Gravitational Waves from Core-Collapse Supernovae

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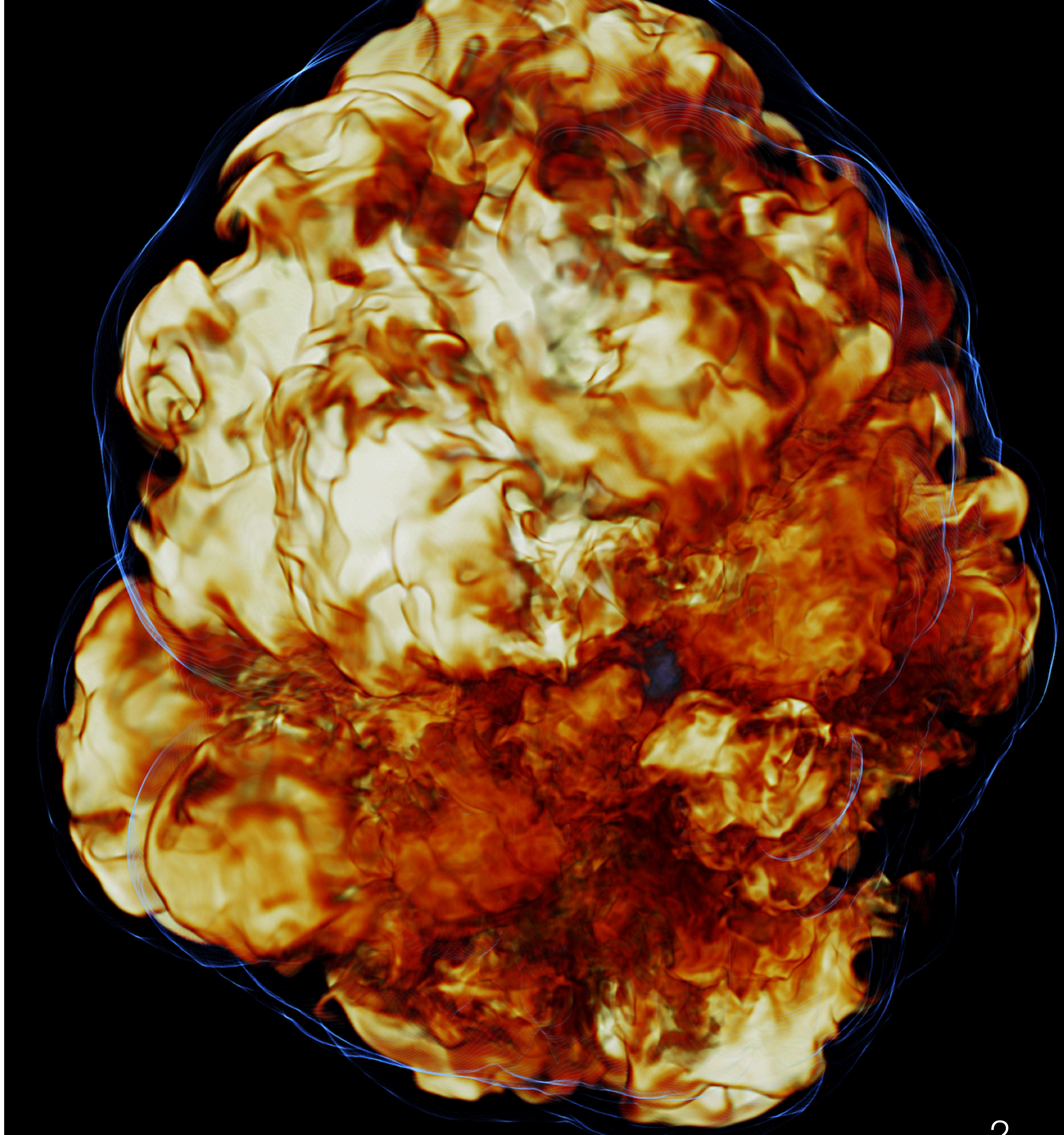
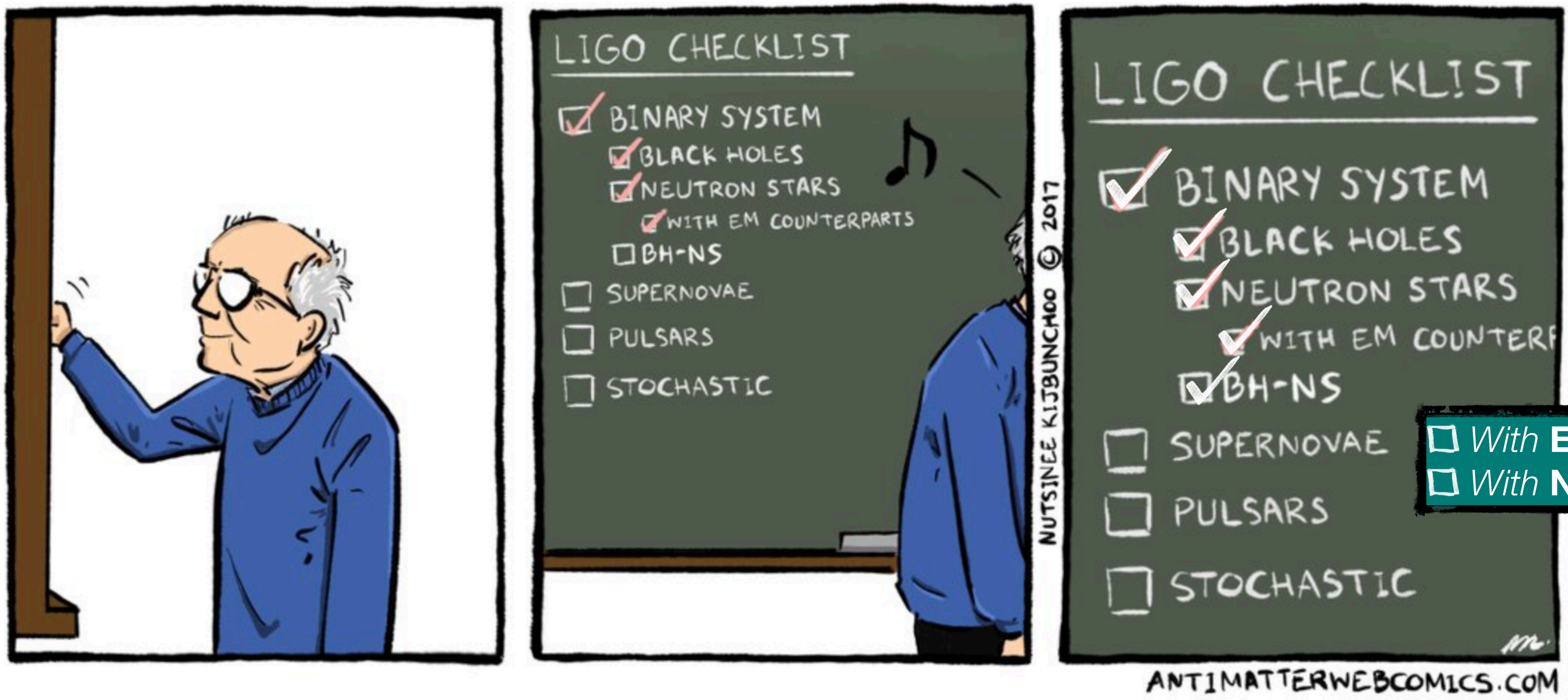
GW Data Workshop @ KIW-10

Outline

- Introduction to Core-collapse supernova (CCSN)
- Multi-messenger signals from CCSN
- CCSN numerical simulations
- CCSN Waveforms
- Lab: CCSN waveforms

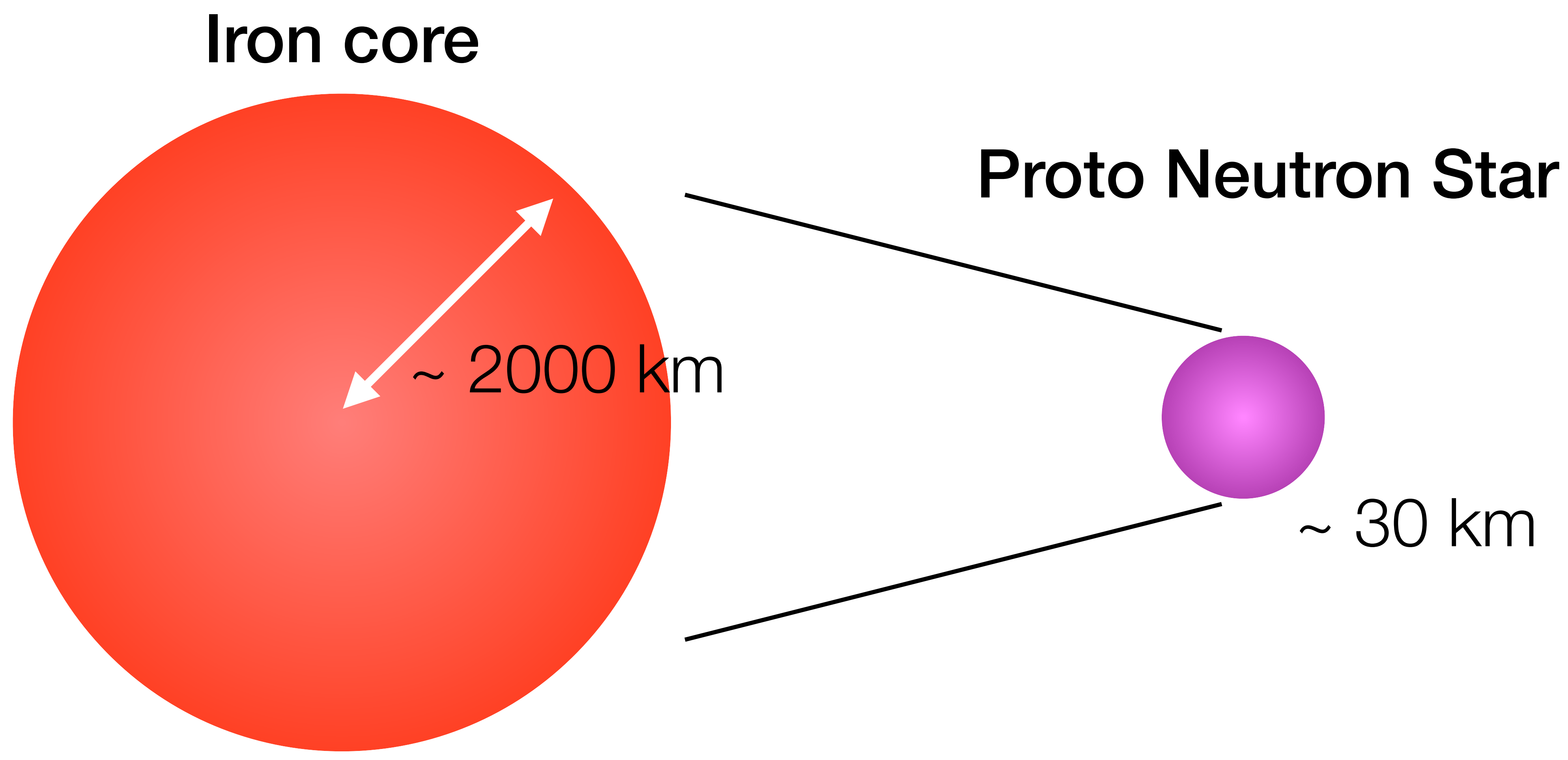


Masses in the Stellar Graveyard

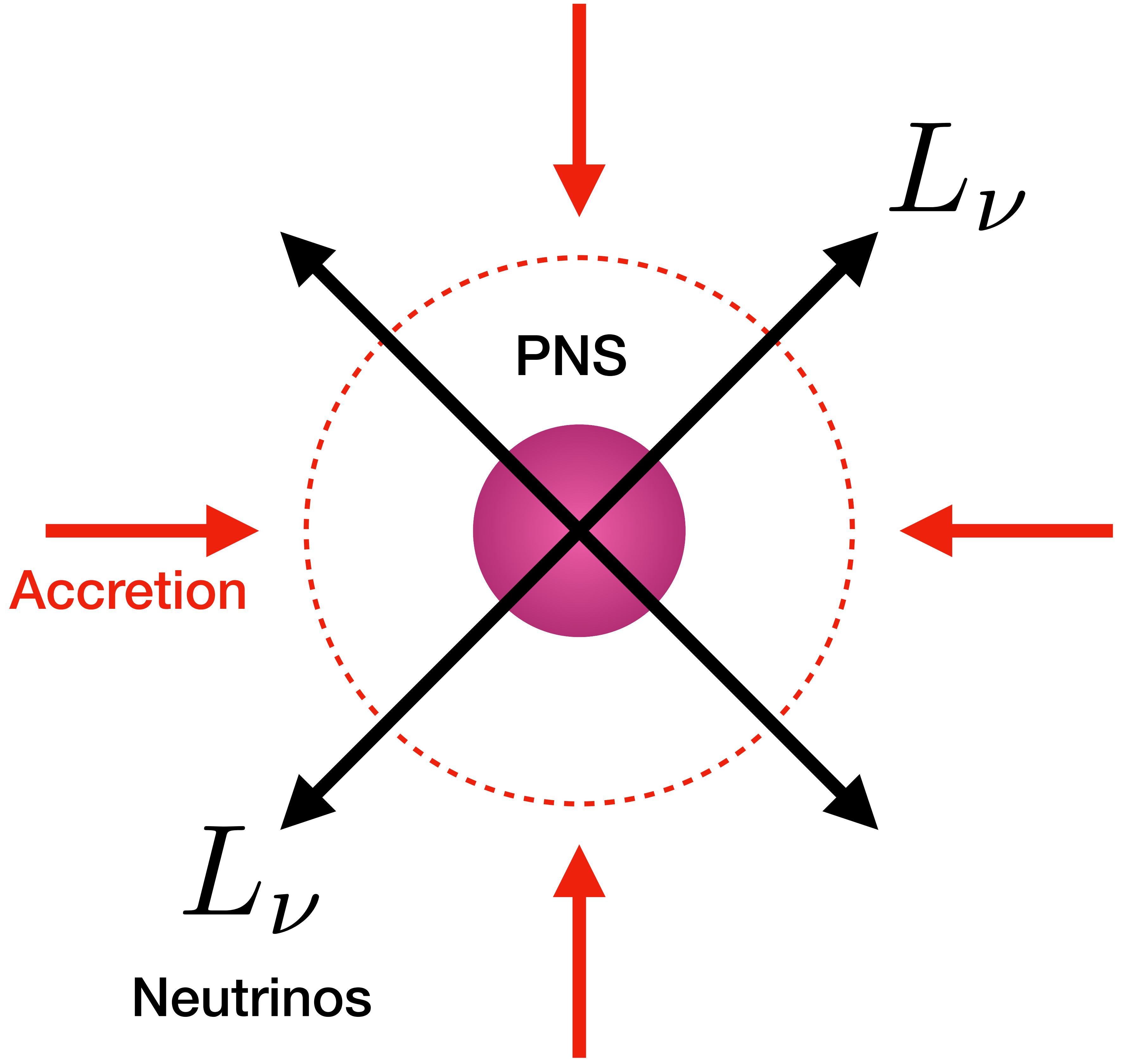


- ☐ *With* ***EM*** *counterpart*
- ☐ *With* ***Neutrino*** *counterpart*

Collapse Physics and neutrino mechanism



d ~ 10^{10} g/cm^3
T ~ 1 MeV ~ 10^{10}K
Y_e ~ 0.5



Iron core collapse to ~ 30 km in less than a second. The infall speed reaches to ~0.3 c at core bounce

The core is hot and dense enough to produce a huge amount of neutrinos (~ 100B)

Small cross section in the outer core allows efficient cooling

Shock loses energy and stalled at ~ 100 km

If a few % of neutrino's energy can be absorbed by the matter, it is enough to power the explosion

Numerical Challenge

Fully coupled

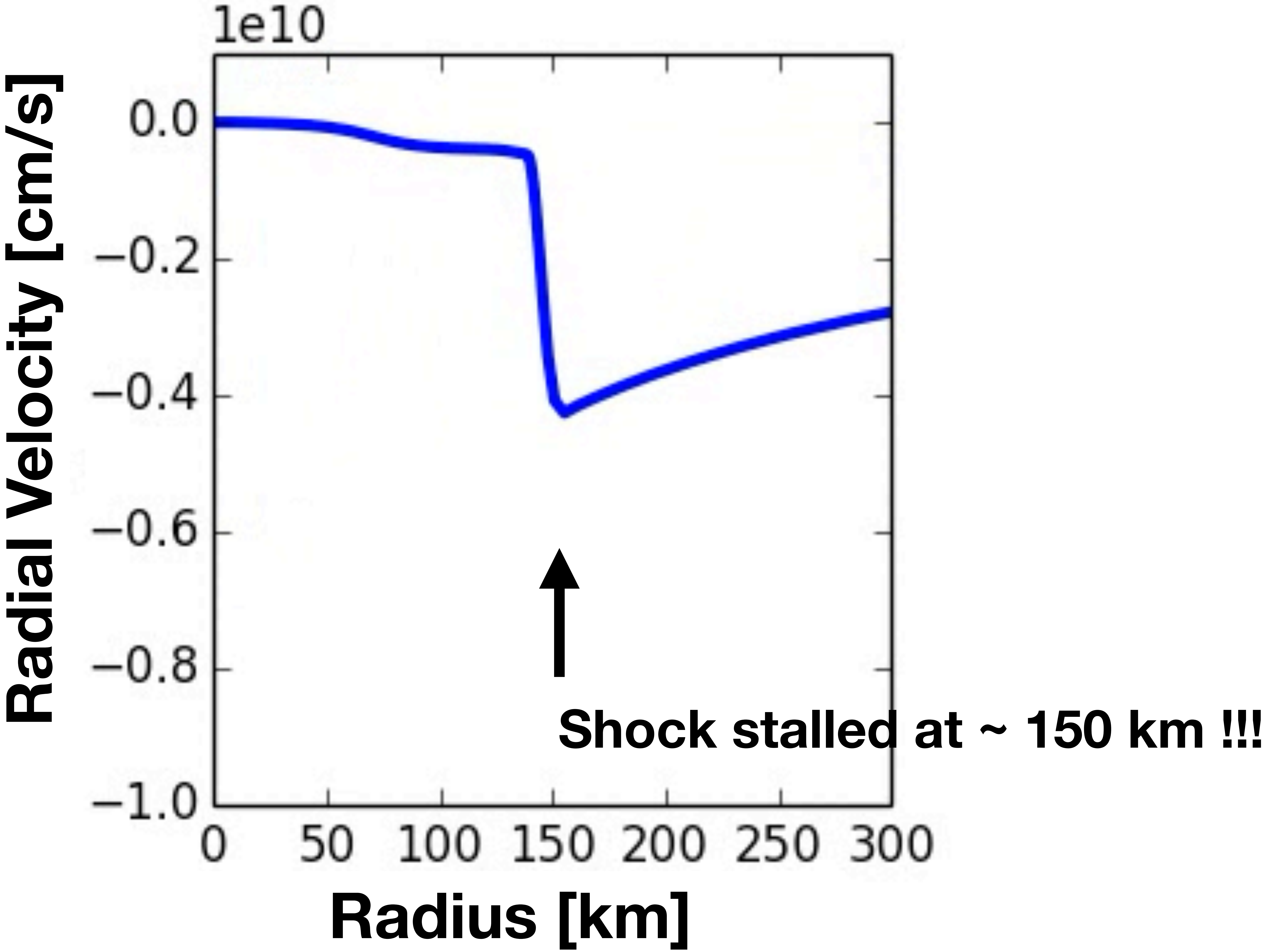
(Magneto) hydrodynamics →	(Plasma) /fluid dynamics
General Relativity →	Gravity
Nuclear and Neutrino Physics →	Nuclear EoS, nuclear reactions & neutrino interactions
Boltzmann Transport Theory →	Neutrino Transport

Additional complexity:

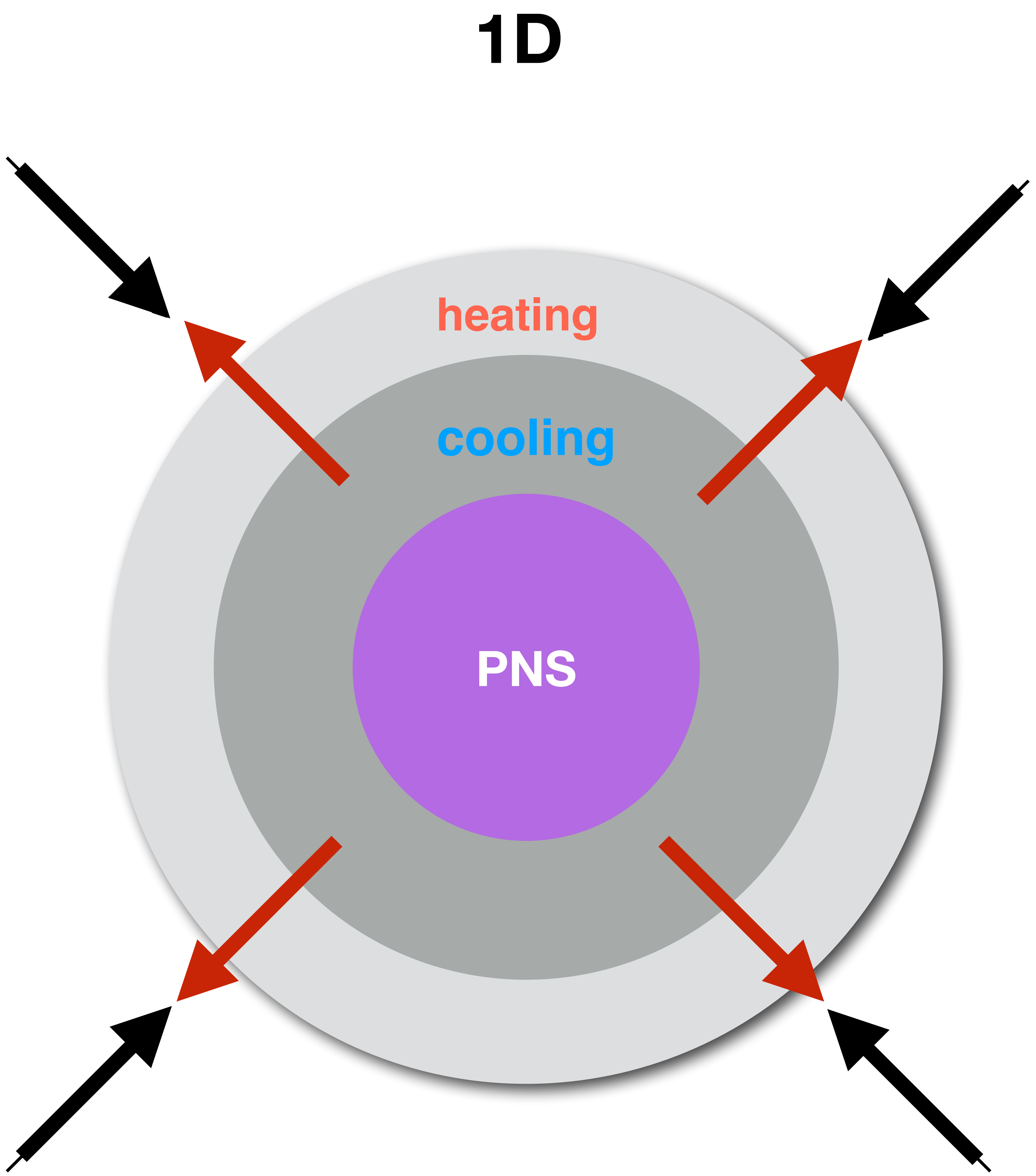
Multi-dimensional effects, rotation, fluid and MHD instabilities, turbulences
Wide range density and temperature range,
Wide range of neutrino optical depth
Require high accuracy (100 B vs 1B)

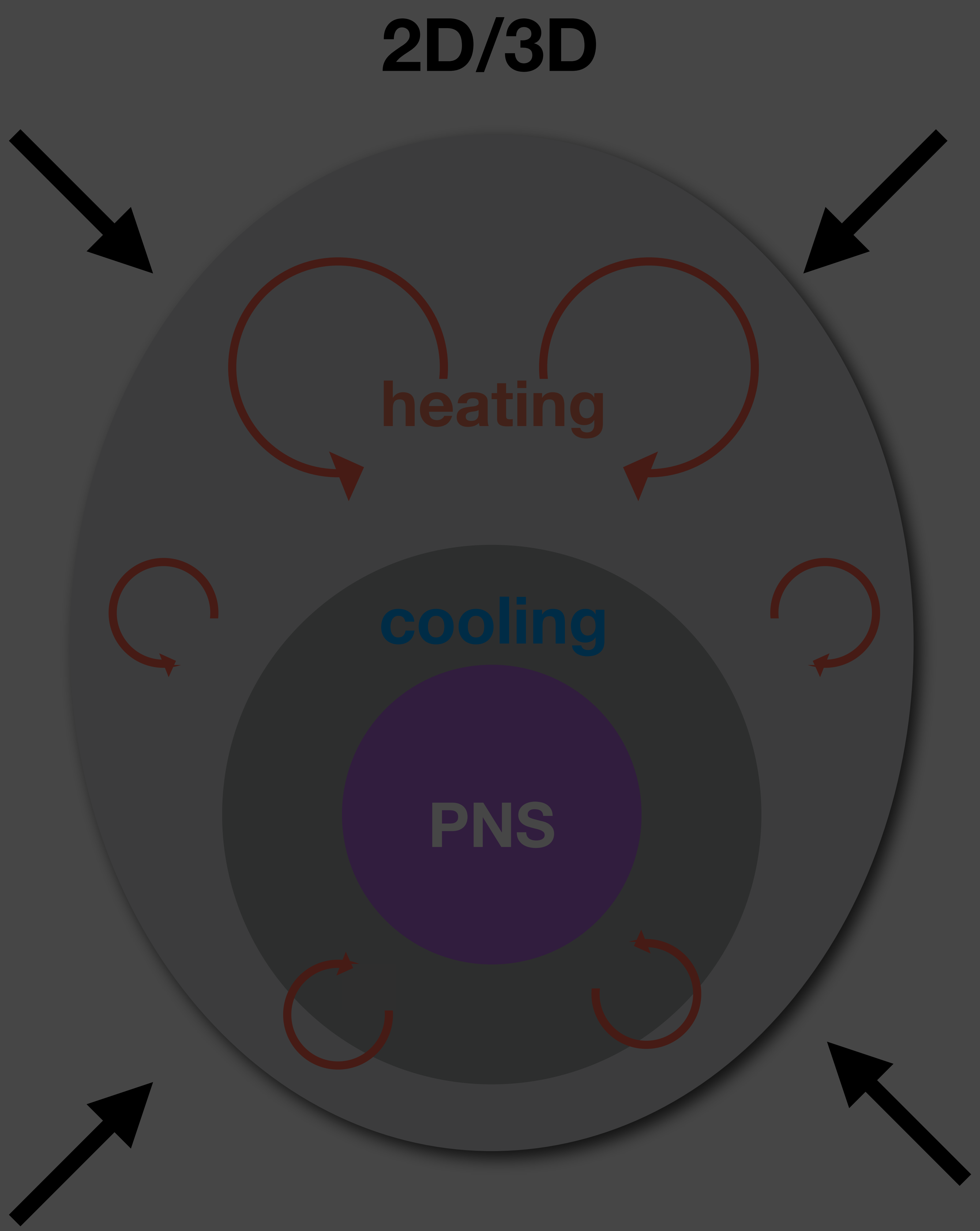
(Adjusted from C. Ott & P. Moesta)

Supernova Problem



Multi-dimensional Effects





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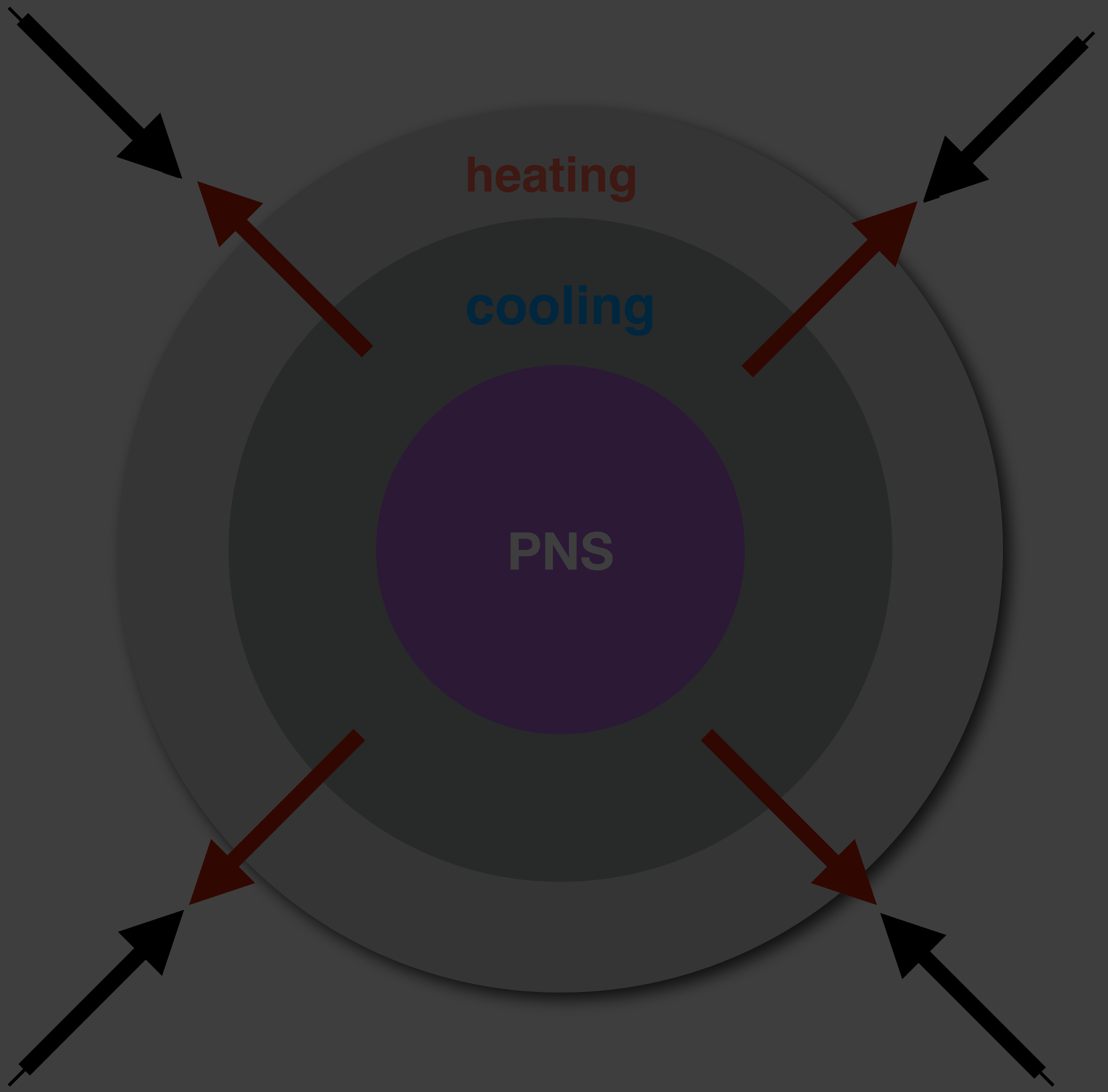
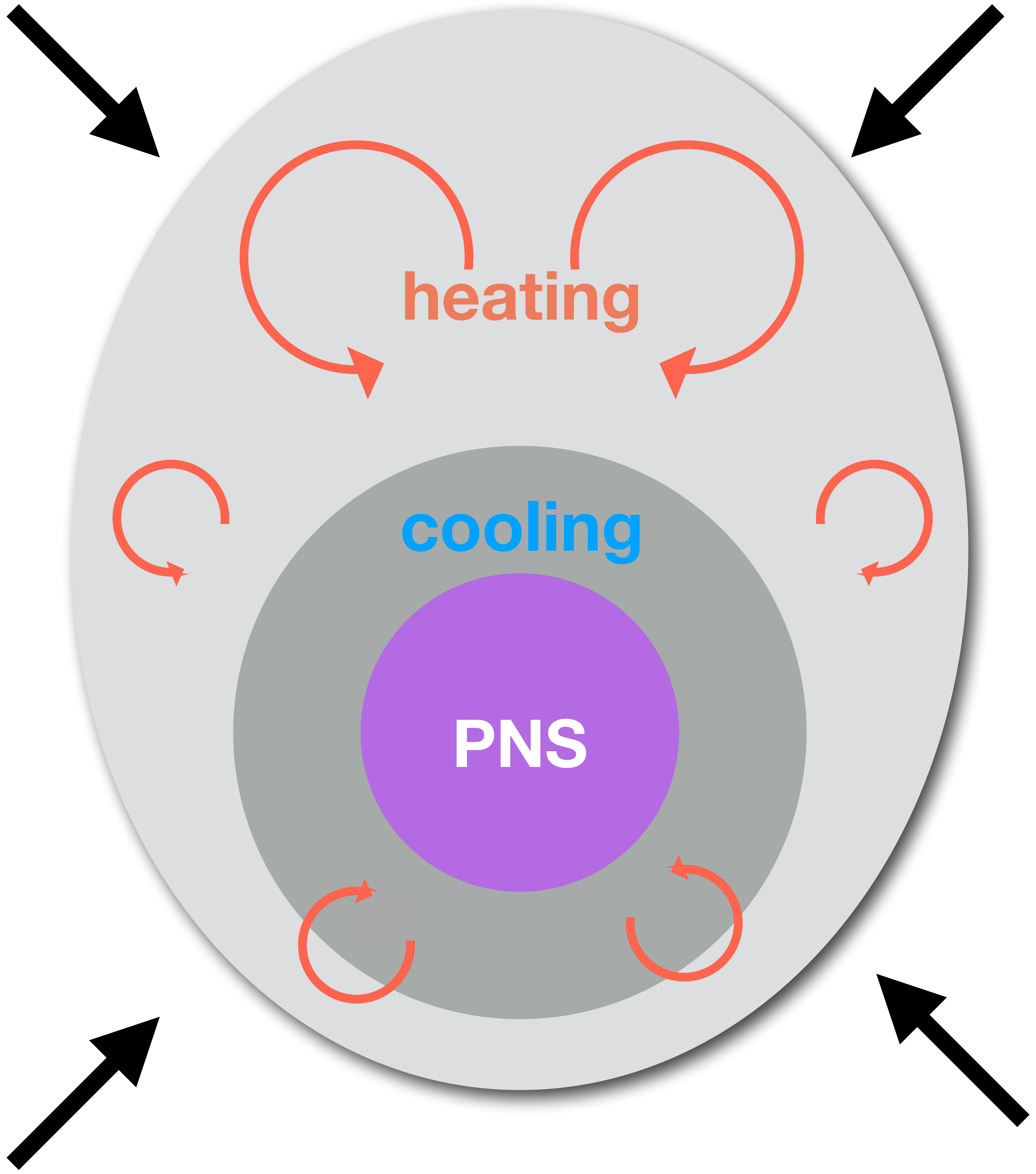
Multi-dimensional Effects

1D



2D/3D



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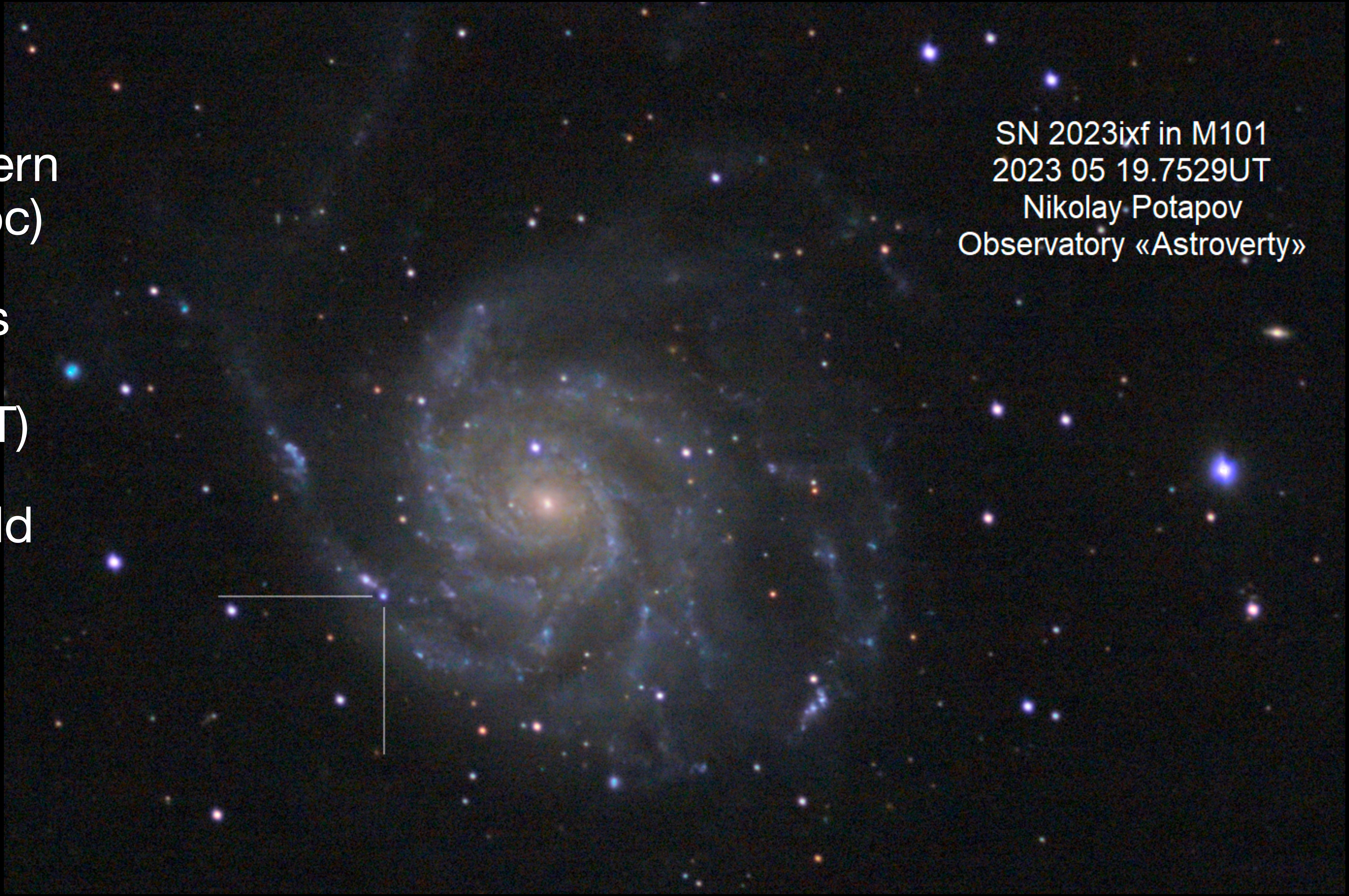
Multi-messenger Signals from CCSNe

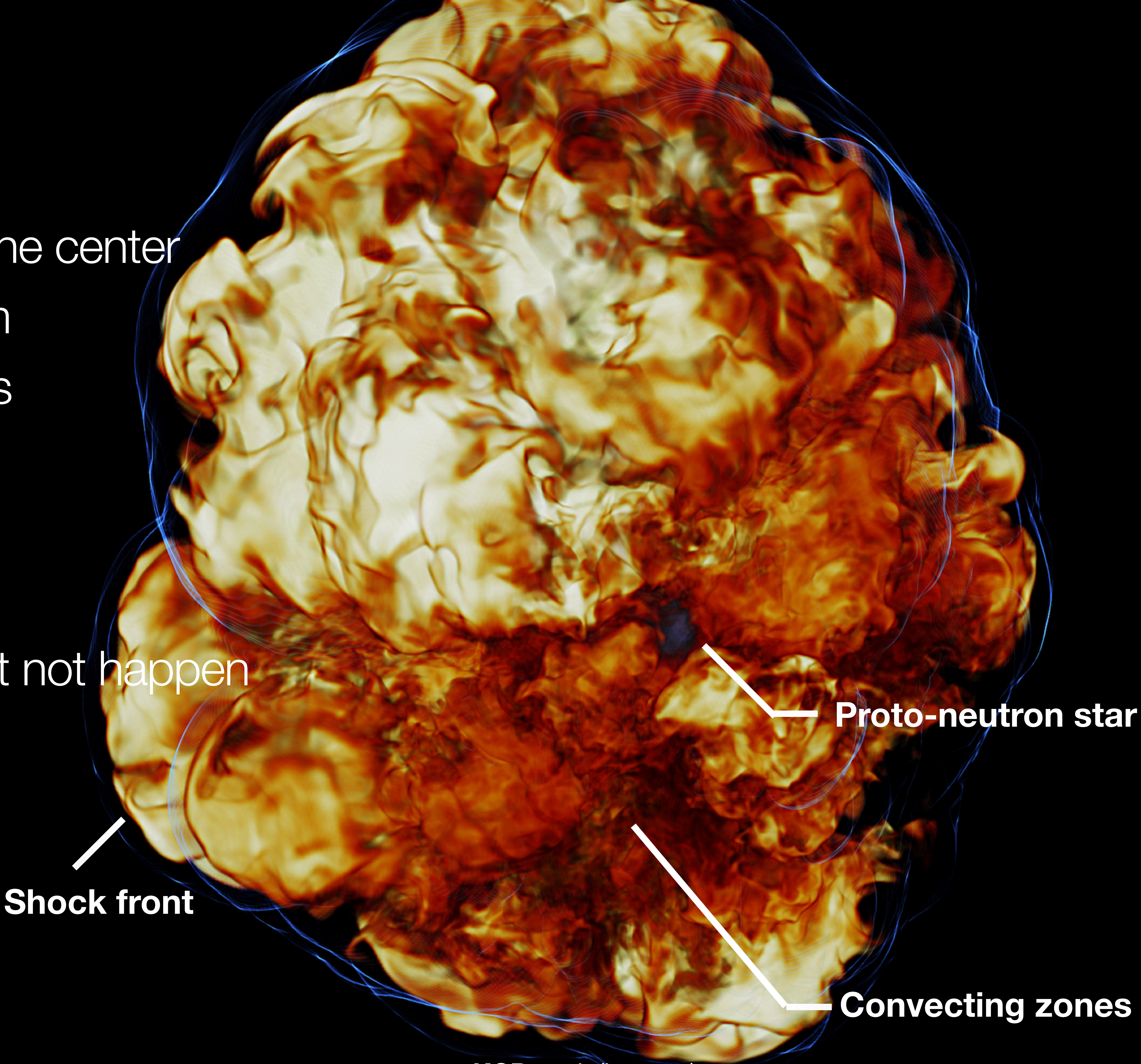
SN 2023ixf

- Closest CCSN in modern astronomy (d = 6.7 Mpc)
- Shock breakout time is well constrained (May 18th 10:00 — 21:30 UT)
- Core bounce time could be a few hours or day earlier
- GW or Neutrino counterparts?



Simulation overview

- A proto-neutron star (PNS) is formed at the center
- Shock wave stalled at around r ~ 200 km
- The PNS emits strong neutrino emissions
- Strong neutrino heating/cooling
- Shock revival might or might not occur
- Explosion is asymmetry
- Black hole (BH) formation might or might not happen



KCP et al. (in prep.)

國立清華大學
NATIONAL TSING HUA UNIVERSITY

MOST 科技部
Ministry of Science and Technology

NARLabs 財團法人國家實驗研究院
NCHC 國家高速網路與計算中心
National Center for High-performance Computing

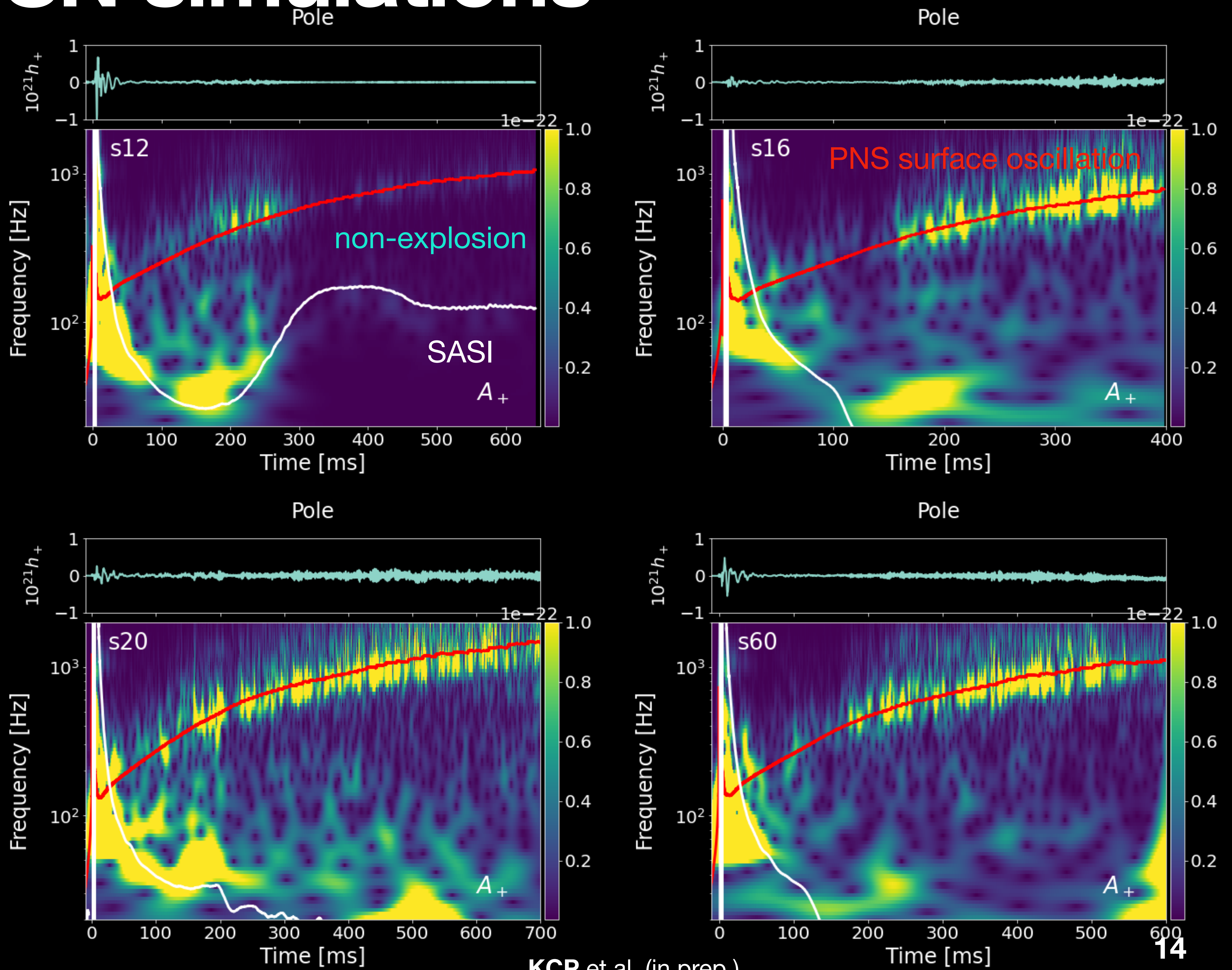
Core-Collapse Supernova Simulation

Visualization: Kuo-Chuan Pan (潘國全)
Department of Physics
Institue of Astronomy
National Tsing Hua University, Taiwan

剪輯/ 字幕：清華科技藝術中心 曾鈺雯

High Res. 3D CCSN simulations

- Convection & Turbulence are important to drive GW emissions.
- High-resolution simulations reveal the sounds of GW
- Red: PNS surface oscillations (g-modes)
- White: SASI component
- GW frequencies very different with different progenitor models



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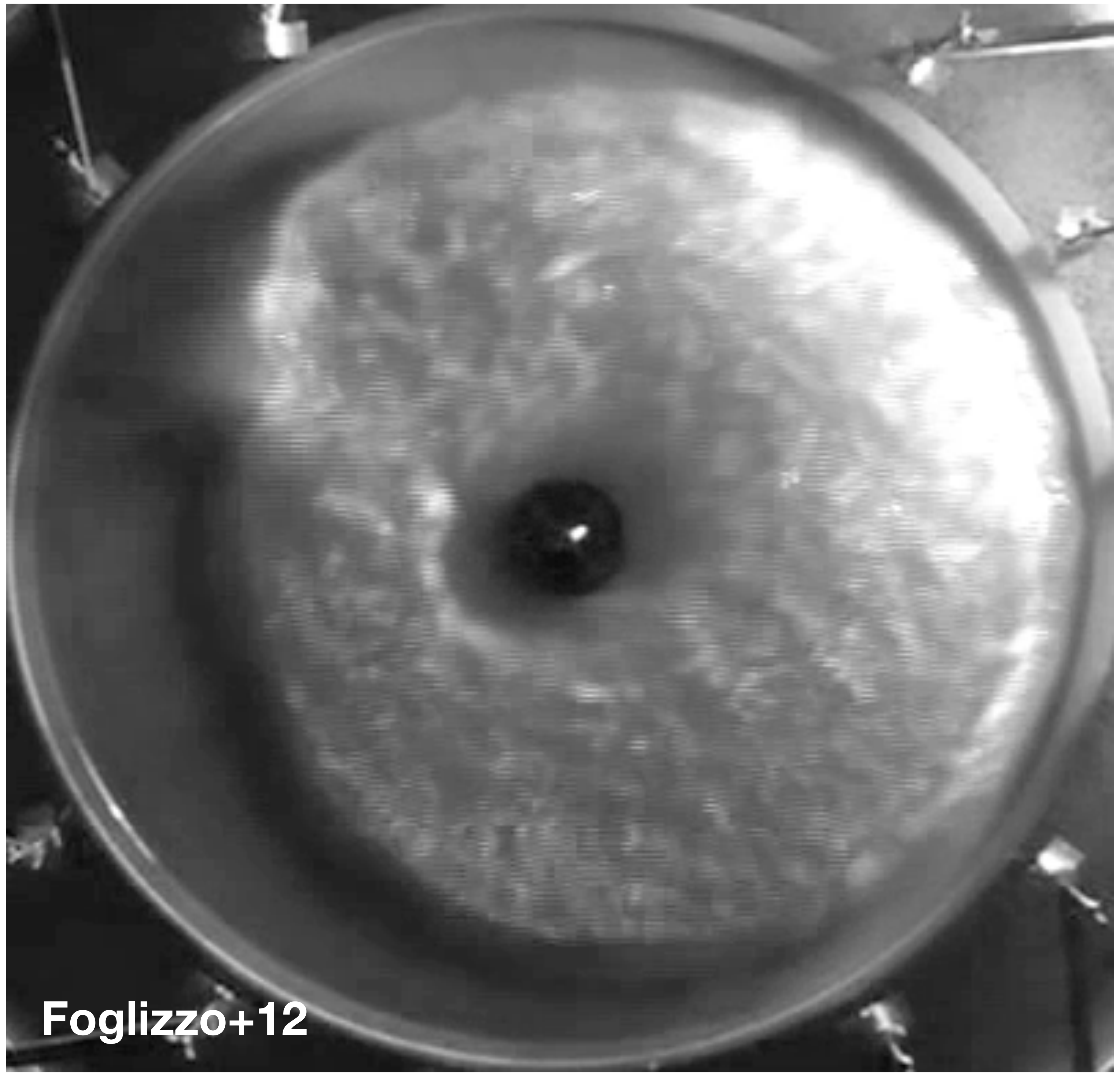
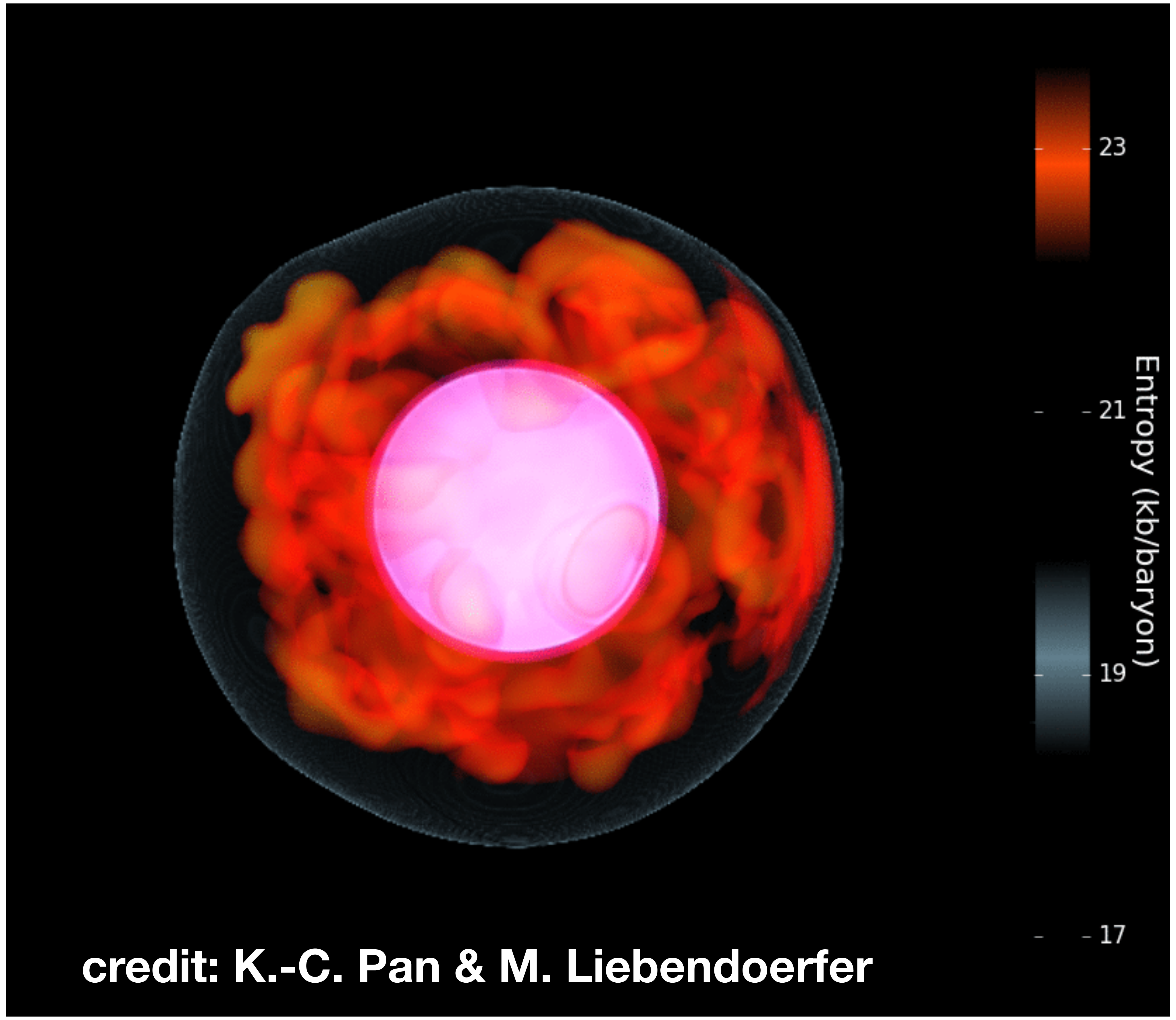
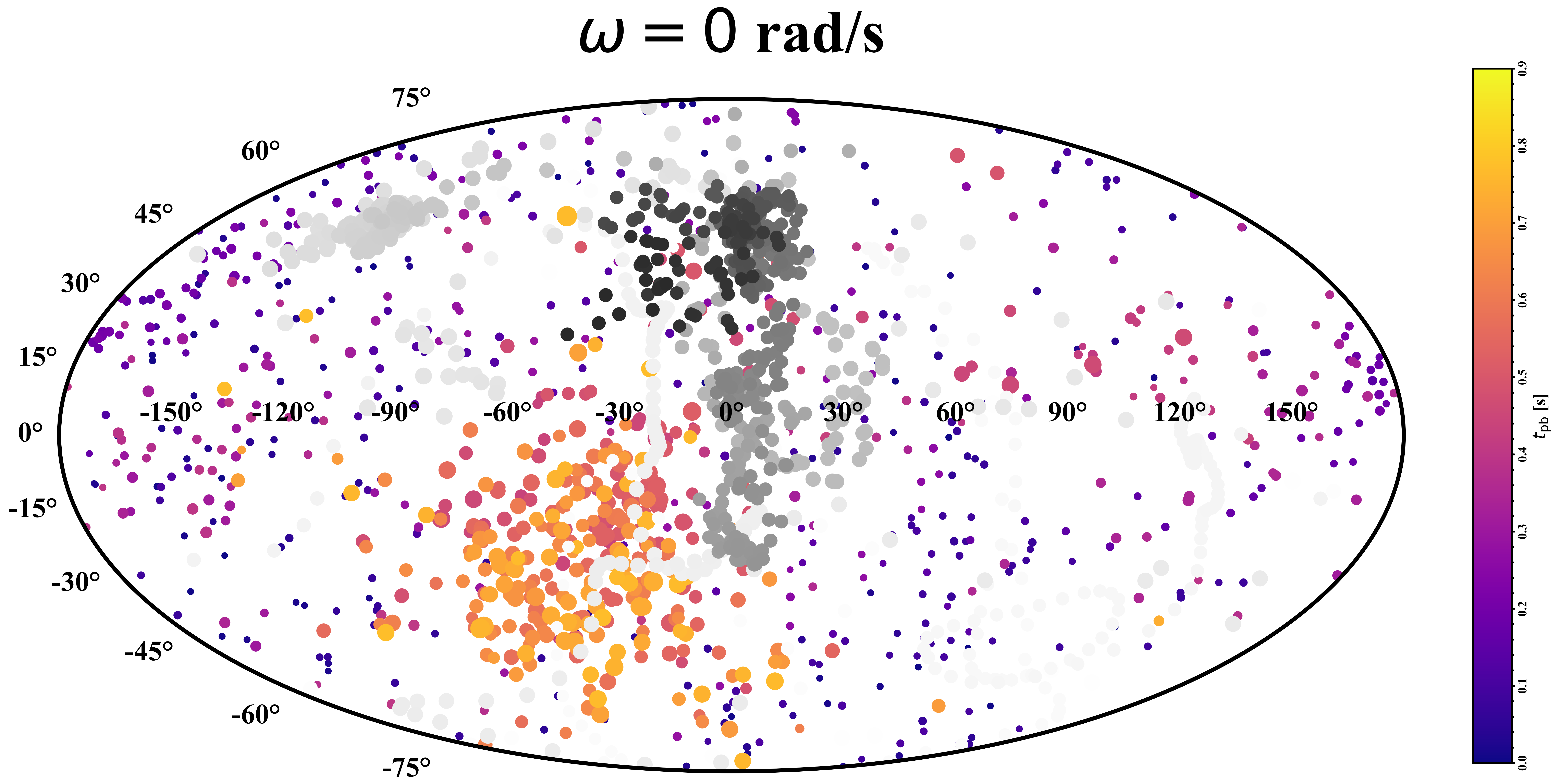
Standing Accretion Shock Instability (SASI)





SASI induced Rotation



Pan et al. (2021)

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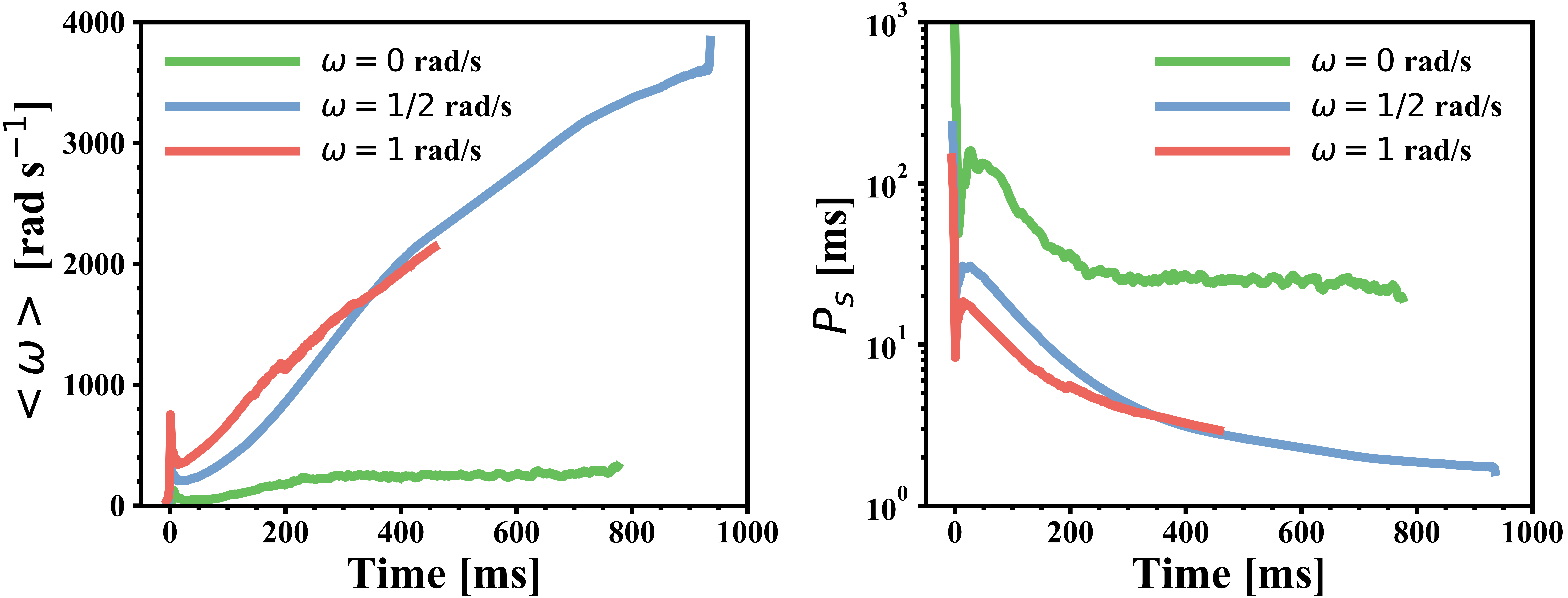
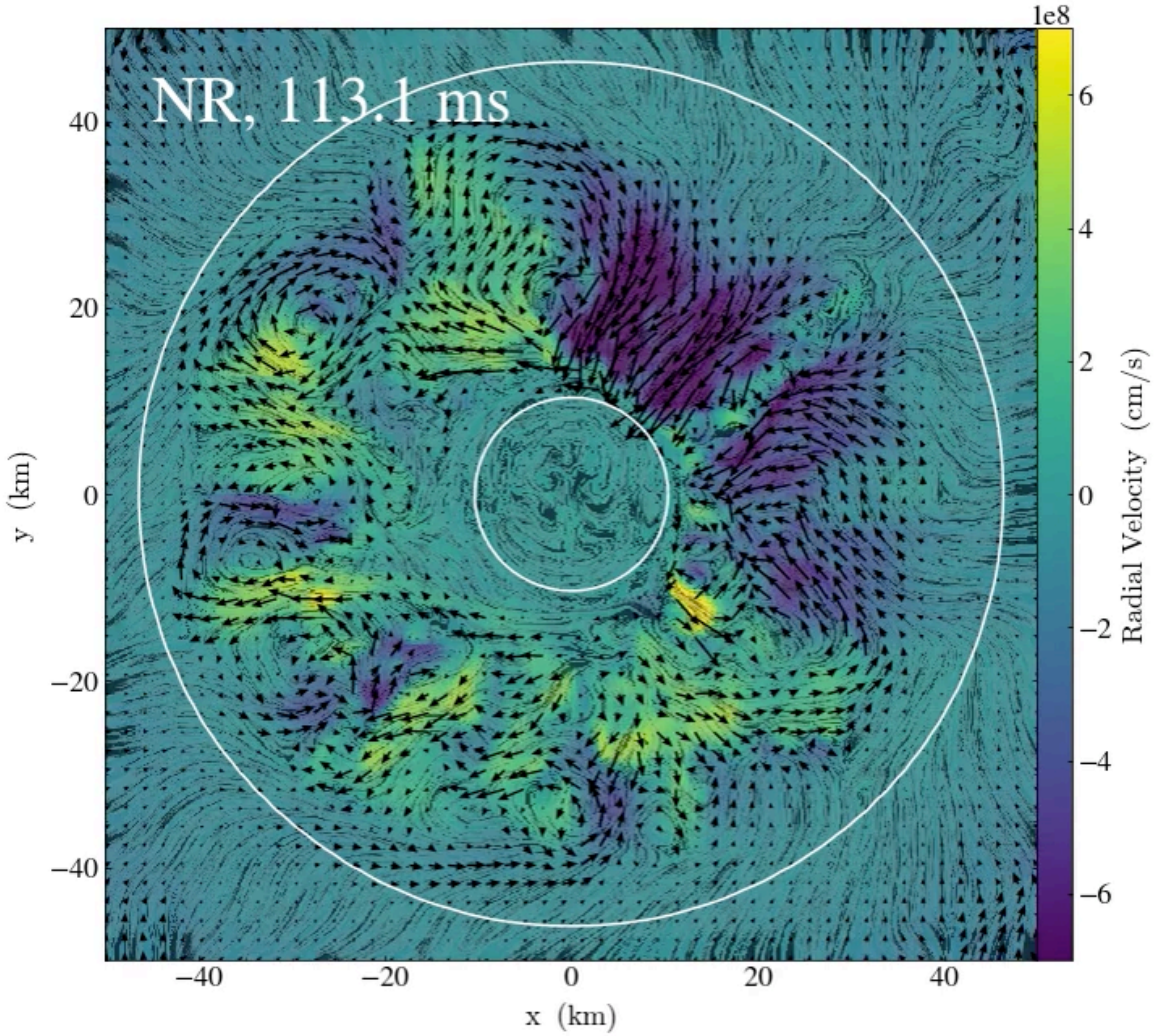
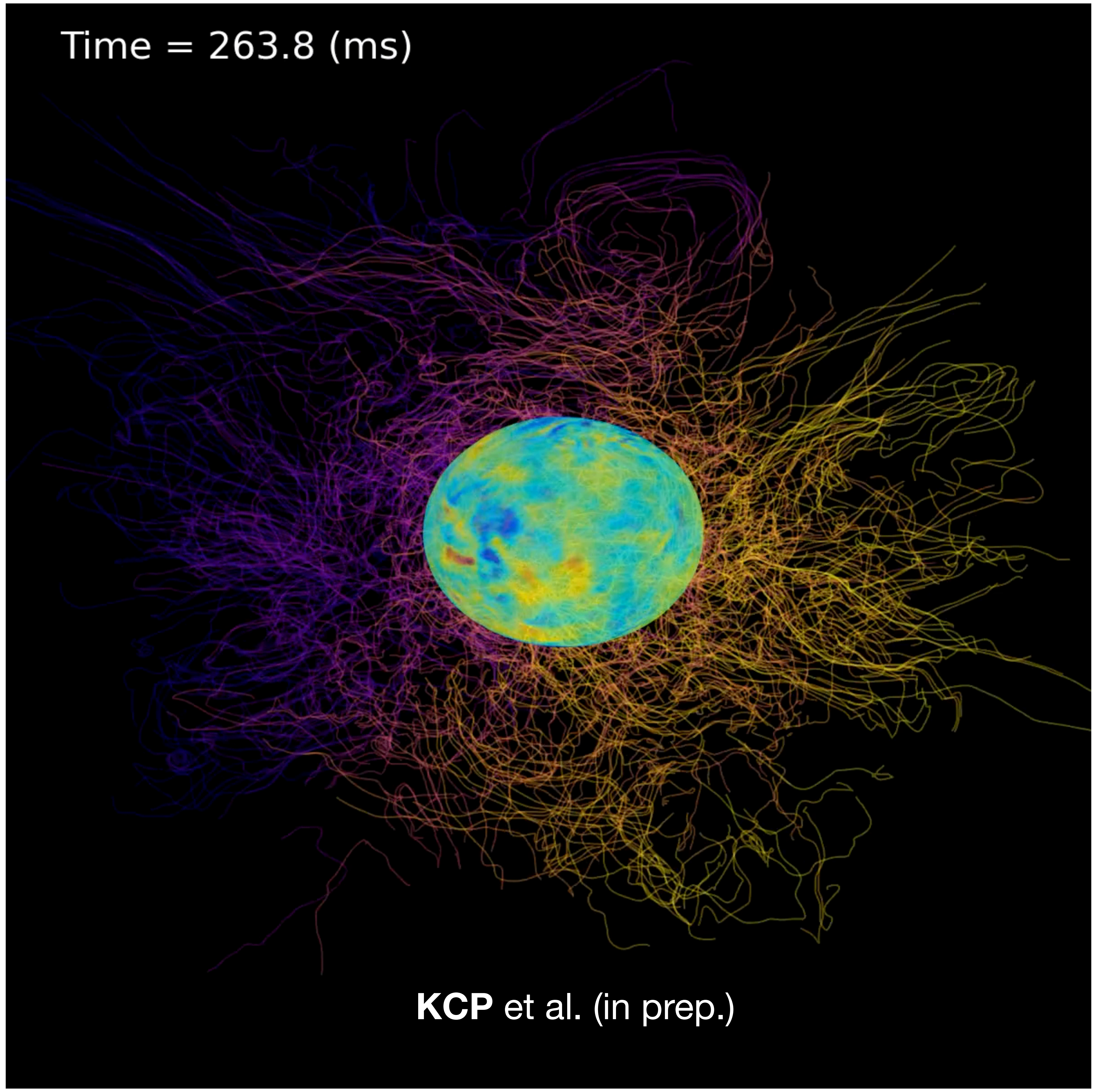


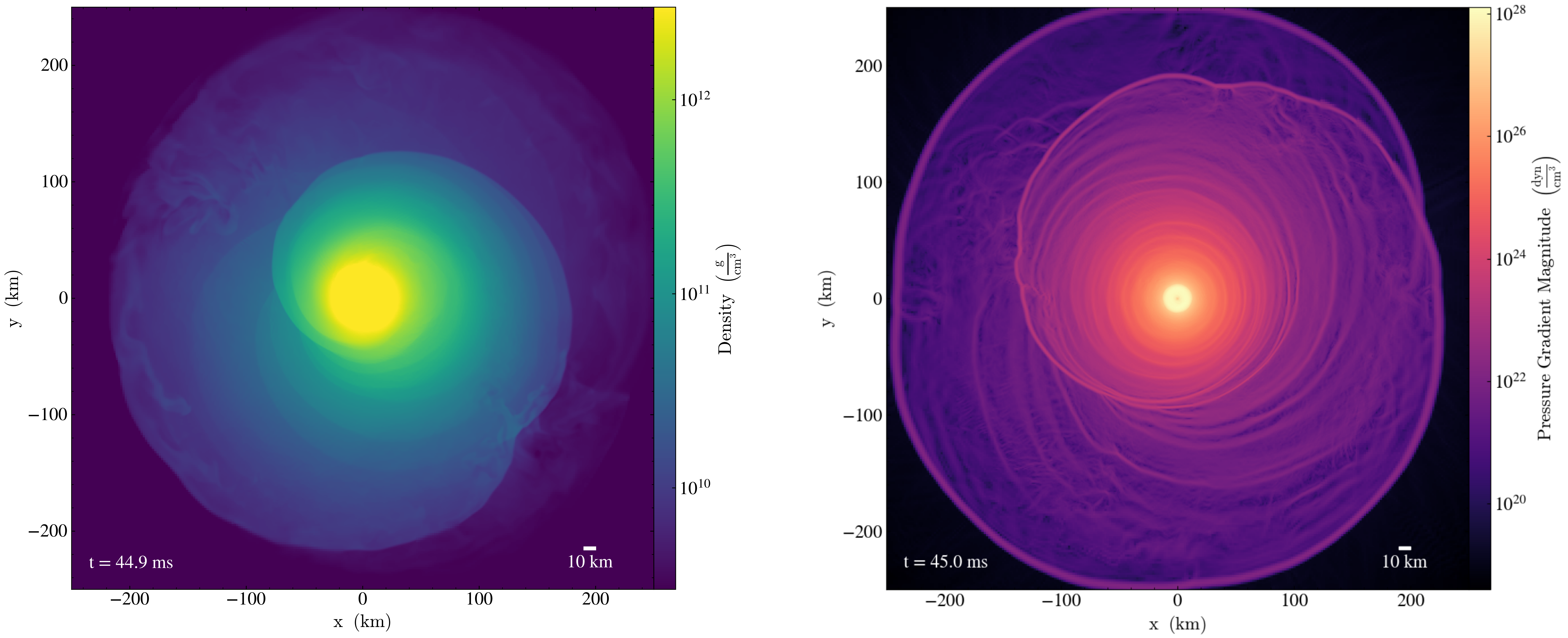
Pan et al. (2021)

Proto-Neutron Star Convection

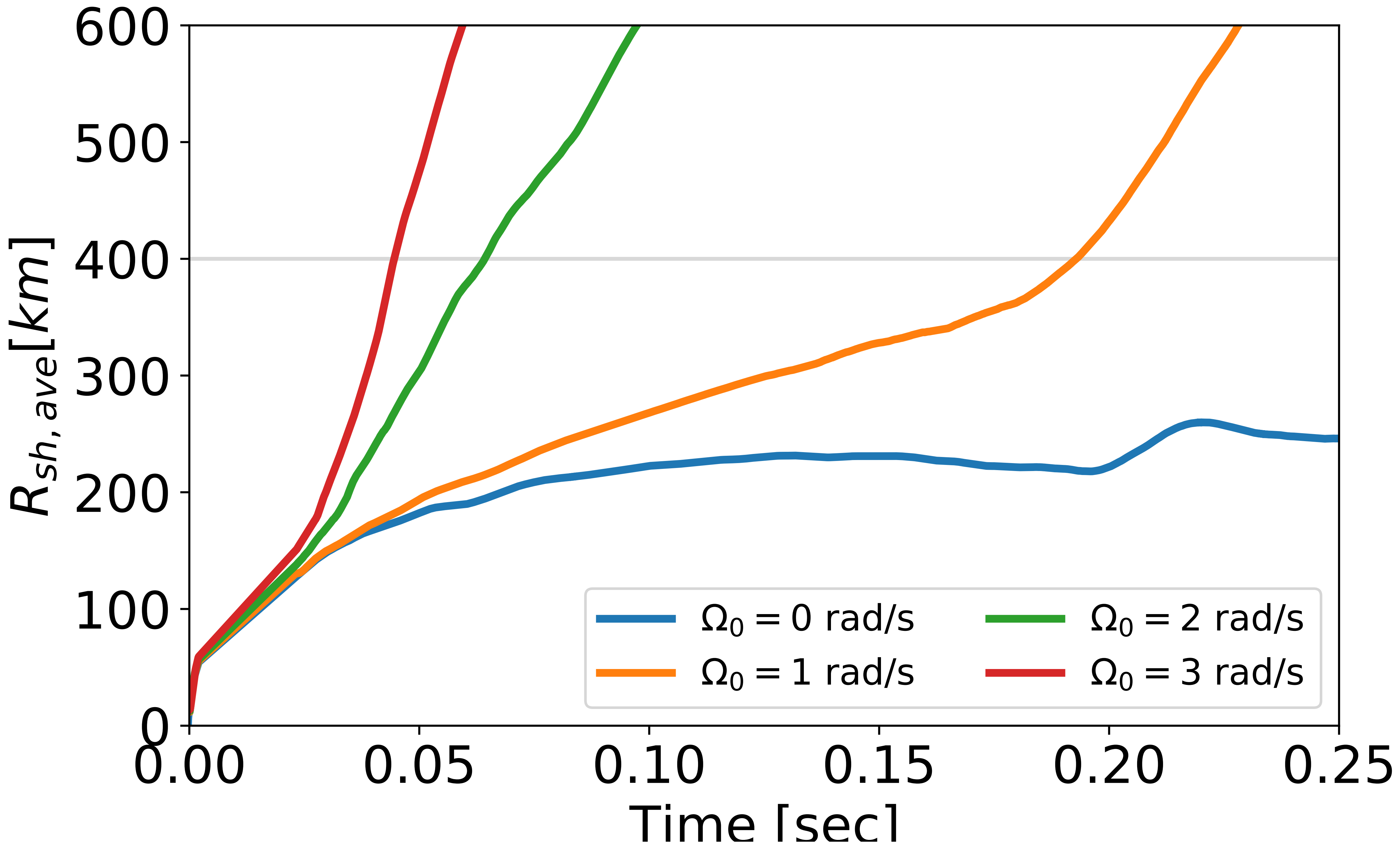


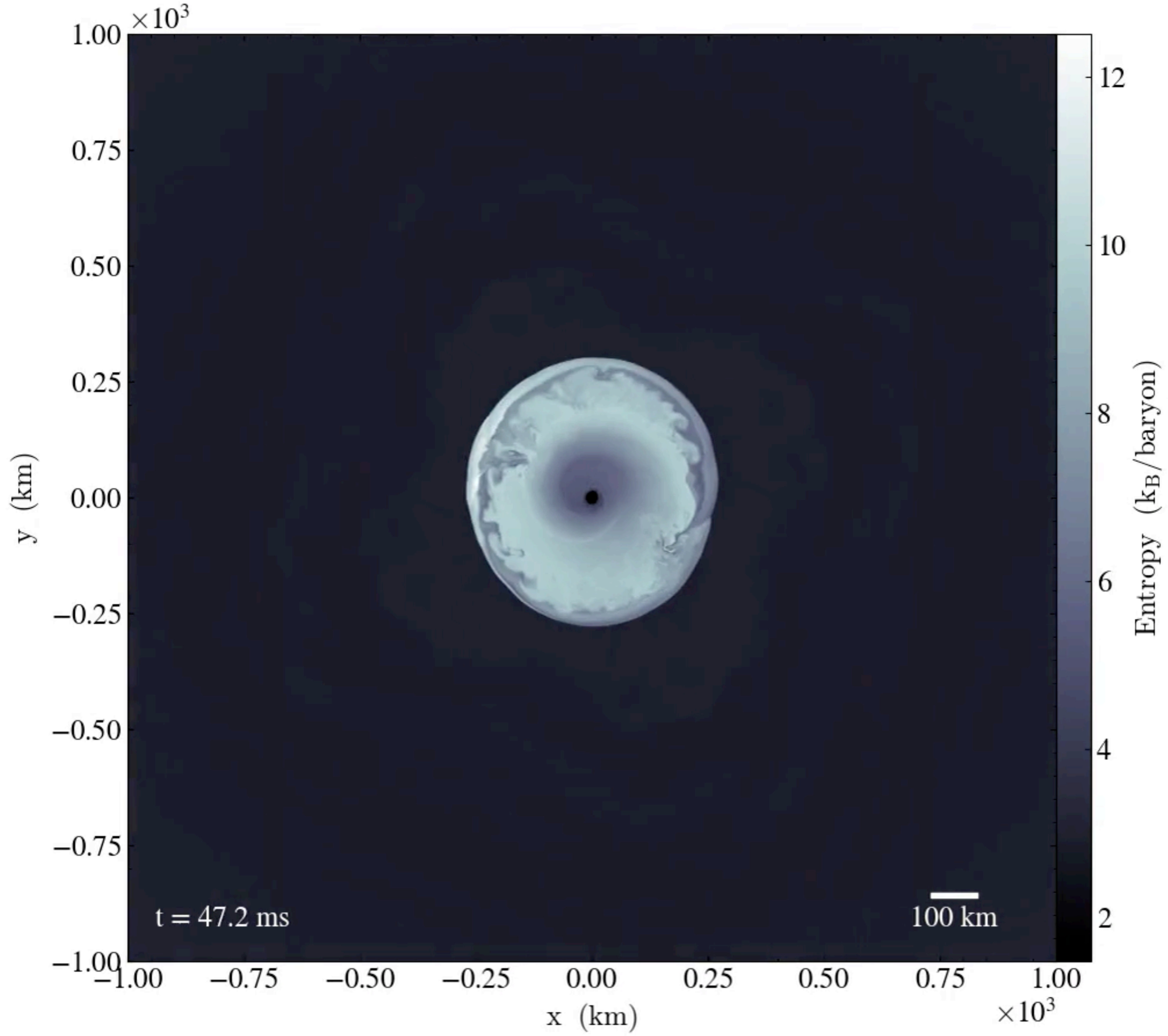


Rotational Effects



Rotational Effects





Lab Session

CCSN waveforms

- Open the Jupiter notebook “gw-odw-ccsn.ipynb” in https://github.com/KAGRA-TW-ML/2023-GW-Workshops-in-Taiwan
- Use either “Google Colab” or “Conda”