Core collapse supernovae and gravitational wave emission

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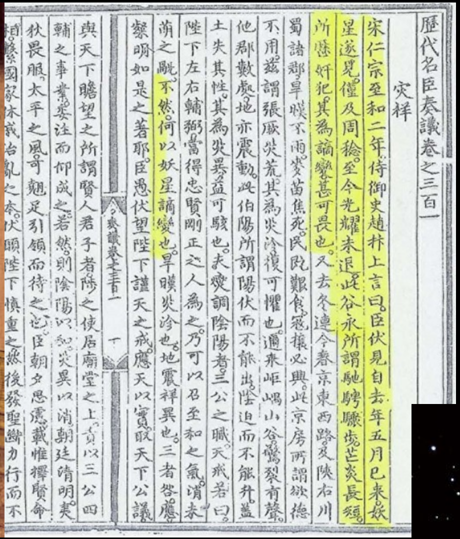
Thematic school GWsNS-2023: Gravitational Waves from Neutron Stars – Aussois – June 2023

Historic SNe

Historical records: Chinese, Japanese, European, Arab…

- SN 185
- SN 386
- SN 393
- SN 1006
- SN 1054
- SN 1181
- SN 1572 (Tycho SN)
- SN 1604 (Kepler SN)
- …



歷代名臣奏議卷之三百一

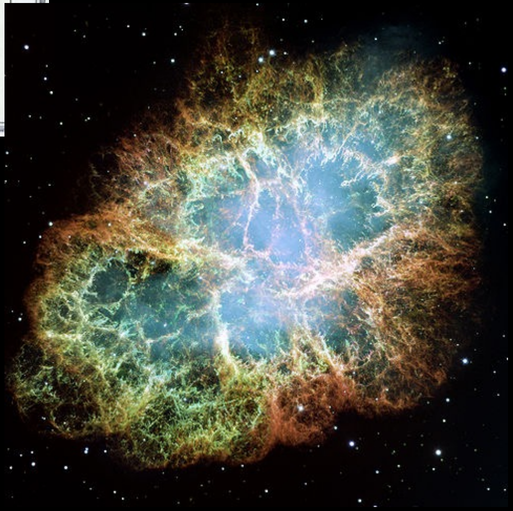
災祥

宋仁宗至和二年侍御史趙抃上言曰臣伏見自去年五月已來妖星遂見僅及周稔至今光耀未退此谷永所謂馳騁驟步芒炎長緐所歷奸犯其為譴變甚可畏也又去冬違令春京東西路及陝右川蜀諸郡旱暵不雨麥苗焦死民既艱食寇攘必興此京房所謂欲德不用茲謂張厥災荒其為災沴復可懼也邇來峄嶋山谷驚裂有聲他郡數處地亦震動此伯陽所謂陽伏而不能出陰迫而不能升蓋土失其性其為災異益可駭也夫燮調陰陽者三公之職天戒若曰陛下左右輔弼當得忠賢剛正之人為之乃可以召至和之氣消未萌之亂不然何以妖星譴變也旱暵災沴也地震祥異也三者咎應粲明如是之著耶臣愚伏望陛下謹天之戒應天以實取天下公議

奏議卷之三百一　十

與天下瞻望之所謂賢人君子者陟之使居廟堂之上貢以三公四輔之事業委注而仰成之若然則陰陽以和災異以消朝廷清明矣秋畏服太平之風可翹足引領而待之也臣朝夕思慮載惟擇賢命輔繫國家休戚治亂之本伏願陛下慎重之然後發聖斷力行而不

SN 1054: “Guest star” in Chinese records



Crab nebula (HST)

Historic SNe

SN 185
SN 386
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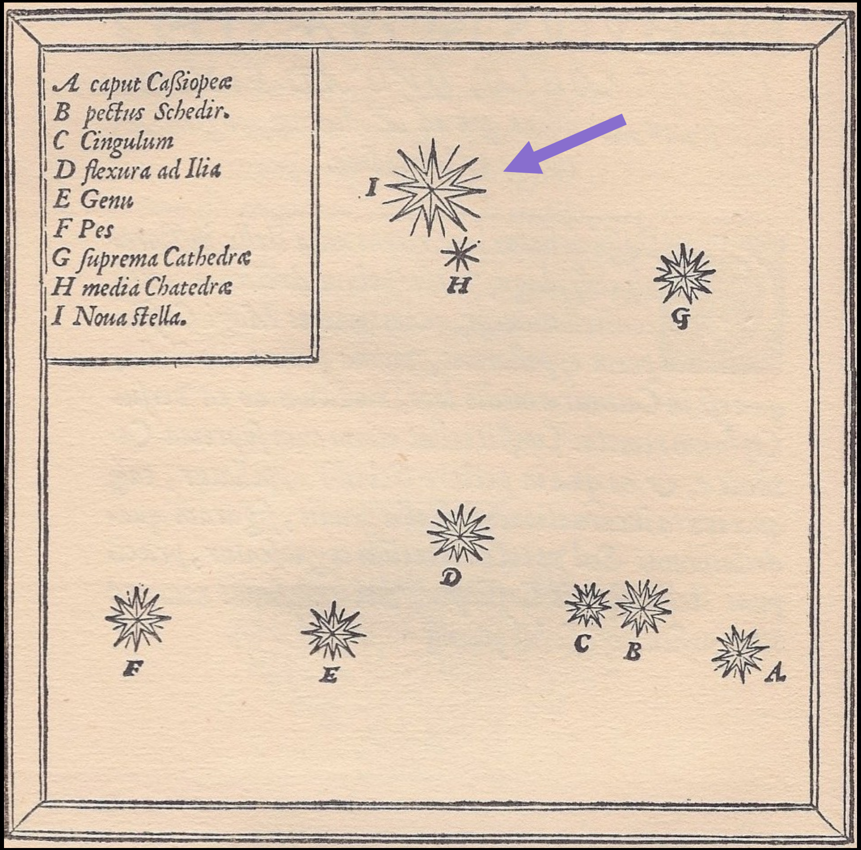
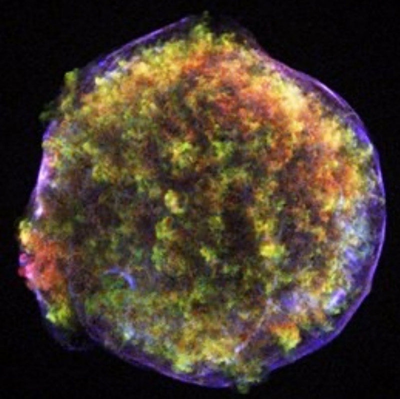
SN 1572 (Tycho SN)
SN 1604 (Kepler SN)
…

Historical records: Chinese, Japanese, European, Arab…

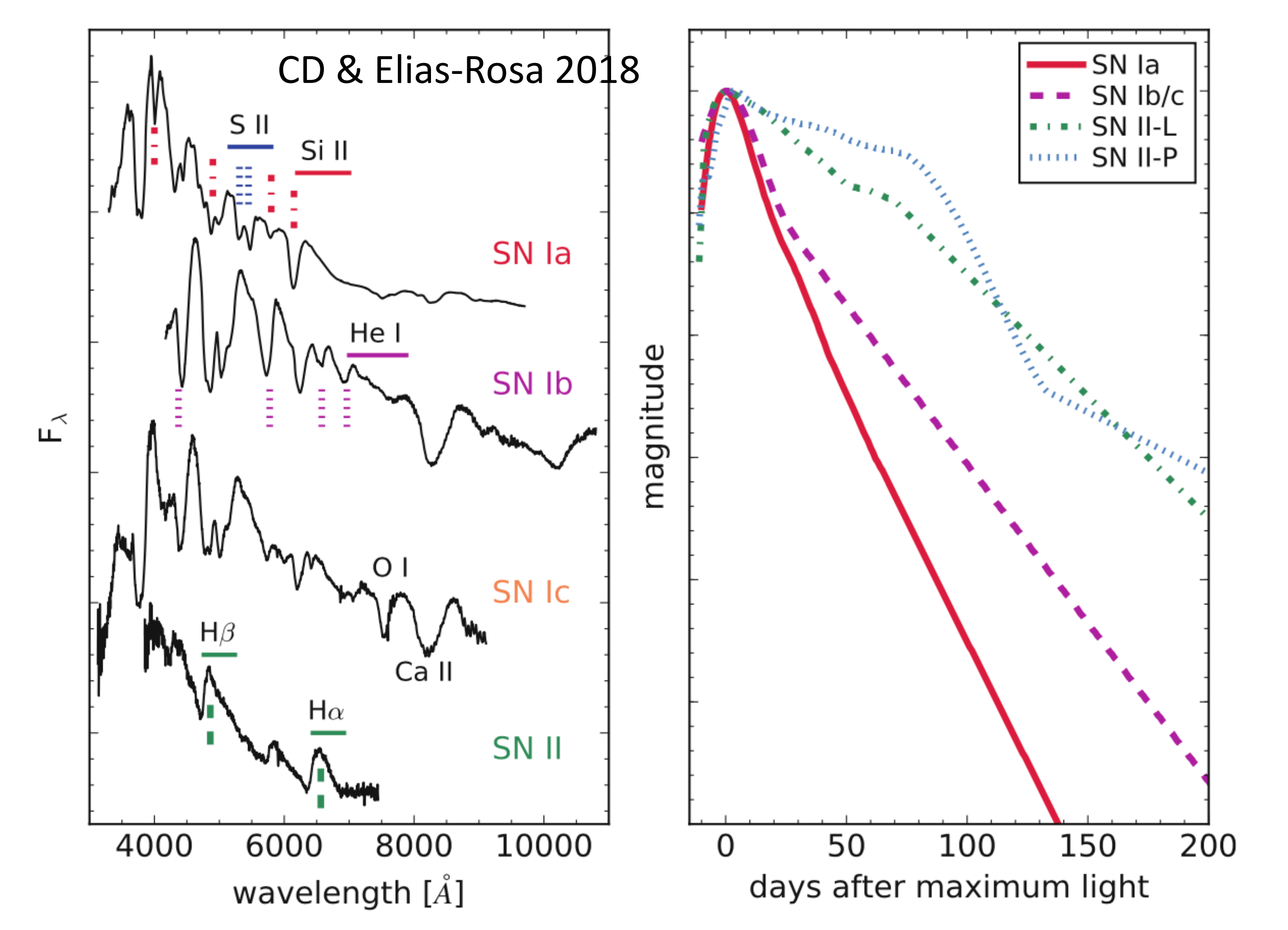


SN 1572:
Tycho Brahe
“New star”



(CHANDRA)

Supernova classification



Supernova classification

Hydrogen?	Silicon?	Helium?	Type	Sub-types	
NO	NO		Ia		Thermonuclear explosions
NO	YES	YES	Ib	Ibn	Core collapse SN (CCSN)
NO	YES	NO	Ic	Ic-BL, SLSN	Core collapse SN (CCSN)
YES			II	II-P, II-L, IIn, IIb	Core collapse SN (CCSN)

SN 1987A

David Malin

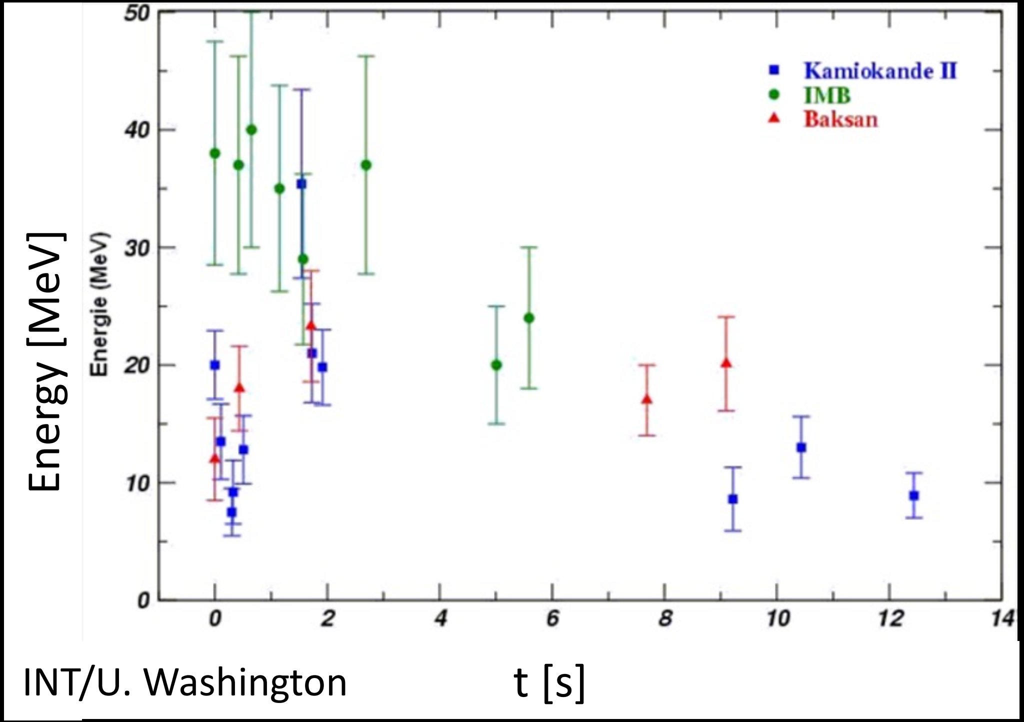
SN 1987A

At the LMC (51.4 kpc)

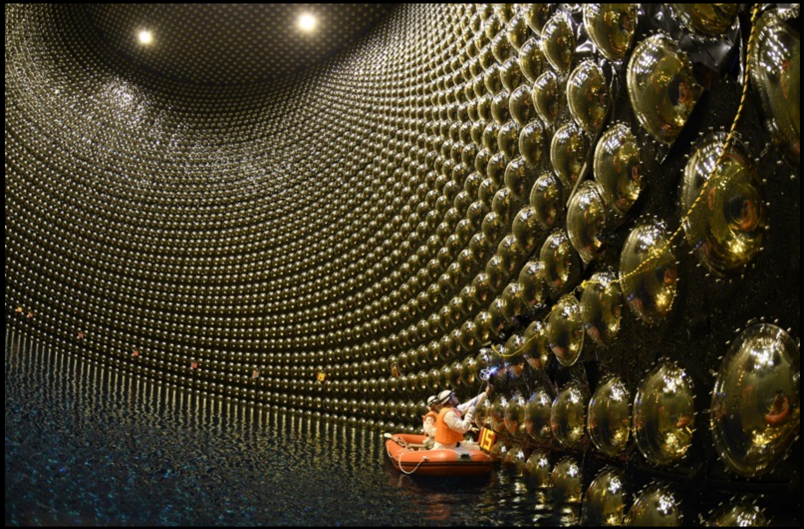
First observed nearby SN
in 383 yr

David Malin

SN 1987A – Birth of multi-messenger astronomy

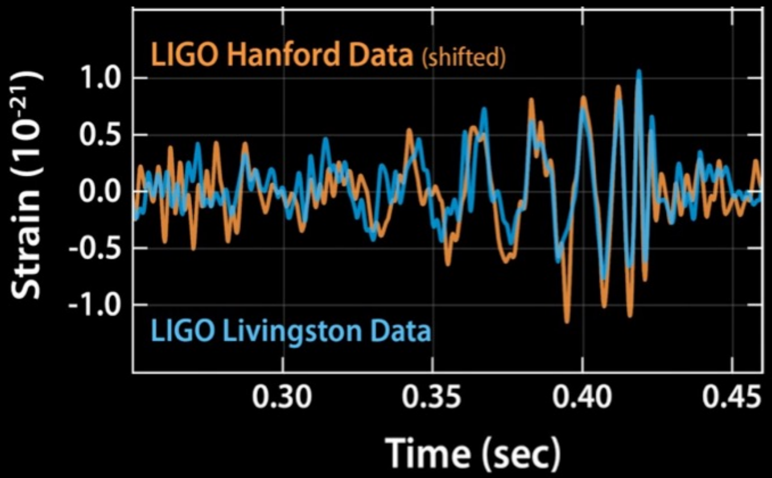


Kamiokande II (Japan): 12 antineutrinos
IMB (USA): 8 antineutrinos
Baksan (Russia): 5 antineutrinos



Gravitational wave era

2015: First BBH detection



2017: First BNS merger + kilonova

2019: First BH-NS merger

2015-20: 90 GW events detected (O1-O3)

Gravitational wave era

2015: First BB

O4 started on May 24 with improved sensitivity

What are the chances of detecting a supernova?
What could be learn from that detection?

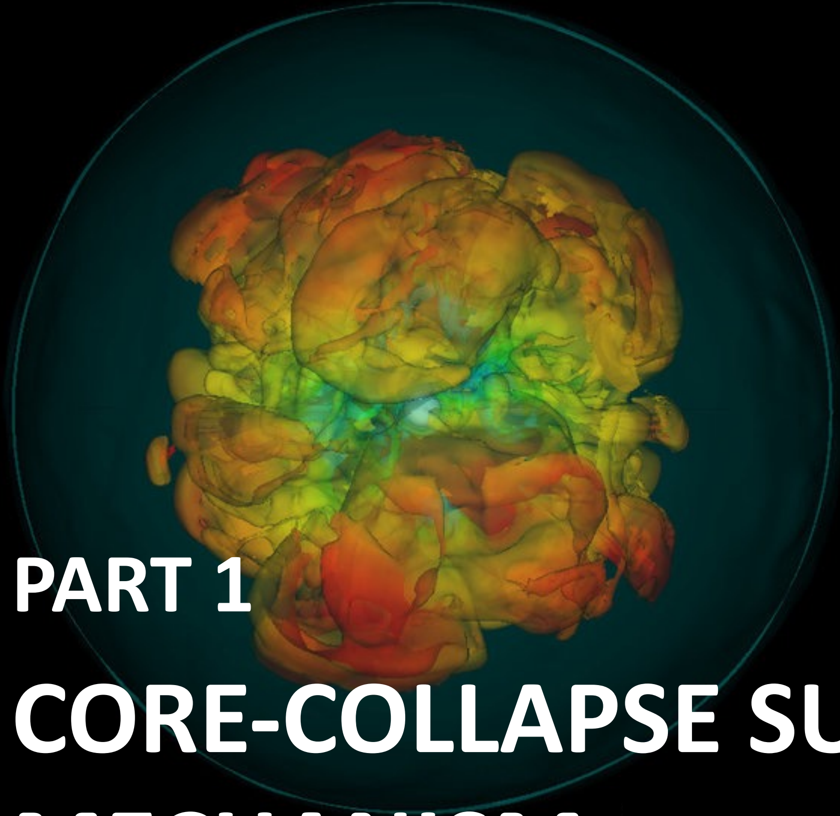
2017: First BNS merger + kilonova

2019: First BH-NS merger

2015-20: 90 GW events detected (O1-O3)

Part 1 – Core-collapse supernova mechanism

Part 2 – Gravitational waves from CCSNe



PART 1

CORE-COLLAPSE SUPERNOVA MECHANISM

Outline:

1.1 Evolution of massive stars

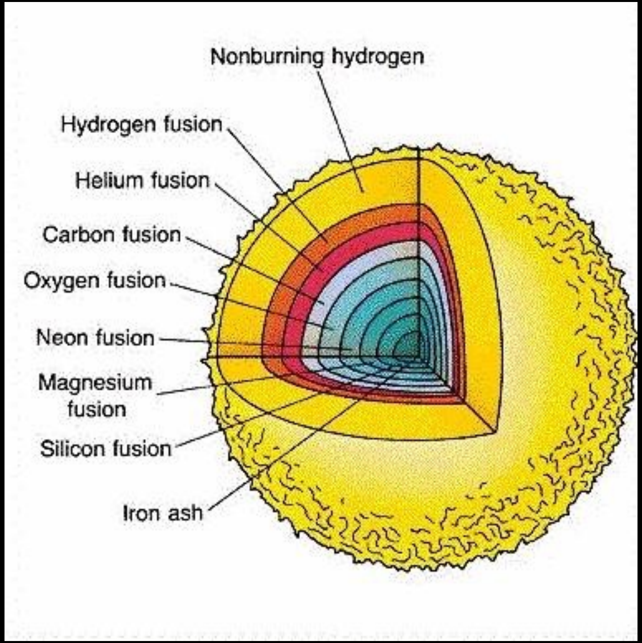
1.2 The standard supernova engine

1.3 Numerical simulations

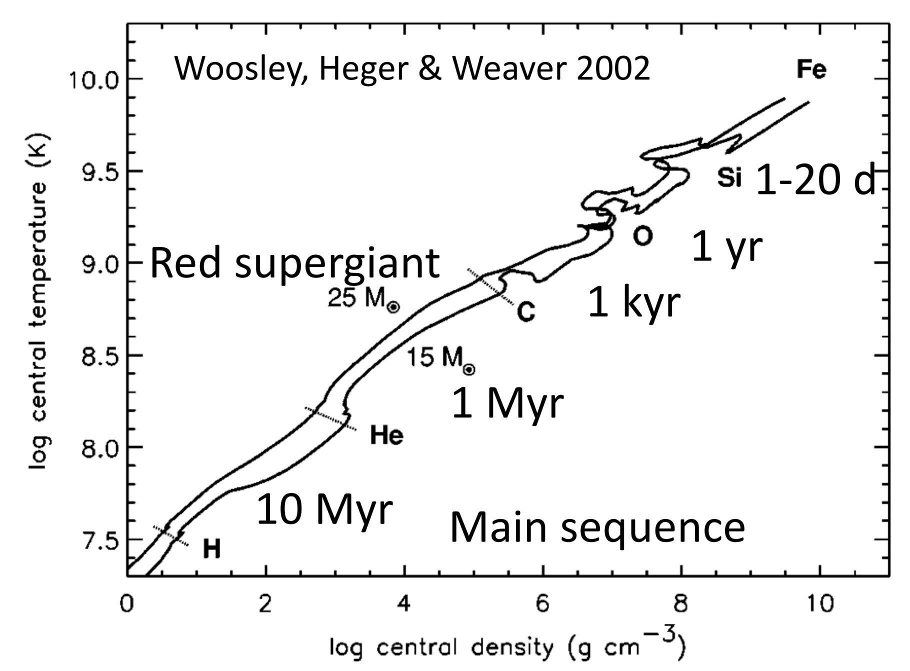
1.4 Magneto-rotational explosions

1.1 Evolution of massive stars

Stellar evolution



Thermonuclear combustion in phases creates an onion-like structure



Iron is the element with highest nuclear binding energy and the end of the fusion reaction chain

For a review see e.g. Woosley, Heger & Weaver 2002

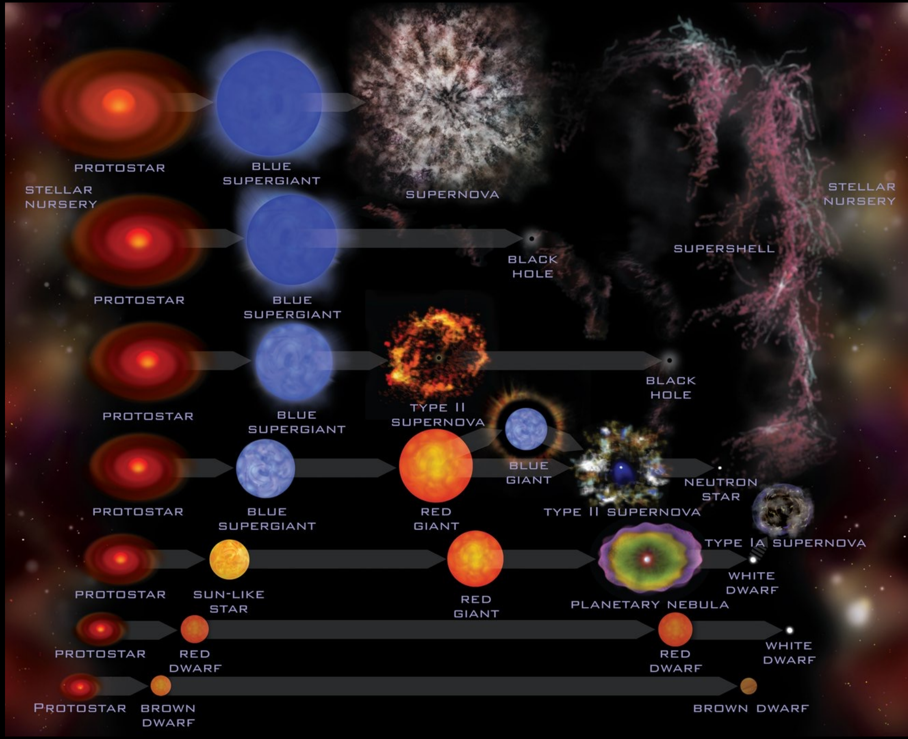
What determines the final fate of a star?

Initial conditions at birth (ZAMS*)

- Mass (M_{ZAMS})
- Rotation
- Metallicity ($Z/Z_\odot$)
- Binarity

* ZAMS = Zero Age Main Sequence

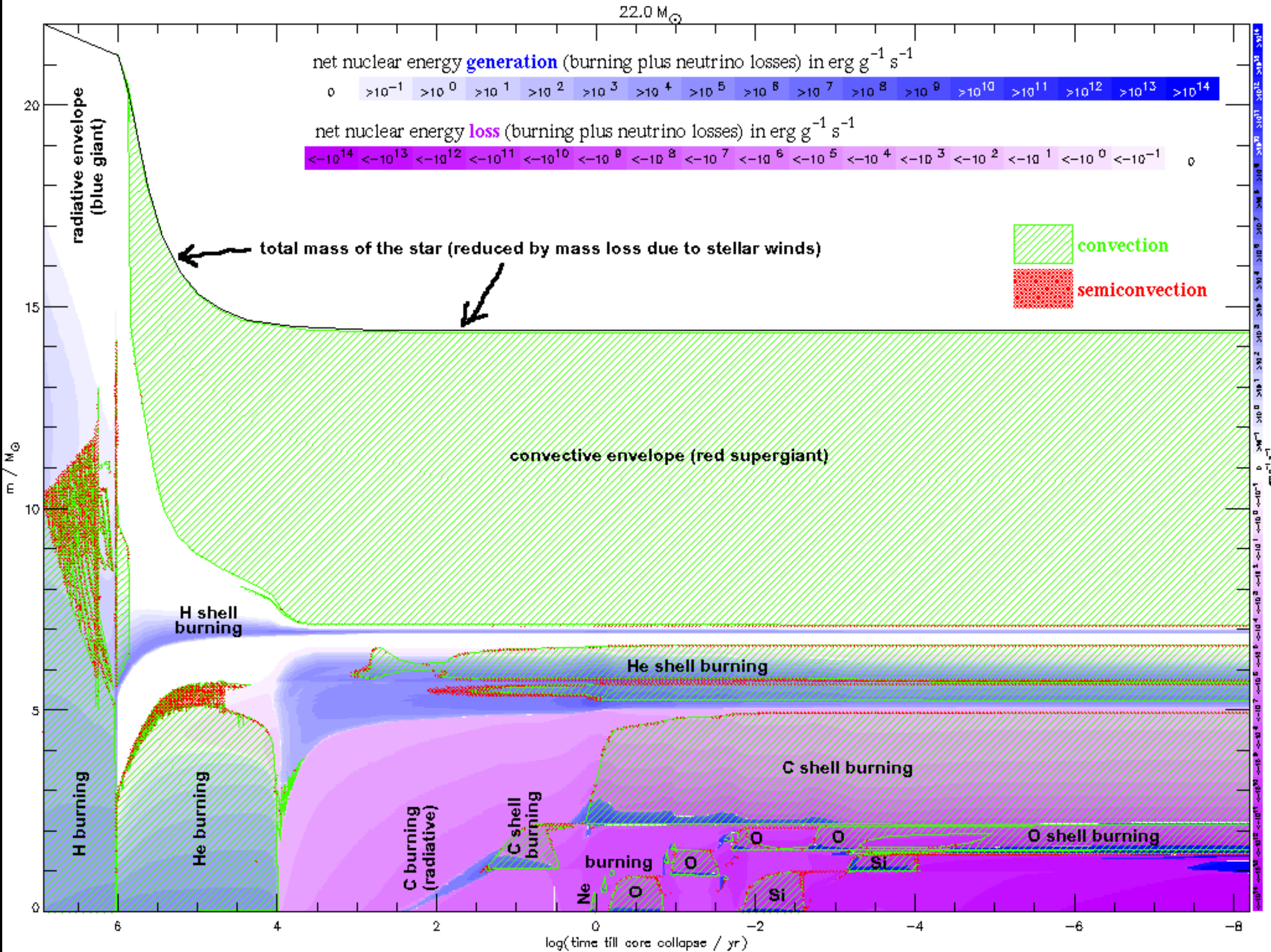
Core-collapse supernovae are produced in stars forming <u>iron cores</u>**



** It is also possible for O-Ne-Mg cores

Kippenhahn diagram

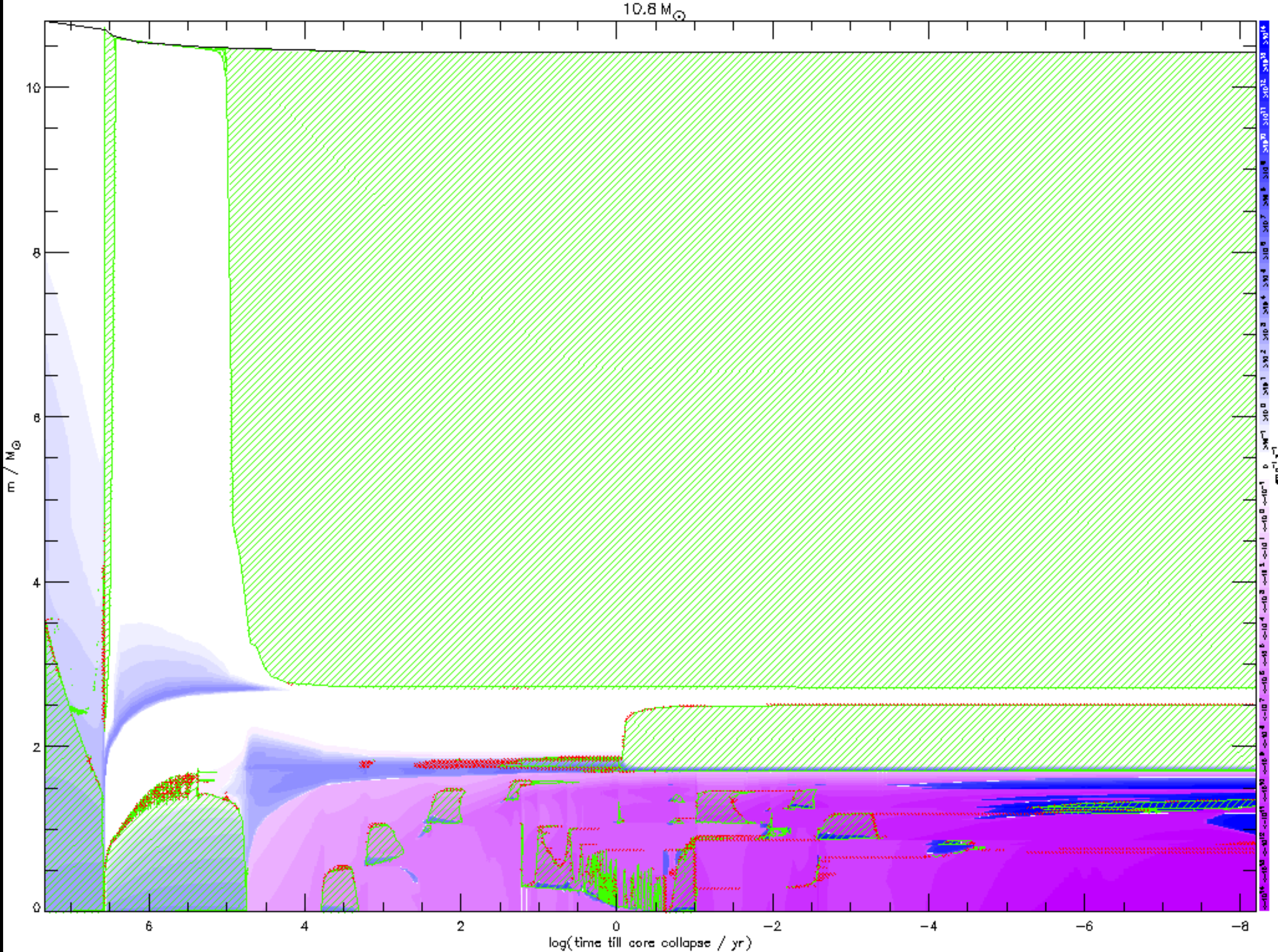
Stellar structure vs time ($10\text{-}30\ M_\odot$)



Source: A. Heger
https://2sn.org

Kippenhahn diagram

Stellar structure vs time
(10-30 $M_\odot$)



Source: A. Heger
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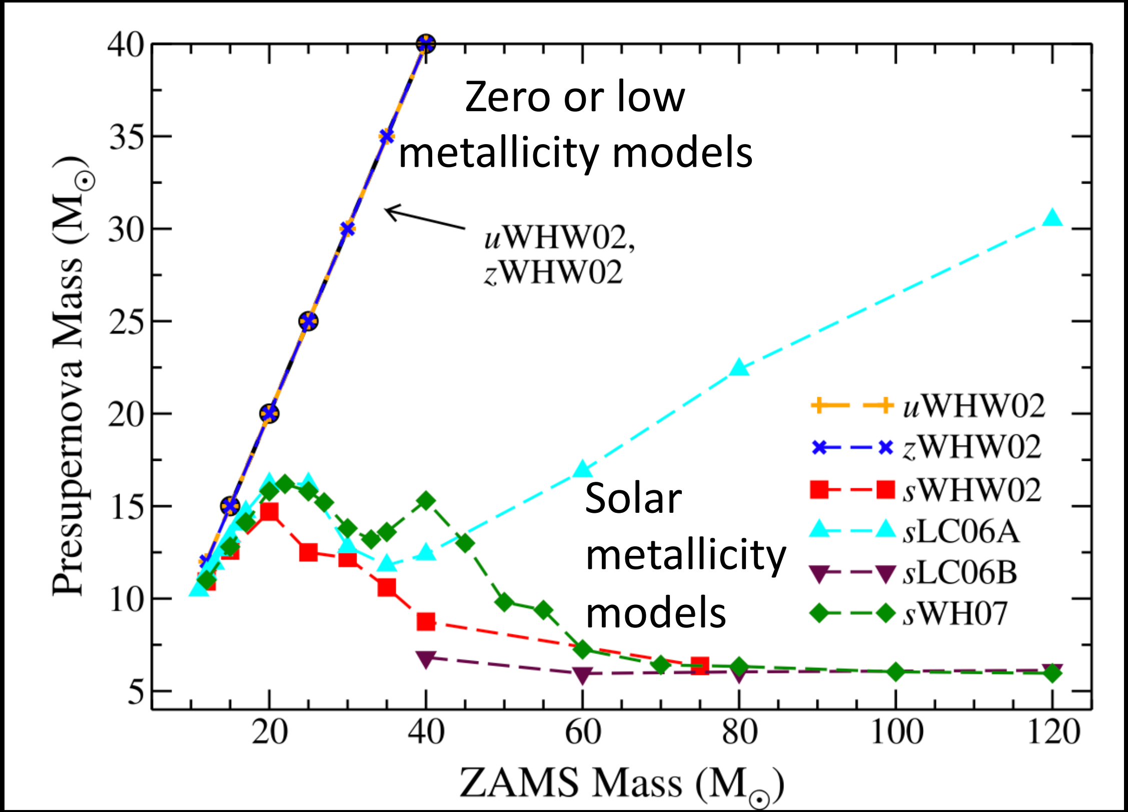
Metallicity and mass loss



O'Connor & Ott 2011

Massive stars loss mass through stellar winds

Mass loss rates:

- Large uncertainties
- rate ∝ opacities ∝ metallicity

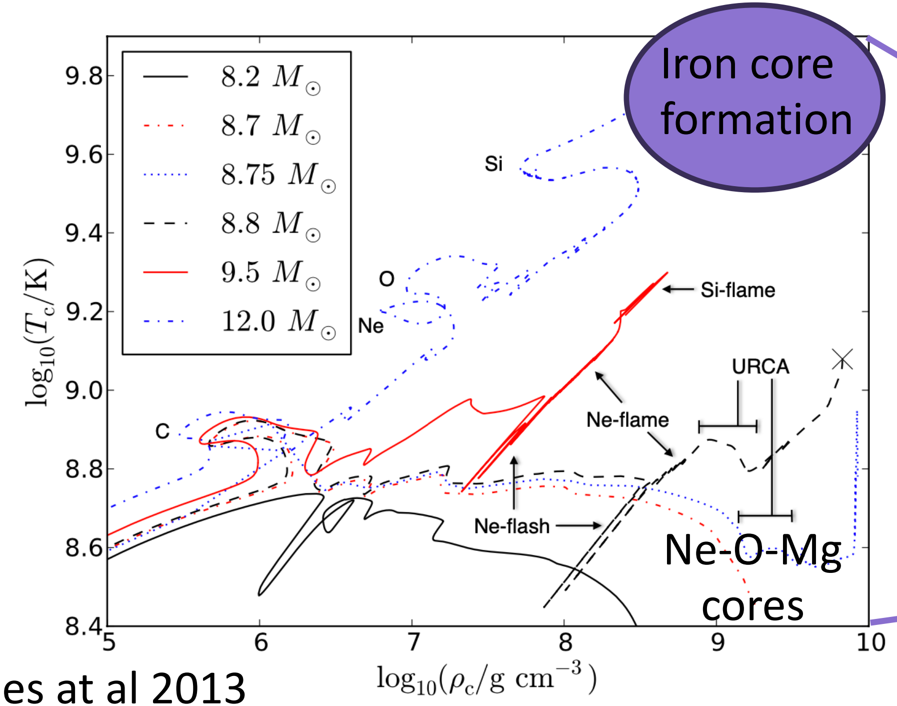
Iron-core formation – lower mass limit

Silicon burns to form Iron at T~3x10^9 K

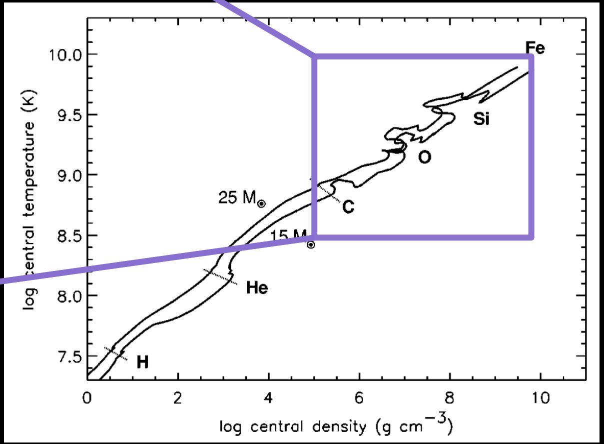
For solar metallicity, non-rotation, non interacting stars:

$M_{ZAMS} < 8\ M_\odot$: white dwarf → no CC
$M_{ZAMS} \sim 8\text{-}10\ M_\odot$: O-Ne-Mg cores → EC-SNe*
$M_{ZAMS} > 10\ M_\odot$: Fe cores → CCSN or BH formation

*EC-SNe = Electron capture supernovae



Jones at al 2013



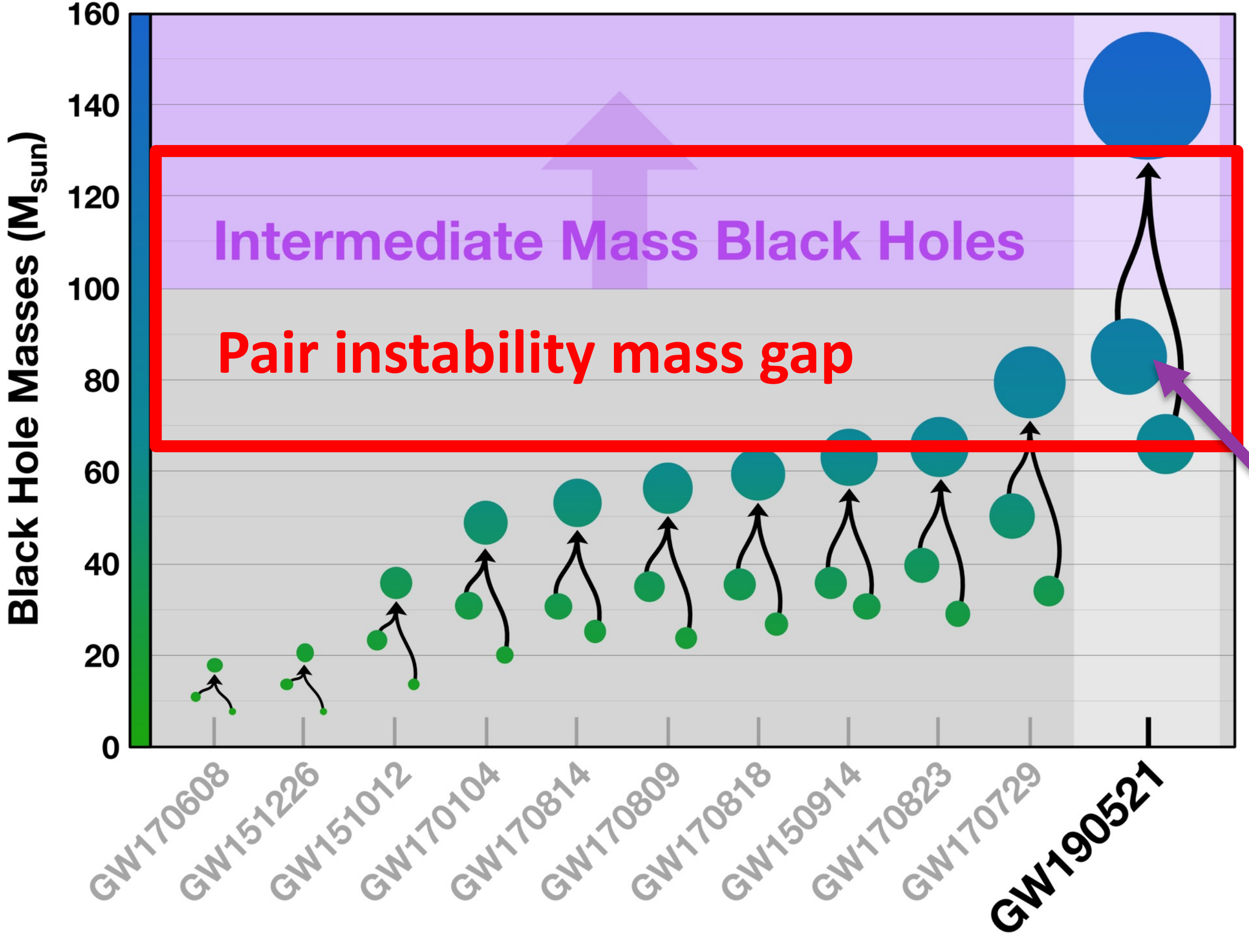
Iron-core formation – upper mass limit

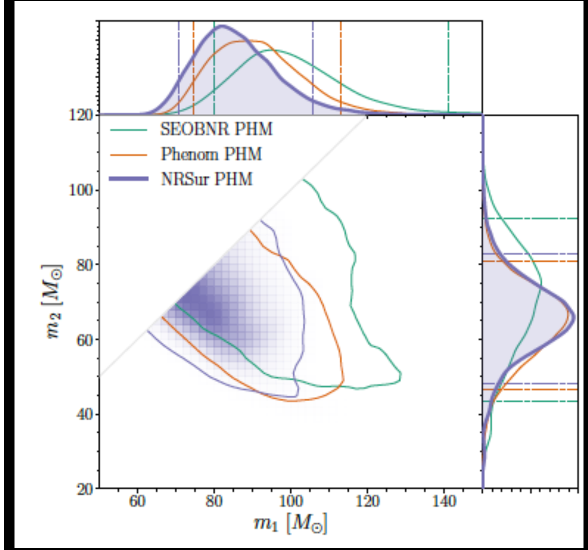
* There are uncertainties: 32-65 $M_\odot$

At the red-supergiant phase (He→ C burning):

M_{He} <40 $M_\odot$*	40-65 $M_\odot$	65-130 $M_\odot$	>130 $M_\odot$
$T<2\times10^9$ K No pair instability	$T>2\times10^9$ K → **Pair instability**: e^--e^+ pair production (energy goes into pairs → loss of pressure support) Runaway collapse → rapid C+O burning Gravity vs burning rate		
Normal evolution until iron core formation $M_{pre\text{-}SN}$ < 40 $M_\odot$	Partial mass ejection + Fe core formation Pulsating Pair Instability supernovae + CCSNe $M_{pre\text{-}SN}$ < 40 $M_\odot$	Complete disruption of the star Pair Instability supernova No iron core or black hole formation **PI mass gap**	Direct black hole formation M_{BH} > 130 $M_\odot$

LIGO-Virgo BH mergers in the PI mass gap





Inside the PI mass gap!
(65-130 $M_\odot$)

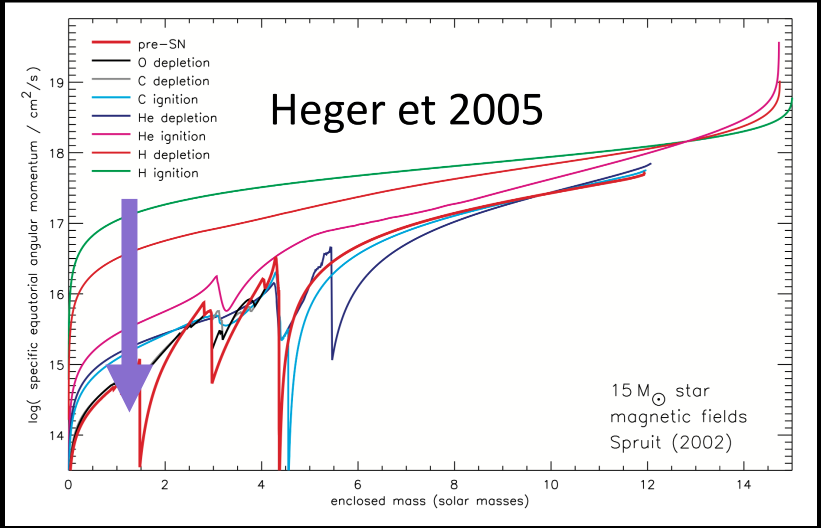
<65 $M_\odot$: 0.3%
<50 $M_\odot$: 0.1%

Abbott et al 2020

Rotation

Main sequence stars rotate rapidly ($v_{surface}$~200 km/s, Fukuda 1982)

Rotation → magnetic field generated by dynamos (Spruit 2002) → magnetic torques → rigid rotation



Supergiant phase

- Expansion of the envelope
  \+ angular momentum transport + winds
  → loss of angular momentum
  → **slow rotating iron cores**

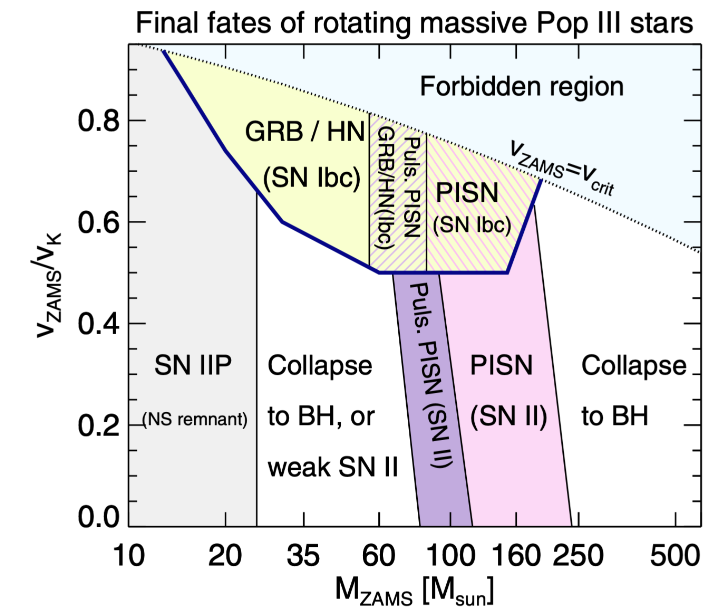
- Rotational mixing
  - Accelerated burning
  - Red→blue supergiant
  - Loss of H envelope → produce type Ib/Ic SN

Rotation

Very fast rotating stars at birth ($v_{surface}$~400 km/s)

Very efficient rotational induced mixing → chemically homogeneous evolution (efficient burning of H)

- No supergiant phase
- No hydrogen envelope (bare He cores, Wolf-Rayet-like stars) → may produce type Ib/Ic SN
- At low metallicity (pop III) → fast rotating Fe cores (Yoon & Langer 2005, Woosley & Heger 2006) → progenitors of long GRBs?



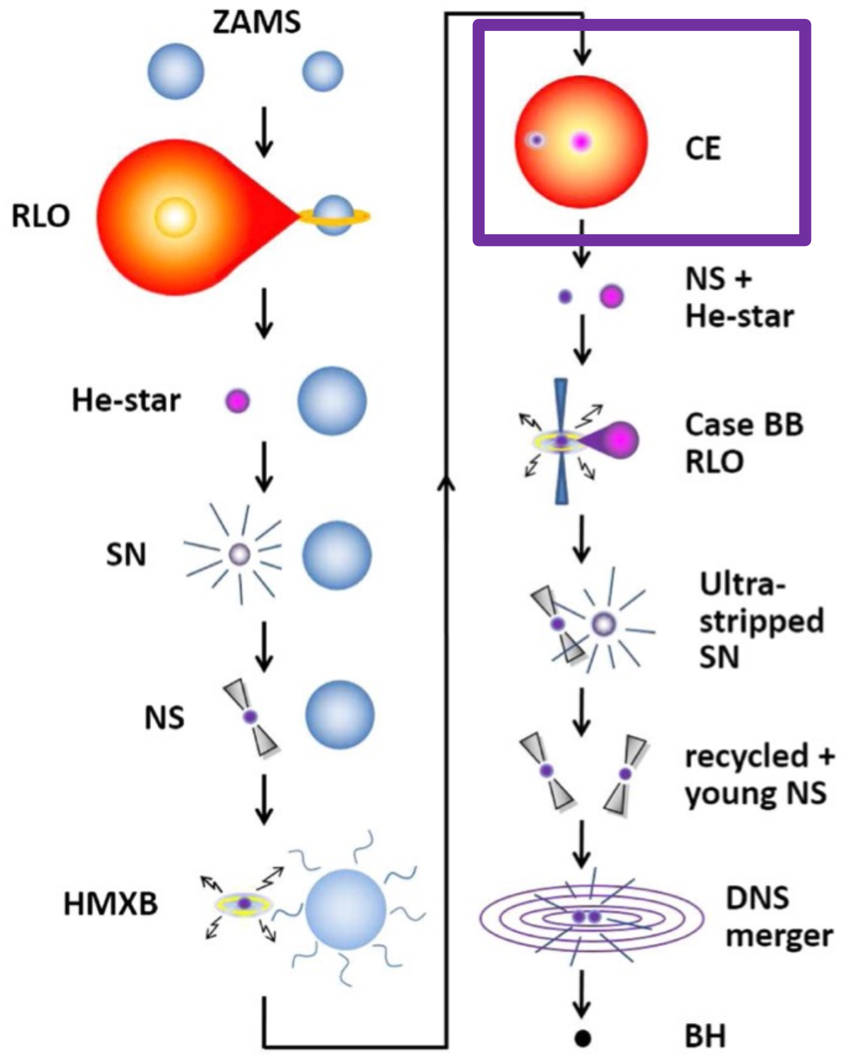
Yoon et al 2012

Stars in binaries

~70% of massive stars are in interacting binaries (Sana et al 2013)

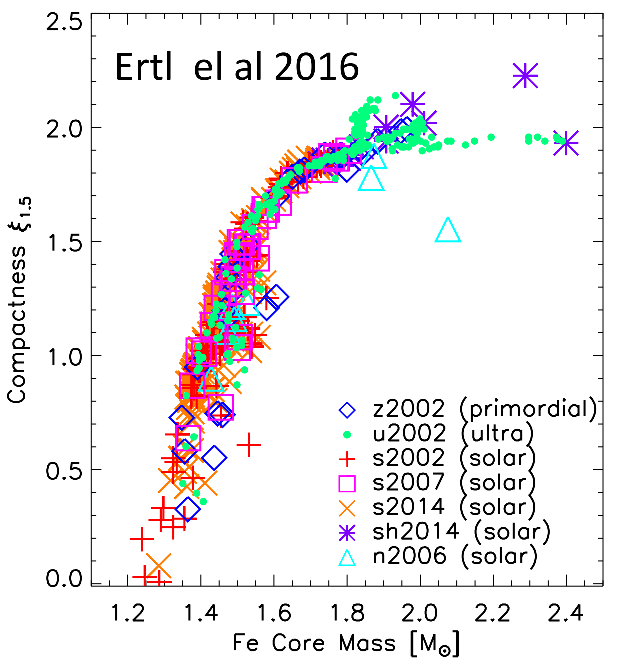
Large impact in stellar evolution:

- Envelope stripping during CE phase
- Mass accretion
- Extreme cases: ultra-stripped He cores (Tauris et al 2015)
- Binary mergers → highly magnetized stars (Schneider et al 2019)



Tauris et al 2017

Iron core stability



Iron core: supported by electron degeneracy pressure

Maximum mass – **Chandrasekhar mass** limit:

$$\frac{M_{\rm Ch}}{M_\odot} \approx 1.03 \left(\frac{Y_e}{0.42}\right)^2 \left[1 + 0.15\left(\frac{kT}{1\rm MeV}\right)^2\right]$$

C+O White dwarf: Y_e~0.5, kT << 1MeV → M_{Ch} = 1.46 $M_\odot$
Cold iron core: Y_e~0.42 → M_{Ch} = 1.03 $M_\odot$
Realistic iron core: Y_e~0.42, kT>1Mev → M_{Ch} ~ 1.4 $M_\odot$ (1.2-2 $M_\odot$)

Y_e : electron fraction
= electrons per baryon

M_{Fe}>M_{CH} → core becomes unstable to radial perturbations → collapse

Iron core properties

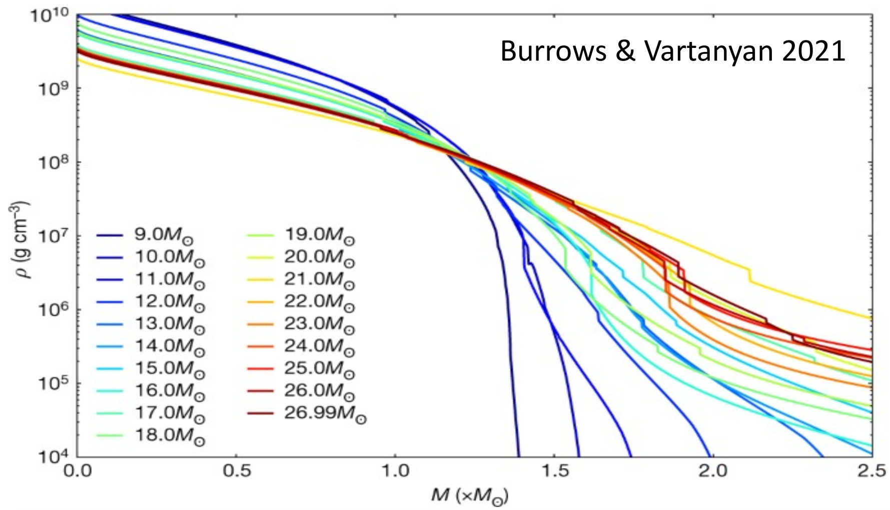
… at the onset of collapse

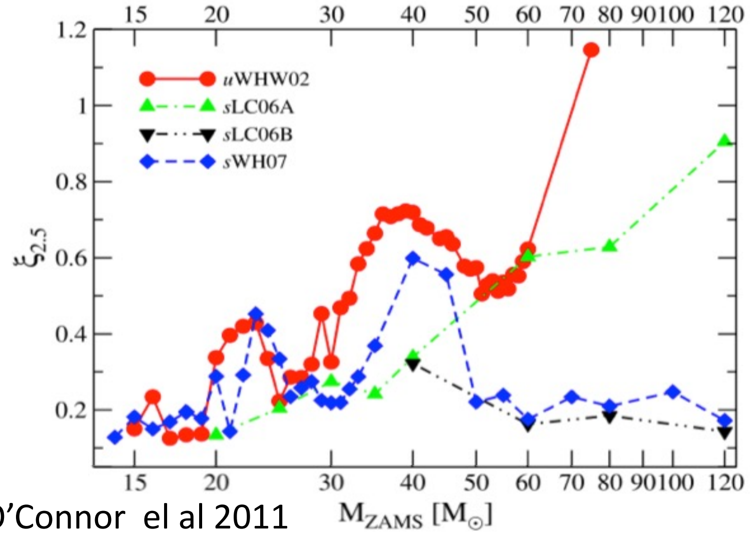
- Mass: 1.2-2.0 $M_\odot$
- Radius: ~3000 km
- Central density: ~10^{10} g cm^3
- Temperature: ~10^{10} K
- Compactness parameter @ 2.5 $M_\odot$

$$\xi_M = \frac{M/M_\odot}{R(M_{\rm bary} = M)/1000\,{\rm km}}\bigg|_{t=t_{\rm bounce}}$$

  – Small ξ_M : low densities outside the Fe core
  – Large ξ_M : high densities outside the Fe core

- Properties of the Fe core:
  – Depend on: initial mass, metallicity, rotation …
  – **Non-monotonic dependence**!





O'Connor el al 2011

1.2 The standard supernova engine

(neutrino-driven explosions)

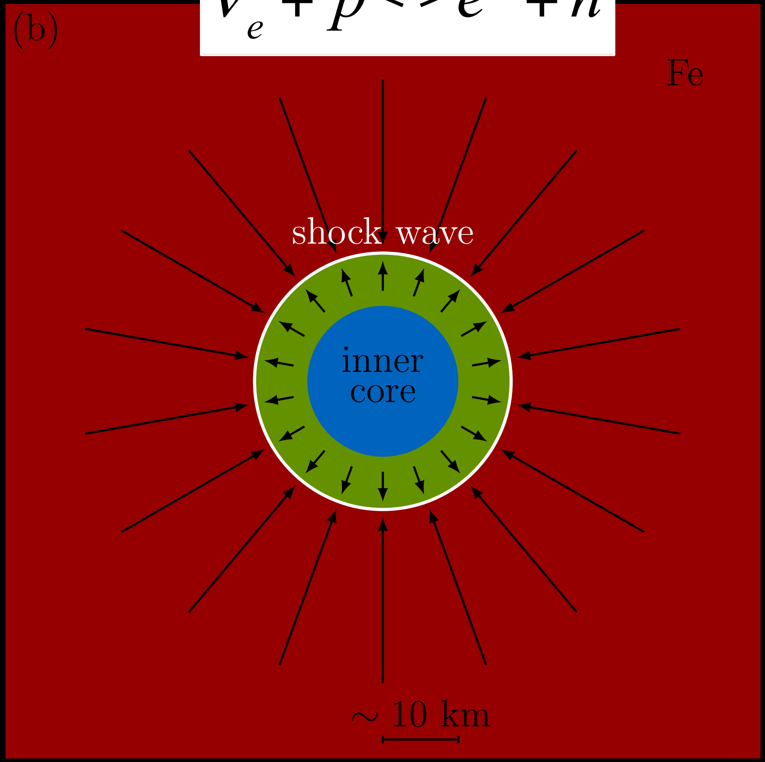
Core collapse and bounce

- Collapse acceleration
  - Electron captures decrease electron pressure
  - Photo-disintegration of Fe nuclei cools the core
- Inner region collapses supersonically
  - Electron captures
  - Neutrino/antineutrino production
- $\rho \sim 10^{12}$ g/cm^3: neutrinosphere
  - Trapped neutrinos
- $\rho \sim 10^{13}$ g/cm^3: neutrinos in thermal equilibrium
- $\rho \sim 2 \times 10^{14}$ g/cm^3: nuclear matter density
  - Phase transition from nuclei to free nucleons
  - Nuclear force dominant interaction
  - Equation of state (EOS) stiffens ($\Gamma_1 \sim 4/3 \rightarrow 2.5$)

Shock formation (bounce)

$$\nu_e + n \leftrightarrow e^- + p$$

$$\bar{\nu}_e + p \leftrightarrow e^+ + n$$

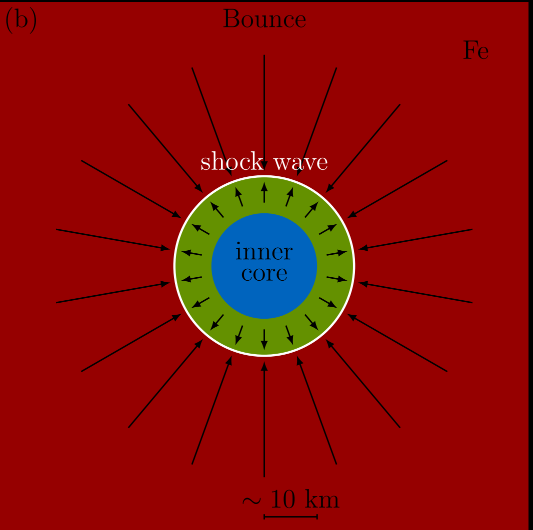


Core collapse - bounce

$M_{envelope} > M_{core}$

Proto-neutron star formation

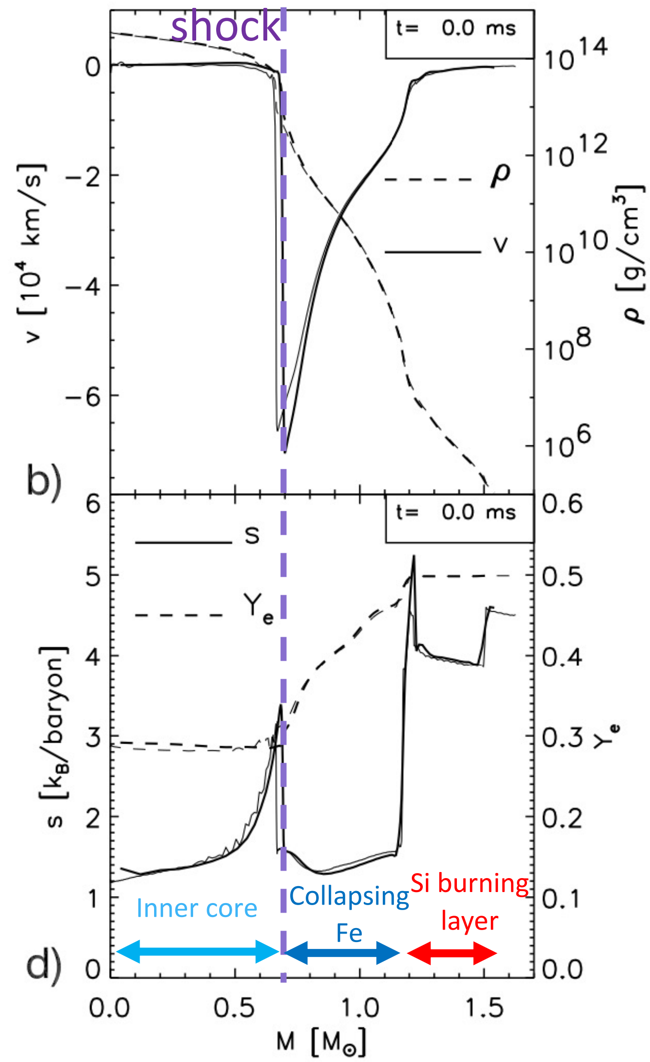
- **Mass inside the shock at bounce** : ~0.5 $M_\odot$
    - Depends weakly on EOS (sound speed) and neutrino interactions.
    - Barely depends on progenitor structure
- Inner core: unshocked cold material (s~1 k_B/nucleon)
- Hot PNS envelope (s~5 k_B/nucleon)



ALL COLLAPSING IRON CORE BOUNCE AND FORM A PNS

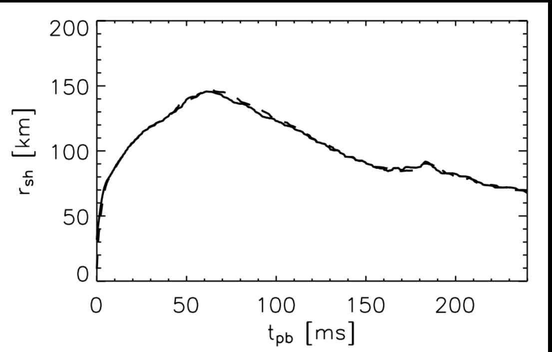
IT IS NOT POSSIBLE TO HAVE DIRECT BLACK HOLE FORMATION

Liebendörfer et al 2005



Proto-neutron star formation

- **Mass inside the shock at bounce** : ~0.7 $M_\odot$
  - Depends weakly on EOS (sound speed) and neutrino interactions.
  - Barely depends on progenitor structure
- Inner core: unshocked cold material (s~1 k_B/nucleon)
- Hot PNS envelope (s~5 k_B/nucleon)

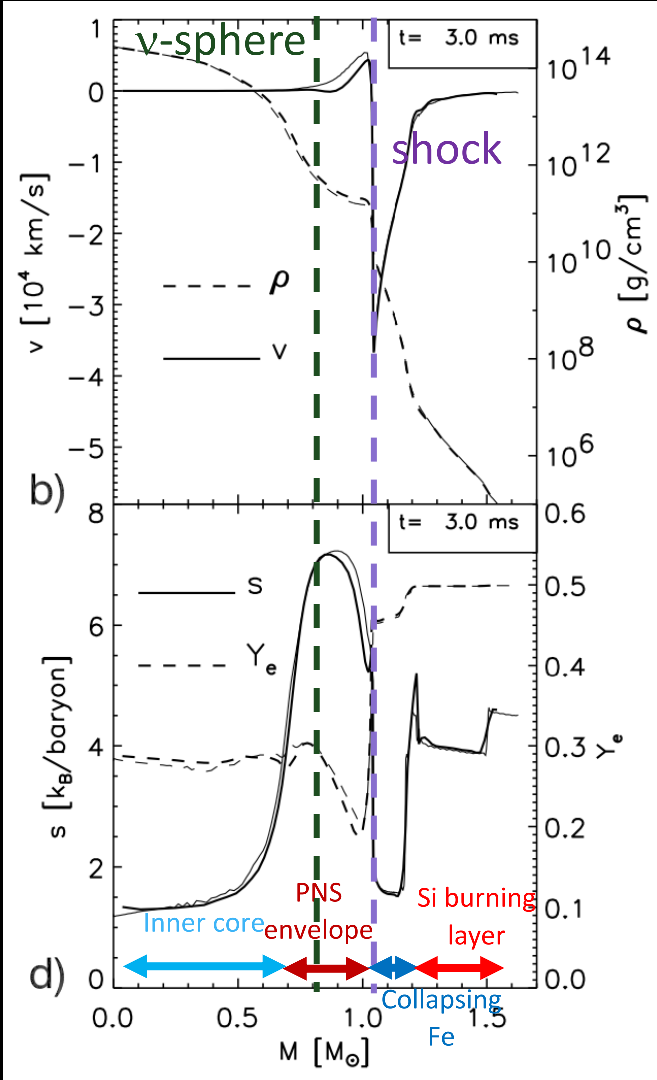


Buras et al 2006

Shock stalls at ~100 km
- Continuous infall of material:

Mass accretion rate depends on progenitor structure
- Disintegration of nuclei falling through the shock:

Iron binding energy ~8.8 MeV/nucleon



Liebendörfer et al 2005

Energetics

10^{53} erg!

Gravitational binding energy

$$U \sim \frac{GM^2}{R_{PNS}} - \frac{GM^2}{R_{core}} \sim 10^{53}\ \text{erg}$$

($M = 1.4 M_\odot$; R: 3000 km → 30 km)

↓

Kinetic energy

↓ ↓

Thermal energy
$\sim 10^{53}$ erg

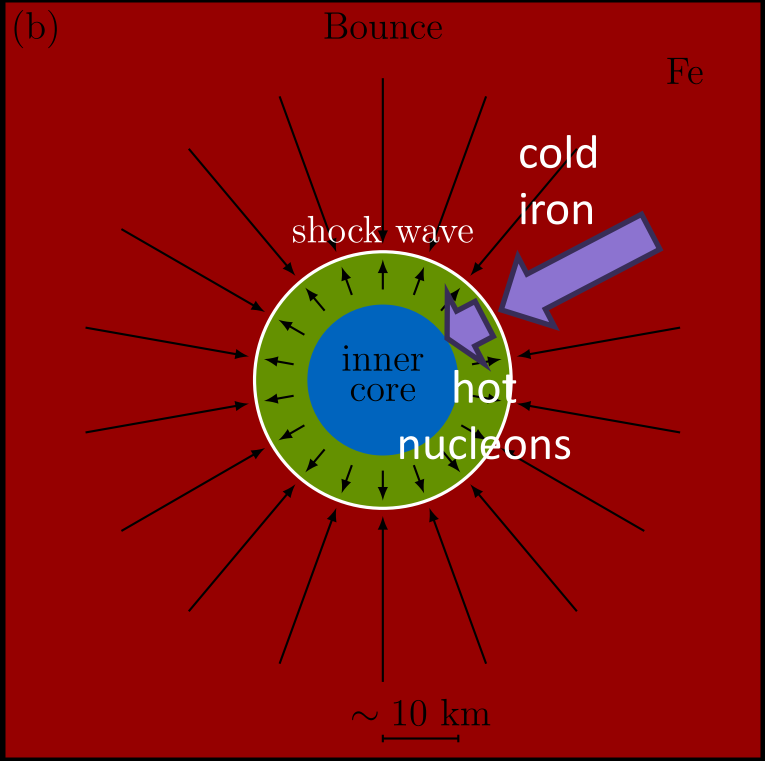
Iron disintegration
$0.5\ M_\odot$ of Fe
→ 10^{52} erg

↓

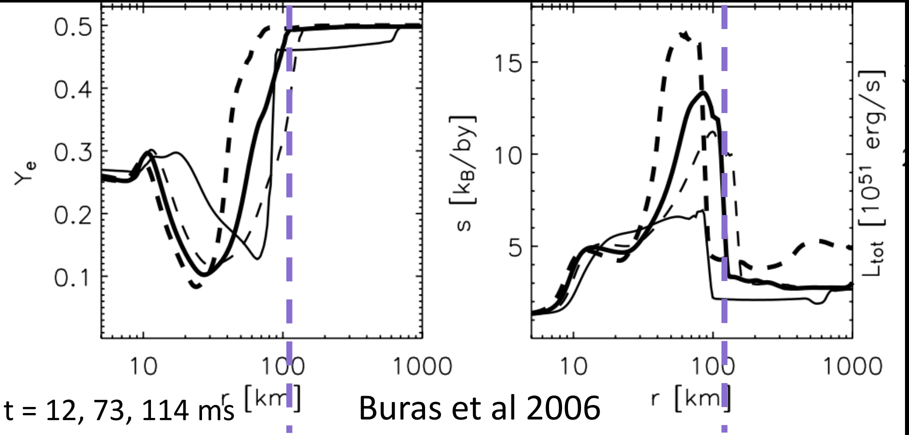
Neutrino emission
$\sim 10^{53}$ erg

→ 1% →

Explosion
$\sim 10^{51}$ erg



PNS neutrino emission



t = 12, 73, 114 ms Buras et al 2006

$\nu + e^{\pm} \rightleftharpoons \nu + e^{\pm}$ ......
$\nu + A \rightleftharpoons \nu + A$ ....
$\nu + N \rightleftharpoons \nu + N$ ....

Scattering

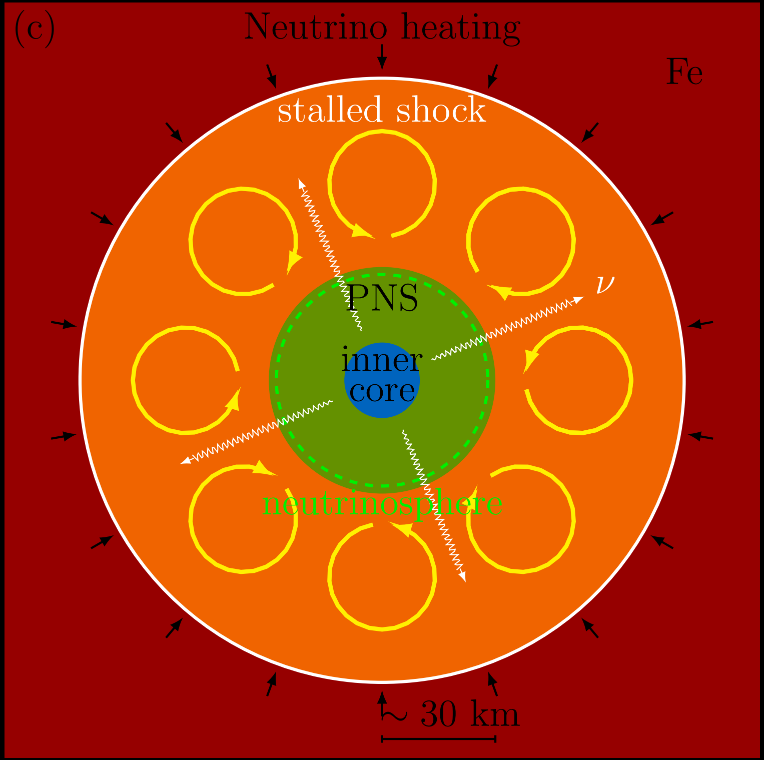
$\nu_e + n \rightleftharpoons e^- + p$ ....
$\bar{\nu}_e + p \rightleftharpoons e^+ + n$ ....
$\nu_e + A' \rightleftharpoons e^- + A$ .....

Absorption/emission of neutrinos by free nucleons and nuclei

$\nu + \bar{\nu} \rightleftharpoons e^- + e^+$ ....

Pair processes

Details on neutrino interactions:
Mezzacappa & Bruen 1993, Rampp & Janka 2002



Neutrino energy deposition

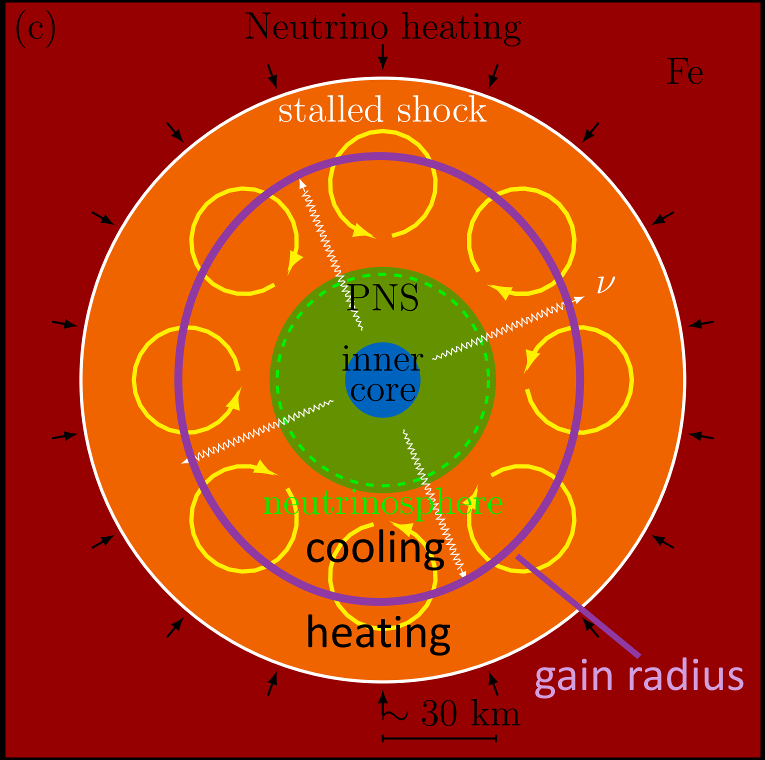
Gain radius:

neutrino energy absorption = emission

Gain layer:

net energy deposition

“hot bubble” convection



Hammer et al 2010

3D simulation

15.5 $M_\odot$ progenitor

color= entropy

Blue surface=shock front

Neutrino energy deposition

Energy deposition for radial flows (spherical symmetry)

$$\tau_{\rm adv} = \frac{M_{\rm g}}{\dot{M}},$$

advection time-scale

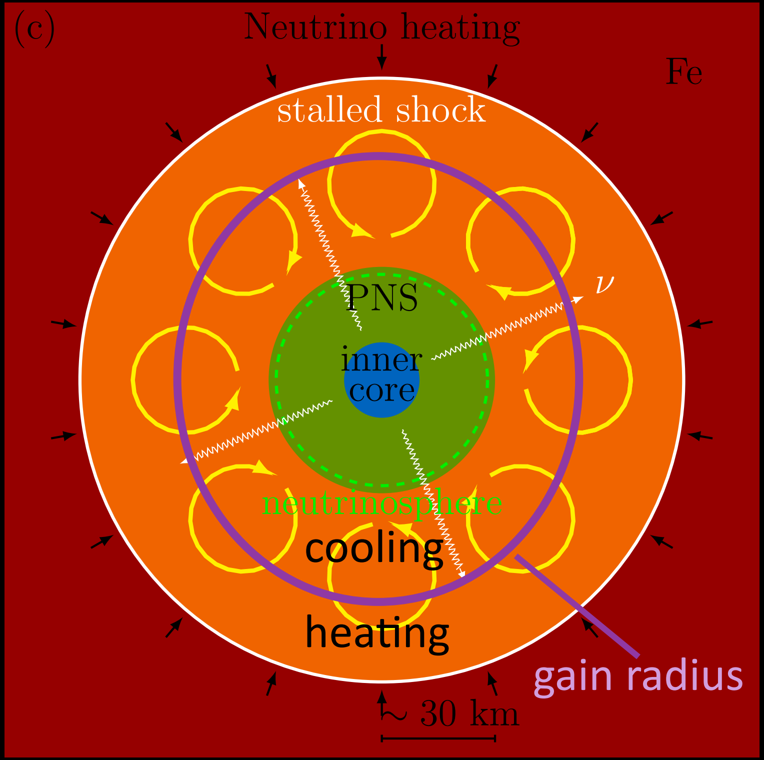
$$\tau_{\rm heat} = \frac{|E_{\rm g}|}{\dot{Q}_\nu}.$$

heating time-scale

$\dot{Q}$ = total heating rate in the gain layer

$\dot{M}$ = accretion rate

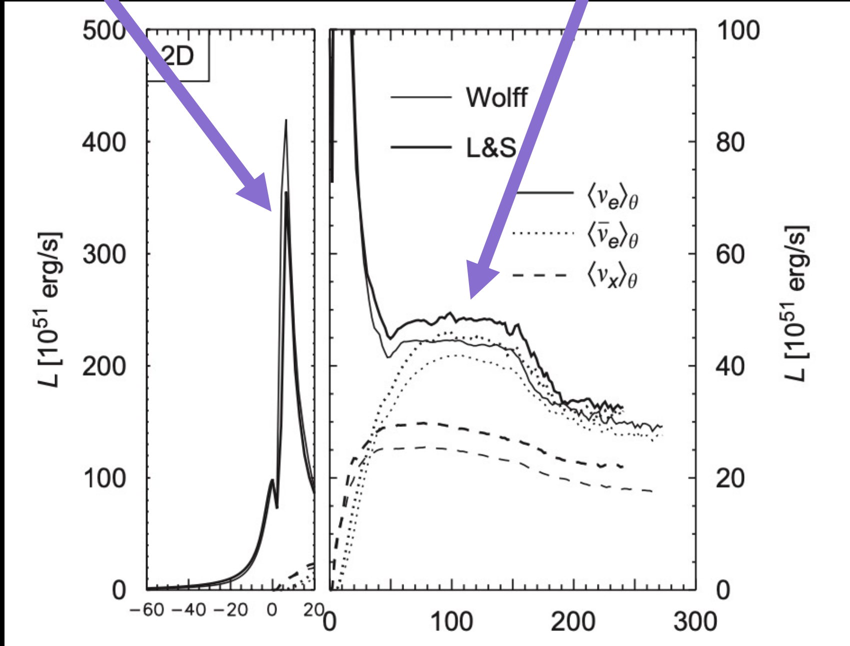
$\tau_{\rm adv}/\tau_{\rm heat} \gtrsim 1$: runaway explosion



Neutrino luminosity

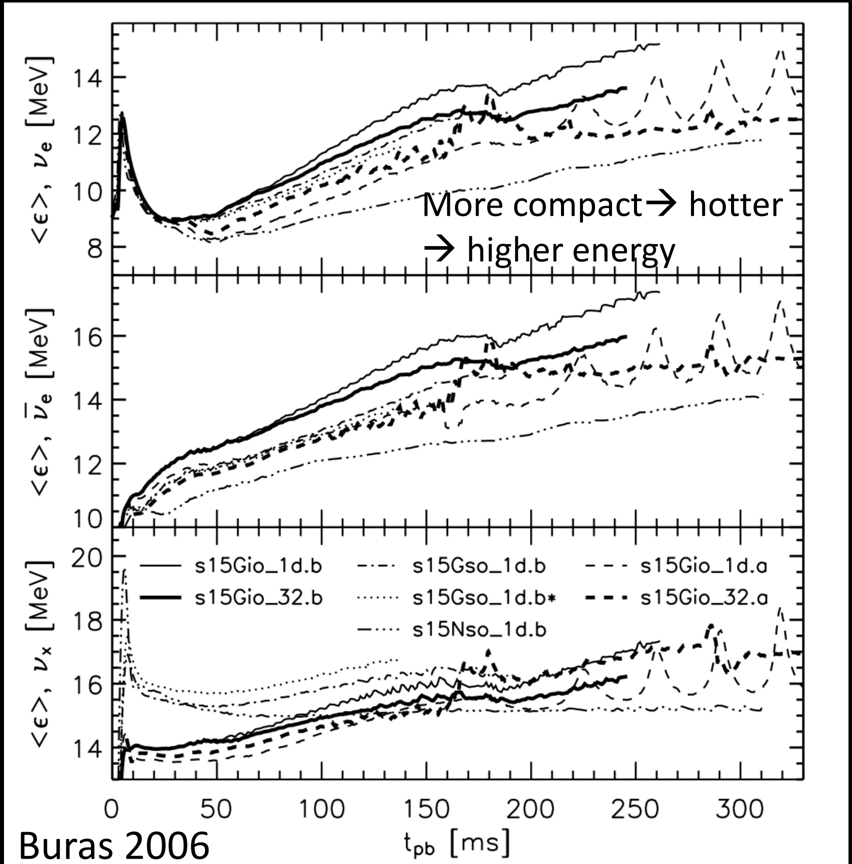
Neutrino burst (electron captures at PNS shock break out)

PNS neutrino/anti-neutrino diffusion



Janka 2007

Mean neutrino energy



Buras 2006

Explosion …

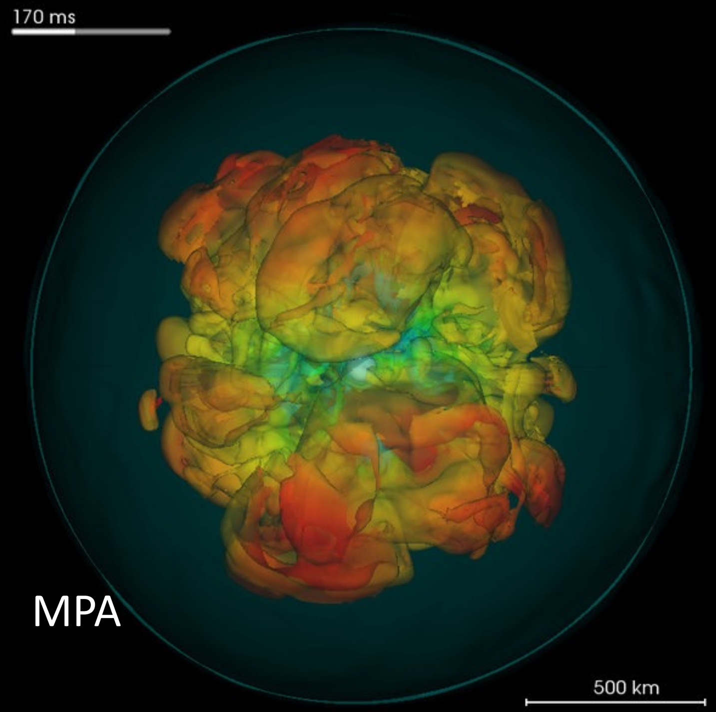
If ~1% of the neutrino energy is deposited behind the shock

Shock expansion

Ejection of all matter outside the shock

Core-Collapse Supernova (CCSN) explosion (neutrino-driven SN explosion)

PNS cools down into a neutron star



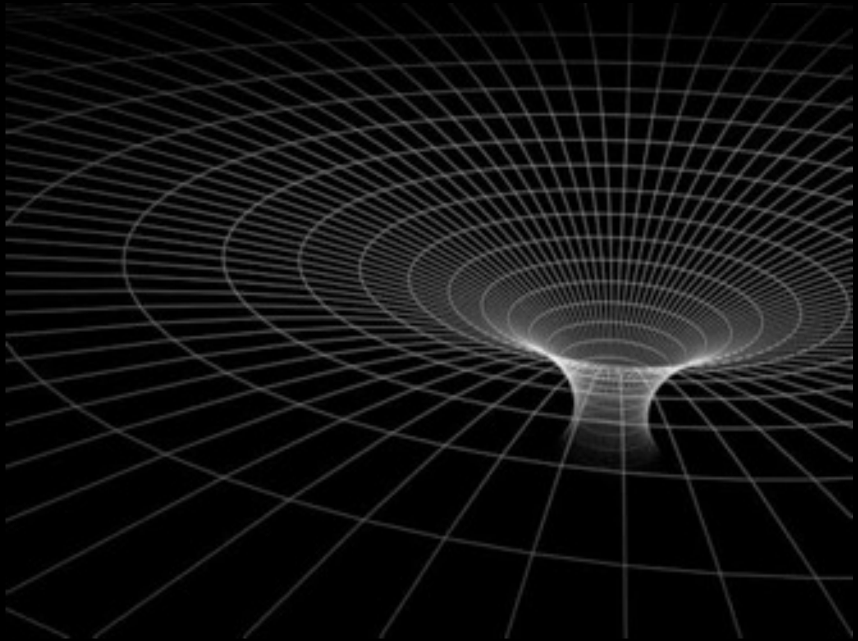
… or black hole formation

If neutrinos do not revive the shock

PNS mass grows by accretion

Maximum mass supported by EOS

Collapse to black hole
No SN explosion (unnovae)*



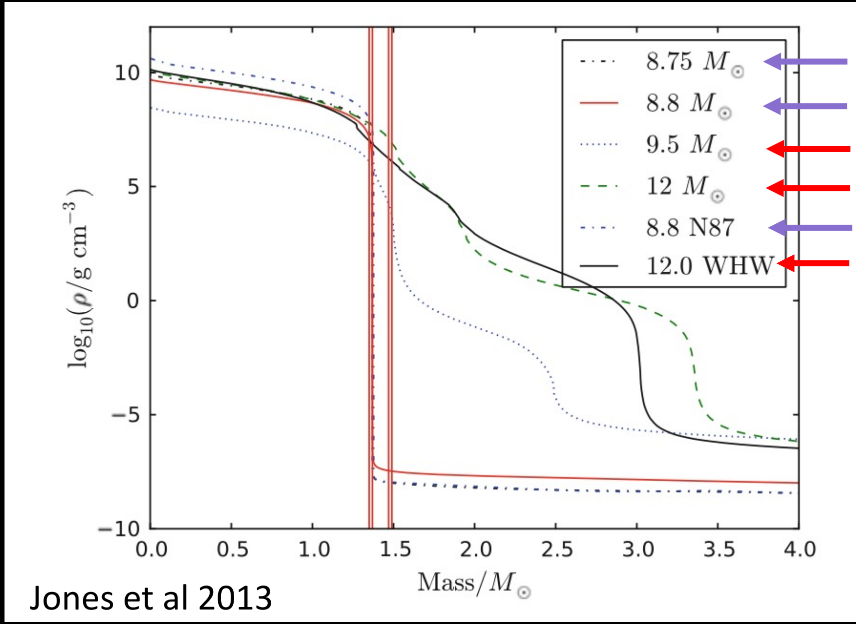
* In some cases you may have BH formation and SN (see e.g. Chan et al 2020)

Low mass progenitors

8-9 $M_\odot$: Ne-O-Mg cores → electron capture SN (ECSN)
9-12 $M_\odot$: Fe cores → Weak supernovae

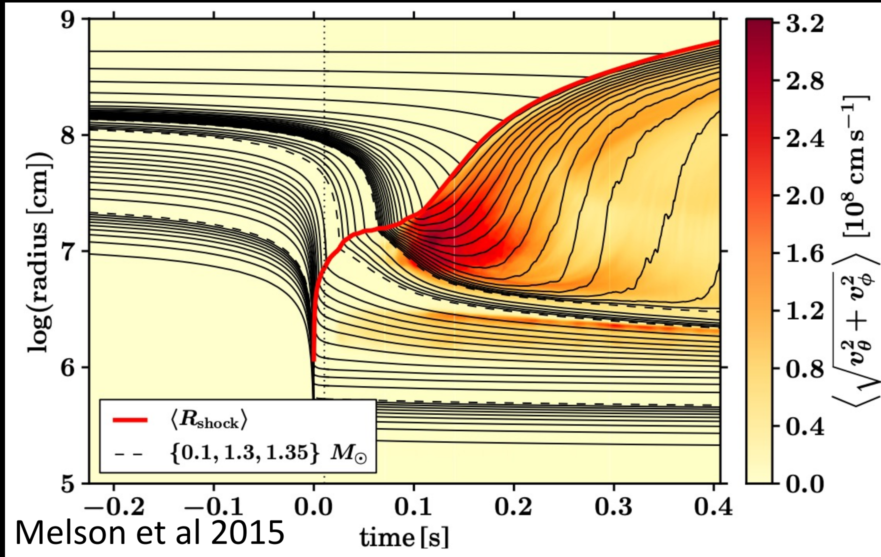
Low mass progenitors explode easily and produce weak SN explosions and low mass NS

Stellar structure in low mass progenitors



Jones et al 2013

"Prompt" explosion of a 9.6 $M_\odot$ (3D)



Melson et al 2015

Standing Shock Accretion Instability (SASI)

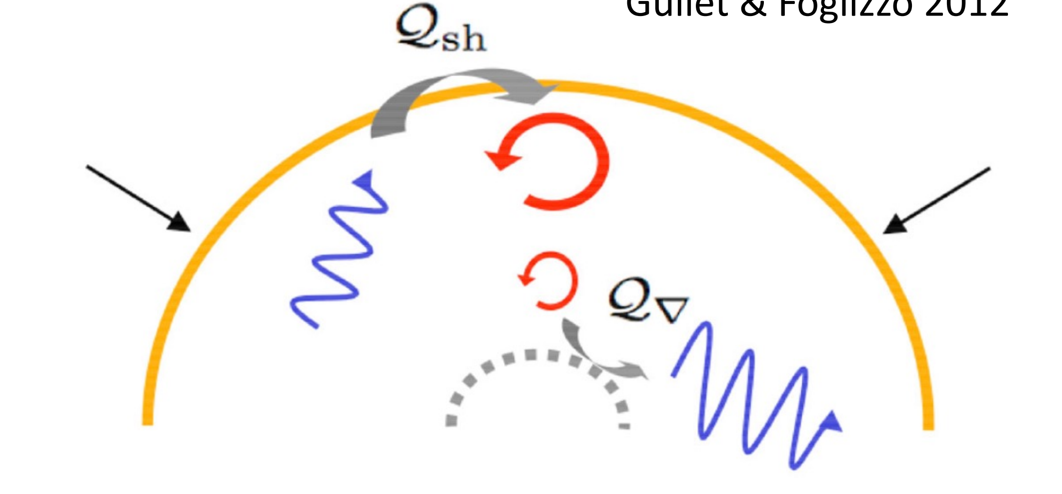
Unstable advection-acoustic cycle (Bondin et al 2003, Foglizzo et al 2006)
Oscillating low-l modes (l=1, 2)

For l=1 (sloshing modes):

$$T_{\rm SASI} = 19\,{\rm ms}\left(\frac{R_{\rm sh}}{100\,{\rm km}}\right)^{3/2}\ln\left(\frac{R_{\rm sh}}{R_{\rm PNS}}\right)$$

SASI does not appear generically.
Appropriate conditions are necessary.

Guilet & Foglizzo 2012



97 ms

Hanke et al 2013
3D simulation
27 $M_\odot$ progenitor
color= entropy
Blue surface=shock front

SWASI: Swallow water analogue of SASI
T. Foglizzo, CEA-Saclay

Role of instabilities

$$\tau_{\rm adv} = \frac{M_{\rm g}}{\dot{M}},$$

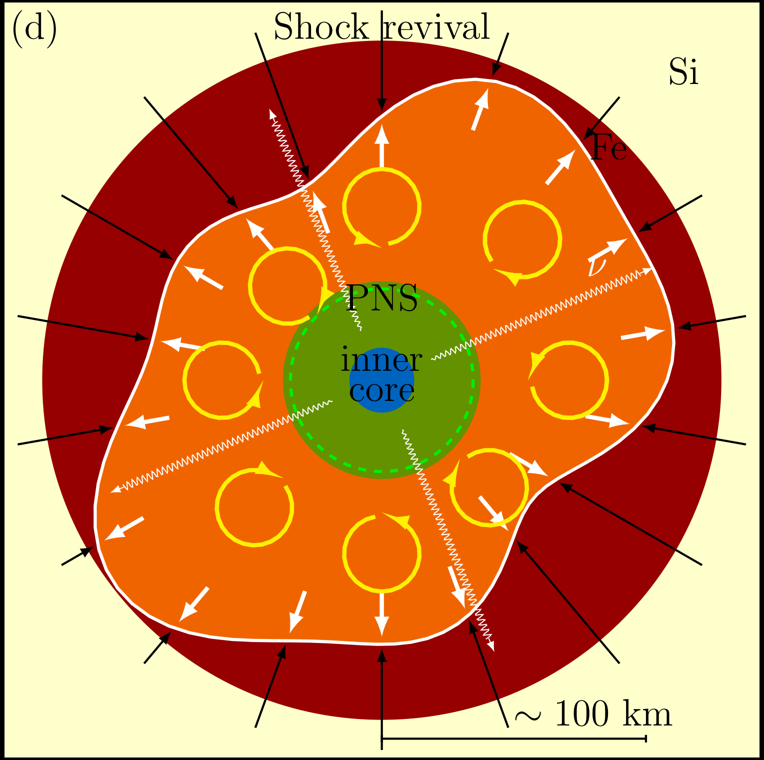
$$\tau_{\rm heat} = \frac{|E_{\rm g}|}{\dot{Q}_\nu}.$$

$$\tau_{\rm adv}/\tau_{\rm heat} \gtrsim 1$$

Convection / SASI → non-radial flows

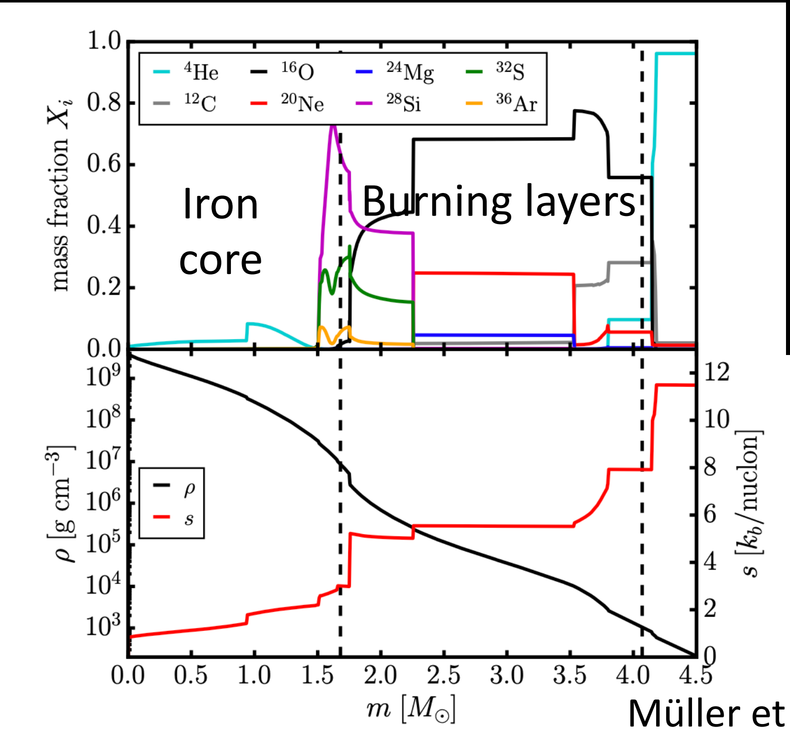
- Longer advection time in the gain layer
  → more energy absorbed
- More efficient neutrino-energy transfer
  → increased luminosity
- Extra turbulent pressure behind the shock

Non-radial flows are critical for most SN explosions



Perturbation-aided explosions

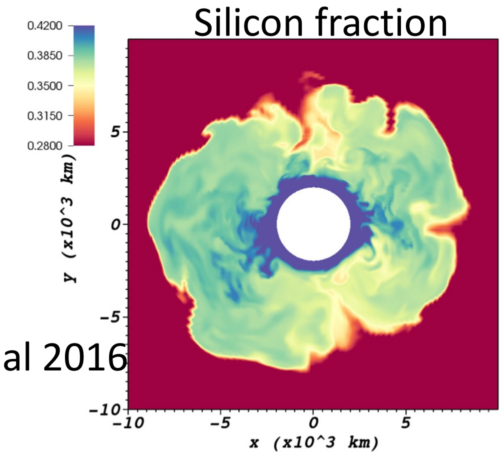
Burning at O and Si shells

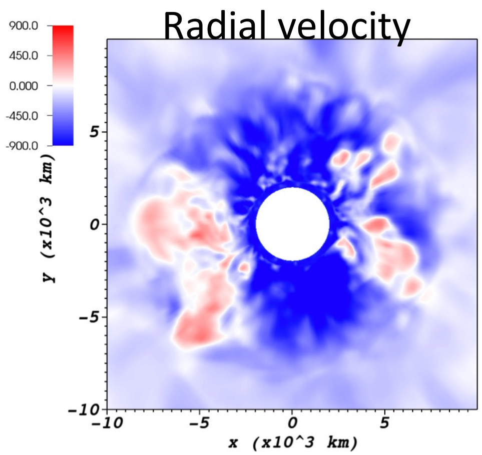


Müller et al 2016

Abundances of combustible elements close to core-collapse

Si layer at the onset of the collapse (18 $M_\odot$, 3D simulation)



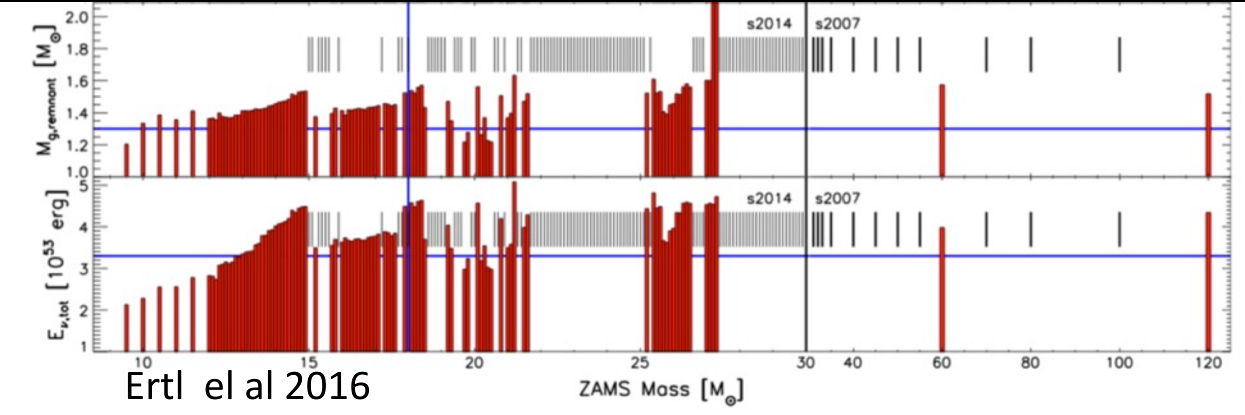


Explodability

Which progenitors produce SN explosions vs BHs → complex answer (no single mass threshold)

Remnant mass

Energy radiated in neutrinos



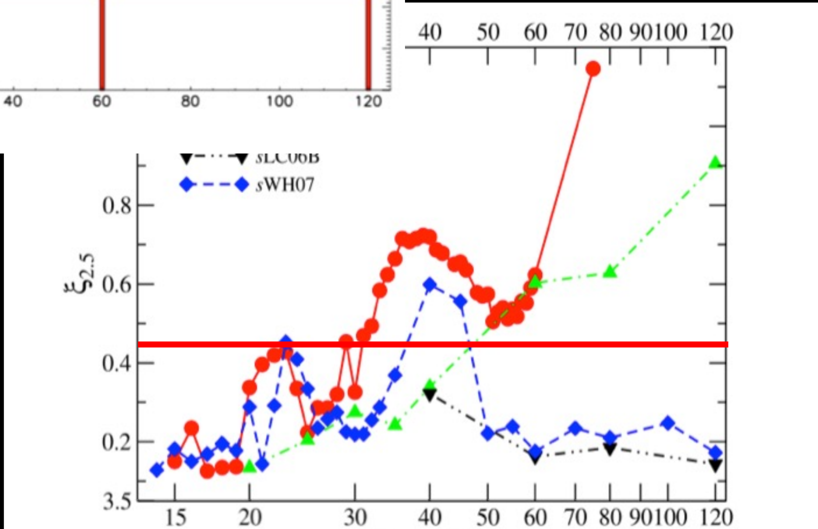
Ertl el al 2016

Details are an open question

Crude one-parameter criterion (O'Connor'2011)

$$\xi_{2.5} \gtrsim 0.45$$

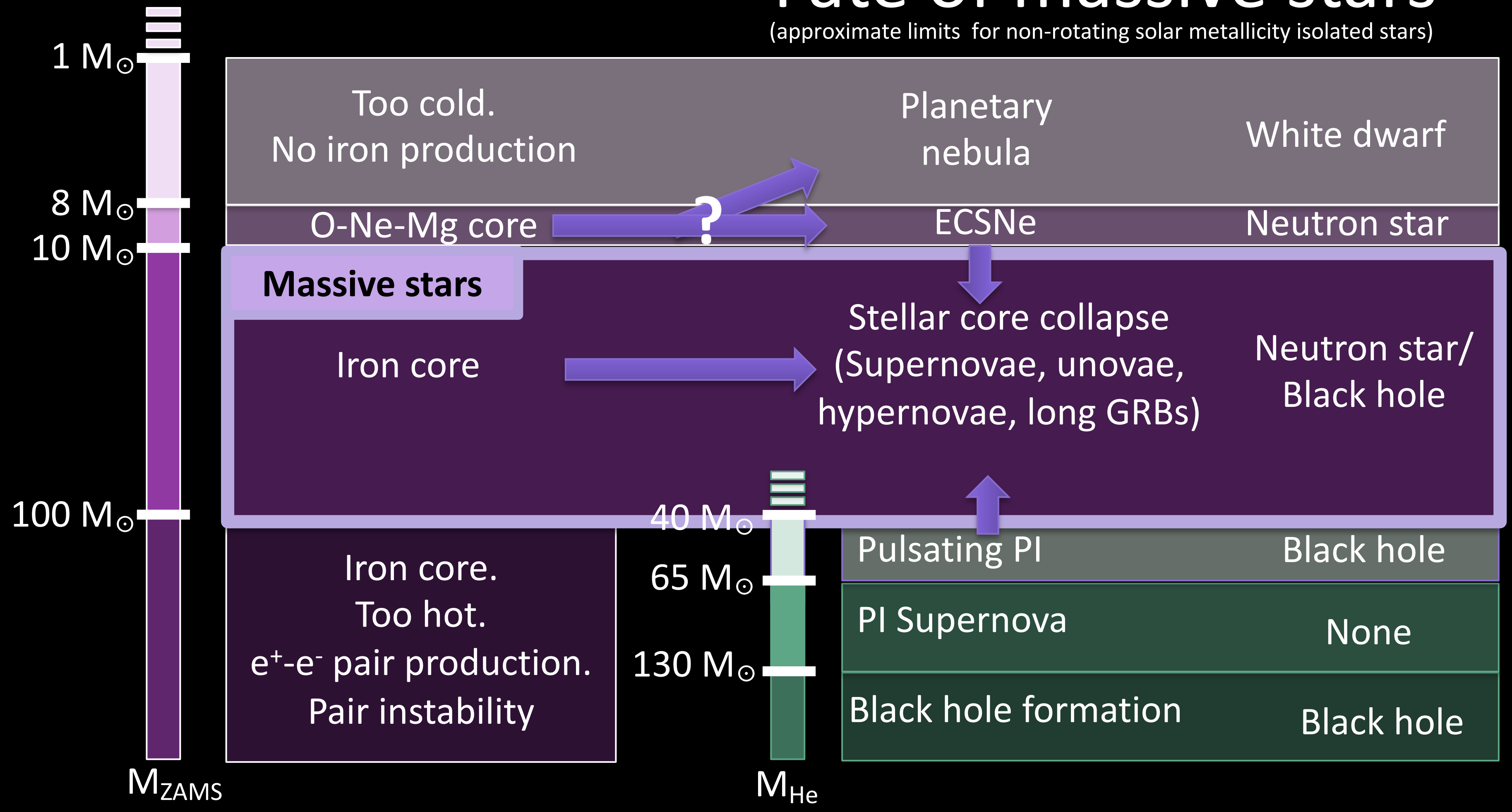
More sophisticated analysis/criteria are possible (Ertl et al 2016, Sukhbold et al 2016)



O'Connor el al 2011

Fate of massive stars

(approximate limits for non-rotating solar metallicity isolated stars)



1.3 Numerical simulations

Early numerical simulations - 60s

Colgate & White 1965, Arnett 1966, Wilson 1971 …

THE HYDRODYNAMIC BEHAVIOR OF SUPERNOVAE EXPLOSIONS*

STIRLING A. COLGATE AND RICHARD H. WHITE
Lawrence Radiation Laboratory, University of California, Livermore, California
Received June 29, 1965

ABSTRACT

We regard the release of gravitational energy attending a dynamic change in configuration to be the primary energy source in supernovae explosions. Although we were initially inspired by and agree in detail with the mechanism for initiating gravitational instability proposed by Burbidge, Burbidge, Fowler, and Hoyle, we find that the dynamical implosion is so violent that an energy many times greater than the available thermonuclear energy is released from the star's core and transferred to the star's mantle in a supernova explosion. The energy released corresponds to the change in gravitational potential of the unstable imploding core; the transfer of energy takes place by the emission and deposition of neutrinos.

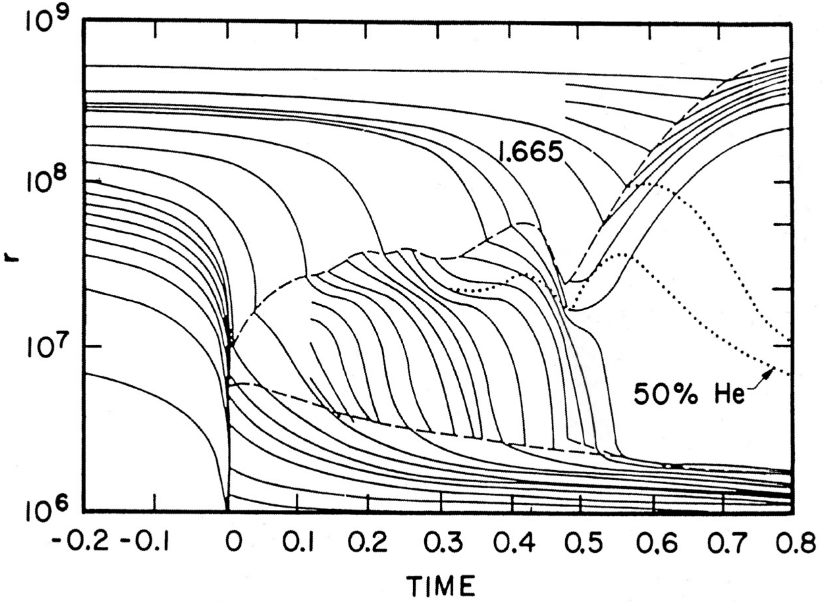
Early numerical simulations - 80s

REVIVAL OF A STALLED SUPERNOVA SHOCK BY NEUTRINO HEATING

HANS A. BETHE
Laboratory of Nuclear Studies, Cornell University
AND
JAMES R. WILSON
Lawrence Livermore National Laboratory
Received 1984 March 23; accepted 1985 February 5

"As the legend goes, it was Jim Wilson who made this discovery by accidentally forgetting to stop one of his simulations, allowing it to run much longer than he had intended" (Couch 2017)

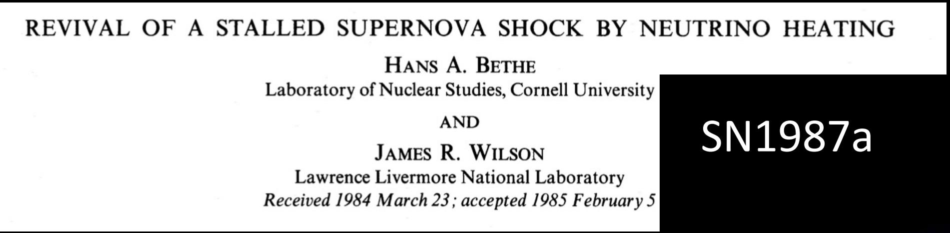
Bethe and Wilson 1985



Jim Wilson's computer running for too long

Jim Wilson going somewhere else

Early numerical simulations - 80s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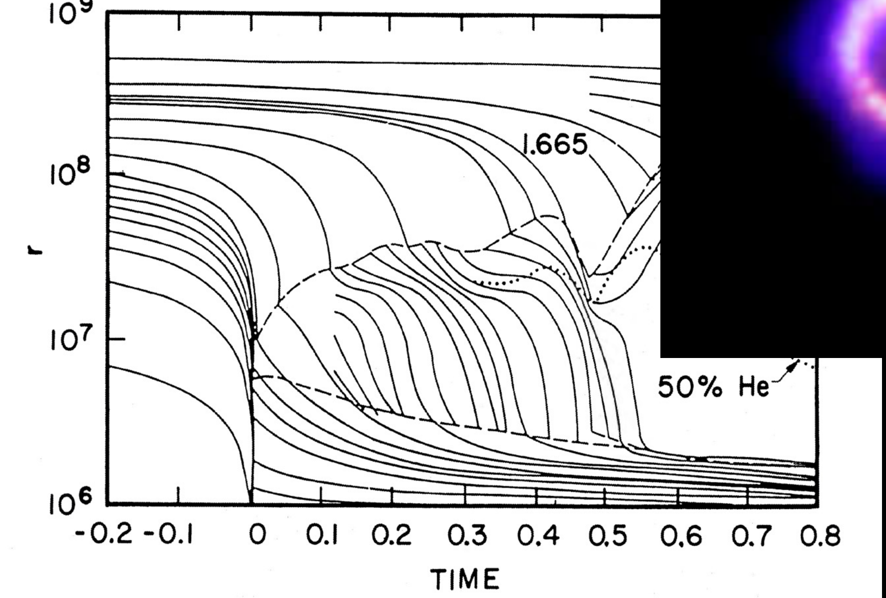
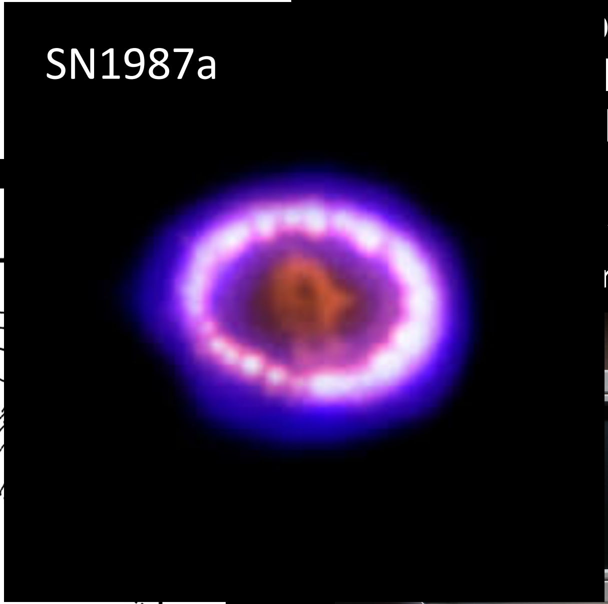


SN1987a



"As the legend goes, it was Jim Wilson who made
y accidentally forgetting to stop
lations, allowing it to run much
had intended" (Couch 2017)

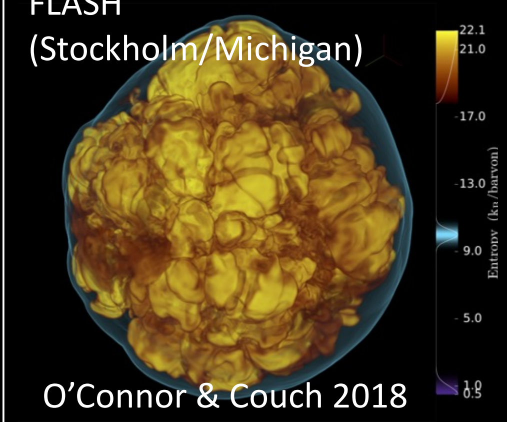
's computer
r too long

Jim Wilson going somewhere else

Current numerical codes

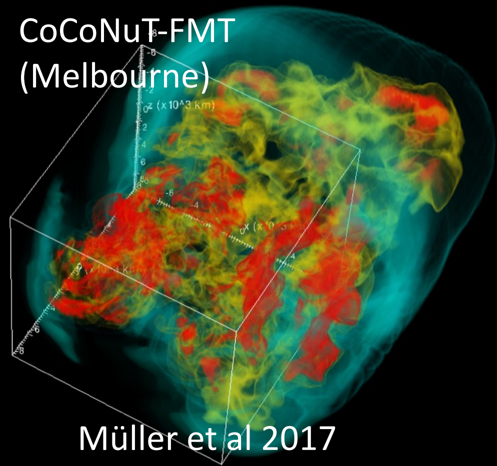
ELEPHANT (Basel)(Käppeli et al 2011)
fGR1 (Kuroda et al 2012)
SPHYNX (Fryer & Warren 2002)
…

FLASH
(Stockholm/Michigan)



O'Connor & Couch 2018

CoCoNuT-FMT
(Melbourne)

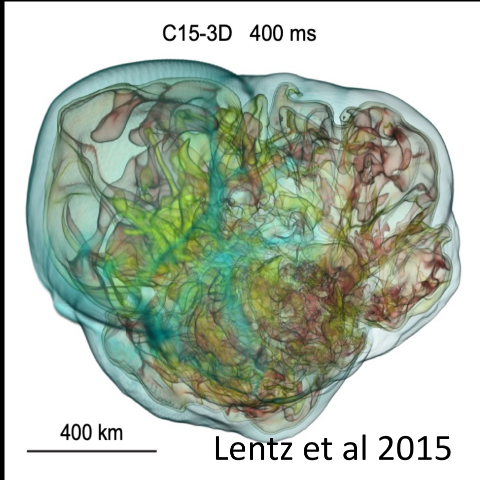


Müller et al 2017

FORNAX (Princeton)

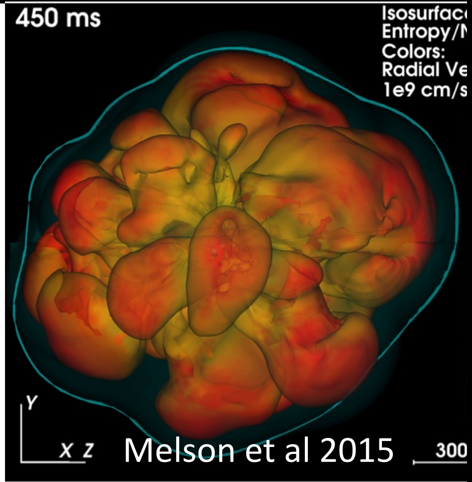
Burrows & Vartanyan 2020

CHIMERA (Oak Ridge)



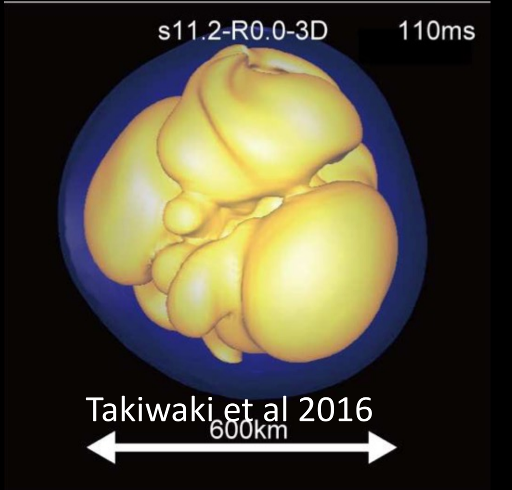
Lentz et al 2015

PROMETHEOUS-VERTEX
(Garching)



Melson et al 2015

Fukuoka/NAOJ



Takiwaki et al 2016

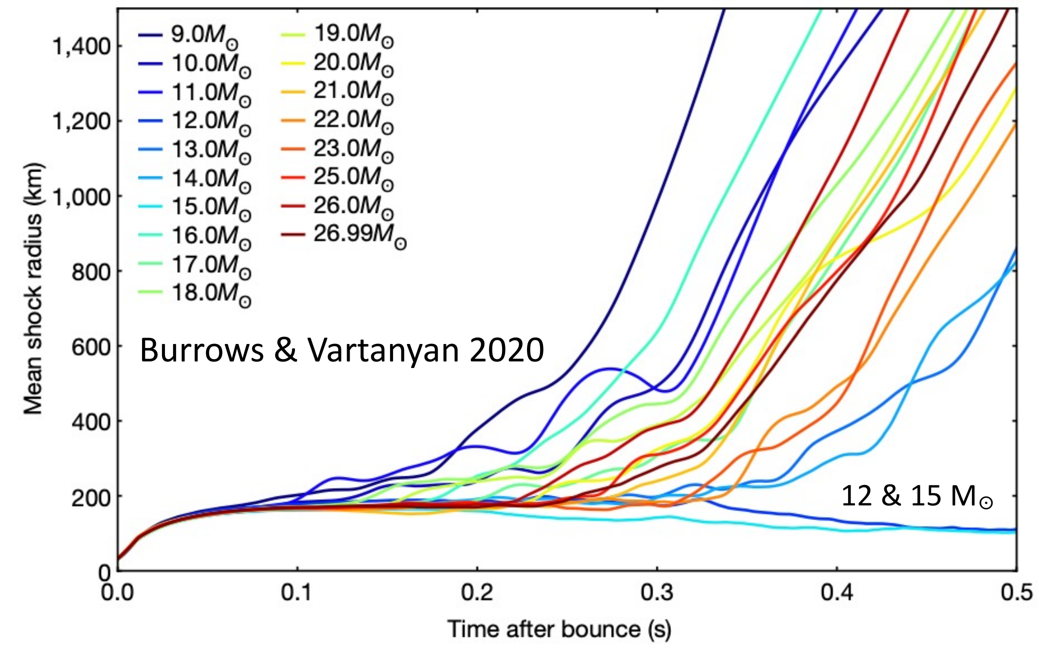
Numerical simulations - uncertainties

Physical unknowns	Physical approximations	Numerical approximations
• Equation of state (EOS) • Progenitor structure	• Neutrino interaction rates • Neutrino transport (leakage, FMT, IDSA, M1, ray-by-ray+, MGFD, Boltzmann …) • Number of neutrino species • Gravity treatment (Newtonian, pseudo-Newtonian/TOV, XCFC, GR)	• Dimensionality (1D, 2D, 3D) • Grid discretization (finite differences, spectral methods, discontinuous Galerking) • Neutrino transport (grid based, MC) • Energy bin discretization

Successful explosions

Successful explosions for a variety of progenitors

Mean shock radius



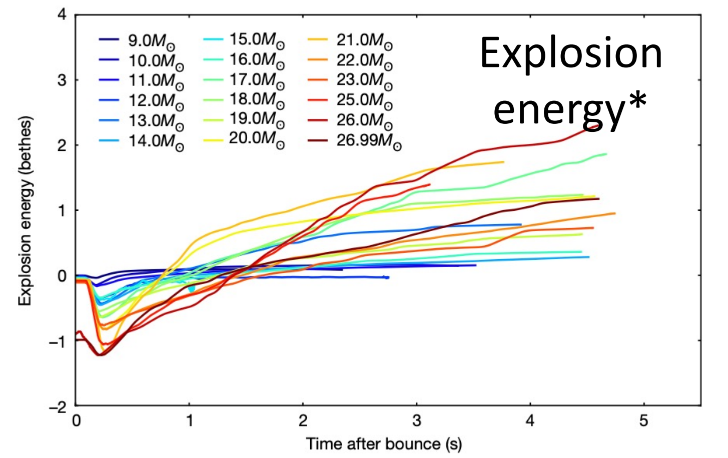
Reviews:
Janka et al. 2007; Janka 2012; Burrows 2013;
Müller 2016; Burrows & Vartanyan 2020

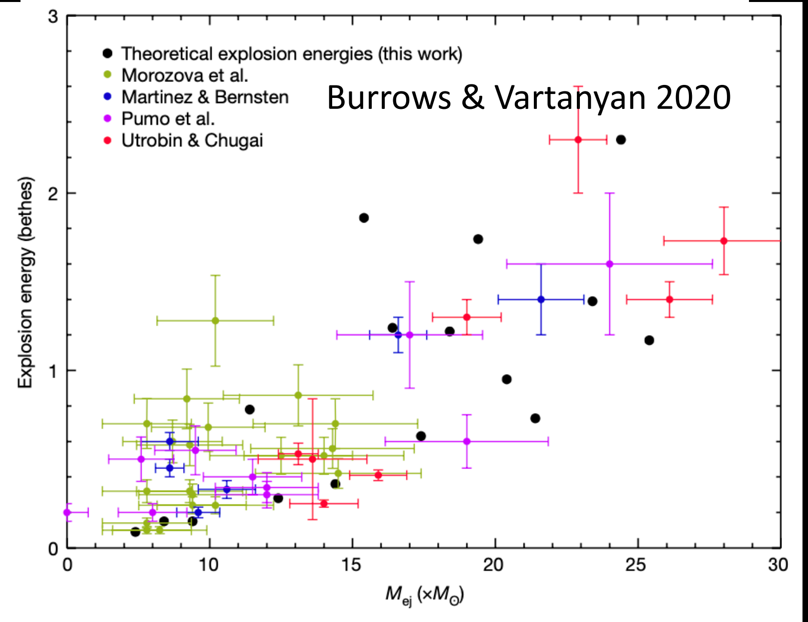
Explosion energy

Explosion energy:

- Evolves with time
- 0.01-2 x 10^{51} erg
- Higher energies typically for $M>16M_{\odot}$
- Thermonuclear combustion of outer layers add additional energy → +0.5-1 x10^{51} erg (Witt et al 2021)

Explosion energy and ejected mass match observations of most common SNe





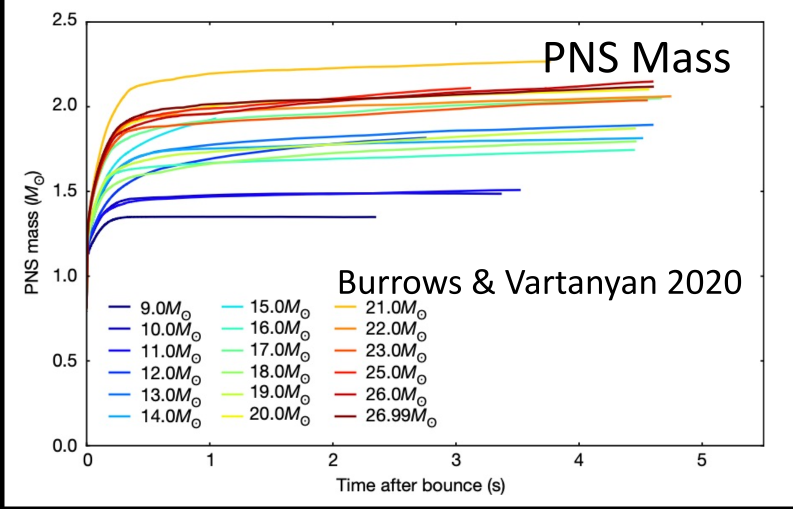
*1 Bethe = 10^{51} erg

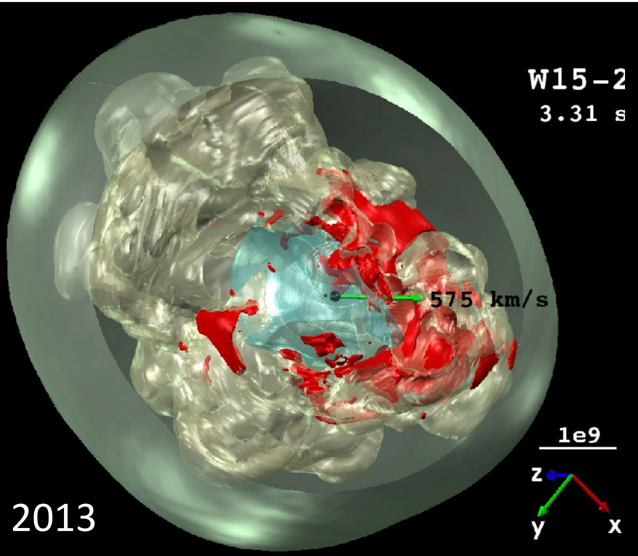
Compact remnant properties

PNS mass → **NS mass**: 1.3-2.3 $M_\odot$

Non rotation progenitors can produce

- pulsar-like rotating NS with **periods** ~100-8000 ms (Wongwathanarat et al 2013)
- NS **kick velocities** ~1000 km/s (Wongwathanarat et al 2013, Janka 2017)





Wongwathanarat et al 2013

Everything explained?

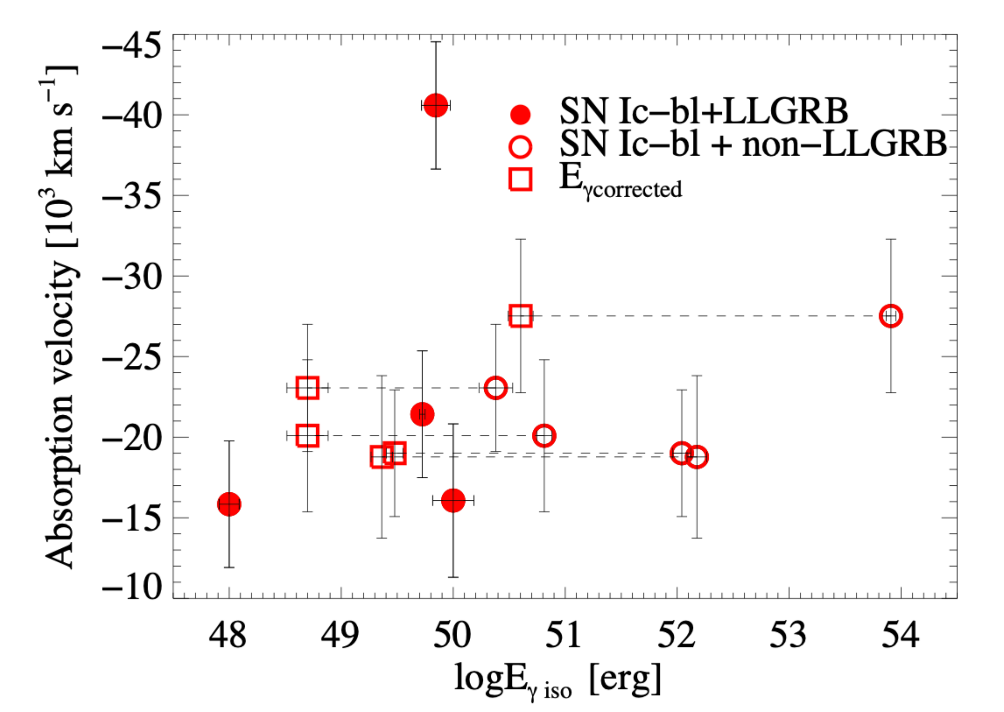
Type Ic-BL (broad line) or hypernovae

- Broad lines → fast expanding ejecta ~20 000 km/s
- Up to 10^{53} erg (isotropic energy)
- Indications of beaming
- Associated to long GRBs

- Large asymmetries
- Additional energy source
- Black hole + accretion disk (jet)

- Magneto-rotational explosions
- Collapsar model of GRBs

Modjaz et al 2016



1.4 magneto-rotational explosions

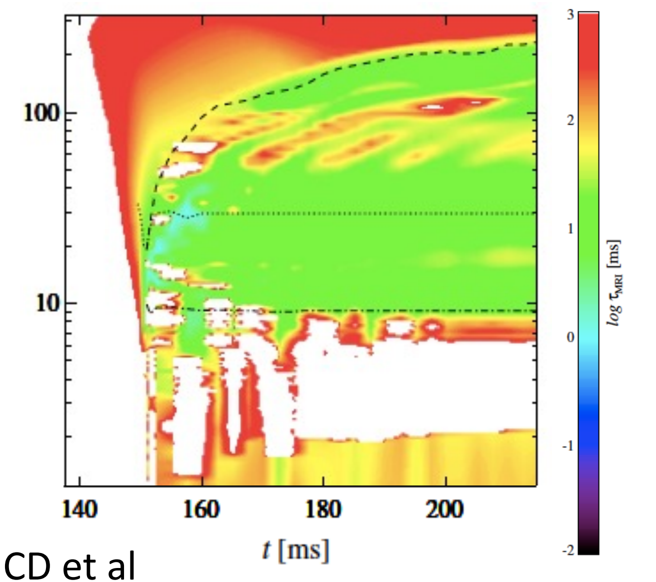
Magnetic field amplification

- Radial compression (magnetic flux freezing) ~ x100 – 1000
- Winding up (Ω-term) → linear amplification (slow)
- Convection, SASI and turbulence (α-term) → slow (~1s) and limited (x100) (Endeve et al 2010, 2012, Obergaulinger et al 2015)
- Small-scale turbulent dynamo (α^2 dynamo)
- Large-scale turbulent dynamo (α-Ω dynamo) (Thompson & Duncan 1992, 1993)
- Magneto-rotational Instability (MRI)

Poorly understood

Magneto-rotational instability (MRI)

- Instability of differentially rotating magnetized fluids (Velikhov 1959, Chandrasekhar 1960, Balbus & Hawley 1991)
- Simplest case: vertical field + differential rotation



CD et al

- Instability criterion →

$$\partial_r \Omega^2 < 0$$

- Growth rate →

$\gamma_{MRI} \sim \Omega \sim$ 1-10 ms

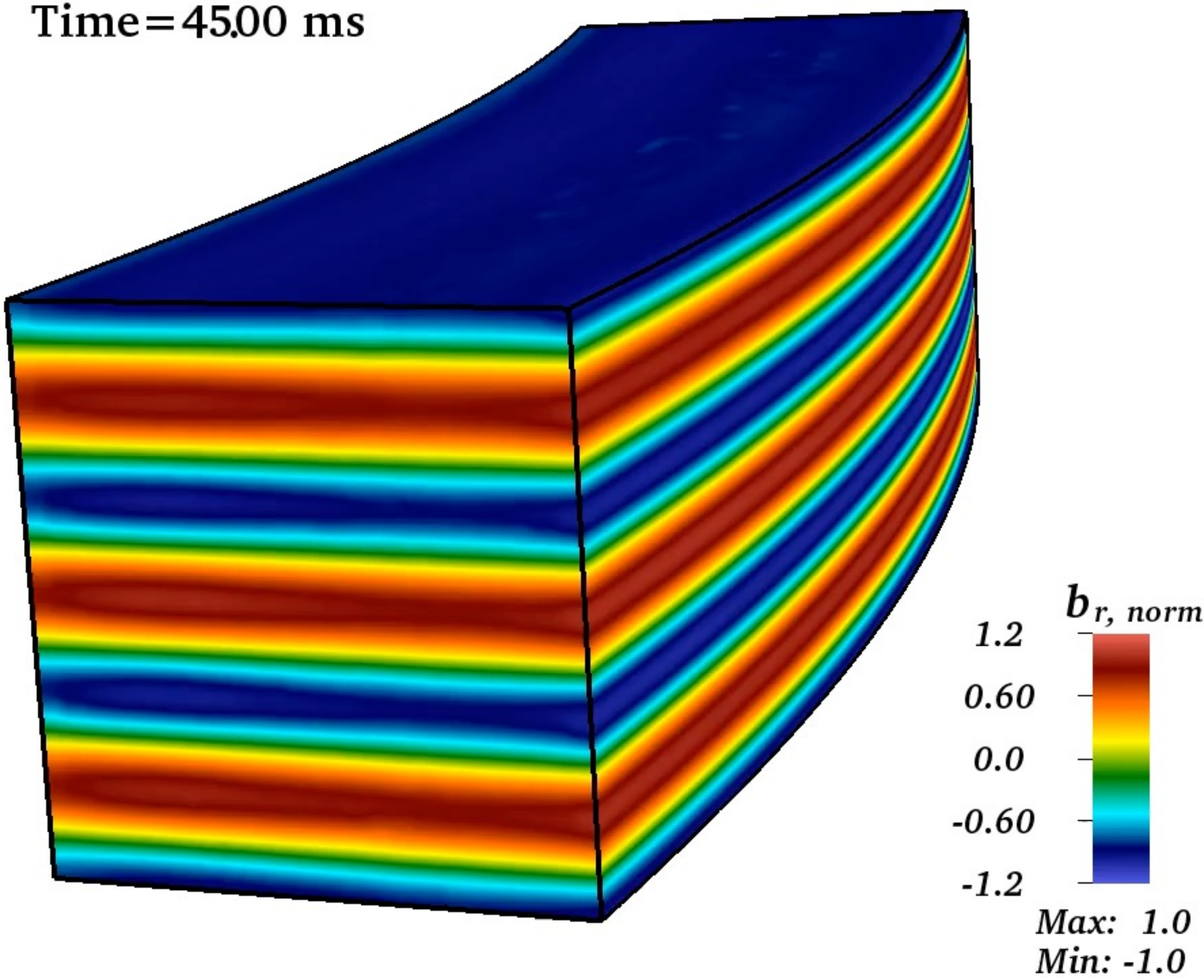
- Size of channel modes →

$$\lambda_{MRI} \approx 20\left(\frac{B_{PNS}}{10^{11}\mathrm{G}}\right)\left(\frac{1\mathrm{ms}}{P}\right)\mathrm{cm}$$

MRI

Field amplification limited by shear instabilities (KHI) (Rembiasz et al 2016)

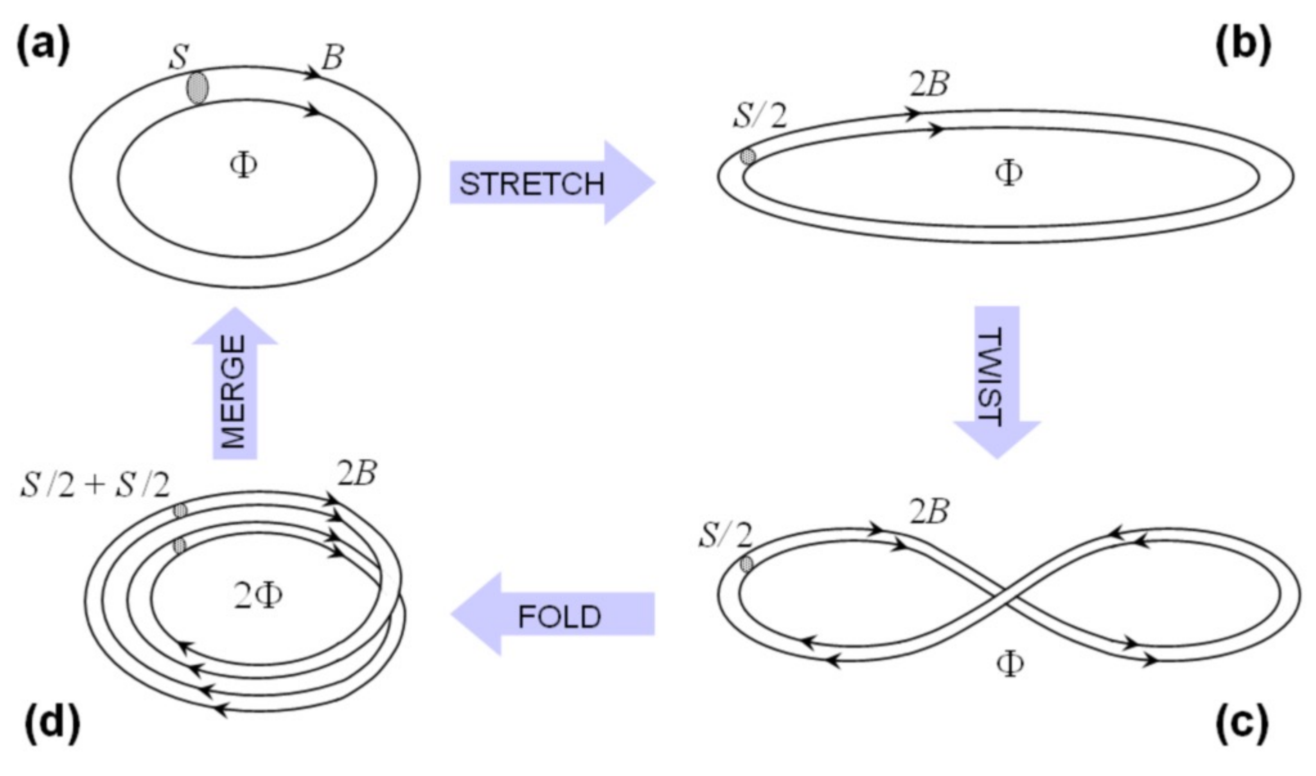
Efficient generator of turbulence



Dynamos

$$\mathrm{Pr_m} = \frac{\mathrm{Re_m}}{\mathrm{Re}} = \frac{\nu}{\eta} = \frac{\text{viscous diffusion rate}}{\text{magnetic diffusion rate}}$$

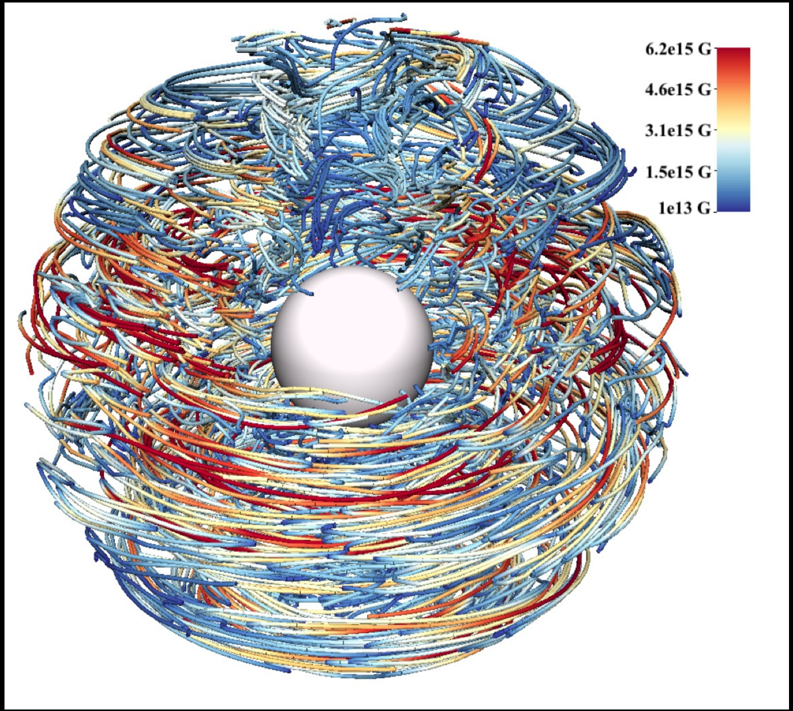
Magnetic Prandtl number



Dynamos

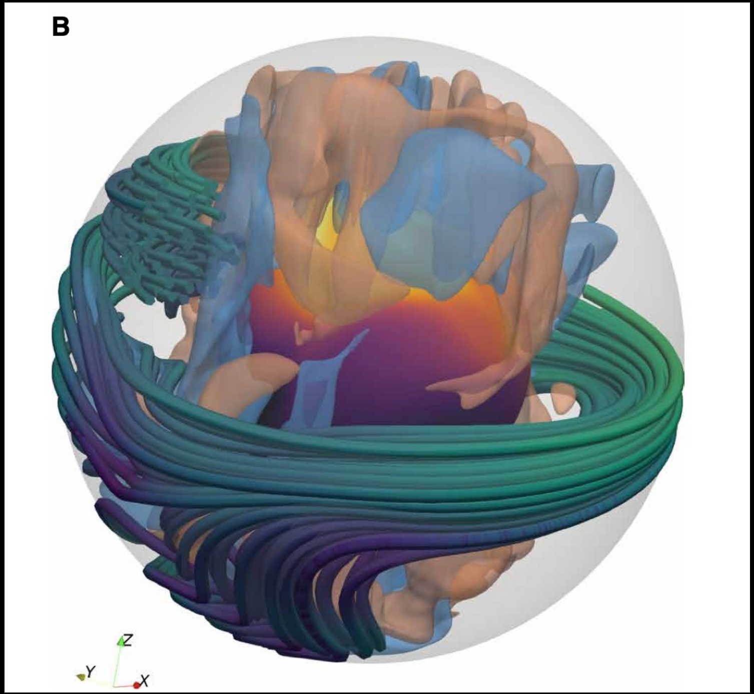
Strong indication that magnetar-like magnetic fields are possible

MRI-driven dynamos



Reboul-Salze et al 2020

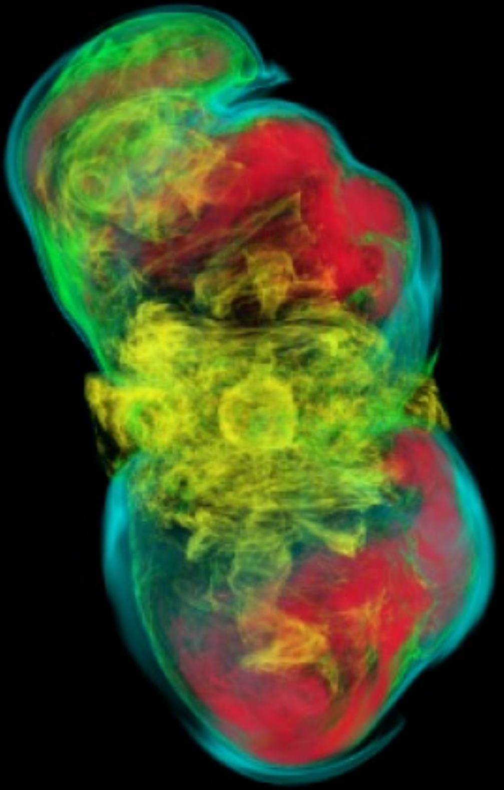
Convective dynamo



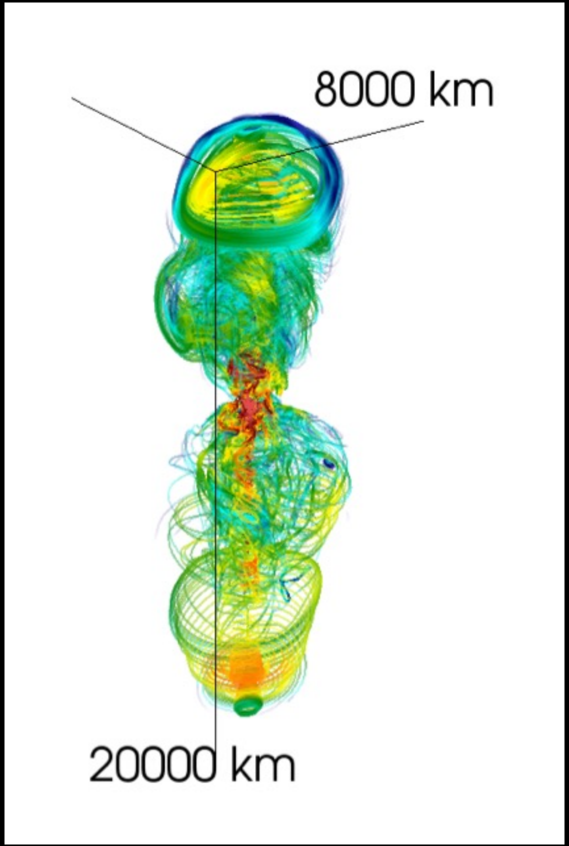
Raynaud et al 2020

Magneto-rotational explosions

Mösta el al 2014



Obergaulinger & Aloy 2021



Asymmetric explosions

Fast moving ejecta

Magnetar formation