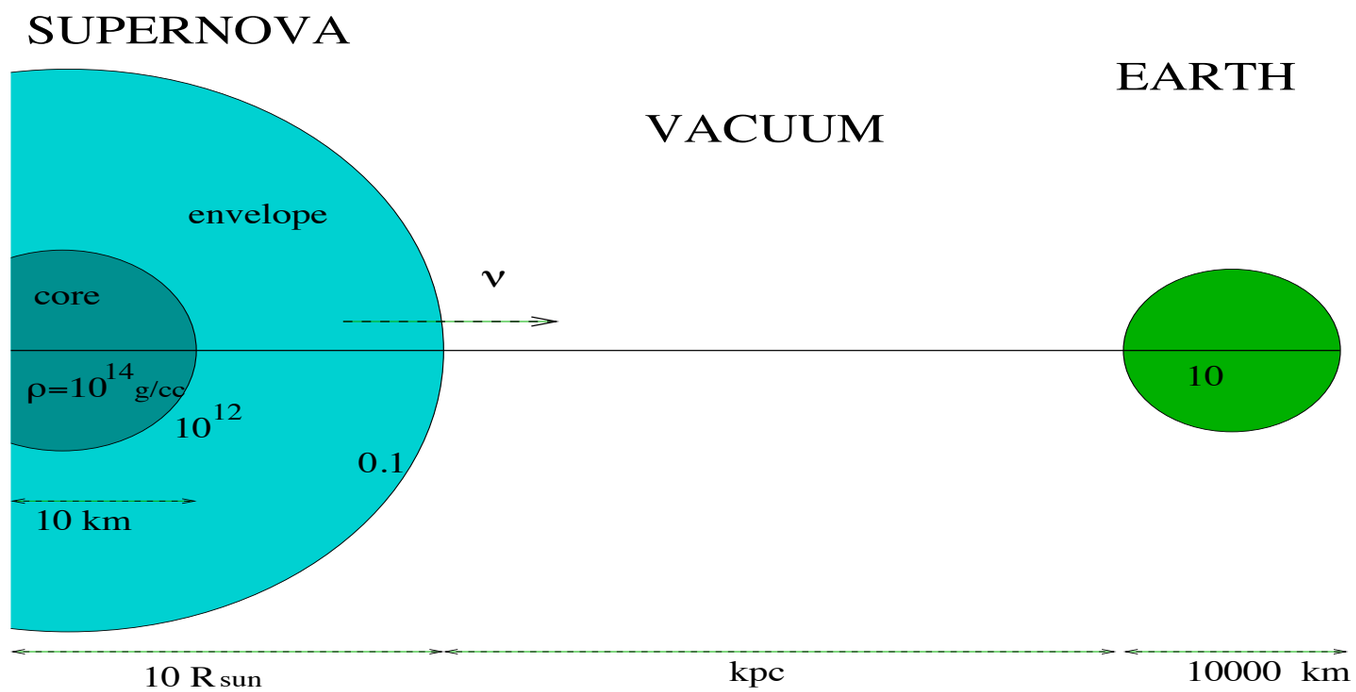








Propagation through matter of varying density



Inside the SN: *flavour conversion*

Collective effects and MSW matter effects

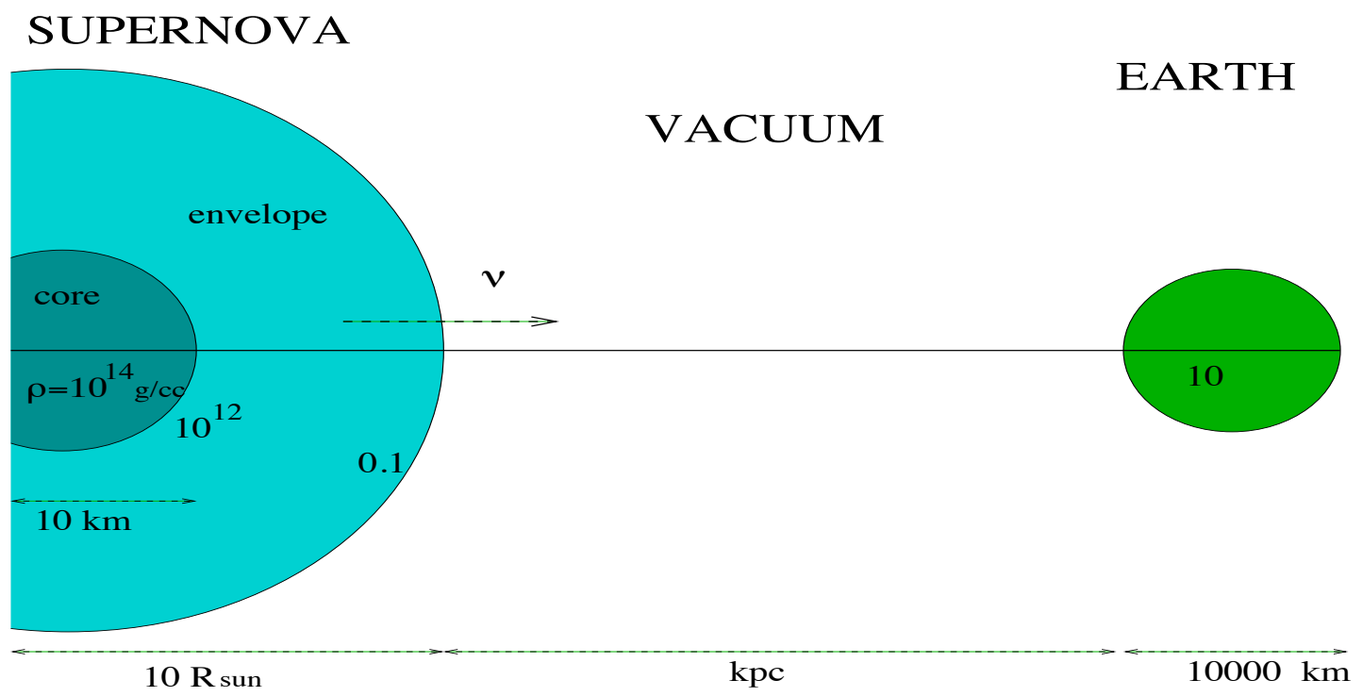
Between the SN and Earth: *no flavour conversion*

Mass eigenstates travel independently

Inside the Earth: *flavour conversion*

MSW matter effects (*if detector is on the other side*)

Propagation through matter of varying density



Inside the SN: *flavour conversion*

Collective effects and MSW matter effects

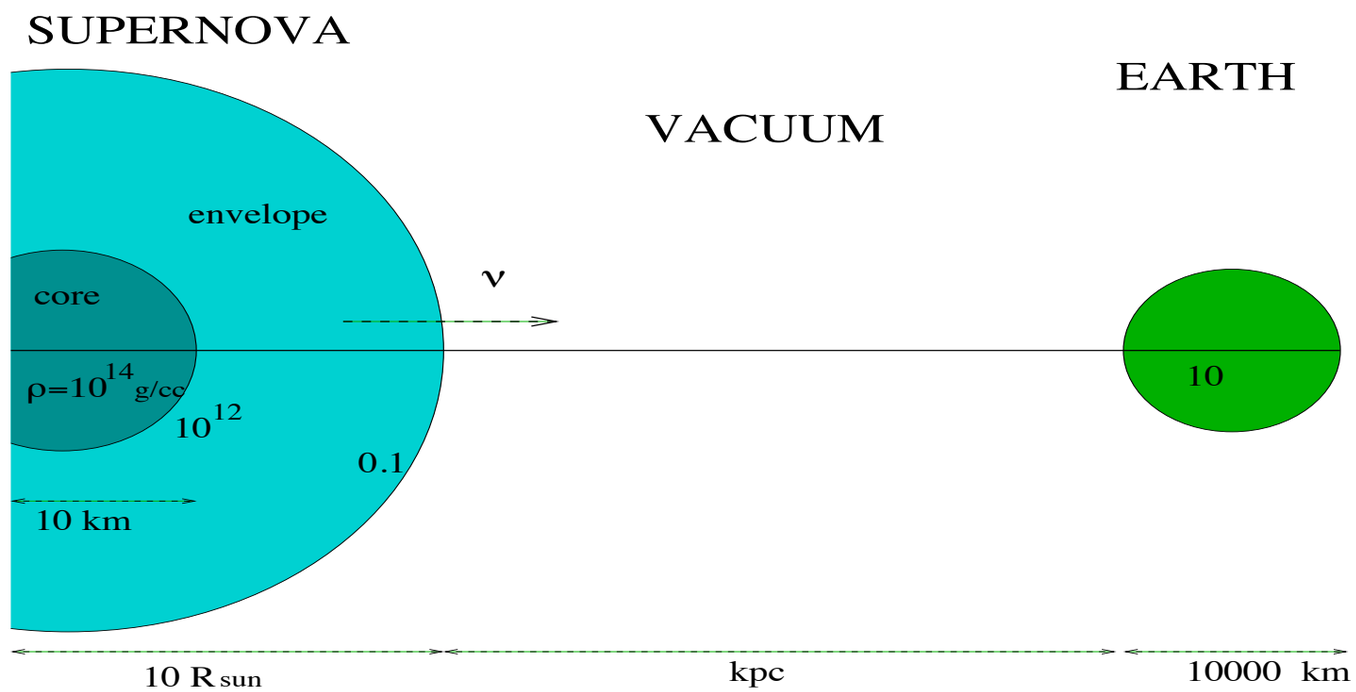
Between the SN and Earth: *no flavour conversion*

Mass eigenstates travel independently

Inside the Earth: *flavour conversion*

MSW matter effects (*if detector is on the other side*)

Propagation through matter of varying density



Inside the SN: *flavour conversion*

Collective effects and MSW matter effects

Between the SN and Earth: *no flavour conversion*

Mass eigenstates travel independently

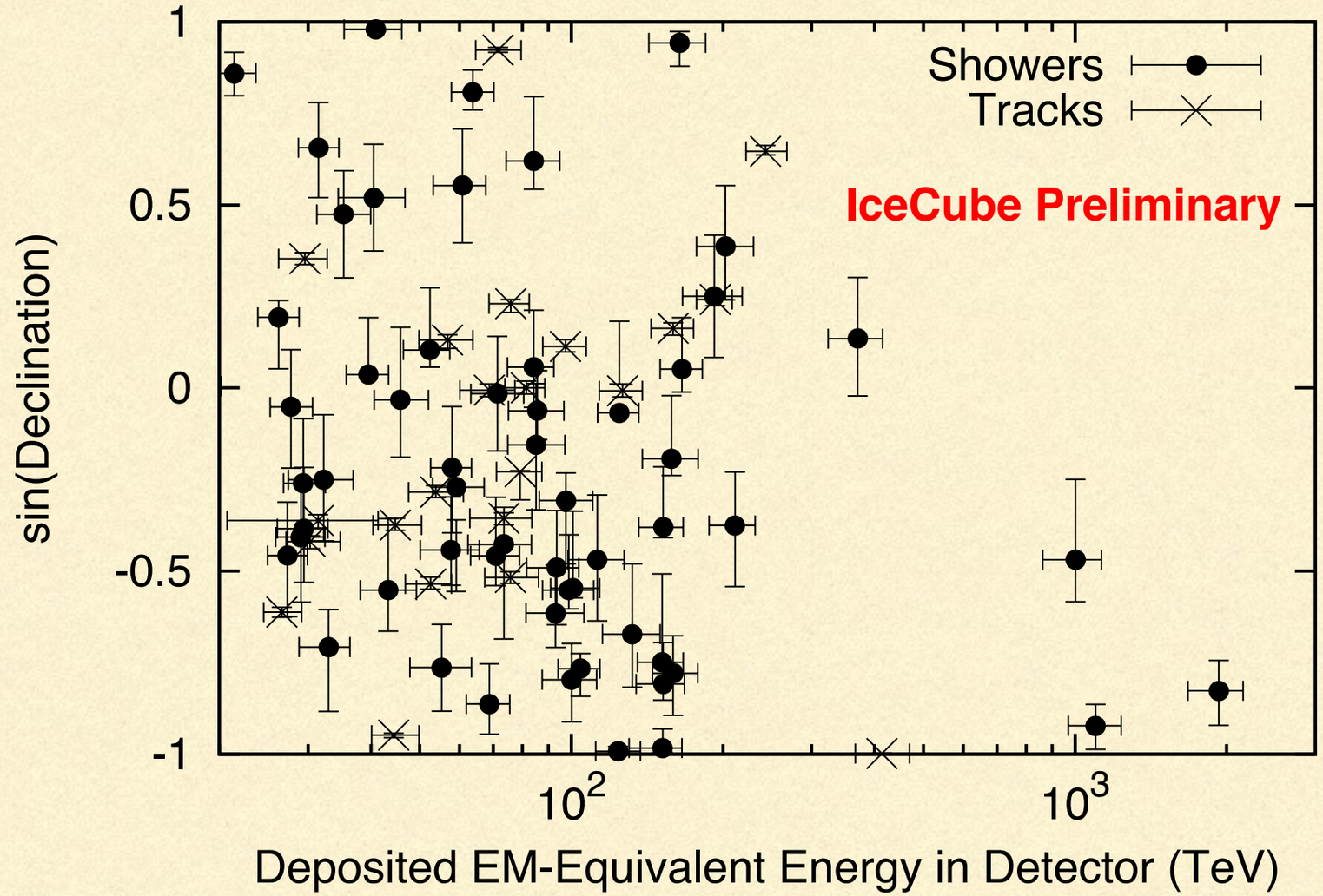
Inside the Earth: *flavour conversion*

MSW matter effects (*if detector is on the other side*)

Starting events.....6 years

80 (+2) events observed, mix of track (muon) and cascades.

Expected background: 15.6 atmospheric, 25.2 atmos muons

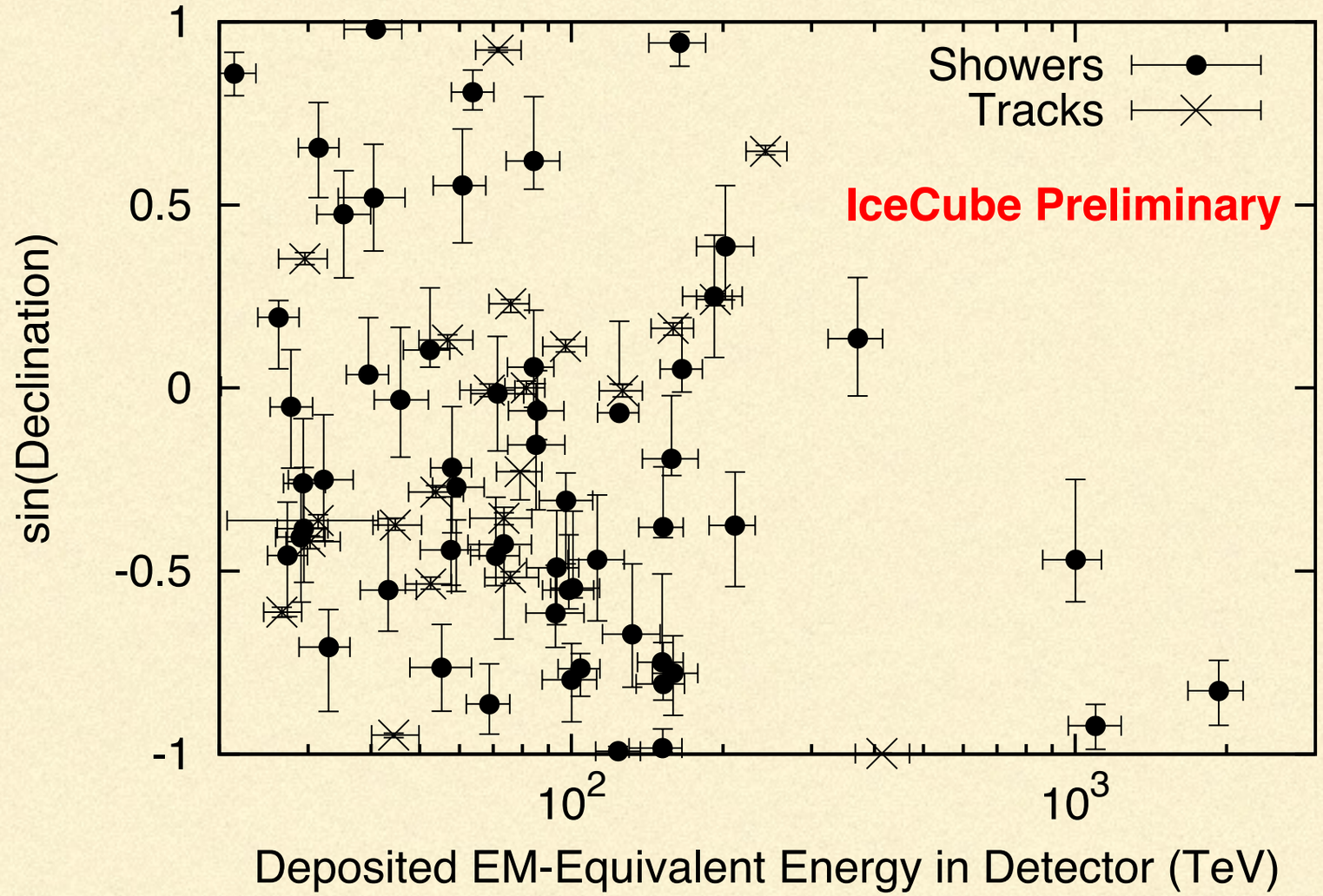


Angular Distribution of events is isotropic, indicating that most events are extragalactic.

Starting events.....6 years

80 (+2) events observed, mix of track (muon) and cascades.

Expected background: 15.6 atmospheric, 25.2 atmos muons

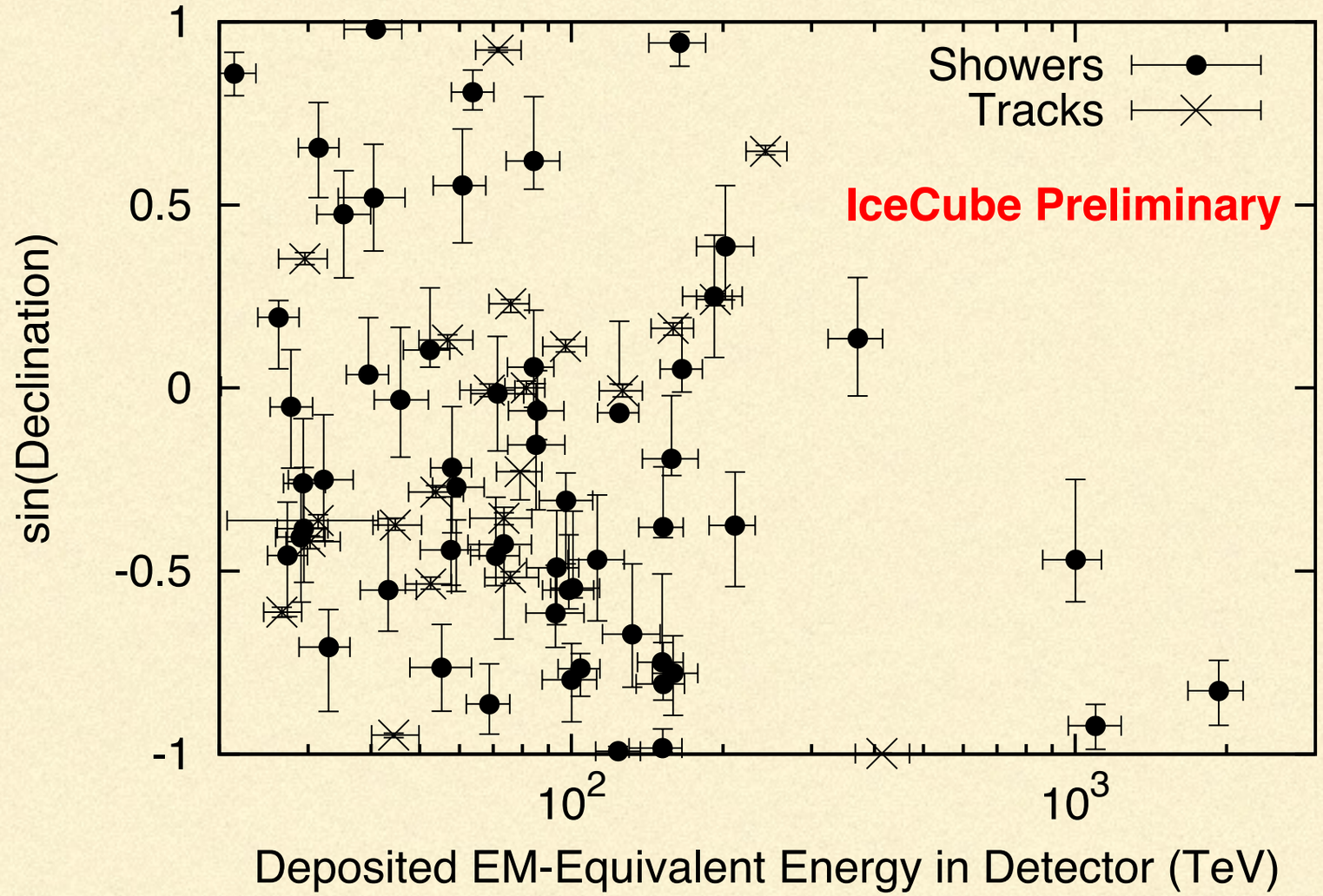


Angular Distribution of events is isotropic, indicating that most events are extragalactic.

Starting events.....6 years

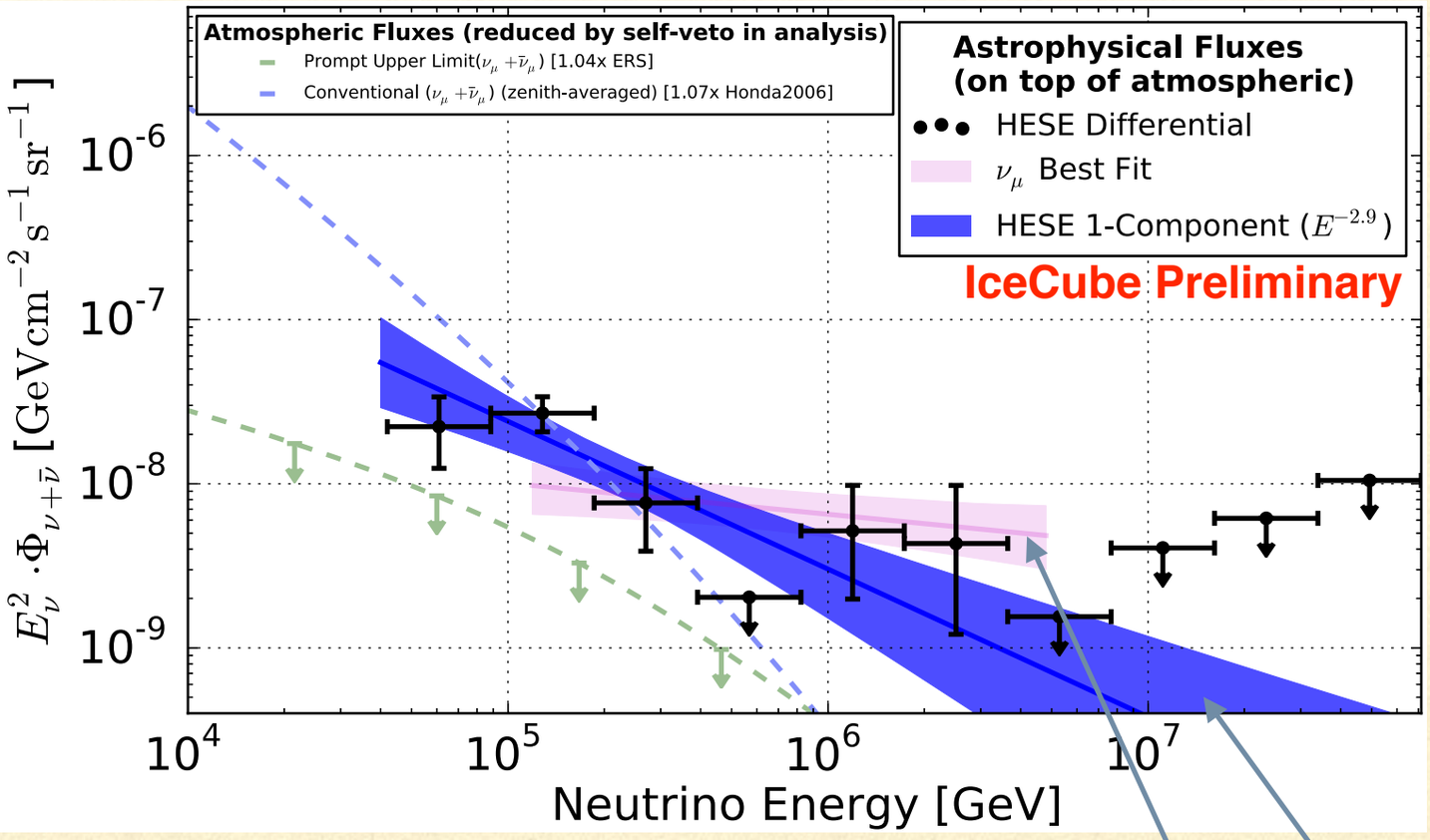
80 (+2) events observed, mix of track (muon) and cascades.

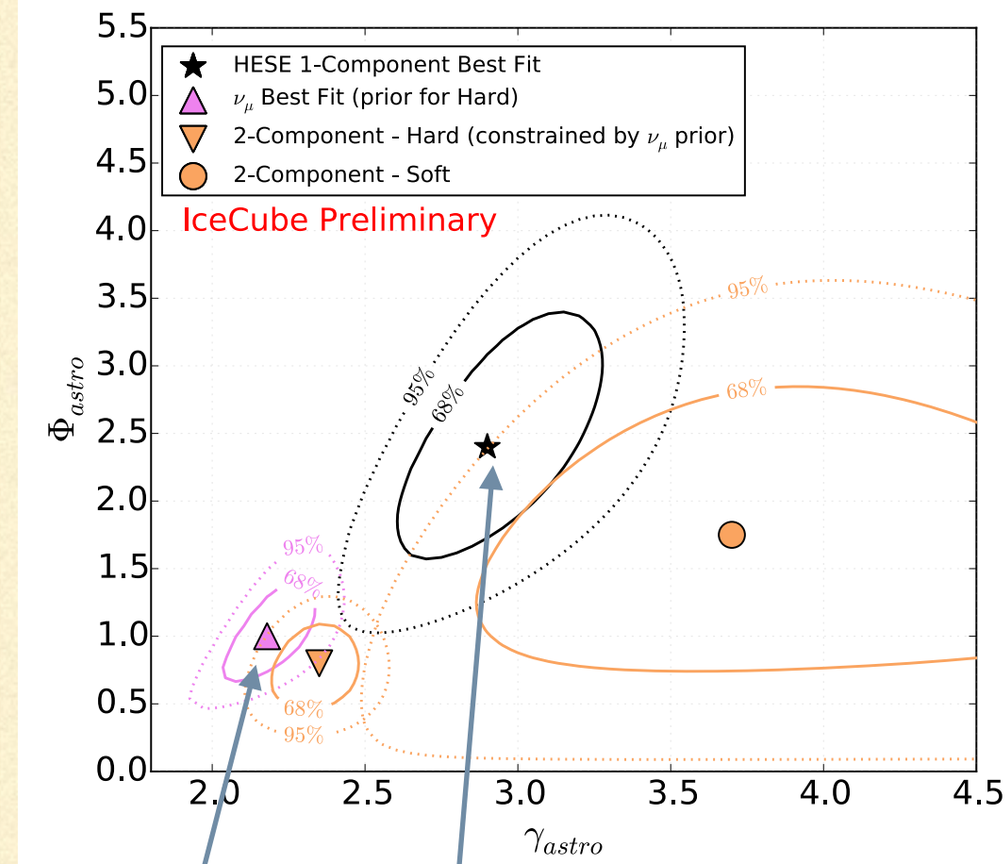
Expected background: 15.6 atmospheric, 25.2 atmos muons



Angular Distribution of events is isotropic, indicating that most events are extragalactic.

Power-law behavior of observed neutrino fluxes.....



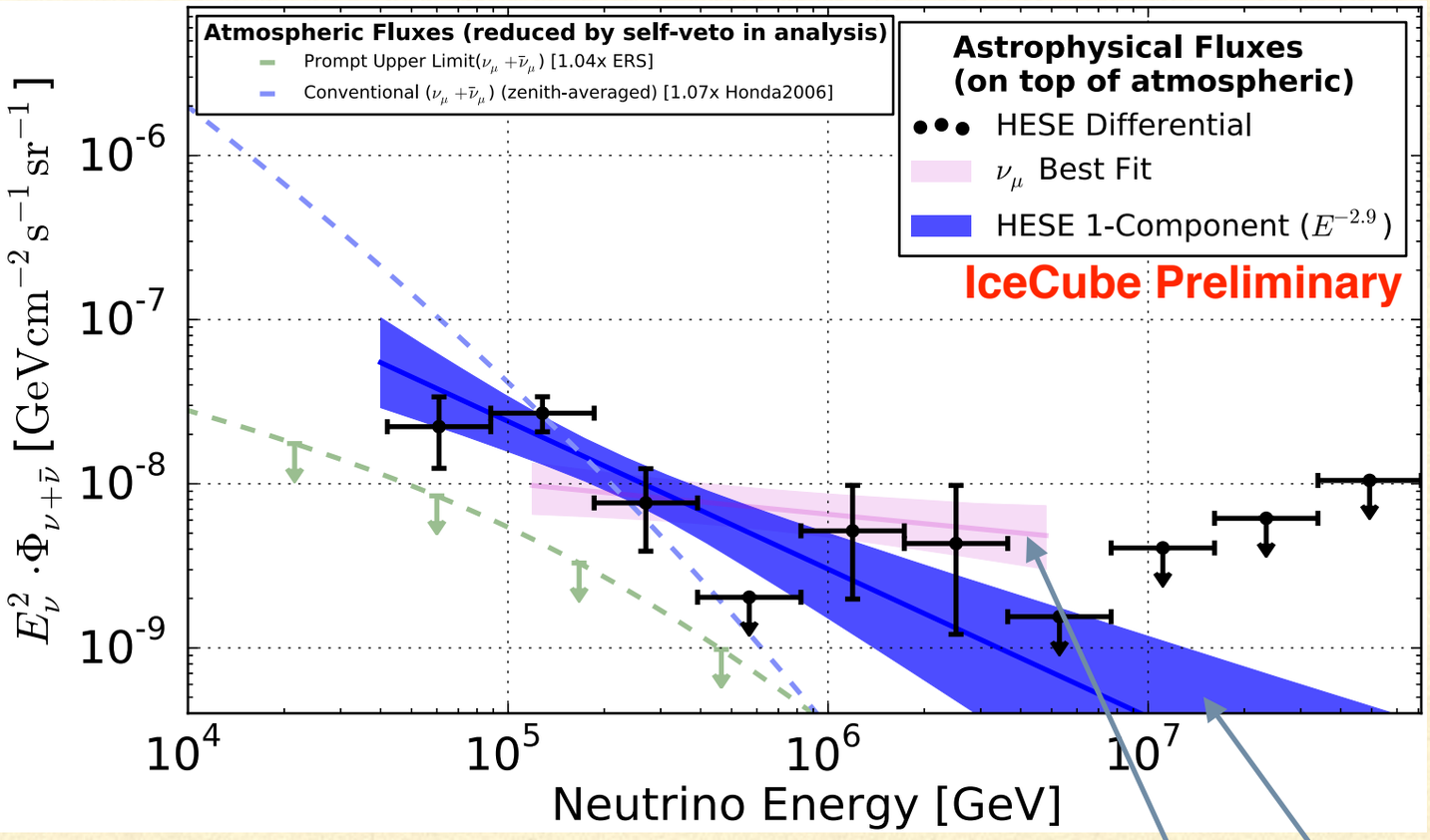


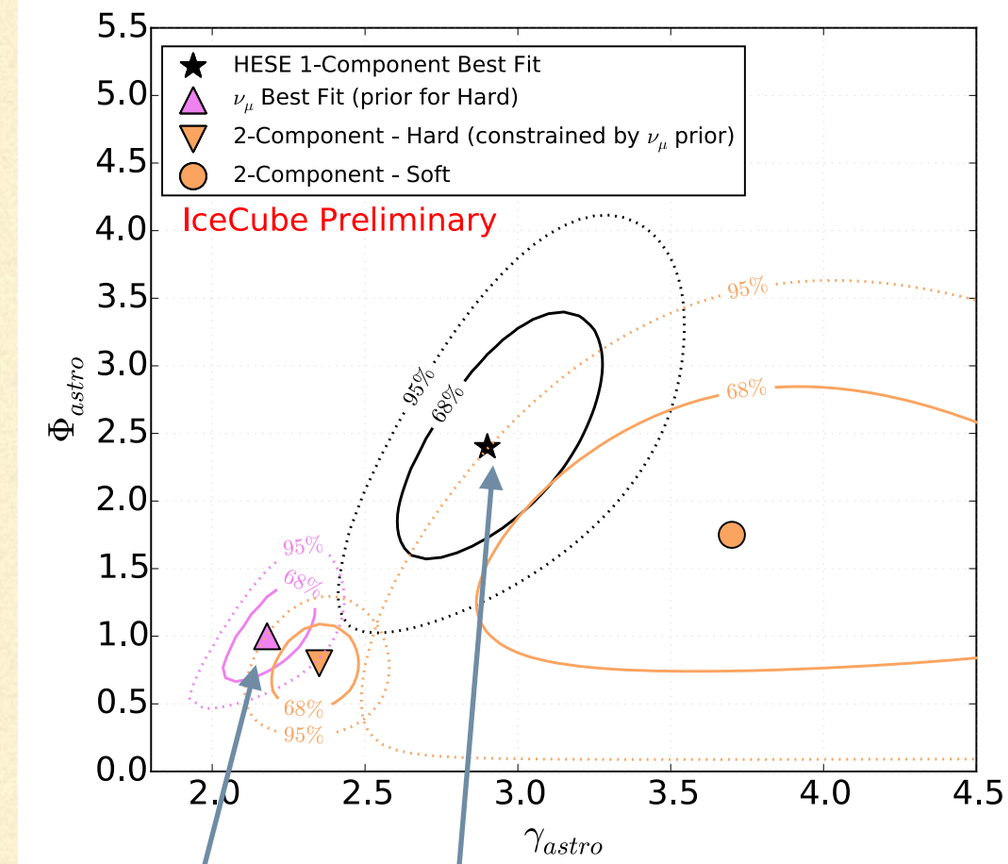
It is widely believed that UHE neutrinos are produced in charged pion decays produced in pp and or pγ interactions in the source. Such neutrinos are expected to follow a E^{-2} spectrum

However....

Power-law behavior (index) of 8 yr up-going muon data and HESE data significantly different.

Power-law behavior of observed neutrino fluxes.....



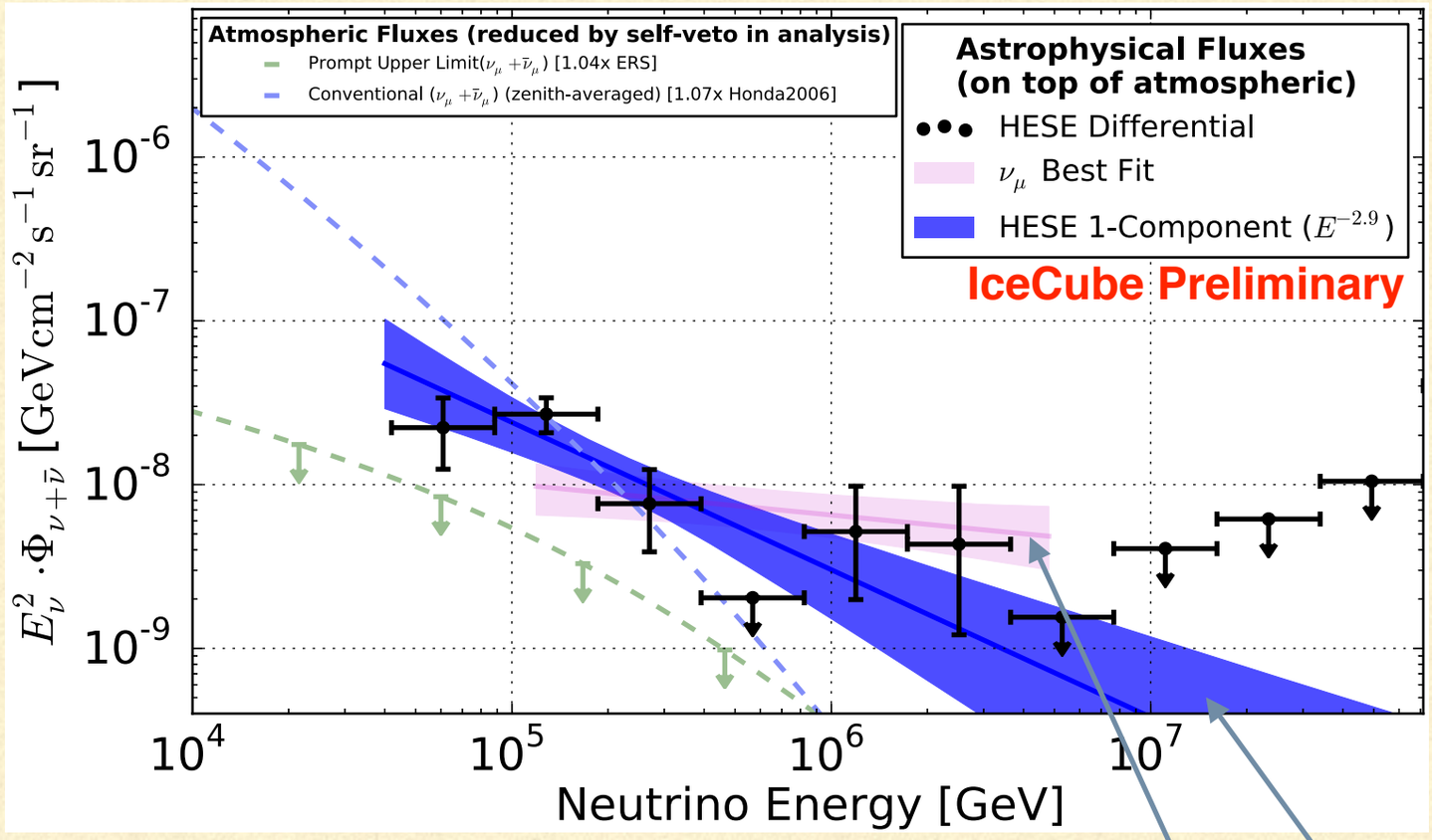


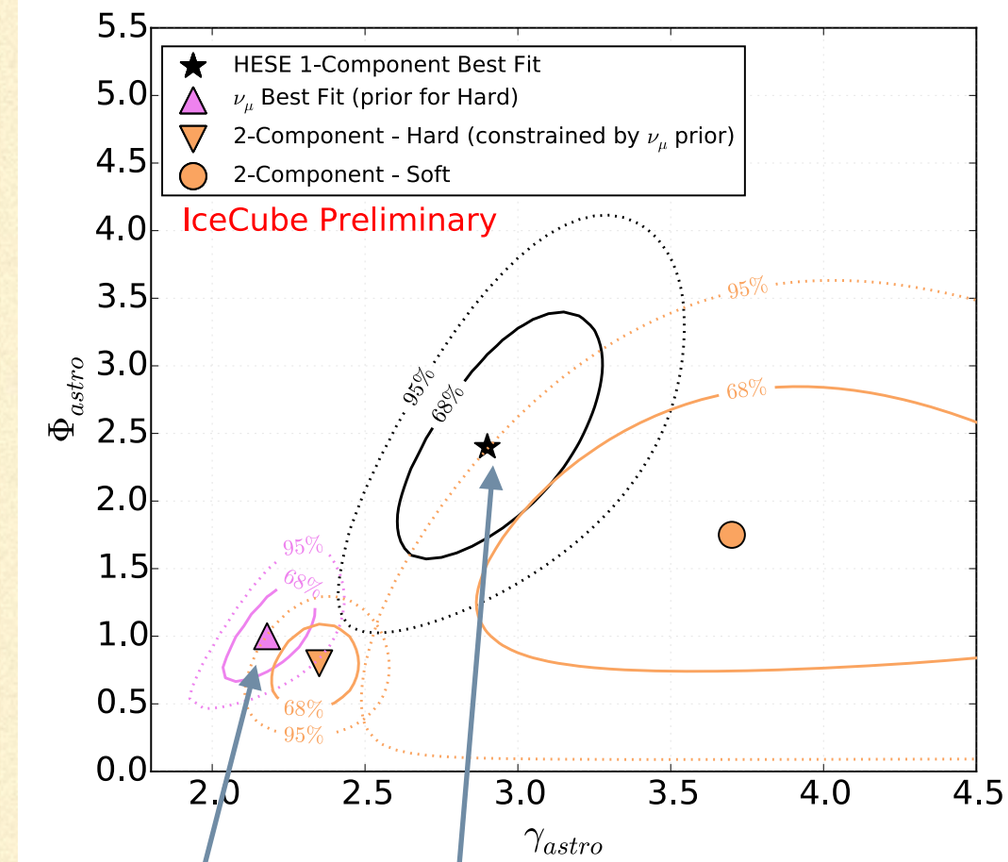
It is widely believed that UHE neutrinos are produced in charged pion decays produced in pp and or pγ interactions in the source. Such neutrinos are expected to follow a E^{-2} spectrum

However....

Power-law behavior (index) of 8 yr up-going muon data and HESE data significantly different.

Power-law behavior of observed neutrino fluxes.....





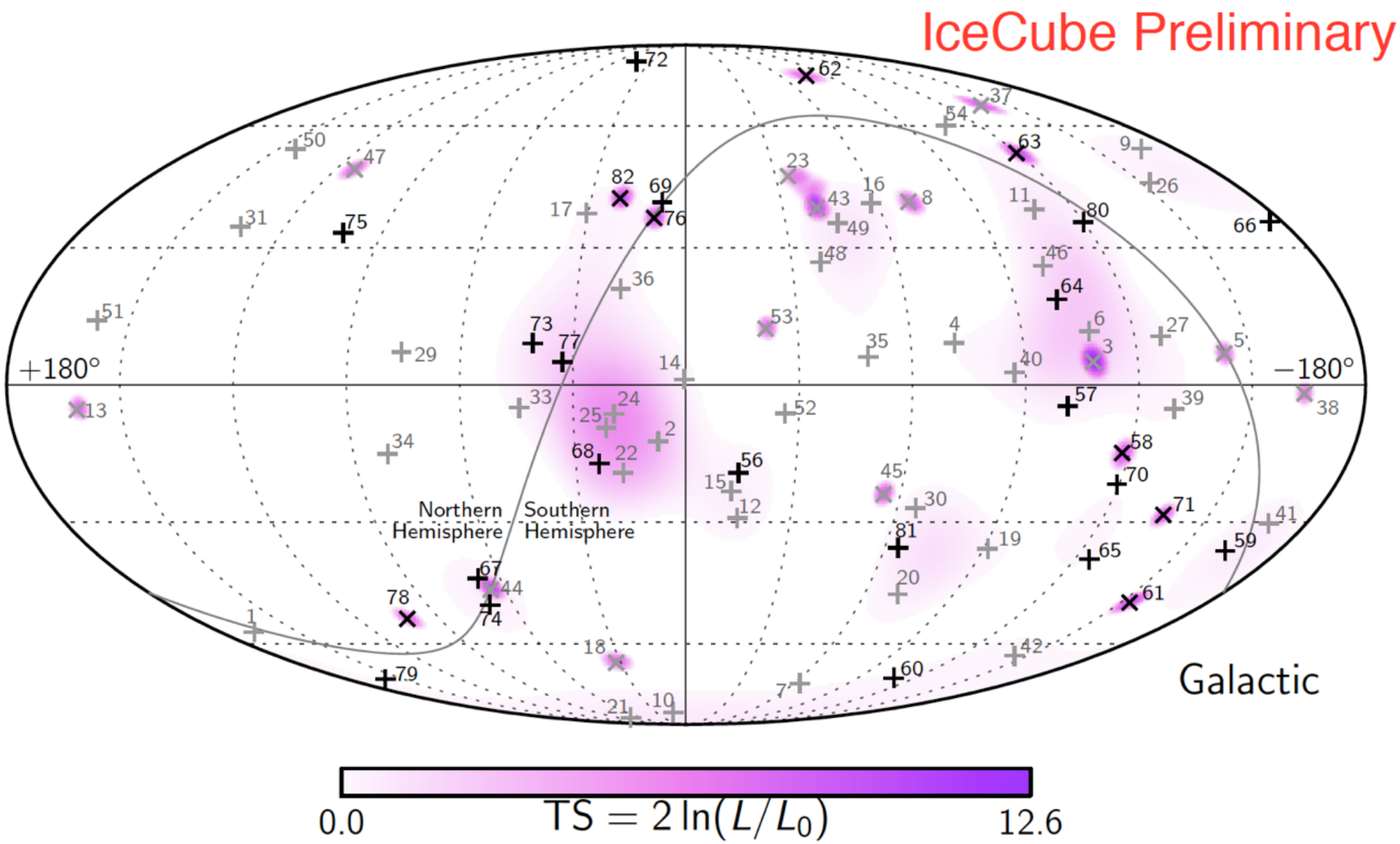
It is widely believed that UHE neutrinos are produced in charged pion decays produced in pp and or pγ interactions in the source. Such neutrinos are expected to follow a E^{-2} spectrum

However....

Power-law behavior (index) of 8 yr up-going muon data and HESE data significantly different.

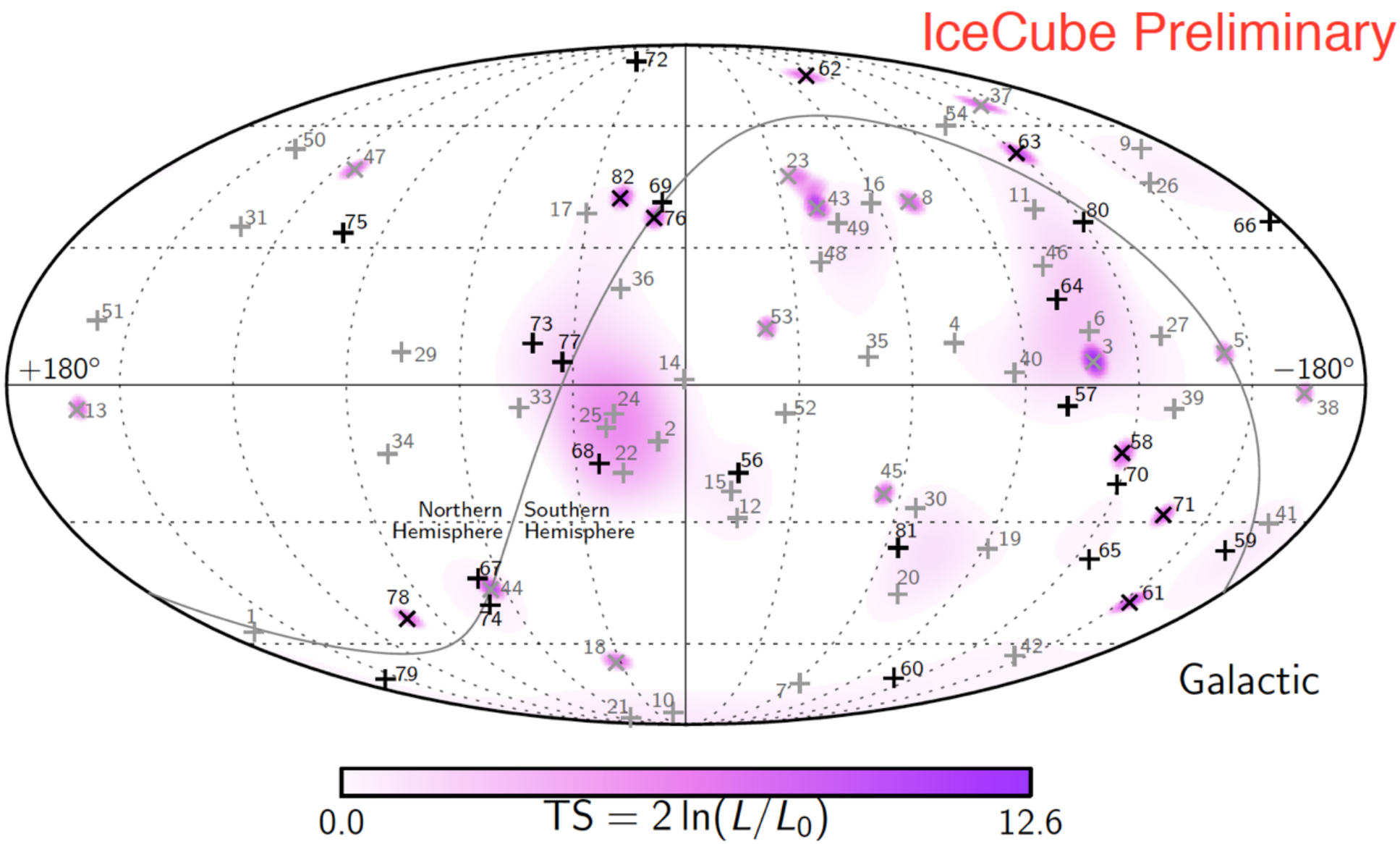
Raj Gandhi

Skymap - High Energy Neutrino Events



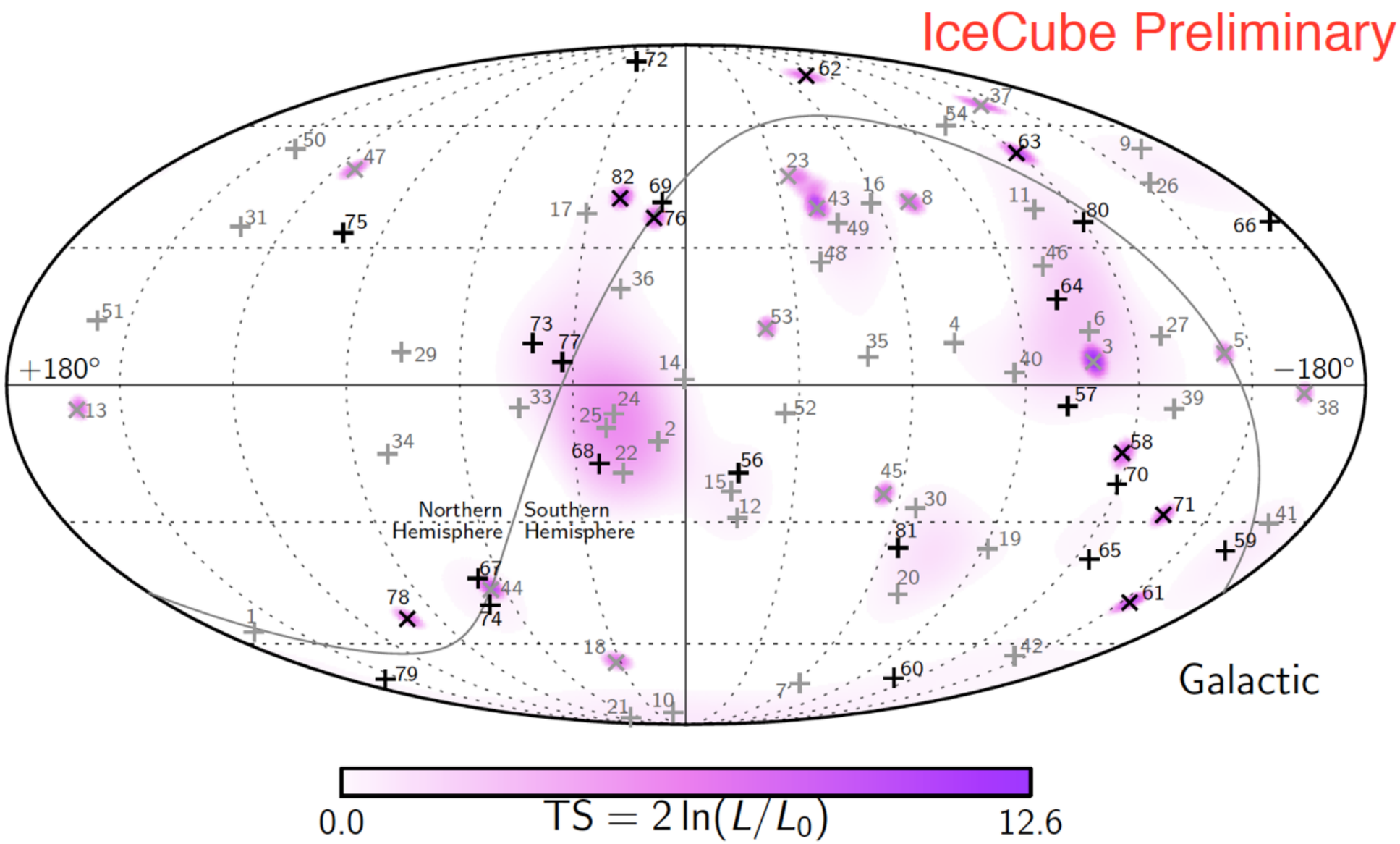
No Significant Clustering Found Including Around Galactic Plane

Skymap - High Energy Neutrino Events



No Significant Clustering Found Including Around Galactic Plane

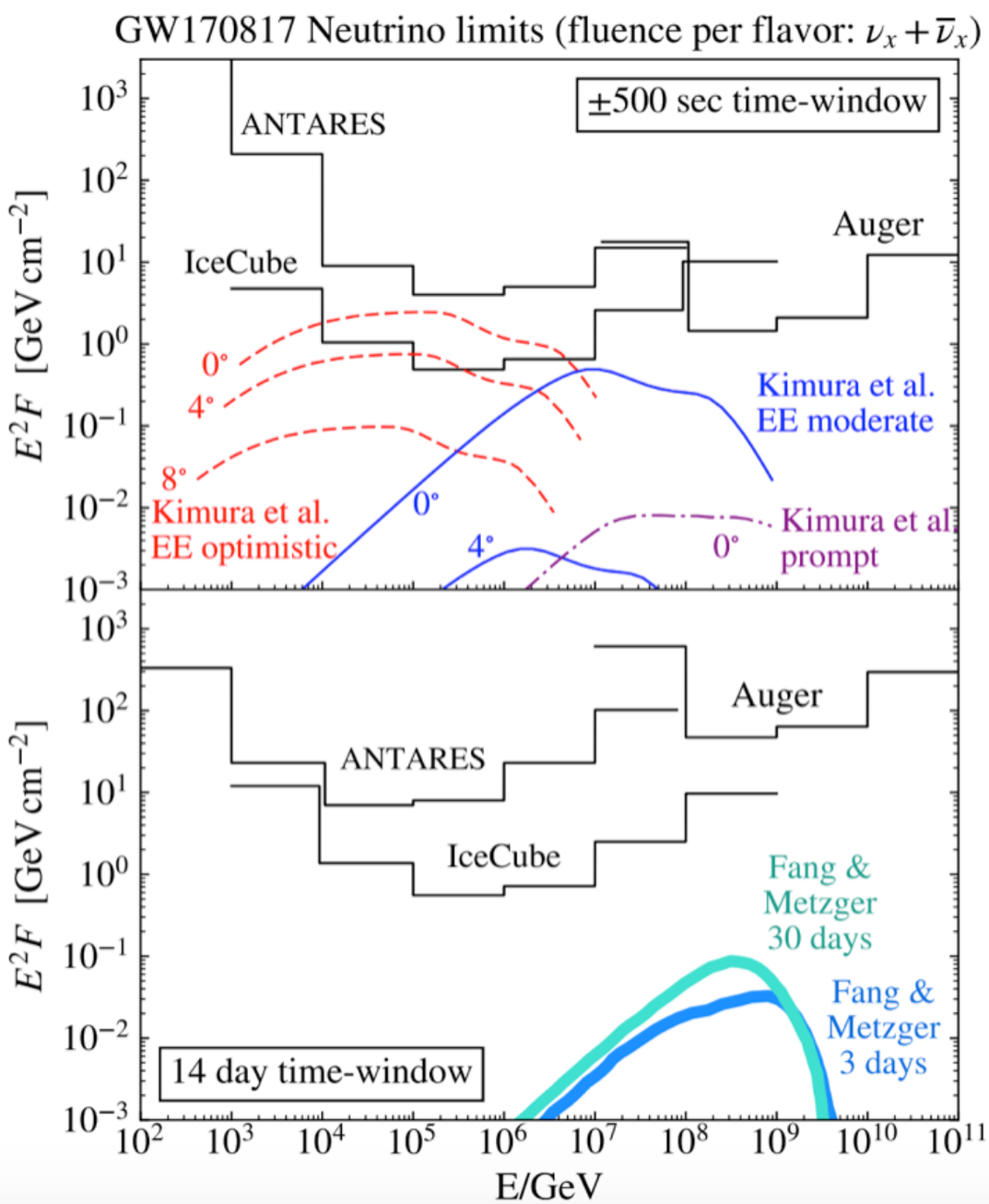
Skymap - High Energy Neutrino Events



No Significant Clustering Found Including Around Galactic Plane

Debanjan Bose

No Neutrinos found correlated in space/ time with GW170817



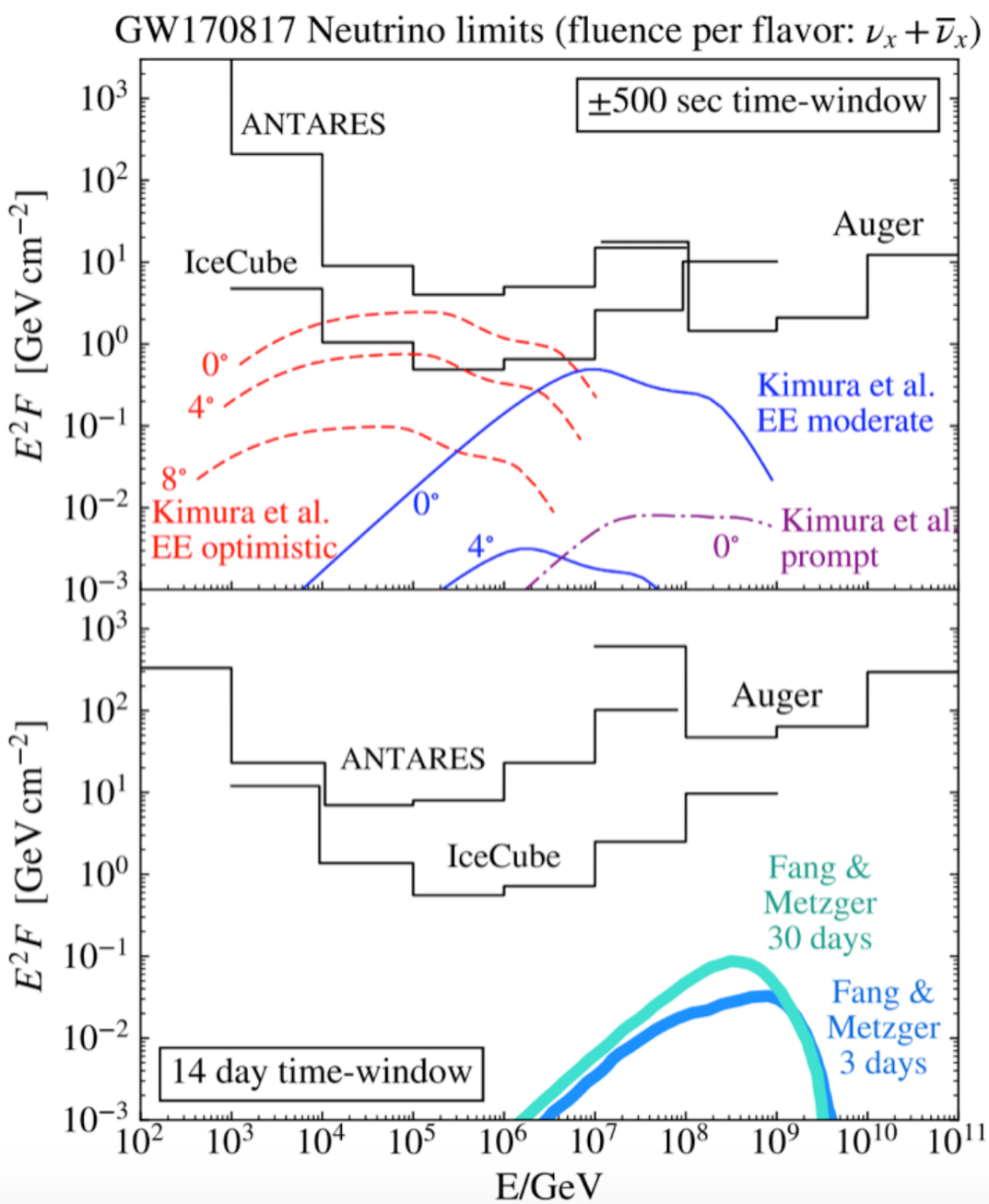
IF rapidly rotating NS formed & doesn't collapse into BH immediately, can power relativistic wind - EE, gamma-ray attenuate due optical depth, HE neutrinos can escape (± 500 s)

Also it may trap wind energy until it expands and becomes transparent. This process can convert some of the wind energy to HE particles, producing a long term neutrino radiation, which can last for several days (14 days)

IceCube detector is also sensitive to outbursts of MeV neutrinos via a simultaneous increase in all PMTs for Galactic core-collapse SNs

But this event was located too far

No Neutrinos found correlated in space/ time with GW170817



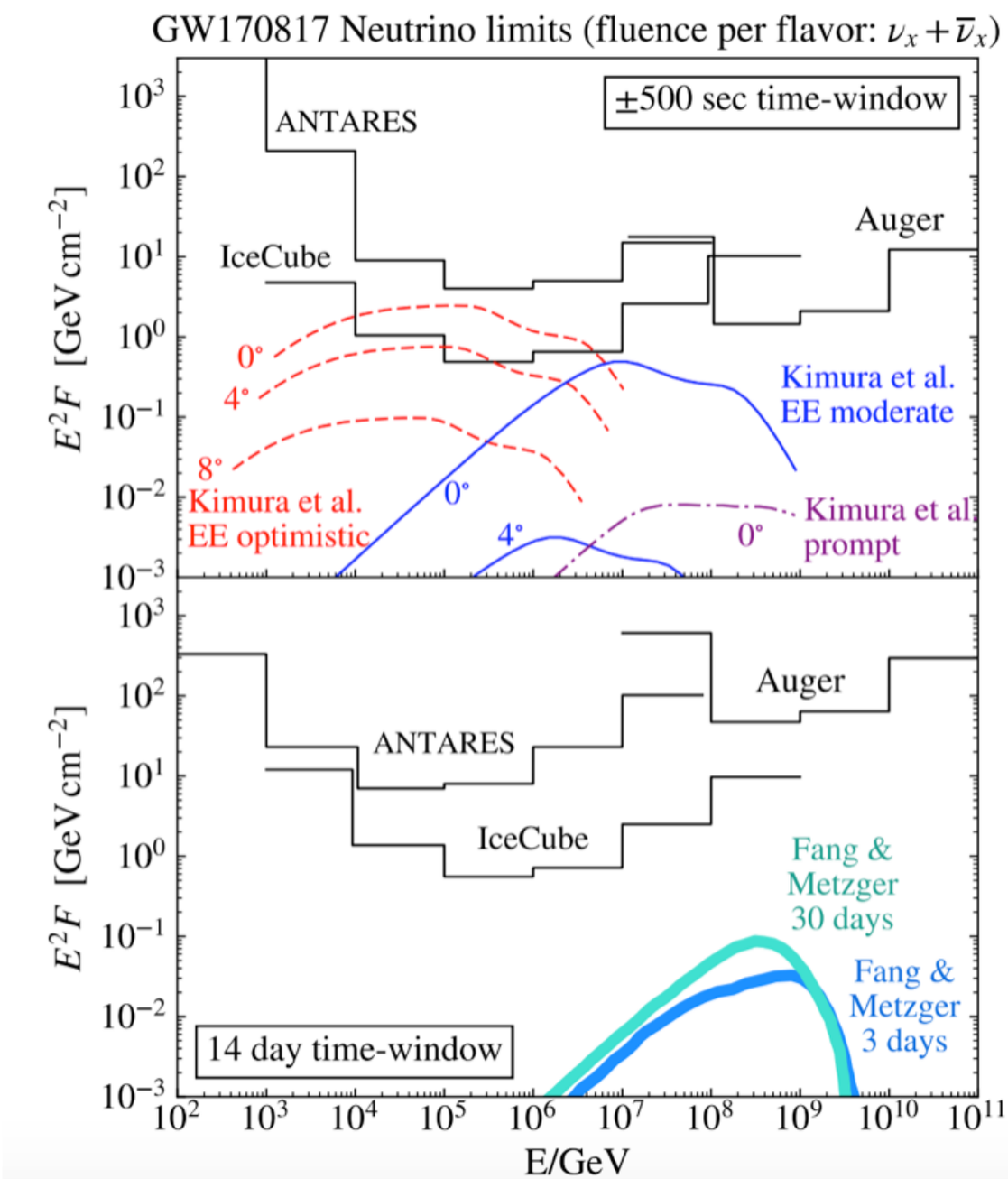
IF rapidly rotating NS formed & doesn't collapse into BH immediately, can power relativistic wind - EE, gamma-ray attenuate due optical depth, HE neutrinos can escape (± 500 s)

Also it may trap wind energy until it expands and becomes transparent. This process can convert some of the wind energy to HE particles, producing a long term neutrino radiation, which can last for several days (14 days)

IceCube detector is also sensitive to outbursts of MeV neutrinos via a simultaneous increase in all PMTs for Galactic core-collapse SNs

But this event was located too far

No Neutrinos found correlated in space/ time with GW170817



IF rapidly rotating NS formed & doesn't collapse into BH immediately, can power relativistic wind - EE, gamma-ray attenuate due optical depth, HE neutrinos can escape (± 500 s)

Also it may trap wind energy until it expands and becomes transparent. This process can convert some of the wind energy to HE particles, producing a long term neutrino radiation, which can last for several days (14 days)

IceCube detector is also sensitive to outbursts of MeV neutrinos via a simultaneous increase in all PMTs for Galactic core-collapse SNs

But this event was located too far

Debanjan Bose

Cosmic Gall

-John Updike-

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids through a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed-you call
It wonderful; I call it crass.

The New Yorker Magazine, Inc. , 1960