Title: Secluded Neutrinos: From the Early Universe to IceCube

Date: Apr 08, 2016 01:00 PM

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Abstract: <p>Light sterile neutrinos are predicted in many theories beyond the Standard Model and may be hinted at in short-baseline data. However cosmological data seems to rule out these neutrinos. Intriguingly, this tension is ameliorated when these new neutrinos are self-interacting. I will explore the impact of this self-interaction on their evolution in the early universe and on the spectrum and flavor of IceCube's ultrahigh energy neutrinos.</p>

Secluded Neutrinos: From The Early Universe to IceCube

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Penn. State & Institute for
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Institute for Gravitation & the Cosmos

8th of April, 2016

Based on: Cherry, Friedland, **IMS** [1411.1071]
IMS, Murase [1512.07228]
Cherry, Friedland, **IMS** [in prep.]

OUTLINE

- ***Part I***: IceCube has discovered a new source of UHE neutrinos. Some peculiarities. What's the status?

- In addition to high-energy astro, we can use the data to search for new particle physics scenarios:

    - Neutrino decay, new oscillation lengths, **neutrino self-scattering.**

- ***Part II***: Who cares about nu self-interactions?

    - Predicted in a model motivated by tension between eV sterile hints and cosmology.

    - Flavor/spectral distortions & source correlations can constrain or discover the model.

Neutrinos have mass

- 2015 Nobel prize for neutrino oscillations implying they have mass. This time for a **particle physics** property of neutrinos.
- 2002 Nobel: Davis & Koshiba for “pioneering contributions to **astrophysics**, in particular for the detection of cosmic neutrinos.”

History shows neutrinos have been excellent probes of both astro- and particle physics.

The State of Neutrinos: Particle Physics Perspective

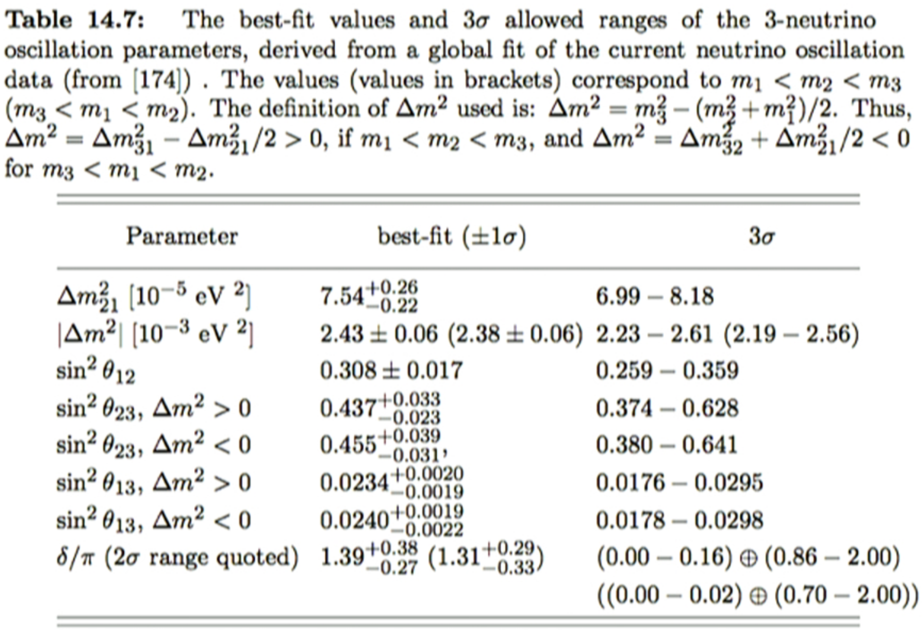


Table 14.7: The best-fit values and 3σ allowed ranges of the 3-neutrino oscillation parameters, derived from a global fit of the current neutrino oscillation data (from [174]) . The values (values in brackets) correspond to $m_1 < m_2 < m_3$ $(m_3 < m_1 < m_2)$. The definition of Δm^2 used is: $\Delta m^2 = m_3^2 - (m_2^2 + m_1^2)/2$. Thus, $\Delta m^2 = \Delta m_{31}^2 - \Delta m_{21}^2/2 > 0$, if $m_1 < m_2 < m_3$, and $\Delta m^2 = \Delta m_{32}^2 + \Delta m_{21}^2/2 < 0$ for $m_3 < m_1 < m_2$.

Parameter	best-fit ($\pm 1\sigma$)	3σ
Δm_{21}^2 [10^{-5} eV ^{2}]	$7.54^{+0.26}_{-0.22}$	$6.99 - 8.18$
$\lvert\Delta m^2\rvert$ [10^{-3} eV ^{2}]	2.43 ± 0.06 (2.38 ± 0.06)	$2.23 - 2.61$ $(2.19 - 2.56)$
$\sin^2\theta_{12}$	0.308 ± 0.017	$0.259 - 0.359$
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$	$0.374 - 0.628$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$,	$0.380 - 0.641$
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$	$0.0176 - 0.0295$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$	$0.0178 - 0.0298$
δ/π (2σ range quoted)	$1.39^{+0.38}_{-0.27}$ $(1.31^{+0.29}_{-0.33})$	$(0.00 - 0.16) \oplus (0.86 - 2.00)$ $((0.00 - 0.02) \oplus (0.70 - 2.00))$

Known unknowns: $\delta_{CP} = ?$ $\Delta m^2_{\rm atm} \lesseqgtr 0$ $\theta_{23} \gtrless 45^0$

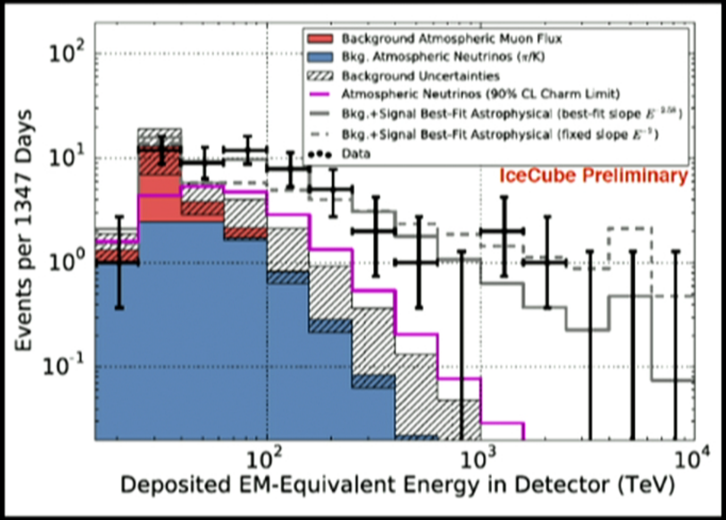
Unknown unknowns: $3\nu?$ $\sigma_\nu = \sigma_{SM}?$

Neutrino Interactions

- ***Pheno***: Neutrinos are hard to detect, so much about them remains unknown.
  - Could easily be hiding signs of new forces.
  - Also a comparative advantage: Could be seen "easily" since not mired by other complicated forces (no color/electric charge).

- ***Theory***: Origin of neutrino mass is not known.
  - Many models invoke *sterile neutrinos*.
  - Neutrino mass mixing may be a *portal* to a larger sector of particles/fields.
  - Simple example: "sterile" neutrinos carry a new U(1) gauge charge -> exchange new gauge boson.
  - Not really sterile any more: ***secluded neutrinos.***

New Era of Neutrino Astronomy

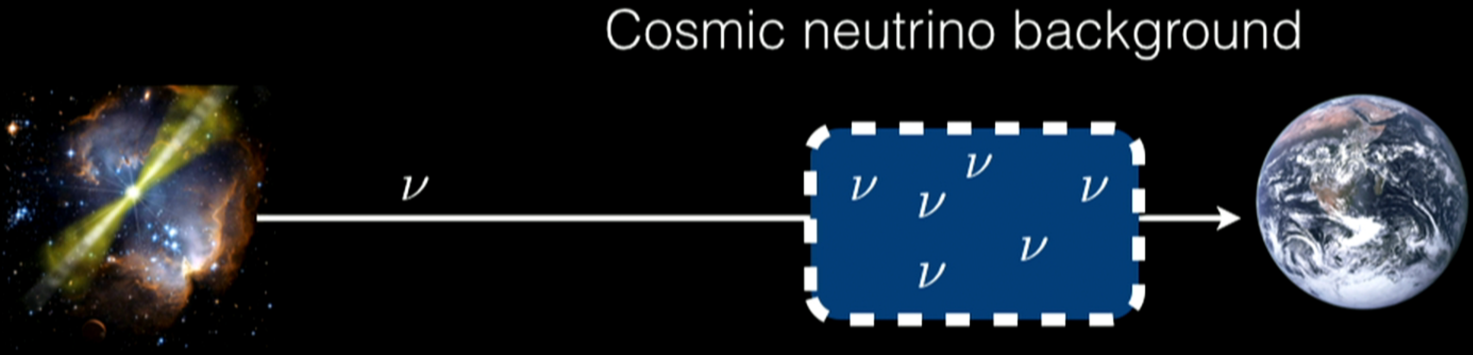


A new tool for high-energy astrophysics.

BUT, also a new tool for particle physics.

Is the Universe transparent to neutrinos?

A **100% Natural** Neutrino Collider



- IceCube's neutrino source is the“beam.”
- CnuB is the “fixed target.”

Secluded Neutrinos

- Cast of characters and their interactions

$$\boxed{\mathscr{L}_{\mathrm{S}\nu} \supset m_\phi^2 \phi^\mu \phi_\mu + g_s \phi^\mu \bar{\nu}_s \gamma_\mu \nu_s + \frac{(LH)(H'\nu_s)}{\Lambda},}$$

ϕ_μ =new U(1) gauge mediator

ν_s =secluded neutrino

H =SM Higgs

H' =secluded Higgs

L =SM Lepton doublet

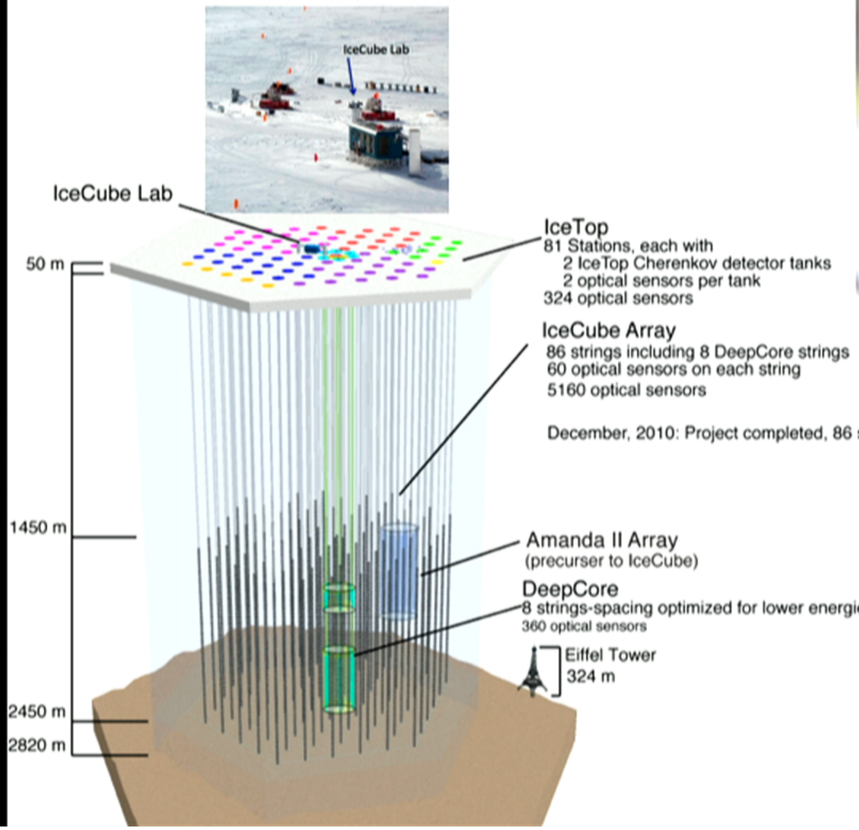
$\xrightarrow{\text{Both Higgs get VEVs}}$

<u>Low-energy parameters:</u>

mediator mass,
gauge coupling,
mixing angle.

IceCube Status Updates

The IceCube Detector



IceCube Lab

IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors

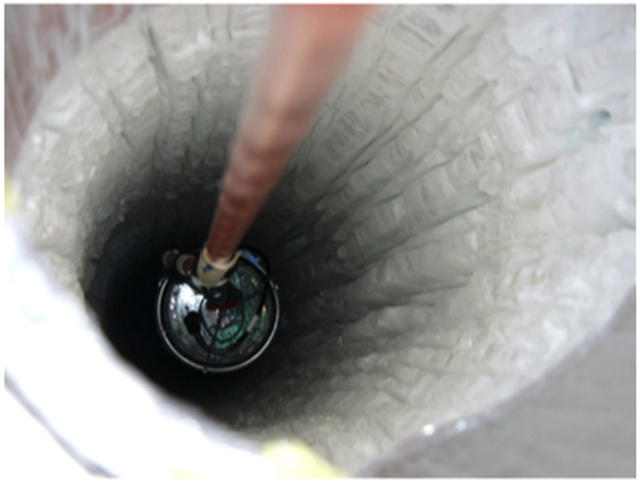
IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors

December, 2010: Project completed, 86 strings

Amanda II Array
(precurser to IceCube)

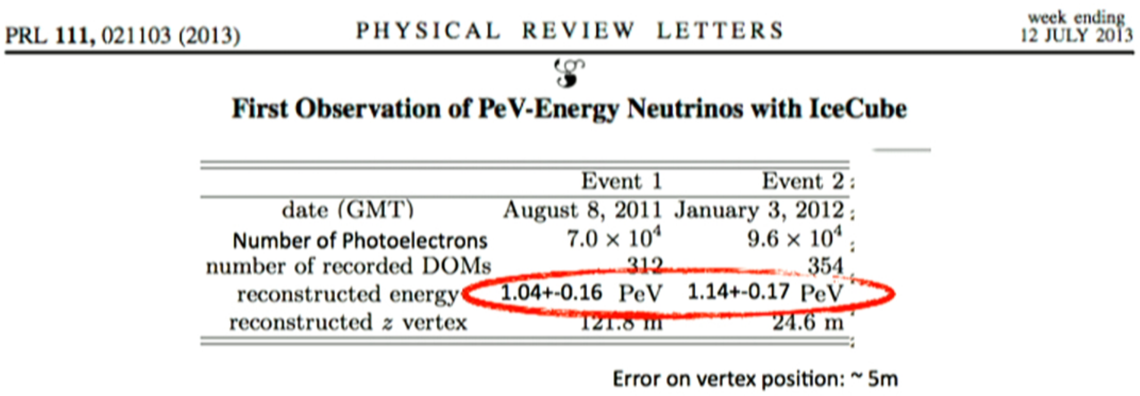
DeepCore
8 strings-spacing optimized for lower energies
360 optical sensors

Eiffel Tower
324 m



Need large volumes since:
i) these are rare events
ii) they are also large events

Just when IceCube was getting
really good at placing limits...



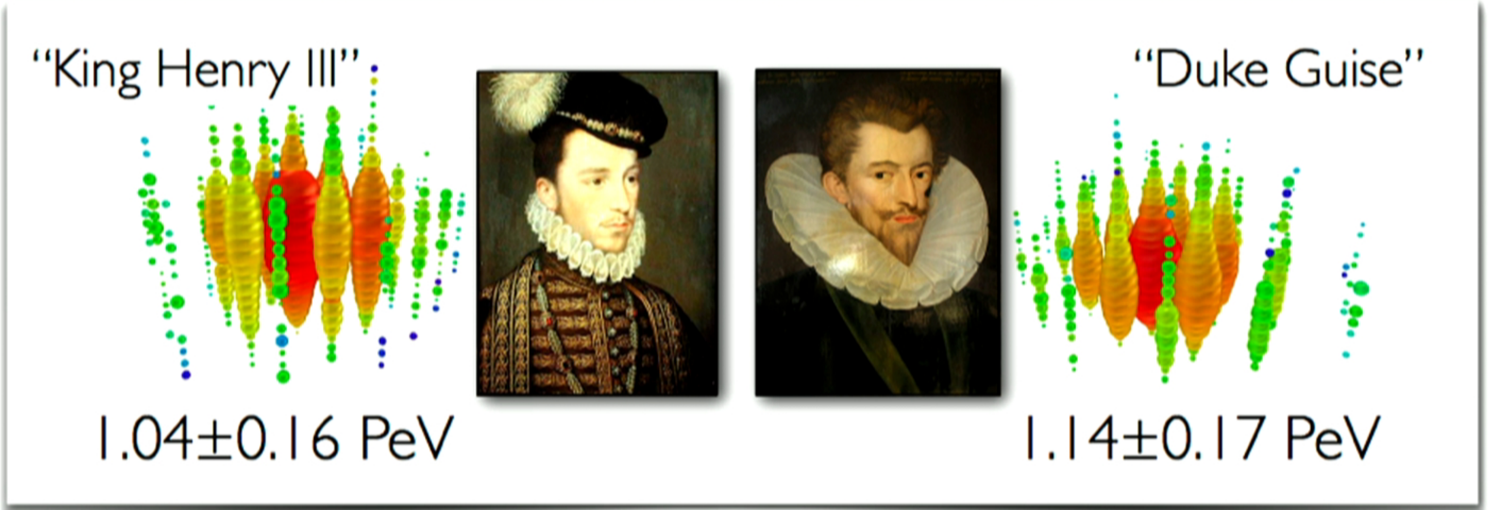
PRL 111, 021103 (2013) PHYSICAL REVIEW LETTERS week ending 12 JULY 2013

First Observation of PeV-Energy Neutrinos with IceCube

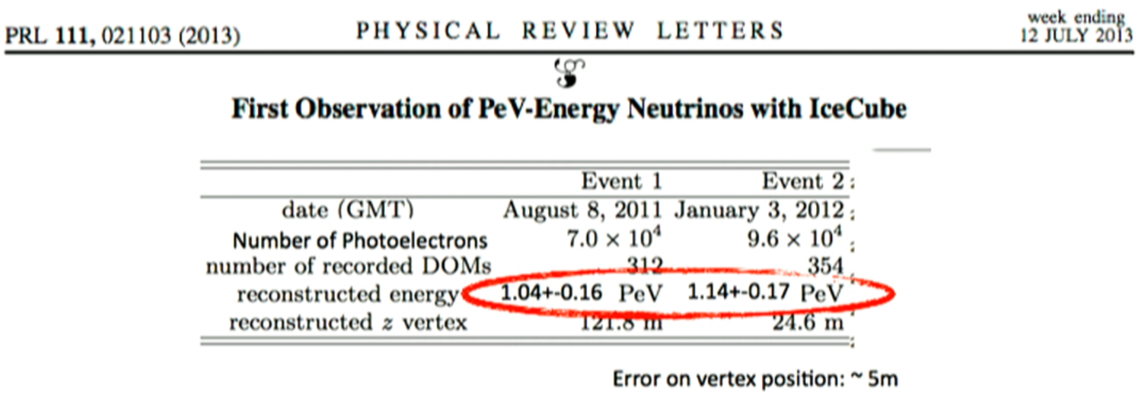
	Event 1	Event 2
date (GMT)	August 8, 2011	January 3, 2012
Number of Photoelectrons	7.0×10^4	9.6×10^4
number of recorded DOMs	312	354
reconstructed energy	1.04+-0.16 PeV	1.14+-0.17 PeV
reconstructed z vertex	121.8 m	24.6 m

Error on vertex position: ~ 5m

Given names befitting this monumental discovery:



[slide courtesy of N. Whitehorn]



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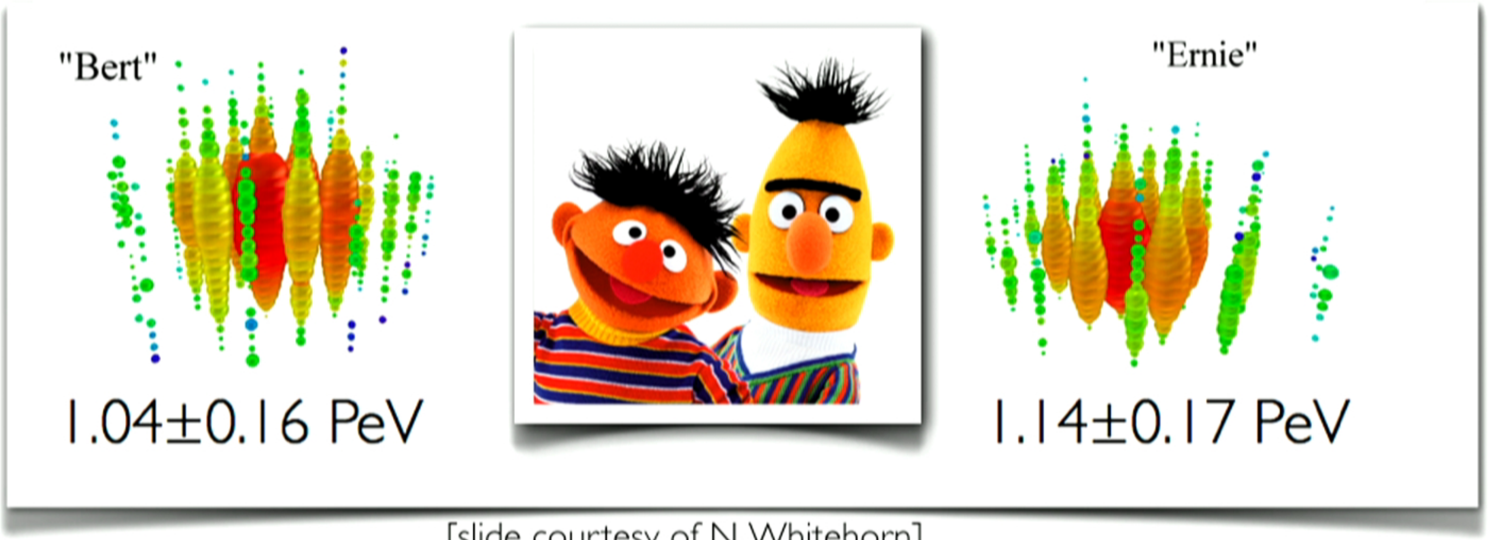
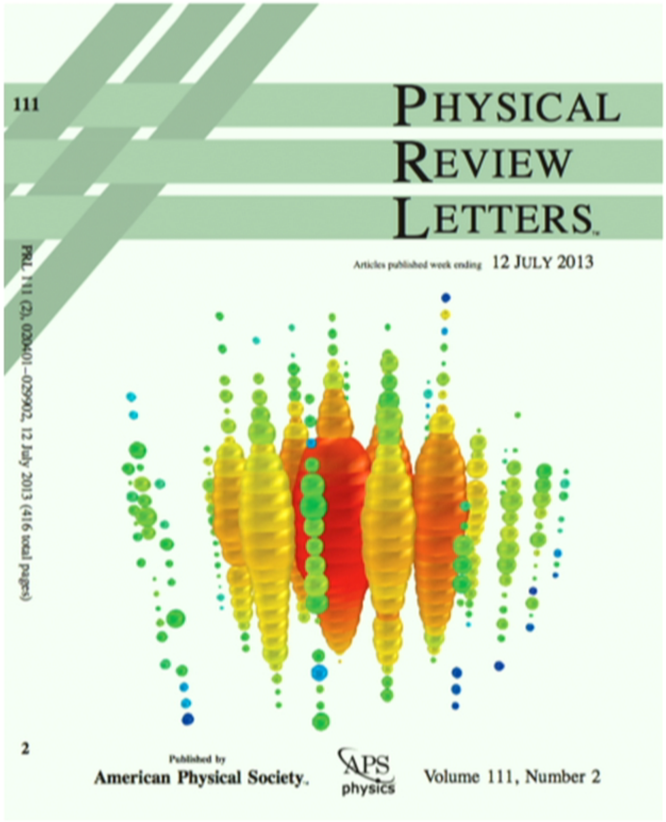


[slide courtesy of N. Whitehorn]

High-Energy Neutrino Astronomy



111

PHYSICAL REVIEW LETTERS.

Articles published week ending 12 JULY 2013

PRL 111 (2), 020401–029902, 12 July 2013 (416 total pages)

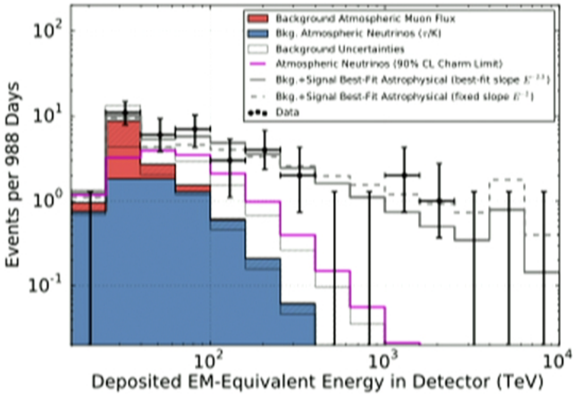
2

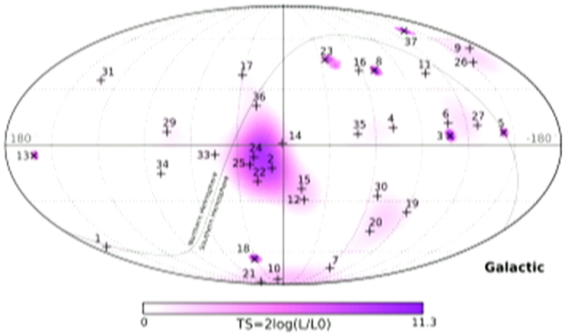
Published by
American Physical Society.

APS physics

Volume 111, Number 2

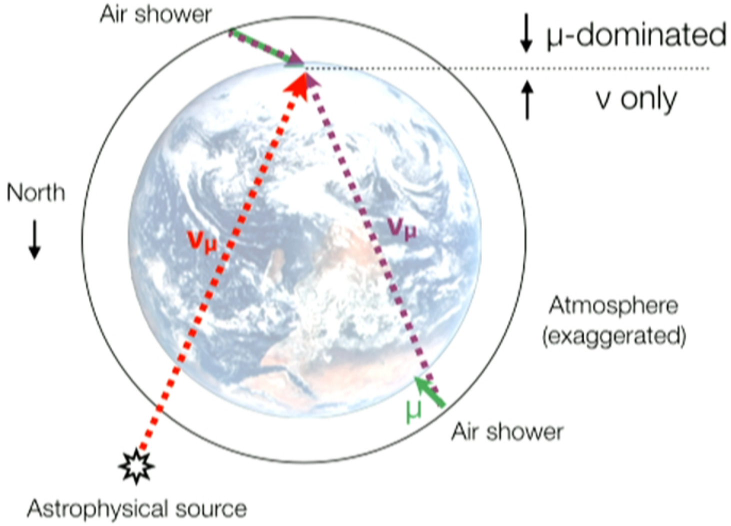
Three year data: 37 events, 5.7σ
above bkg., consistent with isotropy.





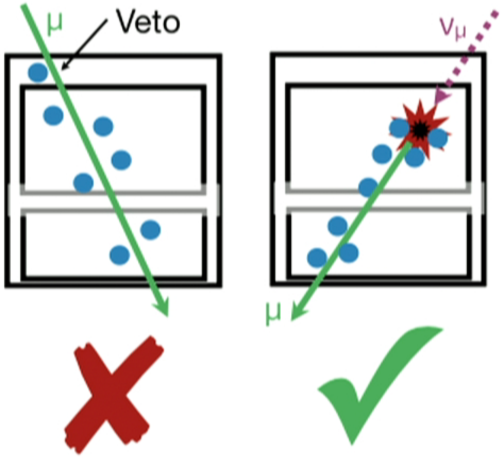
Two Search Strategies

Up-going tracks



- Earth stops penetrating muons
- Effective volume larger than detector
- Sensitive to ν_μ only
- Sensitive to half the sky
- Signal dominated above ~100 TeV

Active veto



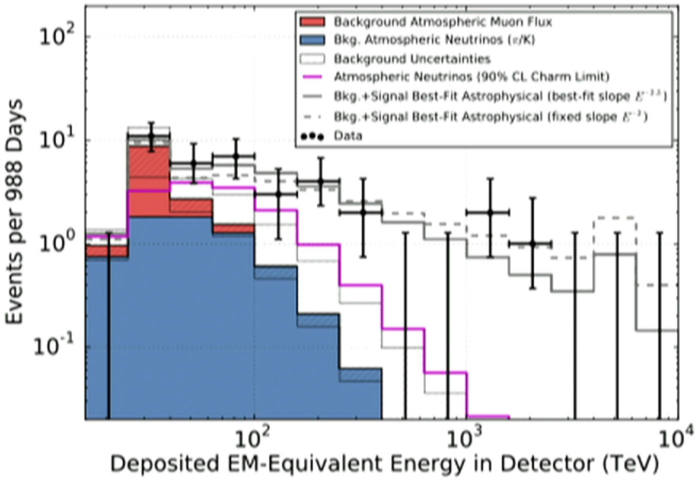
- Veto detects penetrating muons
- Effective volume smaller than detector
- Sensitive to all flavors
- Sensitive to the entire sky
- Signal dominated above ~10-100 TeV

[Slide courtesy of Jakob van Santen]

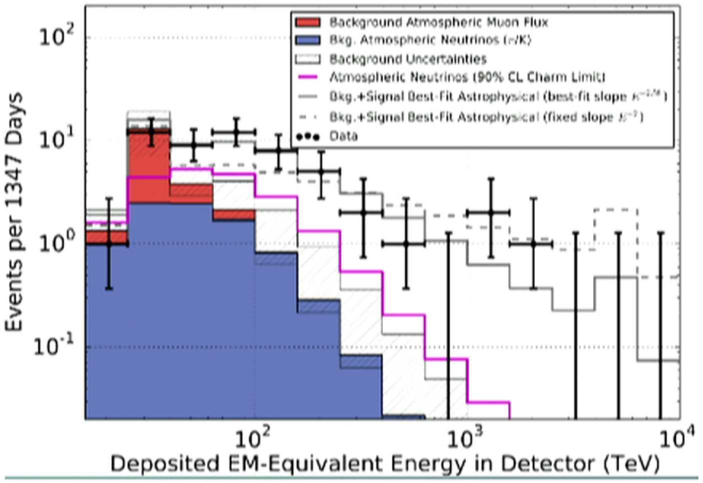
Latest updates

TeVPA 2015, Kashiwa, Japan

3 year HESE



4 year HESE



- Still no clustering, consistent with isotropy.

Power law fits: $\Phi_\nu = \phi_0 E_\nu^{-\gamma}$

- Upgoing-muon analysis (mu only): $\gamma = 2.08 \pm 0.13$
- HESE (all flavors): $\gamma = 2.58 \pm 0.25$

Latest updates

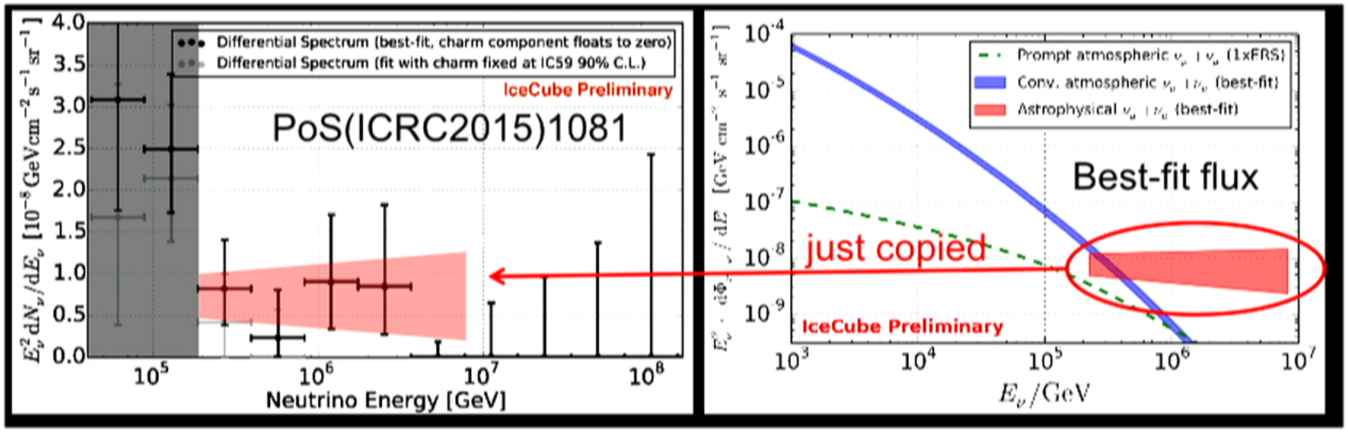
TeVPA 2015, Kashiwa, Japan

- Upgoing-muon analysis (mu only): $\gamma = 2.08 \pm 0.13$
  - HESE (all flavors): $\gamma = 2.58 \pm 0.25$

???

Tension apparently driven by low-energy HESE bins.

HESE muons



PoS(ICRC2015)1081

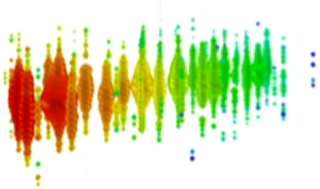
just copied

Best-fit flux

Flavor probes

ν_μ CC

(data)

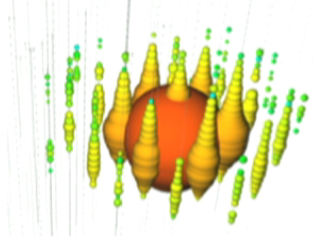


Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

$\nu_{e,\tau}$ CC+ ν_x NC

(data)

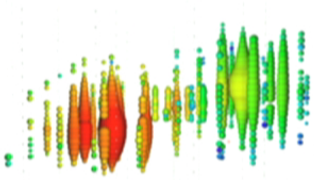


Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10 degree angular resolution (above 100 TeV)

ν_τ CC

(simulation)



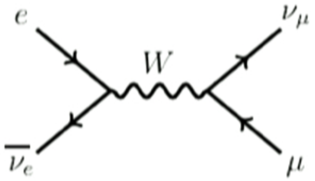
"Double-bang"

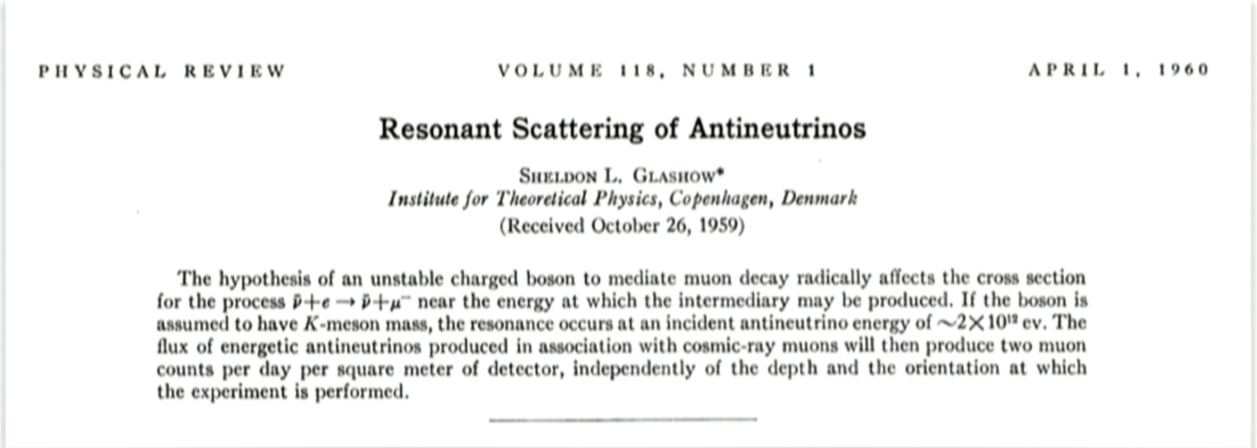
(none observed yet: τ decay length is 50 m/PeV)

Early  Late

[slide credit: Jakob van Santen]

A unique flavor/*antineutrino* probe



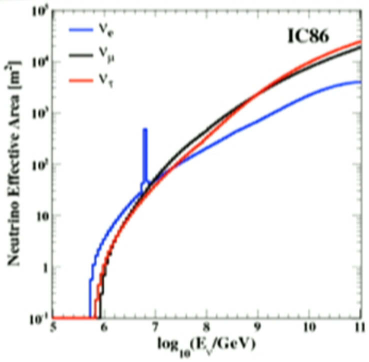


PHYSICAL REVIEW VOLUME 118, NUMBER 1 APRIL 1, 1960

Resonant Scattering of Antineutrinos

Sheldon L. Glashow*
Institute for Theoretical Physics, Copenhagen, Denmark
(Received October 26, 1959)

The hypothesis of an unstable charged boson to mediate muon decay radically affects the cross section for the process $\bar{\nu}+e \rightarrow \bar{\nu}+\mu^-$ near the energy at which the intermediary may be produced. If the boson is assumed to have K-meson mass, the resonance occurs at an incident antineutrino energy of $\sim 2\times 10^{12}$ ev. The flux of energetic antineutrinos produced in association with cosmic-ray muons will then produce two muon counts per day per square meter of detector, independently of the depth and the orientation at which the experiment is performed.



Only s-channel detection mode = huge increase in effective area.

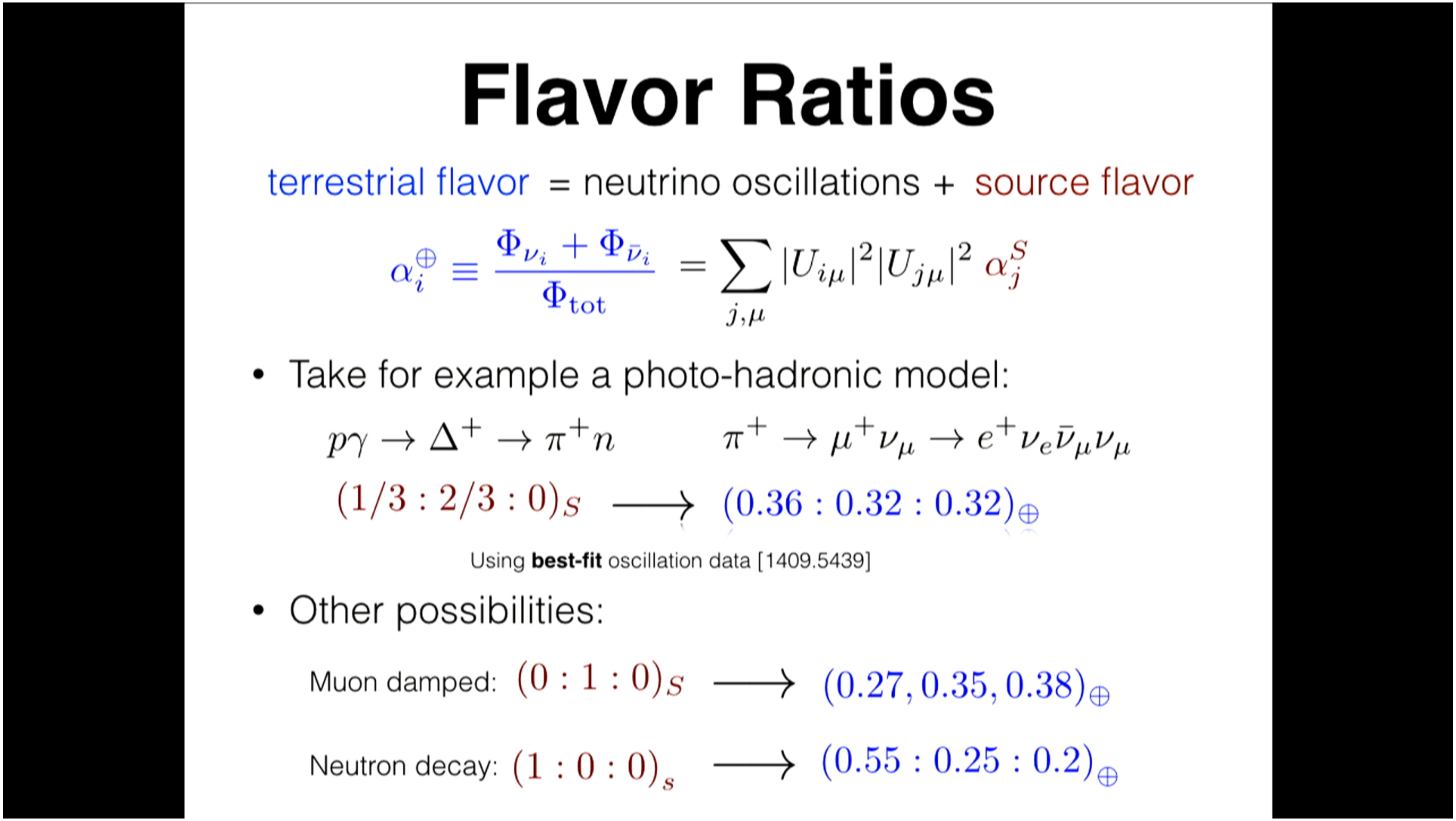
Predicted before EW theory completed!

Flavor in High-Energy Neutrinos

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4\sum_{k>j} \mathrm{Re}(J_{\alpha\beta jk}) \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right) + \sum_{k>j} \mathrm{Im}(J_{\alpha\beta jk}) \sin\left(\frac{\Delta m^2_{kj} L}{4E}\right)$$

- Taking $E \sim \mathrm{PeV}$ & $\Delta m^2 \sim 10^{-4}\ \mathrm{eV}^2$ ⇒ $L_{\mathrm{osc}} \sim 10^{-10}\ \mathrm{Mpc}$

- Thus oscillations are fast, only the $\sin^2$ term survives averaging



Flavor Ratios

terrestrial flavor = neutrino oscillations + source flavor

$$\alpha_i^{\oplus} \equiv \frac{\Phi_{\nu_i} + \Phi_{\bar{\nu}_i}}{\Phi_{\text{tot}}} = \sum_{j,\mu} |U_{i\mu}|^2 |U_{j\mu}|^2 \, \alpha_j^S$$

- Take for example a photo-hadronic model:

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

$$(1/3 : 2/3 : 0)_S \longrightarrow (0.36 : 0.32 : 0.32)_{\oplus}$$

Using **best-fit** oscillation data [1409.5439]

- Other possibilities:

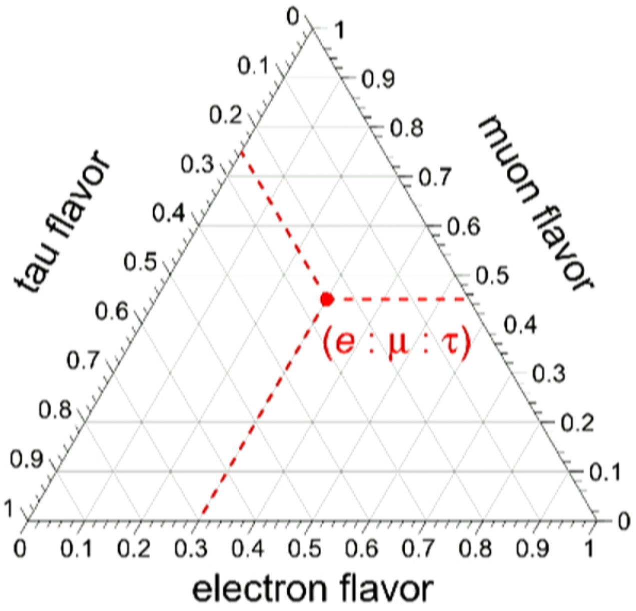
Muon damped: $(0 : 1 : 0)_S \longrightarrow (0.27, 0.35, 0.38)_{\oplus}$

Neutron decay: $(1 : 0 : 0)_s \longrightarrow (0.55 : 0.25 : 0.2)_{\oplus}$

Flavor triangles

Sum of projections on each flavor axis sums to unity.

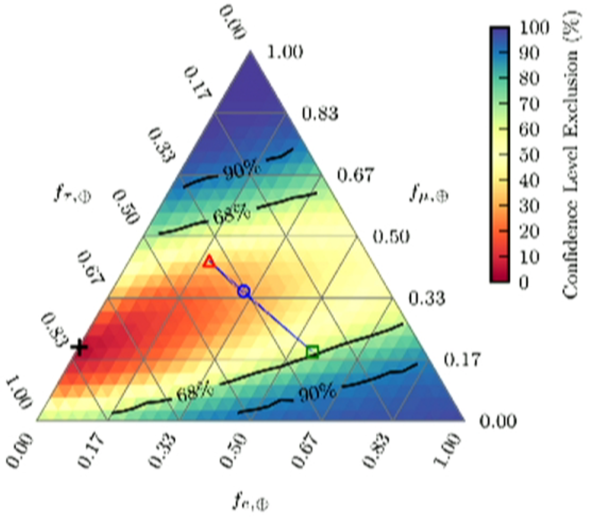
To read: follow the tilt of the ticks.



Current Status of **Flavor**

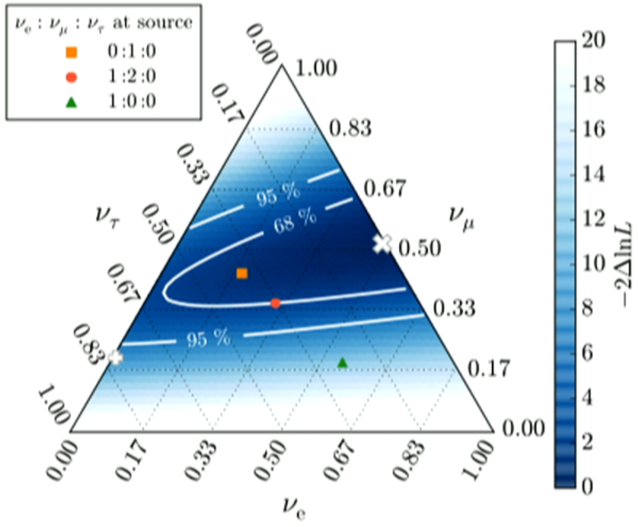
3yr, only starting events.

Count tracks/showers.



Best-fit flavor: (0: 0.2: 0.8)
[1502.03376]

3-4yr, multi-search combined likelihood.

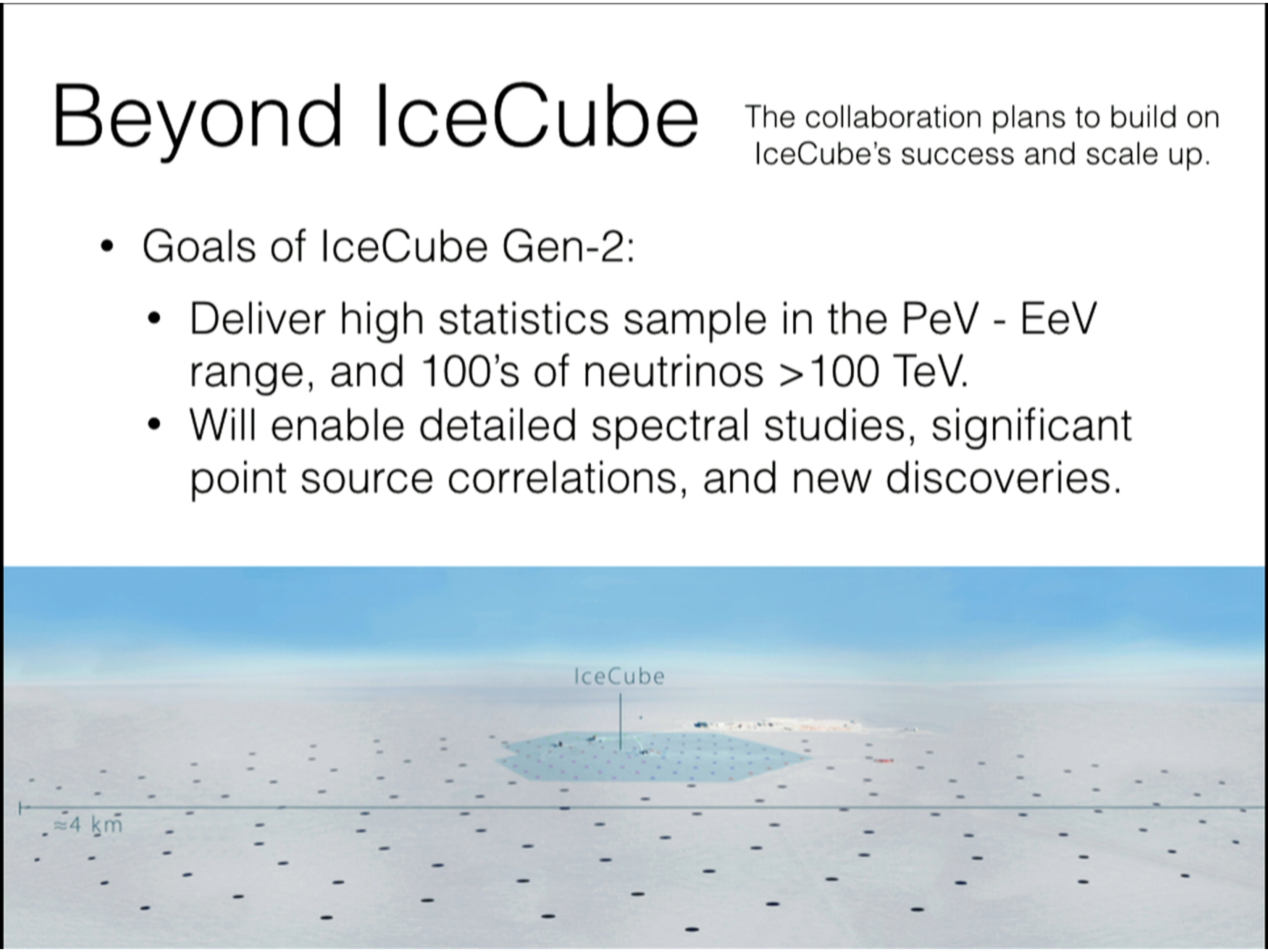


Best-fit flavor: (0: 0.5: 0.5)
[1507.03991]

How can this improve?

Build an even bigger detector/wait

Hopefully start seeing higher E events



Beyond IceCube

The collaboration plans to build on IceCube's success and scale up.

- Goals of IceCube Gen-2:
  - Deliver high statistics sample in the PeV - EeV range, and 100's of neutrinos >100 TeV.
  - Will enable detailed spectral studies, significant point source correlations, and new discoveries.

Our implementation

Two approaches to event rates.

- Optimistic “theorist’s approach”:

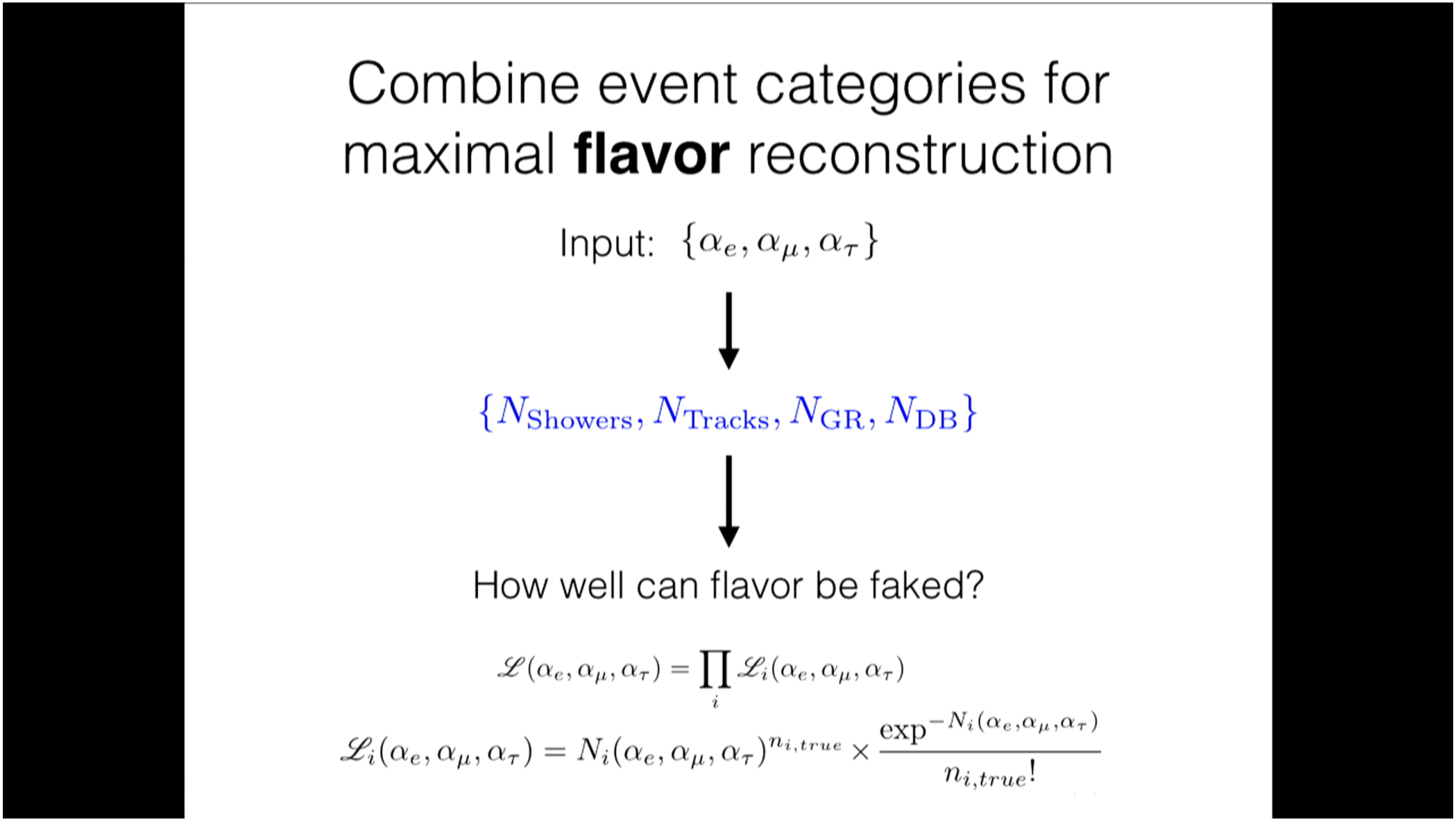
$$\frac{dN}{dE_{\rm casc}} = \frac{dN_e^{\rm CC}}{dE_{\rm casc}} + \frac{dN_\tau^{\rm CC}}{dE_{\rm casc}} + 3 \cdot \frac{dN_x^{\rm NC}}{dE_{\rm casc}}$$

$$\begin{aligned} \frac{dN_\alpha^j}{dE_{\rm casc}} \simeq 2\pi\rho N_{\rm A} VT \int_{-1}^{+1} d\left(\cos\theta_z\right) \\ \left(\frac{d\Phi_\alpha}{dE_\nu}\left(E_\nu\right)\sigma_\alpha^j\left(E_\nu\right) e^{-\tau_\alpha^j\left(E_\nu,\cos\theta_z\right)} + \right. \\ \left. \frac{d\Phi_{\bar\alpha}}{dE_\nu}\left(E_\nu\right)\sigma_{\bar\alpha}^j\left(E_\nu\right) e^{-\tau_{\bar\alpha}^j\left(E_\nu,\cos\theta_z\right)}\right) , \end{aligned}$$

- More conservatively, use collaboration’s effective areas and focus on starting events:

$$\frac{dN}{dE_{casc}} = 4\pi\, A_{\rm eff}\, T \times \frac{d\Phi}{dE_\nu}(E_\nu)$$

$A_{\rm eff}$ includes cross section, Earth attenuation, and detailed search cuts.



Combine event categories for maximal **flavor** reconstruction

Input: $\{\alpha_e, \alpha_\mu, \alpha_\tau\}$

$$\downarrow$$

$$\{N_{\text{Showers}}, N_{\text{Tracks}}, N_{\text{GR}}, N_{\text{DB}}\}$$

$$\downarrow$$

How well can flavor be faked?

$$\mathscr{L}(\alpha_e, \alpha_\mu, \alpha_\tau) = \prod_i \mathscr{L}_i(\alpha_e, \alpha_\mu, \alpha_\tau)$$

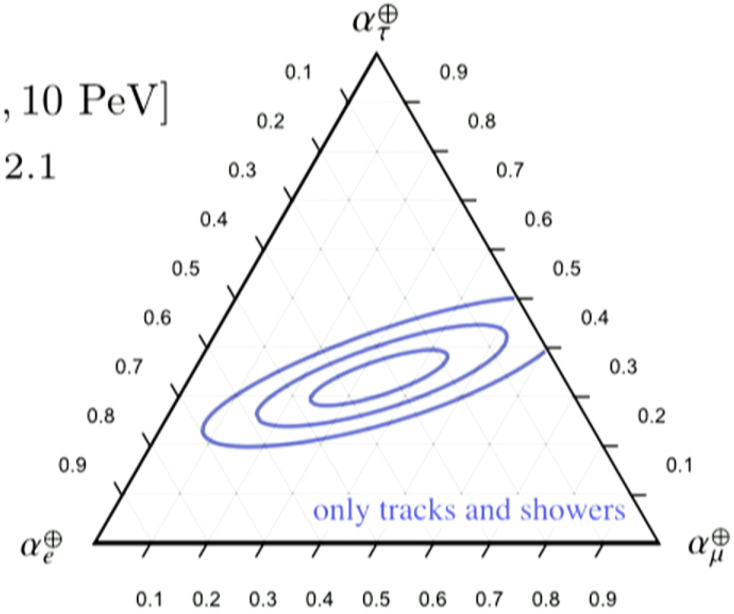
$$\mathscr{L}_i(\alpha_e, \alpha_\mu, \alpha_\tau) = N_i(\alpha_e, \alpha_\mu, \alpha_\tau)^{n_{i,true}} \times \frac{\exp^{-N_i(\alpha_e, \alpha_\mu, \alpha_\tau)}}{n_{i,true}!}$$

Future of Flavor

10 years at IC Gen-2

$$E_{\rm dep} = [100\ {\rm TeV}, 10\ {\rm PeV}]$$

$$\Phi_\nu \propto E^{-2.1}$$



IMS, Murase [1512.07228]

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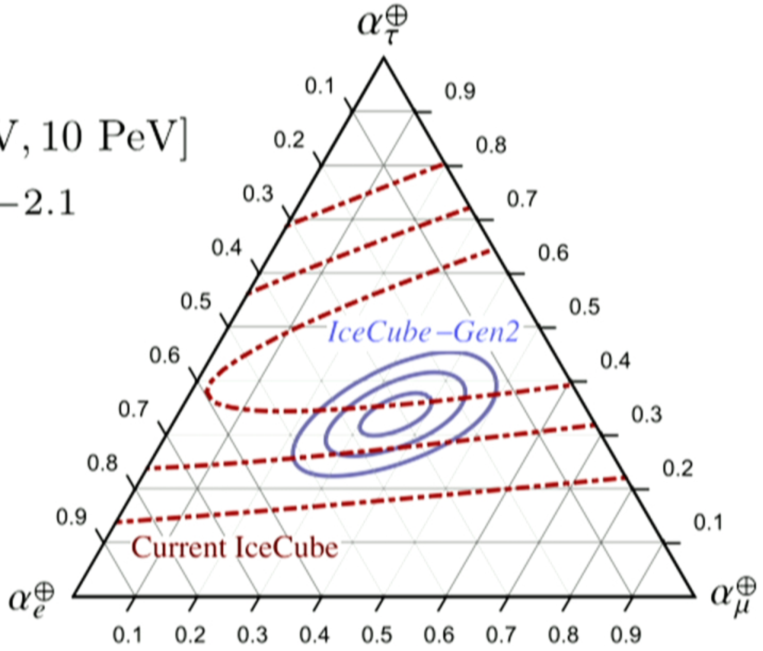

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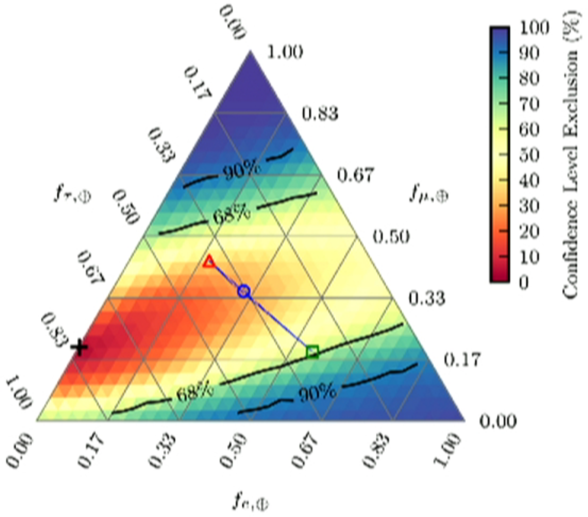

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[1502.03376]

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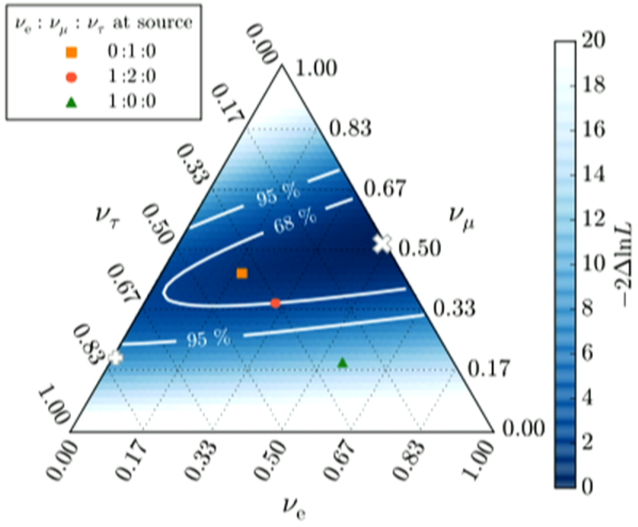

Best-fit flavor: (0: 0.5: 0.5)

[1507.03991]

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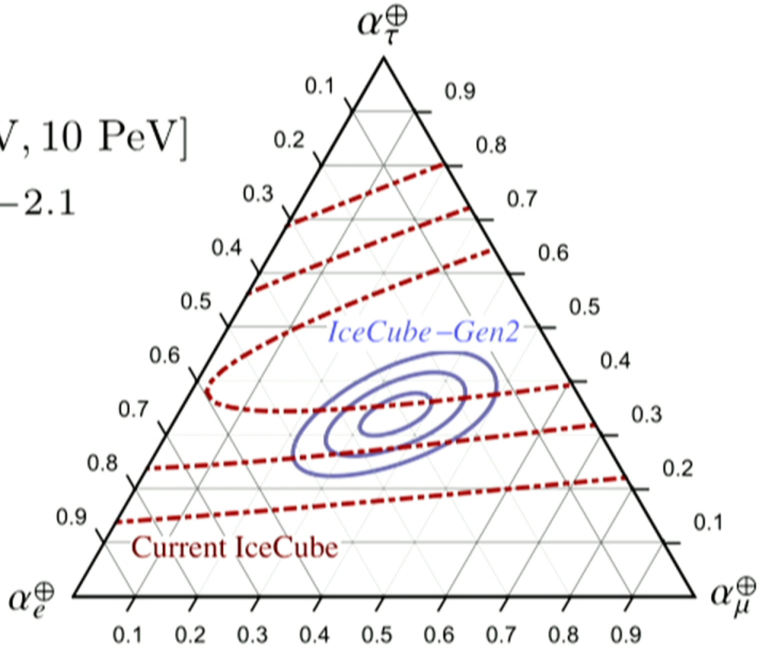


IMS, Murase [1512.07228]

Flavor probes = BSM probes

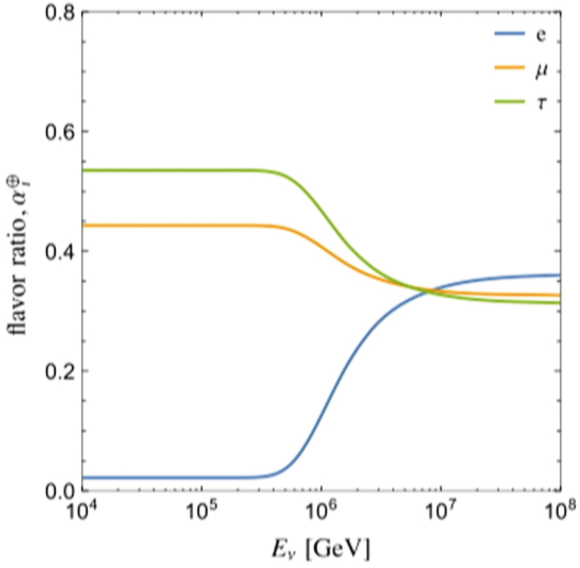
What BSM scenarios can alter these predictions?

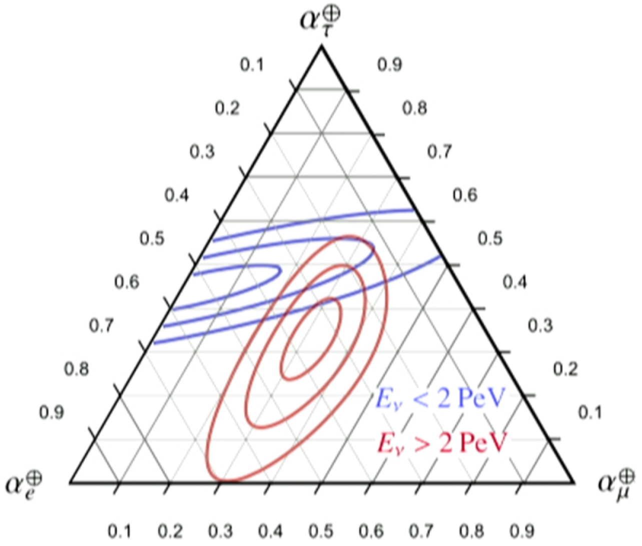
BSM neutrino physics

Ex. 1: Neutrino Decay (e.g. only ν_3 stable)

Long baselines are good for long **lifetimes**

$$\alpha_i^{\oplus}(E) = \sum_{j,k} \alpha_j^S |U_{ik}|^2 |U_{jk}|^2 \exp\left[-\kappa_k L/E\right], \qquad \kappa^{-1} \equiv \tau_\nu / m_\nu$$





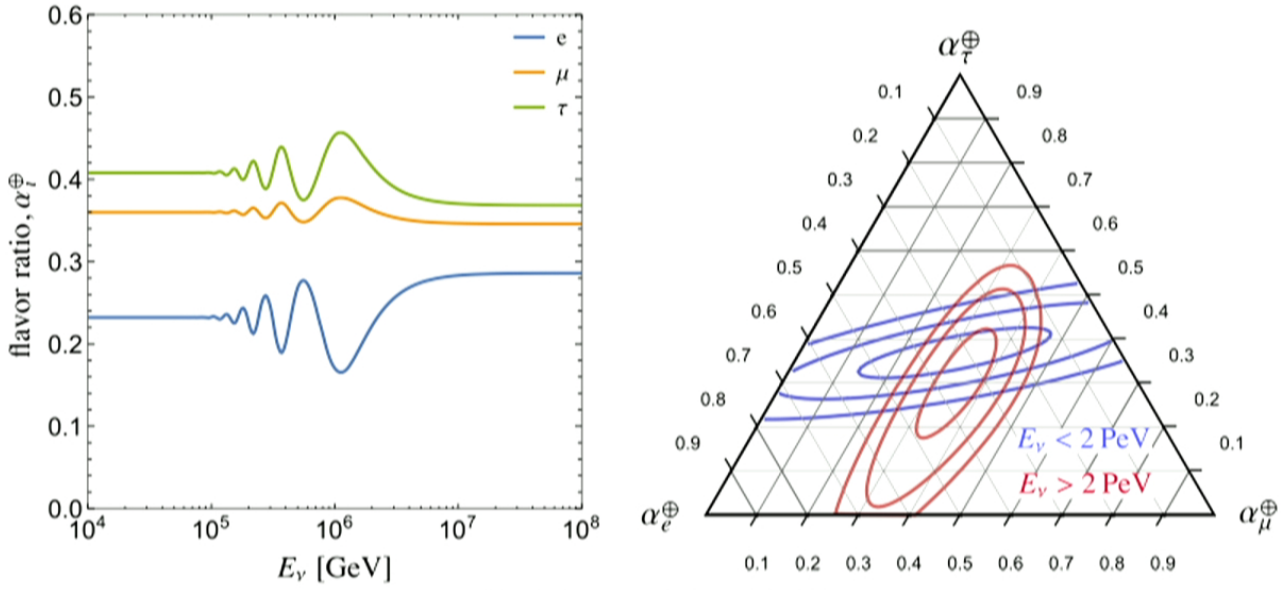
IMS, Murase [1512.07228]

BSM neutrino physics

Ex. 2: Pseudo-Dirac oscillations

Long baselines are good for long **oscillation lengths**

$$\alpha_i^{\oplus} = \sum_{j,k} \alpha_j^S |U_{ik}|^2 |U_{jk}|^2 \cos^2\left(\frac{\Delta m_k^2 L}{4E}\right). \qquad \Delta m^2 = 10^{-17}\ \mathrm{eV}^2$$



IMS, Murase [1512.07228]

BSM neutrino physics

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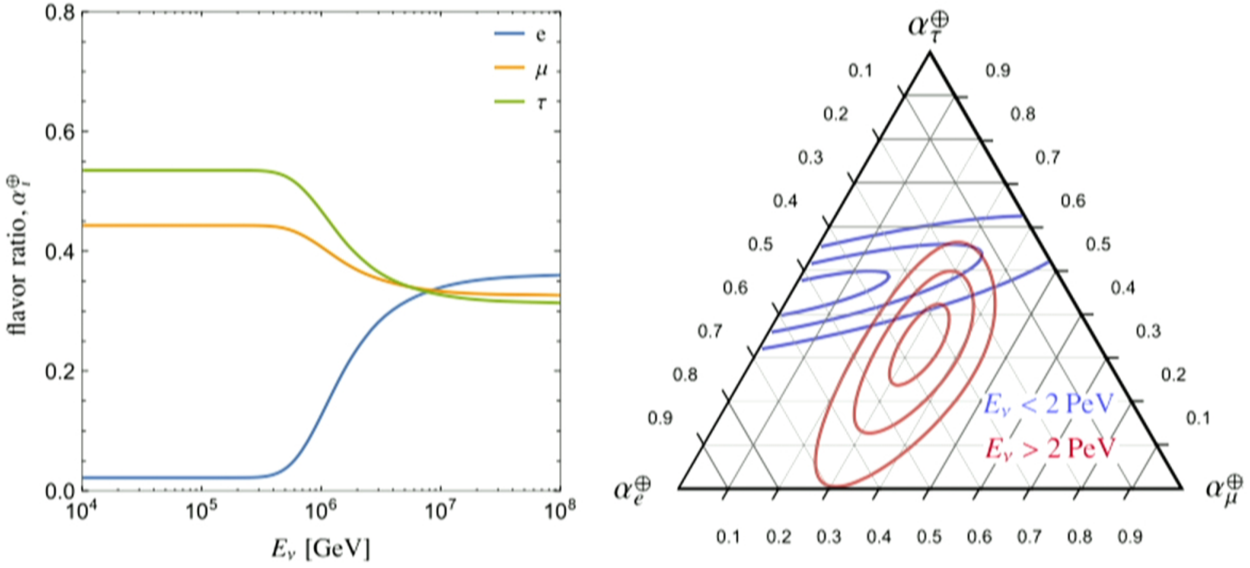


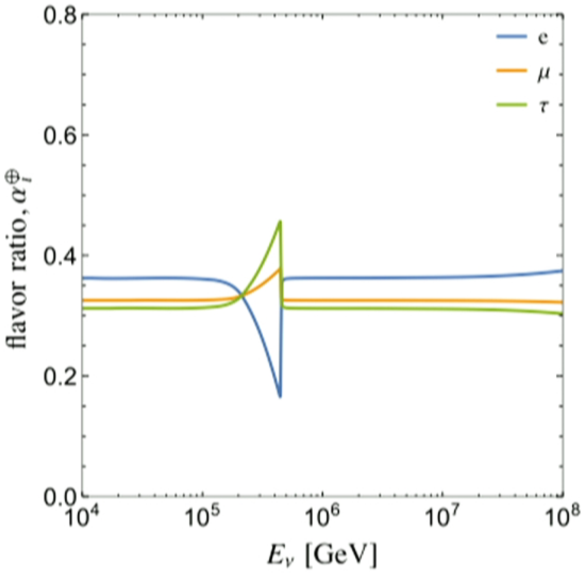
IMS, Murase [1512.07228]

BSM neutrino physics

Ex. 3: neutrino self-interactions

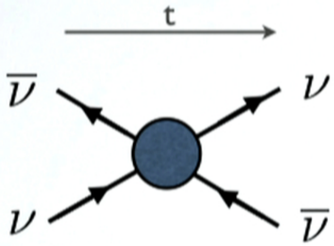
Long baselines are good for long **mean free path lengths.**

flavor impact typically minimal



IMS, Murase [1512.07228]

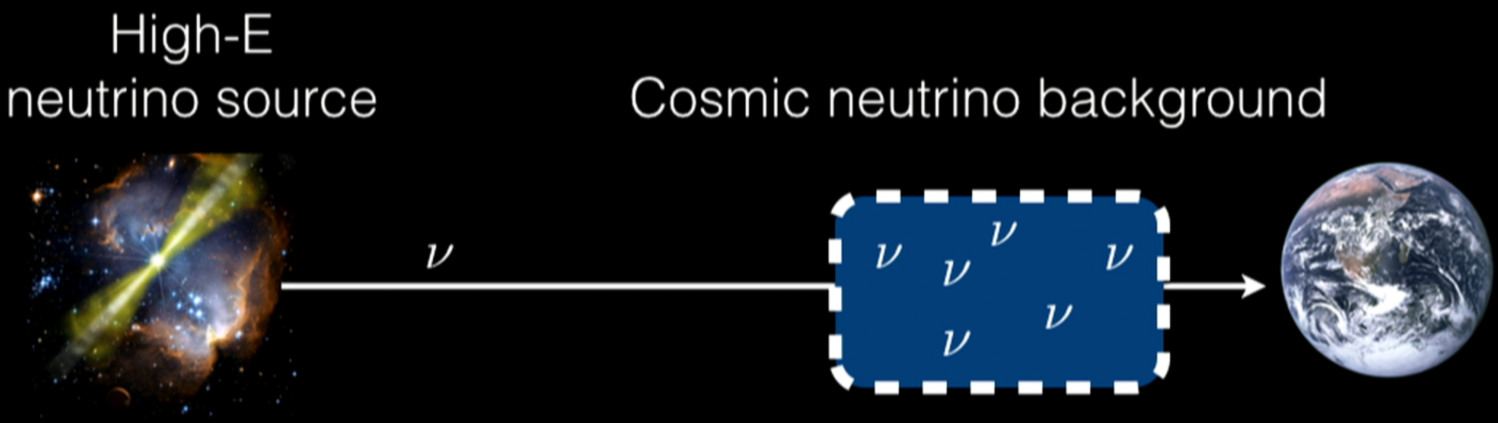
PART II:
ICECUBE-EARLY UNIVERSE COMPLEMENTARITY



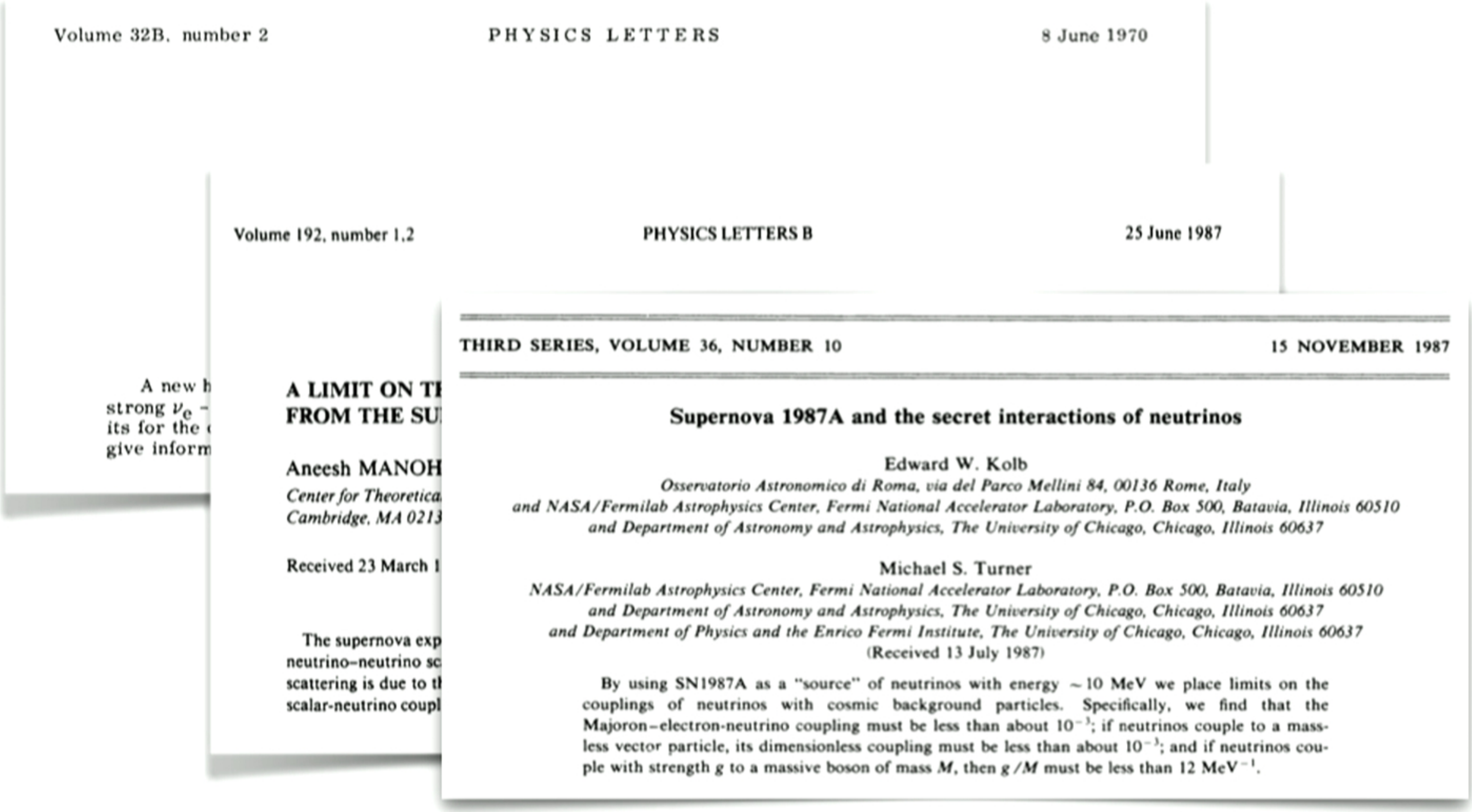
Based on:

Cherry, Friedland, *IMS* [1411.1071]
Cherry, Friedland, *IMS* [1511.XXXX]

Test Neutrino Interactions: build a nu-nu collider



- IceCube's neutrino source is the "beam."
- CnuB is the "fixed target."
- With significant scattering, can **deplete neutrino flux** and **alter flavor content**.



Volume 32B, number 2 PHYSICS LETTERS 8 June 1970

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Volume 192, number 1,2 PHYSICS LETTERS B 25 June 1987

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Center for Theoretica
Cambridge, MA 0213

Received 23 March 1

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THIRD SERIES, VOLUME 36, NUMBER 10 15 NOVEMBER 1987

Supernova 1987A and the secret interactions of neutrinos

Edward W. Kolb
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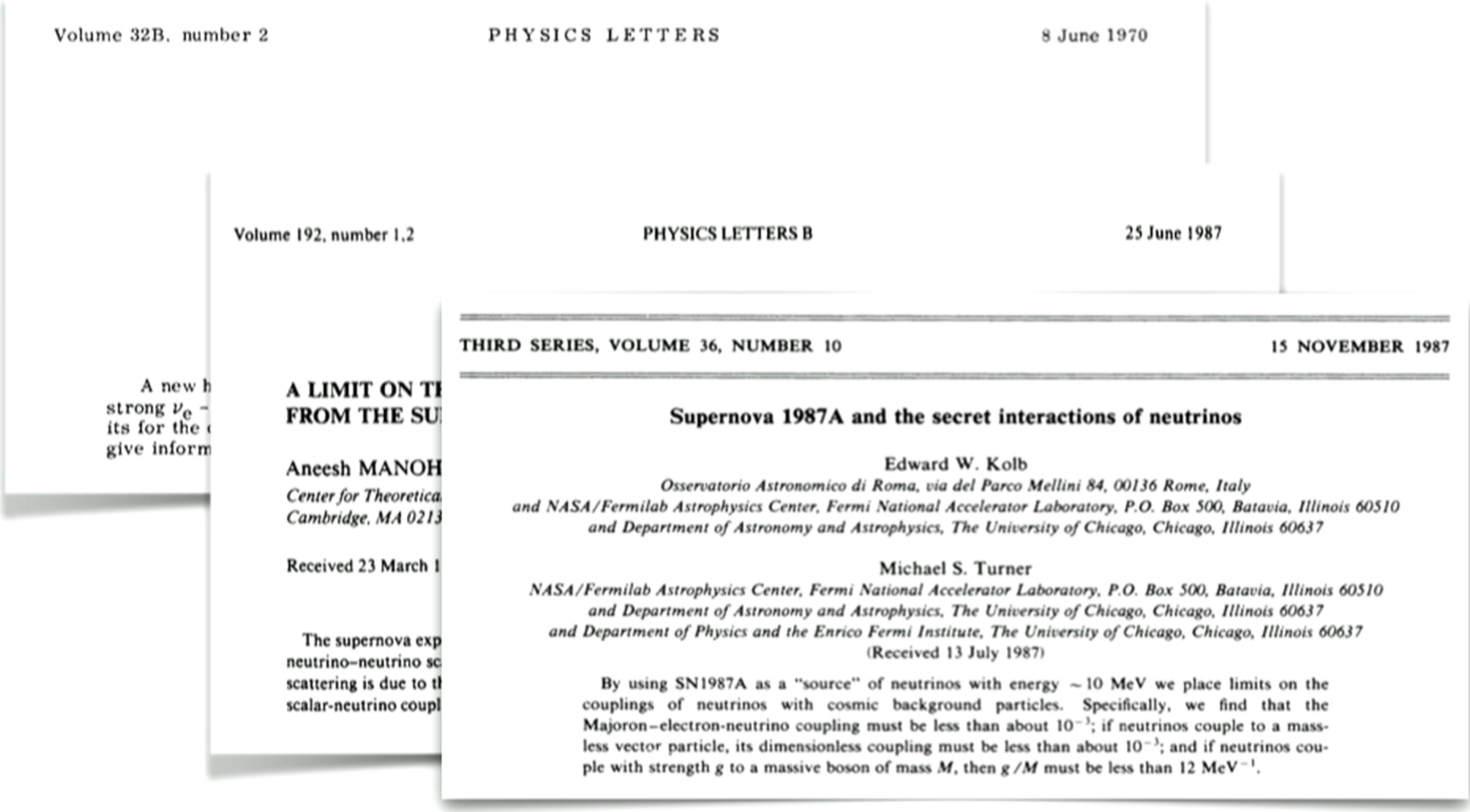
(Received 13 July 1987)

By using SN1987A as a "source" of neutrinos with energy ~ 10 MeV we place limits on the couplings of neutrinos with cosmic background particles. Specifically, we find that the Majoron–electron-neutrino coupling must be less than about 10^{-3}; if neutrinos couple to a massless vector particle, its dimensionless coupling must be less than about 10^{-3}; and if neutrinos couple with strength g to a massive boson of mass M, then g/M must be less than 12 MeV^{-1}.



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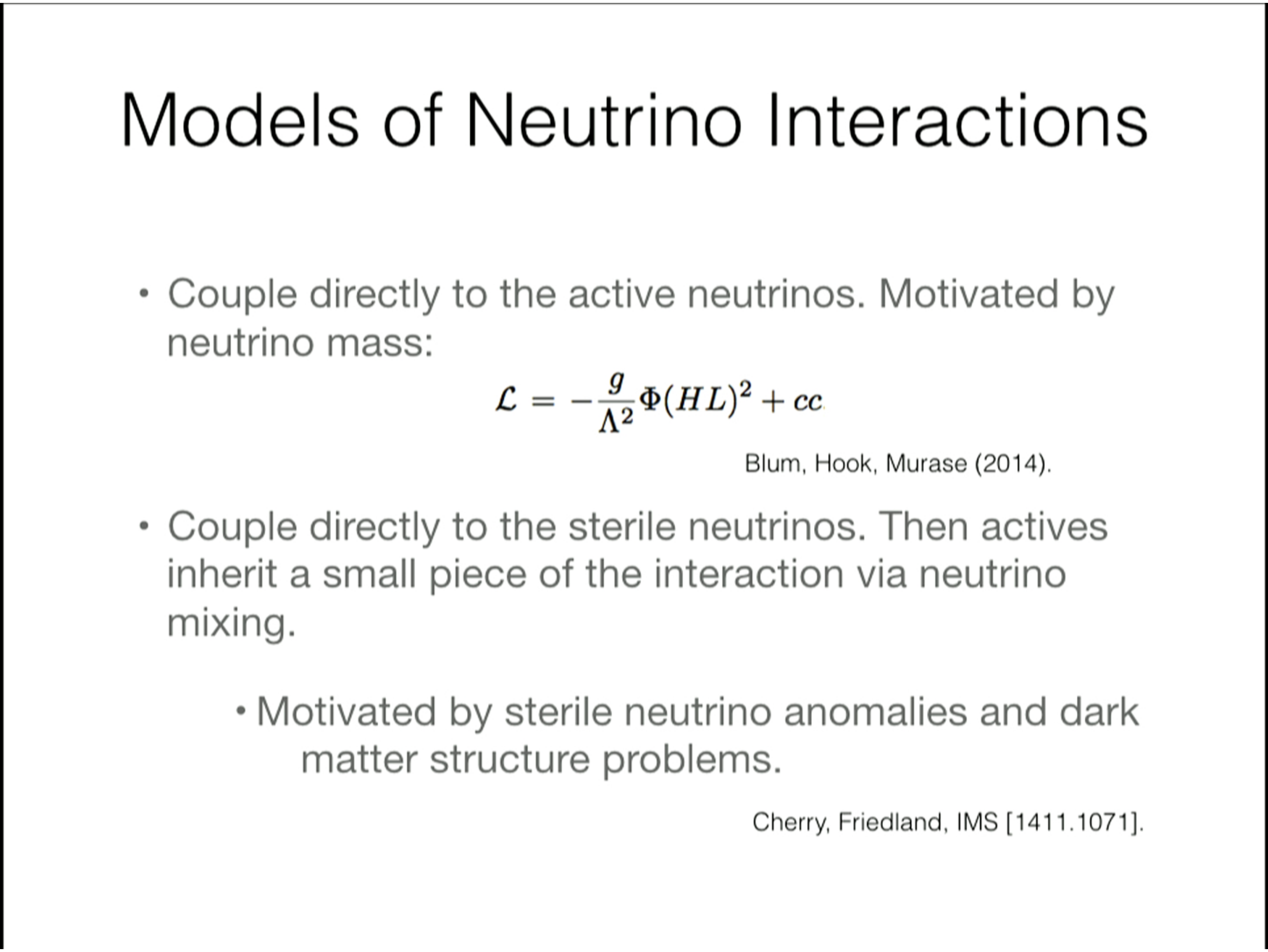
- **Using IceCube to probe nu-nu interactions**: Beacom, Ng (2014), Ioka, Murase (2014), Ibe, Kaneta (2014), Blum, Hook, Murase (2014), Araki et al. (2014), Cherry, Friedland, IMS (2014), Kamada, Yu (2014), DiFranzo, Hooper (2015), …



Models of Neutrino Interactions

- Couple directly to the active neutrinos. Motivated by neutrino mass:

$$\mathcal{L} = -\frac{g}{\Lambda^2}\Phi(HL)^2 + cc$$

Blum, Hook, Murase (2014).

- Couple directly to the sterile neutrinos. Then actives inherit a small piece of the interaction via neutrino mixing.
    - Motivated by sterile neutrino anomalies and dark matter structure problems.

Cherry, Friedland, IMS [1411.1071].

Sterile neutrinos vs. Cosmology

- Long-standing hints of a light sterile,

$$\Delta m^2 \sim 1 \text{ eV}^2$$

↓

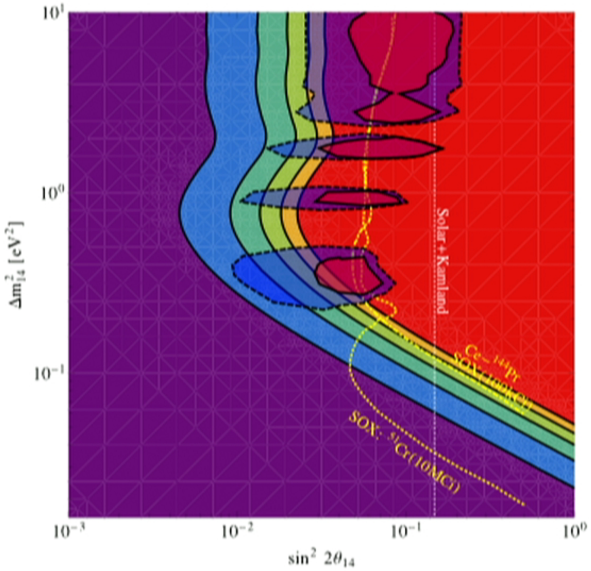
Stable & count as relativistic energy density.

↓

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

One unit of $N_{\rm eff}$ is contribution from a single thermalized neutrino.

χ^2 Significance, 100Kg, 3yr, 5m, Unbinned, E_R>10 eV



CMB: $N_{\rm eff} = 3.15 \pm 0.23$ *Planck* TT+lowP+BAO [1502.01589]

Sterile Neutrinos in the early universe

Oscillations + Collisions

- SM active neutrinos decouple at ~ 2 MeV from rest of plasma.
- If the sterile neutrino is in equilibrium with the bath before then, and they fully equilibrate, then we have $N_{\text{eff}} = 4$.
- From oscillations

$$P(\nu_a \to \nu_s) = \sin^2 2\theta_{as} \sin^2(\Delta m^2/4Et) \to (1/2) \sin^2 2\theta_{as}$$

- Collisions are flavor-sensitive, and project onto |e> |s> flavor basis state, allowing oscillations to restart. Rate of this flavor change is:

$$G_F^2 T^2 \times T^3 \times \frac{1}{2} \sin^2 2\theta_{as}$$

- Equilibration happens when this rate is of order the Hubble rate

$$G_F^2 T^2 T^3 \sin^2 2\theta_{as} \sim T^2/M_{pl} \to T_{eq}^{SM} \sim (G_F^2 M_{pl} \sin^2 2\theta_{as})^{-1/3} \sim 10 \text{ MeV}$$

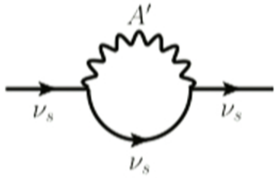
Doesn't look good for truly sterile neutrinos.

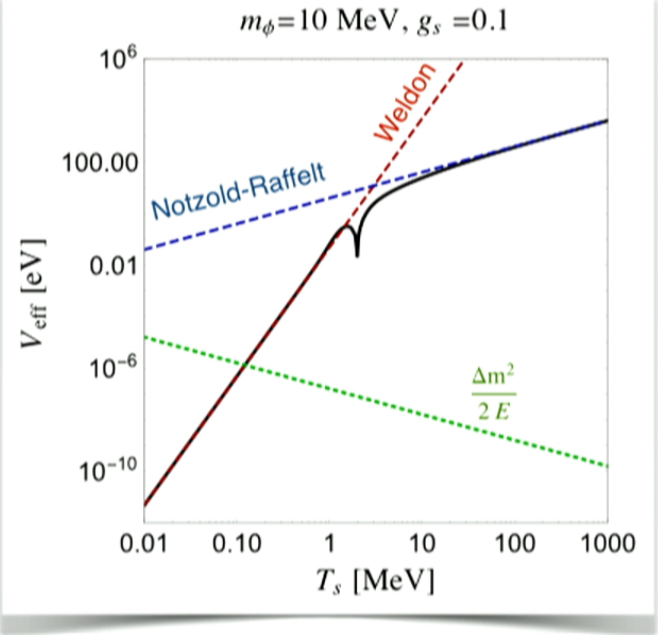
An interacting neutrino loophole

- In medium mixing angle modified as: $\sin^2 2\theta_{\mathrm{M}} = \frac{\sin 2\theta_0}{\left(\cos 2\theta + \frac{2E_s V_{\mathrm{eff}}}{\Delta m^2}\right)^2 + (\sin 2\theta)^2}$
  - Suppress the mixing angle with a new term in the MSW potential.

B. Dasgupta, J. Kopp PRL (2014)

S. Hannestad, R. S. Hansen, and T. Tram, PRL (2014);





- Strong suppression when

$$V_{\mathrm{eff}} \gg \frac{\Delta m^2}{2E}$$

- Basic estimates done >25 years ago:

$$V_{\mathrm{eff}} \simeq \begin{cases} -\frac{7\pi^2 g_s^2 E_s T_s^4}{45 m_\phi^4}, & \text{if } E_s, T_s \ll m_\phi \\ \frac{g_s^2 T_s^2}{8E_s}, & \text{if } E_s, T_s \gg m_\phi. \end{cases}$$

Notzold
Raffelt (1988)

Weldon
(1982)

Early Universe Oscillations/Scattering

- The new interaction can **recouple** the two populations: $\nu_a \nu_s \to 2\nu_s$
- Dangerous if this happens before active decoupling (~few MeV).
  - *Naively*, the rate of flavor change is

$$\Gamma \sim \theta(T)^2 \times \sigma_s \times n_s$$

- Recall $\sin^2 2\theta_m = \frac{\sin^2 2\theta_0}{\left(\cos 2\theta_0 + \frac{2E}{\Delta m^2} V_{\text{eff}}\right)^2 + \sin^2 2\theta_0}$ $\sim \sin^2(2\theta_0) \times \left(\frac{\Delta m^2}{2EV_{eff}}\right)^2$ at high T

- Roughly estimate recoupling via $H(T_0) \sim \Gamma(T_0)$ and assuming $E \sim V_{eff} \sim T$

$$\sin^2(2\theta_0) \times \left(\frac{\Delta m^2}{2EV_{eff}}\right)^2 \times T^{-2} \times T^3 \simeq \frac{T^2}{M_{Pl}}$$

$T_0 \sim \left[(\Delta m^2 \sin(2\theta_0))^2 M_{Pl}\right]^{1/5} \sim 0.2\ \text{MeV}$ not much room!

Early Universe Oscillations/Scattering

- The new interaction can **recouple** the two populations: $\nu_a \nu_s \to 2\nu_s$
- *Naively*, the rate of flavor change is

$$\Gamma \sim \theta(T)^2 \times \sigma_s \times n_s$$

- ***Fails to incorporate the effects of medium induced decoherence when scattering is rapid.***
- Take the extreme case: $n_s \sigma_s \gg \omega_{vac}$

flavor evolves as $\sim \sin^2(\omega_{vac} t)$ until being interrupted by a flavor measure.

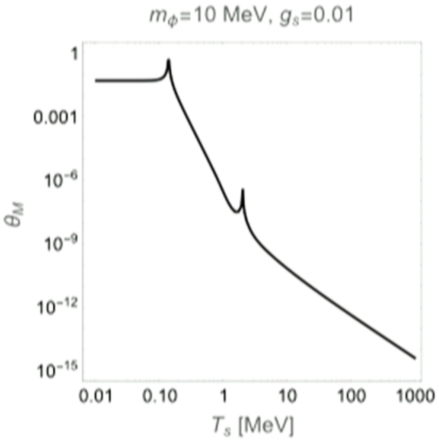
Only small amplitude of flavor builds up between scatterings $\sin^2(\omega_{vac} t) \sim \omega_{vac}^2 t_D^2$

which occur with rate $t_D^{-1} = n_s \sigma_s$

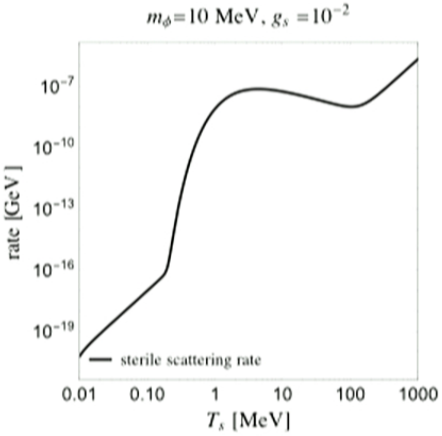
Early Universe Oscillations/Scattering

- The new interaction can **recouple** the two populations:
- Dangerous if this happens before active decoupling (~few MeV).

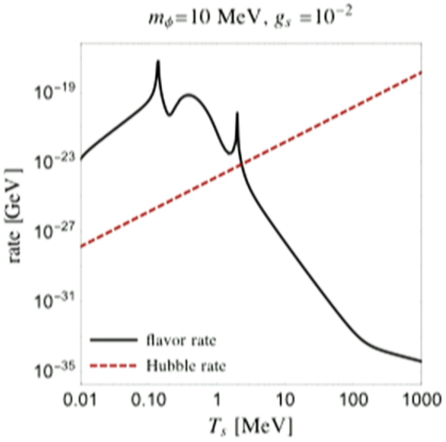
mixing angle



scattering rate



recoupling rate



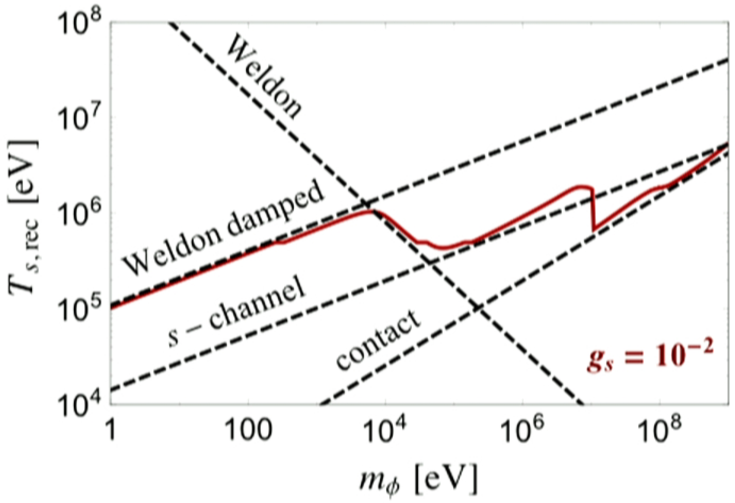
Sharp features $\Longrightarrow$ precise recoupling temperature depend sensitively on the mass/coupling.

Recoupling regimes

Cherry, Friedland,
IMS [in prep.]

$$\nu_a \nu_s \rightarrow 2\nu_s$$

$$H(T_{rec}) \sim \Gamma(T_{rec})$$

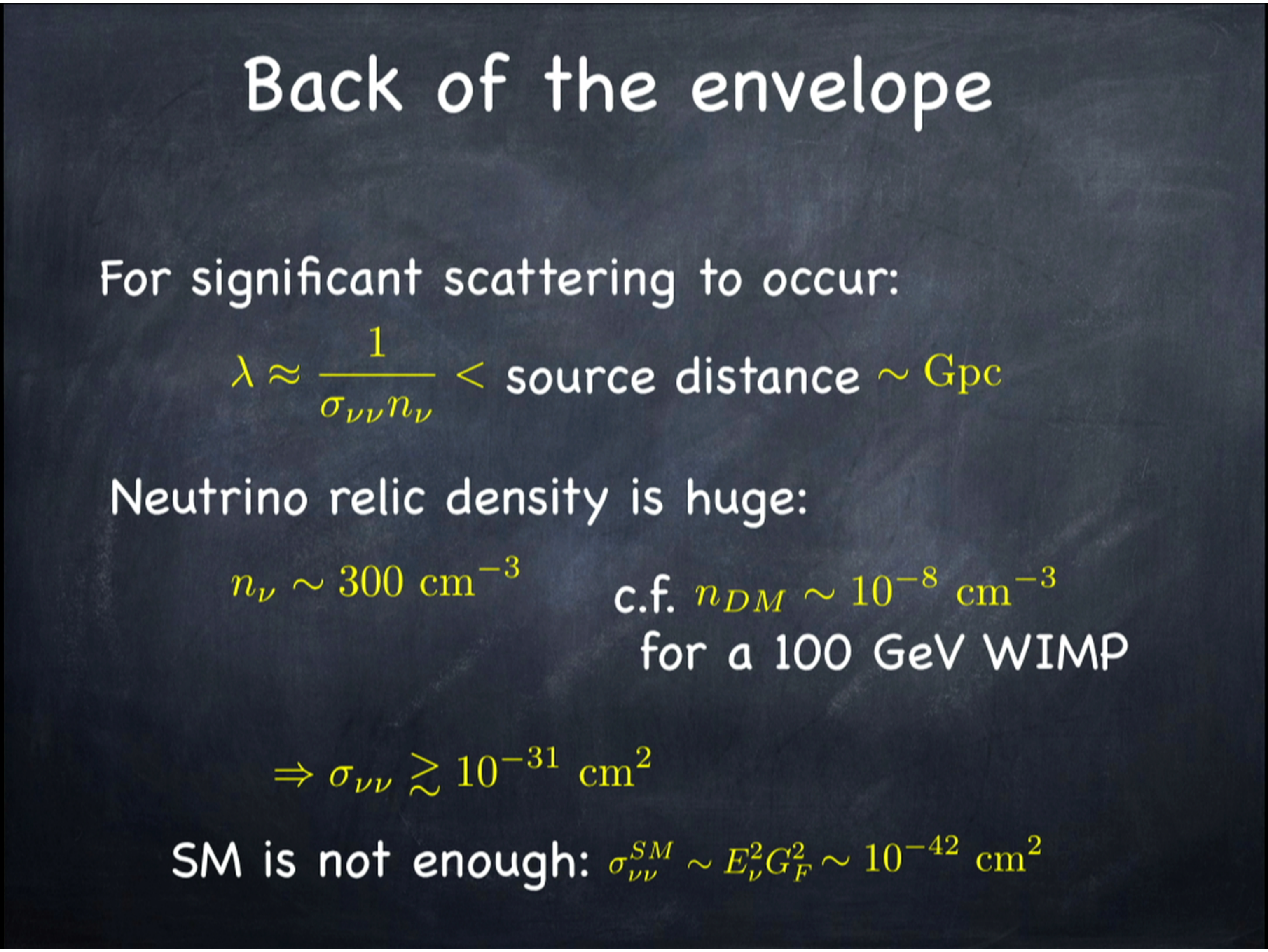


- A few windows with sub-MeV recoupling.
- Works down to coupling

$$g_s \simeq 10^{-6}$$

below which, mixing angle suppression turns off.

Back to antarctica…



Back of the envelope

For significant scattering to occur:

$$\lambda \approx \frac{1}{\sigma_{\nu\nu} n_\nu} < \text{source distance} \sim \mathrm{Gpc}$$

Neutrino relic density is huge:

$n_\nu \sim 300\ \mathrm{cm}^{-3}$

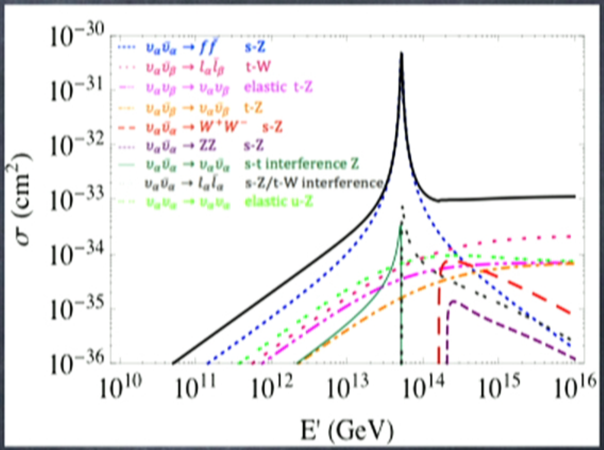
c.f. $n_{DM} \sim 10^{-8}\ \mathrm{cm}^{-3}$
for a 100 GeV WIMP

$$\Rightarrow \sigma_{\nu\nu} \gtrsim 10^{-31}\ \mathrm{cm}^2$$

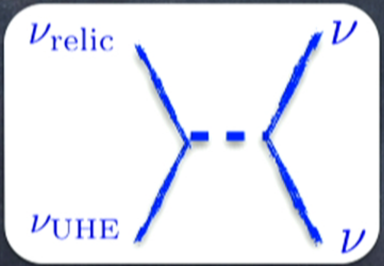
SM is not enough: $\sigma_{\nu\nu}^{SM} \sim E_\nu^2 G_F^2 \sim 10^{-42}\ \mathrm{cm}^2$

Getting large cross sections

- Look at SM first. S-channel Z-exchange work best.
- Use PeV neutrinos to produce new <u>resonance</u>



Lunardini, Sabancilar, Lili (2013)



CM energy available: $2m_\nu E_\nu = m_\phi^2$

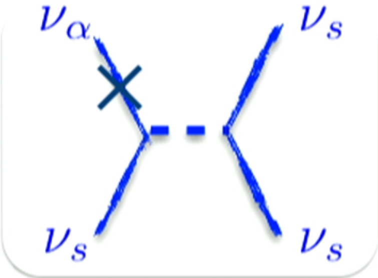
As an example, take $m_\nu \approx \sqrt{\Delta m_\odot^2} \approx 50 \text{ meV}$

@ $E_\nu \sim 10^6 \text{ GeV} \Longrightarrow m_\phi \sim 10 \text{ MeV}$

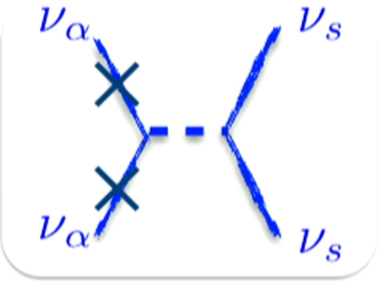
Effect on IceCube Data

ν_α source flux scatters is sterilized by scattering ~ essentially disappears.

$$2m_\nu E_\nu = m_\phi^2$$



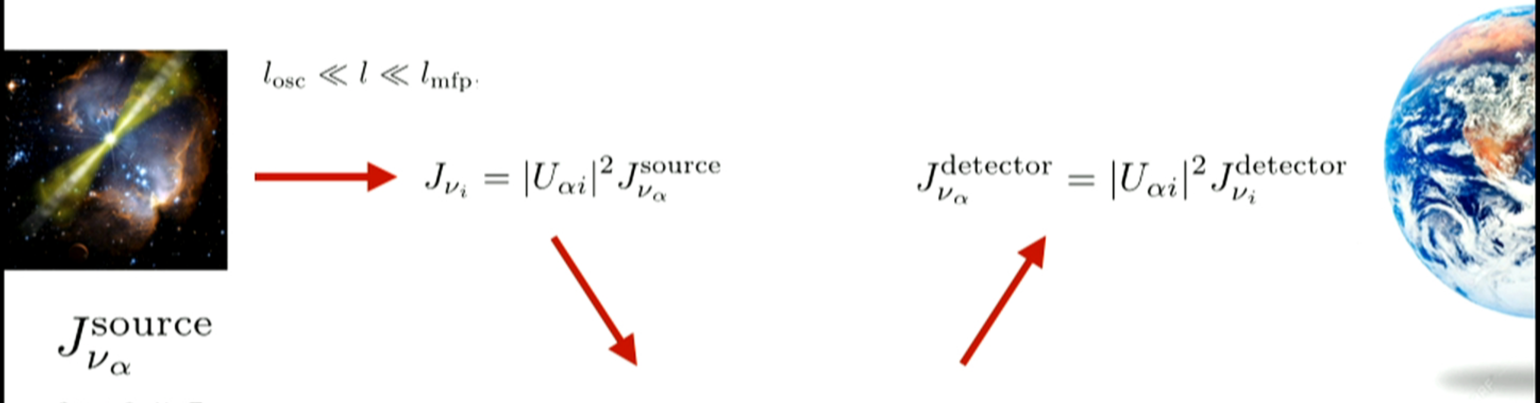
Heavy CνB particle
= Lower resonance energy



Light CνB particle
= Higher resonance energy

Scattering impact

Oscillations are fast compared to scattering.



$l_{\rm osc} \ll l \ll l_{\rm mfp}.$

$J_{\nu_i} = |U_{\alpha i}|^2 J^{\rm source}_{\nu_\alpha}$

$J^{\rm detector}_{\nu_\alpha} = |U_{\alpha i}|^2 J^{\rm detector}_{\nu_i}$

$J^{\rm source}_{\nu_\alpha}$

$\alpha = e, \mu, \tau.$

Scattering & redshift evolution

$$\boxed{-(1+z)H(z)\frac{d\Phi_i}{dz} = J_i(E_0, z) - \Phi_i \sum_j \langle n_{\nu_j} \sigma_{ij}(E_0, z)\rangle}$$

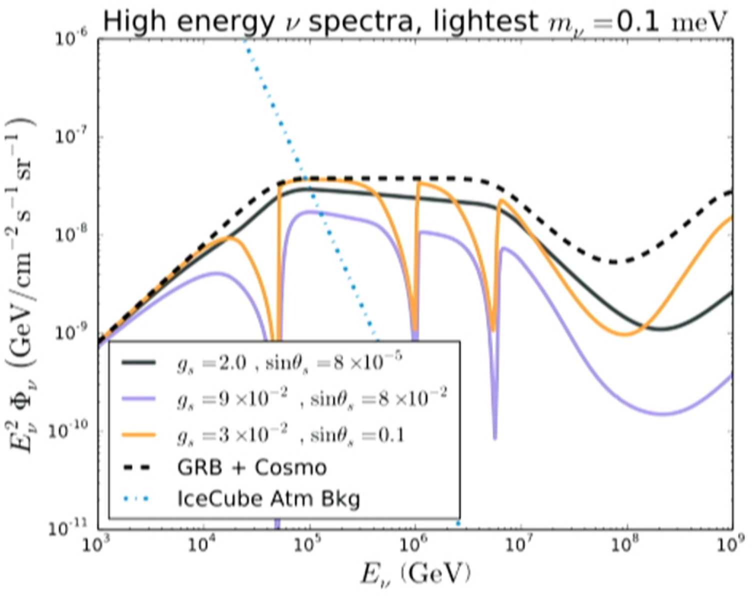
Example spectrum

4 absorption features, but sterile feature behind bkg.

increase m_ν

absorption moves to low-E

Cherry,
Friedland,
IMS [in prep.]



See also:Ioka, Murase (2014),
Ng, Beacom (2014), Blum,
Hook, Murase (2014).

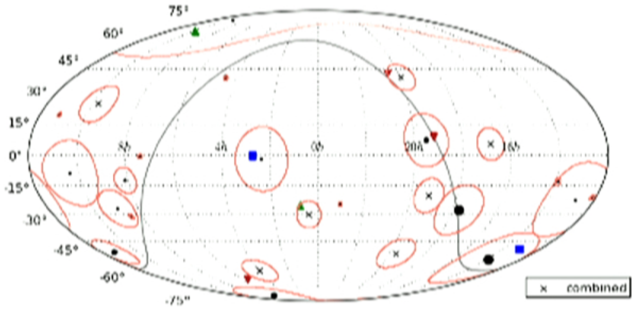
increase m_ϕ

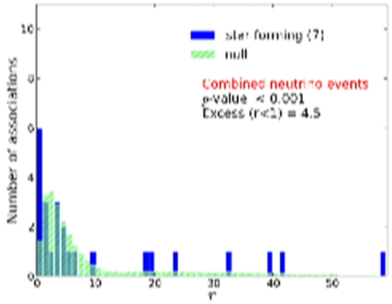
absorption move to high-E

Implications for source correlations

- Source correlations can reveal astrophysical origin of the events: correlate neutrino directions with photon data.
- The scattering induced by neutrino self-interactions *screens distant sources*. Implies a higher local-to-diffuse flux ratio.
- As an example, consider a recent study that finds correlation with star-forming regions.

Emig, Lunardini, Windhorst [1507.05711]



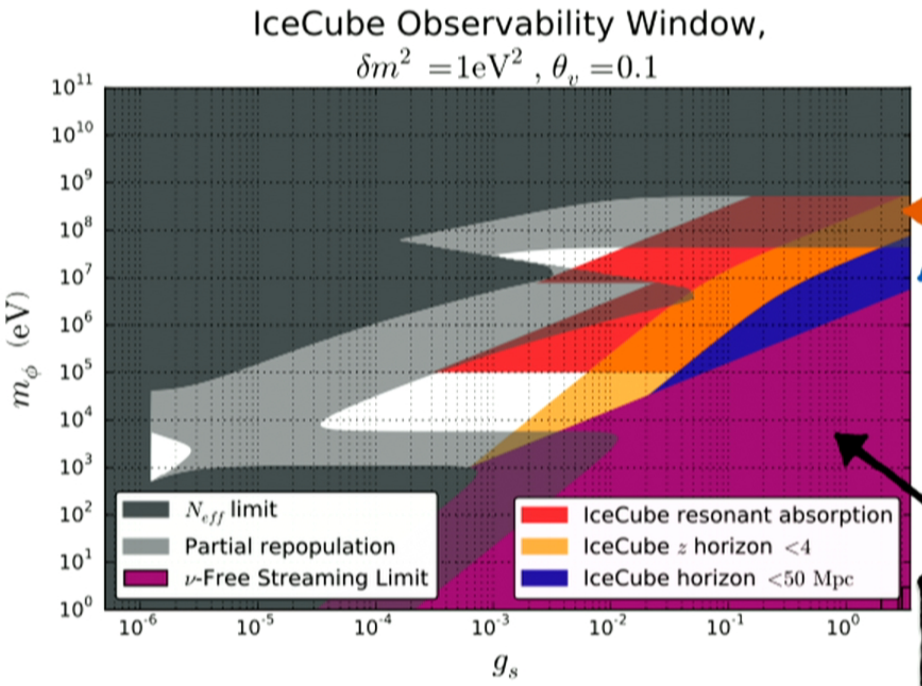


- Since the local contribution to the neutrino flux should have a diffuse counterpart from objects that can't be resolved individually. **They estimate that only 2% of total neutrino flux should come from < 15 Mpc, but observe 20%.**

Summary of Constraints

PRELIMINARY RESULTS

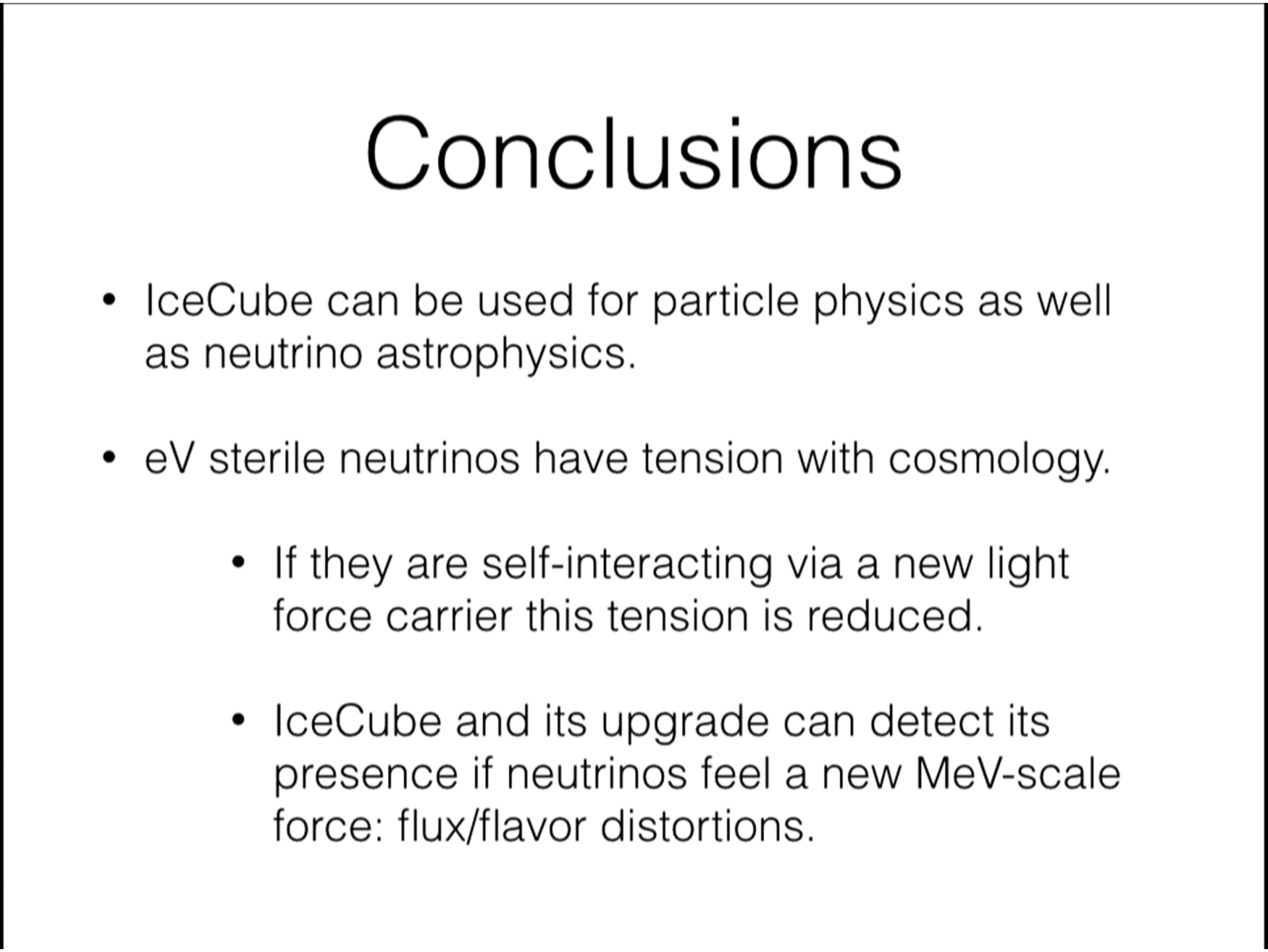
Cherry, Friedland,
IMS [in prep.]



IceCube Observability Window,
$\delta m^2 = 1\mathrm{eV}^2$, $\theta_v = 0.1$

Different neutrino horizons

Upper bound on g for active neutrinos to still be free-streaming at CMB times.



Conclusions

- IceCube can be used for particle physics as well as neutrino astrophysics.

- eV sterile neutrinos have tension with cosmology.

    - If they are self-interacting via a new light force carrier this tension is reduced.

    - IceCube and its upgrade can detect its presence if neutrinos feel a new MeV-scale force: flux/flavor distortions.