Ultra high energy neutrinos from gamma ray burst sources

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invisibles

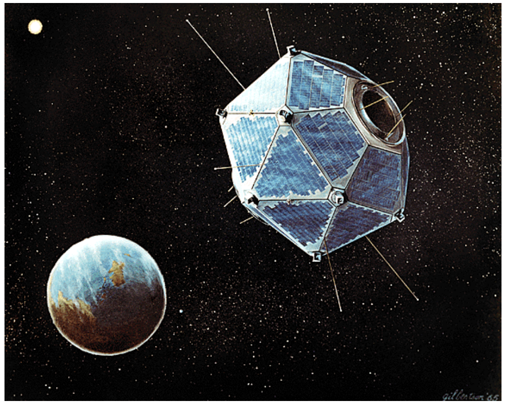
neutrinos, dark matter & dark energy physics

Outline

- Gamma ray bursts (GRB)
- Fireball model and neutrinos
- UHECR and Waxman Bahcal limit
- ICECUBE bounds
- Pseudo-Dirac neutrinos
- Pseuso-Dirac neutrinos and GRBs
- Pseuso-Dirac neutrinos and diffuse Supernova neutrinos

History of discovery of Gamma ray busters

VELA satellite: (1967)



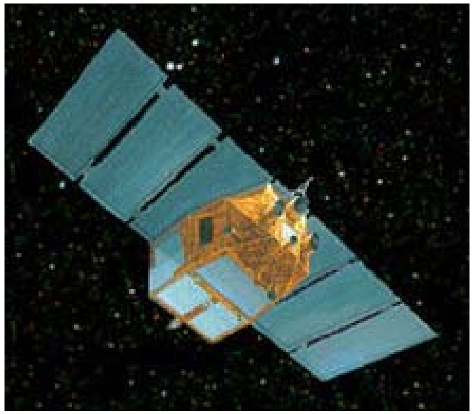
Discovery announcement: 1973

Russians confirm in 1974

Galactic versus extragalactic

- Coming from all direction not just galactic disc

1997: Observation of red-shift of X-ray and Gamma ray afterglow



Luminosity

- $10^{51} - 10^{53}\ \mathrm{erg}$ in few seconds

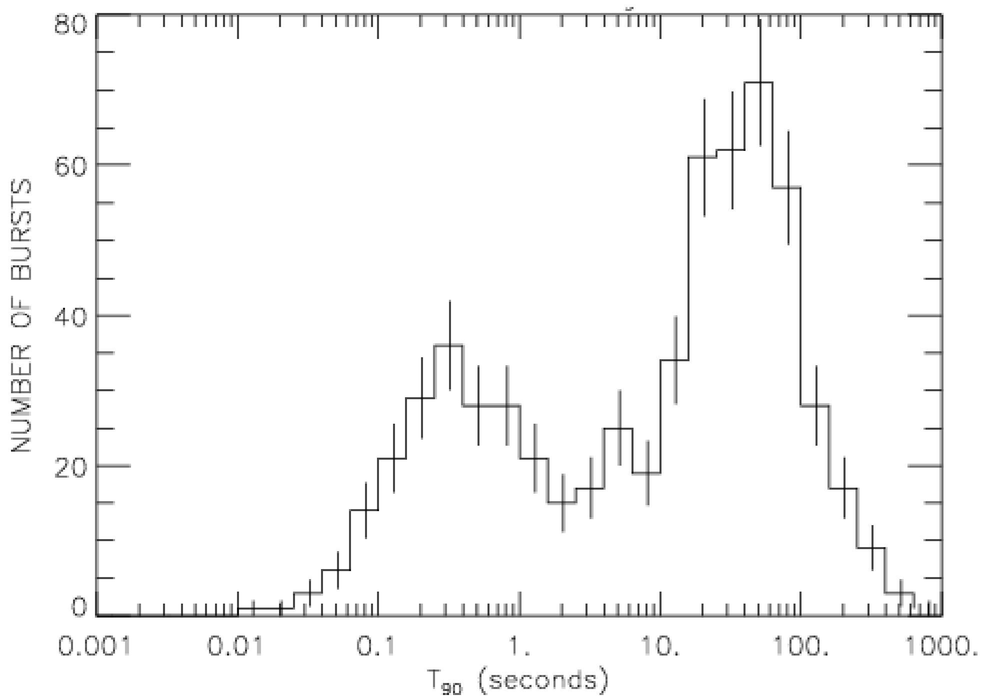
(ten milliseconds to several minutes)

- Most (electromagnetically) luminous

- The same energy emitted by sun during 10 billion year

Duration

- BATSE results



Progenitors

- Hypernova: stars with mass greater than 40 solar mass

Long bursts

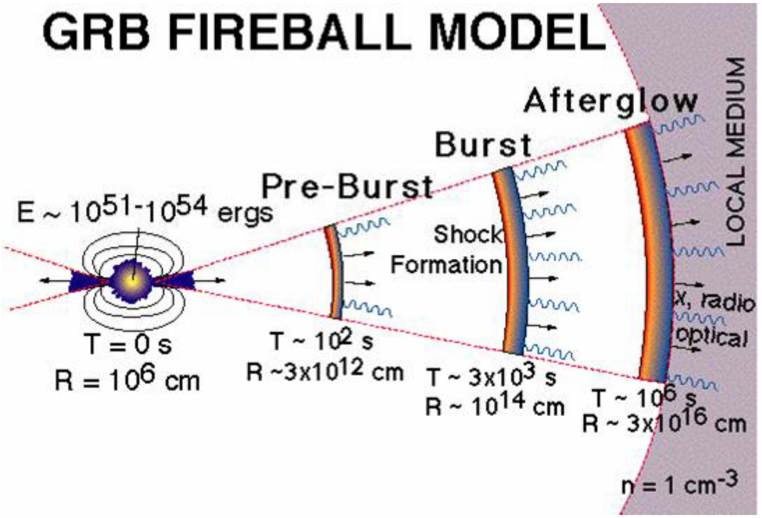
- Neutron star mergers

Short bursts

Source

- Fireball

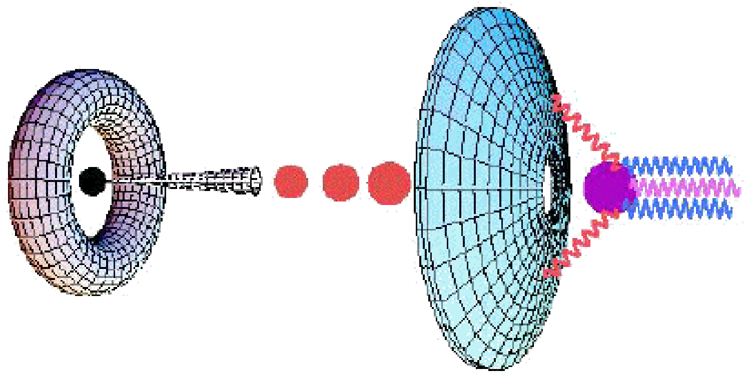
(jet+hard core)



- Cannonball:

De Rujula, Dar

(…+accretion disk)



Effect on life

- Rate: One per galaxy in million years.

Few percent directed towards us

Life has existed on Earth for about billion years

(Ordovicion-Silurian extinction of 450 million years ago)

Our Galaxy

The threat to life from Eta Carinae and gamma ray bursts

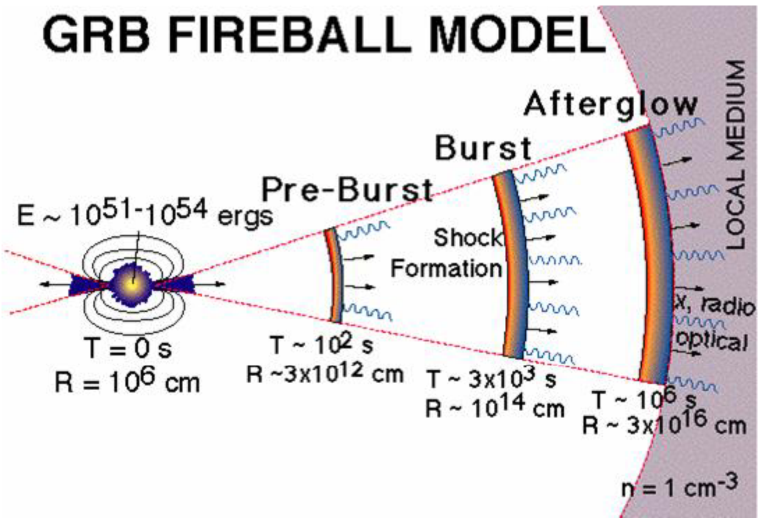
Dar and De Rujula

Don't worry the jet does not point towards us.

Photon production

- Dissipation of the kinetic energy of fireball

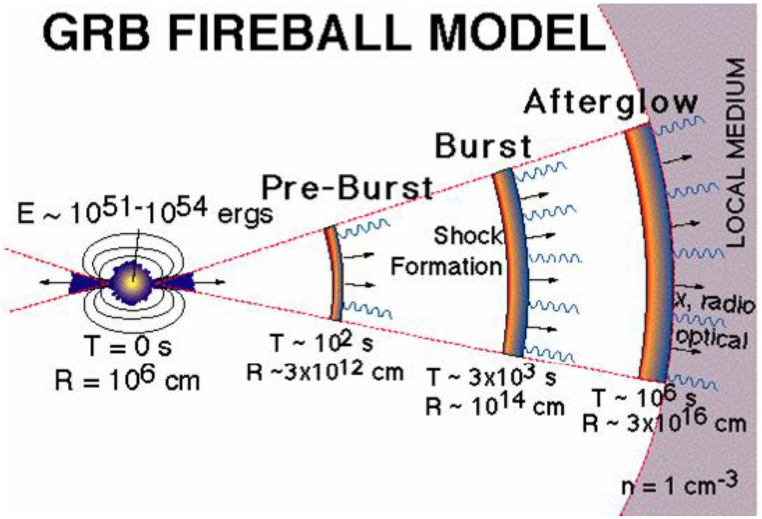
- Photon production



Photon production

Protons are Fermi accelerated

$$E_p > 10^{20} \text{ eV}$$



Neutrino and Cosmic ray production

- Fireball model

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

Neutrino production

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

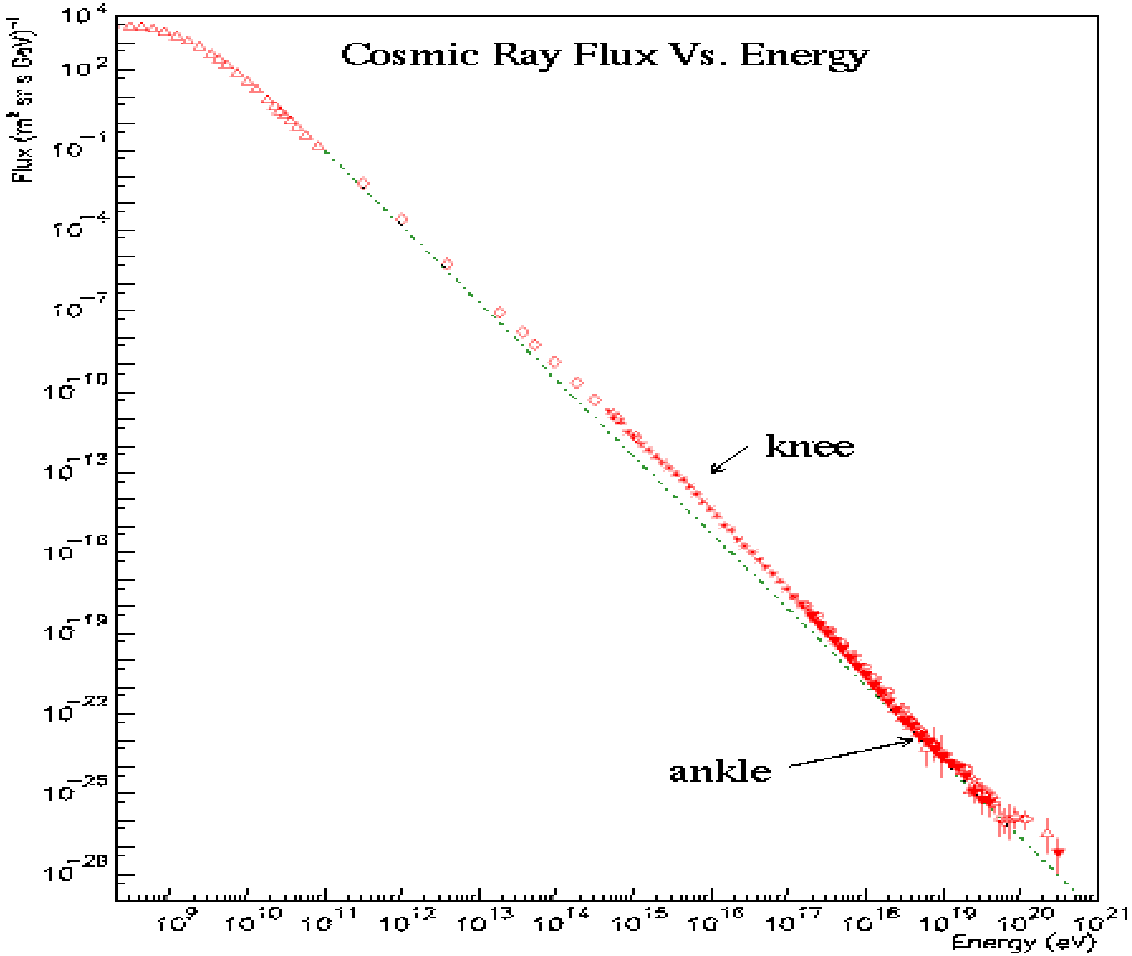
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu ,$$

Cosmic ray

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

UHECR

$$10^{18}\ \text{eV} < E < 5 \times 10^{19}\ \text{eV}$$



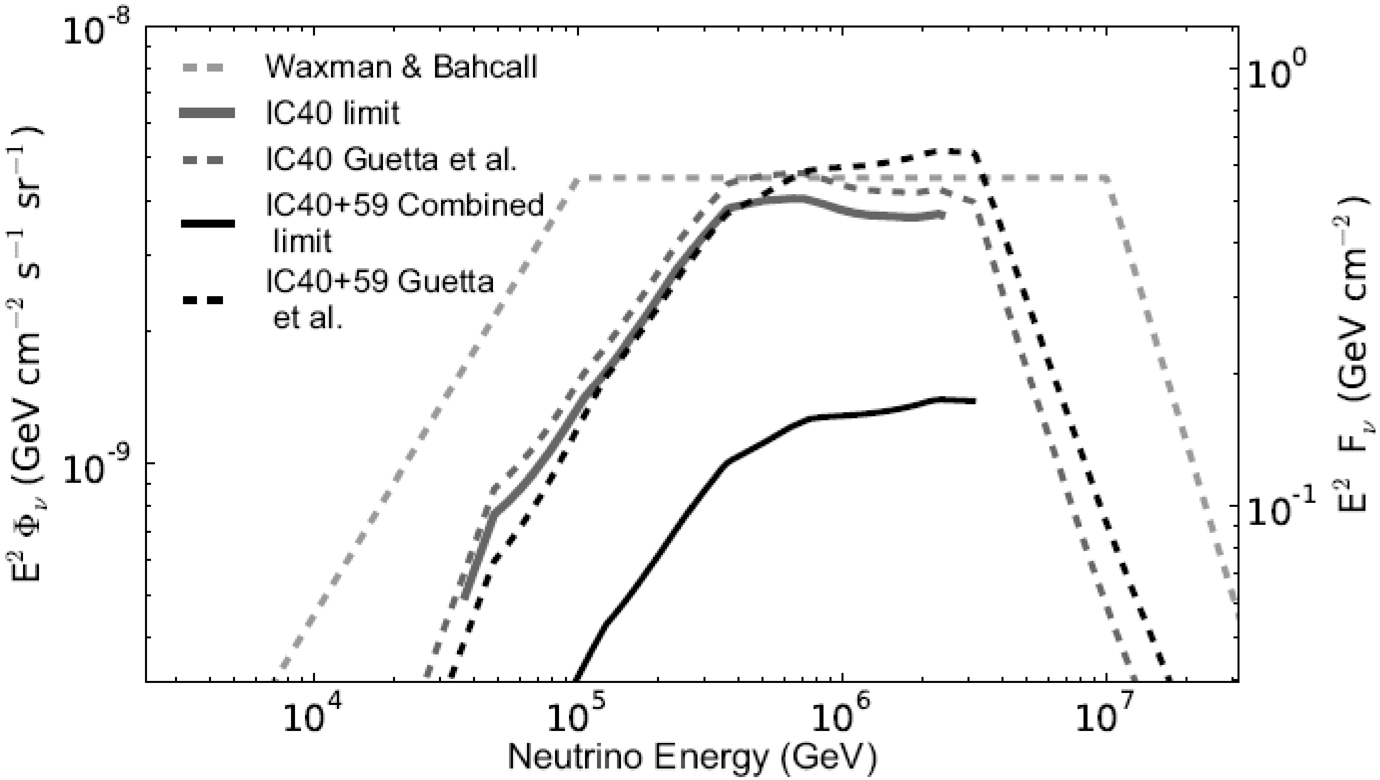
Waxman-Bahcall limit

- Neutrino energies $\sim 100\,\mathrm{TeV} - 10\,\mathrm{PeV}$

$$E_\nu^2 dN_\nu/dE_\nu \sim 5 \times 10^{-9}\,\mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}}$$

- Waxman and Bahcall, PRL78 (1997) 2292.

- ICECUBE collaboration, Nature 484 (2012) 351



3.7 times tighter bound

Cannonball model?

- Arnon Dar (1205.3479):

The upper limit on the flux of ultra high energy neutrinos from gamma-ray bursts (GRBs) that was reported recently by the IceCube collaboration contradicts predictions based on the Fireball model of GRBs, but does not exclude GRBs as a main source of ultra-high energy cosmic rays.

- Baerwald, Bustamante and Winter, 1301.6163:

1. **Optically thin to neutron escape regime.** Neutrons from photohadronic interactions, which are not magnetically confined, can escape from the source ("neutron model").

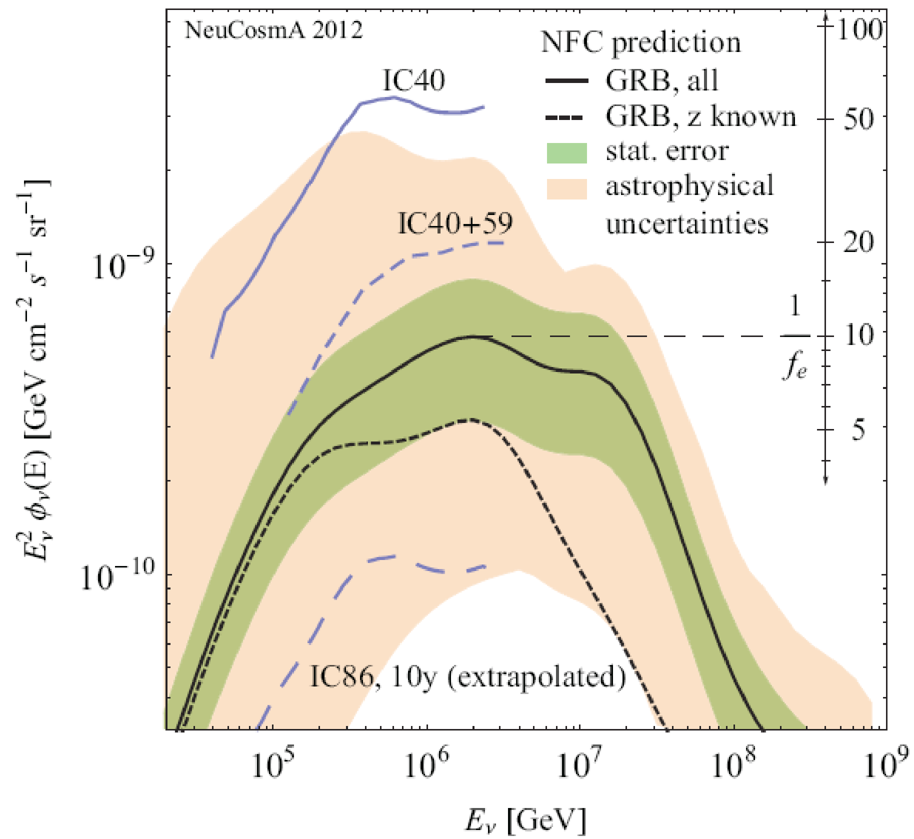
2. **Direct escape regime.** Directly escaping protons from the outer edges of the shells dominate the UHECR injection, at least at the highest energies.

3. **Optically thick to neutron escape regime.** Only neutrons from the outer edges of the shells can escape.

Saving fireball Within the SM

Uncertainties in fireball model

Hummer, Baerwald and Winter, PRL108 (2012)



Saving fireball with beyond SM

- Neutrino spin precession to sterile neutrinos inside the source

Barranco et al, PLB 718 (2012) 26 $\mu_\nu \sim 10^{-15} \mu_B$

- Neutrino decay

Baerwald, Bustamante and Winter, JCAP 1210 (2010) 20

Pseduo-Dirac neutrinos

- Cocker Melia Volkas (2002,2000);
- Karenan et al, PLB 574 (2003) ;
- Beacom et al, PRL 92 (2004) ;
- Esmaili, PRD81 (2010)

PseudoDirac neutrinos

- Implications of the Pseudo-Dirac Scenario for Ultra High Energy Neutrinos from GRBs
  Esmaili and Farzan, **JCAP 1212 (2012) 014**

- Explanation for the low flux of high energy astrophysical muon-neutrinos
  Pakvasa, Joshipura and Mohanty, 1209.5630

- Effects of Beyond Standard Model Physics on GRB Neutrinos
  Moharana and Borah, 1301.4097

Neutrino mass matrix

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\overline{\Psi^c} M \Psi,$$

$$\Psi \equiv \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

$$M = \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix}$$

Lepton number conserving

Lepton number violating

Seesaw scenario

$$\mathcal{L}_{\mathrm{mass}} = -\frac{1}{2}\overline{\Psi^c} M \Psi,$$

$$M = \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix}$$

$$m_M \gg m_D$$

Mass eigenvalues:

$$-\frac{m_D^2}{m_M}\ , \quad m_M$$

PseudoDirac scenario

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\overline{\Psi^c} M \Psi,$$

$$\boxed{M = \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix}}$$

$$m_M \ll m_D$$

Mass eigenvalues: $m_D + m_M/2 \quad -m_D + m_M/2$

Pseudo-Dirac scenario

$$\mathcal{L}_{\mathrm{mass}} = -\frac{1}{2}\overline{\Psi^c} M \Psi,$$

$$\Psi = (\nu_{L1}, \nu_{L2}, \nu_{L3}, \nu^c_{R1}, \nu^c_{R2}, \nu^c_{R3})^T$$

$$M = \begin{pmatrix} 0 & m_D^T \\ m_D & m_M^* \end{pmatrix} \qquad m_M \ll m_D$$

Mass Basis

$$m_D = \mathrm{diag}\left(m_1, m_2, m_3\right)$$

$$m_2 = \sqrt{m_1^2 + \Delta m_{\mathrm{sol}}^2} \text{ and } m_3 = \sqrt{m_1^2 + \Delta m_{\mathrm{atm}}^2},$$

Mass eigen-system

$$\boxed{\begin{aligned} \nu_i^+ &= \frac{\nu_{Li} + \nu_{Ri}^c}{\sqrt{2}} + \sum_{j\neq i} (\alpha_{ij}^+ \nu_{Lj} + \beta_{ij}^+ \nu_{Rj}^c) \ , \\ \nu_i^- &= \frac{\nu_{Li} - \nu_{Ri}^c}{\sqrt{2}} + \sum_{j\neq i} (\alpha_{ij}^- \nu_{Lj} + \beta_{ij}^- \nu_{Rj}^c) \ , \end{aligned}}$$

$$\boxed{\alpha_{ij}^{\pm}, \beta_{ij}^{\pm} \sim m_M/m_D \ll 1}$$

Mass eigen-system

$$\nu_i^+ = \frac{\nu_{Li} + \nu_{Ri}^c}{\sqrt{2}} + \sum_{j \neq i} (\alpha_{ij}^+ \nu_{Lj} + \beta_{ij}^+ \nu_{Rj}^c) \ ,$$

$$\nu_i^- = \frac{\nu_{Li} - \nu_{Ri}^c}{\sqrt{2}} + \sum_{j \neq i} (\alpha_{ij}^- \nu_{Lj} + \beta_{ij}^- \nu_{Rj}^c) \ ,$$

$$\langle \nu_i^+ | \nu_i^- \rangle = 0 \ \text{and} \ \langle \nu_i^- | \nu_j^- \rangle = \langle \nu_i^+ | \nu_j^+ \rangle = 0$$

Mass eigensystem

$$\boxed{\begin{aligned}\nu_i^+ &= \frac{\nu_{Li} + \nu_{Ri}^c}{\sqrt{2}} + \sum_{j\neq i}(\alpha_{ij}^+ \nu_{Lj} + \beta_{ij}^+ \nu_{Rj}^c)\ , \\ \nu_i^- &= \frac{\nu_{Li} - \nu_{Ri}^c}{\sqrt{2}} + \sum_{j\neq i}(\alpha_{ij}^- \nu_{Lj} + \beta_{ij}^- \nu_{Rj}^c)\ ,\end{aligned}}$$

$$(m_i^-)^2 = m_i^2 - \Delta m_i^2/2,$$

$$(m_i^+)^2 = m_i^2 + \Delta m_i^2/2$$

$$\boxed{\Delta m_i^2 \sim m_D m_M \ll \Delta m^2_{\rm sol,atm}}$$

Evolution in time of neutrinos

$$|\nu_\alpha, t=0\rangle = \sum_i U^*_{\alpha i} \frac{|\nu_i^+\rangle + |\nu_i^-\rangle}{\sqrt{2}}$$

$$\Big\Downarrow \text{ In time}$$

$$|\nu_\alpha, t\rangle = \sum_i U^*_{\alpha i} \frac{e^{i\phi_i^+}|\nu_i^+\rangle + e^{i\phi_i^-}|\nu_i^-\rangle}{\sqrt{2}}$$

Evolution in time of antineutrinos

$$|\bar{\nu}_\alpha, t=0\rangle = \sum_i U_{\alpha i} \frac{|\bar{\nu}_i^+\rangle + |\bar{\nu}_i^-\rangle}{\sqrt{2}}$$

$$\Big\Downarrow \quad \text{In time}$$

$$|\bar{\nu}_\alpha, t\rangle = \sum_i U_{\alpha i} \frac{e^{i\phi_i^+}|\bar{\nu}_i^+\rangle + e^{i\phi_i^-}|\bar{\nu}_i^-\rangle}{\sqrt{2}}$$

Origin of difference

$$\psi = u\ \mathbf{a} + v\ \mathbf{a^{c\dagger}}$$

$$\left\{ \begin{array}{l} \boxed{\psi\ |\mathrm{Vac}\rangle \propto |\mathrm{antiparticle}\rangle} \\ \\ \boxed{\psi^\dagger\ |\mathrm{Vac}\rangle \propto |\mathrm{particle}\rangle} \end{array} \right.$$

Evolution in time of neutrinos

$$|\nu_\alpha, t=0\rangle = \sum_i U^*_{\alpha i} \frac{|\nu_i^+\rangle + |\nu_i^-\rangle}{\sqrt{2}}$$

$\Big\Downarrow$ In time

$$|\nu_\alpha, t\rangle = \sum_i U^*_{\alpha i} \frac{e^{i\phi_i^+}|\nu_i^+\rangle + e^{i\phi_i^-}|\nu_i^-\rangle}{\sqrt{2}}$$

Oscillation probability in pseudo-Dirac scenario

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta, t=0|\nu_\alpha, t\rangle|^2 =$$

$$\left| \sum_i U^*_{\beta i} U_{\alpha i} \frac{e^{i\phi_i^+} + e^{i\phi_i^-}}{2} \right|^2$$

Pure Dirac limit $\quad m_i^+ = m_i^- \;\Rightarrow\; \phi_i \equiv \phi_i^+ = \phi_i^-$

Oscillation probability in Standard case

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta, t=0 | \nu_\alpha, t\rangle|^2 =$$

$$\left| \sum_i U^*_{\beta i} U_{\alpha i} e^{i\phi_i} \right|^2$$

$$\phi_i = \frac{m_i^2 L}{2E}$$

Limits

- No non-Standard effect

$$\boxed{\phi_i^+ - \phi_i^- \longrightarrow 0}$$

- Sensitivity to oscillation to sterile effect:

$$\boxed{|\phi_i^+ - \phi_i^-| \gtrsim \pi}$$

- For solar neutrinos with MeV energy:

$$\boxed{\Delta m_j^2 \sim 10^{-12}\ \mathrm{eV}^2}$$

$$\boxed{\Delta m_j^2 < 1.8 \times 10^{-12}\ \mathrm{eV}^2 \ \text{at}\ 3\sigma\ \text{level}}$$

De Gouvea, Huang and Jenkins, **PRD** 80 (2009)

Oscillation probability in Standard case

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta, t = 0 | \nu_\alpha, t \rangle|^2 =$$

$$\left| \sum_i U^*_{\beta i} U_{\alpha i} e^{i m_i^2 L / 2E} \right|^2$$

$$\boxed{L \gg 10^8 \ km \frac{E}{\mathrm{PeV}}} \Rightarrow \boxed{\frac{m_i^2 L}{2E} \gg 1}$$

Averaging out

- For a comparison: Sun-Earth distance=150000000 km

- For cosmic neutrinos, the interference term averaged out:

$$P(\nu_\alpha \to \nu_\beta) = \langle |\langle \nu_\beta, t=0|\nu_\alpha, t\rangle|^2 \rangle =$$

$$\sum_i \left| U_{\beta i}^* U_{\alpha i} \right|^2$$

Unitarity: $\boxed{\sum_\beta P_{\alpha\beta} = \sum_\alpha P_{\alpha\beta} = 1}$

Pseudo-Dirac scenario

$$|(m_i^+)^2 - (m_i^-)^2| \ll |(m_i^+)^2 - (m_j^+)^2|_{i\neq j} \simeq |(m_i^-)^2 - (m_j^-)^2|_{i\neq j}$$

$$L \gg 10^8 \ km \frac{E}{\text{PeV}}$$

$$\boxed{P_{\alpha\beta} = \sum_{j=1}^{3} |U_{\alpha j}|^2 |U_{\beta j}|^2 \cos^2\left(\frac{\Delta\Phi_j}{2}\right) \quad \text{where} \quad \Delta\Phi_j \equiv \Phi_j^+ - \Phi_j^-}$$

- Oscillation to sterile neutrinos $\nu_R \simeq \frac{\nu^+ - \nu^-}{\sqrt{2}}$:

$$\boxed{\sum_\beta P_{\alpha\beta}, \sum_\alpha P_{\alpha\beta} < 1}$$

Phase at cosmological distances

$$\Phi_j^{\pm} = \int_t^{t_0} \frac{k}{a(t')} \left[1 + \left(\frac{m_j^{\pm} a(t')}{k}\right)^2\right]^{1/2} \mathrm{d}t'$$

$$\simeq \int_t^{t_0} \frac{k}{a(t')} \,\mathrm{d}t' + \frac{(m_j^{\pm})^2}{2} \int_t^{t_0} \frac{a(t')}{k} \,\mathrm{d}t' \,.$$

$$\boxed{\Delta\Phi_j \equiv \Phi_j^{+} - \Phi_j^{-} = \frac{\Delta m_j^2}{2} \int_t^{t_0} \frac{a(t')}{E_\nu} \,\mathrm{d}t' \,,}$$

$$E_\nu = k \qquad\qquad E_\nu = E_\nu^0/(1+z)$$

Phase

$$\Delta\Phi_j = \frac{\Delta m_j^2}{2E_\nu} D_H \int_0^z \frac{\mathrm{d}z'}{(1+z')^2\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}} \,,$$

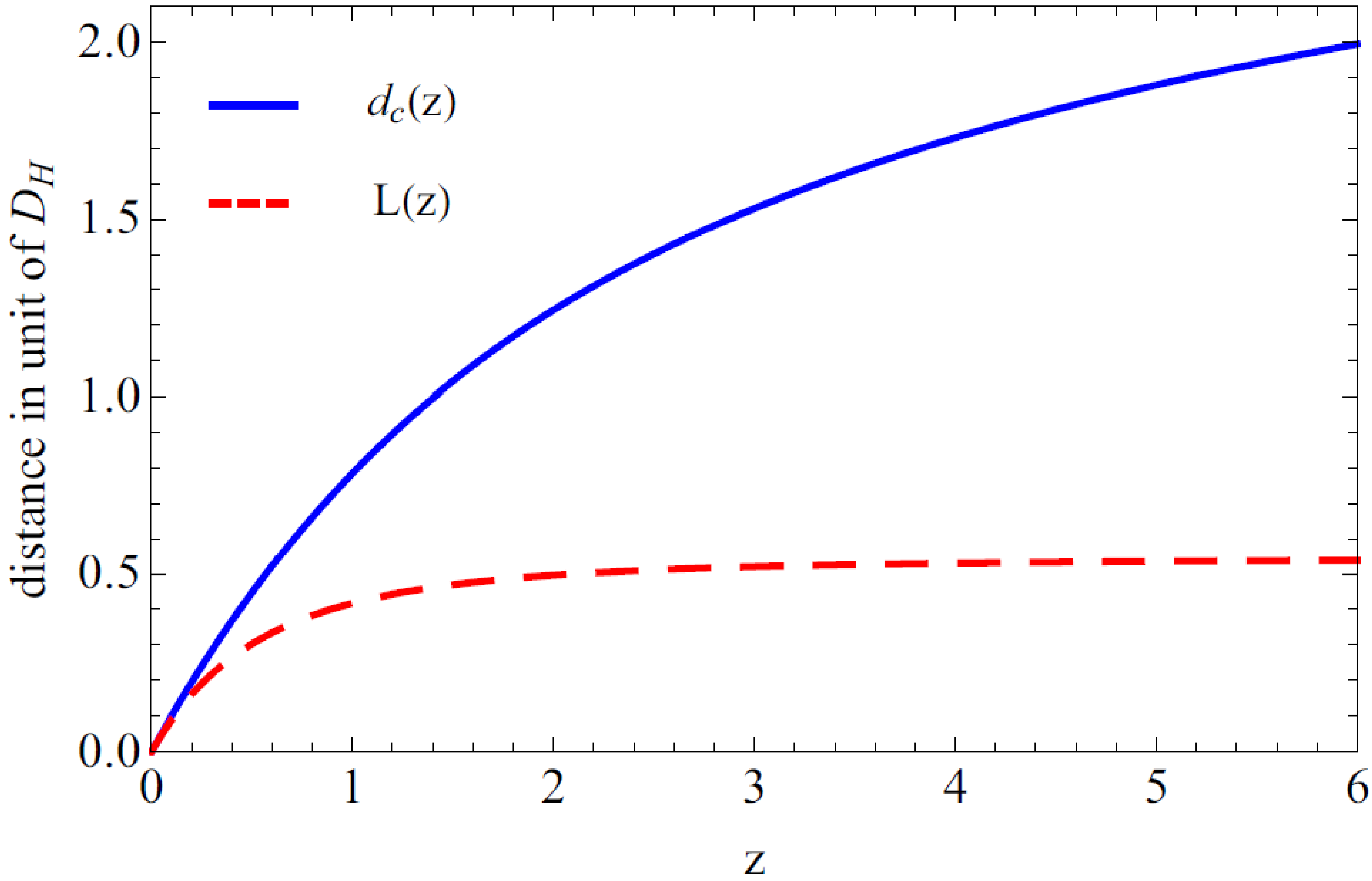
$\boxed{D_H = c/H_0 \text{ is the Hubble length with } H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}}$

$$\boxed{\Omega_m = 0.27 \text{ and } \Omega_\Lambda = 0.73}$$

Saturation of baseline

$$\Delta\Phi_j = \frac{\Delta m_j^2}{2E_\nu} L(z) \ ,$$

$$L(z) = D_H \int_0^z \frac{\mathrm{d}z'}{(1+z')^2\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} \ .$$



$$d_c(z) = D_H \int_0^z \frac{\mathrm{d}z'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} \, .$$

Averaging out limit

$L \gg L_{\mathrm{osc}}$

- Independent of the spatial distribution of sources:

$$P_{\alpha\beta} = \frac{1}{2}\sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

- Half the conventional 3 neutrino scenario
- Robust result against matter effects

- Averaging over sources $\boxed{L \sim L_{\rm osc},}$
- Effective suppression factor

$$S_{\rm eff}(\Delta m_j^2, E_\nu) = \frac{\sum_k \left\langle \cos^2\left(\frac{\Delta\Phi_j(z_k, E_\nu^0)}{2}\right)\right\rangle \frac{dN_\nu(z_k, E_\nu^0)}{dE_\nu^0} \frac{(1+z_k)}{[d_c(z_k)]^2}}{\sum_k \frac{dN_\nu(z_k, E_\nu^0)}{dE_\nu^0} \frac{1+z_k}{[d_c(z_k)]^2}}$$

- Averaging over energy resolution

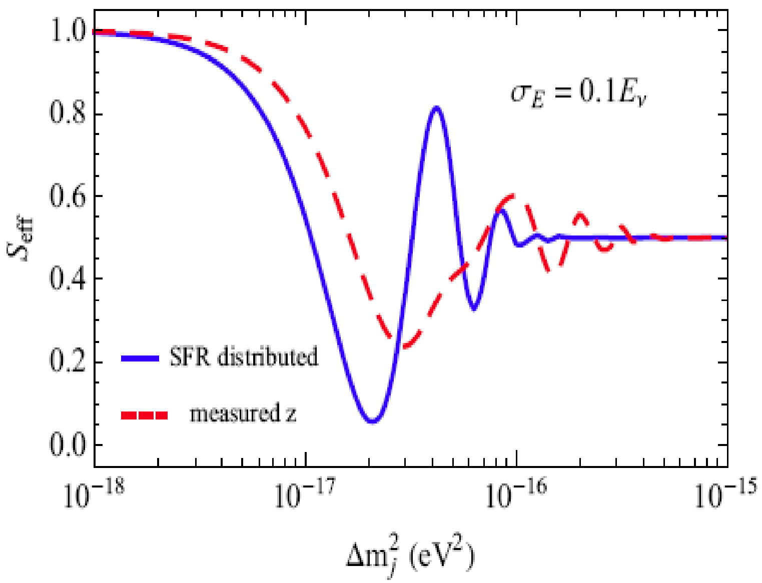
Do we know know the redshift of sources?

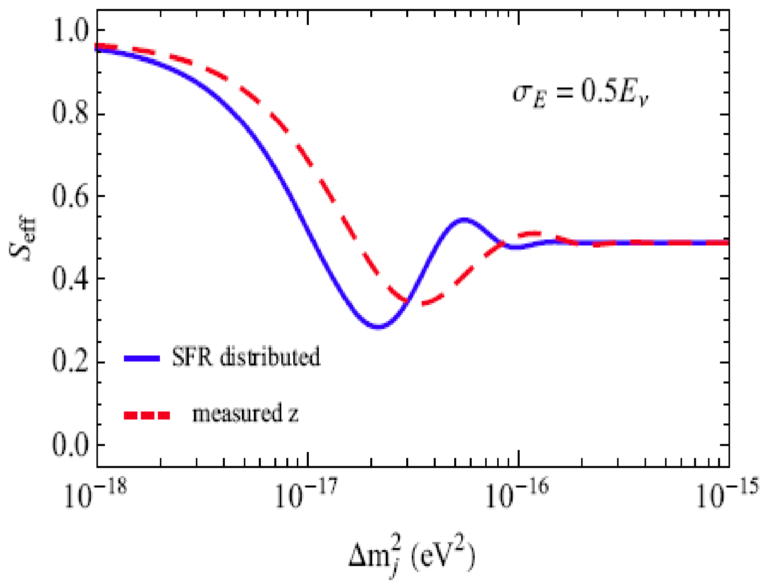
- Measuring the X-ray spectrum of aftergolw
- Only the redshift of 13 sources out of 300 is measured

- Assumption: GRB rate ⟺ star formation

Madau and Pozzetti (2001)

Suppression factor

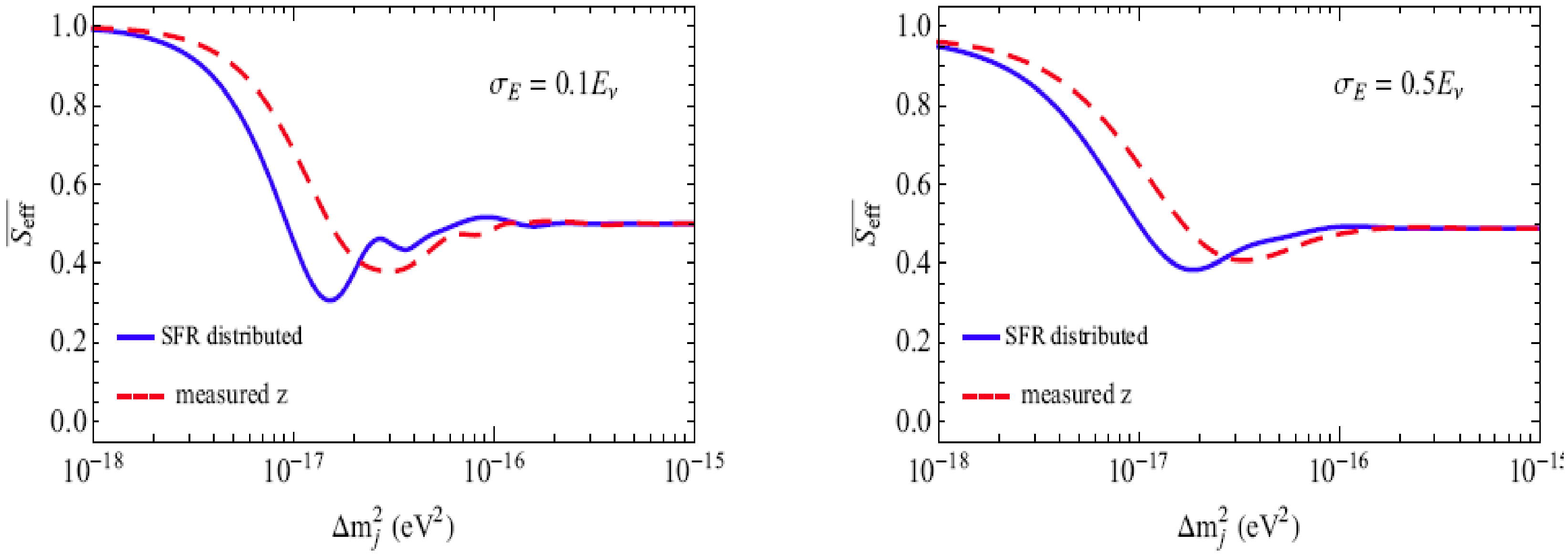




The neutrino energy at Earth is fixed to $E_\nu = 1$ PeV.

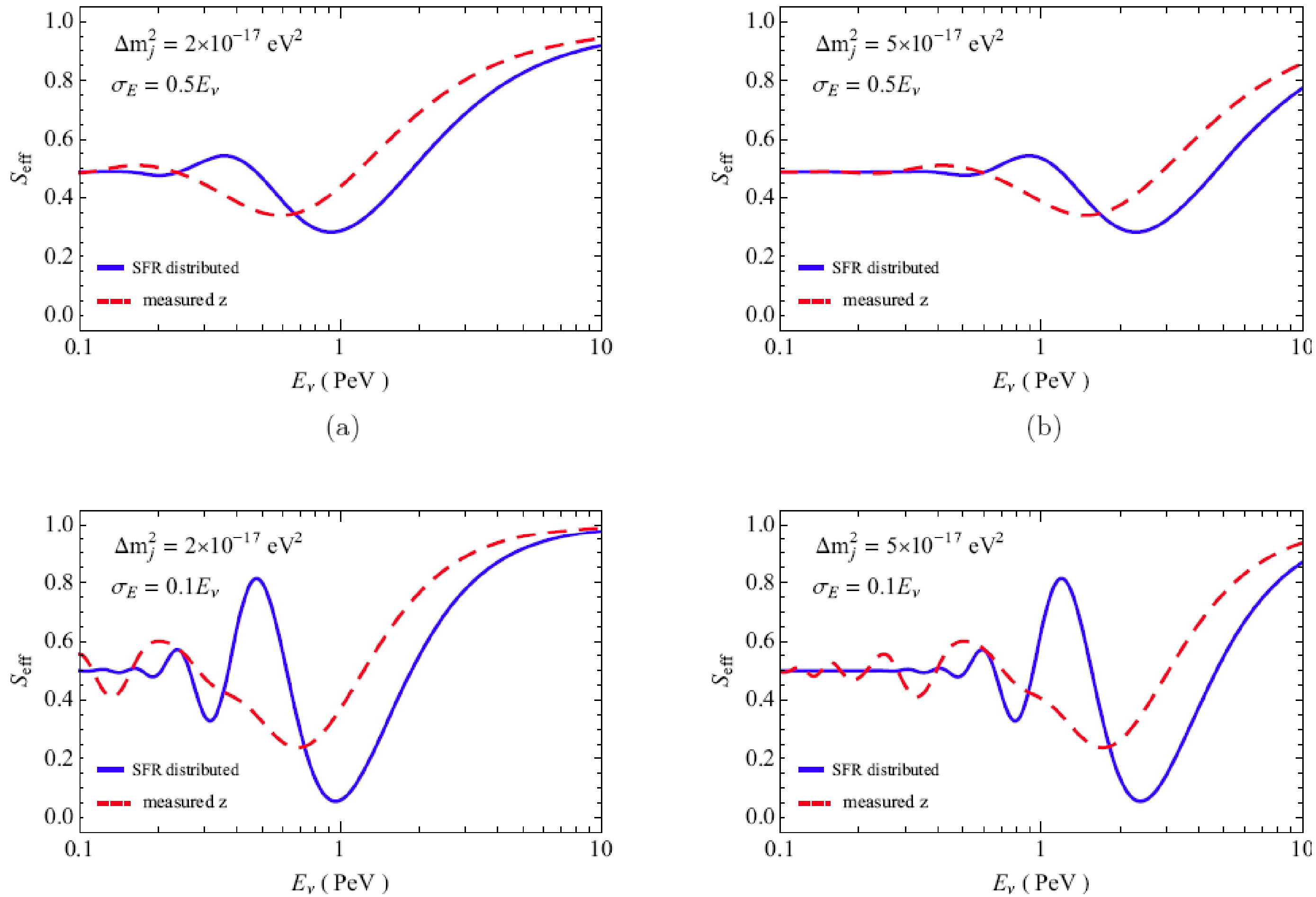
Suppression over energy range

$$\overline{S_{\text{eff}}(\Delta m_j^2; E_\nu^1, E_\nu^2)} = \frac{\int_{E_\nu^1}^{E_\nu^2} \sum_k \left\langle \cos^2\left(\frac{\Delta\Phi_j(z_k, E_\nu^0)}{2}\right)\right\rangle \frac{dN_\nu(z_k, E_\nu^0)}{dE_\nu^0} \frac{(1+z_k)}{[d_c(z_k)]^2}\, \mathrm{d}E_\nu}{\int_{E_\nu^1}^{E_\nu^2} \sum_k \frac{dN_\nu(z_k, E_\nu^0)}{dE_\nu^0} \frac{(1+z_k)}{[d_c(z_k)]^2}\, \mathrm{d}E_\nu}$$



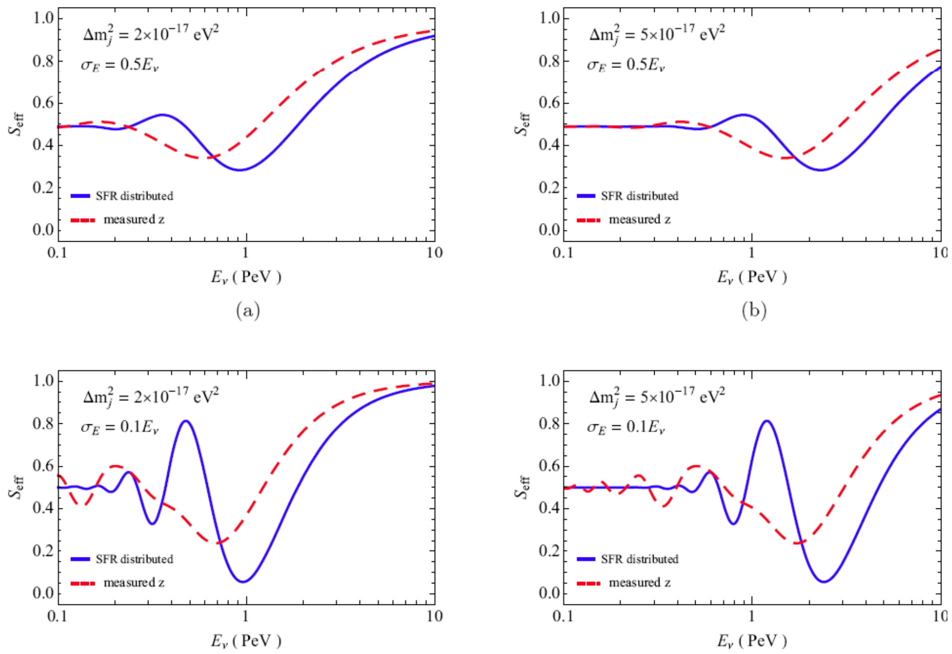
The assumed energy range is $(E_\nu^1, E_\nu^2) = (0.1, 3)$ PeV.

Distortion of energy spectrum



Short summary

- Pseudo-Dirac scenario can partially solve the problem of missing neutrinos from GRB sources.



$$\Delta m^2 \sim 10^{-17}\ \mathrm{eV}^2$$

Diffuse neutrinos from supernova

- If SN is inside our galaxy, Super-Kamiokande can detect thousands.

- Neutrinos from SN at cosmological distances

$$\Downarrow$$

diffuse neutrinos

Energy $\sim 10\ \mathrm{MeV}$ $\Rightarrow$ Down to $\Delta m_j^2 \sim 10^{-18}\mathrm{eV}^2$ total averaging

Conclusions on Diffuse SN neutrino

- An energy-independent suppression of ½;
- Uncertainty in prediction of the flux of diffuse SN neutrinos:
- A factor of 4

- Observation cannot rule out pseudo-Dirac scenario but can rule in those models that predict too much.

- Distortion of spectrum: $\boxed{\Delta m_j^2 \sim 10^{-25}\ \mathrm{eV}^2}$

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- Special thanks to Belen Gavela and Silvia Pascoli
- Allameh Tabatabii grant of Prof Sheikh-Jabbari

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….

Thanks

- To all speakers and participants

- 1/3 of speakers were female. In sending invitation, I did not have gender issue in mind. It turned out to be like that. Considering the mix of younger participants, I hope and predict that in recent future, we can reach 50/50 just naturally without any doping!

Special thanks to

- Ms Pileroudi
- Ms Jam
- Ms Babanzadeh
- Mr Iman Bagheri
- Mr Aliabadi
- Mr Zare