

IJC Colloquium 2026
IJCLab, Orsay, France, September 25, 2026

Supernova Explosions of Massive Stars

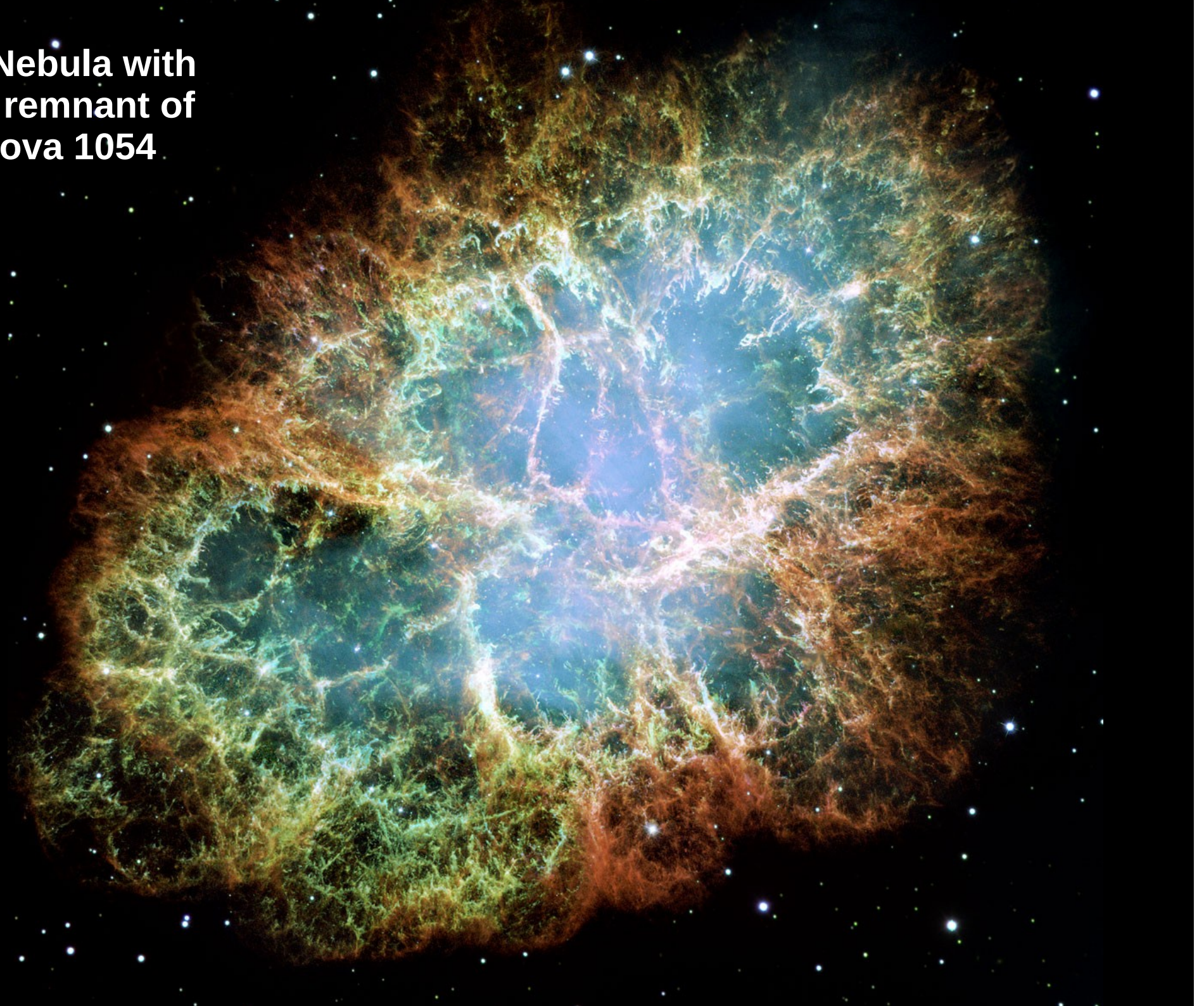
Connecting Models and Observations in Three Dimensions

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

Relevance, Questions & Challenges

- End stages of massive stars: Brightest explosions in the Universe; tracers of star formation; cosmic distance scale
- Core-collapse SN explosion mechanism(s) is interesting physics
- SN explosion properties; explosion asymmetries, mixing, gaseous remnant properties
- NS/BH formation paths and probabilities (binary GW sources!)
- NS/BH birth properties: masses, kicks, spins, magnetic fields
- Neutrino and gravitational-wave signals
- Neutrino flavor oscillations, sterile neutrinos, impact of Beyond Standard Model (BSM) particle physics
- Heavy-element formation: Main sources and distributors of elements with $Z > 2$; what are the sites of the r-process(es)?
- What is the equation of state (EOS) of ultra-dense matter?

**CRAB Nebula with
pulsar, remnant of
Supernova 1054**



NIRCam

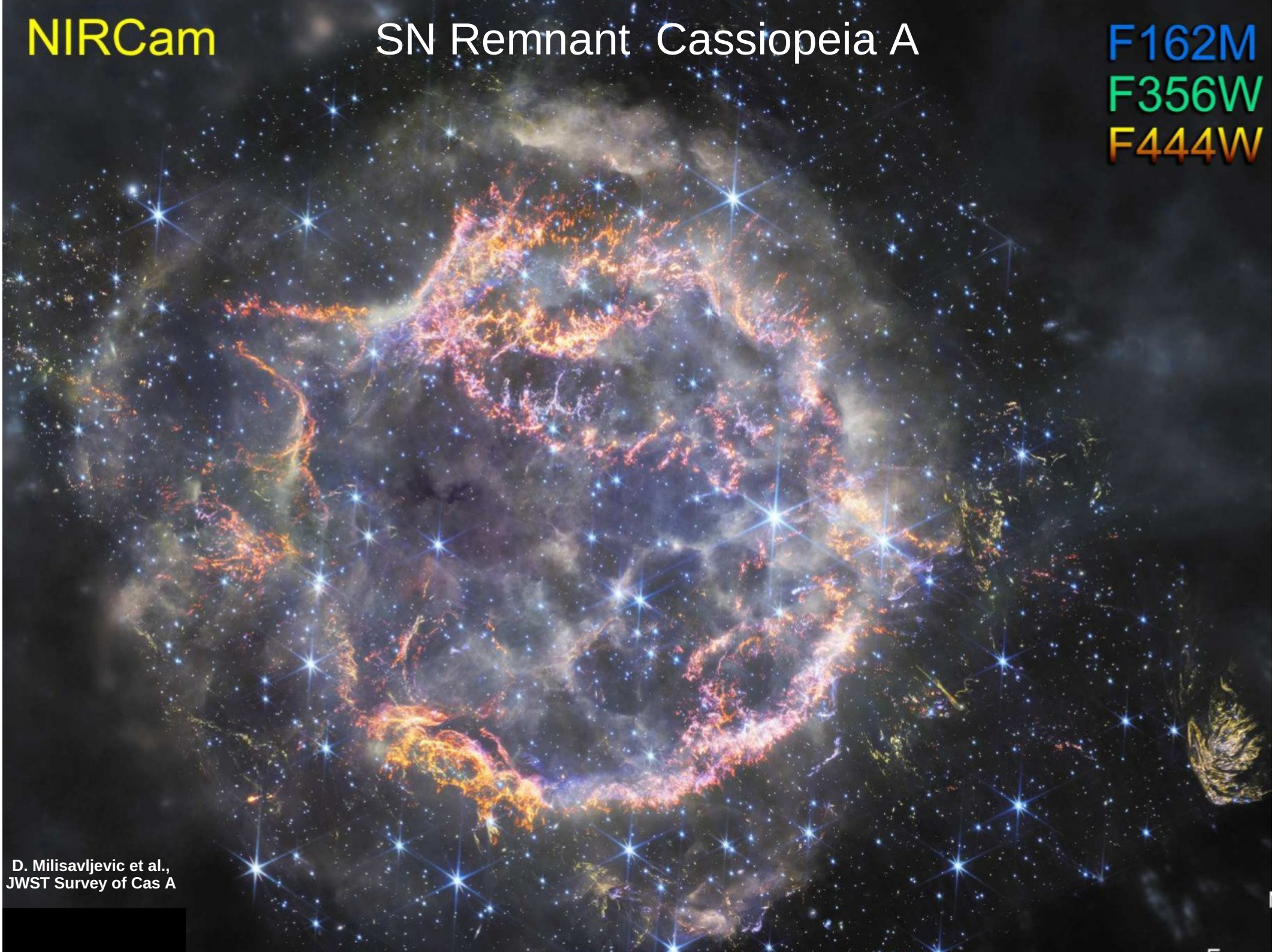
SN Remnant Cassiopeia A

F162M

F356W

F444W

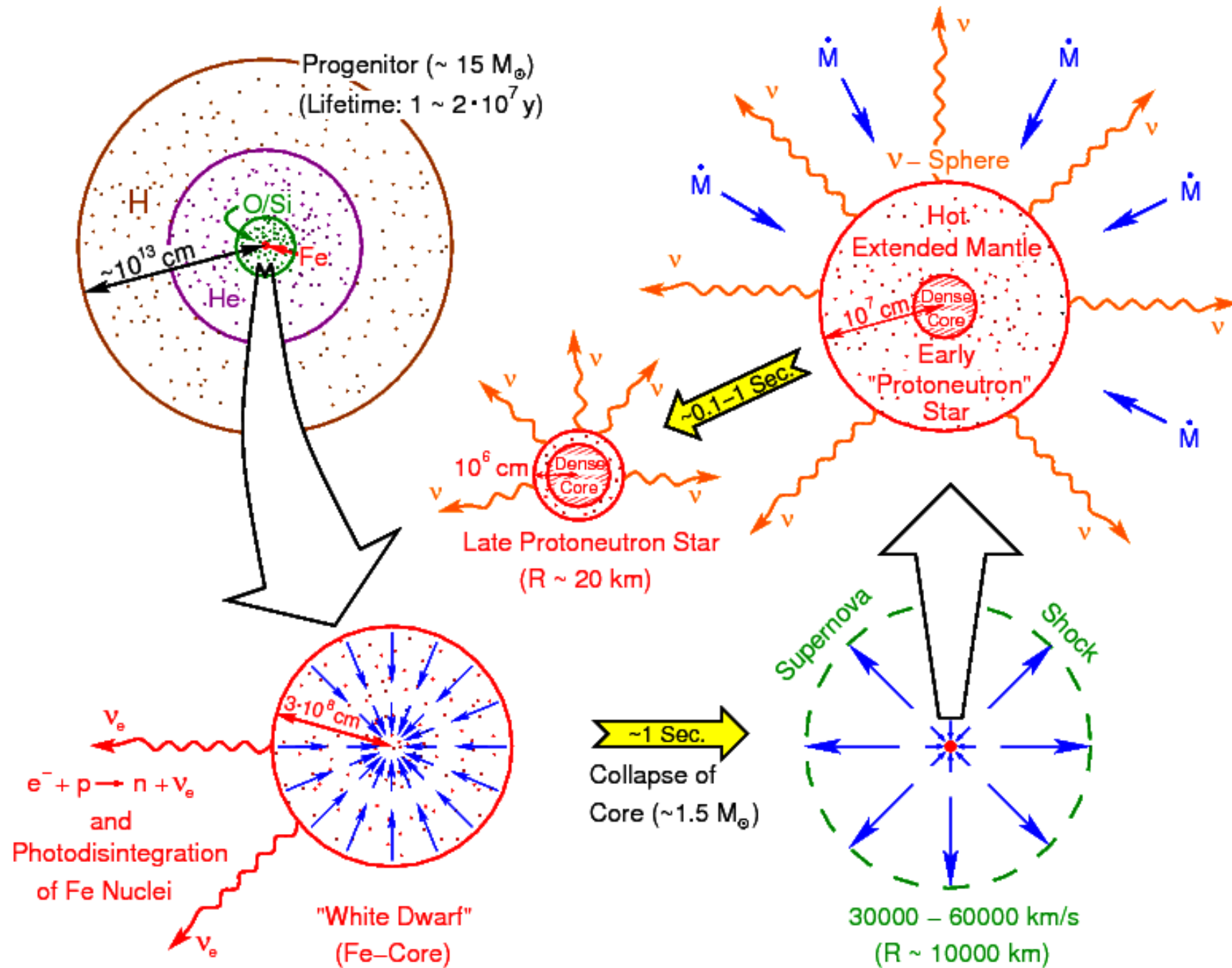
D. Milisavljevic et al.,
JWST Survey of Cas A



Outline

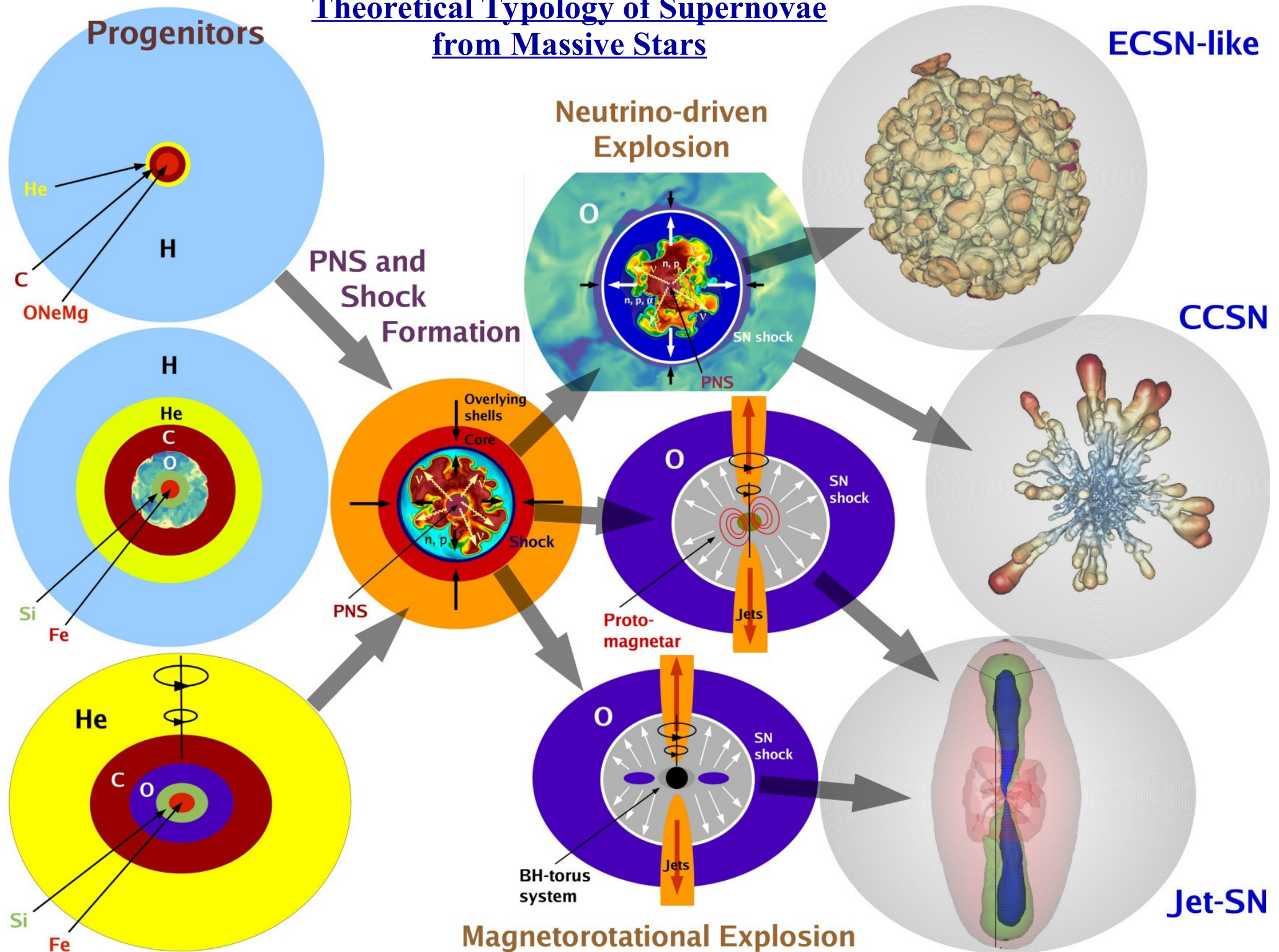
- **Introduction: Supernovae and how they explode**
- **Neutrino signals**
- **Gravitational-wave signals**
- **Relevant physics beyond astrophysics**
- **Electromagnetic emission (some aspects)**

Stellar Collapse and Supernova Stages

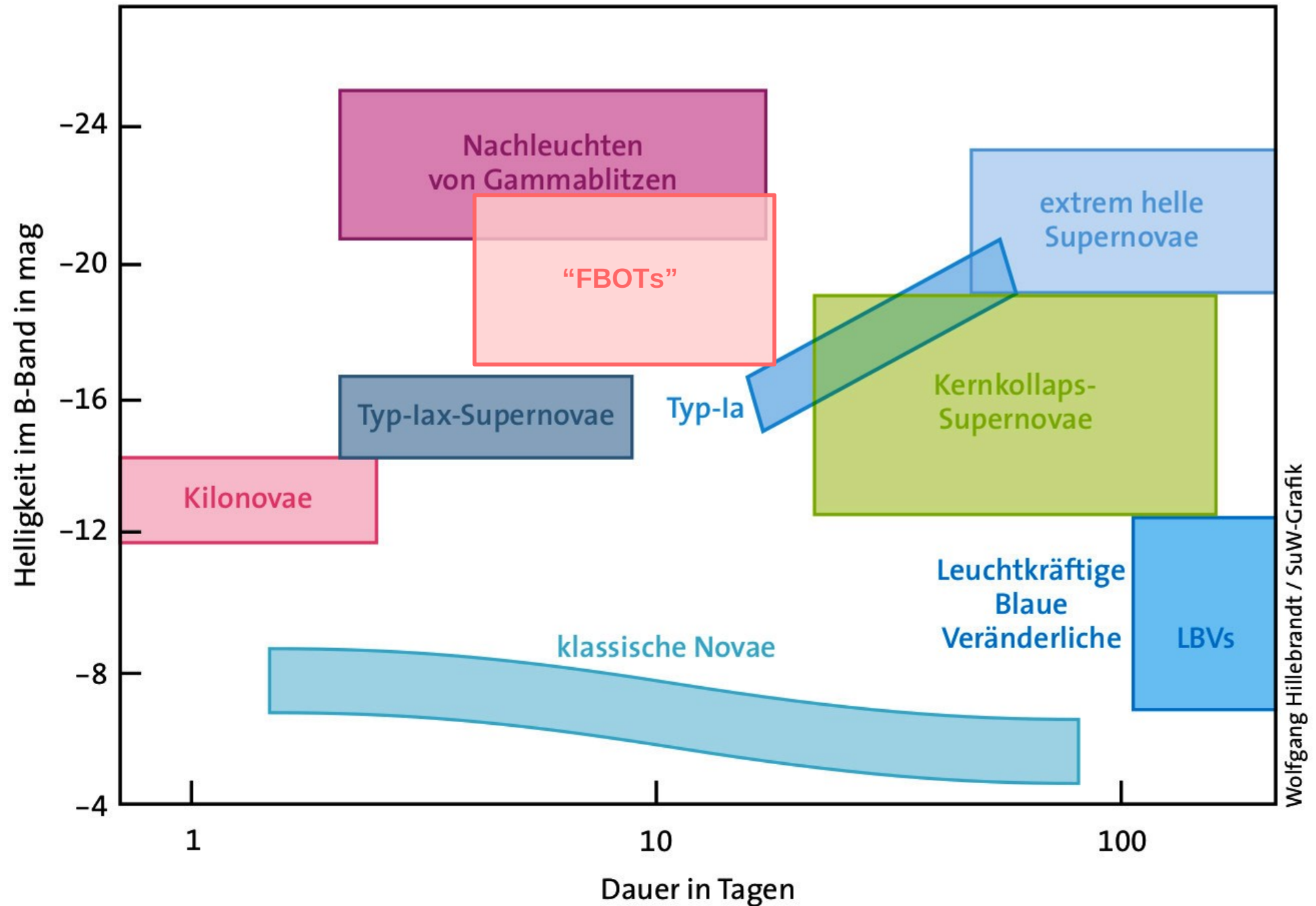


adapted from A. Burrows (1990)

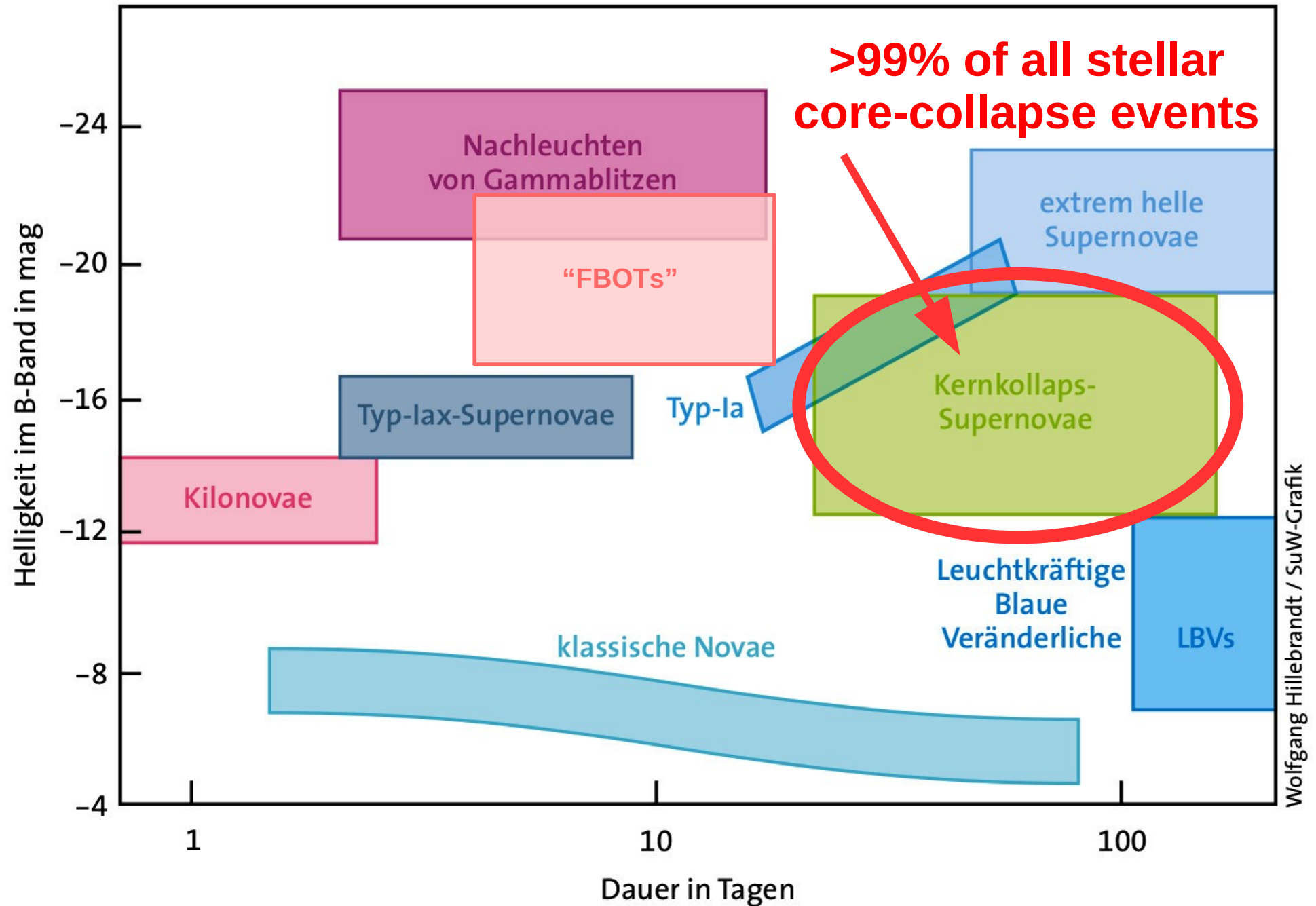
Theoretical Typology of Supernovae from Massive Stars



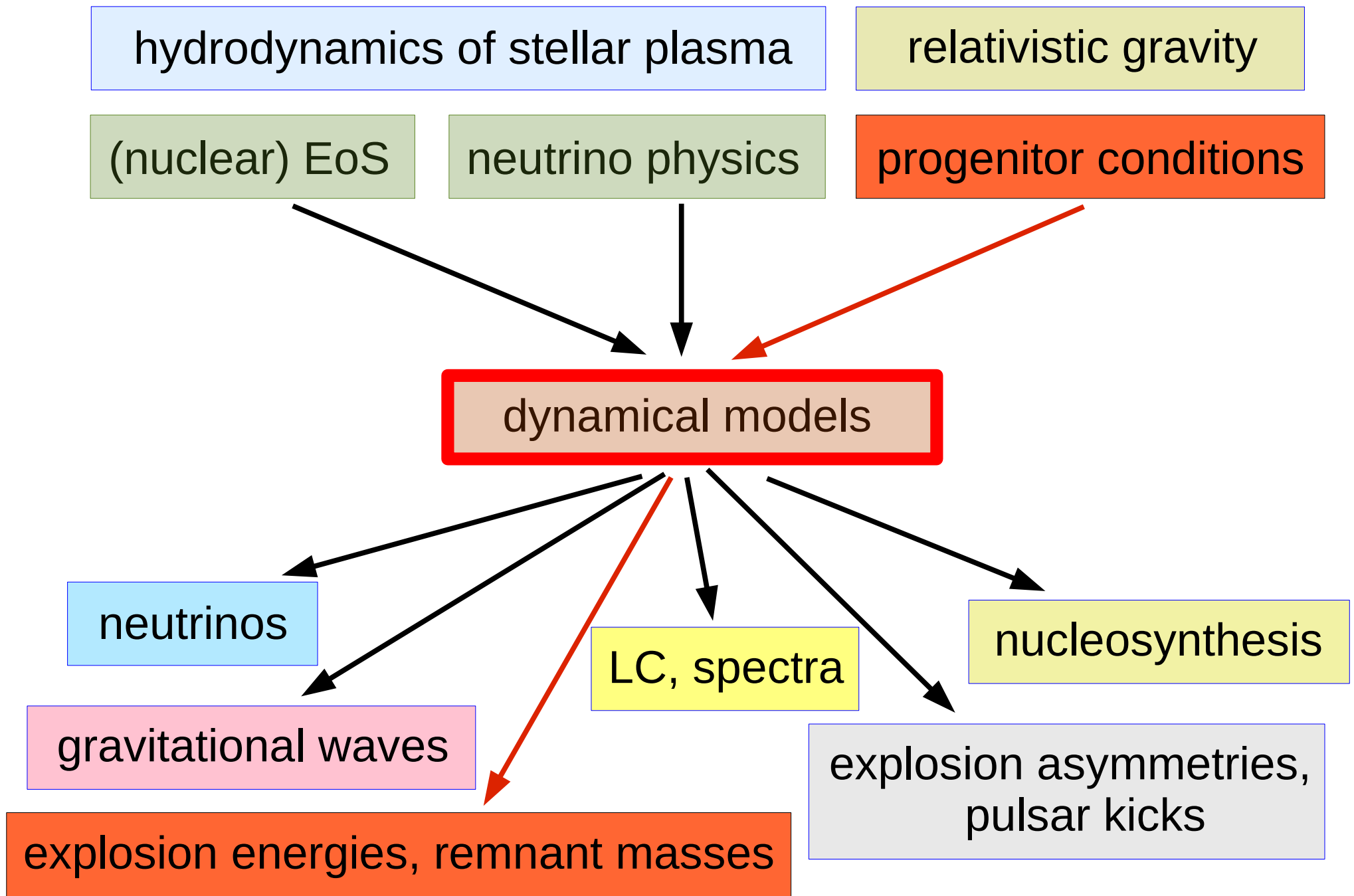
The Puzzling Zoo of Supernova-like Transients

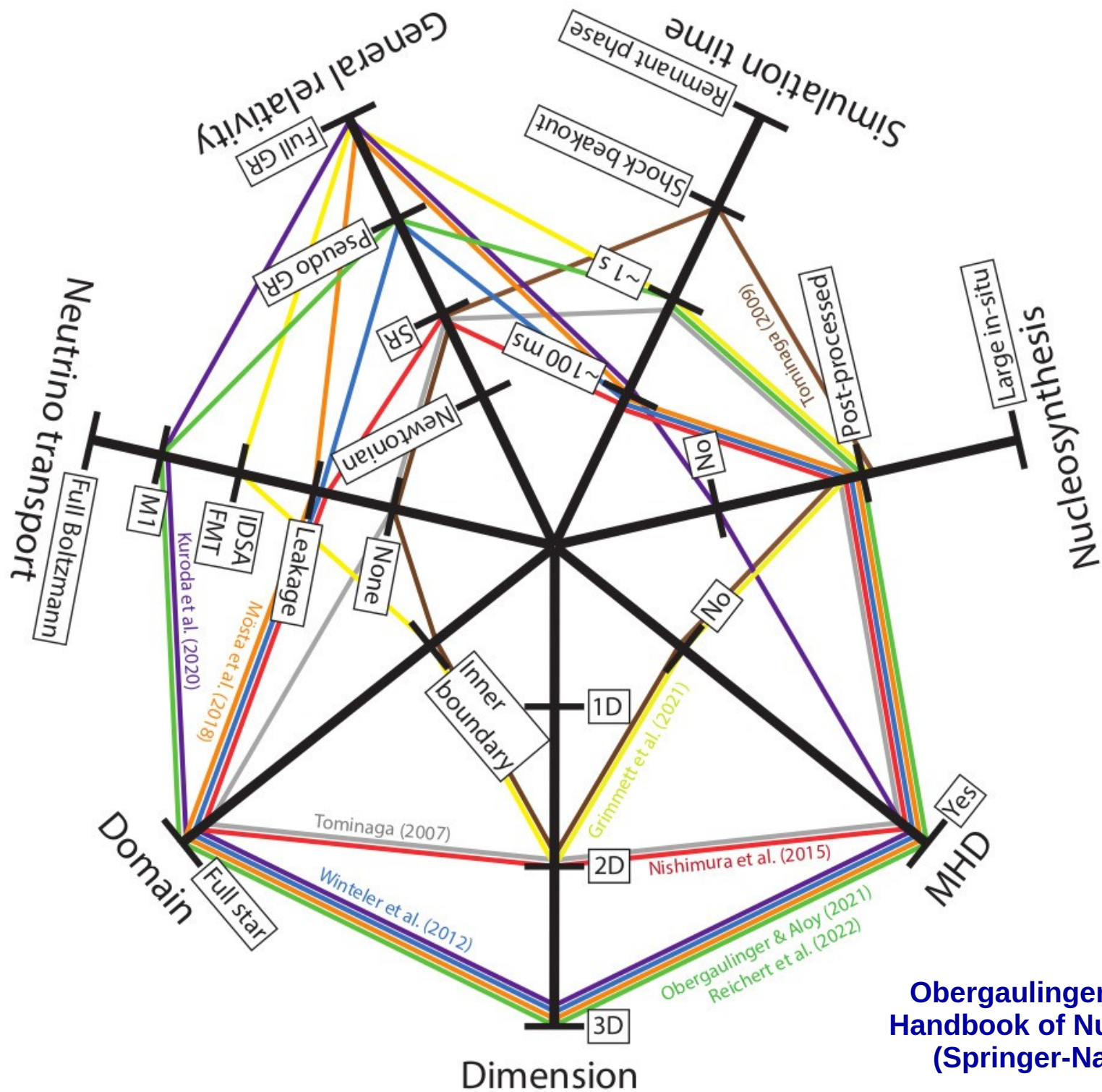


The Puzzling Zoo of Supernova-like Transients



Dynamics and Signals of SNe & hot NSs





Obergaulinger & Reichert,
Handbook of Nuclear Physics
(Springer-Nature, 2023)

Neutrino Reactions in Supernovae

Beta processes:

- $e^- + p \rightleftharpoons n + \nu_e$
- $e^+ + n \rightleftharpoons p + \bar{\nu}_e$
- $e^- + A \rightleftharpoons \nu_e + A^*$

Neutrino scattering:

- $\nu + n, p \rightleftharpoons \nu + n, p$
- $\nu + A \rightleftharpoons \nu + A$
- $\nu + e^\pm \rightleftharpoons \nu + e^\pm$

Thermal pair processes:

- $N + N \rightleftharpoons N + N + \nu + \bar{\nu}$
- $e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$

Neutrino-neutrino reactions:

- $\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$
($\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \text{ or } \bar{\nu}_\tau$)
- $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

Muons in Hot Neutron-Star Medium

- In proto-neutron stars **temperatures of $T > 30$ MeV** and **electron chemical potentials $\mu_e > 100$ MeV** can be reached.
- **Muon abundance can become relevant** ($m_\mu c^2 \approx 105.66$ MeV).
- Additional **reactions of neutrinos with muons** need to be included and **couple neutrinos of different flavors**:

Neutrino reactions with muons.

$$\nu + \mu^- \rightleftharpoons \nu' + \mu^{-\prime}$$

$$\nu_\mu + e^- \rightleftharpoons \nu_e + \mu^-$$

$$\nu_\mu + \bar{\nu}_e + e^- \rightleftharpoons \mu^-$$

$$\bar{\nu}_e + e^- \rightleftharpoons \bar{\nu}_\mu + \mu^-$$

$$\nu_\mu + n \rightleftharpoons p + \mu^-$$

$$\nu + \mu^+ \rightleftharpoons \nu' + \mu^{+\prime}$$

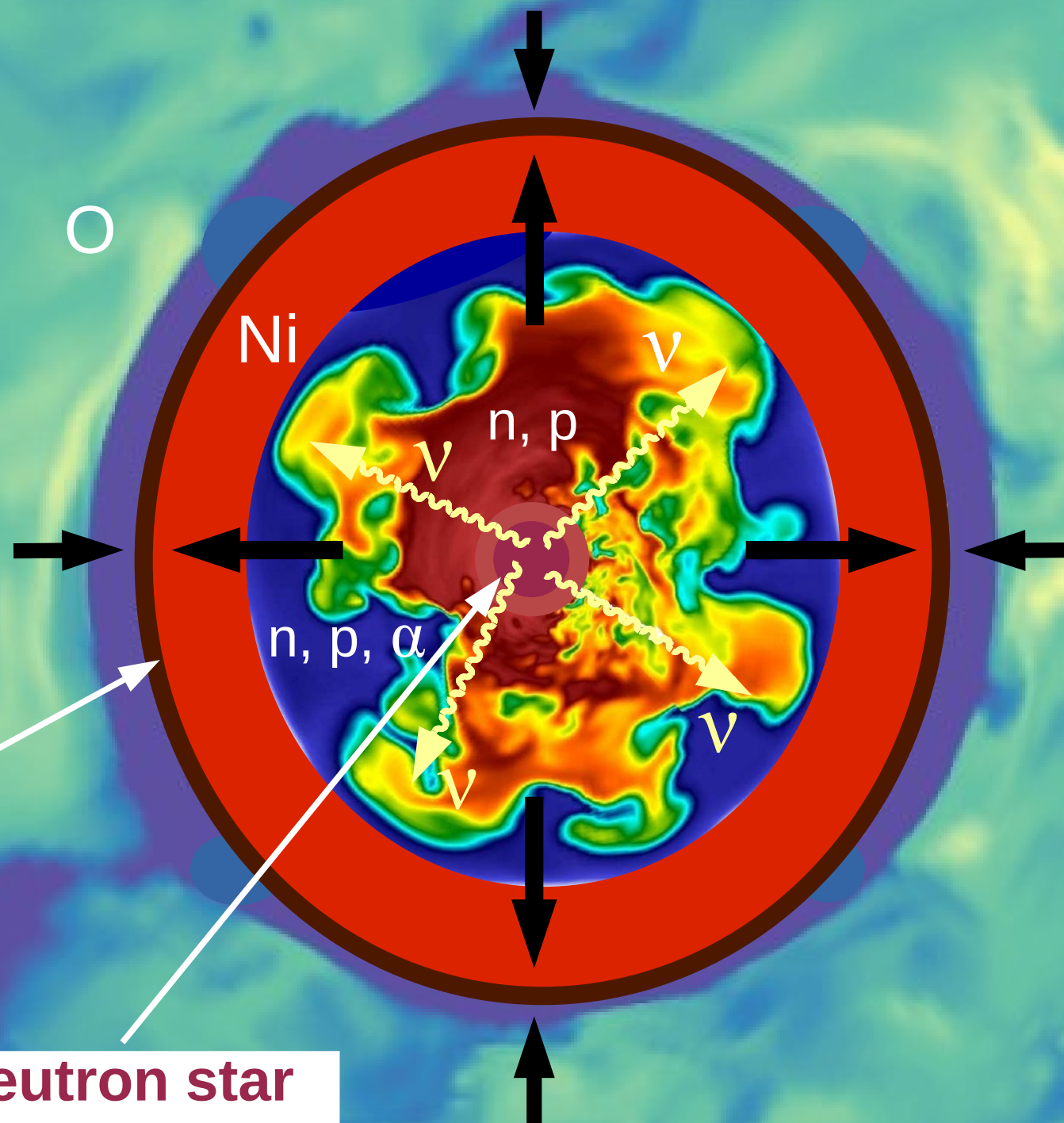
$$\bar{\nu}_\mu + e^+ \rightleftharpoons \bar{\nu}_e + \mu^+$$

$$\bar{\nu}_\mu + \nu_e + e^+ \rightleftharpoons \mu^+$$

$$\nu_e + e^+ \rightleftharpoons \nu_\mu + \mu^+$$

$$\bar{\nu}_\mu + p \rightleftharpoons n + \mu^+$$

Shock Revival by Neutrino Heating

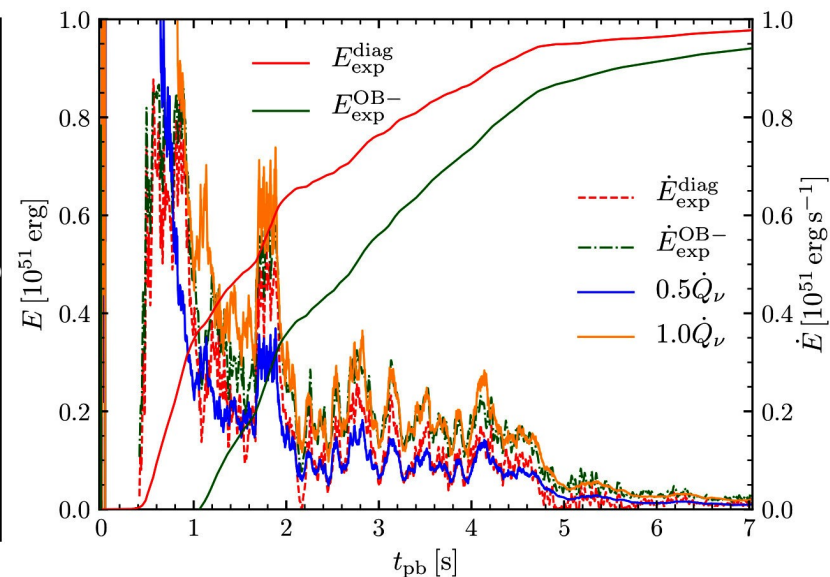
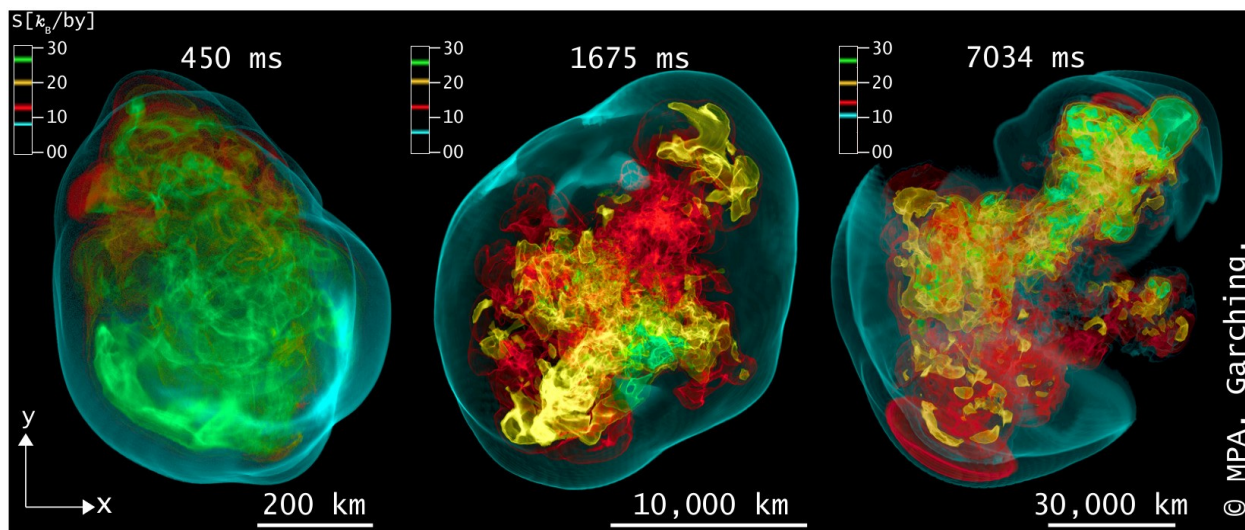
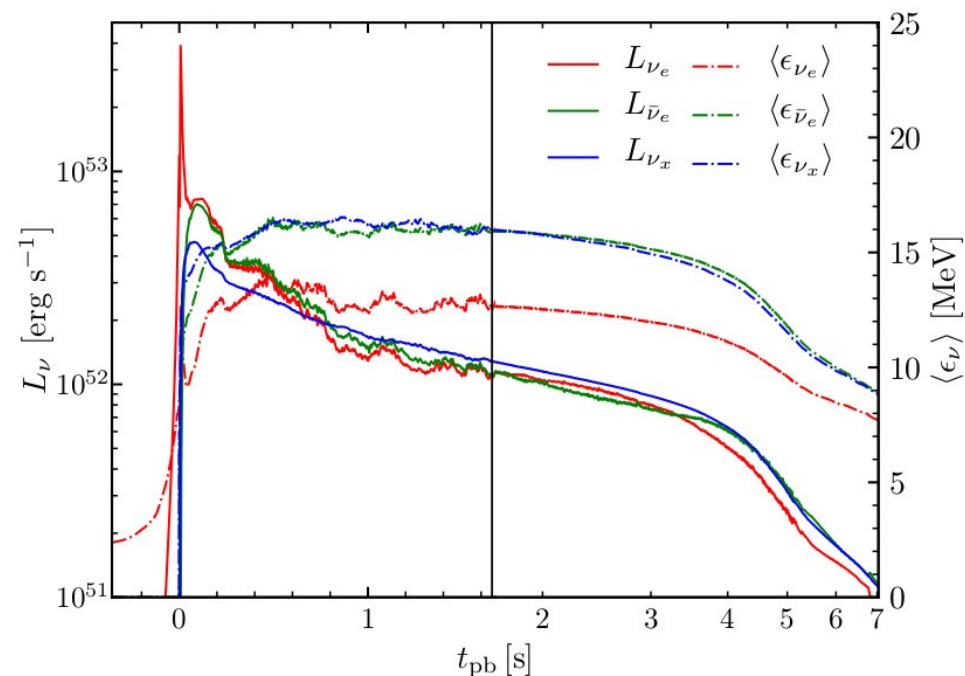
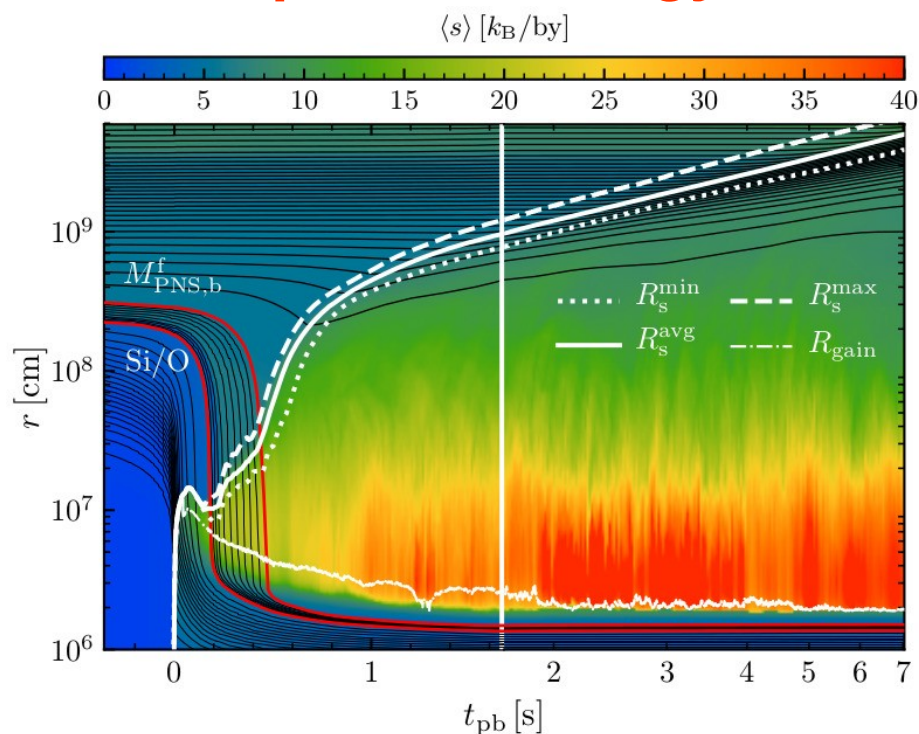


**Shock
wave**

Proto-neutron star

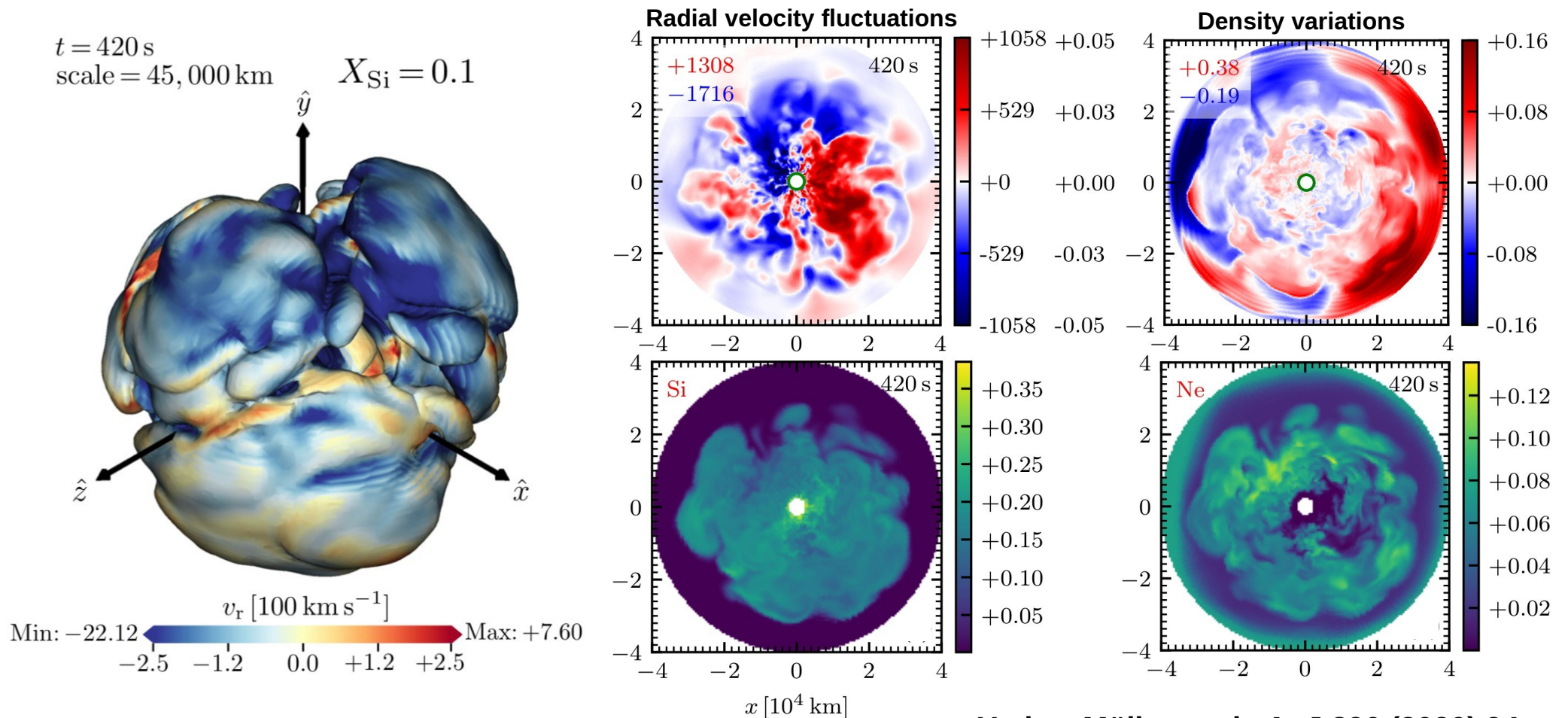
3D Explosion of $\sim 19 M_{\text{sun}}$ Star

Explosion energy saturates at 10^{51} ergs after 7 seconds

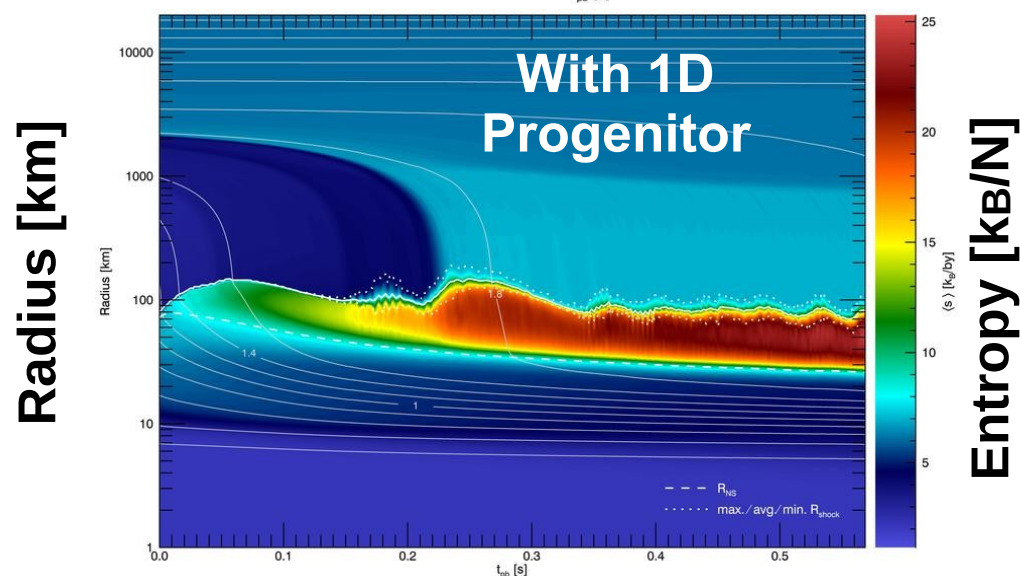
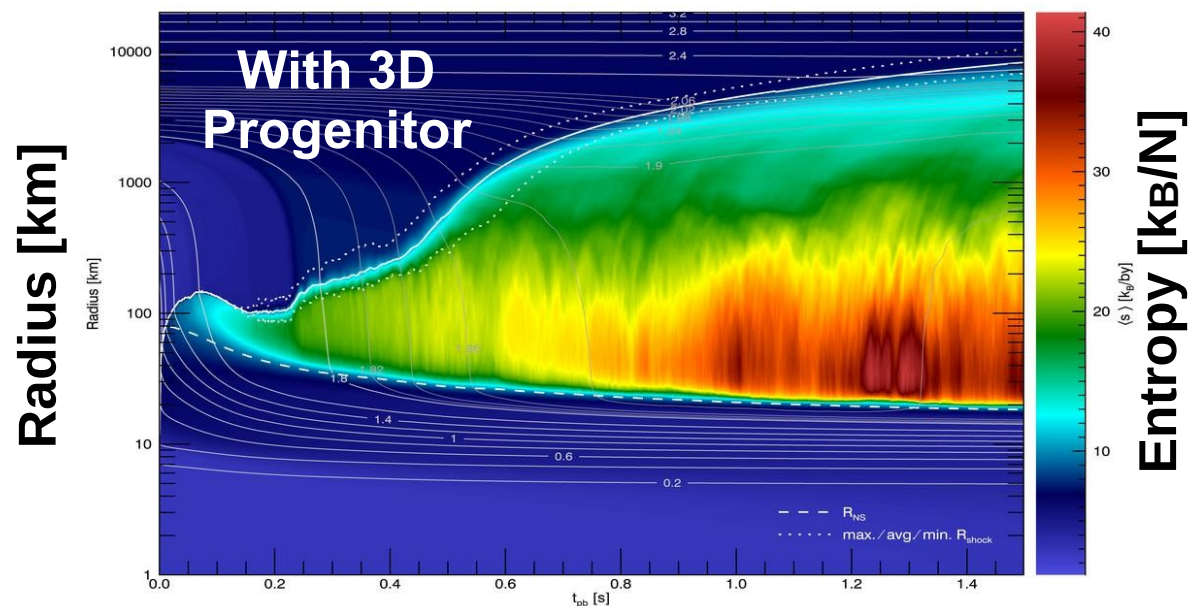


Neon-oxygen-shell Merger in a 3D Pre-collapse Star of $\sim 19 M_{\text{sun}}$

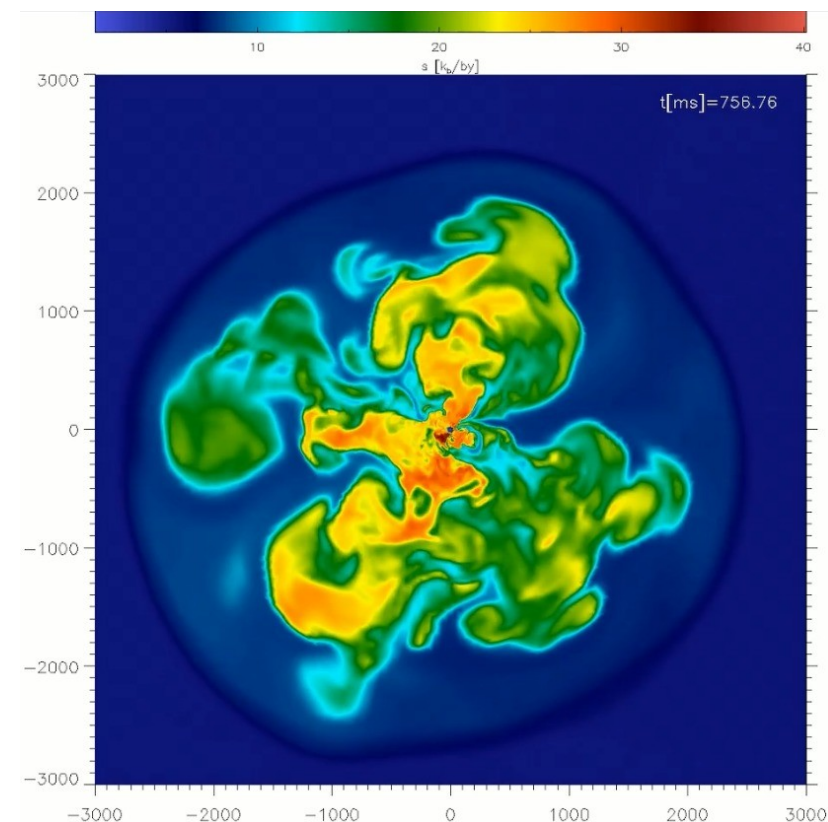
Flash of Ne+O burning in a shell merger creates large-scale asymmetries in density, velocity, Si/Ne composition



3D Explosion of $\sim 19 M_{\text{sun}}$ Star after Neon-oxygen-shell Merger



Post-bounce Time [sec]



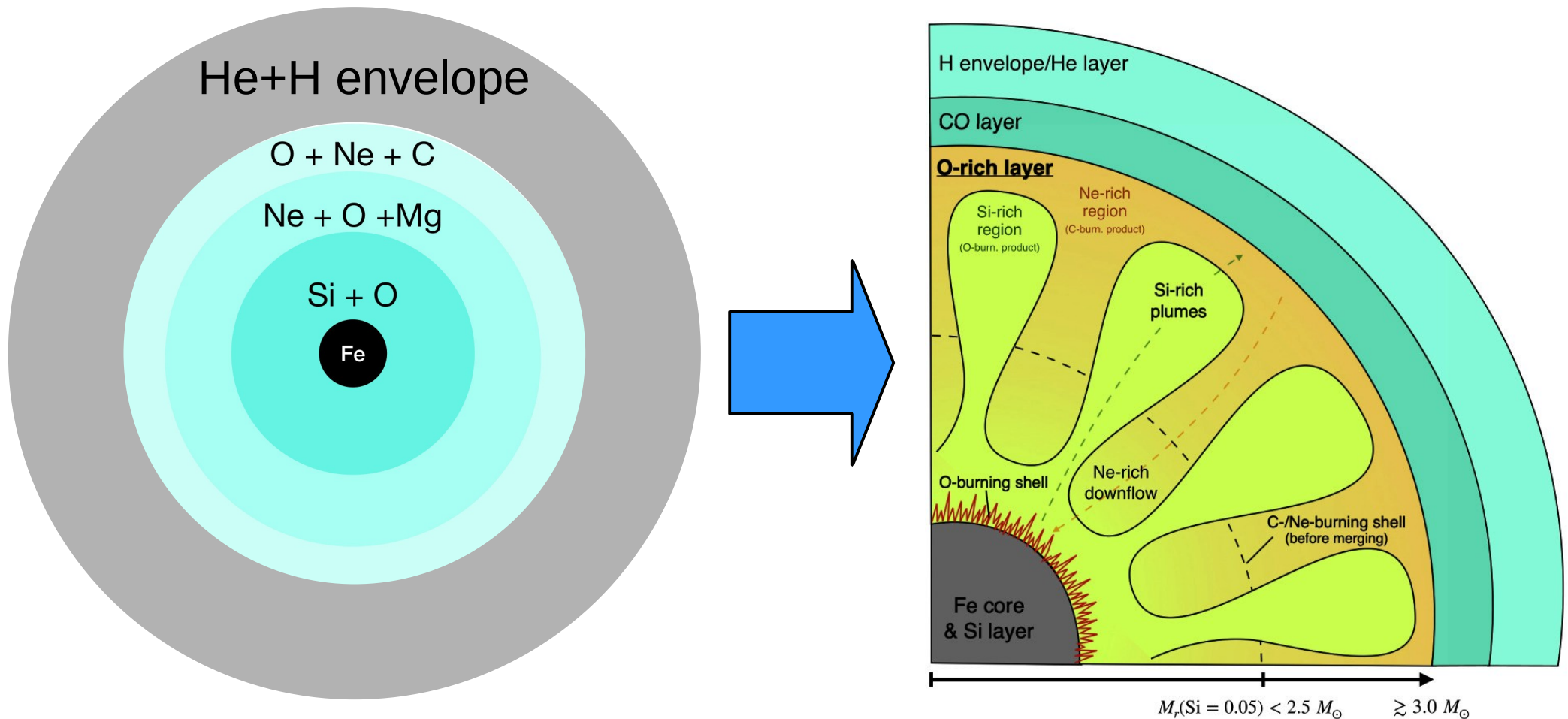
Pre-collapse perturbations in convectively burning O-shell aid explosion because they stir strong postshock convection.

Neon-Oxygen-Shell Merger in a 3D Pre-collapse Star of $\sim 19 M_{\text{sun}}$

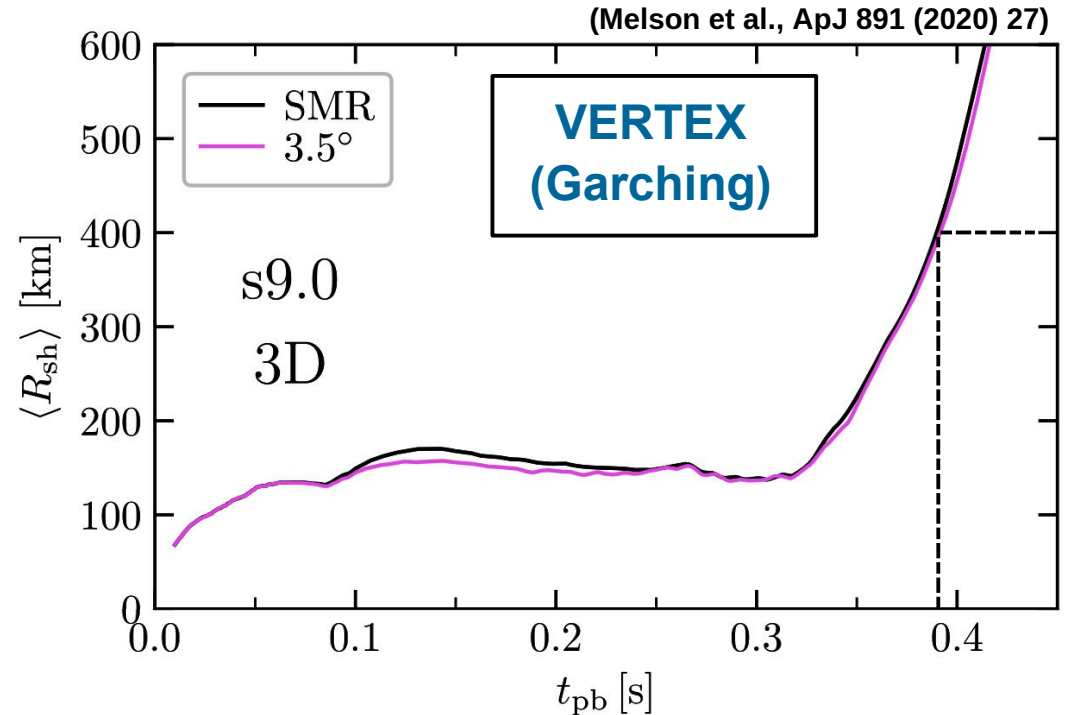
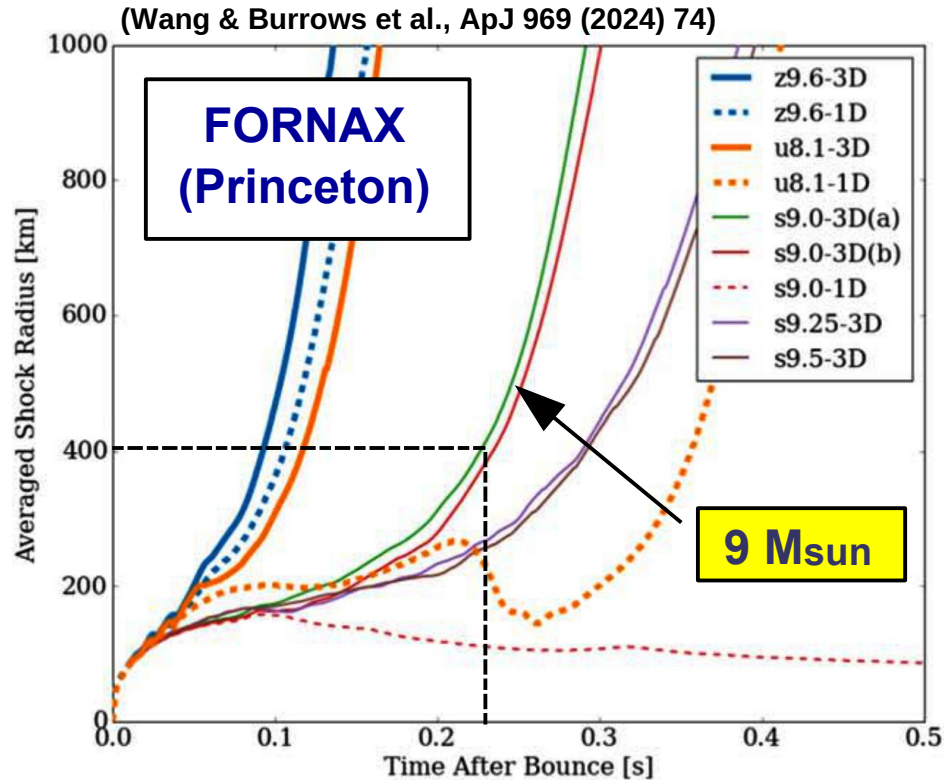
Ne+O shell merger changes the mixture of chemical elements
and therefore their abundance ratios in the Si, O, Ne layers.



Sophia Schnauck
(MPA) PhD student

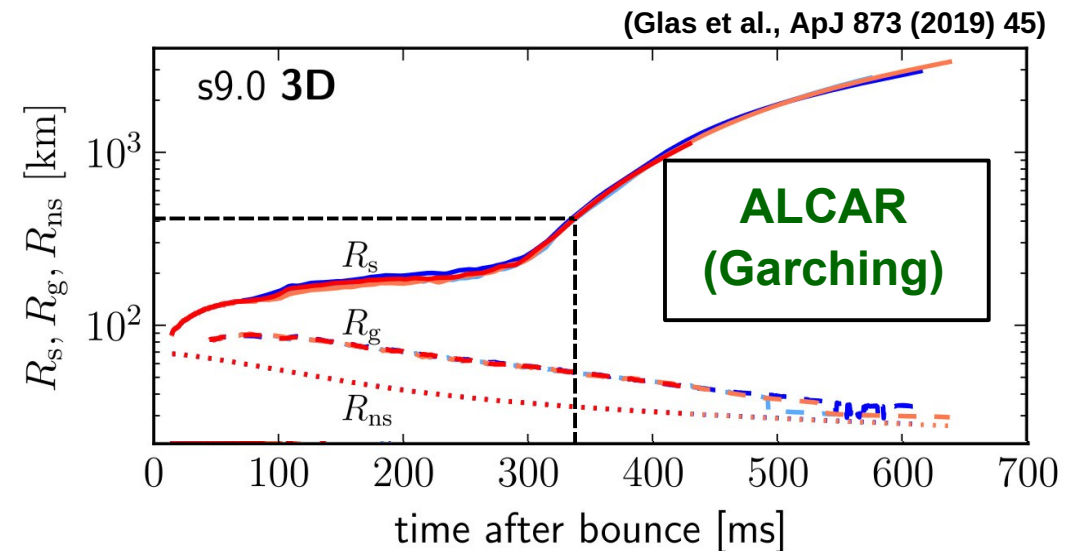


Explosion Differences in 3D Simulations of a 9 M_{sun} Progenitor

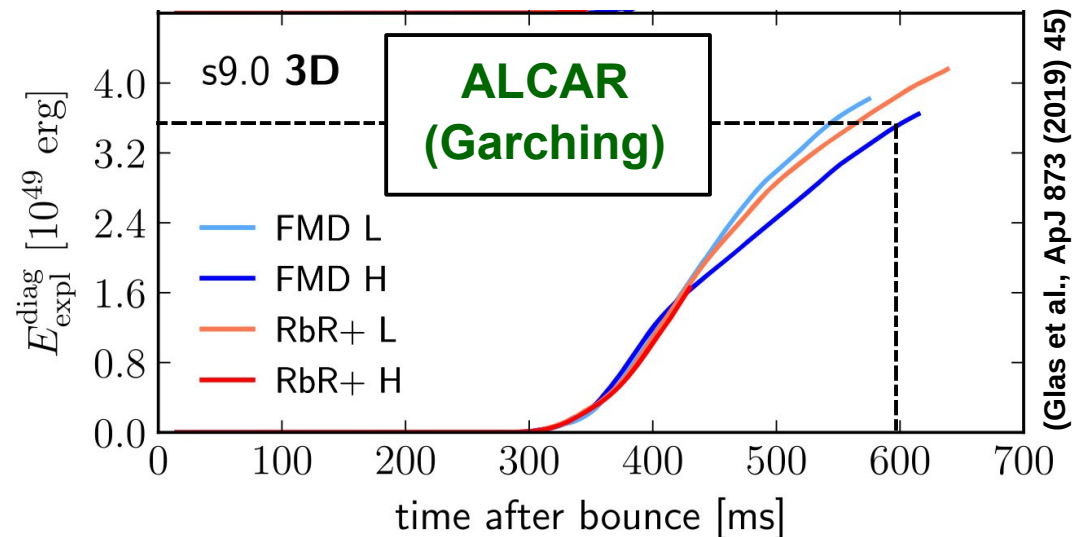
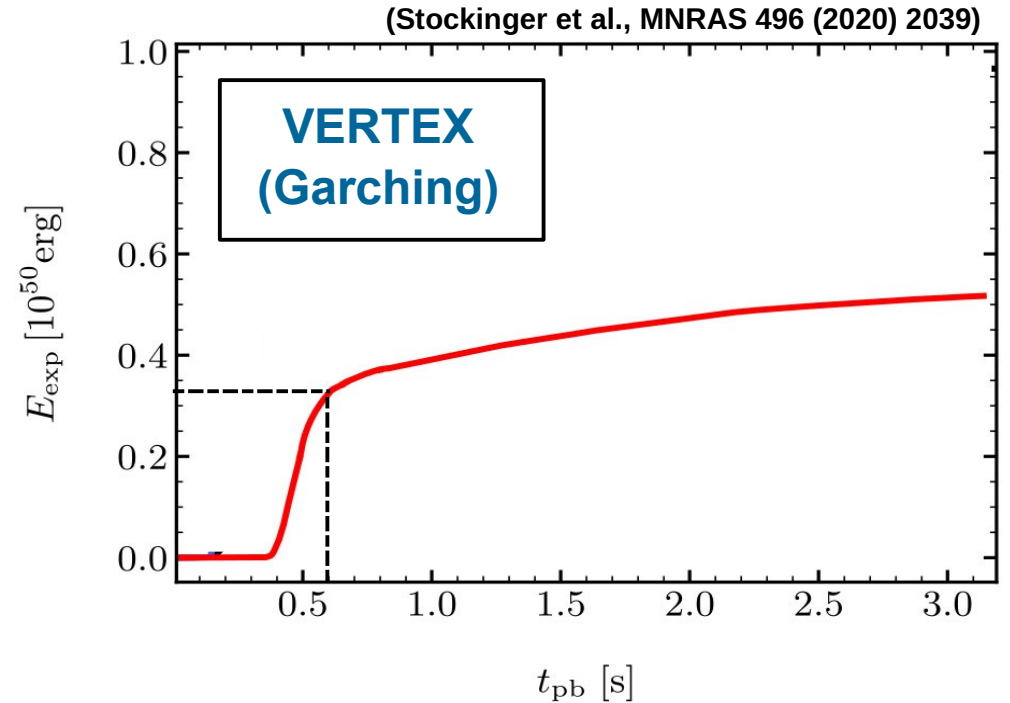
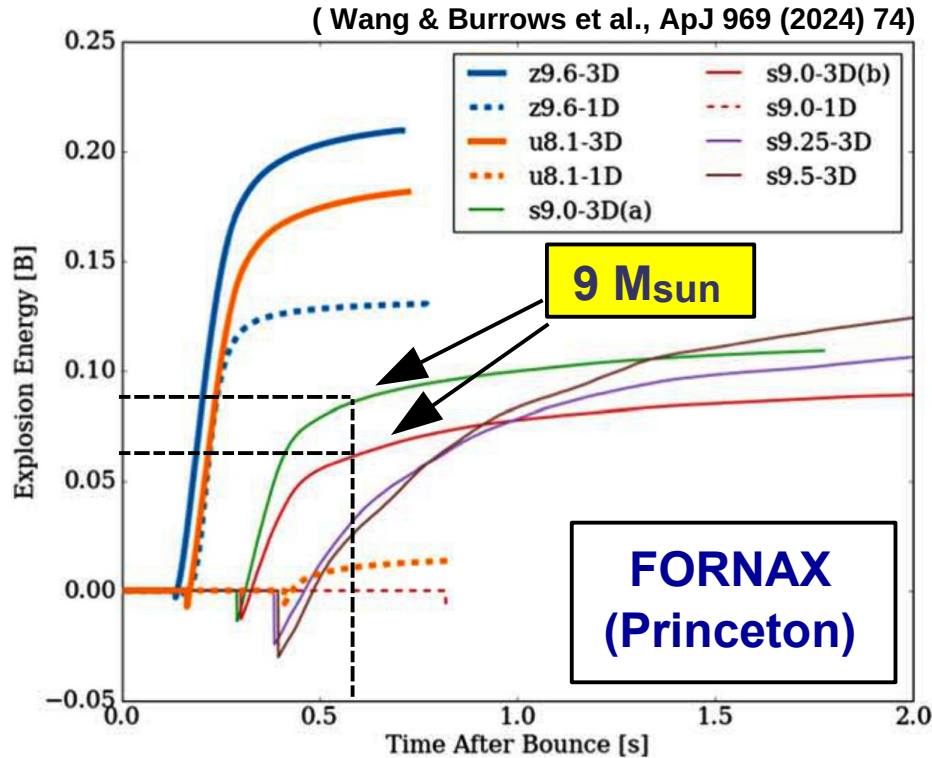


**Significant quantitative differences
between 3D results of different
groups:**

**The SN shock expands earlier and
faster in simulations with FORNAX
code.**



Explosion Differences in 3D Simulations of a 9 M_{sun} Progenitor



Significant quantitative differences between 3D results of different groups:

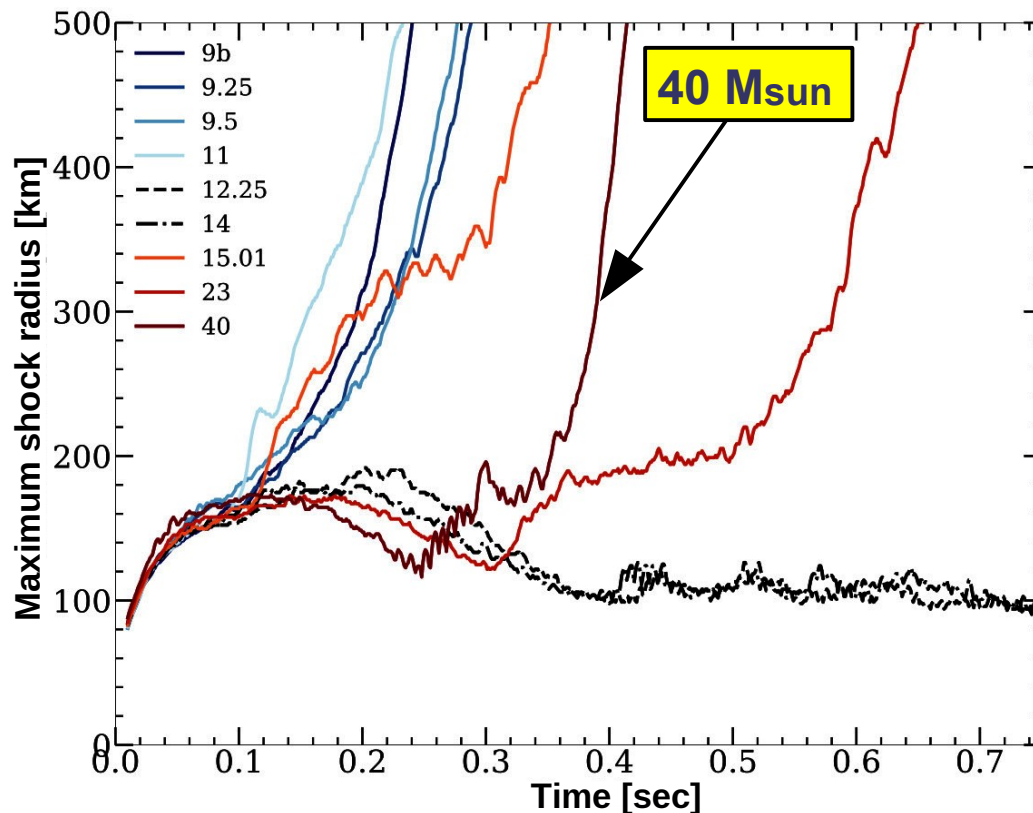
The SN explosion energy rises faster and becomes higher in simulations with FORNAX code.

BH Formation w/wo SN Explosion in a 40 M_{sun} Progenitor?

Qualitative differences between 3D results of different groups:
Explosion with FORNAX code, no explosion with VERTEX code.

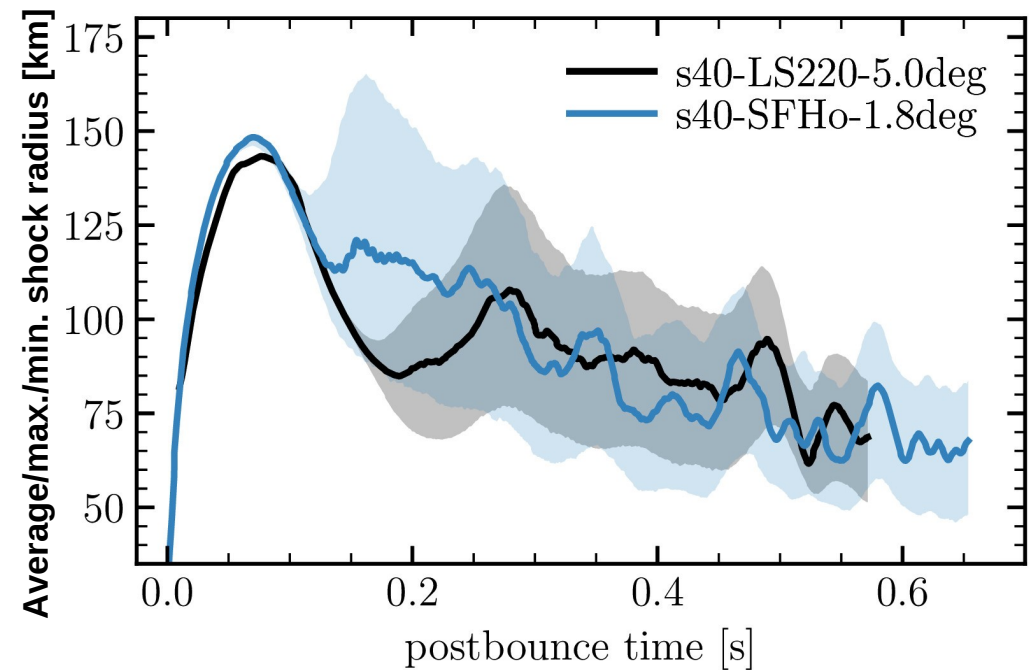
Princeton group with FORNAX code:

(Burrows et al., ApJ 957 (2023) 68)



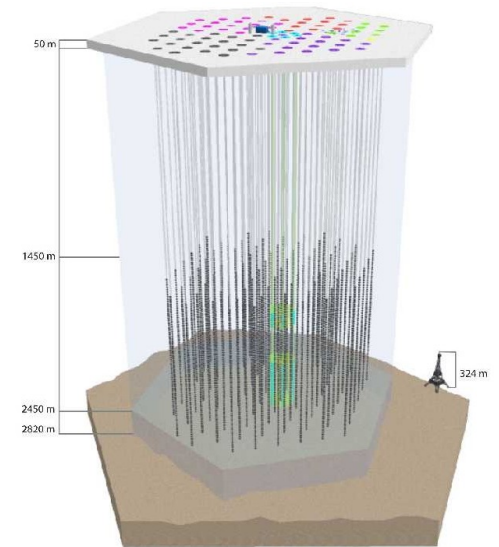
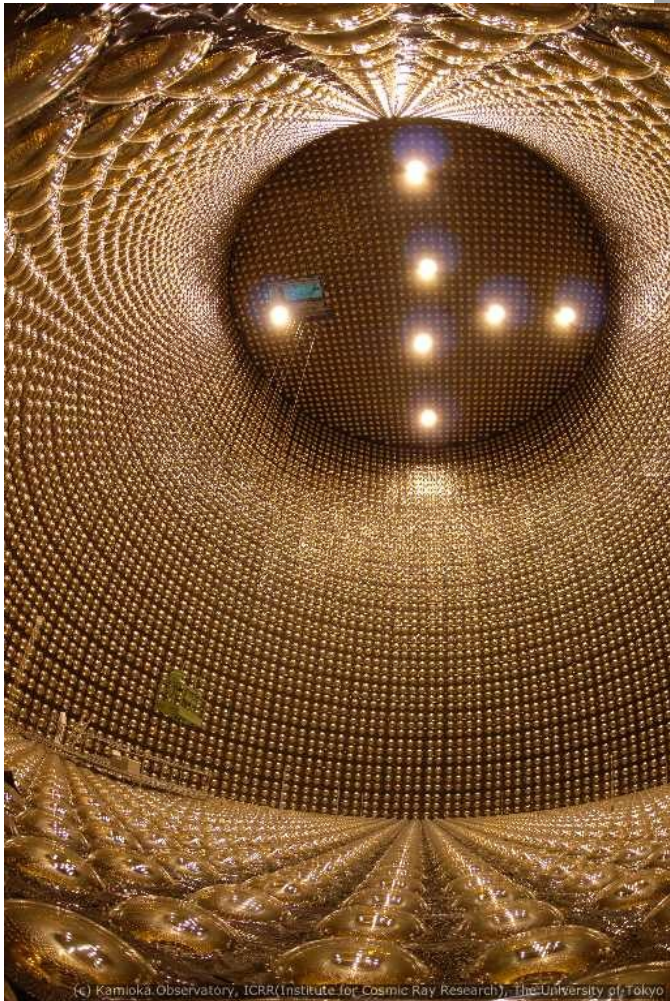
Garching group with VERTEX code:

(M. Heinlein, D. Kresse, & A. Summa)



Detecting Signals From the SN Core

Superkamiokande



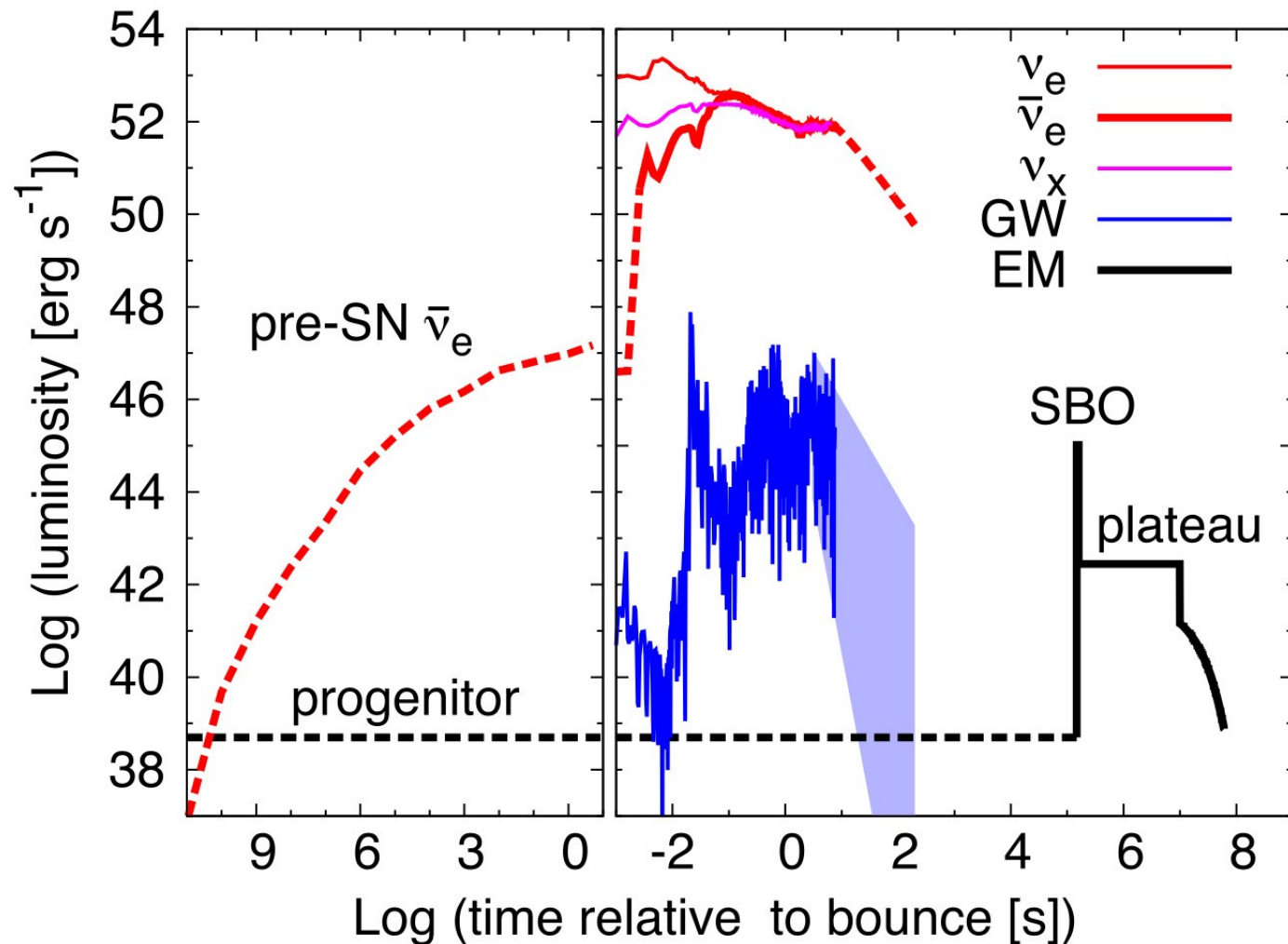
IceCube



VIRGO

Multi-Messenger Signals from Core-Collapse Supernovae

Total energy emitted after bounce in the form of electron anti-neutrino, photons, and GWs is $\sim 6 \times 10^{52}$ erg, $\sim 4 \times 10^{49}$ erg, and $\sim 7 \times 10^{46}$ erg, respectively.



Nakamura et al. MNRAS 461, 3296–3313 (2016)

Neutrino Signals
for
Neutrino-Driven
Explosion Models

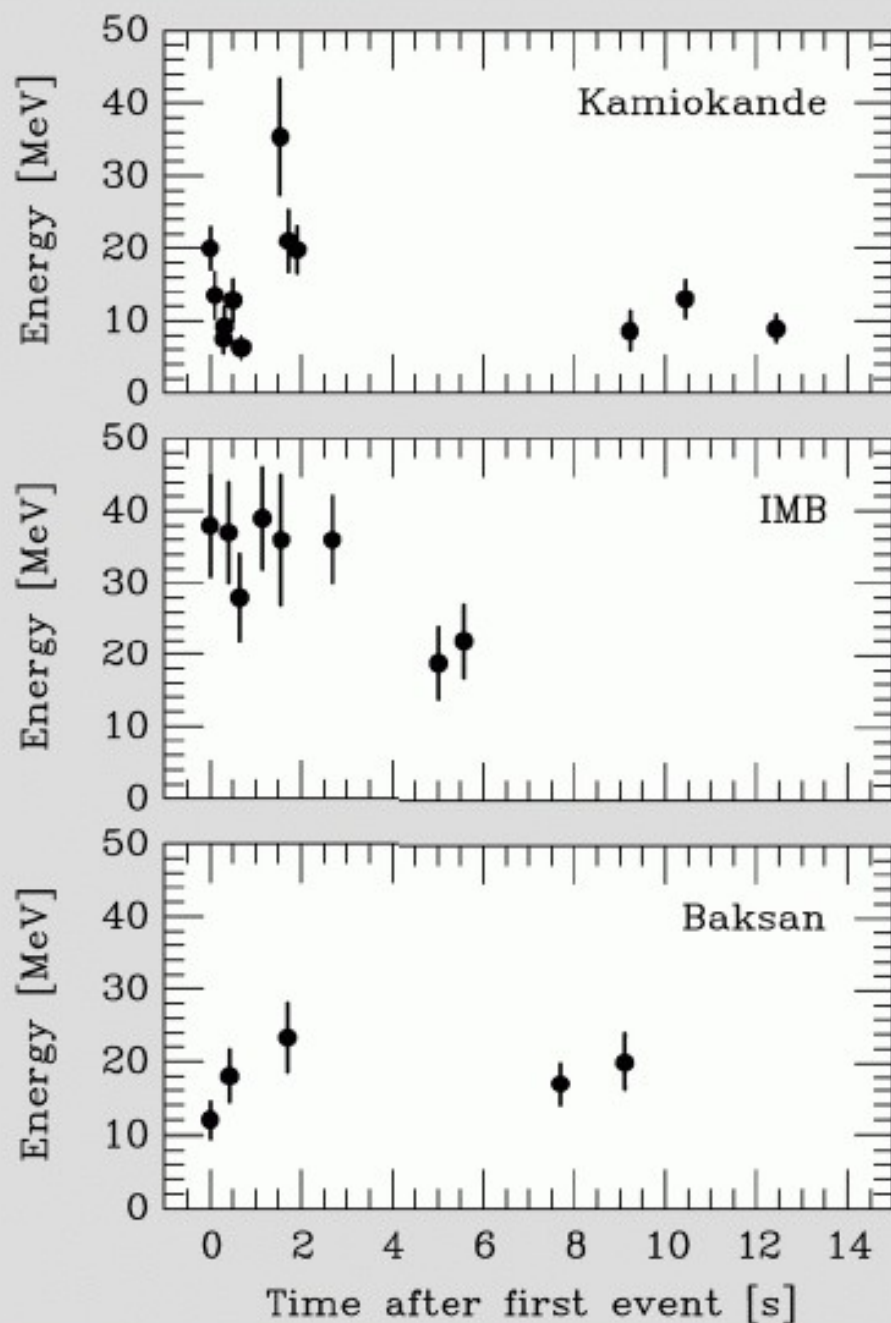
Sanduleak -69 202

Supernova 1987A 23.
Februar 1987



Supernova 1987A (SN 1987A)

Neutrino Burst of Supernova 1987A



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

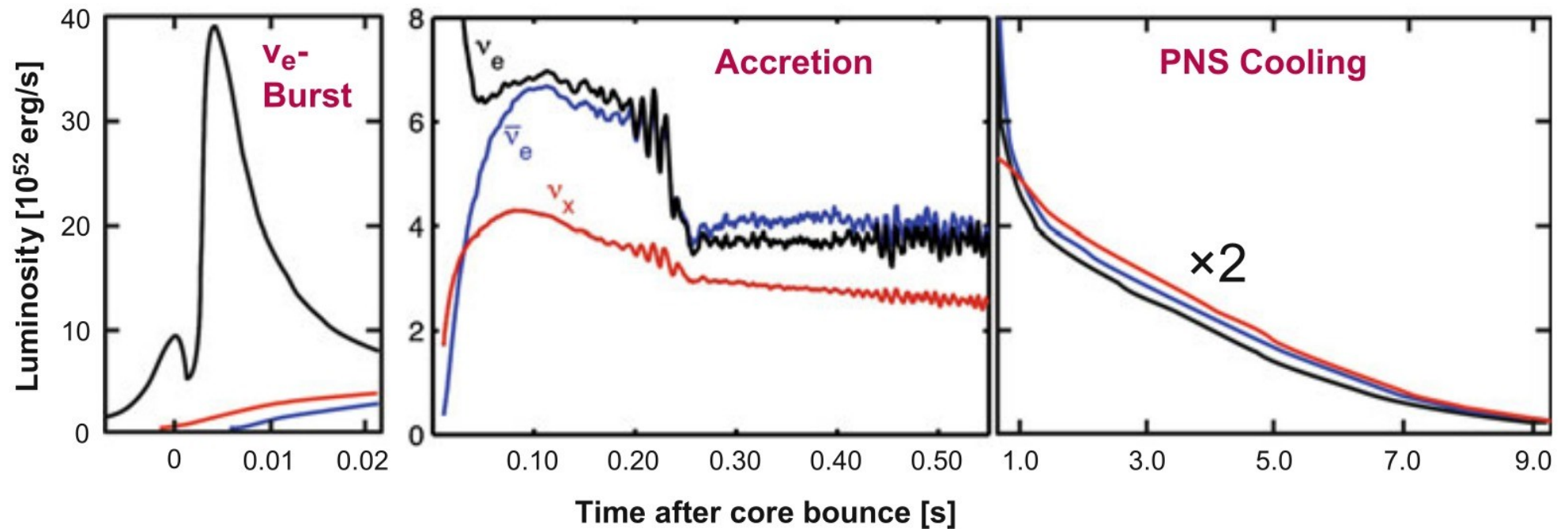
Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ± 50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster $\sim 0.7/\text{day}$
Clock uncertainty $+2/-54$ s

Within clock uncertainties,
signals are contemporaneous

Neutrino-Signal Features

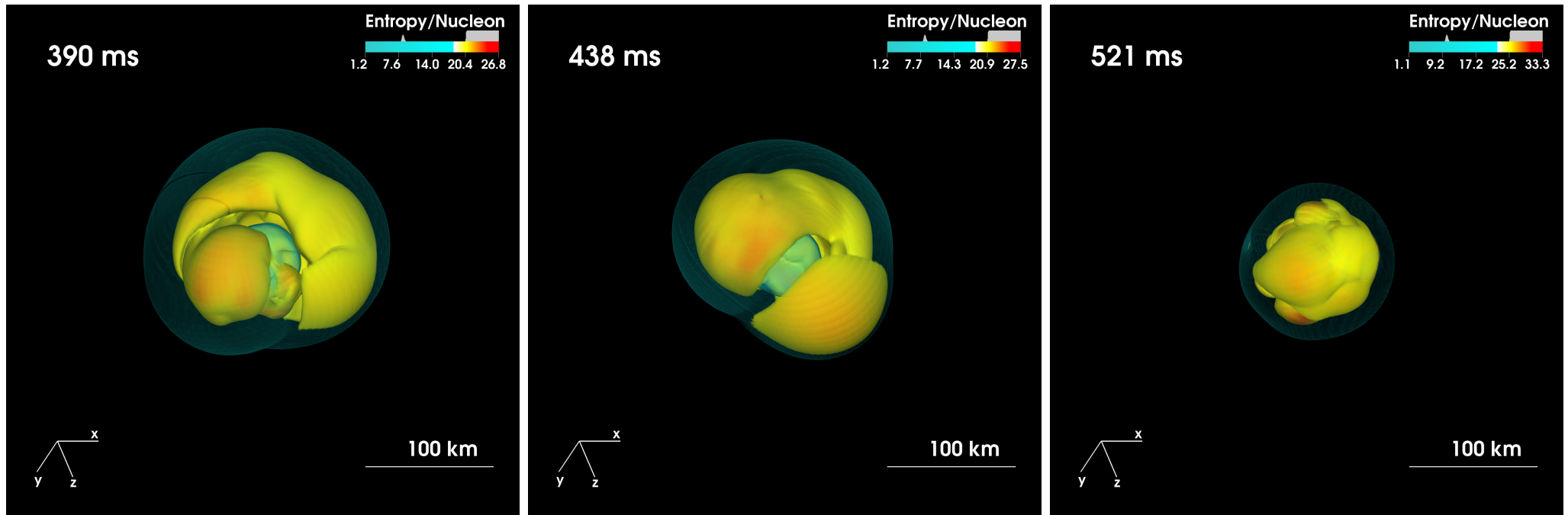
SASI induced quasi-periodic modulations during accretion phase



Janka H.-T., in: *Handbook of Supernovae* (2016); arXiv:1702.08713

SASI in 3D Core-Collapse Models

Shock and mass motions around the proto-neutron star by the sloshing and rotation modes of the standing accretion shock instability (SASI) in a 40 Msun simulation with black-hole formation.

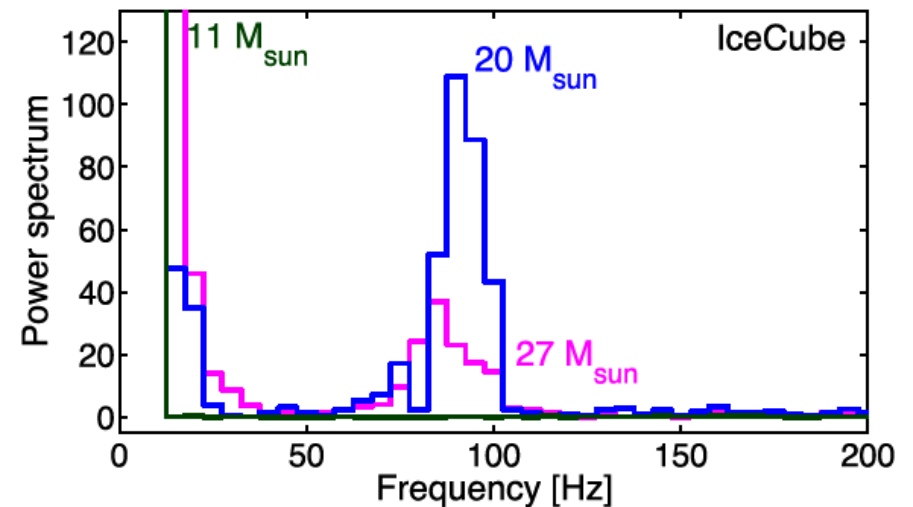
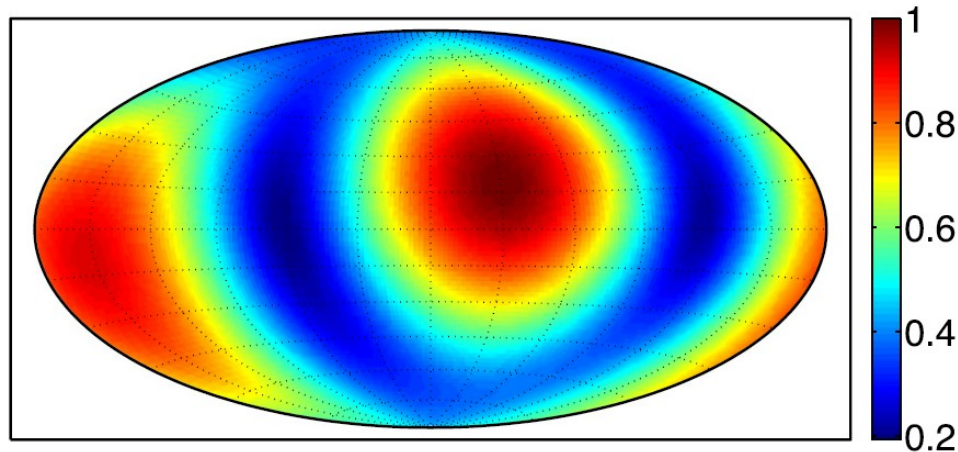
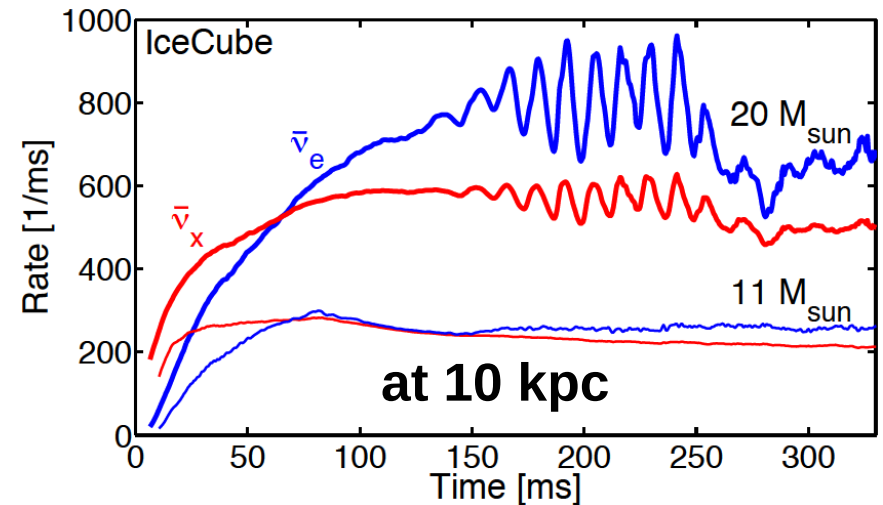
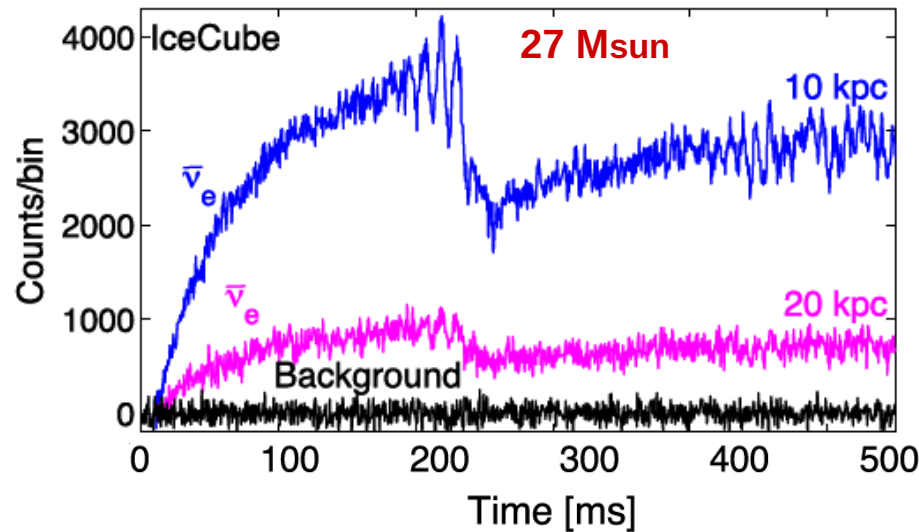


A. Summa & S. Zhang (2018); unpublished

3D Core-Collapse Models: Neutrino Signals

11.2, 20, 27 M_{sun} progenitors (WHW 2002)

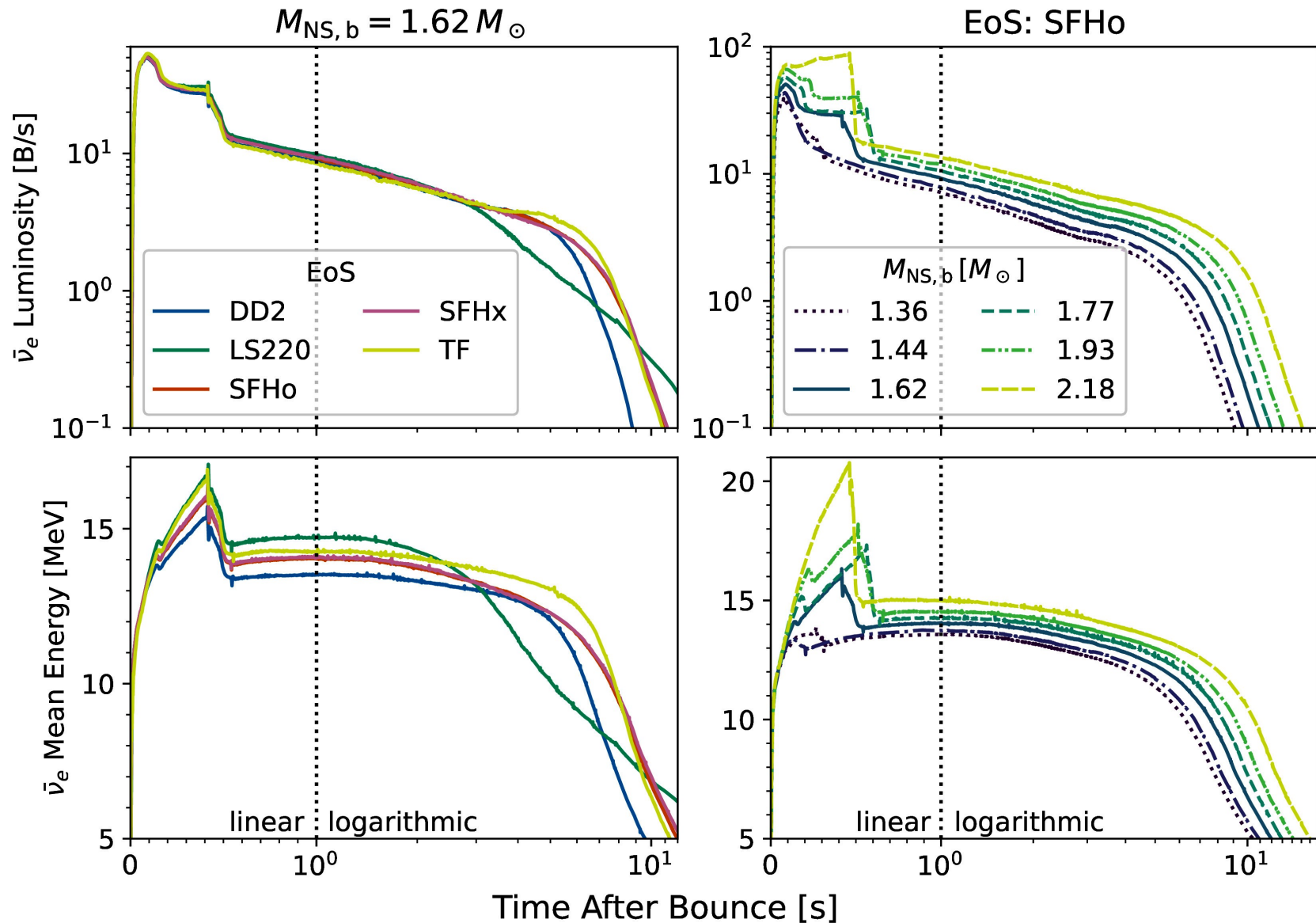
SASI produces modulations of neutrino emission (and gravitational-wave signal).



Tamborra et al., PRL 111, 121104 (2013);
PRD 90, 045032 (2014)

$$f_{\text{SASI}}^{-1} \sim \int_{R_{\text{NS}}}^{R_s} \frac{dr}{|v|} + \int_{R_{\text{NS}}}^{R_s} \frac{dr}{c_s - |v|}$$

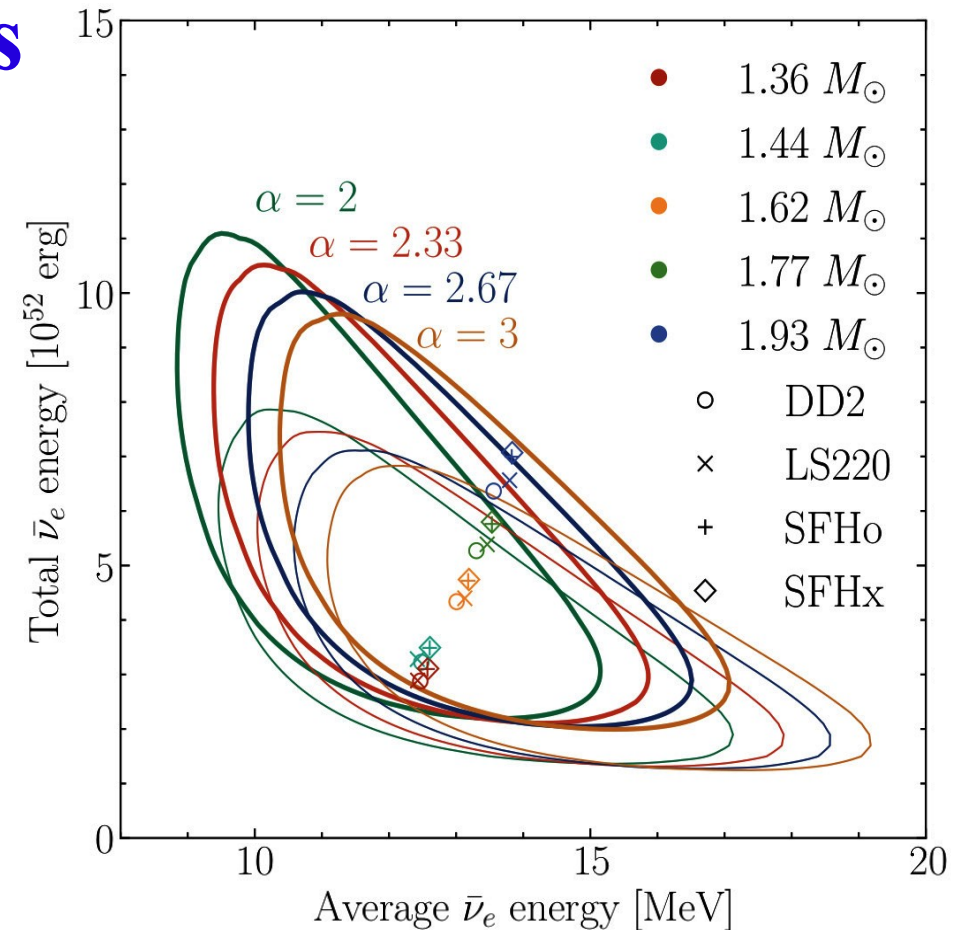
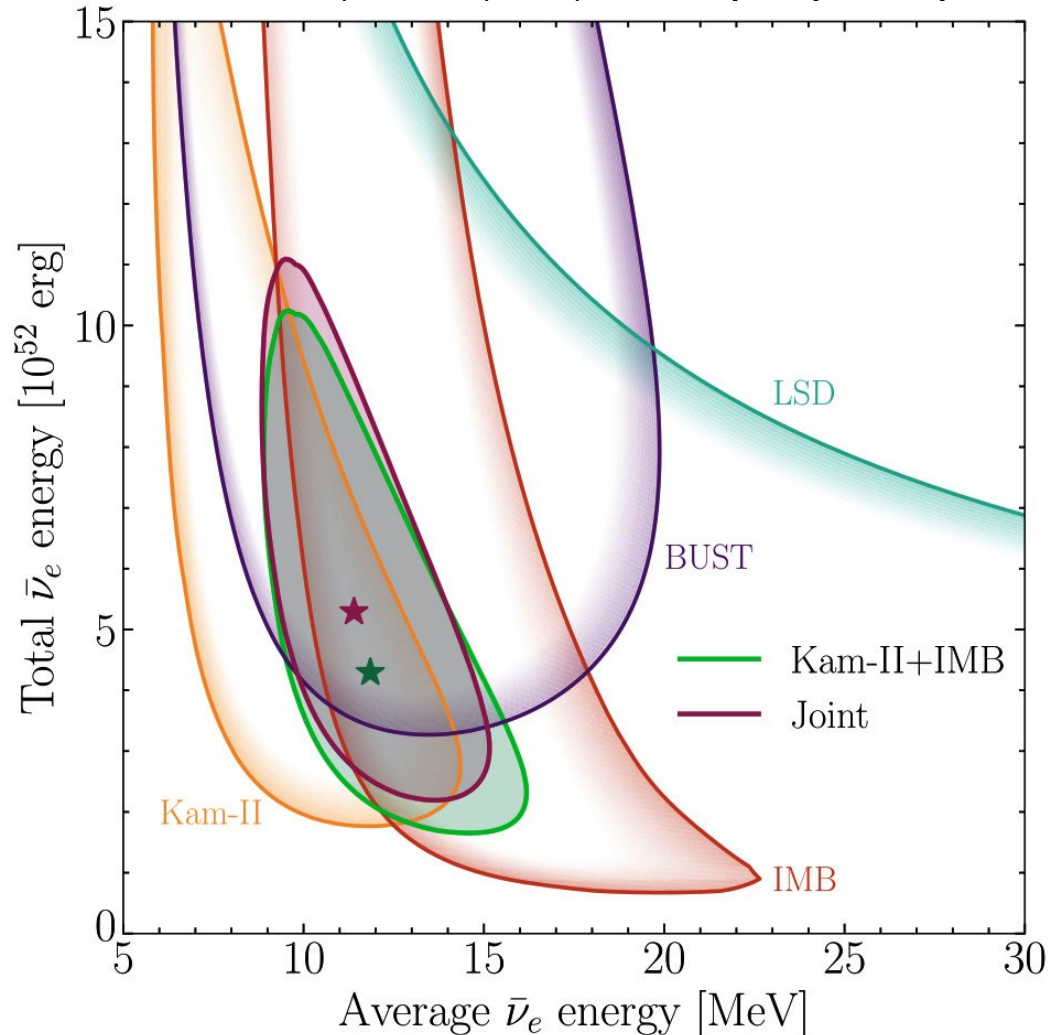
State-of-the-art Proto-NS Cooling Models vs. SN1987A Neutrinos



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

Models are compatible with confidence region of all experiments combined

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

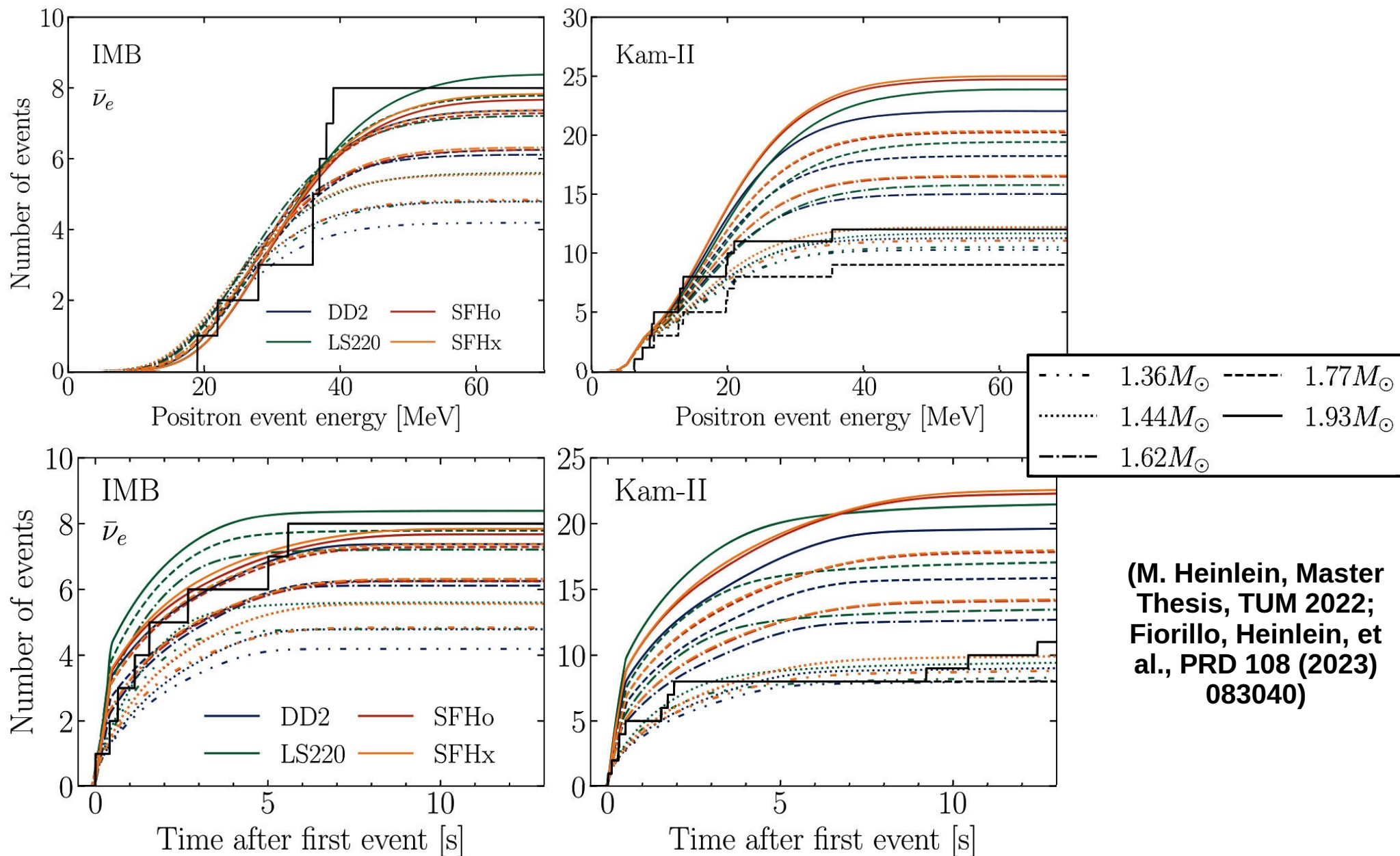


Damiano Fiorillo
(DESY), Postdoc



Malte Heinlein
(MPA), PhD

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



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

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

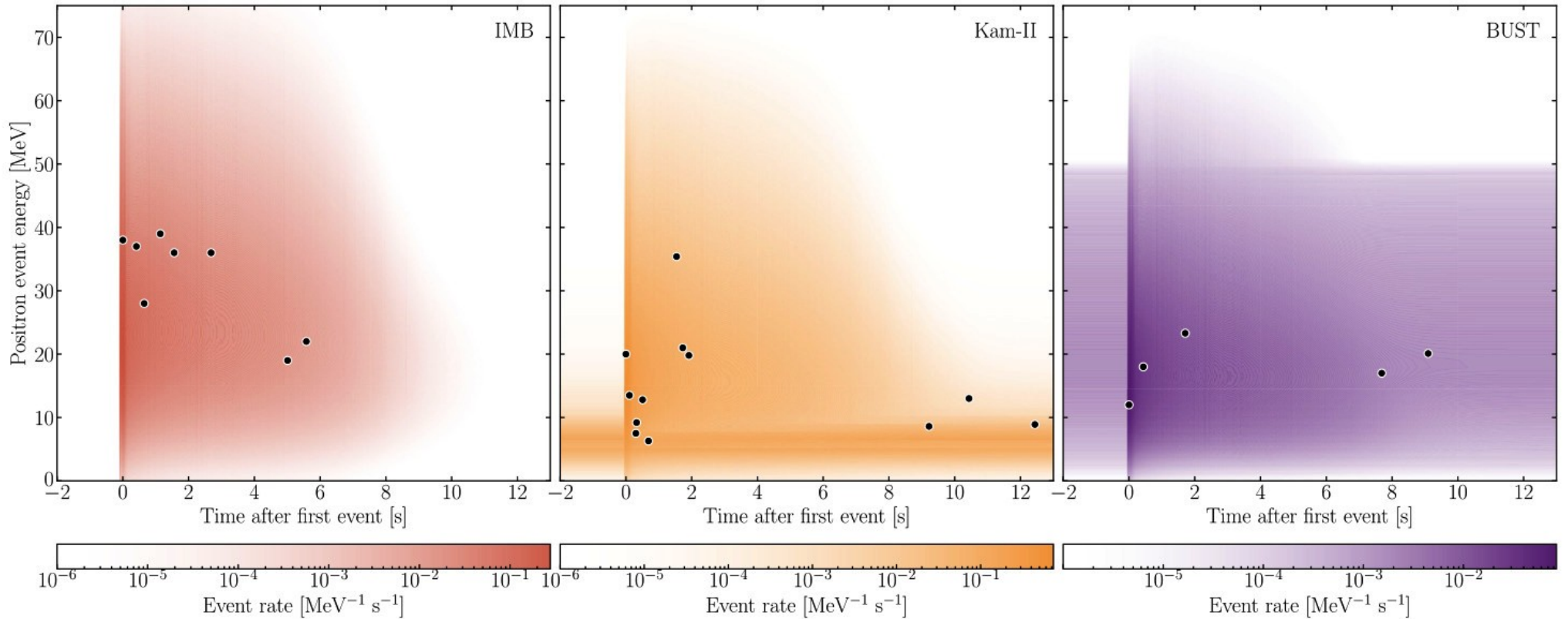
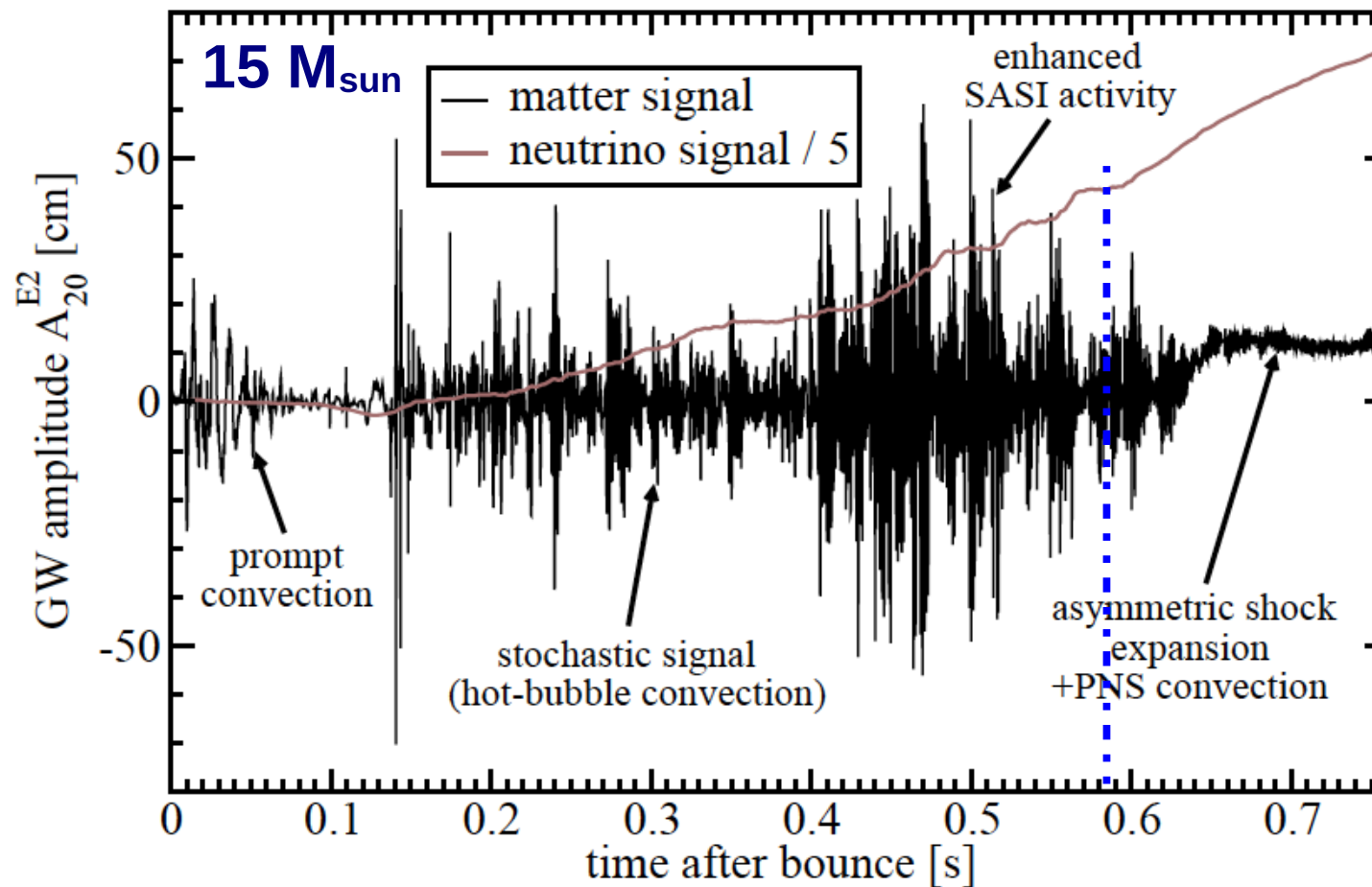


FIG. 17. Differential event distribution (signal and background) at each experiment, compared with the observations. Results are shown for model 1.44-SFHo without flavor swap; the offset time for each experiment is chosen as the best-fit value reported in Table VII.

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

Gravitational Waves
for
Neutrino-Driven Explosion
Models of 3D Progenitors

Gravitational Waves from SN Explosions



(Müller, THJ, & Marek, ApJ 766 (2013) 43)

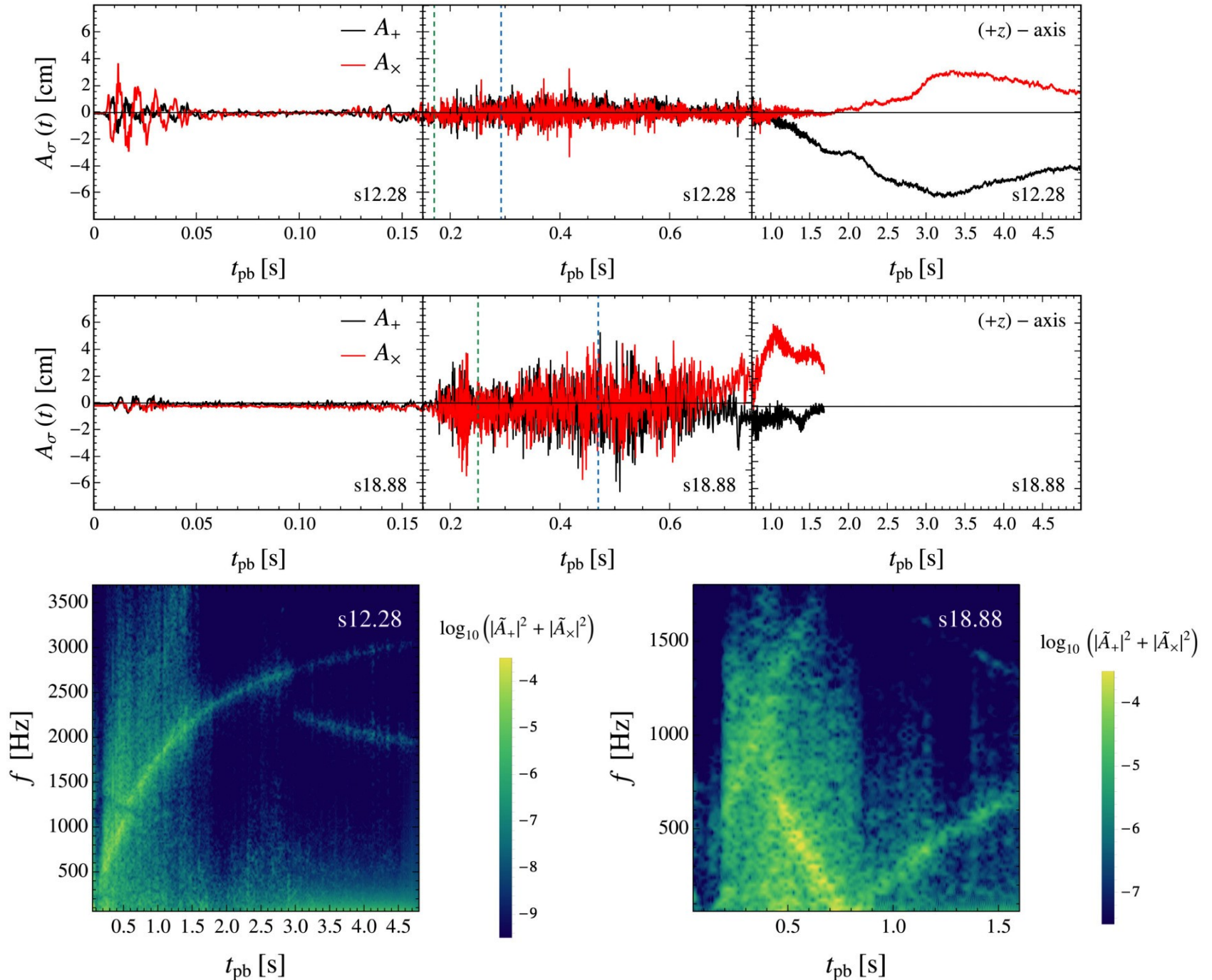
$$h = \frac{1}{8} \sqrt{\frac{15}{\pi}} \sin^2 \Theta \frac{A_{20}^{E2}}{R}$$

$$h_v = \frac{2G}{c^4 R} \int_0^t L_v(t') \alpha_v(t') dt'$$

$$\alpha_v = \frac{1}{L_v} \int \pi \sin \theta (2|\cos \theta| - 1) \frac{dL_v}{d\Omega} d\Omega$$

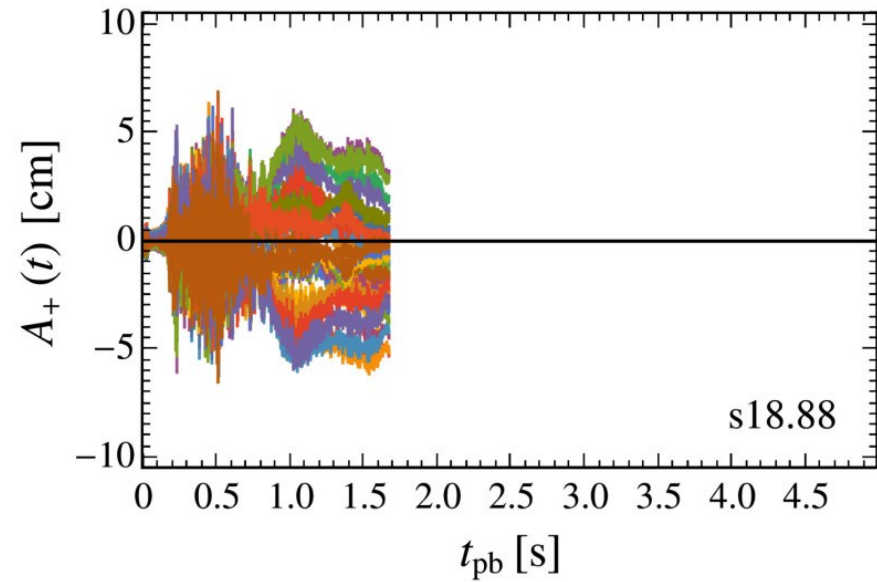
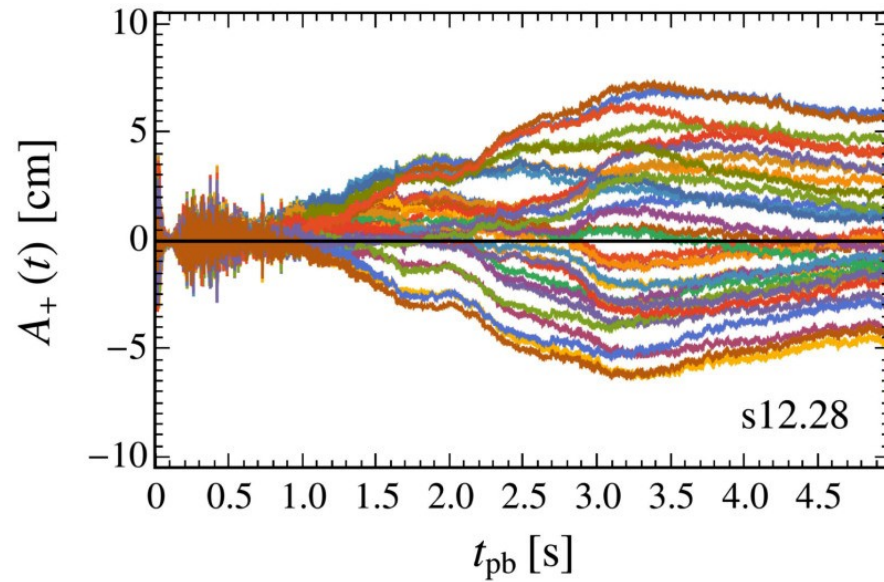
Gravitational Waves from 3D SN Explosions

GW matter
signals

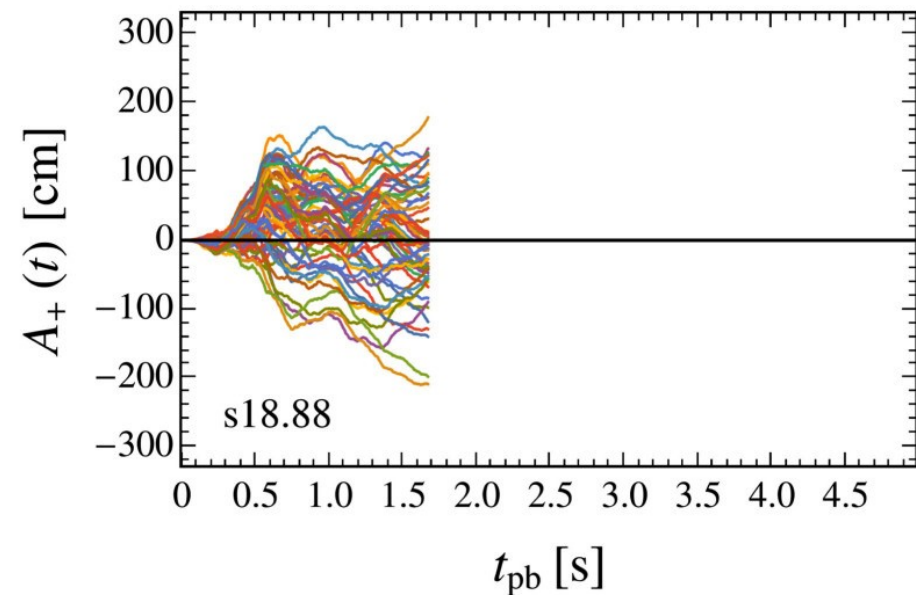
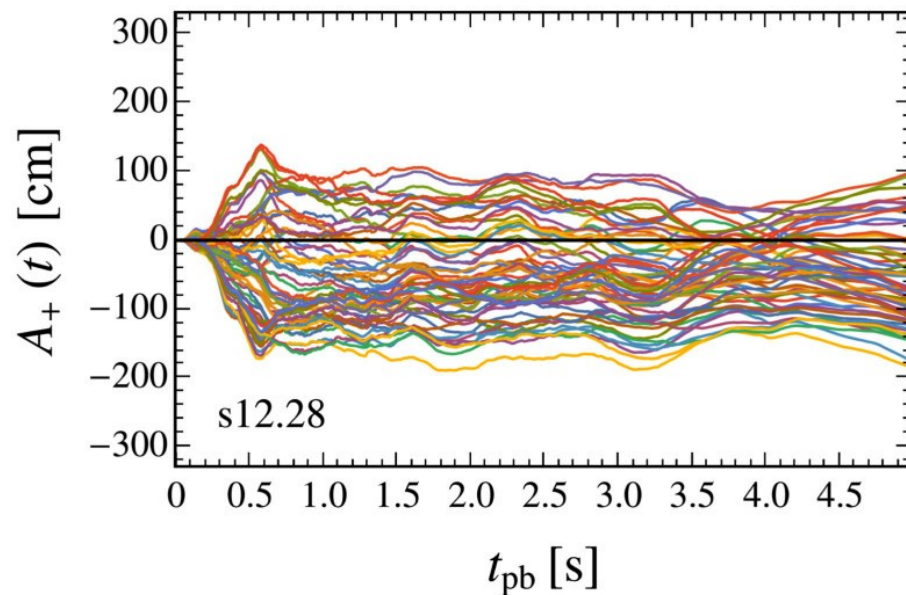


Gravitational Waves from 3D SN Explosions

Gravitational-wave amplitudes from matter motions

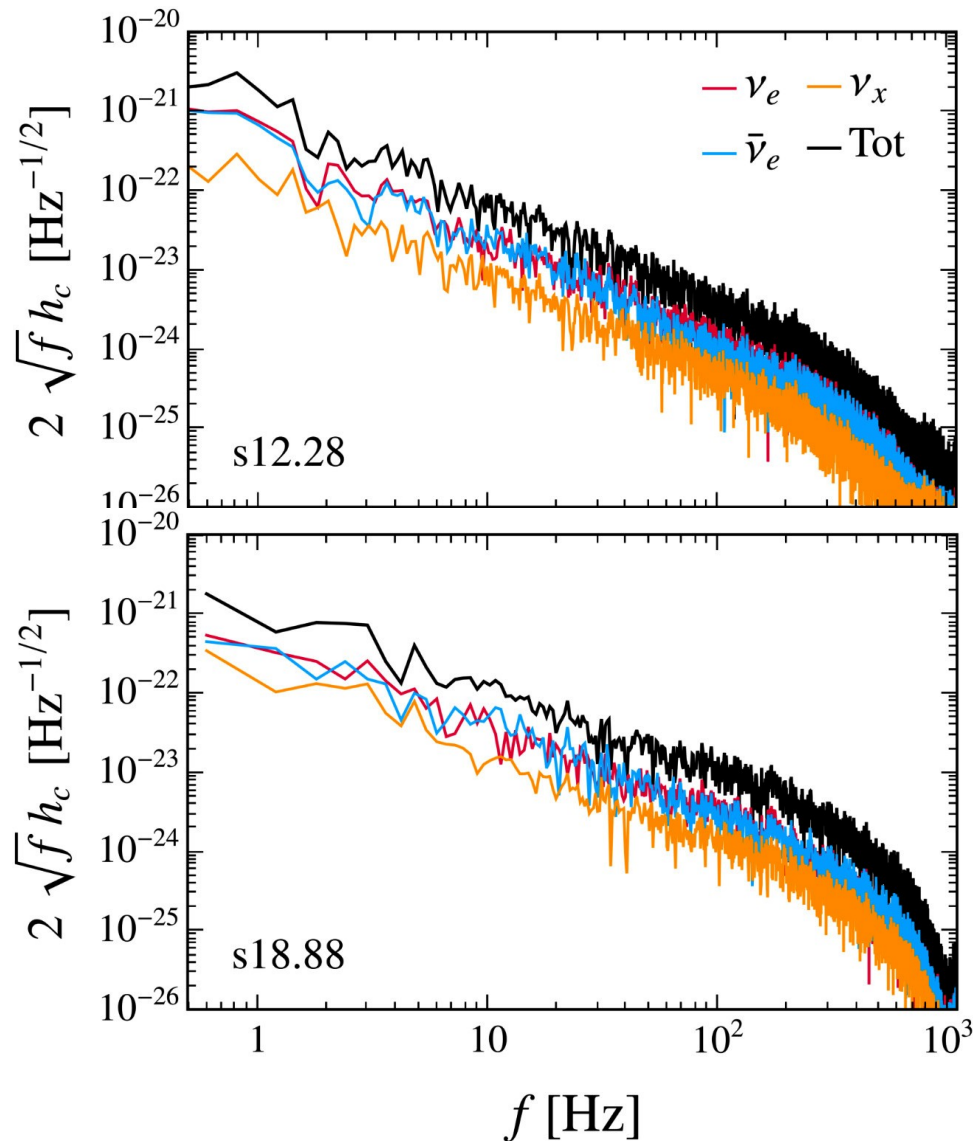


Gravitational-wave amplitudes from asymmetric neutrino emission

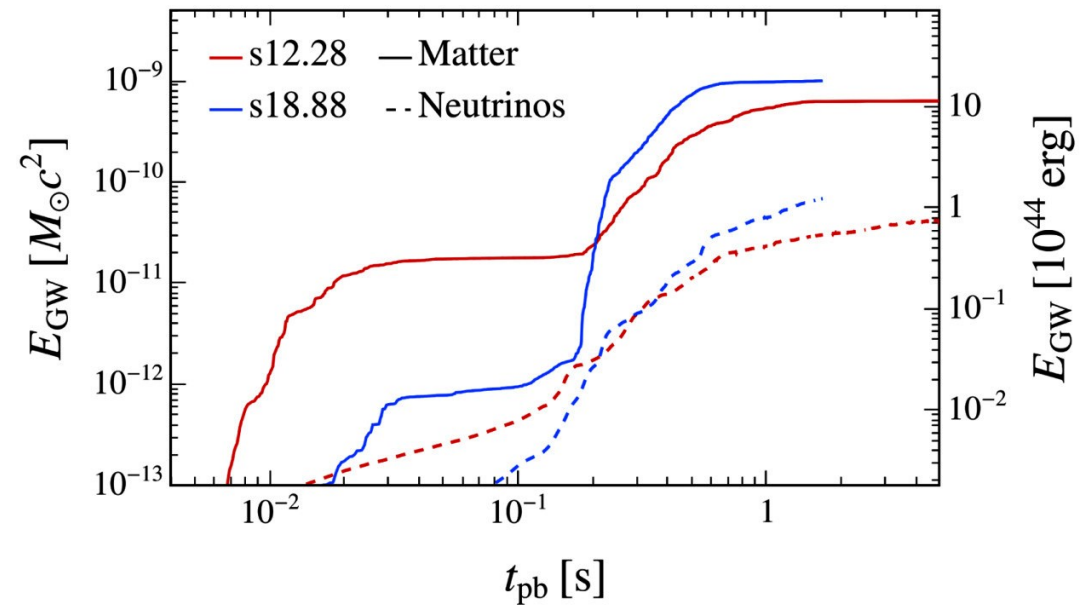


Gravitational Waves from 3D SN Explosions

**Amplitude spectral densities
(ASDs) for GWs due to
anisotropic neutrino emission**



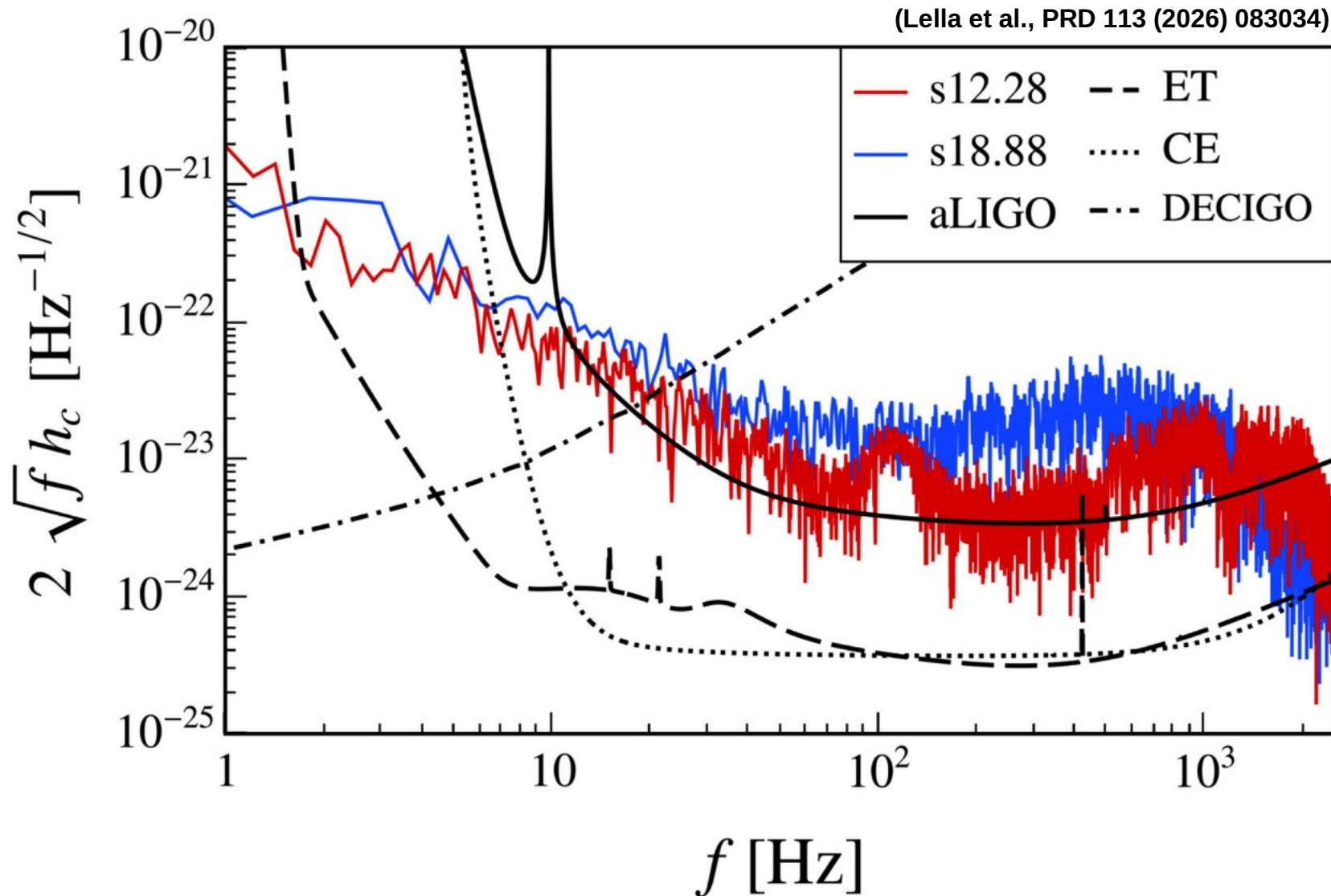
**VERTEX (Garching) simulations
of 12.28 M_{sun} and 18.88 M_{sun} stars**



(Lella et al., PRD 113 (2026) 083034)

Gravitational Waves from 3D SN Explosions

Gravitational-wave amplitude spectral densities for combined matter and neutrino GW signals (source distance: 10 kpc) compared to detector sensitivity curves



Microphysics Sensitivities
of
Neutrino-Driven Explosions

SN Simulations with Different Nuclear Equations of State

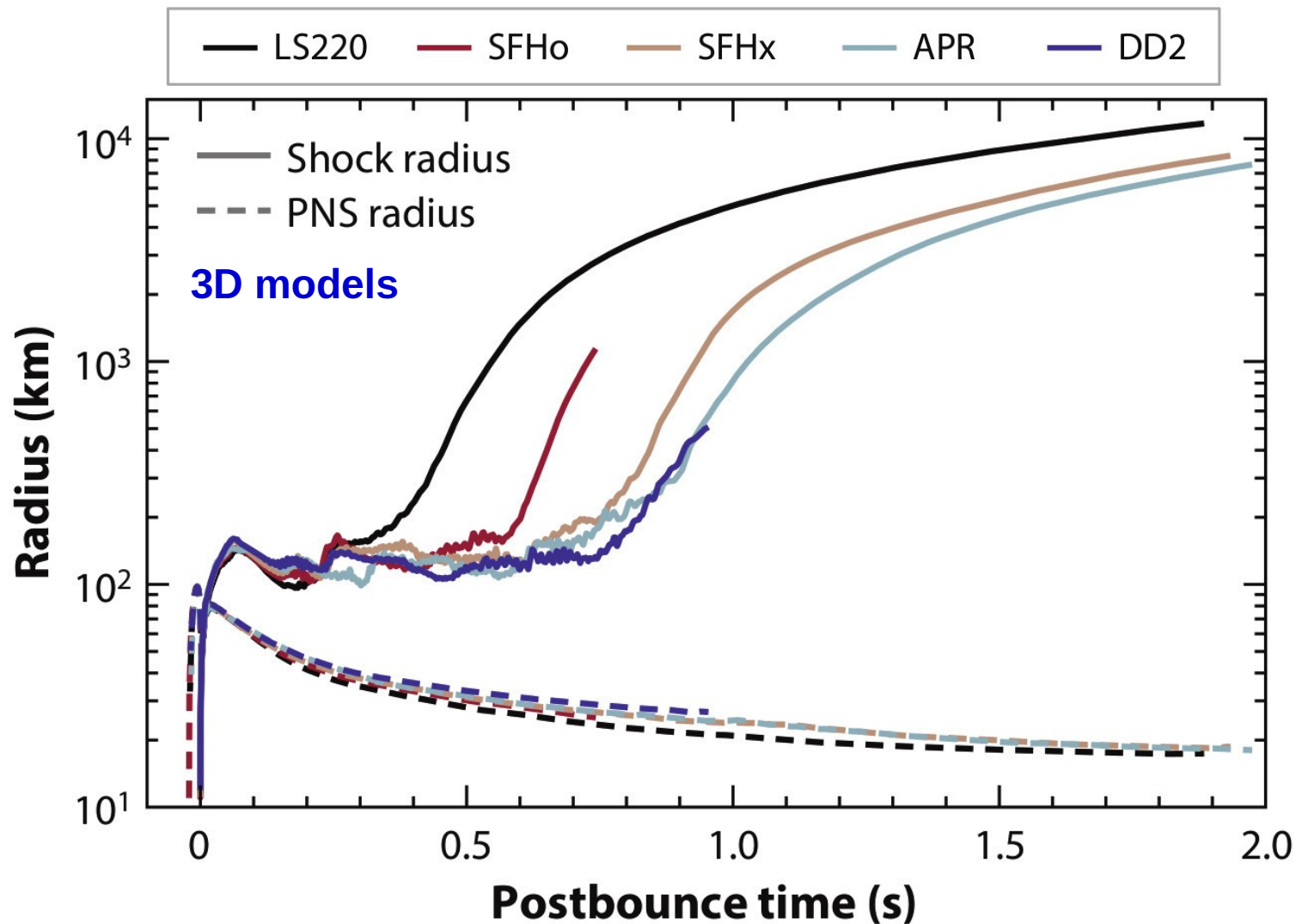


Daniel Kresse
(MPA) Postdoc



Robert Bollig
(MPA), Ex-Postdoc

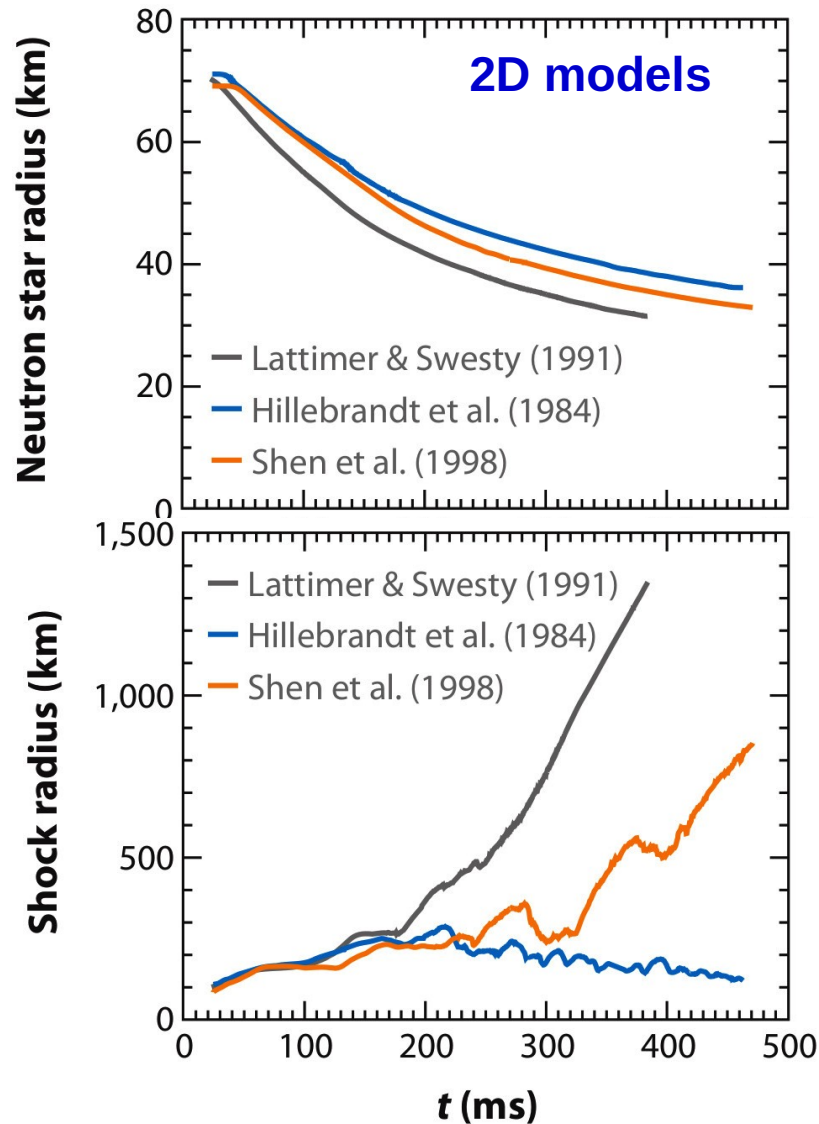
Onset of explosion depends on nuclear EoS



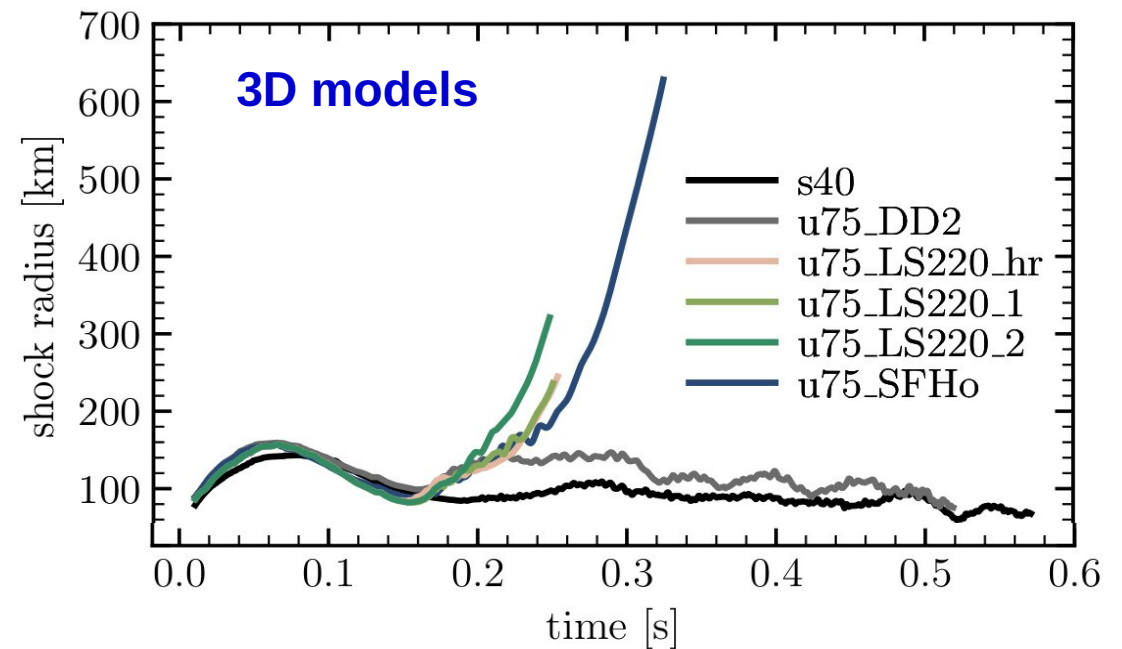
HTJ & Bauswein, Handbook of Nuclear Physics
(Springer-Nature, 2023); HTJ, ARNPS 75 (2025) 425;
Figure courtesy of Daniel Kresse

BH Formation is Depends on Nuclear Equation of State

(HTJ, ARNPS 62 (2012) 407)

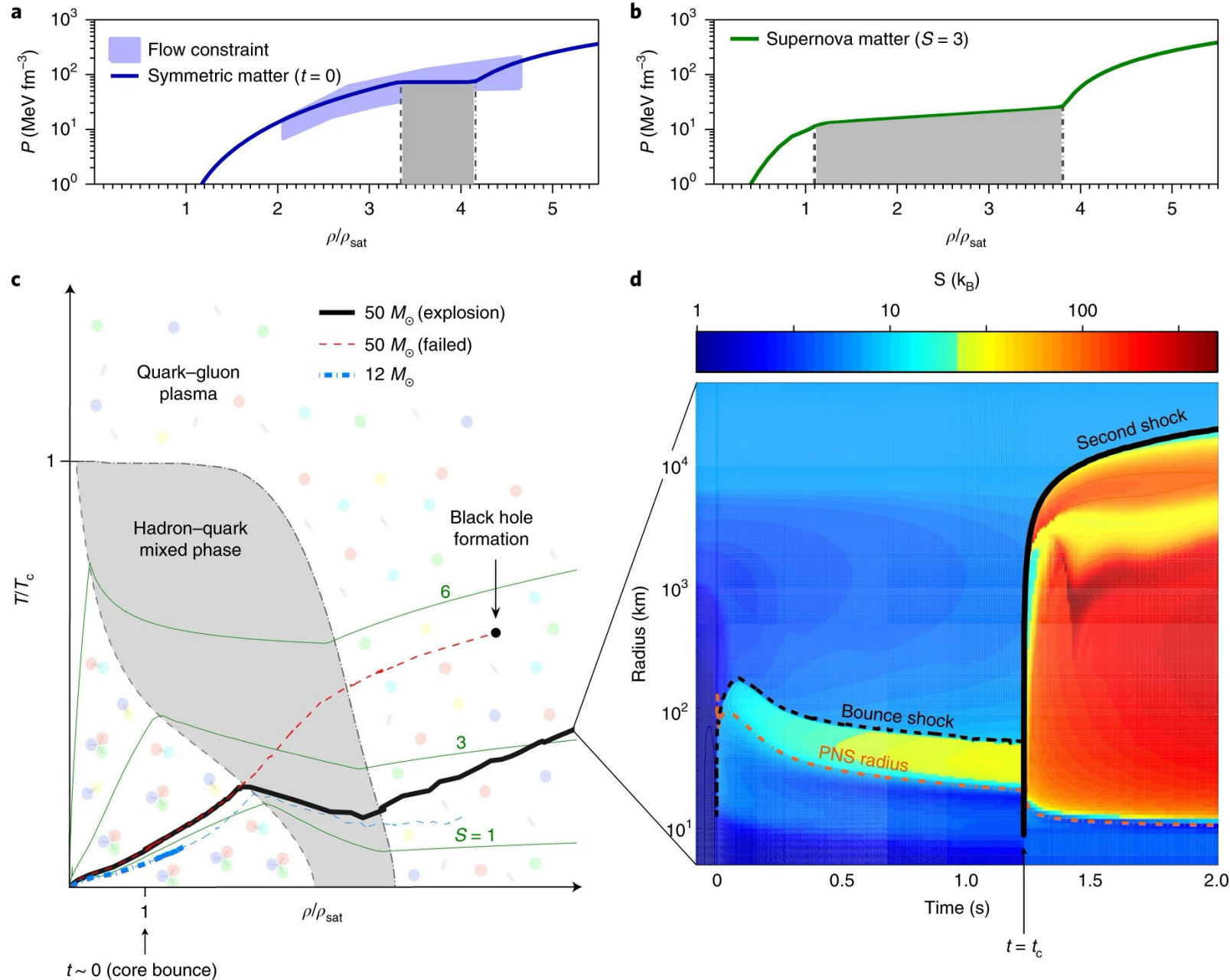


Explosion vs. BH formation and BH formation w/wo shock expansion depend on nuclear EoS



(D. Kresse, PhD Thesis, TUM, 2023;
HTJ & D. Kresse, A&SS 369 (2024) 80)

Does a Hadron-Quark Phase Transition Occur?



Kinetic Equation for Neutrino Transport

Flavor-dependent phase-space densities (occupation number matrices)

$$\varrho = \begin{pmatrix} f_{\nu_e} & f_{\langle \nu_e | \nu_\mu \rangle} & f_{\langle \nu_e | \nu_\tau \rangle} \\ f_{\langle \nu_\mu | \nu_e \rangle} & f_{\nu_\mu} & f_{\langle \nu_\mu | \nu_\tau \rangle} \\ f_{\langle \nu_\tau | \nu_e \rangle} & f_{\langle \nu_\tau | \nu_\mu \rangle} & f_{\nu_\tau} \end{pmatrix}$$

Diagonal: Usual occupation numbers
Off-diag: Flavor coherence information

and similar for $\bar{\nu}$

Transport equation

$$\underbrace{(\partial_t + \vec{v} \cdot \vec{\nabla}_r)}_{\text{Streaming}} \underbrace{- \vec{F} \cdot \vec{\nabla}_p}_{\text{Gravitational forces}} \varrho(t, \vec{r}, \vec{p}) = \underbrace{-i [\mathcal{H}(t, \vec{x}, \vec{p}), \varrho(t, \vec{x}, \vec{p})]}_{\text{Flavor oscillations}} + \underbrace{\mathcal{C}[\varrho(t, \vec{x}, \vec{p})]}_{\text{Collisions}}$$

Hamiltonian for **flavor oscillations**

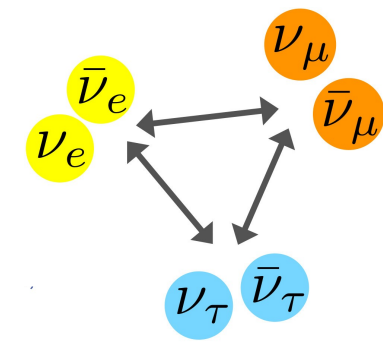
$$H = \underbrace{\frac{M^2}{2E}}_{\text{vacuum}} + \underbrace{\sqrt{2}G_F n_e}_{\text{MSW effect}} + \underbrace{\sqrt{2}G_F \int \frac{d^3p}{(2\pi)^3} (\rho - \bar{\rho}) (1 - v_q v_p)}_{\nu\nu \text{ self-induced}}$$

$$\beta \begin{cases} \bullet e^- + p \rightleftharpoons n + \nu_e \\ \bullet e^+ + n \rightleftharpoons p + \bar{\nu}_e \\ \bullet e^- + A \rightleftharpoons \nu_e + A^* \end{cases}$$

$$\begin{cases} \bullet \nu + n, p \rightleftharpoons \nu + n, p \\ \bullet \nu + A \rightleftharpoons \nu + A \\ \bullet \nu + e^\pm \rightleftharpoons \nu + e^\pm \\ \bullet N + N \rightleftharpoons N + N + \nu + \bar{\nu} \\ \bullet e^+ + e^- \rightleftharpoons \nu + \bar{\nu} \\ \bullet \nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e \\ \quad (\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \text{ or } \bar{\nu}_\tau) \\ \bullet \nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau} \end{cases}$$

- Flavor evolution is caused by off-diagonal $\mathcal{H}$ elements (vacuum or nu-nu term)
- For $\Delta m^2 = 0$, nu-nu term can still cause run-away modes!

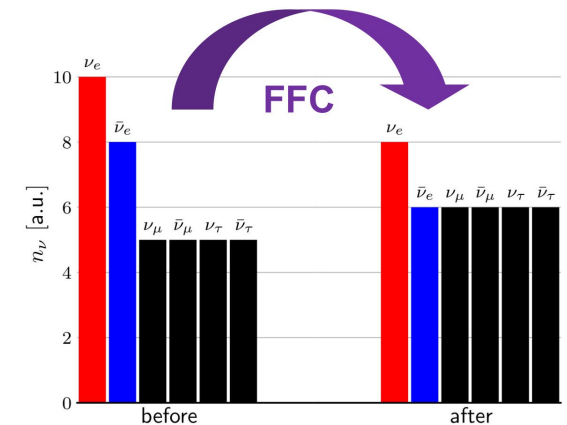
Neutrino Flavor Conversion (FC) in SN Explosions



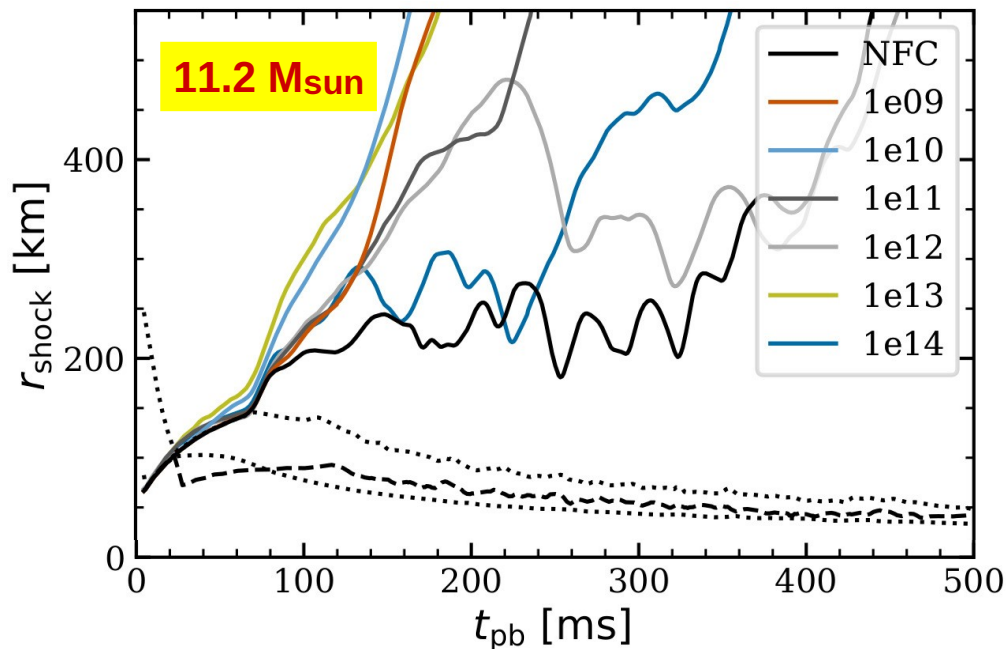
Jakob Ehring
(MPP/MPA), PhD

Fast pair-wise conversion $\nu_x \rightarrow \nu_e, \bar{\nu}_e$
can boost the neutrino heating due to
higher mean energies

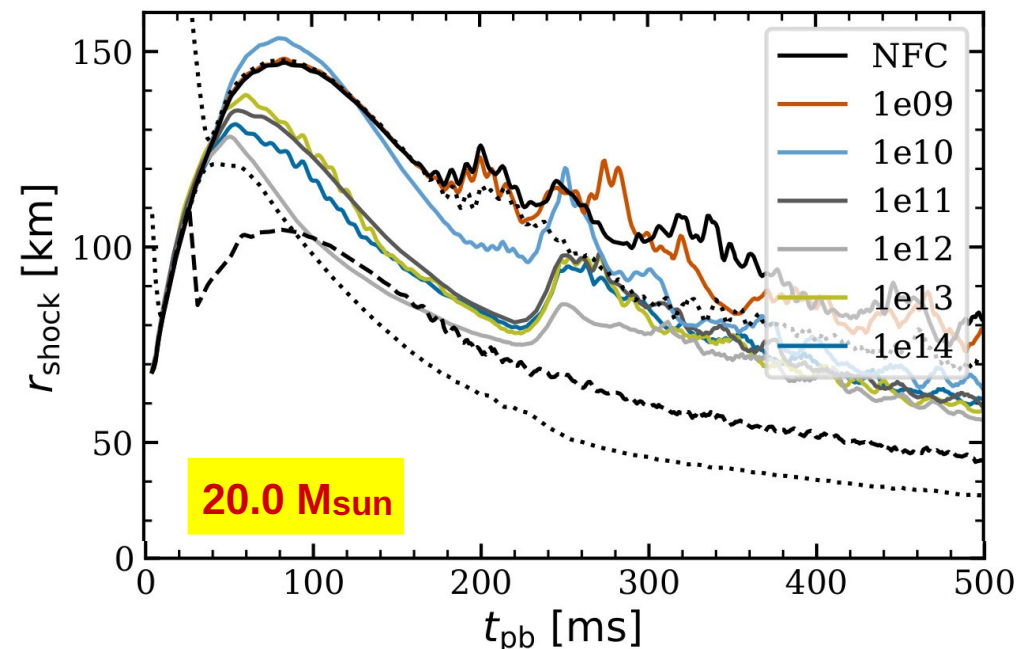
=====> **Earlier explosions of low-mass
progenitors; but $\nu_e, \bar{\nu}_e \rightarrow \nu_x$ conversion tends
to disfavor explosions of high-mass progenitors.**



[NFC = no flavor conversion]



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

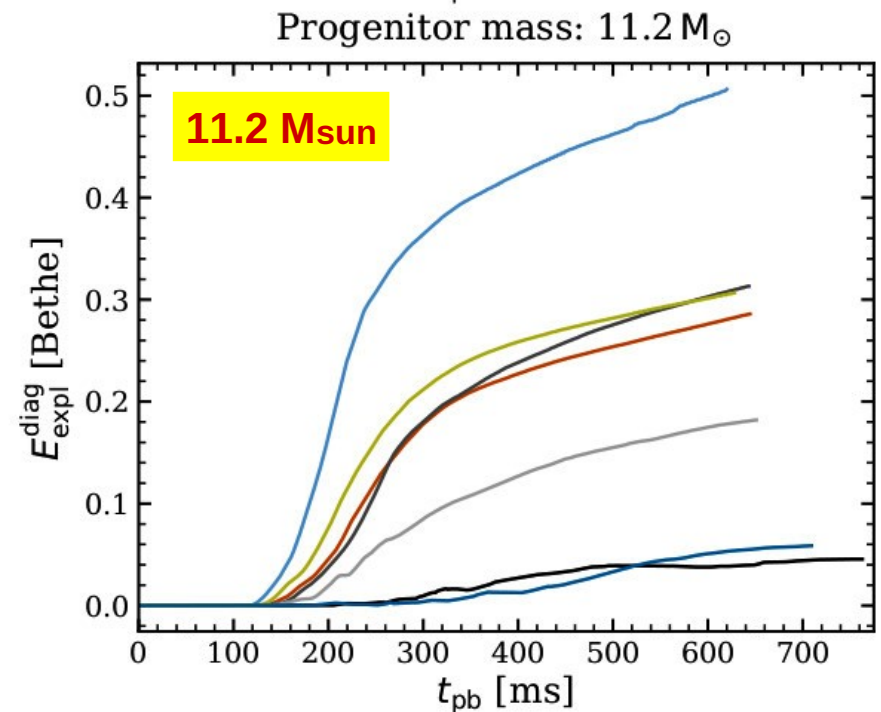
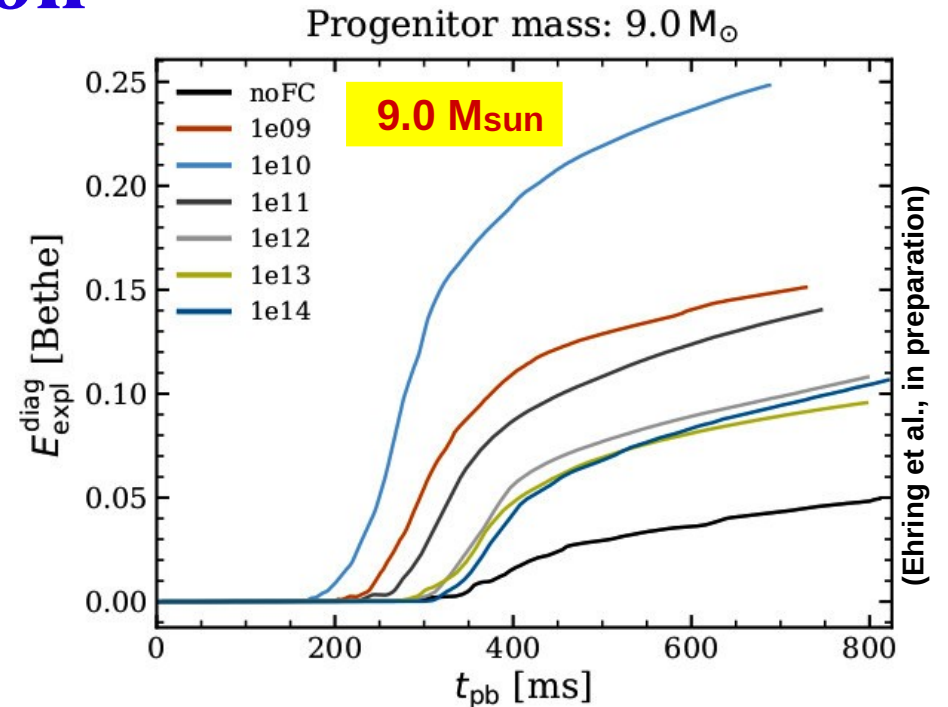


Neutrino Flavor Conversion (FC) in SN Explosions



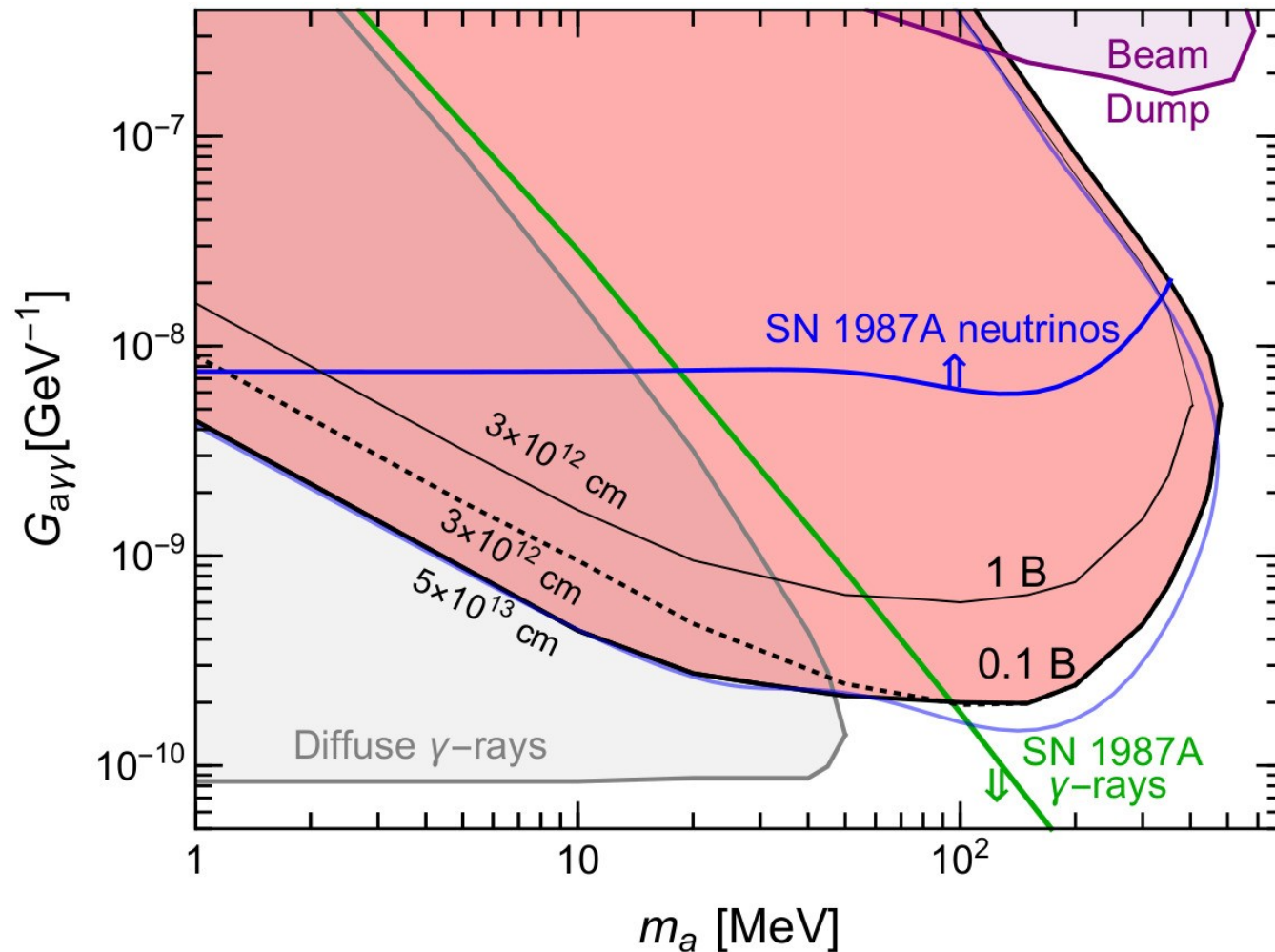
Jakob Ehring
(MPP/MPA), PhD

Neutrino FC can change the onset time of the explosion and the explosion energy, depending on when and where it occurs.



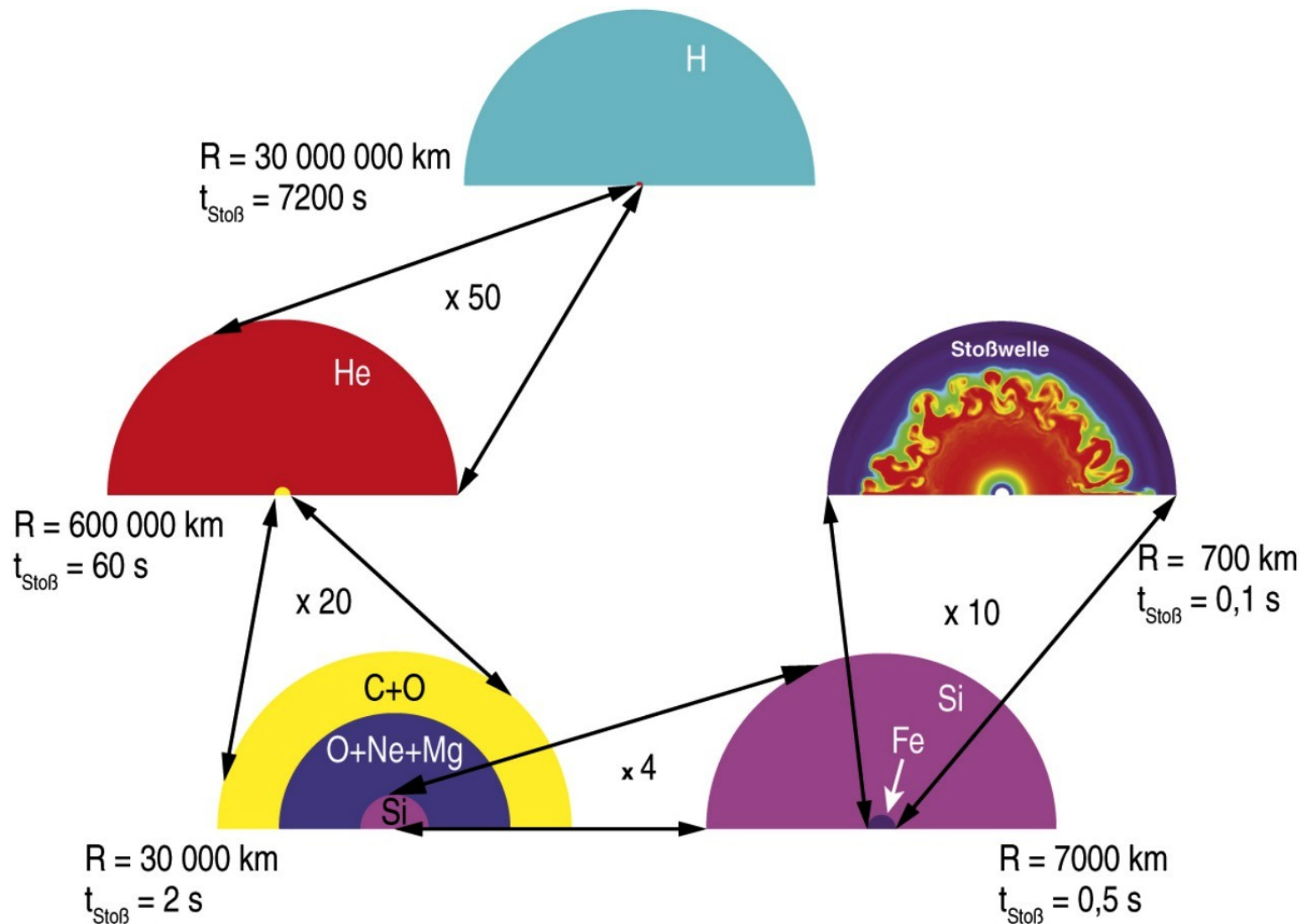
Low-energy Supernovae Constrain Radiative Particle Decays

Energy deposition by radiative decays of axion-like particles (ALPs) must not over-power low-energy, low-luminosity SNe



Caputo, THJ, et al., PRL 128 (2022) 221103

**3D asymmetries from the onset of the explosion
determine asymmetry of the SN ejecta and SN remnant.
Modeling of the explosion has to be performed in 3D
consistently from pre-collapse stage to SNR phase !**

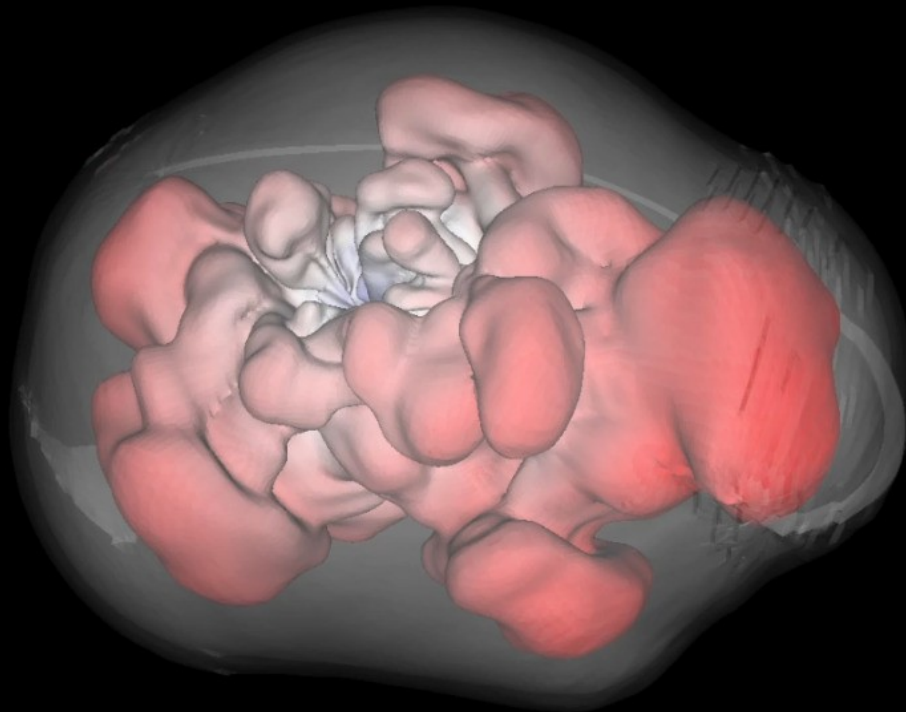


3D Long-Term Evolution Beyond Shock Breakout

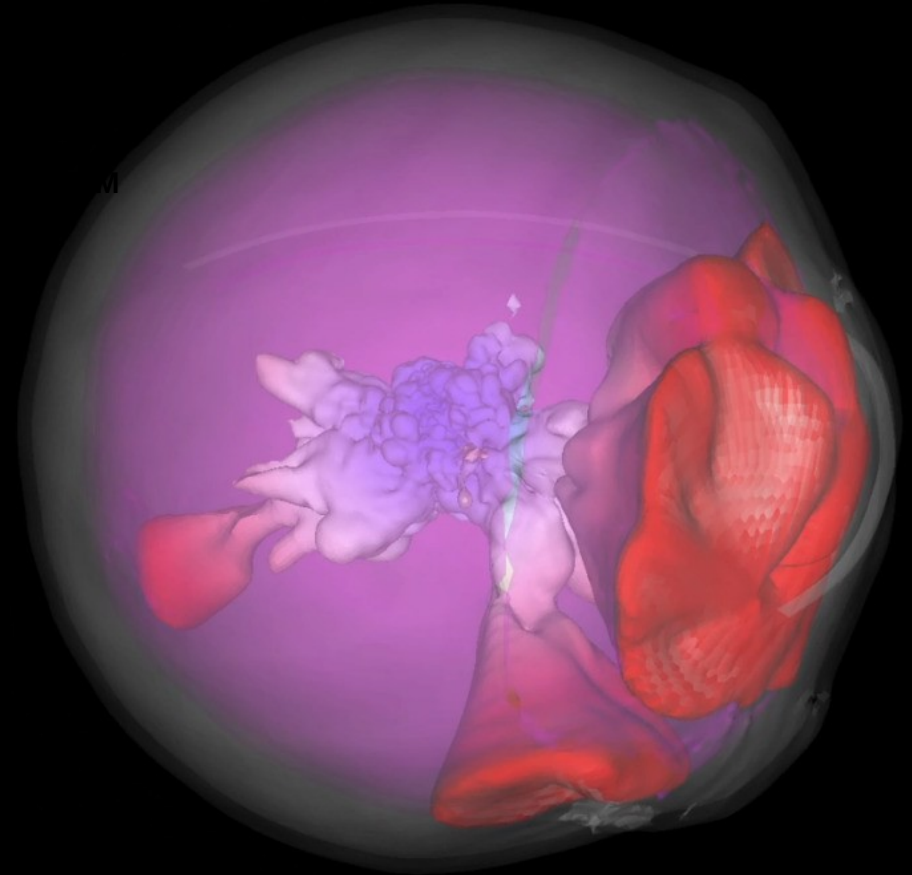
3D morphology of early explosion is reflected by the late-time geometry of the distribution of ejected iron

Courtesy: B. Giudici (2025)

2.5 seconds



1 year



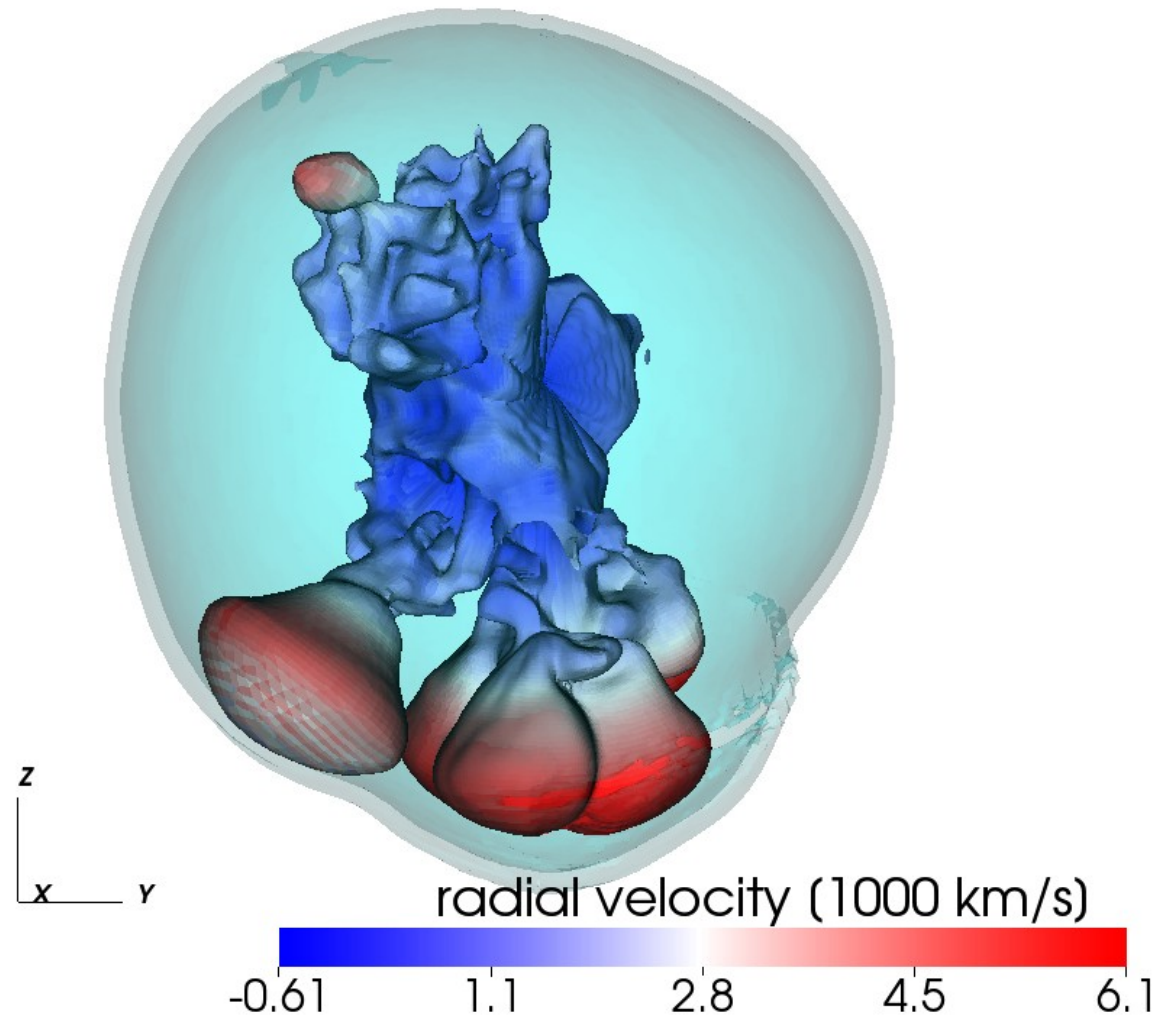
3D Long-Term Evolution Beyond Shock Breakout

WH12.5

1e14 cm

Time=1.6 d

96% mass of
NiCoFe+0.5X

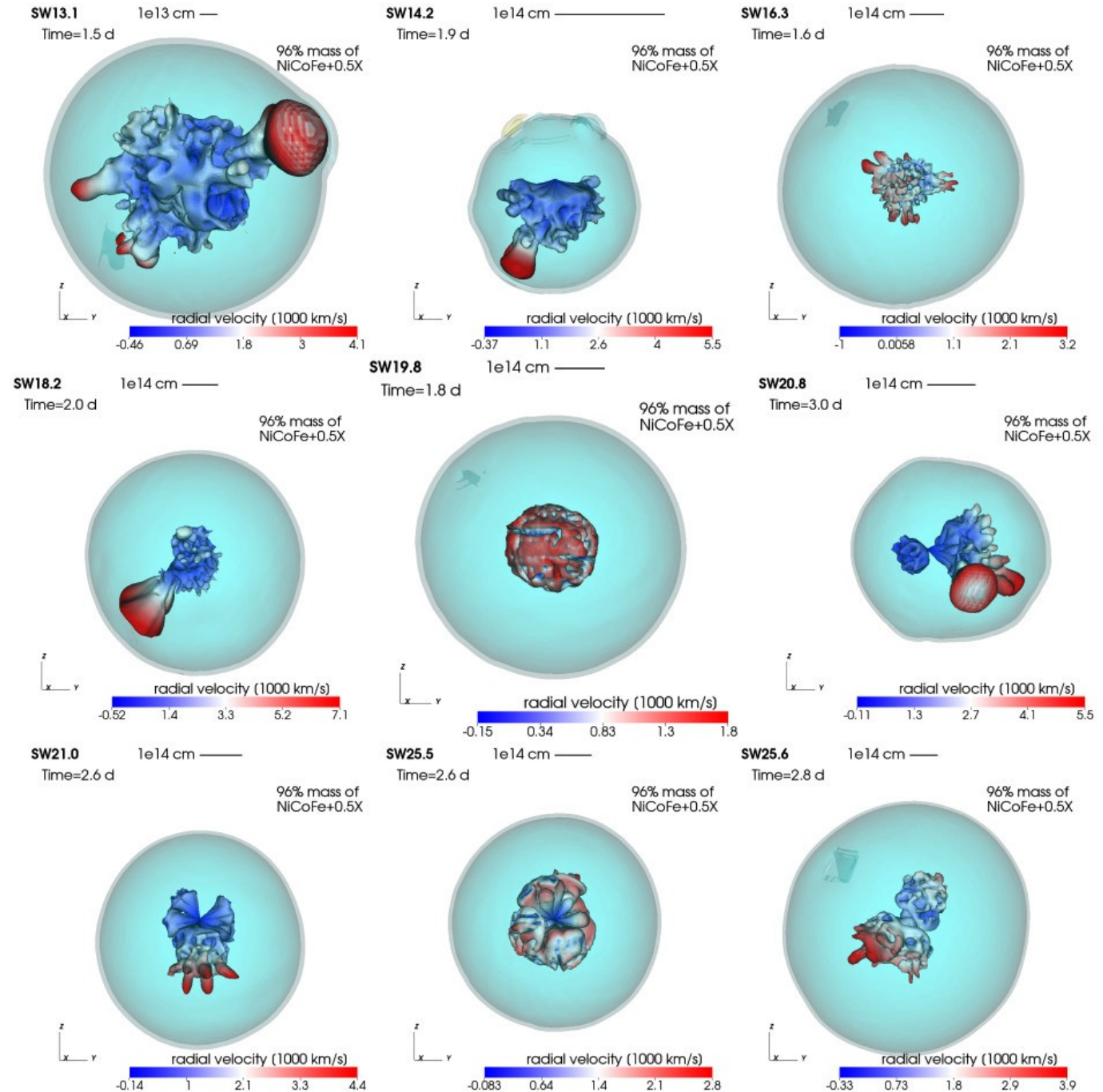


(Giudici, Gabler, & HTJ, eprint arXiv:2511.11796)

3D Long-Term Evolution Beyond Shock Breakout

3D morphology of the explosion in terms of the distribution of radioactive ^{56}Ni and its decay products depends on stochastic effects and the progenitor structure.

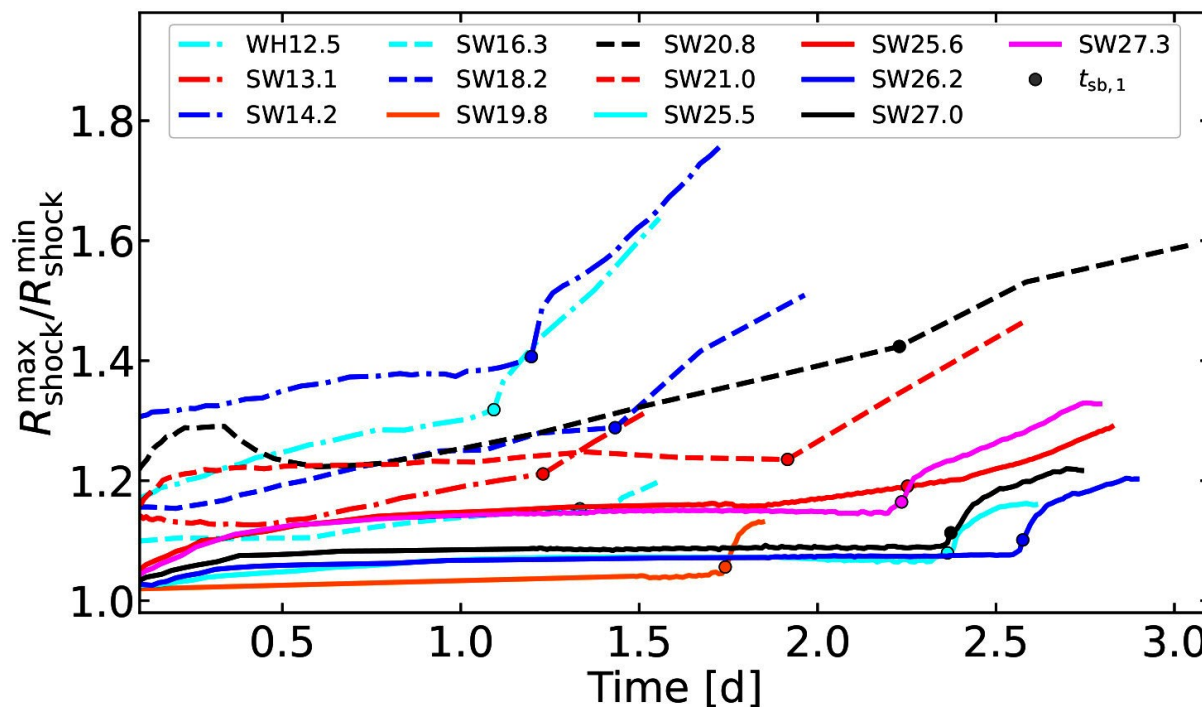
It is different for every progenitor and explosion.



3D Long-Term Evolution Beyond Shock Breakout

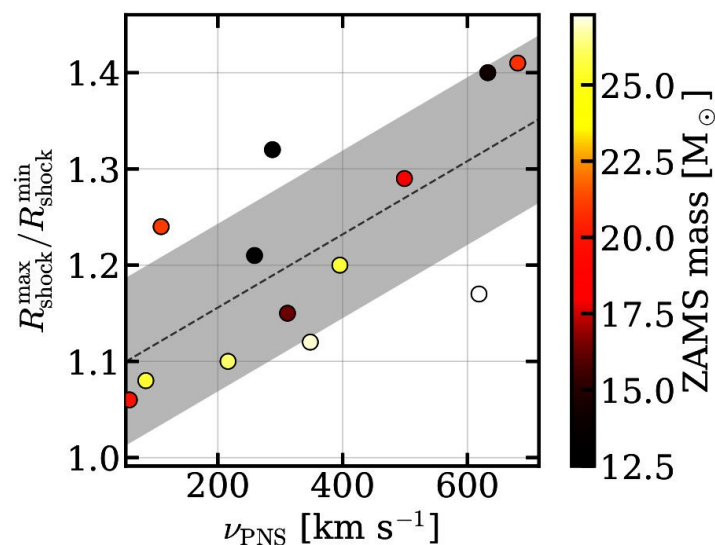
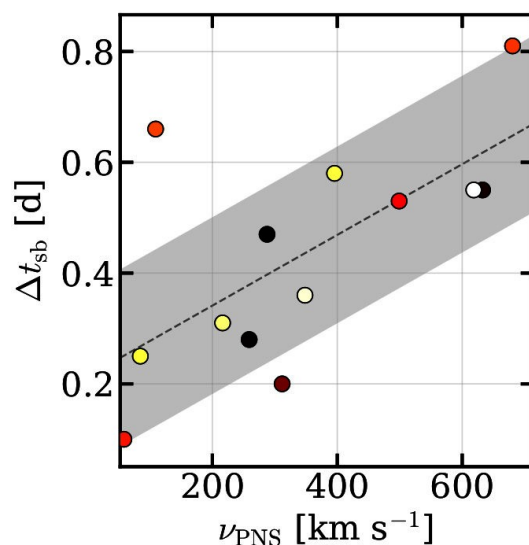
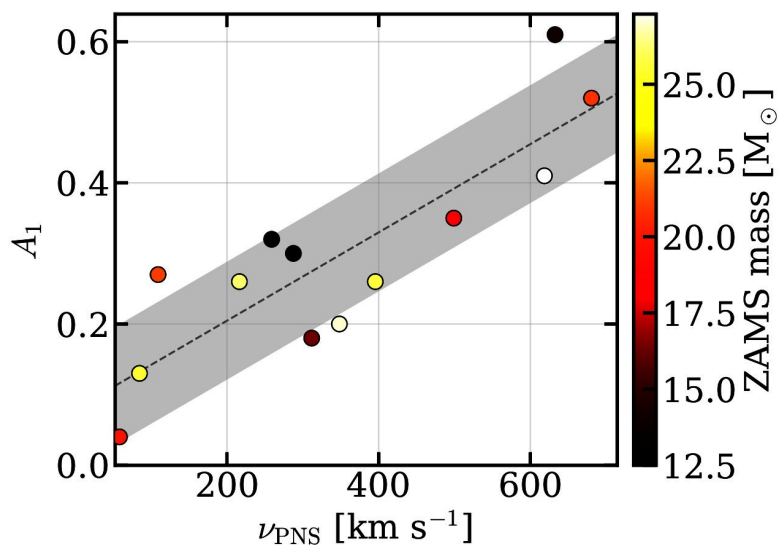
Strong correlation of neutron-star kick velocity with ^{56}Ni momentum asymmetry.

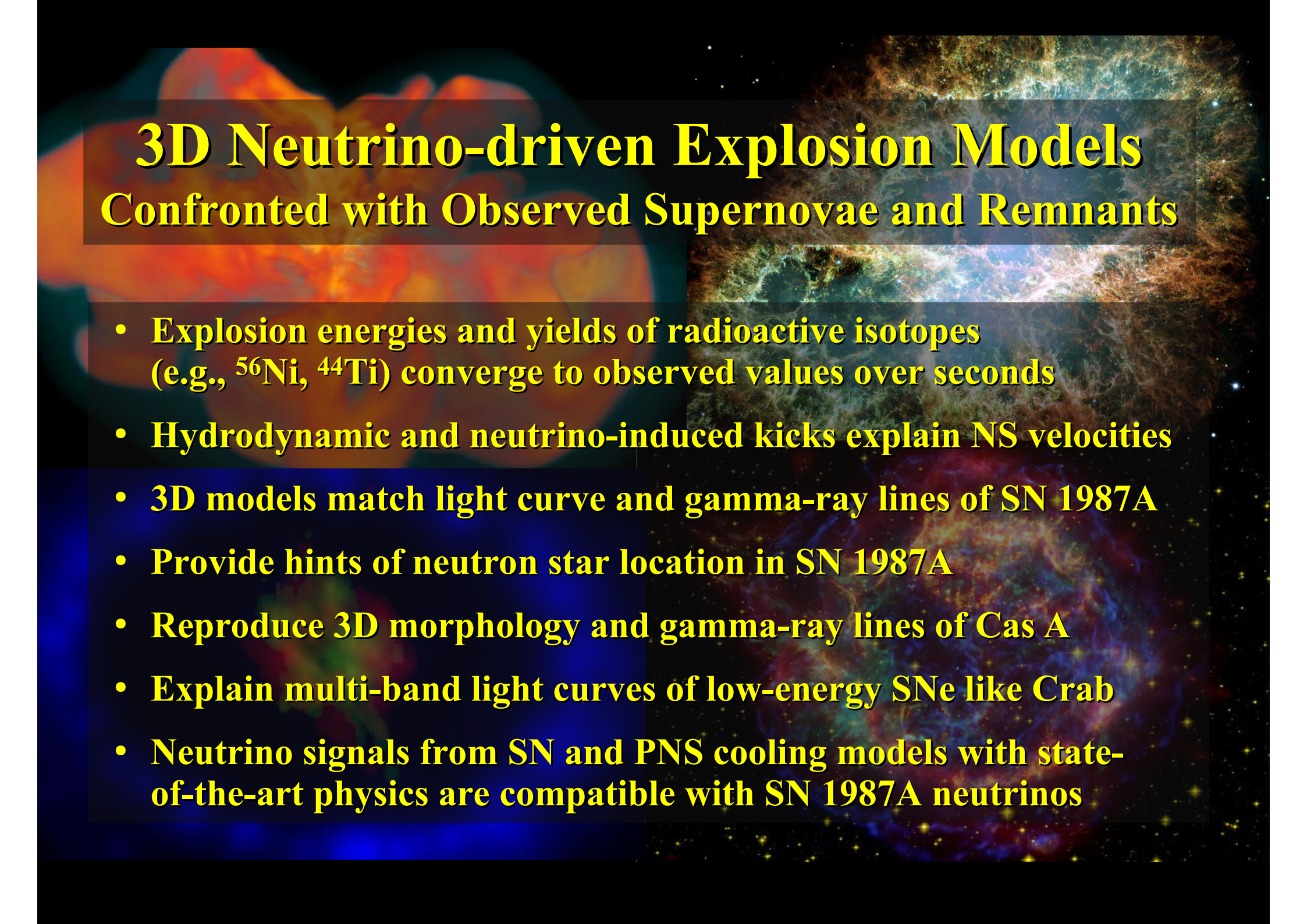
Weak correlation of neutron-star kick velocity with asymmetry of shock breakout.



(Giudici, Gabler, & HTJ, eprint arXiv:2511.11796)

A₁ : Dipole moment of ^{56}Ni momentum distribution at 2.5 s post bounce





3D Neutrino-driven Explosion Models

Confronted with Observed Supernovae and Remnants

- **Explosion energies and yields of radioactive isotopes (e.g., ^{56}Ni , ^{44}Ti) converge to observed values over seconds**
- **Hydrodynamic and neutrino-induced kicks explain NS velocities**
- **3D models match light curve and gamma-ray lines of SN 1987A**
- **Provide hints of neutron star location in SN 1987A**
- **Reproduce 3D morphology and gamma-ray lines of Cas A**
- **Explain multi-band light curves of low-energy SNe like Crab**
- **Neutrino signals from SN and PNS cooling models with state-of-the-art physics are compatible with SN 1987A neutrinos**

Summary

- Self-consistent 3D models can yield neutrino-driven explosions, but cannot (yet) predict *which* massive stars explode.
- 2D and 3D simulations by different groups do not agree in predicting explosions and explosion properties.
- Self-consistent Garching models (*Vertex* and *Alcar* codes) need special ingredients (low-mass or 3D progenitors, rapid rotation, slightly reduced neutrino scattering opacities) for explosions.
- Neutrino-driven explosions reproduce properties of supernovae (SNe), neutron stars, and SN remnants, e.g. Cas A and SN 1987A.
- Gravitational waves from a Galactic SN at 10 kpc are (barely) detectable with current interferometers but will be well measurable with future instruments.
- Signals predicted by different groups differ significantly in many aspects.