Large-scale neutrino-transport simulations of core-collapse supernovae and multi-messenger signals

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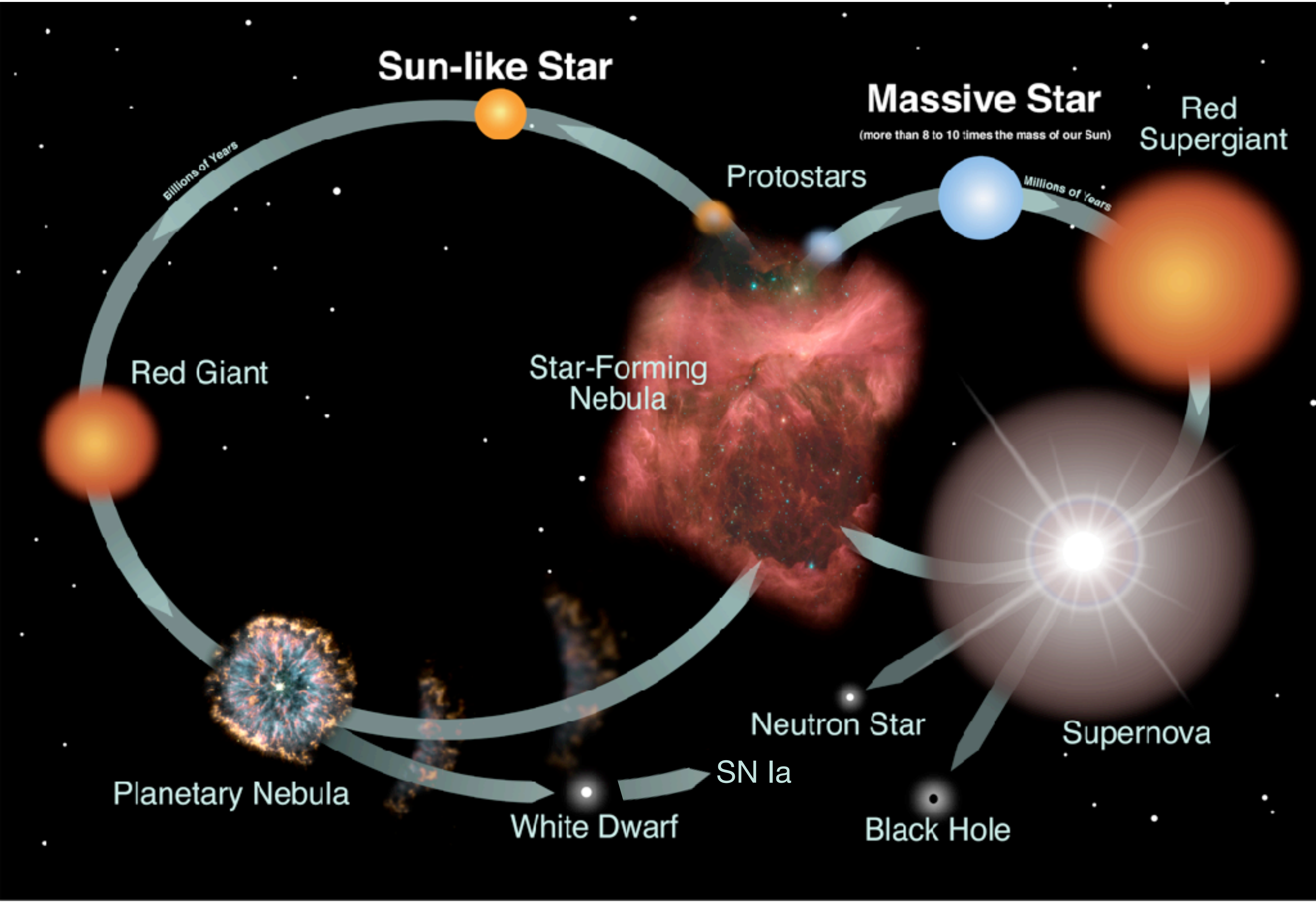
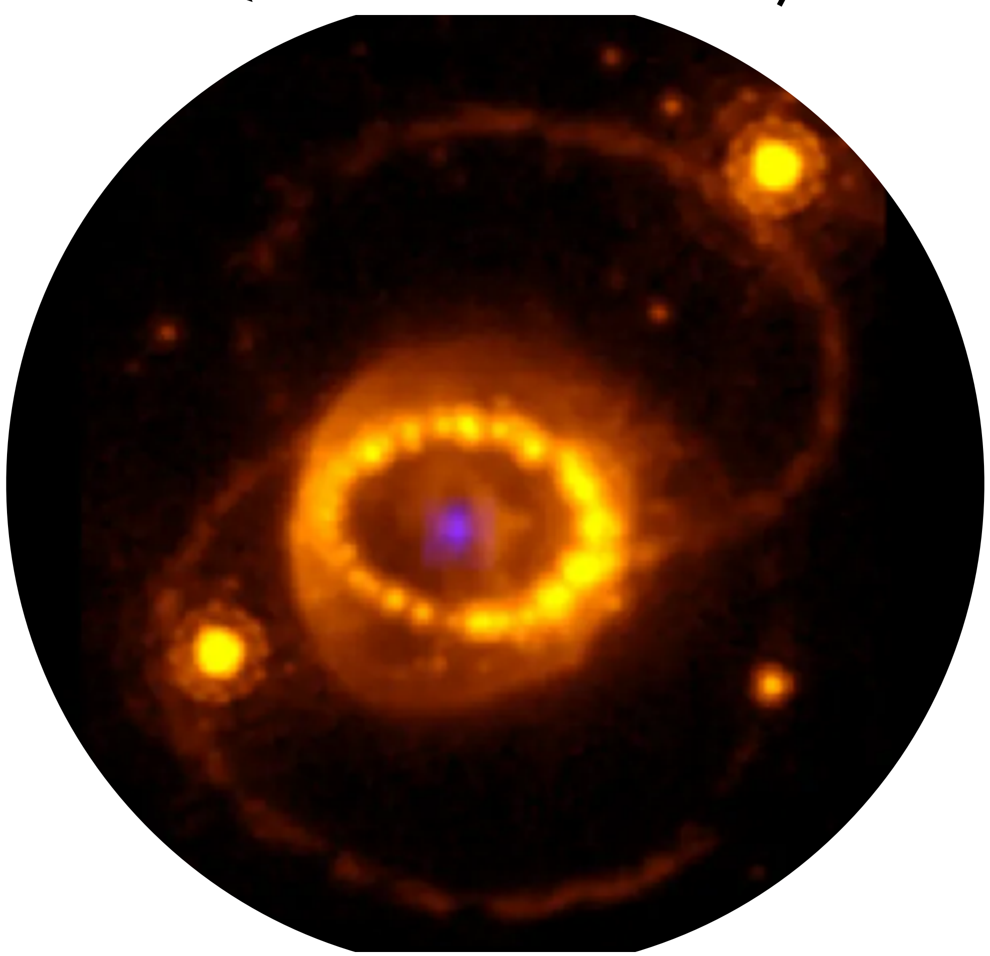


Sun-like Star
Massive Star
(more than 8 to 10 times the mass of our Sun)
Red
Supergiant
Billions of Years
Protostars
Millions of Years
Red Giant
Star-Forming
Nebula
Neutron Star
Supernova
SN Ia
Planetary Nebula
White Dwarf
Black Hole

Supernova (SN)
Death of stars
- White dwarfs → SN Ia
- Massive stars → Core-Collapse SN

SN feedbacks by
- explosion shocks
- nucleosynthesis
to galatic evolution

From: H. Nomoto



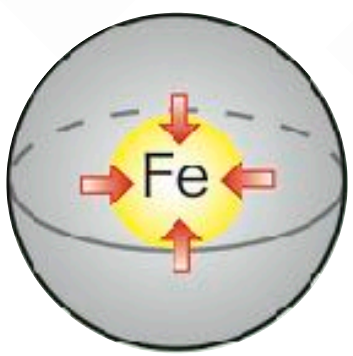
SN1987A, Credit: HST, JWST

Remnant neutron stars/black holes

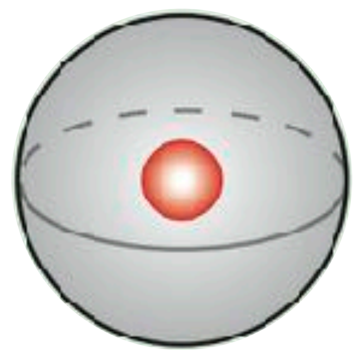
Multi-messenger sources
- Radio, IR, Optical, UV, X-ray
- Long gamma-ray burst
- Gravitational waves (GW)
- Neutrino signals

Core-collapse Supernova

Massive stars
~8-100 $M_\odot$



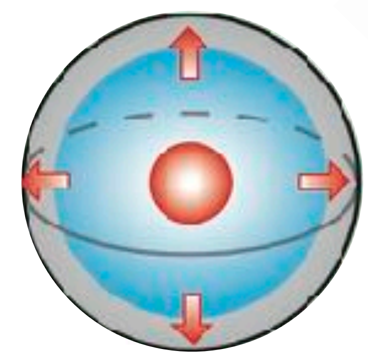
Core collapse
$\rho_c \sim 10^{9-10}\,\mathrm{g/cm^3}$
$\gamma + {}^{56}\mathrm{Fe} \rightarrow 13\alpha + 4n$
$A + e^- \rightarrow A^* + \nu_e$



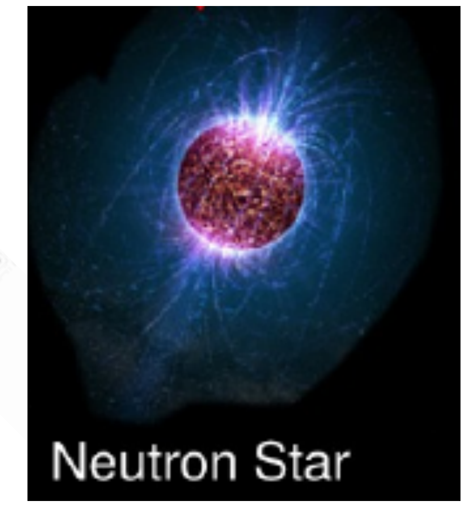
Core bounce
EOS stiffens
$\rho_c \sim 10^{14}\,\mathrm{g/cm^3}$

?

Shock revives
& propagate out



Successful CCSN



Shock fails

Failed CCSN

ρ_c : central density

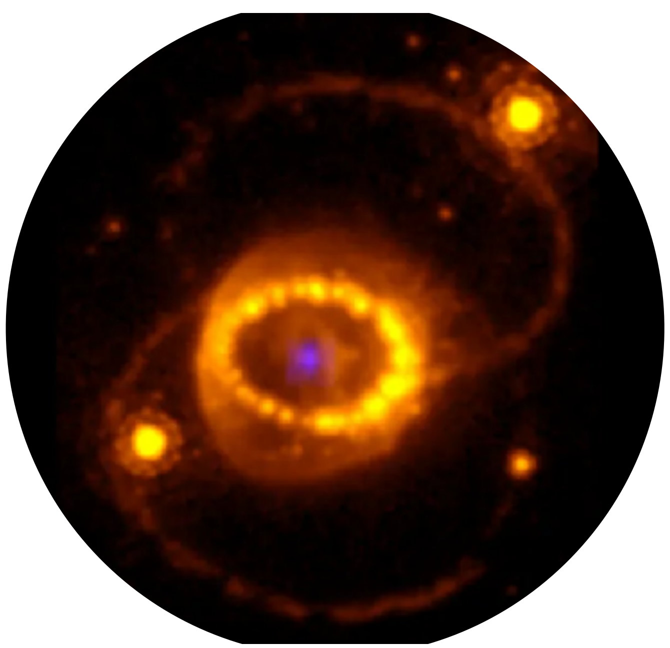
Adapted from A. Suzuki

Neutrinos from core-collapse supernova

A stellar collapse releases ~10^{53}erg gravitational energy

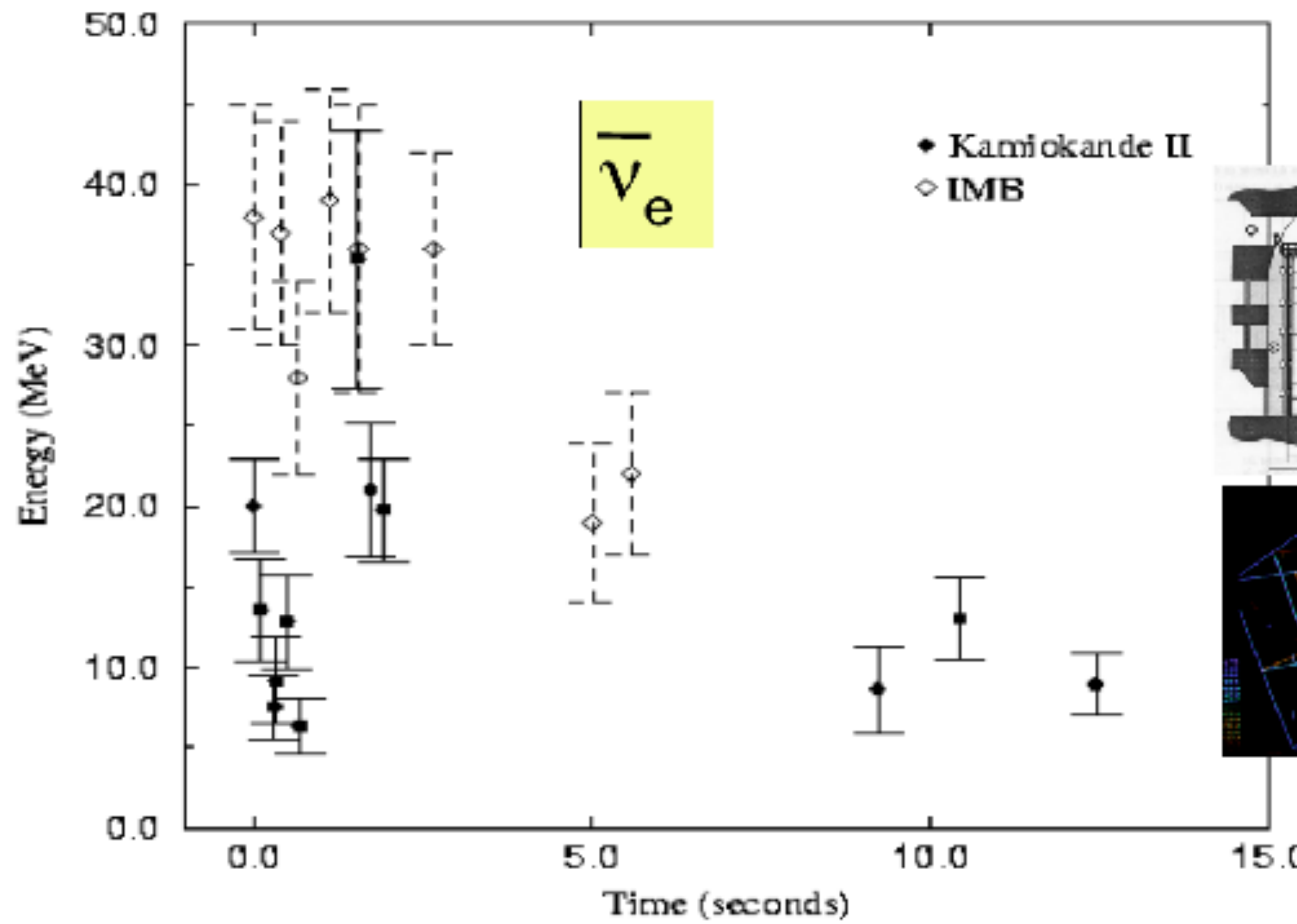
- ~99% is carried away by neutrinos

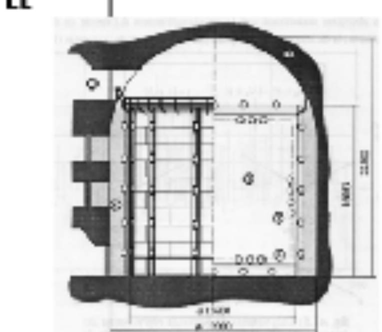
SN explosion energy ~10^{51} erg (Bethe 1990)
Explosion energy of a nuclear bomb ~10^{24} erg (*The World Book Encyclopedia*)

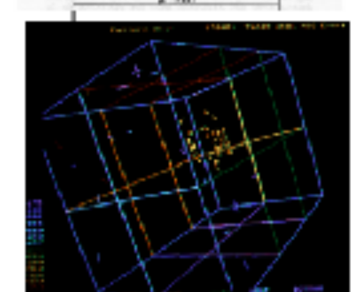


SN1987A (*Hubble/JWST)*

1987 Feb. found in LMC
168,000 light-years away
Seen with naked eye



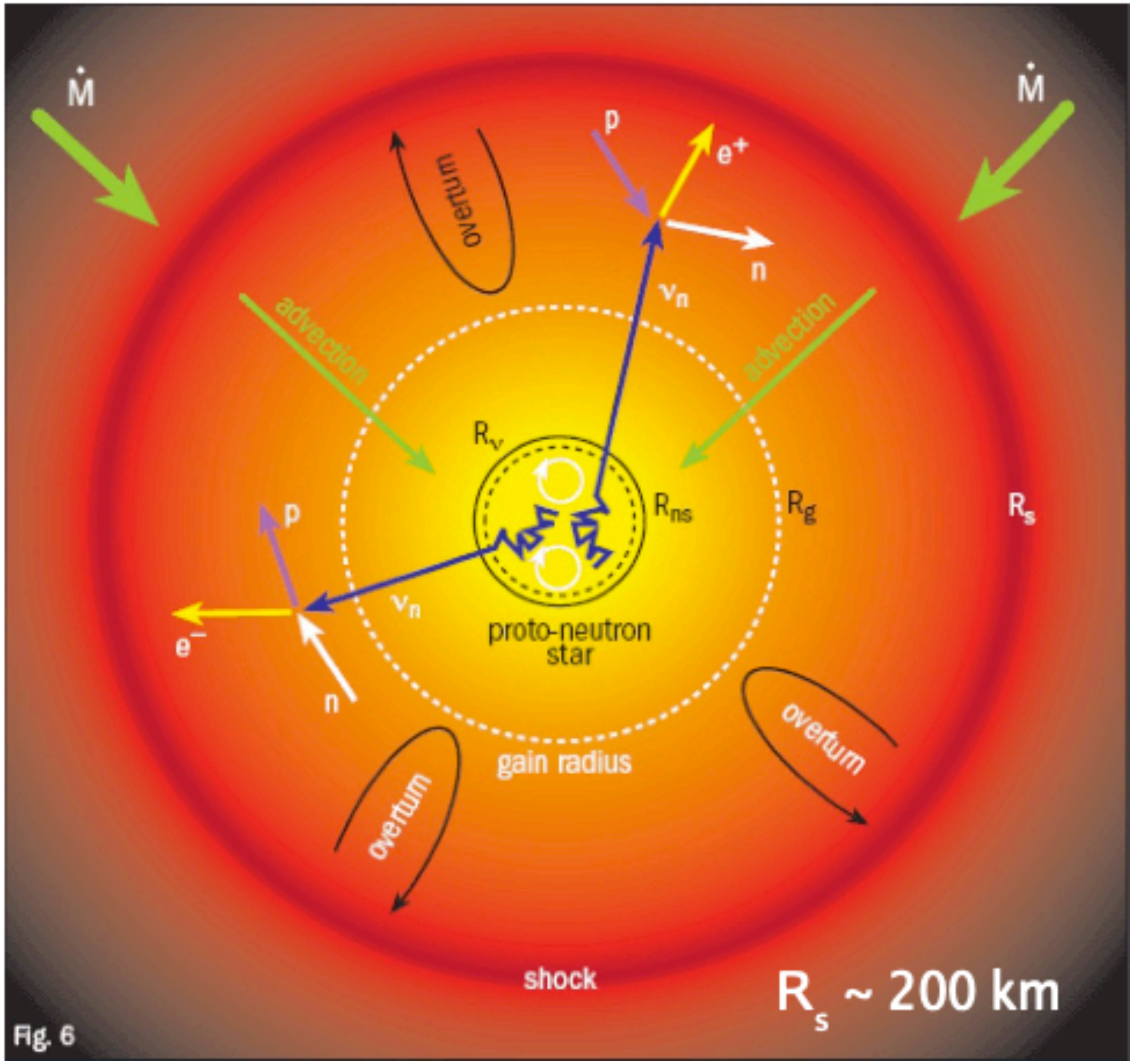




From Scholberg 2017

- Confirmed the baseline model, i.e., SN II -> iron core of massive stars collapses to a compact star, which was proposed by Baade & Zwicky in 1934

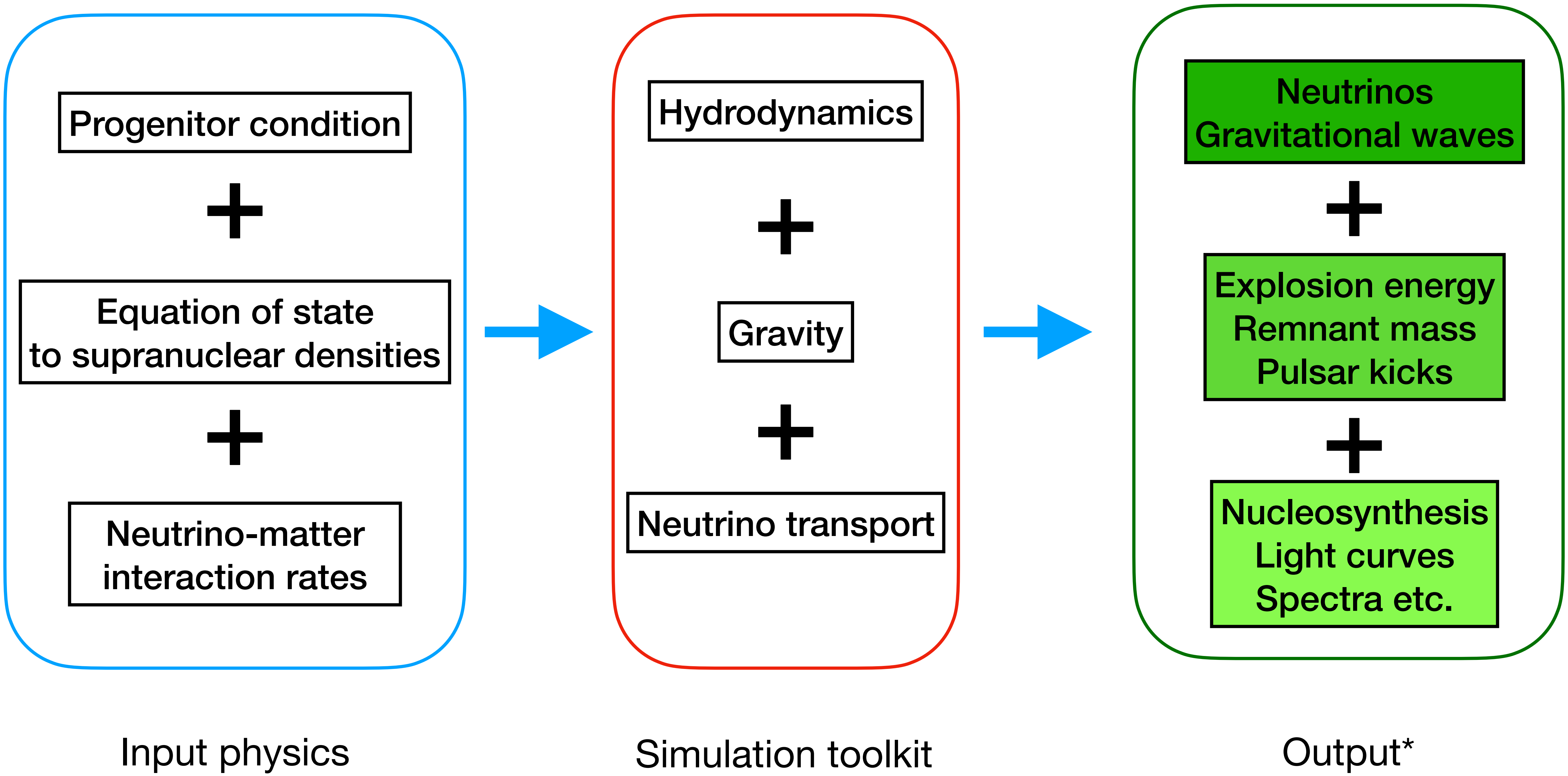
CCSN explosion driven by neutrino heating



From: Janka

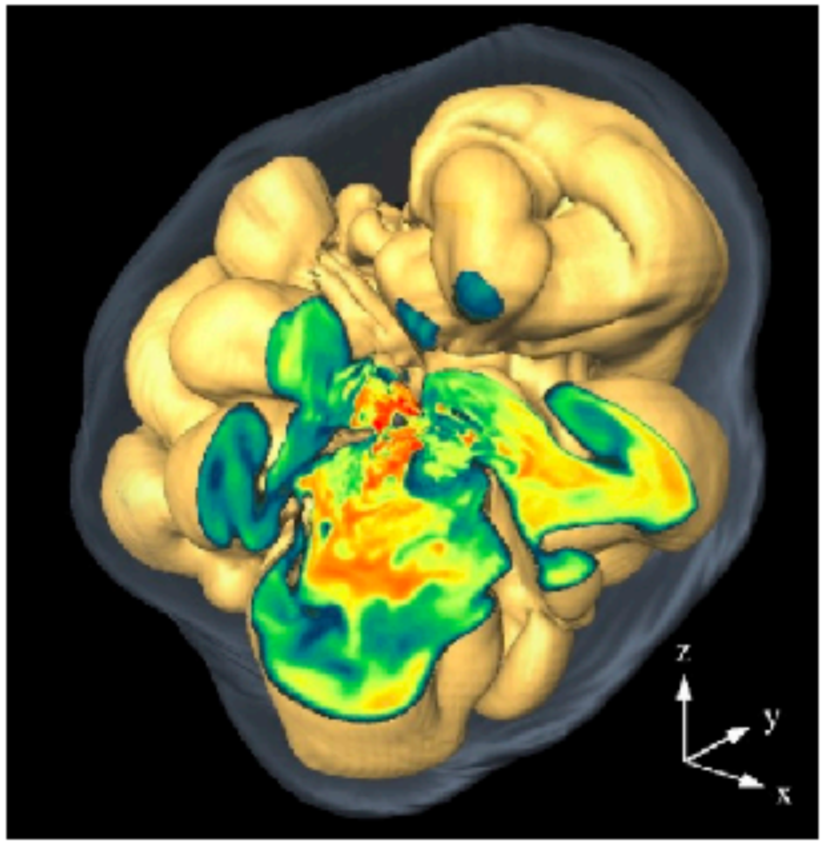
Neutrino-heating explosion mechanism aided by hydrodynamic instabilities in the post-shock layer

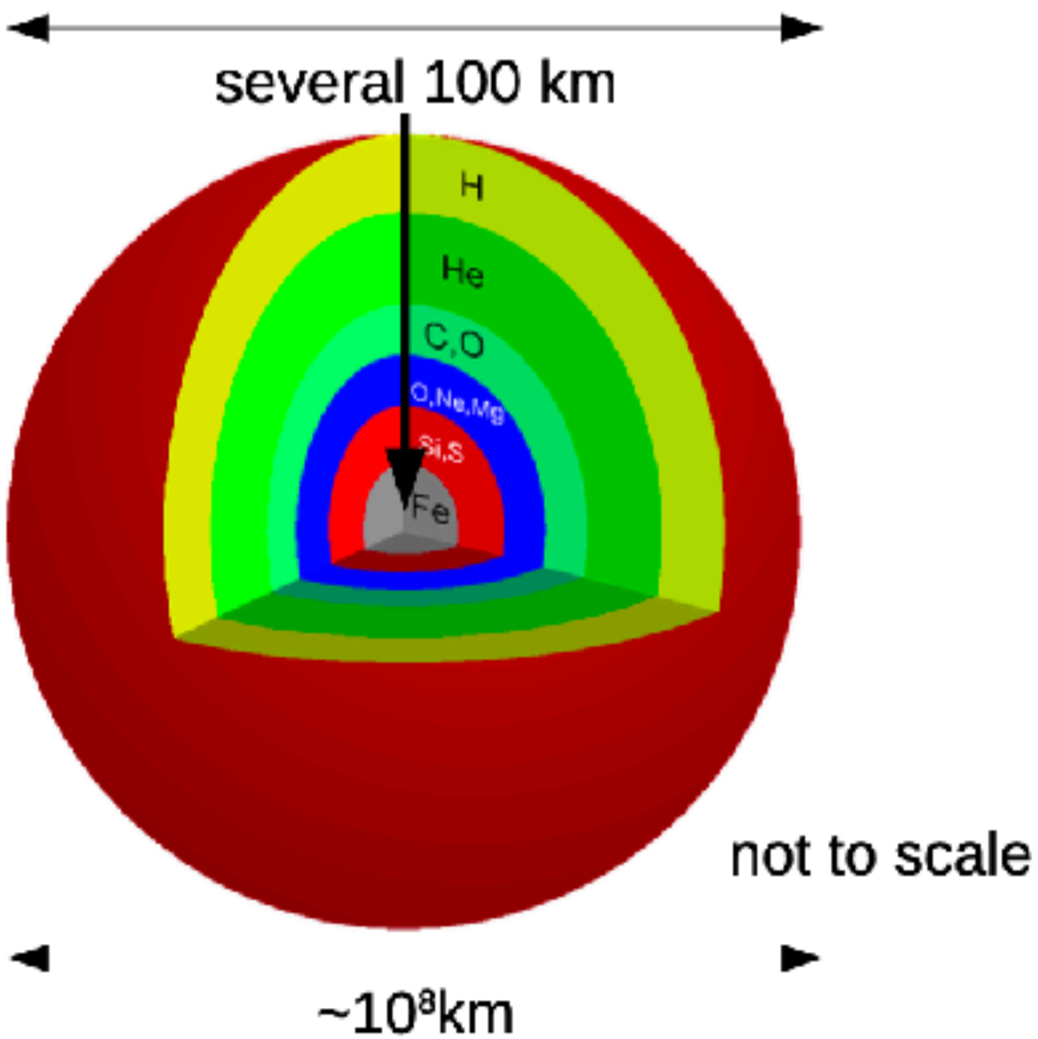
Simulation overview, input and output



Challenges of simulation

- 3-dimension flows
- Multi-scale: 10's km to 10^8 km
- Neutrinos from diffusion to free-streaming -> require kinetic theory -> a 6D problem
- Unclear physics: equation of state & neutrino interaction rates
- Strong gravity (M/r~0.1-0.2) & high velocities -> relativistic effects
- Combine strong, weak, gravity, EM interactions in ab-initio simulations
- 3D models take 1-10's million core hrs

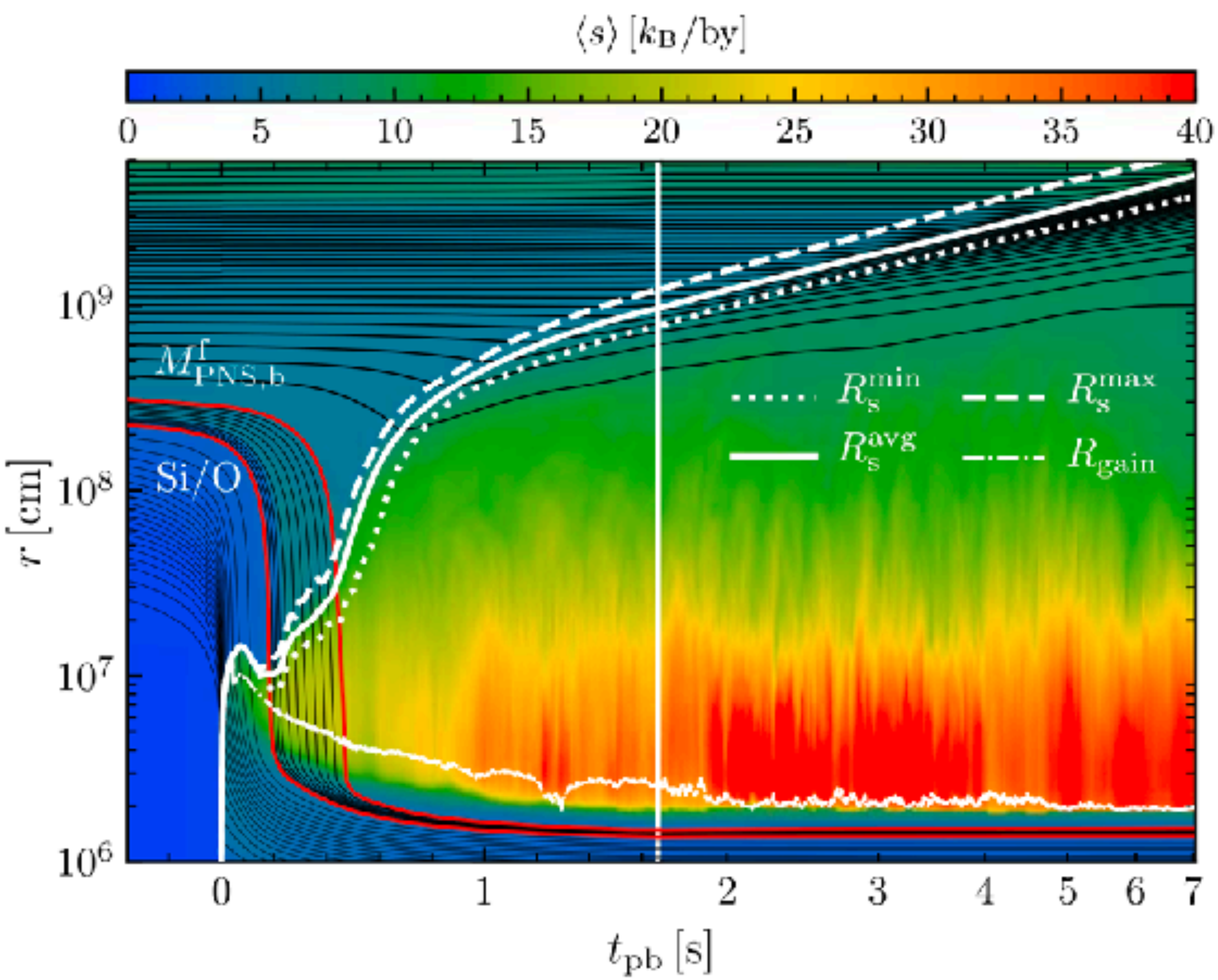




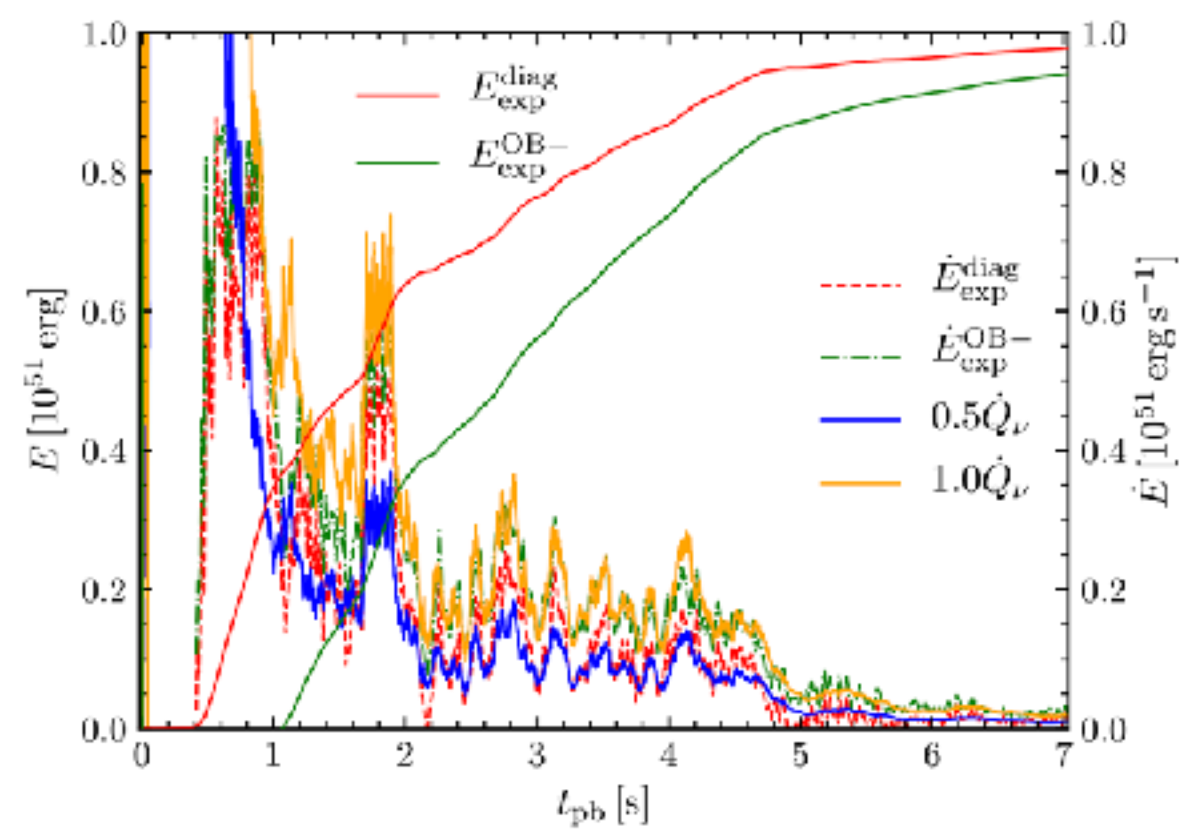
Adapted from Müller

Simulation results in the forefront

MPA Garching ~7 mins (3D progenitor evolution) **to ~7s**



Reaching 1 Bethe

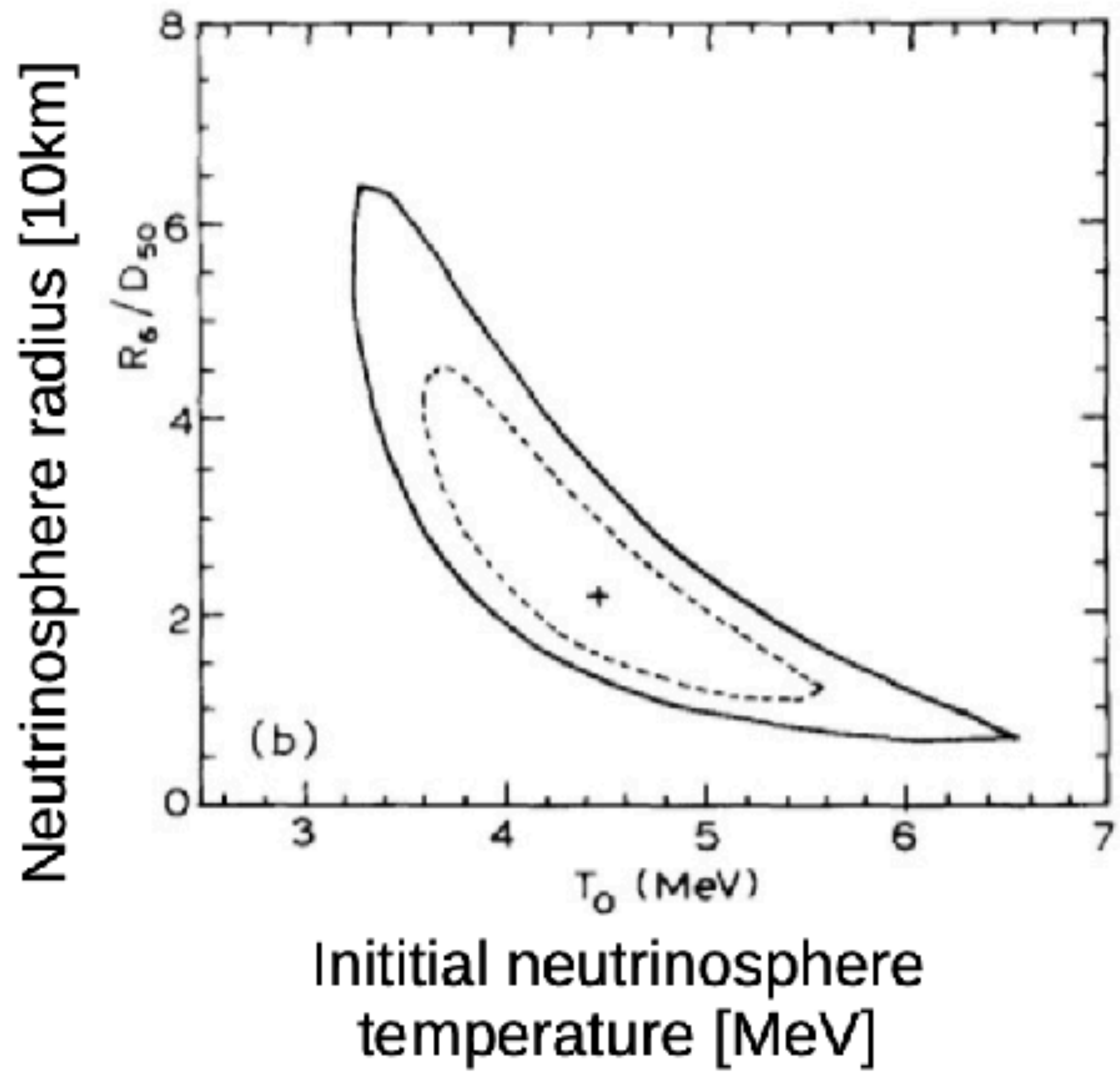


Bollig et al. 2021

What can we learn from neutrinos?

SN1987A detection, 24 events

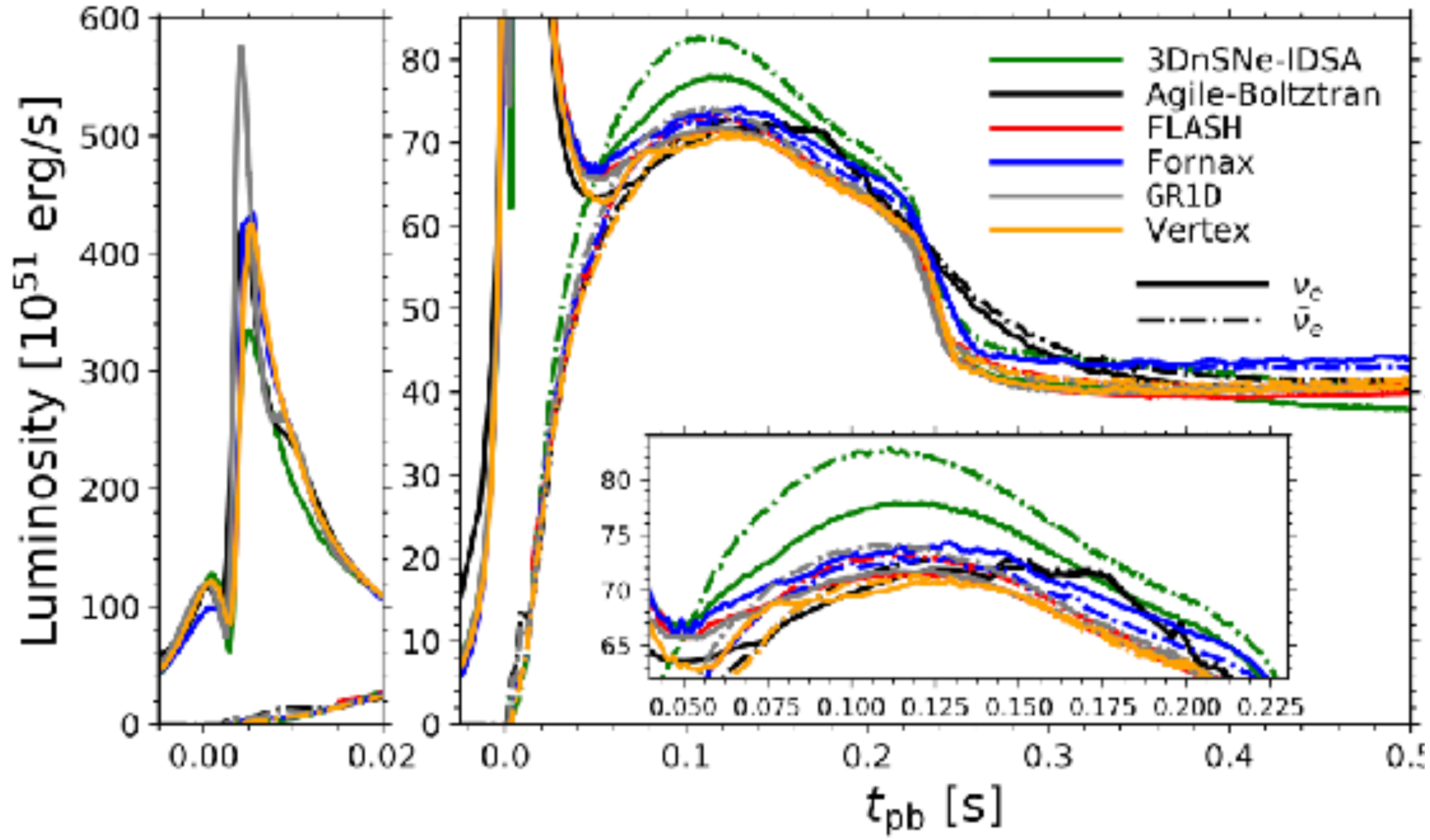
- ~3×10^{53} ergs radiated in ν's
- Mean temperature: ~4MeV
- Neutrinosphere radius ~20km
- $\bar{\nu}_e$ lifetime > 5×10^{12}s
- $\bar{\nu}$ mass <30eV
- Indicates a modest core mass (Bruenn 1987, later by O'Connor & Ott 2013)
- Constraints on hypothetic axion mass



adapted from Loredo & Lamb (1998)

Time-dependent neutrino signals

- **Spherically-symmetric simulations converging**



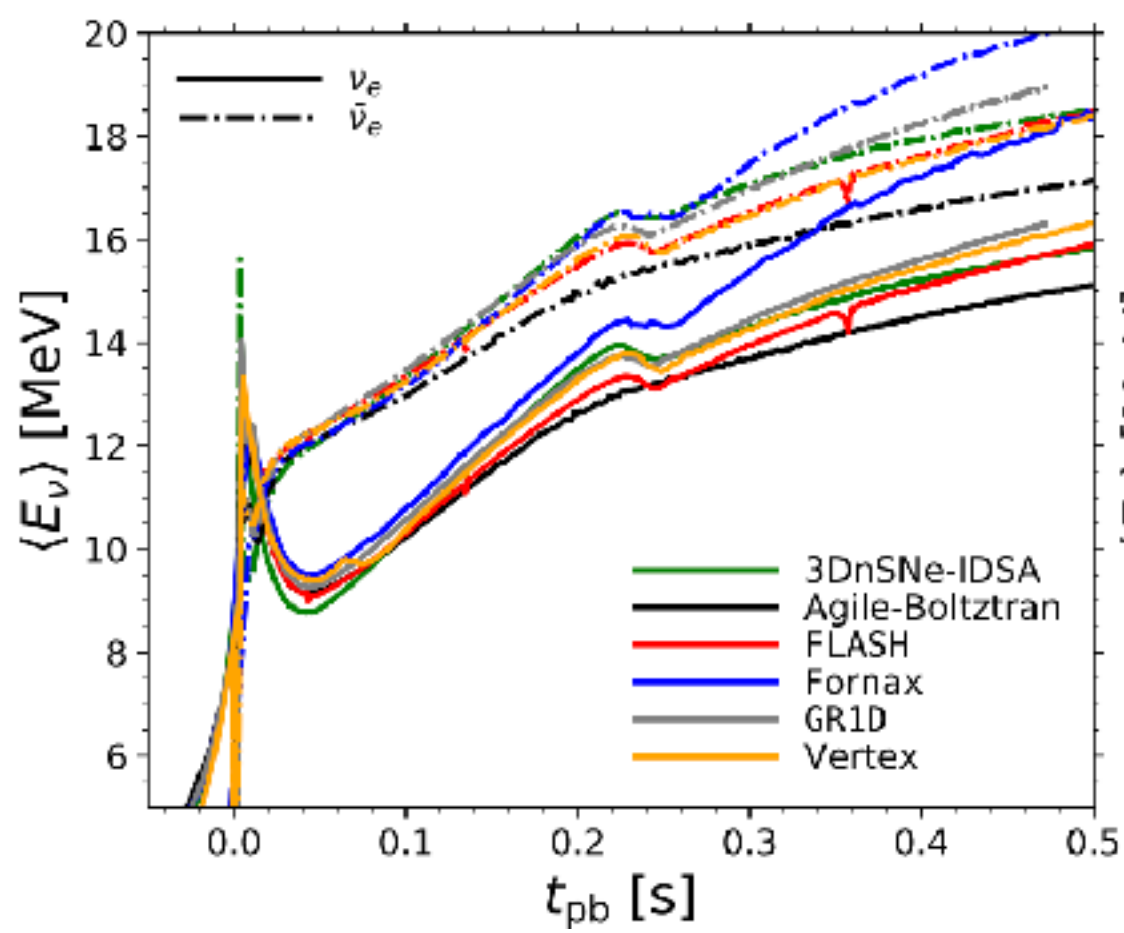
- **Electron neutrino burst after bounce (neutronization)**
- **Accretion phase**
  - **Gray-body law for $\nu_{\mu/\tau}$**

$$L_{\mu,\tau} \sim 4\pi\epsilon\sigma R^2 T^4$$

  - **Additional accretion contribution**

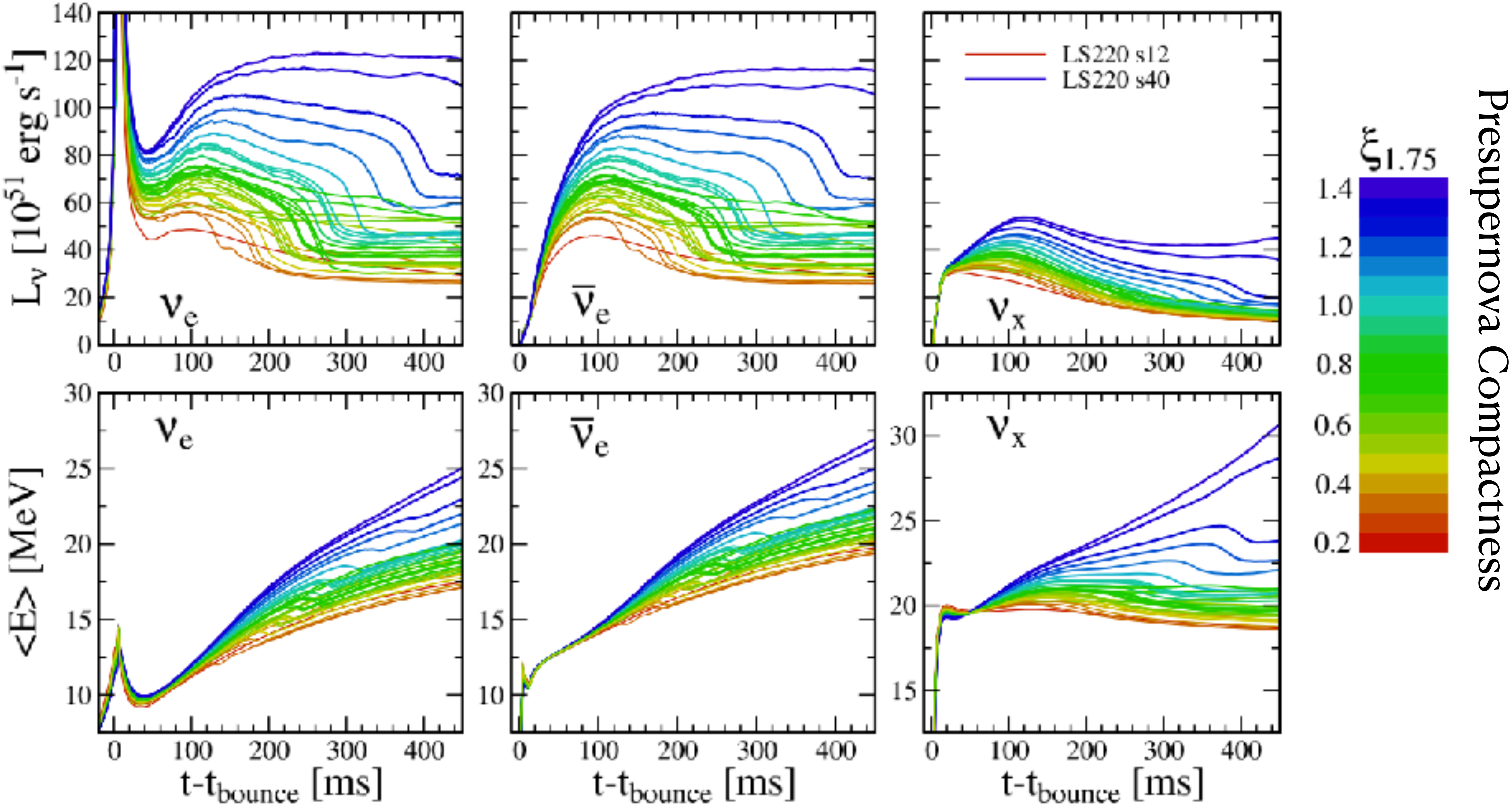
$$L_{\rm acc} \sim \alpha G M \dot{M}/R$$

for ν_e and $\bar{\nu}_e$



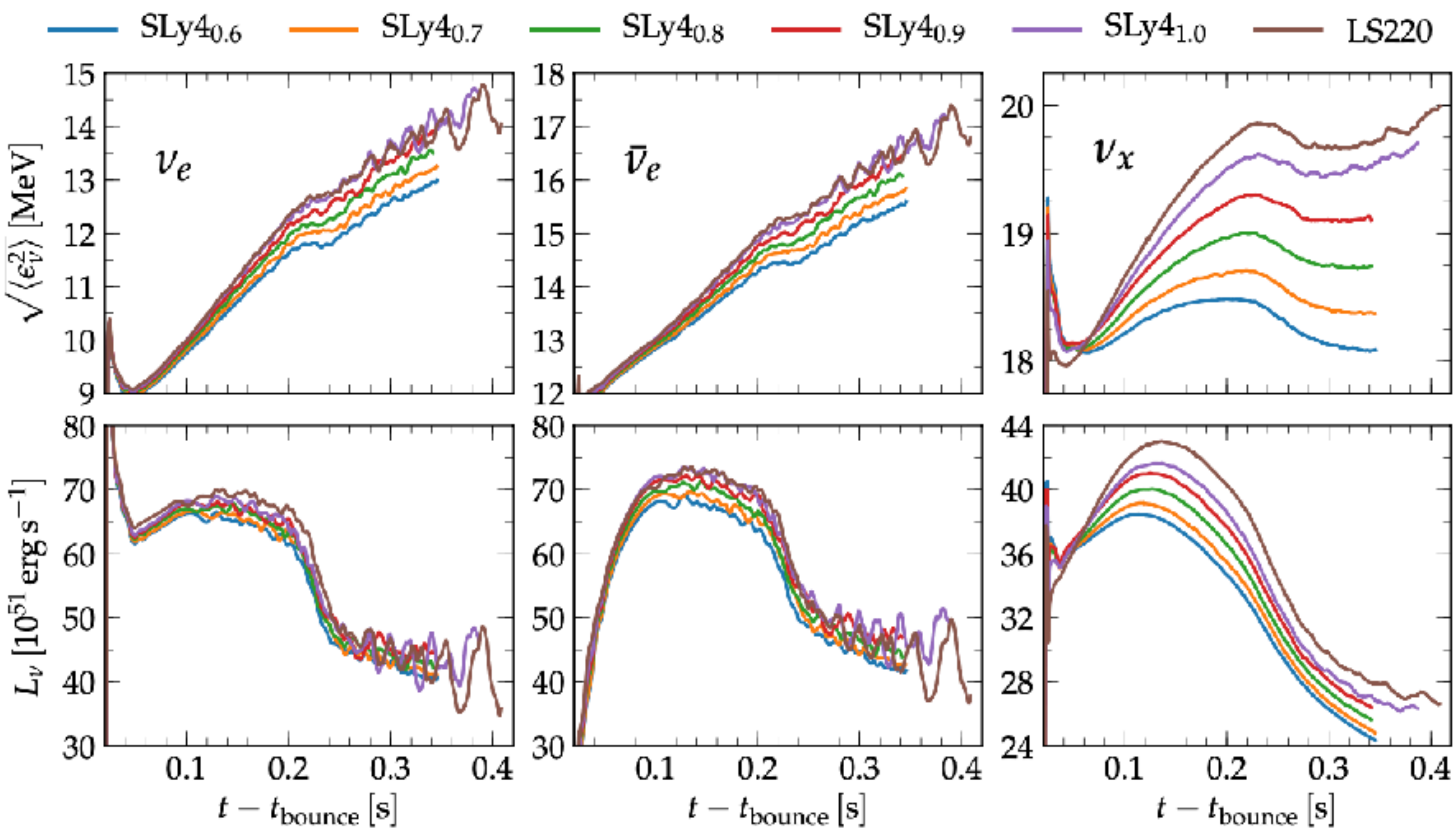
O'Connor et al. 2018 JPhG

Dependence on progenitor star



O'Connor&Ott 2012

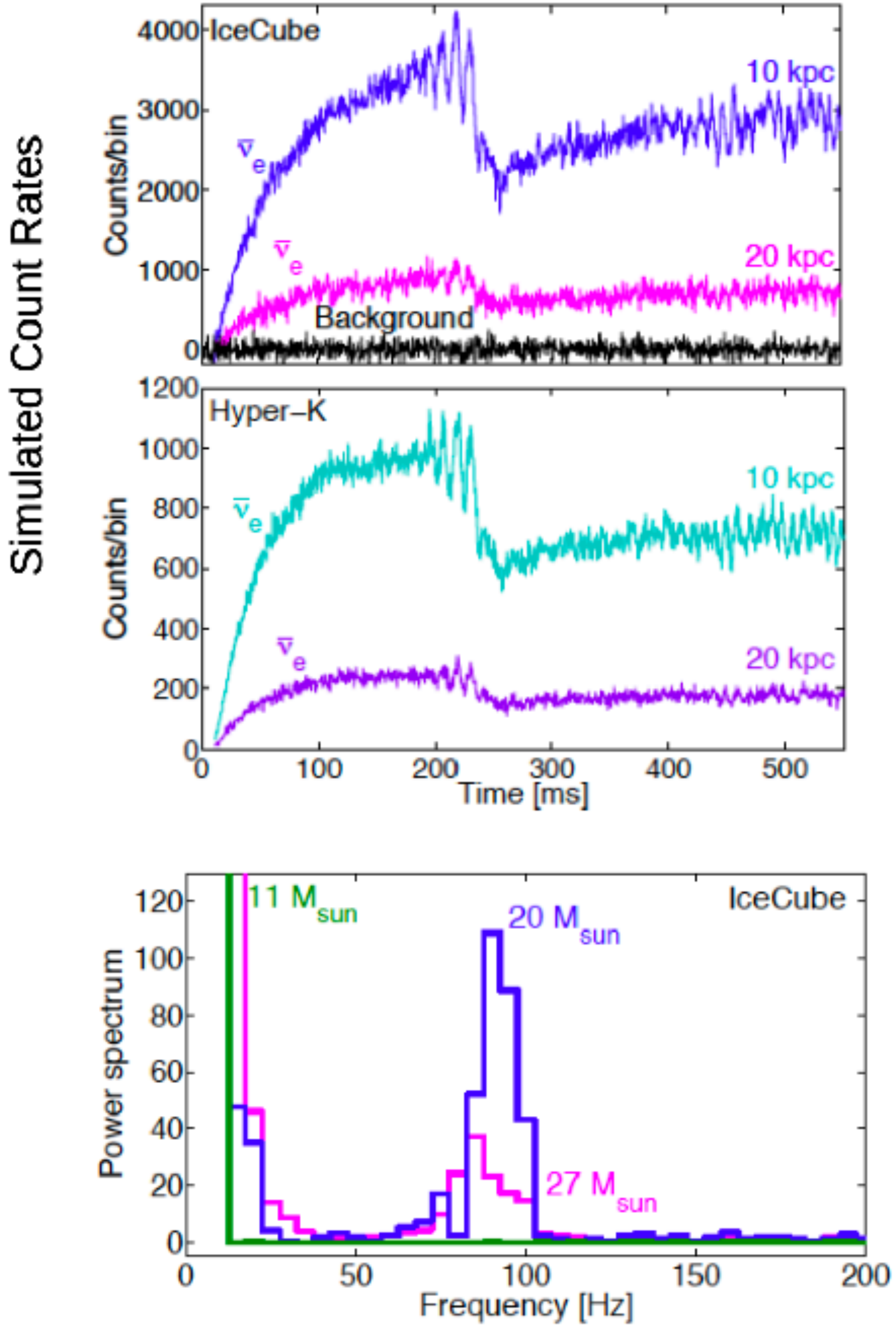
Dependence on Equation of State (EoS)



Schneider+2019

SASI-induced variations

- **SASI: Standing Accretion Shock Instability**
- **Sloshing motions (of stalled shock) result in quasi-periodic and asymmetric neutrino emission**
- **Sloshing frequency relates to shock and proto-neutron star radius**
- **May help to reconstruct the shock trajectory**

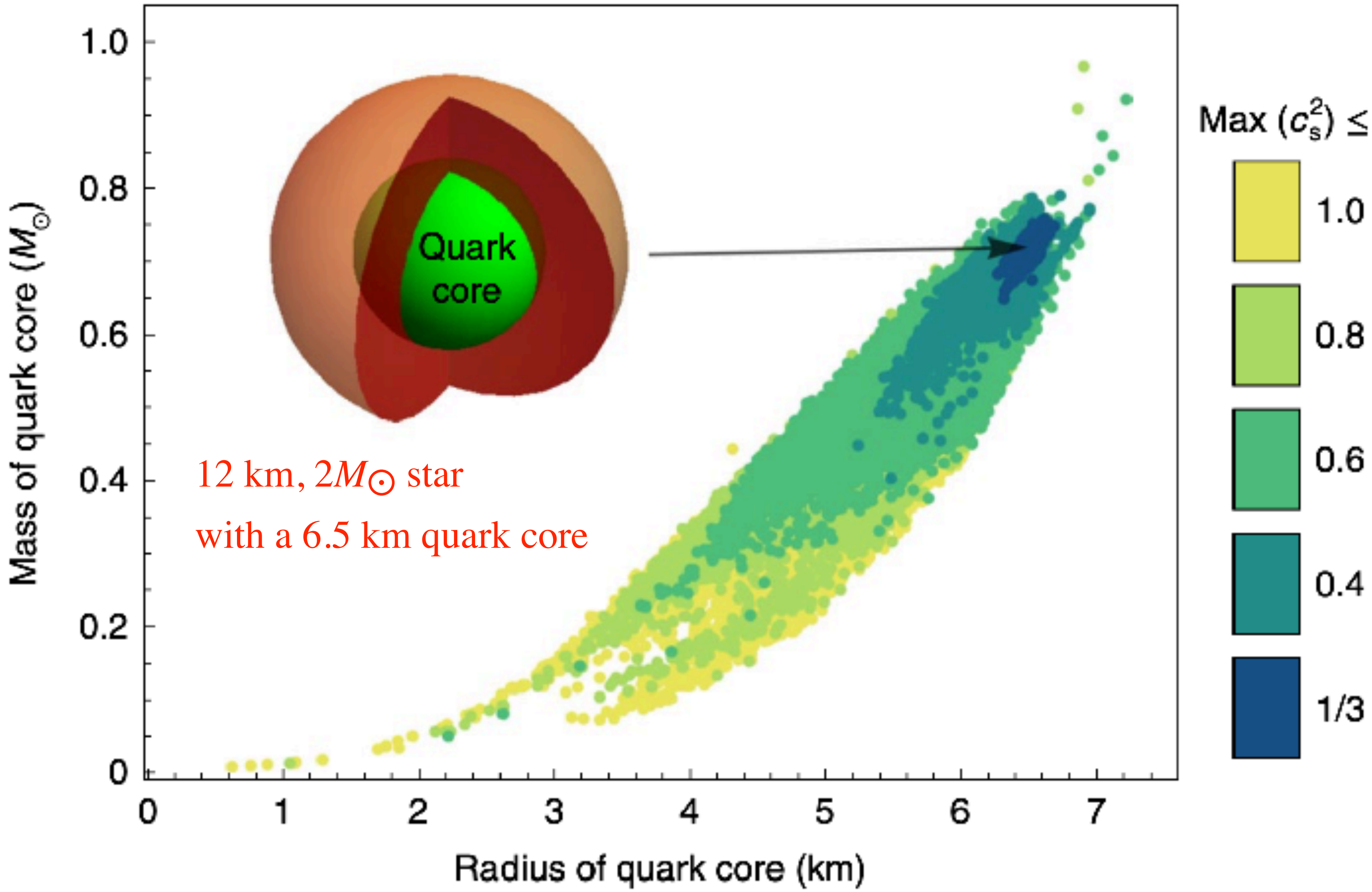


Tamborra et al. (2013)

Quark (hybrid) stars

- More stable than neutron matter at high density (?)
- Smaller radius than neutron stars (?)

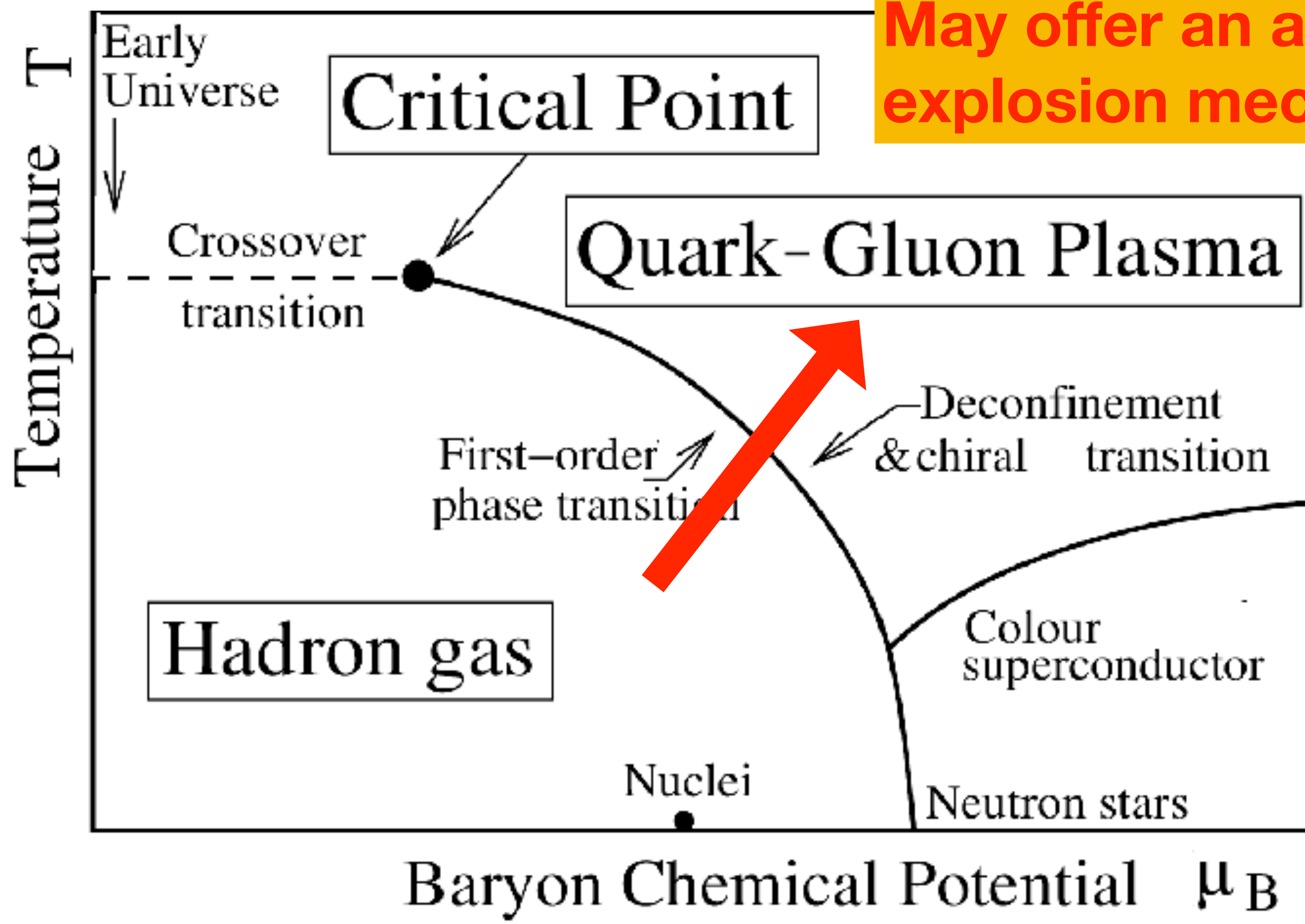
Witten 1984; Haensel et al. 1986



Annala et al. Nature physics (2020)

Hadron-quark phase transition

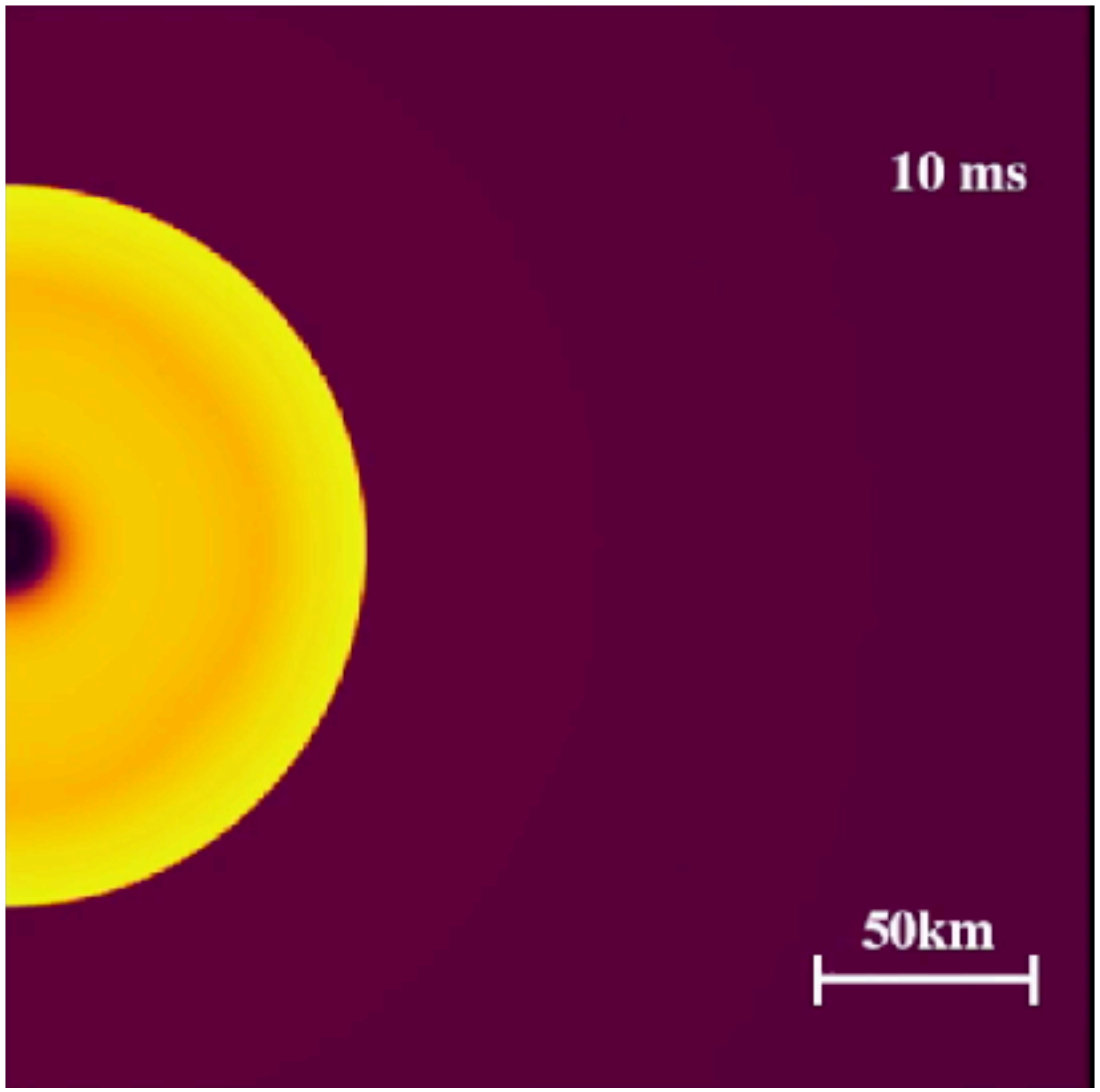
May offer an alternative explosion mechanism



Source: CERN

Baryon number density

1st-order phase-transition-driven successful CCSN

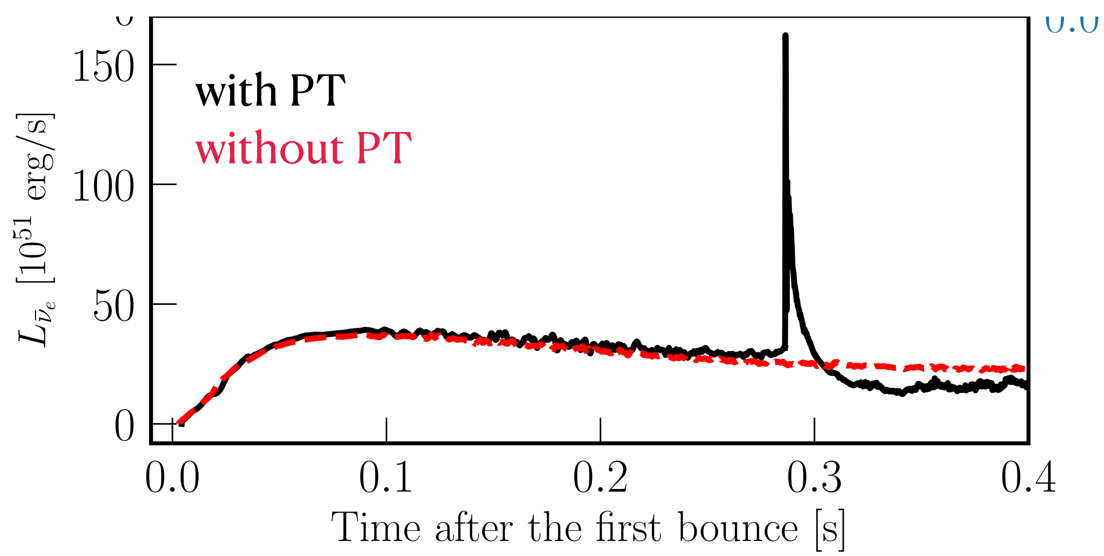


Entropy rendering of 2D simulation with *FLASH*

Progenitor mass 12 $M_\odot$

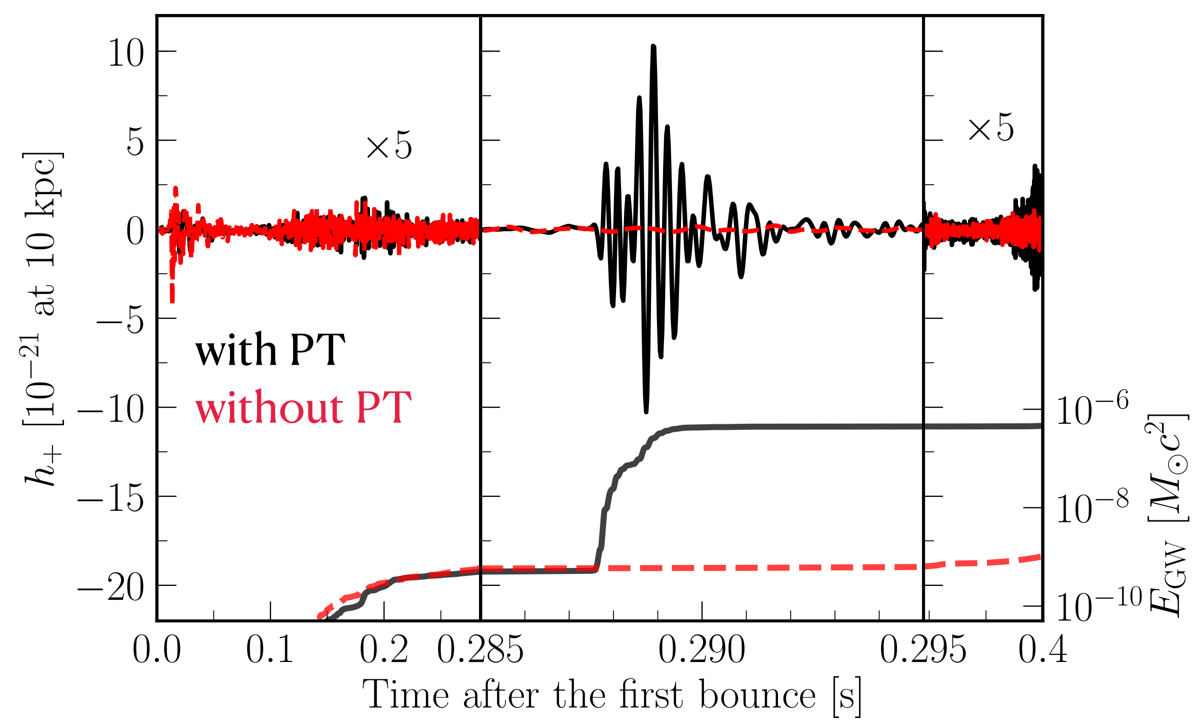
EOS: STOS+B165 *(CompOSE)*

Electron anti-neutrino



Also see Sagert+2009

Gravitational waves

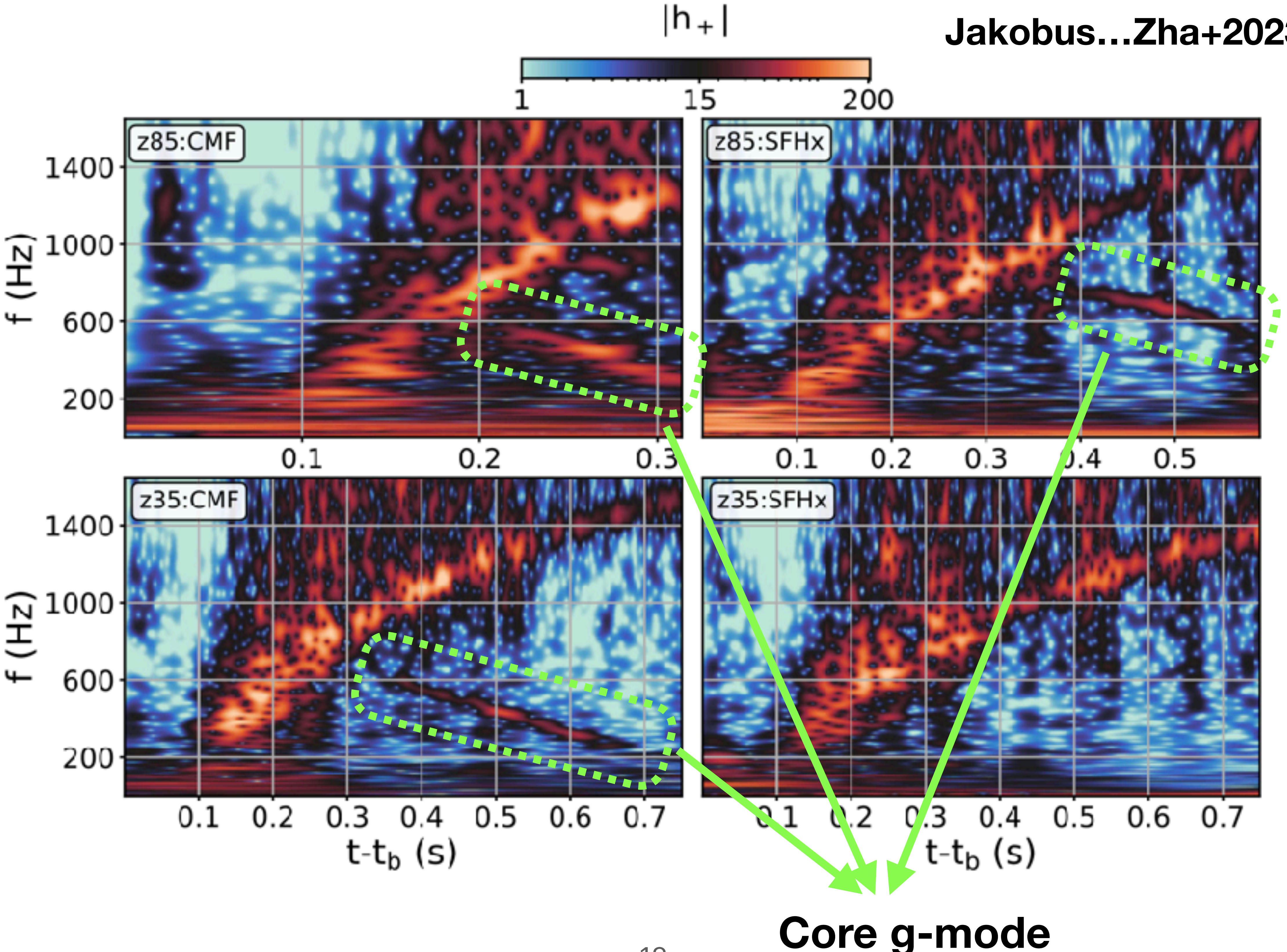


Zha+2020 PRL

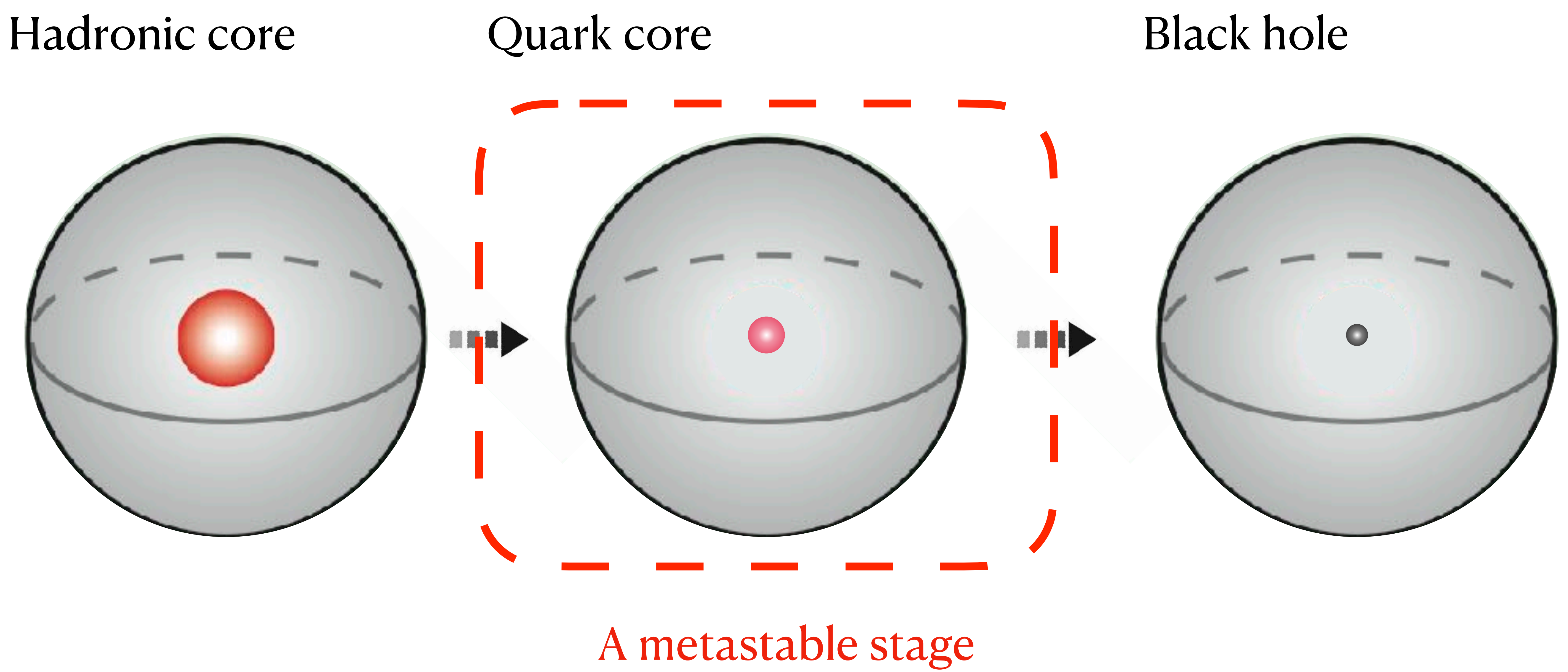
arxiv: 2007.04716

Unique signature of cross-over phase transition

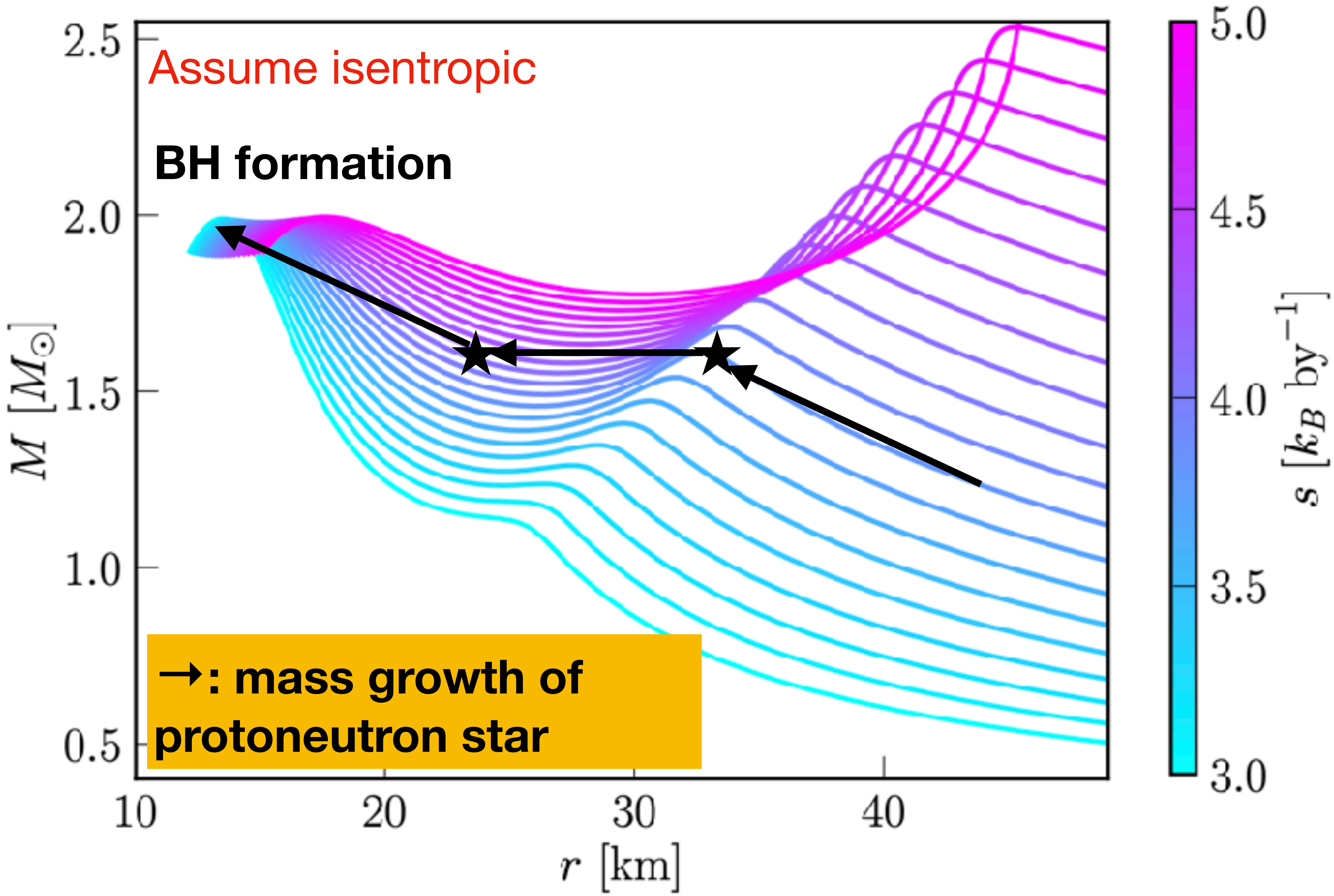
Jakobus…Zha+2023 PRL



A more likely evolution scenario



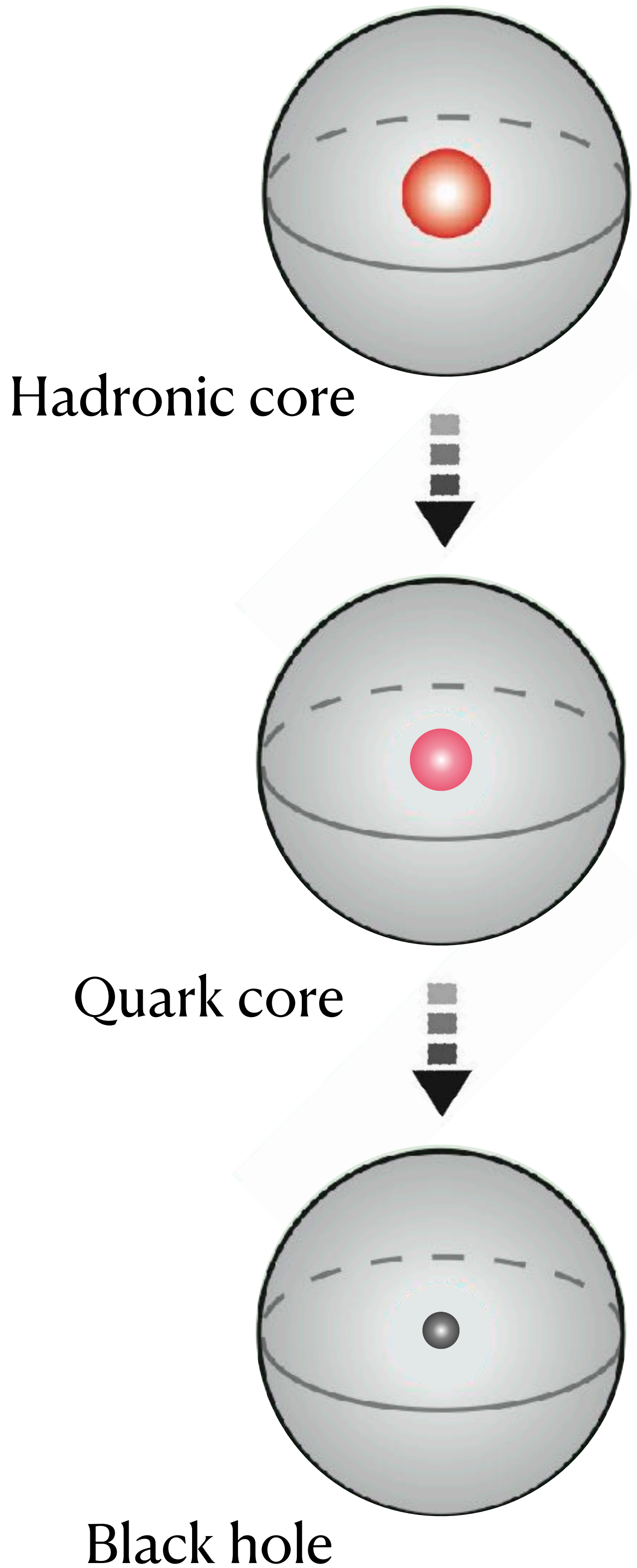
M-R relation for hot proto-compact star with PT

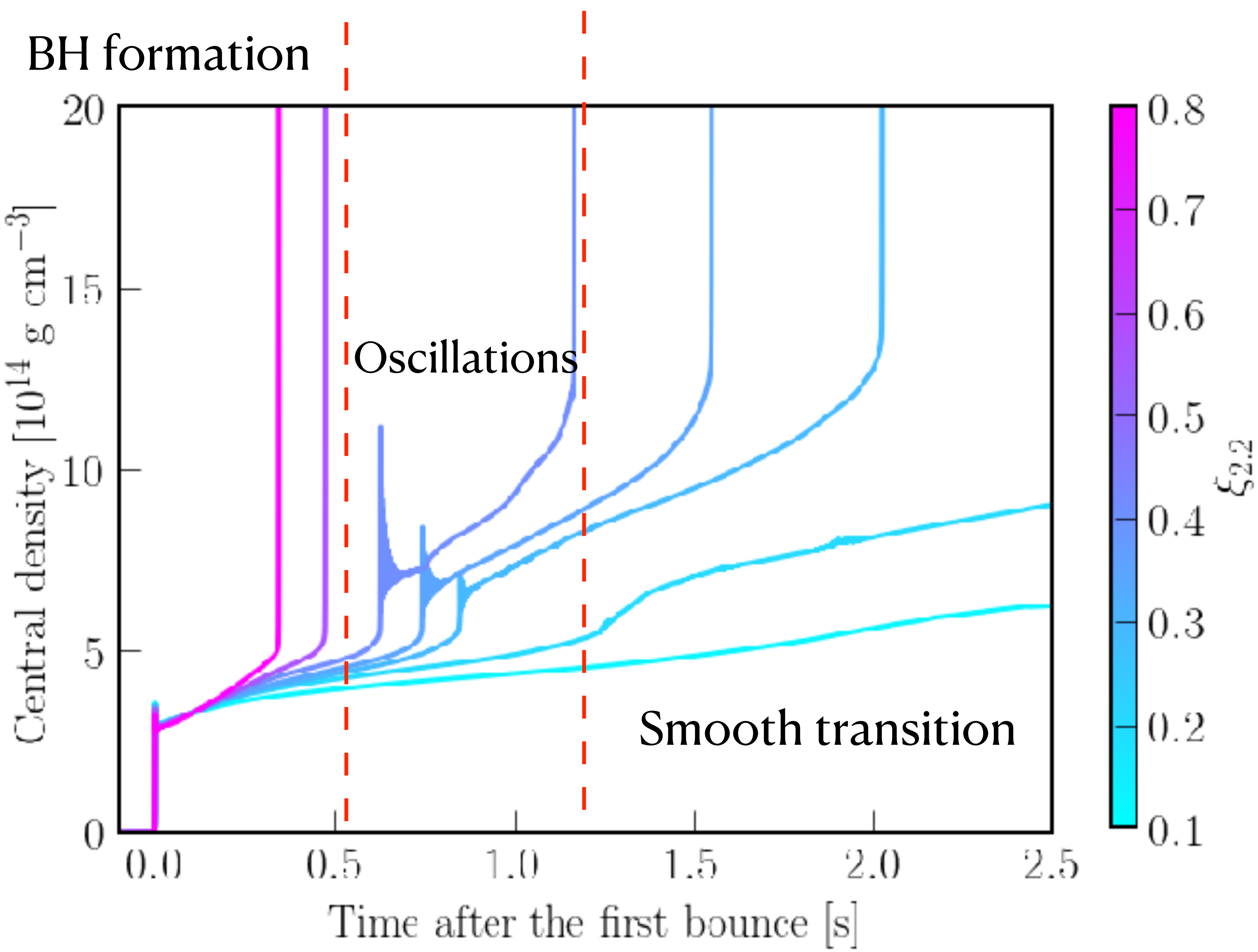


STOS+B145 hybrid EOS

Alford+2013; Hempel+2016; Heinimann+2016

Consequences of phase transition in Failed CCSNe





Simulations with *GR1D*

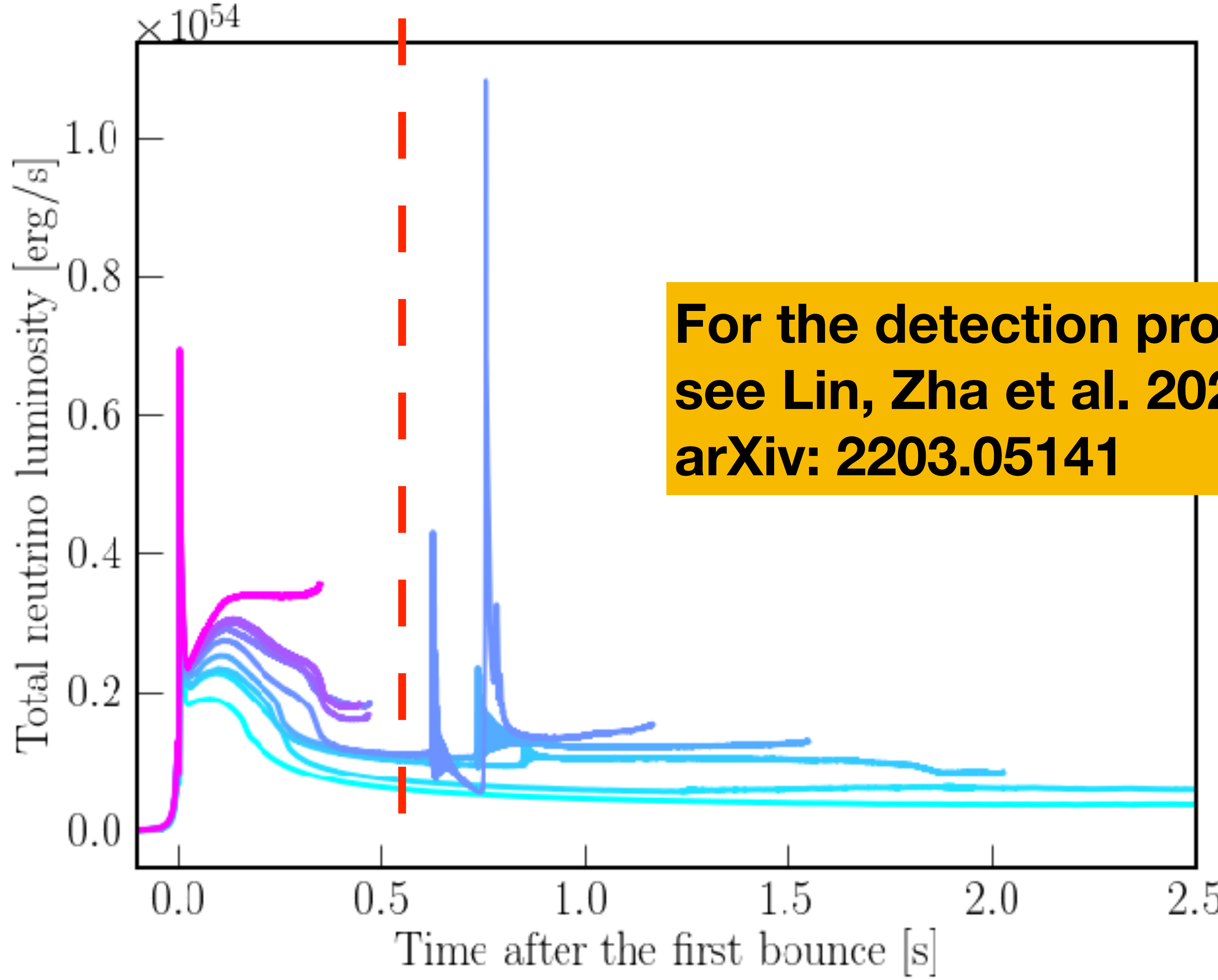
EOS: STOS+B145 *(CompOSE)*

Zha+2021

arXiv: 2103.02268

Neutrino signals

Terminate at BH formation | Variations after 2nd collapse

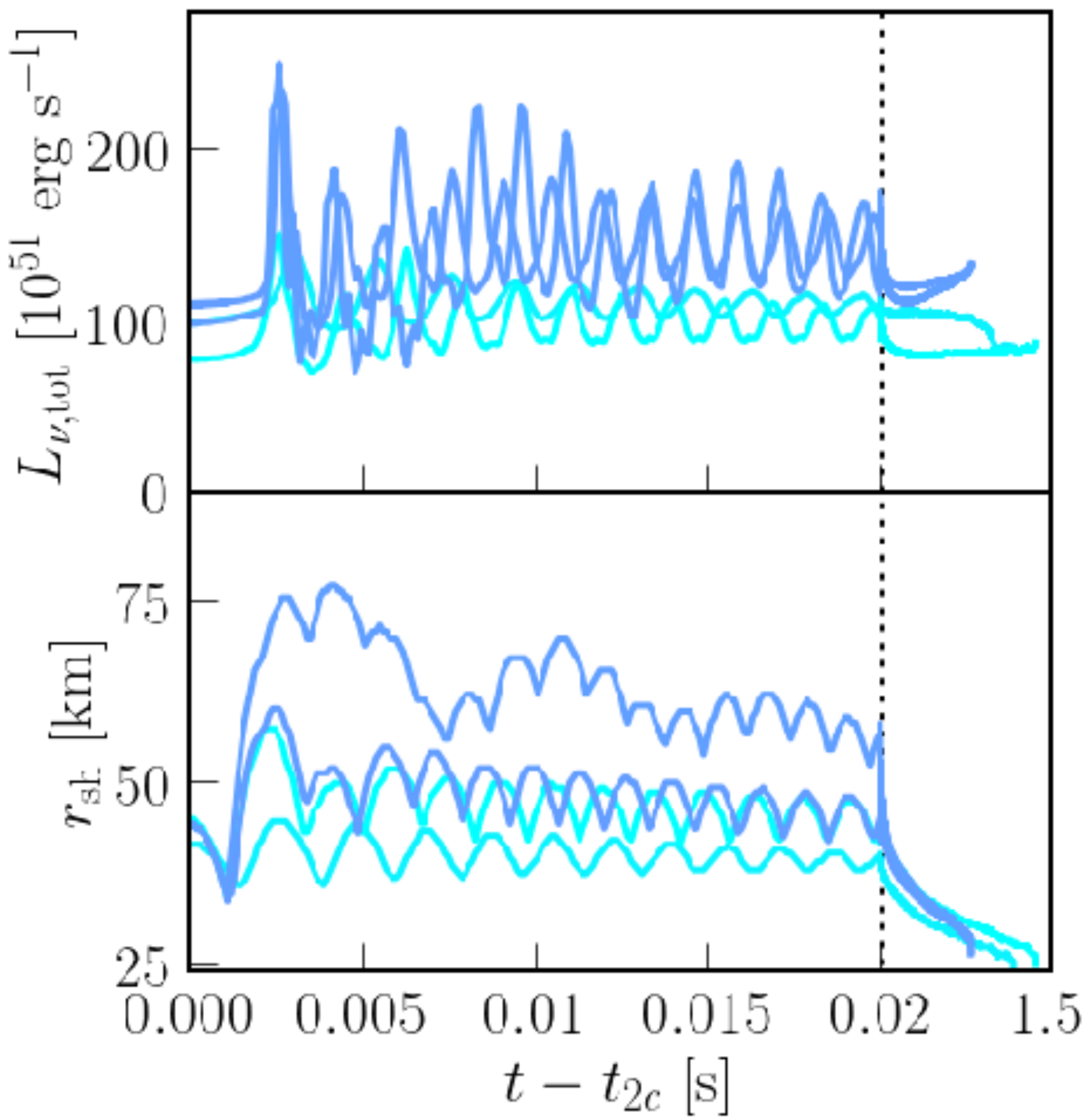


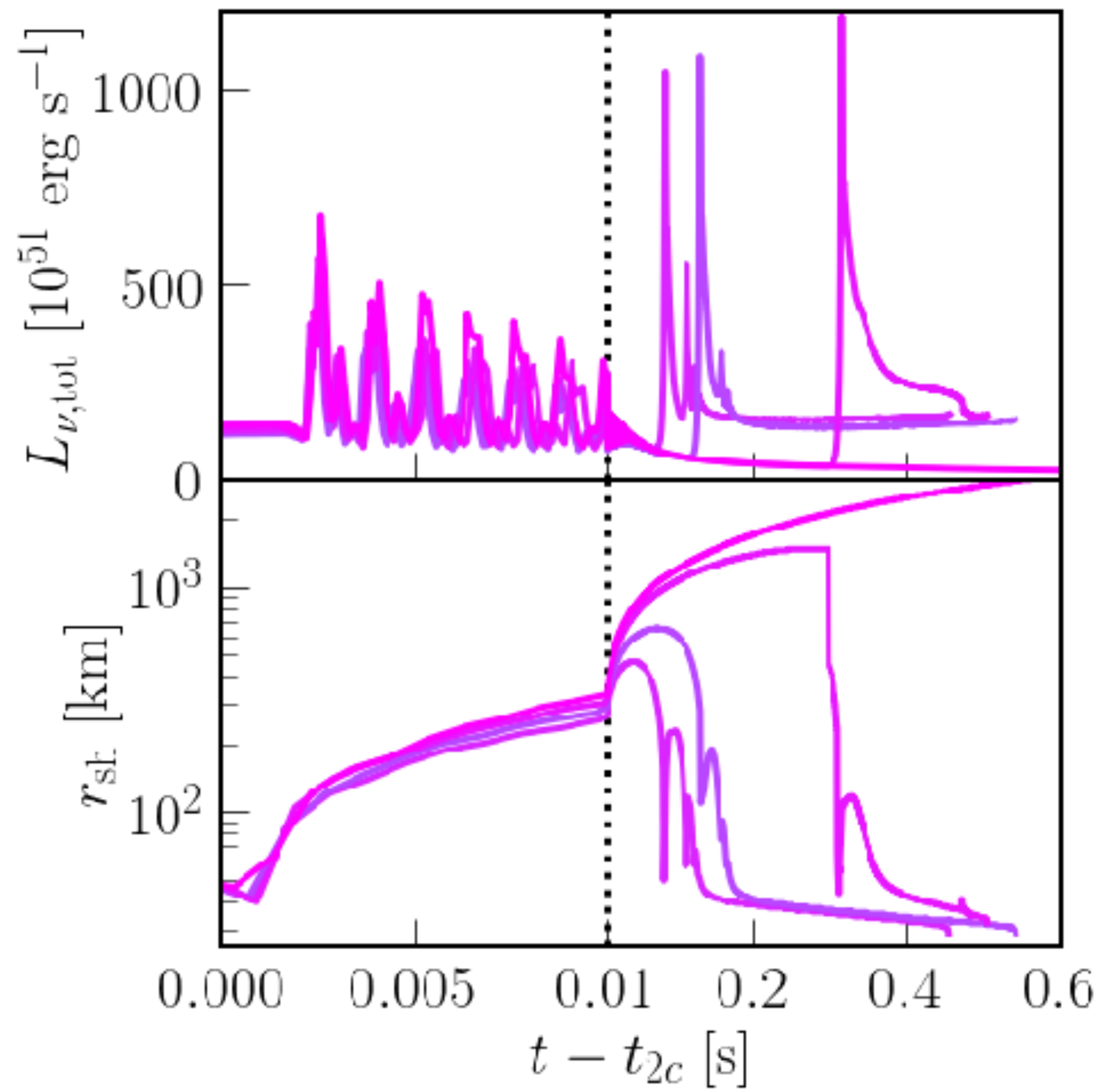
For the detection prospect see Lin, Zha et al. 2024 PRD arXiv: 2203.05141

Zha+2021
arXiv: 2103.02268

Two subclasses

Less compact	More compact





~ 1 ms period, last for ~50 ms

+ secondary bursts

Zha+2021
arXiv: 2103.02268

A roadmap for future developments

Partially an answer for Xiaodong's question

Neutrino Boltzmann equation:

$$p^\alpha \left[\frac{\partial f}{\partial x^\alpha} - \Gamma^\beta_{\alpha\gamma} p^\gamma \frac{\partial f}{\partial p^\beta} \right] = \left[\frac{\mathrm{d} f}{\mathrm{d}\tau} \right]_{\mathrm{coll}}$$

Neutrino distribution function

$$f = f(t, \vec{r}, \vec{p}_\nu) \qquad \text{7D}$$

Assuming spherical symmetry

$$f = f(t, r, p_\nu, \mu) \qquad \text{still 4D}$$

Numerical methods

S_N > VE > M_1 > FLD, IDSA > leakage

← ab initio, higher cost **approximate, lower cost →**

2 moments (VE > M_1) 1 moment (FLD, IDSA)

Moment eqs:

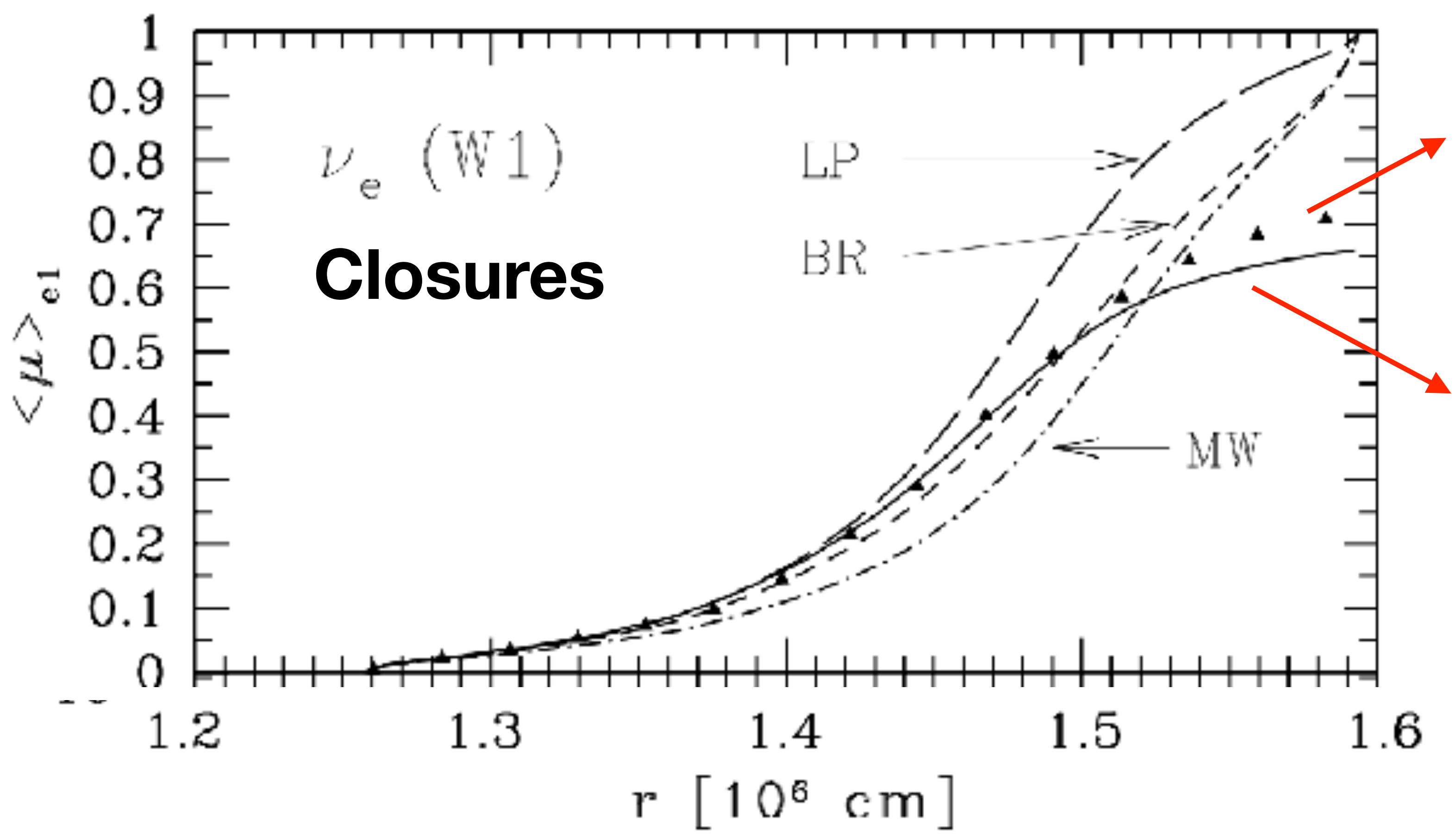
$$\partial_t[E] + \frac{1}{r^2}\partial_r\left[\frac{\alpha r^2}{X^2} F_r\right] + \partial_\epsilon\left[\epsilon\left(R_t + O_t\right)\right] = G_t + C_t,$$

$$\partial_t[F_r] + \frac{1}{r^2}\partial_r\left[\frac{\alpha r^2}{X^2} P_{rr}\right] + \partial_\epsilon\left[\epsilon\left(R_r + O_r\right)\right] = G_r + C_r.$$

Require a closure to close the equations!

A new-generation MC transport solver alongside dynamic simulations

A 3-5 years project



Yamada, Janka, Suzuki 1998

No dynamic simulations yet

Good for

- **Inelastic scatterings**
- **Fast flavor conversion**

Thank you for your attention!