Cosmic Neutrinos

... From the Highest Energies to the Lowest

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Outline

- Quick review

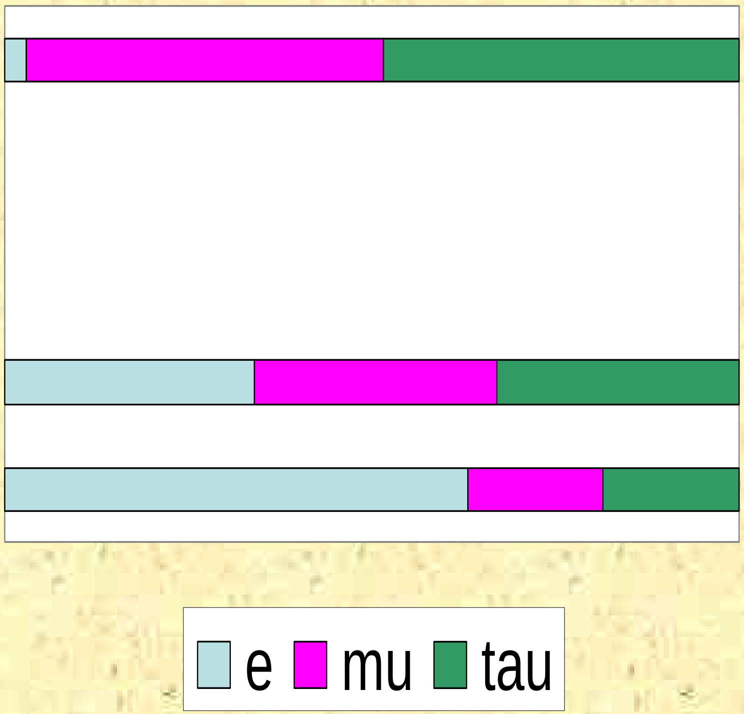
- The Highest Energies:

Ultra High Energy neutrino astrophysics

- The Lowest Energies:

Relic neutrinos & neutrino masses from cosmology

Neutrinos: What have we learnt?



$$\delta m^2_{\text{atm}} \approx 2\times10^{-3}\ \text{eV}^2$$
$$\tan^2\theta_{\text{atm}} \approx 1$$

SuperKamiokande

$$\delta m^2_{\text{solar}} \approx 7.1\times10^{-5}\ \text{eV}^2$$
$$\tan^2\theta_{\text{solar}} \approx 0.42$$

SNO, Kamland, SuperK

Uncovering the neutrino mass/mixing angle pattern was **necessary** in order to search for exotic **new physics** in the neutrino sector.

OPEN QUESTIONS

- Majorana or Dirac?
- Overall mass scale?
- CP violation?
- Is the seesaw mechanism correct?
- Extra/exotic neutrino interactions?
- Baryogenesis/Leptogenesis?
- Magnetic moments?
- Neutrino lifetimes?
- Are there sterile states?
- …

To answer these questions, astrophysical/cosmological and terrestrial experimentals will go hand in hand.

The Highest Energies:

Neutrino Astronomy

Physics potential: what might we learn?

- Conditions at the astrophysical source

- Exotic neutrino properties

- Probe neutrino cross sections at extreme energies, where new physics might show up

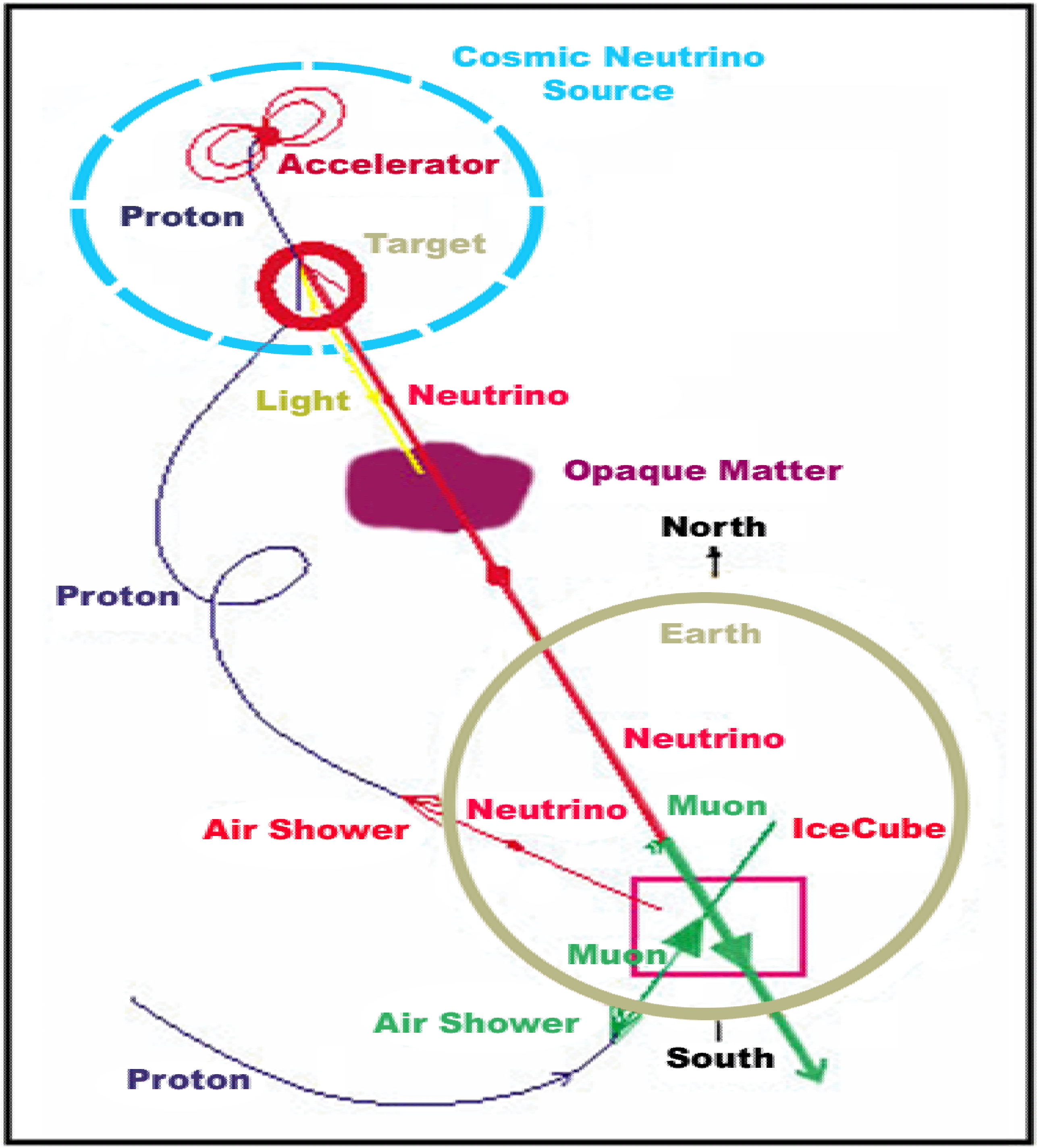
To uncover new physics, we need to discriminate flavors

High energy neutrinos as messengers

- Neutrinos interact weakly, so are not attenuated

- They are not deflected by magnetic fields – their arrival direction points back to the source

So, we can use them to probe astrophysical sources/cosmology that are perhaps inaccessible with photons



Cosmic Neutrino Source
Accelerator
Proton
Target
Light
Neutrino
Opaque Matter
North
Proton
Earth
Neutrino
Neutrino
Muon
IceCube
Air Shower
Muon
Air Shower
South
Proton

UHE neutrino sources

❖“Cosmic beam dumps”, eg, active galactic nuclei, gamma ray bursts, supernovae remnants.

→Flux limit set by the Waxman-Bahcall bound. Cosmic ray connection.

❖Annihilation or decay of WIMPs, super-heavy dark matter particles, topological defects, etc.

→Fluxes related to dark matter properties and distributions.

❖Interaction of UHE cosmic rays with the microwave background the GZK neutrinos, a “guaranteed” neutrino source.

→Flux related to the cosmic ray spectrum.

Astrophysical Neutrino Sources

High energy neutrino fluxes expected to be produced in "cosmic accelerators" which accelerate protons.

Eg, Gamma Ray Bursts (GRBs) and Actice Galactic Nuclei (AGNs)

pp and pγ collisions produce charged pions → Decay to neutrinos

$$\pi^+ \rightarrow \nu_\mu + \mu^+$$
$$\downarrow$$
$$\bar{\nu}_\mu + e^+ + \nu_e$$

Expected flavor ratio at the source: $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$

The ratio of flavors at the source is expected to be

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

In the limit of exact $\nu_\mu - \nu_\tau$ symmetry, the ratios in the mass basis are:

$$\nu_1 : \nu_2 : \nu_3 = 1:1:1$$

Exact mu-tau symmetry occurs when:

$$\theta_{\mathrm{atm}} = 45^\circ \quad \text{and} \quad \mathrm{Re}\,\mathrm{U}_{\mathrm{e}3} = \sin\theta_{13}\cos\delta = 0$$

Since: oscillation length is <<< distance to source

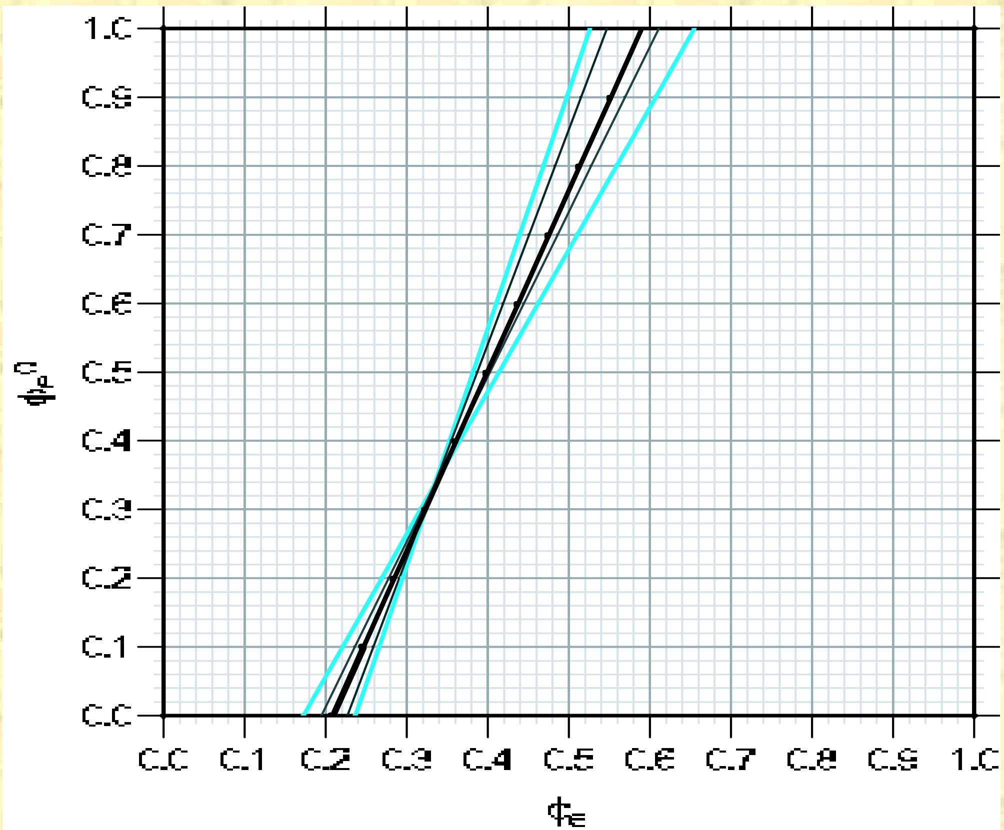
→ Averaged oscillations (incoherent mixture of mass eigenstates)

→ 1:1:1 in ANY basis (in particular, the flavour basis)

Inverting the observed flavor ratios to obtain the mixture at the source:

Maximally mixed ν_μ and ν_τ → not possible to uniquely invert the measured flavor ratios to obtain all three source fluxes.

However, we may reconstruct the ν_e fraction.



Barenboim and Quigg, PRD67, 073024 (2003)

If we don't see 1:1:1

Different flavor ratio at the source

Eg. 0:1:0 (Rachen and Meszaros, 1998)

→ becomes 0.5 : 1 : 1 at Earth

Exotic neutrino properties

- Neutrino decay (Beacom, Bell, Hooper, Pakvasa & Weiler)
- CPT violation (Barenboim & Quigg)
- Oscillation to steriles with very tiny delta δm^2 (Crocker et al; Berezinsky et al.)
- Pseudo-Dirac mixing (Beacom, Bell, Hooper, Learned, Pakvasa & Weiler)
- 3+1 or 2+2 models with sterile neutrinos (Dutta, Reno and Sarcevic)
- Magnetic moment transitions (Enqvist, Keränen, Maalampi)
- Varying mass neutrinos (Fardon, Nelson & Weiner; Hung & Pas)
- …

Neutrino Lifetimes

The strongest model-independent limit on the neutrino lifetime is quite weak:

$$\tau / m \geq 10^{-4} \quad \text{s/eV}$$

Neutrinos might have “invisible” decay modes of the form:

$$\nu_2 \rightarrow \nu_1 + \phi$$

Where ϕ is a very light or massless scalar/pseudo-scalar. (e.g. a Majoron)

$$\mathsf{L} = g_{ij}\overline{\nu}_i \nu_j \phi + h_{ij}\overline{\nu}_i \nu_j \gamma_5 \phi + h.c.$$

Neutrino-light scalar couplings

Cosmological consequences:

→ for the CMB   Chacko et al. (2003)
→ Large Scale Structure & Neutrino Mass Measurements

Beacom, Bell and Dodelson (2004)

→ Can be used to connect neutrino mass with dark energy

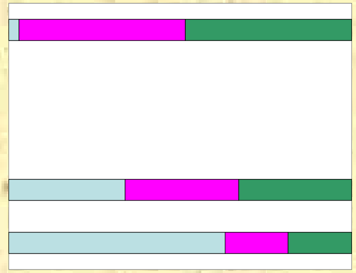
Fardon, Nelson and Weiner (2003);   Kaplan, Nelson and Weiner (2004)

Neutrino Source	L/E	Lifetime/m (s/eV)
Accelerator	30 m / 10 MeV	10^{-14}
Atmosphere	10^4 km / 300MeV	10^{-10}
Sun	500s / 5 MeV	10^{-4}
Supernova	10 kpc / 10 MeV	10^5
AGN	100 Mpc / 1 TeV	10^4

UHE ν Decay – Flavor Ratios

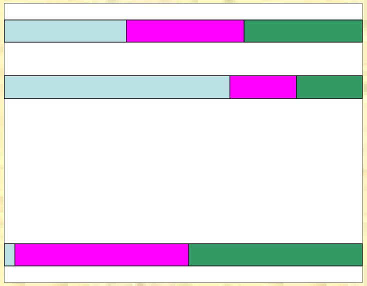
The lightest neutrino should be stable.

Normal hierarchy



$\nu_e : \nu_\mu : \nu_\tau = 5:1:1$

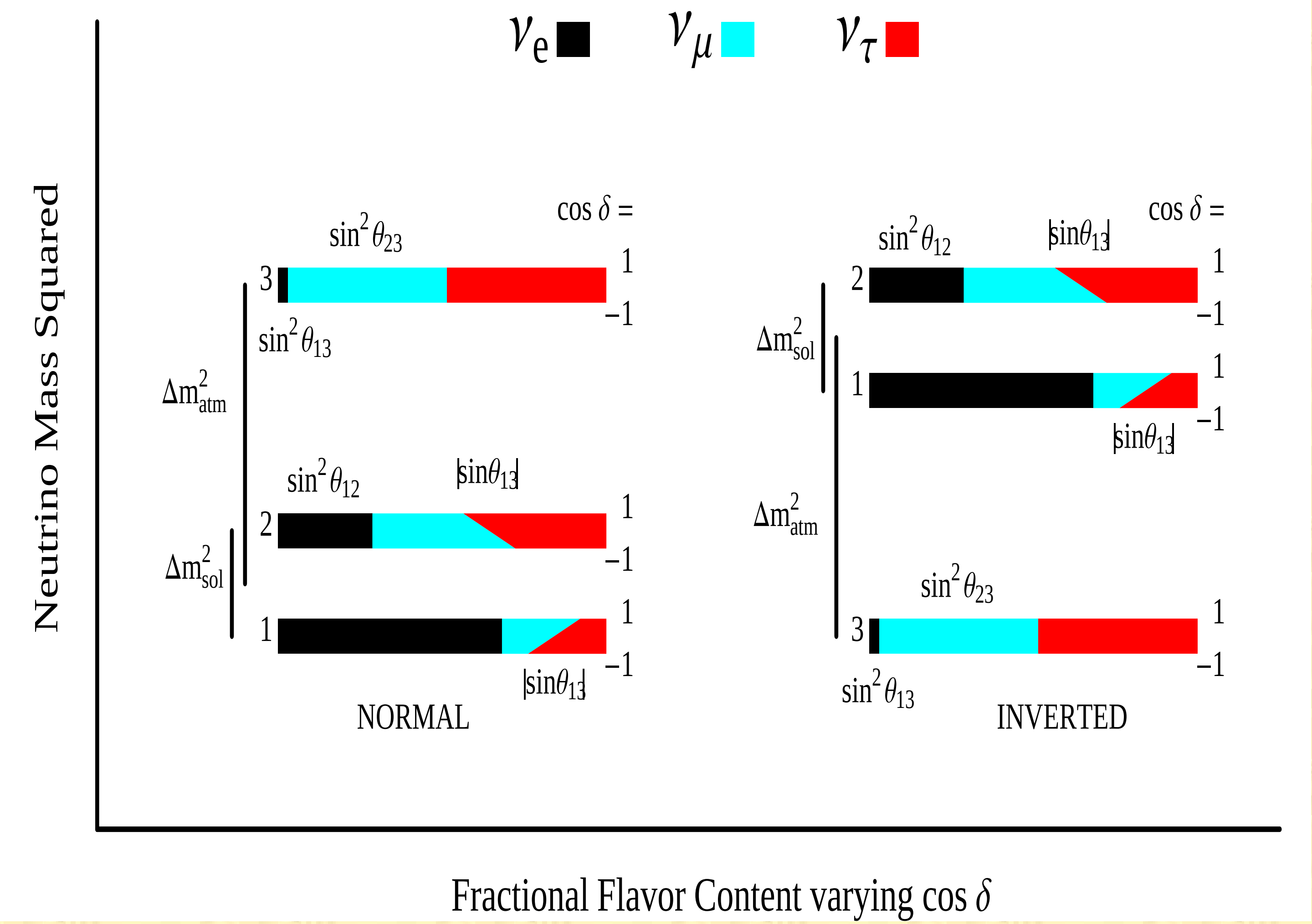
Inverted hierarchy



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

Such extreme deviations of the expect ratios, 1:1:1, should be identifiable in current or planned neutrino telescopes, such as IceCube

How good is mu-tau symmetry?

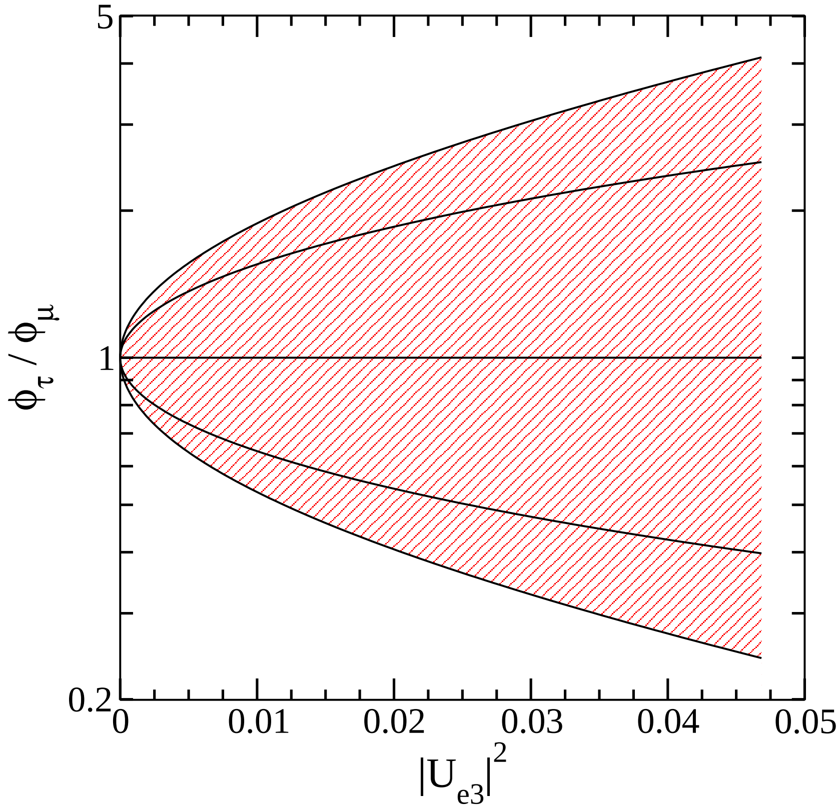


S. Parke and O. Mena

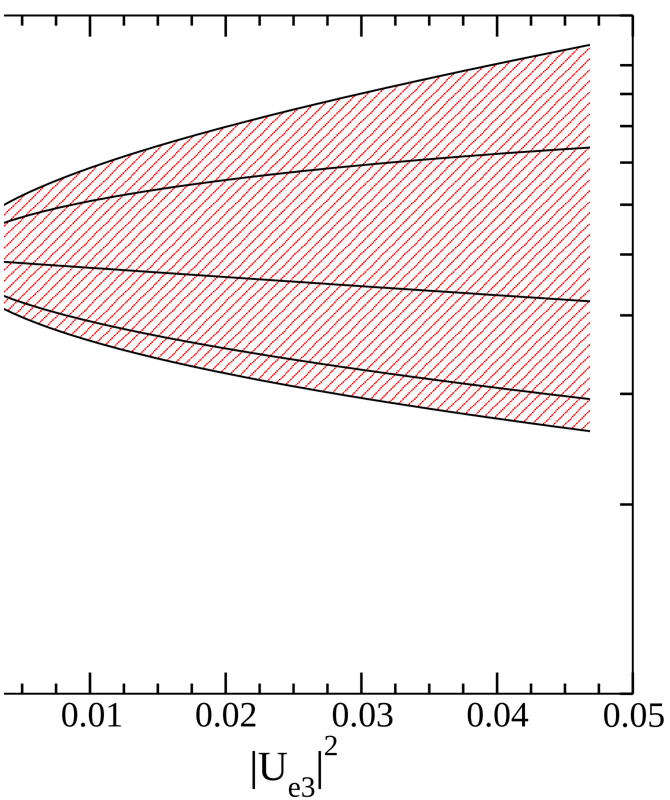
Neutrino decay, θ_{13} and the CP phase δ

Nonzero θ_{13} breaks mu-tau symmetry

Tau/mu components of ν_1



e/mu ratio in decay scenario



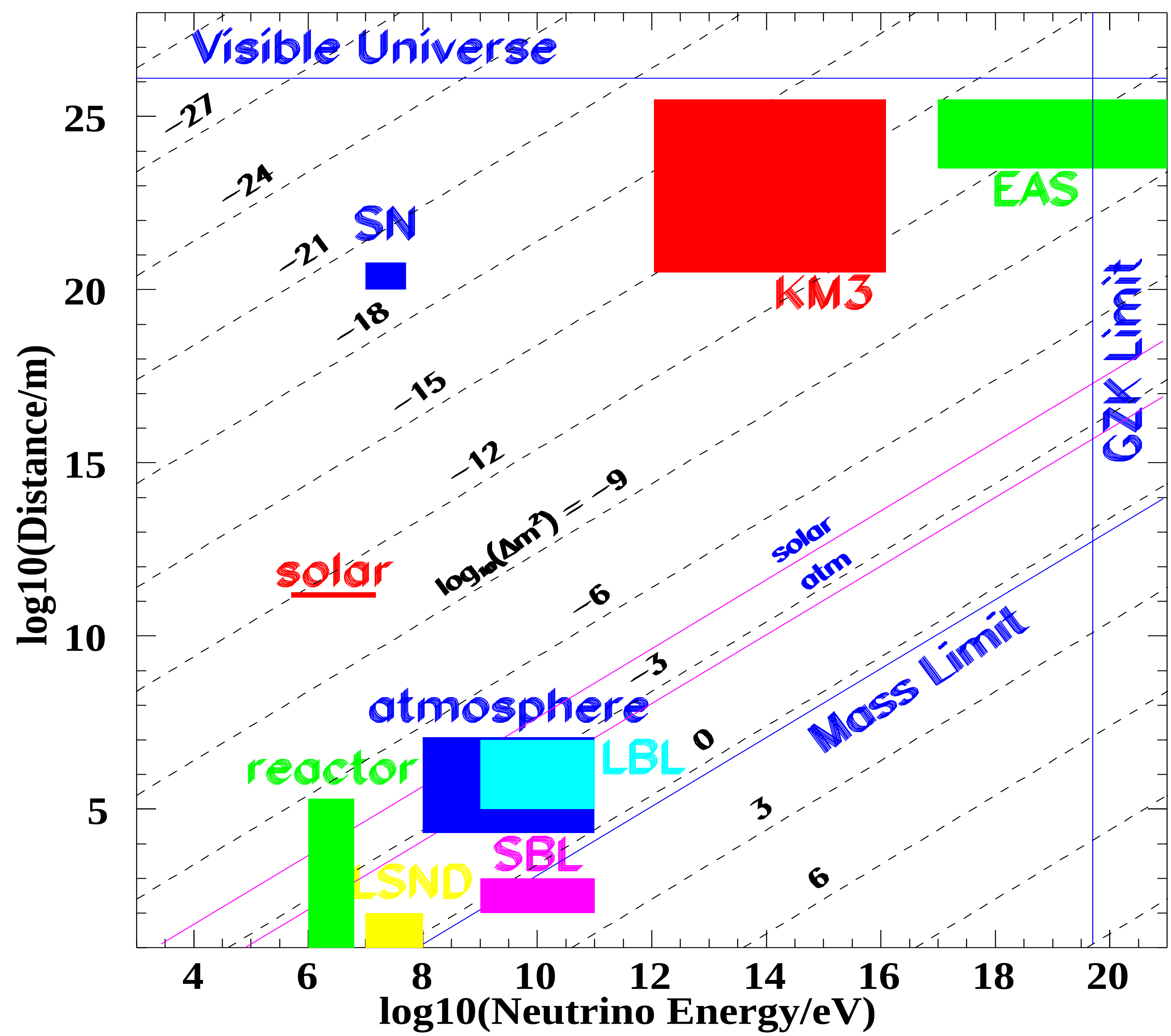
Ultimate Long Baseline Experiment

Astrophysical sources provide baselines almost as big as the visible universe.

This allows a sensitivity to oscillations with tiny δm^2

Eg. Active-sterile oscillation modes that have a sub-dominant or completely negligible effect on the solar or atmospheric neutrinos may show up here.

Crocker, Melia and Volkas (2000, 2002)
Berezinsky, Narayan and Vissani (2002)
Keranen, Maalampi, Myyrylainen and Riittinen (2003)


Visible Universe
25
20
15
10
5
log10(Distance/m)
4
6
8
10
12
14
16
18
20
log10(Neutrino Energy/eV)
−27
−24
−21
−18
−15
−12
−9
log10(Δm²) = −9
−6
−3
0
3
6
SN
KM3
EAS
GZK Limit
solar
atm
Mass Limit
atmosphere
reactor
LBL
SBL
LSND

Pseudo-Dirac Neutrinos

Suppose:

Neutrinoless double beta decay experiments reach a sensitivity where we expect a positive signal, but we get a null result.

Does that mean neutrino masses are of Dirac type?

Not necessarily: they might be pseudo-Dirac. (Wolfenstein)

Majorana mass terms might be subdominant in size to Dirac terms.

The fundamental question would still remain:
Do Majorana mass terms (of any size) exist in nature?

Generic neutrino mass matrix: $\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$

Pseudo-Dirac limit is where: $m_{L,R} << m_D$

→Two closely degenerate, maximally mixed active and sterile states

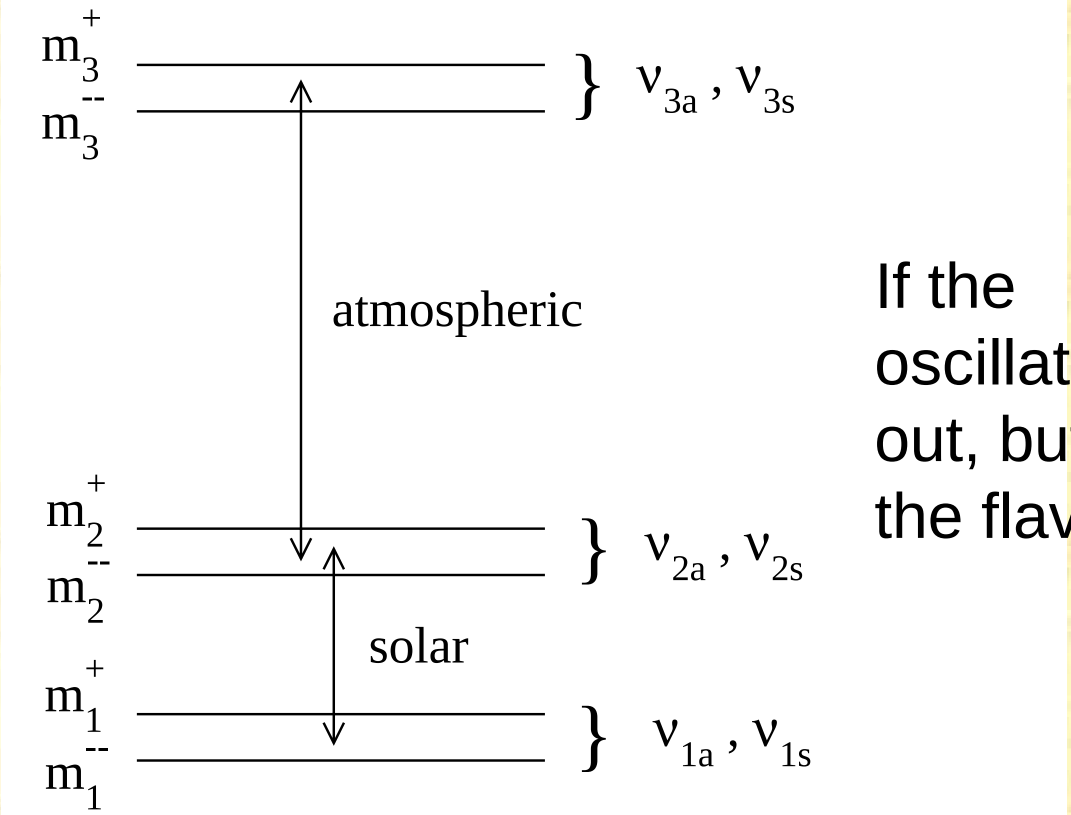
$$\nu_\alpha = \frac{1}{\sqrt{2}}\left(\nu^+ + i\nu^-\right)$$

$$m^+ \approx m^- \qquad \delta m^2 << m^2$$

$$\nu_s = \frac{1}{\sqrt{2}}\left(\nu^+ - i\nu^-\right)$$

$$\theta \approx 45°$$

Pseudo-Dirac mass spectrum

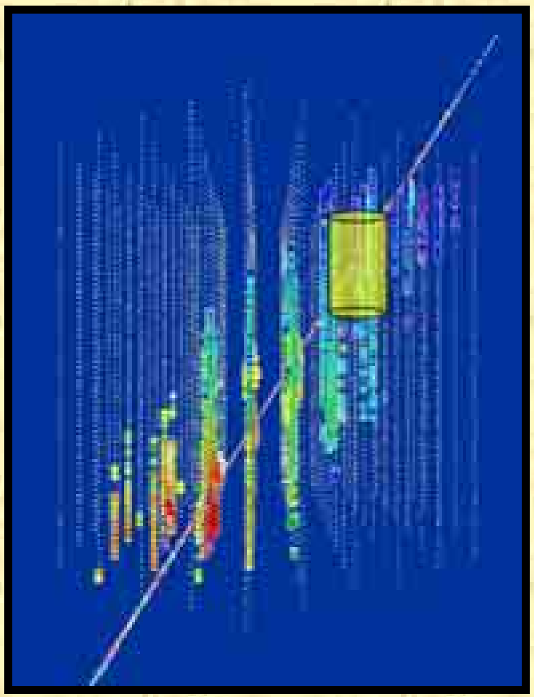


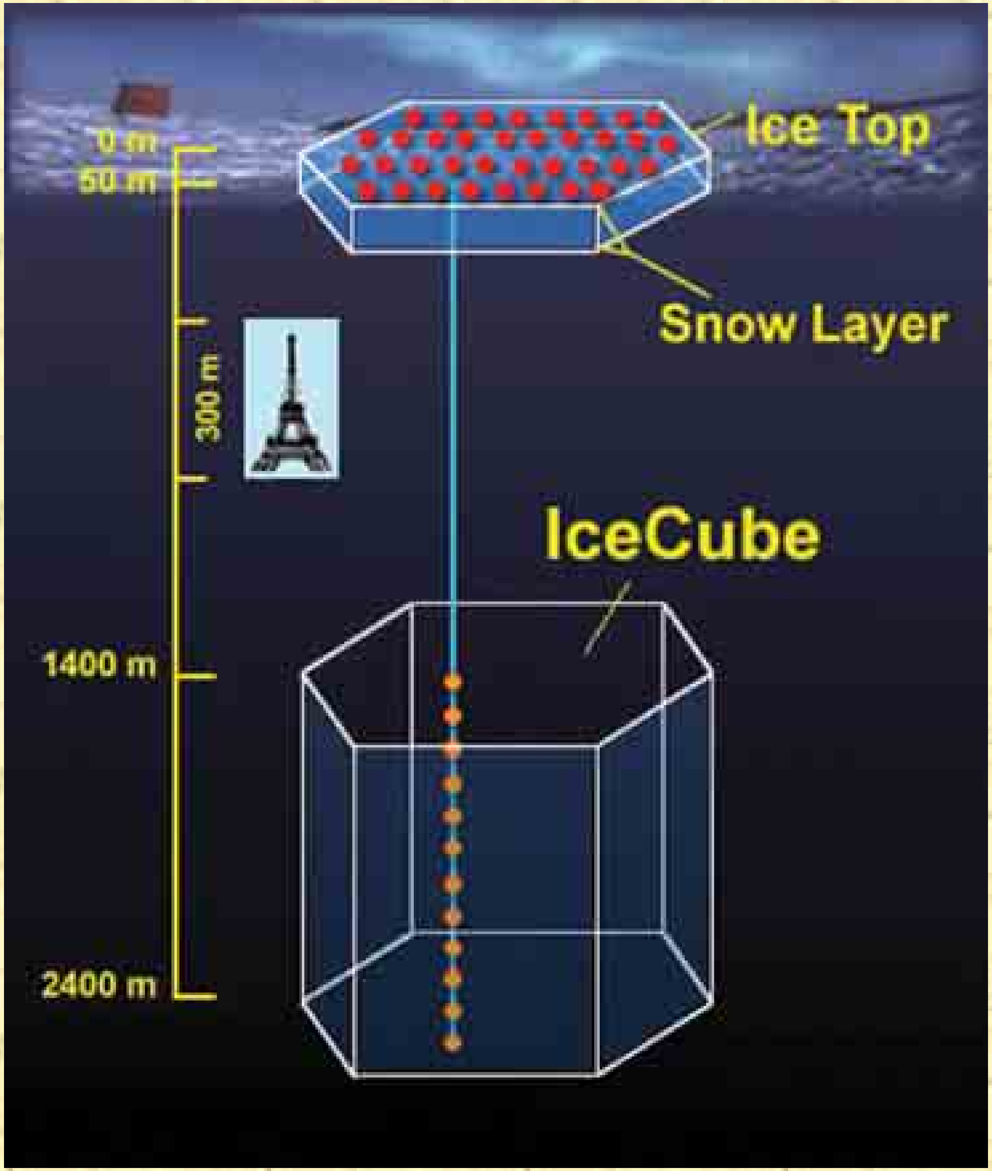
If the $\{\nu_{2,}^{+}\nu_{2,}^{-}\}$ and $\{\nu_{3,}^{+}\nu_{3,}^{-}\}$ oscillations have averaged out, but not the $\{\nu_{1,}^{+}\nu_{1,}^{-}\}$, the flavour ratios become:

$$1.5 : 1 : 1$$

Flavor-Ratio Measurements

IceCube





Event types

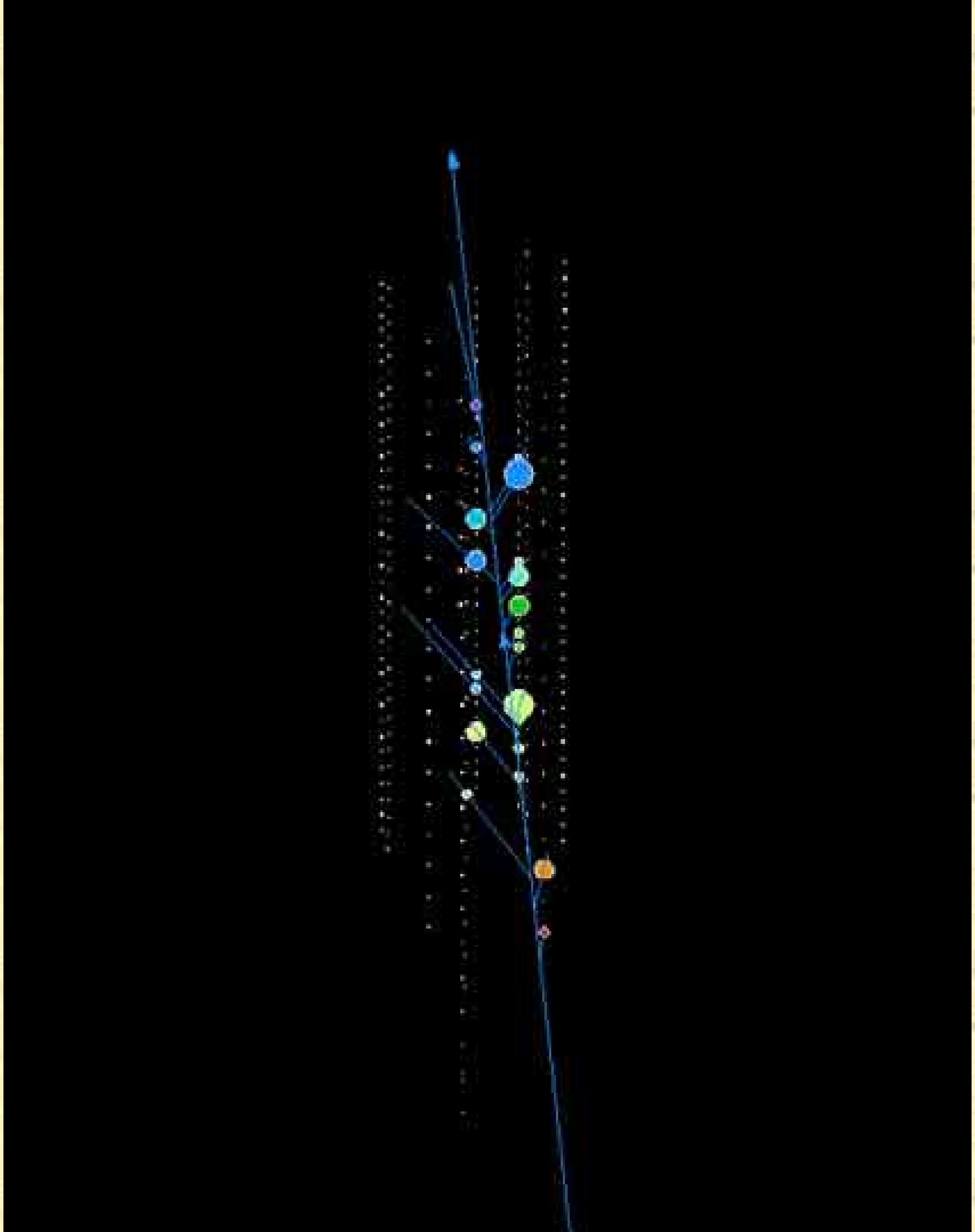
- Muon tracks

- Showers – neutral current interactions of all flavors, plus CC interactions of ν_e and ν_{τ}.

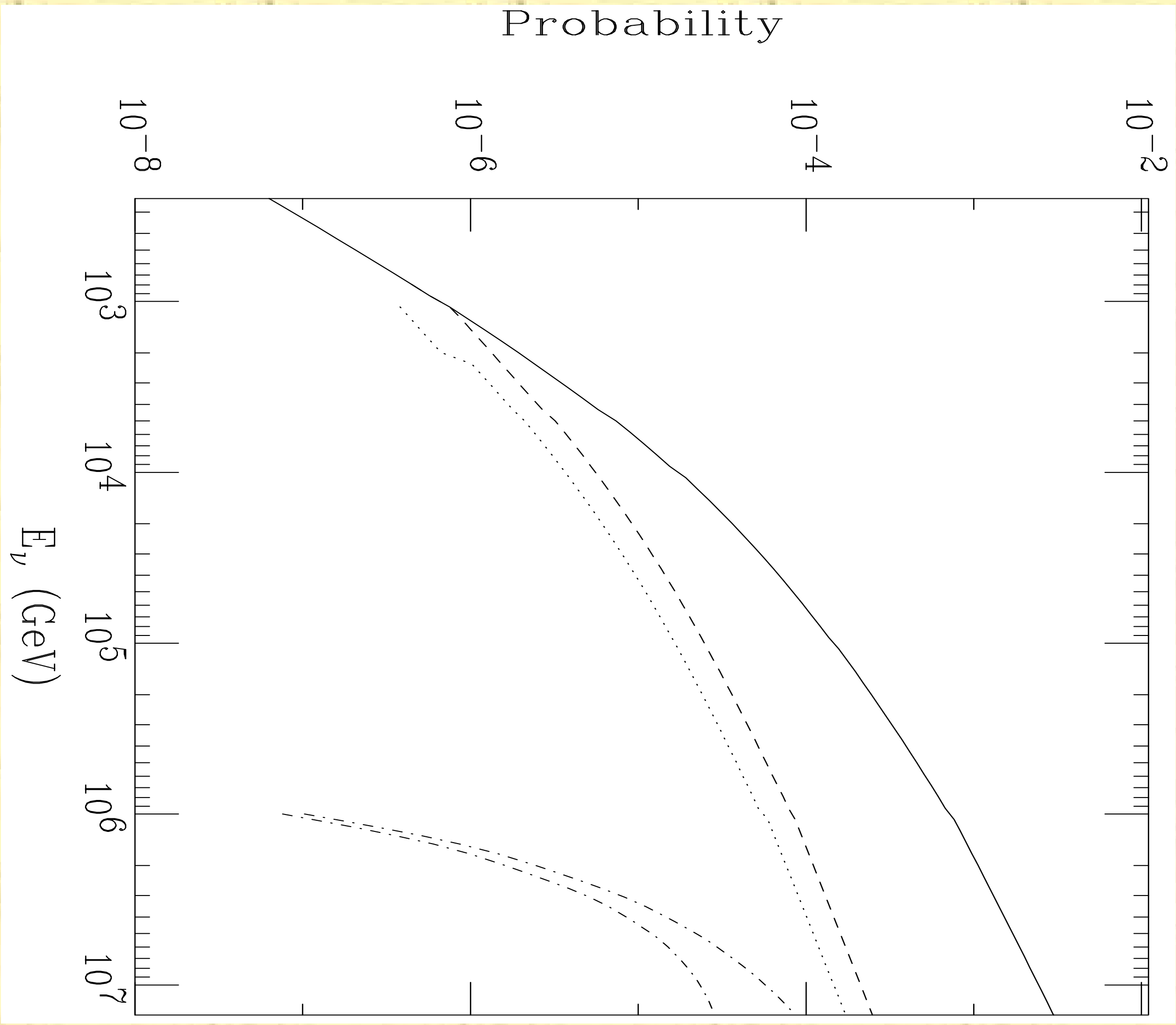
- Double bang and lollipop events for ν_{τ}

To determine the ν_e/ν_{μ} ratio
→ compare muon tracks to showers.

Muon Track event



Detection probabilities:



Muon track - horizontal ν_μ

Muon track - downgoing ν_μ

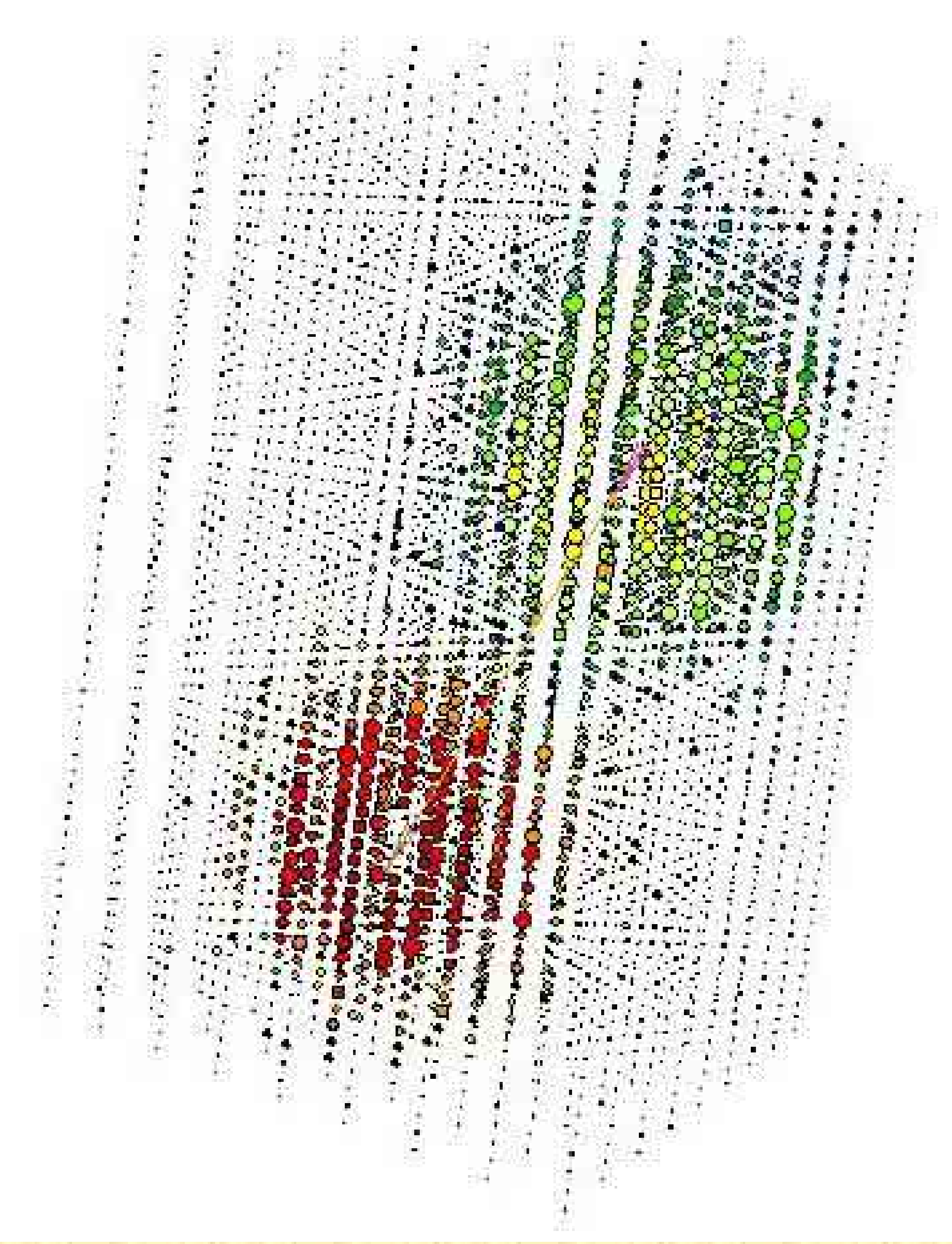
ν_e showers

ν_τ double-bangs and lollipops (shower events)

Beacom, Bell, Hooper, Pakvasa, Weiler

Simulation of a Double-Bang

IceCube



Double Bangs and Lollipops

Double Bang: Hadronic shower from $\nu_{\tau.}$ CC interaction followed by second shower when the tau lepton decays, connected by a tau track

Lollipop: The second of these two bangs (plus the tau track)

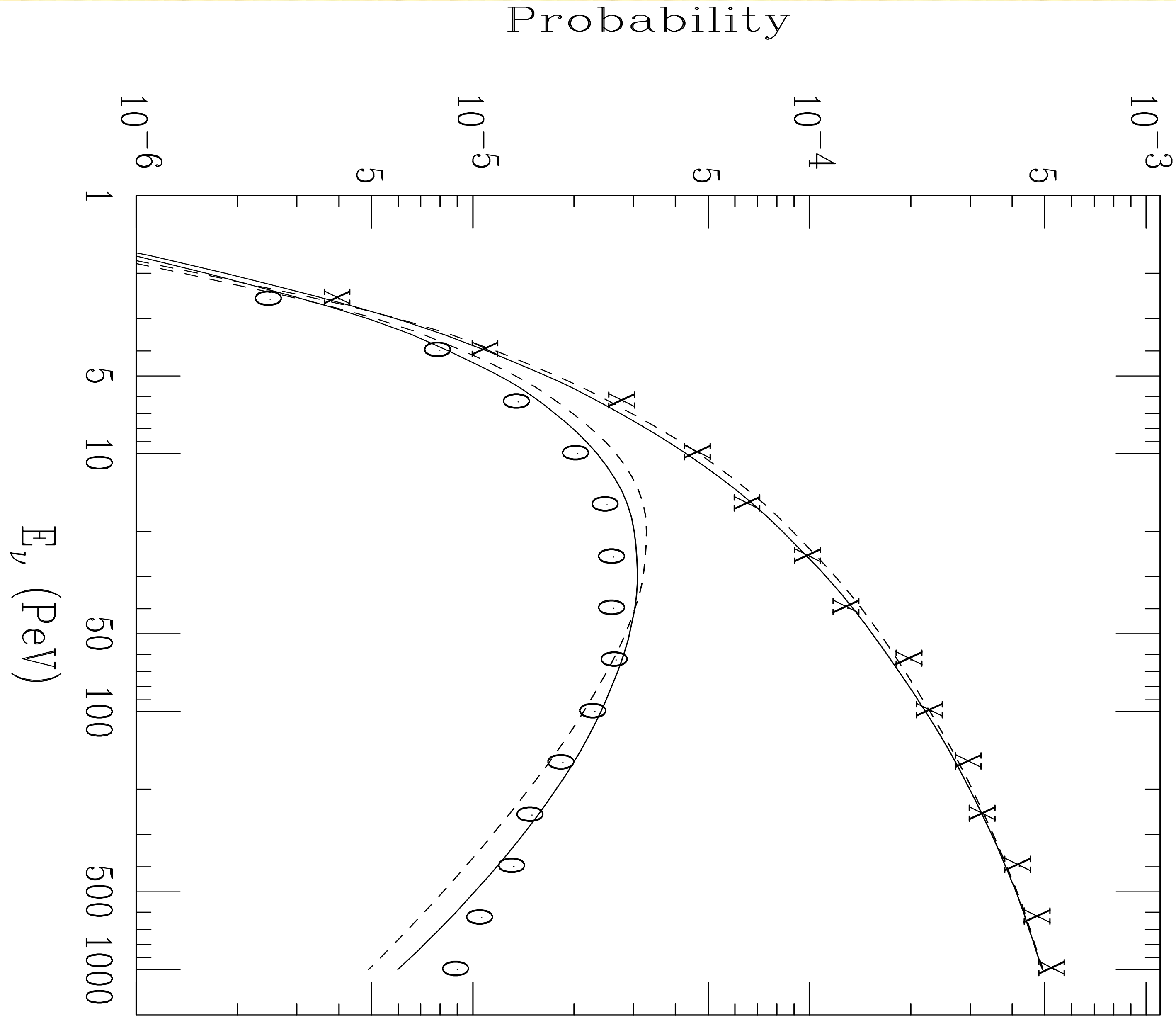
$$P_{\mathrm{DoubleBang}}(E_\nu) = \rho N_A \sigma [(L - x_{\min} - R) e^{-x_{\min}/R} + \mathrm{Re}^{-L/R}]_{y=<y>}$$

$$P_{\mathrm{Lollipop}}(E_\nu) = \rho N_A \sigma (L - x_{\min})[e^{-x_{\min}/R}]_{y=<y>}$$

L=detector size ~ 1km
R = tau decay length,
x_{min}=minimum shower separation / track length

See also: Jones, Mocioiu, Reno and Sarcevic (2003).

Lollipop and Double Bang detection probabilities in IceCube



Backgrounds

Atmosphere neutrino background a problem below ~ 100 TeV

→Overcome this by looking at known point sources – the temporal and angular resolution can be used to effectively remove backgrounds.

For example, the angular resolution for muon tracks at IceCube is ~1°.

e.g. ν's from GRB's in the BATSE catalogue. Guetta, Hooper Alvarez-Muniz, Halzen & Reuveni, Astropart Phys. (2004)

Absorption in the Earth

Earth start to become opaque to neutrinos at ~ 100 TeV

Tau regeneration

Halzen and Saltzberg

ν_e and ν_μ are absorbed in the Earth via charged current interactions

Above 10-100 TeV the Earth is opaque to ν_e and ν_μ.

But, the Earth never becomes completely opaque to ν_τ

Due to the short τ lifetime, τ's produced in ν_τ charged-current interactions decay back into ν_τ

$$\nu_\tau \rightarrow \tau \rightarrow \nu_\tau \rightarrow \ldots$$

Also, secondary ν_e and ν_μ fluxes are produced in the tau decays.

Beacom, Crotty and Kolb

Measuring the spectral shape → muon track events

❖Muon range substantially less than its decay length.
→Muons created outside the detector are seen
→effective volume much larger than the detector.

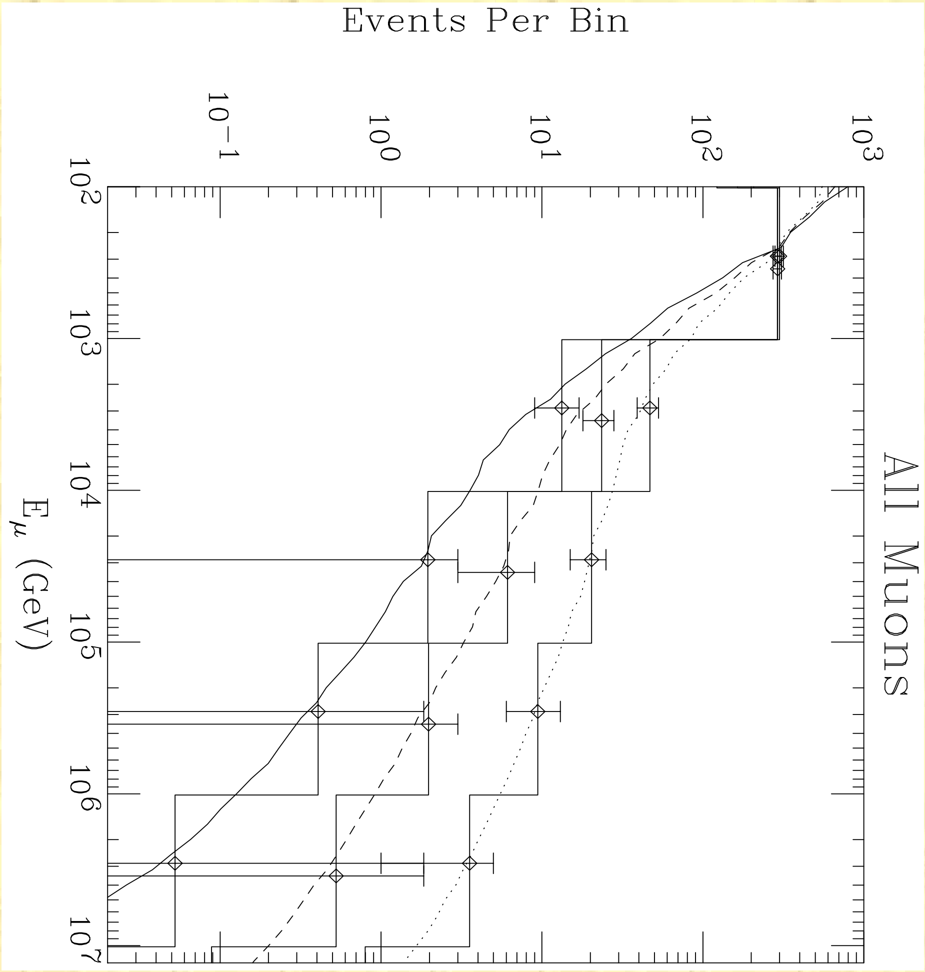
❖The energy of muons produced via CC interaction of ν_μ faithfully represent the neutrino energy

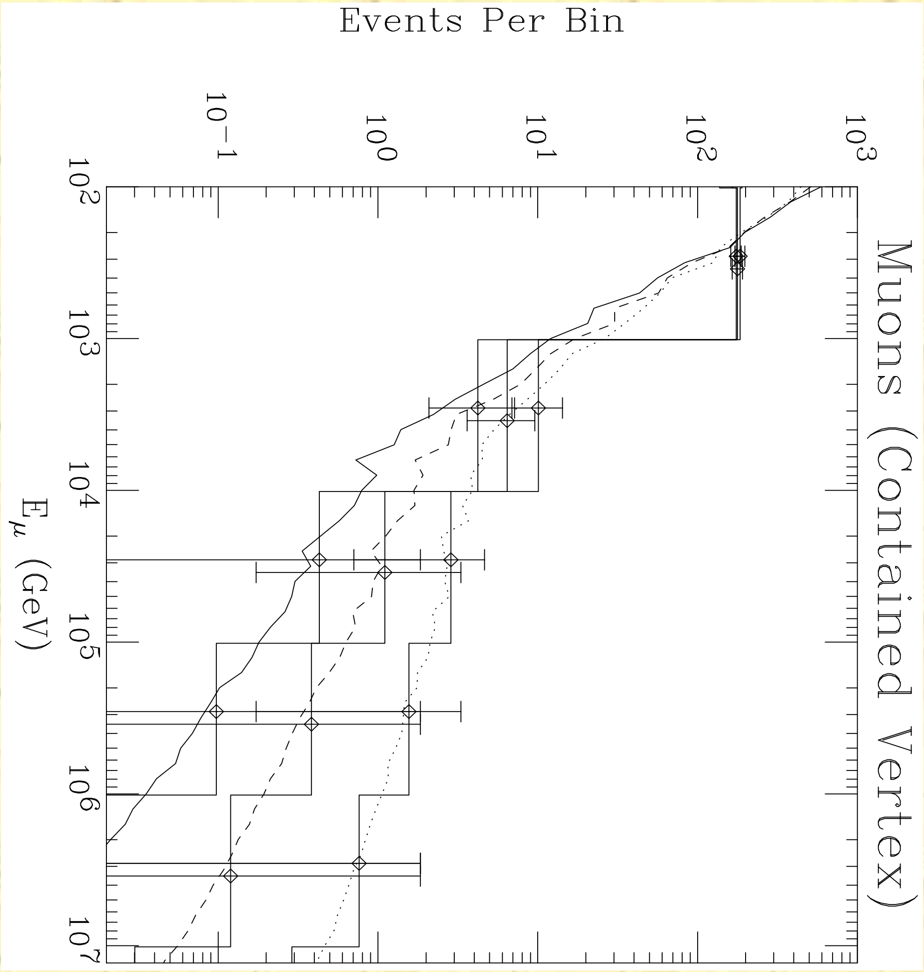
$$y = 1 - E_\mu / E_\nu$$

The cross section is peaked at y=0, and the average is: $\langle y \rangle \approx 0.2$

Measuring the spectral shape with muon track events

$E^2\, dN/dE = 10^{-7}\ \mathrm{GeV\,cm^{-2}s^{-1}}$ for 1 year

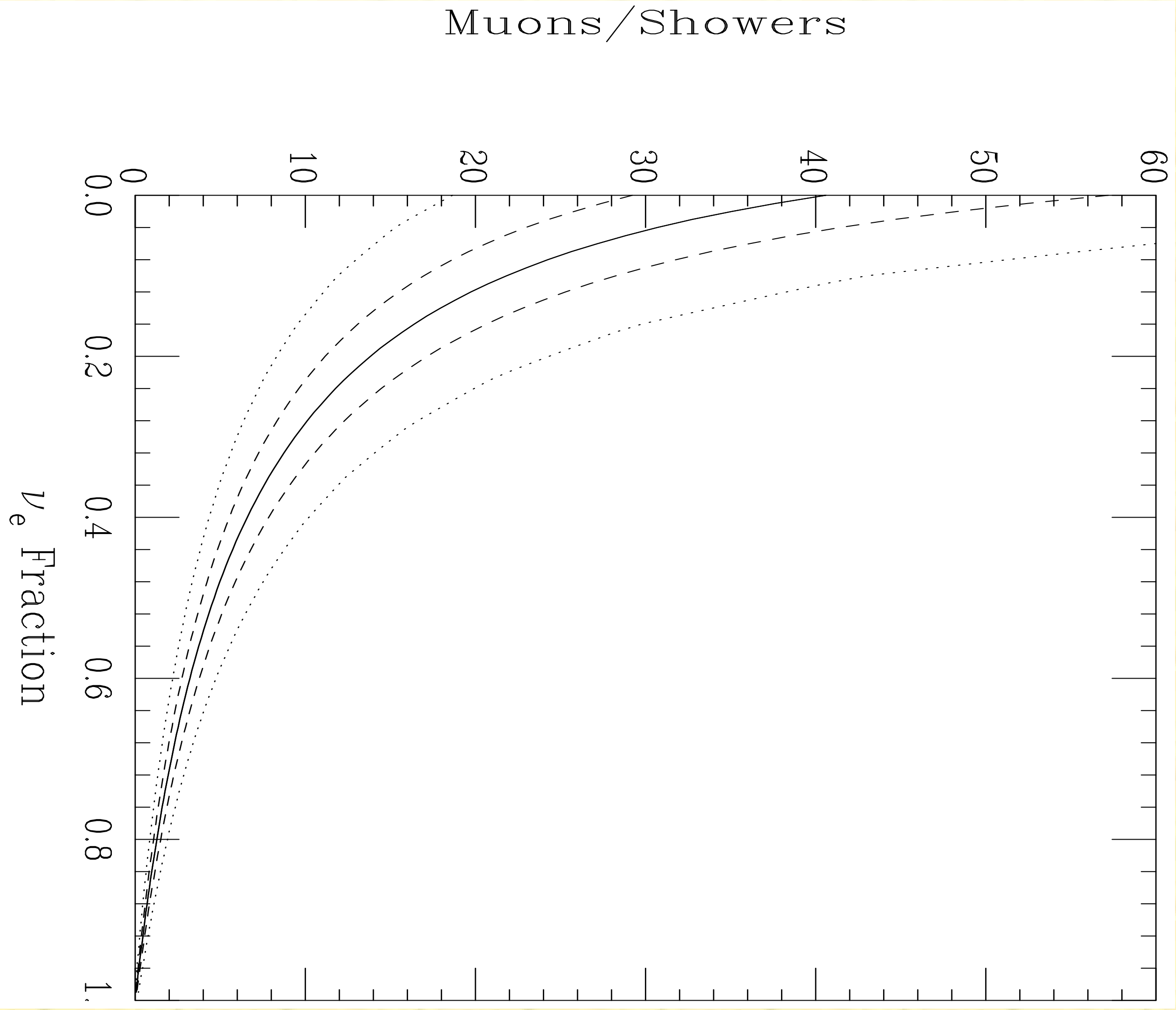




Neutrino spectra proportional to $E^{-1.8}$, E^{-2} and $E^{-2.2}$

Muons/Showers rate for different electron fractions.

Mu-tau symmetry assumed



Outlook

UHE neutrino observations:

•neutrino properties at energies and baselines far beyond those reachable with terrestrial experiments.

•Interesting connections with cosmic ray physics.

•In order to uncover possible exotic neutrino physics, flavor information will be very useful (essential?)

→ Good flavor discrimination will be important.

Many new experiments are being built/planned, so the future is bright!

The Lowest Energies:

The Relic Neutrino Background

Measuring neutrino mass

Neutrino mass in the lab - Tritium endpoint experiments:

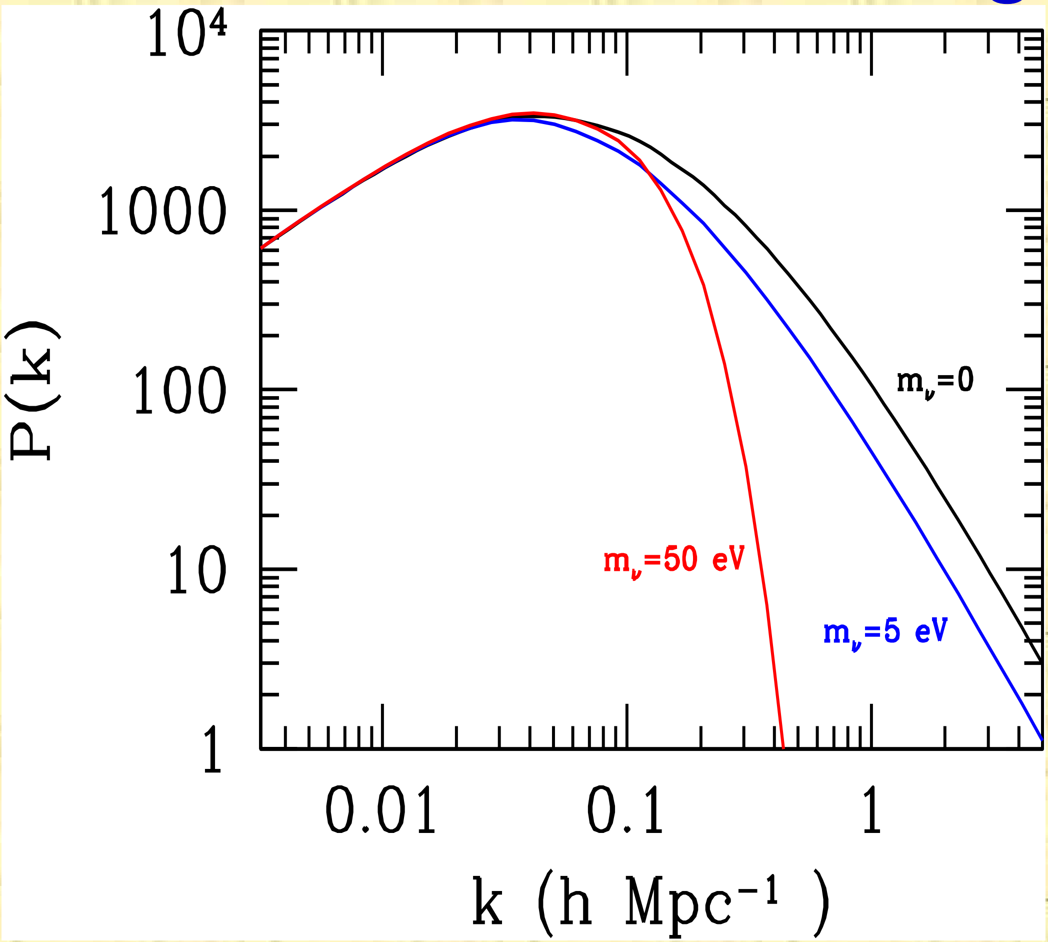
$$m_\nu < 2.2 \text{ eV} \quad \Rightarrow \quad \sum m_\nu < 6.6 \text{ eV}$$

"Weighing" neutrinos with cosmology - Large scale structure:

$$\sum m_\nu < 0.7 \text{ eV}$$ WMAP

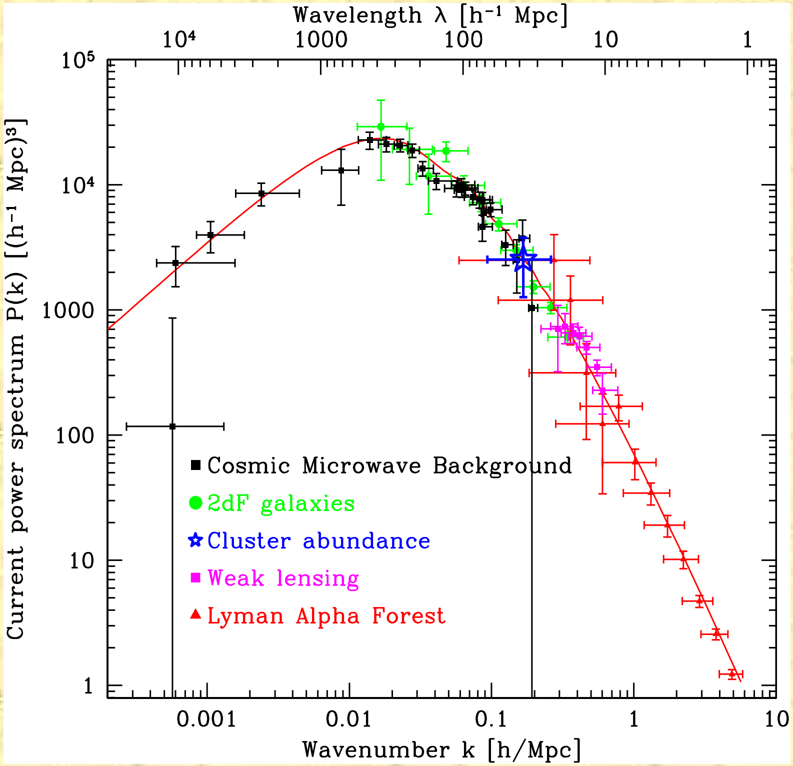
$$\sum m_\nu < 1.7 \text{ eV}$$ Tegmark et al. (SDSS)

Neutrino Mass & Large scale structure



Dodelson

Tegmark and Zaldarriaga



Neutrino mass and Cosmology

Neutrinos are only a small component of the dark matter
… but the effects of the neutrino component can be large.

$$\frac{\Delta P}{P} \approx -8 \frac{\Omega_\nu}{\Omega_m}$$

Hu, Eisenstein and Tegmark

- Free-stream from density perturbations when relativistic
- Behave more like cold dark matter when non-relativistic

→Suppression of the growth of structure on all scales below the size of the horizon at the time the neutrinos became non-relativistic

Neutrino contribution to the matter density:

$$\rho_\nu = \sum m_\nu n_\nu \rightarrow \frac{\sum m_\nu}{93.5 h^2 \mathrm{eV}} \rho_{\mathrm{critical}}$$

This assumes the standard cosmological neutrino abundance.
i.e. We can weigh neutrinos with cosmology ***provided we know N_ν =3.***

If the relic neutrinos had large chemical potentials, N_ν would be significantly enhanced…but this is no longer permitted (BBN+LMA).

Could the relic neutrino abundance be lower than we think?

Neutrinoless Universe

Vanishing relic neutrino density ?

If the neutrinos remained in thermal equilibrium until non-relativistic, their abundance would be suppressed by a Boltzmann factor:

$$n_\nu \propto e^{-m/T}$$

This would require non-standard neutrino couplings to a light boson.

Couplings in the allowed range can lead to a *vanishing cosmic neutrino density today* and *evade the cosmological neutrino mass limits*

Interaction model

$$\mathcal{L} = g_{ij}\bar{\nu}_i \nu_j \phi + g'_{ij}\bar{\nu}_i \nu_j \gamma_5 \phi + h.c.$$

Where ϕ is a massless (or light compared to m_ν) boson.

Couplings constraints

$g < 10^{-2}$ neutrino decay and meson decay limits

$g_{ee} < 10^{-4}$ neutrinoless double beta decay

Supernova constraints exclude a narrow range of couplings around $g \sim 10^{-5}$

The ϕ boson can be brought into thermal equilibrium through:

$$\nu + \phi \leftrightarrow \nu + \phi$$

$$\nu_i \leftrightarrow \nu_j + \phi$$

$$\nu + \nu \leftrightarrow \phi + \phi$$

The process $\nu + \nu \rightarrow \phi + \phi$ will deplete the neutrino number density once the temperature drops below the neutrino mass.

If $g > 10^{-5}$, all neutrinos annihilate into bosons when T ~ 1eV,
→ A “Neutrinoless Universe” today.

Energy Density

The neutrino/boson fluid is heated as the neutrinos annihilate.

In the standard scenario: $\frac{T_\nu}{T_\gamma} = \left(\frac{4}{11}\right)^{1/3}$

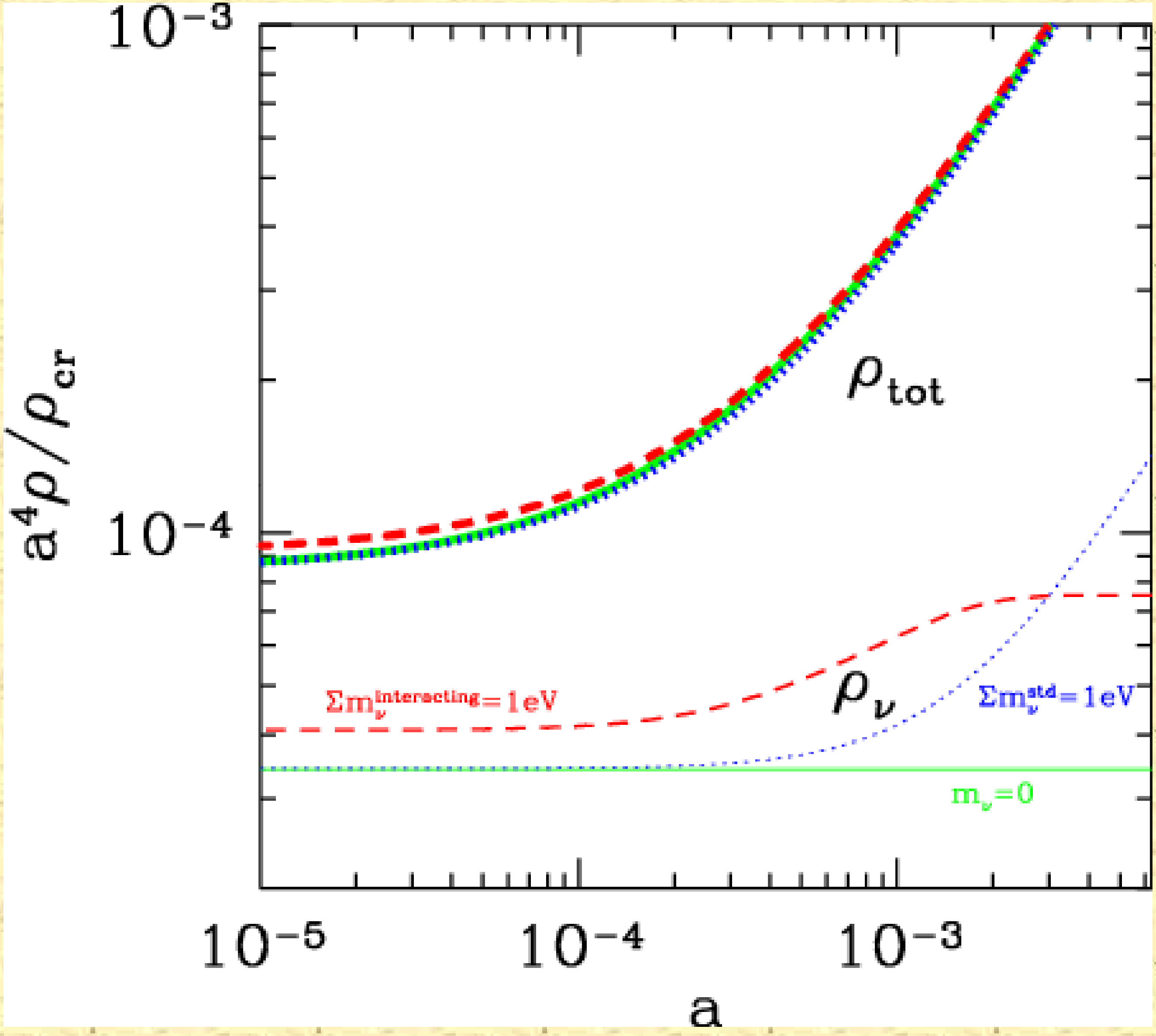
As the neutrinos annihilate, the neutrino temperature falls less sharply than usual.

$$\frac{T_{\nu\phi}}{T_\gamma} = \left(\frac{25}{11}\right)^{1/3}$$

This implies an increase in the energy density corresponding to an effective number of neutrinos: $N_\nu^{\text{eff}} = 6.6$

This delays the epoch of matter domination
→ Small suppression of the power spectrum.

Evolution of the Energy Density



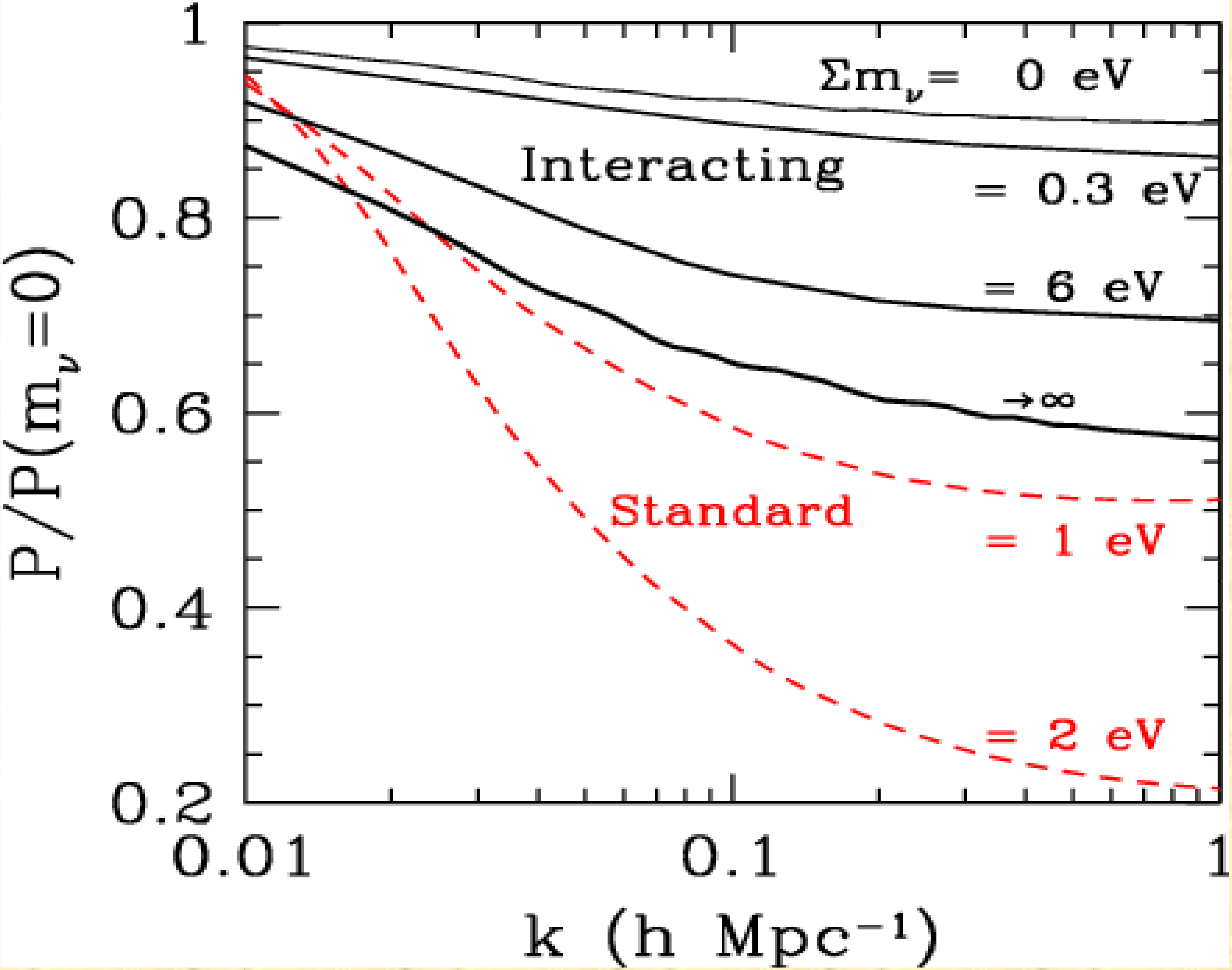
In the interacting scenario:

❖Neutrinos don't freestream like usual, but density perturbations in the neutrinos/scalar fluid still cannot grow, due to pressure.

❖The usual power spectrum suppression due to neutrino mass is absent, because the neutrinos all annihilated away and so make no contribution to the matter density today.

Effect on the power spectrum
→ entirely due to the slightly modified expansion history

Power Spectrum suppression:



Summary

Extra interactions might keep the neutrinos in equilibrium until late times → leaving a *Neutrinoless Universe* today.

This evades the cosmological neutrino mass limits.

(Beacom, Bell and Dodelson astro-ph/0404585)

This scenario is falsifiable:

❖neutrinos would decay over astronomical distances

→ Signals in neutrino telescopes (Beacom, Bell, Hooper Pakvasa & Weiler)

❖Extra energy density and lack of freestreaming has CMB effects

→ Future high precision CMB experiments

(Z. Chacko, L. Hall, T. Okui & S. Oliver; Bashinsky & Seljak)