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Neutrino signatures of the incoming core-collapse supernova

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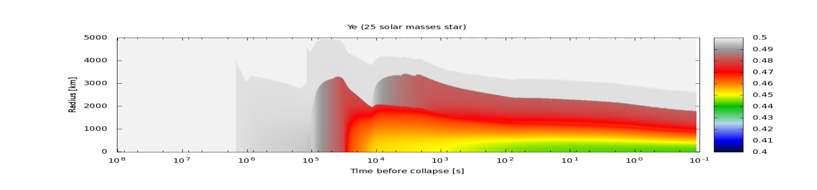
Tuesday, 14.07.2009, 17:15



When next supernova in the Galaxy will explode?

- Everybody here would like to know ...
- But no one knows ...
- Why?

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Why we can't answer this "simple" question?

Why we are unable to estimate time remaining to the core-collapse with accuracy better than 100 000 years, even for nearest candidate, Betelgeuse at distance of only 130 parsecs?

1. Core evolution decouples from surface evolution
2. Core size ($R_c \simeq 10^4$ km) *vs* surface $R_s \simeq 10^7 \ldots 10^9$
3. Evolution is too fast $\tau \sim 100$ years
4. No C burning star is known

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- all the above is due to neutrinos !
- **Solution:** direct and indirect (?) ν detection

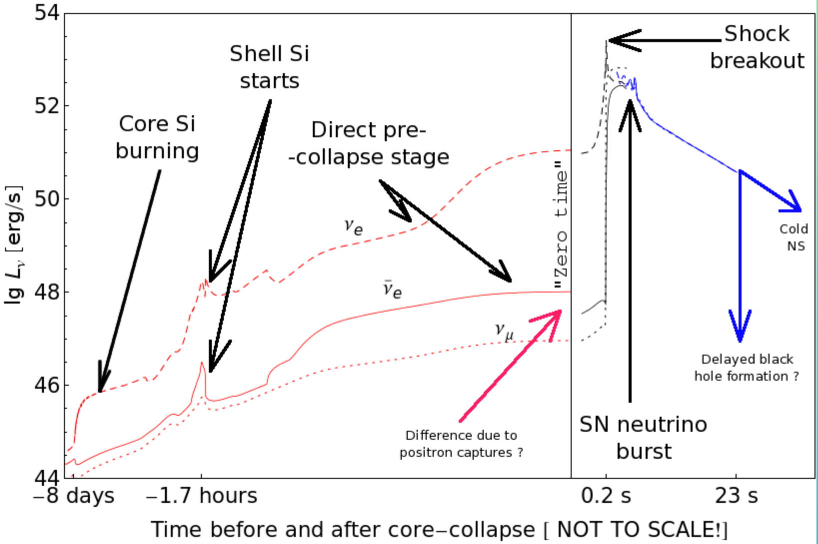
Informations on ν emission in the course of pre-SN life

Stellar life for `neutrino astronomer`

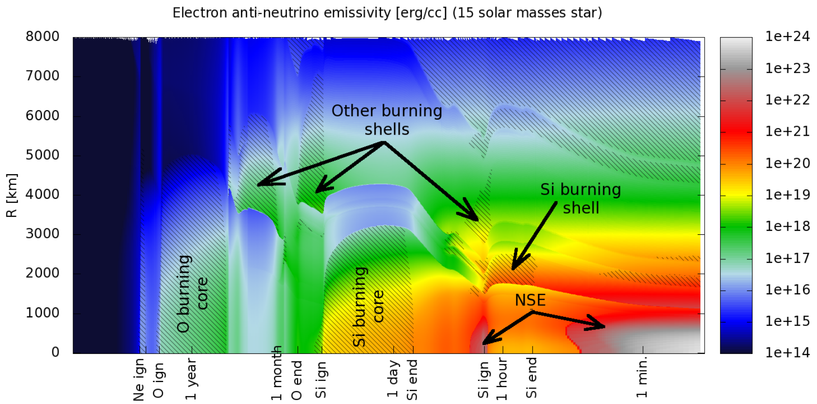
Stage	$\langle L_\nu \rangle$ [erg/s]	E_ν^{tot} [erg]	Time	$\langle \mathcal{E}_\nu \rangle$ [MeV]	Process	Flavors
H burning	10^{36}	10^{52}	10^7 yrs	0.5-1.7	CNO	ν_e
He burning	10^{31}	10^{49}	10^6 yrs	0.02	plasma	all
ν-Cooled	10^{38}-10^{46}	10^{51}	10^4 yrs	0.5-1.5	pair	all
Neutronization	10^{54}	10^{51}	10^{-2} sec	10	ϵ^-	ν_e
SN neutrinos	10^{52}-10^{48}	10^{53}	10 sec	10-40	ν transport	all
NS cooling	$< 10^{48}$	$< 10^{51}$	10^4 yrs	1	d(m)URCA	$\nu_e, \bar{\nu}_e$

1. detection of the ν's from core-collapse within the Galaxy is no longer a challenge now
2. focus should be redirected for *shock breakout ν_e pulse*, *late cooling of neutron stars* and **Neutrino-Cooled stage of pre-supernova**

Before and after core-collapse

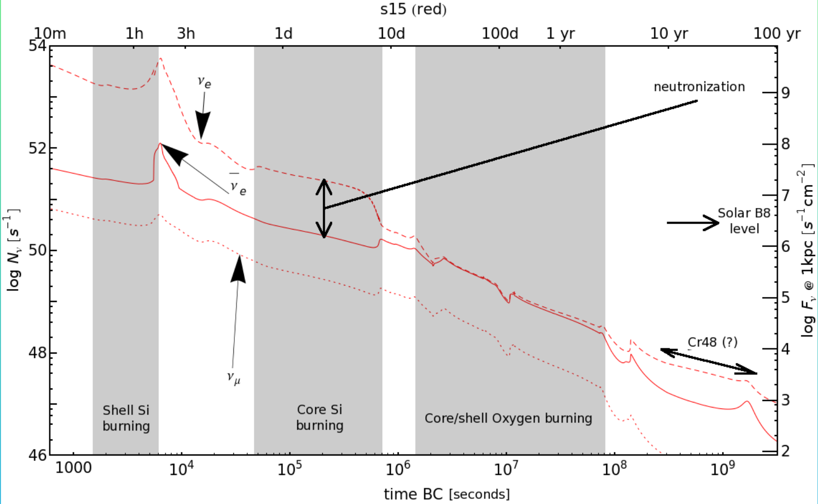


Final stages of the 15 $M_\odot$ pre-supernova star (s15)

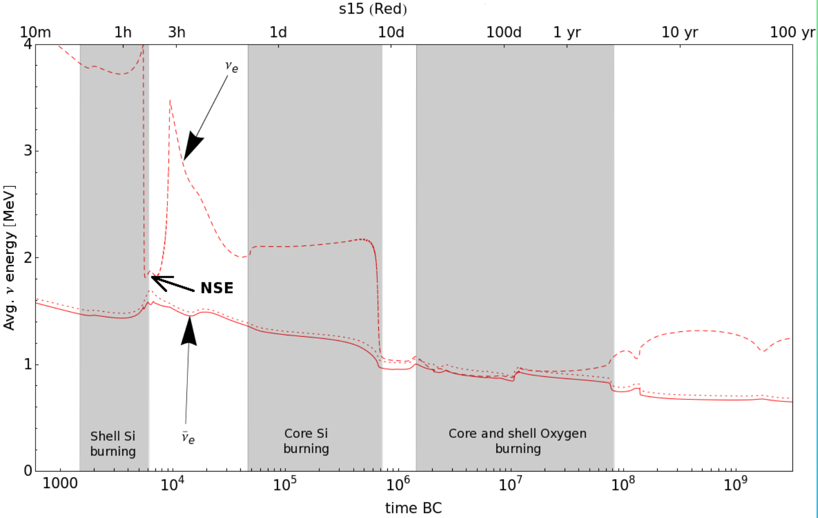


Typical sequence of events leading to the core-collapse supernova with important sources of the ν's .

Neutrino flux 100 years before supernova explosion



$\langle E_\nu \rangle$ 100 years before supernova explosion



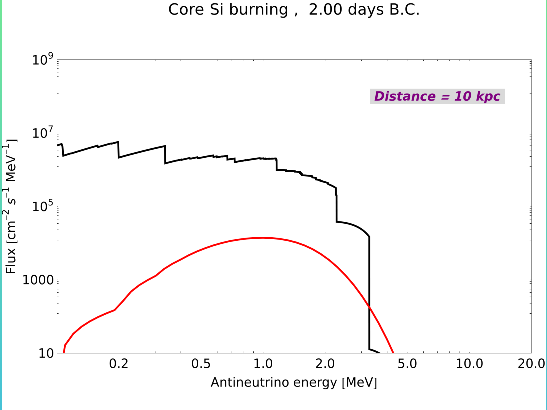
Possible detectable signatures of the incoming SN

Prominent neutrino features of the 15 $M_\odot$ star

1. core/shell O burning (months before core-collapse)
   – *detection limited to Betelgeuse ($d = 100 \dots 200$ pc)*
2. core Si burning (8 - 0.5 days before core-collapse)
   – *for stars closer than 1-2 kpc*
3. max. contraction and shell Si burning (2-0.5 hours b.c.)
   – *up to 10 kpc*
4. direct pre-collapse stage (30 - 0 minutes b. c.)
   – *this should be considered as an initial stage of the core-collapse, as most of ν_e come in last minutes with smooth transition to neutronization peak*
   [cf. previous talk of W. Fulgione]

Both pair annihilation $\bar{\nu}_e$ and electron capture on nuclei ν_e are sources of detectable events.

Pre-supernova $\bar{\nu}_e$ spectra *vs* geo-neutrinos



Black - geoneutrino $\bar{\nu}_e$ spectrum (Sanhiro Enomoto PhD)
Red - thermal pre-SN spectrum: pair + plasma
Blue - weak pre-SN spectrum:
– e^- capture for α-network nuclei for kT$<$0.4 MeV
– NSE neutrinos for kT$>$0.4 MeV (arXiv:0903.2311v1)

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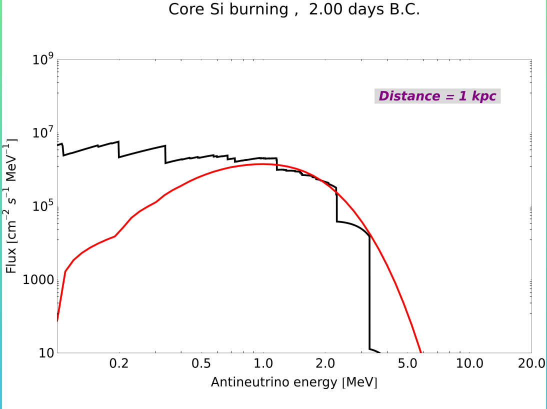

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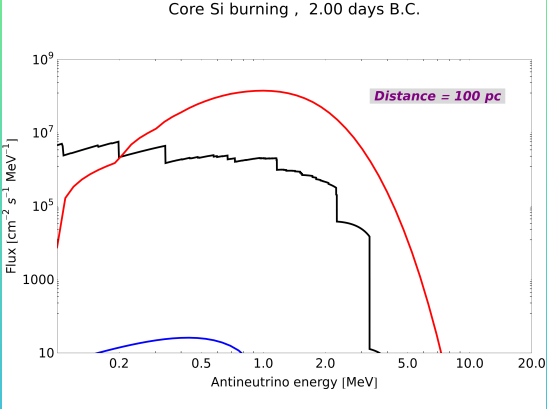

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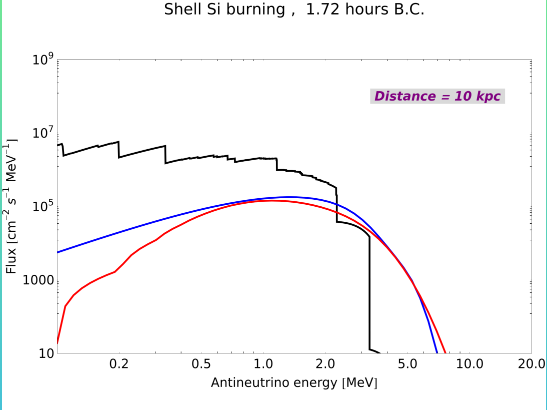

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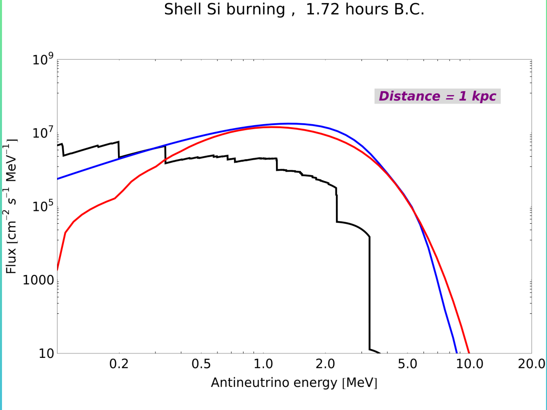

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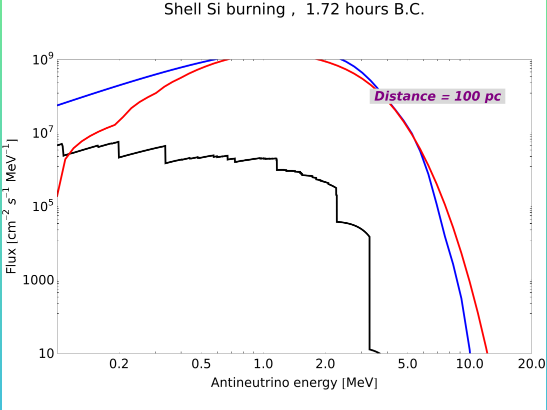

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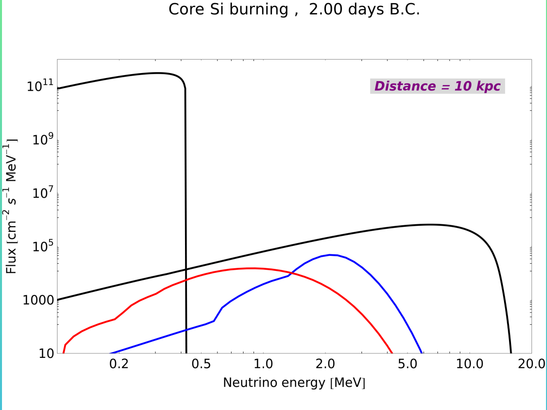
Pre-supernova ν_e spectra *vs* solar neutrinos



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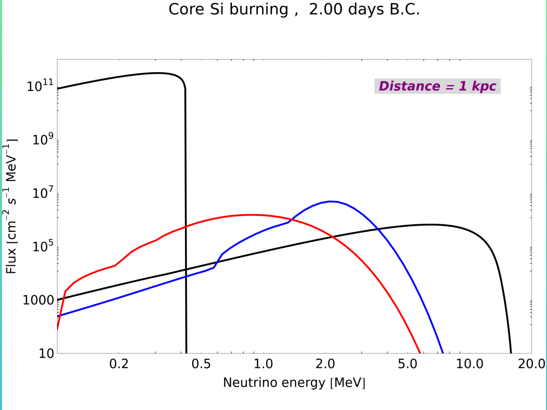

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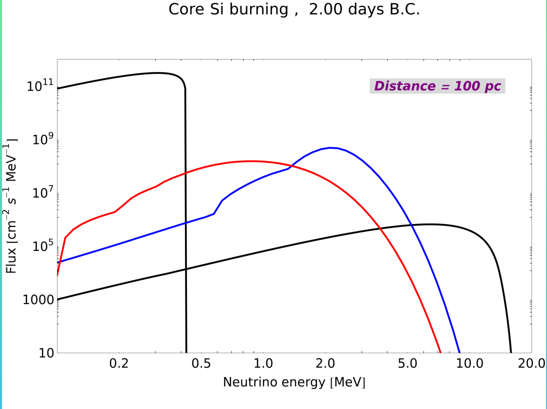

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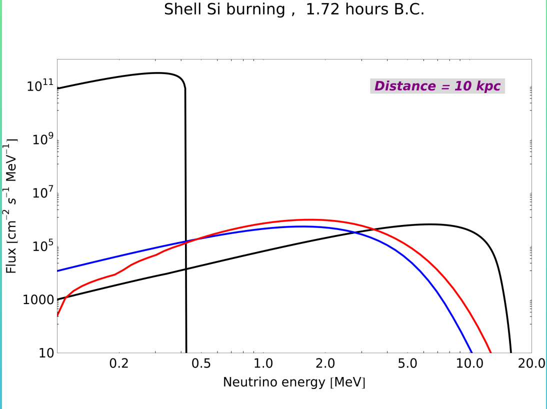

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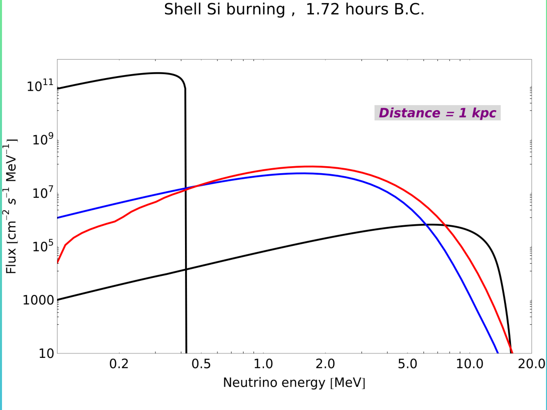

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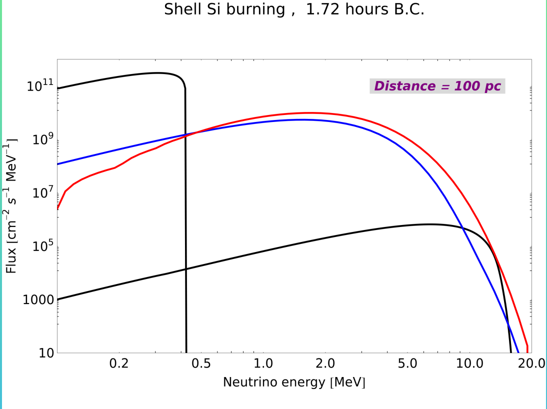

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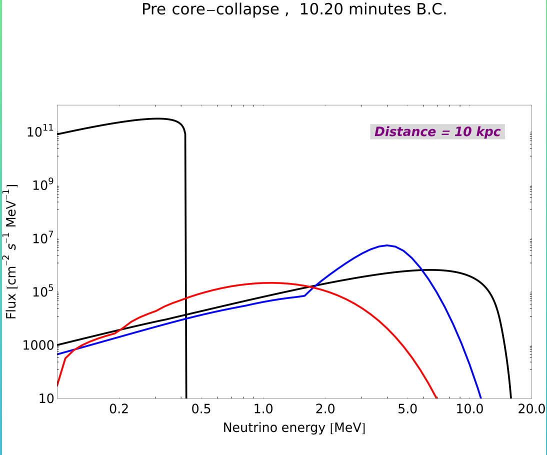

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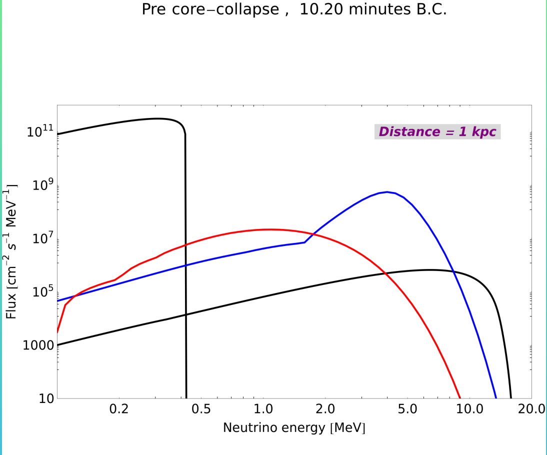

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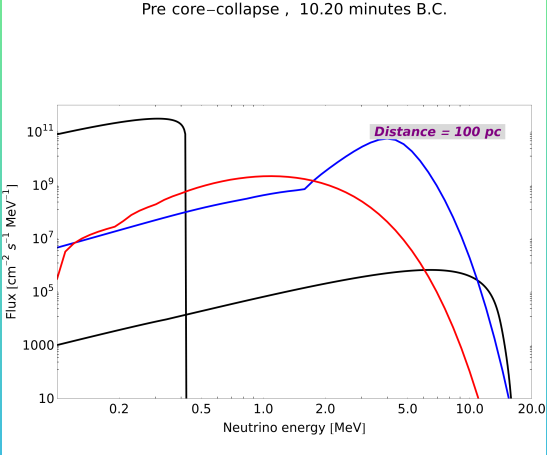

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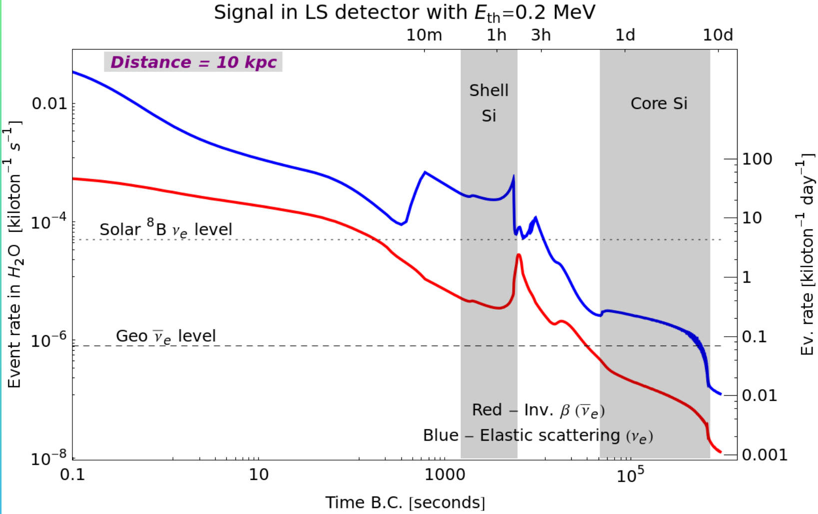
Signal expected in Liquid Scintillator detector



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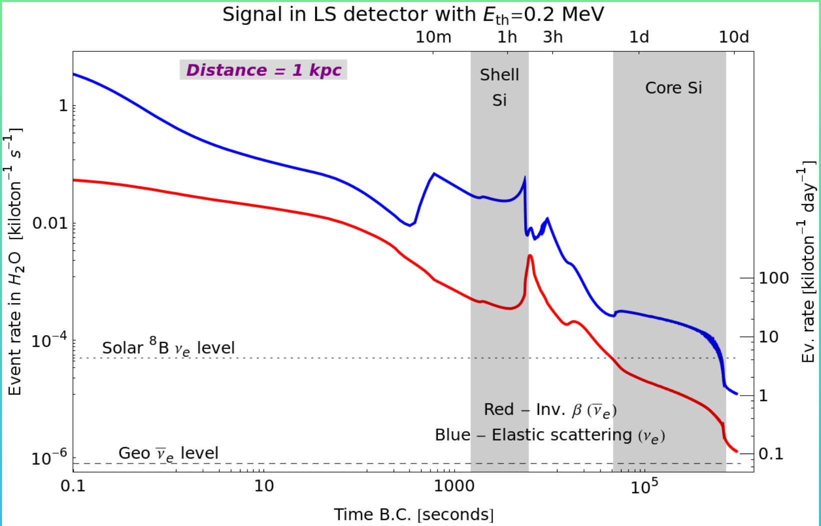
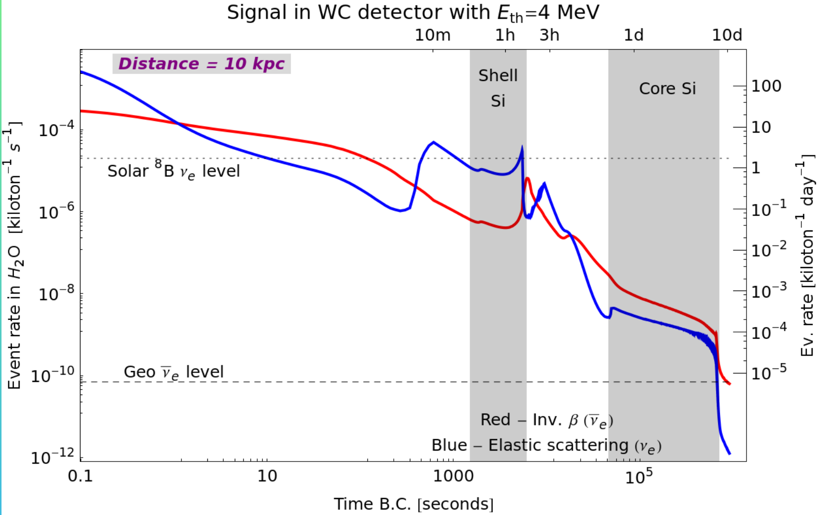


Signal expected in Water Cherenkov detector



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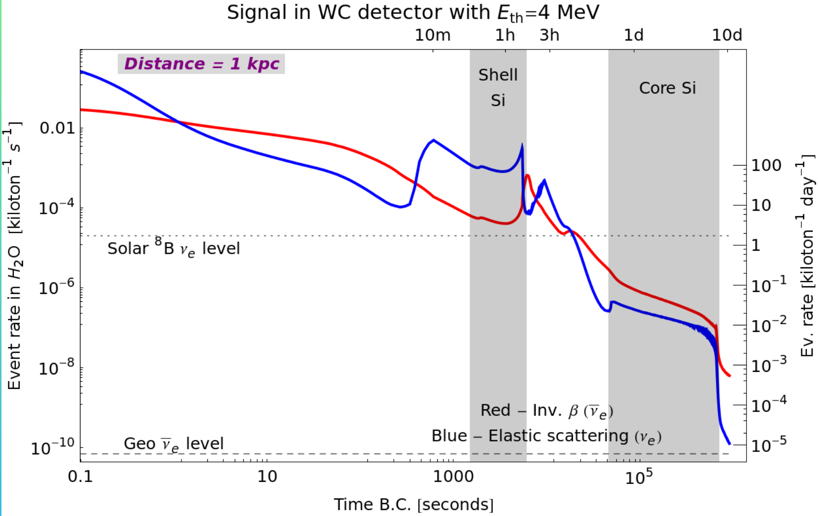
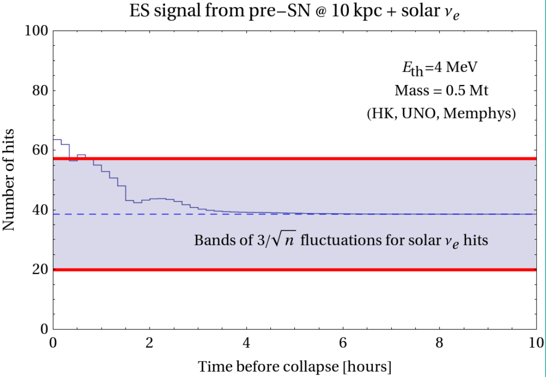


Warning scenario Ia: shell Si burning (0.5 Mt WC detector)

1-Hour moving window signal from 10 kpc



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2. simultaneous $\nu_e + \bar{\nu}_e$ positive fluctuation are of low probability

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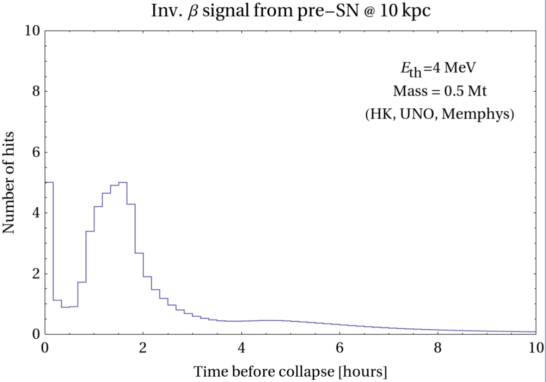
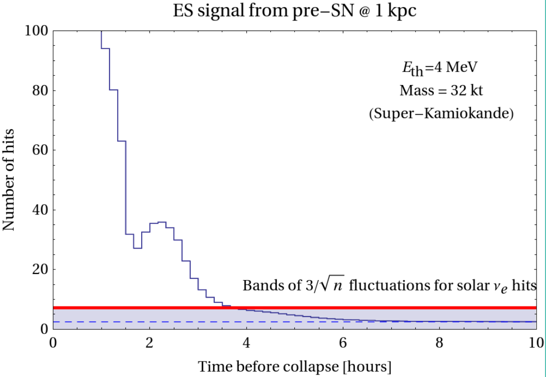


1. Both ν_e (ES) and $\bar{\nu}_e$ (IBD) signals provide ~1 hour warning of the CC SN in 0.5 Mt class WC detector from 10 kpc
2. simultaneous $\nu_e + \bar{\nu}_e$ positive fluctuation are of low probability

Warning scenario Ib: shell Si burning (Super-Kamiokande)

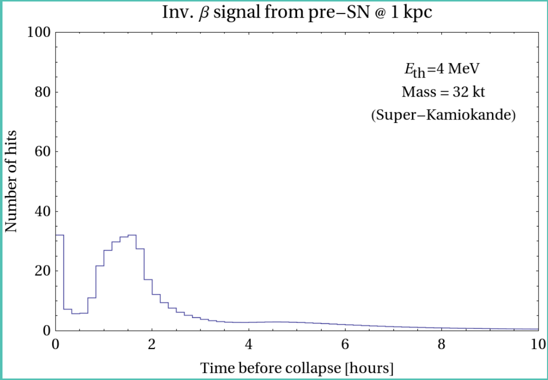
1-Hour moving window signal from 1 kpc



1. ν_e (ES) and $\bar{\nu}_e$ (IBD) signals provide clear ∼1 hour warning in Super-Kamiokande from 1 kpc

Warning scenario Ib: shell Si burning (Super-Kamiokande)

1-Hour moving window signal from 1 kpc



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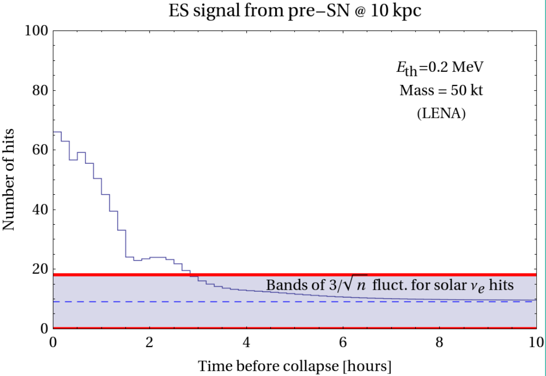
Warning scenario Ic: shell Si burning (LENA)

1-Hour moving window signal from 10 kpc

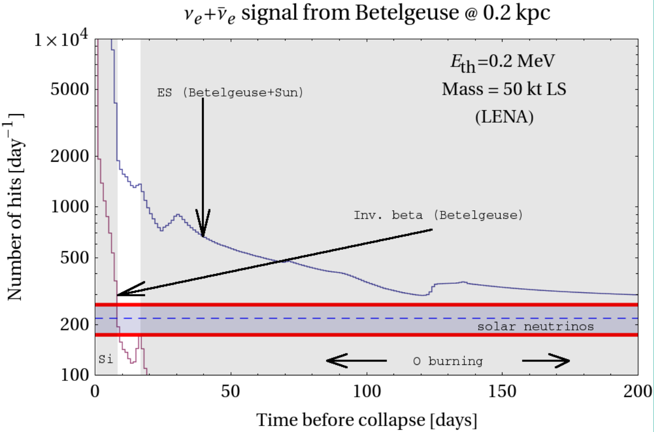


1. ν_e (ES) signal provide clear ~1 hour warning in LENA from 10 kpc
2. Inv. β negligible, only 0-2 hits expected

Warning scenario II: core Si/O burning

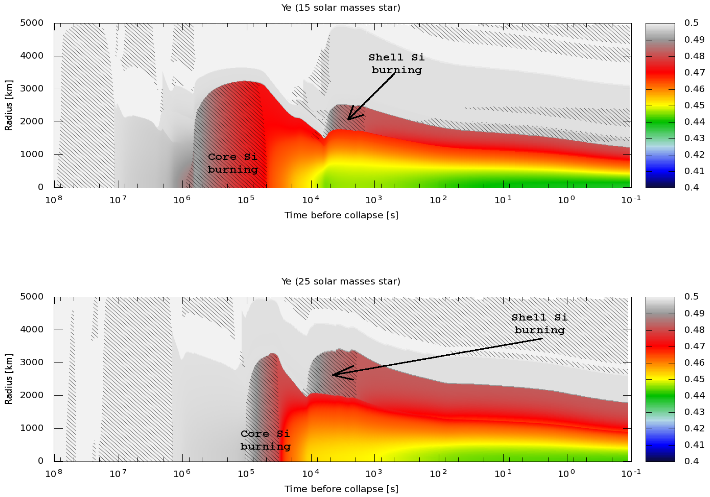
NOTE: this is limited only to nearby stars at distance $d \ll 10$ kpc.

Daily binned signal from Betelgeuse (d=130 pc)



15 $M_\odot$ and 25 $M_\odot$ pre-supernova neutronization

What can be expected from other stellar models?



How generic Si core/shell burning signature is?

Evolutionary sequence for other massive stars

- two full outputs for 15 $M_{\odot}$ and 25 $M_{\odot}$ pre-supernovae has been thoroughly analysed: both provide core Si/shell Si signals
- presented case should be typical
- known exceptions are:
  – stars in the range of initial mass 8-11 $M_{\odot}$ might do not enter O and Si burning stages before collpase
  – some stars might collapse without entering shell Si burning
  – on the other way, two shell Si burning stages are possible

25 $M_{\odot}$ *versus* 15 $M_{\odot}$ pre-supernova

- evolution of 25 $M_{\odot}$ is much faster, so ν flux is therefore higher
- neutrinos are emitted under less degenerate conditions and have smaller energies: **detected signals are lower**
- more massive stars are less numerous (IMF)

Conclusions

- pre-supernova produces steadily increasing ν_e and $\bar{\nu}_e$ flux with progresively higher energy
- new results now inlude weak nuclear neutrinos: **strong (up to 100× pair)** ν_e **flux after core Si ignition has been calculated** in addition to previously know thermal $\bar{\nu}_e$ flux
- energy of ν_e is estimated using FFN rates from α-network ($\sim$4 MeV) and NSE ($\sim$2.5 MeV)
- evolutionary processes: core/shell O, core Si, shell Si burning and direct pre-collapse contraction provide sequence of events in the neutrino detectors
- detection possibility highly depends on the distance; for nearby Betelgeuse future LS detecors (LENA) are able to detect ν_e flux **months** before supernova
- 50% of Galactic stars lie within distance of 10 kpc; from this distance we can detect only shell Si burning $\sim$1 hour B.C.
- terrestial $\bar{\nu}_e$ and solar ν_e are main irremovable backgrounds; *directional analysis can possibly help*

Important References

- **Stellar models s15 and s25:** Woosley, S. E.; Heger, A.; Weaver, T. A., *The evolution and explosion of massive stars*, Reviews of Modern Physics, 2002 **74**, 1015-1071
- **Neutrino spectra & basic processes:** Misiaszek, M.; Odrzywolek, A.; Kutschera, M., *Neutrino spectrum from the pair-annihilation process in the hot stellar plasma* , Physical Review D, **74**, 043006.
  A. Odrzywolek, *Plasmaneutrino spectrum*, Eur. Phys. J. C52, 425-434, 2007
  A. Odrzywolek, *NSE neutrino spectrum*, arXiv:0903.2311v1 [astro-ph.SR]
- **Shock breakout ν_e:** Thompson, Todd A.; Burrows, Adam; Pinto, Philip A., *Shock Breakout in Core-Collapse Supernovae and Its Neutrino Signature*, The Astrophysical Journal, 2003 **592** 434-456
- **Protoneutron star neutrino cooling and delayed black hole formation:** J. A. Pons, J. A. Miralles, M. Prakash and J. M. Lattimer, *Evolution of Proto-Neutron Stars with Kaon Condensates*, The Astrophysical Journal, 2001 **553** 382-393
  A. Odrzywolek, M. Kutschera, *Kaon condensate with trapped neutrinos and high-density symmetry energy behavior*, Acta Phys. Polon. B40, 195, 2009 (arXiv:astro-ph/0703686v1)

More information

PSNS WWW devoted to post-processing of astrophysical models with focus on detailed state-of-art neutrino spectra:
http://ribes.if.uj.edu.pl/psns

Extra slides

Animation for s15 model

Comparison of the solar ν_e spectrum and pre-supernova from 1 kpc (left) and geoneutrinos at Kamioka with pre-supernova $\bar{\nu}_e$. Animation show last 40, 000 years before supernova, after end of the He burning.

Animation link

Express introduction to pre-supernova stars

Definition of **massive star**

- star massive enough to explode as a core-collapse supernova
- lower range end is not precisely known: 8-11 $M_{\odot}$
- I will talk about ,,genuine" massive stars $M > 15 M_{\odot}$
- particularly, analysed stars enter **core** and **shell** *Si burning* stages
- two complete stellar models: s15 and s25 of A. Heger are used to examine detection scenarios
- *real-world* examples: *Betelgeuse, Eta Carinae*