Exploring the core-collapse supernova engine and multi-messenger signals from high-resolution 3D simulations

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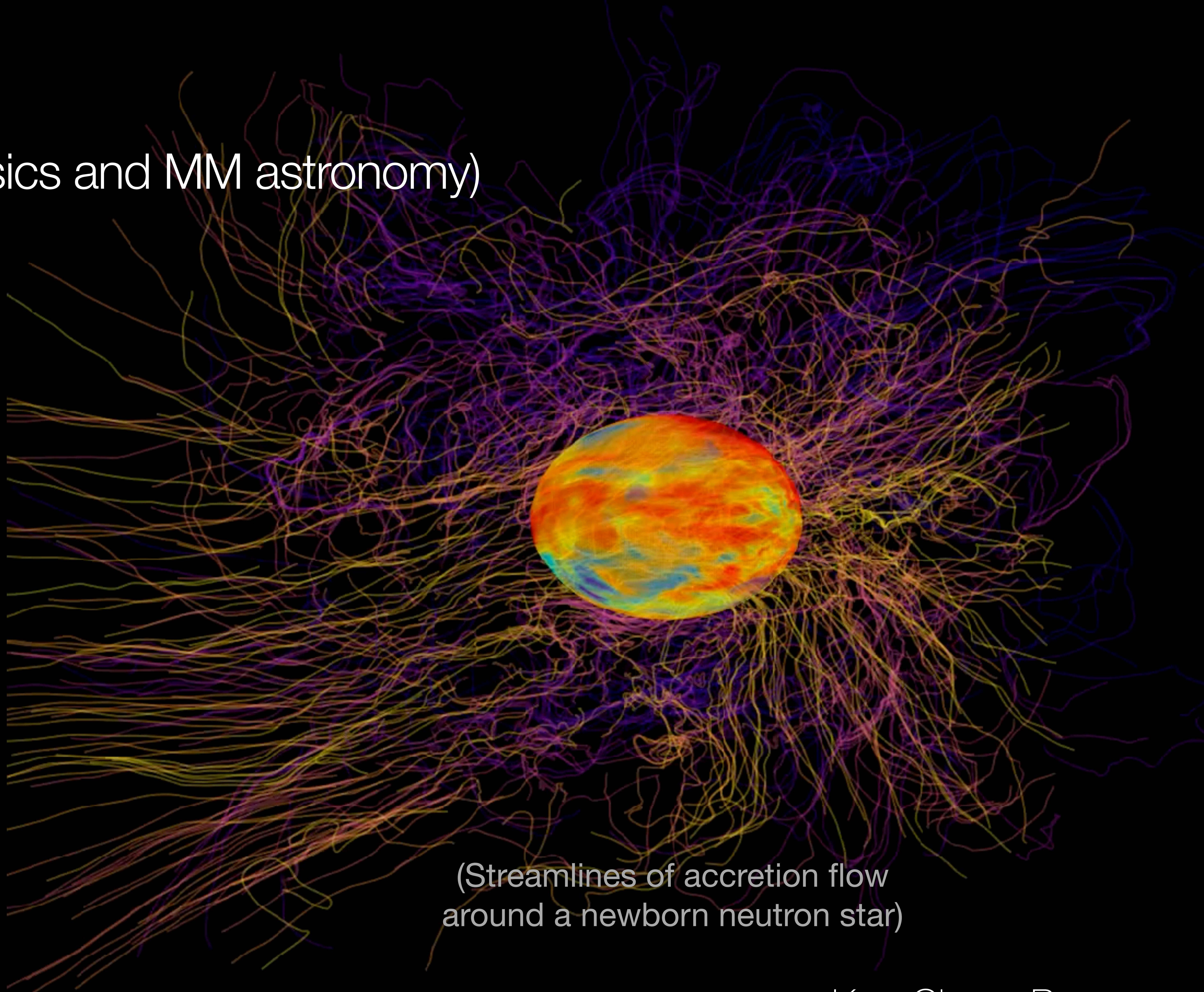
Outline

- Introduction (Supernova, GW astrophysics and MM astronomy)
- How to blow up a star (the SN Eegine)
- 3D supernova simulations
- Shock dynamics
- Neutron star / black hole formation
- Multimessenger signals
- Detectability of such events
- Summary and conclusions



(Streamlines of accretion flow around a newborn neutron star)

Core-collapse supernovae (SNe) are energetic stellar explosions

- Very luminous (foe); as bright as a galaxy
- birth places of neutron stars and stellar mass black holes
- Factory of heavy elements
- Enrich galactic chemical abundance
- Excellent multi-messenger sources

Image credit: NASA

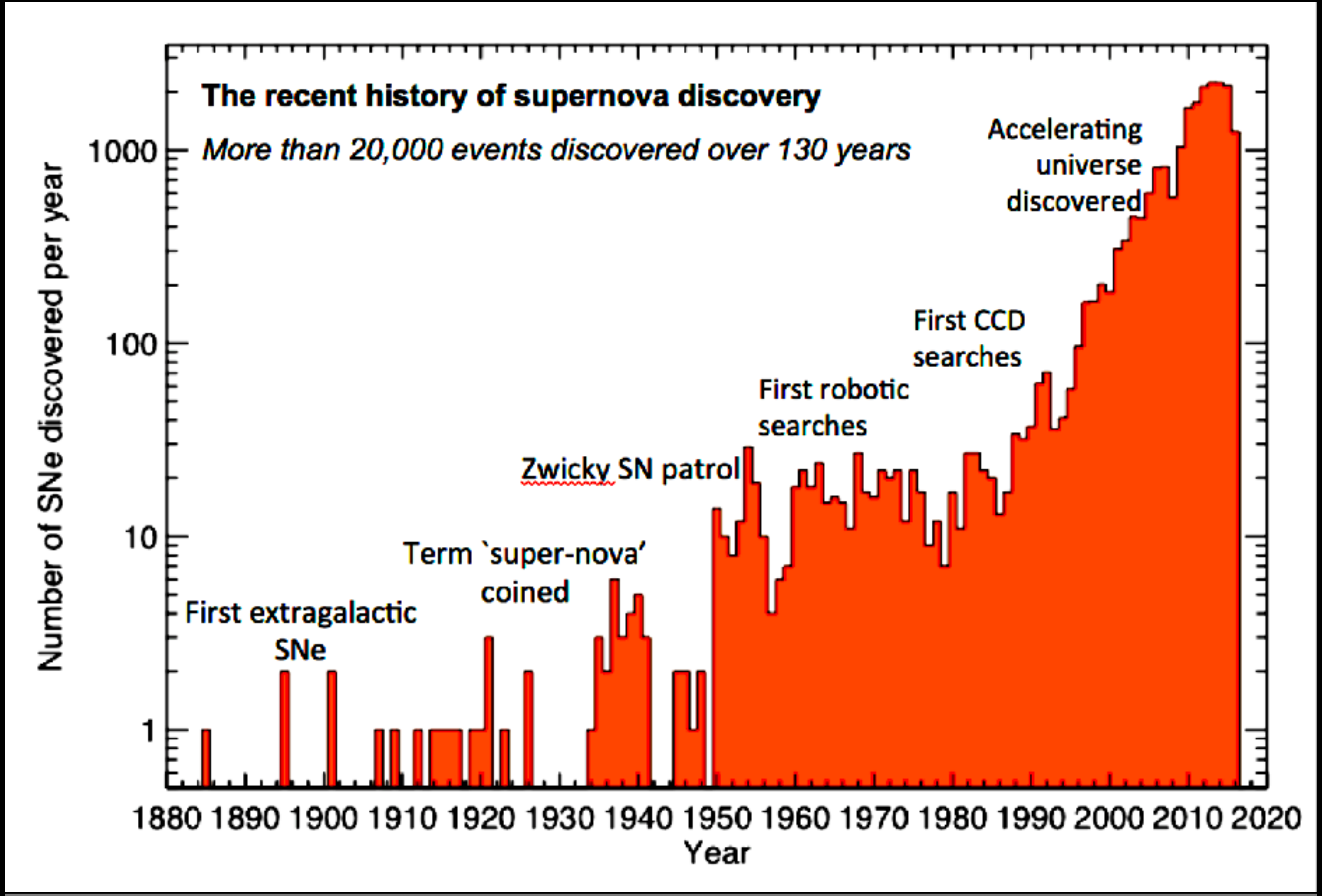
Image credit: ESO

Detect more than 1,000 SNe a year

Stritzinger & Moriya (2018)

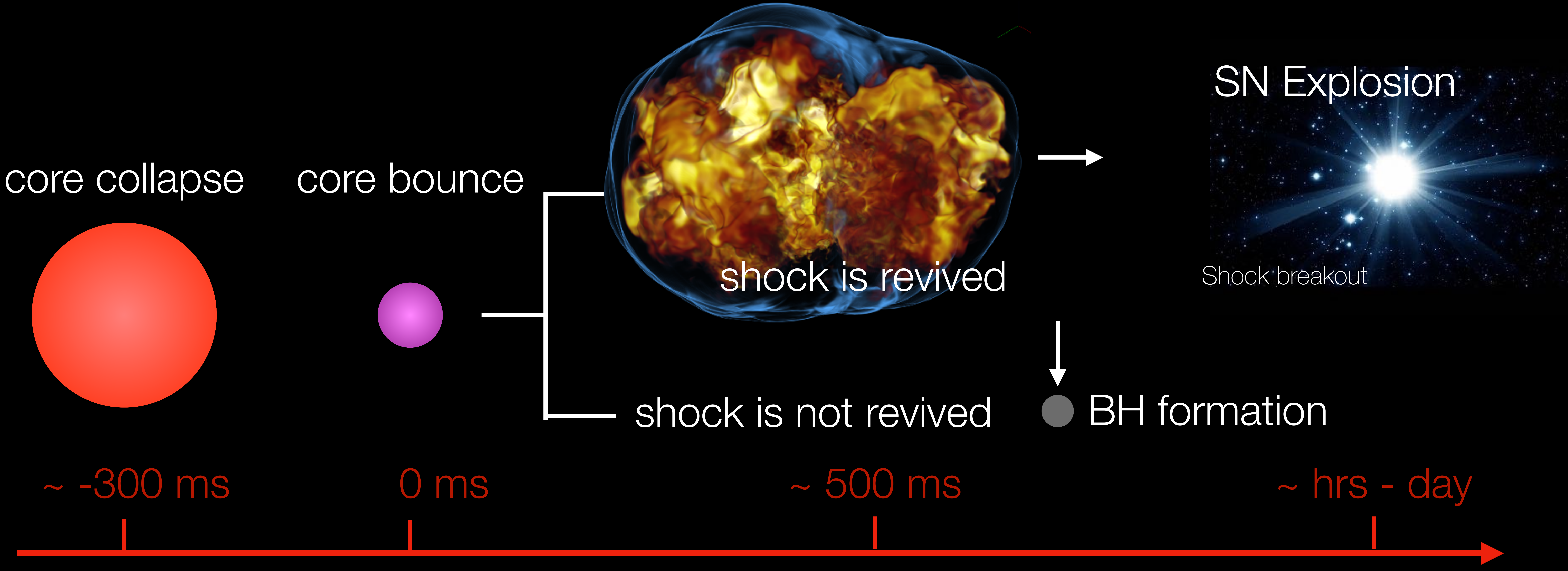
Supernova Fact

- ~ 1 SN / sec in the Universe
- > 1 SN / day discover
- ~ 1 SN / 30 -50 years in the Milky Way
- Era of multi-messenger astrophysics
- Data-driven science (Big data / ML / AI)



Stellar evolution of massive stars

Multi-messenger signals from core-collapse supernovae



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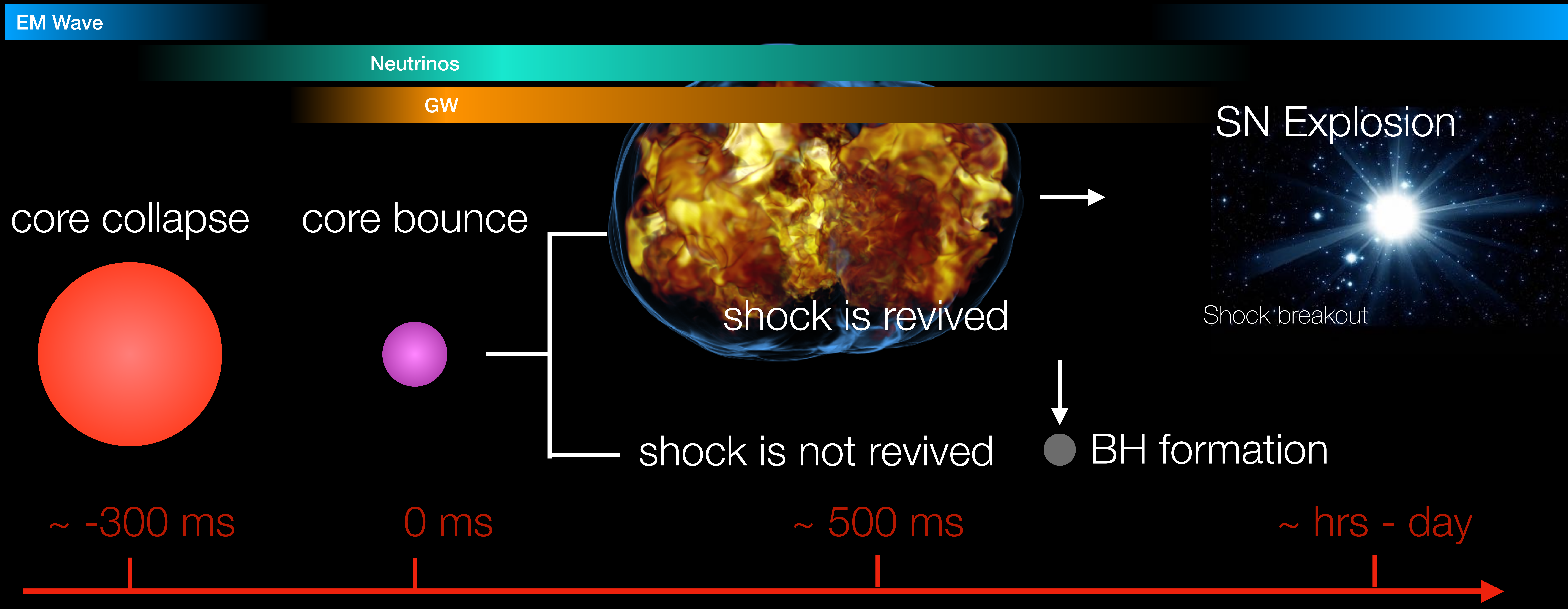
Multi-messenger signals from core-collapse supernovae



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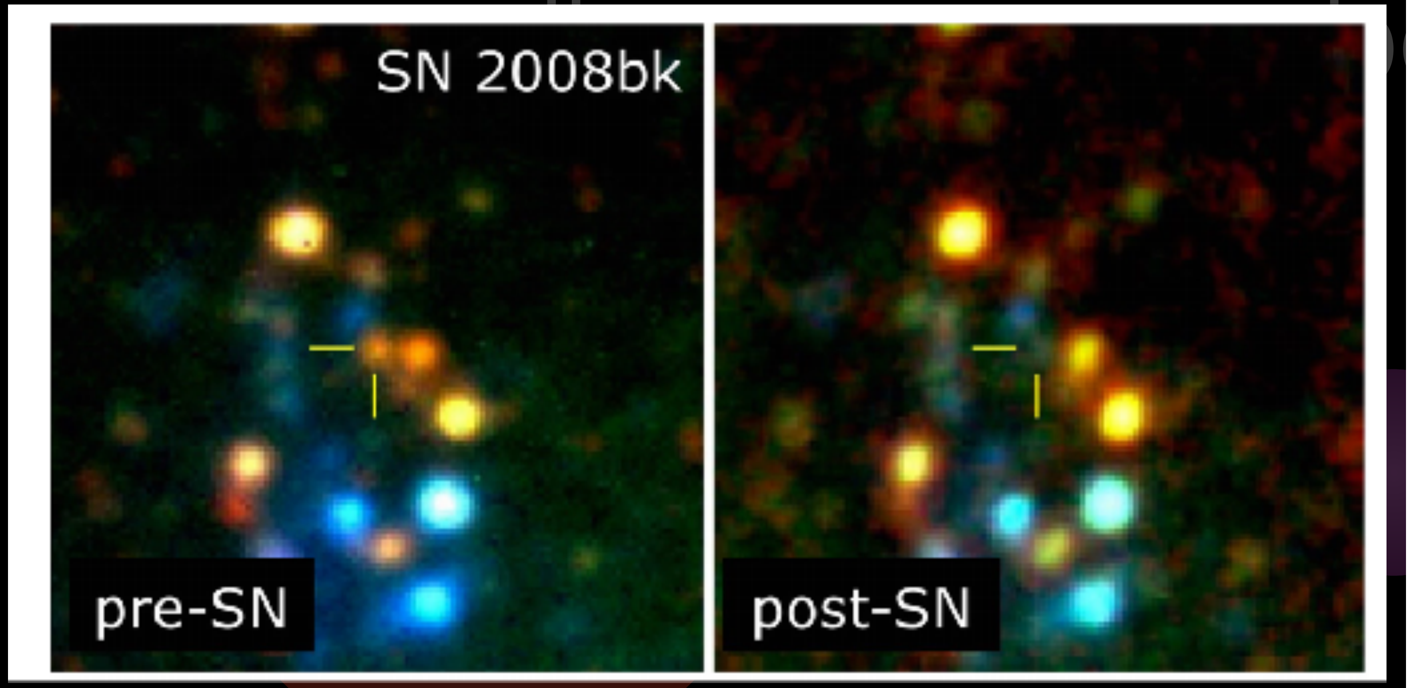
Multi-messenger signals from core-collapse supernovae

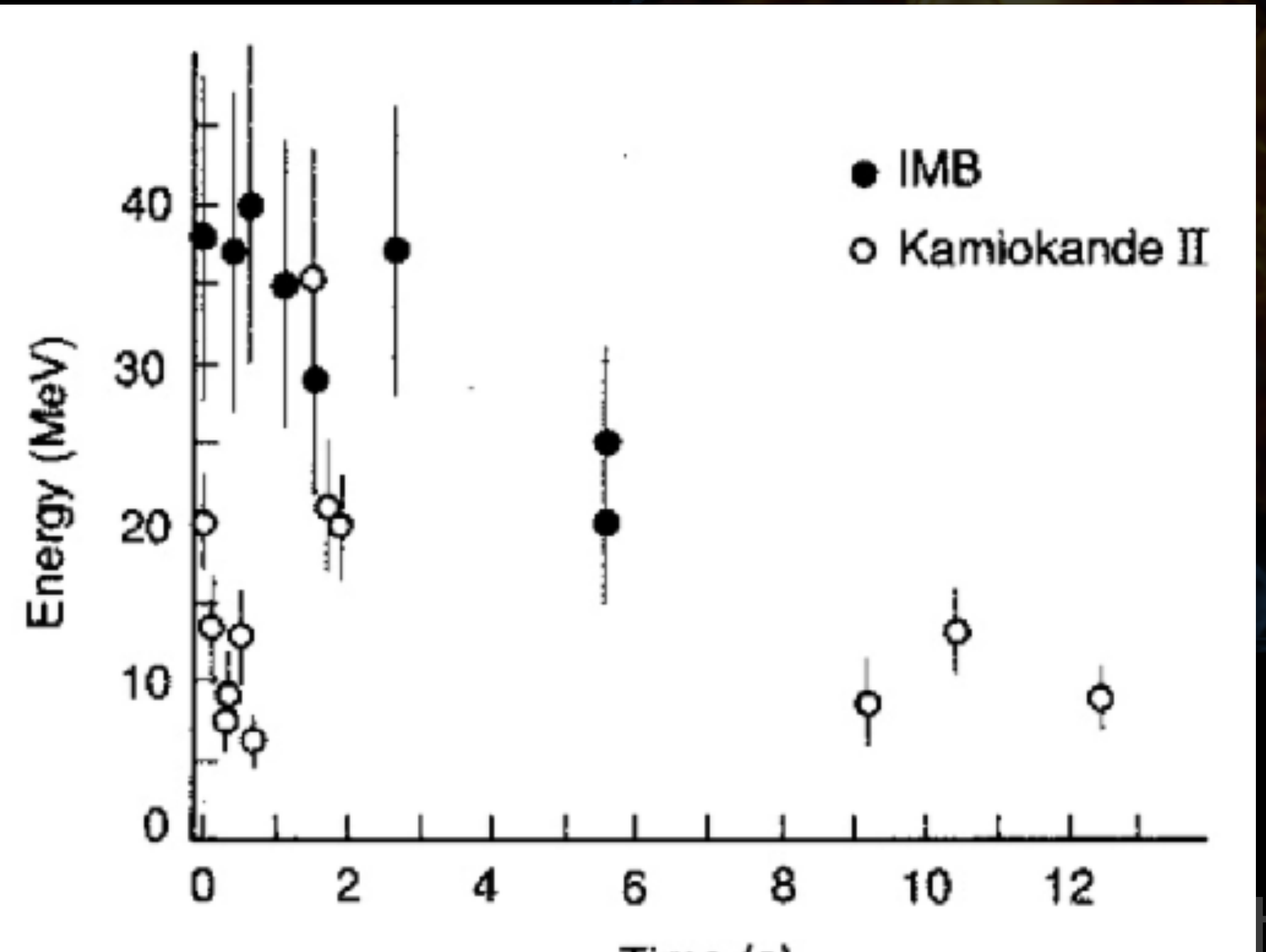
EM Wave

Neutrinos

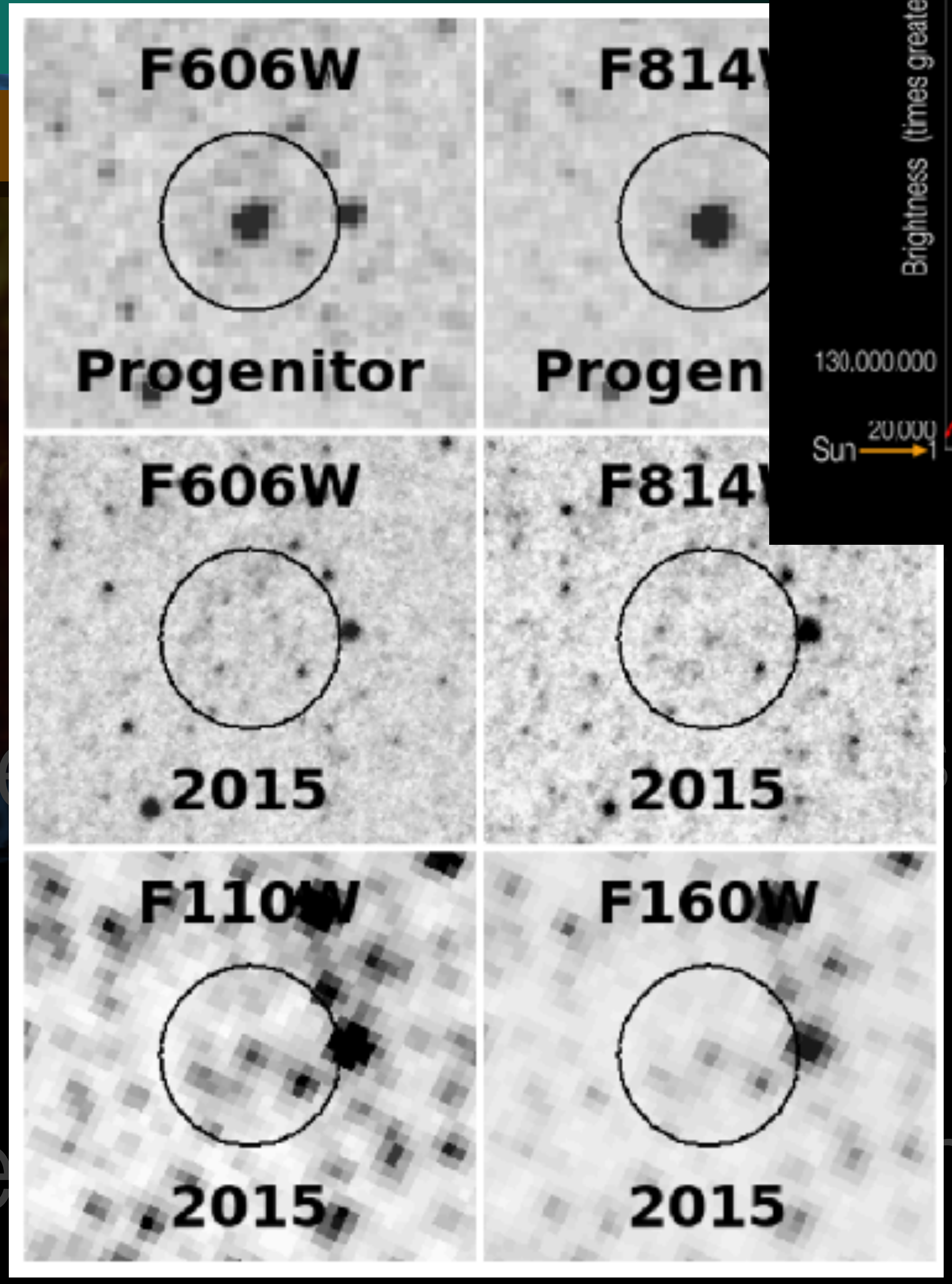
GW

SN 2008bk, red supergiant progenitor (Mattila et al. 2013)

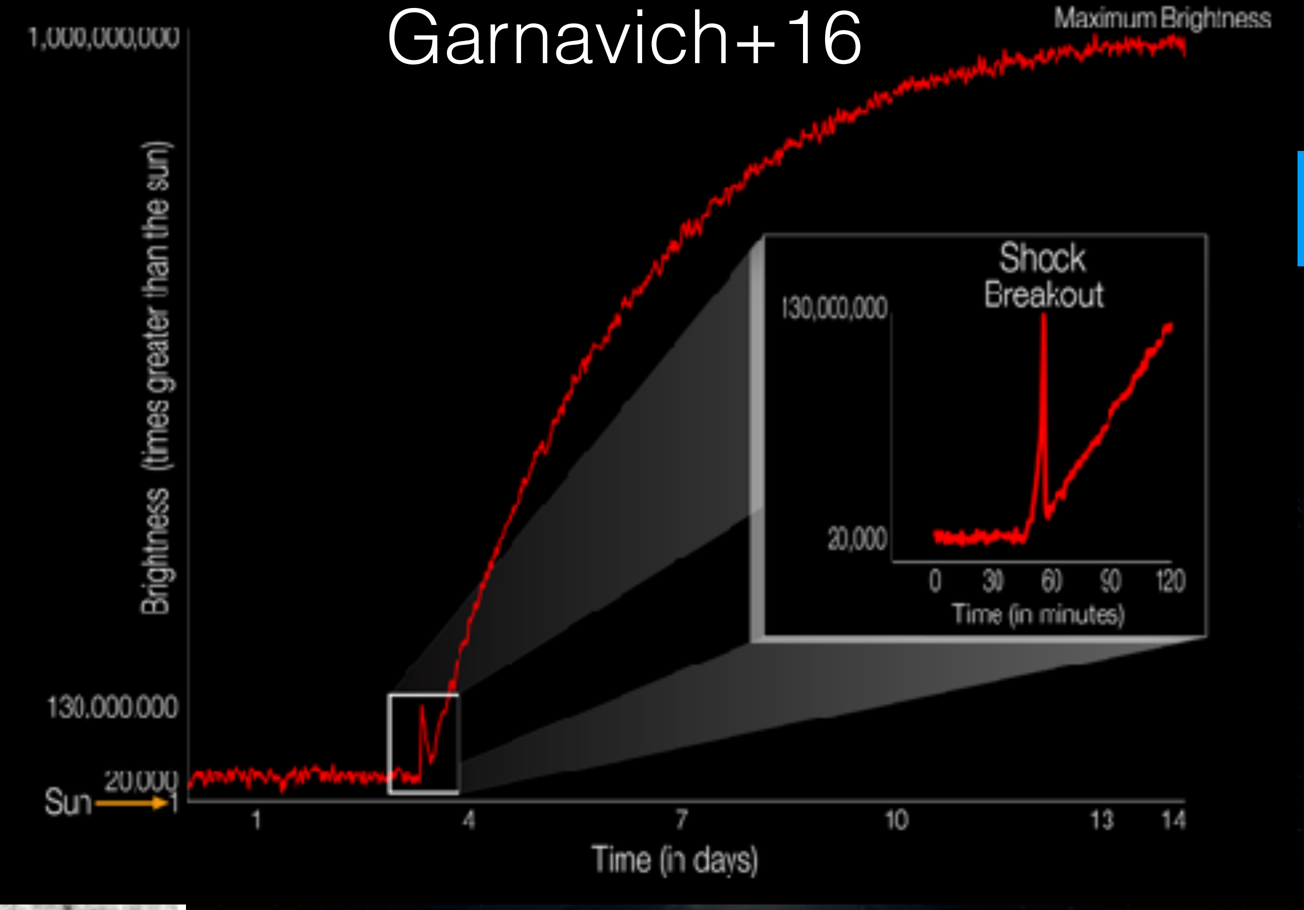




Fargion+12



Adams et al. 2016, arXiv: 1609.01283



Garnavich+16

~ -300 ms

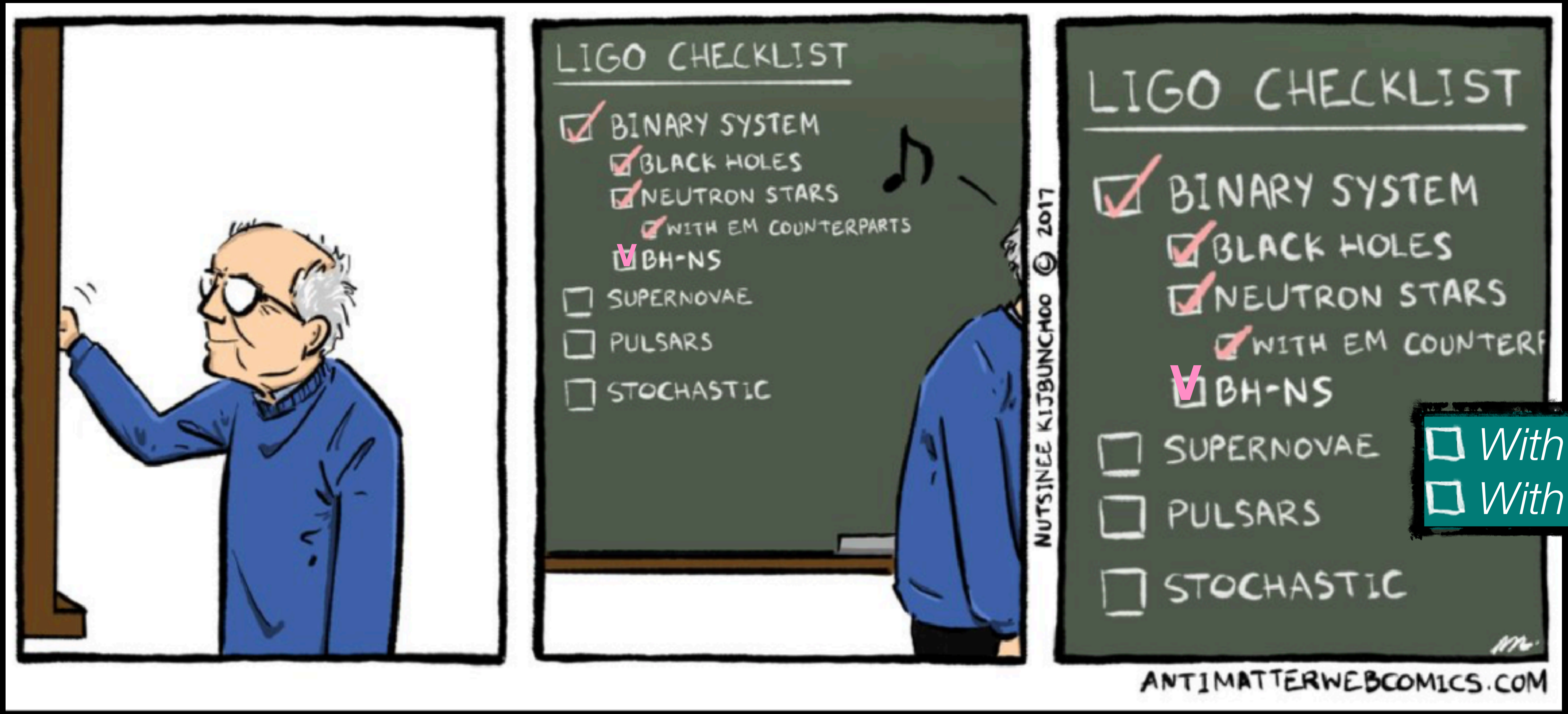
0 ms

~ 500 ms

~ hrs - day

We are expecting to see GW emissions from core-collapse supernovae as well

- The next milestone of GW astrophysics
- The most promising sources for multi-messenger sources including EM, neutrinos, and GW



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

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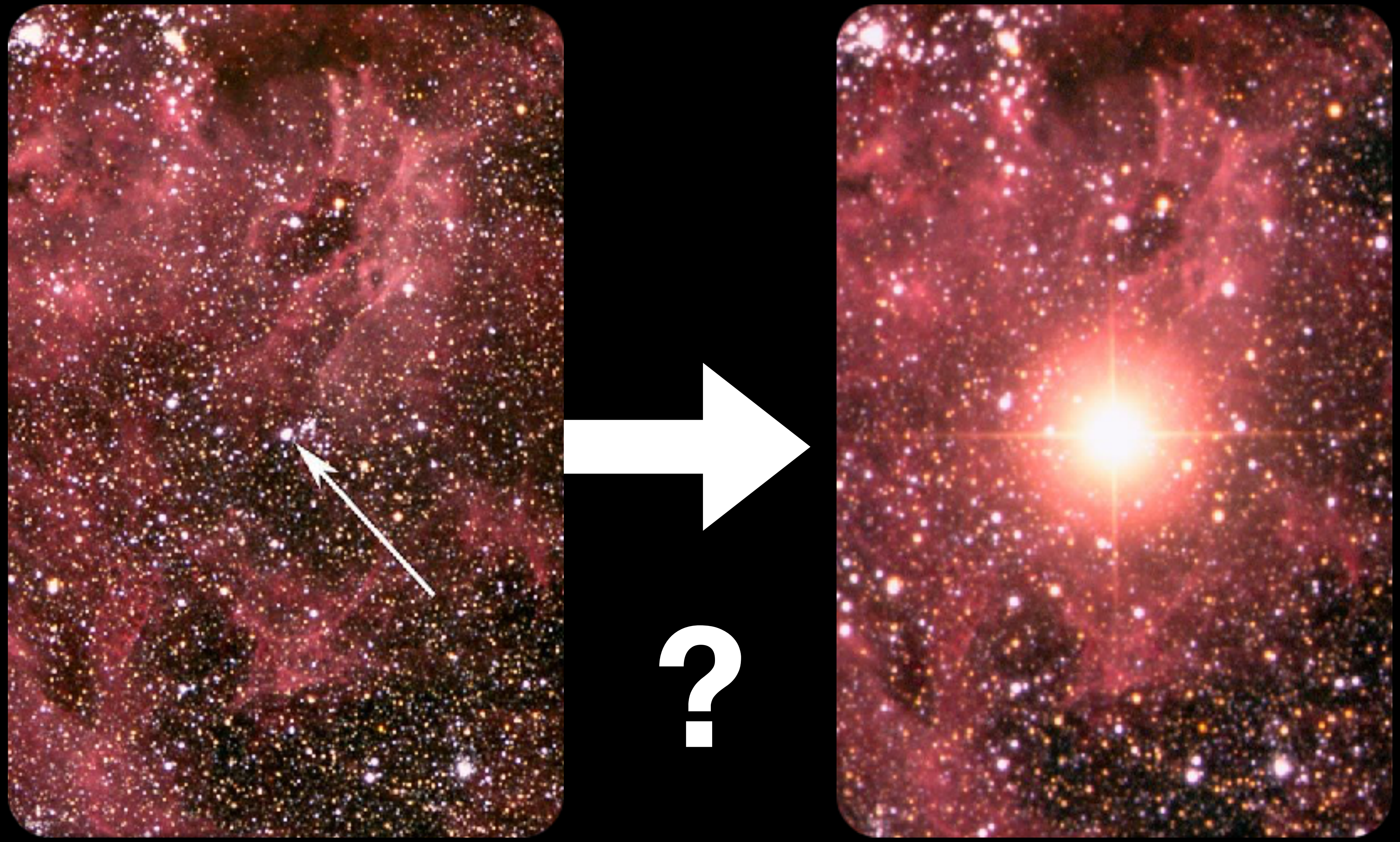
Motivation: Several fundamental questions

How to blow up a star?

- We do see CCSN progenitors (EM wave)
- We see many CCSN explosions (EM wave)
- We do see neutrinos from SN1987A
- The SN engine remains unclear
- SN problem: the shock stalled
- Neutrino is a key
- Neutrino-driven mechanism (Colgate & White 1966)

Image credit: Anglo-Australian Observatory



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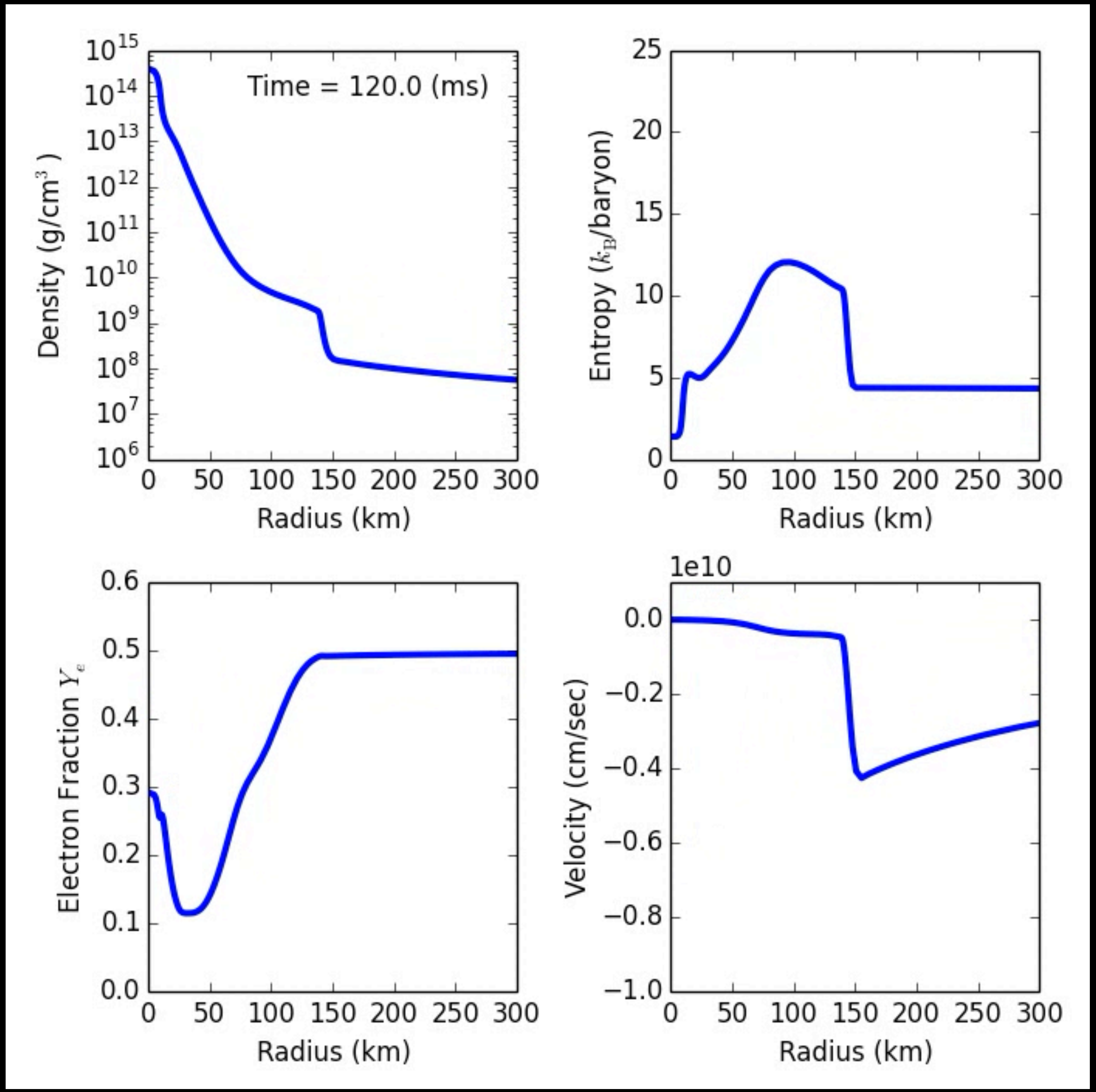
The Supernova Problem

- The bounce shock stalled (at around 150km)
- Neutrino-driven mechanism is the main-stream engine but …
- Neutrino-driven mechanism still failed in spherically symmetry simulations (except a few less massive cases)
- Key: the heating efficiency is not enough to power the explosion



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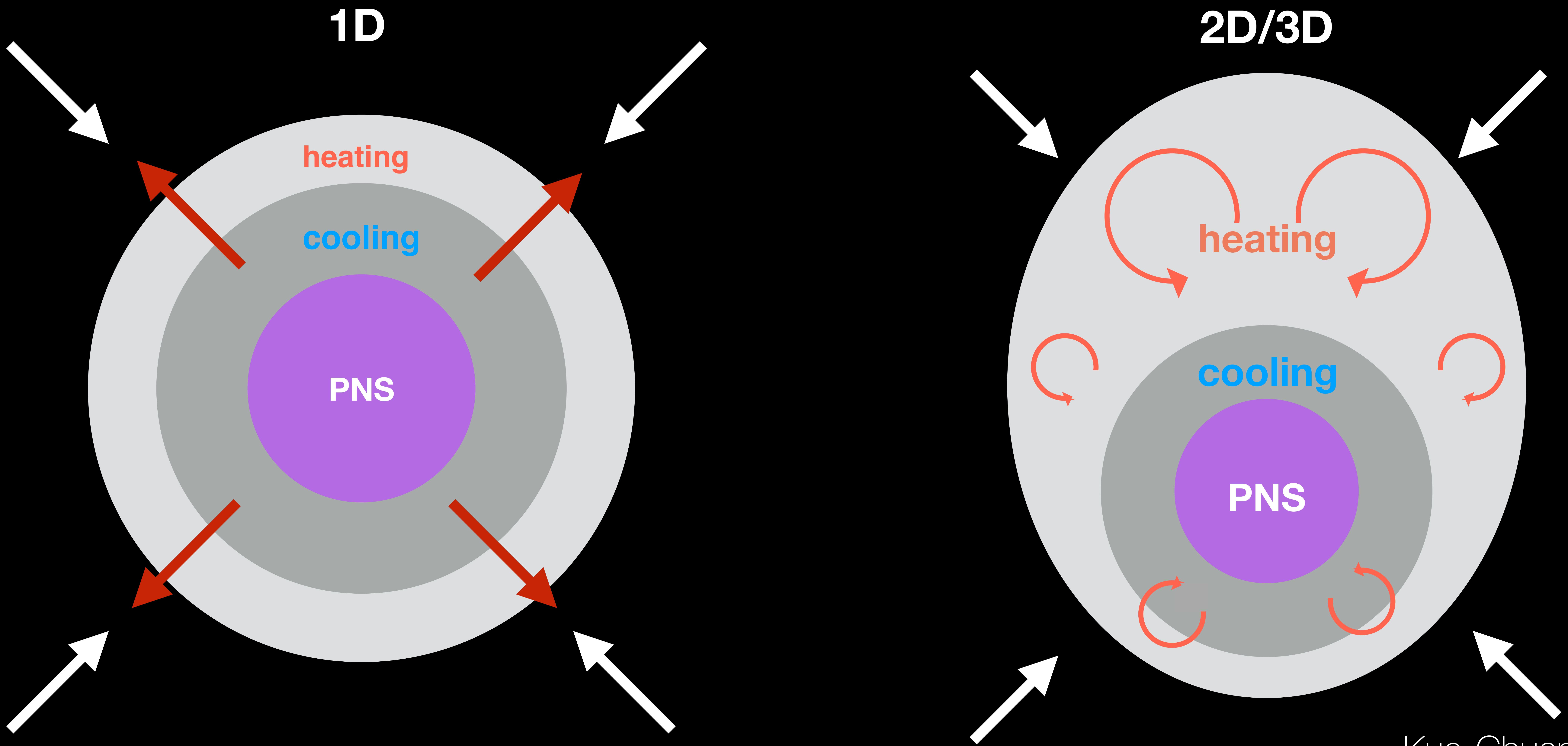
Multi-dimensional effects could enhance the heating efficiency



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Modeling CCSN is numerically challenging

- (Magneto-) hydrodynamics —> (Plasma) fluid dynamics
- General Relativity —> Gravity
- Nuclear and Neutrino physics —> Nuclear EoS, nuclear reactions, & neutrino interactions
- Boltzmann Transport Theory —> Solve multi-D multi-flavor neutrino transport
- Additional complexity —> Multi-D effects; stellar rotation; fluid/MHD instabilities; turbulence; wide density and temperature ranges; wide neutrino optical depth; require high accuracy

The computational explosive astrophysics group in IoA, NTHU

- FLASH Code
- IDSA for neutrino transport (Pan et al. 2016, 2019)
- Effective general relativity (Pan et al. 2017, 2018, 2021)
- Nuclear EoS from stellar collapse.org
- GPU acceleration (Pan et al. 2021)
- Code comparison studies (Pan et al. 2019, Cabezon et al. 2018)
- GW emission modules (Pan et al. 2018, 2021)
- State-of-the-art resolutions (using Taiwania 3)
- … and more …

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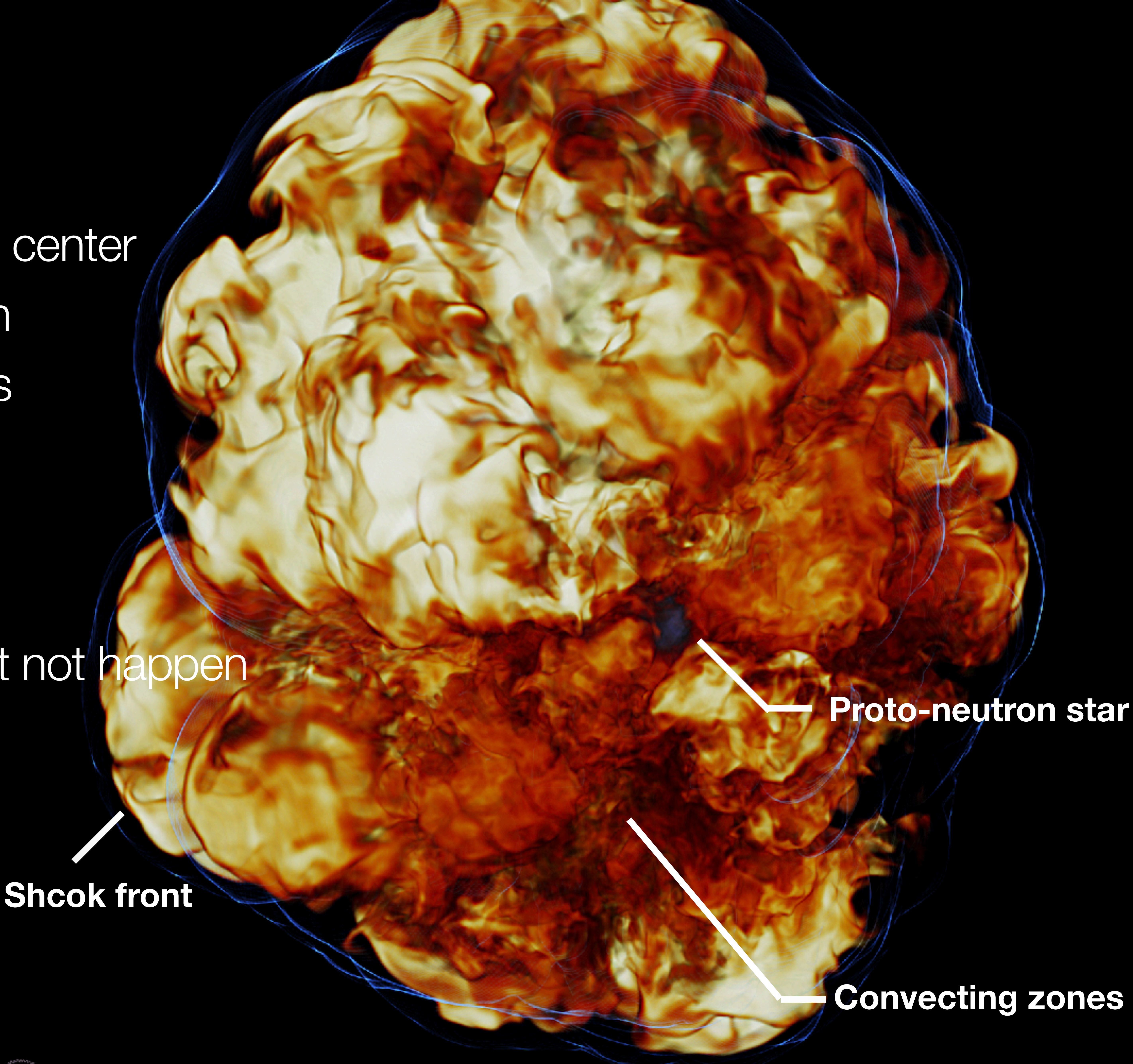
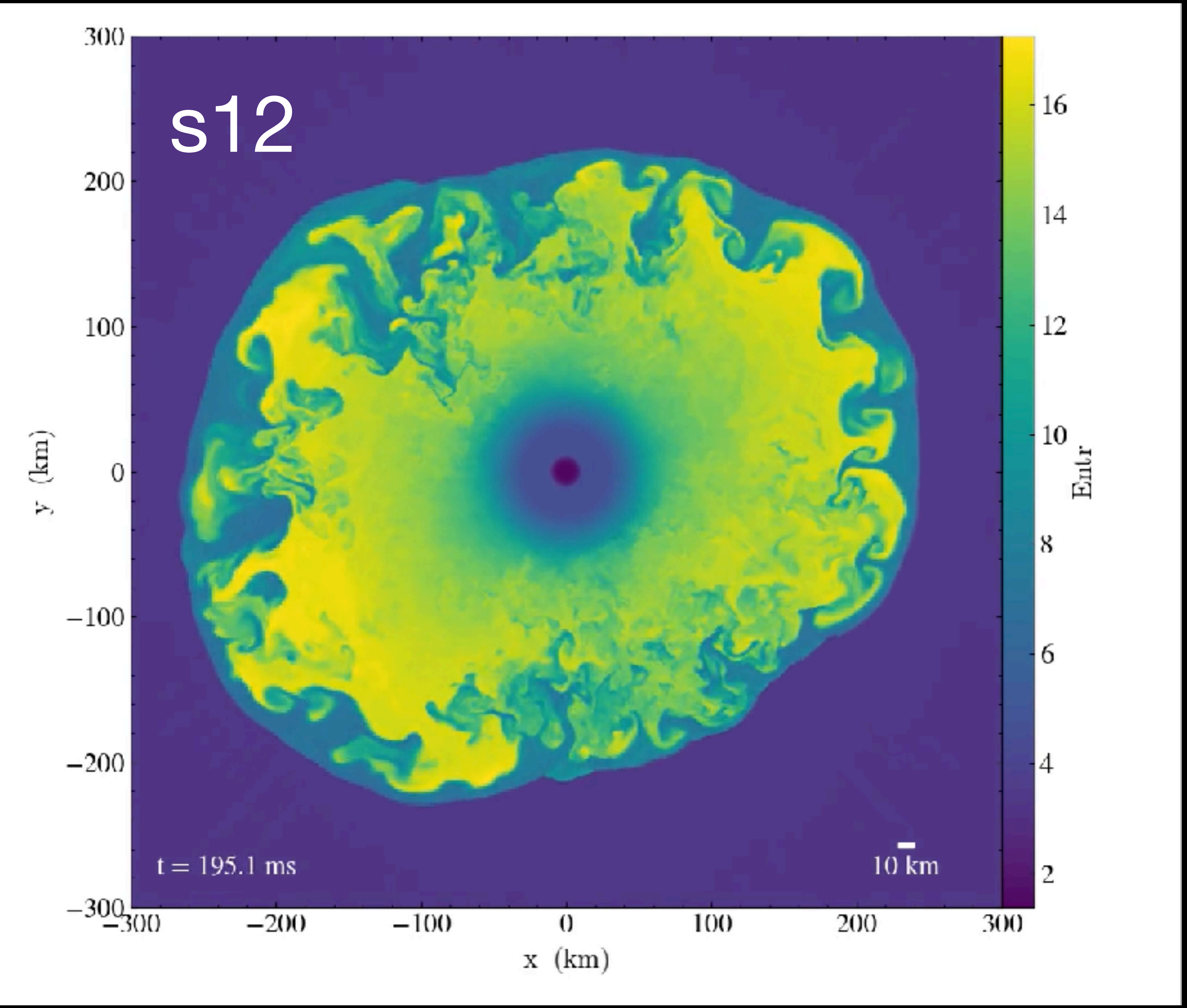
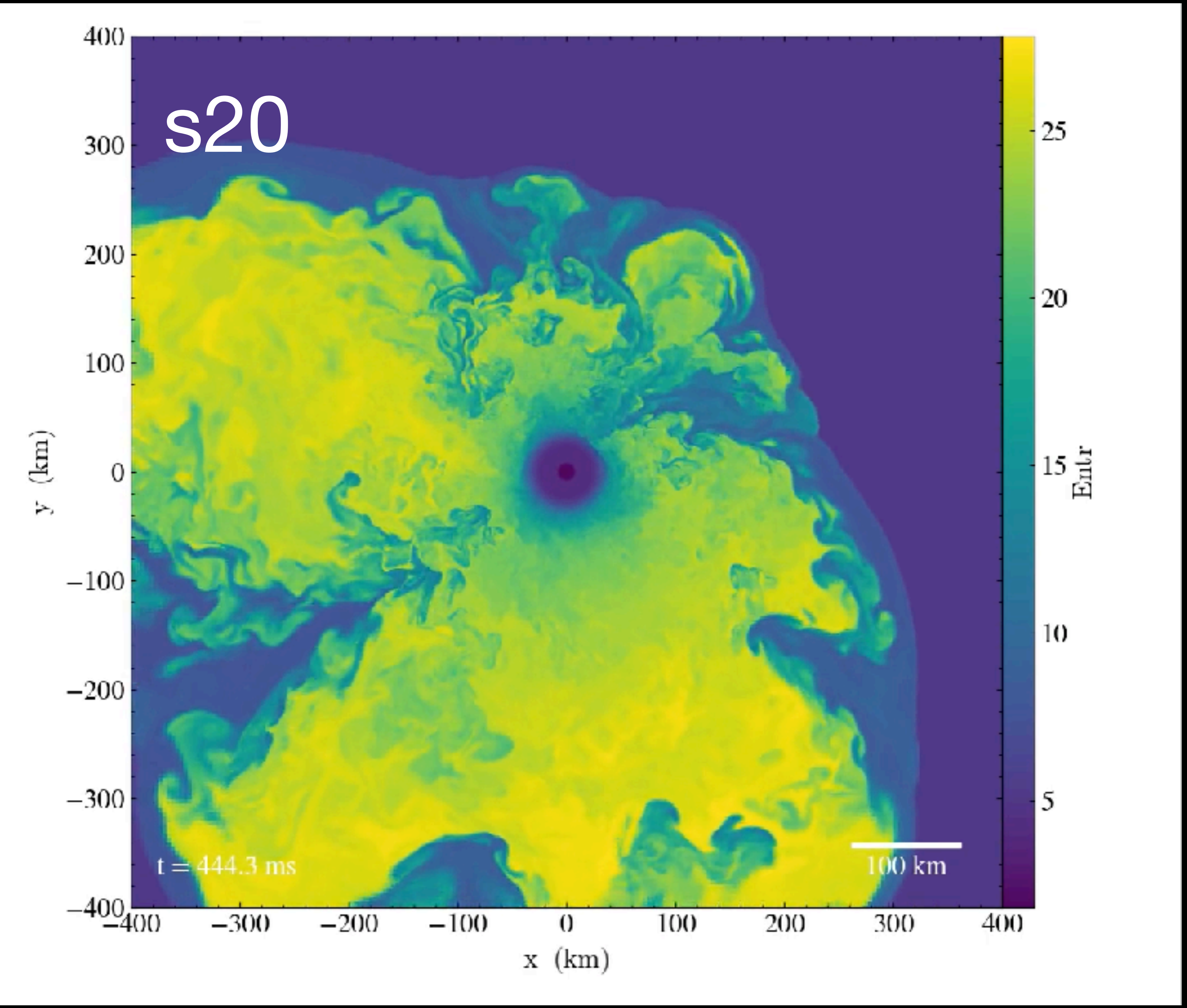
Simulation overview

- A proto-neutron star (PNS) 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



CCSN Simulations (entropy slices on the equatorial plane)





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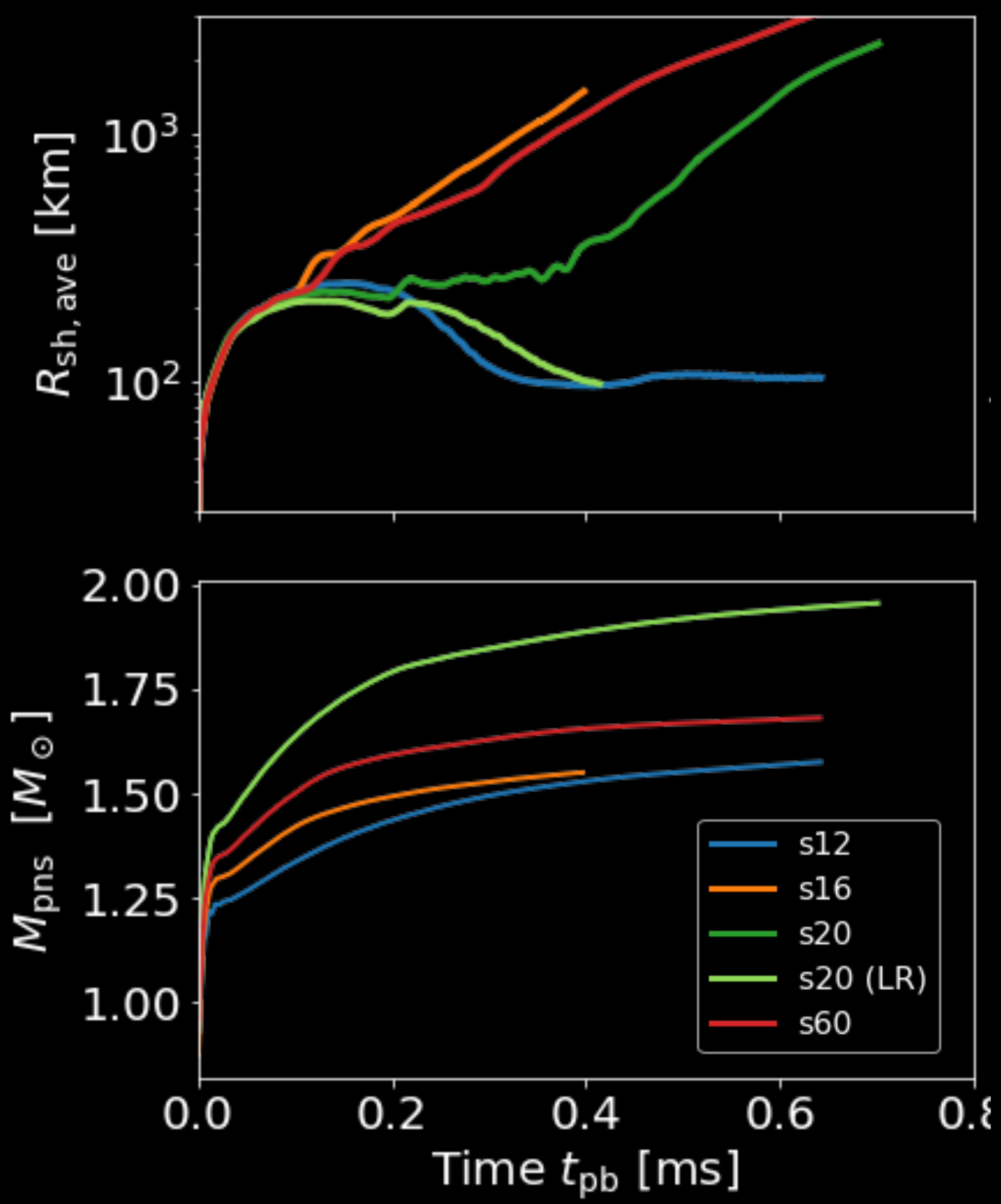
Supernova Shock dynamics

- (Upper) Shock radius evolution
- (Lower) Porto-neutron star mass evolution
- s16, s20, and s60 explode
- The low resolution case (s20 LR) failed to explode, but the high resolution case exploded
- PNS mass keep increasing even in exploded cases



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Supernova Shock dynamics (conti.)

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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)
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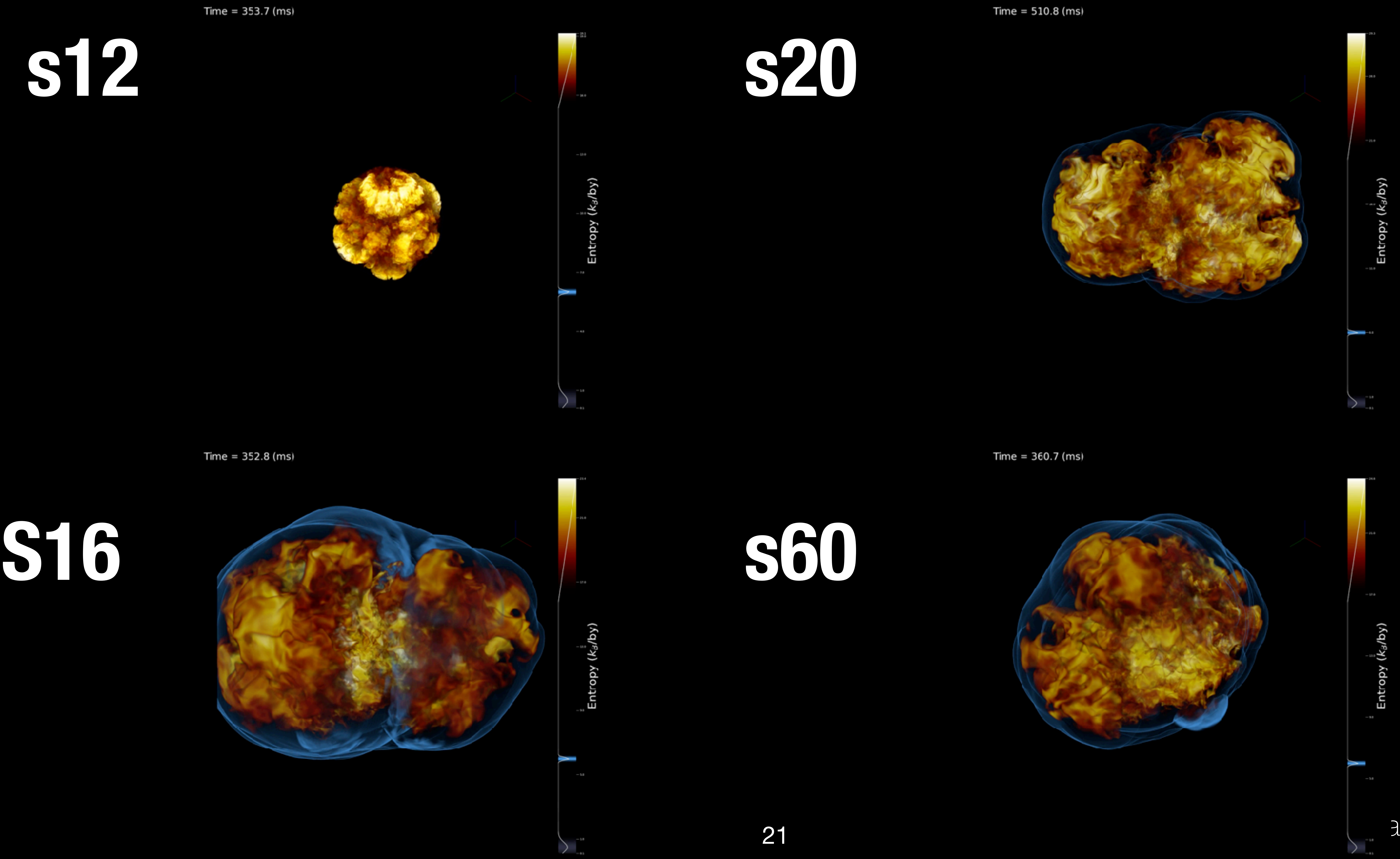
剪輯/ 字幕：清華科技藝術中心 曾鈺雯



Time = 353.7 (ms)
s12
Entropy (k_B/by)
Time = 510.8 (ms)
s20
Entropy (k_B/by)
Time = 352.8 (ms)
S16
Entropy (k_B/by)
Time = 360.7 (ms)
s60
Entropy (k_B/by)

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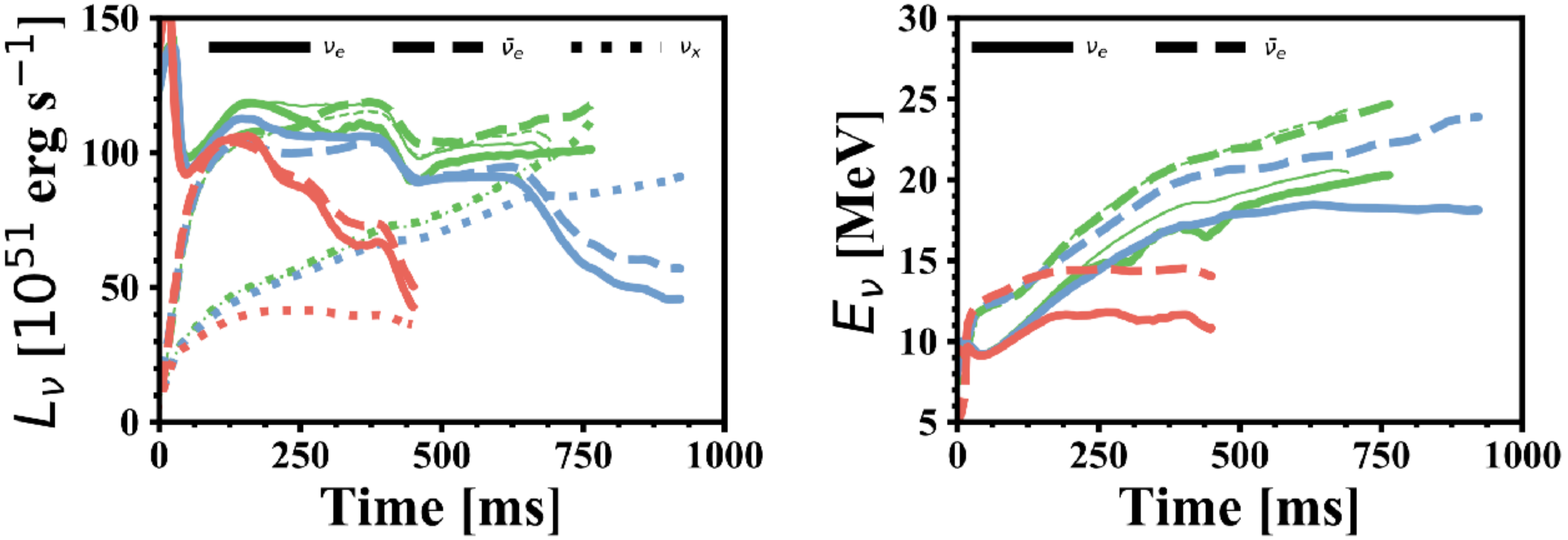
Neutrino Signals



$$R \sim \sigma \frac{2}{18} \frac{M_{\rm det}}{m_{\rm amu}} \frac{L_{\bar{\nu}_e} / < E_{\bar{\nu}_e} >}{4\pi D^2} \frac{< E^2_{\bar{\nu}_e} >}{(m_e c^2)^2}$$

$$\sim \frac{1.6}{\rm ms} \left[\frac{M_{det}}{32{\rm kT}}\right] \left[\frac{L_{\bar{\nu}_e}}{10^{52}{\rm ergs}^{-1}}\right] \left[\frac{15{\rm MeV}}{< E_{\bar{\nu}_e} >}\right] \left[\frac{< E^2_{\bar{\nu}_e} >}{15{\rm MeV}}\right]^2 \left[\frac{10{\rm kpc}}{D}\right]^2,$$

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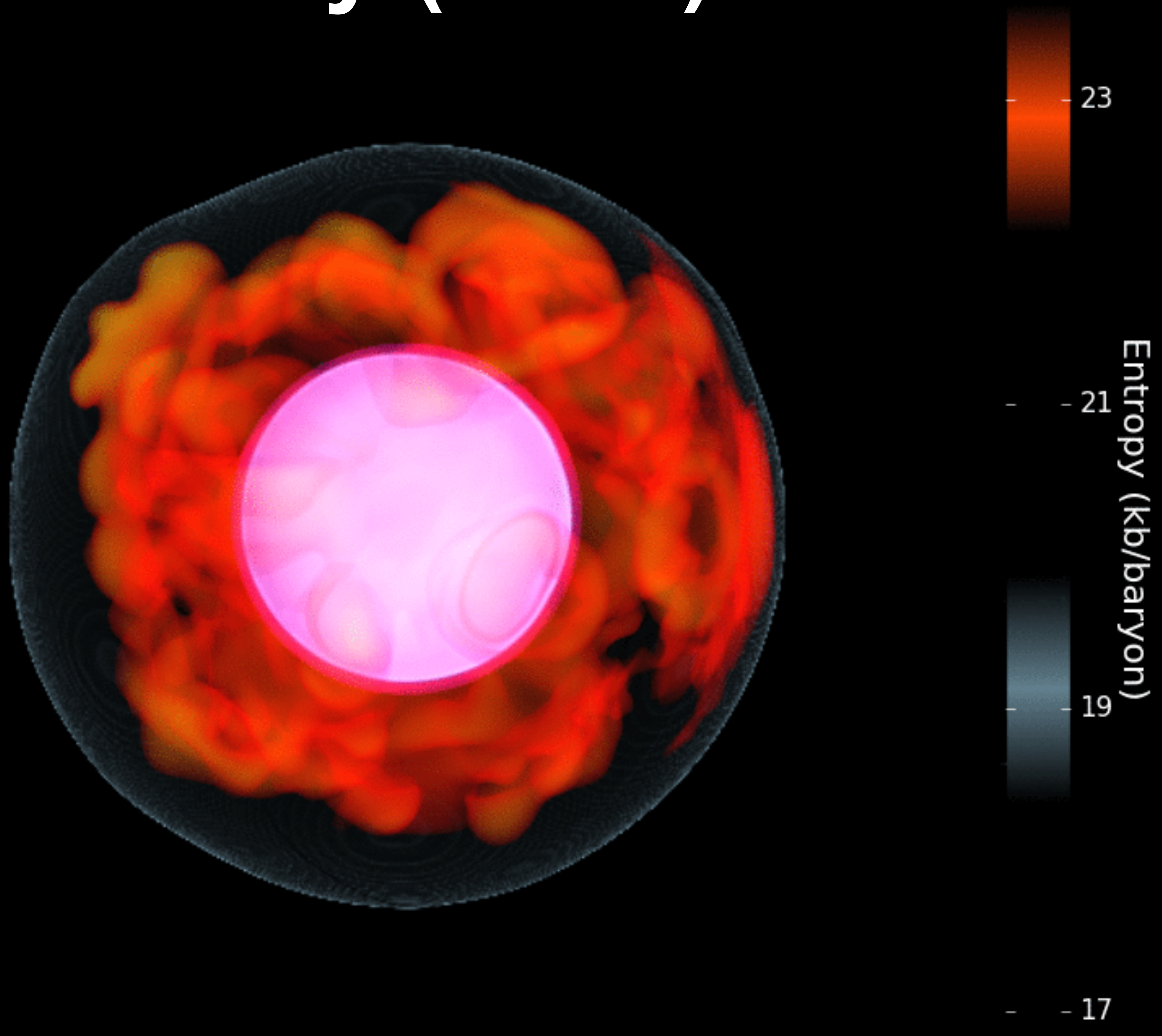
Standing Accretion Shock Instability (SASI)

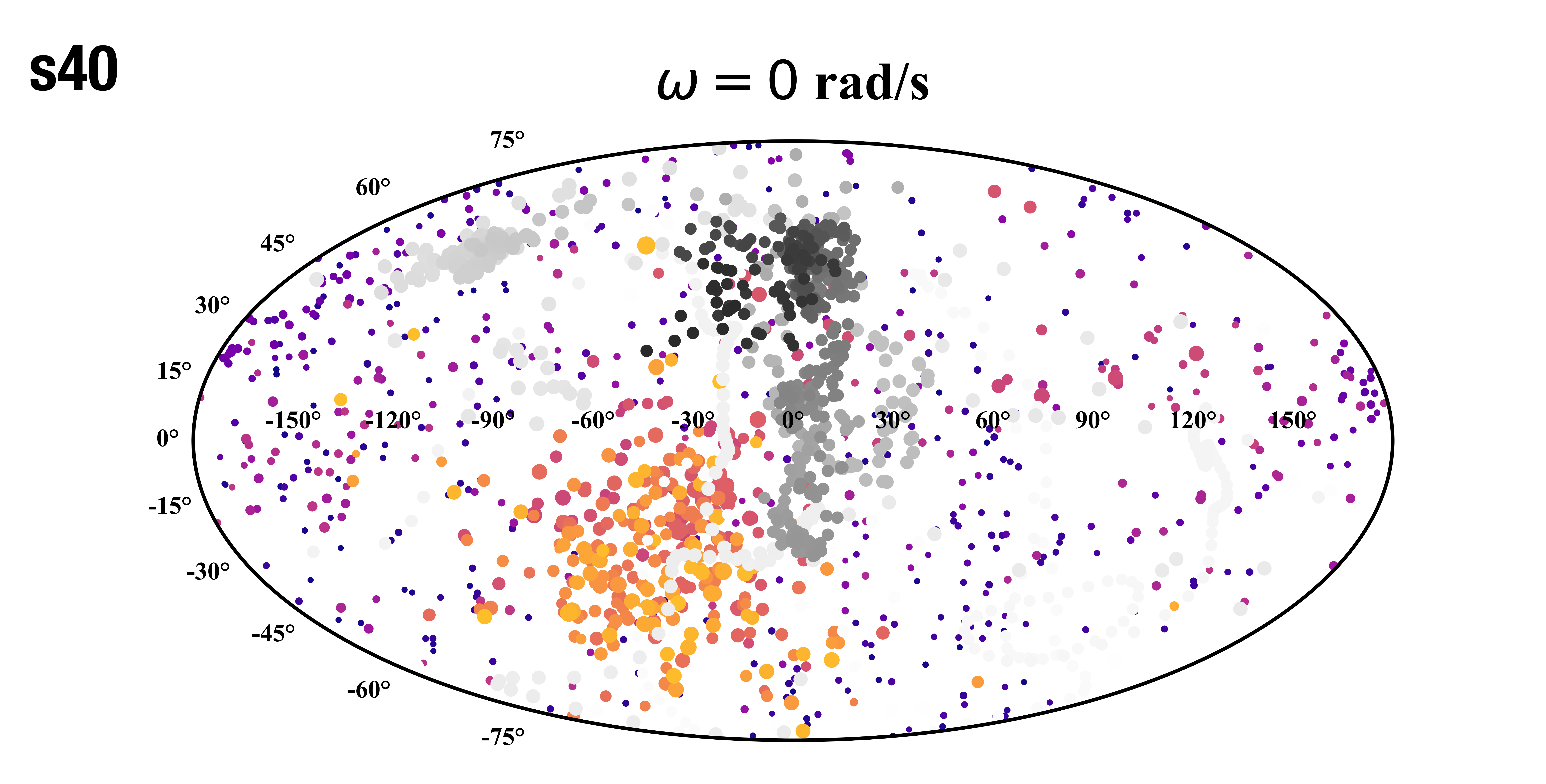
- SASI is a natural fluid instability
- It helps to redistribute angular momentum
- The “spiral” mode appeared in 3D simulations only
- Could aid explosion
- Emit unique GW features (see later slides)

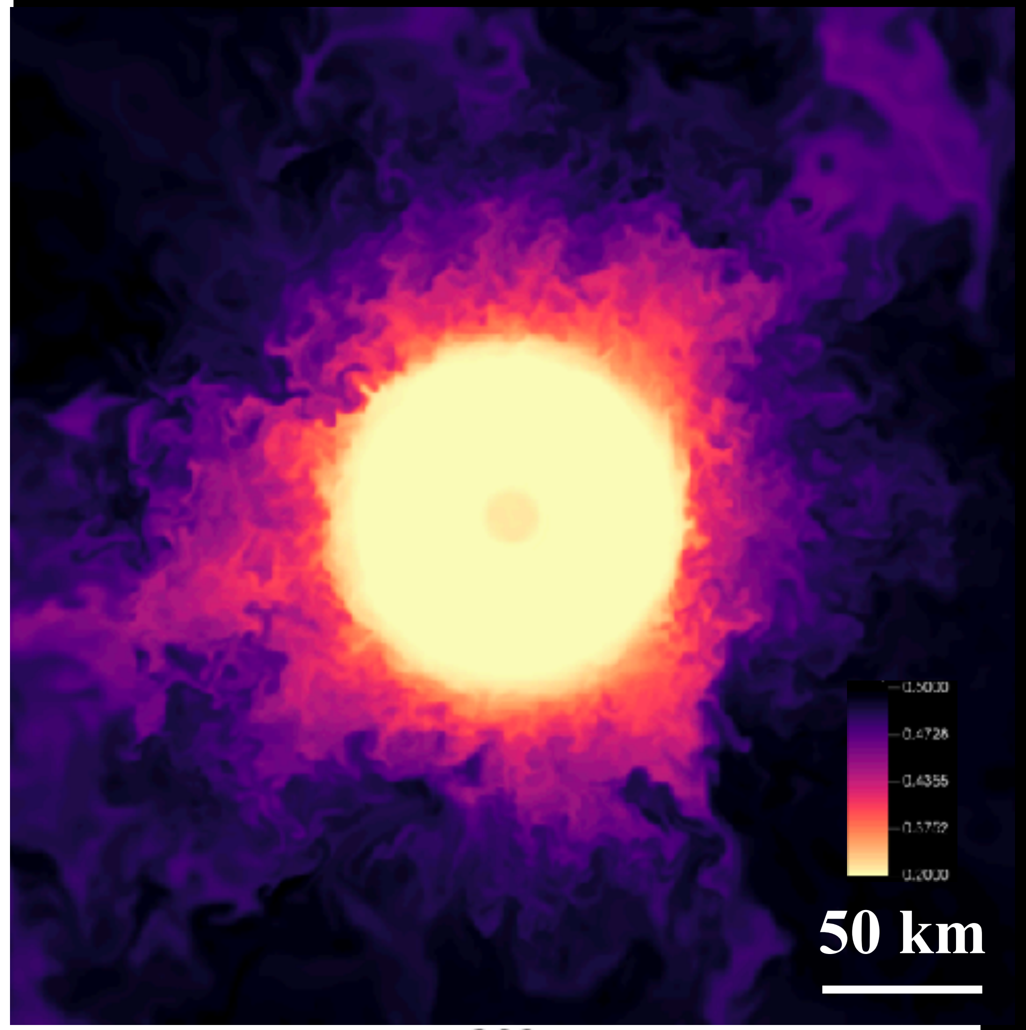


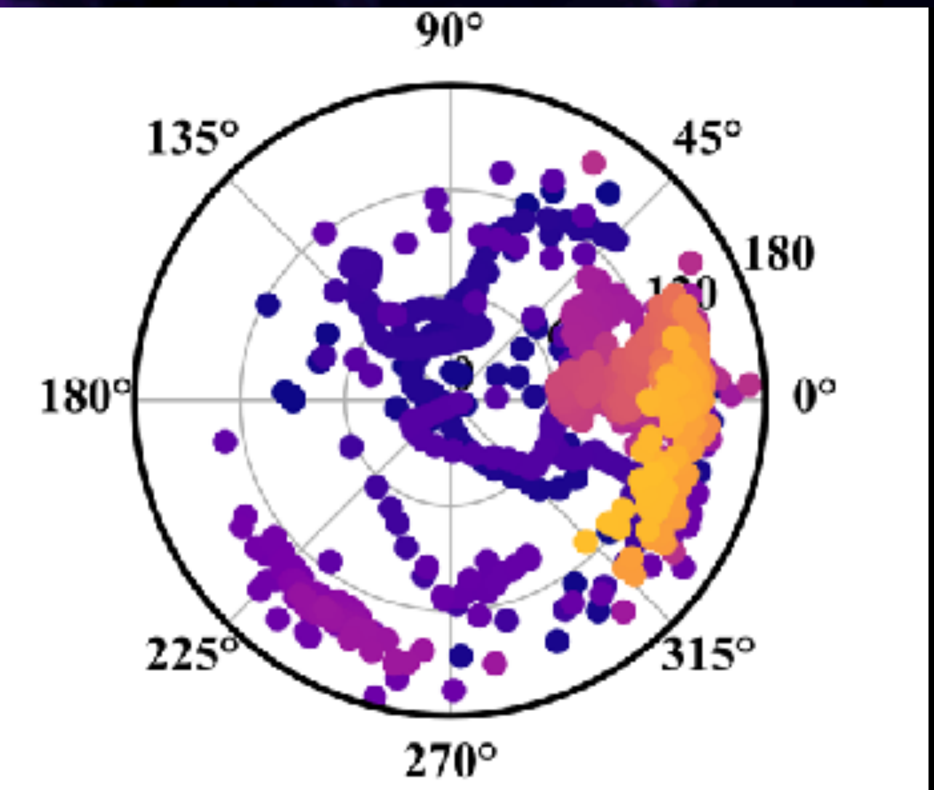
credit: K.-C. Pan & M. Liebendoerfer

SASI induced rotation

Spin direction







SASI direction

Time

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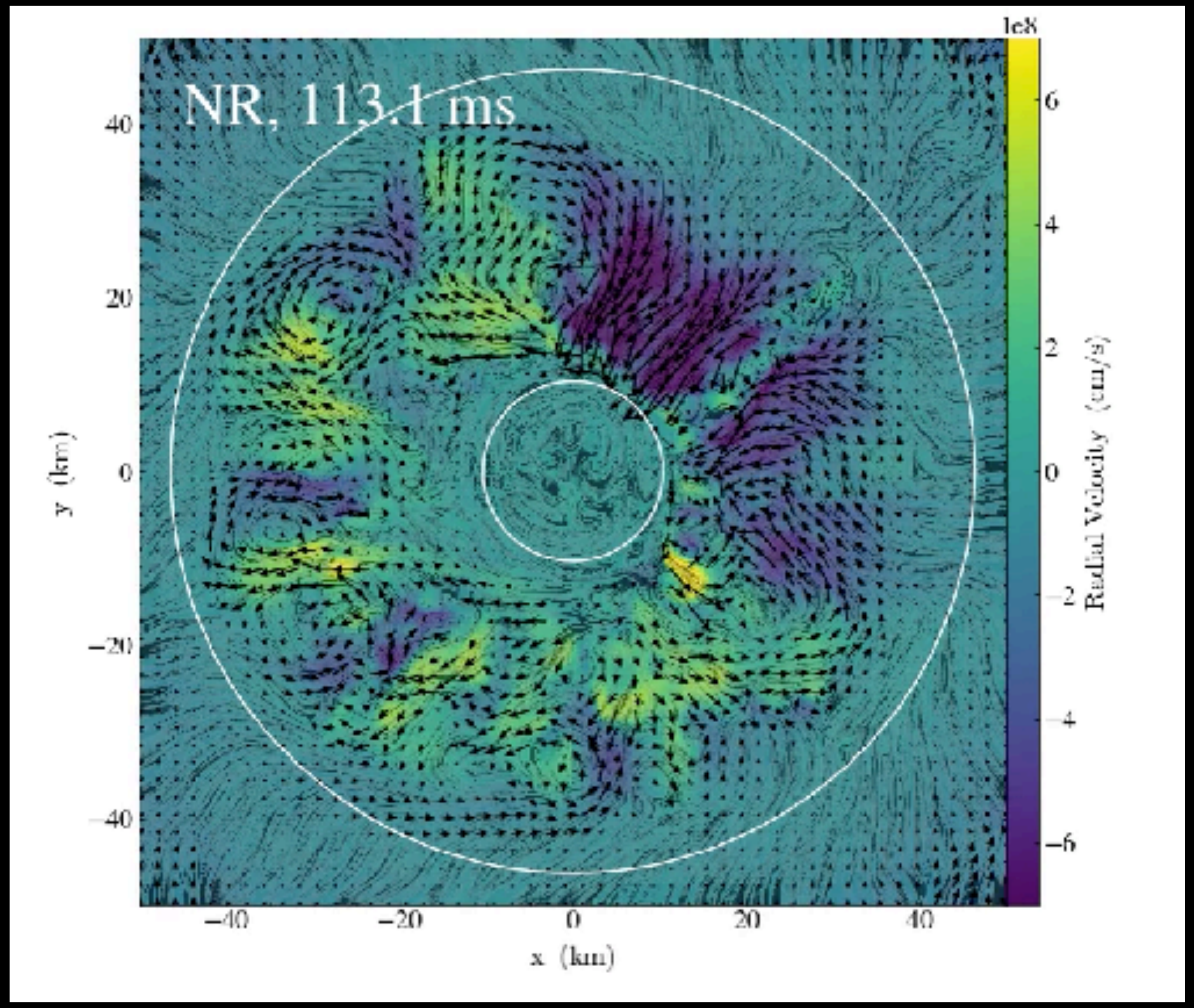
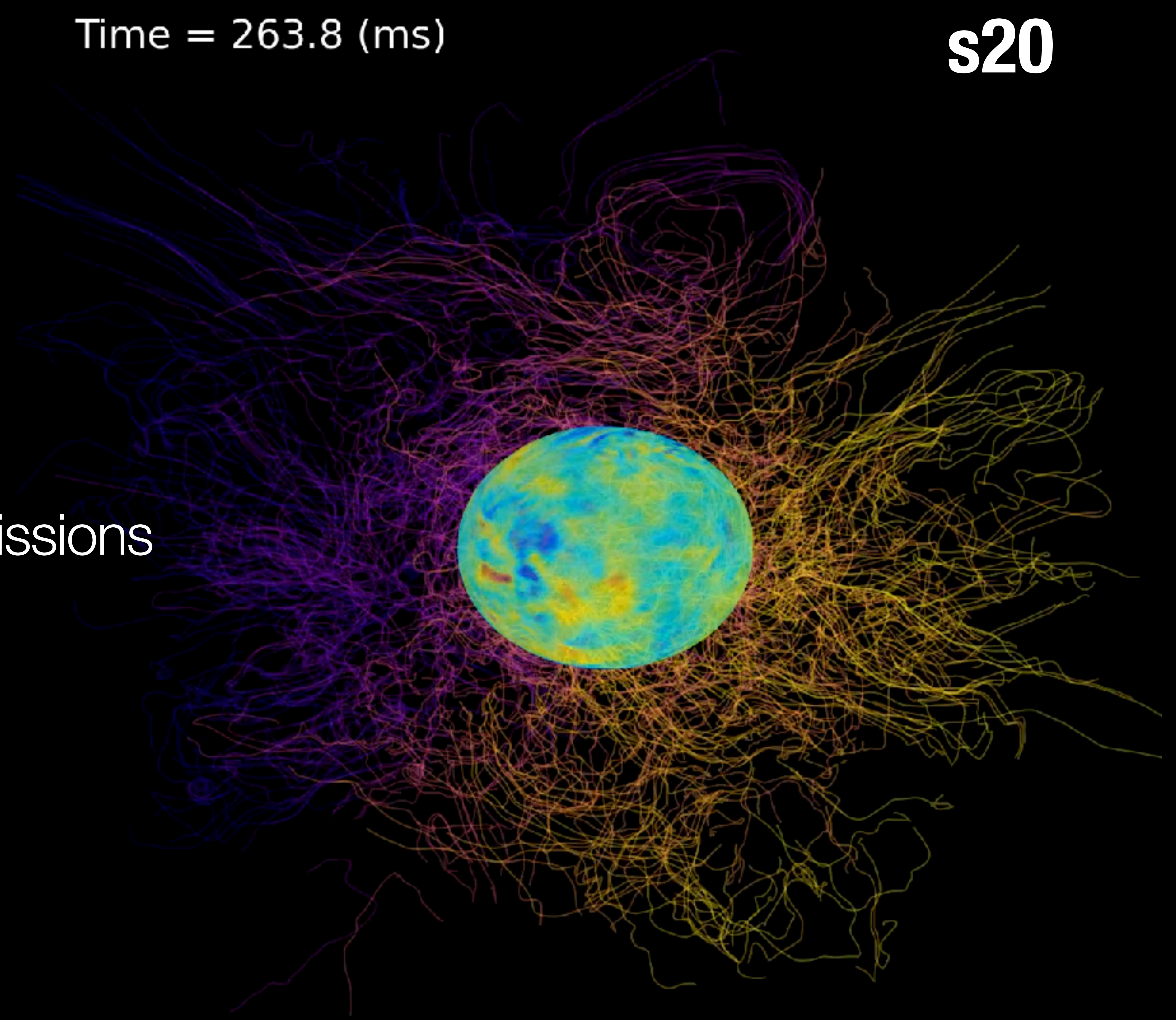
The Proto-Neutron Star

- SASI could induce rotation
- Accretion flow perturb the PNS
- PNS surface convection
- PNS inner core convection
- All these non-spherical variation cause GW emissions
- 



s20

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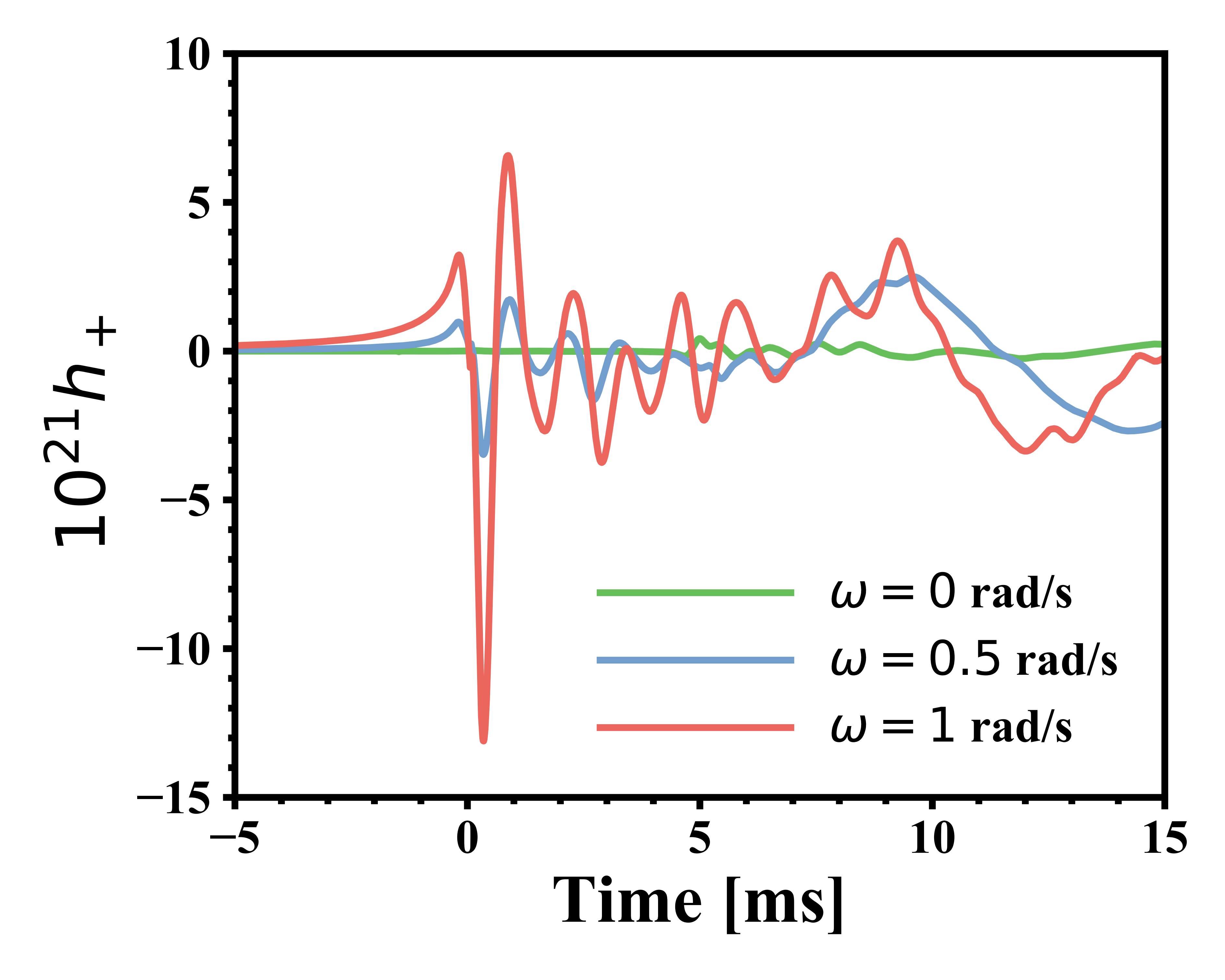
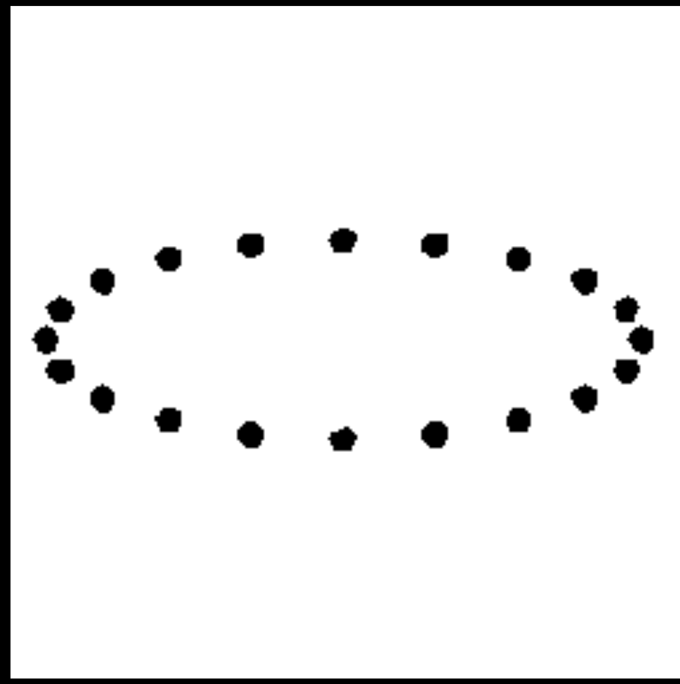
Gravitational waves

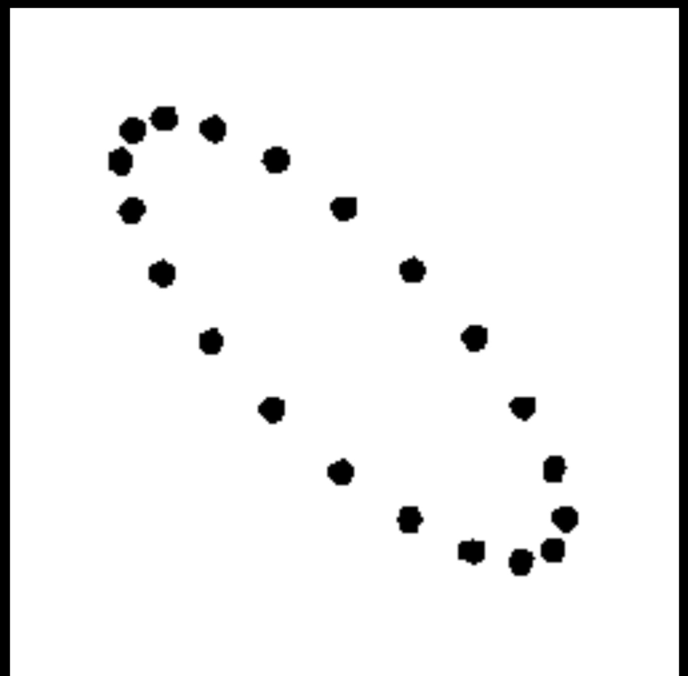
- Quadrupole approximation
- Assuming a distance at 10 kpc
- Two polarizations

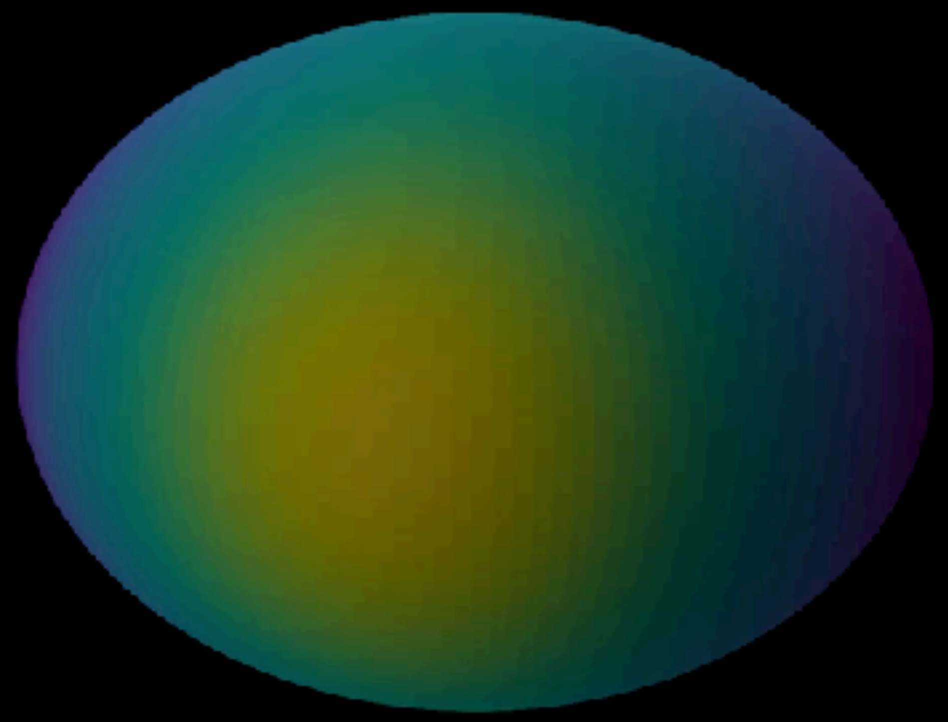


h_+




h_x



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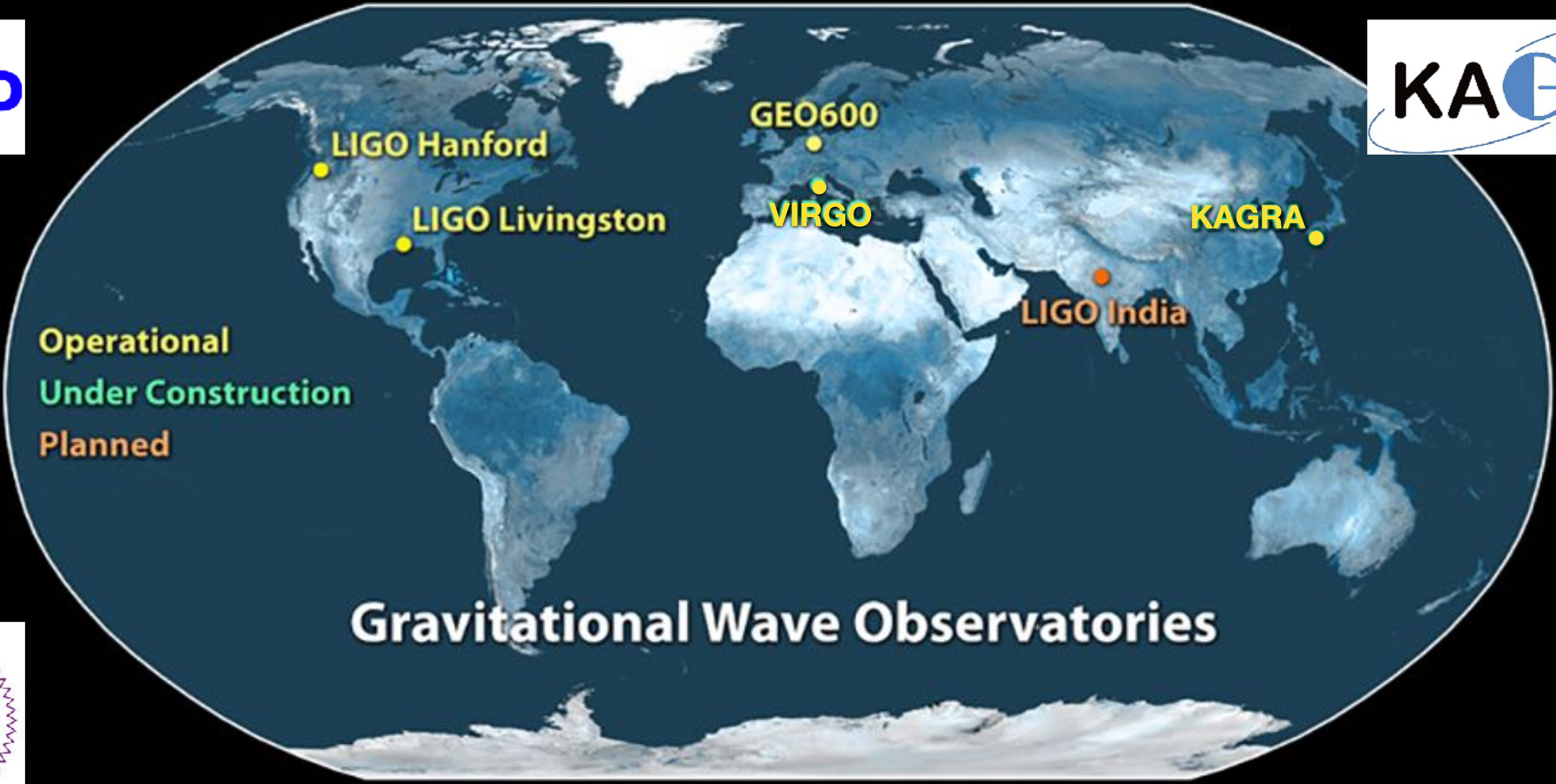
Gravitational wave detectors



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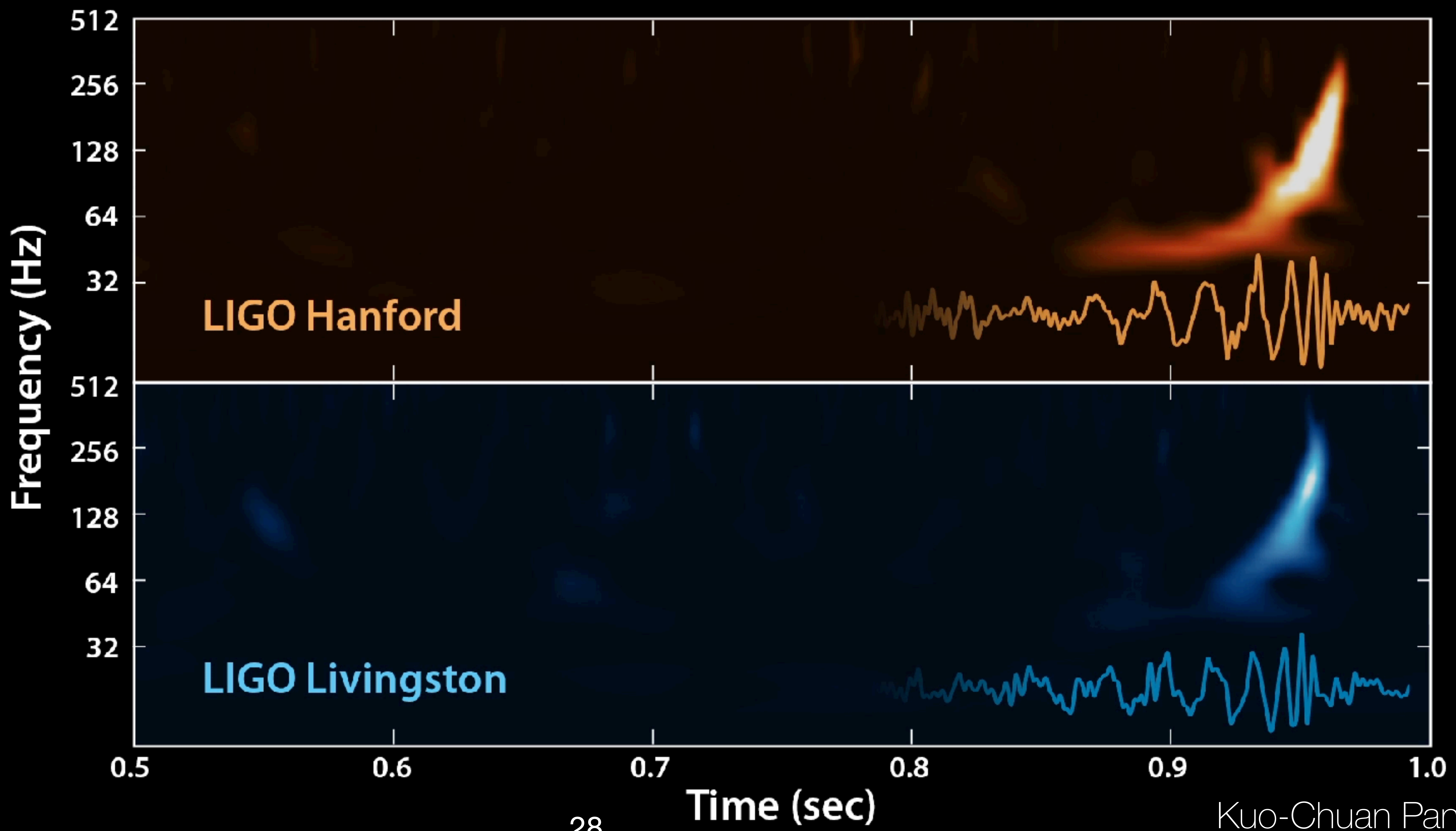
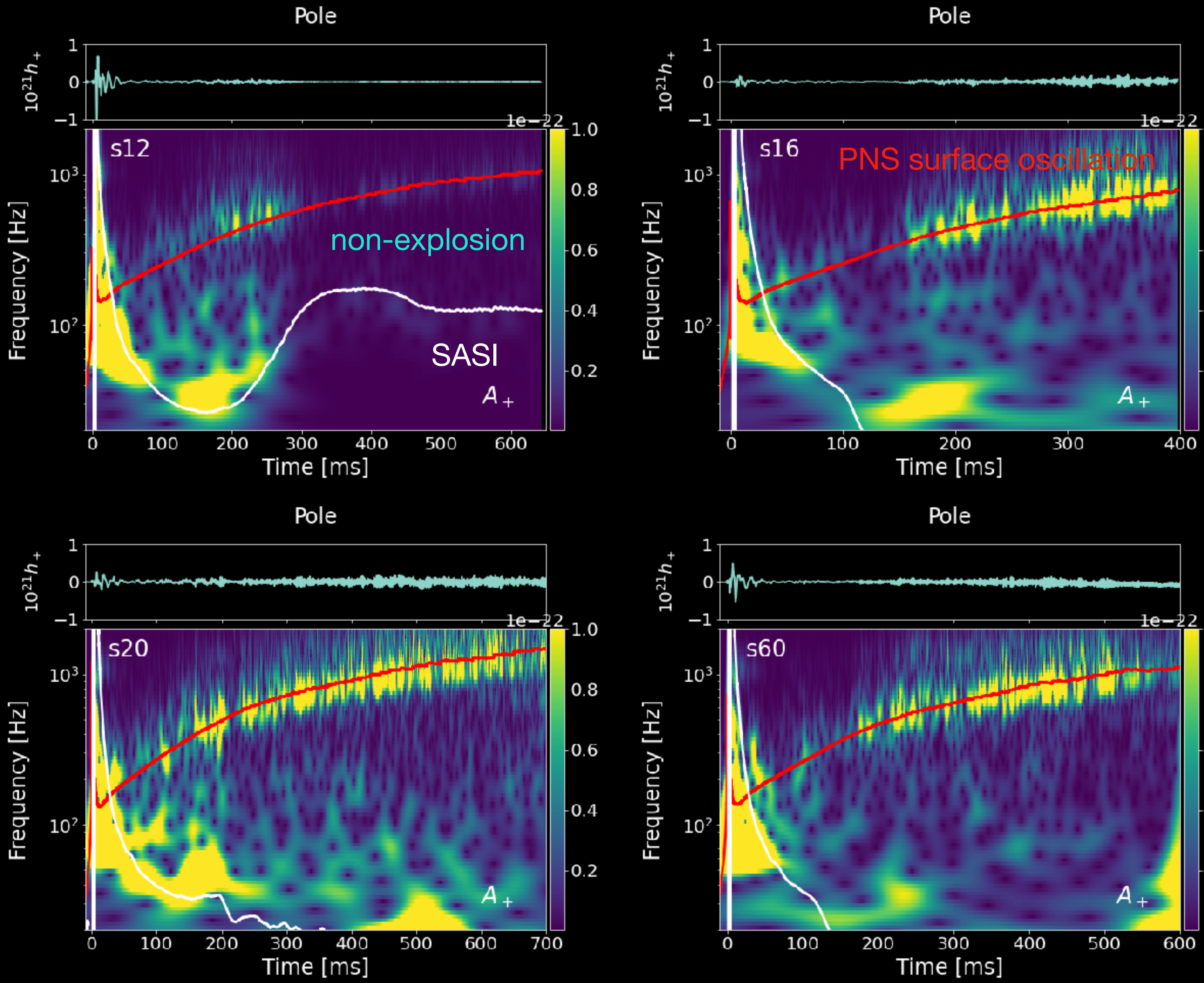
Recall: GW sounds from binary BH mergers

- GW150914



Spectrograms

- Frequency-time evolution
- red: PNS surface oscillation (g-mode)
- white: the SASI signal
- Frequencies ranged from hundred hertz to kilohertz
- GW “Sounds”



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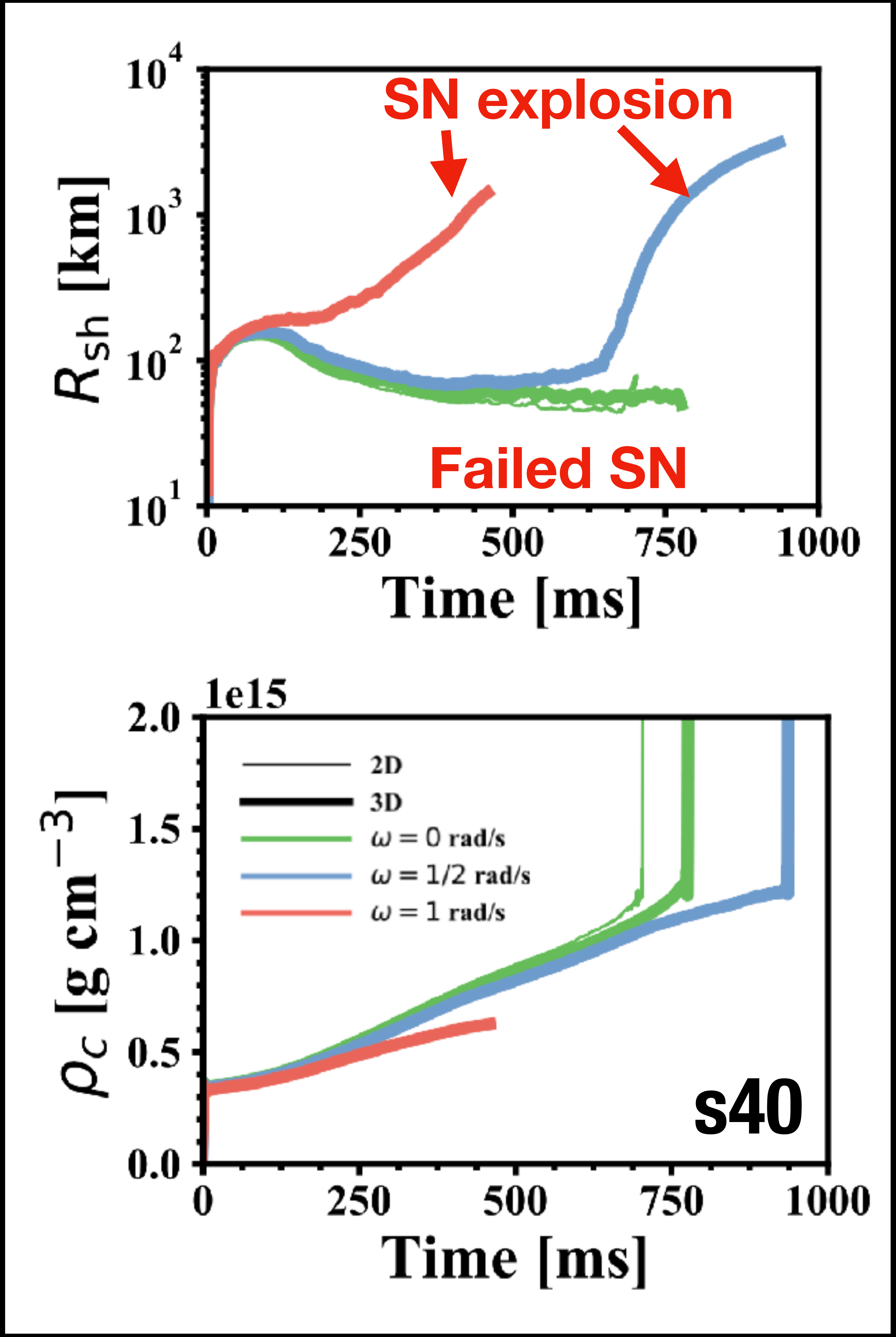
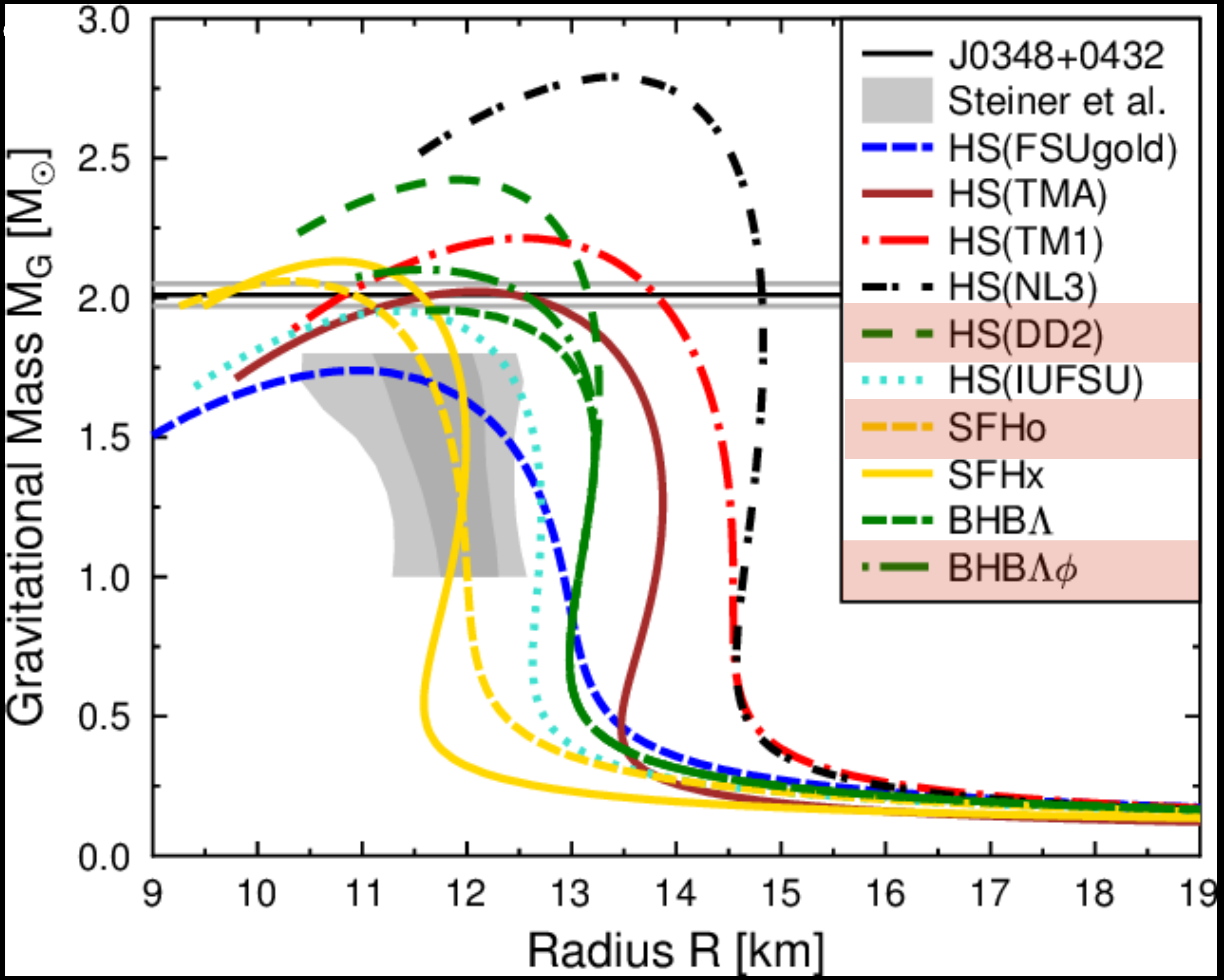
Black Hole Formation

- The s40 progenitor with 0, 0.5, or 1 rad/sec initial rotation
- A second collapse happens at ~700 - 1000 ms post bounce, forming a BH
- Explosion and BH formation could co-exist



Pan et al. (2016, 2018, 2021)

Nuclear Equation of States (EoS)



(From M. Hempel's website)

Neutron stars have a maximum mass

1.97 Msun (Demorest+2010)

Degeneracy pressure limit

Nucleon-nucleon interactions (strong force) responsible for maintain neutron star stability

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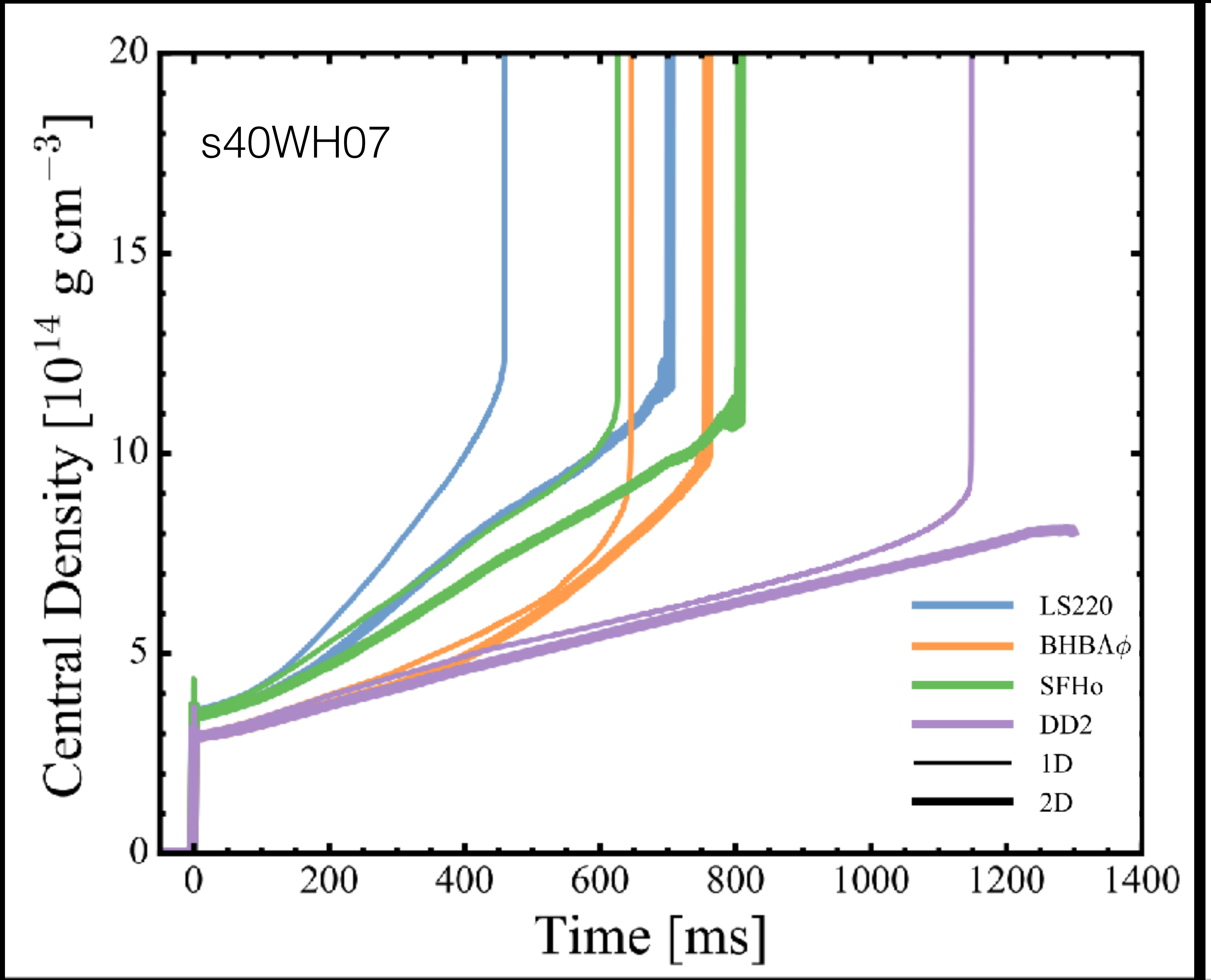
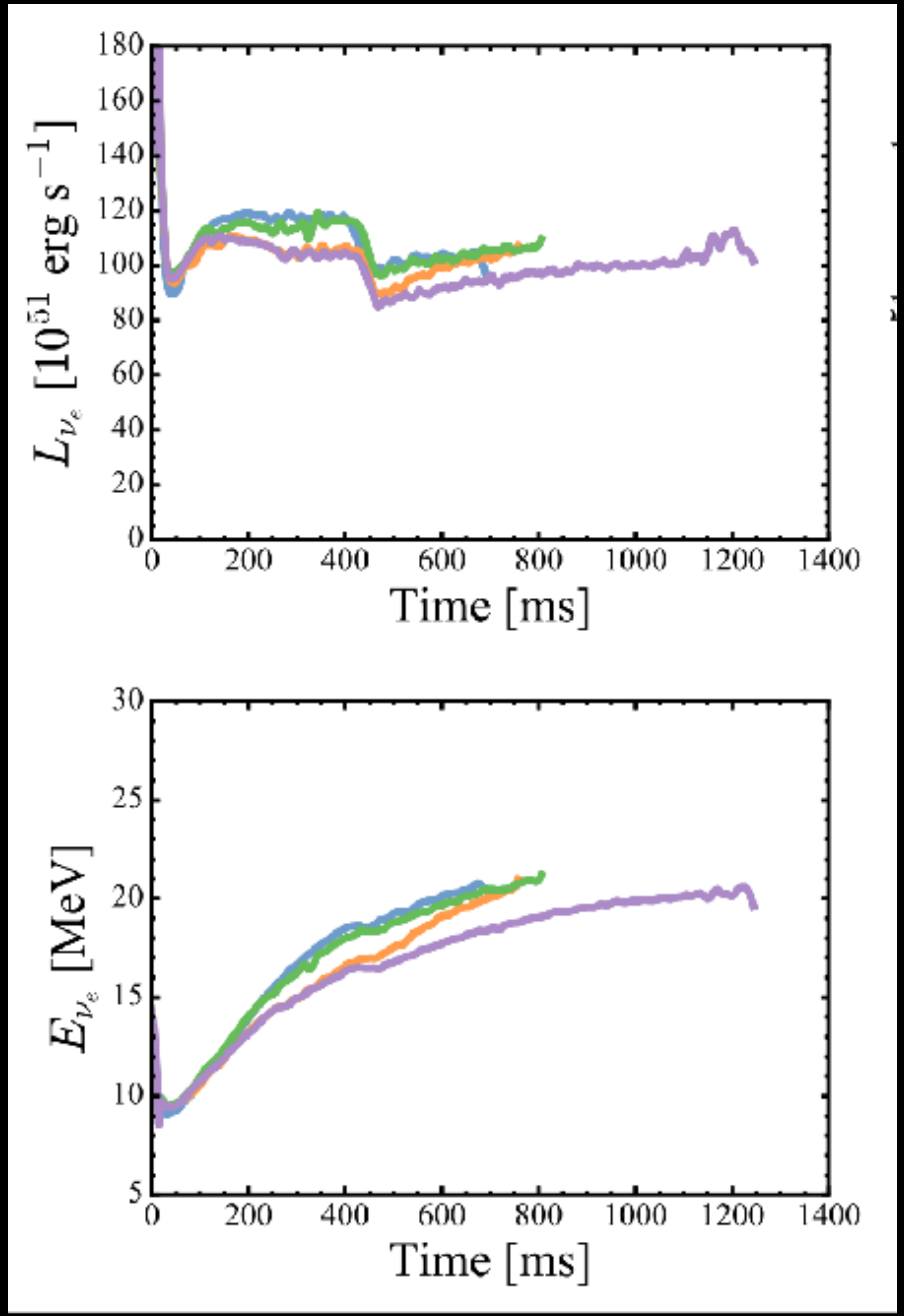
Nuclear Equation of States (EoS)

Different EoS:

- Different PNS structure
- Different BH formation time
- Different neutrino number emissions





Pan et al. 2018

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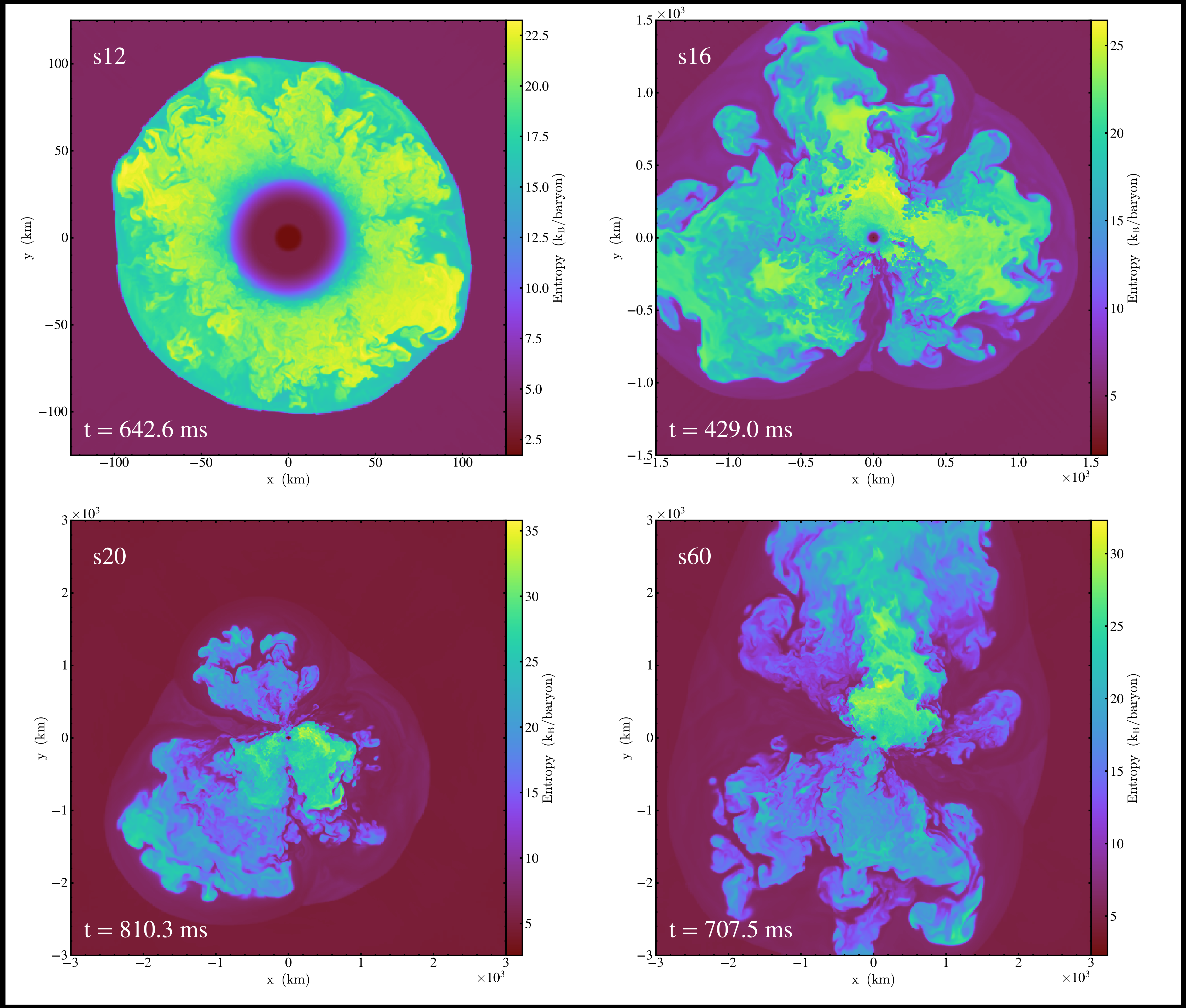
Long-term evolutions

- Although we start from a spherically symmetric collapse, the SN ejecta is asymmetric.
- Accretion and outflow happen together



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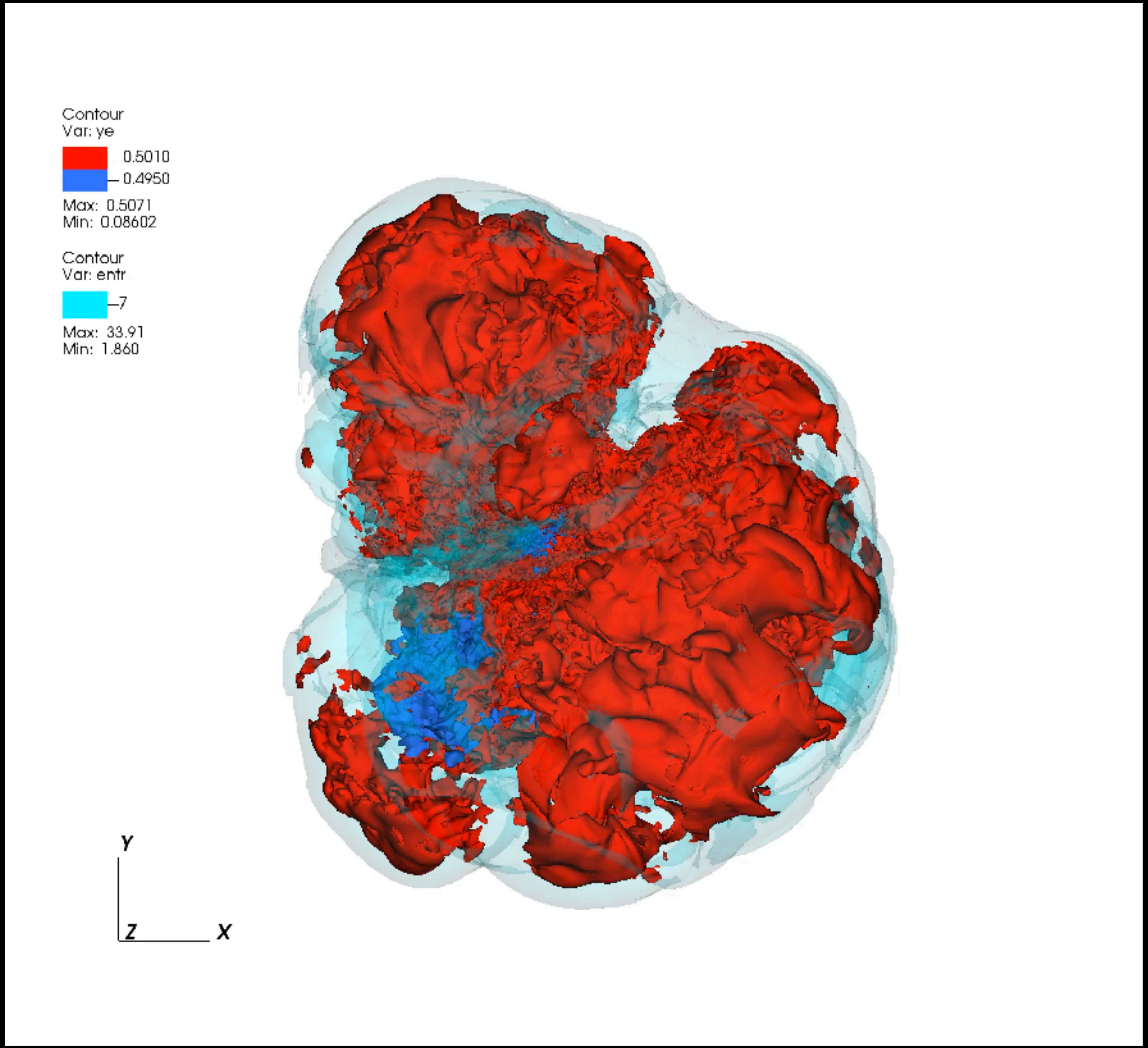
Long-term evolutions

- Asymmetric ejecta
- Red: high Ye component
- Blue: low Ye component

Cas A SNR Observation by Chandra



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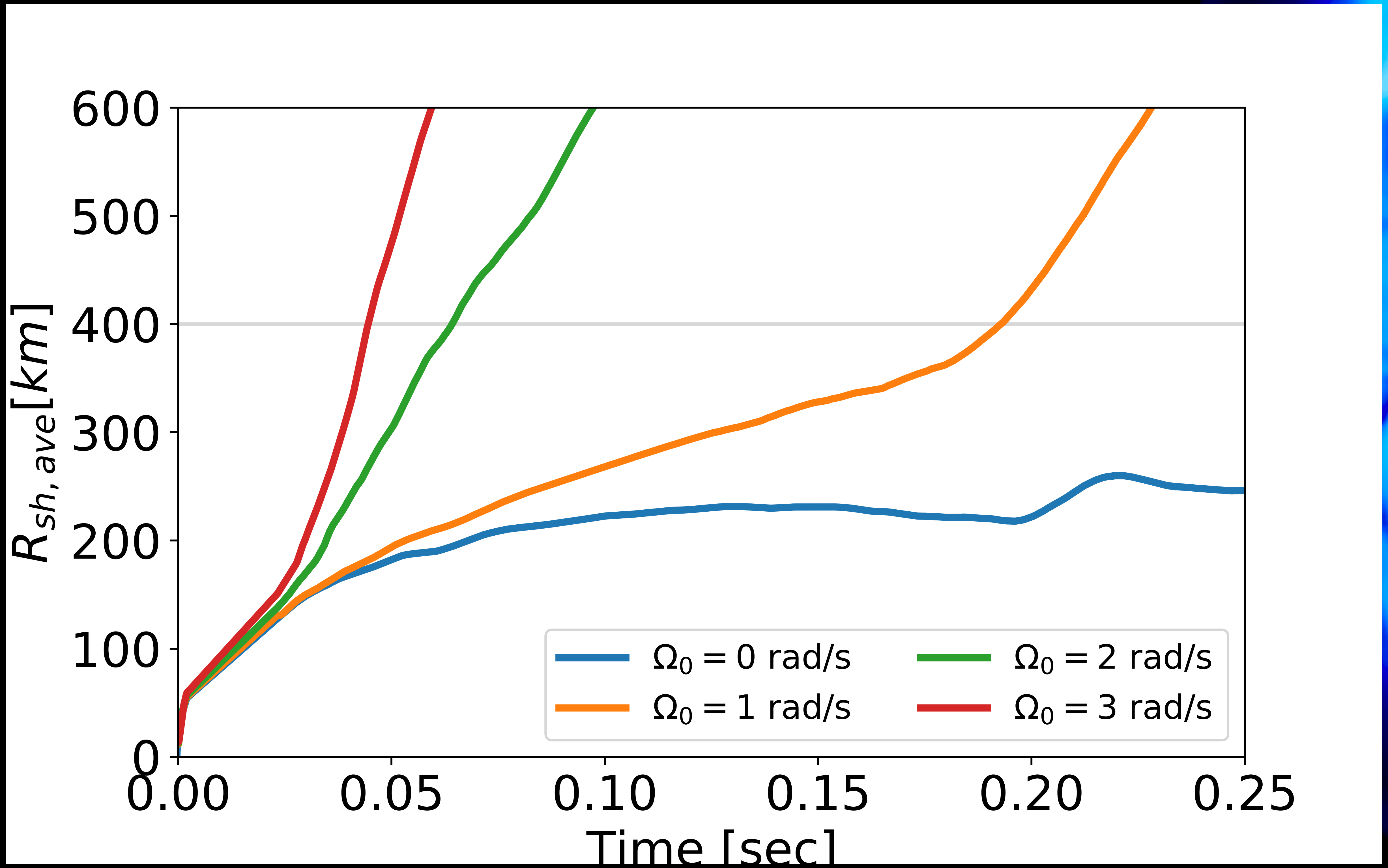
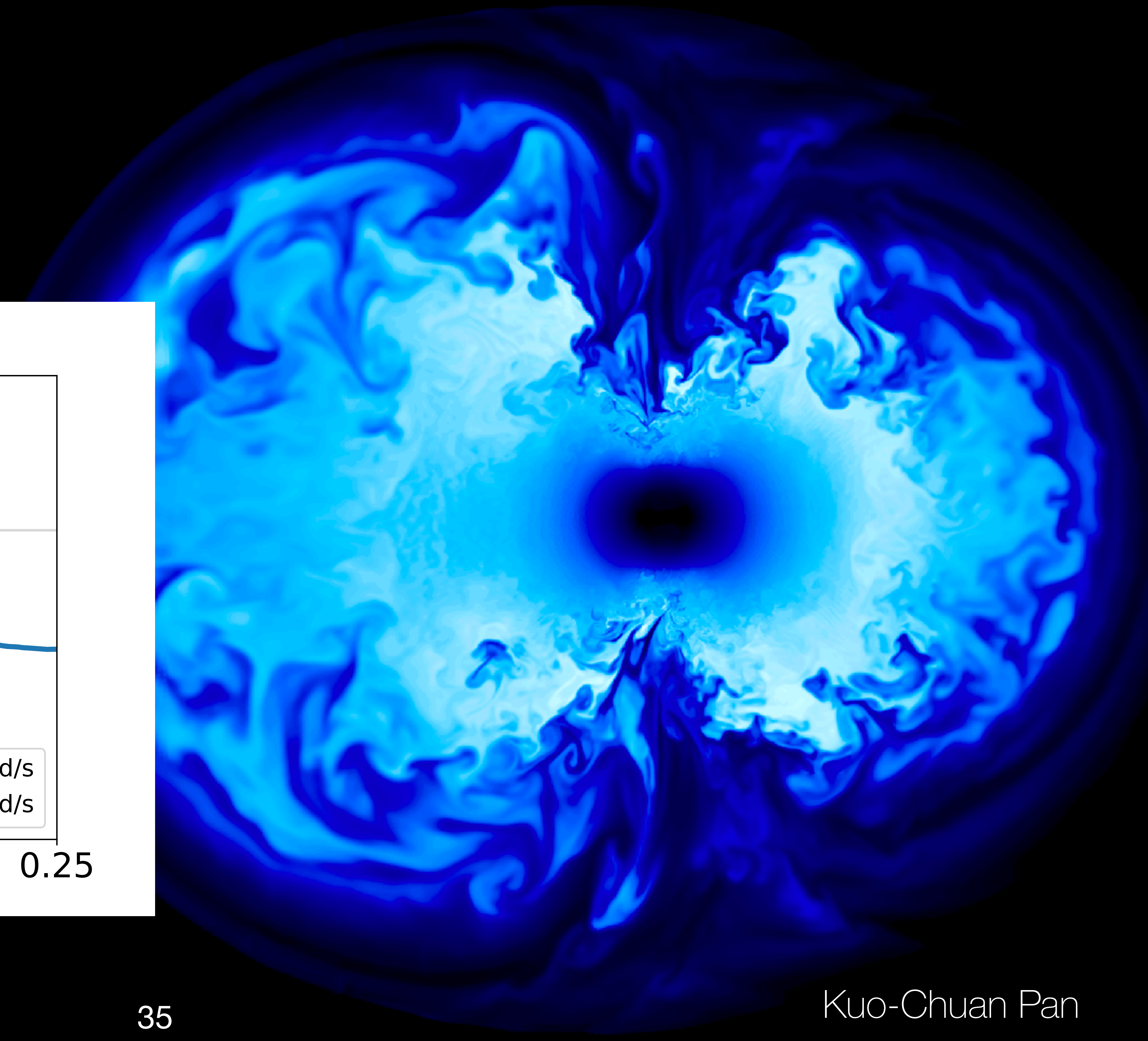
Rotational Effects





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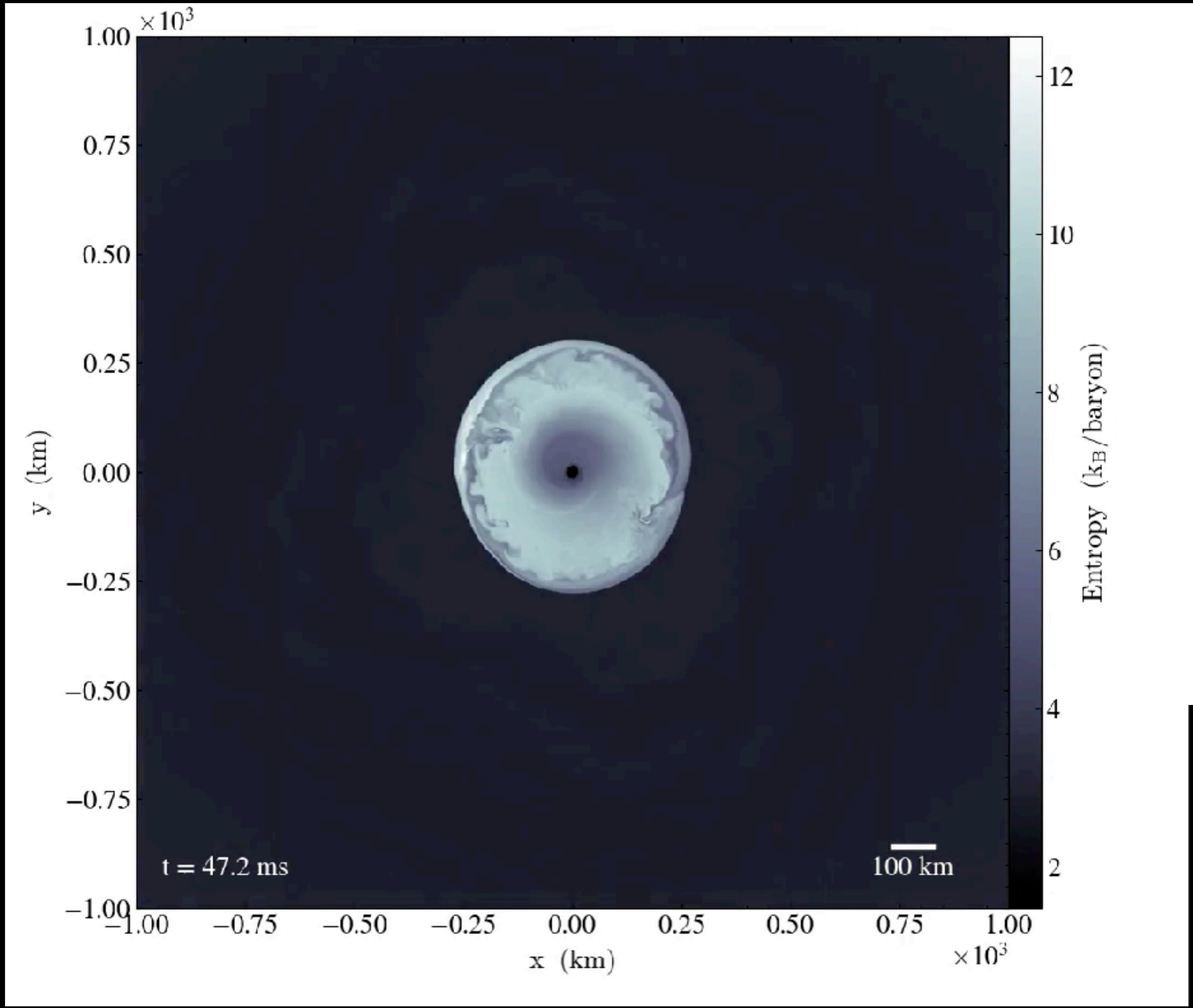
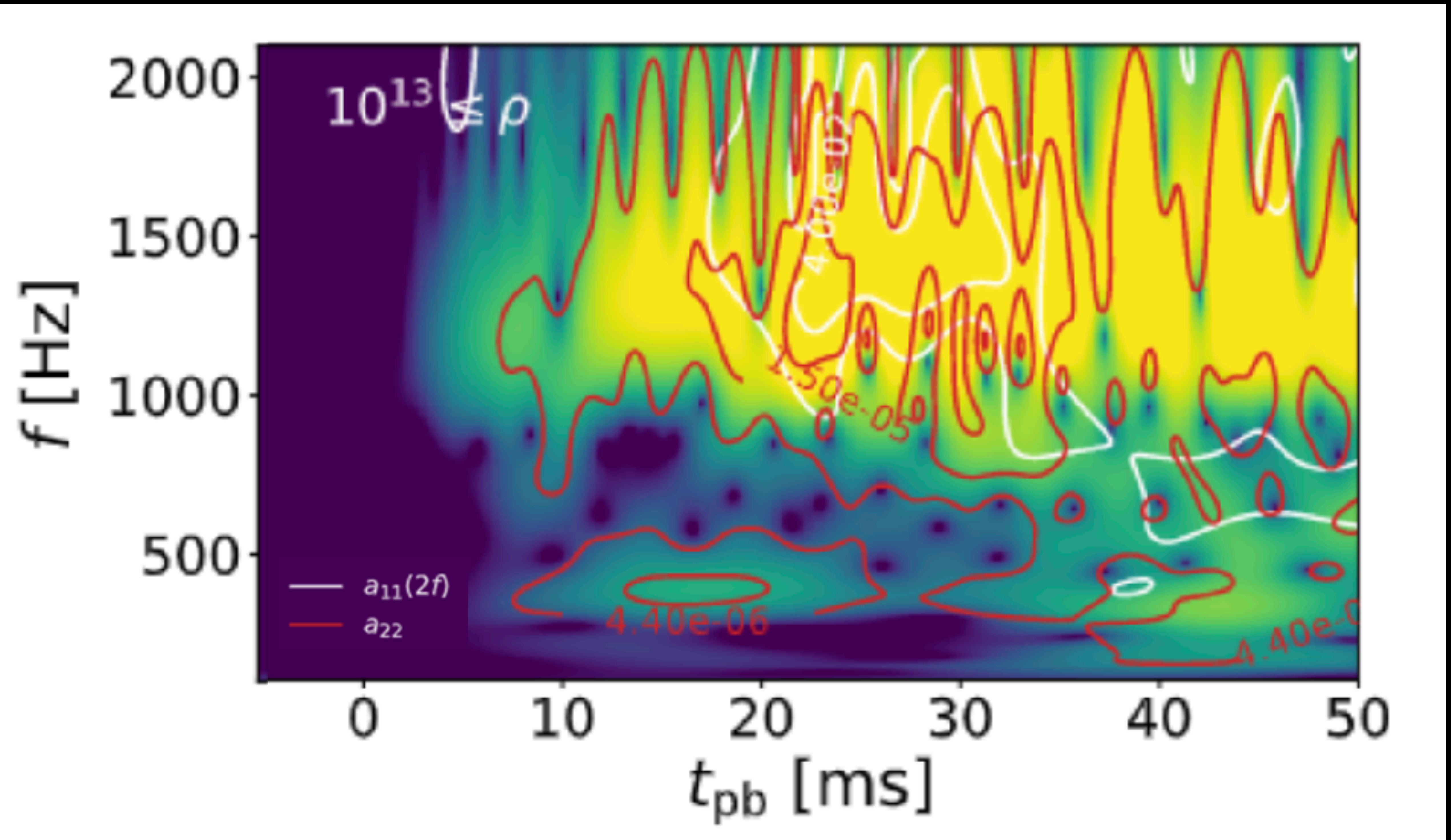
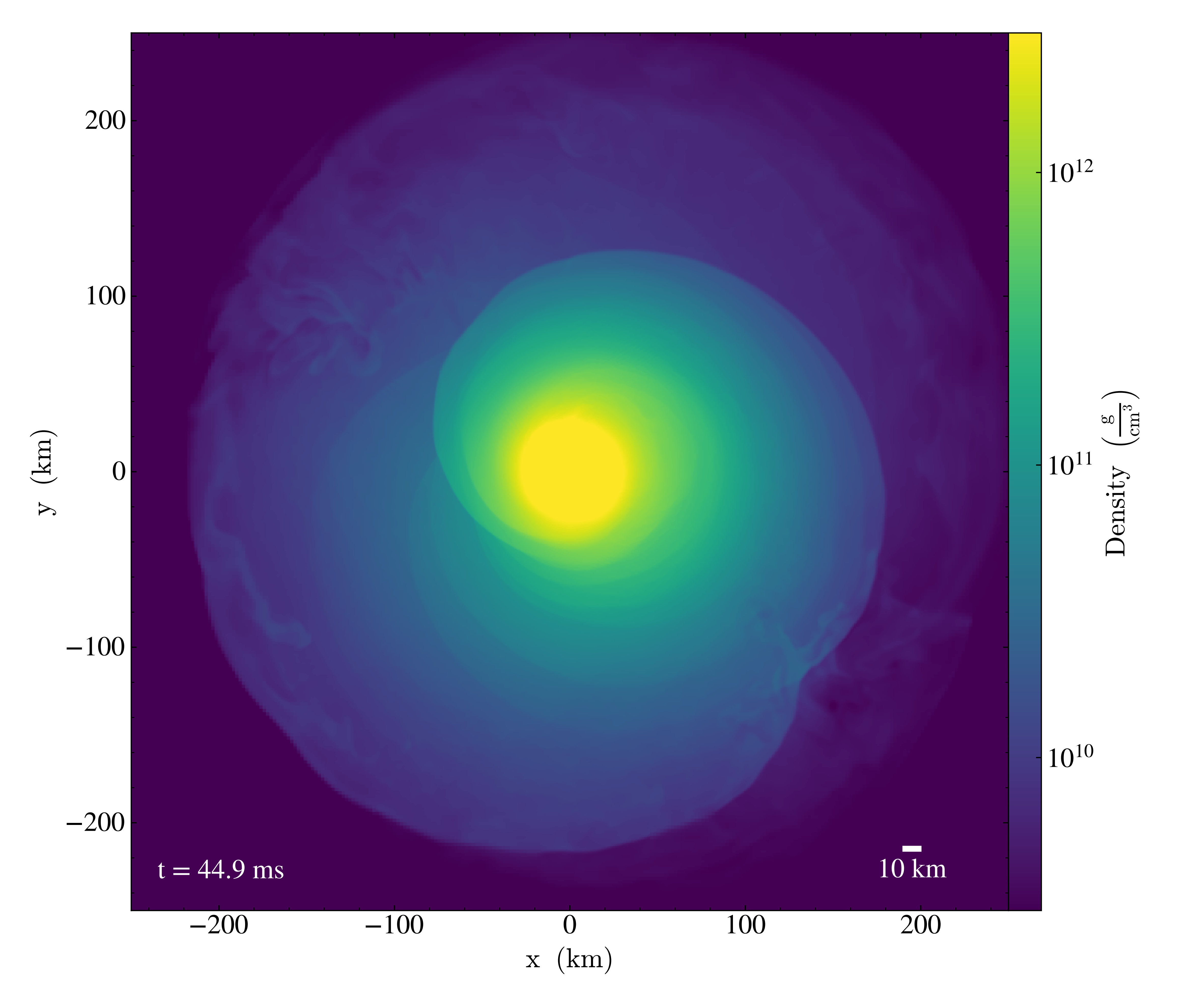
The low T/W instability

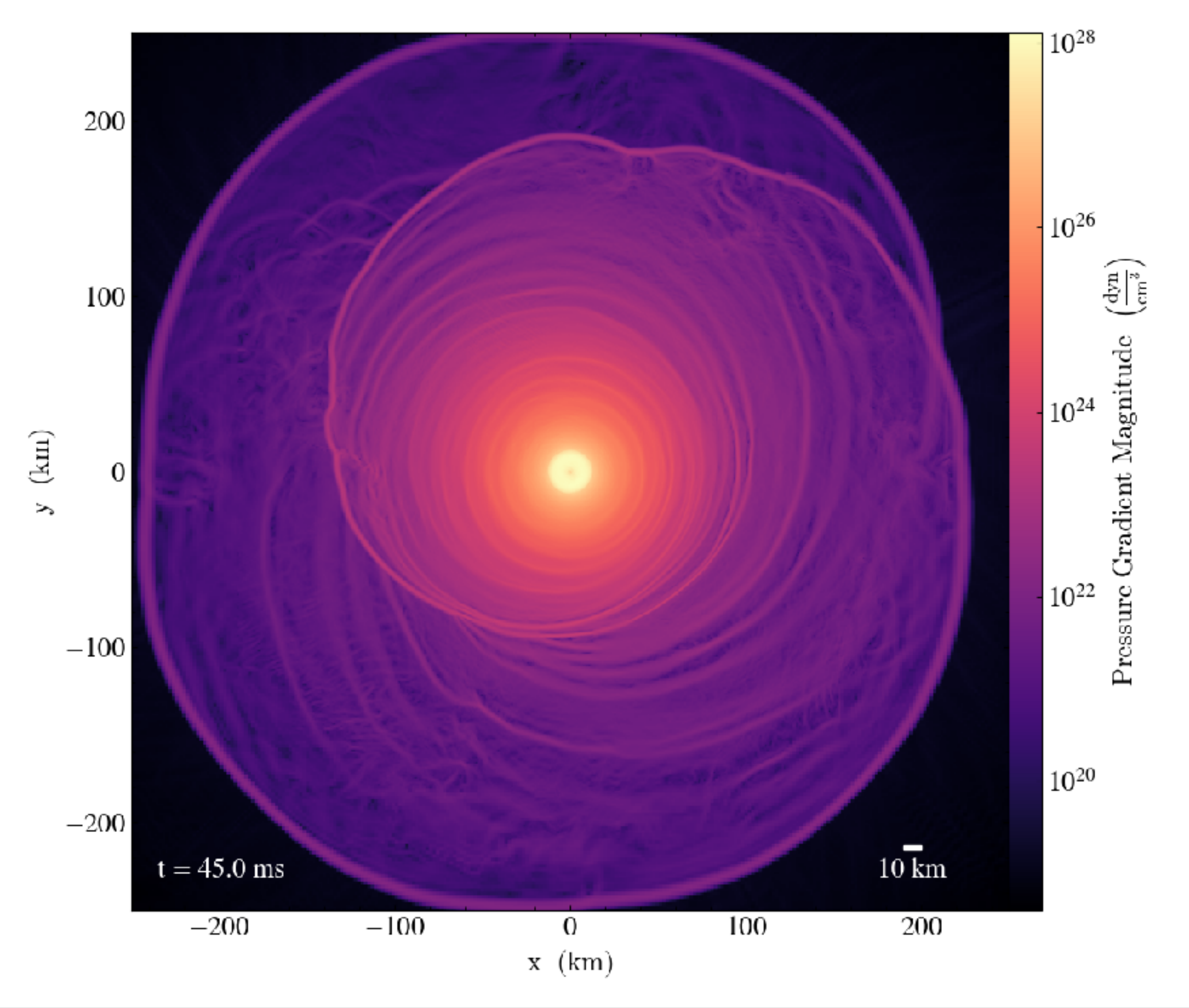




Hsieh et al. in prep.

The low T/W instability





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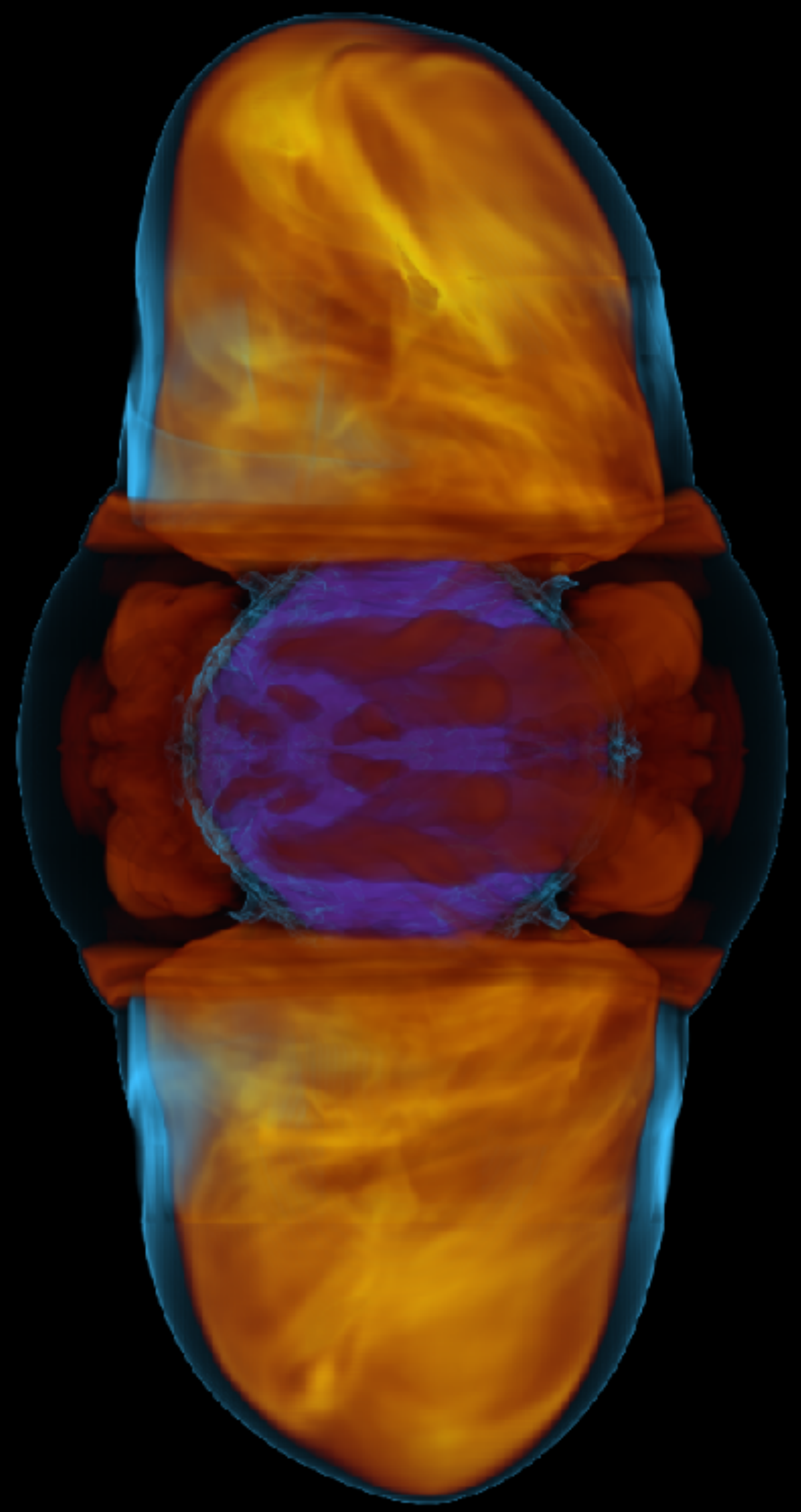
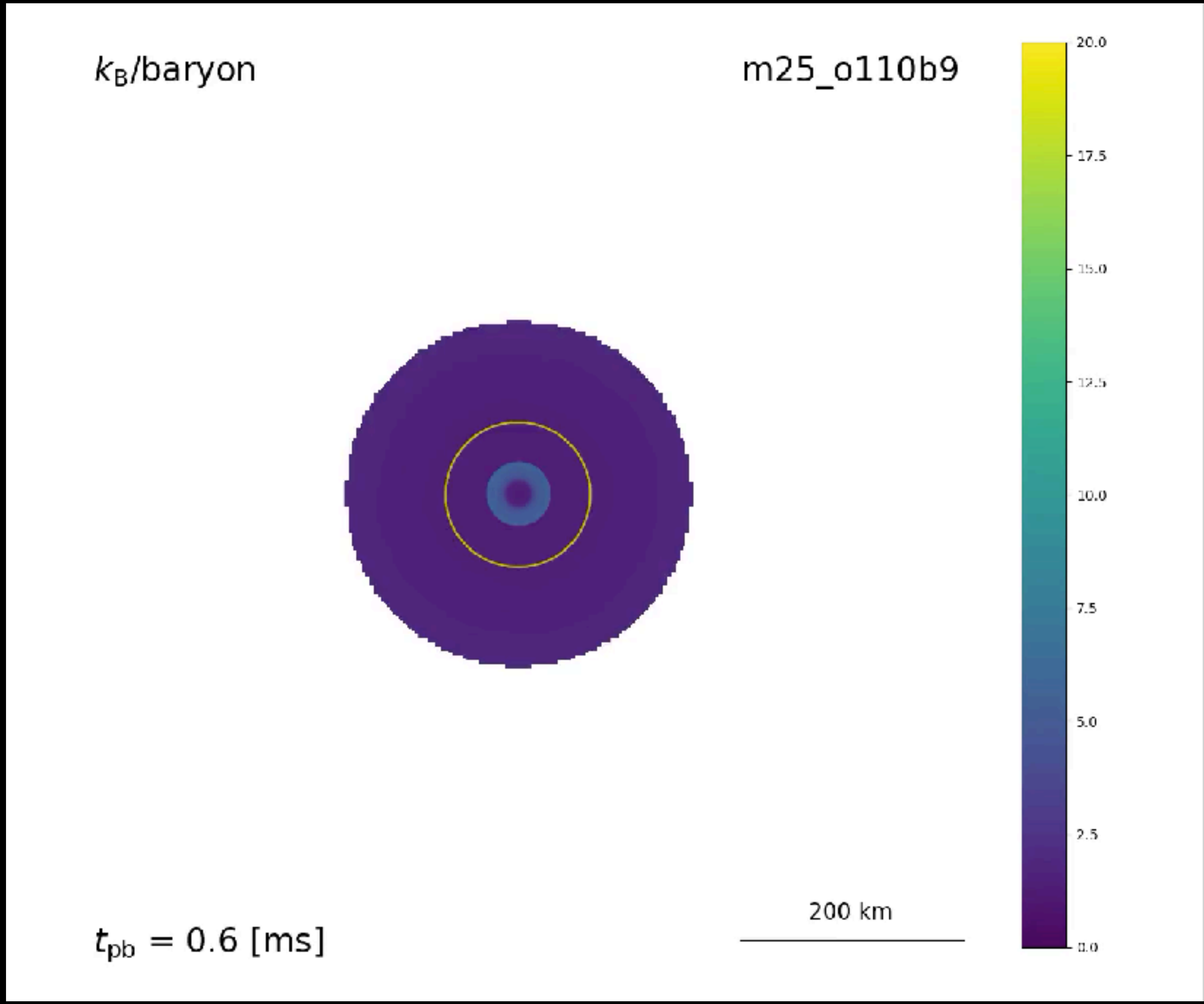
Magneto-hydrodynamics effects

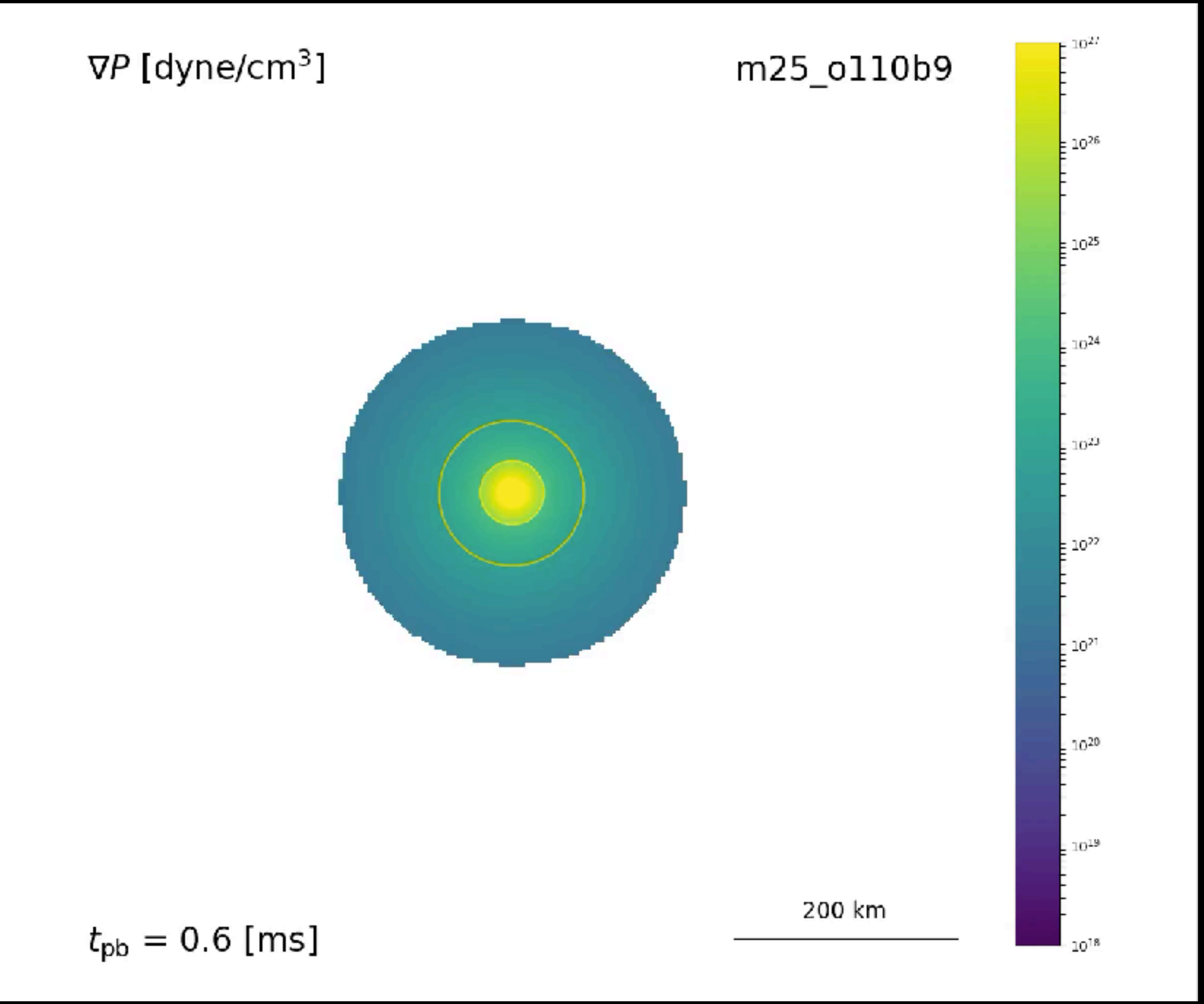
- Might be the origin of some long-GRBs
- Might be the mechanism of super-luminous supernovae (or hypernovae)
- Results in ms-period proto-magnetar



Couch, et al. (+ KCP) in prep.

Magneto-hydrodynamics effects





$$m25, \Omega = 1.1, B = 10^9$$

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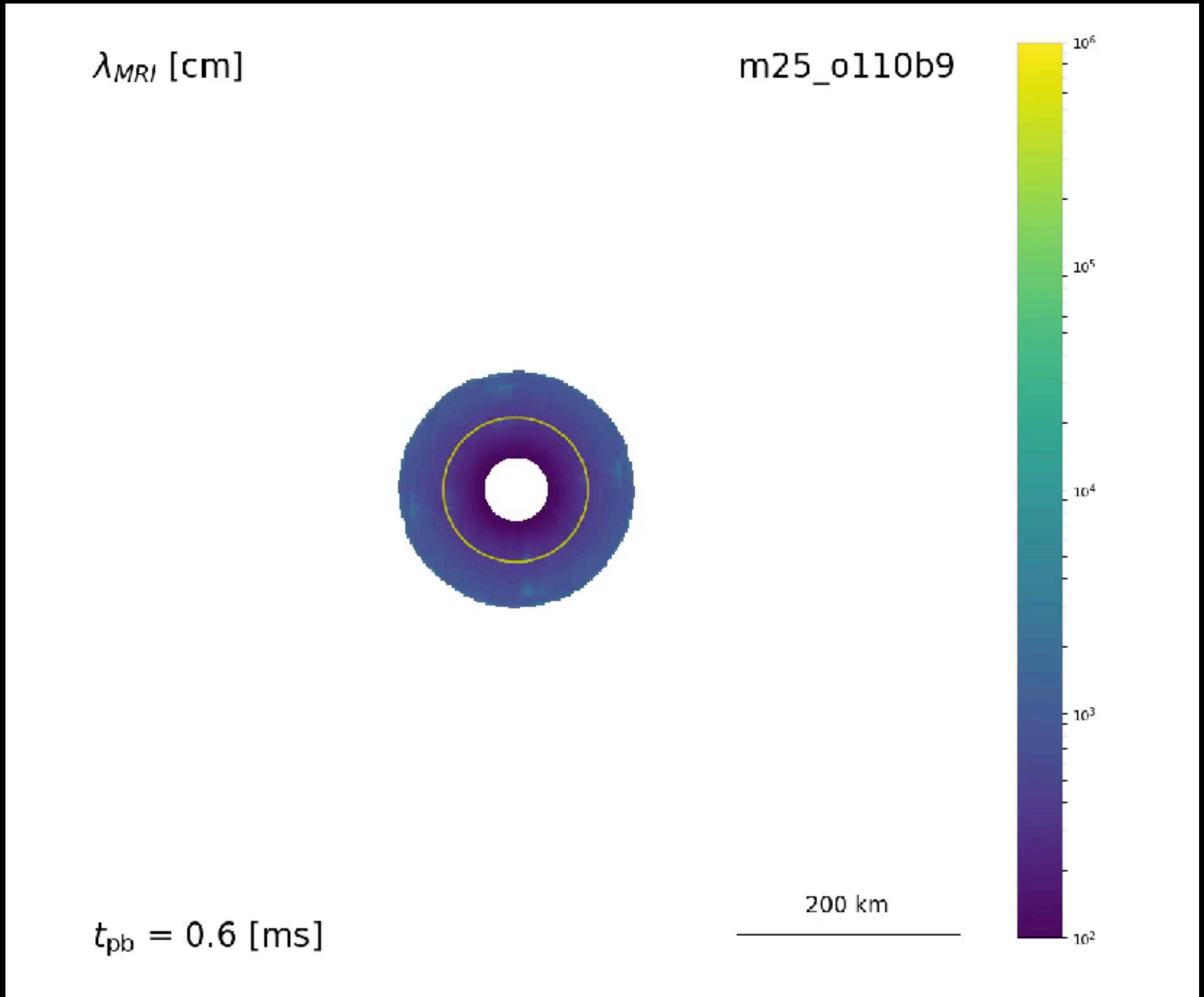
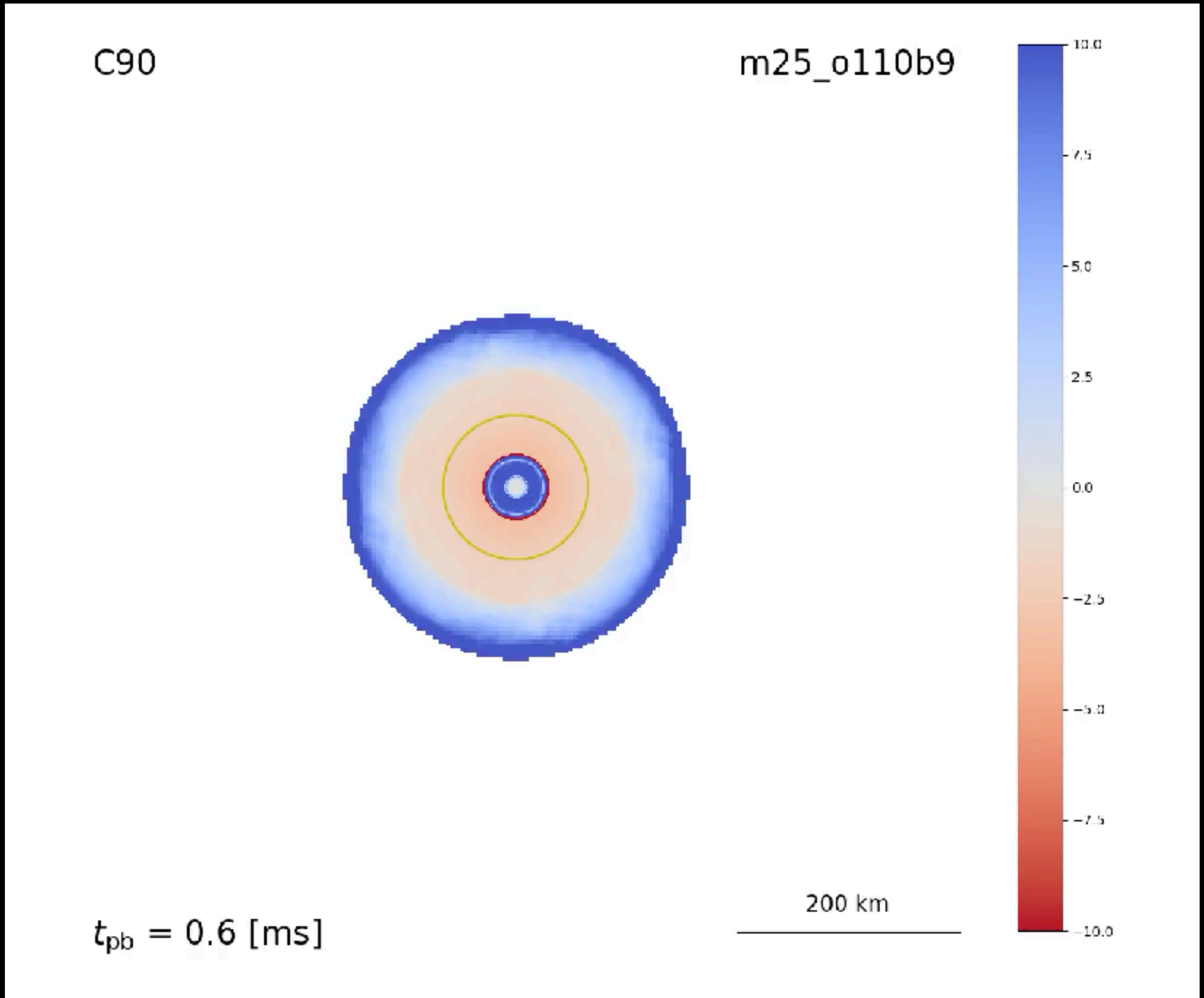
$$\lambda_{crit} = \frac{2\pi}{k_{crit}} = \frac{2\pi|v_A|}{\sqrt{-(N^2 + R_\omega)}}$$

$$C_{90} = (N^2 + R_\omega)/\Omega^2$$





$$m25, \Omega = 1.1, B = 10^9$$

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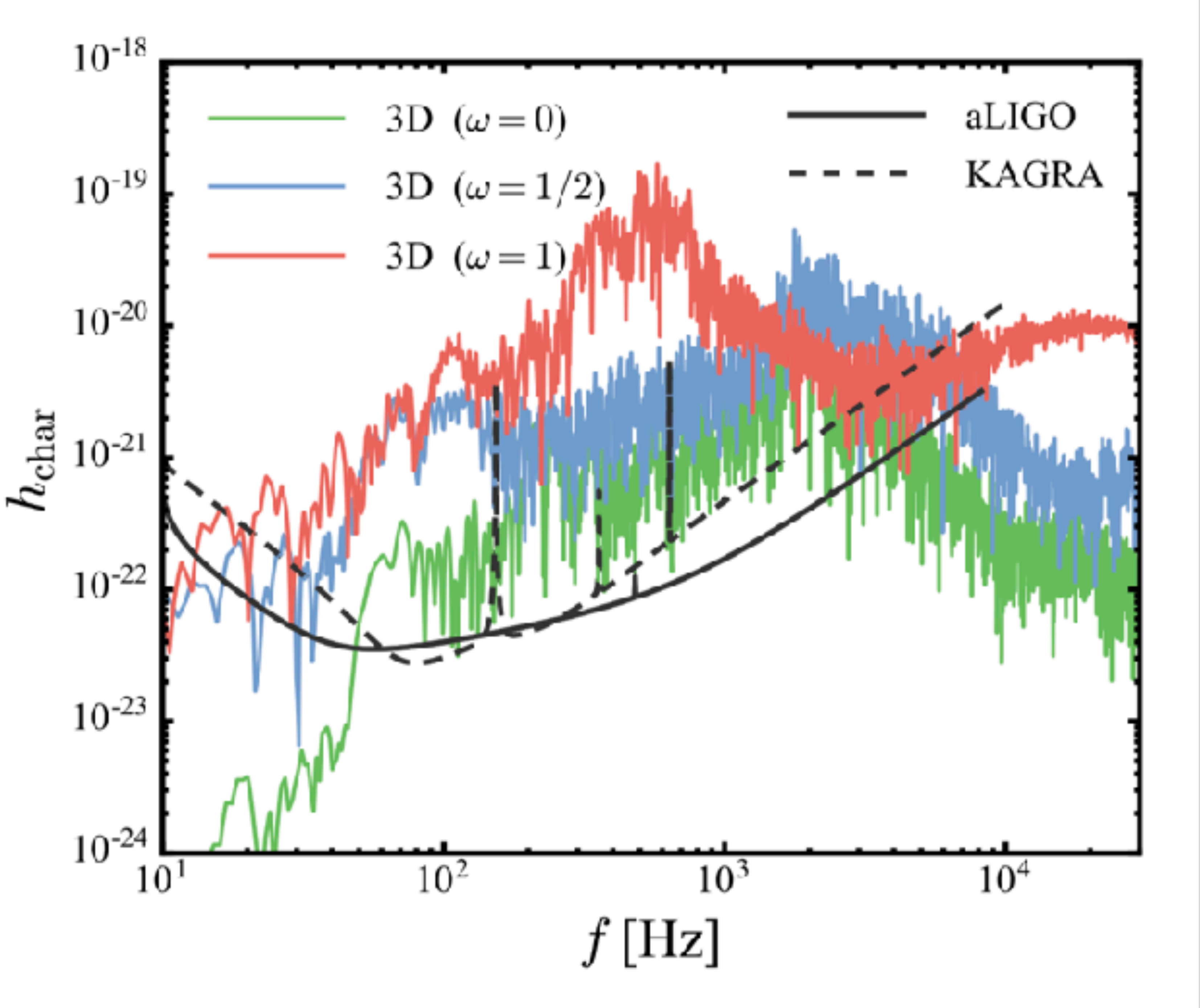
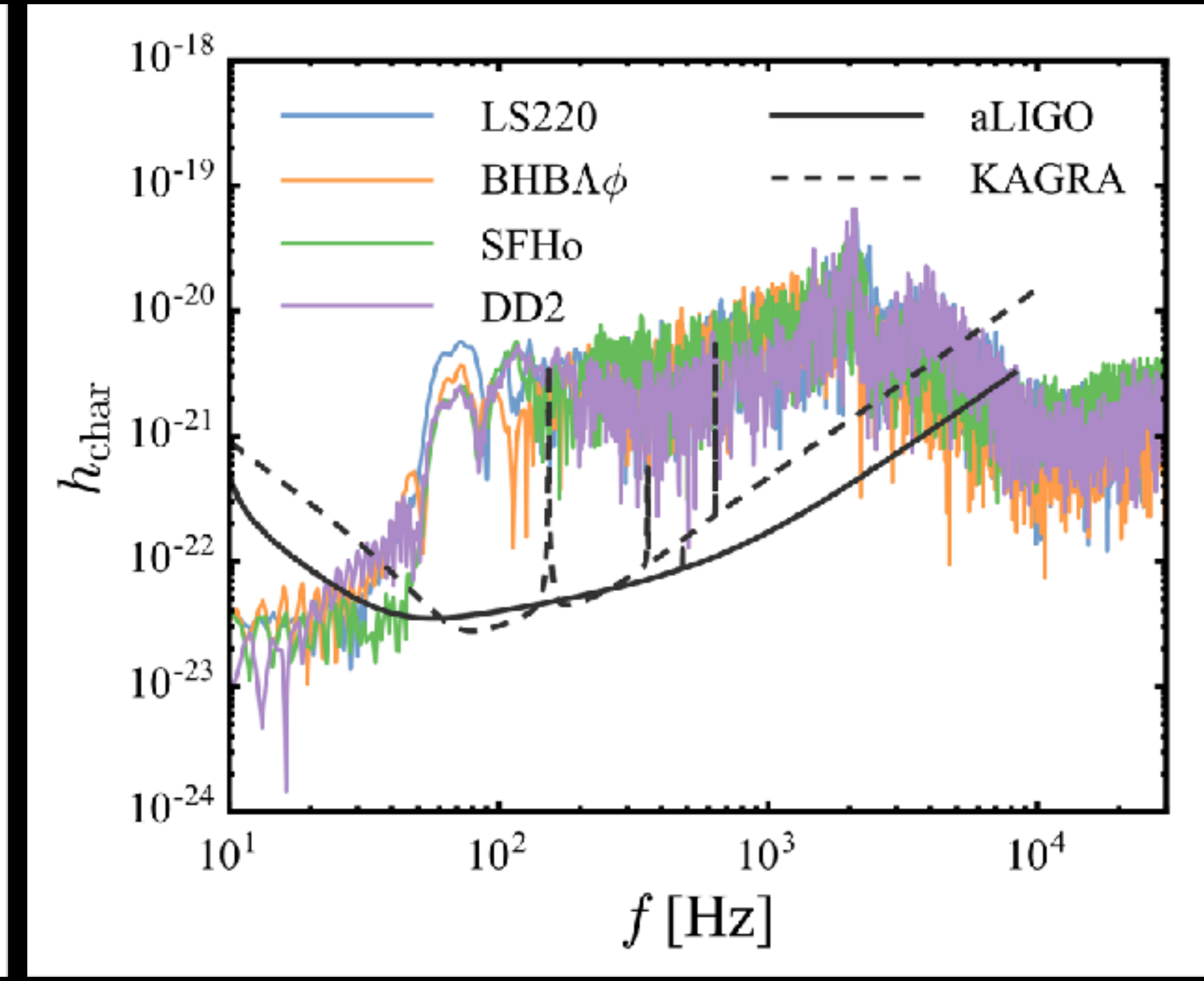
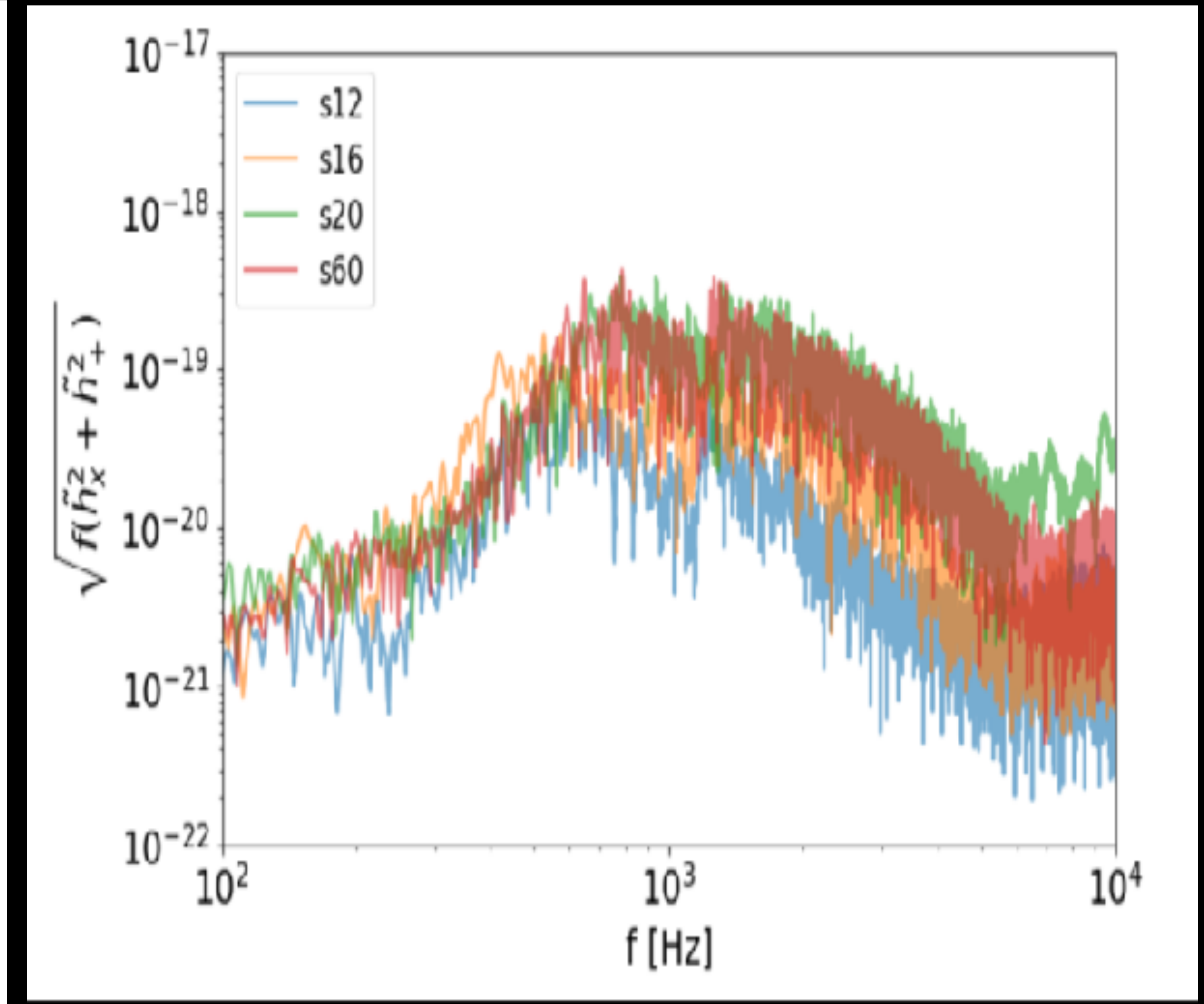
Detectability of GW emissions



Pan et al. 2021



Pan et al. 2018



Pan et al. in prep.

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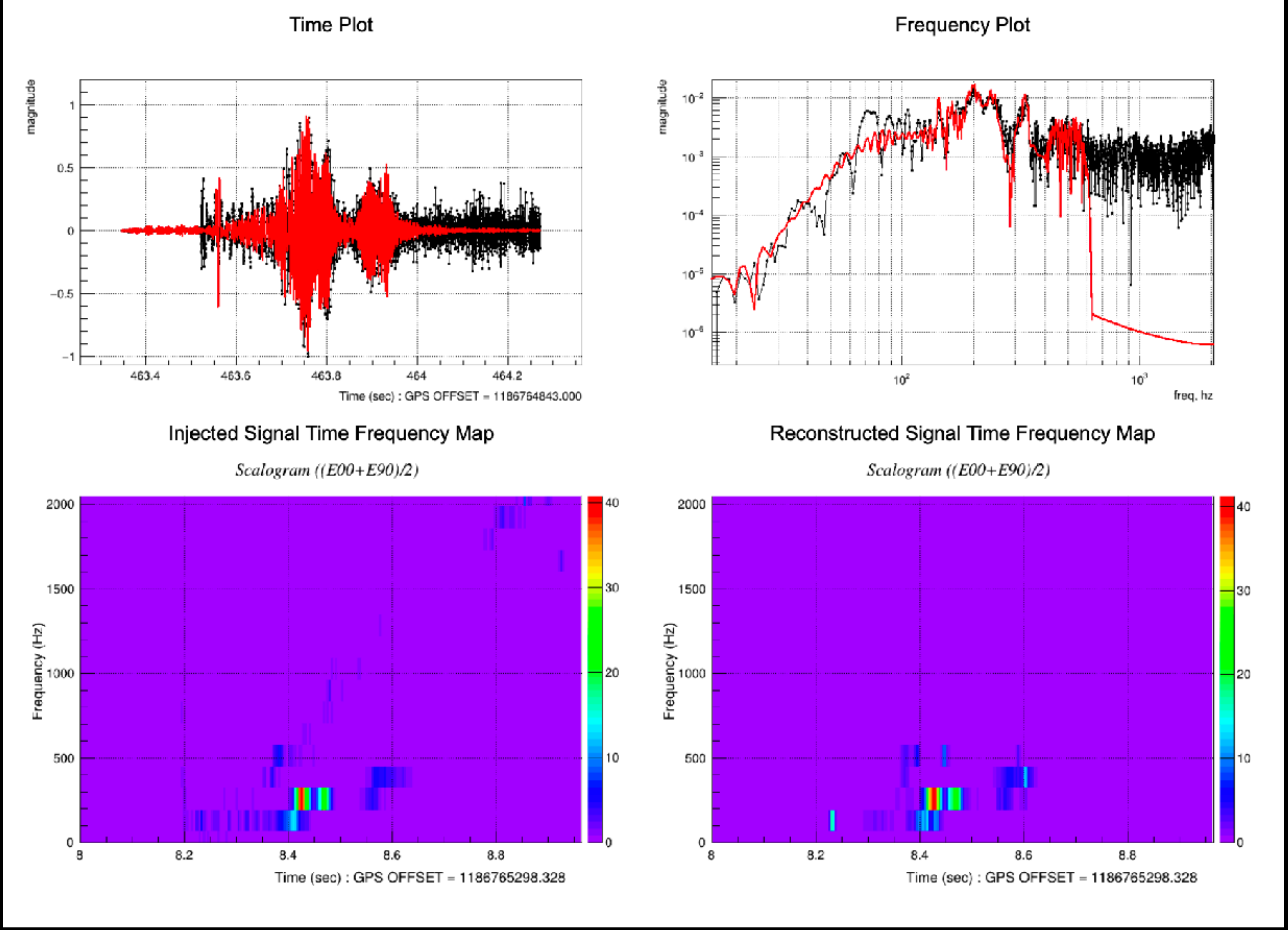
cWB analysis

Made by M. Szczepańczyk (Couch et al. in prep.)

SNR 30

O2 data
Livingston-Hanford network
100 source angles and locations



Non-Rotating SN

Black: injected
Red: reconstructed

Made by M. Szczepańczyk (Couch et al. in prep.)

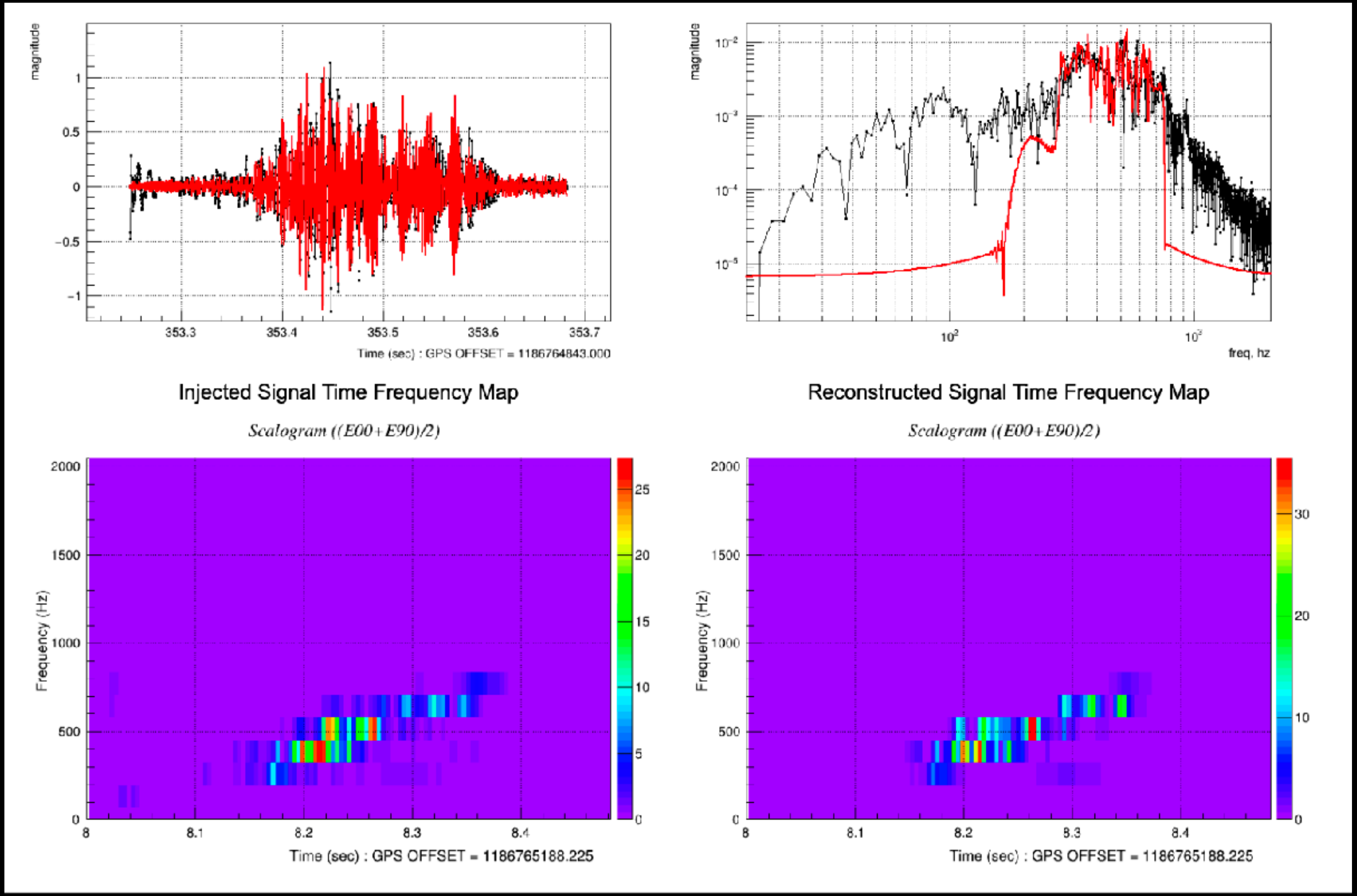
cWB analysis

SNR 30

O2 data
Livingston-Hanford network
100 source angles and locations

Fast Rotating Collapsar

Black: injected
Red: reconstructed



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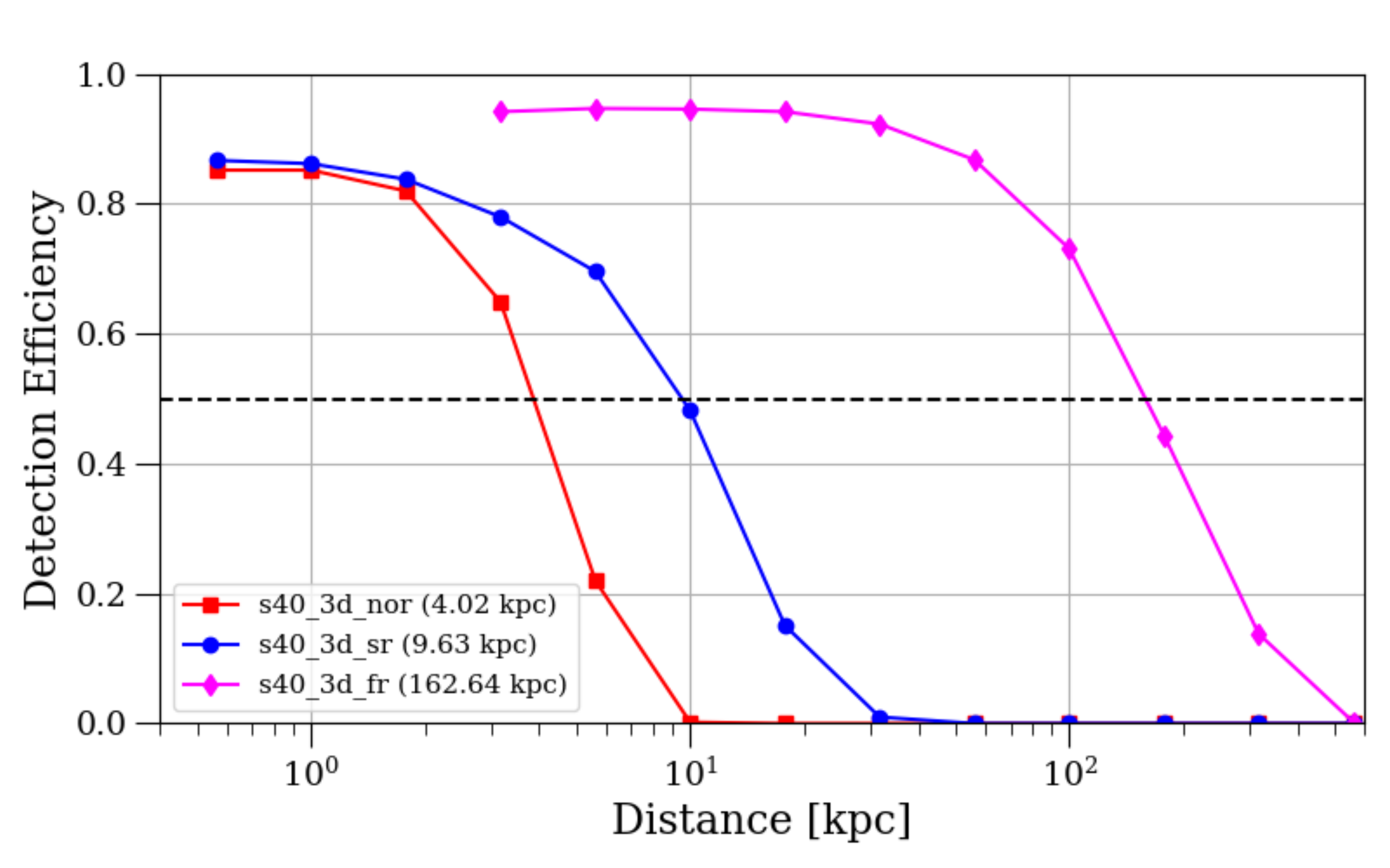
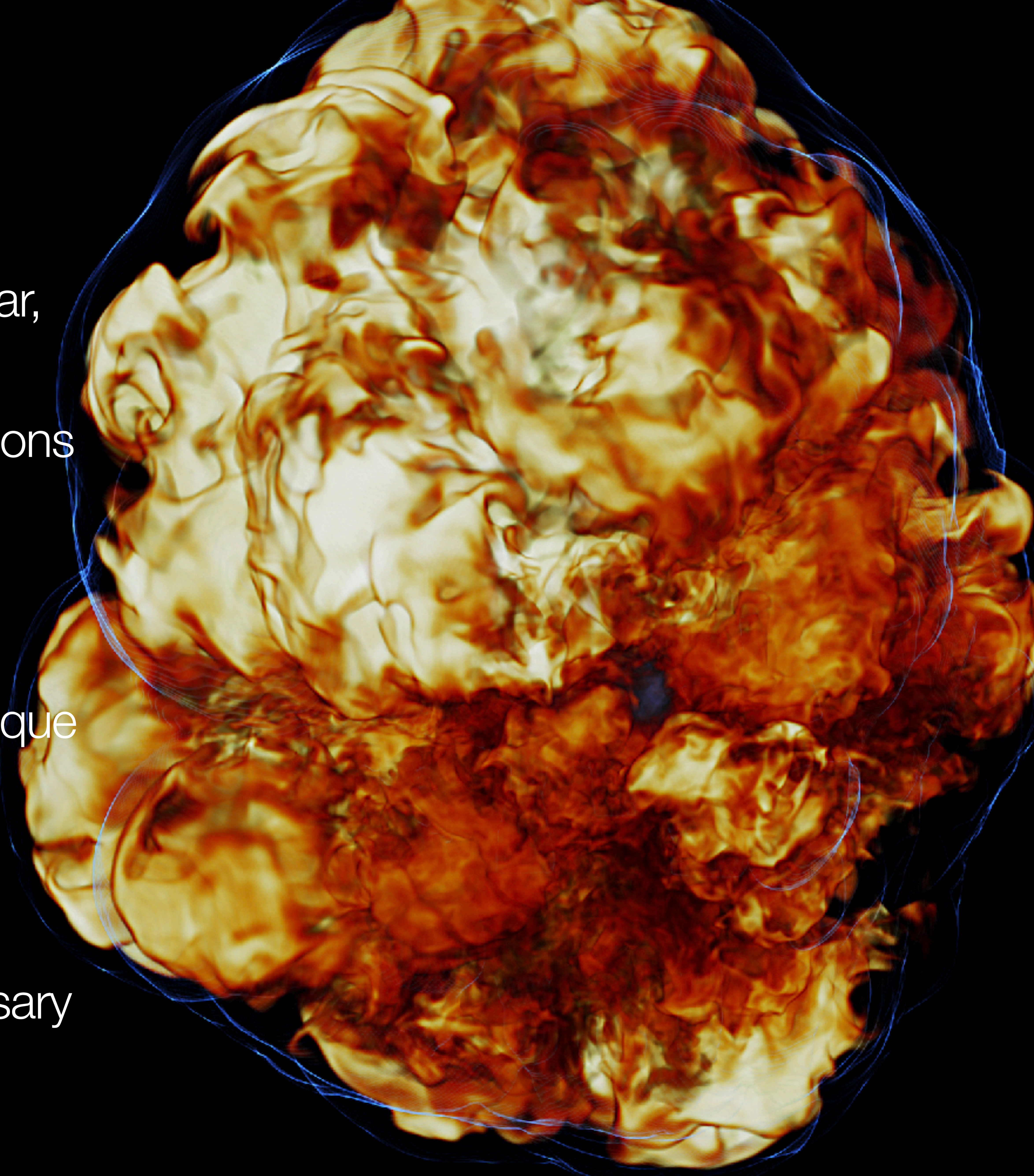
Detection Efficiency

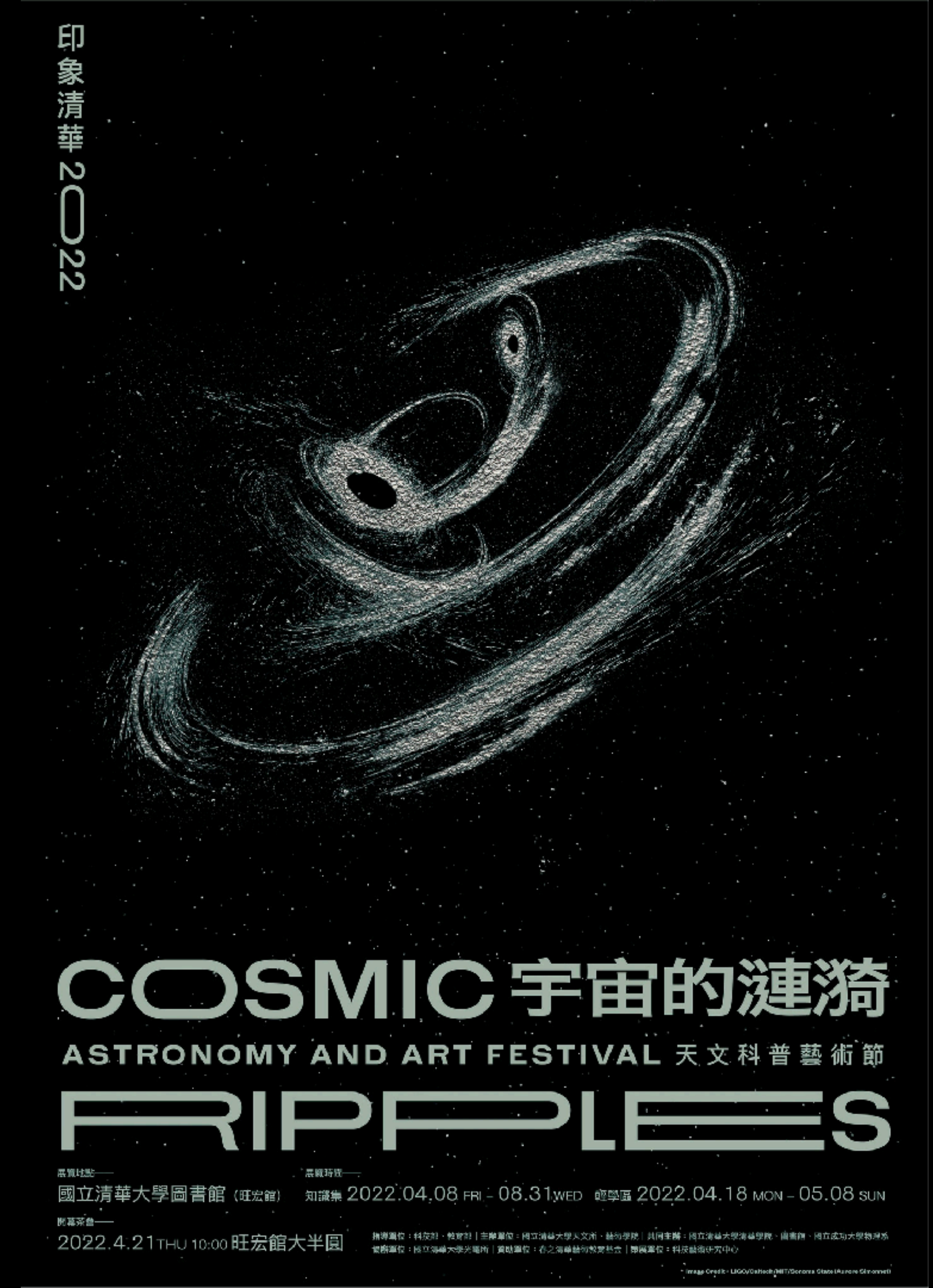
Made by M. Szczepańczyk (Couch et al. in prep.)



Summary & Conclusions

- Neutrino and GW probe the SN explosion, progenitor star, and nuclear EoS
- Turbulence (require high resolution) affect the GW emissions
- NS/BH spins can be induced by spiral SASI
- GW features from SASI (~100-200 Hz) is possible to be detected
- The serial instabilities in fast rotating progenitors emit unique GW signals
- GW from fast rotating CCSNe can be detected beyond Milky Way
- Improve the detector sensitivity at kHz window is necessary for studying long-term CCSN evolutions





宇宙的漣漪 Cosmic Ripples

知識集：04/08 - 08/31

輕學區：04/18 - 05/08

Kuo-Chuan Pan


印象清華2022
COSMIC 宇宙的漣漪
ASTRONOMY AND ART FESTIVAL 天文科普藝術節
RIPPLES
展覽地點——
國立清華大學圖書館（旺宏館）
展覽時間——
知識集 2022.04.08 FRI – 08.31 WED 輕學區 2022.04.18 MON – 05.08 SUN
開幕茶會——
2022.4.21 THU 10:00 旺宏館大半圓
指導單位：科技部、教育部｜主辦單位：國立清華大學天文所、藝術學院｜共同主辦：國立清華大學清華學院、圖書館、國立成功大學物理系
協辦單位：國立清華大學光電所｜贊助單位：春之清華藝術教育基金｜策展單位：科技藝術研究中心