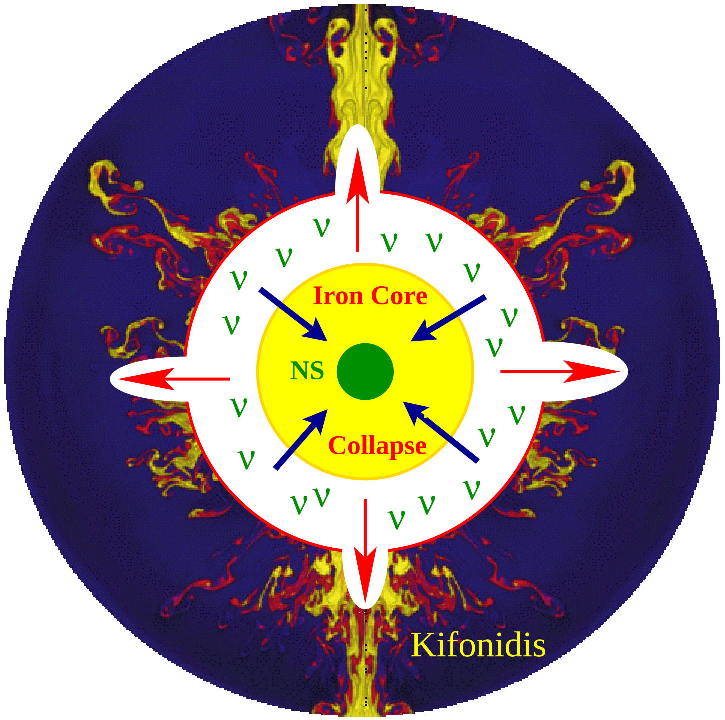
EXPLOSION MECHANISMS

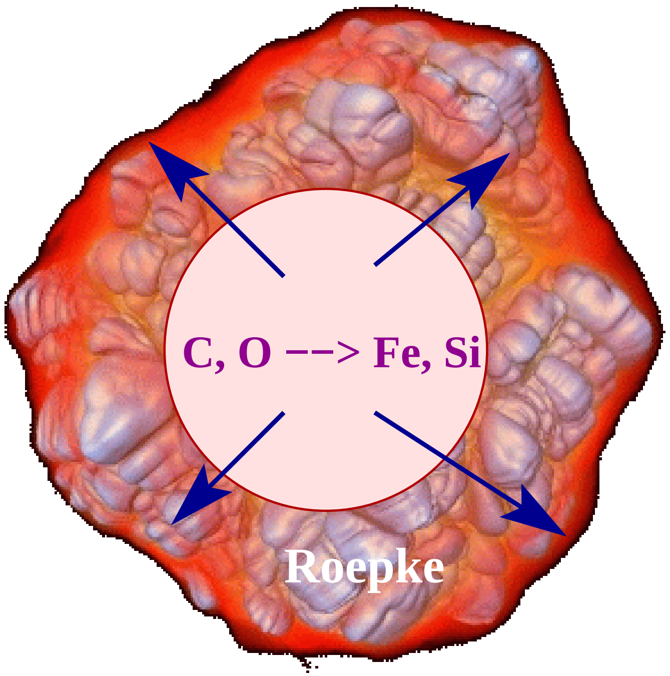
- two main, completely different mechanisms

Core-Collapse Supernovae



- triggered after the exhaustion of nuclear fuel in the core of a massive star, if the iron core mass > Chandrasekhar mass
- energy source is gravitational energy from the collapsing core ($\sim 10\,\%$ of neutron star rest mass $\sim 3 \times 10^{46}$ J)
- most of the energy comes out in neutrinos (SN 1987A!)
  - ▷ unsolved problem: how is some of the neutrino energy deposited ($\sim 1\,\%$, 10^{44} J) in the envelope to eject the envelope and produce the supernova?
- leaves compact remnant (neutron star/black hole)

Thermonuclear Explosions



- occurs in accreting carbon/oxygen white dwarf when it reaches the Chandrasekhar mass
  - → carbon ignited under degenerate conditions: nuclear burning raises T, but not P
  - → thermonuclear runaway
  - → incineration and complete destruction of the star
- energy source is nuclear energy (10^{44} ergs)
- no compact remnant expected
- main producer of iron
- standard candle (Hubble constant, acceleration of Universe?)

but: progenitor evolution not understood

- ▹ single-degenerate channel: accretion from non-degenerate companion
- ▹ double-degenerate channel: merger of two CO white dwarfs

Supernova Classification

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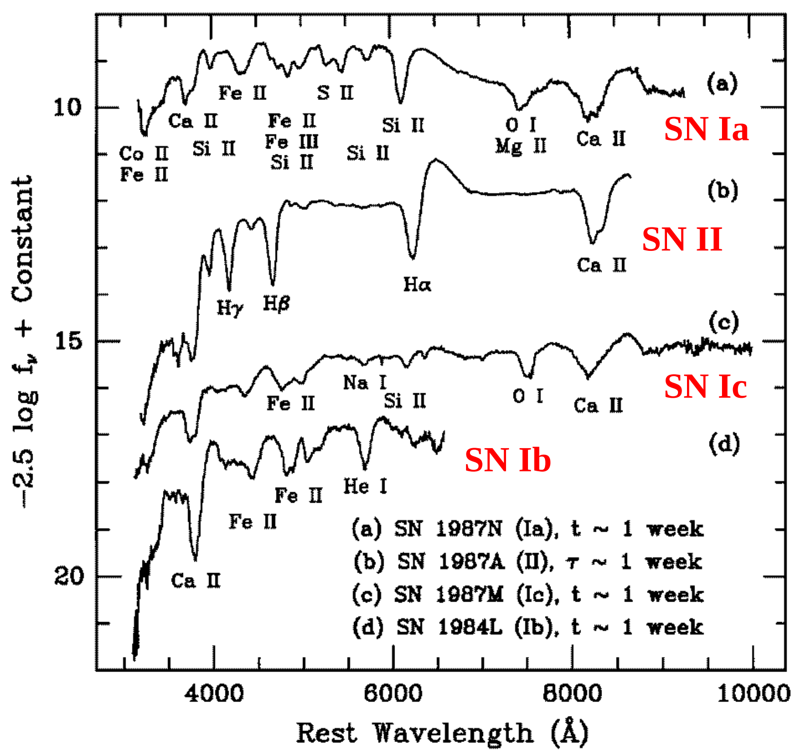


SUPERNOVA CLASSIFICATION

observational:

- Type I: no hydrogen lines in spectrum
- Type II: hydrogen lines in spectrum

theoretical:

- thermonuclear explosion of degenerate core
- core collapse → neutron star/black hole

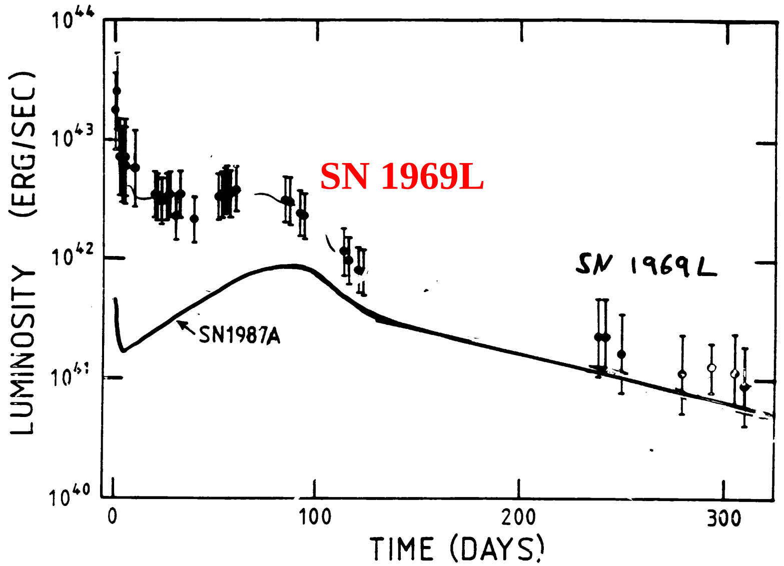
relation no longer 1 to 1 → confusion

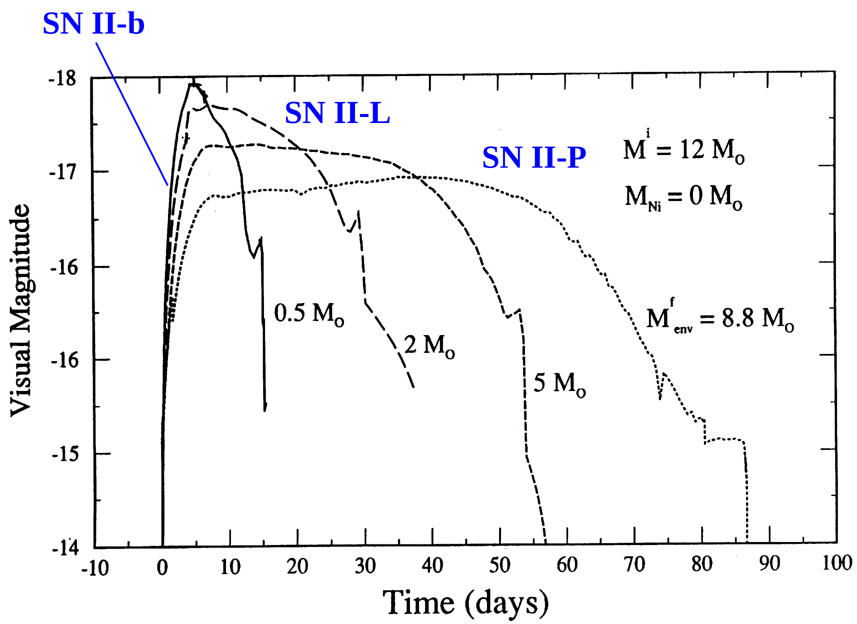
- Type Ia (Si lines): thermonuclear explosion of white dwarf
- Type Ib/Ic (no Si; He or no He): core collapse of He star
- Type II-P: "classical" core collapse of a massive star with hydrogen envelope
- Type II-L: supernova with linear lightcurve (thermonuclear explosion of intermediate-mass star? probably not!)

complications:

- special supernovae like SN 1987A
- Type IIb: supernovae that change type, SN 1993J (Type II → Type Ib)
- some supernova "types" (e.g., IIn) occur for both explosion types ("phenomenon", not type; also see SNe Ic)
- new types: thermonuclear explosion of He star (Type Iab?)

Supernova lightcurves (core collapse)





Hsu, Ross, Joss, P.

LIGHTCURVES OF CORE-COLLAPSE SUPERNOVAE

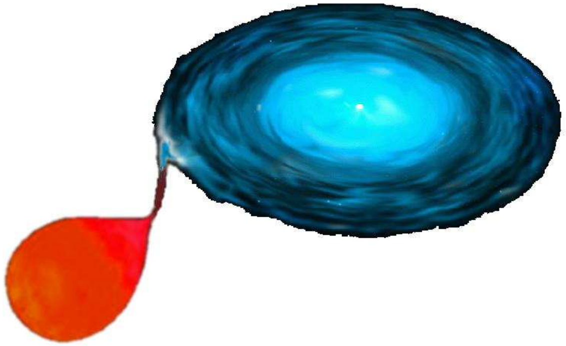
- central explosion may be very similar in all cases (with $E \sim 10^{44}$ J)
- variation of lightcurves/supernova subtypes mainly due to varying envelope properties
  - ▷ envelope mass: determines thermal diffusion time and length/existence of plateau
  - ▷ envelope radius: more compact progenitor → more expansion work required → dimmer supernova
- binary interactions mainly affect stellar envelopes
- a large fraction of all stars are in interacting binaries

→ binary interactions are, at least in part, responsible for the large variety of supernova (sub-)types

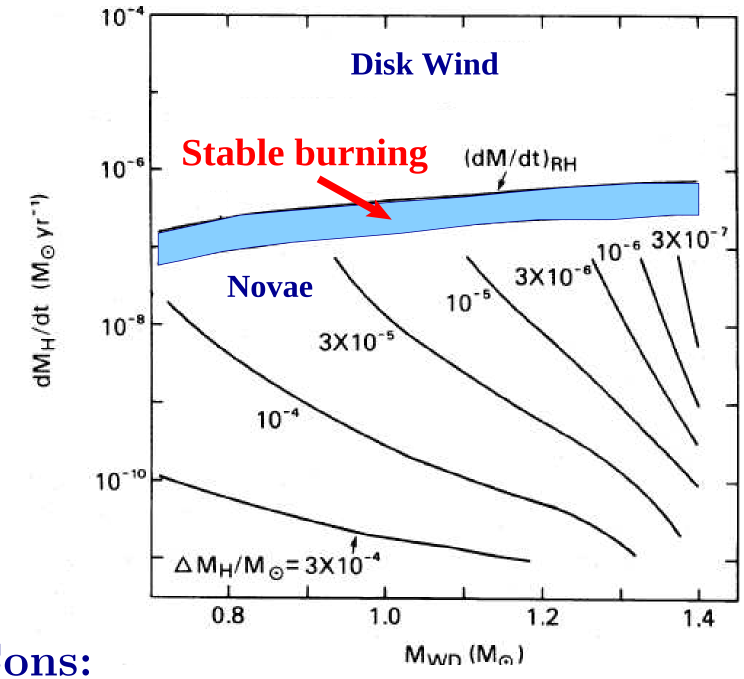
The Progenitors of Type Ia Supernovae

- SNe Ia are thermonuclear explosions in CO white dwarfs approaching the Chandrasekhar mass
- typical rate: a few $10^{-3}\,\mathrm{yr}^{-1}$ (Galaxy)
- occur in young and old populations (Branch 95)
  - ▷ but: low level star formation even in many elliptical galaxies (e.g. Schawinski, Kaviraj)
  - ▷ relative ratio of young to old unclear
  - ▷ SNe Ia in old populations are systematically fainter than in young populations
- the nature of their progenitors is still not resolved
  - ▷ numerous progenitor models
  - ▷ more than one (two, three?) channels

Single-degenerate models



- accretion from non-degenerate companion (MS star, sub-/giant, He star)
- supersoft channel
  - ▷ **mass donor:** late main-sequence star, early subgiant ($M > 1.8\,M_\odot$; $P_{orb} \lesssim$ d)
- Pros:
  - ▷ observed systems (e.g. U Sco)
  - ▷ rate close to the needed rate (but binary assumptions; Yungelson)



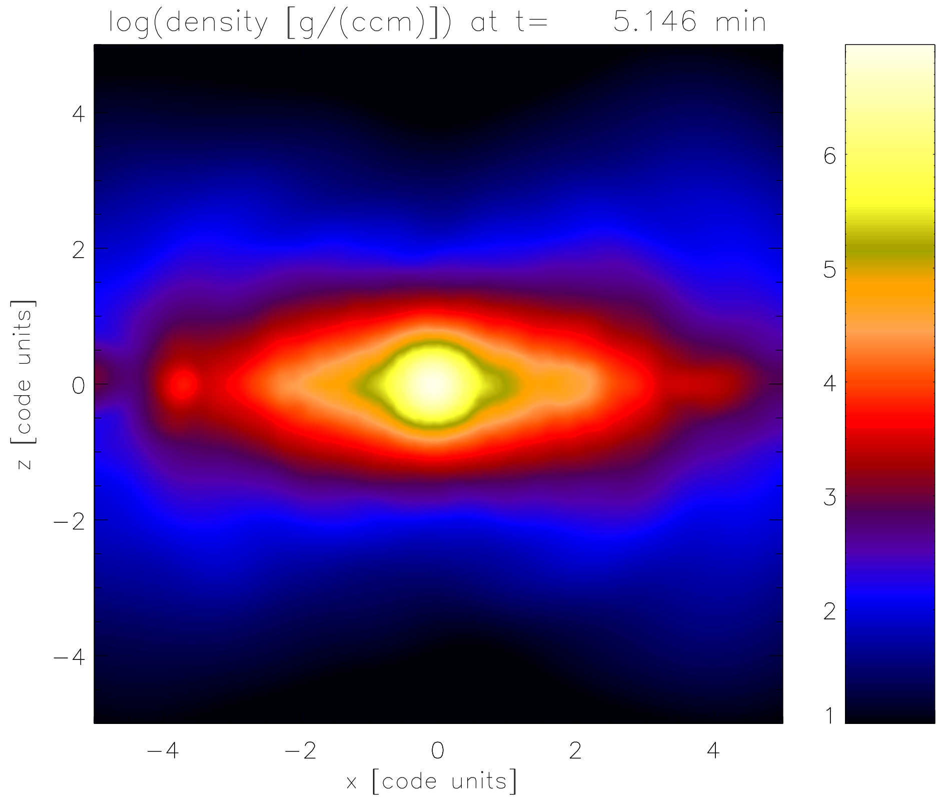
- Cons:
  - ▷ model requires fine-tuning of $\dot{M}$
  - ▷ uncertain accretion efficiency
  - ▷ supersoft channel does not produce systems with time delays $> 1.5\,$Gyr

$\rightarrow$ second channel: red-giant channel

- ▷ RS Oph prototype progenitor?

The double-degenerate (DD) channel

- two CO WDs with a combined mass $> 1.4\,M_\odot$ merge (driven by gravitational radiation)
- Pros:
  - ▷ theoretically predicted rate is high (Yungelson, Nelemans, Han, etc.)
  - ▷ probably consistent with observations of DDs (SPY [Napiwotzki])
  - ▷ can produce systems with short and long time delays
- Cons:
  - ▷ CO WD mergers are more likely to lead to core collapse (i.e. neutron stars) (Nomoto, Iben)



- but: situation presently unclear

(see Yoon et al. 2007) studied the post-merger evolution

- some DD mergers may produce SNe Ia with a time delay of 10^5 yr between the merger and the exlosion coupled to nuclear reaction networks. The electron/positron EOS has been calculated without approximations, that is, it makes no

tons as blackbody radiation. The EOS is used in tabular form with densities ranging from $10^{-10} \leqslant \rho Y_e \leqslant 10^{11}$ g cm^{-3} and temperatures

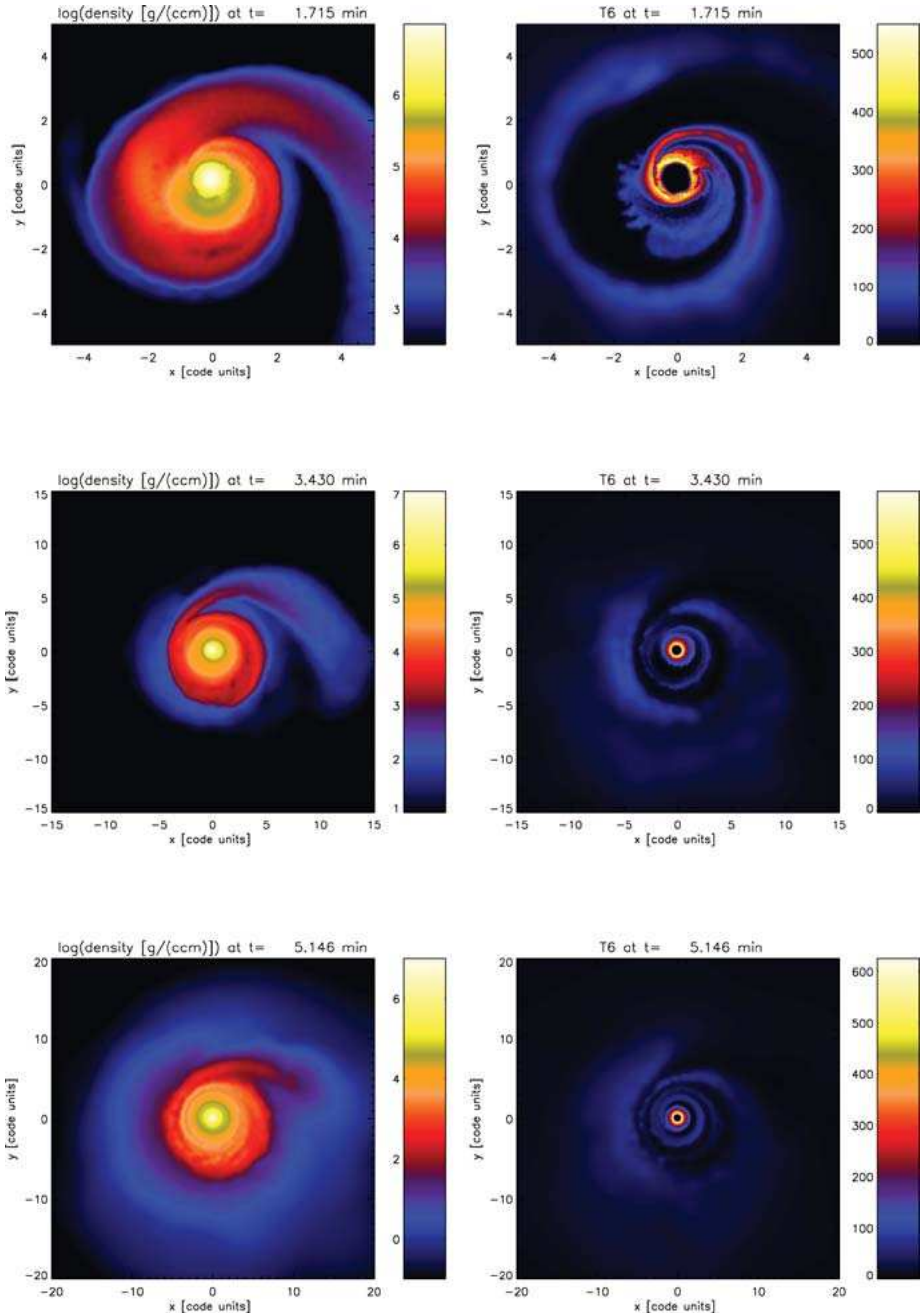


Figure 3. Dynamical evolution of the coalescence of a $0.6\,M_\odot + 0.9\,M_\odot$ CO white dwarf binary. Continued from Fig. 2.

Binary Evolution and the Final Fate of Massive Stars

Recent: binary evolution affects not only the envelope structure, but also the core evolution

- generically: after mass loss/accretion during an early evolutionary phase, a star behaves like a less/more massive star
- the core evolution is very different for stars that lose their hydrogen envelopes before helium ignition (no hydrogen burning shell during He core burning → no growth of the convective core) leading to smaller CO and finally smaller iron cores
  - ▷ stars in binaries up to at least $50/60\,M_{\odot}$ may end as neutron stars rather than as black holes (Brown, Lee, Heger, Langer)
  - ▷ black-formation without rotation → faint supernova?

Evidence for Large Supernova Birth Kicks

- **single radio pulsars have large space velocities (Lyne & Lorimer; Hobbs et al. 2005): $\sigma_v = 265\,\mathrm{km\,s^{-1}}$ without evidence for a low-velocity component**
- **some double-NS systems (DNSs) appear to require large kicks (Fryer & Kalogera 1997)**
- **PSR J0045−7319 (Kaspi et al. 1996): retrograde companion**
- **Be/X-ray binaries with large eccentricities (Verbunt, van den Heuvel, Bildsten)**

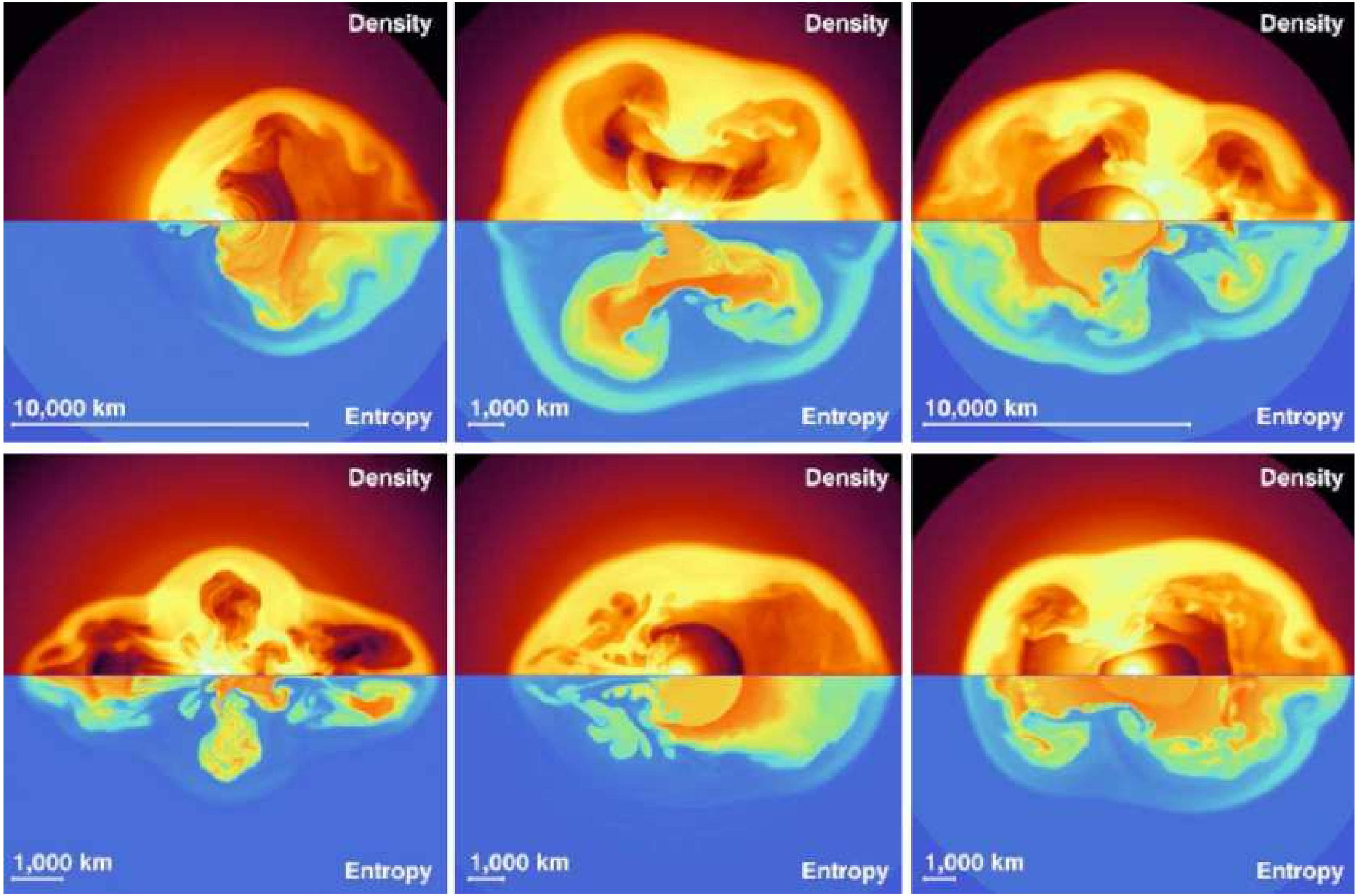
Evidence for Low Supernova Birth Kicks

- **neutron star retention in globular clusters (e.g. Pfahl, Ivanova)**
- **the existence of wide Be/X-ray binaries with low eccentricities (e.g. X Per) (Pfahl)**
- **DNSs with low eccentricities (van den Heuvel, Dewi)**
- **the spin period – eccentricity relation of DNSs (Dewi)**
- **preference for low-kick NSs in binaries?**

The origin of supernova kicks

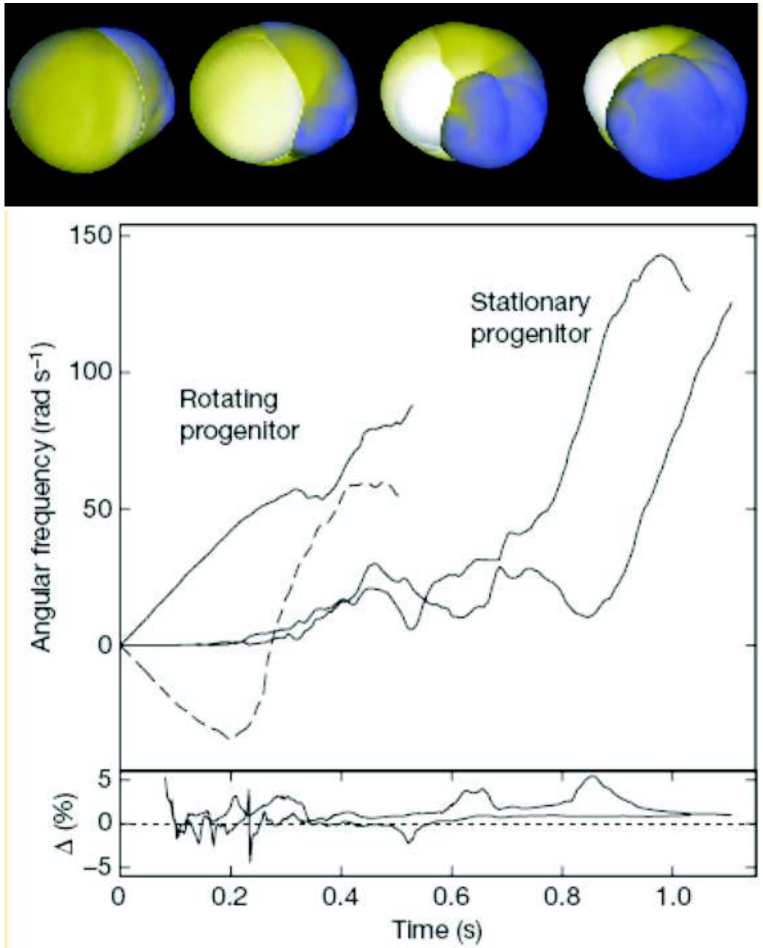
- dramatic recent progress in neutrino-driven core-collapse simulations
- supernova kicks produced by standing accretion shock instability (SASI) (Blondin, Mezzacappa, Foglizzo, Janka)
- driven by advective-acoustic instability
- $l = 1$ instability
- comes in two flavours:
  - ▷ sloshing instability ($m = 0$)
  - ▷ spiral mode ($m = \pm 1$)
- can produce kicks of a few $100\,\mathrm{km\,s^{-1}}$ if the collapse phase lasts $> 500\,\mathrm{ms}$ (many growth timescale)
- can torque the proto-NS and produce the pulsar spin ($P_{\rm spin} \sim 100 - 200\,\mathrm{ms}$) (Blondin & Mezzacappa 2007)

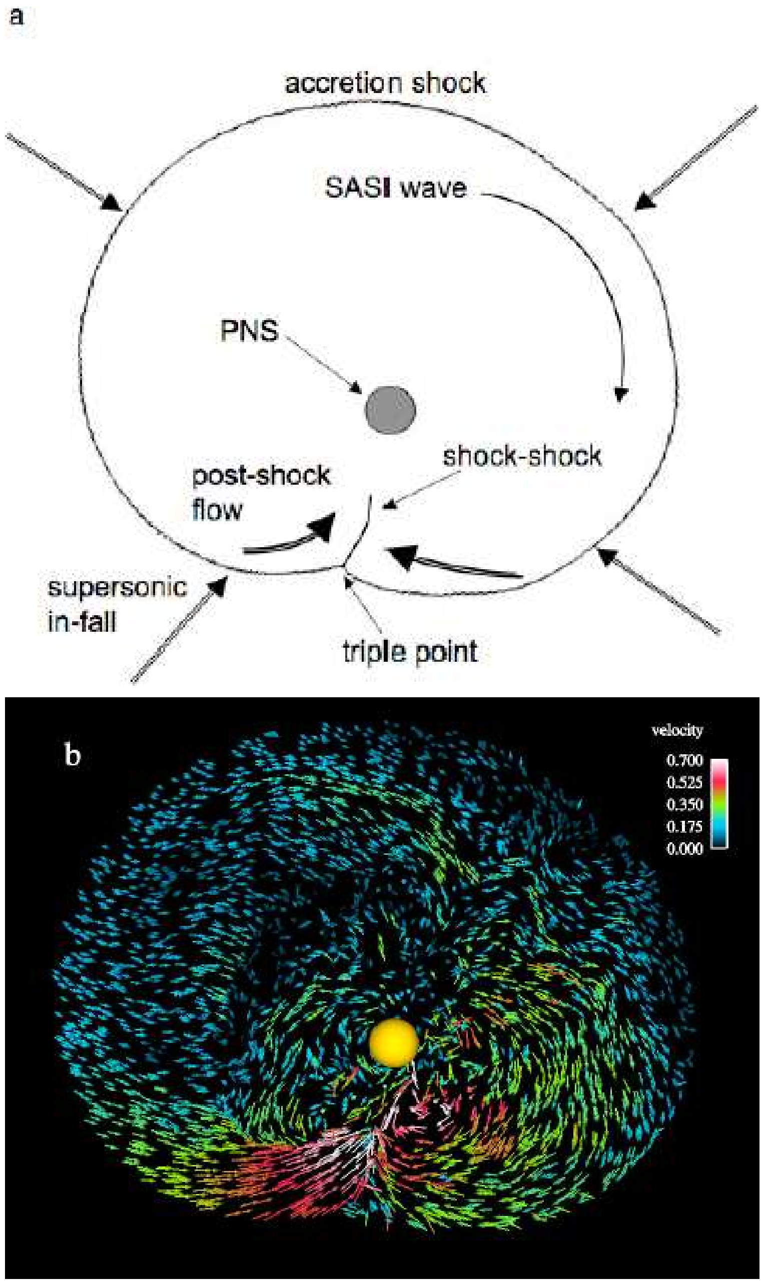
Sloshing Instability
(l = 1, m = 0)



(Janka, Scheck, Foglizzo)

Spiral Mode
($l = 1$, $m = \pm 1$)
(Blondin, Mezzacappa)

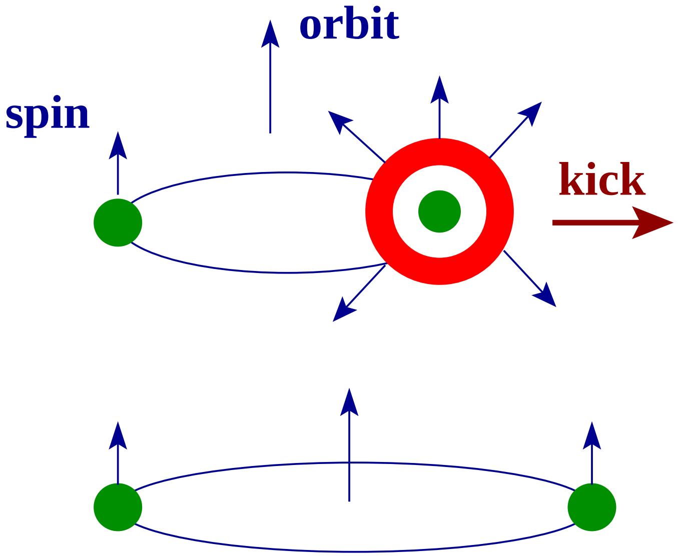




Kicks and Binary Orbits

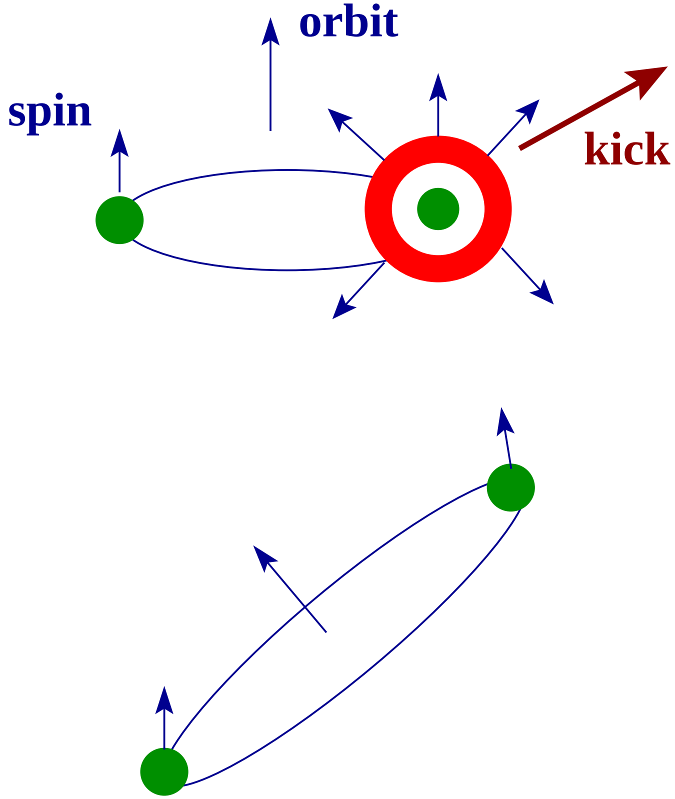
Blaauw Kick

- only due to supernova mass loss



- orbit increases
- spin + orbit remain aligned
- disruption if more than half the mass is lost
- system kick

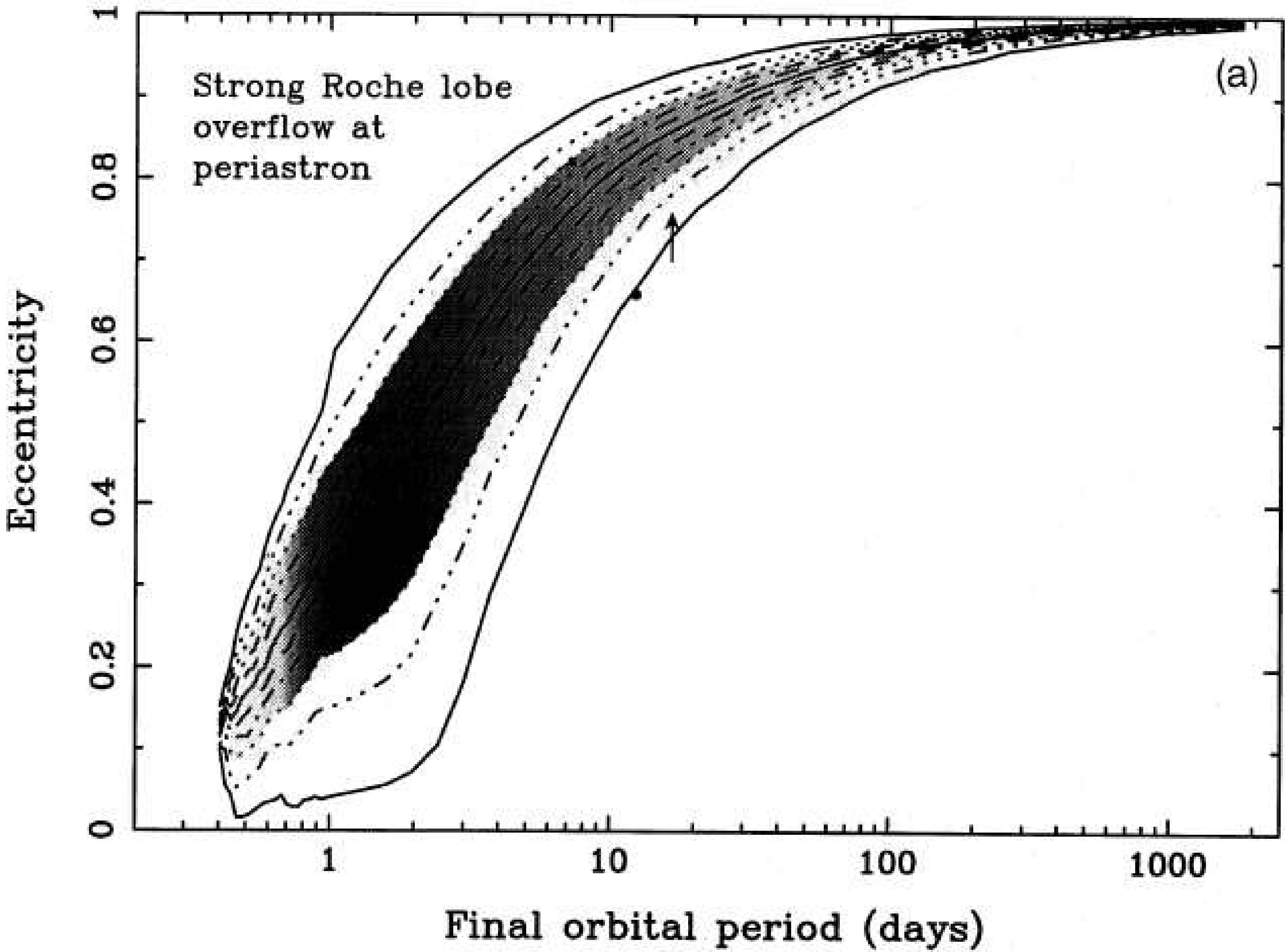
Asymmetric Explosion



- orbit increases or decreases
- spin/orbit misalignment (retrograde orbits possible)
- system can remain bound that could not otherwise

Note: if kick along spin axis → retrograde orbits impossible

- system kick

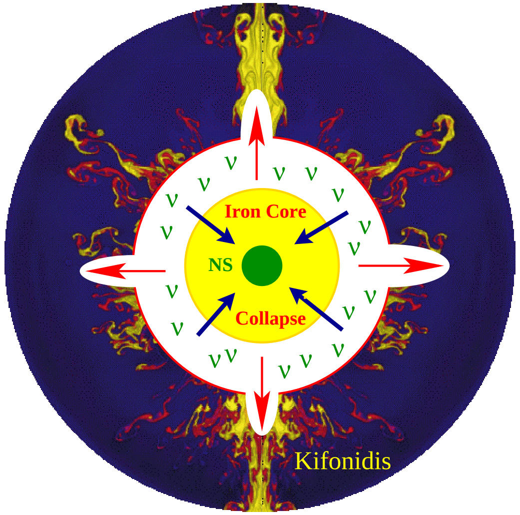


Brandt & Podsiadlowski (1995)

Neutron Star Formation Channels

Iron core collapse

- inert iron core ($> M_{Ch}$) collapses
  - ▷ presently favoured model: delayed neutrino heating to drive explosion



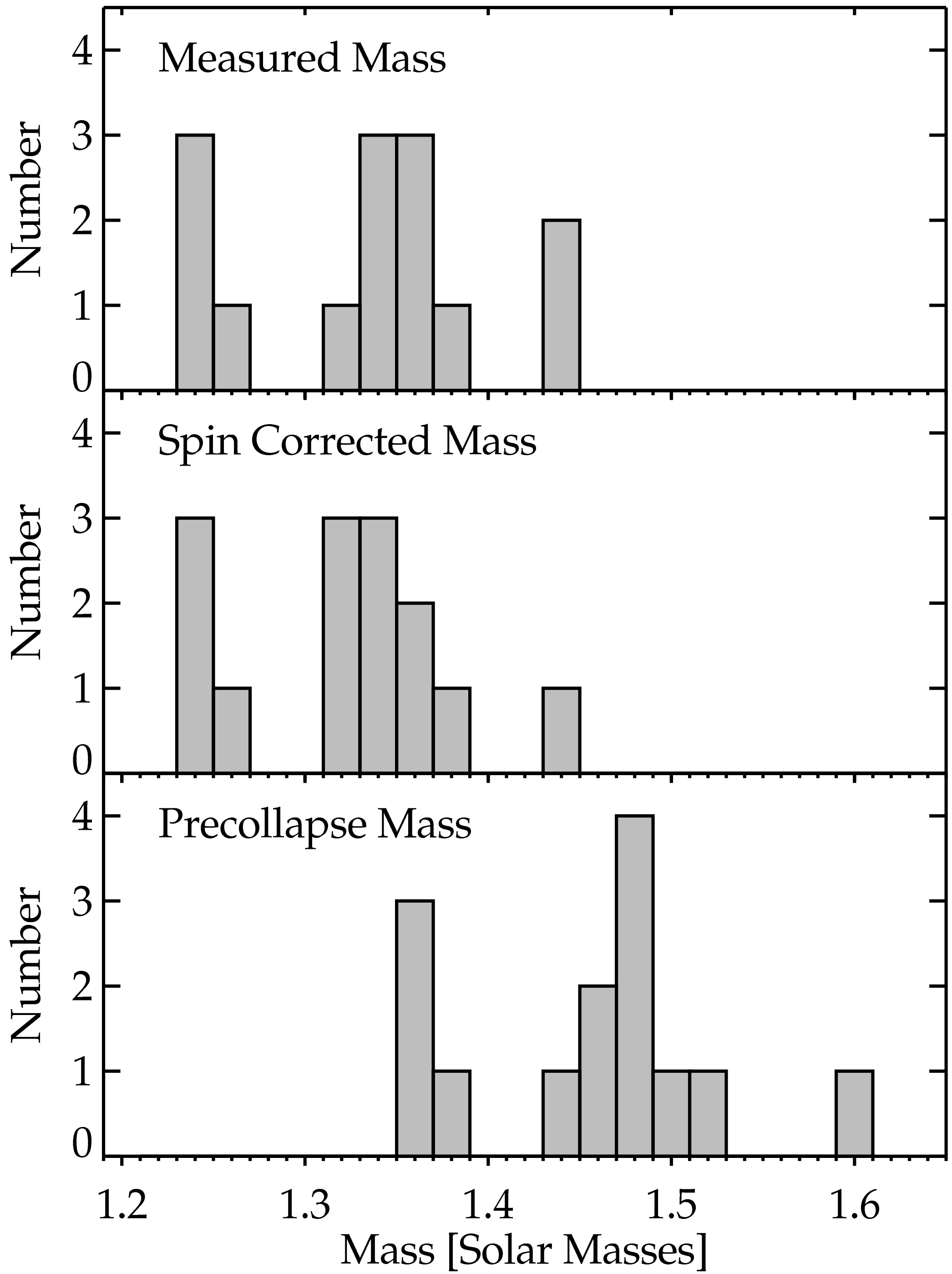
Electron-capture supernovae

- occurs in degenerate ONeMg core (preferentially in binary systems)
  - ▷ at a critical density ($4.5 \times 10^9\,\mathrm{g\,cm^{-3}}$), corresponding to a critical ONeMg core mass ($1.370 \pm 0.005\,M_\odot$), electron captures onto ^{24}Mg and ^{20}Ne removes electrons (pressure support!)

$\rightarrow$ triggers collapse to form a low-mass neutron star

note: the whole core collapses

- $\rightarrow$ easier to eject envelope/produce supernova
- $\rightarrow$ no significanct ejection of heavy elements
- $\rightarrow$ low supernova kicks? (e.g. double pulsar [PSR J0737-303])



Schwab, Podsiadlowski & Rappaport (2010)

The Final Fates of Stars

- the effects of binary evolution

	single/wide binary	close binary
CO white dwarf	$< 7\,M_\odot$	$< 7 - 17\,M_\odot$
ONeMg white dwarf	$7 - 10\,M_\odot$	$7 - 8\,M_\odot$
Neutron star:		
electron-capture	$\sim 10\,M_\odot$	$7/8 - 10\,M_\odot$
iron core collapse	$10 - 20/25\,M_\odot$	$10 - 50/60\,M_\odot$
Black hole:		
two-step	$20/25 - 40(?)\,M_\odot$	$> 50/60\,M_\odot$
prompt	$> 40\,M_\odot(?)$	
no remnant (Z?)	$> 140\,M_\odot$	

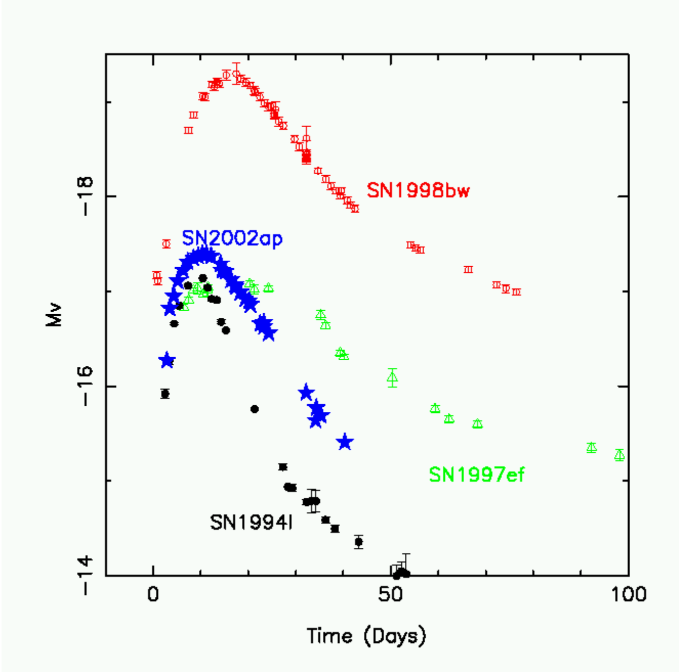
Note: (wide binary includes Case C mass transfer)

- the effects of metallicity
  - ▷ affects mass loss and compactness → supernova appearance (lower metallicity stars have less mass loss and are more compact)
  - ▷ affects core evolution (e.g. importance of CNO burning) and final core structure
  - ▷ example: the core structure of a $5\,M_\odot$ ($Z = 0.001$) is similar to the core structure of a $7\,M_\odot$ ($Z = 0.02$) star

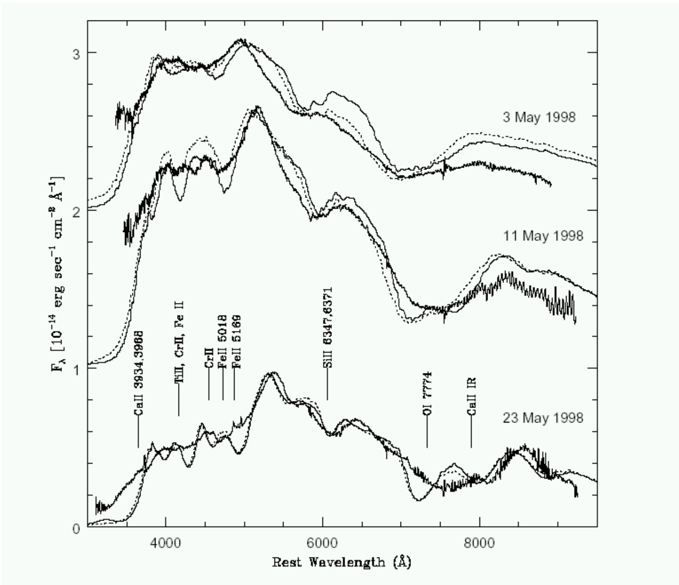
Hypernovae, Collapsars and GRBs

- a "new" explosion type?
- a more energetic supernova with a range of explosion energies: $5 - 50 \times 10^{44}$ ergs (Mazzali, Nomoto, Maeda)
- classification criterion: few broad lines → high kinetic energy → high explosion energy
- asymmetric explosions?
- some are associated with long-duration gamma-ray bursts (GRBs, SN 98bw, SN 03dh)
- possibly associated with the formation of a black hole from a rapidly rotating compact core (Woosley)

Hypernova (SN 1998bw, SN 2002ap, SN 1997ef) and (normal) Type Ic (SN 1994I) Lightcurves (Nomoto)

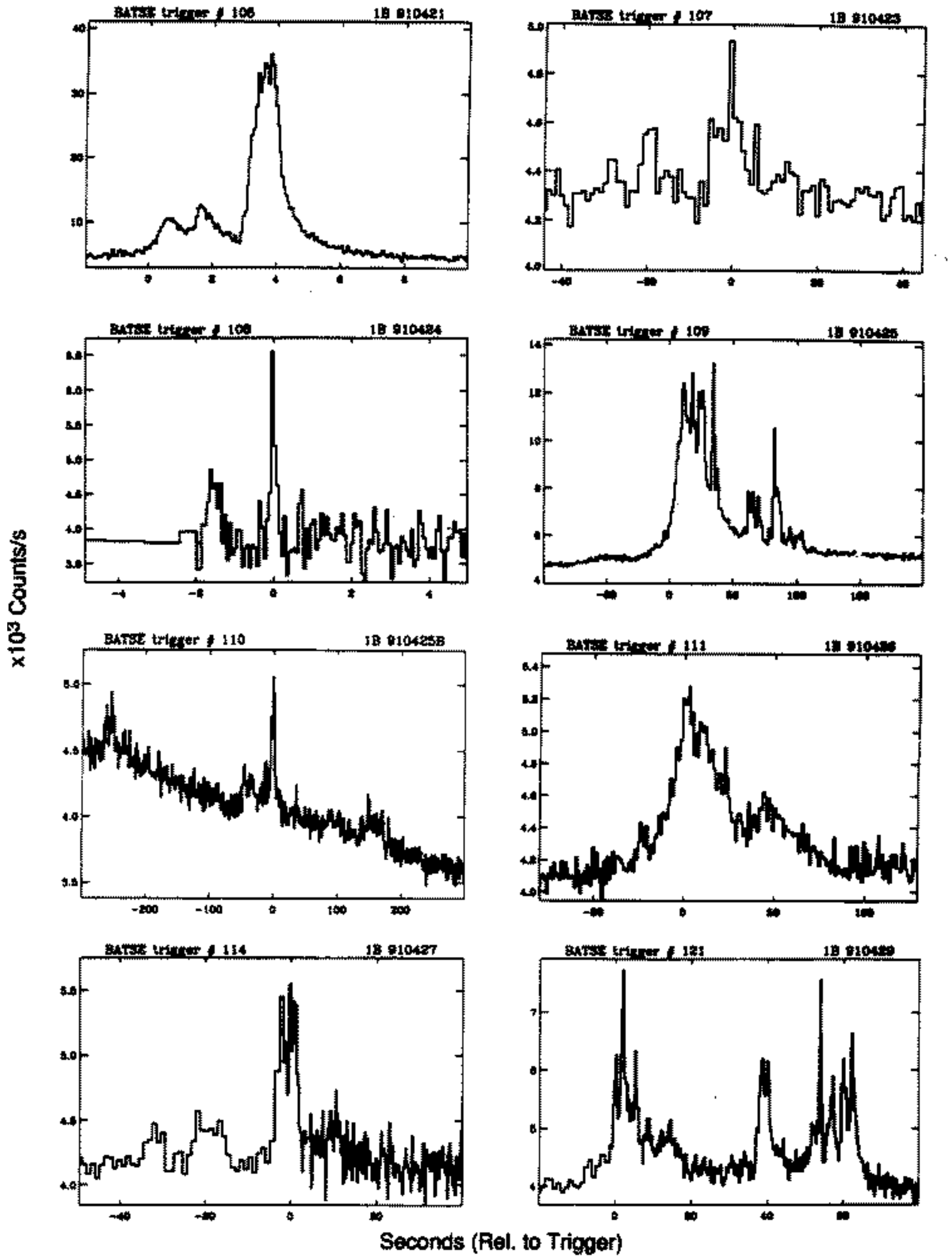


Hypernova Spectral Classification

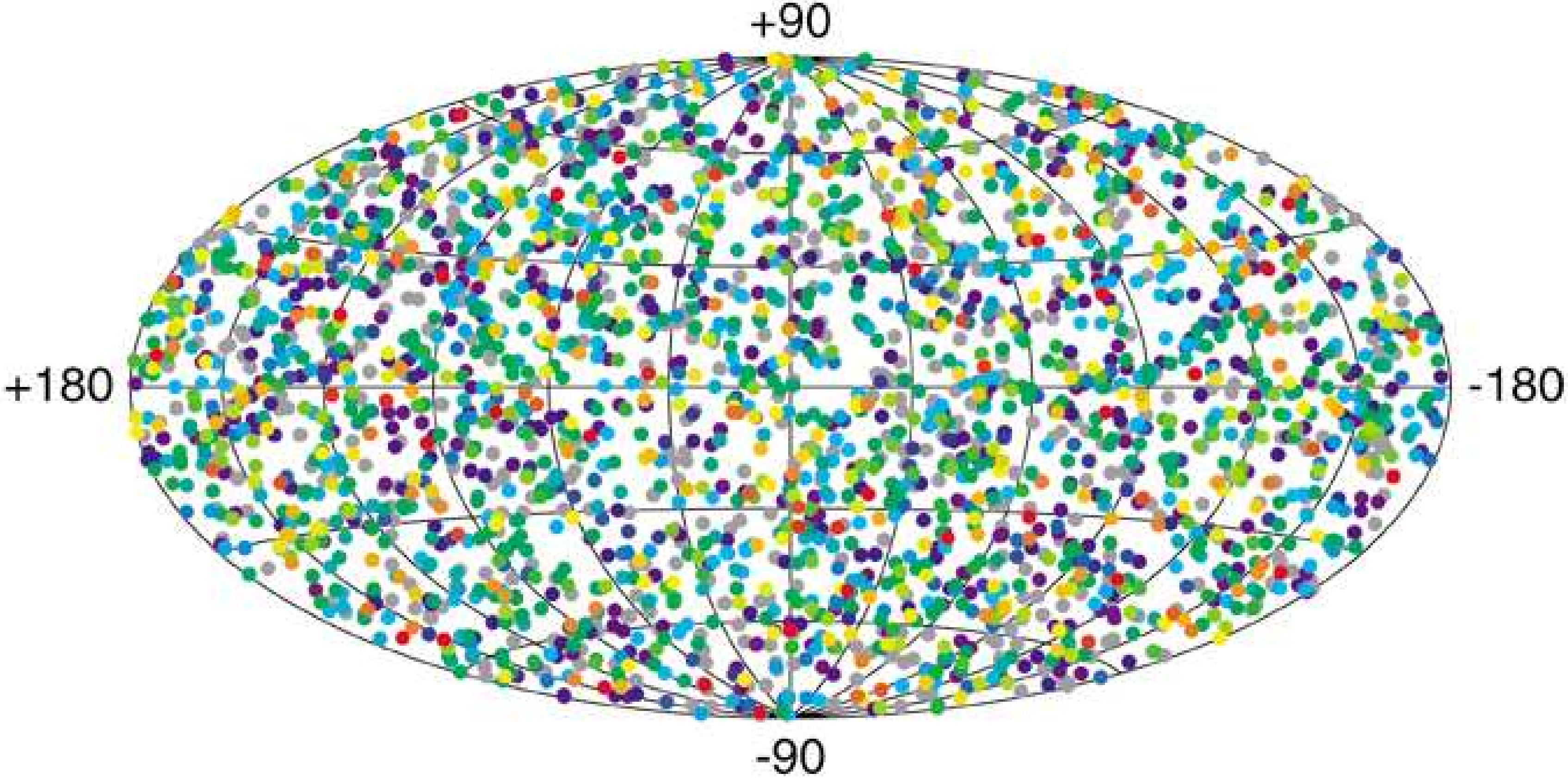


Gamma-Ray Bursts (GRBs)

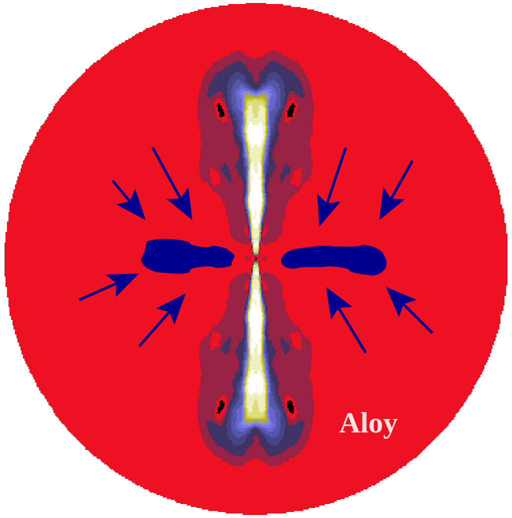
- discovered by U.S. spy satellites (1967; secret till 1973)
- have remained one of the biggest mysteries in astronomy until 1998 (isotropic sky distribution; location: solar system, Galactic halo, Universe?)
- discovery of afterglows in 1998 (X-ray, optical, etc.) with redshifted absorption lines has resolved the puzzle of the location of GRBs $\rightarrow$ GRBs are the some of the most energetic events in the Universe
- duration: 10^{-3} to $10^{3}\,$s (large variety of burst shapes)
- GRBs are no standard candles! (isotropic) energies range from 5×10^{44} to $2 \times 10^{47}\,$J and are highly beamed ($\gamma > 100$; corrected energy: $10^{44}\,$J?)
- GRBs are produced far from the source ($10^{11} - 10^{12}\,$m): interaction of outflow with surrounding medium (external or internal shocks) $\rightarrow$ fireball

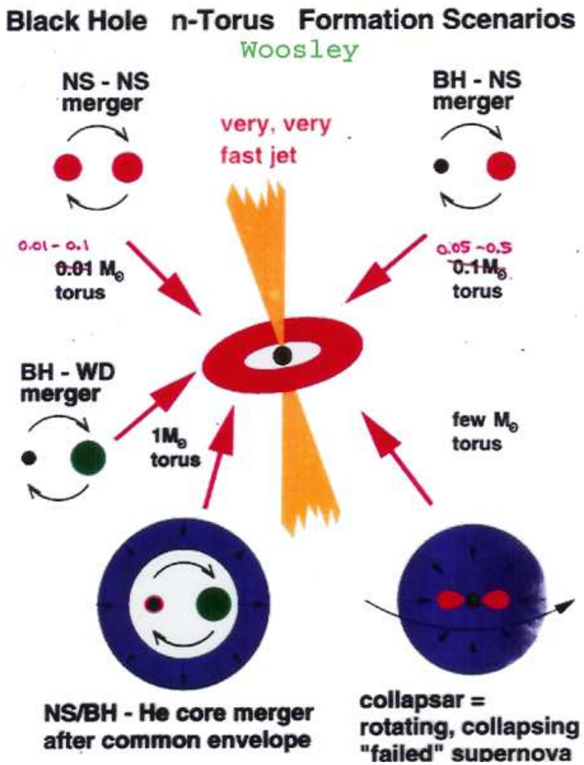


2704 BATSE Gamma-Ray Bursts



The collapsar model

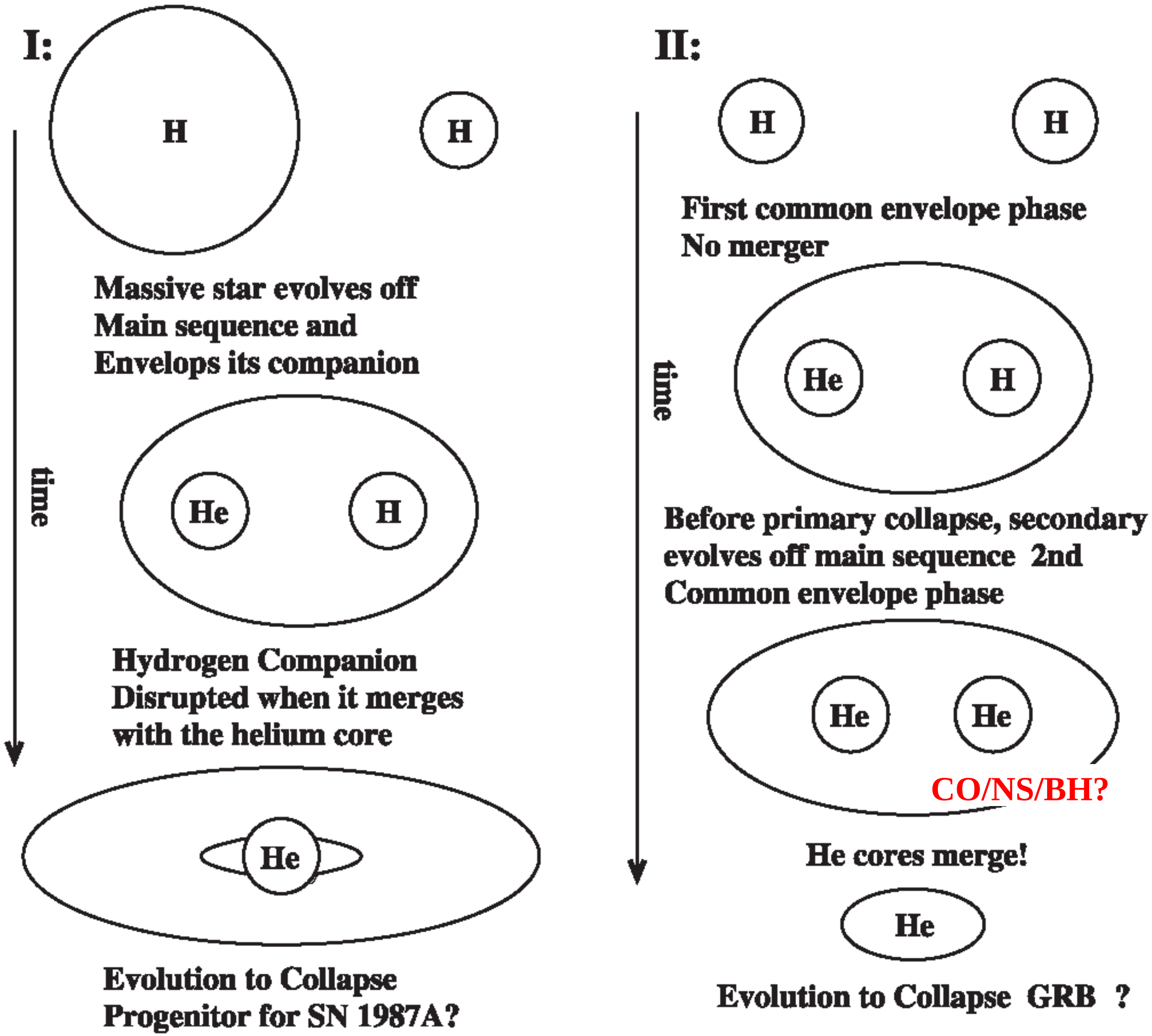




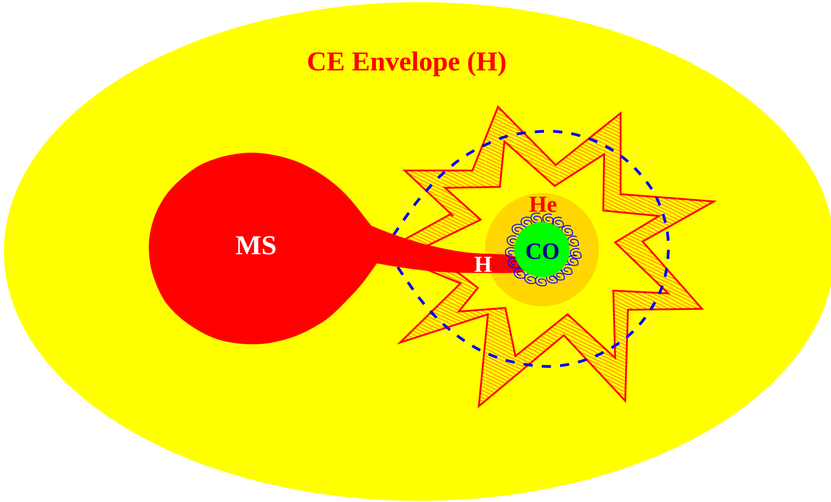
- two-step black-hole formation: neutron star, accretion from massive disk → black hole → relativistic jet → drills hole through remaining stellar envelope → escaping jet → GRB
- requires rapidly rotating He/CO star
- presently all hypernovae have been classified as SNe Ic (i.e., no H, He); only 1 in 100 Ib/Ic SNe are HNe
- HNe/GRBs are rare! ($10^{-5}\,\mathrm{yr}^{-1}$)
- single star model: homogeneous evolution with low mass loss (Yoon & Langer; Heger & Woosley)
  - ▷ requires low metallicity ($< 0.2\,Z_\odot$)
  - ▷ not consistent with observations?
- binary channels? (e.g. mergers of a He + CO core in common envelope [CE]; explosive CE ejection)

Merger Ideas

(from Fryer & Heger)



Explosive Common-Envelope Ejection

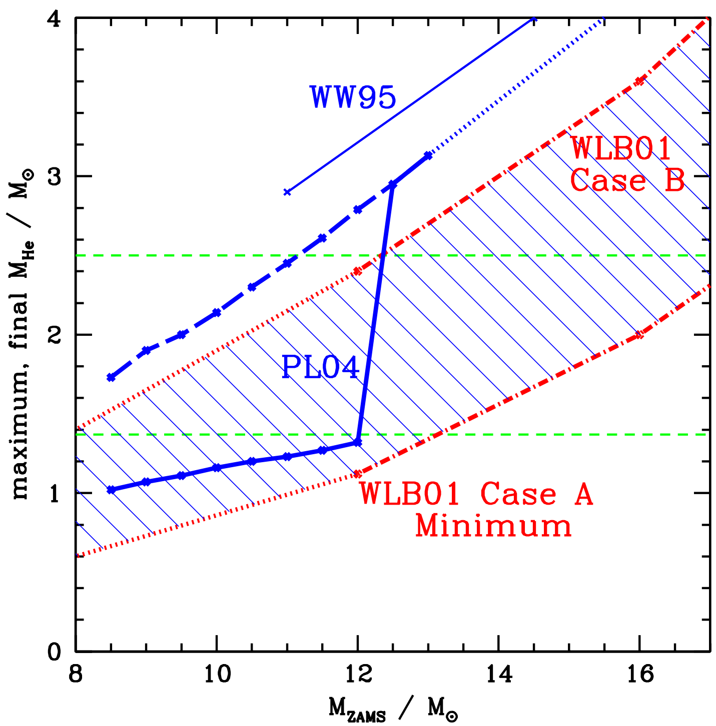


- discovered by Natasha Ivanova when studying the slow merger of massive stars
- spiralling secondary fills its Roche lobe inside common envelope (CE)
  - → mass transfer from secondary to the core of the supergiant
  - → H-rich stream penetrates helium core
- for large mass ratio:
  - → sudden mixing of H into very hot layer (few 10^8 K) → nuclear runaway (hot CNO cycle)
  - → rapid expansion of He layer and ultimate ejection of He-rich shell and rest of envelope
- energy source for CE ejection is nuclear energy (not orbital energy) → new CE ejection mechanism (application to short-period black-hole binaries, Nova Sco)
- works best for relatively low-mass companions ($\lesssim 3\,M_\odot$)

Causes of Supernova Diversity

- binarity
  - ▷ supernova appearance (mass loss/accretion, merging)
  - ▷ core structure
- metallicity
  - ▷ appearance (mass loss, compactness)
  - ▷ core evolution
- rotation/magnetic fields
  - ▷ important in early evolutionary phases (only?), e.g. through mixing (magnetic fields prevent rapidly rotating evolved cores (Spruit))
  - ▷ high rotation+low metallicity: homogeneous evolution?
- dynamical environment
  - ▷ e.g. in dense clusters → dynamical interactions → different final products (dynamical mergers → more HNe?)

Binary Evolution Effects



- dredge-up in AGB phase may prevent ONeMg core from reaching M_{crit} → ONeMg WD instead of collapse
- can be avoided if H envelope is removed by binary mass transfer

→ dichotomous kick scenario (P. et al. 2004)

  ▷ e-capture SN in close binaries → low kick

  ▷ iron core collapse → high kick

- can explain

  ▷ all single pulsars seem to have received large kicks (Hobbs, Lyne, Lorimer)

  ▷ but need low kicks in some X-ray binaries (e.g. X Per) with low eccentricity (Pfahl)

  ▷ retention of neutron stars in globular clusters (Pfahl, Ivanova, Belczyński)

  ▷ double neutron star properties (v.d. Heuvel, Dewi), specifically the double pulsar