Gravitational Wave Signatures from Rotating Core Collapse Supernovae

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European Einstein Toolkit Meeting 2024

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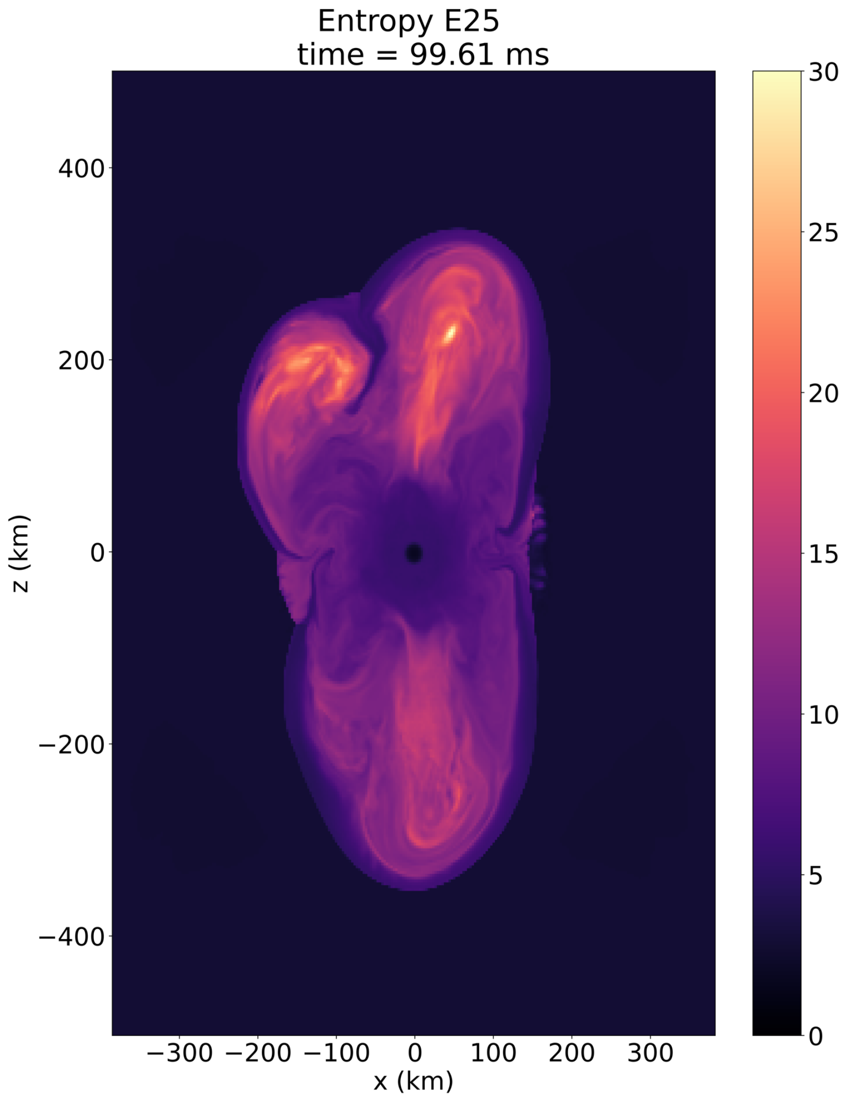
NASA

1. An Overview: Core-Collapse Supernovae

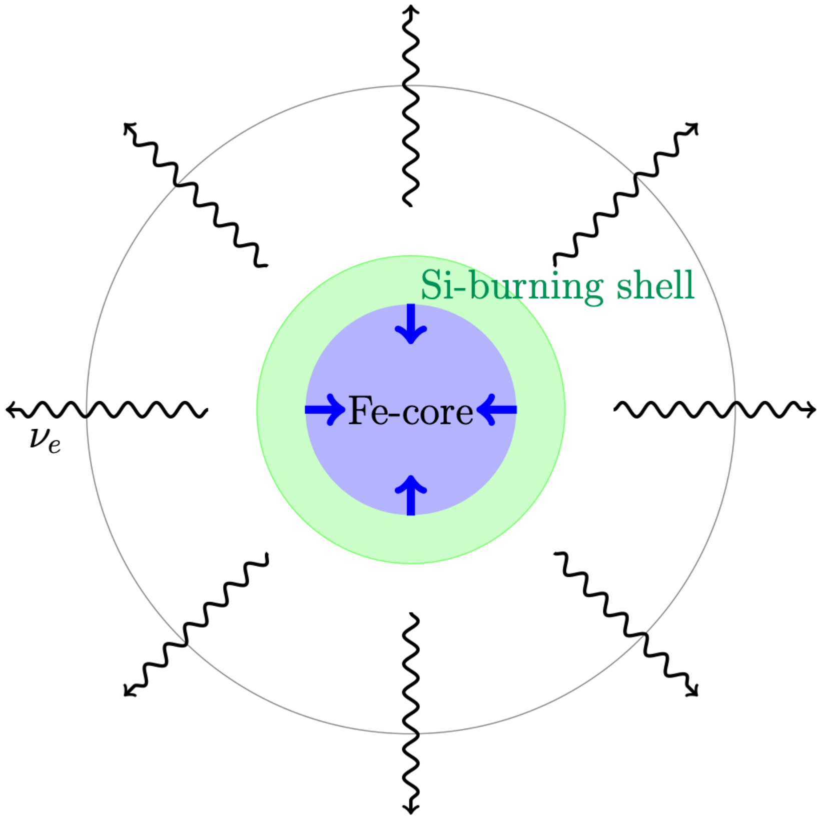


- Stars with $M \geq 8M_{\odot}$ may result in CCSN

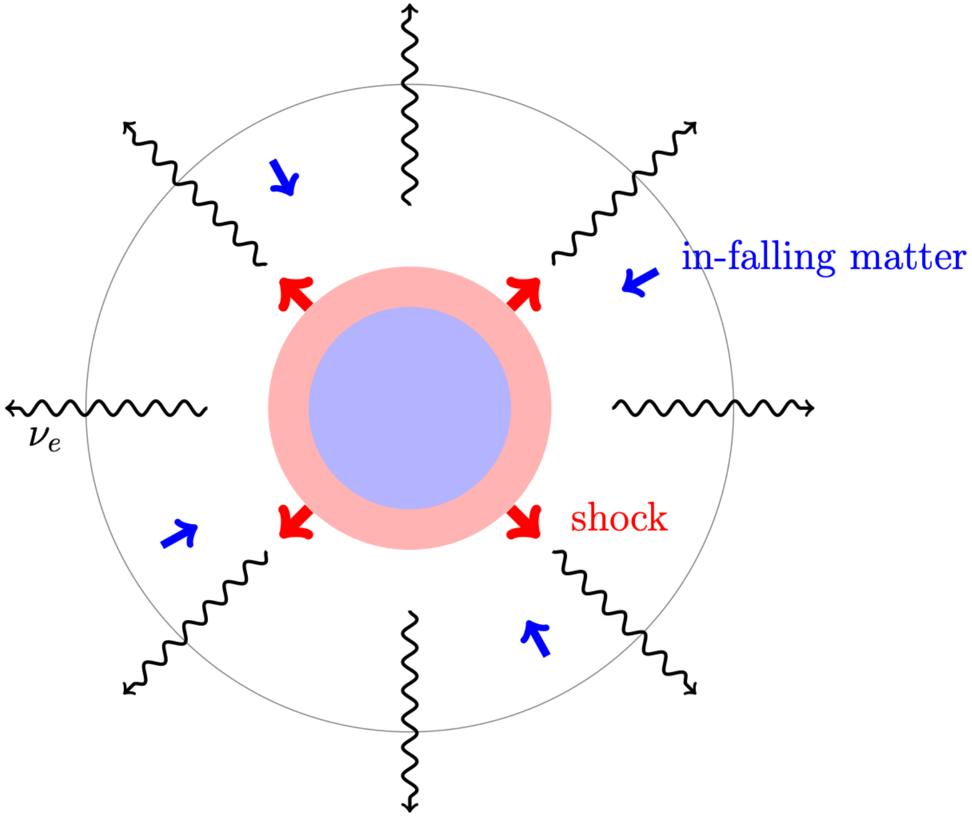
- Stellar collapse liberates gravitational energy ~ 10^{53} erg (1 erg = 10^{-7} J)
  - 99% of energy is carried away by neutrinos
  - remainder of energy powers CCSN explosion ~ 10^{51} erg

- Explosion Mechanisms:
  - neutrino mechanism
  - magneto-rotational mechanism

1. An Overview: Core-Collapse Supernovae

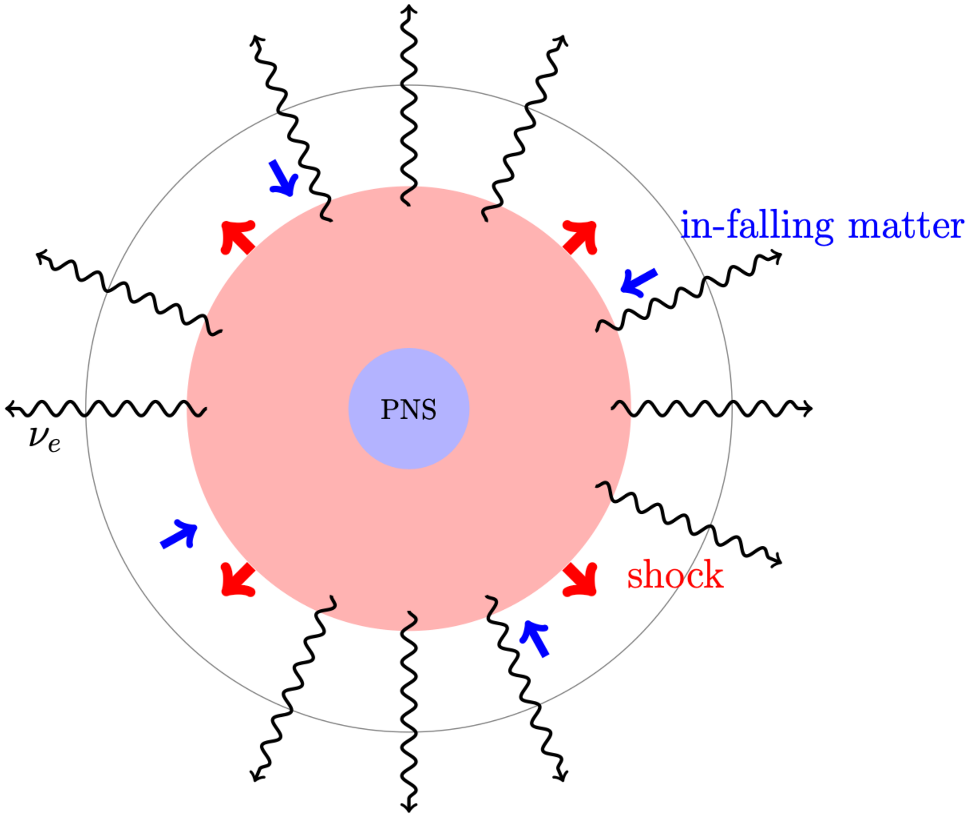


Initial Phase of Collapse $t \sim 0$

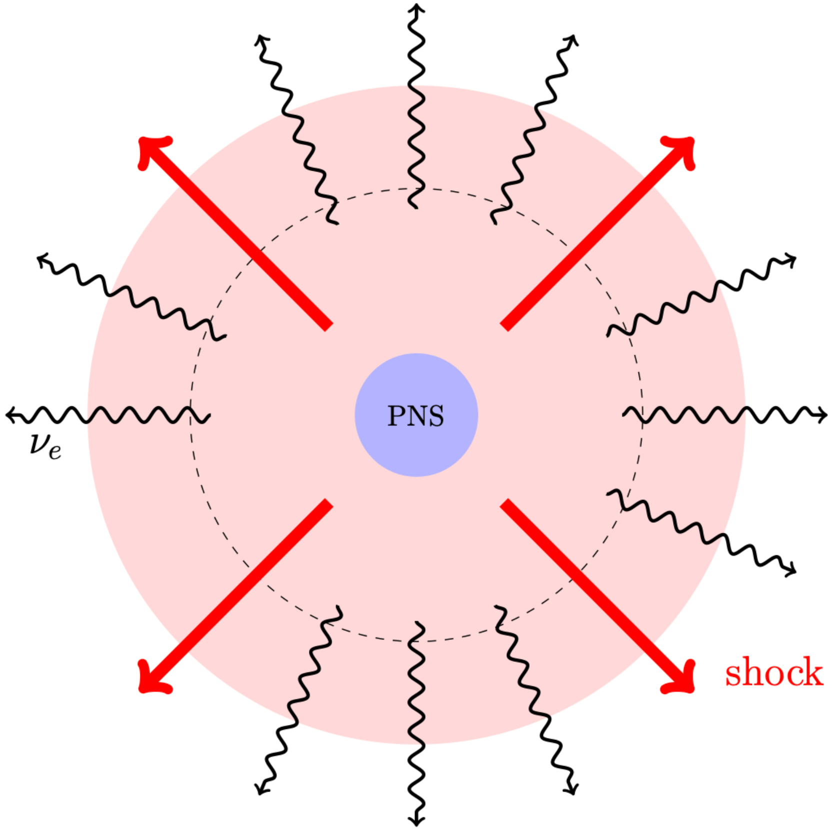


Bounce and Shock Formation

1. An Overview: Core-Collapse Supernovae



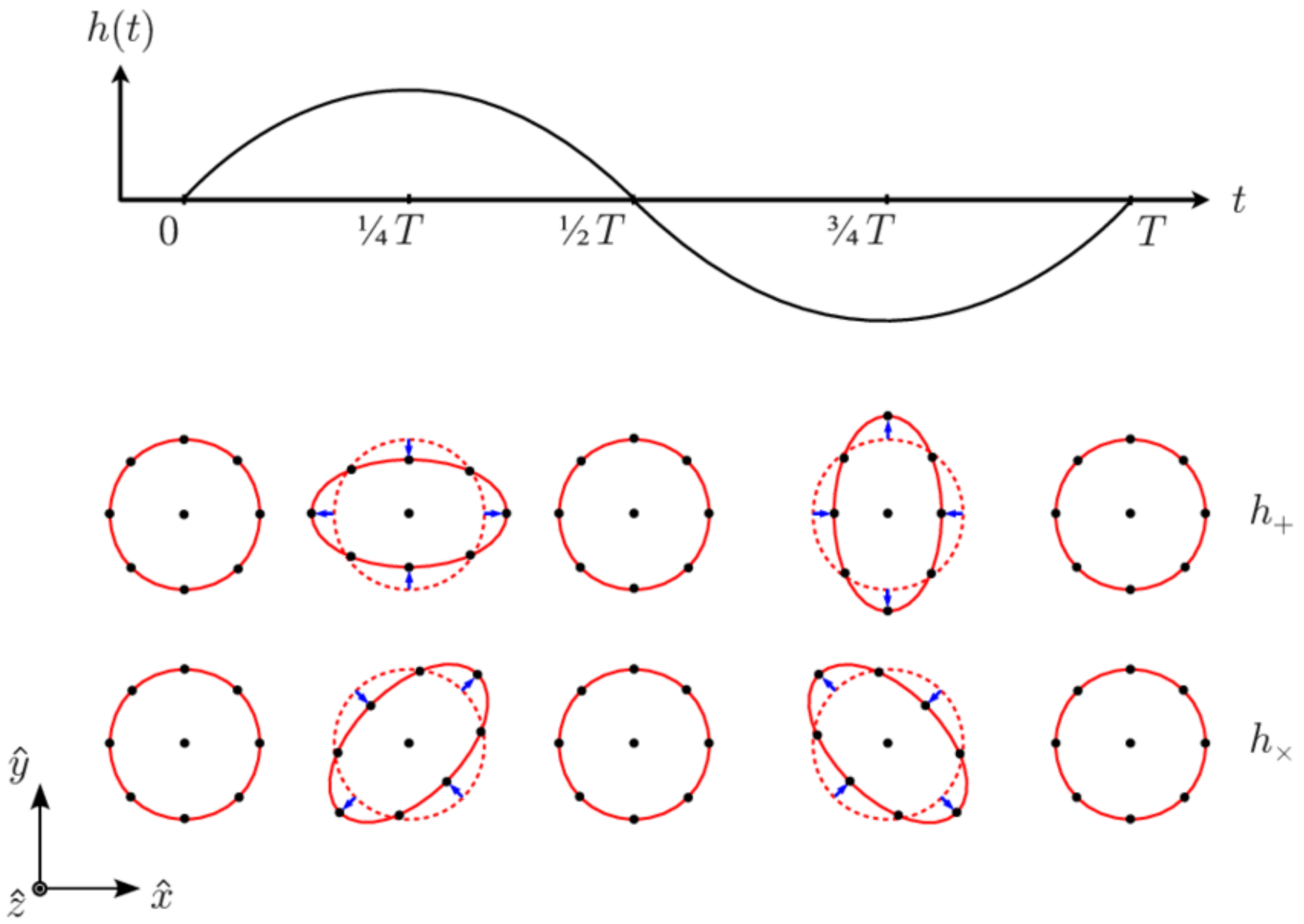
Shock Propagation and ν_e Burst



Shock Breakout, SN Explosion

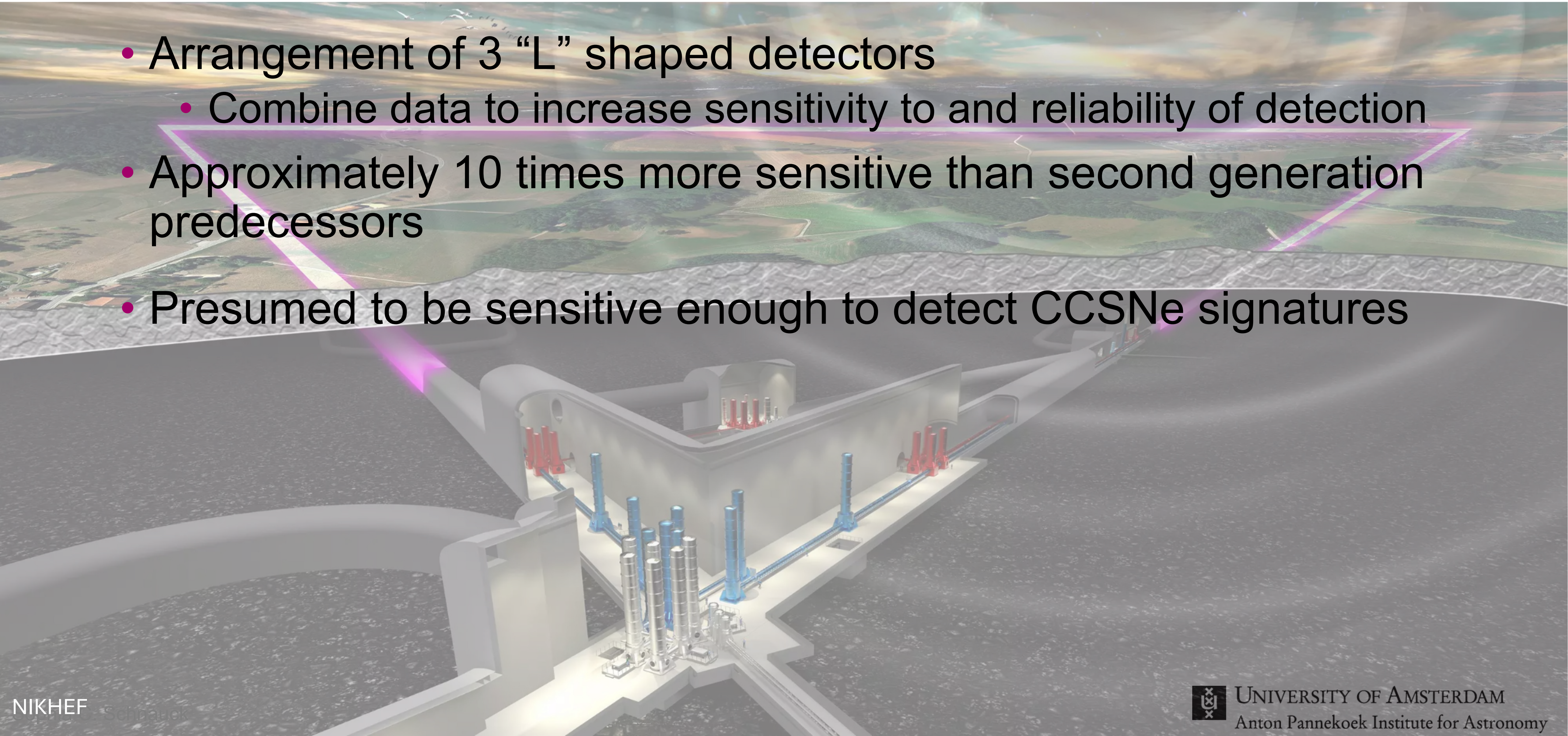
1. Gravitational Waves

Using the gravitational wave mass-quadrupole tensor I_{jk}, we can determine $h_{+,eq}$, $h_{x,eq}$, $h_{+,p}$, and $h_{x,p}$



(Le Tiec et al. 2019)

1. The Einstein Telescope



- Arrangement of 3 “L” shaped detectors
  - Combine data to increase sensitivity to and reliability of detection
- Approximately 10 times more sensitive than second generation predecessors
- Presumed to be sensitive enough to detect CCSNe signatures

Outline

1. Introduction
2. Methods

2. Numerical Methods: Einstein Toolkit

We use the open source code from the Einstein Toolkit, in particular:

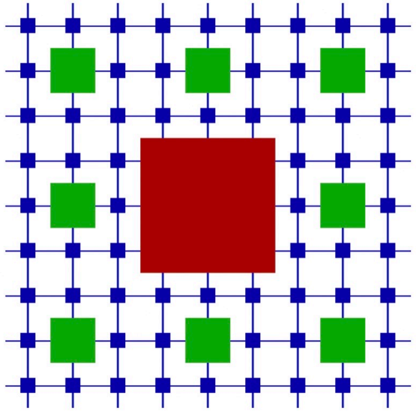
- ~~Carpet~~

➔ CarpetX driver for adaptive mesh refinement with AMReX

- ~~GRHydro~~

➔ **G**eneral **R**elativistic **a**ccelerated **M**agnetohydrodynamics on AMRe**X** (GRaM-X) code

➔Extends GRMHD capability of Einstein Toolkit to GPU-based exascale systems



2. GRaM-X: GPUs

GRaM-X features:

- Z4c formalism to evolve equations of GR
- Valencia formulation to evolve equations of GRMHD
- Analytic as well as tabulated equations of state
- TVD and WENO reconstruction methods
- HLLE Riemann solver

Dr. Swapnil Shankar et al.

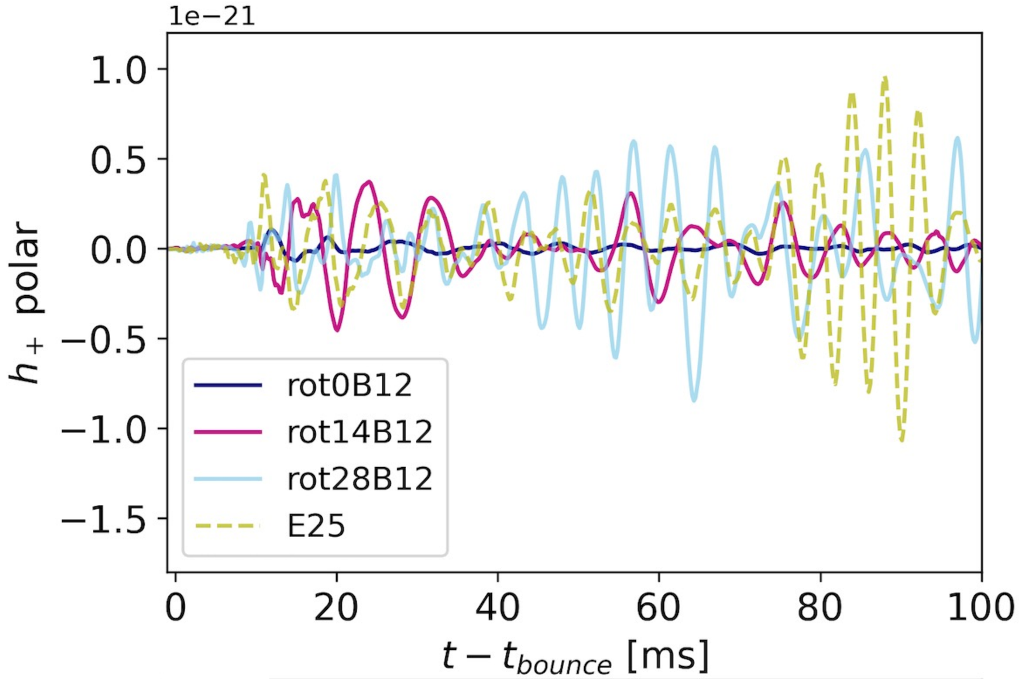
Frontier Supercomputer

- Located at Oak Ridge Leadership Computing Facility in Tennessee (USA)
- 1.1 exaflops, 10^{18} floating point operations per second
- Made up of CPUs and GPUs

https://www.ornl.gov/news/frontier-supercomputer-debuts-worlds-fastest-breaking-exascale-barrier

2. ZelmaniQuadWaveExtract & Post-processing

- Extracts quadrupole wave based on rest mass density and velocity
- produces first time derivative of the mass quadrupole tensor as output



GPU accelerated thorn:

- for-loops from the CPU code ➔ lambda functions in the GPU-accelerated version

Post-processing:

- Scripts for computation of strains, energies, and time-frequency content

2. Initial Setup

- Pre-supernova models:

  Reference case: $25M_\odot$ of solar-metallicity
  - ❖ $\Omega_0 = 2.8$ rad s^{-1}
  - ❖ $B_0 = 10^{12}$ G

  E25

  Production level: $35M_\odot$ of 10% solar-metallicity
  - ❖ $\Omega_0 = 0, 1.4, 2.8$ rad s^{-1}
  - ❖ $B_0 = 10^{12}$ G

  rot0B12 rot14B12 rot28B12

- LS220 nuclear equation of state[1]
- 9 refinement levels

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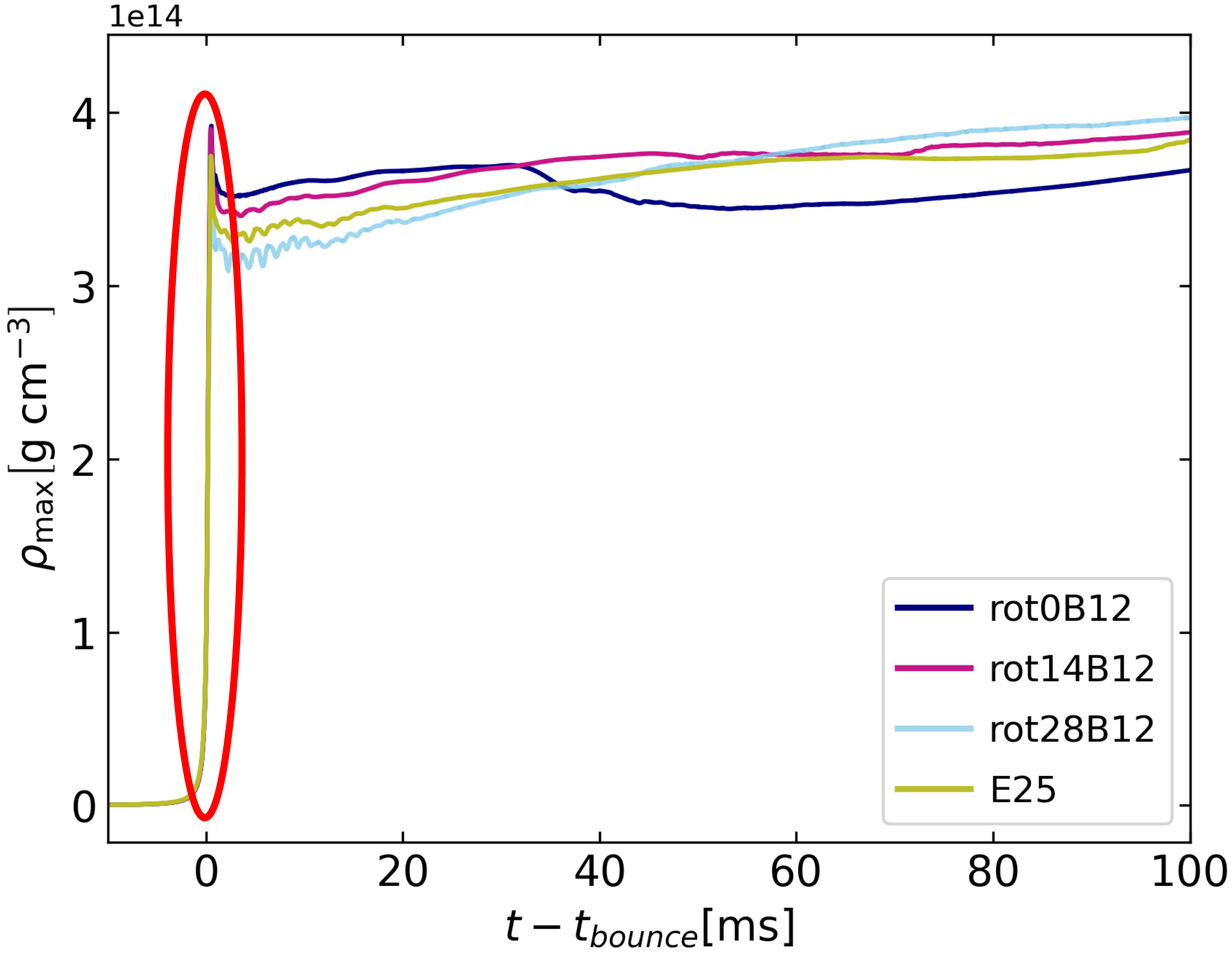
[1] Lattimer, J. M. and Swesty, D. F., "A generalized equation of state for hot, dense matter", *Nuclear Physics A*, vol. 535, no. 2, pp. 331–376, 1991

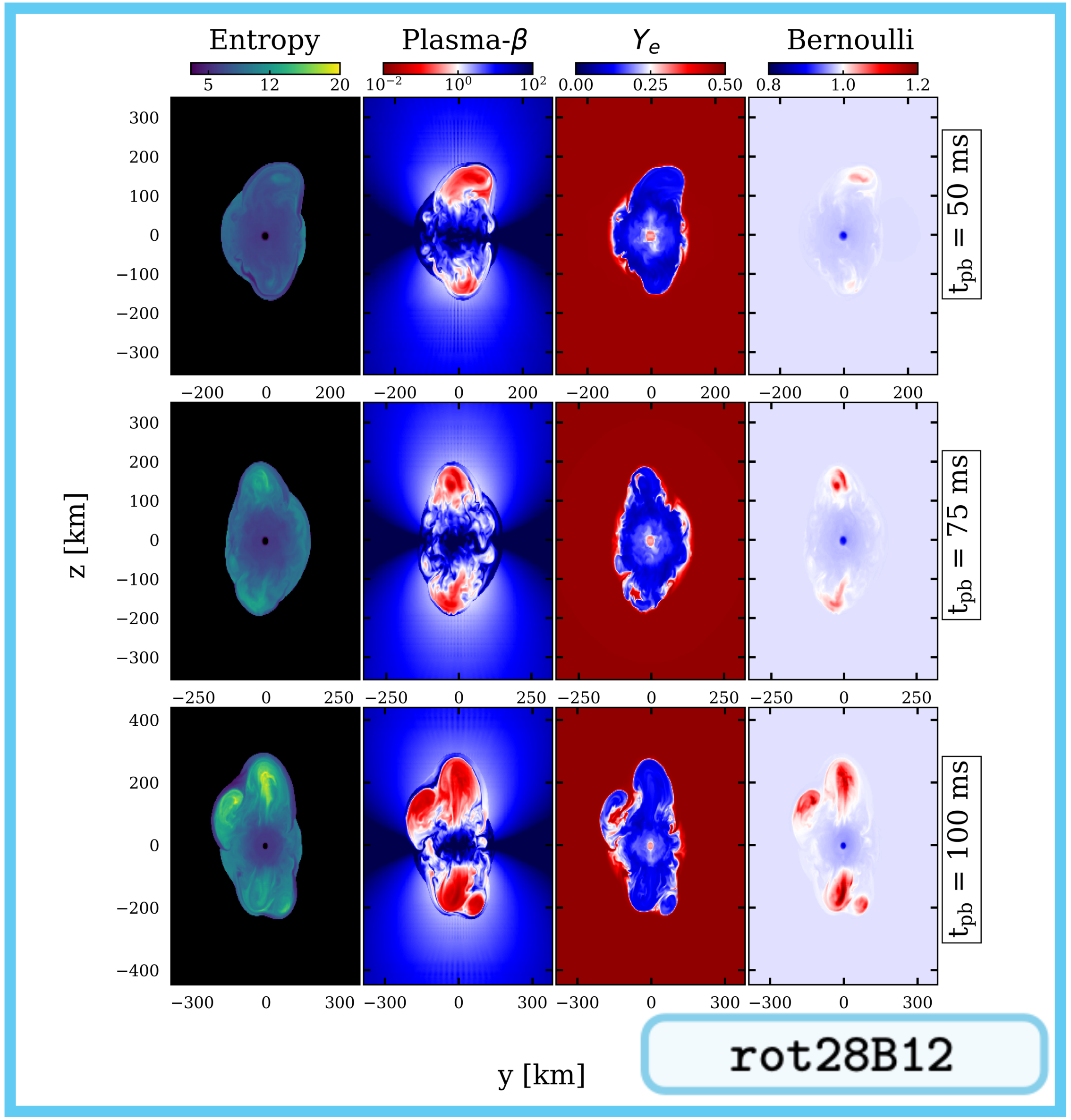
Outline

1. Introduction
2. Methods
3. Results

3. Density Profiles and Lapse

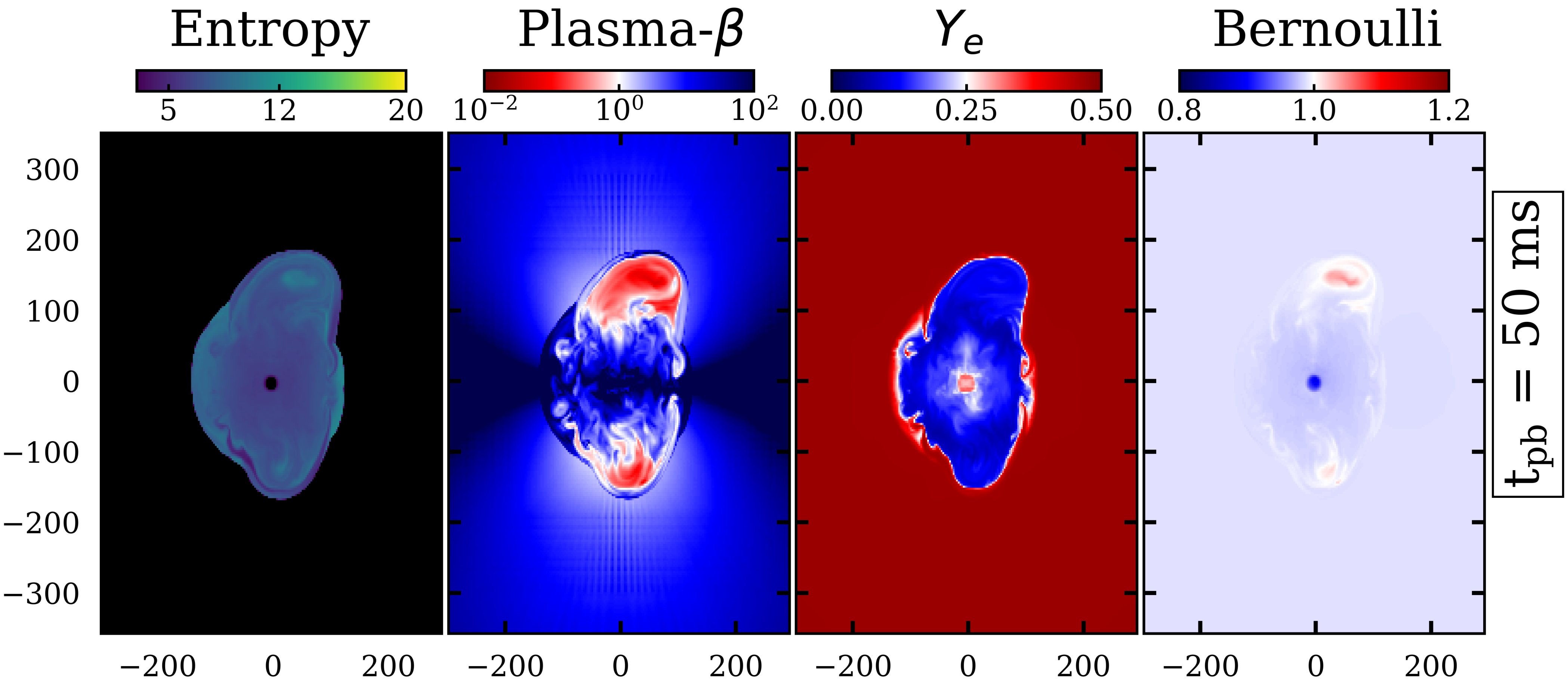


3. Explosion Dynamics

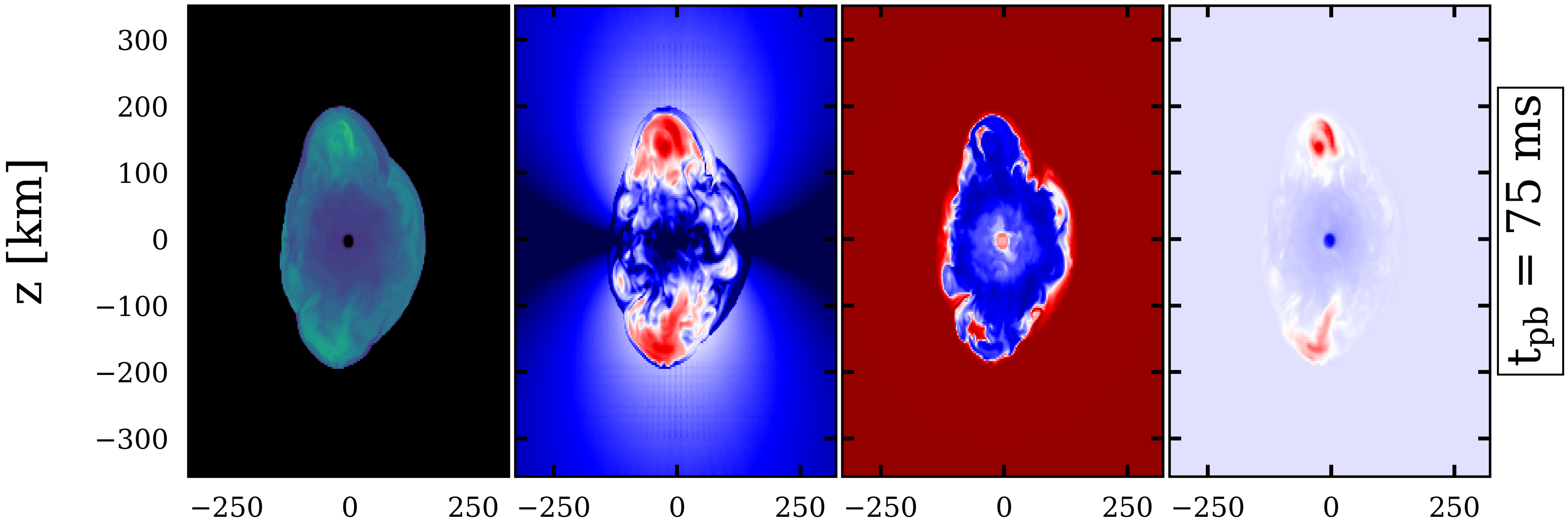


- Entropy: indicates the thermodynamic state and disorder
- Plasma β: $\beta = P_{gas}/P_{mag}$
- Y_e: (electron fraction) info about neutrino production, and neutronization
- Bernoulli criterion ($-hu_t$): info about how bound matter is to the PNS

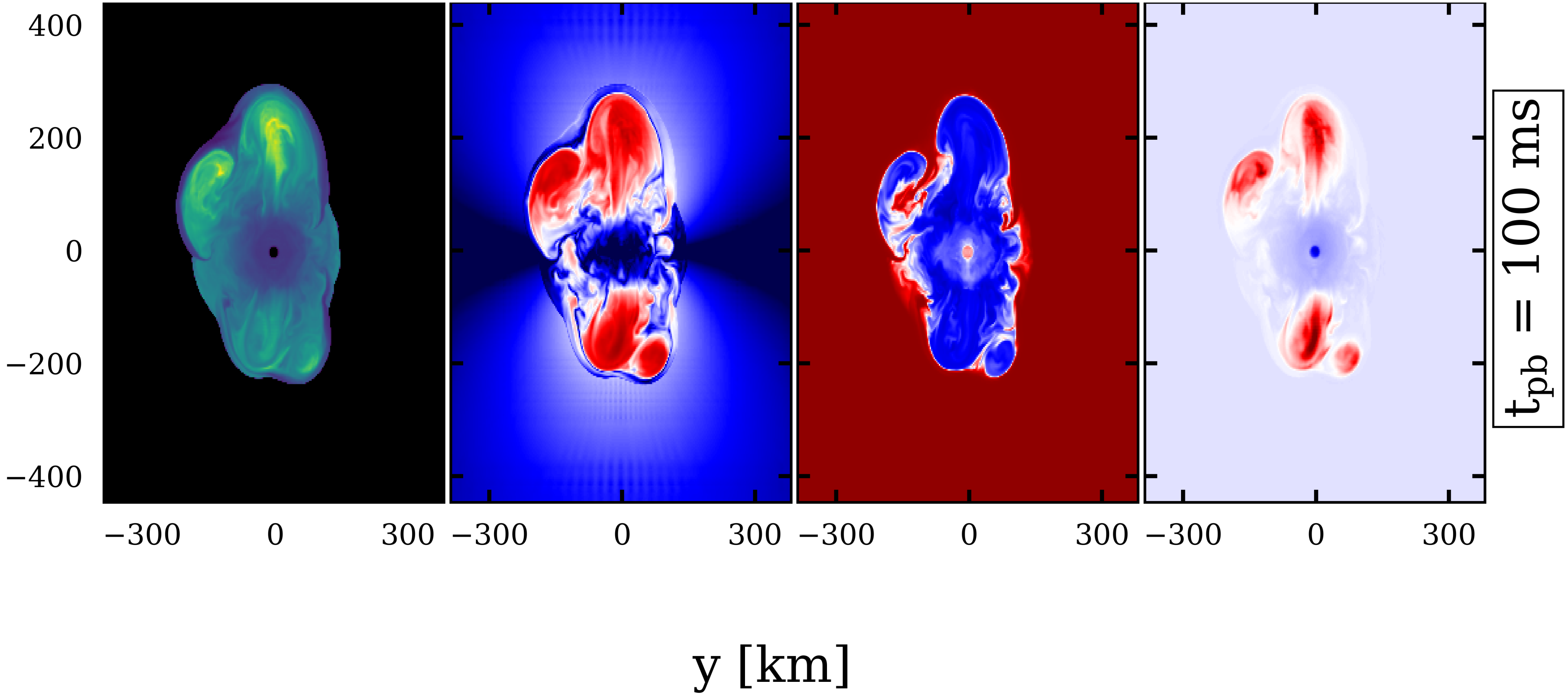
3. Explosion Dynamics

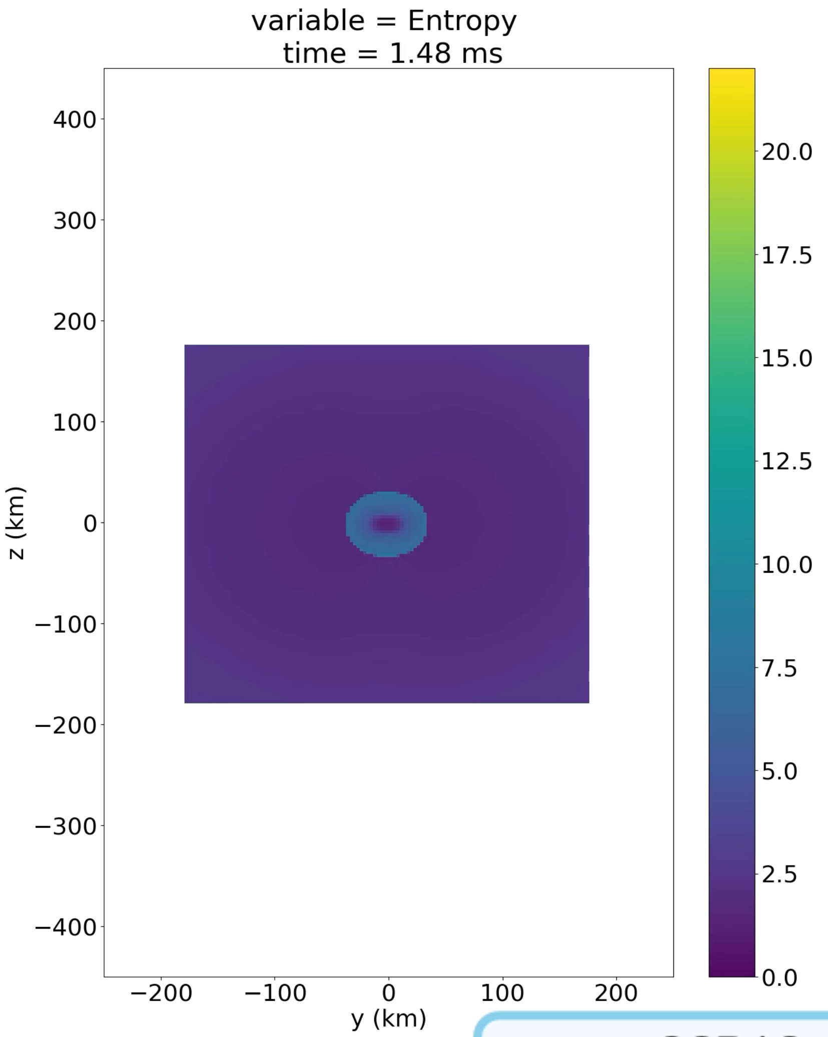


3. Explosion Dynamics



3. Explosion Dynamics

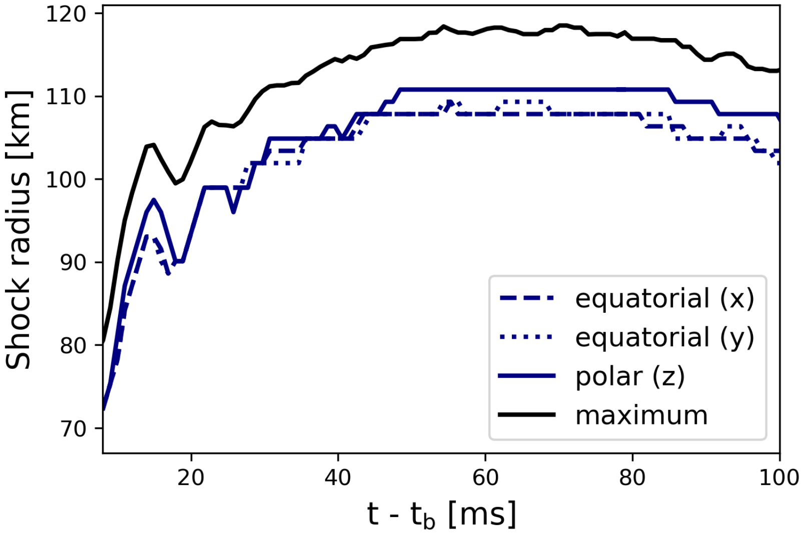


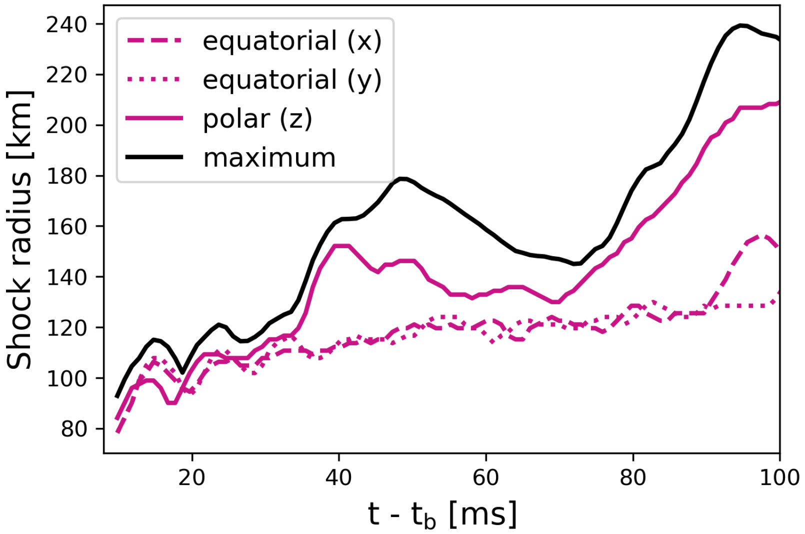

variable = Entropy
time = 1.48 ms
400
300
200
100
0
−100
−200
−300
−400
z (km)
−200
−100
0
100
200
y (km)
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0

rot28B12

3. Explosion Dynamics

rot0B12





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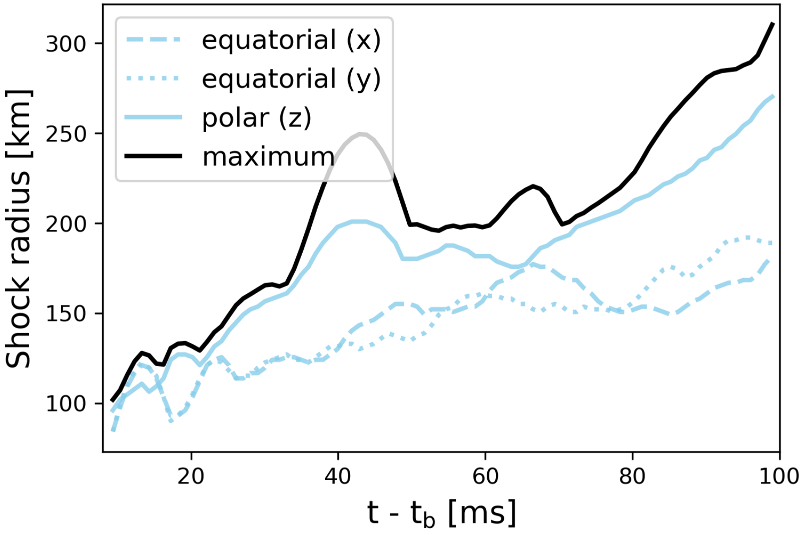
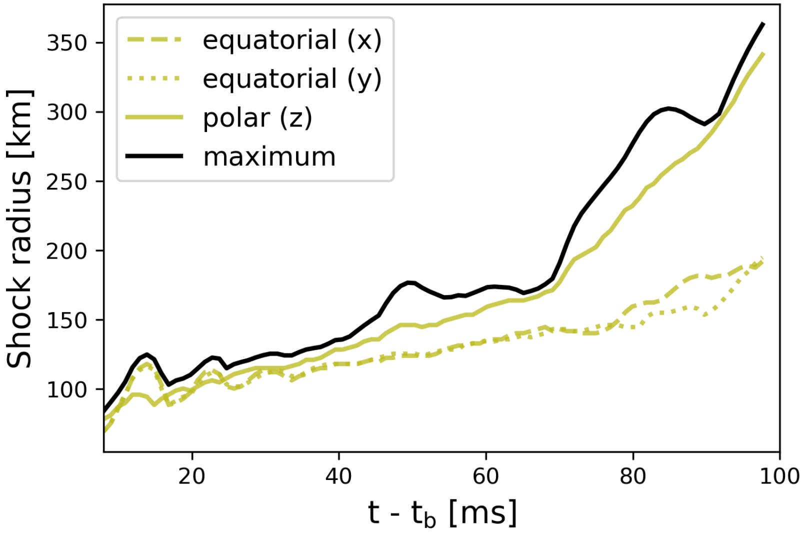
rot28B12

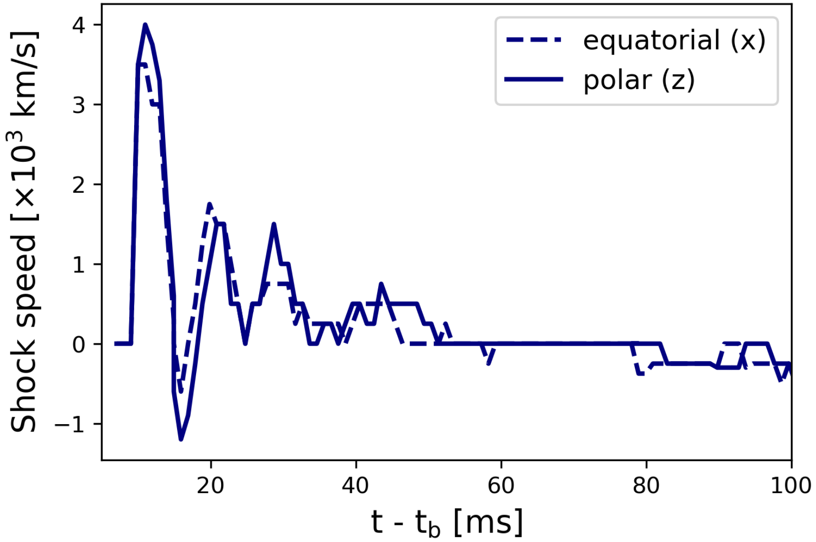




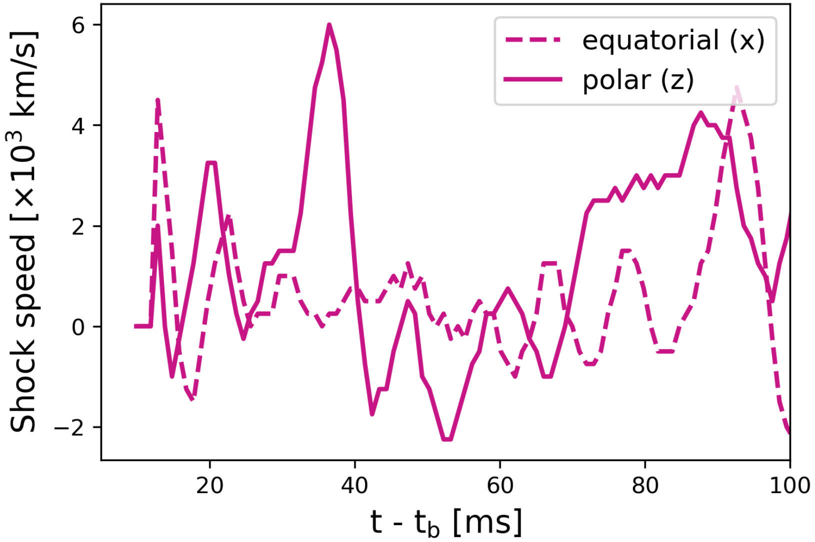
E25

3. Explosion Dynamics

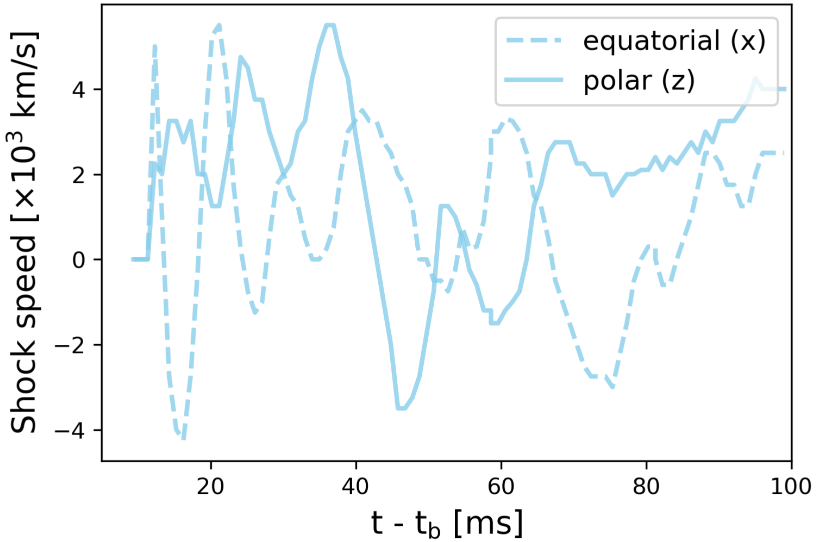
rot0B12



rot14B12



rot28B12



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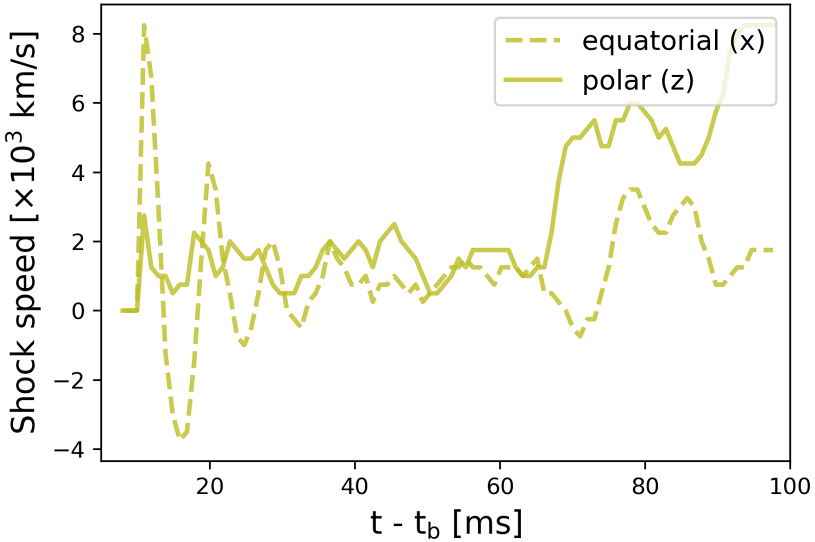
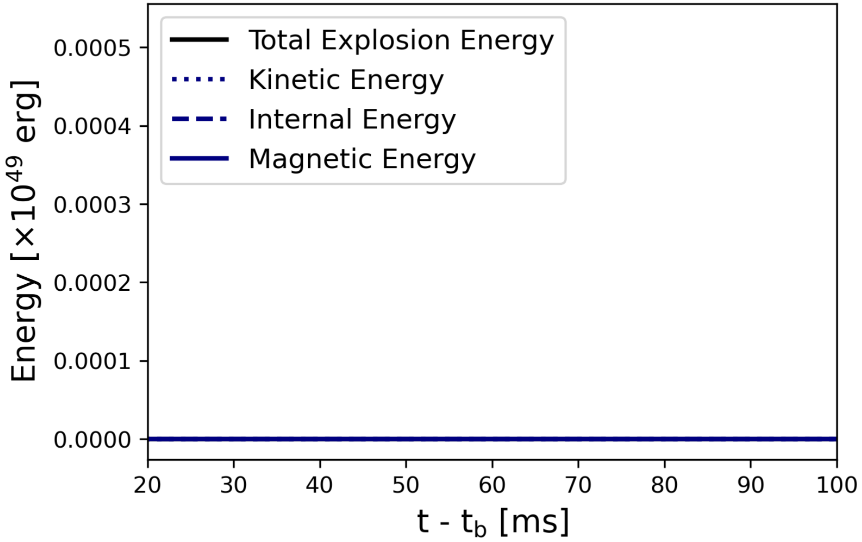
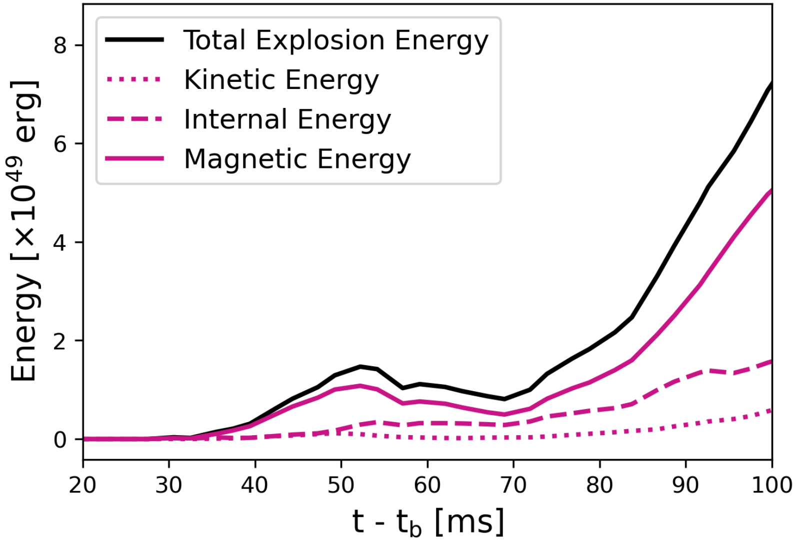


3. Explosion Dynamics

rot0B12





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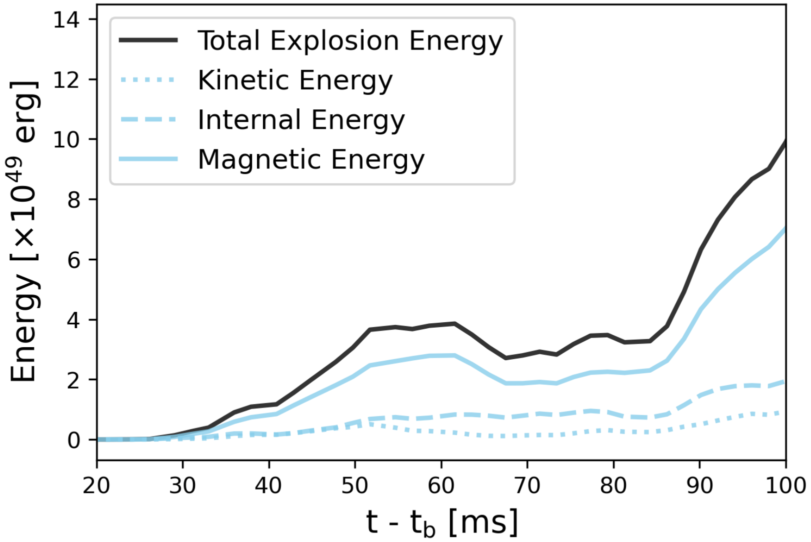

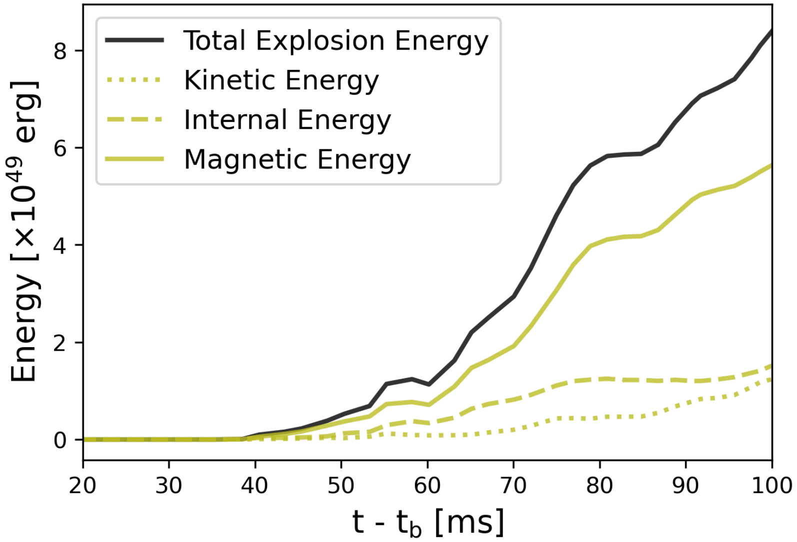

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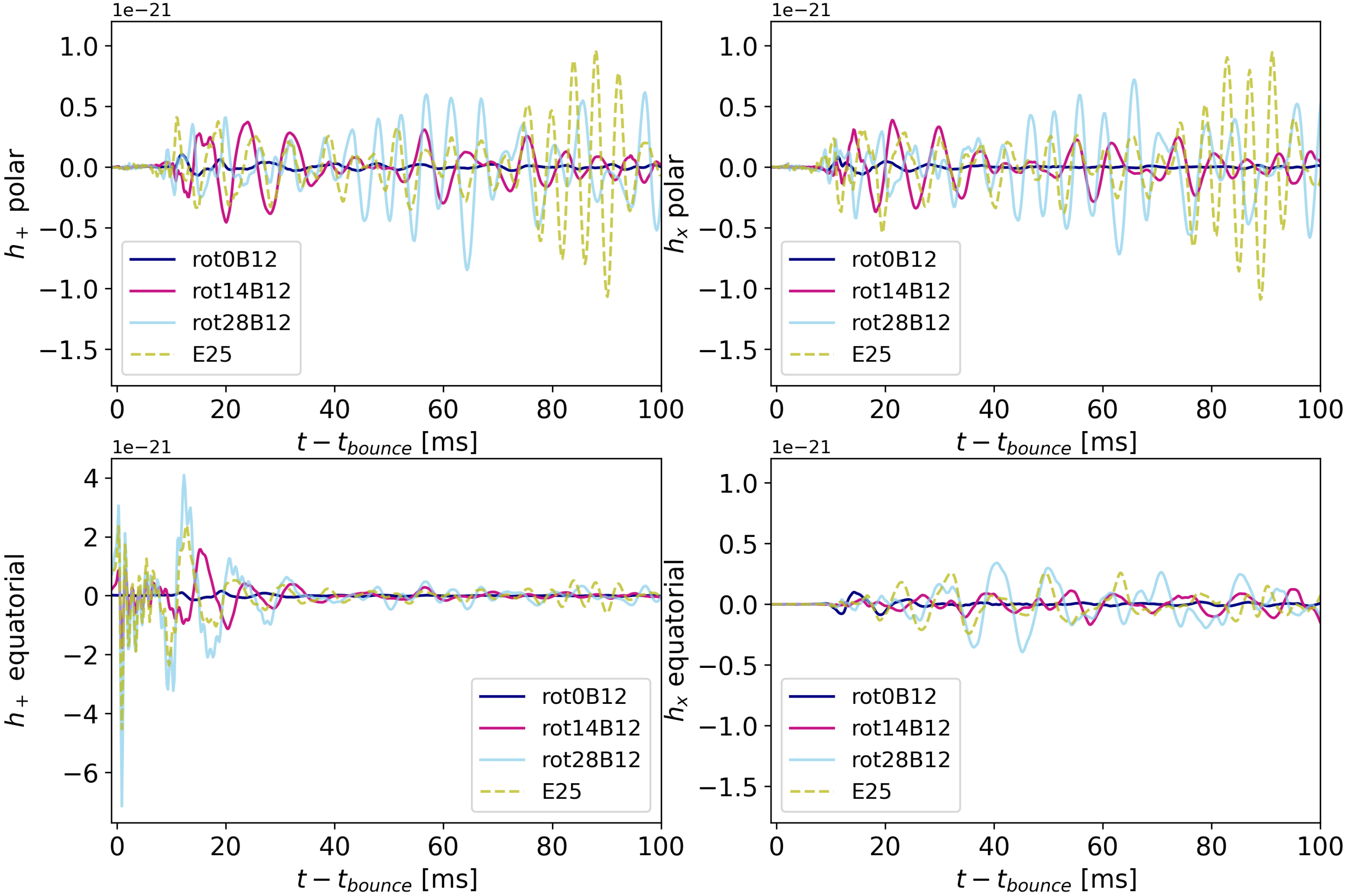
3. Gravitational Wave Strains



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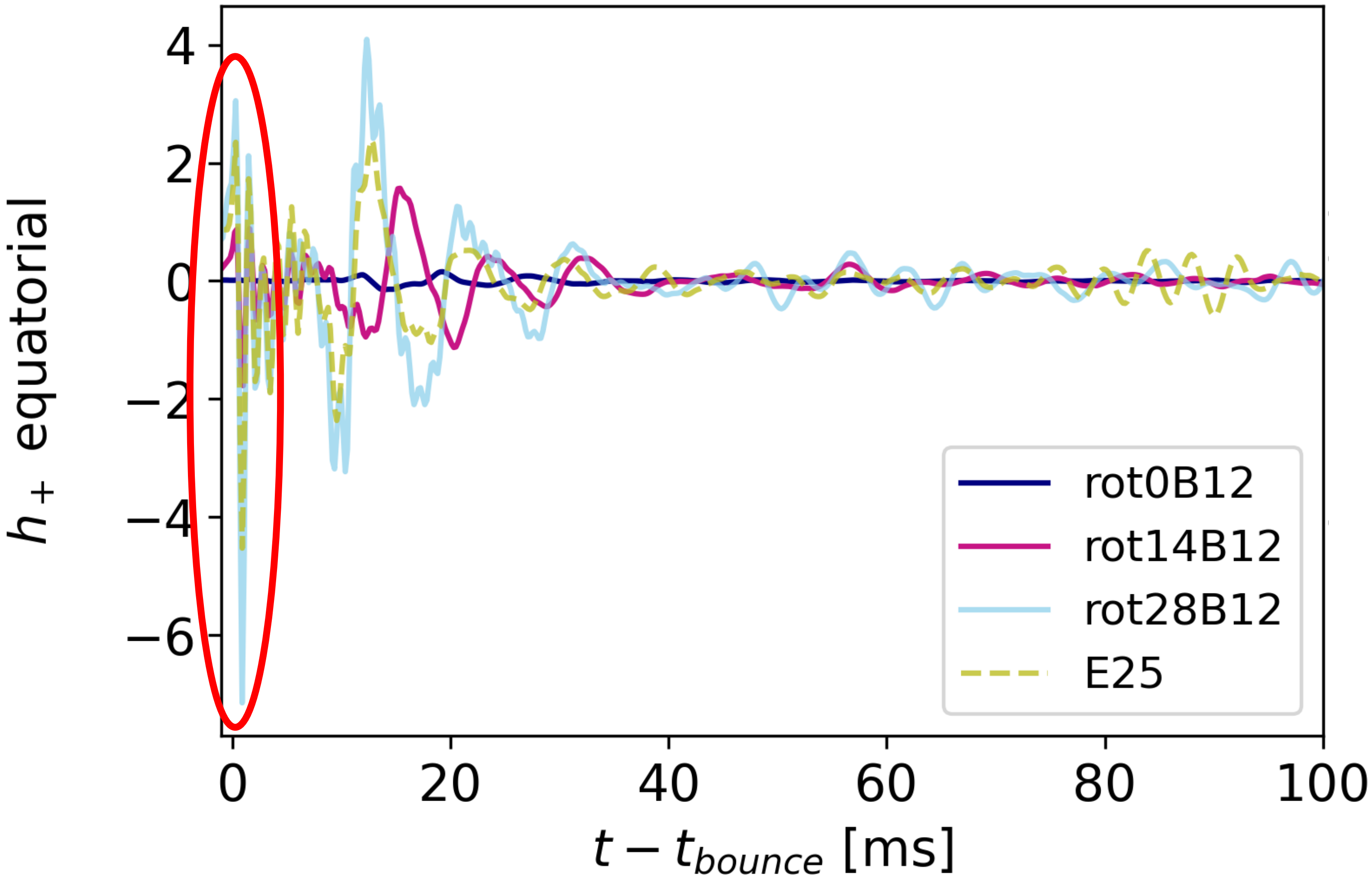

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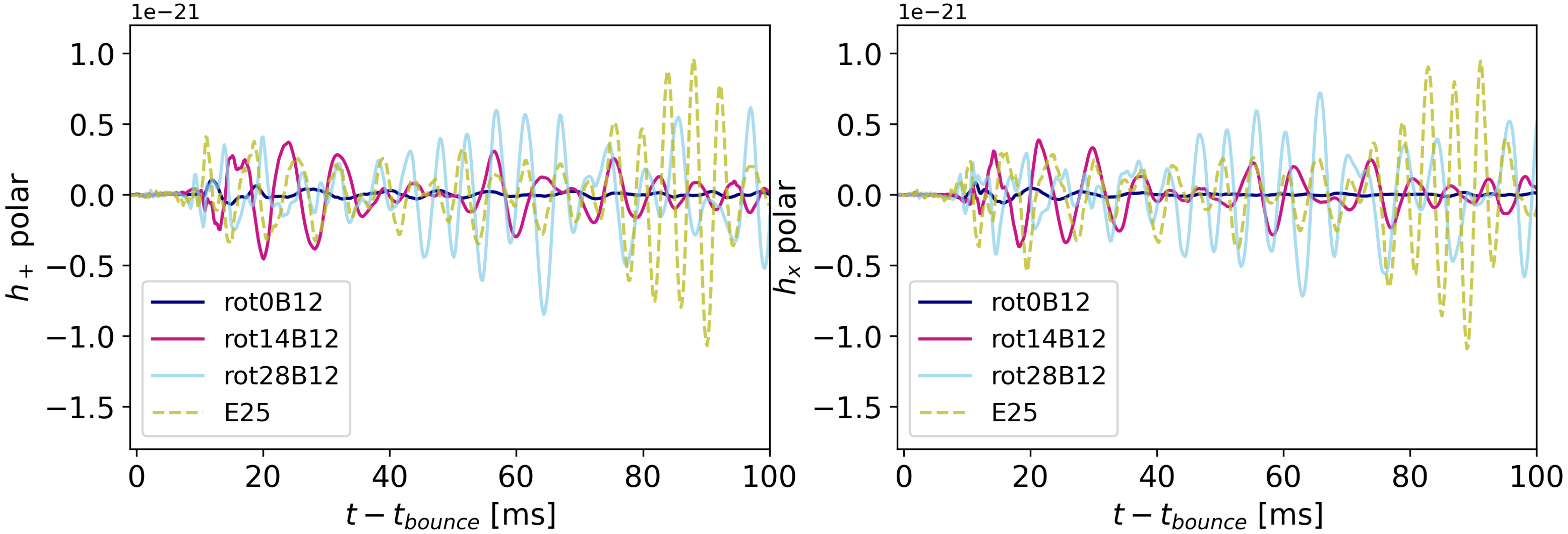
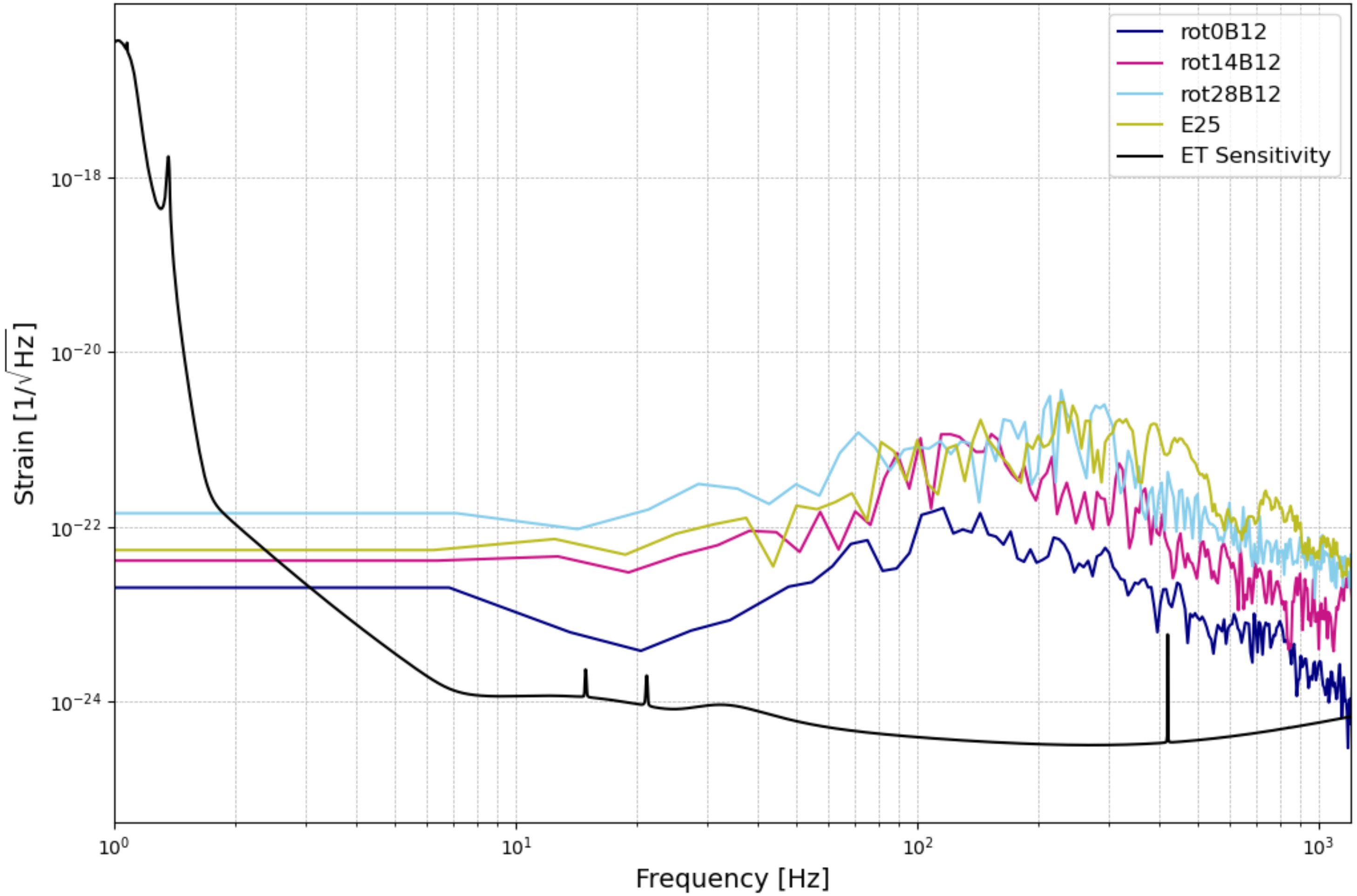


Can we detect gravitational waves from our CCSNe with the Einstein Telescope?

3. Detectability

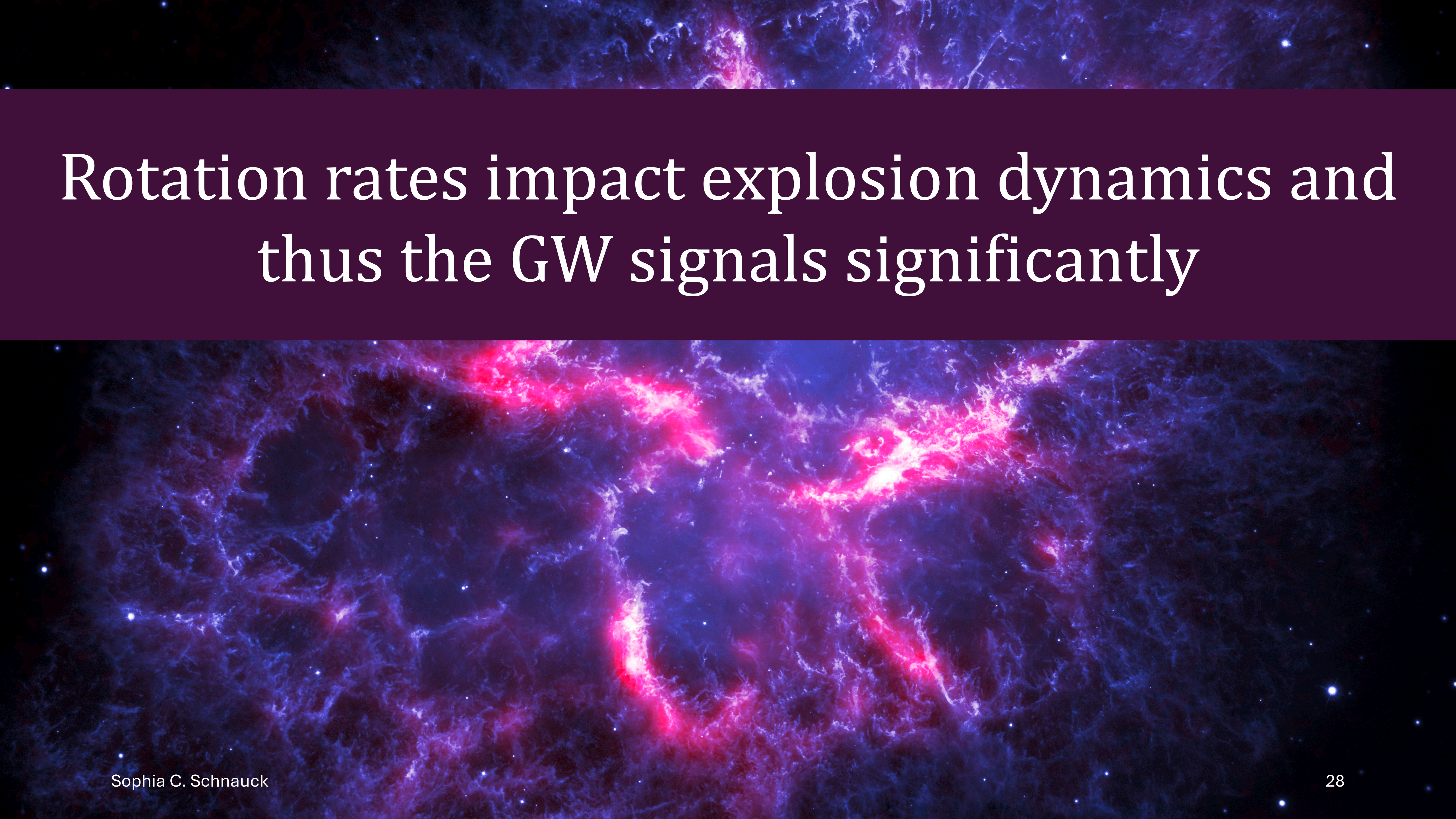
Yes...



Outline

1. Introduction
2. Methods
3. Results
4. Conclusion

Rotation rates impact explosion dynamics and thus the GW signals significantly

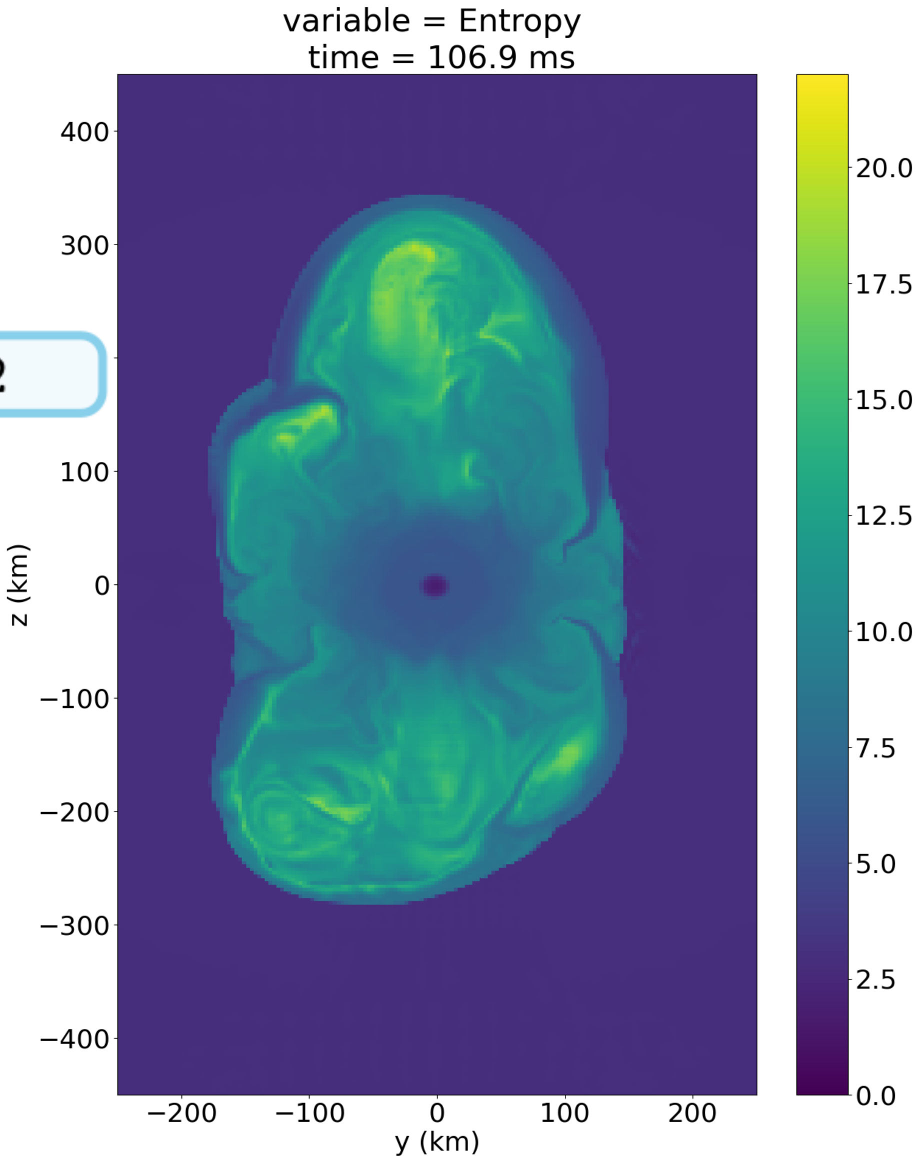


4. Conclusion

- Achieved the main goals of the project:
  - ❖Ran 4 CCSNe with different Ω_0

E25 **rot0B12** **rot14B12** **rot28B12**

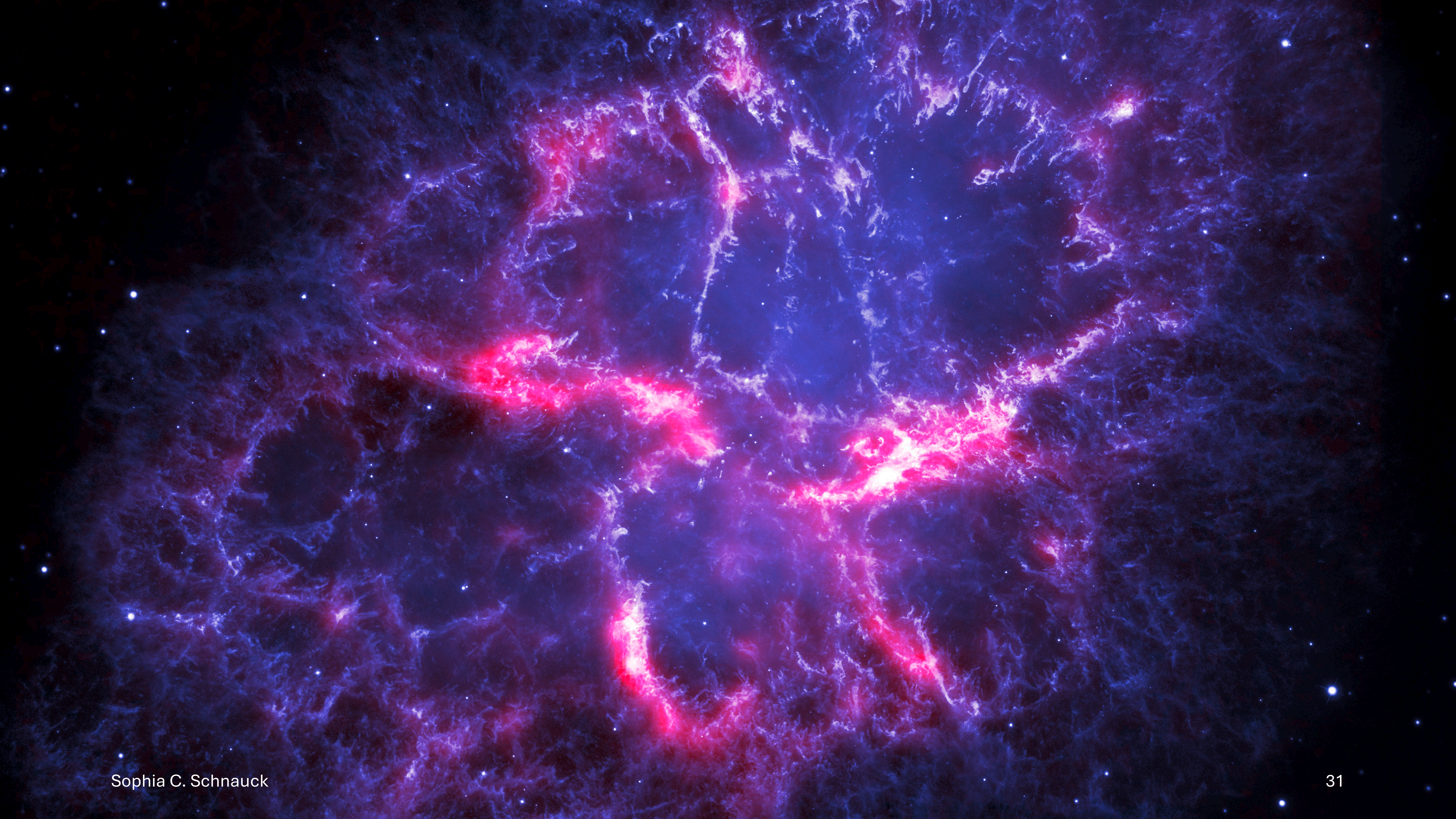
  - ❖Extracted and analyzed GW signals
  - ❖Interpreted GW signatures for detectability with ET



4. What is next?

We want to:

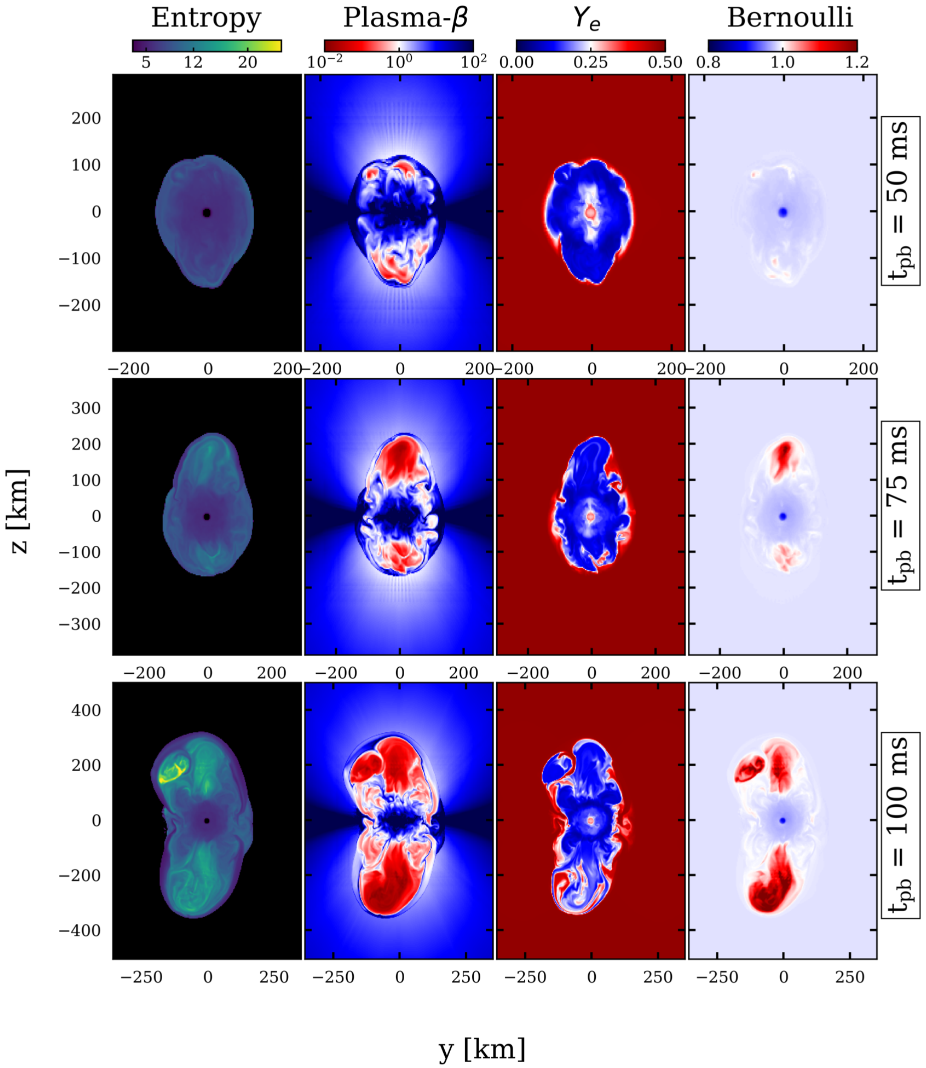
- Drive the simulations to 1s post-bounce
- Vary the progenitor mass
- Run a model with $B_0 = 10^{13}$ G
- Run a models with $\Omega_0 = 1.4$, 4.2, and 5.6 rad s^{-1}
- Plot the time-frequency content of GW signals and analyze for PNS oscillations
- Implement M1 neutrino transport



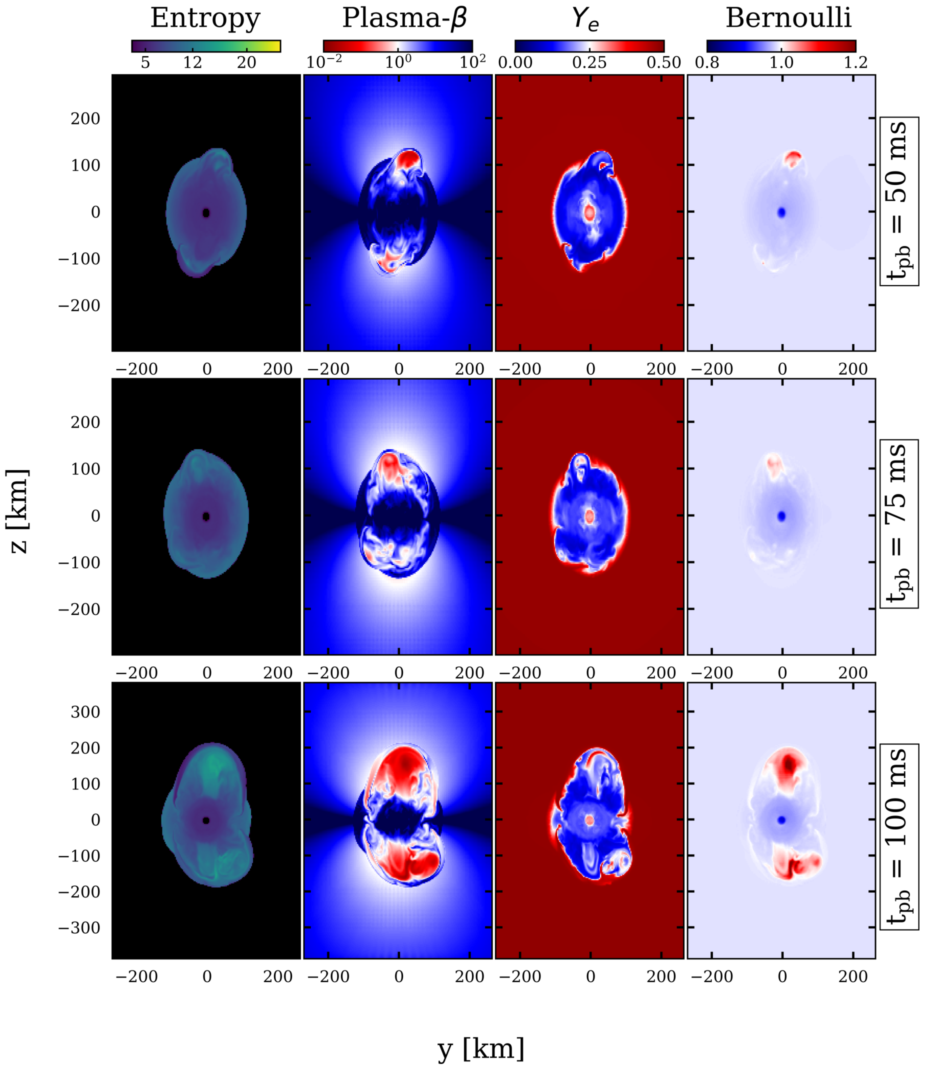
Extra Slides

Explosion Dynamics

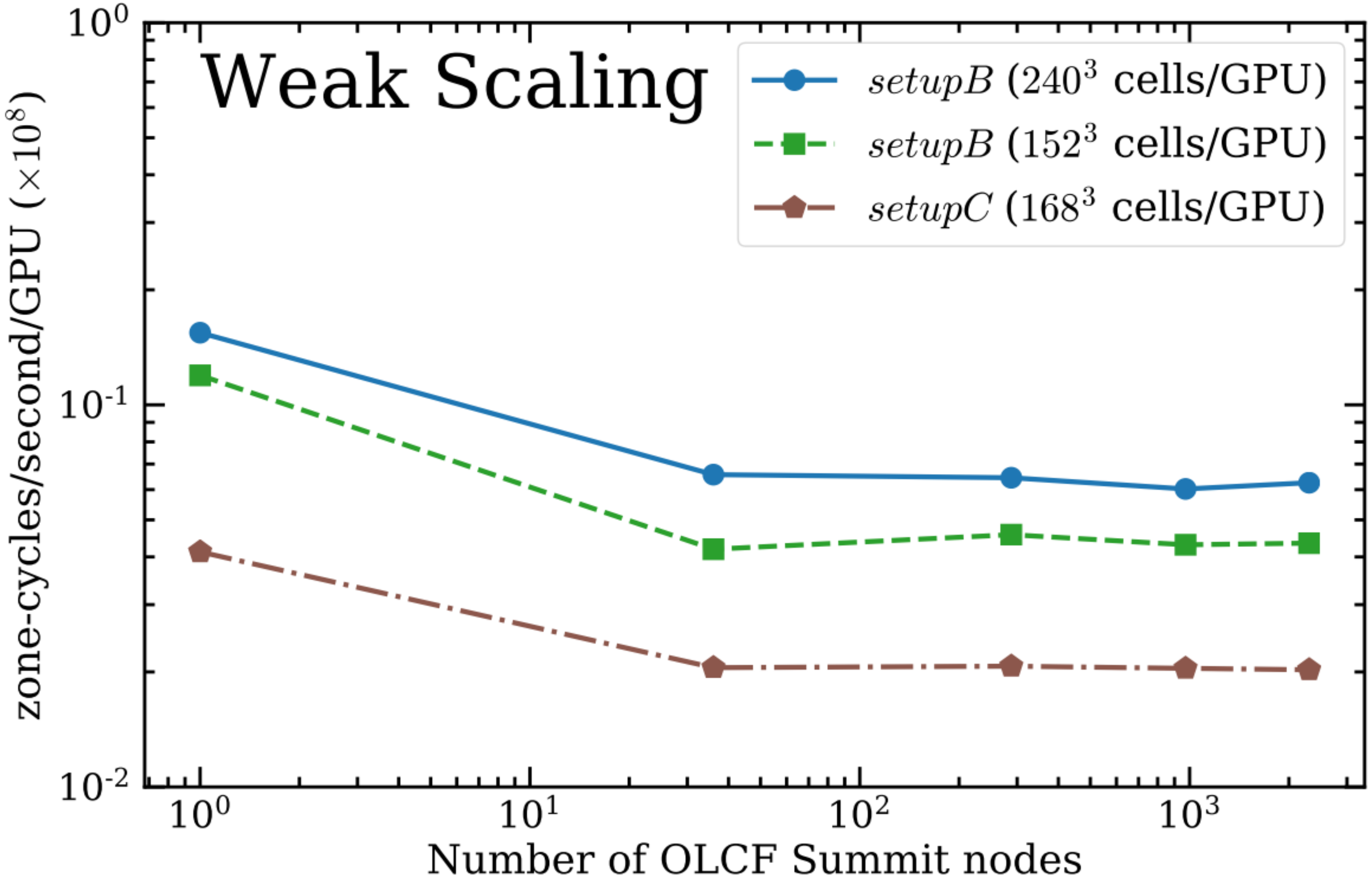
E25



rot14B12

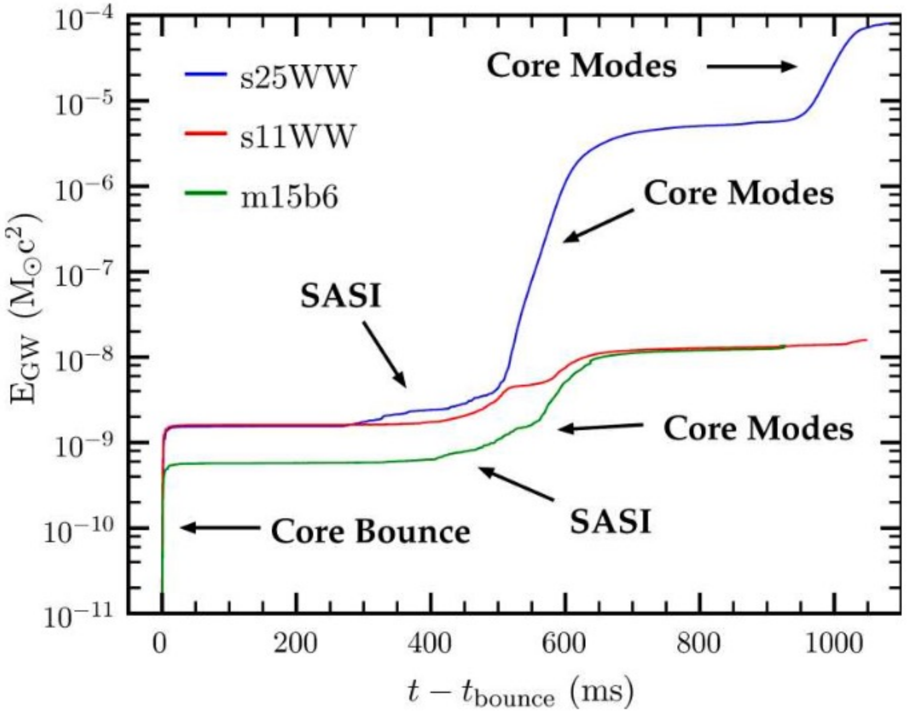


2. GRaM-X: Scaling Tests

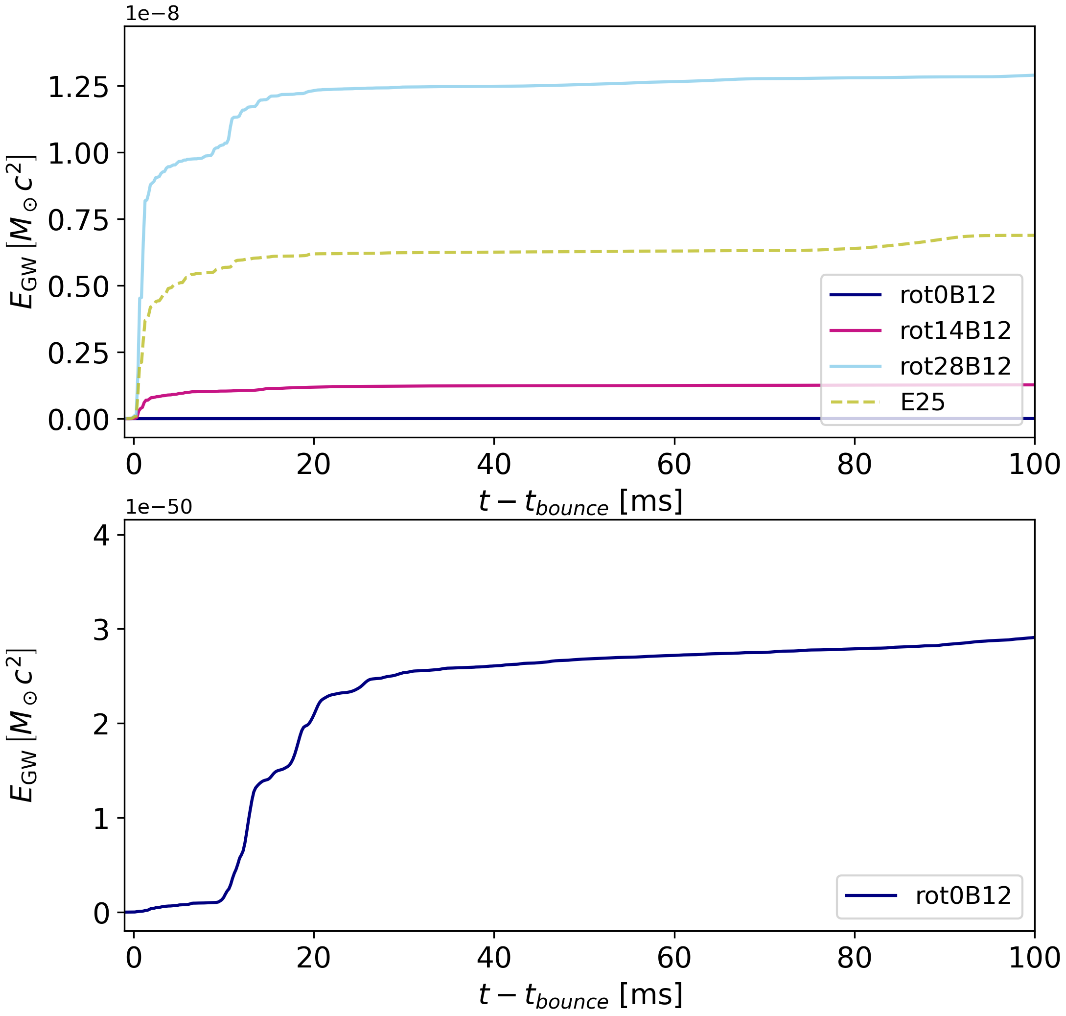


(Shankar et al. 2023)

Gravitational Wave Energies



(Ott et al. 2006)



Gravitational Waves

- Using the gravitational wave mass-quadrupole tensor I_{jk}, we can determine $h_{+,eq}$, $h_{x,eq}$, $h_{+,p}$, and $h_{x,p}$[1]

$$h_{+,\mathrm{eq}} = \frac{G}{c^4}\left(\ddot{I}_{zz} - \ddot{I}_{yy}\right) \qquad h_{+,\mathrm{p}} = \frac{G}{c^4}\left(\ddot{I}_{xx} - \ddot{I}_{yy}\right)$$

$$h_{\times,\mathrm{eq}} = \frac{2G}{c^4}\left(\ddot{I}_{yz}\right) \qquad h_{\times,\mathrm{p}} = \frac{-2G}{c^4}\left(\ddot{I}_{xy}\right)$$

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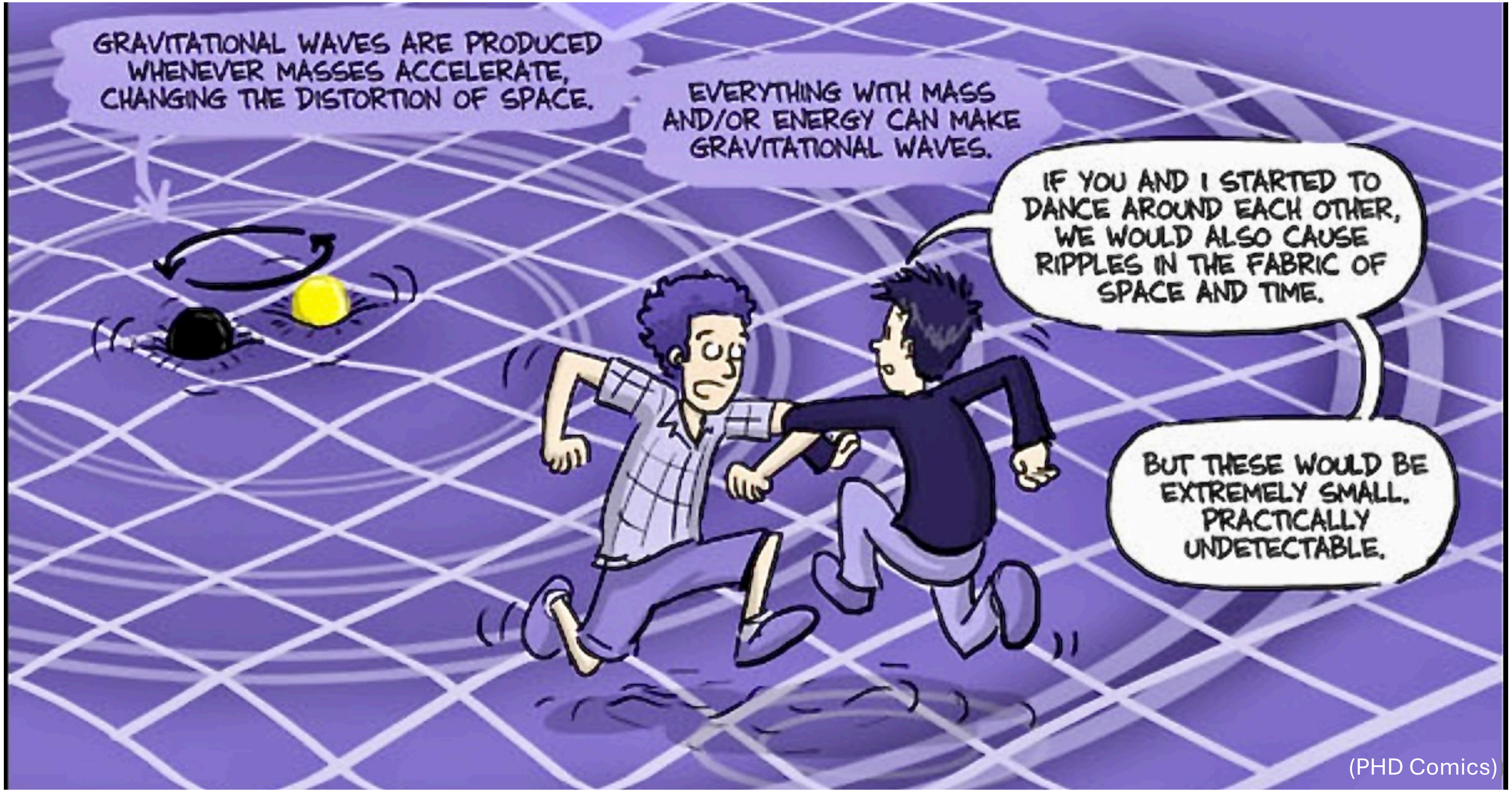
1. Kuroda, T., Takiwaki, T., and Kotake, K., “Gravitational wave signatures from low-mode spiral instabilities in rapidly rotating supernova cores”, *Physical Review D*, vol. 89, no. 4, APS, 2014.

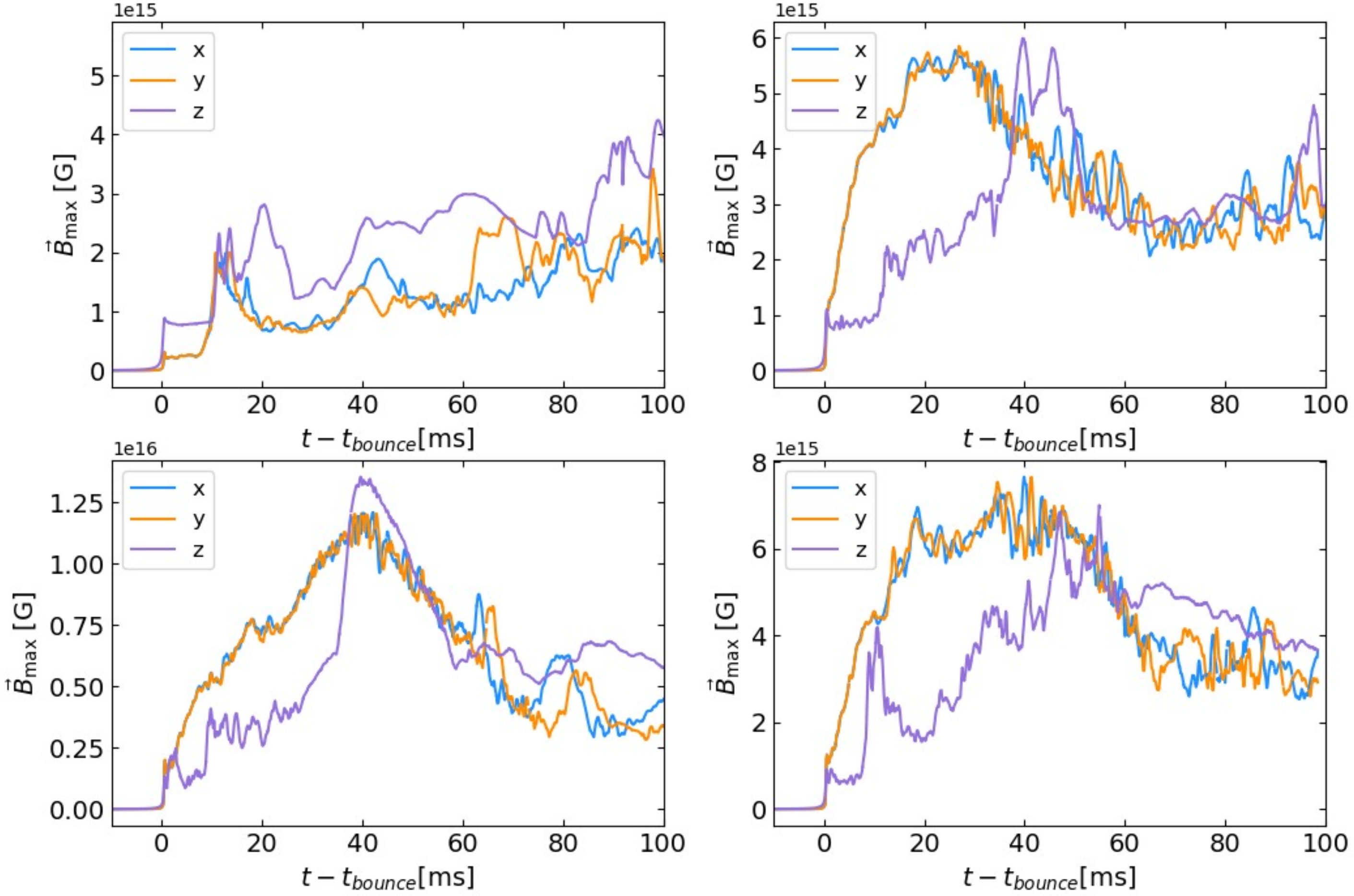
1. Gravitational Waves

What are Gravitational Waves?

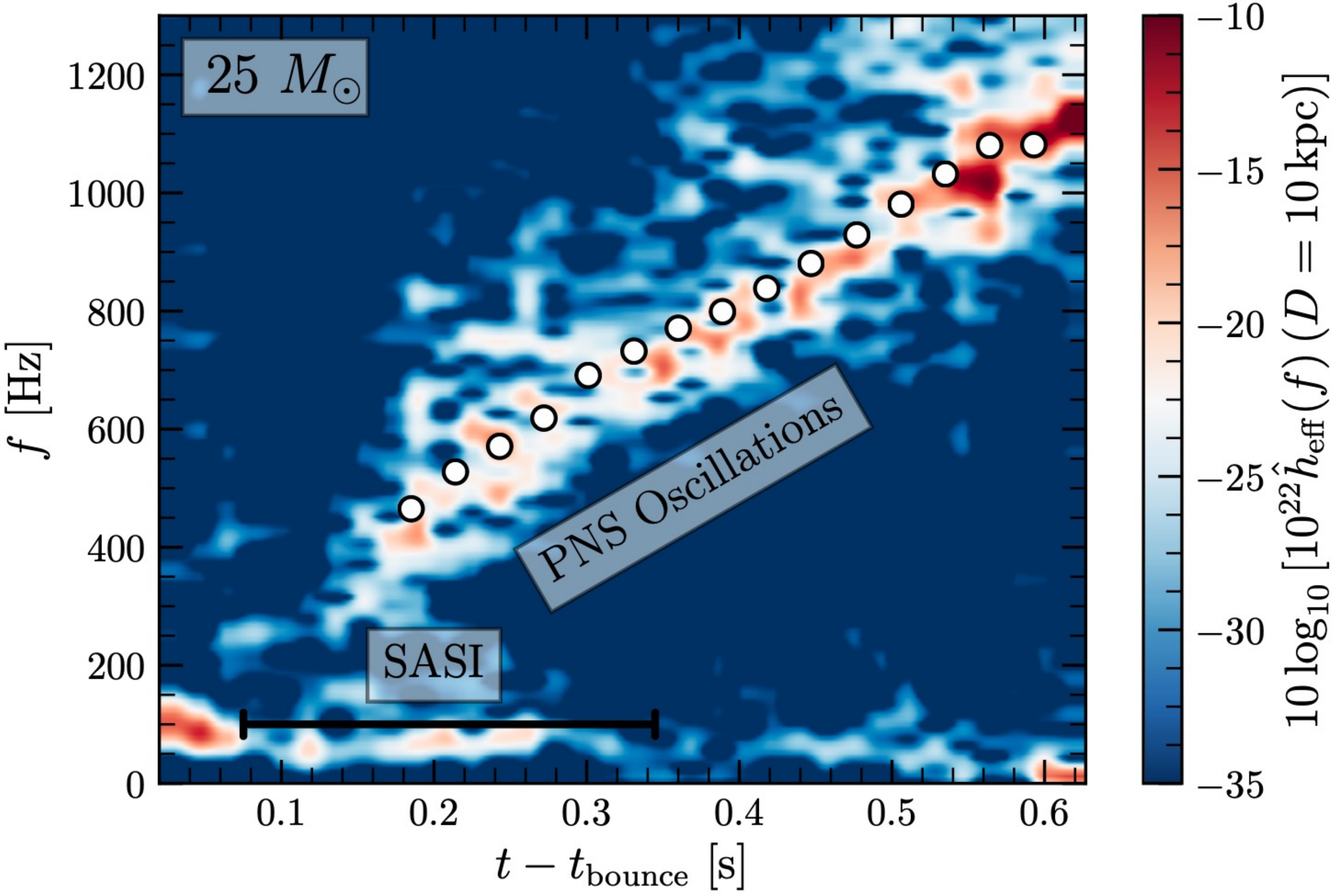


(PHD Comics)

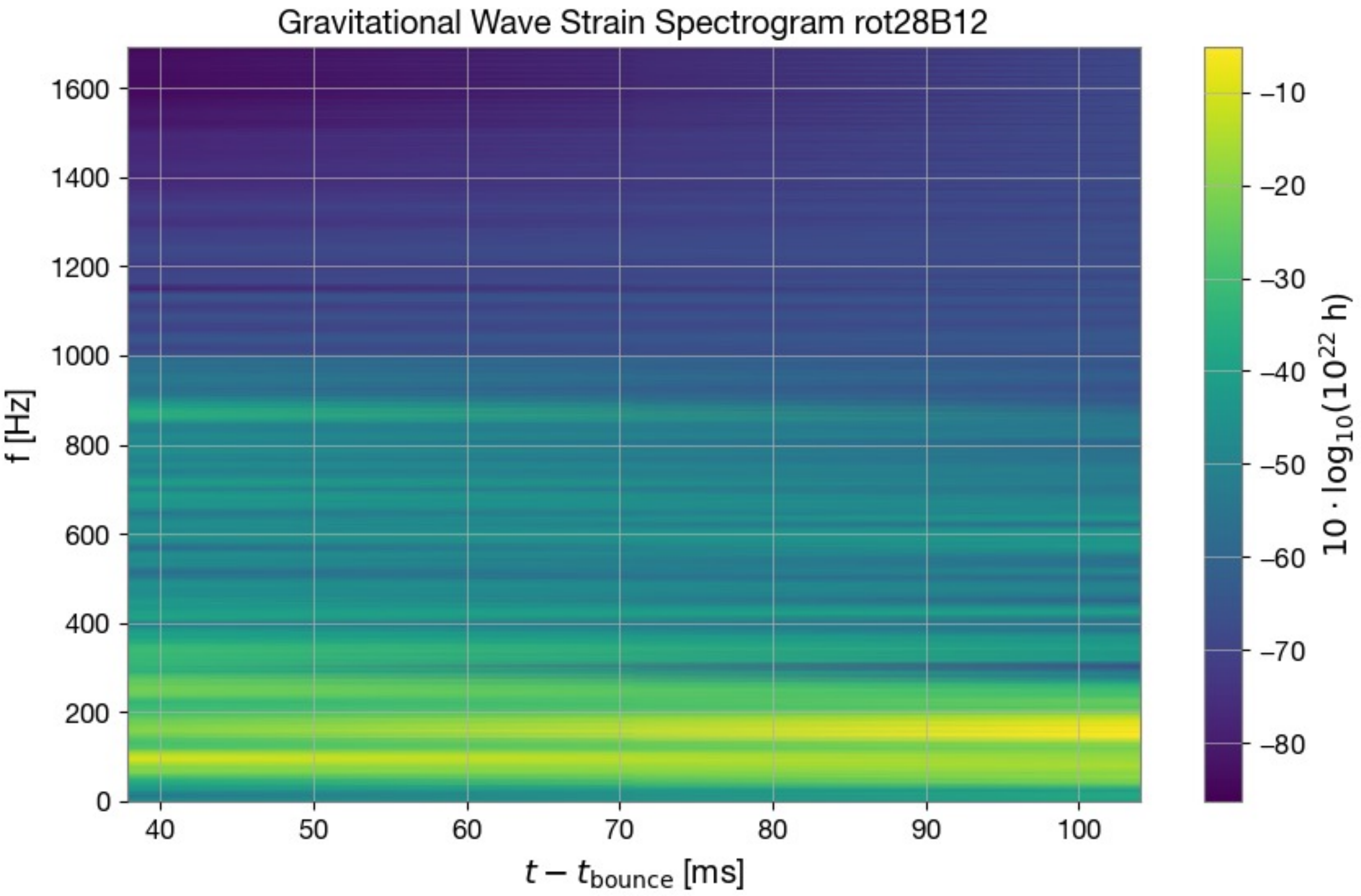
Magnetic Fields



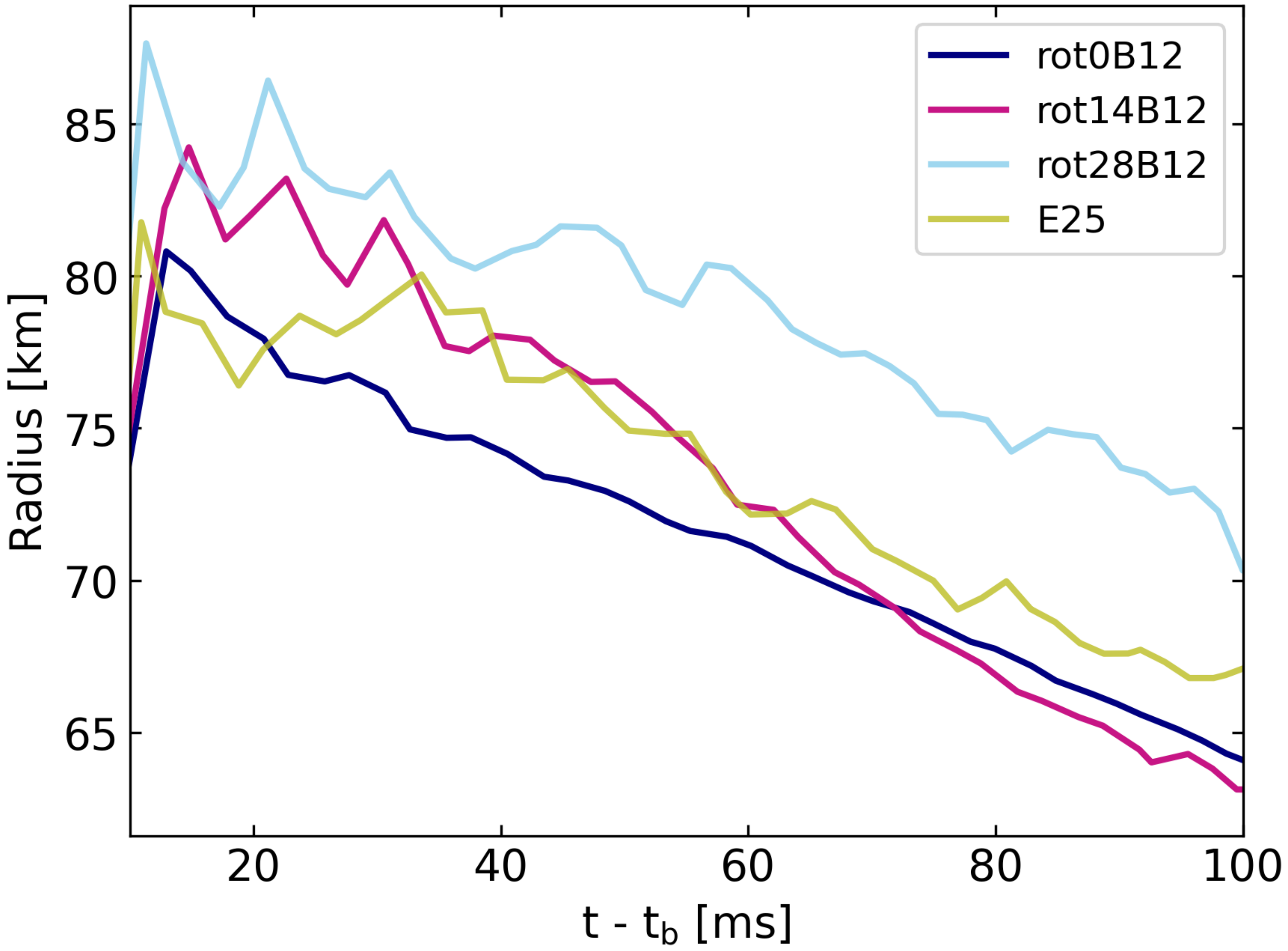
Gravitational Wave Spectrogram – Radice et al. 2019



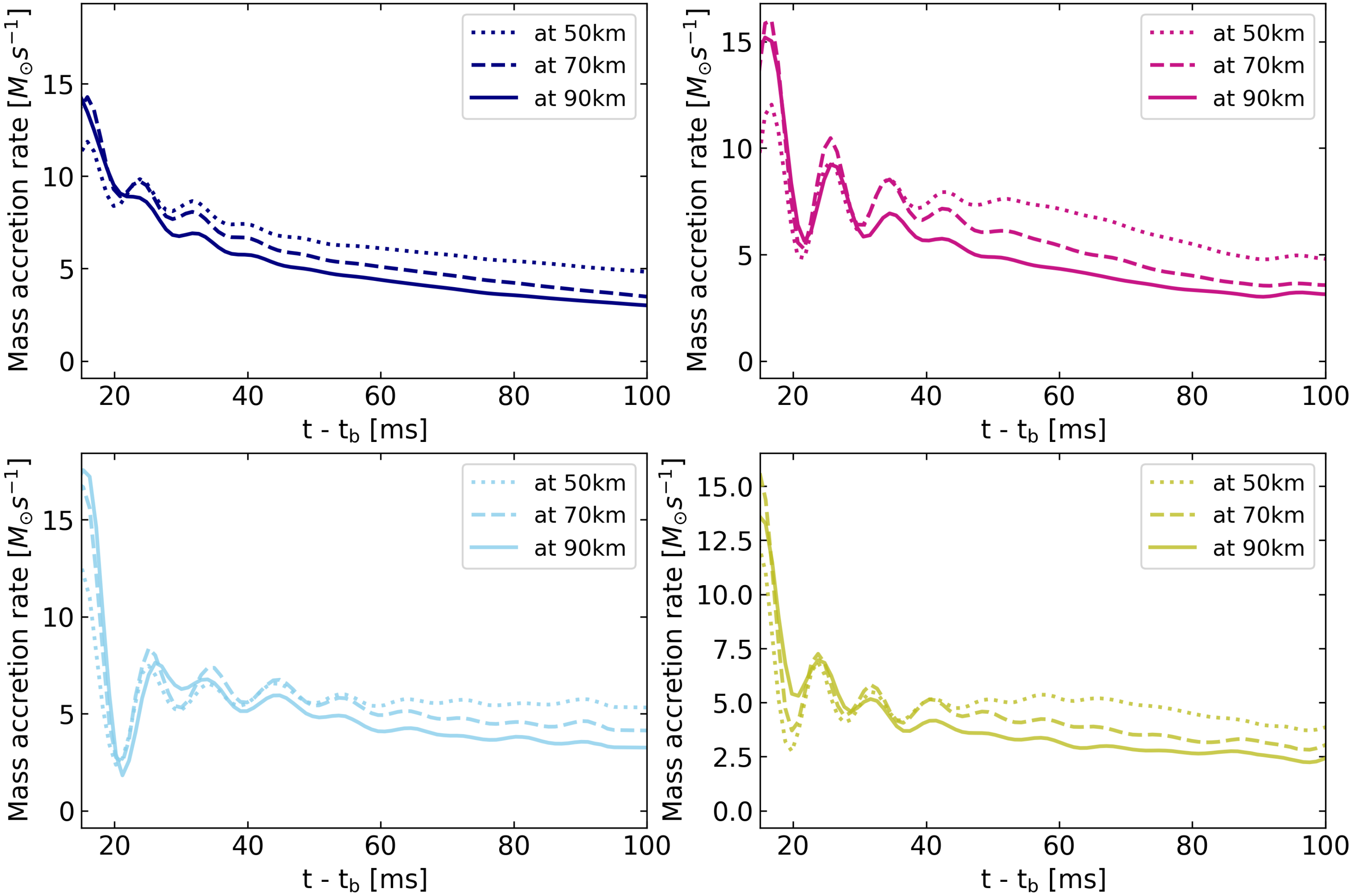
Gravitational Wave Spectrogram



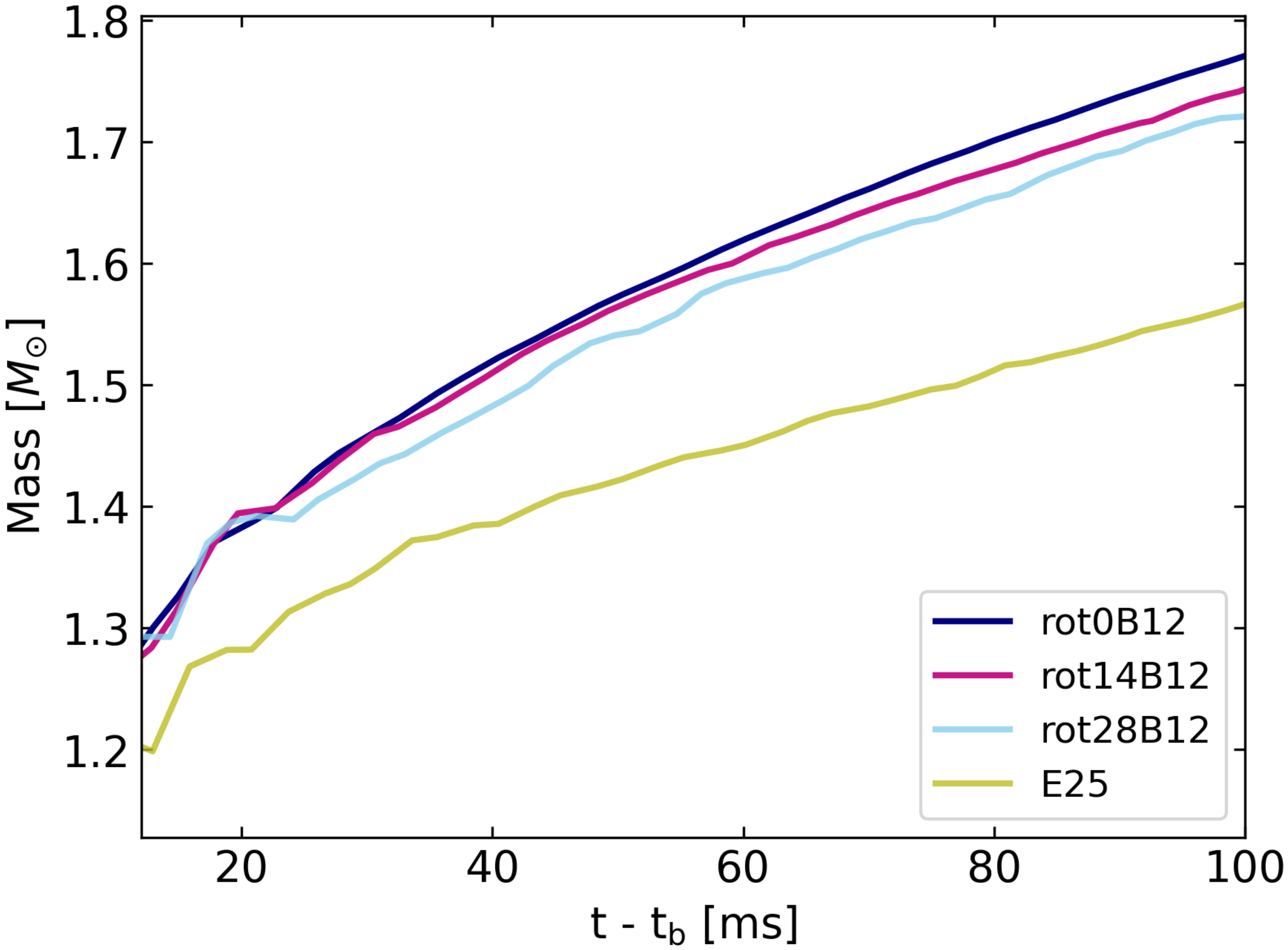
PNS Radius


rot0B12
rot14B12
rot28B12
E25
Radius [km]
85
80
75
70
65
20
40
60
80
100
t - t_b [ms]

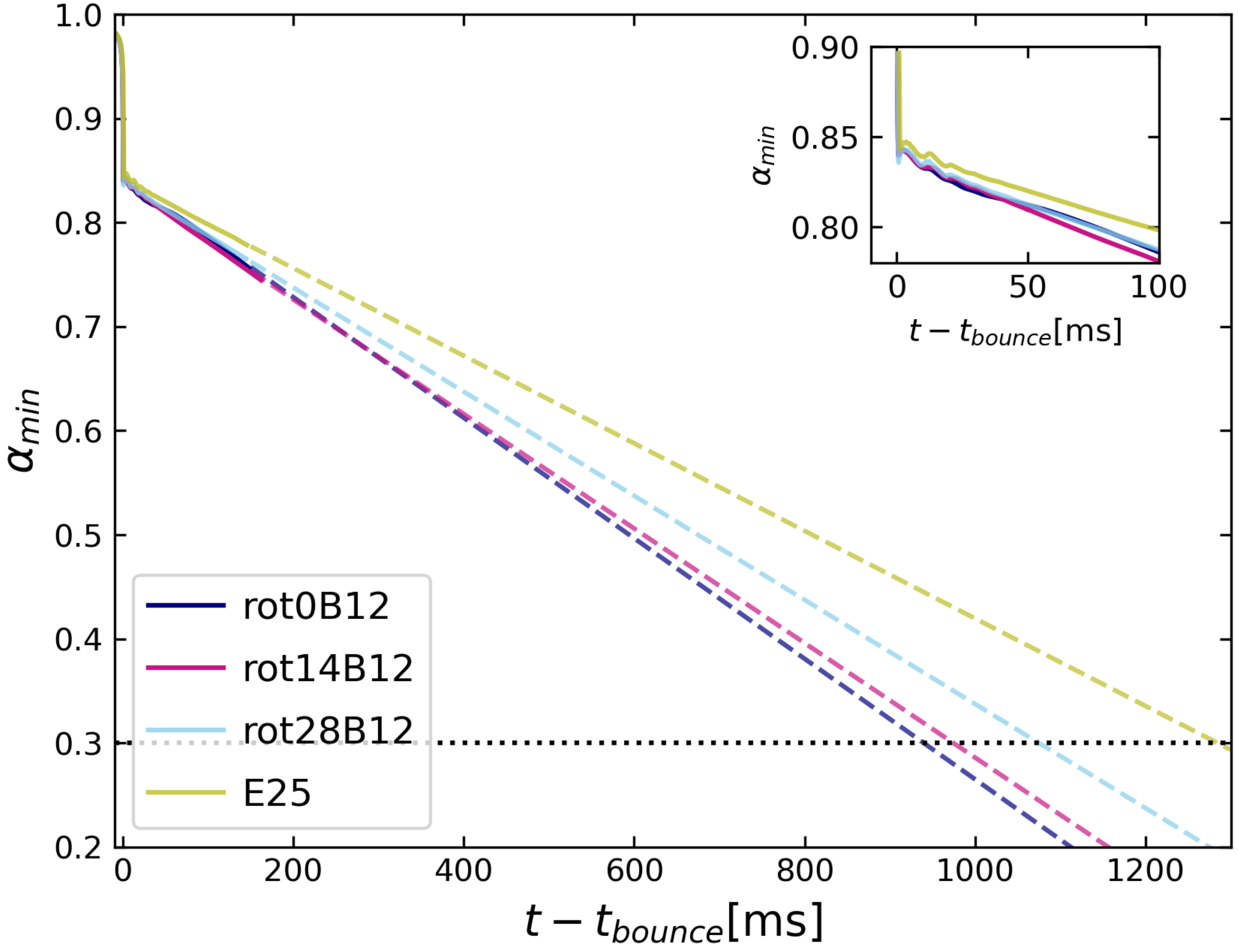
Accretion Rates



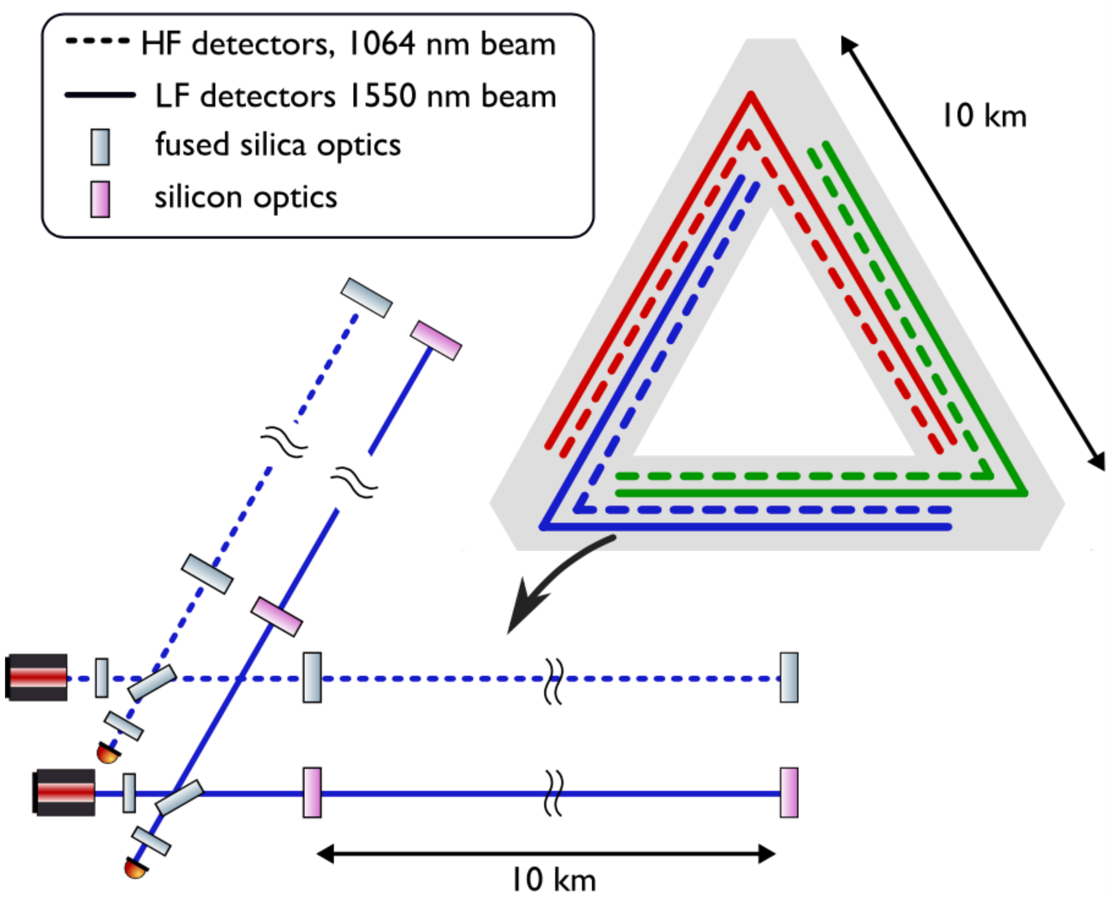
3. PNS Evolution



Fate of the Remnant

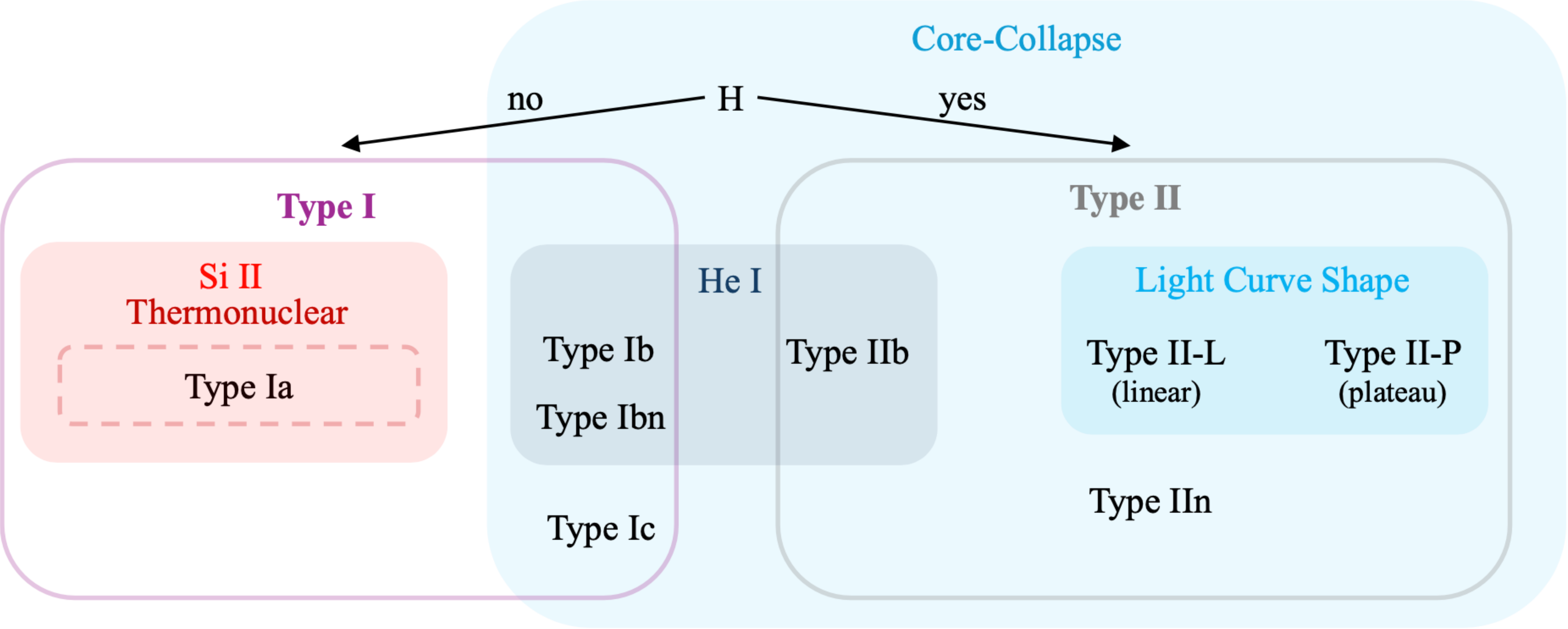


The Einstein Telescope



- Arrangement of 3 “L” shaped detectors
- Separate low and high frequency detectors
- Idea: combine data from each detector, increasing sensitivity and thus the reliability of a detection

The Supernova “Zoo”



Magnetic Fields and Rotation Profile

- Constraints on magnetic fields from High mass stars
- No strong observational constraints, just theoretical
- Upward constraint: if field is ~ 1016G star explodes immediately and not necessarily realistic
- Lower constraint: need at least 1012G in order to have dynamically relevant field (reverse engineered)
- Strong B-fields may be rare, but so are CCSNe