Numerical modeling of core-collapse supernovae

Matteo Bugli[1]

[1]Astrophysics Department, IRFU/CEA-Saclay, Gif-sur-Yvette, Paris

Progress in algorithms and numerical tools for QCD
GdR "QCD" - 8th June 2022

Outline of talk

1. Introduction
2. Numerical Algorithms
3. Simulations and data
4. Magneto-rotational explosions
5. Conclusions

Table of Contents

1 Introduction

2 Numerical Algorithms

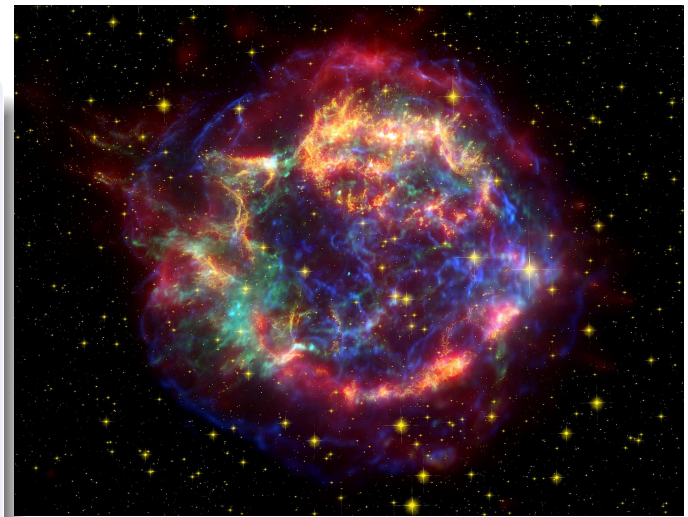
3 Simulations and data

4 Magneto-rotational explosions

5 Conclusions

Core-collapse Supernovae

- Gravitational collapse of a massive star (unstable iron core)
- Shock formation when nuclear densities are reached (stalling) $\Rightarrow$ Proto Neutron Star
- Shock expansion and ejection of unbound material (explosion)

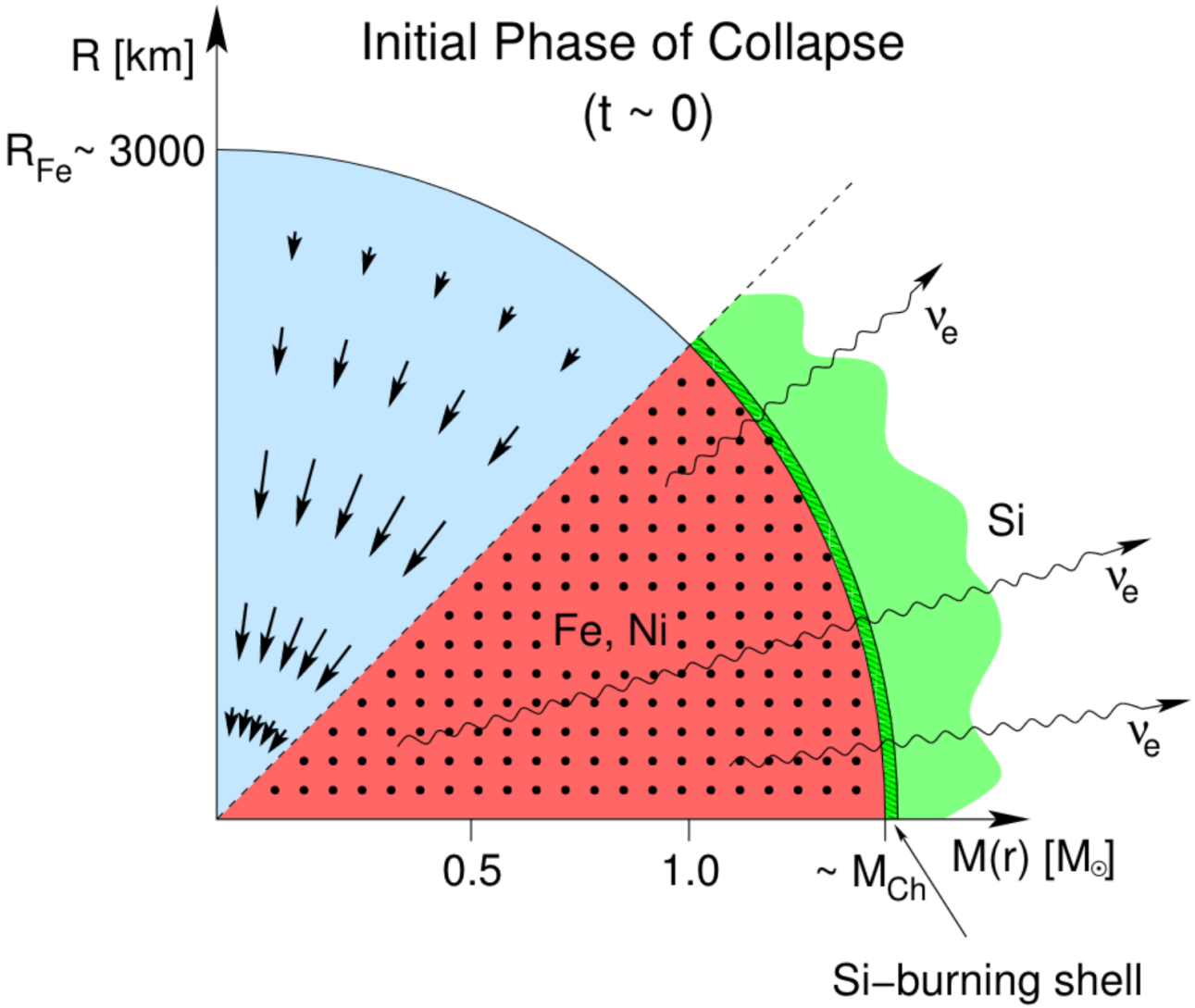


Credit: NASA/JPL-Caltech

Where does the binding energy ($\sim 10^{53}$ erg) end up?

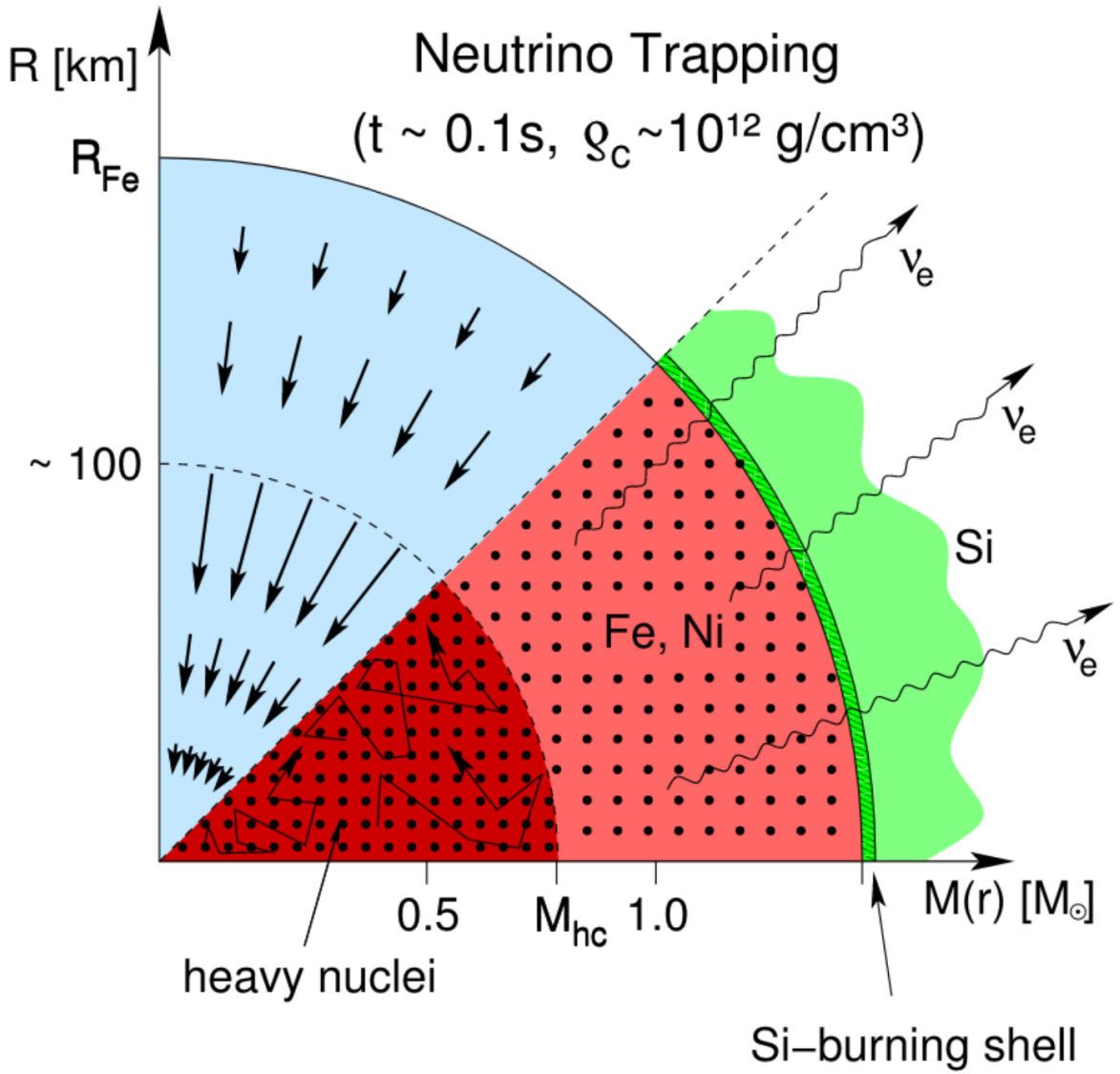
- Neutrino emission ($\sim 99\%$)
- Ejecta ($\sim 1\%$)
- Gravitational waves ($\sim 10^{-8}$)

Death of a massive star (1)



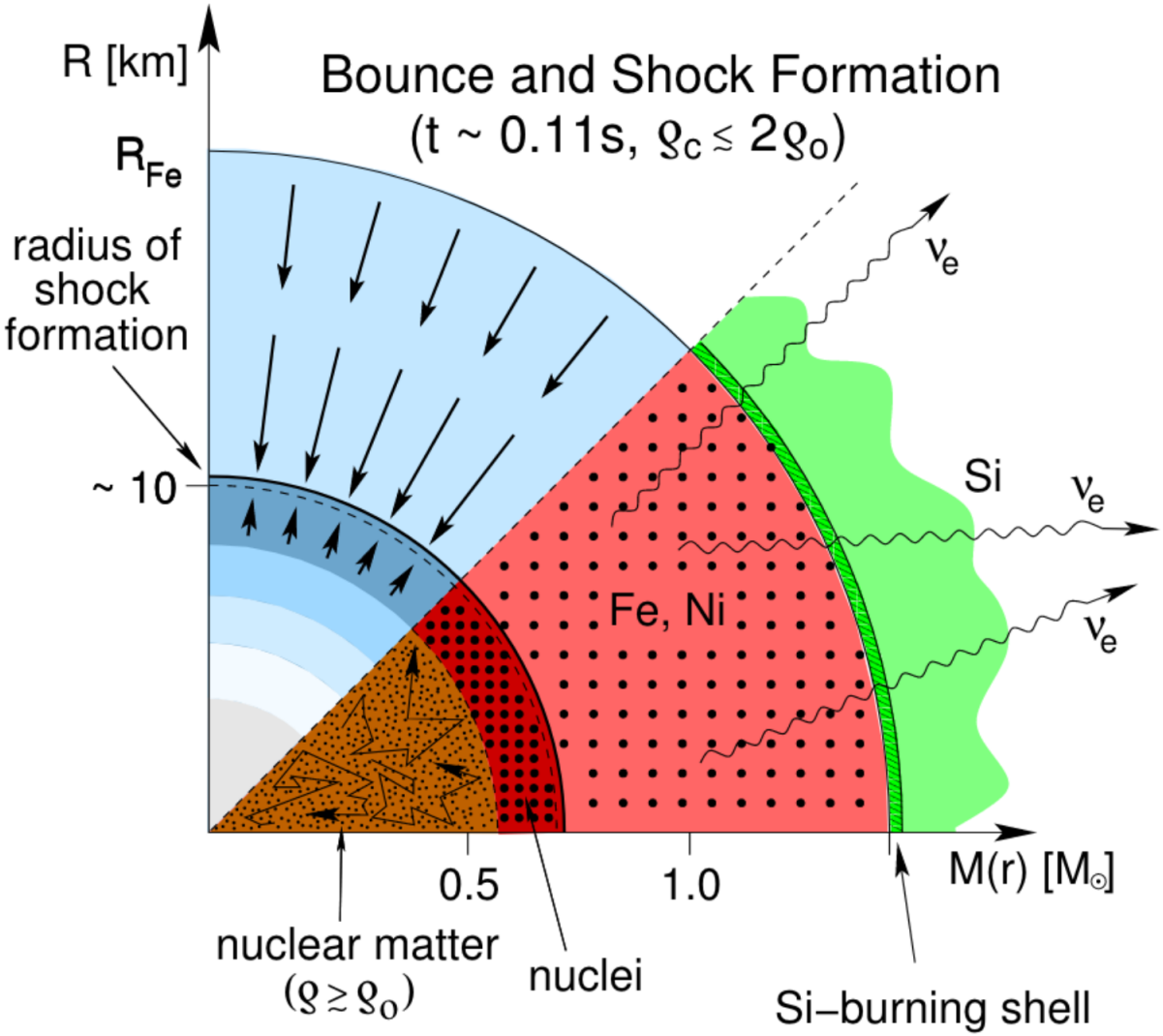
Janka (2017)

Death of a massive star (2)



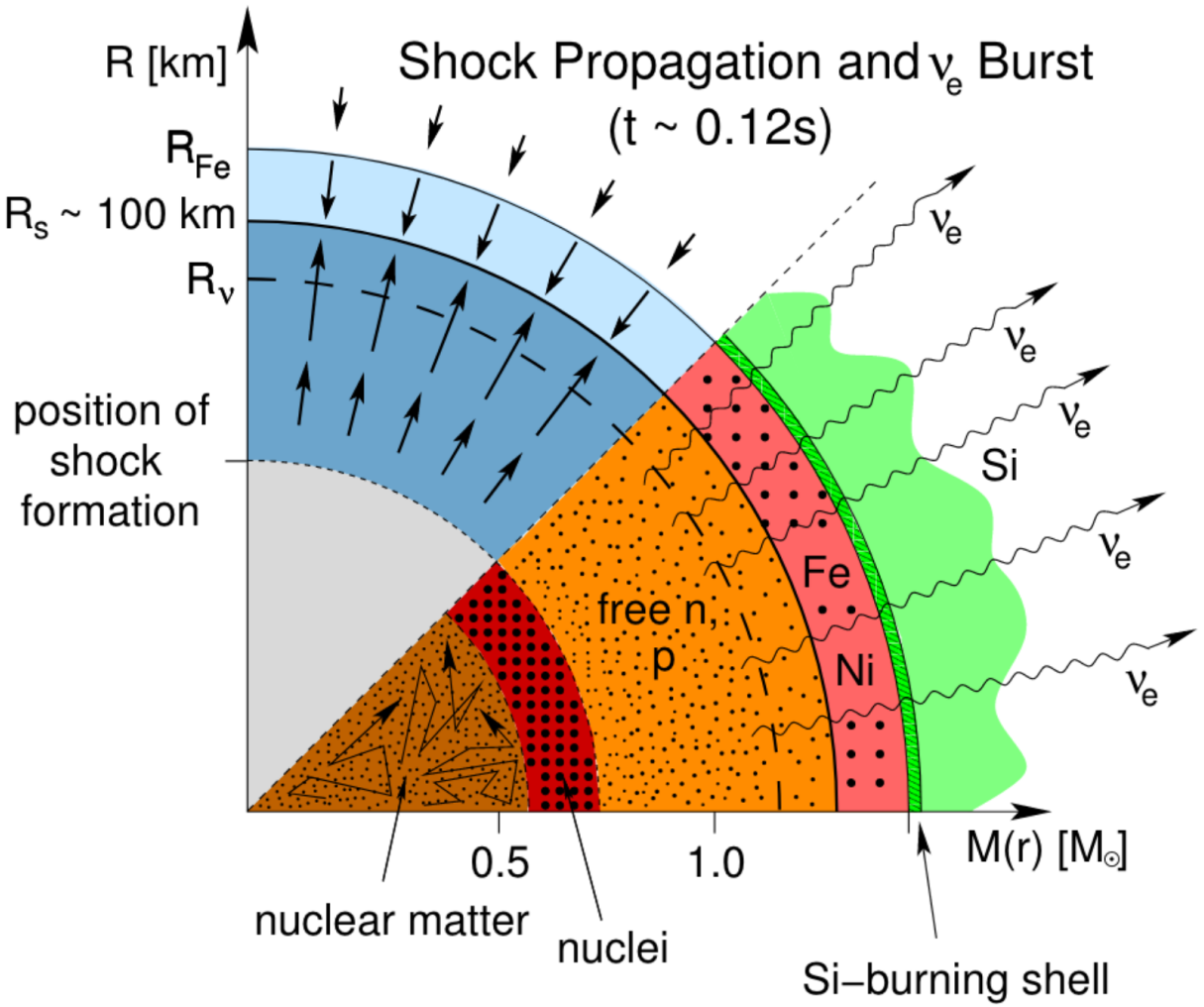
Janka (2017)

Death of a massive star (3)



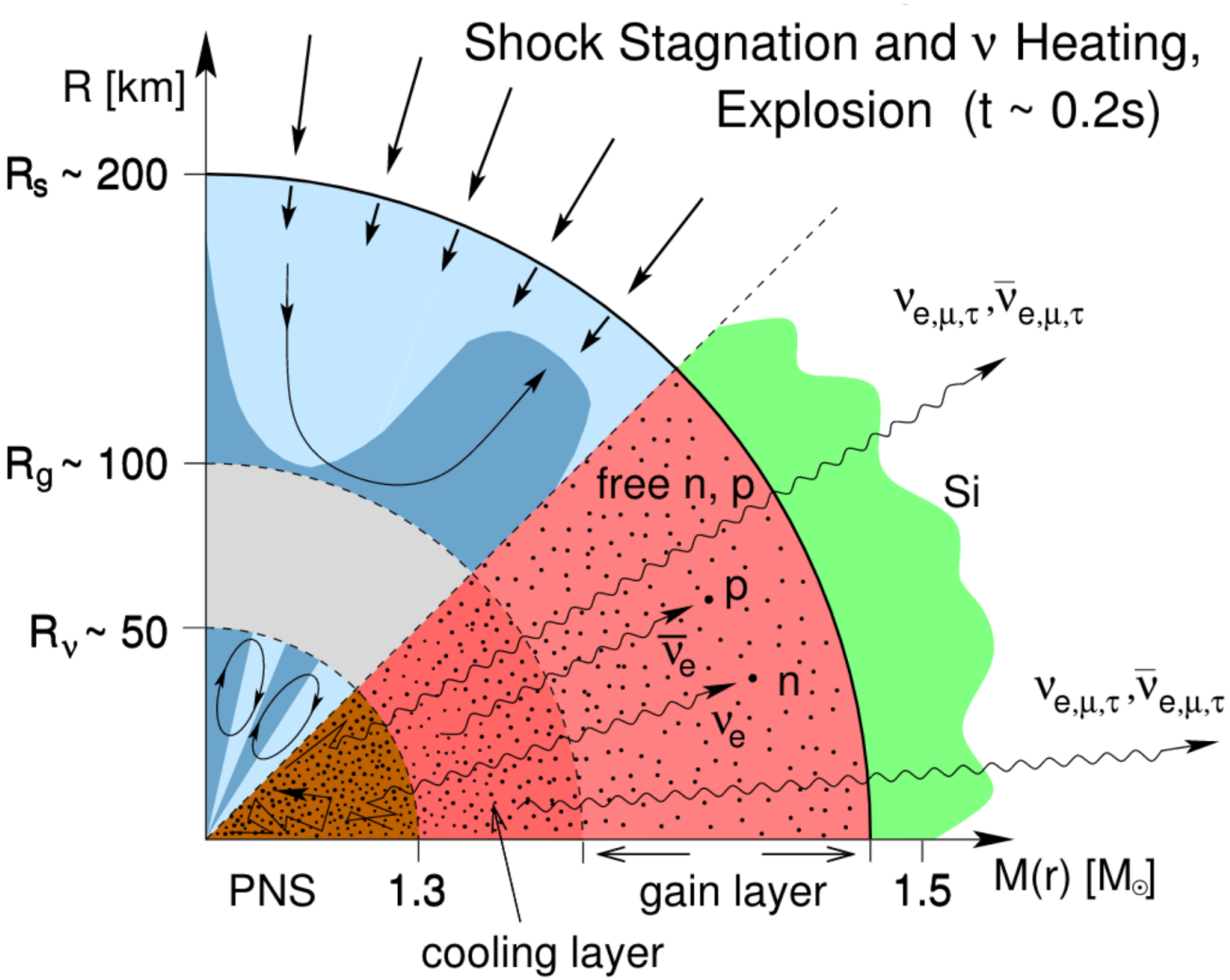
Janka (2017)

Death of a massive star (4)



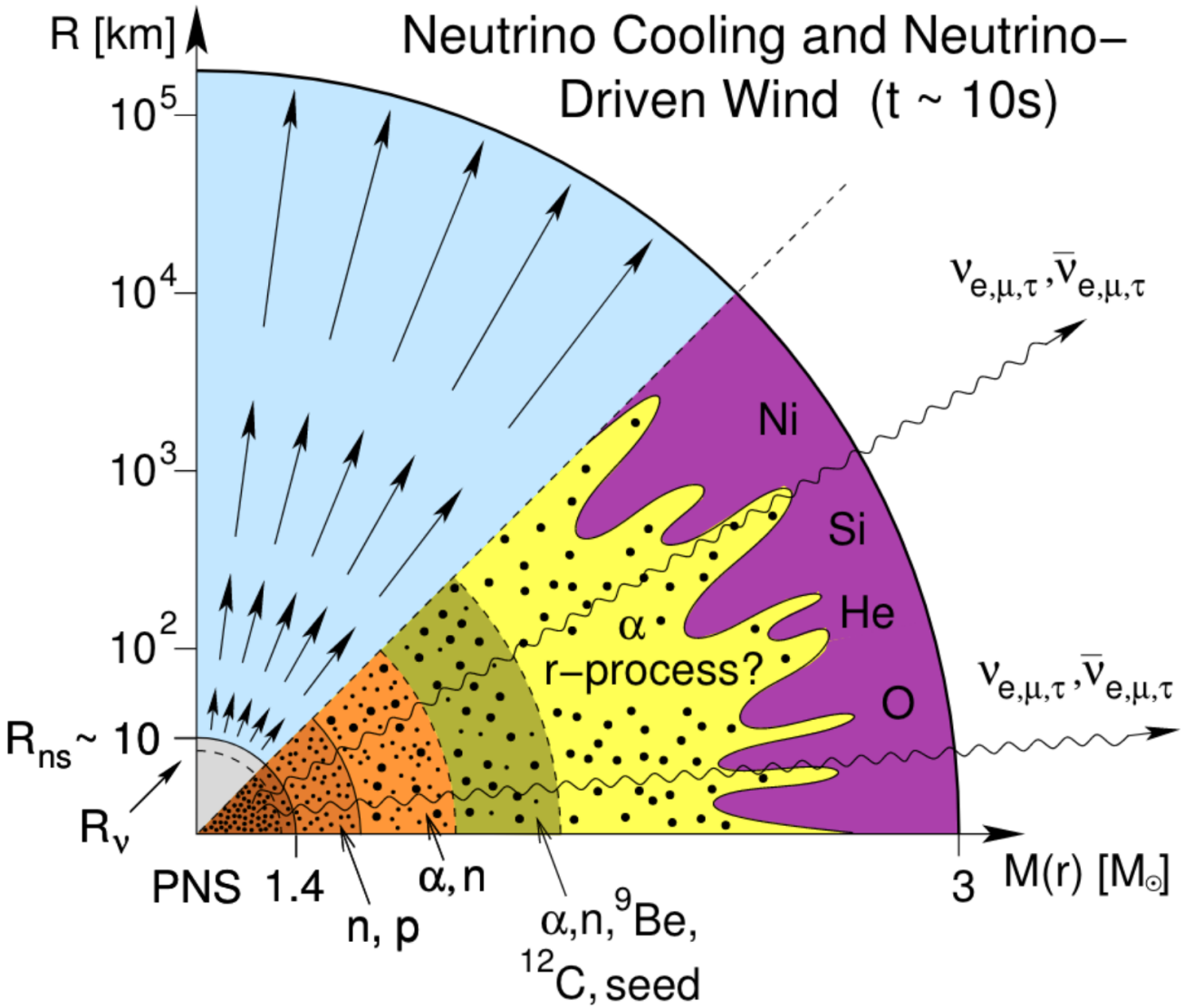
Janka (2017)

Death of a massive star (5)



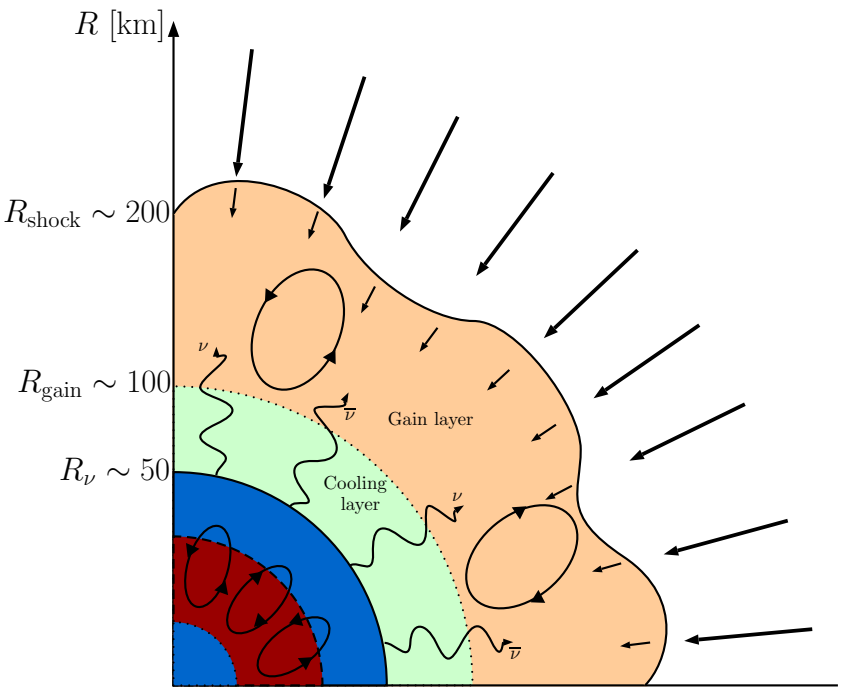
Janka (2017)

Death of a massive star (6)



Janka (2017)

Standard neutrino-driven CCSN



- PNS contraction ⇒ higher ν energies
- ν-cooling rate drops faster than ν-heating ⇒ Gain radius
- Energy deposition by ν_e and $\bar{\nu}_e$ absorption in gain layer
- Multi-D hydrodynamic instabilities aid the explosion (i.e. convection, SASI)

Neutrinos and GW directly probe the explosion mechanism

Table of Contents

1 Introduction

2 Numerical Algorithms

3 Simulations and data

4 Magneto-rotational explosions

5 Conclusions

(Magneto)Hydrodynamics

- Godunov-type, shock-capturing, finite-volumes(differences) schemes
- Divergence-free B field: constrained transport/divergence cleaning
- Cartesian/spherical grids
- Hybrid `MPI-OpenMP` parallelization schemes

Gravitational force

Full GR

- Dynamical evolution of the space-time
- More accurate, higher computational cost
- Mösta et al. (2014); Kuroda et al. (2018)

Newtonian Gravity

- Relativistic corrections to Φ (Marek et al., 2006)
- Cheaper computational cost, less accurate
- Just et al. (2015); O'Connor and Couch (2018); Takiwaki et al. (2021)

High-density EoS

Popular choices

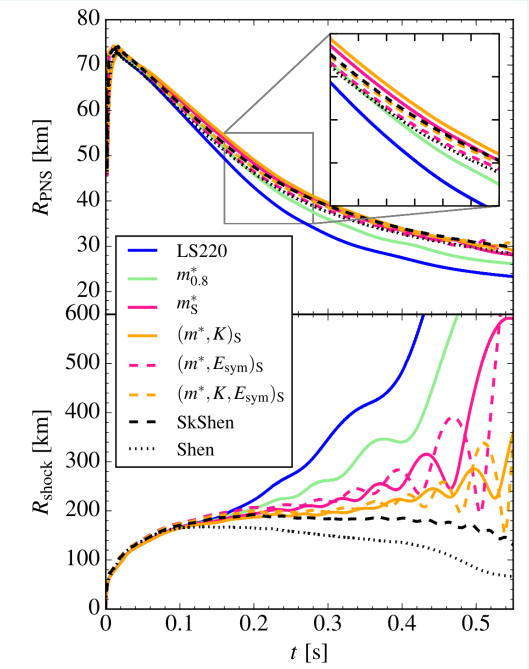
- LS220 (Lattimer and Swesty, 1991): compressible liquid-drop model
- Shen (STOS) (Shen et al., 1998): RMF with TM1 parameter set
- SFHo (Steiner et al., 2013): RMF consistent with observations

The CompOSE catalogue

- Online repo of CCSN-NS EoS
- ∼240 entries
- Free download of tables, M-R relations, references

PNS and shock properties

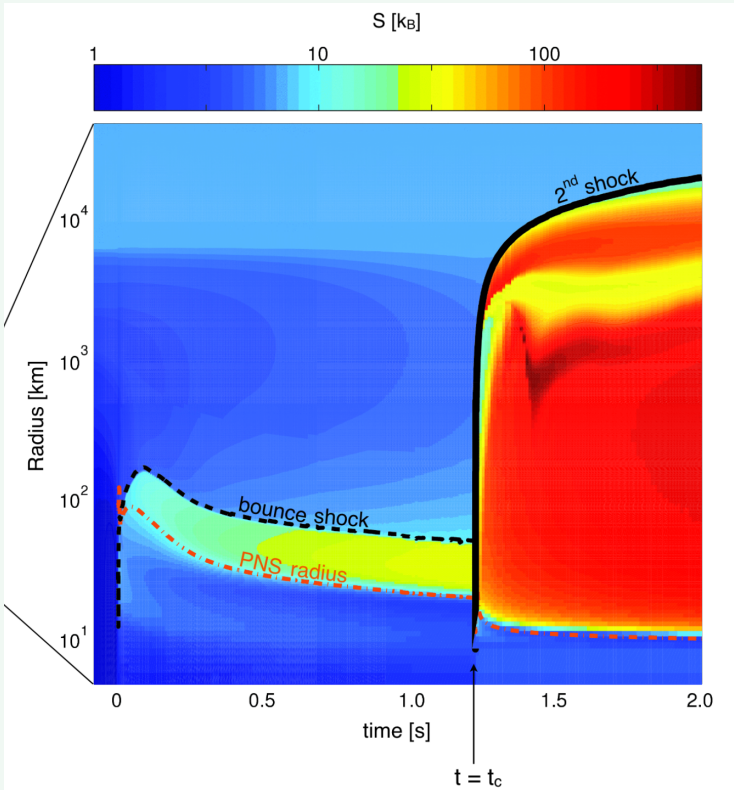
- Lower effective mass ⇒ lower contraction and ν energies
- Higher incompressibility ⇒ larger PNS radius (Yasin et al., 2018)



More recent EoS

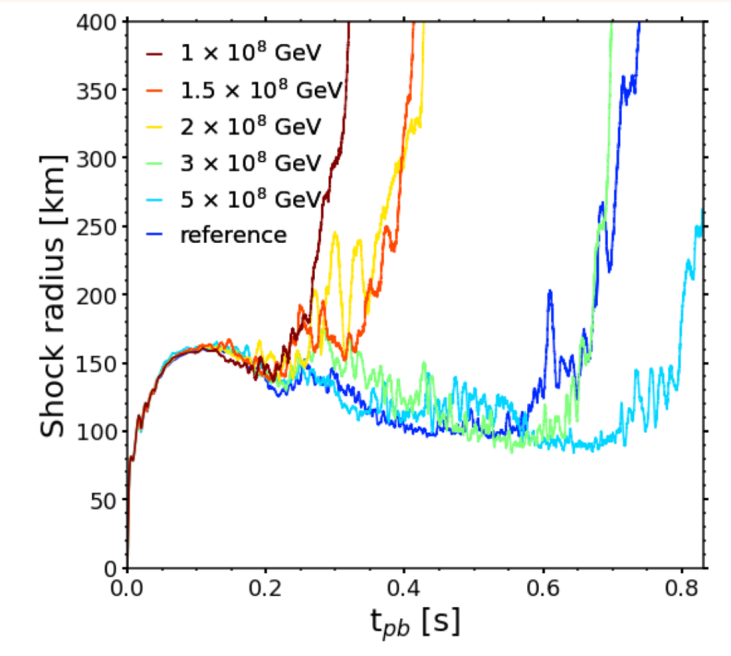
Quark-hadron phase transition

- BBKF (DD2F-SF) (Fischer et al., 2018)
- Release of latent heat ⇒ secondary shock



Axions in core-collapse supernovae

- Enhanced cooling (Betranhandy and O'Connor, 2022):
  $N + N \rightleftarrows N^* + N^* + a$
- Faster contraction ⇒ faster explosion



Neutrino Transport

Leakage/heating schemes

- Sink/source terms in the HD equations (O'Connor and Ott, 2010; Mösta et al., 2014)

Spectral M1 ν-transport

- Evolution of first two moments of specific intensity $\mathcal{I}$, i.e. energy and flux.
- Full 3D fluxes (Just et al., 2015); RbR approx: $F_\nu^\theta = F_\nu^\phi = 0$ (Buras et al., 2006)
- All flavors are included: $\nu_e, \bar{\nu}_e, \nu_x \rightarrow \{\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\}$ (Bollig et al., 2020)
- ~ 20 energy bins $\in \{1, 300\}$ MeV, logarithmically stretched.

ν-matter interactions

- β-processes
- pair production and annihilation processes
- reactions between neutrinos
- scattering processes with medium particles

Table of Contents

1 Introduction

2 Numerical Algorithms

3 Simulations and data

4 Magneto-rotational explosions

5 Conclusions

Standard neutrino explosions

Uncertain initial conditions

- Progenitor thermodynamic profiles: ρ,s,P
- Non-spherical perturbations

(Müller et al., 2017)

Explodability

- Very compact cores resist to shock revival (O'Connor and Ott, 2011);
- Combination of mass accretion and entropy profiles

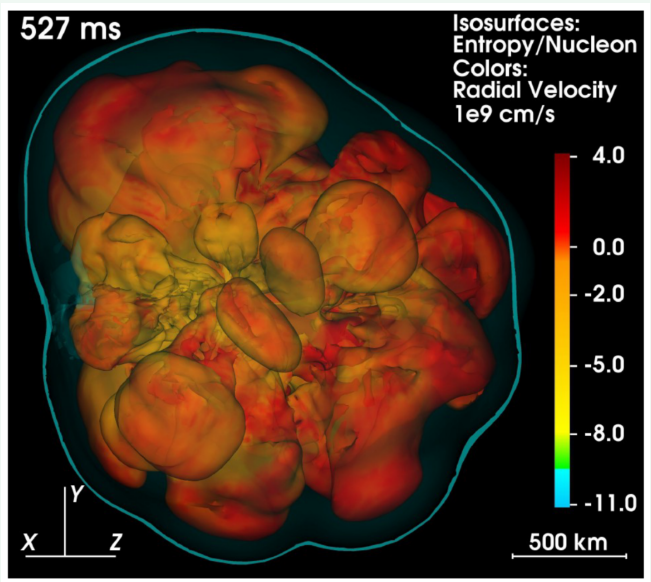
Ertl et al. (2016)

PNS proper motions

- Asymmetries and fallback accretion ⇒ PNS kick velocity and spin (Janka et al., 2021)

Hydrodynamic instabilities

- Post-shock convection (ν energy deposition) and SASI
- 3D crucial
- Longer dwelling in gain region ⇒ more efficient heating



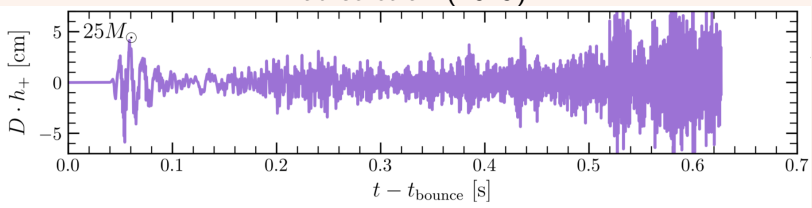
Janka et al. (2016)

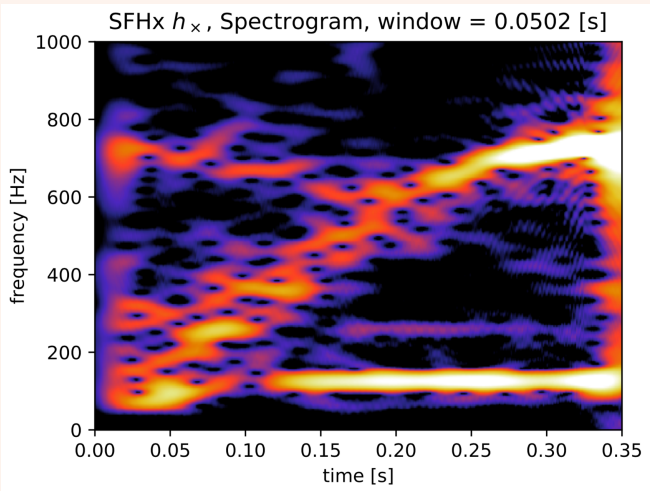
GW signals from standard CCSN

Main features

- Perturbations induced in the PNS
- Highly stochastic
- g/f modes and SASI

Radice et al. (2019)

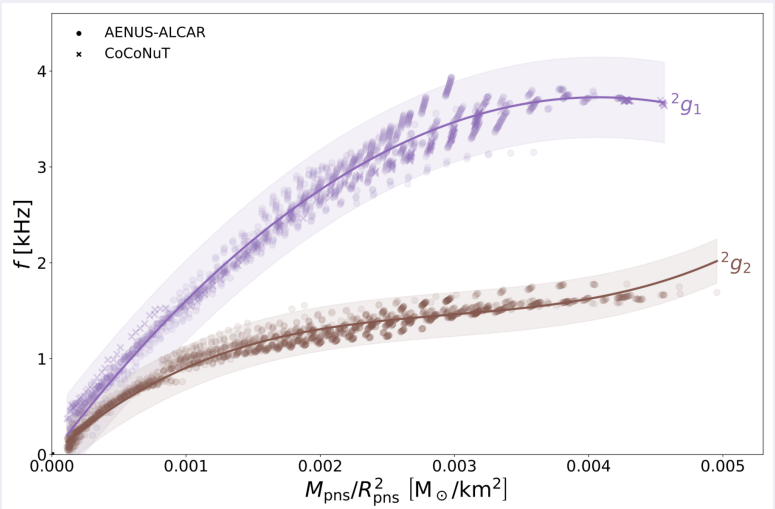




Kawahara et al. (2018)

Asteroseismology

- Universal relations between g/f modes freq. and M_{PNS}, R_{PNS}
- Same in 3D models?
- Othe r modes?



Torres-Forné et al. (2019)

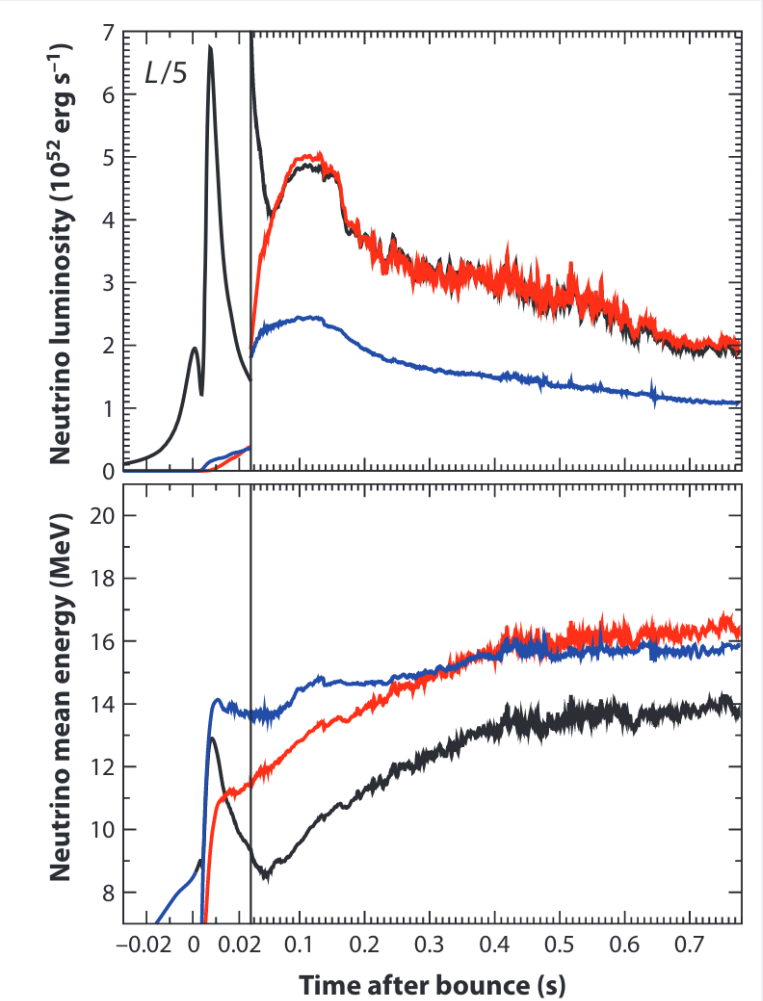
Neutrino emission

CCSN models

- Onset of collapse: ν_e released from the core, then trapped
- Neutronization burst: ν_e set free once the shock reaches low enough densities
- Accretion phase: high fluxes of ν_e and $\bar{\nu}_e$ in addition to the core luminosity

Late PNS models

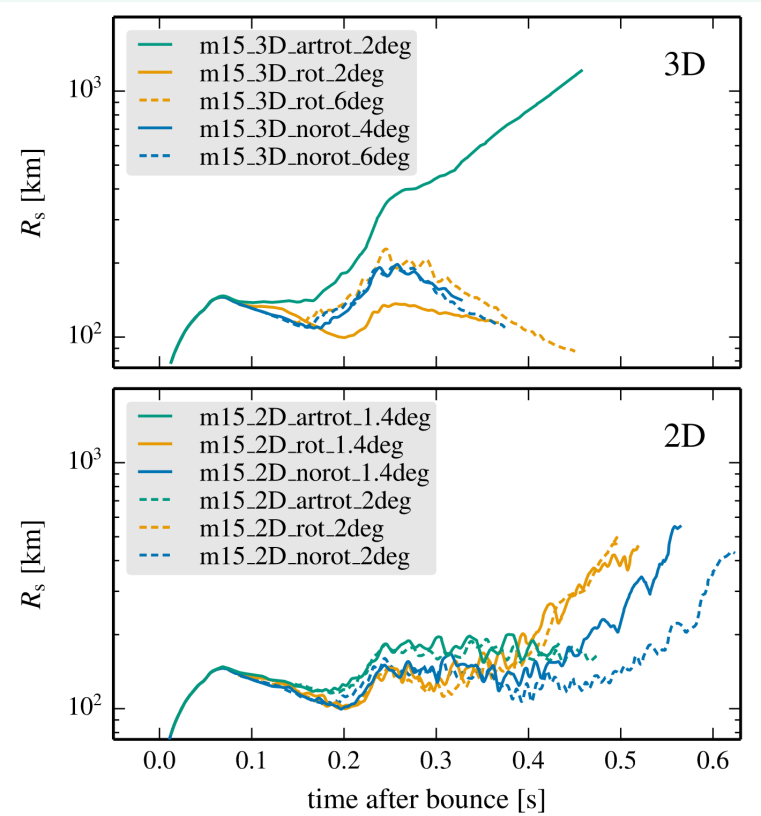
- Cooling phase: residual deleptonization and loss of binding energy



Janka (2012)

The impact of rotation

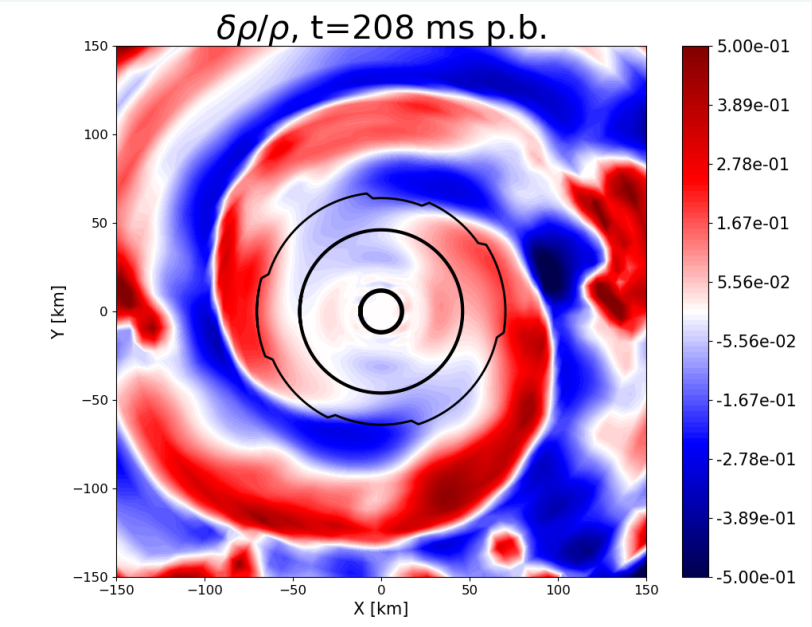
- Small fraction of fast rotating progenitors
- Rotation favors the explosion in 3D models (Summa et al., 2018)
- Development of spiral SASI modes (Foglizzo et al., 2015; Kazeroni et al., 2017)
- Enhanced neutrino heating (longer dwelling times in the gain region)
- Qualitatively different results in axisymmetry



Summa et al. (2018)

Corotational instabilities

Development of low $T/|W|$



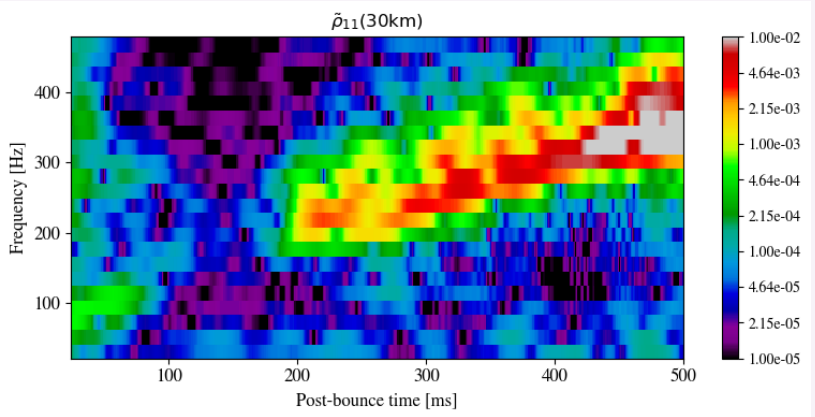
(Bugli et al., prep)

- Spiral structures forming at $\sim$ 200 ms p.b.
- Observed for different progenitors/rotation profiles

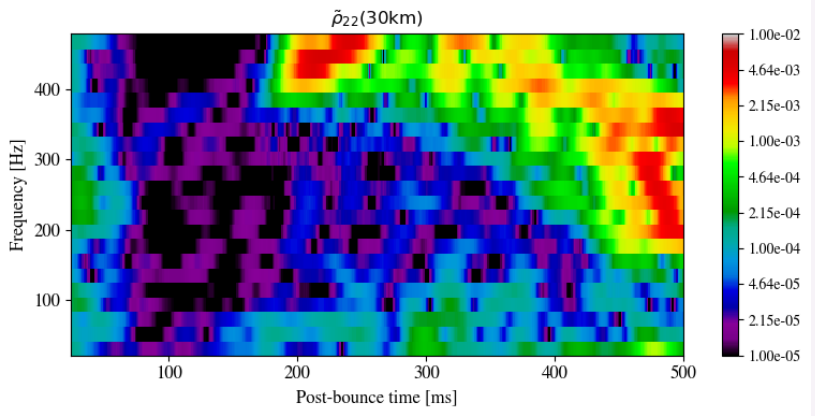
(Takiwaki et al., 2016, 2021)

PNS modes

- Density distribution at 30 km $l = 1, m = 1$

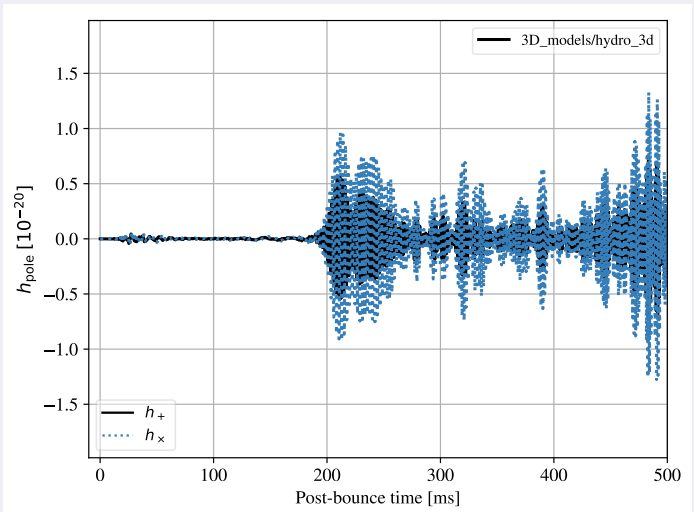


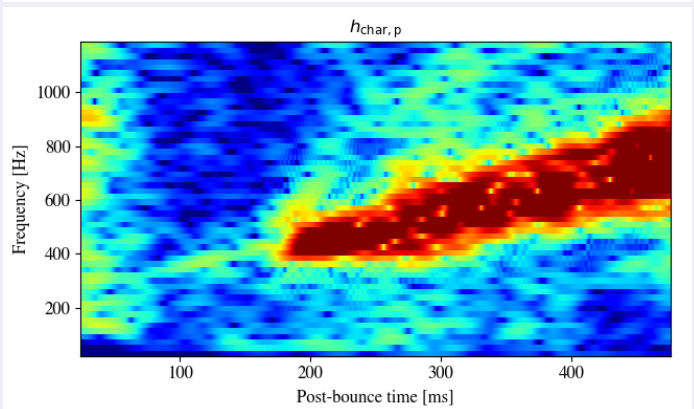
$l = 2, m = 2$



(Bugli et al., prep)

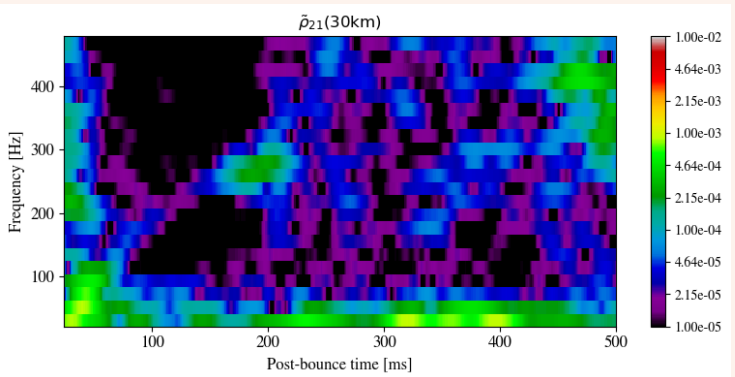
GW emission from low $T/|W|$



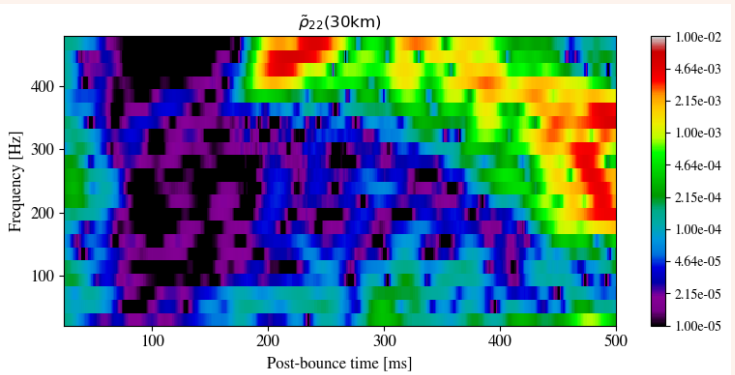


- 400 Hz emission at 200 ms
- $h \sim 10^{-20}$ for $D = 10$ kpc

$l = 2, m = 1$

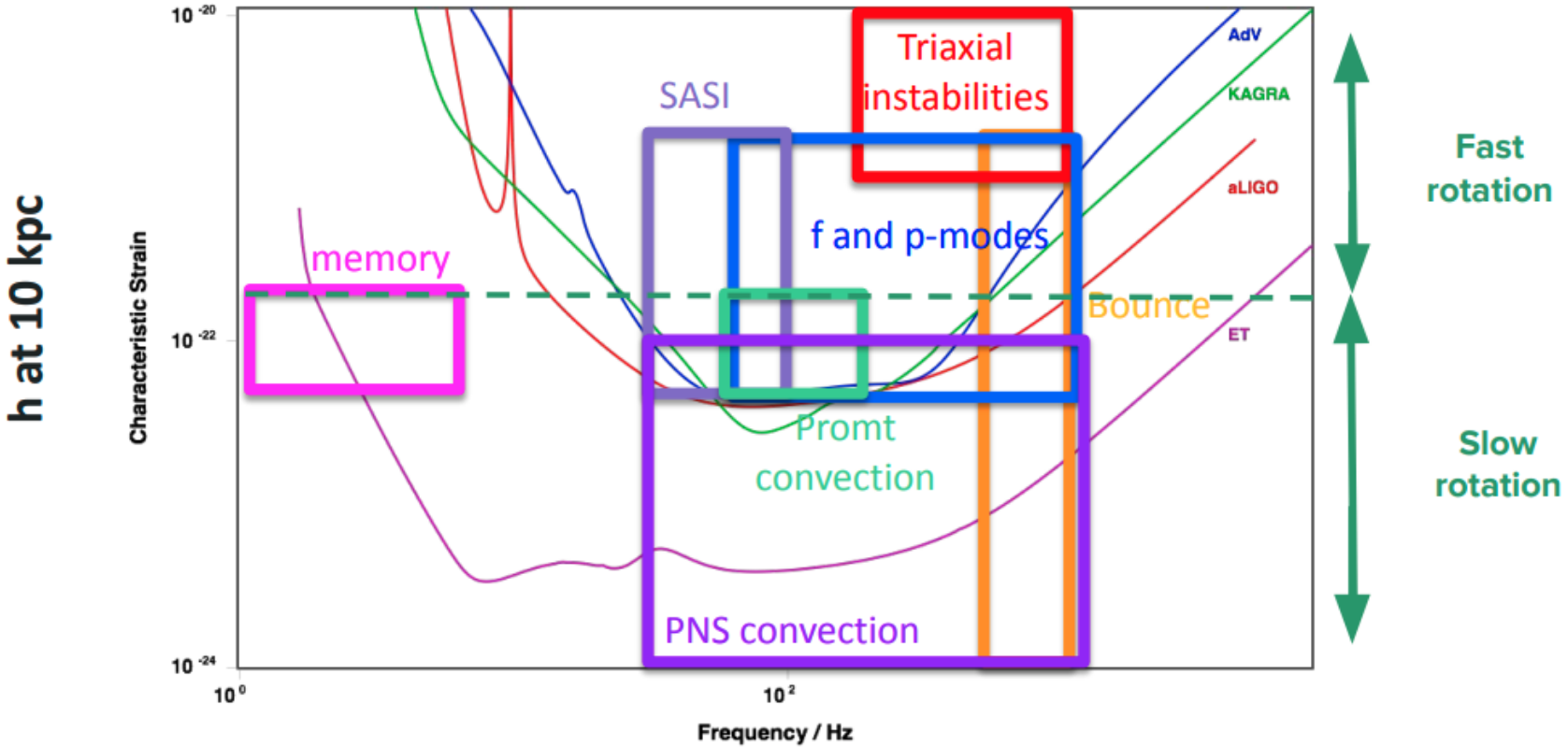


$l = 2, m = 2$



- Correlation with PNS modes
- (l=2,m=2) dominant

Gravitational waves from CCSN



Credit: Pablo Cerdà-Duràn

Table of Contents

1 Introduction

2 Numerical Algorithms

3 Simulations and data

4 Magneto-rotational explosions

5 Conclusions

Outstanding explosions and magnetic fields

Explosion kinetic energy

- Typical supernova: 10^{51} erg
- Rare hypernovae and GRBs: 10^{52} erg

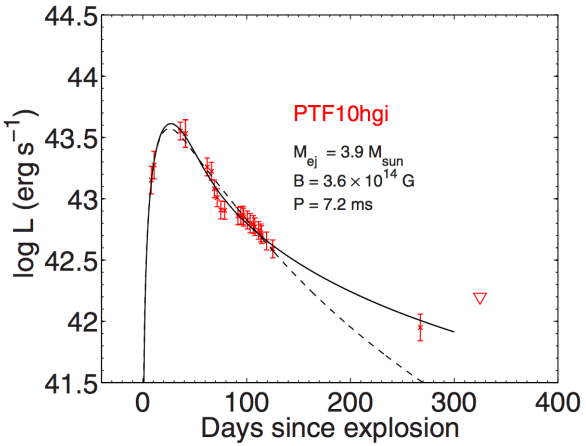
Total luminosity

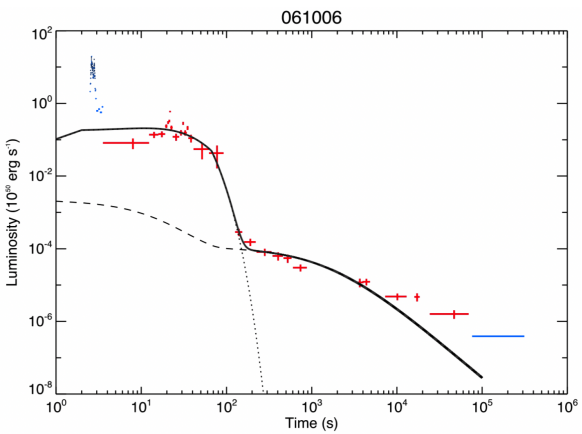
- Typical supernova: 10^{49} erg
- Superluminous SN: 10^{51} erg

Lightcurves and X-ray plateaus

- Strong dipolar magnetic field: $B \sim 10^{14} - 10^{15}$ G
- Fast rotation: $P \sim 1 - 10$ ms
- Kasen and Bildsten (2010); Dessart et al. (2012); Nicholl et al. (2013); Zhang and Mészáros (2001); Metzger et al. (2008); Lü et al. (2015); Gao et al. (2016)

Inserra et al. (2013)





Gompertz et al. (2014)

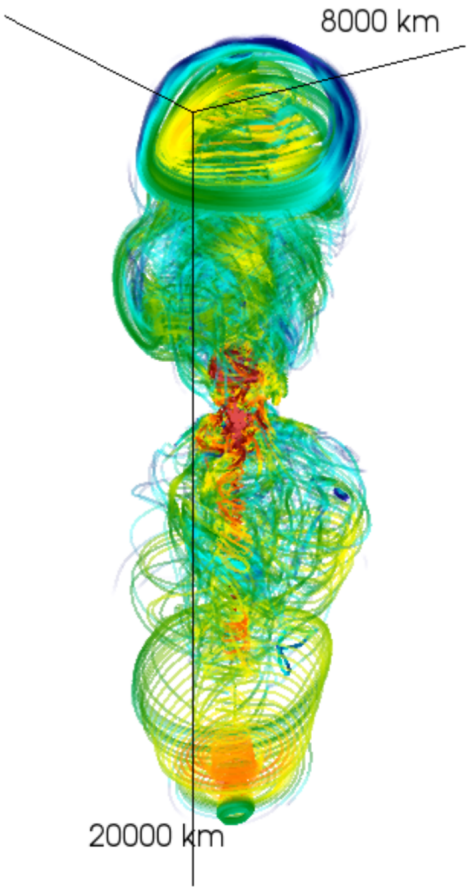
Magneto-rotational explosions

Core mechanism

- Rotation ⇒ energy reservoir
- Magnetic fields ⇒ means to extract that energy through magnetic stresses
- Powerful jet-driven explosions (Shibata et al., 2006; Burrows et al., 2007; Dessart et al., 2008; Winteler et al., 2012; Kuroda et al., 2020; Obergaulinger and Aloy, 2021; Bugli et al., 2021)

Origin of the magnetic field

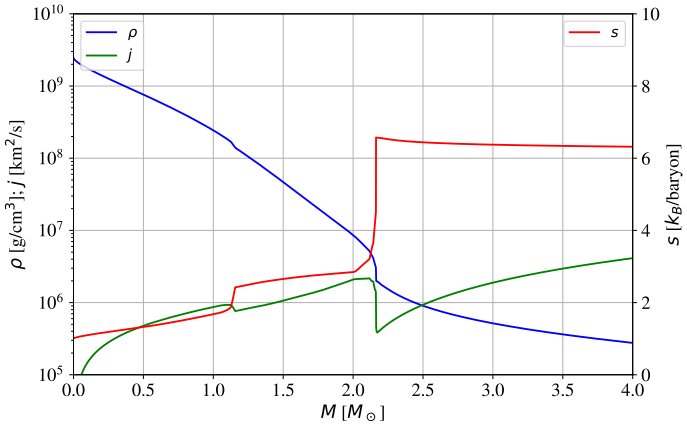
- Progenitor (Woosley and Heger, 2006; Aguilera-Dena et al., 2020)
- Stellar mergers (Schneider et al., 2019)
- PNS dynamo:
  - Convection (Raynaud et al., 2020)
  - Magnetorotational Instability (Reboul-Salze et al., 2021, tted)
  - Tayler-Spruit (Barrère et al., prep)

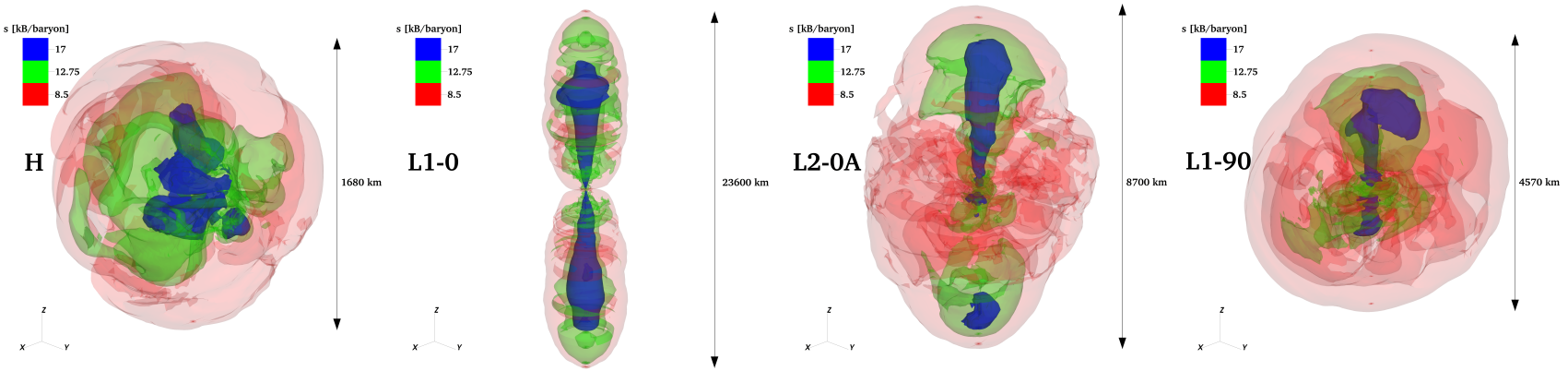


Obergaulinger and Aloy (2021)

3D MHD explosion models

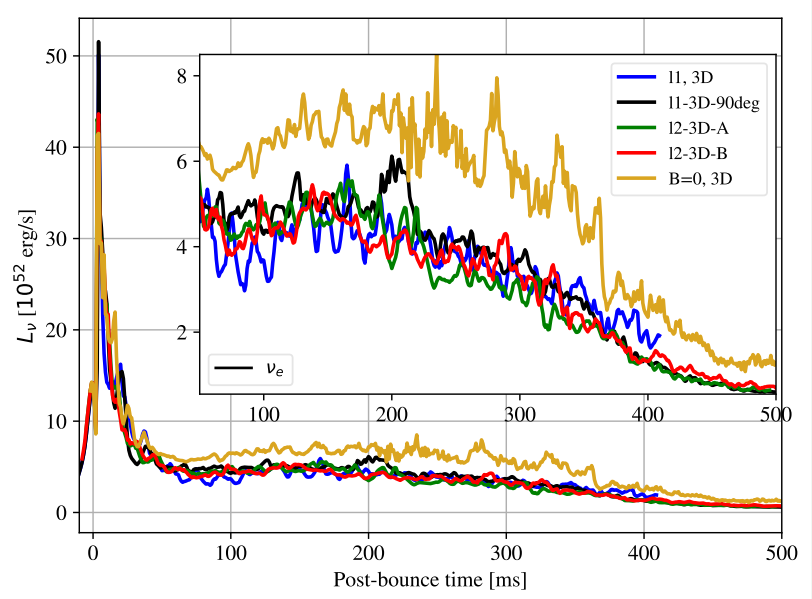
- Massive, fast rotating stellar progenitors (Woosley and Heger, 2006, 2007)
- Rotation profile from stellar evolution models (Obergaulinger and Aloy, 2021) or ad-hoc (Kuroda et al., 2020)
- Different magnetic configurations (Bugli et al., 2021): dipole (aligned and equatorial) or quadrupole
- Qualitative impact on shock dynamics





Neutrino emission

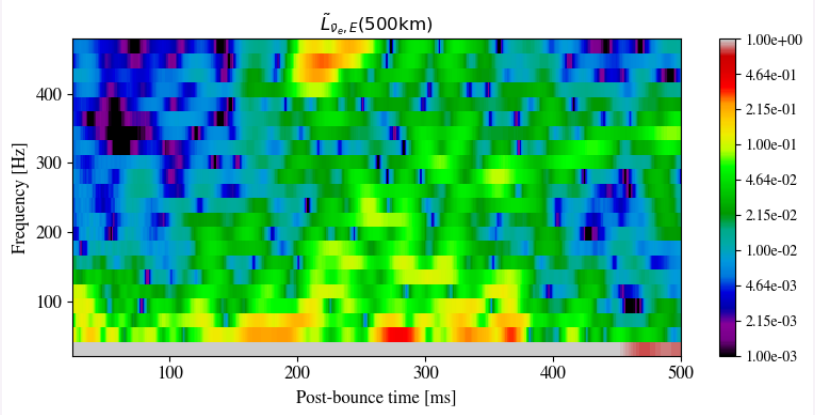
Lightcurves (ν_e - equator)



- Magnetic fields ⇒ more oblate PNS ⇒ lower neutrinosphere temperature

PNS modes signatures

Hydrodynamic



Aligned dipole

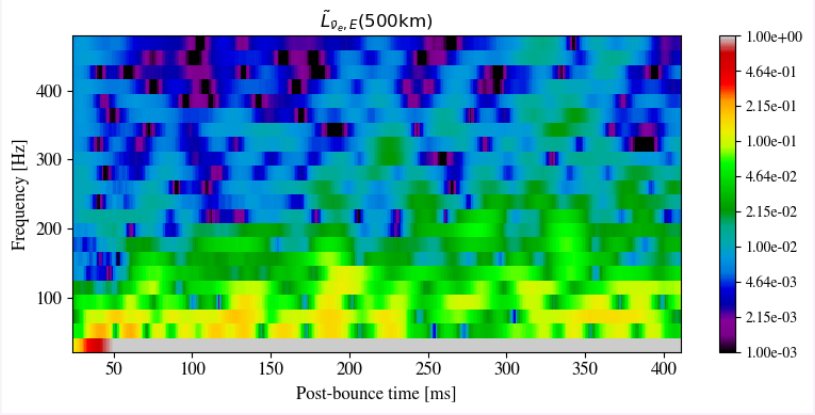


Table of Contents

1 Introduction

2 Numerical Algorithms

3 Simulations and data

4 Magneto-rotational explosions

5 Conclusions

Conclusions

- CCSN modeling is a multiphysics, multiscale problem
- Strong impact of microphysics on the large-scale dynamics
- GW and neutrinos open a unique window on the central engine dynamics
- Both rotation and magnetic fields deeply affects the GW emission
- Low $T/|W|$ produces high amplitude GW, but quenched by strong magnetic fields
- Important correlations between GW and neutrinos

Perspectives

- Improve the state-of-the-art EoS used in CCSN models
- Probe more combinations of EoS and stellar progenitors
- Impact on nucleosynthesis yields
- Identify possible rotation/B field thresholds

References I

Aguilera-Dena, D. R., Langer, N., Antoniadis, J., and Müller, B. (2020). Pre-collapse Properties of Superluminous Supernovae and Long Gamma-Ray Burst Progenitor Models. arXiv:2008.09132 [astro-ph]. arXiv: 2008.09132.

Barrère, P., Guilet, J., Reboul-Salze, A., Raynaud, R., and Janka, H.-T. (in prep.). A new scenario for magnetar formation: Tayler-spruit dynamo in a proto-neutron star spun up by fallback.

Betranhandy, A. and O'Connor, E. (2022). Neutrino Driven Explosions aided by Axion Cooling in Multidimensional Simulations of Core-Collapse Supernovae. Technical report, arXiv. arXiv:2204.00503 [astro-ph] type: article.

Bollig, R., Yadav, N., Kresse, D., Janka, H.-T., Mueller, B., and Heger, A. (2020). Self-consistent 3D Supernova Models From -7 Minutes to +7 Seconds: a 1-bethe Explosion of a ~19 Solar-mass Progenitor. arXiv e-prints, 2010:arXiv:2010.10506.

References II

Bugli, M., Guilet, J., and Obergaulinger, M. (2021). Three-dimensional core-collapse supernovae with complex magnetic structures - I. Explosion dynamics. Monthly Notices of the Royal Astronomical Society, 507:443–454. ADS Bibcode: 2021MNRAS.507..443B.

Bugli, M., Guilet, J., and Obergaulinger, M. (in prep.). Three-dimensional core-collapse supernovae with complex magnetic structures - II. corotational instabilities and multi-messenger signals.

Buras, R., Rampp, M., Janka, H.-T., and Kifonidis, K. (2006). Two-dimensional hydrodynamic core-collapse supernova simulations with spectral neutrino transport. I. Numerical method and results for a 15 M star. Astronomy and Astrophysics, 447:1049–1092.

Burrows, A., Dessart, L., Livne, E., Ott, C. D., and Murphy, J. (2007). Simulations of Magnetically Driven Supernova and Hypernova Explosions in the Context of Rapid Rotation. The Astrophysical Journal, 664(1):416.

References III

Dessart, L., Burrows, A., Livne, E., and Ott, C. D. (2008). The Proto-Neutron Star Phase of the Collapsar Model and the Route to Long-Soft Gamma-Ray Bursts and Hypernovae. \apjl, 673:L43.

Dessart, L., O'Connor, E., and Ott, C. D. (2012). THE ARDUOUS JOURNEY TO BLACK HOLE FORMATION IN POTENTIAL GAMMA-RAY BURST PROGENITORS. The Astrophysical Journal, 754(1):76.

Ertl, T., Janka, H.-T., Woosley, S. E., Sukhbold, T., and Ugliano, M. (2016). A Two-parameter Criterion for Classifying the Explodability of Massive Stars by the Neutrino-driven Mechanism. The Astrophysical Journal, 818(2):124.

Fischer, T., Bastian, N.-U. F., Wu, M.-R., Baklanov, P., Sorokina, E., Blinnikov, S., Typel, S., Klähn, T., and Blaschke, D. B. (2018). Quark deconfinement as a supernova explosion engine for massive blue supergiant stars. Nature Astronomy, 2:980–986. ADS Bibcode: 2018NatAs...2..980F.

References IV

Foglizzo, T., Kazeroni, R., Guilet, J., Masset, F., González, M., Krueger, B. K., Novak, J., Oertel, M., Margueron, J., Faure, J., Martin, N., Blottiau, P., Peres, B., and Durand, G. (2015). The Explosion Mechanism of Core-Collapse Supernovae: Progress in Supernova Theory and Experiments. Publications of the Astronomical Society of Australia, 32:e009. Citation Key Alias: foglizzo2015a.

Gao, H., Zhang, B., and Lü, H.-J. (2016). Constraints on binary neutron star merger product from short GRB observations. Physical Review D, 93(4).

Gompertz, B. P., O'Brien, P. T., and Wynn, G. A. (2014). Magnetar powered GRBs: explaining the extended emission and X-ray plateau of short GRB light curves. Monthly Notices of the Royal Astronomical Society, 438:240–250.

References V

Inserra, C., Smartt, S. J., Jerkstrand, A., Valenti, S., Fraser, M., Wright, D., Smith, K., Chen, T.-W., Kotak, R., Pastorello, A., Nicholl, M., Bresolin, F., Kudritzki, R. P., Benetti, S., Botticella, M. T., Burgett, W. S., Chambers, K. C., Ergon, M., Flewelling, H., Fynbo, J. P. U., Geier, S., Hodapp, K. W., Howell, D. A., Huber, M., Kaiser, N., Leloudas, G., Magill, L., Magnier, E. A., McCrum, M. G., Metcalfe, N., Price, P. A., Rest, A., Sollerman, J., Sweeney, W., Taddia, F., Taubenberger, S., Tonry, J. L., Wainscoat, R. J., Waters, C., and Young, D. (2013). Super-luminous Type Ic Supernovae: Catching a Magnetar by the Tail. The Astrophysical Journal, 770(2):128.

Janka, H.-T. (2012). Explosion Mechanisms of Core-Collapse Supernovae. Annual Review of Nuclear and Particle Science, 62:407–451.

Janka, H.-T. (2017). Neutrino Emission from Supernovae. arXiv:1702.08713 [astro-ph, physics:hep-ph, physics:nucl-th], pages 1575–1604. arXiv: 1702.08713.

References VI

Janka, H.-T., Melson, T., and Summa, A. (2016). Physics of Core-Collapse Supernovae in Three Dimensions: A Sneak Preview. Annual Review of Nuclear and Particle Science, 66:341–375.

Janka, H.-T., Wongwathanarat, A., and Kramer, M. (2021). Supernova Fallback as Origin of Neutron Star Spins and Spin-kick Alignment. arXiv:2104.07493 [astro-ph, physics:hep-ph]. arXiv: 2104.07493.

Just, O., Obergaulinger, M., and Janka, H.-T. (2015). A new multidimensional, energy-dependent two-moment transport code for neutrino-hydrodynamics. \mnras, 453:3386–3413.

Kasen, D. and Bildsten, L. (2010). Supernova Light Curves Powered by Young Magnetars. The Astrophysical Journal, 717(1):245.

Kawahara, H., Kuroda, T., Takiwaki, T., Hayama, K., and Kotake, K. (2018). A Linear and Quadratic Time-Frequency Analysis of Gravitational Waves from Core-collapse Supernovae. The Astrophysical Journal, 867:126. ADS Bibcode: 2018ApJ...867..126K.

References VII

Kazeroni, R., Guilet, J., and Foglizzo, T. (2017). Are pulsars spun up or down by SASI spiral modes? Monthly Notices of the Royal Astronomical Society, 471:914–925.

Kuroda, T., Arcones, A., Takiwaki, T., and Kotake, K. (2020). Magnetorotational Explosion of A Massive Star Supported by Neutrino Heating in General Relativistic Three Dimensional Simulations. arXiv:2003.02004 [astro-ph]. arXiv: 2003.02004.

Kuroda, T., Kotake, K., Takiwaki, T., and Thielemann, F.-K. (2018). A full general relativistic neutrino radiation-hydrodynamics simulation of a collapsing very massive star and the formation of a black hole. Monthly Notices of the Royal Astronomical Society, 477:L80–L84.

Lattimer, J. M. and Swesty, D. F. (1991). A generalized equation of state for hot, dense matter. Nuclear Physics A, 535(2):331–376.

Lü, H.-J., Zhang, B., Lei, W.-H., Li, Y., and Lasky, P. D. (2015). The Millisecond Magnetar Central Engine in Short GRBs. The Astrophysical Journal, 805(2):89.

References VIII

Marek, A., Dimmelmeier, H., Janka, H.-T., Müller, E., and Buras, R. (2006). Exploring the relativistic regime with Newtonian hydrodynamics: An improved effective gravitational potential for supernova simulations. Astronomy & Astrophysics, 445(1):273–289.

Metzger, B. D., Quataert, E., and Thompson, T. A. (2008). Short-duration gamma-ray bursts with extended emission from protomagnetar spin-down. \mnras, 385:1455–1460.

Mösta, P., Richers, S., Ott, C. D., Haas, R., Piro, A. L., Boydstun, K., Abdikamalov, E., Reisswig, C., and Schnetter, E. (2014). Magnetorotational Core-collapse Supernovae in Three Dimensions. The Astrophysical Journal, 785(2):L29. Citation Key Alias: mosta2014a.

Müller, B., Melson, T., Heger, A., and Janka, H.-T. (2017). Supernova simulations from a 3D progenitor model - Impact of perturbations and evolution of explosion properties. Monthly Notices of the Royal Astronomical Society, 472:491–513. ADS Bibcode: 2017MNRAS.472..491M.

References IX

Nicholl, M., Smartt, S. J., Jerkstrand, A., Inserra, C., McCrum, M., Kotak, R., Fraser, M., Wright, D., Chen, T.-W., Smith, K., Young, D. R., Sim, S. A., Valenti, S., Howell, D. A., Bresolin, F., Kudritzki, R. P., Tonry, J. L., Huber, M. E., Rest, A., Pastorello, A., Tomasella, L., Cappellaro, E., Benetti, S., Mattila, S., Kankare, E., Kangas, T., Leloudas, G., Sollerman, J., Taddia, F., Berger, E., Chornock, R., Narayan, G., Stubbs, C. W., Foley, R. J., Lunnan, R., Soderberg, A., Sanders, N., Milisavljevic, D., Margutti, R., Kirshner, R. P., Elias-Rosa, N., Morales-Garoffolo, A., Taubenberger, S., Botticella, M. T., Gezari, S., Urata, Y., Rodney, S., Riess, A. G., Scolnic, D., Wood-Vasey, W. M., Burgett, W. S., Chambers, K., Flewelling, H. A., Magnier, E. A., Kaiser, N., Metcalfe, N., Morgan, J., Price, P. A., Sweeney, W., and Waters, C. (2013). Slowly fading super-luminous supernovae that are not pair-instability explosions. Nature, 502(7471):346.

References X

Obergaulinger, M. and Aloy, M. (2021). Magnetorotational core collapse of possible GRB progenitors - III. Three-dimensional models. Monthly Notices of the Royal Astronomical Society, 503:4942–4963. ADS Bibcode: 2021MNRAS.503.4942O tex.ids= obergaulinger2020, obergaulinger2020b arXiv: 2008.07205.

O'Connor, E. and Ott, C. D. (2010). A new open-source code for spherically symmetric stellar collapse to neutron stars and black holes. Classical and Quantum Gravity, 27:114103. ADS Bibcode: 2010CQGra..27k4103O.

O'Connor, E. and Ott, C. D. (2011). Black Hole Formation in Failing Core-Collapse Supernovae. The Astrophysical Journal, 730:70. ADS Bibcode: 2011ApJ...730...70O.

O'Connor, E. P. and Couch, S. M. (2018). Two-dimensional Core-collapse Supernova Explosions Aided by General Relativity with Multidimensional Neutrino Transport. The Astrophysical Journal, 854:63.

References XI

Radice, D., Morozova, V., Burrows, A., Vartanyan, D., and Nagakura, H. (2019). Characterizing the Gravitational Wave Signal from Core-collapse Supernovae. The Astrophysical Journal, 876(1):L9.

Raynaud, R., Guilet, J., Janka, H.-T., and Gastine, T. (2020). Magnetar formation through a convective dynamo in protoneutron stars. Science Advances, 6:eaay2732.

Reboul-Salze, A., Guilet, J., Raynaud, R., and Bugli, M. (2021). A global model of the magnetorotational instability in protoneutron stars. Astronomy and Astrophysics, 645:A109.

Reboul-Salze, A., Guilet, J., Raynaud, R., and Bugli, M. (submitted). Mri-driven $\alpha\omega$ dynamos in protoneutron stars.

Schneider, F. R. N., Ohlmann, S. T., Podsiadlowski, P., Röpke, F. K., Balbus, S. A., Pakmor, R., and Springel, V. (2019). Stellar mergers as the origin of magnetic massive stars. Nature, 574(7777):211. Citation Key Alias: schneider2019a.

References XII

Shen, H., Toki, H., Oyamatsu, K., and Sumiyoshi, K. (1998). Relativistic Equation of State of Nuclear Matter for Supernova Explosion. Progress of Theoretical Physics, 100:1013–1031. ADS Bibcode: 1998PThPh.100.1013S.

Shibata, M., Liu, Y. T., Shapiro, S. L., and Stephens, B. C. (2006). Magnetorotational collapse of massive stellar cores to neutron stars: Simulations in full general relativity. Physical Review D, 74(10).

Steiner, A. W., Hempel, M., and Fischer, T. (2013). CORE-COLLAPSE SUPERNOVA EQUATIONS OF STATE BASED ON NEUTRON STAR OBSERVATIONS. The Astrophysical Journal, 774(1):17. Publisher: American Astronomical Society.

Summa, A., Janka, H.-T., Melson, T., and Marek, A. (2018). Rotation-supported Neutrino-driven Supernova Explosions in Three Dimensions and the Critical Luminosity Condition. The Astrophysical Journal, 852(1):28.

References XIII

Takiwaki, T., Kotake, K., and Foglizzo, T. (2021). Insights into non-axisymmetric instabilities in three-dimensional rotating supernova models with neutrino and gravitational-wave signatures. arXiv:2107.02933 [astro-ph]. arXiv: 2107.02933.

Takiwaki, T., Kotake, K., and Suwa, Y. (2016). Three-dimensional simulations of rapidly rotating core-collapse supernovae: finding a neutrino-powered explosion aided by non-axisymmetric flows. Monthly Notices of the Royal Astronomical Society: Letters, 461(1):L112–L116.

Torres-Forné, A., Cerdá-Durán, P., Obergaulinger, M., Muller, B., and Font, J. A. (2019). Universal relations for gravitational-wave asteroseismology of proto-neutron stars. arXiv e-prints, page arXiv:1902.10048.

Winteler, C., Käppeli, R., Perego, A., Arcones, A., Vasset, N., Nishimura, N., Liebendörfer, M., and Thielemann, F.-K. (2012). MAGNETOROTATIONALLY DRIVEN SUPERNOVAE AS THE ORIGIN OF EARLY GALAXY r -PROCESS ELEMENTS? The Astrophysical Journal, 750(1):L22.

References XIV

Woosley, S. E. and Heger, A. (2006). The Progenitor Stars of Gamma-Ray Bursts. The Astrophysical Journal, 637(2):914.

Woosley, S. E. and Heger, A. (2007). Nucleosynthesis and remnants in massive stars of solar metallicity. Physics Reports, 442:269–283.

Yasin, H., Schäfer, S., Arcones, A., and Schwenk, A. (2018). Equation of state effects in core-collapse supernovae. arXiv:1812.02002 [astro-ph, physics:nucl-ex, physics:nucl-th]. arXiv: 1812.02002.

Zhang, B. and Mészáros, P. (2001). Gamma-Ray Burst Afterglow with Continuous Energy Injection: Signature of a Highly Magnetized Millisecond Pulsar. The Astrophysical Journal, 552(1):L35–L38.