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Is there a supernova bound on axions?

Based on Bar, Blum, GDA

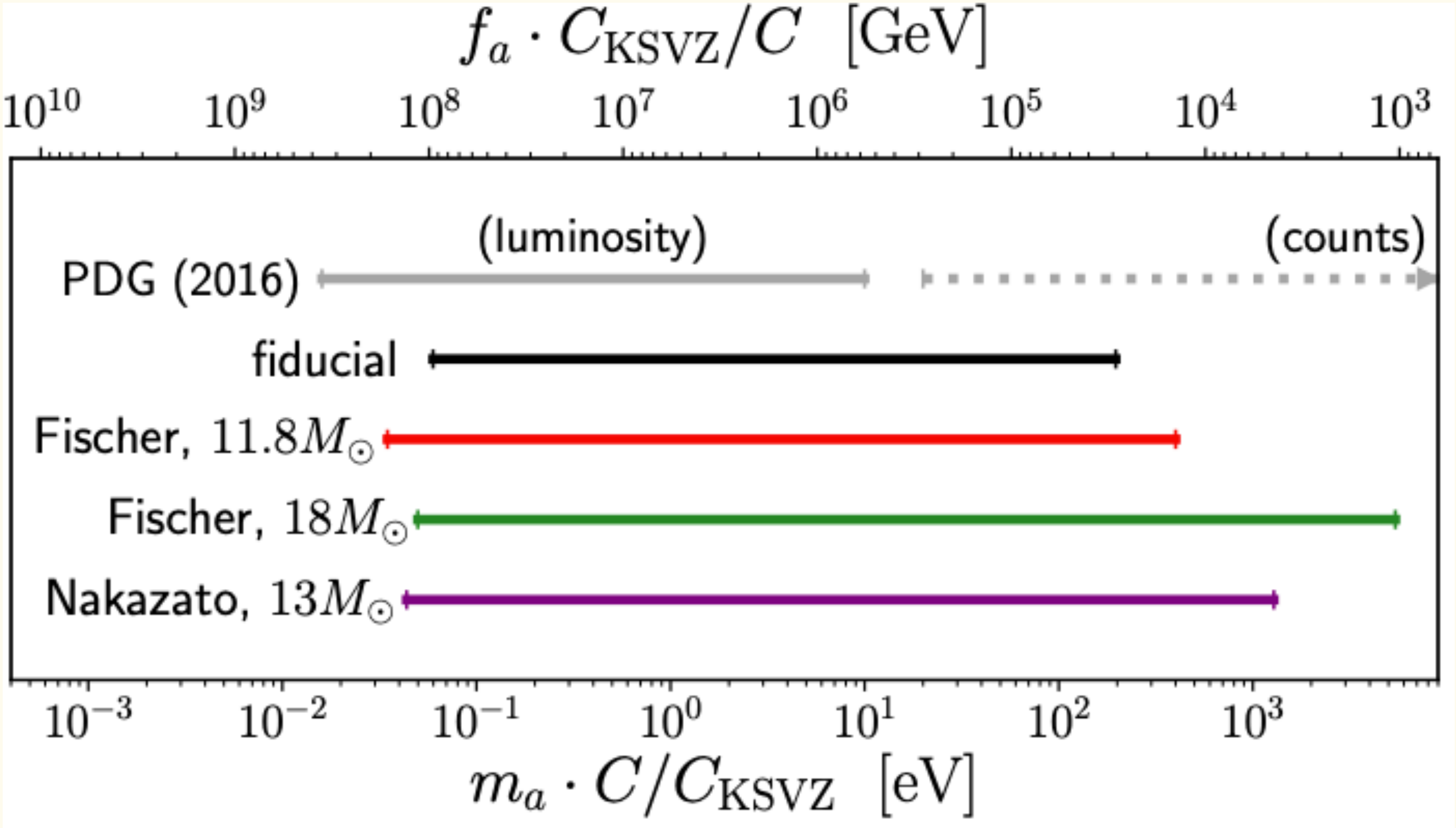
arXiv:1907.05020 (PRD 101, 123025)

IBS-ICTP Workshop on ALP, 21/10/2020

Outline

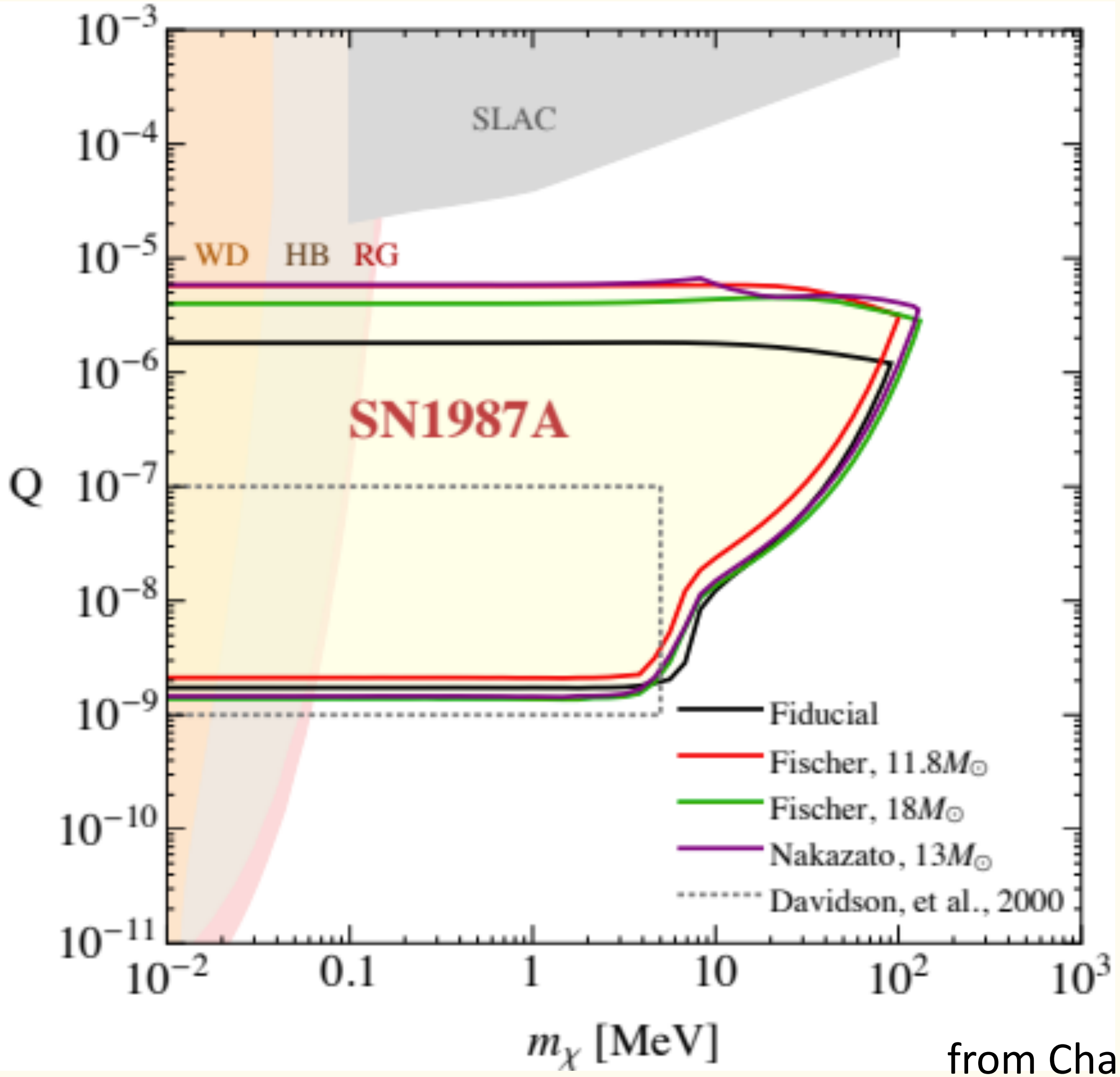
- Axion bounds from SN 1987A
- Origin of the bounds and assumptions
- Where do the late-time neutrinos come from?
- Alternative collapse scenario will invalidate axion bounds

SN bounds on QCD axion



from Chang, Essig, McDermott 1803.00993
(JHEP 1809 051)

SN bounds on millicharge



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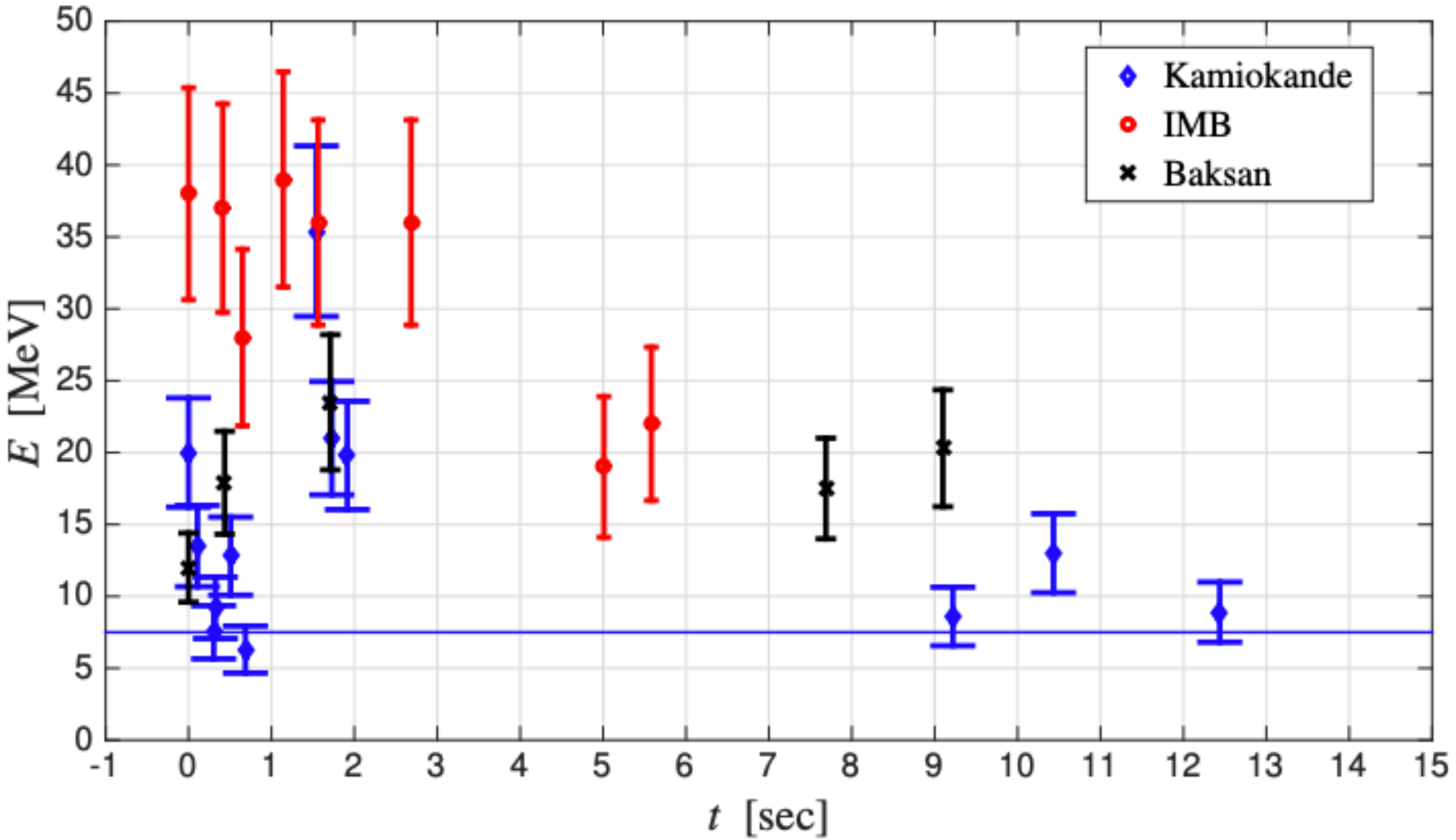
Neutrinos from SN1987A



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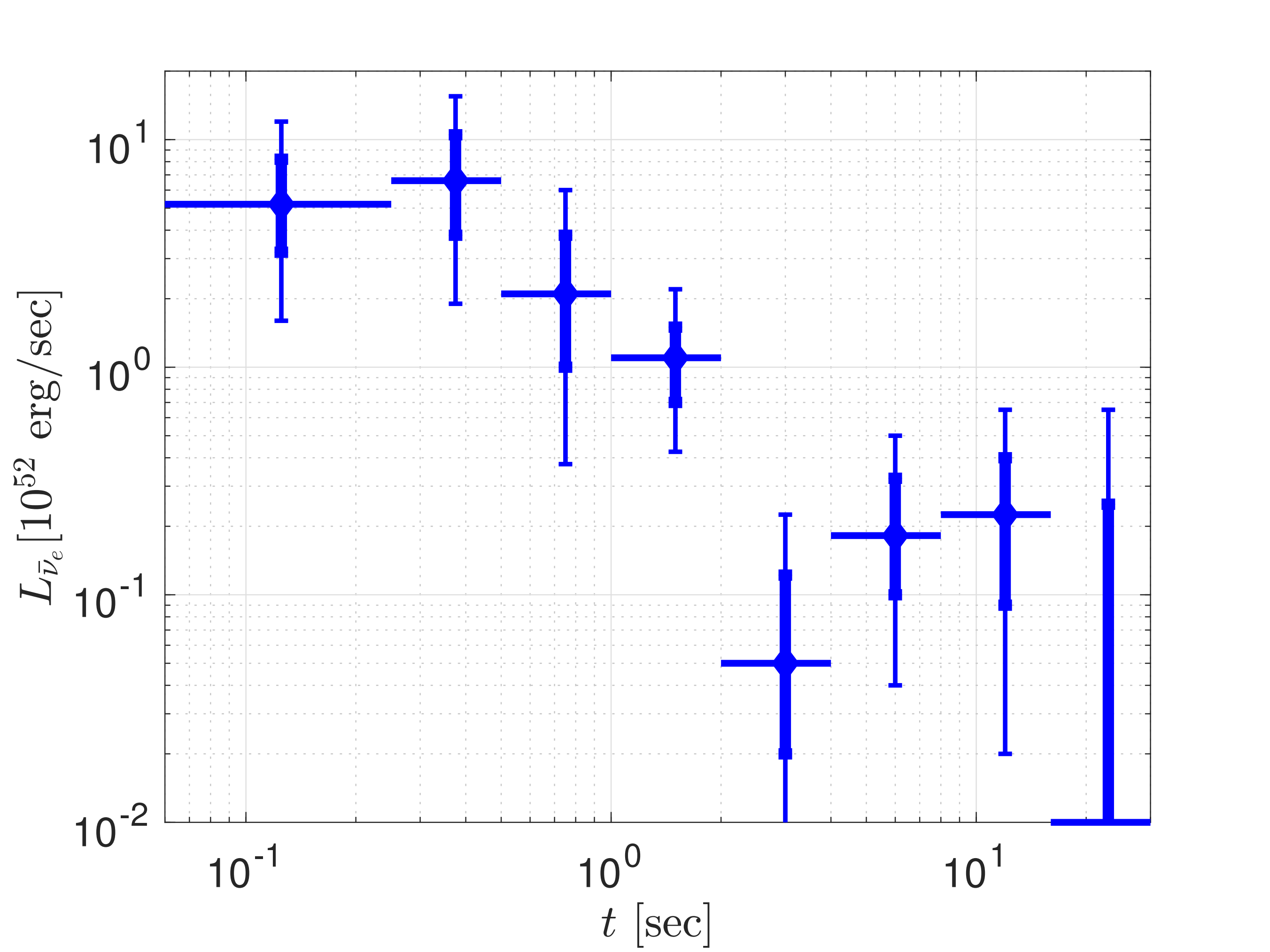


Where do the bounds come from?

- Need to explain neutrino signal

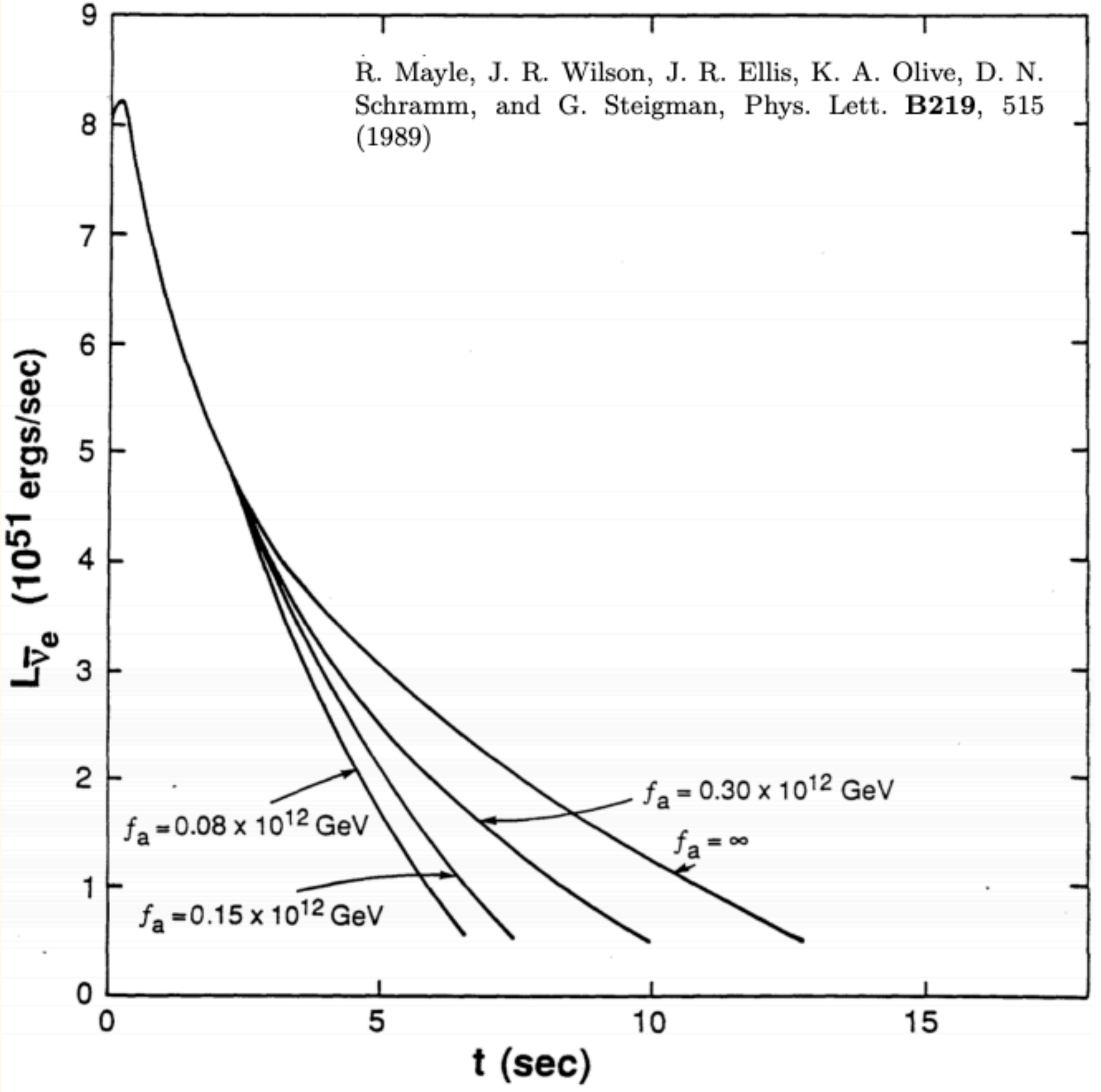
- Raffelt criterion: if there are weakly interacting light particles, they affect the neutrino cooling.
  Roughly, we require that $L_X \leq L_\nu$, but only in the 'cooling tail' of the signal

- As $L_\nu \sim 3 \cdot 10^{52} \mathrm{erg/s}$, and core mass $\sim 1 M_\odot$, the bound is
  $\varepsilon_X < 10^{19} \frac{\mathrm{erg}}{\mathrm{s\,g}}$
  (for $\rho \sim 3 \cdot 10^{14} \mathrm{g/cm^3}$ and $\mathrm{T} \sim 30\ \mathrm{MeV}$)

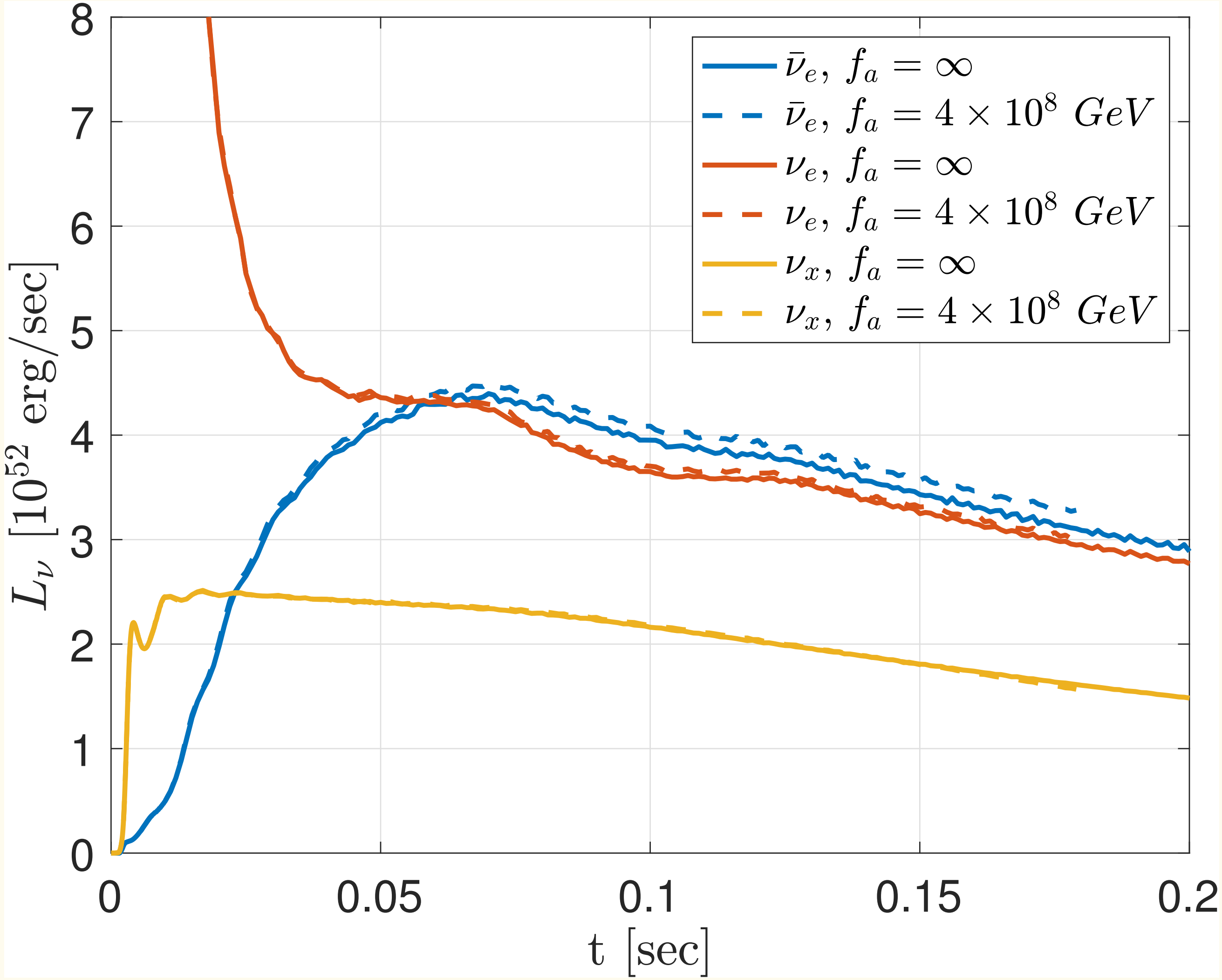
Why the cooling tail?

- Result based on early simulations:
  Mayle et al. (1989), Burrows et al. (1989)

- Early ($t < 3s$) neutrinos not sensitive to axions



Axions don't affect early burst



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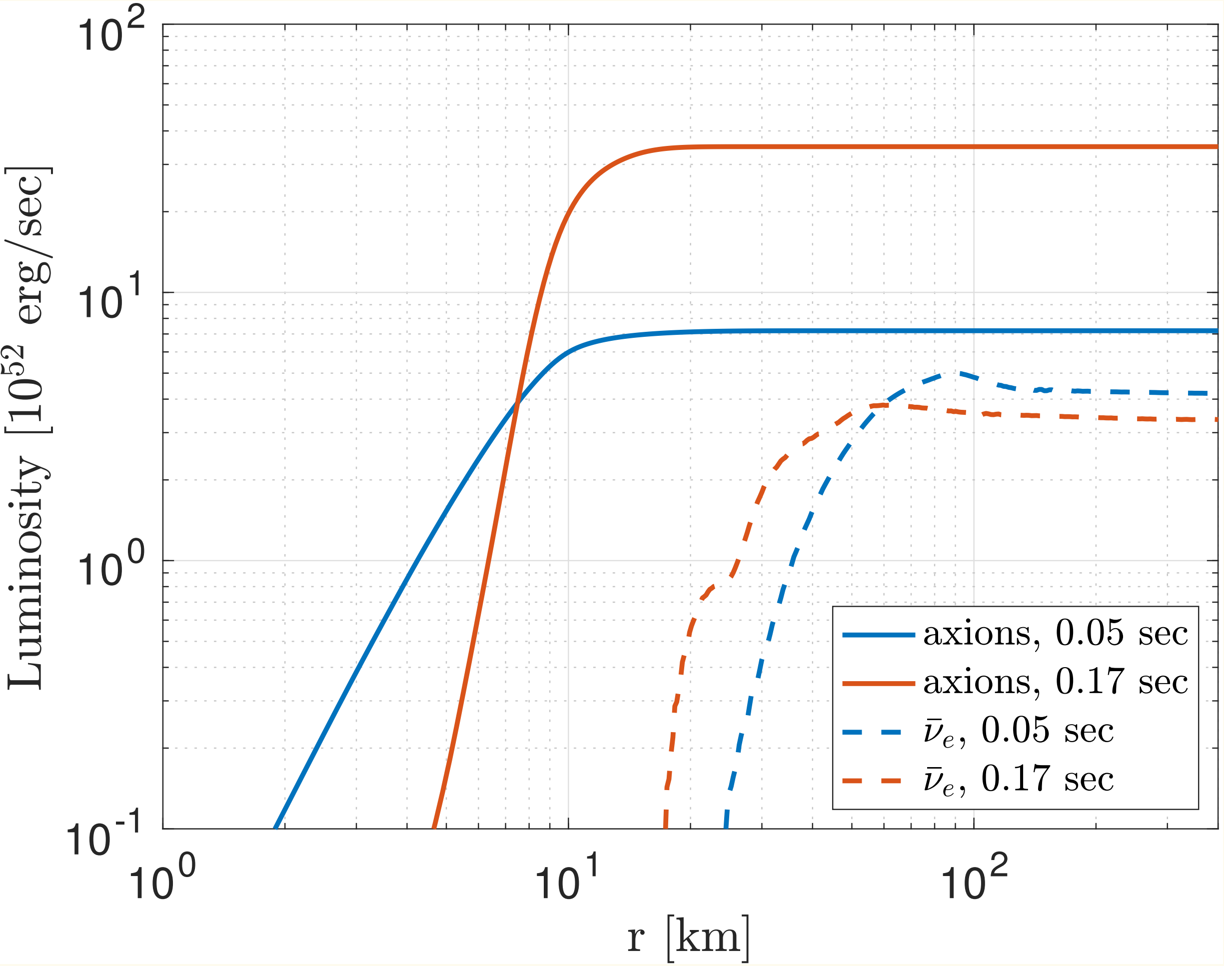
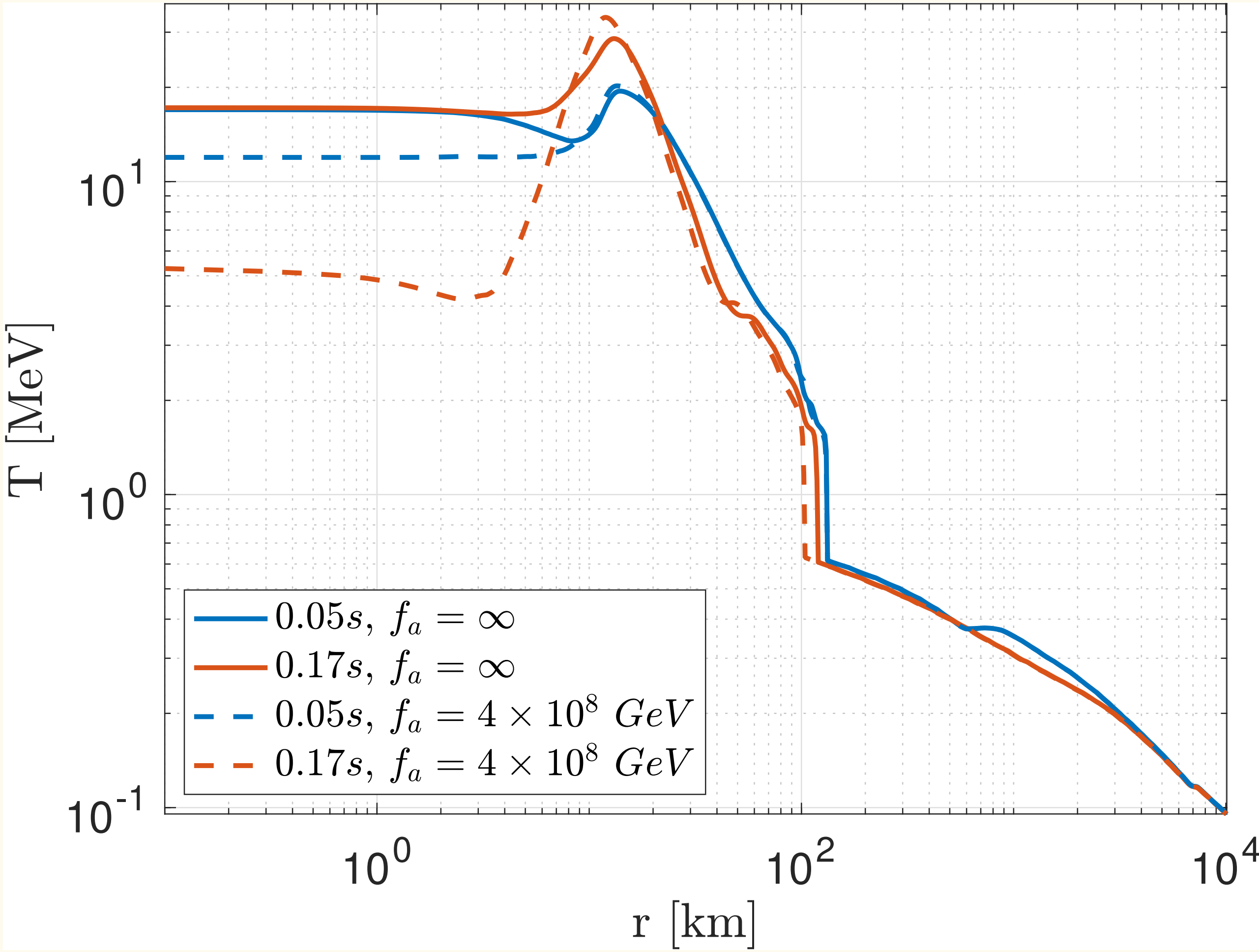
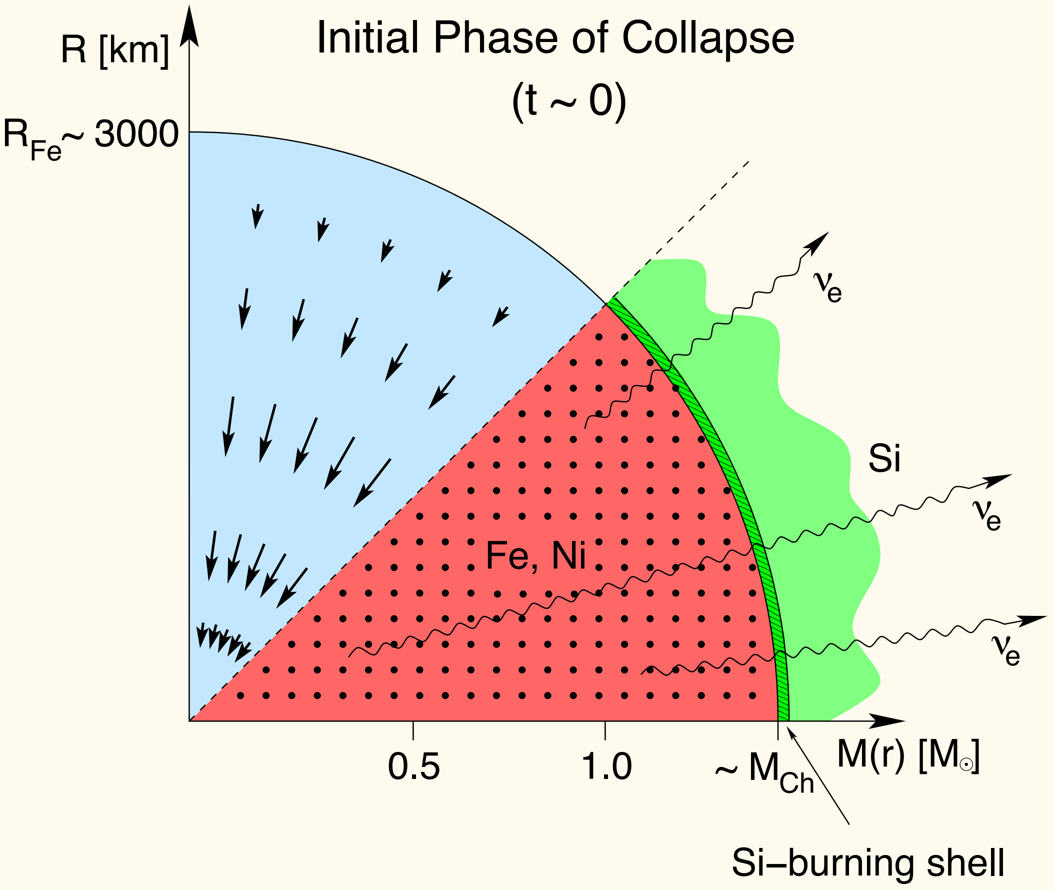
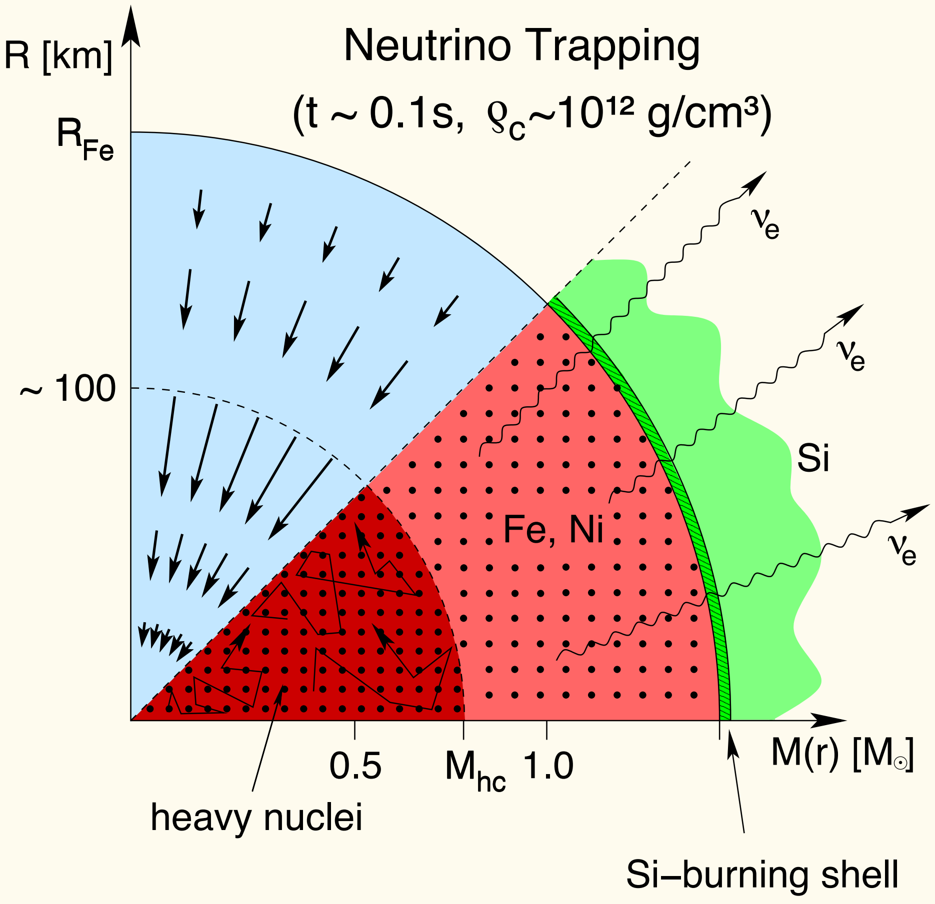




How does a SN explode?





Janka et al. 2007

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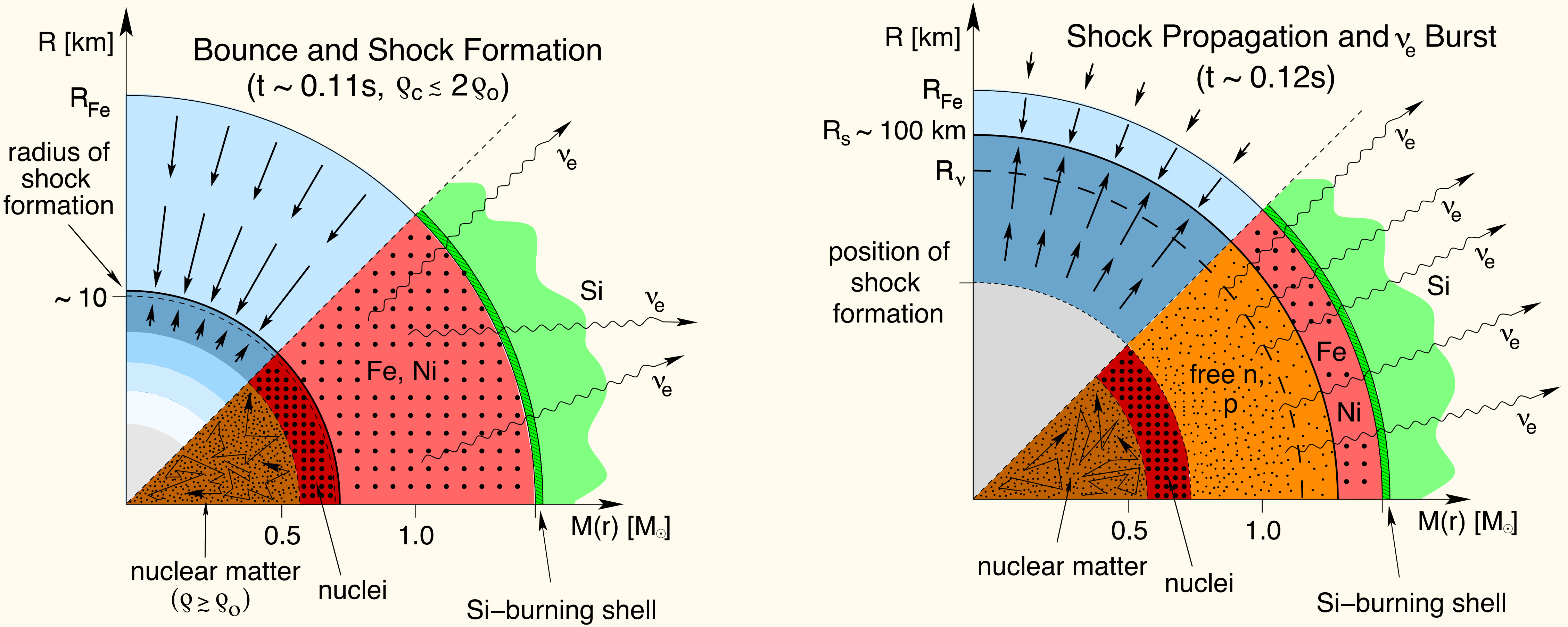

Janka et al. 2007

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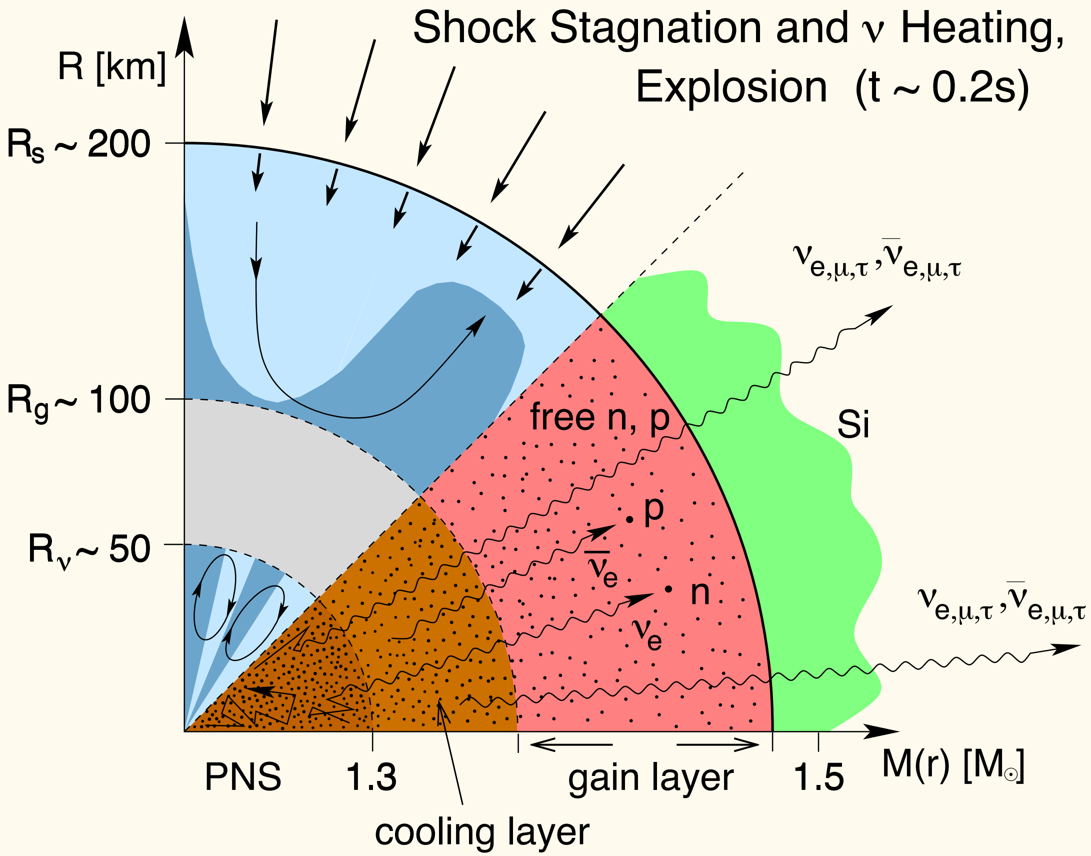
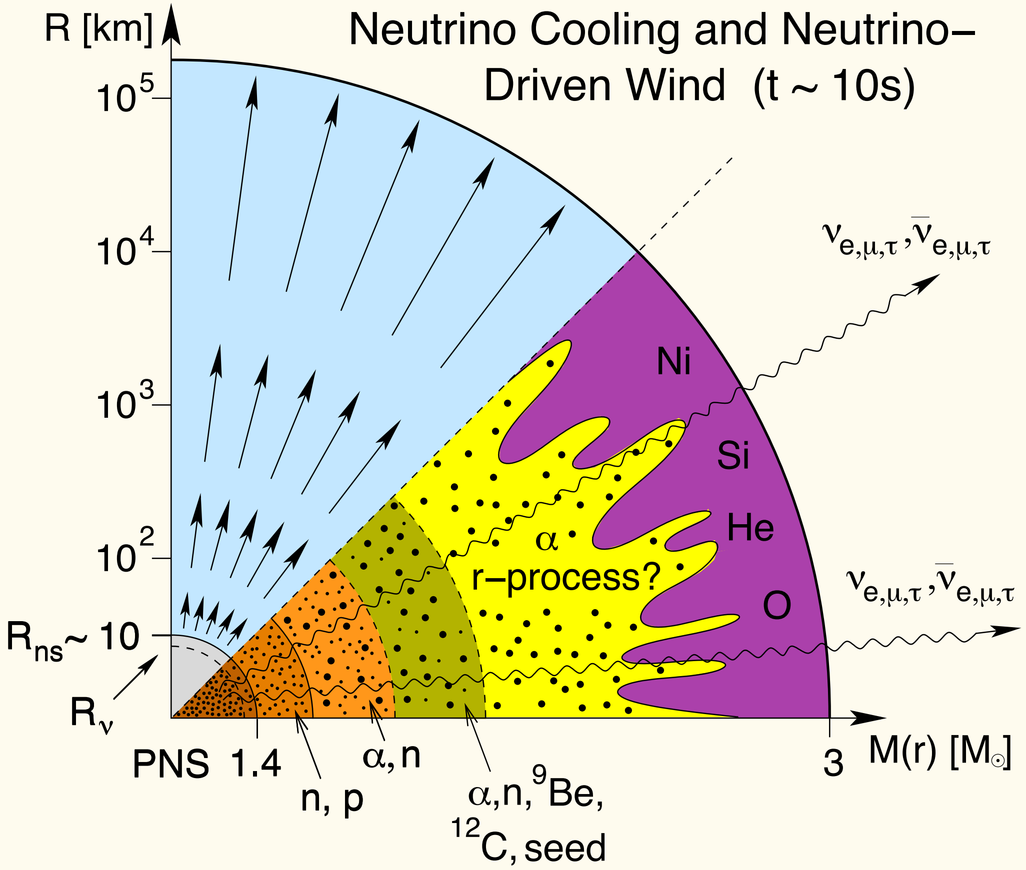
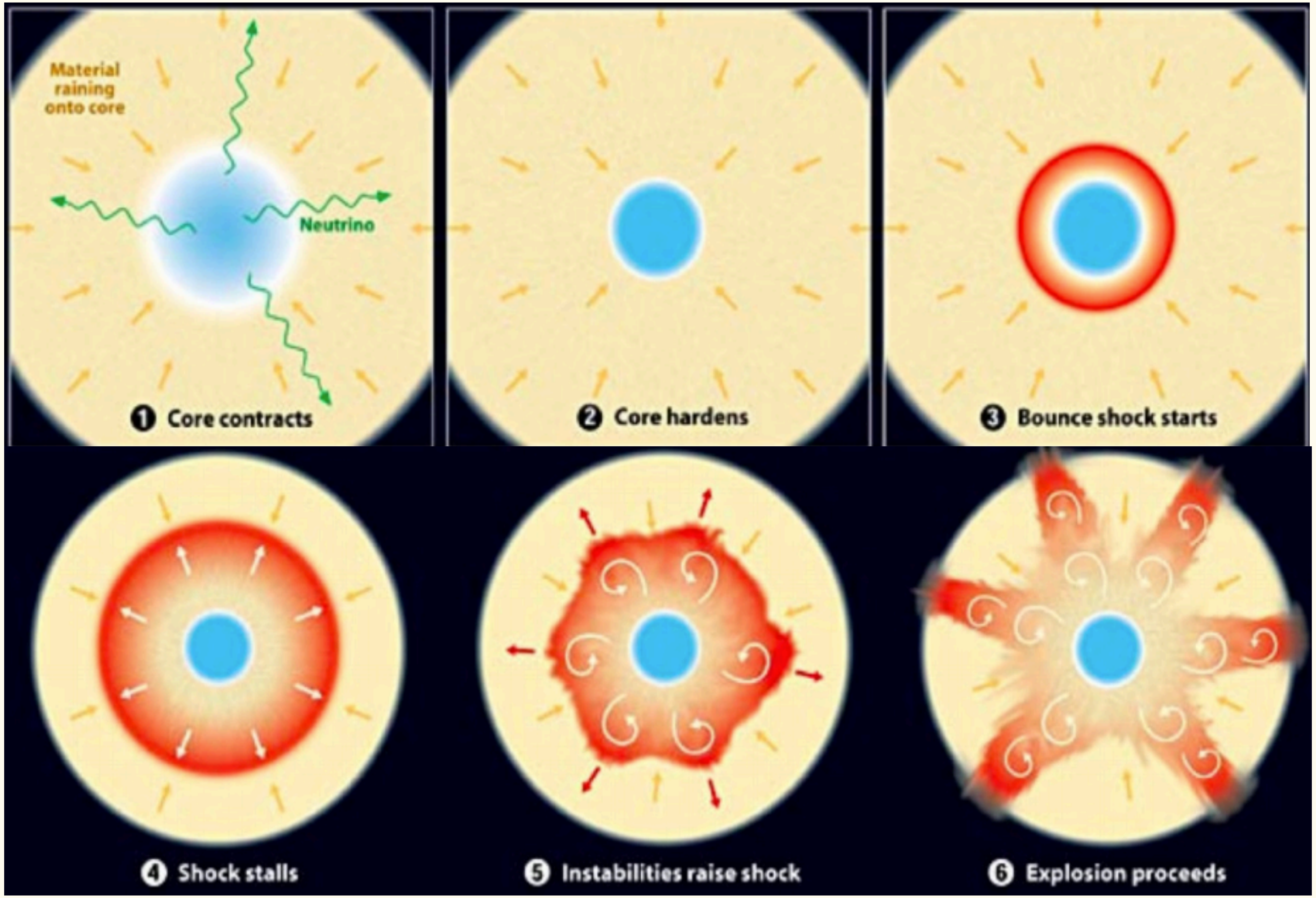




Janka et al. 2007

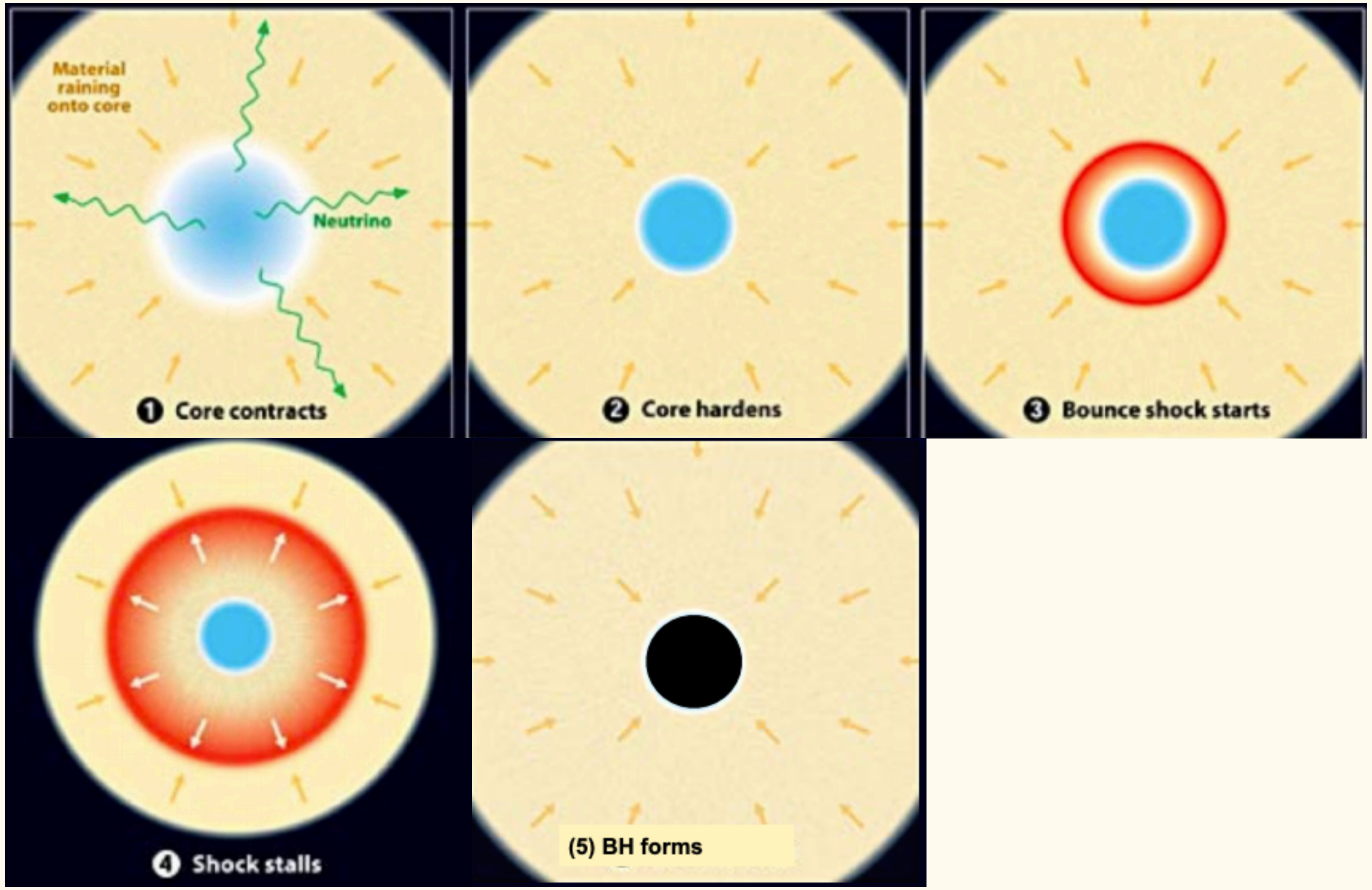
Delayed neutrino mechanism (DνM)



Bethe, Wilson
APJ 295, 14 (1985)

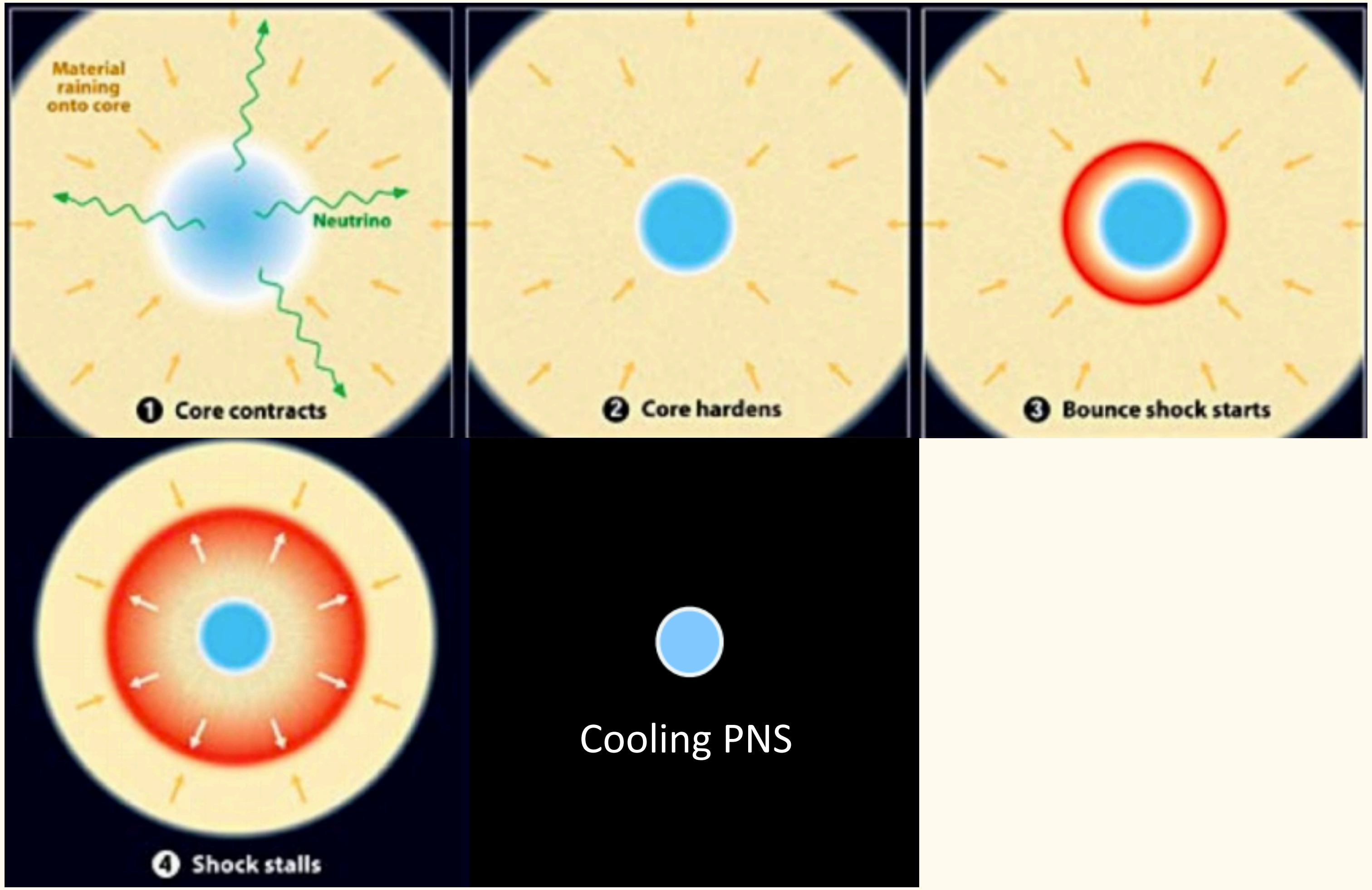
By S. Simpson

What happens in simulations?



No DνM simulation convincingly explodes (yet) with the energetics of SN1987A!

What are the results based on?



Courtesy of K. Blum

So what?

- Axion bounds come from observation of late time neutrino events, as the early burst is unaffected

- But they are based on simulations of… a bare cooling proto-neutron star, which is the only source of neutrinos

- If SN1987 happened like this, bounds are valid

- However, a NS is not (yet?) seen in the remnant
  There is not (yet?) proof of the delayed neutrino mechanism

An alternative scenario

- Suppose simulations are true: shock is stalled and not revived, a BH is formed in 1-3 sec

- Neutrino emission is now quenched, which is consistent with the gap in arrival times

- And then? If the star was rotating, we expect the formation of an accretion disk

$$R_{\rm disk} \simeq \frac{j^2}{2GM} \simeq 50 \left(\frac{j}{5\times 10^{16}{\rm cm}^2/{\rm s}}\right)\left(\frac{2M_\odot}{M}\right) {\rm km}$$

$$t_{\rm disk} \simeq \pi\sqrt{\frac{r_0^3}{2GM}} \simeq 4 \left(\frac{r_0}{10^9 {\rm cm}}\right)^{3/2}\left(\frac{2M_\odot}{M}\right)^{1/2} {\rm s}$$

Neutrinos from the disk

$$L_{\bar\nu_e} \simeq \frac{GM_{\rm rem}\dot M}{2R_{\rm disk}} \simeq 2.6\times 10^{51}\left(\frac{M_{\rm rem}}{2M_\odot}\right)\left(\frac{\dot M}{0.05M_\odot/{\rm s}}\right)\left(\frac{50{\rm km}}{R_{\rm disk}}\right){\rm erg/s}$$

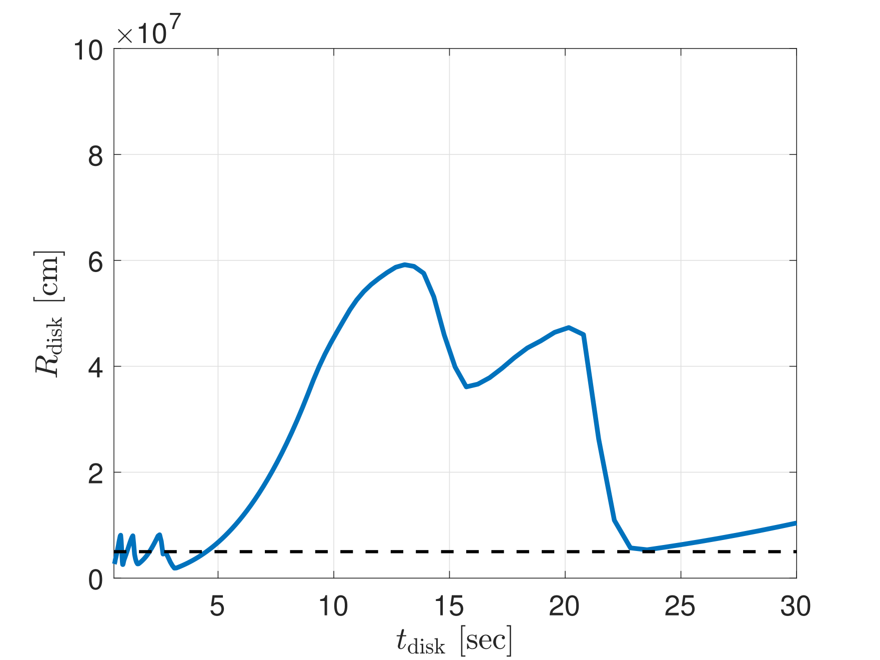
Accretion luminosity consistent with late events, for t > 5s

$$\frac{\epsilon_{\bar\nu_e}}{\epsilon_a} \simeq 3.4\times 10^{8}\left(\frac{X_n}{0.5}\right)\left(\frac{10^9{\rm g/cm^3}}{\rho}\right)\left(\frac{T}{2.5{\rm MeV}}\right)^{2.5}\left(\frac{f_a}{4\times 10^8{\rm GeV}}\right)^{2}$$

$$\ell_{\bar\nu_e} \simeq 3\times 10^{3}\left(\frac{10^9{\rm g/cm^3}}{\rho}\right)\left(\frac{10{\rm MeV}}{E_\nu}\right){\rm km}$$

10^3km disk
10^{-2}km PNS

Large neutrino emissivity, but more importantly, free-streaming in the disk



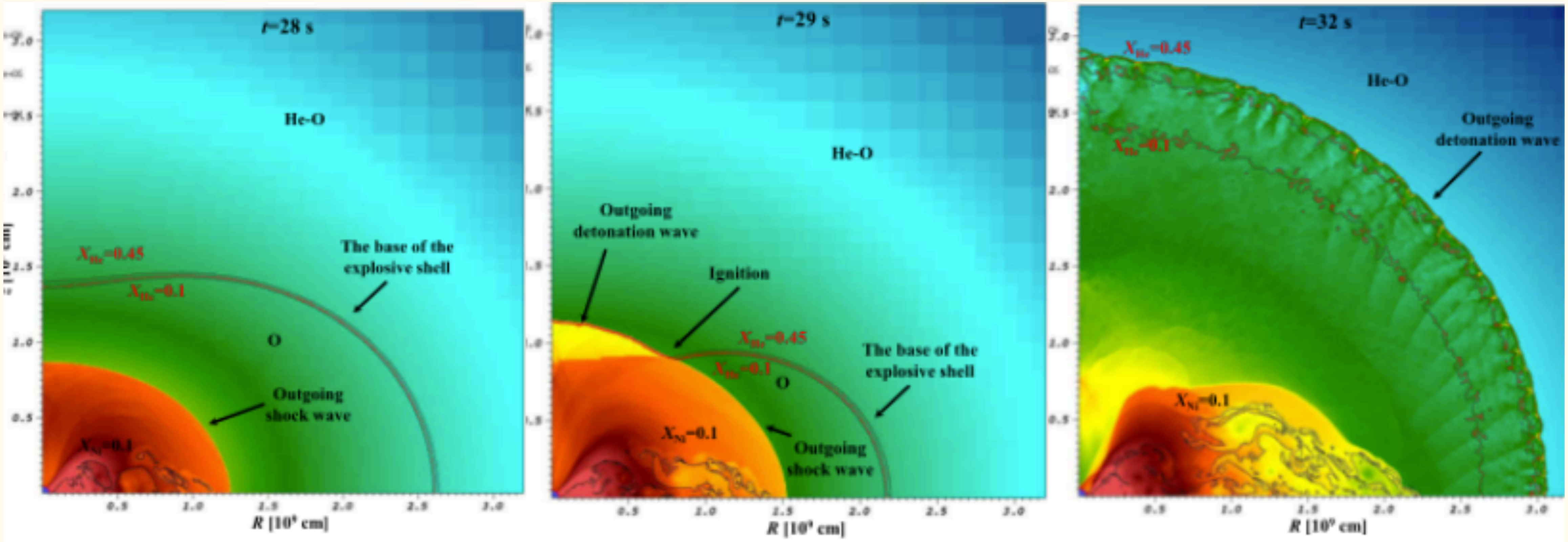
And the explosion?

- An alternative explanation: CITE (Collapse-induced thermonuclear explosion)

- CITE mechanism: infall is stopped $O(10^4\ \mathrm{km})$ from the center by an angular momentum barrier, and the shock ignites thermonuclear explosion in a He-O shell, which is what we see

Kushnir, Katz, 1412.1096 [ApJ 811, 97]
Kushnir, 1502.03111, 1506.02655
Blum, Kushnir, 1601.03422 [ApJ 828, 31]

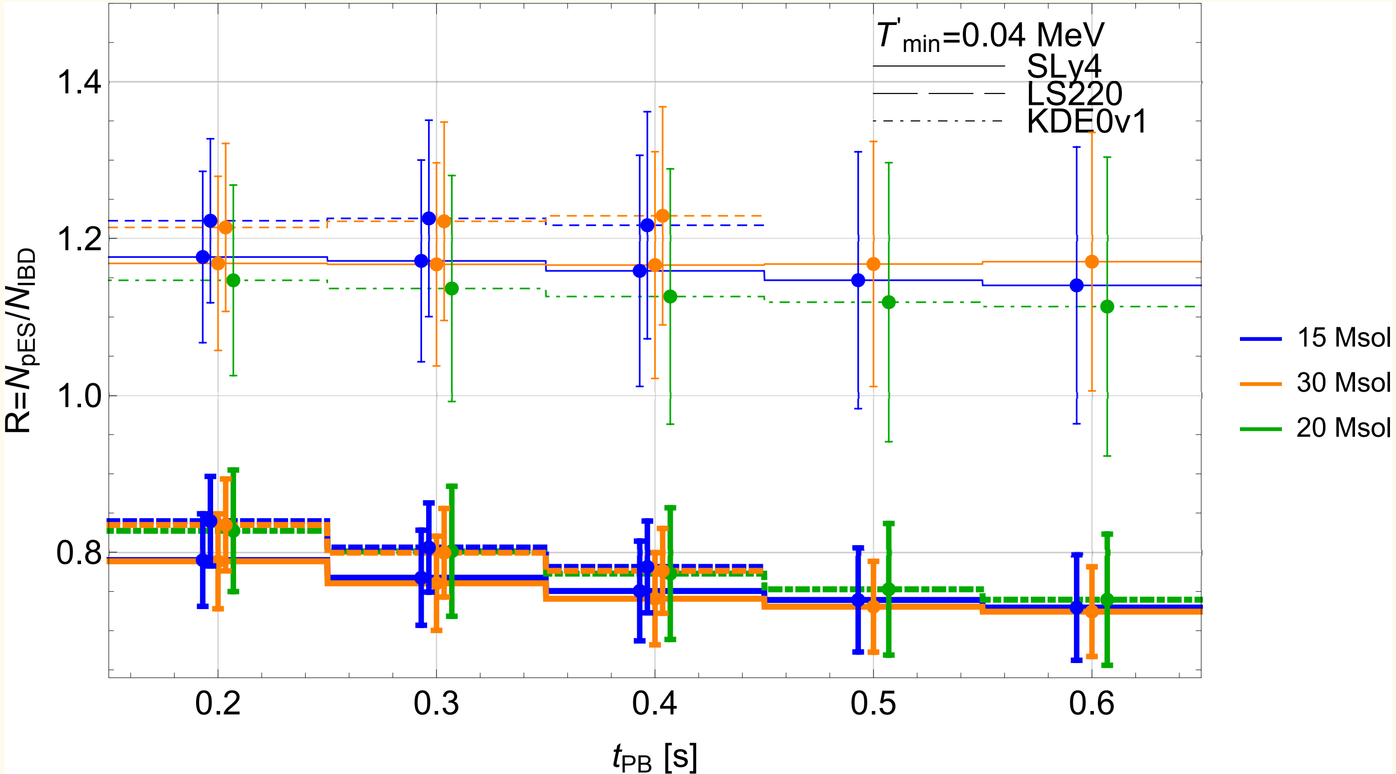
And the explosion?



Kushnir, 1502.03111

Neutrinos will be smoking gun

- The next galactic SN will give us an idea about the collapse mechanism, via neutrino flavor composition and time structure of the burst
  (Bar, Blum, GDA 1811.11178 PRD 99,123004)



Conclusions

- The explosion mechanism of CCSNe is still unknown
- But neutrinos from SN 1987A are used to put constraints on new physics
- DνM has not been shown to work numerically: simulations don't explode and only consider bare PNS
- If DνM fails, BH formation, and disk accretion: data compatible with this! So, no axion bounds…

Outlook

- Very important to establish standard physics to put constraints on new physics
- If DνM simulations convincingly explode and rule out residual accretion, axion bounds stand
- If CITE scenario is shown to work, then axion bounds will not apply
- Eventually, we'll know from neutrino observations of the next galactic supernova!

Thank you!