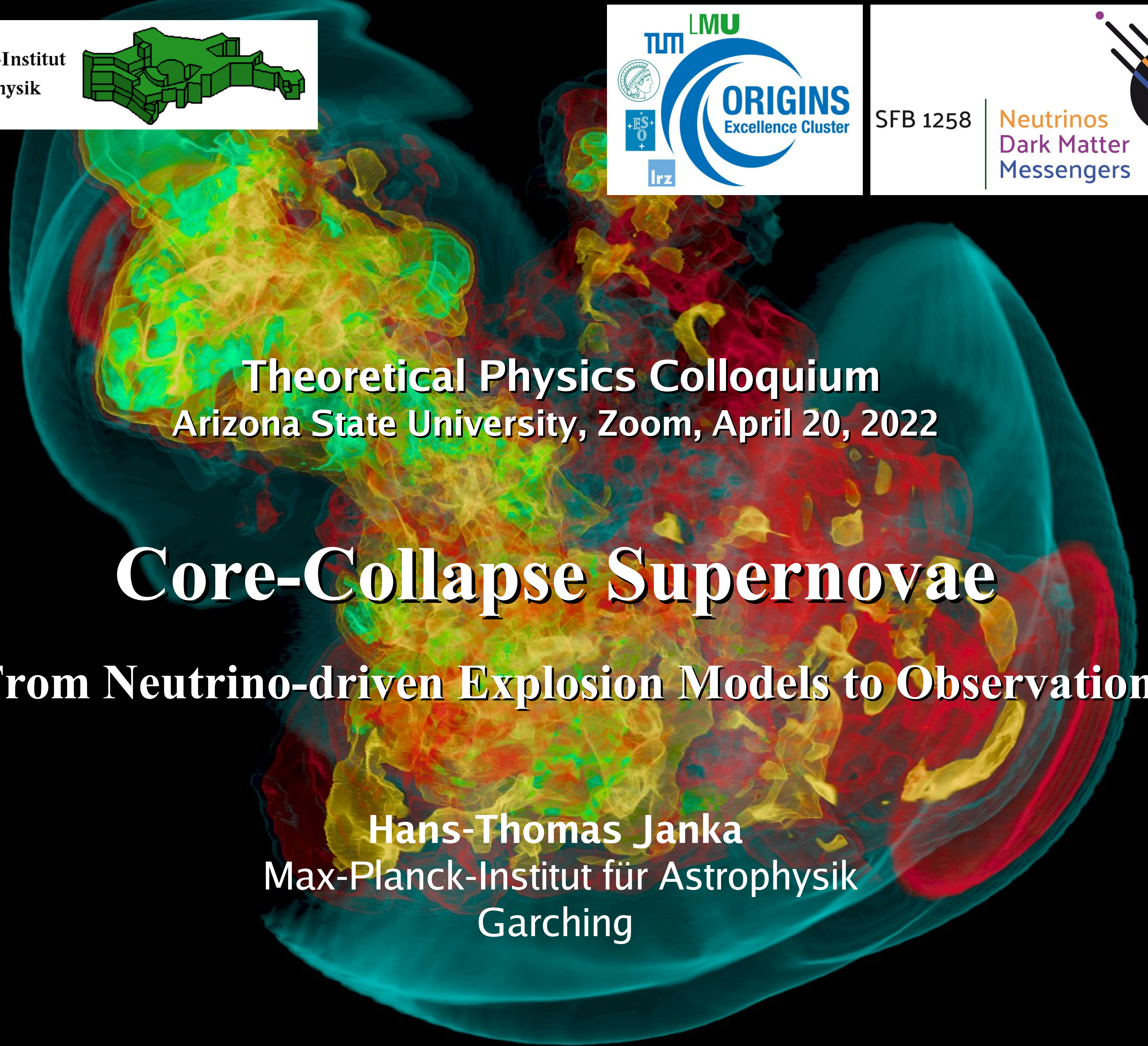
Max-Planck-Institut für Astrophysik

TUM LMU ORIGINS Excellence Cluster

SFB 1258 Neutrinos Dark Matter Messengers



Theoretical Physics Colloquium
Arizona State University, Zoom, April 20, 2022

Core-Collapse Supernovae

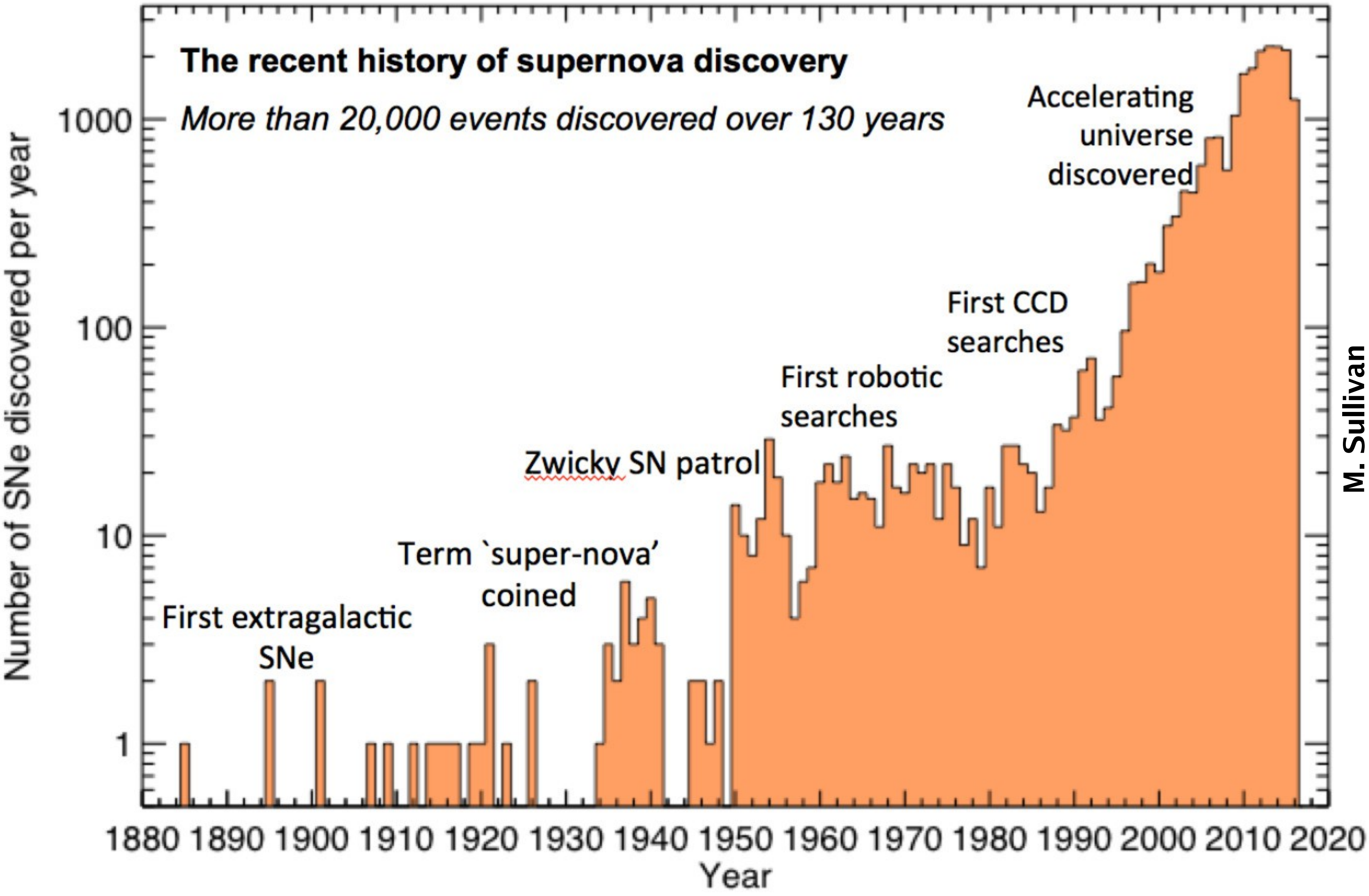
From Neutrino-driven Explosion Models to Observations

Hans-Thomas Janka
Max-Planck-Institut für Astrophysik
Garching

Contents

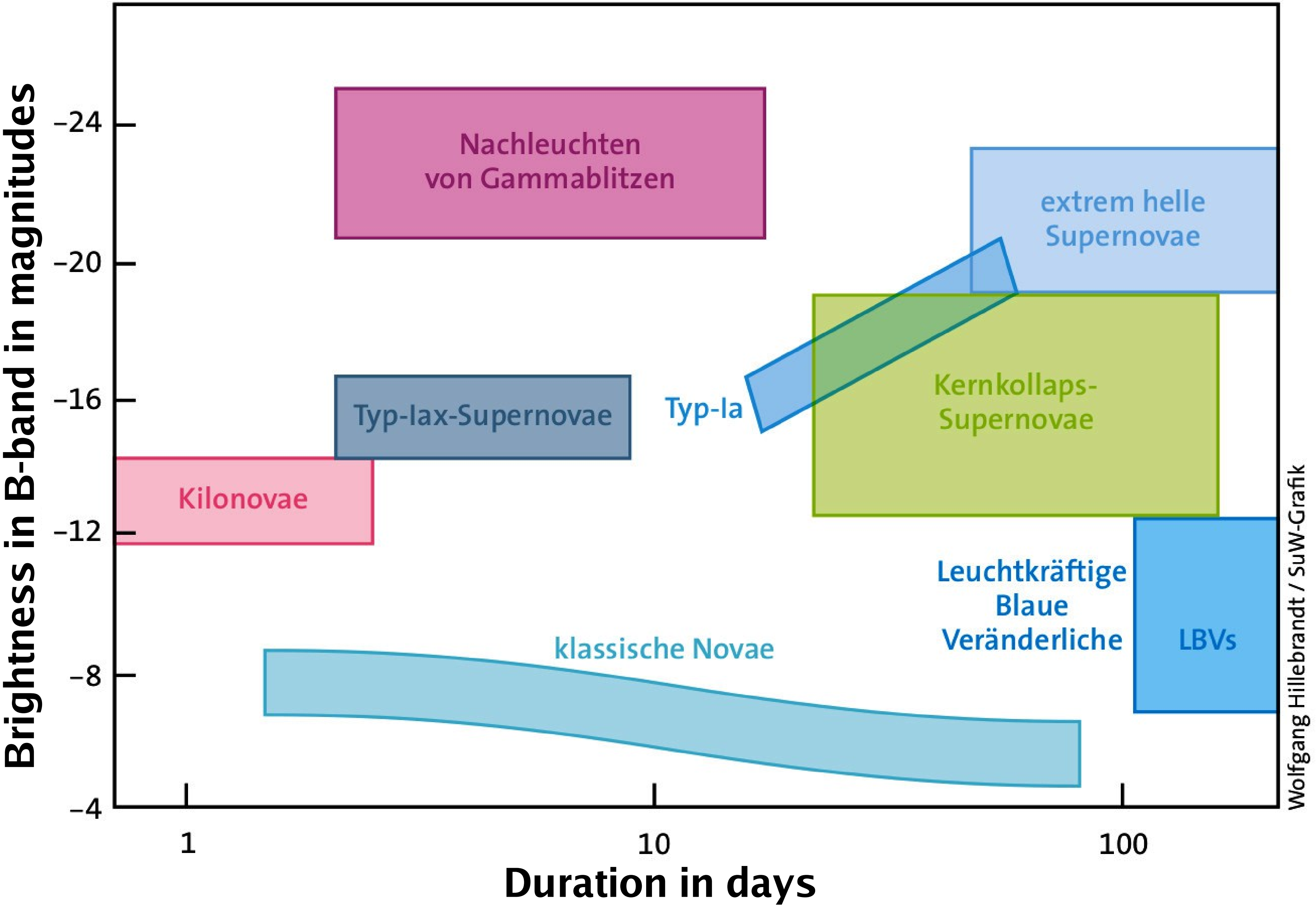
1. Basic core-collapse supernova (CCSN) physics
2. Status of "ab initio" 3D CCSN modeling of the neutrino-driven explosion mechanism
3. Importance of pre-collapse progenitor asymmetries for SN explosions in 3D
4. Some observational implications (supernova properties, neutron star kicks, SN remnant morphology)
5. Open questions & perspectives

Supernova Discoveries



M. Sullivan

Growing Diversity in the Zoo of "Transients"



Wolfgang Hillebrandt / SuW-Grafik

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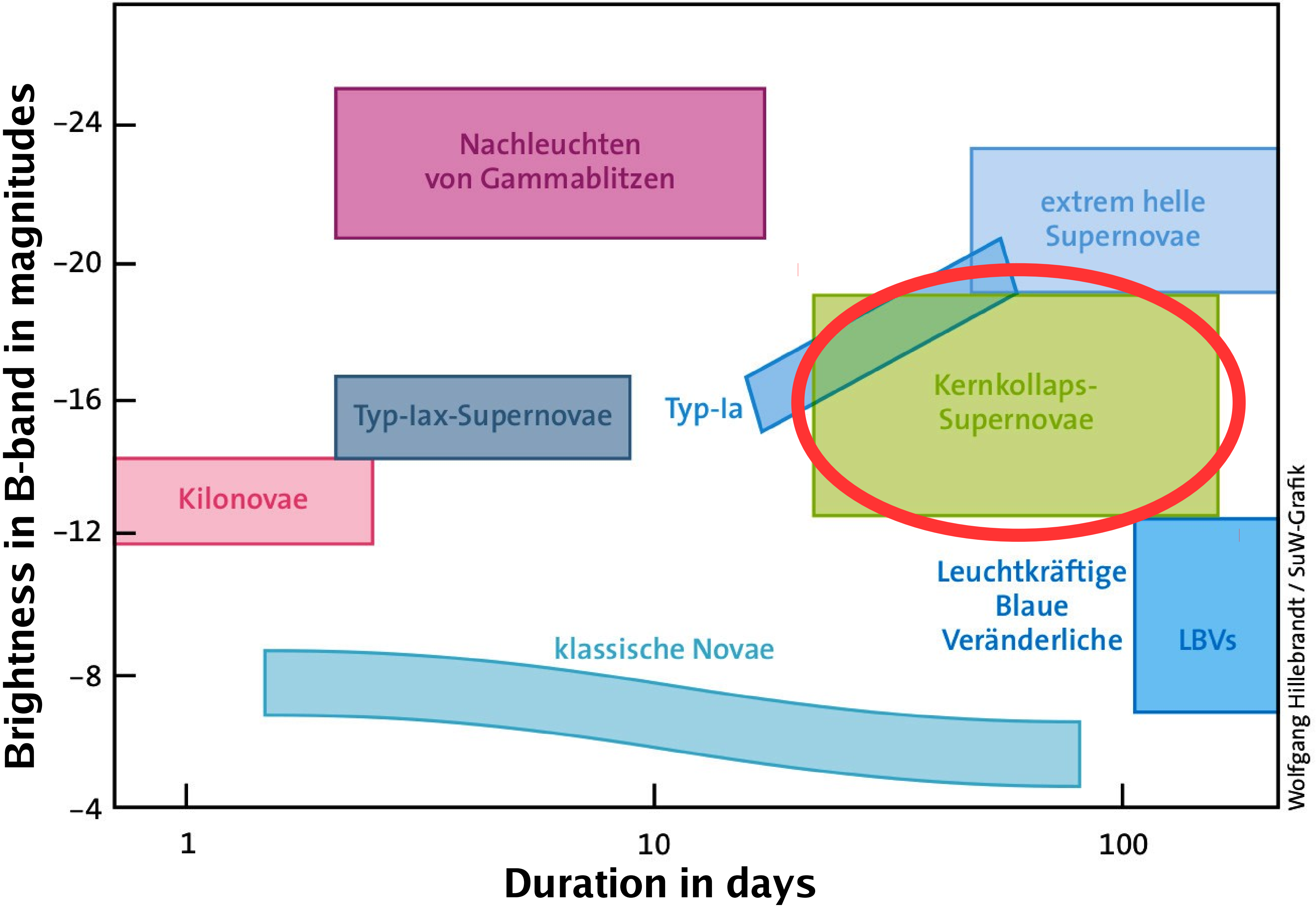
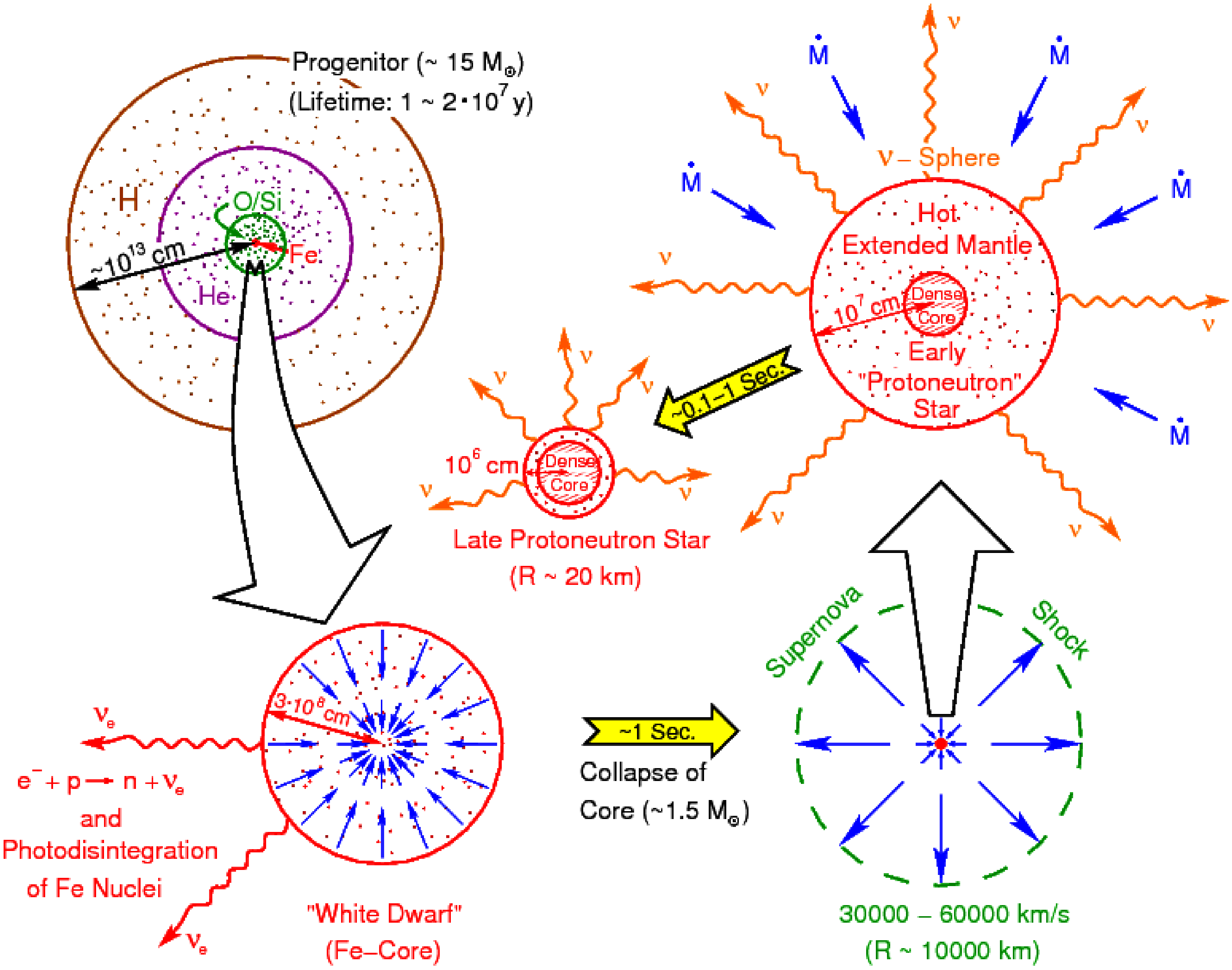


Wolfgang Hillebrandt / SuW-Grafik

Stellar Collapse and Supernova Stages



adapted from A. Burrows (1990)

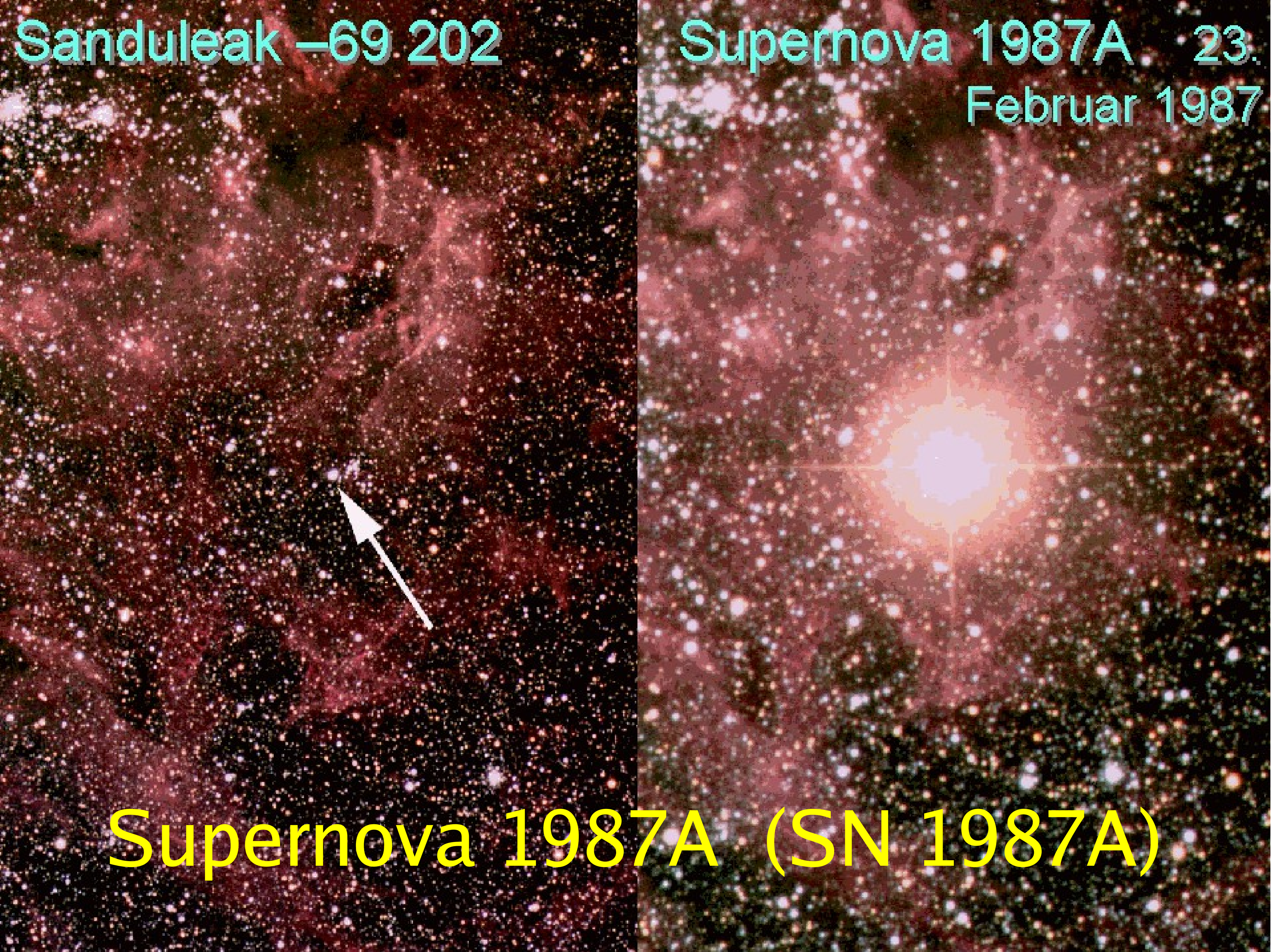
Neutrinos

play a crucial role!

They carry away the gravitational binding energy of the new-born NS:

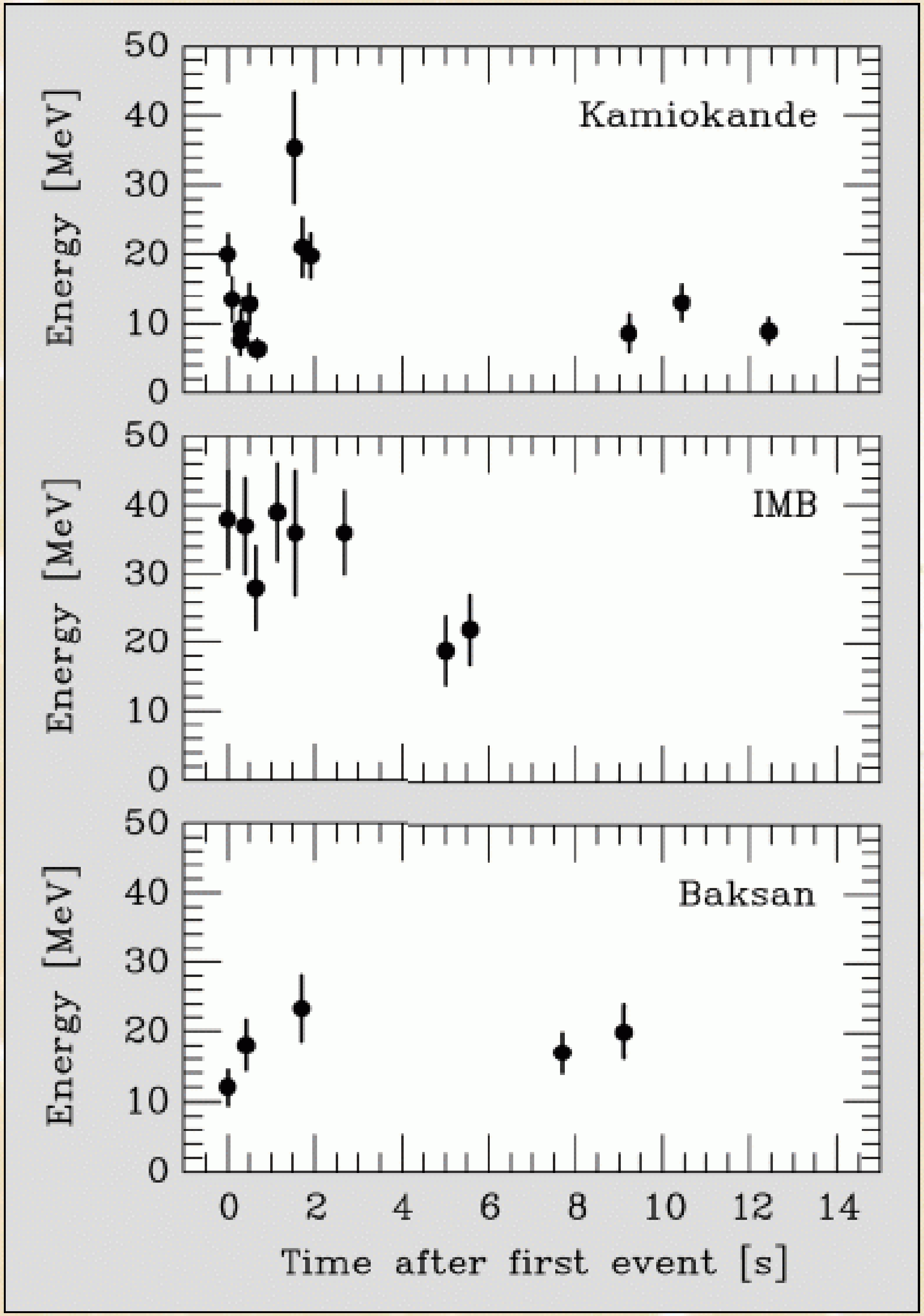
$E = f^{*}GM^{2}/R \sim$ several 10^{53} erg

>100 times the SN explosion energy!



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 ~ 0.7/day
Clock uncertainty +2/-54 s

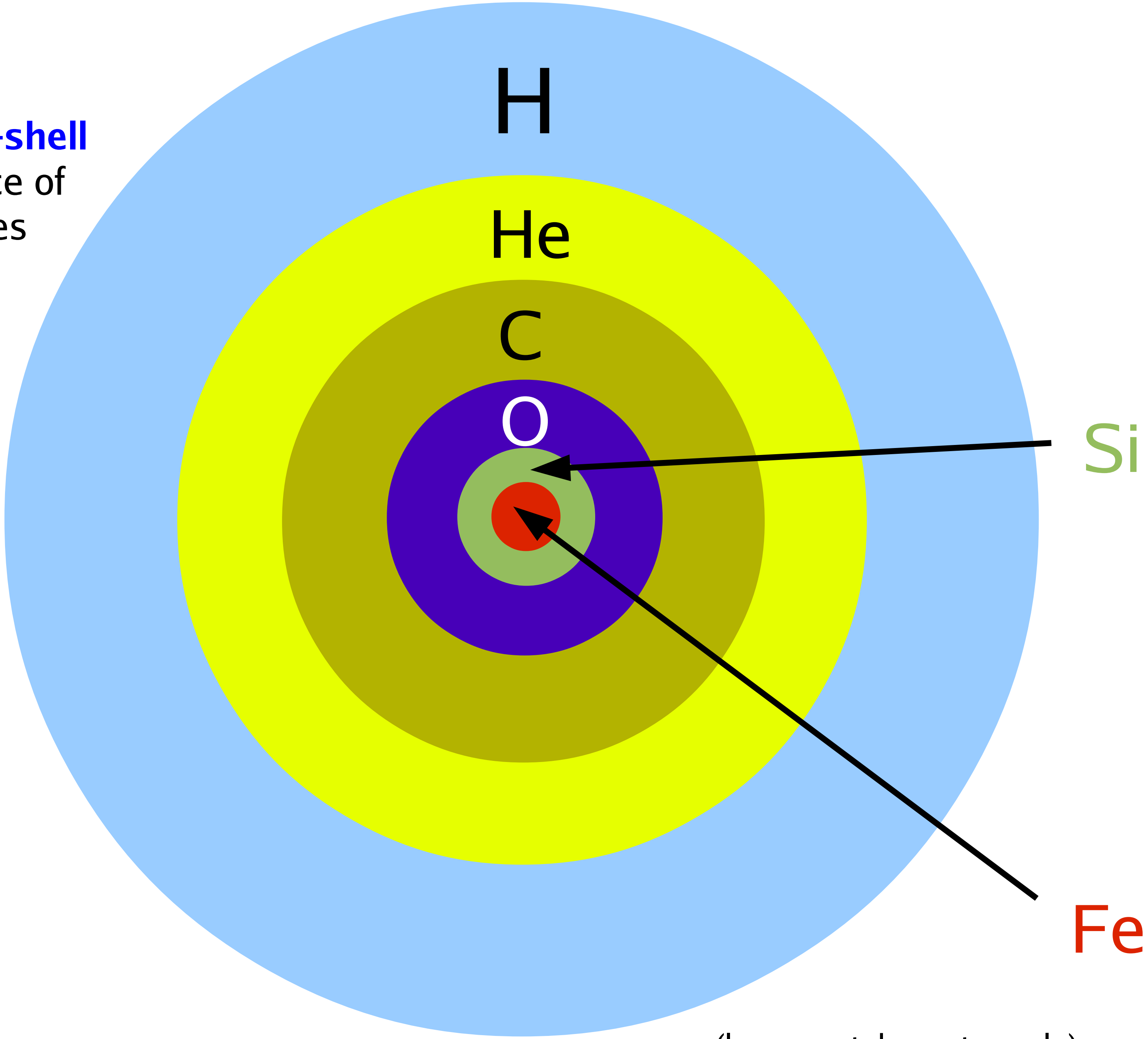
Within clock uncertainties,
signals are contemporaneous

Questions & Challenges

- Core collapse SN explosion mechanism(s)
- SN explosion properties; explosion asymmetries, mixing, gaseous remnant properties
- NS/BH formation paths and probabilities (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) physics
- Heavy-element formation;
  what are the sites of the r-process(es)?
- What is the equation of state (EOS) of ultra-dense matter?

Onion-shell structure of pre-collapse stars

Star develops **onion-shell structure** in sequence of nuclear burning stages over millions of years



(layers not drawn to scale)

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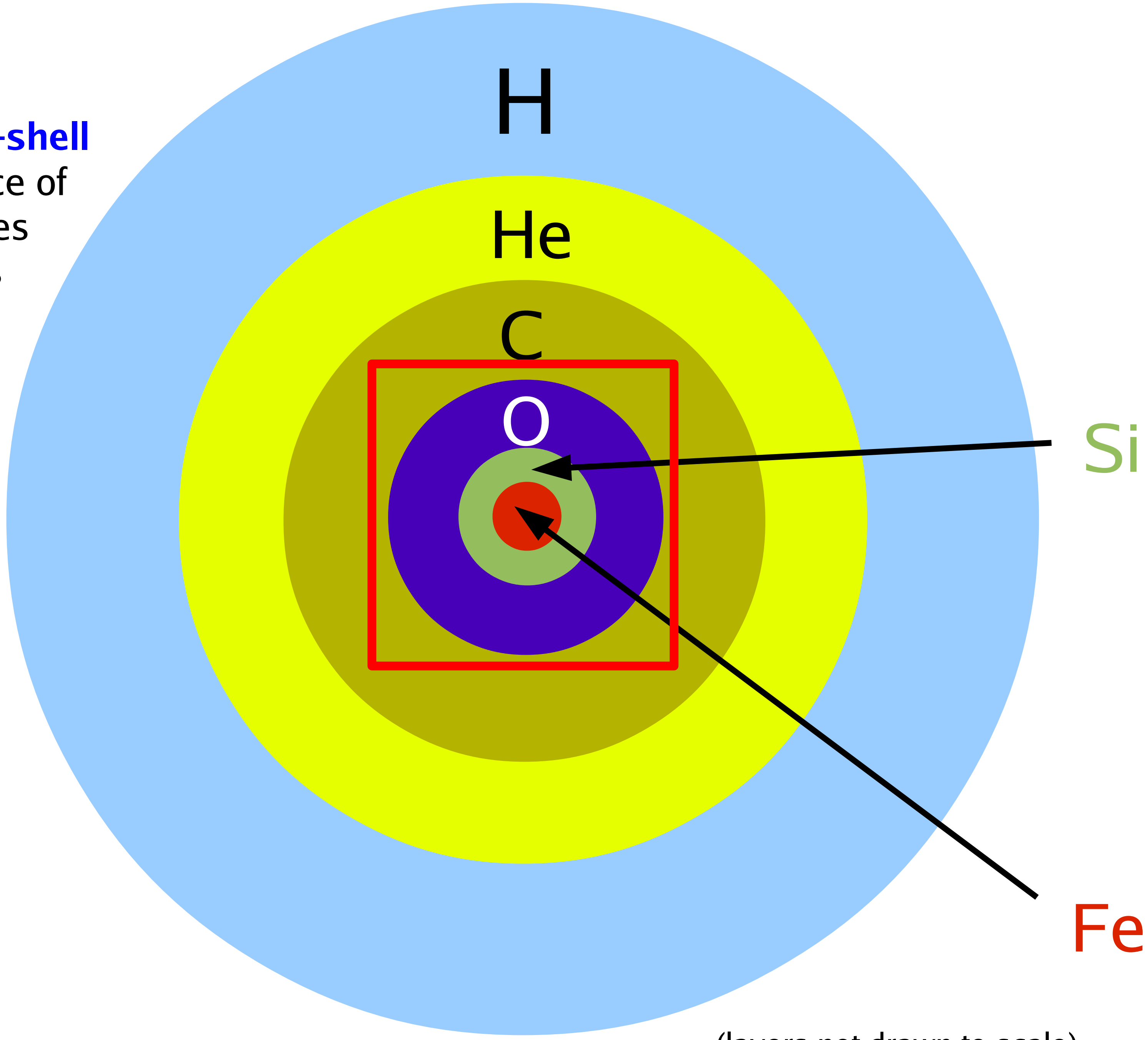
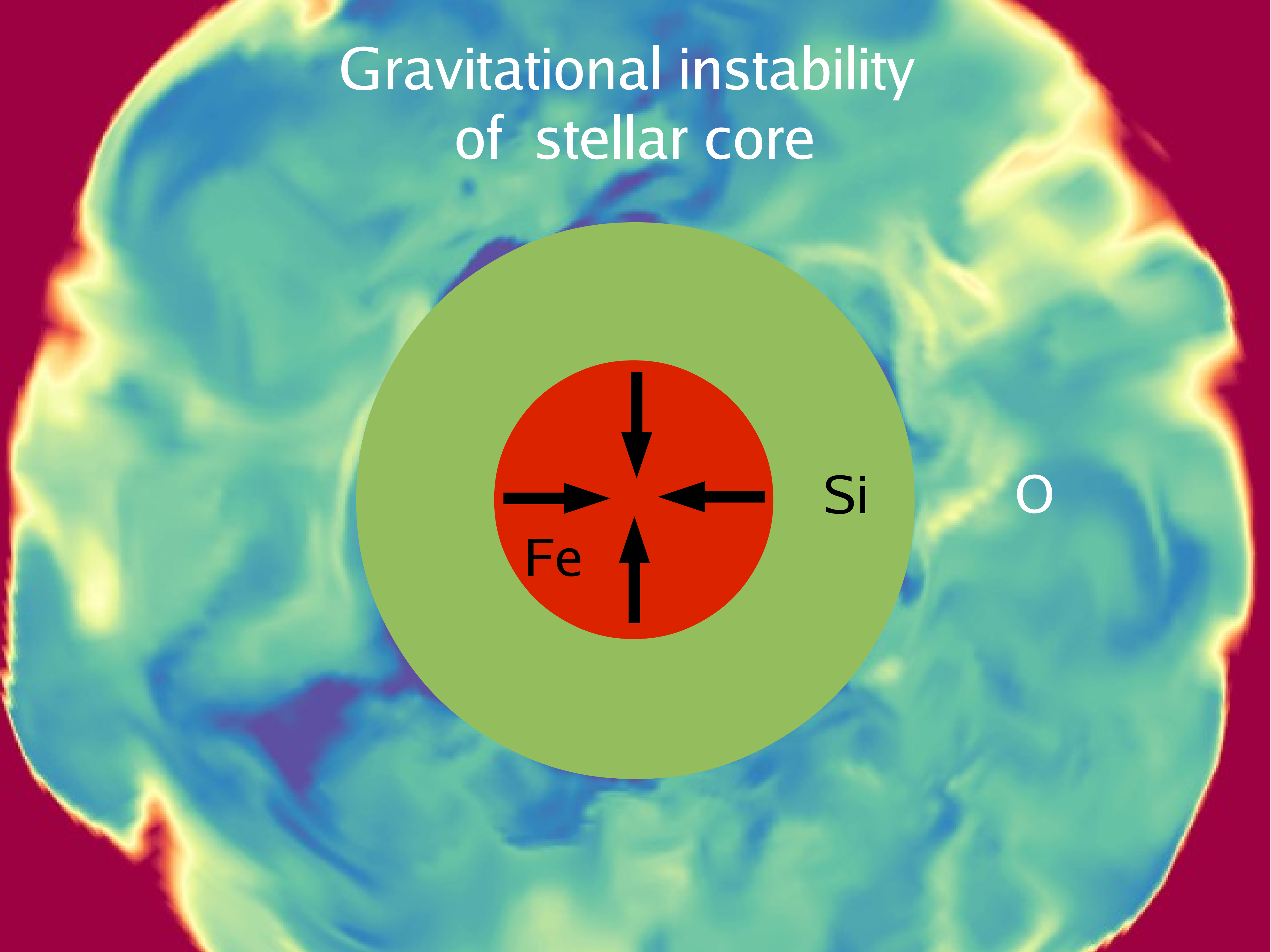
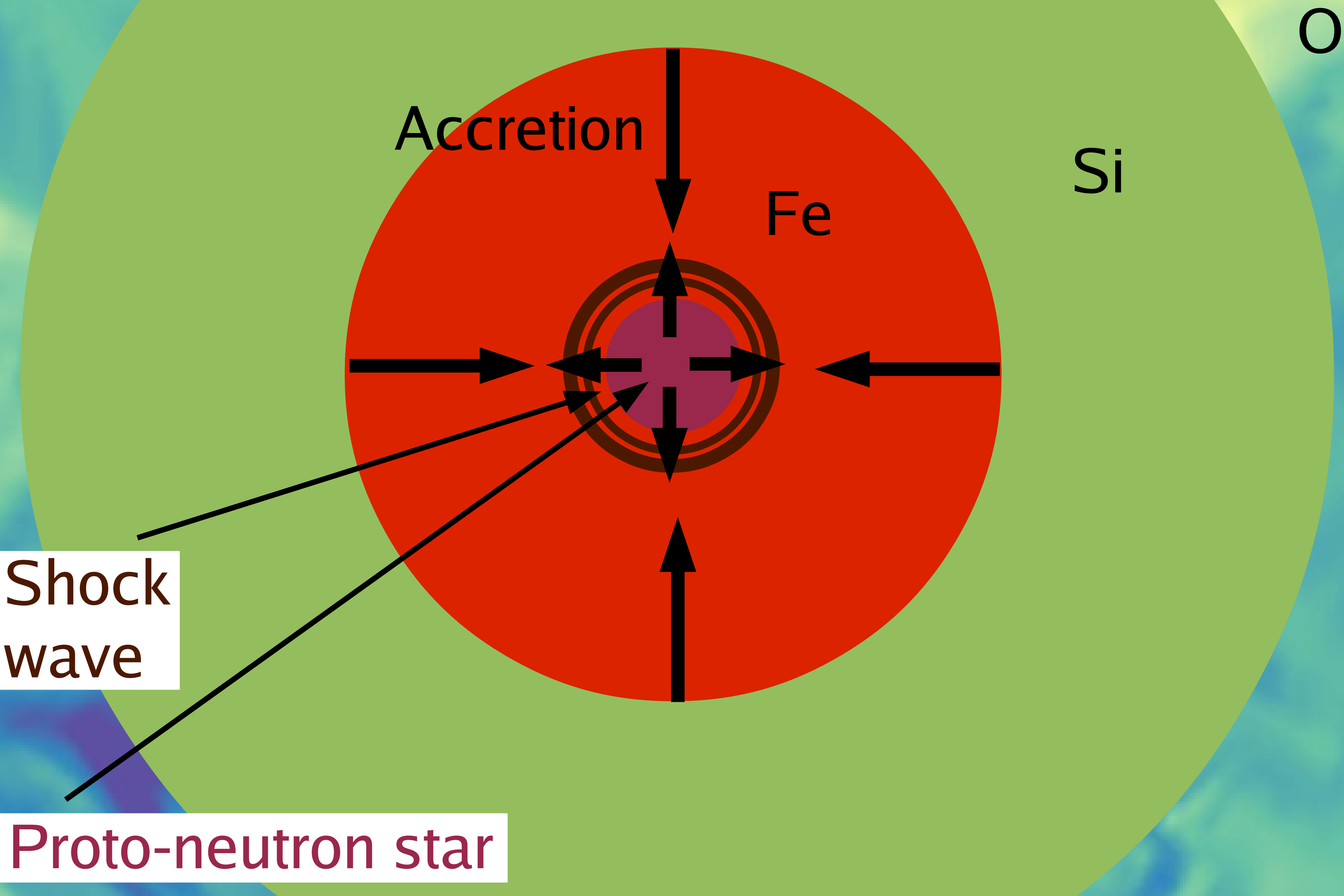


(layers not drawn to scale)

Gravitational instability of stellar core



Core bounce at nuclear density



O

Accretion

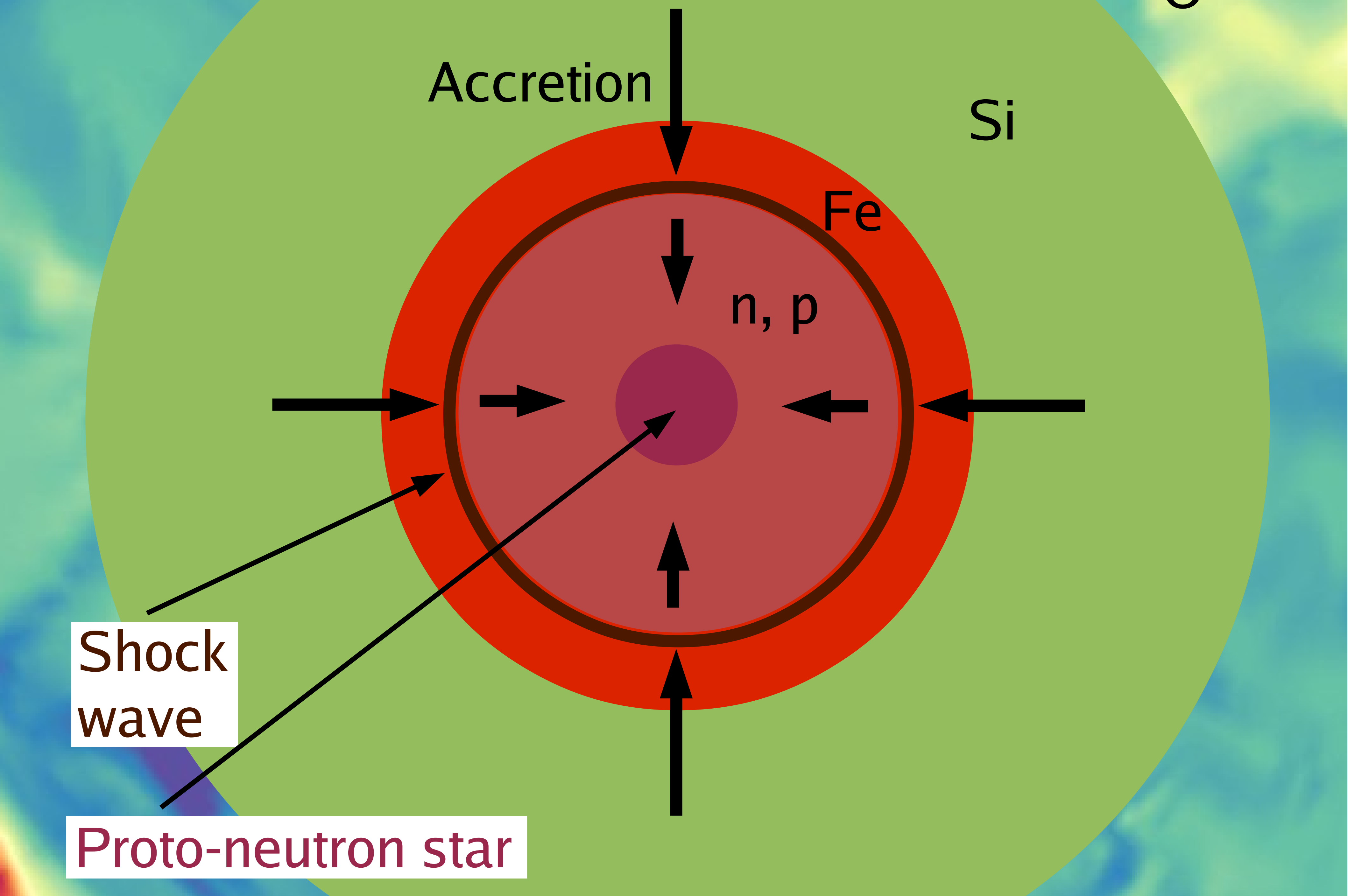
Si

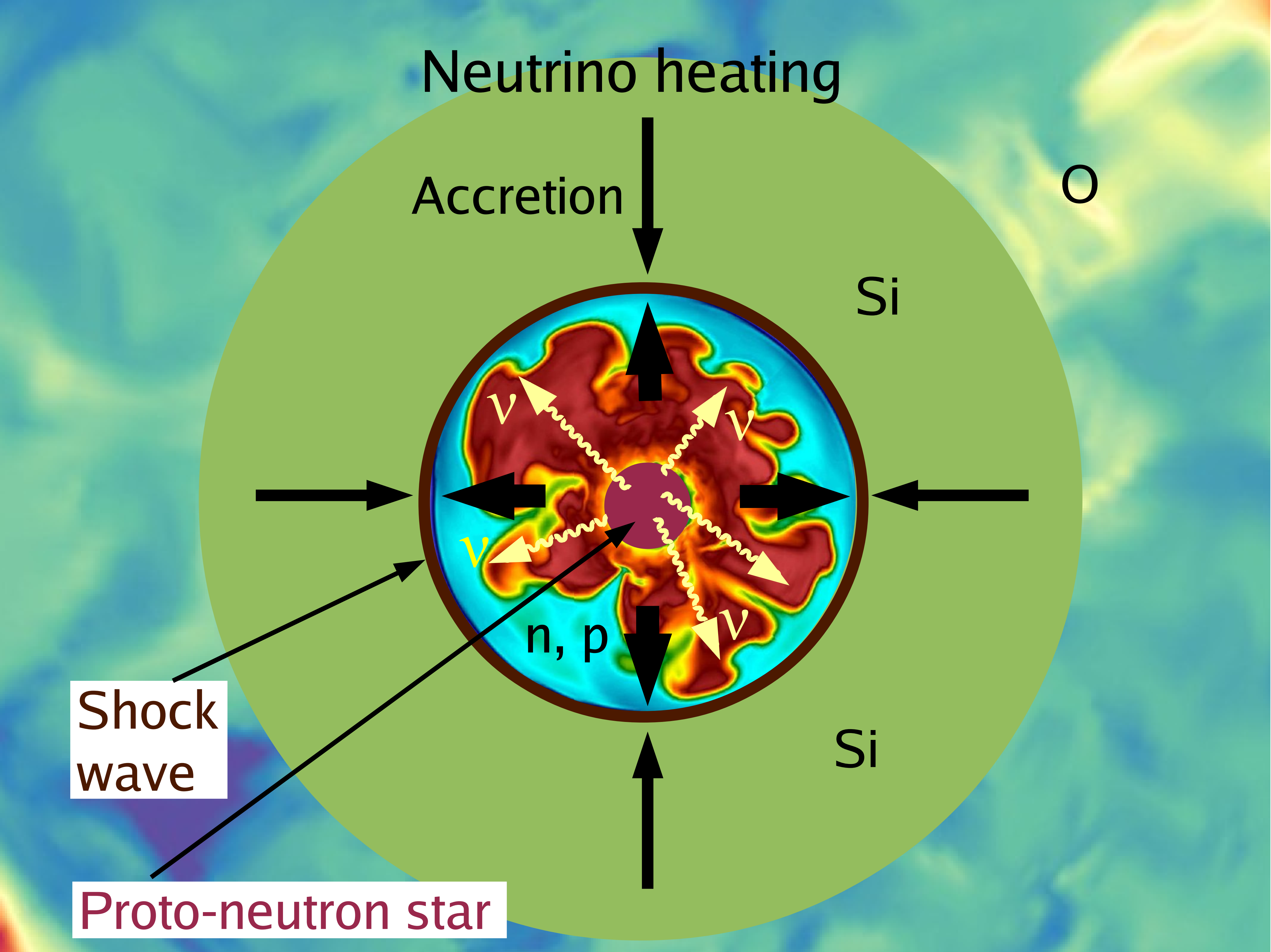
Fe

Shock wave

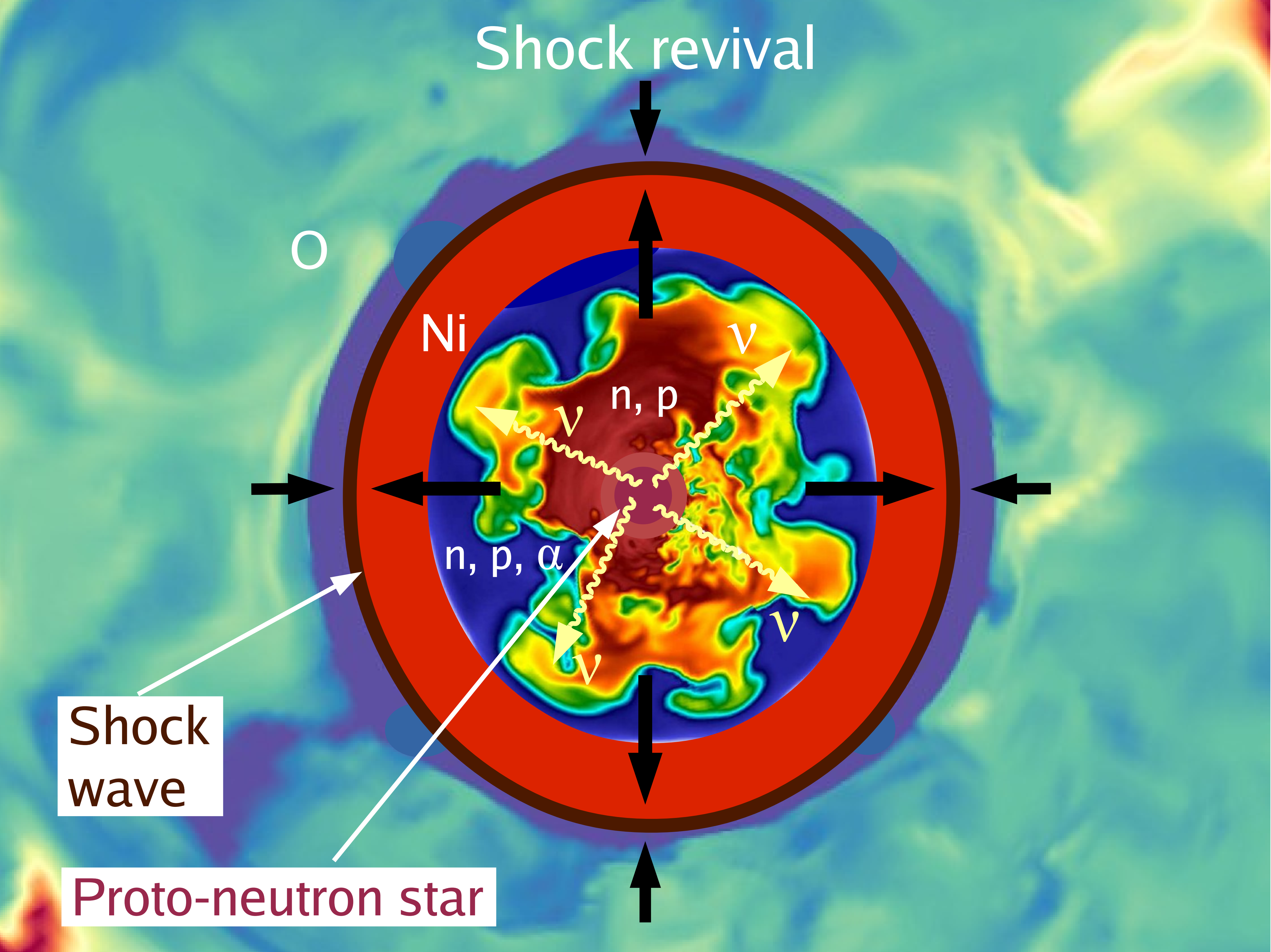
Proto-neutron star

Shock stagnation




Neutrino heating
Accretion
O
Si
ν
ν
ν
ν
n, p
Si
Shock wave
Proto-neutron star

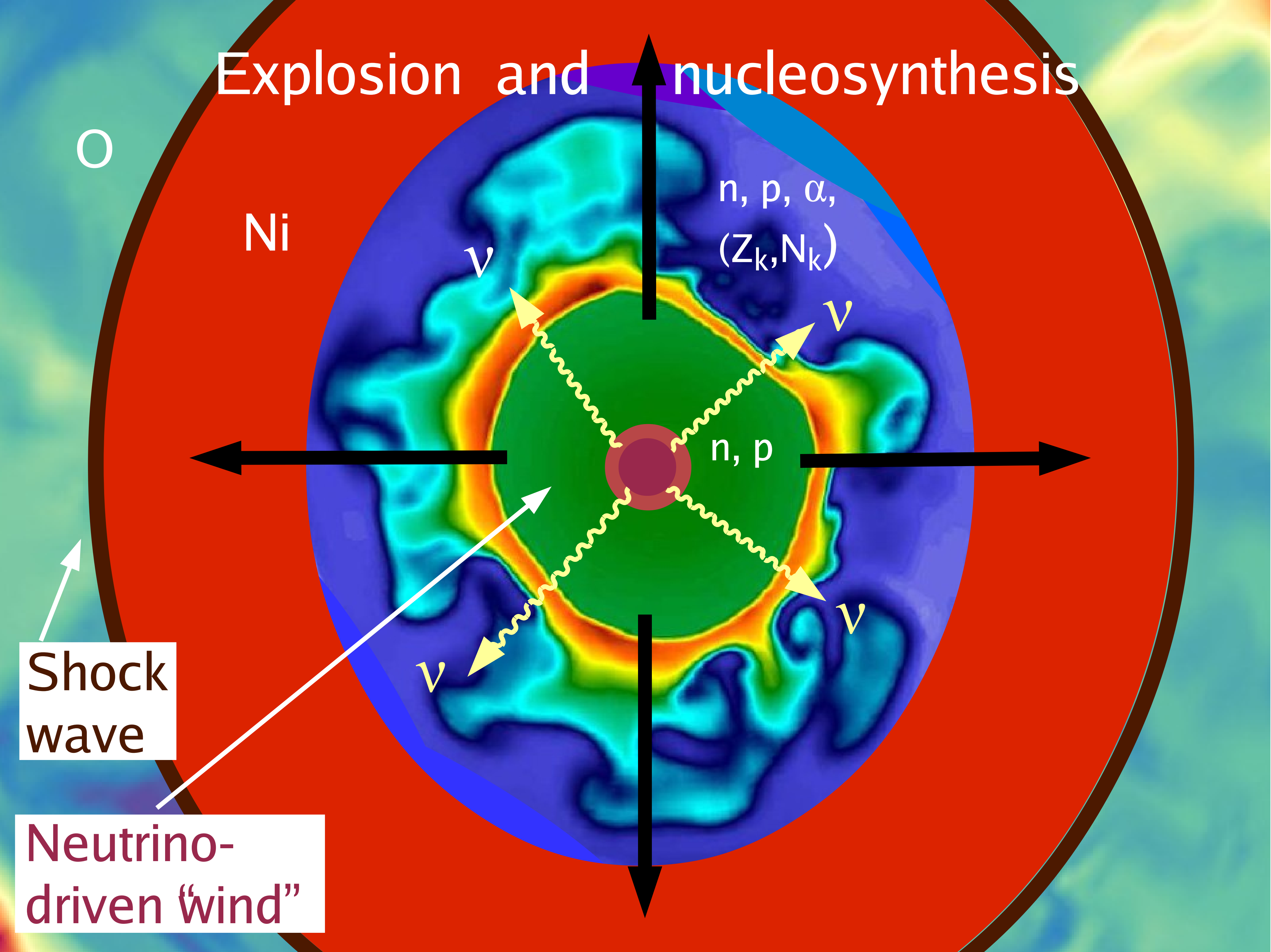
Shock revival



Shock wave

Proto-neutron star

Explosion and nucleosynthesis



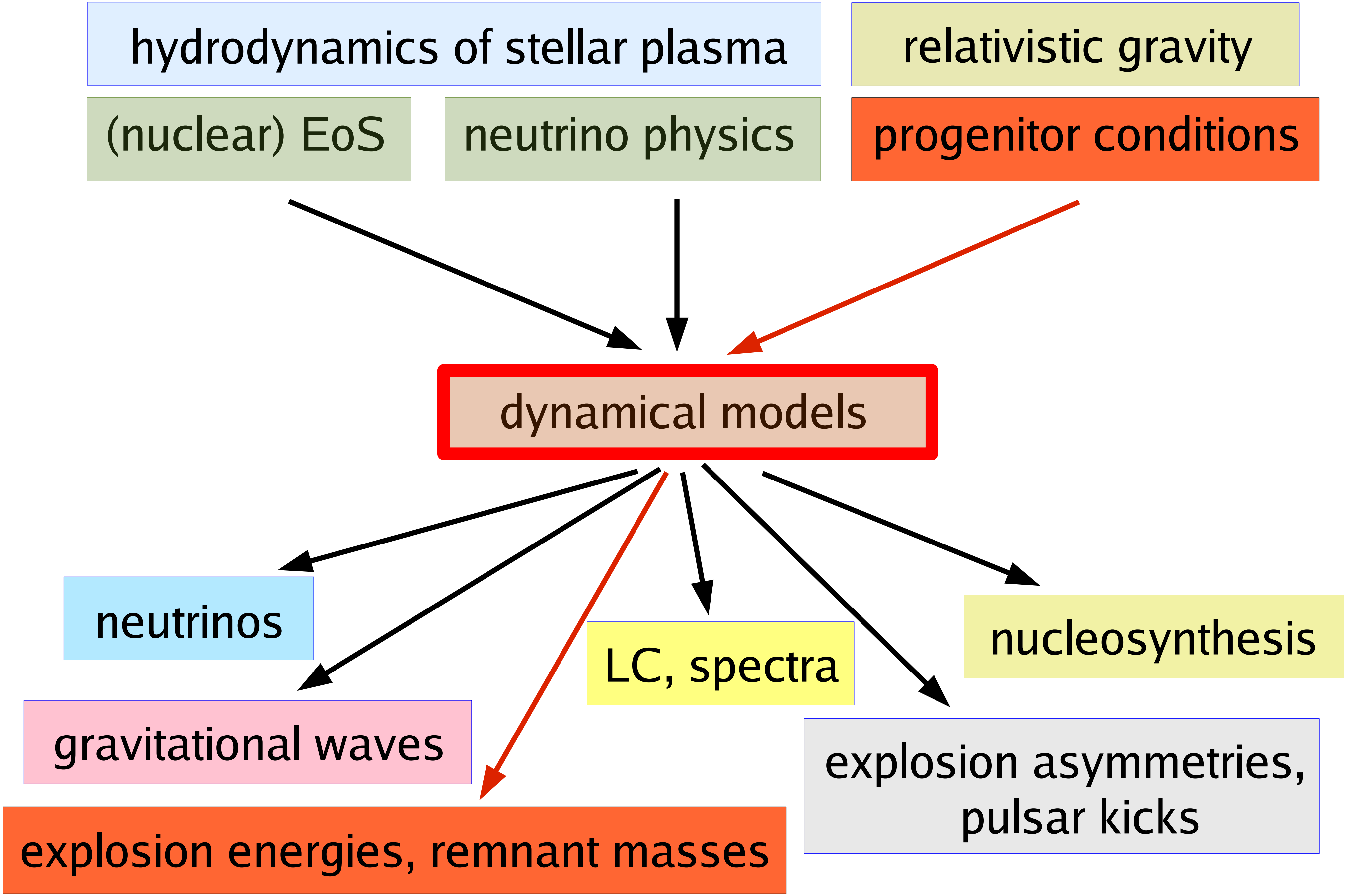
Shock wave

Neutrino-driven “wind”

Necessary Effort:

Self-consistent "ab-initio"
3D neutrino-hydrodynamical
simulations of
neutrino-driven explosions

Predictions of Signals from SNe & NSs



hydrodynamics of stellar plasma

relativistic gravity

(nuclear) EoS

neutrino physics

progenitor conditions

dynamical models

neutrinos

gravitational waves

explosion energies, remnant masses

LC, spectra

explosion asymmetries, pulsar kicks

nucleosynthesis

Improvements in Simulations since about 2000

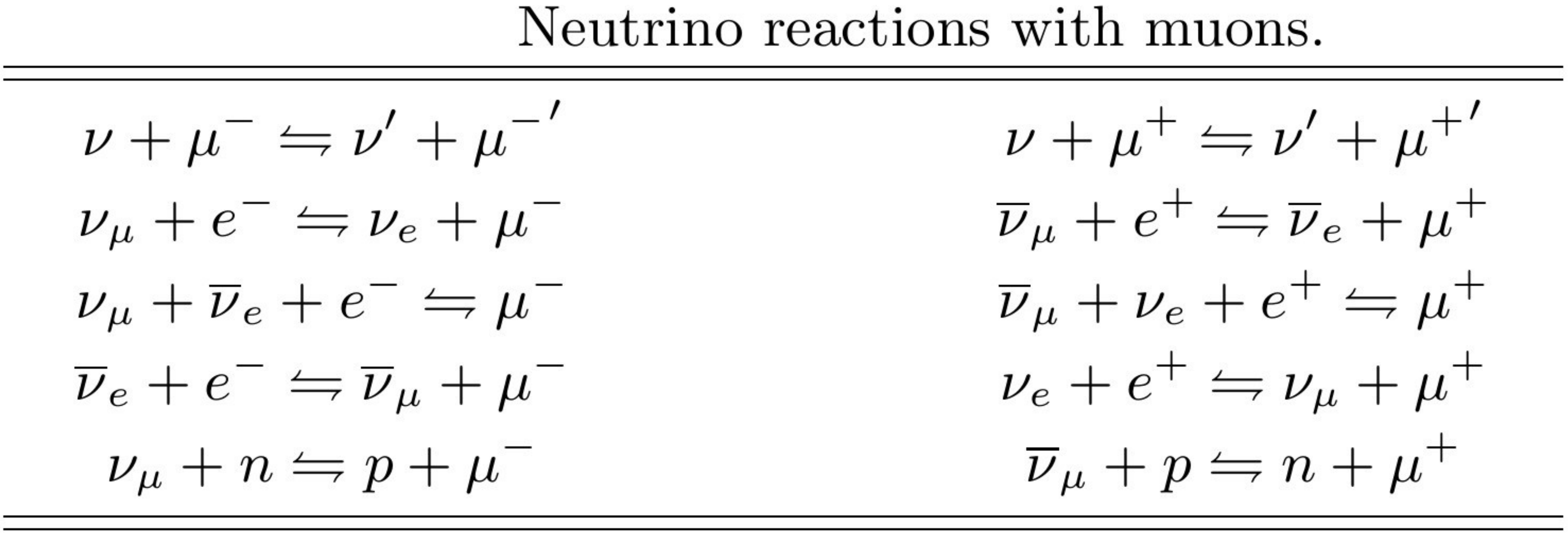
- State-of-the-art neutrino transport methods (two-moment schemes with Eddington closure, Boltzmann solvers)
- More complete set of neutrino interactions with more consistent and accurate treatment of the reaction rates
- Modern nuclear equations of state for hot neutron star matter, compatible with all experimental and astrophysical constraints
- General relativistic gravity or well-tested approximate GR
- Modern progenitor models, partly 3D pre-collapse conditions
- 3D core-collapse and explosion modeling

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 μ_e > 100 MeV** can be reached.
- **Muon abundance can become relevant** ($m_\mu c^2 \approx 105.66\,\mathrm{MeV}$).
- Additional **reactions of neutrinos with muons** need to be included and **couple neutrinos of different flavors**:

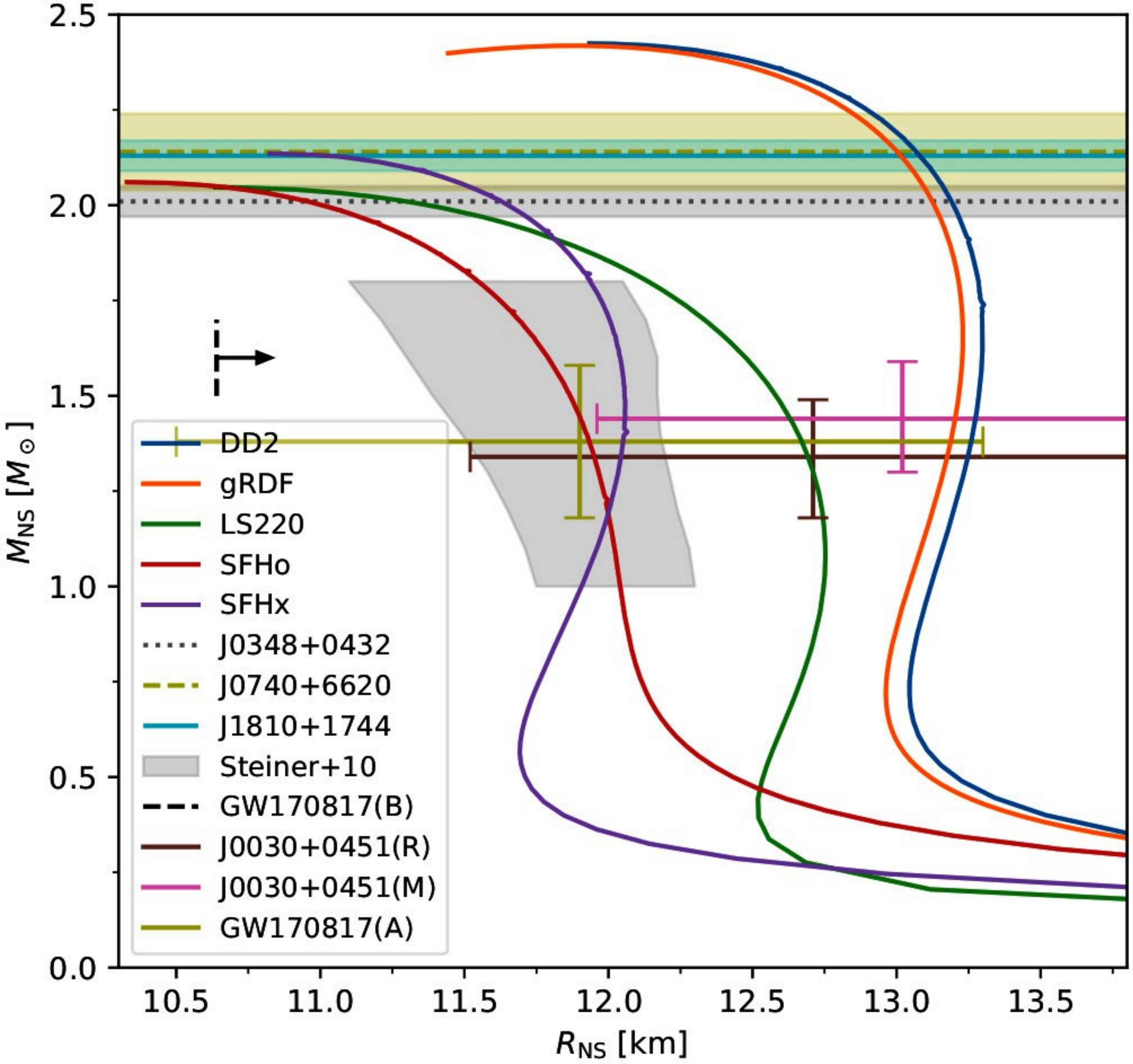


Neutrino reactions with muons.

$\nu + \mu^- \leftrightharpoons \nu' + \mu^{-\prime}$	$\nu + \mu^+ \leftrightharpoons \nu' + \mu^{+\prime}$
$\nu_\mu + e^- \leftrightharpoons \nu_e + \mu^-$	$\overline{\nu}_\mu + e^+ \leftrightharpoons \overline{\nu}_e + \mu^+$
$\nu_\mu + \overline{\nu}_e + e^- \leftrightharpoons \mu^-$	$\overline{\nu}_\mu + \nu_e + e^+ \leftrightharpoons \mu^+$
$\overline{\nu}_e + e^- \leftrightharpoons \overline{\nu}_\mu + \mu^-$	$\nu_e + e^+ \leftrightharpoons \nu_\mu + \mu^+$
$\nu_\mu + n \leftrightharpoons p + \mu^-$	$\overline{\nu}_\mu + p \leftrightharpoons n + \mu^+$

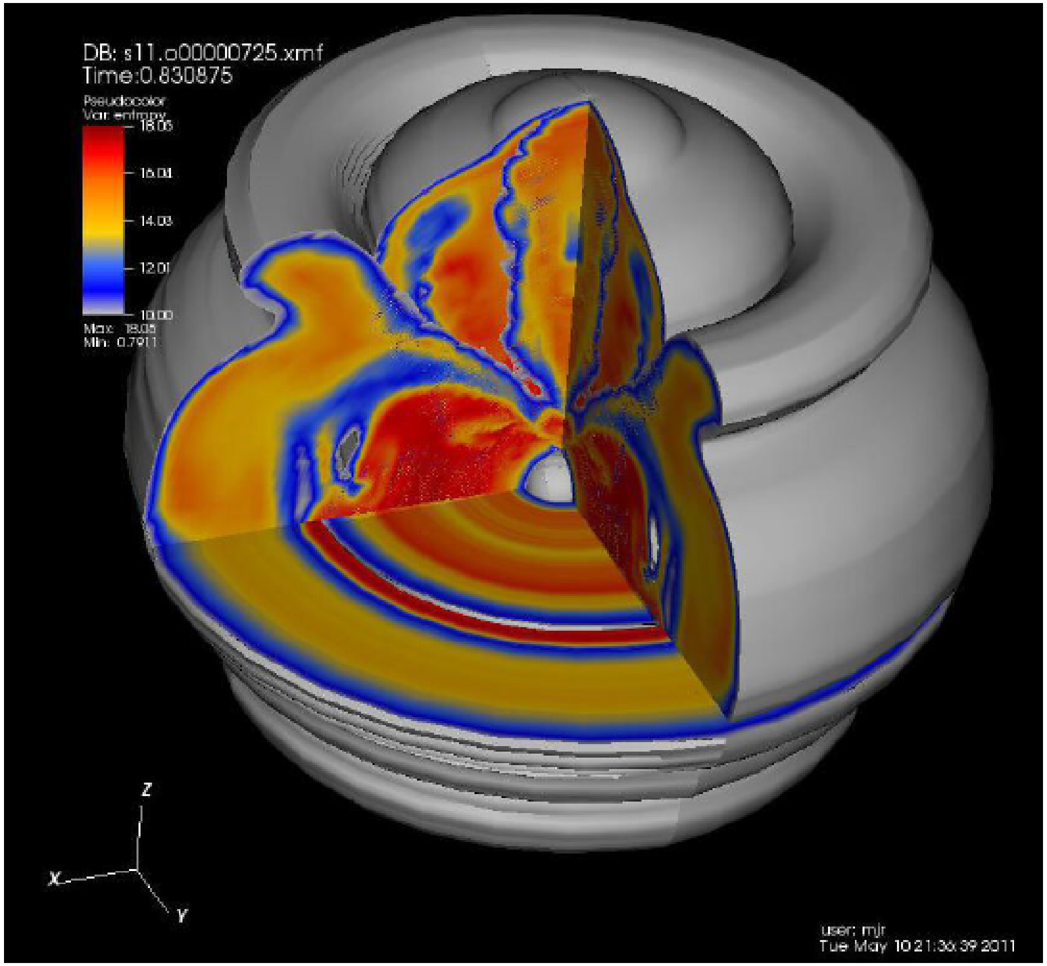
R. Bollig et al., PRL 119 (2017) 242702; ApJ 915 (2021) 28

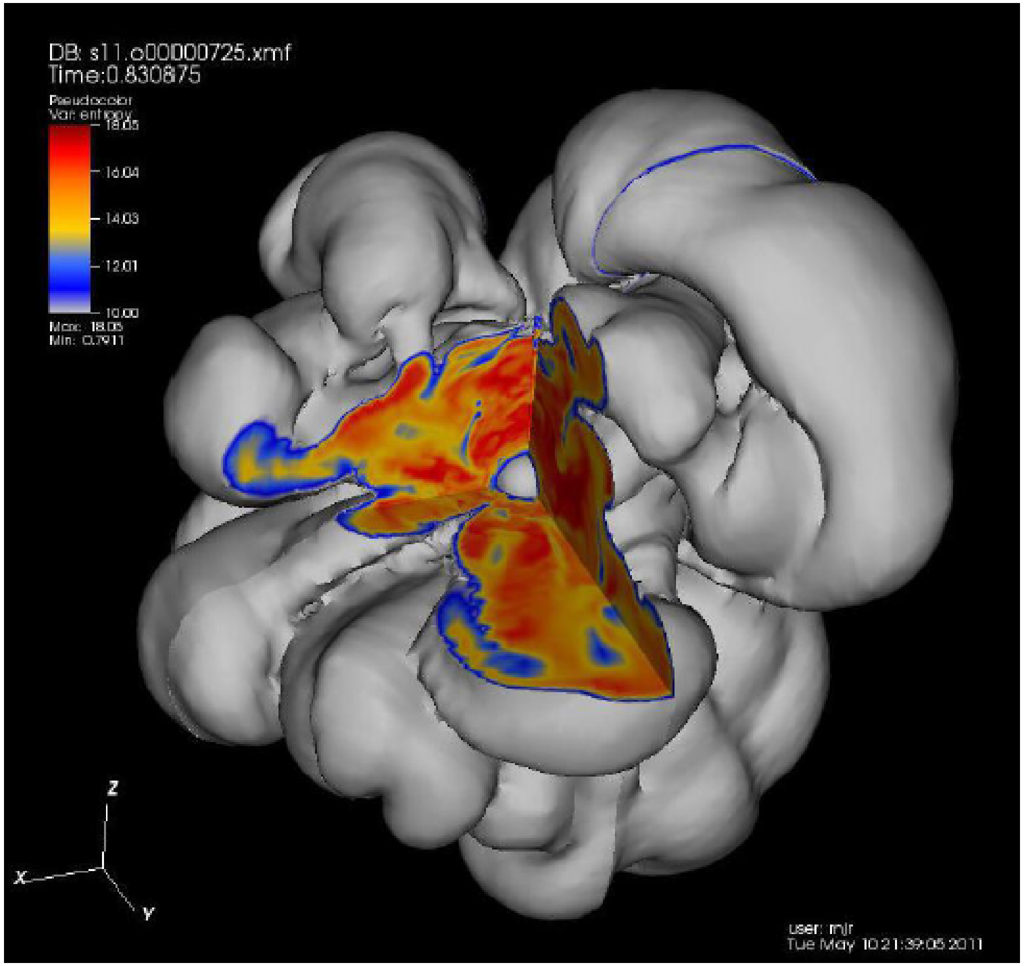
Nuclear Equations of State & Constraints



Courtesy of M. Heinlein, Master Thesis, TUM 2022

2D and 3D Morphology



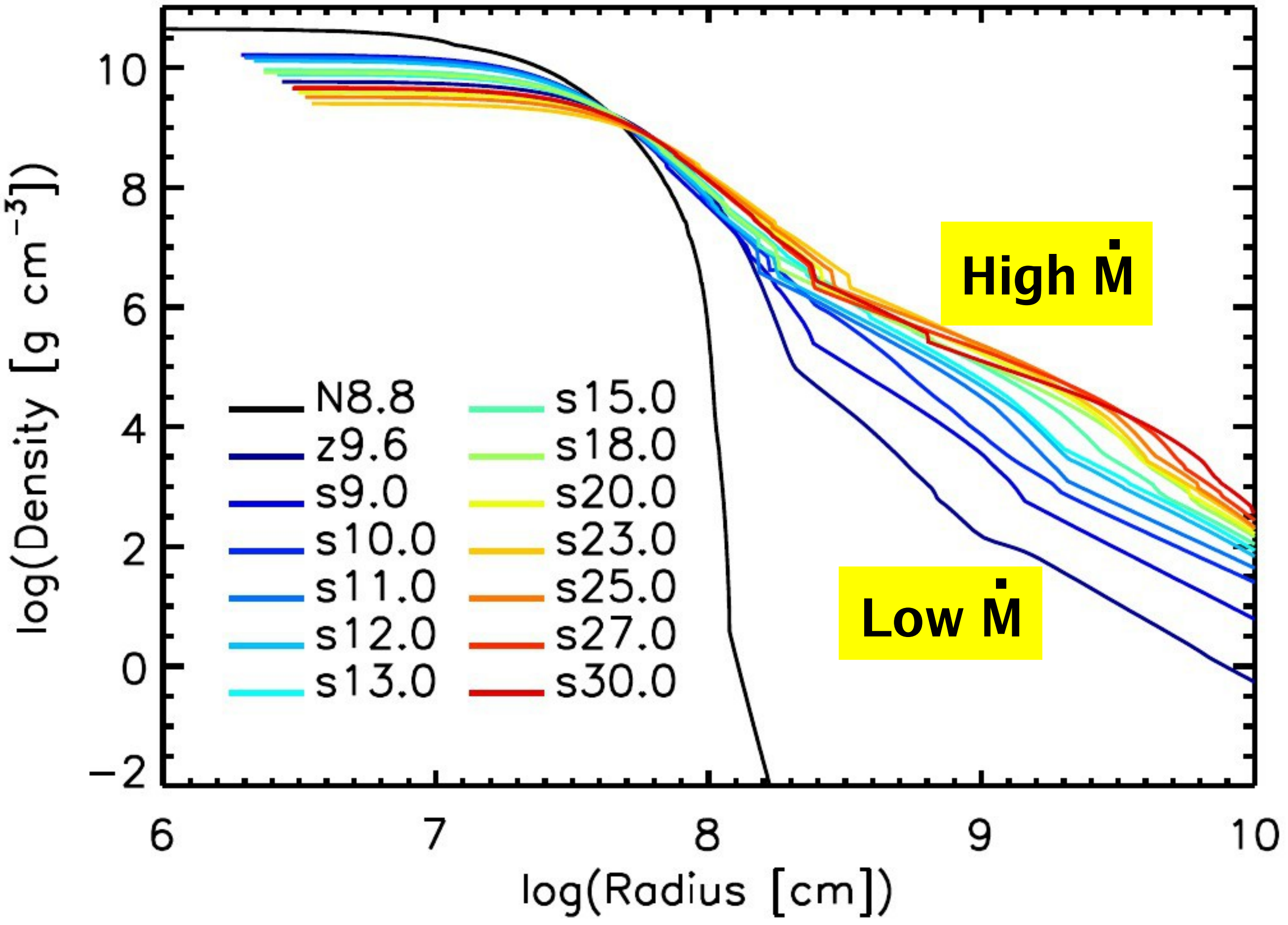


(Images from Markus Rampp, RZG)

3D Simulations with Modern Physics: First Successful Explosions

Stellar Density Structure and Explosion

“Explodability” depends on steepness of core-density profile of the progenitor stars; can be a non-monotonic function of ZAMS mass



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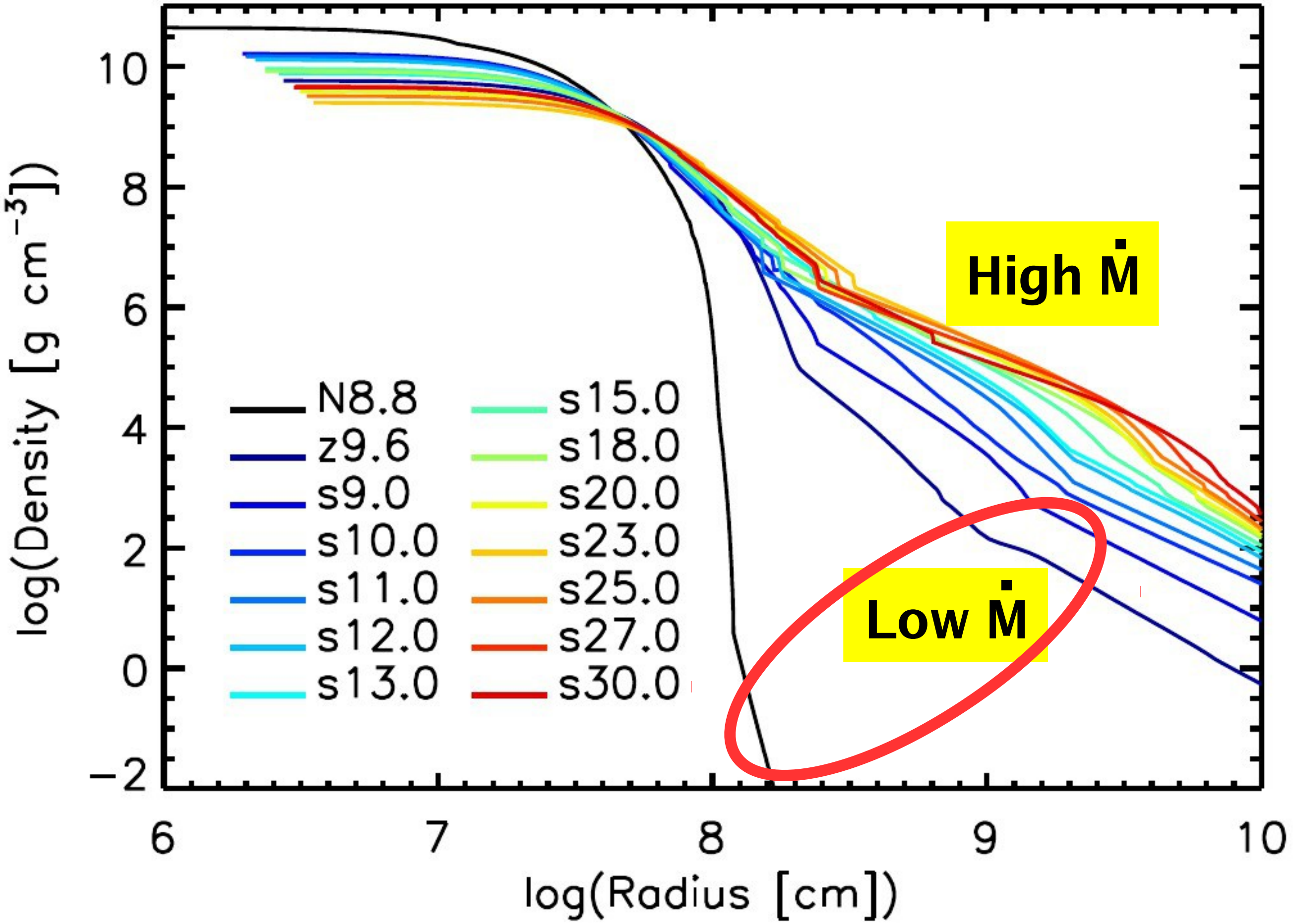
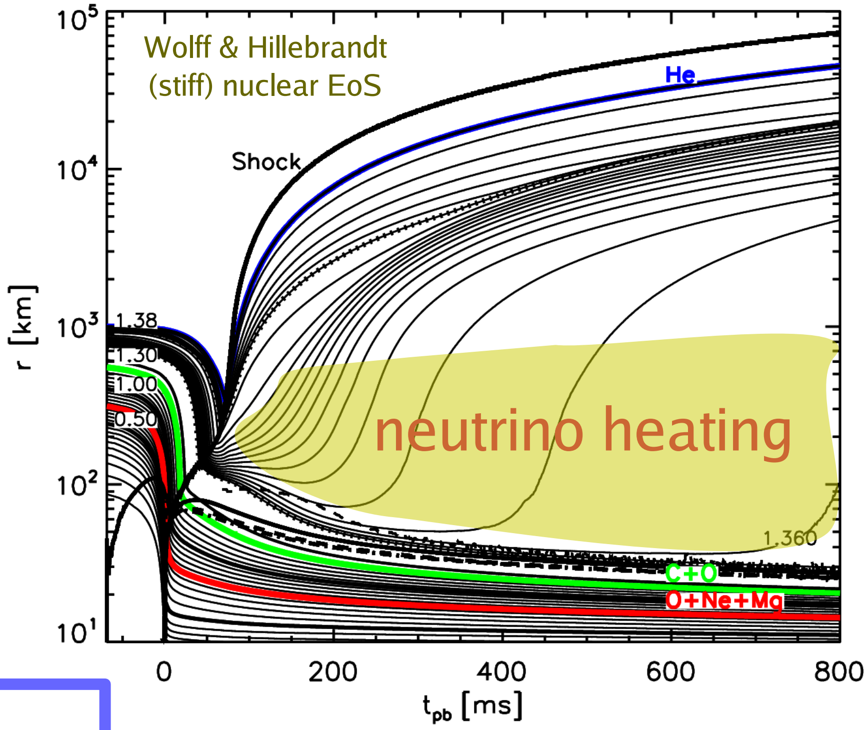


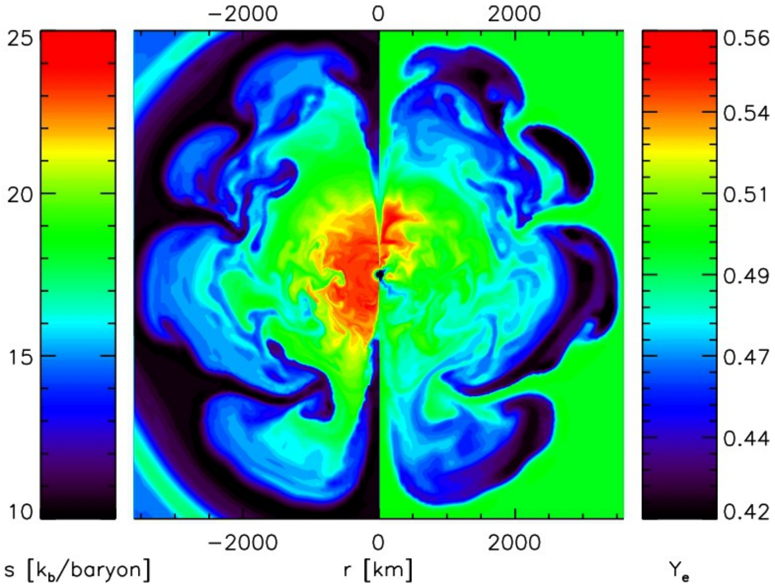
2D and 3D Electron-Capture SN Models

ECSNe:

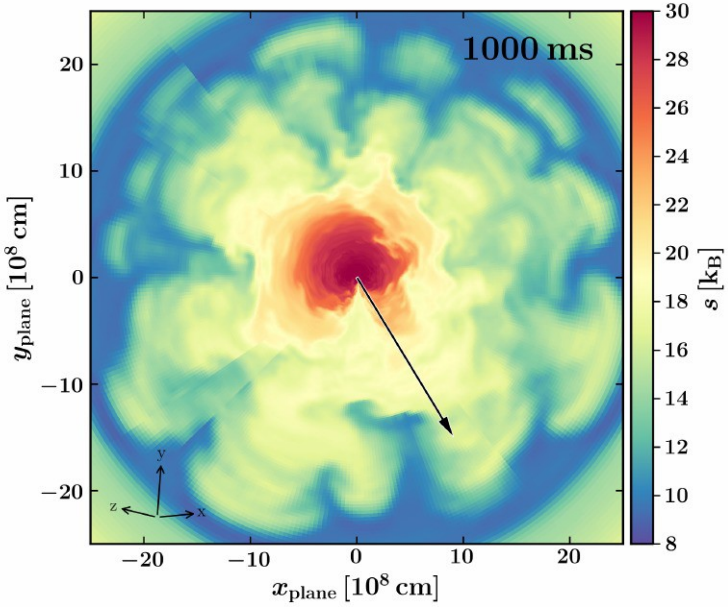
Explosions of low-mass stars ($\sim$9 M_{sun}) with O-Ne-Mg cores

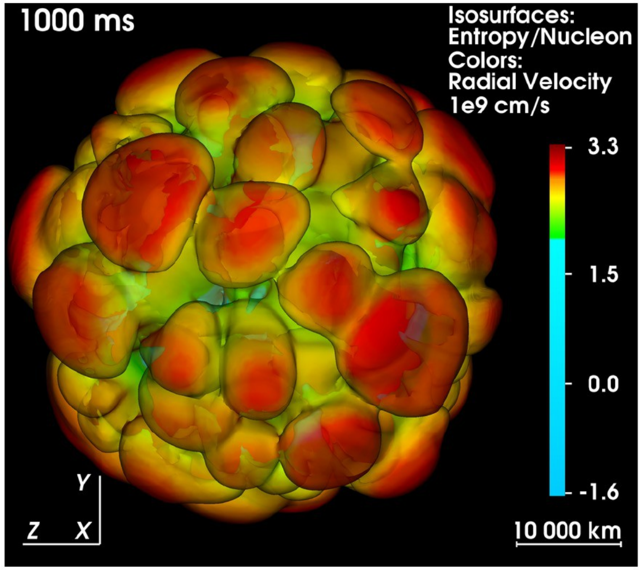


Kitaura et al., A&A 450 (2006) 345;
Janka et al., A&A 485 (2008) 199



E_{exp} ~ 10^{50} erg
= 0.1 bethe
M_{Ni} ~ 0.003 M_{sun}





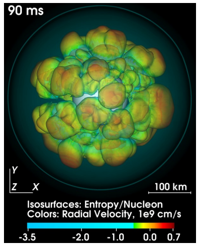
Gessner & Janka,
ApJ 865 (2018) 61

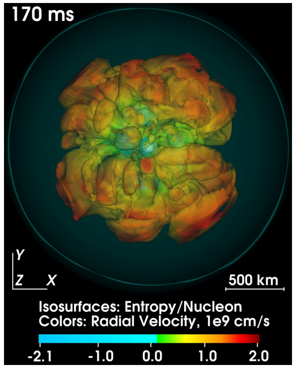
3D Core-Collapse SN Explosion Models

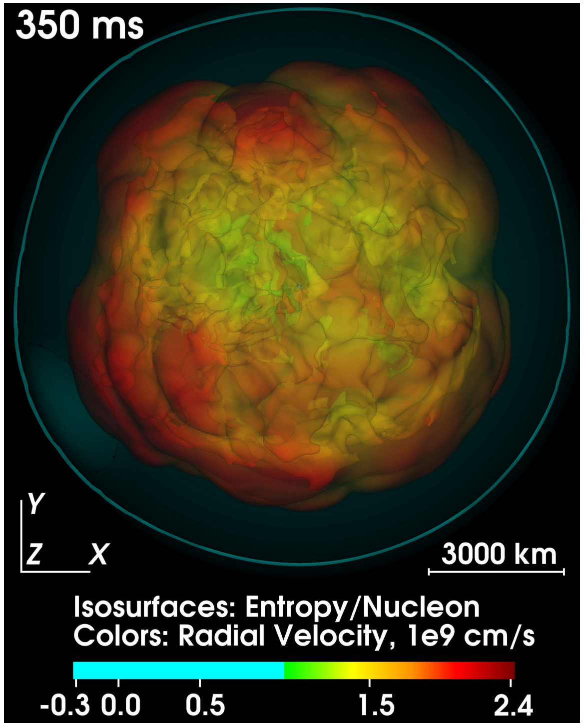
9.6 M_{sun} (zero-metallicity) progenitor (Heger 2010)

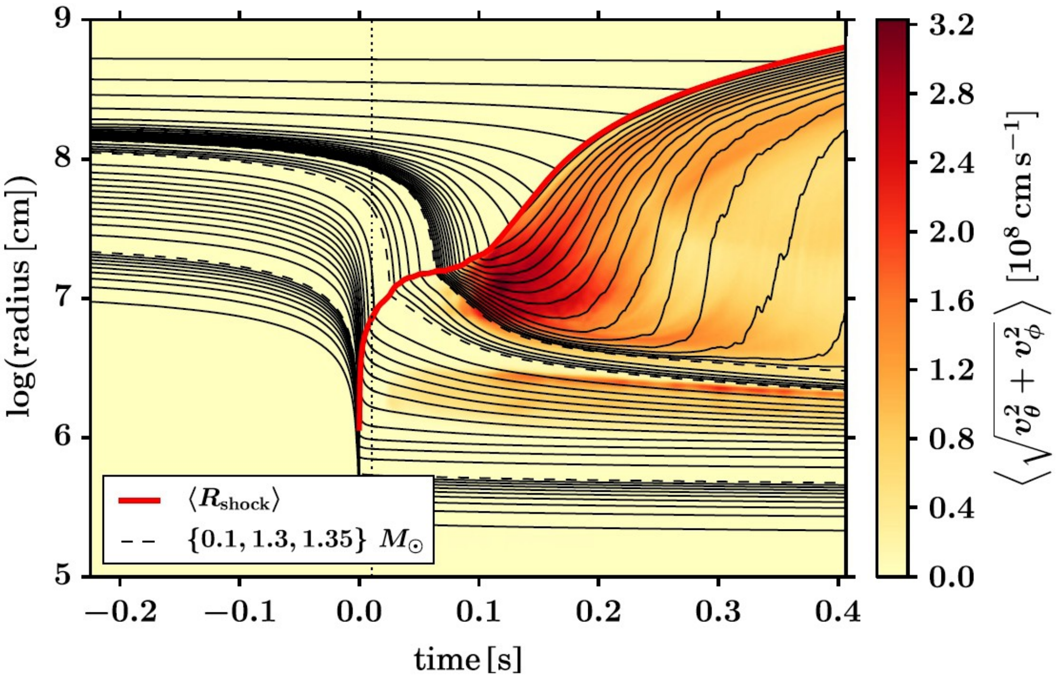
Fe-core progenitor (Heger 2012) with ECSN-like density profile and explosion behavior.

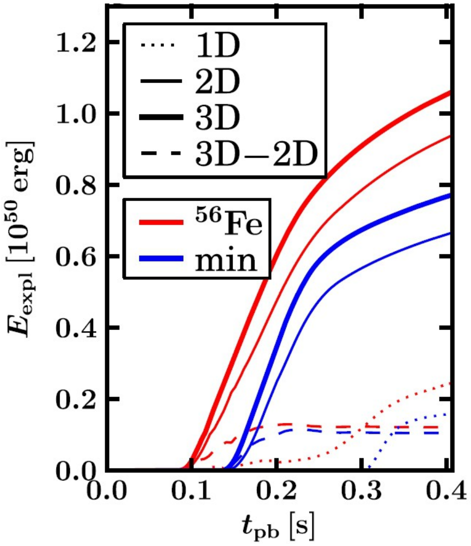
Melson et al.,
ApJL 801 (2015) L24

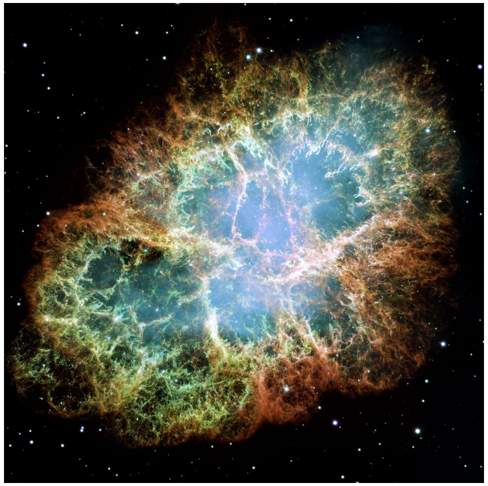






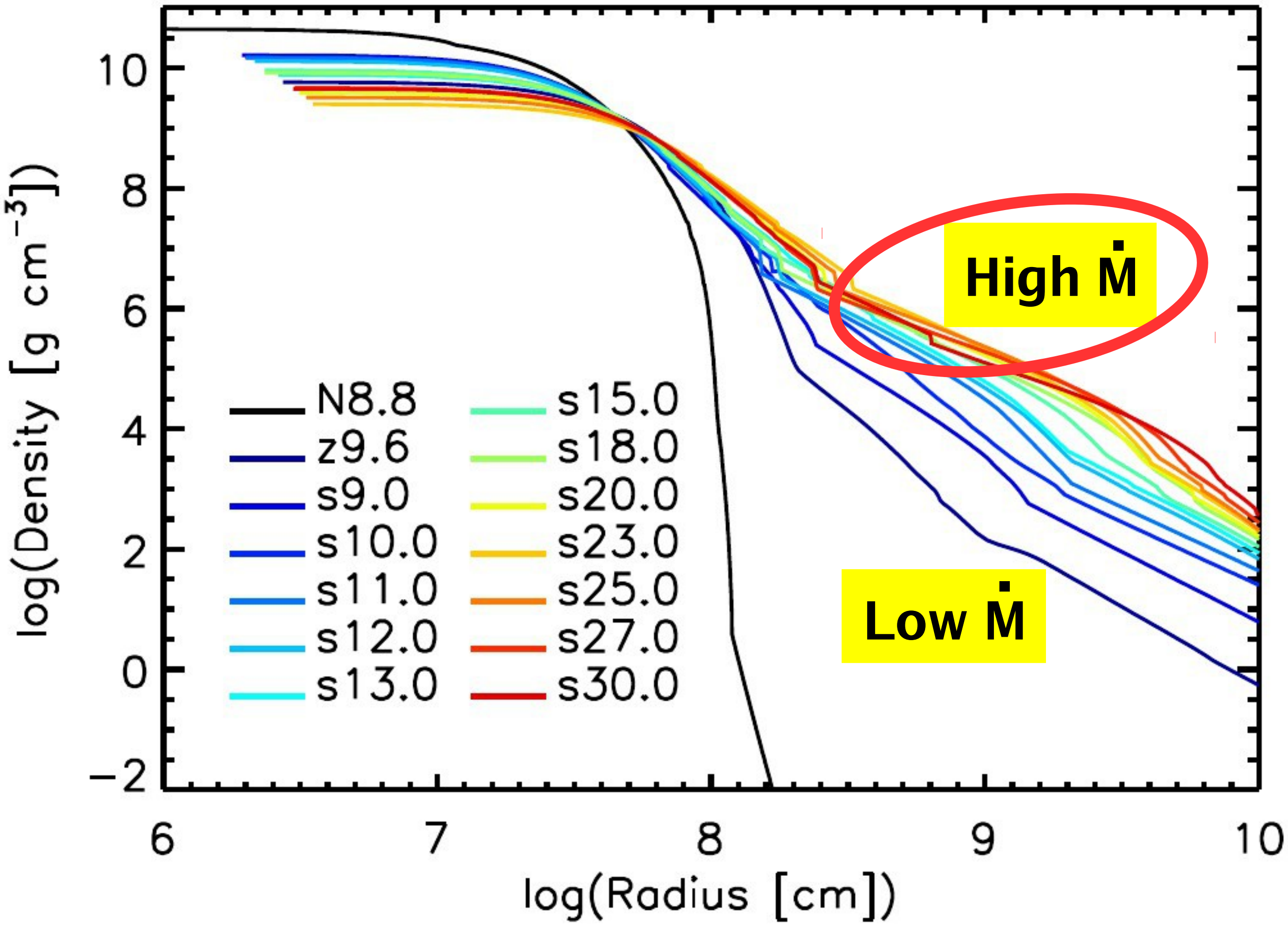






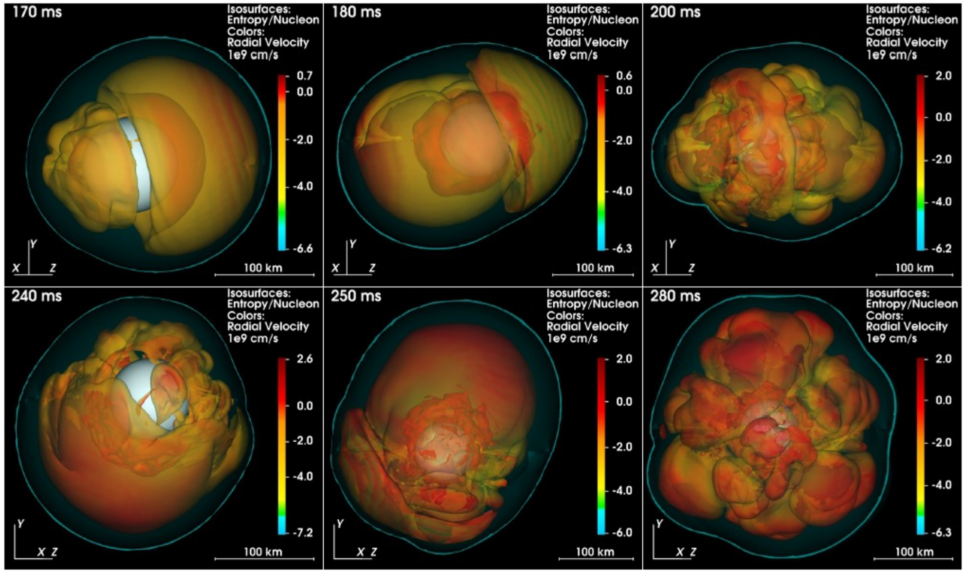
Stellar Density Structure and Explosion

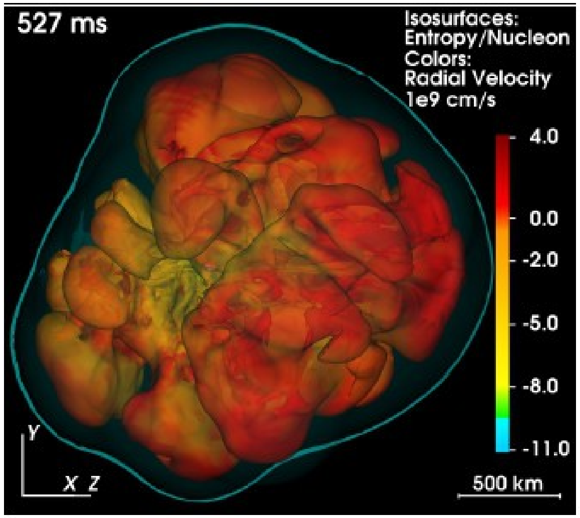
"Explodability" depends on steepness of core-density profile of the progenitor stars; can be a non-monotonic function of ZAMS mass



3D Core-Collapse SN Explosion Models

20 M_{sun} (solar-metallicity) progenitor (Woosley & Heger 2007)





Explore uncertain aspects of microphysics in neutrinospheric region:

Example: strangeness contribution to nucleon spin, affecting axial-vector neutral-current scattering of neutrinos on nucleons

$$\frac{d\sigma_0}{d\Omega} = \frac{G_F^2\epsilon^2}{4\pi^2}\left[c_v^2(1+\cos\theta) + c_a^2(3-\cos\theta)\right], \qquad (1)$$

$$\sigma_0^t = \int_{4\pi} d\Omega\, \frac{d\sigma_0}{d\Omega}(1-\cos\theta) = \frac{2G_F^2\epsilon^2}{3\pi}\left(c_v^2 + 5c_a^2\right). \qquad (2)$$

$$c_a = \frac{1}{2}\left(\pm g_a - g_a^s\right), \qquad (3)$$

We use:
$g_a = 1.26$
$g_a^s = -0.2$

Currently favored theoretical & experimental (HERMES, COMPASS) value:
$g_a^s \sim -0.1$

Effective reduction of neutral-current neutrino-nucleon scattering by ~15%

Melson et al., ApJL 808 (2015) L42

3D CCSN Explosion Model with Rotation

15 M_{sun} rotating progenitor

(Heger, Woosley & Spruit 2005)

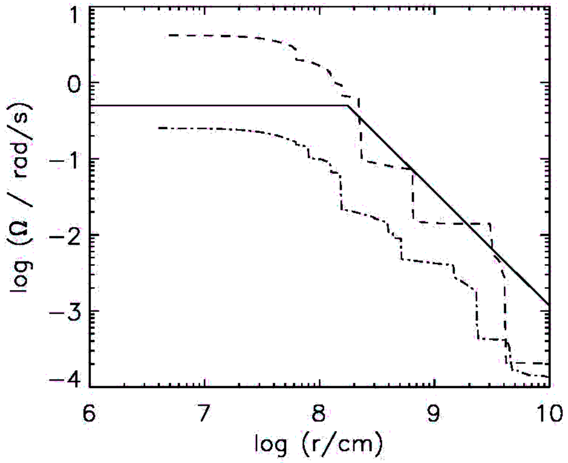
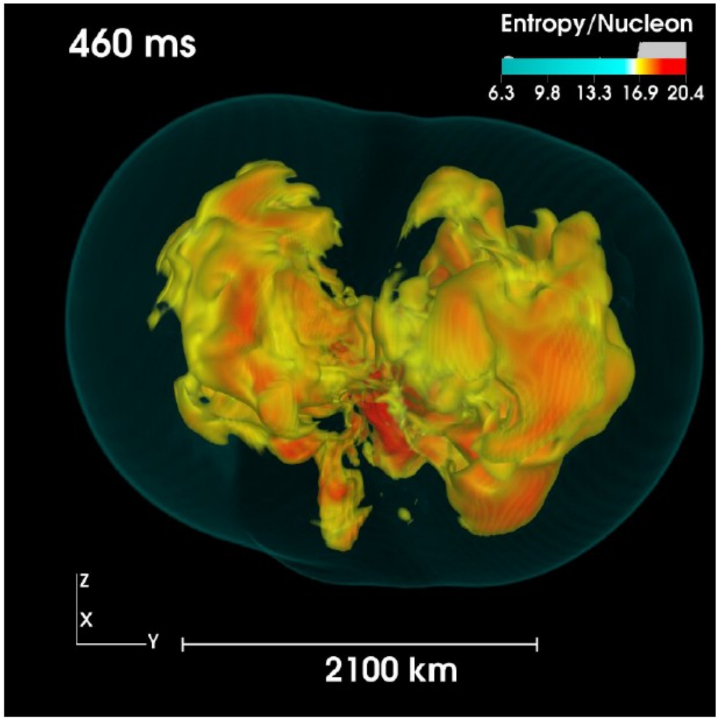
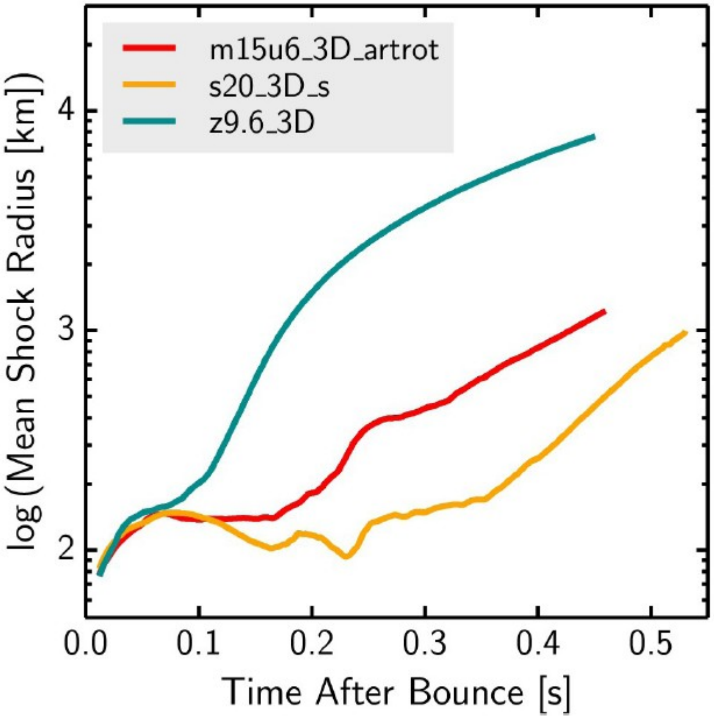


FIG. 1.—Angular velocity Ω as a function of radius *r* for the rotating 15 $M_\odot$ presupernova model (*dashed curve*) of Heger, Langer, & Woosley (2000), for the magnetic rotating 15 $M_\odot$ presupernova model (*dash-dotted curve*) of Heger et al. (2004), and for our rotating model s15r (*solid curve*).

Explosion occurs for angular velocity of Fe-core of 0.5 rad/s, rotation period of ~12 seconds (several times faster than predicted for magnetized progenitor by Heger et al. 2005).
Produces a neutron star with spin period of ~1–2 ms.



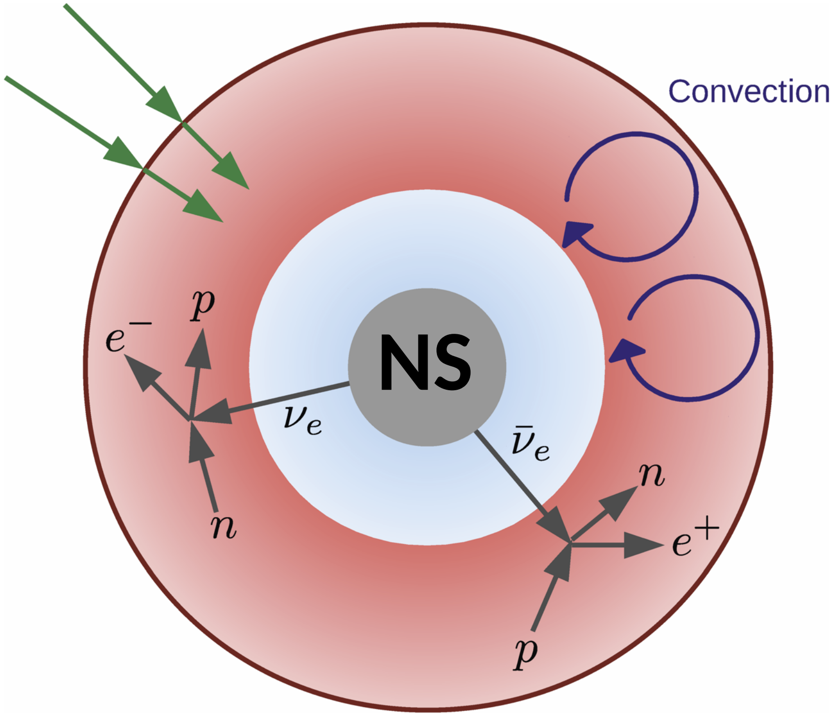


Janka, Melson & Summa,
ARNPS 66 (2016);
Summa et al., ApJ 852 (2018) 28

Nonradial Hydrodynamic Instabilities

Convection

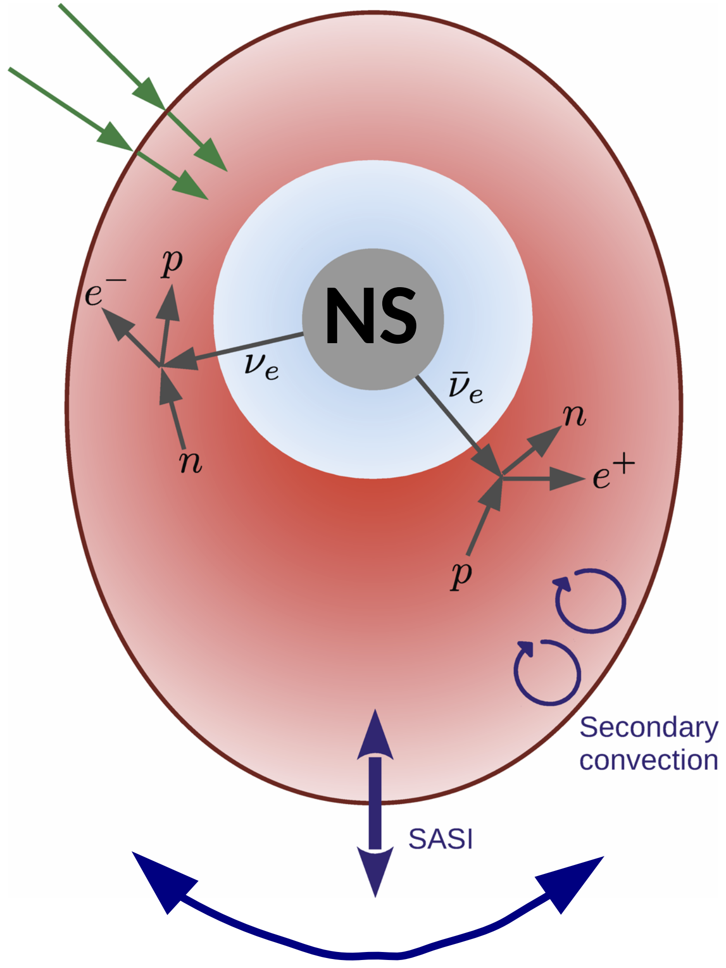
Convective Overturn



Images: Tobias Melson

SASI

Standing accretion shock instability



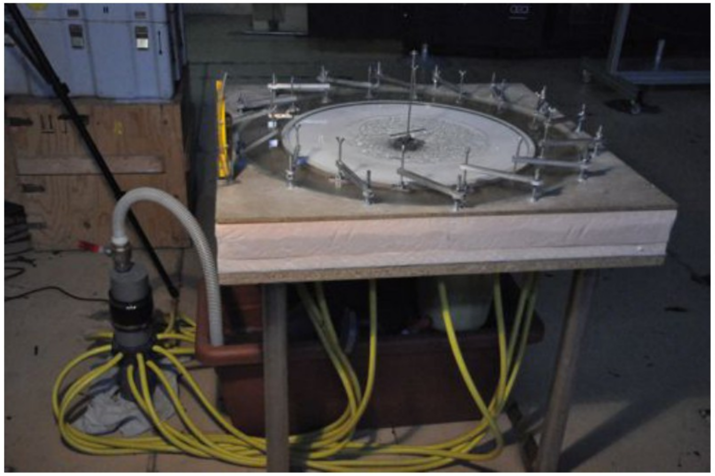
Spiral SASI

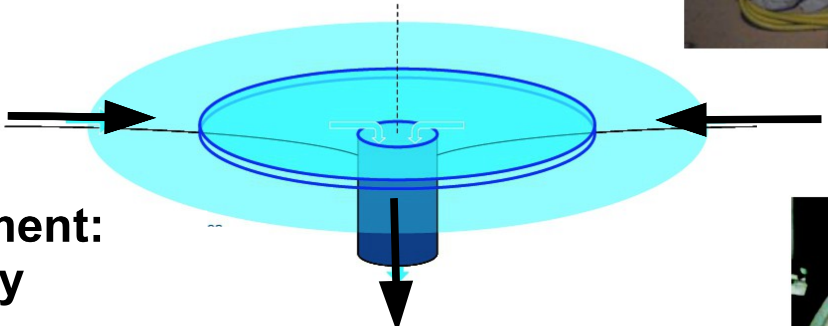
Laboratory Astrophysics

"SWASI" Instability as an analogue of SASI in the supernova core

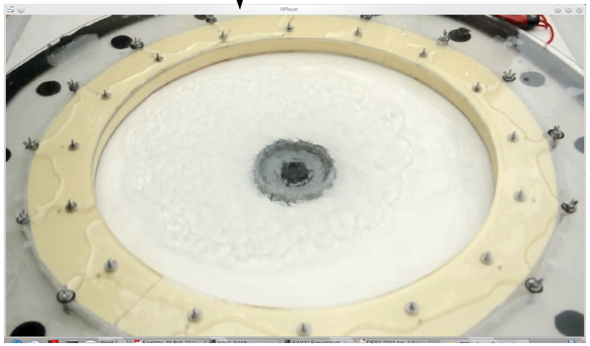
Foglizzo et al., PRL 108 (2012) 051103;

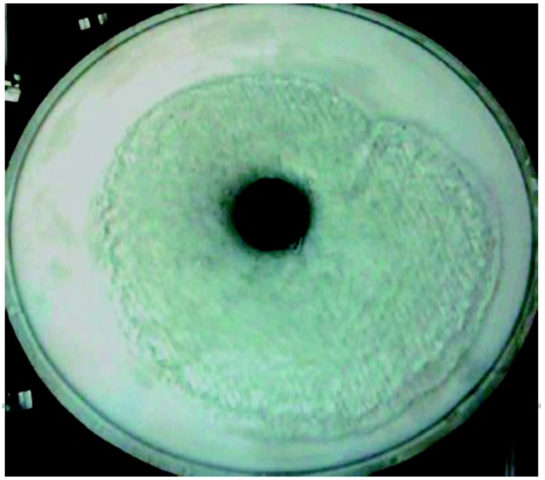
Sebold et al., Phys. Rev. E 102 (2020) 063103; Günzkofer & Manz, Phys. Rev. Fluids 6 (2021) 05441





Constraint of experiment:
No convective activity

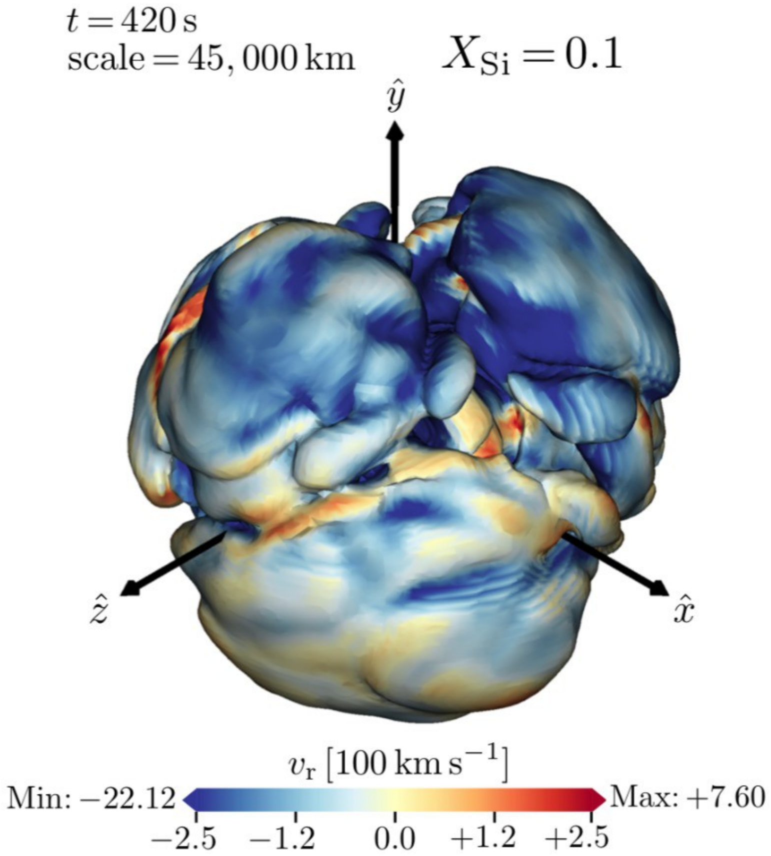


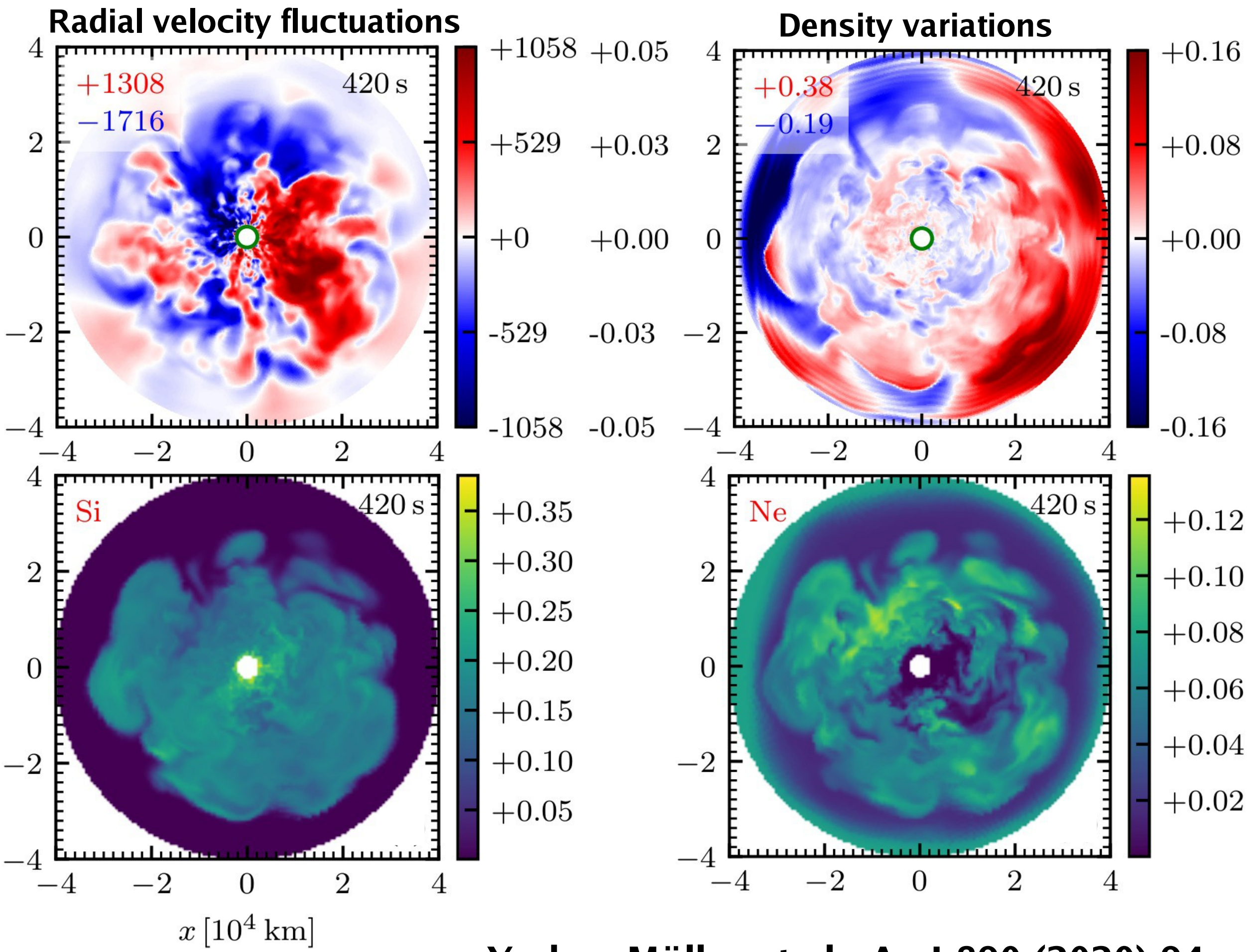


Pre-collapse
3D Asymmetries
in Progenitors

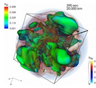
Neon-oxygen-shell Merger in a 3D Pre-collapse Star of ~19 M_{sun}

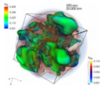
Flash of Ne+O burning creates large-scale asymmetries in density, velocity, Si/Ne composition




Radial velocity fluctuations

Density variations

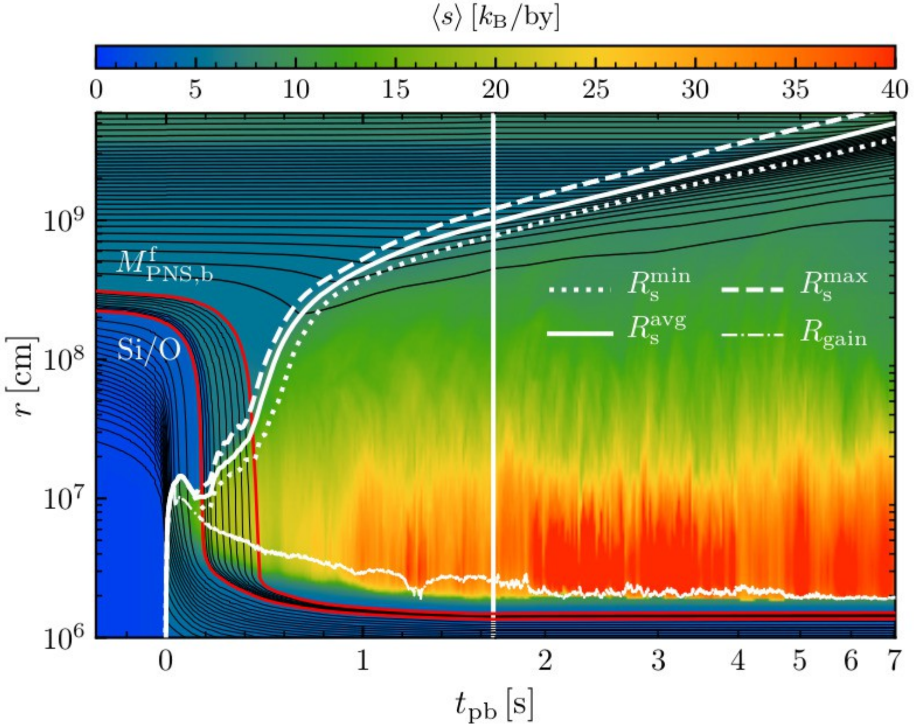


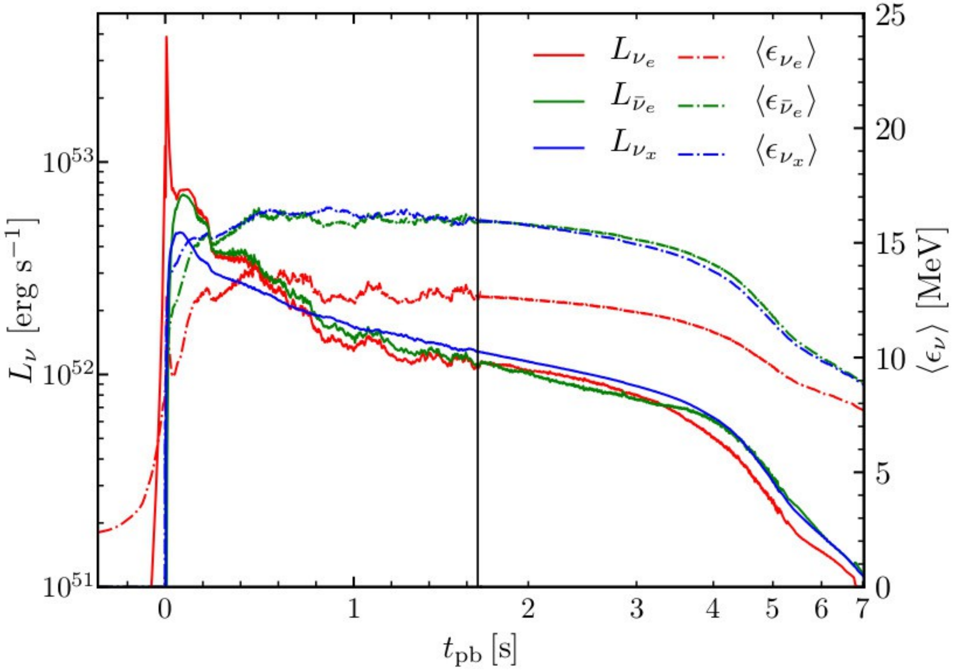


Yadav, Müller et al., ApJ 890 (2020) 94

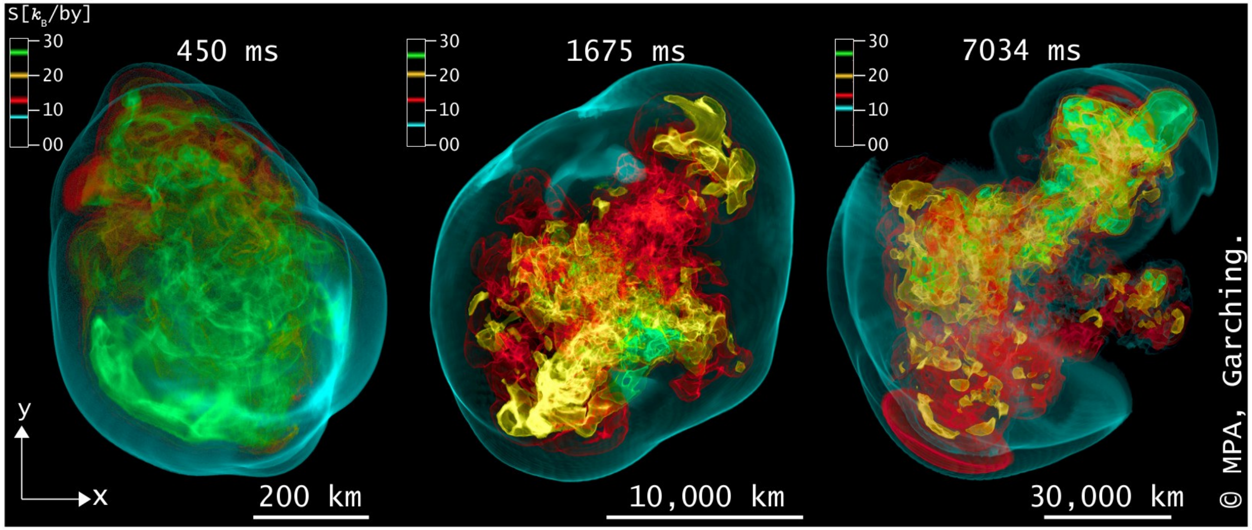
3D Explosion of ~19 M_{sun} Star

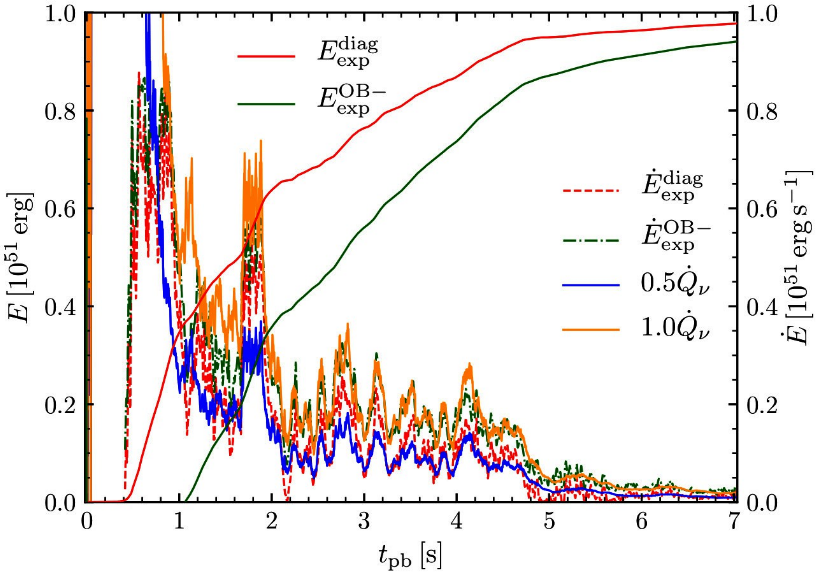
Explosion energy saturates at 10^{51} ergs after 7 seconds



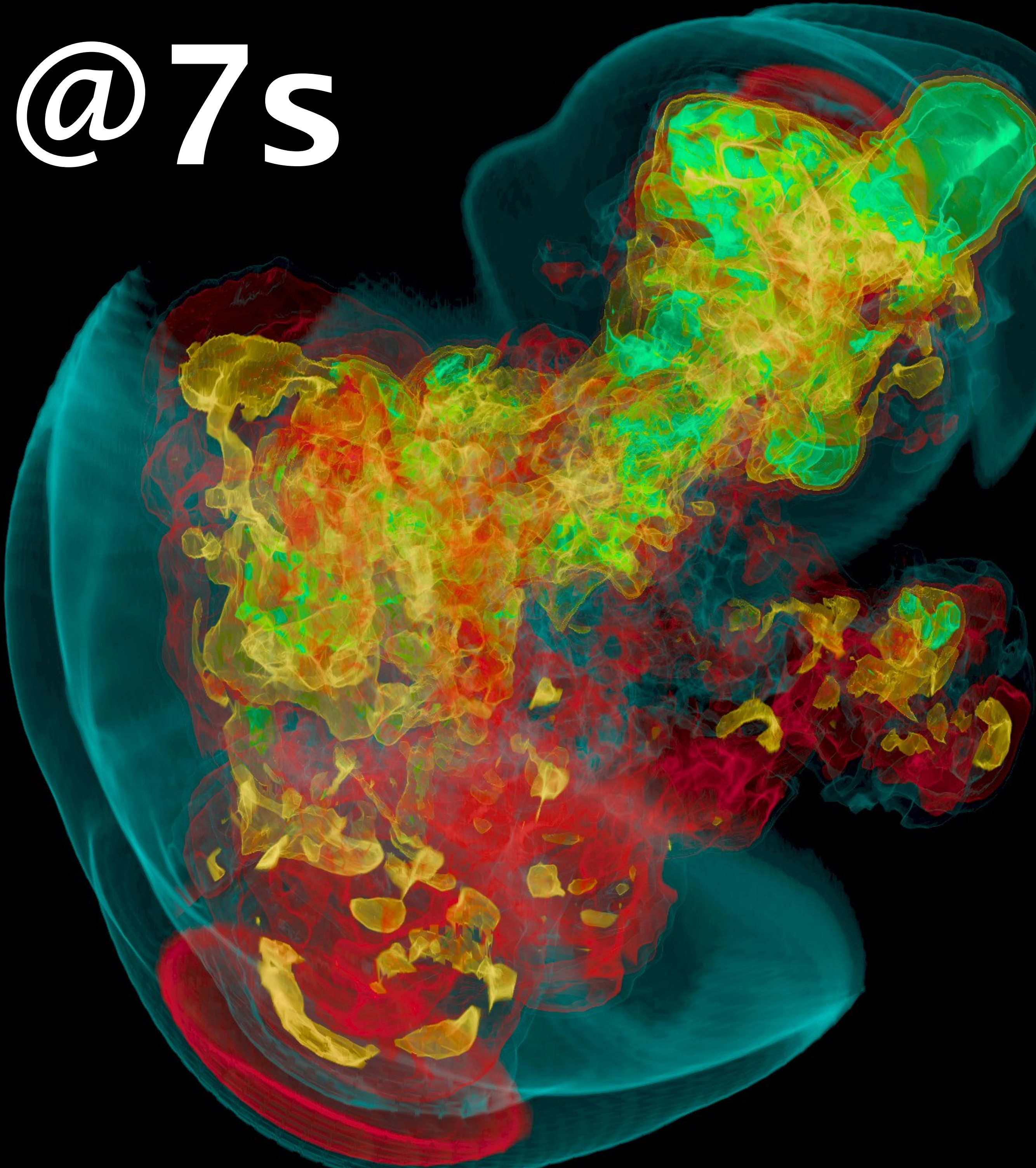


R. Bollig et al., arXiv:2010.10506





@7s



3D Core-Collapse SN Explosion Models

Garching/QUB/Monash (Melson+ ApJL 2015a,b; Müller 2016; Janka+ ARNPS 2016, Müller+ MNRAS 2017, Summa+ ApJ 2018, Glas+ ApJ 2019):

- 9.6, 20 M_{sun} nonrotating progenitors (Heger 2012; Woosley & Heger 2007)
- 18 M_{sun} nonrotating progenitor (Heger 2015)
- 15 M_{sun} rotating progenitor (Heger, Woosley & Spuit 2005, modified rotation)
- 9.0 M_{sun} nonrotating progenitor (Woosley & Heger 2015)
- ~19.0 M_{sun} nonrotating progenitor (Sukhbold, Woosley, Heger 2018)

Monash/QUB (Müller+ MNRAS 2018, Müller+MNRAS 2019):

- z9.6, s11.8, z12, s12.5 M_{sun} nonrotating progenitors (Heger 2012)
- he2,8, he3.0, he3.5 M_{sun} He binary stars, ultrastripped SN progenitors (Tauris 2017)
- Black-hole forming very massive stars

3D Core-Collapse SN Explosion Models

Oak Ridge (Lentz+ ApJL 2015): 15 M_{sun} nonrotating progenitor (Woosley & Heger 2007)

Tokyo/Fukuoka (Takiwaki+ ApJ 2014): 11.2 M_{sun} nonrotating progenitor
more massive progenitors with rapid rotation (Woosley et al. 2002,2007)

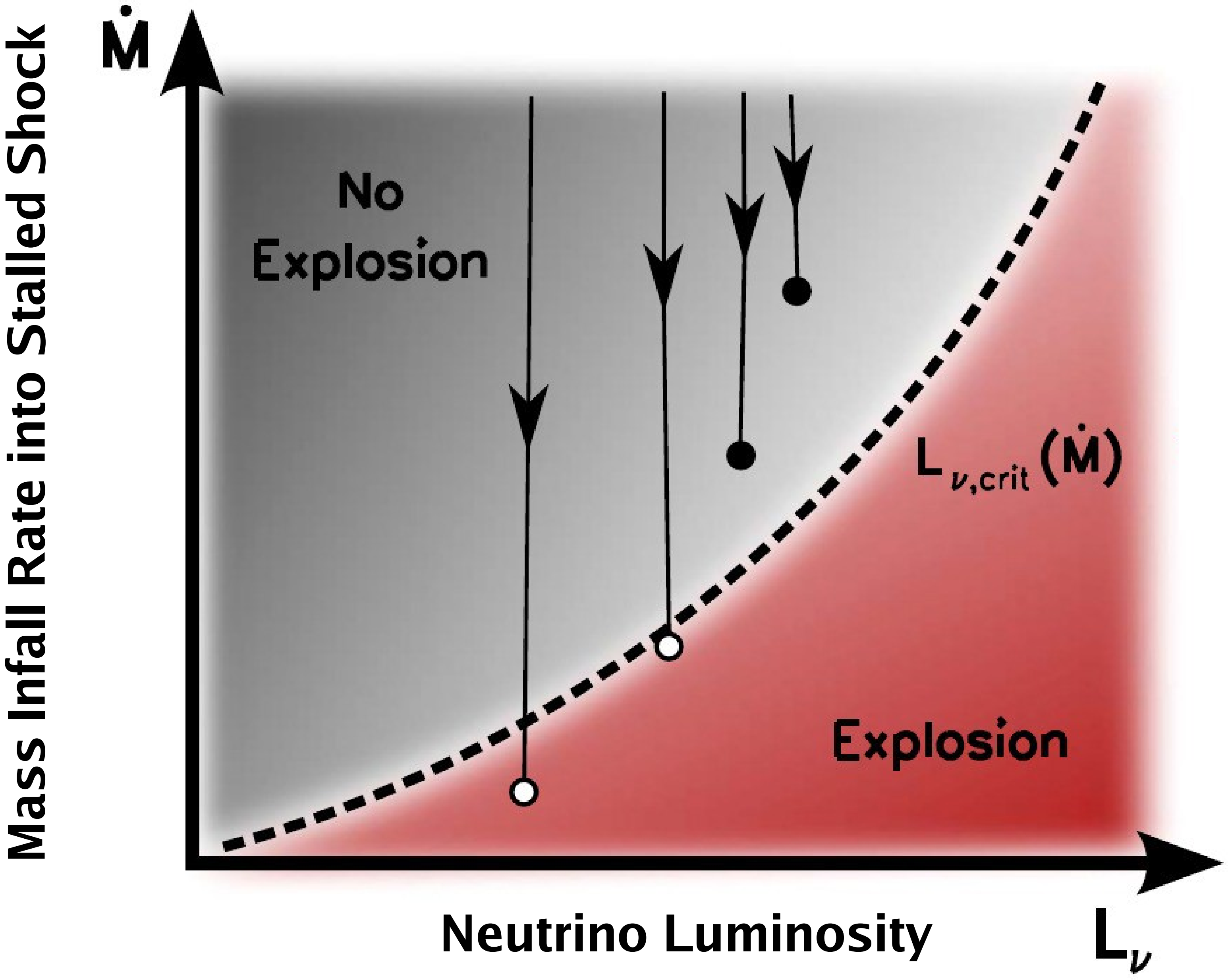
Caltech/NCSU/LSU/Perimeter (Roberts+ ApJ 2016; Ott+ ApJL 2018):
27 M_{sun} nonrotating progenitor (Woosley et al. 2002),
15, 20, 40 M_{sun} nonrotating progenitors (Woosley & Heger 2007)

Princeton (Vartanyan+ MNRAS 2019, Burrows+ MNRAS 2020):
9–40 M_{sun} suite of nonrot. progenitors (Woosley & Heger 2007, Sukhbold+2016)

Modeling inputs and results differ in various aspects.
3D code comparison is missing and desirable

Critical Condition for Explosion

Burrows & Goshy, ApJL (1993)



Universal Critical Neutrino Luminosity for Explosion

$$\left(L_\nu \langle E_\nu^2\rangle\right)_{\rm crit} \propto \left(\dot{M} M\right)^{3/5} \xi_{\rm g}$$

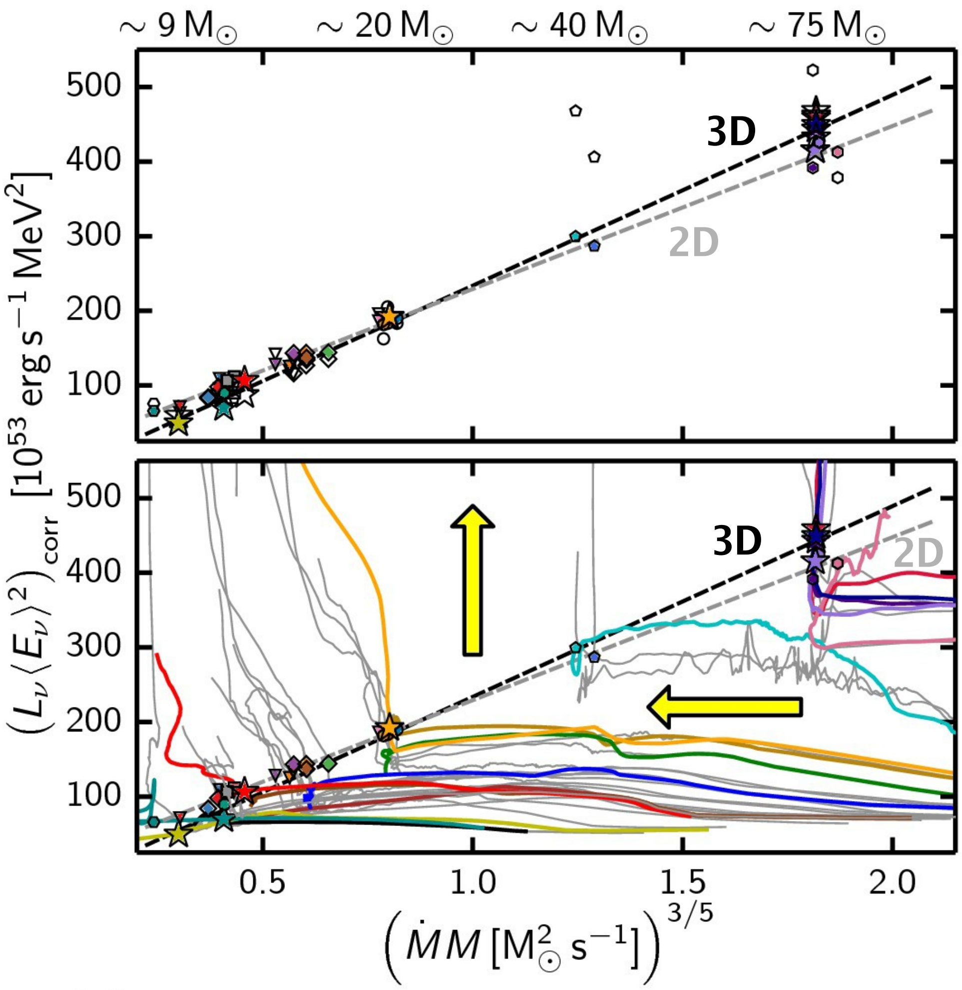
$$\xi_{\rm g} \equiv \left|\bar{e}_{\rm tot,g}\right|^{3/5} R_{\rm g}^{-2/5}\, \xi_{\rm turb}^{-3/5}\, \xi_{\rm rot}^{6/5}$$

$$\xi_{\rm turb} = 1 + \frac{4}{3}\langle {\rm Ma}^2\rangle \geq 1$$

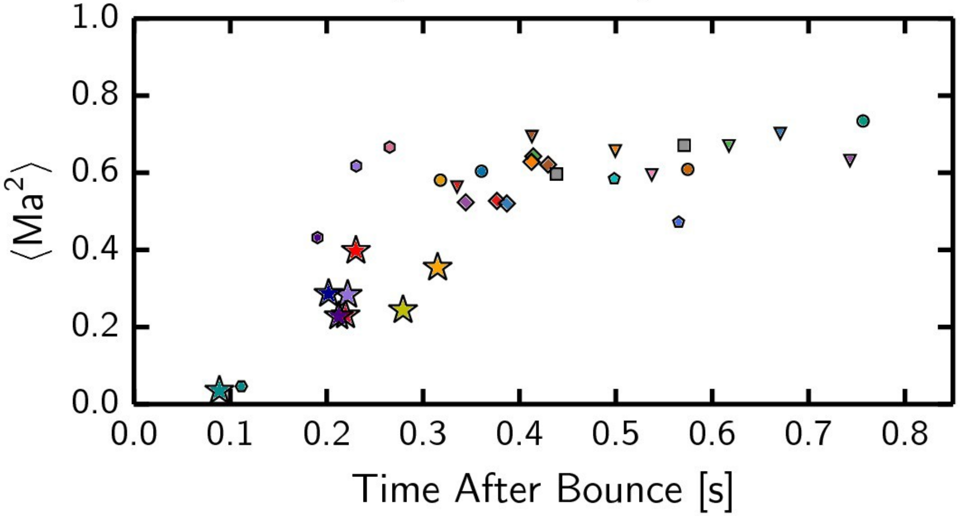
$$\bar{e}_{\rm tot,g} = \frac{E_{\rm tot,g}}{M_{\rm g}}$$

$$\xi_{\rm rot} = \sqrt{1 - \frac{j_0^2}{2GMR_{\rm s}}} \leq 1$$

$$\boxed{\left(L_\nu \langle E_\nu^2\rangle\right)_{\rm crit,corr} \equiv \frac{1}{\xi_{\rm g}/\xi_{\rm g}^*}\left(L_\nu \langle E_\nu^2\rangle\right)_{\rm crit} \propto \left(\dot{M} M\right)^{3/5}}$$



Summa et al., ApJ 852 (2018) 28



Status of Neutrino-driven Mechanism in 3D Supernova Models

- **3D modeling has reached mature stage.**
- **3D differs from 2D in many aspects, explosions more difficult than in 2D.**

- **Neutrino-driven 3D explosions for progenitors between 9 and 40 M_{sun}**
  (with rotation, 3D progenitor perturbations, or slightly modified neutrino opacities)
- **Explosion energy can take many seconds to saturate! $\underline{10^{51}\text{ erg possible!}}$**

- **Progenitor models are provided in 1D**, but composition-shell structure and initial progenitor-core asymmetries can be crucial for onset of explosion.
- 3D simulations may **still need higher resolution** for convergence.

Neutrino-driven Explosion Models

vs.

Observations

Observational consequences

Direct and indirect evidence for neutrino heating and hydrodynamic instabilities at the onset of stellar explosions:

- **Neutrino signals (characteristic time dependencies)**
- **Gravitational-wave signals**
- **Neutron star kicks**
- **Asymmetric mass ejection & large-scale radial mixing in supernovae (elm. light curve shape, spectral features)**
- **Detailed comparison to young supernova remnants (e.g., Crab, Cas A, SN 1987A)**
- **Progenitor – explosion – remnant connection**
- **Nucleosynthesis**

Observational consequences

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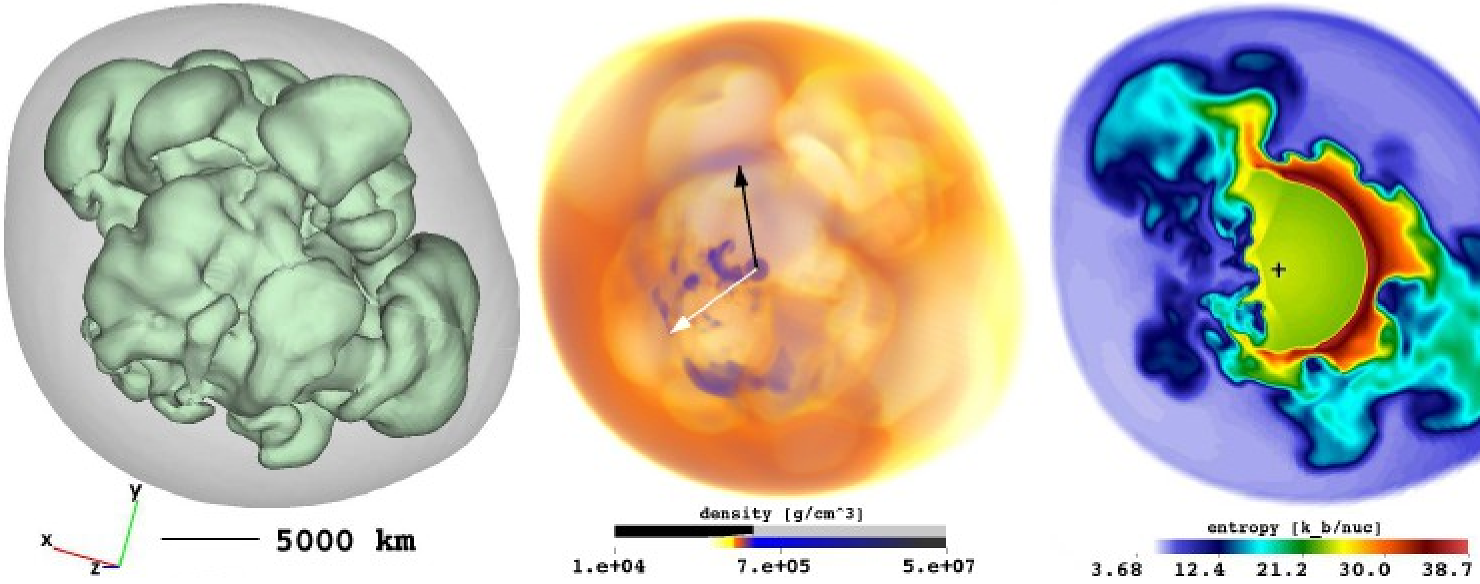
Neutron Star Recoil in 3D Explosion Models

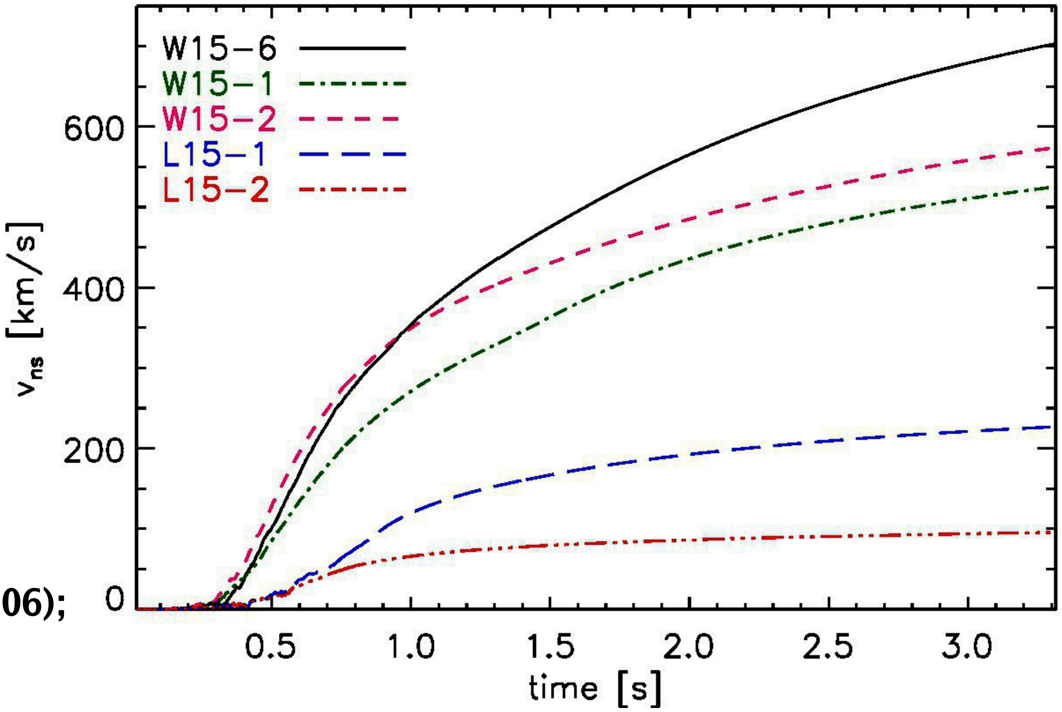


W15-2
@ 1.3 s

Gravitational tug-boat mechanism

$$v_{\rm NS} = 211\,{\rm km\,s^{-1}} \left(\frac{f_{\rm kin}}{\epsilon_5\,\beta_\nu}\right)^{1/2} \left(\frac{\alpha_{\rm ej}}{0.1}\right) \times \\ \times \left(\frac{E_{\rm exp}}{10^{51}\,{\rm erg}}\right)\left(\frac{M_{\rm NS}}{1.5\,M_\odot}\right)^{-1}$$

Wongwathanarat, Janka, Müller,
ApJL 725, 106 (2010); A&A 552, 126 (2013);
Scheck et al., PRL 92, 011103 (2004), A&A 457, 963 (2006);
Janka, ApJ 837, 84 (2017)



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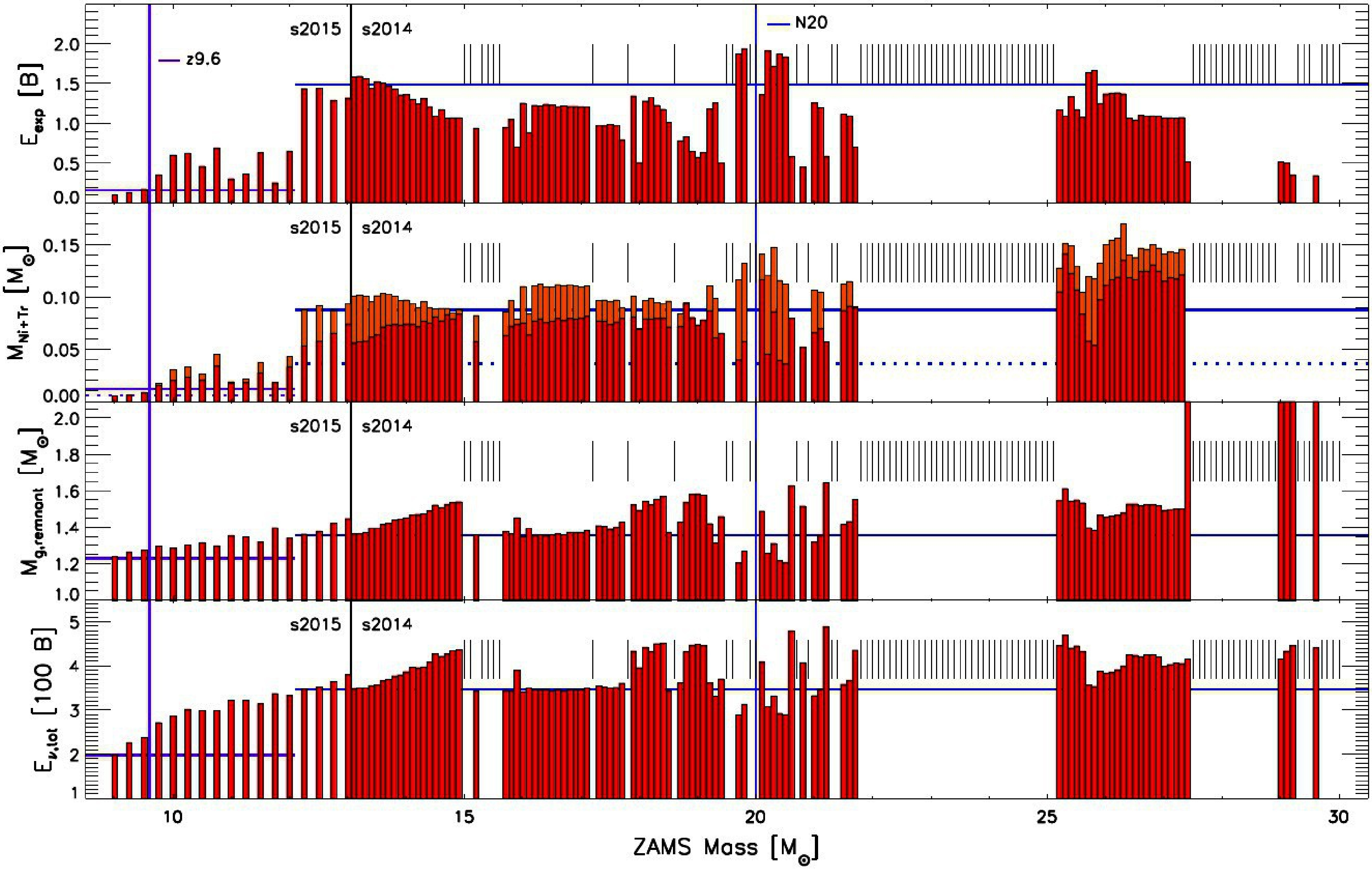
Systematics of Neutrino-driven Explosions

Exploration by 1D modeling with neutrino-driven “engines”

Neutrino-driven Explosions vs. ZAMS mass



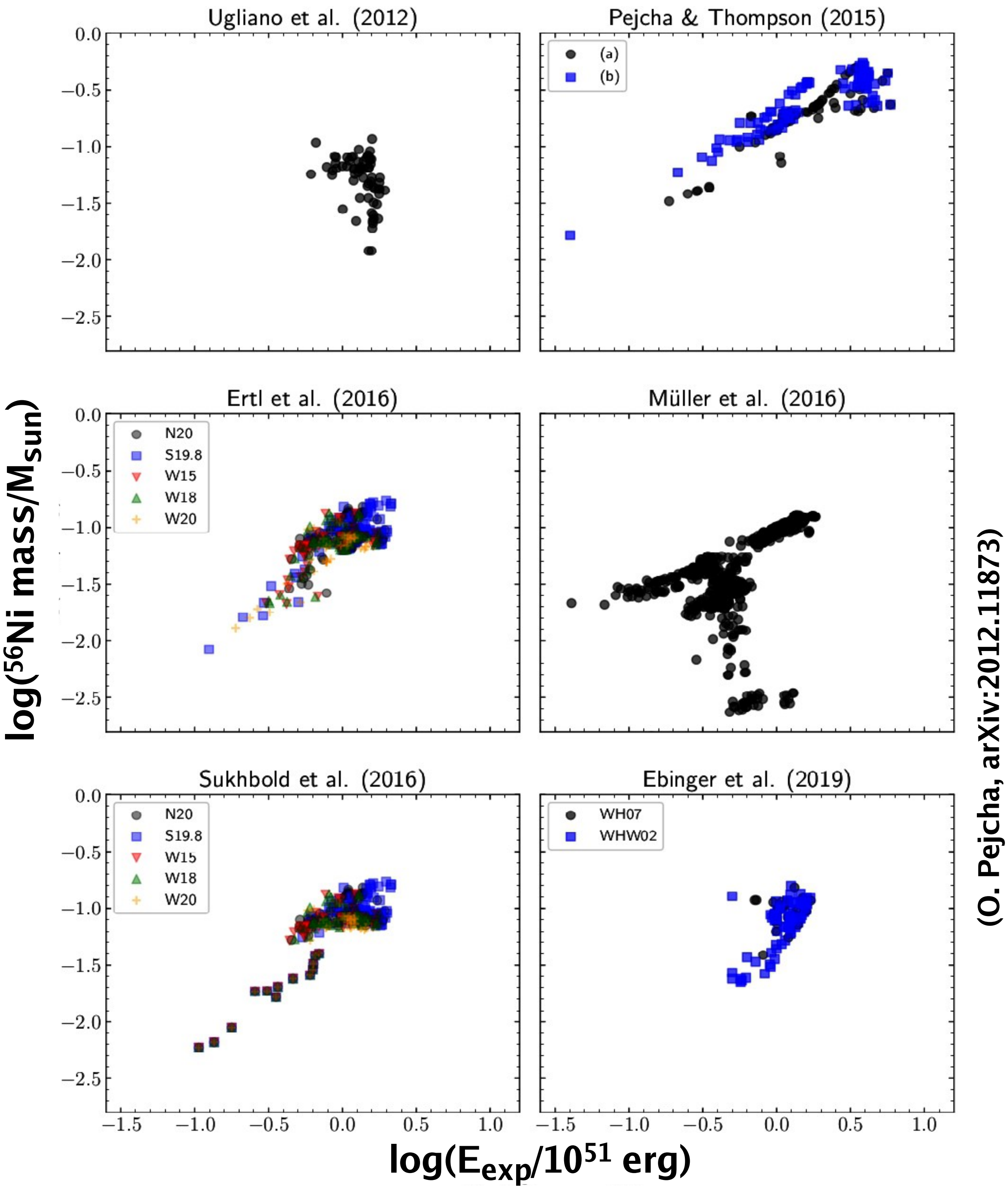
(Ertl et al., ApJ 808 (2016) 124; Sukbold et al., ApJ 821 (2016) 38; Ertl et al., ApJ 890 (2020) 51)

Neutrino-driven Explosions: Predictions

Compare theoretical predictions with observations for properties that depend specifically on explosion mechanism, e.g.:

correlation M_{Ni} vs. E_{exp}

In contrast:
Remnant (NS, BH) mass distributions depend strongly on nature of stellar progenitor (single or binary) populations



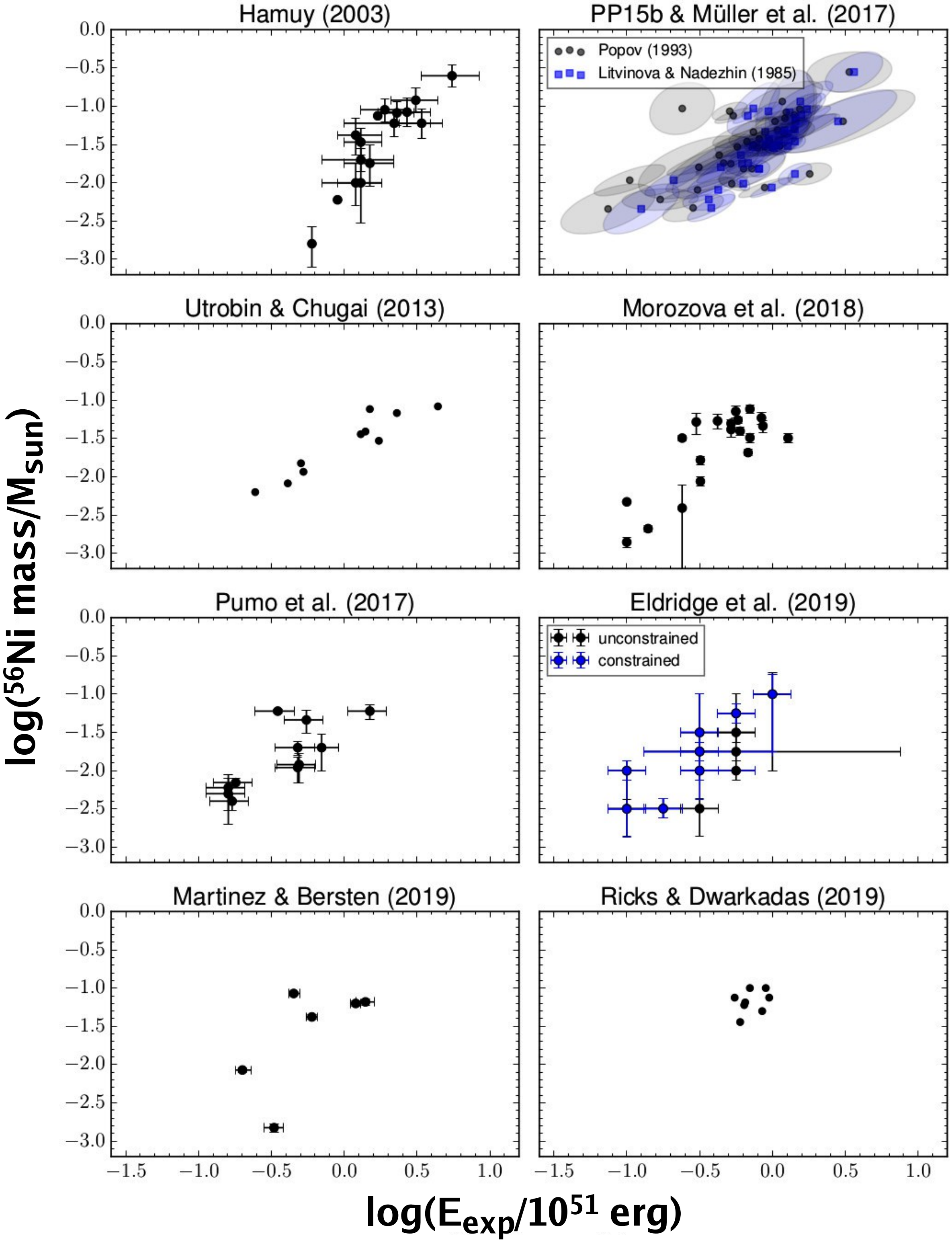
(O. Pejcha, arXiv:2012.11873)

Supernova Explosions: Observations

Compare theoretical predictions with observations for properties that depend specifically on explosion mechanism, e.g.:

correlation M_{Ni} vs. E_{exp}

In contrast:
Remnant (NS, BH) mass distributions depend strongly on nature of stellar progenitor (single or binary) populations



(O. Pejcha, arXiv:2012.11873)

Conclusions

Neutrino-driven Explosions in Supernova Simulations

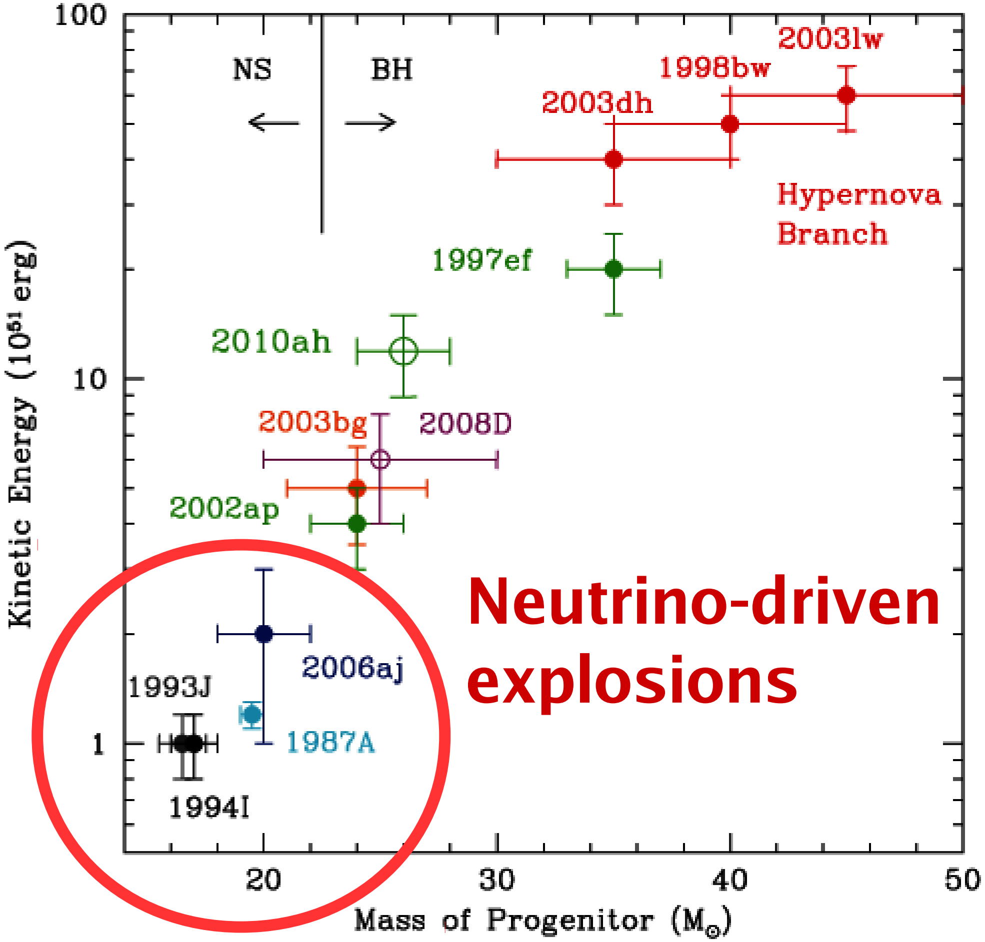
- **Ab initio, self-consistent 2D and 3D simulations demonstrate viability of delayed neutrino-driven explosion mechanism**

- **Multi-D models of neutrino-driven explosions are sufficiently mature to test them against observations**

- **Unsolved aspects, e.g.:**
  - * **Nuclear equation of state in neutron stars**
  - * **Neutrino flavor oscillations in interaction in dense matter**
  - * **Relevance of rotation and strong magnetic fields**
  - * **Stripped-envelope supernovae: Jets? Magnetars?**
  - * **Progenitors and explosions of extreme SNe?**

Observational Supernova-Progenitor Connection

What is the role of rapid rotation? Which progenitors do spin rapidly? Which stars explode by magnetorotational mechanism? When with jets?



Neutrino-driven explosions

Figure 11. The E_{kin} derived from spectral/LC modelling of a number of SNe Ib/c plotted against the inferred ZAMS mass of the progenitor star using single-star evolutionary models. Colour coding is by spectral type, and it is the same as in Fig. 9.

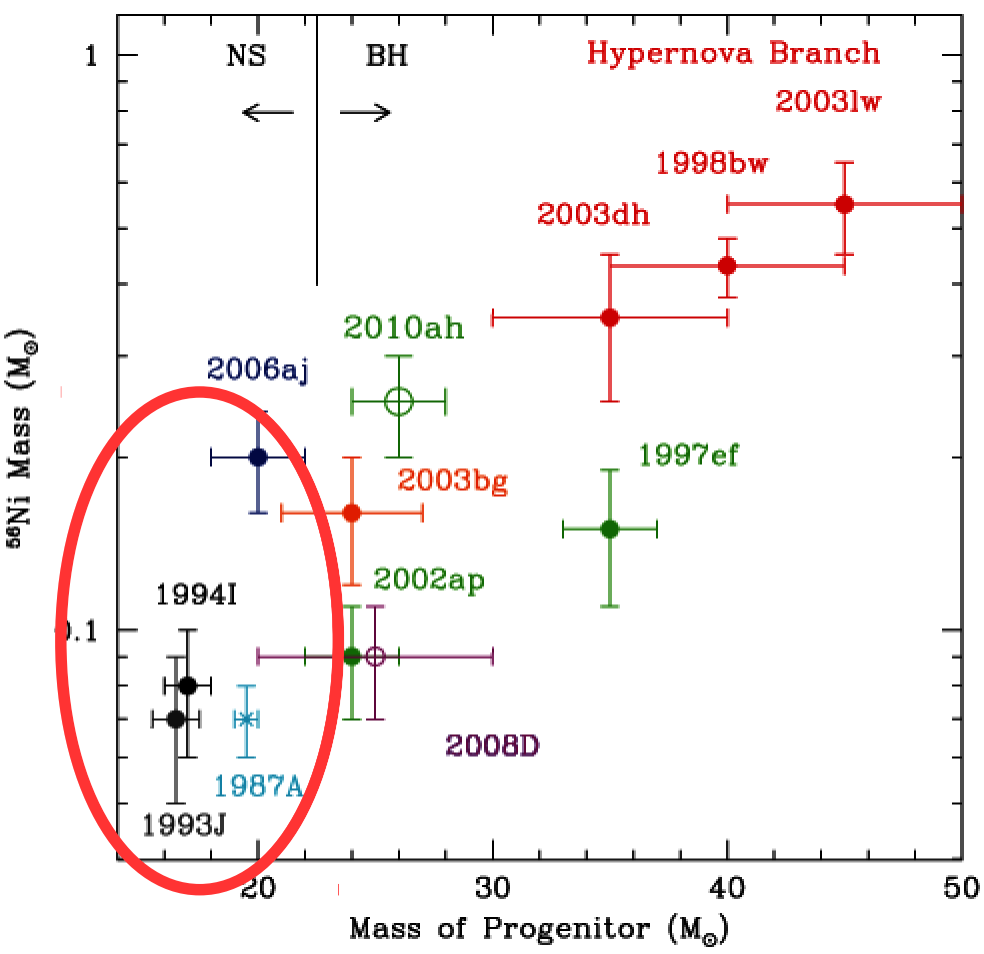
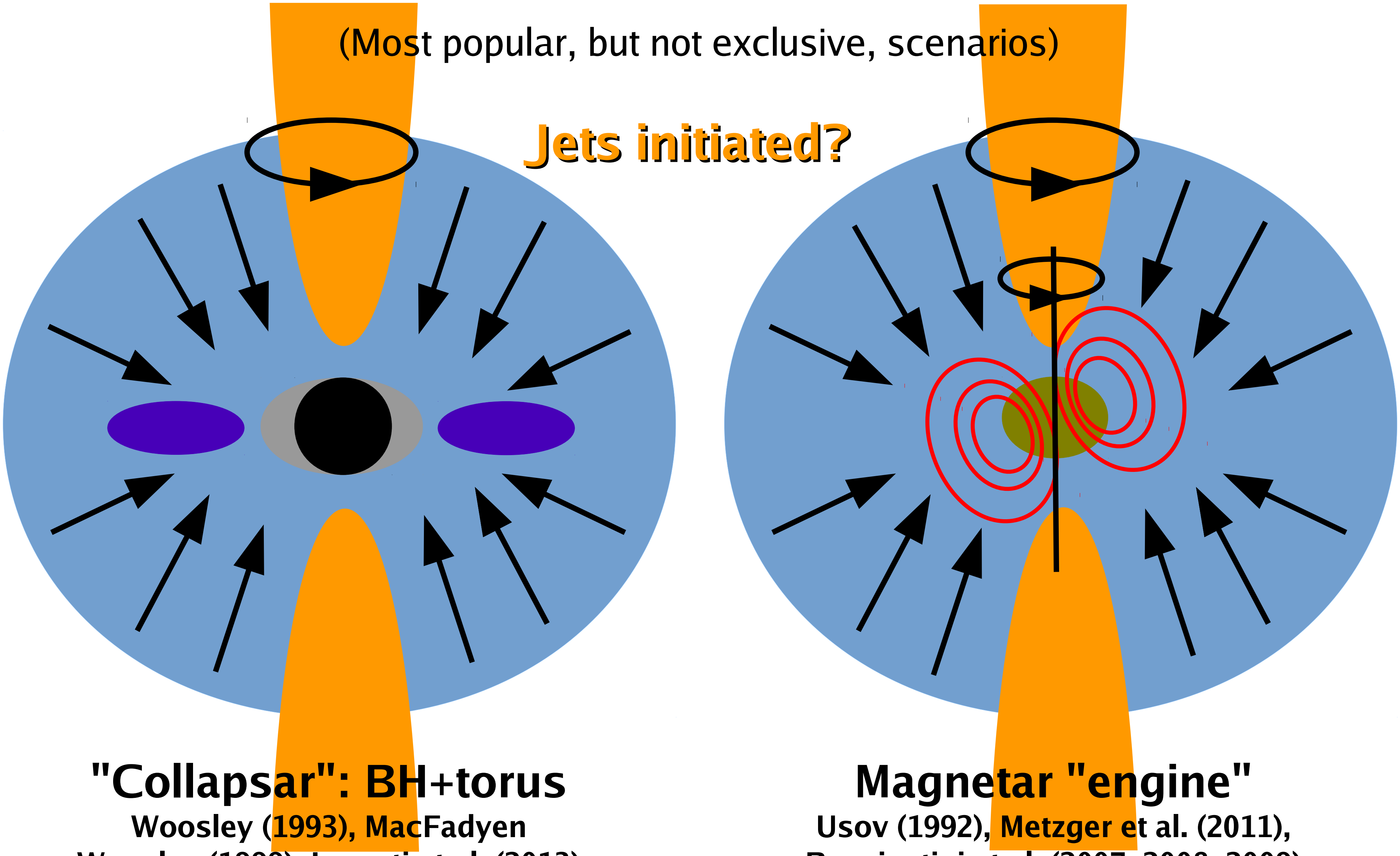


Figure 10. The mass of ^{56}Ni derived from spectral/LC modelling of a number of SNe Ib/c plotted against the inferred zero-age main sequence (ZAMS) mass of the progenitor star using single-star evolutionary models. Colour coding is by spectral type, and it is the same as in Fig. 9.

Mazzali et al., MNRAS 432 (2013) 2463

GRB-Hypernova & SLSN Central Engines



(Most popular, but not exclusive, scenarios)

Jets initiated?

"Collapsar": BH+torus

Woosley (1993), MacFadyen
Woosley (1999), Lazzati et al. (2013)

Magnetar "engine"

Usov (1992), Metzger et al. (2011),
Bucciantini et al. (2007, 2008, 2009)