Probing New Physics with Astrophysical Neutrinos

Nicole Bell
The University of Melbourne

Introduction

New Physics → **New Particle Physics**

Astrophysical Neutrinos → **Neutrinos from beyond the solar system**

Neutrinos detected so far:

- MeV energies

  Neutrinos from the Sun and SN1987A

- Up to ~ 1 TeV (SuperK and others)

  & above 1 TeV (AMANDA, Frejus)

  Only atmospheric neutrinos

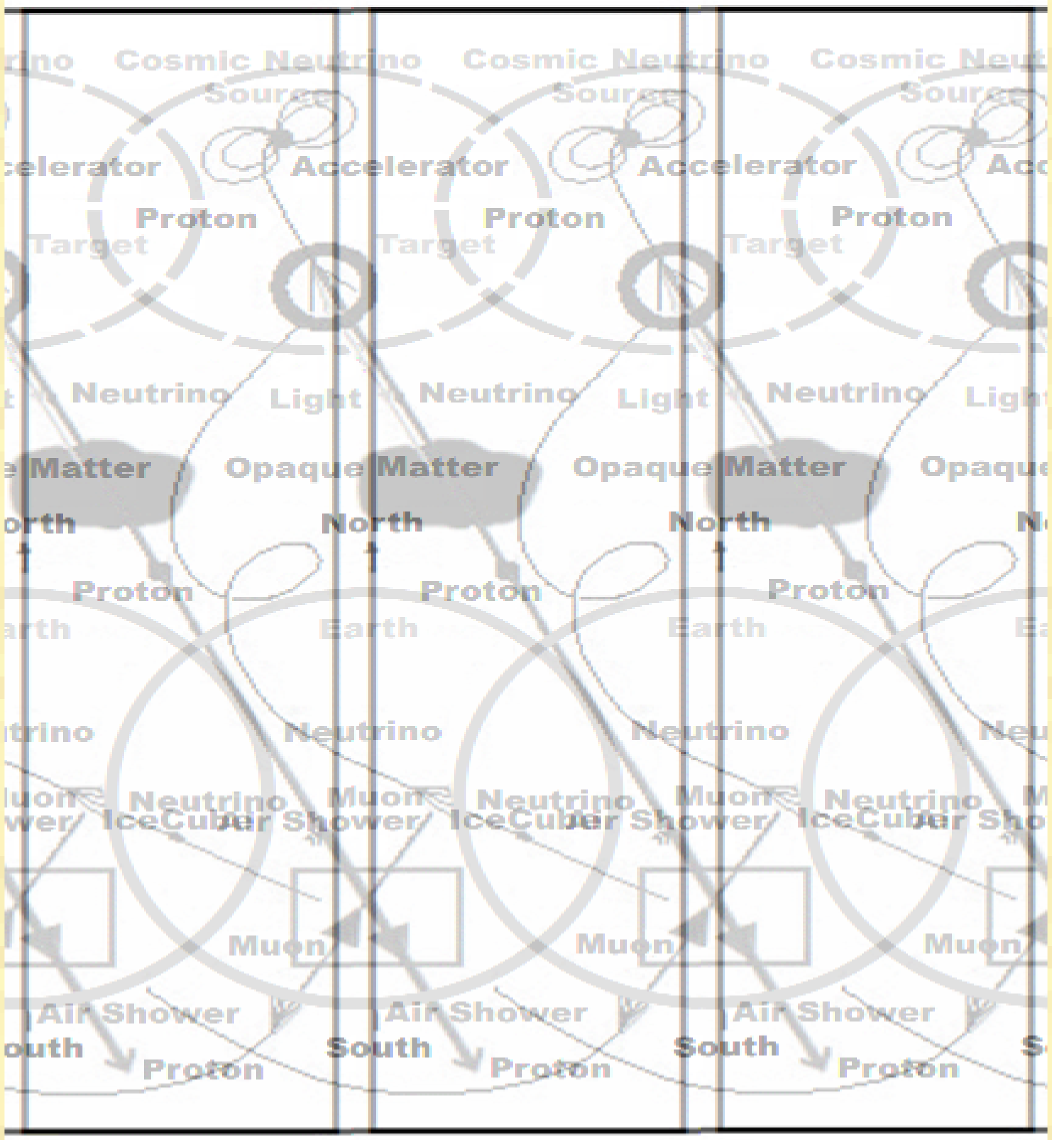
- Higher energies

  Upper limits on fluxes

BUT, excellent prospects for many experiments now coming on line

Astrophysical neutrino beam

- ❖ May eventually be as useful/revealing as the solar neutrino beam
- ❖ But we first need to detect and calibrate it!



Neutrino Sources

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

→ Optically thin sources → ν, γ and CR fluxes related. (e.g. Waxman & Bahcall; Mannheim, Protheroe & Rachen.)

→ Optically thick → "hidden" sources → neutrinos only

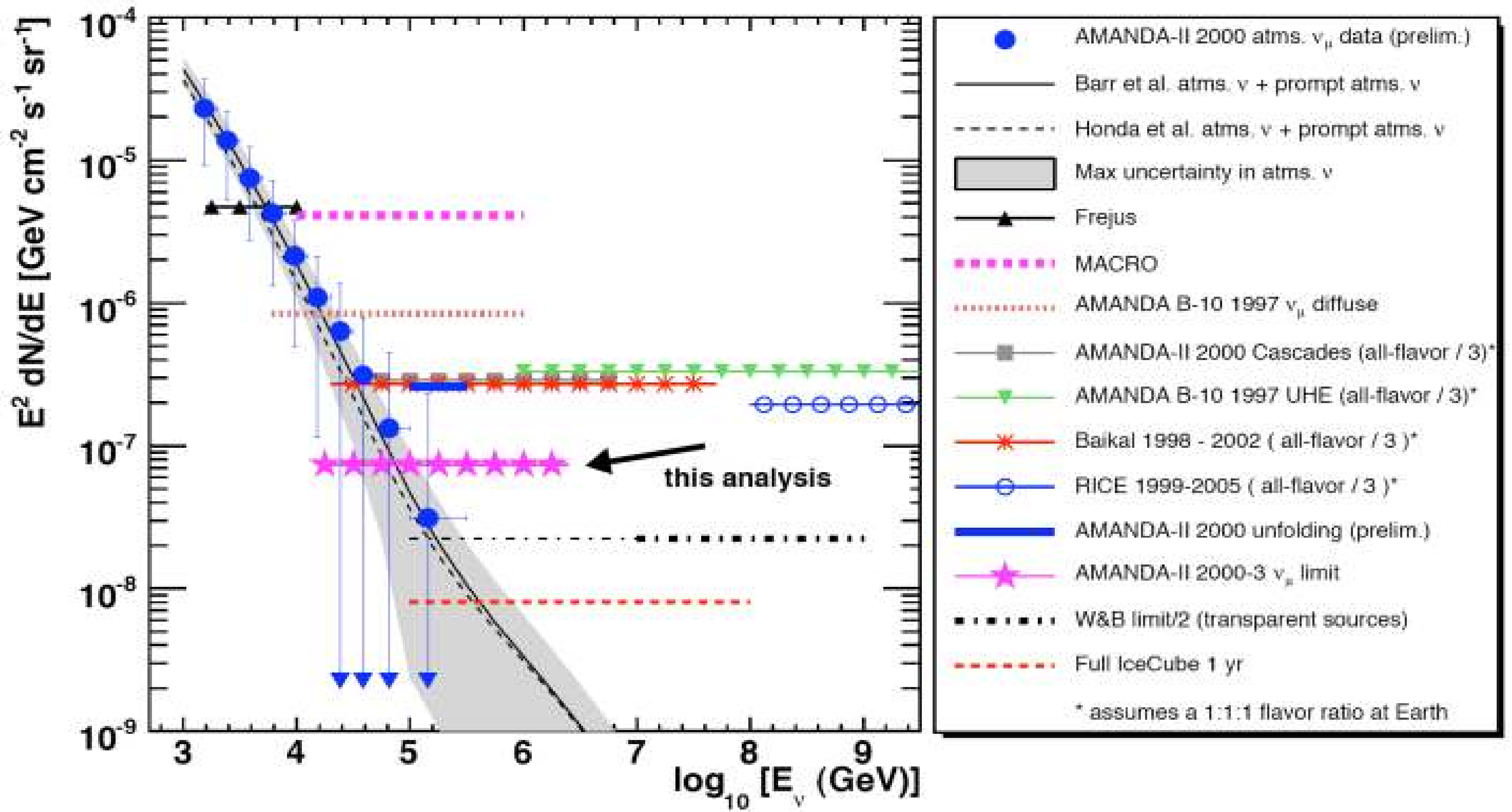
❖ Cosmogenic (GZK) neutrinos. (Guaranteed)

→Interaction of cosmic rays with the cosmic microwave background

❖ Annihilation or decay of dark matter

→Fluxes related to dark matter cross-sections and density distributions.

Astrophysical flux limits



AMANDA collaboration 2007

Above the electroweak scale

• UHE neutrinos probe energies far above the EW scale

→ Sensitivity to new physics via new contributions to cross-sections.

• Neutrino-nucleon cross-section must be extrapolated to energies where we have no experimental data points. (Ghandi, Quigg, Reno and Sarcevic)

• Suppressed cross-sections (w.r.t. simple parton model):

→ Possible new physics?

→ Saturation effects at high energy (Growth of cross-section with energy must saturate to preserve unitarity, Froissart bound.)

• Enhanced cross-sections:

→ Exchange of towers of Kaluza Klein gravitions (Feng & Shapere)

→ Black hole production (Banks & Fischler; Giddings & Thomas; Dimopoulos & Landsberg.)

→ Electroweak Instantons (Fodor, Katz, Ringwald, & Tu.)

Event rates → cross sections

- Event rates depend upon (flux)×(cross-section)
  How do we disentangle astrophysics from particle physics?

- Events rates for up and down going neutrinos depend differently on neutrino cross-sections.

Kusenko & Weiler, PRL 88, 161101 (2002)
Feng & Shapere, PRL 88, 021303 (2002)

- Enhanced cross-sections would:

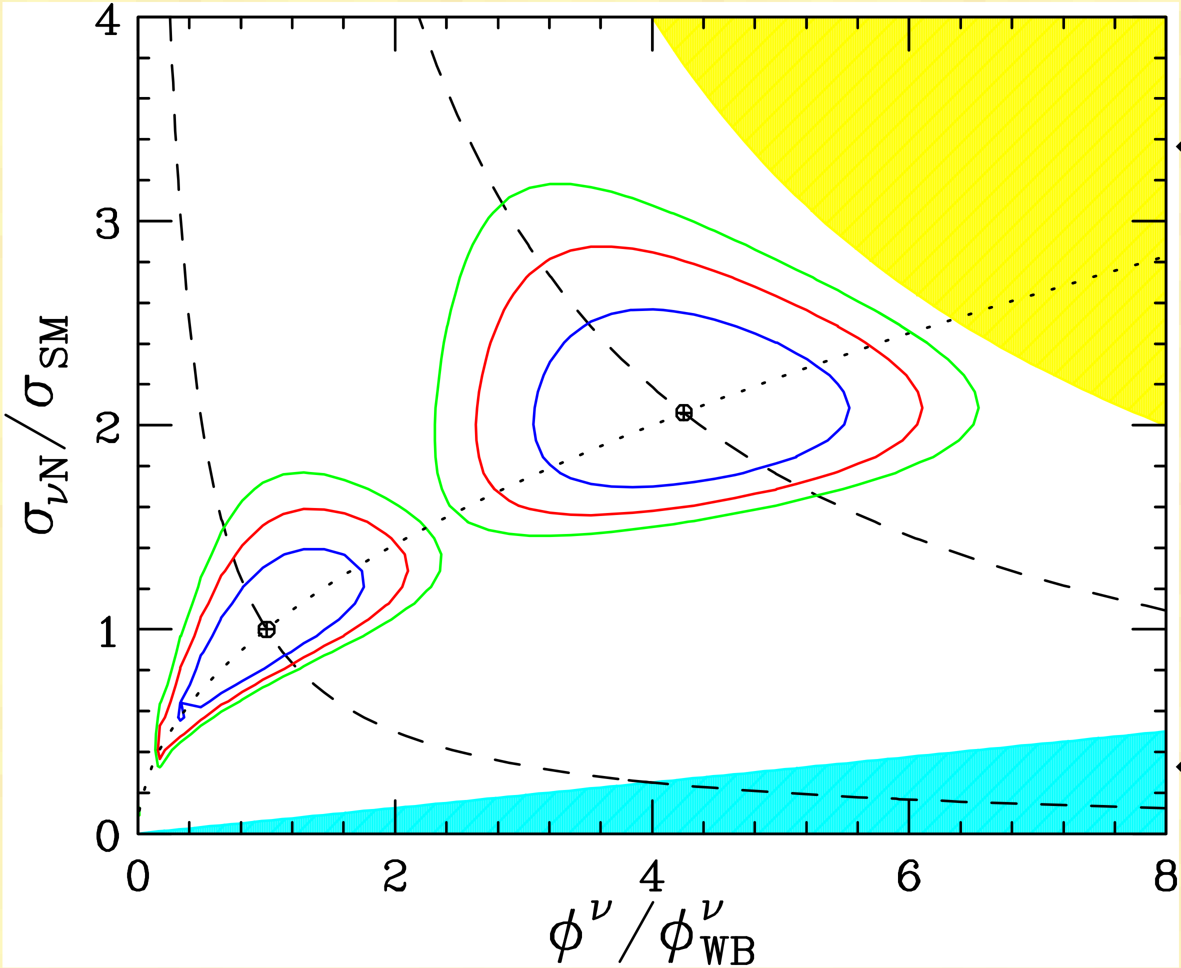
→ increase down-going event rate
→ decrease up-going event rate (due to greater absorption in Earth)

- Amanda *already* provides constraints at 6 TeV CoM energy:

$$E_\nu = 10^{7.25}\ \text{GeV} \quad \Rightarrow \quad \sqrt{s} = 6\ \text{TeV}$$

Cross-sections/fluxes at IceCube

Anchordoqui, Feng & Goldberg, PRL 96, 021101 (2006).



← Ruled out by Amanda down-going data

$E_{\nu} = 10^{7.25}$ GeV

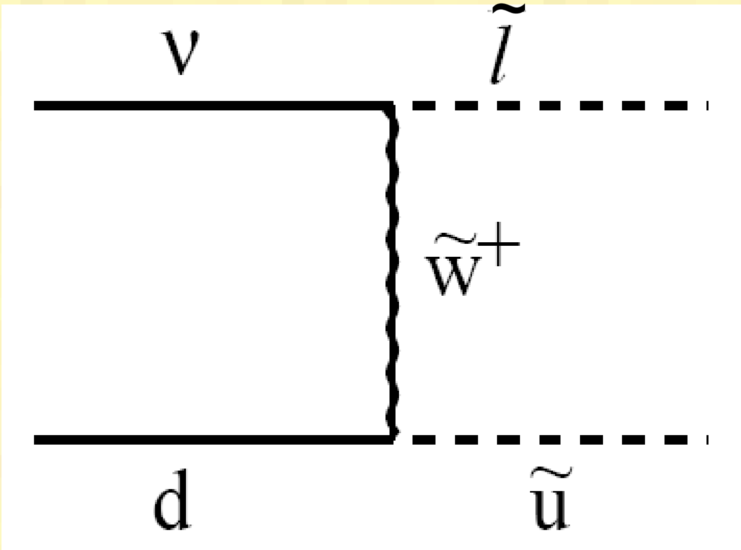
←Ruled out by Amanda up-going data

Neutrino probe of SUSY

Albuquerque, Burdman and Chacko, PRL 92, 221802 (2004)

•Neutrinos make NLSP pairs in the Earth

•NLSP is charged and long lived → long range.



Energetic NLSP pairs make a new signal in IceCube
→ Two parallel charged tracks, ~ 100 m apart.

Can also use atmospheric neutrinos. Ando, Beacom, Profumo, Rainwater, JCAP 0804, 029 (2008)

Neutrino Production

- pp and pγ interactions produce charged and neutral pions

$$pp \to NN + \text{pions}; \qquad p\gamma \to \mathrm{p}\pi^0,\ n\pi^+$$

- Neutrinos from pion decay:

$$\begin{aligned}\pi^+ \to \nu_\mu + \;&\mu^+\\ &\downarrow\\ &\bar{\nu}_\mu + e^+ + \nu_e\end{aligned}$$

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

- After oscillations: $\nu_\mu \leftrightarrow \nu_\tau$ $\qquad \nu_e : \nu_\mu : \nu_\tau = 1:1:1$

Learned & Pakvasa

- For hadronic production, $\phi_\nu \sim \phi_\gamma$

Deviations from 1:1:1 ~ Particle Physics

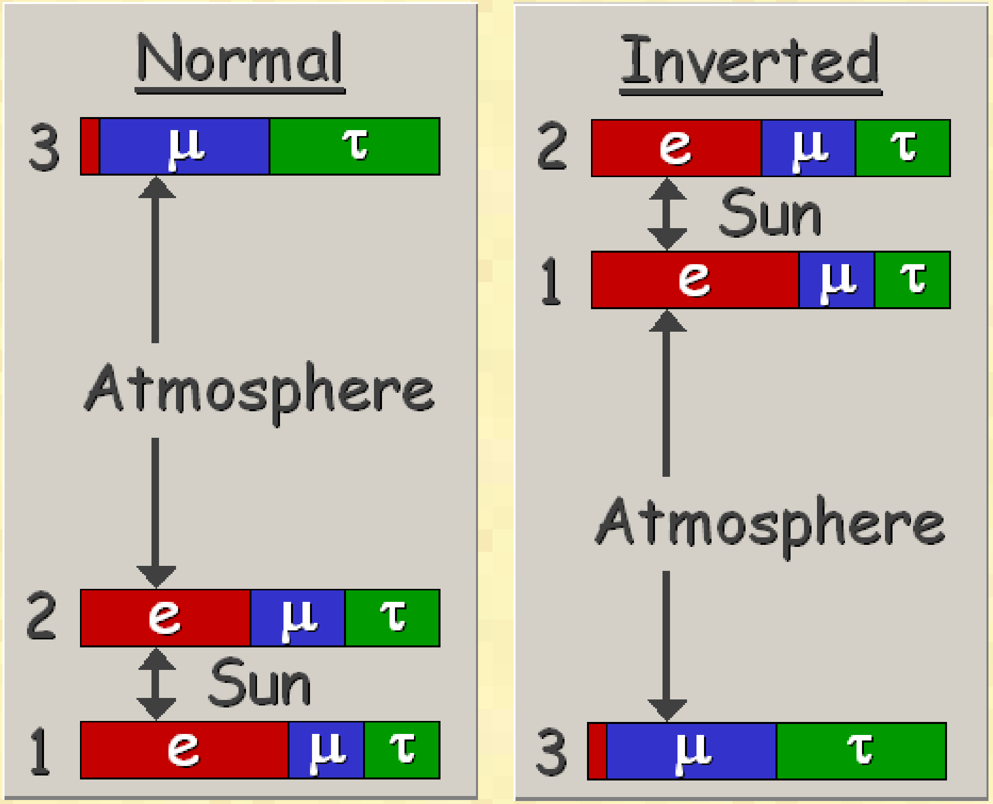
Exotic neutrino properties

- Neutrino decay (Beacom, Bell, Hooper, Pakvasa, & Weiler)
- CPT violation (Barenboim & Quigg)
- Oscillation to steriles (Dutta, Reno and Sarcevic)
- Oscillations with tiny delta δm^2 (Crocker, Melia, & Volkas; Berezinsky et al.)
- Pseudo-Dirac mixing (Beacom, Bell, Hooper, Learned, Pakvasa, & Weiler)
- Magnetic moment transitions (Enqvist, Keränen, Maalampi)
- Mass varying neutrinos (Fardon, Nelson & Weiner; Hung & Pas)
- ...

Flavor Ratios – ν decay

Neutrino invisible decays are not ruled out, and would greatly alter the ratios

Other new physics can lead to different ratios



~ 5:1:1 ~ 0:1:1

Beacom, Bell, Hooper, Pakvasa, Weiler, PRL 90, 181301 (2003);
Beacom, Bell, Hooper, Pakvasa, Weiler, PRD 69, 017303 (2004)

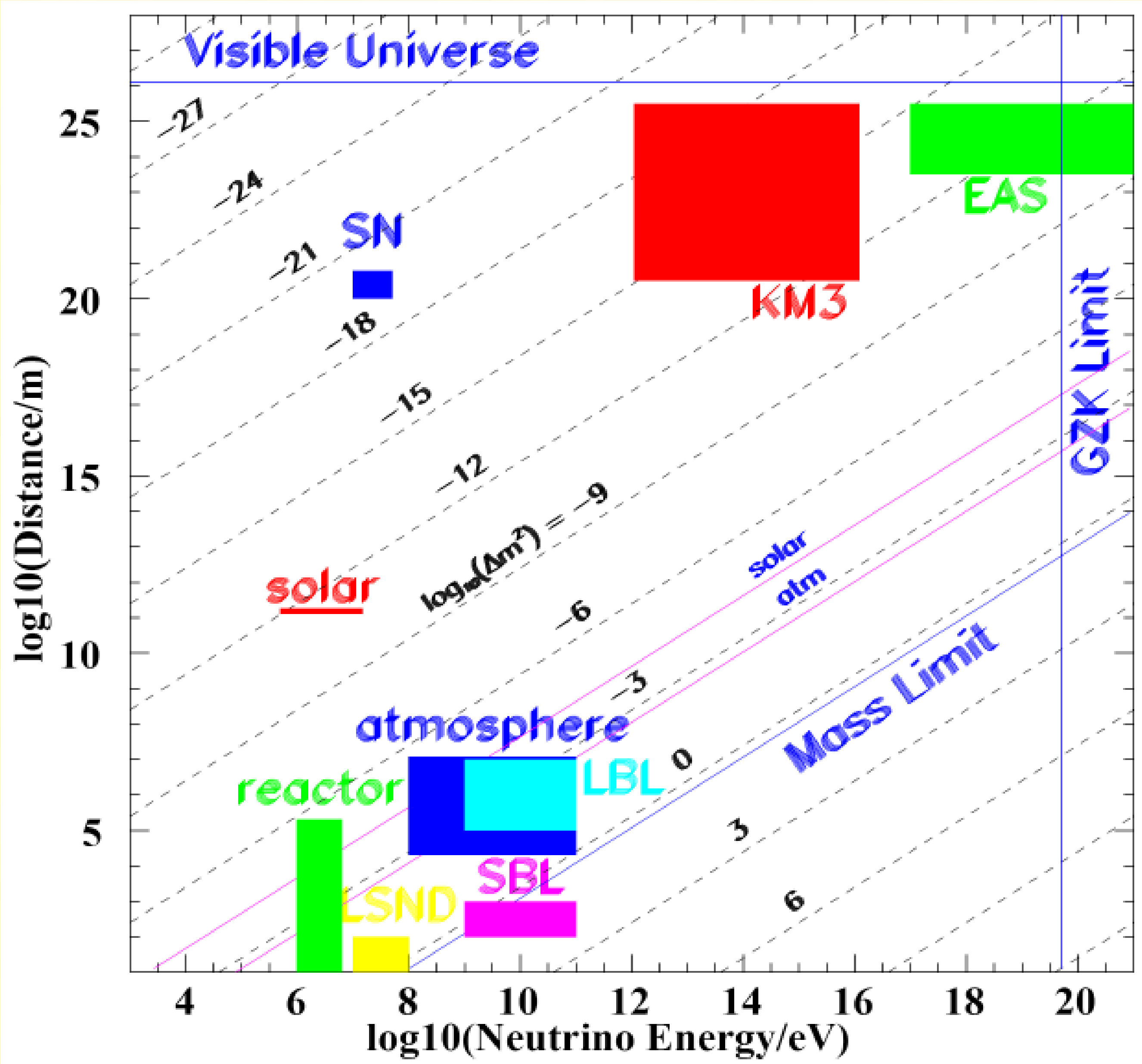
Ultimate long-baseline experiment

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

This allows a sensitivity to oscillations with tiny $\delta \mathbf{m}^2$

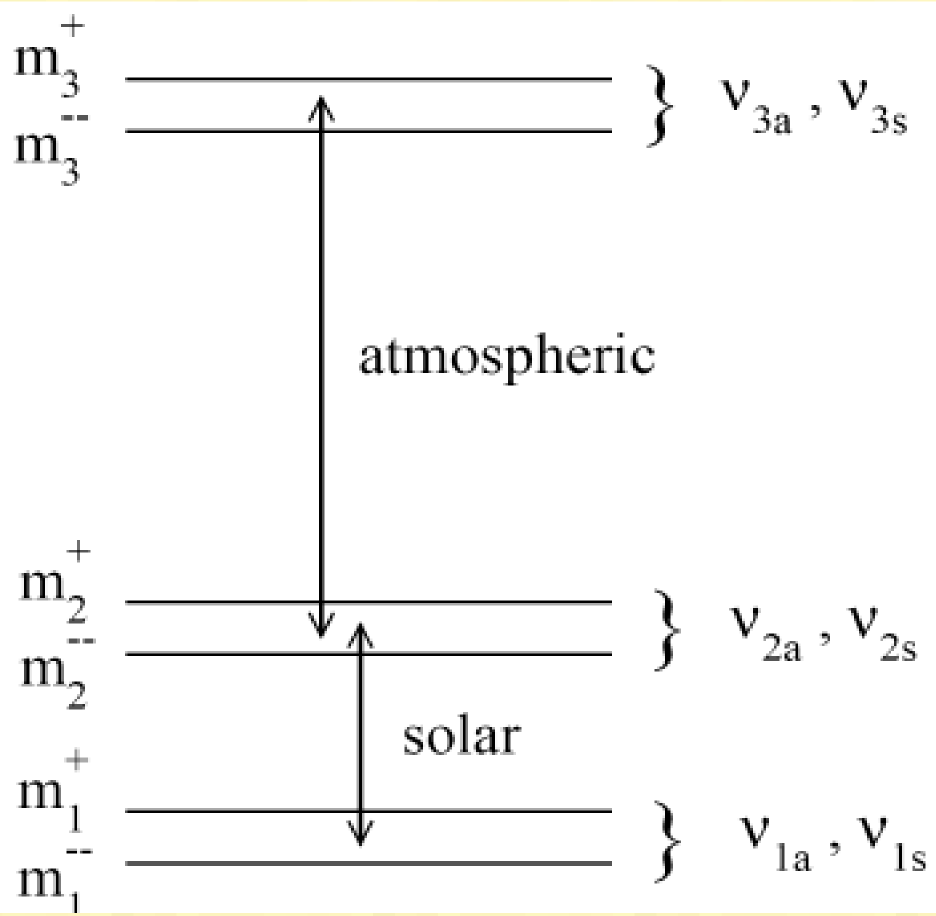
Eg. Oscillation modes that have a sub-dominant or completely negligible effect on the solar or atmospheric neutrinos may show up here.

Crocker, Melia and Volkas (2000, 2002)
Berezinsky, Narayan and Vissani (2002)
Keranen, Maalampi, Myyrylainen and Riittinen (2003)
Beacom, Bell, Hooper, Pakvasa, Learned, and Weiler (2004)



Beacom, Bell, Hooper, Pakvasa, Learned, and Weiler (2004) PRL, 92, 011101 (2004)

Pseudo-Dirac Neutrinos



Neutrinos appear to be Dirac, but in fact have subdominant Majorana mass terms.

→Oscillations driven by tiny mass differences.

→ Would show up in astro-nu flavor ratios.

Deviations from 1:1:1 ~ Astrophysics

Galactic β beams:

Photo-disintegration of heavy nuclei → neutrons→ Pure $\bar{\nu}_e$ flux

$\nu_e : \nu_\mu : \nu_\tau$ = **1 : 0 : 0** → **5 : 2 : 2** after oscillations

Muon-damped source:

If muons loose energy before decaying:

$\nu_e : \nu_\mu : \nu_\tau$ = **0 : 1 : 0** → **1 : 2 : 2** after oscillations

We can do oscillation experiments with such sources!

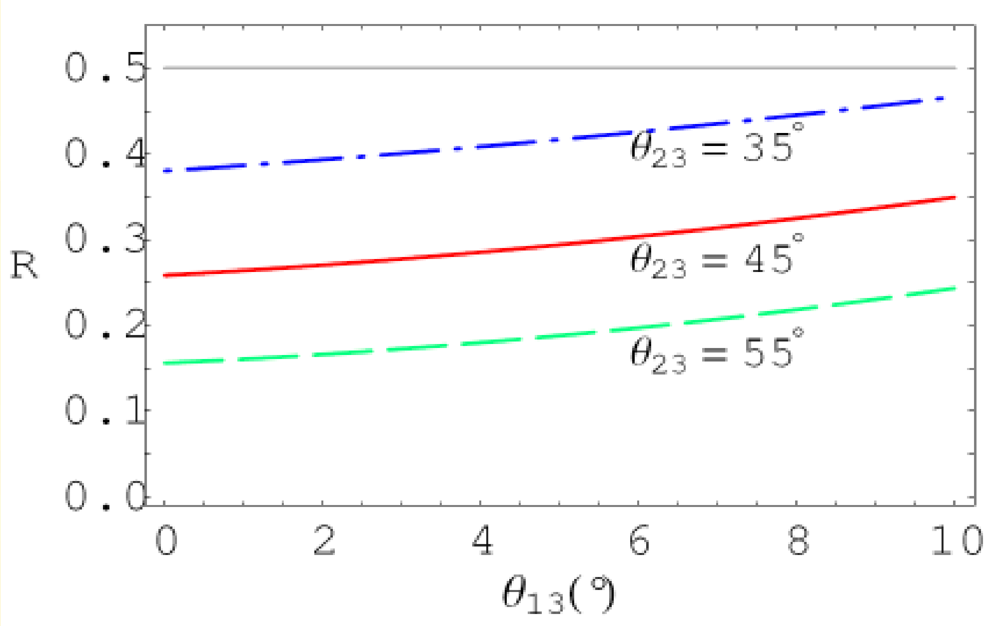
Measuring the 1-3 mixing angle and the CP phase:

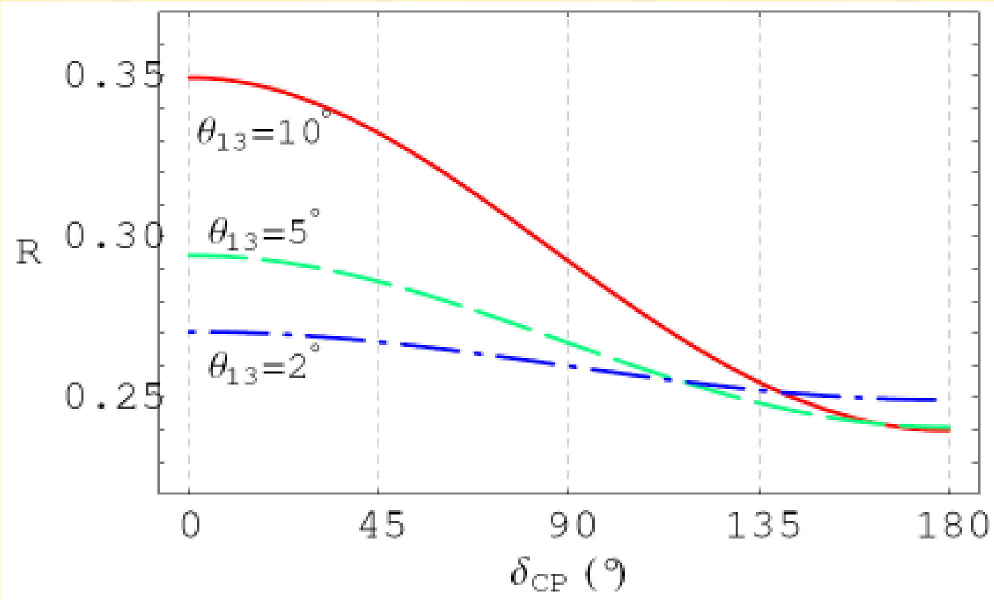
e.g. Serpico & Kachelreiss, PRL 94, 21102 (2005); Winter, PRD 74, 033015 (2006); Blum, Nir, & Waxman, arXiv:0706.2070; Pakvasa, Rodejohann, & Weiler, arXiv:0711.4517.

Measuring mixing parameters with a β beam source:

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

$$R = \phi_\mu^D / (\phi_e^D + \phi_\tau^D)$$





Serpico & Kachelreiss, PRL 94, 21102 (2005);

Can we measure it?

FLAVOR INFORMATION

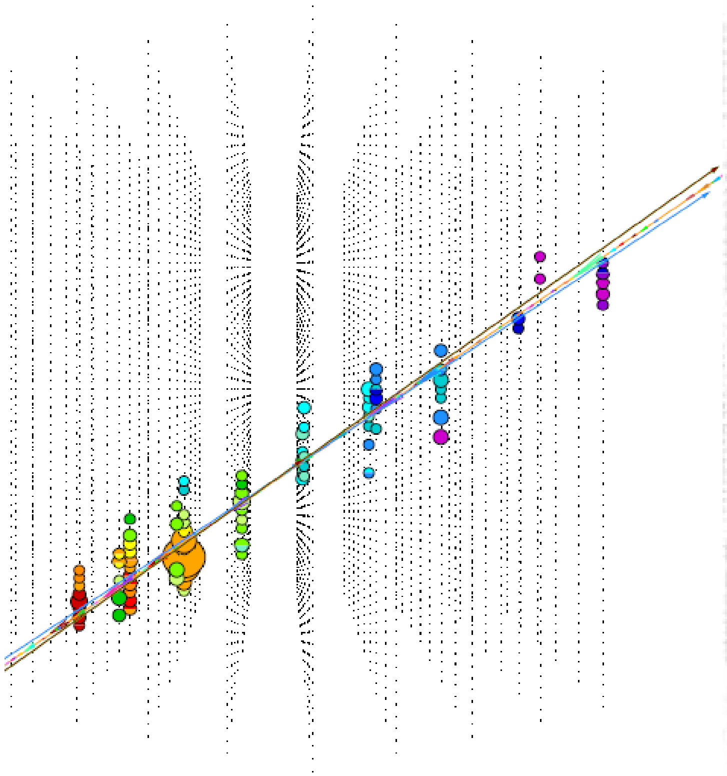
- **Muon tracks** – CC interactions of ν_μ
- **Showers** – neutral current interactions of all flavors, plus CC interactions of ν_e and ν_τ.
- **Double bang and lollipop events** - only ν_τ
- **Glashow resonance** – only $\bar{\nu}_e$, at E=6.3PeV.

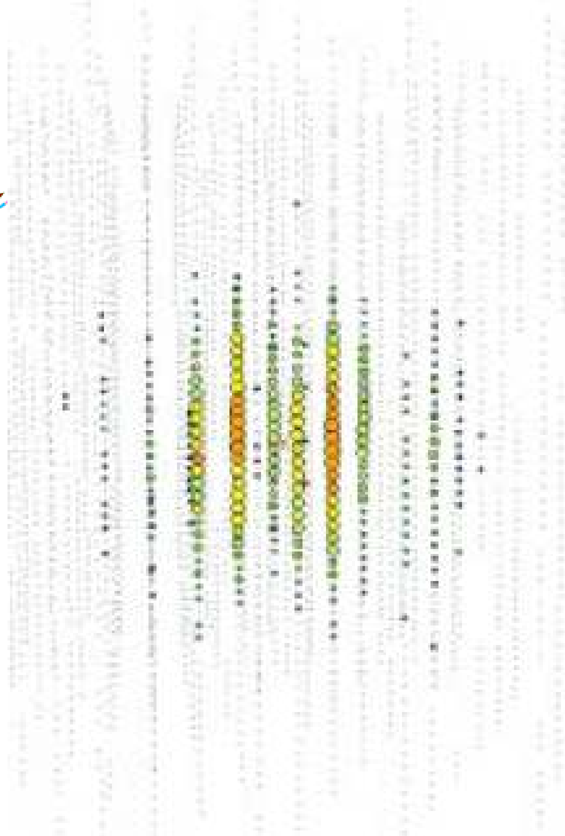
To determine the ν_e / ν_μ. ratio
→ compare muon tracks to showers.

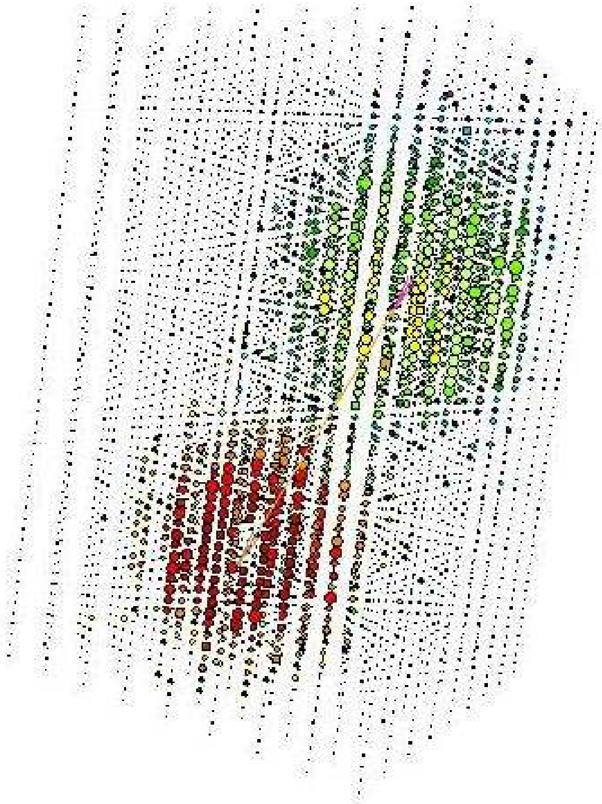
Muon Track

Shower

Double-Bang







ν_μ

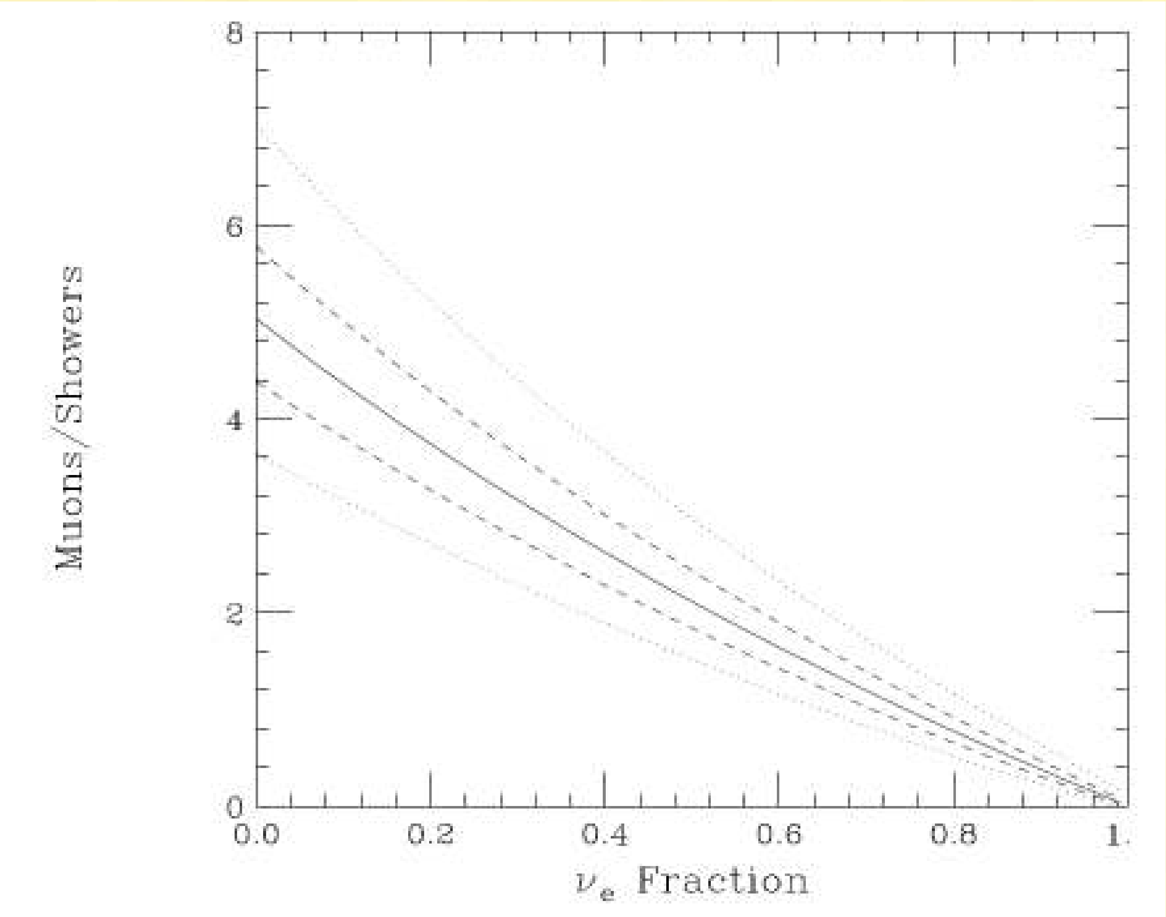
ν_e, ν_μ , ν_τ

ν_τ

IceCube

Muons/Showers rate for different electron fractions.

(Waxman-Bahcall flux, 1yr at Icecube)



Beacom, Bell, Hooper, Pakvasa, and Weiler, PRD 68, 093005 (2003)

Constraining Dark Matter with Neutrino Astrophysics

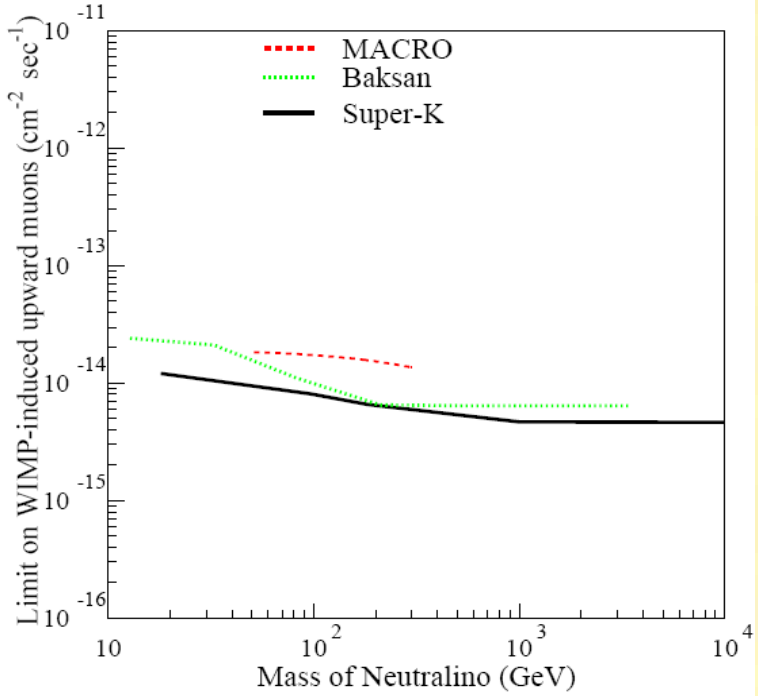
Dark Matter may be a source of high energy neutrinos

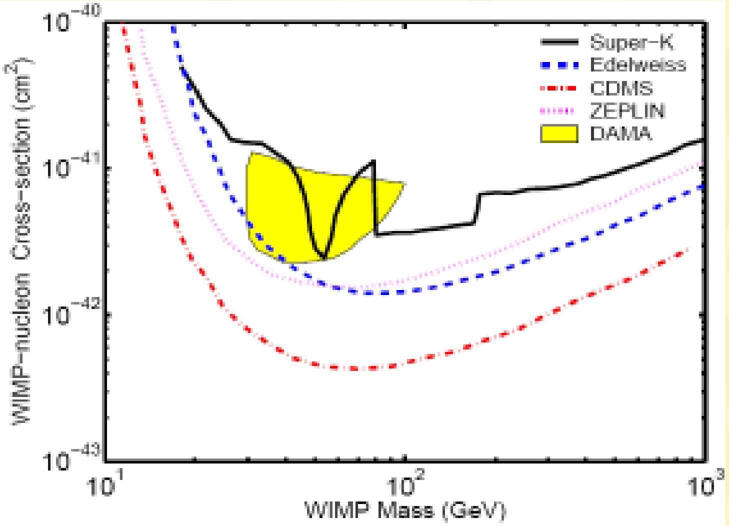
WIMP annihilation in the Sun/Earth

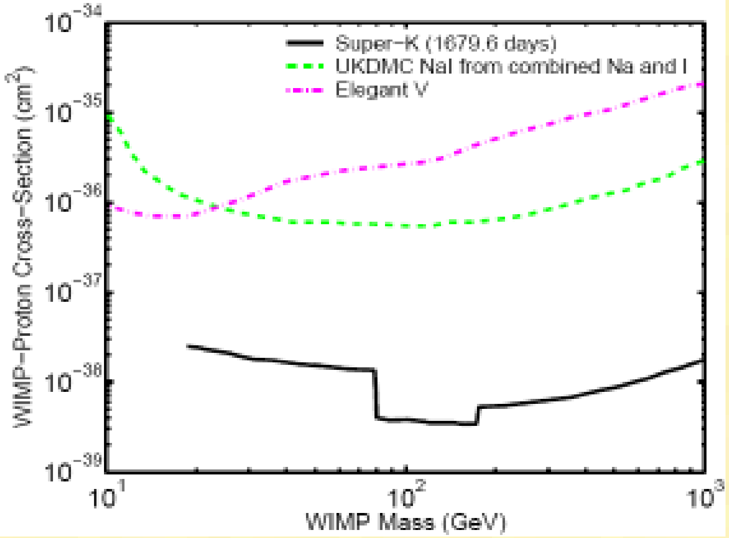
- ❖ WIMPS captured by the gravitational field of Sun
- ❖ Annihilation in Sun → all products absorbed except neutrinos

SuperK limits using upward-going neutrinos:

Desai, et al., PRD 70, 083523 (2004).







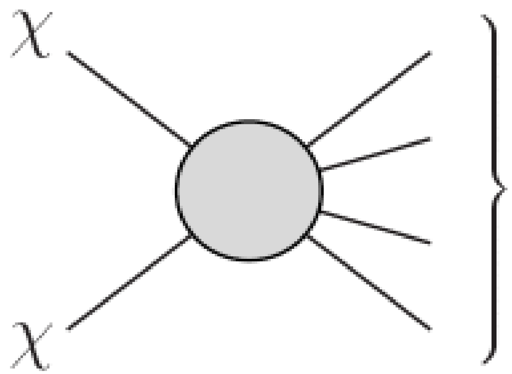
Neutrinos and Dark Matter - indirect detection

❖ Annihilation in our Galaxy
→ look for flux coming from Galactic center

❖ Annihilations in galaxies throughout the universe
→ cosmic diffuse flux

❖ **Despite being harder to detect than gamma rays, neutrinos provide important information and *strong bounds.***

If the dark matter is the lightest new particle:

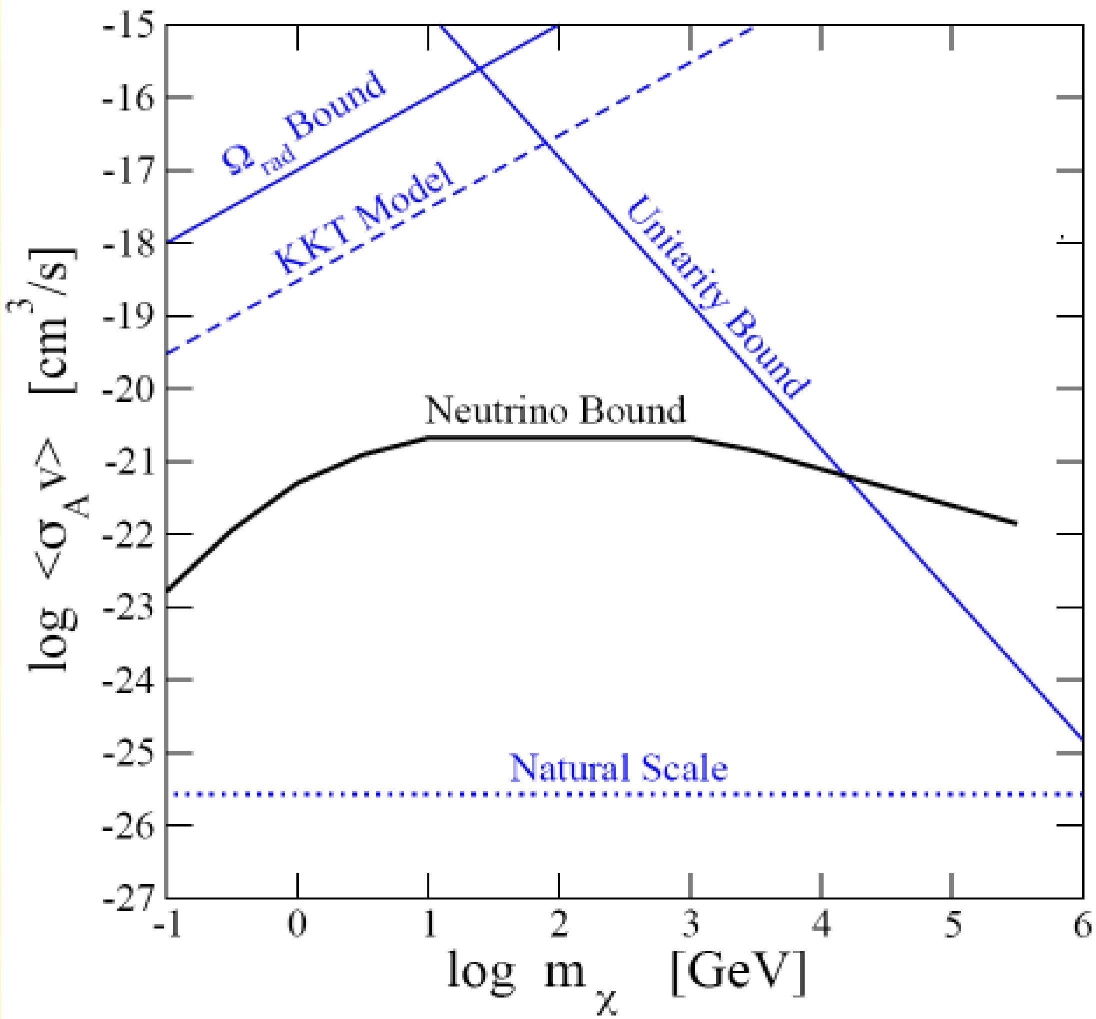


$$\left.\right\} \begin{array}{c}\text{All Standard}\\ \text{Model}\\ \text{final states}\end{array} = \begin{array}{c}\text{“Visible” states:}\\ \gamma\gamma,\ \overline{q}q,\ e^+e^-,\ \ldots\\ +\\ \text{“Invisible” states:}\\ \overline{\nu}\nu\end{array}$$

❖All final states except neutrinos produce gamma rays,

→Bound the *total* cross-section with the neutrino signal limit i.e. Assume Br(“invisible”) = 100%

Upper bounds on the dark matter total annihilation cross-section



Beacom, Bell, & Mack, PRL99, 231301, 2007.

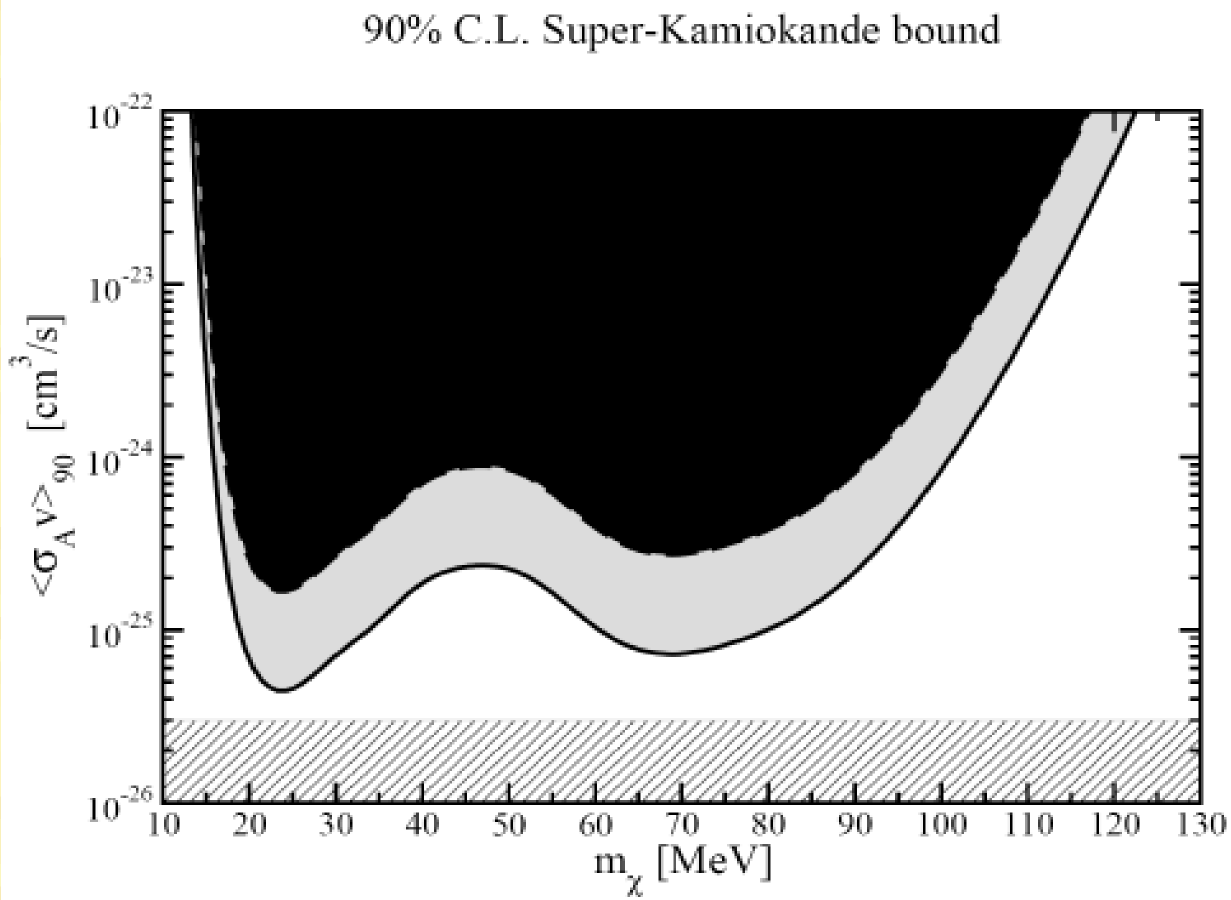
Also:

Yuksel, Horiuchi, Beacom, & Ando, PRD 76, 123506, 2007.

Kachelriess and Serpico, PRD 76, 063516 (2007).

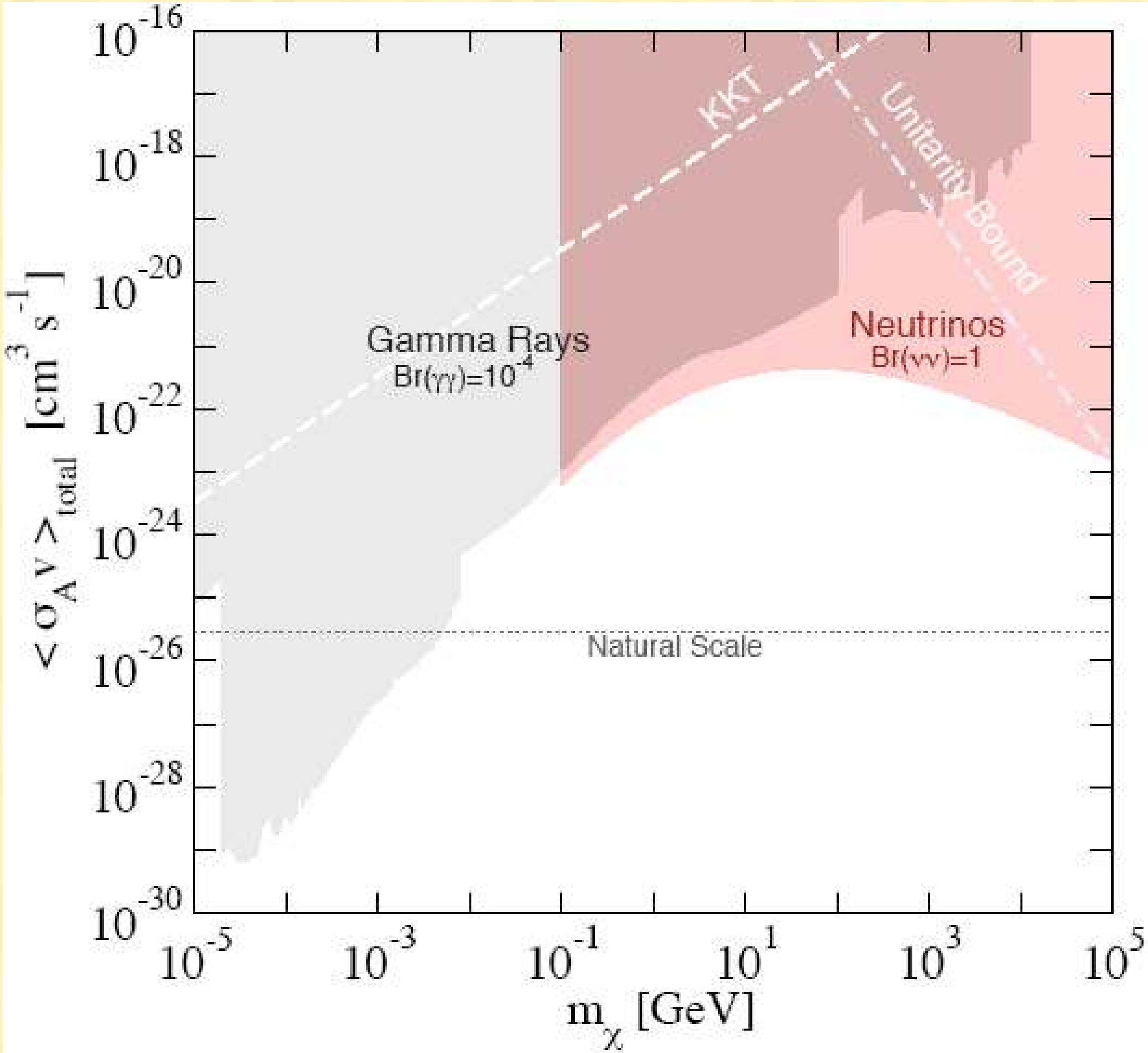
Bell, Dent, Jacques, & Weiler, arXiv:0805.3423

Dark matter annihilation – MeV mass



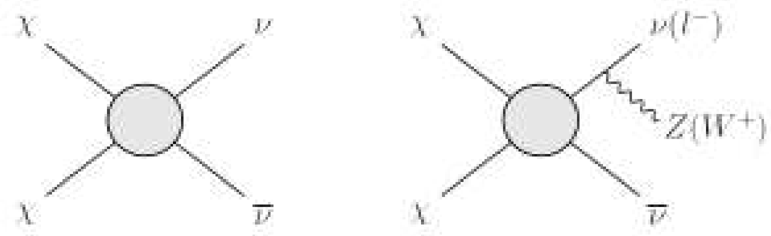
Palomares-Ruiz & Pascoli, PRD 77, 025025 (2008)

Comparison of neutrino and photon limits on dark matter annihilation



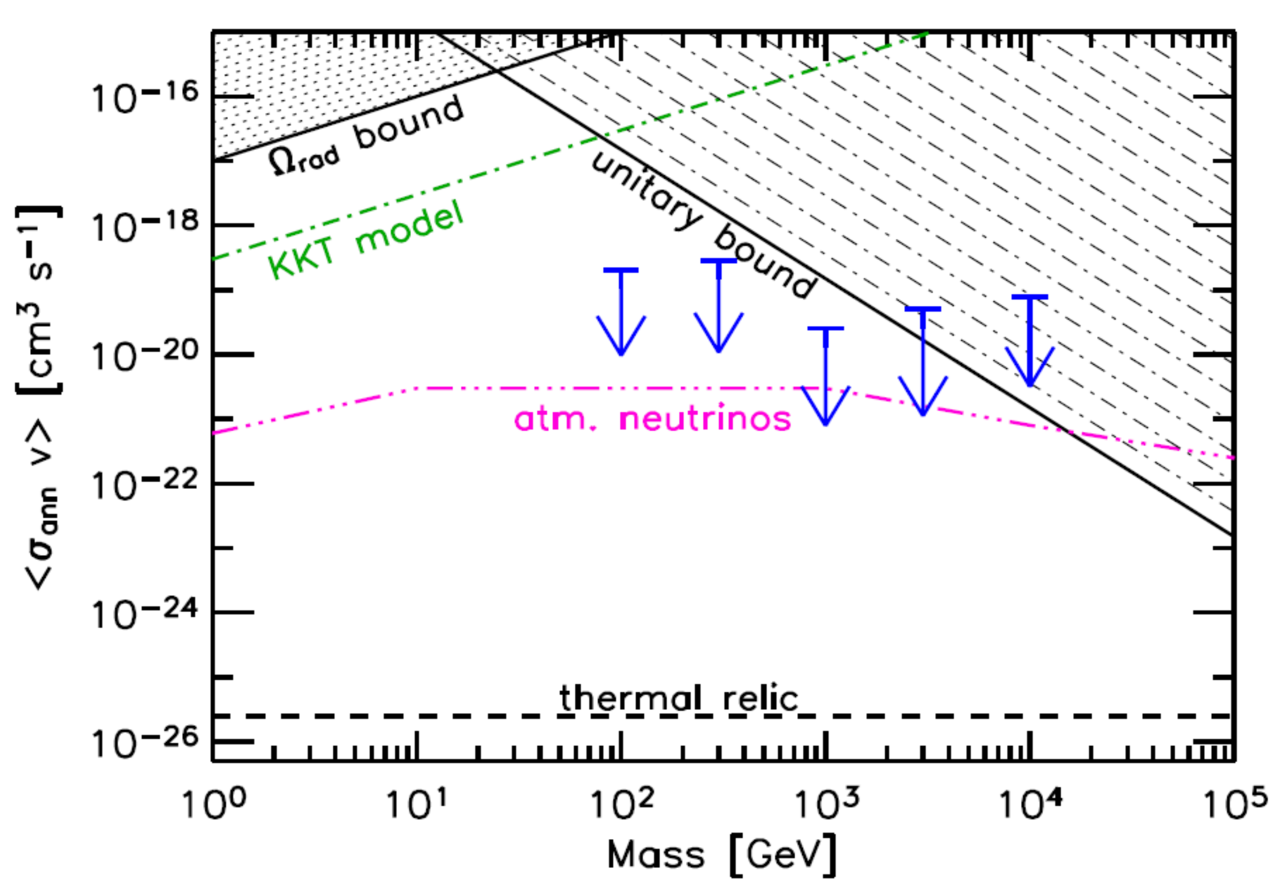
Mack, Jacques, Beacom, Bell, and Yuksel, arXiv:0803.0157

Radiative corrections to neutrino processes give photons



$\chi\chi \rightarrow \nu\bar{\nu}$ is accompanied by:

$\chi\chi \rightarrow \nu\bar{\nu}Z \rightarrow$ gamma rays



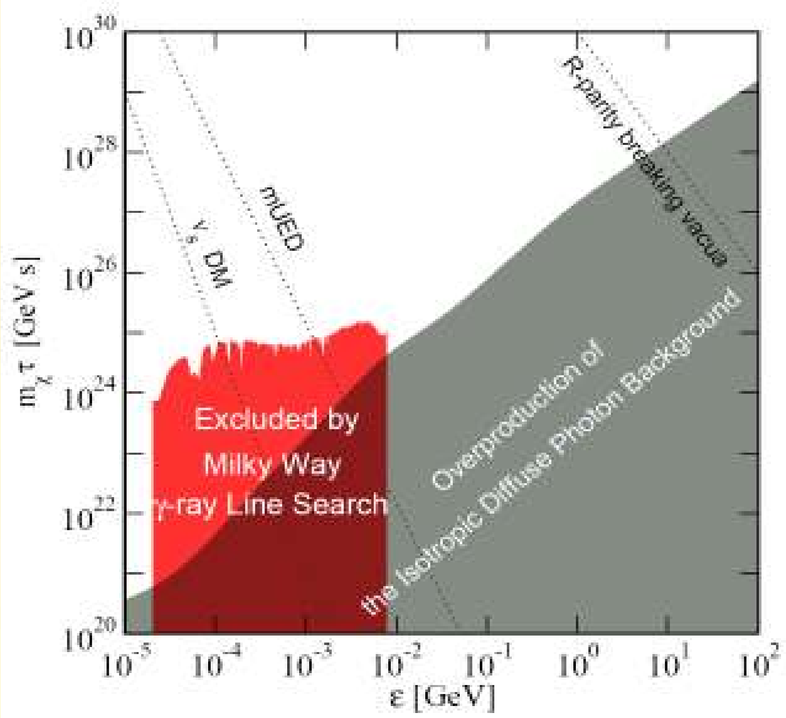
But direct neutrino limits are stronger!

Kachelriess and Serpico, PRD 76, 063516 (2007).

Bell, Dent, Jacques, & Weiler, arXiv:0805.3423

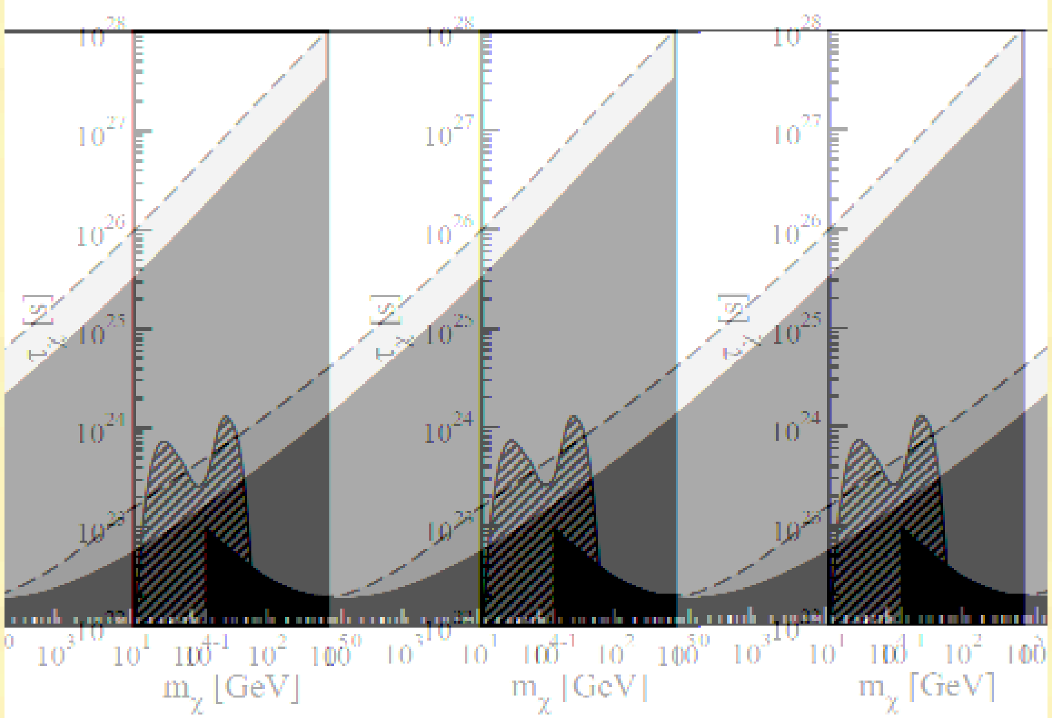
Dark Matter Lifetime

Photons X→X'γ
… strong limit



Yuksel & Kistler

Neutrinos X→νν
… *model-independent* limit



Palomares-Ruiz

Outlook

- Have not yet detected astrophysical neutrinos beyond the Sun and SN1987A.
- Many new detectors coming on line, with excellent prospects of seeing a signal.
- Will have complementary data from neutrinos, gamma rays and cosmic rays.
- Flavor discrimination important for both understanding the production mechanism, and probing exotic particle physics.
- High energy neutrino observation/limits provide important and restrictive *dark matter* limits.