Neutrinos from Black Hole - Neutron Star Mergers

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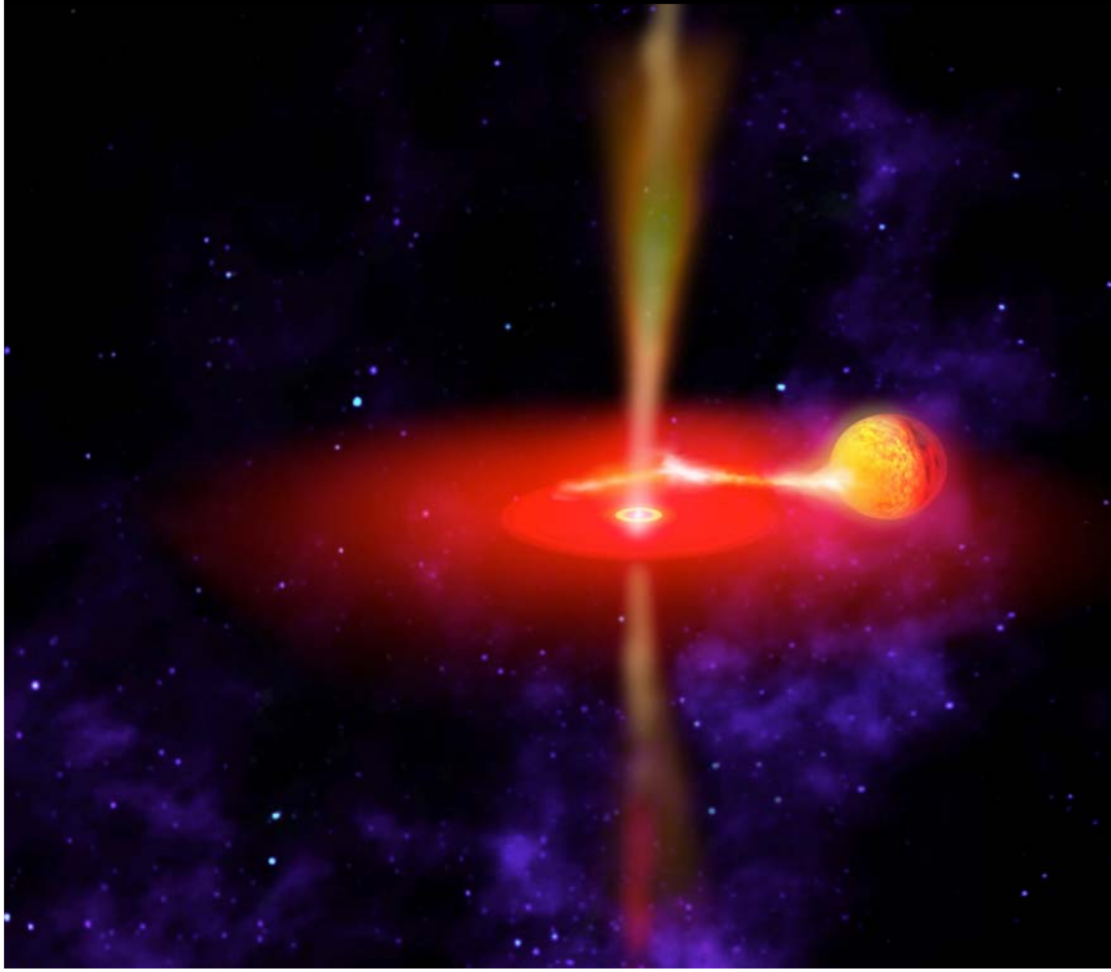
Accretion Disk around Black Hole-Neutron Star (BH-NS) mergers



- Gamma Ray Burst : most energetic explosion known
- $E=10^{52}$ -10^{54} ergs
- May follow from a collapse of compact objects

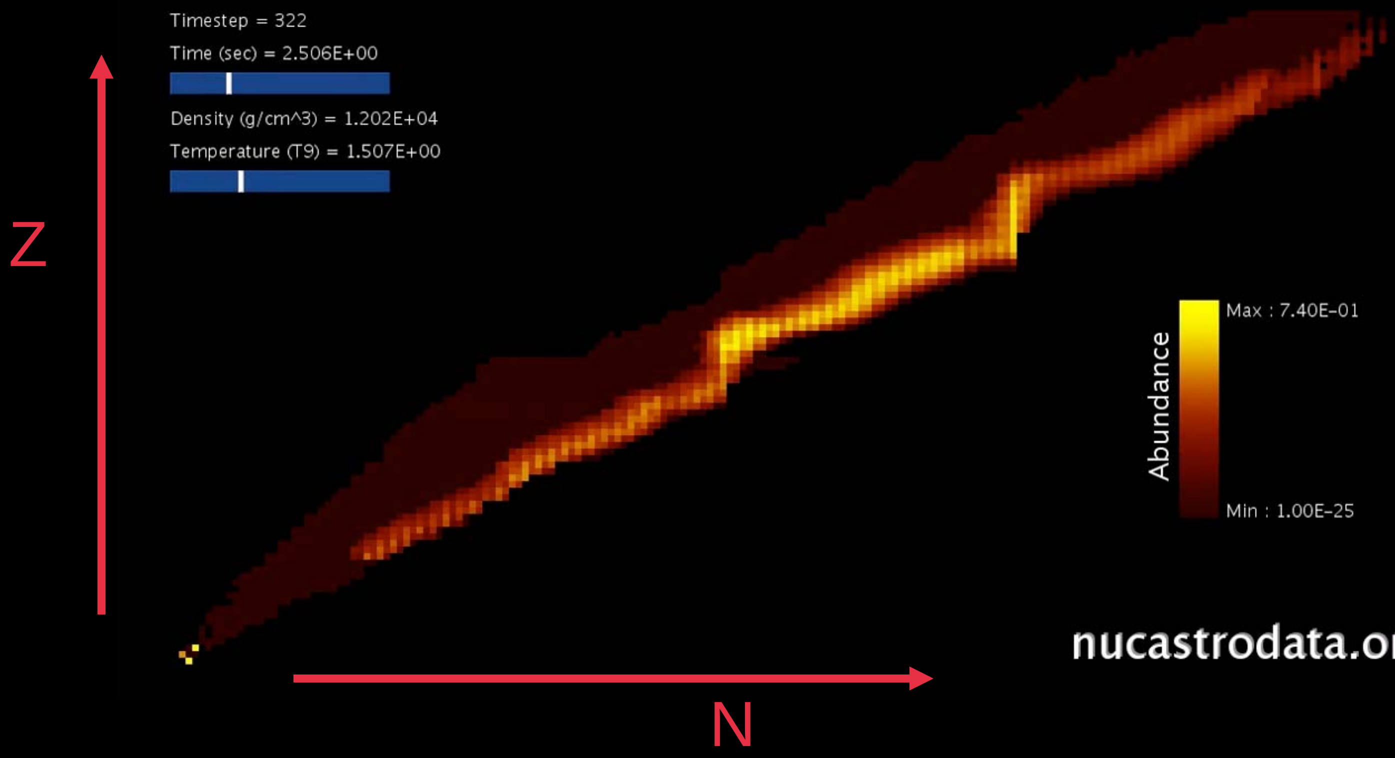
$$\nu+\bar{\nu}\rightarrow e+e^{+}$$

Nucleosynthesis

Disk's conditions would favor r-process

- Tidal tails: cold crust NS matter
- Winds: hot ejected material from the disk

At least 1 weak process (Surman et al, 2008).



nucastrodata.org

Diffusive Neutrino background

Neutrino flux from the past:

Supernovae

Gamma ray burst

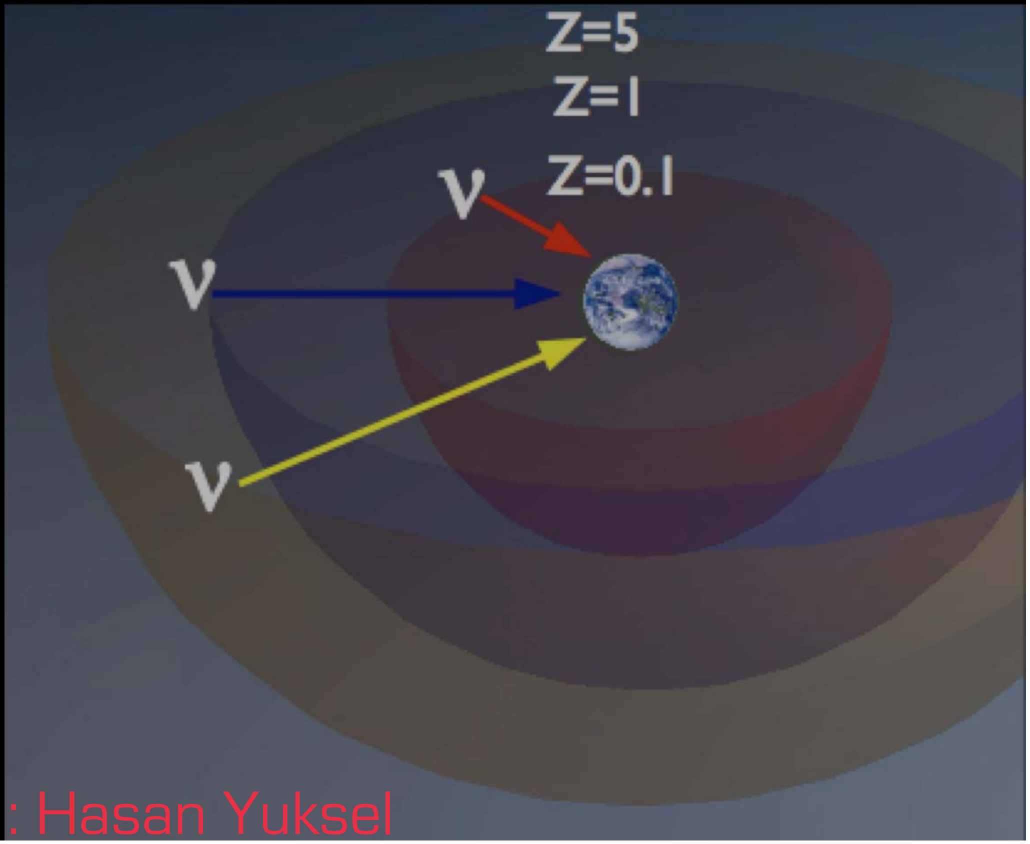


Image credit : Hasan Yuksel

Neutrinos from accretion disk black holes

Mergers are RARE

BH-NS= 10^{-7} -10^{-4}/year

NS-NS =10^{-6} -5x10^{-4} /year

What is Spectra?

What are the average neutrino energies?

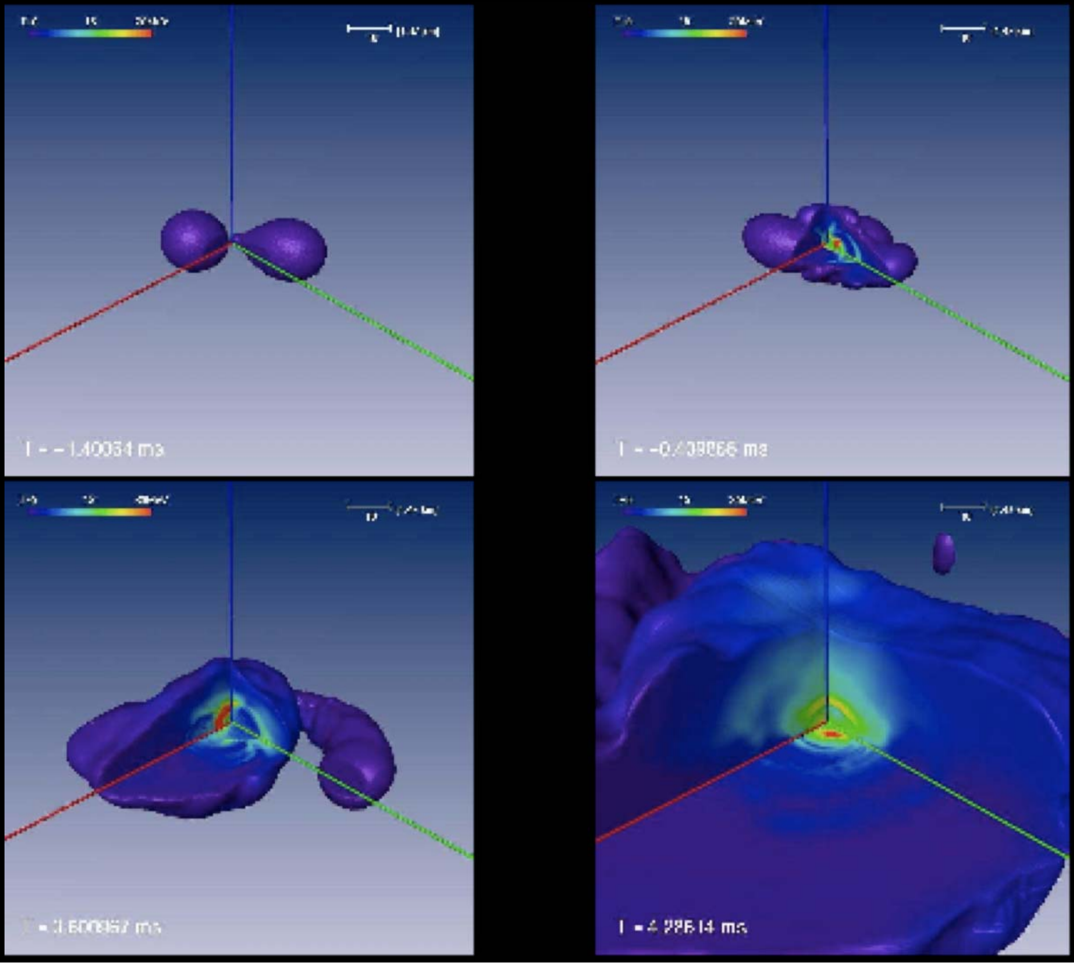
Luminosity?

Flux?

What signal would be registered?

Accretion Disk Model

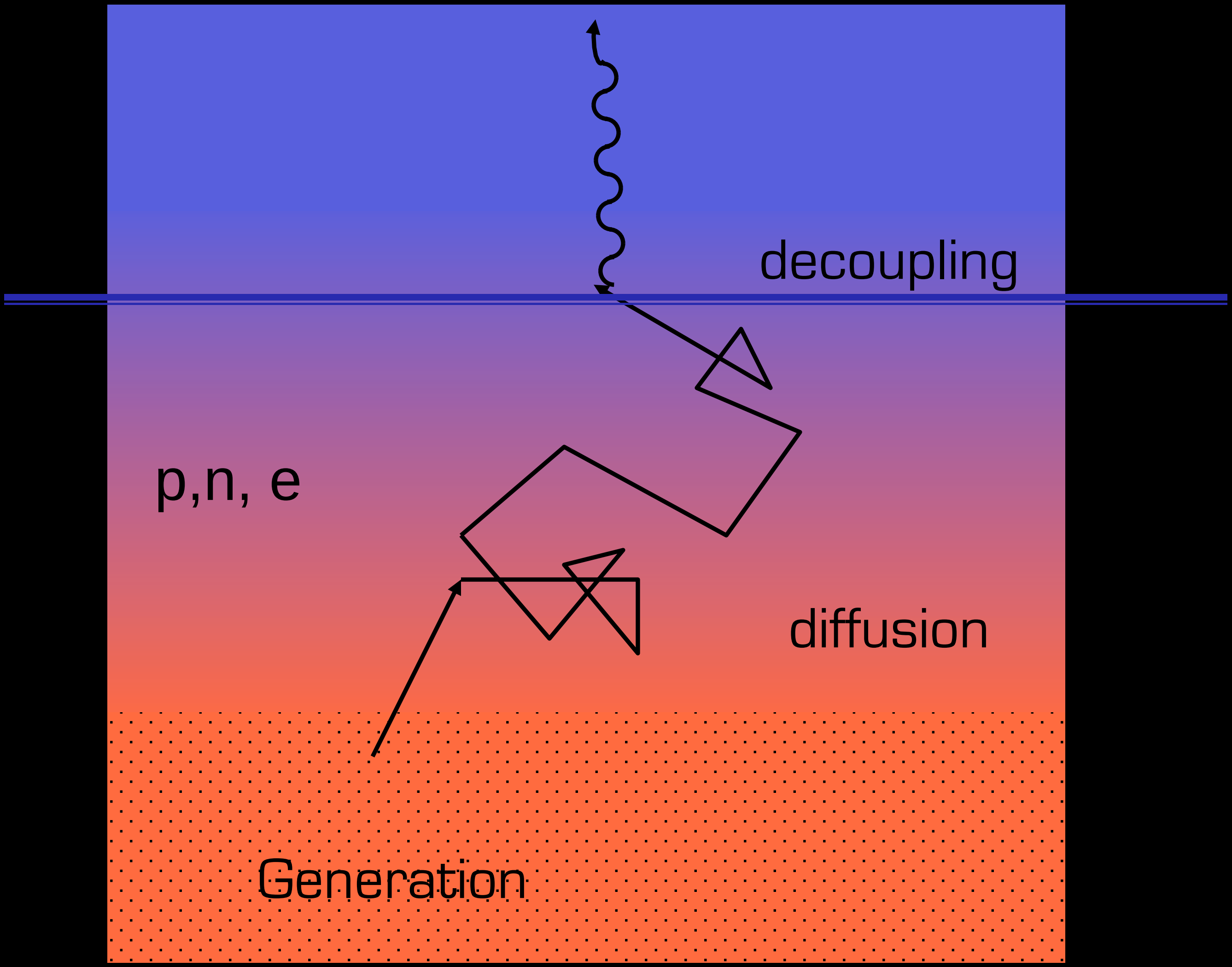
BH=2.5 solar masses, NS= 1.6. Hydrodynamics including GW and neutrino emission, M. Ruffert, H. Janka (2001)



Neutrinos in Proto-Neutron Stars

- Huge amounts of neutrinos are produced and emitted
- Most energy is lost by neutrino emission
- Neutrinos get trapped at high densities and temperatures
- Trapping defines the region where neutrinos decouple = neutrino sphere

Neutrino Sphere



Neutrino Optical Depth

$$\tau_\nu = \int_{h_\nu}^{h_{max}} \frac{1}{l_\nu(r)} dr$$

$l_\nu(r)$ Neutrino mean free path

$\tau_\nu < \frac{2}{3}$ Optically Thin Region

$\tau_\nu > \frac{2}{3}$ Optically Thick Region

Neutrino Interactions in the Disk

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

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

Charged Current

$$\nu + \bar{\nu} \rightarrow e + e^+$$

$$\nu + n \rightarrow \nu + n$$

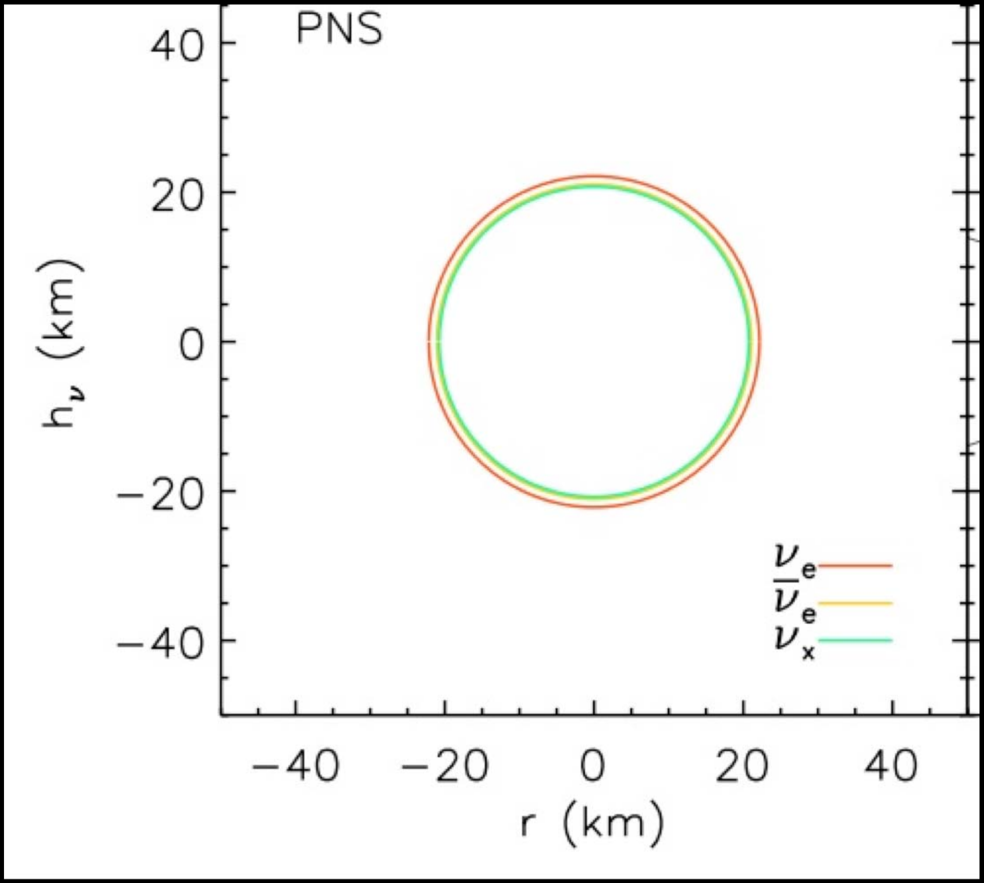
$$\nu + p \rightarrow \nu + p$$

$$\nu + e \rightarrow \nu + e$$

Neutral Current

(All flavors)

Neutrino sphere in proto-neutron stars

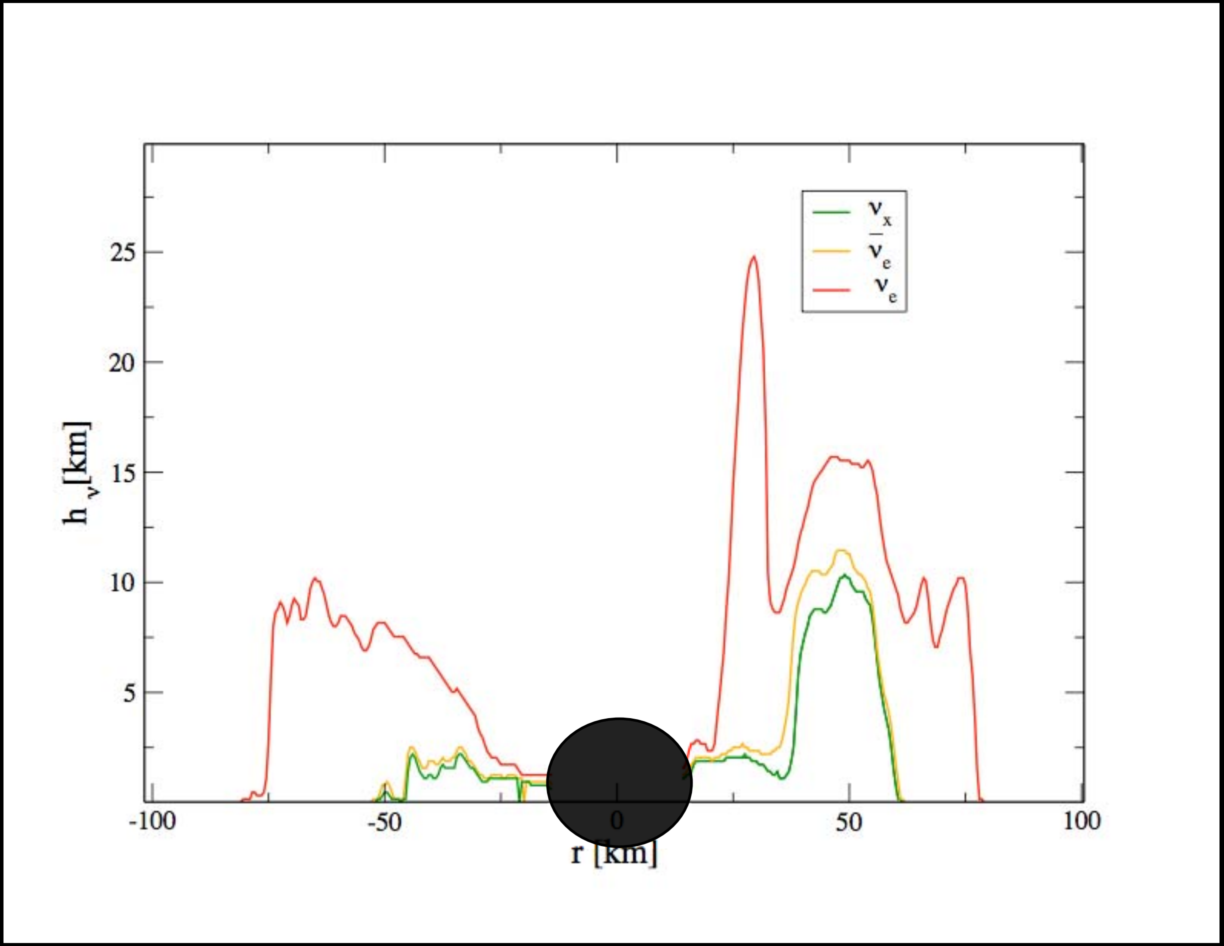


Electron neutrinos decouple latter at smaller T and densities

McLaughlin, Surman (2007)

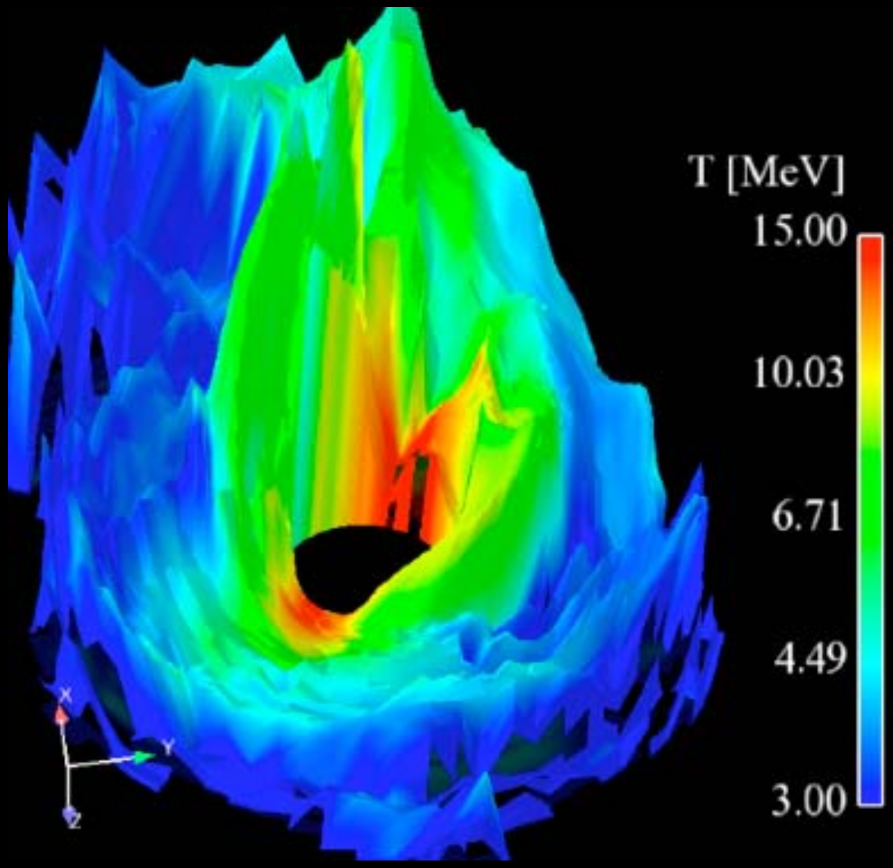
Neutrino Surface in the Accretion Disk

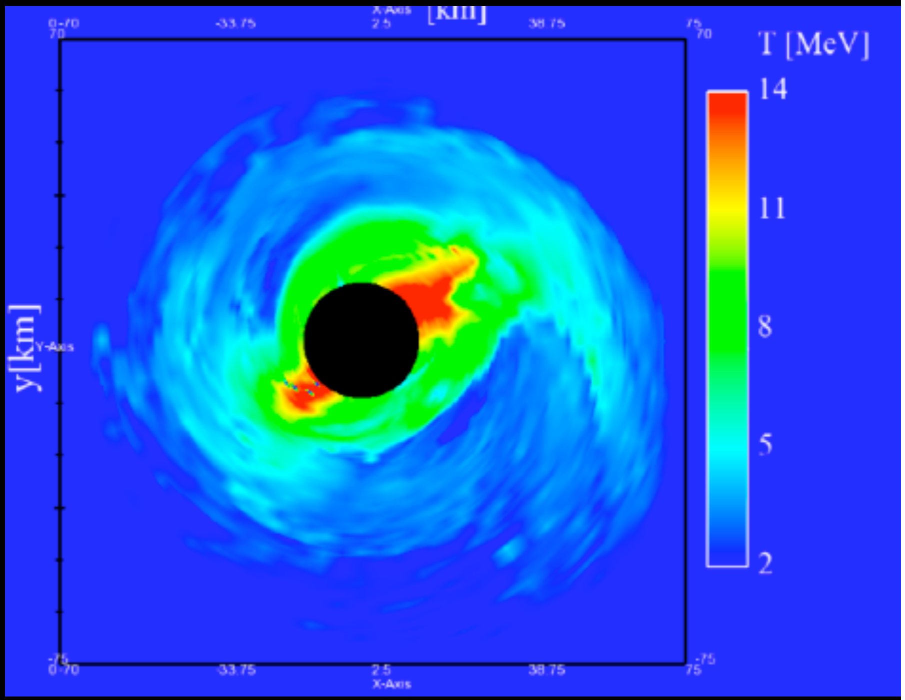
Neutrino surface defines the neutrino decoupling Temperature T_ν



(Caballero et al 2009)

QuickTime™ and a
Motion JPEG OpenDML decompressor
are needed to see this picture.

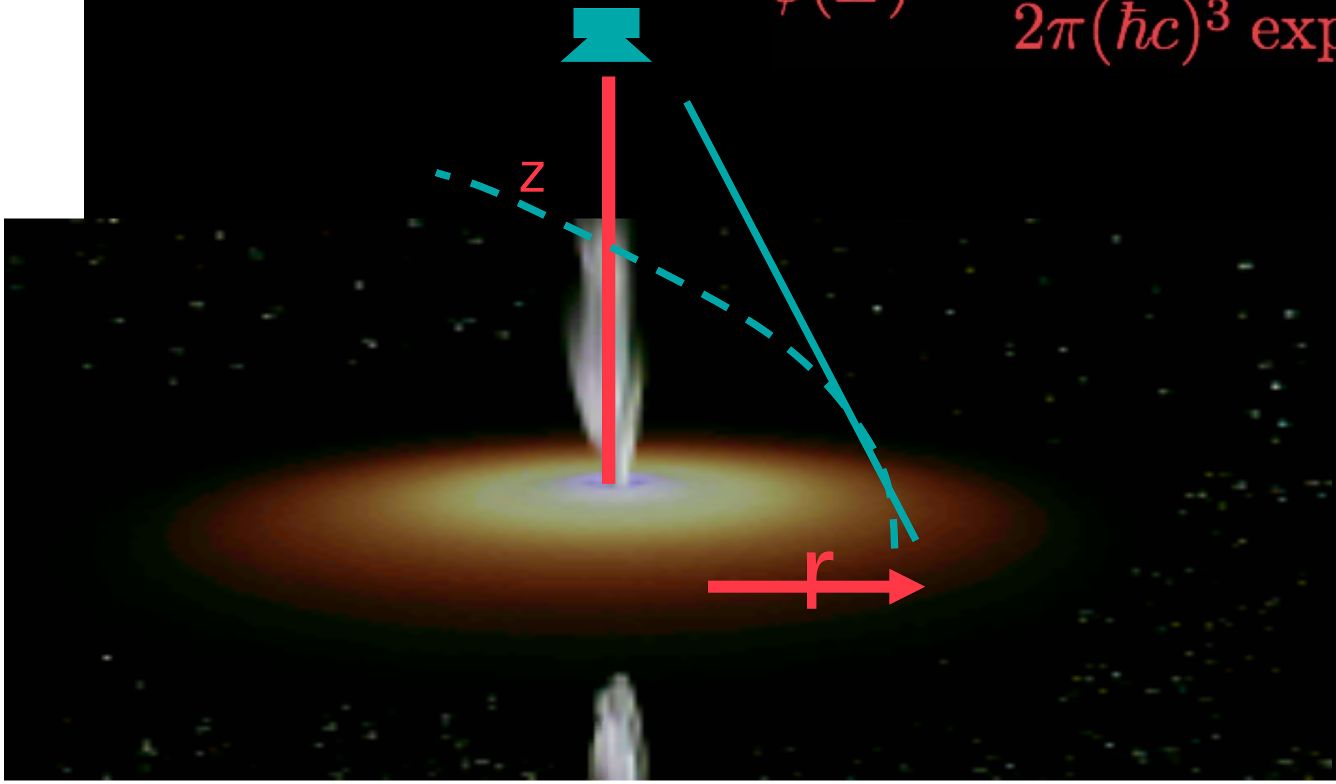

T [MeV]
15.00
10.03
6.71
4.49
3.00
X
Y
Z


X-Axis
[km]
0-70
70
-33.75
2.5
38.75
75
70
T [MeV]
14
11
8
5
2
y[km]
Y-Axis
-75
0-70
-33.75
2.5
38.75
75
-75
X-Axis

Neutrino Spectrum

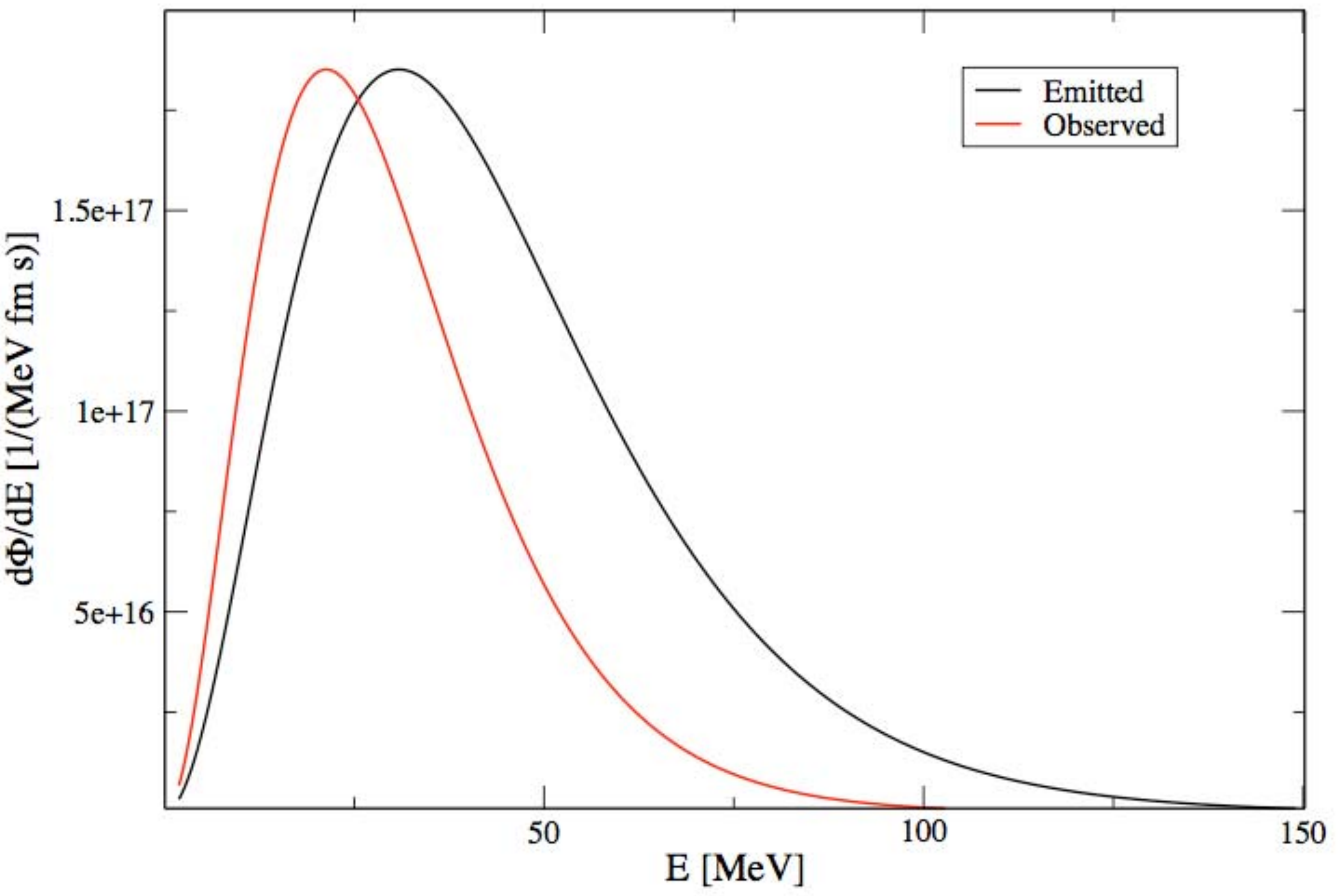
$$\Phi = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\theta_{max}} \sin\theta\, d\theta\, d\phi \int_0^{\infty} \phi(E_\nu^*)\, dE^*$$

$$\phi(E) = \frac{c}{2\pi(\hbar c)^3}\frac{E^2}{\exp(E/T_\nu)-1}$$



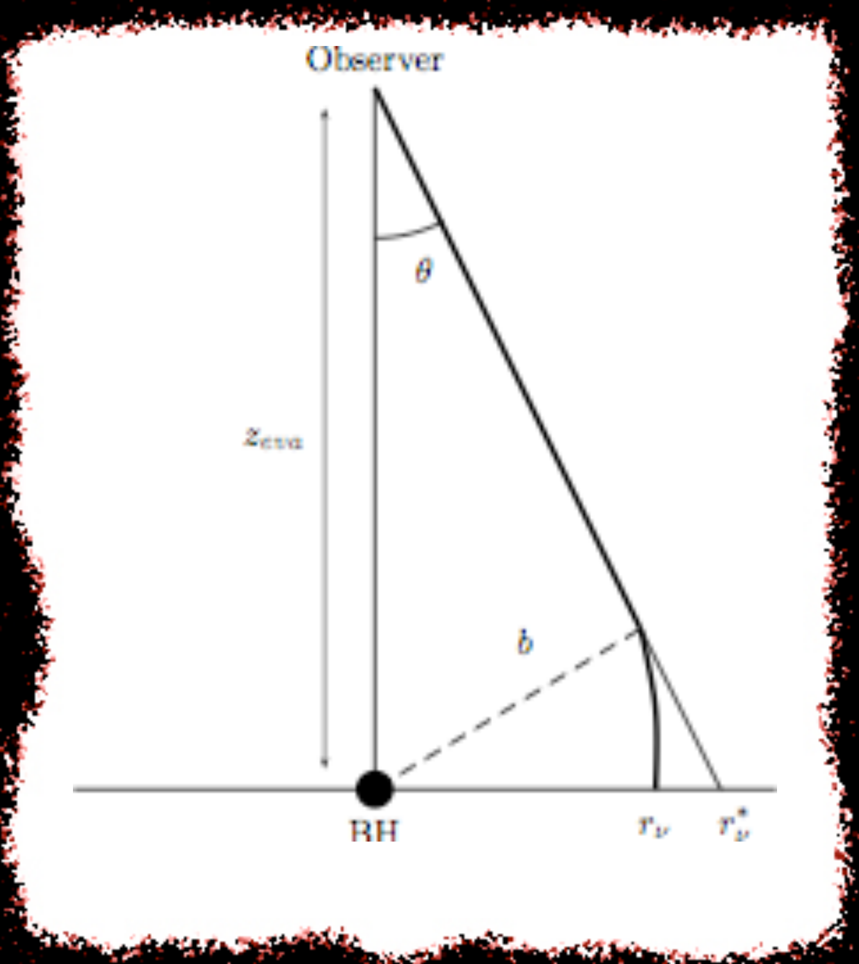
- Energy is Red-shifted E*
- Deflection of trajectories
- Oscillations

Energy Red Shift



n

Ray bending

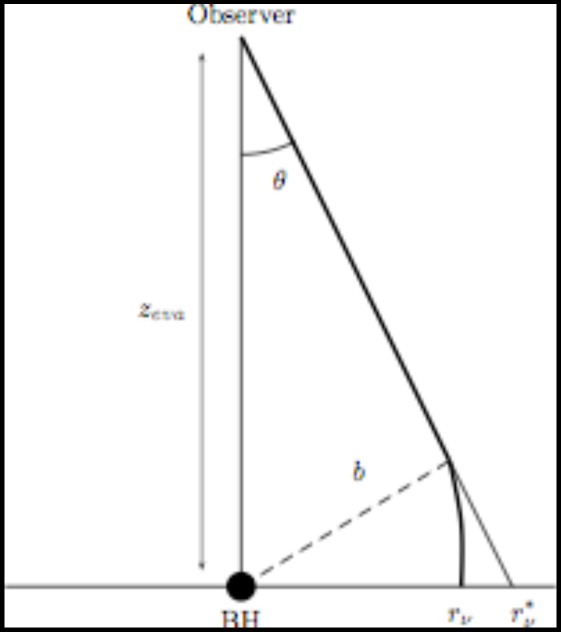


Ray bending

$$\Omega = \int_0^{2\pi} \int_0^{\theta_{max}} \sin\theta d\theta d\phi$$

Observed radius is larger

$$\Omega^* = \int_0^{2\pi} d\phi \int \frac{bdb}{z_{eva}^2}$$



Neutrino Oscillations

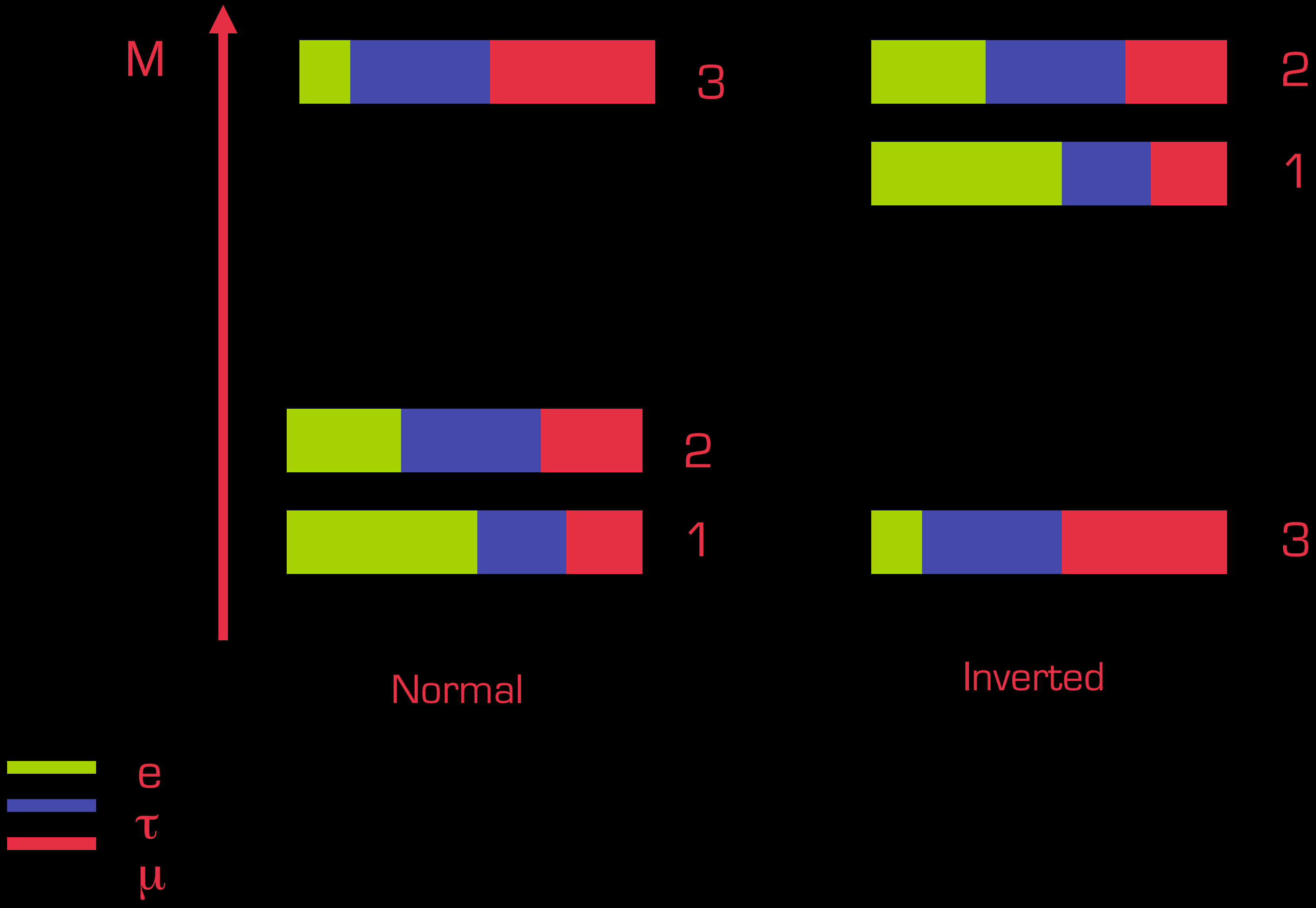
Weak states ≠ Mass states

$$|\nu_\alpha\rangle = \sum_{k=1}^{n} U^*_{\alpha k} |\nu_k\rangle$$

P = survival probability

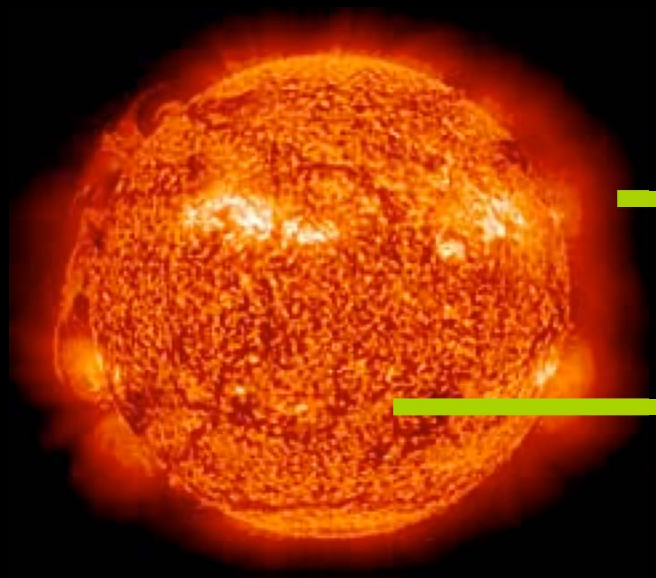
$$\begin{aligned} \phi_{\nu_e} &= p\phi^0_{\nu_e} + (1-p)\phi^0_{\nu_x} \\ \phi_{\nu_x} &= \frac{1}{2}\left[(1-p)\phi^0_{\nu_x} + (1+p)\phi^0_{\nu_e}\right] \end{aligned}$$

Hierarchy



Resonances

P changes with density, then neutrino mixing can be maximal



P_L=Low resonance

P_H=High resonance

Adiabatic

Non-Adiabatic

0

1

Self-interactions $P_{SI}(E) = \Theta(E - E_c), E_c = 10MeV$

Kneller et al (2008)

Oscillation scenarios

Completely adiabatic or non-adiabatic P_H, P_L=0,1

$$\sin^2\theta_{13} = 10^{-4}$$

$$\sin^2 2\theta_{13} < 0.19$$

$$\sin^2\theta_{12} = 0.311$$

$$\theta_{12} = \theta_\odot$$

PDG

8 scenarios → maximal cases:

S1= P_L=1, P_H=0, NH

S2= P_L= P_H= 0, IH

Results

	E(MeV) Disk	E(MeV) PNS	L(erg/s) Disk	L(erg/s) PNS
$\bar{\nu}_e$	23.4	15	2.4×10^{53}	
ν_e	17.3	12	1.6×10^{53}	
$\bar{\nu}_\tau$	26	25	3.0×10^{53}	
ν_τ	26	25	3.0×10^{53}	
Total			1.6×10^{54}	10^{52}

Δt Disk = 0.15 s , Δt PNS = 10 s

Applications

Detection

Diffusive Neutrino Background

Nucleosynthesis

Gamma Ray Bursts

Detectors

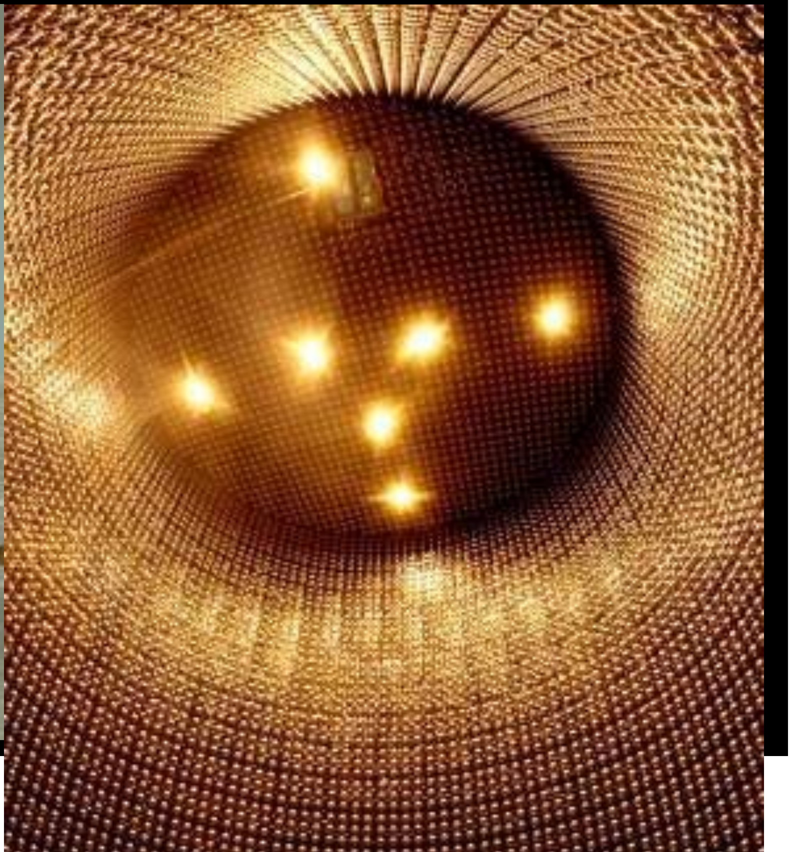
Water Cherenkov

Super Kamiokande (Japan)

Amanda, ICE CUBE (South Pole)

$$\boxed{\bar{\nu}_e + p \rightarrow e^+ + n}$$

$$\nu + {}^{16}O$$



Detectors

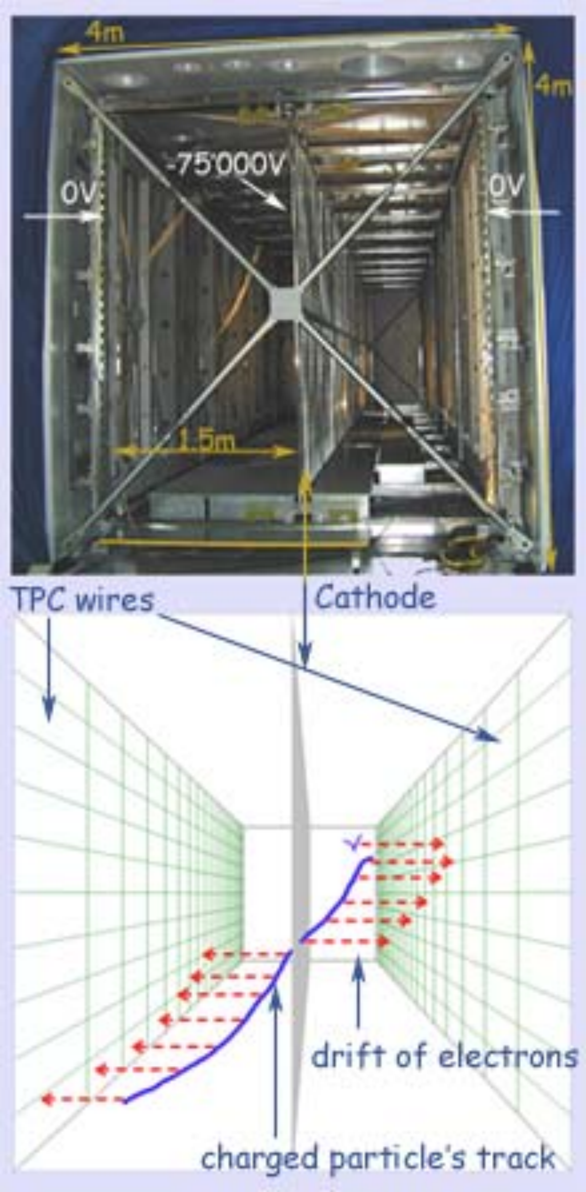
LANNDD (proposed)
ICARUS (Italy)
Liquid Argon

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

$$\bar{\nu}_e + {}^{40}Ar \rightarrow e^- + {}^{40}Cl^*$$

$$\nu + e^- \rightarrow \nu + e^-$$

Cross Sections: E. Kolbe et al, (2003)

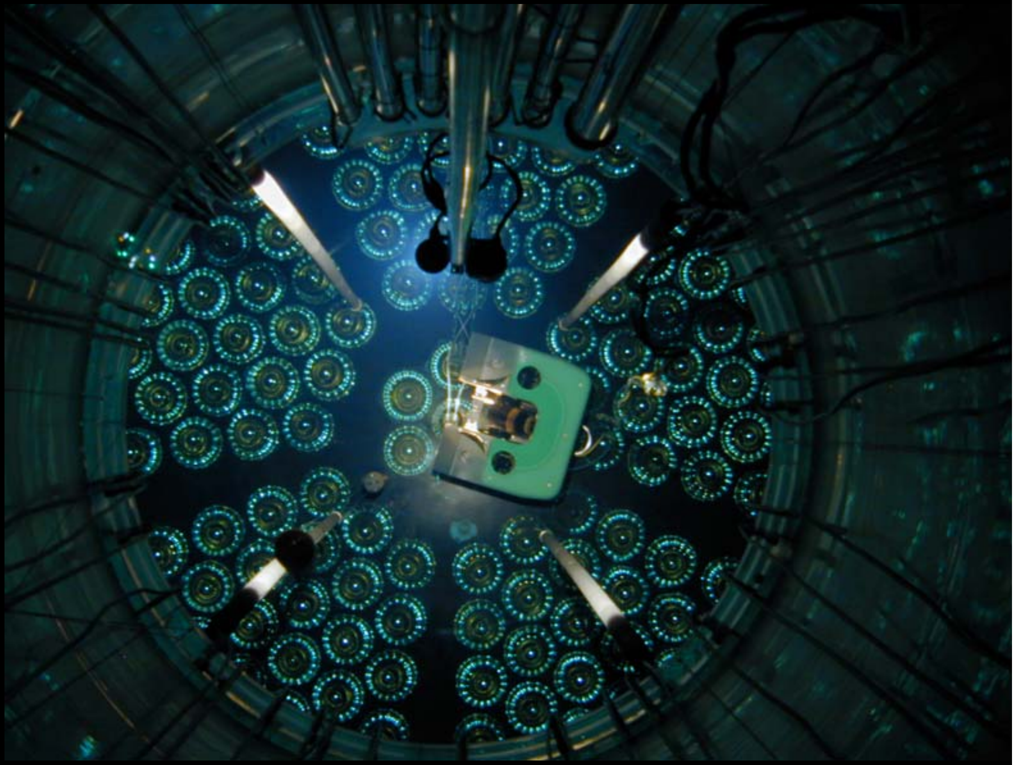


Detectors

HALO (Canada)

^{208}Pb target

^{3}He Neutron Detector



$$\nu_e +^{208} Pb \rightarrow^{207} Bi + n + e^-$$

$$\nu_e +^{208} Pb \rightarrow^{206} Bi + 2n + e^-$$

$$\nu +^{208} Pb \rightarrow^{207} Pb + n$$

$$\nu +^{208} Pb \rightarrow^{206} Pb + 2n$$

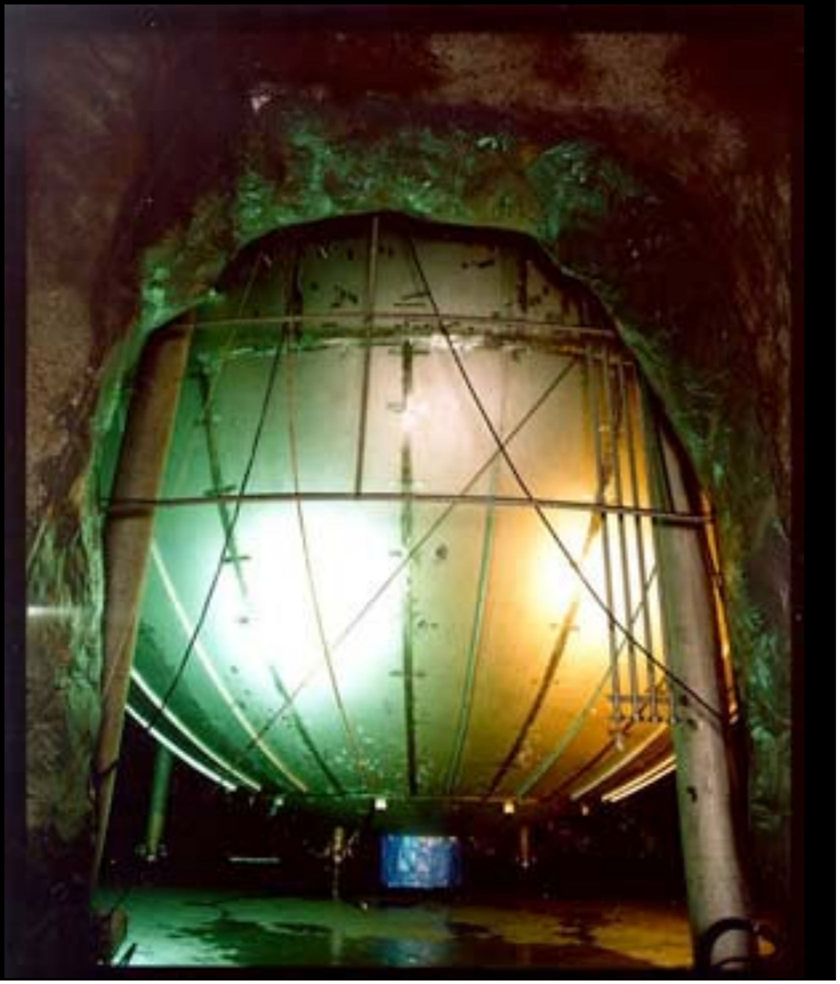
Cross Sections: Engel, McLaughlin, Volpe (2003)

Detectors

KamLAND (Japan)
Liquid Scintillator
Target CH_2

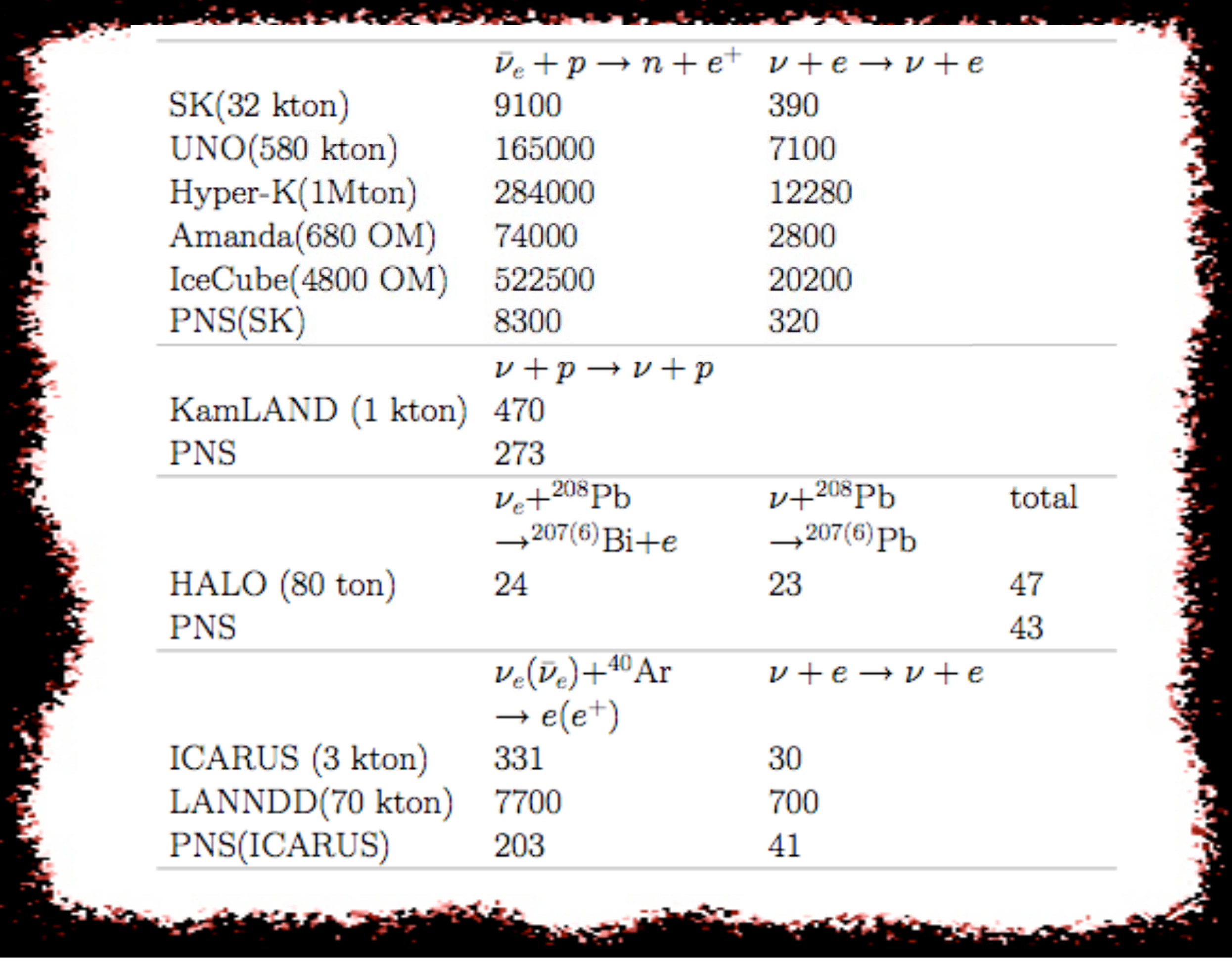
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\boxed{\nu + p \rightarrow \nu + p}$$



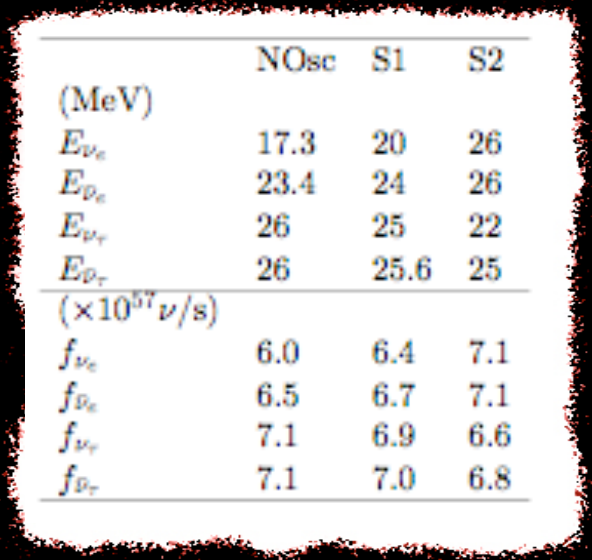
How Many at 10 kpc?

$$R = \frac{N_T}{4\pi}\int_0^{2\pi}\int_0^{\theta_{max}} \sin\theta d\theta d\phi \int_{E_{th}}^{\infty} \phi(E^*_\nu)\sigma(E^*)dE^*$$

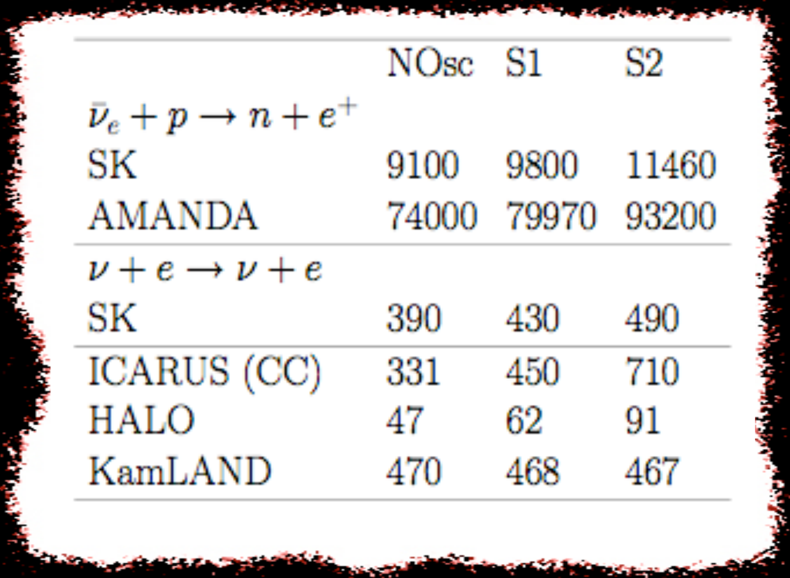


	$\bar{\nu}_e + p \rightarrow n + e^+$	$\nu + e \rightarrow \nu + e$	
SK(32 kton)	9100	390	
UNO(580 kton)	165000	7100	
Hyper-K(1Mton)	284000	12280	
Amanda(680 OM)	74000	2800	
IceCube(4800 OM)	522500	20200	
PNS(SK)	8300	320	
	$\nu + p \rightarrow \nu + p$		
KamLAND (1 kton)	470		
PNS	273		
	$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207(6)}\mathrm{Bi} + e$	$\nu + {}^{208}\mathrm{Pb} \rightarrow {}^{207(6)}\mathrm{Pb}$	total
HALO (80 ton)	24	23	47
PNS			43
	$\nu_e(\bar{\nu}_e) + {}^{40}\mathrm{Ar} \rightarrow e(e^+)$	$\nu + e \rightarrow \nu + e$	
ICARUS (3 kton)	331	30	
LANNDD(70 kton)	7700	700	
PNS(ICARUS)	203	41	

Oscillations



	NOsc	S1	S2
(MeV)			
E_{ν_e}	17.3	20	26
$E_{\bar{\nu}_e}$	23.4	24	26
E_{ν_τ}	26	25	22
$E_{\bar{\nu}_\tau}$	26	25.6	25
$(\times 10^{57}\nu/\mathrm{s})$			
f_{ν_e}	6.0	6.4	7.1
$f_{\bar{\nu}_e}$	6.5	6.7	7.1
f_{ν_τ}	7.1	6.9	6.6
$f_{\bar{\nu}_\tau}$	7.1	7.0	6.8



	NOsc	S1	S2
$\bar{\nu}_e + p \to n + e^+$			
SK	9100	9800	11460
AMANDA	74000	79970	93200
$\nu + e \to \nu + e$			
SK	390	430	490
ICARUS (CC)	331	450	710
HALO	47	62	91
KamLAND	470	468	467

Energies and fluxes for different flavors get closer

Counts for a specific flavor increase

Conclusions and future work

- Neutrino temperatures, fluxes, luminosities and energies in the Disk are higher than in a PNS
- More luminous, signal is shorter (100 times) but we will have more counts
- Using current detectors we can see as far as:
  - 983 kpc in SK

  In UNO we could see as far as:

  4 Mpc

  (Andromeda is at 780 kpc)

  LIGO can reach up to 20 Mpc for NS-NS, 40 Mpc BH-NS

- Diffusive background (NS-NS event rate 10^{-6}-10^{-4}/yr)