Title: Core-Collapse Supernovae as Laboratories for Fundamental Physics

Speakers: Evan O'Connor

Series: Strong Gravity

Date: April 22, 2021 - 1:00 PM

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Abstract: Core-Collapse Supernovae are a fantastic laboratory to study fundamental physics. The messengers from the core, neutrino and gravitational waves, carry a wealth of information about the dynamics, thermodynamics, underlying physics, and structure of massive stars at the end of their lives. In this talk, I will discuss some of the ways we can use supernovae to probe this physics. From quark-hadron phase transitions emitting unique gravitational wave and neutrino signals, to neutrinos telling us precise information about the distance to and progenitor mass (!) of galactic supernovae, even before the optical signal is emitted. I will also talk about current efforts to model the population of core-collapse supernovae using parameterized 1D models.

Core-Collapse Supernovae as Laboratories for Fundamental Physics

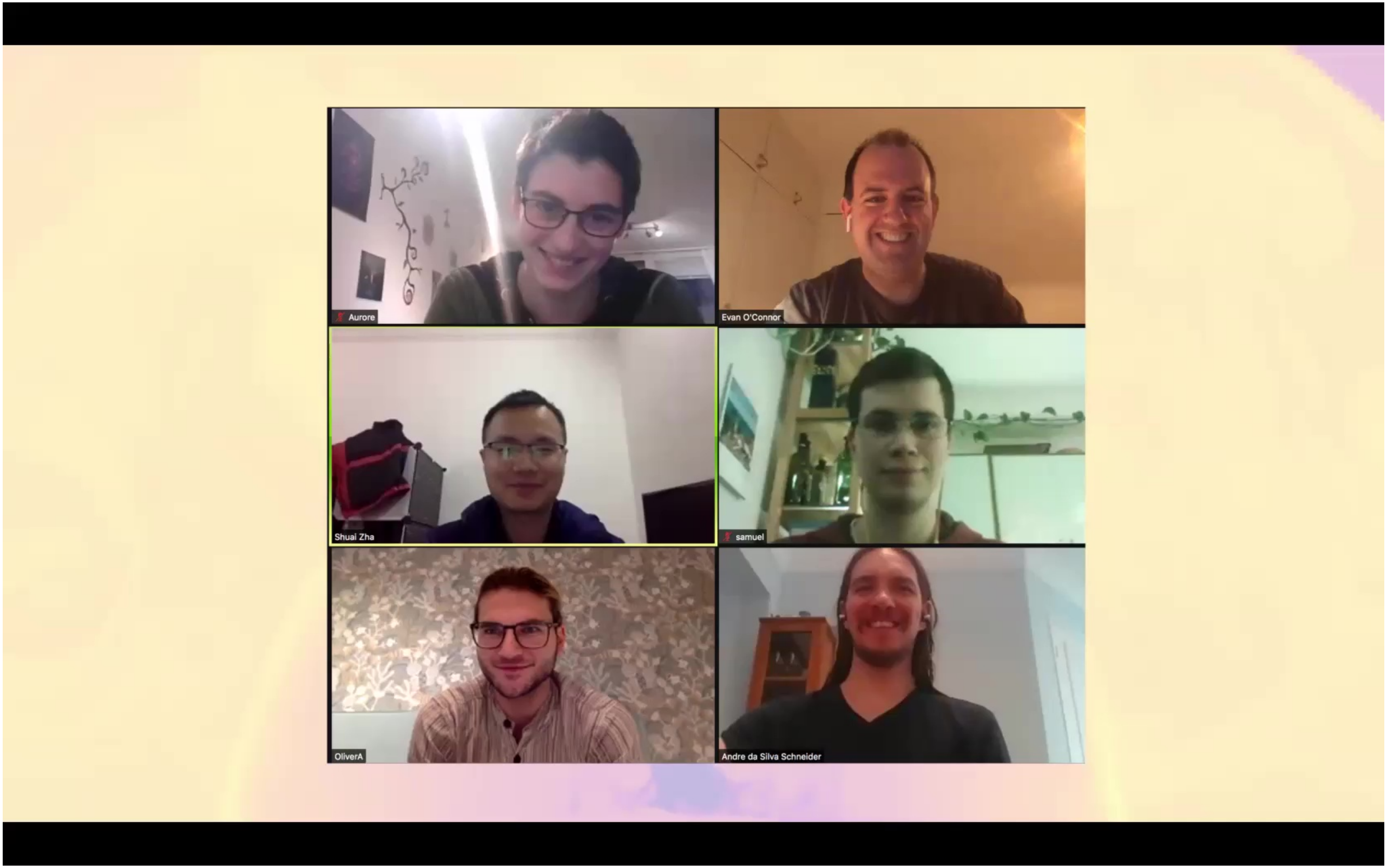
Evan O'Connor
Stockholm University

Stockholm:	Aurore Betranhandy, Andre da Silva Schneider, Shuai Zha, Oliver Andersen, Samuel Gullin
Collaborators:	Sean Couch (MSU), MacKenzie Warren (NCSU), Erin O'Sullivan (Uppsala), Manne Segerlund (Luleå), Luca Boccioli (Notre Dame)

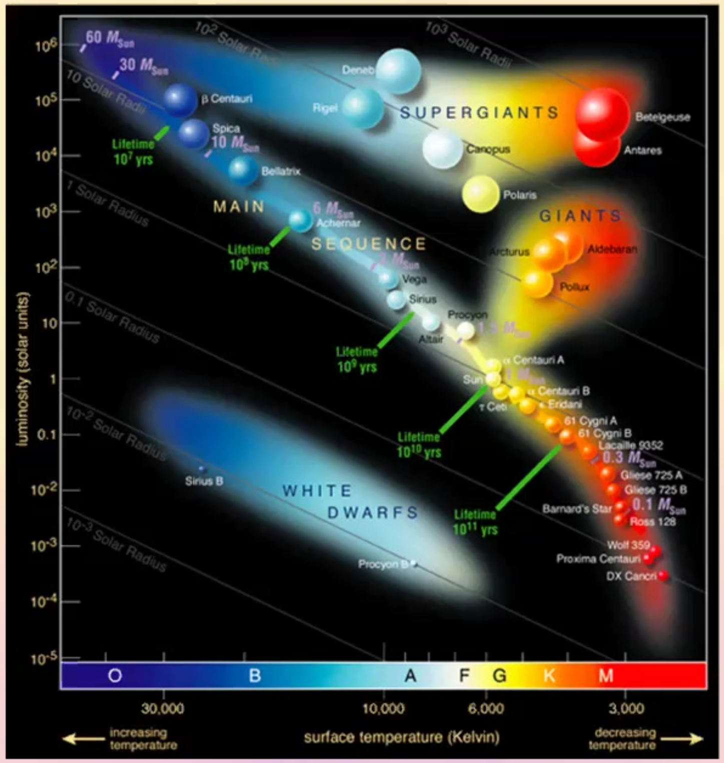
Swedish Research Council

Oskar Klein centre

Stockholms universitet


Aurore
Evan O'Connor
Shuai Zha
samuel
OliverA
Andre da Silva Schneider

Supernovae have a broad connection to the Universe



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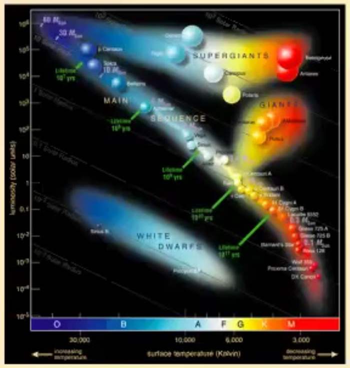
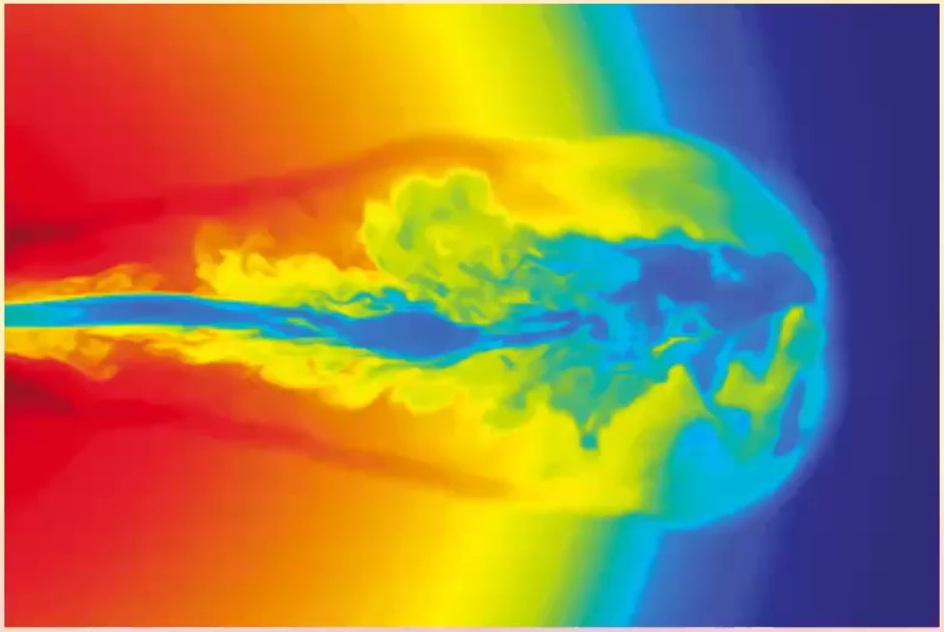
Stellar Evolution



ESO



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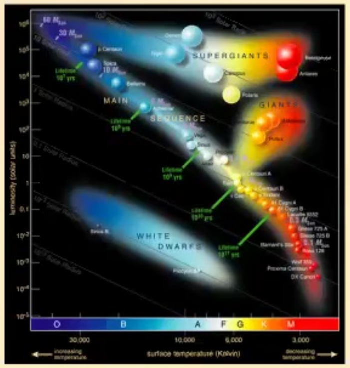
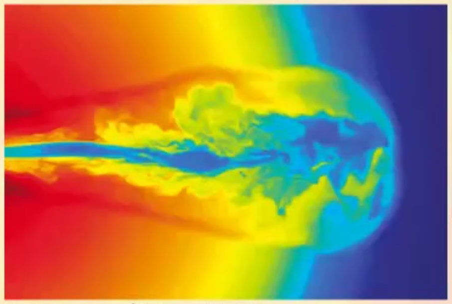
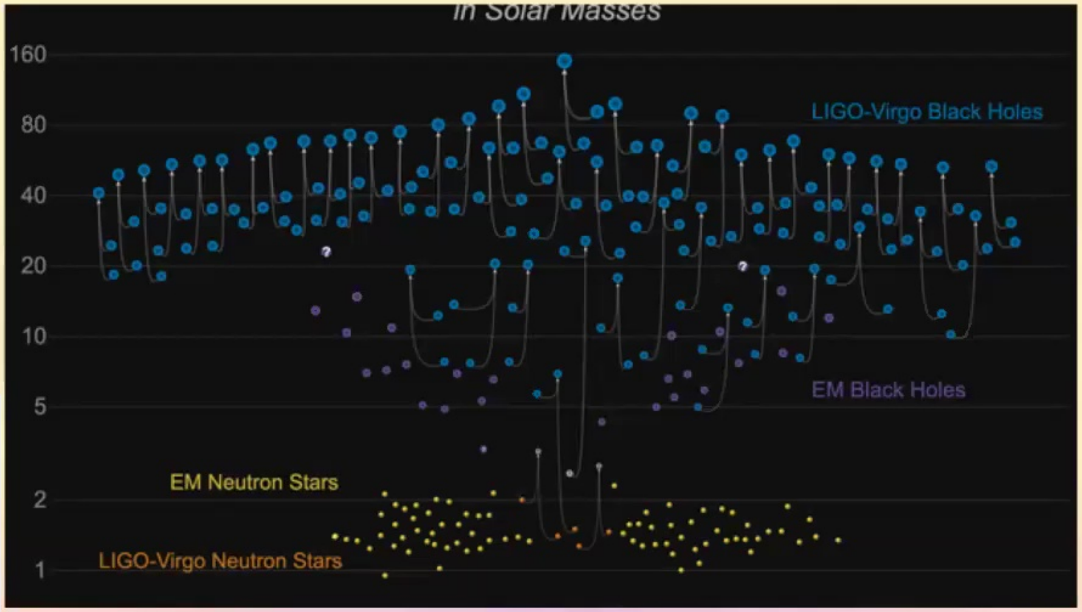


ESO

Long gamma-ray burst



Science/MacFadyen



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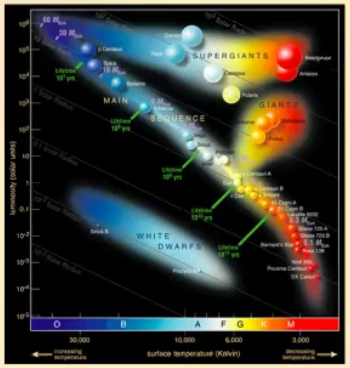

ESO

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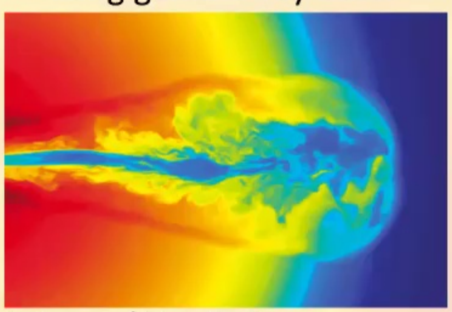


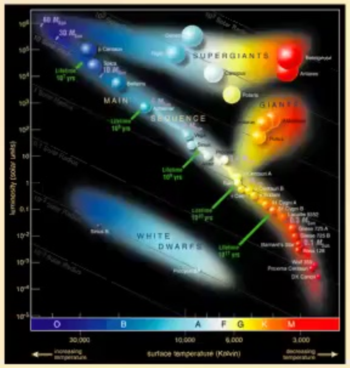
Science/MacFadyen

Ne

LIGO/VIRGO

Supernovae have a broad connection to the Universe

Stellar Evolution



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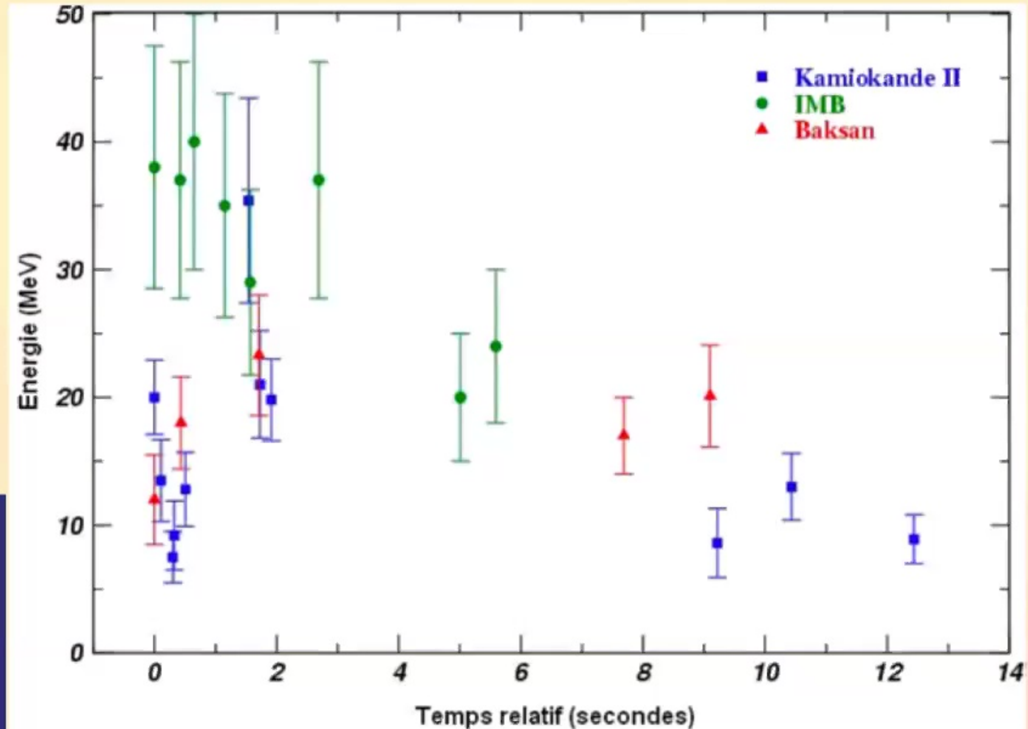

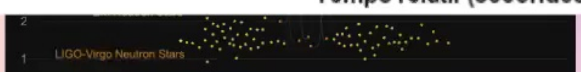

LIGO/VIRGO

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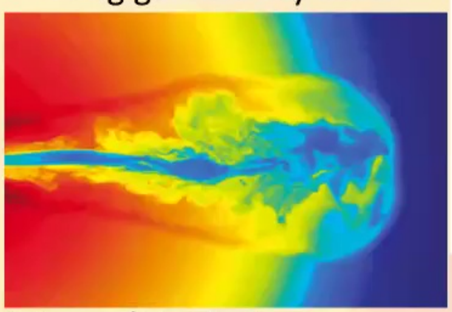


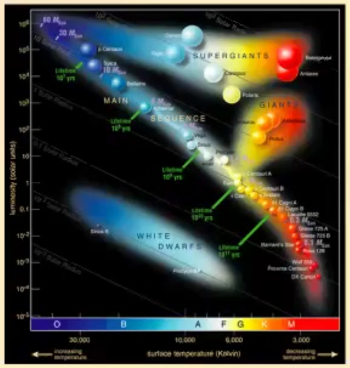
Science/MacFadyen

Galaxy Evolution

Hubble

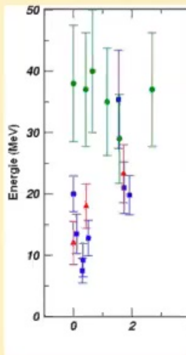
Supernovae have a broad connection to the Universe

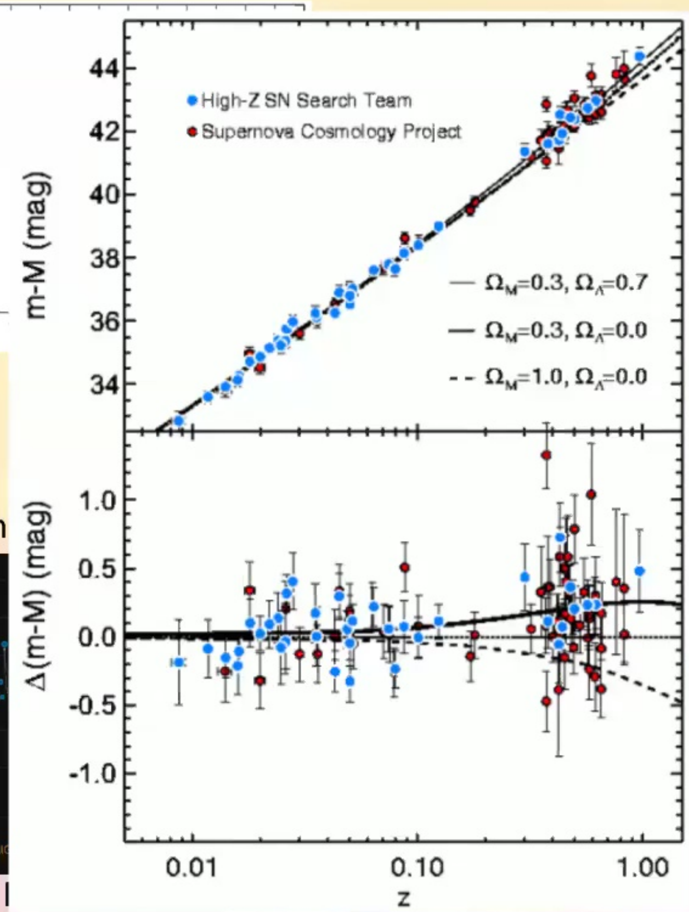
Stellar Evolution



ESO

Neutrinos & Gravitational Waves





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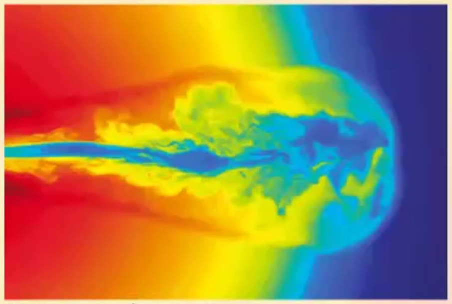


Science/MacFadyen

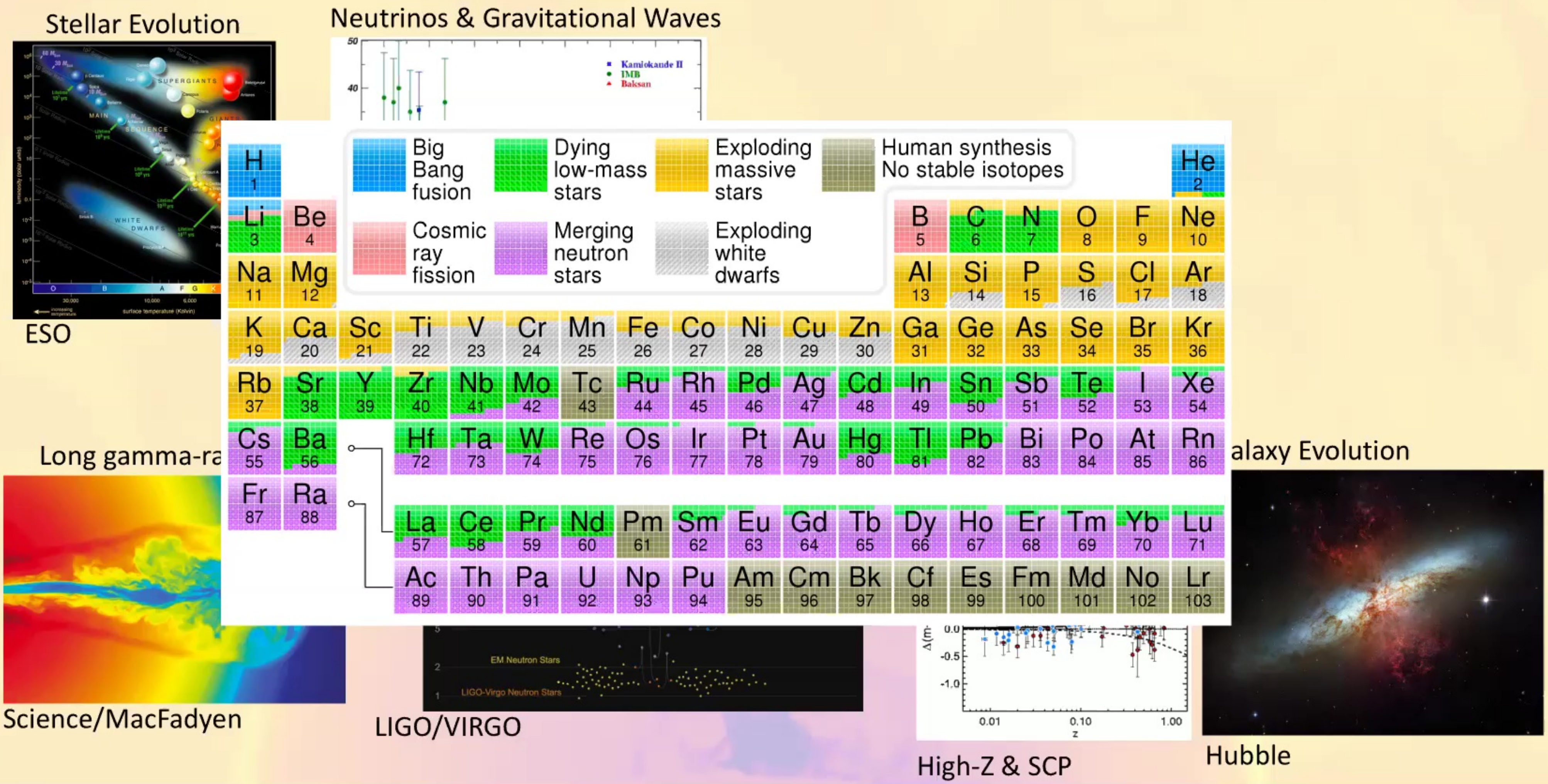
Neutron

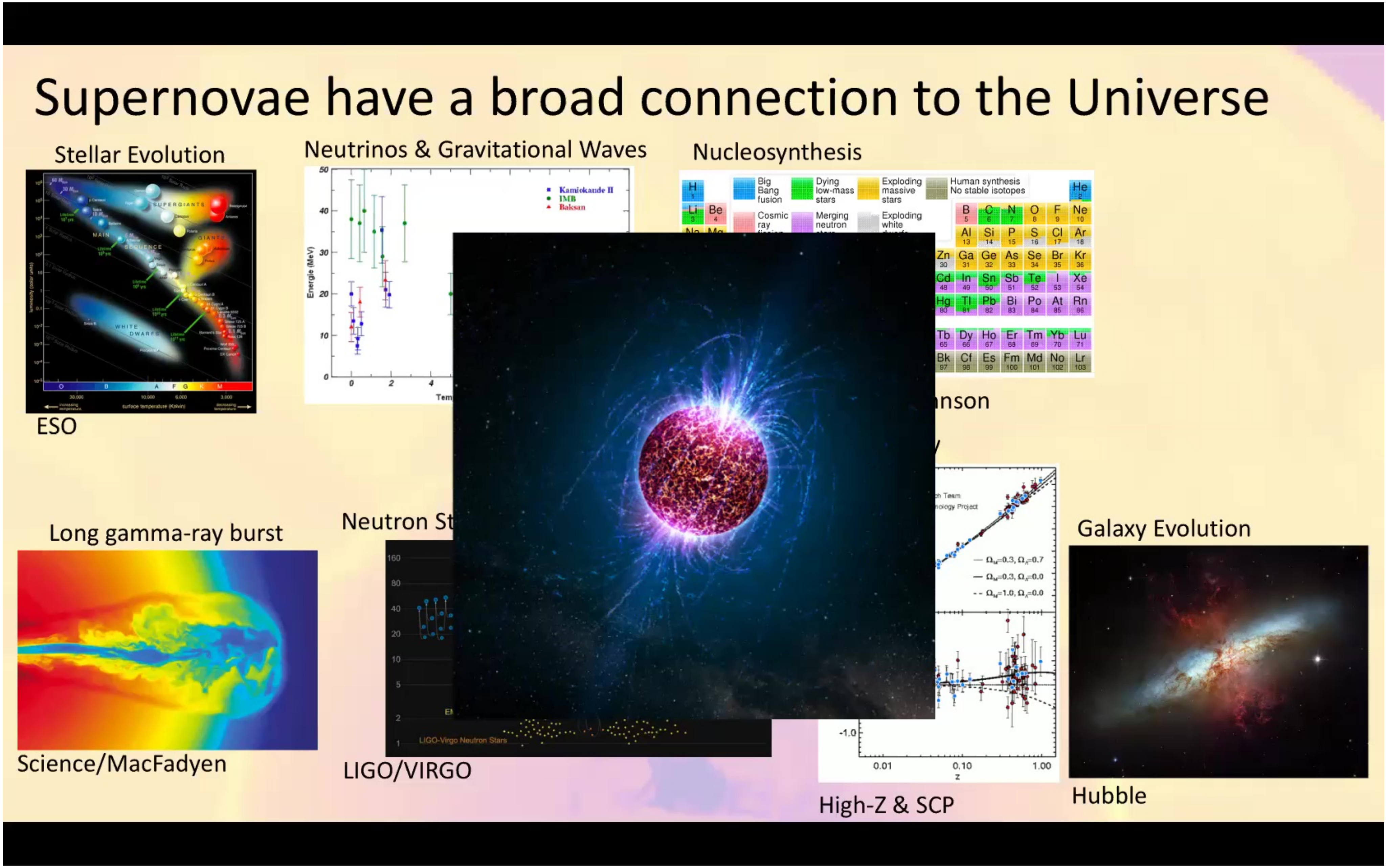
LIGO/VII

Galaxy Evolution

Hubble

Supernovae have a broad connection to the Universe




Supernovae have a broad connection to the Universe
Stellar Evolution
ESO
Neutrinos & Gravitational Waves
Kamiokande II
IMB
Baksan
Nucleosynthesis
Long gamma-ray burst
Science/MacFadyen
Neutron St
LIGO-Virgo Neutron Stars
LIGO/VIRGO
High-Z & SCP
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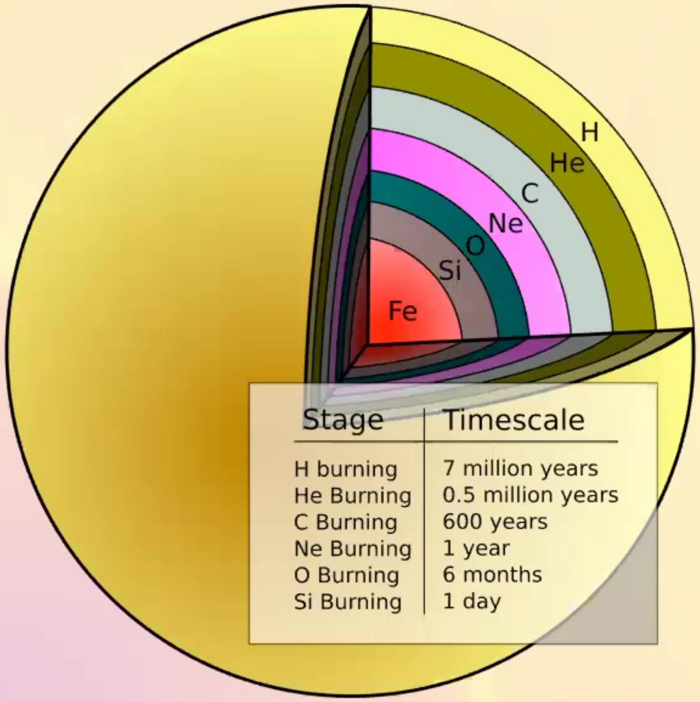
Core-Collapse Supernovae as Laboratories for Fundamental Physics

- The Death of Massive Stars: Core-Collapse Supernovae
- Probing fundamental physics
  - Hadron-Quark phase transition
  - Nuclear Equation of State
- Neutrinos as Messengers
- Parameterized Explosion models

Massive Stars: Burning Stages

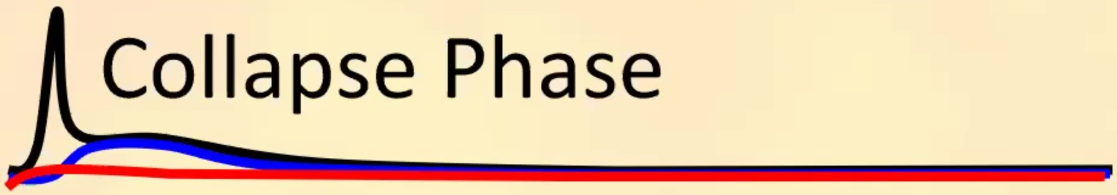
- Stars spend most of their lives burning hydrogen.
- For massive stars ($M > 8\text{-}10M_{sun}$), the process continues through helium, carbon, … , up to iron.
- This process does not continue past iron as iron is one of the most tightly bound nuclei.
- Iron cores however are supported by electron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

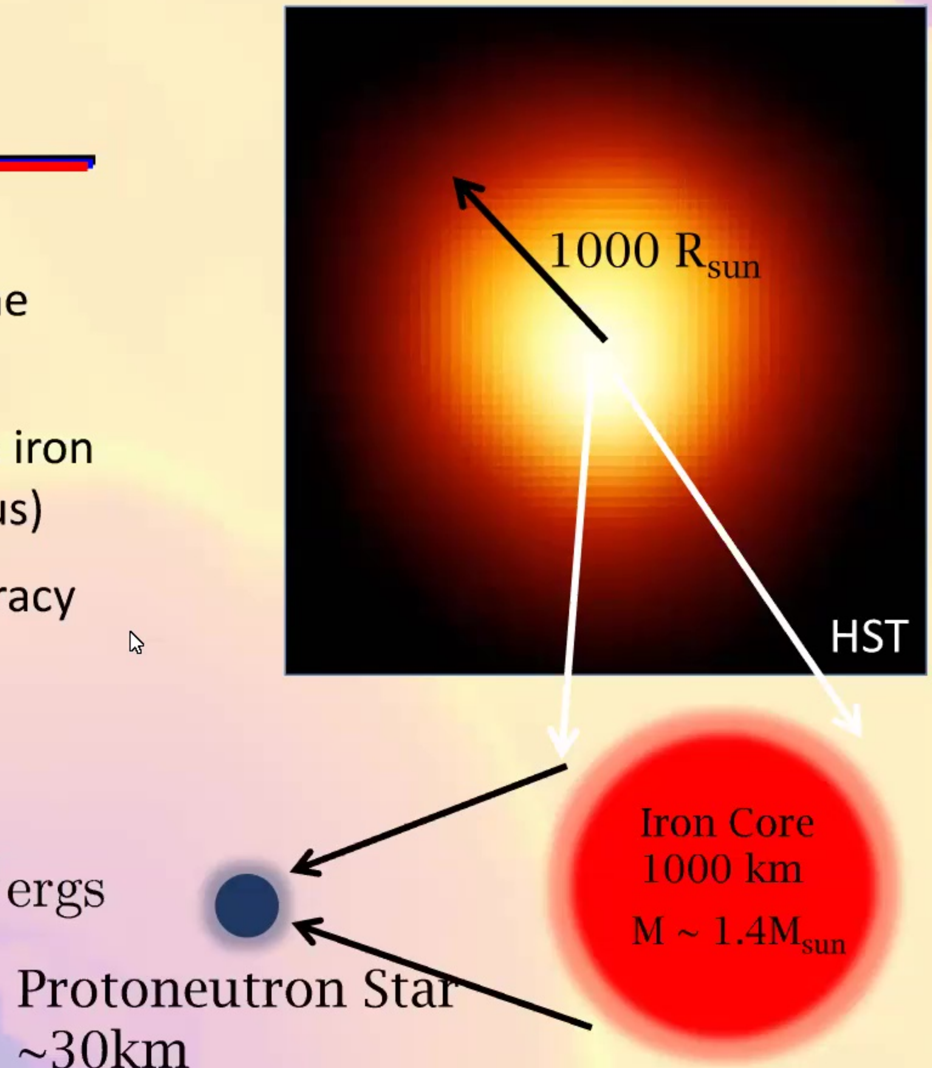
A. C. Phillips, *The Physics of Stars*, 2nd Edition (Wiley, 1999).

Collapse Phase

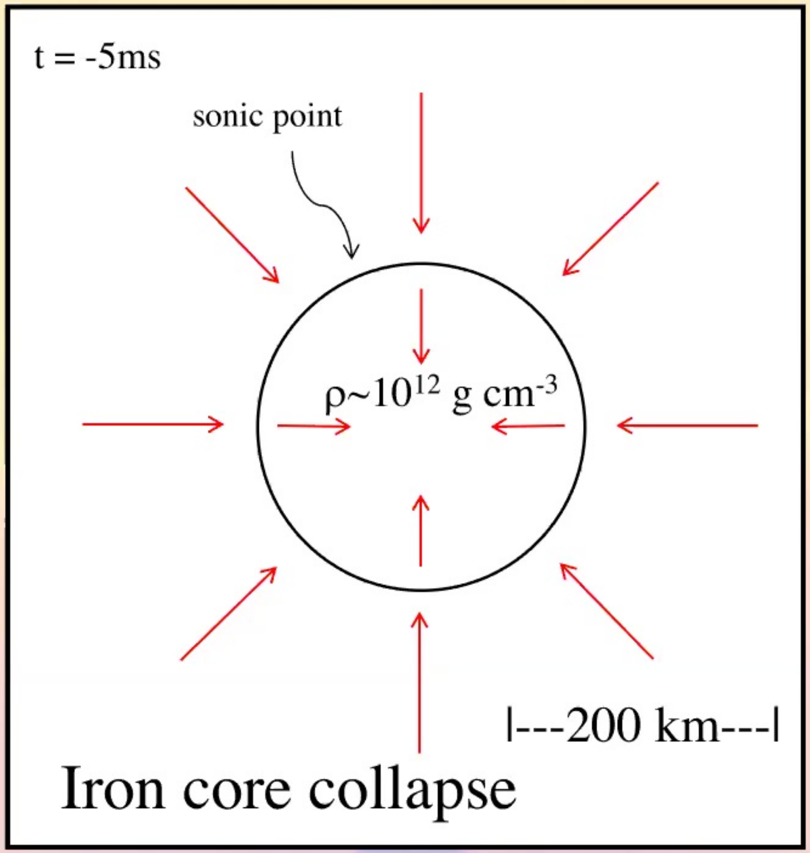


- Most massive stars core collapse during the red supergiant phase
- CCSNe are triggered by the collapse of the iron core (~1000km, or 1/10^6 of the star's radius)
- Collapse ensues because electron degeneracy pressure can no longer support the core against gravity

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



CCSNe: The Stages



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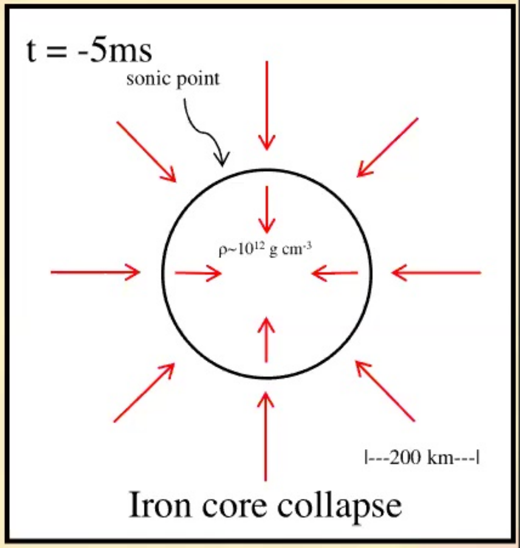

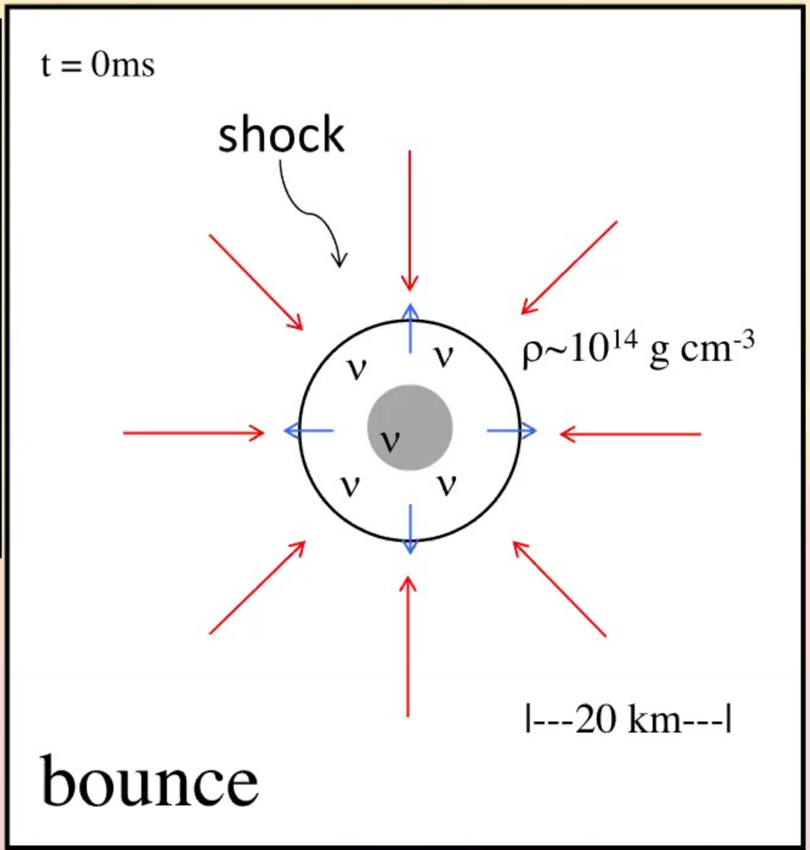

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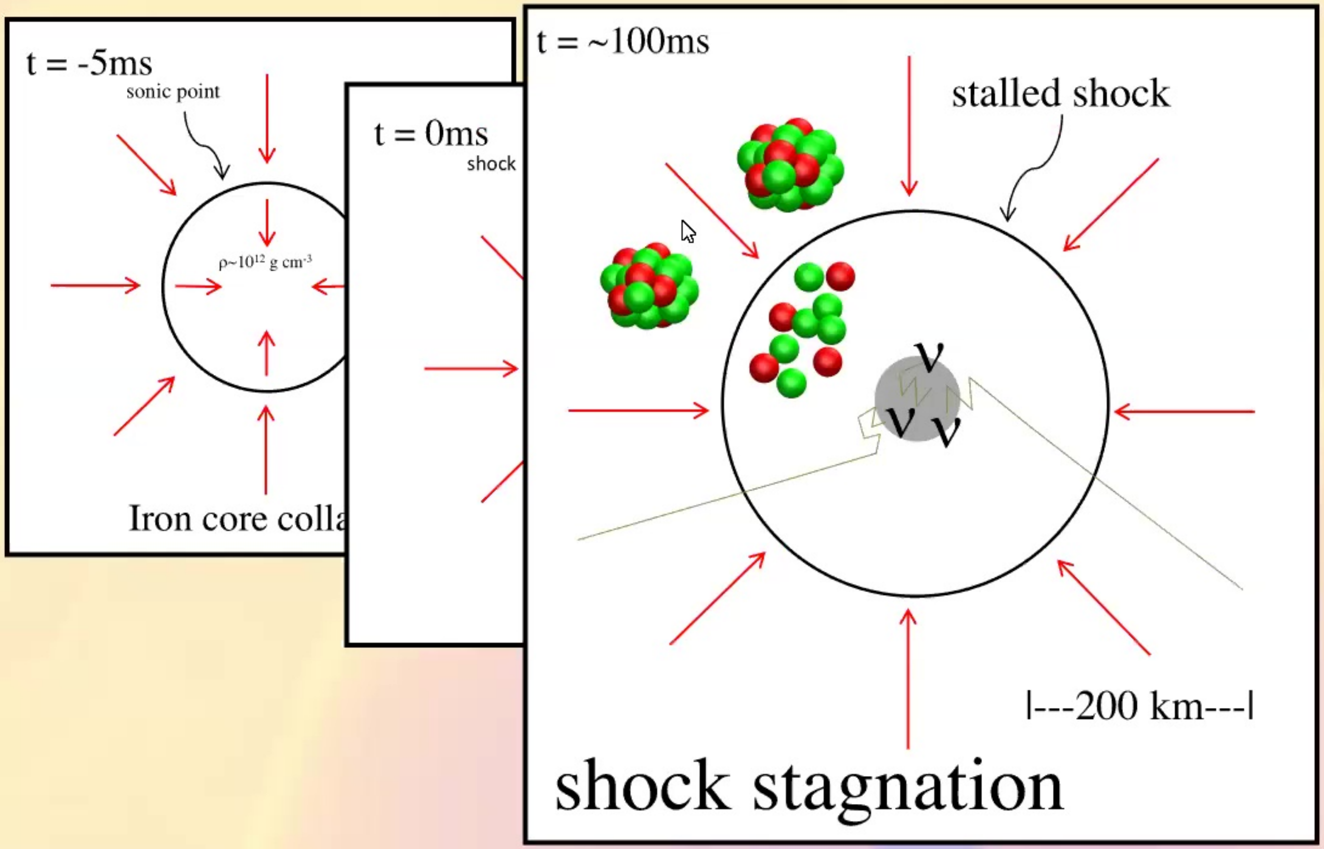
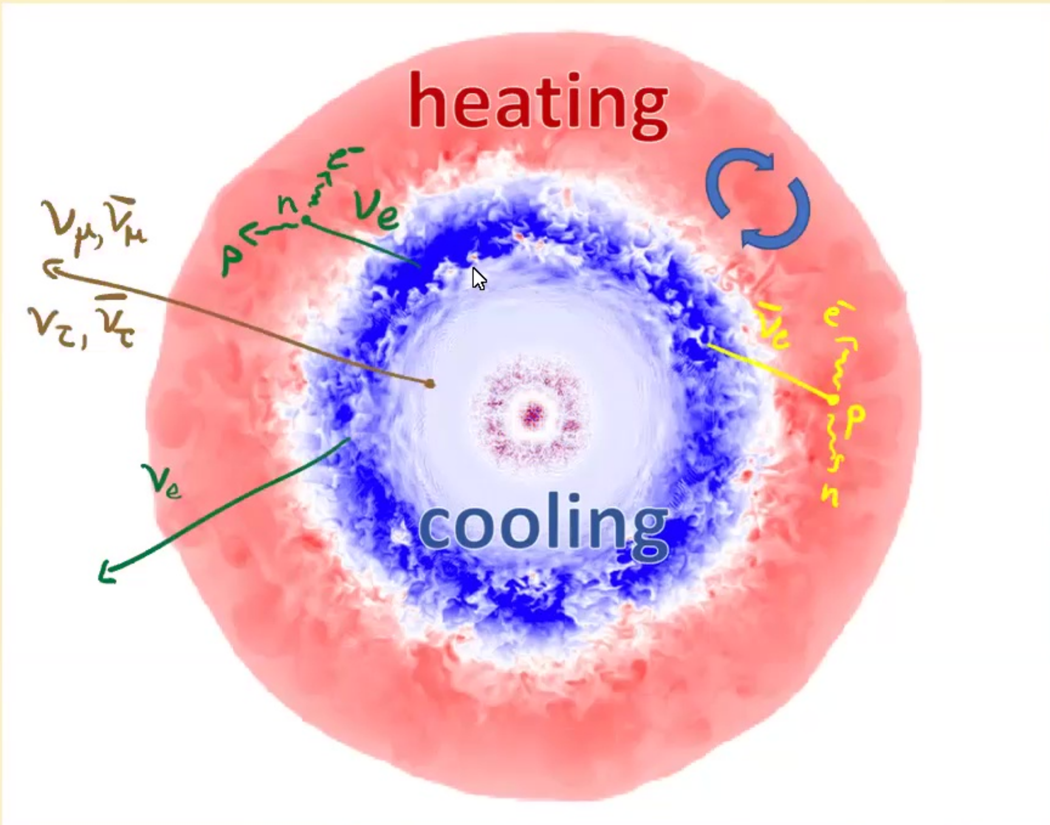


The Core-Collapse Supernova Problem



- 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

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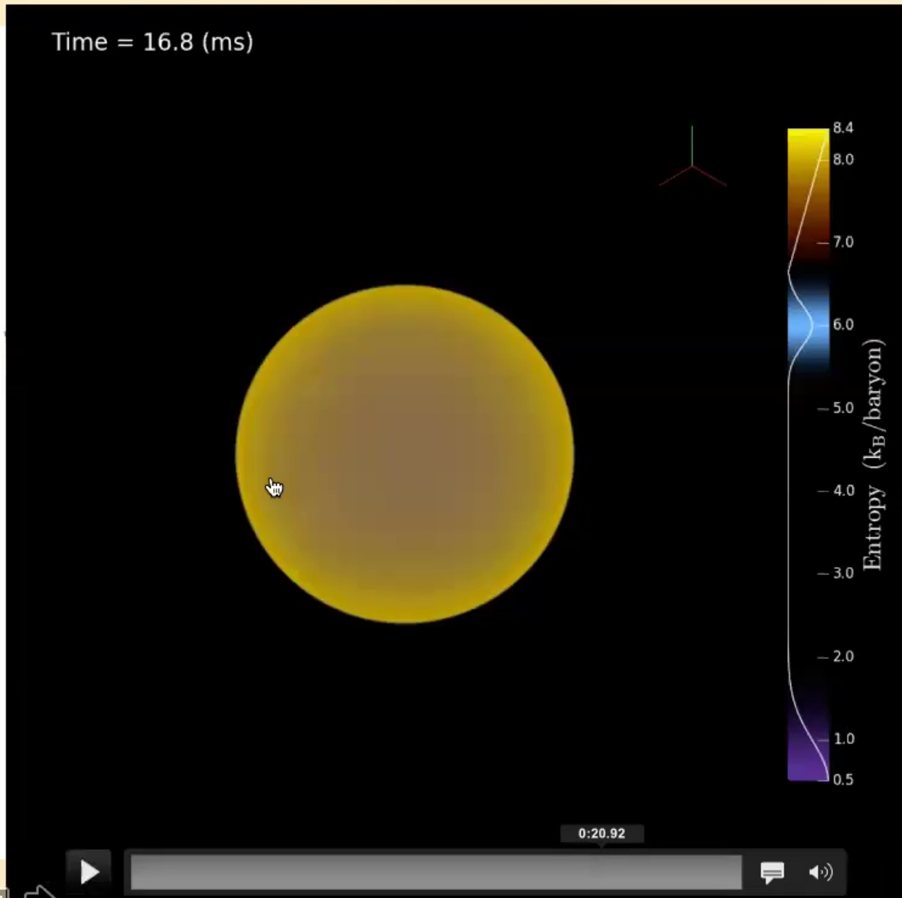

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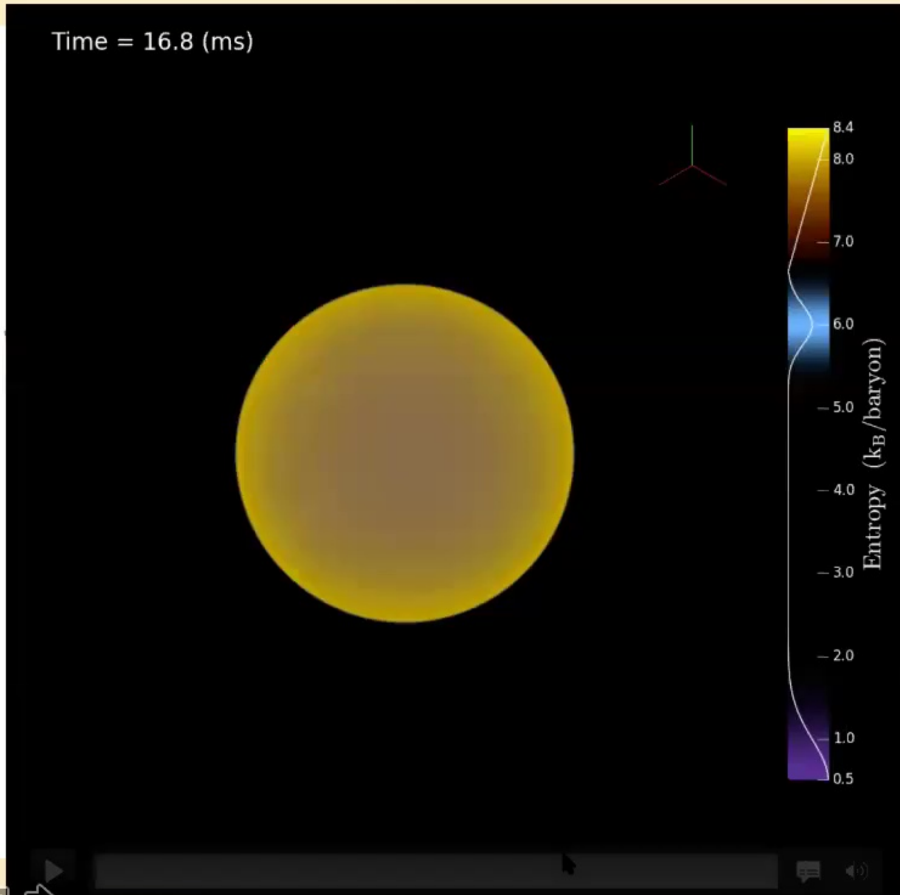

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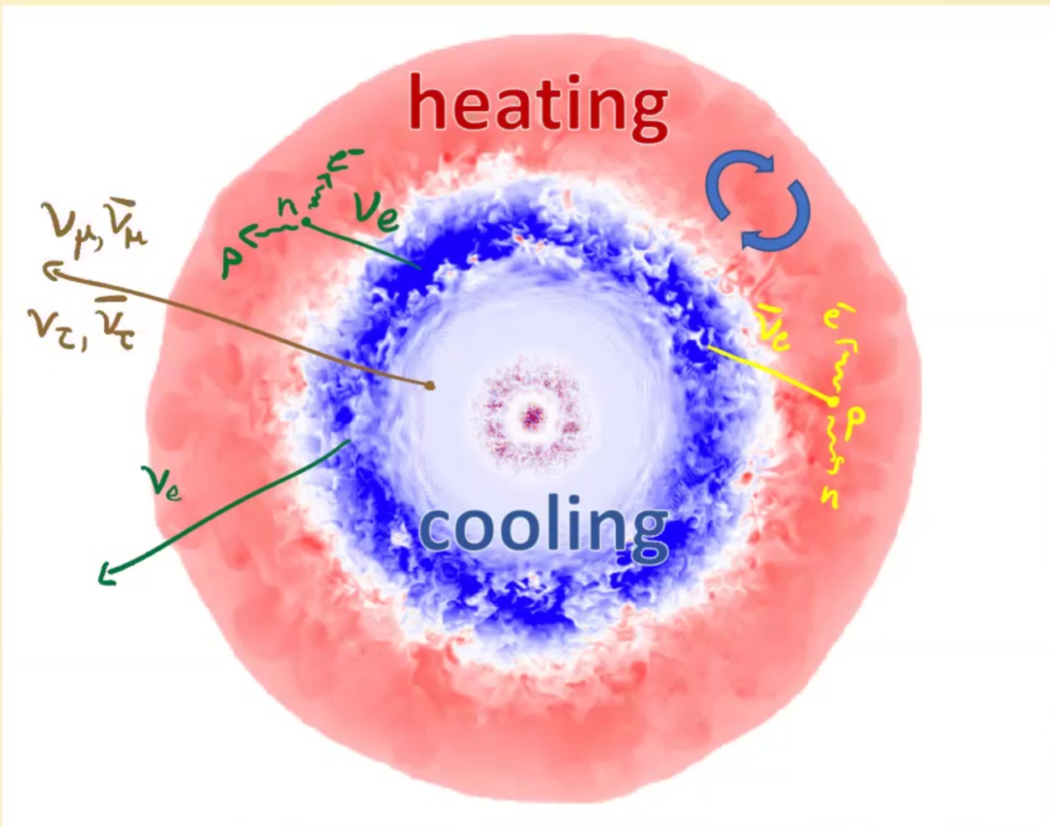

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Global effort towards agreement

- 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 Supernova 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

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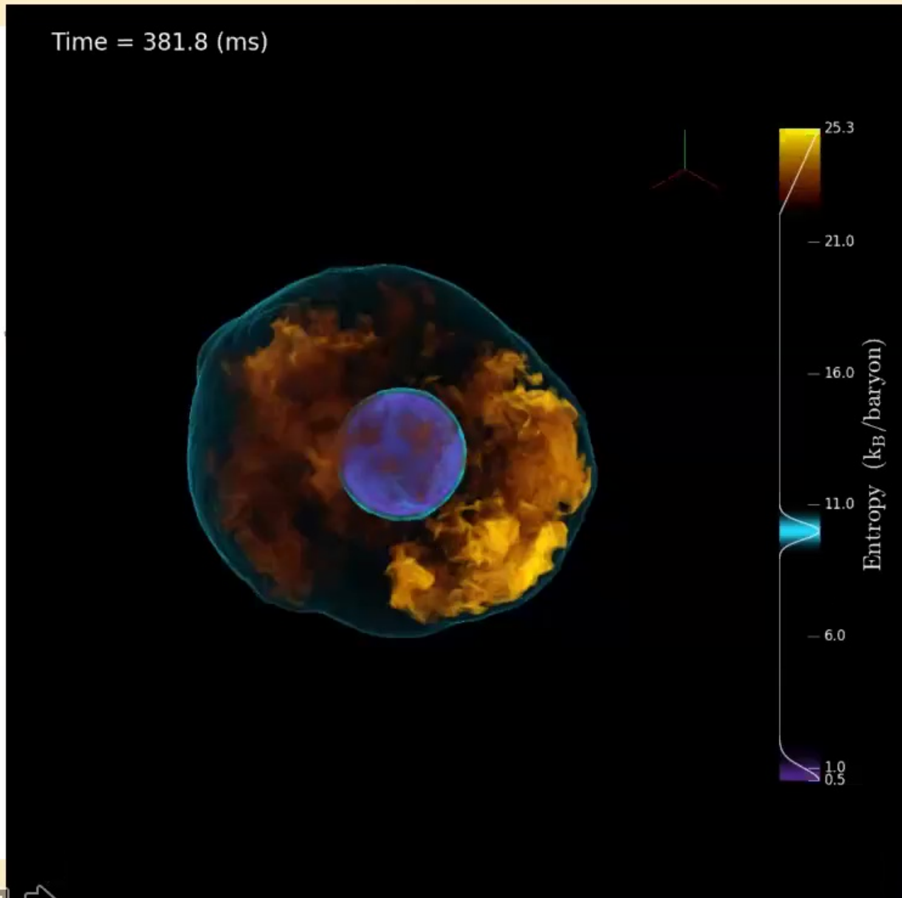

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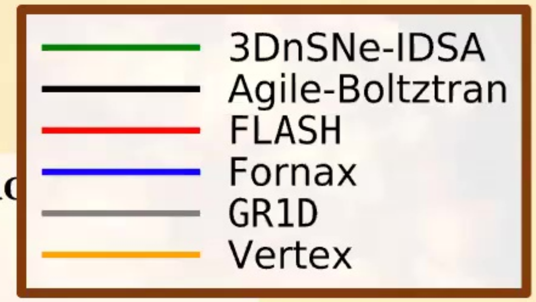

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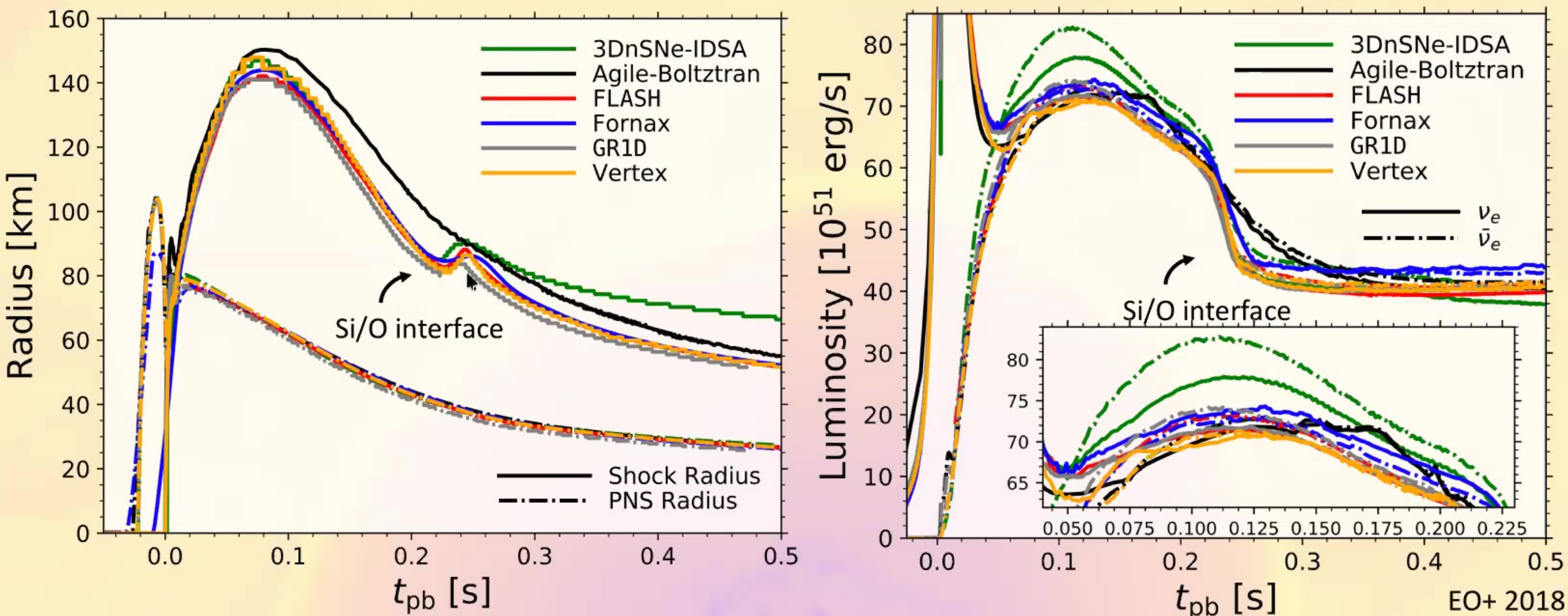
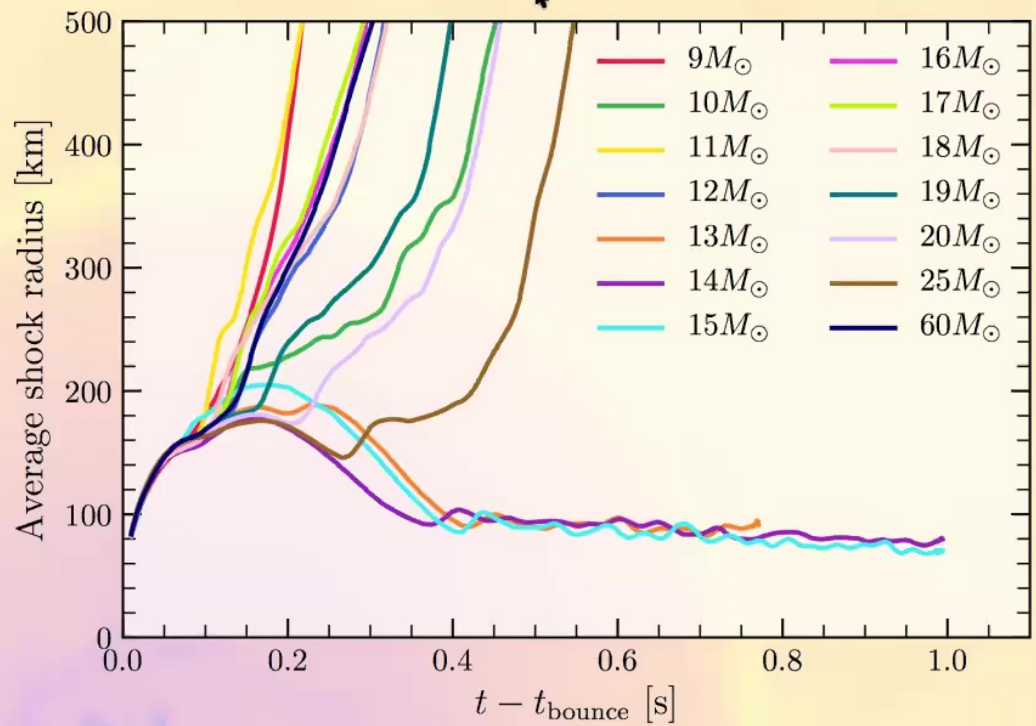
Excellent Agreement in 1D



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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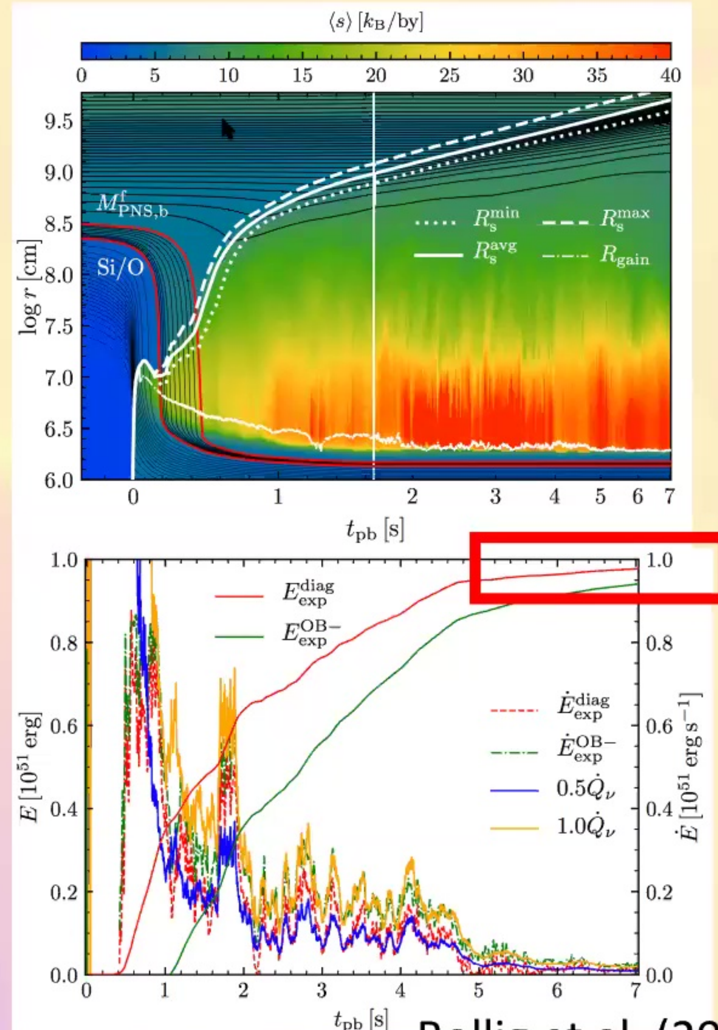

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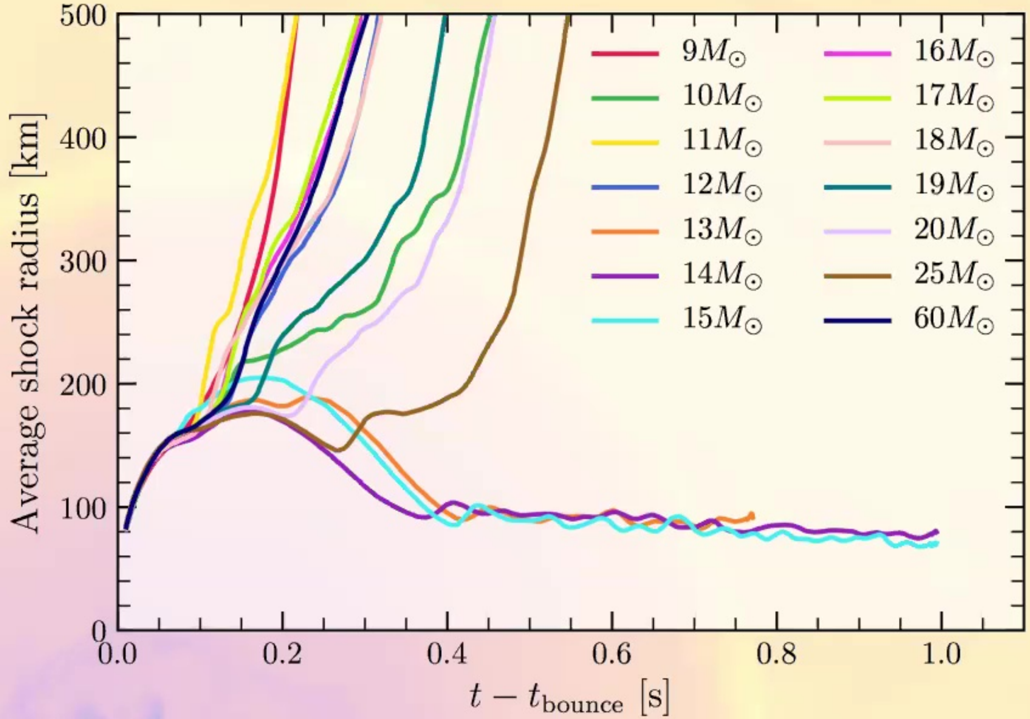

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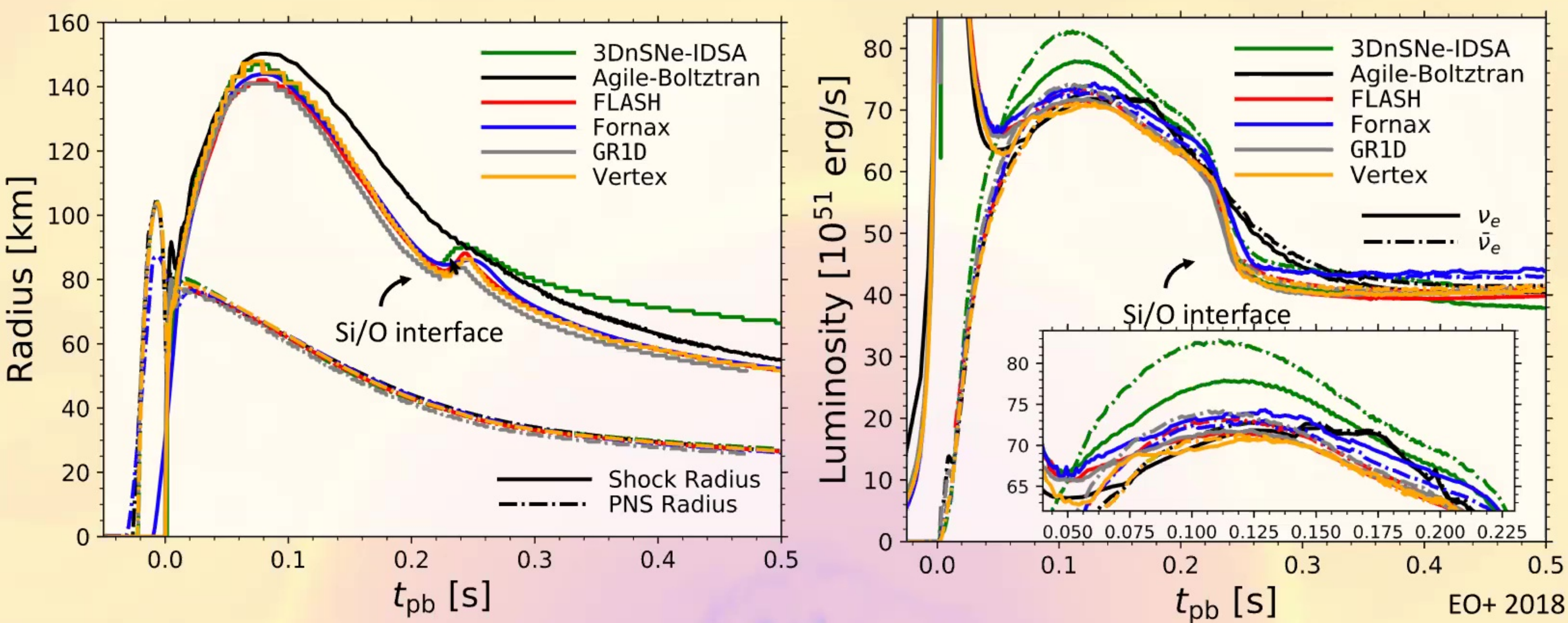

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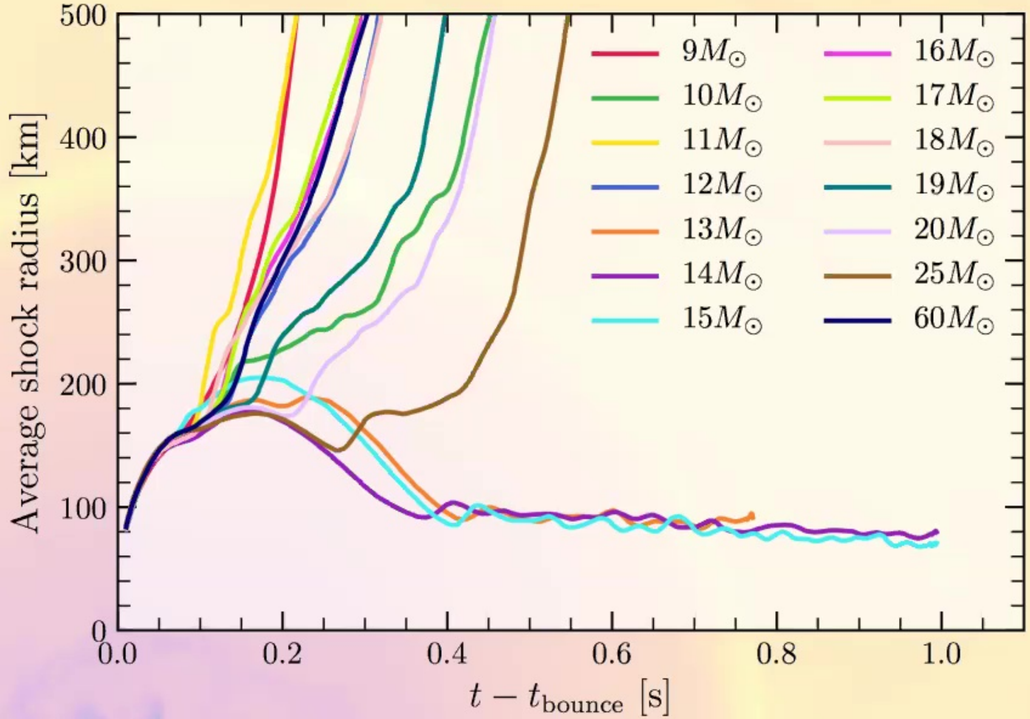
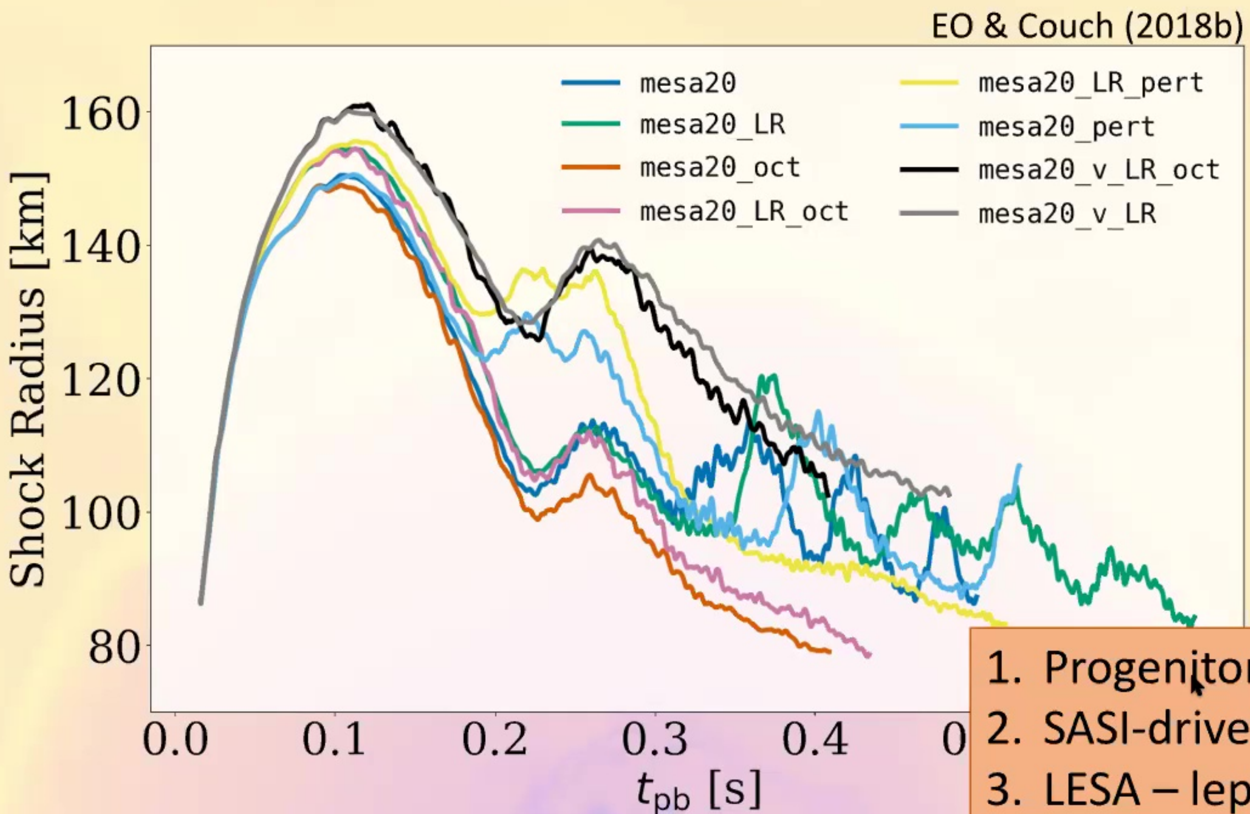


… and no explosions



1. Progenitor Perturbations
2. SASI-driven expansions
3. LESA – lepton-number asymmetry

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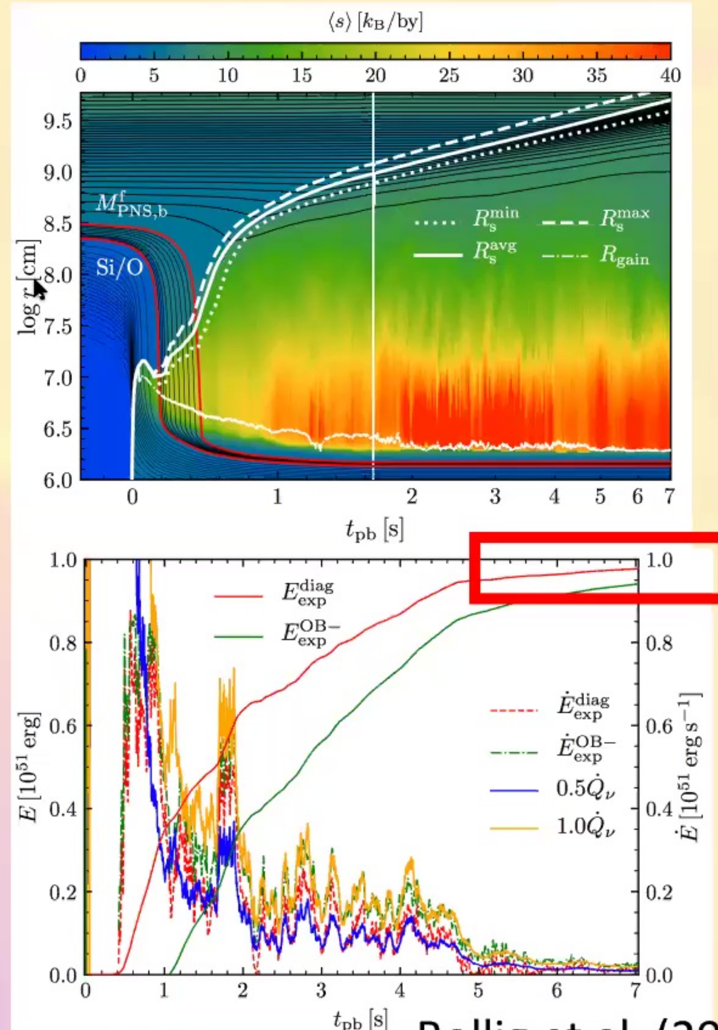
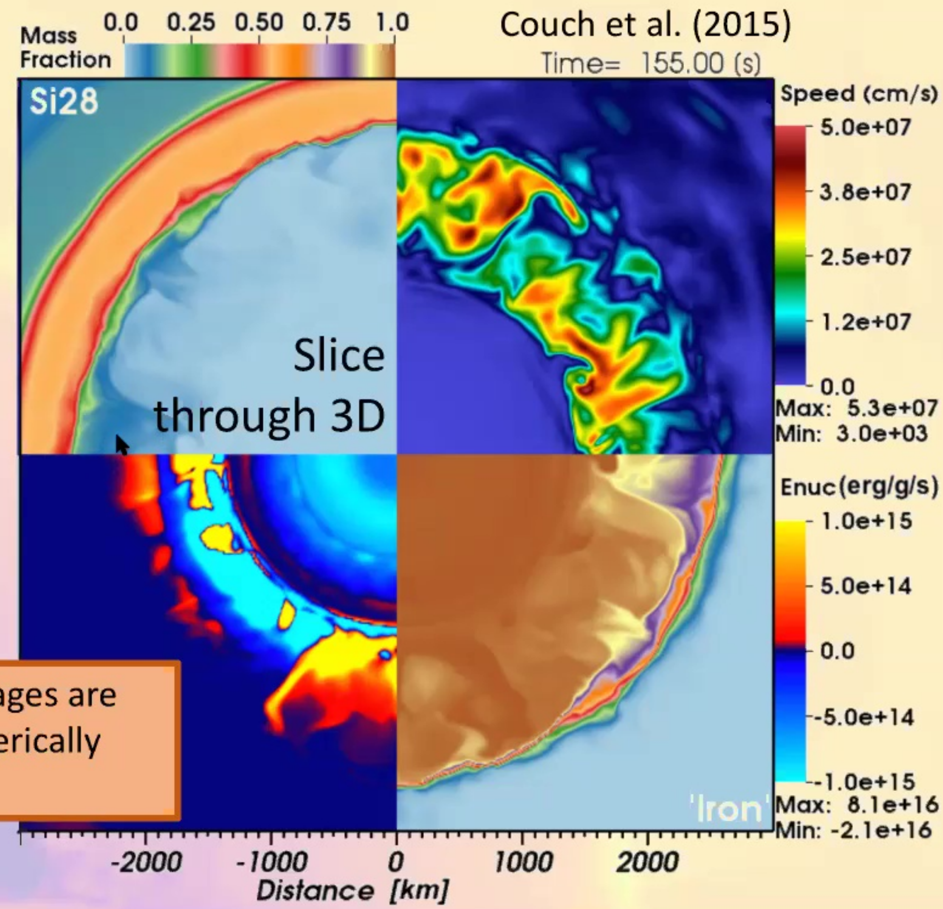


Bollig et al. (2020)

Presupernova Perturbations

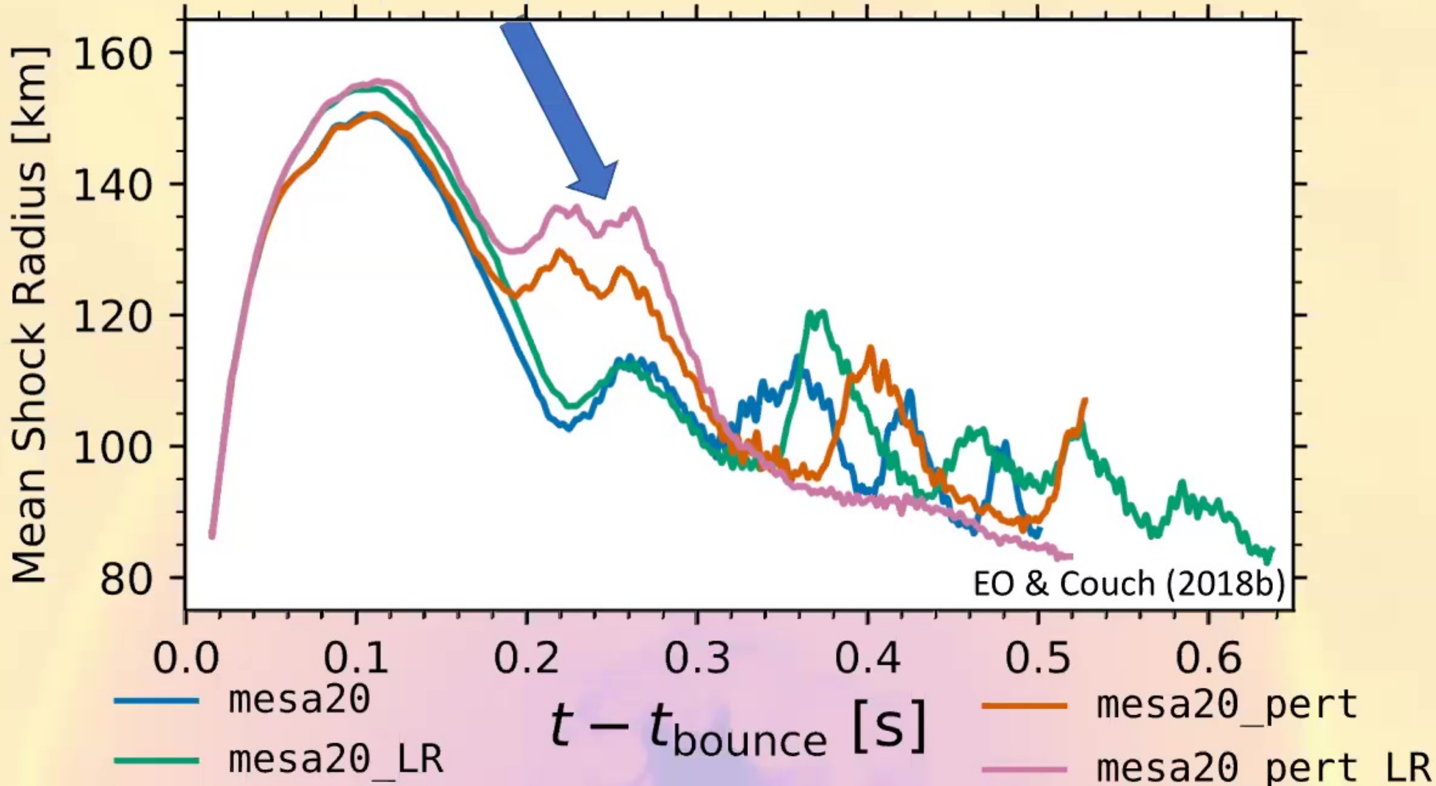
Has been shown recently (Müller & Janka 2015; Müller et al. 2017; …) that perturbations in the progenitor star can *aid* in the development of an explosion



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

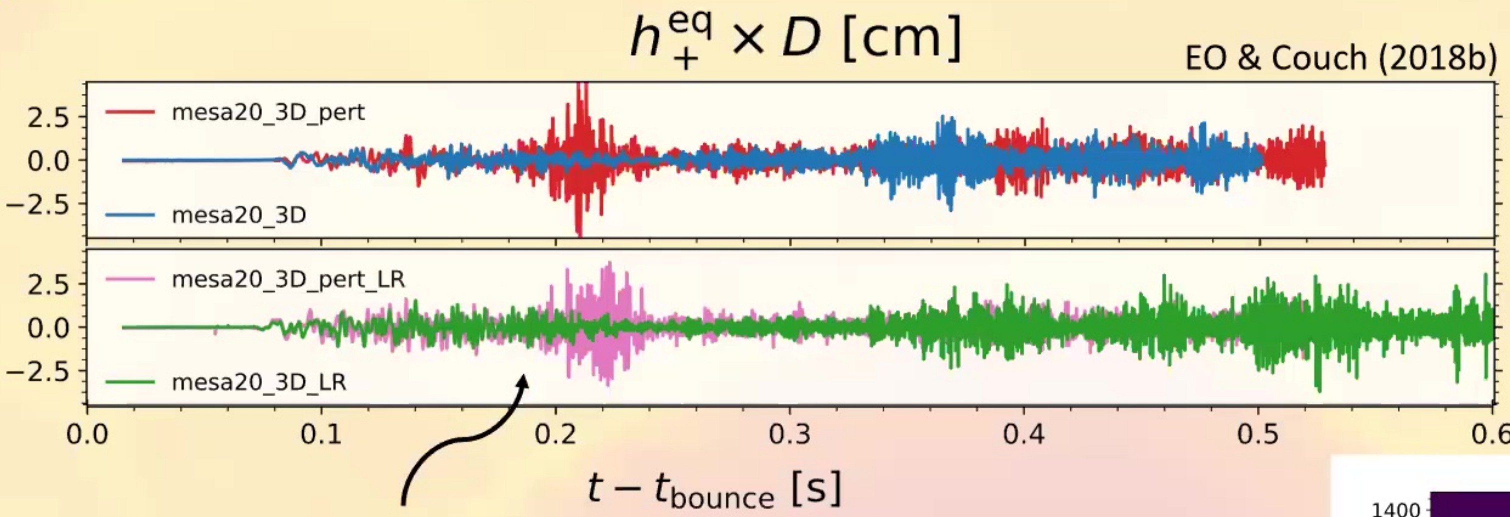
Progenitor asphericities are important

Pre-collapse structures in Si shell induce turbulence, provide pressure and support the shock

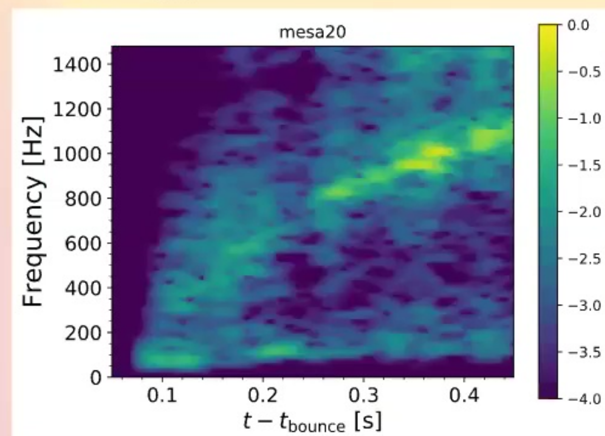


Gravitational Wave Signature

EO & Couch (2018b)

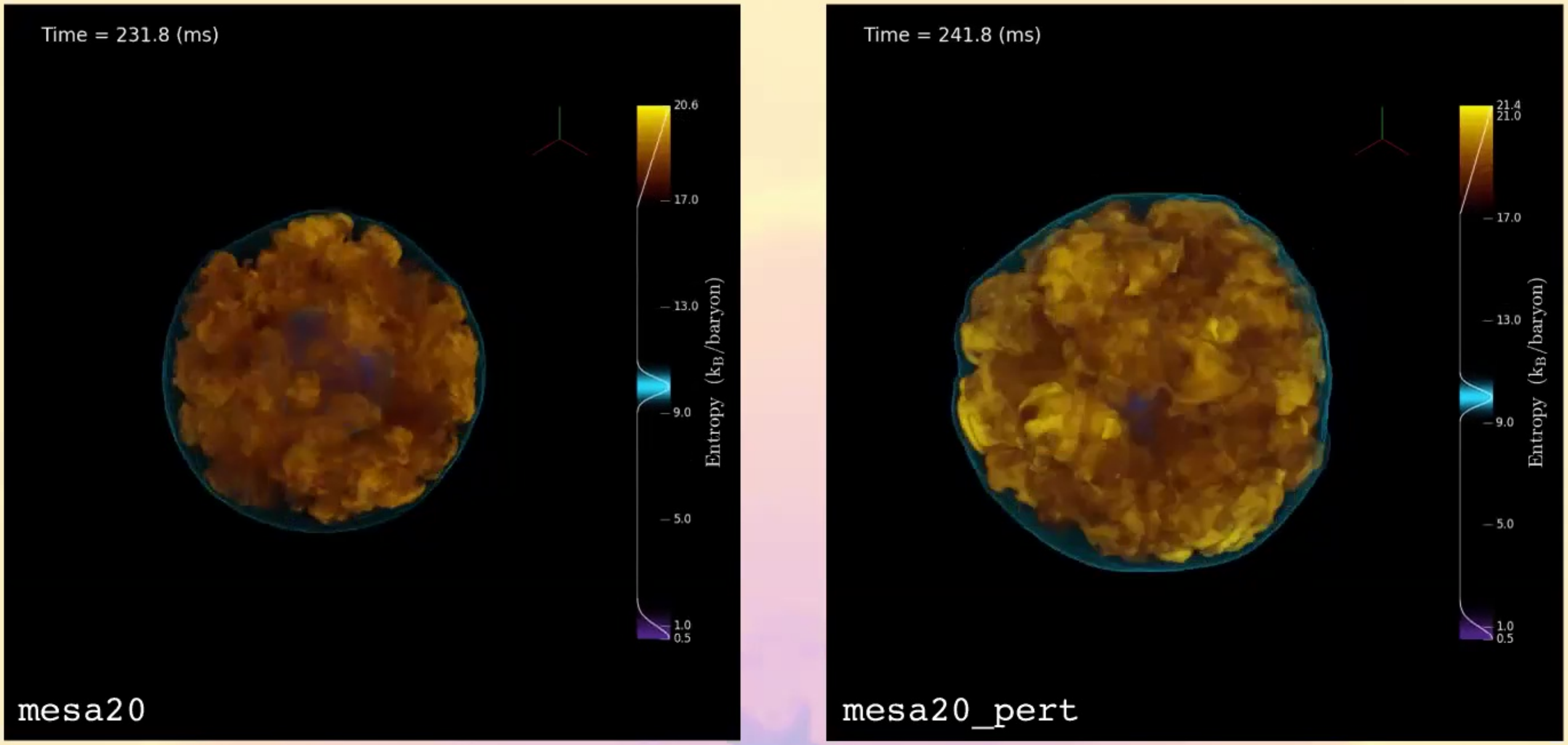


Burst of turbulence excites PNS and gives rise to GW



Impact of Progenitor Perturbations

EO & Couch (2018b)

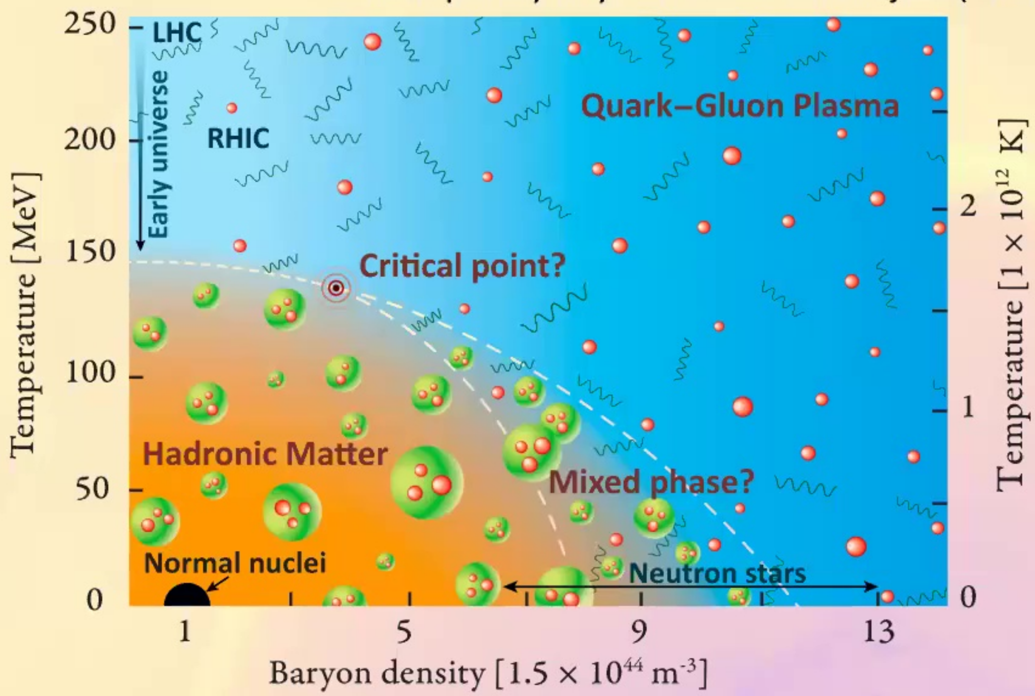


Core-Collapse Supernovae as Laboratories for Fundamental Physics

- The Death of Massive Stars: Core-Collapse Supernovae
- Probing fundamental physics
  - Hadron-Quark phase transition
  - Nuclear Equation of State
- Neutrinos as Messengers
- Parameterized Explosion models

Quarks in CCSNe

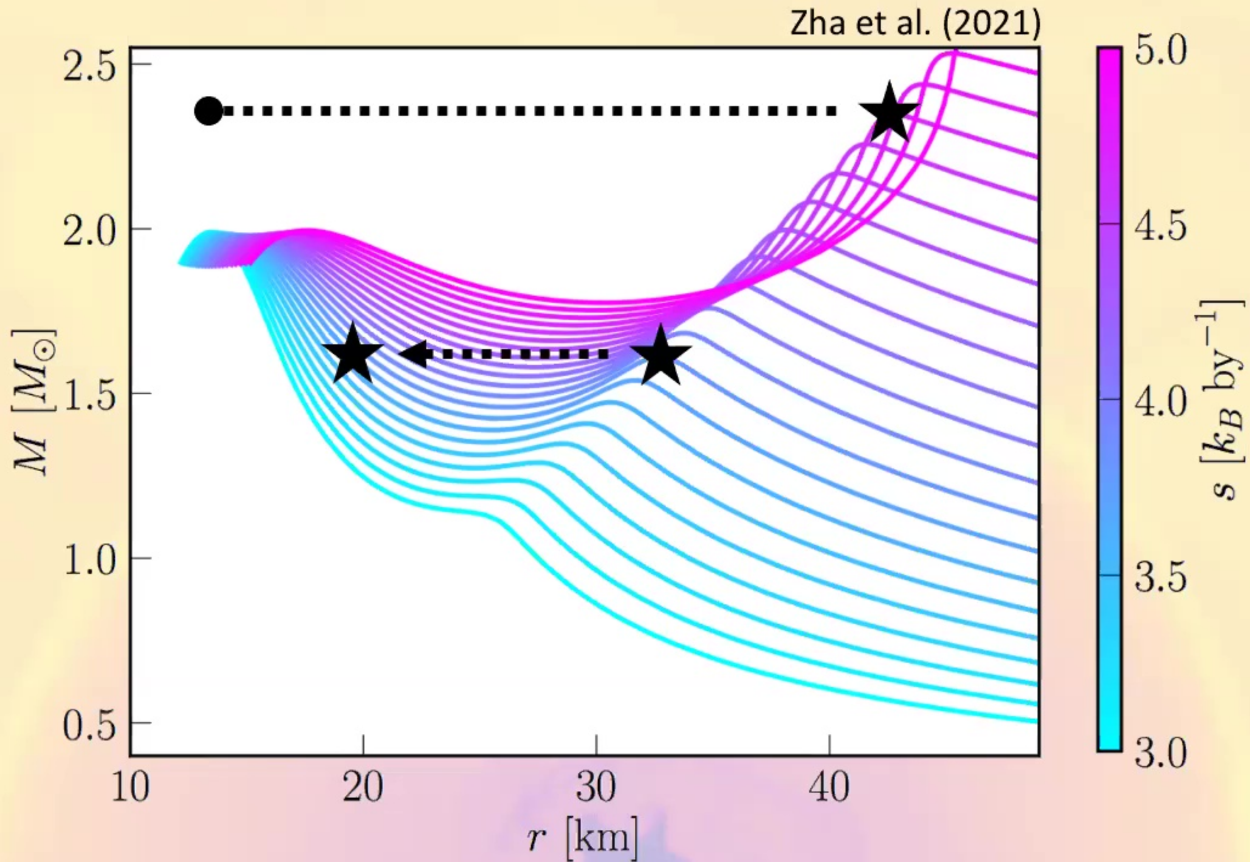
Contemporary Physics Education Project (CPEP)



Nuclear matter at extreme temperatures and densities is very uncertain!

CCSN environment is one of the only places these conditions exist

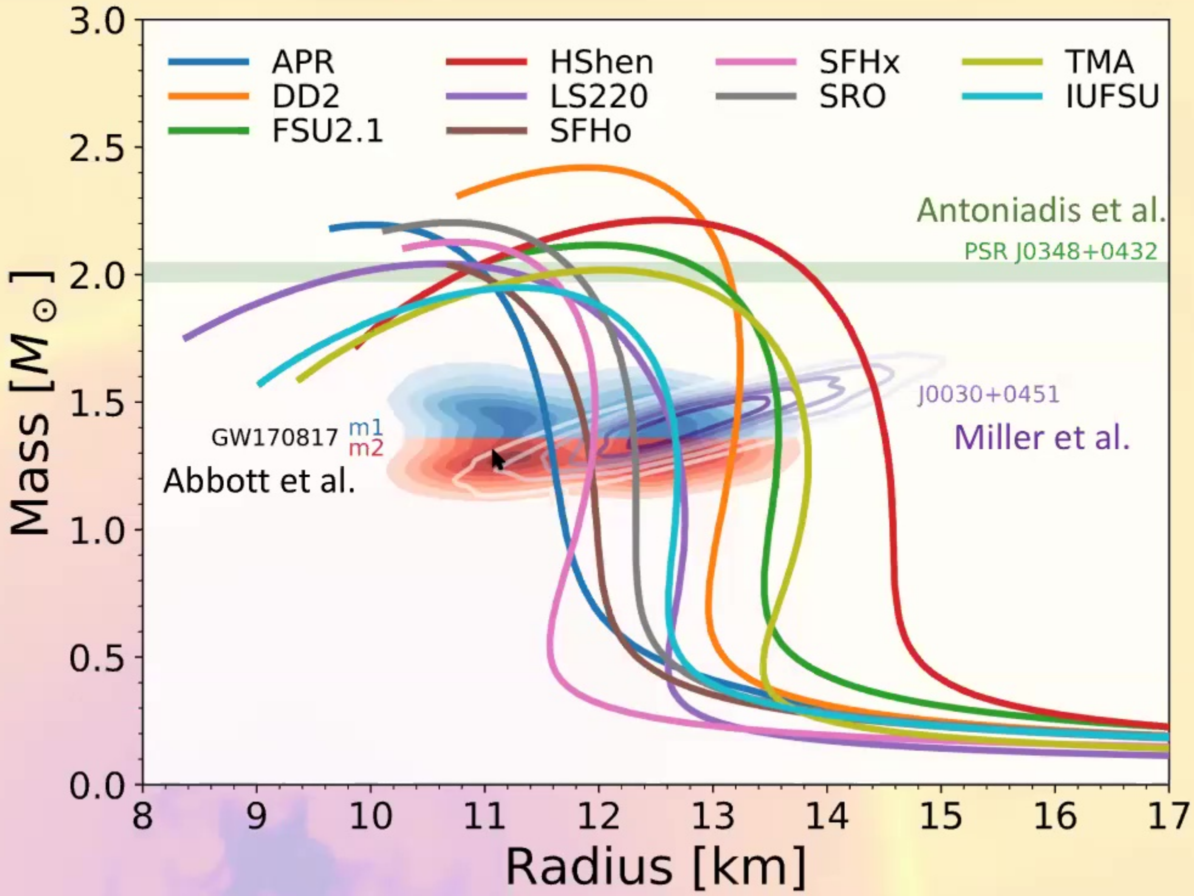
Quarks in CCSNe



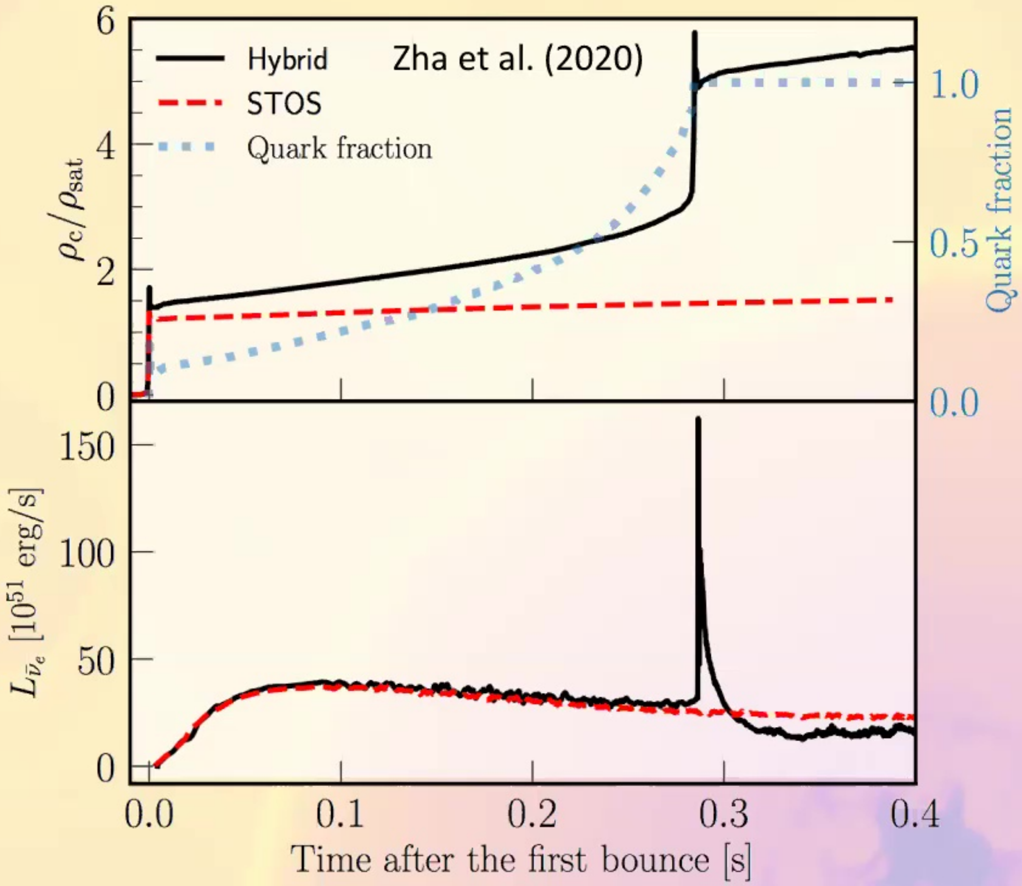
Nuclear Equation of State and Core Collapse

Wide variety of finite temperature EOS to choose from

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

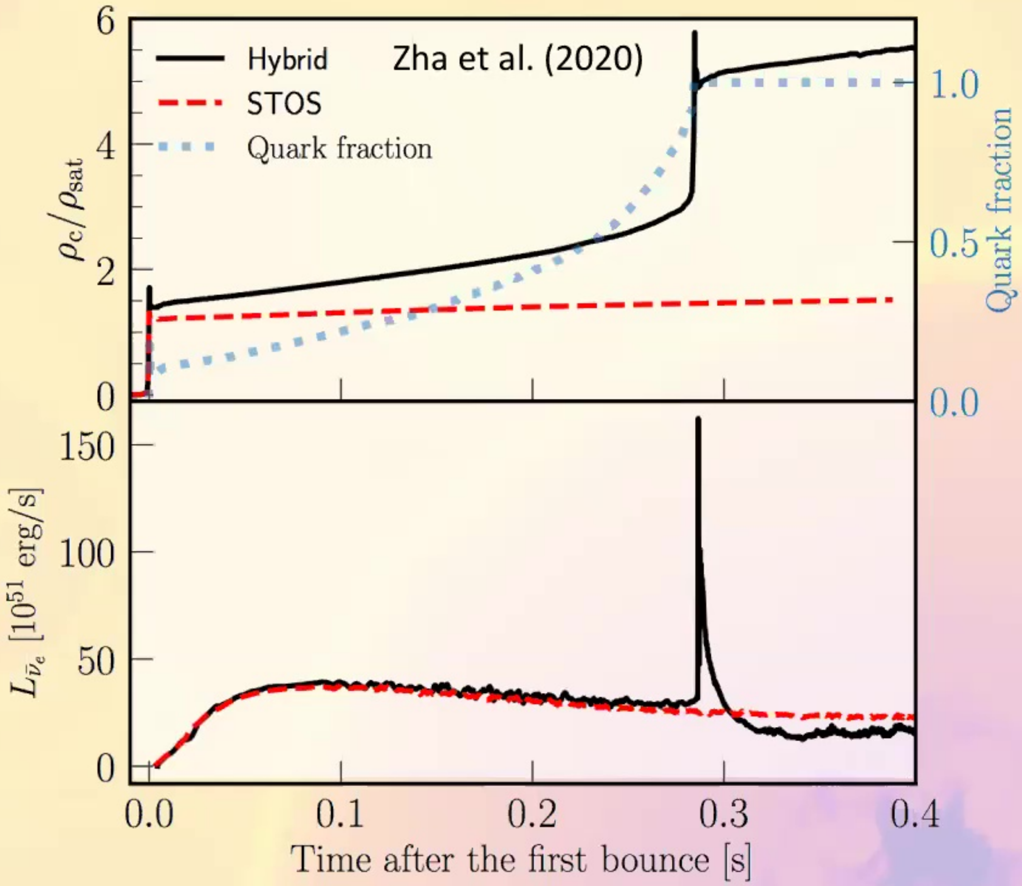


Quarks in CCSNe



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

Quarks in CCSNe



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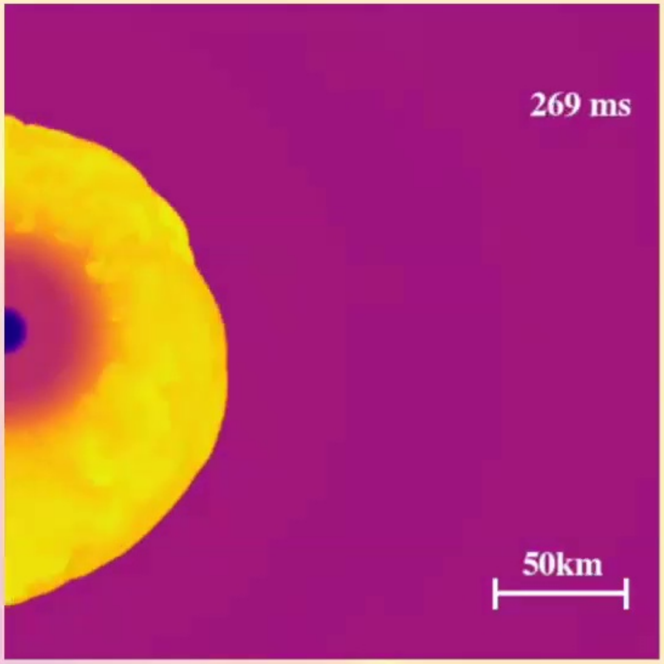
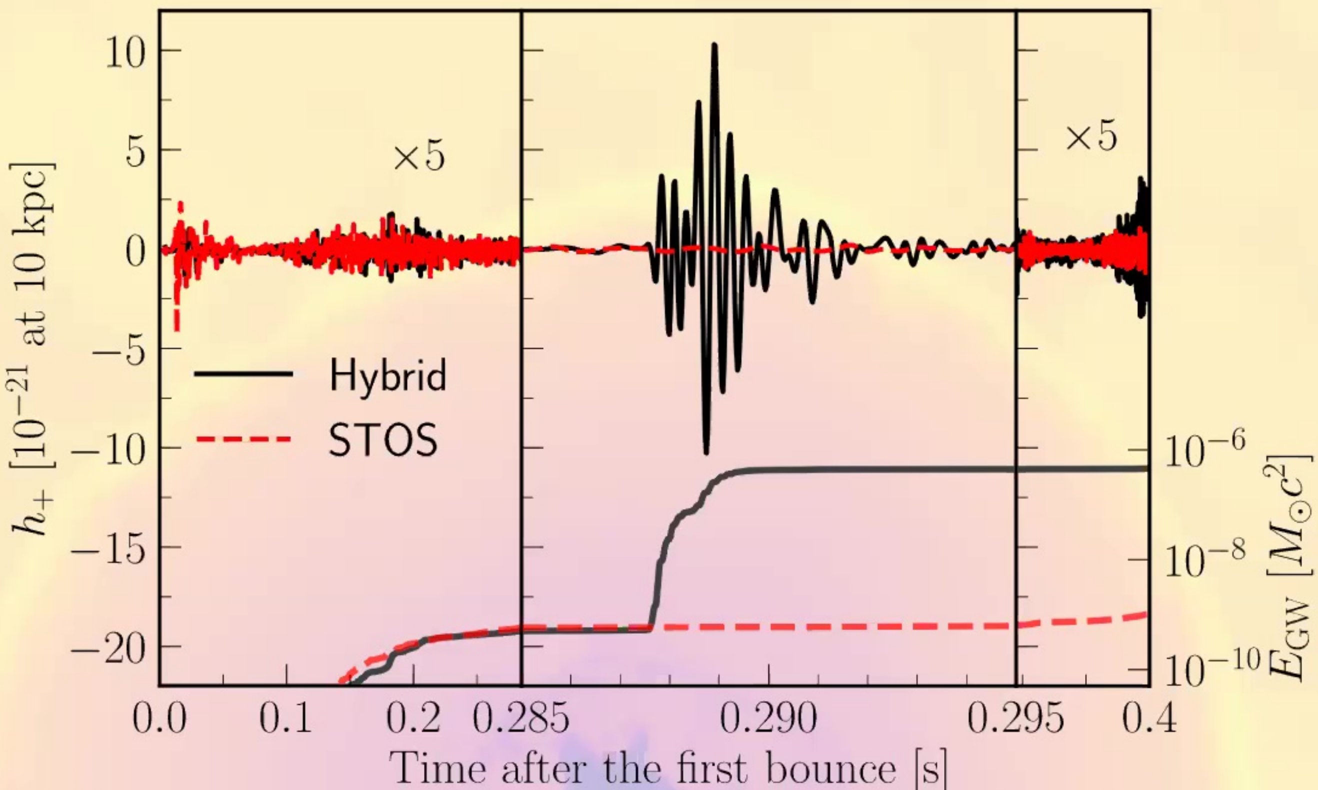


2D FLASH simulations

*First shown in 1D in Sagert 2009

Strong, short, high frequency, gravitaitonal waves

Zha et al. (2020)



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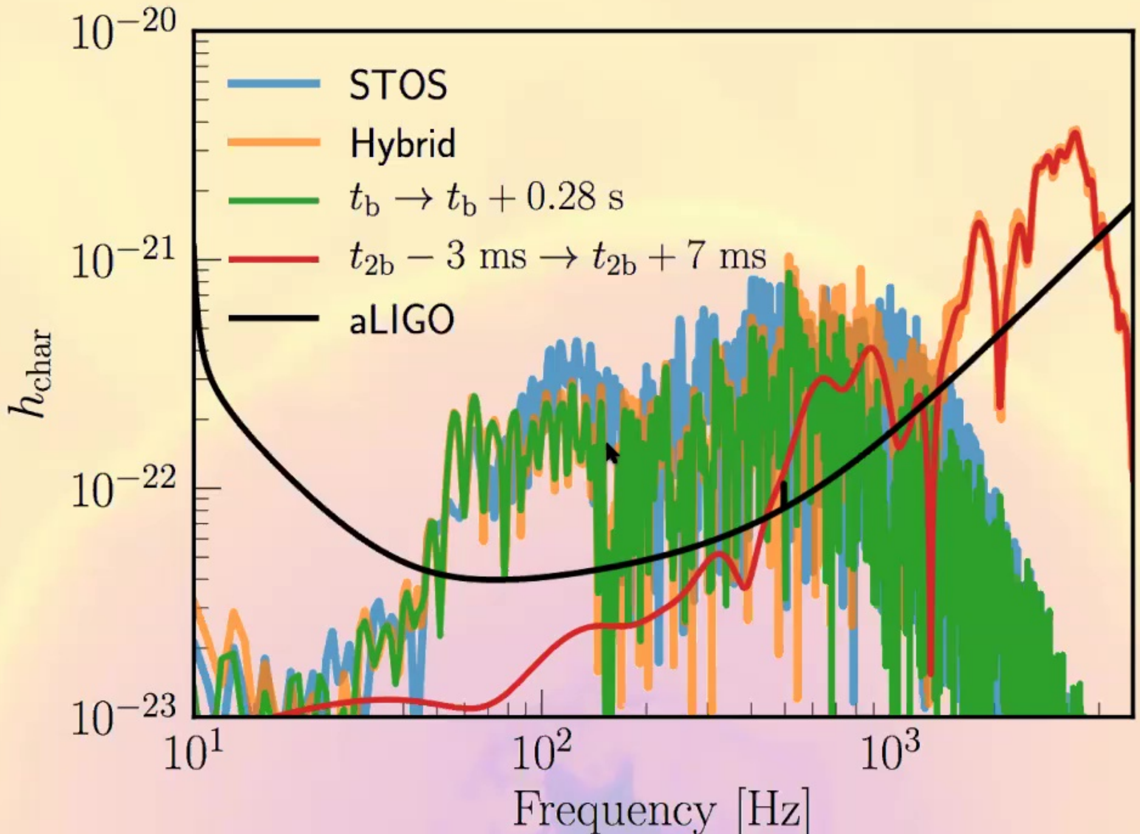
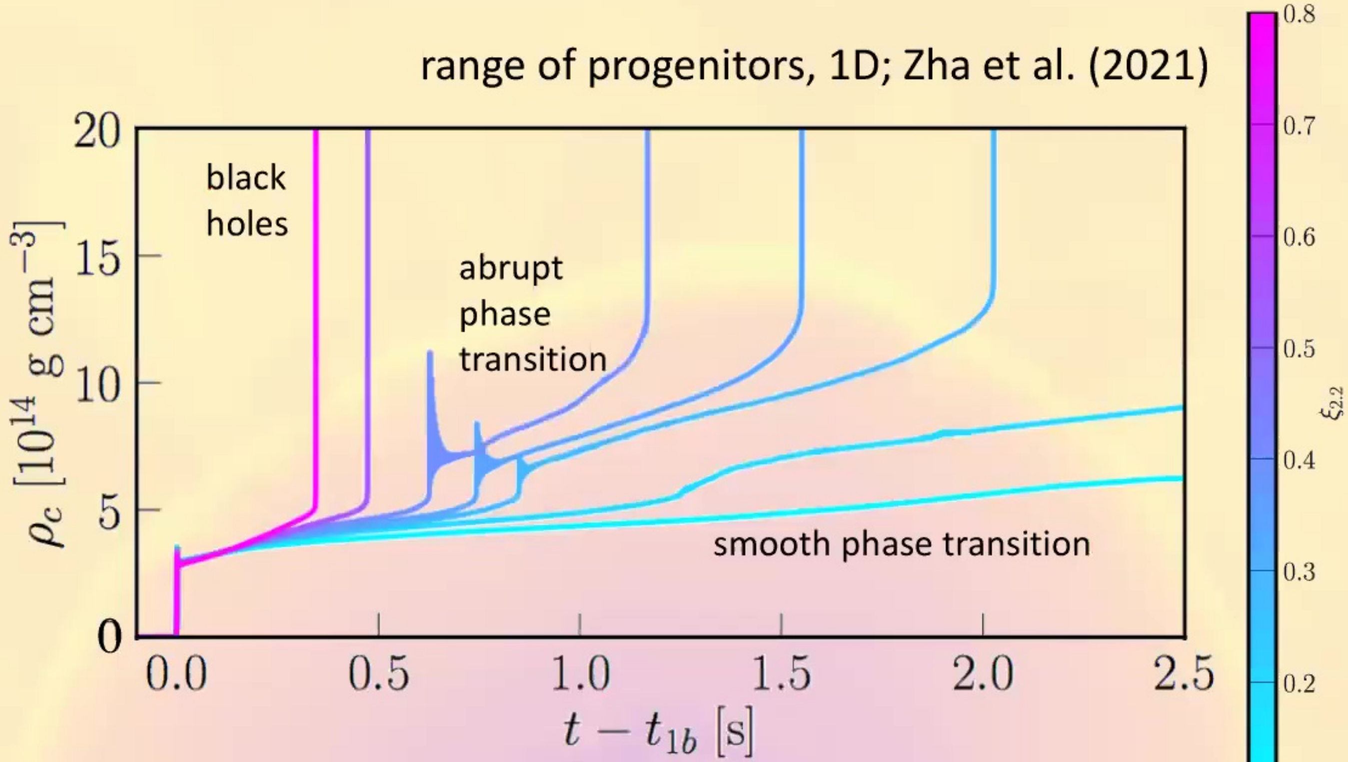


Progenitor dependence of QCD phase transition

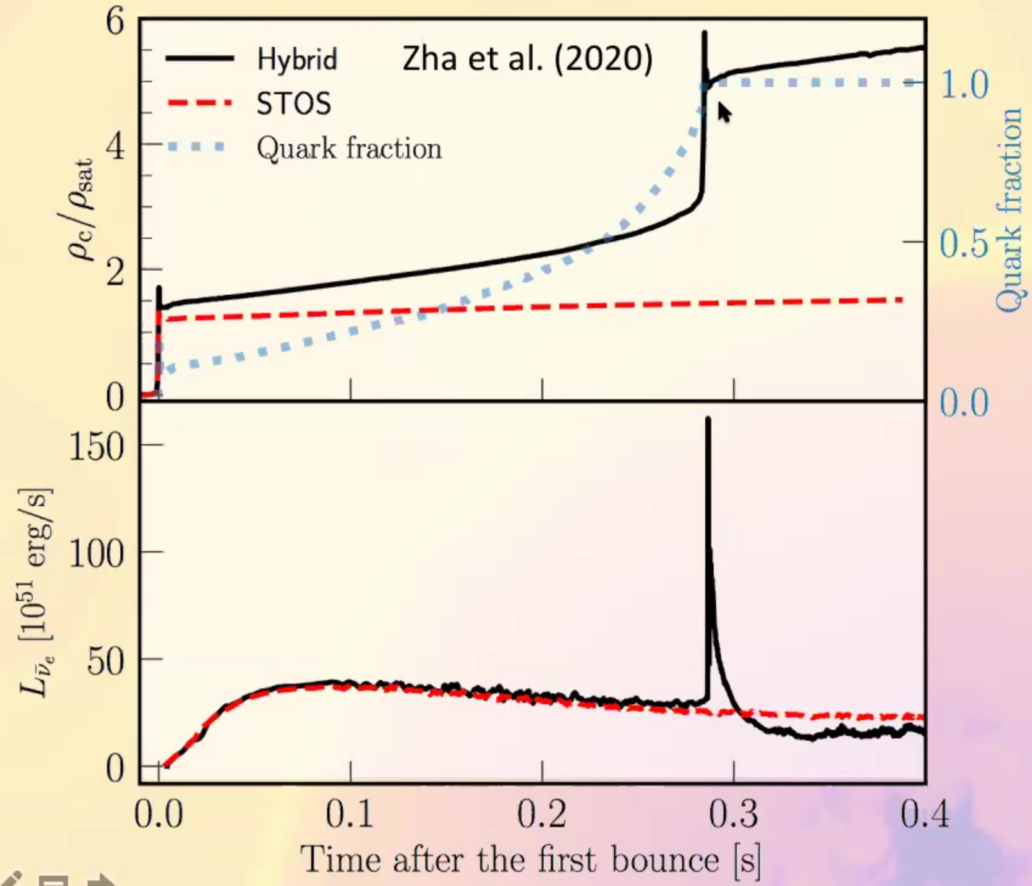
range of progenitors, 1D; Zha et al. (2021)



*different hadron-quark EOS; no explosions

Quarks in CCSNe

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



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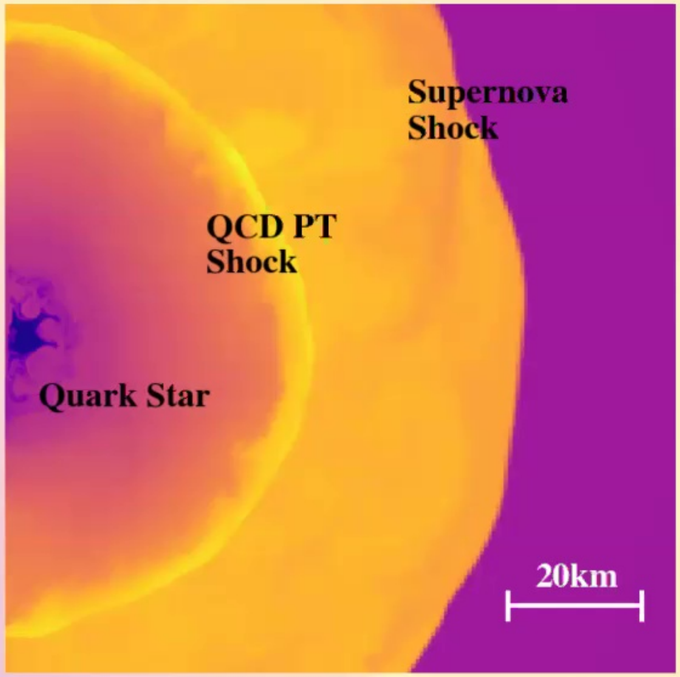

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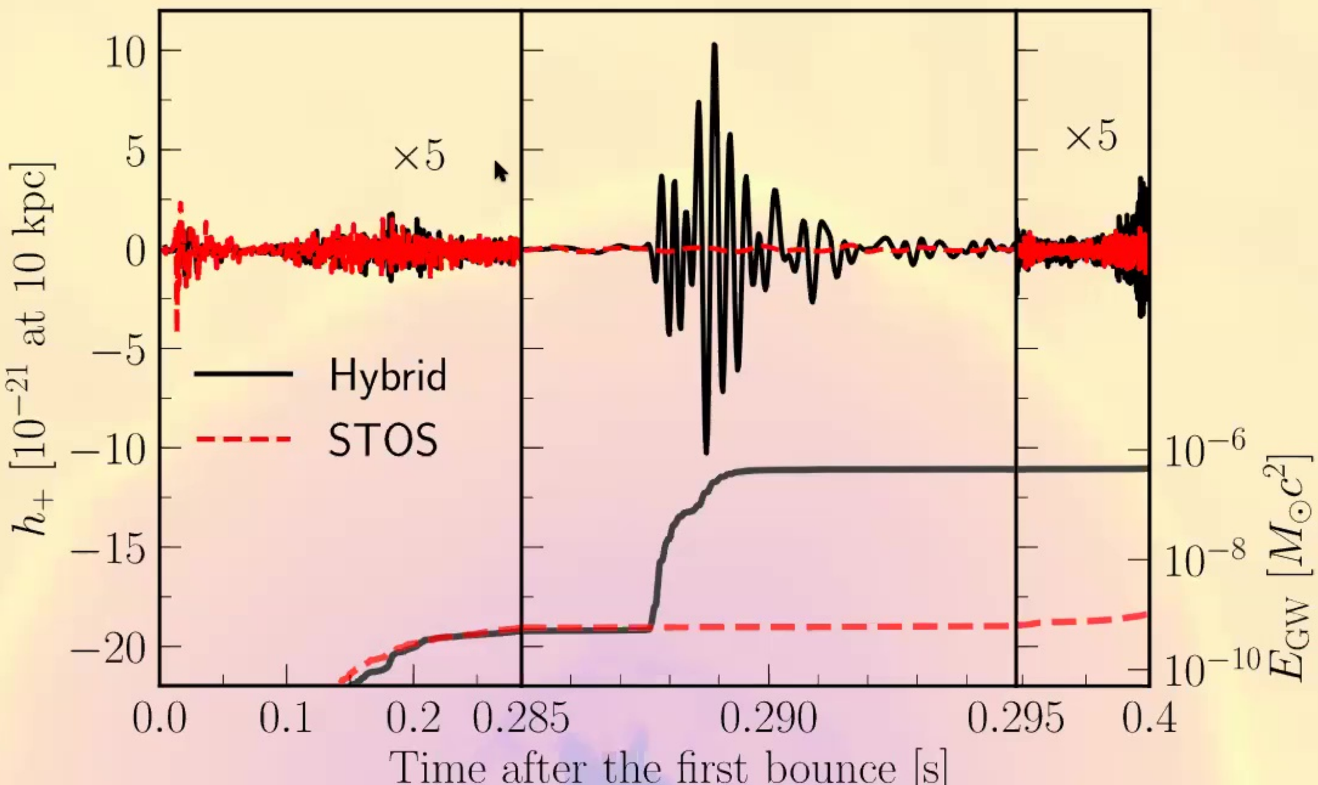

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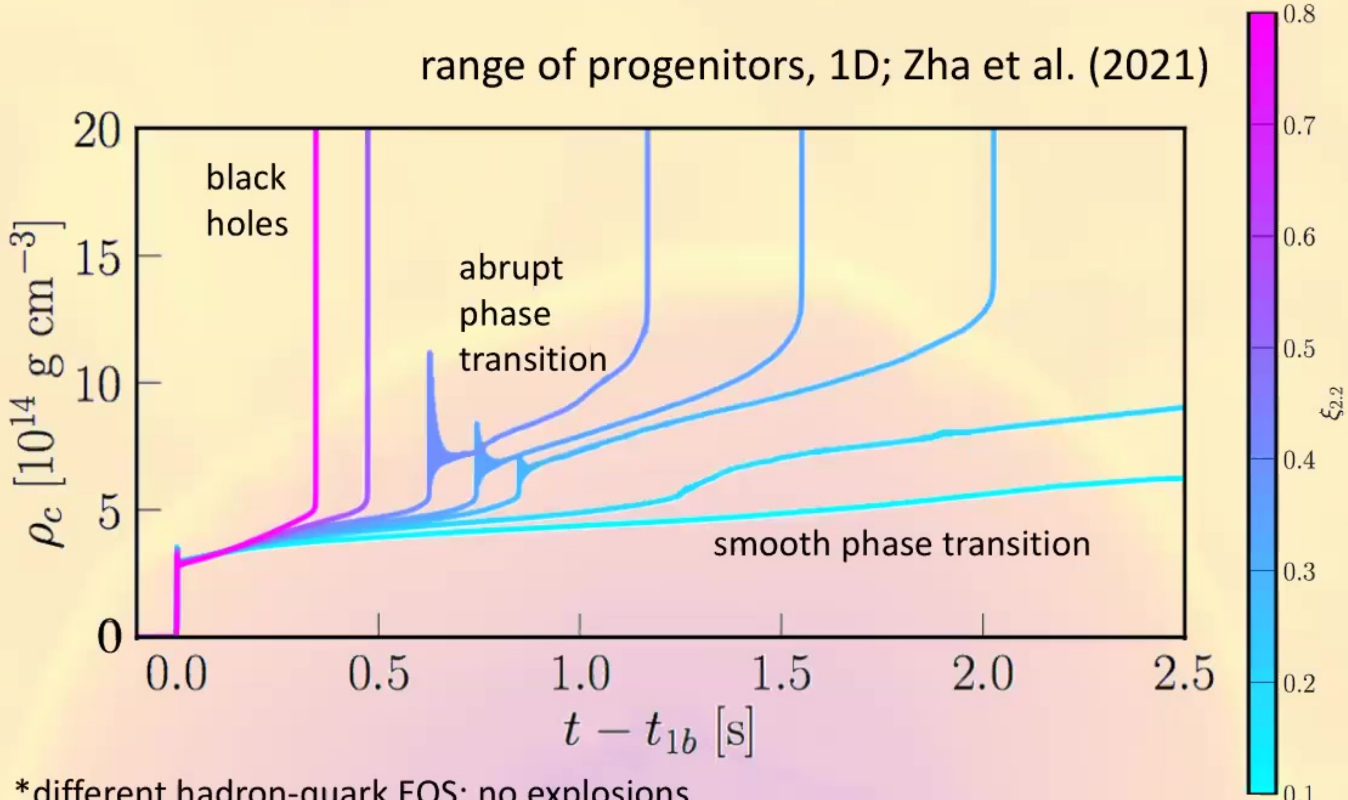

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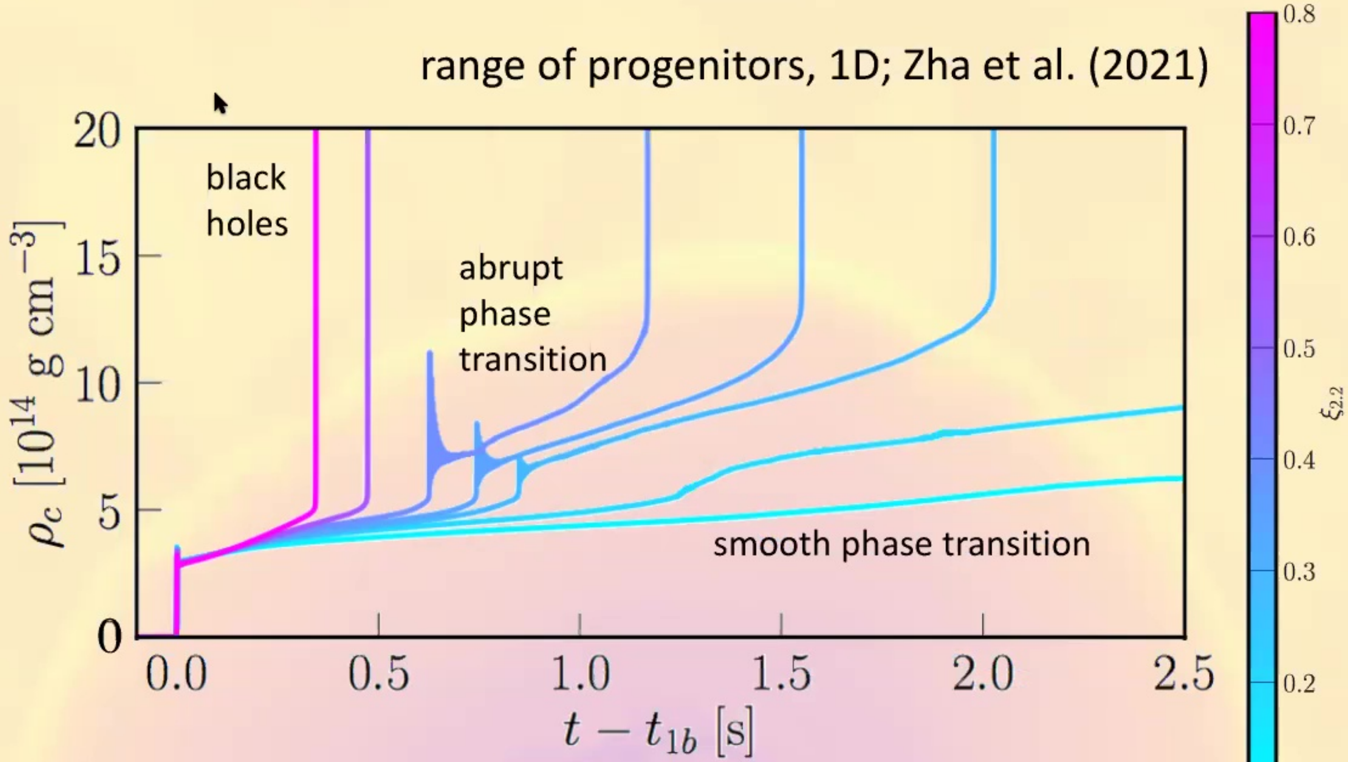

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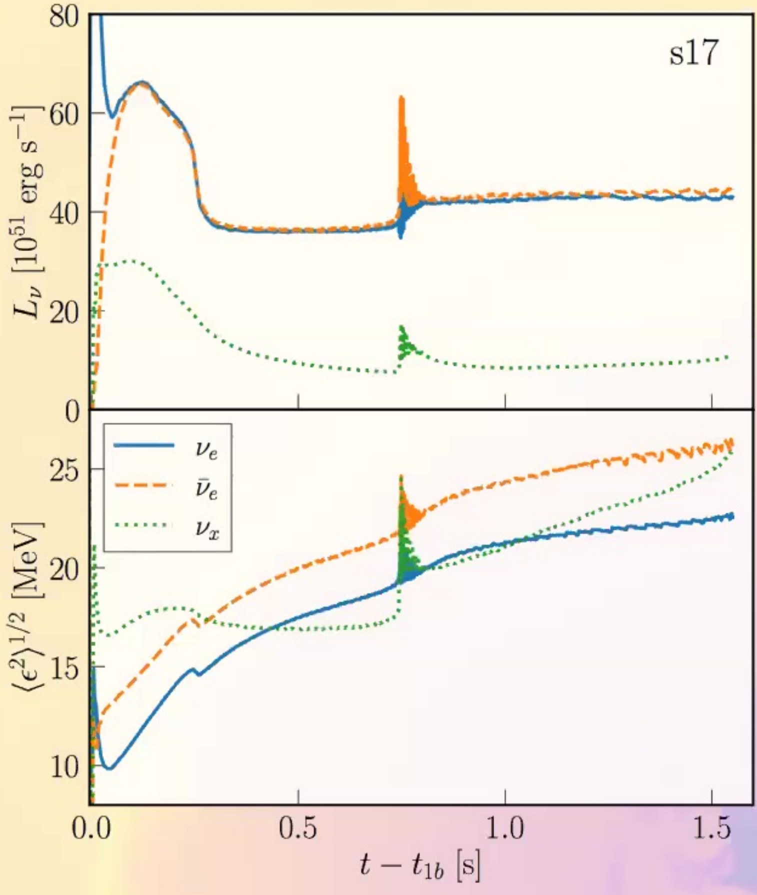
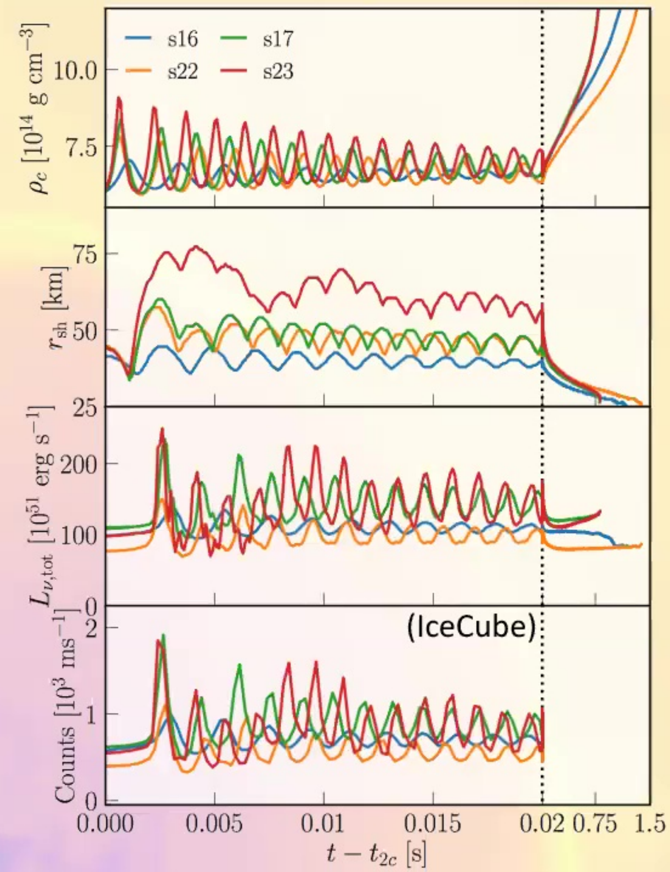
Neutrino signal from QCD PT



1D GR1D simulations
Zha et al. (2021)



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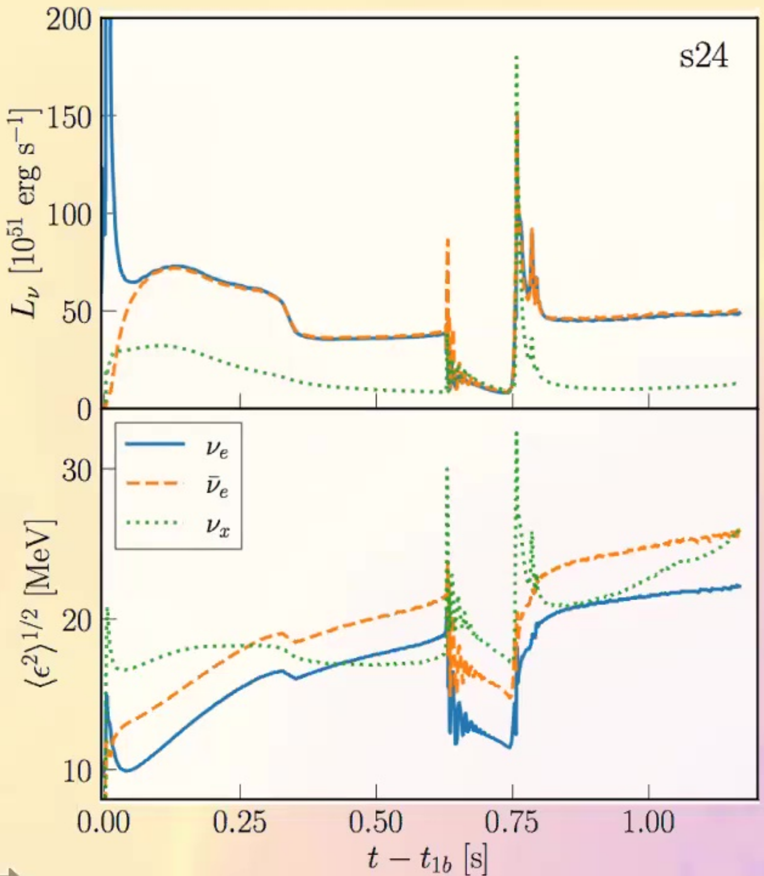
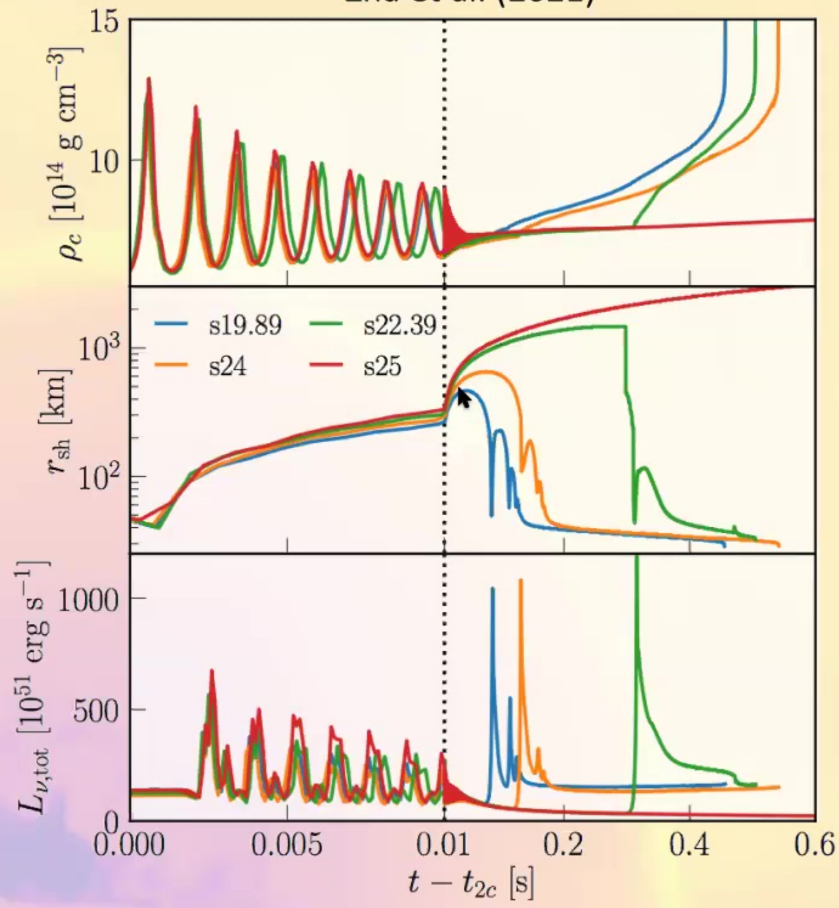
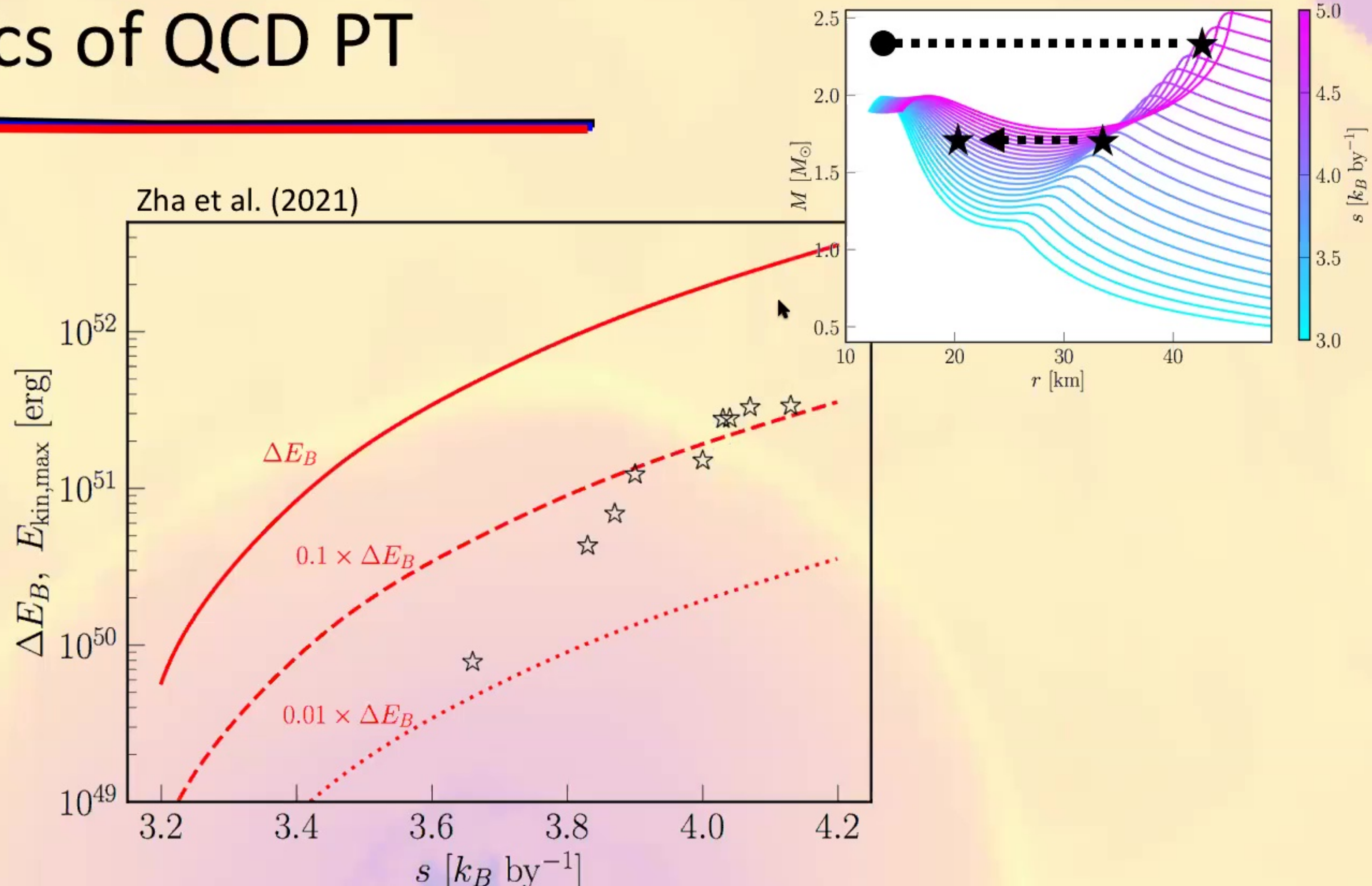




Energetics of QCD PT

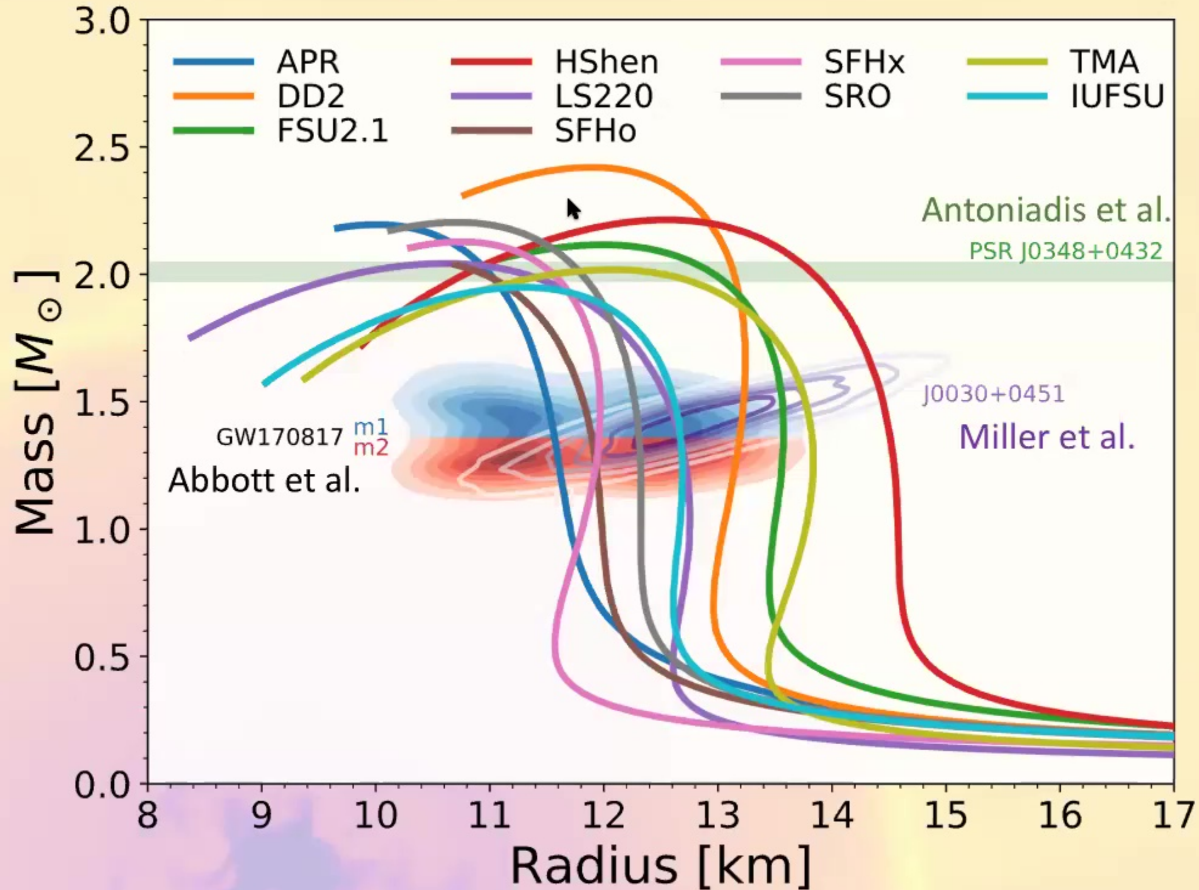
Zha et al. (2021)



Nuclear Equation of State and Core Collapse

Wide variety of finite temperature EOS to choose from

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

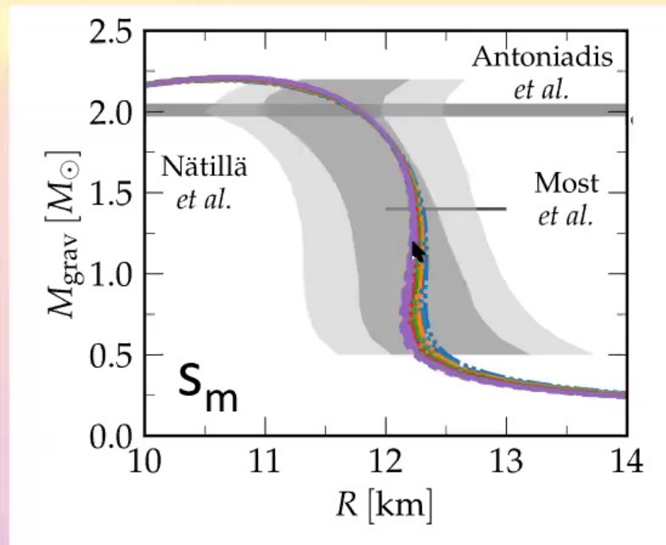


Impact assessed only with systematic studies

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_{sat}	0.155±0.005	0.155	fm^{-3}
	ϵ_{sat}	−15.8±0.3	−15.8	MeV baryon^{-1}
s_S	ϵ_{sym}	32±2	32±2	MeV baryon^{-1}
	L_{sym}	60±15	45±7.5	MeV baryon^{-1}
s_K	K_{sat}	230±20	230±15	MeV baryon^{-1}
	K_{sym}	−100±100	−100±100	MeV baryon^{-1}
s_P	$P^{(4)}_{\text{SNM}}$	100±50	125±12.5	MeV fm^{-3}
	$P^{(4)}_{\text{PNM}}$	160±80	200±20	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)

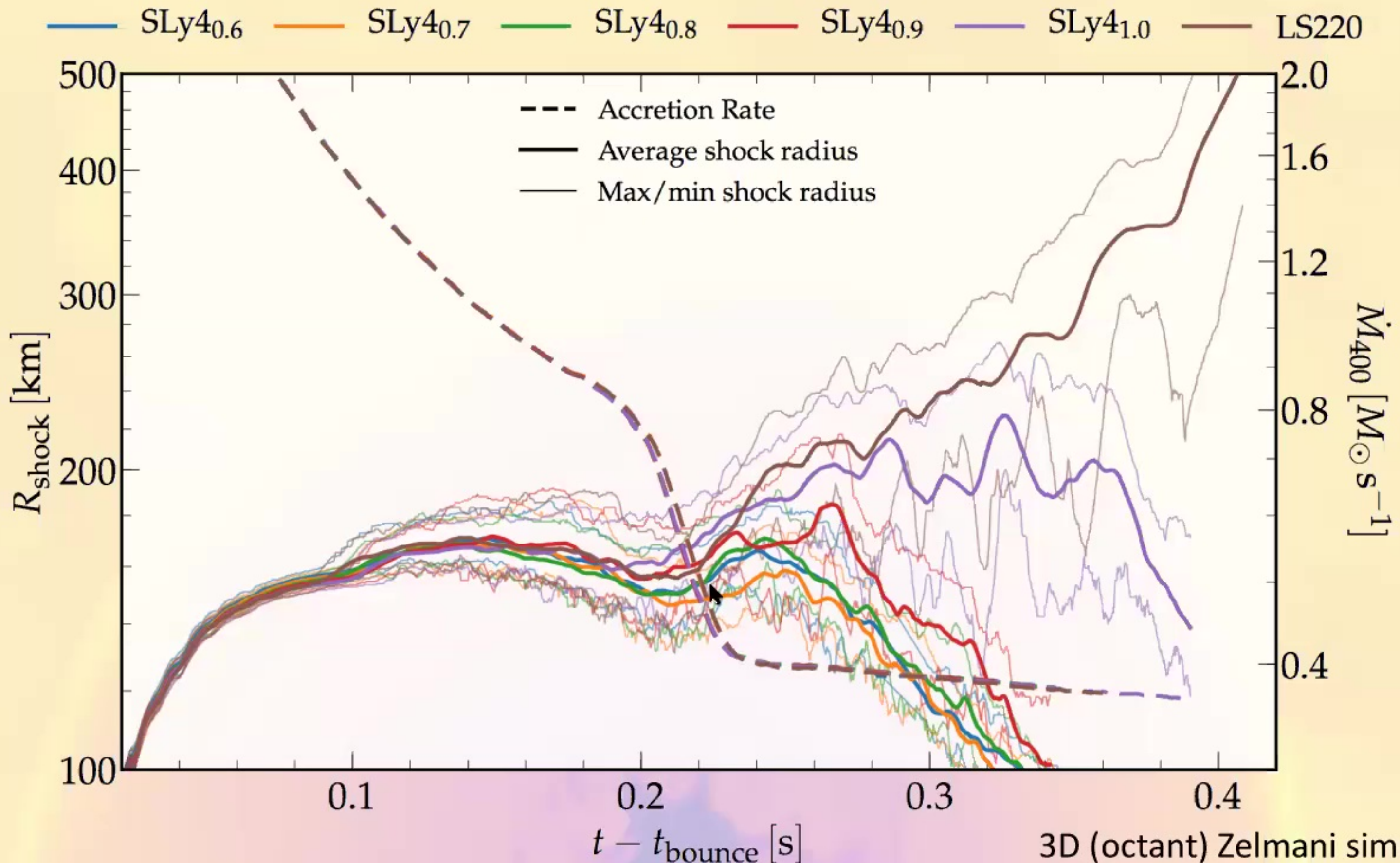


$m^\star\ [m_n]$: 0.55 0.65 0.75 0.85 0.95

$\Delta m^\star\ [m_n]$: −0.10 0.00 0.10 0.20 0.30

It does impact the evolution in 3D!

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

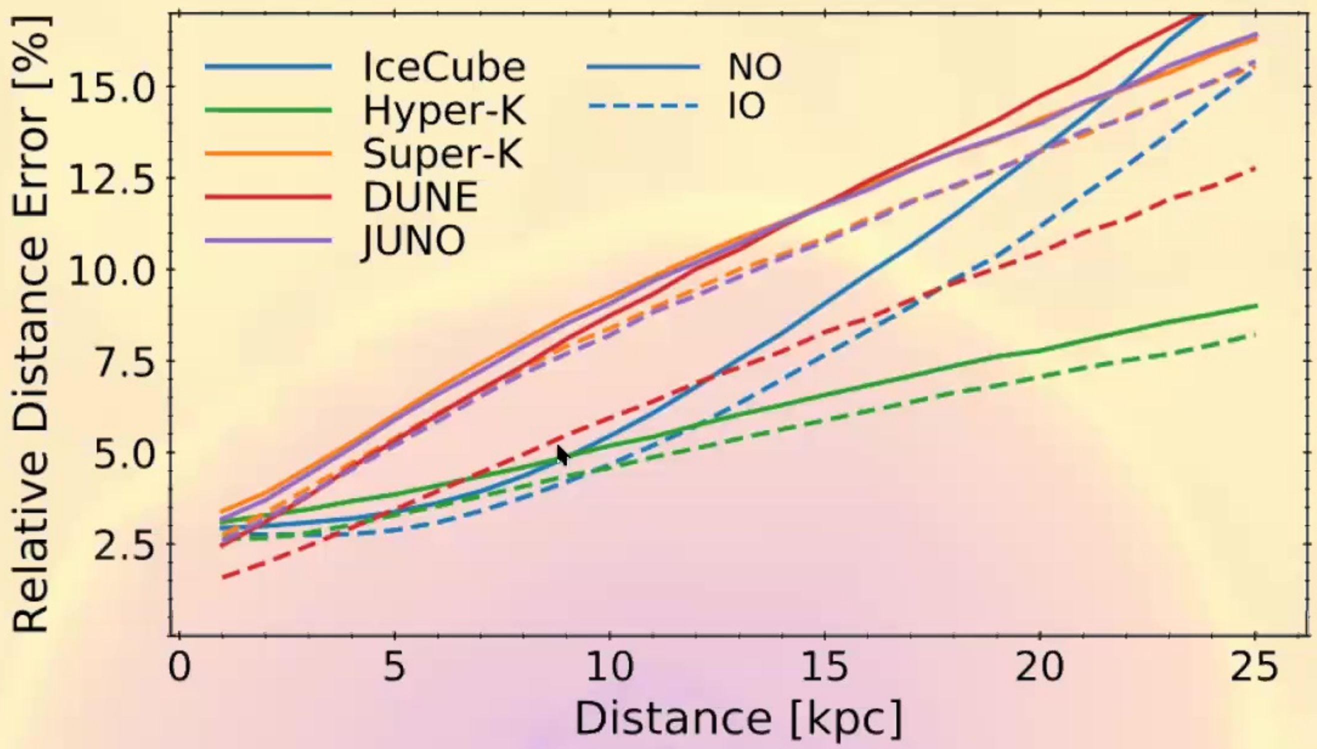


3D (octant) Zelmani simulations

Core-Collapse Supernovae as Laboratories for Fundamental Physics

- The Death of Massive Stars: Core-Collapse Supernovae
- Probing fundamental physics
  - Hadron-Quark phase transition
  - Nuclear Equation of State
- Neutrinos as Messengers
- Parameterized Explosion models

How well can we determine distance?



Segerlund et al. arXiv:2101.10624

Parameterized explosions

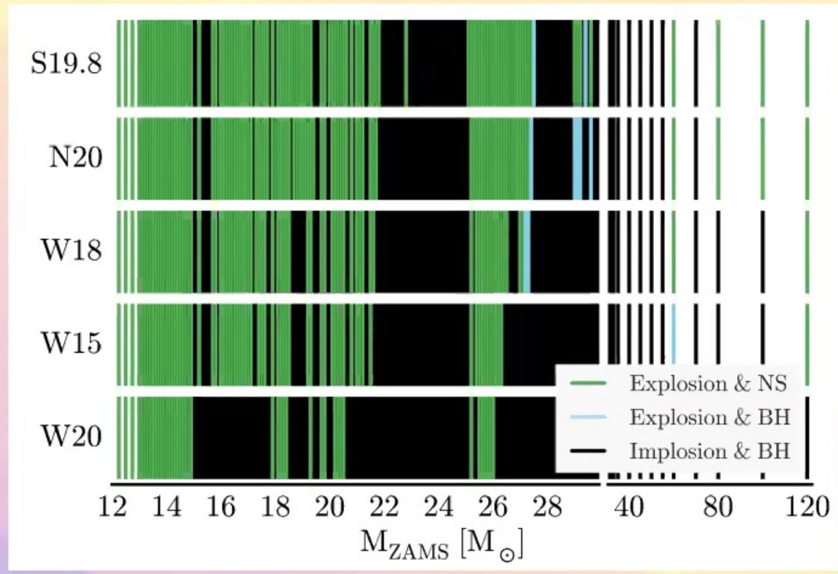
To study populations, we need a way to determine success/failure with 1D simulations – must alter the physics to achieve explosions

Method 1:

Since neutrino heating is present in 1D, but doesn't work, just boost neutrino heating

Sukhbold et al. (2016), but see others: Ertl et al. (2016), Ugliano et al. (2012), Pechja & Thompson (2015), Ebinger et al. (2019), EO & Ott (2011)

Calibrate different progenitors to SN1987A properties



Woosley & Heger (2007) progenitors

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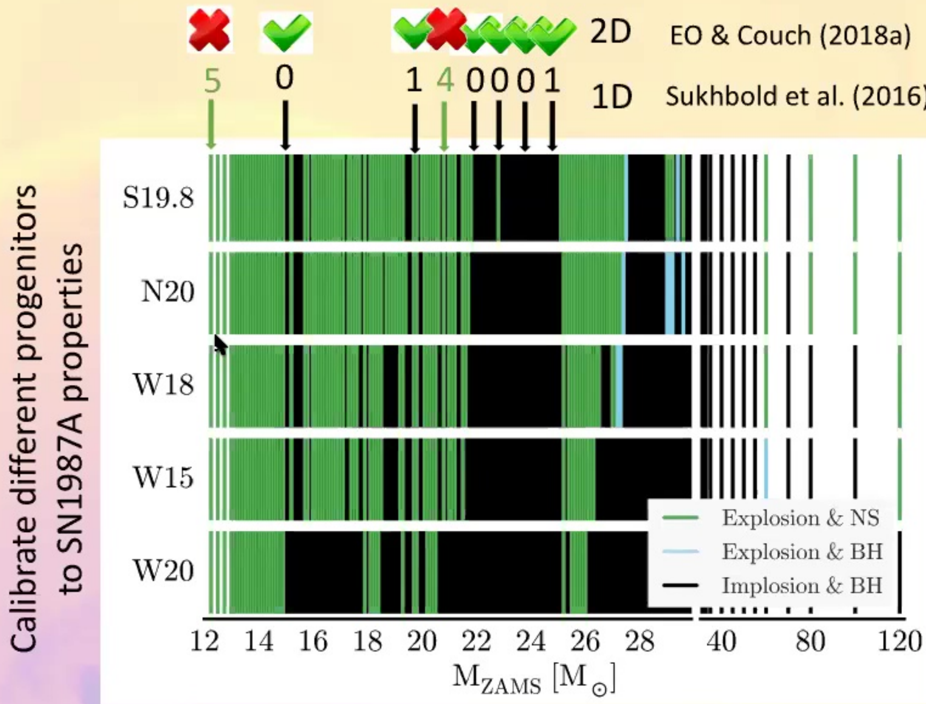

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Method 2:

Since turbulence is important for making 2D and 3D simulations explore, add it in 1D

Couch et al. (2020), see also Mabanta et al. (2018,2019), Boccioli et al. (2021)

One line summary:
"Evolve turbulent kinetic energy, sourced by convection, that then contributes to Reynolds stress and aids shock revival"

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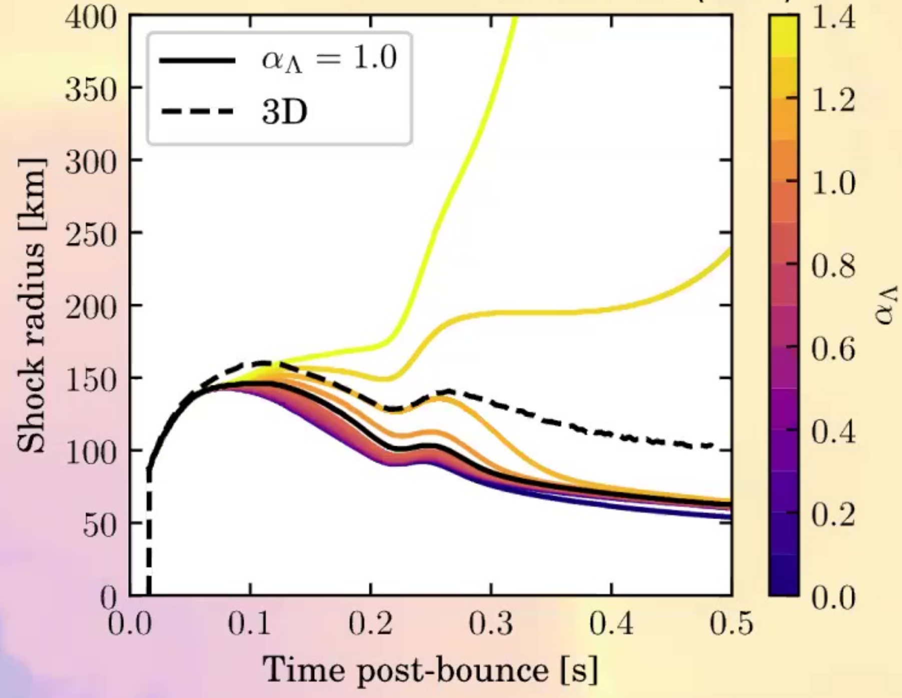

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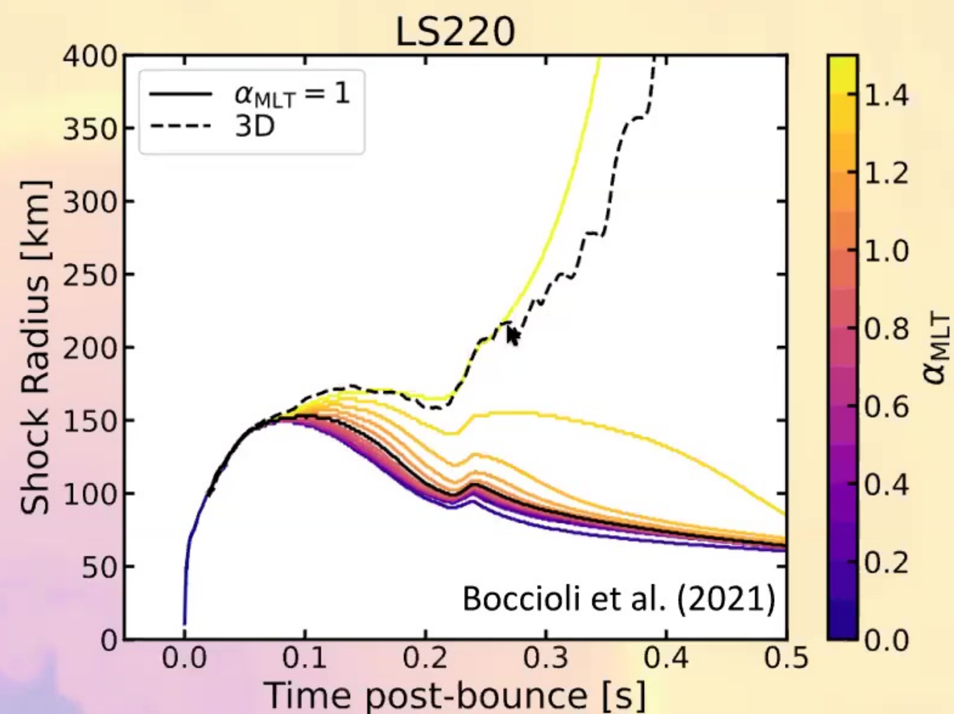

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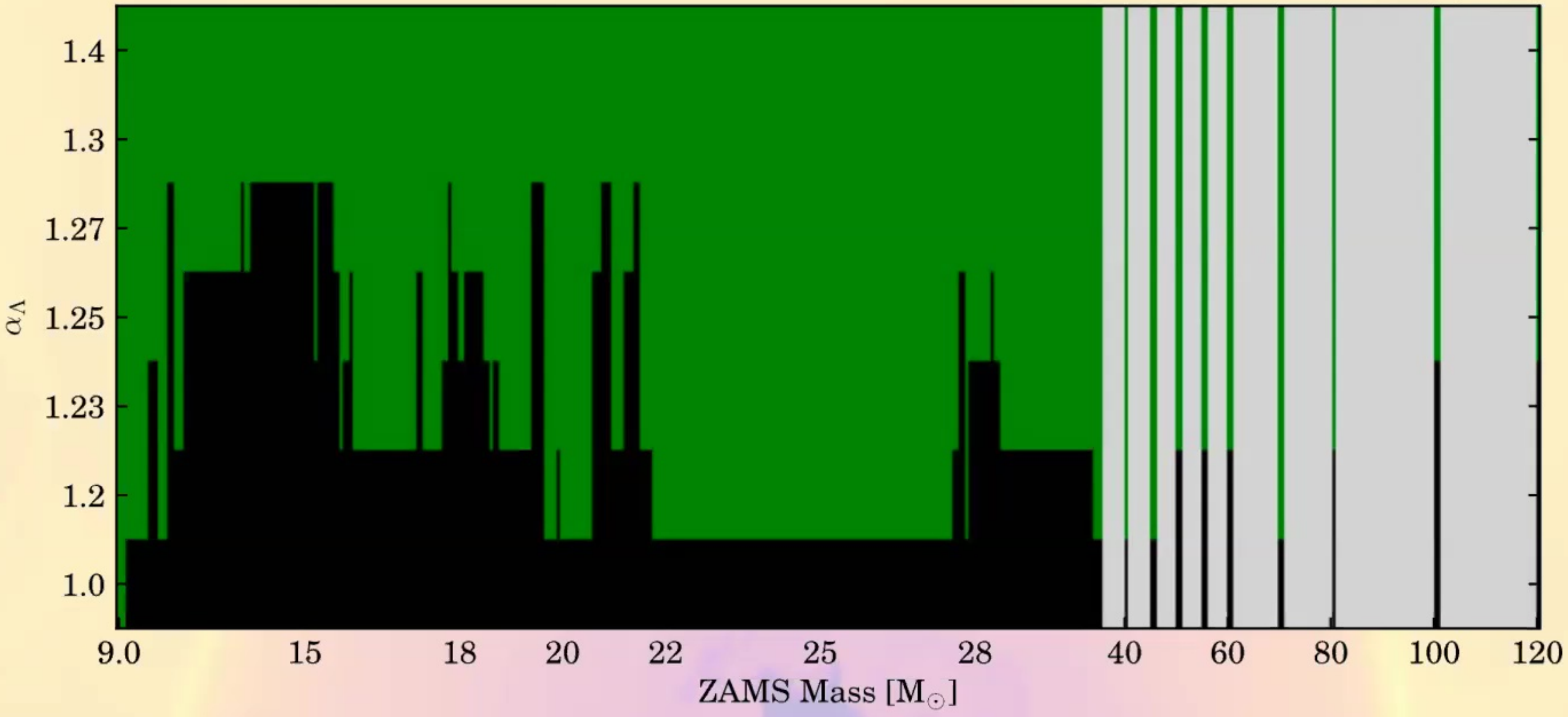
Population Results

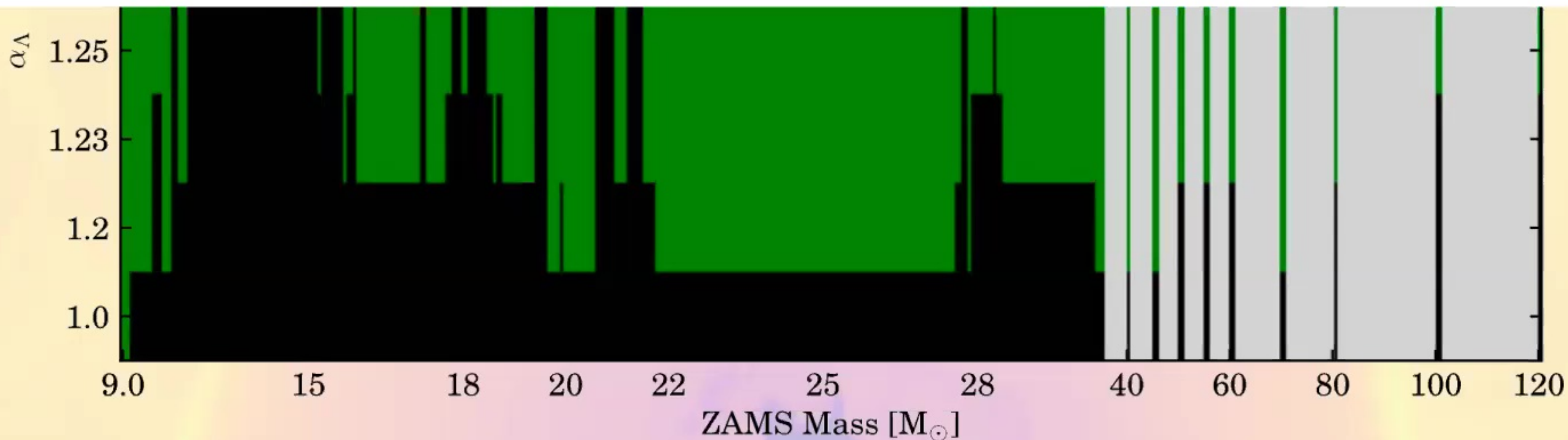
Couch et al. (2020)



Population Results

Explosion Times from Recent Studies in 1D, 2D, and 3D Using Similar Methods and Progenitors Compared to STIR with $\alpha_\Lambda = 1.25$

		Progenitor Mass ($M_\odot$)												
		9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	25.0
STIR (this work)	1D	0.24 s	0.40 s	0.29 s	0.40 s	⋯	⋯	⋯	0.43 s	0.39 s	0.64 s	0.47 s	0.40 s	0.39 s
Sukhbold et al. (2016)[a]	1D	0.66 s	0.80 s	1.56 s	1.1 s	0.8 s	0.71 s	⋯	0.78 s	0.77 s	1.2 s	1.2 s	⋯	⋯
Ebinger et al. (2019)[b]	1D			0.39 s	0.47 s	0.41 s	0.41 s	0.44 s	0.35 s	0.33 s	0.42 s	0.36 s	0.42 s	0.49 s
Burrows et al. (2020)[d]	3D	0.21 s	0.45 s	0.21 s	0.31 s	⋯	⋯	⋯	0.30 s	0.30 s	0.32 s	0.40 s	0.45 s	0.55 s



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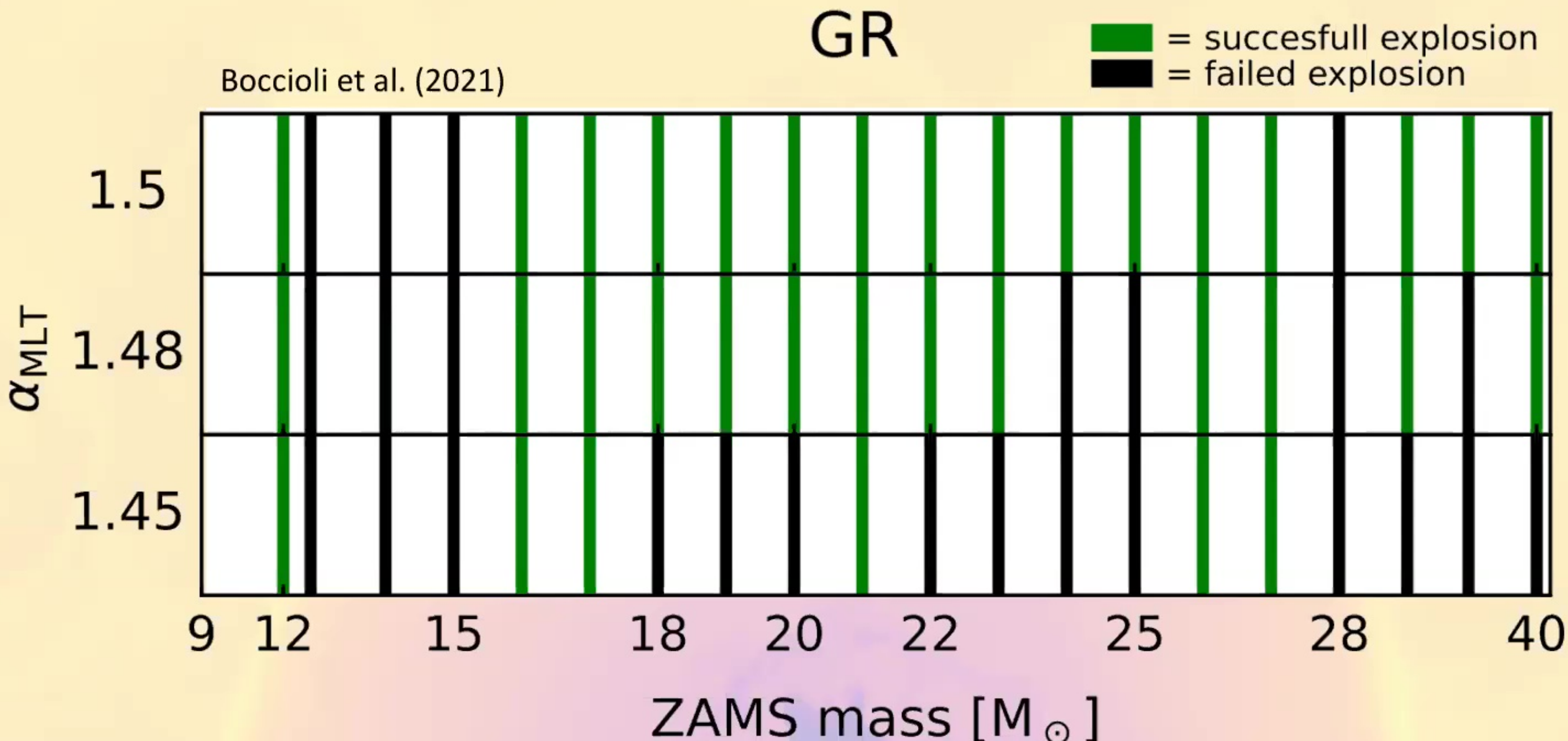

Core-Collapse Supernovae as Laboratories for Fundamental Physics

Summary

- The CCSN community is able to produce robust explosions in 3D and agrees well in direct comparisons in 1D
- QCD phase transitions produce unique multimessenger signals in gravitational waves and neutrinos
- Nuclear Equation of state uncertain, thermal effects important for the core collapse dynamics and thermodynamics
- Neutrinos can constrain (quickly and robustly), within 5%, the distance to Galactic supernovae and relay information about the progenitor star.
- Parameterized explosion models can be useful to understand the systematics of massive star populations