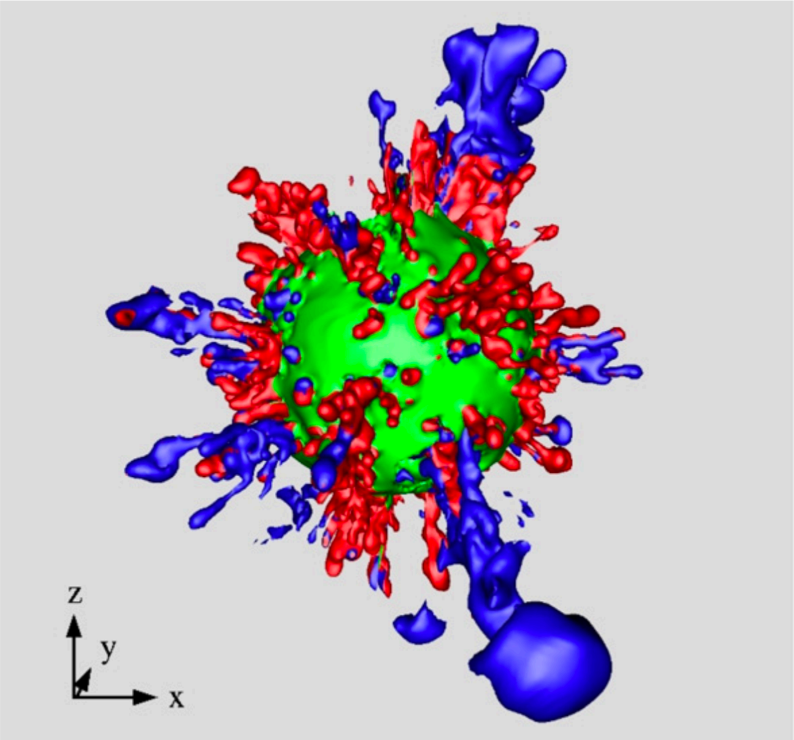
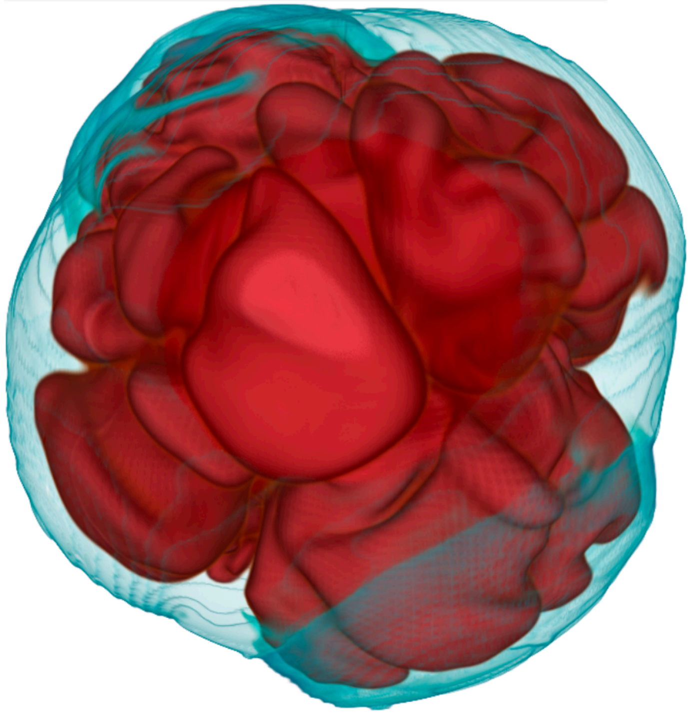
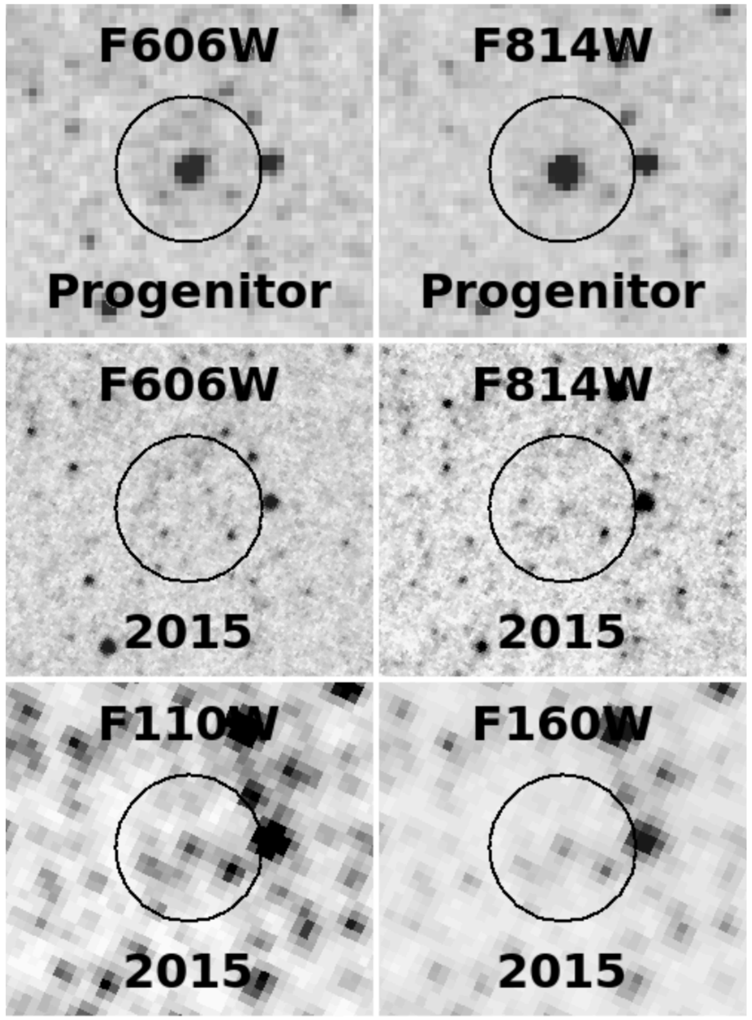


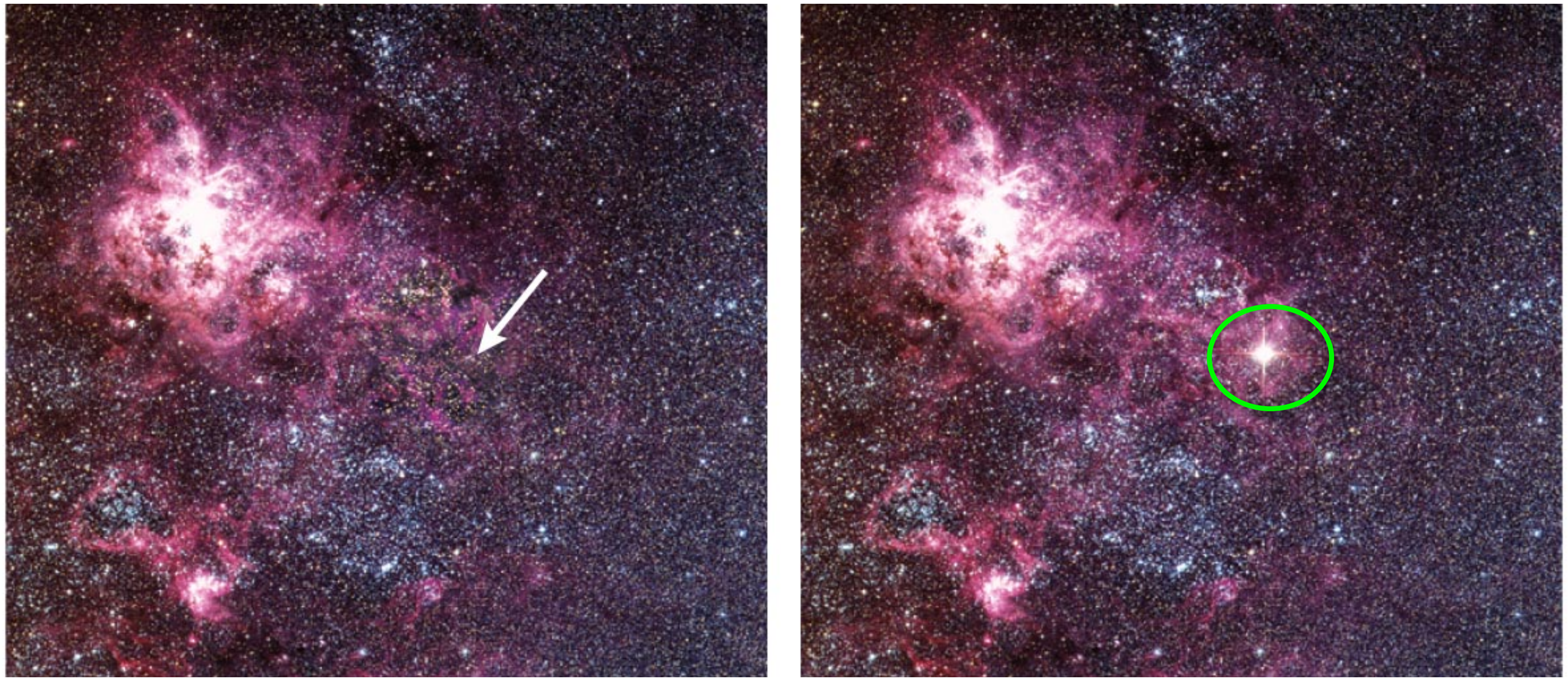
Hammer et al. (2009)



Vartanyan et al. (2022)



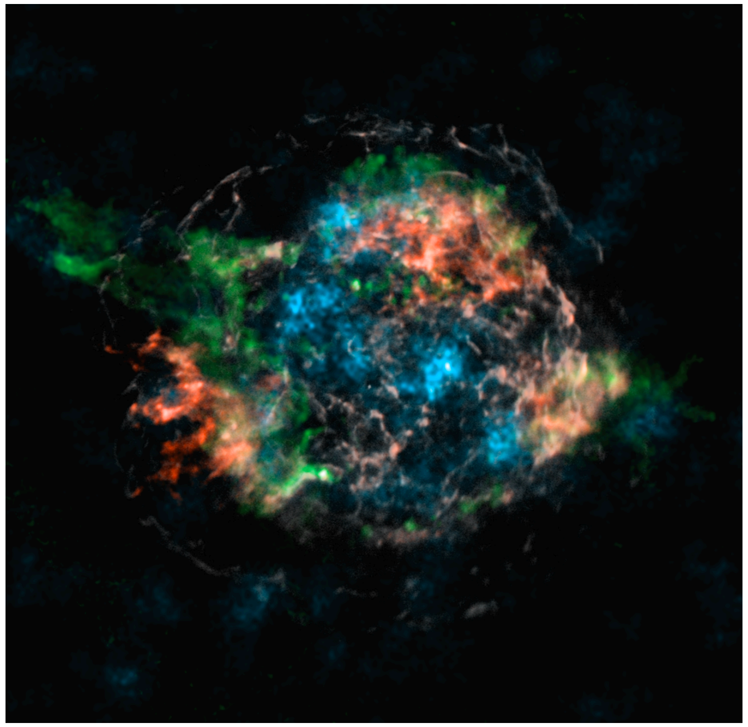
Adams+ (2017): N6946-BH1



SN 1987A (ESO)

Supernovae II

Rodrigo Fernández (University of Alberta)



Grefenstette et al. (2014)

Outline

~~1) Supernovae: Thermonuclear vs Gravitational~~

~~2) Pair-Instability Supernovae~~

~~3) Progenitors & Core-Collapse~~

4) Delayed Neutrino Explosions

5) Shock propagation into stellar envelope

6) BH-forming Supernovae

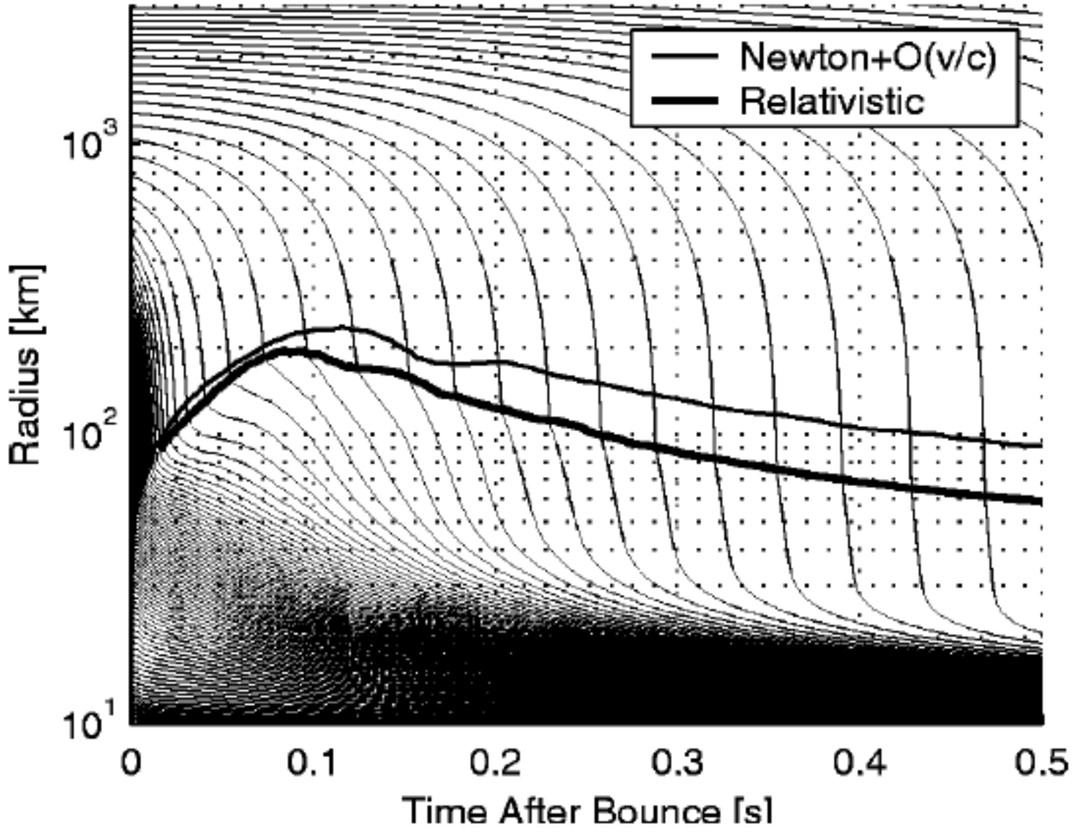
7) Phase Transition aided Explosions

8) Remnants: NS or BH & Kicks

Neutrino Mechanism: Iron cores

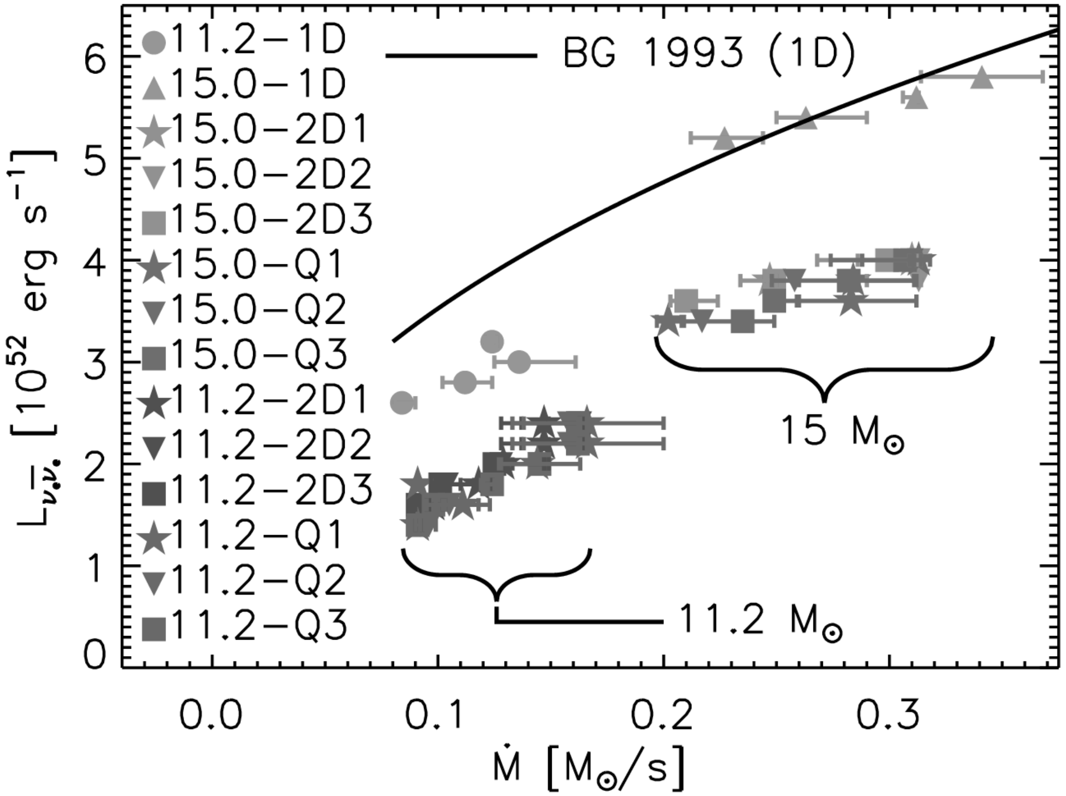
In contrast, Fe cores fail to explode in spherical symmetry (1D). All supernova groups that achieved Boltzmann neutrino transport in general relativity obtained the same result.

(Liebendörfer et al. 2001, Thompson et al. 2003, Rampp & Janka 2002, Sumiyoshi et al. 2005)



Liebendoerfer et al. (2001)

The physical reason for the failure is that in 1D, explosion shuts off accretion and its contribution to the neutrino luminosity (roughly comparable to that from the core in ν_e and anti-ν_e).

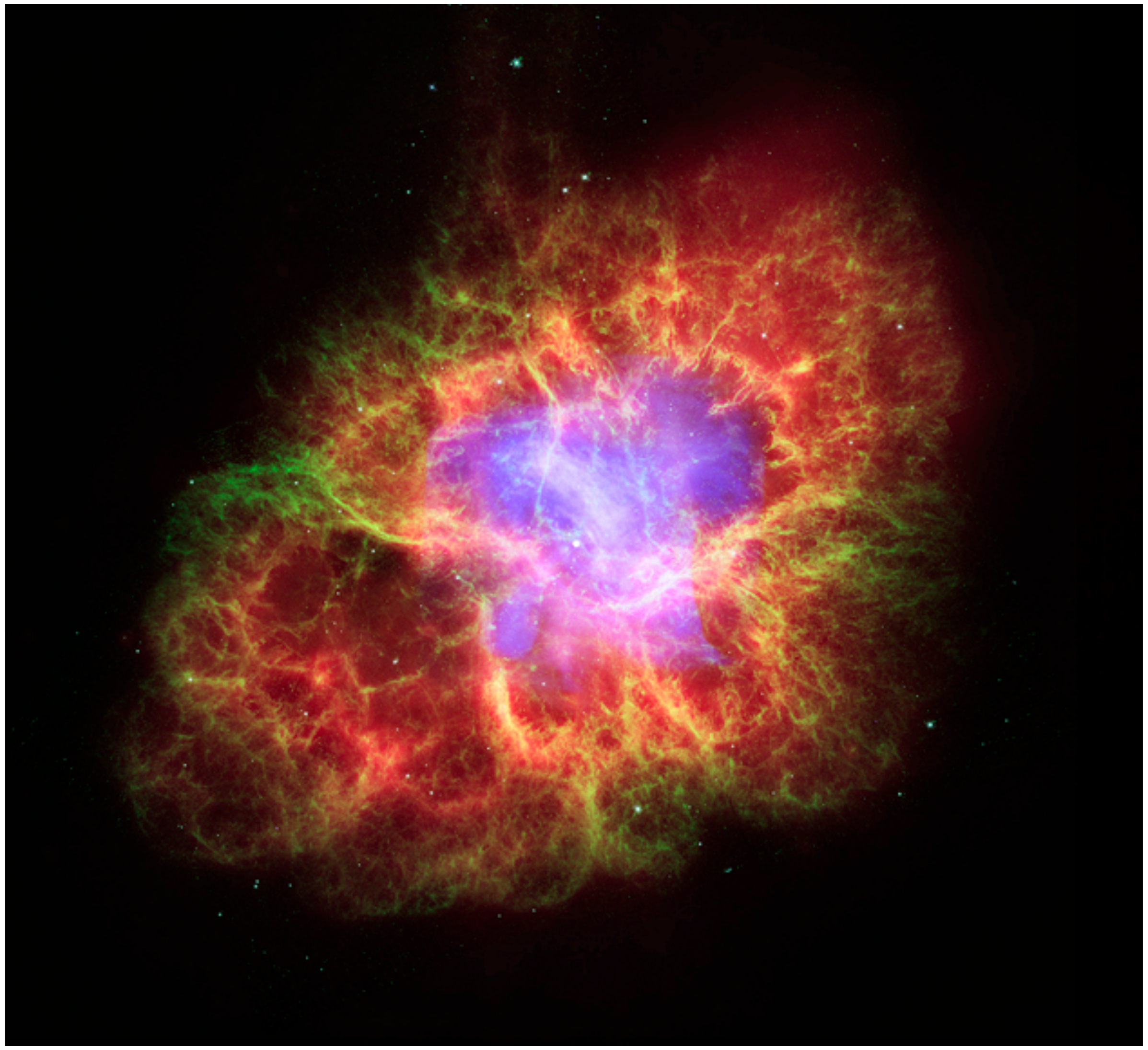


Murphy & Burrows (2008)

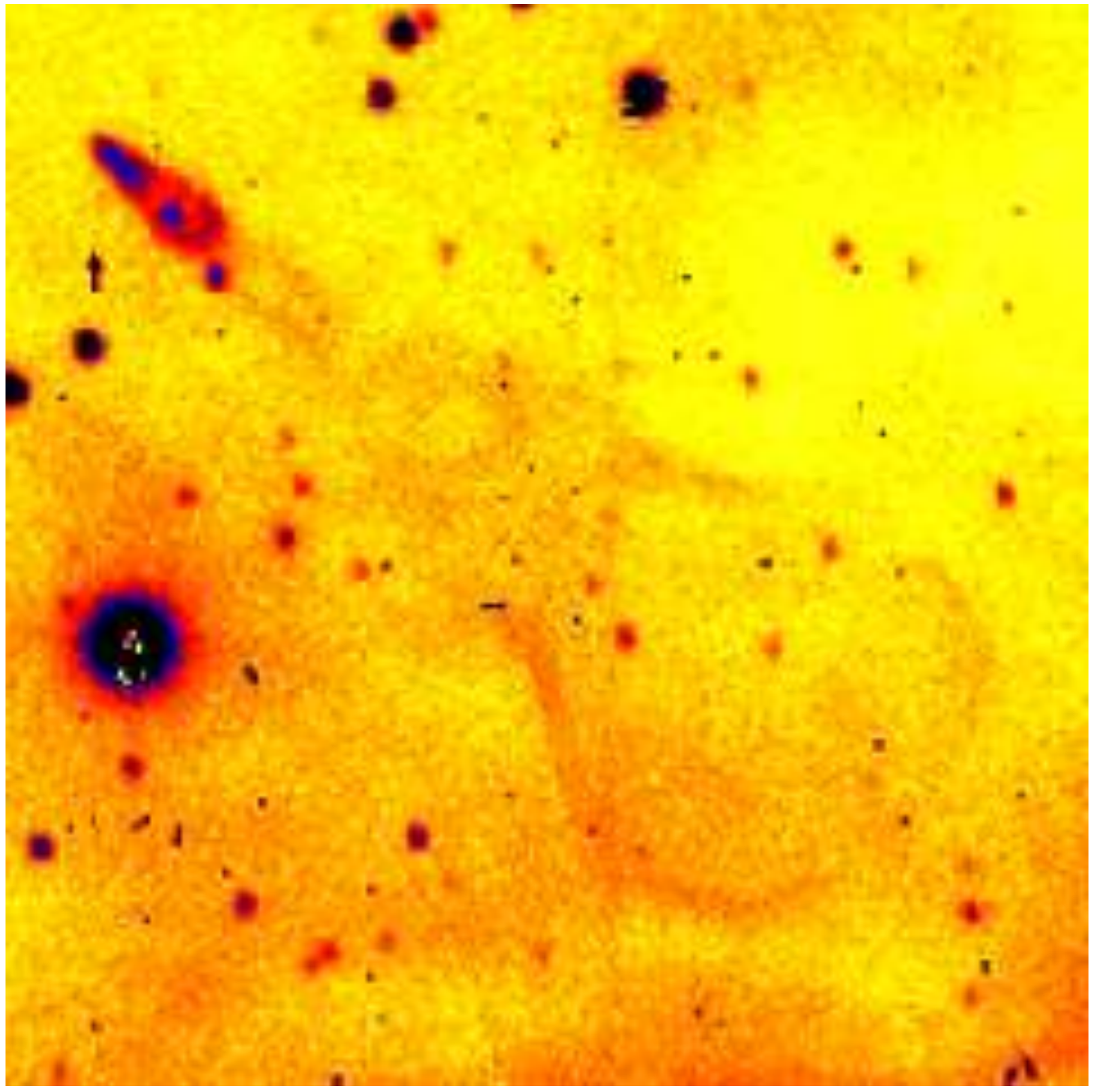
Significant work has been done since the mid 1990s to model CCSNe in 2D or 3D. Parametric models showed that multi-D effects had promise in leading to success.

Evidence for Asymmetries

There is observational evidence for asymmetries in CCSNe: many supernova remnants are asymmetric, and there are many examples of pulsars with high space velocities (~1000 km/s), likely originating in an asymmetric explosion.



Crab SN remnant (Chandra X-ray Center)

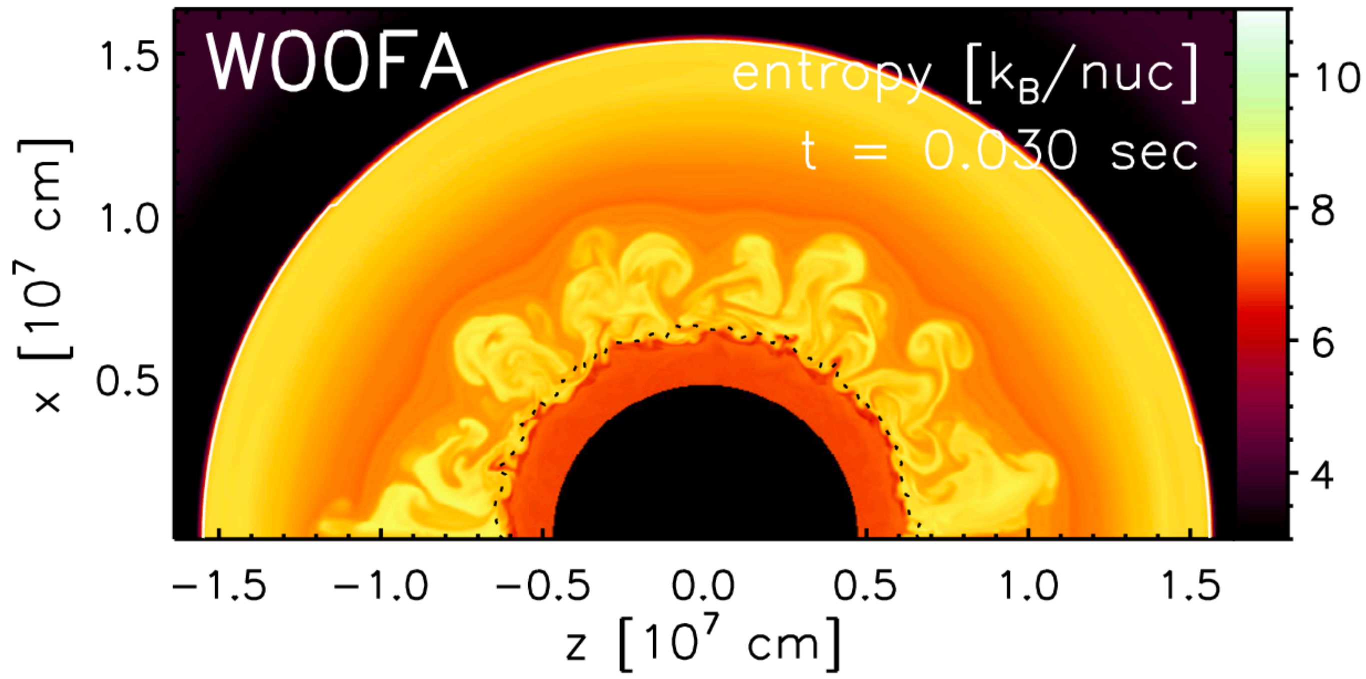


Guitar Nebula (Chatterjee & Cordes 2002)

Neutrino Mechanism: Postshock Convection

The gain region in which neutrino heating dominates over cooling is convectively unstable due to a negative entropy gradient established by neutrino heating.

Herant et al. (1992)



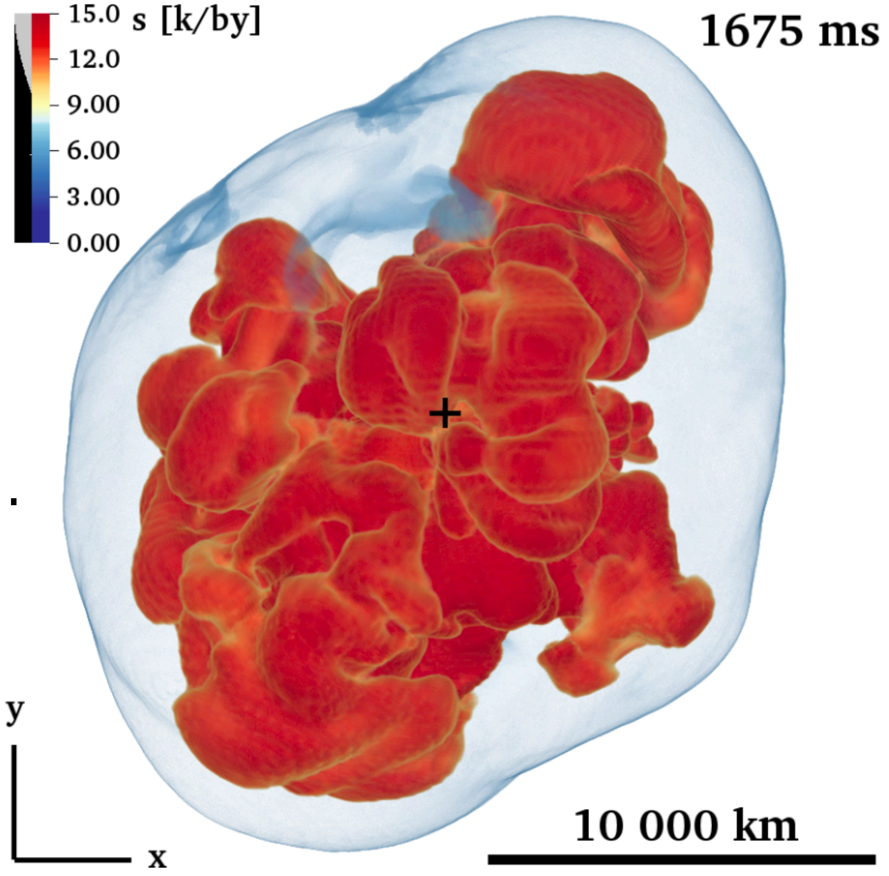
Scheck et al. (2008)

Buoyant plumes drive vigorous convective overturn, with 2 effects:

1) Increasing the efficiency of neutrino heating

2) Generating asymmetries in the shock, allowing simultaneous accretion and expansion.

Most successful 3D CCSNe simulations with advanced neutrino transport have convection as the dominant instability.

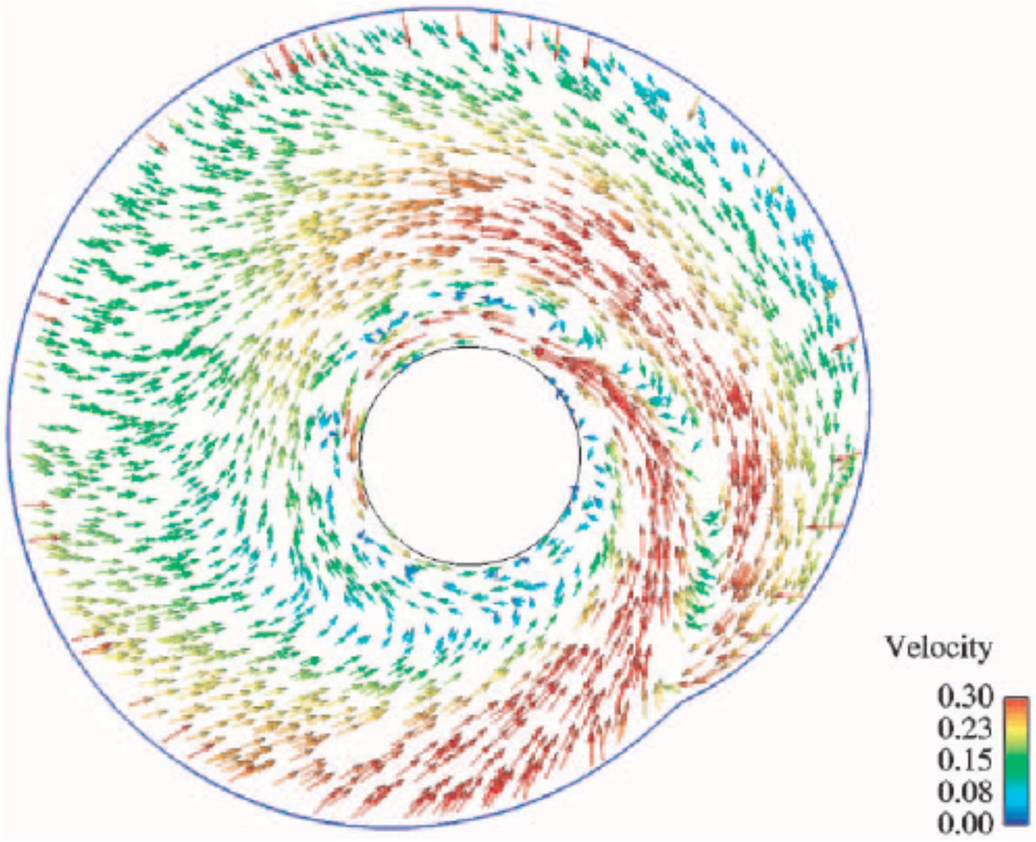


Bollig et al. (2021)

Neutrino Mechanism: SASI

The stalled shock is also subject to an oscillatory instability driven by a cycle of advected perturbations converted into returning acoustic waves, trapped inside the shock-PNS cavity. This goes by the name of Standing/Stationary Accretion Shock Instability (SASI).

Blondin et al. (2003), Foglizzo et al. (2007)



Blondin & Shaw (2007)

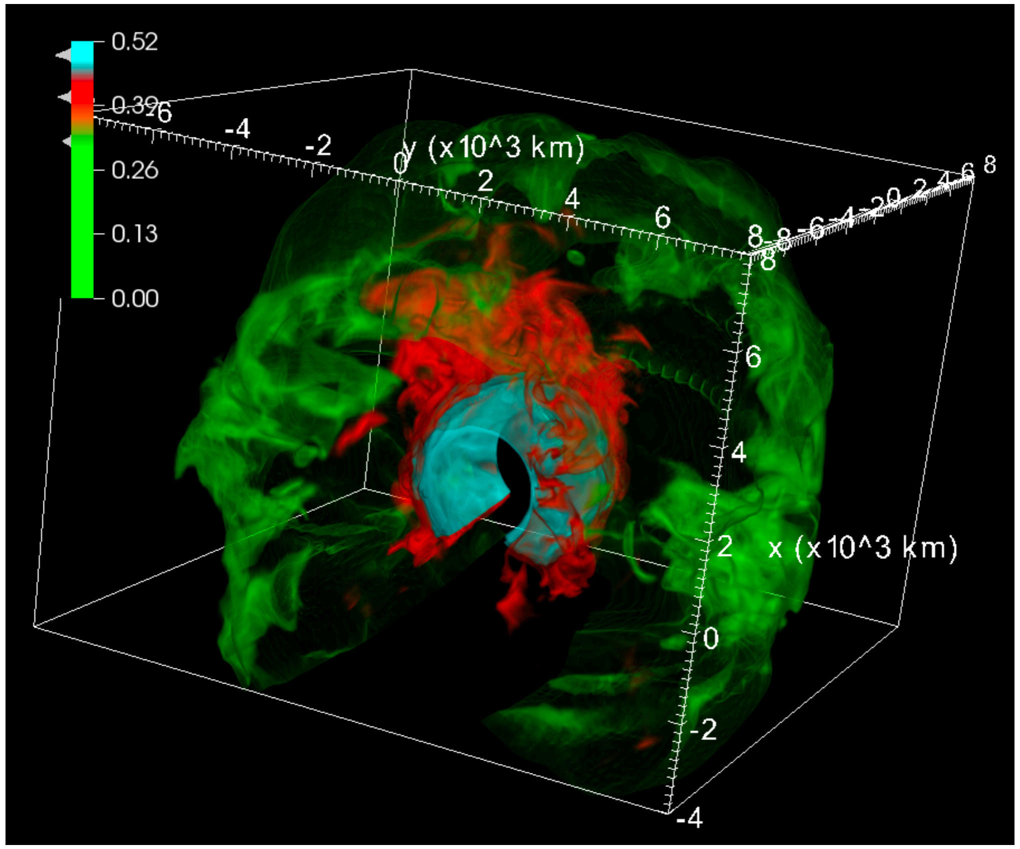
Progenitors that result in a high accretion rate and more compact shocks tend to yield a strong SASI, in some cases associated with failures and BH formation.

Foglizzo et al. (2012)

The instability breaks spherical symmetry and can impart a moderate spin to the NS in the absence of progenitor rotation. Modulates neutrino signal.

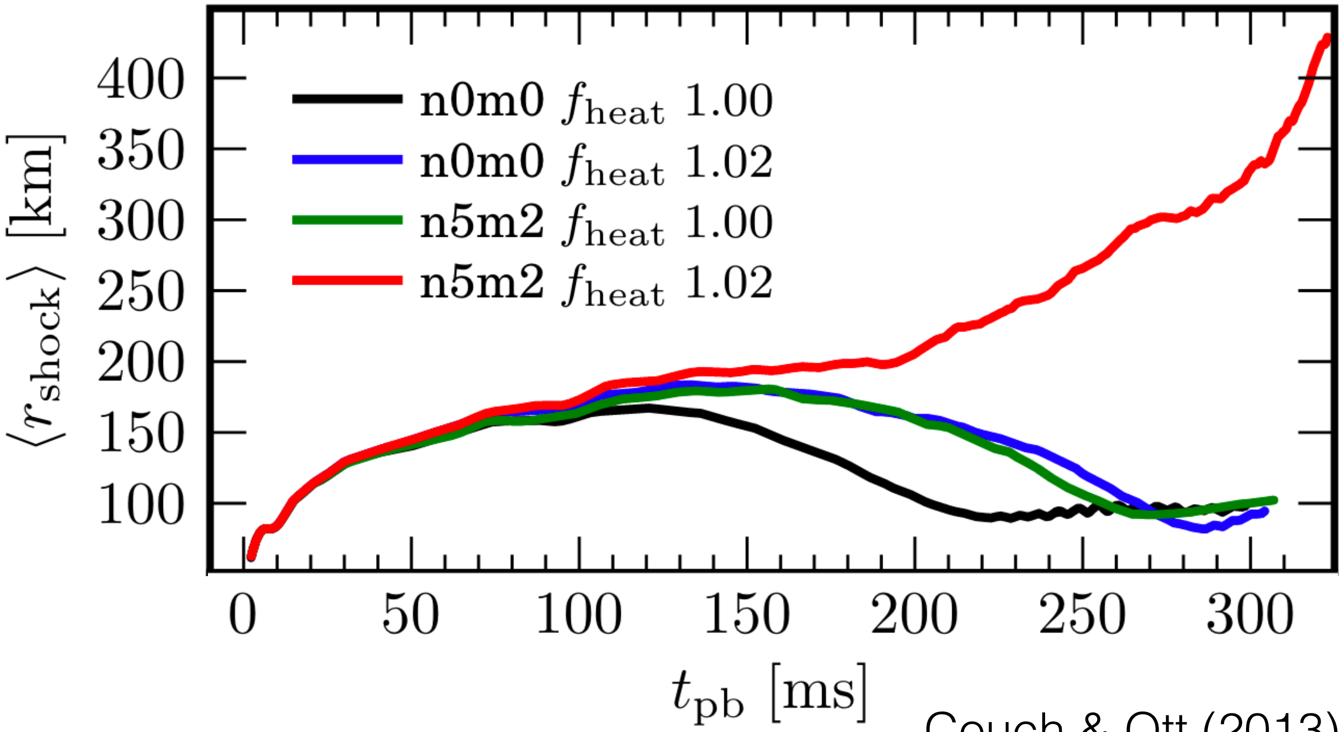
Neutrino Mechanism: Pre-collapse Perturbations

The nuclear burning shells in the pre-supernova progenitor are convective, and convection is turbulent. Over the last decade, 3D simulations of oxygen or silicon shell burning have become possible. These simulations have shown that density fluctuations are significant, leaving an inhomogeneous density profile prior to collapse.



Müller et al. (2016)

For models that are close to (but not quite at) an explosion, pre-collapse density perturbations can enhance post-shock turbulence via convective or SASI activity, improving conditions for an explosion.



Couch & Ott (2013)

Neutrino Mechanism: Explosion Energies

Ultimately, explosions powered by the delayed neutrino mechanisms prove to be successful when modeled in 3D and with sophisticated neutrino transport, given the delicate balance required to revive the shock.

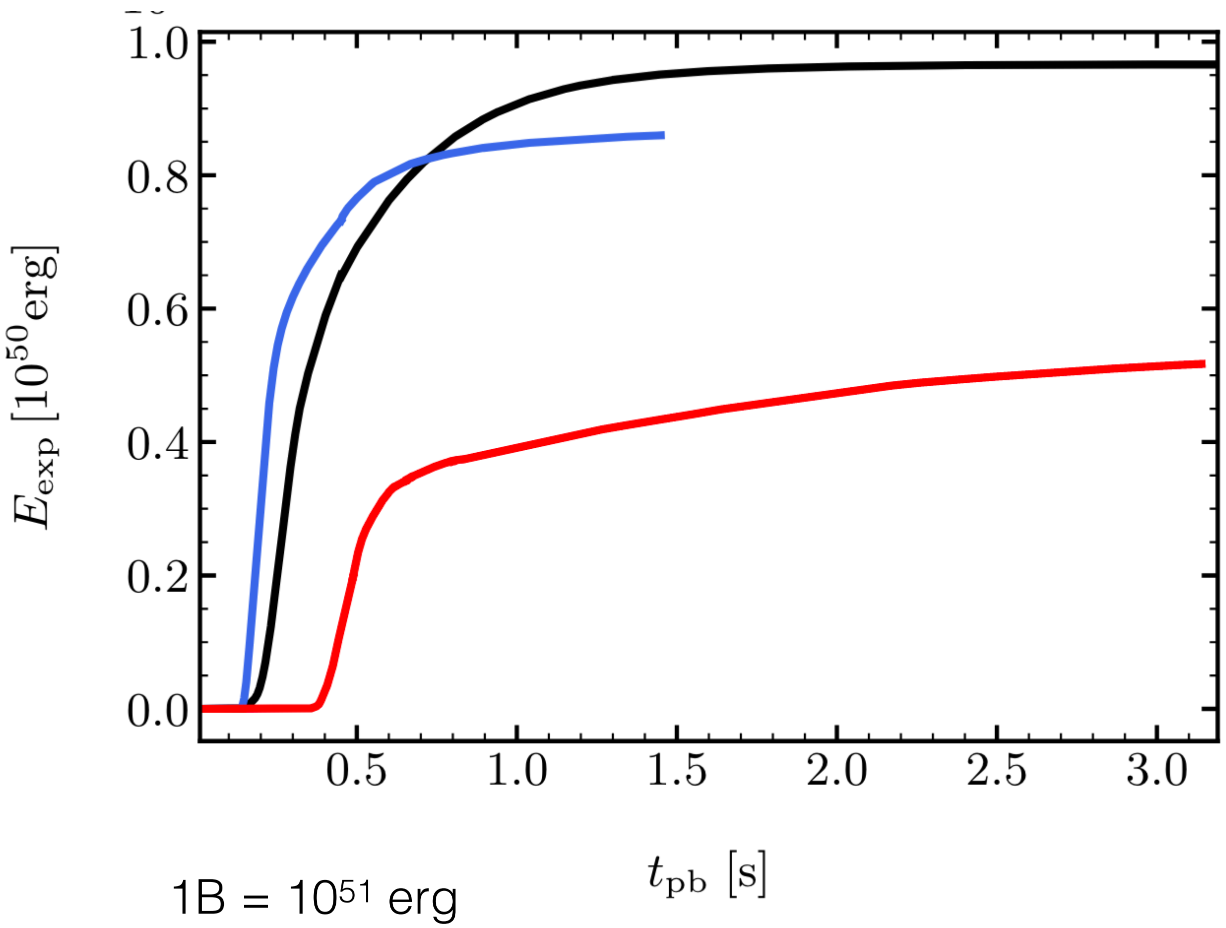
At present, self-consistent models yield under-energetic explosions, with energies at most a few times 10^{50} erg.

Current issues being studied:

1) Presupernova star uncertainties

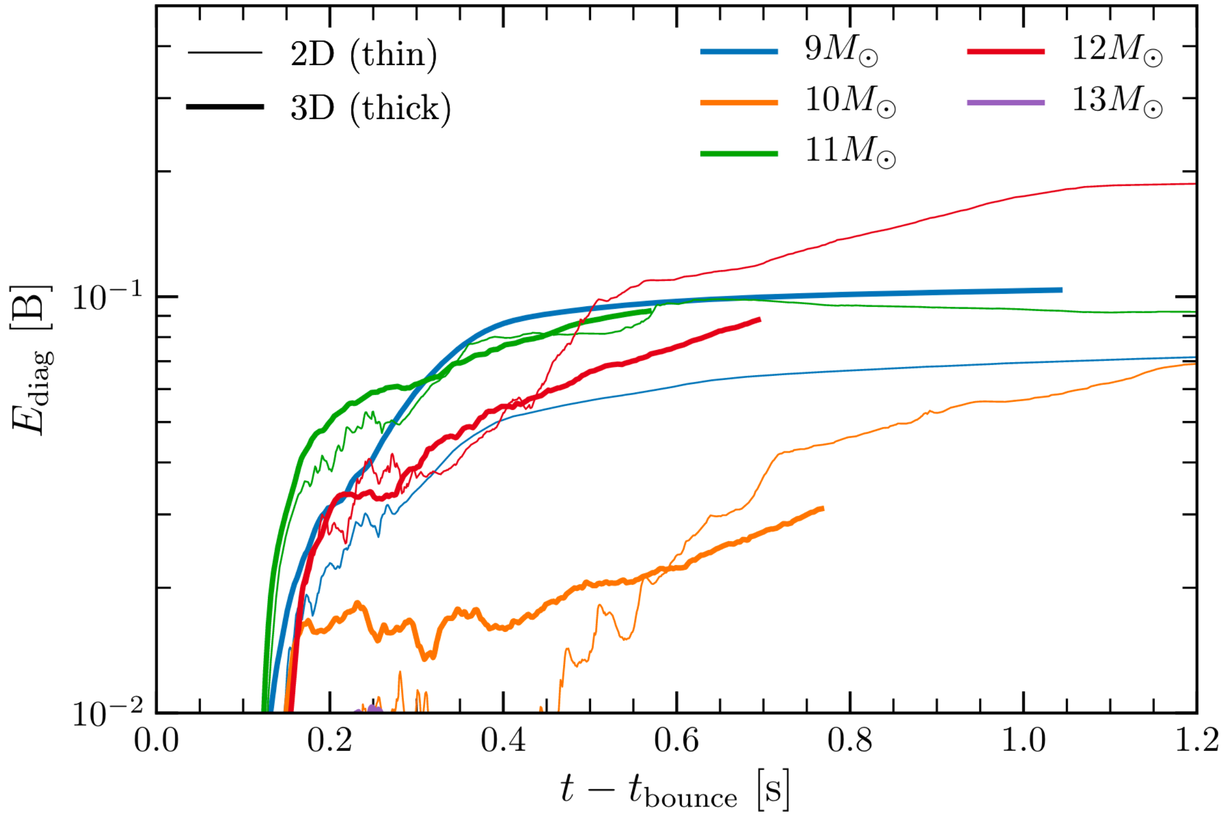
2) Microphysics (weak interactions, inclusion of muons).

3) Mapping to late time evolution, including nuclear burning.



Stockinger et al. (2020)

1B = 10^{51} erg



Burrows et al. (2019)

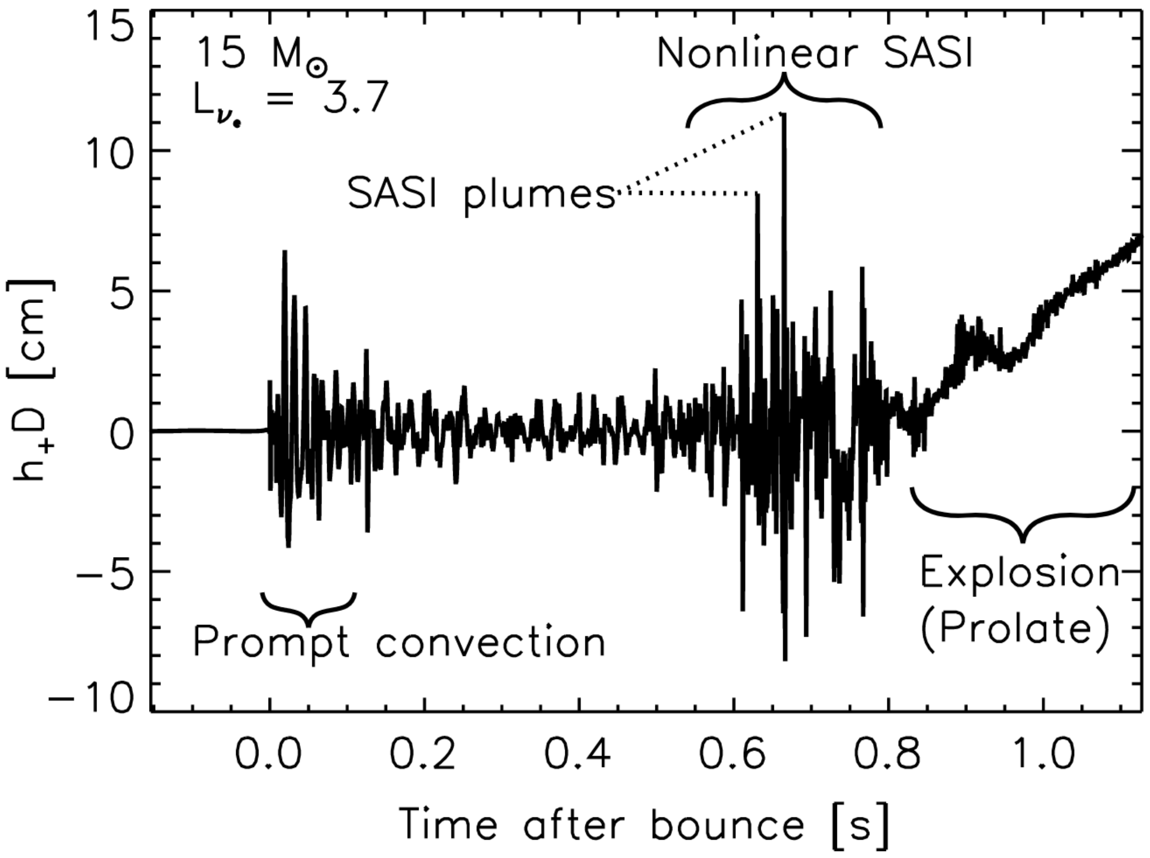
Neutrino Mechanism: GW Emission

Non-rotating supernova explosion are a source of gravitational waves due to time-varying mass-energy quadrupole moment.

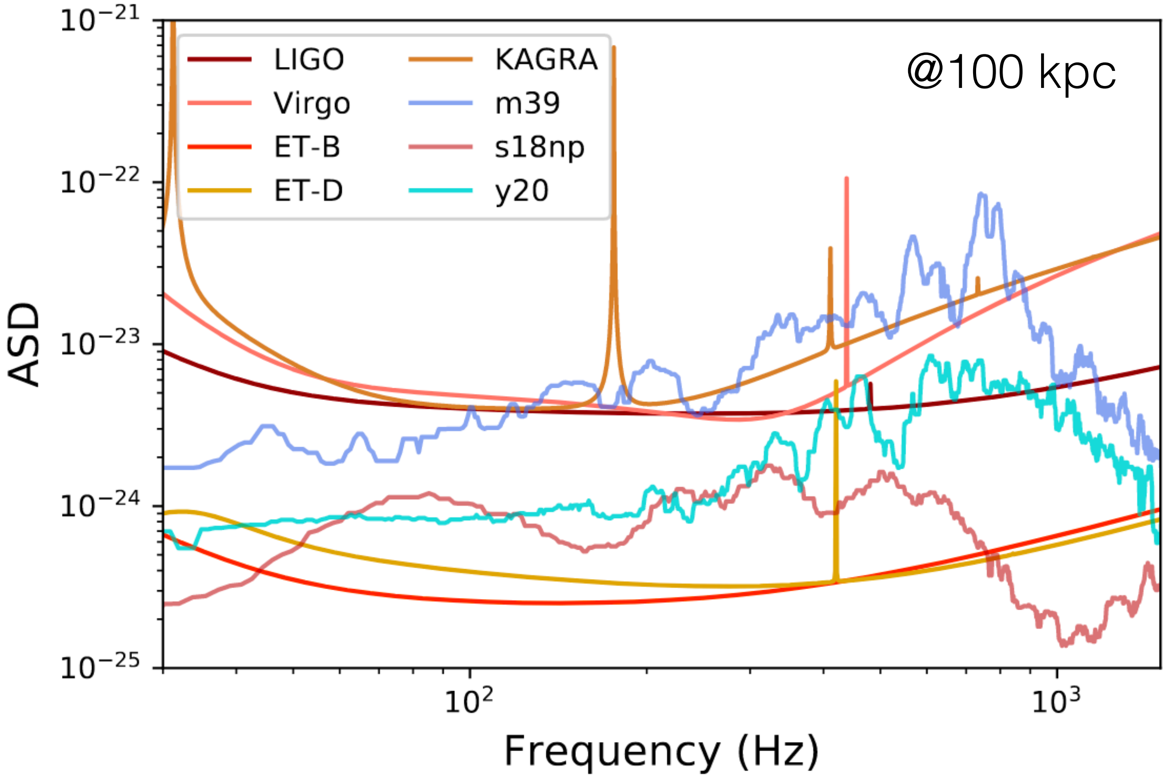
The GW waveform has distinctive components:

1) PNS convection
2) Anisotropic neutrino emission
3) Accretion phase & SASI
4) Explosion

The amplitude of the signal is weak, however, with current detectors only able to detect a CCSNe in the MW.



Murphy et al. (2009)



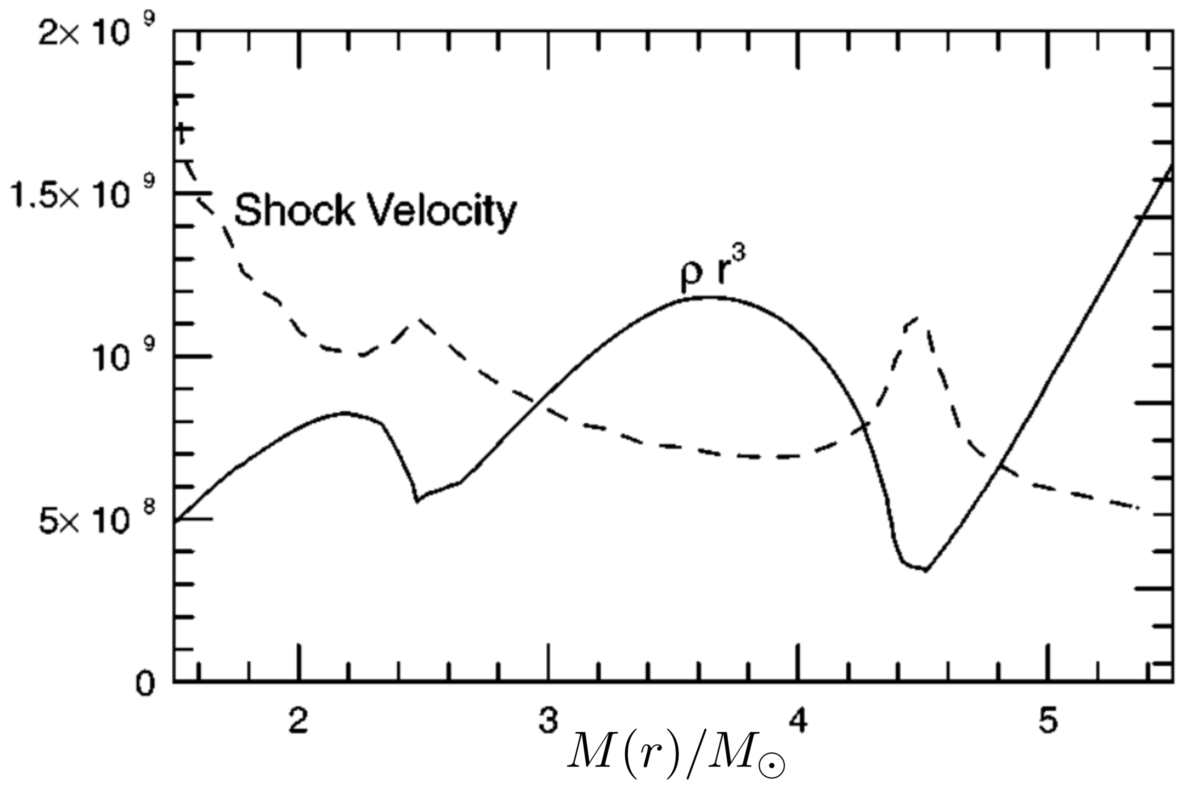
Powell & Müller (2020)

Neutrino Mechanism: Late-Time & Mixing

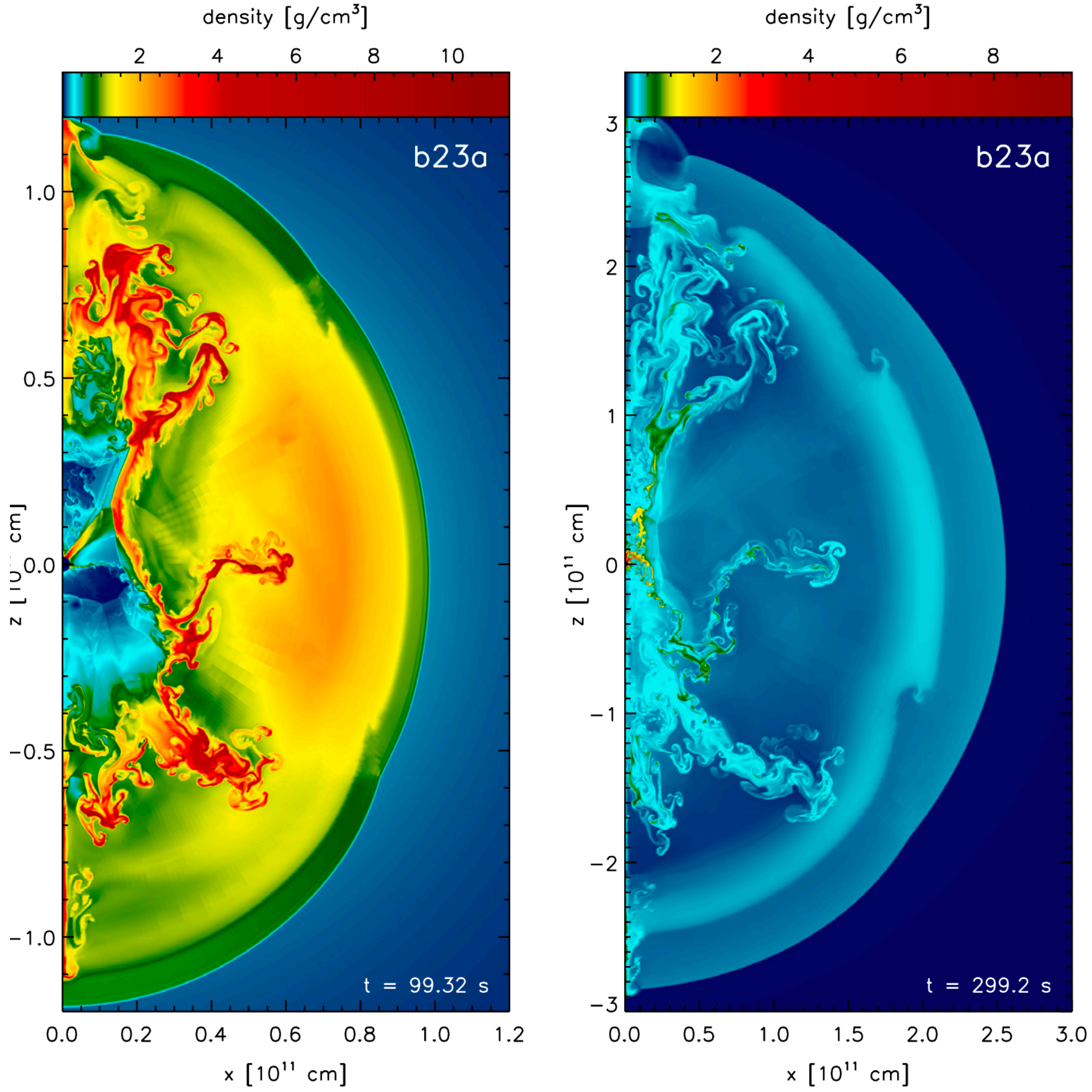
In a successful explosion, the shock propagates out through the progenitor envelope.

The shock speed is dependent on the local density profile, with a balance between speedup due to the pressure gradient and slowdown due to the mass swept. Self-similar solutions show that the sign of the acceleration depends on the sign of the quantity ρr^3.

The composition interfaces in the envelope involve density jumps, which become unstable to fluid instabilities (Rayleigh-Taylor & Richtmeyer-Meshkov) when the shock crosses them, generating complex flow patterns.



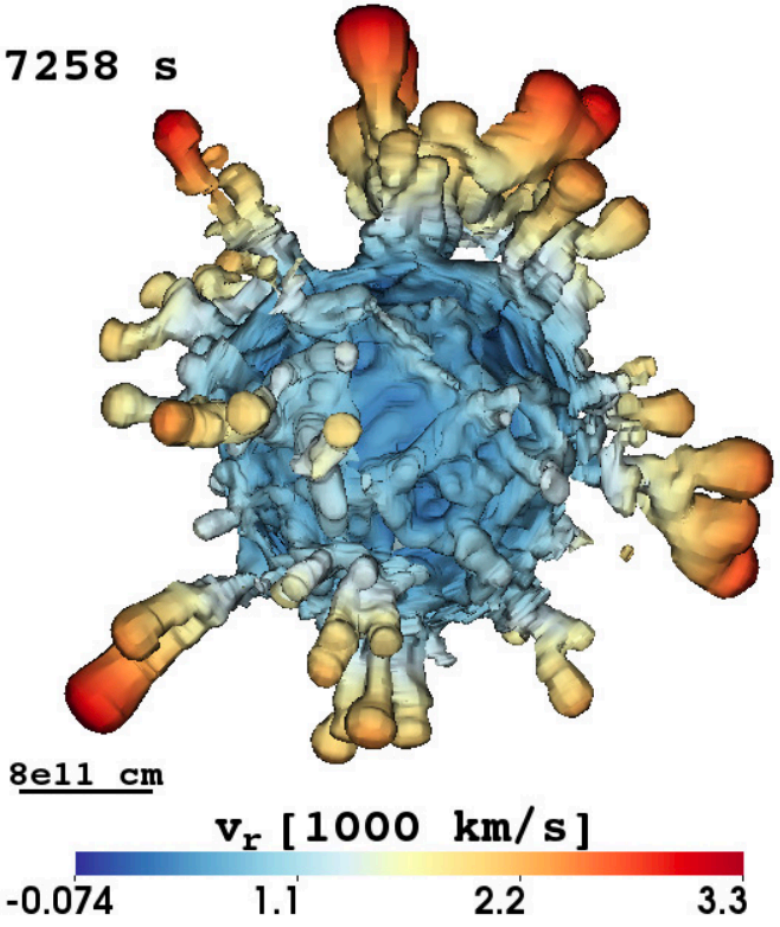
Woosley & Weaver (1995)



Kifonidis et al. (2006)

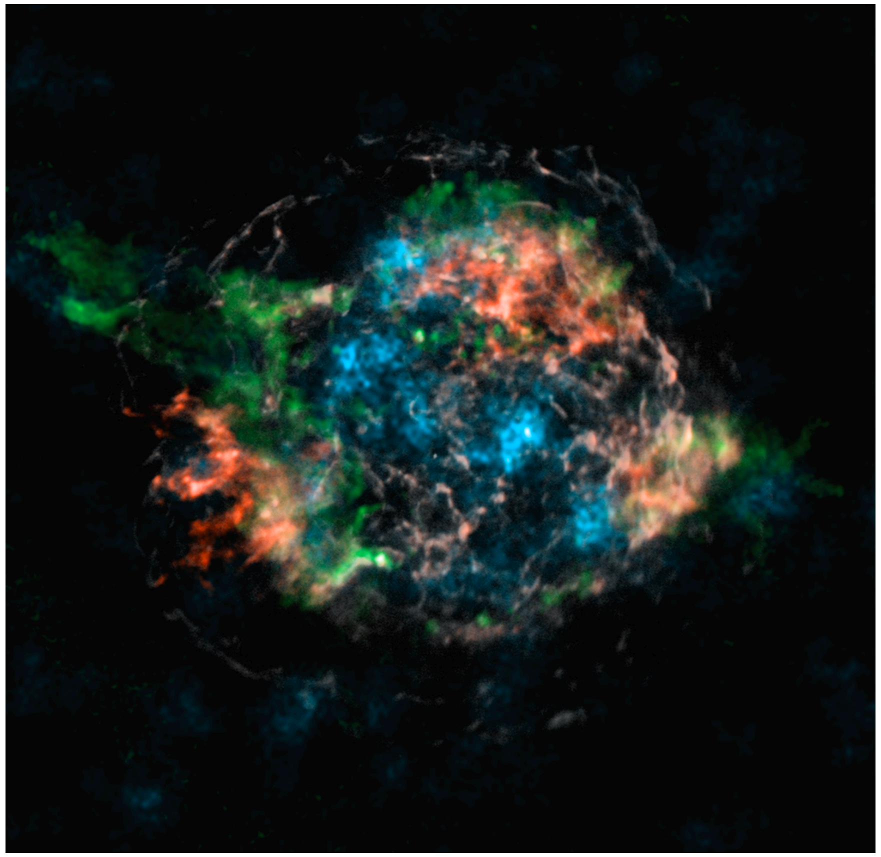
Neutrino Mechanism: Late-Time & Mixing

Modern 3D simulations of the shock propagation through the envelope show that these overturn patterns behind the shock mix heavier elements from deeper layers into outer layers of the shocked ejecta at high speed. For example, giving rise to so-called “Nickel bullets”.



Wongwathanarat et al. (2015)

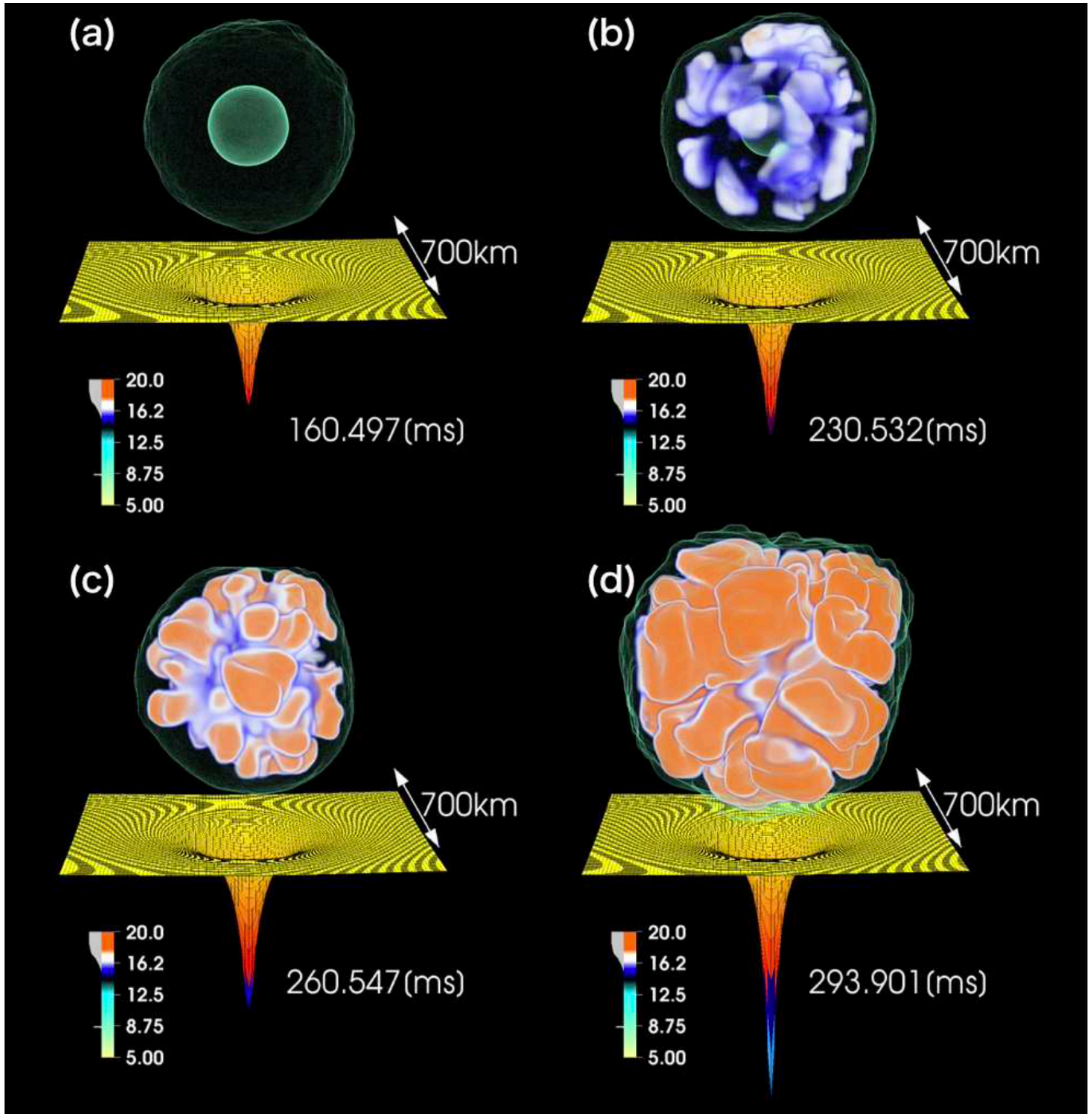
Observational evidence supporting this complex envelope mixing came from hard X-ray observations by NuStar, which identified lines from different elements. The occurrence of this mixing is connected to deeper asymmetries of the shock, which seed the late-time fluid instabilities.



Grefenstette et al. (2014)

Fallback supernovae

Successful supernova with BH formation



Kuroda+ (2018)

Accretion pushes PNS above maximum mass supported by the EOS of dense matter.

Recent work in multi-D

Chan+ (2018)

Kuroda+ (2018)

Walk+ (2020)

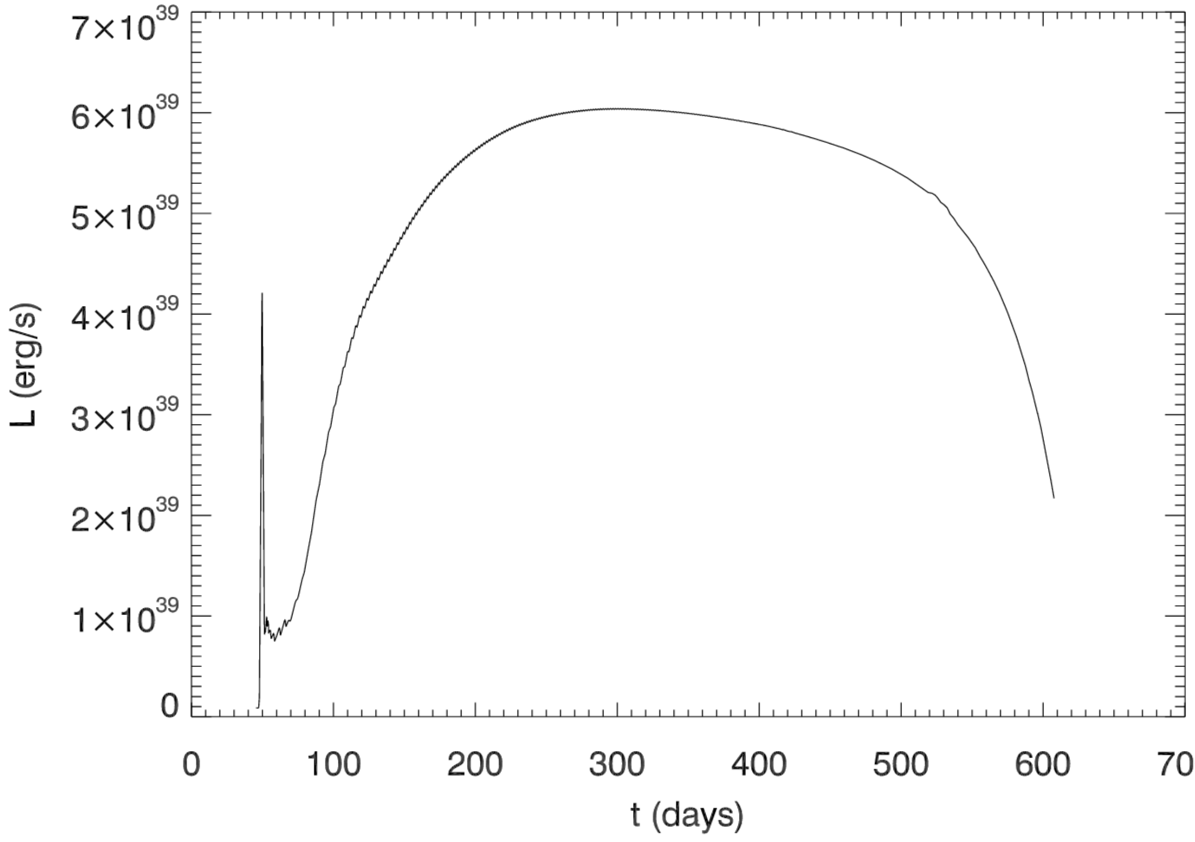
Pan+ (2020)

From 1D work: fine tuning?

Ugliano+ (2012)

Failed Supernovae: Slowly Rotating

If the shock is never revived, and there is little rotation, most of the progenitor mass goes into forming a BH

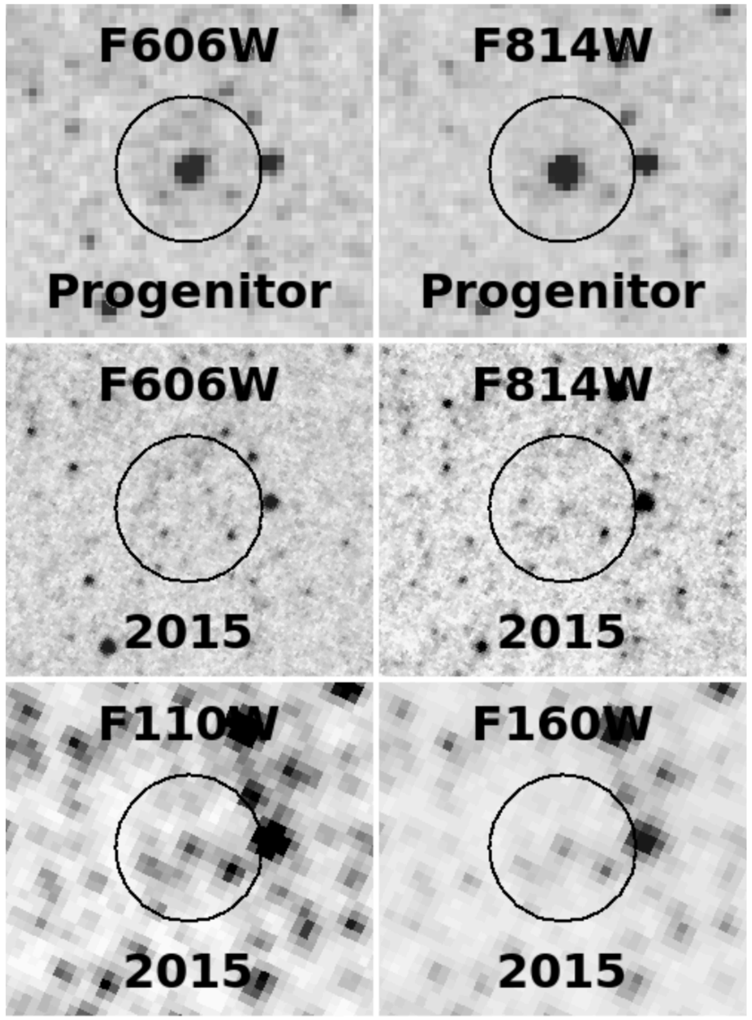


Lovegrove & Woosley (2013)

A low energy sound pulse is generated by the loss of mass-energy to neutrino emission: the gravitational mass decreases. Most significant for RSGs, low-luminosity transient, few $M_{\rm sun}$ ejected.

Nadyozhin (1980), RF et al. (2018), Antoni et al. (2023)

A survey monitoring RSGs for stellar disappearances found one case in which progenitor disappearance was accompanied by a ~1yr long transient consistent with predictions.



Adams+ (2017): N6946-BH1

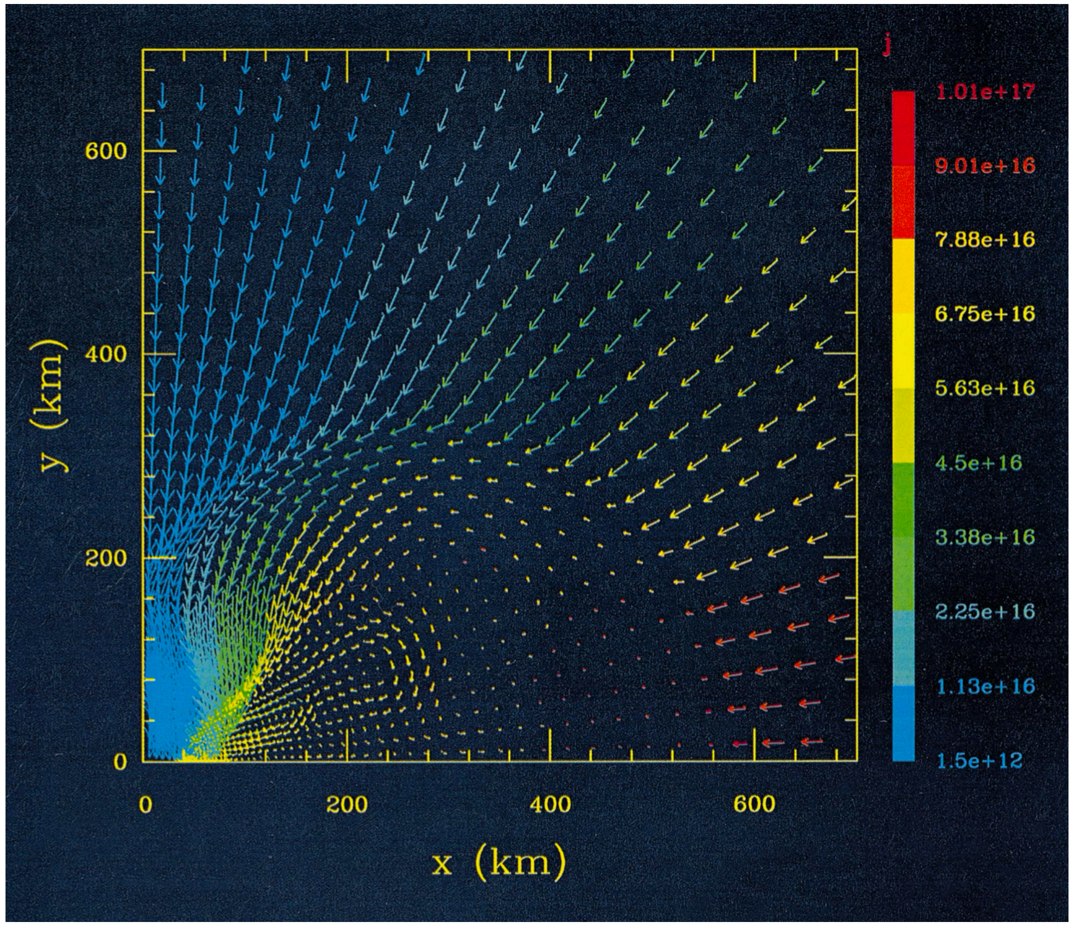
Collapsars / Long GRBs

If the failed supernova occurs in a rotating progenitor, the collapsing flow can circularize into a accretion disk around the BH. If the disk forms deep enough, it can be neutrino-cooled and it's called a collapsar. Woosley et al. (1993)

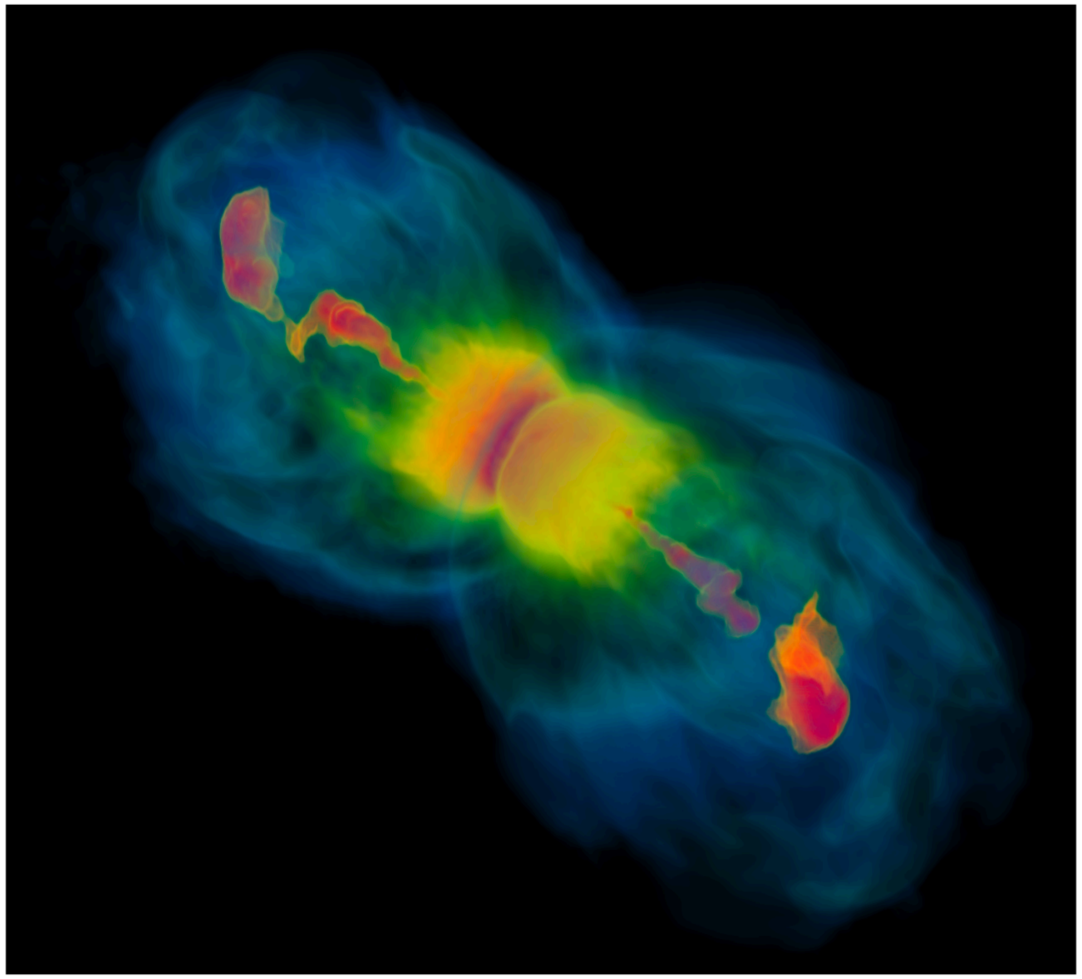
The disk can give rise to a relativistic jet, powering a long-duration Gamma-Ray Burst and possibly exploding the star. The disk can also launch a sub-relativistic wind which can explode the star by itself.

The collapsar model is the leading candidate to explain LGRBs & the accompanying Type Ic-BL SNe. Also considered as an r-process site.

Woosley & Bloom (2006), Just et al. (2022)



MacFadyen & Woosley (1999)



Gottlieb et al. (2022)

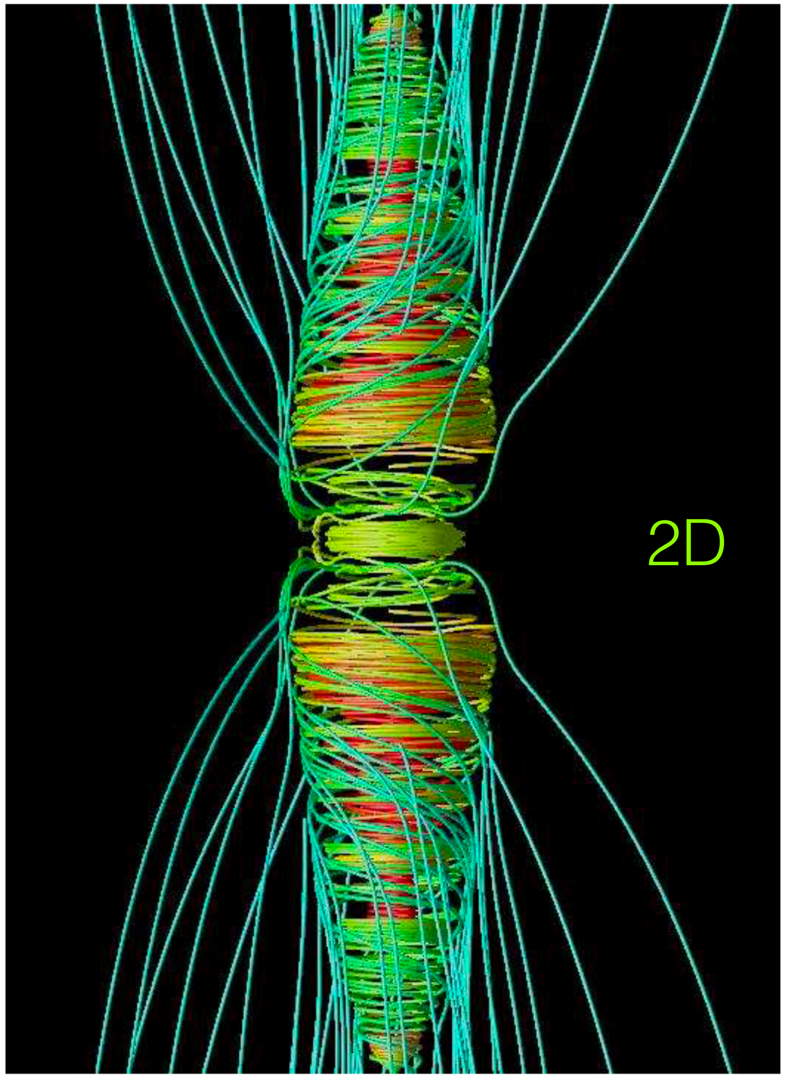
Magneto-rotational SNe

For very rapid-rotation, magnetic field amplification can in fact explode the supernova independent of neutrino emission.

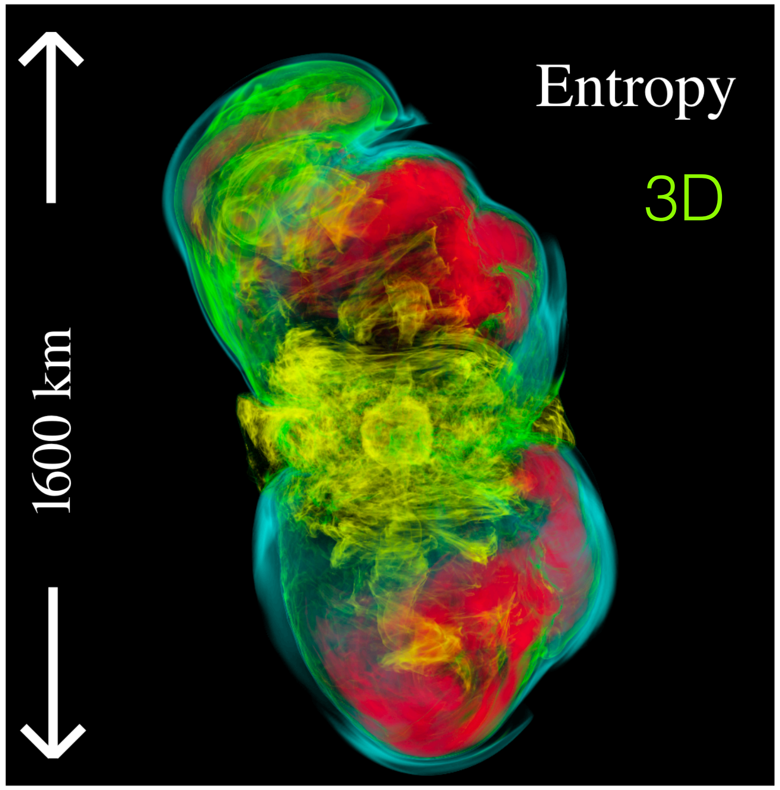
Field is amplified by compression (flux freezing), winding (toroidal), and by the magnetorotational instability. A collimated outflow is produced, possibly subject to MHD instabilities. Neutron-rich matter can be removed quickly before neutrinos re-process it: candidate r-process site.

Magnetorotational SNe cannot be the dominant explosion mechanism: the rapid rotation of the NS (magnetar?) would imprint itself in the supernova remnants. Also explosions are too energetic (~10^{52} erg).

e.g., Kuroda et al. (2020), Obergaulinger & Aloy (2021), Powell et al. (2023)



Burrows et al. (2007)



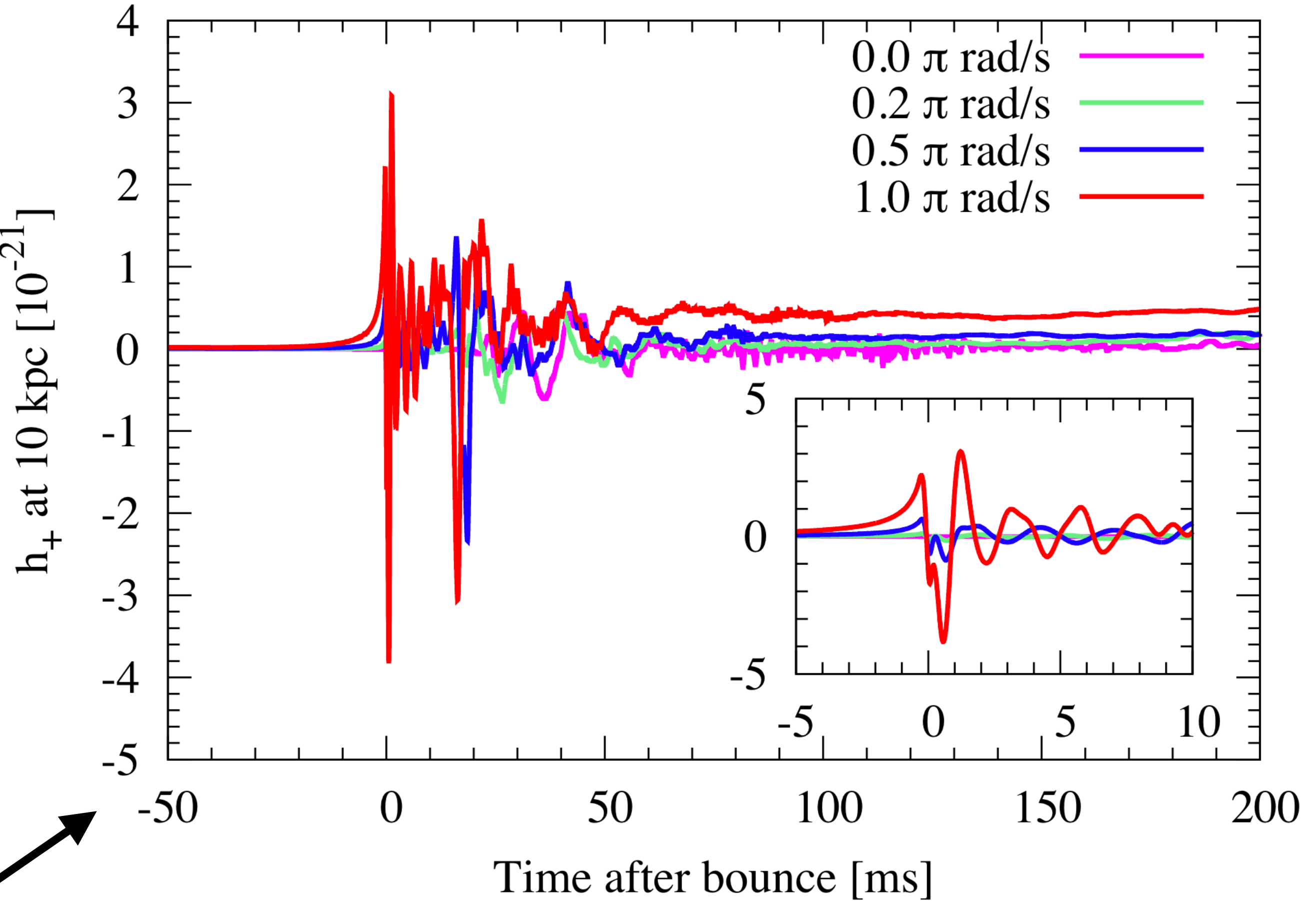
Mösta et al. (2014)

Rapid Rotation & GW Emission

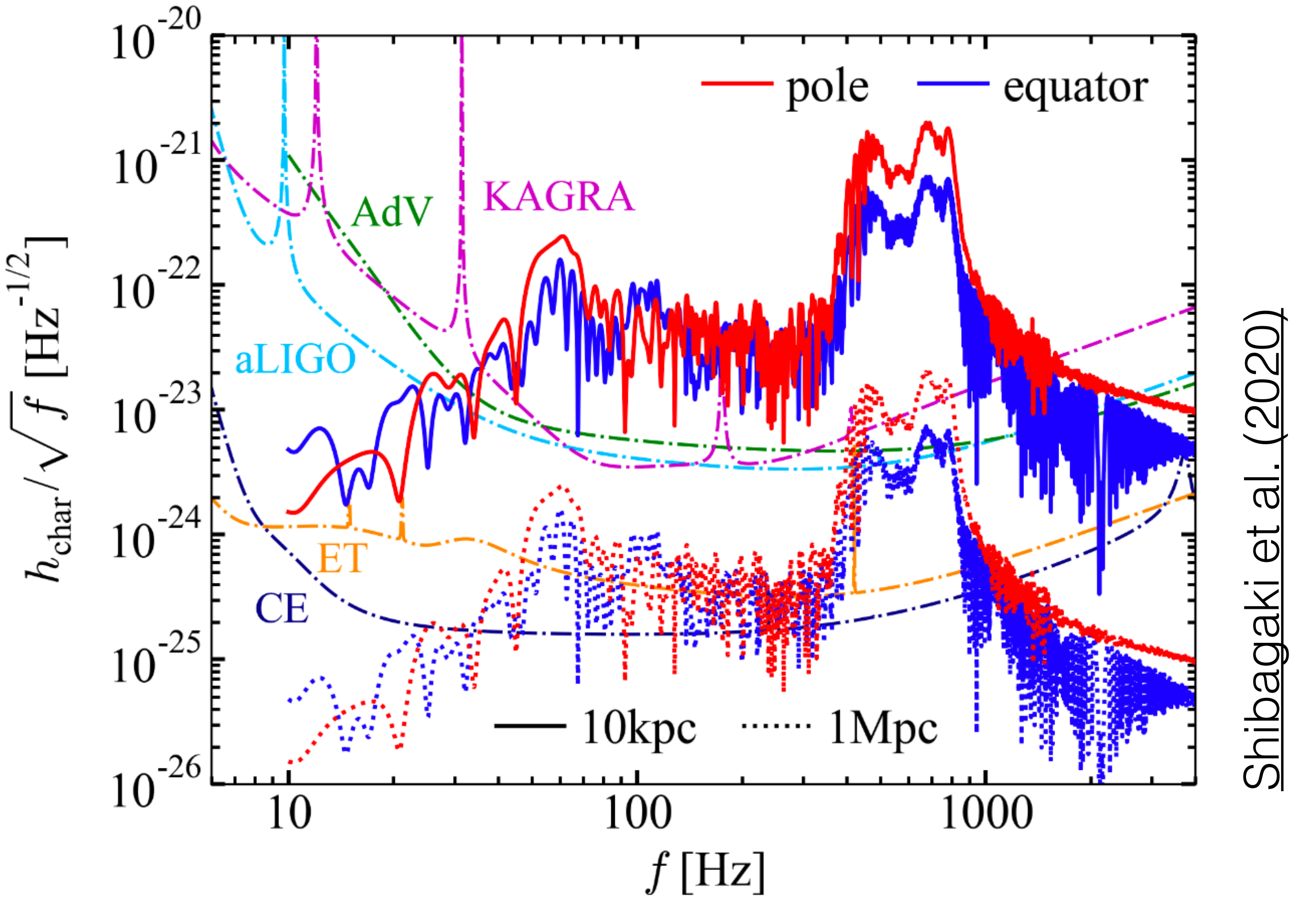
Rapid rotation can enhance GW emission relative to the non-rotating case, particularly at bounce time.

The centrifugal force makes the core asymmetric, increasing the mass quadrupole moment at bounce time.

Rapidly-rotating CCSNe have a higher GW luminosity than non-rotating CCSNe, being detectable out to much larger distances.



Yokozawa et al. (2015)



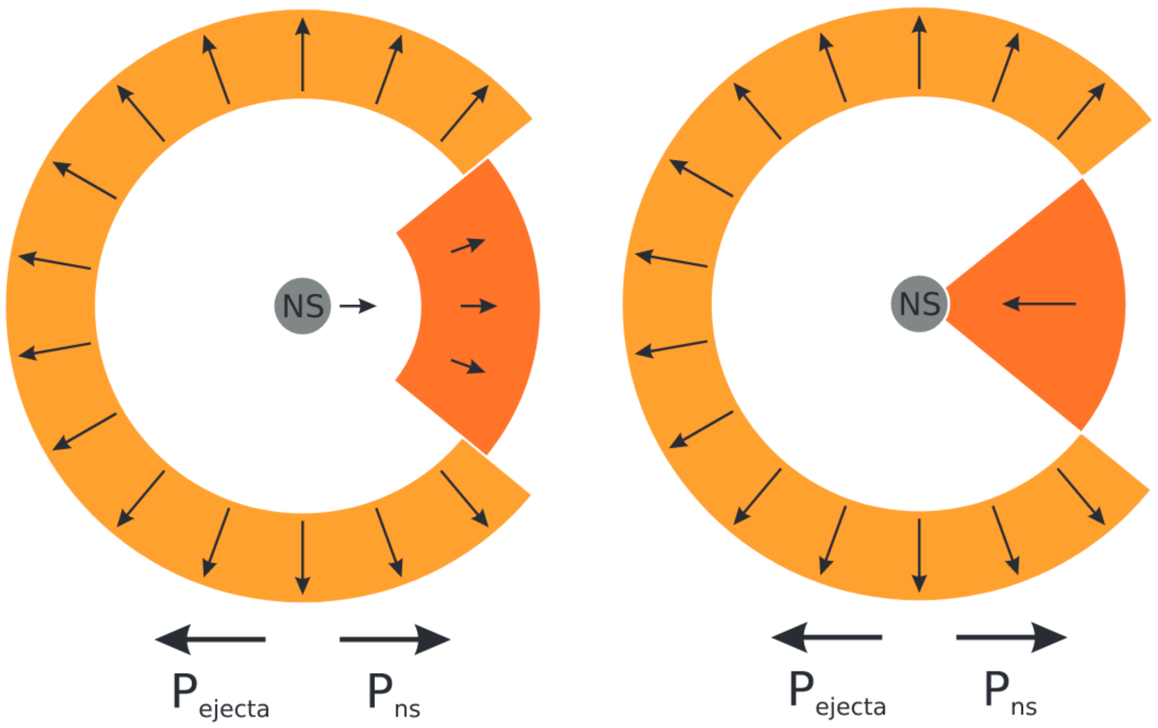
Shibagaki et al. (2020)

Remnants: Kicks

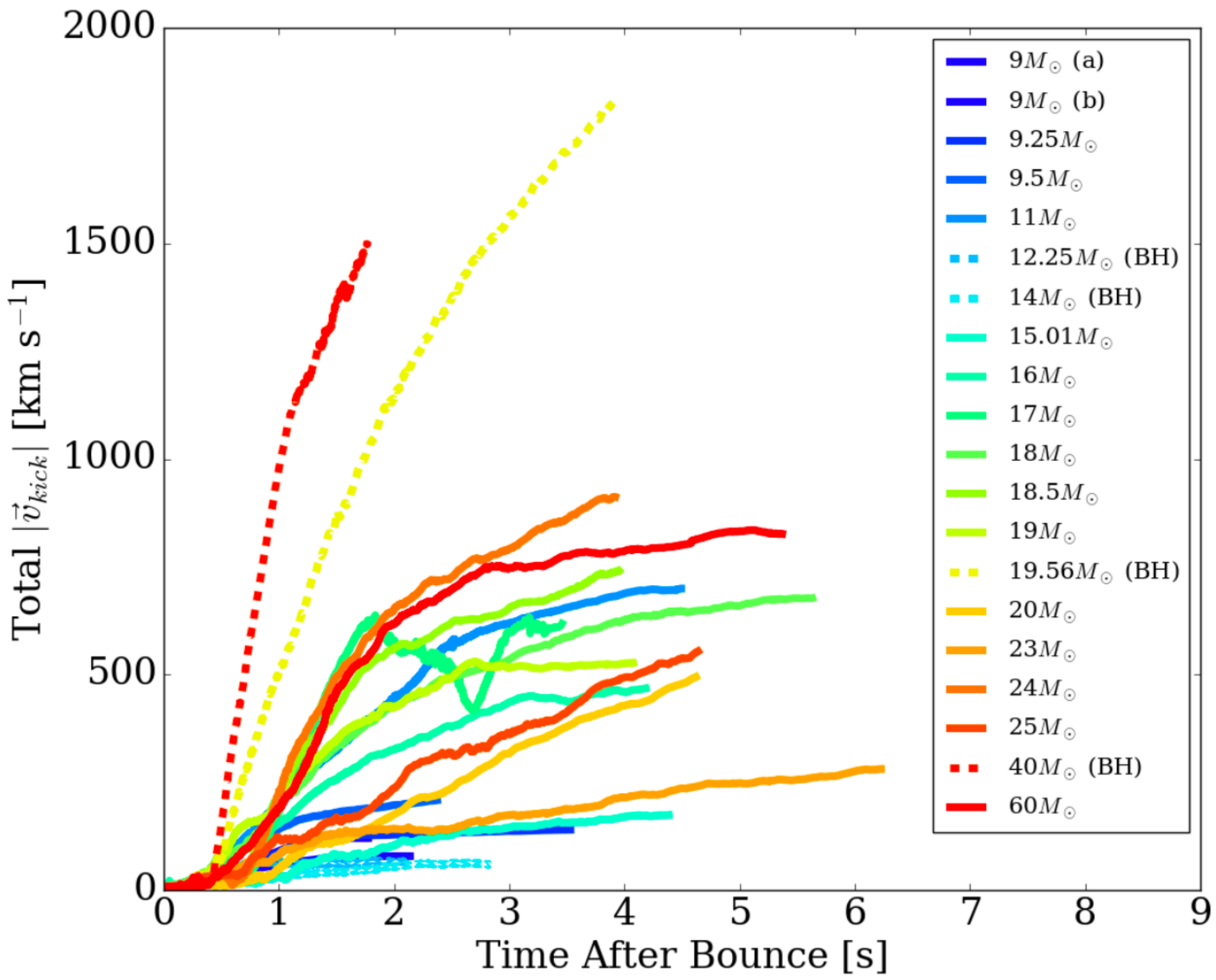
During a successful explosion, center of mass of the system continues to move a the same speed as the progenitor did.

An asymmetric explosion means that the remnant will have a momentum equal and opposite of that of the ejecta: a kick!

Modern 3D CCSNe (neutrino-driven) simulations yield kick velocities that span the full range of pulsar speeds observed (up to ~1000 km/s). For any given system, the final kick is a complex function of the explosion dynamics.



Scheck et al. (2006)



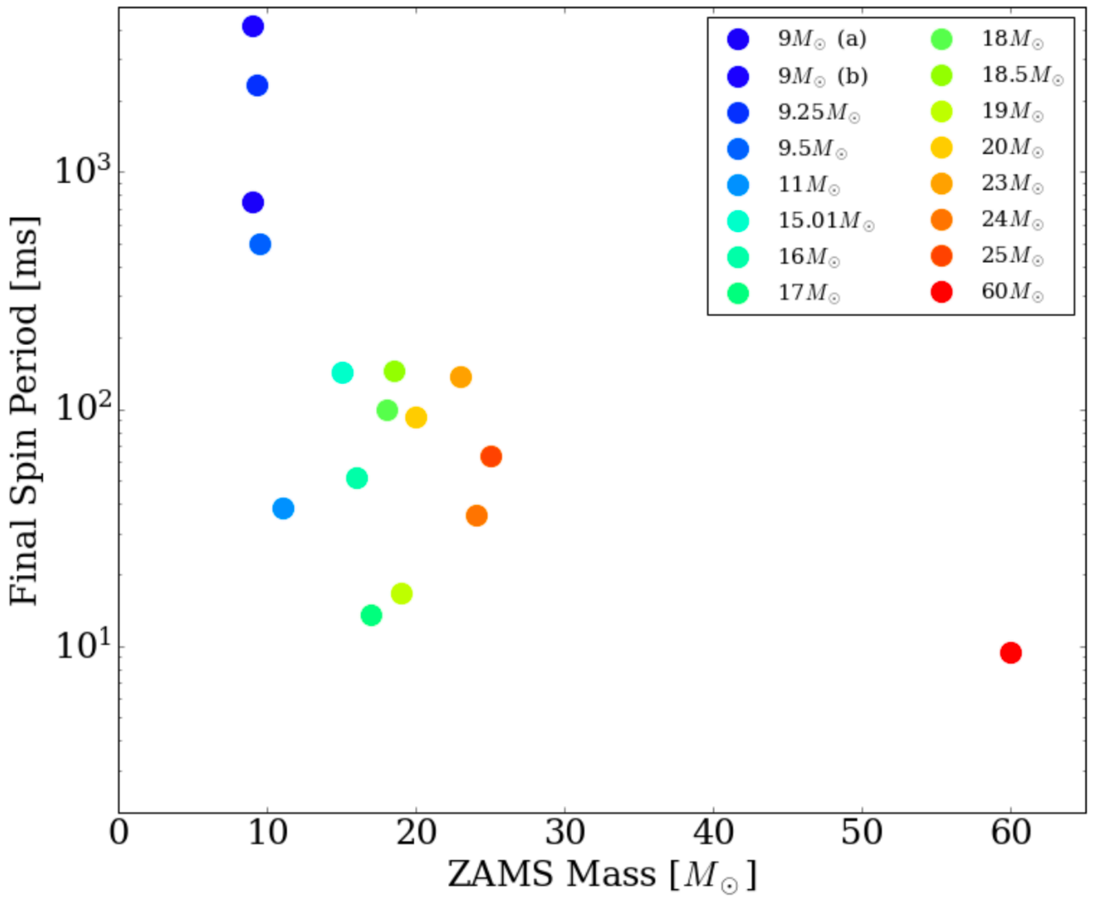
Burrows et al. (2023)

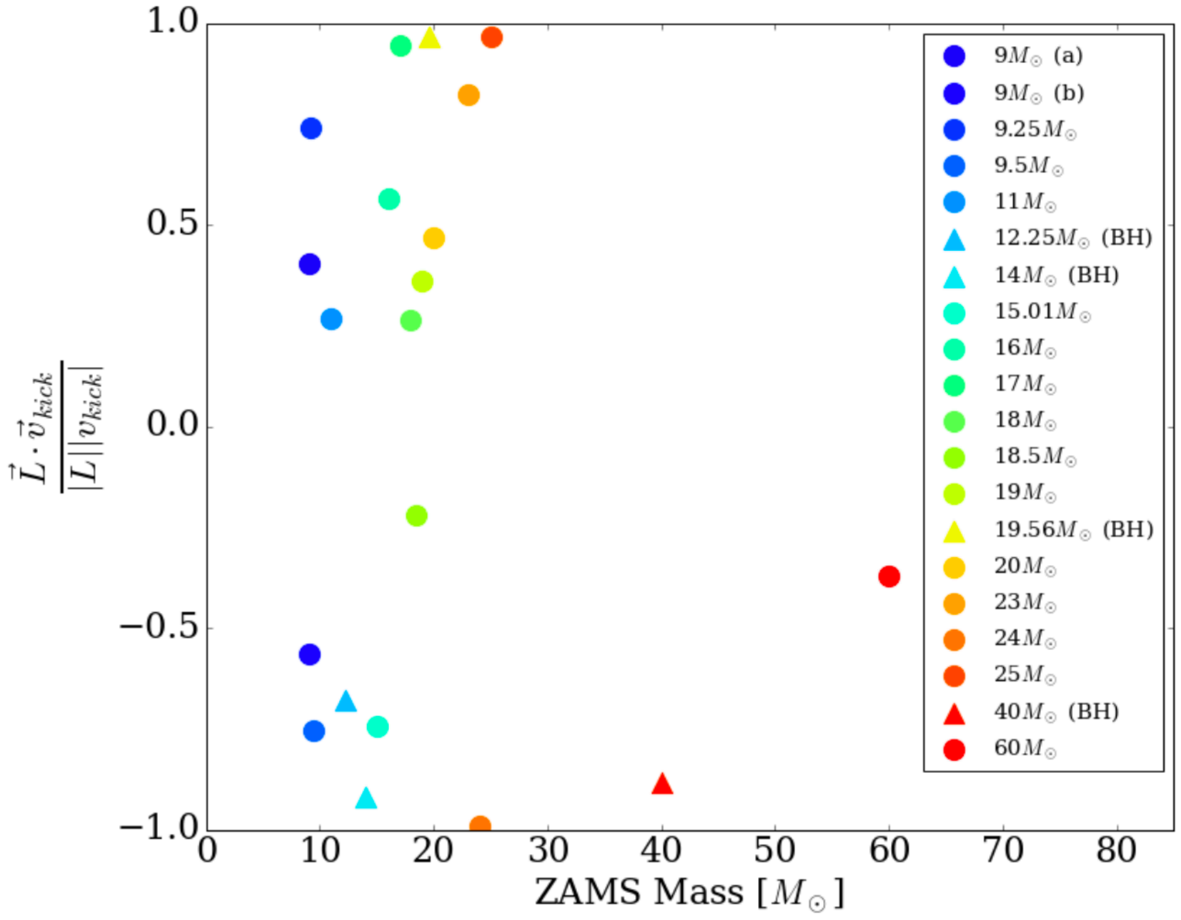
Remnants: Spins

Anisotropic mass accretion can impart a spinup to the remnant, neutron star or BH.

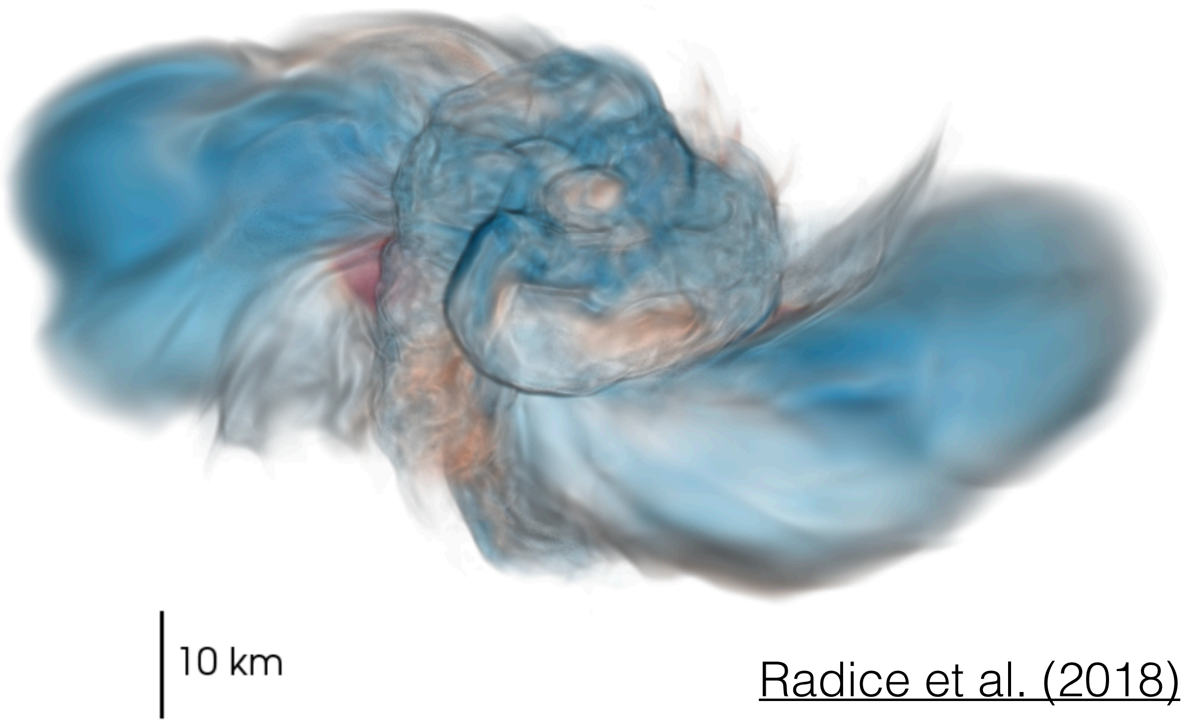
Possible correlation between magnitude of kick and magnitude of spin with ZAMS mass due to magnitude of asymmetries: ECSNe have low kicks and slow rotation periods, iron CCSNe have higher kicks and spinup.

No clear correlation of kick direction with spin direction, although prevalence of aligned and anti-aligned configurations.

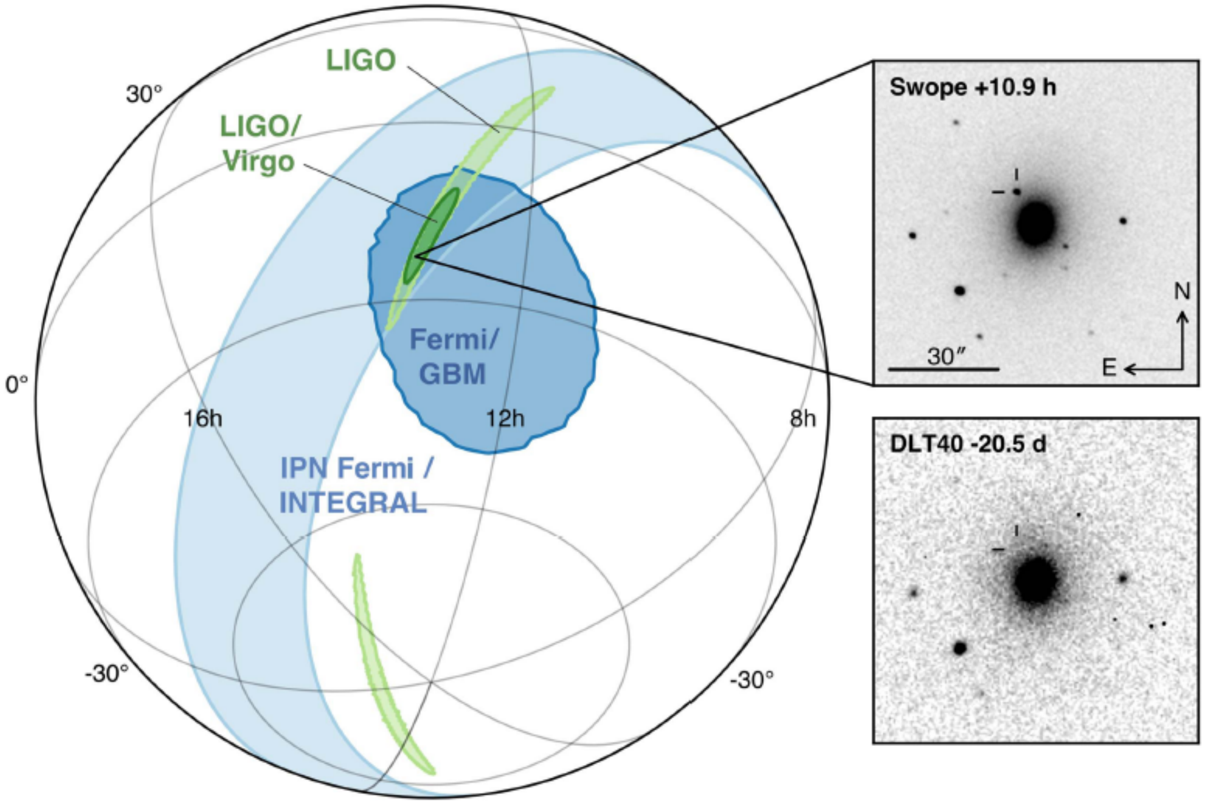




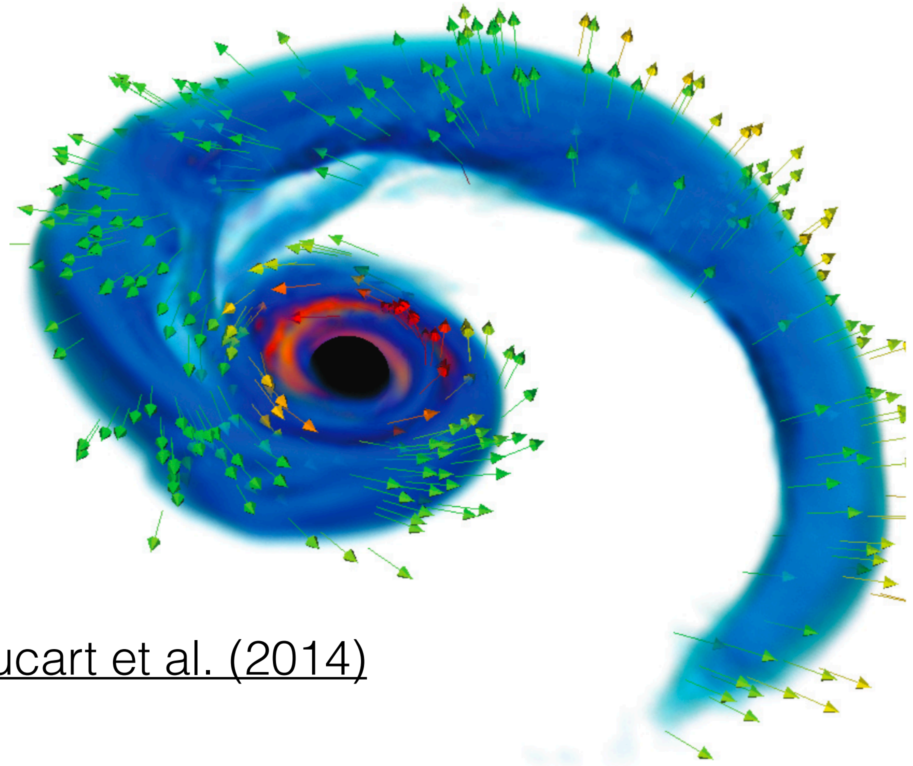
Burrows et al. (2023)



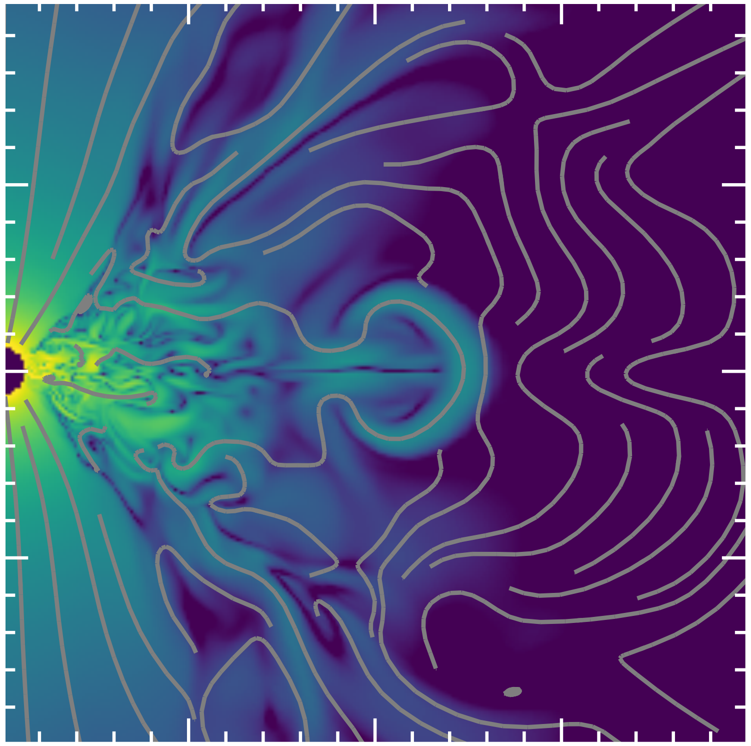
Radice et al. (2018)



Abbott et al. (2017) [LVC]: GW170817



Foucart et al. (2014)



RF et al. (2019)

Neutron Star Mergers II

Rodrigo Fernández (University of Alberta)

Outline

~~1) Neutron stars~~

~~2) Overview of Merger Phases~~

~~3) Inspiral Phase: GW & EM precursors~~

~~4) Dynamical Phase: Mass Ejection, NSNS vs NSBH~~

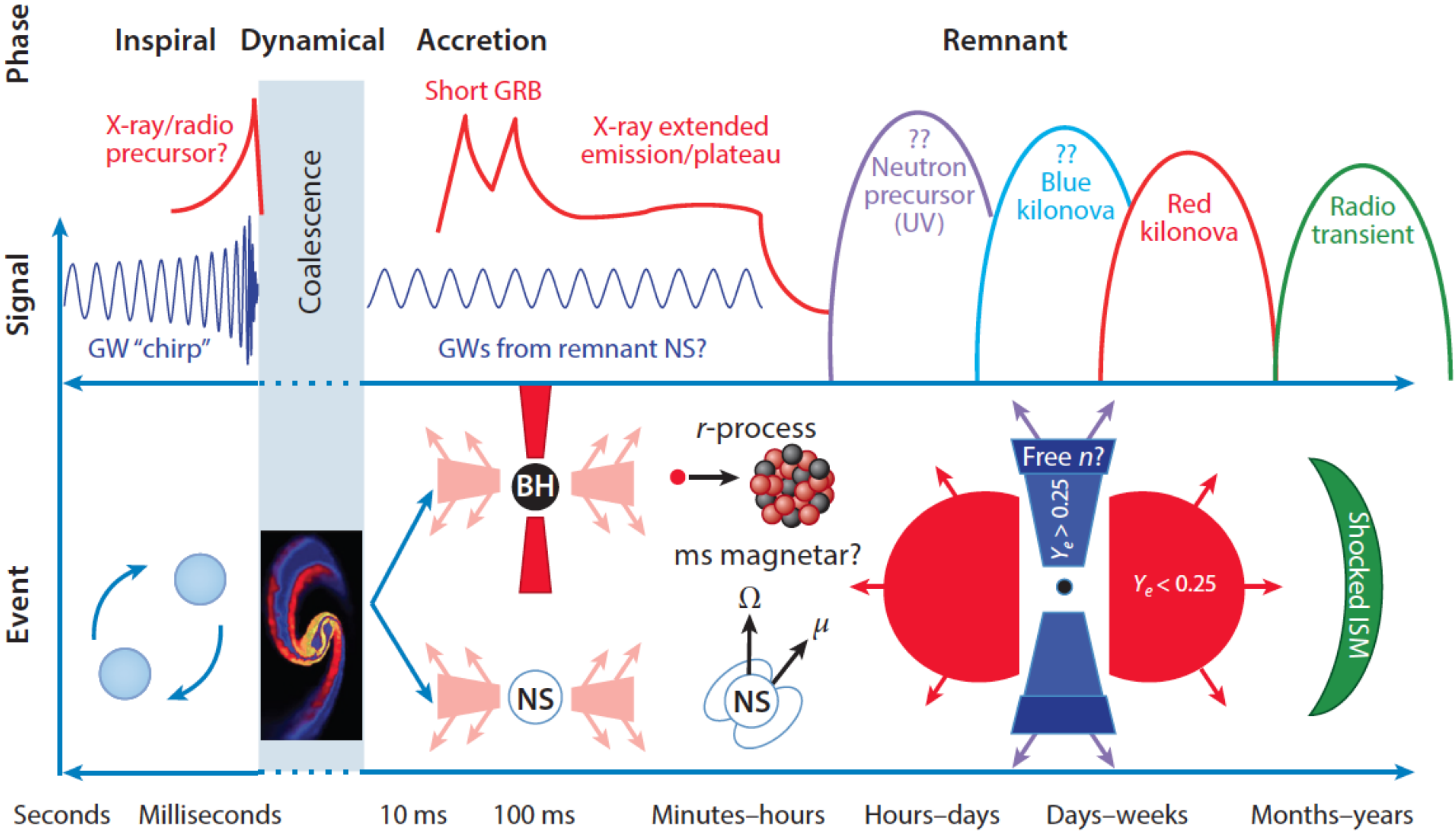
~~5) Merger Remnant: Post-merger GWs, EOS~~

~~6) r-process in a nutshell~~

7) Accretion Disk: evolution & mass ejection

8) EM Counterpart Overview: GRBs, Kilonovae, and more

Neutron Star Mergers: Overview



RF & Metzger (2016)

Accretion Disk

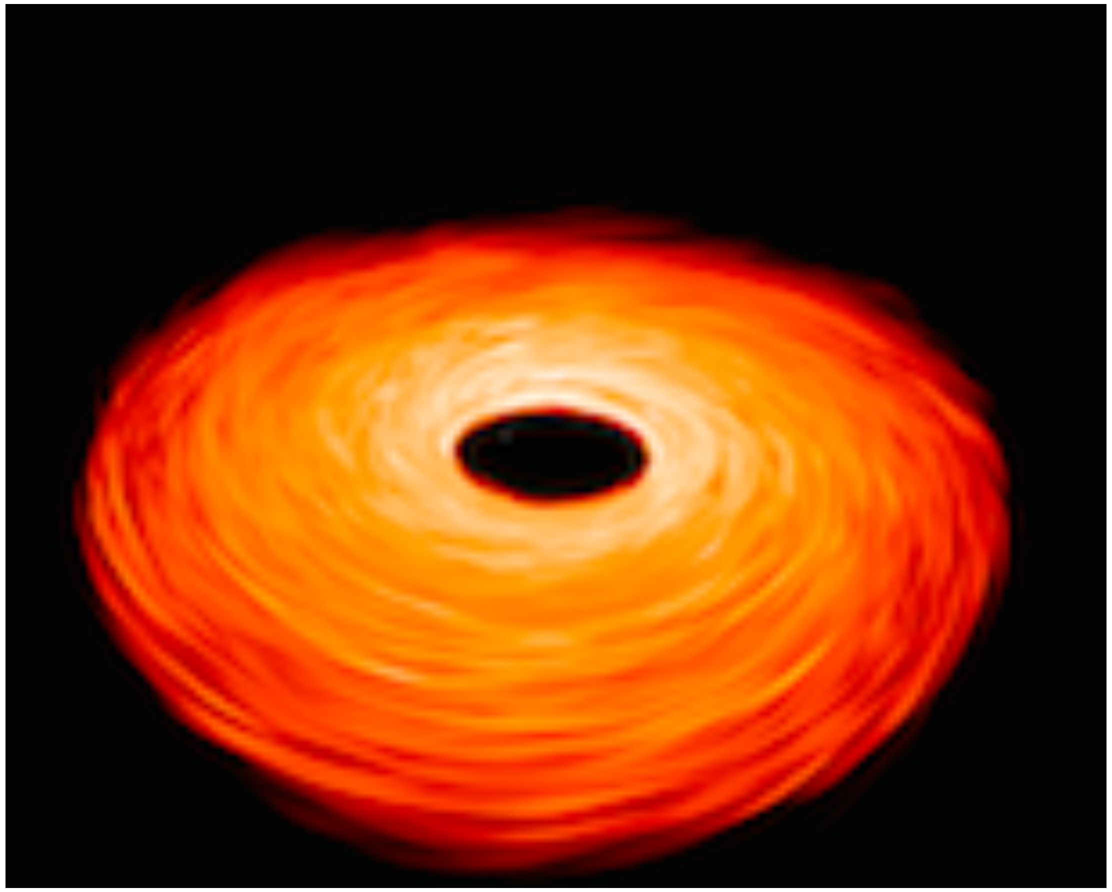
Structure formed by gas orbiting a central object. Gravity balanced mostly by centrifugal acceleration (angular momentum). Matter is (initially) bound gravitationally.

Thermal pressure provides partial support, determines vertical extent of disk ("puffiness").

Settling of mass onto central object ("accretion") requires gas to lose angular momentum and thermal energy.

- angular momentum transport mechanism
- neutrino cooling (for NS mergers)

Mass can be unbound from the accretion disk by a variety of mechanisms: disk outflow



Mario Flock / KITP

Q1: outflow mass, properties

Q2: r-process contribution

Q3: observational EM signature (contribution to kilonova, jet, etc.)

Accretion Disk: Mass ejection mechanisms

Lorentz force

t ~ms

depends on existence and strength of poloidal field at disk formation

e.g. Blandford & Payne (1982)
Blandford & Znajek (1977)

Neutrino absorption

t ~10ms

important for HMNS, sub-dominant for BH

e.g. Ruffert & Janka (1996)

“Thermal” Ejection

t ~100ms

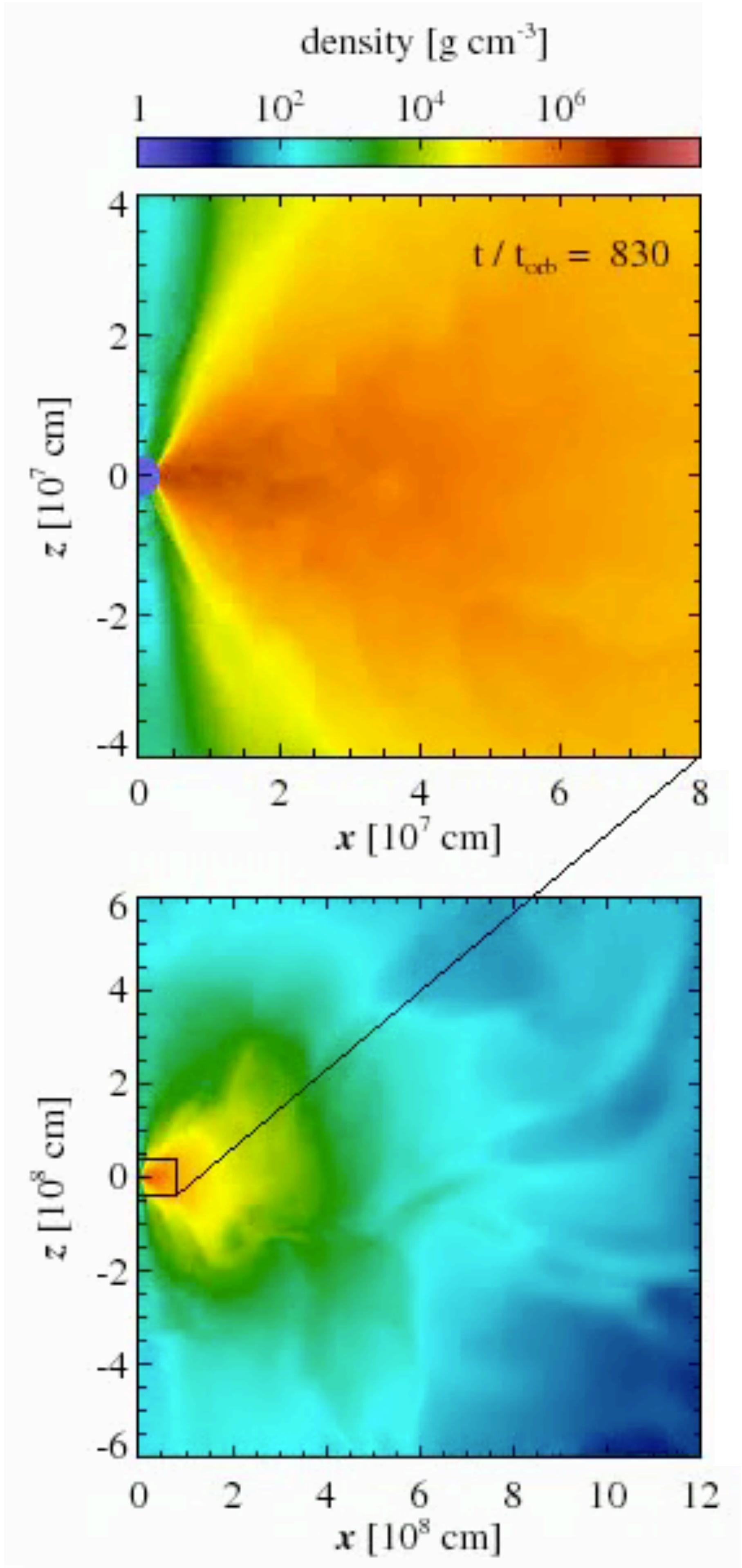
neutrino cooling drops on viscous time

- MRI turbulence (viscous) heating

- nuclear recombination (n,p into alpha)

Metzger, Piro, & Quataert (2009)

Outflow in Viscous Hydrodynamics



- Neutrino cooling shuts down as disk spreads on accretion timescale (~300ms)
- Viscous heating & nuclear recombination are unbalanced
- Fraction ~10-20% of initial disk mass ejected, ~1E-3 to 1E-2 solar masses
- Material is neutron-rich (Ye ~ 0.2-0.4)
- Wind speed (~0.05c) is slower than dynamical ejecta (~0.1-0.3c)

RF+ (2013, 2015, 2020)

Just et al. (2015, 2022)

Fujibayashi et al. (2020a-b)

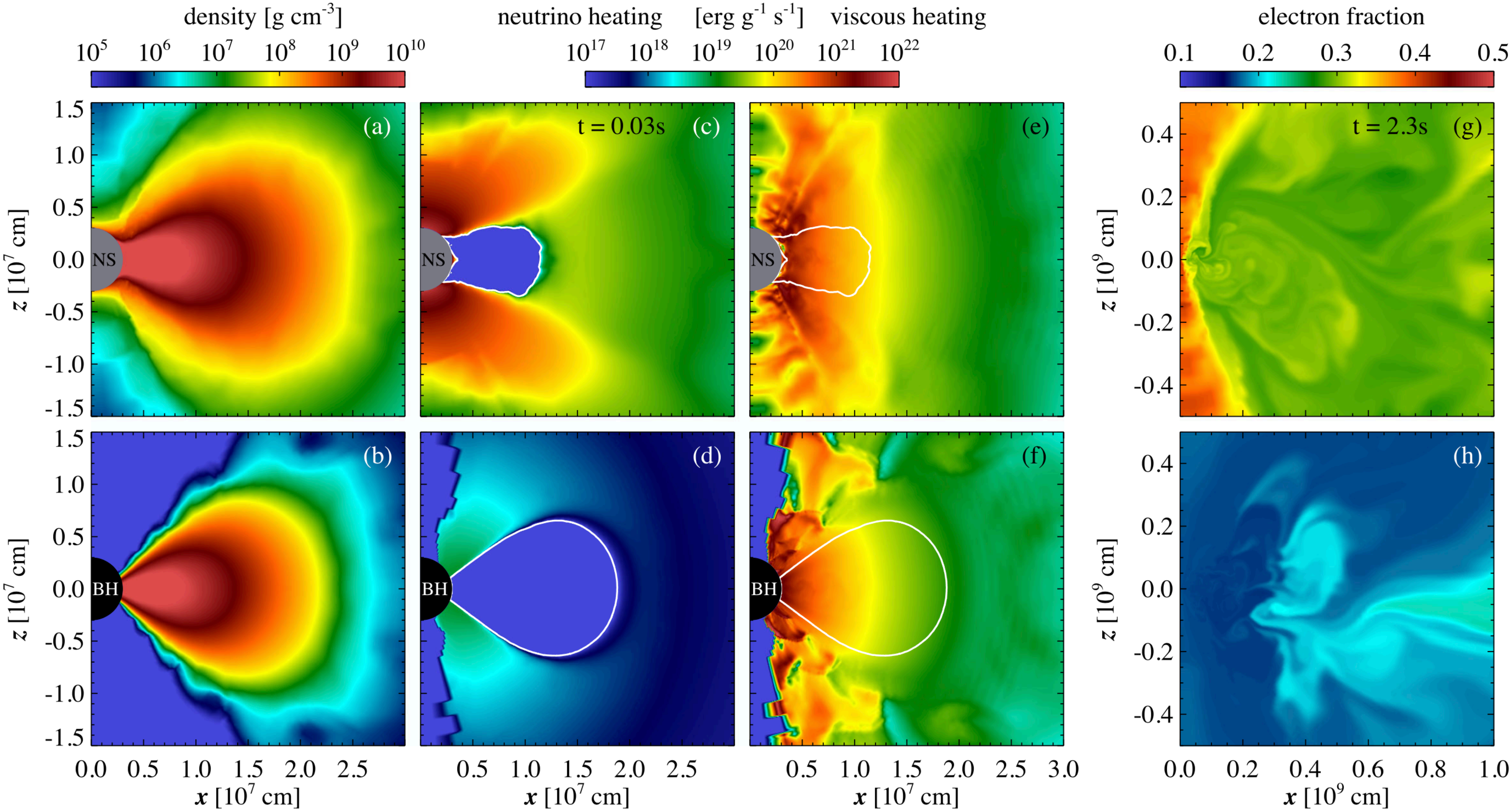
Haddadi et al. (2023)

Setiawan et al. (2006)

Lee, Ramirez-Ruiz, & Lopez-Camara (2009)

Metzger (2009)

Hypermassive NS versus BH



Metzger & RF (2014)

See also: Dessart+ (2009) Martin+ (2015) Moesta+ (2020)

Perego+ (2014) Fujibayashi+ (2017,2018) Ciolfi+ (2020)

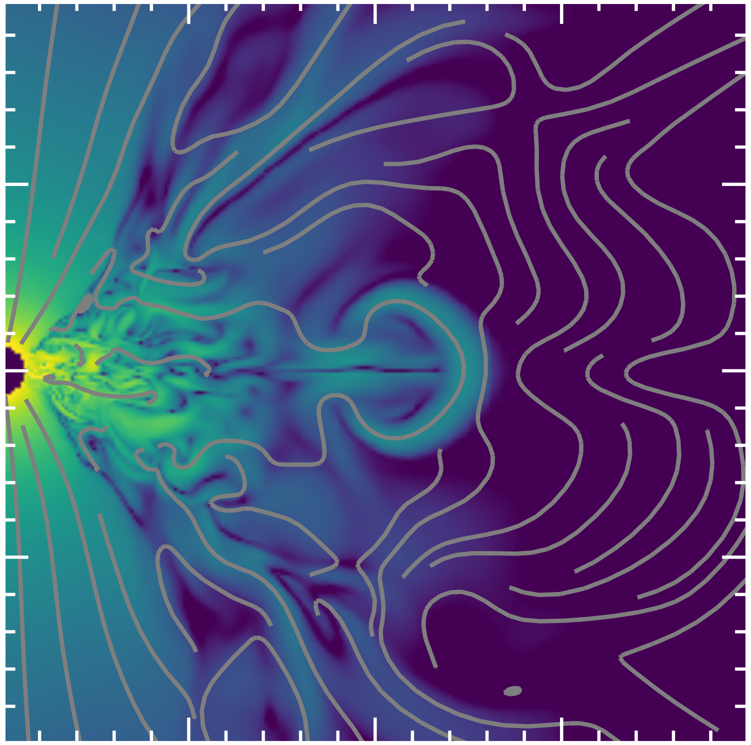
Disk Evolution in GRMHD

Must be done in 3D and with sufficient spatial resolution to capture the MRI. Computationally expensive, but metric can be taken as fixed, so cheaper than numerical relativity.

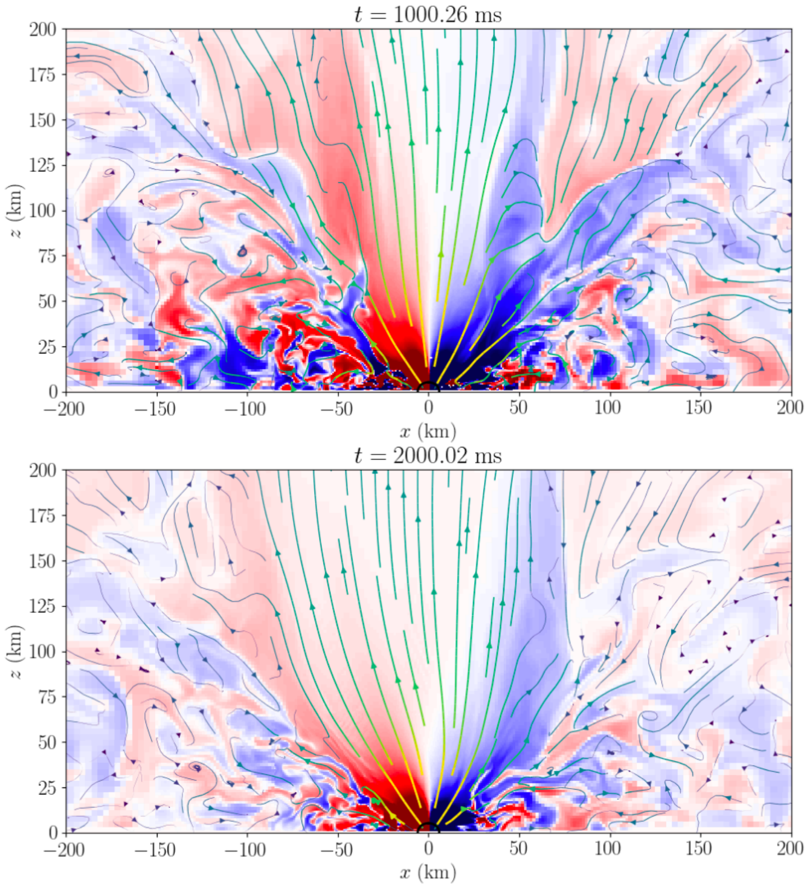
Several groups have carried out GRMHD simulations of accretion disks starting from equilibrium initial conditions, or mapped from a hydrodynamic merger simulation but with an equilibrium initial magnetic field.

Siegel & Metzger (2017), RF et al. (2019), Miller et al. (2019), Just et al. (2022)

More recently: ab-initio simulations of magnetized BHNS and NSNS mergers.



RF et al. (2019)



Hayashi et al. (2022)

GRMHD: poloidal, toroidal & hydro

	Model Name	$M_{\rm ejec}$		$\langle v_r \rangle$	$\langle Y_{\rm e} \rangle$
		(%)	$(10^{-2}\ M_{\odot})$		
GRMHD	BPS	40	1.3	0.18	0.16
	BPW	30	0.99	0.08	0.19
	BT	27	0.89	0.05	0.18
Hydro	$\alpha = 0.1$	22	0.67	0.05	0.17
	$\alpha = 0.03$	21	0.63	0.03	0.20
	$\alpha = 0.01$	16	0.48	0.03	0.26

Main caveat: Ye set only by neutrino cooling

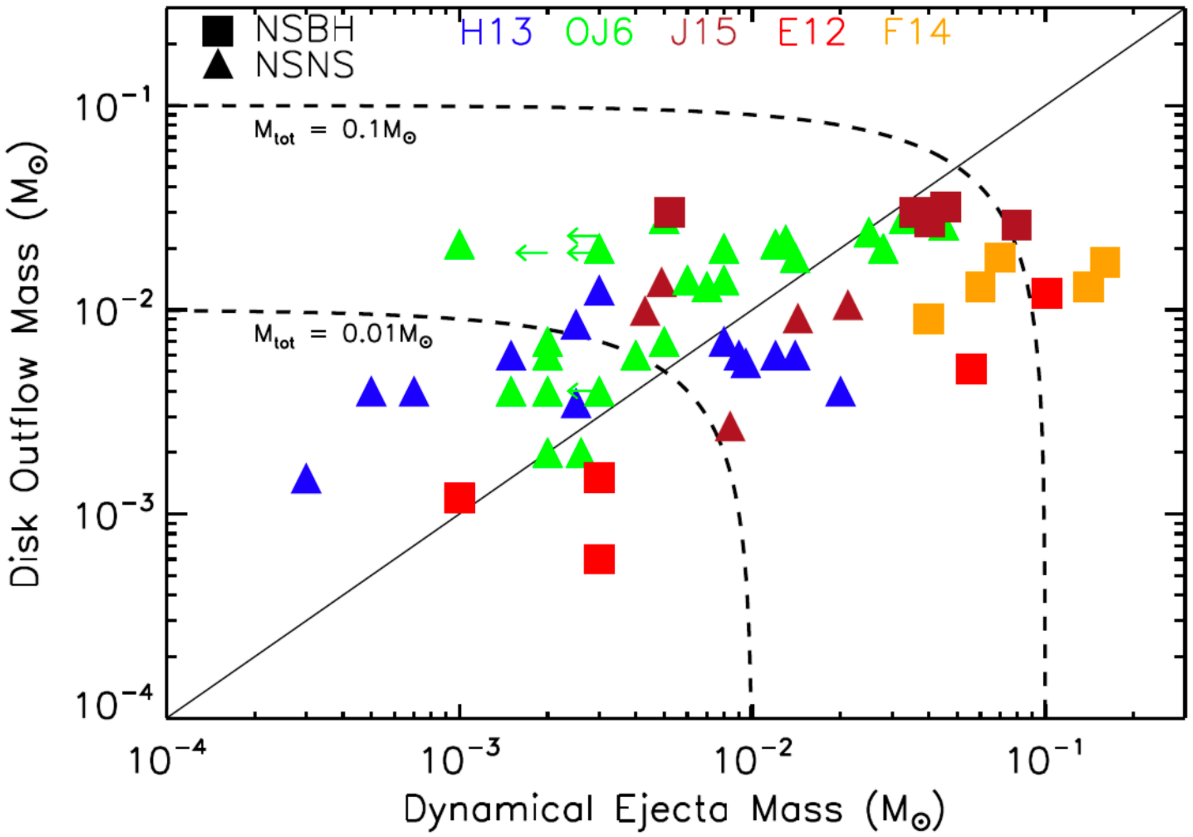
RF et al. (2019)

Christie, Lalakos, Tchekhovsoy, RF+ (2019)

Comparison with Dynamical Ejecta

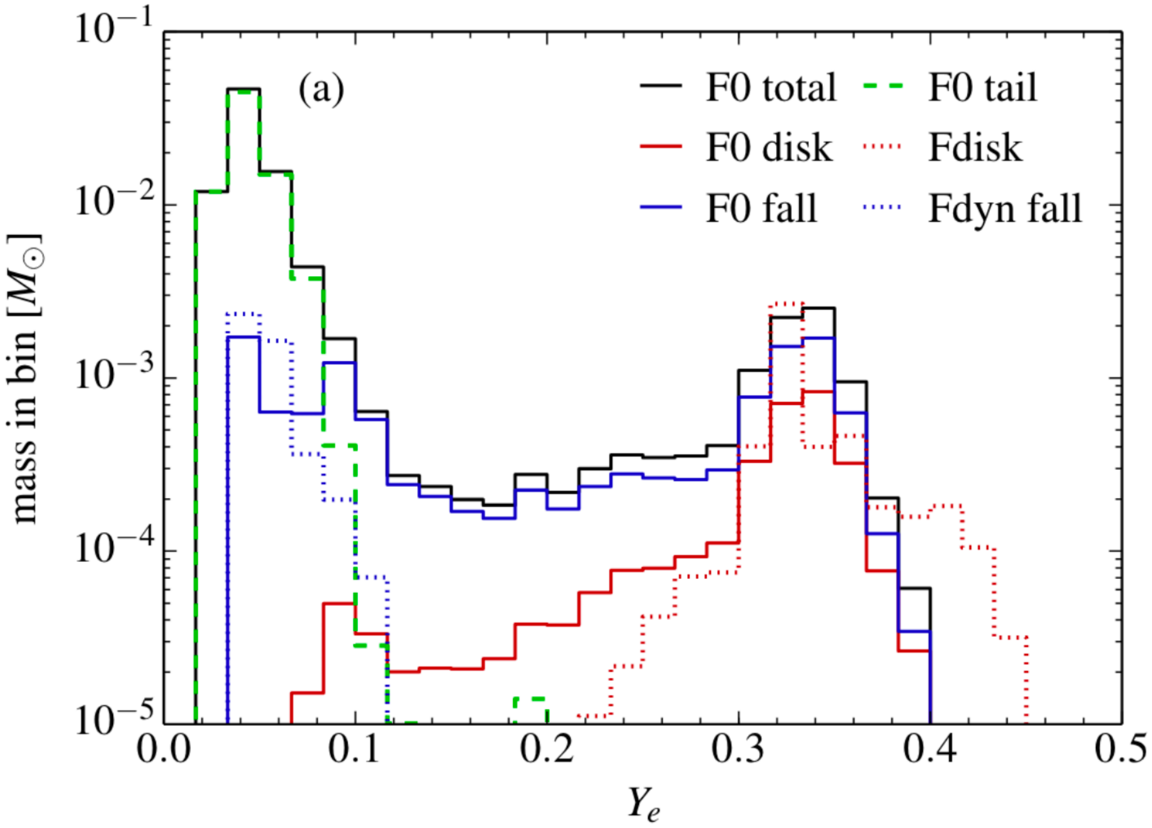
The amount of mass ejected in the disk outflow vs dynamical ejecta depends on the binary properties. For GW170817, the ejecta was most likely dominated by the disk.

e.g., Shibata et al. (2017), Radice et al. (2020)



Wu et al. (2016)

The disk outflow ejecta is in general less neutron rich and slower than the dynamical ejecta, although distinction is not sharp.



RF et al. (2017)