New physics effects in neutrino fluxes from cosmic accelerators

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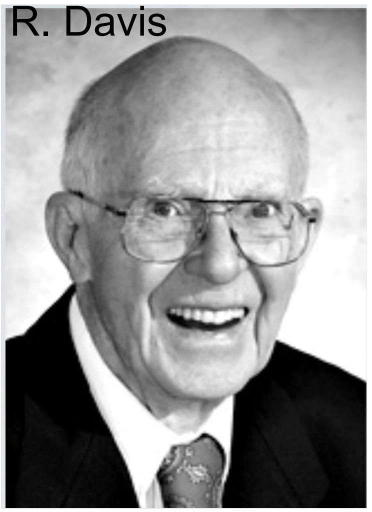
What is nu ? @ The Galileo Galilei Institute for Theoretical Physics, Florence **[June 22, 2012]**

Plan

- Motivation
- High energy neutrino production
- Propagation (standard oscillations) effects
- Flavor detection at neutrino telescopes
- Energy-dependent new physics effects during propagation
- Summary and Outlook

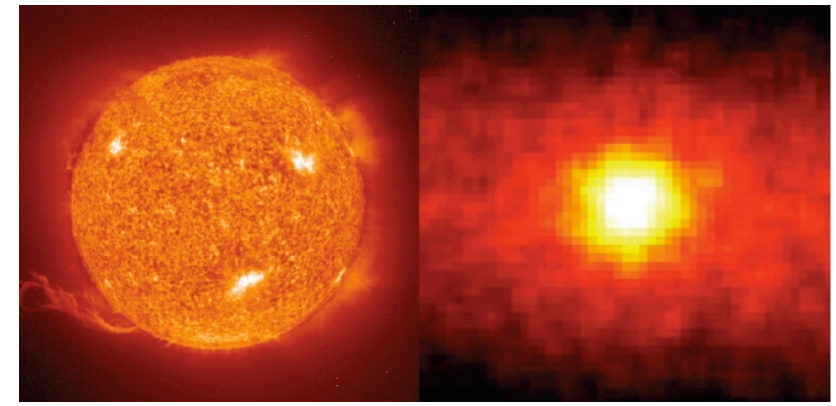
High energy astrophysical neutrinos

Extra-terrestrial neutrino signals



Low (~10 MeV) energy neutrinos

stellar evolution + evidence for new neutrino physics



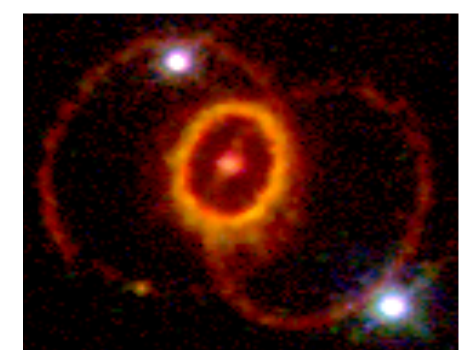
- Solar neutrinos - Sun shines due to the nuclear fusion reactions

2002 Noble prize

- Neutrinos from SN1987A - core collapse of massive stars

LECTURE BY G. RAFFELT

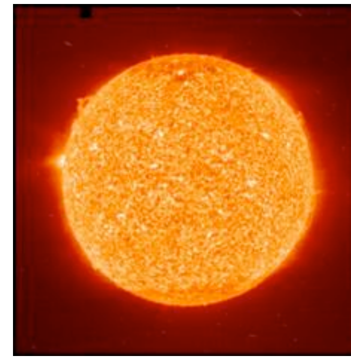
core collapse + neutrino properties



Natural "MeV neutrinos"

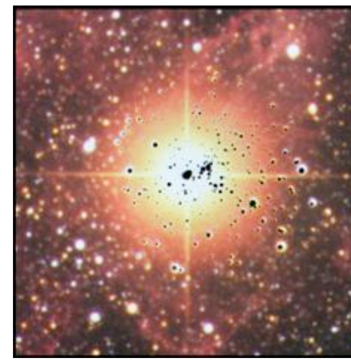
Sources of neutrinos

✓ Nuclear Reactors



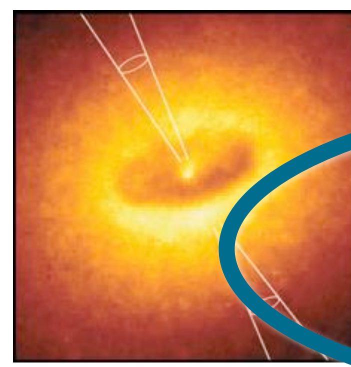
Sun ✓

✓ Particle Accelerators



Supernovae
(Stellar Collapse)
SN 1987A ✓

✓ Earth Atmosphere
(Cosmic Rays)



Astrophysical
Accelerators Soon ?

✓ Earth Crust
(Natural
Radioactivity)

Big Bang
(Today 330 ν/cm^3)
Indirect Evidence

The neutrino sky

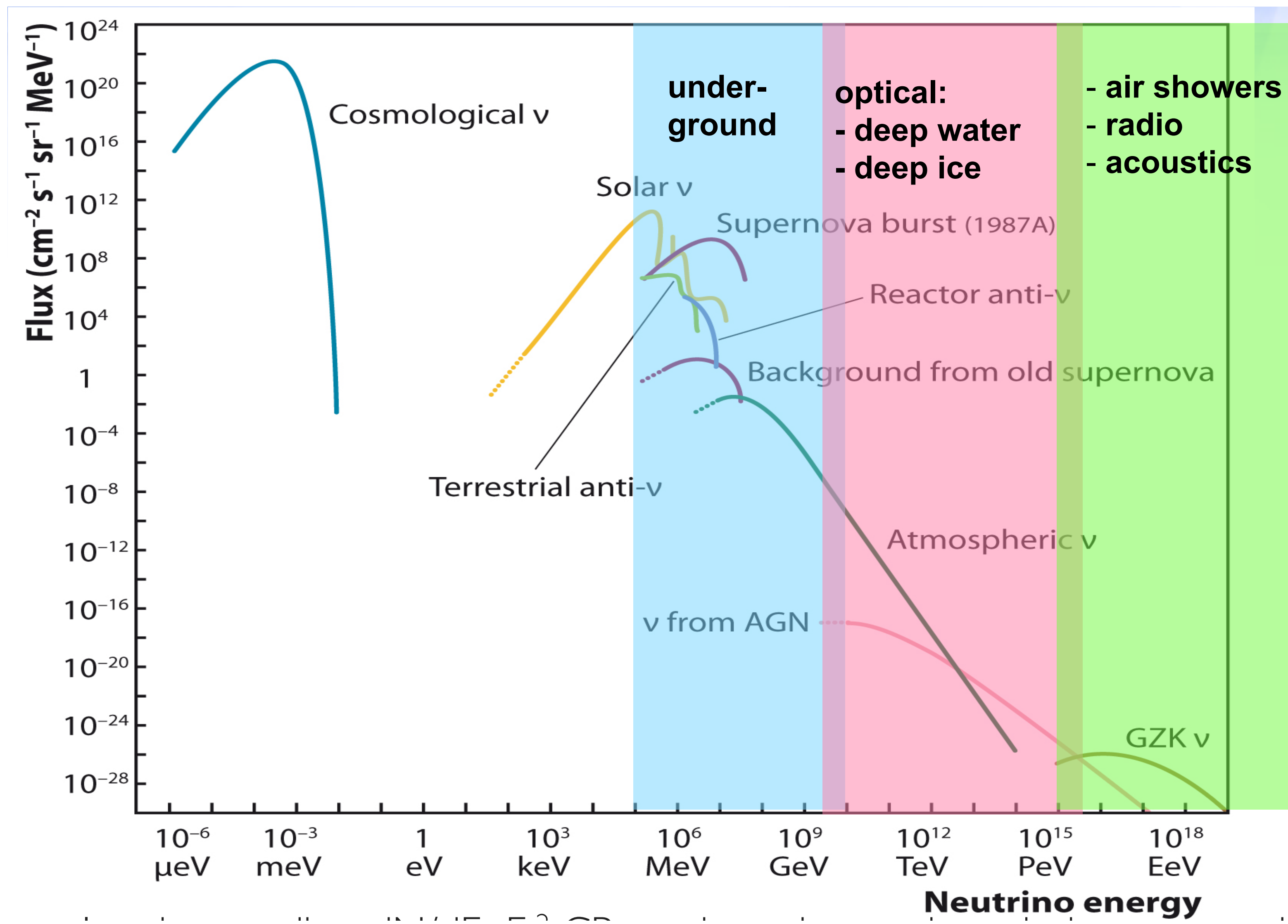
Astrophysical neutrinos

- sub-eV: Cosmological neutrinos
- MeV: SN, Sun
- TeV: GRB, AGN
- EeV:

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

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

"GZK neutrinos"



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

Why are high energy neutrinos special ?

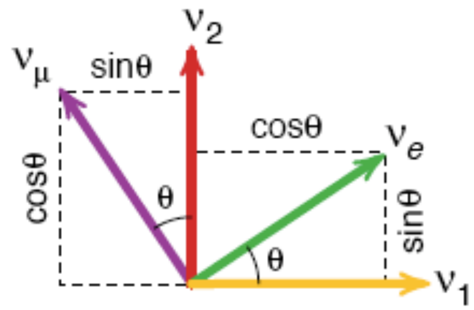
- Astrophysics and cosmology
  - physical processes in core of sources, probe the acceleration mechanism, effects due to magnetic field
  - cosmological parameters such as source redshift using neutrinos

Ref: Wagner and Weiler, MPLA12, 2497 (1997) Weiler, Simmons, Pakvasa and Learned, hep-ph/9411432

- Particle Physics
  - Flavor ratios are sensitive probes of new physics effects (beyond the reach of terrestrial experiments)
  - Probe of neutrino-nucleon cross section at UHE: $E_{cm} = \sqrt{2m_p E_{lab}}$
- Hints of high energy neutrinos in recent IC data - two ~PeV cascades

TALK BY ISHIHARA@NEUTRINO 2012

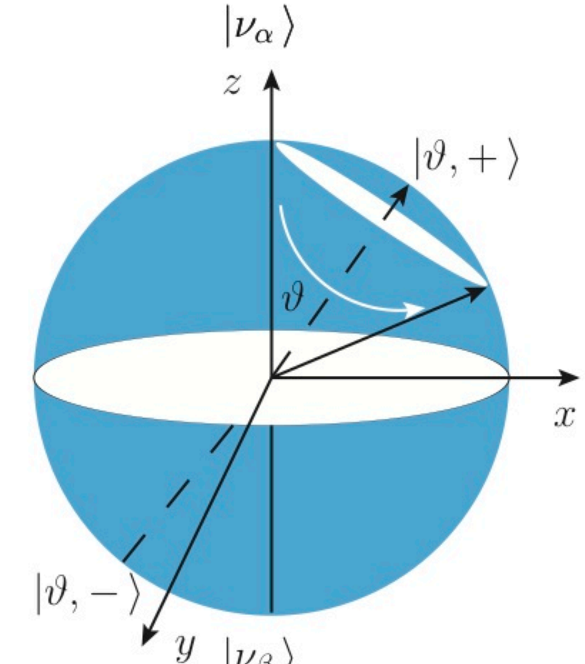
Neutrino flavor oscillations



- Neutrinos are produced and detected via weak interactions in states of definite flavor
- Flavor states differ from the stationary (mass) eigenstates $\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$
- Hamiltonian is non-diagonal in flavor basis eg. for the two flavor case in vacuum :

$$\omega = \delta m^2/2p$$

$$\mathbb{H} = \left(p + \frac{m_1^2 + m_2^2}{4p}\right)\mathbb{I} + \frac{1}{2}\begin{pmatrix} -\omega\cos 2\theta & \omega\sin 2\theta \\ \omega\sin 2\theta & \omega\cos 2\theta \end{pmatrix}$$



- In the ultra-relativistic limit, 2 flavor oscillations analogous to a 2 state system (in the limit of equal and fixed momenta) and Hilbert space can be mapped to the Poincare/Bloch sphere
- The effect of oscillation is precession about mass (eigen) axis

Ref: Mehta, PRD79 (2009);
see also Kim, Sze and Nussinov, PRD35 (1987); Kim, Kim and Sze, PRD37 (1988).

Neutrino mass and new physics

Beyond the new physics that gives rise to neutrino mass

- Neutrinos are strictly massless in the Standard Model
- Observation of neutrino flavor oscillations implies that neutrinos are massive
- However, the nature of neutrinos is unknown
- A positive signal from neutrinoless double beta decay experiment would imply Majorana neutrino mass
- Seesaw mechanism : Elegant possibility to generate tiny Majorana neutrino masses
- But, it is hard to obtain the desired mixing pattern
- One of the several attempts :
    - use hybrid seesaws to explain large mixing angles

Ref: Chakrabortty, Joshipura, Mehta and Vempati, 0909.3116 (2009)

New physics at very long baselines

- Neutrino decay
  Ref: Beacom, Bell, Hooper, Pakvasa, Weiler, PRL90, 181301 (2003), Maltoni and Winter, (2008), Bhattacharya, Choubey, Gandhi and Watanabe, JCAP 1009 (2010) 009 and PLB 690, 42 (2010), Mehta and Winter, JCAP 1103, 041 (2011),

- Quantum Decoherence
  Ref: Hooper et al, PRD72, 065009 (2005), Anchordoqui et al. , PRD72, 065019 (2005), Bhattacharya, Choubey, Gandhi and Watanabe, JCAP 1009 (2010) 009 and PLB 690, 42 (2010), Mehta and Winter, JCAP 1103, 041 (2011)

- Pseudo-Dirac nature
  Ref: Beacom, Bell, Hooper, Learned, Pakvasa and Weiler, PRL92, 011101 (2004)

- Violation of Lorentz invariance and CPT invariance
  Ref: Hooper, Morgan and Winstanley, PRD72, 065009 (2005), Bhattacharya, Choubey, Gandhi and Watanabe, JCAP 1009 (2010) 009 and PLB 690, 42 (2010)

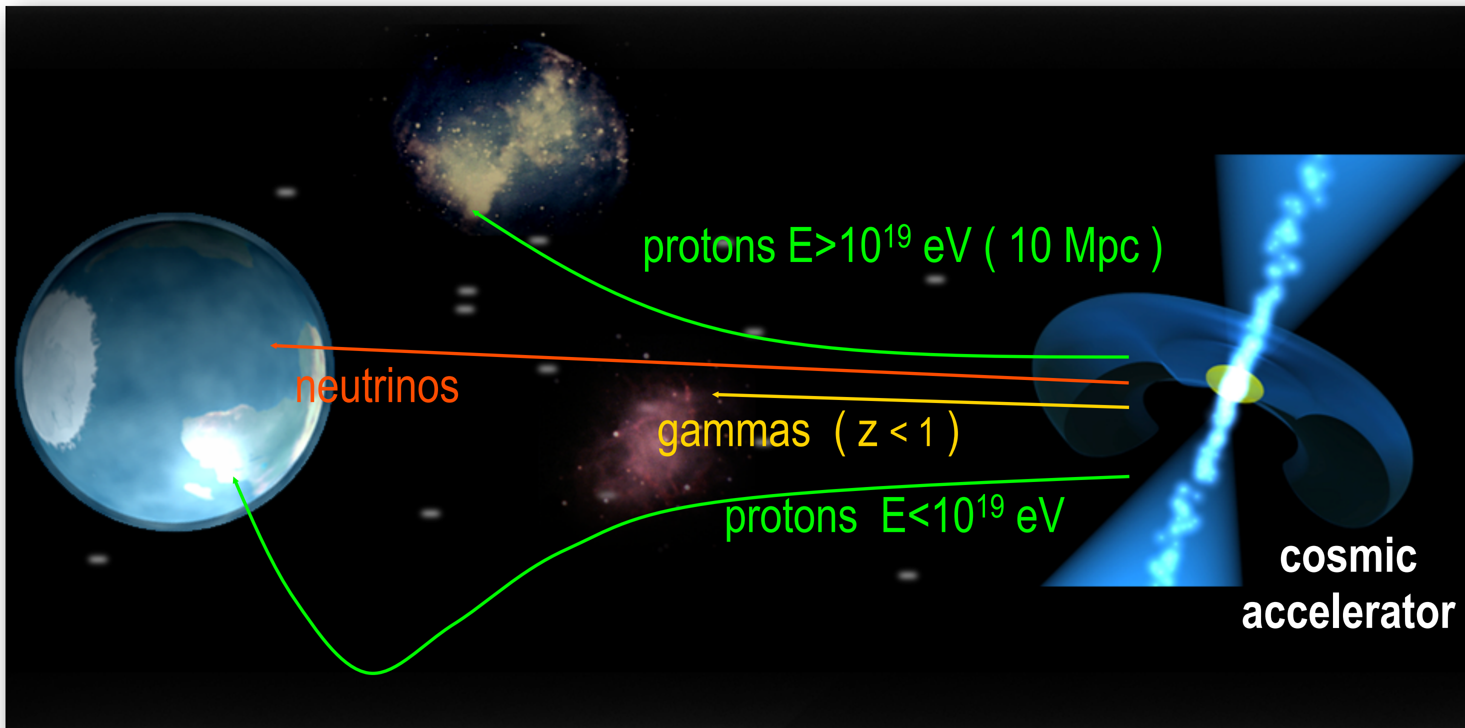
- Unitarity violation
  Ref: Bustamante, Gago and Pena Garay, JHEP 1004 (2010) 066

- Violation of Equivalence principle
  Ref: Pakvasa, Simmons and Weiler, PRD39, 1761(1989); Minakata and Smirnov, PRD54, 3698 (1996)

E-dependent and E-independent effects

Sources

The three messengers



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

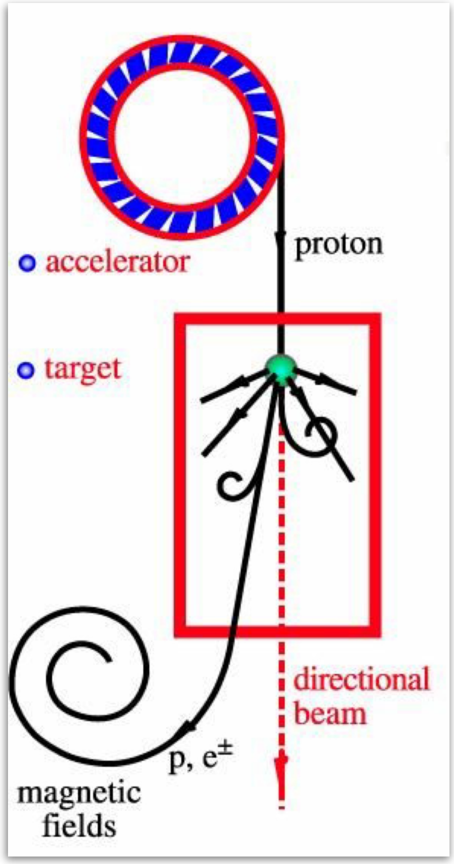
$1pc = 3.1 \times 10^{13}\ km$

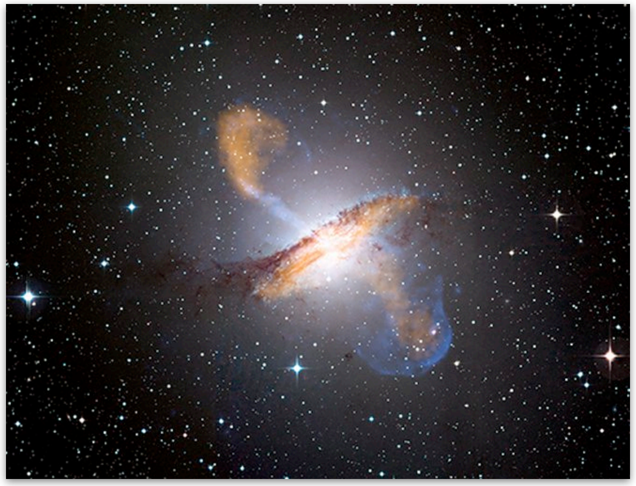
Terrestrial vs cosmic accelerators

- **Terrestrial :**
  - neutrinos in a directional beam
  - At LHC-14 TeV cms energy implies a 0.1 EeV proton in the lab frame

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

- **Cosmic :**
  - cosmic rays, photons and neutrinos escape with linked fluxes





Ref: Halzen, ICRC'07

A typical cosmic accelerator

Pion photoproduction

$$p + \gamma \to \Delta_{1232} \to p + \pi^0 \quad \text{BR=2/3}$$

$$p + \gamma \to \Delta_{1232} \to n + \pi^+ \quad \text{BR=1/3}$$

Weak decays

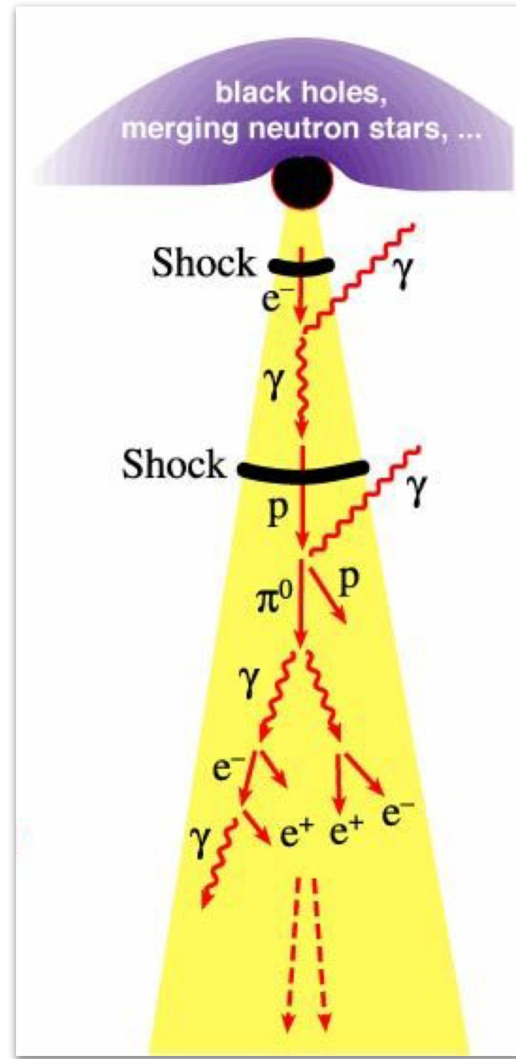
1:2:0

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

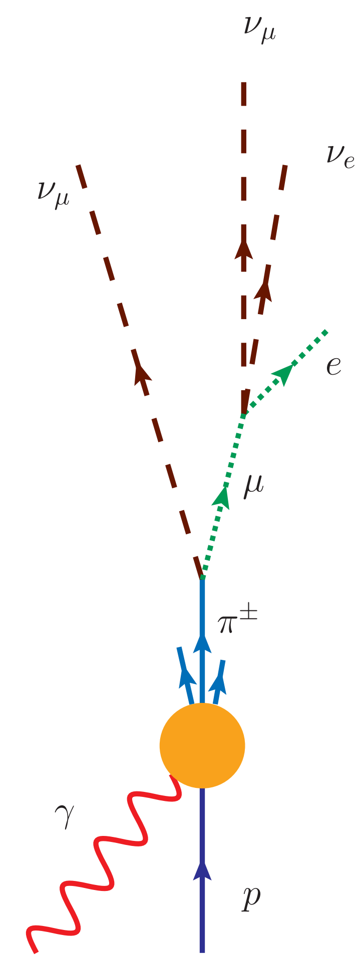
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

If n exits the source

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



Ref: Halzen, ICRC'07

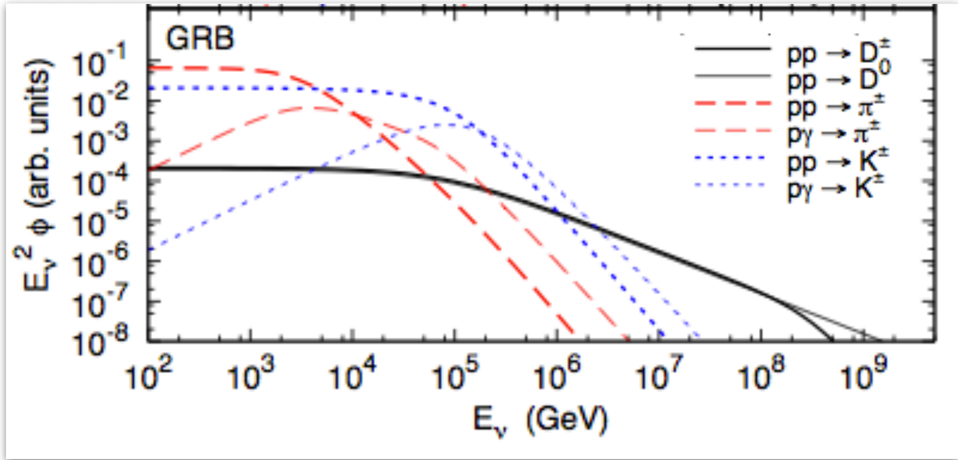


Hadron-hadron interactions

$$p + p \to \pi^\pm$$

Caveats...

- The generic composition at source (1:2:0) is due to an over-simplified treatment and does not take into account :
  - other source types
  - decay of n (from p \gamma) $n \rightarrow p + e^- + \bar{\nu}_e$
  - Production and decay of charm mesons (1:1:0)
  - E dependent effects
    - muons loose E, cooled muons pile up at low E
    - Kaon decay contribution at high E
  - Charged pion production is underestimated (factor ~ 2.4) in the simplistic \delta resonance approach (no negatively charged pions)



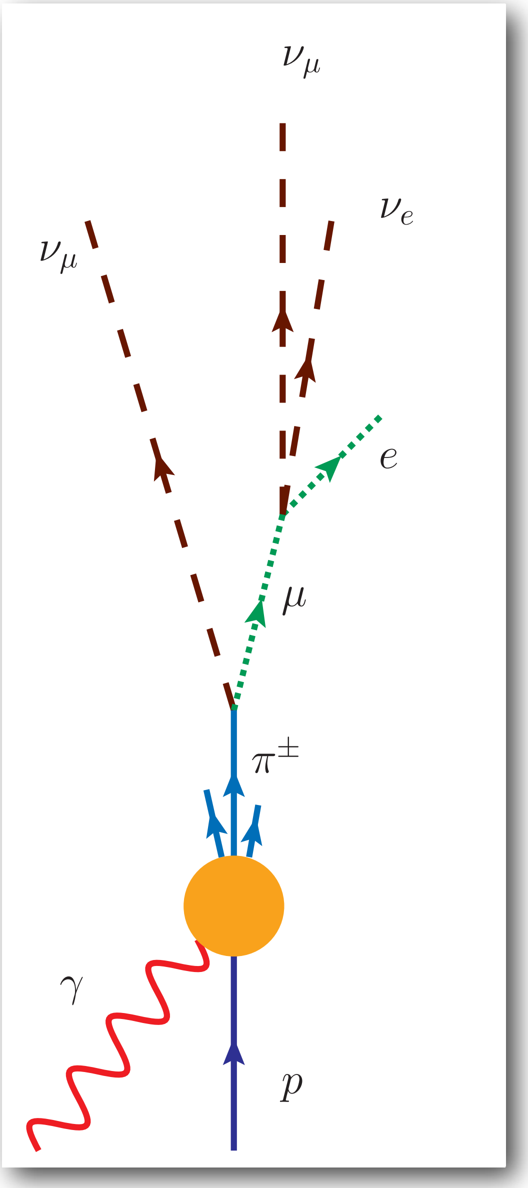
Ref: Enberg et al., PRD79 (2009),
see also Gandhi et al., JCAP0909 (2009)

Ref: Hummer et al., APJ721 (2010)

Source types

- New production mechanisms
- A source can be characterized by $\widehat{X} = \Phi_e^0/\Phi_\mu^0$
- Different source classes :

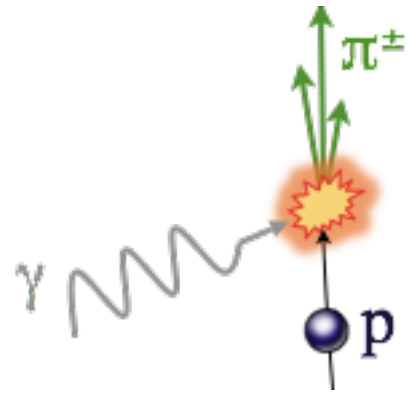
Source	$\Phi_e^0 : \Phi_\mu^0 : \Phi_\tau^0$	$\widehat{X} = \Phi_e^0/\Phi_\mu^0$
Pion beam	1:2:0	0.5
Neutron beam	1:0:0	>> 1
Muon beam/prompt	1:1:0	1
Muon-damped	0:1:0	0



Our toy model and parameter space

The HMWY Model

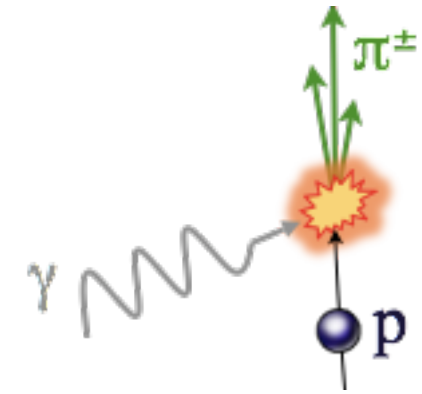
Ref: Hummer, Maltoni, Winter and Yaguna, Astropart. Phy. 34, 205 (2010)



Ref: DeYoung

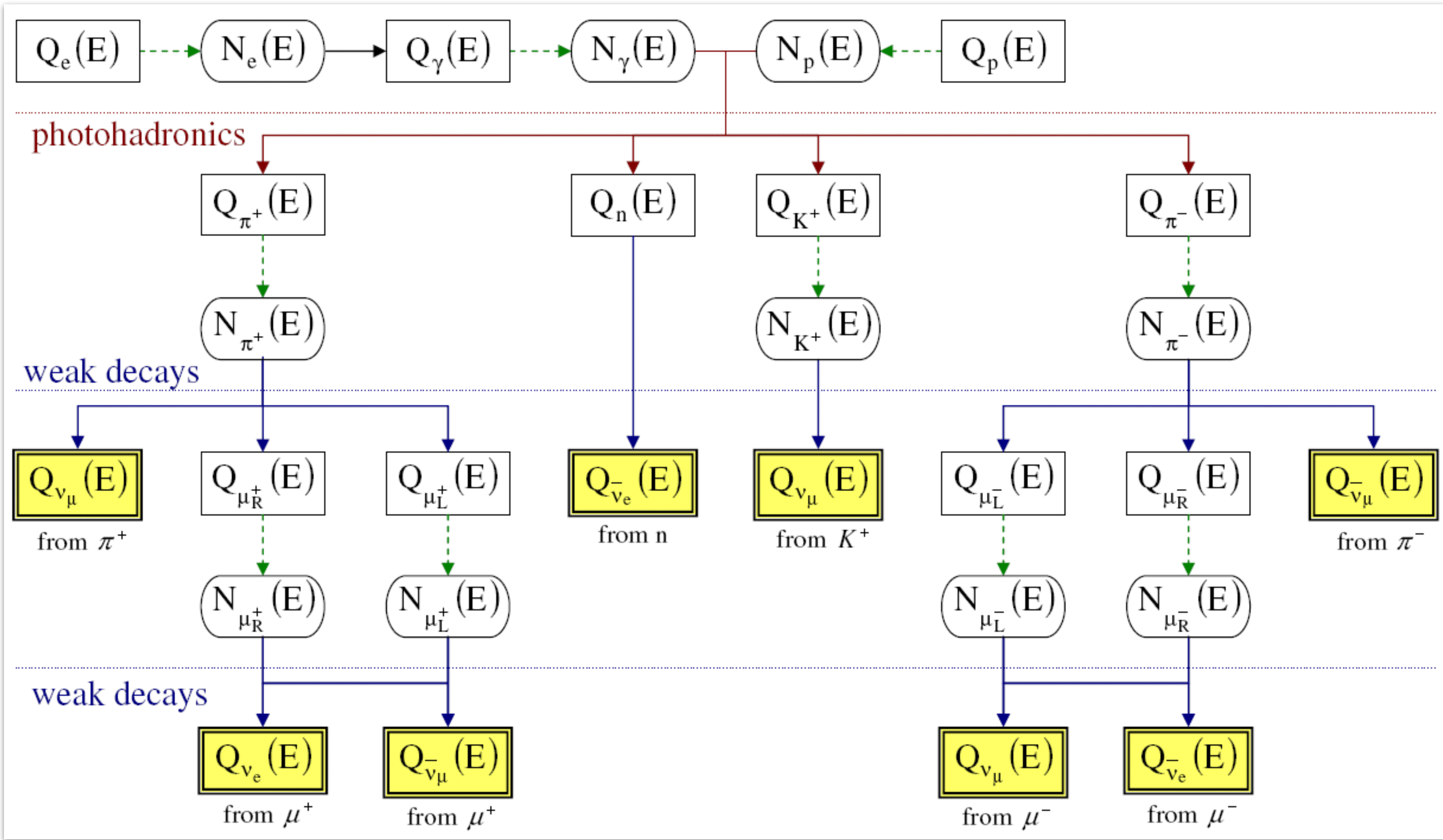
- A self-consistent approach used to compute meson photoproduction
  - Target photon field - synchrotron radiation of co-accelerated e $p + \gamma \to \pi + p'$
  - Predicts charged pion ratio
  - Kaon production at high E $p + \gamma \to K^+ + \Lambda/\Sigma$
  - Losses and weak decay of secondaries π, K, μ, n
- Few input astrophysical parameters
  - B, R, injection index (universal for primary e, p)
- No biased connection with cosmic ray and gamma fluxes
- Fast enough to do parameter space scans

Model summary



Ref: DeYoung

p interact with synchrotron radiation from co-accelerated electrons/positrons



Ref: Hummer et al, Astropart. Phy. 34, 205 (2010)

Astrophysical parameter space

- Hillas criterion for acceleration and confinement :

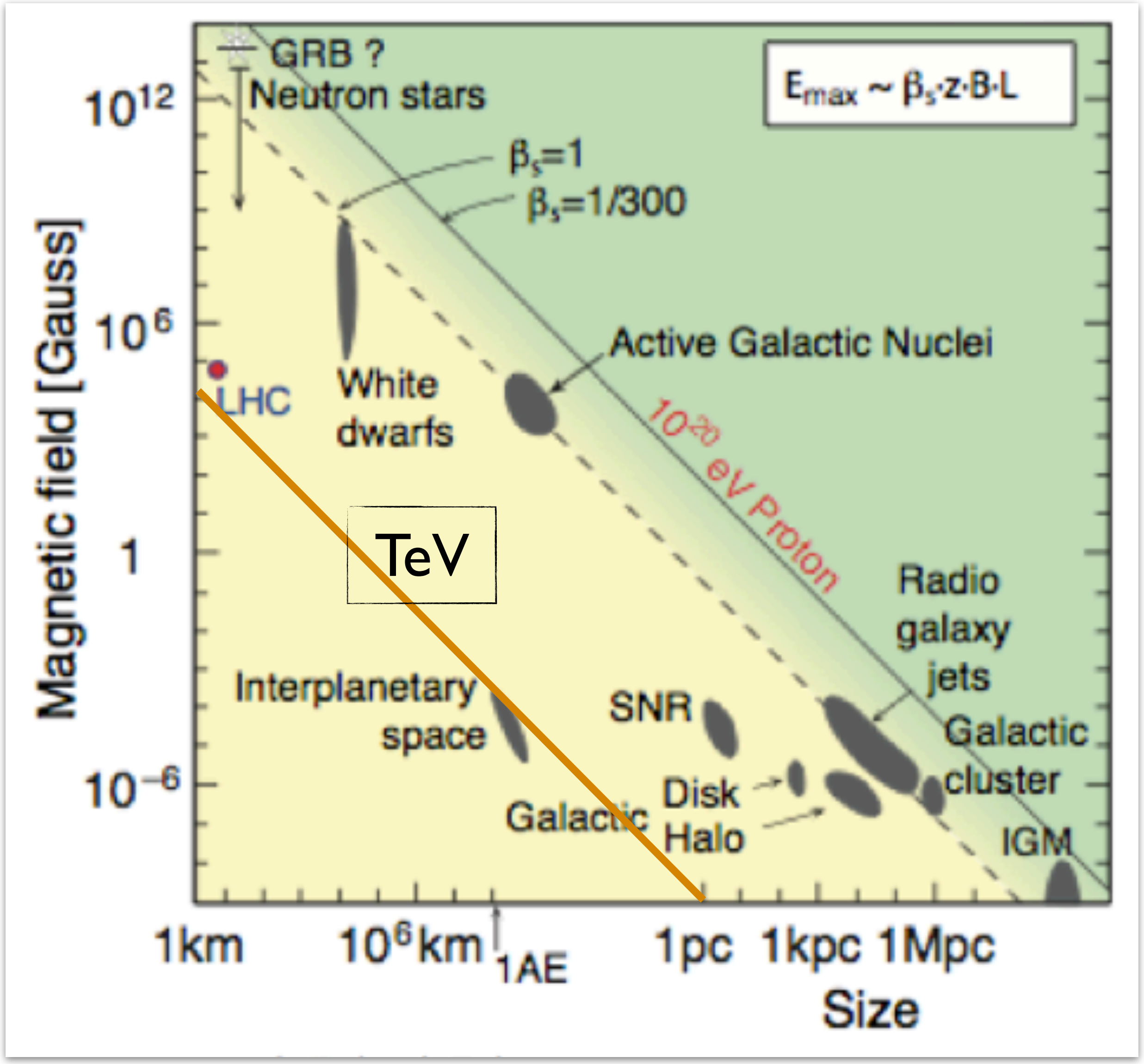
$$r_L < R$$

Larmor radius size of accelerator

$$E \leq E_{max} = qBR$$

- constraint on B and R

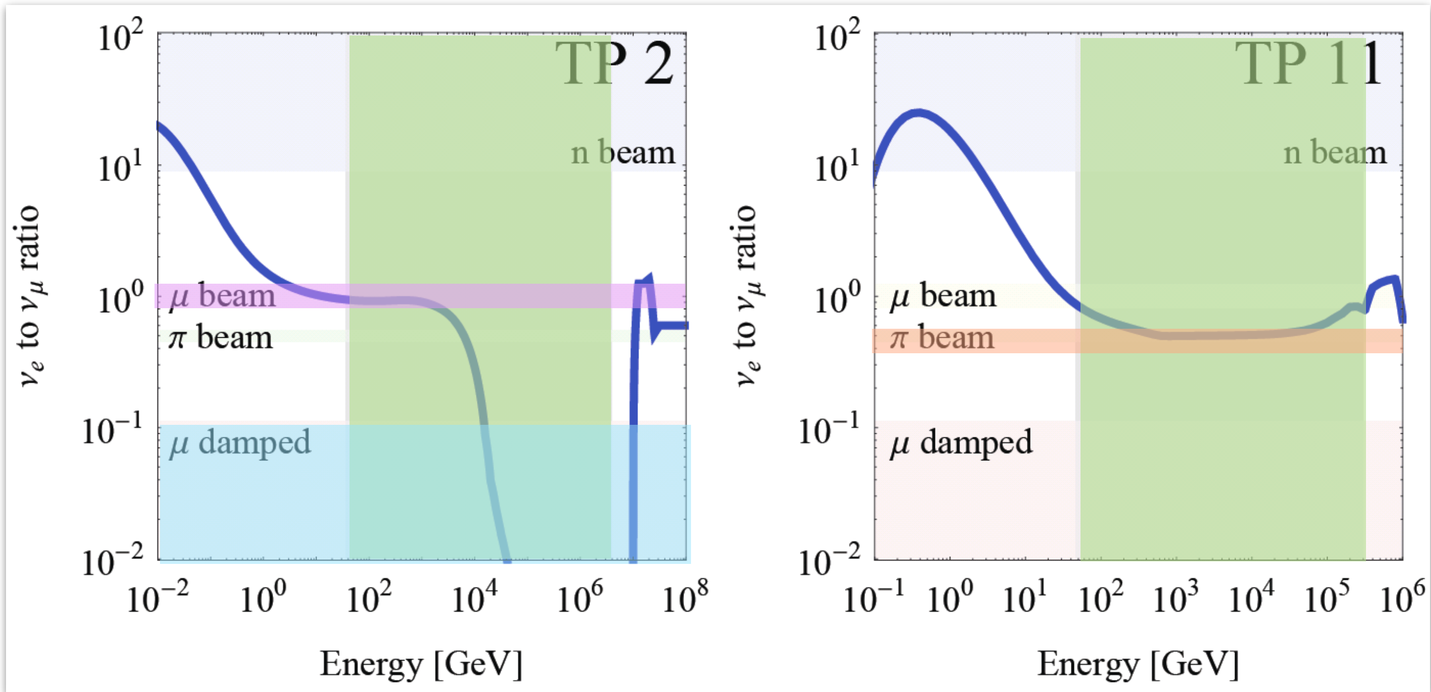
Ref: Hillas (1984), Boratav (2001), Hummer et al. (2010)



- Call sources as "test points" in order to discuss E-dependent effects at source

E-dependence at source

Muon beam to Muon damped　　　　Pion beam

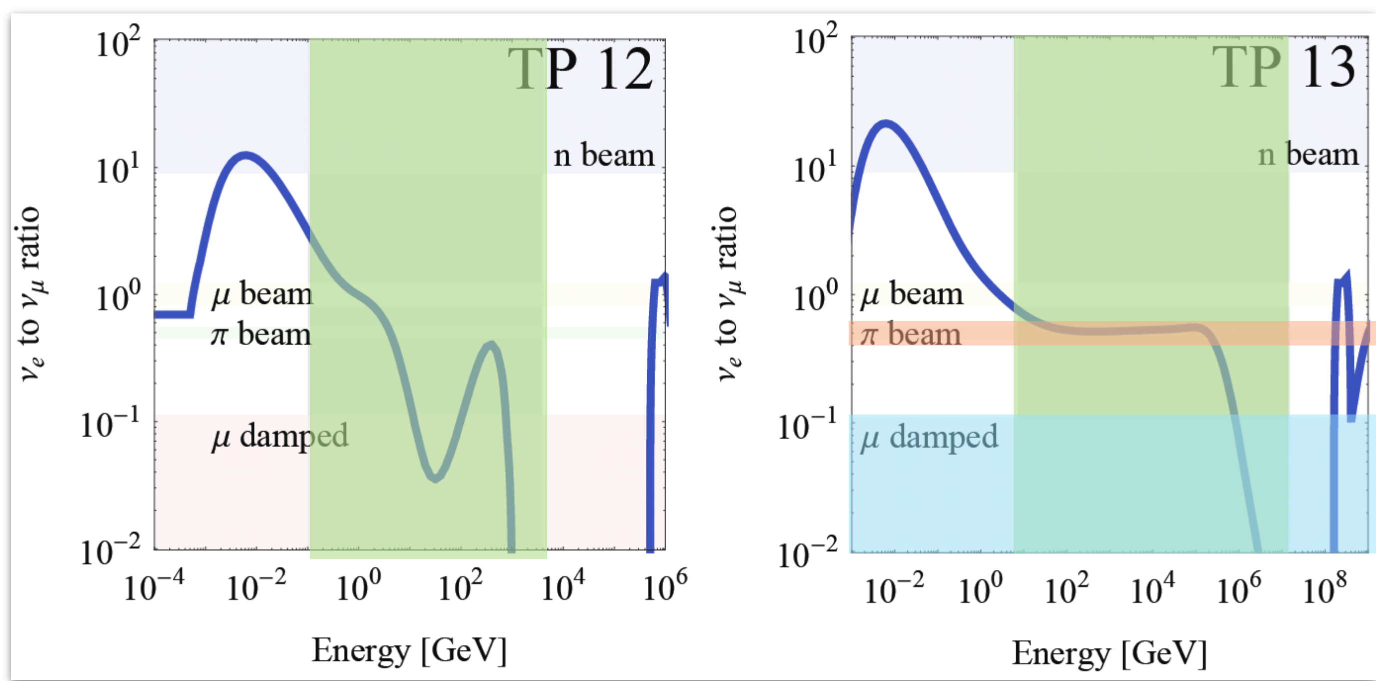


- Horizontal shaded region : approximate regions for different sources
- Vertical shaded region : flux large

Ref: Hummer et al, Astropart. Phy. 34, 205 (2010), see also Kashti and Waxman, PRL (2005)

- Smooth transition
- Transition energy depends on a particular source
- Mixes up the flavor ratios at sources

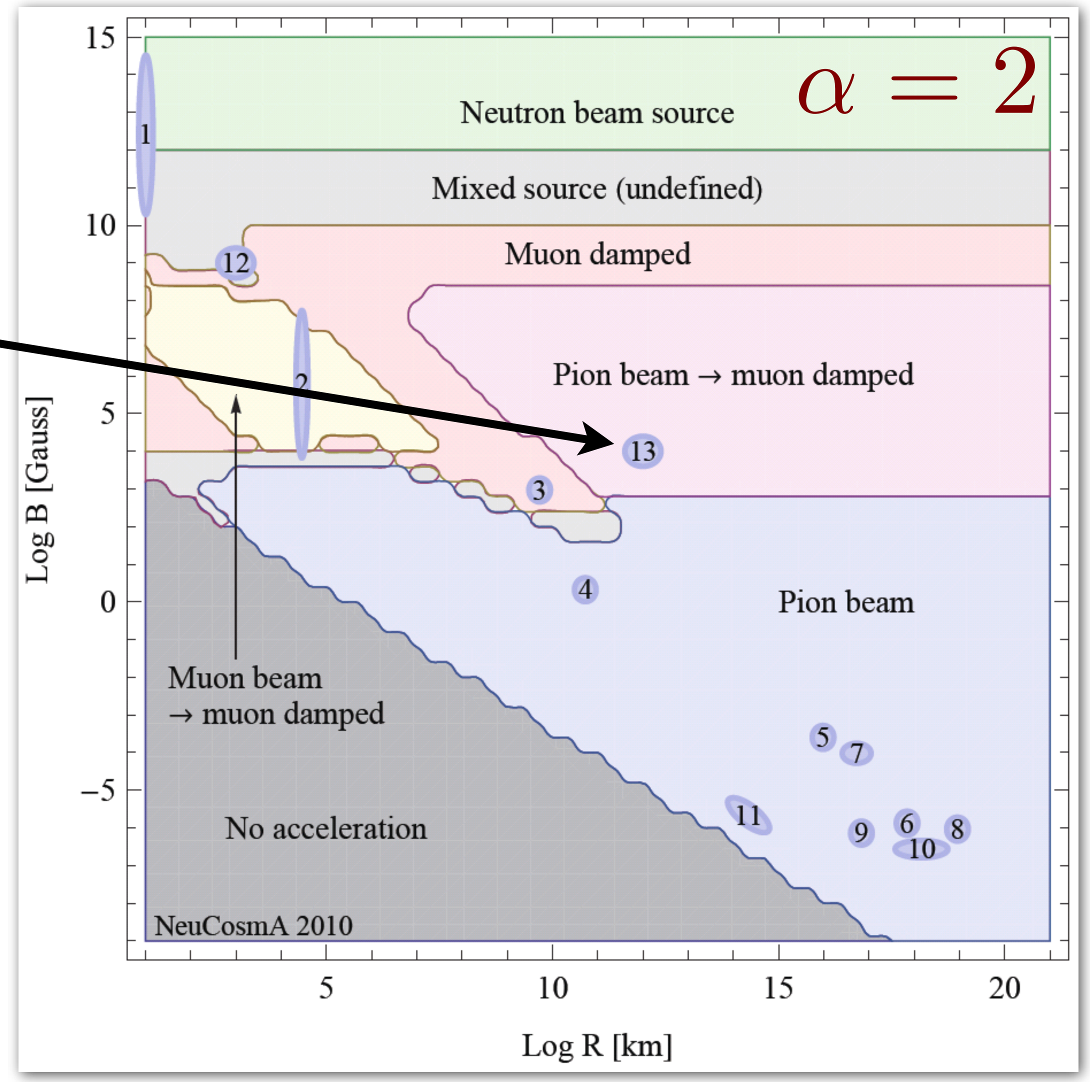
Mixed　　　　Pion beam to muon damped

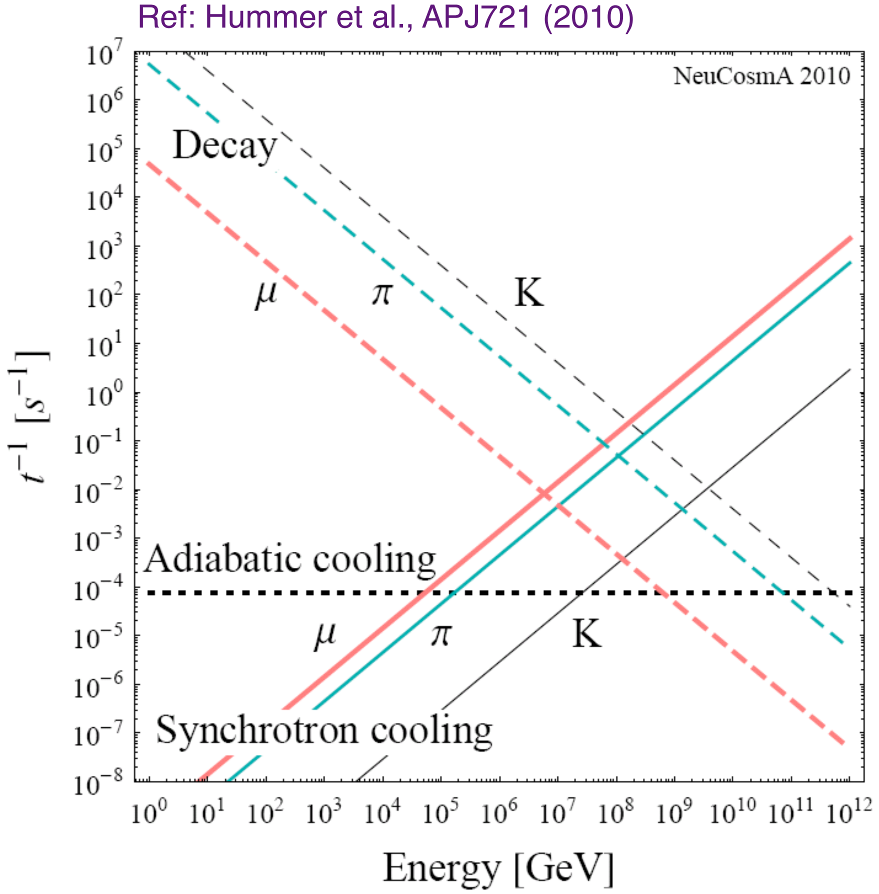


Neutrino sources on the Hillas plot

- Classification is a function of source parameters: R, B
- TP 13 - pion beam to muon damped, need B and R to be large
- Competition between decay and cooling

Ref: Hummer et al., APJ721 (2010)





$$E_c = \sqrt{\frac{9\pi\epsilon_0 m^5 c^5}{\tau_0 e^4 B^2}}$$

Propagation effects

Flavor flux at detector

Ref: Pakvasa, MPLA23, 1313 (2008), talk@GGI 2012

- The flux at the detector is given by

Flux at source

$$\Phi_\beta^{Det} = \sum_{\alpha=e,\mu,\tau} P_{\alpha\beta}\Phi_\alpha^0$$

achromatic

- Average oscillation probability in vacuum (same expression for anti-neutrinos)

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

$$L_{osc} = 4\pi E/\delta m^2 \simeq 10^{-10}\ Mpc\ (for\ E = PeV)$$

  - mass states do acquire relative phases but the uncertainities in L and E leads to a wash out

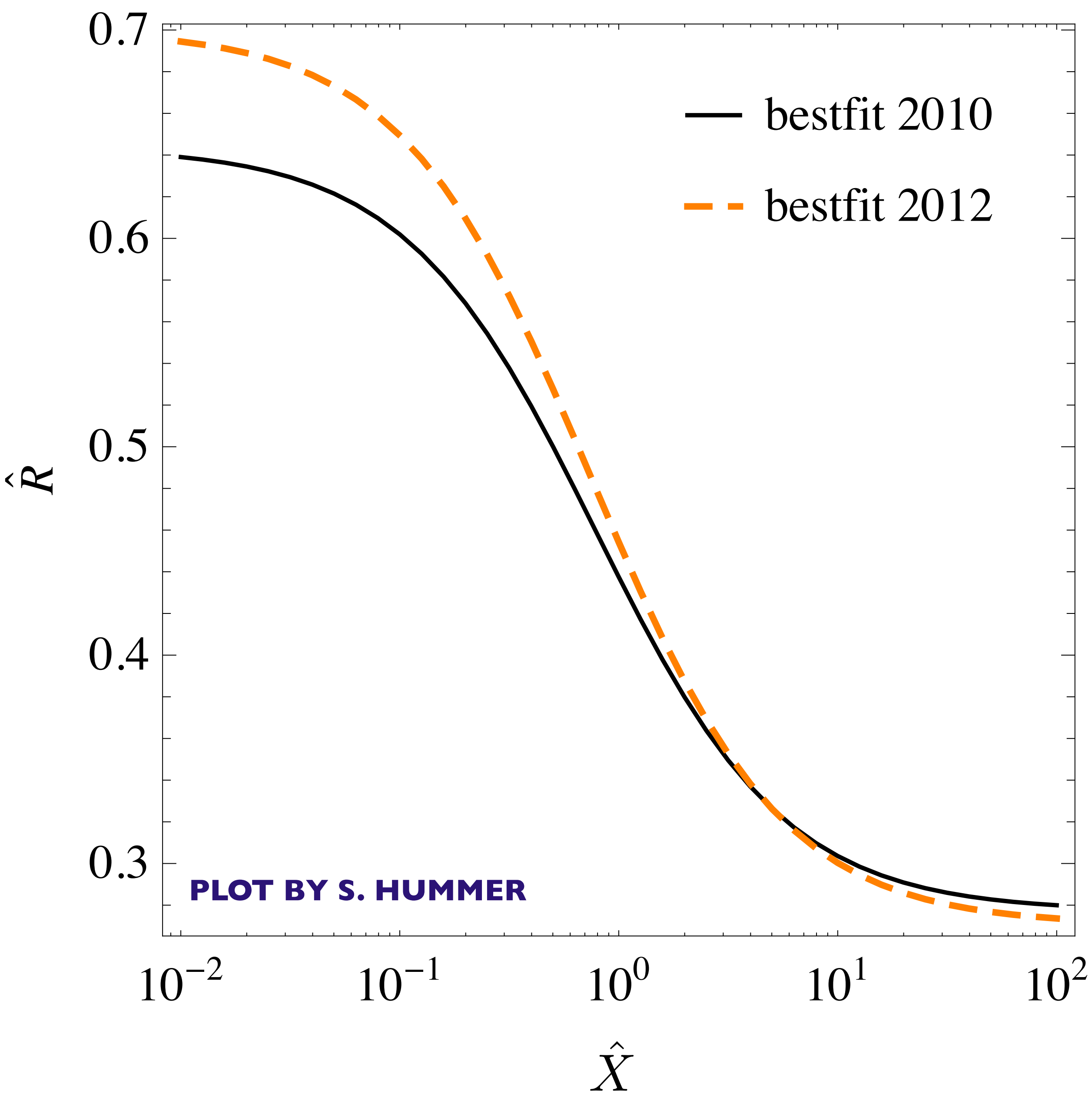
- FLAVOR EQUILIBRATION at the detector (1:1:1) for the conventional pion beam source !

Different source classes

- Using the neutrino mixing angles in tri-bi-maximal form $\theta_{13} = 0, \theta_{12} = \pi/6, \theta_{23} = \pi/4$
- Equal mu-tau fluxes irrespective of source !

Source	$\Phi_e^0 : \Phi_\mu^0 : \Phi_\tau^0$	$\Phi_e^{Det} : \Phi_\mu^{Det} : \Phi_\tau^{Det}$
Pion beam	1:2:0	1:1:1
Neutron beam	1:0:0	3:1:1
Muon beam/prompt	1:1:0	1.3:1:1
Muon-damped	0:1:0	0.5:1:1

Parameter dependence



- Bestfit 2012 :
  Forero et al., arXiv:1205.4018

- Effect of nonzero theta13 depends on source type

- Visible effect for muon damped source but other source types, the effect is tiny

Can we identify flavors ?

IceCube

Completed in Dec 2010

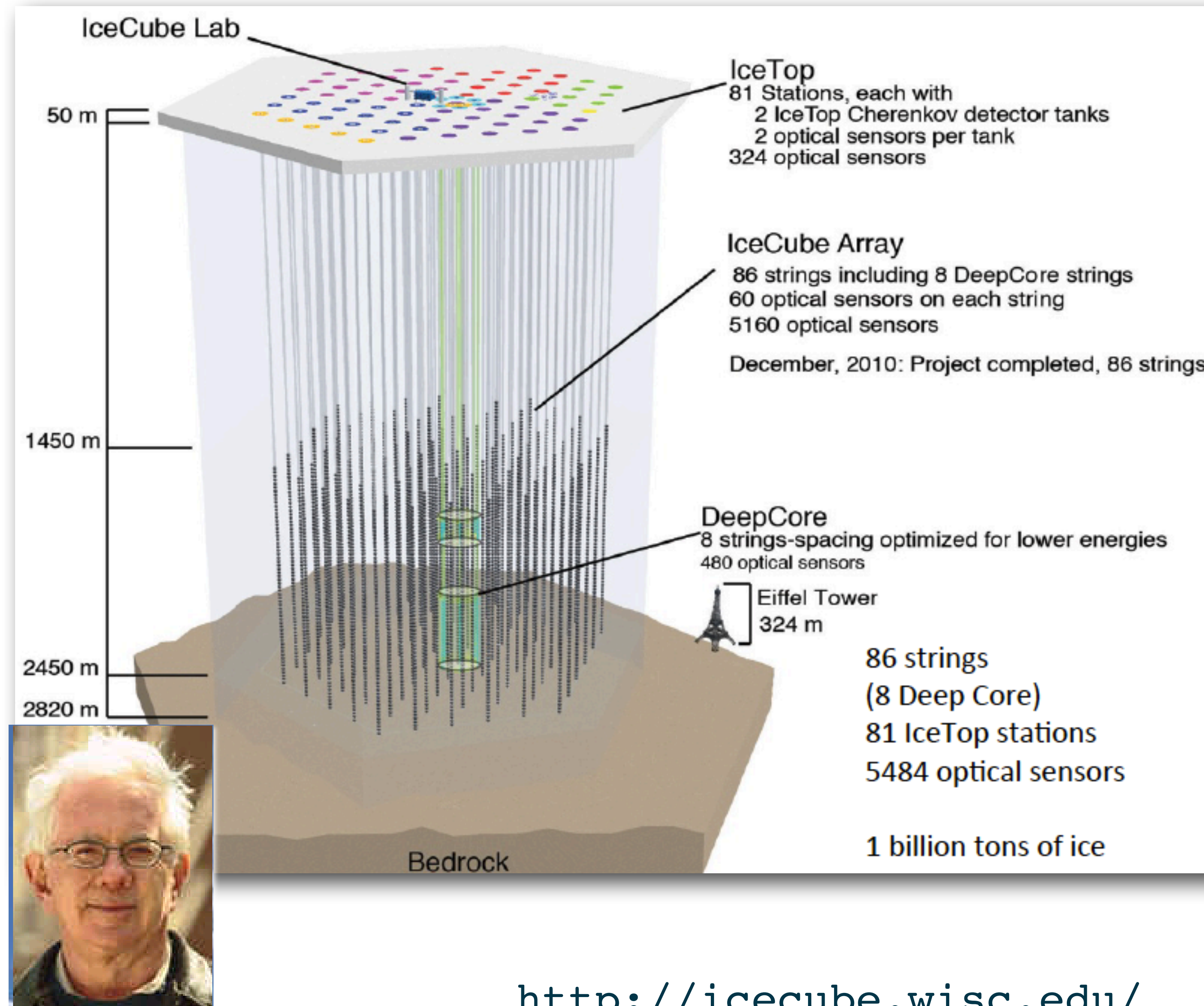
E = 100 GeV - EeV

- At south pole, antarctic ice, 1 cubic km
- Secondary charged particles from neutrino-Nucleon scattering produce Cherenkov radiation seen by optical sensor arrays
- FLAVOR id possible: First flavor analysis

  Ref: IC22 Cascade detection, 1101.1692
- CHARGE id (almost) impossible:
- except at the Glashow resonance (6.3 PeV) - sensitive to neutrino/anti-neutrino ratio

$$\overline{\nu}_e + e^- \to W^- \to \text{anything}$$

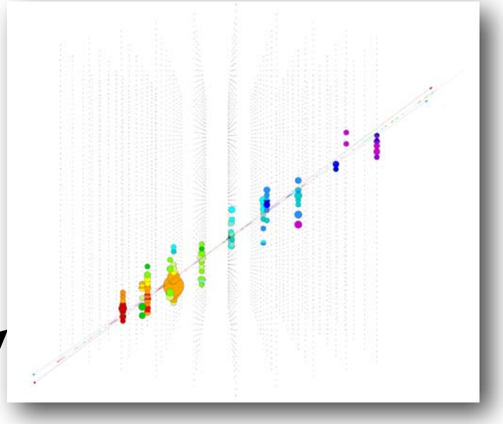
$$E_{\overline{\nu}_e} \simeq \frac{M_W^2}{2m_e} \simeq 6.3 PeV$$



http://icecube.wisc.edu/

Event topologies

10 TeV muon track



- Muon tracks due to ν_μ (threshold 100 GeV)
- Cascades or showers : em or hadronic (threshold TeV)
    - CC interactions of ν_e, ν_τ
    - NC interactions of all active flavors

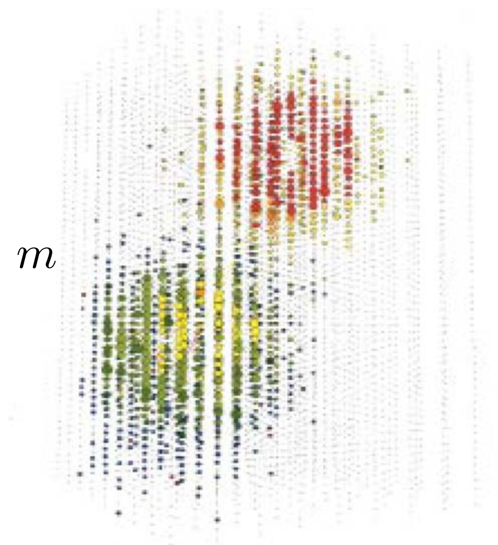
375 TeV cascade

- High energy (threshold PeV) due to ν_τ
    - double bang
    - lollipop

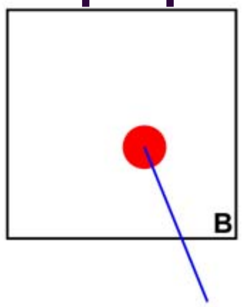
double bang

a few PeV

$$l_\tau = \gamma c t_\tau \sim 50 \left(\frac{E_\tau}{PeV}\right) m$$



lollipop



Ref: Learned and Pakvasa (1995), Beacom et. al, (2003)

http://icecube.wisc.edu/

Flavor ratios at detector

Ref: Pakvasa, MPLA23, 1313 (2008), talk@GGI 2012

- Define flavor-dependent ratios :

unknown flux normalization drops out, detector specific

- Muon tracks to cascades

$$\widehat{R} = \frac{\Phi_{\mu}^{Det}}{\Phi_{e}^{Det} + \Phi_{\tau}^{Det}}$$

easiest

- Electromagnetic to hadronic cascades

$$\widehat{S} = \frac{\Phi_{e}^{Det}}{\Phi_{\tau}^{Det}}$$

hard near threshold

- Resonant production of electron antineutrinos to muon tracks at 6.3 PeV

$$\widehat{T} = \frac{\Phi_{e}^{Det}}{\Phi_{\mu}^{Det}}$$

Glashow resonance

- Flavor is inferred from different event topologies

Flavor flux and observable ratio

- Muon tracks to cascades

$$\widehat{R} = \frac{\Phi_\mu^{Det}(E)}{\Phi_e^{Det}(E) + \Phi_\tau^{Det}(E)}$$

$$= \frac{P_{e\mu}(E)\widehat{X}(E) + P_{\mu\mu}(E)}{[P_{ee}(E) + P_{e\tau}(E)]\widehat{X}(E) + [P_{\mu e}(E) + P_{\mu\tau}(E)]}$$

  - In general, two energy-dependent terms
  - holds even if unitarity is violated

- We will quantify new physics effects using R

New physics effects

Neutrino Decay

Ref: Beacom et al. PRL (2003), Maltoni and Winter, JHEP07, 064 (2008)

- Neutrino decay is described by

$$e^{-\frac{t}{\tau}} = e^{-\frac{tm}{\tau^0 E}} \qquad \tau = \gamma\tau^0$$

$$\gamma = E/m$$

- Lifetime for neutrinos is quoted as τ^0/m

- Astrophysical neutrinos : Typically L~Mpc and E~TeV which implies that

$$\frac{\tau_i^0}{m_i} \leq 10^2 \frac{L}{Mpc}\frac{TeV}{E}\ s \cdot eV^{-1}$$

~5 orders of magnitude more sensistive !

- Solar neutrinos (invisible decay) :

$$\frac{\tau_i^0}{m_i} \geq 10^{-4}\ s \cdot eV^{-1}$$

- Weak model-independent bounds imply that (invisible) decay of neutrinos over extragalactic distances is not ruled out !

TALK BY S. PAKVASA

Neutrino Decay

- The modified probability has an overall damping factor

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

$$D_i(E) = e^{-\hat{\alpha}_i \frac{L}{E}}$$

$$\hat{\alpha}_i^{-1} = \frac{\tau_i^0}{m_i} \leq 10^2 \frac{L}{Mpc} \frac{TeV}{E} \; s \cdot eV^{-1}$$

- Damping term characterizes complete $D_i \to 0$ and incomplete $0 \leq D_i \leq 1$ decays
- Considered (invisible) decay scenarios : 8 - 1 (all unstable) = 7
- In general, decays can be classified into visible, invisible, complete or incomplete

Quantum decoherence

- Generic prediction emerging from quantum gravity
- Modified propagation using the density matrix formalism

pure to mixed states

$$\dot{\rho} = -i[H, \rho] + \mathcal{D}[\rho]$$

- Expand all operators in SU(3) Hermitian basis to write EOM in component form

$$\dot{p}_\mu = (h_{\mu\nu} + d_{\mu\nu}) p_\nu \qquad \mu, \nu = 0, 1, \ldots 8$$

- Solve the coupled set of differential equations and compute probability using

$$P_{\alpha\beta}(t) = Tr[\rho_{\nu_\alpha}(t)\rho_{\nu_\beta}(0)]$$

pure state neutrino density matrix at t=0

mixed state neutrino density matrix at t

Quantum decoherence

- On averaging over sin and cos terms for astrophysical neutrinos,

$$P_{\alpha\beta} = \frac{1}{3} + \frac{1}{2}(U_{\alpha 1}^2 - U_{\alpha 2}^2)(U_{\beta 1}^2 - U_{\beta 2}^2)D_\psi + \frac{1}{6}(U_{\alpha 1}^2 + U_{\alpha 2}^2 - 2U_{\alpha 3}^2)(U_{\beta 1}^2 + U_{\beta 2}^2 - 2U_{\beta 3}^2)D_\delta$$

- E-dependence of the damping terms depend on model

$$D_\kappa(E) = e^{-2\kappa L E^n}$$

n depends on the specific model, n=-1,0,2

- For a model, four sub-cases :
  - case 1 $\psi \neq 0, \delta = 0$ $\quad P_{\alpha\beta}(L \to \infty) = \frac{1}{3} + \frac{1}{6}(U_{\alpha 1}^2 + U_{\alpha 2}^2 - 2U_{\alpha 3}^2)(U_{\beta 1}^2 + U_{\beta 2}^2 - 2U_{\beta 3}^2)$
  - case 2 $\psi = 0, \delta \neq 0$ $\quad P_{\alpha\beta}(L \to \infty) = \frac{1}{3} + \frac{1}{2}(U_{\alpha 1}^2 - U_{\alpha 2}^2)(U_{\beta 1}^2 - U_{\beta 2}^2)$
  - case 3 $\psi = 0, \delta = 0$ $\quad P_{\alpha\beta}(L \to \infty) = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$
  - case 4 $\psi \neq 0, \delta \neq 0$ $\quad P_{\alpha\beta}(L \to \infty) = \frac{1}{3}$
- Recall pion beam+TBM gave 1:1:1 and here also 1:1:1 (equally populated flavors)
- Only 2 decoherence parameters appear in probability - coherences vanish.

Ref: Mehta and Winter, JCAP 1103, 041 (2011)

Results

Neutrino Decay

7 Invisible (complete) decay scenarios

stable: ❶

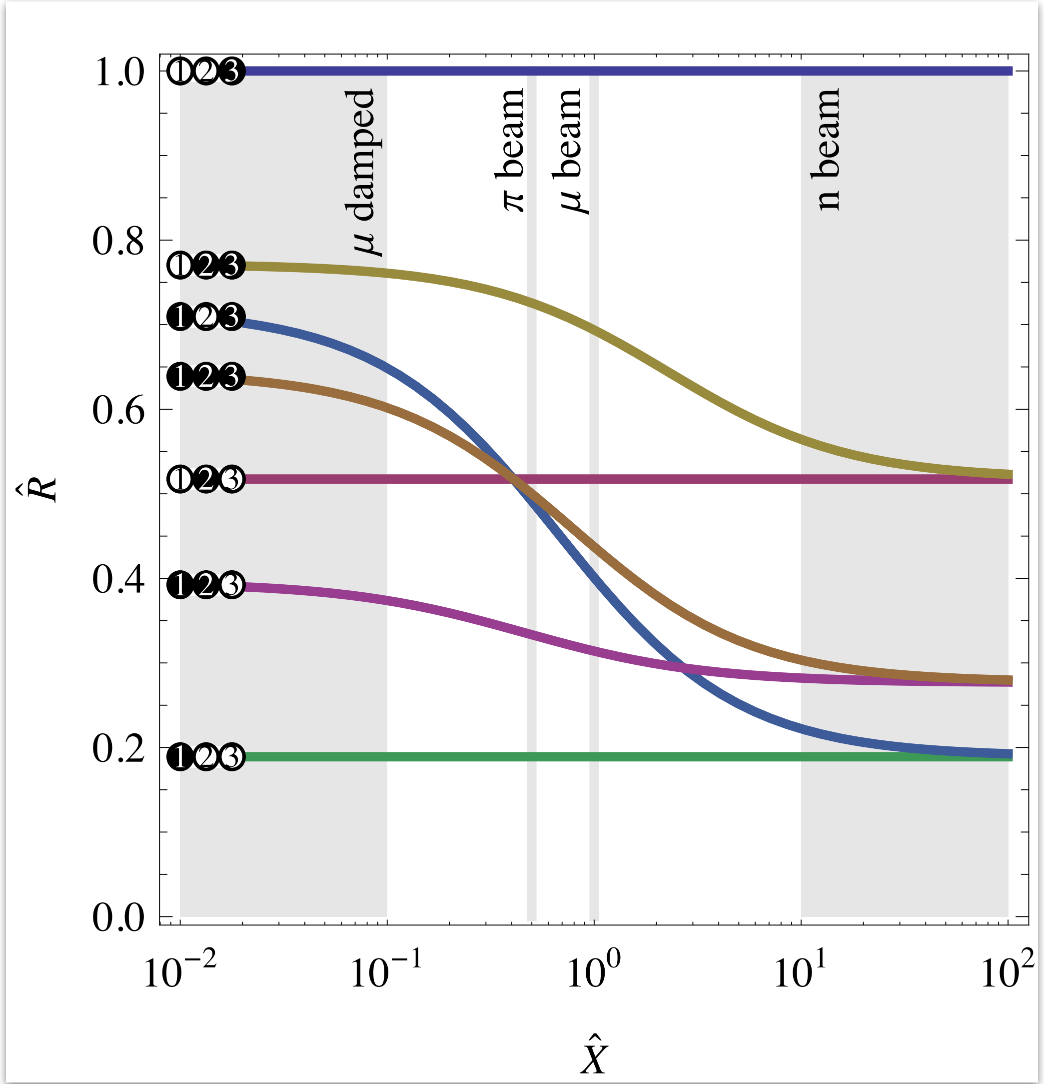
unstable: ①

pion beam: 4 scenarios clear, 3 degenerate

muon beam/muon damped: 7 scenarios clear

single stable mass eigenstate

$$\hat{R} = \frac{|U_{\mu f}|^2}{|U_{ef}|^2 + |U_{\tau f}|^2}$$



sources with changing X can be useful to have clean identification of decay scenario !

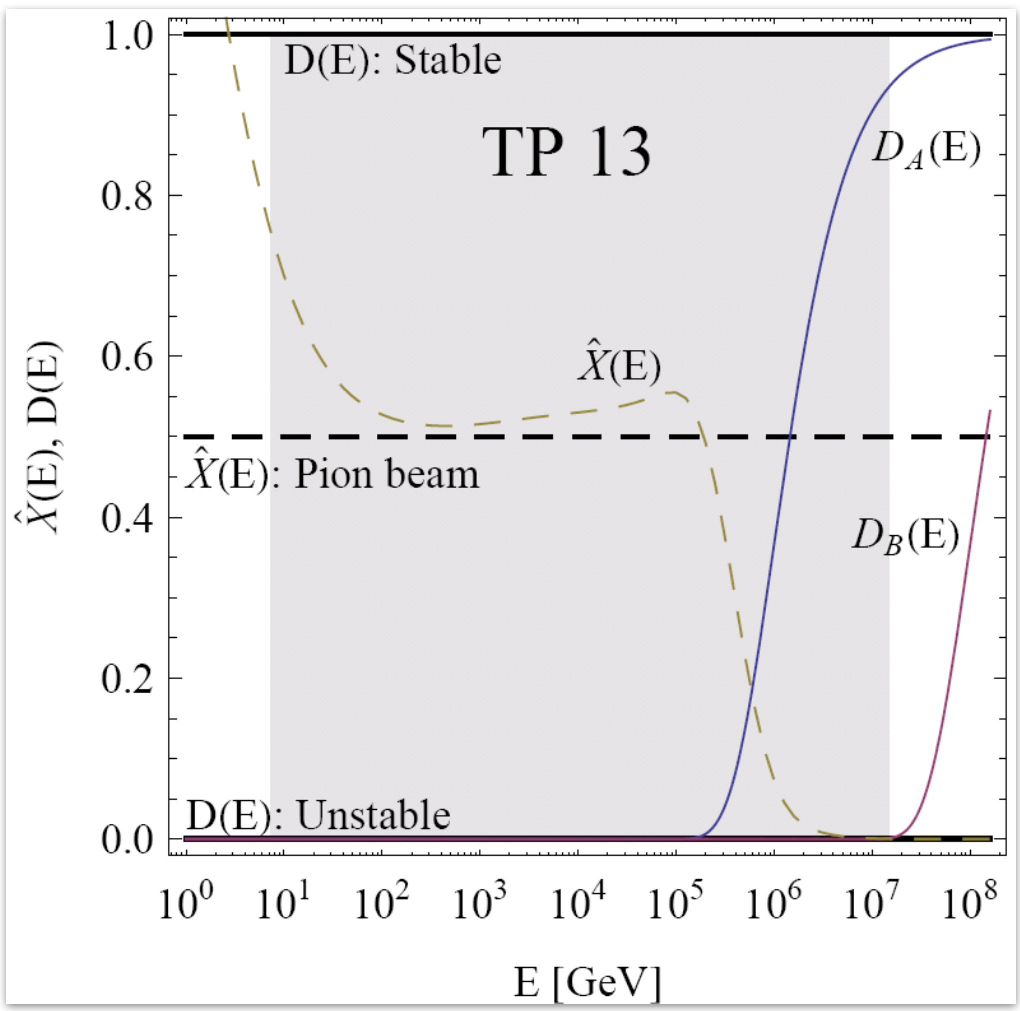
Neutrino Decay

stable ❶

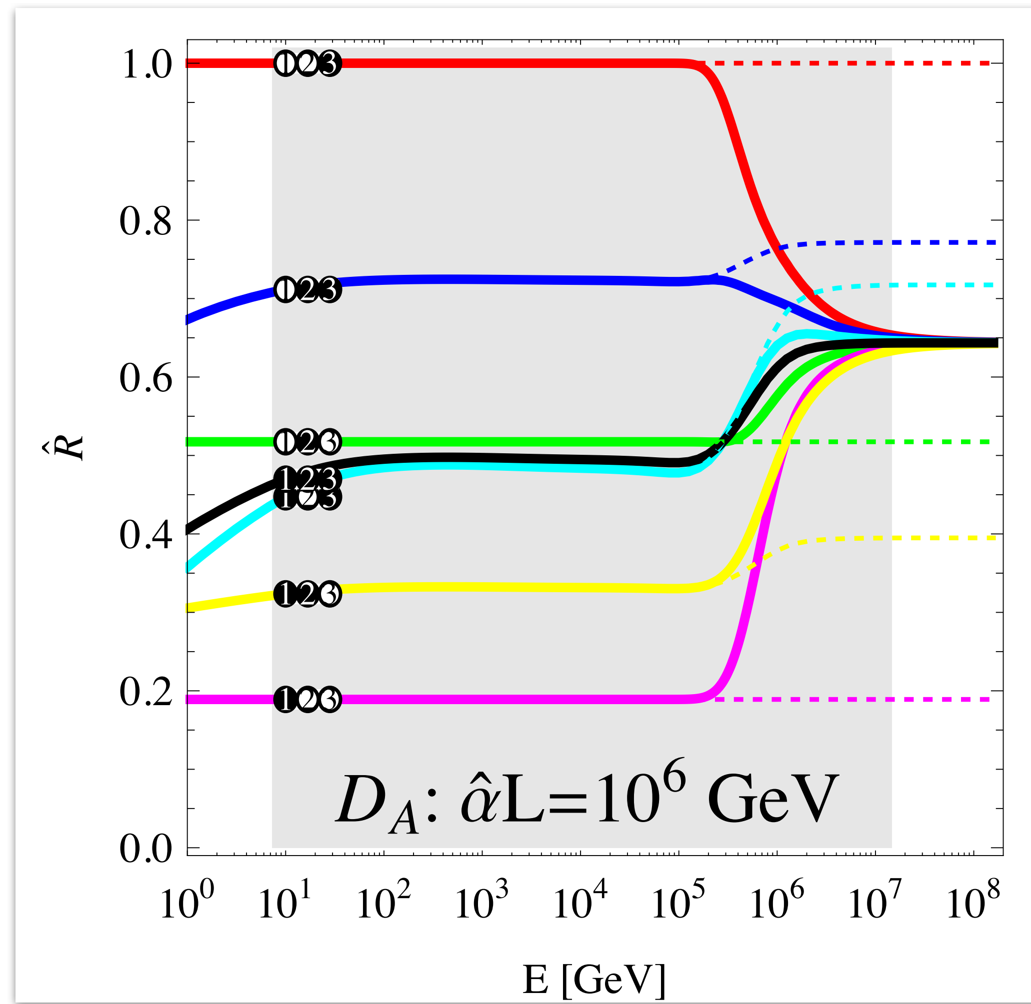
unstable ①

Decay effective at low E - 7 scenarios separate out

pion beam to muon-damped



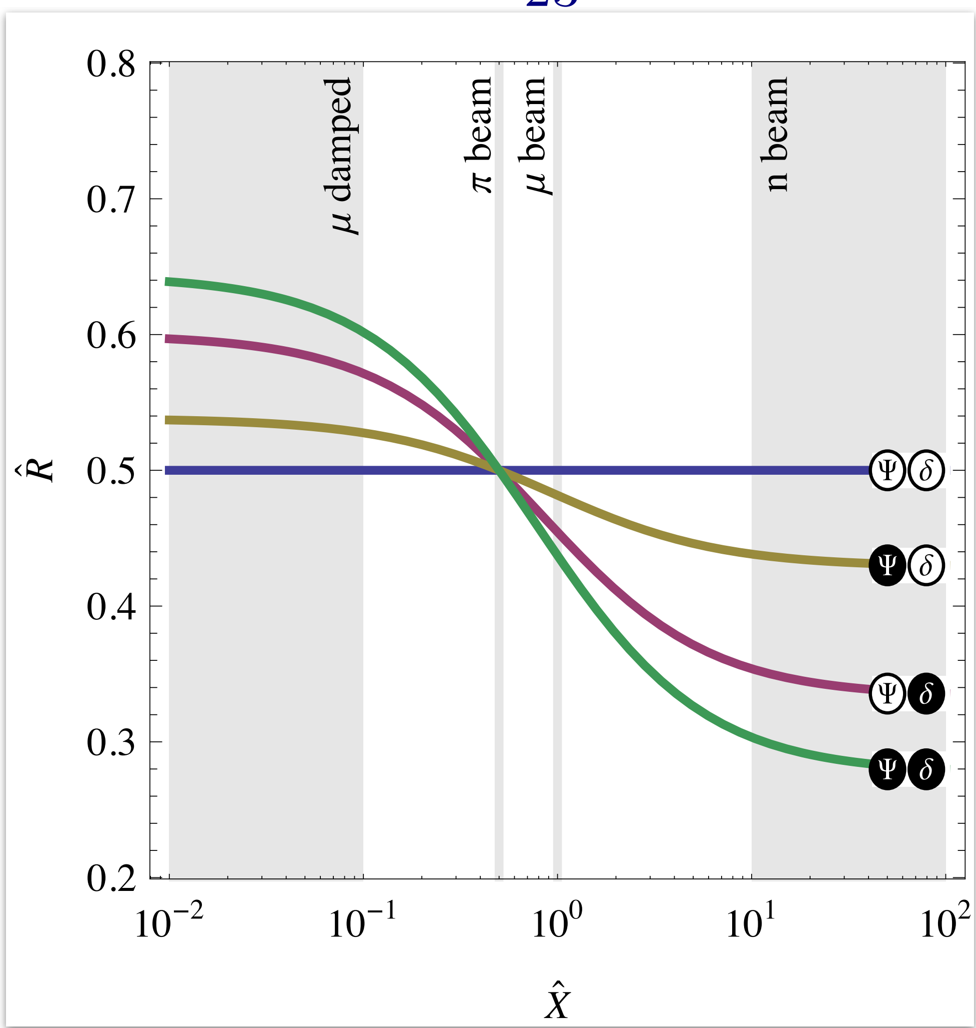
decay effective | stable



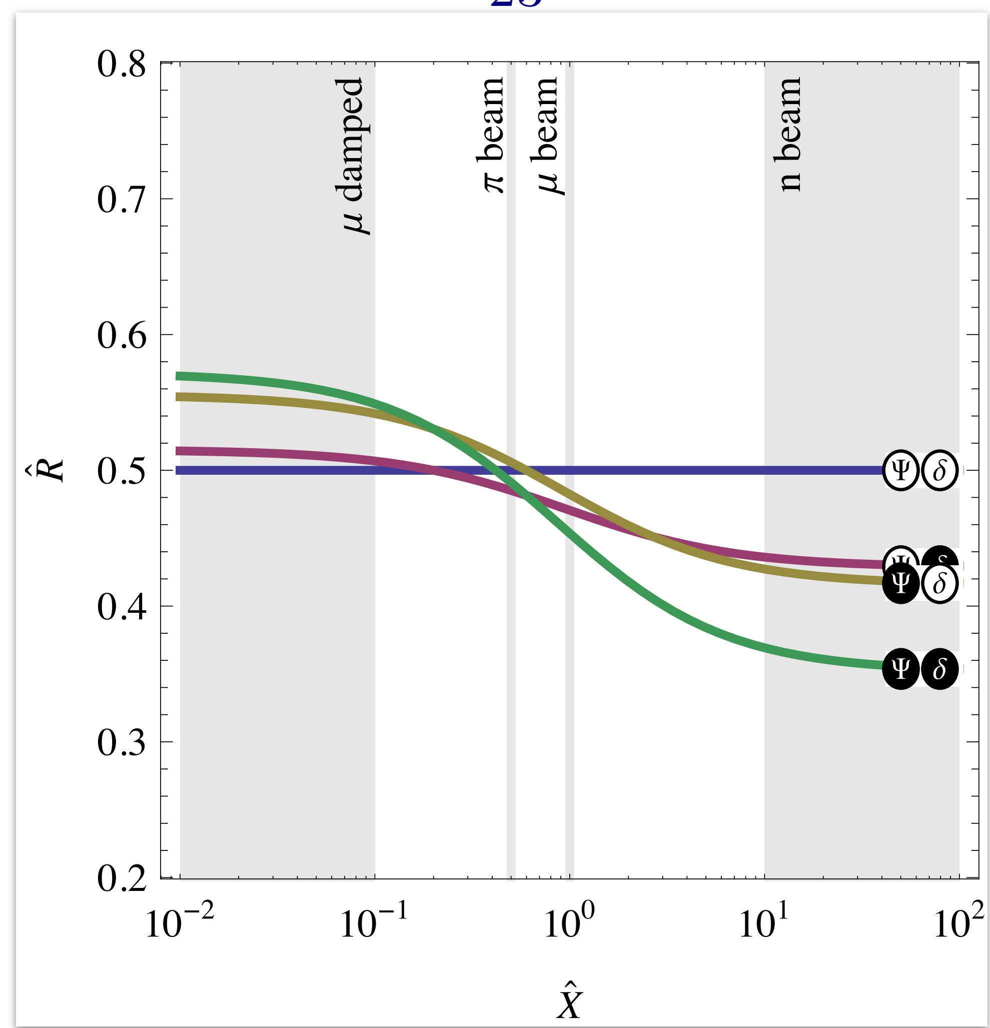
Decoherence

Prediction in aysymptotic limit - Complete quantum decoherence always leads to 1:1:1 (R=0.5) (blue curves) for any source but this requires both decoherence parameters to be non-zero.

$\sin^2\theta_{23} = 0.5$



$\sin^2\theta_{23} = 0.4$



Pion beam + TBM angles : all the 4 decoherence cases are degenerate

Pion beam + non-maximal atmospheric mixing : breaks degeneracy

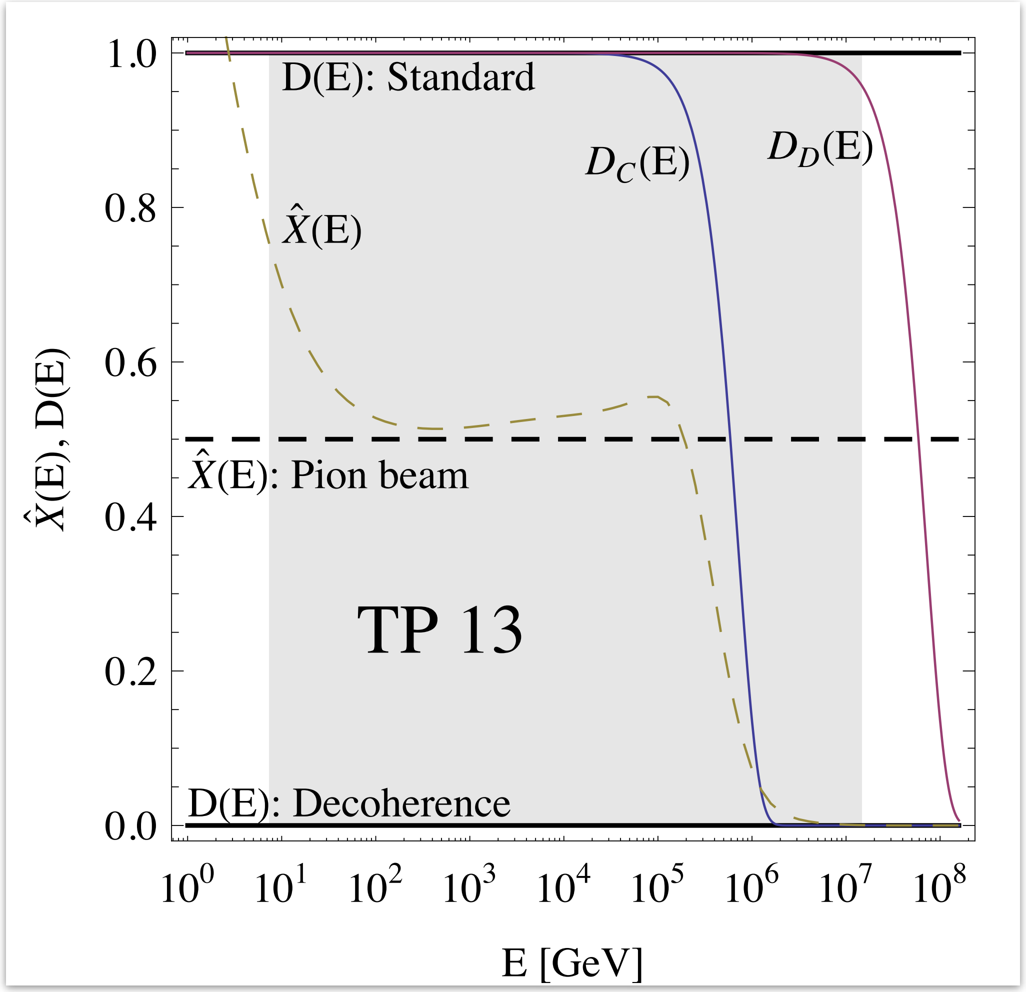
Decoherence

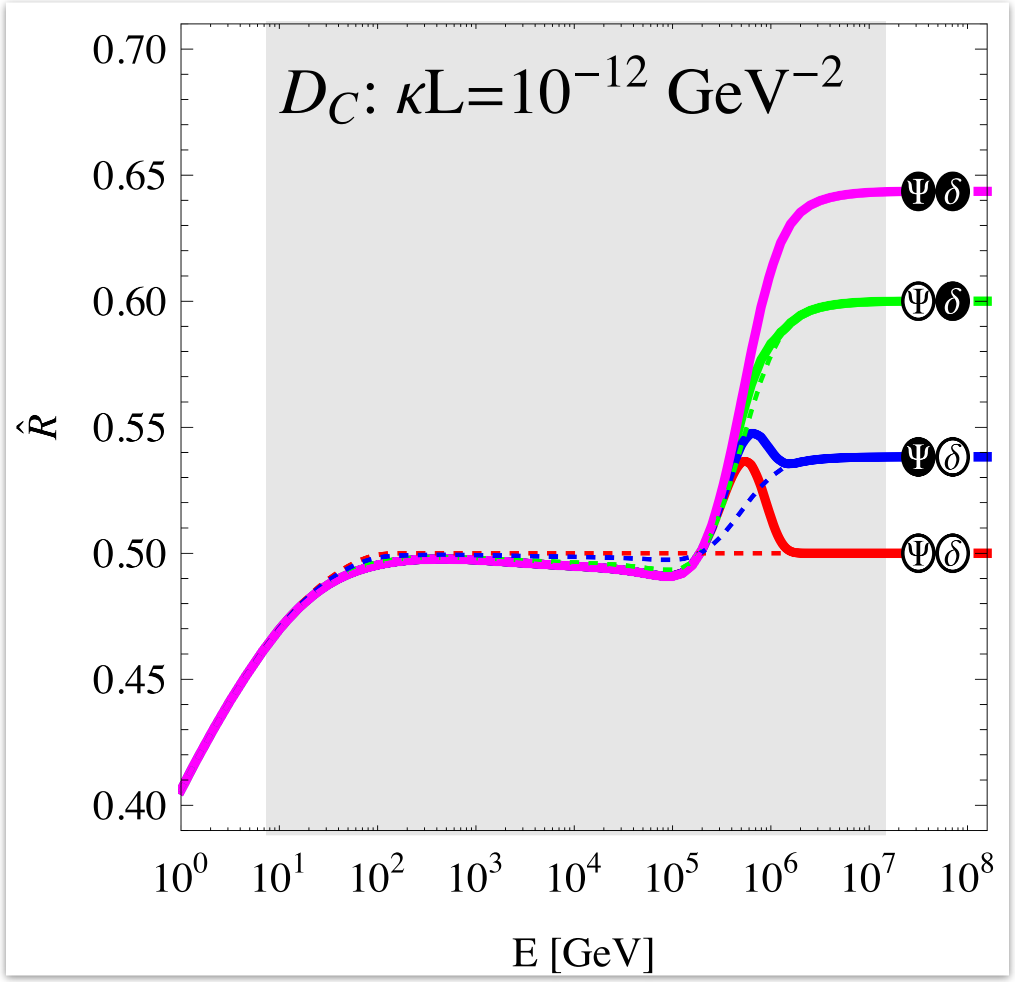
coherent ❶

decoherent ①

Decoherence (n=2) effective at high E - 4 scenarios separate out

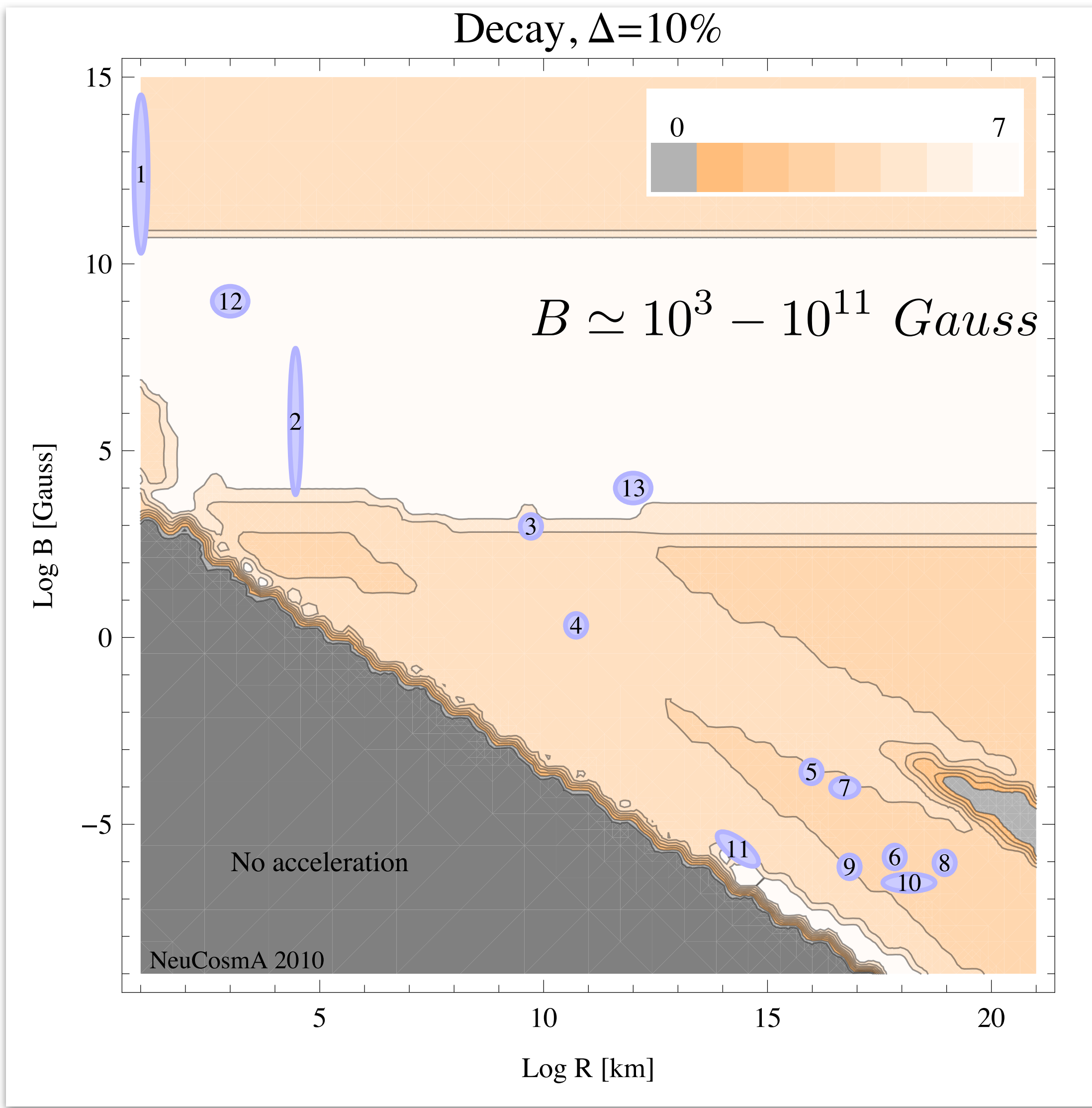
pion beam to muon-damped

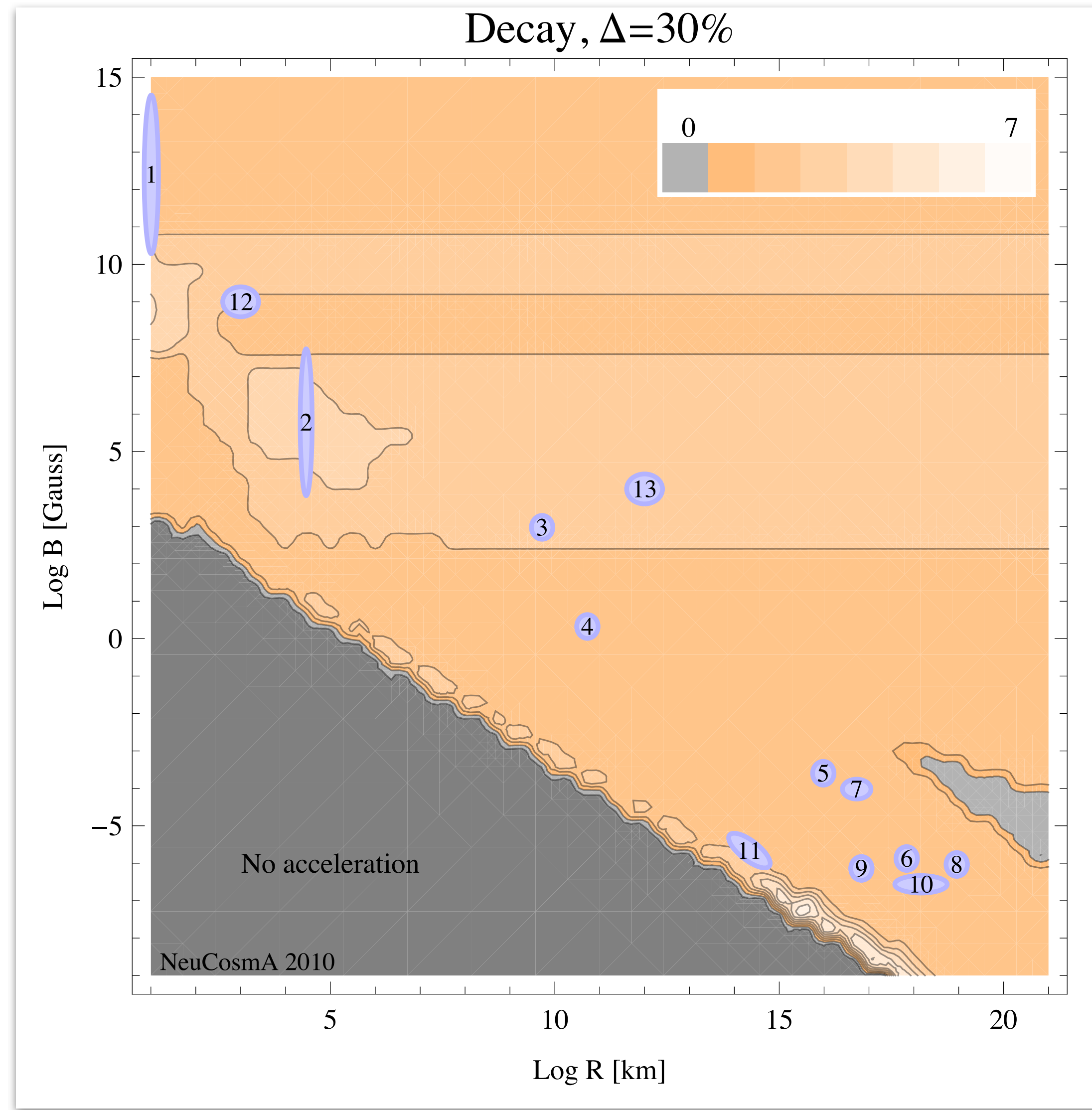




Useful sources

$$\hat{\alpha}L = 10^8\ GeV$$





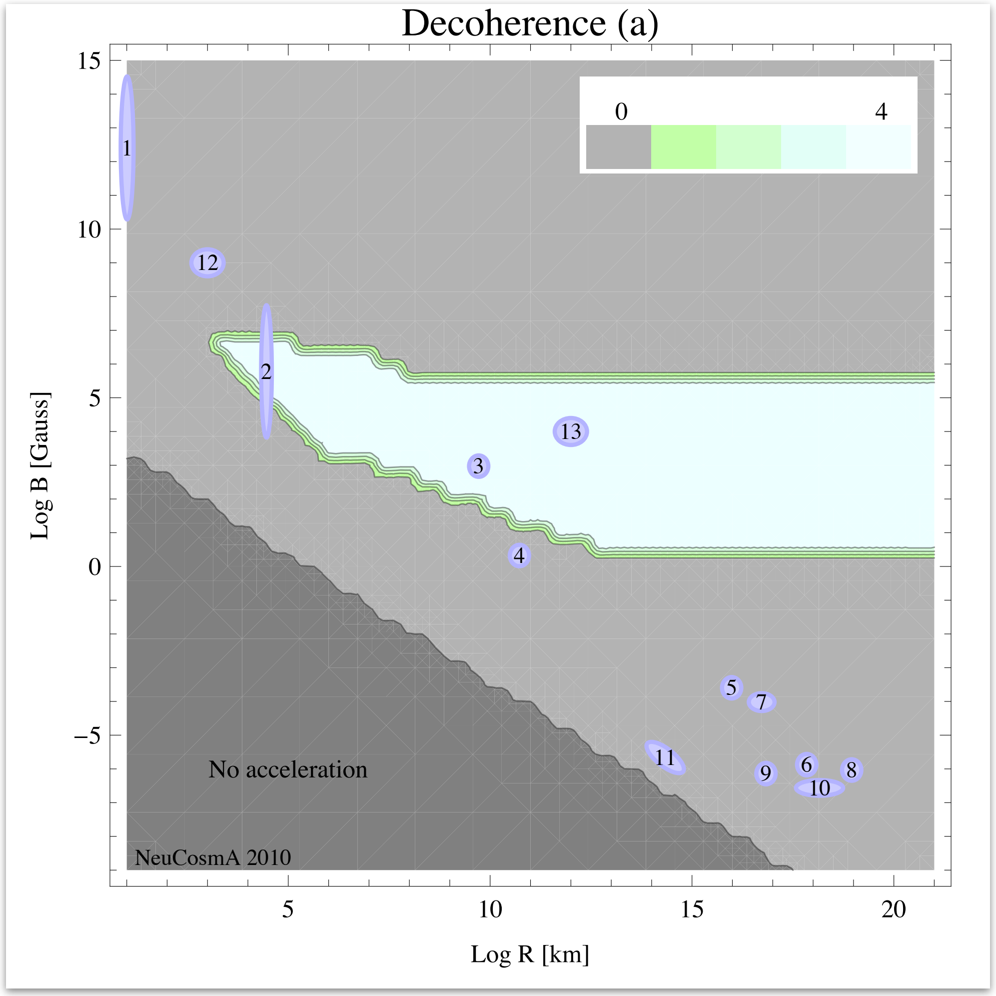
Useful sources : TP 2, 12, 13

Useful sources : TP 2

Useful sources

n=2 case

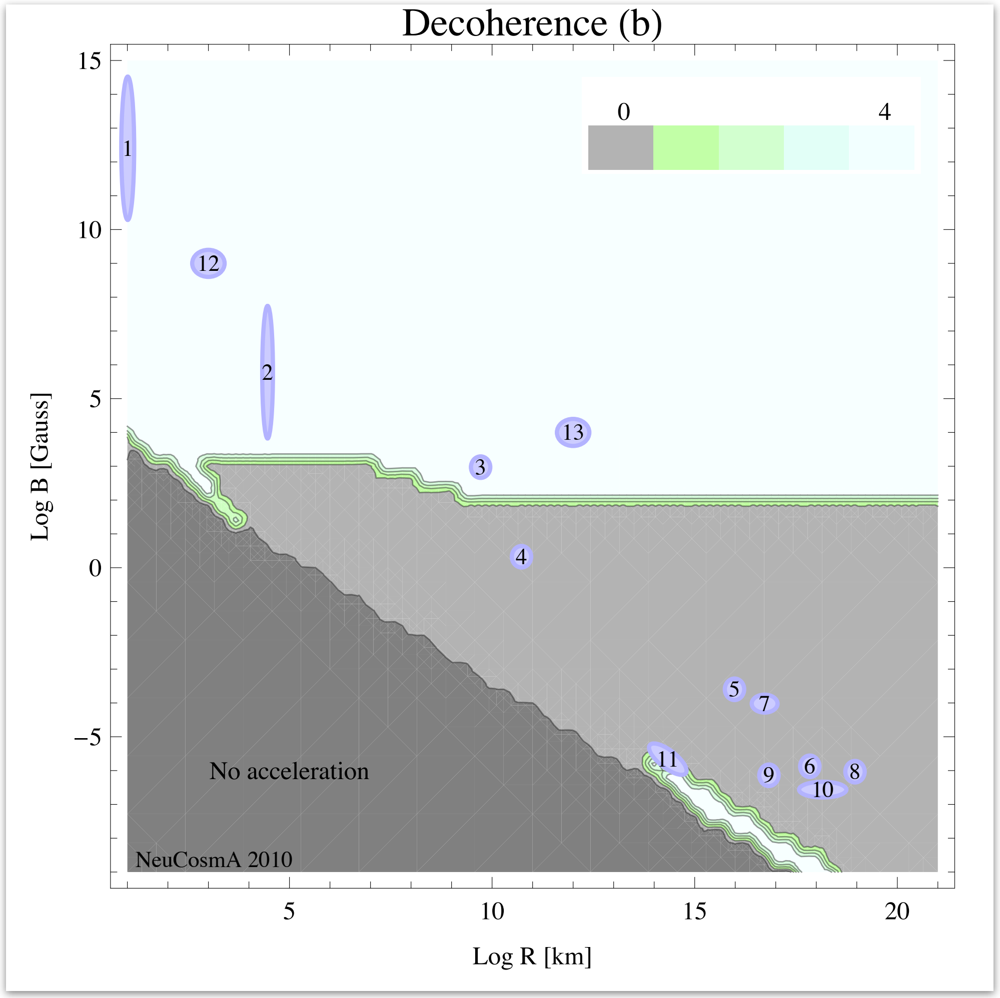
$$\kappa L = 10^{-12}\ GeV^{-2}$$



Useful sources :TP 2, 3, 13

n=-1 case, like decay

$$\kappa L = 10^{8}\ GeV$$

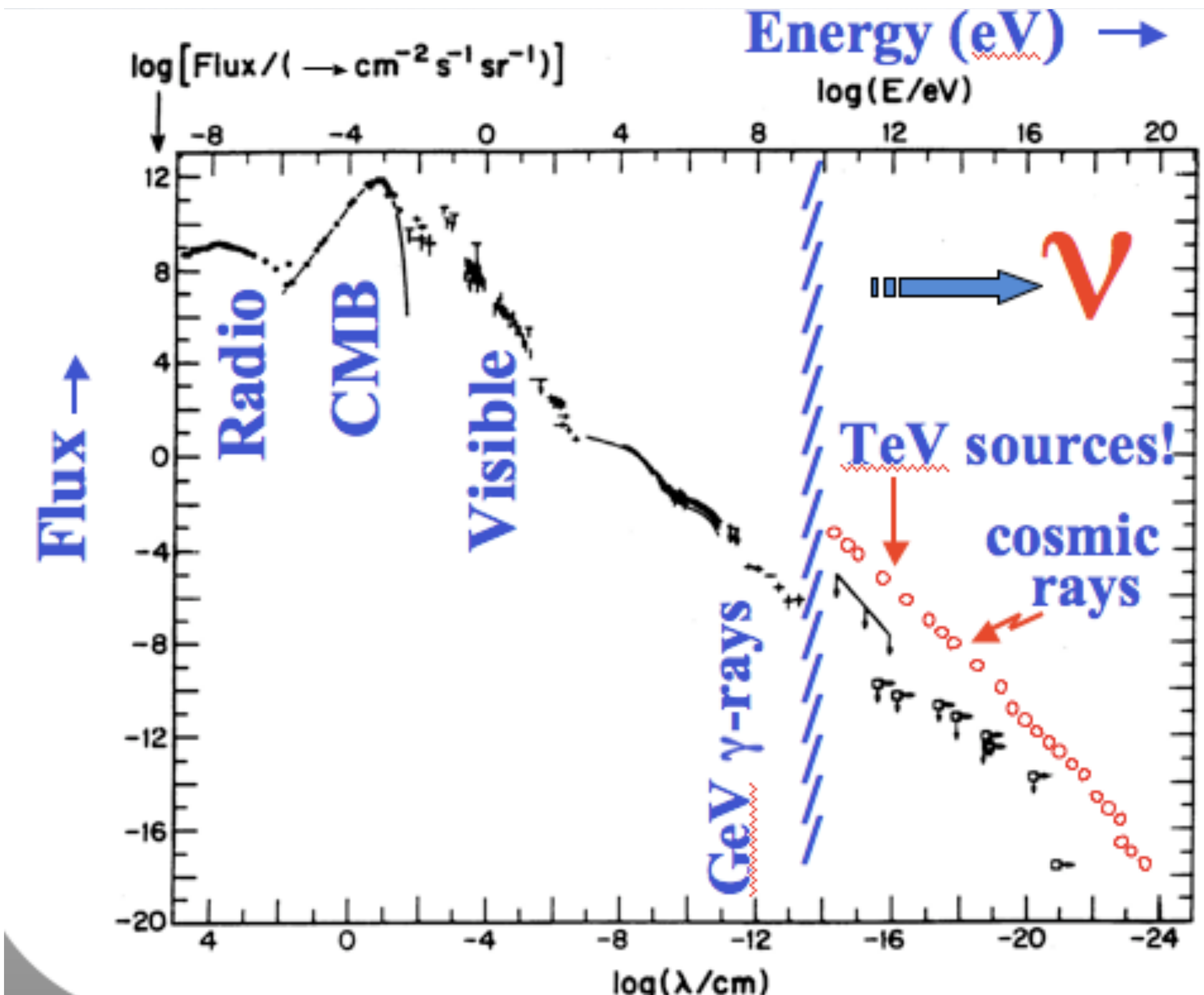


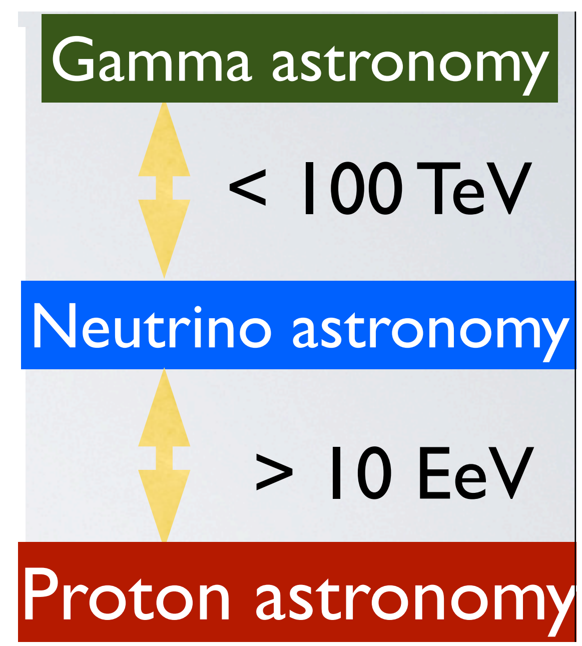
Useful sources :TP 1, 2, 3, 12, 13

Summary

- Flavor degree of freedom of neutrinos plays an indispensible role in revealing interesting particle physics effects and also can give some information on the astrophysics of source.
- Flavor is not directly measured at telescopes but can be indirectly inferred, for instance at IceCube. Need identification of distinct event topologies at UHE detectors.
- Neutrino observatories have reached the precision to constrain multi-messenger signals - gamma rays, cosmic rays and neutrinos.

Multi-messenger connection





Outlook

- High energy extra-galactic neutrino astronomy will lead us to an understanding of the acceleration processes in the Universe.
- The next decade should be very exciting
    - if high energy neutrinos are detected - will answer a lot of open questions such as clues towards identifying UHECR sources with neutrinos, understanding astrophysics of such sources, particle physics effects, nature and properties of neutrinos.
    - hints of high energy neutrino events in recent IC data...