Detection of Pre-supernova neutrinos

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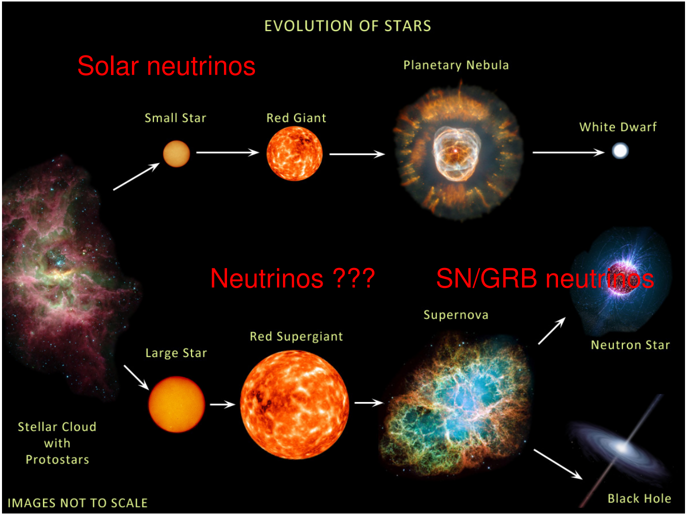
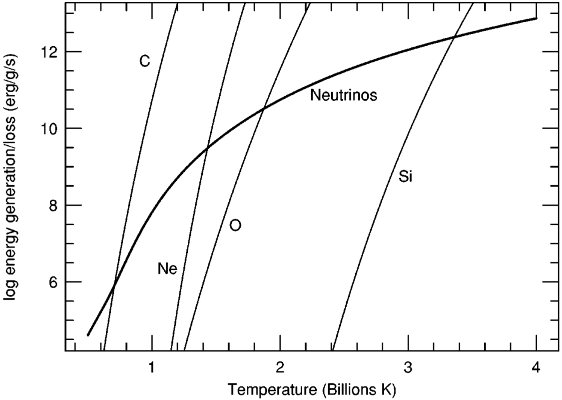
July 10-11, 2015, IHEP

Neutrino astronomy



Neutrino loss driving the evolution of massive stars



(1) "neutrino" star from C-burning stage;

(2) neutrino loss speed up the evolution of massive stars;
$\tau \simeq E_{\rm nun}/L_\nu$, $E_{\rm nuc} \sim 10^{17}$ erg/g
10^3 years for C; years for O; days for Si.

(3) To study neutrino detection, neutrino ($\bar{\nu}_e$) spectra are needed.

Neutrino production in stars

Weak interactions for neutrinos: CC + NC

- Nuclear neutrinos:

  CC: $e^{\pm}$ capture, $\beta^{\pm}$ decay

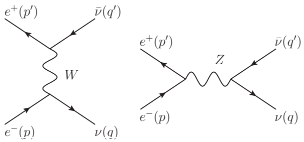
  NC: nuclear de-excitation, etc

- Thermal neutrinos:

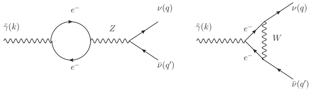
  pair process, plasma process,
  photo-process, Bremsstrahlung process, etc.

stage	L_ν(ergs/s)	Process	Flavor
main sequence	10^{36}	CNO (pp)	ν_e
He burning	10^{31}	photo/plasma	all
advanced stages	10^{38-46}	pair	all
Si burning	10^{45-48}	e^- capture	ν_e
collapse	10^{51-53}	e^- capture	ν_e
collapse	10^{47-50}	de-excitation	all

4 typical thermal processes



Pair: $e^- e^+ \to \nu_\alpha \bar{\nu}_\alpha$



Plasma: $\tilde{\gamma} \to \nu_\alpha \bar{\nu}_\alpha$

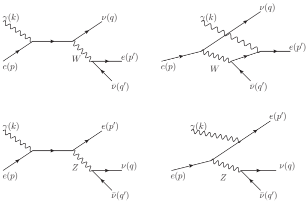
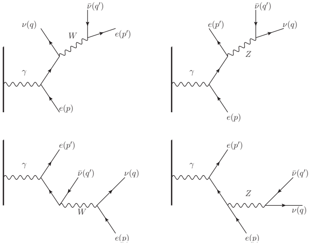
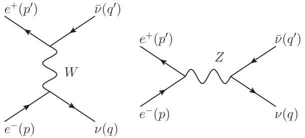


Photo: $e^- \gamma \to e^- \nu_\alpha \bar{\nu}_\alpha$



Bremsstrahlung: $(N, Z)e^- \to (N, Z)\nu_\alpha \bar{\nu}_\alpha$

One example: pair process



- Amplitude and cross section

  $$i\mathcal{M} = i(\mathcal{M}_Z + \mathcal{M}_W) = \frac{-ig^2}{8m_W^2}\bar{u}_\nu(q)\gamma^\mu(1-\gamma^5)v_\nu(q')\bar{v}_e(p')\gamma^\mu(C_V - C_A\gamma^5)u_e(p)$$

  with $C_V = (1+4s_W^2)/2$ and $C_A = 1/2$ for ν_e; $C_V' = 1 - C_V$ and $C_A' = 1 - C_A$ for $\nu_{\mu,\tau}$.

- Thermal plasma in stars (T, $\rho Y_e \equiv \rho/\mu_e$, composition)

  Fermi distribution for $e^\pm$ & Bose distribution for photons;

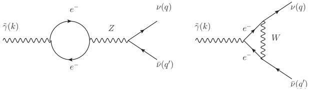
- Neutrino energy loss rate and spectra,

  $$F(E_\nu) = \frac{4}{(2\pi)^6}\int \frac{d^3p}{e^{(E-\mu)/kT}+1}\frac{d^3p'}{e^{(E'+\mu)/kT}+1} v\frac{d\sigma}{dE_\nu}, \quad [\nu/\text{MeV/cm}^3/\text{s}]$$

  $$Q = \int F(E_\nu)E_\nu dE_\nu, \quad [\text{ergs/cm}^3/\text{s}]$$

  High dimensional intergrals !

A few words on other thermal processes



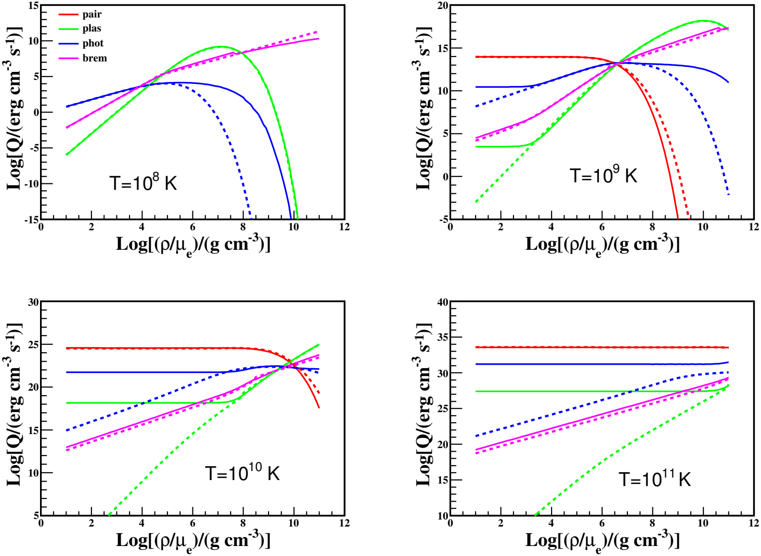
- Plasmon "=" modified photons + collective oscillation electrons "

  2 Transvers Modes 1 Longitudinal Mode

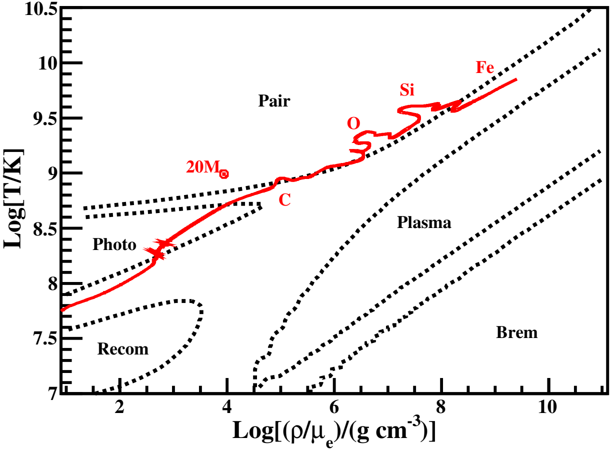
  Photon has a non-zero mass and can decay to neutrino pairs.

- Neutrino spectra from photo-process and Bremsstrahlung are difficulty to calculate.
- Thermal neutrino emission from these three processes in massive stars can always be neglected (see later).

Comparison with Itoh's results

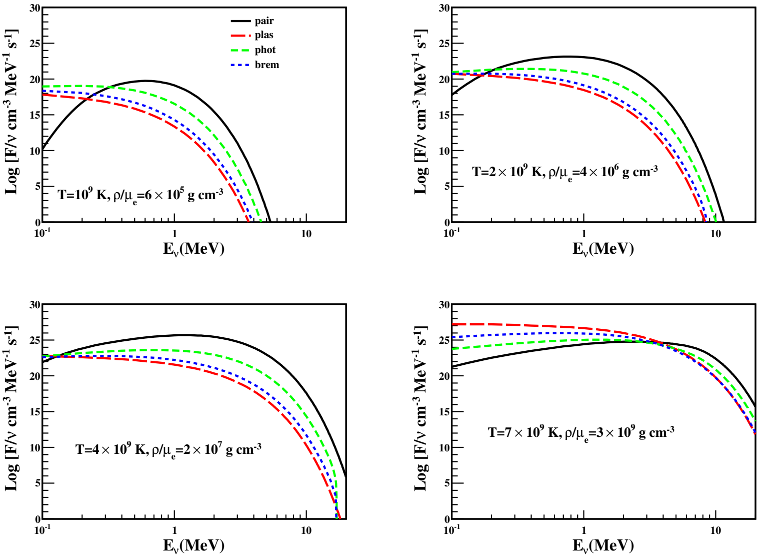


Dominance region

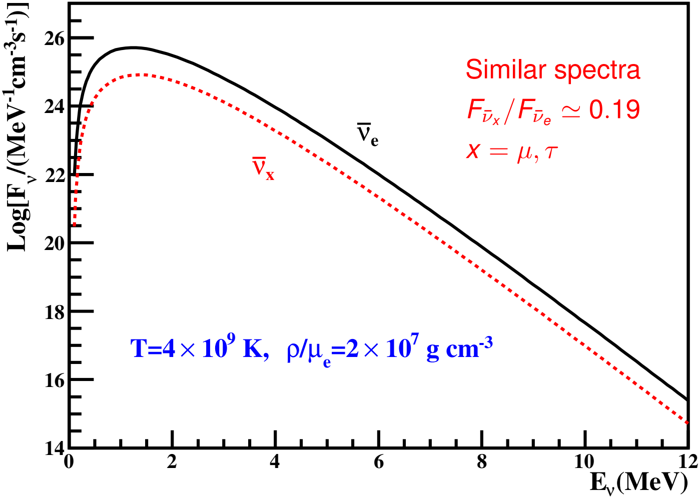


Pair: $\gtrsim$ 99%

Typical $\bar{\nu}_e$ spectra for different processes



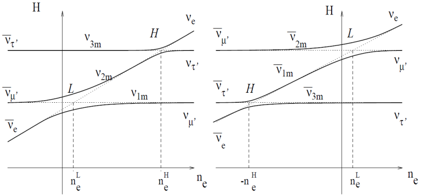
Spectra of $\bar{\nu}_e$ & $\bar{\nu}_x$ from pair process



- $F_{\bar{\nu}_e} = pF^0_{\bar{\nu}_e} + (1-p)F^0_{\bar{\nu}_x}$, $x = \mu, \tau$
  NH: $p = |U_{e3}|^2 = \sin\theta_{13}^2 \simeq 0.025$;
  IH: $p = |U_{e1}|^2$
  $= \cos^2\theta_{12}\cos^2\theta_{13} \simeq 0.7$;
- Similar spectrum for $\bar{\nu}_e$ and $\bar{\nu}_{\mu,\tau}$, and $F_{\bar{\nu}_x}/F_{\bar{\nu}_e} \simeq 0.19$ at silicon burning stage;
- Overall effect of stellar matter effect,

  NH: $F_{\bar{\nu}_e} = 0.76\ F^0_{\bar{\nu}_e}$,

  IH: $F_{\bar{\nu}_e} = 0.21\ F^0_{\bar{\nu}_e}$,

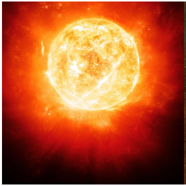


(NH) (IH)

- The Earth matter effect can be safely neglected.

Nearby supergiants

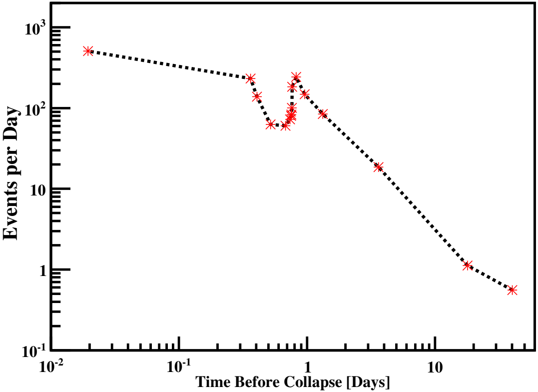
Betelgeuse Antares Zeta Puppis



Several nearby supergiants (incomplete list):
Antares(150 pc, 17 $M_{\odot}$), Betelgeuse (200 pc, 20 $M_{\odot}$), Epsilon Pegasi (210 pc, 12 $M_{\odot}$), Pi Puppis (250 pc, 12 $M_{\odot}$), Zeta Puppis (330 pc, 22 $M_{\odot}$), Sigma Canis Majoris (340 pc, 12 $M_{\odot}$), NS Puppis (520 pc), CE Tauri (550 pc, 8 $M_{\odot}$), etc.

Betelgeuse has been studied extensively & considered as one of the most promising SN candidates. Exploding today or 1 million years later!

Event rate at JUNO



20 $M_\odot$ massive star at L = 0.2 kpc

$$R = N_p/(4\pi L^2) \times \int F_{\bar{\nu}_e}(E_\nu)\sigma(E_\nu)dE_\nu$$

No oscillations (0.76/0.21 for NH/IH);

100% detection efficiency;

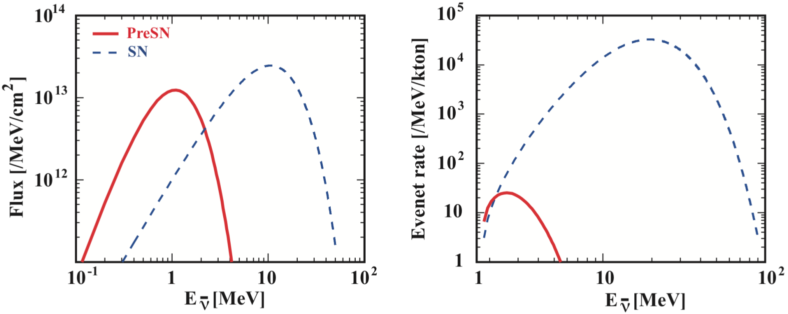
Perfect energy resolution;

Backgrounds in $1.8 < E_\nu < 3.27$ MeV:

Reactor νs: $\sim$ 5 events/day;

Geo-νs: $\sim$ 1 events/day;

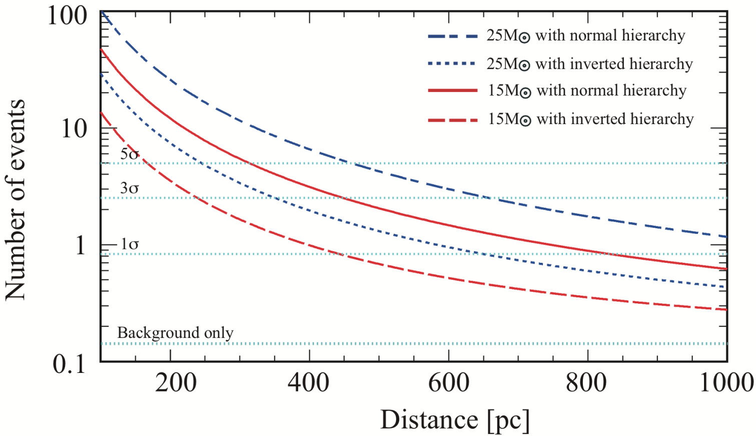
Neutrinos in Pre-SN & SN



15 $M_{\odot}$ at 200 pc; last 2 two days before SN;
$E_{\bar{\nu}_e} = 15$ MeV; no oscillation

KamLAND, arXiv:1506.01175

Sensitivity in KamLAND



$B_{\mathrm{low}} = 0.071$ event/day, Rate-only Analysis
Last two days before SN

KamLAND, arXiv:1506.01175

Related physics of pre-SN signals

- Pre-warning of nearby SN

In SN explosion, neutrinos are hours ahead of photons.

(SNEWS, see Zhe Wang's talk)

Pre-SN neutrinos hours/days ahead of SN explosion could be detected, if the star is close enough.

Pre-warning of nearby SN at KamLAND

Mass [$M_\odot$]	Distance [pc]	Mass hierarchy	Reactor status	Time before collapse [hr]
15	150	Normal	Low	79.0
15	150	Inverted	Low	6.44
25	250	Normal	Low	15.6
25	250	Inverted	Low	3.99
15	150	Normal	high	38.0
15	150	Inverted	high	2.36
25	250	Normal	high	9.72
25	250	Inverted	high	1.04

$B_{\mathrm{low}} = 0.071$ event/day, $B_{\mathrm{high}} = 0.355$ event/day
Rate-only Analysis

KamLAND, arXiv:1506.01175

Related physics of pre-SN signals

- Pre-warning of nearby SN
- Telling SN progenitors

Telling SN progenitors

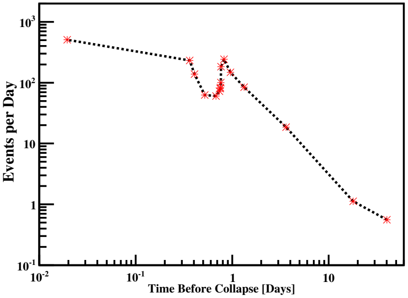
detector	8.4 $M_\odot$		12 $M_\odot$		15 $M_\odot$	
	normal	inverted	normal	inverted	normal	inverted
Super-K	2.47×10^{-2}	9.68×10^{-3}	21	7	61	21
KamLAND	1.06×10^{-3}	1.50×10^{-3}	31	9	43	13
Hyper-K	0.30	0.13	9	3	77	28
JUNO	2.12×10^{-2}	8.03×10^{-3}	618	189	864	266

L = 0.2 kpc

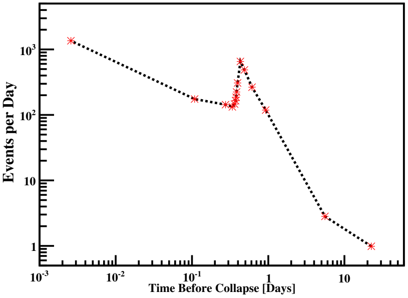
C. Kato etal., arXiv:1506.02358

Telling SN progenitors

(JUNO, No Osc)



20 $M_\odot$



25 $M_\odot$

Both rate & and shape the Light curve are important

Related physics of pre-SN signals

- Pre-warning of nearby SN
- Telling SN progenitors
- Hints on mass hierarchy

Hints on neutrino mass hierarchy

- The distance & progenitor can be determined via pre-SN images, optical light and neutrino burst signals from SN explosion.
- Comparison between the observed neutrino rate and the theoretical expectation gives important information on the mass hierarchy.

A clean way to determine mass hierarchy
if theoretical uncertainties are under control

Summary

- The spectra of the thermal neutrinos (pair/plasma/photo/Bremsstrahlung) have been well calculated;
- Detection of thermal neutrinos from massive stars at JUNO is possible and could be important (neutrino mass order/pre-warning of SN/progenitor, etc.);
- Sensitivity studies of thermal neutrinos at JUNO will be done.

Thank you !