Neutrino Physics and Neutrino Astrophysics

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Properties of Neutrinos

Mass?	$m_{\nu_e} < 2$ eV from tritium β decay $m_{\nu_\mu} < 170$ keV from π decay $m_{\nu_\tau} < 18$ MeV from τ decay
Spin	$s = 1/2$
Type?	Dirac $\nu \neq \bar{\nu}$ Majorana $\nu = \bar{\nu}$
Charge	$Q = 0$
Interactions	weak (and gravitational) only
Flavors	3 active flavors (from Z width) sterile flavors?

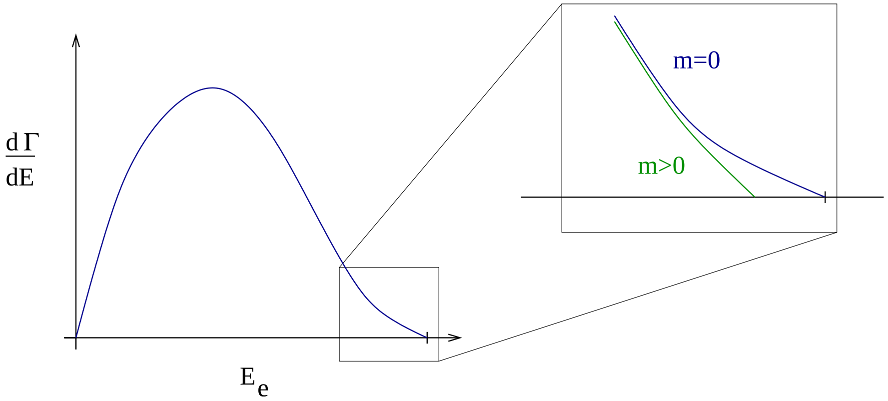
Direct Measurements: Tritium β Decay

tritium beta decay

$$^3H \to {}^3He + e^- + \bar{\nu}_e$$

$$E_0 = 18.6\,keV, \qquad T_{1/2} = 12.3\,a$$

Neutrino mass modifies electron spectrum near end point

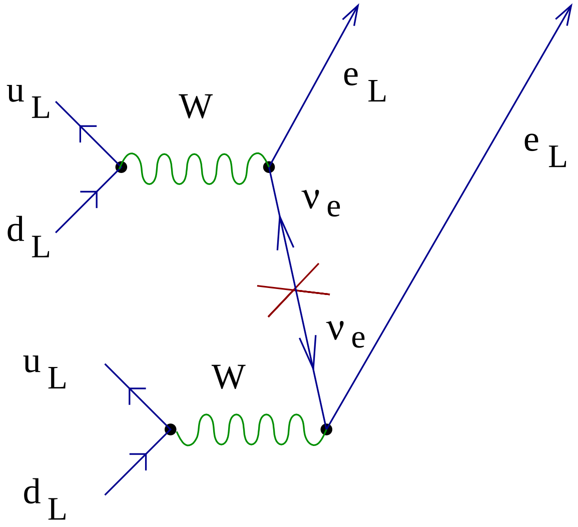


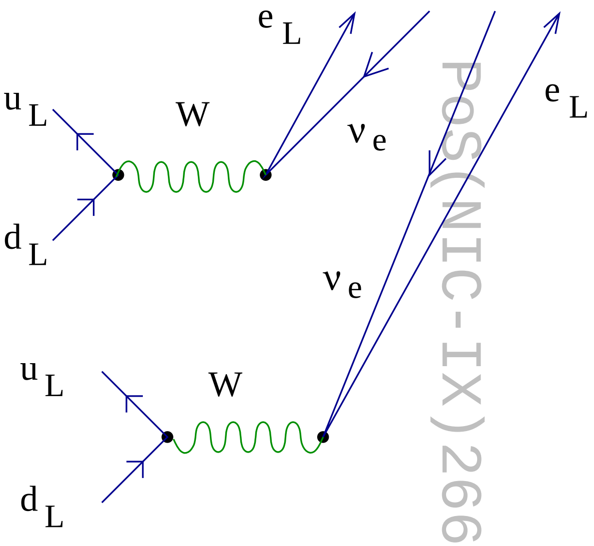
Mainz neutrino mass experiment (1998-2001)

$$m_{\nu_e} < 2.2\,\mathrm{eV} \qquad (95\%\ \mathrm{CL})$$

Double Beta Decay

$2\nu 2\beta$ vs $0\nu 2\beta$ decay



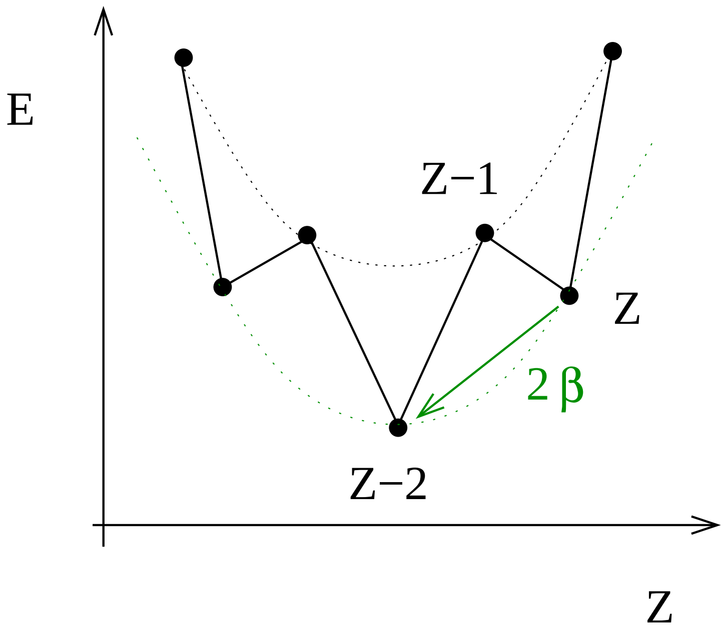


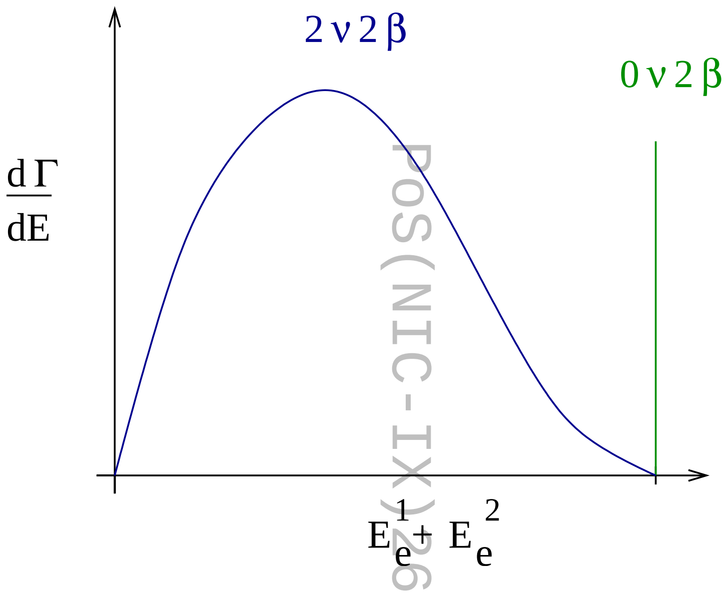
$$(T^{0\nu}_{1/2})^{-1} \sim (\text{phase space}) \times (\text{nuclear m.e.})^2 \times \langle m^M_\nu \rangle^2$$

$$\langle m^M_\nu \rangle = \left| \Sigma_k U^2_{ek} m^M_k \right|$$

where U_{ek} is the MNS matrix

need nucleus which is β stable, but 2β unstable





look for events with $E_e^1 + E_e^2 = Q$

Heidelberg-Moscow (1999-2000)

^{76}Ge $\quad T_{1/2}^{0\nu} > 1.9 \cdot 10^{25}\,\mathrm{yr}$ $\quad \langle m_\nu \rangle < 0.35\,\mathrm{eV}$

Neutrino Dark Matter

Early universe: photons in thermal equilibrium

$$e^+ + e^- \leftrightarrow \gamma + \gamma, \qquad \gamma + e^- \leftrightarrow \gamma + e^-, \ldots$$

Photons decouple at $T_\gamma^{recom} = 4000\,\mathrm{K}$, get red-shifted to

$$T_\gamma^{now} = 2.7\,\mathrm{K}$$

Energy density given by Stefan-Boltzmann law

$$\rho_\gamma = 4\frac{\pi^2}{60}T_\gamma^4 = 4 \cdot 10^{-34}\mathrm{g\,cm}^{-3}$$

Early universe: neutrinos equilibrate via

$$e^+ + e^- \leftrightarrow \nu_e + \bar{\nu}_e, \quad \nu_e + e^- \leftrightarrow \nu_e + e^-, \ldots$$

Neutrinos decouple at $T_\nu^{dec} = 10^{10}\,\mathrm{K}$.

Photons get reheated by $e^+ + e^- \to \gamma\gamma$. Today

$$T_\nu = T_\gamma \left(\frac{4}{11}\right)^{1/3} = 1.94\,\mathrm{K}$$

Energy density of massless neutrinos

$$\rho_\nu = \frac{7}{2} N_\nu \frac{\pi^2}{60} T_\nu^4 = 0.7\,\rho_\gamma \qquad (N_\nu = 3)$$

Number density today $n_\nu \sim 330\,\mathrm{cm}^{-3}$.

Massive neutrinos contribute to the energy density of the universe. If neutrinos relativistic at decoupling then the number density is not affected by m. Energy density

$$\rho_\nu = m n_\nu$$

Simplest constraint:

universe is flat → restricts the neutrino mass

Energy budget of the universe

$$\begin{aligned} \Omega_{DM} &\approx 0.23 \pm 0.04 \\ \Omega_{\Lambda} &= 0.73 \pm 0.04 \\ \Omega_{B} &= 0.044 \pm 0.004 \end{aligned}$$

$$\Omega_\nu = 0.02 \left(\sum \frac{m_\nu}{1\mathrm{eV}}\right) \left(\frac{72\mathrm{km\,sec}^{-1}\ \mathrm{Mpc}^{-1}}{H_0}\right)^2$$

$$m_{\nu_e} + m_{\nu_\mu} + m_{\nu_\tau} < 25\,\mathrm{eV}$$

Power spectrum of background radiation (WMAP) provides much stronger constraints

$$m_{\nu_e} + m_{\nu_\mu} + m_{\nu_\tau} < 1\,\mathrm{eV}$$

How? One way is that m_ν changes the expansion rate of the universe

At the surface of last scattering, this leads to a change in the sound horizon

This changes the position of peaks and troughs in the anisotropy spectrum which is measured by WMAP

Another avenue: Power spectrum + large scale structure

Neutrino mass also changes large scale structure

On small scales $(\lambda_{fs} < 1\mathrm{Mpc}\left(\frac{1\mathrm{eV}}{\mathrm{m}_\nu}\right)(1+z)^{1/2})$ it damps the growth of large scale structure since it can freely stream in and out of small density perturbations (larger thermal speed of the neutrino as opposed to the dark matter)

On large scales it acts like dark matter

Combination analysis of WMAP and large scale structure could put limits on the sum of the active neutrino masses of tenths of an eV.

Where are we with 'direct' measures of neutrino mass?

1. $m_{\nu_e} < 2.2\mathrm{eV}$ from $^3\mathrm{H}$ decay
2. No detection yet from double beta decay
3. From the Cosmic Microwave Background $\sum m_\nu < 1\mathrm{eV}$

High Energy Astrophysical Neutrinos

Atmospheric neutrino flux dies off at 10^{14} - 10^{15} eV

What is beyond?

1. Look for sources in the distant high energy universe
   $\longrightarrow$ photons absorbed
   $\longrightarrow$ cosmic rays deflected from magnetic fields
   $\longrightarrow$ but the neutrinos survive

2. Exotic Sources $\rightarrow$ dark matter annihilation and decay
3. GZK neutrinos $\rightarrow$ Neutrinos from Cosmic Rays

How to detect? Ice Cube, ANITA, etc...

GZK neutrinos

Origin and Nature of the Cosmic Rays

Particles are accelerated by extragalactic sources

Proton hits microwave background photon $p + \gamma \to n + \pi^-$, $\pi^- \to \mu^- + \bar{\nu}_\mu$, $\mu^- \to e^- \bar{\nu}_e \nu_\mu$

This is the “GZK effect” and it sets in about 4×10^{19} eV.

Look for the 10^{18} eV neutrinos from this scattering in km^3 detectors.

Event rates for neutrinos about 10^{15} eV are predicted to be at 0.1 to 1 event per km^3 per year.

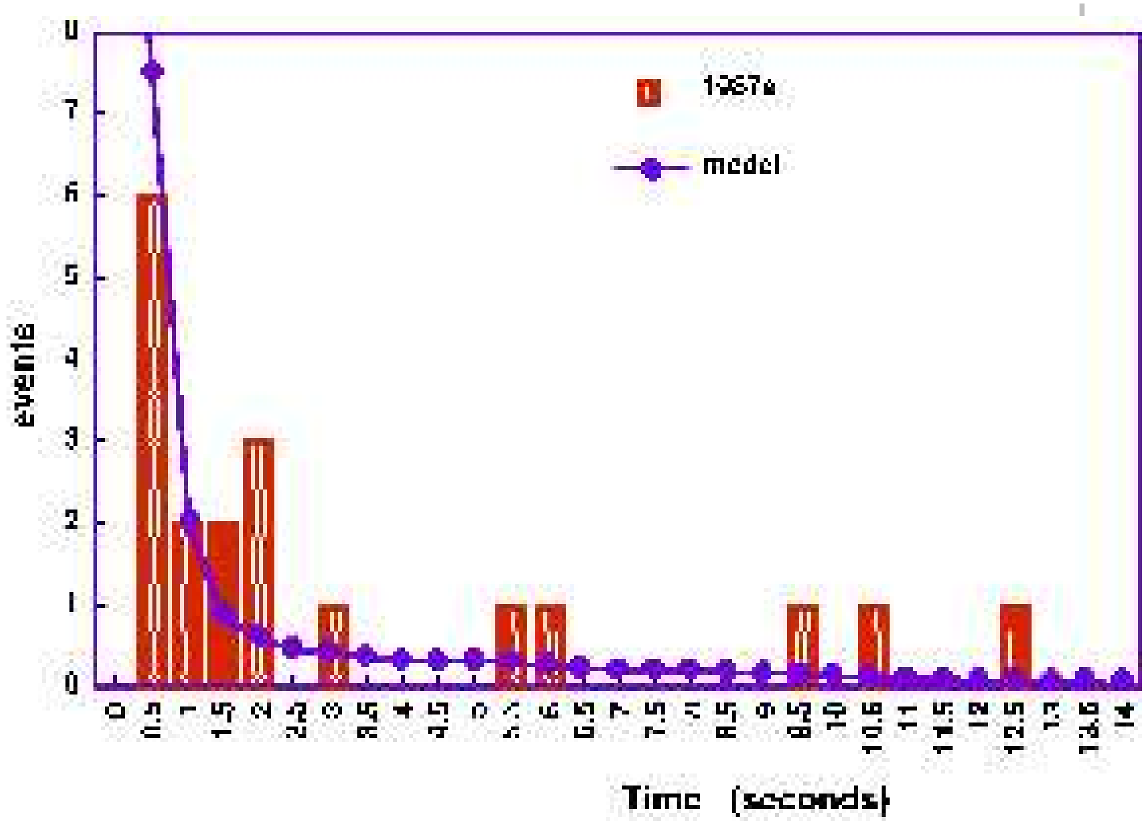
Supernova Neutrinos

Most neutrinos emitted during the first ~ 10 sec

Galactic supernovae estimated to occur ~ 1 every 30 years

Supernova neutrinos detected from SN1987a:

~ 20 events observed in Kamiokande and IMB.

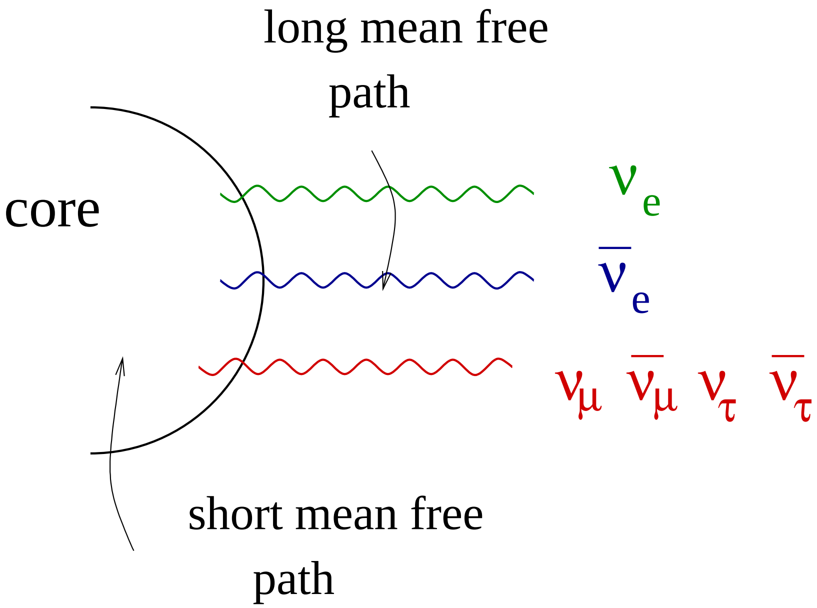


Current detectors will record 1000's of events

SuperK:	~ 8000	$\bar{\nu}_e + p \rightarrow e^+ + n$ events
SNO:	~ 500	$\nu + d \rightarrow \nu + p + n$
SNO:	~ 80	$\nu_e + d \rightarrow e^- + p + n$
KamLAND:	~ 300	$\bar{\nu}_e + p \rightarrow n + e^+$
KamLAND:	$\sim$ 100s	$\nu + p \rightarrow \nu + p$

Supernova Neutrinos

All types of neutrinos emanate from the proto-neutron star core. They travel through the outer layers of the SN, then to earth.

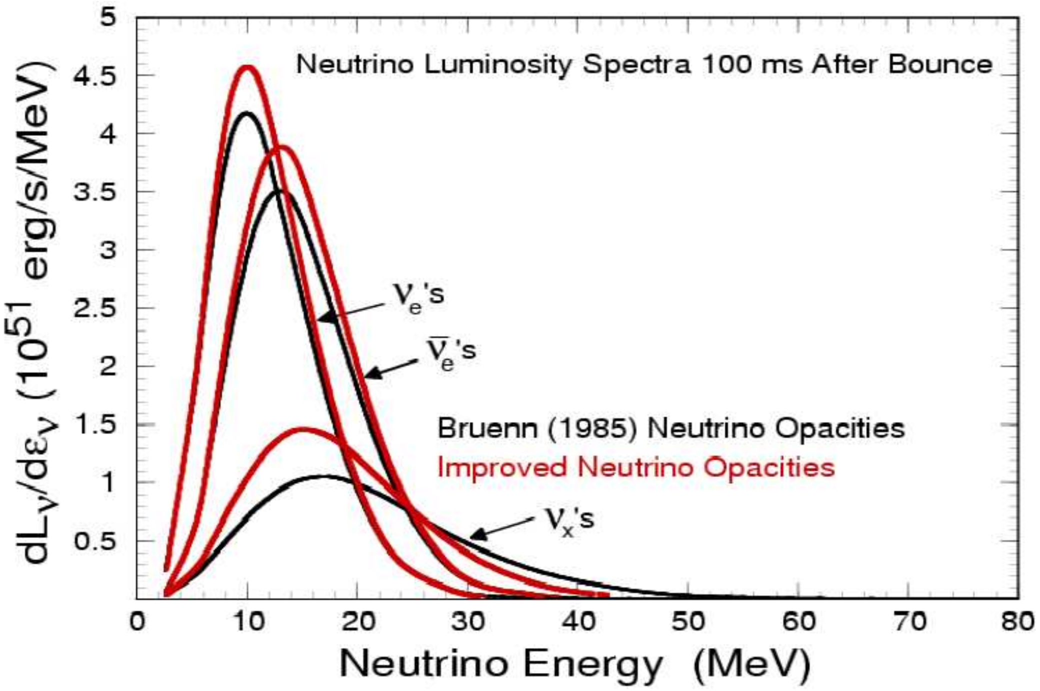


SN neutrinos provide unique opportunity to "see" the center of a SN.

Measuring the Supernova Neutrino Signal

Why? Neutrinos are our window deep into the core of the Supernova

Different neutrino transport calculations predict different spectra



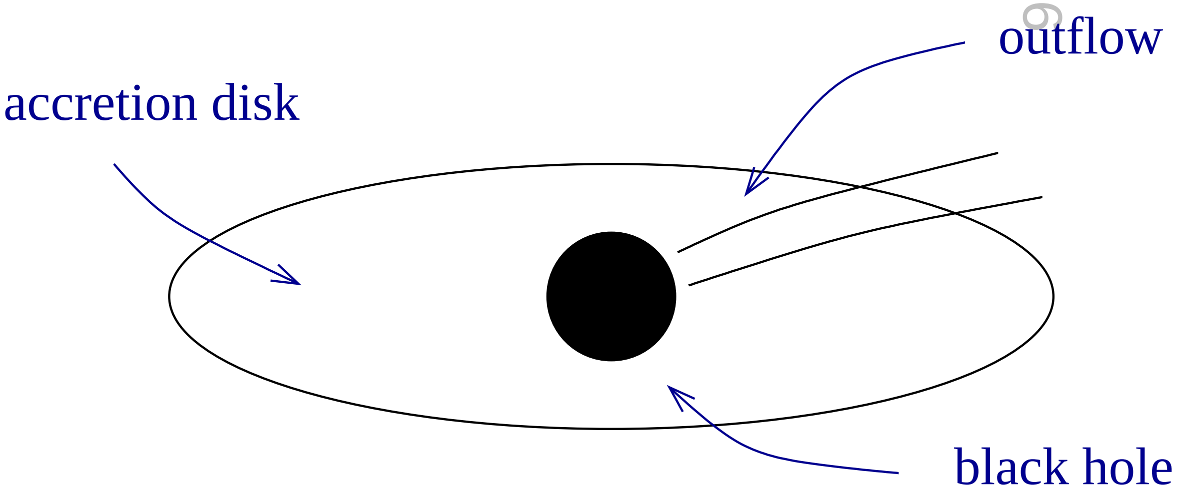
Roughly the range is

- $\langle E_{\nu_\mu}\rangle = \langle E_{\bar{\nu}_\mu}\rangle = \langle E_{\nu_\tau}\rangle$
  $= \langle E_{\bar{\nu}_\tau}\rangle = 20 - 30\,\mathrm{MeV}$
- $\langle E_{\bar{\nu}_e}\rangle = 13 - 19\,\mathrm{MeV}$
- $\langle E_{\nu_e}\rangle = 8 - 13\,\mathrm{MeV}$

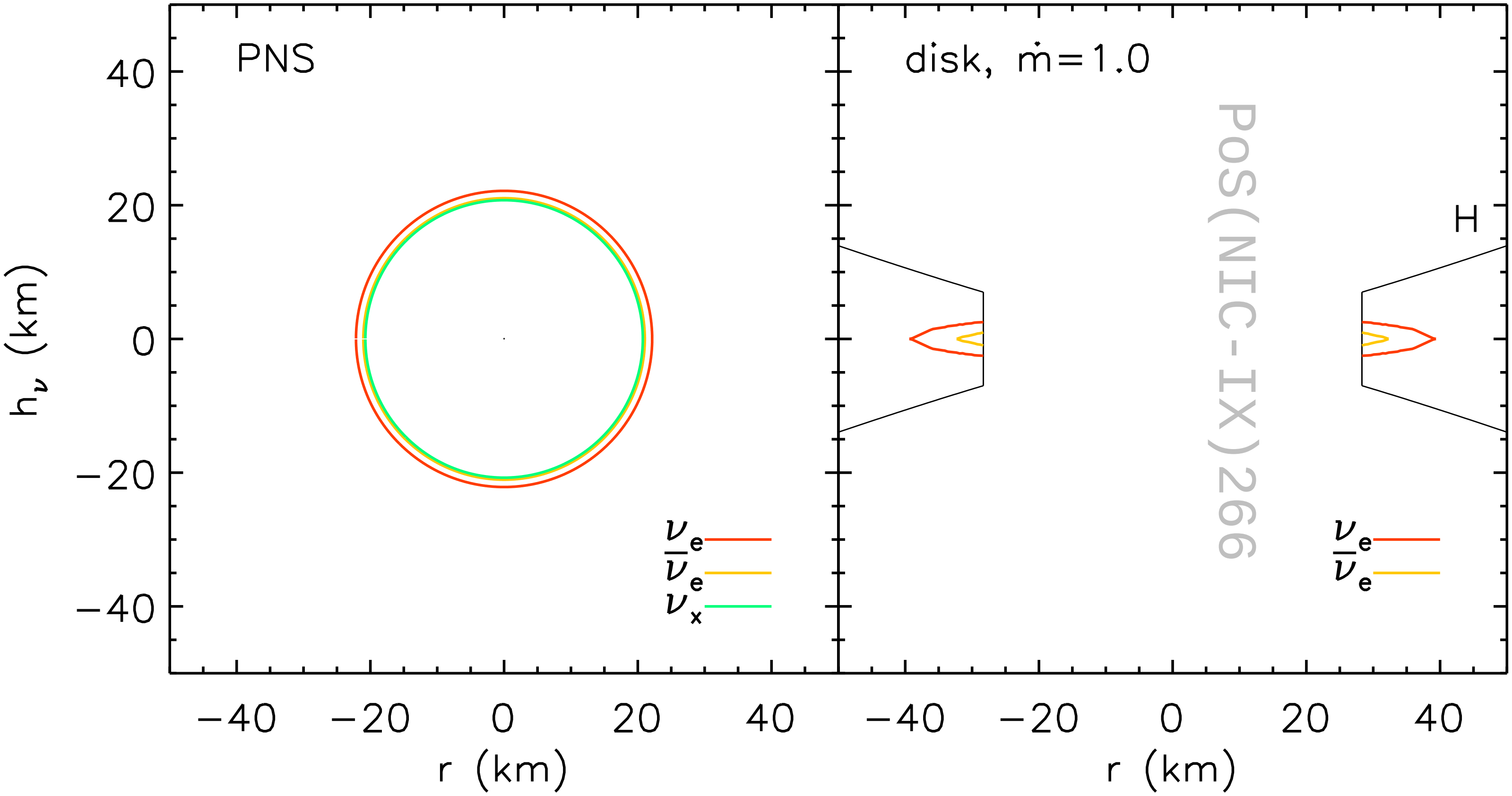
The shape is different, too.

Do all core-collapse events produce these neutrinos?

- Actually, not all core-collapse are predicted to produce proto-neutron stars
- Some are predicted to produce black holes
- And a very small number are predicted to produce accretion disks around black holes...



Neutrino Surfaces for the proto-neutron star and the accretion disk



Energies and Spectra of Neutrinos are similar...

Proto-neutron stars have ν_e,$\bar{\nu}_e$,ν_μ,$\bar{\nu}_\mu$, ν_τ,$\bar{\nu}_\tau$

Disks have primarily ν_e,$\bar{\nu}_e$

Gamma Ray Bursts

- characteristics
  - few second bursts of $\sim$ MeV photons, isotropic on the sky
  - $10^{51} - 10^{54}$ erg if isotropic, but beamed to a few %
  - Two classes: Long (> 0.2s) and short (< 0.2s) Kouvelietou et al 1993
- Long Bursts - afterglows
  - x-ray, radio, optical counterparts, 3 hours-days, months after γs
  - SN bumps in a couple of light curves e.g. Stanek et al 2003
  - Asssociation with Type Ib/c supernovae
- Long Bursts - Association with host galaxies

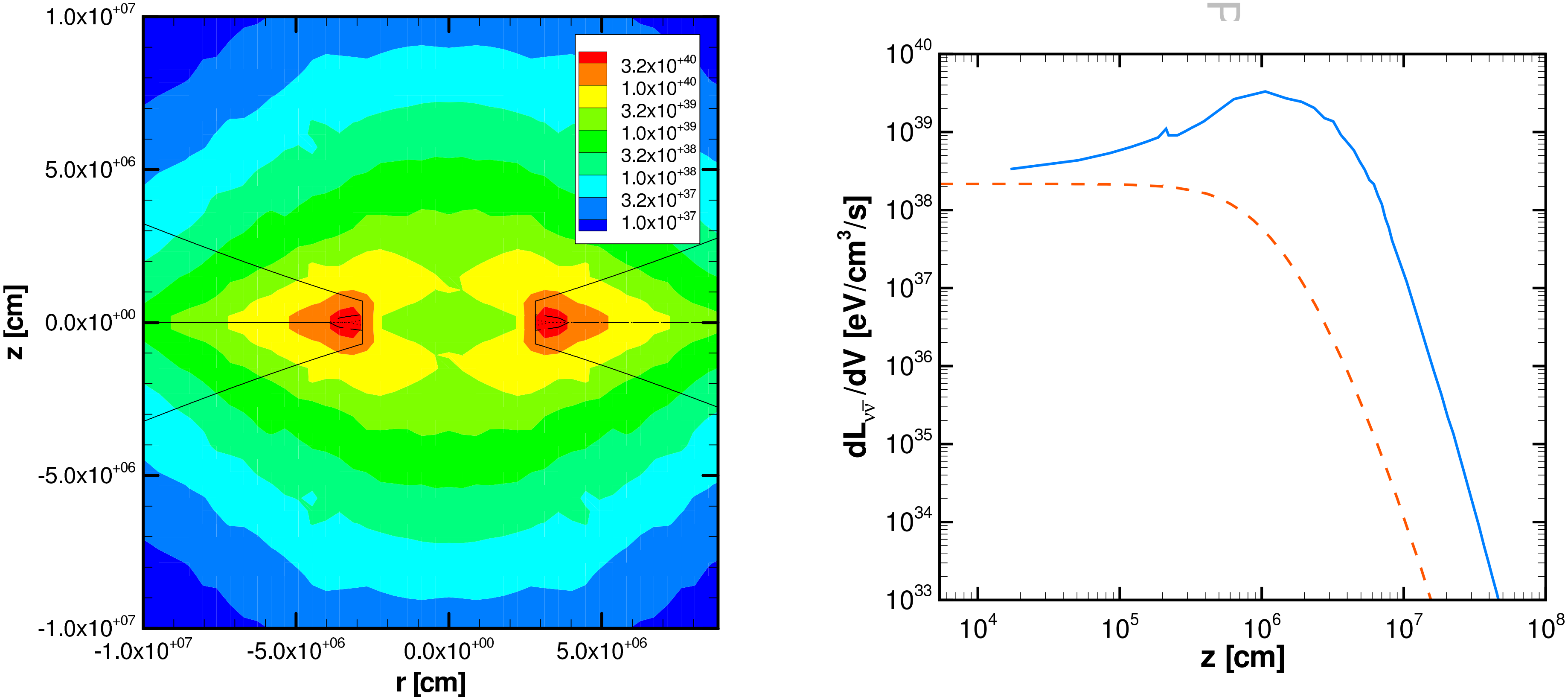
What astrophysical sites?

Long Bursts - Rare type of Core Collapse SN

Short Bursts - Neutron Star Mergers?

Accretion Disks around Black Holes may produce Gamma Ray Bursts

Furthermore, energy deposition from $\nu_e \bar{\nu}_e \to e^+ e^-$ may be important



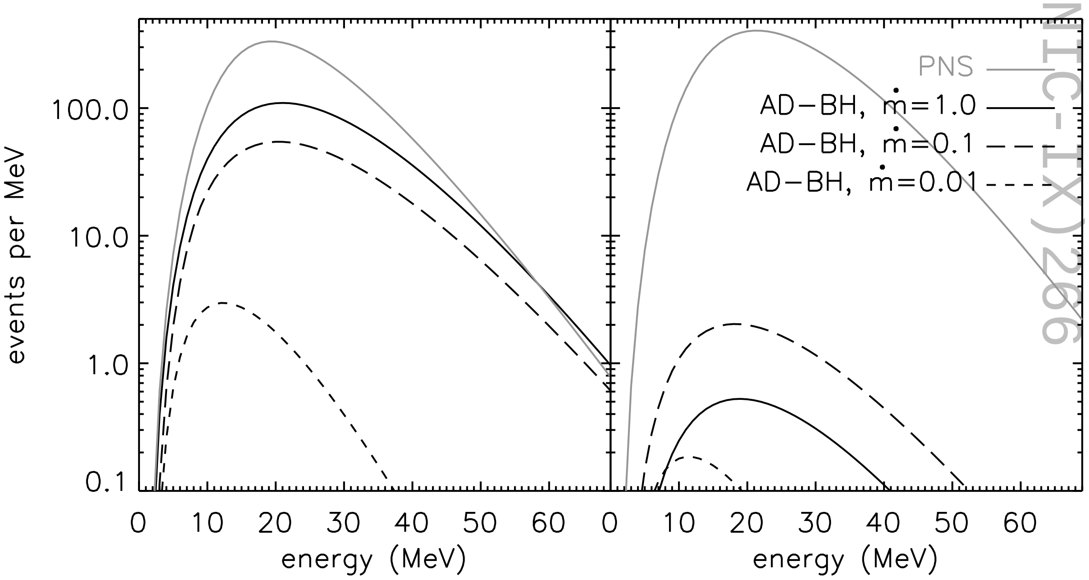
$$\dot{m} = 1\,\mathrm{M}_\odot\,\mathrm{s}^{-1},\ L_{\nu\bar{\nu}} = 10^{50}\mathrm{erg\,s}^{-1},\ L_{\nu\bar{\nu}}/L_\nu = 10^{-3}$$

$$\dot{m} = 0.1\,\mathrm{M}_\odot\,\mathrm{s}^{-1},\ L_{\nu\bar{\nu}} = 4 \times 10^{47}\mathrm{erg\,s}^{-1},\ L_{\nu\bar{\nu}}/L_\nu = 10^{-4}$$

Galactic Accretion Disk Neutrinos in a Supernova Detector

How will you know neutrinos from the next Galactic supernova come from a proto-neutron star?

In SuperK:



But you can distinguish accretion disks from proto-neutron stars by comparing charged and neutral current signals or looking at time profiles

Conclusions from this lecture

- Astrophysical neutrinos can give us information we can't get any other way
- They show up in the early universe, core collapse supernovae, and GRBs
- Future neutrino detections will tell us quite a lot