Computer Simulations of Supernovae

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Collaborators: Erin O’Sullivan (Uppsala), Manne Segerlund (Luleå), Jeff Tsang & Josh Wang (Oxford), Sean Couch (MSU), Michael Pajkos (MSU)

- Theory and Overview of state-of-the-art
- Messengers
  - Neutrino Signal
  - Gravitational Wave Signal

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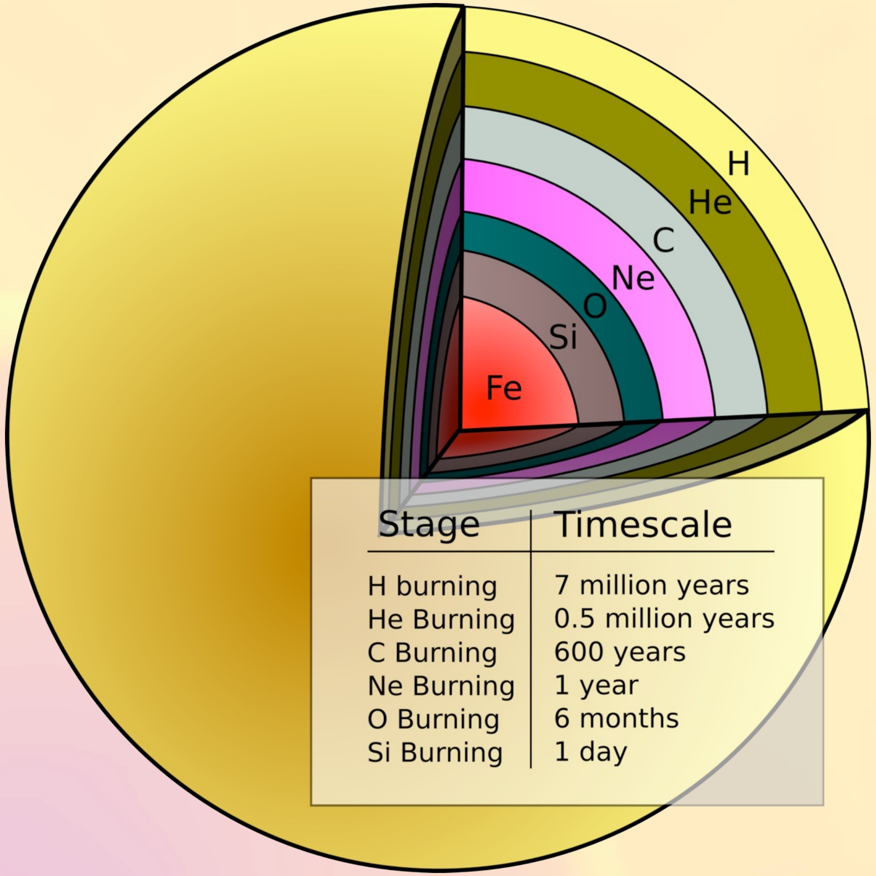
Massive Stars: Burning Stages

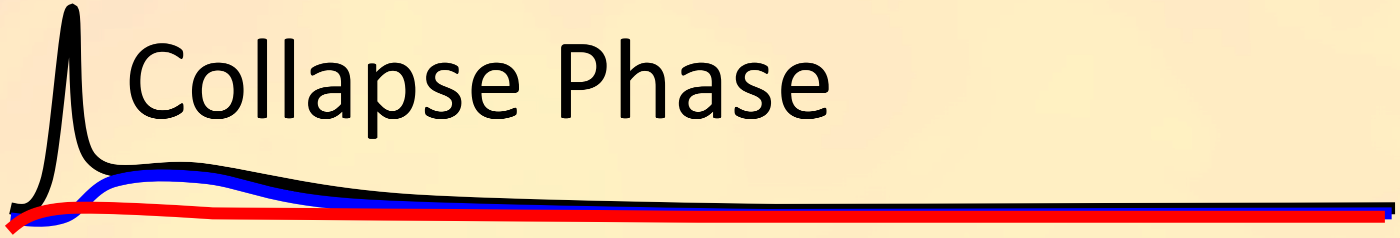
- Stars spend most of their lives burning hydrogen.
- For massive stars ($M > 8\text{-}10M_{sun}$), the process continues through helium, carbon, … , up to iron.
- This process does not continue past iron as iron is one of the most tightly bound nuclei.
- Iron cores however are supported by electron degeneracy pressure, much like a white dwarf, there is a maximum mass that electron degeneracy pressure can support.



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

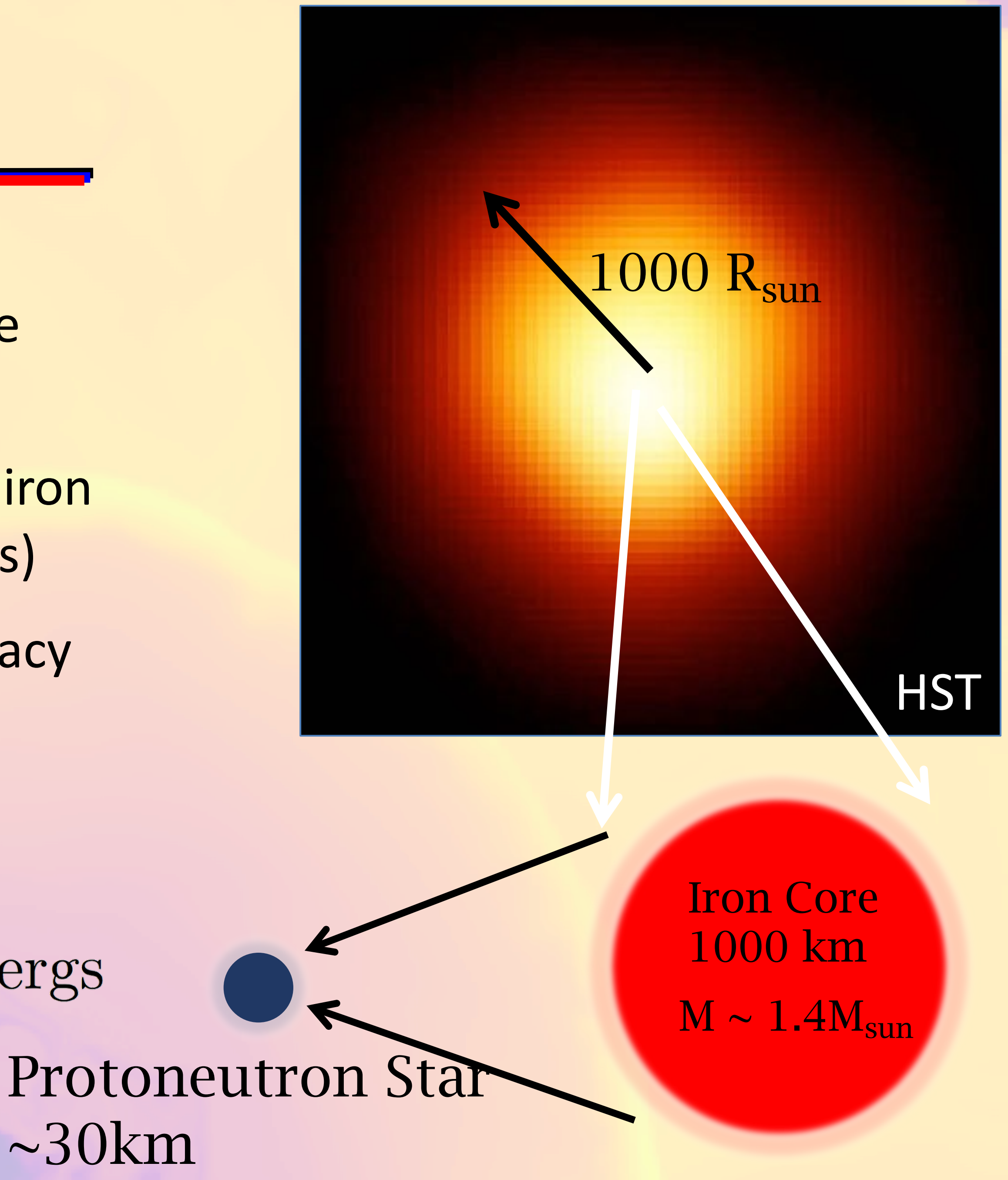
A. C. Phillips, *The Physics of Stars*, 2nd Edition (Wiley, 1999).

Collapse Phase

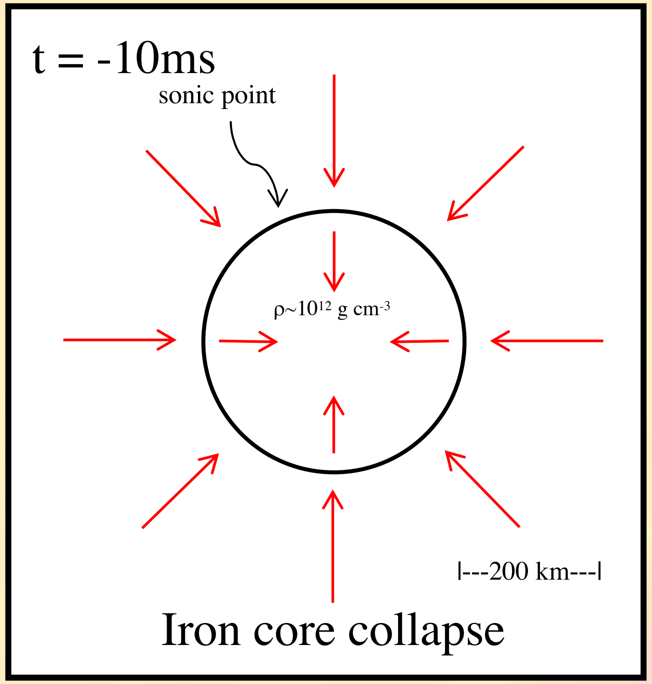


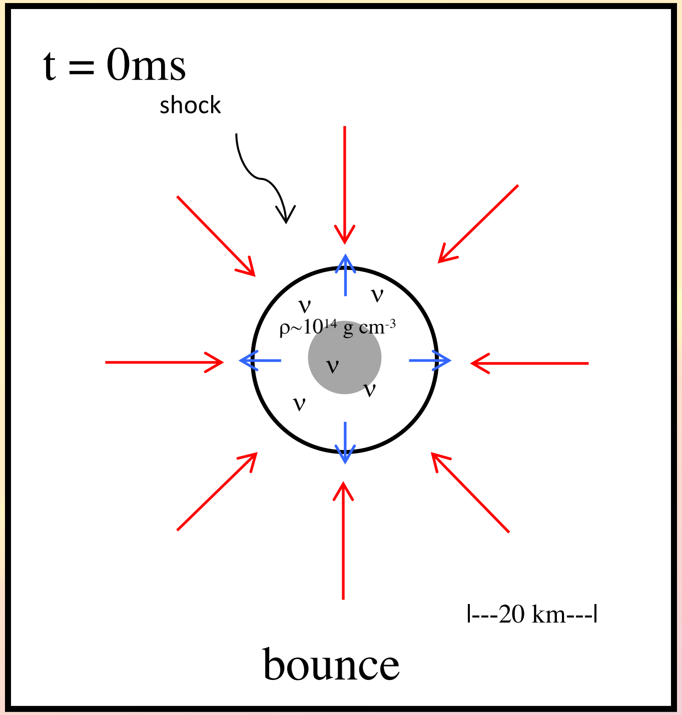
- Most massive stars core collapse during the red supergiant phase
- CCSNe are triggered by the collapse of the iron core (~1000km, or 1/10^6 of the star's radius)
- Collapse ensues because electron degeneracy pressure can no longer support the core against gravity

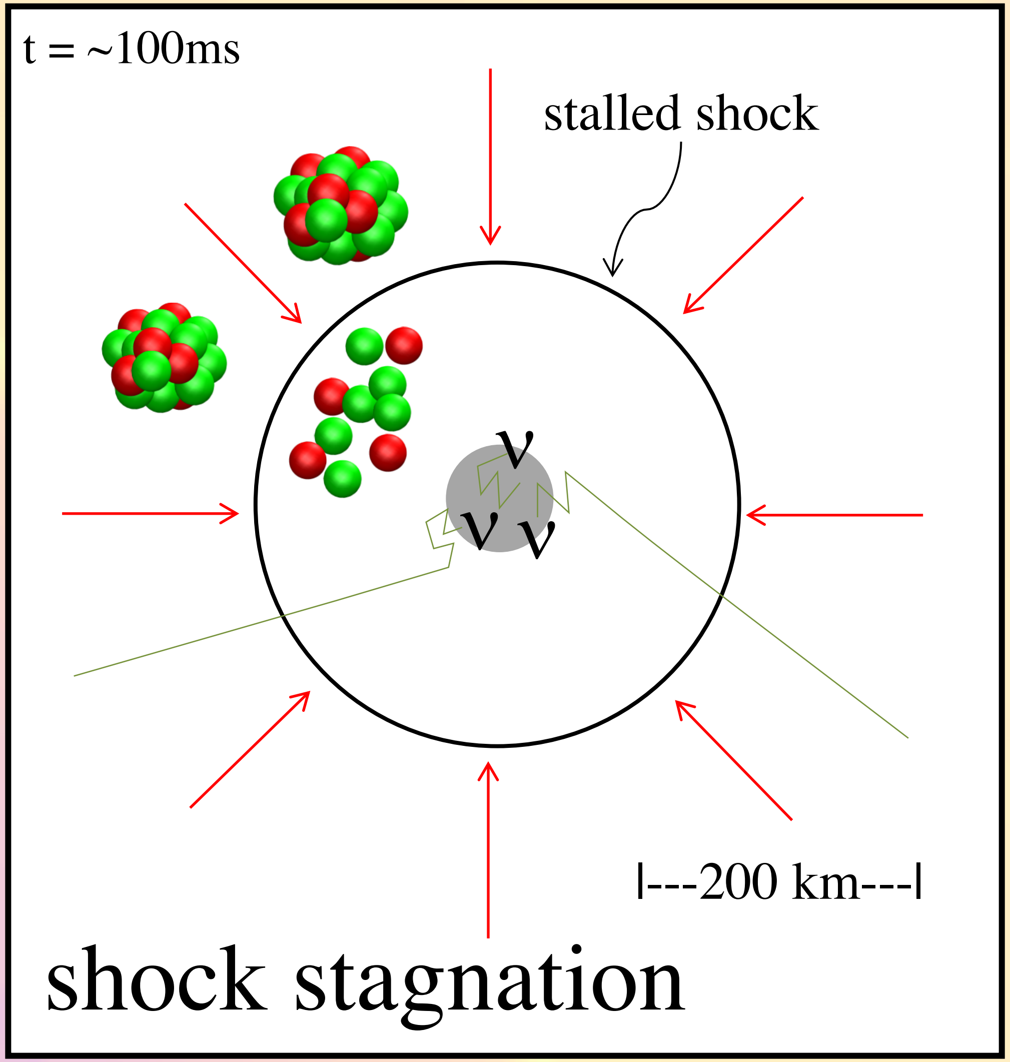
$$-\frac{3}{5}\left[\frac{GM^2}{1000\text{km}} - \frac{GM^2}{12\text{km}}\right] \sim 300 \times 10^{51}\text{ergs}$$



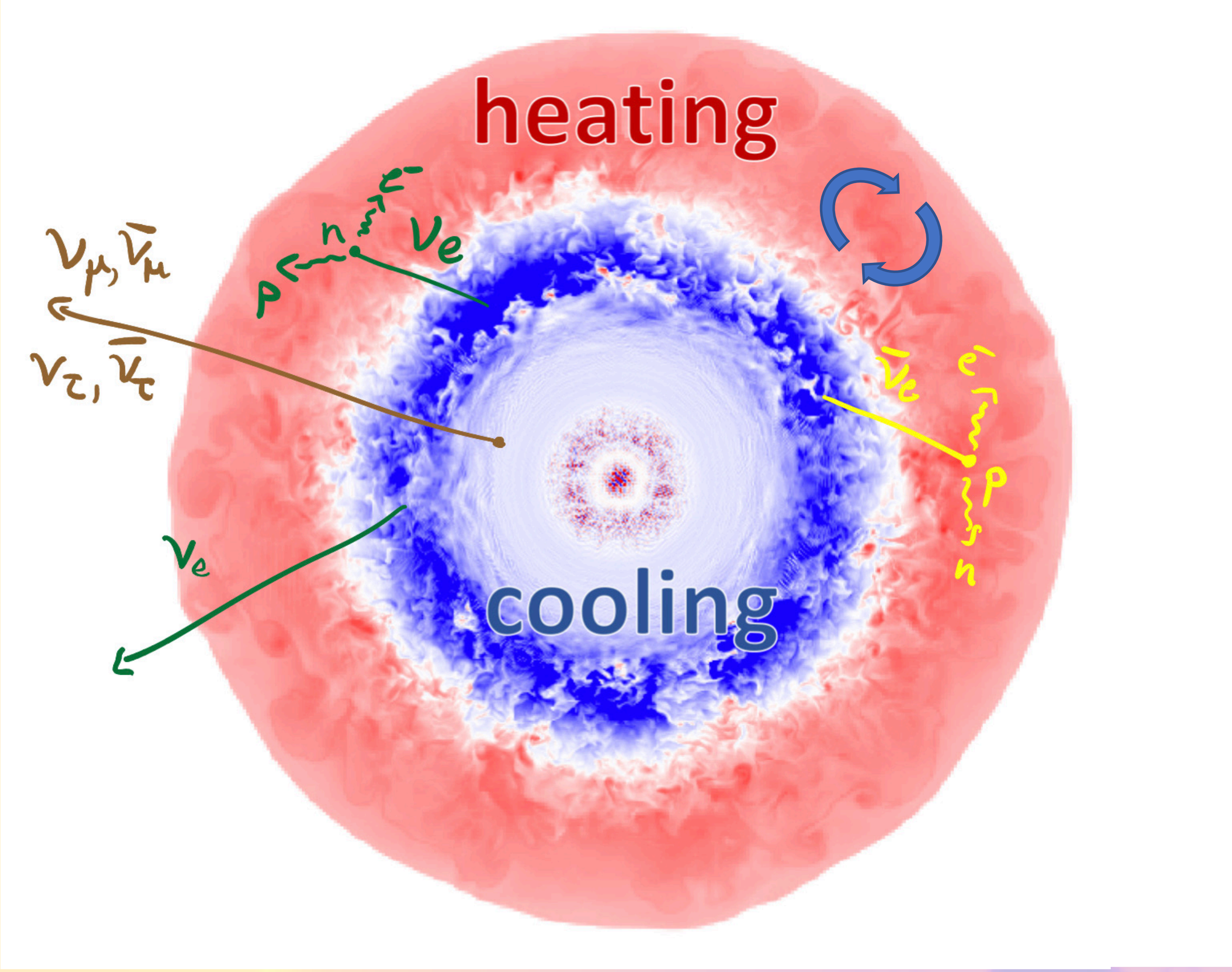
Core-Collapse: The Stages







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*, many successful explosions, also successful in 3D although fewer simulations

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

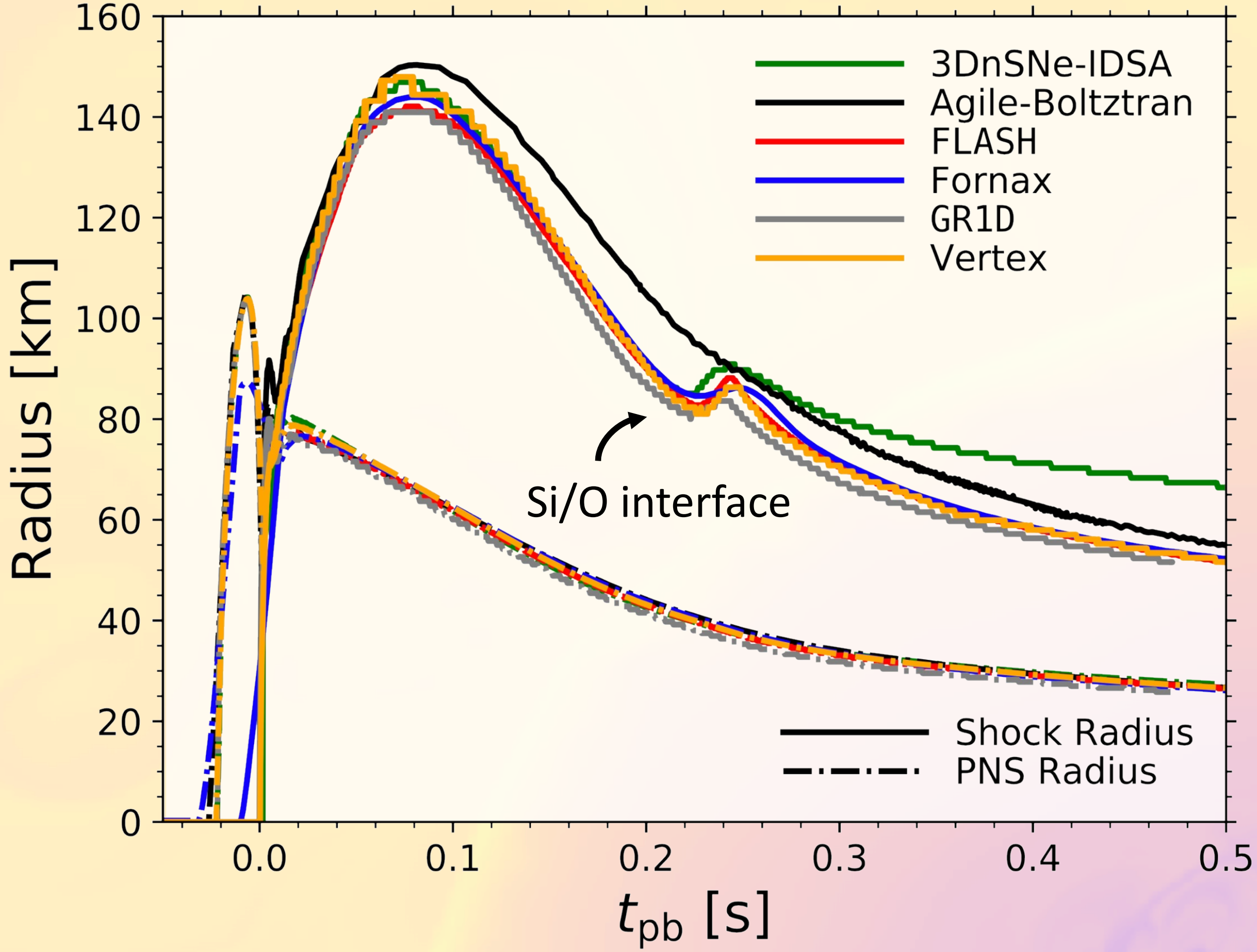
3DnSNe-IDSA
Agile-Boltztran
FLASH
Fornax
GR1D
Vertex

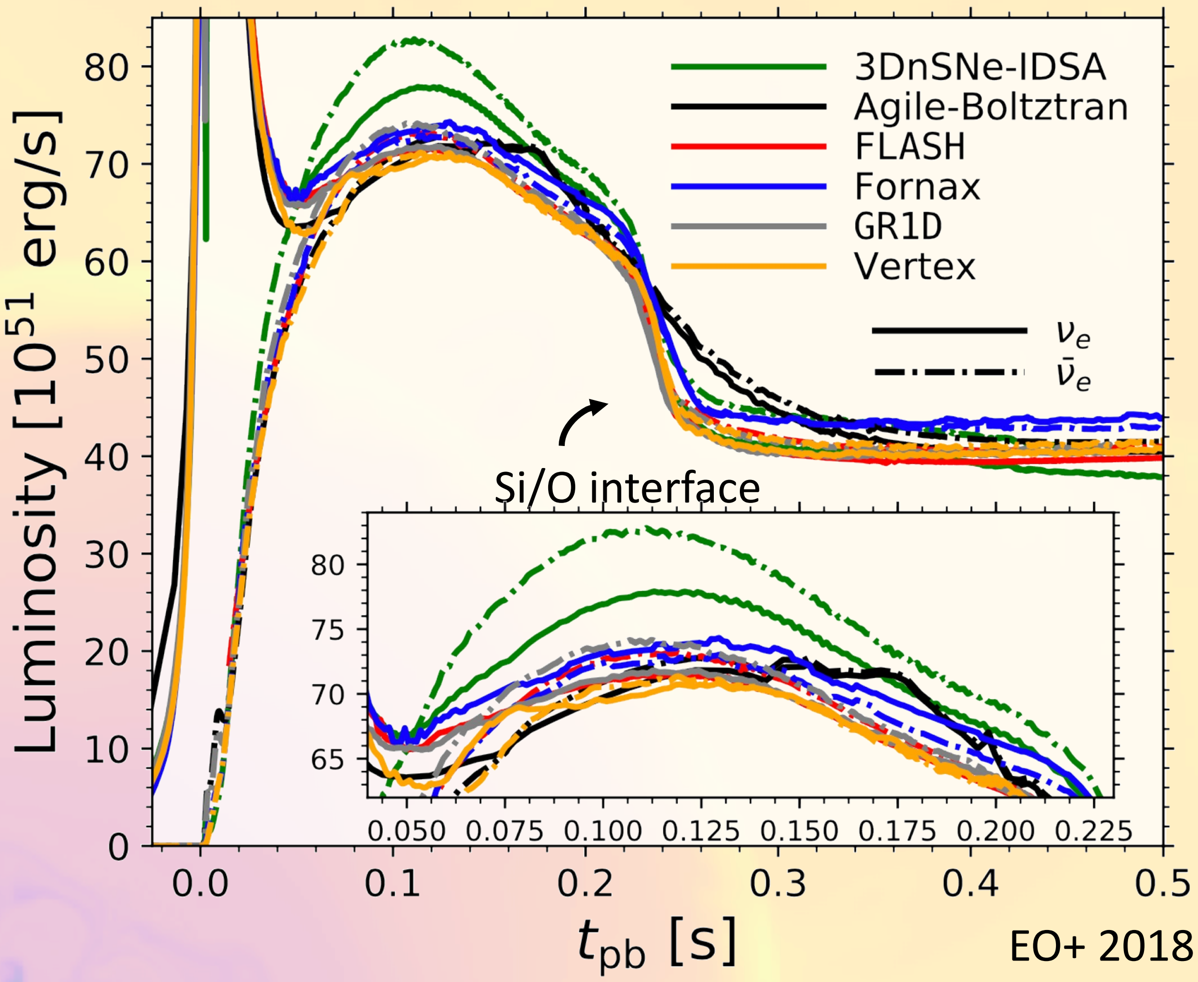
Global Comparison of Core-Collapse Superno
Simulations in Spherical Symmetry

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

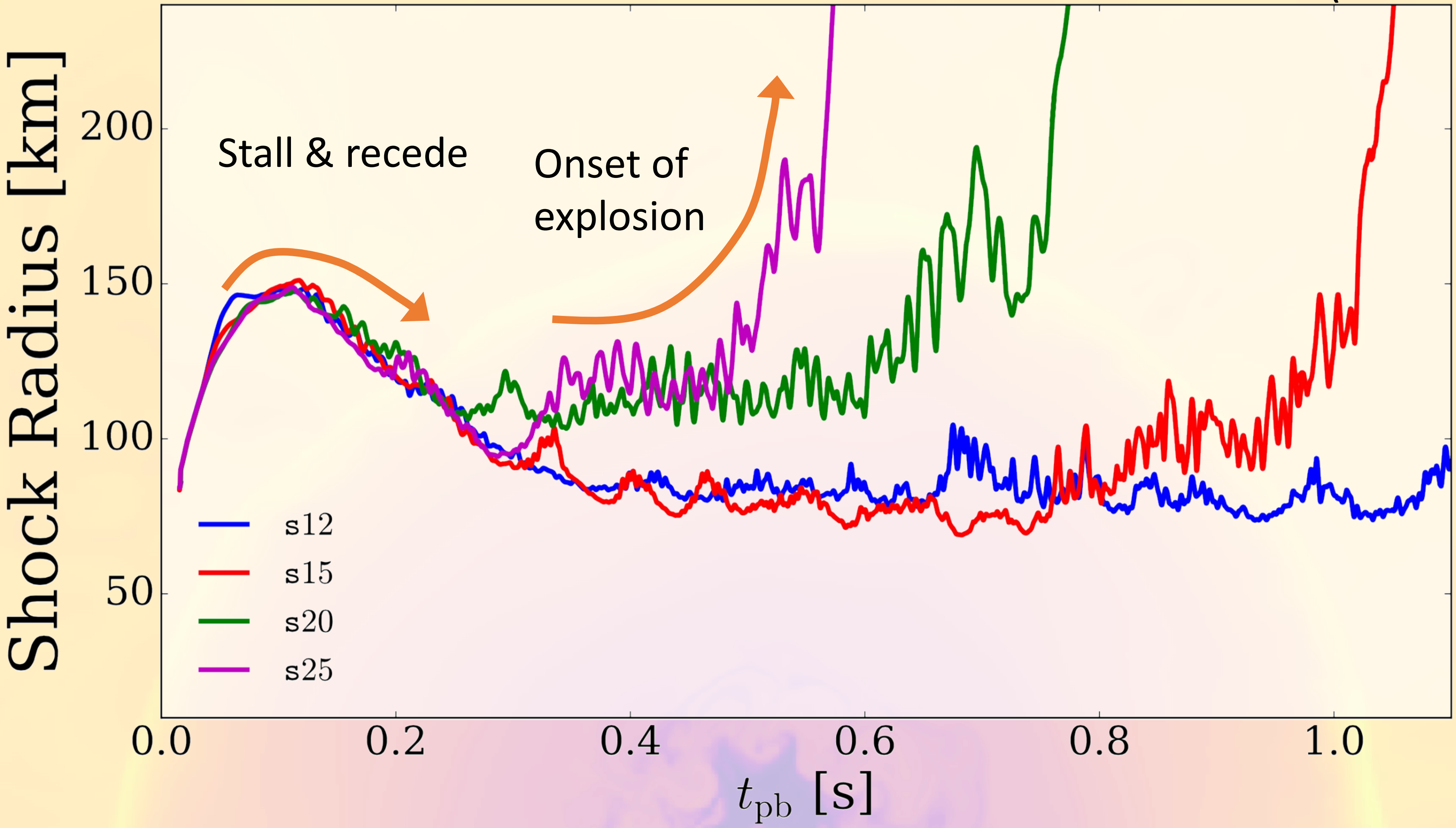




EO+ 2018

Typical Evolution

EO & Couch (2018a)

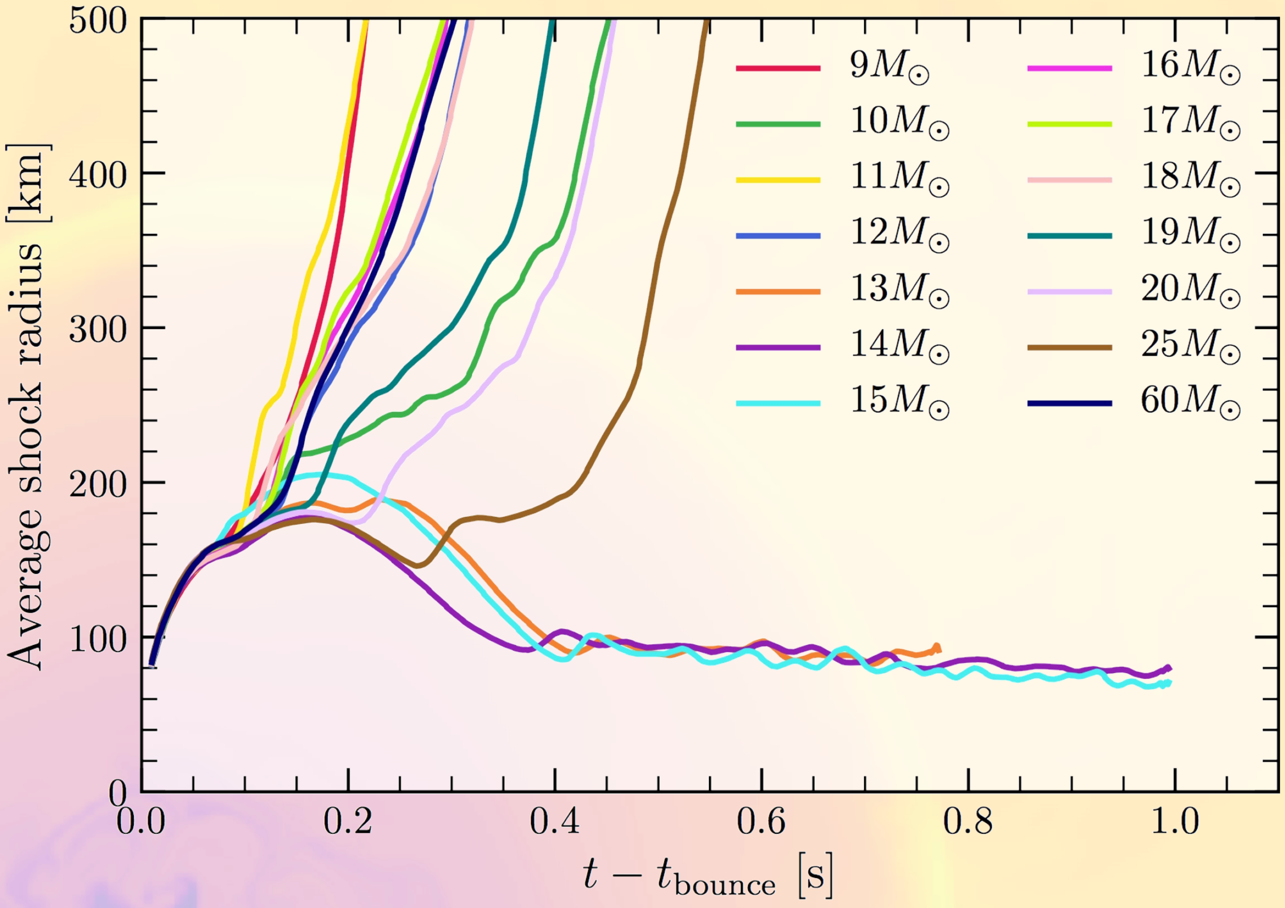


Successful CCSN explosions

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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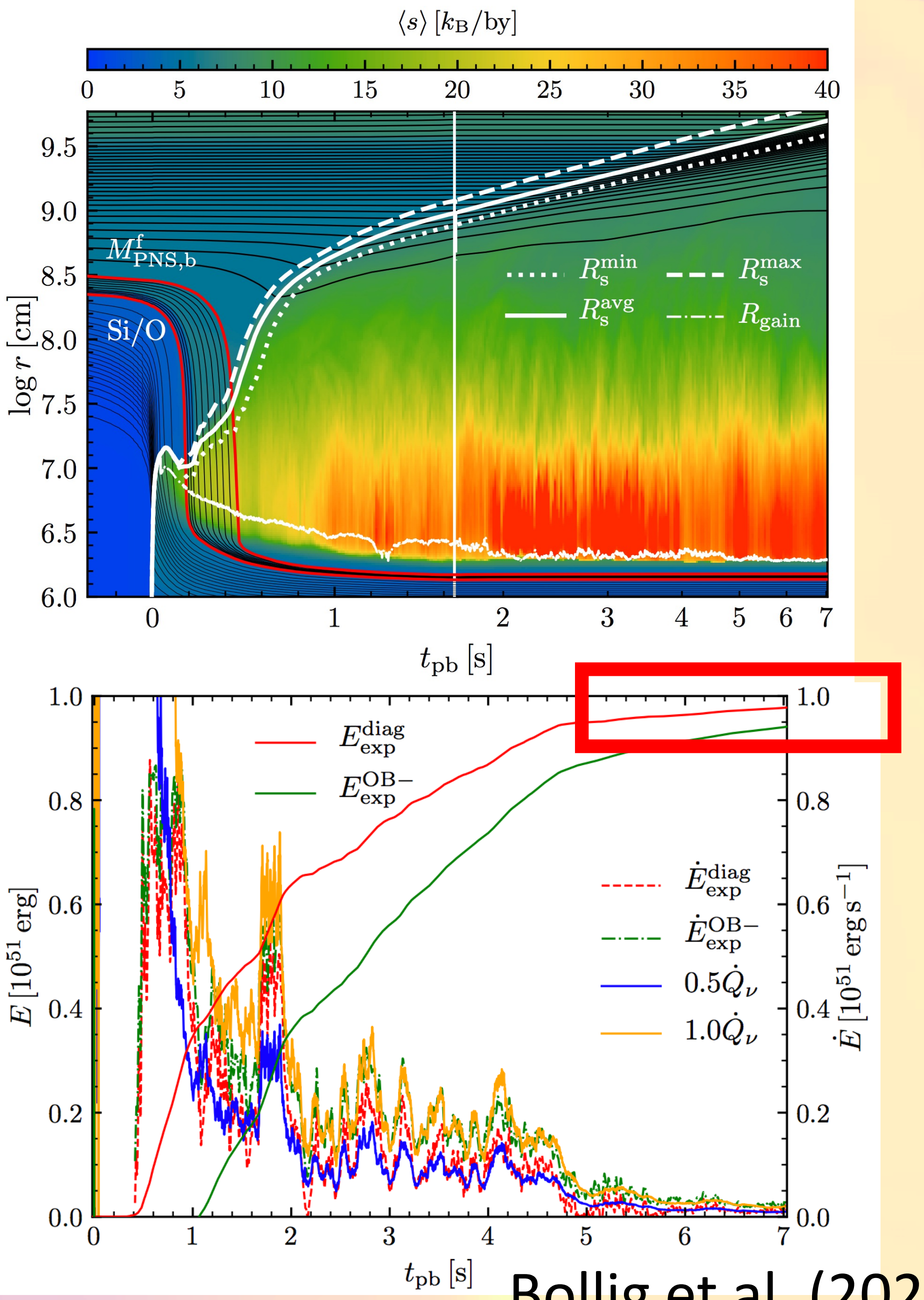
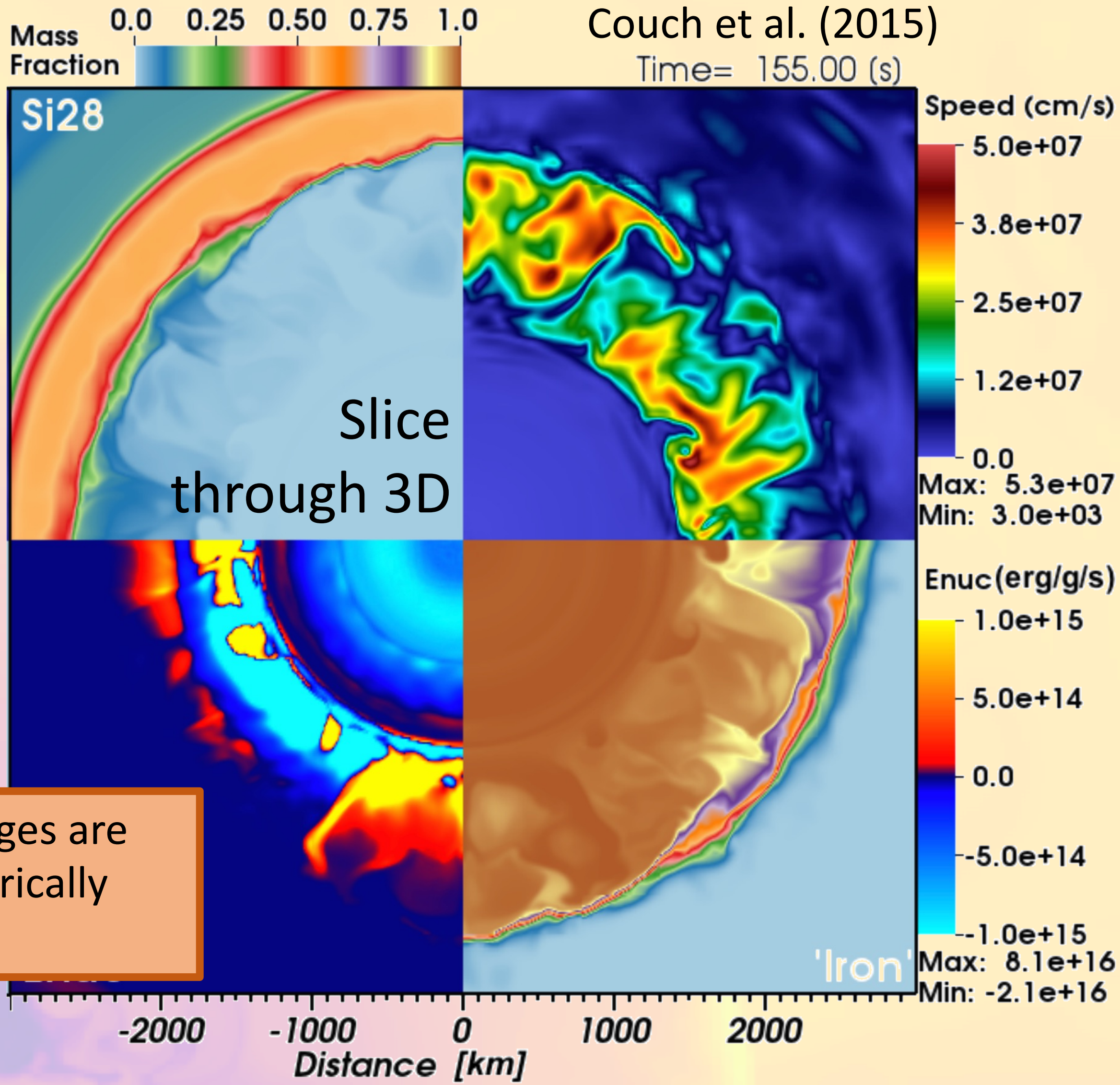


Bollig et al. (2020)

Presupernova Perturbations

All this work with multidimensional simulations, what about multidimensional **progenitors**!

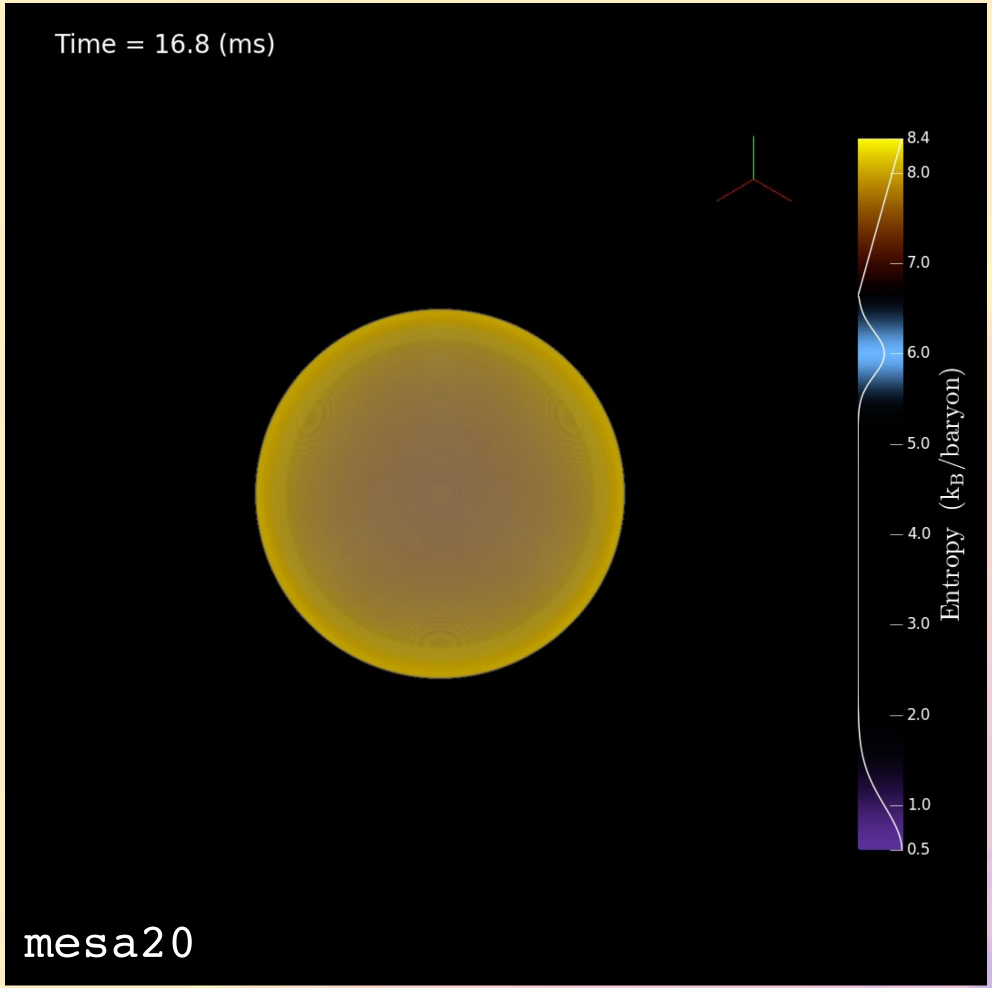


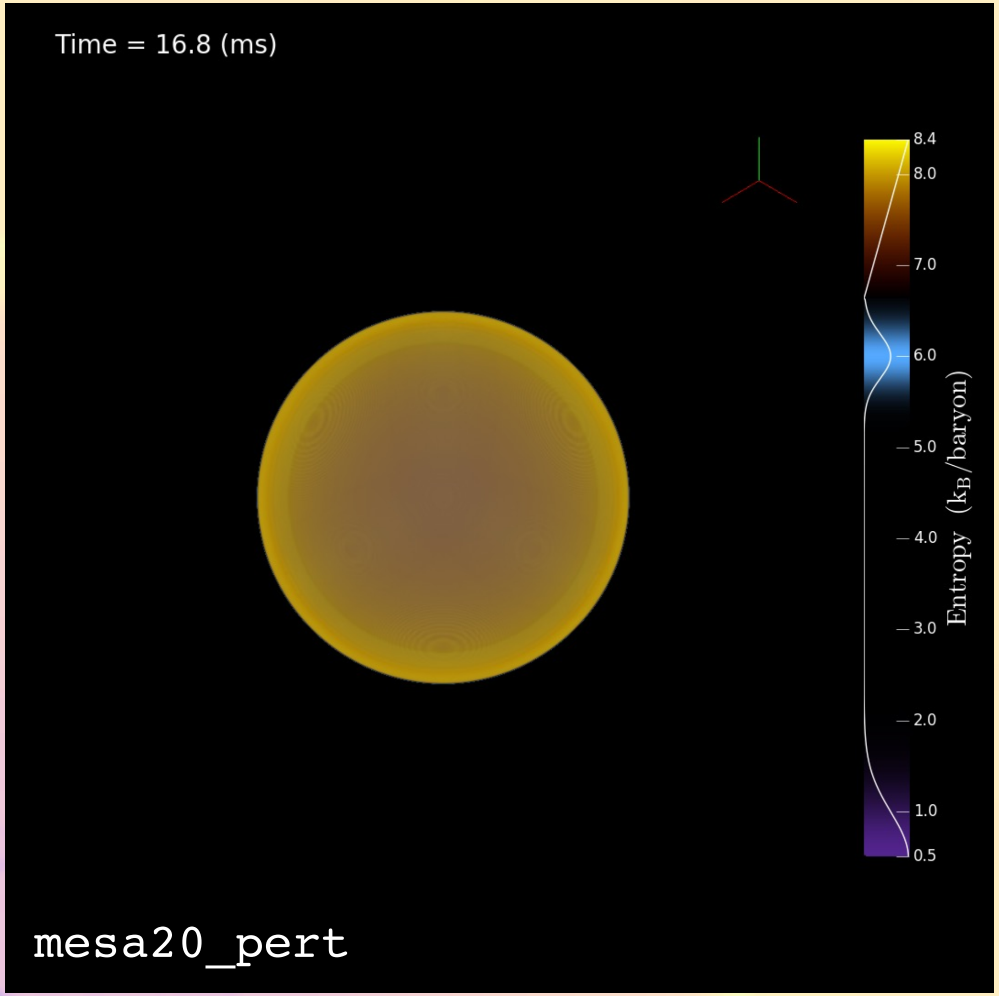
Couch et al. (2015)

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

Impact of Progenitor Perturbations

EO & Couch (2018b)





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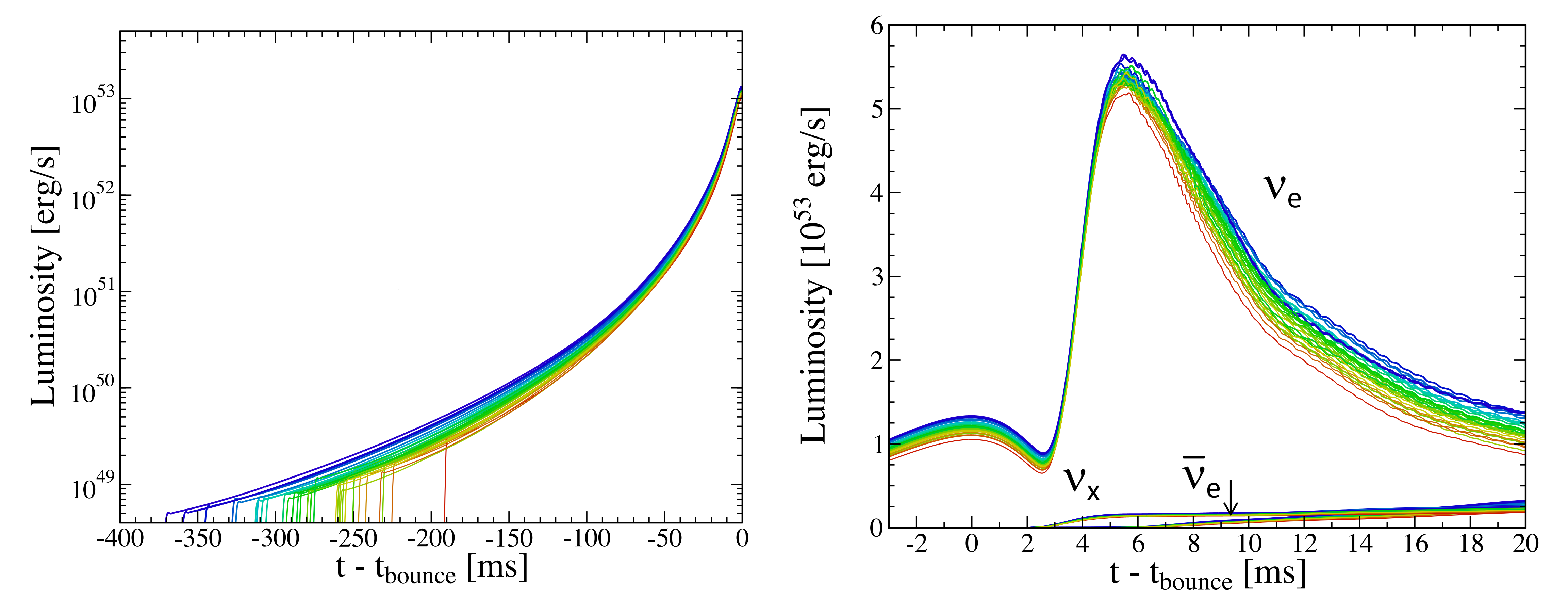
Neutrinos: Collapse Phase

Iron core mass increasing ->

Matter temperature increasing ->

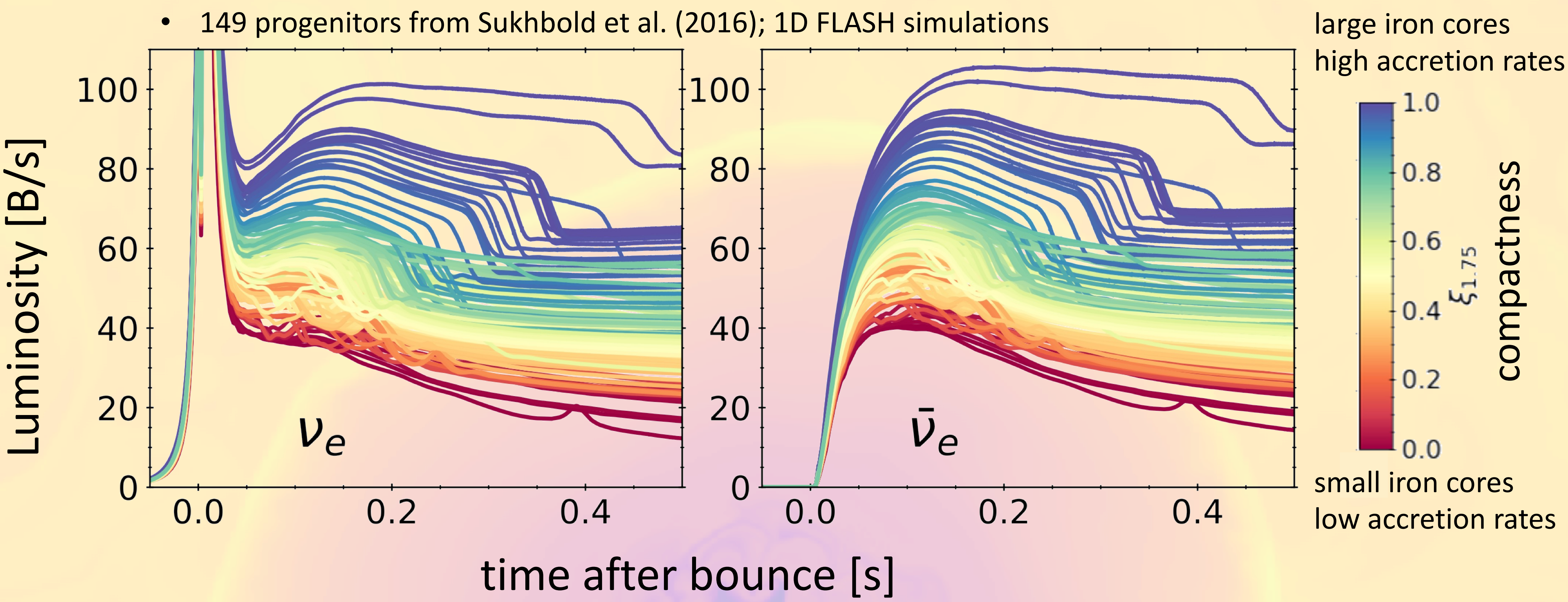
Open source: GR1D (GR1Dcode.org) & NuLib (nulib.org)

32 Progenitors from Woosley & Heger (2007)



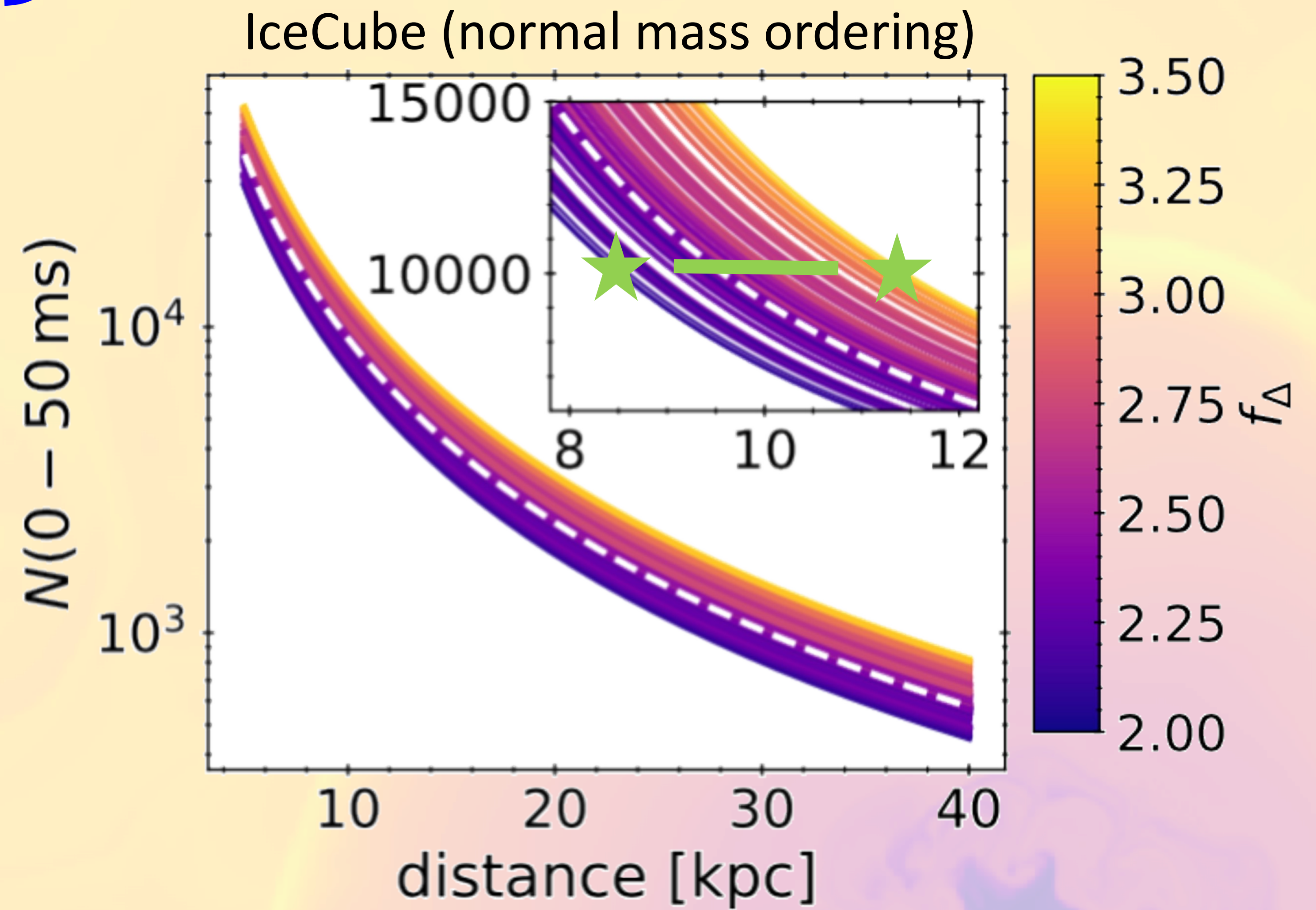
Neutrinos: Accretion Phase

- 149 progenitors from Sukhbold et al. (2016); 1D FLASH simulations



Segerlund et al. arXiv:2101.10624

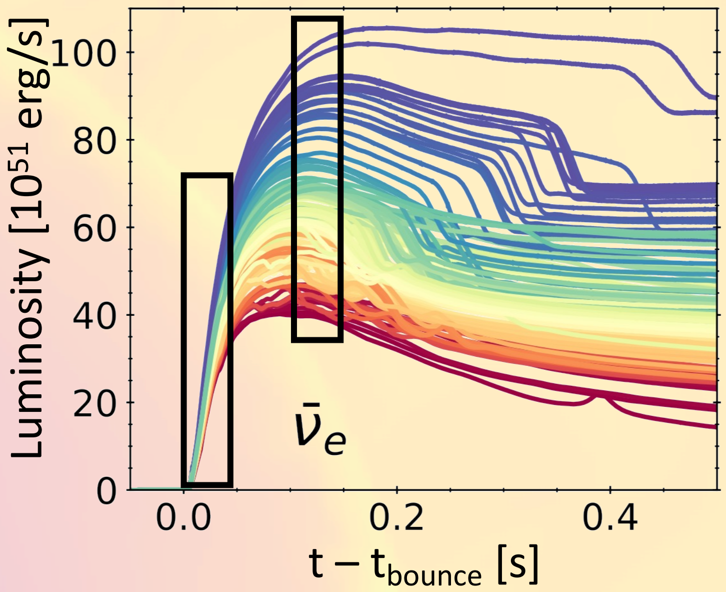
Determining Distance from Neutrinos



Horiuchi et al. (2017)

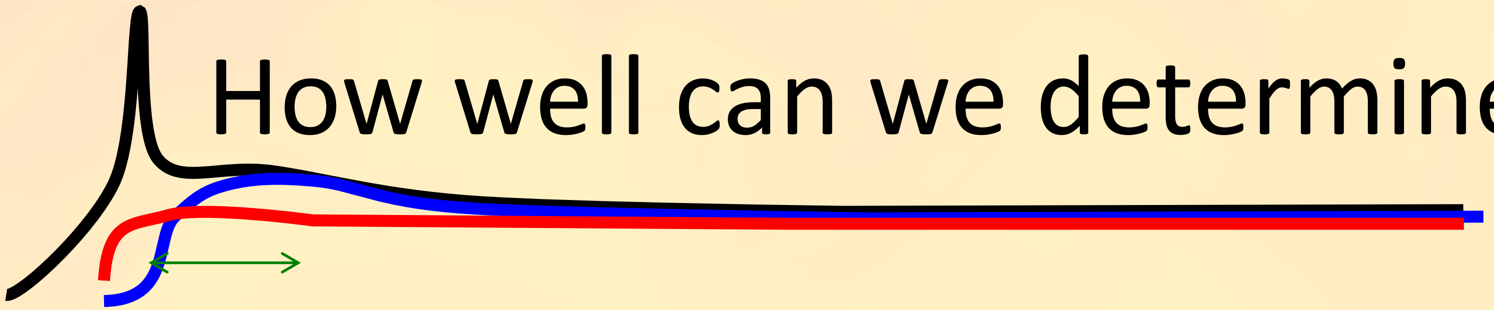
f_Δ is a distance independent observable

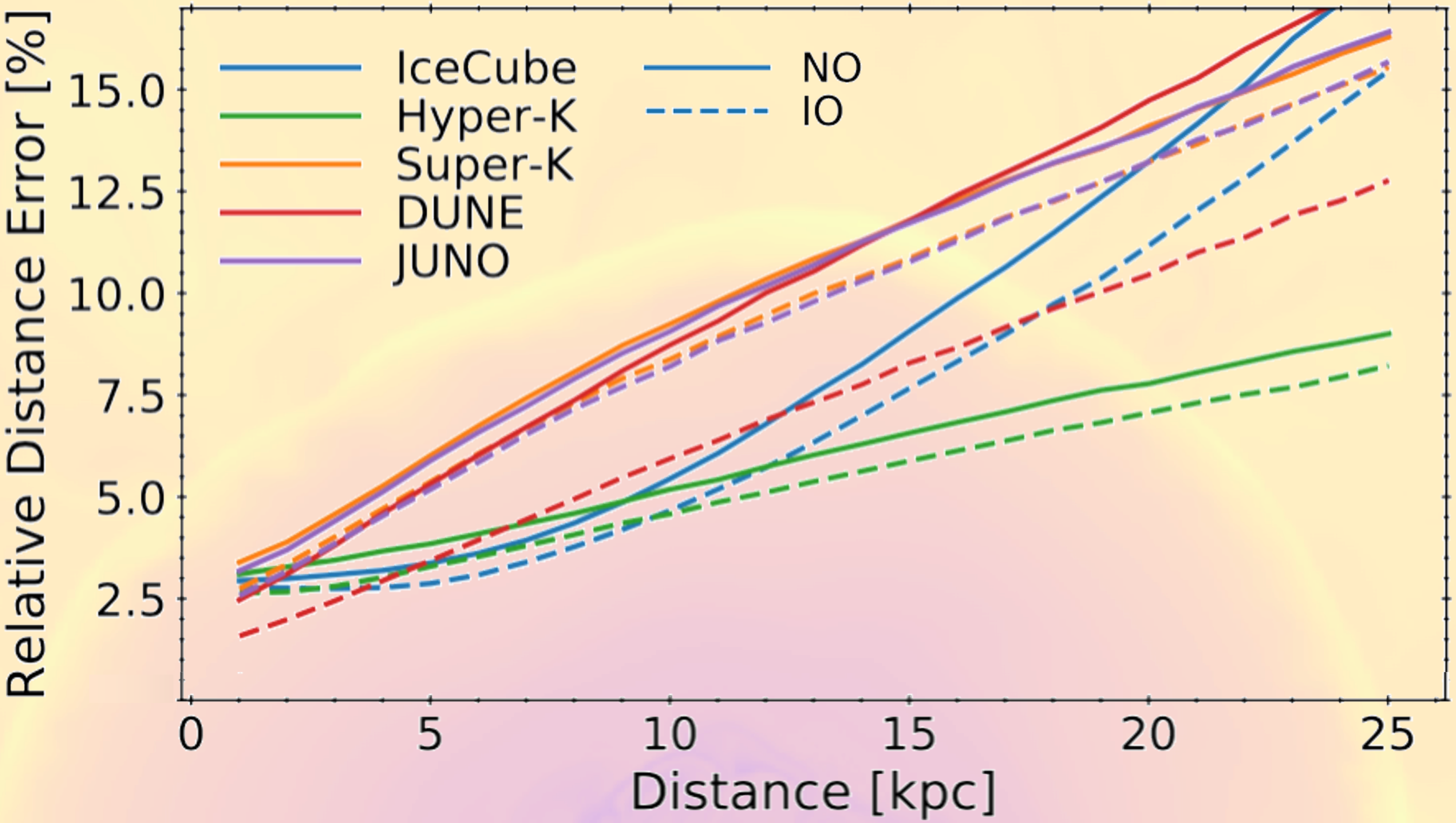
(that correlates with compactness)



Segerlund et al. arXiv:2101.10624

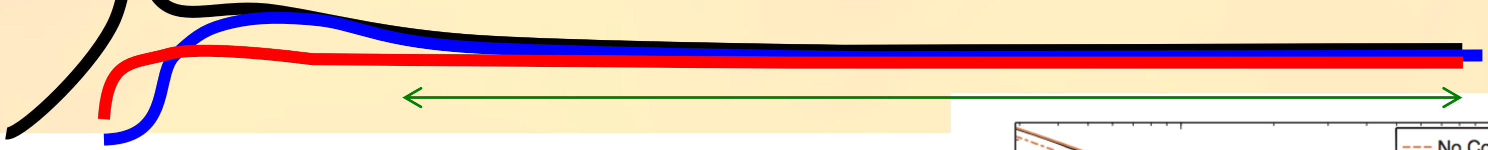
How well can we determine distance?

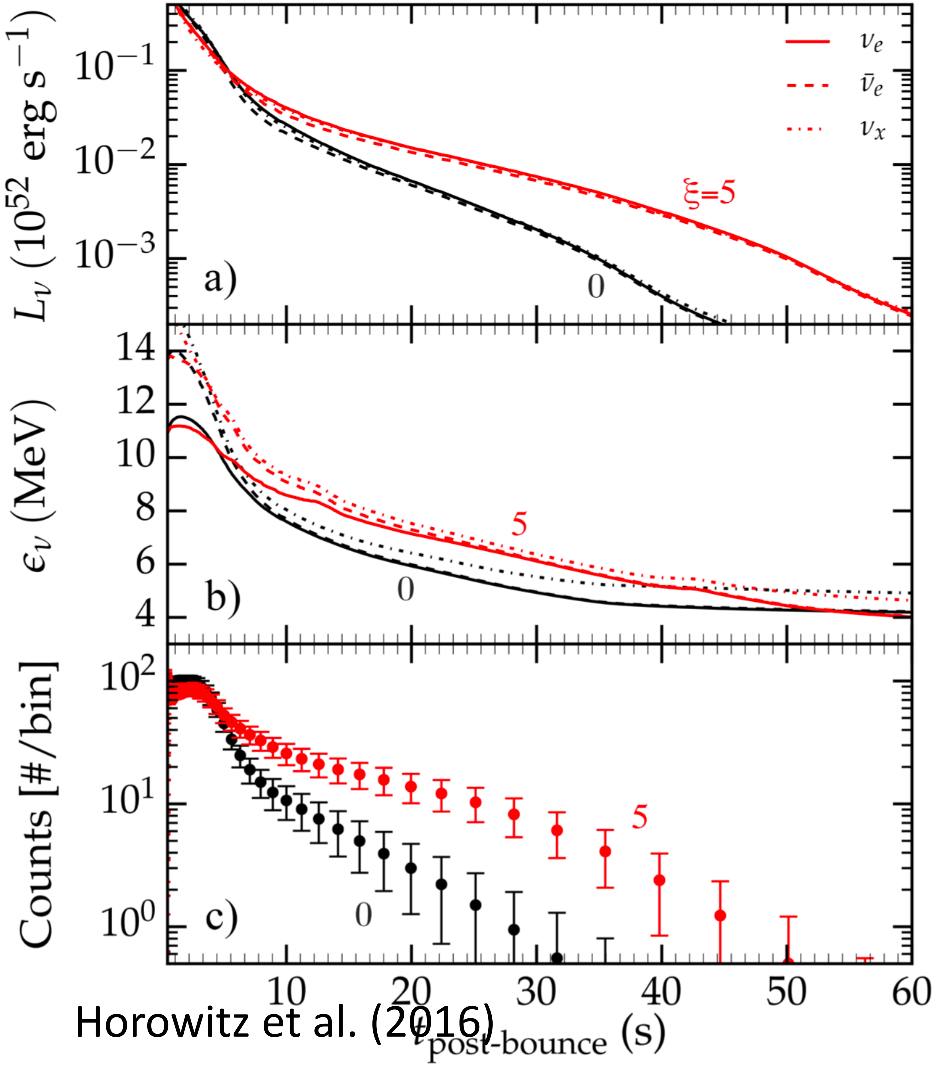




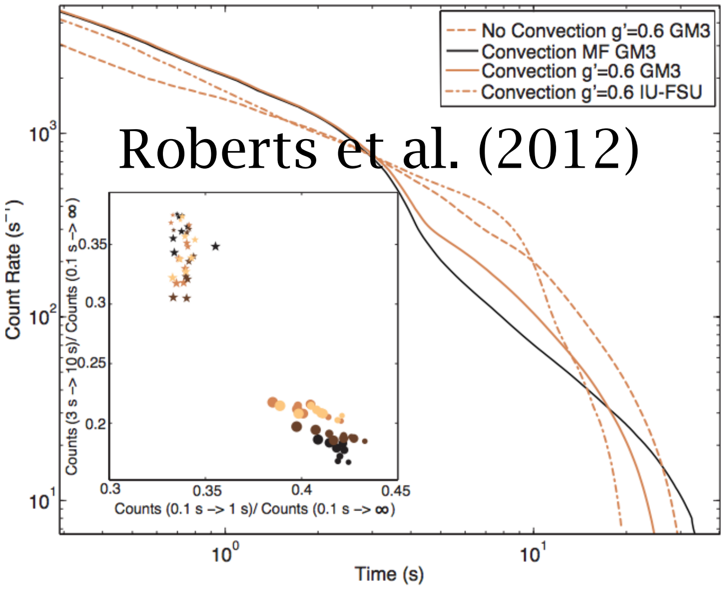
Segerlund et al. arXiv:2101.10624

Neutrinos: Cooling Phase

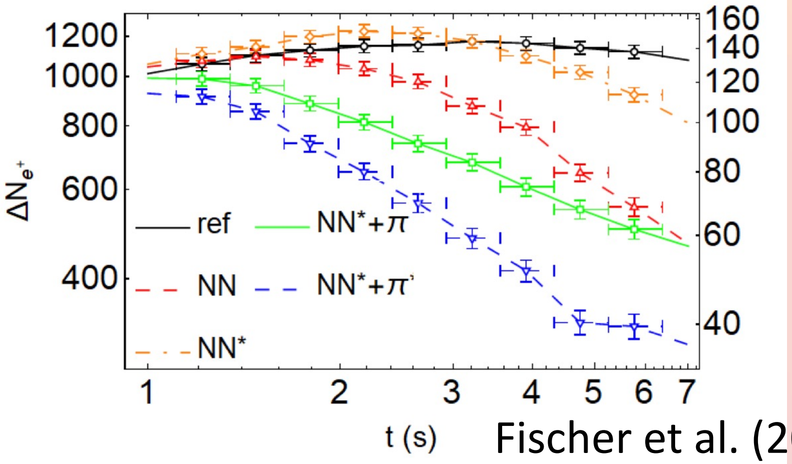




Horowitz et al. (2016)

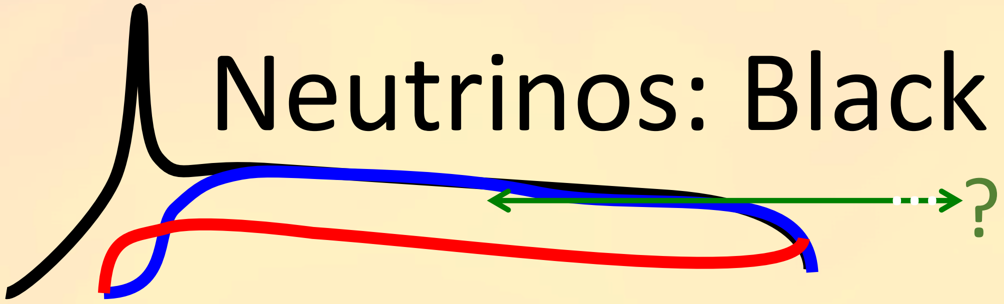


Roberts et al. (2012)



Fischer et al. (2021)

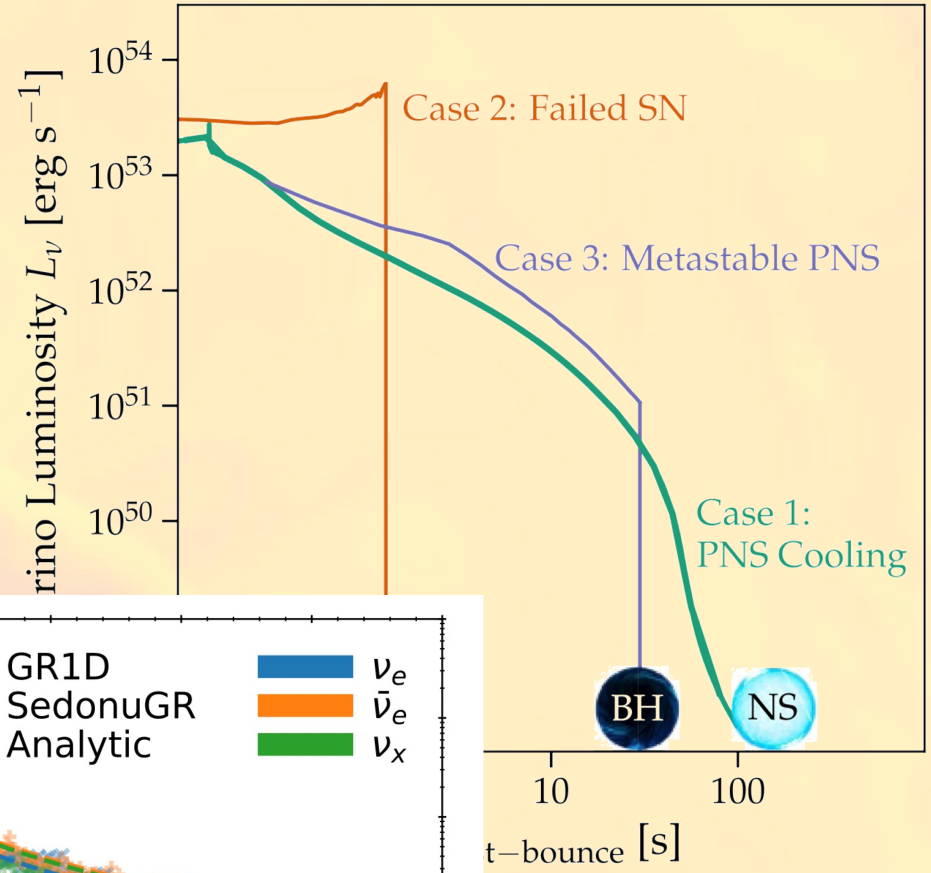
- How the protoneutron star cools relays info about the EOS -> traced by neutrino emission
- Variations in neutrino luminosities and energies can be detectable and help constrain the nuclear EOS and exotic particle (like axion) emission
- Particularly, differences in the <E> between ν_e and ν_e is important and can impact nucleosynthesis

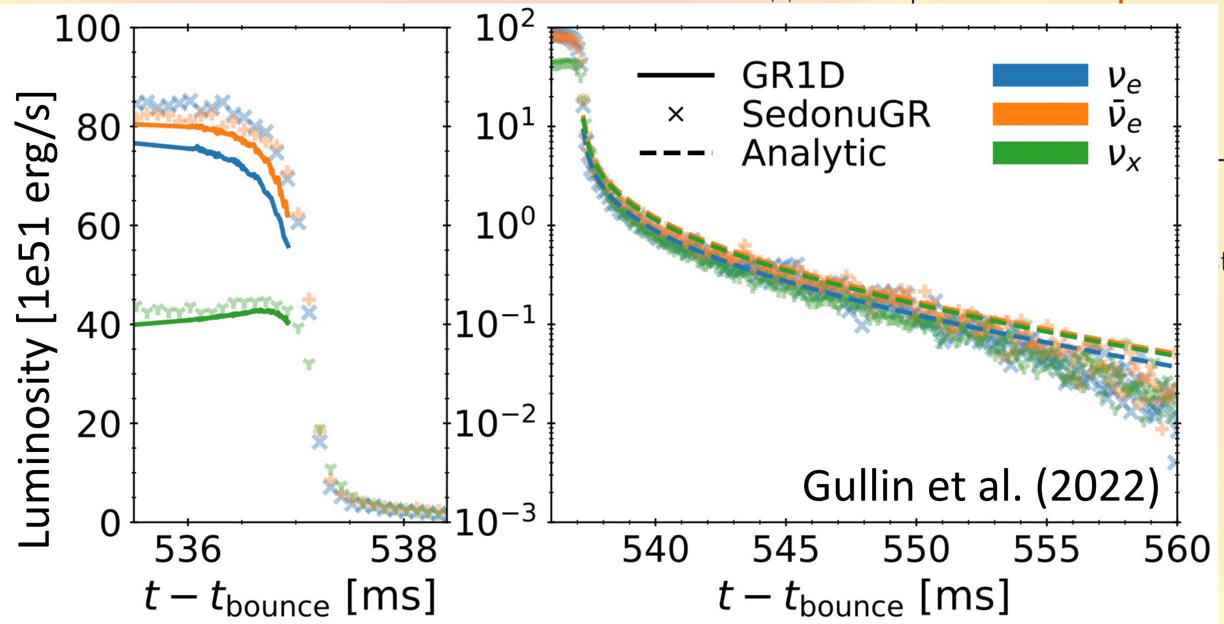


Neutrinos: Black hole formation

- Not at core collapses will explode, some will form a black hole. This impacts the neutrino signal.
- Estimated fraction 0.16 (+0.23, -0.12; 90% confidence, Neustadt et al. 2021)
- Neutrino signal extends past black hole formation due to neutrinos scattering in the remaining star

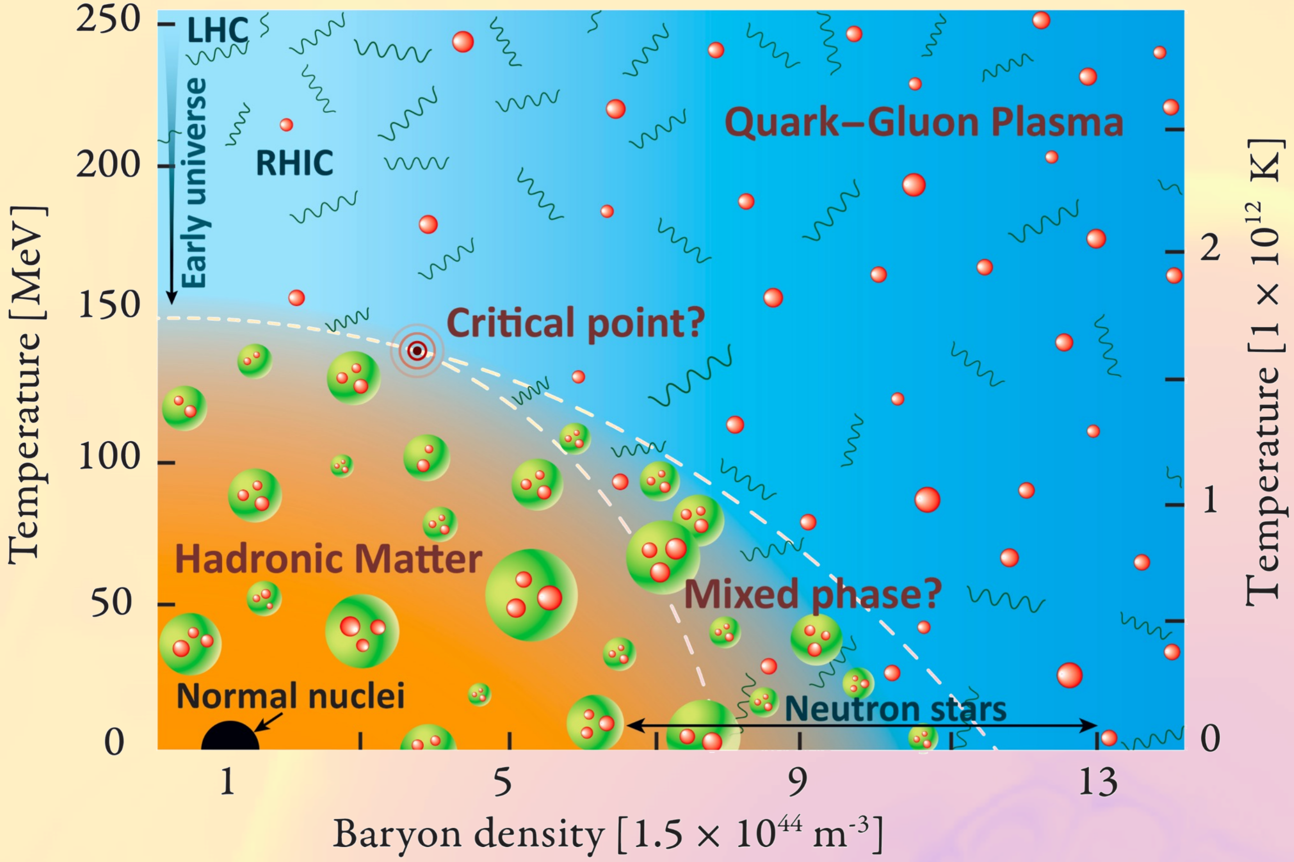
Li, Roberts, Beacom (2021)





Quarks in CCSNe

Contemporary Physics Education Project (CPEP)

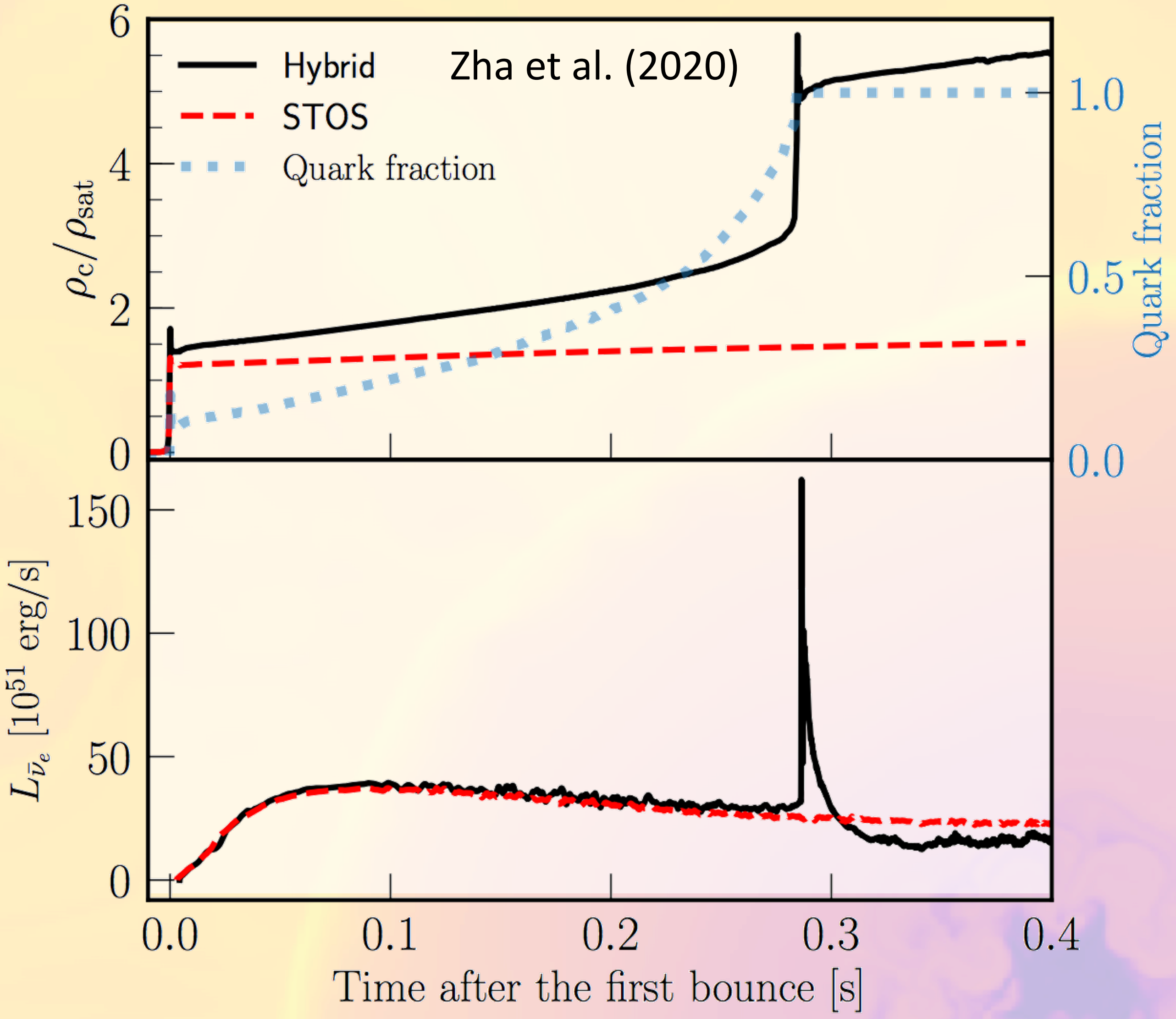


Nuclear matter at extreme temperatures and densities is very uncertain!

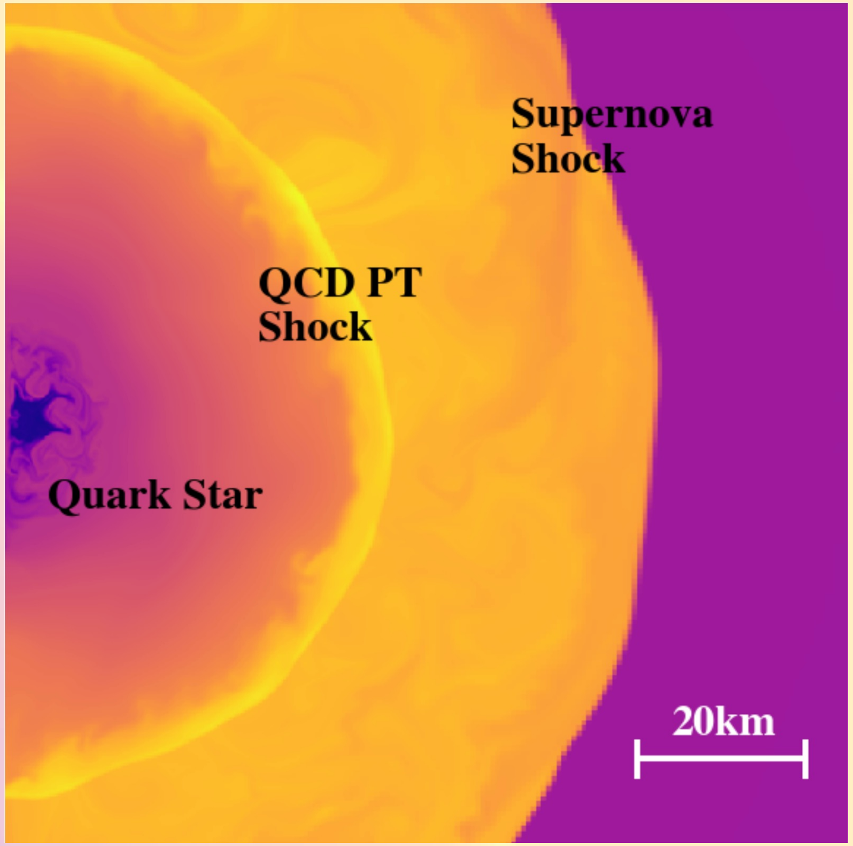
CCSN environment is one of the only places these conditions exist

Quarks in CCSNe

Phase transition to pure quark star causes core to contract and bounce a second time!



Zha et al. (2020)



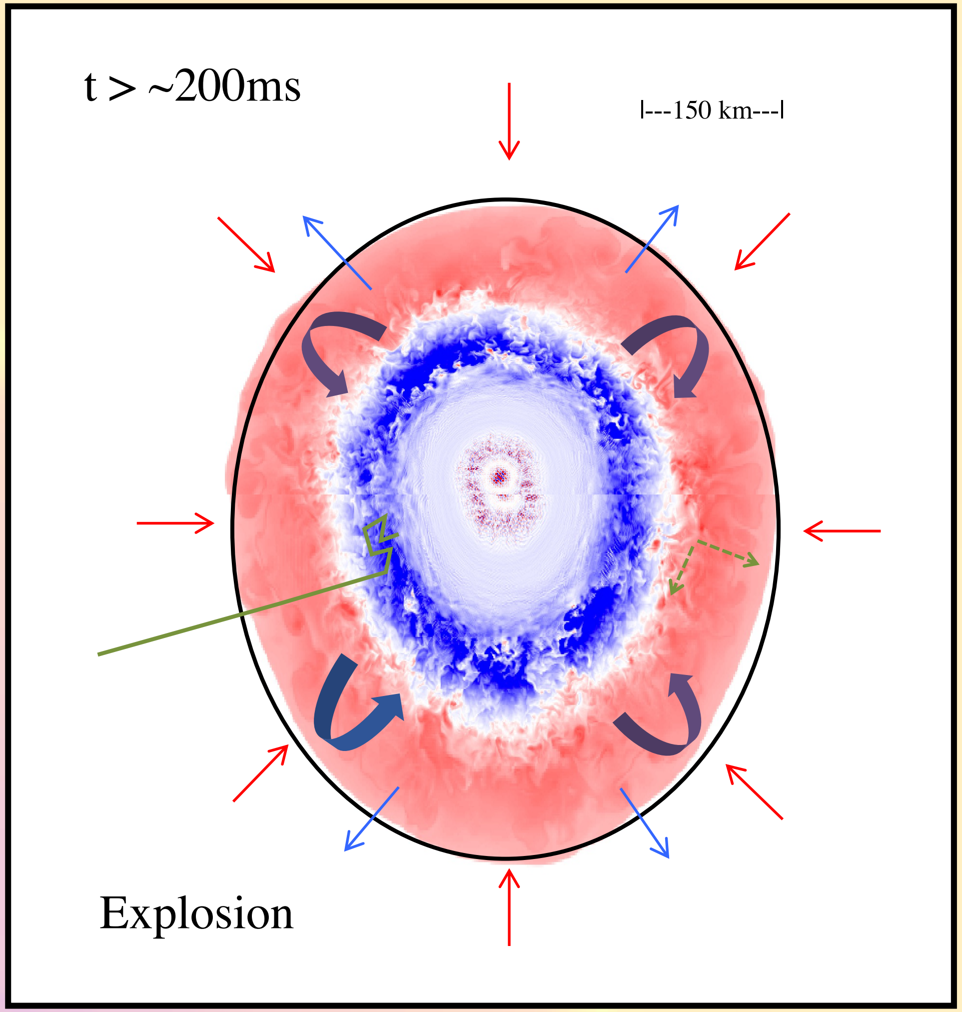
2D FLASH simulations

*First shown in 1D in Sagert 2009

Gravitational Waves

- Gravitational waves generated by asymmetric matter motions
    - Rotational core bounce
    - PNS convection & turbulence
    - SASI & gain region convection
    - Asymmetric neutrinos & explosion

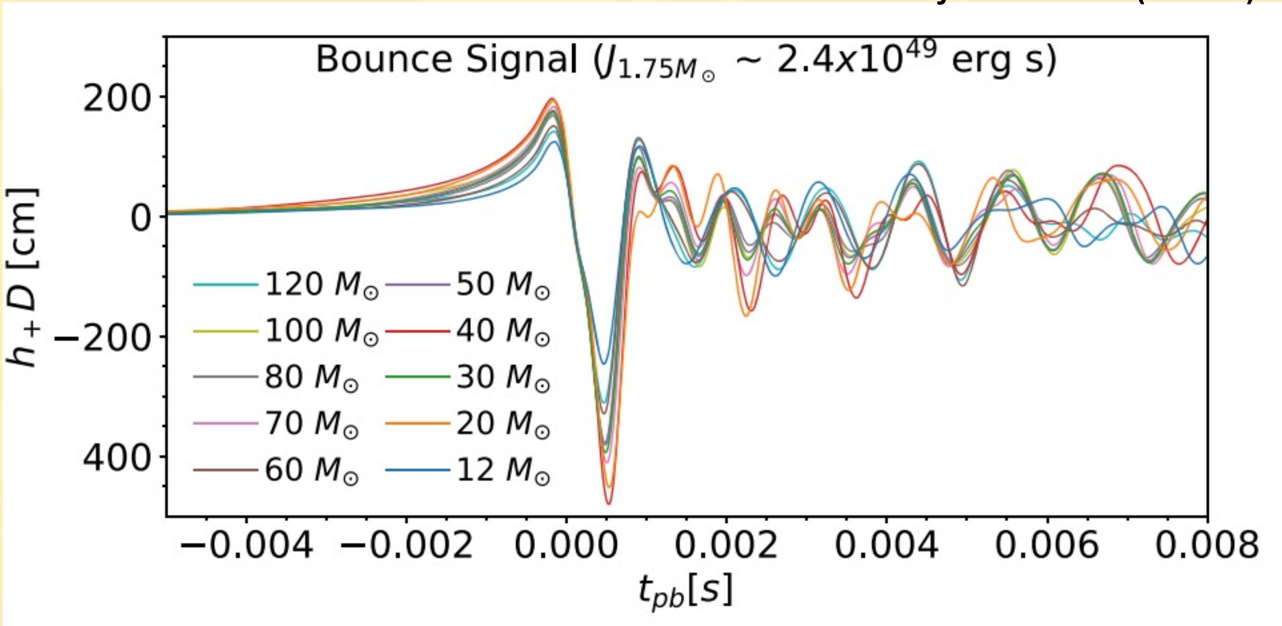
- Detection details (including sensitivities) in the following talks



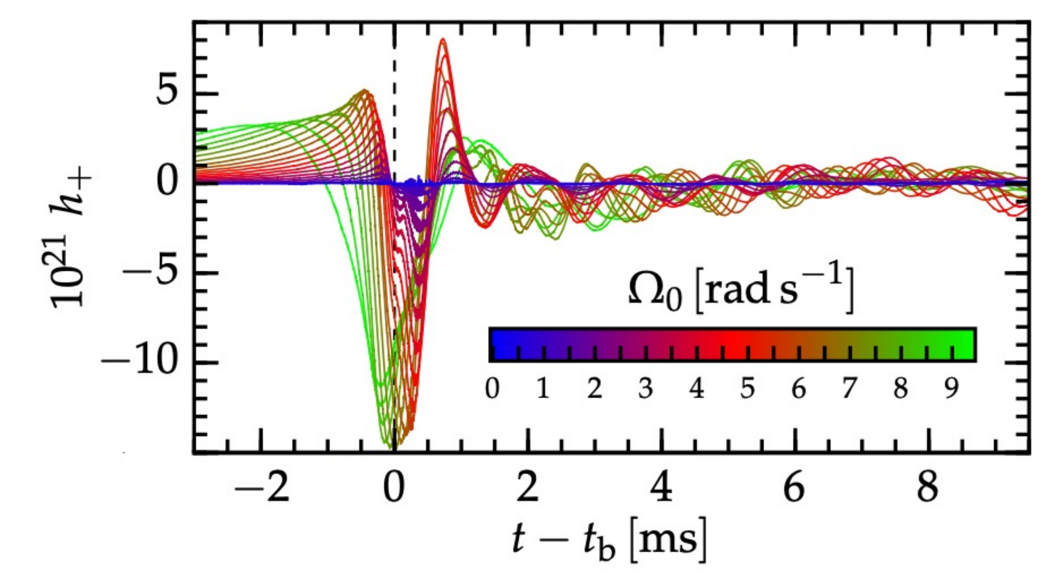
GW from Rotation

- Unique, templatable signal at bounce from the oblate, rotating, collapsing, core

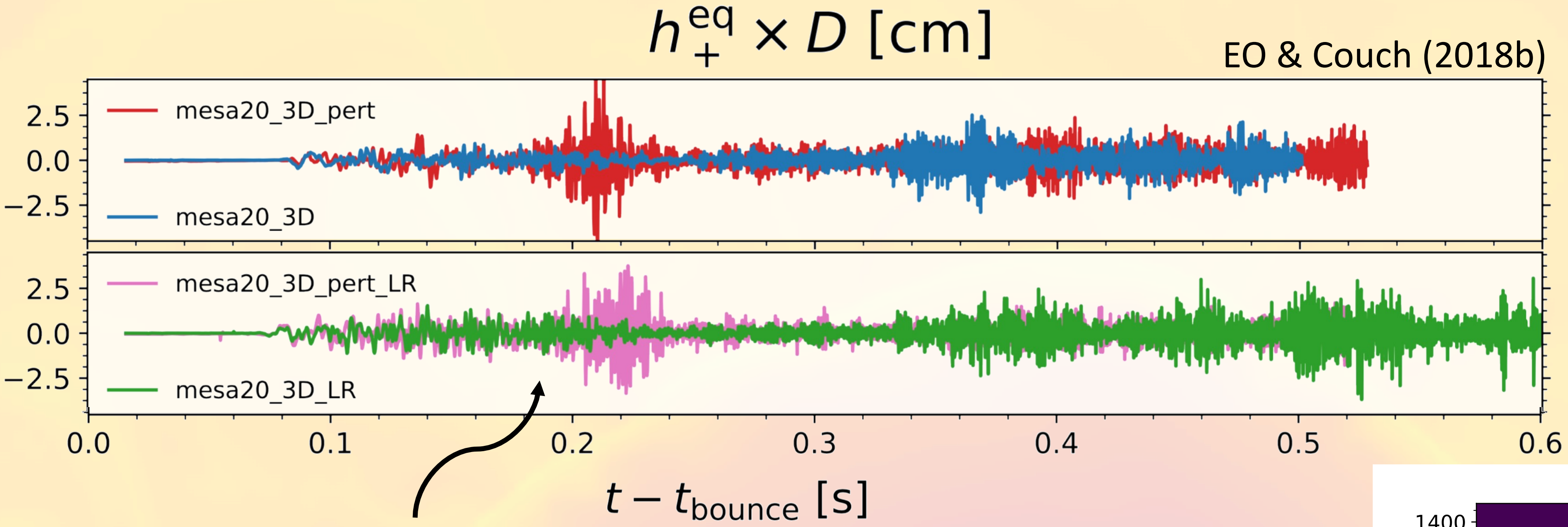
Pajkos et al. (2019)



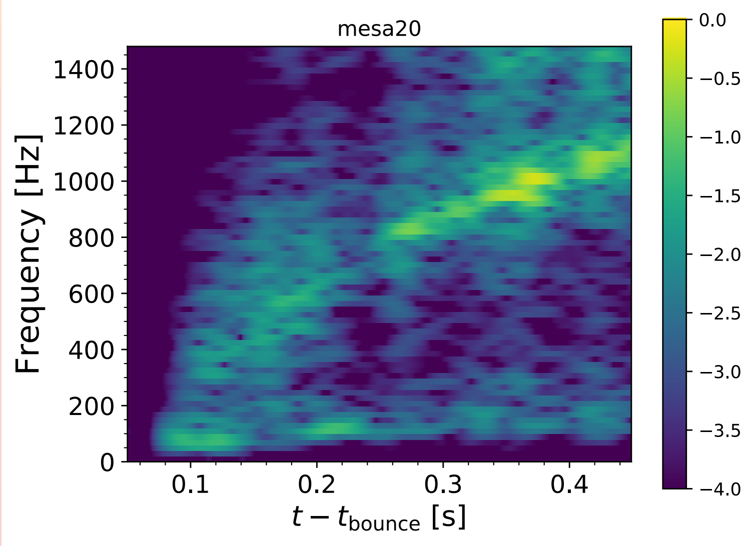
Richers et al. (2017)



Gravitational Wave Signature



Burst of turbulence excites PNS and gives rise to GW



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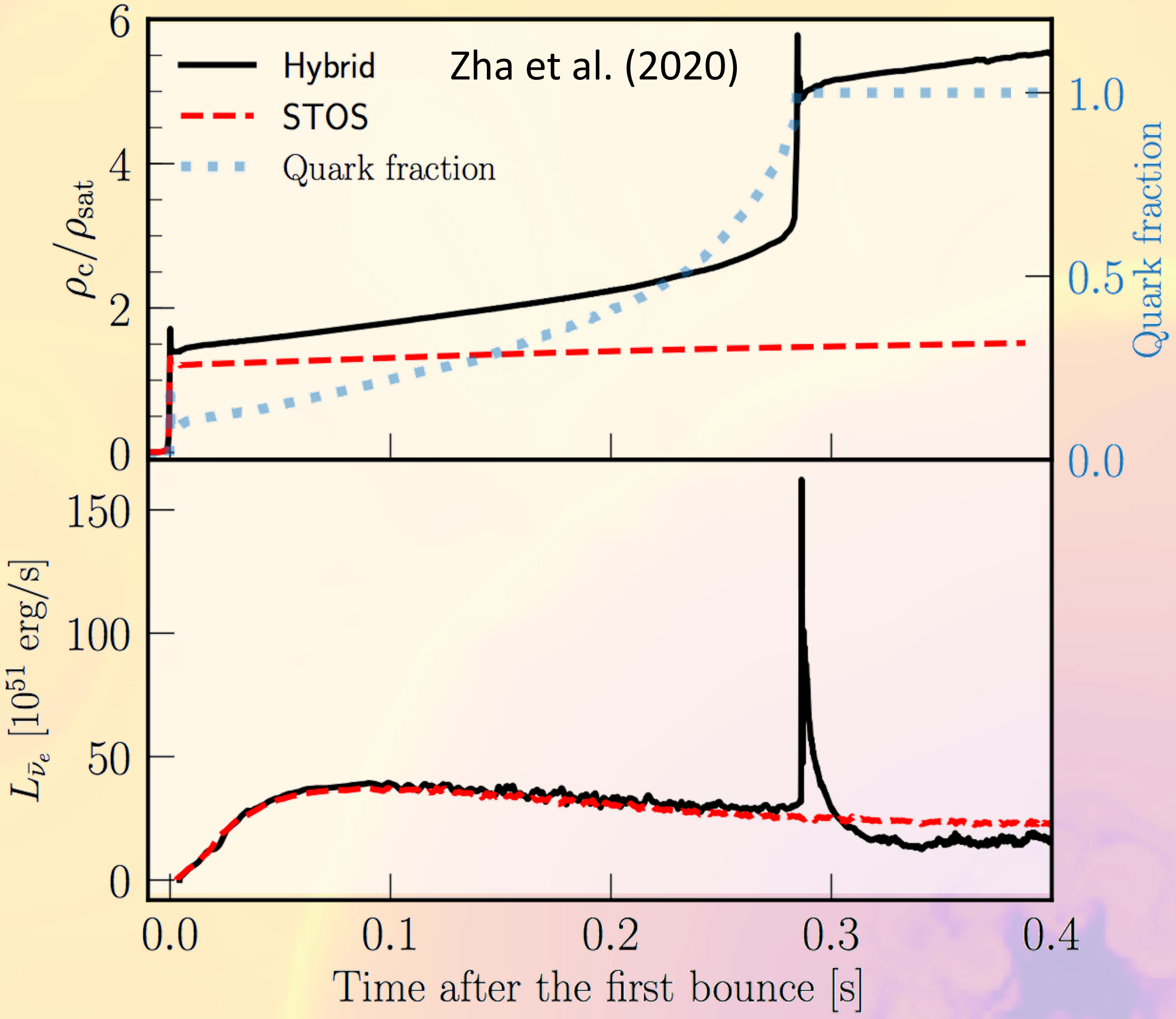
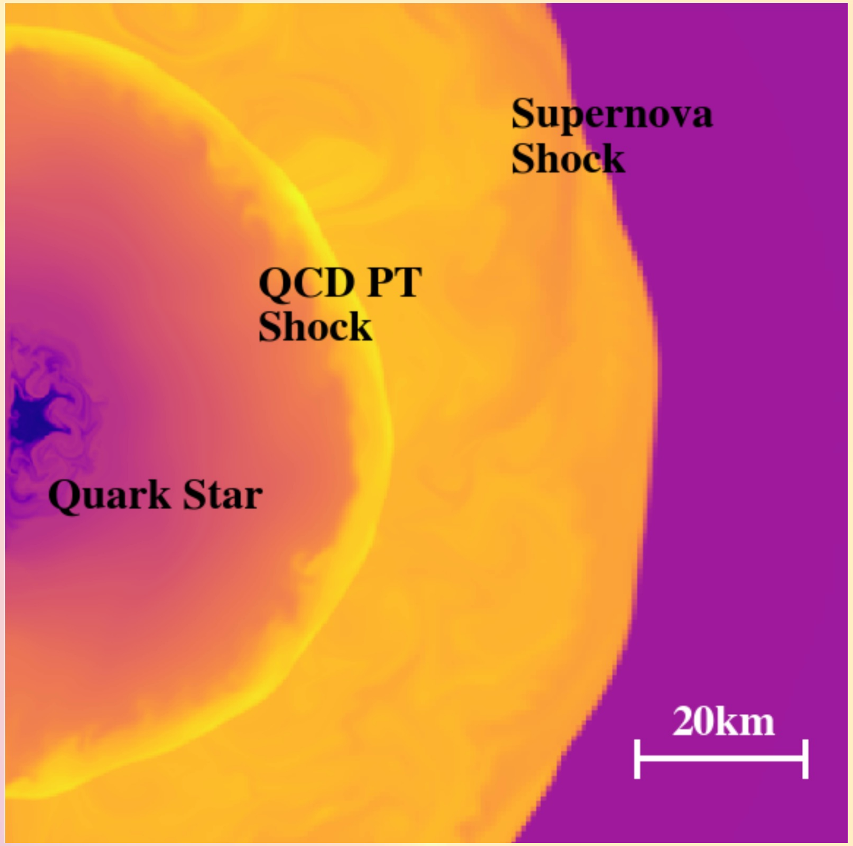


Zha et al. (2020)

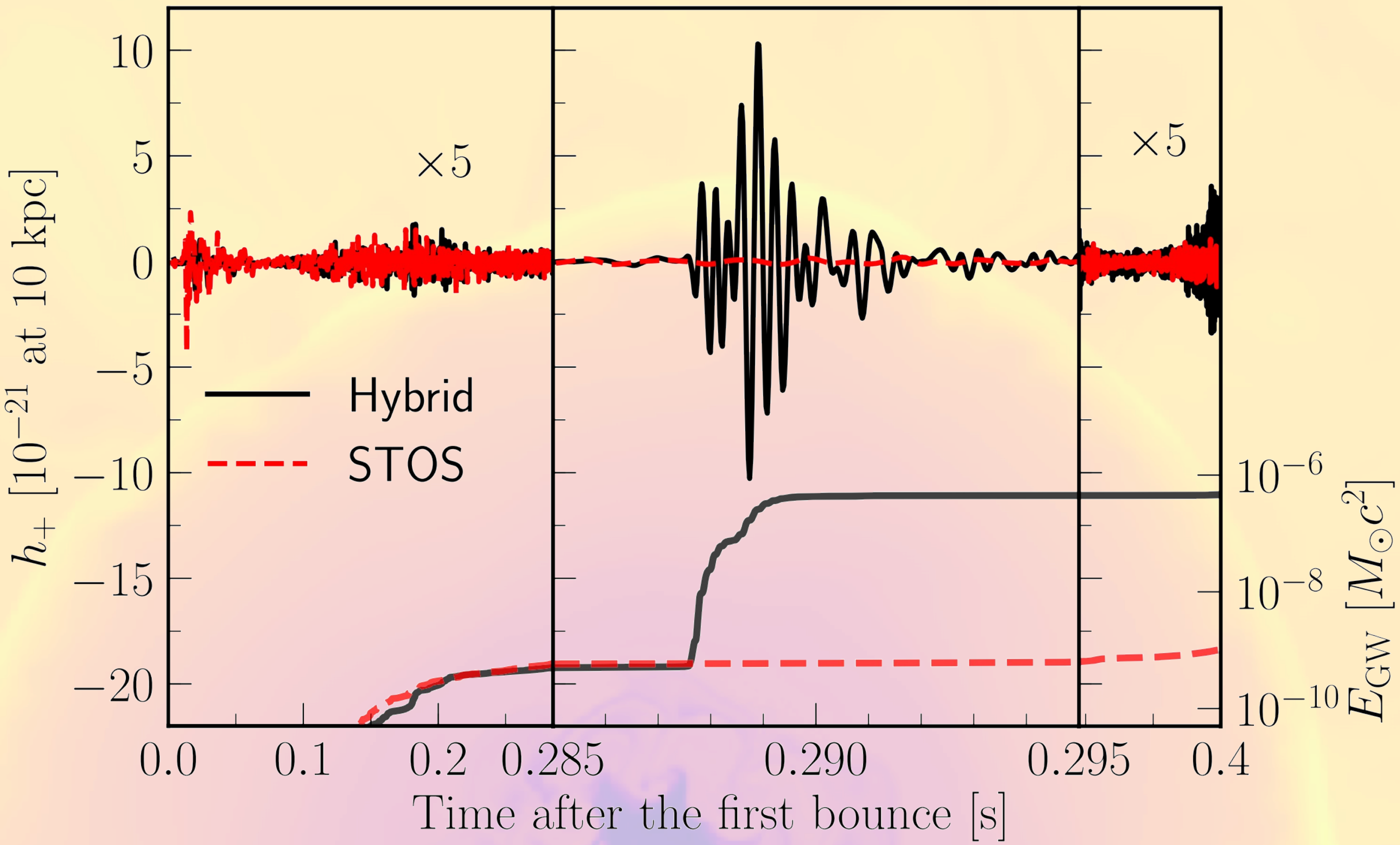


2D FLASH simulations

*First shown in 1D in Sagert 2009

Strong, short, high frequency, gravitaitonal waves

Zha et al. (2020)



Computer Simulations of Supernovae

- The CCSN community is able to produce robust explosions in 3D and agrees well in direct comparisons in 1D
- The neutrino and GW signals carry an incredible amount of information about progenitor, mechanism, and fate
- Joint information among these messengers, and also EM observations will revolution our understanding of massive stars

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