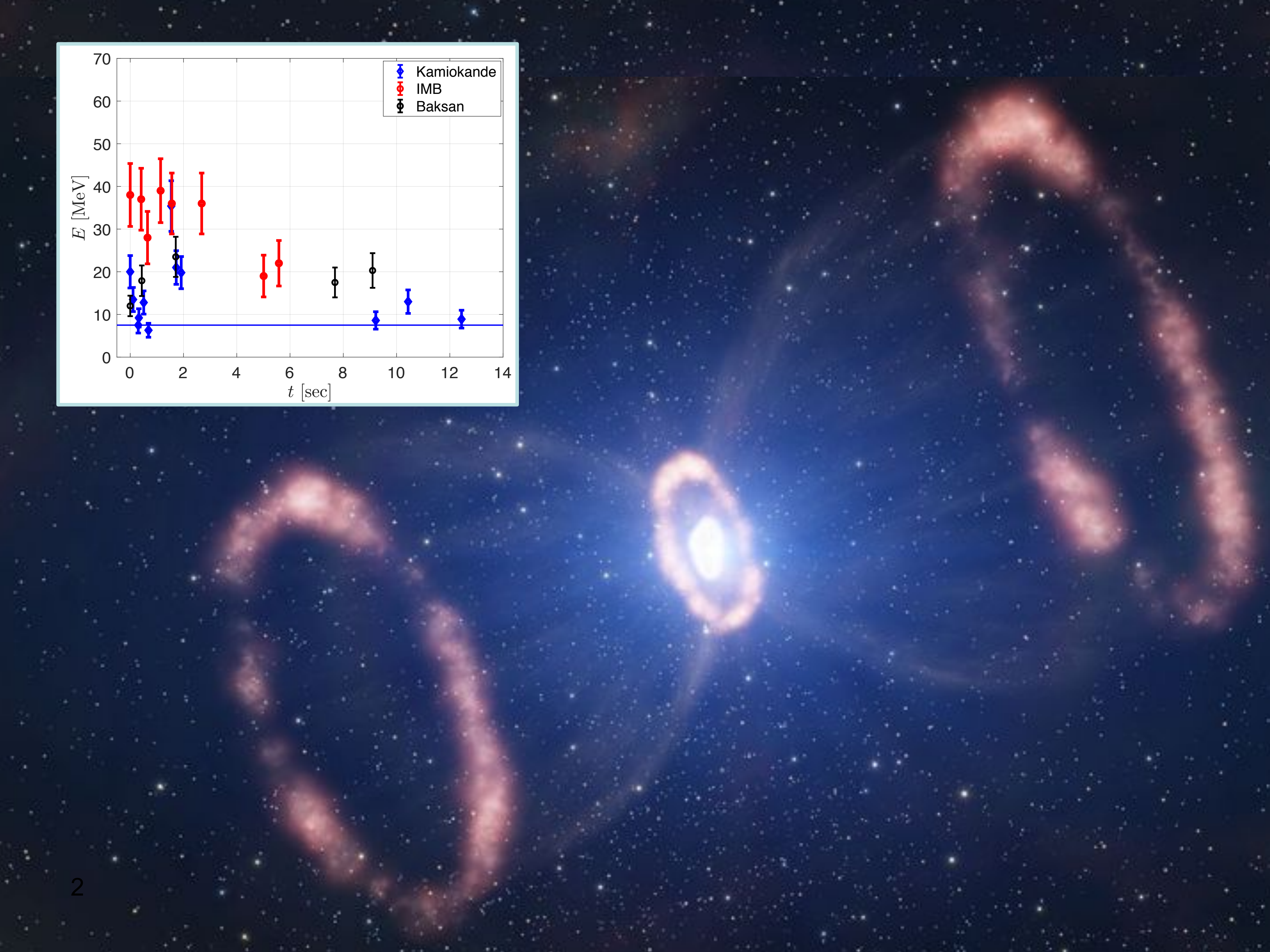
Neutrino signal of thermonuclear supernovae: is there a supernova bound on axions?

Kfir Blum (Weizmann Institute & CERN)

KB & Kushnir, 1601.03422 [ApJ. 828, 31 (2016)]
Bar, KB, D’Amico, 1811.11178 [PRD99 (2019) no.12, 123004]
Bar, KB, D’Amico, 1907.05020

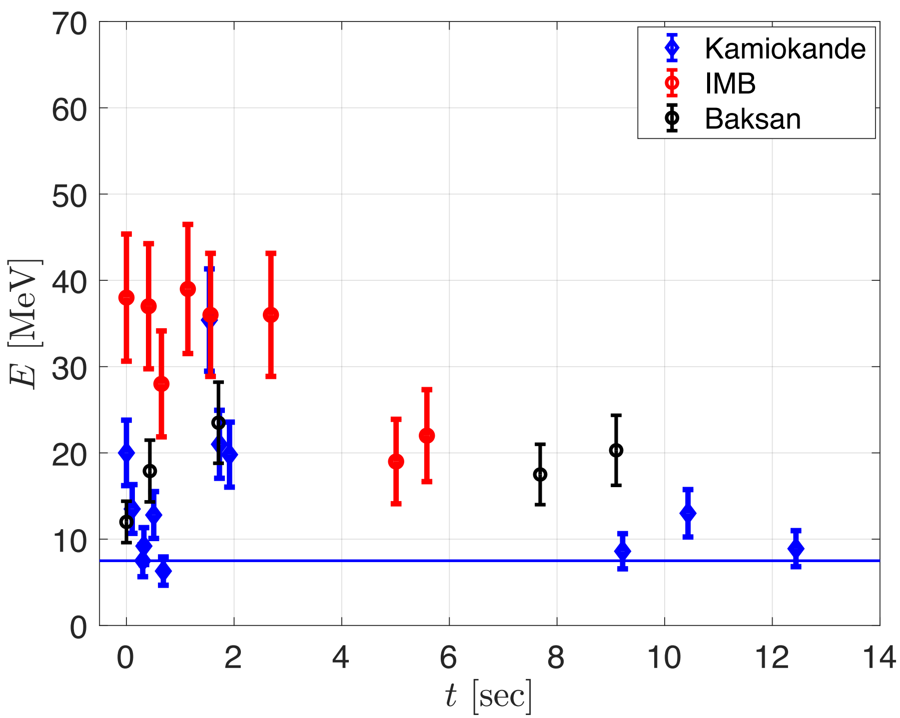
Heidelberg 2020


Kamiokande
IMB
Baksan
E [MeV]
t [sec]
0
10
20
30
40
50
60
70
0
2
4
6
8
10
12
14

The explosion of SN1987A and the neutrino signal are commonly interpreted within — and as sign of — the delayed neutrino mechanism $(\mathrm{D}\nu\mathrm{M})$.

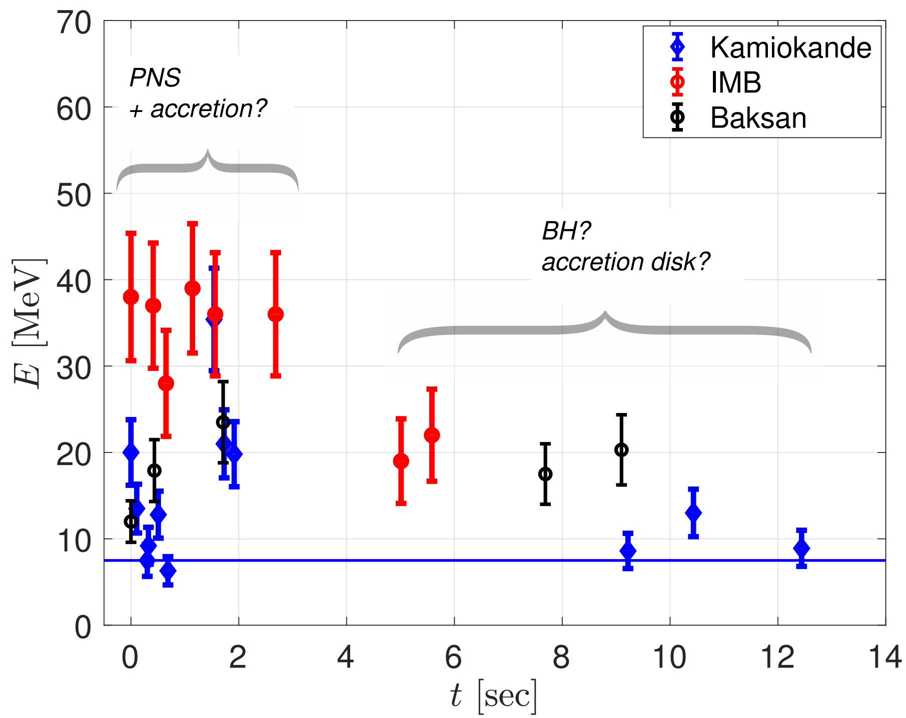
Bethe & Wilson, ApJ. 295, 14 (1985)

But it is not clear if $\mathrm{D}\nu\mathrm{M}$ simulations can obtain explosion energy a-la SN1987A. There is also no clear evidence for a neutron star (NS) in the remnant.



Competing hypothesis: collapse-induced thermonuclear explosion **(CITE)**

Kushnir & Katz, 1412.1096 [ApJ. 811, 97 (2015)]
Kushnir, 1502.03111, 1506.02655
KB & Kushnir, 1601.03422 [ApJ. 828, 31 (2016)]



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Lyman et al, 1406.3667 [MNRAS. 457 (2016) 1, 328-350]

Table 6. Average $v_{\rm ph}$ and explosion parameters for SE SN types.

SN type	$v_{\rm ph}$ (km s^{-1})		$M_{\rm Ni}$ (M$_\odot$)		$M_{\rm ej}$ (M$_\odot$)		$E_{\rm K}$ (10^{51} erg)	
	Mean	Sth. dev.	Mean	Std. dev.	Mean	Sth. dev.	Mean	Sth. dev.
IIb	8300	750	0.11	0.04	2.2	0.8	1.0	0.6
Ib	9900	1400	0.17	0.16	2.6	1.1	1.6	0.9
Ic	10 400	1200	0.22	0.16	3.0	2.8	1.9	1.3
Ic-BL	19 100	5000	0.32	0.15	2.9	2.2	6.0	5.0

Kushnir, 1506.02655:

$$\boxed{\frac{1\ \text{MeV}}{\text{baryon}} \times 1\ \text{M}_\odot \approx 1.9 \times 10^{51}\ \text{erg}}$$

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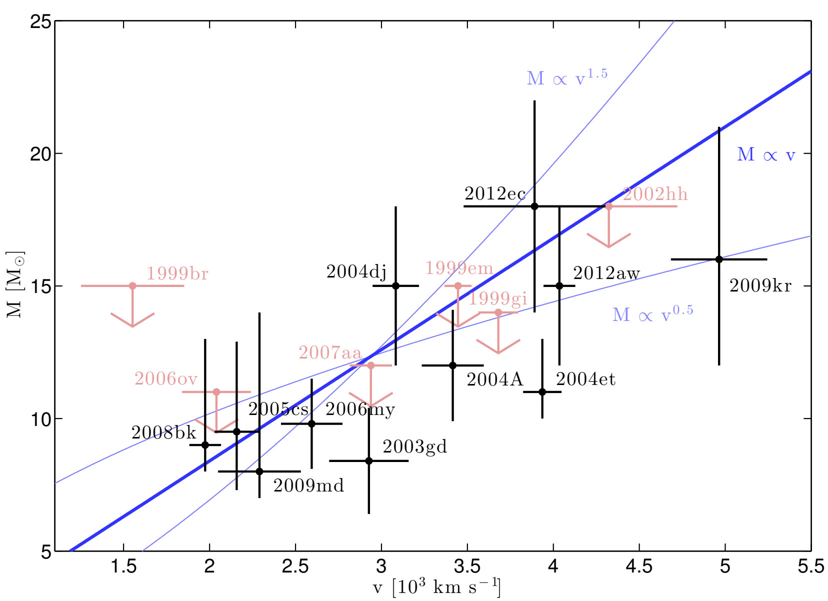
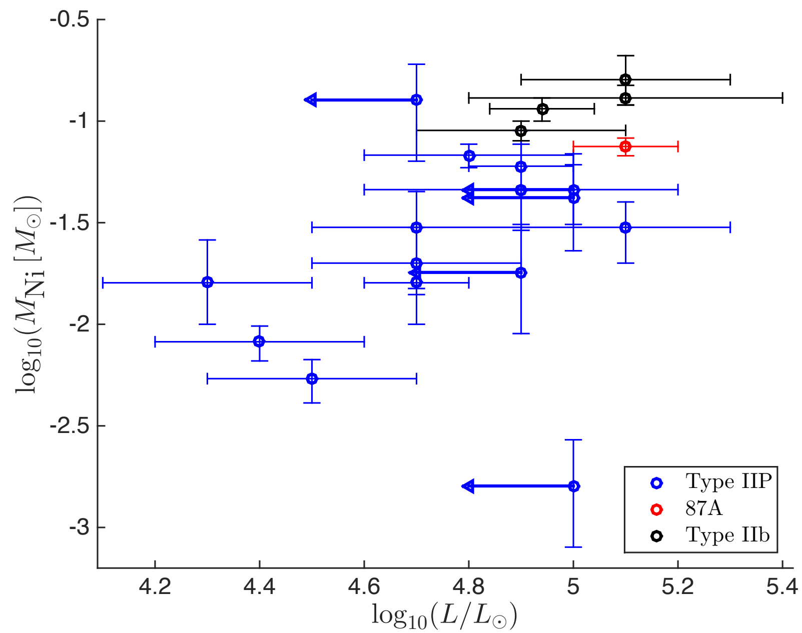
Kushnir & Katz, 1412.1096 [ApJ. 811, 97 (2015)]
Kushnir, 1502.03111, 1506.02655
KB & Kushnir, 1601.03422 [ApJ. 828, 31 (2016)]

Poznanski, 1304.4967 [MNRAS. 436 (2013) 4, 3224–3230]



Kushnir, 1506.02655



If the neutrino mechanism fails: black hole (BH) forms within ~(1-3) sec

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$$t_{\rm BH} \sim \pi \sqrt{\frac{r^3}{2GM}} \qquad\qquad r\left(M = 2\mathrm{M}_\odot\right) \sim 10^9\ \mathrm{cm}$$

O'Connor & Ott, 1010.5550 [ApJ. 730, 70 (2011)]

``Black hole formation in failing core-collapse supernovae"

Table 2
Black Hole Formation Properties

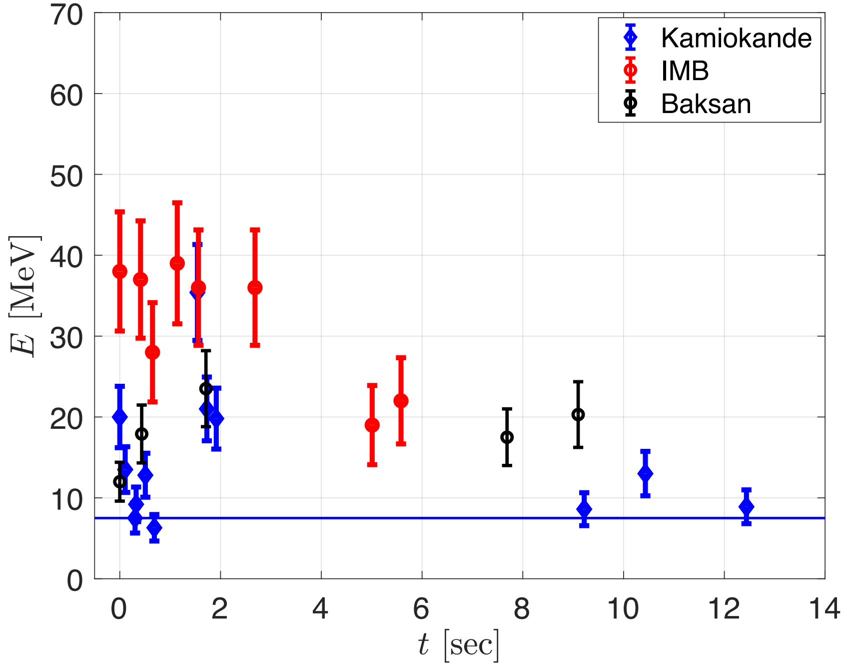
Model	LS180			LS220			LS375			HShen		
	$t_{\rm BH}$ (s)	$M_{\rm b,max}$ ($M_\odot$)	$M_{\rm g,max}$ ($M_\odot$)	$t_{\rm BH}$ (s)	$M_{\rm b,max}$ ($M_\odot$)	$M_{\rm g,max}$ ($M_\odot$)	$t_{\rm BH}$ (s)	$M_{\rm b,max}$ ($M_\odot$)	$M_{\rm g,max}$ ($M_\odot$)	$t_{\rm BH}$ (s)	$M_{\rm b,max}$ ($M_\odot$)	$M_{\rm g,max}$ ($M_\odot$)
s20WW95	0.787	2.238	2.108	1.129	2.377	2.201	3.351	3.060	2.653	2.287	2.751	2.486
s25WW95	0.737	2.246	2.118	1.046	2.383	2.211	2.707	3.054	2.656	1.990	2.760	2.498
s40WW95	0.524	2.263	2.137	0.666	2.406	2.240	1.381	3.043	2.674	1.129	2.815	2.562
s20WHW02	...	(1.949)	(1.794)	...	(1.950)	(1.798)	...	(1.951)	(1.807)	...	(1.943)	(1.805)
s25WHW02	1.021	2.211	2.079	1.504	2.355	2.172	...	(2.917)	(2.559)	2.929	2.736	2.468
s30WHW02	1.820	2.144	1.978	2.986	2.331	2.108	...	(2.416)	(2.182)	...	(2.405)	(2.190)
s35WHW02	2.073	2.141	1.976	3.334	2.328	2.105	...	(2.351)	(2.137)	...	(2.340)	(2.141)

...

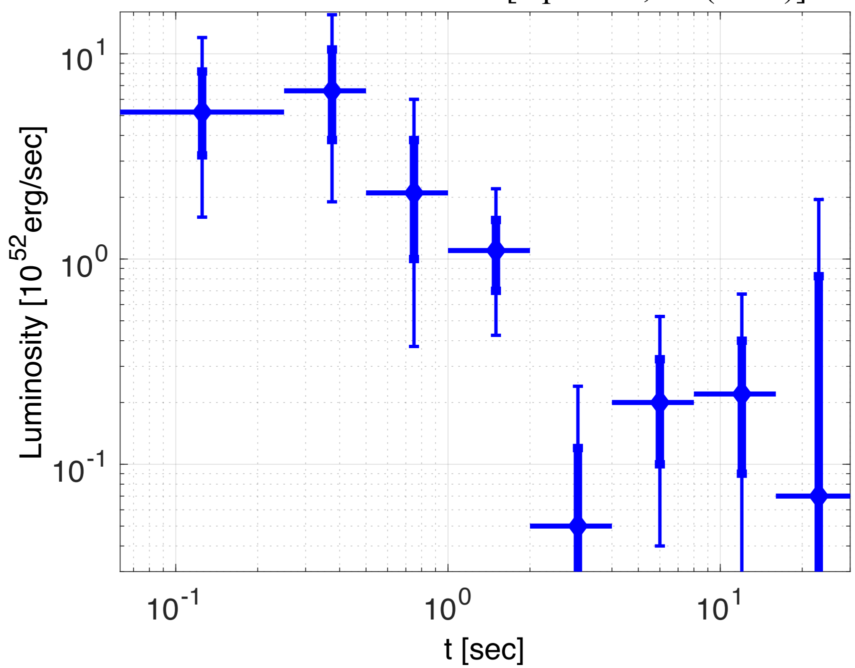
If the neutrino mechanism fails: black hole (BH) forms within ~(1-3) sec

$$\frac{dN^{(0)}_{\bar{\nu}_e}}{dEdt}(t) = \frac{L_{\bar{\nu}_e}(t)}{c_L(\alpha)T^2(t)} \frac{(E/T(t))^{2+\alpha}}{\exp(E/T(t)) + 1}$$

$$\Phi_{\bar{\nu}_e}(t) = \frac{P_{ee}}{4\pi D^2_{\rm SN}} \frac{dN^{(0)}_{\bar{\nu}_e}}{dEdt}(t)$$



KB & Kushnir 1601.03422 [ApJ. 828, 31 (2016)]



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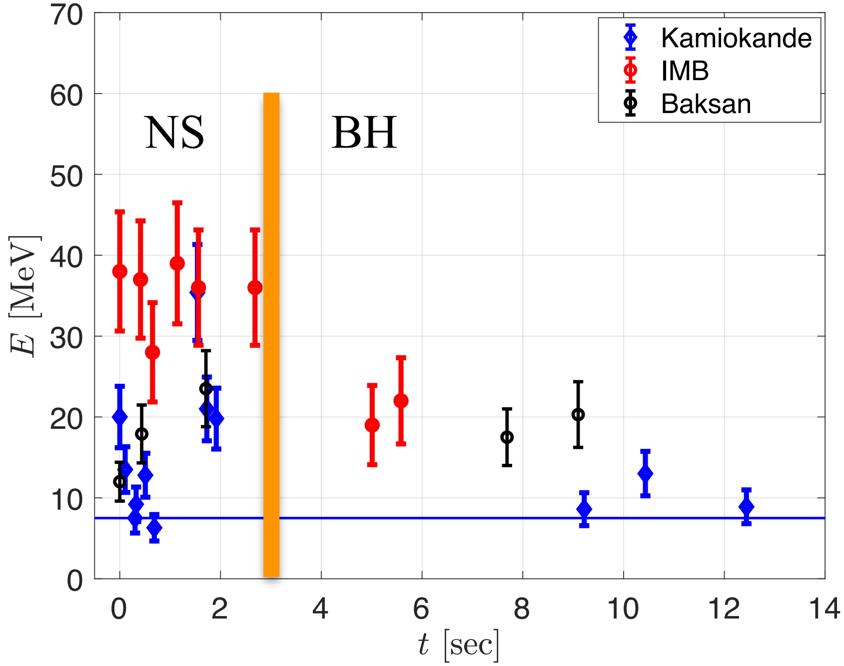

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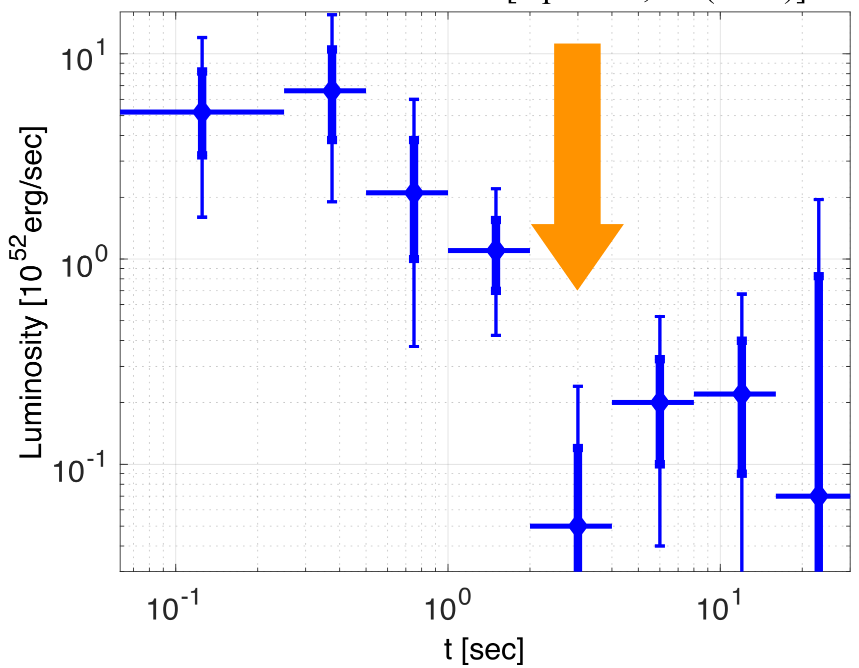


If the neutrino mechanism fails: black hole (BH) forms within ~(1-3) sec

~7sec gap between first 8 and last 3 KII events

Spergel et al, Science 237, 1471 (1987)
Suzuki & Sato, Prog. Th. Phys. 79, 725 (1988)
Lattimer & Yahil, ApJ 340, 426 (1989)

Prog. Theor. Phys. Vol. 79, No. 4, April 1988, Progress Letters

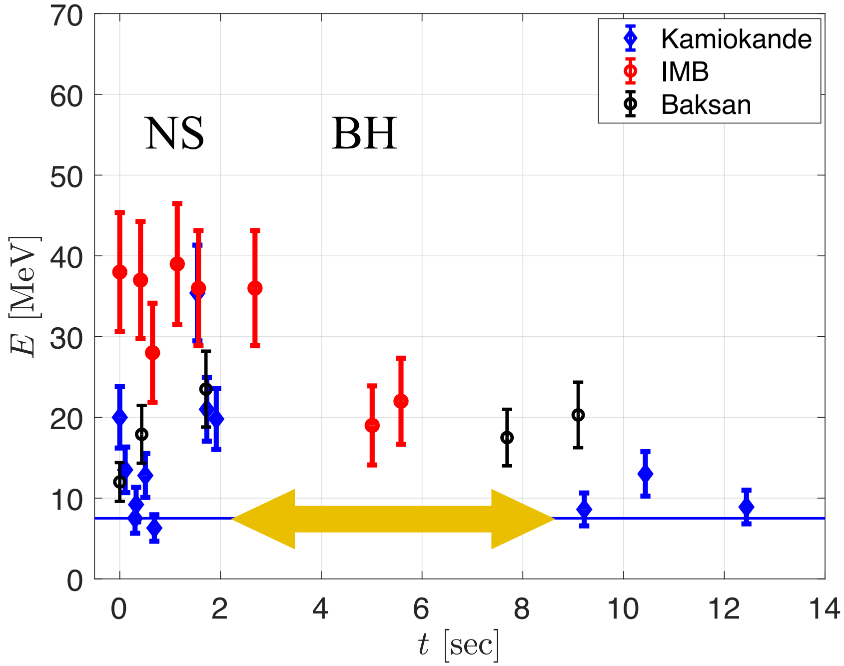
Statistical Analysis of the Neutrino Burst from SN1987A

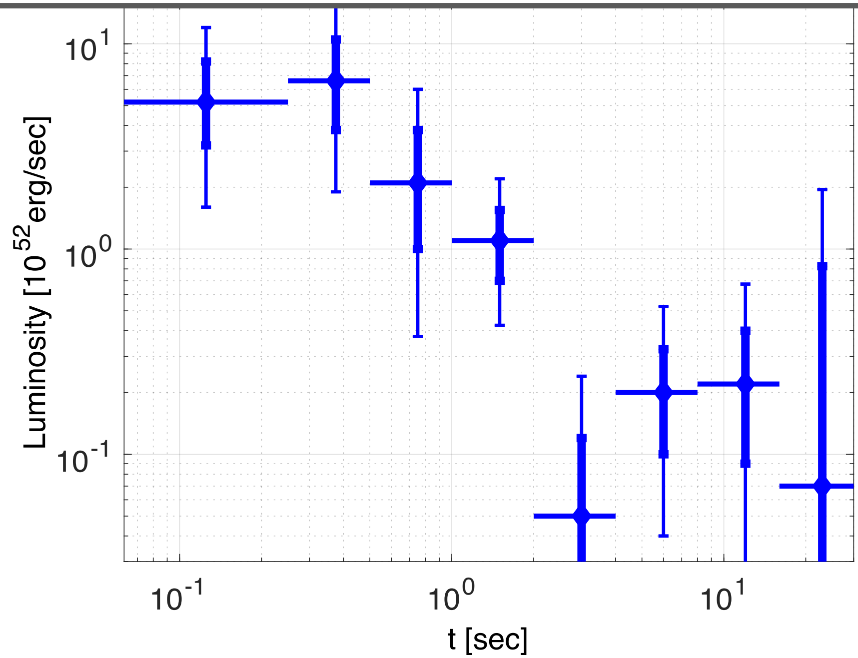
Hideyuki SUZUKI and Katsuhiko SATO

Department of Physics, University of Tokyo, Tokyo 113

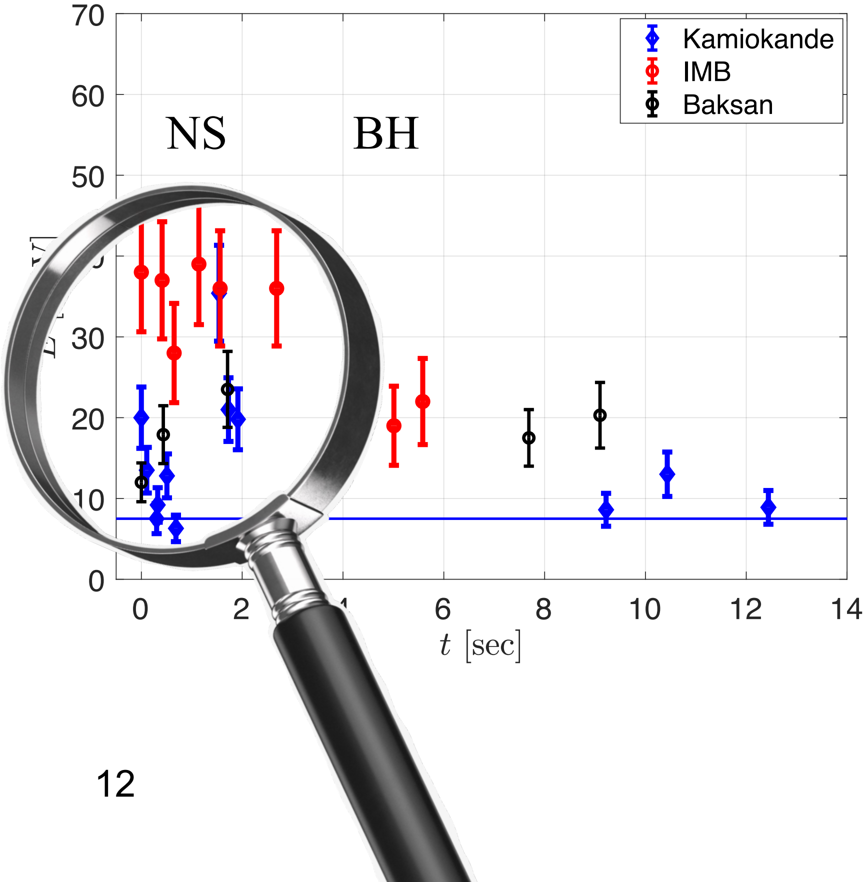
(Received January 19, 1988)

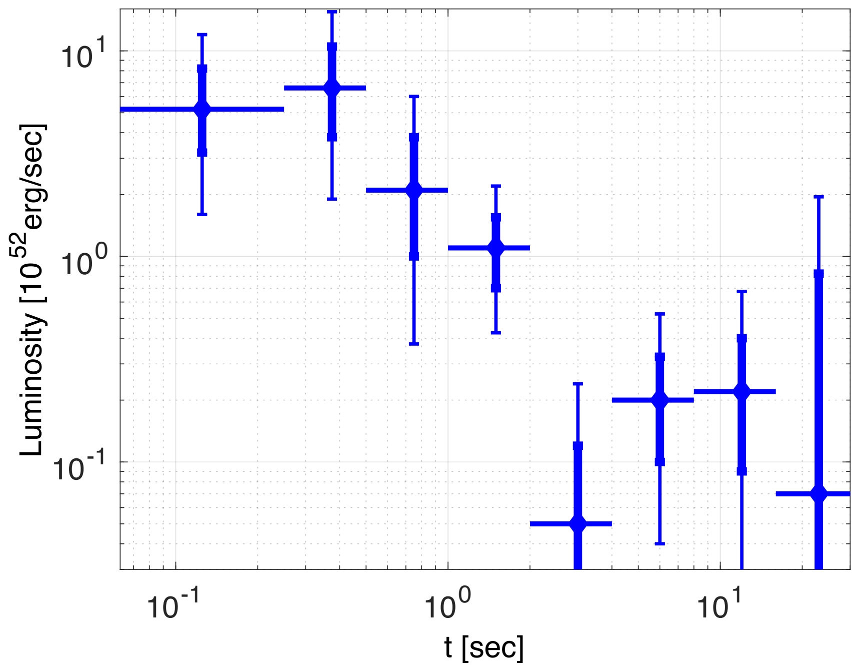
In order to clarify whether the Kamiokande data of the neutrino burst from SN1987A are explained by the "standard" cooling model of the supernova cores, we calculated the probability that the last three events are observed after a 7 second gap. It is obtained that the probability is at most 2%.





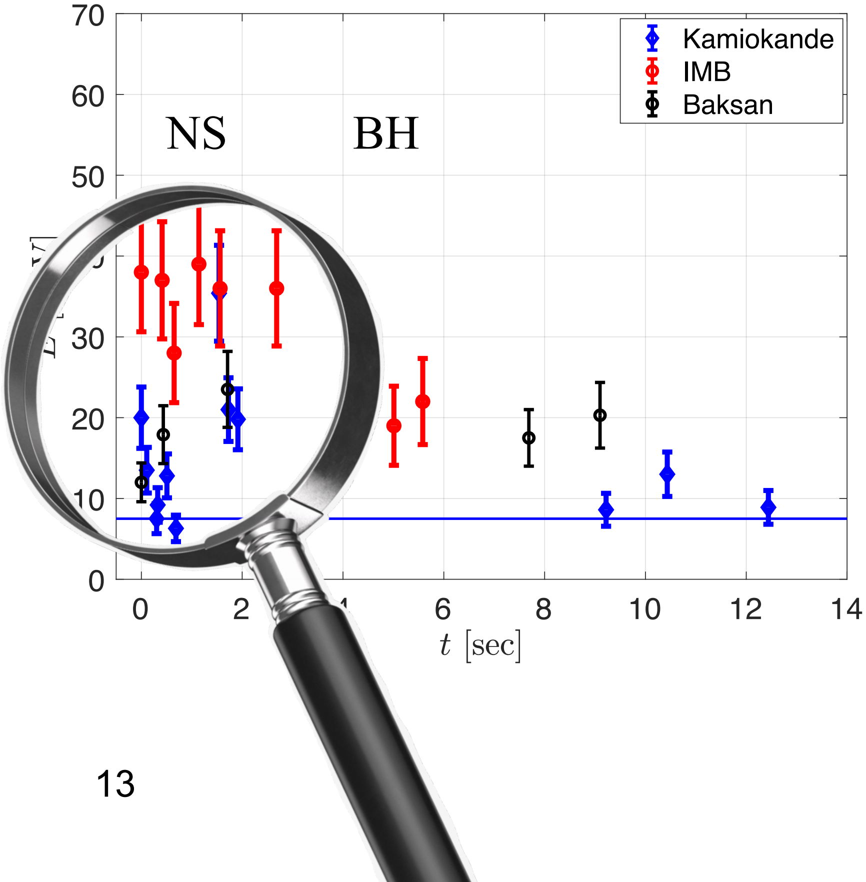
If the neutrino mechanism fails: black hole (BH) forms within ~(1-3) sec

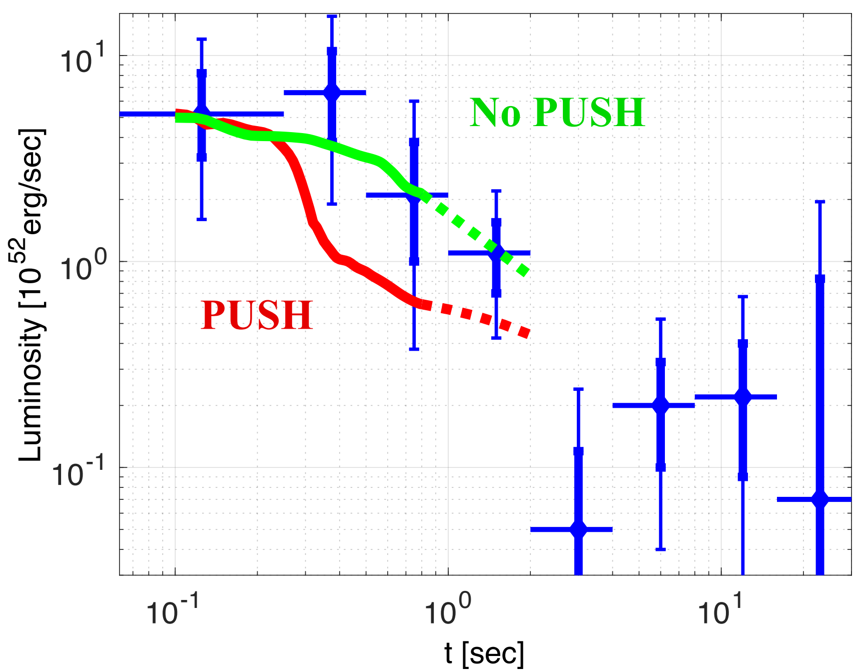




If the neutrino mechanism fails: black hole (BH) forms within ~(1-3) sec

e.g. Perego et al, 1501.02845 [ApJ. 806 (2015), 275]
``Pushing core-collapse supernovae to explosions”





If the neutrino mechanism fails: black hole (BH) forms within ~(1-3) sec

Nothing apparently wrong with direct BH formation in SN1987A.
But essentially no one pursued this possibility.

Why? …Example:

Loredo & Lamb, astro-ph/0107260 [PRD65 (2002), 063002]

Sec. VI.A:

In Table V, we have set $\mu=0.5$ for all accretion models. As we will demonstrate in Sec. VIII, the likelihood function for the two-component models varies rather weakly with μ, and has a very broad maximum at values of μ significantly larger than one. The maximum likelihood values are significantly larger than expected theoretically, and imply an amount of accreted material that would lead to formation of a black hole on the time scale of t_a, which is clearly incompatible with the detection of neutrinos at later times. We thus set $\mu=0.5$ for these models, this being a characteristic value in numerical calculations. This value is not excluded by the broad likelihood function; in essence, we are using prior information to fix a parameter not usefully constrained by the data.

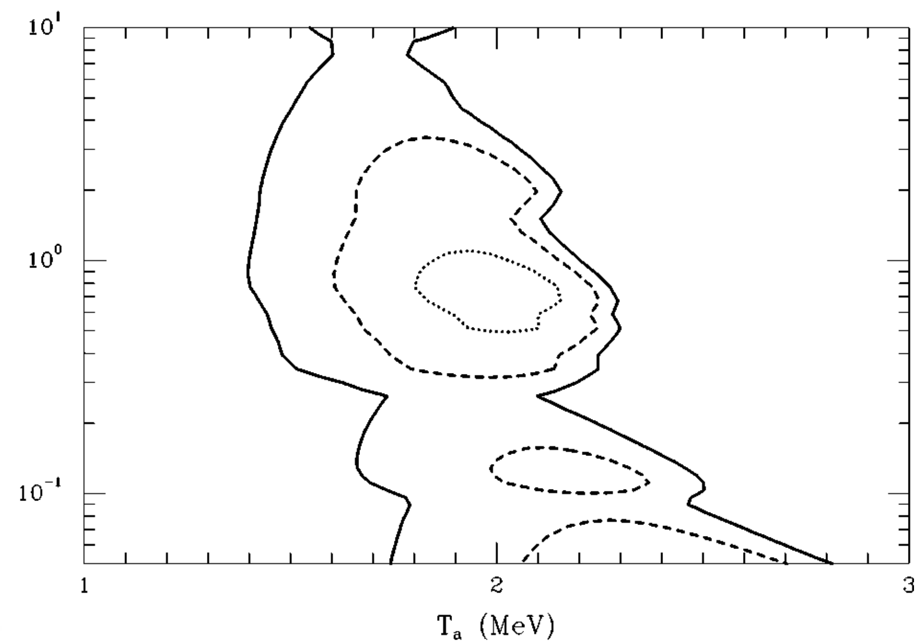


FIG. 7. Summaries of the posterior distribution for parameters

If the neutrino mechanism fails: black hole (BH) forms within ~(1-3) sec

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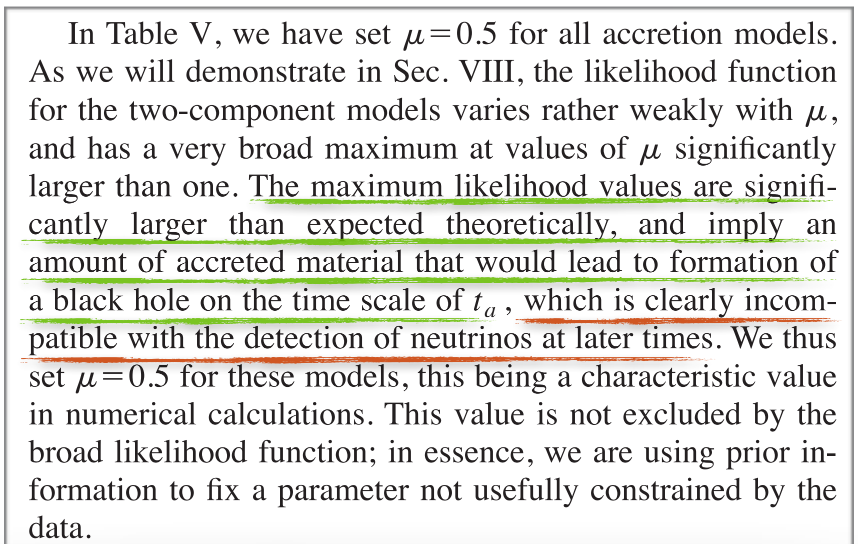
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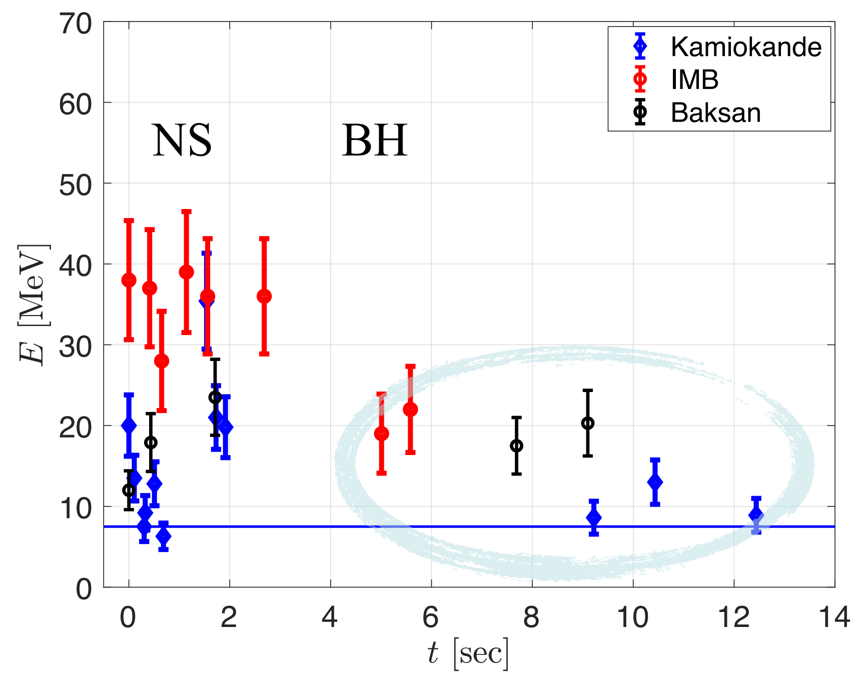
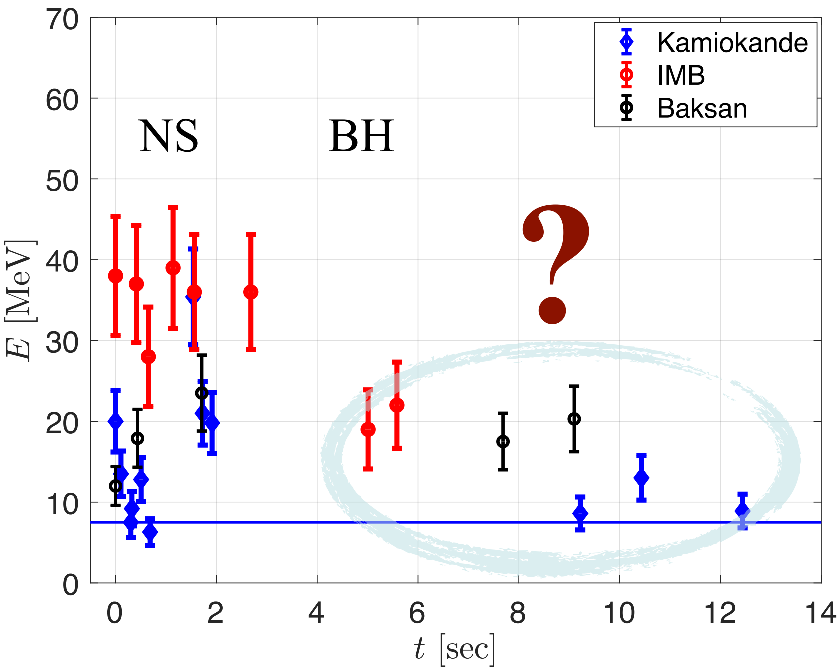
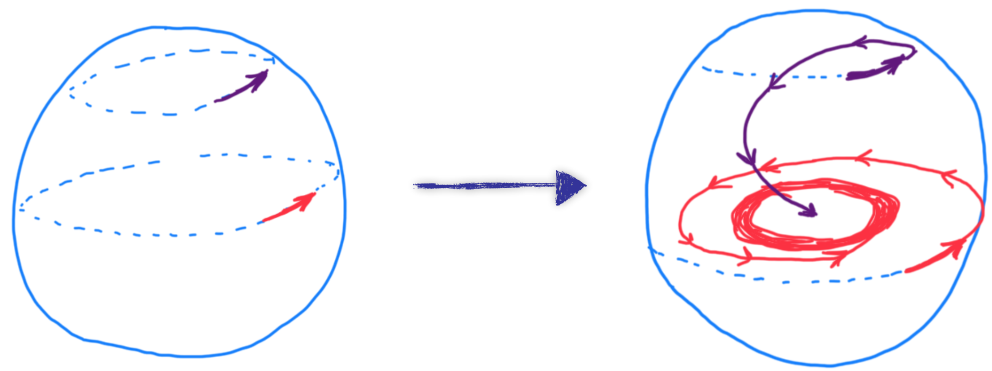


- If the neutrino mechanism fails: black hole (BH) forms within ~(1-3) sec
- What happens next?



- If the neutrino mechanism fails: black hole (BH) forms within ~(1-3) sec
- What happens next? If the star is rotating => accretion disk



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Hirschi, Meynet, Maeder
astro-ph/0406552 [A&A 425 (2004) 649-670]

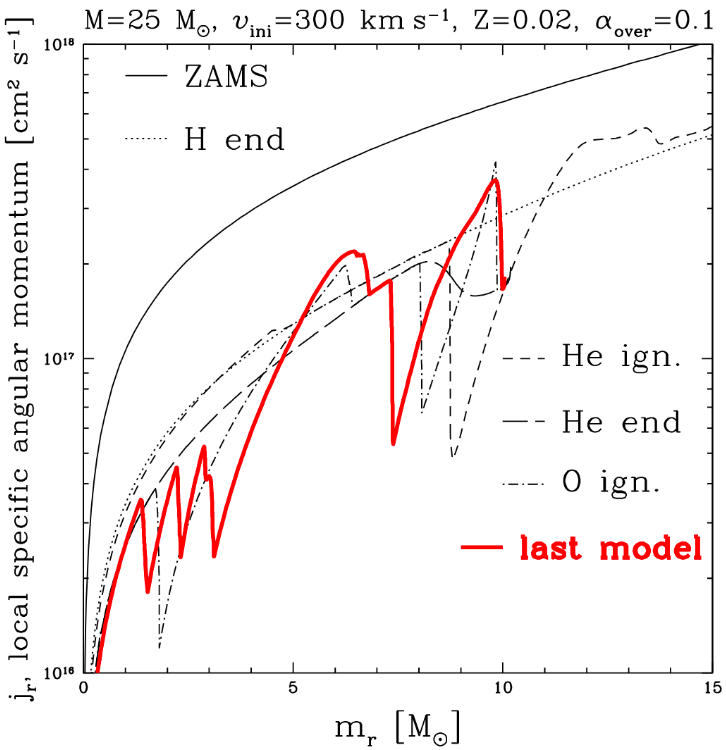
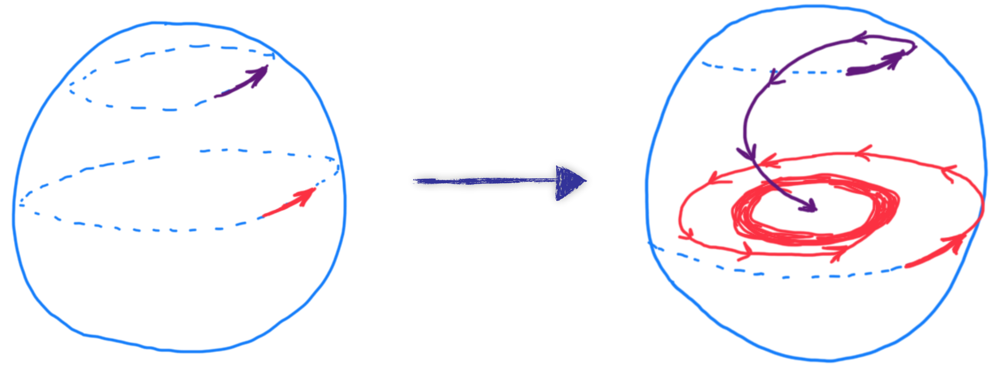
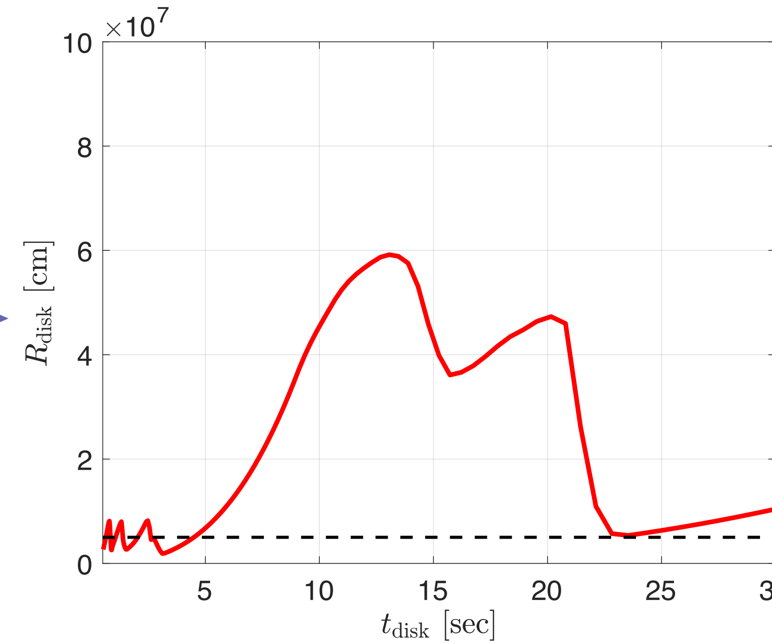


Fig. 7. Local specific angular momentum profiles for the 25 $M_\odot$ model ($v_{\rm ini}$= 300 km s^{-1}) at different evolutionary stages.





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Accretion disk does 2 things:
1. Neutrino luminosity reignites
2. A chain of events is triggered, that can explode the star

MacFadyen & Woosley, astro-ph/9810274 [ApJ. 524, 262 (1999)]

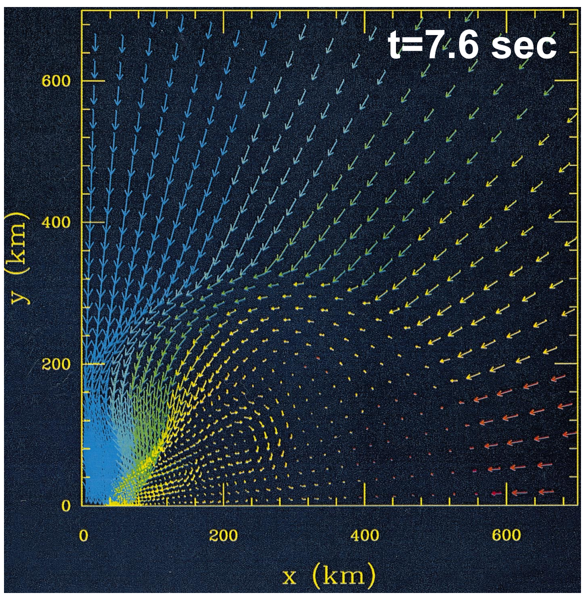

TABLE 1

NEUTRINO EMISSION AND ENERGY DEPOSITION

		CONSERVATIVE			OPTIMISTIC		
$\dot{M}$ ($M_\odot$ s^{-1})	a	L_ν (10^{51} ergs s^{-1})	$L_{\nu\bar{\nu}}$ (10^{51} ergs s^{-1})	Efficiency (%)	L_ν (10^{51} ergs s^{-1})	$L_{\nu\bar{\nu}}$ (10^{51} ergs s^{-1})	Efficiency (%)
0.05	0.50	1.2	0.00023	0.019	1.6	0.0012	0.075
0.05	0.75	2.2	0.0012	0.055	3.6	0.016	0.44
0.05	0.89	4.3	0.017	0.41	8.6	0.18	2.1
0.05	0.95	7.6	0.061	0.81	18	1.3	7.4
0.0631......	0.95	23	1.9	8.2	35	3.7	10
0.0794......	0.95	35	1.9	5.3	39	2.1	5.3
0.1..........	0.50	6.1	0.0083	0.14	7.8	0.027	0.34
0.1..........	0.75	13	0.071	0.56	18	0.27	1.6
0.1..........	0.89	33	1.2	3.6	36	1.2	3.5
0.1..........	0.95	41	1.3	3.2	46	1.7	3.6

$$n\, e^+ \rightarrow p\, \bar{\nu}_e$$
$$p\, e^- \rightarrow n\, \nu_e$$

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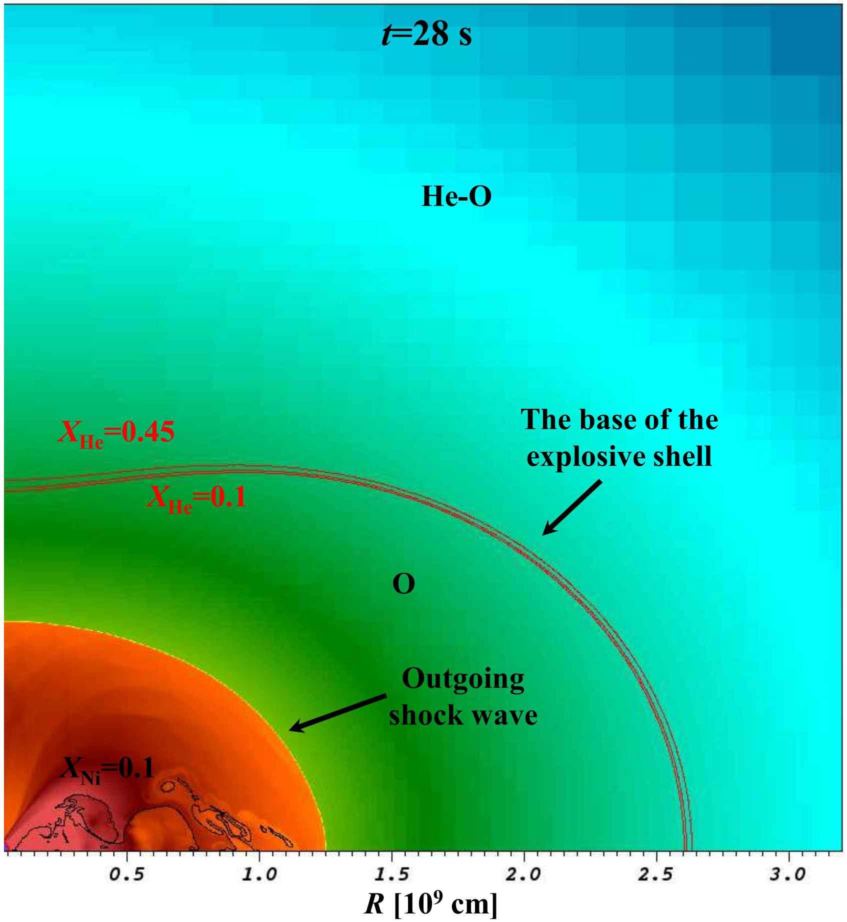
Collapse-induced thermonuclear explosion (CITE)

Kushnir, 1502.03111



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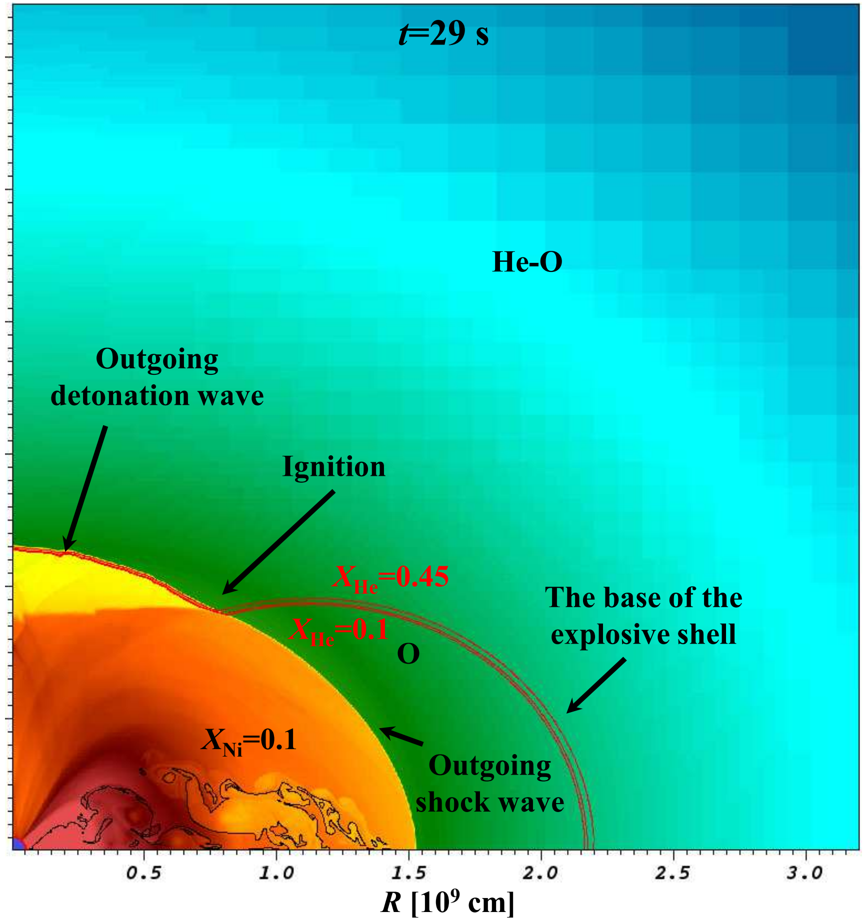

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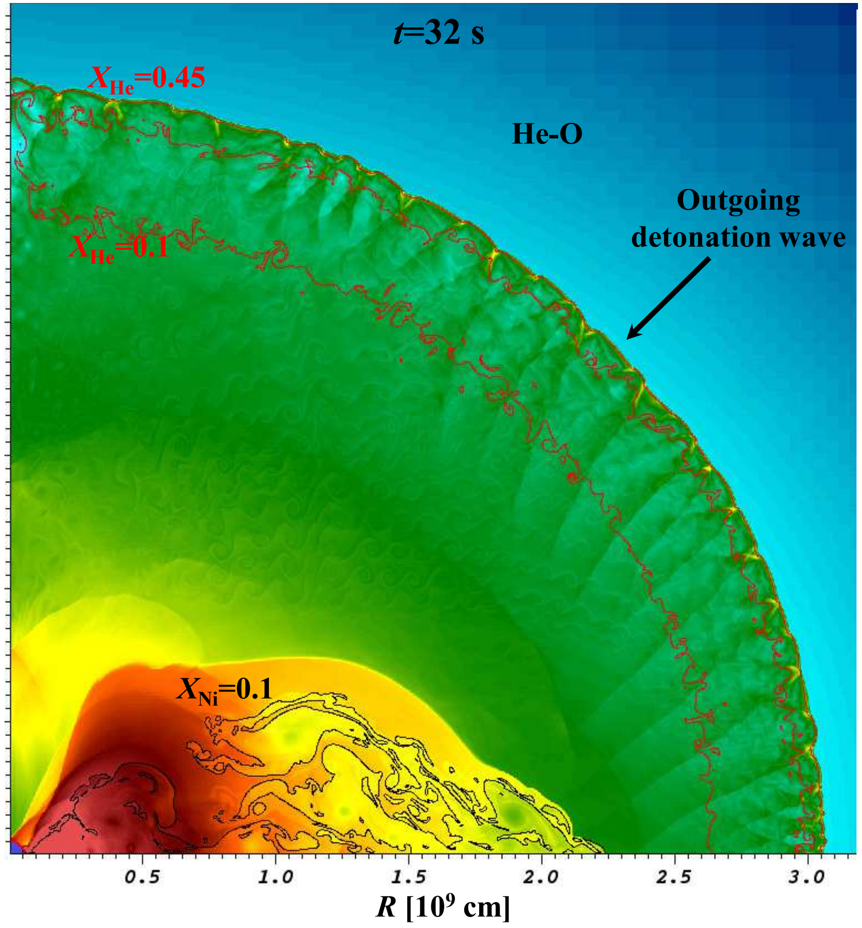

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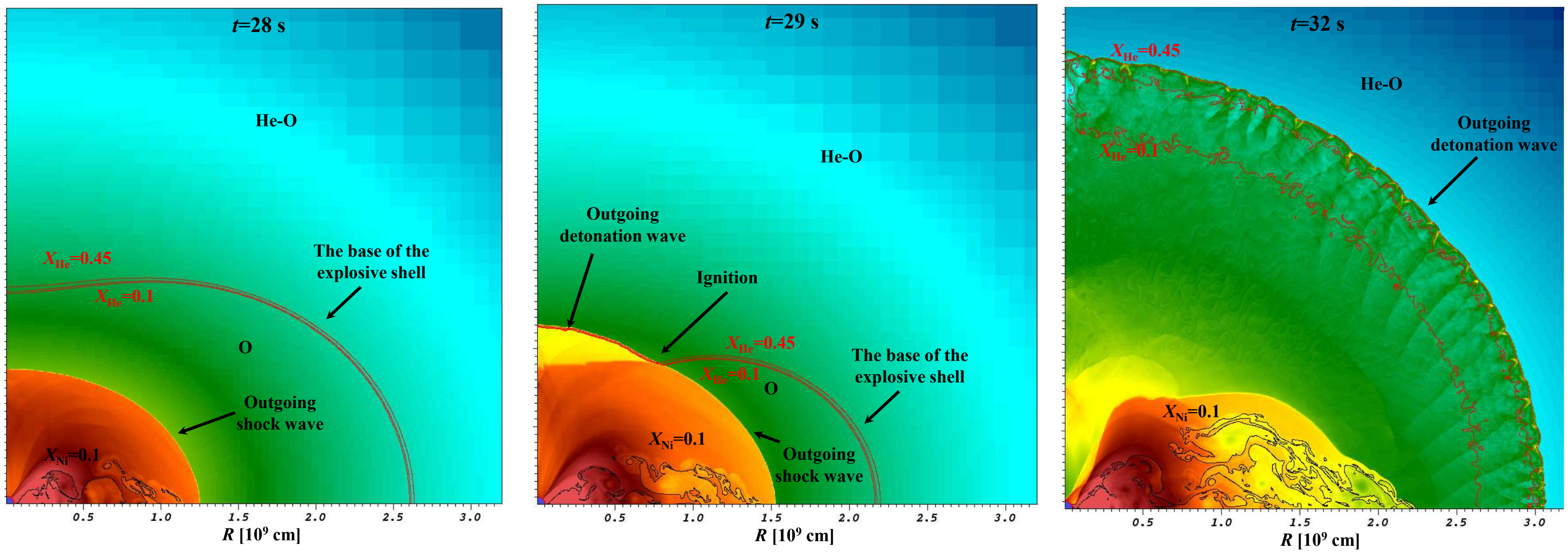
Kushnir, 1502.03111

Explosion well resolved. Rotation compatible with stellar models.

Initial composition of the star *differs* from stellar models: <u>is it sensible?</u>



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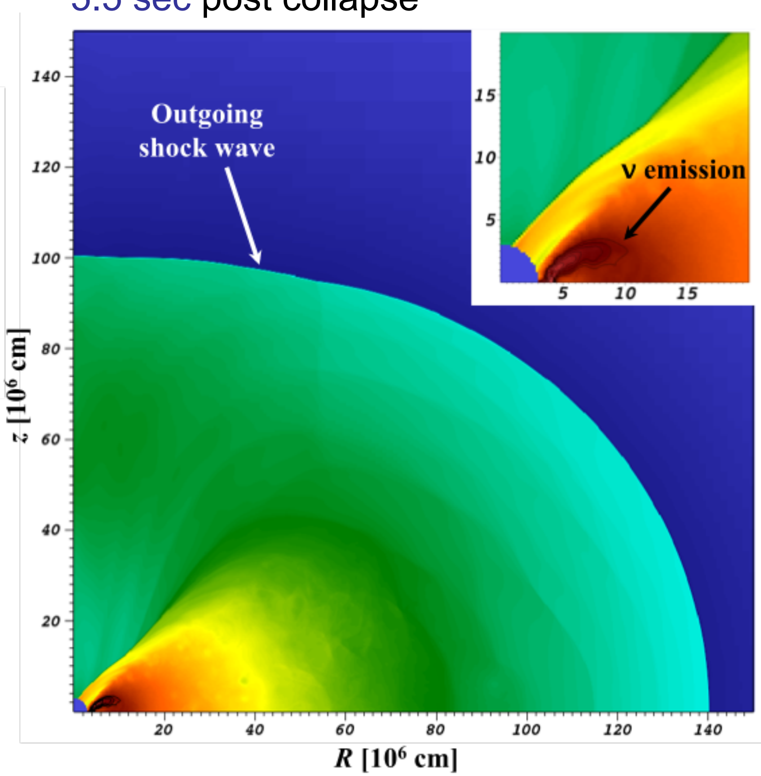
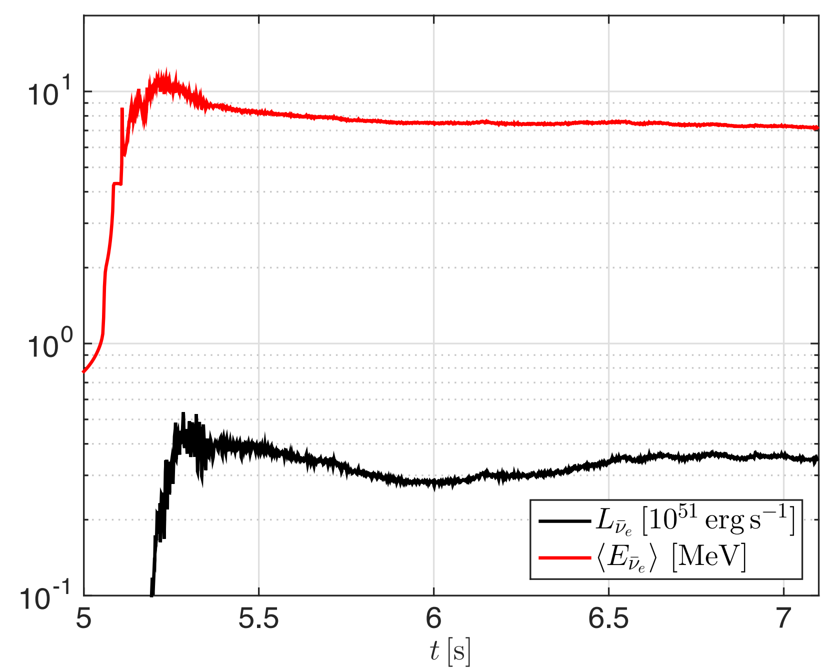
KB & Kushnir, 1601.03422 [ApJ. 828, 31 (2016)]:
The case for prompt black hole formation in SN1987A

Simulation: M_{Ni} ~ 0.035 $M_\odot$, E_{kin} ~ 0.6x10^{51} erg

SN1987A observed: M_{Ni} ~ 0.07 $M_\odot$, E_{kin} ~ 1.5x10^{51} erg

5.5 sec post collapse





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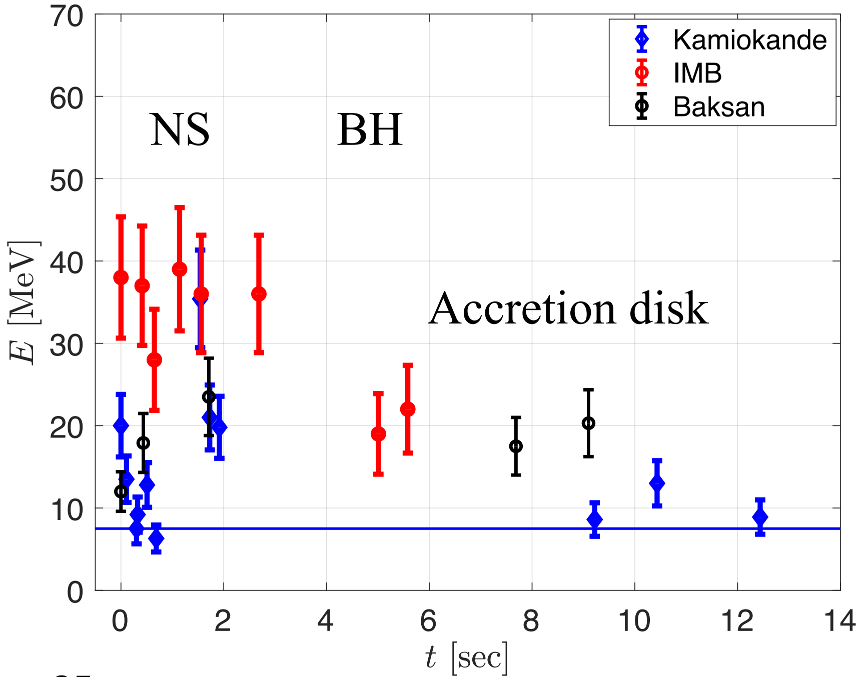
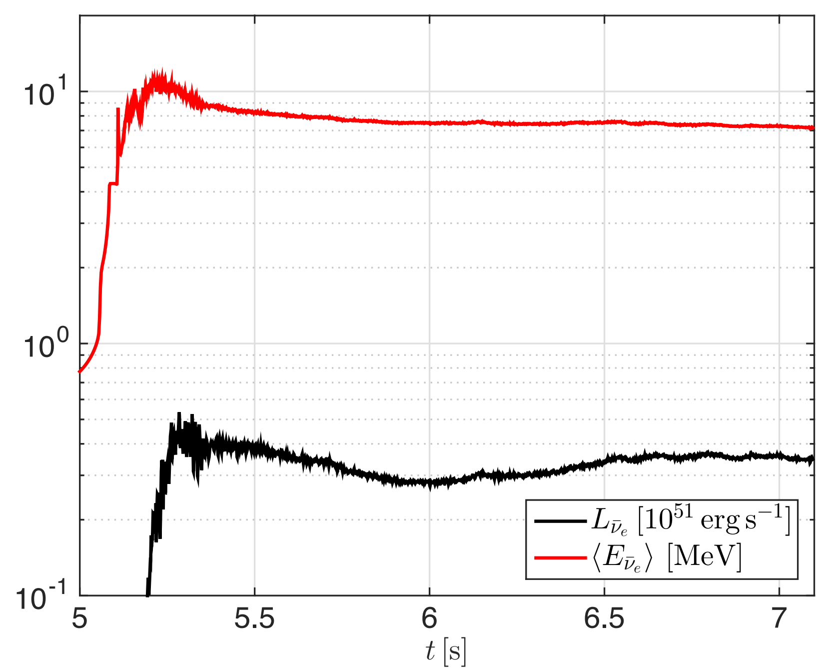




Supernova axion bound: ``**Raffelt criterion**" $\epsilon_a < 10^{19}$ erg/g/sec

G. G. Raffelt, Phys. Rept. **198**, 1 (1990)

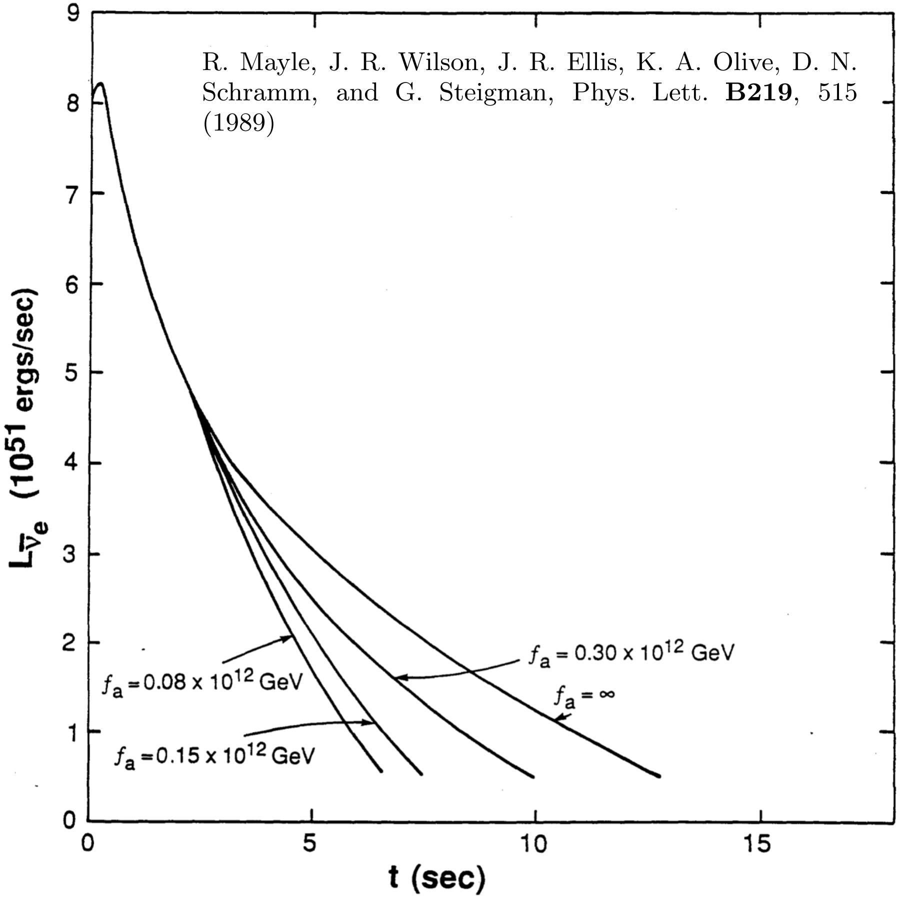
Supernova axion bound: ``**Raffelt criterion**" $\epsilon_a < 10^{19}$ erg/g/sec

G. G. Raffelt, Phys. Rept. **198**, 1 (1990)

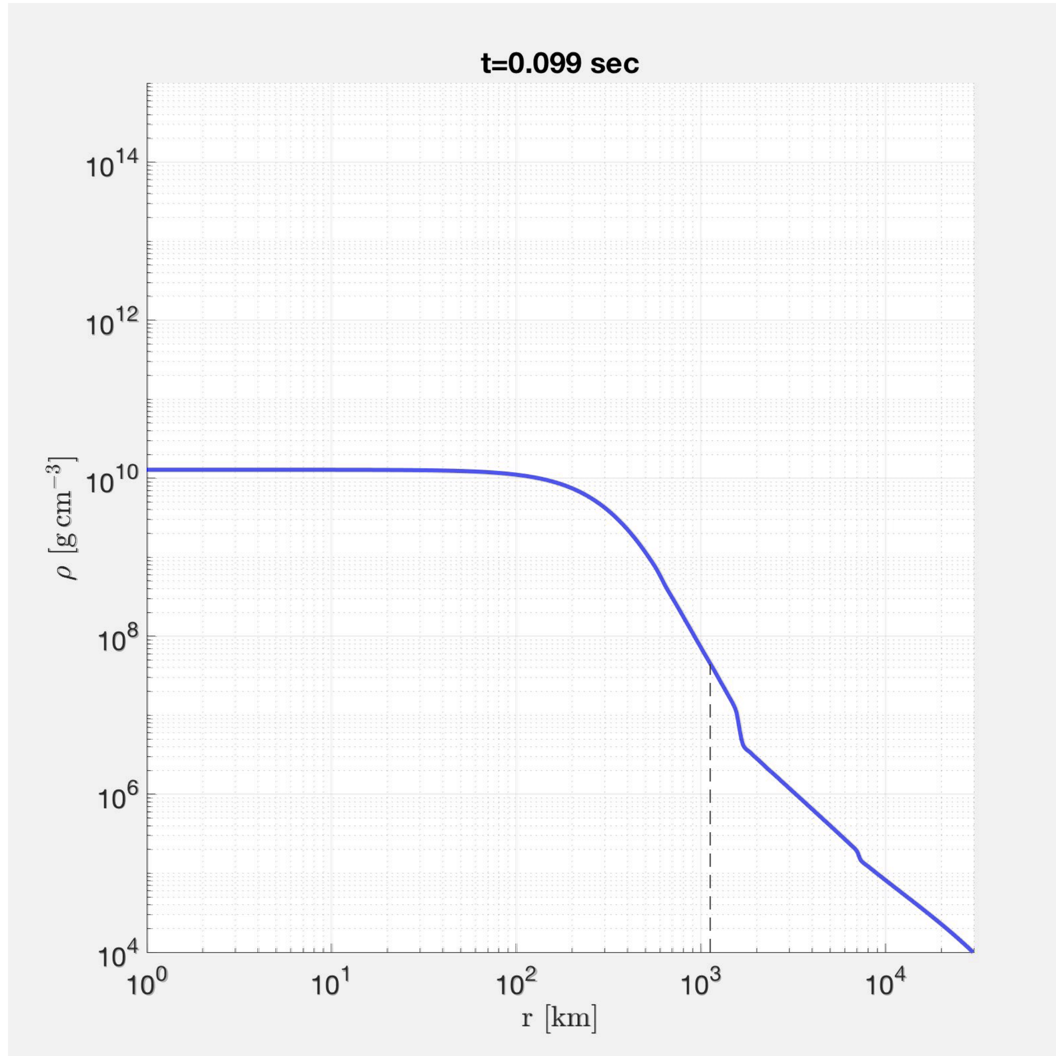
* Based on non-exploding simulations of a neutron star.

* Guarantees that NS neutrinos don't die-off at $t > 7$ sec .

* No use of $t < 5$ sec .



Raffelt criterion based on simulations:
Mayle et al (1989)
Burrows et al (1989)



Bar, KB, D'Amico, 1811.11178 [PRD99 (2019) no.12, 123004]

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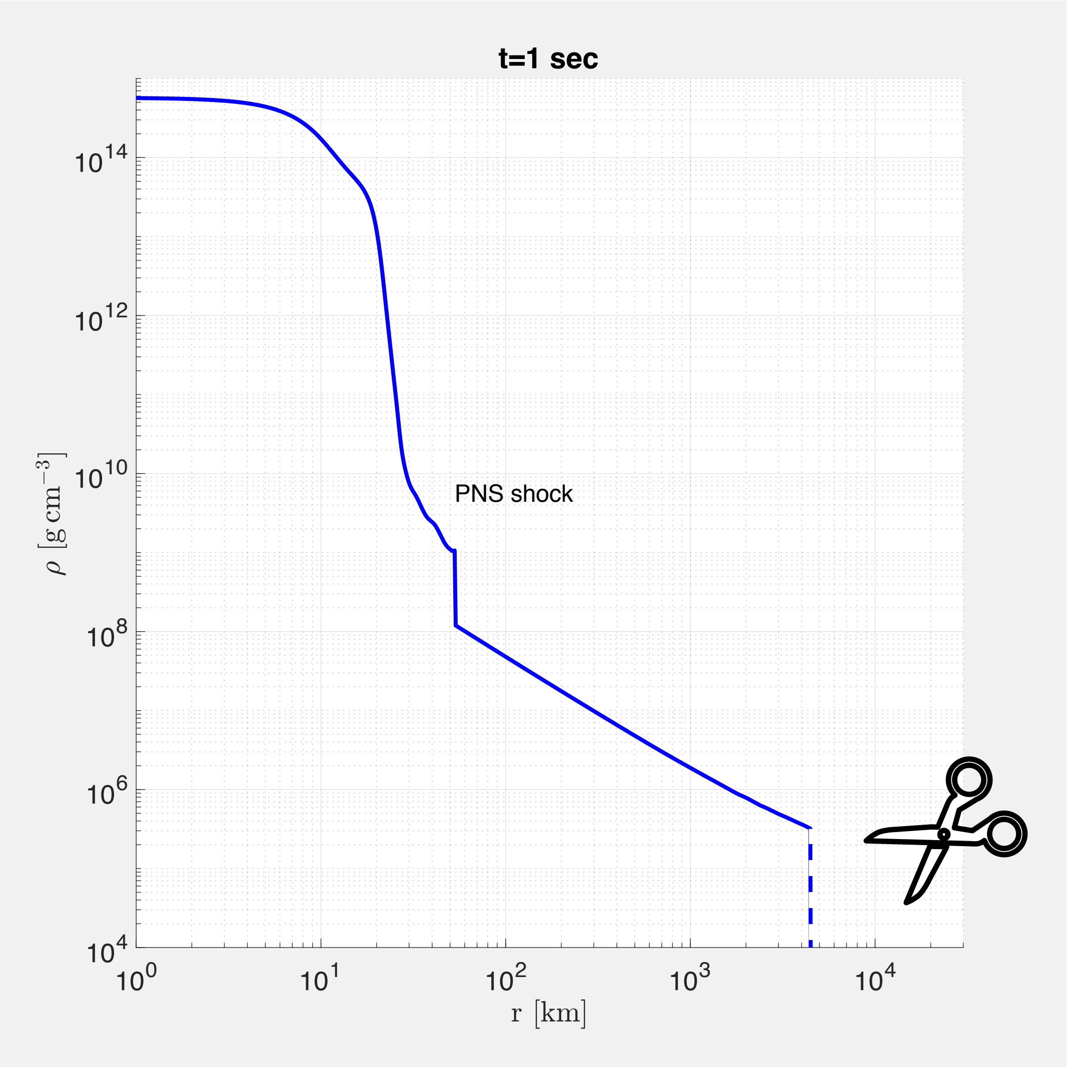

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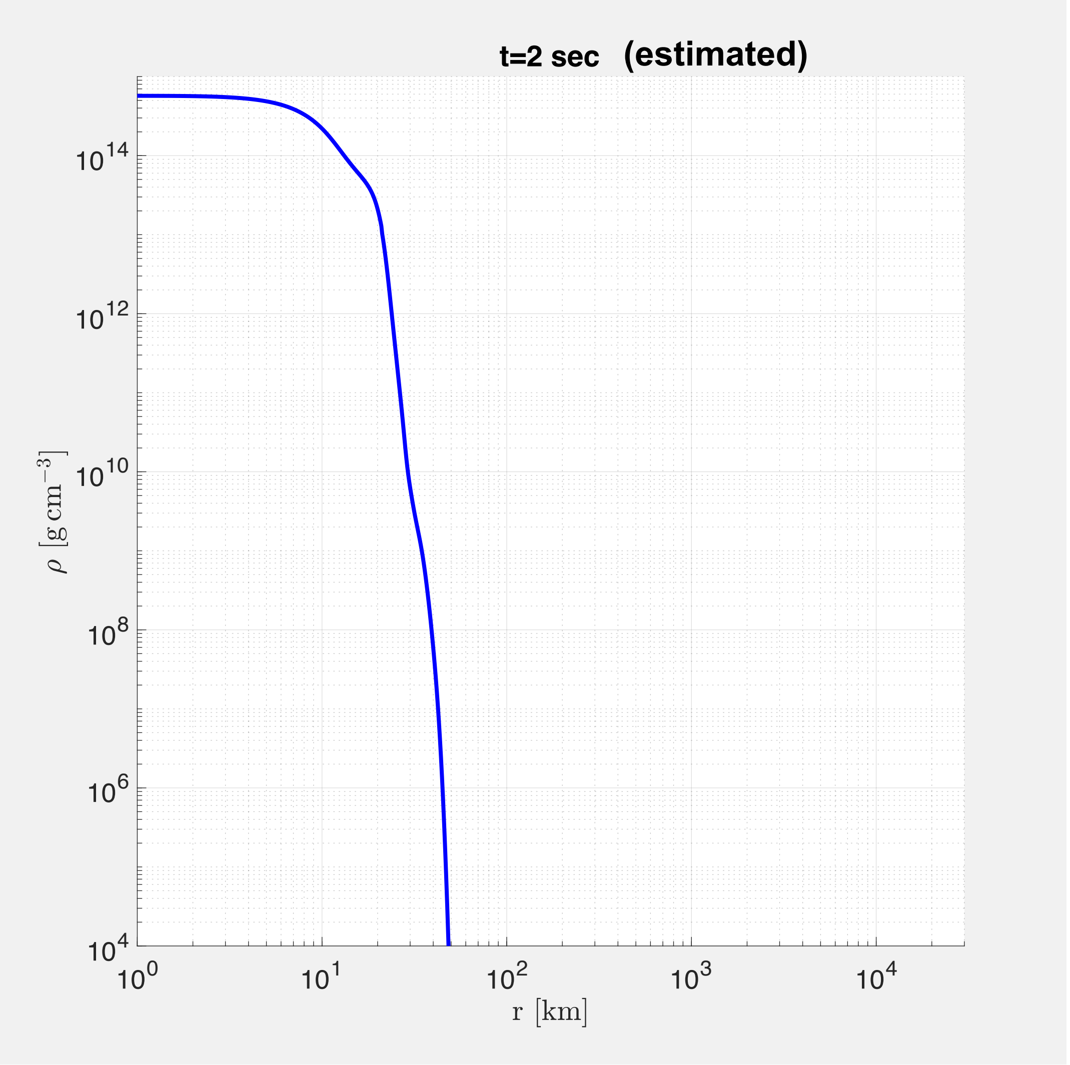

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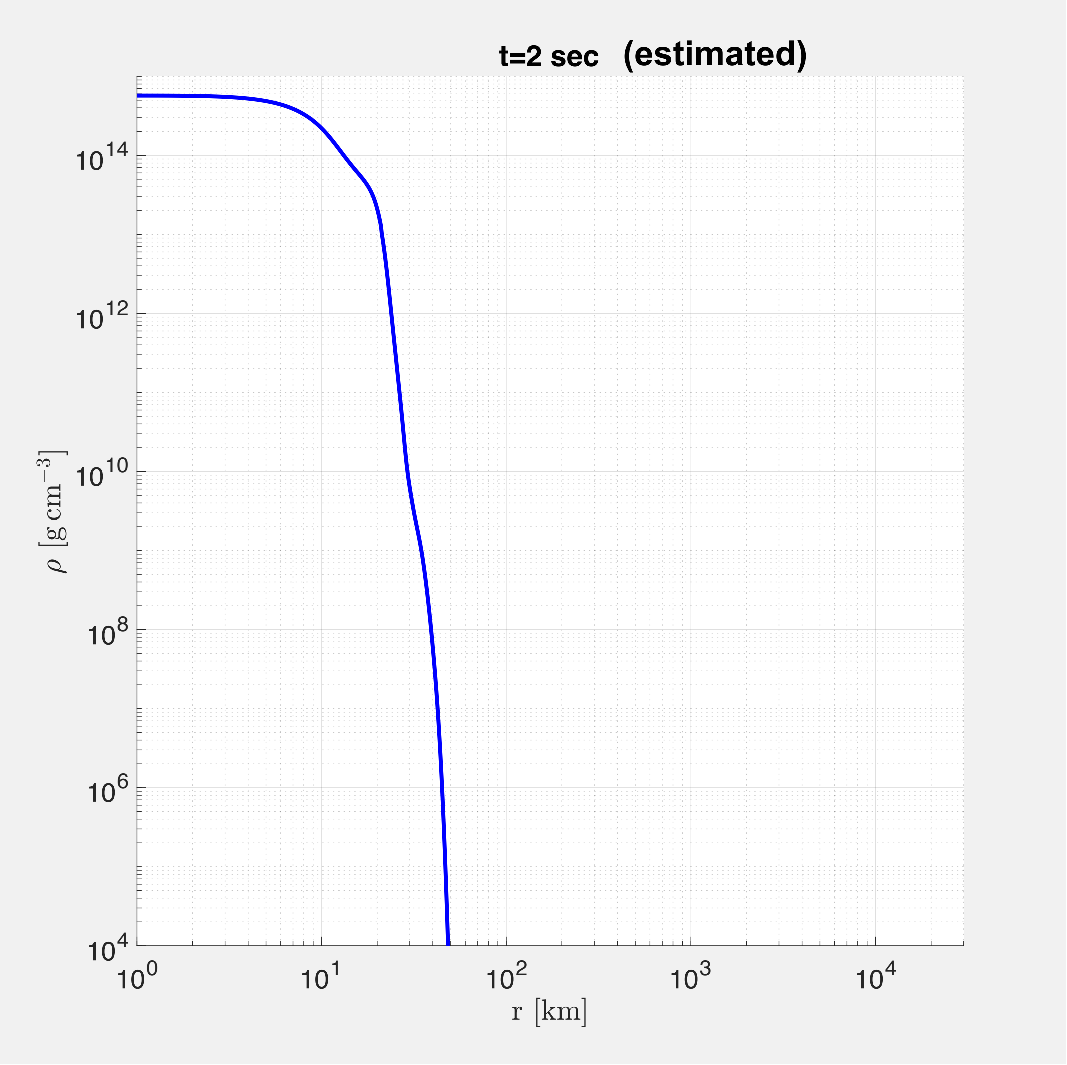
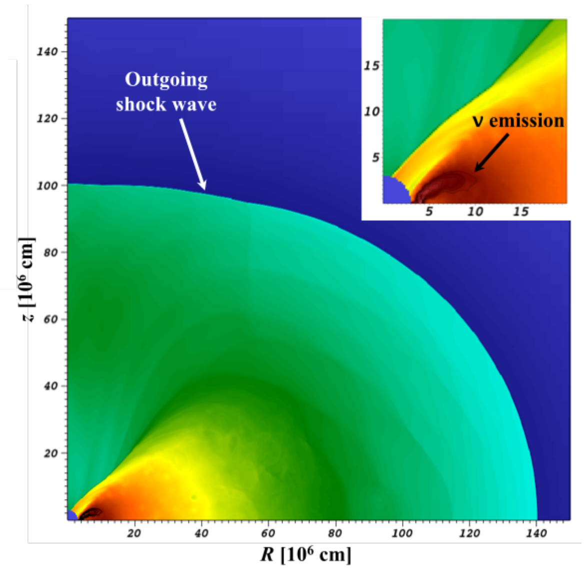
Mayle et al (1989)
Burrows et al (1989)

Not supernova simulations:
Proto-neutron star (PNS)
simulations.

By construction, by t>2 sec
there was nothing there
to make neutrinos
apart from the PNS.

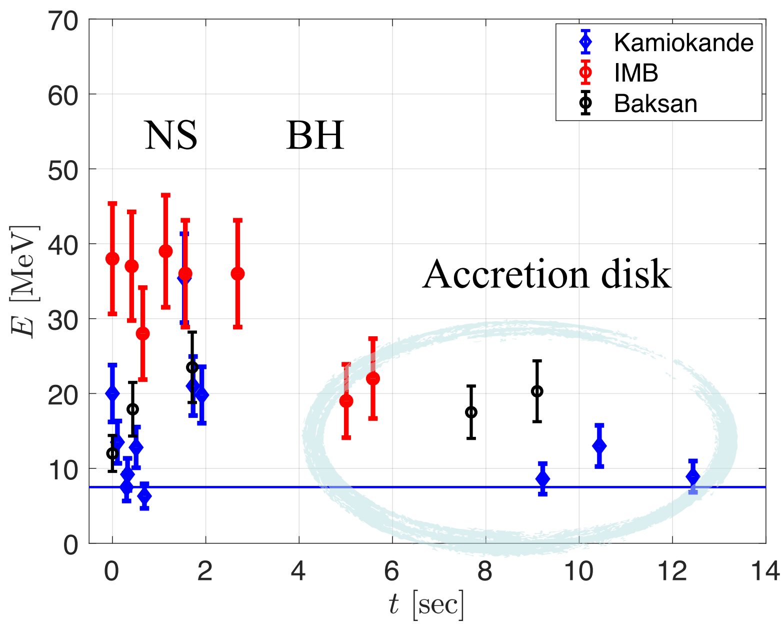


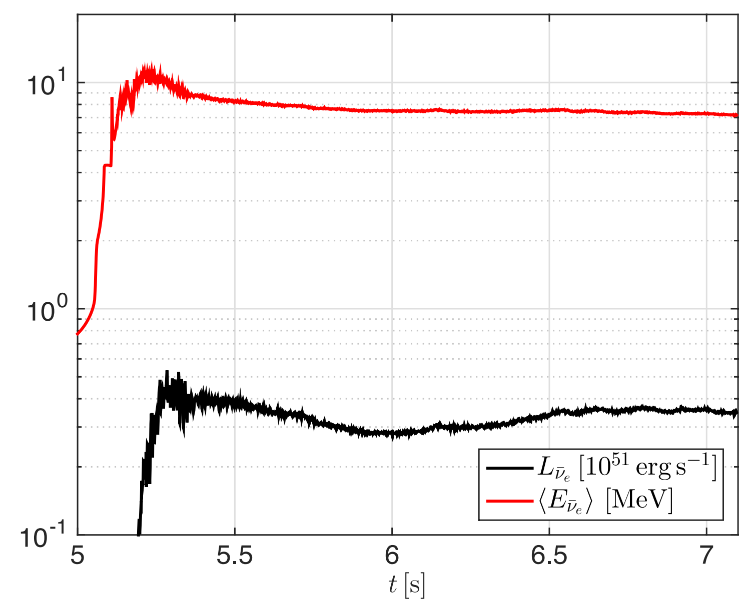
Disk neutrinos can explain late-time events in SN1987A.
It was those late time events,
on which the axion bound was based.



Axions do not affect the neutrino emission of the disk.

Bar, KB, D'Amico, arXiv:1907.05020





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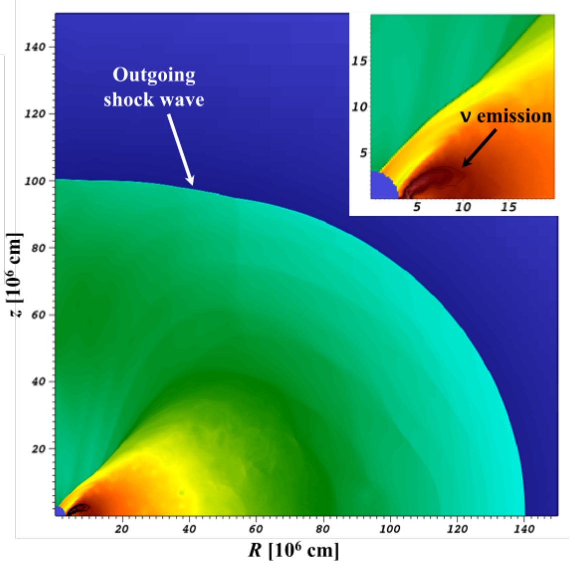

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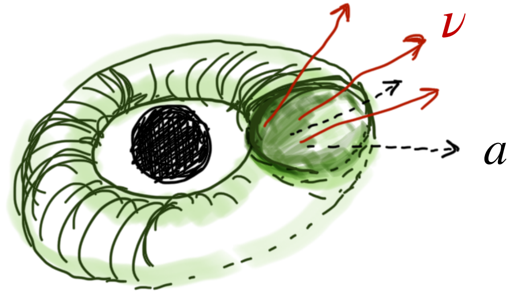
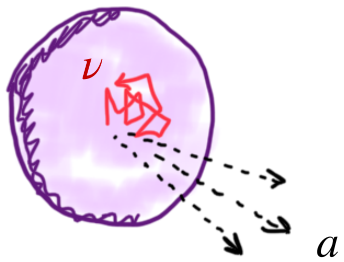
$$\frac{\epsilon_{\bar{\nu}_e}}{\epsilon_a} \approx 3.4 \times 10^8 \left(\frac{10^9\ \mathrm{g\,cm^{-3}}}{\rho}\right)\left(\frac{T}{2.5\ \mathrm{MeV}}\right)^{2.5}\left(\frac{f_a}{4 \times 10^8\ \mathrm{GeV}}\right)^2$$



Neutrinos flow out of the disk, while in the PNS they are stuck, letting axions win.

$$l_{\bar{\nu}_e} \sim 3 \times 10^3 \left(\frac{10^9\ \mathrm{g\,cm^{-3}}}{\rho}\right)\left(\frac{10\ \mathrm{MeV}}{E_\nu}\right)^2 \mathrm{km} \ \sim \begin{cases} 10^3\ \mathrm{km} & \textbf{disk} \\ 10^{-2}\ \mathrm{km} & \textbf{PNS} \end{cases}$$



If SN1987A happened to be CITE,
then I don't see an axion bound.

Summary:

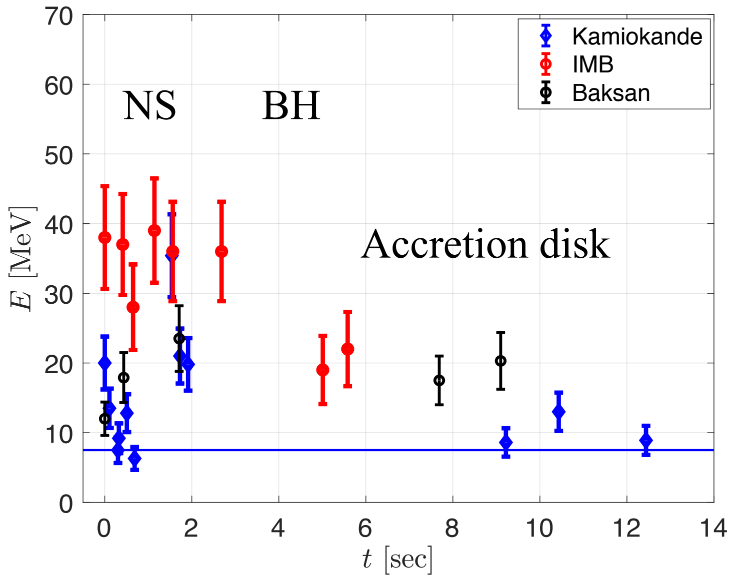
SN1987A may have been a thermonuclear, rather than a neutrino-driven explosion.

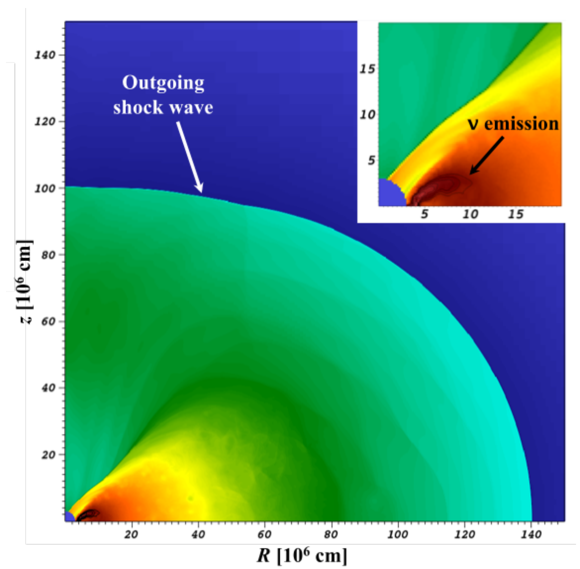
KB & Kushnir, 1601.03422 [ApJ. 828, 31 (2016)]

* Luminosity drop at $t \sim 3$ sec: BH formation?
* No pulsar in the remnant?
* Events at $t > 5$ sec: accretion luminosity $L_{\bar{\nu}_e} \approx L_{\nu_e} \gg L_{\nu_x}$
* Many BHs out there with $M_{\mathrm{BH}} \sim$ few $\mathrm{M}_\odot$?
* *Is there a supernova bound on axions?*

Bar, KB, D'Amico, 1811.11178 [PRD99 (2019) no.12, 123004]

Bar, KB, D'Amico, 1907.05020

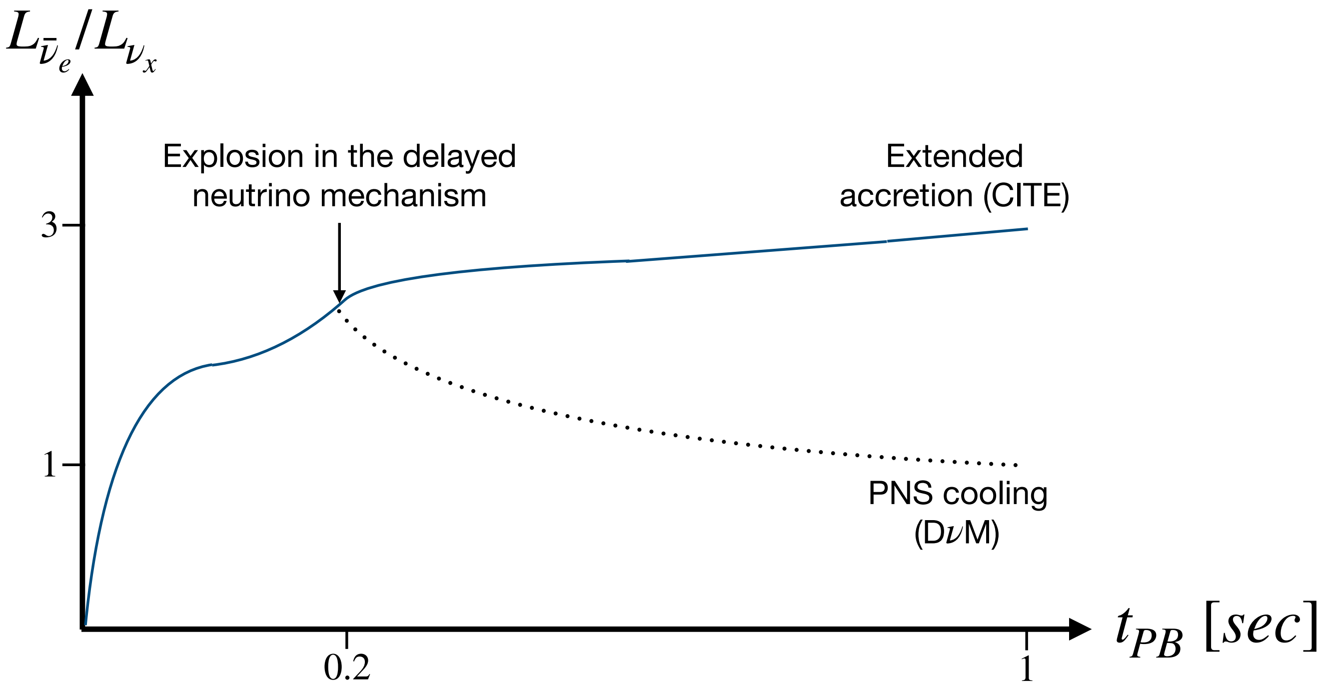




Xtra

Accretion luminosity

Bar, KB, D'Amico, arXiv:1811.11178 [PRD99 (2019) no.12, 123004]



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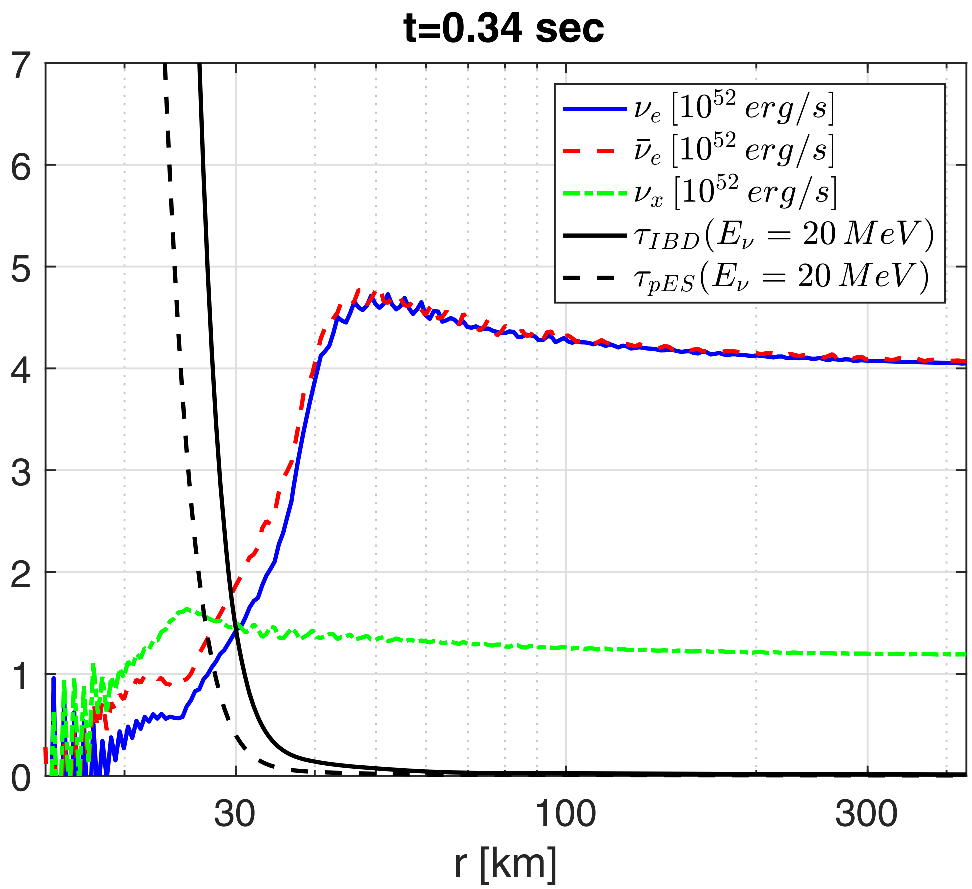
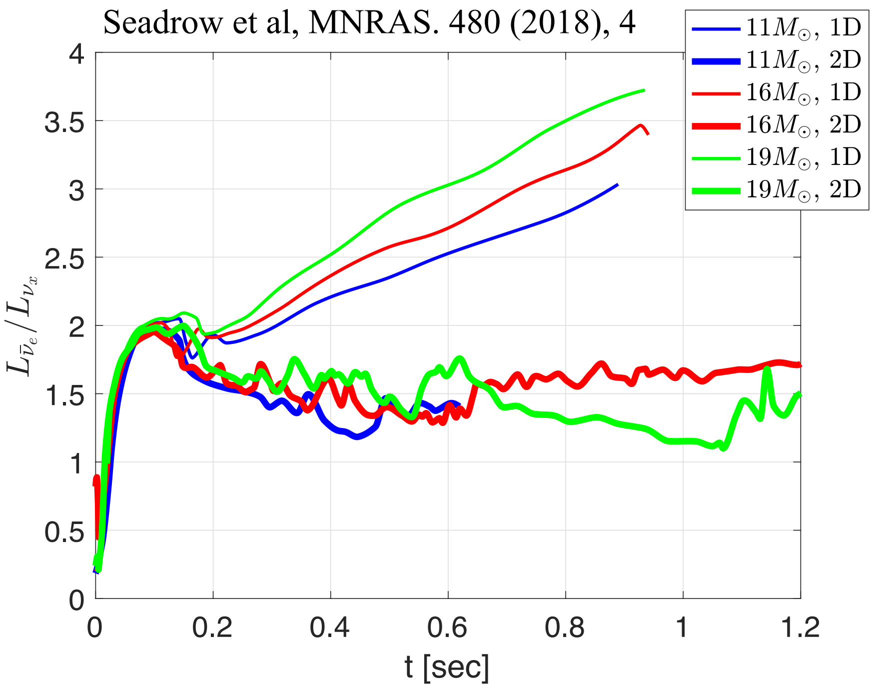
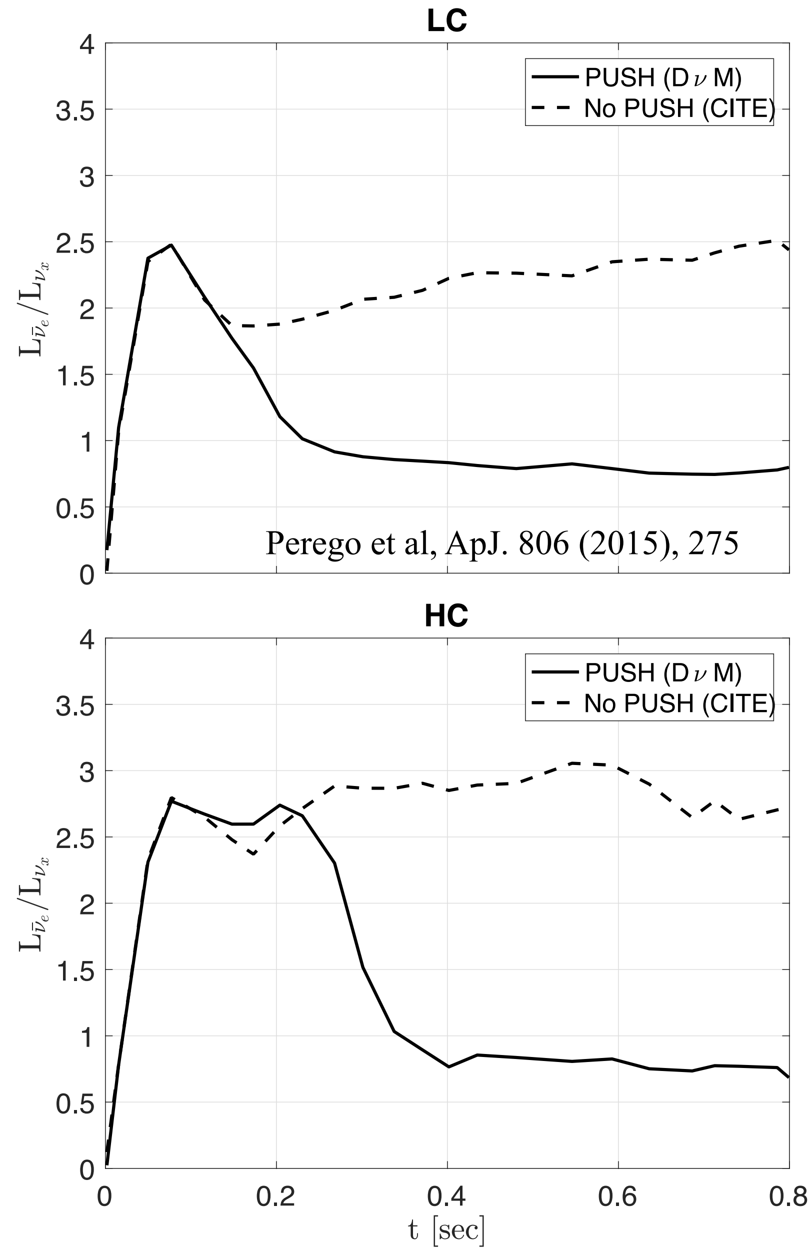
Bar, KB, D'Amico, arXiv:1811.11178 [PRD99 (2019) no.12, 123004]



Accretion luminosity

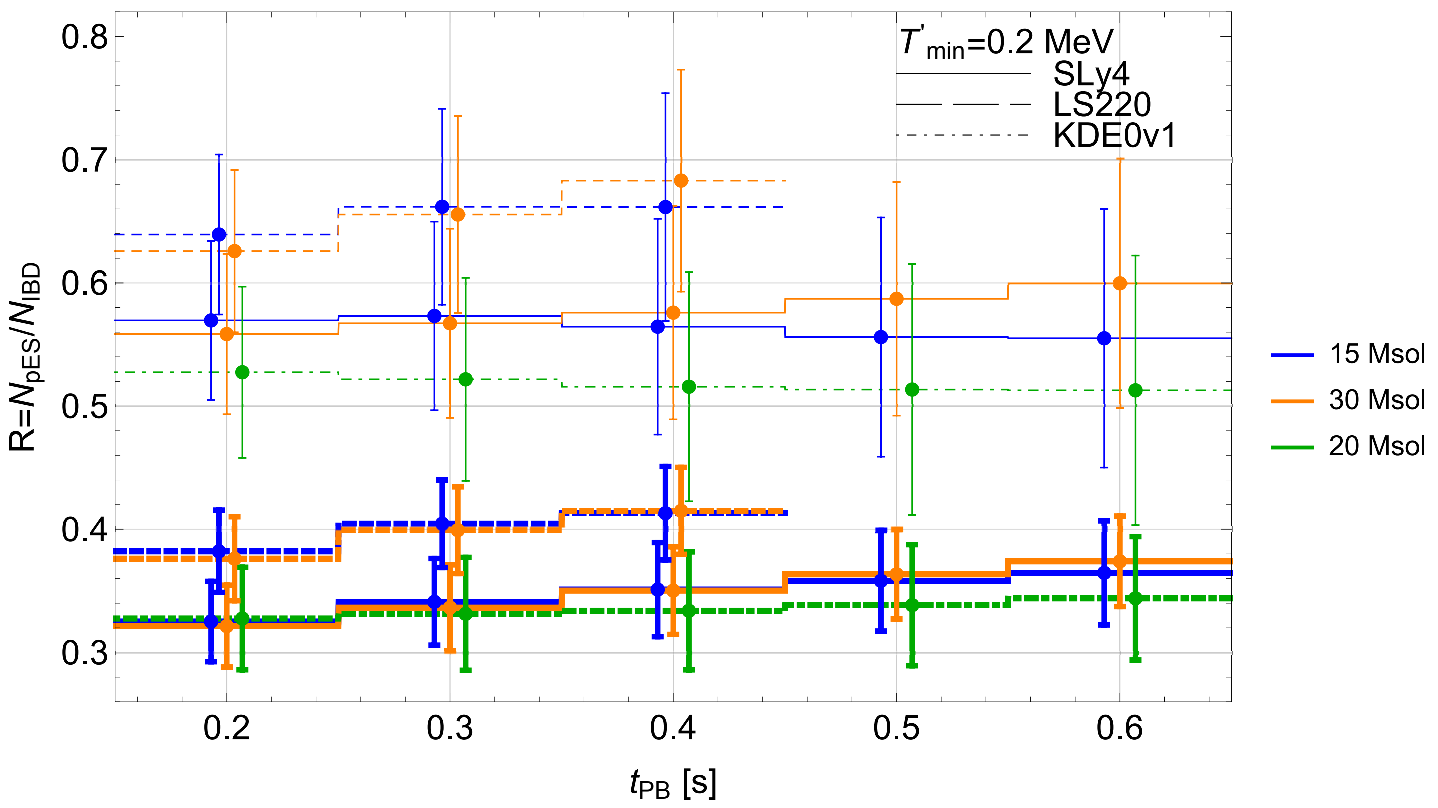




Accretion luminosity

Bar, KB, D'Amico, arXiv:1811.11178 [PRD99 (2019) no.12, 123004]

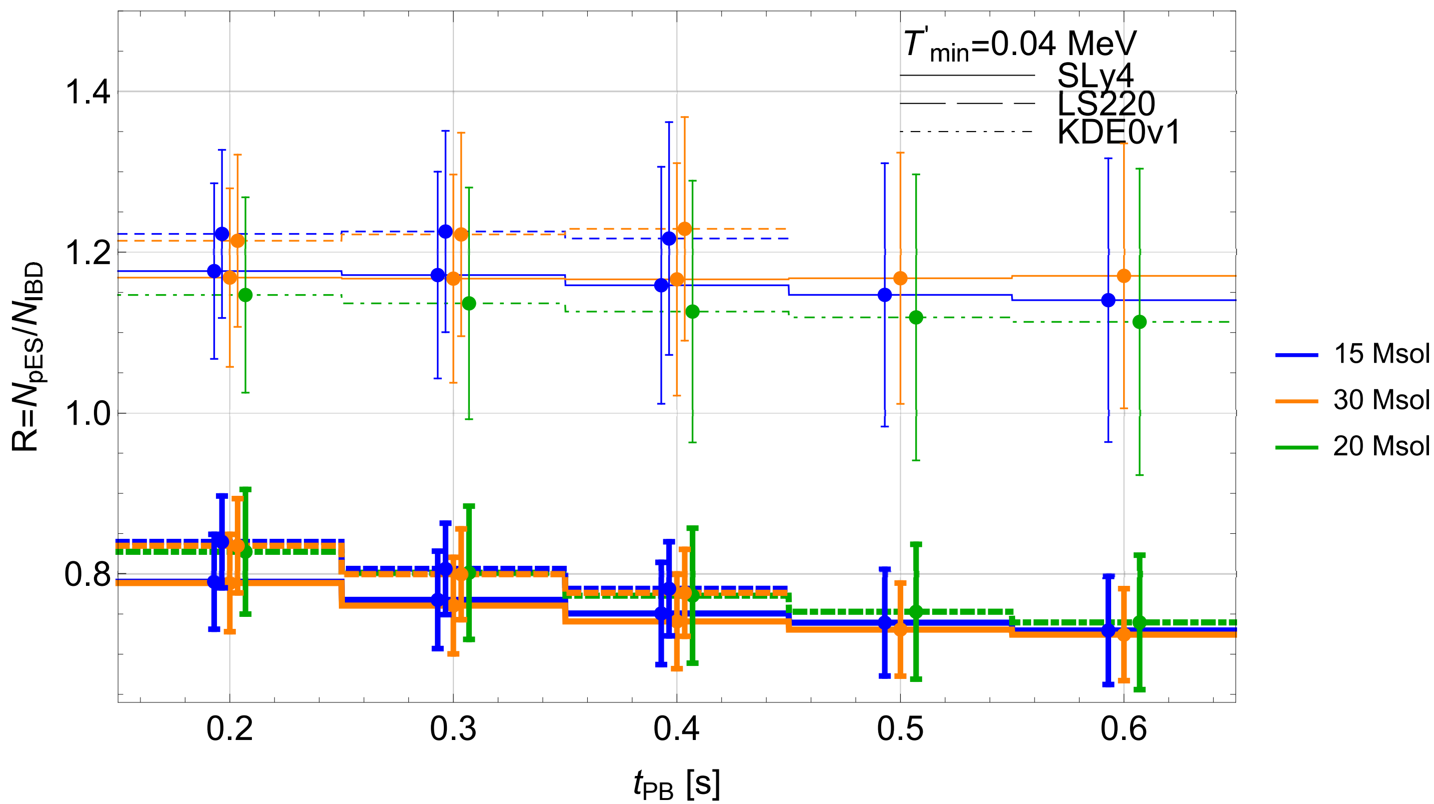
SN1987A-like, 10kpc away, **JUNO** [baseline (?) T' proton recoil threshold**]**



Accretion luminosity

Bar, KB, D’Amico, arXiv:1811.11178 [PRD99 (2019) no.12, 123004]

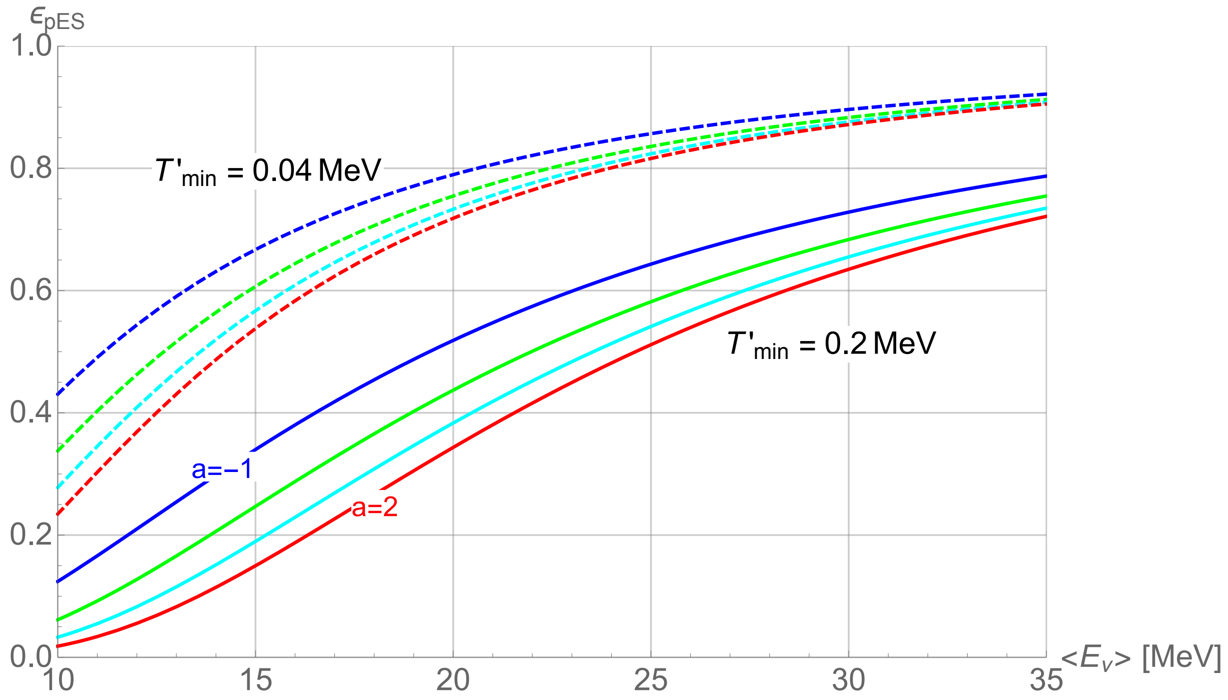
SN1987A-like, 10kpc away, **JUNO** [optimistic (?) T’ proton recoil threshold**]**



Accretion luminosity

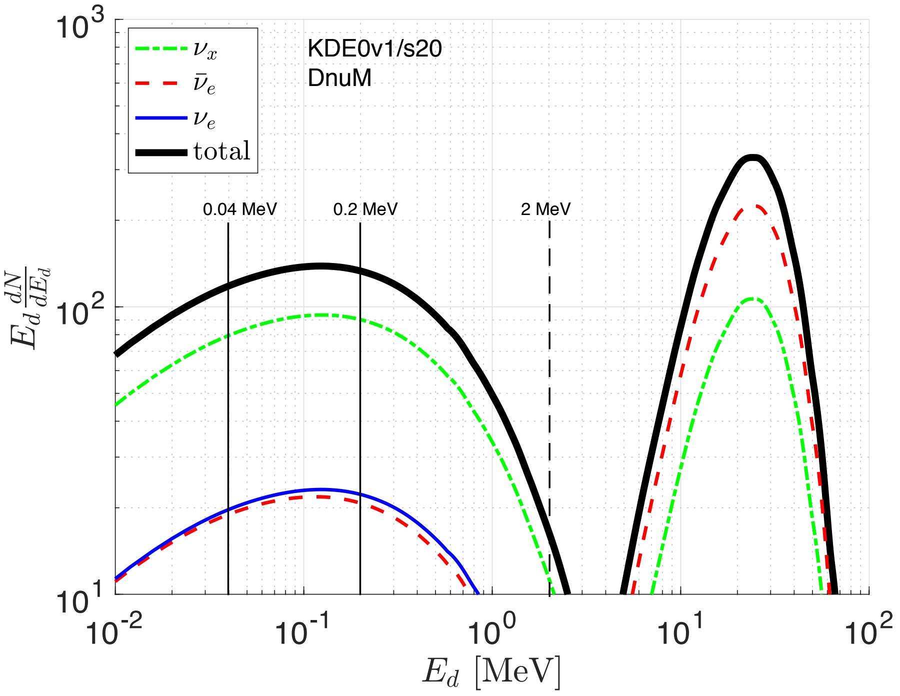
Bar, KB, D'Amico, arXiv:1811.11178 [PRD99 (2019) no.12, 123004]

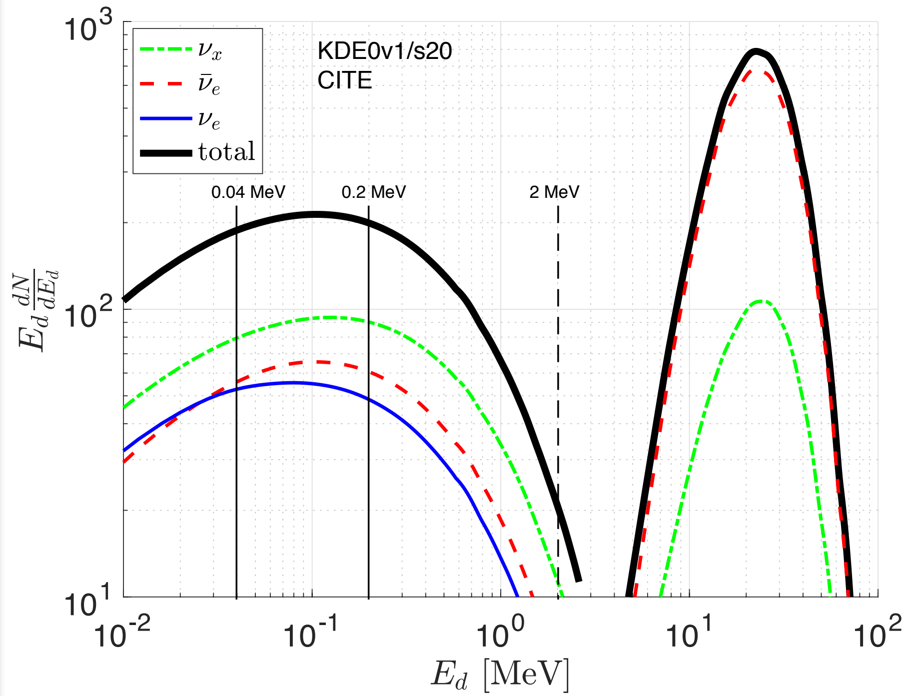
JUNO: impact of proton recoil threshold



Accretion luminosity

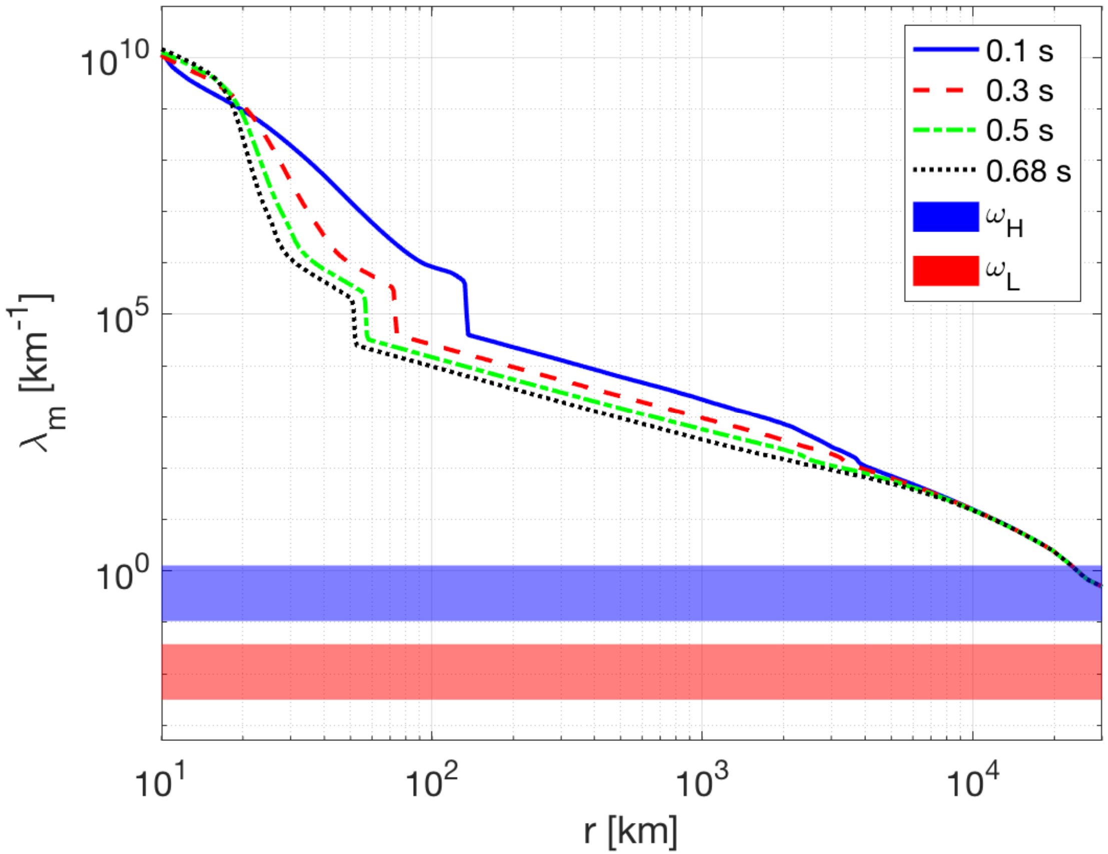
Bar, KB, D'Amico, arXiv:1811.11178 [PRD99 (2019) no.12, 123004]





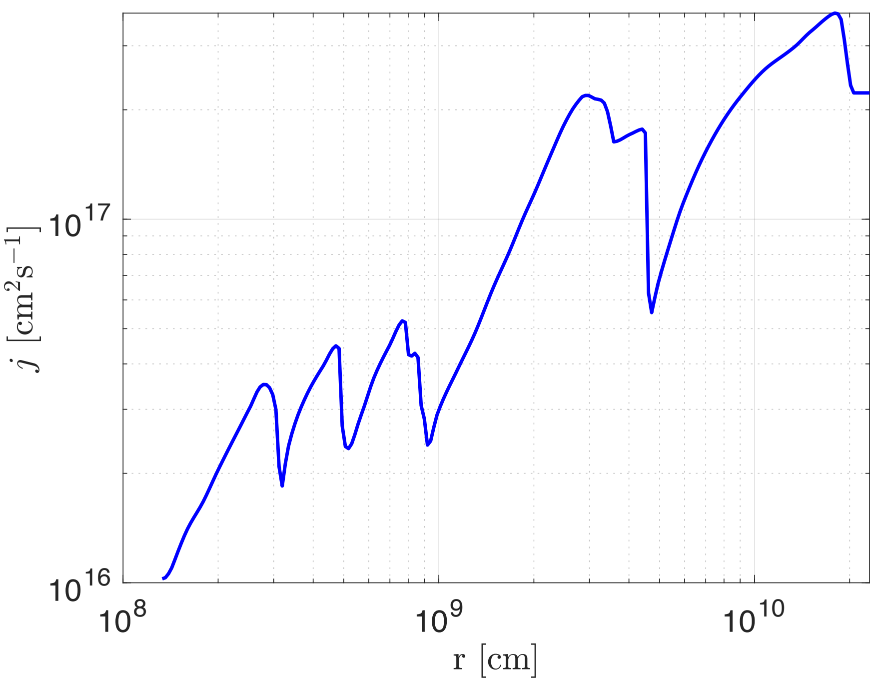
Bar, KB, D'Amico, arXiv:1811.11178 [PRD99 (2019) no.12, 123004]

MSW matter potential deep adiabatic (but self-induced conversion?…)



CITE: rotation

Hirschi, Meynet, Maeder
astro-ph/0406552 [A&A 425 (2004) 649-670]



KB & Kushnir
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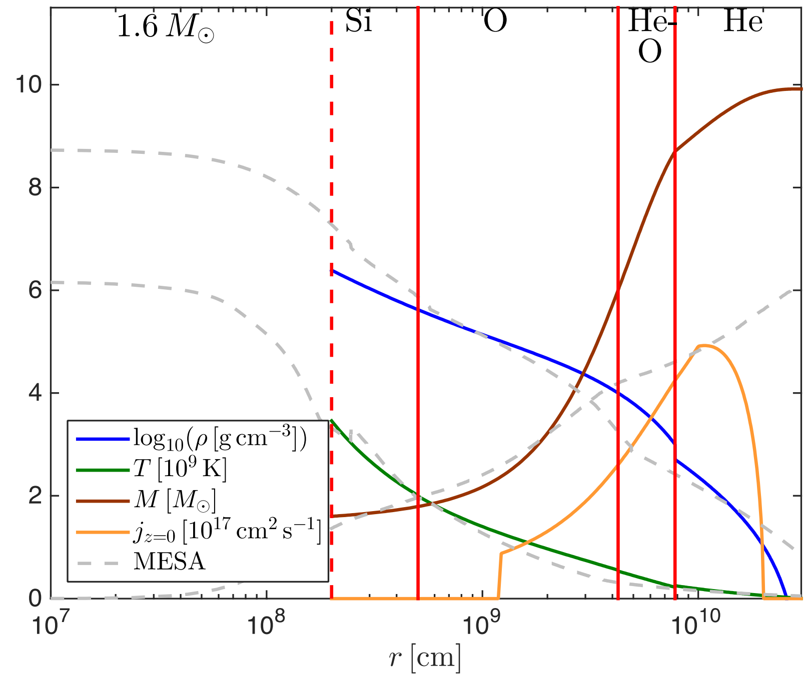
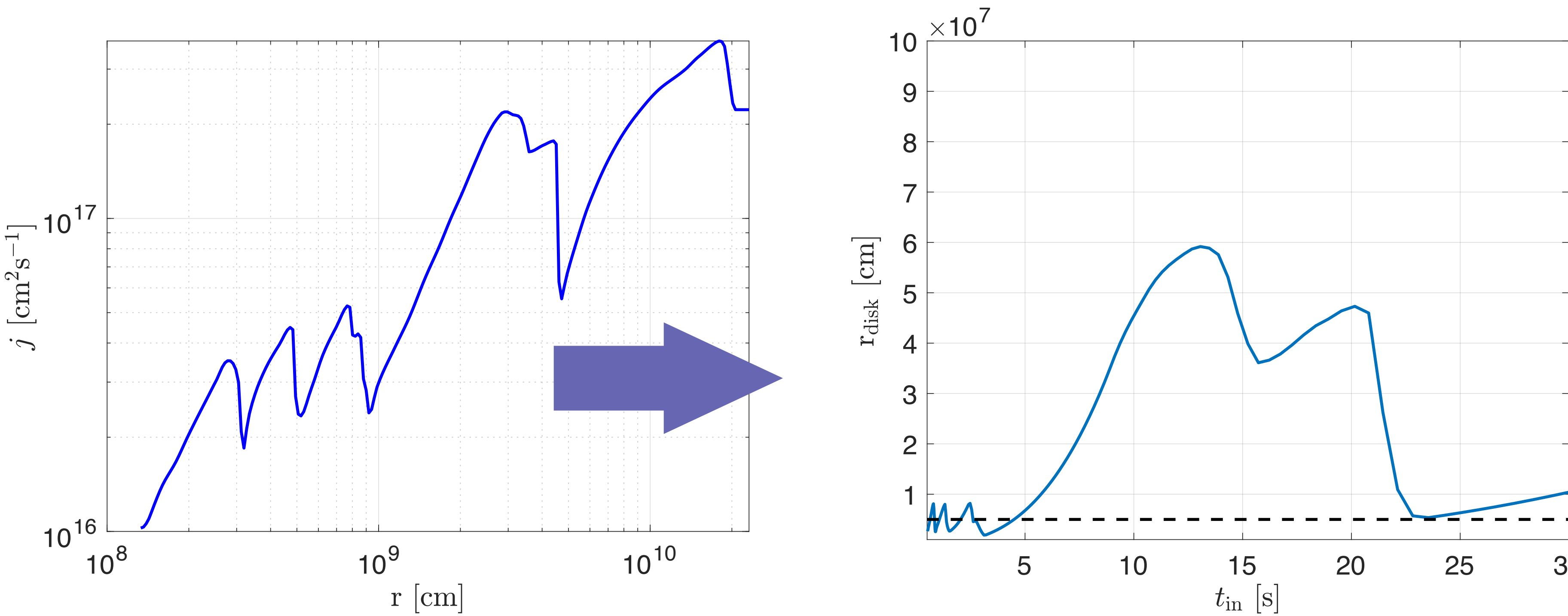


CITE: rotation

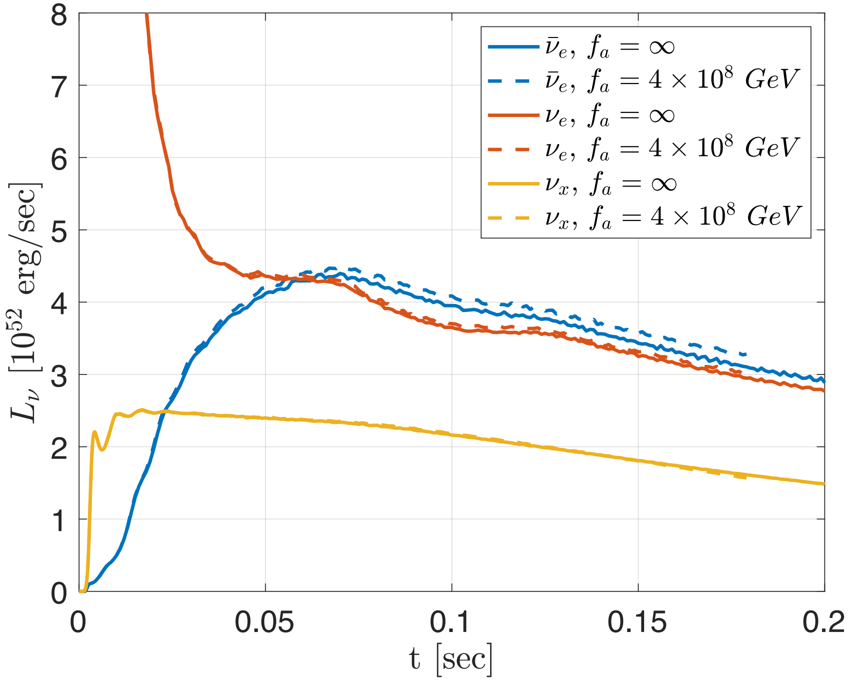
Disk formation time (~5 sec) very compatible.

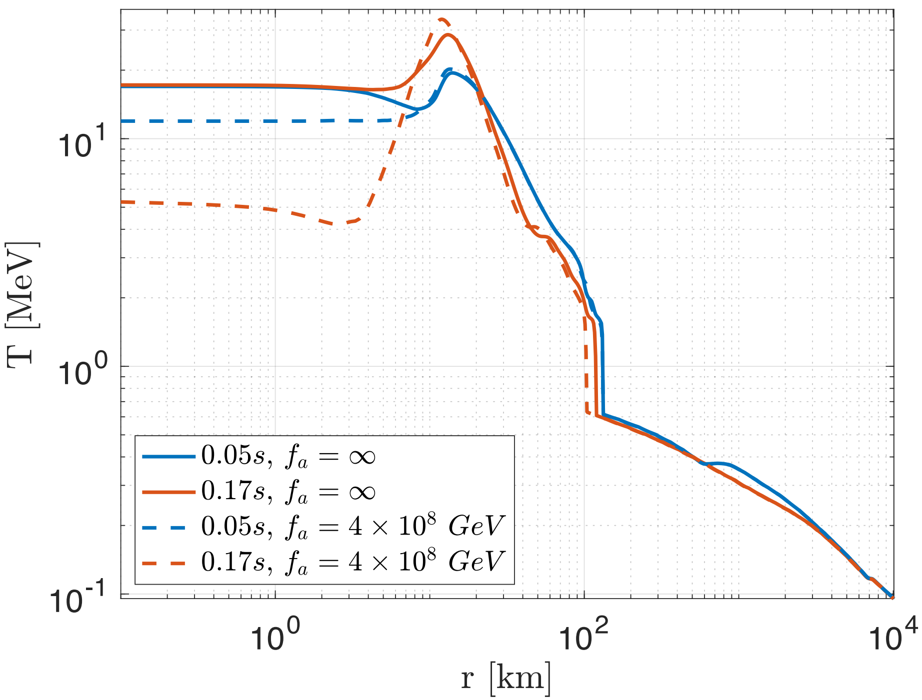
Hirschi, Meynet, Maeder
astro-ph/0406552 [A&A 425 (2004) 649-670]



Bar, KB, D'Amico 1907.05020

Axions can drain the PNS core of energy, but do not affect neutrino luminosity at t<3 sec





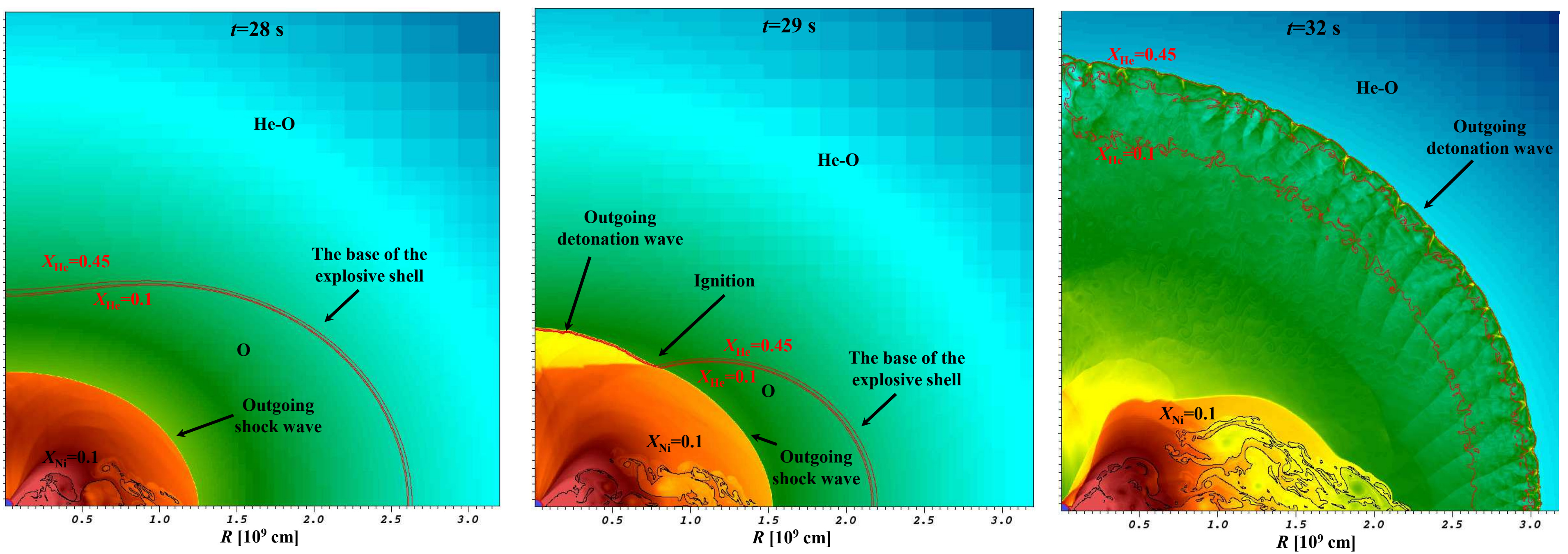
- If the neutrino mechanism fails: black hole (BH) forms within a few sec
- What happens next? If the star is rotating => accretion disk => CITE

Collapse-induced thermonuclear explosion (CITE)

Kushnir, 1502.03111

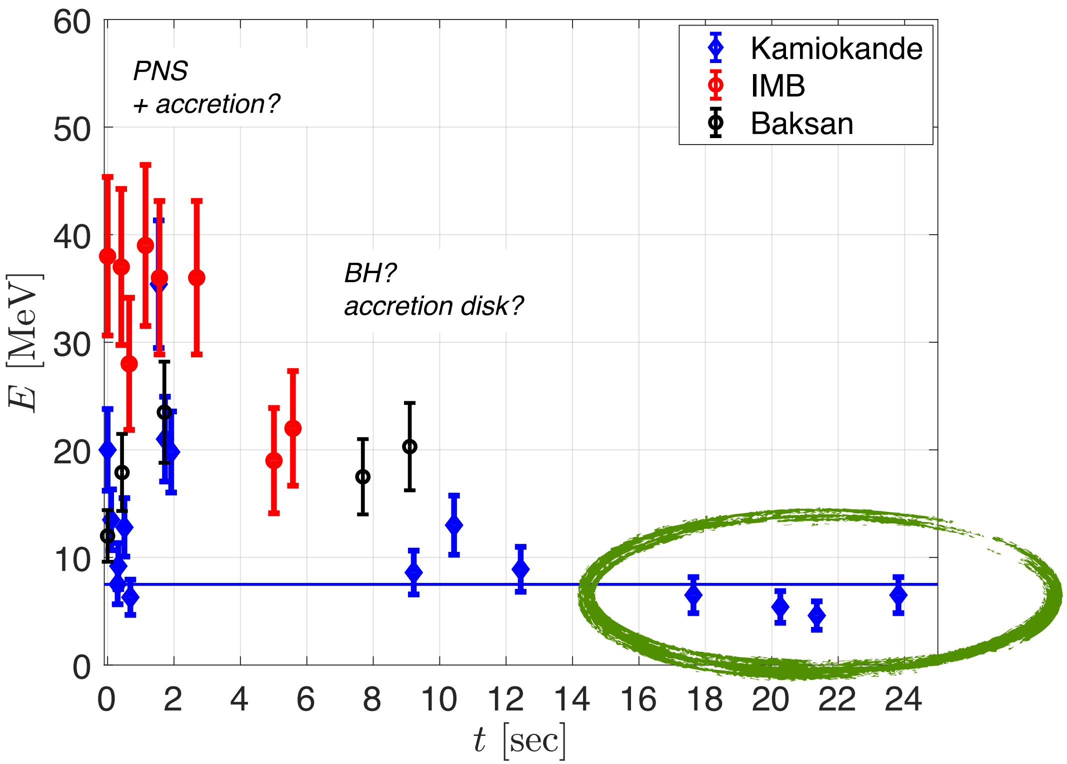
This simulation explodes and gives: $M_{Ni} \sim 0.08\, M_\odot$, $E_{kin} \sim 1.3\times10^{51}$ erg

SN1987A observed: $M_{Ni} \sim 0.07\, M_\odot$, $E_{kin} \sim 1.5\times10^{51}$ erg



Accretion disk luminosity could last for as long as ~25 sec or so.
Amplitude decreasing with decreasing accretion rate.

There are KII events at 17-24 sec;
consistent with background, but may include signal.



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The literature can be confusing.

arXiv.org > astro-ph > arXiv:2004.06078

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Astrophysics > High Energy Astrophysical Phenomena

NS 1987A in SN 1987A

Dany Page, Mikhail V. Beznogov, Iván Garibay, James M. Lattimer, Madappa Prakash, Hans-Thomas Janka

(Submitted on 13 Apr 2020)

The possible detection of a compact object in the remnant of SN 1987A presents an unprecedented opportunity to follow its early evolution. The suspected detection stems from an excess of infrared emission from a dust blob near the compact object's predicted position. The infrared excess could be due to the decay of isotopes like 44Ti, accretion luminosity from a neutron star or black hole, magnetospheric emission or a wind originating from the spindown of a pulsar, or to thermal emission from an embedded, cooling neutron star (NS 1987A). It is shown that the latter possibility is the most plausible as the other explanations are disfavored by other observations and/or require fine-tuning of parameters. Not only are there indications the dust blob overlaps the predicted location of a kicked compact remnant, but its excess luminosity also matches the expected thermal power of a 30 year old neutron star. Furthermore, models of cooling neutron stars within the Minimal Cooling paradigm readily fit both NS 1987A and Cas A, the next-youngest known neutron star. If correct, NS 1987A likely has a light-element envelope and a relatively small crustal n-1S0 superfluid gap. If the locations don't overlap, then pulsar spindown or accretion might be more likely, but the pulsar's period and magnetic field or the accretion rate must be rather finely tuned. In this case, NS 1987A may have enhanced cooling and/or a heavy-element envelope.

Comments: 17 page, 7 figures, submitted to Ap.J

Subjects: **High Energy Astrophysical Phenomena (astro-ph.HE)**; Nuclear Theory (nucl-th)

Cite as: arXiv:2004.06078 [astro-ph.HE]

(or arXiv:2004.06078v1 [astro-ph.HE] for this version)

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Explosion models of Utrobin et al. (2019) for state-of-the-art progenitor models of SN 1987A indicate the baryon mass, M_B, of its compact remnant to be (1.35-1.66)$M_\odot$, while Ertl et al. (2020) predict (1.48-1.56)$M_\odot$ for single-star progenitors and (1.38-1.75)$M_\odot$ for binary progenitor[1]. These baryon masses translate to a gravitational mass $M \simeq$ (1.22-1.62)$M_\odot$ using the EOS-independent relation (Lattimer & Prakash 2001)

$$\frac{M_B - M}{M} \simeq (1.2 \pm 0.1)\frac{\beta}{2-\beta}\,, \qquad (1)$$

where $\beta = GM/Rc^2$ and $R \simeq 11.5 \pm 1$ km is the typical neutron star radius[2]. These values are well below the measured masses, $M \gtrsim 2M_\odot$, of several pulsars (PSR J1614-2230, Demorest et al. 2010; PSR J0348+0432, Antoniadis et al. 2013; and PSR J0740+6620, Cromartie et al. 2020), as well as an inferred upper limit to the neutron star maximum mass $M_{\max} \lesssim (2.2\text{–}2.3)M_\odot$ (Margalit & Metzger 2017) from GW170817, which strongly suggests that a black hole remnant in SN 1987A is unlikely. We assume in this paper that the compact remnant produced by SN 1987A is most likely a neutron star, hereafter called NS 1987A, which is also possibly a pulsar.

2004.06078 Intro

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A&A 624, A116 (2019)
https://doi.org/10.1051/0004-6361/201834976

Astronomy & Astrophysics

Three-dimensional mixing and light curves: constraints on the progenitor of supernova 1987A★

V. P. Utrobin[1,2], A. Wongwathanarat[1], H.-Th. Janka[1], E. Müller[1], T. Ertl[1], and S. E. Woosley[3]

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Sec 2.2:

The revival of the stalled SN shock and the explosion are triggered by imposing a suitable value of the neutrino luminosities at an inner radial grid boundary located at an enclosed mass of $1.1\,M_\odot$, well inside the neutrinosphere...

...The explosion energy of the model is determined by the imposed isotropic neutrino luminosity, whose temporal evolution we prescribe as well, and by the accretion luminosity that results from the progenitor-dependent mass accretion rate and the gravitational potential of the contracting neutron star.

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The literature can be confusing.

This paper assumes a NS based on the results from simulations …that assumed a NS.

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