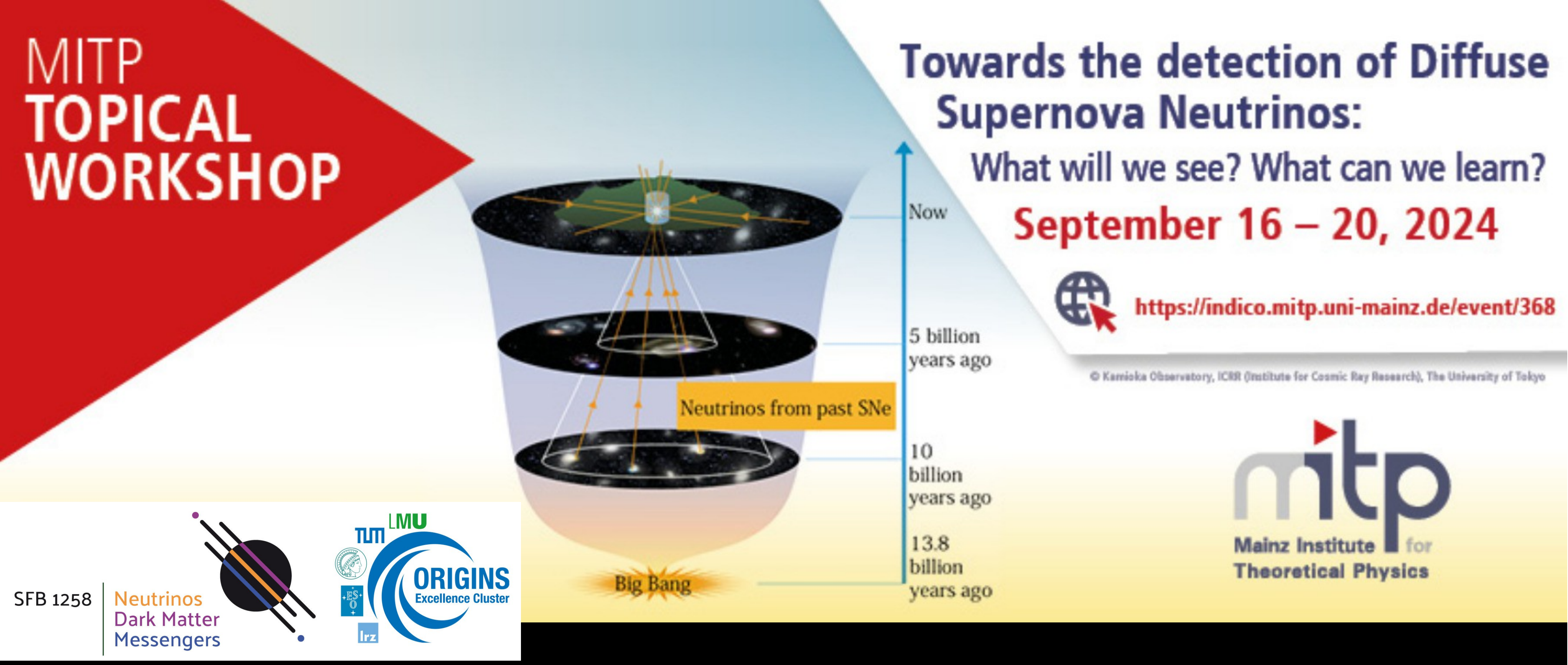


Future of Supernova and DSNB Modeling

Hans-Thomas Janka
Max Planck Institute for Astrophysics
Garching, Germany

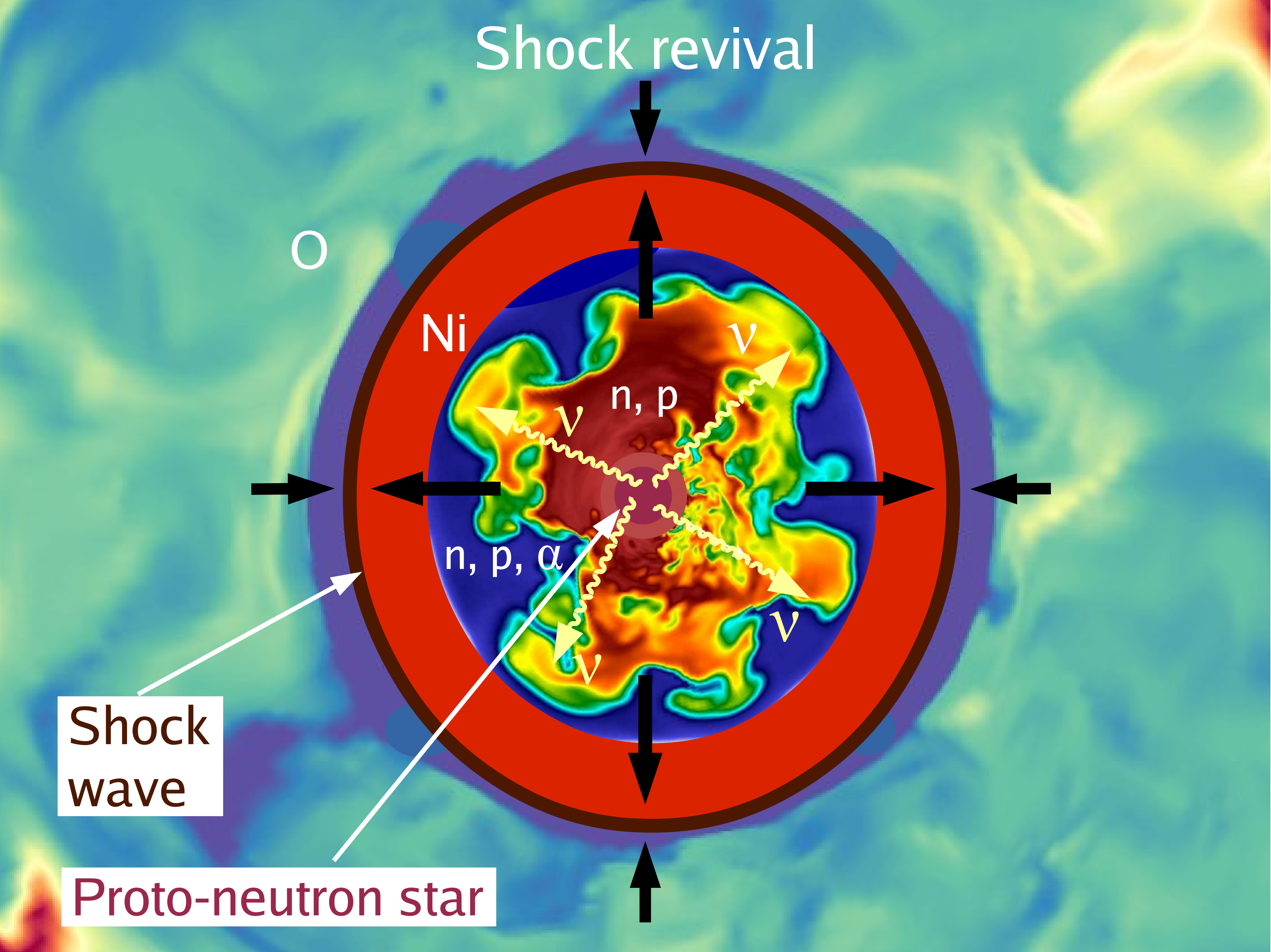
Max-Planck-Institut für Astrophysik

Outline

- **Where are we?**
  Status of 3D modeling of neutrino-driven explosions

- **What do we need to improve?**
  Predictions of stellar "explodability" and progenitor dependencies of SN explosion properties

- **What do we need from other communities?**
  Progress in SN & DSNB predictions requires inputs!


Shock revival
O
Ni
n, p
ν
ν
n, p, α
ν
ν
Shock wave
Proto-neutron star

Neutrino-driven Explosion Models and "Explodability" of Massive Stars

3D Core-Collapse SN Explosion Models

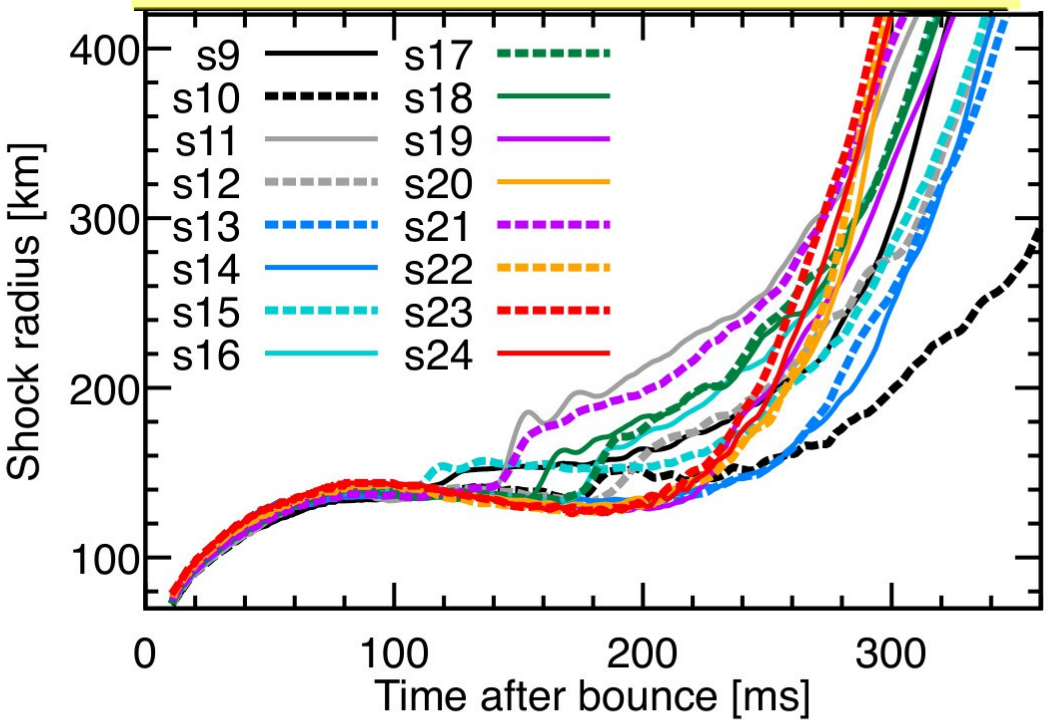
About half a dozen groups are active in 3D CCSN modeling:

Garching, Monash/QUB, Oak Ridge, Fukuoka/Tokyo, Caltech, Princeton/Berkeley, MSU/Stockholm

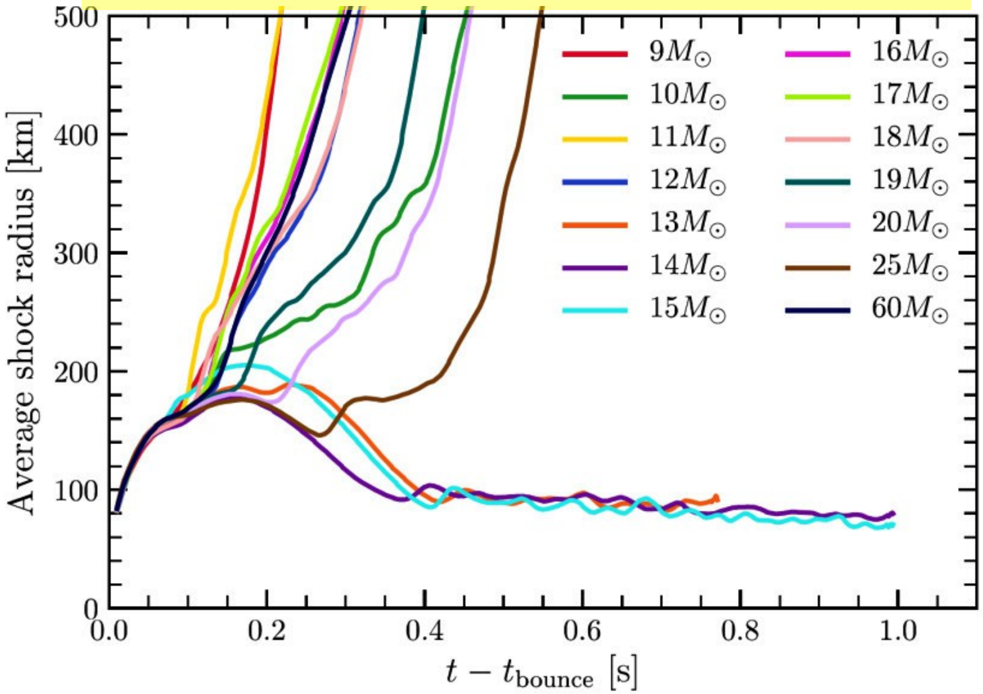
3D simulations differ in many aspects of numerics, physics inputs, seed perturbations, and, qualitatively and quantitatively, in their outcomes.

<u>3D code comparison is highly desirable.</u>

Nakamura+, arXiv:2405.08367, 3D-MHD, LS220 EoS, progenitors: Sukhbold+2016



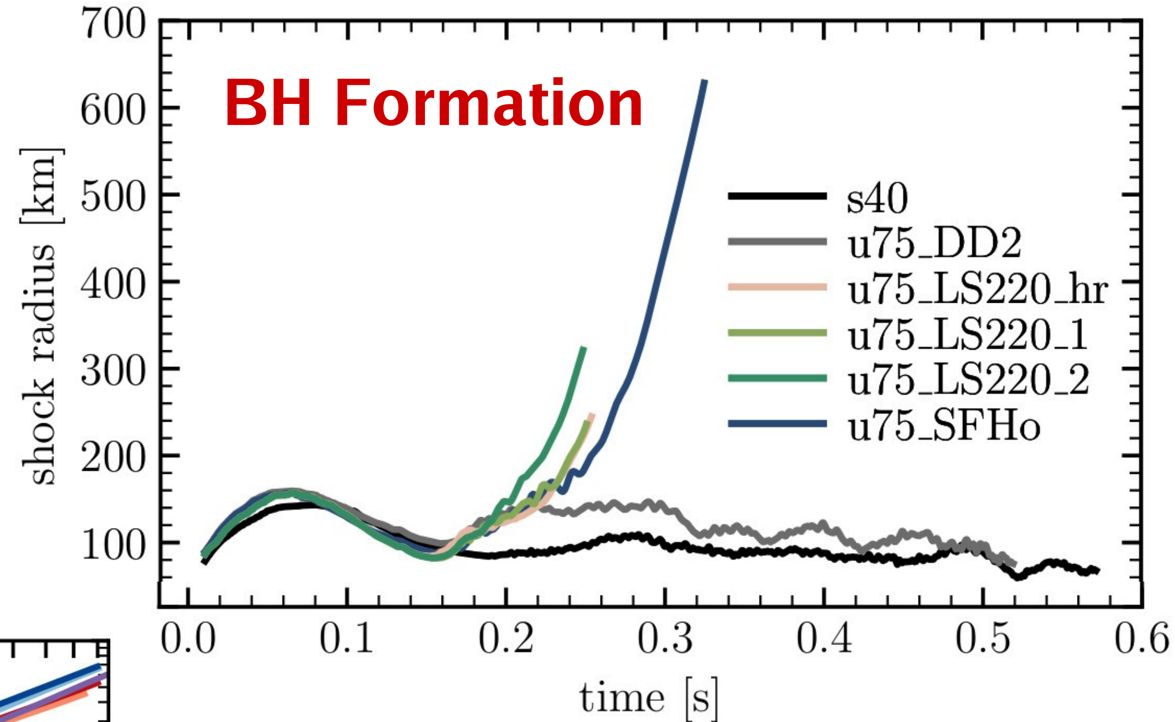
Burrows+2020, MNRAS 491, 2715, 3D-Hydro, SFHo EoS, progenitors: Sukhbold+2018

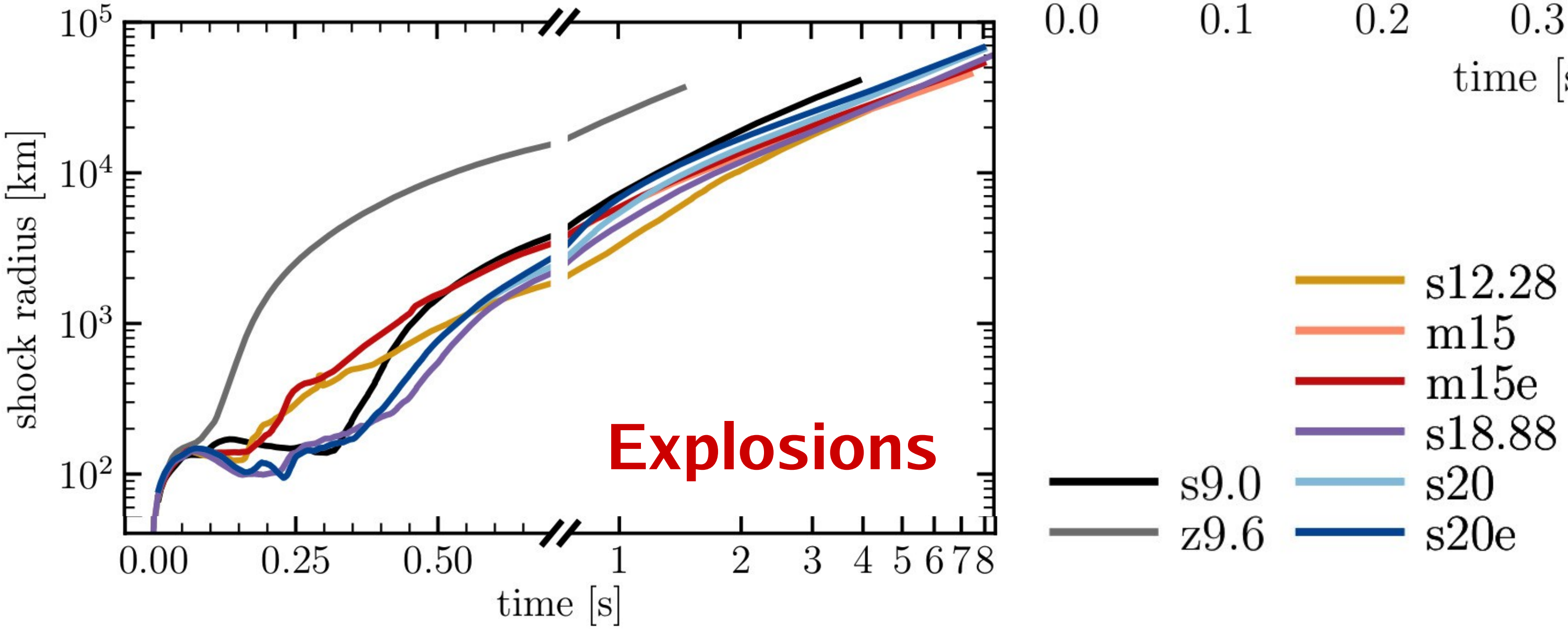


Evolution of 3D Self-consistent CCSN Explosions Towards Energy Saturation

Daniel Kresse
(MPA) Postdoc

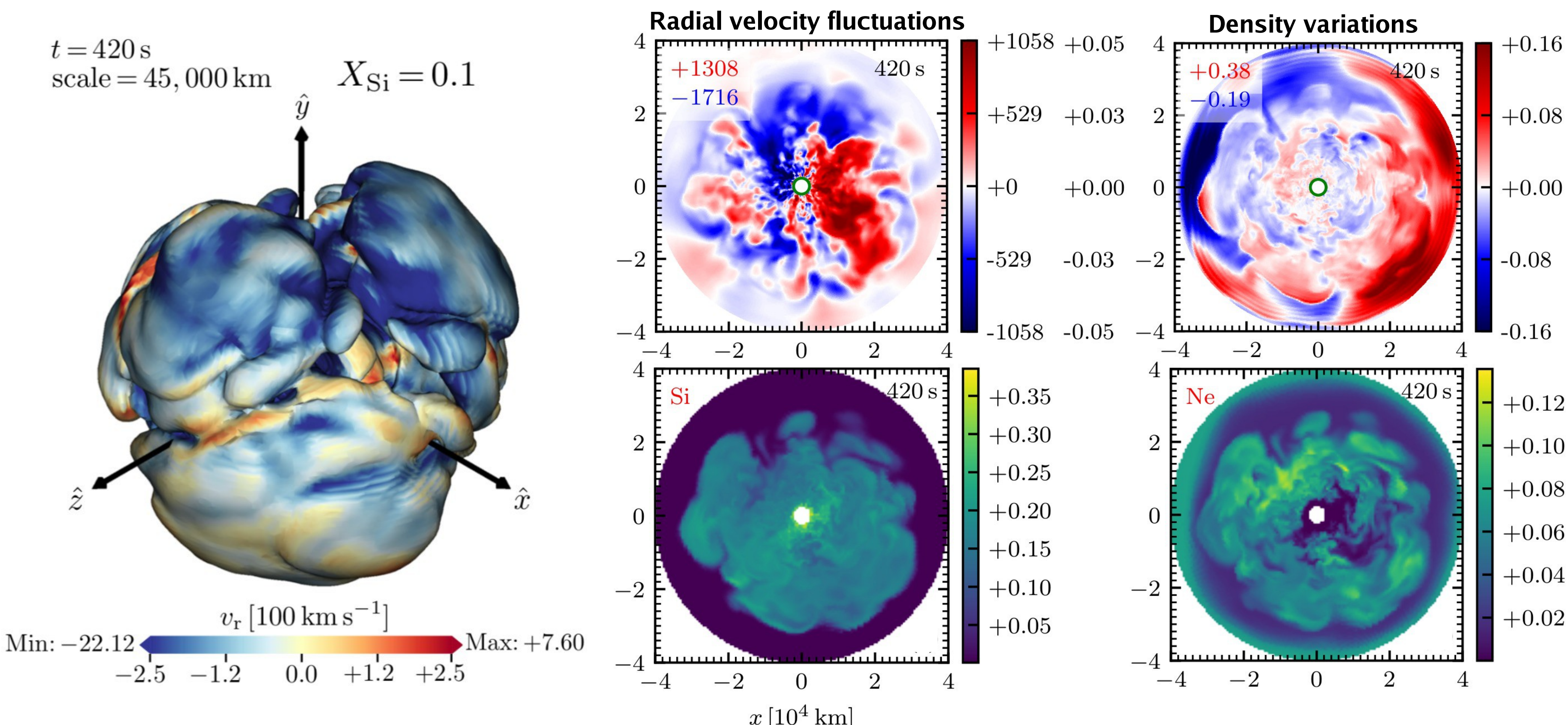
(D. Kresse, PhD Thesis, TUM, 2023;
HTJ & D. Kresse, arXiv:2401.13817)





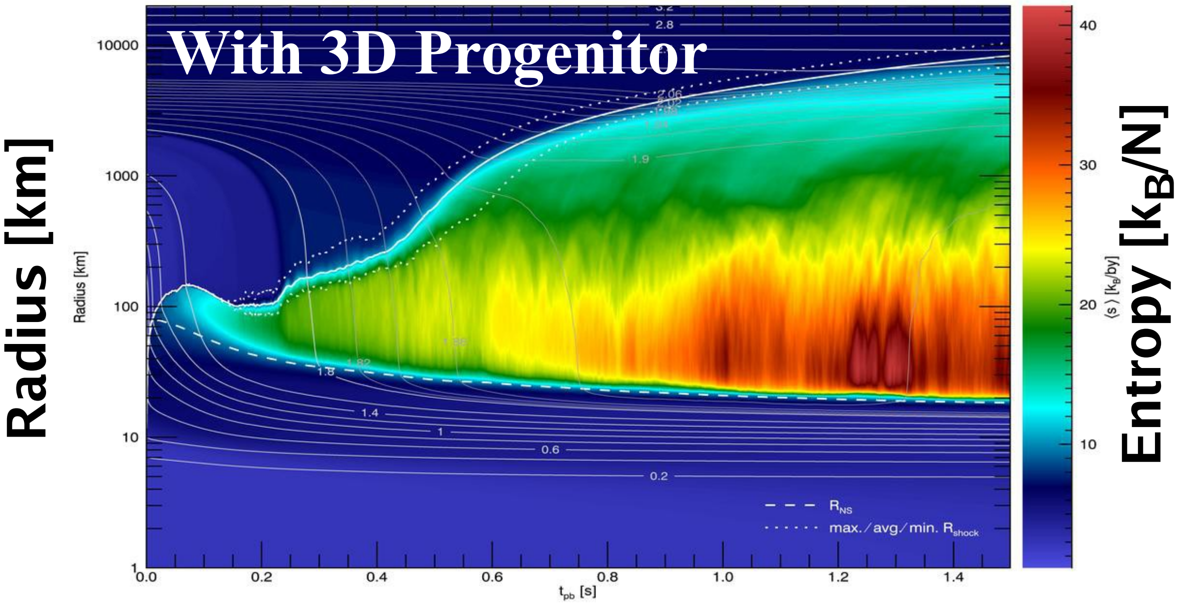
Neon-oxygen-shell Merger in a 3D Pre-collapse Star of ~19 M_{sun}

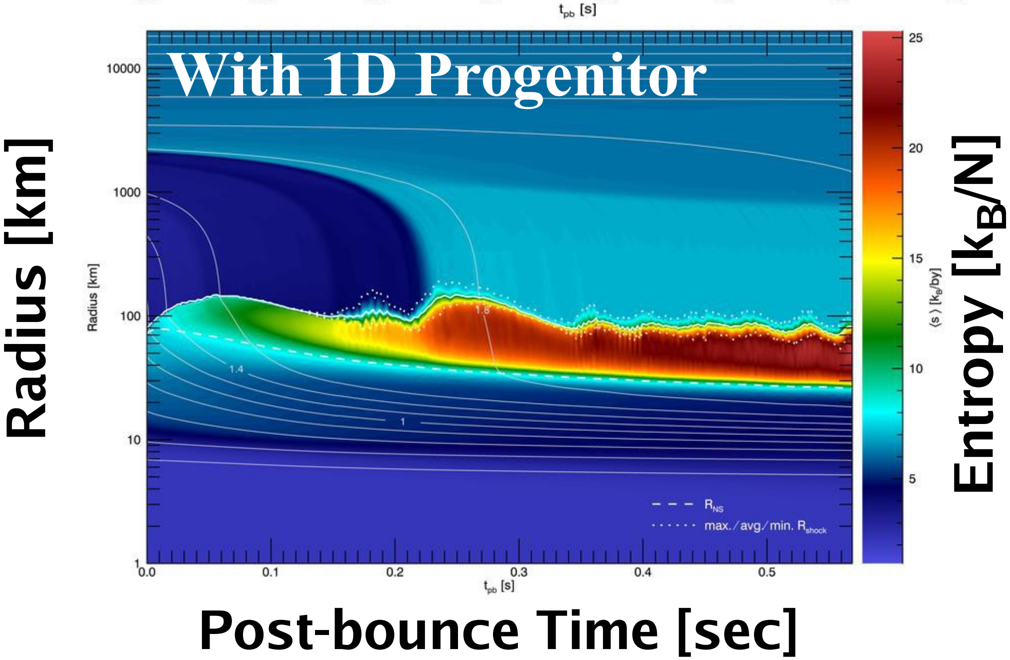
Flash of Ne+O burning in a shell merger creates large-scale asymmetries in density, velocity, Si/Ne composition

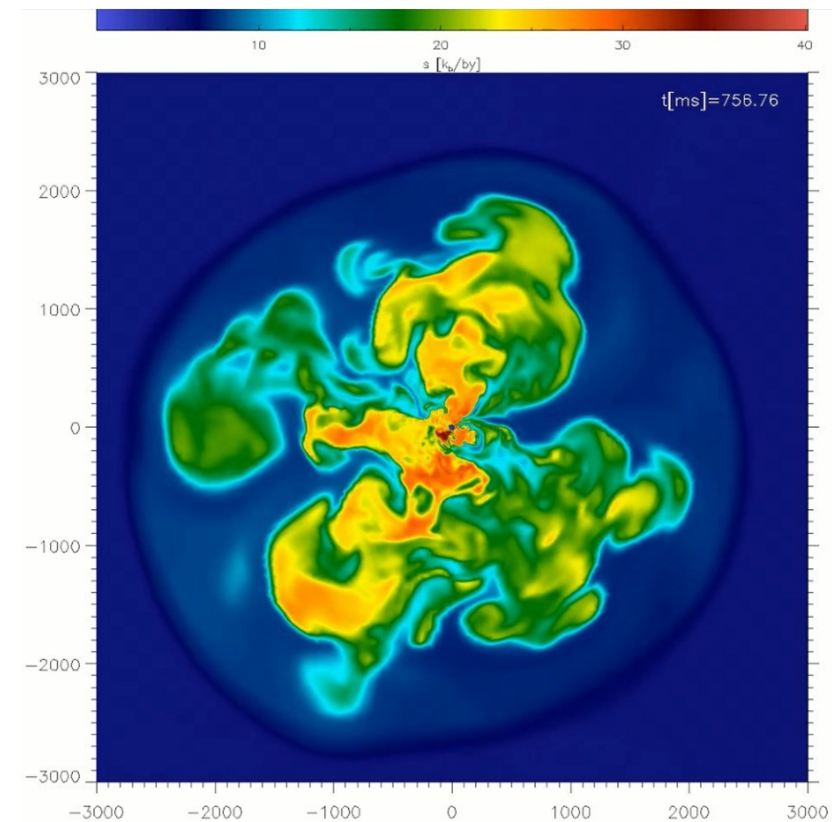


Yadav, Müller et al., ApJ 890 (2020) 94

3D Explosion of ~19 M_{sun} Star after Neon-oxygen-shell Merger



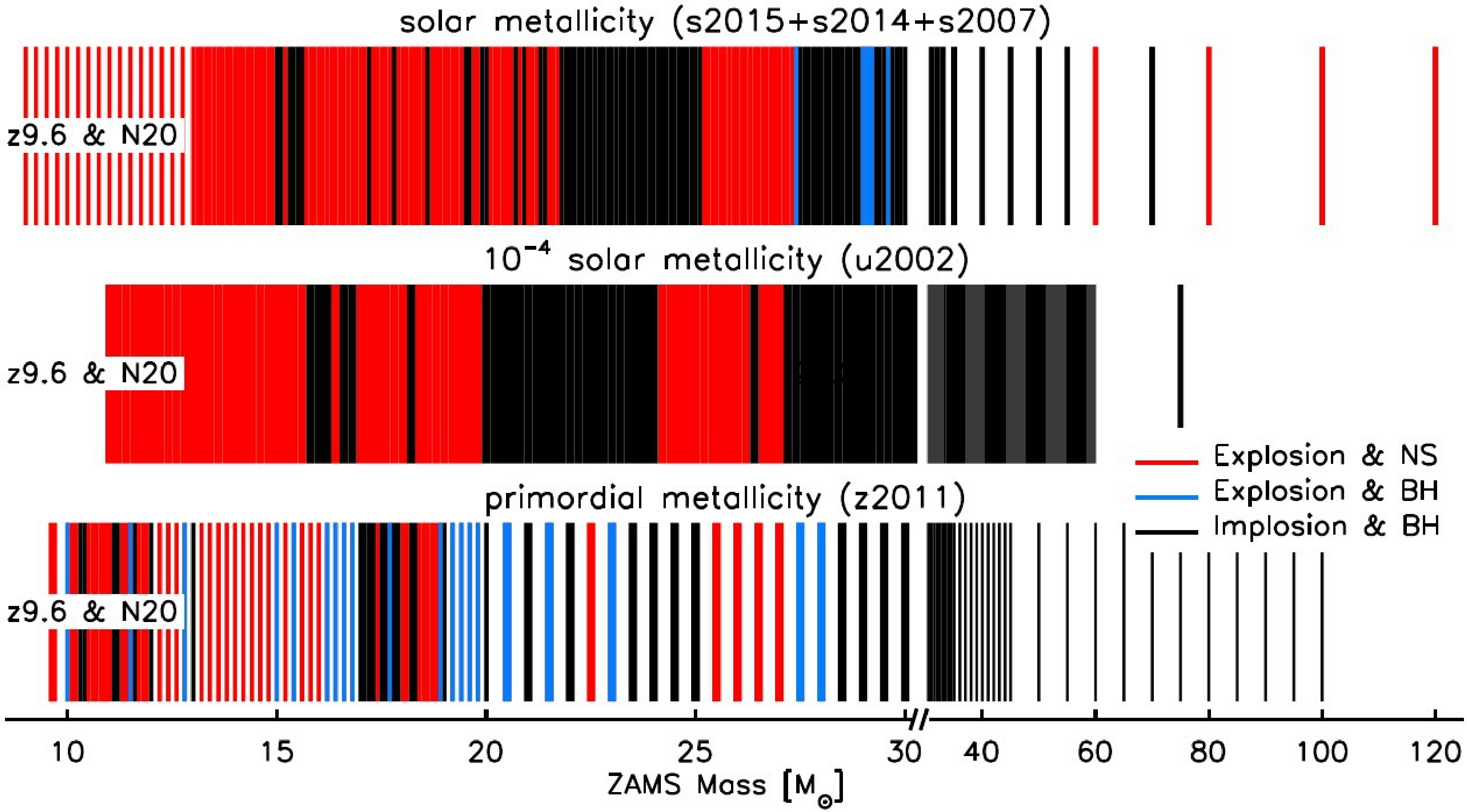




Pre-collapse perturbations in convectively burning O-shell aid explosion because they stir strong postshock convection.

R. Bollig et al., ApJ 915 (2021) 28

Neutrino-driven Explosions vs. Metallicity and ZAMS mass

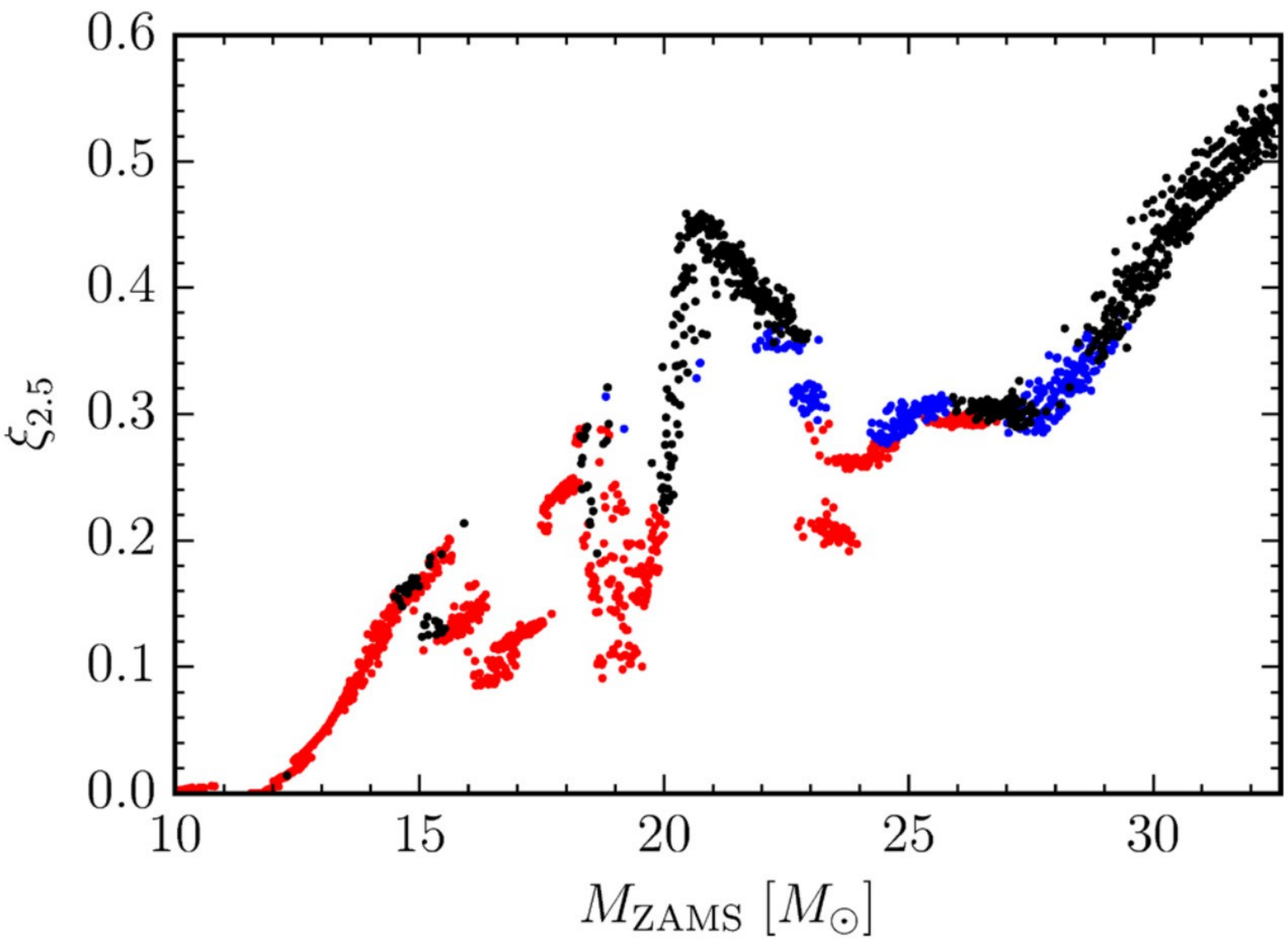


(Ertl, PhD Thesis 2016; Janka, Handbook of Supernovae, arXiv:1702.08825)

Stellar Compactness and Explosion

From semi-analytic theory with free parameters to mimic multi-D effects

(B. Müller et al., MNRAS 460 (2016) 742)



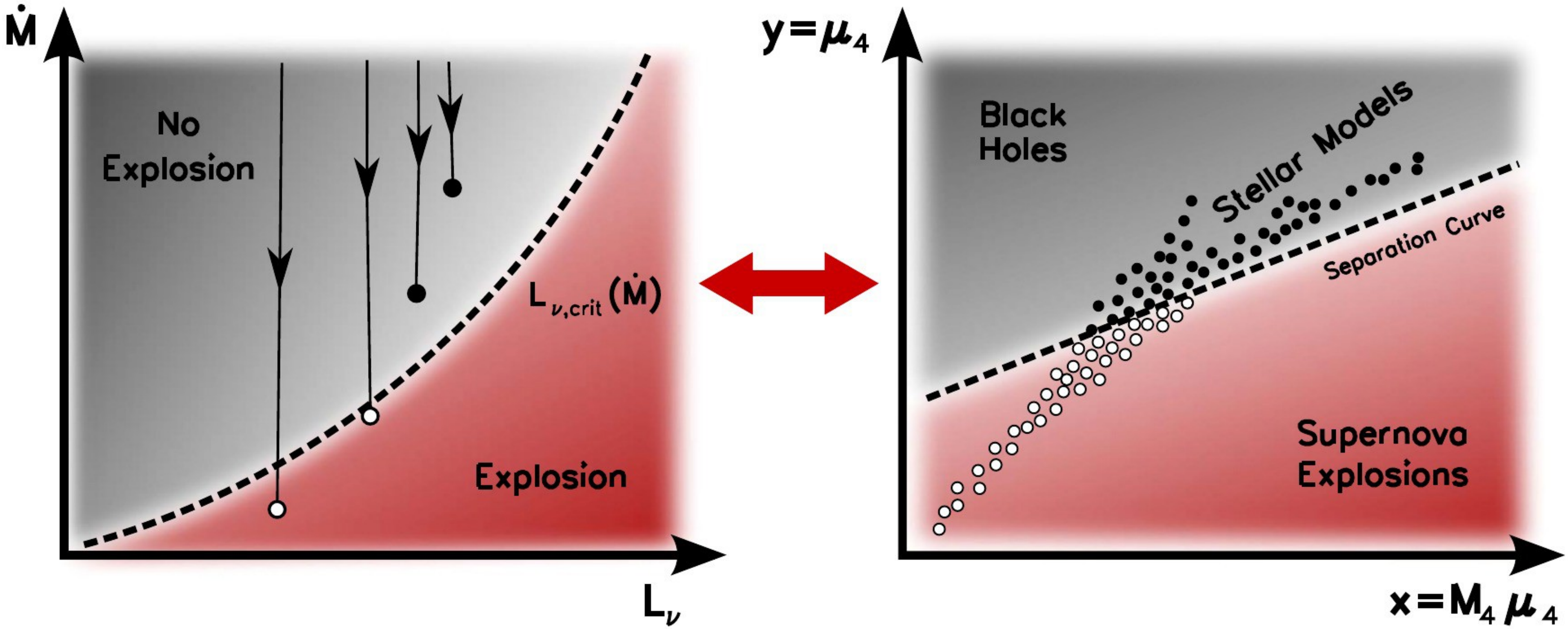
$$\xi_{2.5} \equiv \frac{M/M_\odot}{R(M)/1000\,\mathrm{km}},$$

mass $M = 2.5\ M_\odot$

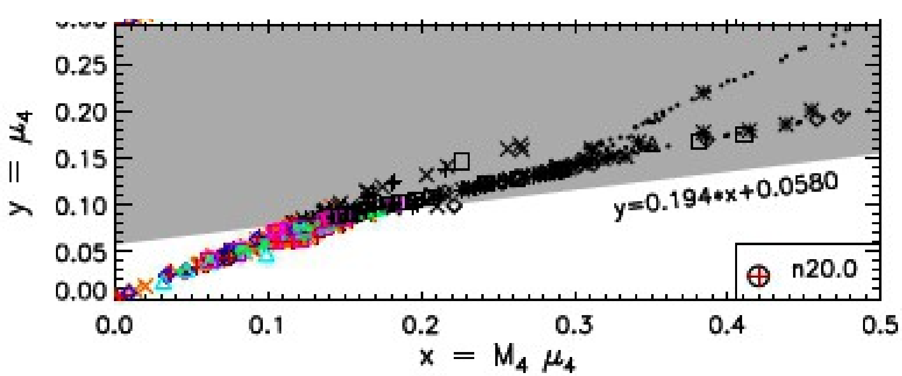
O'Connor & Ott, ApJ 730:70 (2011)

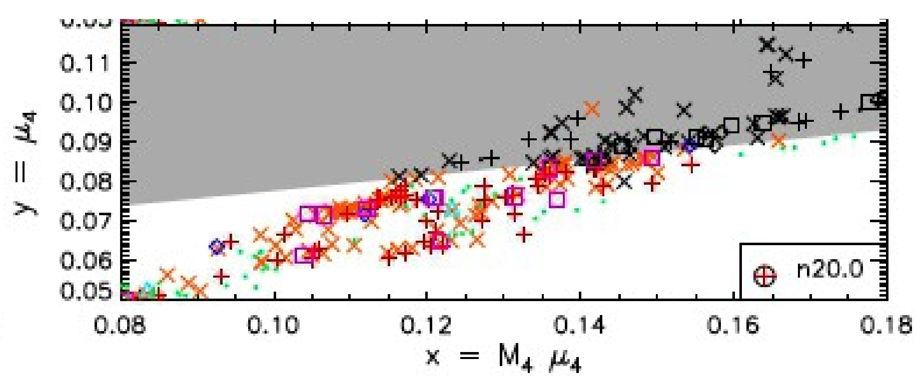
Semi-analytic modeling: depends on >5 parameters and assumes various scaling relations; outcome very sensitive to choice of parameter values.

Theory Insert: Two-Parameter Criterion for Explodability



$$M_4 \equiv m(s=4)/M_\odot \sim M_{NS} \quad ; \qquad \mu_4 \equiv \left.\frac{dm/M_\odot}{dr/1000\ \mathrm{km}}\right|_{s=4} \sim dM_{NS}/dt$$

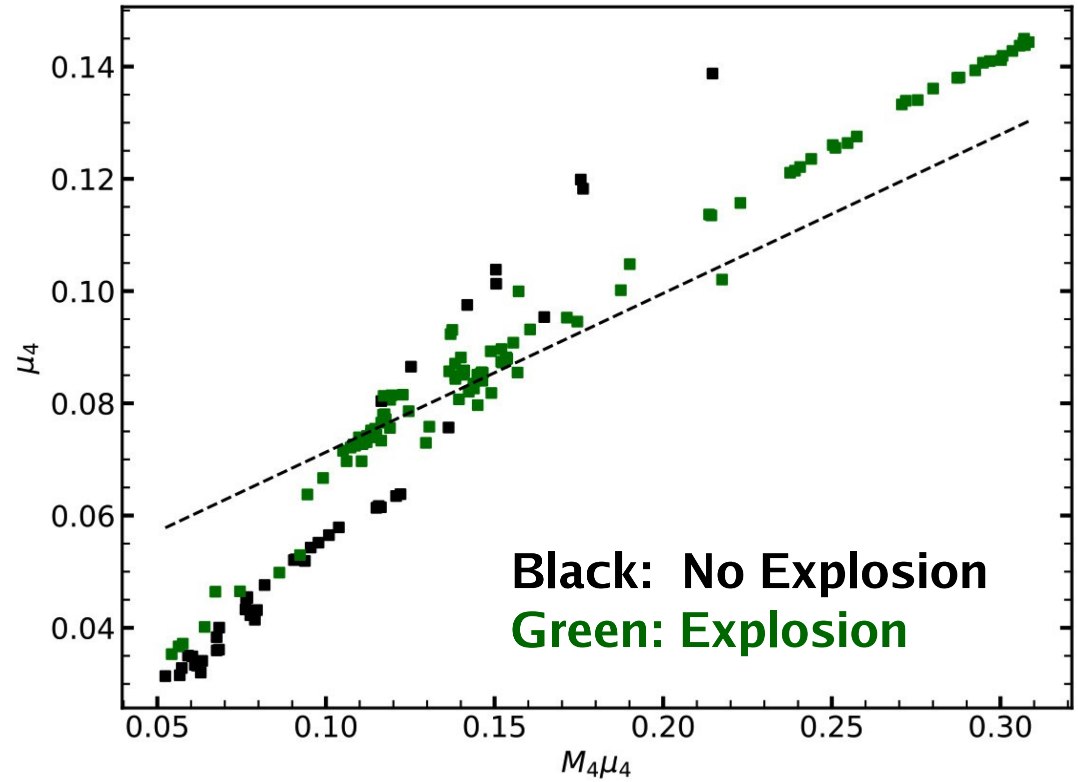


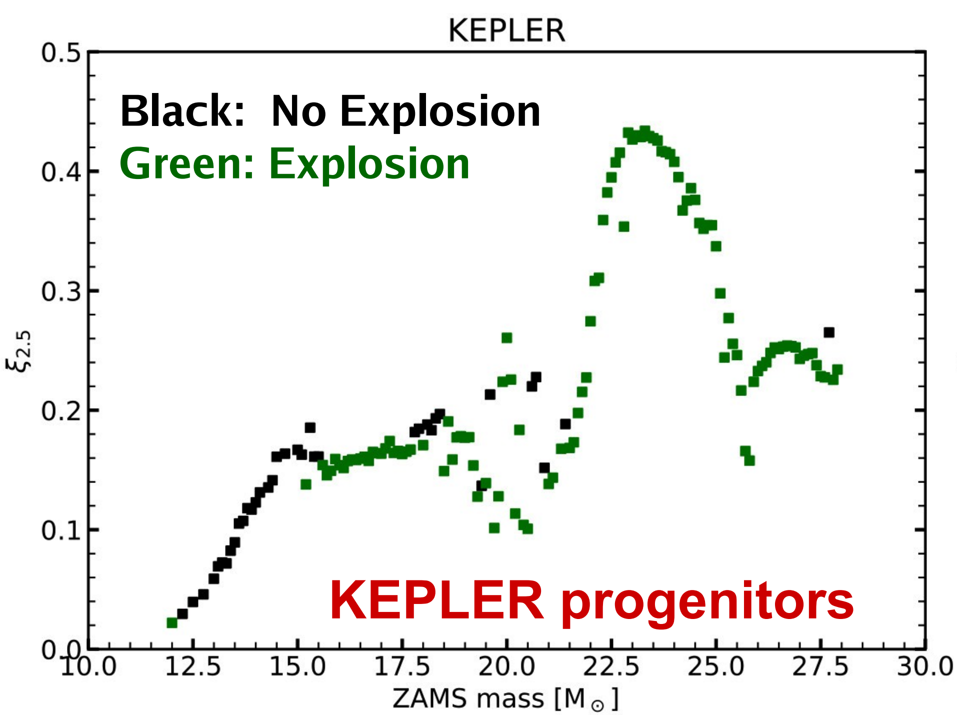


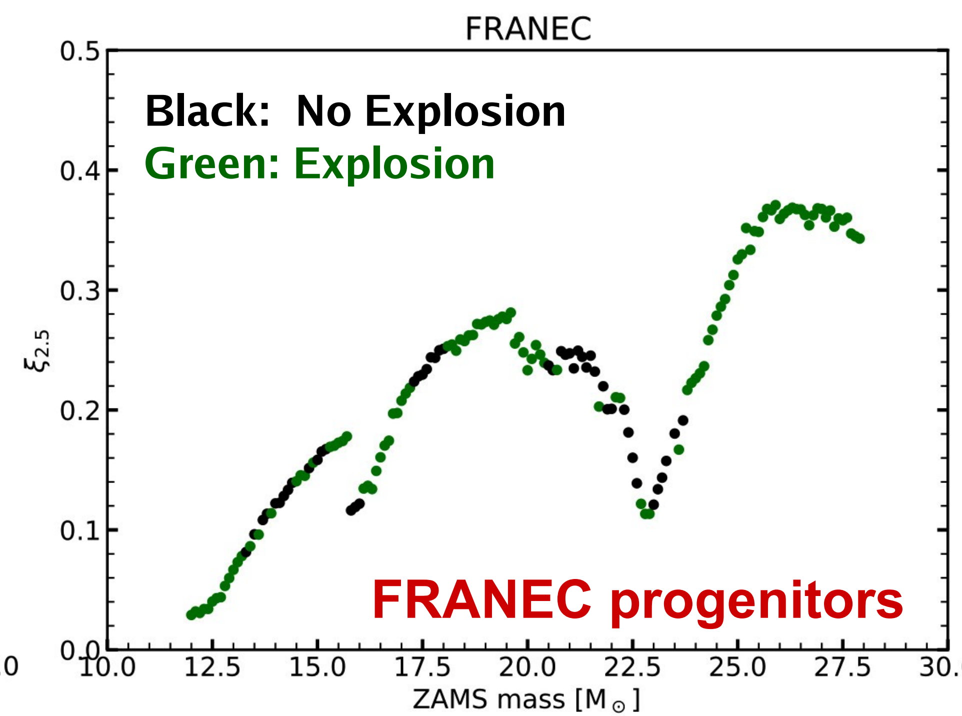
(Ertl, Janka, et al., ApJ 818 (2016) 124)

The Challenge

1D models with mixing-length treatment of postshock "turbulence" are in tension with theory-motivated 1D "neutrino engines" and semi-analytic SN modeling with parametrized multi-D effects.





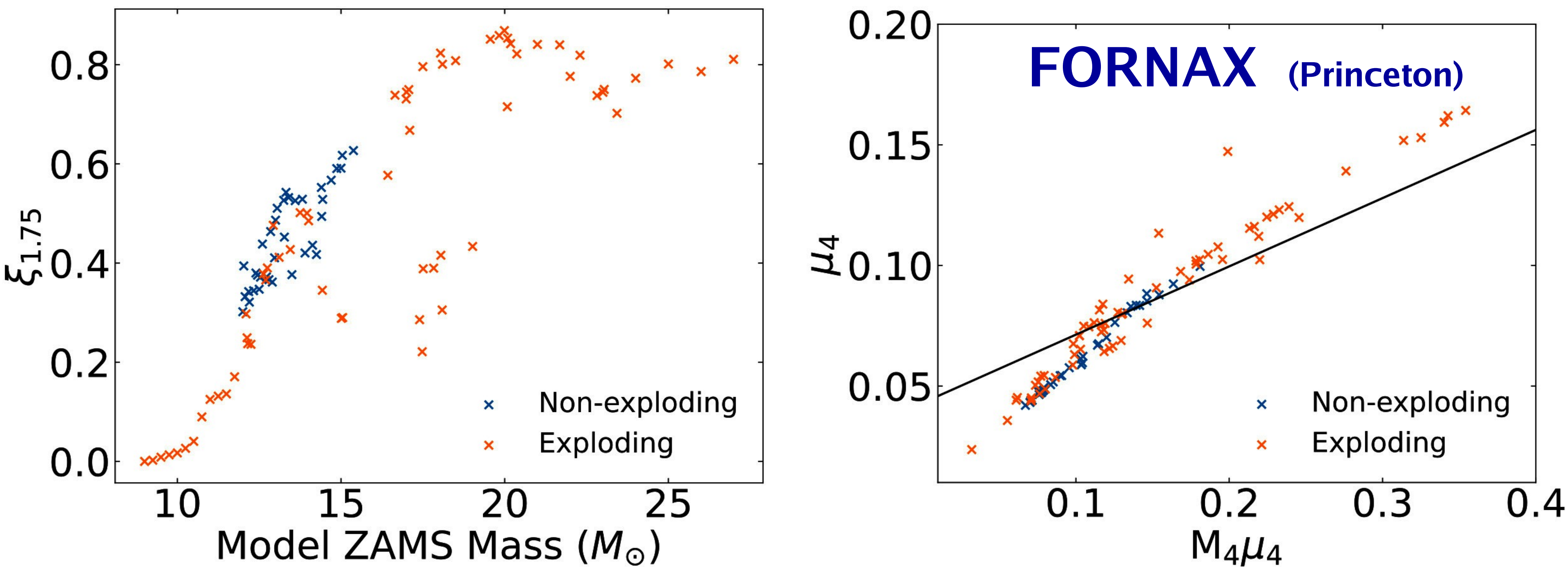


(Boccioli, et al., ApJ 949 (2023) 17)

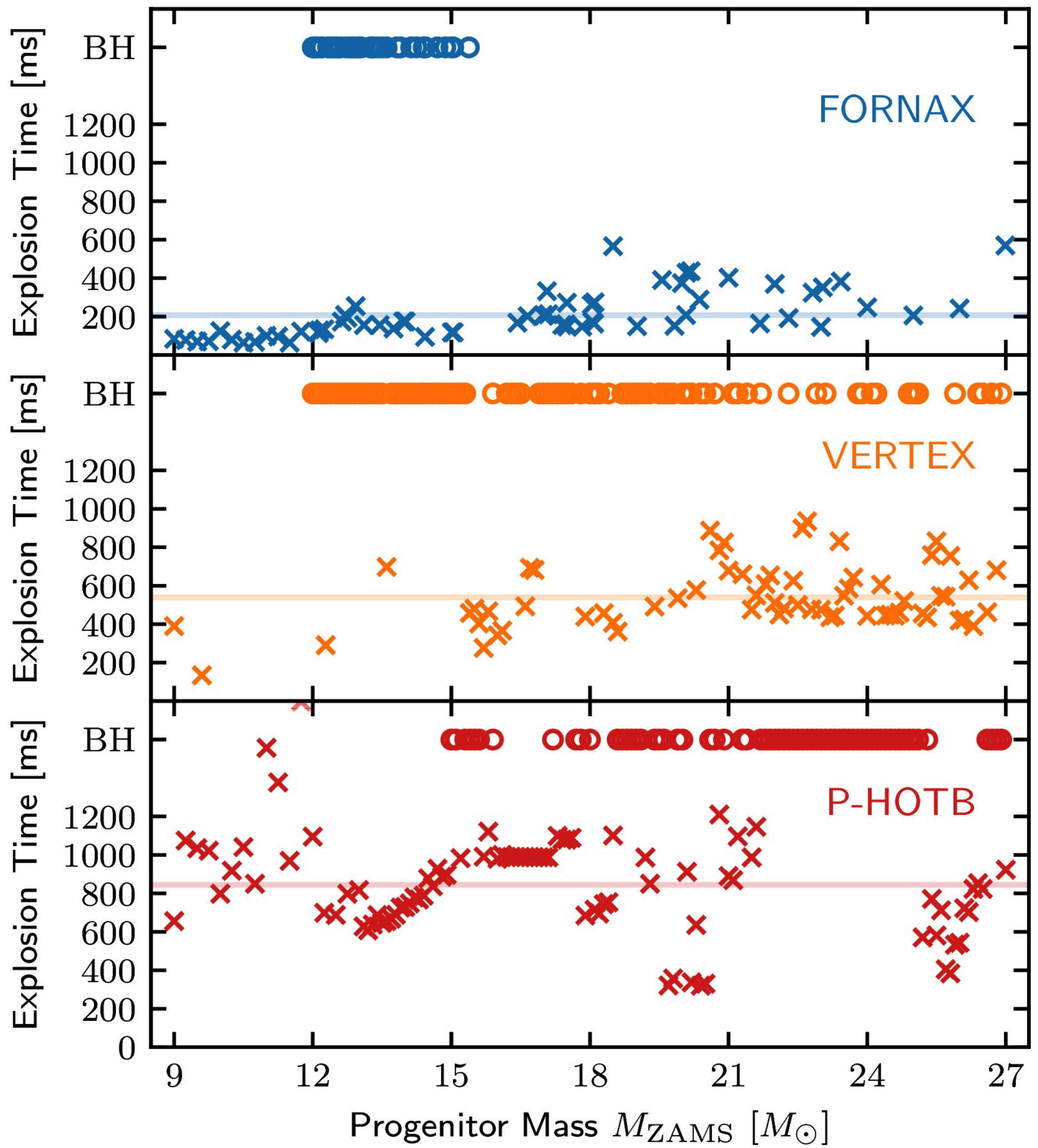
Recent 2D Supernova Simulations

Progenitors from 9.00 to 12 M_{sun} from Woosley & Heger (2015) and Sukhbold et al. (2016);
Progenitors from 12.00 to 26.99 M_{sun} from Sukhbold et al. (2018)

Tsang, Burrows, et al., ApJL 937 (2022) L15

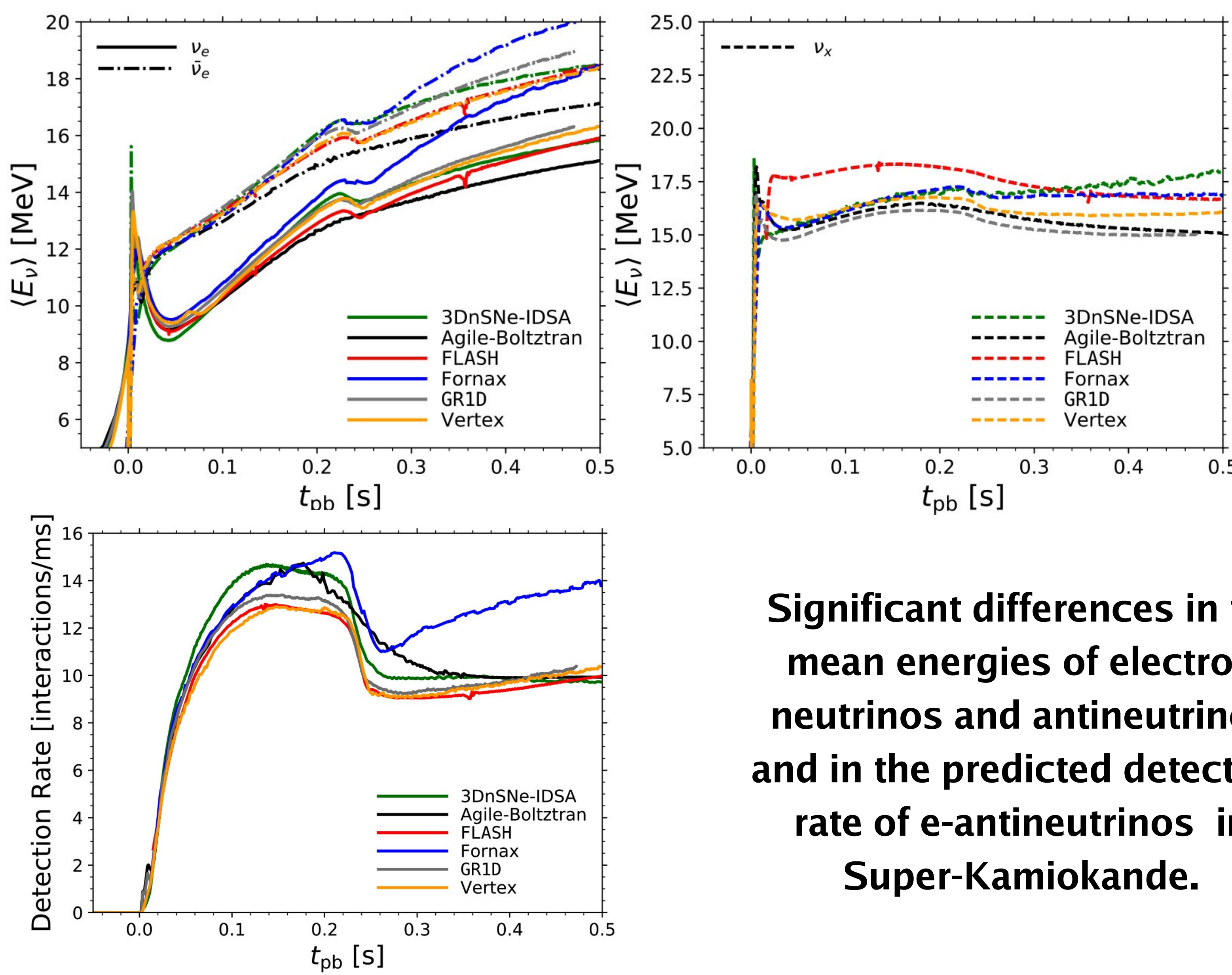


Neutrino-driven Explosions: 1D "Engine" vs. 2D/3D Simulations



Code Comparison in 1D

J. Phys. G: Nucl. Part. Phys. **45** (2018) 104001 E O'Connor *et al*



Significant differences in the mean energies of electron neutrinos and antineutrinos and in the predicted detection rate of e-antineutrinos in Super-Kamiokande.

The Challenge

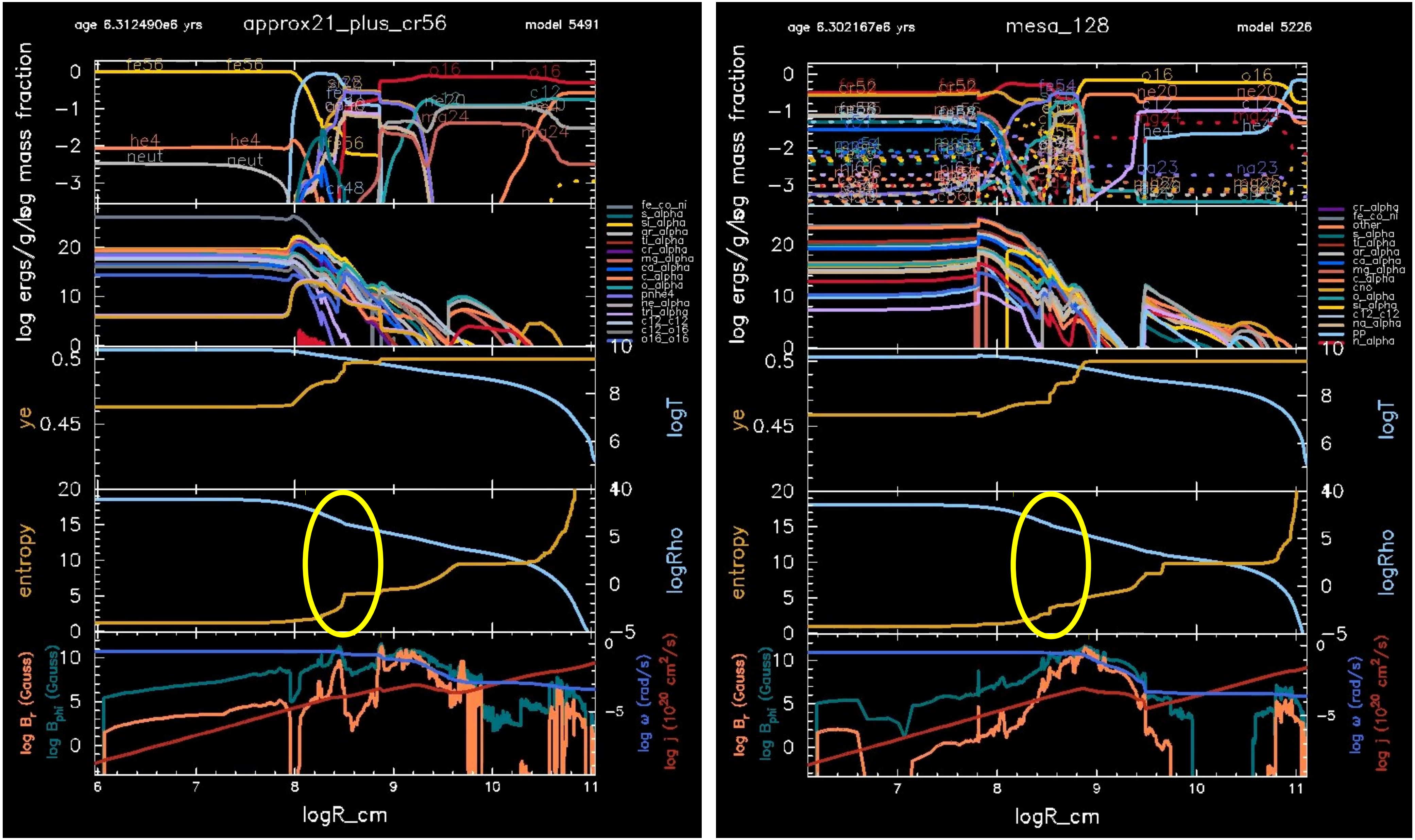
Explodability differences between theory-motivated 1D "neutrino engines", semi-analytic SN modeling incl. parametrized multi-D effects, results from 1D models with mixing-length treatment of postshock "turbulence", and 2D and 3D SN simulations!

<u>However:</u> Also 2D/3D models have (still) severe uncertainties:

- **2D models overpredict explodability due to symmetry axis.**
- **Explodability is interpreted to be connected to the *maximum fractional ram pressure/density/entropy jump* at progenitor composition interfaces.** (Wang+2022, MNRAS 517: 543; Boccioli+2023, ApJ 949: 17)
- **But how realistic is the entropy/entropy jump at s ~ 4 in 1D progenitors?**
- **3D models of different groups do not agree: there are qualitative and quantitative differences!**
- **3D models are no final answers due to missing/uncertain physics!**

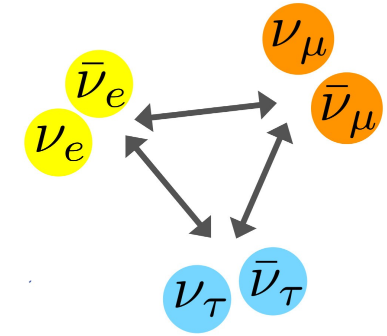
Is the Entropy/Density Jump a Robust Criterion?

Density and entropy profiles smoother with larger nuclear networks in progenitor calculations



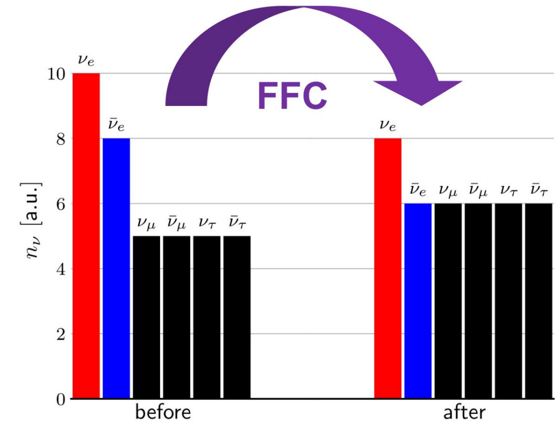
(M. Renzo et al., arXiv:2406.02590 and M. Renzo, private communication)

Fast Neutrino Flavor Conversion (FFC) Affects Explosions

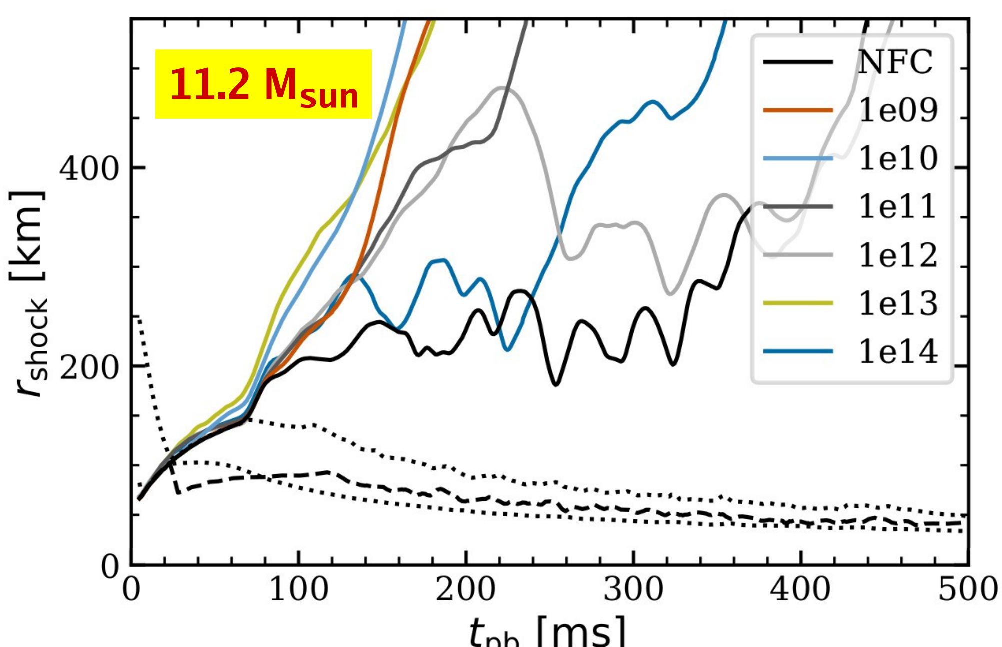


Jakob Ehring
(MPP/MPA), PhD

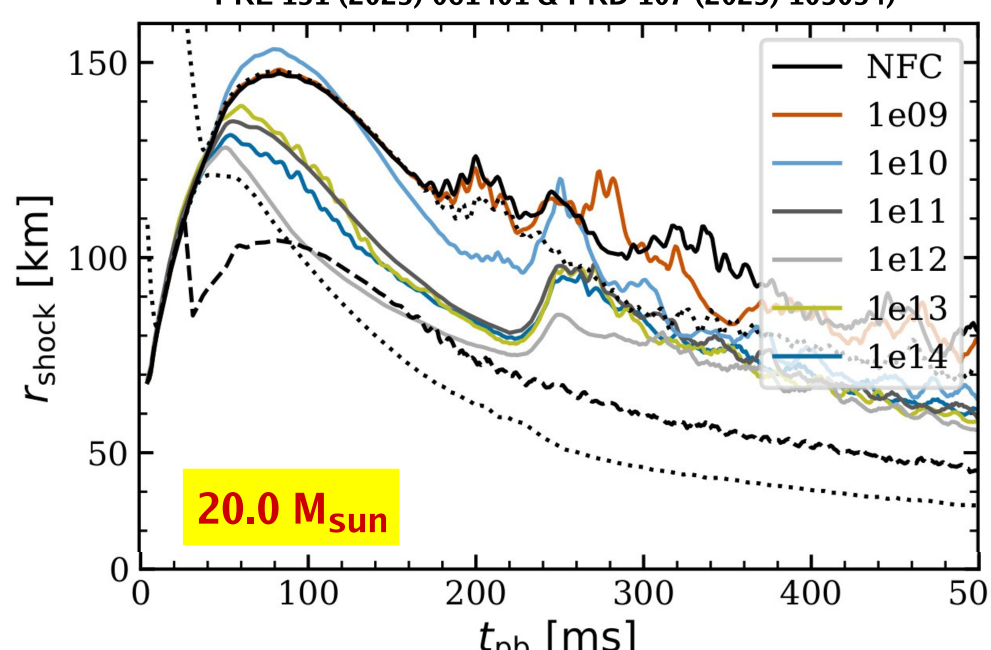
Fast pair-wise conversion $\nu_x \rightarrow \nu_e, \bar{\nu}_e$ can boost the neutrino heating due to higher mean energies
=====> Earlier explosions of low-mass progenitors; but $\nu_e, \bar{\nu}_e \rightarrow \nu_x$ conversion tends to disfavor explosions of high-mass progenitors.



[NFC = no flavor conversion]



(Ehring, Abbar, HTJ, Raffelt, Tamborra,
PRL 131 (2023) 061401 & PRD 107 (2023) 103034)



Onset of Explosion Depends on Nuclear Equation of State

Robert Bollig
(MPA), Ex-Postdoc

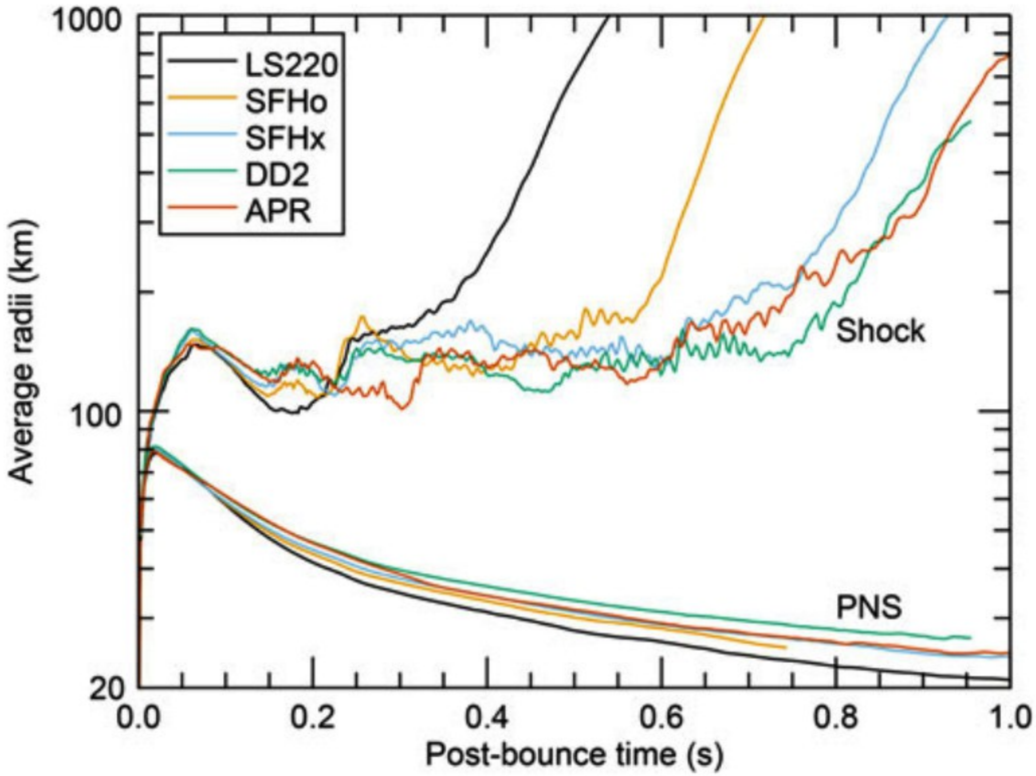
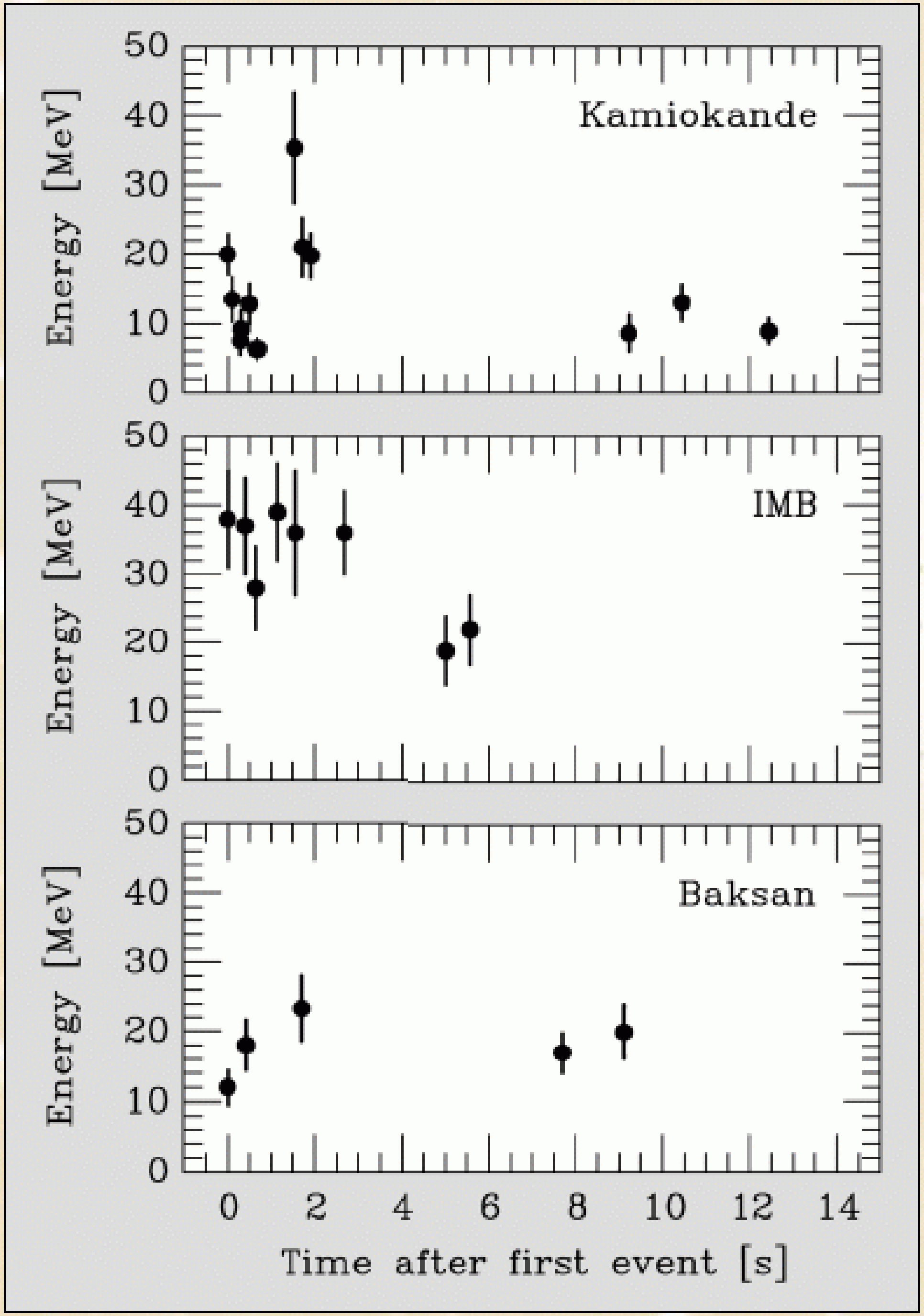


Fig. 11 Shock radii and PNS radii (spherically averaged) in 3D simulations of CCSN explosions of a 19 $M_{\odot}$ progenitor for different nuclear EoSs widely used in SN simulations: LS220 of Lattimer and Swesty (1991), SFHo, SFHx of Steiner et al. (2013) and Hempel and Schaffner-Bielich (2010), DD2 of Typel et al. (2010) and Hempel et al. (2012), and APR of Schneider et al. (2019a). In all cases, successful explosions were obtained in 3D core-collapse simulations started from 3D progenitor conditions (Yadav et al. 2020; Bollig et al. 2021), but there is a clear correlation between the onset of the explosion and the contraction of the PNS. The faster the PNS contracts, the earlier the explosion sets in. This signals the dominant relevance of the PNS radius evolution over other EoS dependent effects. (Figure courtesy of Robert Bollig)

HTJ & Bauswein, Handbook of Nuclear Physics (Springer-Nature, 2023); Figure coutesy of Robert Bollig

Neutrino Burst of Supernova 1987A



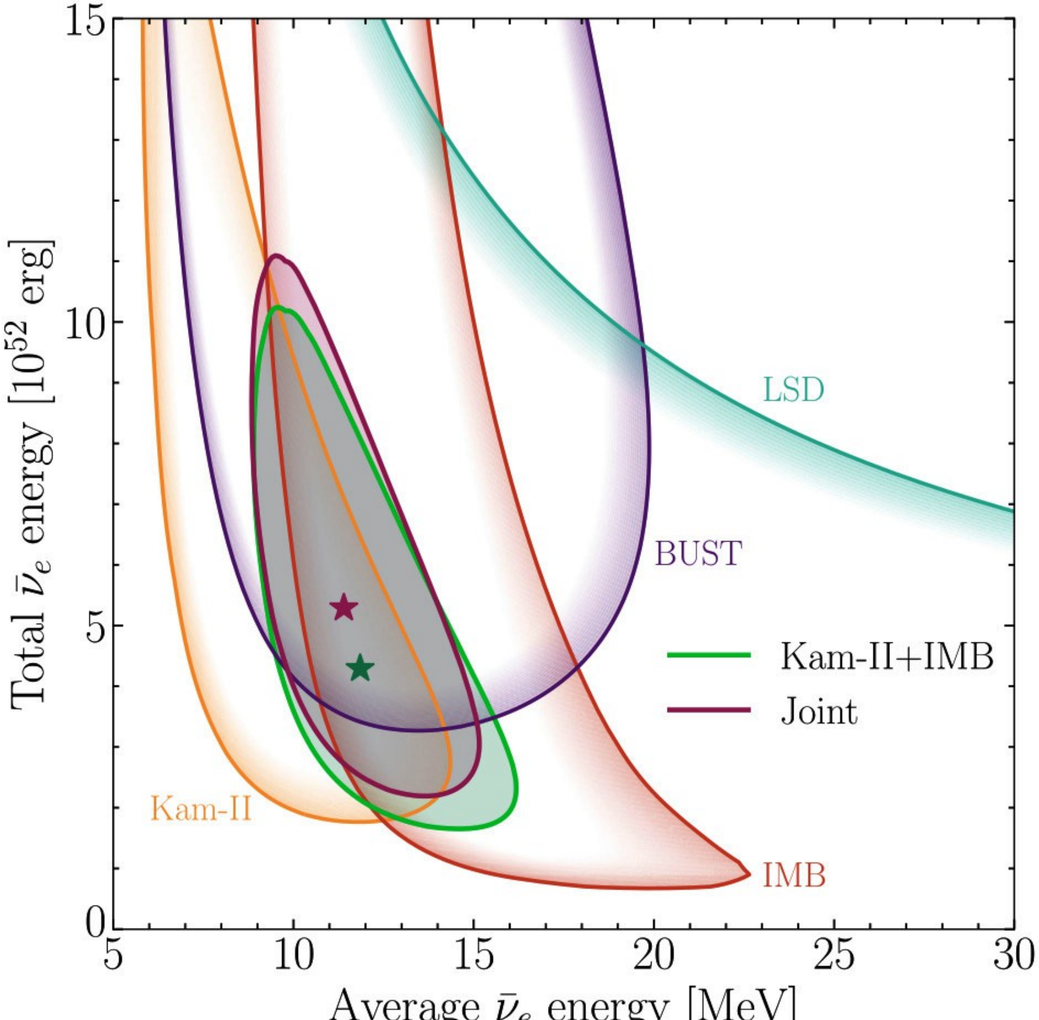
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

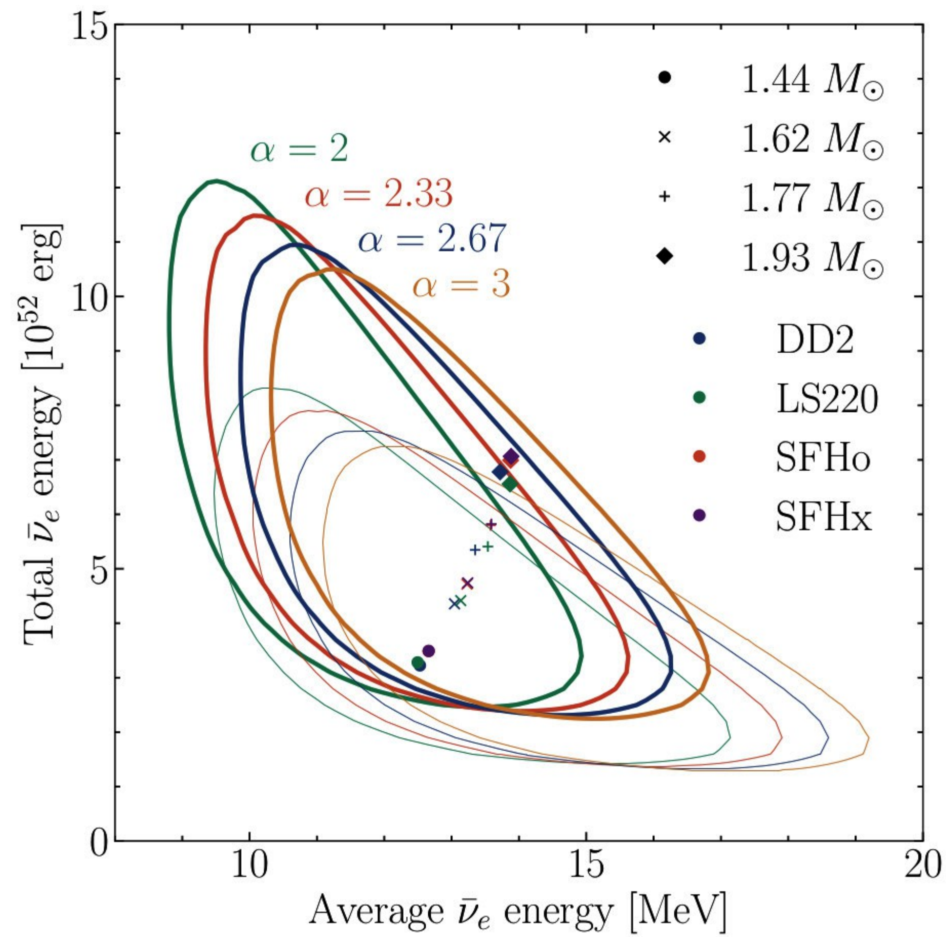
Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

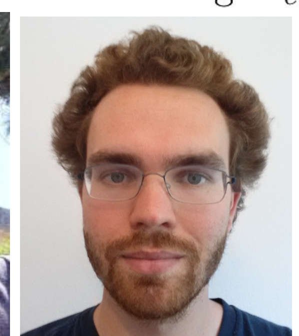
Within clock uncertainties, signals are contemporaneous

State-of-the-art Proto-NS Cooling Models vs. SN1987A Neutrinos





Damiano Fiorillo (DESY), Postdoc

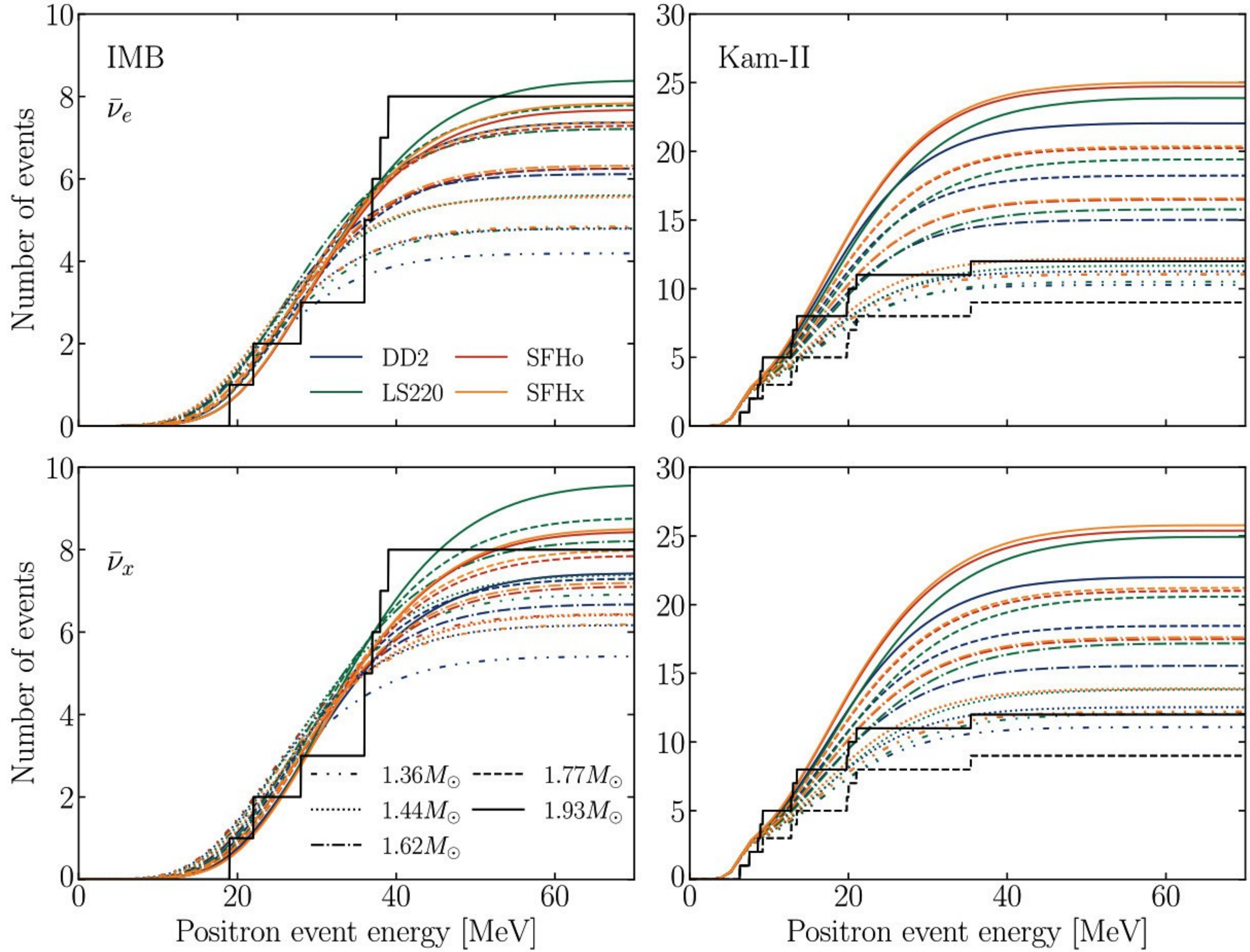


Malte Heinlein (MPA), PhD

(M. Heinlein, Master Thesis, TUM 2022; Fiorillo, Heinlein, et al., PRD 108 (2023) 083040)

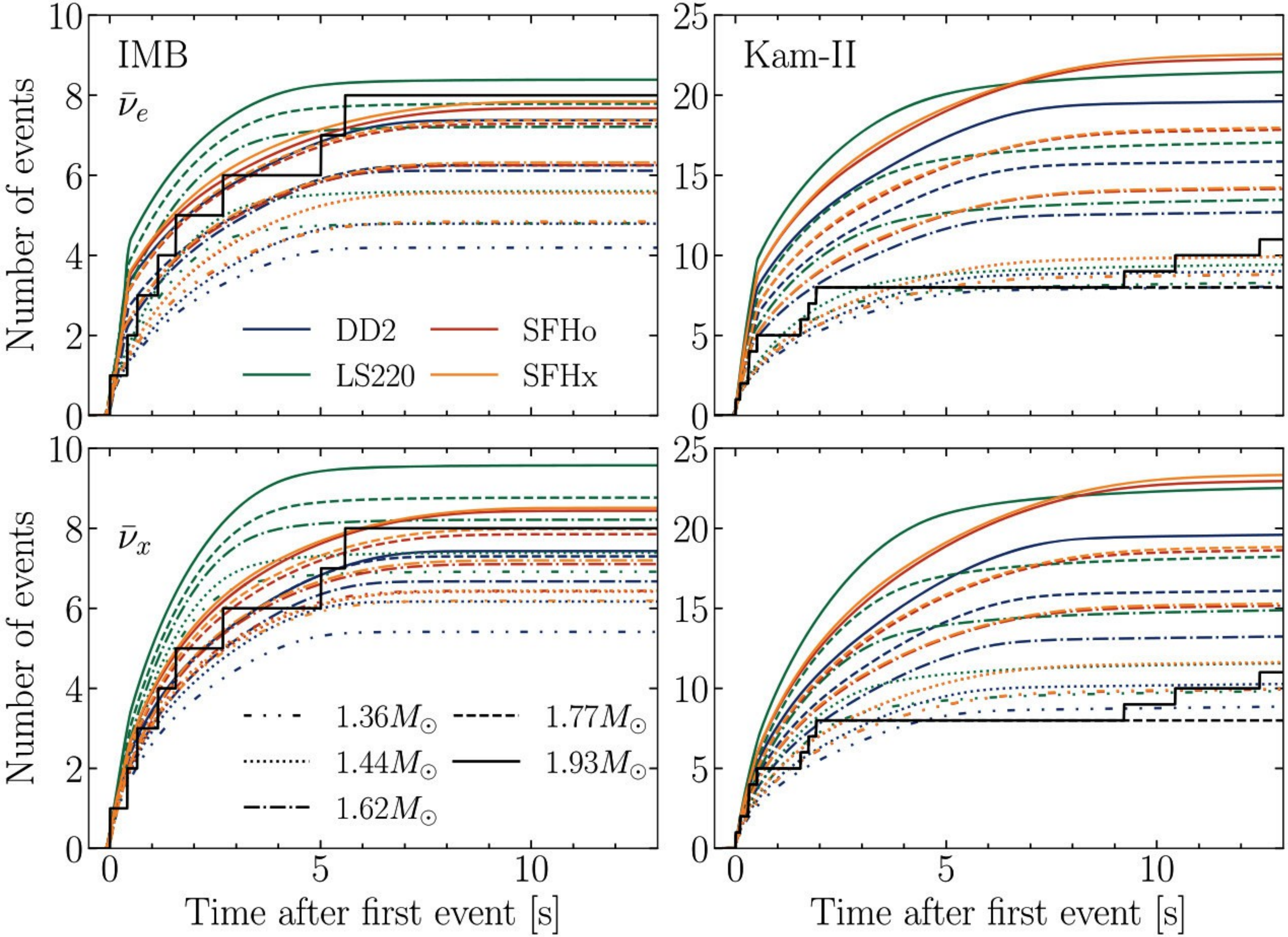
State-of-the-art Proto-NS Cooling Models Versus SN1987A Neutrinos

(M. Heinlein, Master Thesis, TUM 2022; Fiorillo, Heinlein, et al., PRD 108 (2023) 083040)

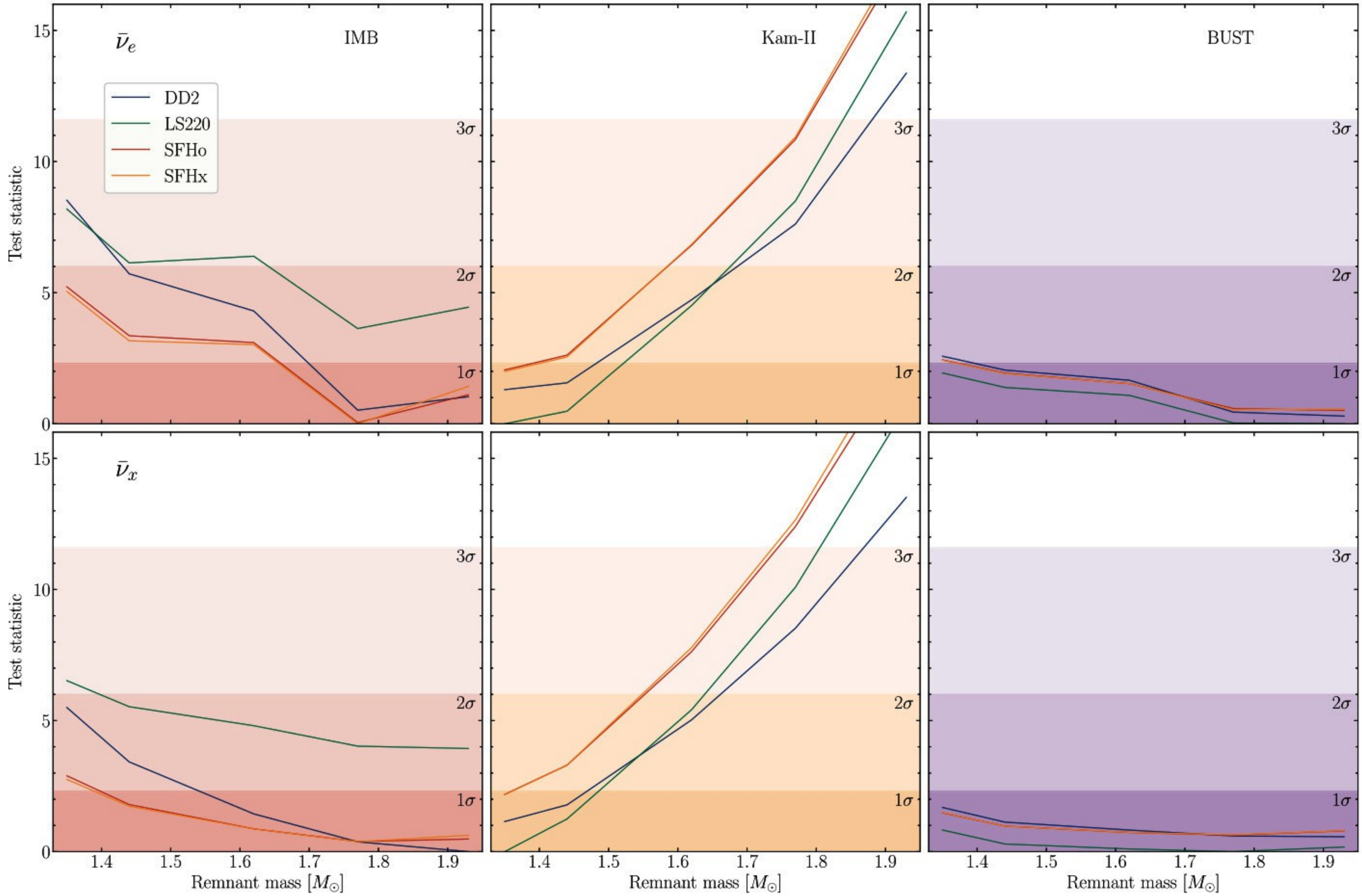


State-of-the-art Proto-NS Cooling Models Versus SN1987A Neutrinos

(M. Heinlein, Master Thesis, TUM 2022; Fiorillo, Heinlein, et al., PRD 108 (2023) 083040)



State-of-the-art Proto-NS Cooling Models Versus SN1987A Neutrinos



State-of-the-art Proto-NS Cooling Models Versus SN1987A Neutrinos

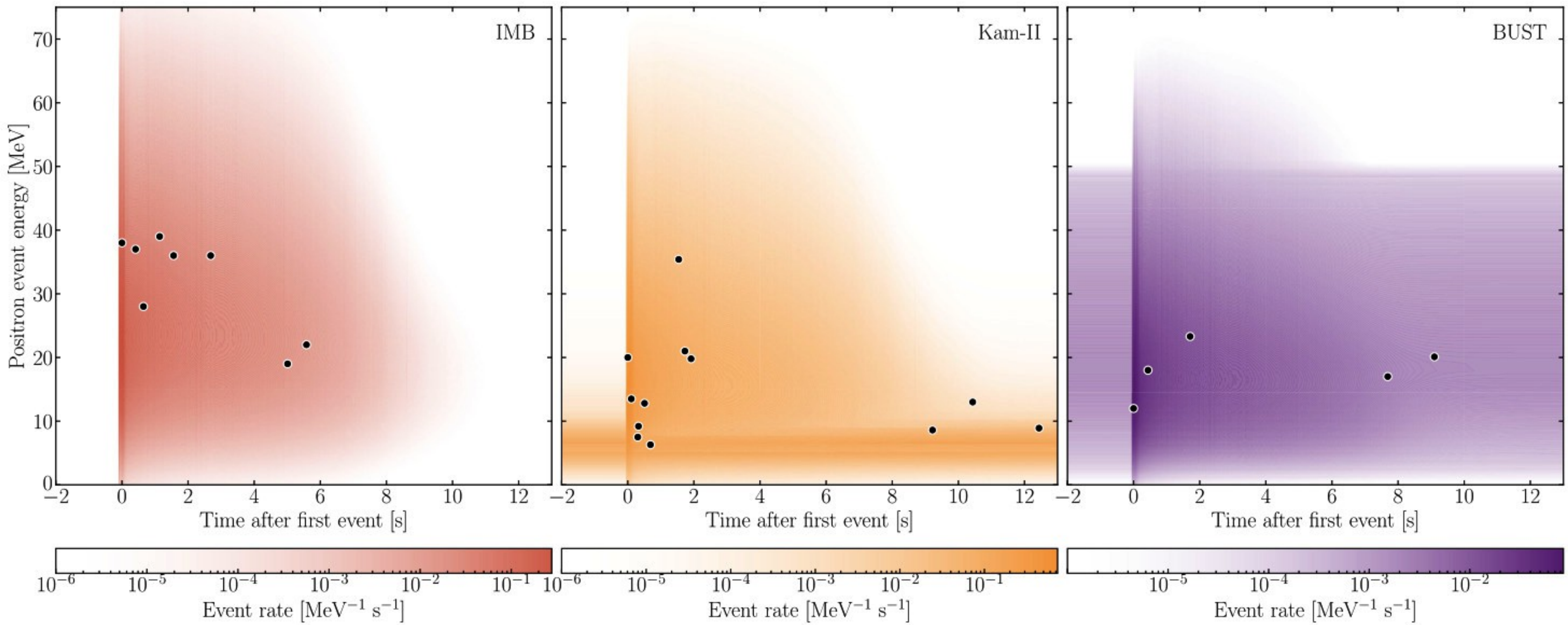


FIG. 17. Differential event distribution (signal and background) at each experiment, compared with the observations. Results are shown for model 1.44-SFHo without flavor swap; the offset time for each experiment is chosen as the best-fit value reported in Table VII.

(M. Heinlein, Master Thesis, TUM 2022;
Fiorillo, Heinlein, et al., PRD 108 (2023) 083040)

Summary: Neutrino-driven SNe

Result that can be taken with confidence within known physics:

- Explosions are powered by neutrino energy deposition.
- Neutrino-driven explosions can explain many properties of observed supernovae and supernova remnants.

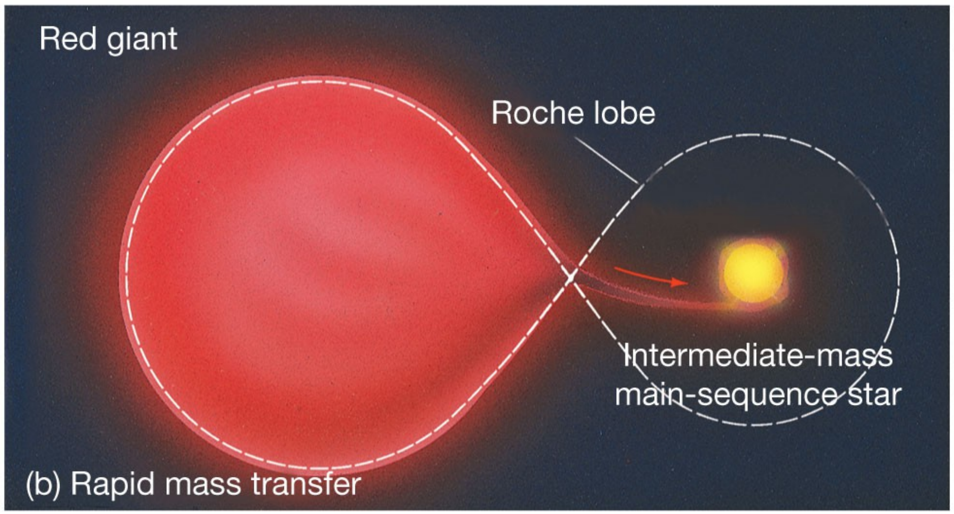
Many open issues and unsolved questions, e.g.:

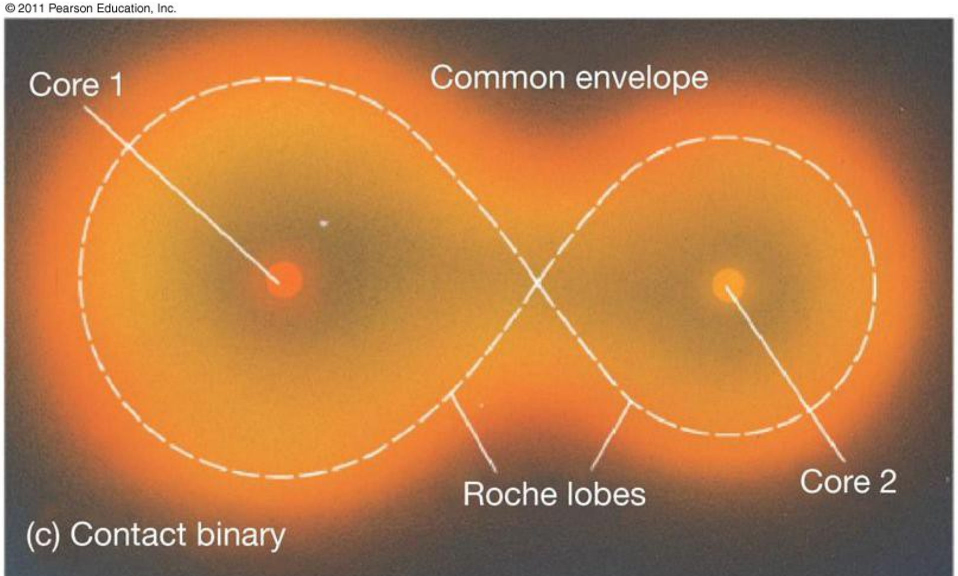
- CCSN results from different groups differ significantly.
- "Explodability" systematics of massive stars is uncertain.
- Microphysics needs to be settled: Fast neutrino flavor conversion, equation of state of nuclear matter?
- Progenitor models are 1D (not 3D) and code-dependent.

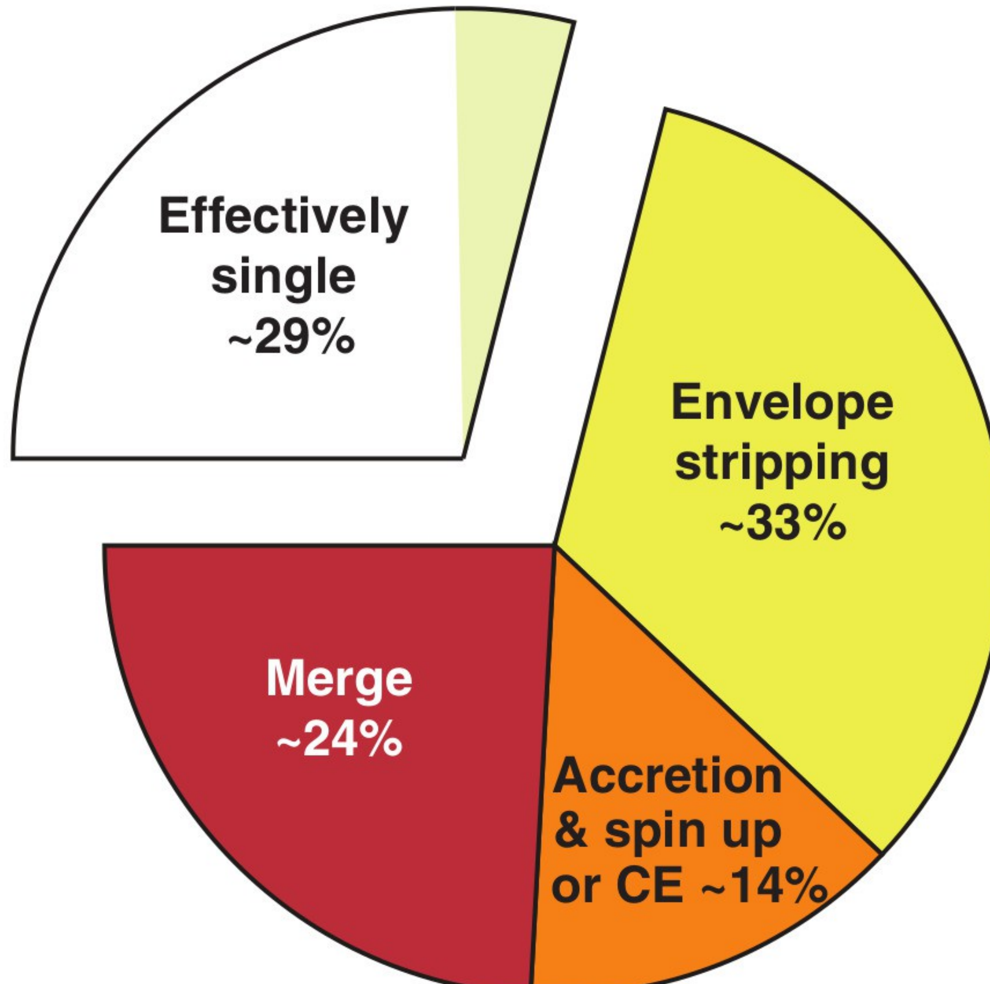
Neutrino signals from supernovae as messengers:

- SN 1987A neutrinos: Modern models raise new questions!
- DSNB neutrinos: Measurement is around the corner!

Binary Evolution of Progenitors of Core-Collapse Supernovae

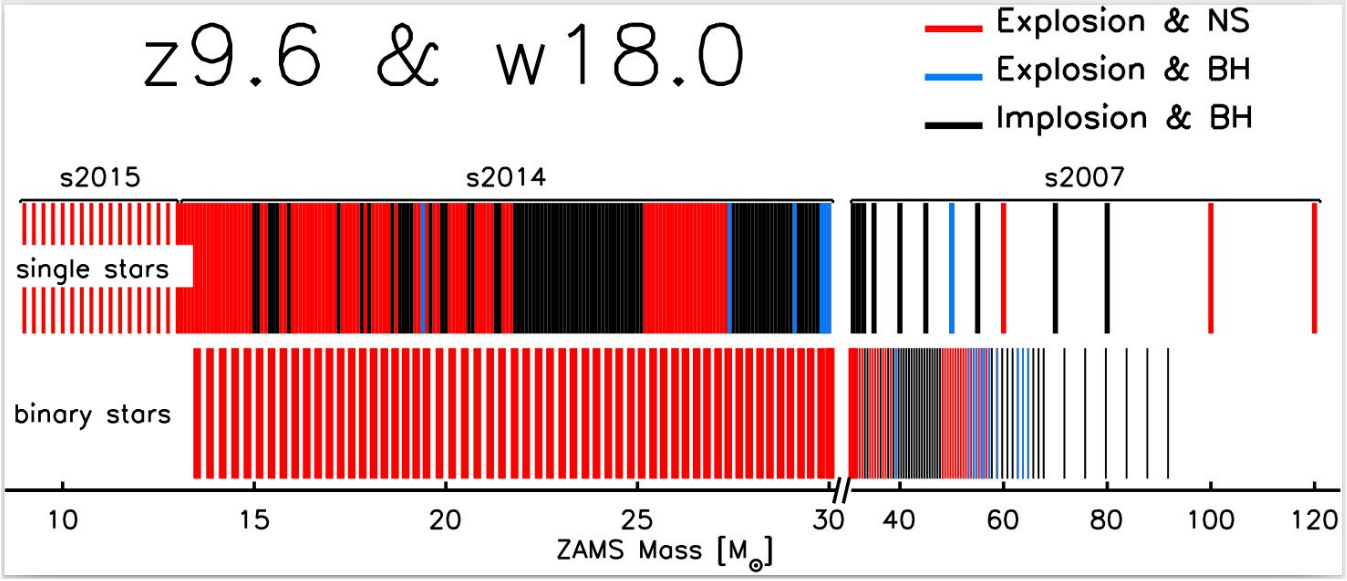






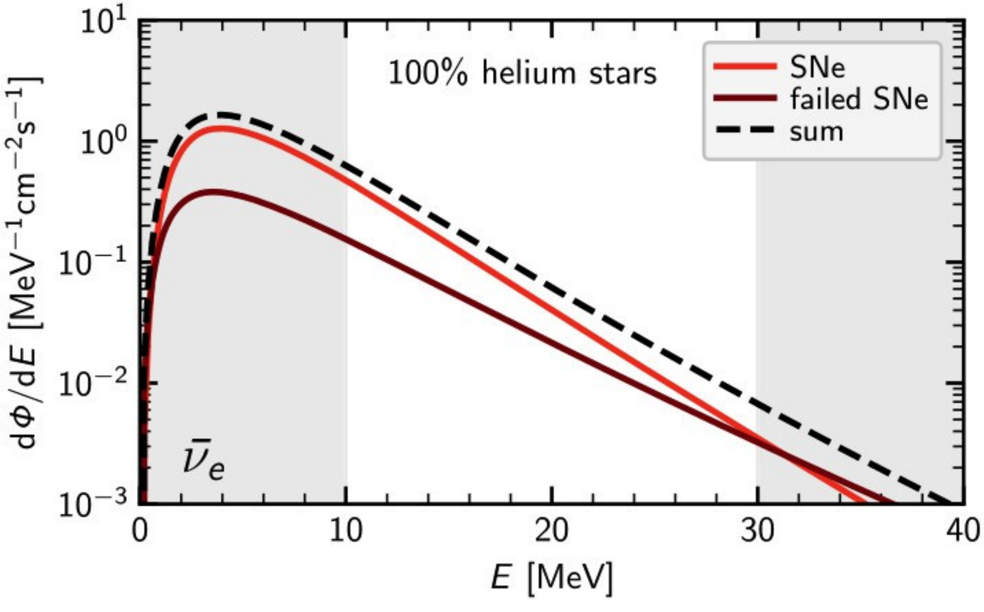
Sana, de Mink, de Koter, et al., Science 337.6093 (2012) 444

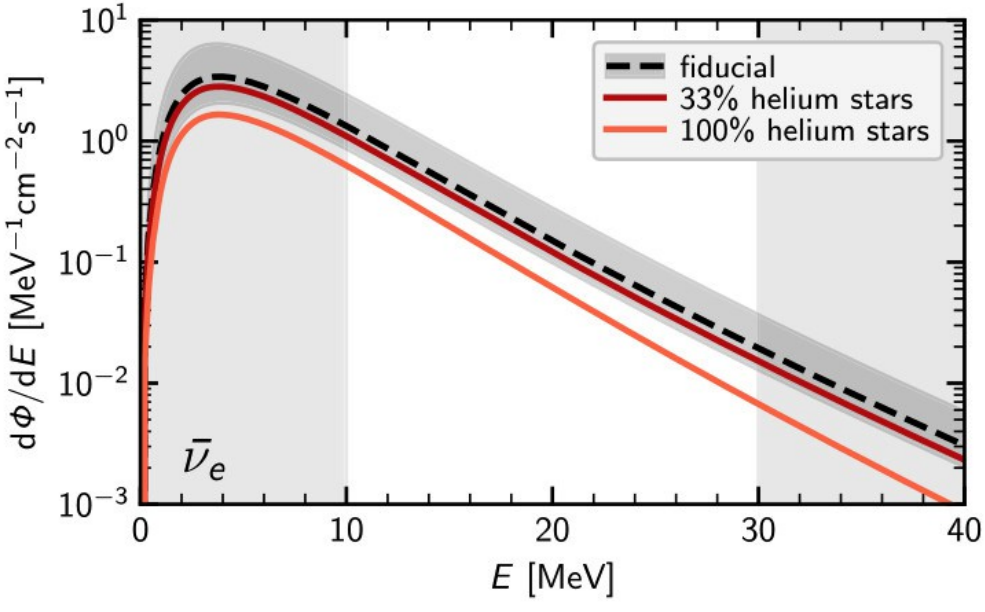
DSNB Spectrum Including Stripped Binary Progenitors of CC Supernovae



(Ertl et al., ApJ 890 (2020) 51)

(Kresse, Ertl, & THJ, ApJ 909 (2021) 169)

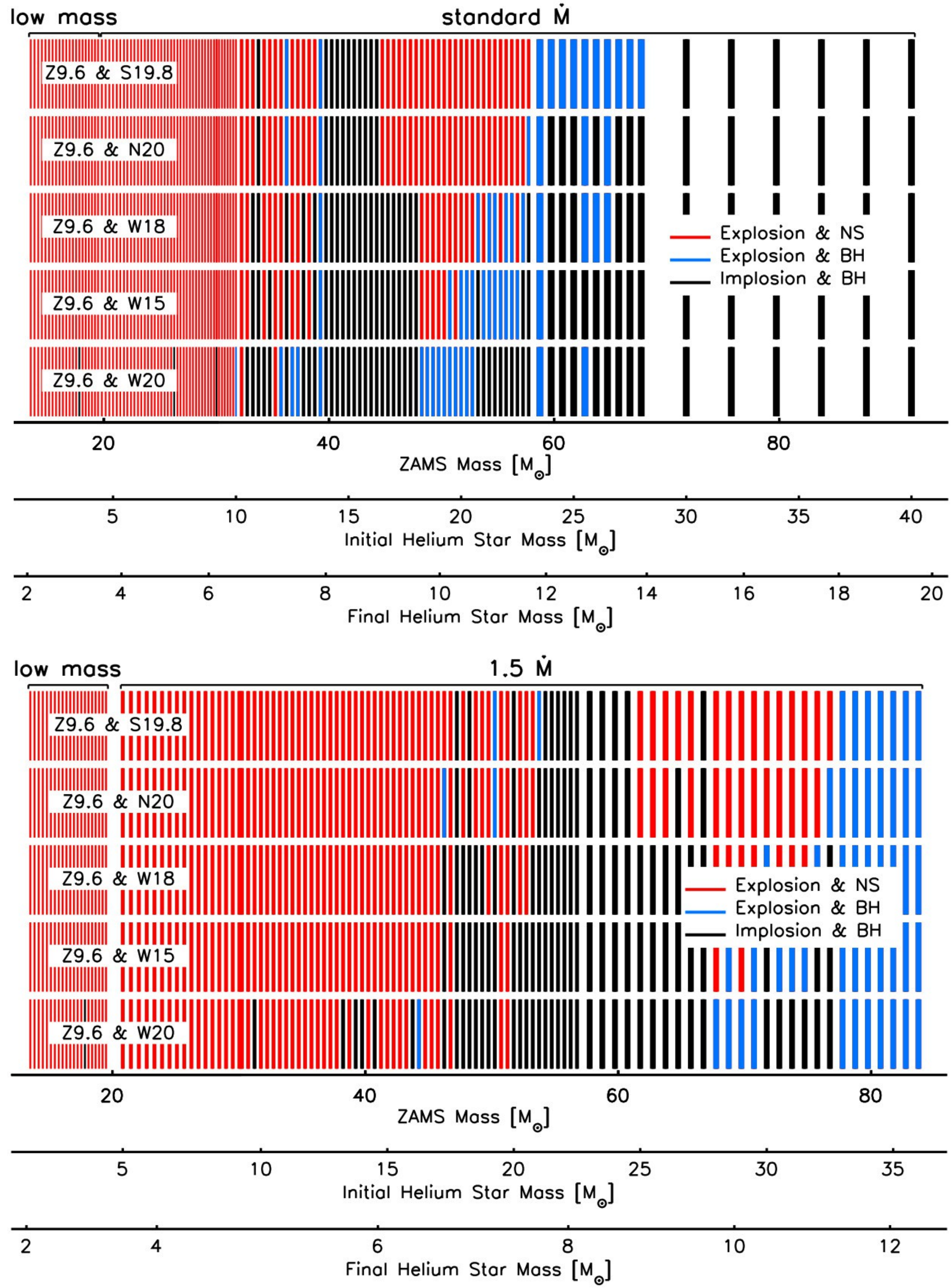




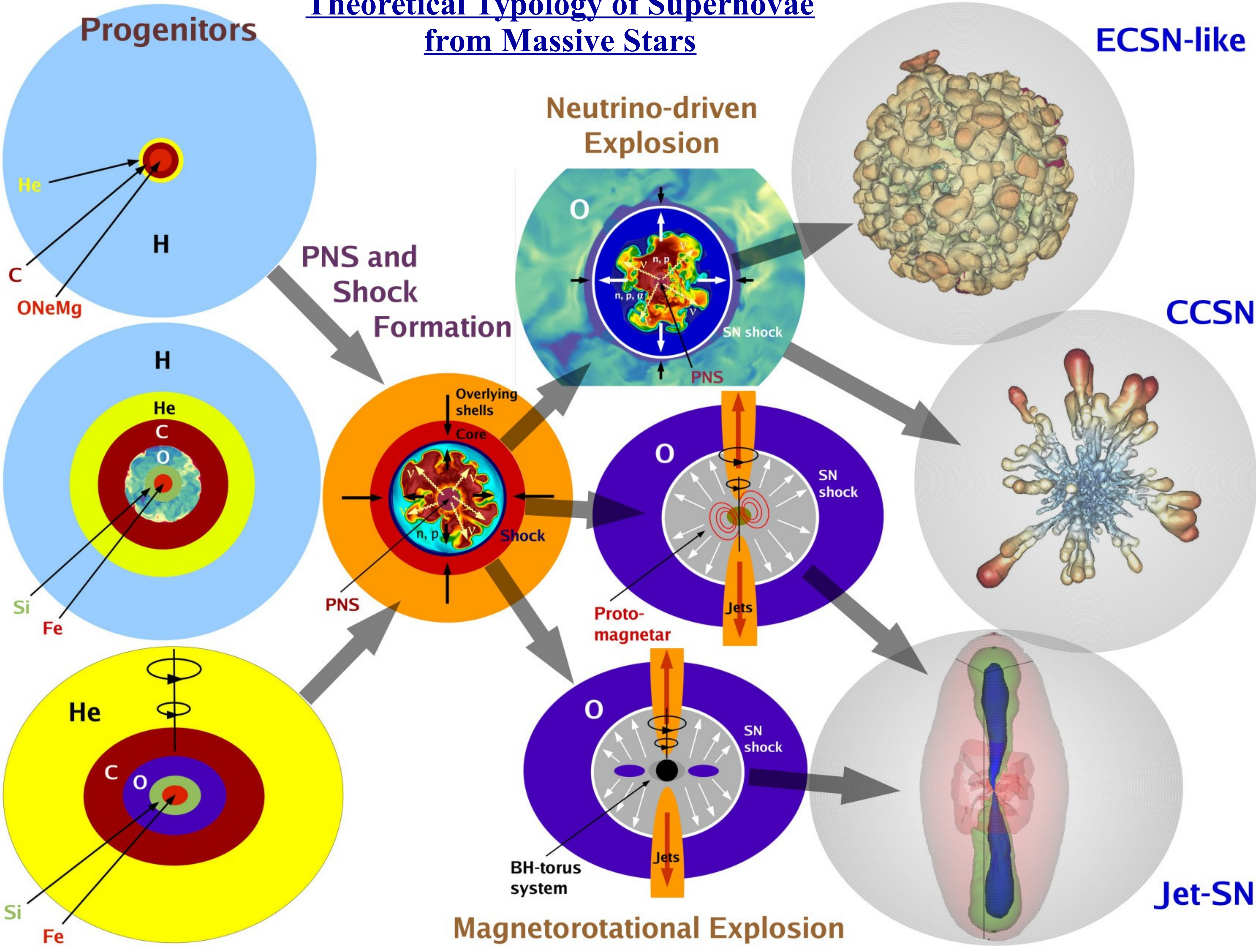
Binary Effects

- Stripped stars (He-stars) lead to a shift of BH formation to higher ZAMS masses because of smaller CO-core masses of progenitors.
- CO-core mass also depends on uncertain mass-loss rate of evolving He-star progenitors.
- Strength of neutrino "engine" also determines "explodability."

- Binary mergers that lead to more massive CO-cores can shift BH formation to lower ZAMS masses.
- But not all accretion and merger cases affect CO-core (e.g., not in exploding BSGs as, e.g., SN 1987A, and SNe IIb as, e.g., Cas A).

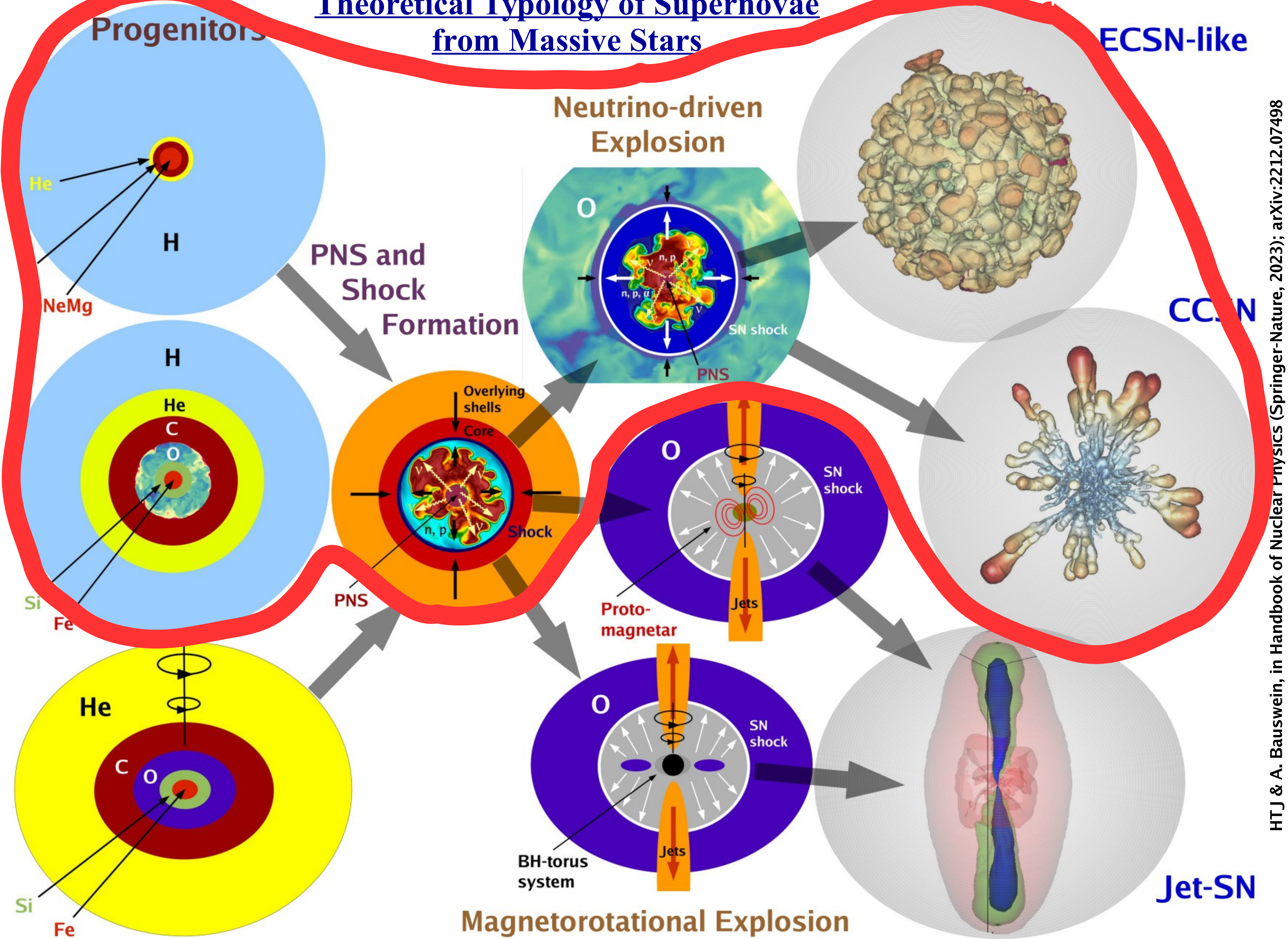


Theoretical Typology of Supernovae from Massive Stars

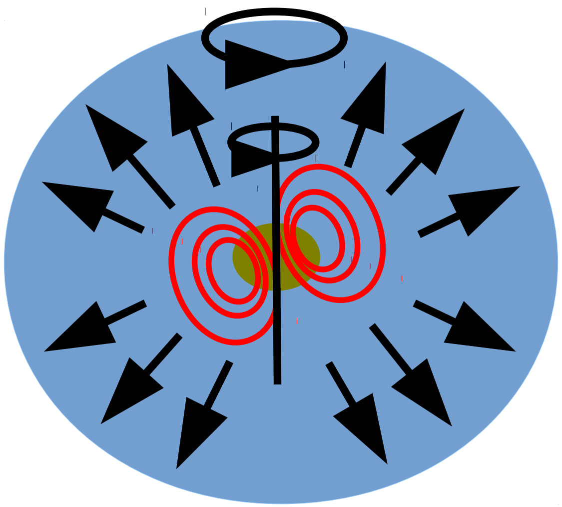


HTJ & A. Bauswein, in Handbook of Nuclear Physics (Springer-Nature, 2023); arXiv:2212.07498

Theoretical Typology of Supernovae from Massive Stars

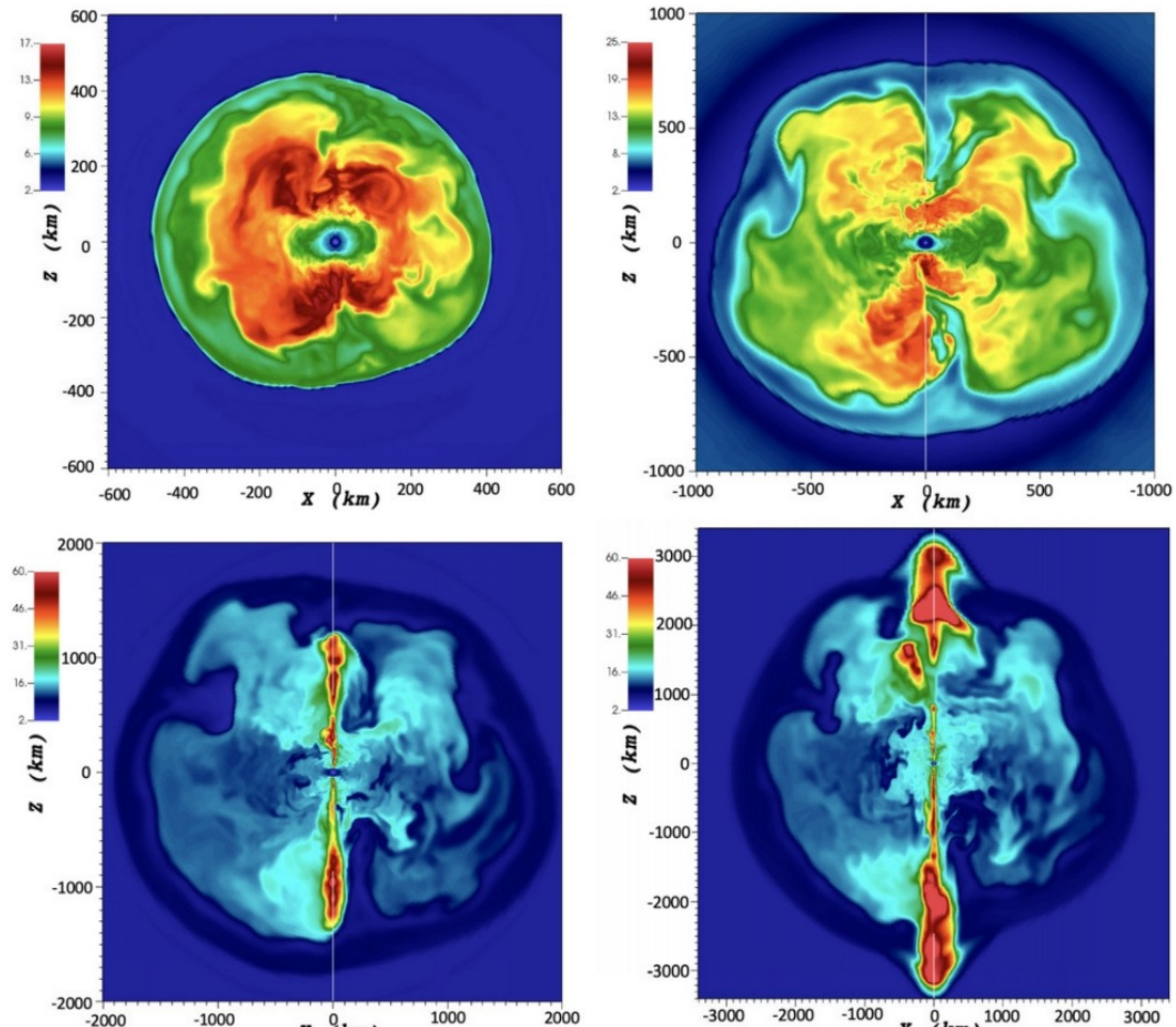


Magnetar (+ Neutrino) "Engines"



SNe with magnetar "engine" require rapid rotation of stellar core at collapse.
<u>That's likely to be rare!</u>

Therefore hypernovae, broad-lined SNe Ib/c, GRB-SNe, and superluminal SNe make less that 1% (probably < 0.1%) of all SNe at z<~2



Powell & Müller, MNRAS (2023)

Take-away Message

Progress in SN modeling and DSNB predictions will be tightly correlated with advancing our understanding of the evolution of single stars and binary/multiple stellar systems