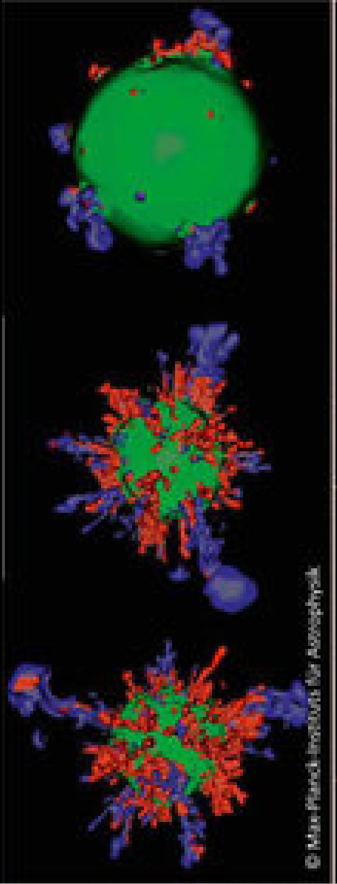

Supernovae

Michael Gabler
Max Planck Institute for Astrophysics

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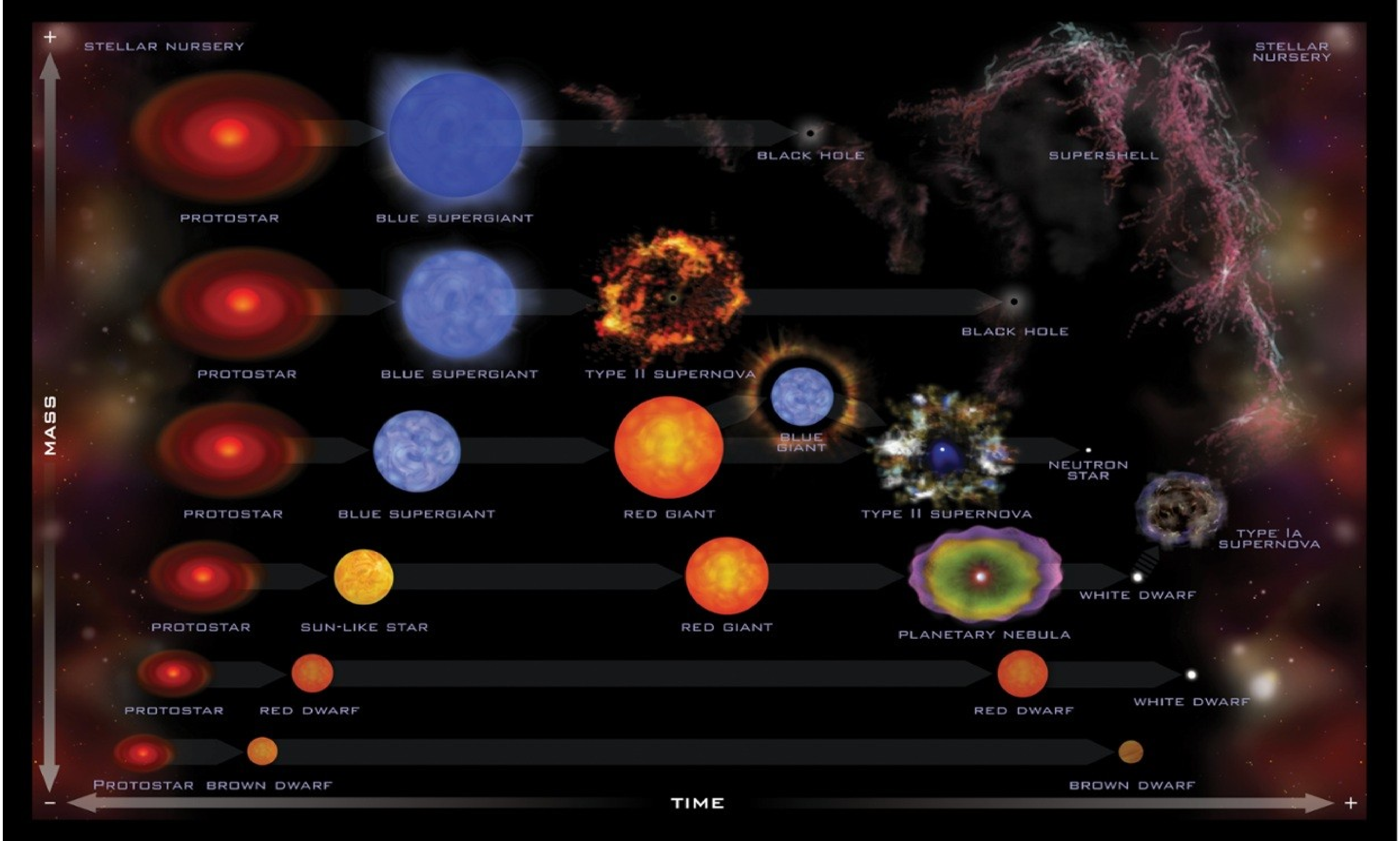
COCO2CASA


STELLAR NURSERY
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
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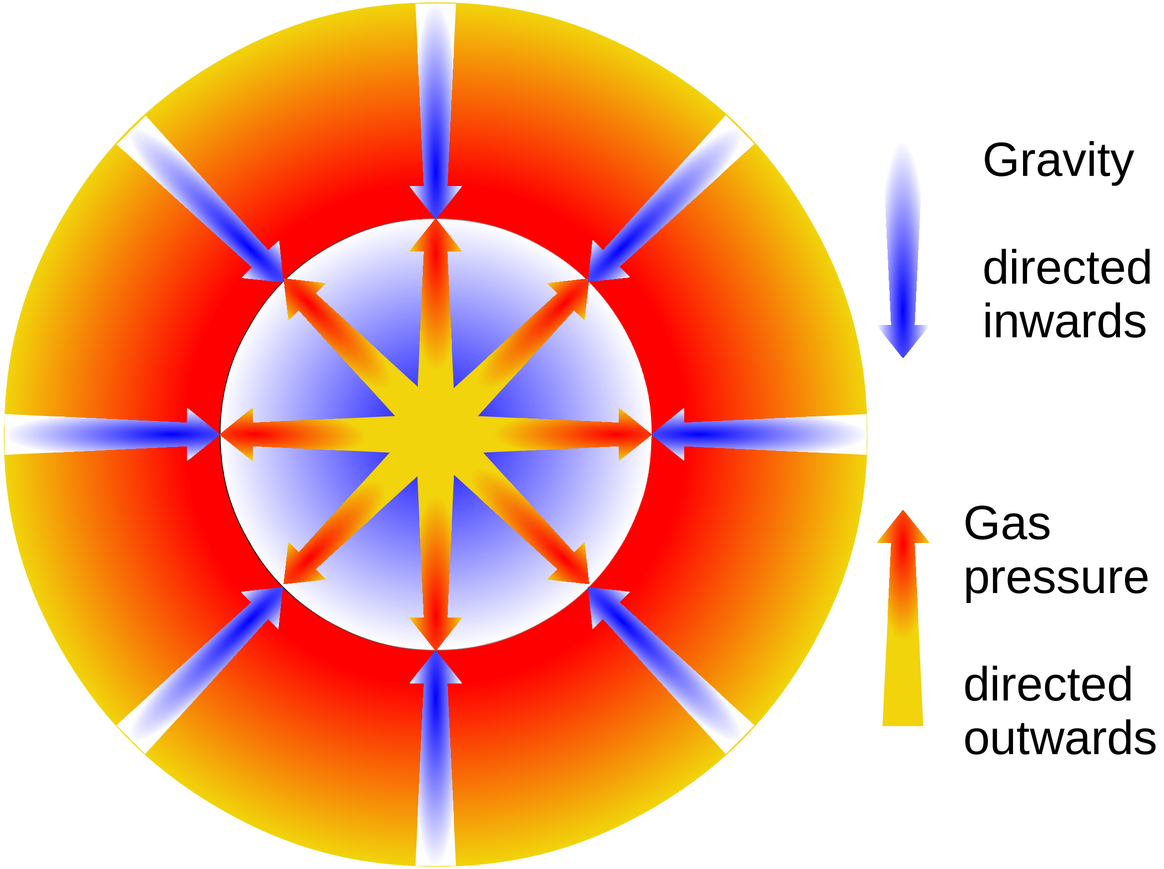
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF
MASS
TIME
+
−
+
−

Nuclear Burning in Stars

- Main sequence:
  central hydro-static H-burning
- Hydrogen and Helium fusion
- Lithium - Carbon – Neon – Oxygen – Silicon burning
- End product stable iron ^{56}Fe
- Hydrostatic equilibrium:

$$\frac{T_c^3}{\rho_c} \sim M^2$$

- More massive stars have higher T_c and can burn heavier elements

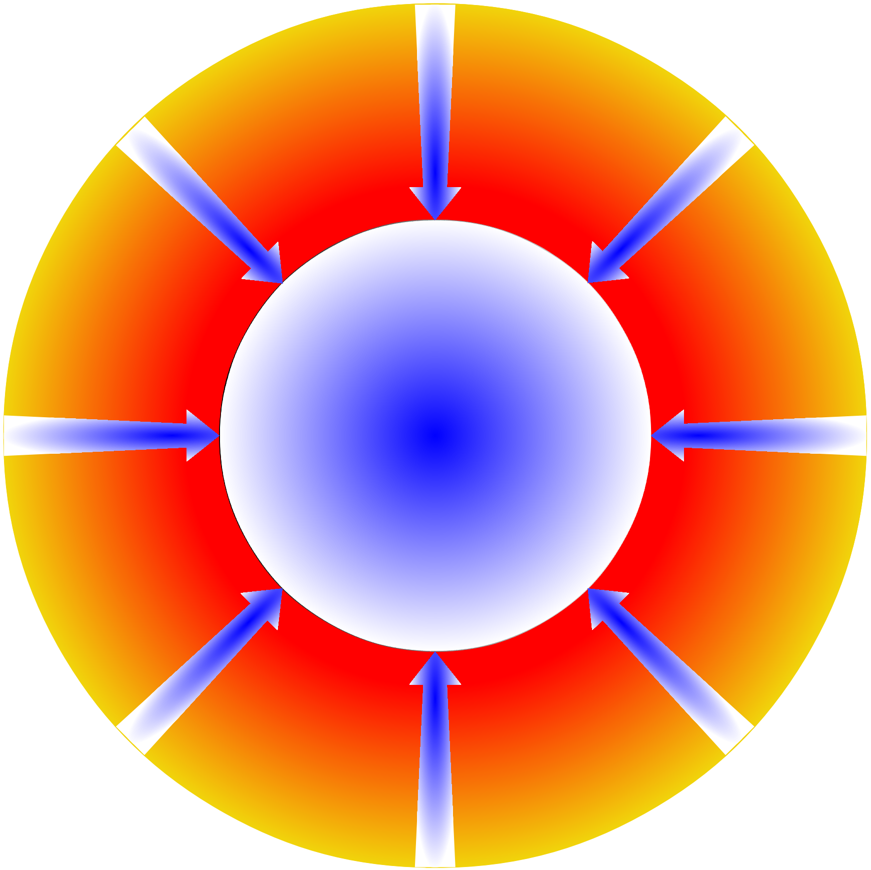


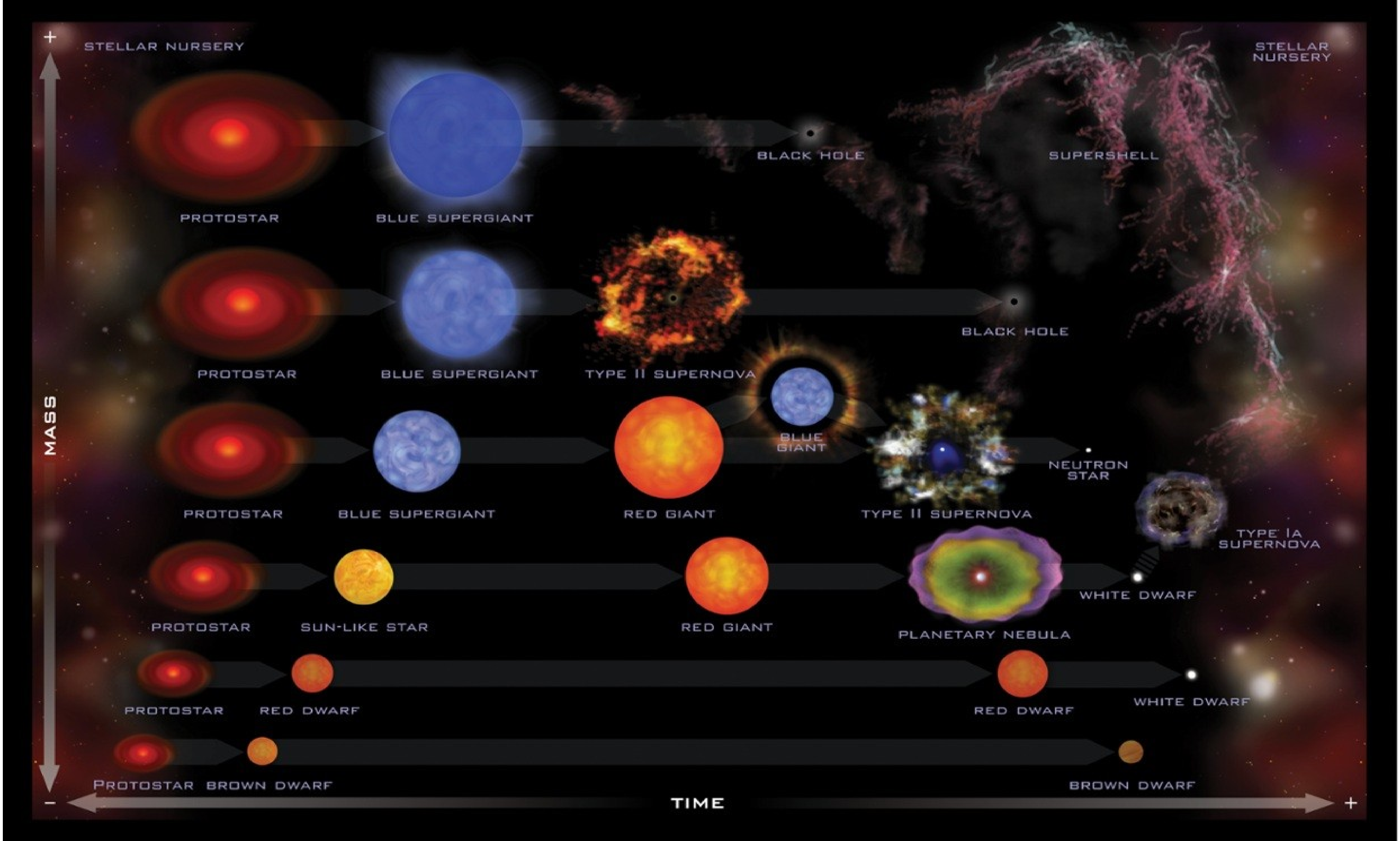
Nuclear Burning in Stars

- All fuel burned
➔ Contraction
➔ Collapse

- Contraction/Collapse halts when other source of pressure can stop it

- The final fate of the star depends on its mass

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RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF
MASS
TIME
+
–
+
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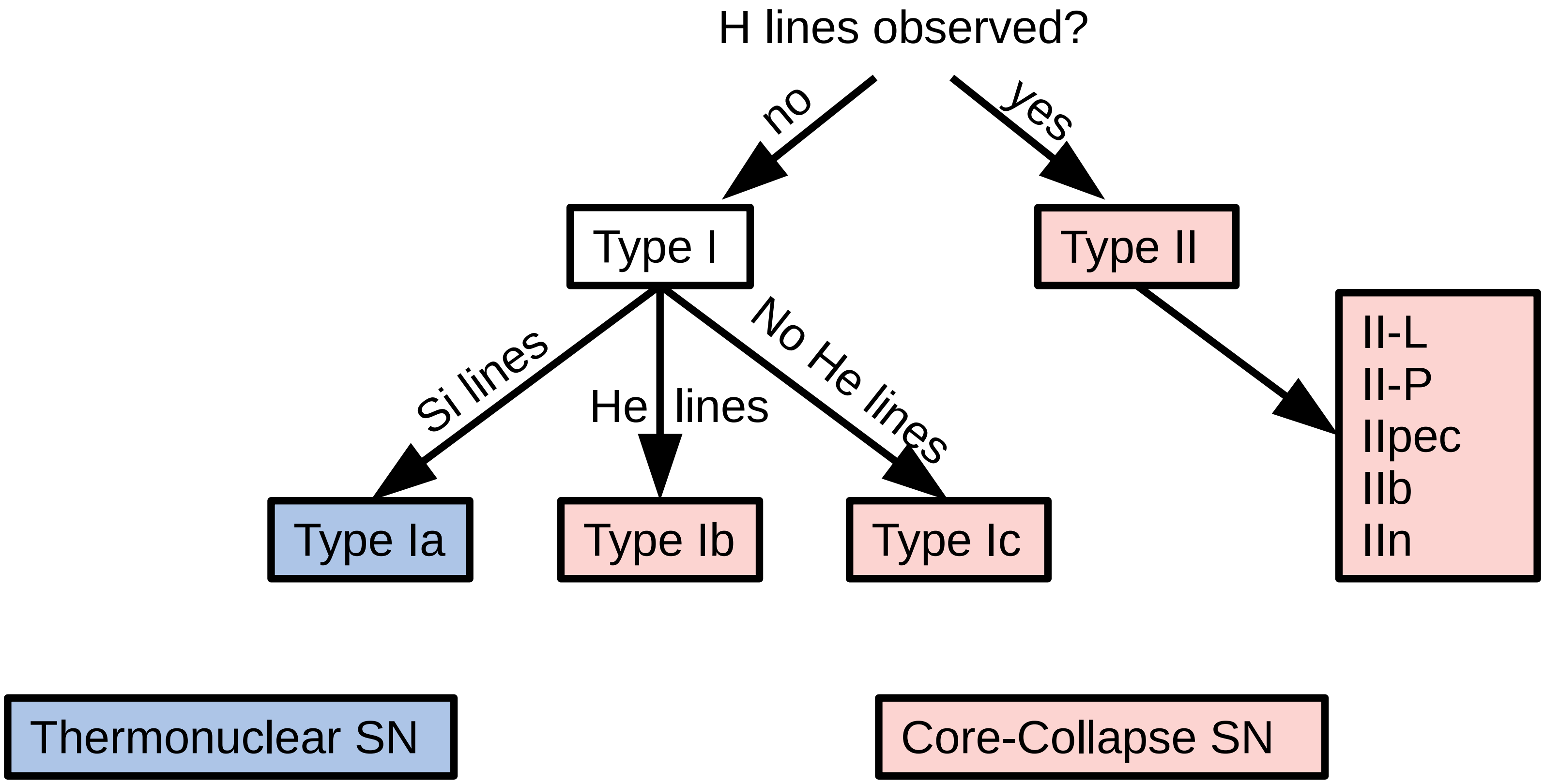
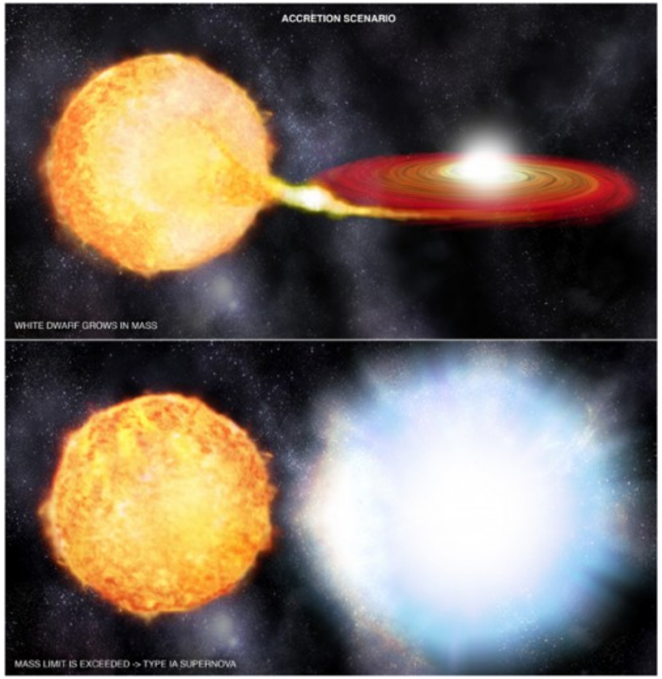
SN Types – spectral classification



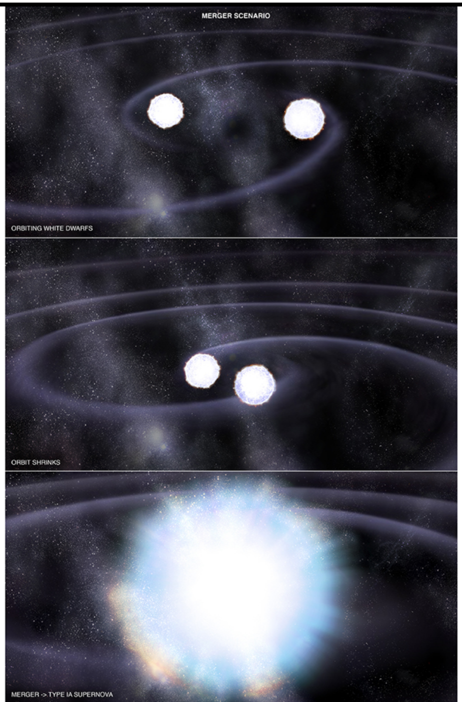
Thermonuclear SN (Ia)

- Isolated White Dwarfs (WD) are stable due to electron degeneracy pressure
- Maximal mass of a White Dwarf: $1.4 M_{\odot}$ (Chandrasekhar mass)
- SN Ia scenarios:

Single degenerate (WD + normal star)



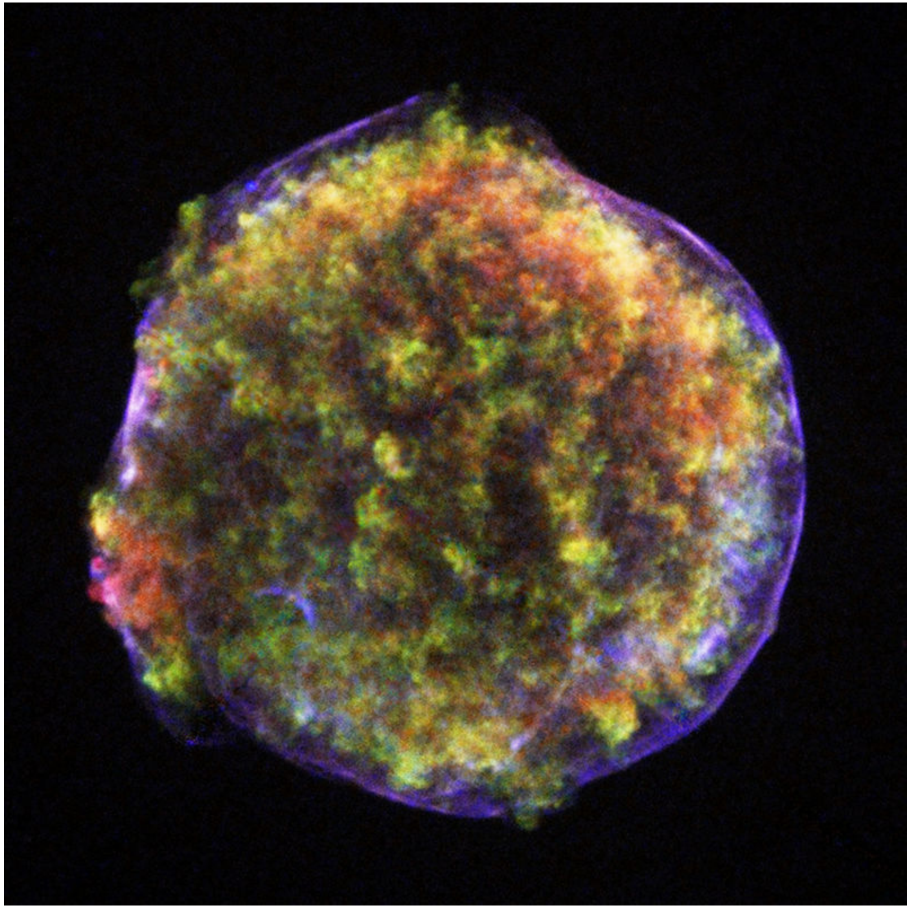
Double degenerate (2 WDs)



Credit: NASA/CXC/SAO

Thermonuclear SN (Ia)

- WD gets completely disrupted
- Nothing left behind, only Supernova Remnant
- Tycho’s SN (SN 1572)
- GW signal calculated for a special case:
  - $E_{\rm kinetic} \sim 10^{51}{\rm erg}$
  - $E_{\rm neutrino} \sim 10^{49}{\rm erg}$
  - $E_{\rm GW} \sim 10^{40}{\rm erg}$



Credit:NASA/CXC/Rutgers/J.Warren & J.Hughes et al.

Core-Collapse SN

- Massive stars, $M \gtrsim 8 M_\odot$ develop cores heavier than the Chandrasekhar mass
- ➔ Collapse can not be stopped by electron degeneracy pressure
- ➔ Only halts when nuclear densities are reached and degenerate n provide pressure

- Binding energy of neutron star is liberated mainly in neutrinos

$$E_b \sim E_g \approx \frac{3}{5}\frac{G M_{\rm NS}^2}{R_{\rm NS}} \approx 3.6 \times 10^{53} \left(\frac{M_{\rm NS}}{1.5 M_\odot}\right)^2 \left(\frac{R_{\rm NS}}{10\mathrm{km}}\right)^{-1} \mathrm{erg}$$

- Two dozens of neutrinos detected from SN1987A

- Observed SN: $E_{\rm SN} \sim 10^{51}\ \mathrm{erg} = 1\ \mathrm{foe} = 1\ \mathrm{fifty\ one\ erg}$

- Many different characteristics of the explosions depending on progenitor

Stellar Evolution

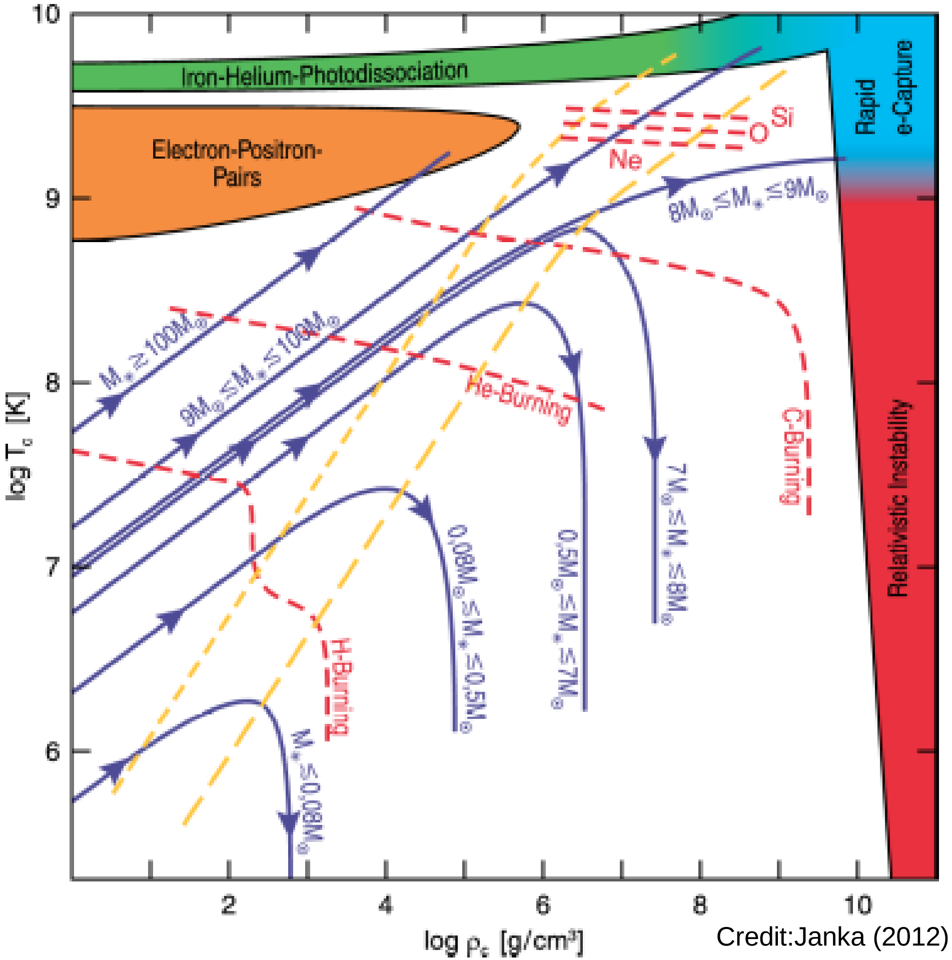
- Depending on mass of progenitor different burning stages are reached

- $M \lesssim 8M_\odot$ barely reach C-burning
  ➔ White Dwarves

- $9M_\odot \gtrsim M \gtrsim 8M_\odot$ develop O-Ne-Mg core
  ➔ Electron-Capture SN

- $100M_\odot \gtrsim M \gtrsim 9M_\odot$ develop Fe core
  ➔ Core-Collapse SN
  ➔ Black hole formation

- $100M_\odot \lesssim M$ formation of e^- - e^+ pairs
  ➔ Pair-Instability-SN

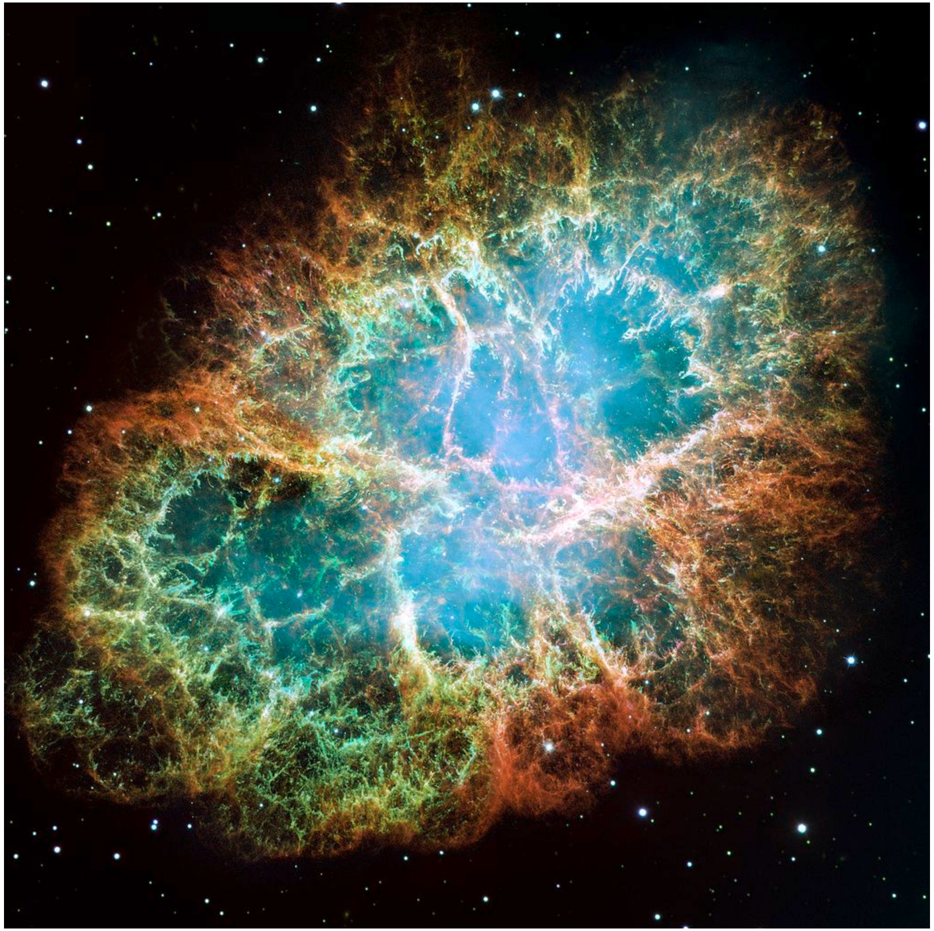


Credit:Janka (2012)

Electron-Capture SN

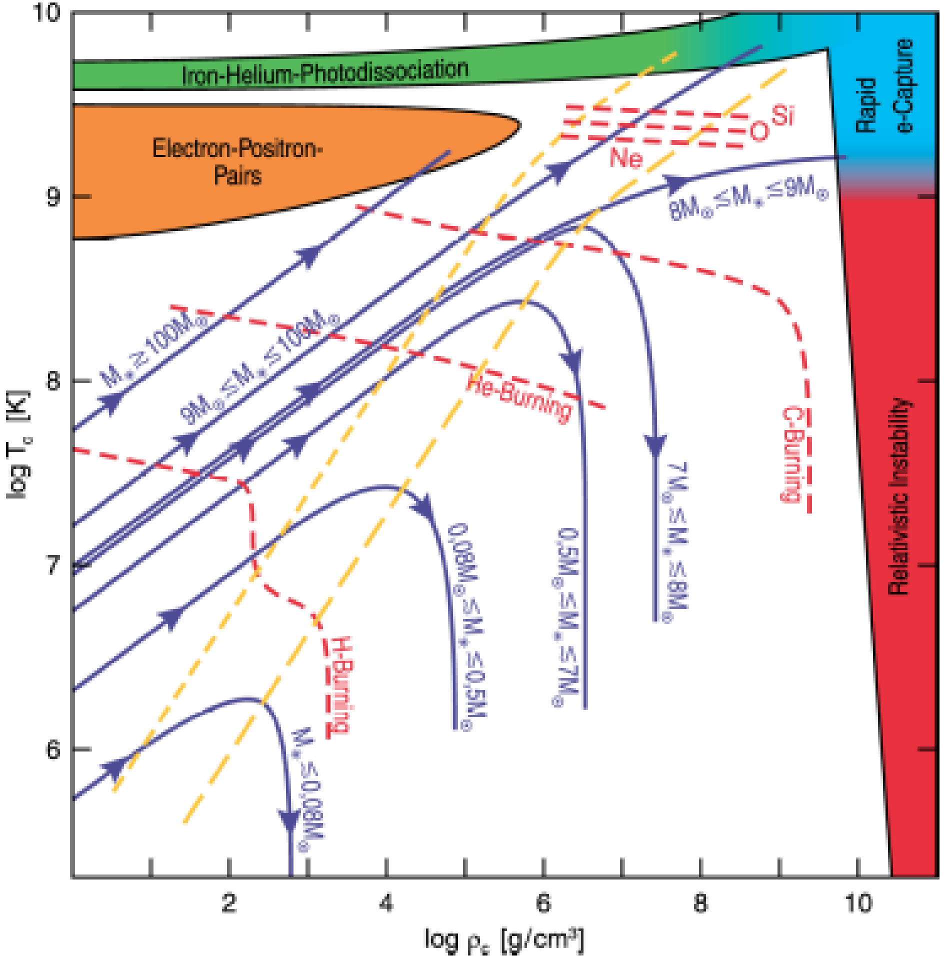
- Stars massive enough to burn C, but no Ne-burning
- O-Ne-Mg core
  (or very low mass Fe-core)
- Very narrow mass window (but depends on metallicity)
- Gravitational collapse is triggered by e^--captures due to low reaction thresholds of Ne / Mg
- Almost prompt explosion → quite spherical explosions

- Crab Nebula:
  remnant of a possible EC SN



NASA, ESA, J. Hester and A. Loll

Stellar Evolution



Iron-Core SN

- Very massive stars can form Fe-core
- Fe-group nuclei dissociate when

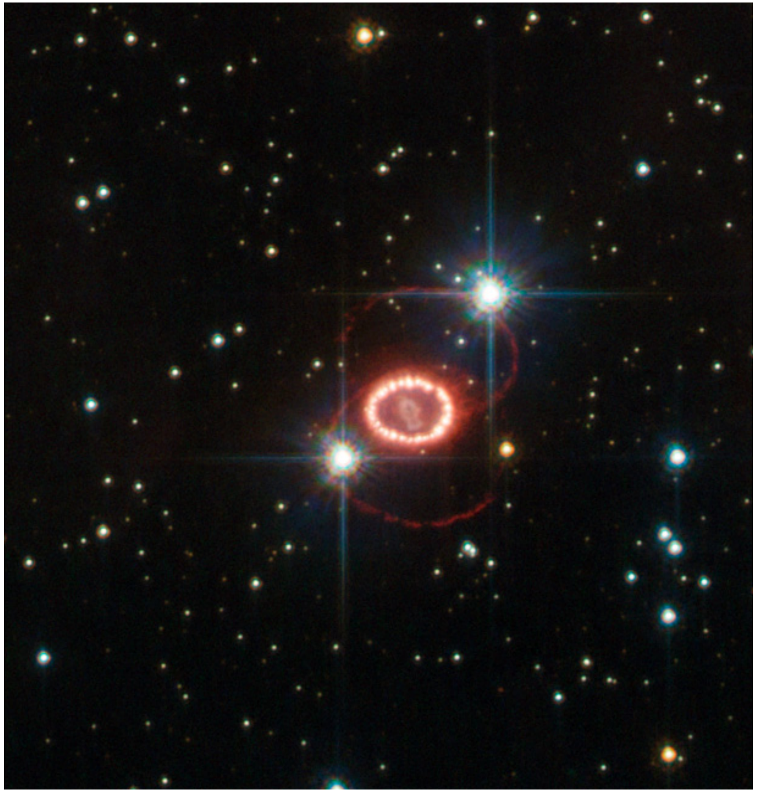
$$T \sim 10^{10} K \quad (k_B T \sim 1 MeV)$$

- Contraction leads to increasing densities and electron chemical potential
- ➔ Electron captures on nuclei (+ protons)
- ➔ Missing pressure support accelerates implosion
- Collapse only stopped at nuclear densities

$$\rho \gtrsim 2.7 \times 10^{14} g/cm^3$$

- Bounce of infalling matter

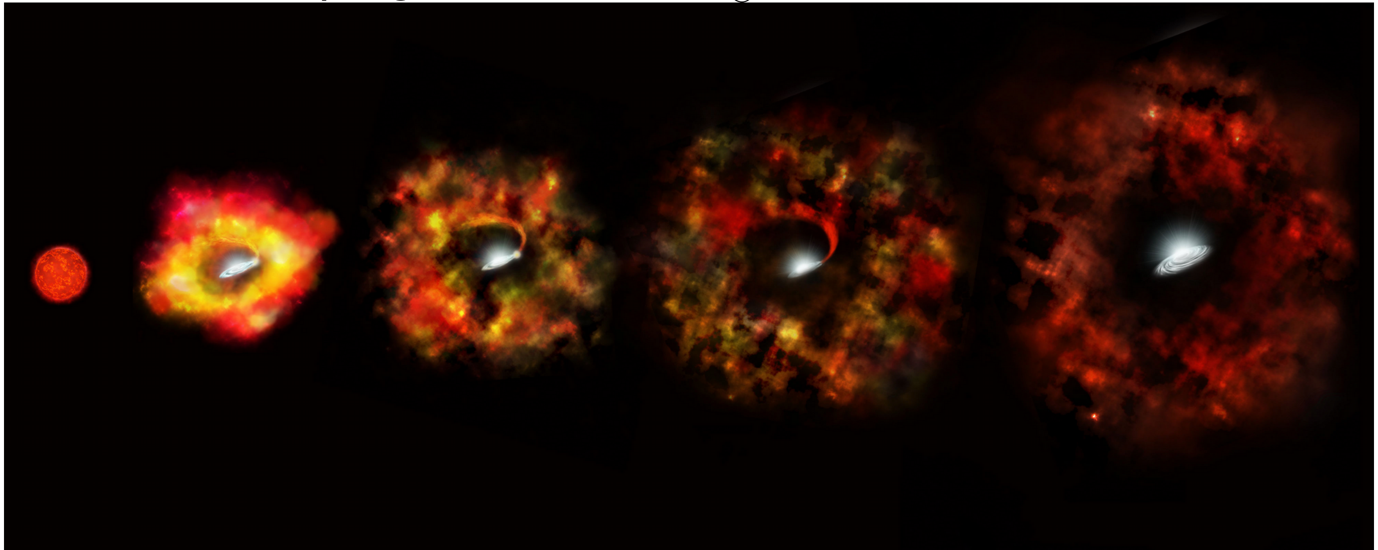
- SN1987A



ESA/Hubble & NASA

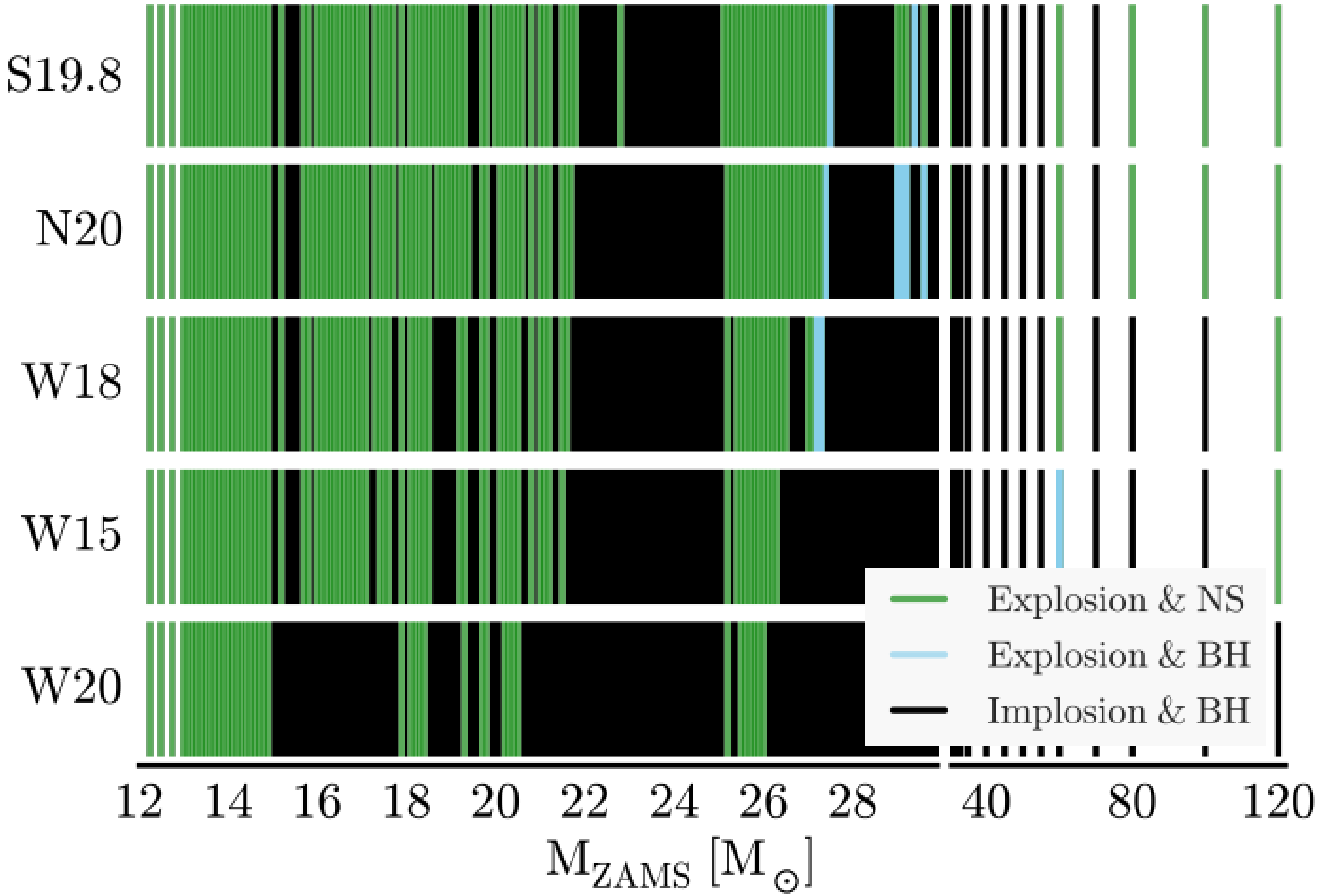
Failed SN / Black Hole formation

- Some stars develop Fe-cores that are too heavy to lead to a stable NS
- During collapse they directly form a black hole (direct collapse)
- Some may be just at the verge and form a proto-neutron star which then collapses to a black hole after accretion (fall back black hole formation)
- Also rotation and initial thermal energy may retard the collapse to the BH
- Appears as a disappearing star
  - NGC3021-candidate-1: F8 Supergiant $25-30M_\odot$
  - N6946-BH1: Red Supergiant $18-25M_\odot$



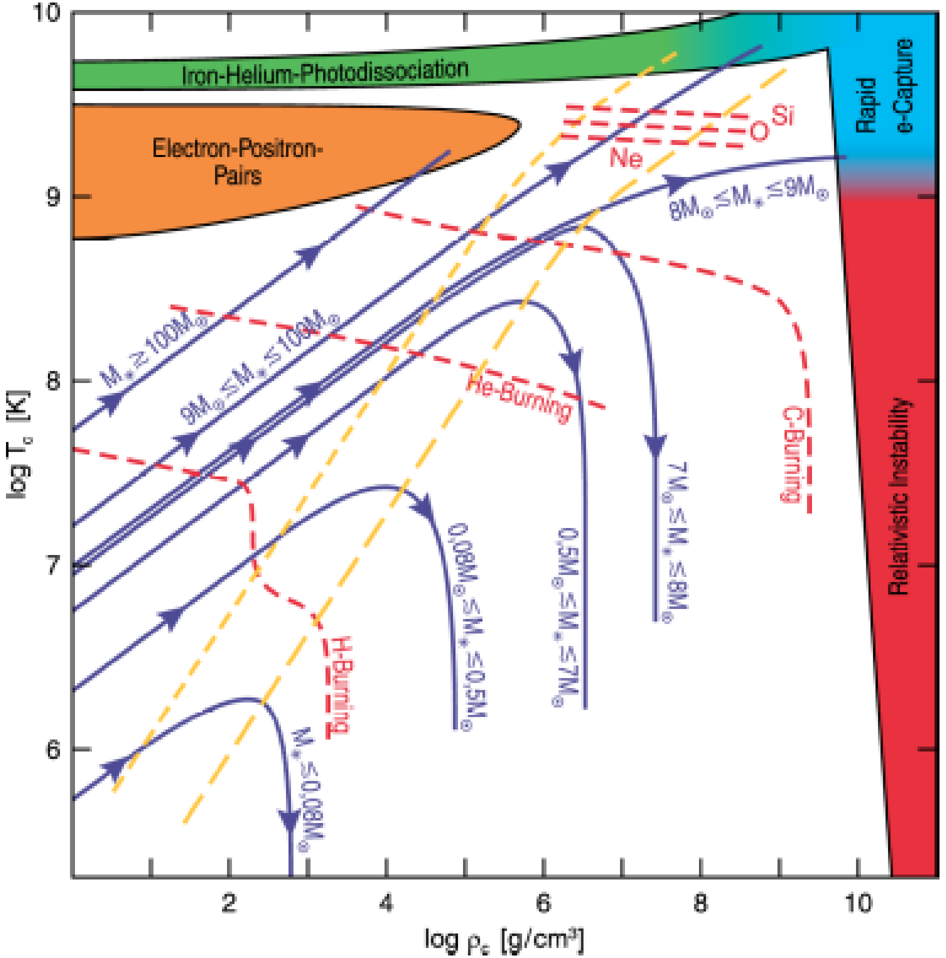
NASA, ESA, and P. Jeffries (STScI)

1D – parametrized simulations



Sukhbold et al. (2015)

Stellar Evolution



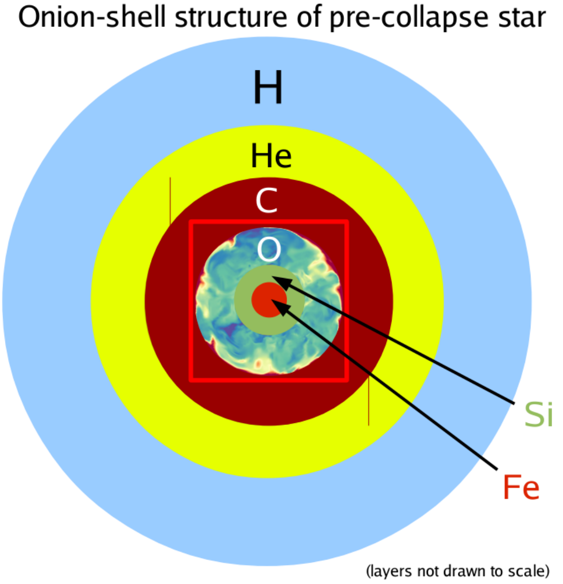
Pair-Instability SN

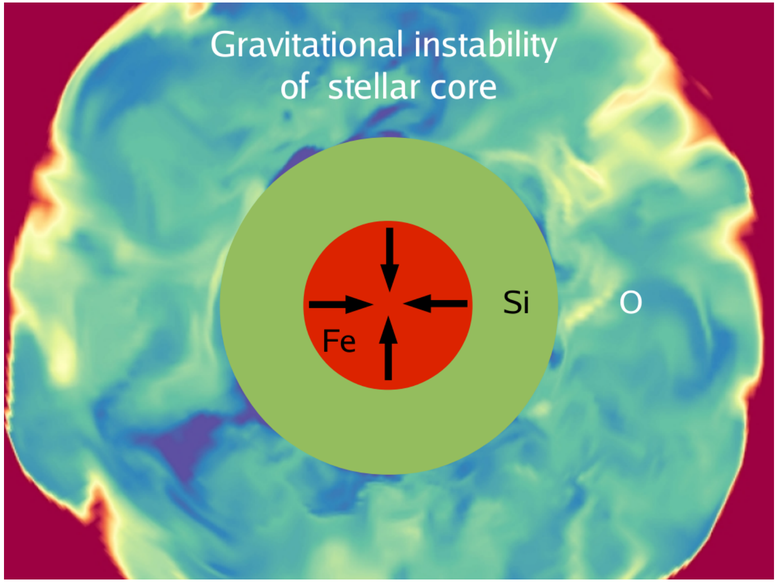
- $M > 100 M_\odot$
- $T > 10^9\ \mathrm{K}$ pair creating sets in
- Thermal energy converted to rest mass
  → no pressure support against collapse
- $140 M_\odot \lesssim M \lesssim 260 M_\odot$ complete disruption
- $M > 250 M_\odot$ black hole formation
- 2 candidates:
  - CSS141118:092034+504148
  - ESSENCEy155

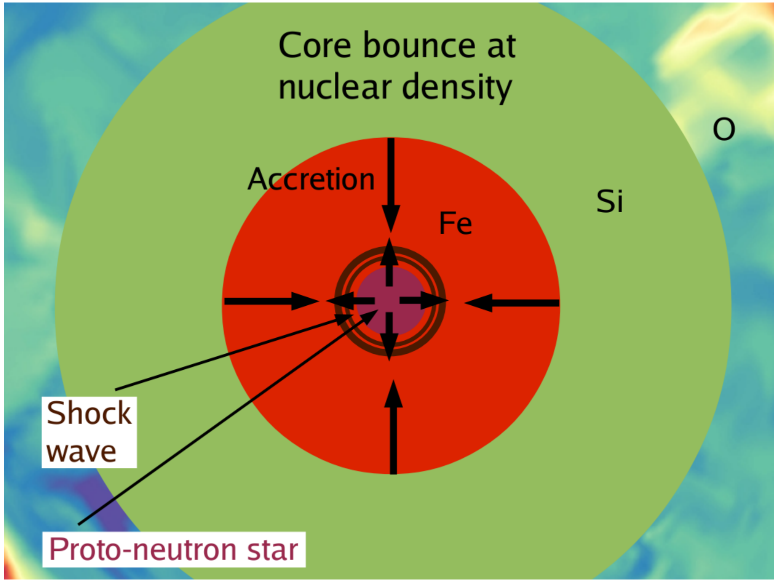
SN2007bi

Core-Collapse SN

Janka (2017)







- Onion shell structure
- Degenerate core
- Convective burning leads to large perturbations

- Gravitational instability initiated by photodissociation of heavy nuclei and electron captures

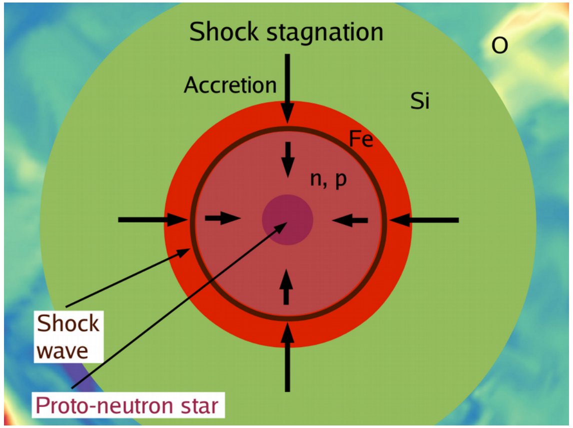
$$e^- + p \to \nu_e + n$$
$$e^- + (A, Z) \to \nu_e + (A, Z-1)$$

- Implosion stopped at

$$\rho \approx 2.7 \times 10^{14} \mathrm{g/cm}^3$$

- n become degenerate
- Matter overshoots and bounces back
- Pressure wave steepens to shock

Core-Collapse SN



Janka (2017)

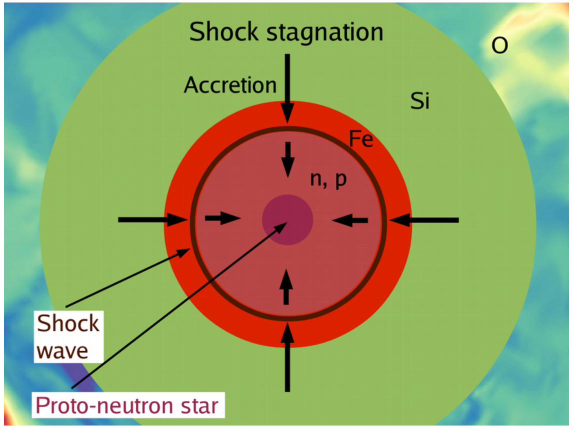
- Shock loses energy due to photodisintegration of iron-group nuclei
- Copious neutrinos from electron captures on protons
- After density drop neutrinos can leave post-shock region -> shock-breakout neutrino burst takes away additional energy
- Shock stalls at around 100 – 200 km

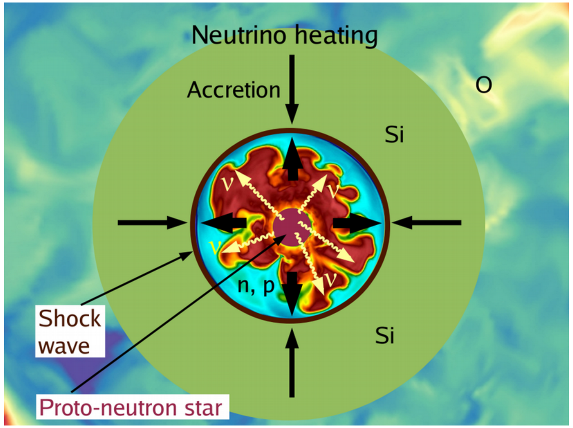
How to revive the shock? Explosion Mechanisms

- Neutrino-driven SN
  - Neutrinos from the proto-neutron star provide the energy
  - 1D simulations show no explosion → inherently 3D problem
- Magneto-hydrodynamical (MHD) mechanism
  - Highly magnetized NS can extract rotational energy efficiently

    magnetic pressure, hoop stress, magnetic buoyancy, gas heating
  - $$\dot{E}_{\mathrm{MHD}} \sim \times 10^{52} \frac{\mathrm{erg}}{\mathrm{s}} \left(\frac{B}{10^{15}\ \mathrm{G}} \right)^2 \left(\frac{r}{30\ \mathrm{km}} \right)^3 \left(\frac{\Omega}{10^3\ \mathrm{rad\ s}^{-1}} \right)$$
- Acoustic mechanism
  - l =1 gravity-mode oscillations of NS may send strong sound waves into surrounding medium which heat post-shock matter
- Phase Transition mechanism
  - First-order hadron-to-quark transition at low enough density leads to second gravitational instability

Neutrino-driven Core-Collapse SN





Janka (2017)

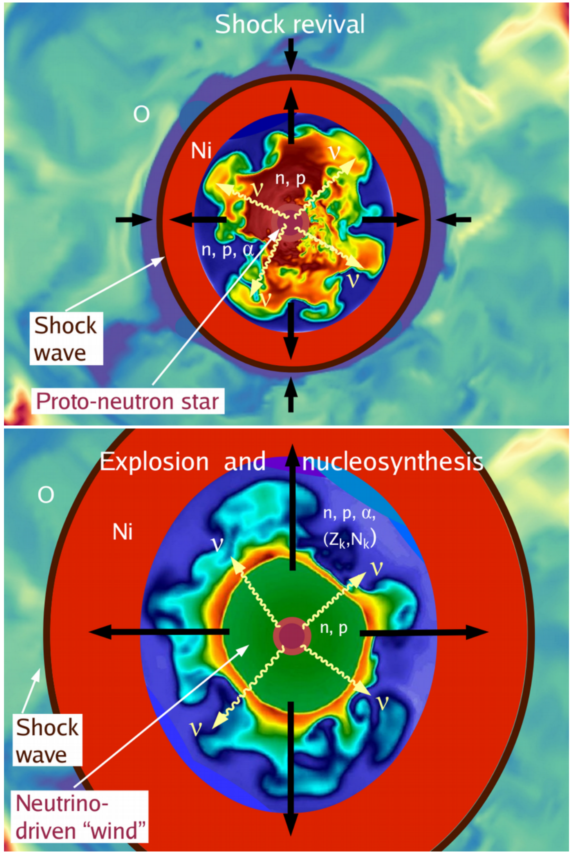
- Shock loses energy due to photodisintegration of iron-group nuclei
- Copious neutrinos from electron captures on protons
- After density drop neutrinos can leave post-shock region -> shock-breakout neutrino burst takes away additional energy
- Shock stalls at around 100 – 200 km

- Neutrino heating provide extra source of energy

$\nu_e + n \rightarrow p + e^-$ $\qquad\qquad$ $\bar{\nu}_e + p \rightarrow n + e^+$

➔ Negative entropy gradient
➔ Convective unstable layer
- Standing-accretion-shock Instability (SASI)
- The more 'turbulence' (all deviations from radial infall) the longer matter can be heated by neutrinos
- Explosion when the $t_{\mathrm{adv}} > t_{\mathrm{heat}}$ (matter heated more than grav. bound)

Neutrino-driven Core-Collapse SN



Janka (2017)

- Postshock pressure rises
- ➔ Shock can be pushed outwards
- $P_{\text{thermal}} > P_{\text{ram,infall}}$ runaway shock expansion
- Nucleosynthesis in shock-heated material begins and provides further energy for the explosion

- Shock expands outwards
- ➔ Continued nucleosynthesis
- ➔ Shock reaches stellar surface after few hours up to one day
- Neutrino-driven (baryonic) wind from surface
- NS cools down in center

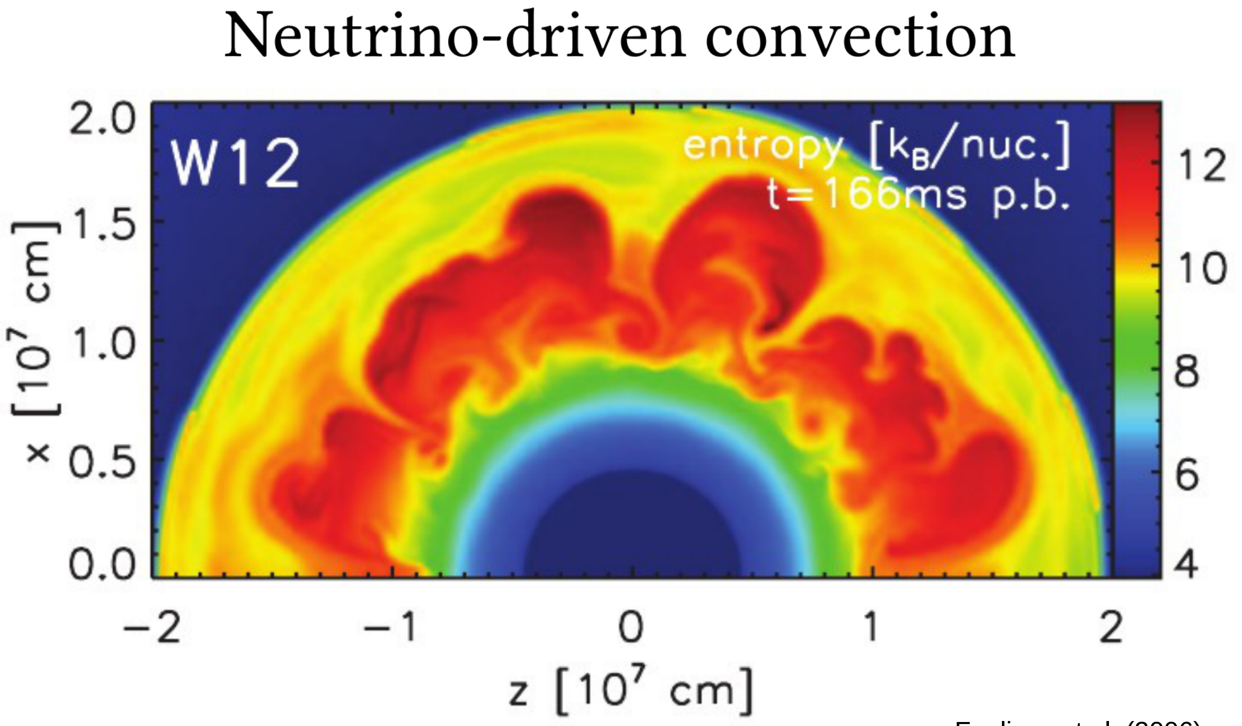
Convection

- Buoyancy-driven convective instability due to negative entropy gradients due to neutrino heating in gain layer
- Growth rate of the order of ω_{BV}
- Brunt-Väisälä frequency:

$$\omega_{\mathrm{BV}}^2 = g\left(\frac{1}{\rho}\frac{\partial\rho}{\partial r} - \frac{1}{\rho c_{\mathrm{S}}^2}\frac{\partial P}{\partial r}\right)$$

- Outwards rising plumes:

$$\chi \equiv \int_{R_{\mathrm{g}}}^{R_{\mathrm{S}}} dr \frac{\omega_{\mathrm{BV}}}{|v_r(r)|} \gtrsim 2\ldots3$$



Foglizzo et al. (2006)

Standing Accrection Shock Instability (SASI)

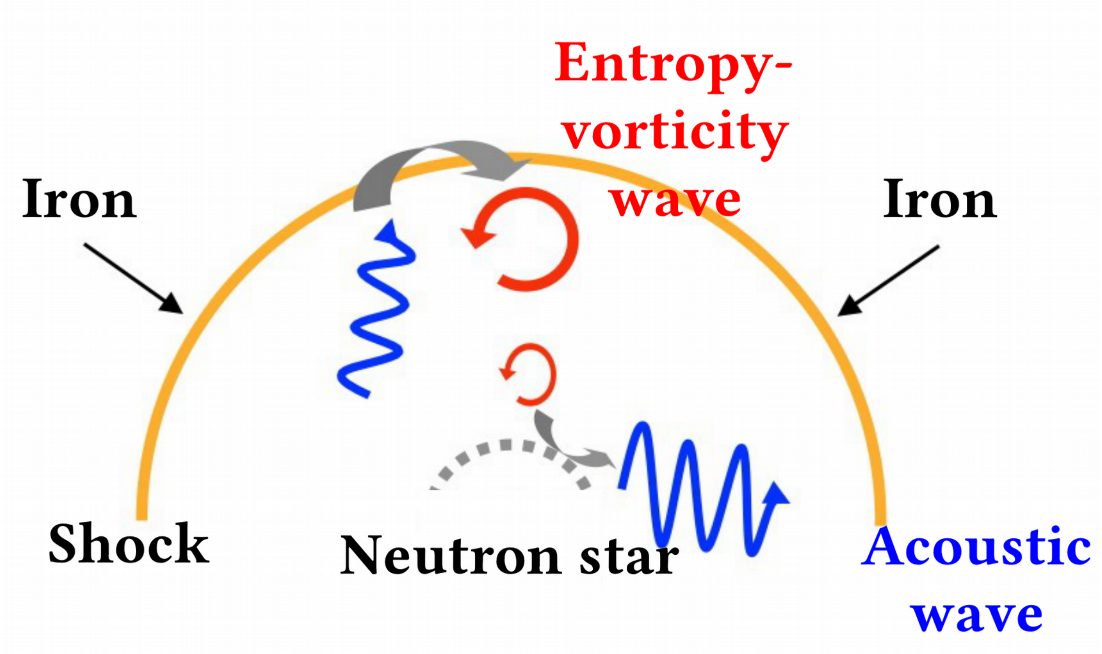
- Amplifying advective-acoustic cycle

$$\omega_{\mathrm{SASI}} \sim \frac{\ln \mathcal{Q}}{t_{\mathrm{cyc}}}$$

- Cycle efficiency: $|\mathcal{Q}| > 1$ for growth
- $t_{\mathrm{cyc}} = \int_{R_0}^{R_{\mathrm{S}}} \frac{dr}{|v_r(r)|} + \int_{R_0}^{R_{\mathrm{S}}} \frac{dr}{c_{\mathrm{S}}(r)} \sim t_{\mathrm{adv}}$
- Growth rate larger for short t_{cyc}

➔ Strong during shock retraction

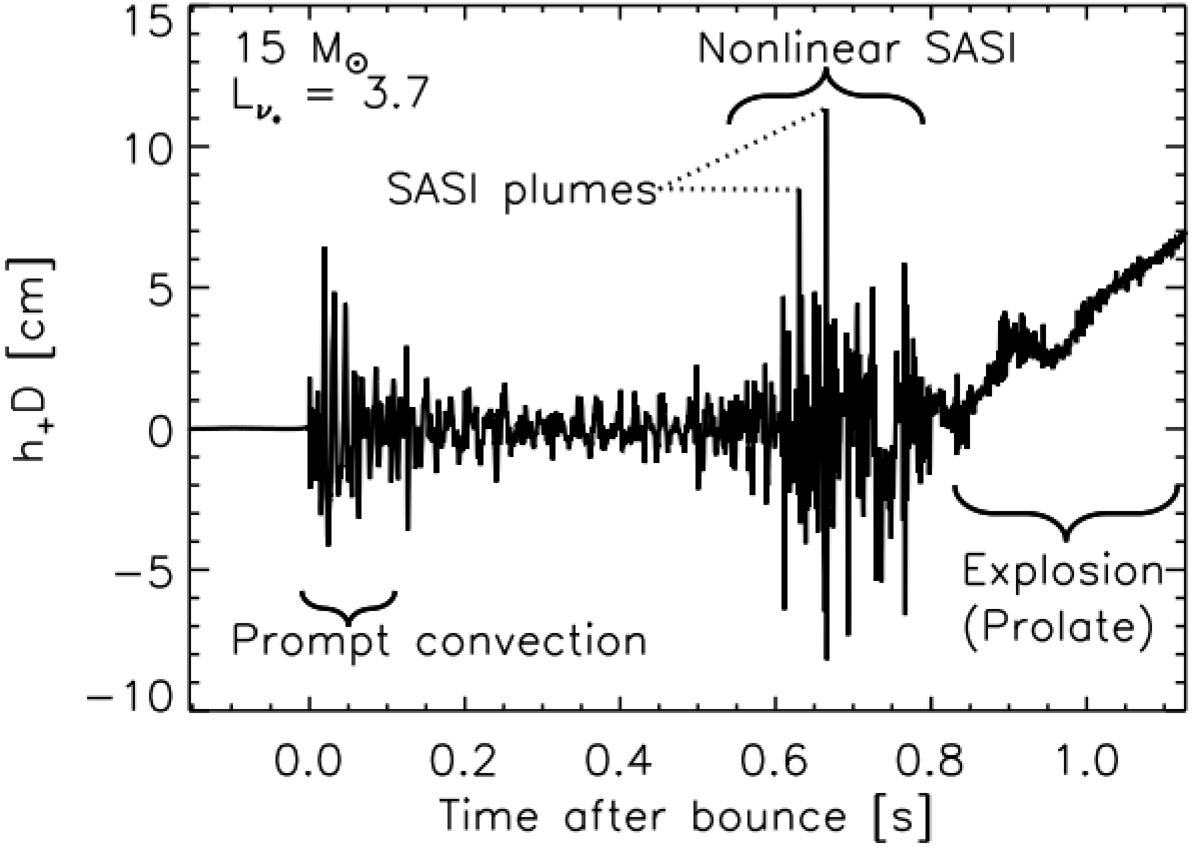
➔ Weak during shock expansion and when $\chi \gtrsim 3$



Foglizzo et al. (2007)

Gravitational waves from SN (2D)

- Parametrized simulations with spherical neutrino emission
  → only matter GW
- Bounce signal
- Short after bounce: prompt convection
- Later strong SASI
- After shock revival:
  asymmetric explosion signal



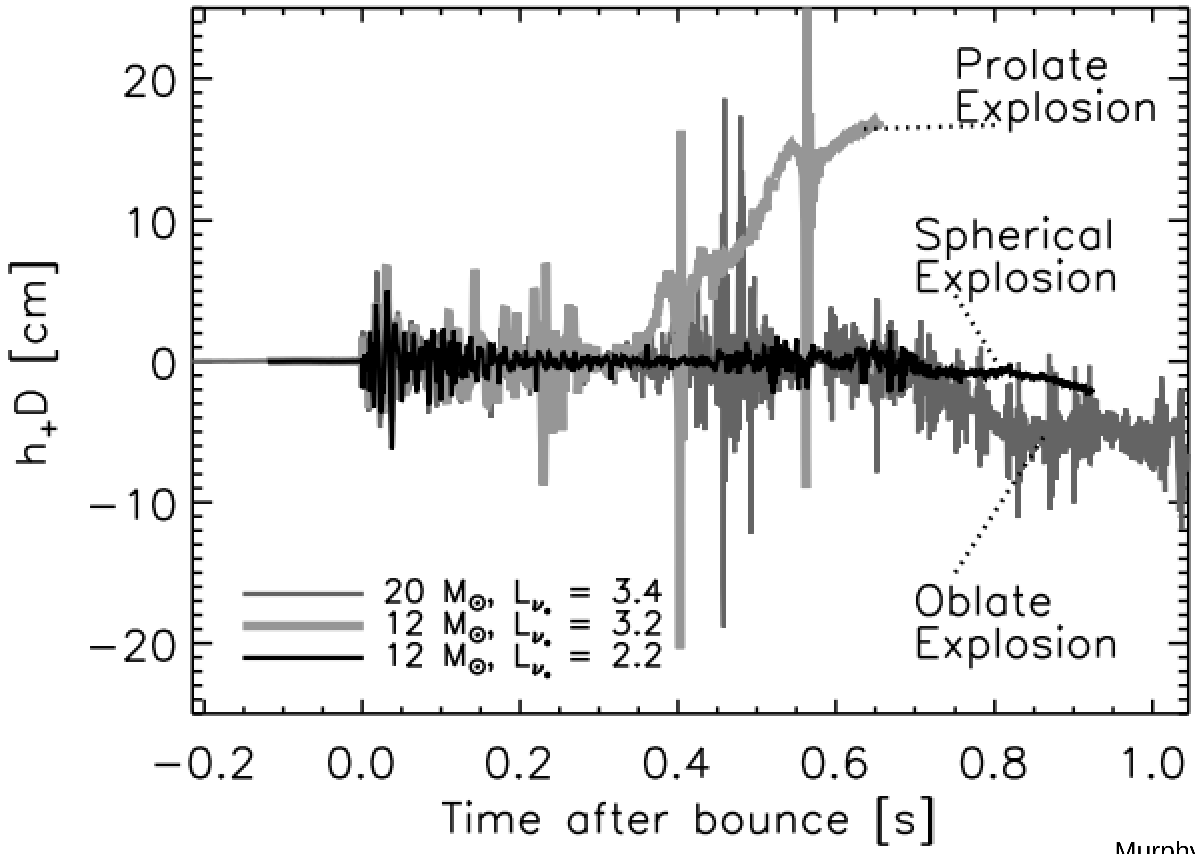
Murphyet al. (2009)

Gravitational waves from SN (2D)

- Prolate explosion
- ➔ Positive amplitude

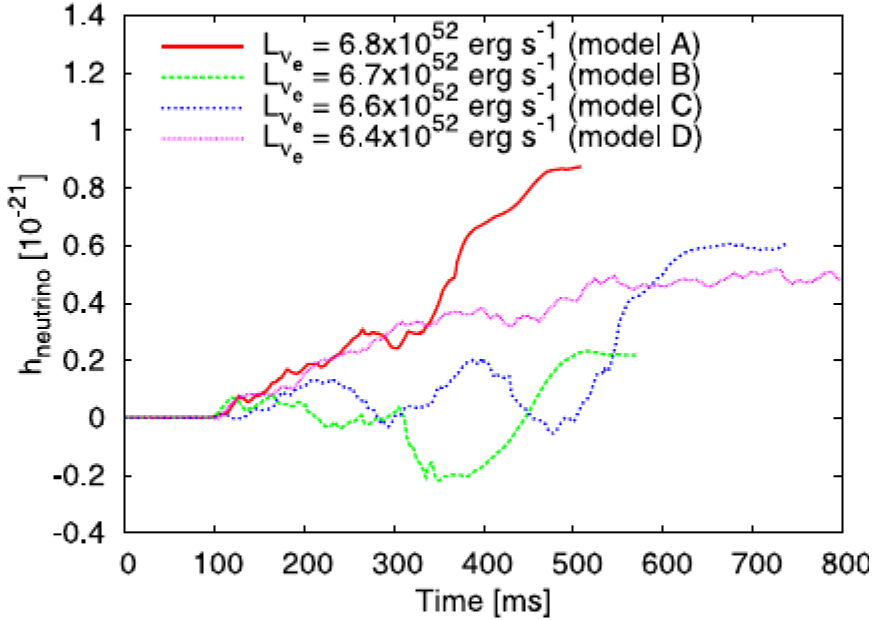
- Oblate explosion
- ➔ Negative amplitude

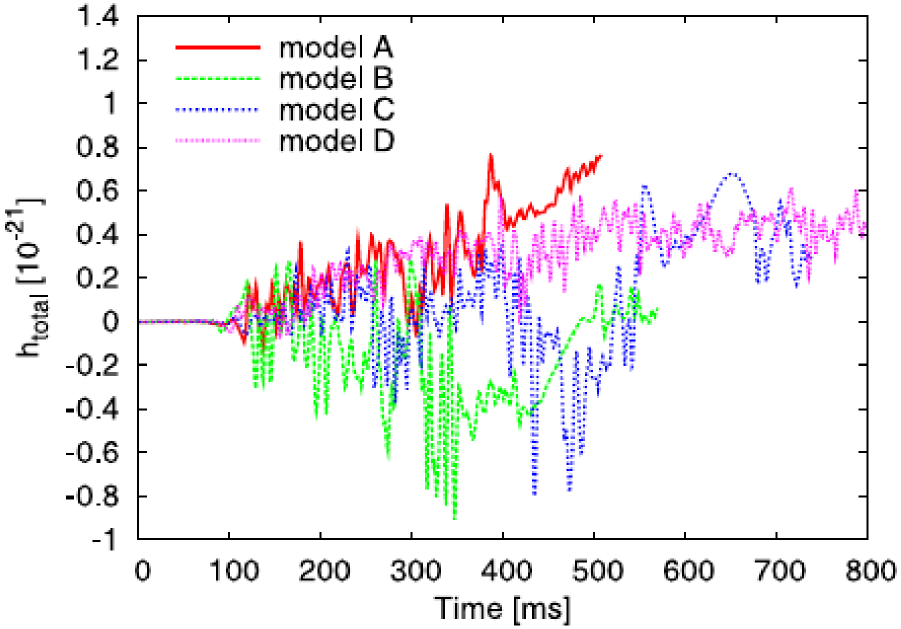
- ➔ Spherical explosion
- ➔ Vanishing amplitude



Murphyet al. (2009)

Gravitational waves from SN (2D)

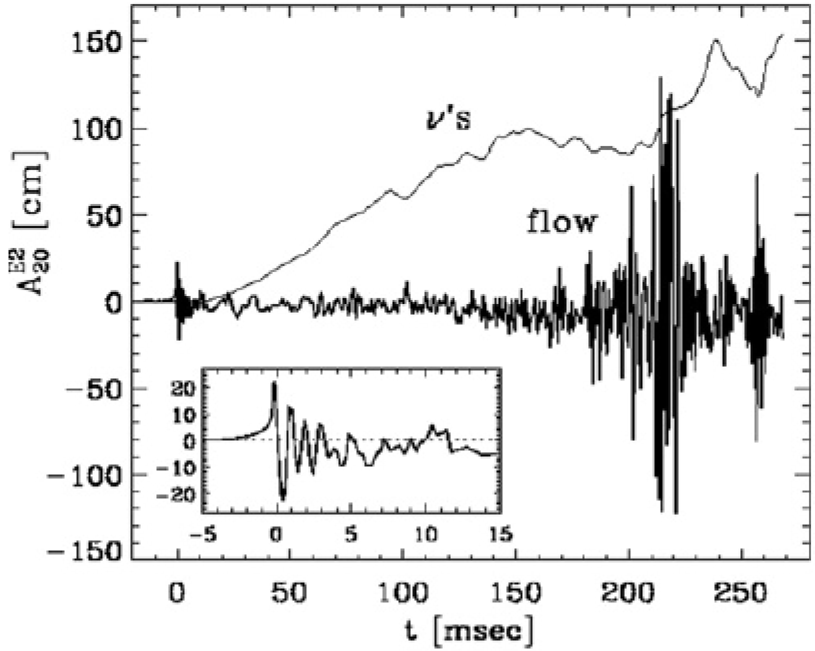


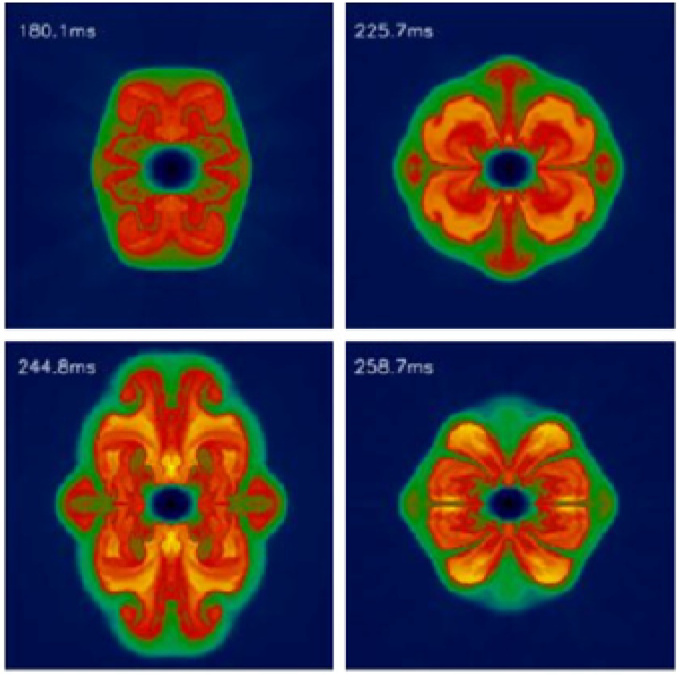


- Left: only neutrino GW, Right: Neutrino + matter GW
- SASI enters after 100ms
- Non spherical downflows cause non spherical neutrino emission

Kotake al. (2009)

Gravitational waves from SN (2D)

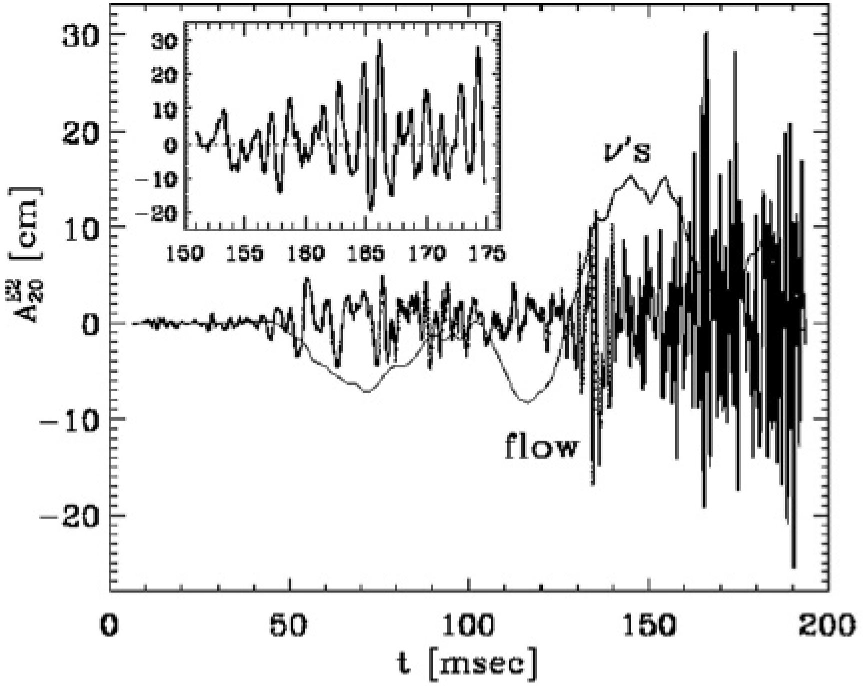


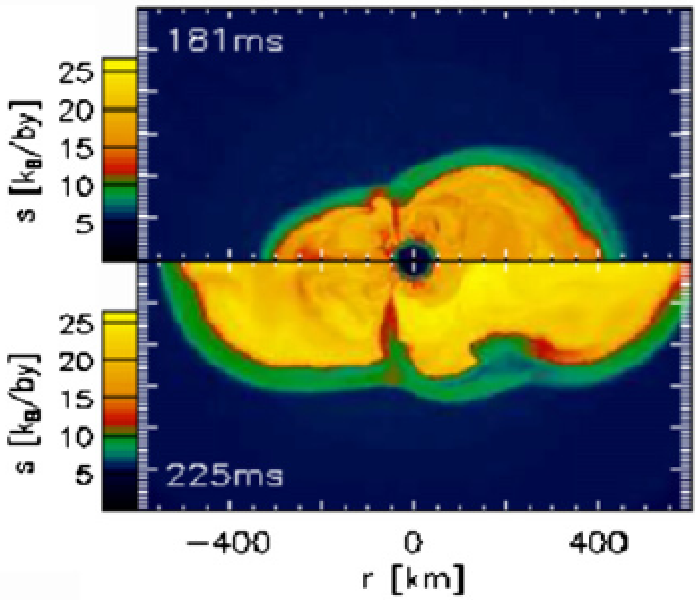


- Realistic 2D simulations
- Rotating model, $15M_{SUN}$ → neutrino emission along the pole can be stronger
- Initial bounce signal

Mueller al. (2004)

Gravitational waves from SN (2D)





- Realistic 2D simulations
- Non-Rotating model, 11.2 M_{SUN}
- No strong bounce signal, generally weaker GW signal

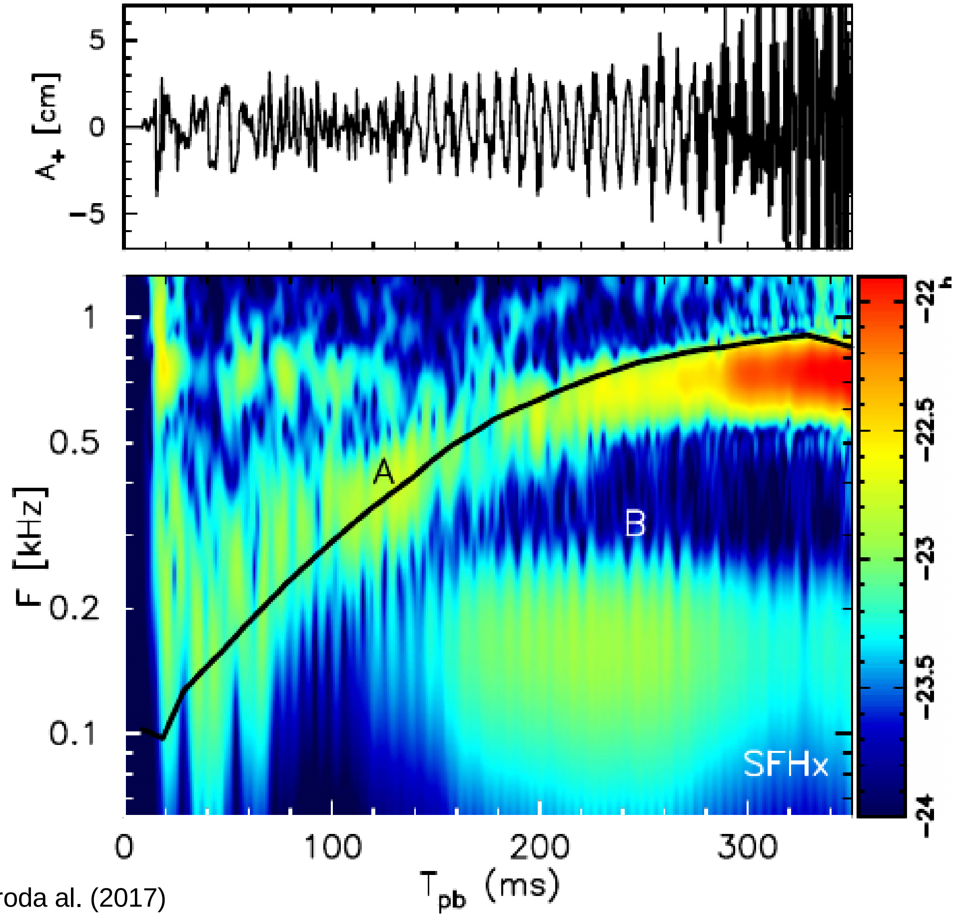
Mueller al. (2004)

2D vs 3D

- Stochastic Signal with:
  - Early, low f Signal 100Hz from prompt convection
  - High f Signal with stochastic amplitude modulation, forced oscillatory motions at surface ~ ω_{BV} (300 – 1000Hz), may be l=2, surface g-modes
  - Hundreds of ms after shock revival PNS convection dominates

- BUT we know that in 3D:
  - Turbulent cascade is inversed → smaller structures
  - Accretion downflows are slower (inverse turbulent cascade + parasitic instabilities)
  - In 3D spiral modes allowed

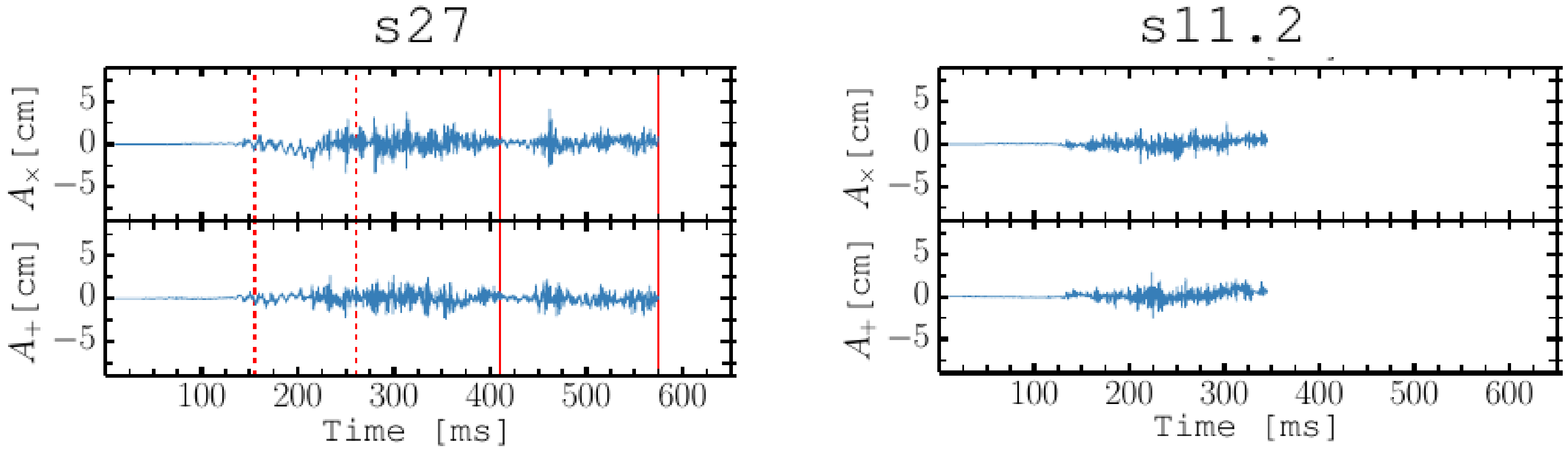
Gravitational waves from SN (3D)



Kuroda al. (2017)

- Initial low f – prompt convection
- Next sloshing SASI
- Spiral mode of SASI
- Finally PNS convection
- Amplitude grows at late times
- Component A: surface g-mode of PNS
- Component B: SASI imprints
- Softer EOS have smaller shock radii and thus more favorable SASI conditions

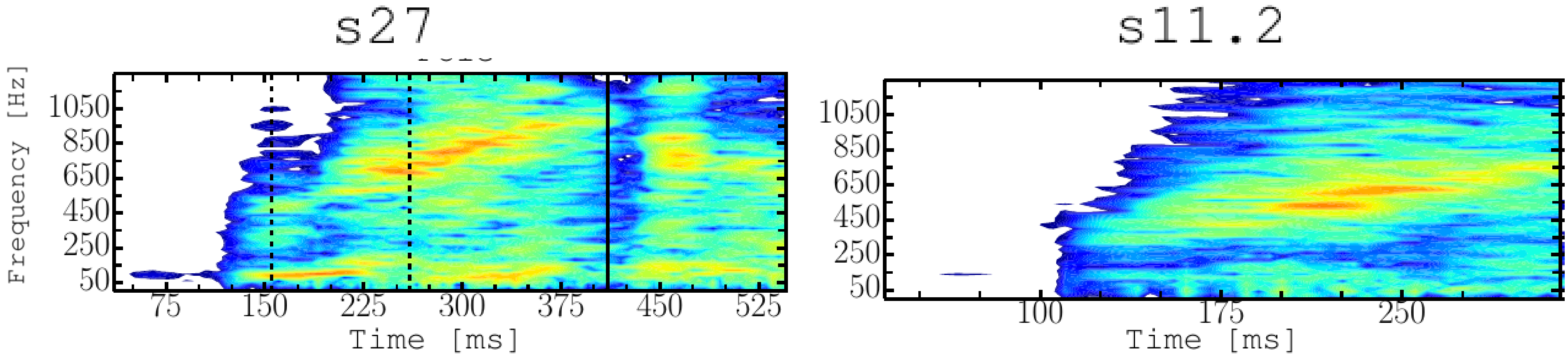
Gravitational waves from SN (3D)



- Non-rotating models → no bounce signal
- Weak post-shock signal
- First significant amplitude with onset of SASI
- Lower amplitudes in 3D than in 2D
- Dominant low frequency component for early times when SASI is present

Andresen al. (2017)

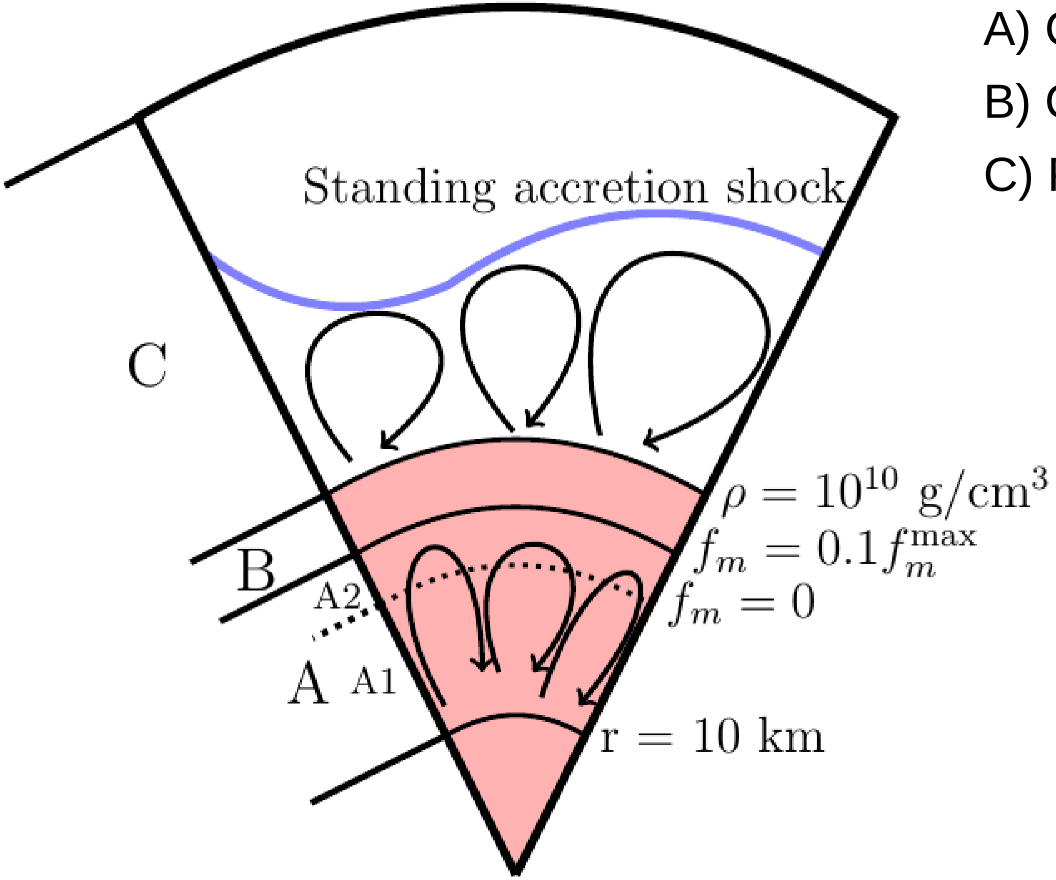
Gravitational waves from SN (3D)



- Slowly increasing, high frequency component
- Models with strong SASI show low frequency component (<250Hz), absent in 2D simulations
- But also some low-f signal between 280 and 350 ms for model s27, where no strong SASI is observed

Andresen al. (2017)

Gravitational waves from SN (3D)

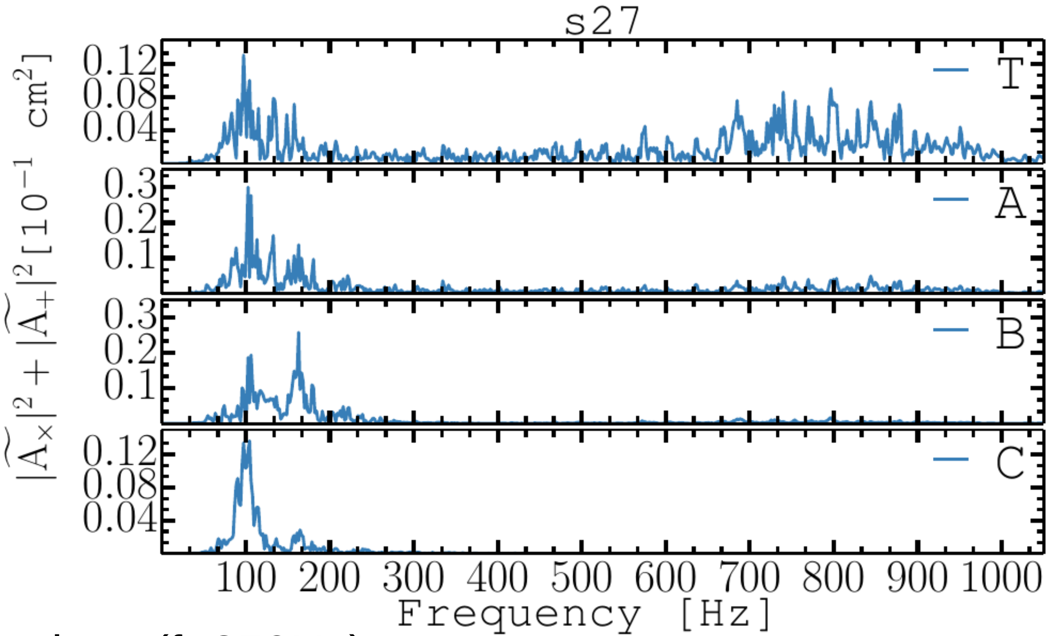


A) Convective layer

B) Convectively stable surface layer

C) Post-shock layer

Gravitational waves from SN (3D)



- SASI imprints in all regions (f<250Hz)
- High frequency mostly in region A (in contrast to 2D simulations where one expects surface g-modes

  → region B, initially excited from SASI only later by PNS convection)
- Frequency of strongest GW emission agrees well with ω_{BV}

Conclusions

- At the end of their lives (all fuel spent) stars become: White Dwarfs, Black Holes or explode as Supernovae that leave a Neutron Star behind
- Supernovae are violent explosions which consist of 5 phases:

  Collapse, Bounce and shock formation, Stalling of the shock, Revival of the shock (neutrino heating aided by hydrodynamical instabilities), Shock Expansion → explosion

- Different shock-revival mechanisms (SN engines) lead to different GW features:

  neutrino driven (SASI, convection), acoustic (strong surface g-modes), strong rotation (strong bounce signal, spiral modes)

- 3D GW allow for differentiation between SASI dominated and convection dominated models
- Imprints of EoS on GW spectrum (softer EOS allow for stronger SASI activity)
- GW presented here have to be improved by more realistic explosion simulations (better neutrino treatment), and / or better treatment of GR effects