スーパーチャンドラセカール質量白色矮星の重力崩壊

arXiv:2306.17381

～中性子星の観測と理論～研究活性化ワークショップ 2023

京都大学　理学研究科セミナールーム

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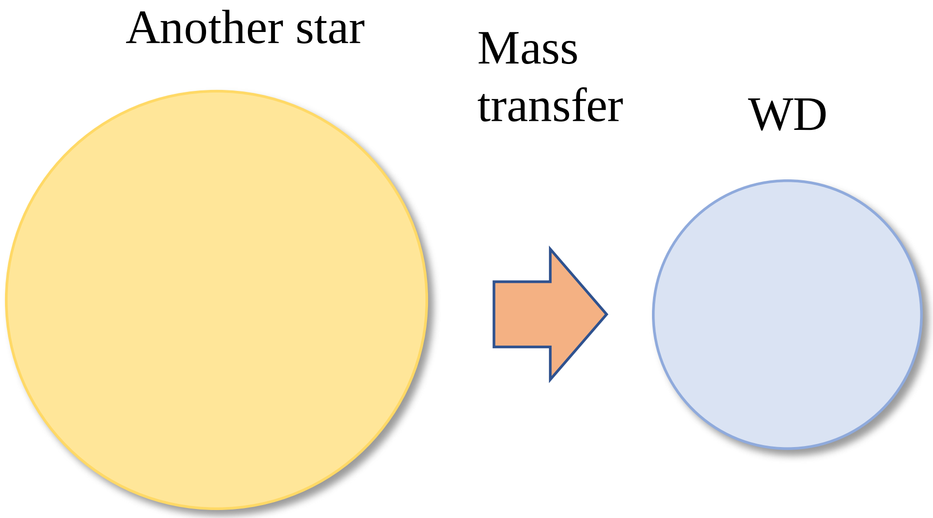
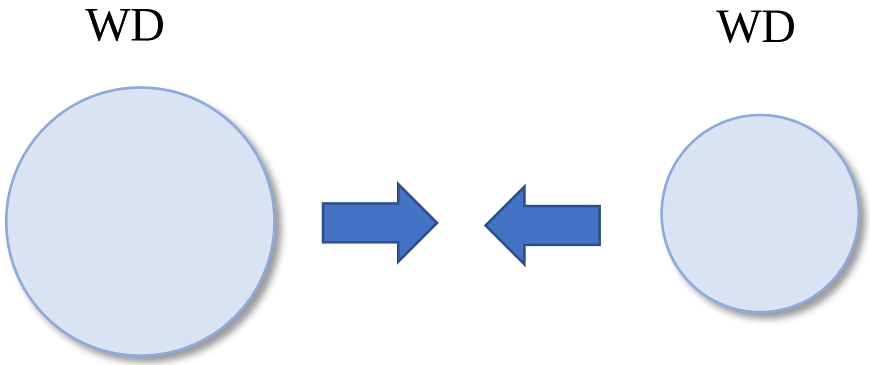
White dwarf (WD) with super-Chandrasekhar mass

- Chandrasekhar mass ($M_{\mathrm{ch}} \sim 1.4 M_{\odot}$).
- Two ways for WDs to get super-Chandrasekhar mass.
  - **Accretion** or **Merger**
- The Fate of massive WDs is Type Ia SNe or **collapse.**

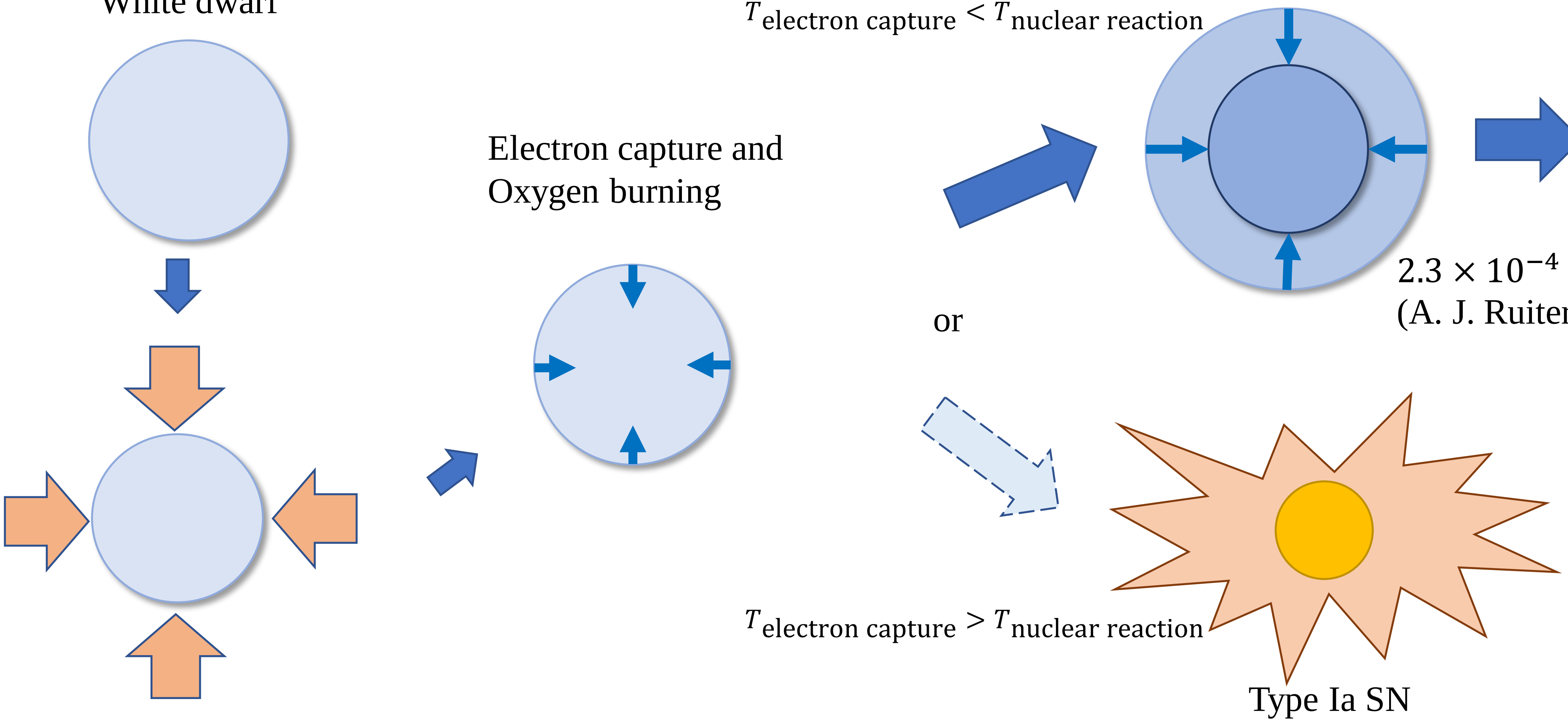


Accretion **I**nduced **C**ollapse (**AIC**)



Merger **I**nduced **C**ollapse (**MIC**)

Evolution of a super Chandrasekar WD



White dwarf

Accretion

Electron capture and
Oxygen burning

$T_{\text{electron capture}} < T_{\text{nuclear reaction}}$

Core-Collapse SN

Neutron star

$2.3 \times 10^{-4}\ \mathrm{yr}^{-1}$ per a galaxy.
(A. J. Ruiter et al. 2019)

or

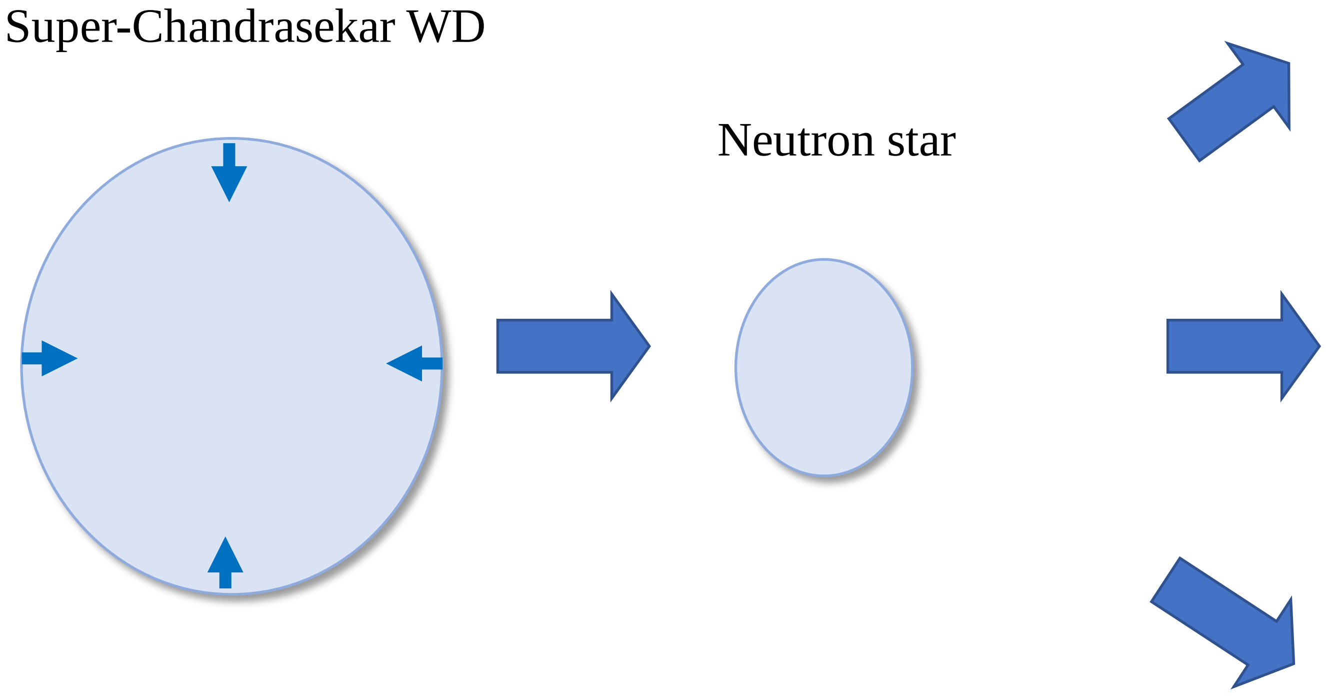
$T_{\text{electron capture}} > T_{\text{nuclear reaction}}$

Type Ia SN

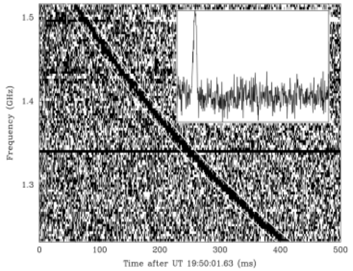
- Can undergo not type-Ia SNe but core collapse SNe.

Why AIC?

- AIC can be candidates of other astrophysical phenomena.



Fast radio burst

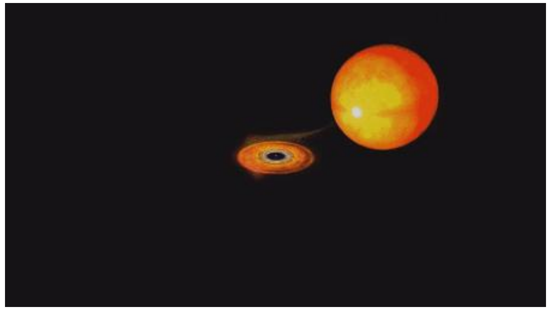


D. R. Lorimer et al. (2007)

Short-GRB

NOIRLab/NSF/AURA/J. da Silva/Spaceengine

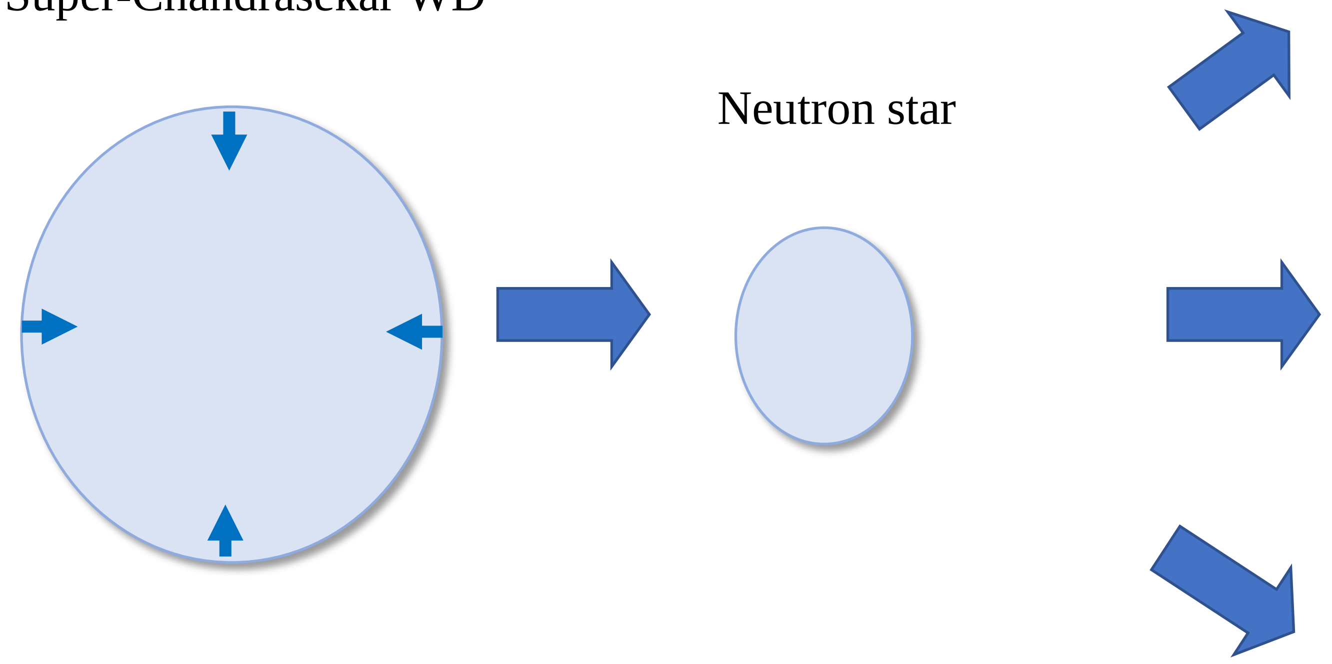
Millisecond pulsar



NASA

Why AIC?

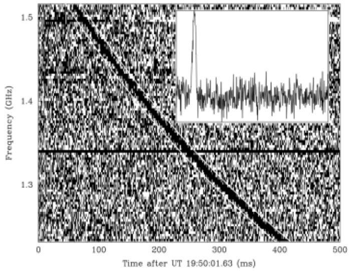
- AIC can be candidates of other astrophysical phenomena.



Super-Chandrasekar WD

Neutron star

Fast radio burst

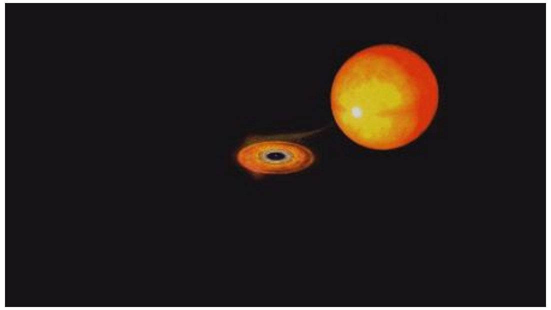


D. R. Lorimer et al. (2007)

Short-GRB

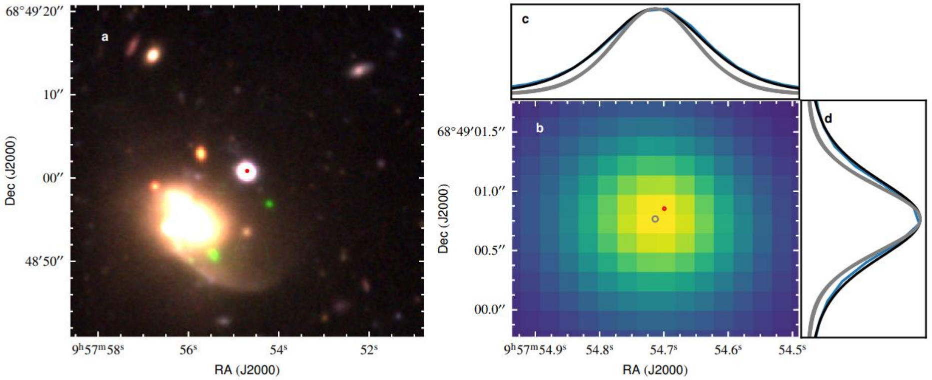
NOIRLab/NSF/AURA/J. da Silva/Spaceengine

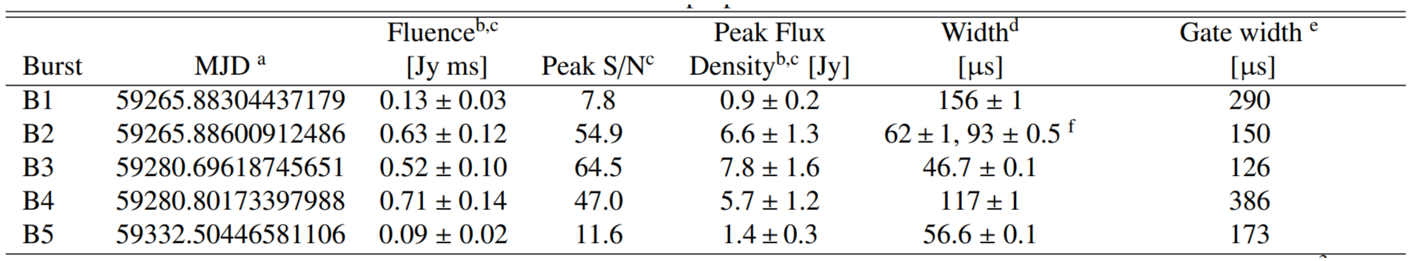
Millisecond pulser



NASA

FRB 20200120E (Kirsten et al. 2022)





Burst	MJD [a]	Fluence[b,c] [Jy ms]	Peak S/N[c]	Peak Flux Density[b,c] [Jy]	Width[d] [µs]	Gate width [e] [µs]
B1	59265.88304437179	0.13 ± 0.03	7.8	0.9 ± 0.2	156 ± 1	290
B2	59265.88600912486	0.63 ± 0.12	54.9	6.6 ± 1.3	62 ± 1, 93 ± 0.5 [f]	150
B3	59280.69618745651	0.52 ± 0.10	64.5	7.8 ± 1.6	46.7 ± 0.1	126
B4	59280.80173397988	0.71 ± 0.14	47.0	5.7 ± 1.2	117 ± 1	386
B5	59332.50446581106	0.09 ± 0.02	11.6	1.4 ± 0.3	56.6 ± 0.1	173

- In 2020, FRB20200120E was found.
- Bursts repeated 5 times.
- Found in an old star population.
  - This leads to a young neutron star in an old population.
  - AIC or MIC may make a young NS?

Previous studies of AIC simulation

	Explosion	Neutrino	Gravity	WD stability?
Dessart et al.(2006)	○	Flux-Limited Diffusion	Newtonian	?
Sharon and Kushnir (2020)	○	Ye of rho	Newtonian	?
Mor et al. (2023)	○	Diffusion + Sn	Newtonian	?
Our study	○	M1	GR	○

Simulation procedure

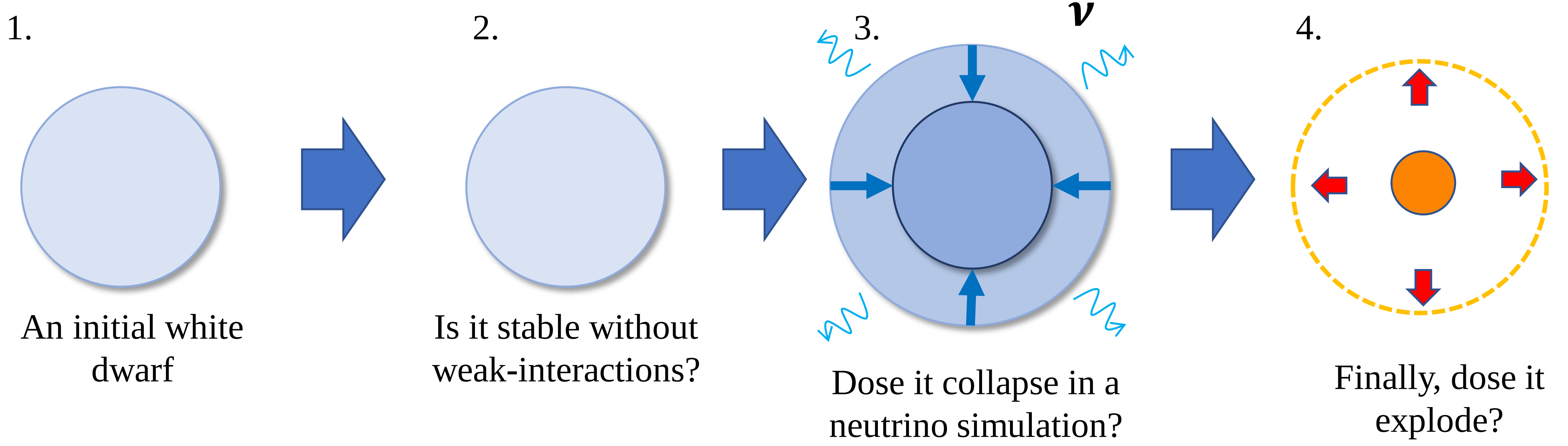
1. Make WDs with super M_{ch}
2. Check stabilities without weak-interactions.
3. Collapse WDs with weak-interactions

} Newtonian

4. Explode WDs

→ General relativity

Simulator: GR1D (O'Connor et al 2015)
EOS: Shen EOS (H.Shen et al. (2020)



An initial white dwarf

Is it stable without weak-interactions?

Dose it collapse in a neutrino simulation?

Finally, dose it explode?

Simulation tools

- Simulator: GR1D (O’Connor et al 2015)
  - 1D
  - Full general relativity or Newtonian gravity
  - Adiabatic or M1 neutrino transport scheme
  - Implemented with some prescriptions

Metric: $ds^2 = -\alpha^2 dt^2 + X^2 dt^2 + d\Omega^2$

- EoS: H.Shen et al. (2020)
  - Relativistic mean field theory
  - Small symmetry energy slope L=40 MeV
  - Broad parameter range
  - Extrapolated lower with the Timmes EoS.

1. Pre-collapse white dwarf models

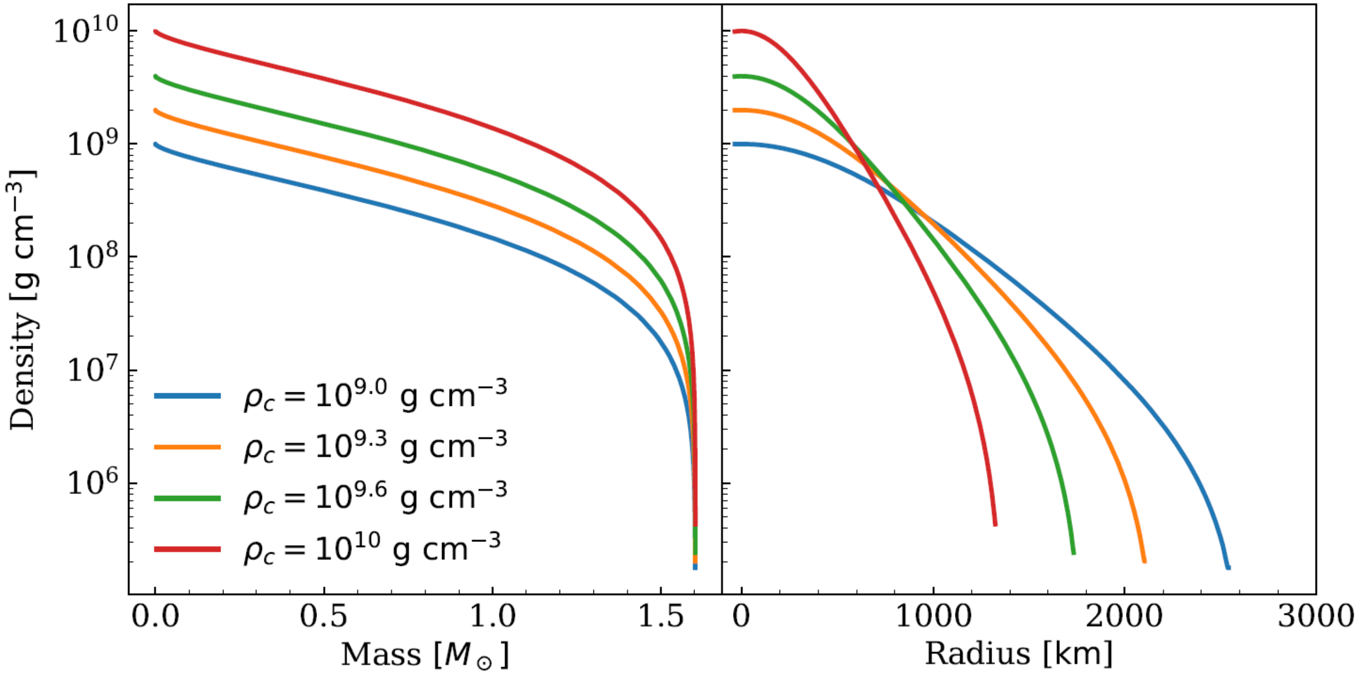
- Quasi-static contraction of WDs is too long (~ days)
- Assumed pre-collapse WDs in equilibrium
  - Parameterize mass and central density
    - Mass range: 1.6 $M_\odot$
    - Central density: $10^{9.0}$~10^{10} g/cc

White dwarf equations

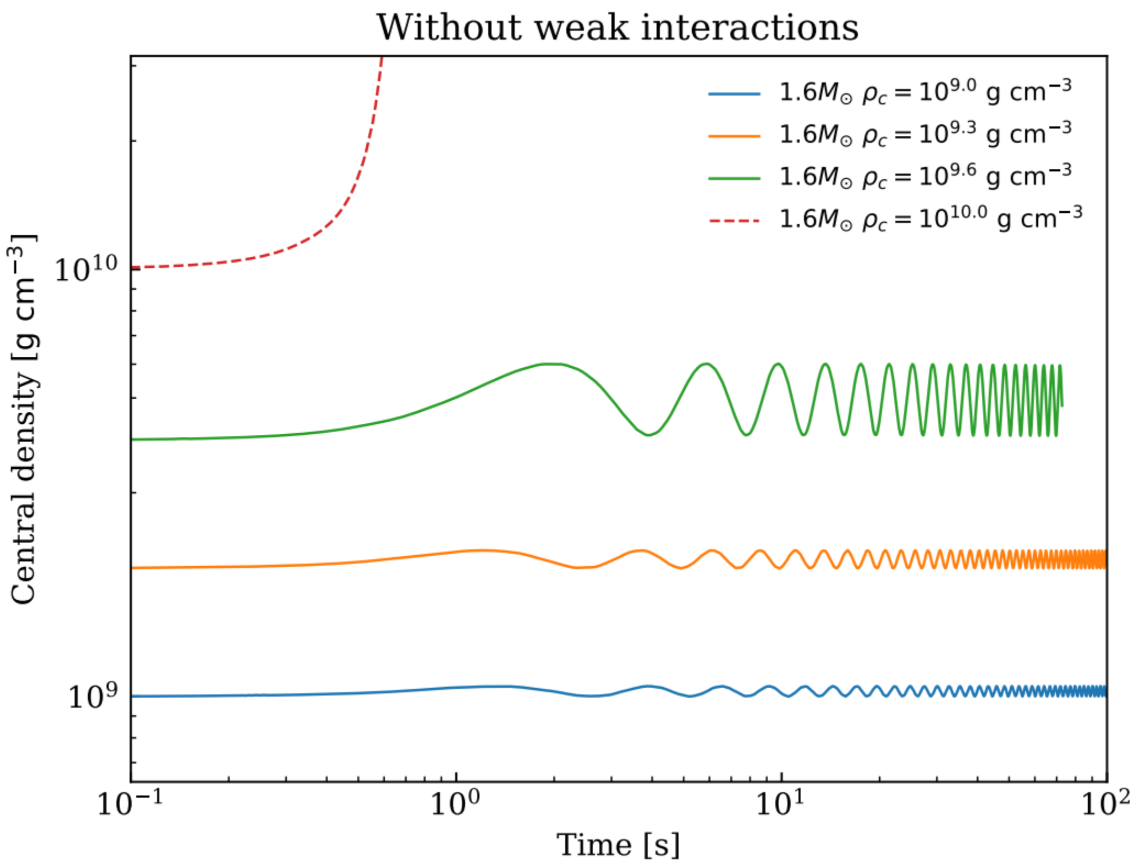
$$\frac{dr}{dm} = \frac{3}{4\pi r^2 \rho},$$

$$\frac{dP}{dm} = -\frac{Gm\rho}{r^2}\frac{dr}{dm},$$

$$\frac{dT}{dm} = \frac{dr}{dm}\frac{T}{P}\left(\frac{\partial \ln T}{\partial \ln P}\right)_{\rm ad},$$



2. Simulation without weak-interactions



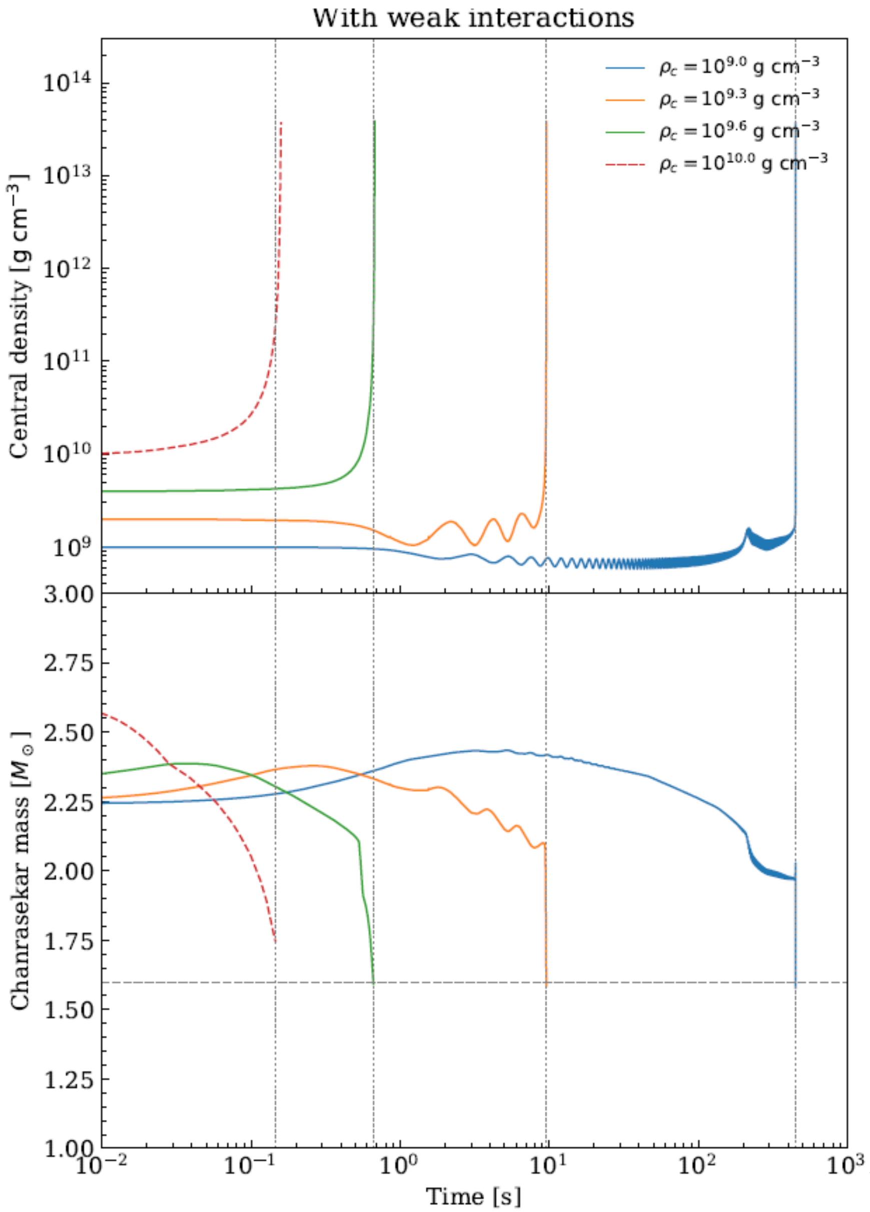
- $1.6M_\odot$ models (mainly shown.)
- Simulated up to 100 s.
- Low density models are stable
- Oscillation according to a sound crossing time

3. Simulation with weak-interactions

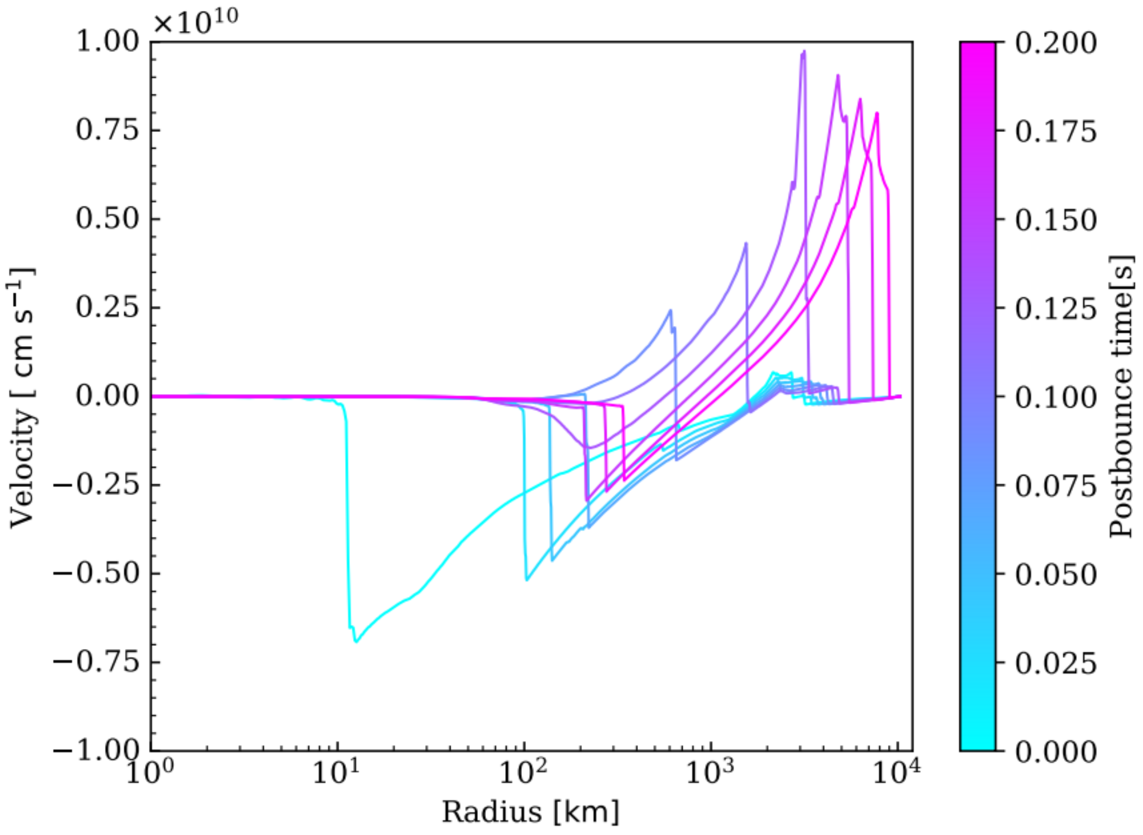
- Simulated with neutrino transport up to core-collapse
- Collapse timescales: 100 ms ~ 100 s.
- Chandrasekar masses go across $1.6M_\odot$

Modified Chandrasekar mass

$$M \approx 1.09 M_\odot \left(\frac{Y_{e,c}}{0.42}\right)^2 \left[1 + \left(\frac{s_{e,c}}{\pi Y_{e,c}}\right)^2\right]$$

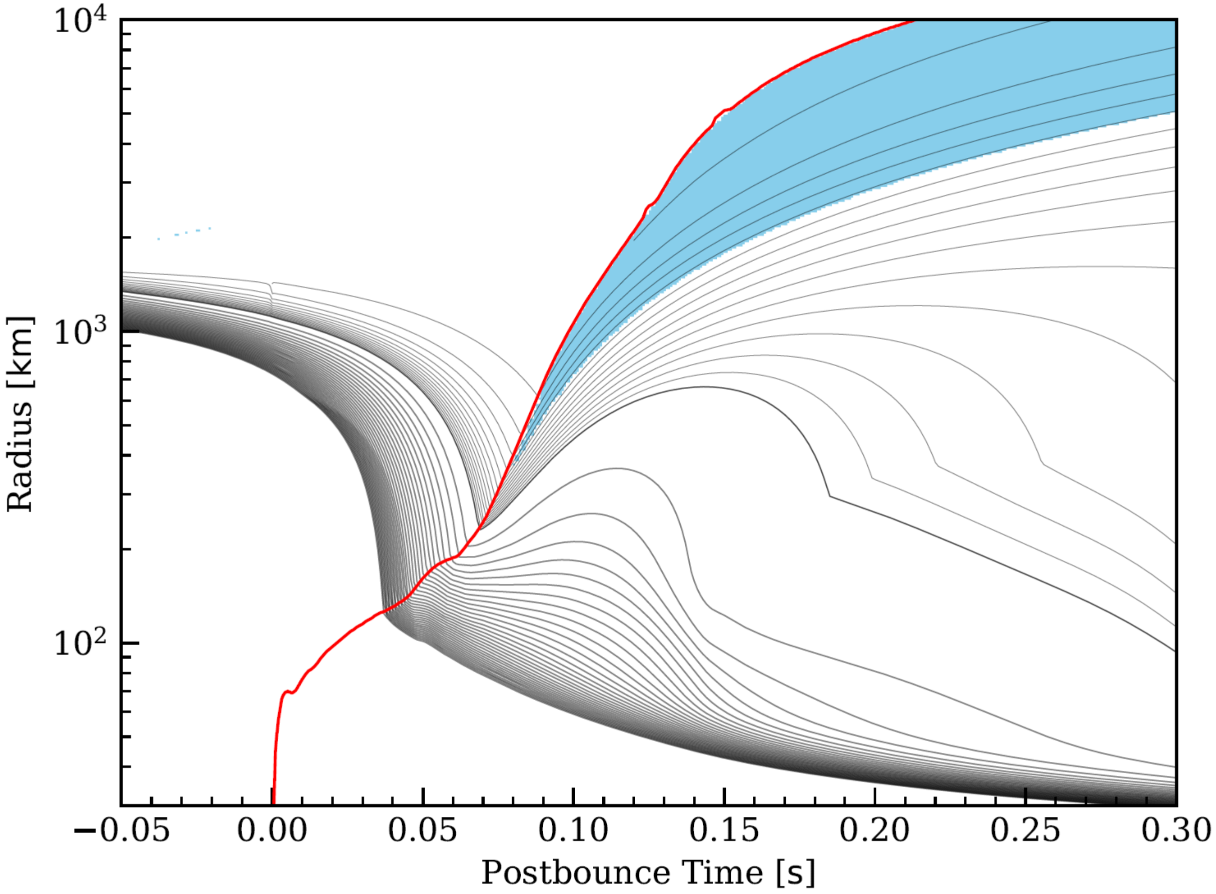


Velocity profiles



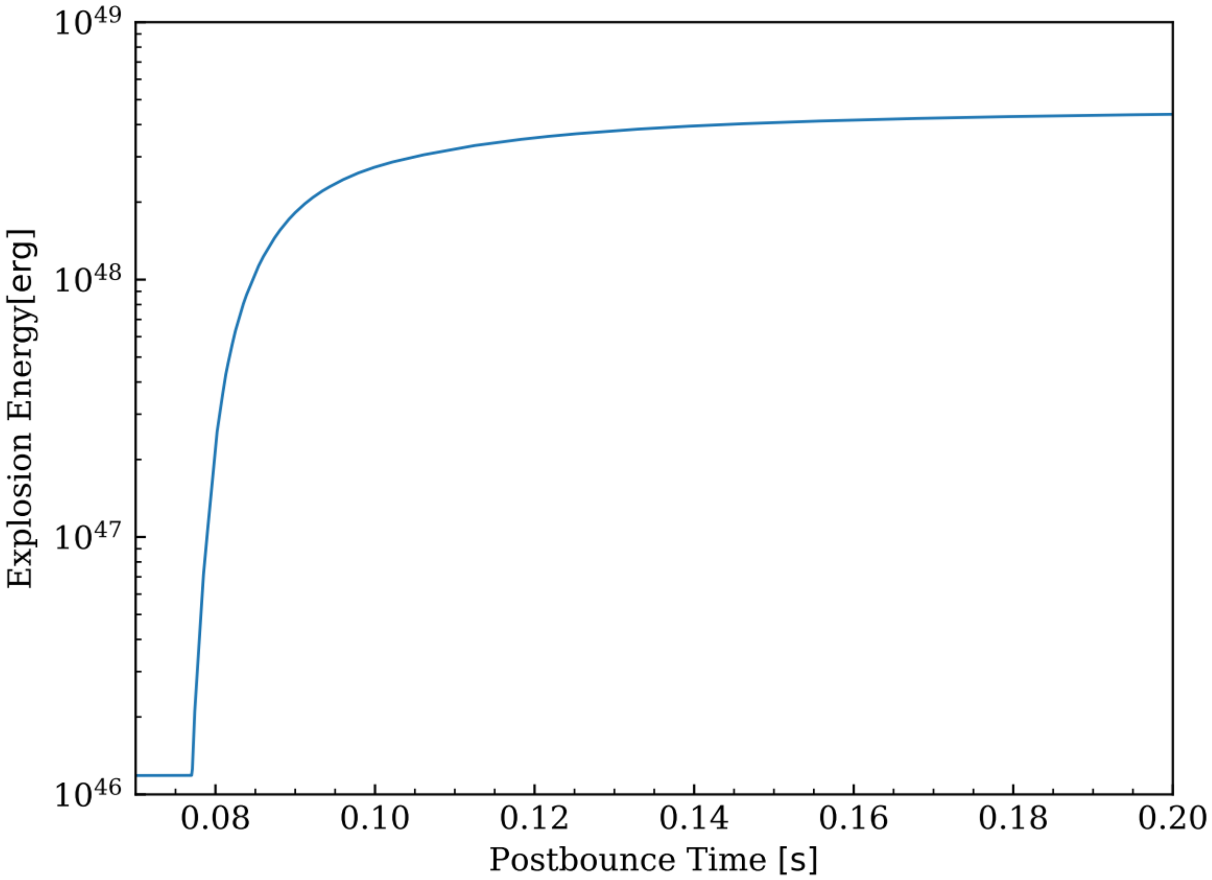
- Velocity profiles after bounce.
- There is a shockwave that propagate to the surface.

4. General relativity simulation



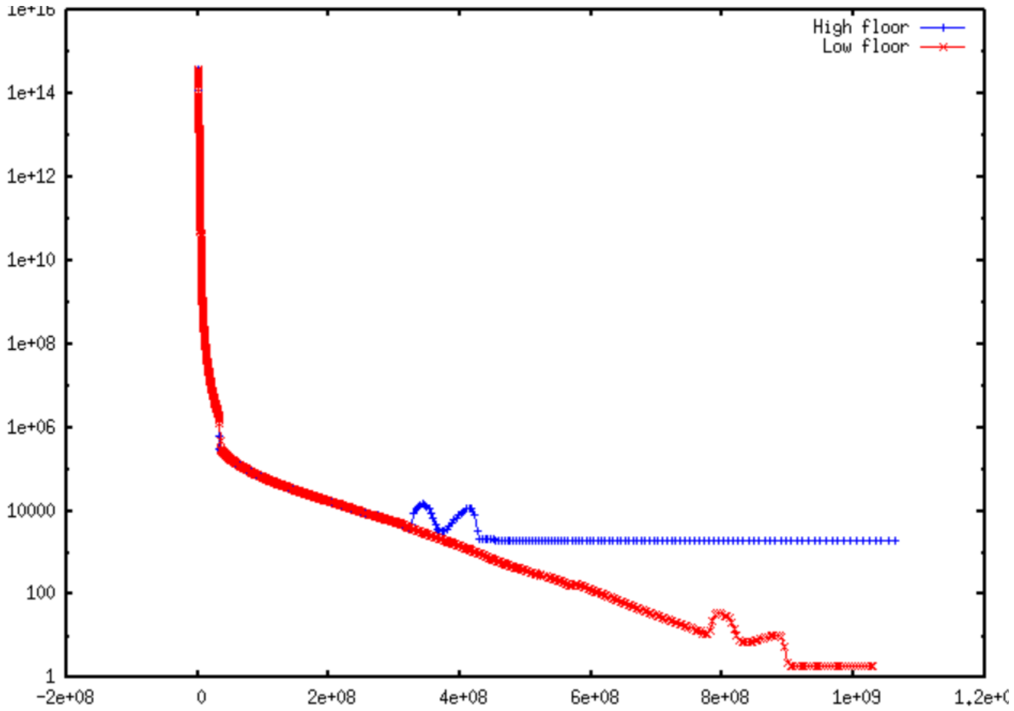
- Black: mass coordinates
- Blue: unbound region
  - Ejecta mass: $\sim 10^{-4} M_\odot$
- Red: shock radius
  - Reaches at the star surface.

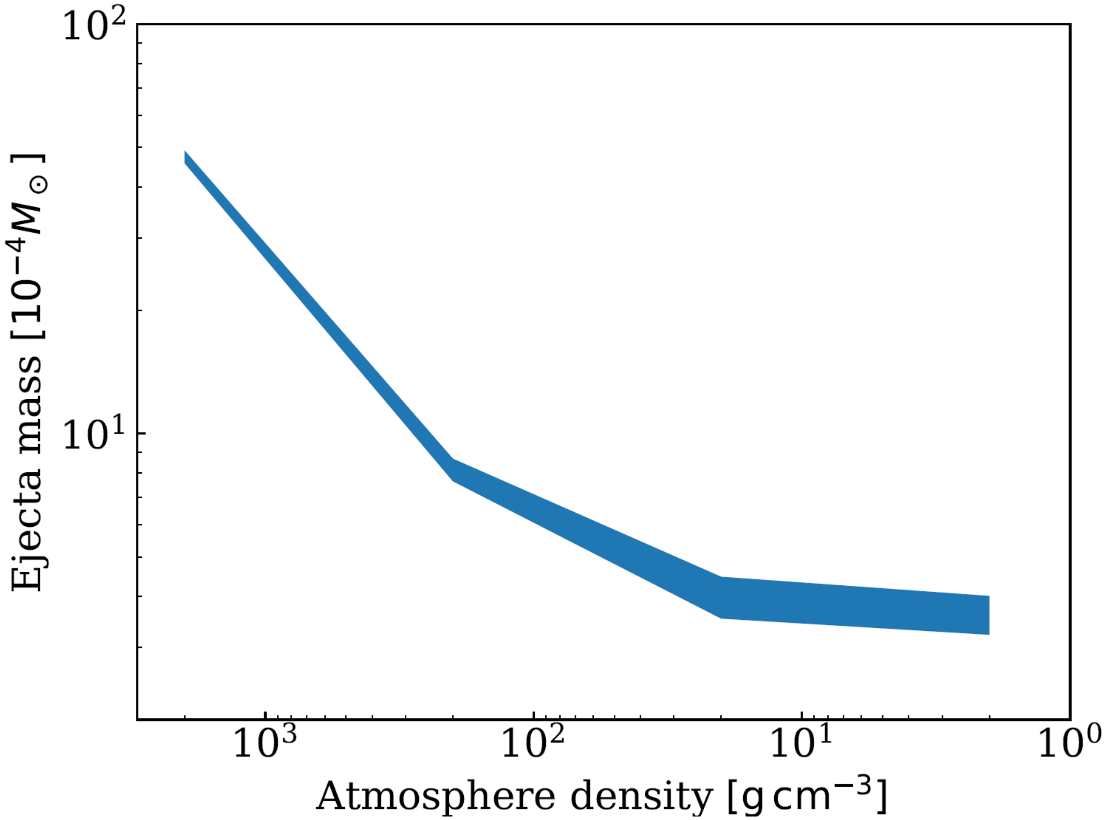
4. Explosion energy



- The explosion energy converge to 3×10^{48} erg.
- It is very small

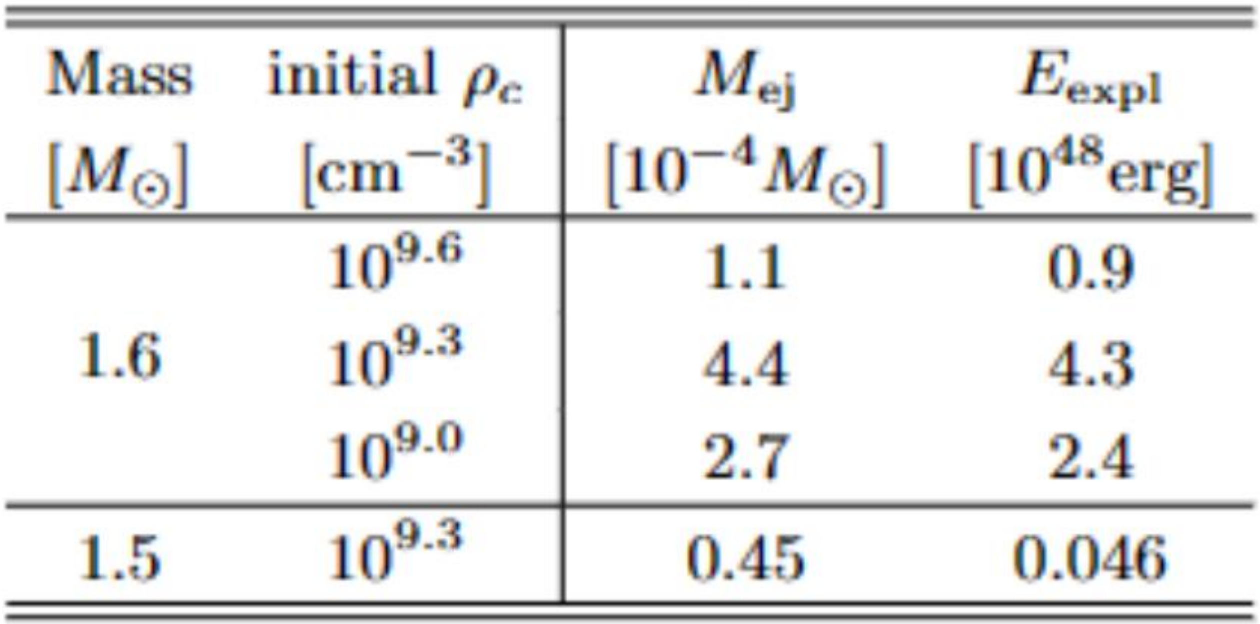
Atmosphere density





- The denser atmosphere leads to more ejecta.
- The ejecta mass converges to $3 \times 10^{-4} M_\odot$

Atmosphere density



Mass $[M_\odot]$	initial ρ_c $[\mathrm{cm}^{-3}]$	M_{ej} $[10^{-4}M_\odot]$	E_{expl} $[10^{48}\mathrm{erg}]$
1.6	$10^{9.6}$	1.1	0.9
	$10^{9.3}$	4.4	4.3
	$10^{9.0}$	2.7	2.4
1.5	$10^{9.3}$	0.45	0.046

Central density Mass	$1.4M_\odot$	$1.5M_\odot$	$1.6M_\odot$
$10^{9.0}$	×	×	○
$10^{9.3}$	×	○	○
$10^{9.6}$	×	×	○
$10^{10.0}$	×	×	×

- We simulated 12 models
- ○: successful to explode
- ×: calculations stopped

- Ejecta mass: $\sim 10^{-4}M_\odot$
- Explosion energy: $\sim 10^{48}$erg

Summary and future

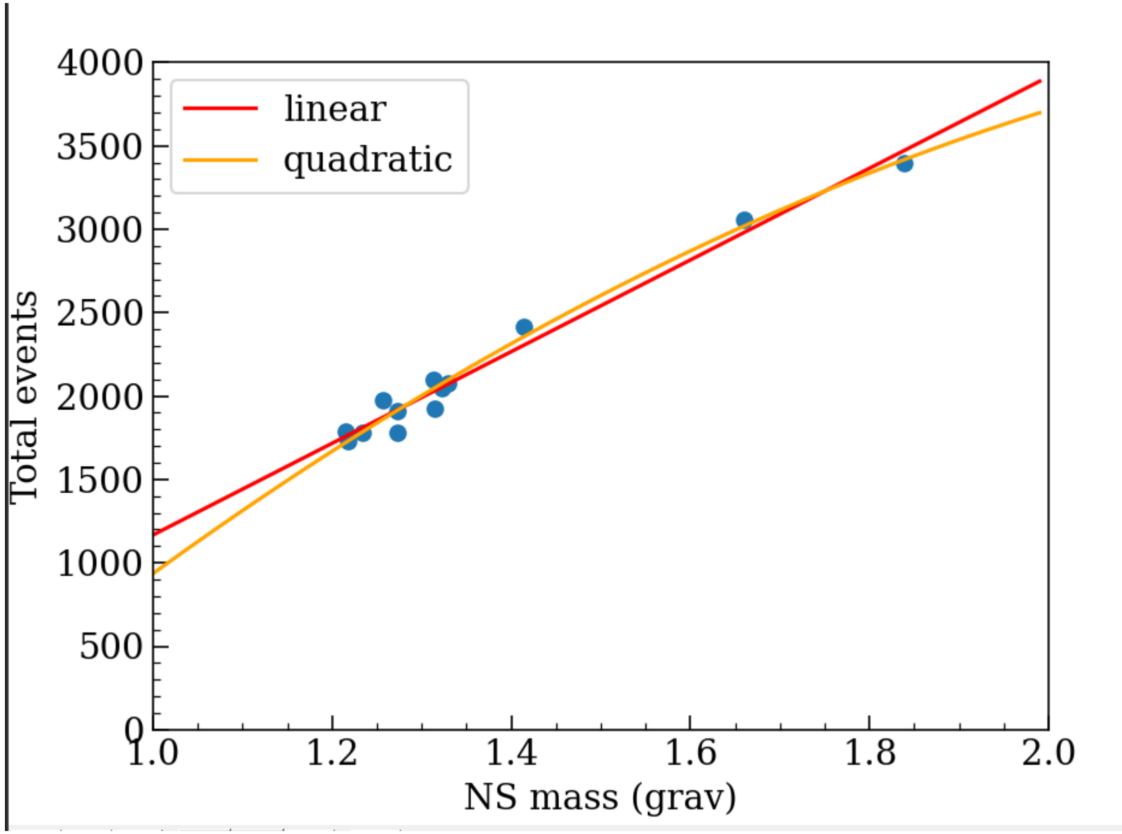
Summary

- White dwarfs with the super Chandrasekhar mass can collapse to NSs.
- Simulated the AIC.
  - Ejecta mass: $3 \times 10^{-4} M_{\odot}$
  - Explosion energy: 3×10^{48} erg
- Very small explosion
- **Mori and Sawada et al. (arXiv:2306.17381)**

Future

- Nucleosynthesis
- Light curve
- Neutrino curve

Neutrino observation



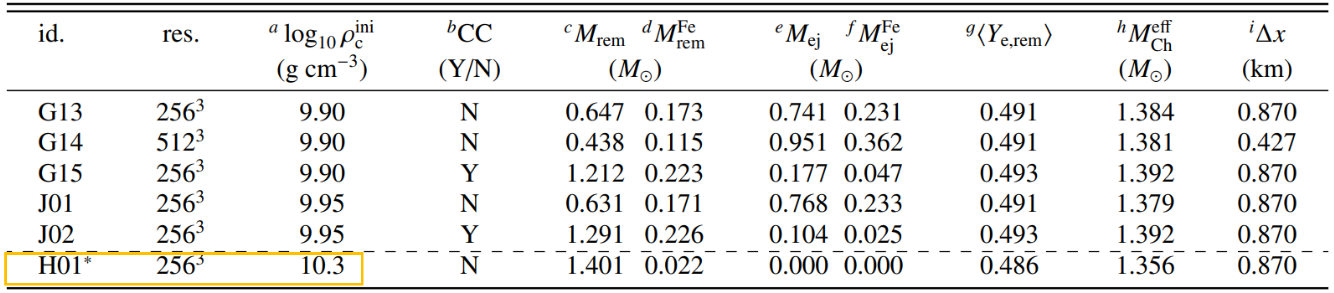
- 10kpc
- SK(32.5kton)

- We can make NSs as we want.

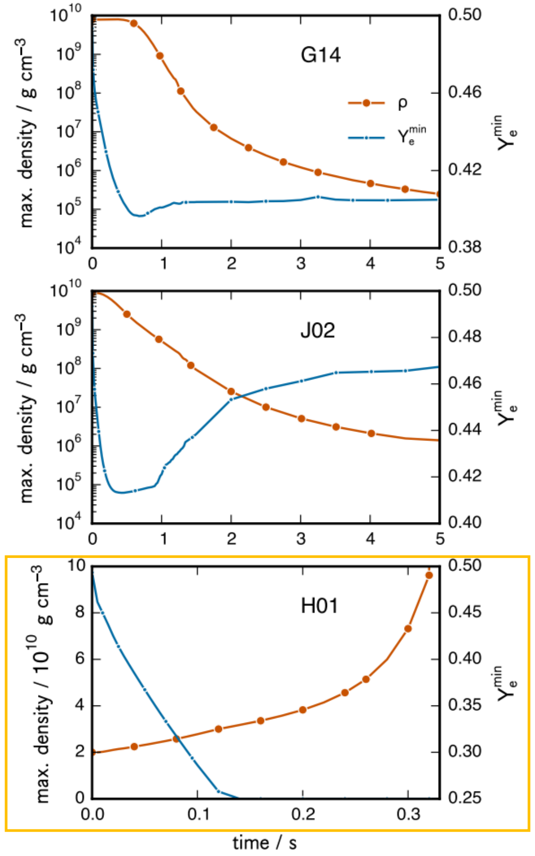
Back up

Which way do WDs go?

- Fates of accreted WDs depends on which is more efficient, electron capture or oxygen burning.
- Central density, accretion rate, composition, convection etc.
    - There are many parameters

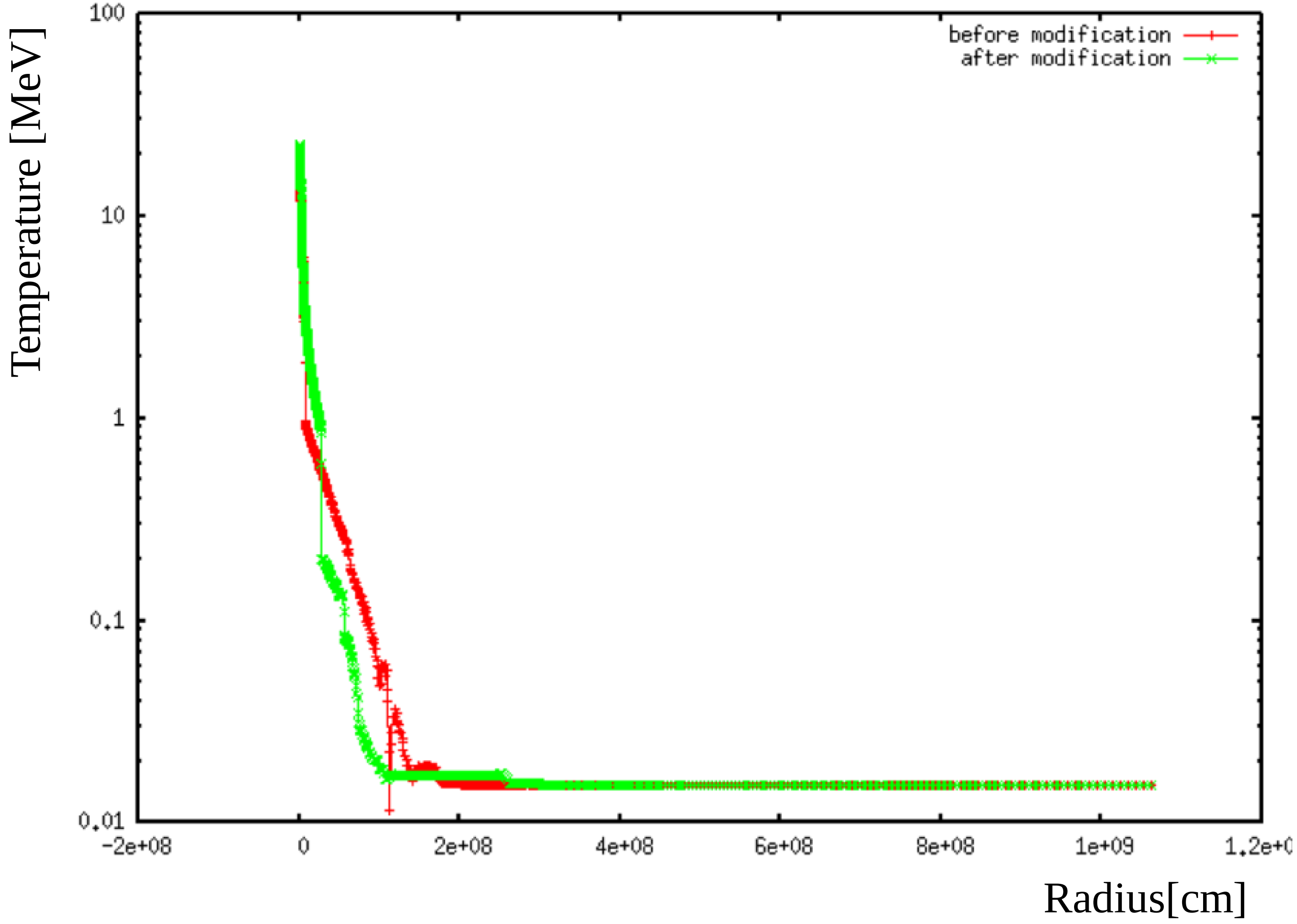


id.	res.	$^a\log_{10}\rho_c^{\rm ini}$ (g cm^{-3})	^{b}CC (Y/N)	$^cM_{\rm rem}$ ($M_\odot$)	$^dM_{\rm rem}^{\rm Fe}$ ($M_\odot$)	$^eM_{\rm ej}$ ($M_\odot$)	$^fM_{\rm ej}^{\rm Fe}$ ($M_\odot$)	$^g\langle Y_{\rm e,rem}\rangle$	$^hM_{\rm Ch}^{\rm eff}$ ($M_\odot$)	$^i\Delta x$ (km)
G13	256^3	9.90	N	0.647	0.173	0.741	0.231	0.491	1.384	0.870
G14	512^3	9.90	N	0.438	0.115	0.951	0.362	0.491	1.381	0.427
G15	256^3	9.90	Y	1.212	0.223	0.177	0.047	0.493	1.392	0.870
J01	256^3	9.95	N	0.631	0.171	0.768	0.233	0.491	1.379	0.870
J02	256^3	9.95	Y	1.291	0.226	0.104	0.025	0.493	1.392	0.870
H01*	256^3	10.3	N	1.401	0.022	0.000	0.000	0.486	1.356	0.870



The WD with high central density
is likely to collapse.
Jounes et al. (2016)

Address of low temperature

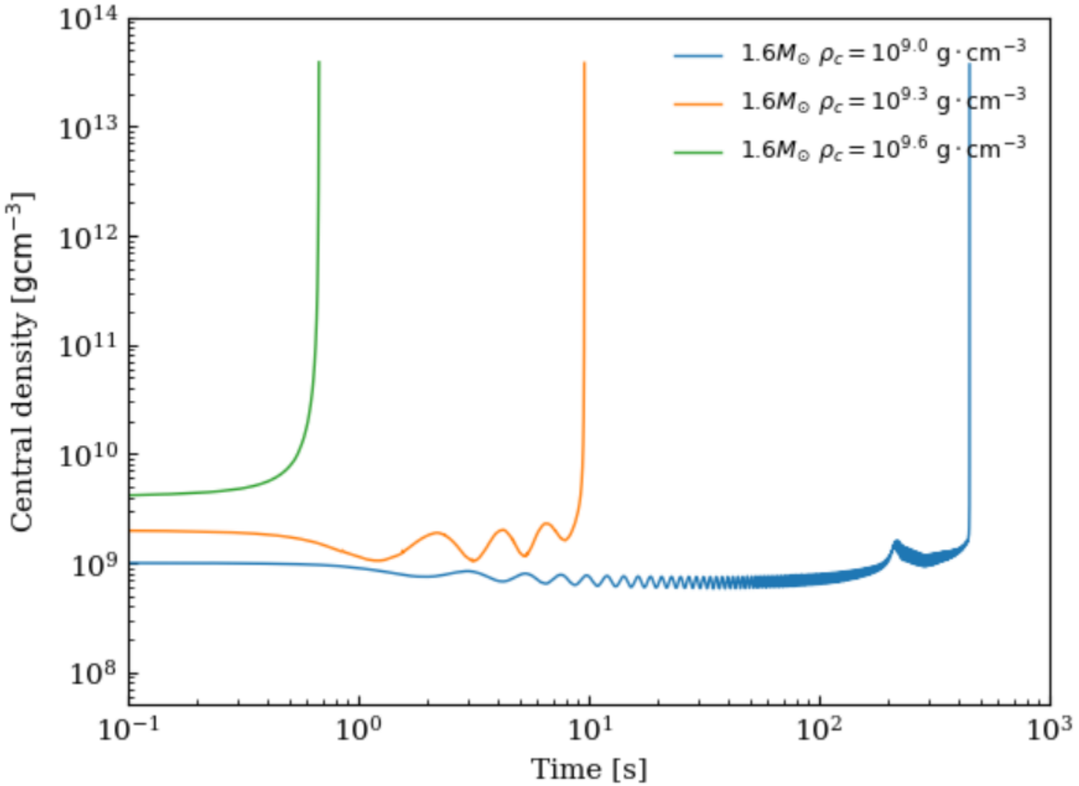


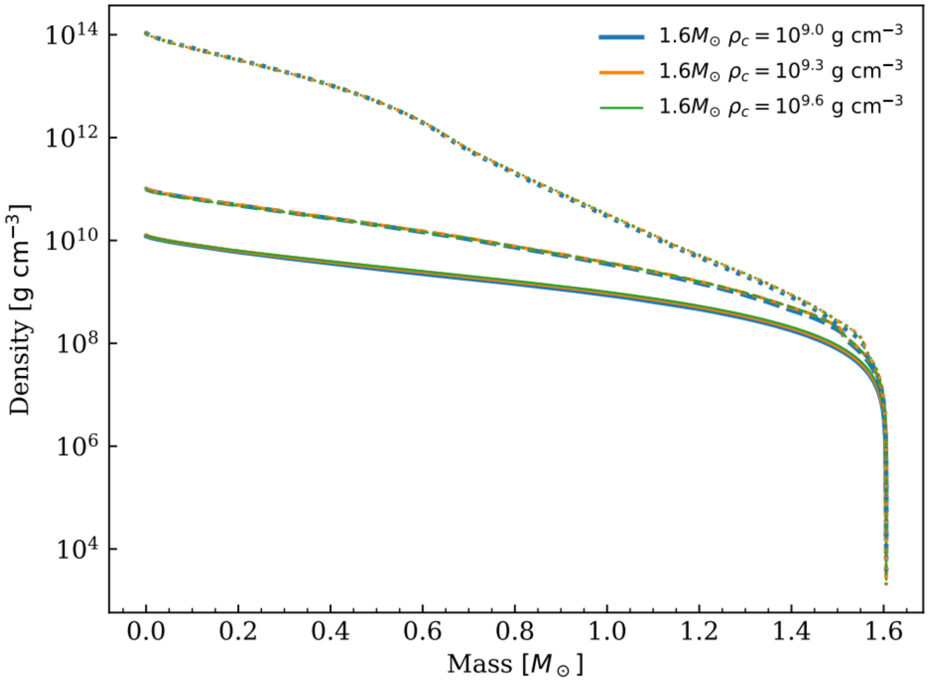
- During calculation, temperature also goes out of the EoS.
- When calculations stop, temperature profiles are modified.

Contents

- White dwarfs with the super Chandrasekhar mass
  - ➢Accretion Induced Collapse
  - ➢Merger Induced Collapse
- Explanation of WDs
- My simulation of WDs
- Discussion of the explosion.

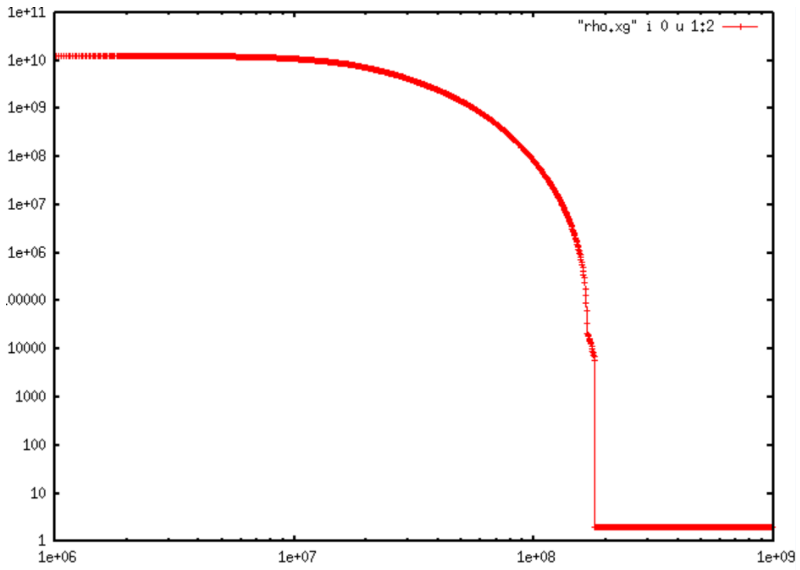
Density structures of different central densities





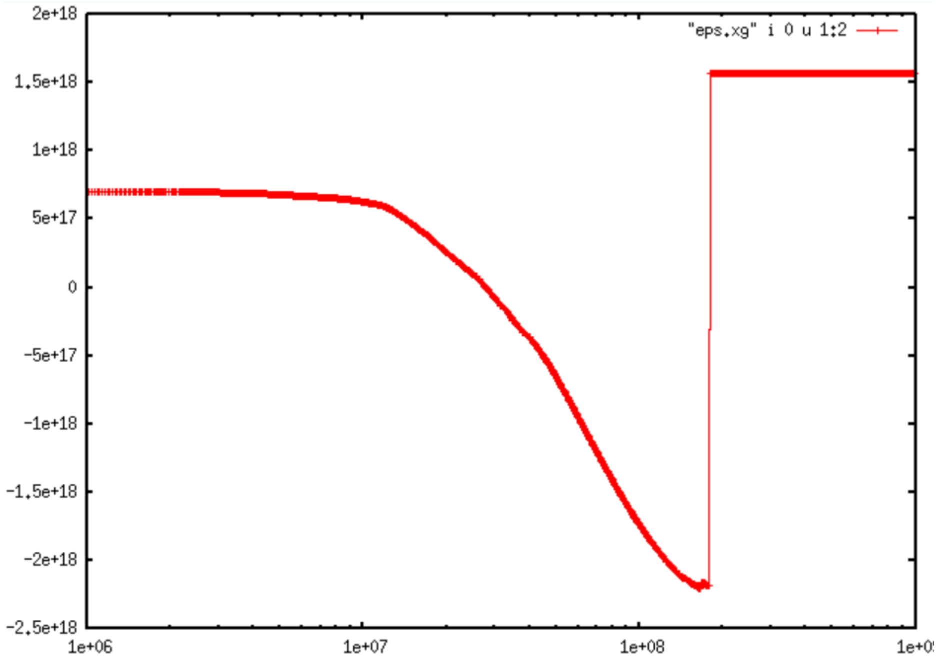
- Timescales of collapse are very different due to initial central densities.
- However, density structures are the same.

Limitation of parameters


Density profile

Density [g/cc]

Radius[cm]


Specific internal energy

Specific internal energy $[\mathrm{cm}^2\mathrm{s}^{-2}]$

Radius[cm]

Set floors to avoid reference of the EoS table

- Density floor: 2 g/cc
- Specific internal energy floor: $-2.21 \times 10^{18}\mathrm{cm}^2\mathrm{s}^{-2}$