Predicting Which Massive Stars Explode

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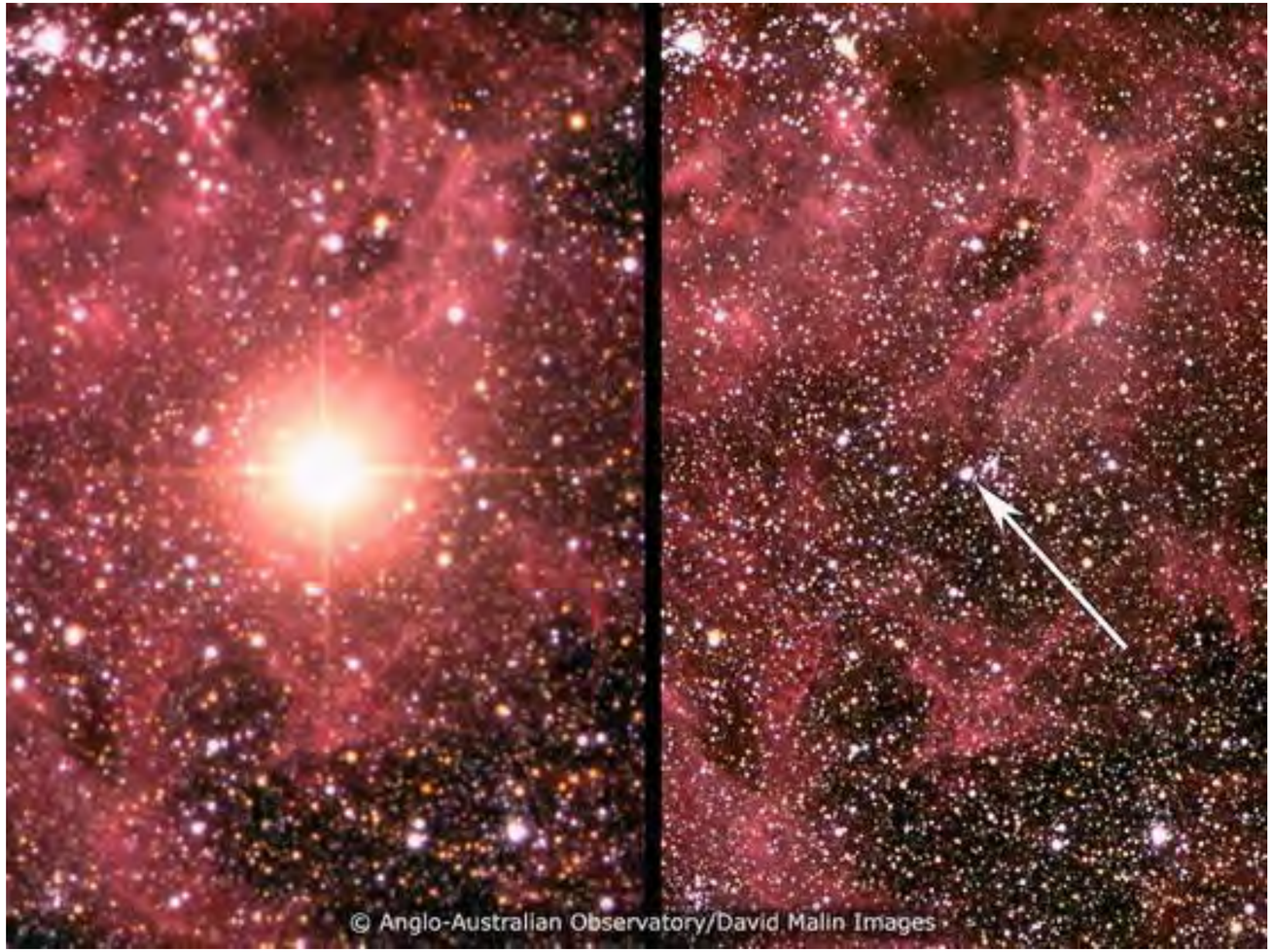
Outline

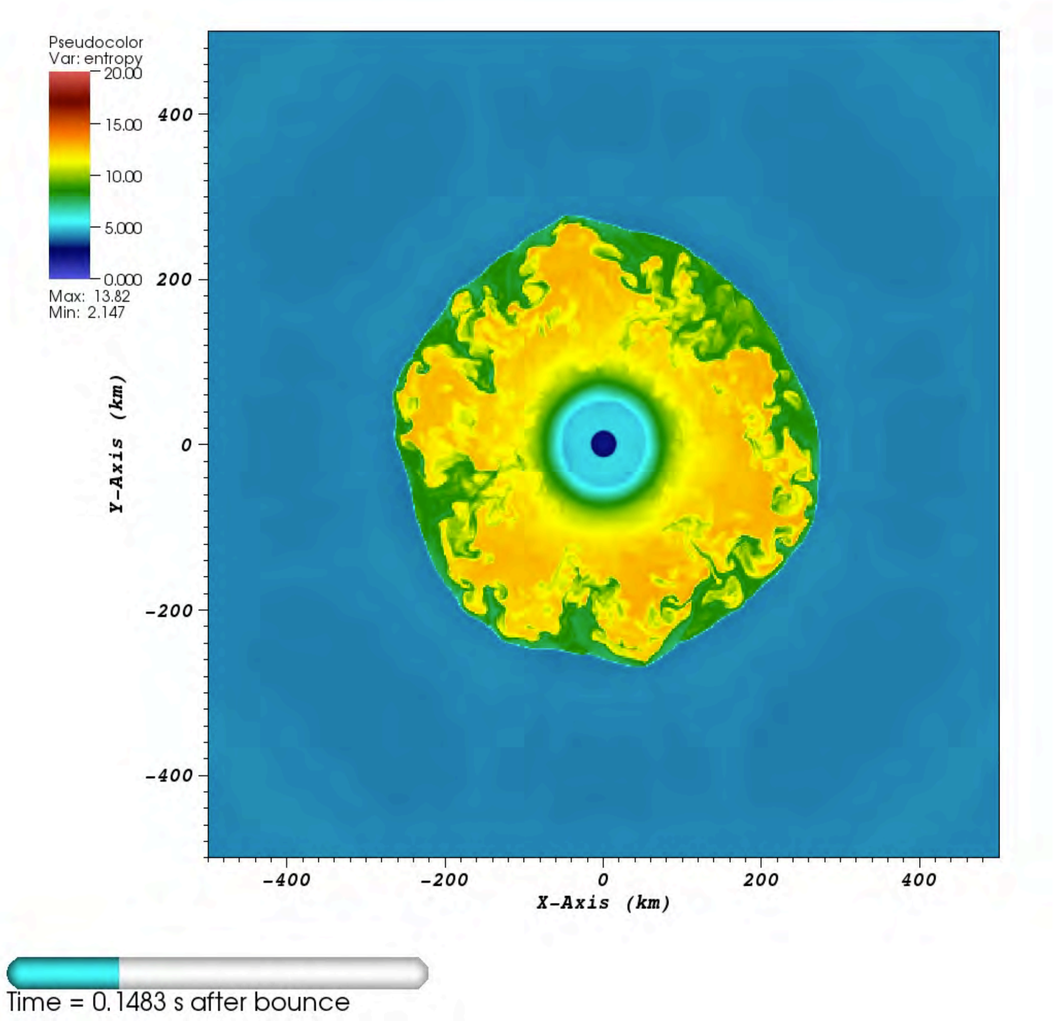
- CCSN Mechanism
- CCSN Theory
- CCSN Simulations

How massive stars die?

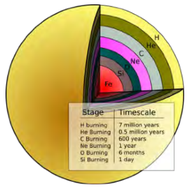
Which massive stars explode?



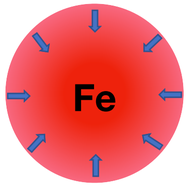
CCSN Mechanism



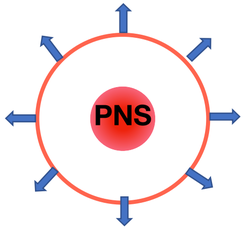
1. Stable core



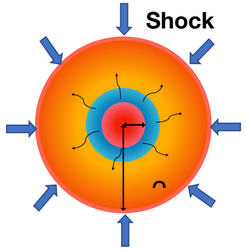
2. Core-collapse phase



3. Bounce and shock formation



4. Stalled shock phase

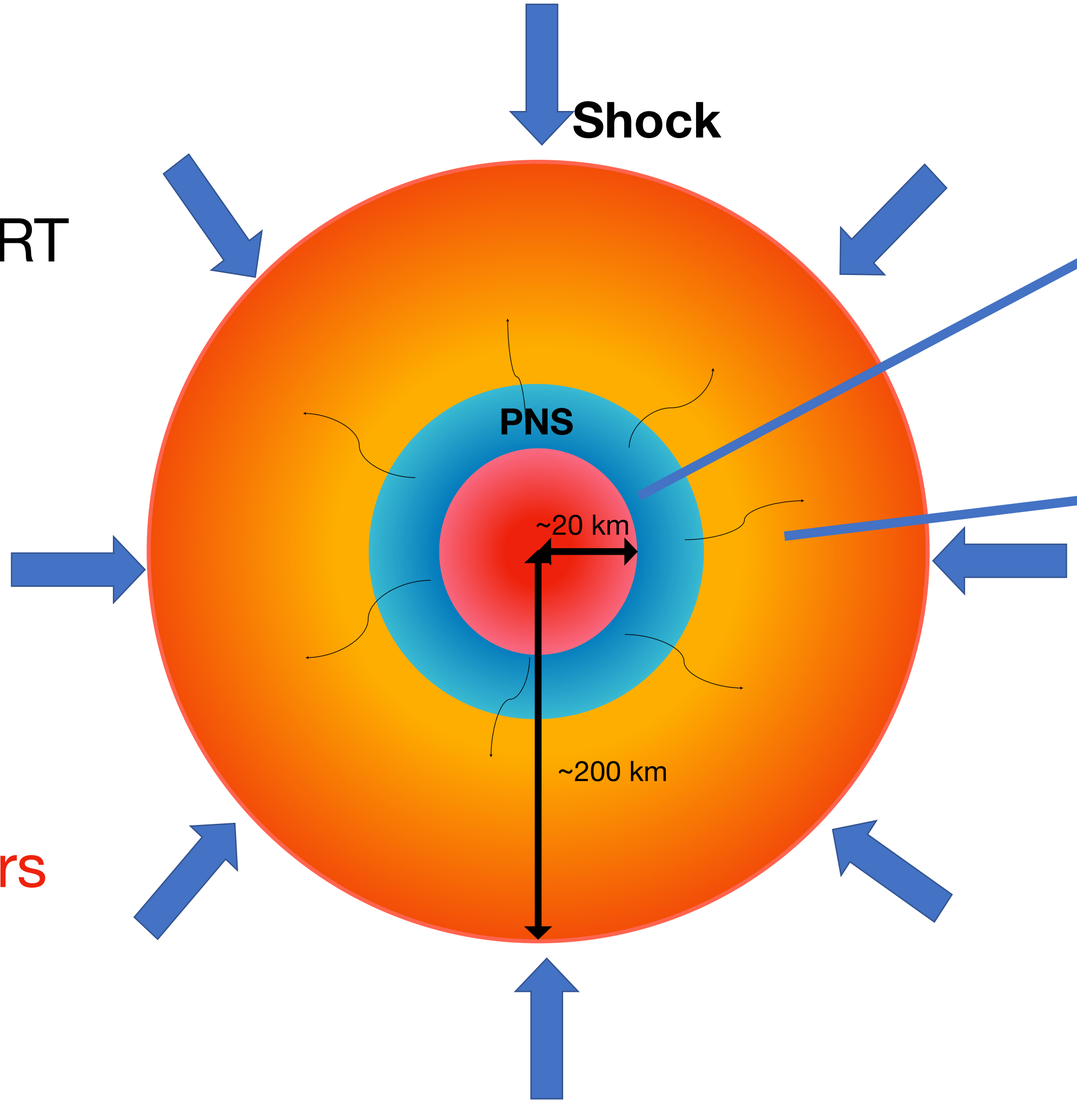


5. Explosion or collapse to BH

Delayed Neutrino Mechanism

- MHD
- RADIATION TRANSPORT
- GENERAL RELATIVITY
- NUCLEAR PHYSICS

3D - ~10 million CPU hours



Cooling Region:

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

Heating Region:

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

1D Analytic Explosion Condition

$$\int_{R_{NS}}^{R_S+\epsilon}$$

$$\cancelto{=0}{\frac{\partial \rho}{\partial t}} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

$$\rho\left(\cancelto{=0}{\frac{\partial \boldsymbol{v}}{\partial t}} + (\boldsymbol{v}\cdot\nabla)\boldsymbol{v}\right) = -\nabla p - \rho\nabla\Phi$$

$$\cancelto{=0}{\frac{\partial(\rho E)}{\partial t}} + \nabla \cdot \left[\rho \boldsymbol{v}\left(\varepsilon + \frac{p}{\rho} + \frac{v^2}{2} + \Phi\right)\right] = \rho q_\nu - \rho q_c$$

$$\tilde{L}_\nu \tau_g = \frac{L_\nu \tau_g R_{NS}}{\left|\dot{M}\right| G M_{NS}}$$

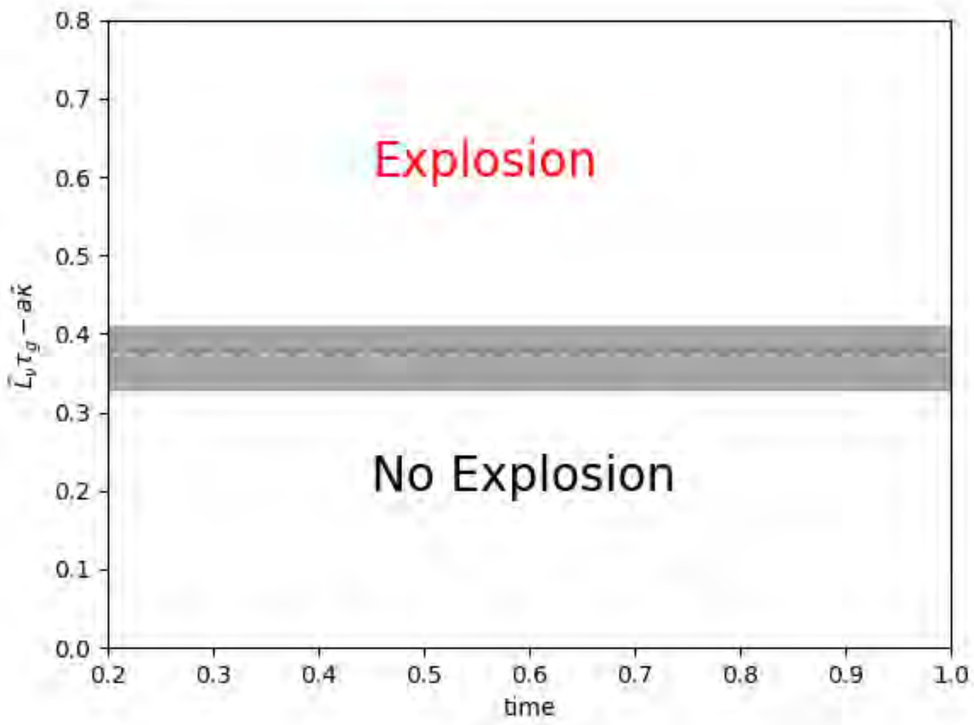
$$\tilde{\kappa} = \frac{\kappa \left|\dot{M}\right|}{\sqrt{G M_{NS} R_{NS}}}$$

$$\boxed{\tilde{L}_\nu \tau_g - a\tilde{\kappa} > b}$$

ν Heating

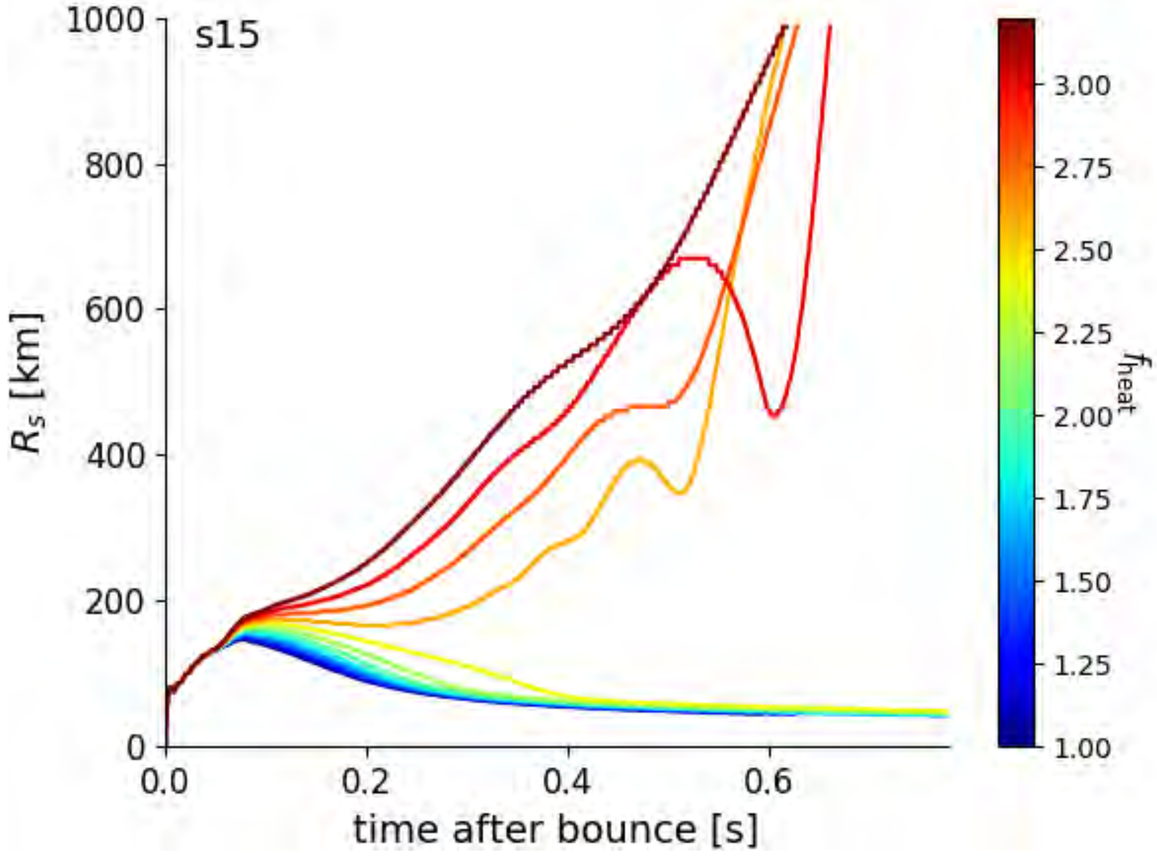
$p - p_{\text{ram}}$

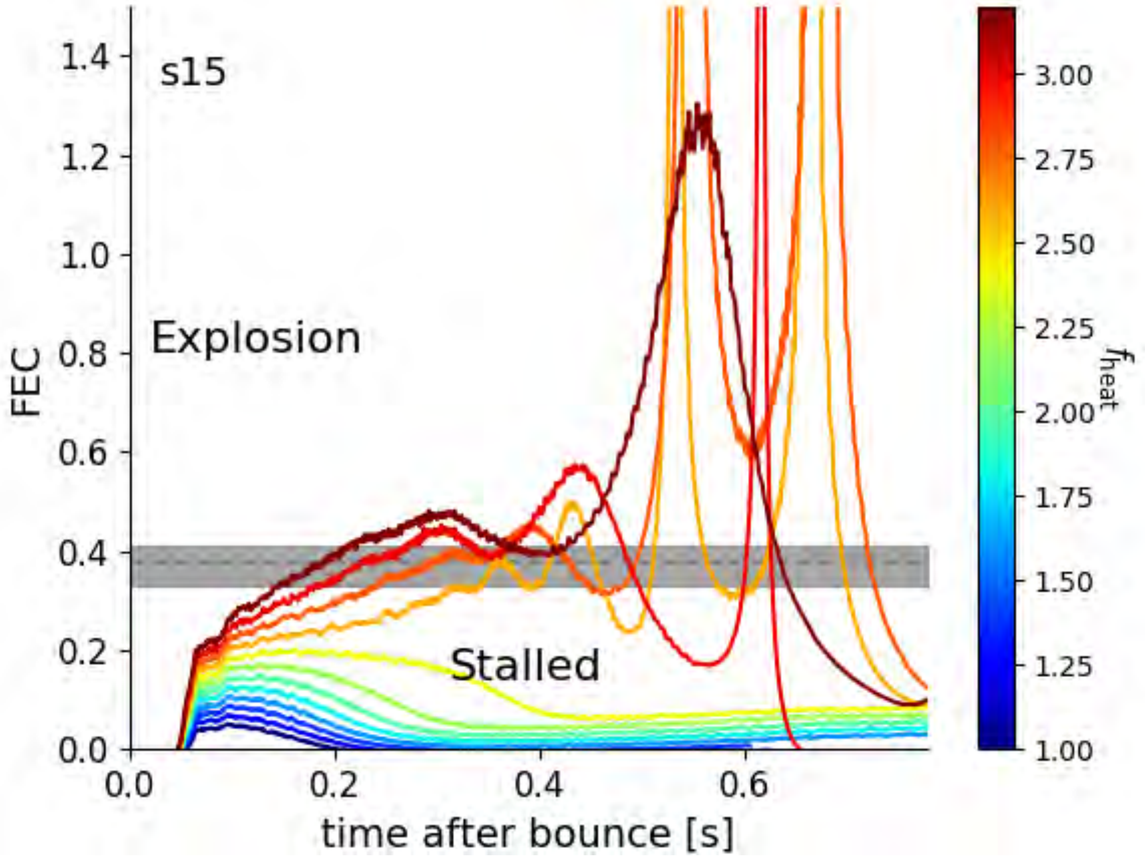
Gravity



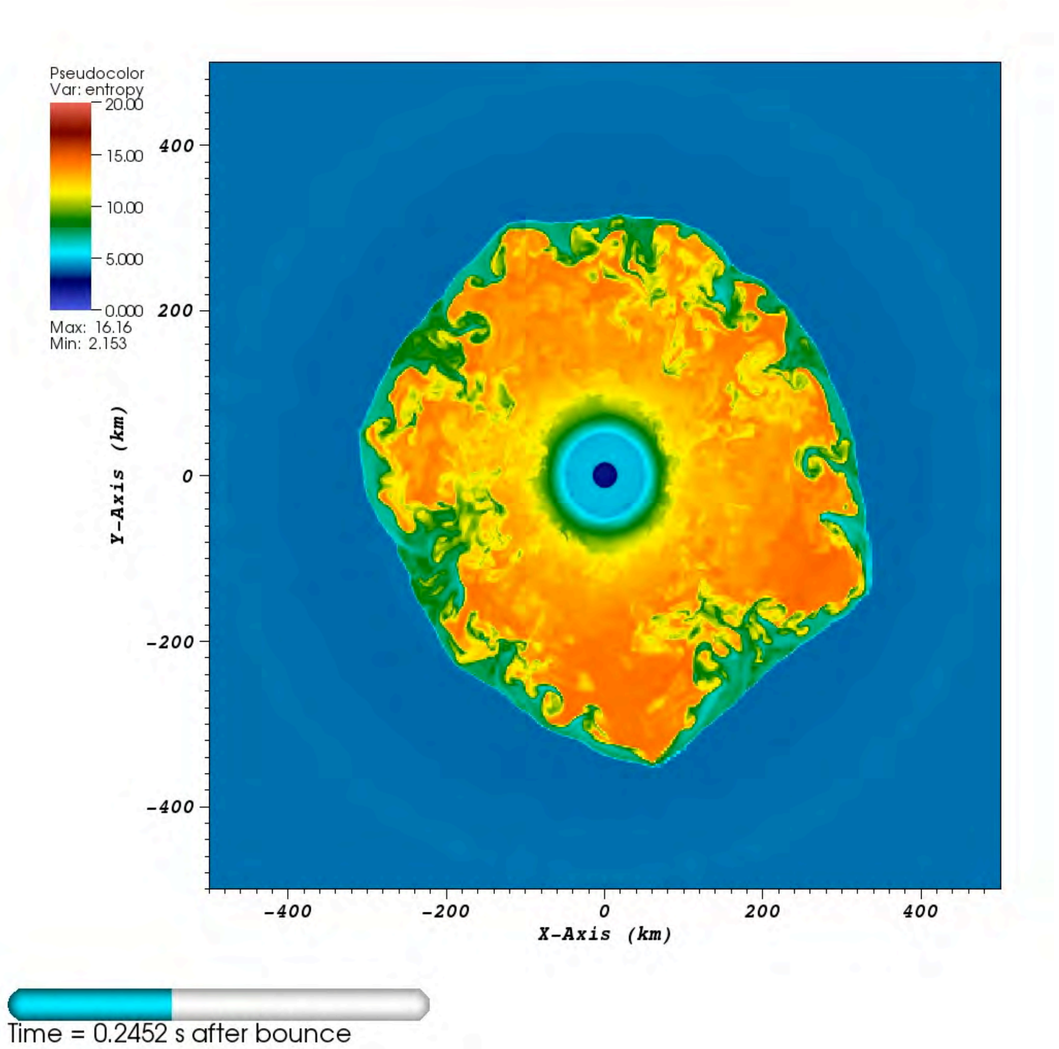
Gogilashvili, Murphy, O'Connor (2023)

Testing 1D FEC

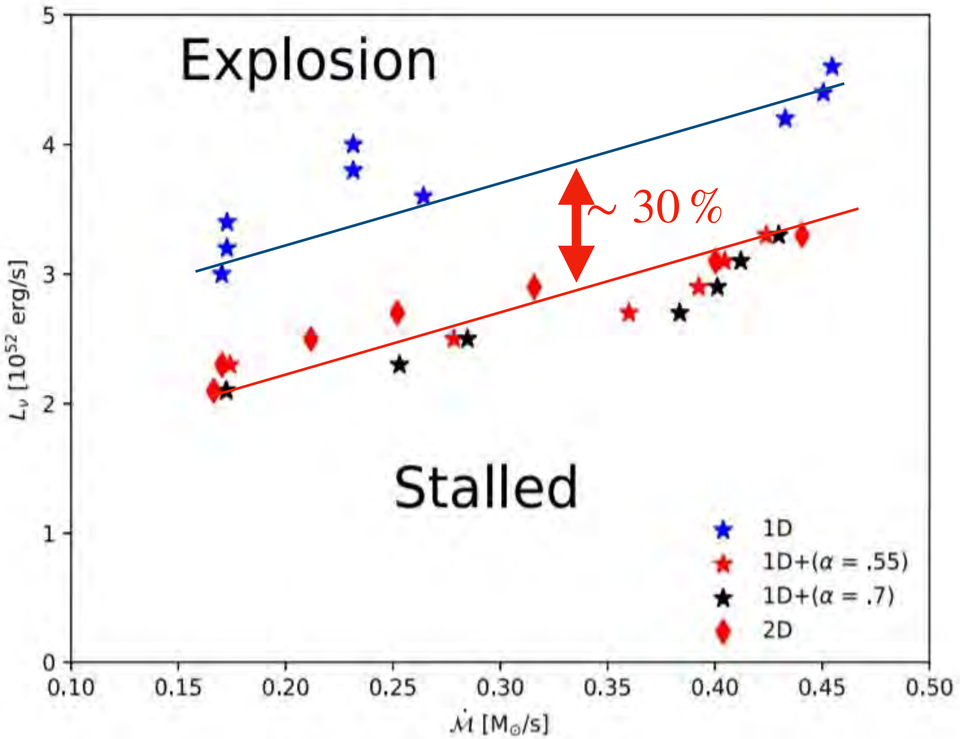




CCSN is NOT Spherical!



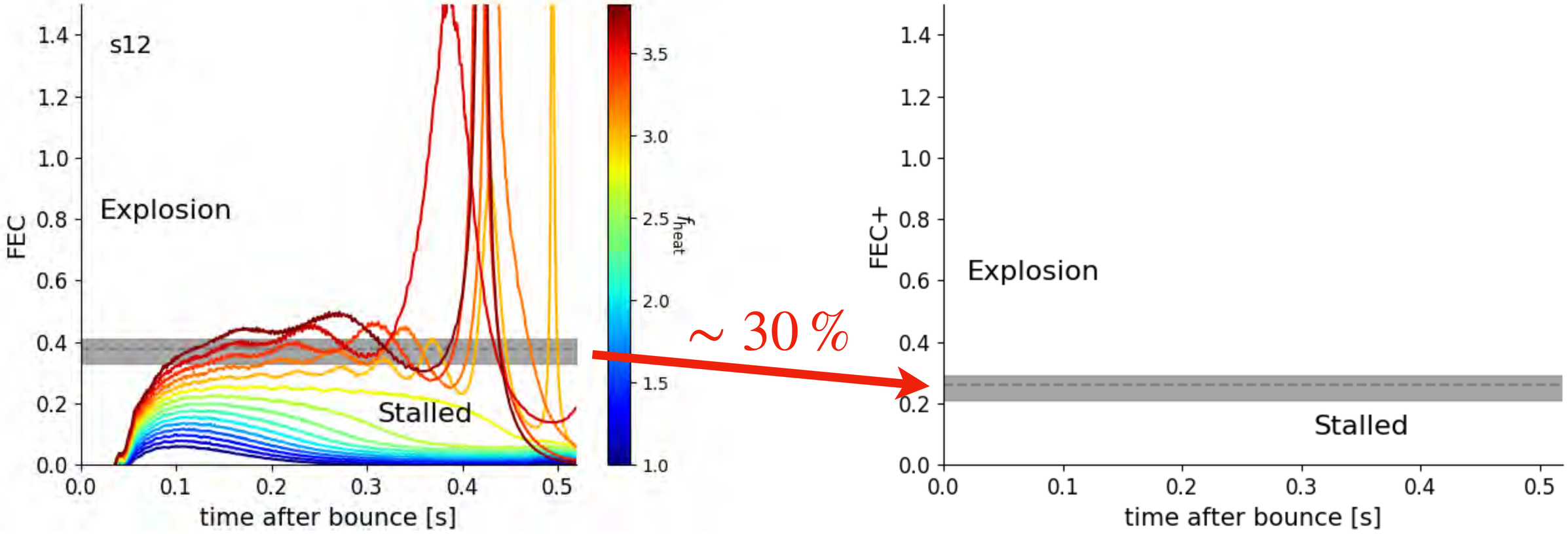
Convection and TD



Mabanta & Murphy (2019)

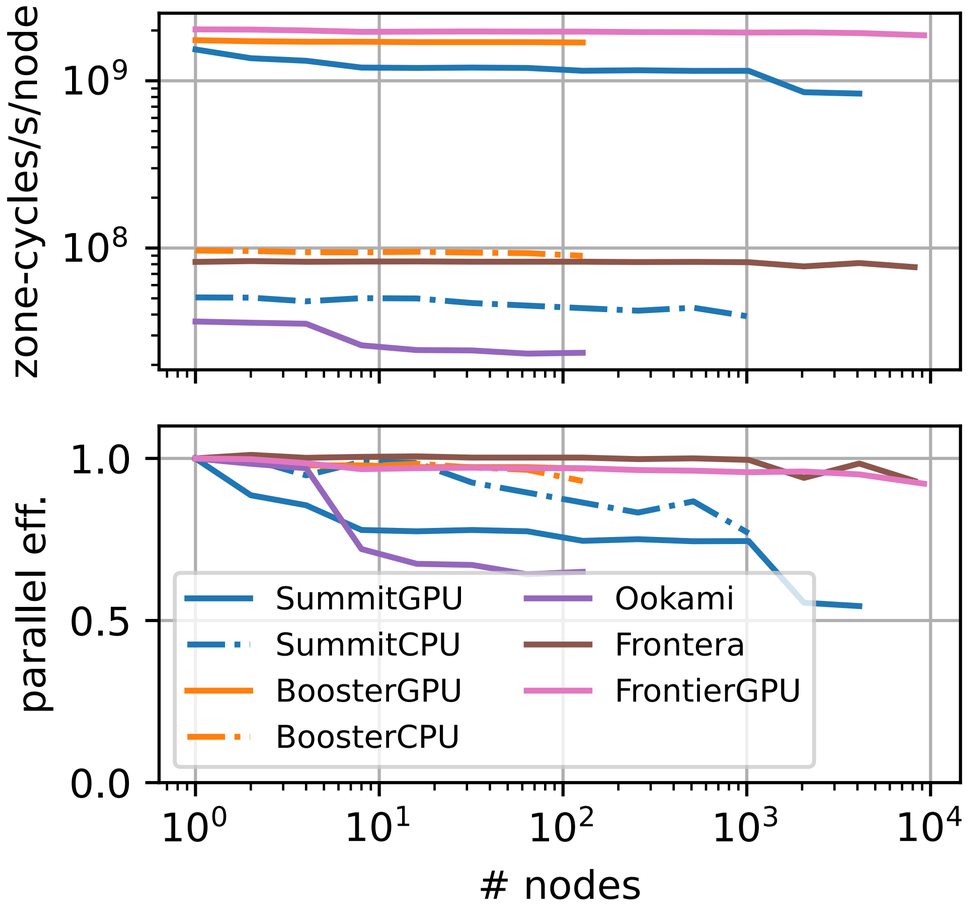
FEC+

$$(1+\beta)\tilde{L}_\nu \tau_g - a\tilde{\kappa} + b\tilde{R}_r^r > c$$



Phifty One Ergs Blows Up A Star (Phoebus)

- MHD
- GR - ADM Formalism
- Advanced radiation transport (e.g., Moments, Monte Carlo, long/short characteristics, etc)
- GPUs - 10-100 times faster



https://github.com/lanl/phoebus

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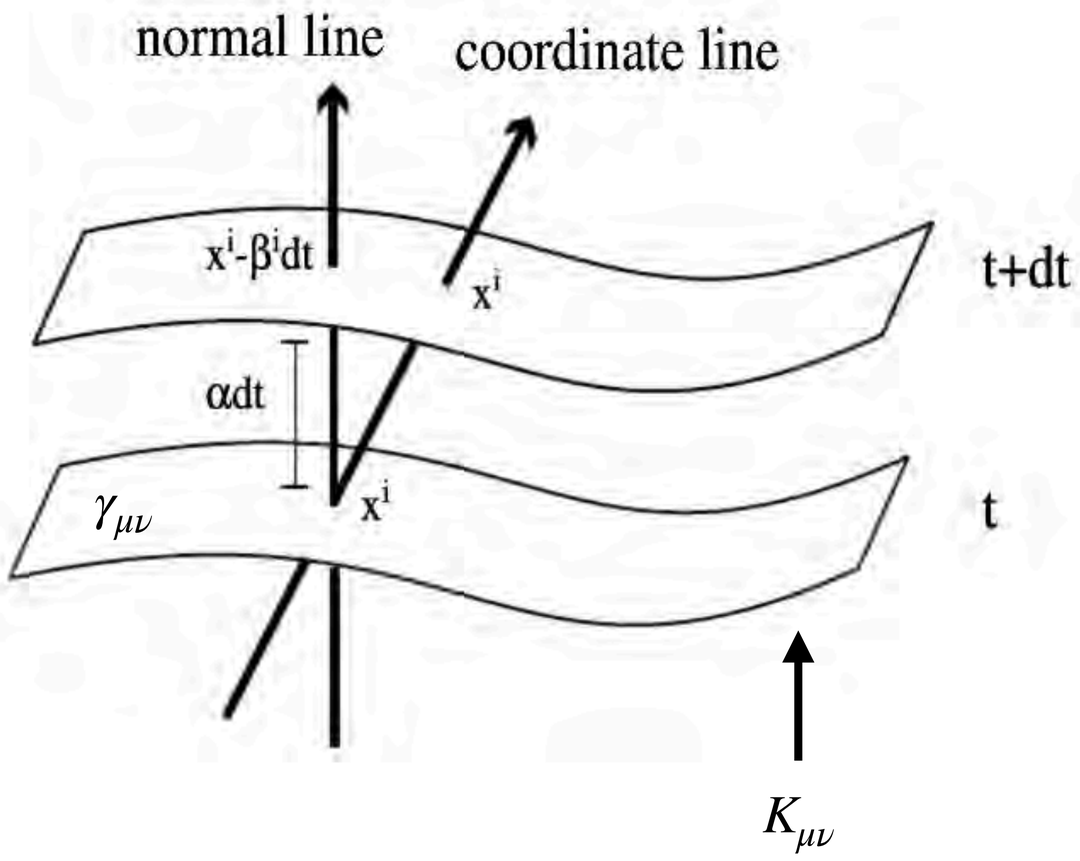
GR Solver

ADM (3+1) Formalism



Spherical Symmetry

$$ds^2 = (-\alpha^2 + a^2(\beta^r)^2)dt^2 + 2a^2\beta^r dtdr + a^2dr^2 + r^2d\Omega^2$$

$$\gamma_{\mu\nu} = g_{\mu\nu} + n_\mu n_\nu$$

Maximal Slicing: $K^\mu_\mu = 0$

Equations:

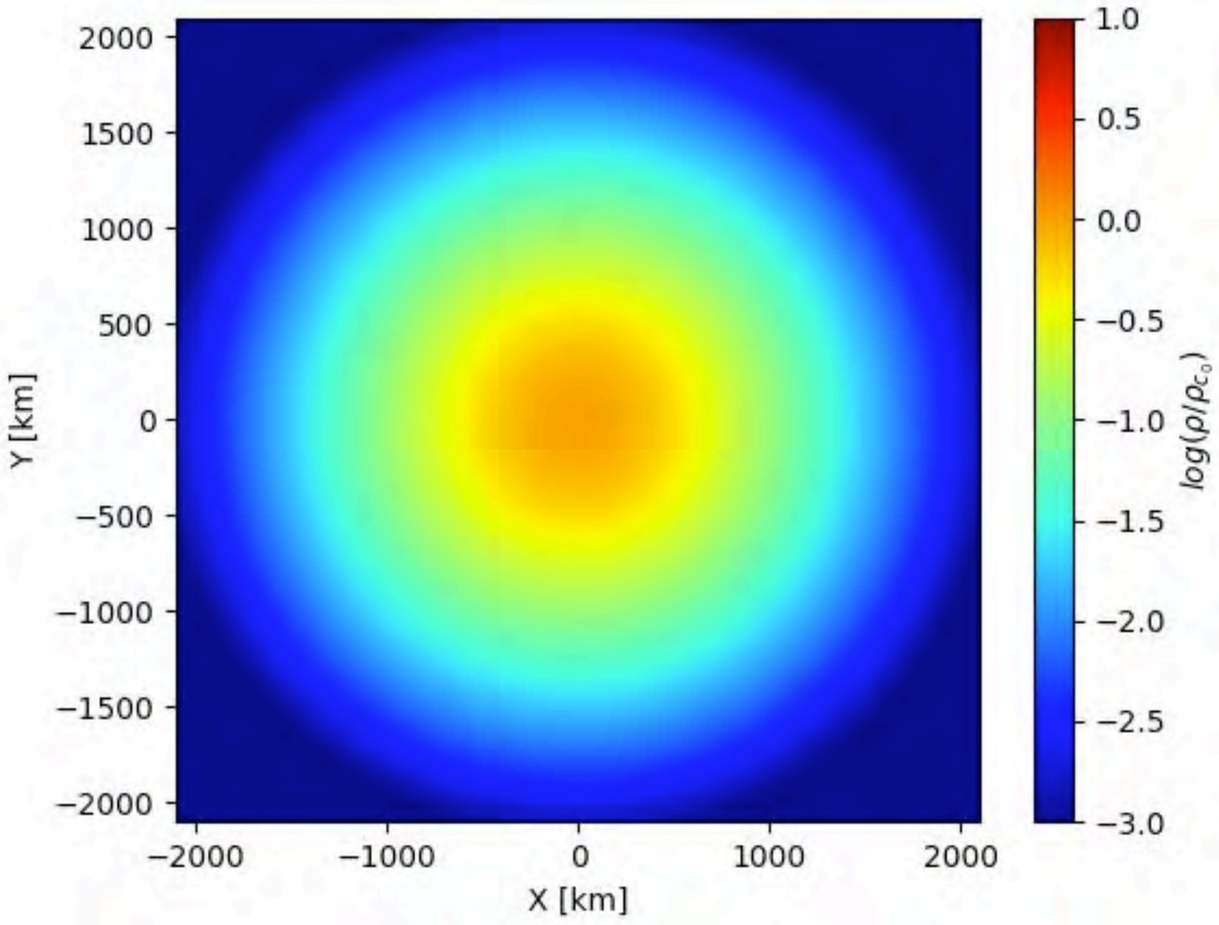
$$\partial_r K^r_r = 8\pi a^2 j^r - \frac{3}{r}K^r_r$$

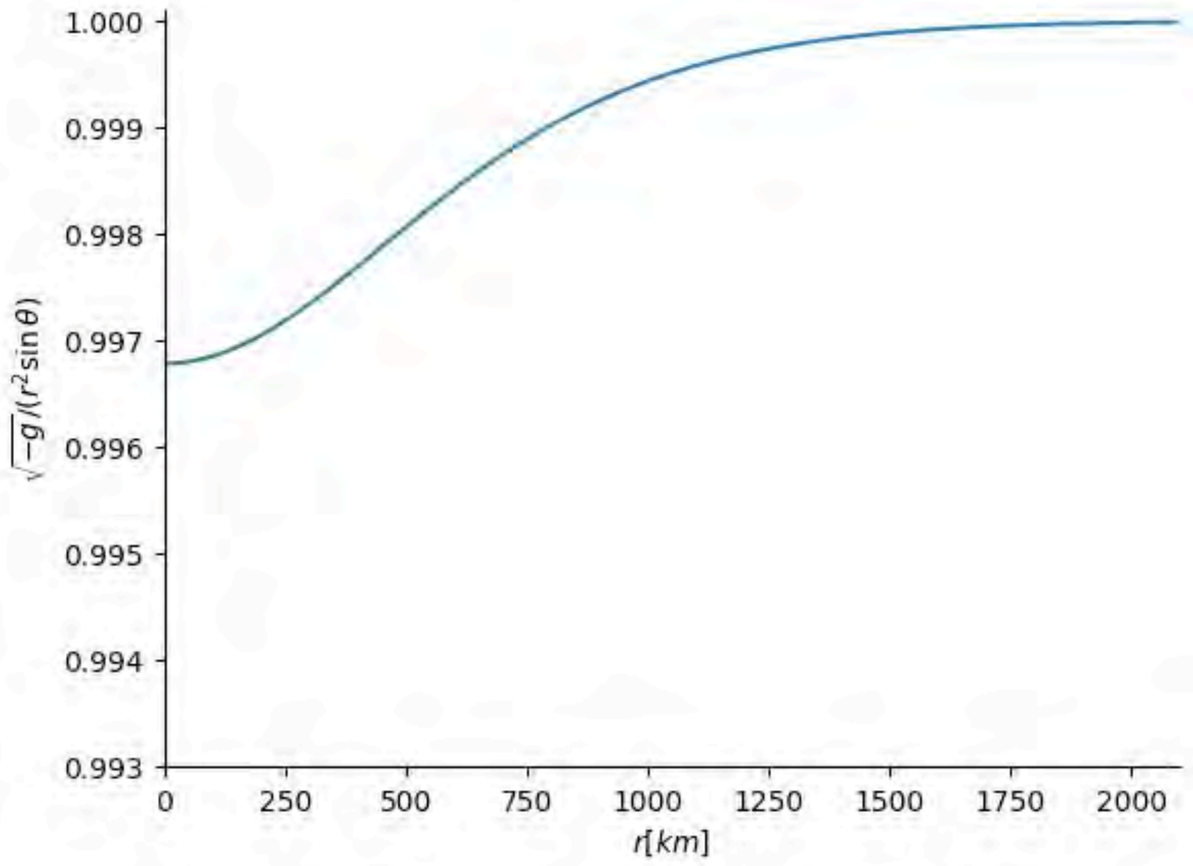
$$\partial_r a = \frac{a}{8r}[32\pi r^2 a^2\rho + 3r^2a^2(K^r_r)^2 + 4 - 4a^2]$$

$$\beta^r = -\frac{1}{2}\alpha r K^r_r$$

$$\frac{1}{a^2}\partial_r^2\alpha = \alpha\left[4\pi(S+\rho) + \frac{3}{2}K_r^{r2}\right] - \frac{2}{a^2r}\partial_r\alpha + \frac{a'}{a^3}\partial_r\alpha$$

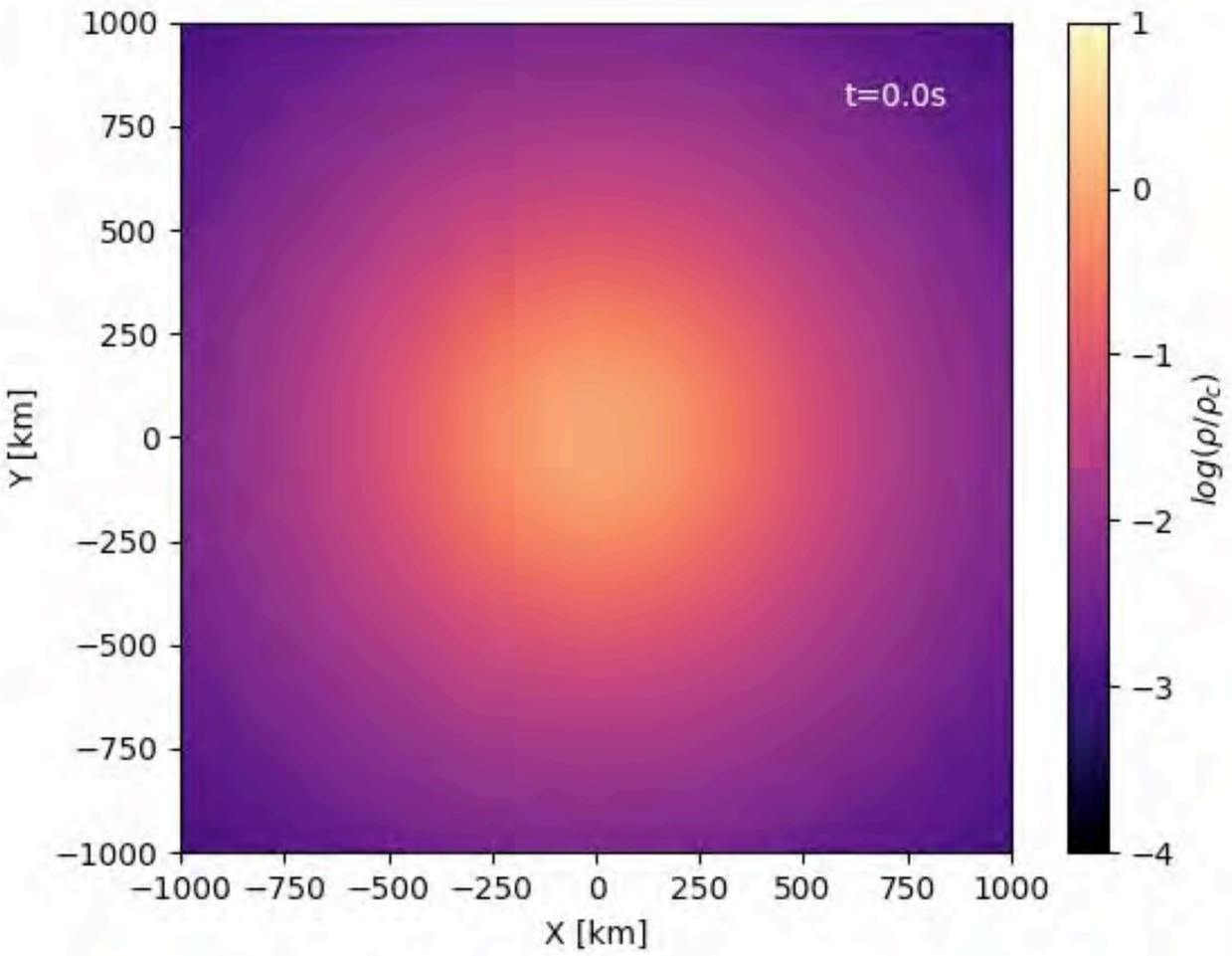
GR Solver


2000
1500
1000
500
0
−500
−1000
−1500
−2000
Y [km]
−2000
−1000
0
1000
2000
X [km]
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
$log(\rho/\rho_{c_0})$


1.000
0.999
0.998
0.997
0.996
0.995
0.994
0.993
$\sqrt{-g}/(r^2 \sin\theta)$
0
250
500
750
1000
1250
1500
1750
2000
$r[km]$

1D CCSN in Phoebus

- MHD
- GR - ADM Formalism
- Advanced radiation transport (e.g., Moments, Monte Carlo, long/short characteristics, etc)
- GPUs - 10-100 times faster



https://github.com/lanl/phoebus

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Summary

- Analytic explosion condition
- Fast multi-dimensional simulations with Phoebus
- Need to simulate progenitors in 2D and 3D and test the theory!

https://arxiv.org/pdf/2110.10173.pdf

https://arxiv.org/pdf/2302.04890.pdf

https://github.com/lanl/phoebus

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