Core Collapse Supernovae and EOS thermal effects

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Evan O'Connor
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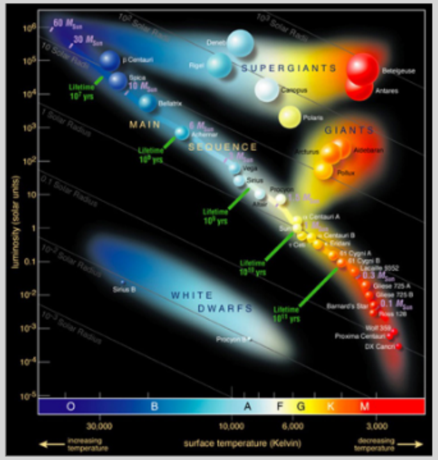
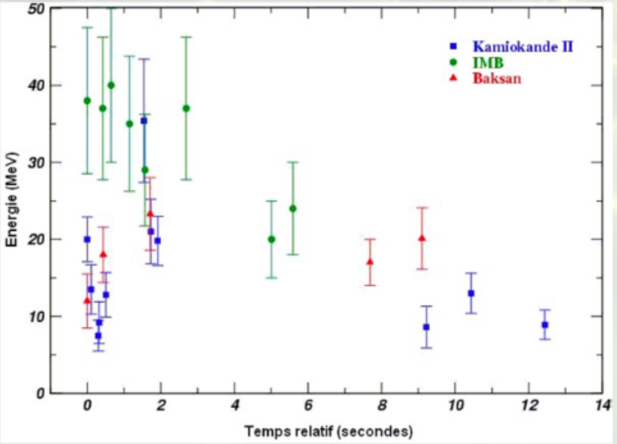
Supernovae have a broad connection to the Universe

Stellar Evolution

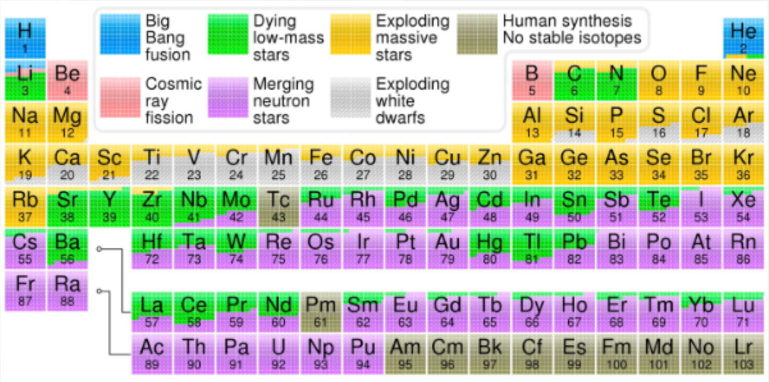


ESO

Neutrinos & Gravitational Waves

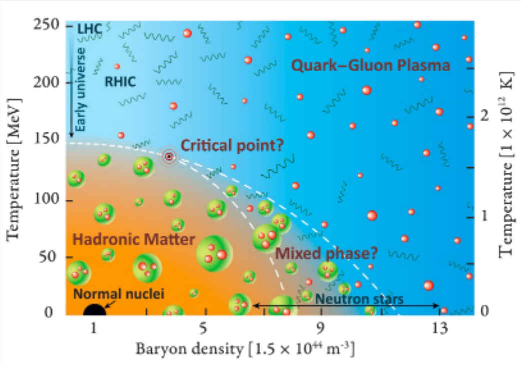


Nucleosynthesis



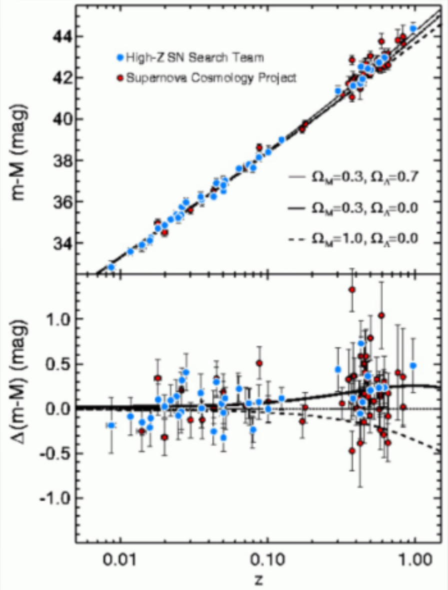
Wikimedia/Jennifer Johnson

Extreme Physics



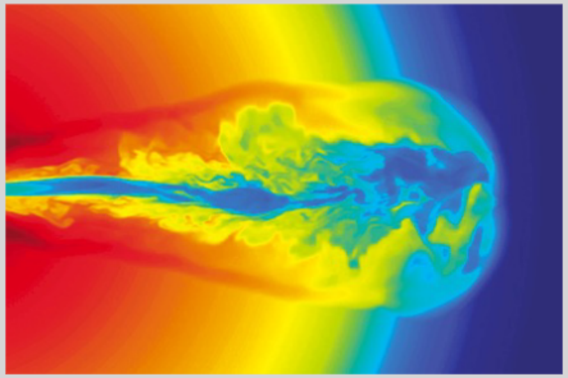
Contemporary Physics Education Project (CPEP)

Cosmology



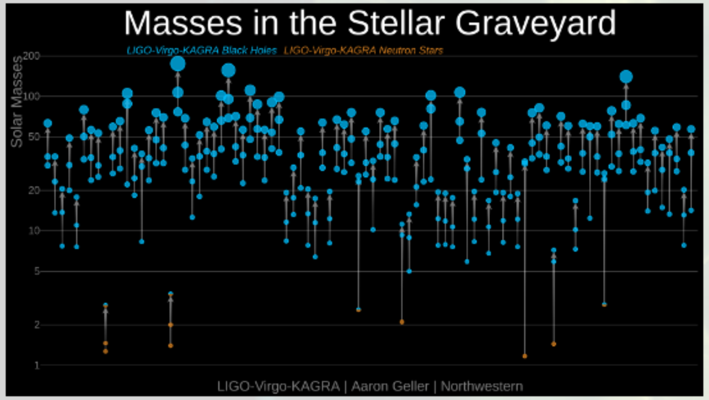
High-Z & SCP

Long gamma-ray burst



Science/MacFadyen

Neutron Stars & Black Holes



LIGO/VIRGO

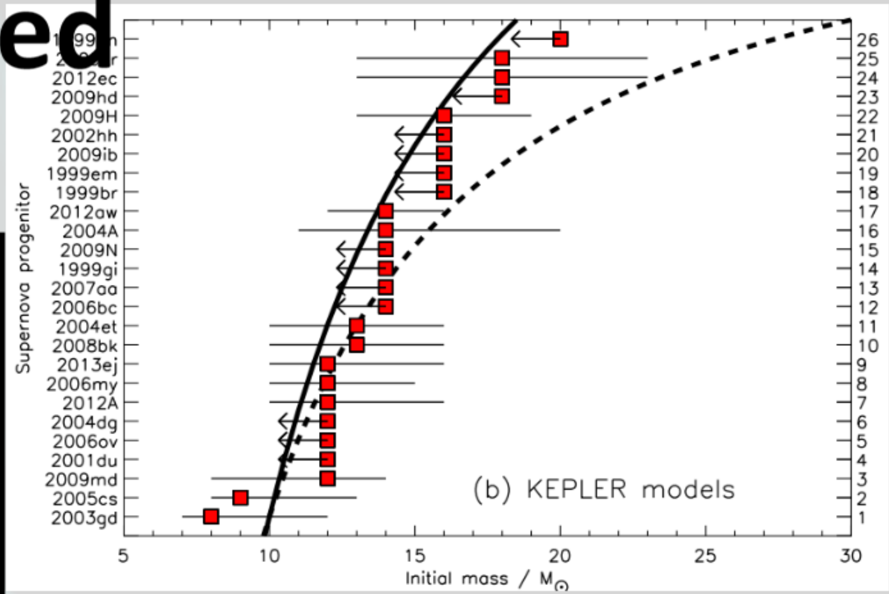
Galaxy Evolution

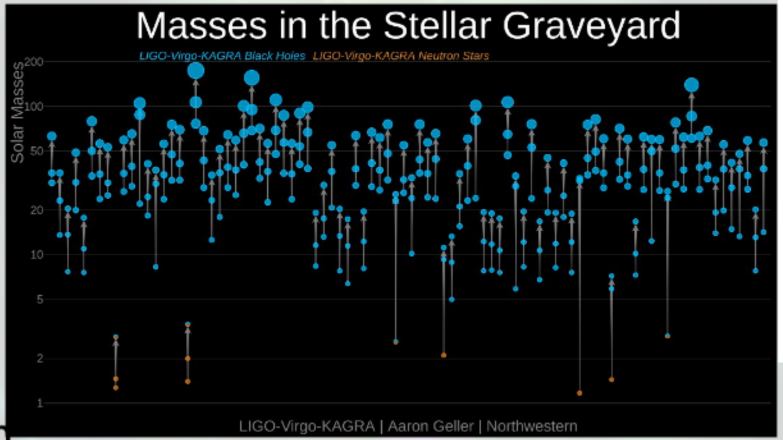
Hubble

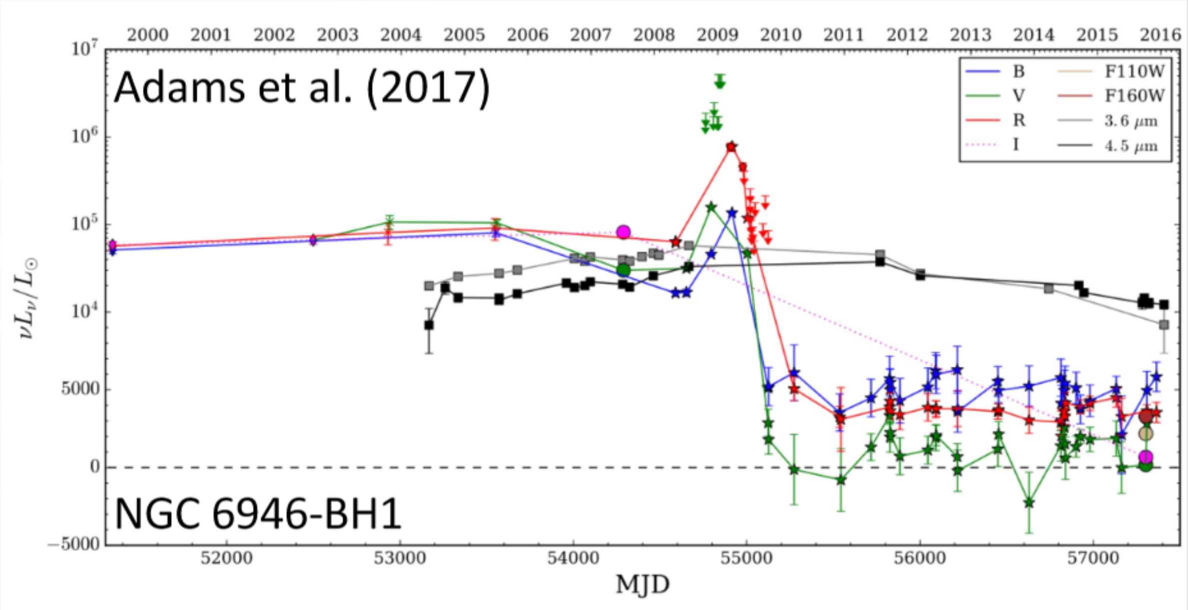
Not all core collapses will succeed

- Progenitors of Type II-P CCSNe suggest a maximum mass of ~16.5 +/- 1.5 M_{sun} – but RSG extend to 25 M_{sun} (Smartt 2015)
- Black holes exist! We see stellar mass black holes in binaries with stars and with other black holes
- We have seen preliminary evidence that massive stars disappear, perhaps following a failed supernovae

Smartt et al.

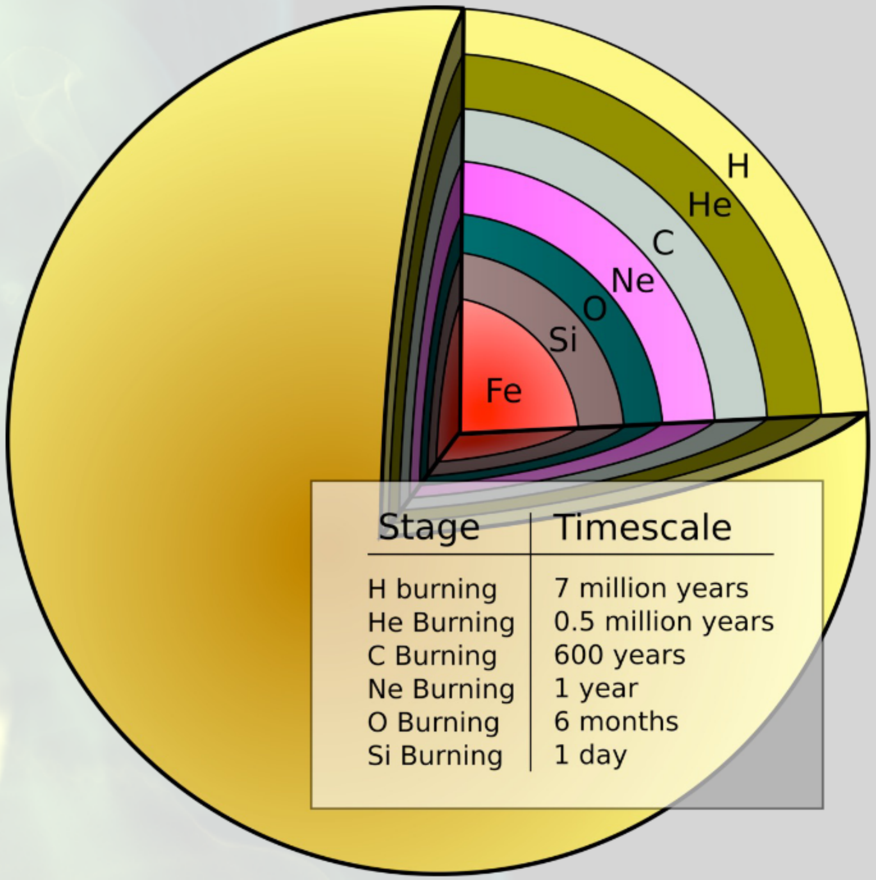






Stellar Collapse: Building the Core

- Stars spend most of their lives burning hydrogen.
- The product – Helium – settles in the core and will burn when temperatures increase sufficiently.
- For massive stars ($M > 8\text{-}10M_{sun}$), the process continues through Carbon, Oxygen, … , up to Iron.
- This process does not continue past iron as iron is one of the most tightly bound nuclei.
- Iron core builds up in center of star.



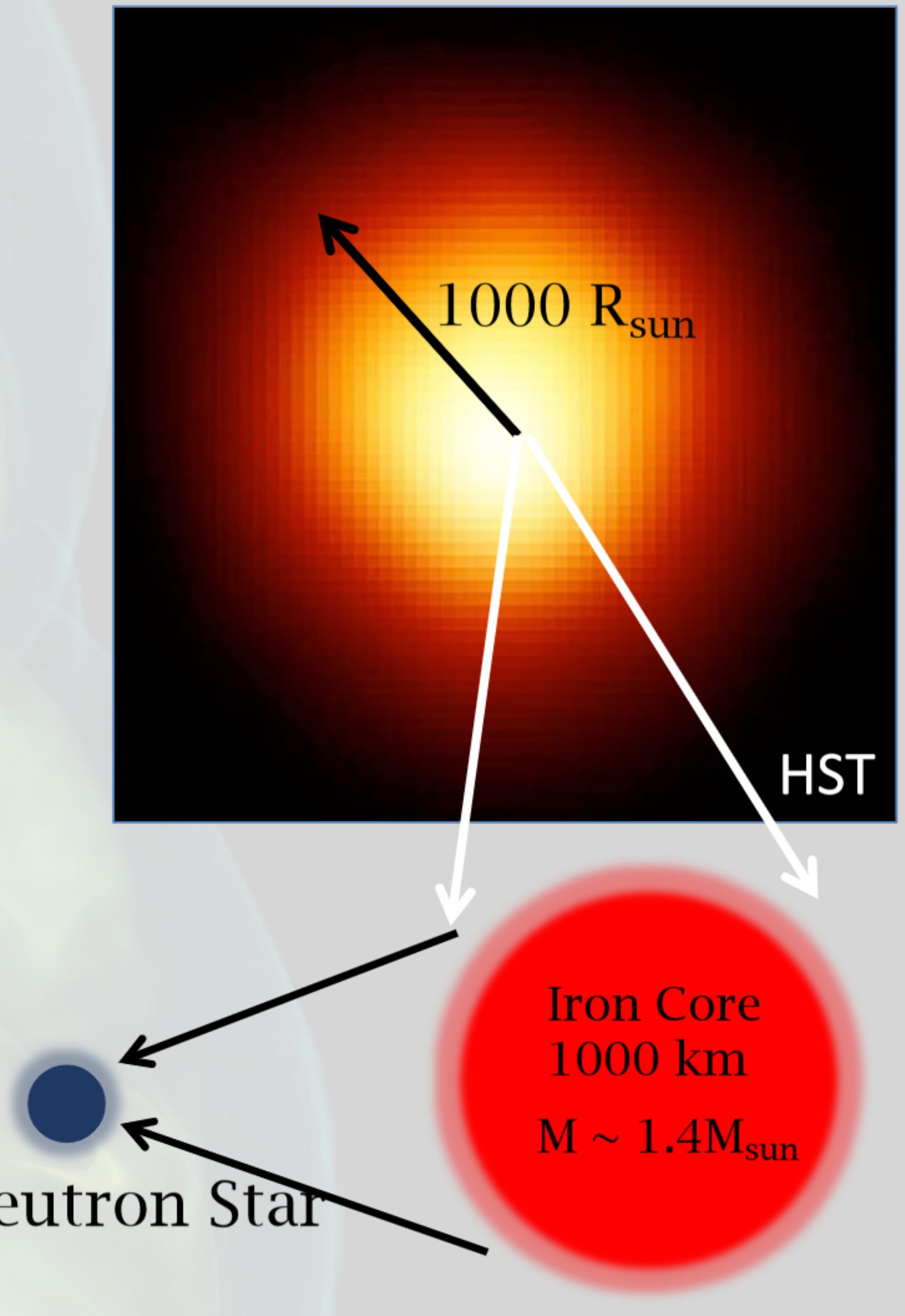
Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day

A. C. Phillips, *The Physics of Stars*, 2nd Edition (Wiley, 1999).

Collapse Phase

- Most massive stars core collapse during the red supergiant phase
- CCSNe are triggered by the collapse of the iron core (~1000km, or 1/10^6 of the star's radius)
- Collapse ensues because electron degeneracy pressure can no longer support the core against gravity

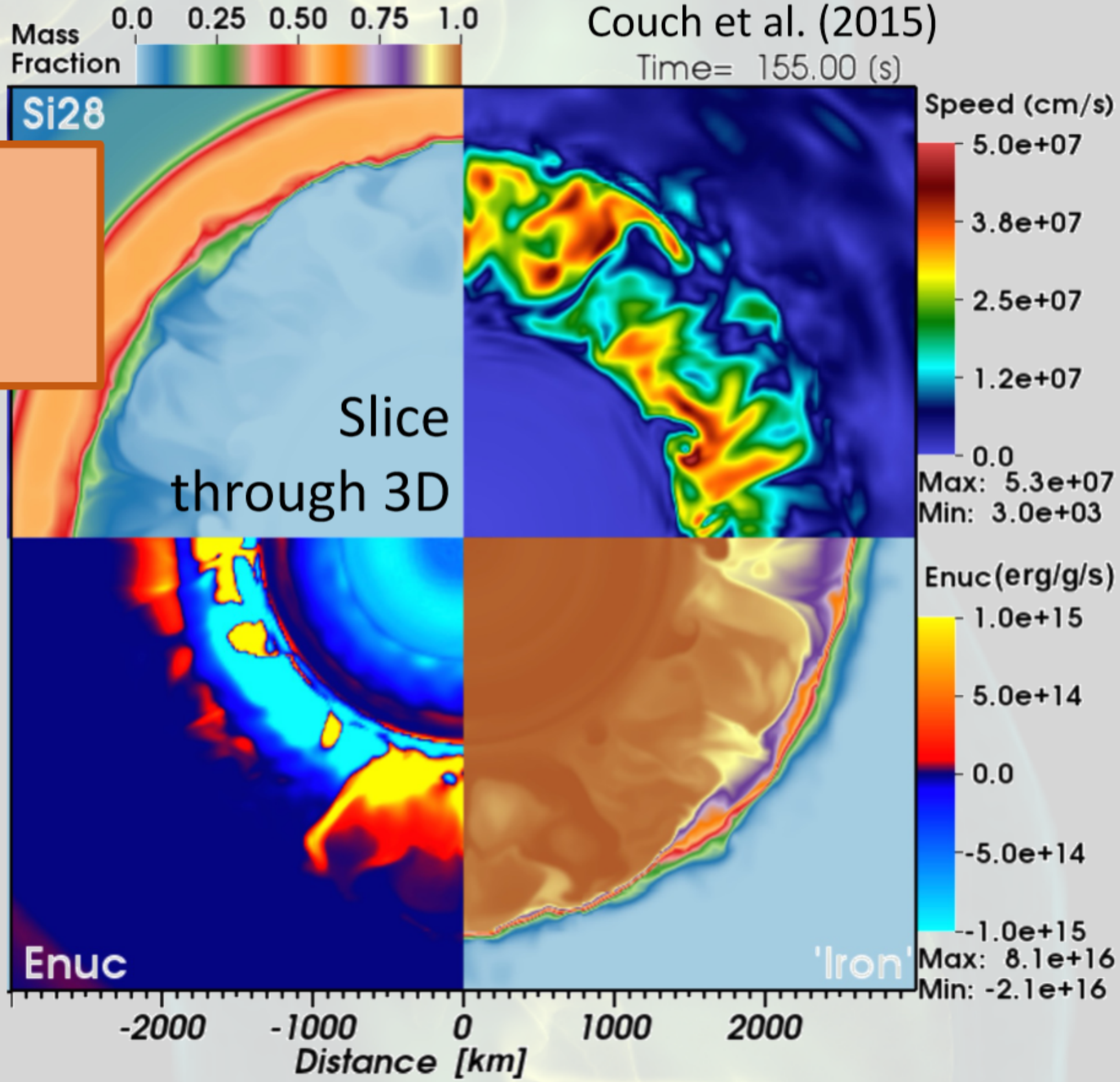
$$-\frac{3}{5}\left[\frac{GM^2}{1000\text{km}} - \frac{GM^2}{12\text{km}}\right] \sim 300 \times 10^{51}\text{ergs}$$



Not a prestine onion...

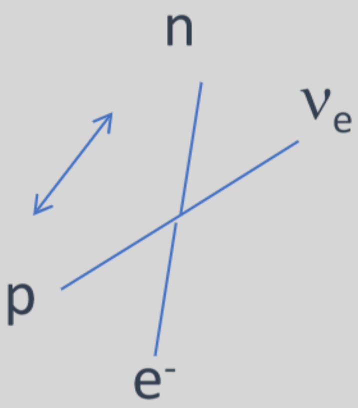
Final burning stages are violent, *not* spherically symmetric.

Couch et al. (2015)



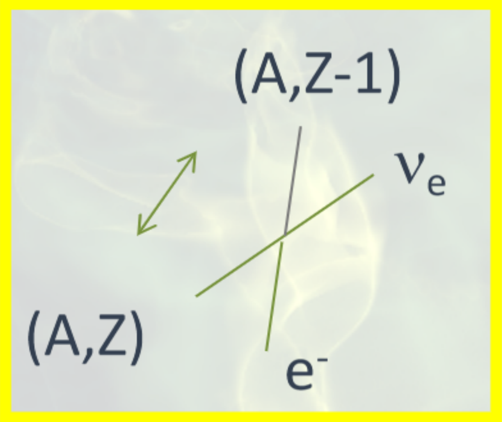
Collapse Phase: Role of Neutrinos

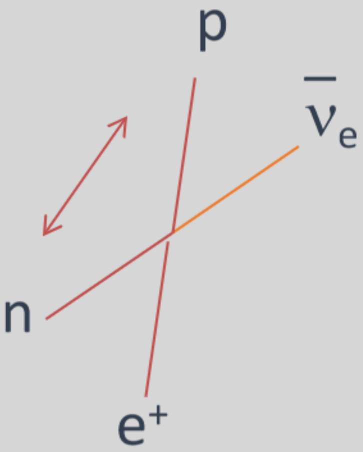
- Emission of neutrinos deleptonizes the core and accelerates collapse
- The emission ultimately sets the final Ye of the core



Electron capture on free protons. Cross section is very high, but suppressed because number of free protons is low

- Heavy-lepton neutrino production is highly suppressed because temperature is so low





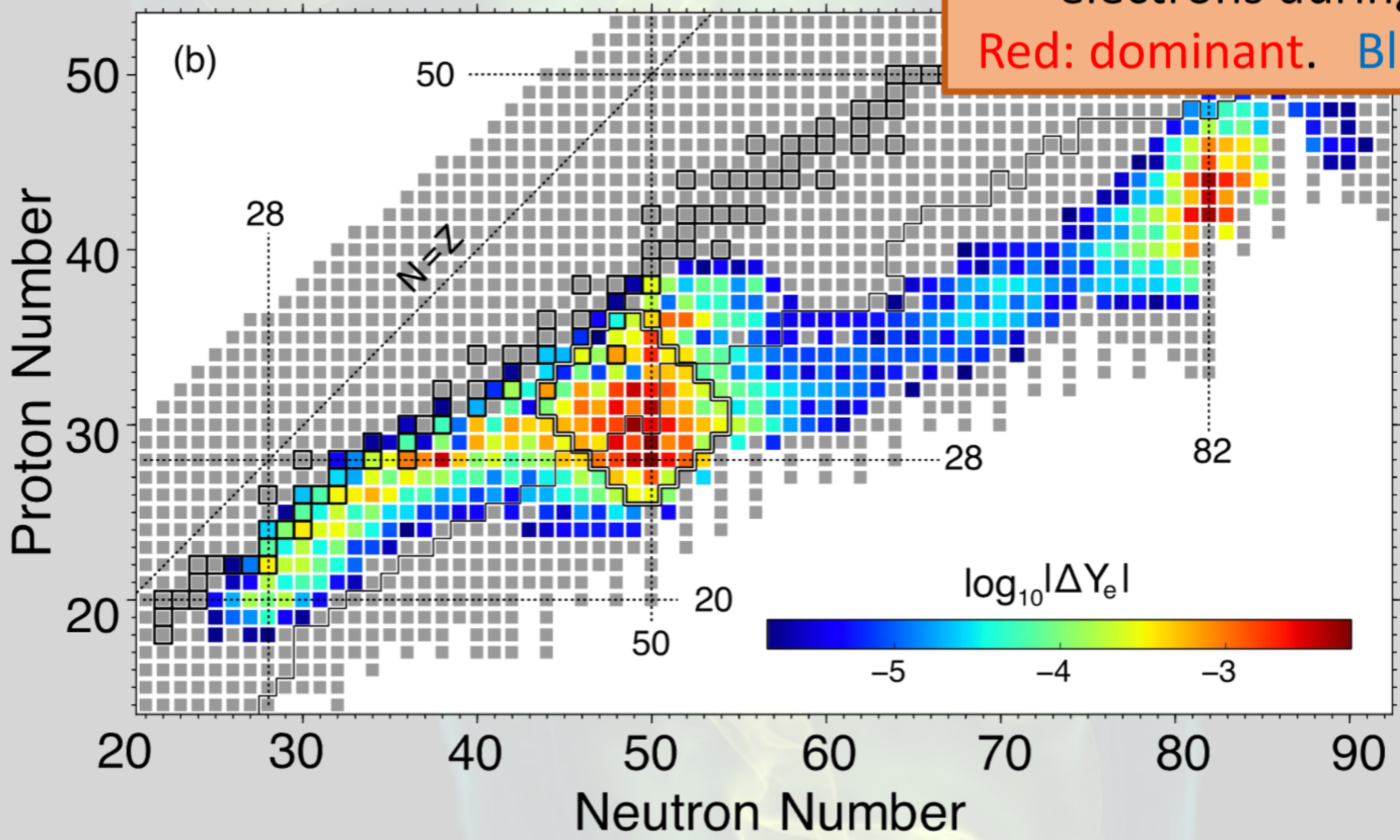
Positron capture on free neutrons. Suppressed because positron density is very low due to high electron chemical potential

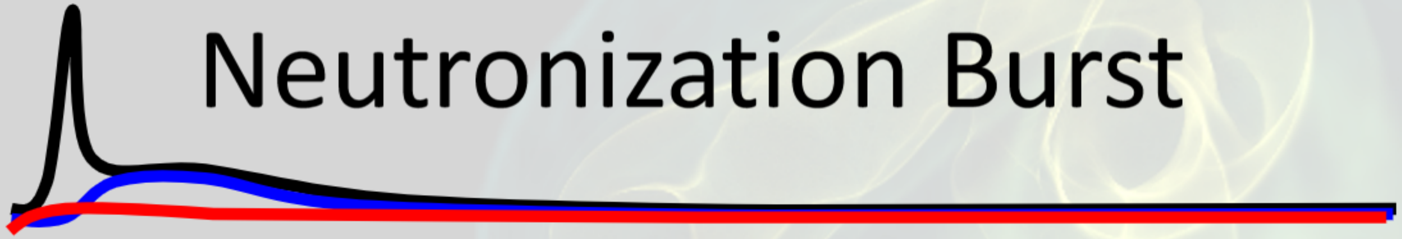
Electron capture on heavy nuclei. Abundance is very high, cross section is somewhat suppressed because of energetic cost of converting proton to neutron in a nucleus.

Electron Captures during Collapse

Sullivan et al. (2016), Titus et al. (2018)

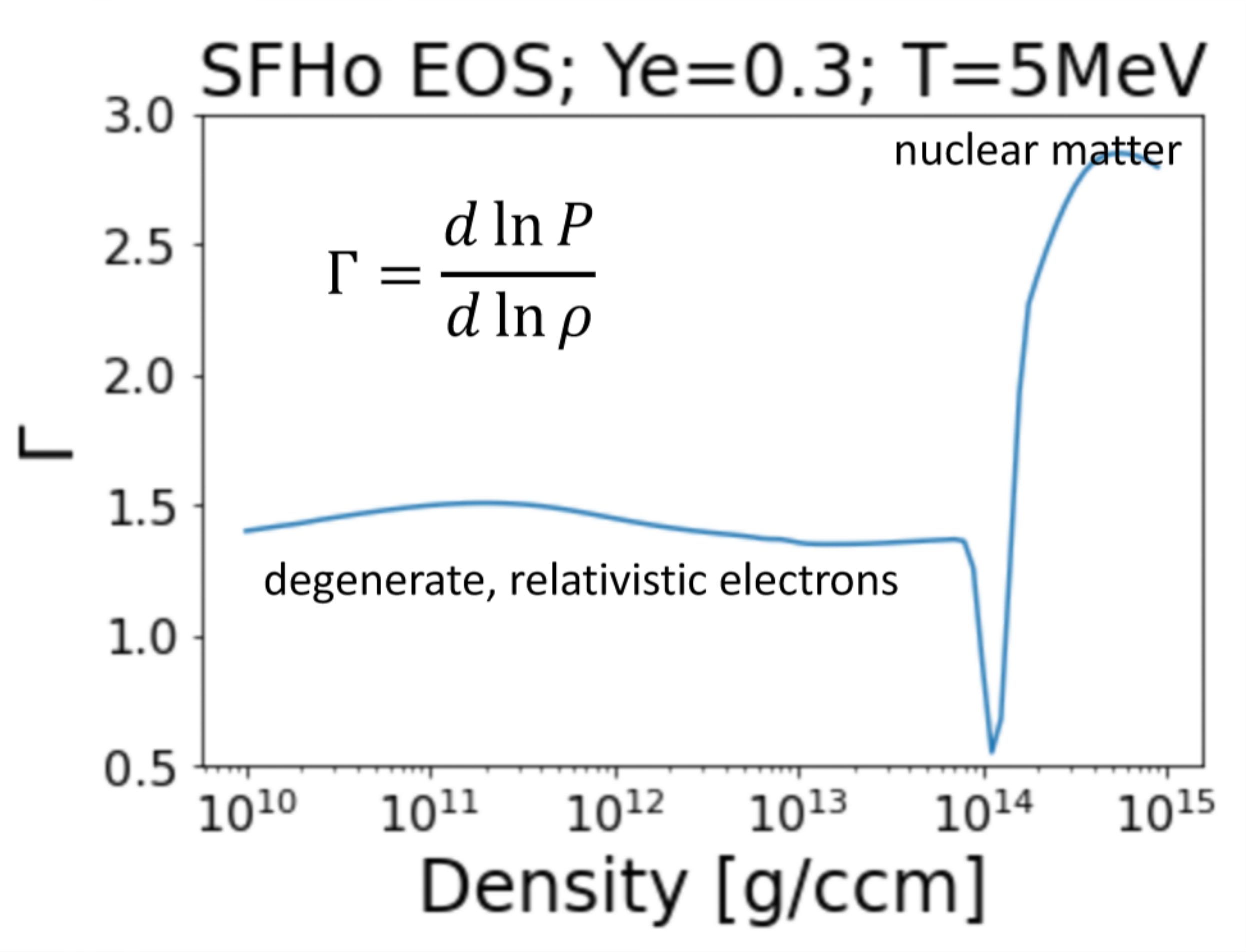
Color: contribution to capturing electrons during collapse
Red: dominant. Blue: negligible



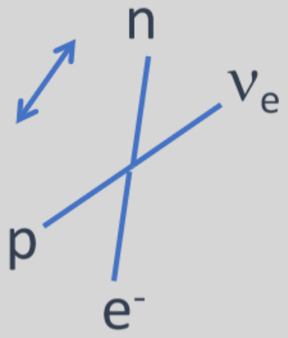


Neutronization Burst

- When the matter reaches nuclear density the “stiffening” of the EOS halts the collapse
- The core elastically rebounds and drives a shock into the infalling matter



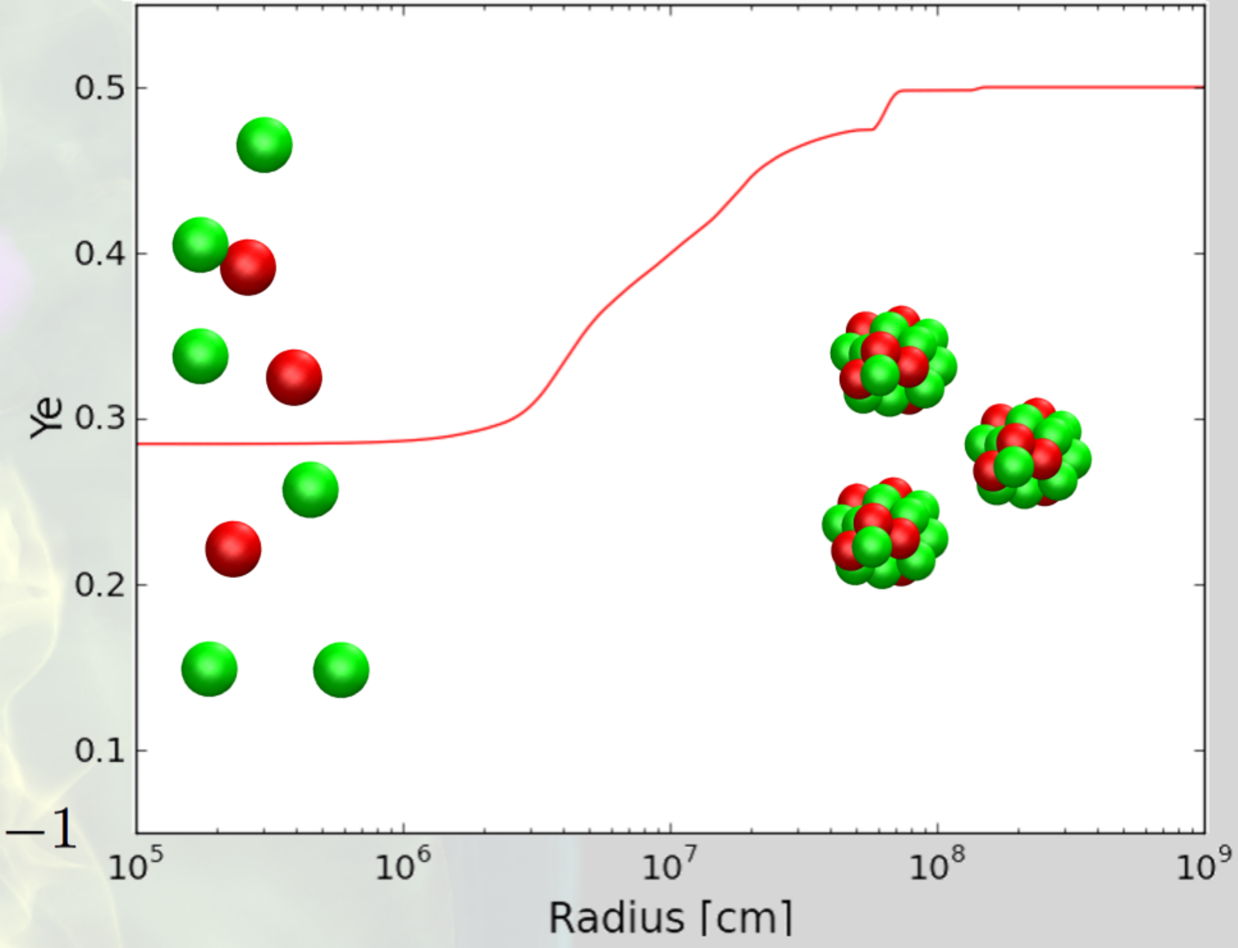
Neutronization Burst



- Recently freed and no longer suppressed, protons now rapidly capture electrons, producing a burst of ν_e
- This neutronization burst is universal across core-collapse progenitors

$$\frac{1}{2}\frac{M_\odot}{m_N} \times 0.2 \times \frac{10\,\mathrm{MeV}}{5\,\mathrm{ms}} \sim 4 \times 10^{53}\,\mathrm{erg\,s^{-1}}$$

from 3ms before bounce to 6 ms after



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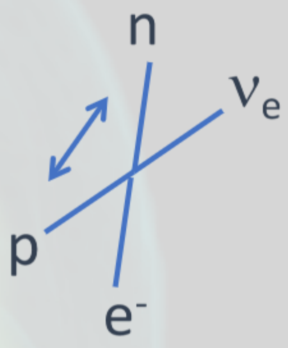

FLASH simulations, 149 progenitors, SFHo EOS, Segerlund et al. (2021)

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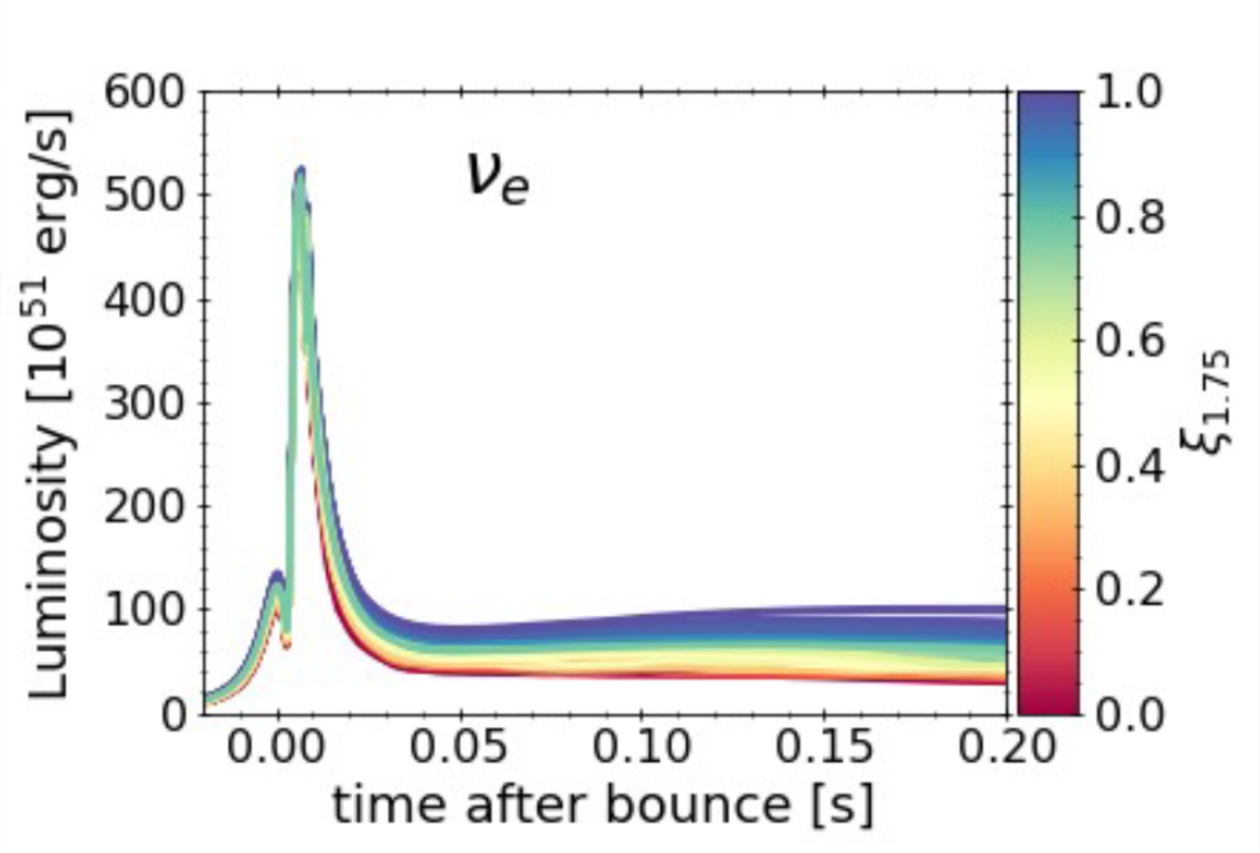

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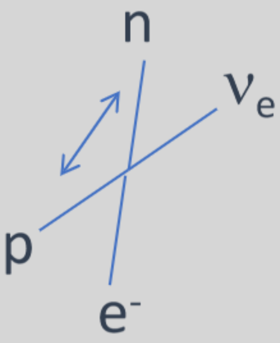
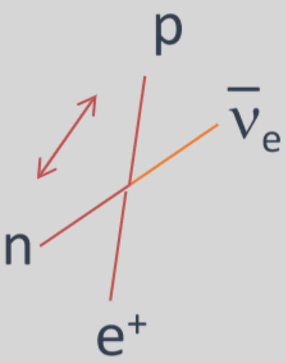
Accretion Phase: Role of Neutrinos

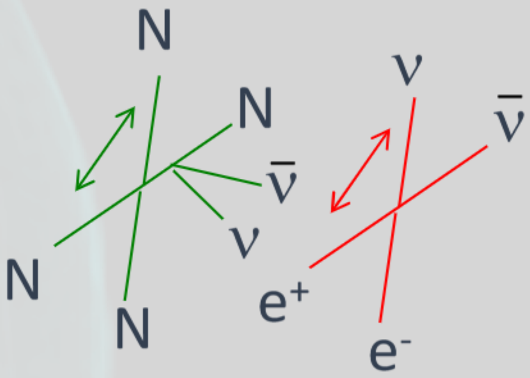
- After the burst, ν_e and anti-ν_e emission is powered by accretion
- Infalling matter is shock heated and then is cooled via neutrino emission



- Charged current processes dominant production
- Thermal production processes dominate at high densities where neutrinos are trapped for seconds



- Thermal emission is dominant production process for heavy lepton neutrinos as T is too low for charged-current processes with μ's and τ's



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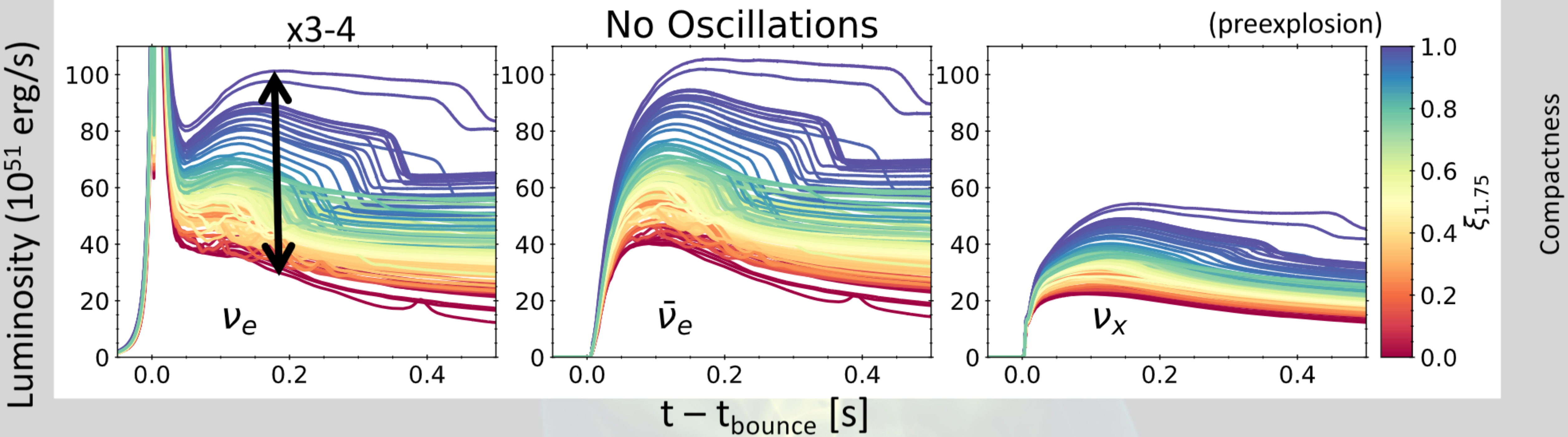
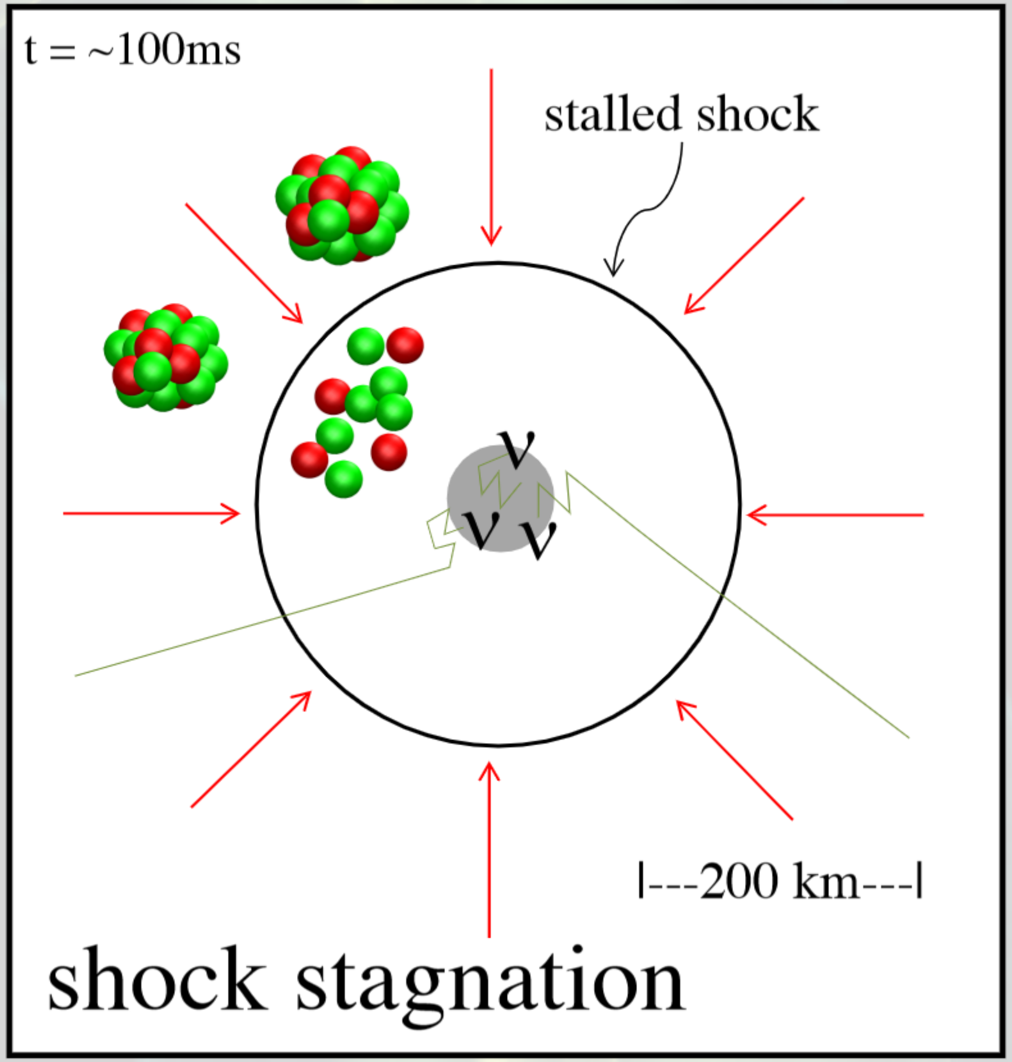
FLASH simulations, 149 progenitors, SFHo EOS, Segerlund et al. (2021)

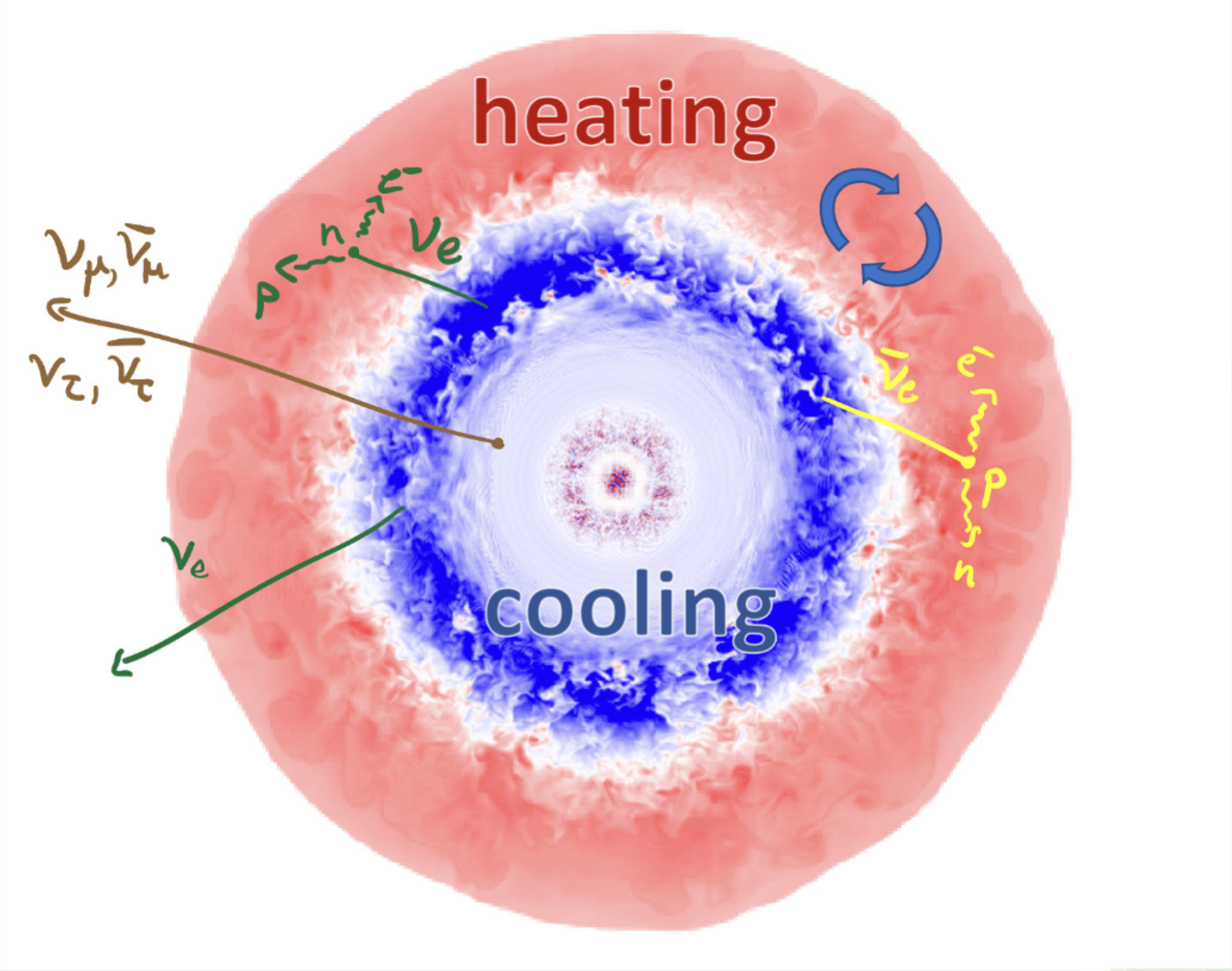


Learn about progenitor structure from neutrino observation of a galactic supernova

CCSNe: The Explosion?



The Core-Collapse Supernova Problem



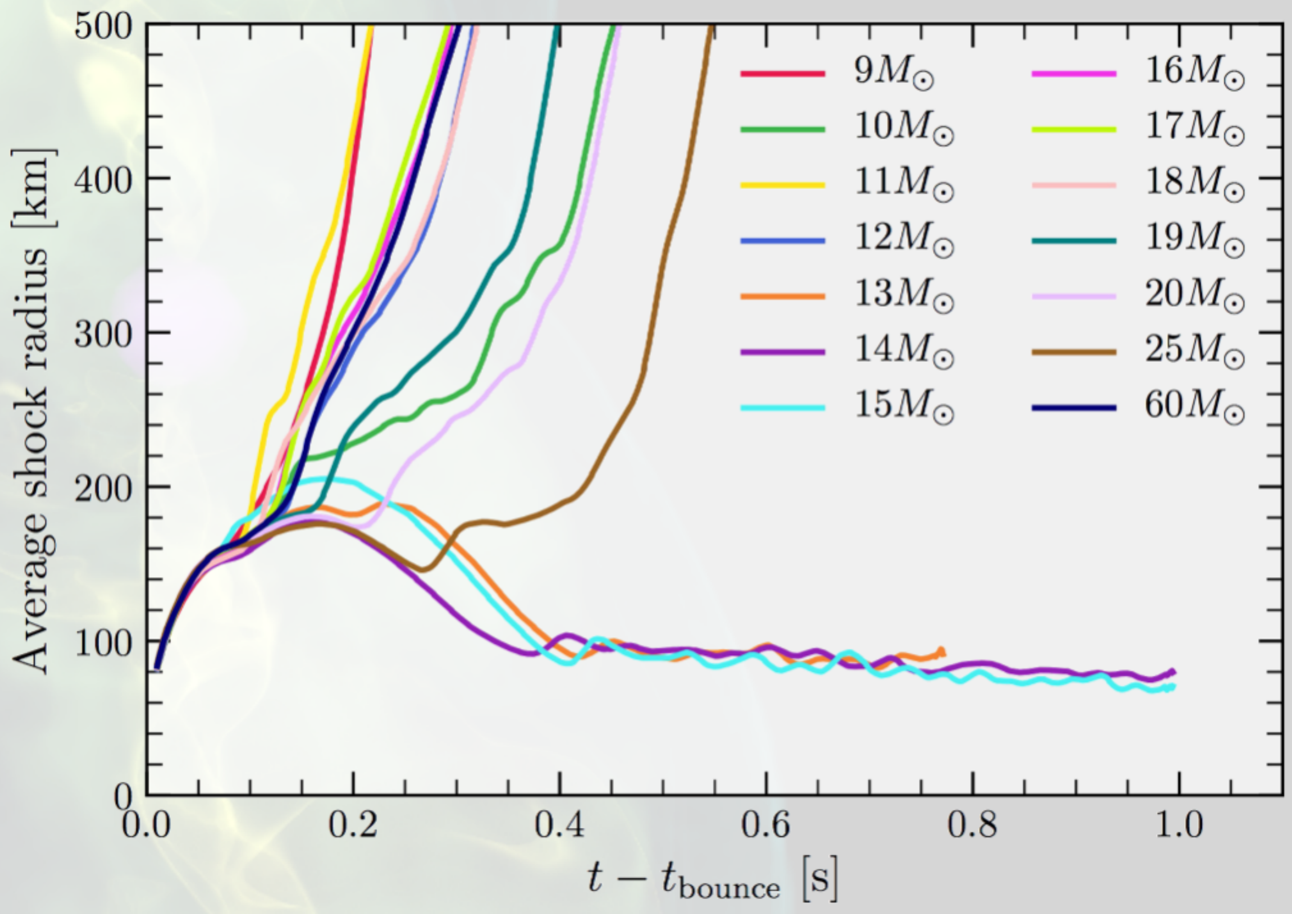
- The naive `prompt` mechanism fails
- The prevailing mechanism is the **turbulence-aided neutrino mechanism**
  - Neutrinos from core heat outer layers
  - Drives convection
  - Turbulence pressure support aids heating and drive explosion
- Very successful in 2D, also successful in 3D.

Successful CCSN explosions

Burrows et al. (2019)

- Routinely, modern, state-of-the-art, symmetry-free, simulation codes obtain explosions across the progenitor spaces

- Suggest that canonical observed energies (0.5-1 Bethe) are achievable in the turbulence-aided neutrino mechanism, if you wait long enough



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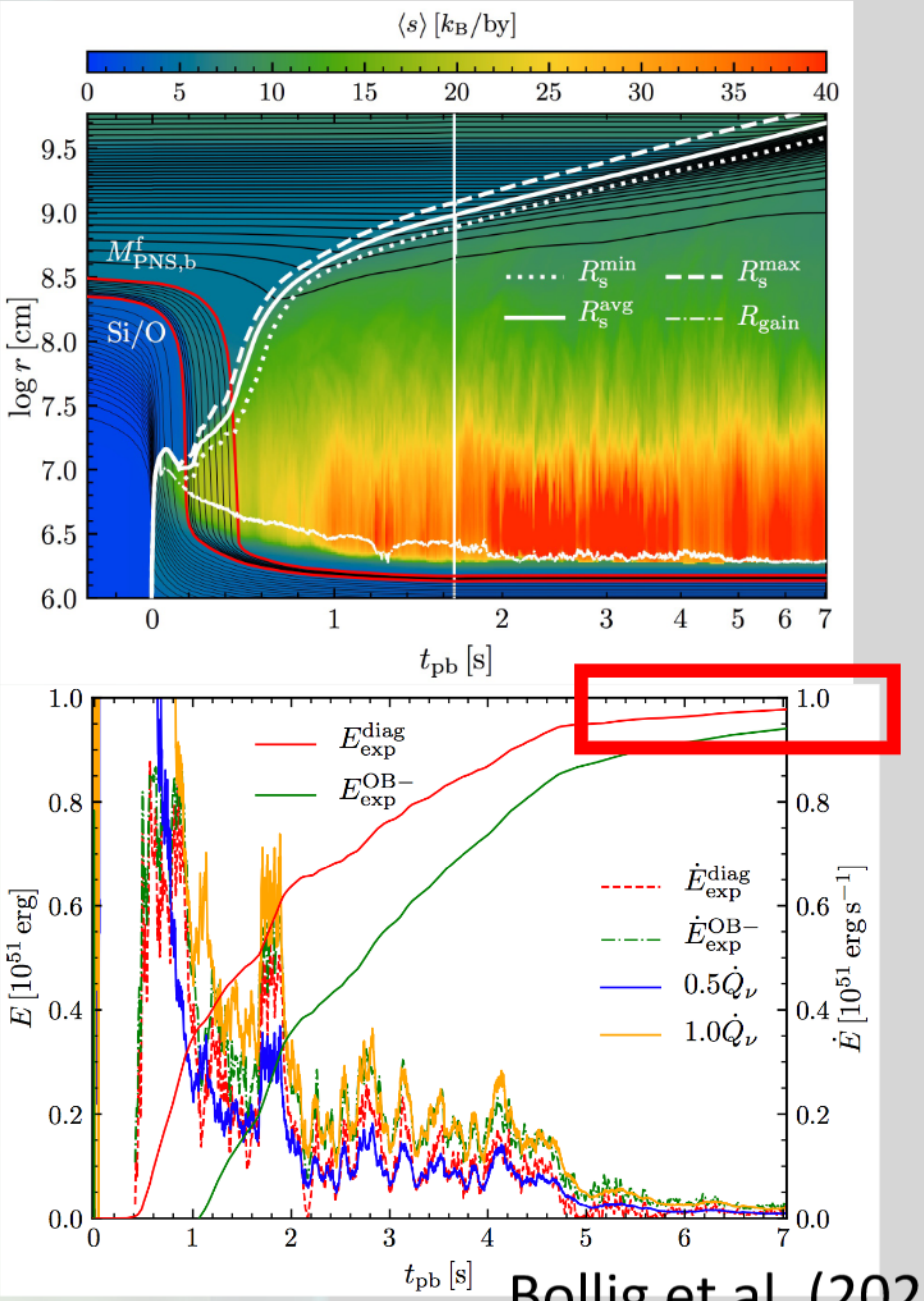
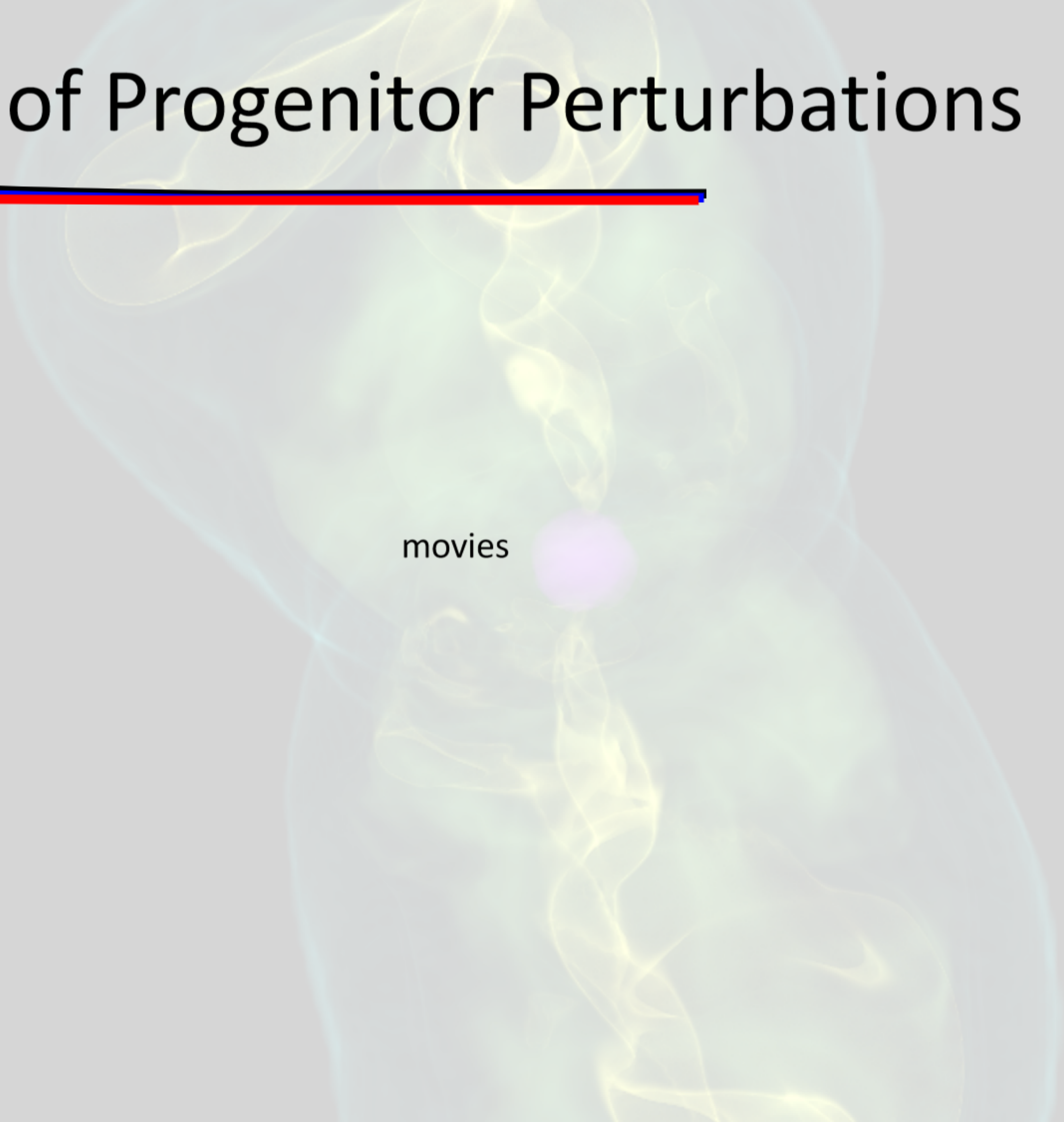


Bollig et al. (2020)

Impact of Progenitor Perturbations



movies

Core Collapse Supernovae and **EOS thermal effects**

Evan O'Connor
NP3M Seminar
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Swedish Research Council

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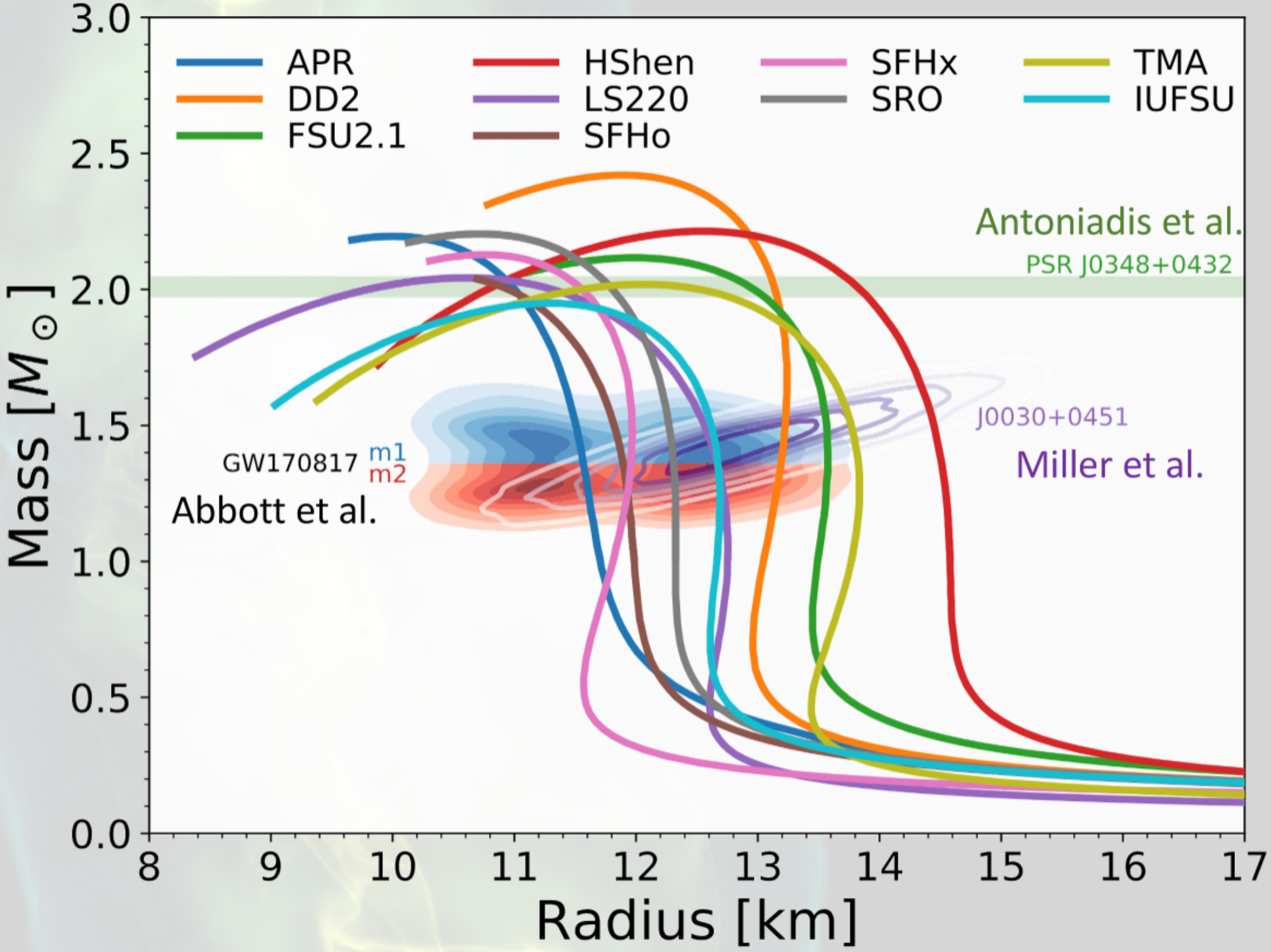
Nuclear Equation of State and Core Collapse

Wide variety of finite temperature EOS to choose from



Need:

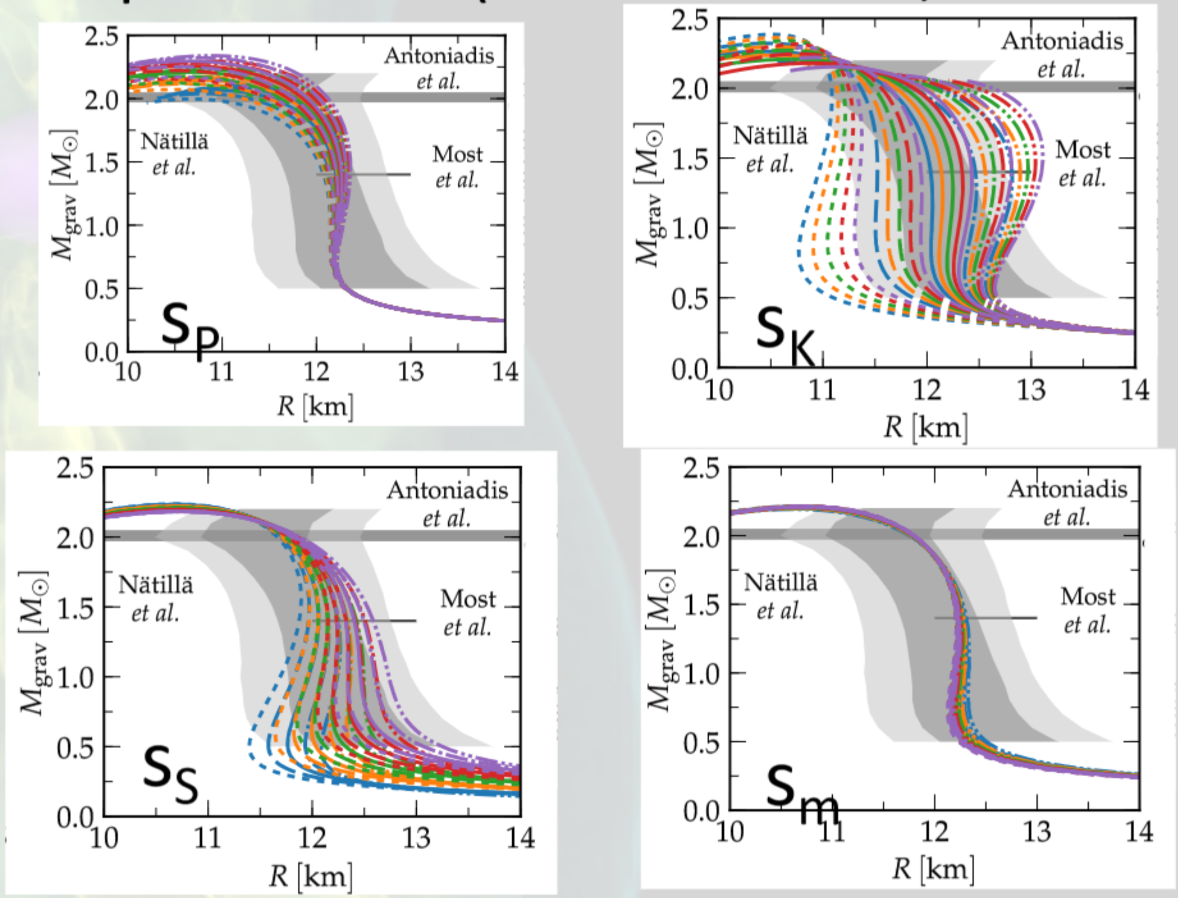
- $1e\text{-}12 < n_b\ [fm^{-3}] < 10$
- $0.01 < T\ [MeV] < 150$
- $0 < Y_p < 0.6$

Impact assessed only with systematic studies

da Silva Schneider et al. (2019b)

Set	Quantity	Range	This work	Units
s_M	$m^\star$	0.75 ± 0.10	0.75 ± 0.10	m_n
	$\Delta m^\star$	0.10 ± 0.10	0.10 ± 0.10	m_n
—	$n_{\rm sat}$	0.155 ± 0.005	0.155	$\rm fm^{-3}$
	$\epsilon_{\rm sat}$	-15.8 ± 0.3	-15.8	MeV $\rm baryon^{-1}$
s_S	$\epsilon_{\rm sym}$	32 ± 2	32 ± 2	MeV $\rm baryon^{-1}$
	$L_{\rm sym}$	60 ± 15	45 ± 7.5	MeV $\rm baryon^{-1}$
s_K	$K_{\rm sat}$	230 ± 20	230 ± 15	MeV $\rm baryon^{-1}$
	$K_{\rm sym}$	-100 ± 100	-100 ± 100	MeV $\rm baryon^{-1}$
s_P	$P^{(4)}_{\rm SNM}$	100 ± 50	125 ± 12.5	MeV $\rm fm^{-3}$
	$P^{(4)}_{\rm PNM}$	160 ± 80	200 ± 20	MeV $\rm fm^{-3}$

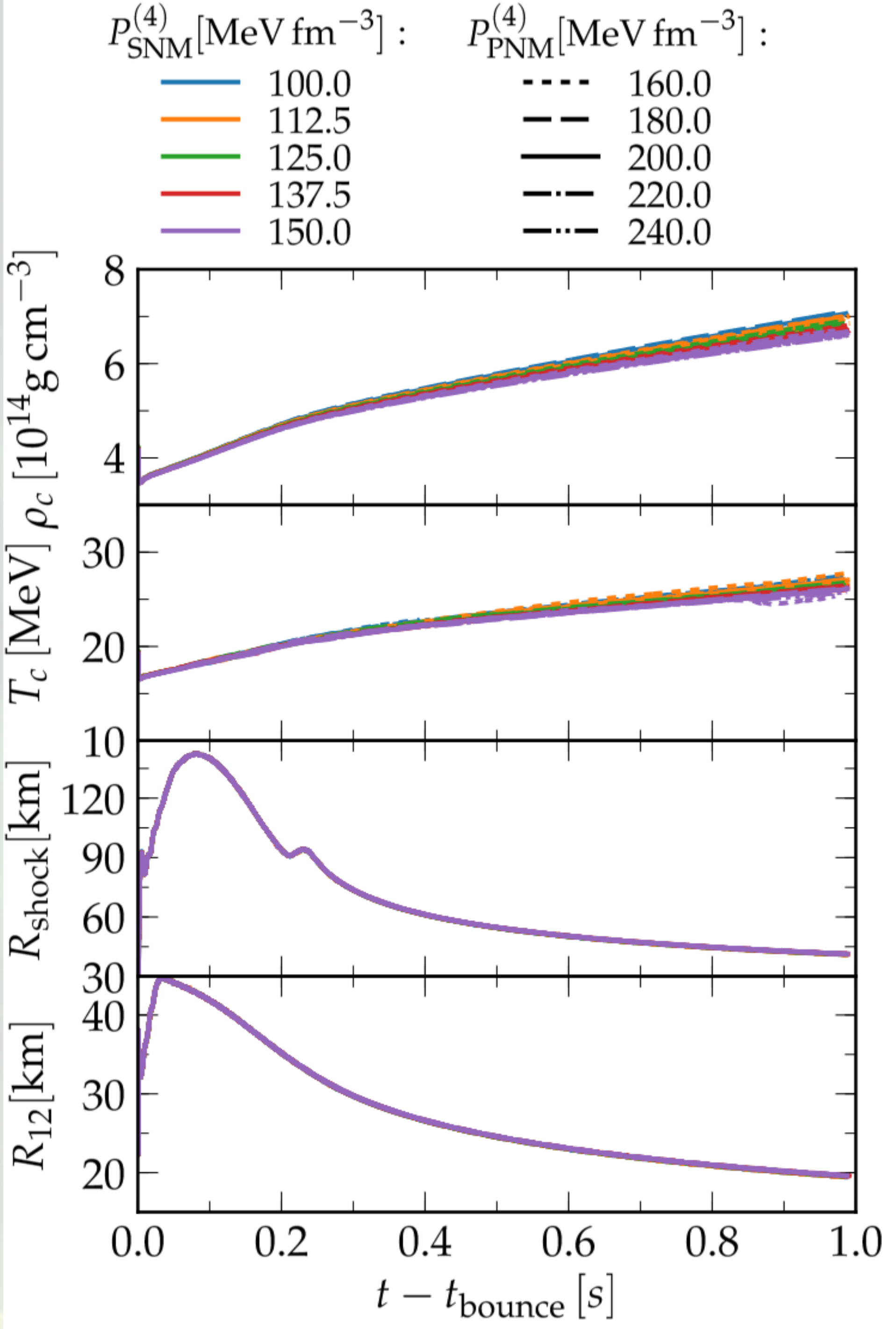
For each of the 4 sets we construct EOSs with 0,+/- 1, and +/- 2 sigma deviations of the parameters (25 for each set, 97 overall)



What about in a supernova?

Cold Neutron Star	Hot Supernova
• S_P: Impacts maximum mass	• S_P: No impact in early stages
• S_K: v. large impact on NS radius	• S_K: Mild impact on radii
• S_S: impact on low mass NS only	• S_S: Mild impact on radii
• S_m: minimal impact	• S_m: strong impact on radii

Effective mass (via the impact on the thermal EOS) plays strong and important role in supernova evolution



da Silva Schneider et al. (2019b)

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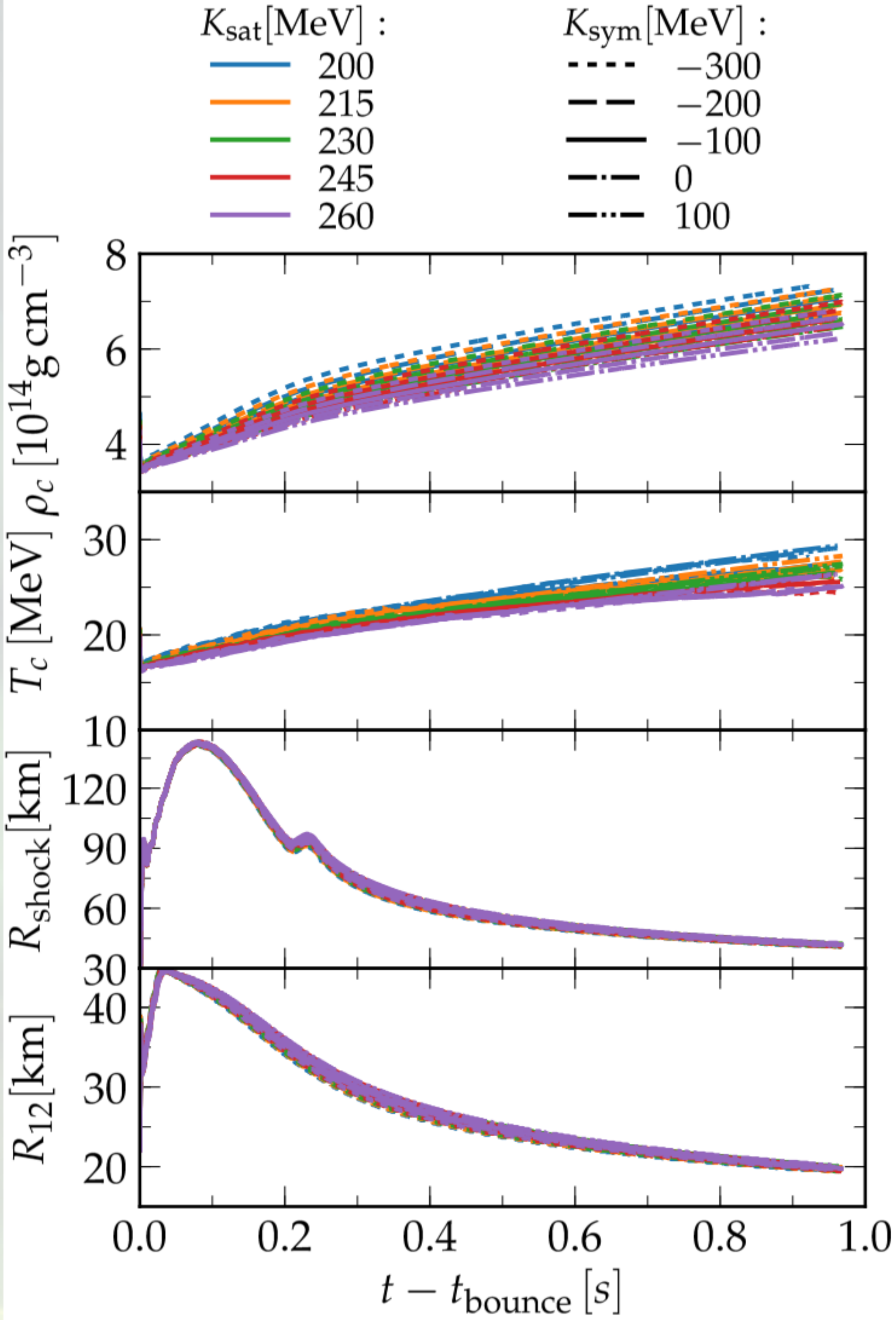

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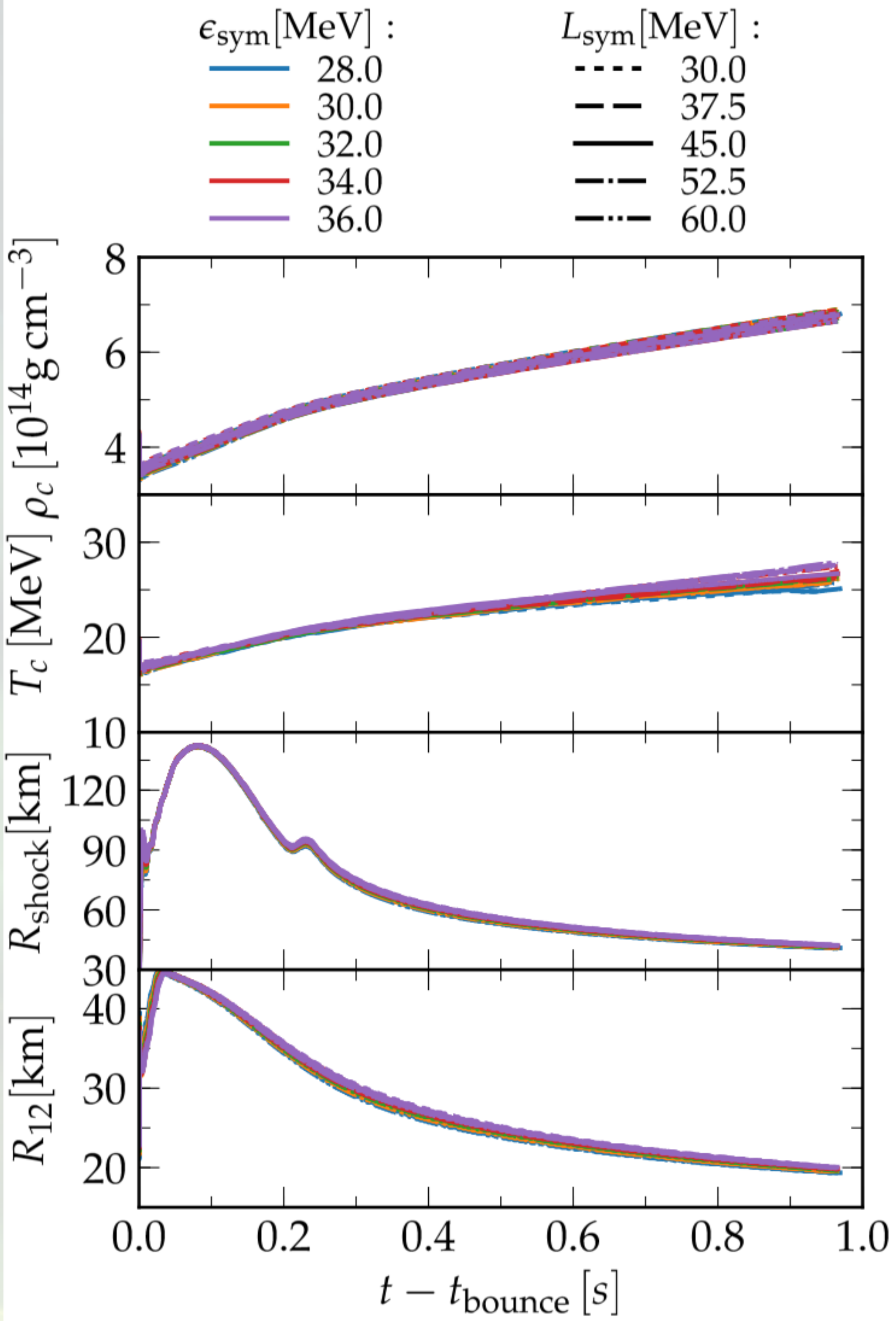

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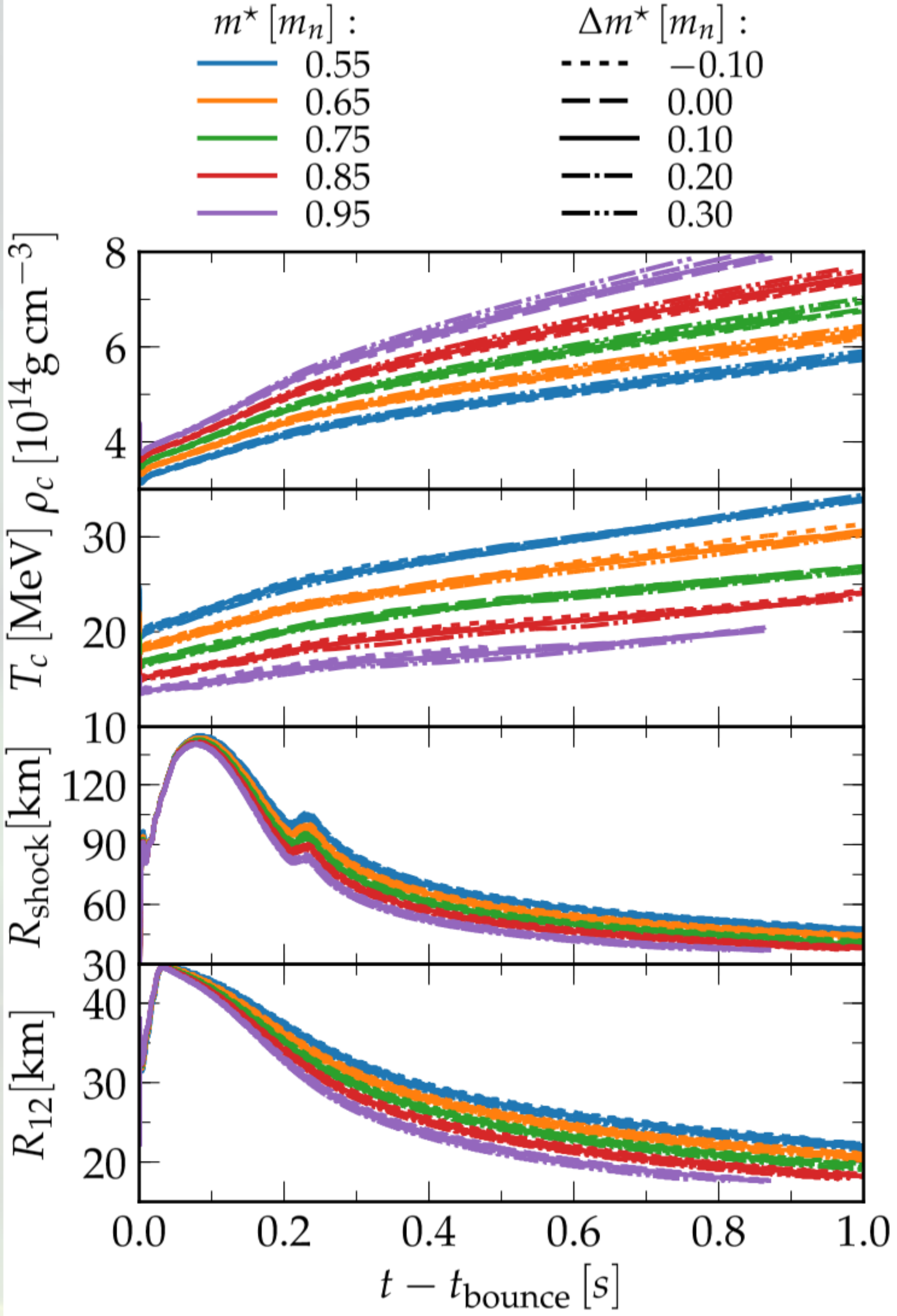

da Silva Schneider et al. (2019b)

How does the effective mass impact the EOS?

EOS specific energy : $$\epsilon_B(n, y, T) = \epsilon_{\text{kin}}(n, y, T) + \epsilon_{\text{pot}}(n, y)$$

Kinetic term (thermal term): $$\epsilon_{\text{kin}}(n, y, T) = \frac{1}{n}\left(\frac{\hbar^2 \tau_n}{2m_n^\star} + \frac{\hbar^2 \tau_p}{2m_p^\star}\right)$$

Kinetic energy density: $$\tau_t = \frac{1}{2\pi^2}\left(\frac{2m_t^\star T}{\hbar^2}\right)^{5/2} \mathcal{F}_{3/2}(\eta_t)$$

Effective masses thru Skyrme terms: $$\frac{\hbar^2}{2m_t^\star} = \frac{\hbar^2}{2m_t} + \alpha_1 n_t + \alpha_2 n_{-t}$$

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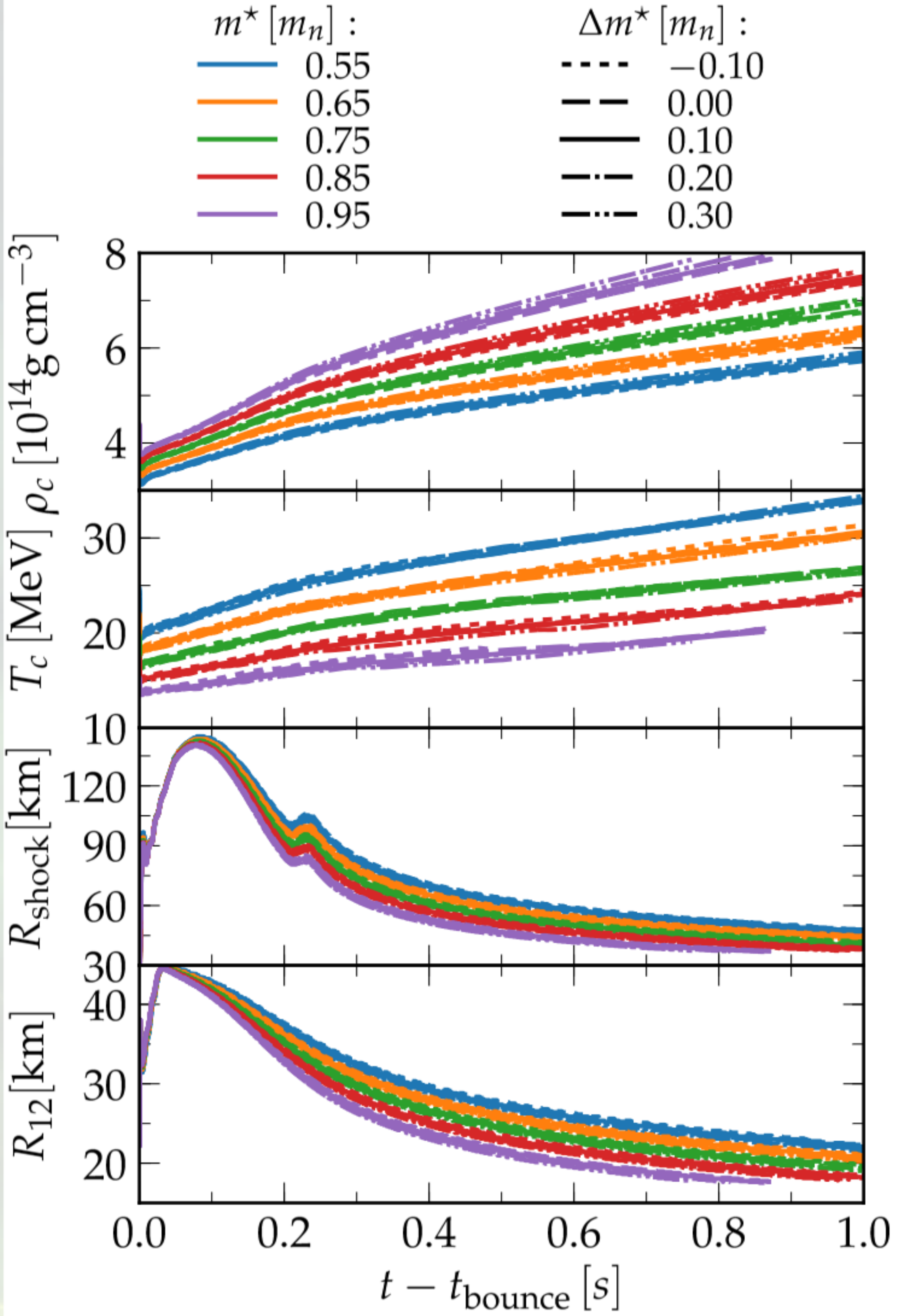
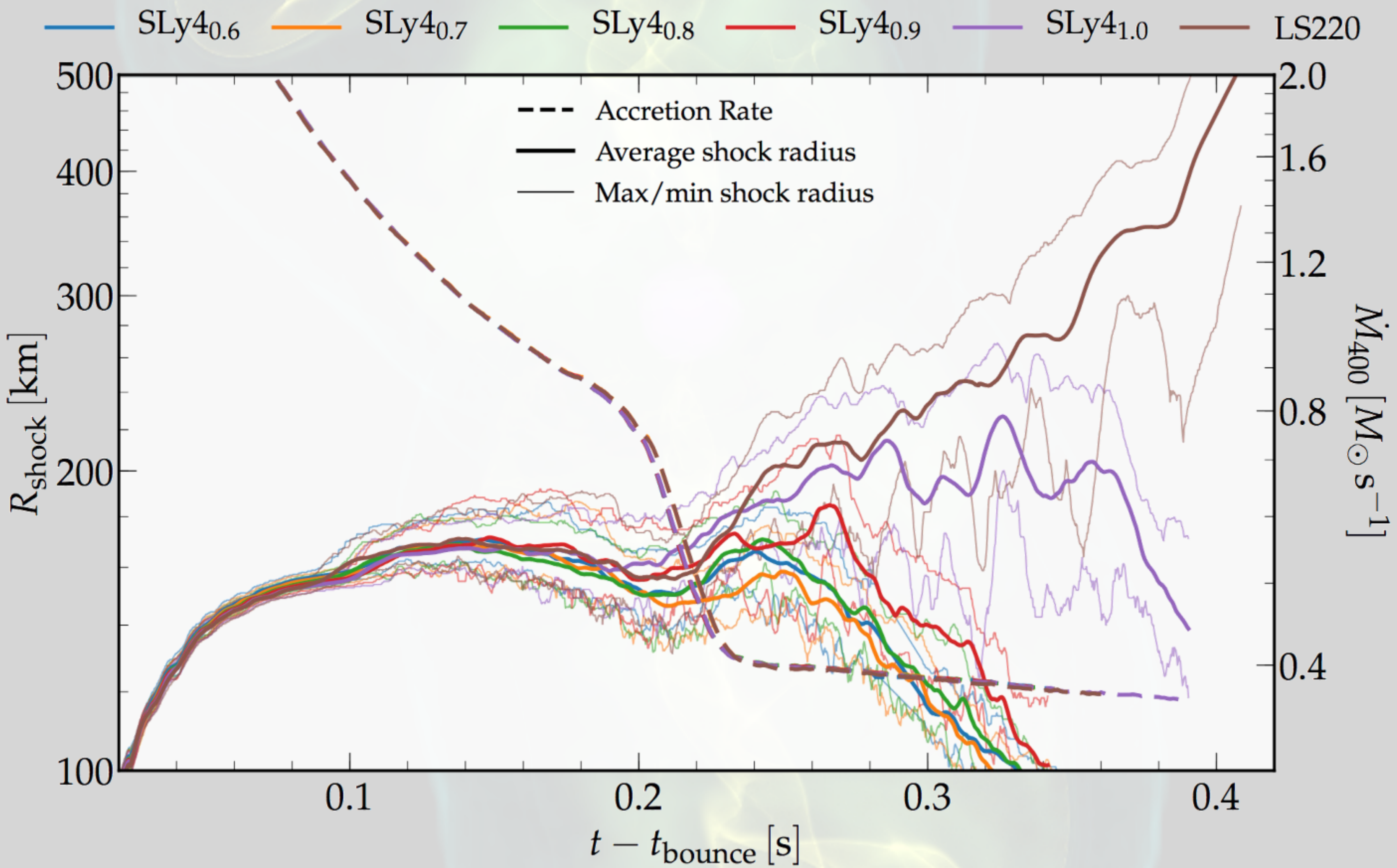


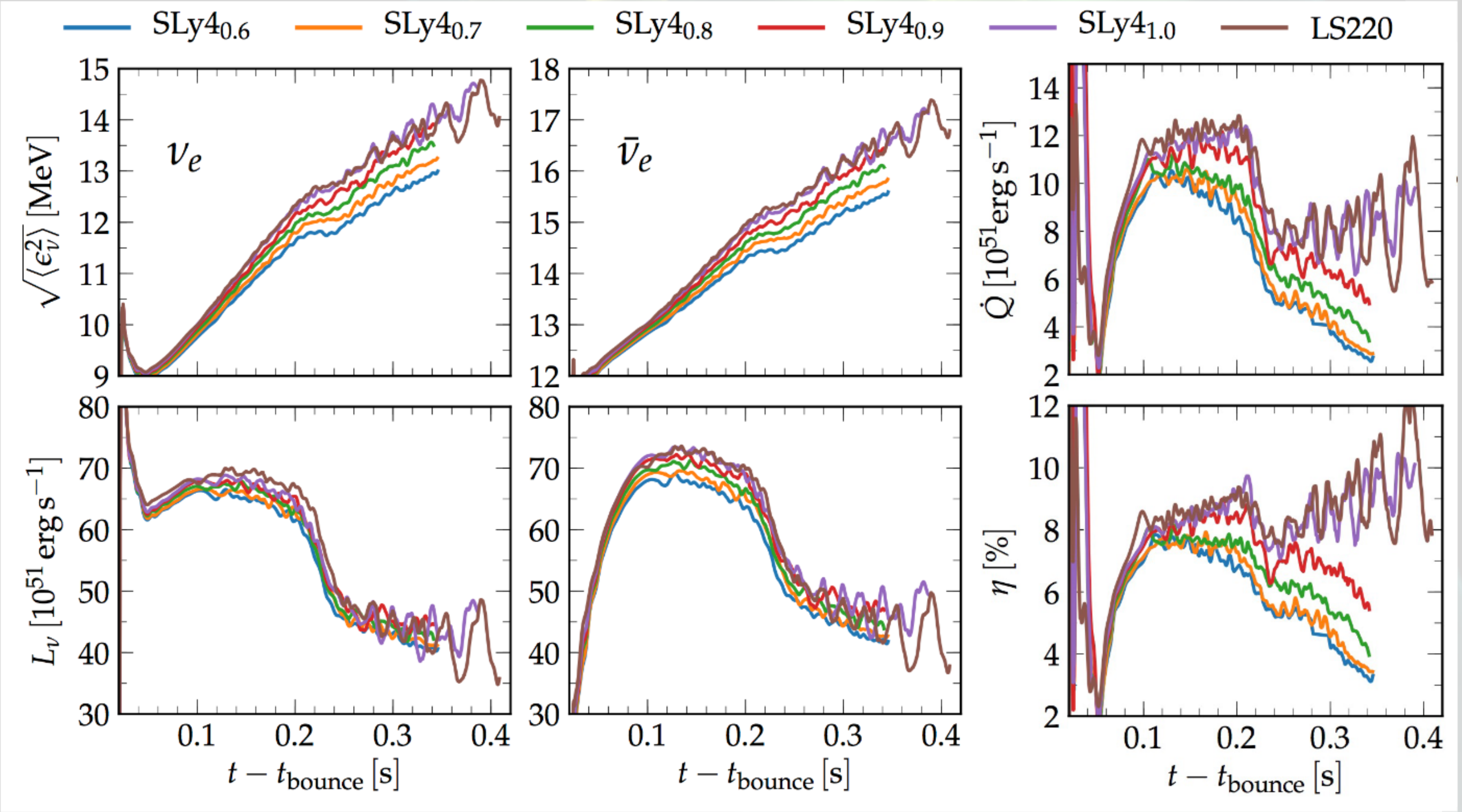
da Silva Schneider et al. (2019b)

It does impact the evolution in 3D!

da Silva Schneider et al. (2019b)
see also Yasin et al. (2018)



high m*, less pressure, more compact, more heating

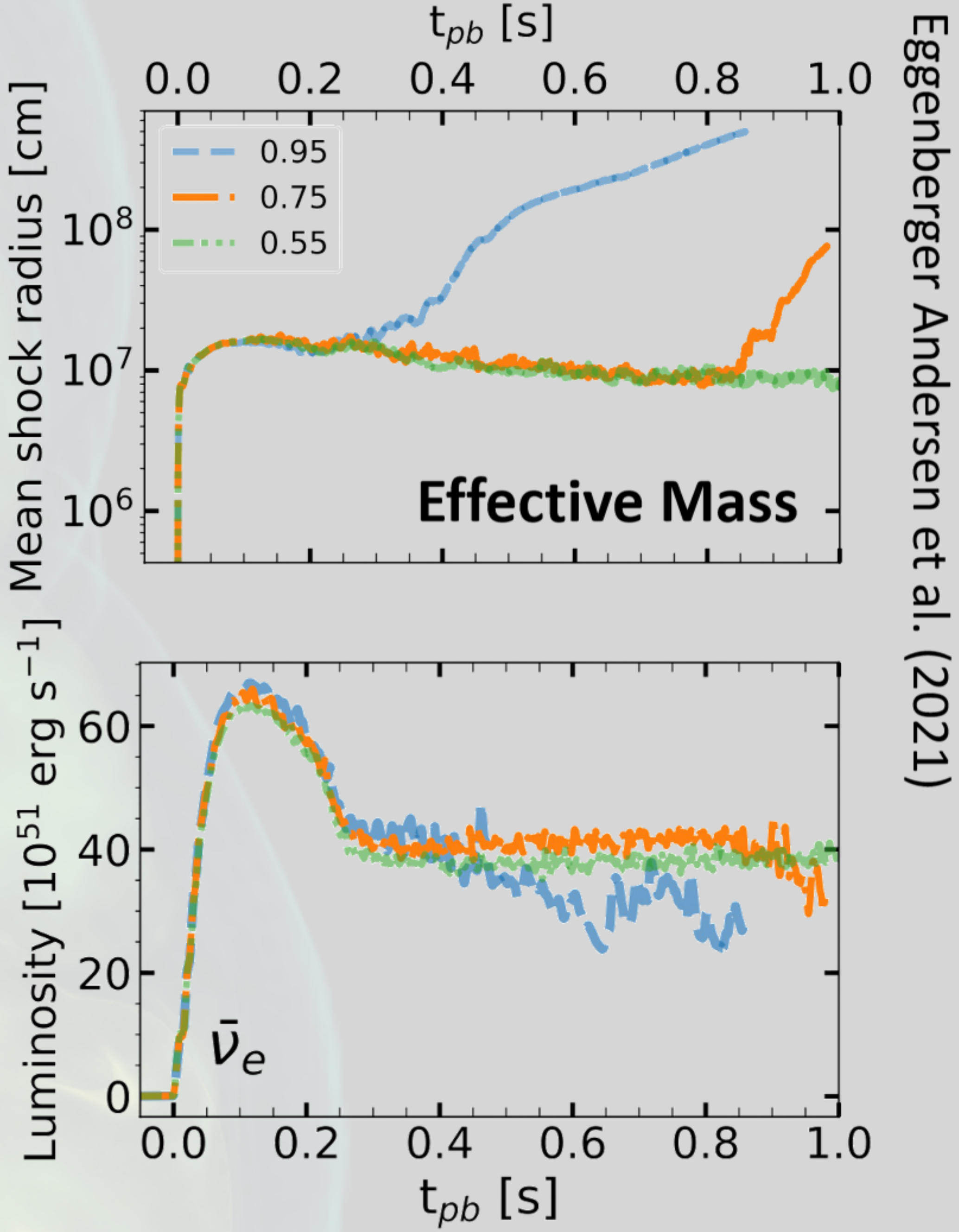


1. High effective mass gives lower thermal pressure, $P_{th} \sim 1/m^*$
2. More compact protoneutron stars
3. More and hotter neutrinos
4. Greater heating and convection
5. Higher chance of explosion

Schneider et al. (2019b)

Let's reenforce this idea

- Eggenberger Andersen et al. (2021)
  - 2D simulations
  - range of EOS with varying effective mass
  - Same result, low effective masses give more compact PNS, higher luminosities, energies, easier explosions



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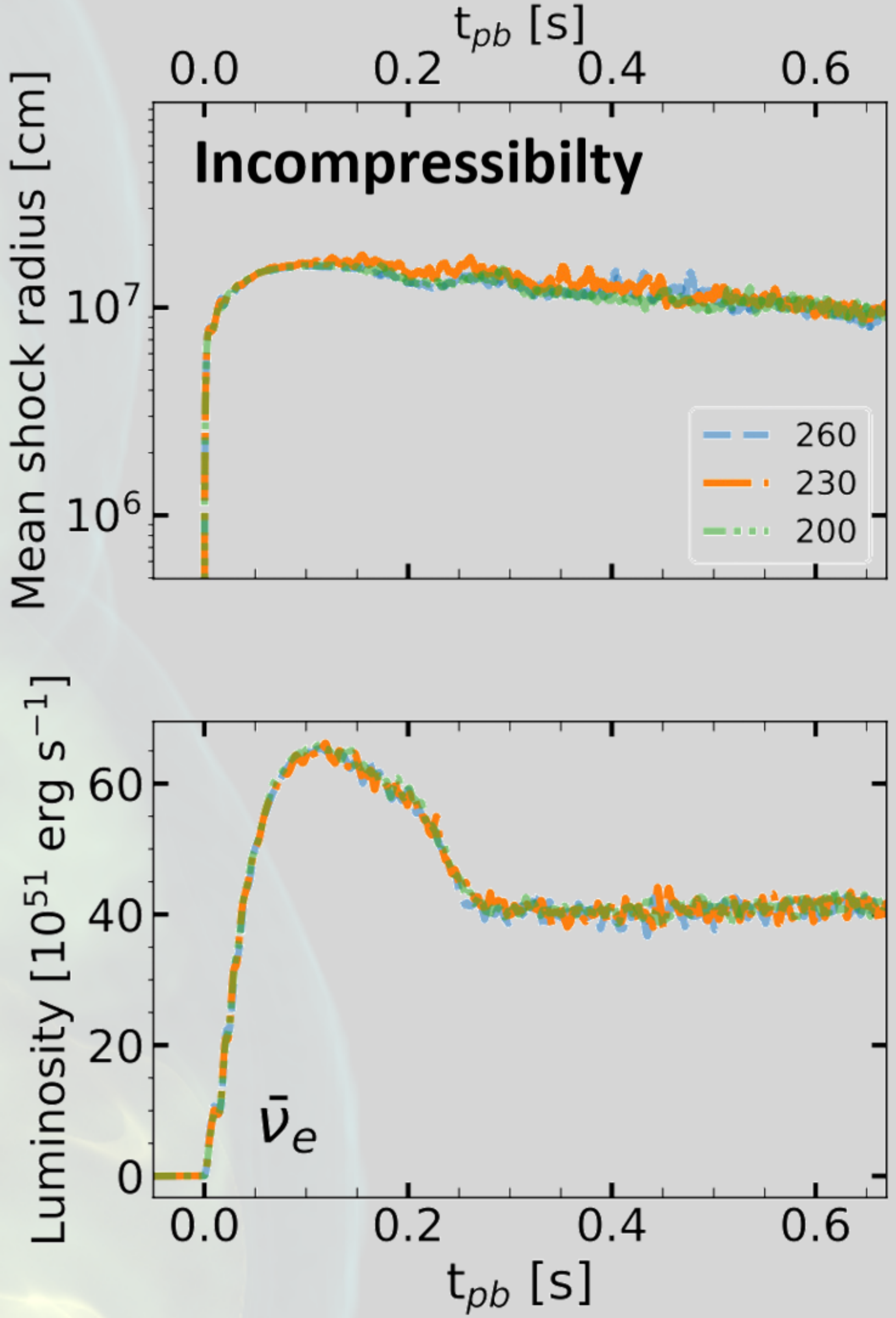
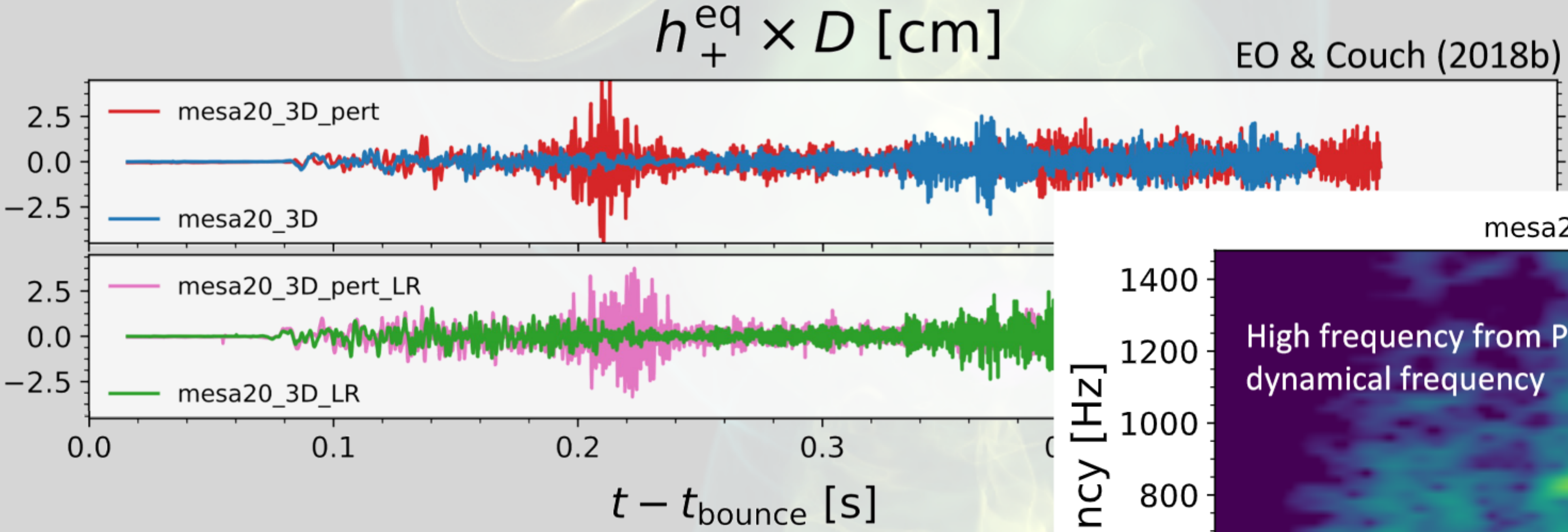
  - range of EOS with varying effective mass
  - Same result, low effective masses give more compact PNS, higher luminosities, energies, easier explosions

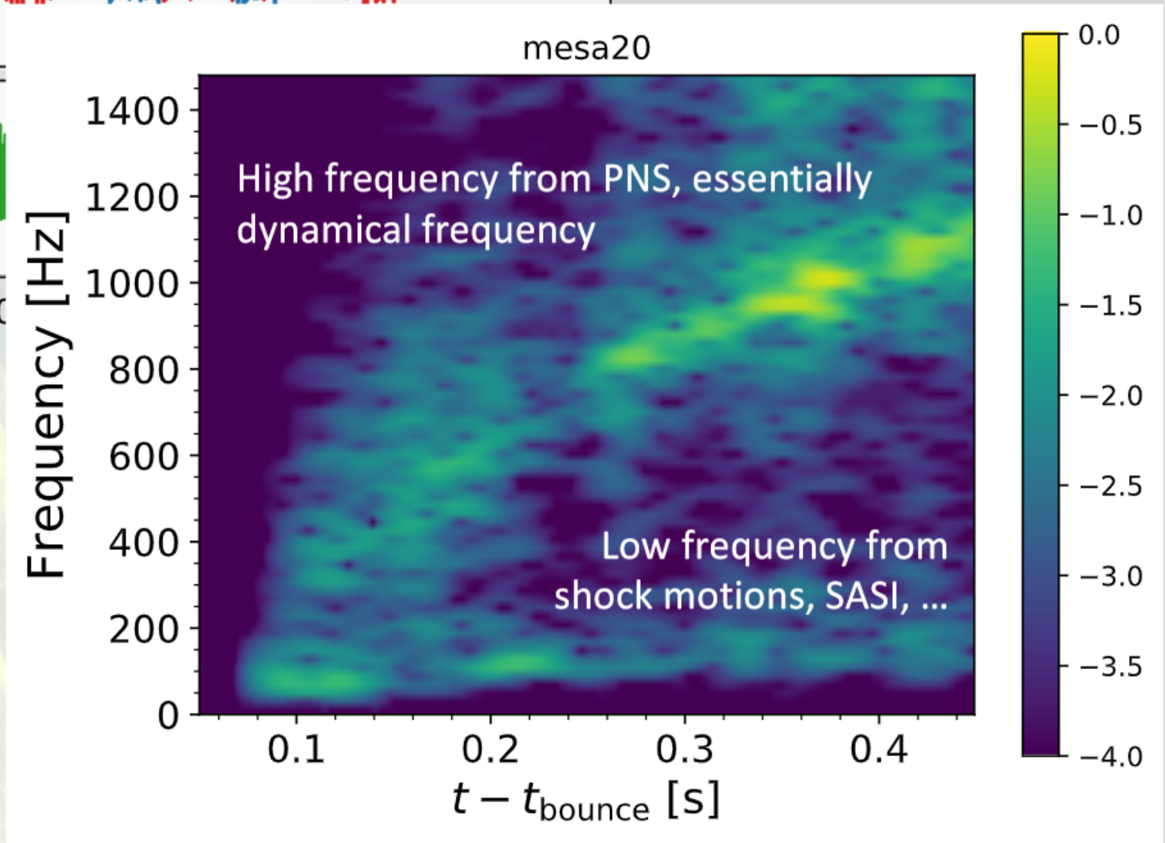
  - Variations in K_{sat} do not impact evolution nearly as much



Eggenberger Andersen et al. (2021)

What other Multimessenger signals?



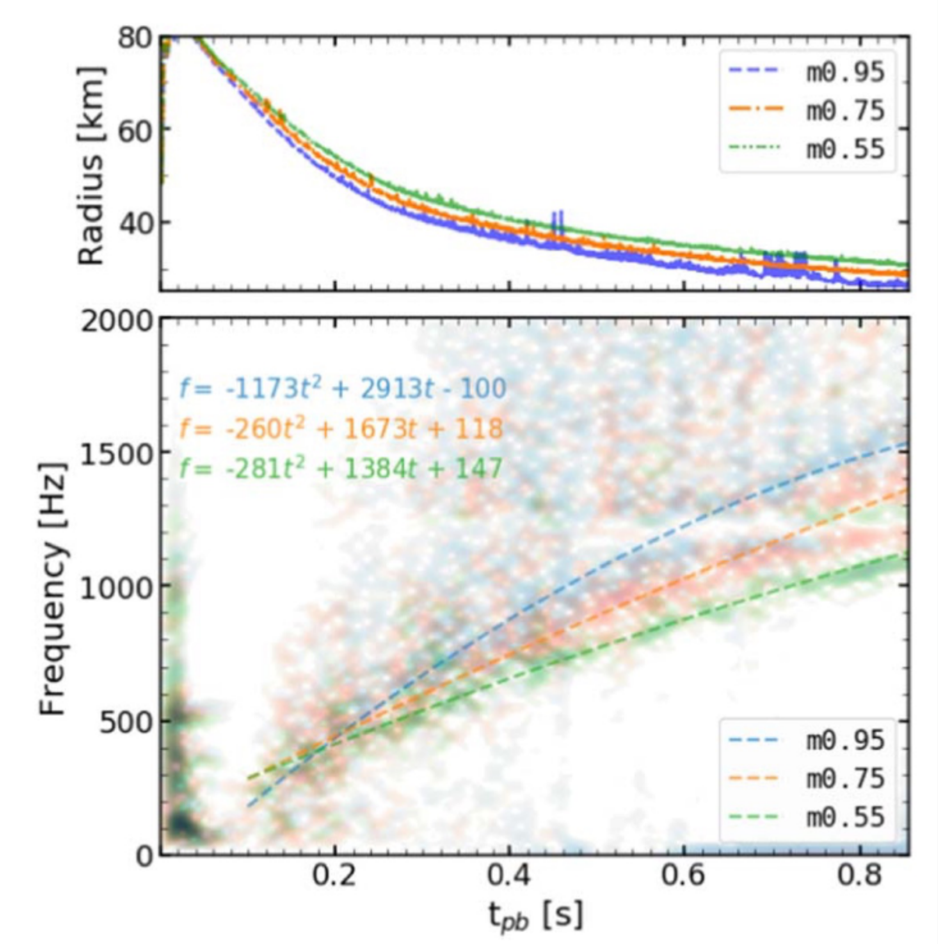


$$f_{\rm peak} \approx \frac{1}{2\pi}\frac{GM}{R^2}\sqrt{1.1\frac{m_n}{\langle E_{\bar{\nu}_e}\rangle}}\left(1-\frac{GM}{Rc^2}\right)^2$$

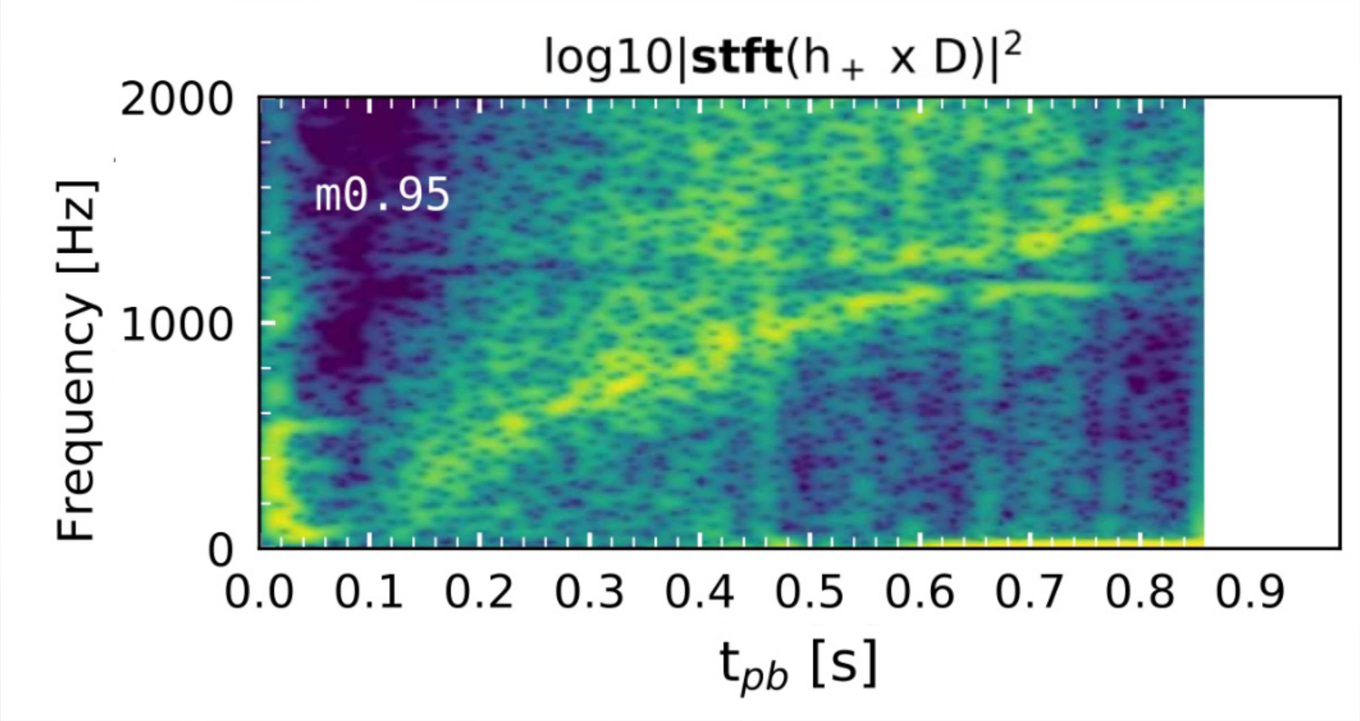
Murphy et al. 2009, Marek et al. 2009, **Mueller et al. 2013, …**

Nuclear EOS and GWs

Eggenberger Andersen et al. (2021)



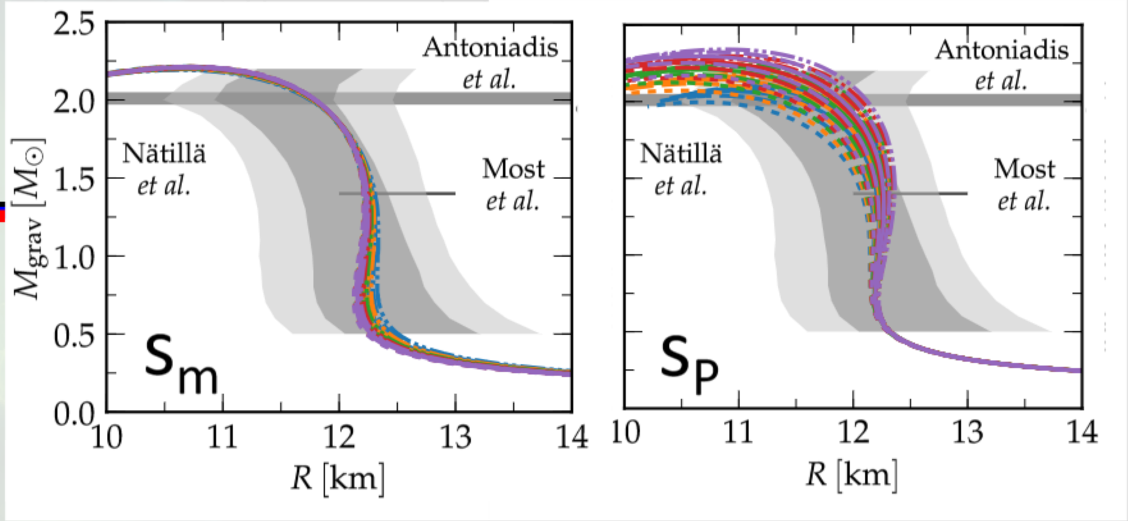
Eggenberger Andersen et al. (2021)



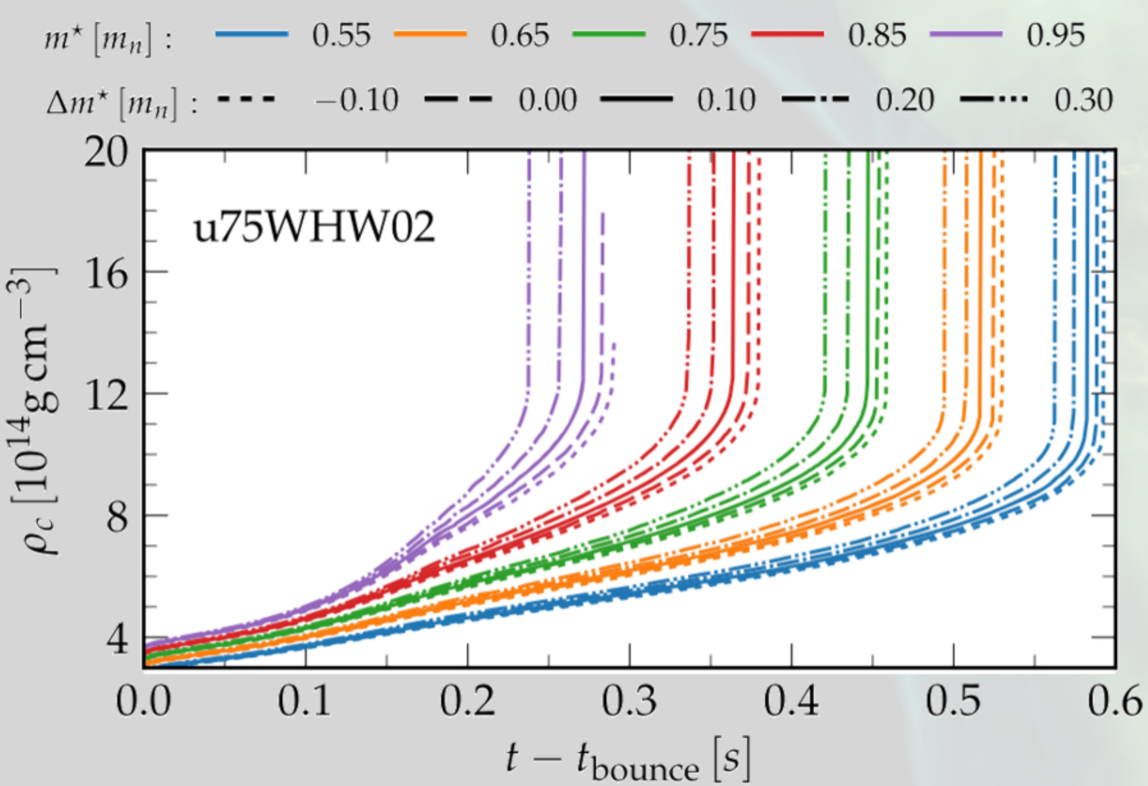
See also Fields et al. (2023) for impact in mergers!

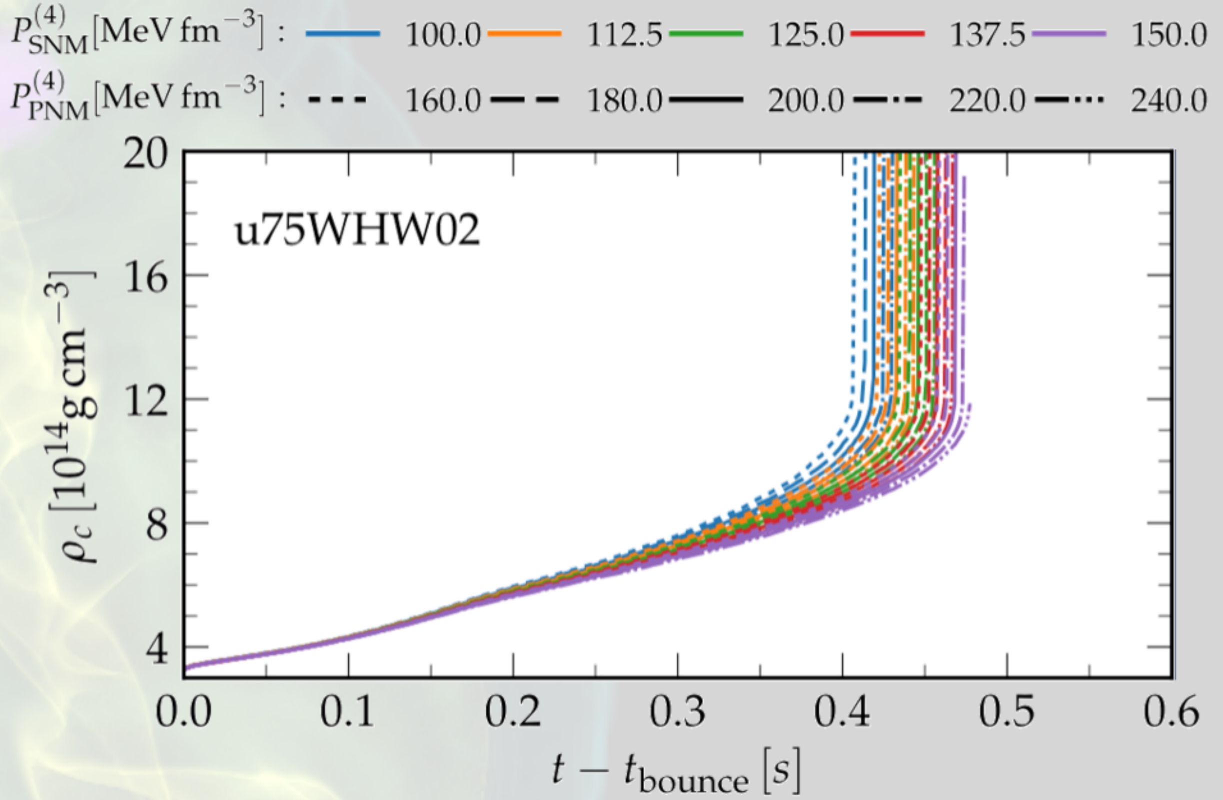
Black Holes in 49 EOS

- What role do the thermal EOS and the cold EOS play in the black hole formation properties?



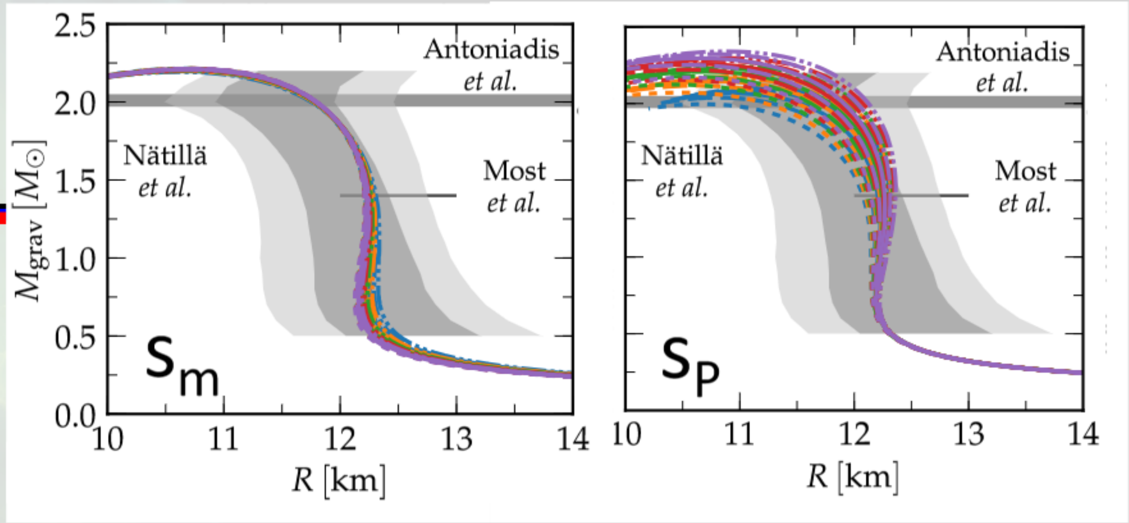
da Silva Schneider et al. (2020)

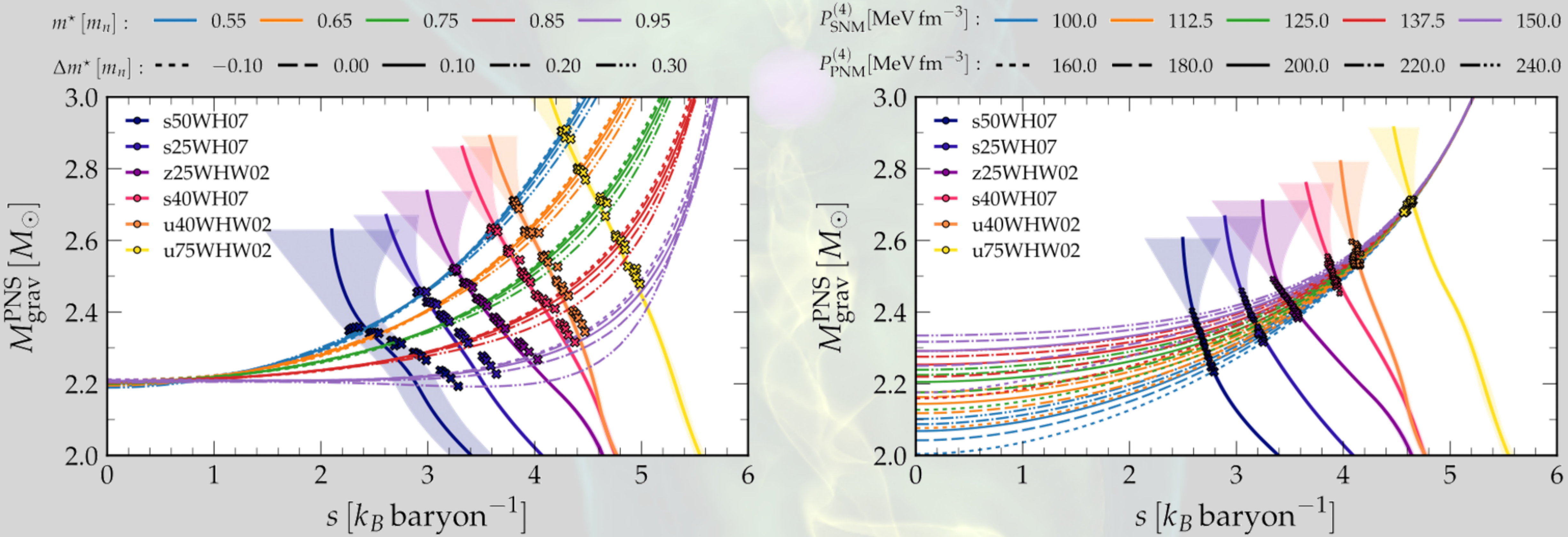




Black Holes in 49 EOS

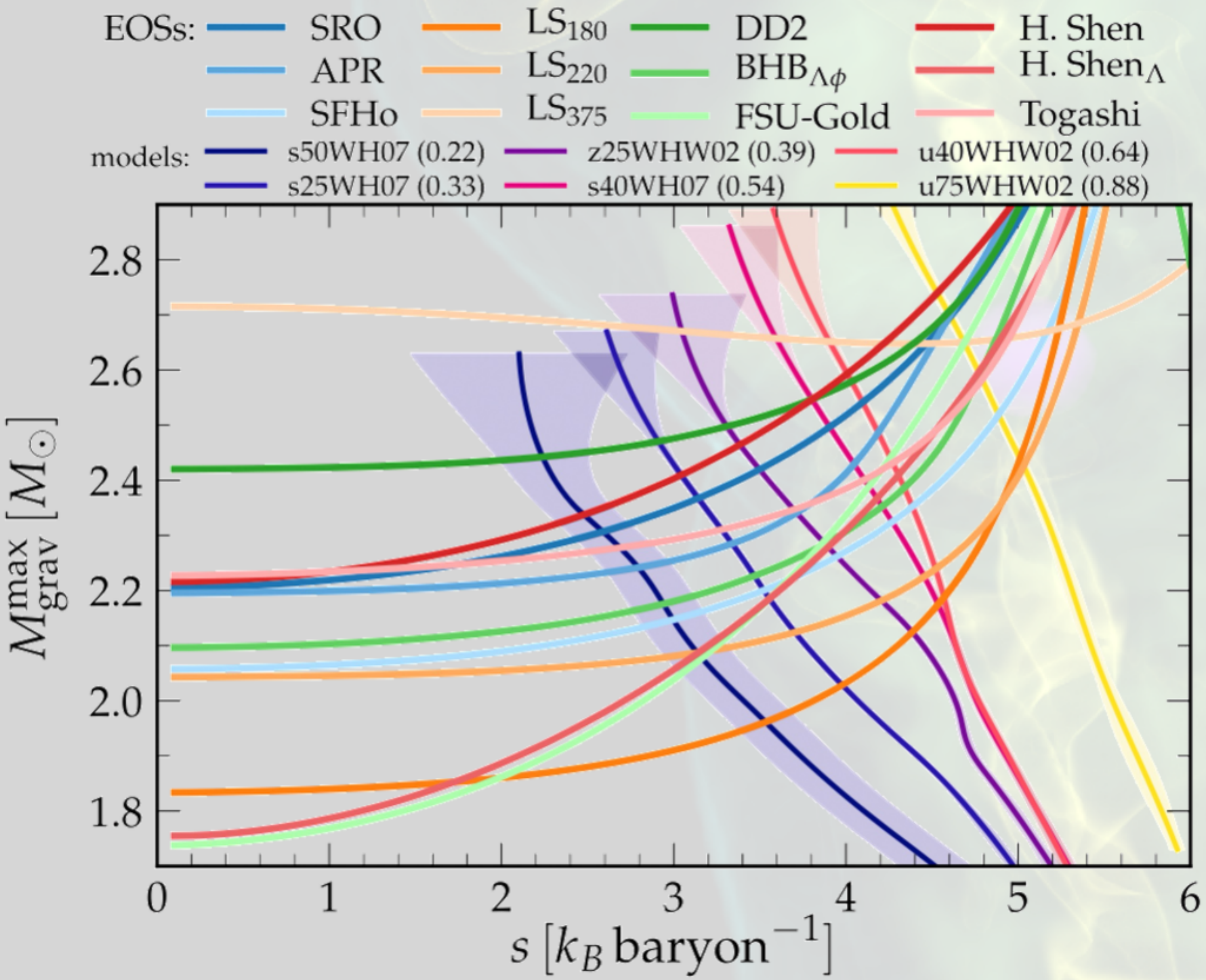
- Need to consider a hot PNS (we take constant entropy; see Hempel et al. 2013)





Thermal Landscape for Supernovae

Schneider et al. (2020)



- A wider spread of finite temperature EOS have a much more rich variety of thermal effects
- Still follow the trend for black hole formation

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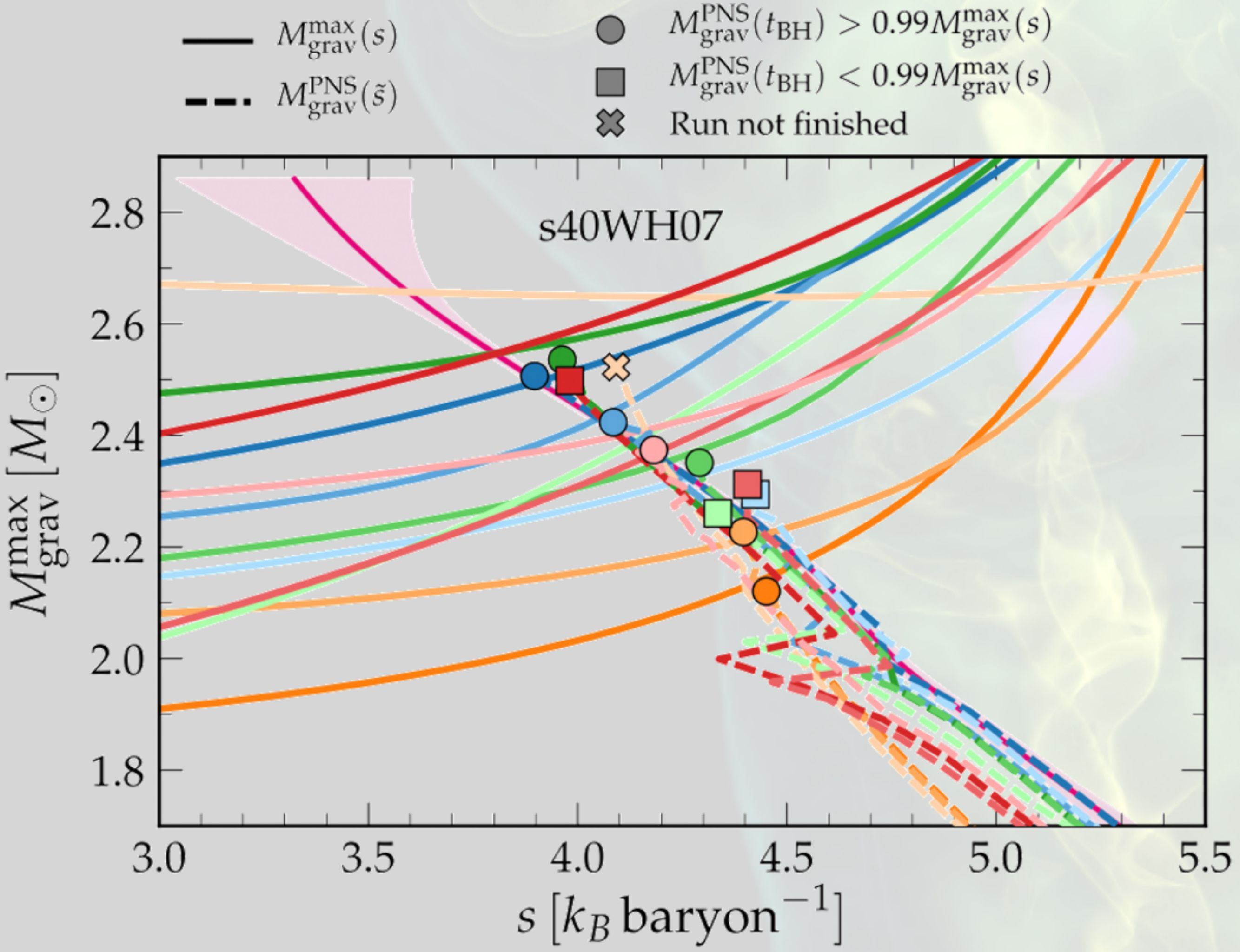

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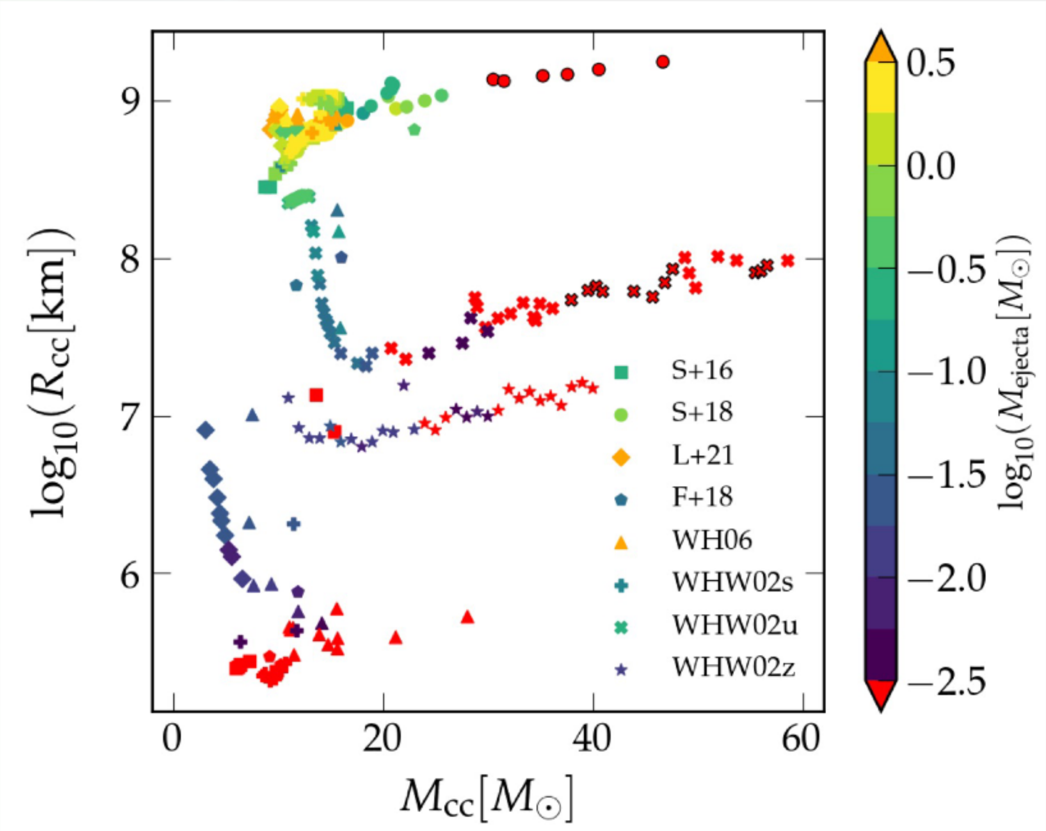
Impact on Ejecta in Failed Supernovae

- Not all core collapse events result in an explosion, some fraction of ”Failed Supernovae”
- Such events can still eject mass due to neutrino emission (Nadyozhin 1980, Lovegrove & Woosley 2013, Fernandez et al. 2018, da Silva Schneider & EO 2022).



da Silva Schneider & EO (2023)

- Considerable energy carried away by neutrinos (several tenths of solar mass)
- Disrupts the hydrostatic balance throughout the star, pressure gradiants dominates over gravity
- Sound pulse moves up, steepens to shock, can unbind loosely bound material

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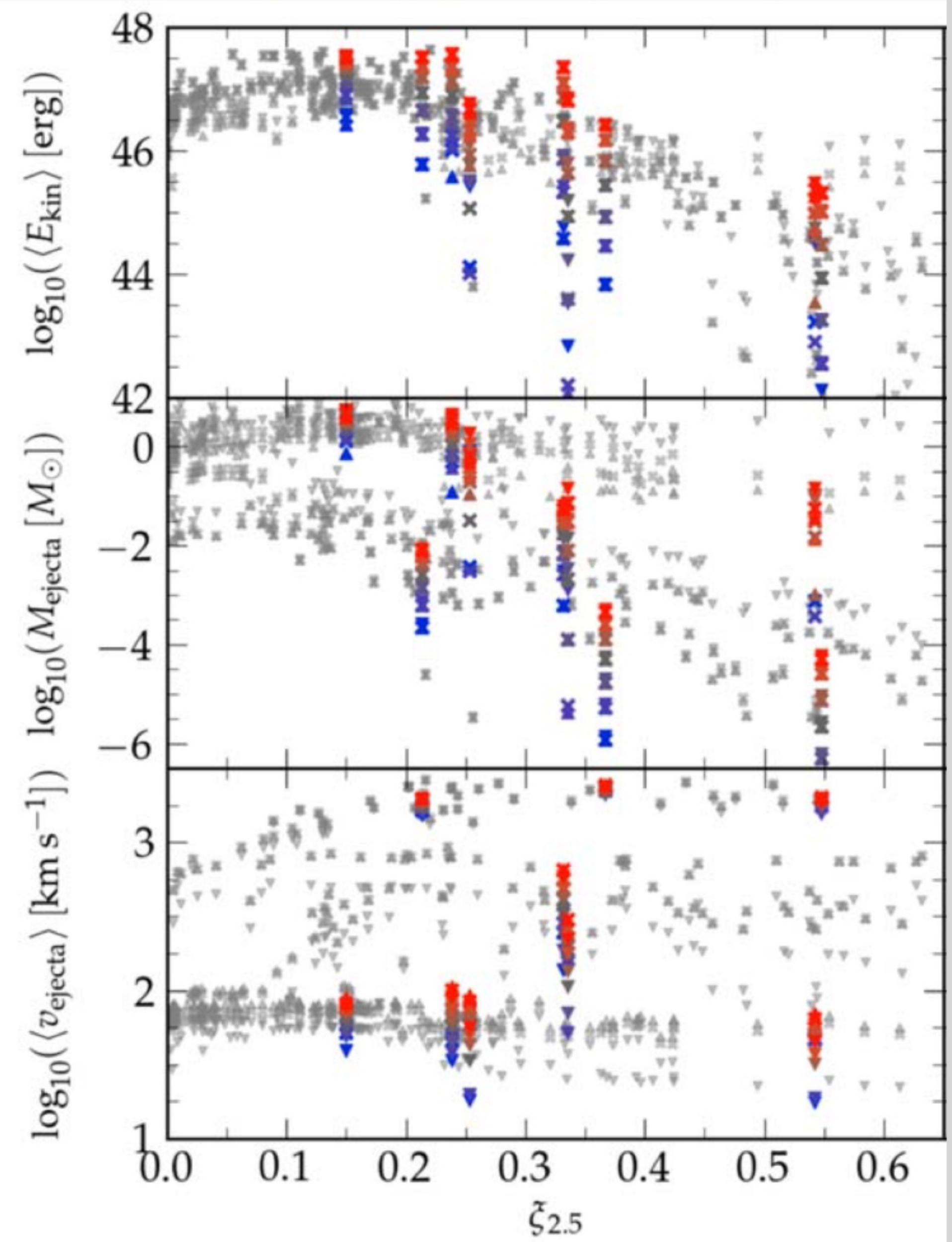

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Summary

- The nuclear matter is supernovae (and merging neutron stars) is **hot** and behaves differently than cold nuclear matter

- One parameterization of this is through the effective mass, the thermal pressure is proportional 1/m*

- low m* -> high thermal pressure -> puffed up PNS -> less, later, and less energetic explosions; lower frequency GWs; low m* -> high thermal pressure -> longer lifetimes -> delayed black hole formation

- Really hot PNS are quite insensitive to high density EOS, dominated by thermal response.