Imperial College London

Using Neutrinos as Cosmic Messengers

Matthew Malek

Fermilab Particle Astrophysics Seminar
07 March 2012

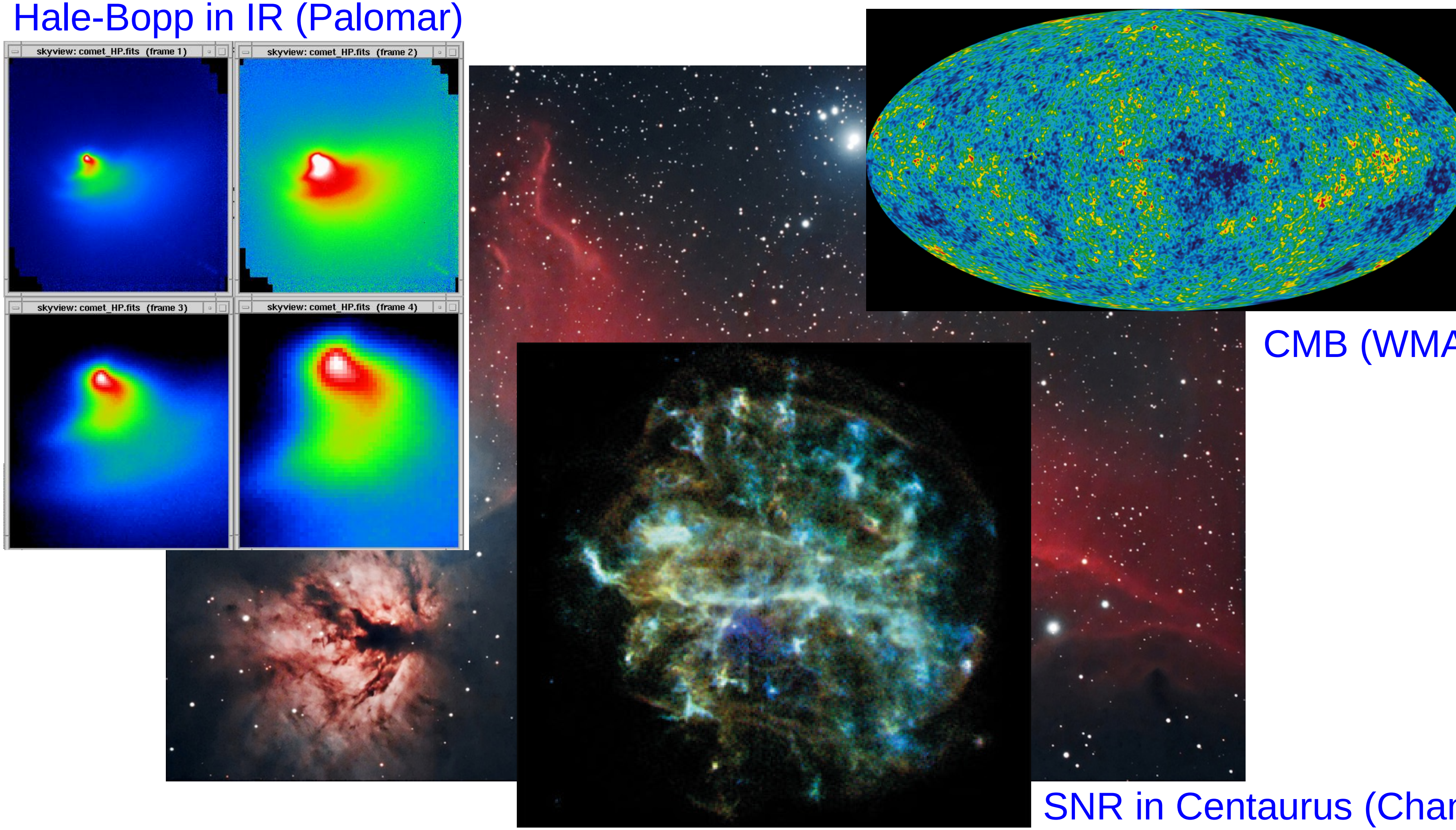
Outline

- Introduction: Cosmic messengers and Neutrinos
- Historical results: Solar neutrinos and SN 1987A
- Recent results: Astronomical neutrinos
  - Supernovae and supernova relic neutrinos
  - Indirect searches for dark matter
  - Other areas of interest
- Recent results: Terrestrial neutrinos
  - Absolute mass measurements and the neutrino mass hierarchy
  - Matter / Anti-matter asymmetry: CP violation and Leptogenesis
- Summary & conclusions

How Do We Look At The Sky?

- For most of our history, humanity could only observe space via visible light…

How Do We Look At The Sky?



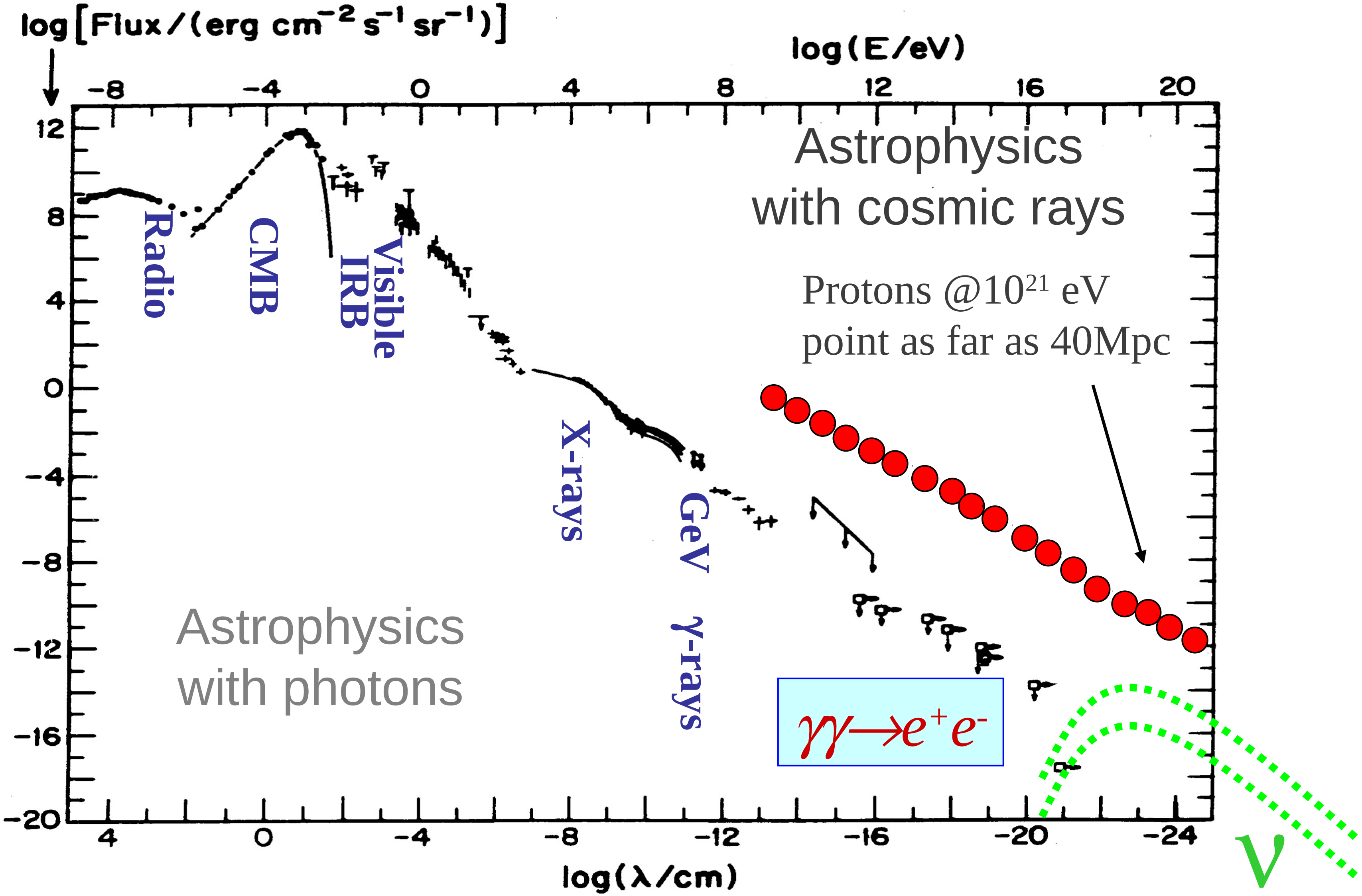
Hale-Bopp in IR (Palomar)

CMB (WMAP)

SNR in Centaurus (Chandra)

- In the 20th century, we learned to use other messengers:
  - Infrared, X-ray, Microwave, Gamma rays, et cetera...

Beyond Photons

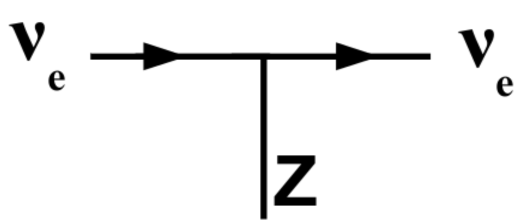


Halzen, Ressell & Turner

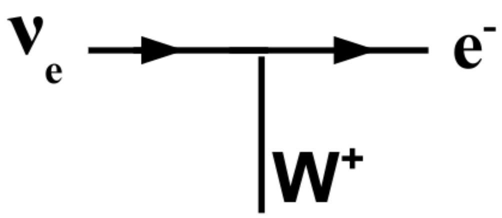
Neutrino Basics

- Weakly interacting isospin partners of charged leptons

Neutral current



Charged current



- Neutrinos have mass!

Flavour eigenstates: ν_e, ν_μ, ν_τ **Mass eigenstates:** ν_1, ν_2, ν_3

$$|\nu_l\rangle = \sum_{i=1}^{3} U_{li} |\nu_i\rangle$$

- Produced and interact as flavour eigenstates; propagate as mass eigenstates:

$$|\nu_l(L)\rangle = \sum_{i=1}^{3} U_{li} e^{-i m_i^2 L/2E} |\nu_i(0)\rangle$$

Outline

- Introduction: Cosmic messengers and Neutrinos
- **Historical results: Solar neutrinos and SN 1987A**
- Recent results: Astronomical neutrinos
  - Supernovae and supernova relic neutrinos
  - Indirect searches for dark matter
  - Other areas of interest
- Recent results: Terrestrial neutrinos
  - Absolute mass measurements and the neutrino mass hierarchy
  - Matter / Anti-matter asymmetry: CP violation and Leptogenesis
- Summary & conclusions

Solar Neutrinos

- First solar neutrino detector:
  - Homestake mine, S. Dakota
  - Ray Davis, Brookhaven
  - 1967 – 1998
  - 615 tons of C_2Cl_4 (cleaning fluid!)
  - "Radiochemical" detector:

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar^* + e^-$$

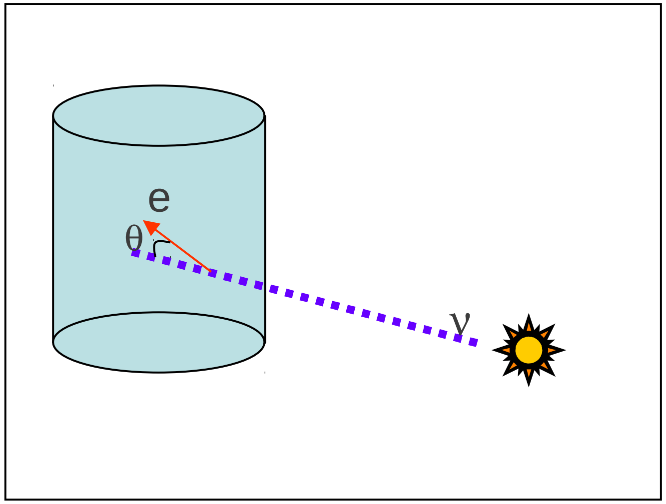
Good News:

First discovery of solar ν!

Bad News:

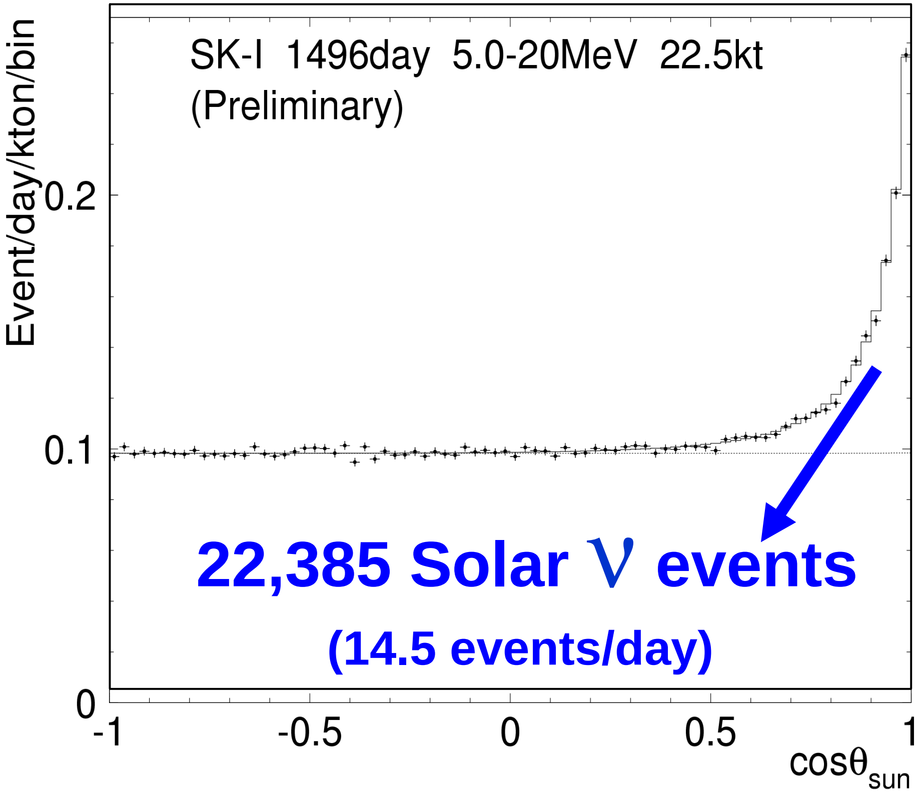
Far fewer than anticipated!

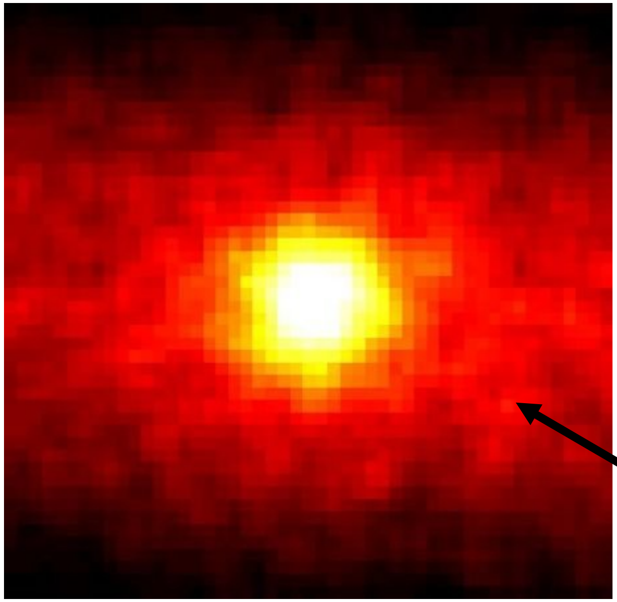
Adding Directionality



The KamiokaNDE detector (Masatoshi Koshiba)

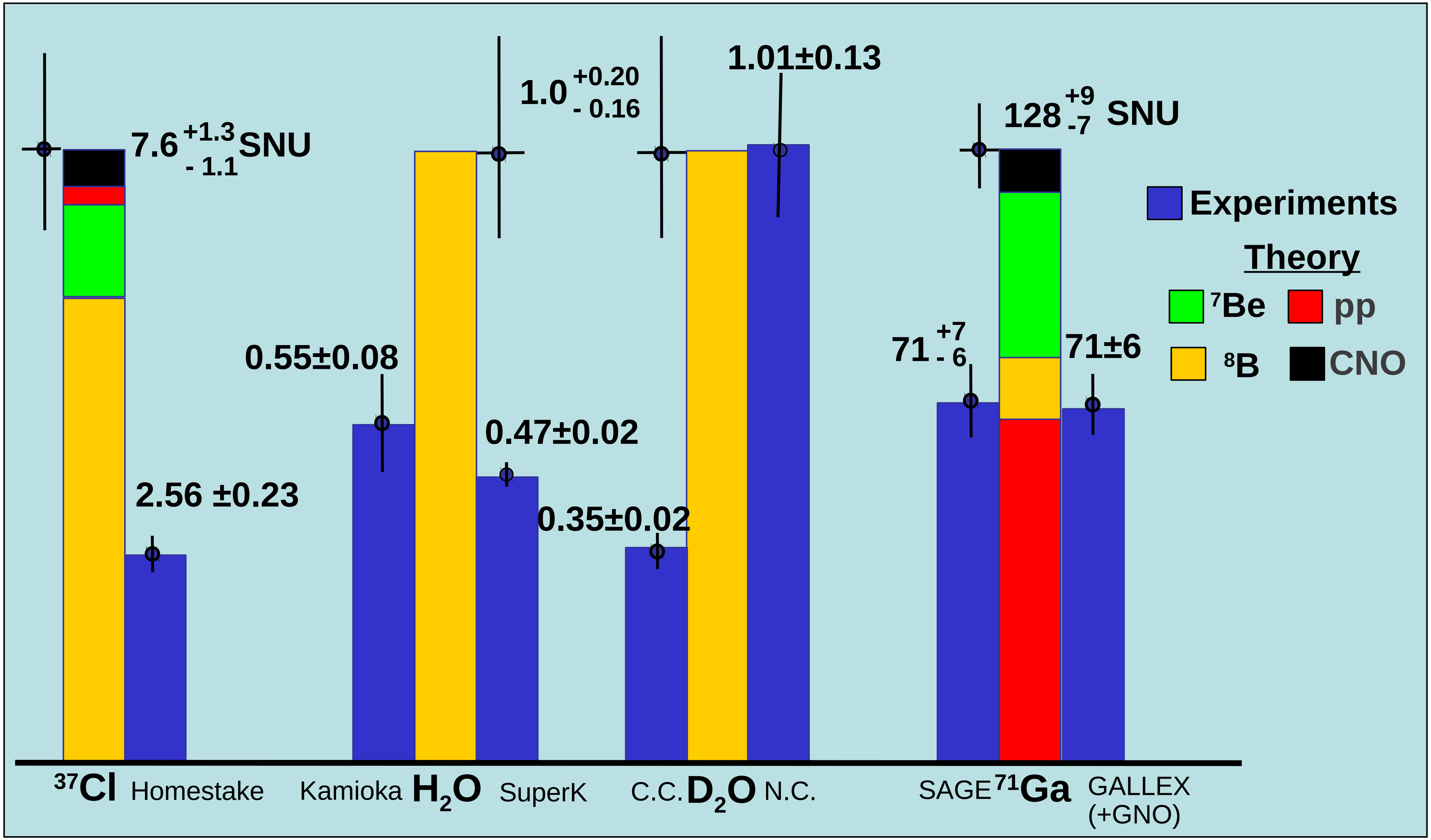
first to prove ν seen from Sun





The Sun (seen in neutrino "light")

Solar Neutrino Problem (1967 - 2001)

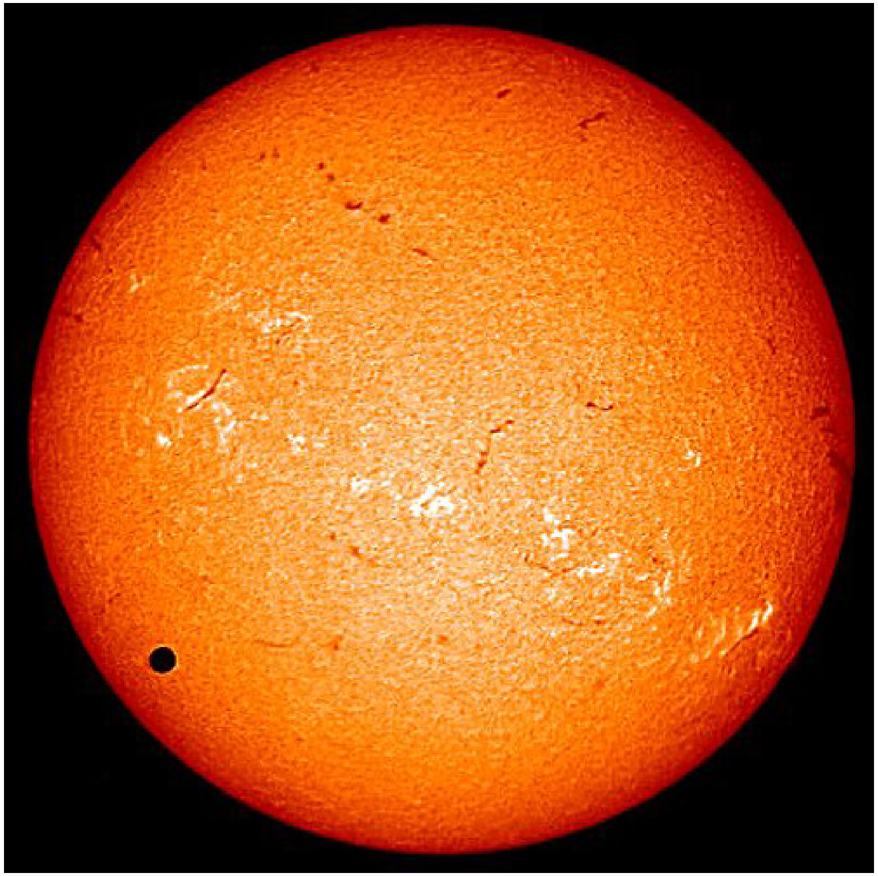


...but what does this teach us about the Sun?

Neutrino Astronomy

Neutrino telescopes provide a unique look inside the sun

- Photons take about 10^6 years to exit
- Neutrinos leave "instantly"



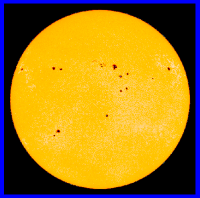
Over the years, solar ν have taught us:

1. Fusion powers the Sun
2. Original verification of SSM (later aided by helioseismology)
3. "pp" neutrinos strongly correlated w/ light
4. Rarer ν types give different information

For instance, from ^{8}B solar ν measurements, we know the temp. at the core of the Sun is: 1.5×10^7 K ± 1%

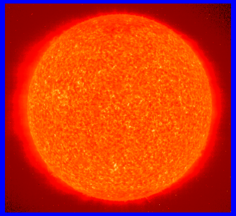
Supernova Progenitors

Main Sequence



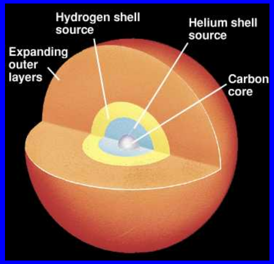
H core

Red Giant



He core
+ H shell

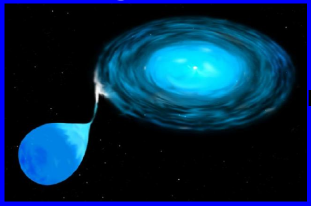
Supergiant



C & O core
He & H shells

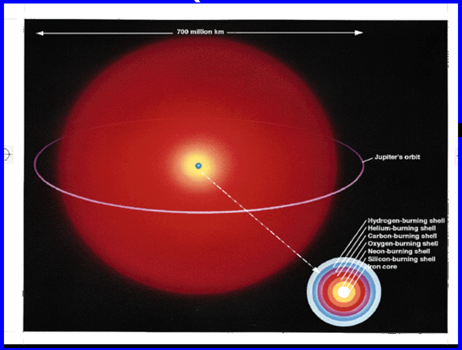
m > 8 M⊙?

Accreting White Dwarf



Carbon deflagration supernova (Type Ia)

"Onion" Shells
(H,He,C,O,Ne,Si,Fe)



Core Collapse!

Images taken from:
http://astron.berkeley.edu/~bmendez/ay10/2000/cycle/cycle.html

Supernovae: Neutrinos vs. Photons

Neutrinos (ν)

99% of the energy from a core-collapse supernova is released as neutrinos

ν emitted during SN, giving unique insight into the process of a supernova & neutron star formation

ν carry information direct from core; no scattering!

Photons (γ)

Only 1% energy appears as γ (+ tiny fraction as kin. energy)

Light (γ) emitted hours later, largely from decay of radioactive elements produced in the supernova's shock wave

γ scatters in dense, turbulent gas, losing information about its source

Supernova 1987A

To date, only SN ν burst came from Sanduleak -69° 202 in Large Mag. Cloud

Spotted on 23-Feb-1987, now more famously known as Supernova 1987A

24 (or 25) SN anti-neutrinos seen in two water Cherenkov experiments:

- 11 (or 12) at KamiokaNDE
- 8 at the competing IMB
- 5 at the Baksan observatory

Hundreds of papers written analysing these few neutrinos!

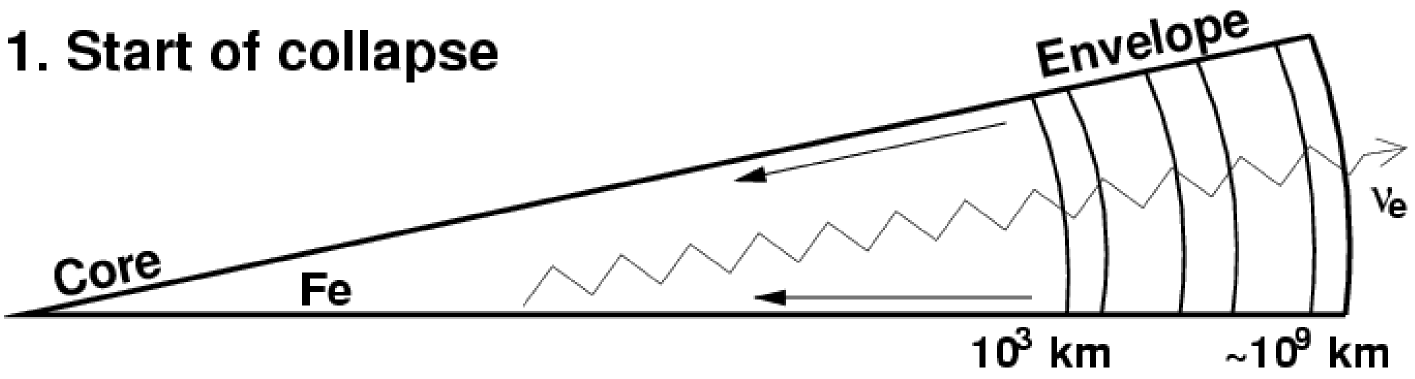
Today, a SN burst from the galactic centre (10 kpc) could provide up to 10,000 events!

Additionally, because ν are emitted first, they can be a useful early warning system for astronomers. SNEWS exists to alert astronomers of a nearby supernova.

Outline

- Introduction: Cosmic messengers and Neutrinos
- Historical results: Solar neutrinos and SN 1987A
- **Recent results: Astronomical neutrinos**
  - **Supernovae and supernova relic neutrinos**
  - Indirect searches for dark matter
  - Other areas of interest
- Recent results: Terrestrial neutrinos
  - Absolute mass measurements and the neutrino mass hierarchy
  - Matter / Anti-matter asymmetry: CP violation and Leptogenesis
- Summary & conclusions

Supernova Neutrino Emission

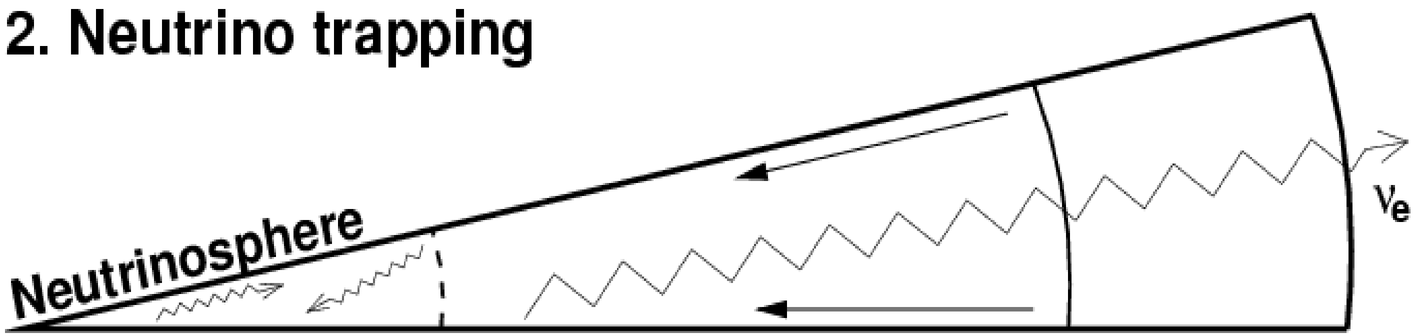


- Electrons captured on nuclei produce ν_e via:

$$e^- + A(N,Z) \rightarrow \nu_e + A(N+1,Z-1)$$

- Mean free path of neutrinos > core size
- Neutrinos escape promptly

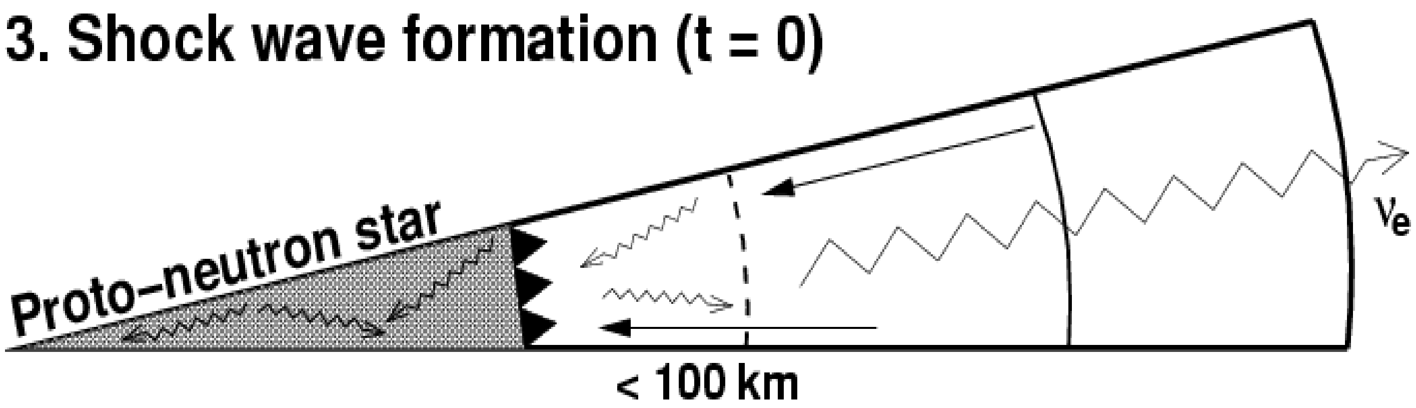
Supernova Neutrino Emission



- Core density increases as collapse continues
- Mean free path of ν shrinks w/ increasing density
- Neutrinos trapped by scattering off nuclei:

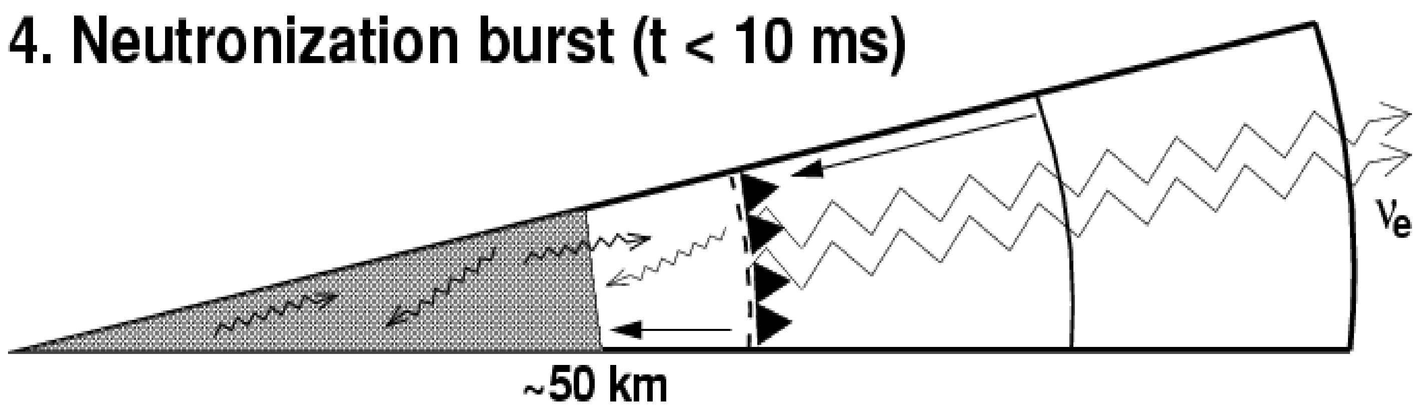
$$\nu + A(N,Z) \rightarrow \nu + A(N,Z)$$

Supernova Neutrino Emission



- Inner core reaches nuclear densities
- Neutron degeneracy halts gravitation attraction
- Inner core rebounds, causing shock wave
- Shock wave propagates through infalling outer core
- Larger ν-sphere; νs still emitted from outer core

Supernova Neutrino Emission



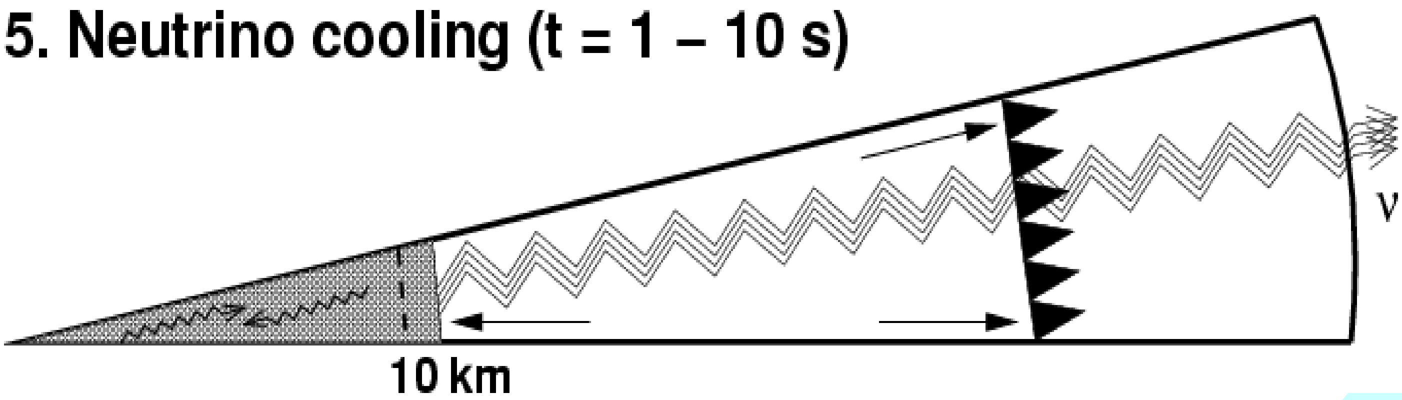
- Shock slows infalling matter and separates nucleons
- Shock loses energy (8 MeV) per dissociated nucleon

→ eventually stalls (revives how?)

- Electrons captured on dis. protons produce ν_e via:

$$e^- + p \rightarrow \nu_e + n$$

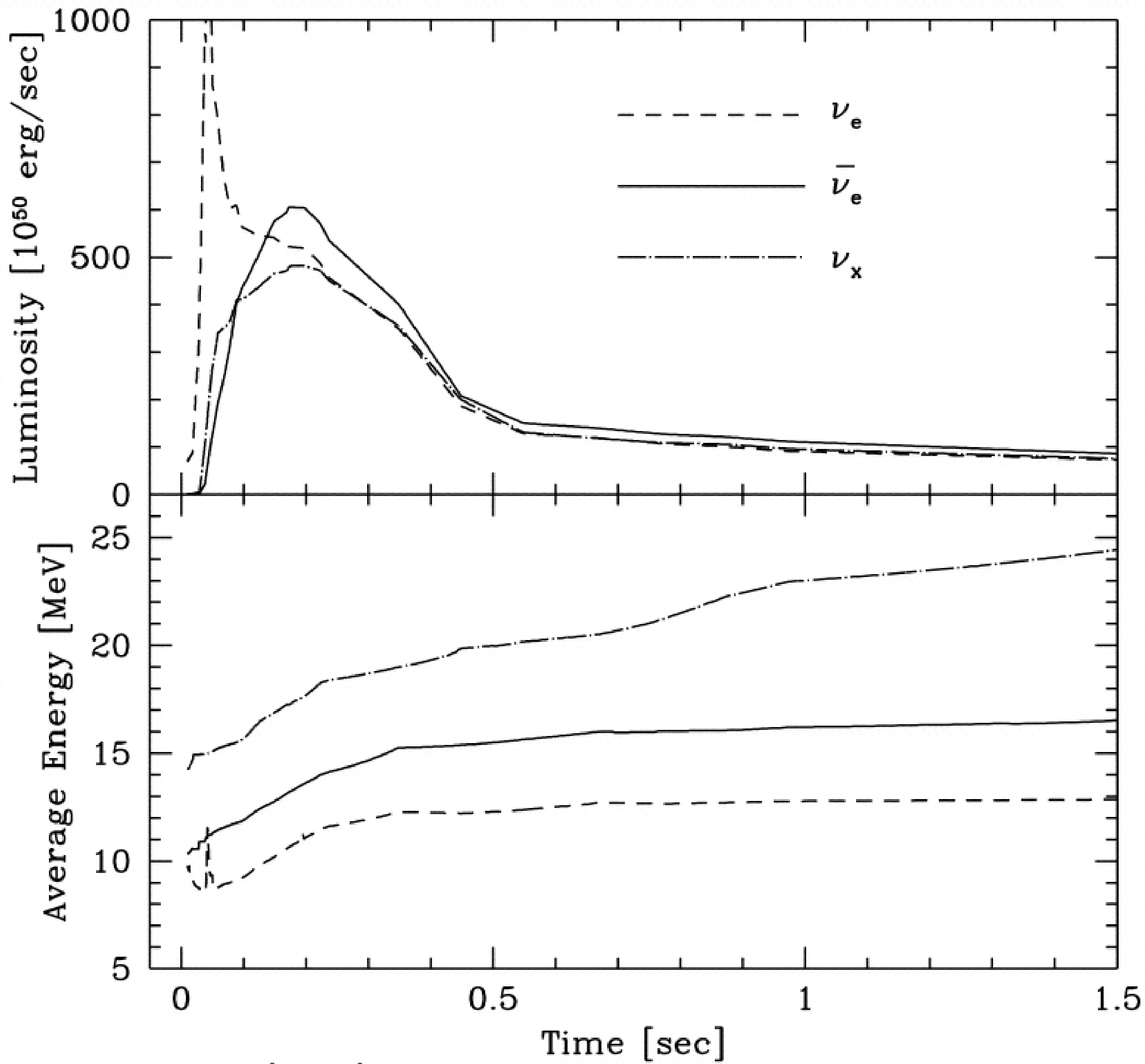
Supernova Neutrino Emission



- $E_{grav} \rightarrow E_{therm}$, about 10^{46} Joules
- $T \approx 40$ MeV $\approx 500{,}000{,}000{,}000$ K
- Proto-neutron star cools, producing ν
  - Unlike previously, all 6 types are generated
- Neutron star (or black hole?) left behind

$$e^- + p \rightarrow \nu_e + n$$
$$e^+ + n \rightarrow \bar{\nu}_e + p$$
$$e^- + e^+ \rightarrow \nu + \bar{\nu}$$
$$e^\pm + N \rightarrow e^\pm + N + \nu + \bar{\nu}$$
$$N + N \rightarrow N + N + \nu + \bar{\nu}$$
$$\gamma\,(+\,e^\pm) \rightarrow \nu + \bar{\nu}$$

Supernova Neutrino Spectra



From Totani and Sato

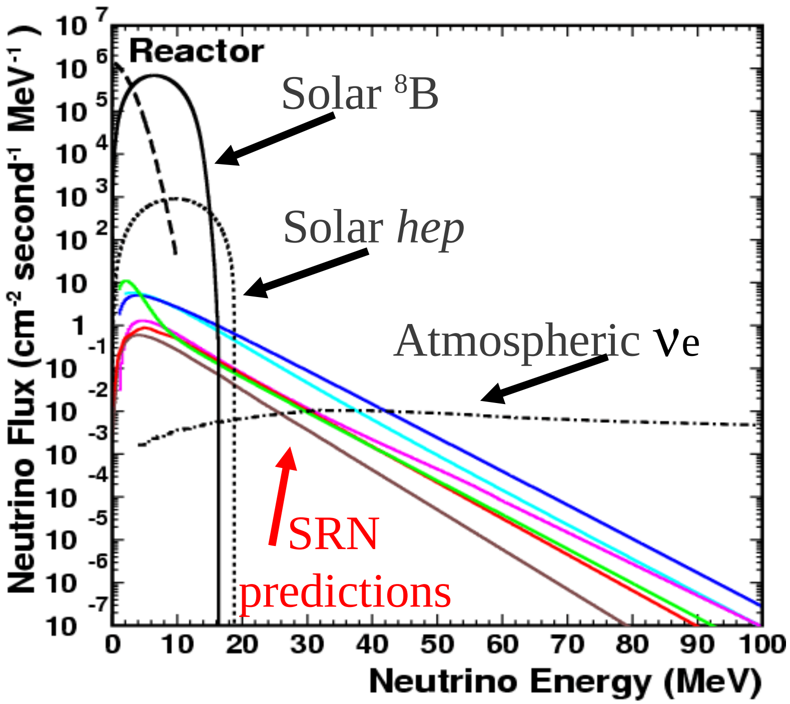
- Time evolution of luminosity and average energy for neutrinos emitted during a supernova
- Roughly equal energy carried away by each of the six species of neutrinos
- However, spectra for ν_x, $\bar{\nu}_e$, ν_e differ due to time of decoupling from neutrinosphere

Supernova Relic Neutrinos

SRN should be an isotropic background composed of ν from **all** SN explosions

Predictions obtained by taking $\overline{\nu_e}$ spectrum from single SN and redshifting according to SN rate

Natural energy window to search



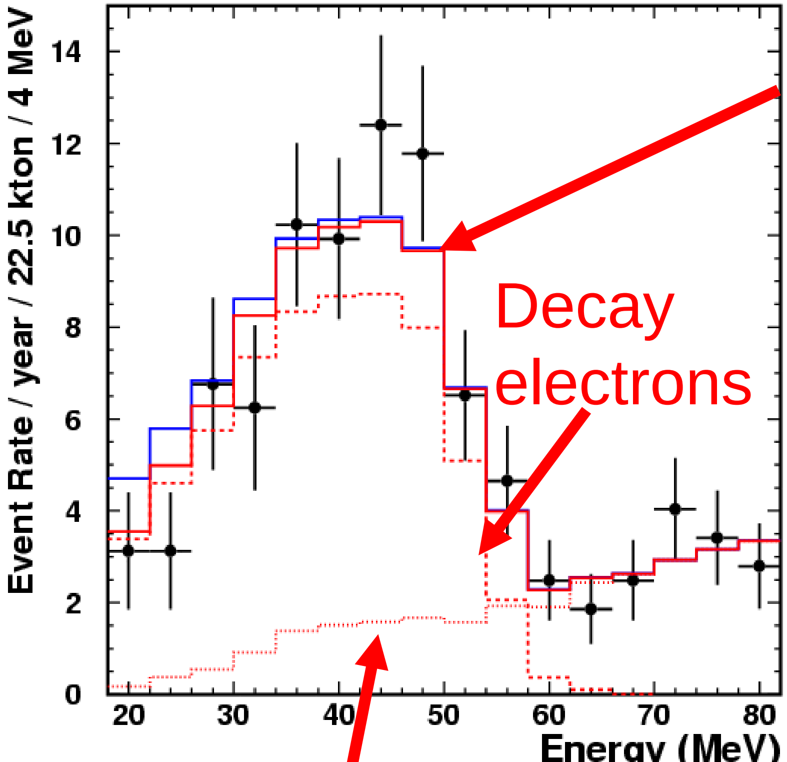
Massive stars – with relatively short lives – die in core-collapse

Thus, SN rate is a good tracker of star formation rate!

→ Birth of ν cosmology??

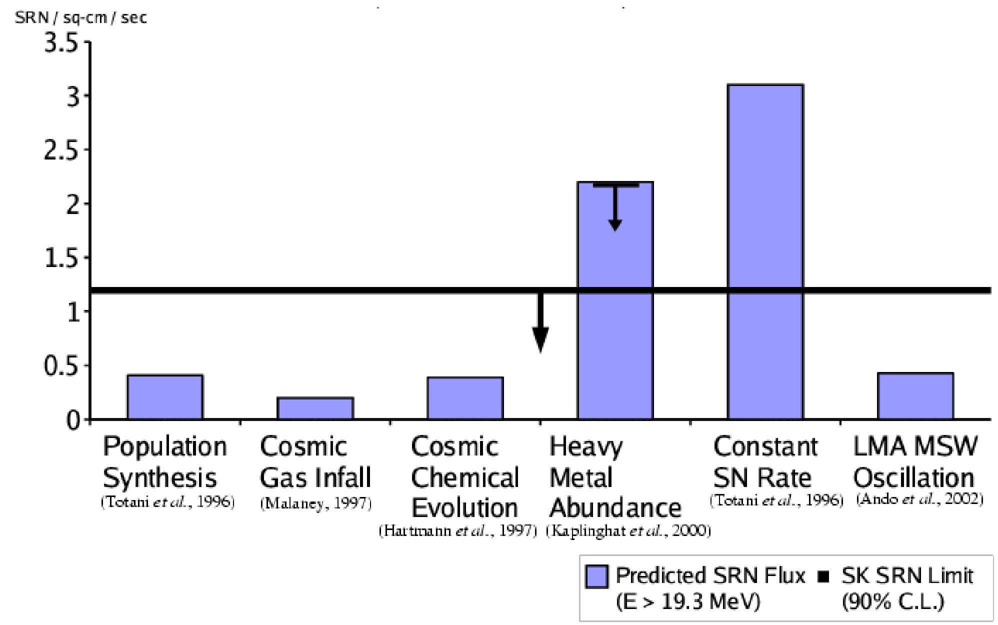
SRN Search Results

From M. Malek *et al* (arXiv:hep-ex/0209028)



Total background (Atm. + decay e)

Atmospheric ν_e

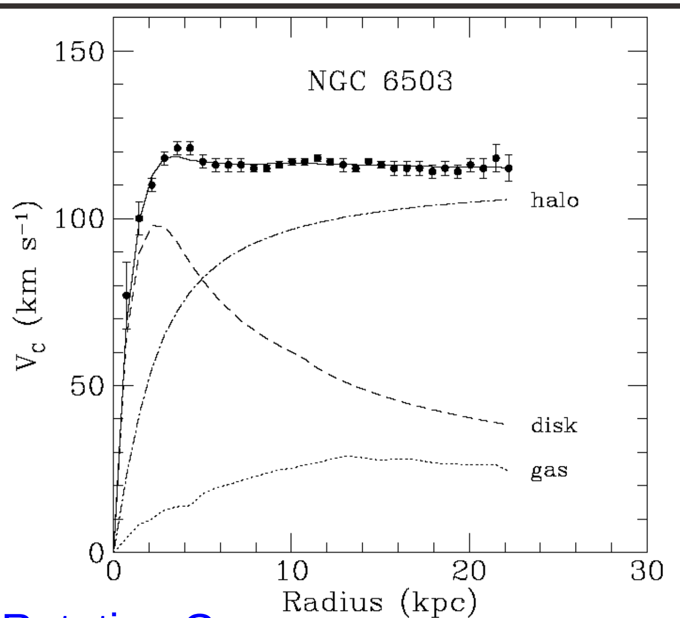


- SRN signal would manifest as distortion of BG
- No such signal seen yet → some models ruled out
- R&D underway on using Gd to tag SRN events

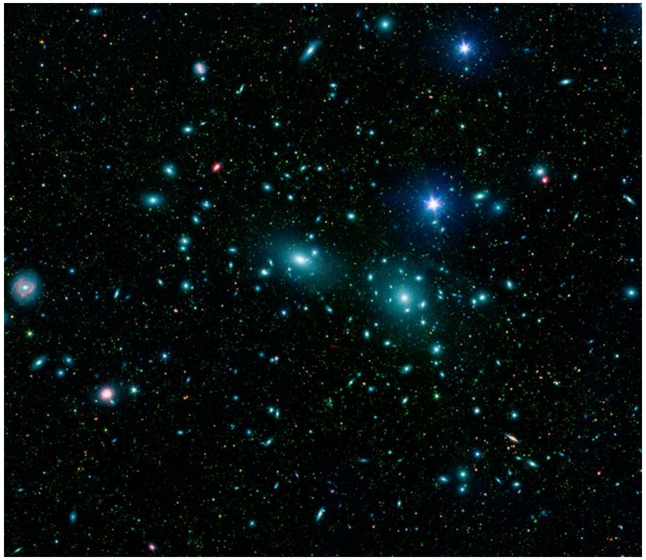
Outline

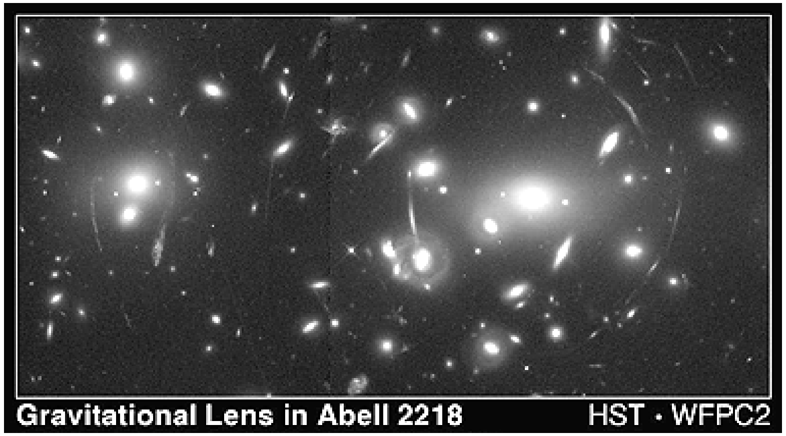
- Introduction: Cosmic messengers and Neutrinos
- Historical results: Solar neutrinos and SN 1987A
- **Recent results: Astronomical neutrinos**
  - Supernovae and supernova relic neutrinos
  - **Indirect searches for dark matter**
  - Other areas of interest
- Recent results: Terrestrial neutrinos
  - Absolute mass measurements and the neutrino mass hierarchy
  - Matter / Anti-matter asymmetry: CP violation and Leptogenesis
- Summary & conclusions

The "Missing Mass" Problem



Rotation Curves


Motion of Galaxies in Clusters



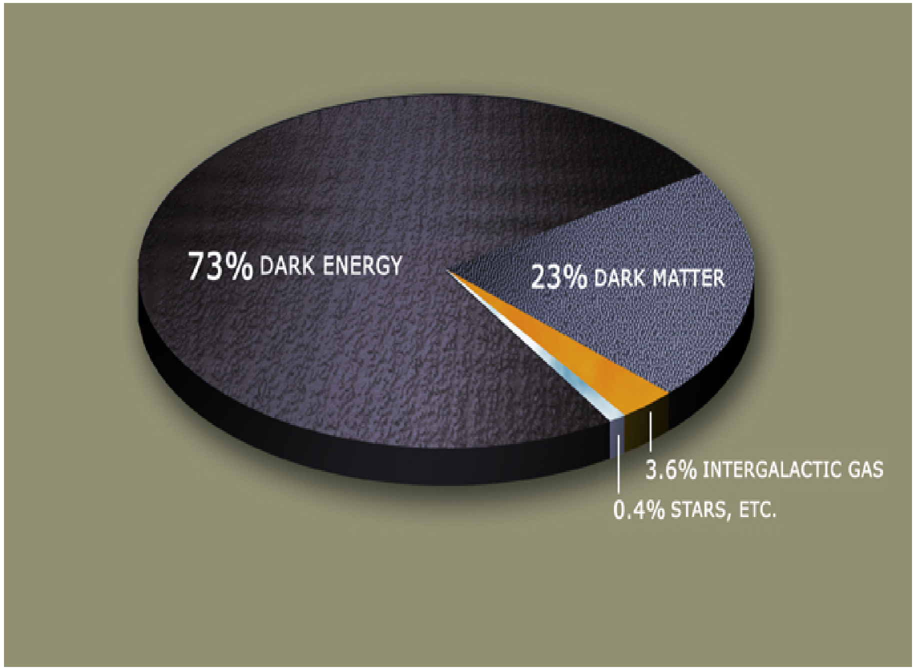
Gravitational lensing

For decades, astrophysical evidence that ***something*** unexpected was going on…

Dark Matter?
New theory of gravity?
(*e.g.*, Modified Newtonian Dynamics)

The Case for Cold Dark Matter

blue = lensing
red = x-rays



- Evidence points to non-relativistic non-baryonic dark matter.
- Several candidates; the "WIMP Miracle" makes SUSY WIMPs in the GeV to TeV mass range particularly intriguing.
- Many dedicated experiments conducting direct searches; indirect searches, via neutrinos, are also possible...

Indirect WIMP Detection

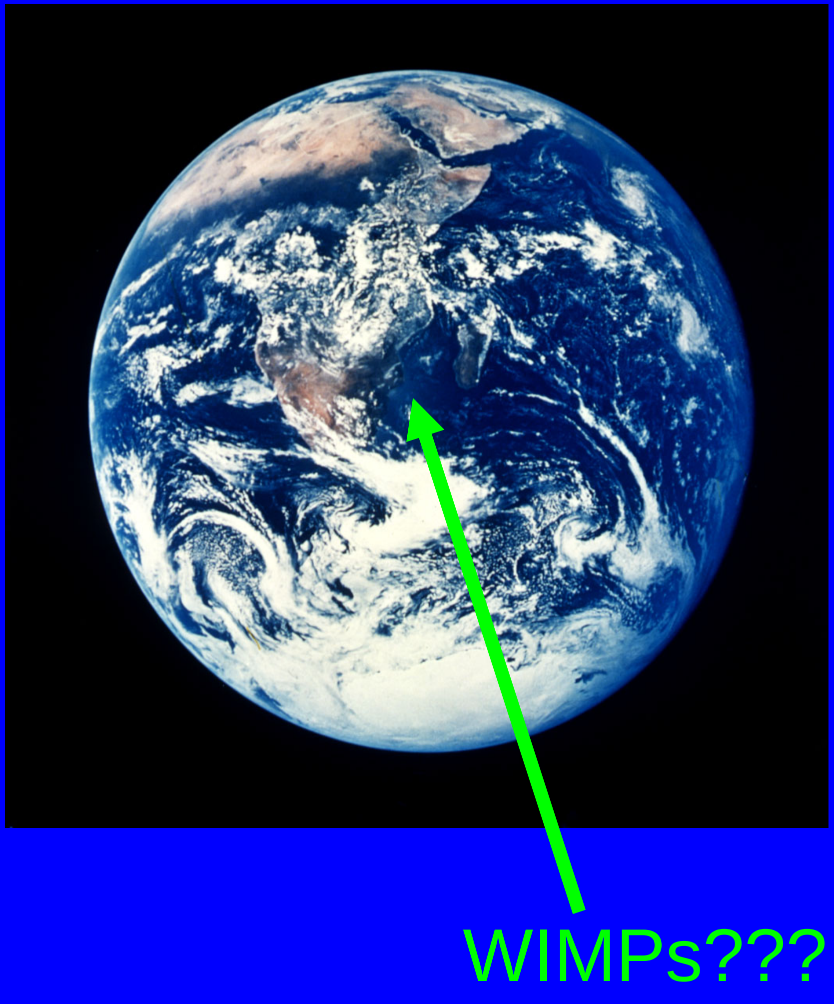
- WIMPs congregate at center of massive objects (*e.g.*, Earth, Sun, galaxy)

- WIMPs are also anti-WIMPs; thus, they annihilate, producing:

  positrons, neutrinos, X-rays,
  gamma rays, anti-protons, etc.

- Use:

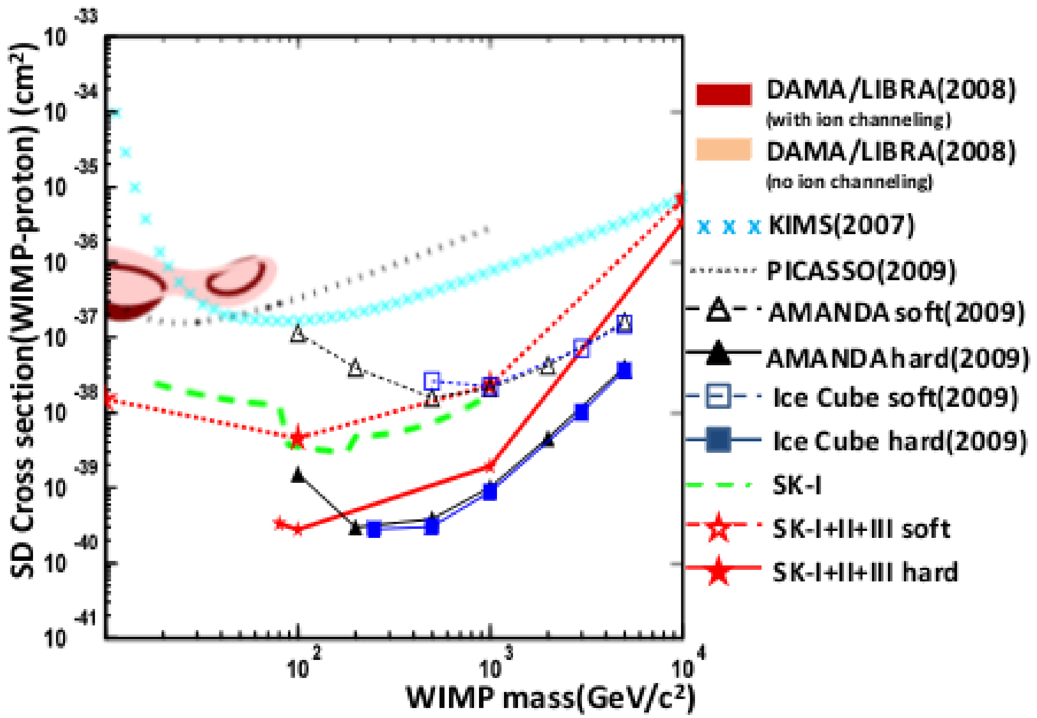
  gamma ray telescopes (Fermi LAT),
  neutrino detectors (Super-K, IceCube),
  anti-matter space probes (PAMELA)
  to search for excess events from those directions



WIMP Search Results

- Direct and indirect WIMP search results compared for several experiments
- "Soft" channel is $b\bar{b}$

  "Hard" channel is W^+W^-
- Indirect searches using the center of the Sun as WIMP annihilation point
- Results are competitive with some direct searches



From arXiv 1108.3384

Outline

- Introduction: Cosmic messengers and Neutrinos
- Historical results: Solar neutrinos and SN 1987A
- **Recent results: Astronomical neutrinos**
  - Supernovae and supernova relic neutrinos
  - Indirect searches for dark matter
  - **Other areas of interest**
- Recent results: Terrestrial neutrinos
  - Absolute mass measurements and the neutrino mass hierarchy
  - Matter / Anti-matter asymmetry: CP violation and Leptogenesis
- Summary & conclusions

Other Sources of Cosmic ν

Thus far, only source of extra-solar ν is SN1987a.

Other possible types include:

- **High E:** Collisions of galactic cosmic rays produce $\pi^{\pm}$, which decay into ν (& other things…)
  [AMANDA, ANTARES, ICECUBE, NESTOR]

- **Ultra-High E:** Collisions of extra-galactic cosmic rays
  [ANITA, GLUE, RICE, Pierre Auger Observatory]

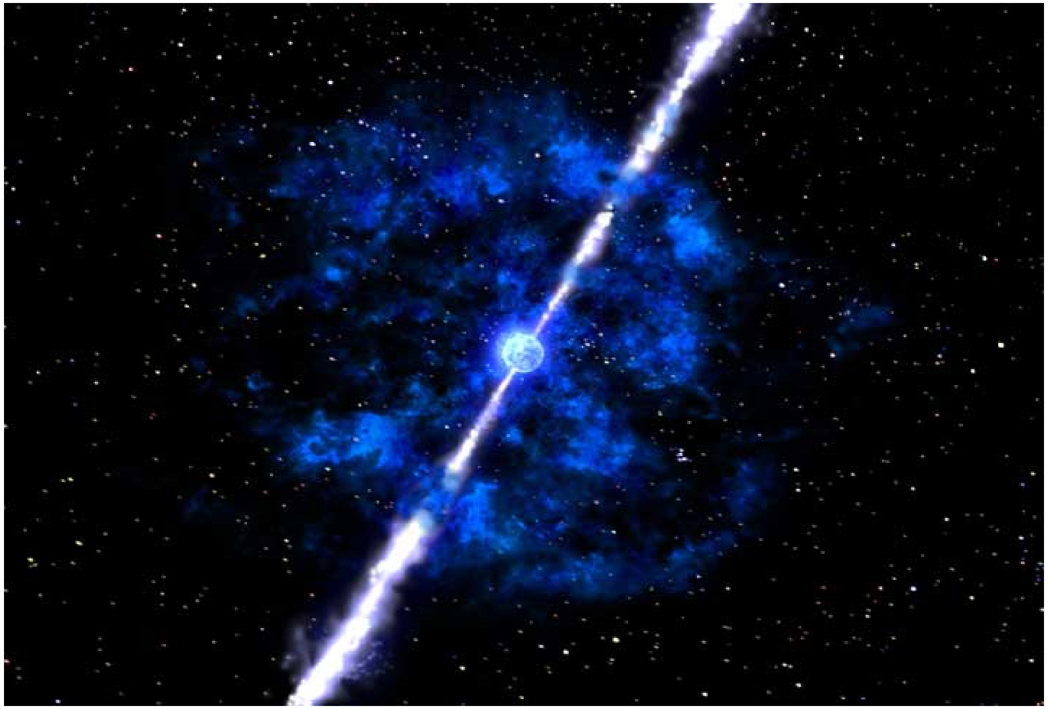
- **Ultra-Low E:** Relics from the Big Bang, with temperature of 1.9 K (equiv. E = 1.7×10^{-4} eV)

High Energy Cosmic ν

- Likely to correlate to point sources (*e.g.*, Gamma Ray Bursts, Active Galactic Nuclei)
- Typical search method involves checking for an excess of ν events around the time of a GRB, using a catalog like BATSE

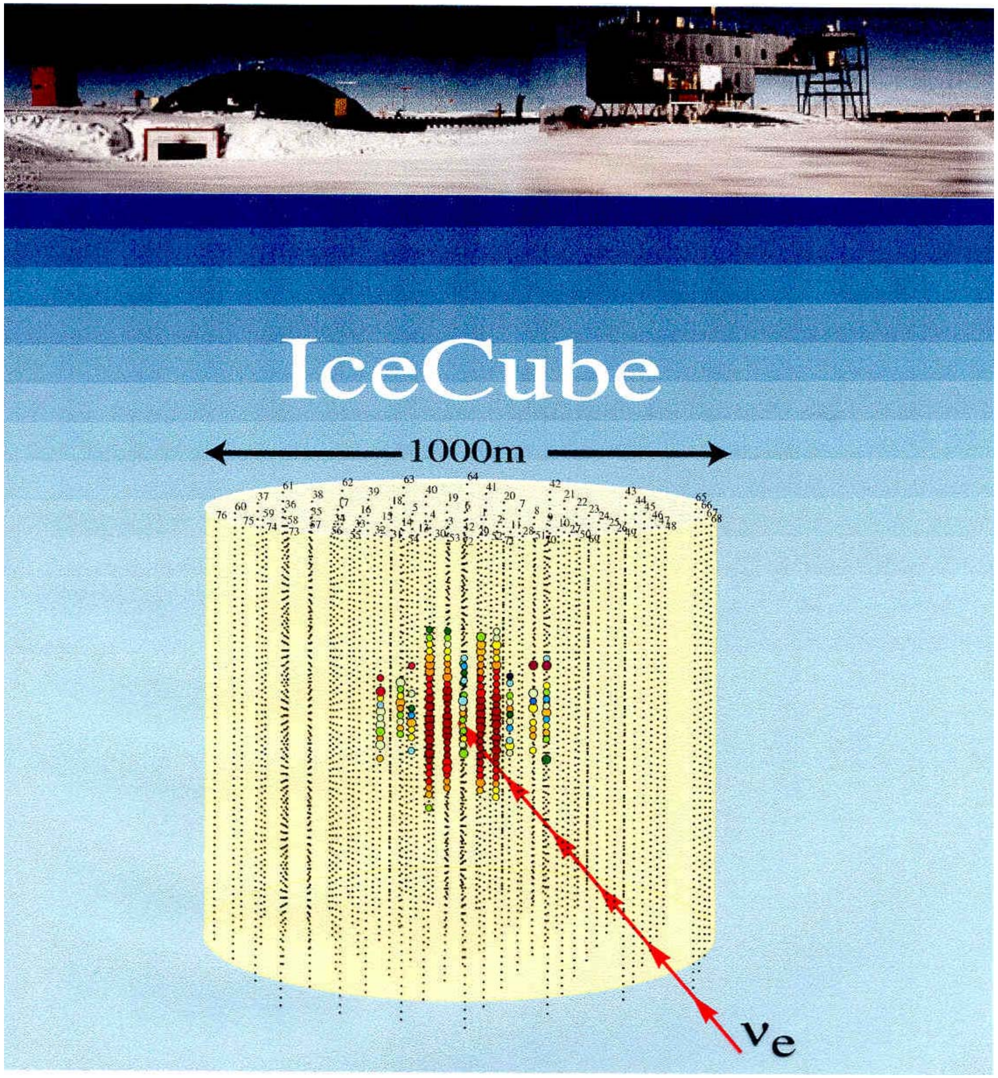
Thus far, searches have been done by MACRO, Super-Kamiokande, etc.

→ No correlations found



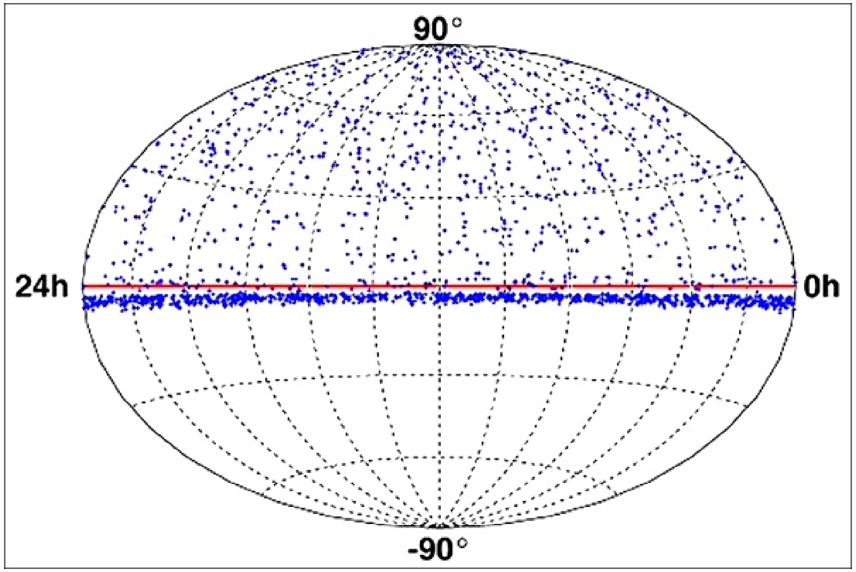
GRB 080916C imaged by Fermi LAT

Dedicated Observatories

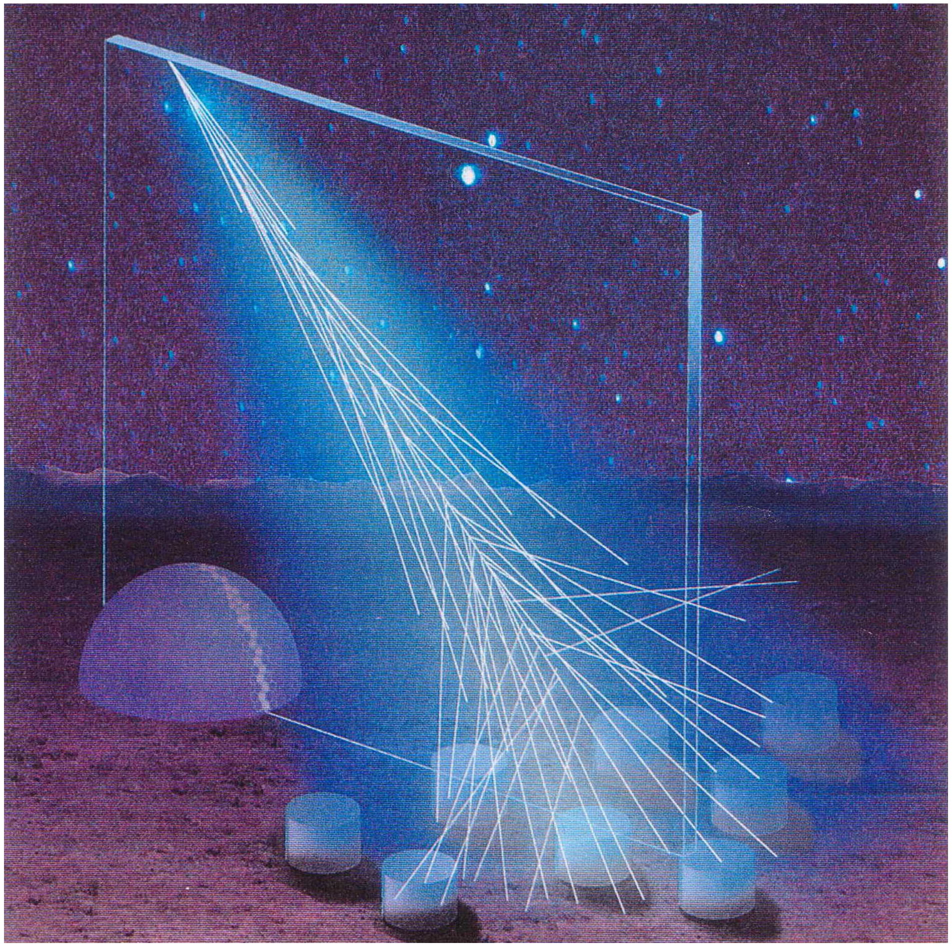


IceCube is an ice Cherenkov observatory at the South Pole, covering 1 km^3 of ice

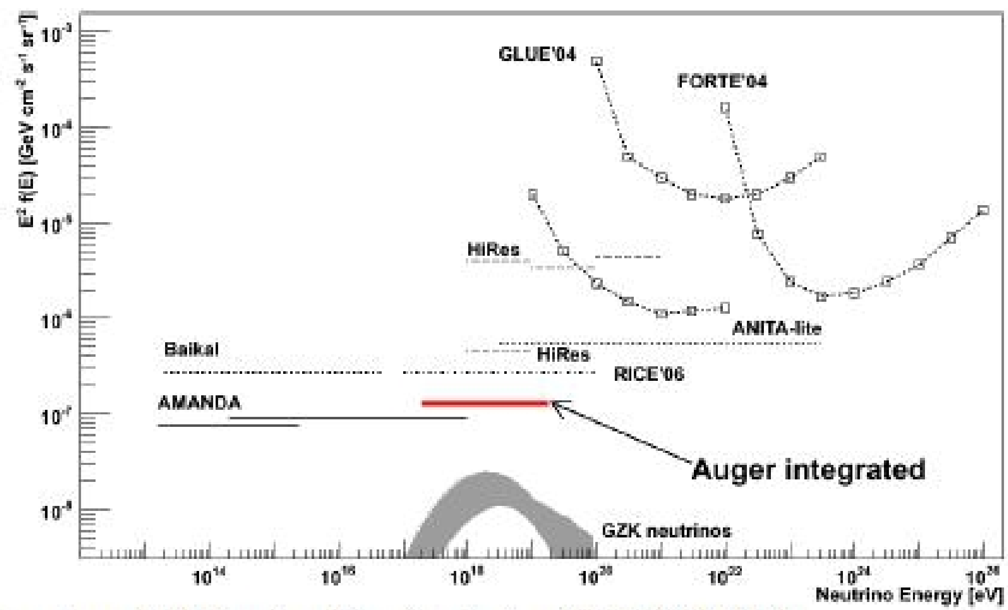
Skymap shows no sign of sources yet...



Ultra-High Energy Cosmic ν



- Unusual detection techniques:
  - GLUE: Uses lunar limb as target and searches for radio emission
  - ANITA: Antarctic balloon searches for radio pulses in ice
  - Pierre Auger: Uses Andes as target; searches for horizontal air showers w/ high EM component



Pierre Auger Collaboration, Phys. Rev. Letters 100 (2008) 211101

No sources discovered yet, though GZK ν seem a "guaranteed" source

Outline

- Introduction: Cosmic messengers and Neutrinos
- Historical results: Solar neutrinos and SN 1987A
- Recent results: Astronomical neutrinos
  - Supernovae and supernova relic neutrinos
  - Indirect searches for dark matter
  - Other areas of interest
- **Recent results: Terrestrial neutrinos**
  - Absolute mass measurements and the neutrino mass hierarchy
  - Matter / Anti-matter asymmetry: CP violation and Leptogenesis
- Summary & conclusions

Neutrino Oscillations

- Parameterization of the PMNS matrix U_{li} (from slide 6):

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Contains a CP violating phase (δ)
- Oscillation probability depends on energy (E), distance travelled (L), the mixing matrix (U), and the difference in the squares of the neutrino masses (Δm^2)

$$P_{\alpha\rightarrow\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$
$$+2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

Oscillation Parameters

- Standard parameterization for Dirac neutrinos has:
  3 mixing angles, 2 mass square differences, 1 CP phase

$\sin^2(2\theta_{12}) = 0.87 \pm 0.03$ $\Delta m^2_{12} = 7.59 \pm 0.20 \times 10^{-5}\ eV^2$ SNO, KAMLAND, SK

$\sin^2(2\theta_{23}) > 0.92\ \ (90\%\ \ C.L.)$ $\Delta m^2_{23} = 2.43 \pm 0.13 \times 10^{-3}\ eV^2$ SK, K2K, MINOS

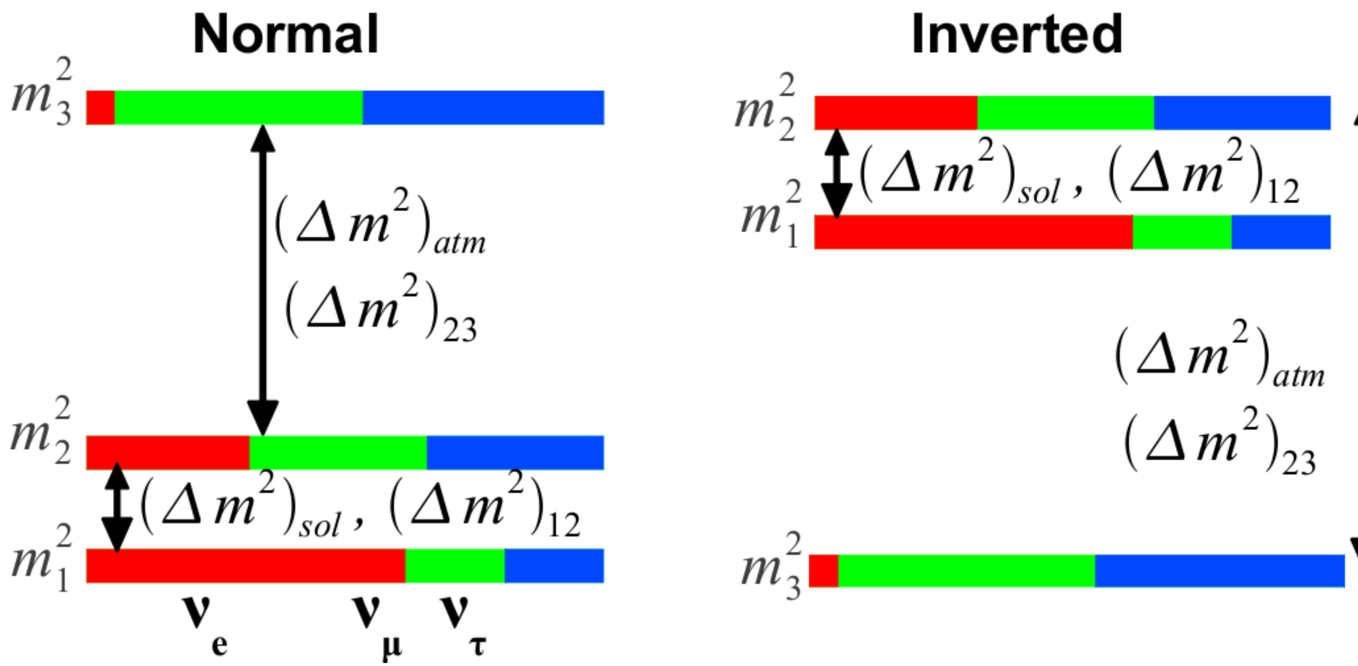
$\sin^2(2\theta_{13}) < 0.12\ \ (90\%\ \ C.L.)$ MINOS(2010), CHOOZ

$\delta = ?$

Ambiguity in sign of

$$m_3^2 - m_2^2$$

Two possible mass hierarchies



Connections to Cosmos

- Determination of mass hierarchy is relevant to:
  - Total mass contribution from neutrinos (by factor ~2)
  - Alters the flavors of supernova neutrinos, where:

$$T_{\text{heavy flavor}} > T_{\bar{\nu}_e} > T_{\nu_e}$$

(affecting nucleosynthesis processes, and changing interpretation of signals seen in terrestrial detectors)

- CP violation (δ) could explain matter/anti-matter asymmetry via leptogenesis.

Leptogenesis

- Today: B ≡ #(Baryons) – #(Anti-baryons) ≠ 0

  Standard cosmology says: B = 0, immediately after Big Bang

  → How do we go from B = 0 to B ≠ 0? CP violation needed!

- CP violating in quark sector measured in K and B decays

  → Too small!

- Perhaps CP violation in the leptonic sector is sufficient?

$$\Gamma\left(N \to \ell^- + H^+\right) \neq \Gamma\left(N \to \ell^+ + H^-\right)$$

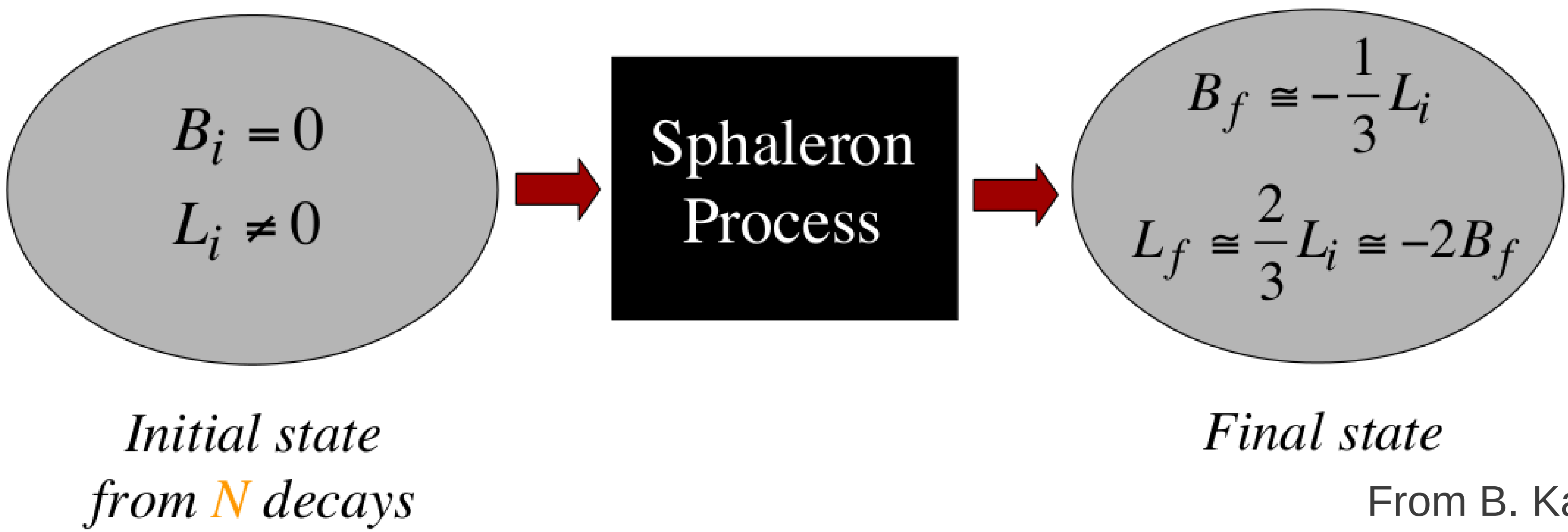
$$\Gamma\left(N \to \nu + H^0\right) \neq \Gamma\left(N \to \overline{\nu} + \overline{H^0}\right)$$

→ L ≡ #(Leptons) – #(Anti-leptons) ≠ 0

Leptogenesis

- The Standard Model includes a static solution to the electroweak field equations, known as the Sphaleron process.
- This non-perturbative process converts three anti-leptons to three baryons (three leptons to three anti-baryons)

  → B and L are not conserved; (B – L) ***is*** conserved



From B. Kayser

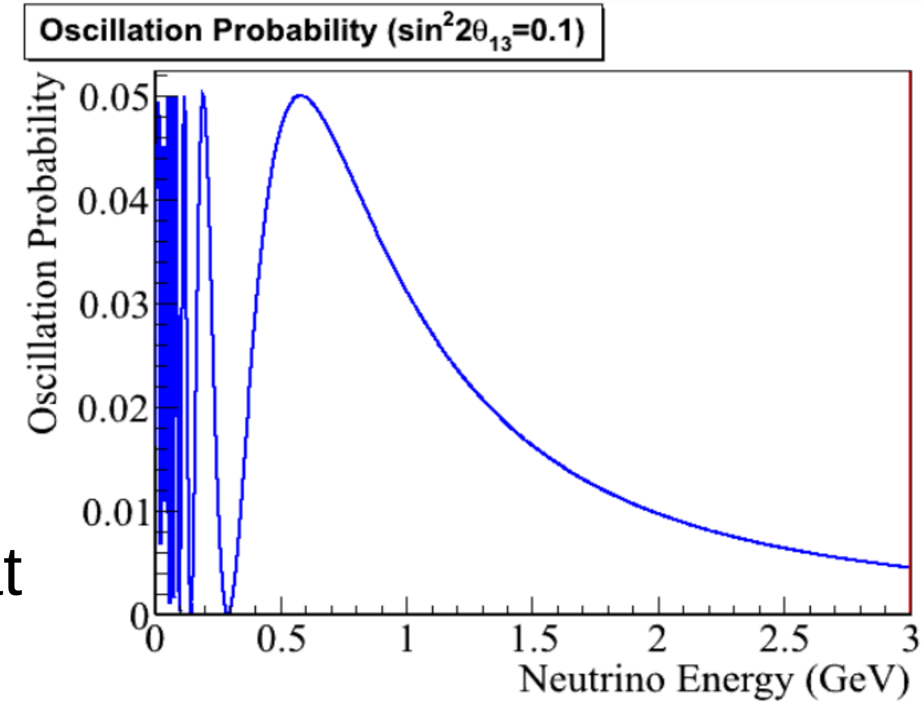
- Leptonic CP violation + Sphaleron process could explain the matter / anti-matter asymmetry in the Universe!

Measure θ_{13} First

At accelerator-based experiments, access to θ_{13} is via oscillation of muon neutrinos to electron neutrinos.

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32} L}{4E_\nu} + \text{subleading terms}$$

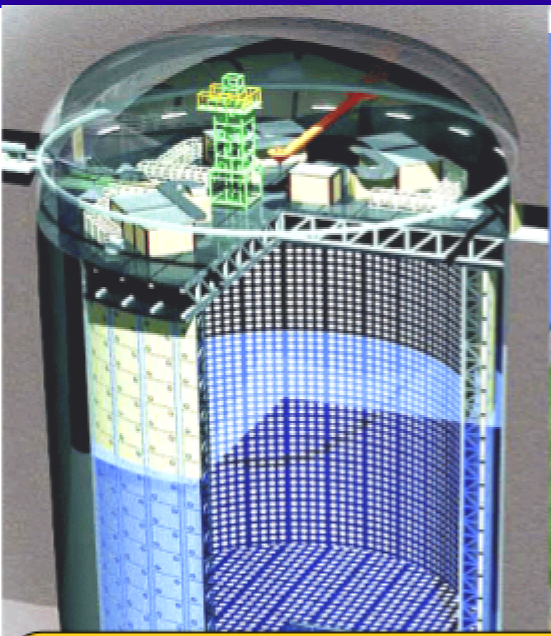
ν_e appearance prob. shown for the T2K baseline (L=295km) and $\sin^2(2\theta_{13}) = 0.1$ (with subleading terms ignored)



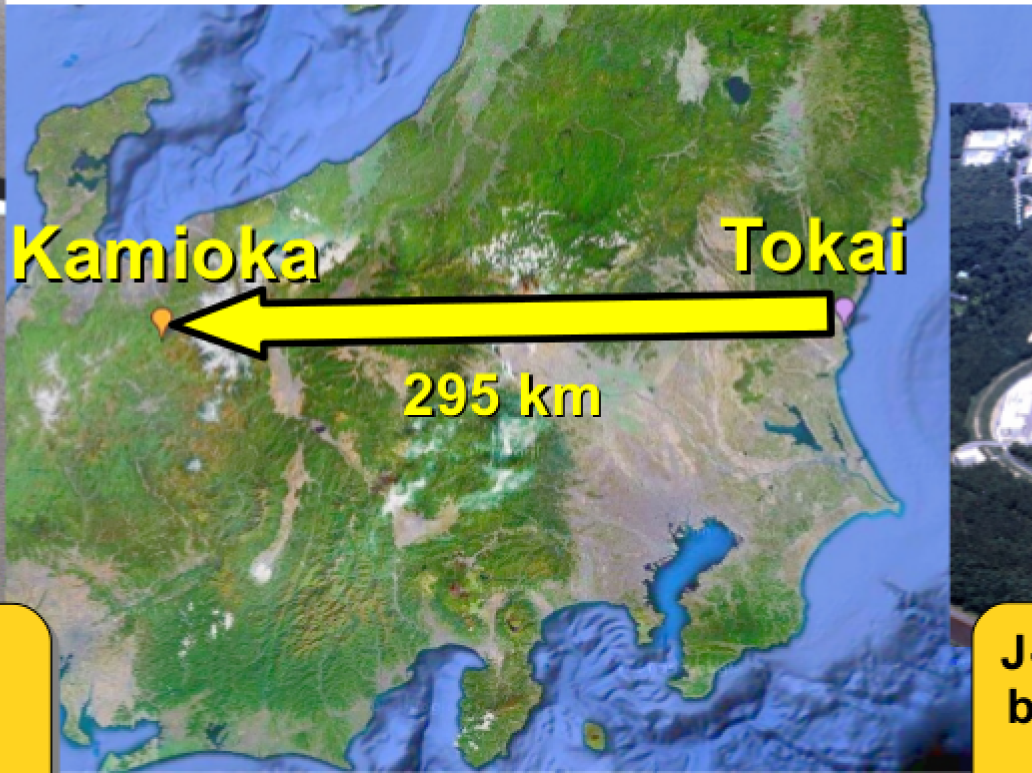
Experiment design:

- ν_μ beam with energy peaked at oscillation maximum
- Search for ν_e appearance

Tokai to Kamioka (T2K)



Super-Kamiokande 22.5 kton (fiducial) water cherenkov detector at 295 km



J-PARC: 30 GeV proton beam, design power of 750 kW

- Experimental goals:
  - Search for ν_e appearance
  - Precision ν_μ disappearance
  - Other (ν cross sections, sterile ν searches, etc.)

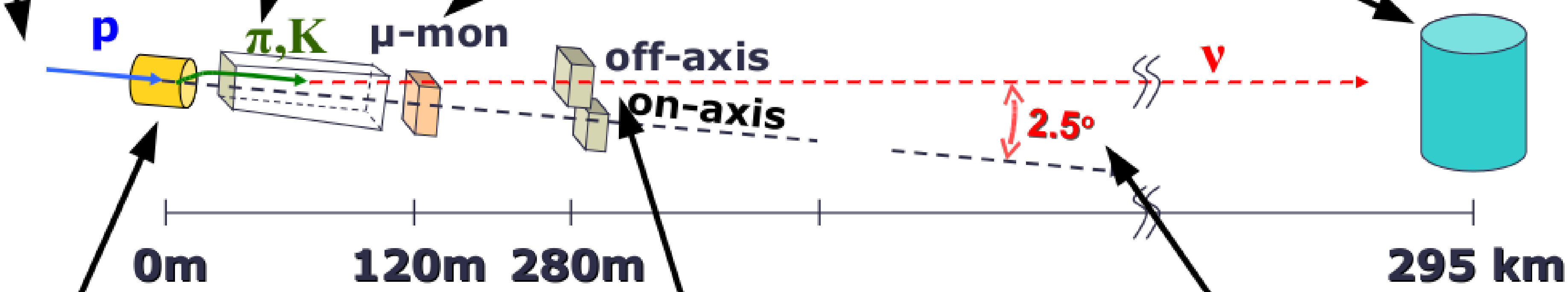
Experimental Overview

30 GeV proton beam from J-PARC

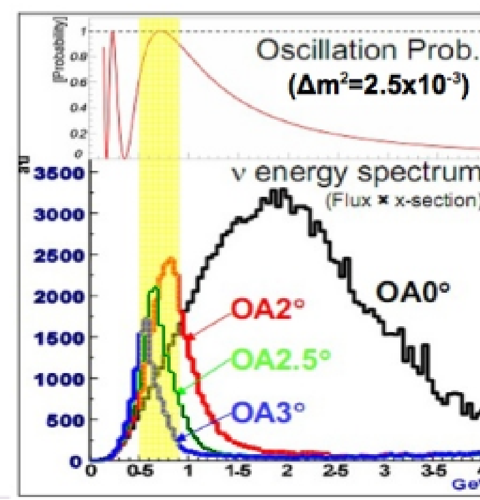
Pions, kaons, muons decay in 96 m decay volume

MUMON measures muons from pion decay

Off-axis **far detector** at 295 km: Super-Kamiokande (SK) water cherenkov detector measures oscillated flux



Off-axis = narrow band beam



Beam on graphite target

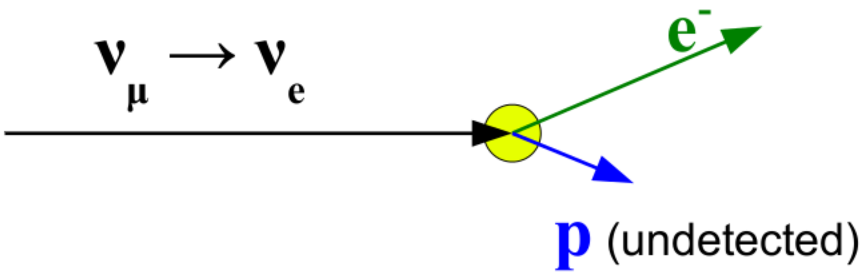
3 magnetic horns focus positively charged hadrons

At 280 m, on-axis INGRID detector measures neutrino rate, beam profile

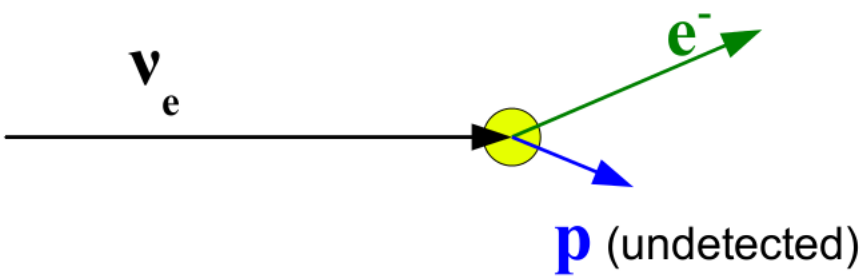
Off-axis **near detector**: ND280 detector measures spectra for various neutrino interactions

ν_e Signal & BG (at SK)

- Oscillation signal:

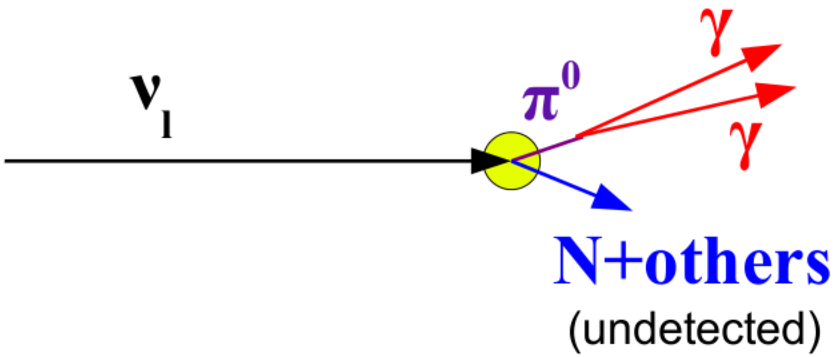


- Beam ν_e background:

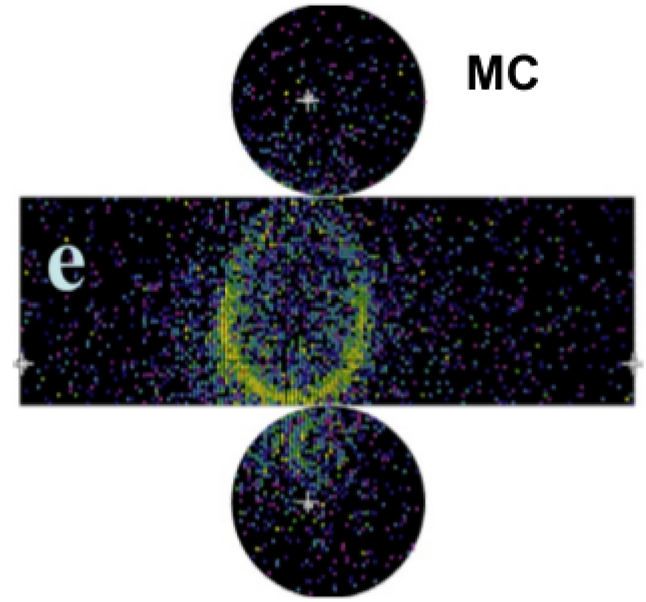


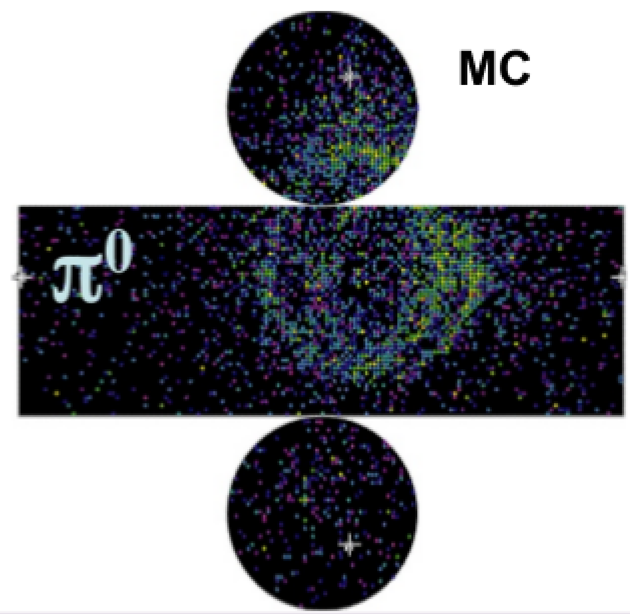
Beam background has harder energy spectrum

- Neutral current π^0 background:



Can be removed by identifying second photon ring



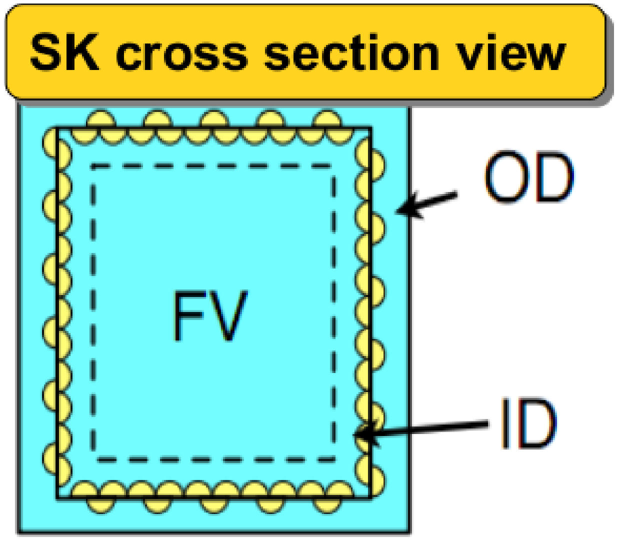


SK ν_e Event Selection

Select a single ring e-like sample, minimize beam and NCπ^0 backgrounds

Optimized for current statistics

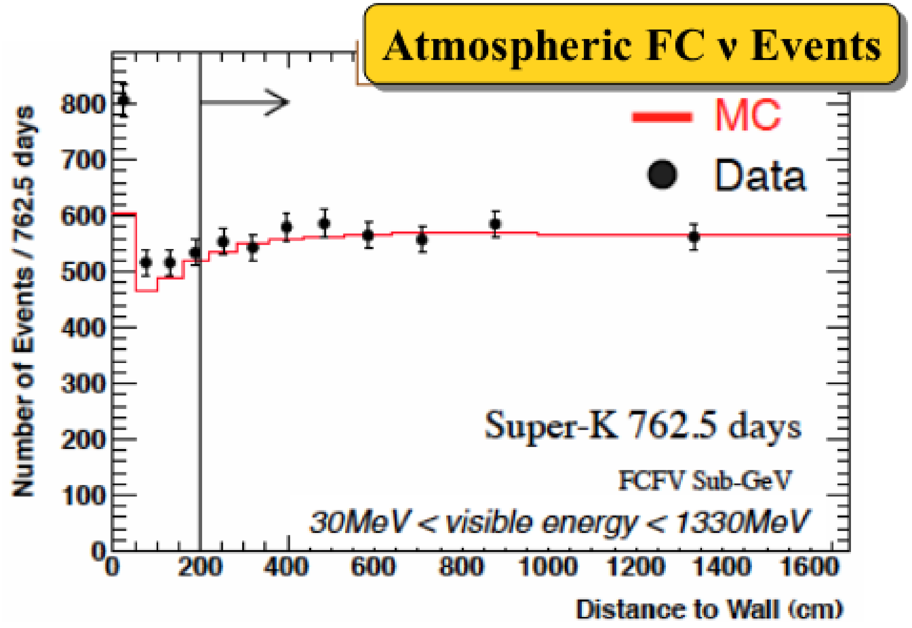
Cuts fixed before looking at data



1. Event falls in beam timing window, is fully contained in the inner detector (ID) (no activity in the OD)

2. Event vertex is >200 cm from the ID wall (fiducial volume cut)

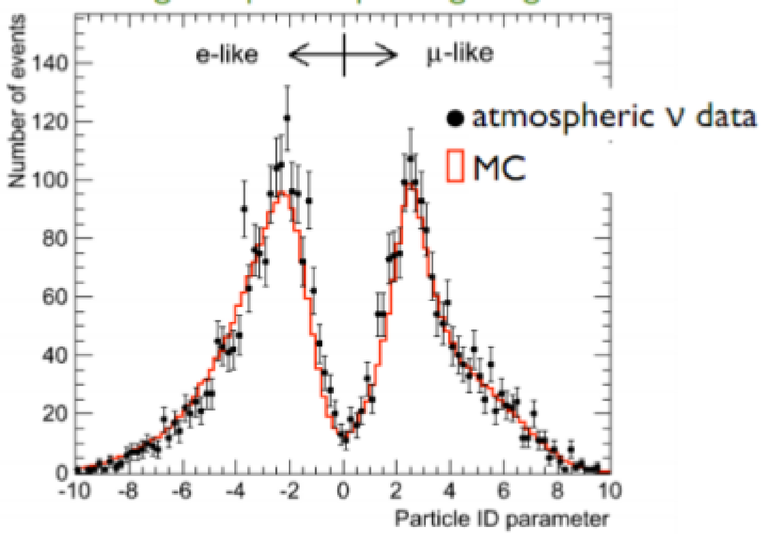
   - If particle direction is towards nearest wall: ring size ~ PMT spacing
   - Rejects events originating in OD
   - 22.5 kton within fiducial volume



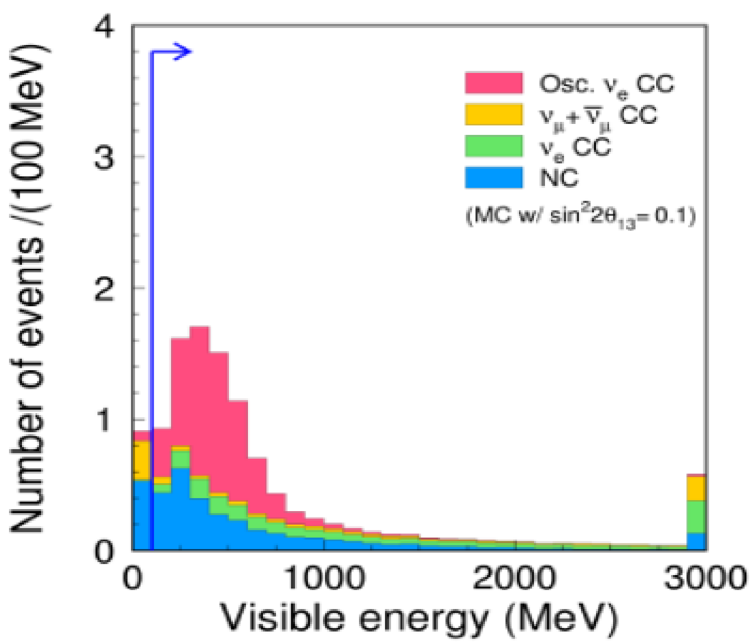
SK ν_e Event Selection

3. Select a single e-like ring
   - Particle ID based on ring shape
   - Good e/μ separation
   - Performance understood on atm. sample
   - ~1% probability to mis-ID μ as e

Particle identification using ring shape & opening angle



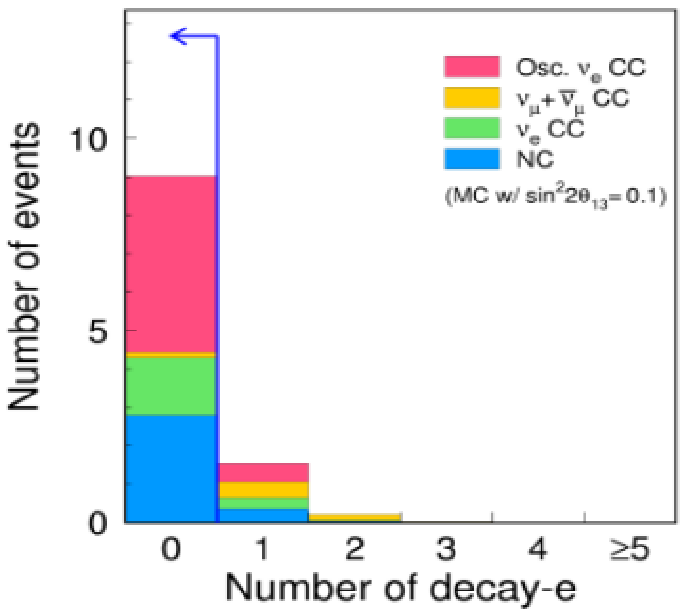
4. Visible energy > 100 MeV
   - Low energy events = NC background and electrons from μ decay



SK ν_e Event Selection

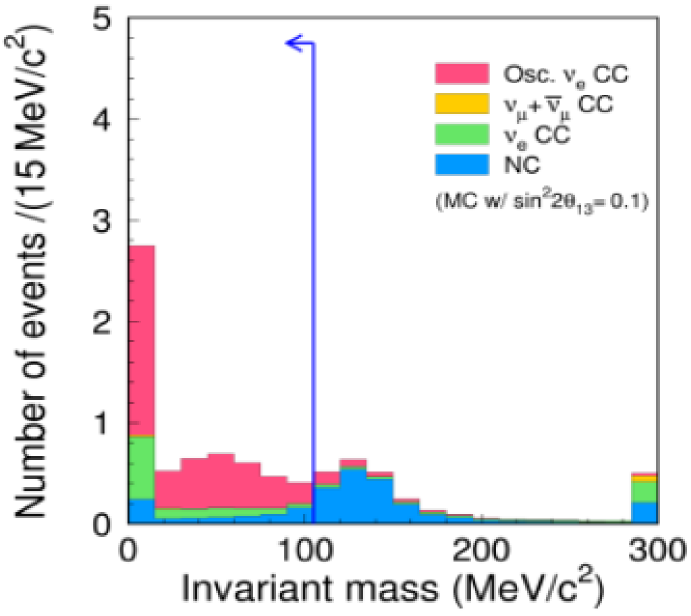
5. No decay electrons

- Reject based on delayed activity in SK
- Rejects events with μ or π below threshold or misidentified as electron



6. π^0 mass cut, $M_{inv} < 105$ MeV/c^2

- Calculate invariant mass with 2-ring hypothesis for each event
- Rejects NCπ^0 background



SK ν_e Event Selection

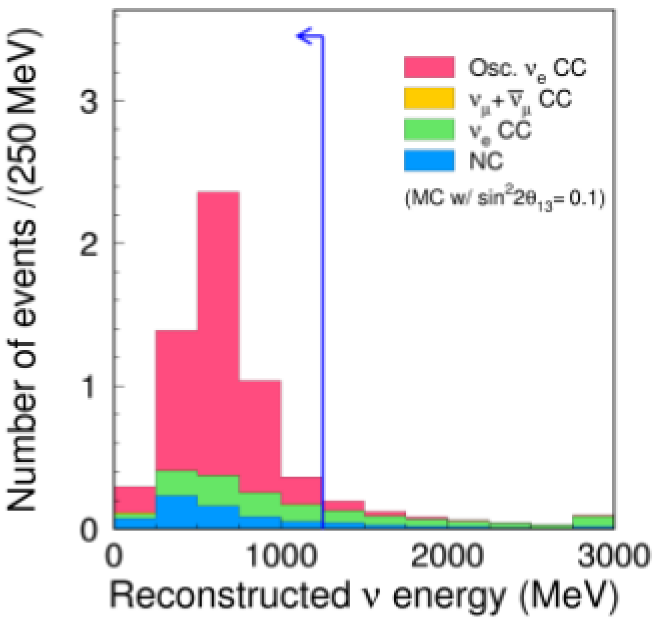
7. Reconstructed neutrino energy < 1250 MeV
   - Reject higher energy intrinsic beam background from kaon decays

Signal Efficiency = 66%

Background Rejection:

77% for beam ν_e

99% for NC

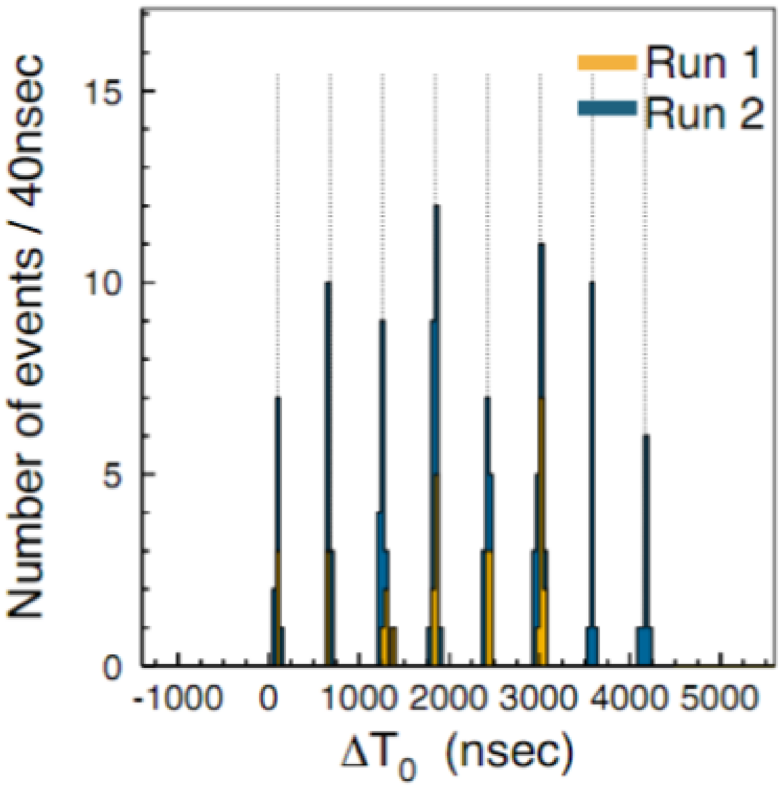


After all cuts, expected background at SK is 1.5 ± 0.3 events.

SK Data Sample

- SK synchronized to beam timing using GPS
- SK events fully contained in the ID show clear beam time structure
- In total, 121 FC events
  - Non beam background from timing sidebands

Clear beam structure !



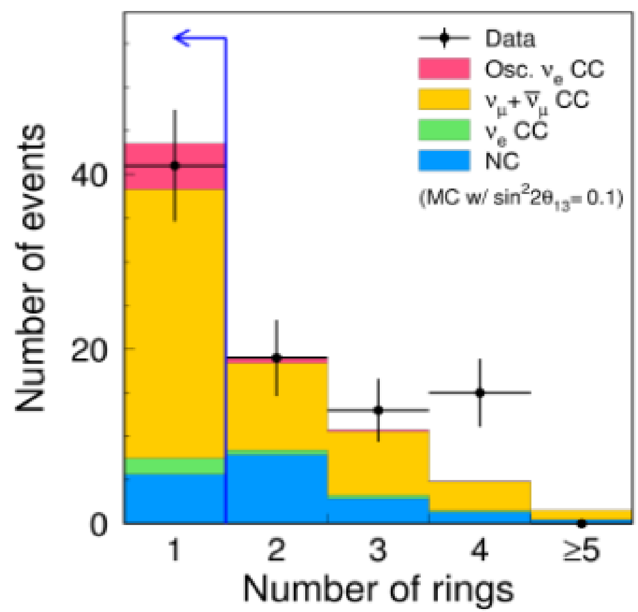
Number of events in on-timing windows (-2 ~ +10 μsec)

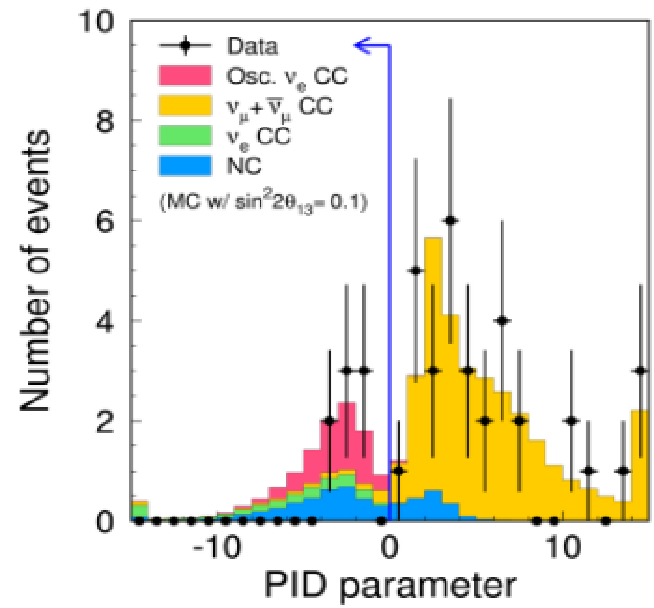
	Class / Beam run	RUN-1	RUN-2	Total	non-beam background
	POT (x 10^{19})	3.23	11.08	**14.31**	
Step 1:	Fully-Contained (FC)	33	88	**121**	0.023

SK ν_e Data Reduction

Step 3: Single e-like ring cut

88 → 8 Events



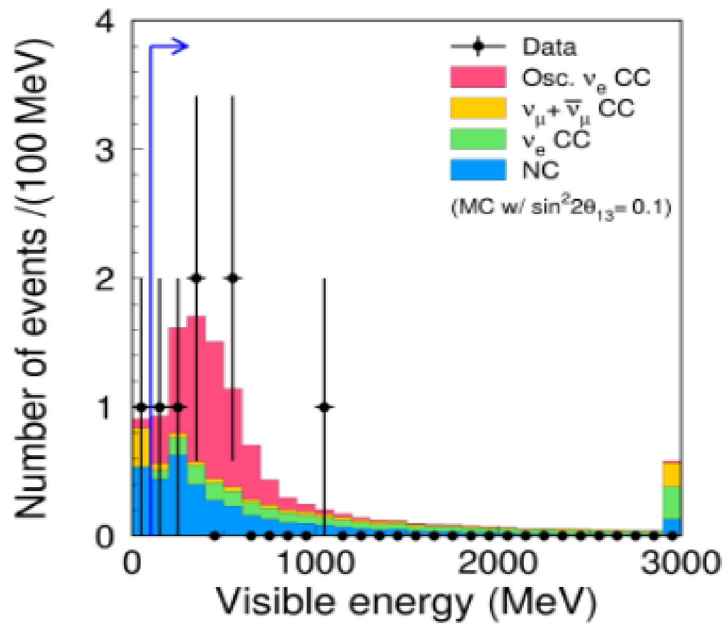


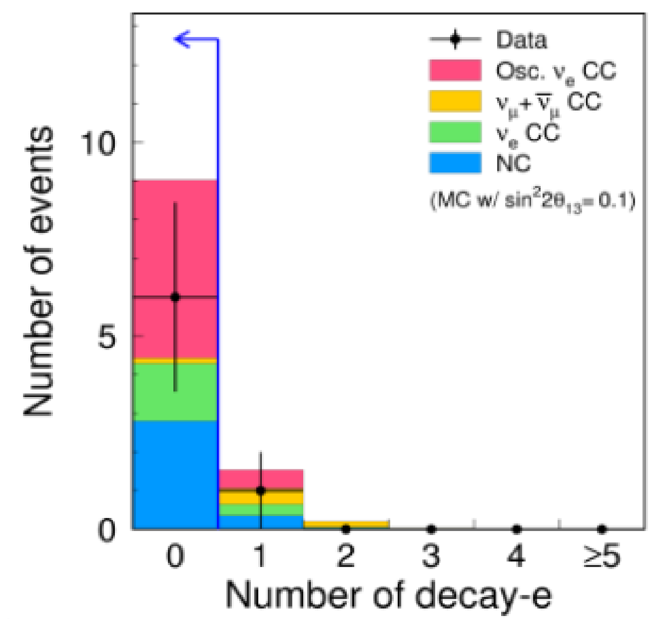
Step 4: Visible energy cut

8 → 7 Events

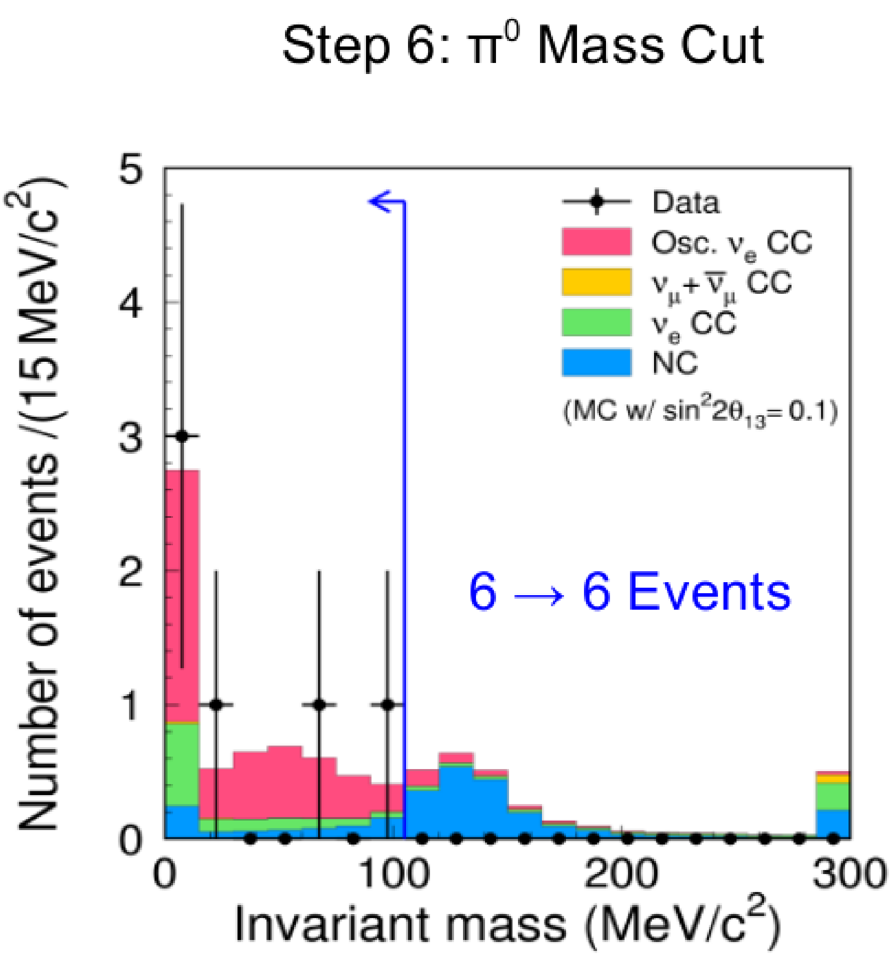
Step 5: Decay electron cut

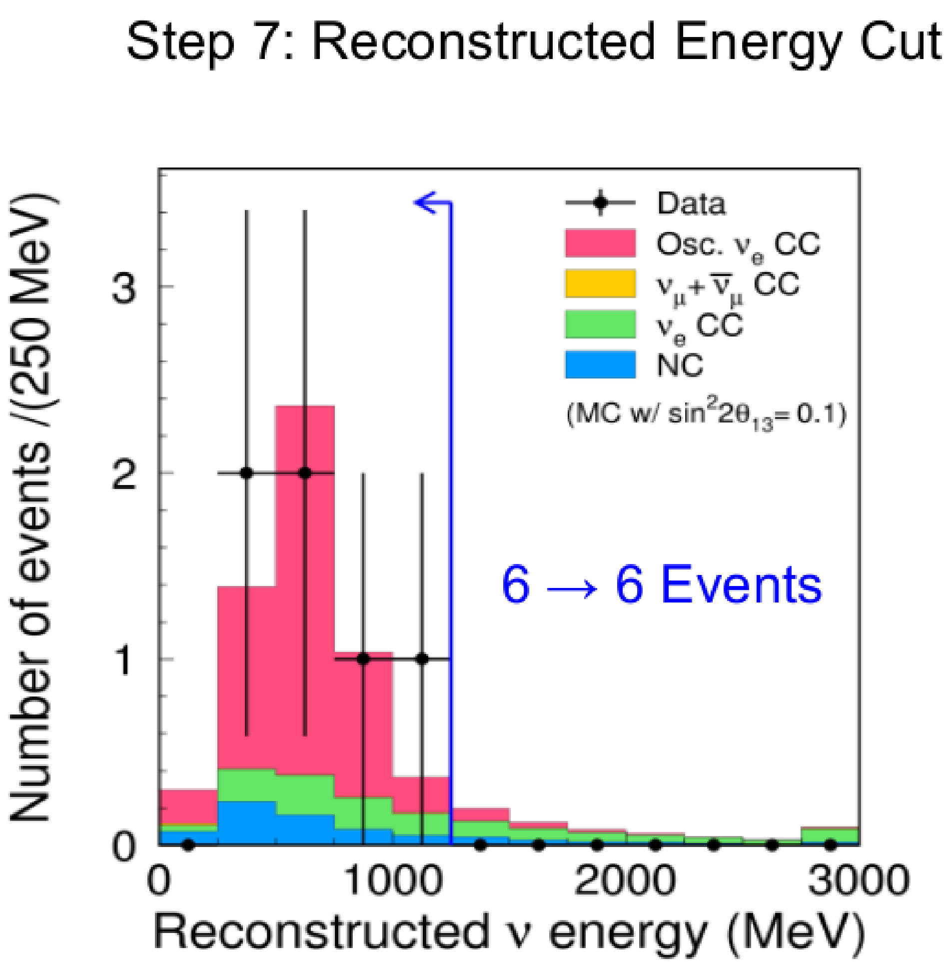
7 → 6 Events





SK ν_e Candidate Sample





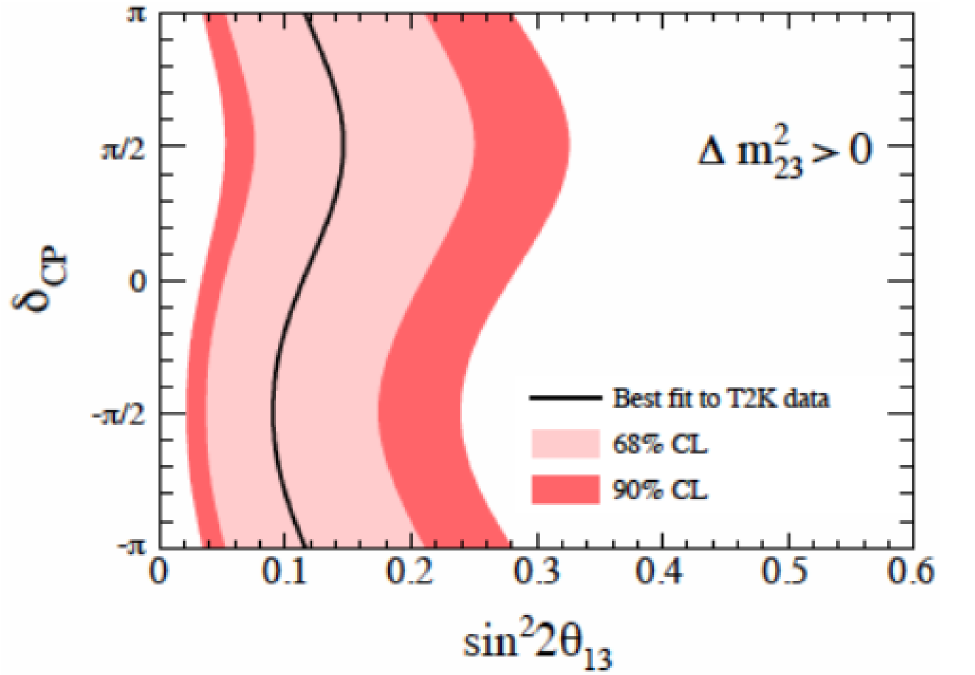
After ν_e selection is applied → **6 candidate events** remain!

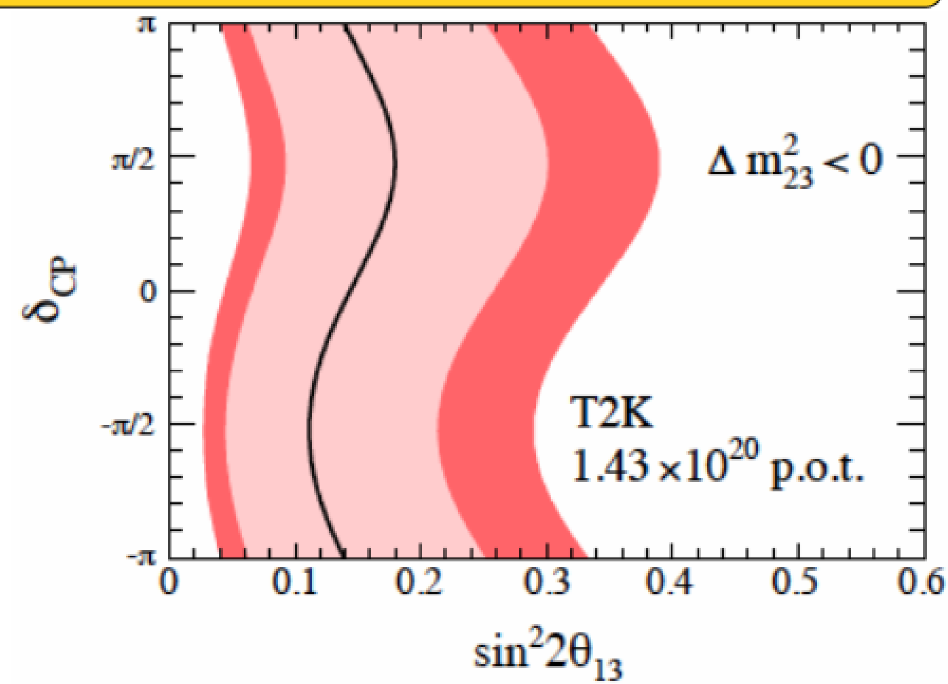
Recall, background expectation is **1.5 ± 0.3** events

Implications for θ_{13}

For $\sin^2(2\theta_{13})=0$ [$\sin^2(2\theta_{23}) = 1.0$, $\Delta m^2_{23}=2.4\times10^{-3}$ eV^2],
probability to observe ≥6 events = 0.007

(fixing $\sin^2(2\theta_{23}) = 1.0$, $\Delta m^2_{23}=2.4\times10^{-3}$ eV^2)





At **$\sin^2(2\theta_{23})=1.0$, $\Delta m^2_{23}=2.4\times10^{-3}$ eV^2, $\delta_{CP}=0$,** 90% CL intervals are:

Normal hierarchy: **$0.03<\sin^2(2\theta_{13})<0.28$**

Best fit: **$\sin^2(2\theta_{13})=0.11$**

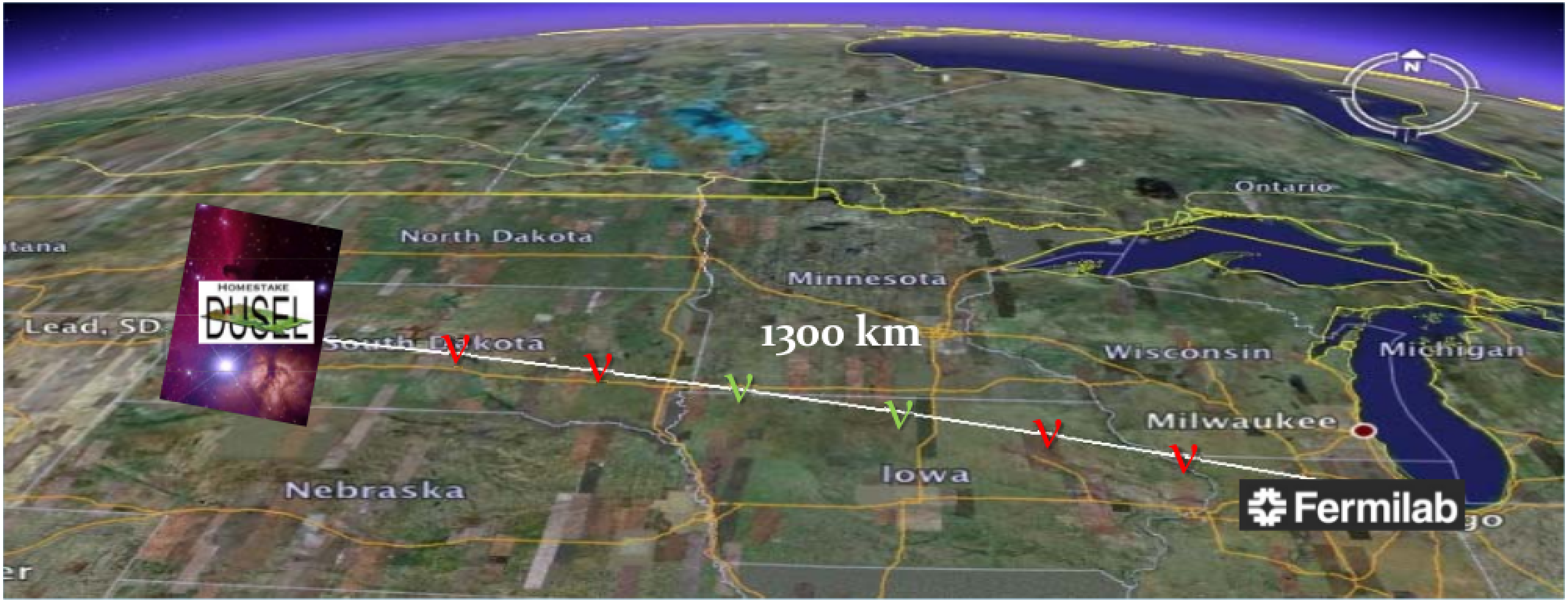
Inverted hierarchy: **$0.04<\sin^2(2\theta_{13})<0.34$**

Best fit: **$\sin^2(2\theta_{13})=0.14$**

Implications for δ

- No sensitivity yet; however, indications of large θ_{13} are encouraging as it would make δ easier to measure.
- Current generation of accelerator neutrino experiments (T2K, MINOS+, NoνA) may reach sensitivity, especially by comparing results from neutrino and anti-neutrino beams.
- Reactor experiments (Double Chooz, Daya Bay) have no inherent sensitivity to δ. Comparing their anti-neutrino result to the neutrino results from accelerators may give sensitivity.

Terrestrial Studies: The Future



- Next generation experiments (T2K w/ Hyper-Kamiokande, LBNE, LBNO) should have significant sensitivity to CP violation
- Extra-long baselines (*e.g.*, 1300 km for LBNE) to determine mass hierarchy (normal vs. inverted) via sign of matter effects

Summary & Conclusions

- Neutrinos are now well established as a tool for understanding the cosmos, providing complementary information to photons.
- Extra-terrestrial neutrinos have helped us understand the core of the Sun and supernovae.
- Future detections could provide a wealth of information on star formation rates, dark matter, GRBs, cosmic rays, the Big Bang, and more.
- Terrestrially produced neutrinos are also valuable for understanding the cosmos:
  - Determining the mass hierarchy has large scale implications
  - CP violation could hold key to matter/anti-matter asymmetry, via leptogenesis
- Now is a very exciting time for both neutrino physics and neutrino astrophysics!