

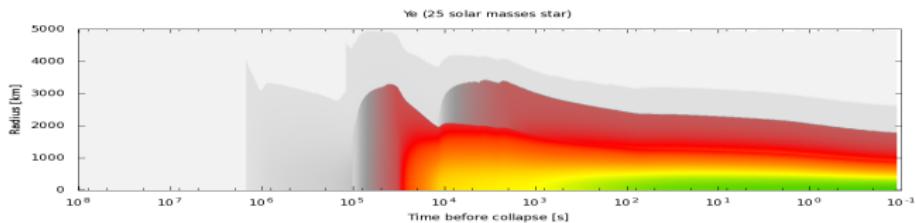
Neutrino signatures related to supernovae

Overview of the neutrino emission: from main sequence to the neutron star

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Modern supernova classification

Class	Thermonuclear	Core-Collapse
Type	Ia	II, Ib/c, L-GRB
Energy source	thermonuclear	gravitational
Explosion energy	10^{51} erg	10^{53} erg
Neutrinos	neutrinos 10^{49} ergs (1%)	neutrinos 10^{53} ergs (99%)
Progenitor	CO white dwarf in binary	massive star $M > 7 - 10 M_{\odot}$
Examples	SN1994D	SN1987A
Remnant	spherical nebula	asymetrical nebula + NS or BH

Massive stars: important facts

- significant fraction of the pre-supernova *initial mass* (ZAMS, **Zero Age Main Sequence**) is lost due to stellar wind, e.g. 15 M_{\odot} solar metalicity star explode as 12 M_{\odot}
- lifetime is relatively short, few millions of years
- 99,9% of lifetime is spent on the *main sequence*, i.e. hydrogen burning via CNO
- relative number of massive stars is given by the IMF (**I**nitial **M**ass **F**unction); Salpeter IMF:

$$\frac{dN}{dM} \propto M^{-\alpha}, \alpha = 2.35$$

- stars with masses above $100 M_{\odot}$ are now extinct in the Galaxy

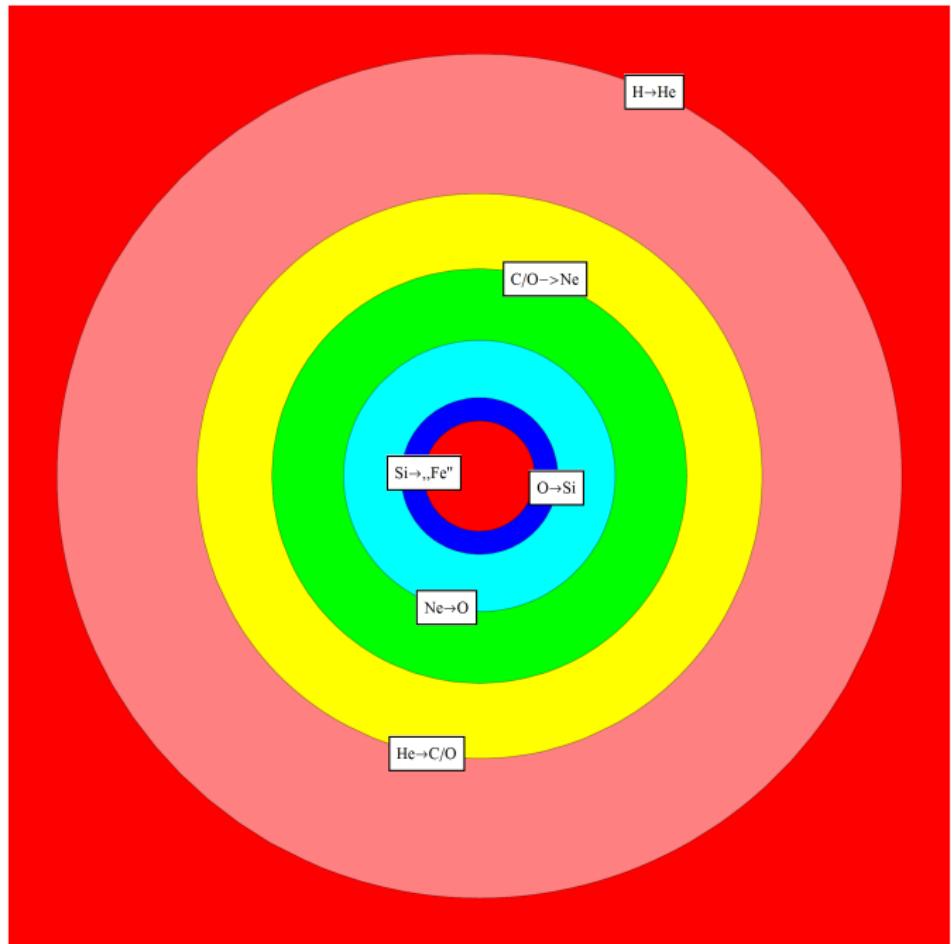
Onion-like structure

Burning cycles

Start: shrinking → release of the gravitational energy → compressional heating → ignition → convective core → fuel shortage → further core contraction GOTO **Start**

Burning in „massive enough” star

- ① $\text{H} \rightarrow {}^4\text{He}$ (main sequence, millions of years)
- ② ${}^4\text{He} \rightarrow {}^{12}\text{C}, {}^{16}\text{O}$ (helium burning, red giant, $\sim 10^5$ years)
- ③ ${}^{12}\text{C} \rightarrow {}^{16}\text{O}$ (carbon burning, hundreds of years)
- ④ ${}^{16}\text{O} \rightarrow {}^{28}\text{Si}$ (oxygen burning, years/months)
- ⑤ ${}^{28}\text{Si} \rightarrow \text{„Fe”}$ (sillicon burning, few weeks/days)
- ⑥ „iron” is no longer source of fuel - cycles terminate leading after short (\sim hour) delay to the *gravitational collapse*



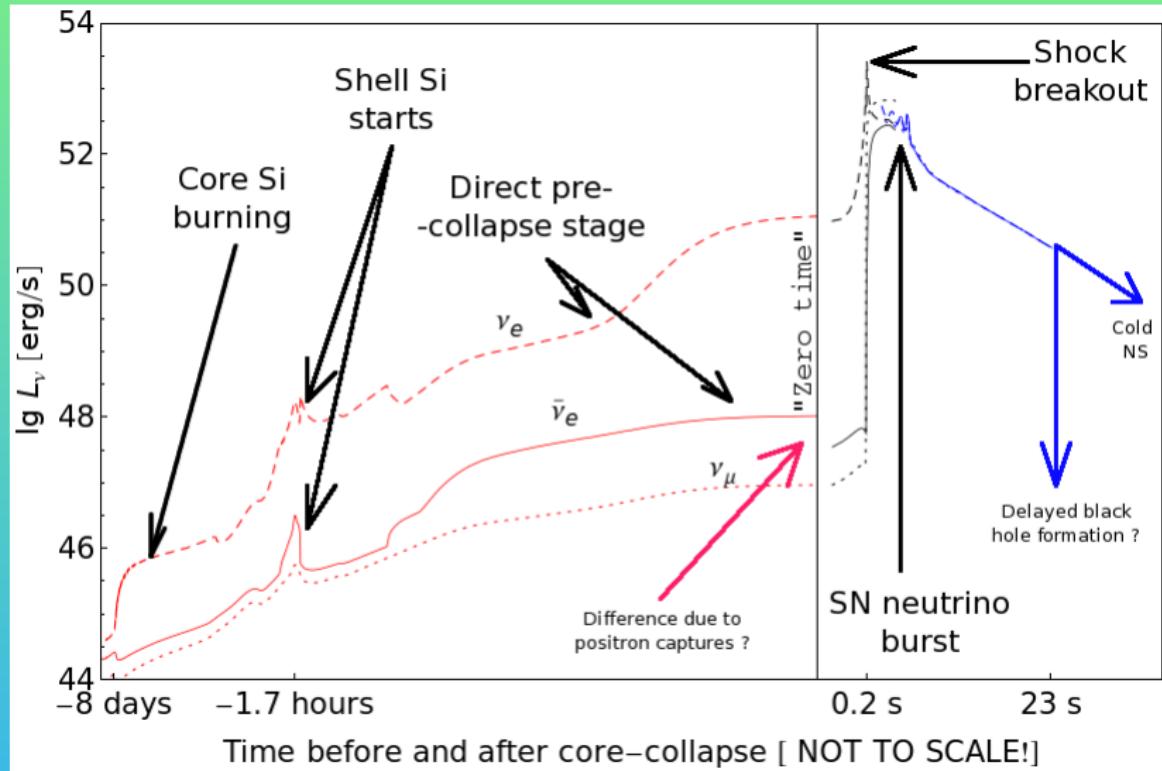
Neutrino emission from massive stars

Stellar evolution for neutrino astronomers

Stage	$\langle L_\nu \rangle$ [erg/s]	E_ν^{tot} [erg]	Time	$\langle E_\nu \rangle$ [MeV]	Process	Flavo
1. H	10^{36}	10^{52}	10^7 yrs	0.5-1.7	CNO	ν_e
2. He	10^{31}	10^{49}	10^6 yrs	0.02	plasma	all
3. ν -cooled	$10^{38}-10^{46}$	10^{51}	10^4 yrs	0.5-1.5	pair	all
4. Neutronization	10^{54}	10^{51}	10^{-2} sec	10	ϵ^-	ν_e
5. SN	$10^{52}-10^{48}$	10^{53}	~ 100 sec	10-40	ν transport	all
6. NS	$< 10^{48}$	$< 10^{51}$	10^4 yrs	1	URCA	$\nu_e, \bar{\nu}_e$

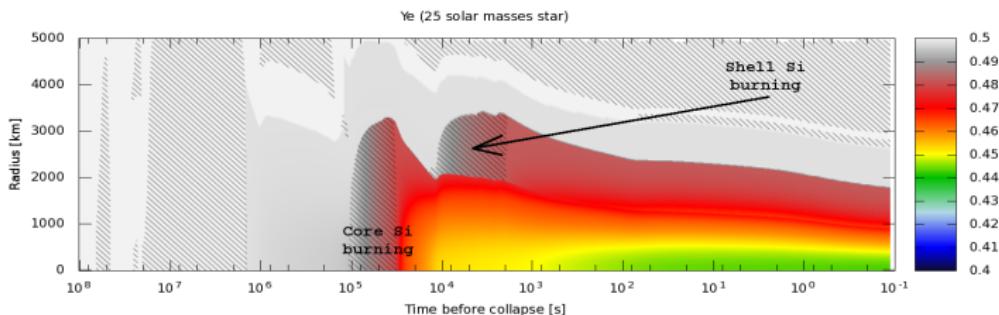
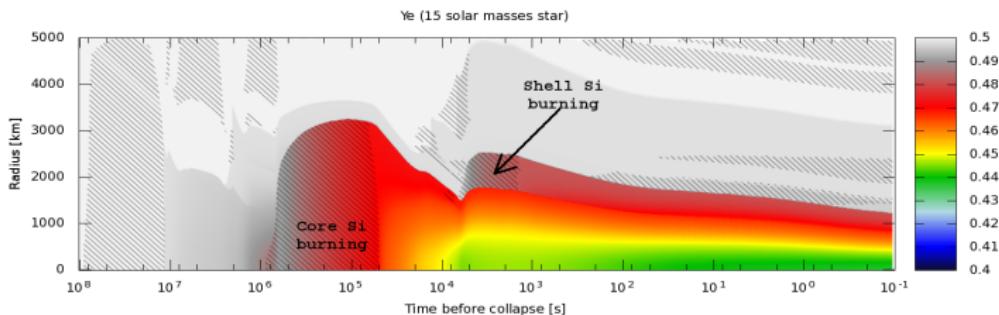
- Stage 5 has been observed in neutrinos during SN 1987A event
- Stage 6 could lead to the black hole formation; neutron star *has not been found* in the SN1987A remnant

Neutrinos BEFORE and AFTER collapse

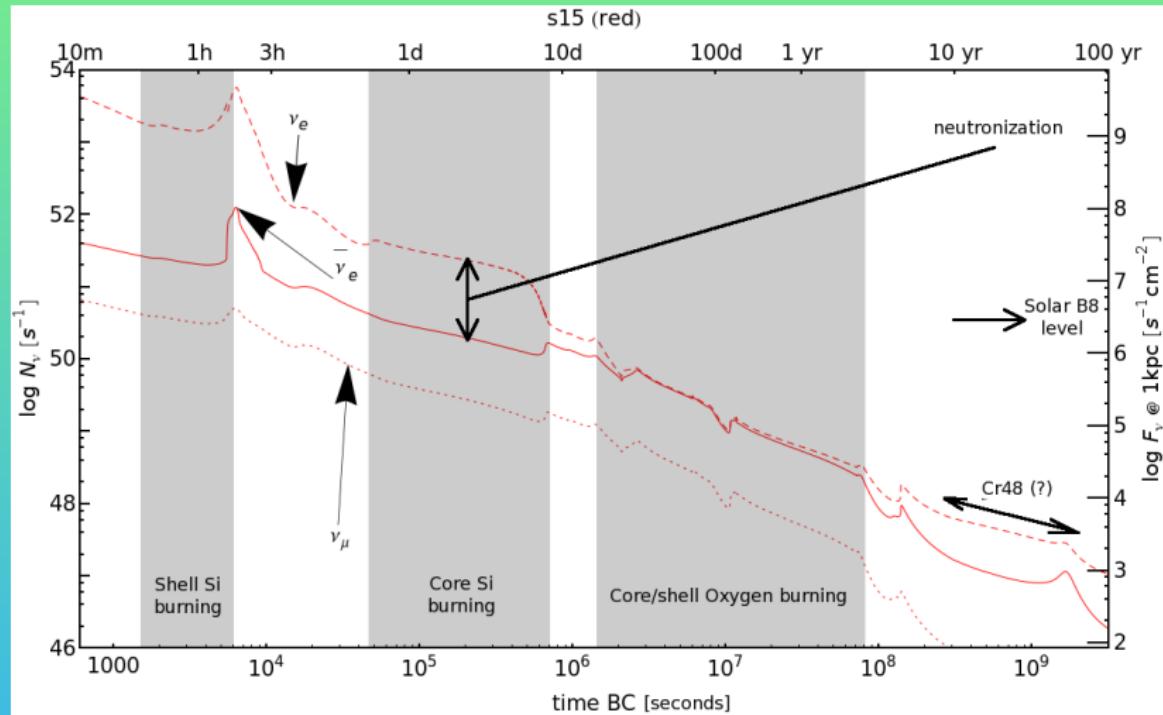


$15 M_{\odot}$ vs $25 M_{\odot}$: neutronization

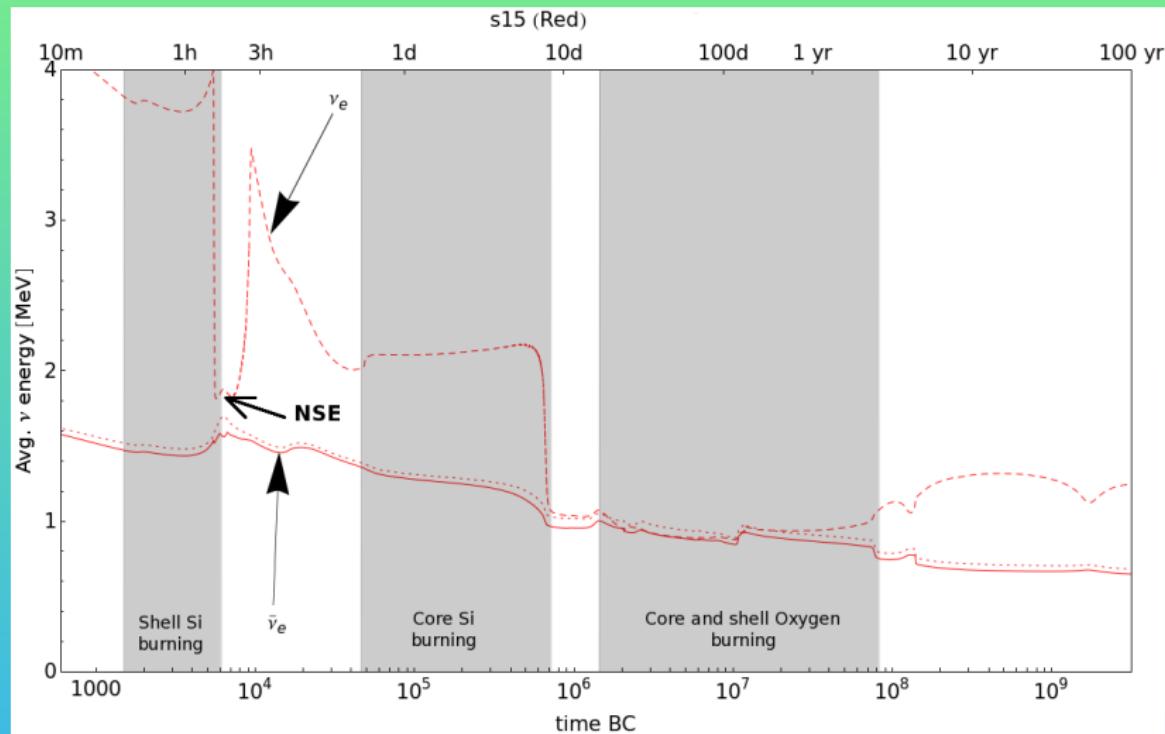
s15 and s25 models



Neutrino flux 100 years before supernova



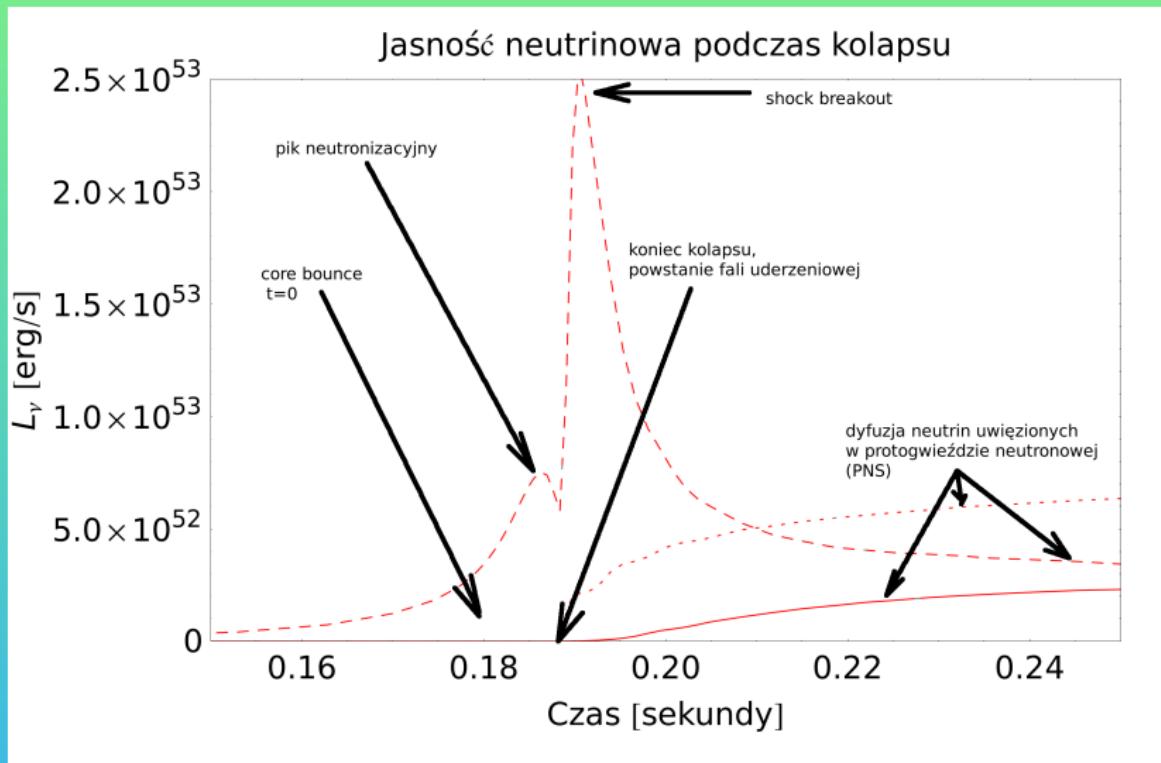
$\langle \mathcal{E}_\nu \rangle$ 100 years before



15 M_⊙ star (s15 model)

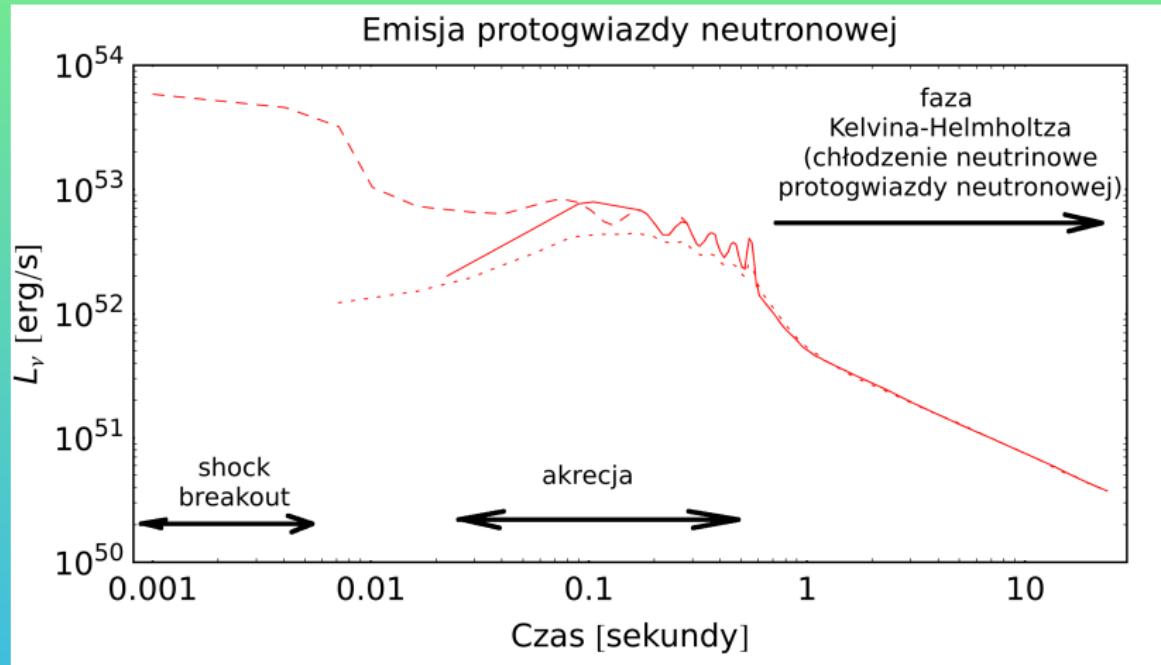
- ① core/shell O burning (months B.C.)
– *limited to the Betelgeuse (d = 100 ... 200 pc)*
- ② core Si burning (8 - 0.5 days B.C)
– *for stars at 1-2 kpc; ~0.5% of the Galaxy stars*
- ③ shell Si ignition (2-0.5 hours B.C.)
– *up to 10 kpc*
- ④ direct pre-collapse stage (30 - 0 minutes B.C)
– *continuous transition into shock breakout ν_e peak*

Neutrino emission from the collapse

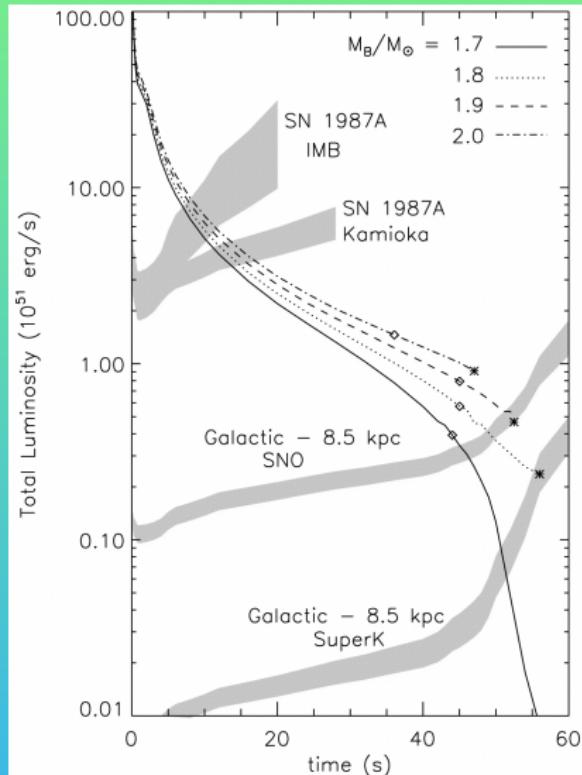


Data source: <http://www.astro.princeton.edu/burrows/tbp/tbp.html>

Protoneutron star evolution



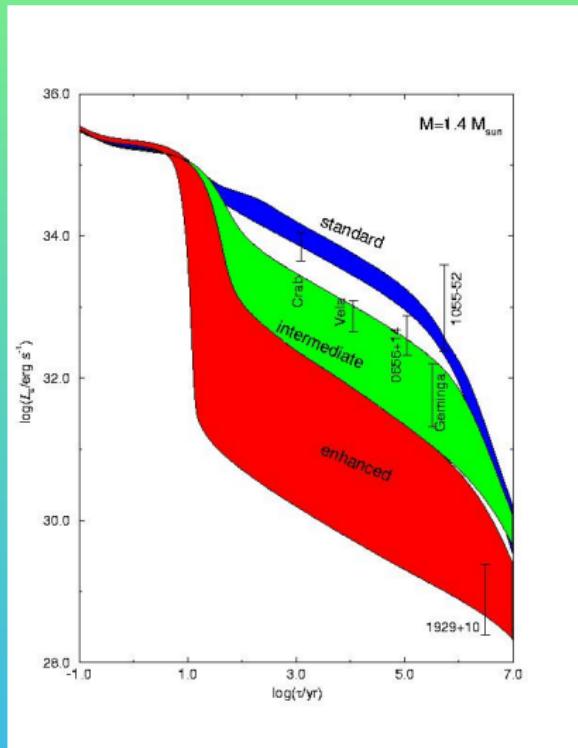
Late cooling of the neutron stars



- PNS (Proto Neutron Star) finally becomes NS cooling by neutrinos for thousands of years
- for some EOS (e.g. kaon condensate) PNS might collapse to the black hole after ~ 100 seconds delay \rightarrow neutrino flux abruptly goes to zero

Source: J. A. Pons et al 2001 ApJ 553 382-393 doi: 10.1086/320642

Neutrino cooling of the neutron stars



- neutrino emission persist for millions of years
- we observe this indirectly via surface temperature

Source: <http://www.astro.umd.edu/~miller/nstar.html>

Summary

Neutrino emission from massive star begins with H ignition, monotonically (on average) grows, peaks during protoneutron star cooling, just after core-collapse. Afterwards, neutrino emission declines again.

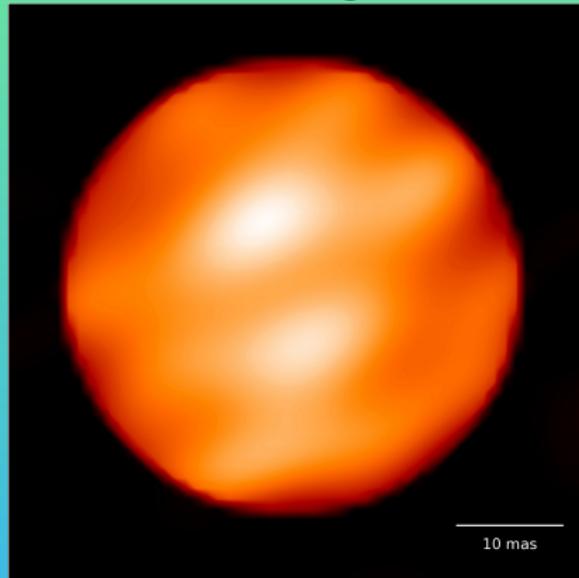
Conclusions

- ① we have just tasted detection of neutrinos related to core-collapse supernova event thanks to SN1987A
- ② core Si burning pair-annihilation ν_e and $\bar{\nu}_e$, shell Si burning $\bar{\nu}_e$, neutronization ν_e after core Si ignition, shock-breakout ν_e peak, and late-cooling protoneutron star neutrinos are a new challenges: goals for the next generations of neutrino detectors (LENA, Memphys, etc.)
- ③ type Ia supernovae are close to reach
- ④ however, nothing can be done without significant progress in neutrino detection technology

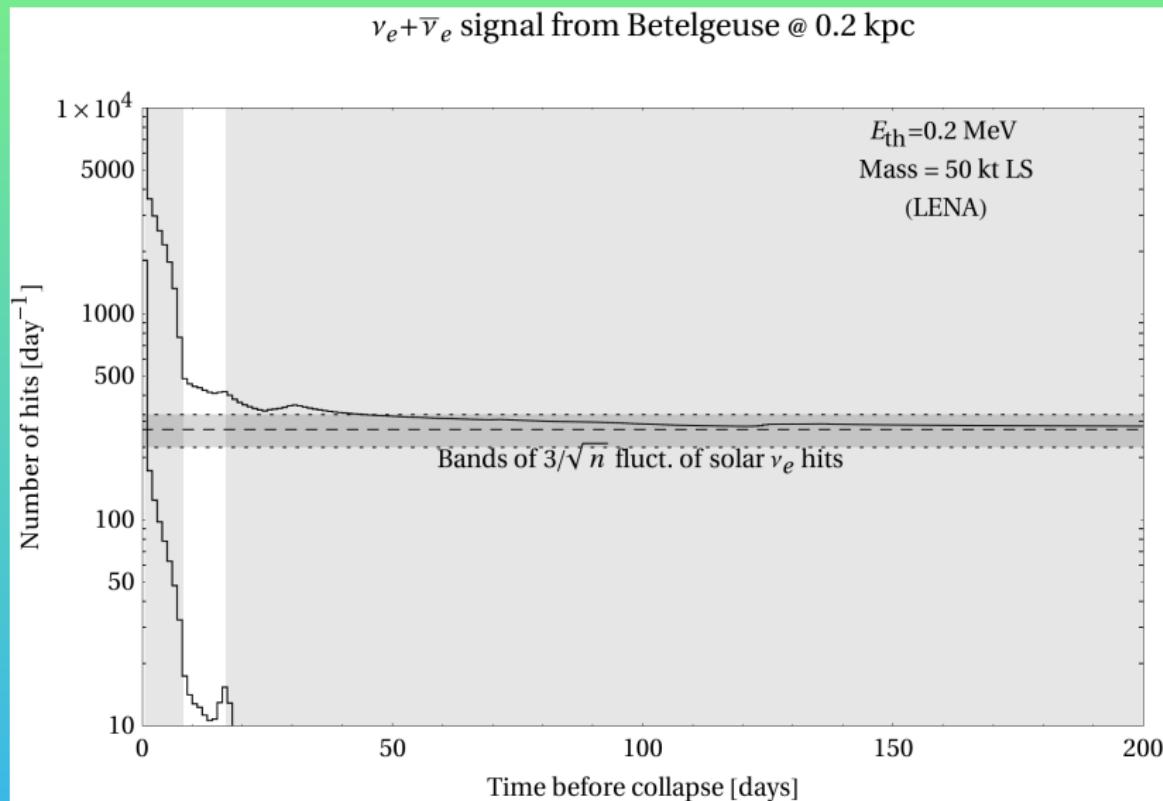
Extra slides

Betelgeuse: case study

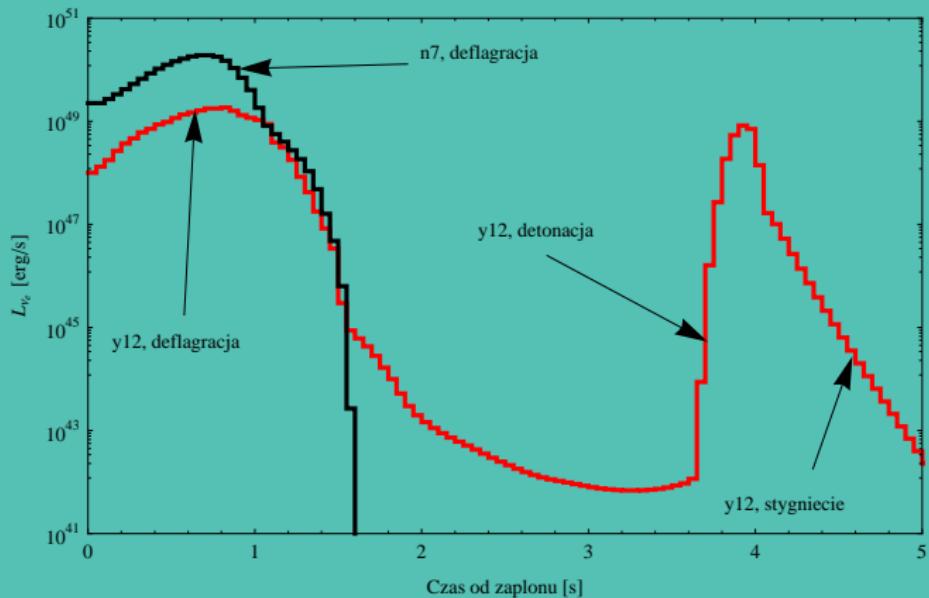
Betelgeuse is fascinating people around the world. This is today's picture from Astronomy Picture Of a Day (APOD); real photo of the surface with huge convective cells.



Betelgeuse: case study (2)



Preliminary results on type Ia supernova neutrinos

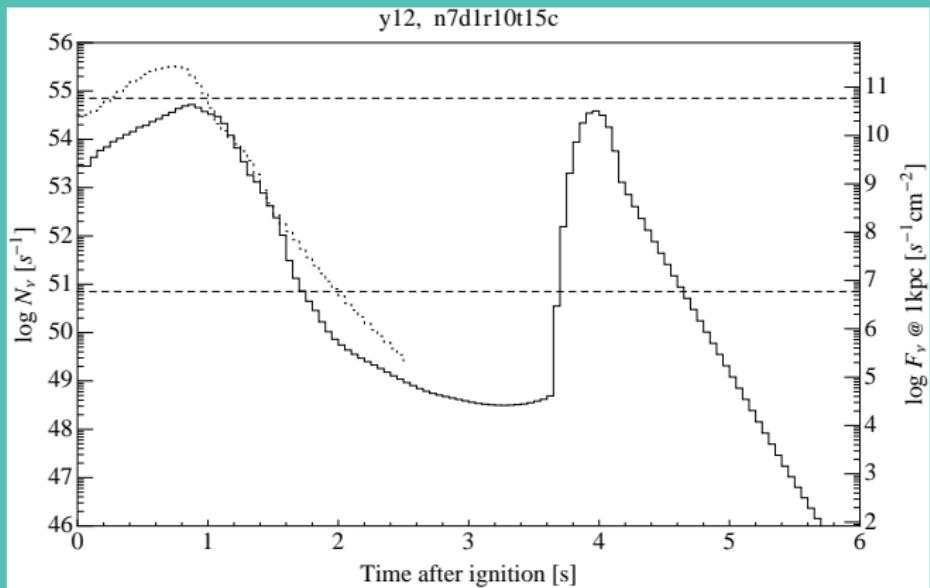


References:

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T. Kulakowski, (M.Sc. thesis, Jagiellonian Univ., Borexino-centric, in polish, deflagration and DDT)

T. Plewa & A. Odrzywolek, in preparation (deflagration and DDT)

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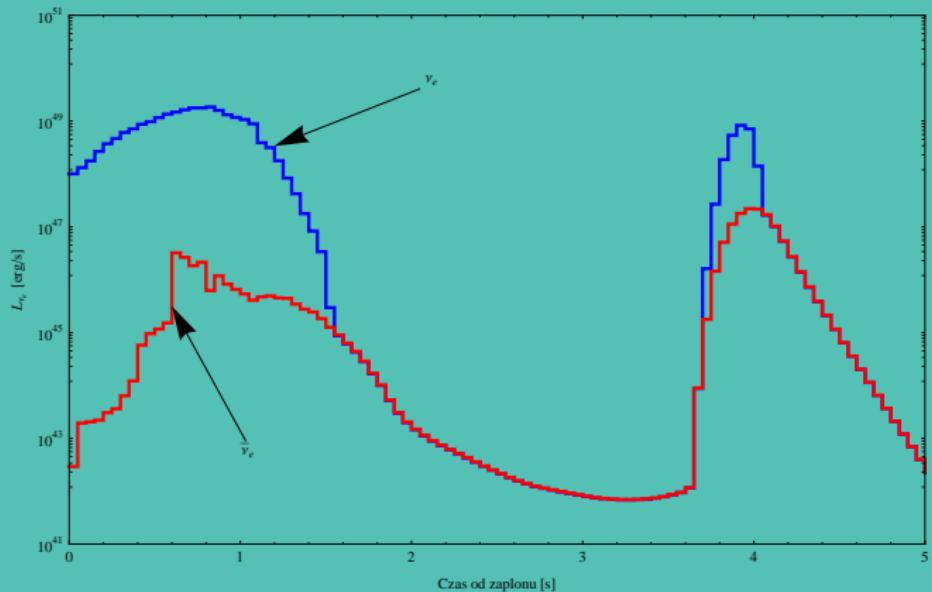
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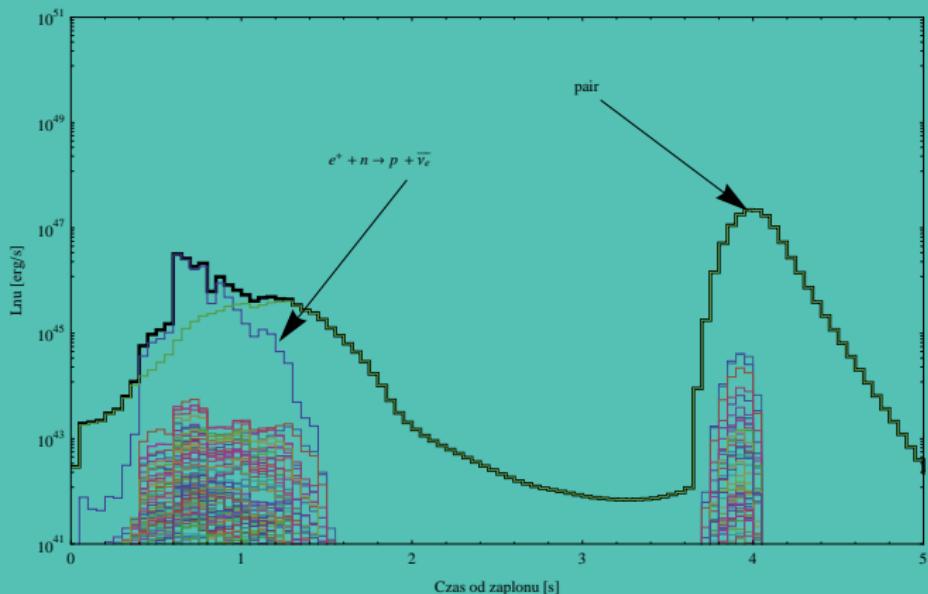
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Selected references

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- **Core-collapse neutrinos 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
<http://www.astro.princeton.edu/~burrows/tbp/tbp.html>
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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](https://arxiv.org/abs/astro-ph/0703686v1))
- **NS cooling** Yakovlev, D. G.; Kaminker, A. D.; Gnedin, O. Y.; Haensel, P. , *Neutrino emission from neutron stars*, Physics Reports, Volume 354, Issue 1-2, p. 1-155 (2001)

More info

PSNS WWW: <http://ribes.if.uj.edu.pl/psns>

Presupernova (s15) neutrino spectrum

[link]