(Pre-)Supernova Betelgeuse 2019?

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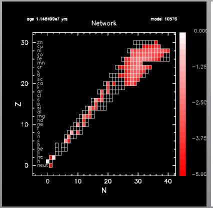

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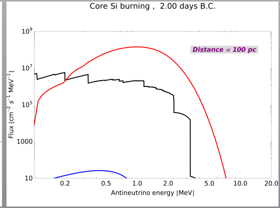

The Big Idea

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

The Sun is excluded from now ...

The Bigger IDEA

Can we forecast supernova explosion?

Is the Betelgeuse excluded ?

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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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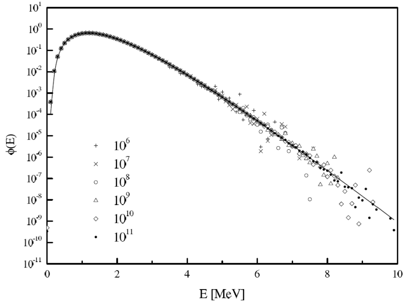

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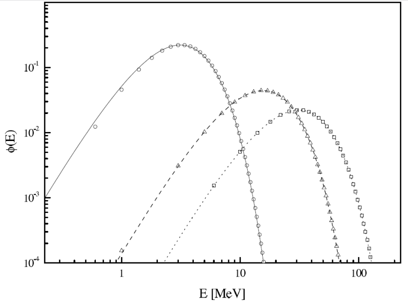

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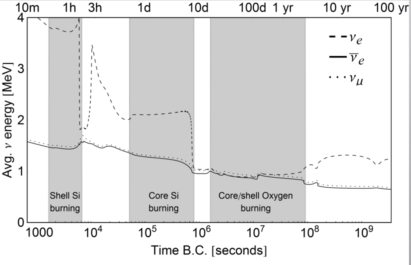

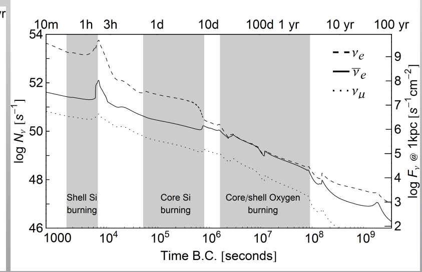

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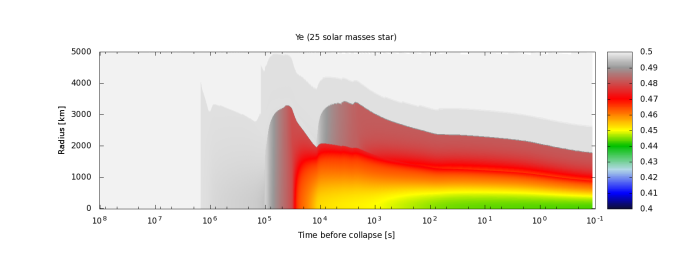

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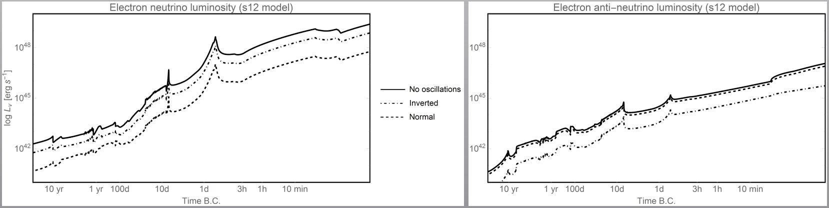

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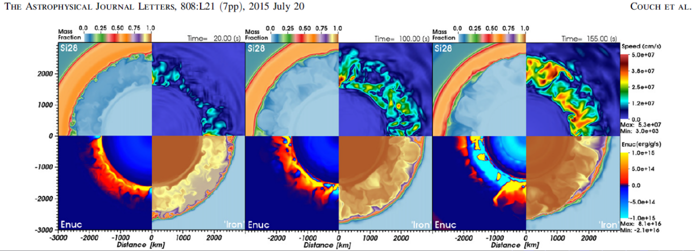

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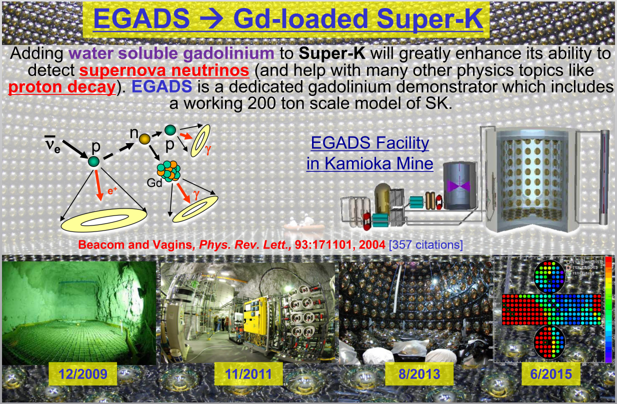

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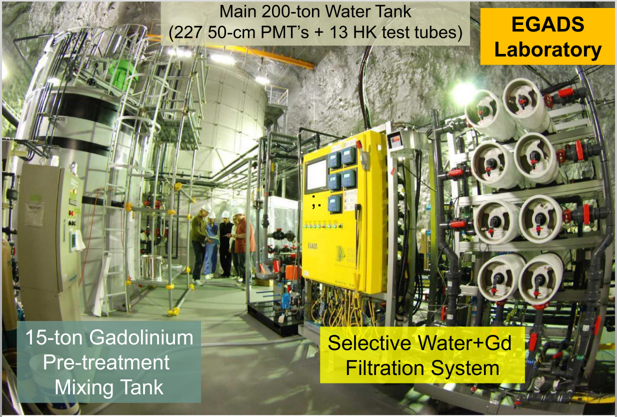

Worldwide, over ¥1.1B (not counting salaries) has been spent developing and proving the viability of the Gd-in-water concept.

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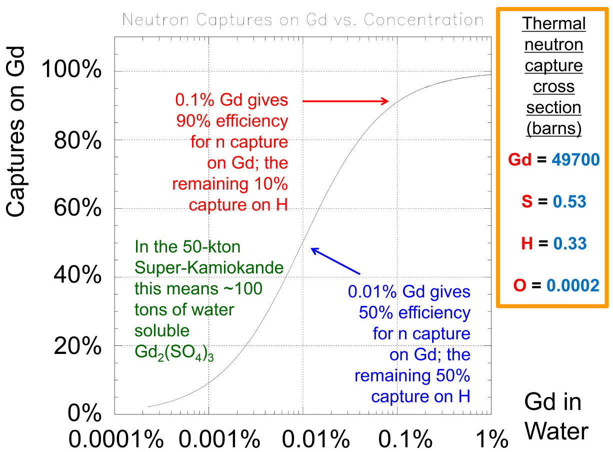

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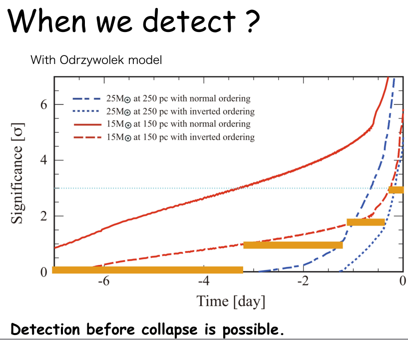

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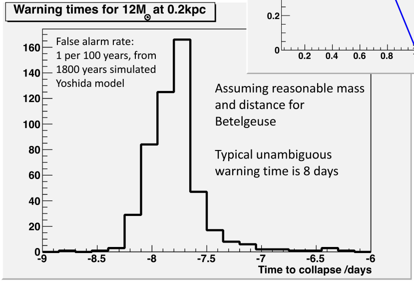
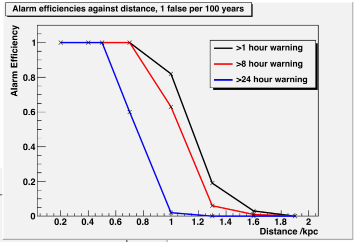
Gd-loaded Super-Kamiokande's Sensitivity to pre-SN ν's
(Super-K internal study)





[C. Simpson]

See related talks by:
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Odrzywolek,
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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.

This is where the fun begins!

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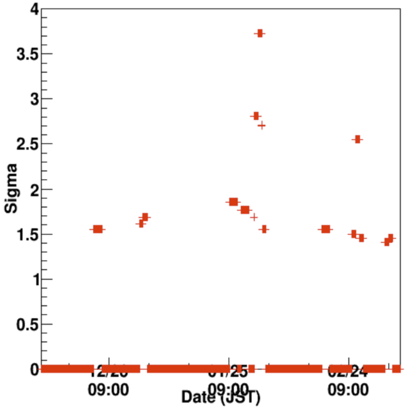

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Recent upgrades to the Super-Kamiokande neutrino observatory will allow it to trace the history of exploding stars.

Davide Castelvecchi

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11. 5 Mar 2019 – flight to Japan
12. 6-9 Mar 2019 – all pre-sn experts invited discuss possible explanations; Kamioka Observatory director 100% sure (very close) supernova has exploded!
13. 10 Apr 2019 (today) — still no trace/confirmation of SN event: what really happened ?

The most recent series of events

1. 1 Feb - 3σ (series of ?) ,,burst" of events in KamLAND (Japan), starting Dec 2018
2. 3 Feb 2019 (Friday) – rumors of Betelgeuse pre-SN warning from Marcin Misiaszek
3. calls in the middle of night
4. A-LIGO upgrade process stopped; GW detector started in emergency
5. Borexino report ZERO events (at least 1 expected)
6. all eyes on Betelgeuse (alternatives: geo/reactor-$\bar{\nu}_e$)
7. 27 Feb 2019 – Nature NEWS on Super-K Gd neutrino supernova observations
8. 1 Mar 2019 - jokes on SNEWS premature warning
9. both KamLAND and SK DAQ crushed simultaneously; SK ready for worldwide announcement of supernova explosion
10. Mar 2019 – still no trace of supernova on the sky (what is going on!?)
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12. Observatory director 100% sure (very close) supernova has exploded!
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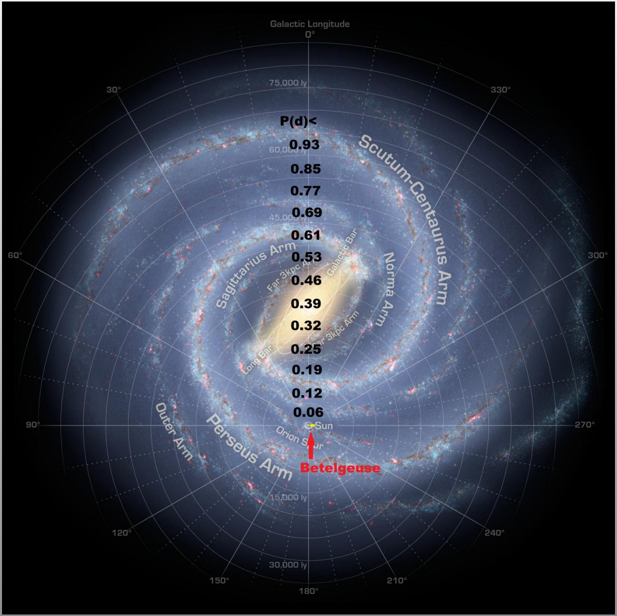
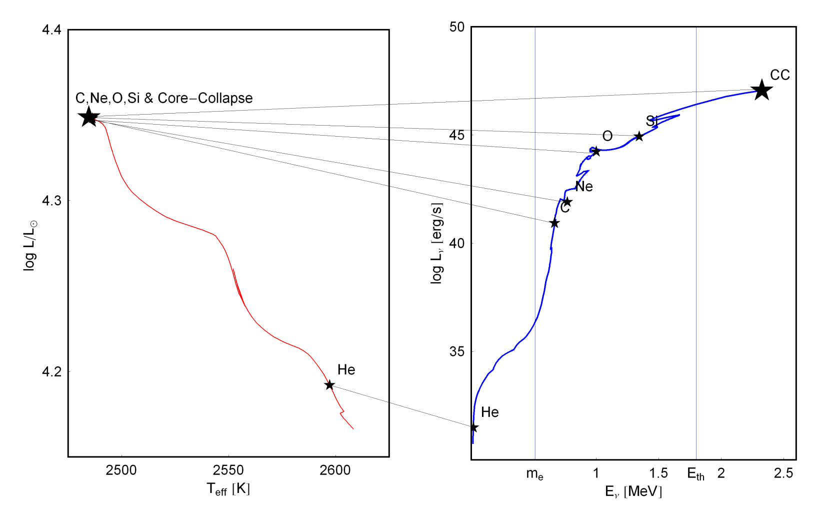
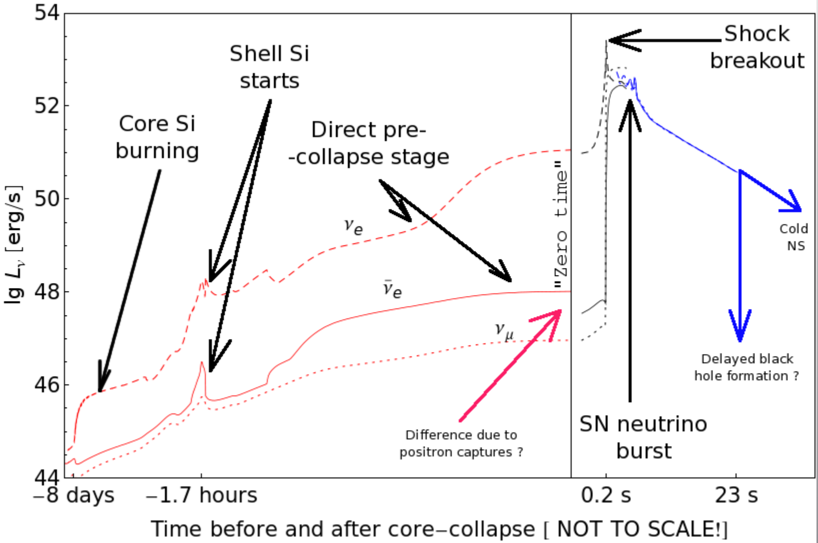


NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

Photon diagram HR & neutrino diagram OMK

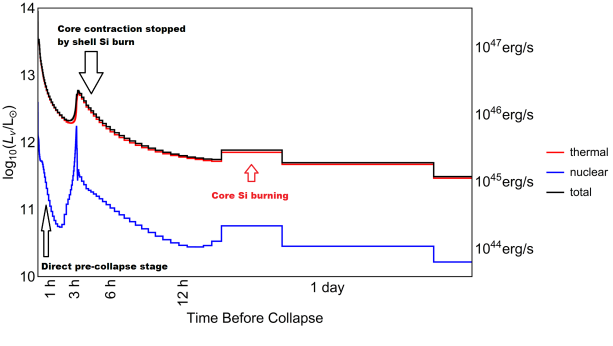


Typical neutrino light curve for 15 $M_\odot$ star

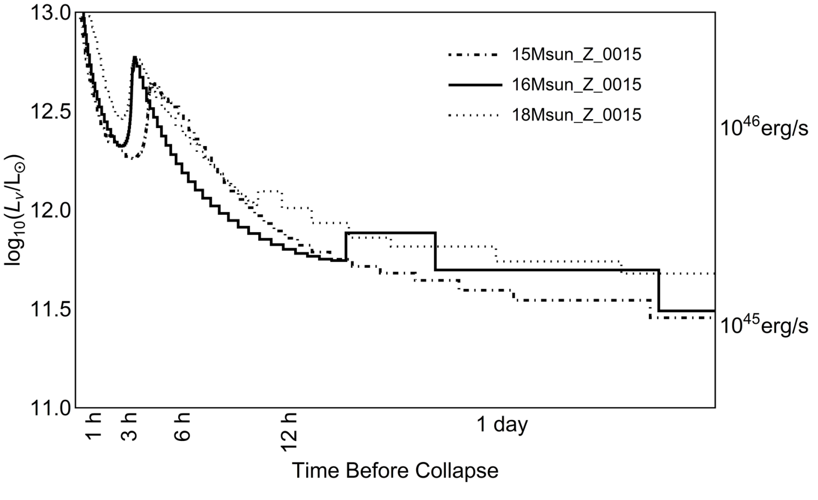


Reference MESA model

1. $M_{\text{ZAMS}} = 16M_{\odot}$
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`

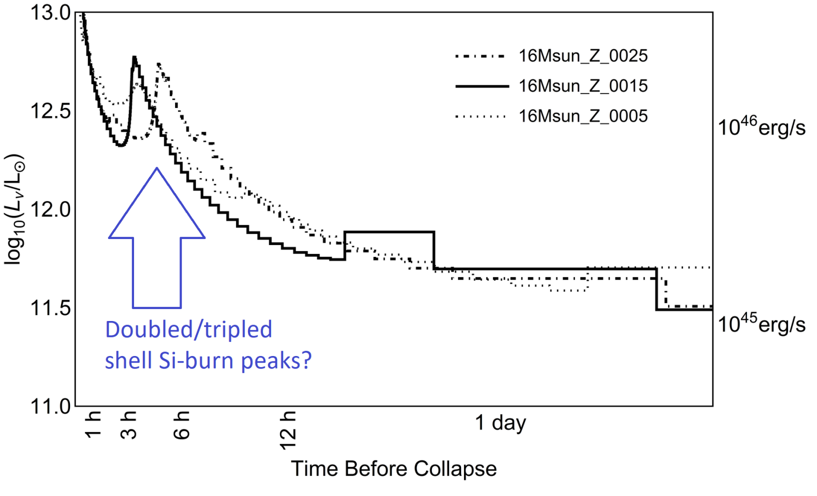


Reference model *vs* ZAMS mass perturbation

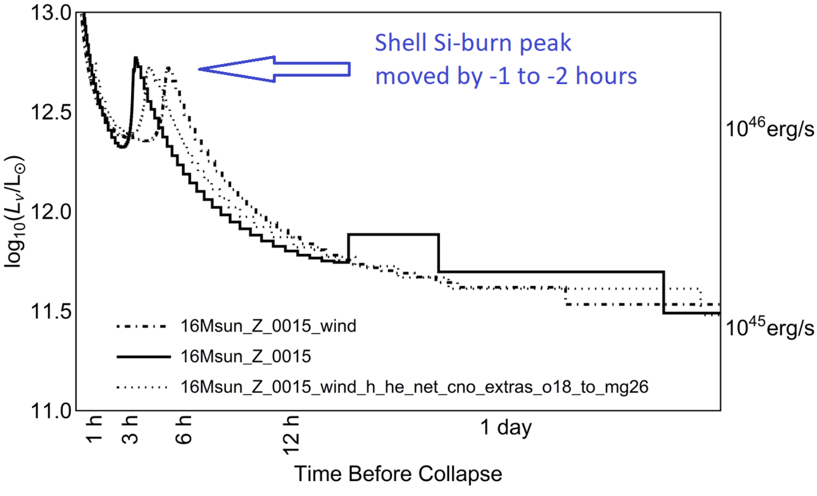


- ALL models end with 1.5 ± 0.02 $M_\odot$ Fe core
- more massive model more luminous
- perturbation $-2M_\odot$ cannot be considered small (ONeMg collapse?)

Reference model *vs* metallicity perturbation

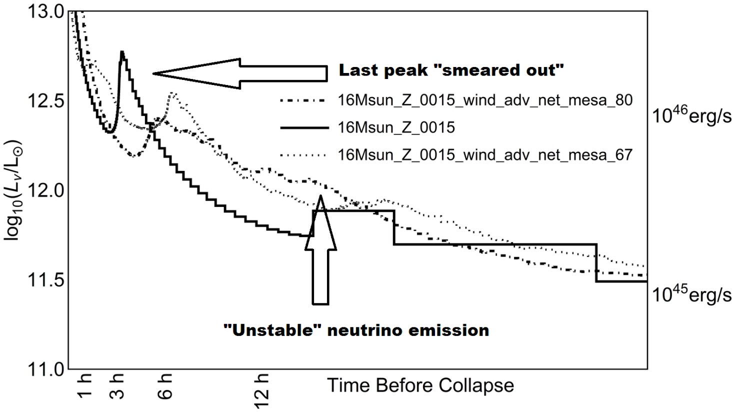


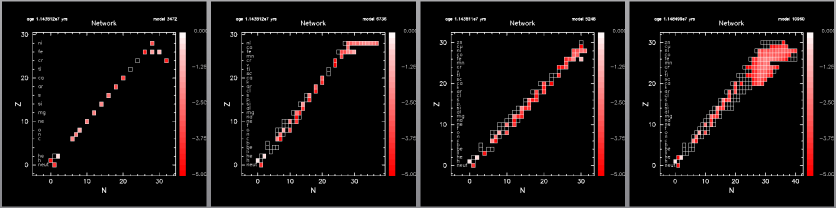
Reference model *vs* wind (on/off/enhanced)



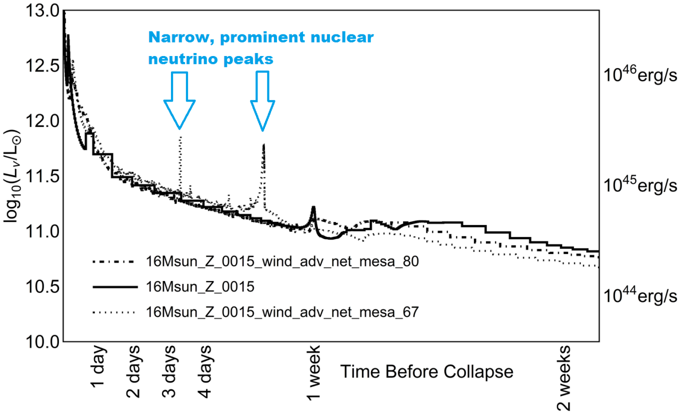
- final stellar mass is: 16, 14.96, and 4.67 $M_\odot$
- despite extreme wind induced by production of intermediate mass metals during shell H/He burn enhanced CNO network, final core evolution is still very similar

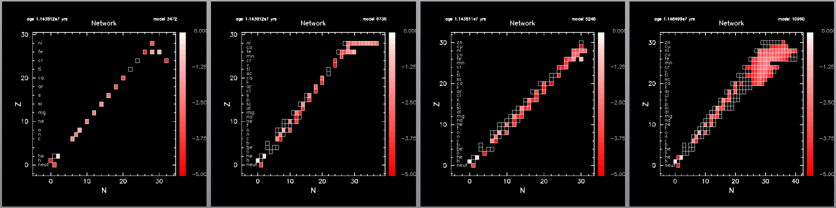
Reference model *vs* nuclear reaction network





Reference model *vs* nuclear reaction network





- bursts/peaks of pre-SN ν days/hours before core-collapse supernova consistent with theory ...
- ...BUT bursts **months** before surprising
- however, (questioned!) ν signal happened 5 hours before SN1987A, consistent with ~8 MeV $\bar{\nu}_e$ neutrino line/peak still mystery (LSD - Deja Vu)
- 2 $M_\odot$ premixed $\bar{\nu}_e$-accelerated H explosive burn, combined with $n + e^+ \to p + \bar{\nu}_e$ emission OR ^{8}Be$^* \to \nu_e + \bar{\nu}_e$ deexcitation
- some estimates 10 Galaxy SN events/century — where are they?
- what about ν emission from stars producing 40 ± 10 $M_\odot$ LIGO binaries?
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Thank you!

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Detection possibility of the pair-annihilation neutrinos from the neutrino-cooled pre-supernova star

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5.1. *Supernova prediction?*

Supernova event is an unpredictable phenomenon. Astronomers await nearby supernova for 400 years. Therefore, many of them speculate on the likely next Galaxy event. The list of candidates includes Betelgeuse, Mira Ceti, Antares, Ras Algheti, γ^2 Vel, Sher25 and Eta Carinae. Unfortu-

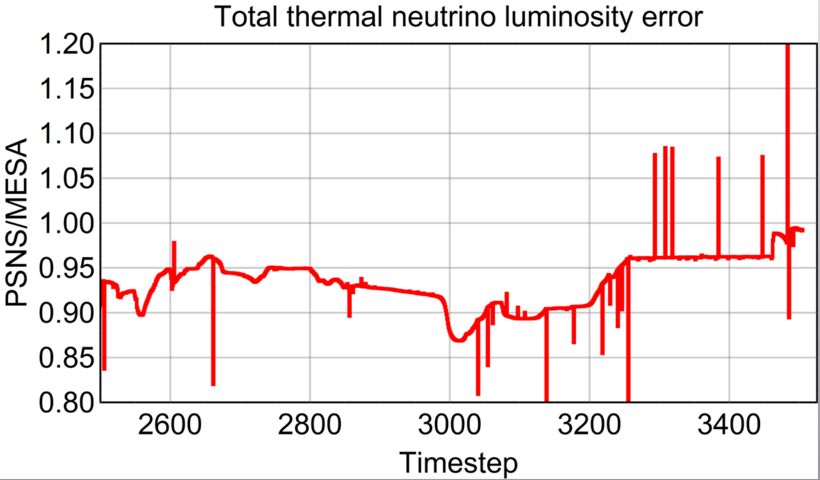
In a very favorable case of a close star, much less than 1 kpc away[4] with operating megaton-scale neutrino observatory modified by addition of appropriate neutron absorber, we could expect detection of oxygen and neon-burning neutrinos a few months before the explosion. The detection, *5.2. Astrophysical importance of Si burning neutrinos*

The aim of our work is to show the feasibility of pair-annihilation neutrinos detection. We did not discuss the calculations of the neutrino luminosities, but actually the silicon burning is very complicated and "potentially numerically unstable

Si-burning neutrinos together with the following observations of optical, neutrino and gravitational signals from the supernova and the identification of the progenitor would establish the relation of pre-supernova conditions and the explosion dynamics. Let's note, that in case of the supernova shrouded in interstellar clouds, Si burning neutrinos carry exclusive information on the progenitor.

Extra slides

Neutrino spectra animation
Reference stellar model animation

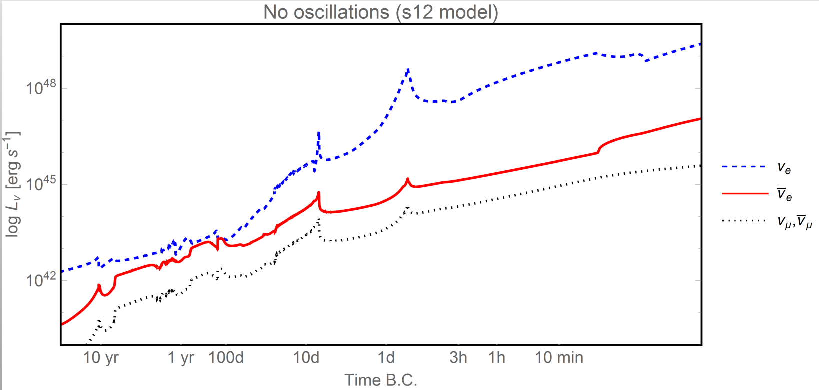

Total thermal neutrino luminosity error
PSNS/MESA
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
2600
2800
3000
3200
3400
Timestep

MSW effect in H envelope leads to flavor exchange:

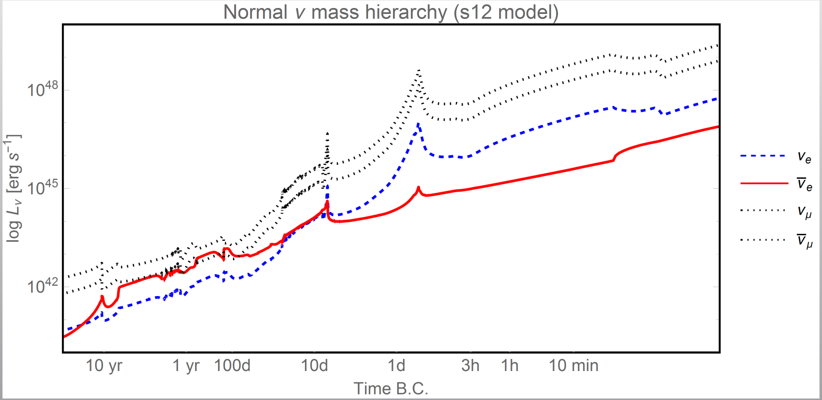
$$\begin{aligned} F_{\nu_e}^{\text{osc}} &= p && F_{\nu_e} + (1-p) && F_{\nu_\mu} \\ F_{\nu_\mu}^{\text{osc}} &= (1-p) && F_{\nu_e} + p && F_{\nu_\mu} \\ F_{\bar{\nu}_e}^{\text{osc}} &= \bar{p} && F_{\bar{\nu}_e} + (1-\bar{p}) && F_{\bar{\nu}_\mu} \\ F_{\bar{\nu}_\mu}^{\text{osc}} &= (1-\bar{p}) && F_{\bar{\nu}_e}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

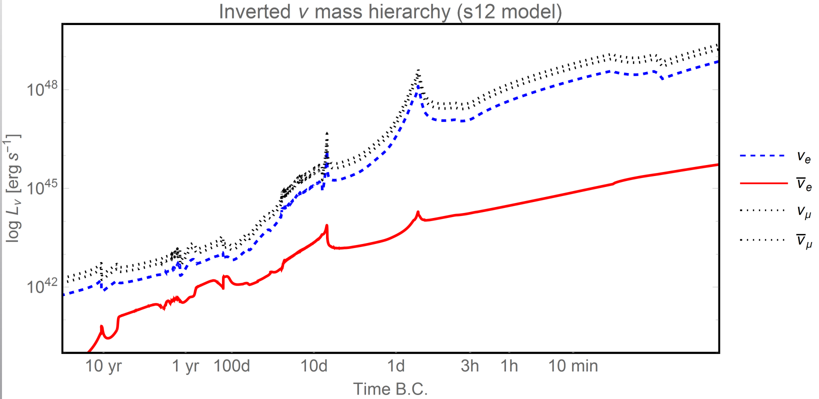
Depending on mass hierarchy of neutrinos coeeficients are:

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



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
$\overline{\nu}_e$
$\nu_\mu, \overline{\nu}_\mu$


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
$\bar{\nu}_e$
ν_μ
$\bar{\nu}_\mu$



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