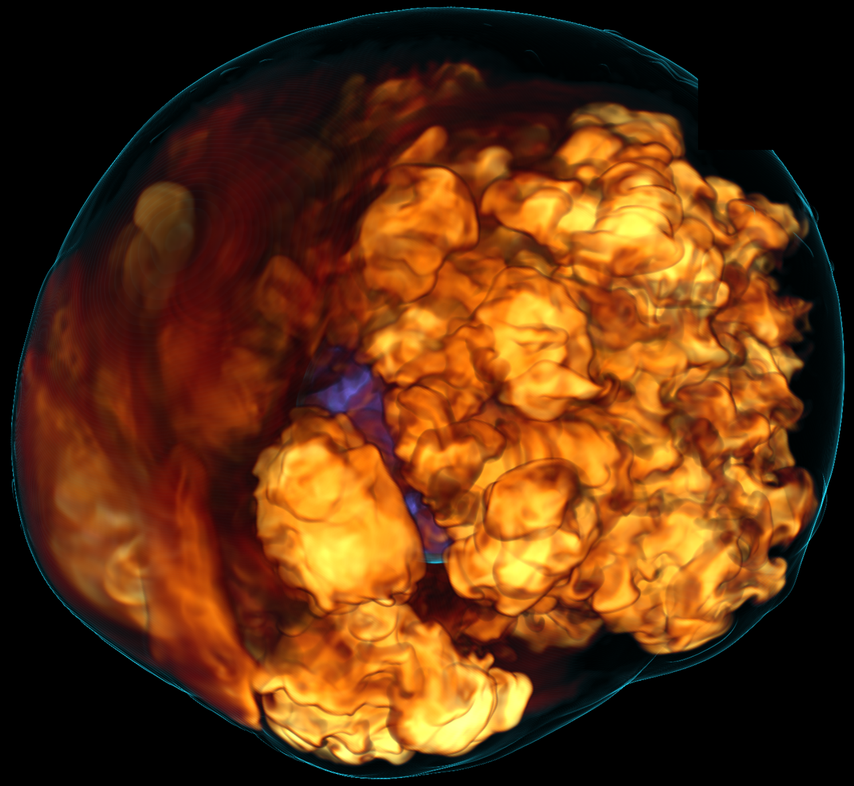
Recent progress in Core-Collapse Supernovae

Evan O'Connor, Stockholm University

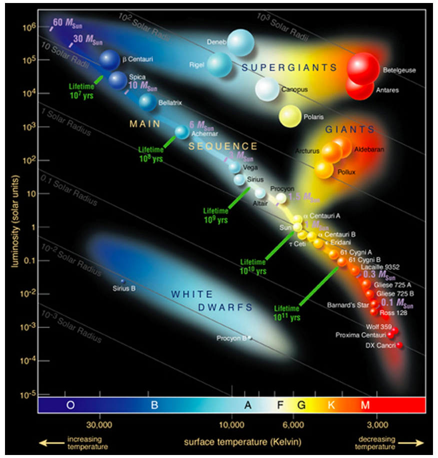
Outline:

- SN theory & status
- Nuclear EOS
  (work by Andre Schneider)



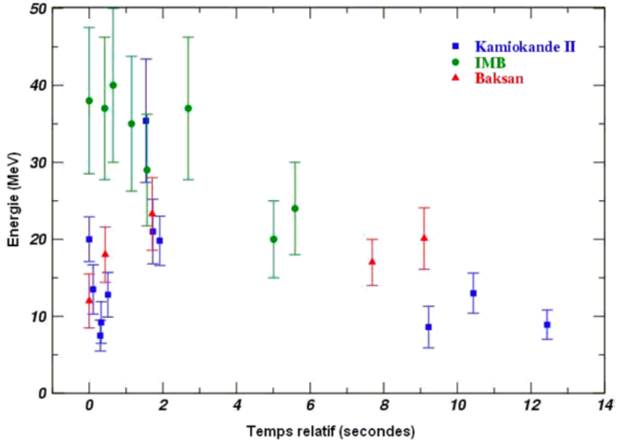
Supernovae have a broad connection to the Universe

Stellar Evolution

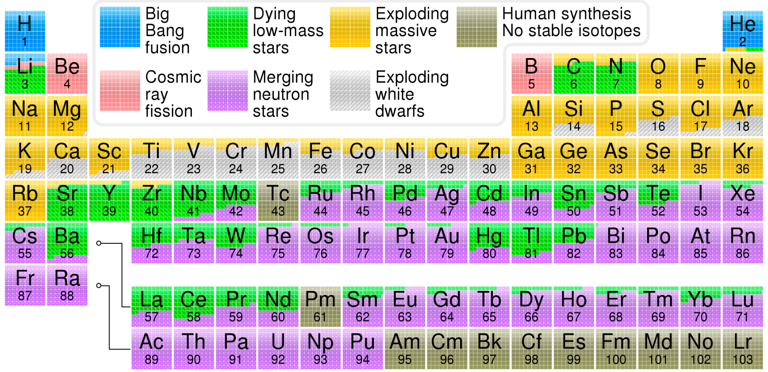


ESO

Neutrinos & Gravitational Waves

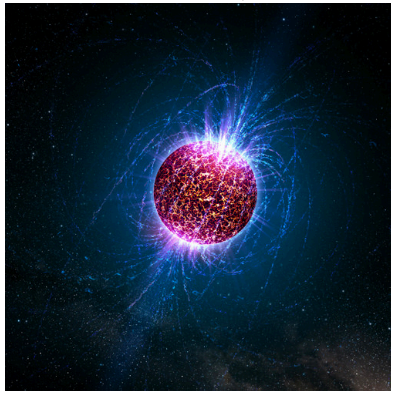


Nucleosynthesis

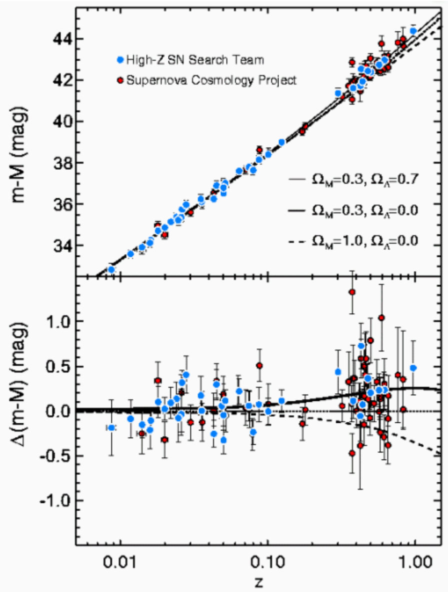


Wikimedia/Jennifer Johnson

Extreme Nuclear Physics

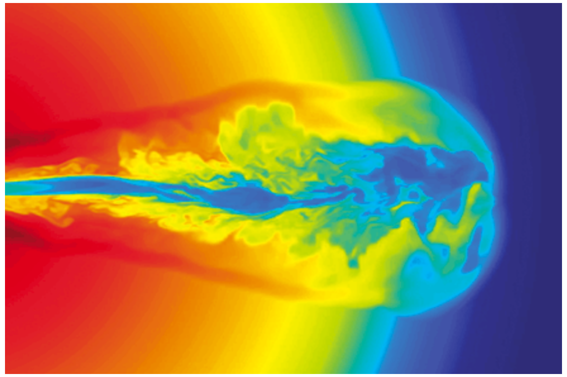


Cosmology



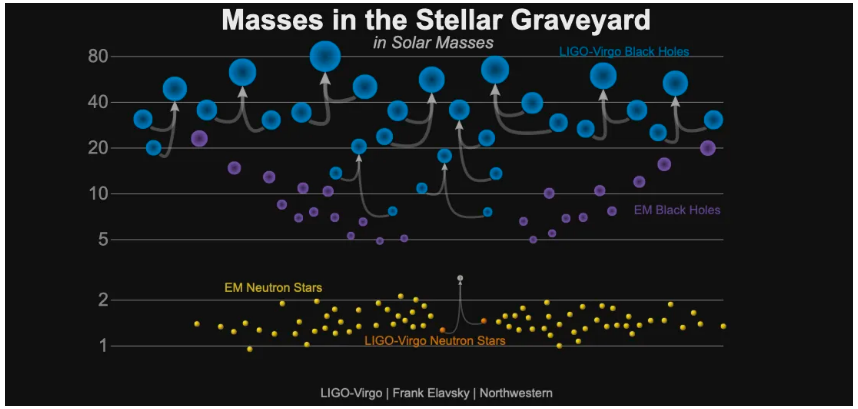
High-Z & SCP

Long gamma-ray burst



Science/MacFadyen

Neutron Star & Black Holes

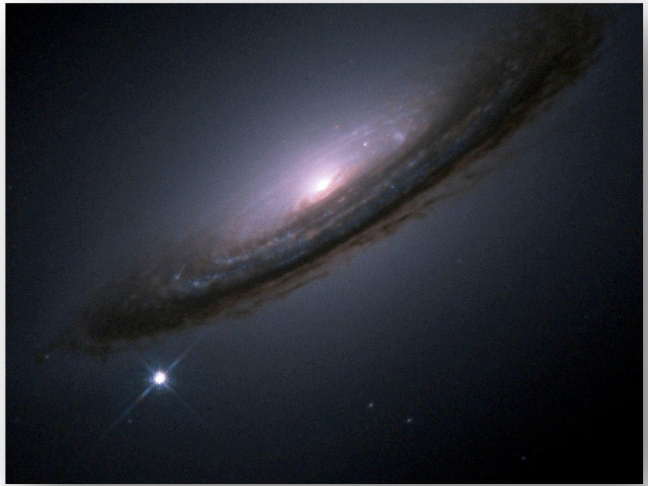


LIGO/VIRGO

Galaxy Evolution

Hubble

Supernova Types

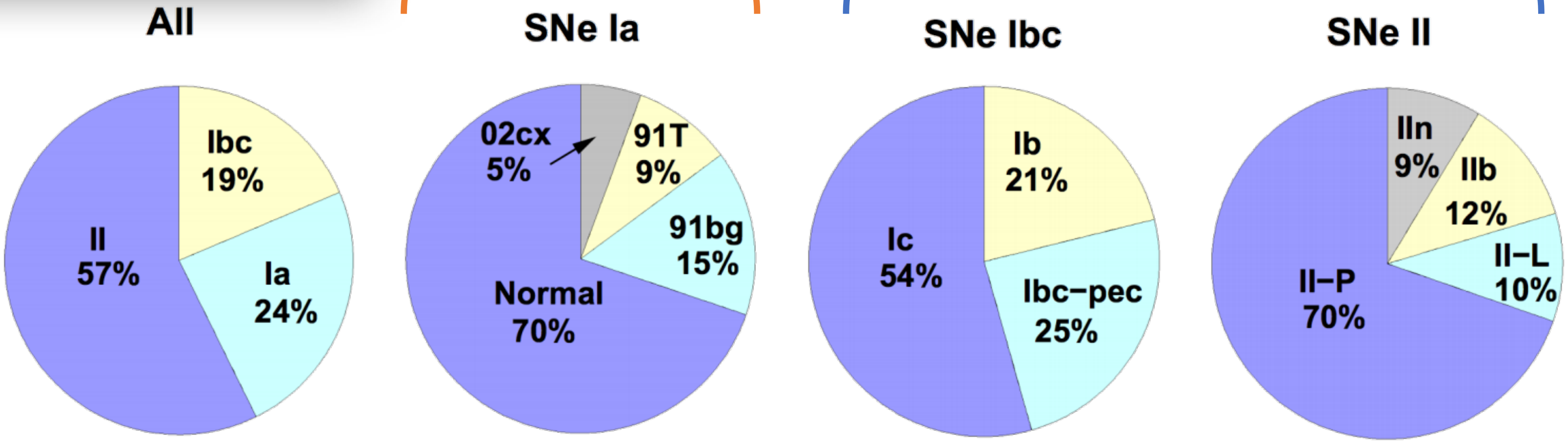


HST

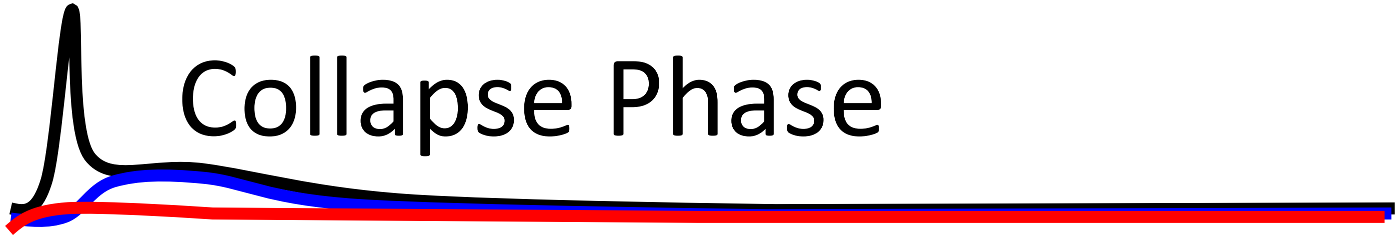
HST

Thermonuclear

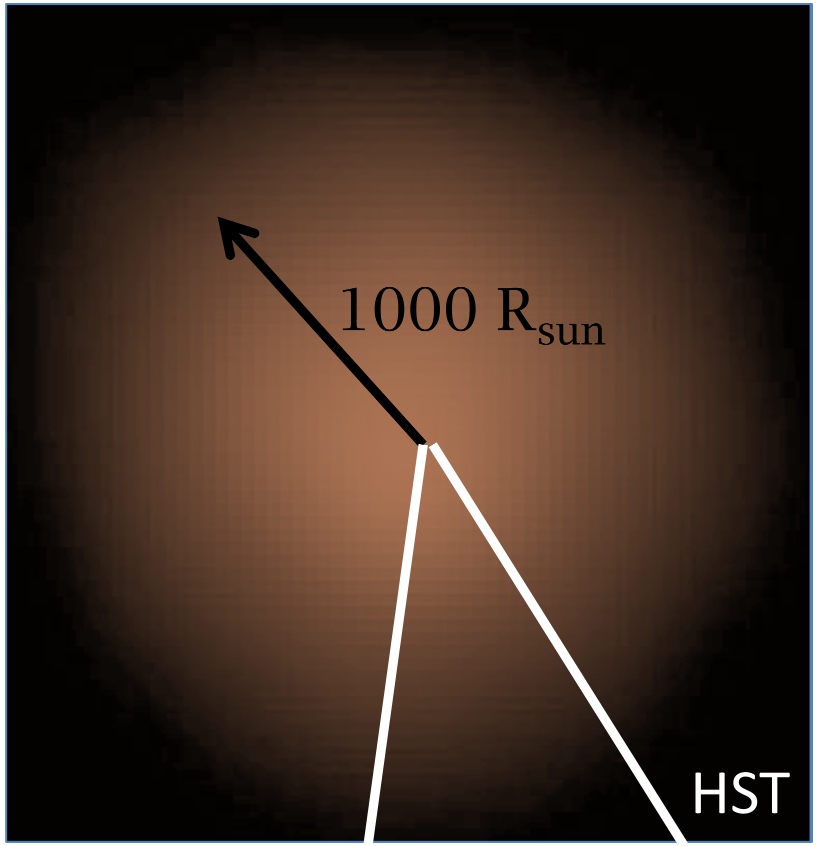
Core Collapse



Volumetric Supernova Survey: Li et al. (2010)

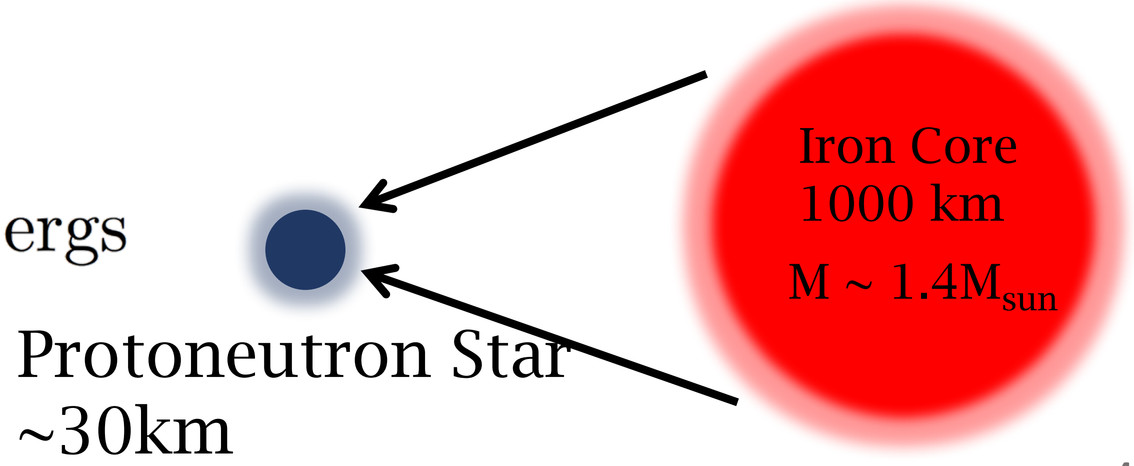


Collapse Phase



- 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

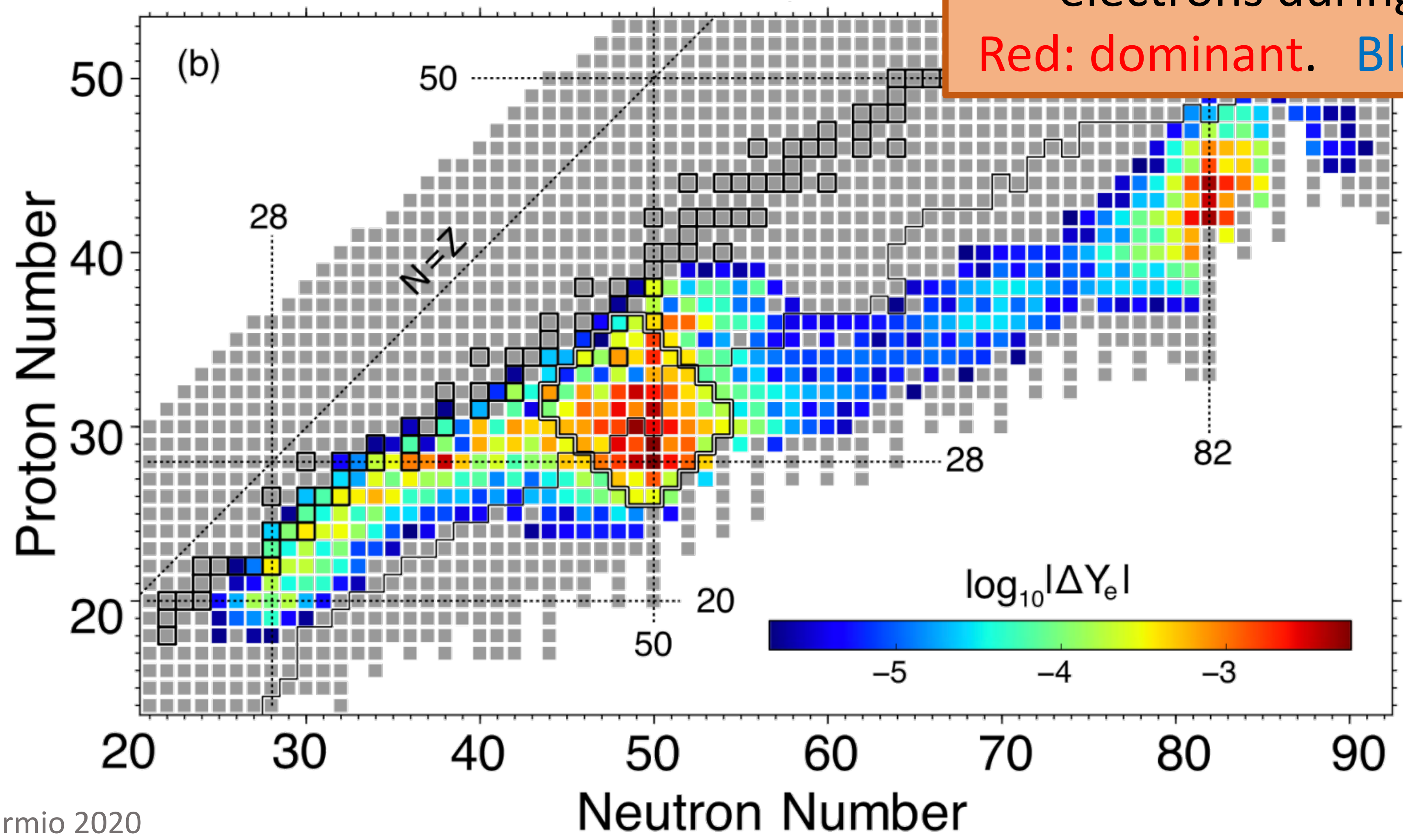
$$-\frac{3}{5}\left[\frac{GM^2}{1000\text{km}} - \frac{GM^2}{12\text{km}}\right] \sim 300 \times 10^{51}\text{ergs}$$



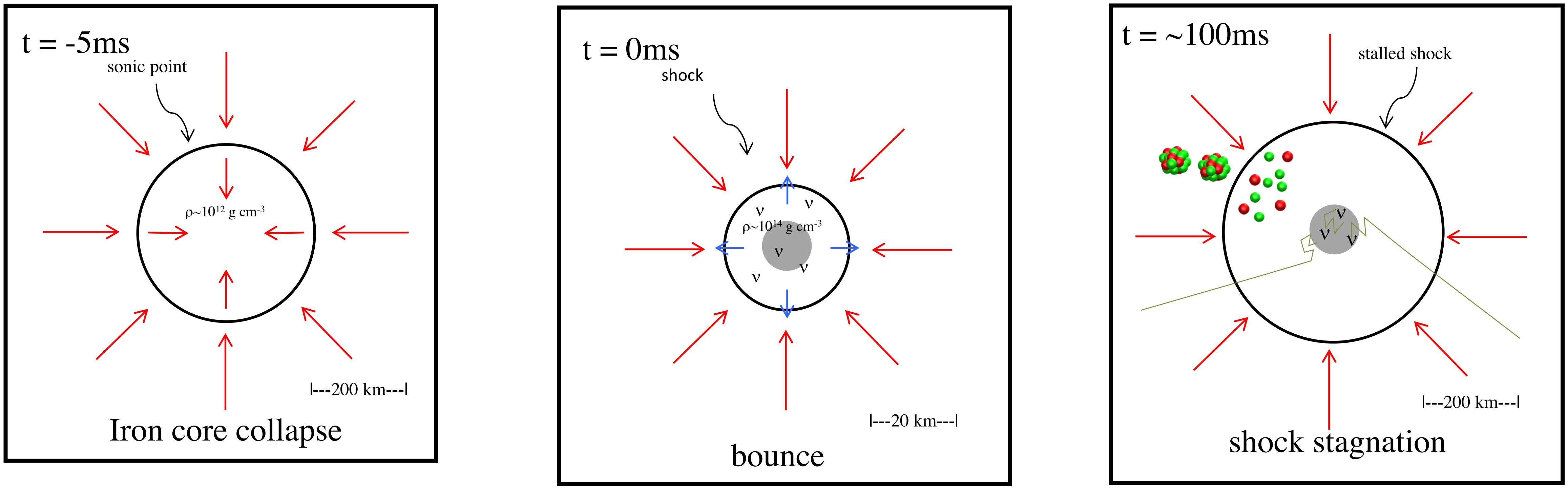
Electron Captures during Collapse

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

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



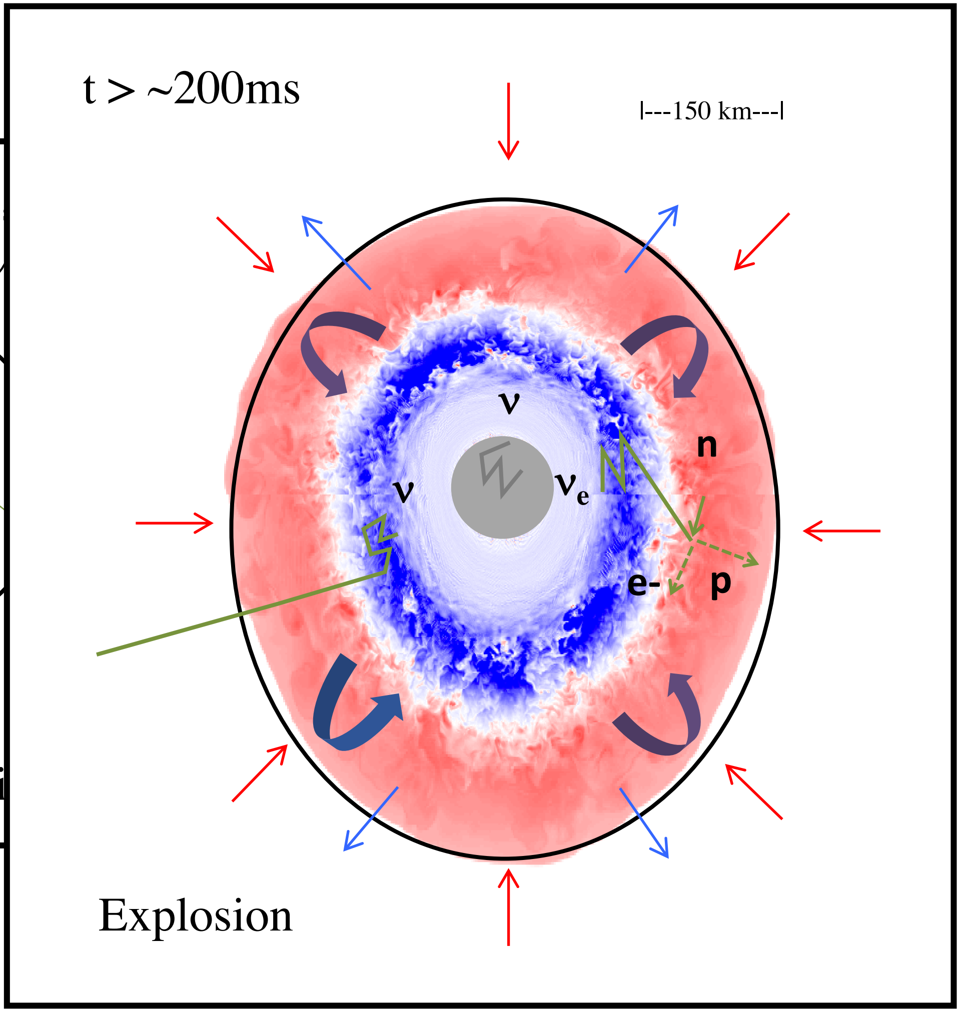
CCSNe: The Stages



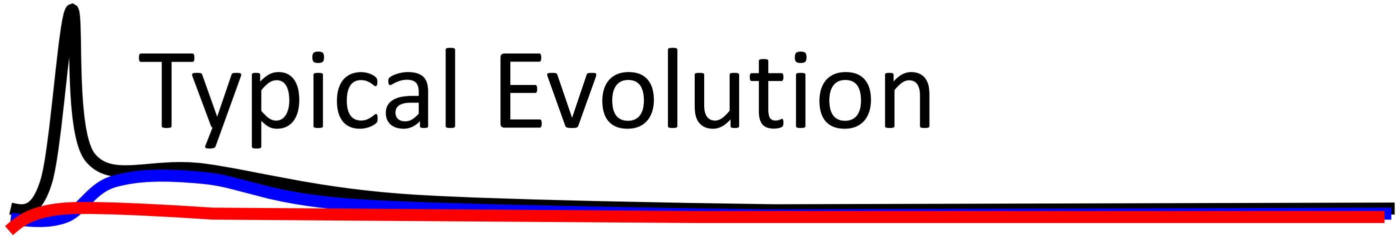
CCSNe: The Stages

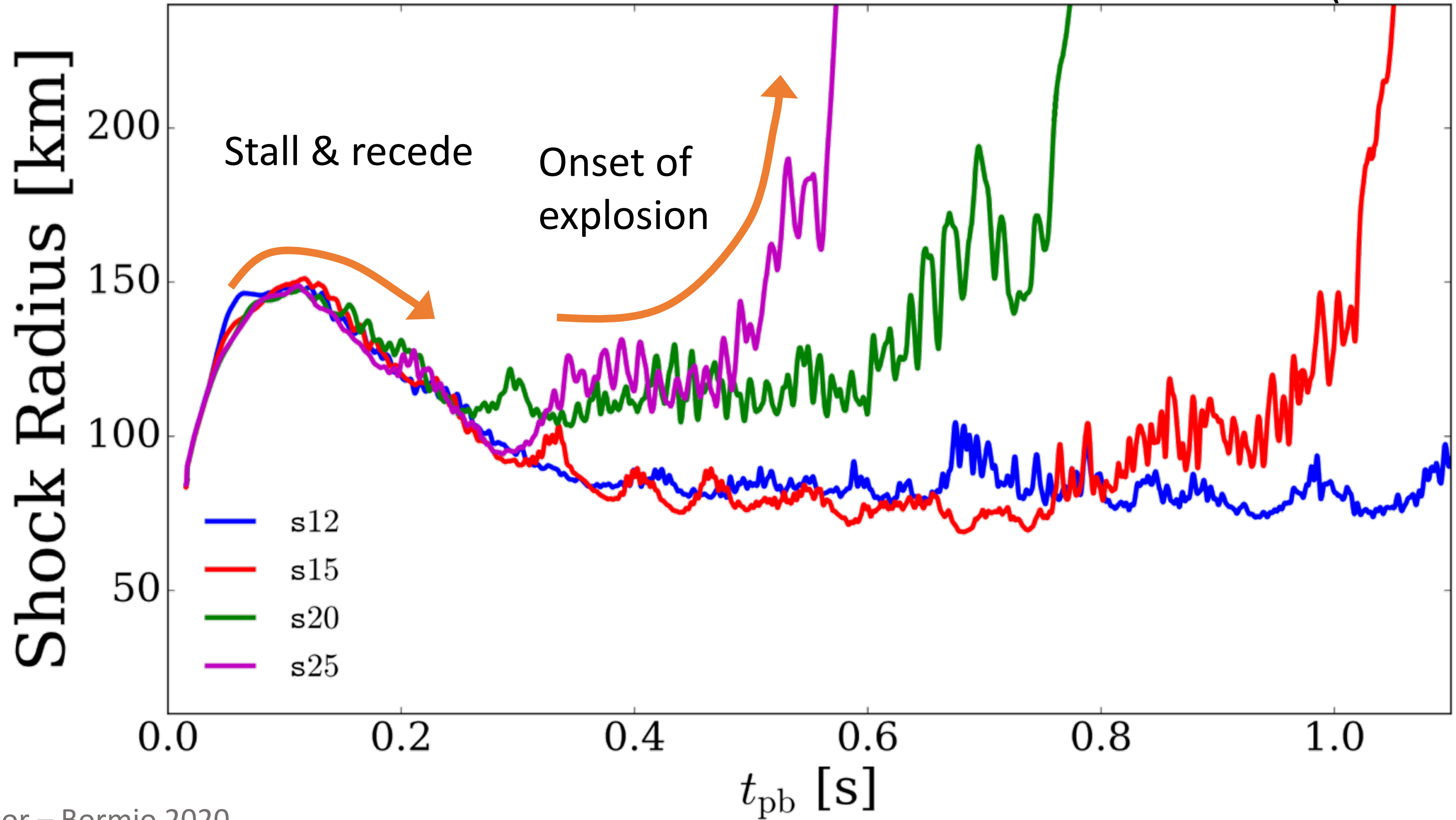
t = -5ms

- The prevailing mechanism is the **turbulence-aided neutrino mechanism**
  - Neutrinos from core heat outer layers
  - Drives convection
  - Turbulence pressure support aids heating and drives explosion
- Very successful in 2D*, many successful explosions
- Success in 3D too: fewer simulations



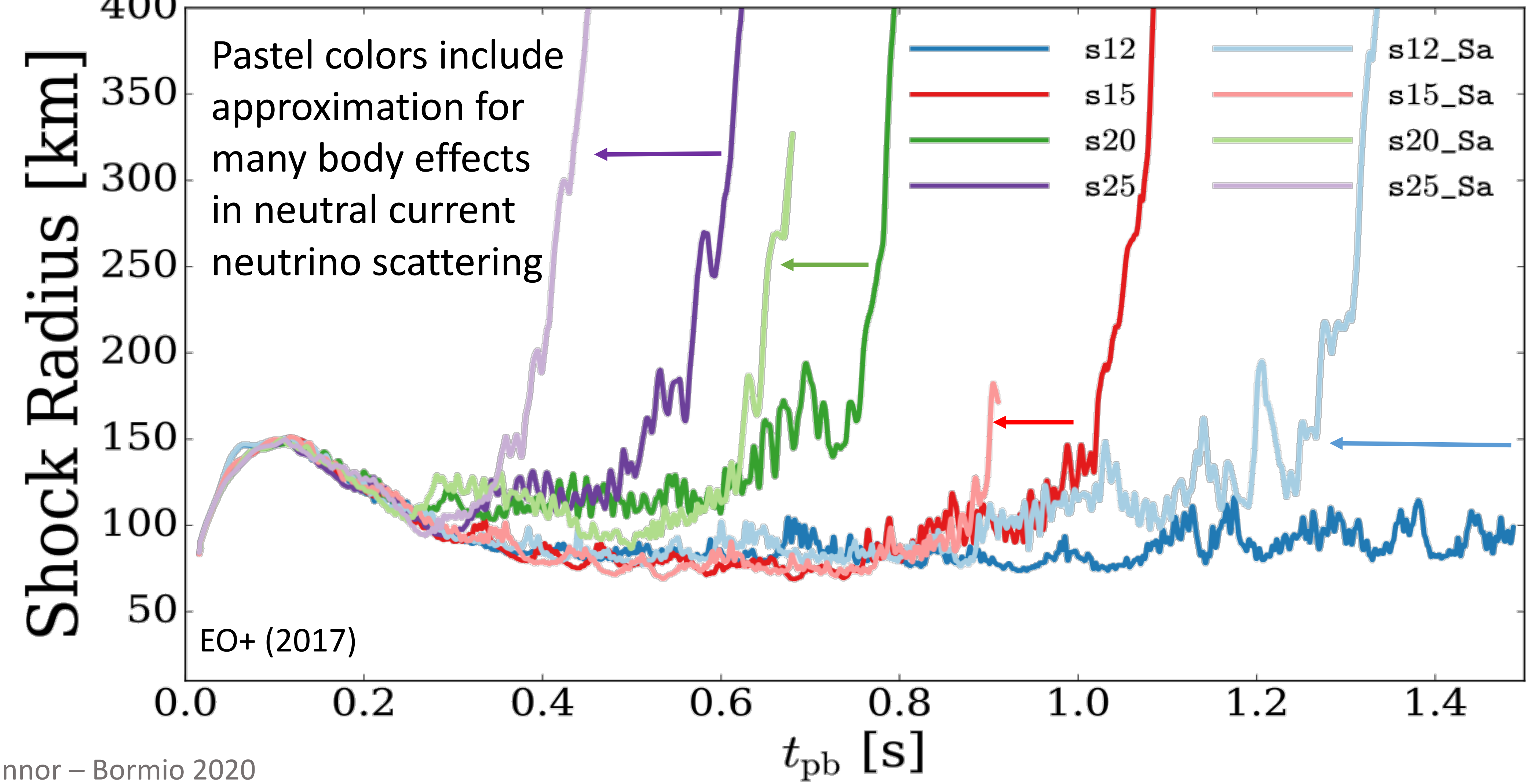
Typical Evolution





Sensitivity to Neutrino Microphysics

EO et al. (2017)



The Core-Collapse Supernova Problem

Understanding the transition from an imploding iron core to an exploding star has been a persistent and difficult problem in astrophysics.

Requires:

3D - (Magneto)hydrodynamics

General Relativity

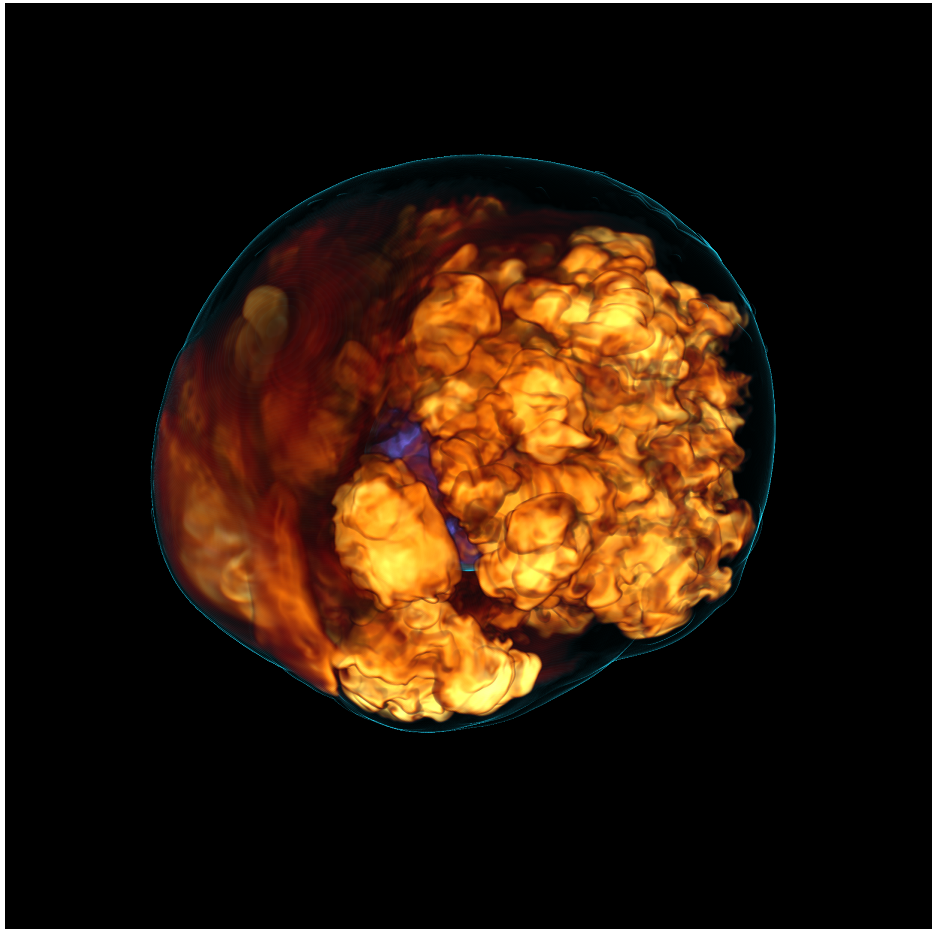
Nuclear Reactions

Progenitors

Nuclear Equation of State

Neutrino Transport & Interactions

Computational Physics



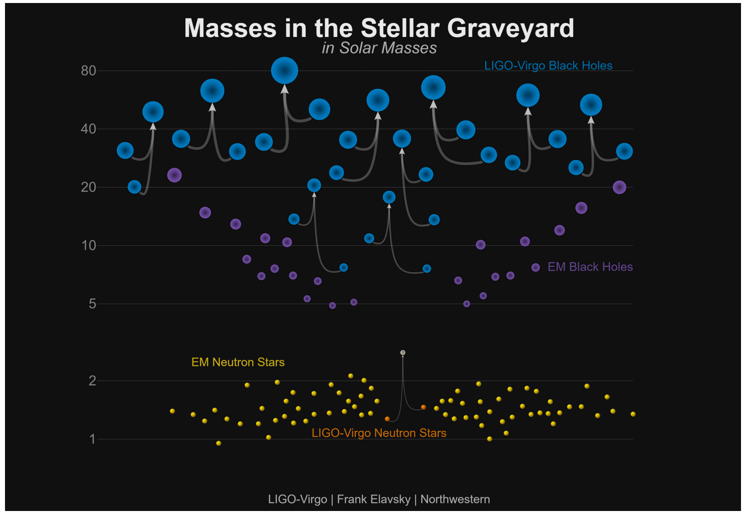
Not all core collapses will succeed

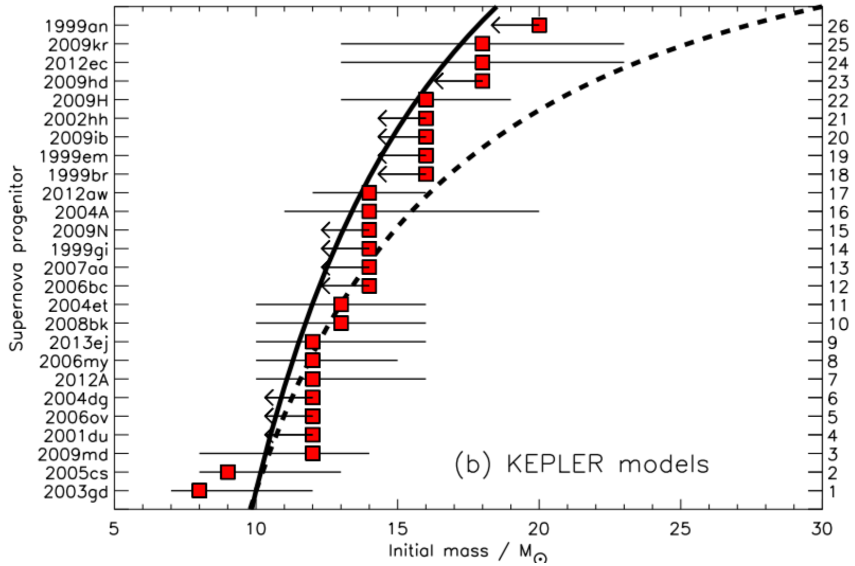
Smartt et al.

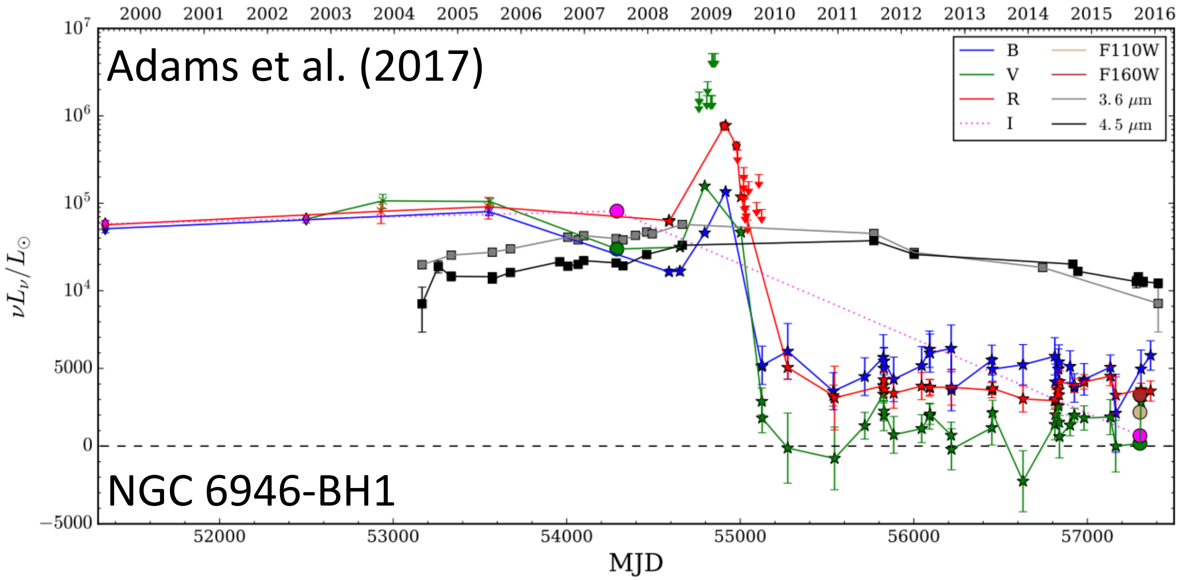
- Progenitors of Type II-P CCSNe suggest a maximum mass of ~16.5 +/- 1.5 M_{sun} – but RSG extend to 25 M_{sun} (Smartt 2015)

- 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

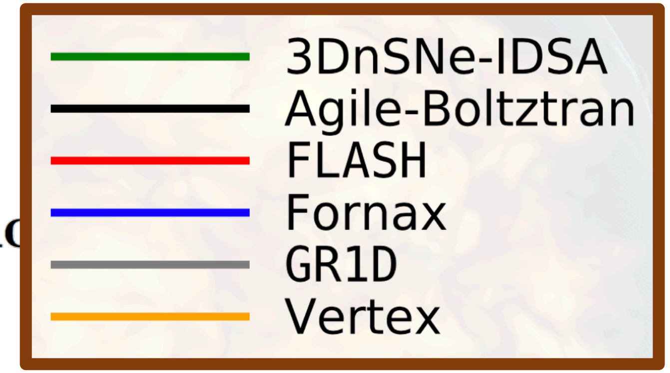


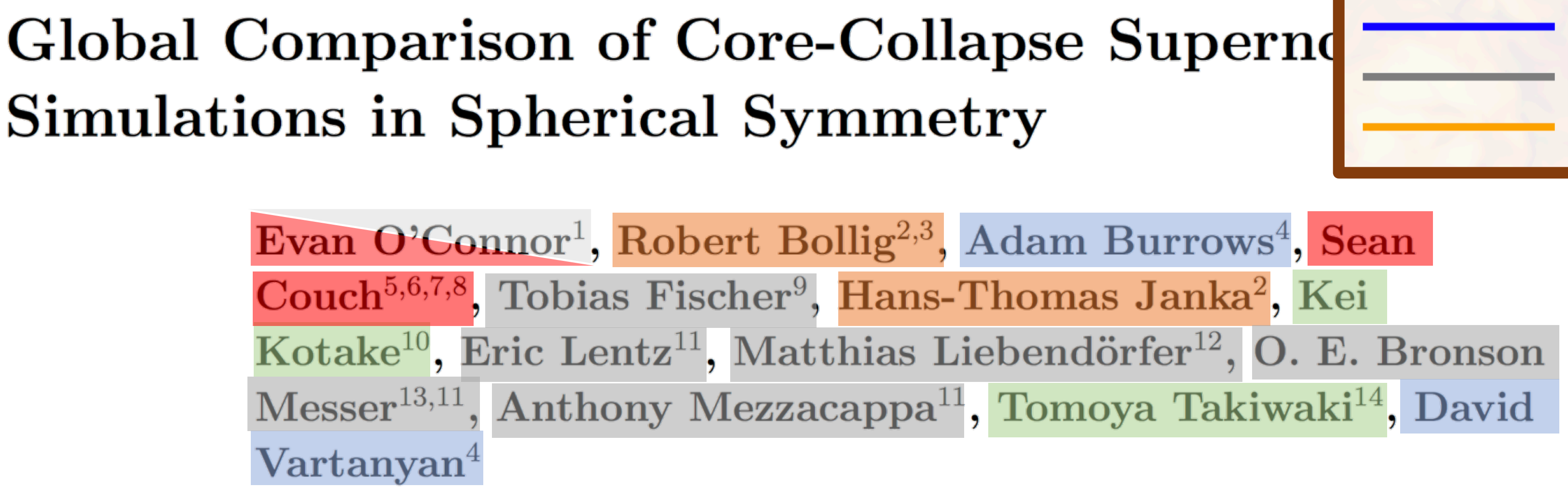




Global effort towards agreement

- Want to demonstrate the community's ability to simulate SN
- Comparison of 6 core-collapse supernova codes
- *Very carefully* control input physics and initial conditions to ensure fair comparison



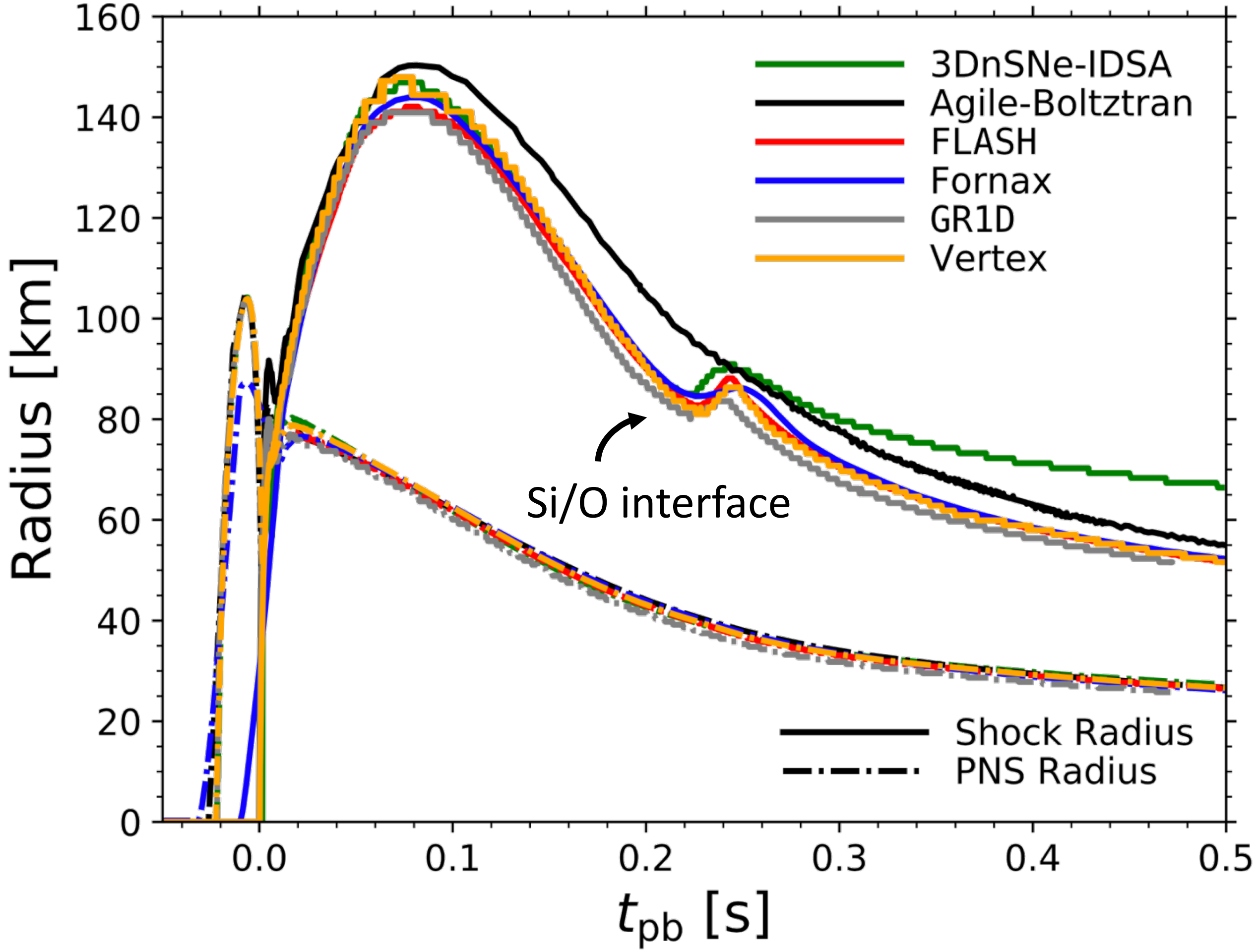


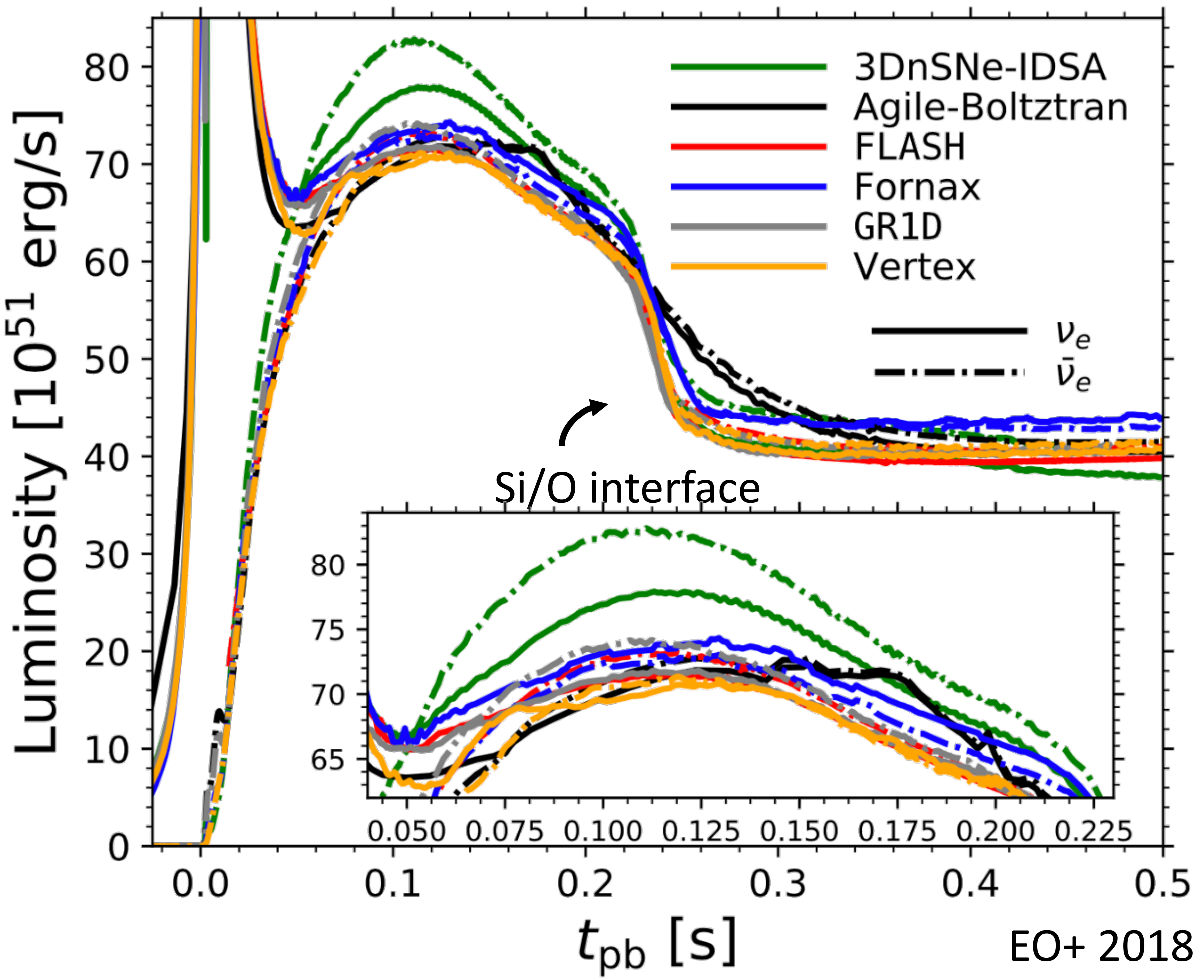
Global Comparison of Core-Collapse Superno
Simulations in Spherical Symmetry

Evan O'Connor[1], Robert Bollig[2,3], Adam Burrows[4], Sean Couch[5,6,7,8], Tobias Fischer[9], Hans-Thomas Janka[2], Kei Kotake[10], Eric Lentz[11], Matthias Liebendörfer[12], O. E. Bronson Messer[13,11], Anthony Mezzacappa[11], Tomoya Takiwaki[14], David Vartanyan[4]

Journal of Physics: G 45 10 2018

Excellent Agreement in 1D





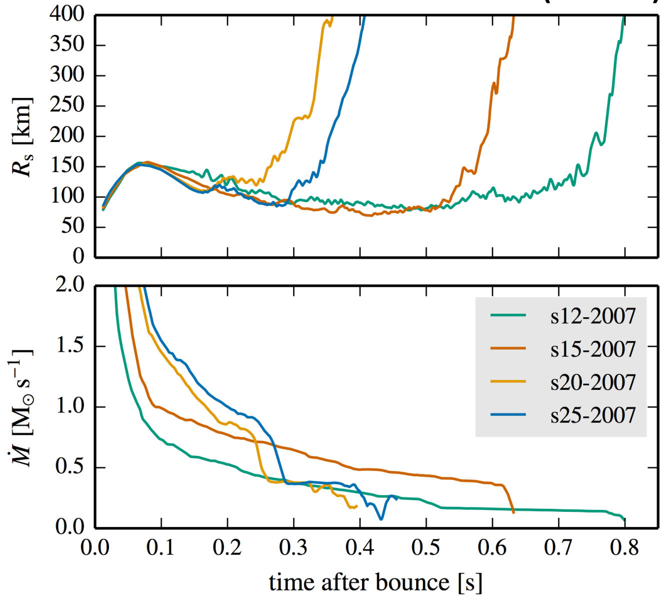
EO+ 2018

Explosion Successes in multiD – 2D

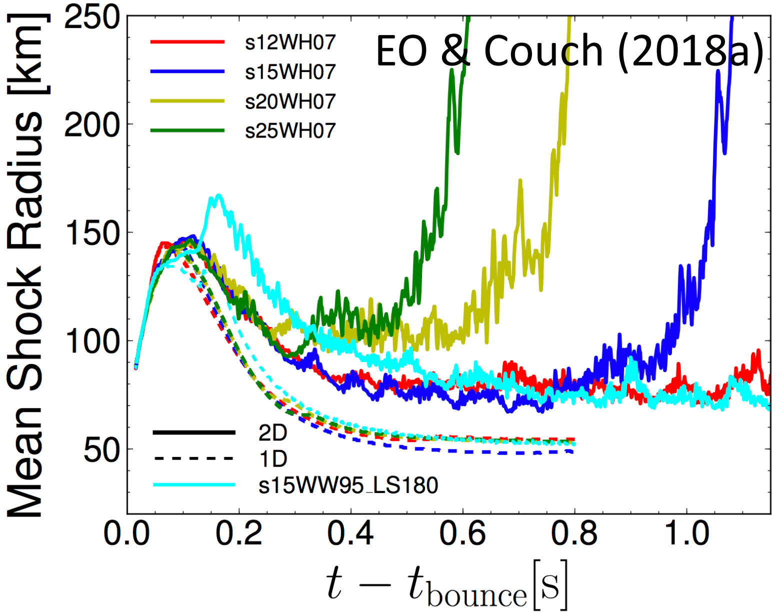
As much as possible

Same EOS, Same progenitors, Same gravity, Same neutrino interactions -

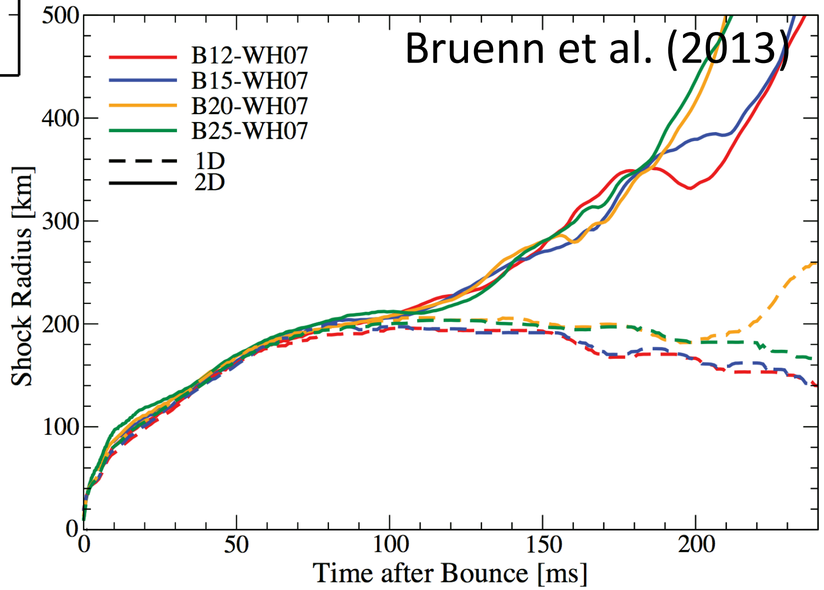
Summa et al. (2016)



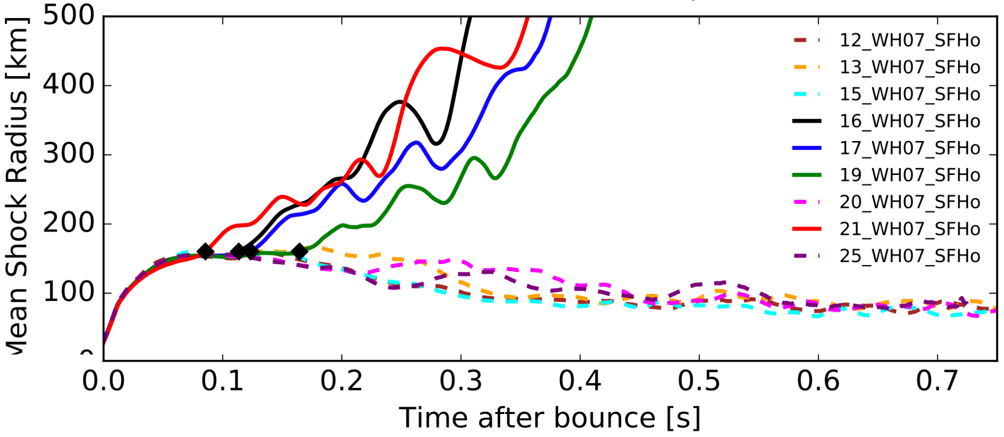
EO & Couch (2018a)



Bruenn et al. (2013)

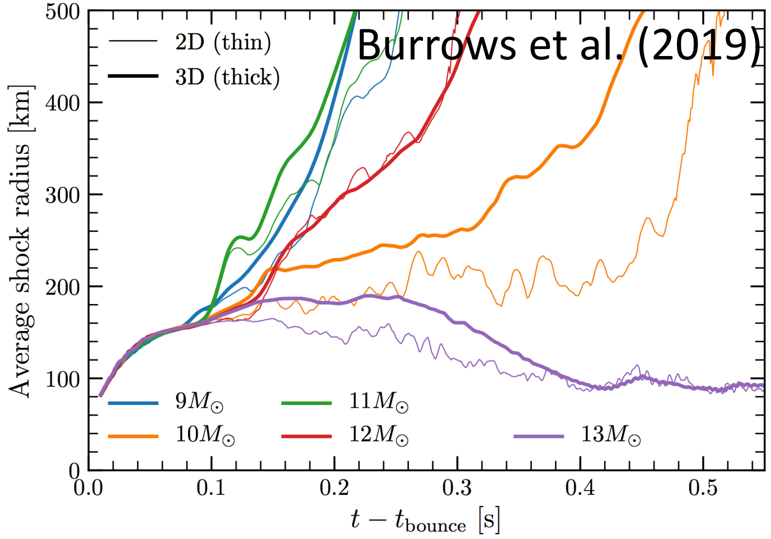


Vartanyan et al. (2018)

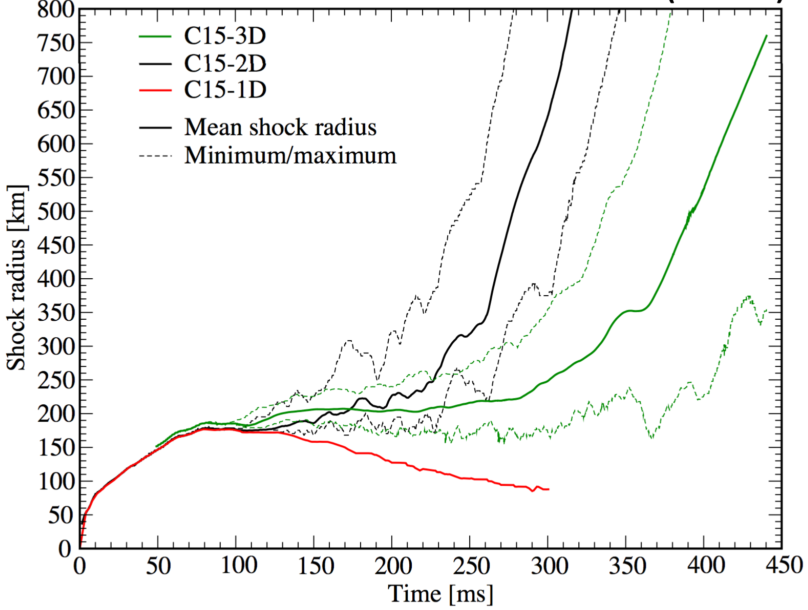


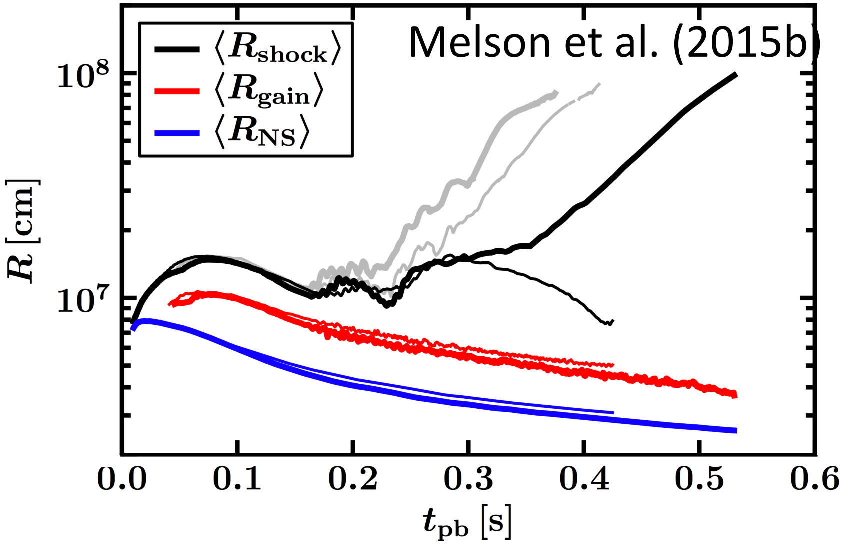
Explosion Successes in multiD – 3D

- Similar progenitors
- GR gravity
- Non-rotating

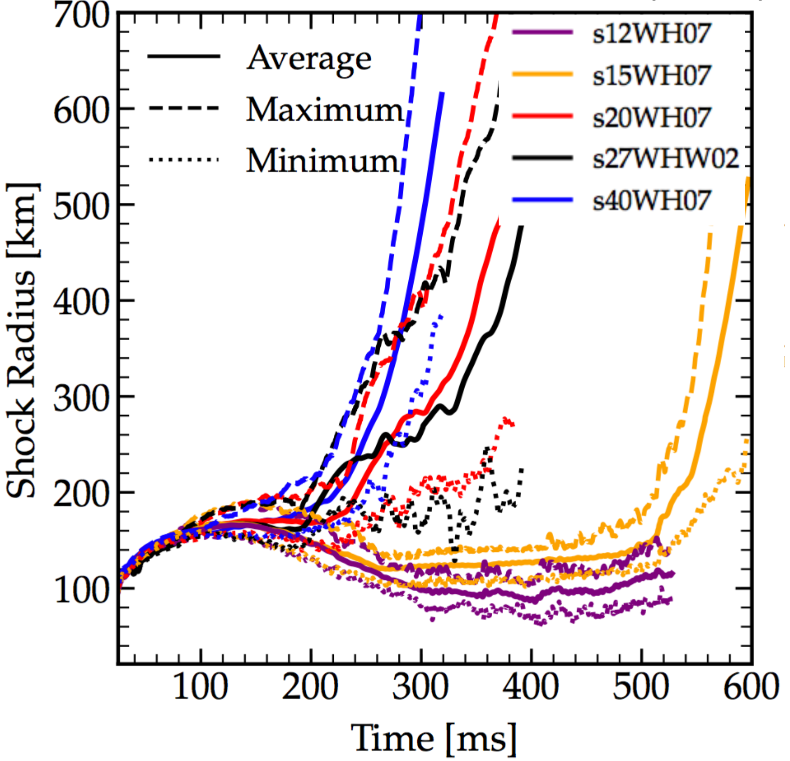


Lentz et al. (2015)



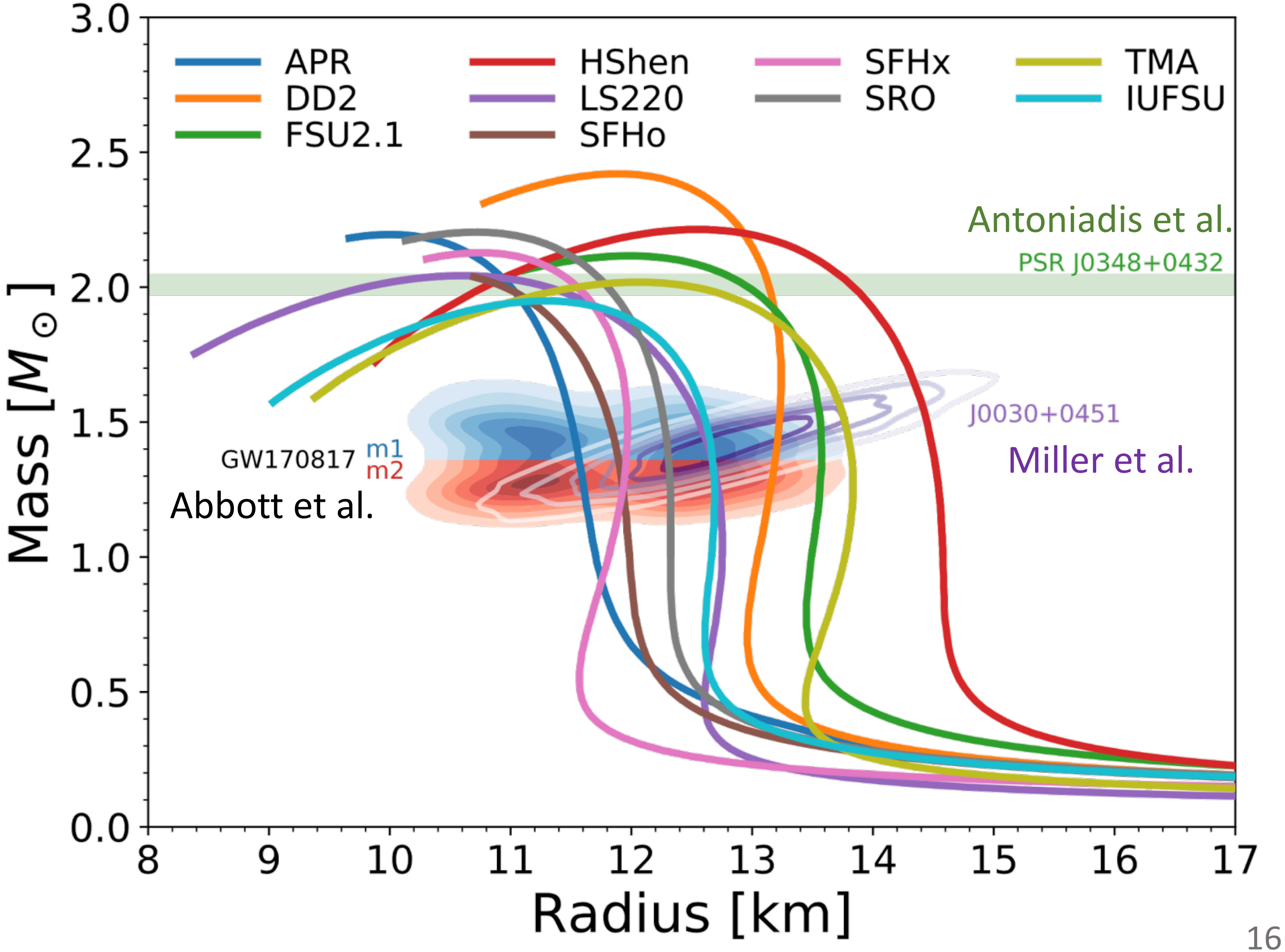


Ott et al. (2018)



Nuclear Equation of State and Core Collapse

Wide variety of finite temperature EOS to choose from



Need:

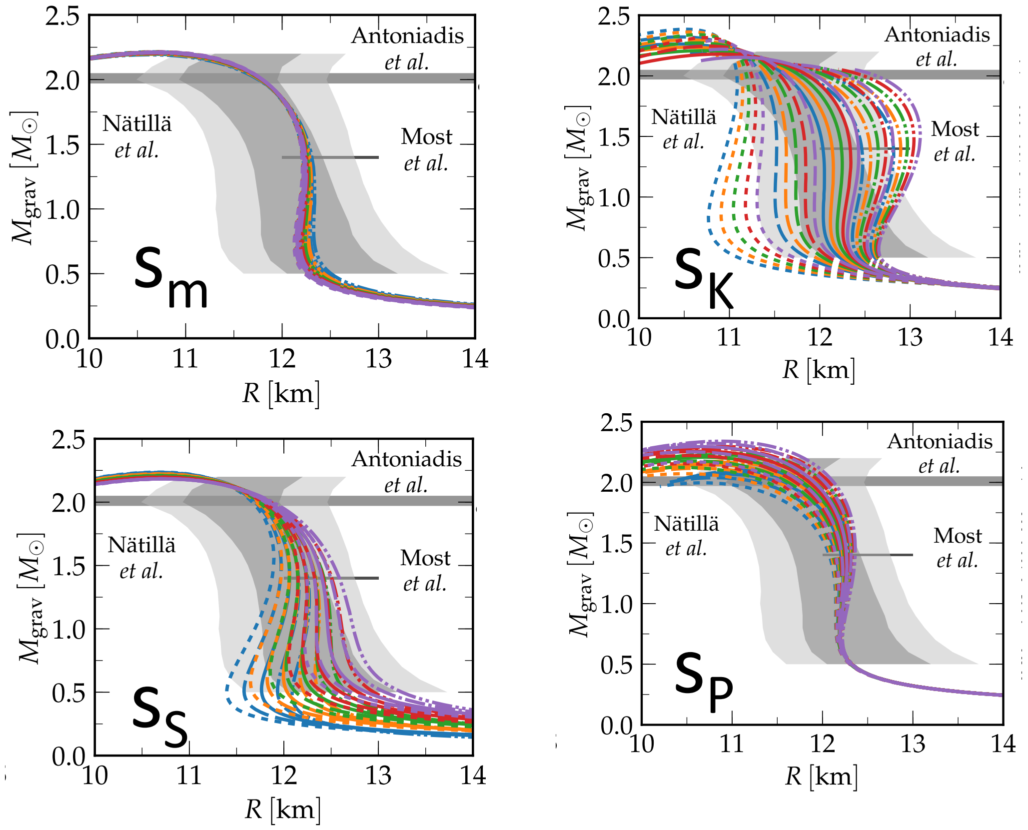
- $1e\text{-}12 < n_b\ [fm^{-3}] < 10$
- $0.01 < T\ [MeV] < 150$
- $0 < Y_p < 0.6$

Impact assessed only with systematic studies

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	$\rm MeV\ baryon^{-1}$
s_S	$\epsilon_{\rm sym}$	32 ± 2	32 ± 2	$\rm MeV\ baryon^{-1}$
	$L_{\rm sym}$	60 ± 15	45 ± 7.5	$\rm MeV\ baryon^{-1}$
s_K	$K_{\rm sat}$	230 ± 20	230 ± 15	$\rm MeV\ baryon^{-1}$
	$K_{\rm sym}$	-100 ± 100	-100 ± 100	$\rm MeV\ baryon^{-1}$
s_P	$P^{(4)}_{\rm SNM}$	100 ± 50	125 ± 12.5	$\rm MeV\ fm^{-3}$
	$P^{(4)}_{\rm PNM}$	160 ± 80	200 ± 20	$\rm MeV\ fm^{-3}$

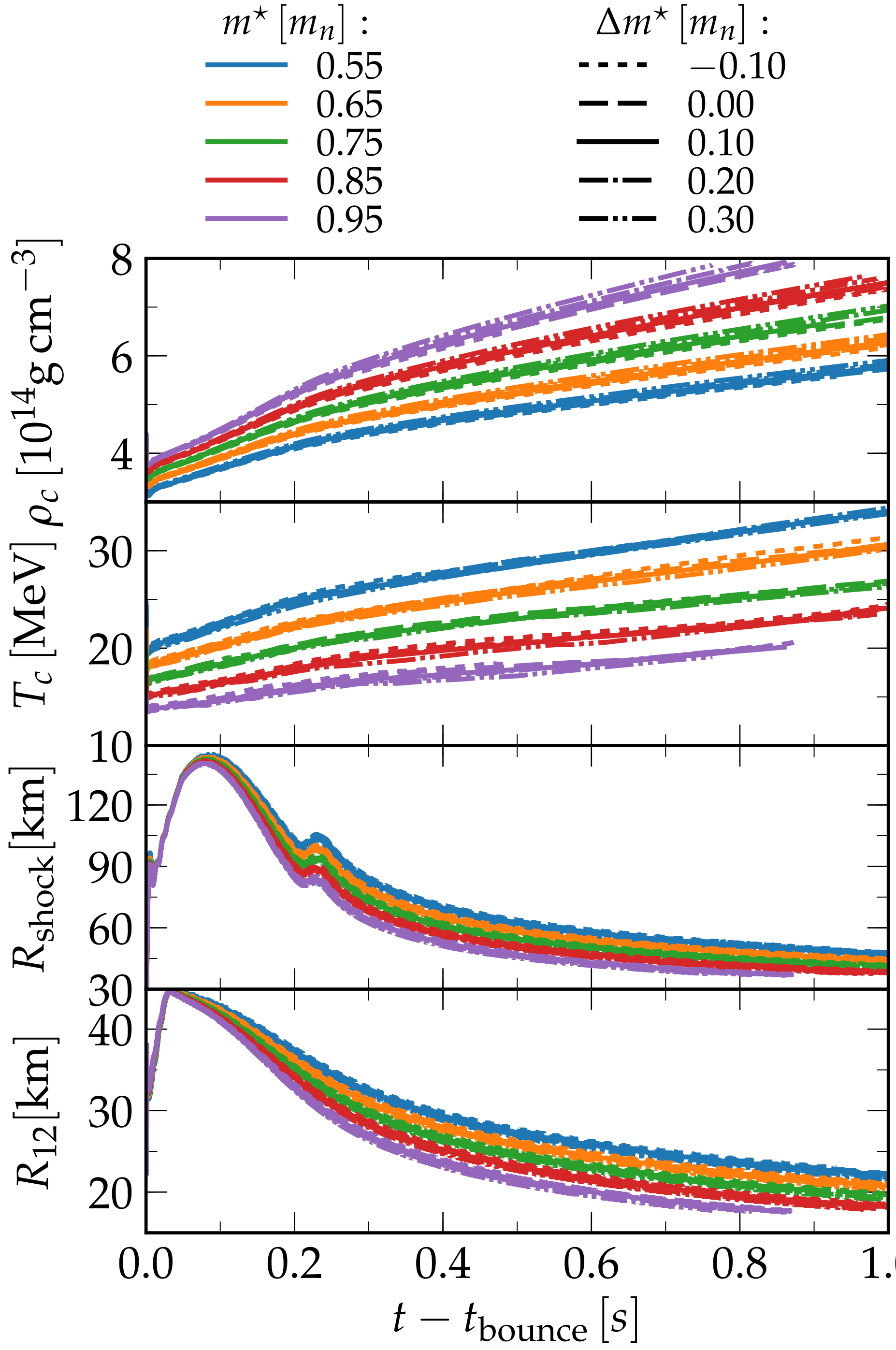
For each of the 4 sets we construct EOSs with 0,+/- 1, and +/- 2 sigma deviations of the parameters (25 for each set, 97 overall)



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

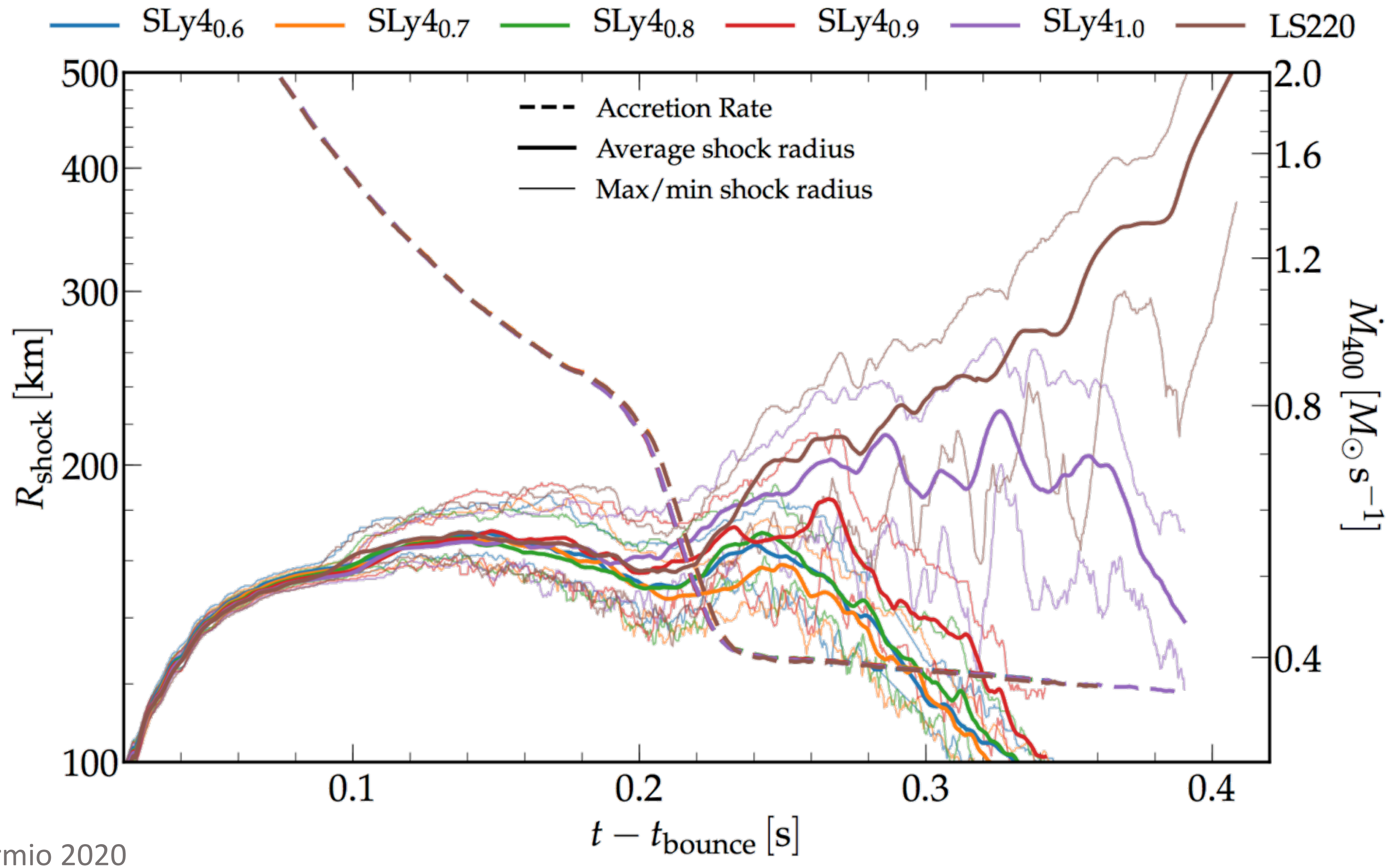
Effective mass (via the impact on the thermal EOS) plays strong and important role in supernova evolution



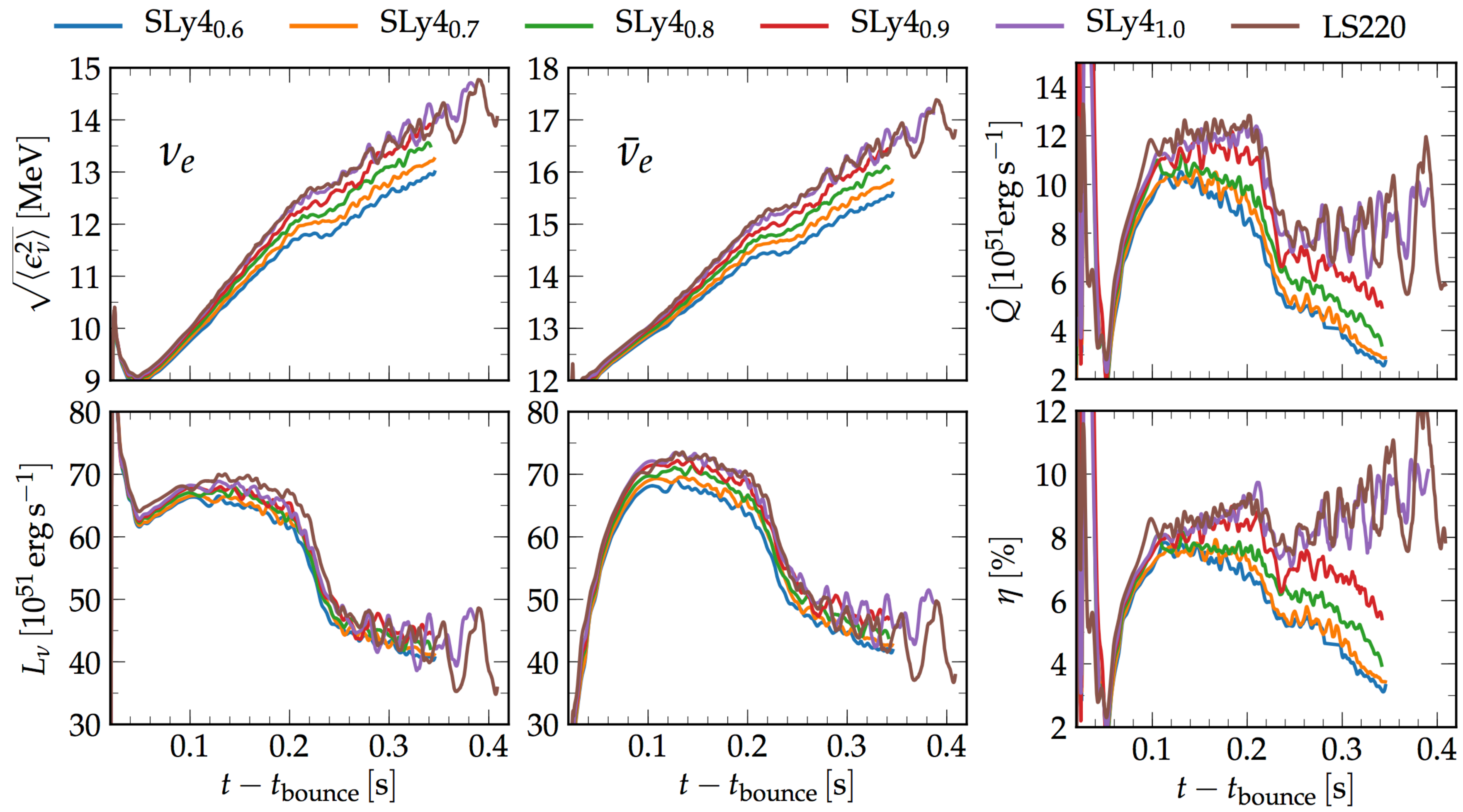
Schneider et al. (2019b)

It does impact the evolution in 3D!

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

Summary

- Core-Collapse supernovae are multi-physics. They require precise nuclear and neutrino microphysics and detailed neutrino transport in 3D
- Core Collapse simulations in multiD explode via the turbulence-aided neutrino mechanism, *across codes and progenitors*
- Equation of state impacts core collapse evolution mainly through thermal effects, less sensitive to cold NS EOS