DEVELOPEMENT OF THE PRE-SUPERNOVA NEUTRINOS

Andrzej Odrzywołek

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Revealing the history of the universe with underground particle and nuclear research
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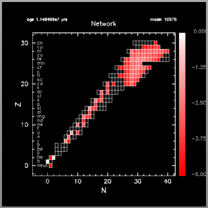

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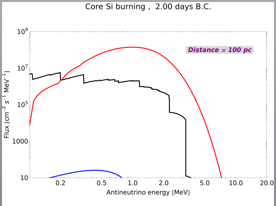

The Big Idea

Can we see neutrinos from other/distant "regular" stars?

The Sun is excluded from now . . .

Early thouths

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TABLE 1

MAJOR NUCLEAR BURNING STAGES FOR 15 AND 25 $M_\odot$ POPULATION I STARS*

Burning Stage	Central Temperature (K)	Central Density (g cm^{-3})	Neutrino Luminosity† (erg s^{-1})	Optical Luminosity (erg s^{-1})	Effective Temperature (K)	Photospheric Radius (cm)	Time Scale (s)
Hydrogen	3.4 (7) 3.7 (7)	5.9 (0) 3.8 (0)	---- ----	8.1 (37) 3.1 (38)	3.26 (4) 3.98 (4)	3.2 (11) 4.2 (11)	3.9 (14) 2.3 (14)
Helium	1.6 (8) 1.8 (8)	1.3 (3) 6.2 (2)	3.9 (33) 7.3 (34)	2.3 (38) 9.5 (38)	1.59 (4) 1.58 (4)	2.2 (12) 4.7 (12)	4.2 (13) 2.1 (13)
Carbon	6.2 (8) 7.2 (8)	1.7 (5) 6.4 (5)	3.4 (38) 1.0 (40)	3.3 (38) 1.2 (39)	4.26 (3) 4.36 (3)	3.7 (13) 6.7 (13)	2.0 (11) 5.2 (9)
Neon	1.3 (9) 1.4 (9)	1.6 (7) 3.7 (6)	6.7 (41) 7.8 (42)	3.7 (38) 1.2 (39)	4.28 (3) 4.36 (3)	3.9 (13) 6.7 (13)	2.2 (8) 3.9 (7)
Oxygen	1.9 (9) 1.8 (9)	9.7 (6) 1.3 (7)	7.9 (42) 2.3 (43)	3.7 (38) 1.2 (39)	4.28 (3) 4.36 (3)	3.9 (13) 6.7 (13)	5.5 (7) 1.6 (7)
Silicon	3.1 (9) 3.4 (9)	2.3 (8) 1.1 (8)	3.4 (44) 3.8 (45)	3.7 (38) 1.2 (39)	4.28 (3) 4.36 (3)	3.9 (13) 6.7 (13)	5.2 (5) 1.2 (5)
Collapse	8.3 (9) 8.3 (9)	6.0 (9) 3.5 (9)	6.8 (48) 8.1 (48)	3.7 (38) 1.2 (39)	4.28 (3) 4.36 (3)	3.9 (13) 6.7 (13)	3.0 (-1) 3.5 (-1)

*All physical parameters refer to conditions just after the core ignition of each fuel, except the time scale which is the period between successive ignitions. The value for the 15 $M_\odot$ star is listed first in each case.

†Excluding neutrino losses during hydrogen burning.

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Table 1 Burning stages in the evolution of a 20-$M_\odot$ star

Fuel	ρ_c (g cm^{-3})	T_c (10^9 K)	τ (yr)	L_{phot} (erg s^{-1})	L_ν (erg s^{-1})
Hydrogen	5.6(0)	0.040	1.0(7)	2.7(38)	—
Helium	9.4(2)	0.19	9.5(5)	5.3(38)	<1.0(36)
Carbon	2.7(5)	0.81	3.0(2)	4.3(38)	7.4(39)
Neon	4.0(6)	1.7	3.8(−1)	4.4(38)	1.2(43)
Oxygen	6.0(6)	2.1	5.0(−1)	4.4(38)	7.4(43)
Silicon	4.9(7)	3.7	2 days	4.4(38)	3.1(45)

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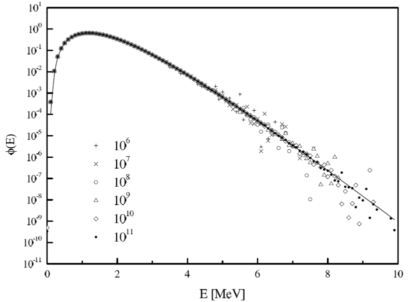

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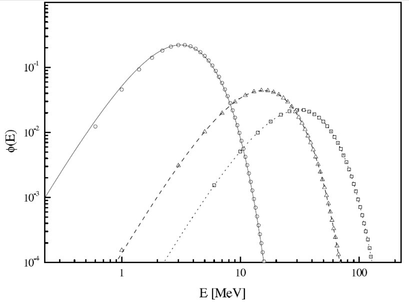

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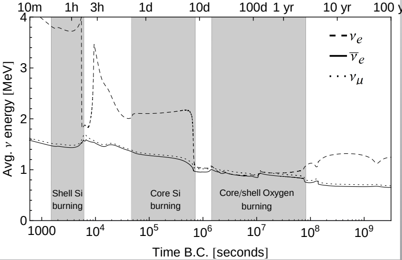

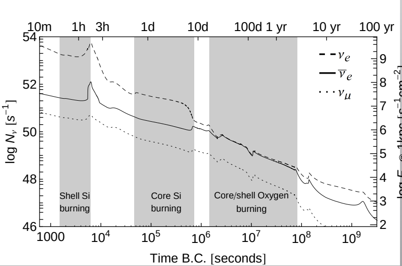

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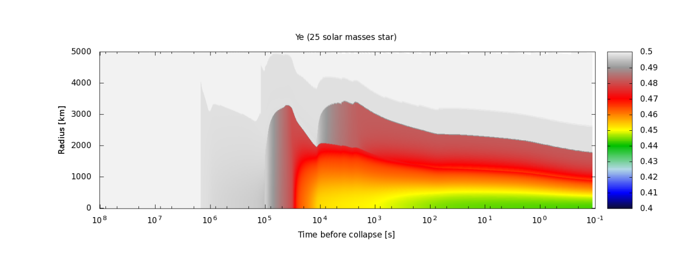

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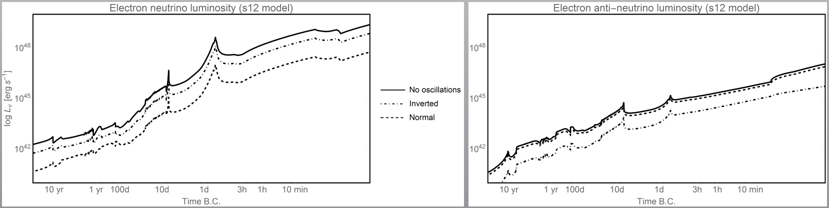

- hydro O/Si burn (last 150 sec) Meakin & Arnett, ApJ, **667**, 448 (2007), S. Couch, Chatzopoulos, Arnett & FXT, ApJ Letters, **808** Number 1, p. L21 (2015) [Suzuki, Nakamura & Takiwaki talks]
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10 years of progress (theory side)

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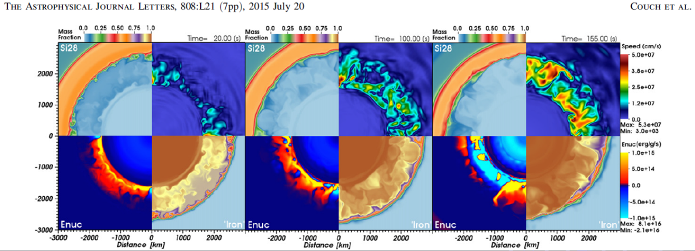

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Recent progress (detector side)

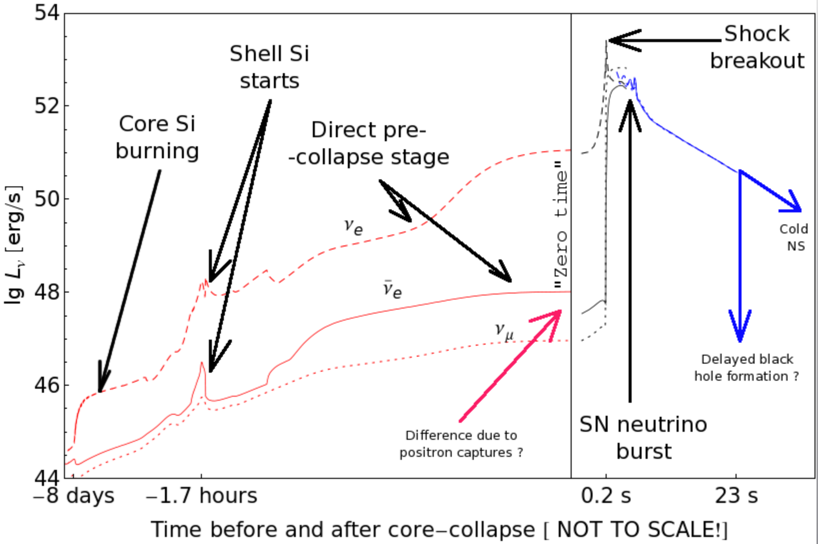
- EGADS — Kamiokande with gadolinium (all tests completed with 100% success)
- Super-Kamiokande with $Gd_2(SO_4)_3$ — SK-Gd starting 2020 [Mark Vagins morning talk]
- DUNE LAr detector [Maury Goodman talk from previous session]
- KamLAND: "Betelgeuse" early warning system operating KamLAND Collaboration, ApJ 818:91 (2016) [Koji Ishidoshiro talk]
- Hyper-Kamiokande project starting construction next year, operating 2027 [Takatomi Yano talk]
- other low threshold (below $\sim$ 2 MeV) large detectors: JUNO, Borexino, coherent, DM search ...

Pre-supernova warning: from sci-fi to reality in 20 years ?

Any day now, nearby (d $\ll$ 1 kpc) Galactic supernova could be observed *via* neutrinos in full time-extent, starting from Si burning week before collapse until late neutron star colling or black hole formation.

In the meantime, gravitational wave astronomy (GW 170817) and neutrino astronomy (SN 1987A) tied in observation of "precious" (not only because of gold&gadolinium production) events... they stay at the same place we did afters 1987.

Typical neutrino light curve for 15 $M_\odot$ star



What could be missing in pre-sn neutrino calculations?

Standard procedure

We take a single stellar model (2-3 models at best), then "fire everything we have":

- do detailed stellar evolution
- integrate all timesteps & all zones of the model
- use the biggest nuclear network/NSE limited only by hardware/nuclear data
- use the most precise neutrino spectrum calculations
- include neutrino oscillations
- ...

Then we say: number of events in detector X from distance D will be N ...

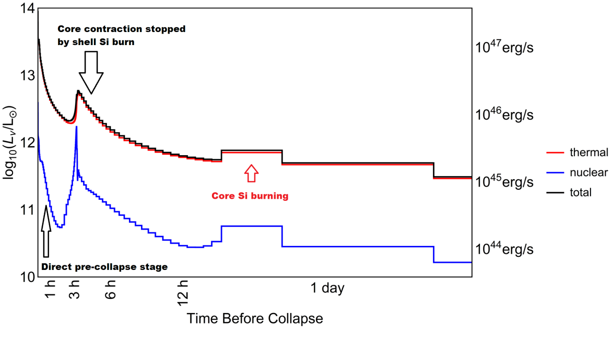
Is this procedure stable?

What if we do, *e.g:*

1. change initial (ZAMS) mass by ± 2 $M_\odot$,
2. increase/decrase metallicity Z by 0.005,
3. switch the stellar wind ON/OFF
4. modify nuclear reaction network by adding 3 or 100 isotopes?

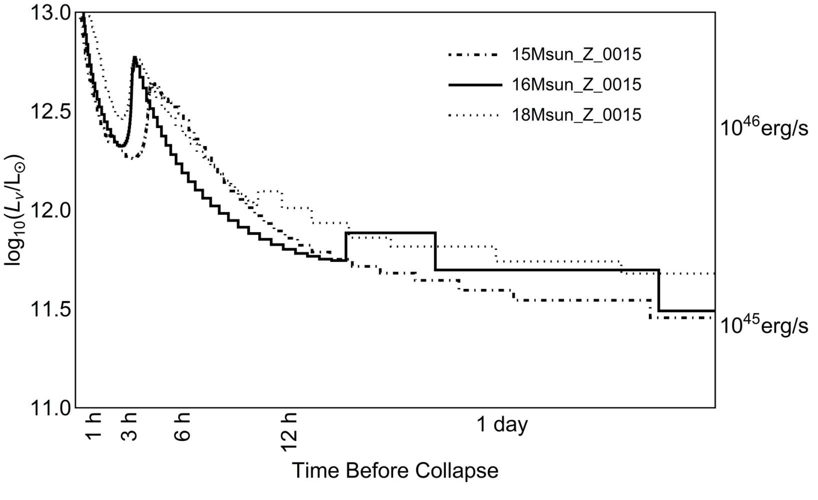
Reference MESA model

1. $M_{\mathrm{ZAMS}} = 16 M_\odot$
2. $Z = 0.015$ (+0.05 dex for Betelgeuse using $Z_\odot$=0.0134)
3. no stellar wind (mass loss zero)
4. standard MESA auto-extended nuclear reaction network:
   - H and He burning: `basic.net`
   - C/O burning: `co_burn.net`
   - Si burning: `approx21.net`



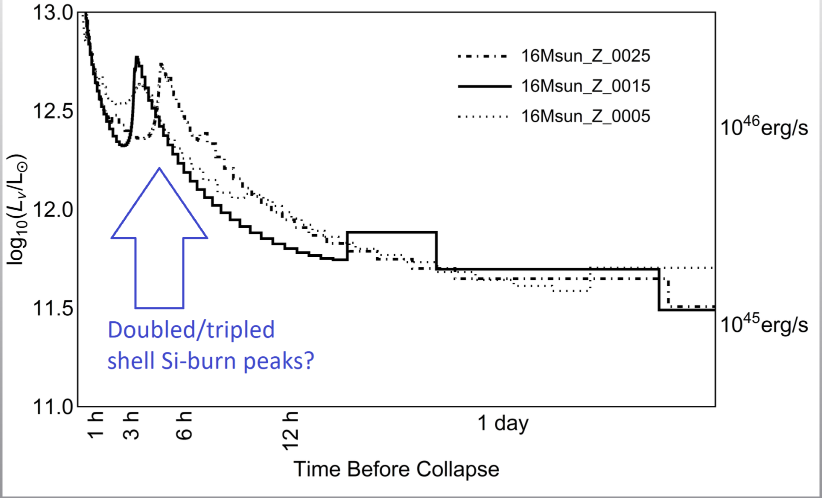
Is the neutrino emission from this model stable with respect to "small" perturbations of the above parameters: M_{ZAMS}, Z, wind, networks?

Reference model *vs* ZAMS mass perturbation

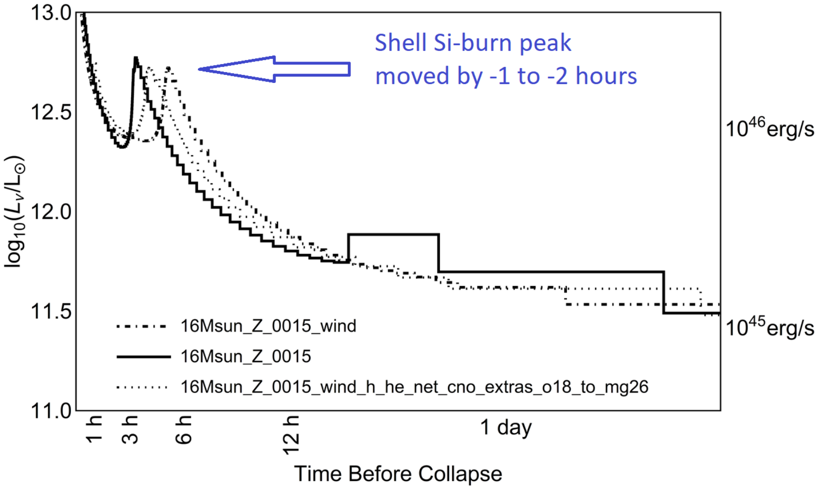


- ALL models end with 1.5 ± 0.02 $M_\odot$ Fe core
- more massive model more luminous
- perturbation $-2M_\odot$ cannot be considered small (ONeMg collapse?)

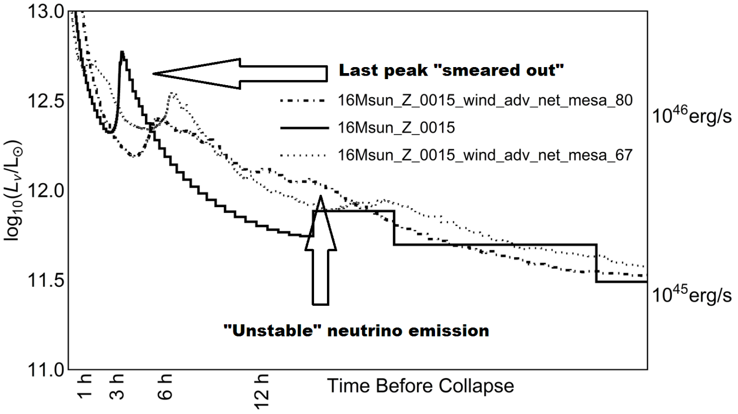
Reference model *vs* metallicity perturbation

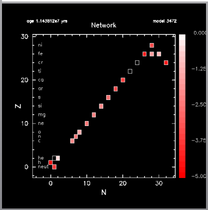


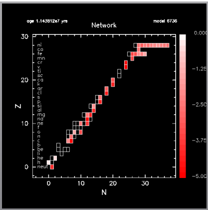
Reference model *vs* wind (on/off/enhanced)

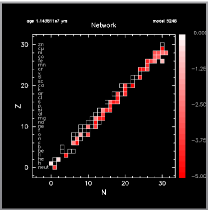


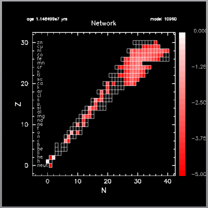
- final stellar mass is: 16, 14.96, and 4.67 $M_\odot$
- despite extreme wind induced by production of intermediate mass metals during shell H/He burn enhanced CNO network, final core evolution is still very similar


Last peak "smeared out"
16Msun_Z_0015_wind_adv_net_mesa_80
16Msun_Z_0015
16Msun_Z_0015_wind_adv_net_mesa_67
"Unstable" neutrino emission
$\log_{10}(L_\nu/L_\odot)$
13.0
12.5
12.0
11.5
11.0
10^{46}erg/s
10^{45}erg/s
1 h
3 h
6 h
12 h
Time Before Collapse

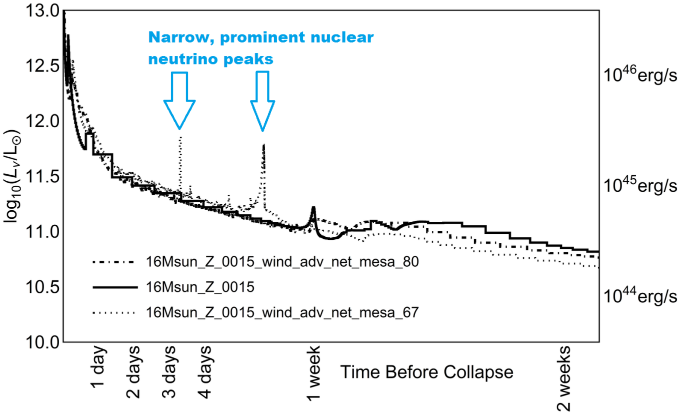

Network
Z
N

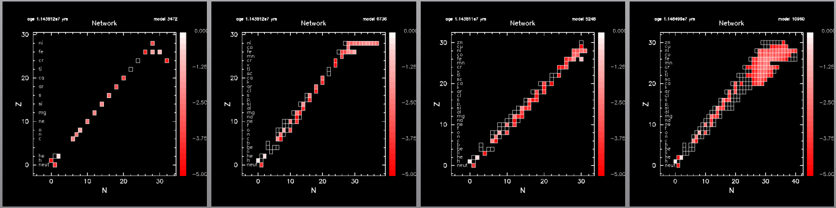

Network
Z
N


Network
Z
N


Network
Z
N

Reference model *vs* nuclear reaction network





Conclusions

- our pre-SN neutrino signal properties verified independently by several groups (Japan, USA) in 2015-2018
- neutrino signal calculations stable with respect to **small** perturbations of mass, metallicity and wind
- reaction network type and size might affect pre-SN signal, especially in nuclear sector; systematic study required
- "ultimate" hydrostatical modelling of pre-SN available; hydrodynamic modelling attempts made
- KamLAND pre-SN early warning works, SK-Gd project on finish
- my wishlist for future: spectral ν emission computed directly from stellar evolution code (without post-process) from H to Si burn, hydro simulation of Si burn, and last but not least: Galactic supernova!

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ありがとうございました

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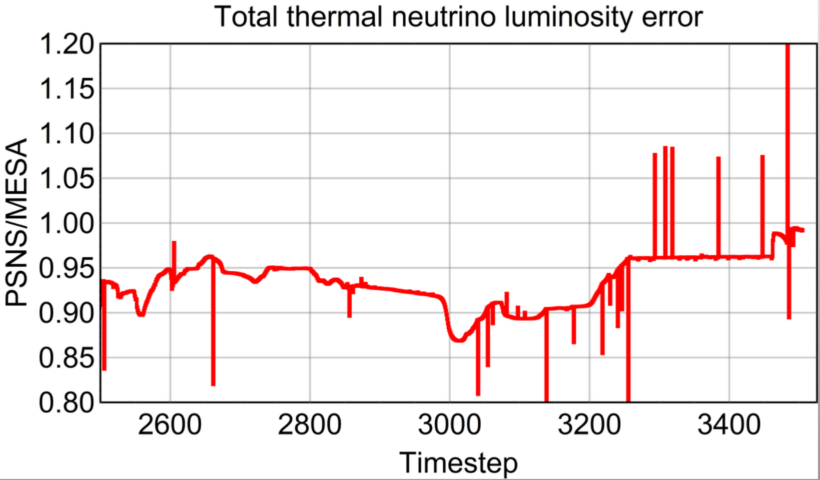
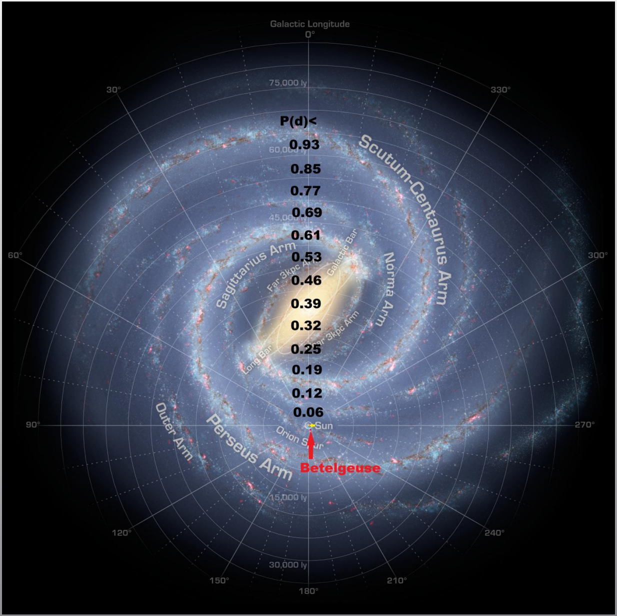
Extra slides

Neutrino spectra animation
Reference stellar model animation

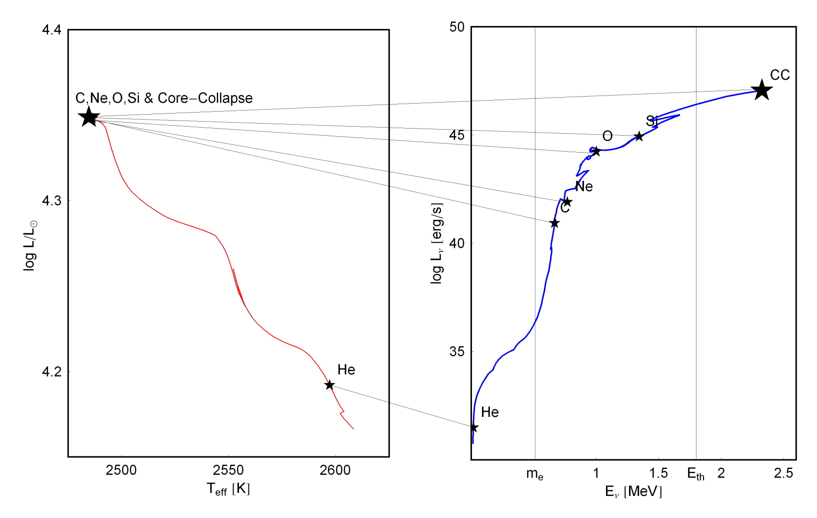
Precision of the thermal neutrino calculations

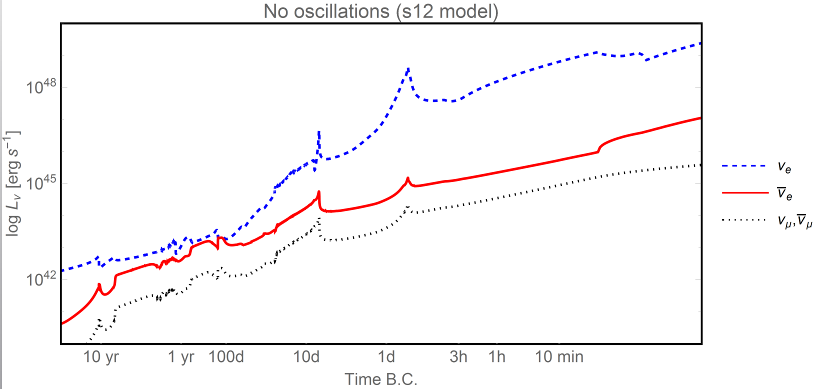




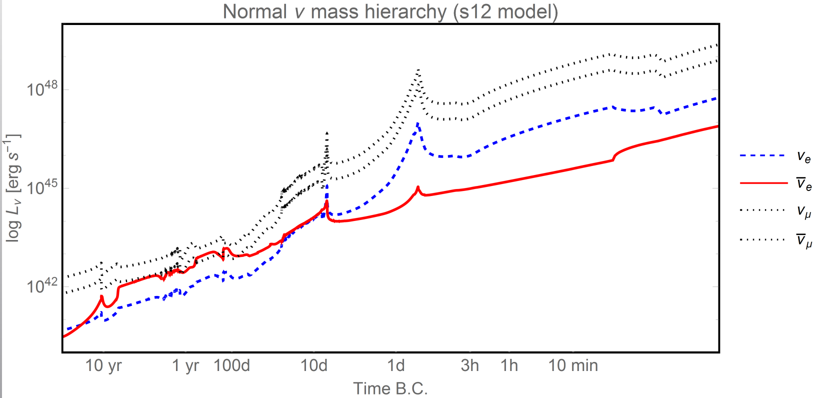
NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

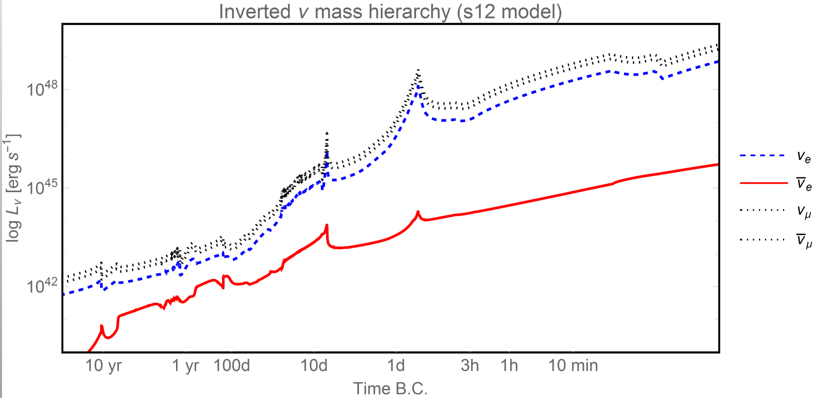
Photon & neutrino HR diagram





No oscillations (s12 model)
log L_ν [erg s^{-1}]
10^{48}
10^{45}
10^{42}
10 yr
1 yr
100d
10d
1d
3h
1h
10 min
Time B.C.
ν_e
$\bar{\nu}_e$
$\nu_\mu, \bar{\nu}_\mu$


Normal ν mass hierarchy (s12 model)
log L_ν [erg s^{-1}]
10^{48}
10^{45}
10^{42}
10 yr
1 yr
100d
10d
1d
3h
1h
10 min
Time B.C.
ν_e
$\overline{\nu}_e$
ν_μ
$\overline{\nu}_\mu$


Inverted ν mass hierarchy (s12 model)
log L_ν [erg s^{-1}]
10^{48}
10^{45}
10^{42}
10 yr
1 yr
100d
10d
1d
3h
1h
10 min
Time B.C.
ν_e
$\overline{\nu}_e$
ν_μ
$\overline{\nu}_\mu$

MSW effect in H envelope leads to flavor exhange:

$$
\begin{aligned}
F^{\text{osc}}_{\nu_e} &= p\, F_{\nu_e} + (1-p)\, F_{\nu_\mu} \\
F^{\text{osc}}_{\nu_\mu} &= (1-p)\, F_{\nu_e} + p\, F_{\nu_\mu} \\
F^{\text{osc}}_{\bar{\nu}_e} &= \bar{p}\, F_{\bar{\nu}_e} + (1-\bar{p})\, F_{\bar{\nu}_\mu} \\
F^{\text{osc}}_{\bar{\nu}_\mu} &= (1-\bar{p})\, F_{\bar{\nu}_e} + \bar{p}\, F_{\bar{\nu}_\mu}
\end{aligned}
$$

Depending on mass hierarchy of neutrinos coeeficients are:

$$
p = \begin{cases} \sin^2\theta_{13} \simeq 0.02 \\ \sin^2\theta_{12}\cos^2\theta_{13} \simeq 0.30 \end{cases}
\qquad
\bar{p} = \begin{cases} \cos^2\theta_{12}\cos^2\theta_{13} \simeq 0.68 & \text{Normal} \\ \sin^2\theta_{13} \simeq 0.02 & \text{Inverted} \end{cases}
$$