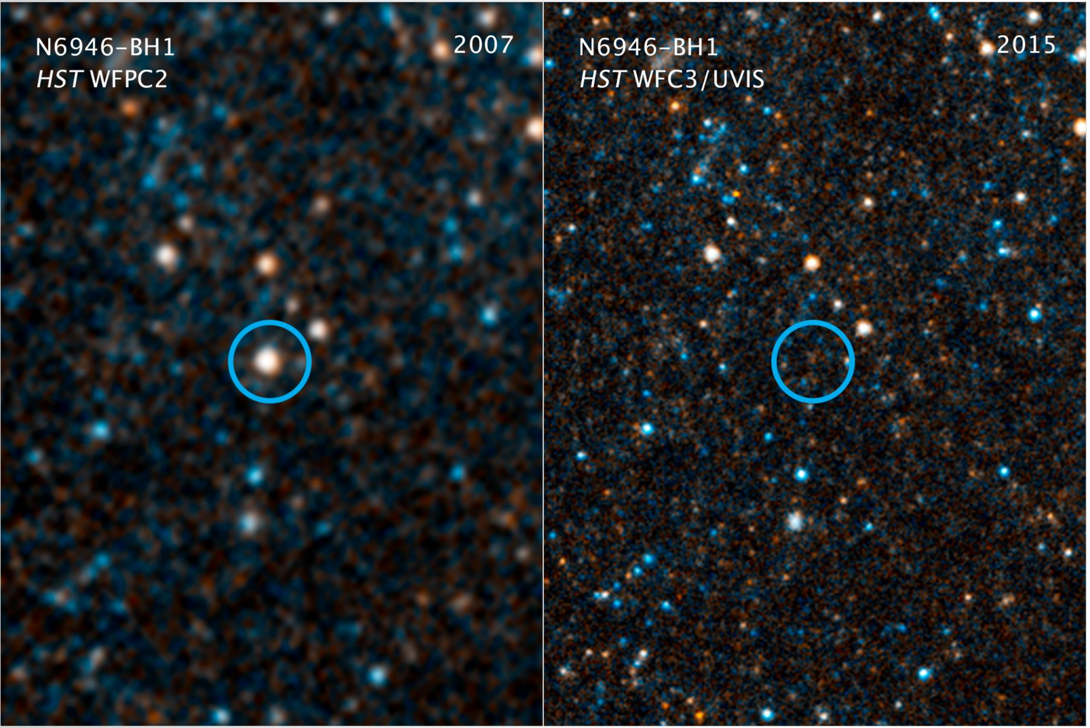


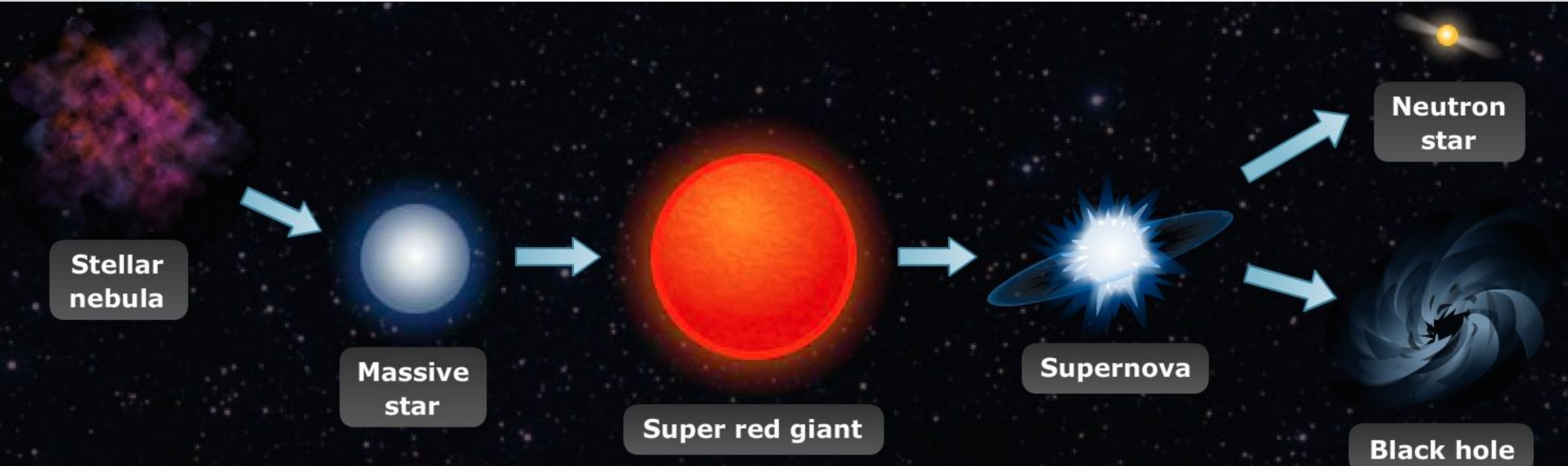
MSc Defense

Physics of black hole formation in failed supernovae

Mario Ivanov

Why study supernovae?

Studying the birth conditions and properties of neutron stars and stellar-mass black holes



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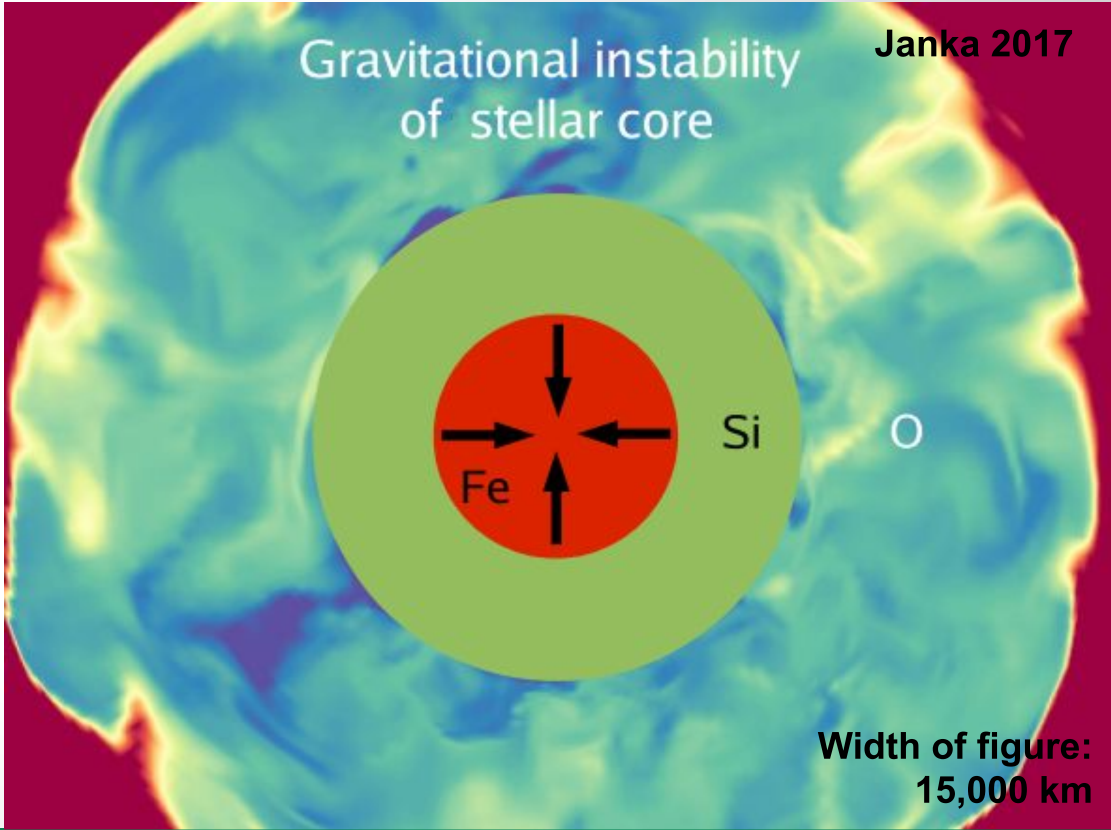
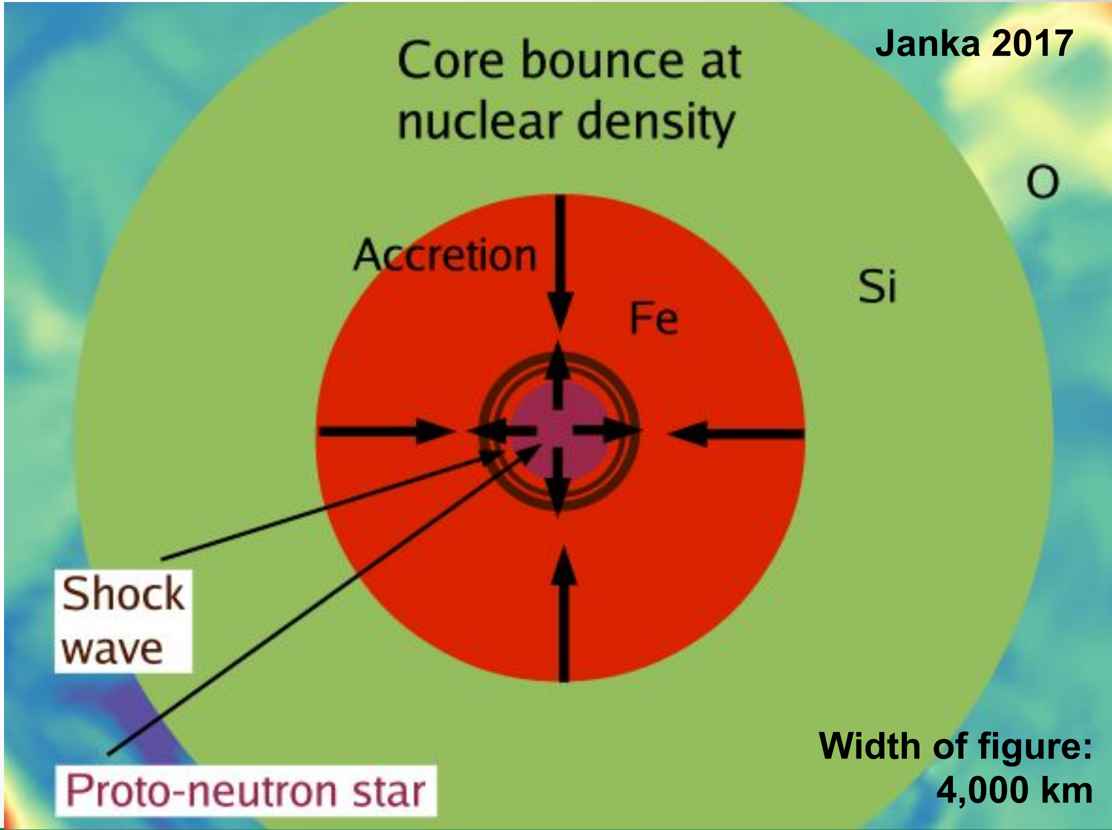
The neutrino-driven explosion

1. **Gravitational instability**



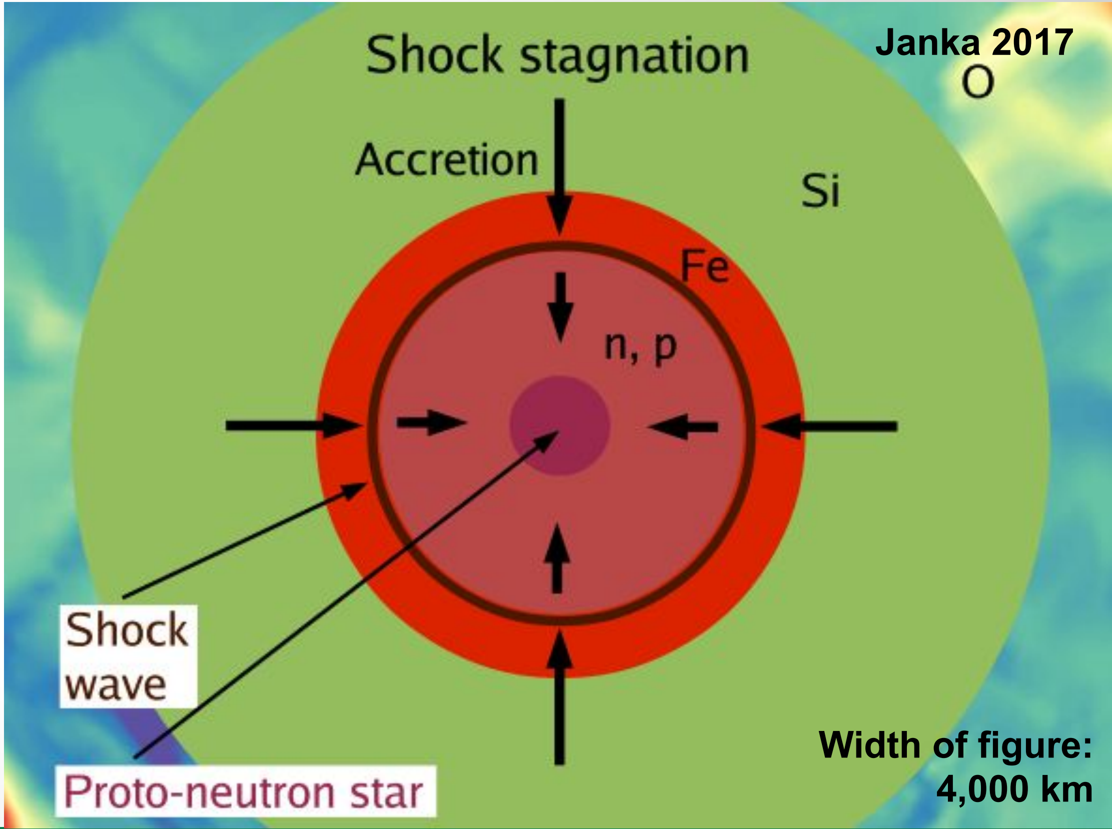
The neutrino-driven explosion

1. Gravitational instability
2. **Core bounce**



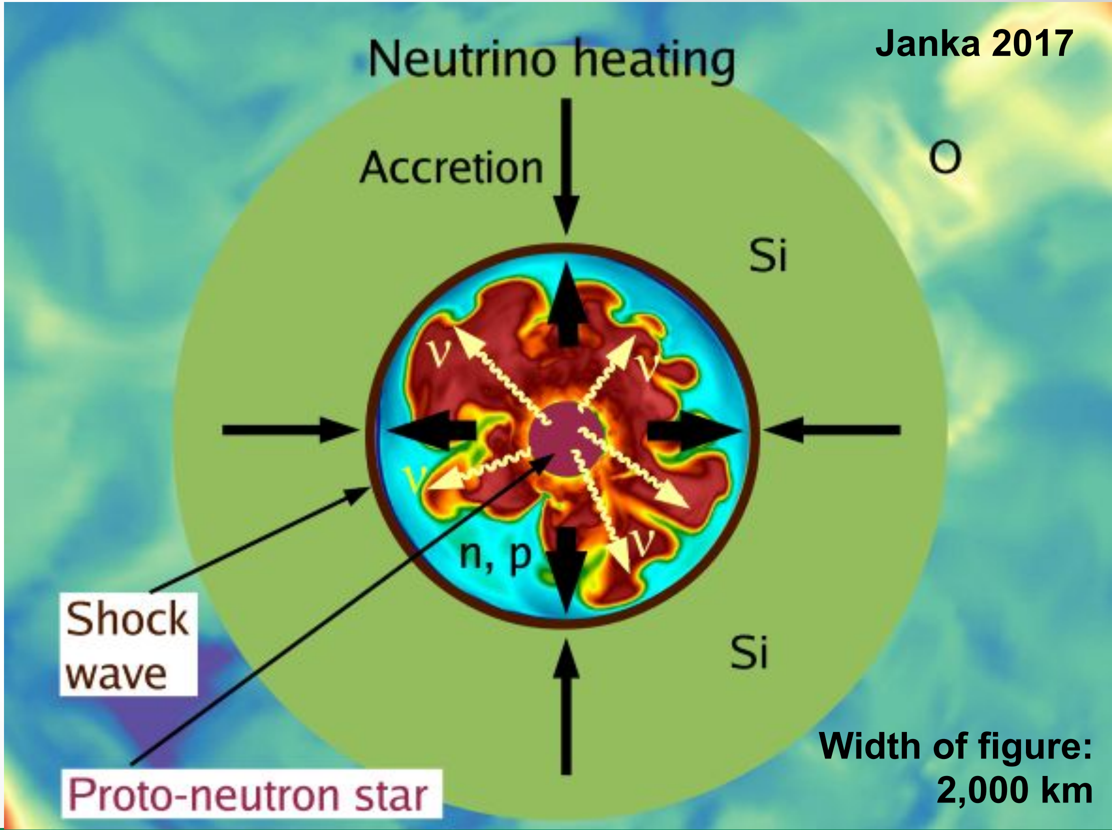
The neutrino-driven explosion

1. Gravitational instability
2. Core bounce
3. **Shock stagnation**



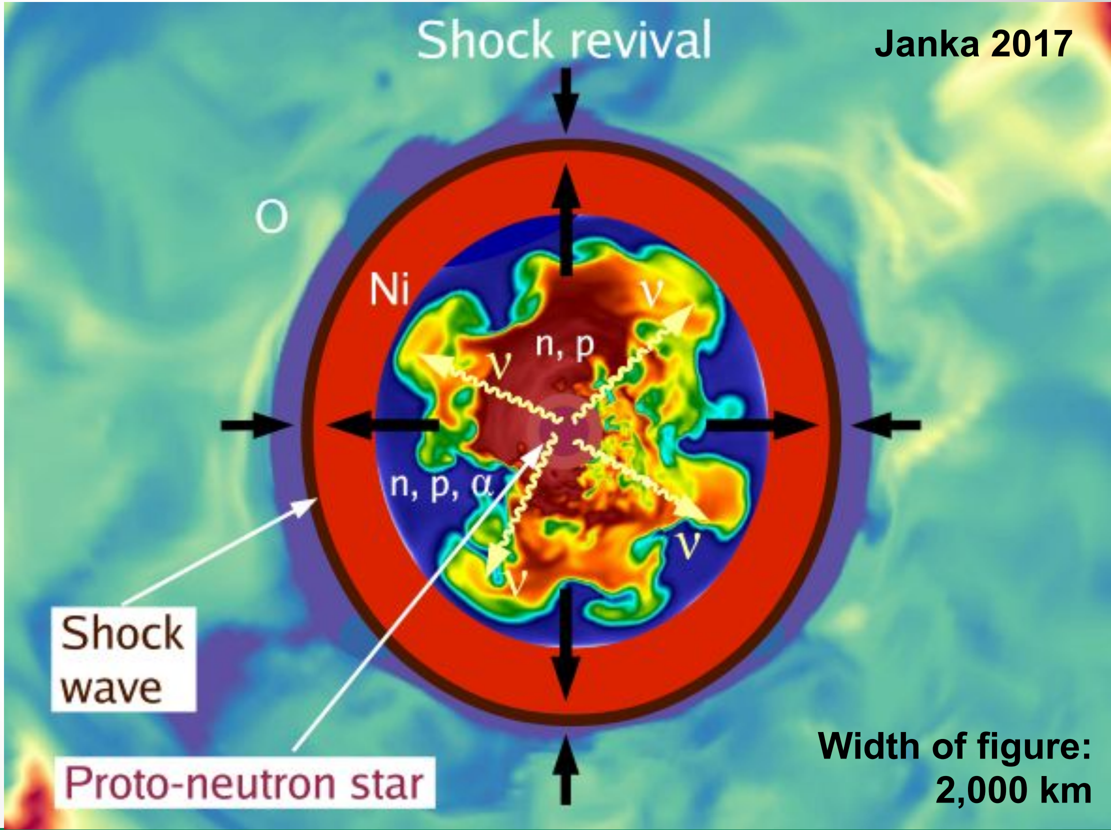
The neutrino-driven explosion

1. Gravitational instability
2. Core bounce
3. Shock stagnation
4. **Neutrino heating**



The neutrino-driven explosion

1. Gravitational instability
2. Core bounce
3. Shock stagnation
4. Neutrino heating
5. **Shock revival**

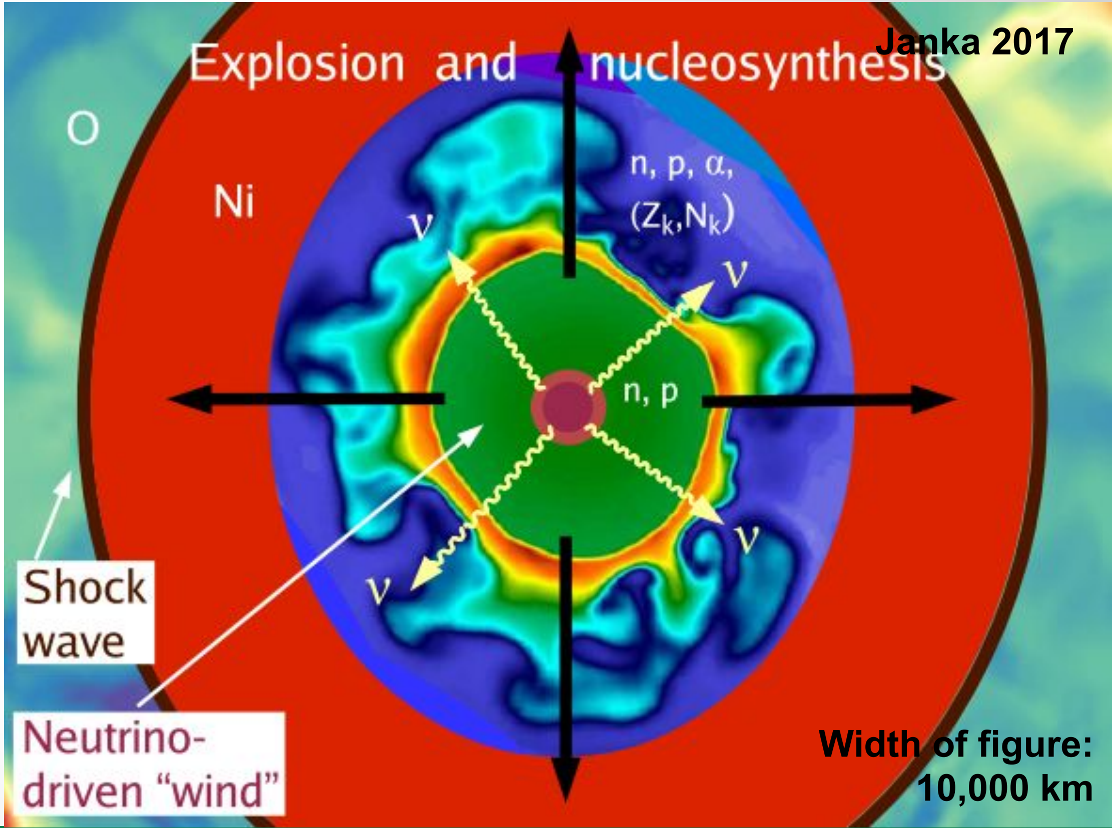


Janka 2017

Width of figure: 2,000 km

The neutrino-driven explosion

1. Gravitational instability
2. Core bounce
3. Shock stagnation
4. Neutrino heating
5. Shock revival
6. **Explosion and nucleosynthesis**



Possible outcomes

NEUTRON STAR	BLACK HOLE

Possible outcomes

NEUTRON STAR	BLACK HOLE
SUCCESSFUL SUPERNOVA (SN)	

Possible outcomes

NEUTRON STAR	BLACK HOLE
SUCCESSFUL SUPERNOVA (SN)	SUCCESSFUL, BUT WEAK, SN “fallback supernova”

Possible outcomes

NEUTRON STAR	BLACK HOLE
SUCCESSFUL SUPERNOVA (SN)	SUCCESSFUL, BUT WEAK, SN “fallback supernova” **SHOCK IS NOT REVIVED** **“failed supernova”**

Failed supernova… can still be seen!

Some stars form a black hole without any transients

Hydrodynamic simulations predict possible transients

1. Neutrinos emitted from core
    - Instantaneous loss of gravitational mass
2. Sound pulse forms → outward shock
3. Mass and energy ejected from star

This mechanism works for many progenitor stars!

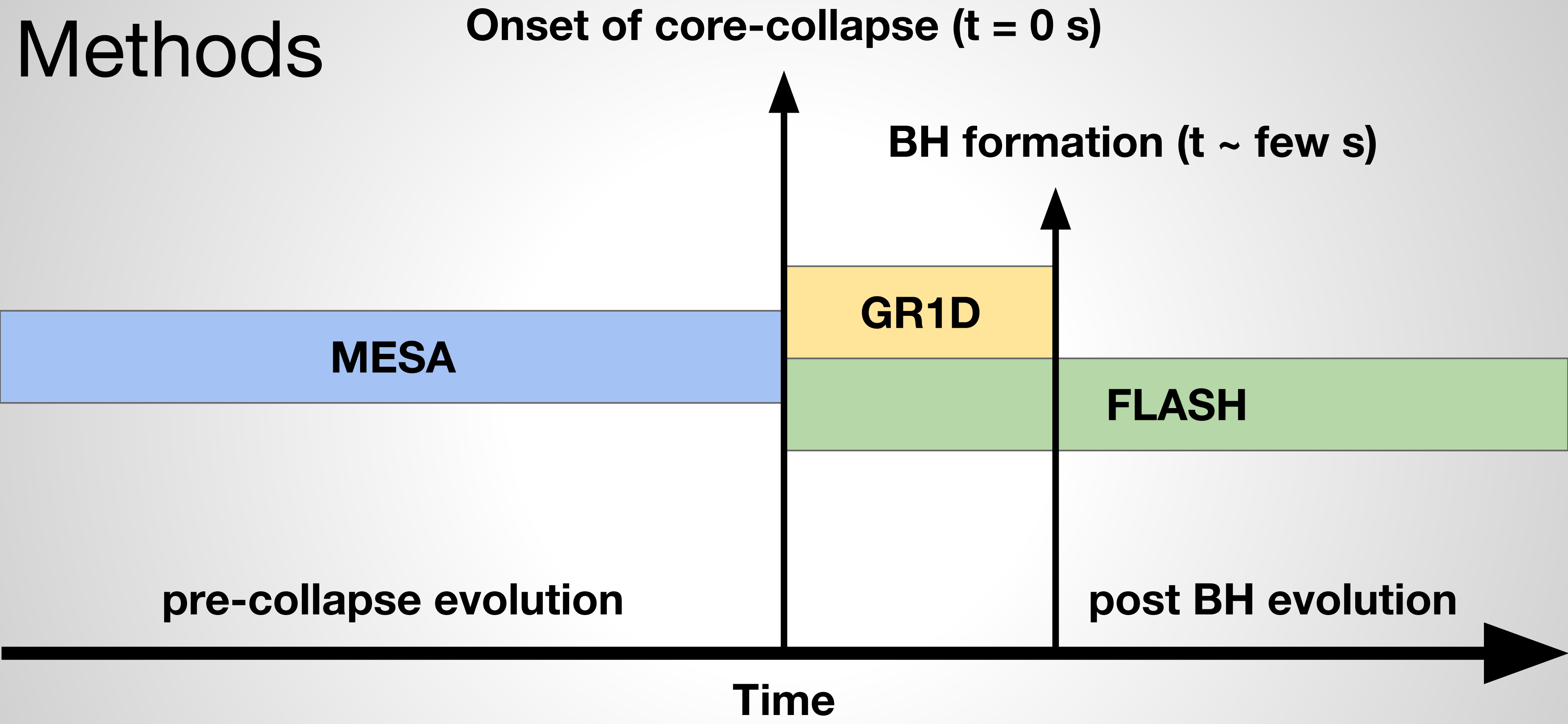
My thesis work

My work improves on the methods of F18:

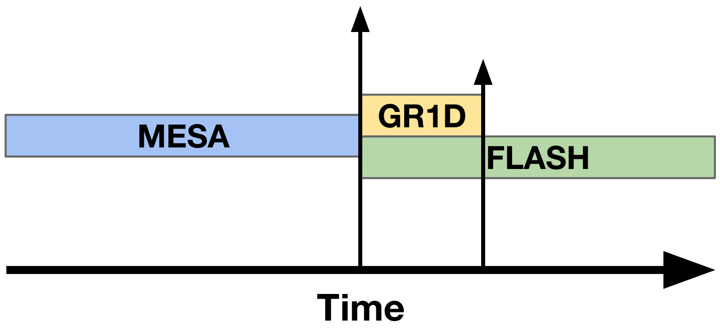
F18	This work
- Parameterized inner core evolution - One equation of state (EOS)	- Inner core evolution with a GR1D, GR neutrino-radiation hydro code - Three new EOSs - Resolution is 4-8X higher

Physically grounded value for gravitational mass lost to neutrinos

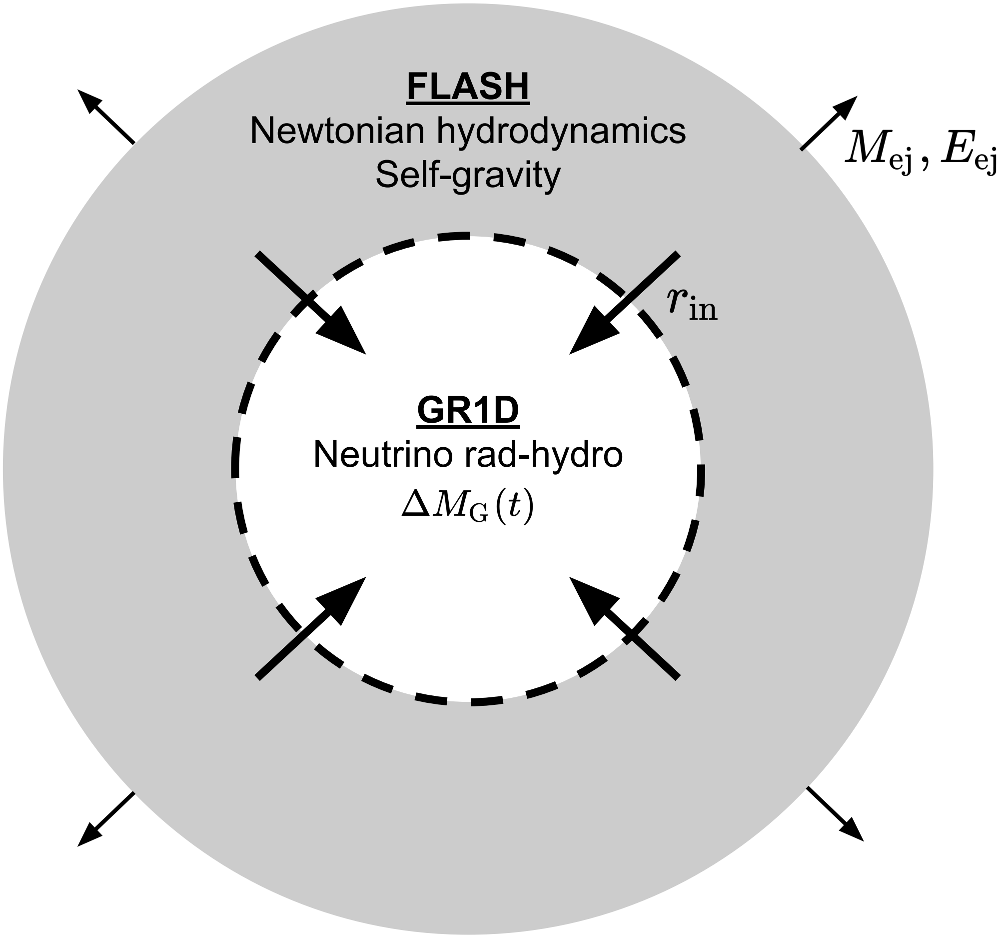
Methods


Onset of core-collapse (t = 0 s)
BH formation (t ~ few s)
GR1D
MESA
FLASH
pre-collapse evolution
post BH evolution
Time

Methods



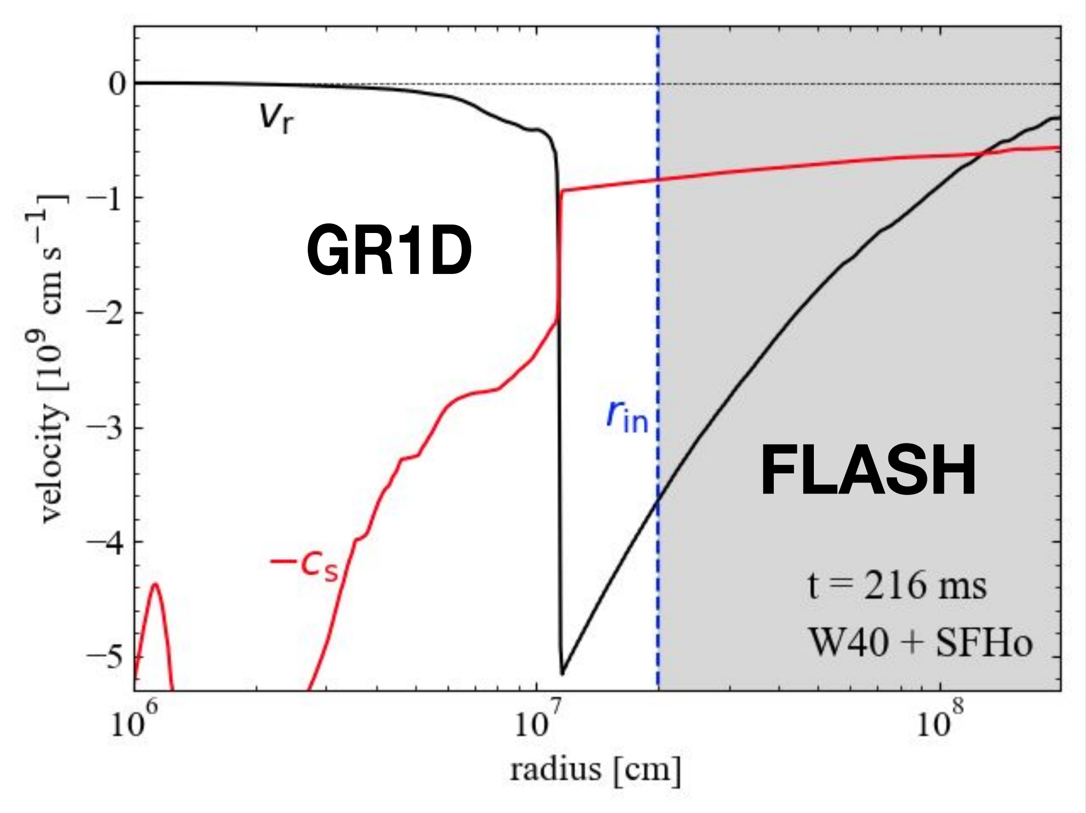
MESA
GR1D
FLASH
Time



FLASH
Newtonian hydrodynamics
Self-gravity
$M_{\rm ej}\,, E_{\rm ej}$
$r_{\rm in}$
GR1D
Neutrino rad-hydro
$\Delta M_{\rm G}(t)$

Remapping GR1D into FLASH

- "remap" means using GR1D hydro variables for inner core evolution
- No hydrodynamic feedback at "r_{in}"
- Discrepancies on the order of ~1% made the results unreliable

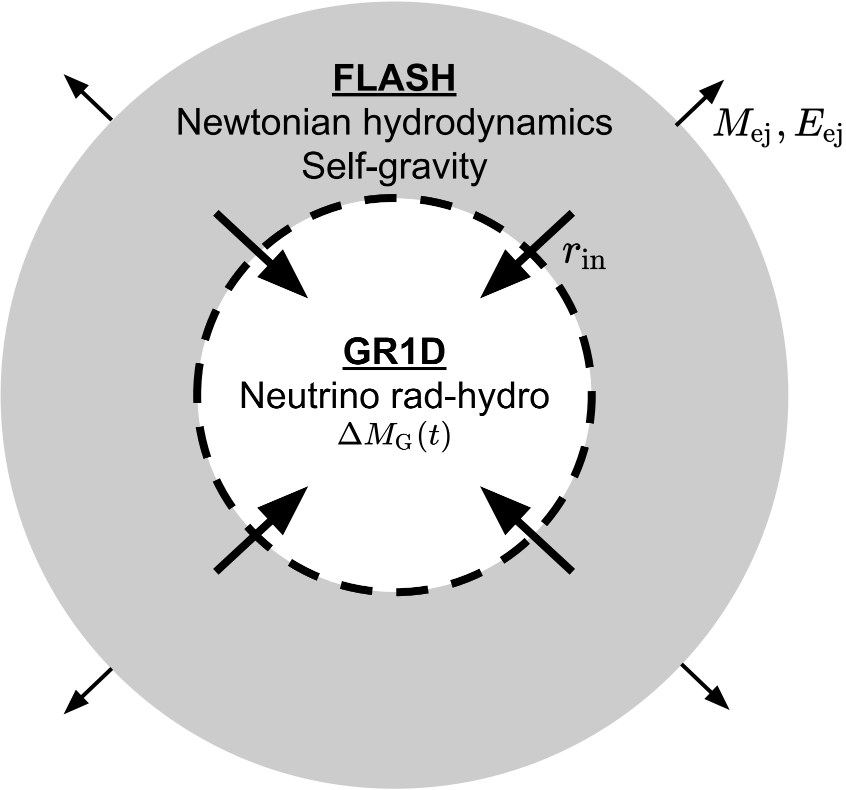


Interpolation of δM_G from GR1D

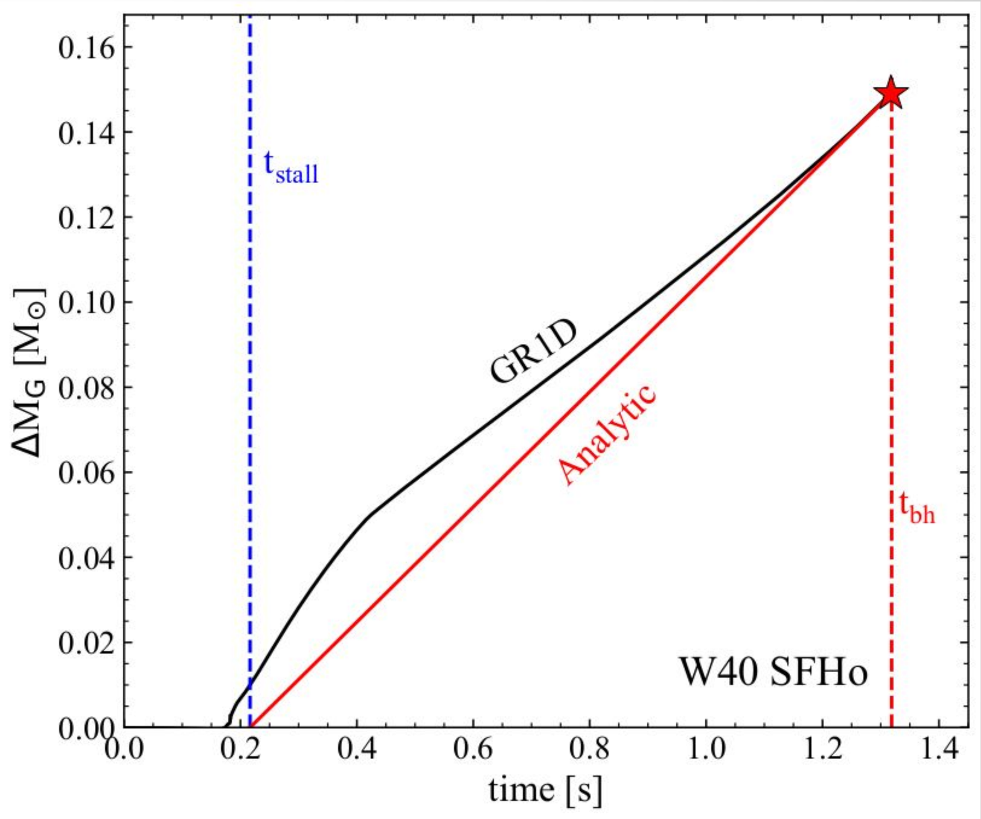
- Full domain of MESA (no remap of GR1D)

- Gravitational mass lost is interpolated from GR1D and included in FLASH

- Default method for results



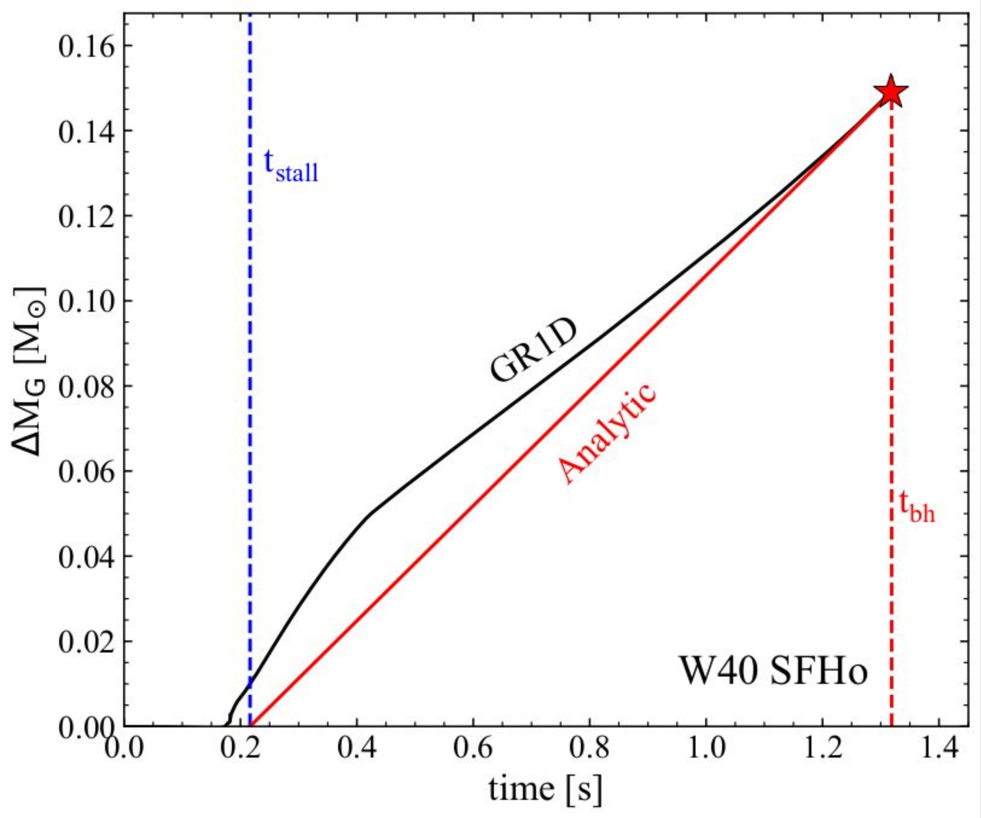
Analytic ramp



Analytic ramp

Three key parameters:

- start time
- end time
- total ΔM_G

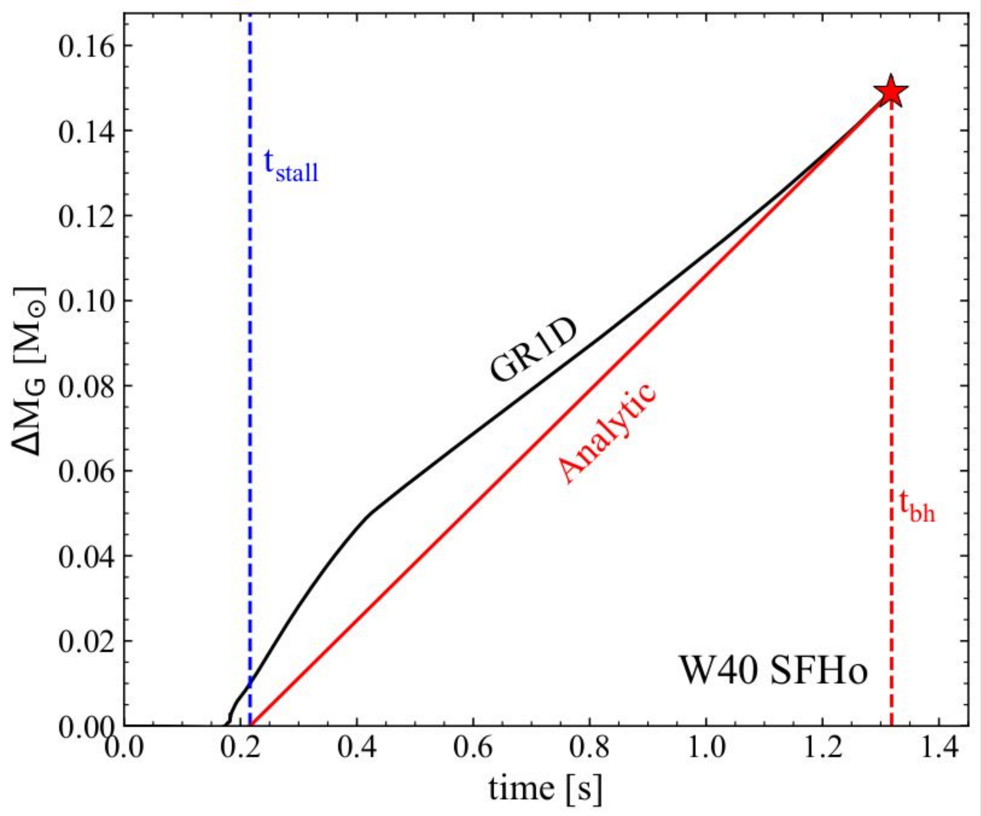


Analytic ramp

Three key parameters:

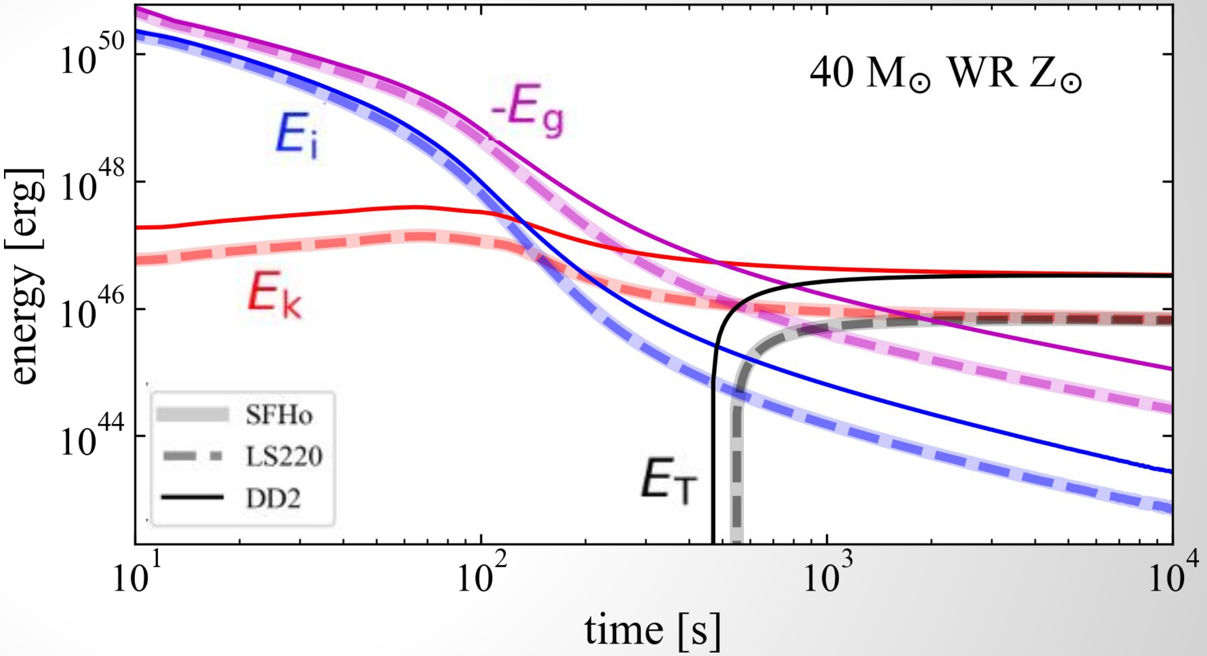
- start time
- end time
- total ΔM_G

How important are the full GR1D simulations versus this approximation?



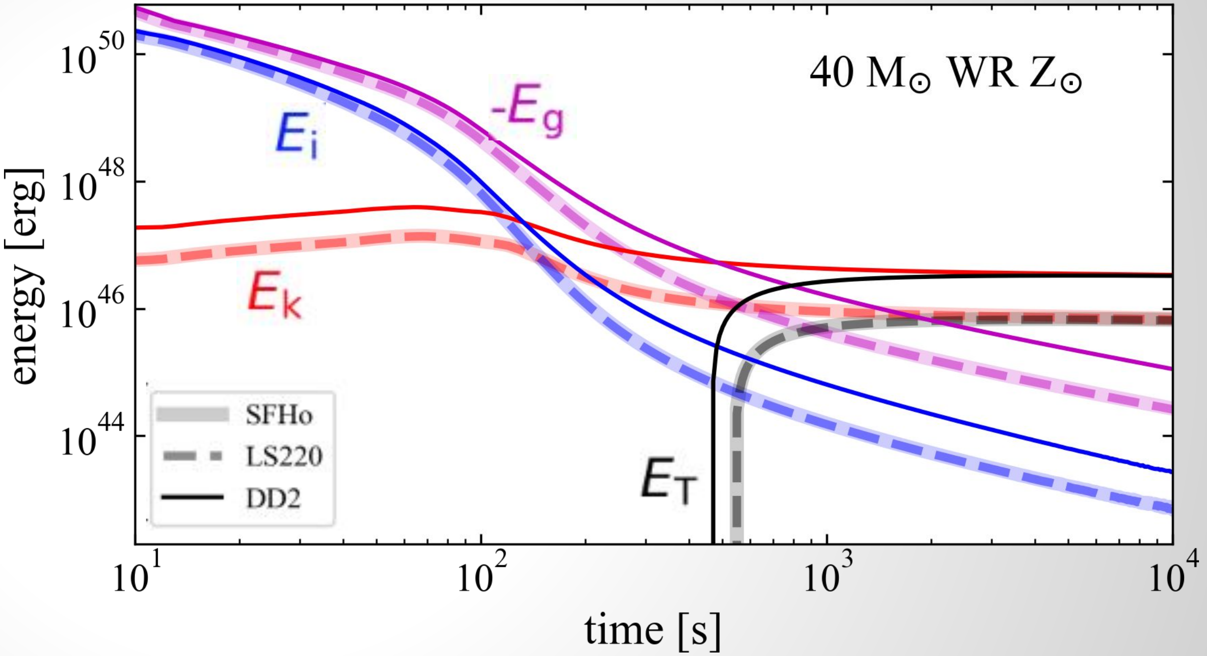
Results

1. Ejecta masses and energies vary by a factor of several for our range of EOSs



Results

- Total energy at 10^4 s is the energy of mass ejecta
- Difference between EOS is related to t_{bh}



Results

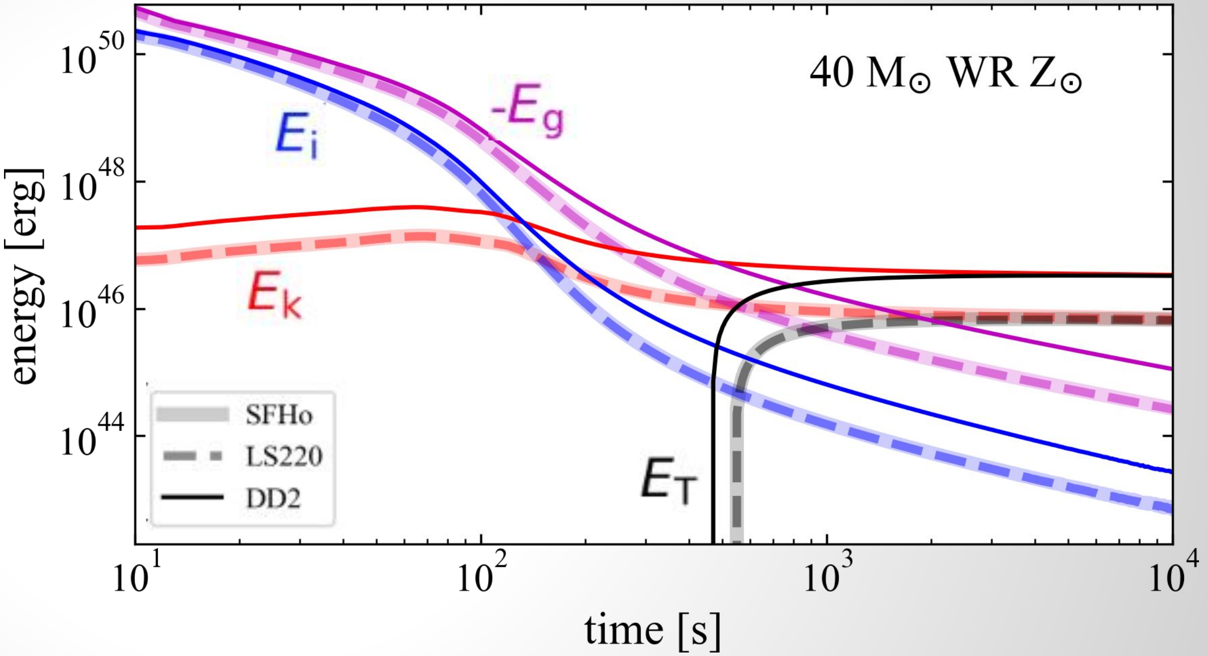
longer t_{bh}

↓

more neutrinos emitted

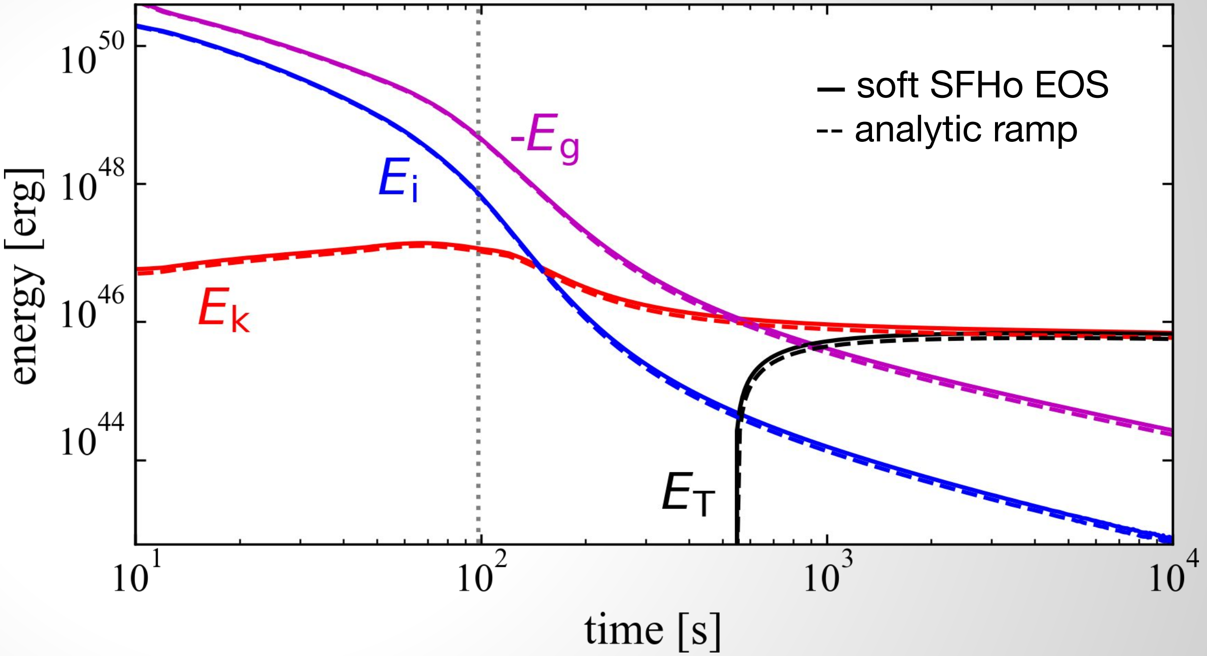
↓

higher ΔM_G



Results

2. Using the analytic ramp leads to results ~20% different for WR and ~5% different in the RSG and BSG cases



Results

3. Observational predictions are consistent with F18 for the stiff DD2 EOS and several times fainter for the soft SFHo EOS.

RSG shock breakout

BSG plateau emission

$t_{pl} \sim$ days

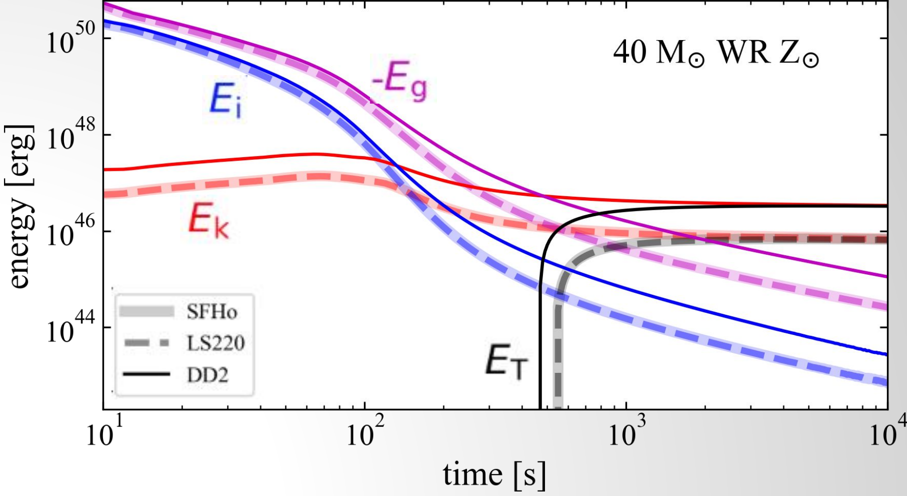
$L_{bo} \sim 10^{39}$ erg/s

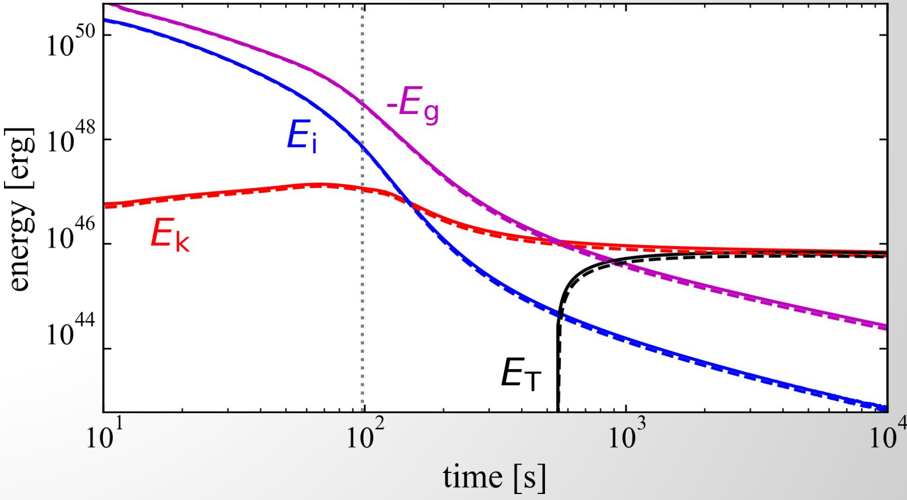
BSG shock breakout

$t_{br} \sim$ hours $\quad T_{br} \sim$ 6-8 x 10^4 K

Summary

- "remap" discrepancies lead to unreliable results
- Ejecta masses and energies vary by a factor of several for our range of EOSs
- Using the linear ramp lead to 5~20% difference in results
- Observational predictions are consistent with F18 for stiff EOS and fainter with soft EOS





Supernova Taxonomy

<table>
<caption>Supernova taxonomy[45][46]</caption>
<tr><td rowspan="3">Type I
No hydrogen</td><td colspan="3">Type Ia
Presents a singly ionised silicon (Si II) line at 615.0 nm (nanometers), near peak light</td><td>Thermal runaway</td></tr>
<tr><td rowspan="2">Type Ib/c
Weak or no silicon absorption feature</td><td colspan="2">Type Ib
Shows a non-ionised helium (He I) line at 587.6 nm</td><td rowspan="6">Core collapse</td></tr>
<tr><td colspan="2">Type Ic
Weak or no helium</td></tr>
<tr><td rowspan="4">Type II
Shows hydrogen</td><td rowspan="3">Type II-P/-L/n
Type II spectrum throughout</td><td rowspan="2">Type II-P/L
No narrow lines</td><td>Type II-P
Reaches a "plateau" in its light curve</td></tr>
<tr><td>Type II-L
Displays a "linear" decrease in its light curve (linear in magnitude versus time).[47]</td></tr>
<tr><td colspan="2">Type IIn
Some narrow lines</td></tr>
<tr><td colspan="3">Type IIb
Spectrum changes to become like Type Ib</td></tr>
</table>

https://en.wikipedia.org/wiki/Supernova