# CC SNe

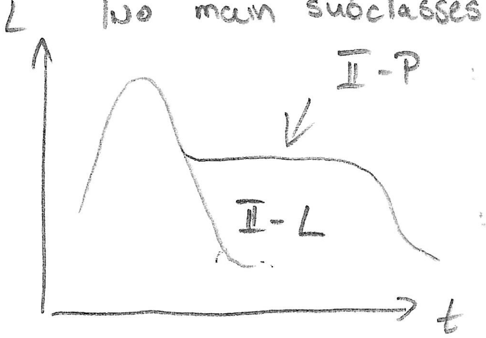


Type Ib, Ic, II Supernovae

Largest fraction: Type II: Exploding star still has H-envelope

Large variety in LC's, spectra even for Type II only:

Two main subclasses:




II-P : Plateau in LC

II-L : Linear decline of LC after peak

Spectroscopic subclasses:

II n : additional narrow emission lines
→ ejecta - CSM interaction

II b : only weak H line that vanishes in later spectra

Spectra and LCs depend mainly on properties of H-envelope, CSM, but NOT on ~~central~~ explosion mechanism!
mixing
→ In contrast to SNe Ia, source of explosion hard to access, hidden by extended envelope.

Only exception so far:
~~Observation~~ Detection of 24 e-antineutrinos ($\bar{\nu}_e$) within 13 s in Kamiokande II, IMB, Baksan from SN 1987A.

→ Total energy in neutrinos $\sim 10^{53}$ erg

compare: $E_{kin} \sim 10^{51}$ erg

$E_{rad} \sim 10^{49}$ erg

→ Most energy lost to neutrinos!

Potential other option: Gravitational waves from collapse, but no detection yet!

# Progenitors of CC SNe

Only in young stellar populations. (age $\lesssim$ 40 Myrs)

→ progenitors are massive stars

Also: so far > 10 pre-explosion detections of progenitor stars, but: no spectra, at best several color bands.

→ Progenitors of Type II SN are blue/yellow/red supergiants. No detection of Type Ib/c SN yet
→ prob. fainter, more compact (lost envelope)

↳ Comparison with stellar evolution tracks:
$M \sim 8 - 17\, M_\odot$

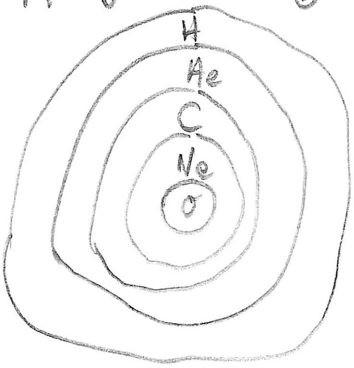
Remnants:

Compact object (NS or BH, obscured for SN 1987A?)
Everything else is ejected, ejecta strongly mixed (RT instabilities!)

# Explosion mechanism:

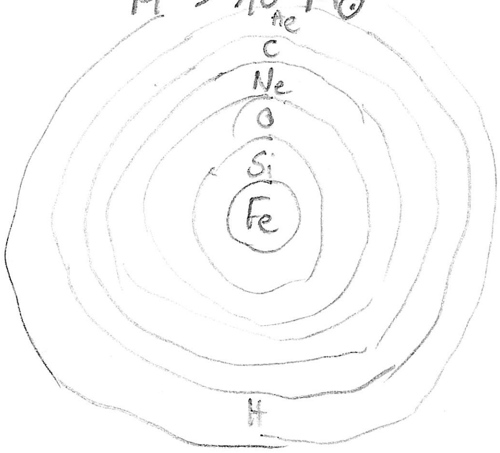
Starting point : massive star

$M = 8 - 10\ M_\odot$ :




not to scale!
Burning still continues in shells!

$M > 10\ M_\odot$




Nuclear burning stops after C-burning, central ONeMg core forms

Core burns all the way to Fe/Ni.

No energy generation in core ⇒ contracts until held by degeneracy pressure of (relativistic) electrons.

Limit: $M_{Ch} \sim 1.4\,(2Y_e)^2\ M_\odot$

Can become unstable when

⇙ $Y_e$ drops

$M = 8 - 10\ M_\odot$

↓

As $\rho_c$ increases to $\sim 10^{10}\ \frac{g}{cm^3}$ $e^-$-capture on Ne, Mg removes pressure support ⇒ collapse

„Electron-capture SN"

⇘ M increases

$M > 10\ M_\odot$

↓

Core mass grows, contracts, T increases

When $T \gtrsim 10^{10}$ K ⇒ NSE favours dissociation: $\gamma + {}^{56}Fe \rightleftharpoons 13\alpha + 4n$

⇒ reduces pressure support ⇒ contraction

⇒ $\rho_c$ increases leading to $e^-$-captures on nuclei and free protons

⇒ collapse

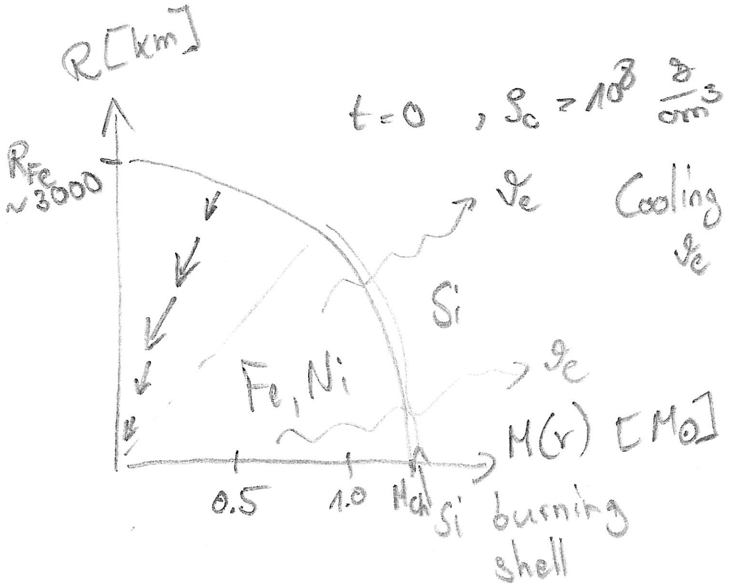
„Ordinary CCSNe)

How do we get an explosion?



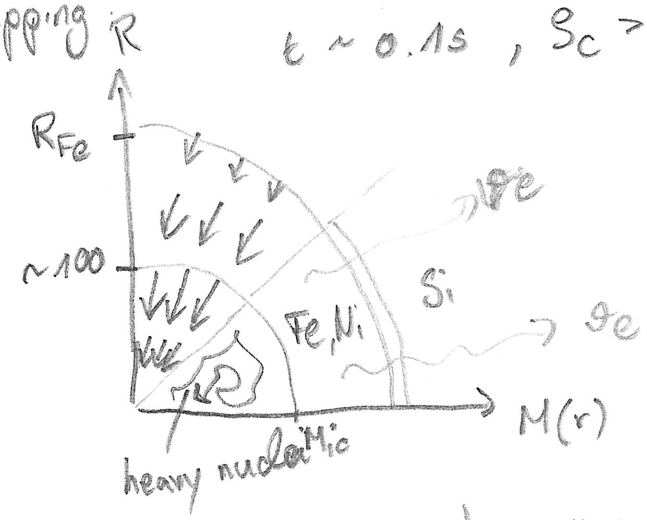
Zoom-in on core:

Onset of collapse:




photodissociation of nuclei + $e^-$-capture on free $p^+$ lead to runaway → collapse on free-fall timescale

Neutrino trapping




For $\rho \gtrsim 10^{12} \frac{g}{cm^3}$ (inner core) collisions of neutrinos with nuclei are frequent enough to trap neutrinos ($\Rightarrow \tau_{diffusion} > \tau_{collapse}$)

→ Deleptonization stops, beta (weak) equilibrium establishes

The inner core collapses homologously ($v \propto r$), outer core falls in with $v > c_s$!

EOS: Pressure dominated by electrons: $P \sim \rho^{4/3}$

Nuclear physics: $R_{nucleus} = A^{1/3} r_0$ with $r_0 = 1.25$ fm

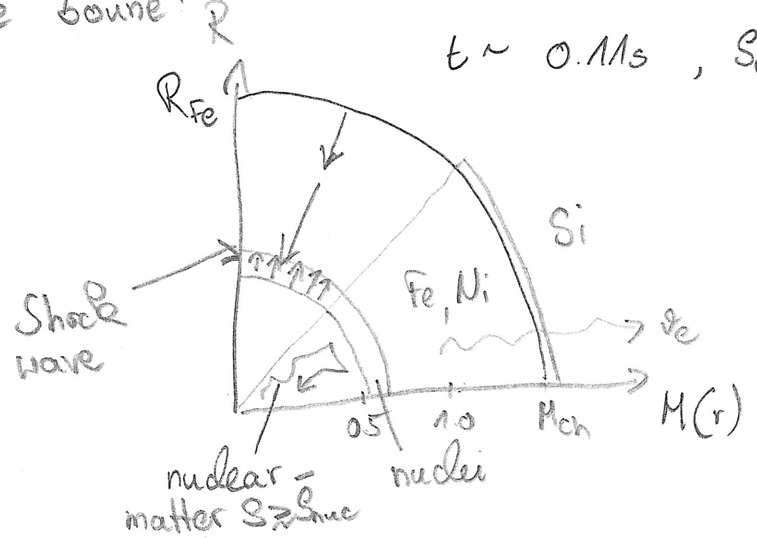
Nuclear Density: $\bar{\rho}_{nuc} = \frac{A\, m_{baryon}}{\frac{4}{3}\pi R^3} \approx 2 \cdot 10^{14}$ g/cm$^3$

→ For $\rho > \bar{\rho}_{nuc}$ EoS stiffens: $P \sim \rho^{\gamma}$ $\gamma > 4/3$
since strong force dominates now!

→ Phase transition from nucleons, $\alpha$, nuclei to pure
pure nucleons

Core boune:

$t \sim 0.11$s, $\rho_c \gtrsim 2 \cdot 10^{14} \frac{g}{cm^3}$




When $\rho_c \gtrsim \rho_{nuc}$: hot proto-NS forms, nuclear (strong) force stabilizes against gravity.

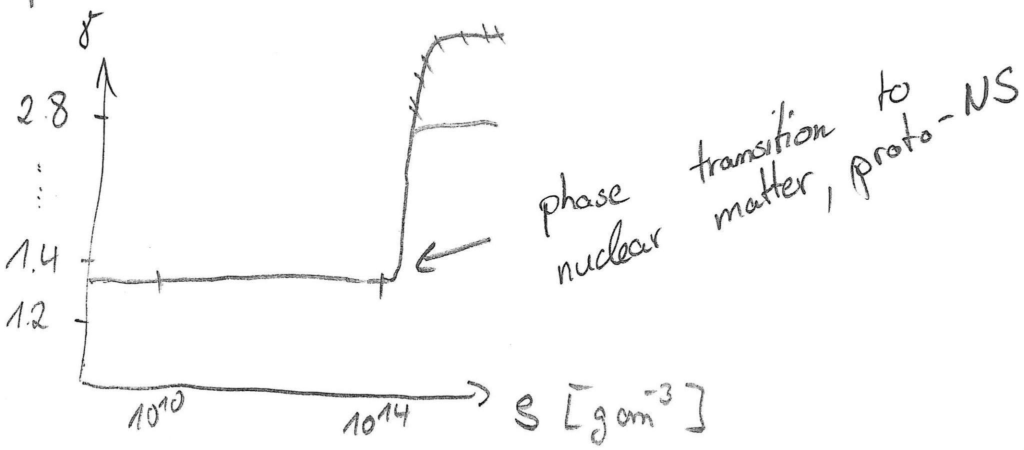
Mass of inner core determined by nuclear physics only: $M_{ic} \sim 0.5 M_\odot$

→ Dynamical infall overshoots hydrostatic equilibrium

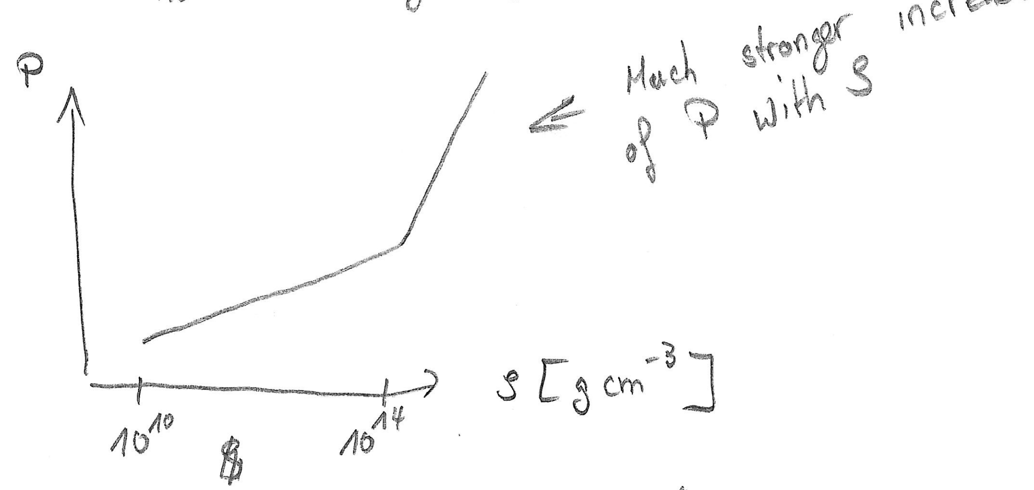
→ Core bounces back, sends shock wave into supersonically infalling material

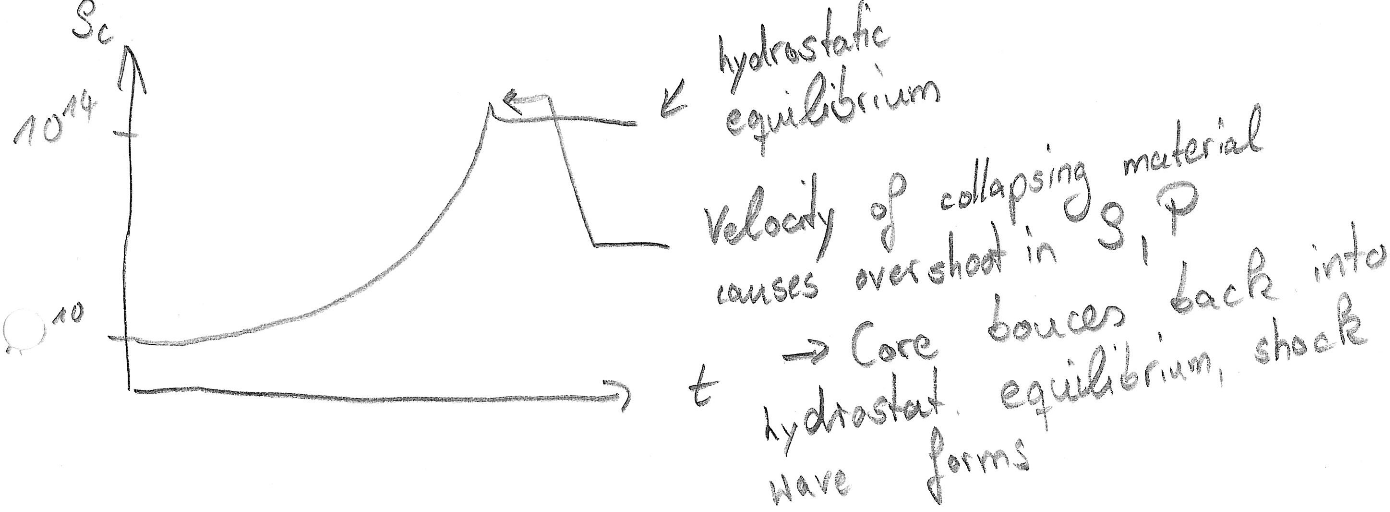
Core bounce:

$P = \rho^{\gamma}$ ← adiabatic index

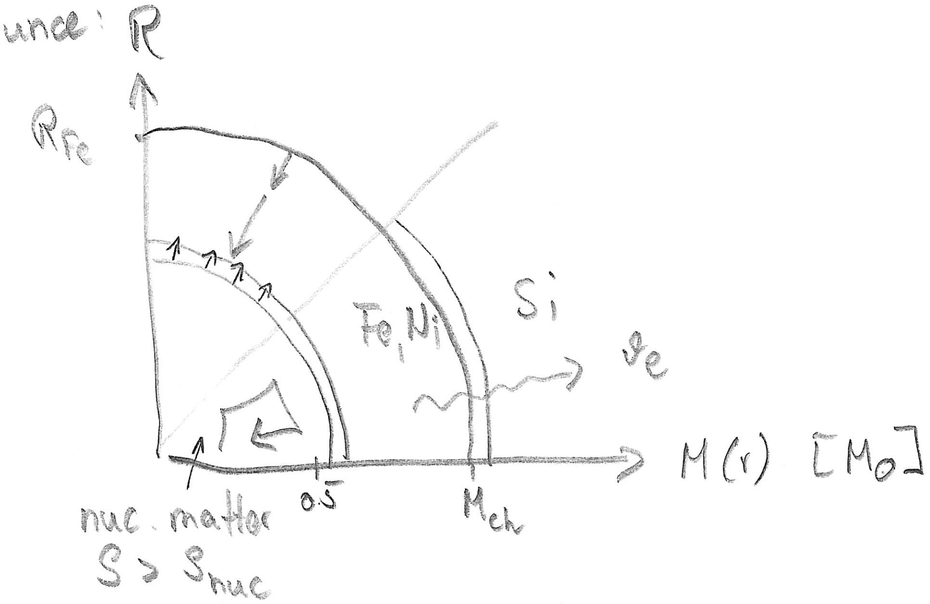



Pressure:




After bounce:



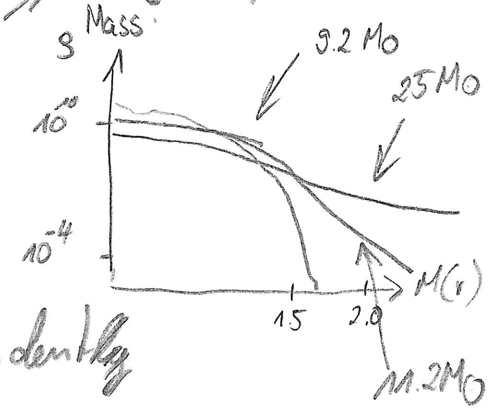
Relevant energies:

$E_{bind, NS\,cold} \approx -3 \cdot 10^{53}$ erg $(M = 1.5\,M_\odot,\ R = 12.5\,km)$

→ goes into heat of hot proto-NS, „radiated" away by ν's

$E_{core, Fe} \sim 5 \cdot 10^{51}$ erg

$E_{bind, envelope}$ (12 $M_\odot$ star) $\sim 4 \cdot 10^{51}$ erg ↗ strong dep on Mass




$E_{shock} \sim \frac{1}{2} m v^2 \sim 1.2 \cdot 10^{51}$ erg

$v_{shock} \sim 0.05c$

$M_{proto-NS} \approx 0.55\,M_\odot$

⇒ Only depends on nuclear physics, independently of star properties

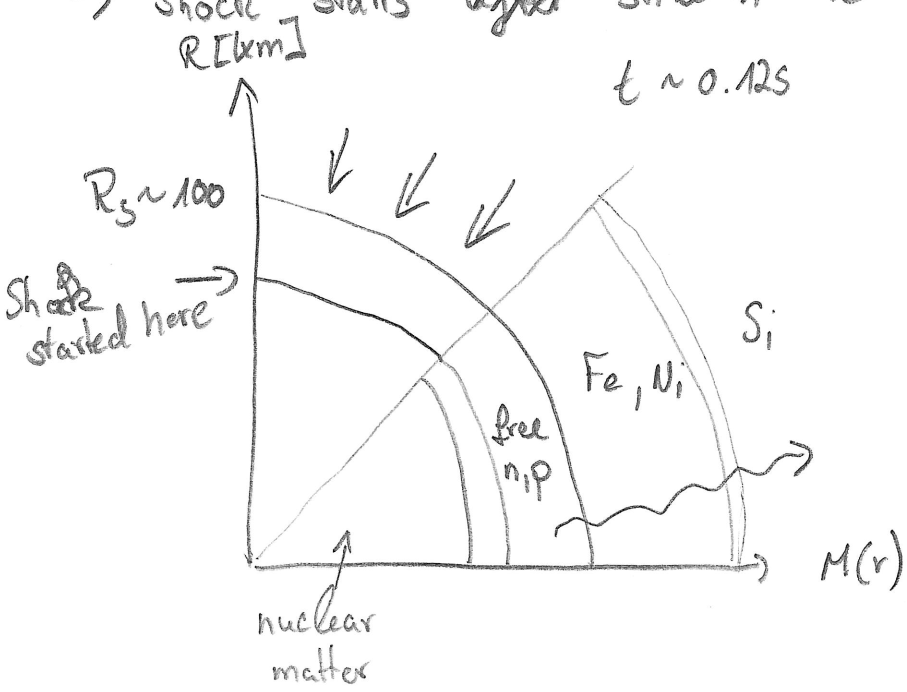
$E_{shock} < E_{bind, env}$ → The shock can not unbind the envelope!

Even worse: The shock has to cross $\sim 1\,M_\odot$ of Fe, Ni which are dissociated by shock heating

→ The shock looses $\sim 8\ \frac{MeV}{nucleon} \mathrel{\hat{=}} 1.6 \cdot 10^{51}\ \frac{erg}{0.1\,M_\odot}$

→ Shock stalls still in Fe-core

$t \sim 0.12s$



$e^-$ - captures on free p behind the shock create
additional neutrinos → additional energy loss

When $\rho_{shock} \lesssim 10^{12} \frac{g}{cm^3}$ (neutrino sphere) neutrinos from behind shock
can escape ⇒ neutrino burst

Shock stalls ⇒ There are no prompt explosions!

3 Possibilities:

- Revive shock that unbinds the complete envelope → NS + SN
- Revive shock, but some part of the envelope remains bound →(weak?) SN + fallback on NS
  →(weak?) SN + BH
- Shock is not revived → BH

The supernova problem: How to revive the shock?
Tap into energy from collapse ($E \sim 10^{53}$ erg), but mostly in $\nu$'s...

Scenarios:

1) Magneto-rotational explosion

Rotational energy of the core is converted to magnetic energy when NS forms and accretes material
Magnetic pressure or heating via MRI then drives the explosion.
Explains magnetars ($B_{NS}$ up to $10^{15}$ G ($10^{11}$ T)),
fast rotating NS (ms-pulsars)

But: very fast rotation needed:

$$E_{rot}^{free} < E_{rot} \approx 2 \cdot 10^{52}\,\mathrm{erg} \left(\frac{M_{NS}}{1.5 M_\odot}\right)\left(\frac{R_{NS}}{10\,\mathrm{km}}\right)^2\left(\frac{1\,\mathrm{ms}}{P_{NS}}\right)^2$$

$$P_{ini} \sim P_{NS}\left(\frac{R_{ini}}{R_{NS}}\right)^2 \sim 10\,\mathrm{s}\left(\frac{P_{NS}}{1\,\mathrm{ms}}\right)$$

Simulations indicate

$P_{INI} < 2\,\mathrm{s}$ needed for explosion, but

$P_{ini} \gtrsim 100\,\mathrm{s}$ for typical ~~pro~~ cores of progenitor stars

⇒ Possible, but not standard mechanism (GRBs...)

2) Acoustic mechanism

Variations in accretion on NS excites $l=1$ g-mode oscillations that transfer energy to shock via sound waves

Seems possible if oscillations are strong enough

→ numerical simulations

Explosions only observed by one group (in 2D sims), not reproduced by others, probably not working in 3D since different modes couple ~~and~~ which limits amplitude of oscillation

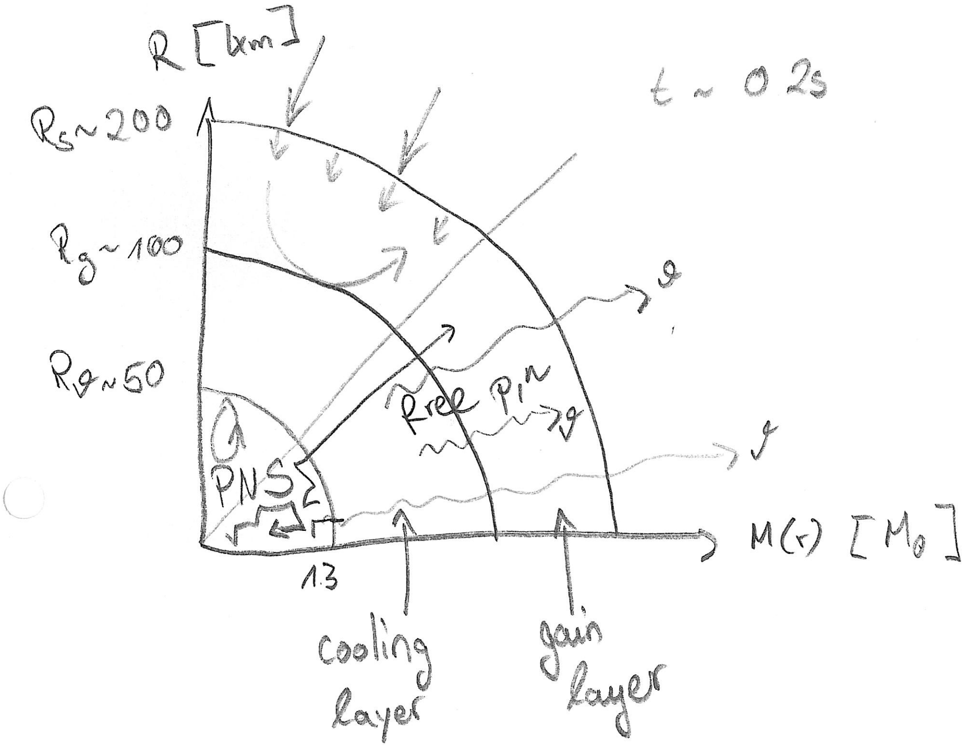
## 3) QCD phase transition

Second phase transition from NS to quark star causes second shock wave that leads to explosion

- No evidence for quark stars
- Most massive NS ($2 M_\odot$) puts limits on exotic physics at high densities → should'nt exist otherwise
- Should lead to second peak in ν-signal

→ Unlikely, playground for particle physicists

## 4) Neutrino-driven explosions




- ν's diffuse out of proto-NS and are generated in cooling layer
- ν's stream freely through stellar envelope
- In The region (behind shock) between 100 and 200 km ~~that~~ is semi-transparent to ν's and heated by ν-interactions „gain layer"

- Convection develops in gain layer
  → material stays longer in it
  → more heating

Is is sufficient for an explosion?

→ still unclear

Only way to understand are multi-D hydrodynamic simulations including GR, nuclear EOS, weak/strong nuc. reactions, detailed $\nu$ - propagation and reactions

Currently first 3D runs are done...

For Electron Capture SNe:

1D simulations already sufficient for explosion, but low explosion energy

More massive SNe:

Multi-D effects are necessary, i.e. SASI (standing accretion shock instability) that keep material in gain-layer longer

<u>The explosion:</u>

If shock is revived it propagates to surface (~hours for blue giants $R \sim 10^{12}$ cm to days for red giants $R \sim 10^{14}$ cm)

Shock heats envelope ($5 \cdot 10^9$ K in Si, $3 \cdot 10^9$ K in O)

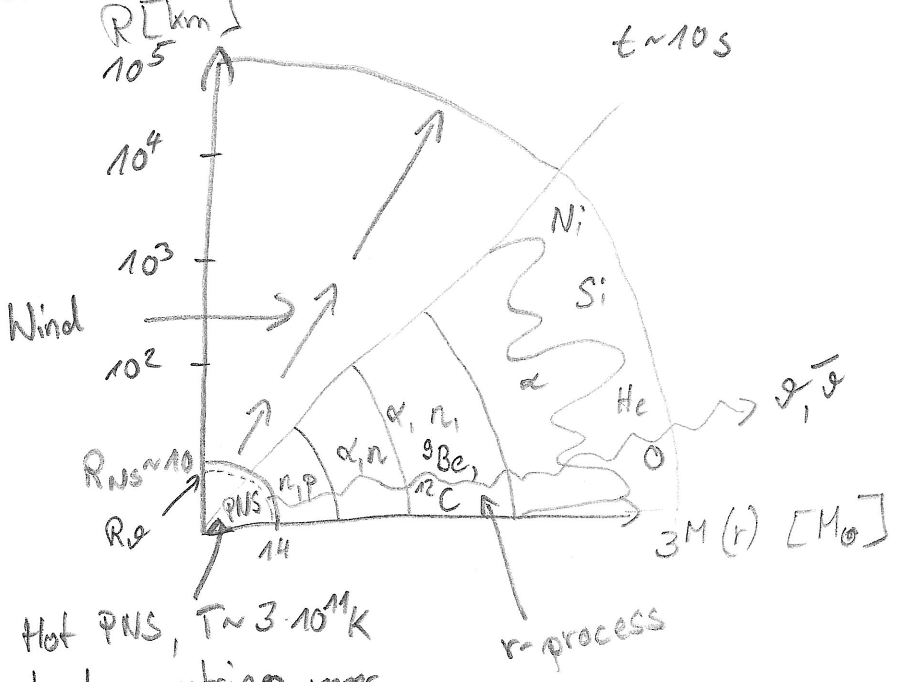
→ explosive nuclear burning to IGE's and IME's

IGE's contain $^{56}Ni$ → powers LC

Density gradient at composition boundaries triggers Rayleigh - Taylor instabilities

→ large-scale asymmetries and mixing in ejecta!

Explosion:




cools by neutrino emission from majority released in a few seconds, ν-emission first from accreted matter, after accretion stops from deeper layers in NS

Dissociated nuclei (→ n, p, α) store energy in central parts of ejecta.

Energy transfer from ν's blows away matter from surface of PNS → Determines final mass of NS

Neutrino driven wind with $v > 10^4 \frac{km}{s}$ → rapid cooling by expansion. Most of the nucleosynthesis due to recombination: N-E material at high T → equilibrium at dissociation → cooling → equilibrium shifts back to heavy nuclei. Temperature can drop fast → possible freeze-out

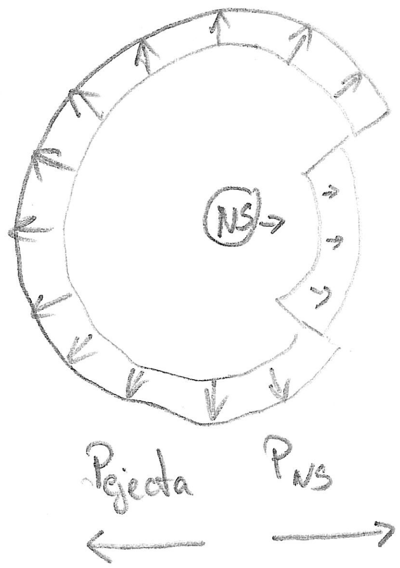
$Y_e$ of material (→ neutron fraction) determined by details of ν-flux and its internal composition ($\nu_e \leftrightarrow \bar{\nu}_e$ ?)

If n-rich, possible site for r-process (rapid neutron capture), but latest simulations predict wind to be p-rich...

After ~ 10-20s $T_{PNS} < 10^{10}$ K → $\nu$ energies drop ~~[illegible]~~ too low to be absorped in ejecta (energy-dependend cross-section) and escape freely → cold NS forms

Asymmetries in SN ejecta (i.e. by SASI) can ~~[illegible]~~ cause large kicks to NS. (up to ~ 1000 $\frac{km}{s}$)

Ejecta in homologous expansion ~~[illegible]~~ $v_r \propto r$




Observables:

Neutrinos
Gravitational waves
} Probe explosion mechanism, formation of PNS, very hard to observe

Optical lightcurves, spectra
Chemical enrichment
Structure of remnant
} Probe nucleosynthesis / condition in $\nu$-driven wind, mixing, envelope
Easier to observe, modelling can be done with black-box explosion model without detailed knowledge about explosion mechanism

Shock-breakout: UV/(X-Ray) burst

Large-scale mixing present in ejecta, i.e.:

Nebular spectra show O-lines

Ejecta transparent to $\gamma$'s, excitation by $e^+$ emitted from decaying $^{56}Co$ with short mean free path → O and $^{56}Co$/$^{56}Ni$ has to be spatially coincident..

# Type Ib/c Supernova

Core collapse SN without hydrogen envelope

→ How to remove it?

1) Massive Wolf-Rayet stars

$M > 10 M_\odot$ (up to 250 $M_\odot$?) typical 40+ $M_\odot$, $T_{surface} \sim 3 \cdot 10^4 - 1.2 \cdot 10^5 K$

Characteristic property: strong mass loss ($\gtrsim 10^{-4} \frac{M_\odot}{yr}$)

→ Loose complete H-envelope

But: possibly bright just before explosion, not observed yet
may be hidden by dust, radiation peaks in UV...

2) Binary systems

Star in binary system, looses H-envelope via binary interaction (Roche-lobe overflow or common envelope) with more compact companion star

Possible explanation for less massive progenitors, easier to hide

⇒ Probably mixture of both channels, if only (1) we should have detected a progenitor already (comparison with MW WR-star population).

Also: $\frac{N_{Ibc}}{N_{II}} \sim 0.4 \pm 0.1$

If only WR-stars, $M_{WR, initial} \gtrsim 16 M_\odot$ to explain fraction, but inconsistent with observations ($M_{WR, initial} \gtrsim 25 M_\odot$)

The most extreme SN: Pair instability SN

relevant range:

$140 M_\odot \leq M_{initial} \leq 260 M_\odot$ (Above: BH's, below pulsational pair instability into CC SN into BH)

leads to

→ He core $60 M_\odot \leq M_{He} \leq 133 M_\odot$

He core is convective and pressure dominated by radiation

Contraction starts C-burning

When $T \gtrsim 10^9 K$, pair production ($e^+e^-$-pairs) converts thermal (radiative) energy into rest mass energy → pressure drops ($\gamma < 4/3$) → contraction → energy release produces more pairs

→ runaway leads to explosive C- and O-burning. For massive end Si burns to $^{56}Ni$, even higher mass causes photodisintegration

→ collapse

Otherwise: partial or full explosion from explosive burning

Theoretical scenario, unclear if observed yet. Best candidate:

SN 2007bi (Gal-Yam et. al 2009) ~ $100 M_\odot$ ejecta, $E_{kin} \sim 10^{53}$ erg

~ $10 M_\odot$ of $^{56}Ni$

Very rare events, probably require very low metallicity to not loose to much mass in earlier evolution. Claimed to be fate of eta Carinae ($100 - 120 M_\odot$)