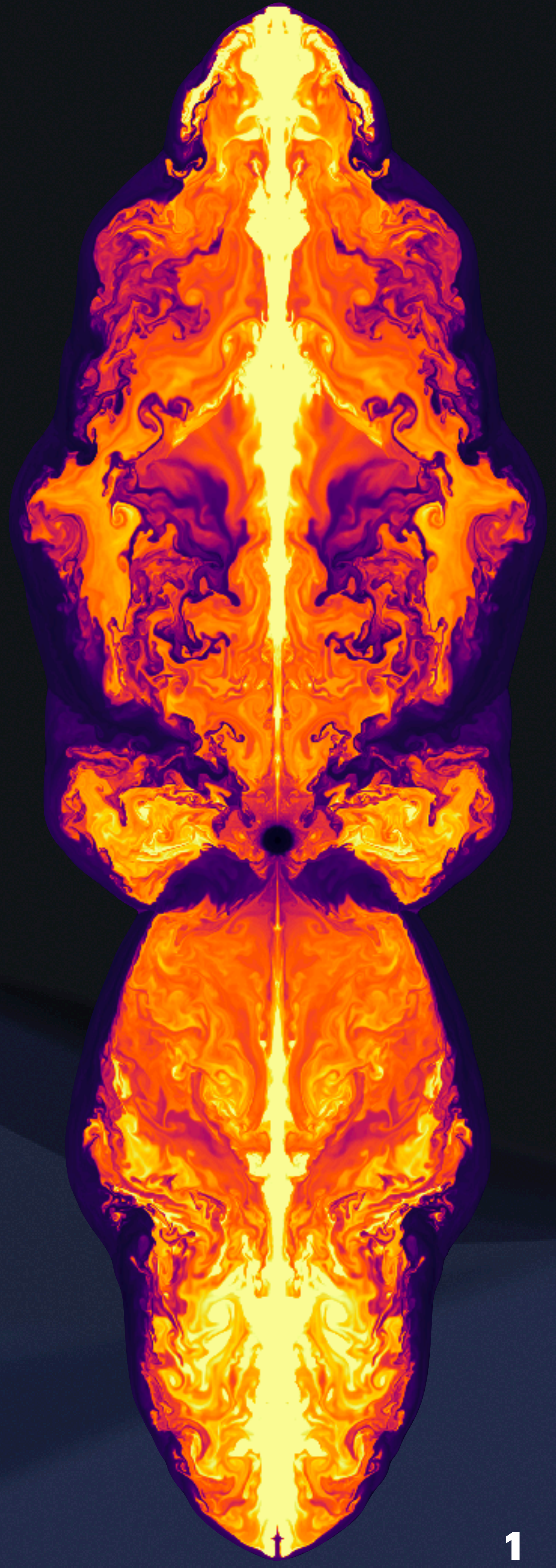
Gravitational wave emissions from Core-Collapse Supernovae



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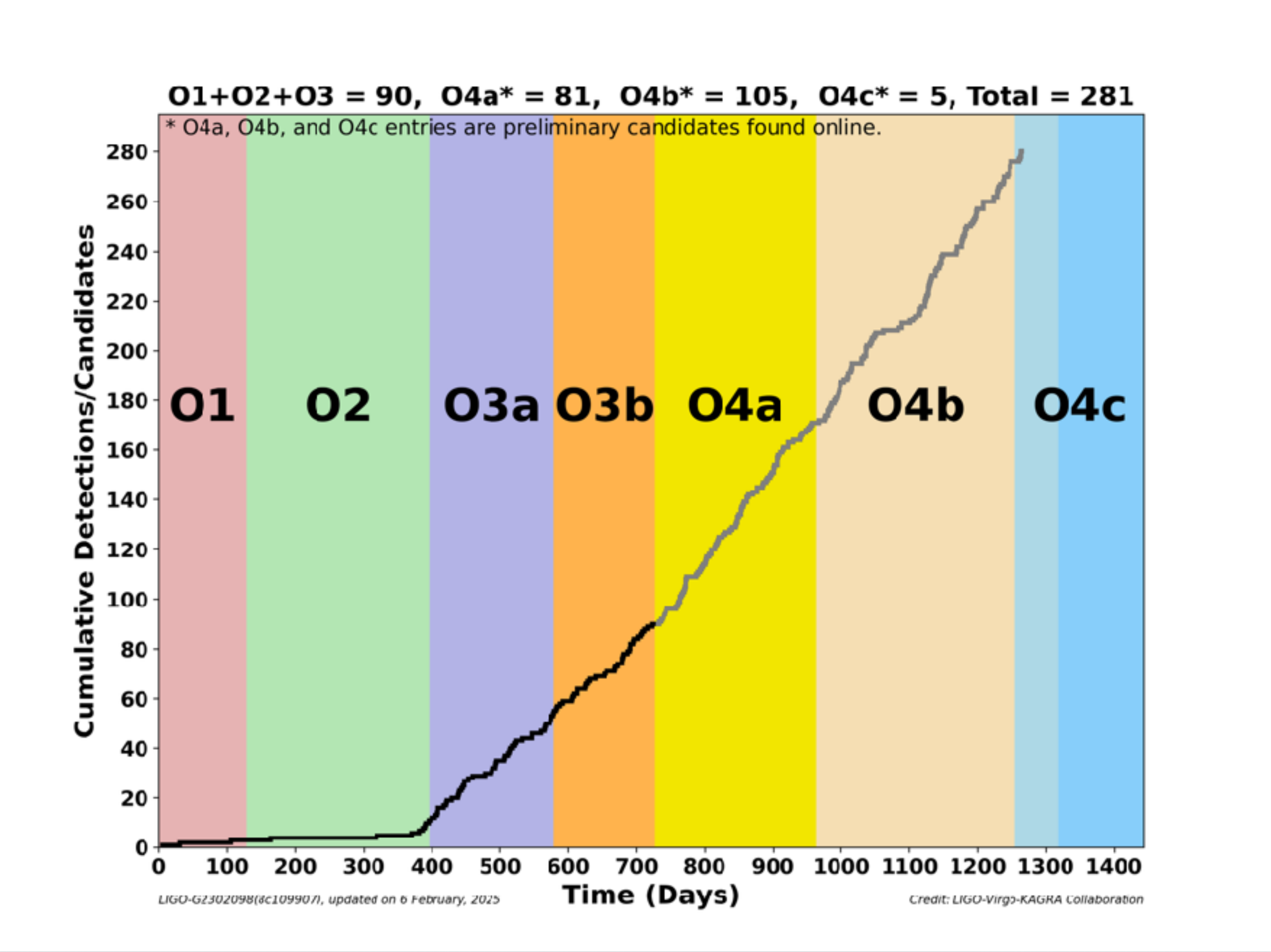
2nd OMU-NTHU joint meeting @ Hsinchu 02/08/2025

Introduction & Motivations

- We have entered the gravitational wave astrophysics era (a whole new way to **HEAR** the Universe)
- There are more than 281 GW events detected. All of them are Compact Binary Coalescences (CBC)
- Detection of GW from Core-Collapse Supernova (CCSN) is the next milestone



Credit: LIGO-Virgo-KAGRA

Introduction & Motivations

- Core-collapse supernovae (CCSNe) are energetic stellar explosions from the deaths of massive stars (M > 8 Msun)
- Very luminous (1 foe); as bright as a galaxy
- Birthplaces of neutron stars and stellar mass black holes
- Chemical enrichment in galaxies
- Observe more than 1 SN per data —> Data-driven science (ML / AI)
- Connections to Gamma-Ray Bursts (GRB) or Fast Radio Bursts (FRB)

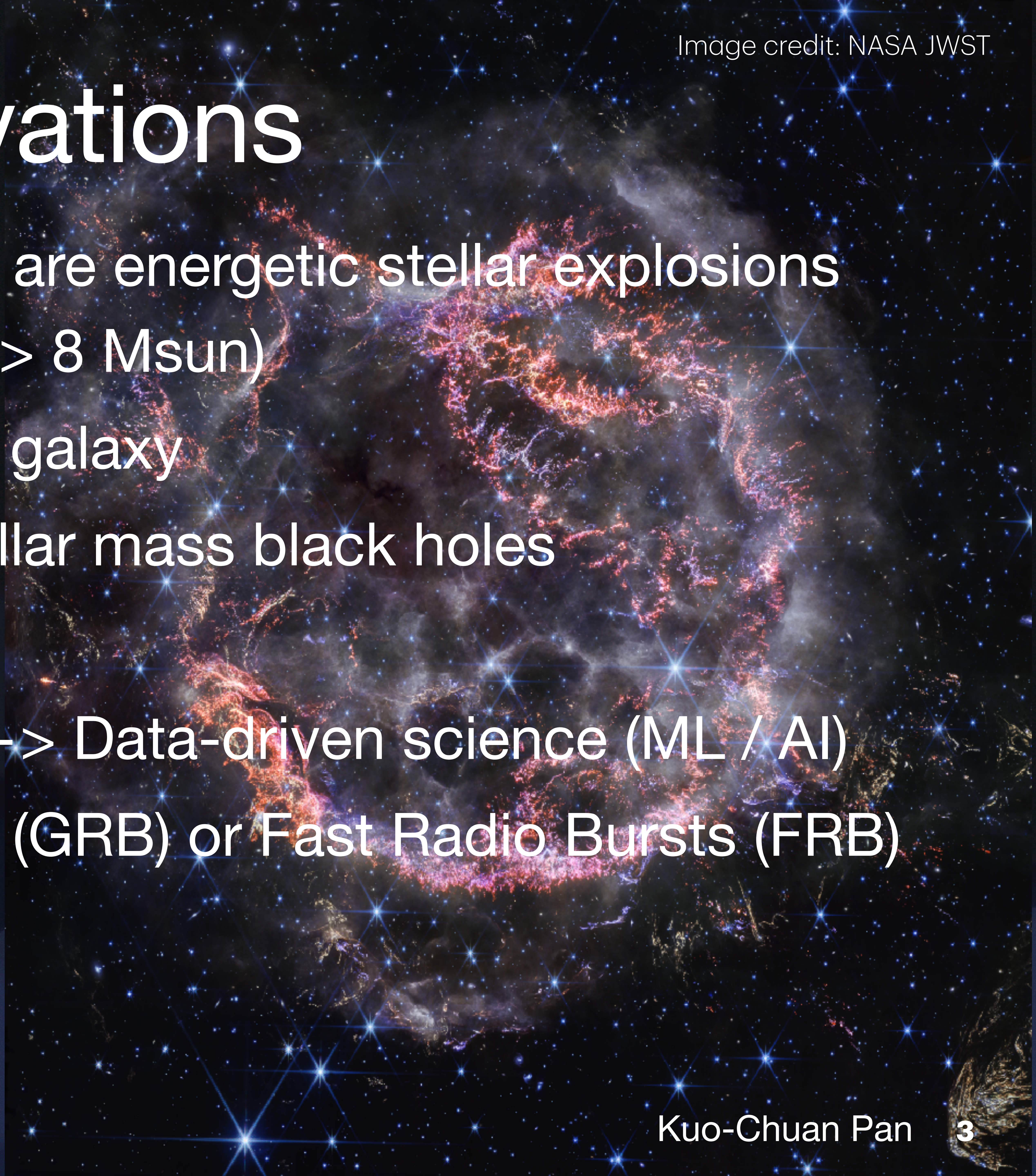
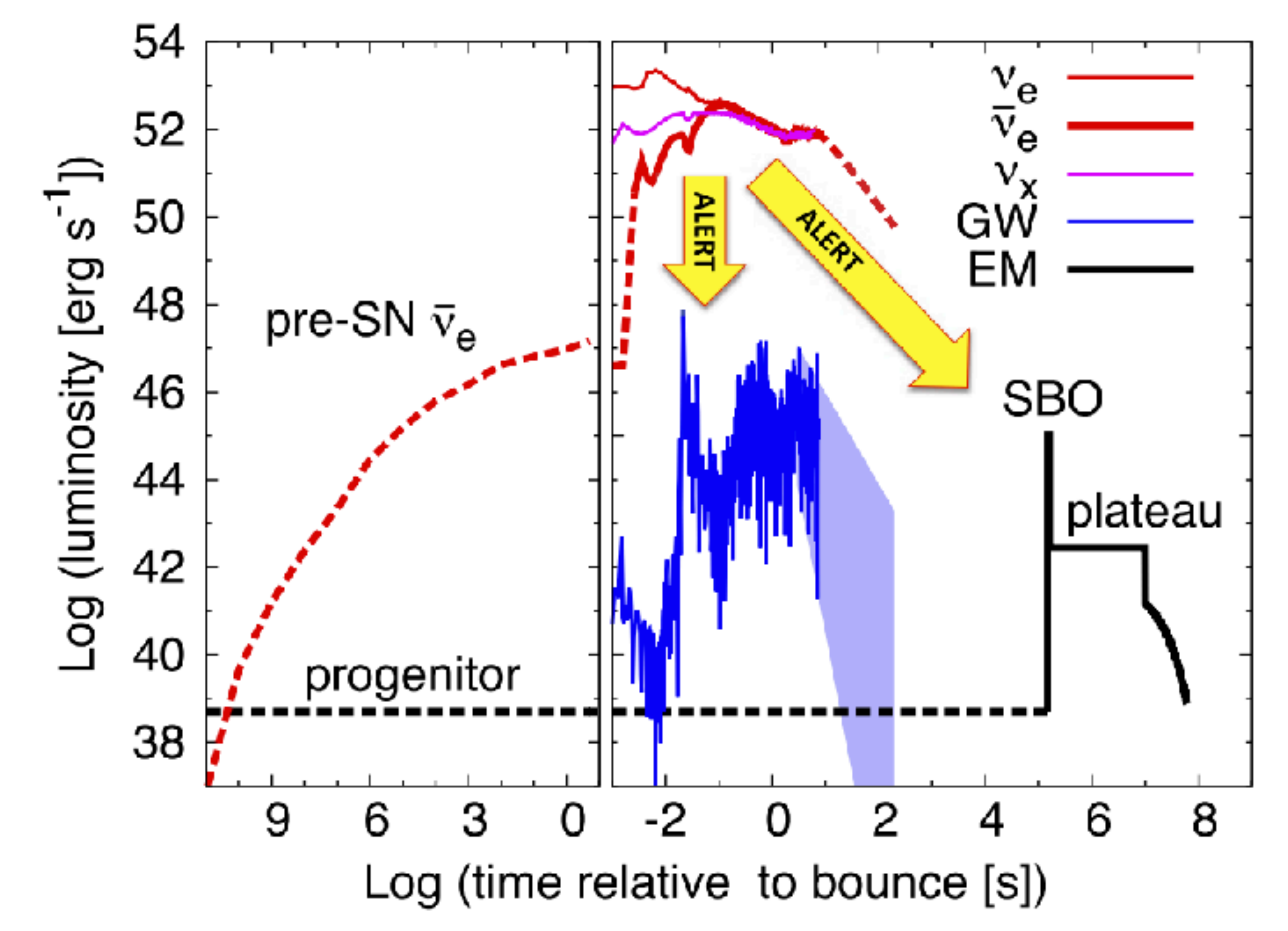


Image credit: NASA JWST

Multi-messenger Signals from CCSNe

- CCSNe are ideal multi-messenger (MM) sources
  - Neutrino (~10^{53} erg)
  - Kinetic (~10^{51} erg)
  - Radiation (~10^{49} erg)
  - Gravitational Waves (~10^{47} erg)

- Co-detection from multiple messengers could provide meaningful constraints on the supernova engine(s) and nuclear physics

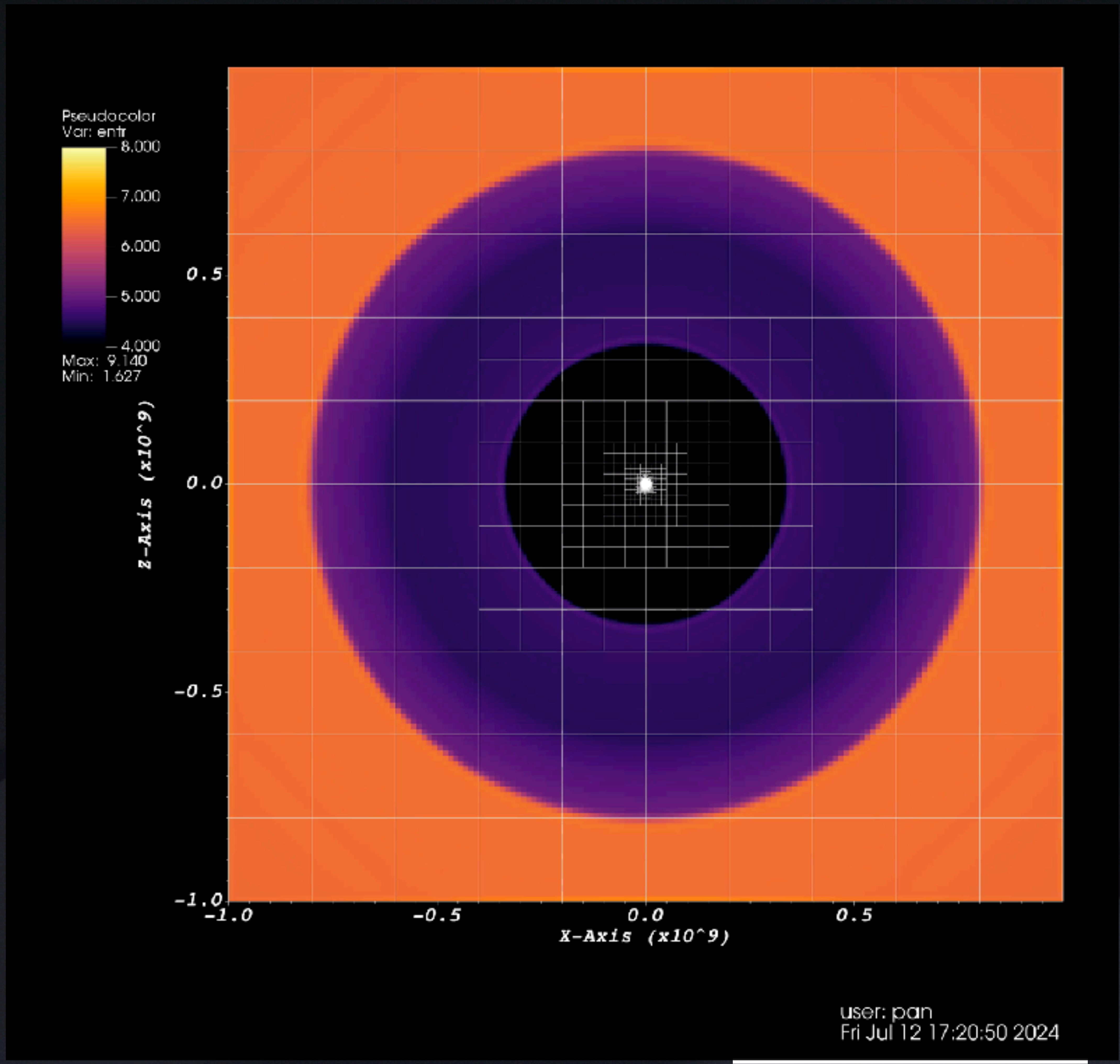


Kharusi et al. (2021)

Motivation: Several fundamental questions

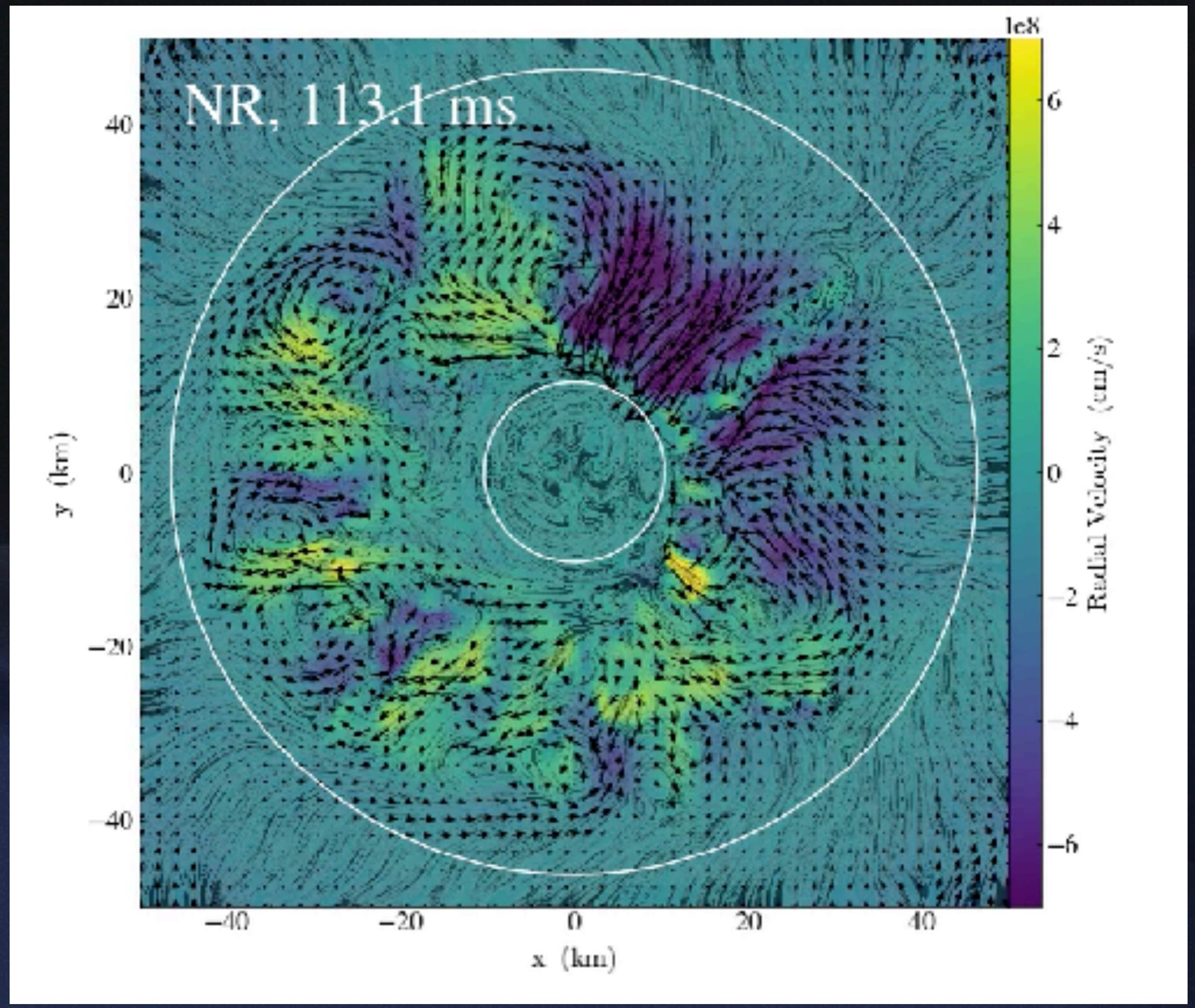
The computational explosive astrophysics group in IoA, NTHU

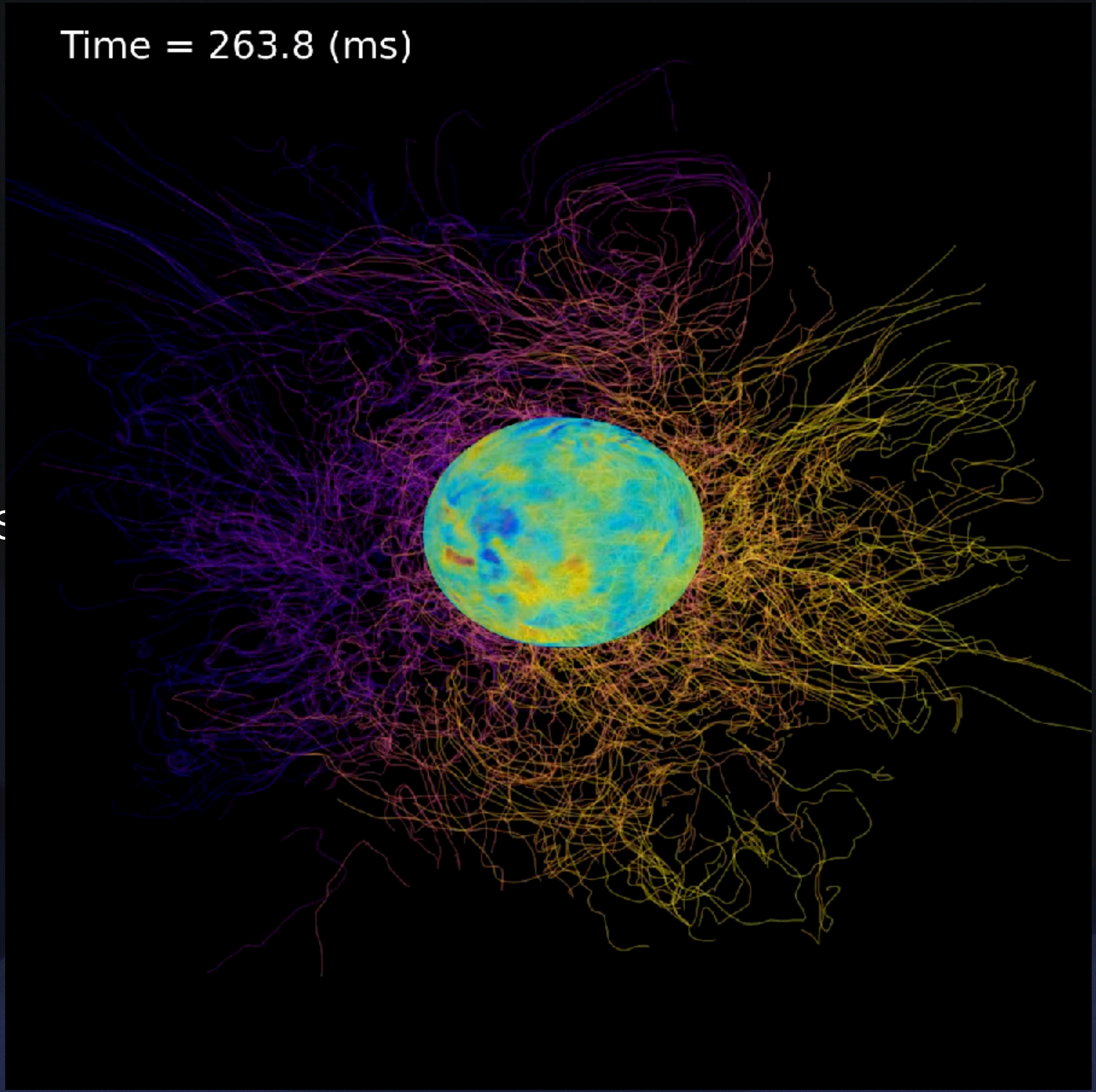
- FLASH Code (1D/2D/3D)
- IDSA for neutrino transport (Pan et al. 2016, 2019)
- Effective general relativity (Pan et al. 2017, 2018, 2021)
- Nuclear EoS from stellar collapse.org
- GPU acceleration (Pan et al. 2021)
- Code comparison studies (Pan et al. 2019, Cabezon et al. 2018)
- GW emission modules (Pan et al. 2018, 2021)
- Binary progenitors (Wang & Pan 2024)
- MHD enabled (Li et al. 2025, in prep.)
- State-of-the-art resolutions (using Taiwania 3)
- … and more …




Time = 548.9 (ms)
Credit: The Institute of Astronomy at National Tsing Hua University, Taiwan.
影像來源：國立清華大學 天文所 動畫模擬
Entropy (k_B/by)
核心坍縮超新星
Core-collapse supernovae

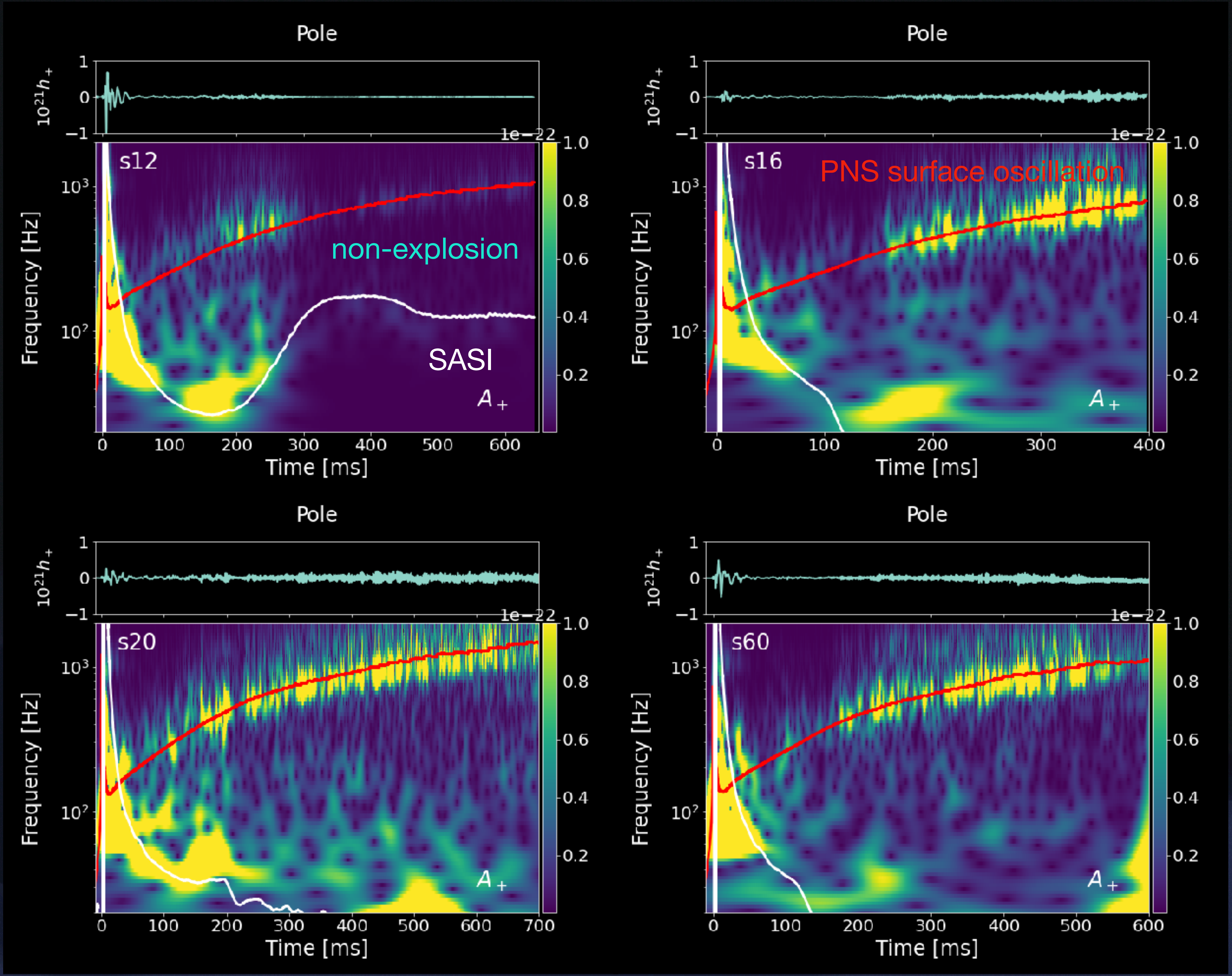
The Proto-Neutron Star

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



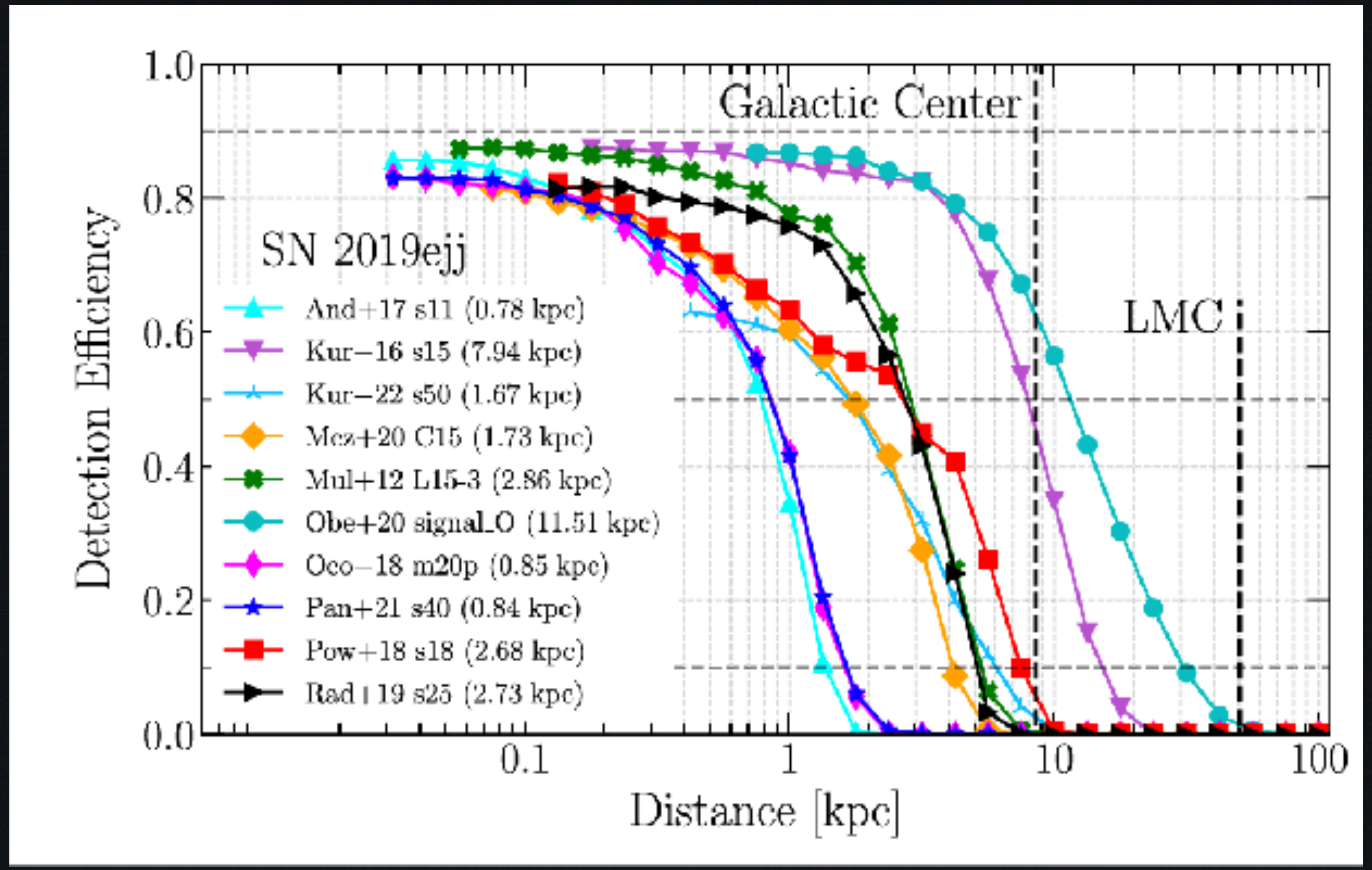
Spectrograms

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

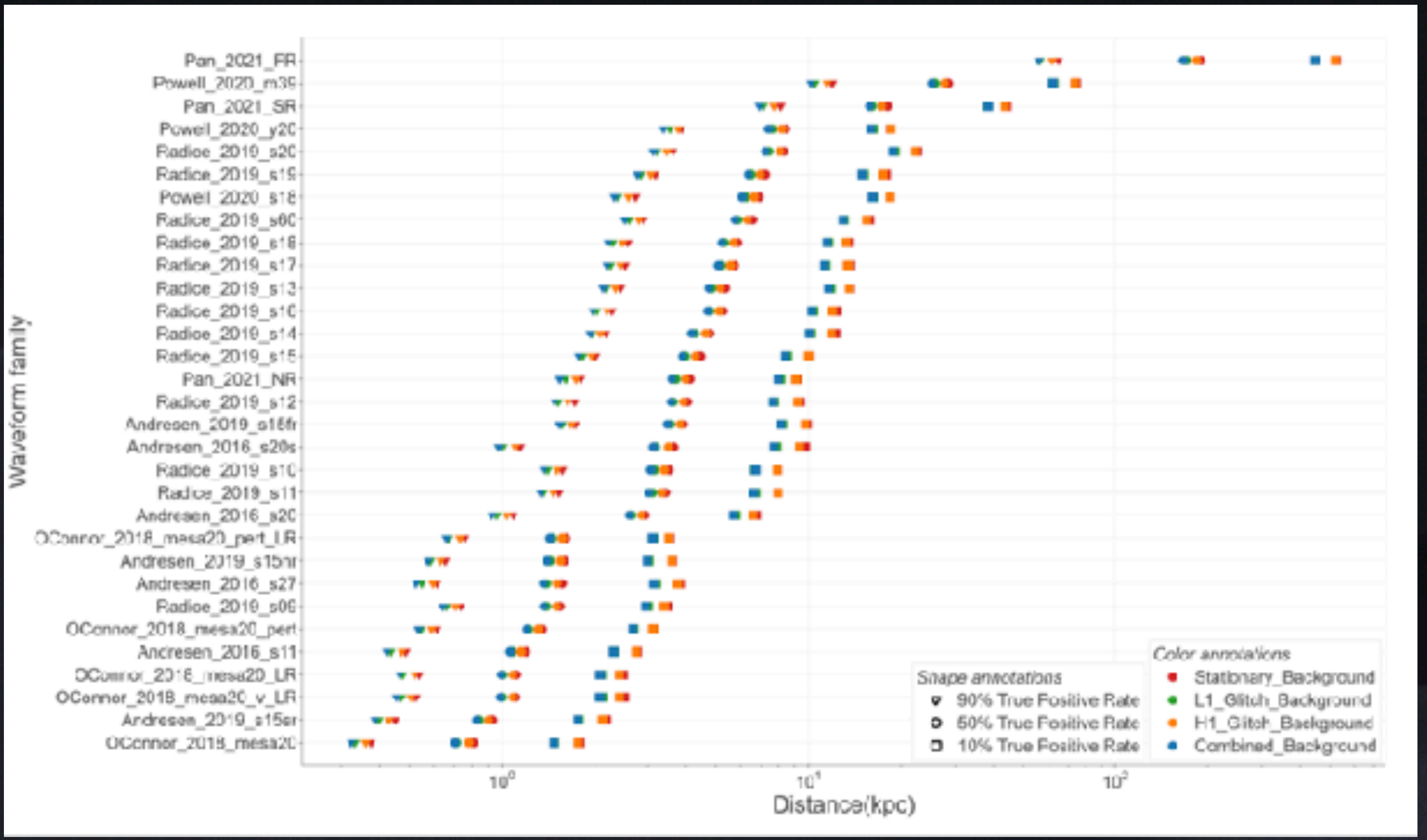


Extreme CCSN events

- Gravitational wave calculations from Multi-D CCSN simulations suggest that only galactic normal CCSNe could be detected by the current LVK network
- Extreme conditions such as fast-rotating or magnetized CCSN are more likely to be detected

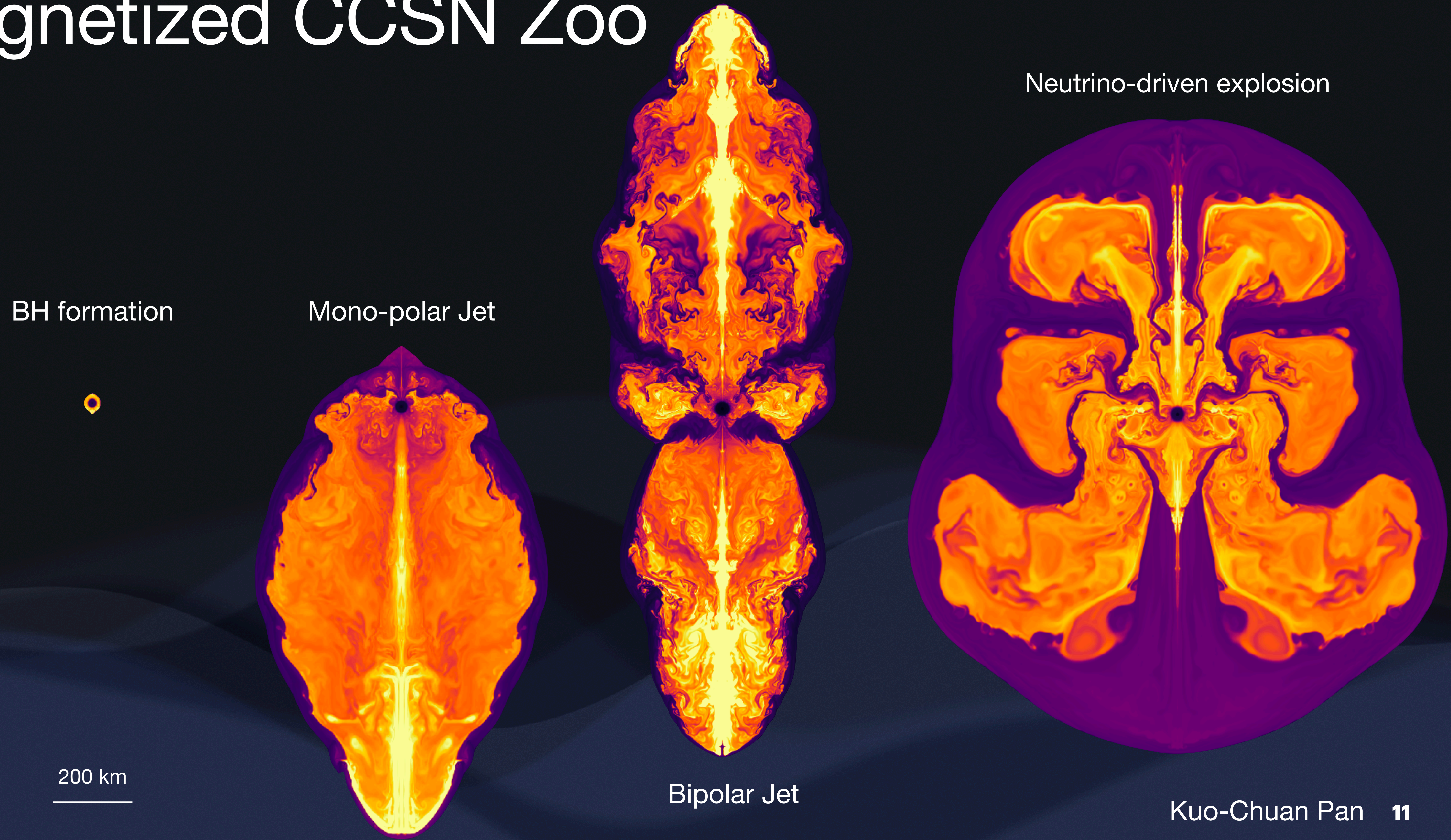


Szczepańczyk et al. (2024)



Chen et al. (+KCP). in prep.

Magnetized CCSN Zoo



Kuo-Chuan Pan

s40 Shock dynamics (rotating models)

- Non-magnetized models all form a BH
- Strong B-field could trigger explosions in non-rotating models
- Neutrino-driven explosions are still possible in magnetized models
- Monopolar jets or bipolar jets could be launched in rotating models

W_0=0.5 rad/s	BH	Bipolar jet	Bipolar jet	Bipolar jet
W_0=0.2 rad/s	BH	Monopolar jet	Bipolar jet	Nu-Exp
W_0=0.1 rad/s	BH	Bipolar jet	Monopolar jet	Nu-Exp
W_0=0.05 rad/s	BH	Monopolar jet	Monopolar jet	Nu-Exp
W_0=0.0 rad/s	BH	BH	BH	Nu-Exp
	B_0=0	$B_0=10^{10}$	$B_0=10^{11}$	$B_0=10^{12}$

Bipolar Jet

Monopolar Jet

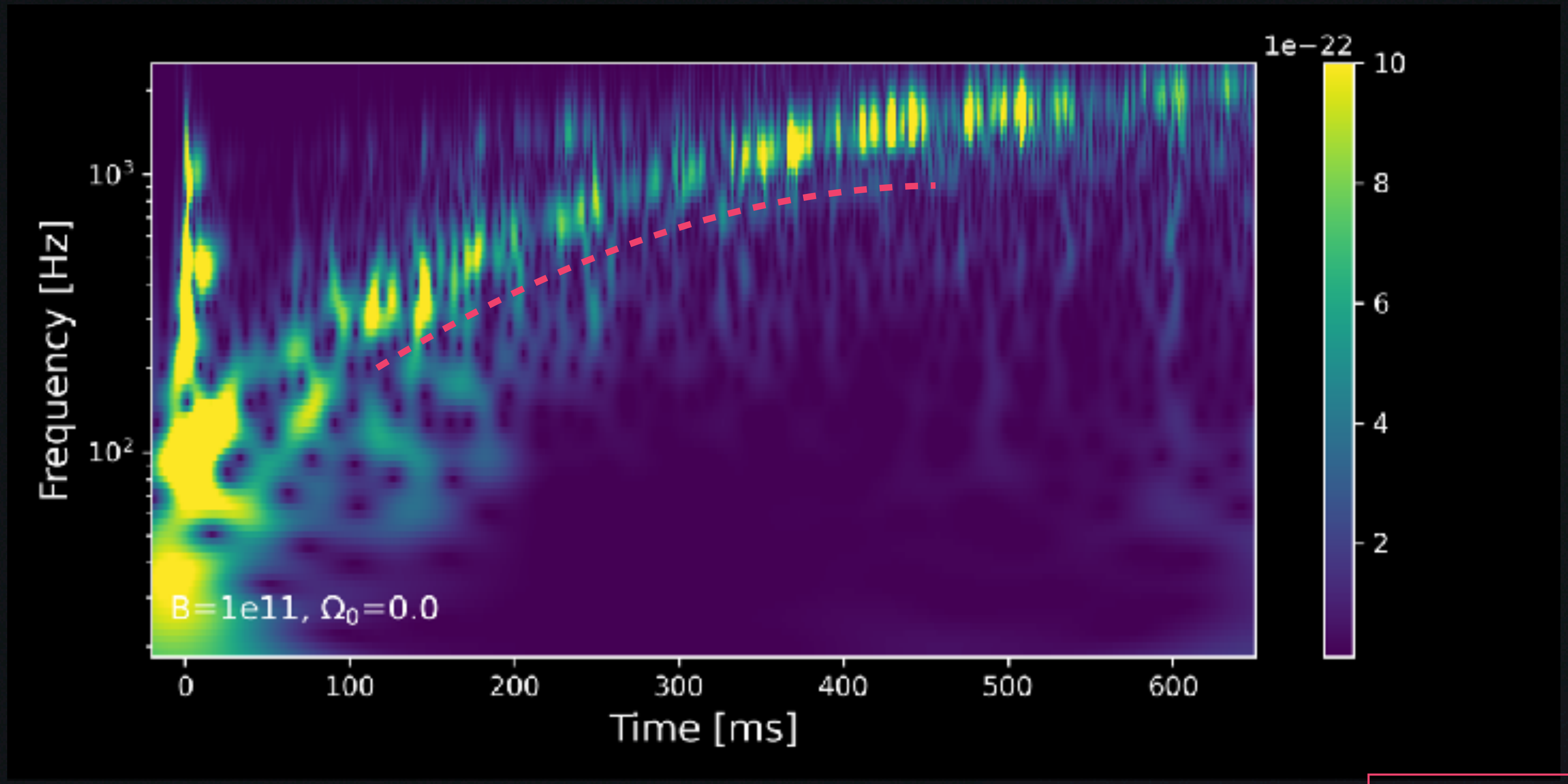
Black Hole formation

Neutrino-driven explosion

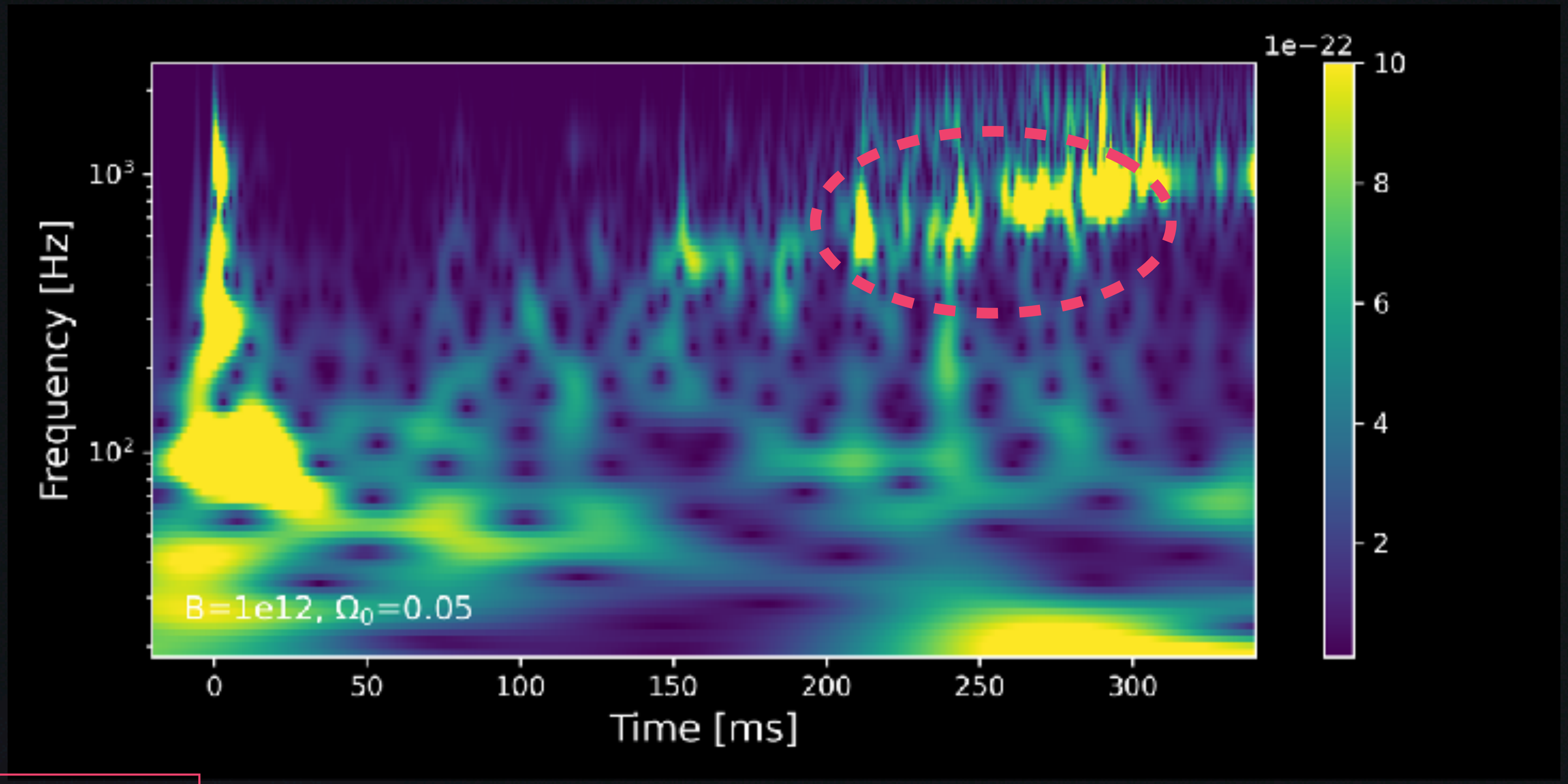
Preliminary

Multi-messenger Signals

BH formation

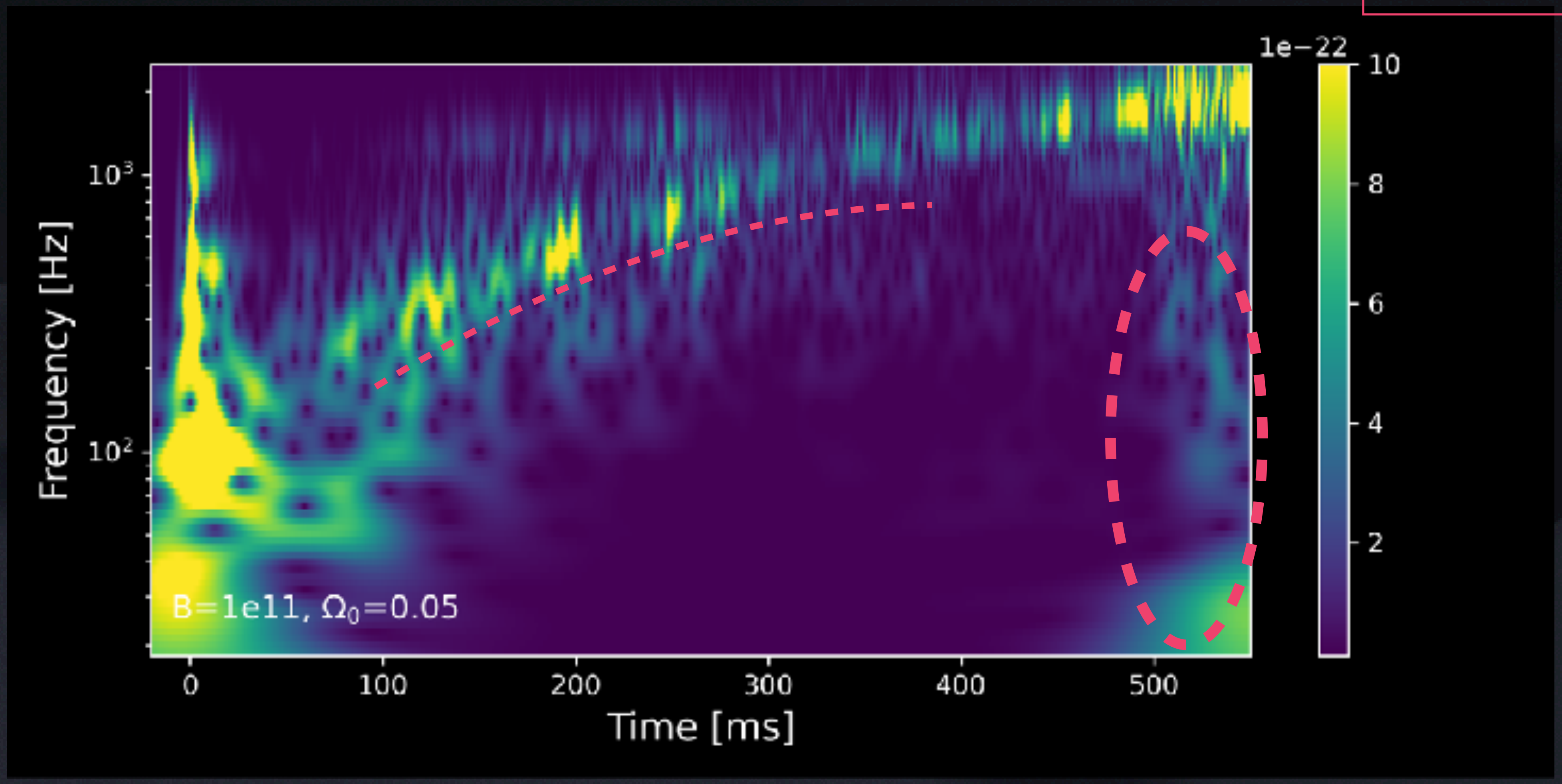


Neutrino-driven explosion

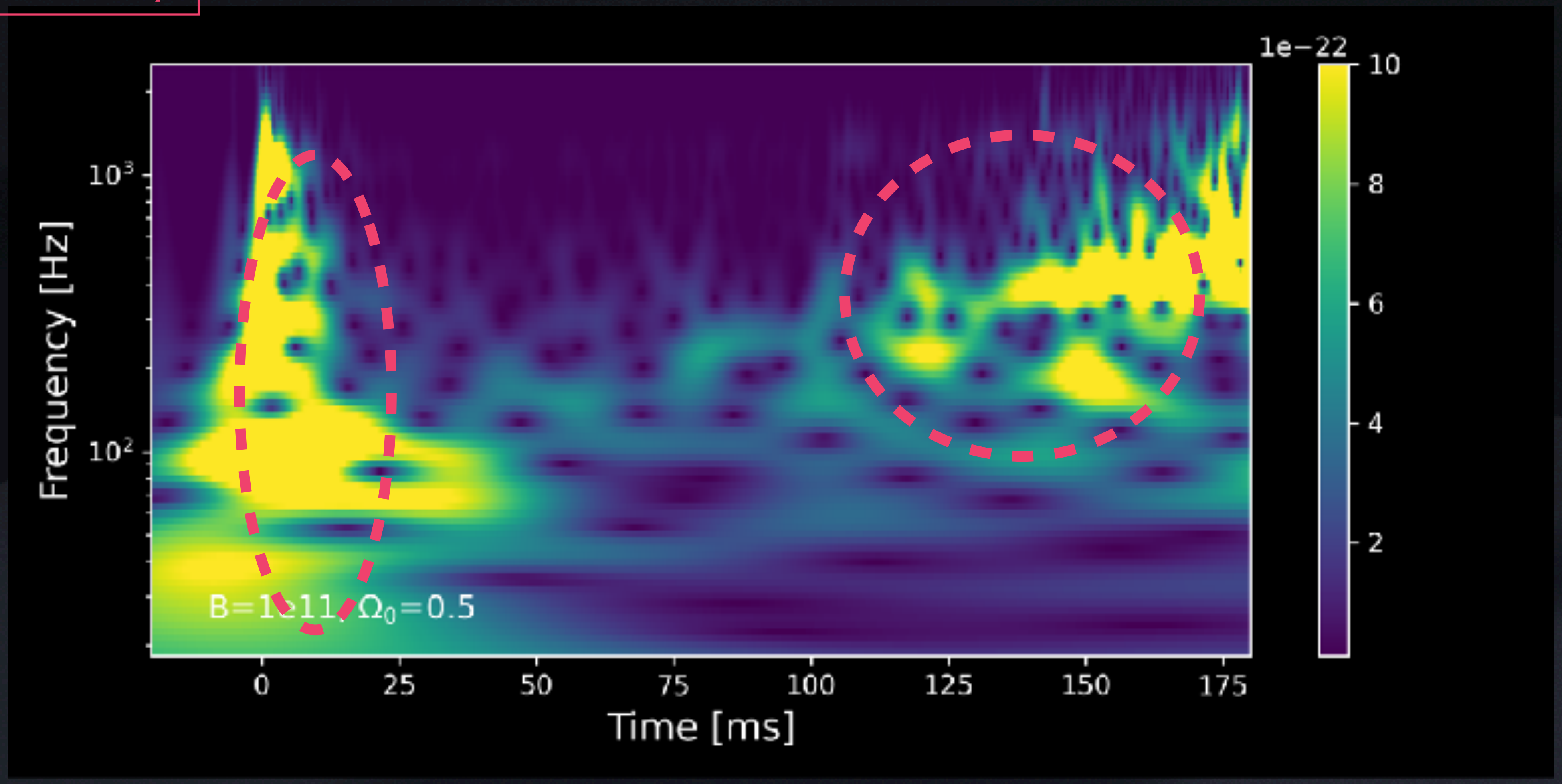


Preliminary

Monopolar Jet



Bipolar Jet



Multi-messenger Signals

- BH formation models show strong kHz signals
- MHD jet models have stronger GW emissions
- Fast rotating models show strong low frequency features

Assume distance = 10 kpc

Non-rotating models

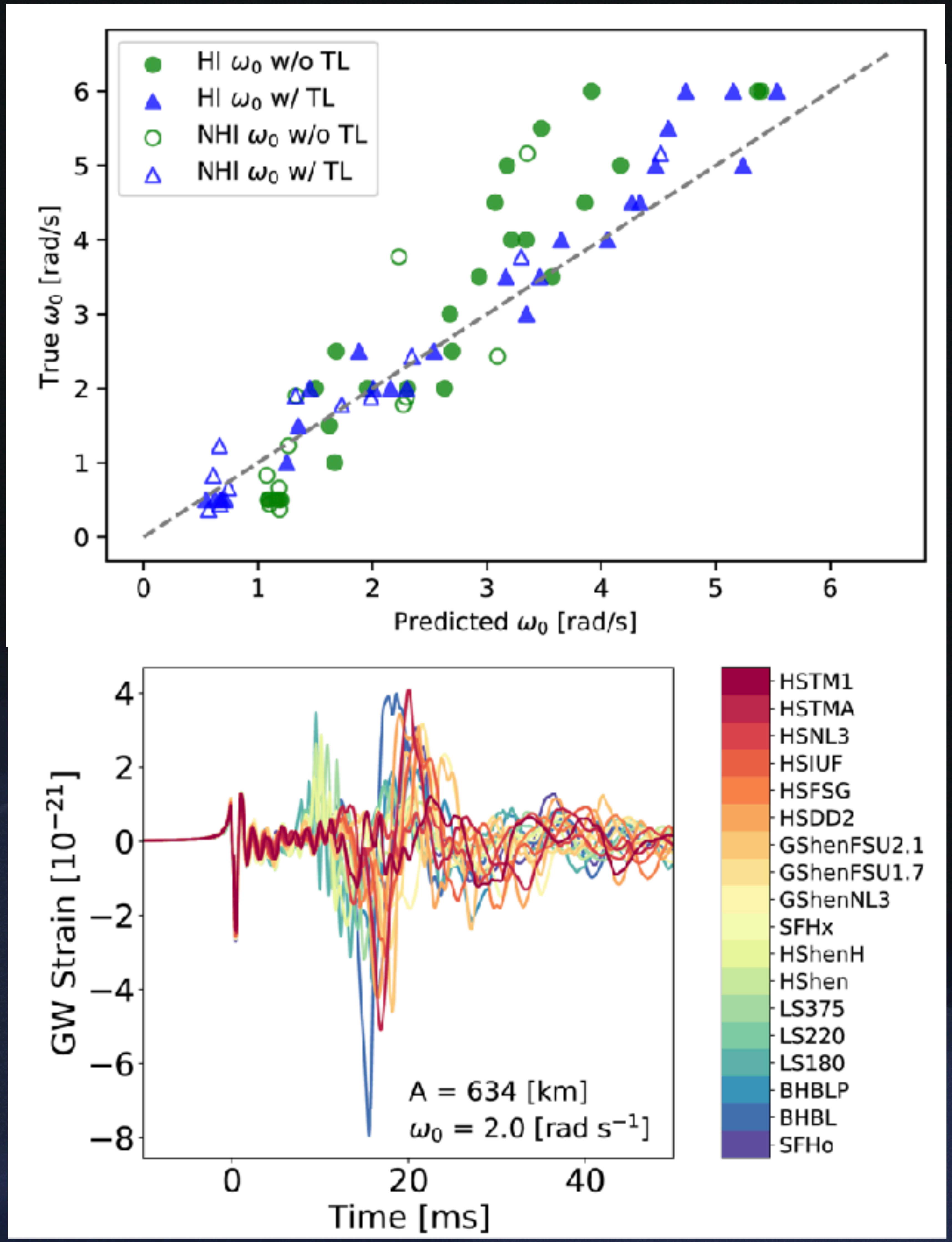
$B_0 = 10^{11}$

$B_0 = 10^{12}$

Searches for GWs from CCSNe

Chao et al., (+ K.-C. Pan) 2022 ApJ, 939, 13 (with Daw-Wei Wang)

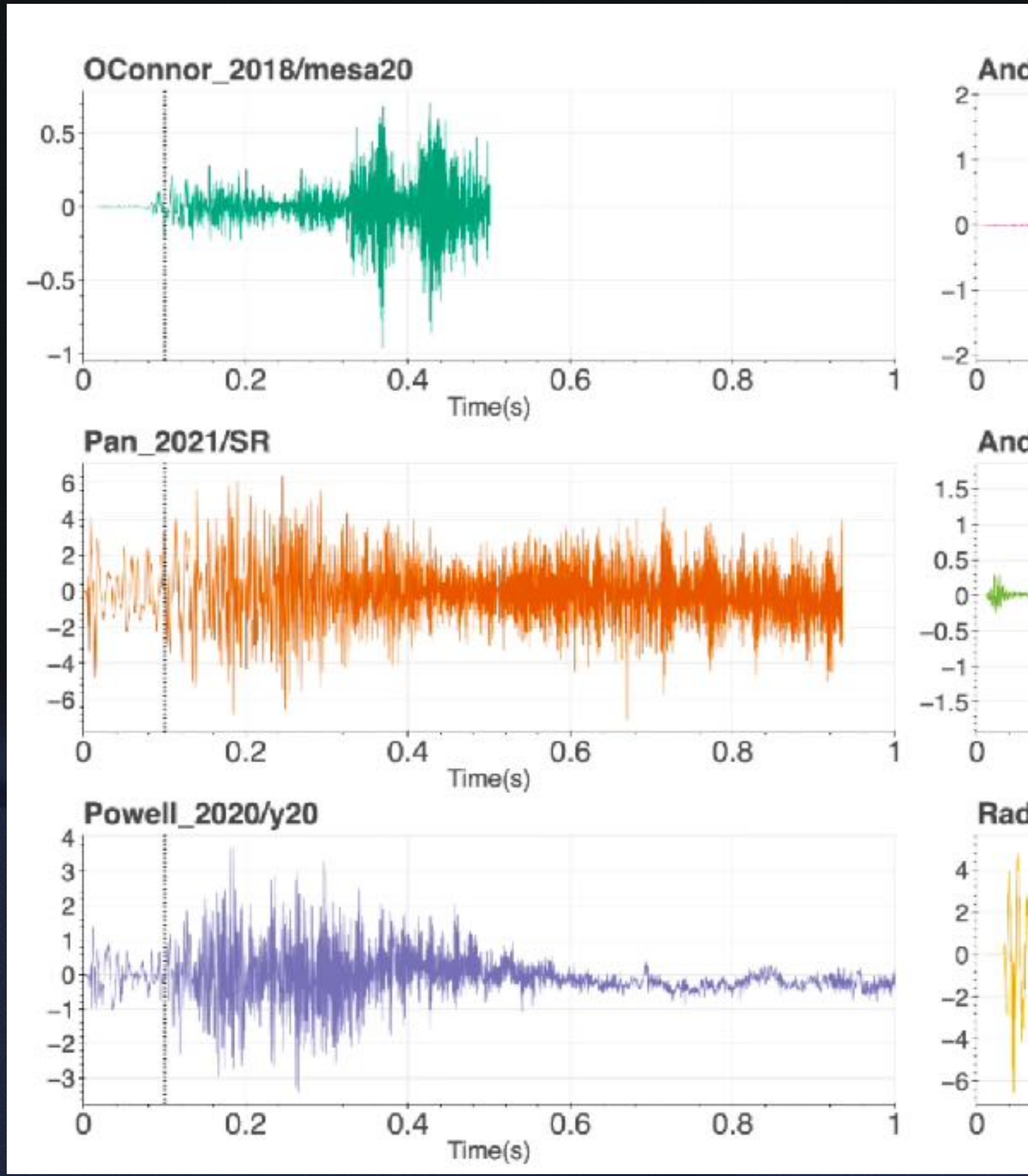
- 1824 waveforms from Richers et al. (2017)
- CNN models to identify the core rotational rates, length scale, and nuclear EoS
- Using [-10 ms, 6 ms] waveforms, 95% (93%) accuracy on identifying the rotational rates (length scale)
- Using [-10 ms, 54 ms], 96% accuracy on identifying the EoS groups
- Additional 84 forms from Pan et al. with Transfer learning is possible



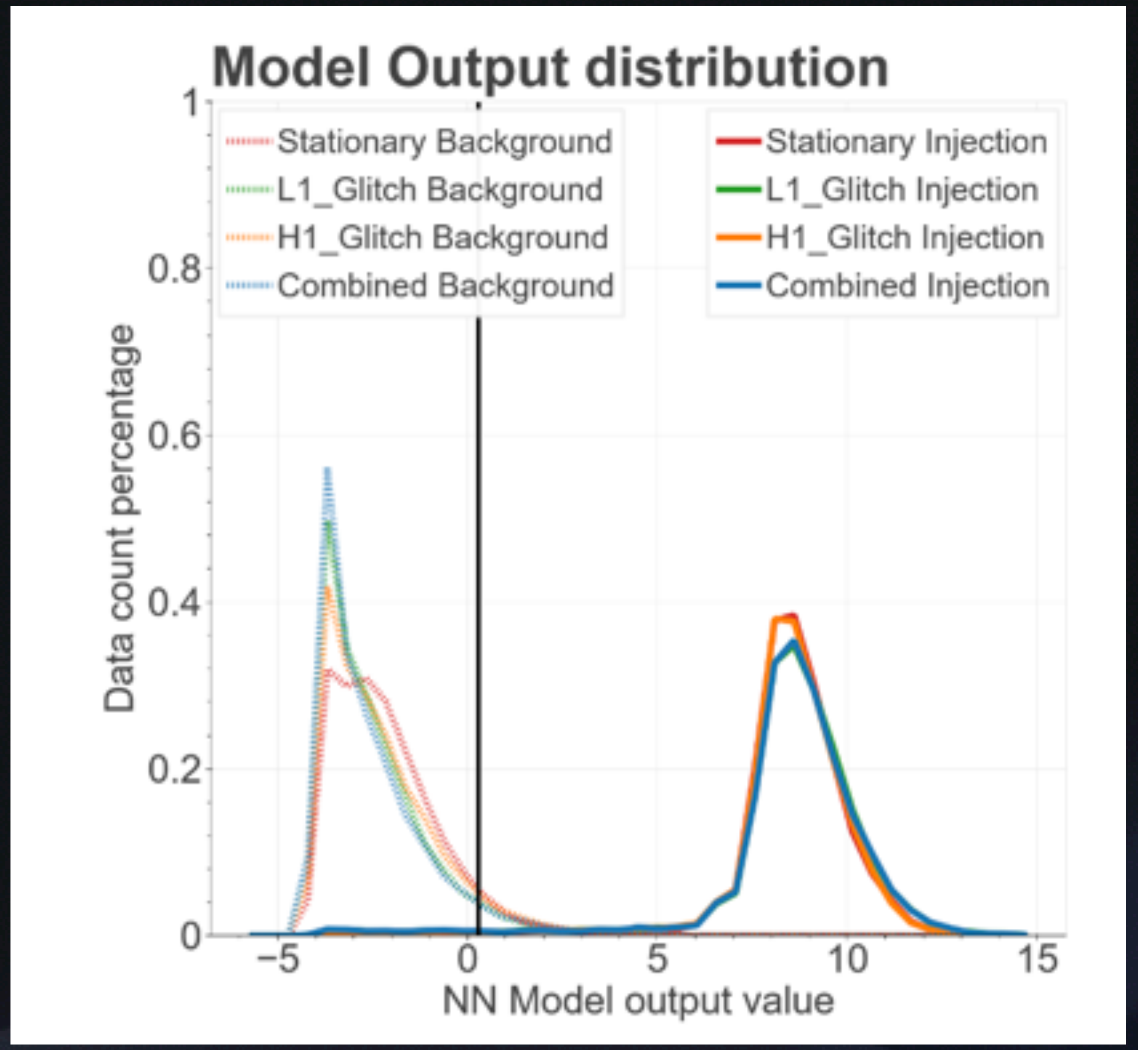
Searches for GWs from CCSNe

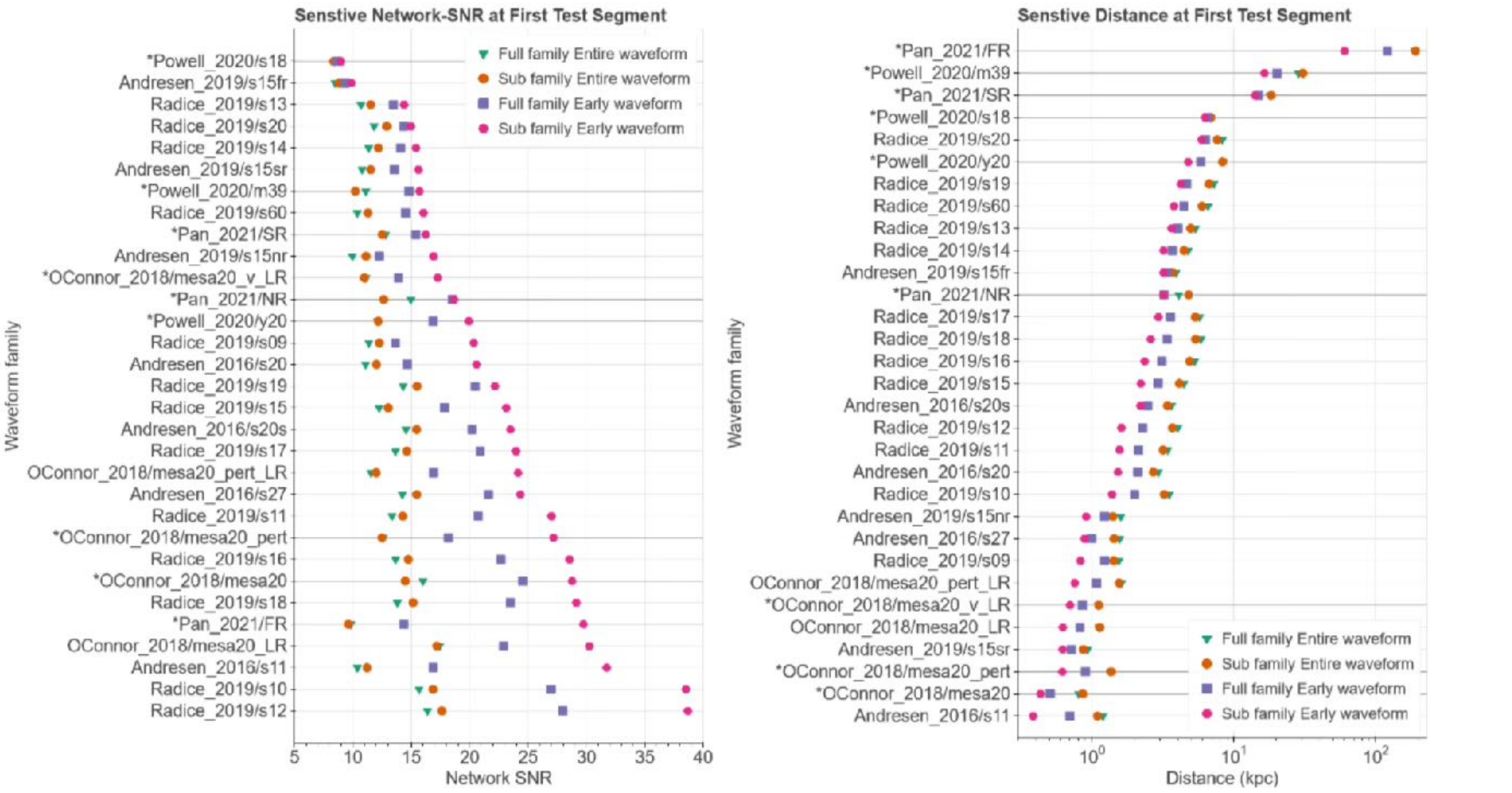
Chen et al., (+ K.-C. Pan) in preparation (with Albert Kong, Yi Yang)

- When applying for real data, glitches could be misclassified as CCSN signals
- We train NN models to identify glitches and CCSN signals (using O3b data; 2020.01-2020.02): *CCSNet*
- **31** state-of-the-art 3D CCSN waveforms
- Real O3b glitches identified by the Omicron pipeline
- Parameters: orientations (RA/Dec), Sky localization (RA/Dec), Polarization Phase & Time shift



Searches for GWs from CCSNe



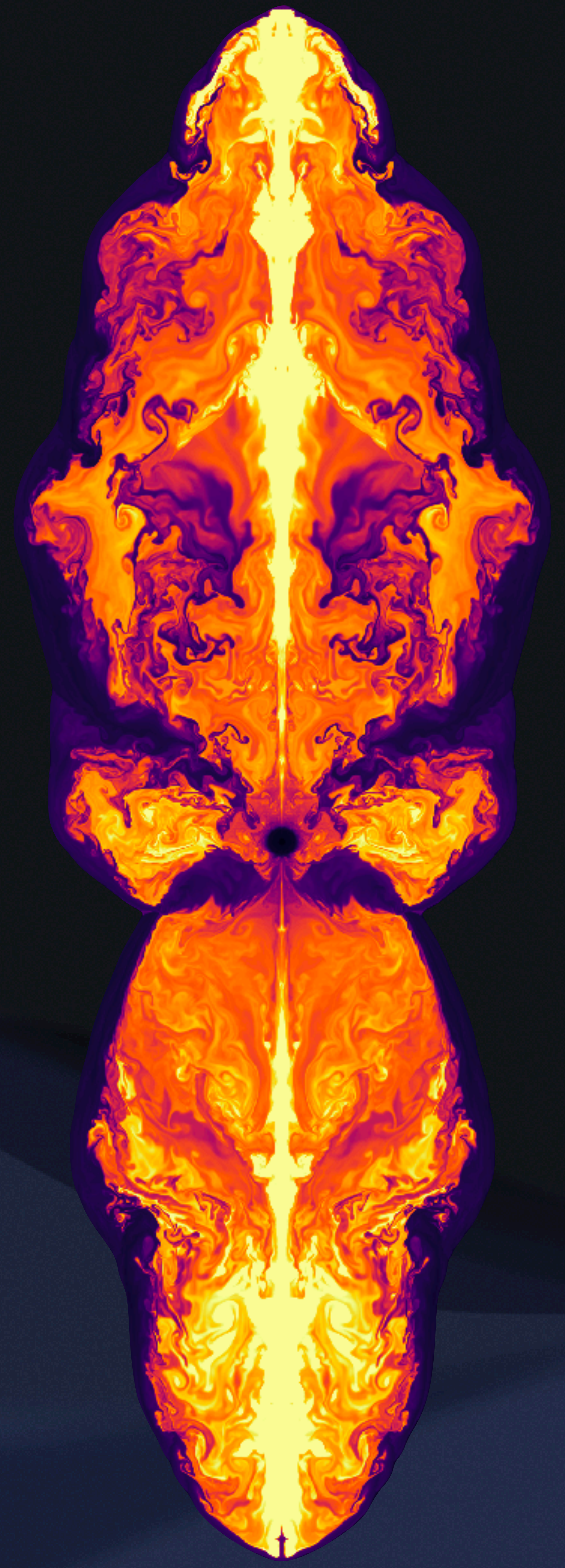


(a) SNR performance

(b) Distance performance

Conclusions & Future work

- The main CCSN GW features are from the surface oscillations of the proto-neutron star, but depending on the dynamics evolution and microphysics, there are additional features, such as SASI, MHD monopolar/bipolar jets, low T/W instabilities, …etc.
- We developed Machine learning techniques to (1) estimate rotational parameters and EoS groups using 2D waveforms (2) classify CCSN signals and glitches (*CCSNet*)
- Our results show that Galactic CCSNe are more likely to be detected, except a few exceptions with fast rotation (maybe also MHD cases)
- Future GW and MMA detections of a nearby CCSN are important for examining the CCSN's physics.



Acknowledgement

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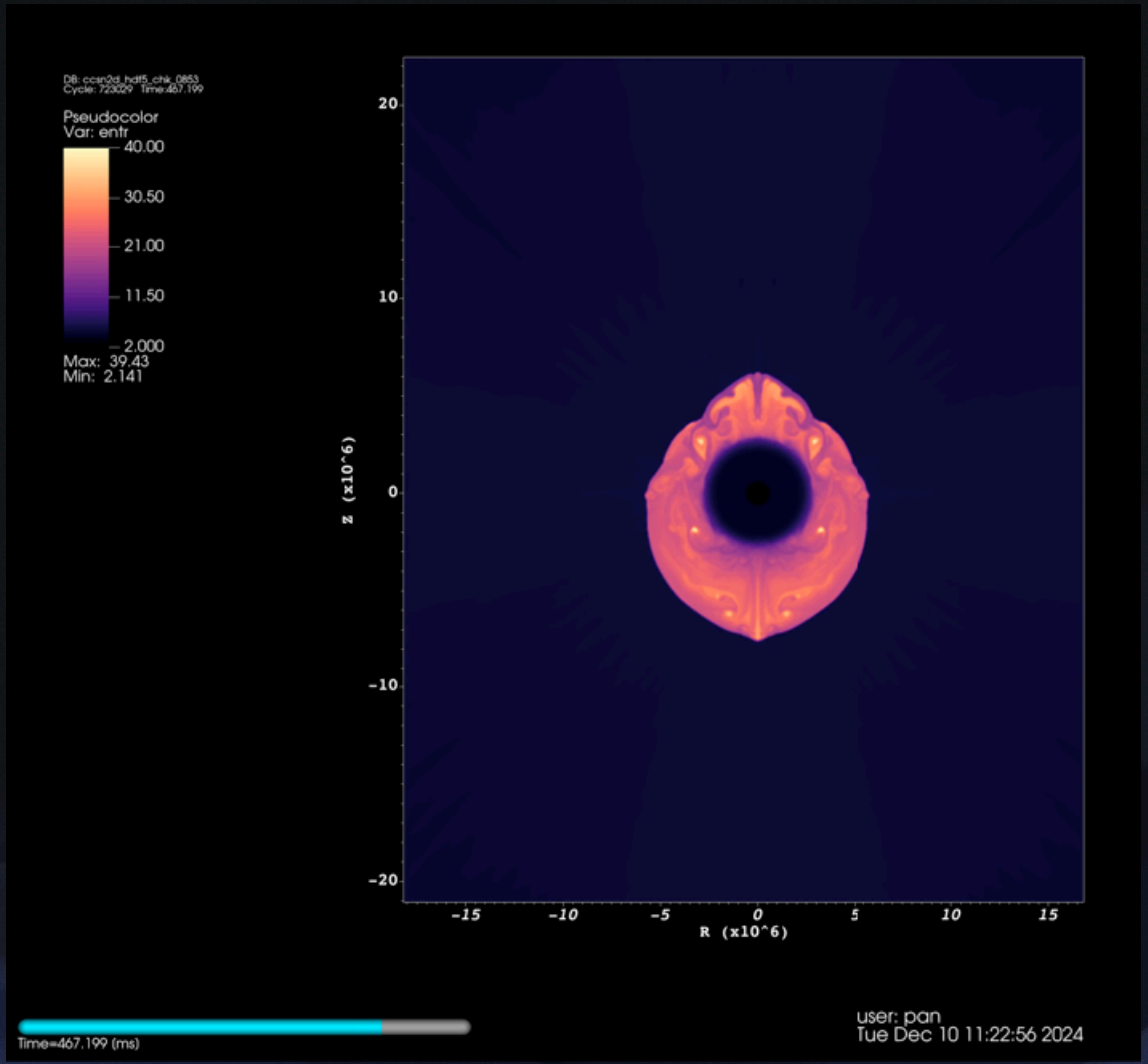
NCHC
NARLabs 財團法人國家實驗研究院
國家高速網路與計算中心
National Center for High-performance Computing

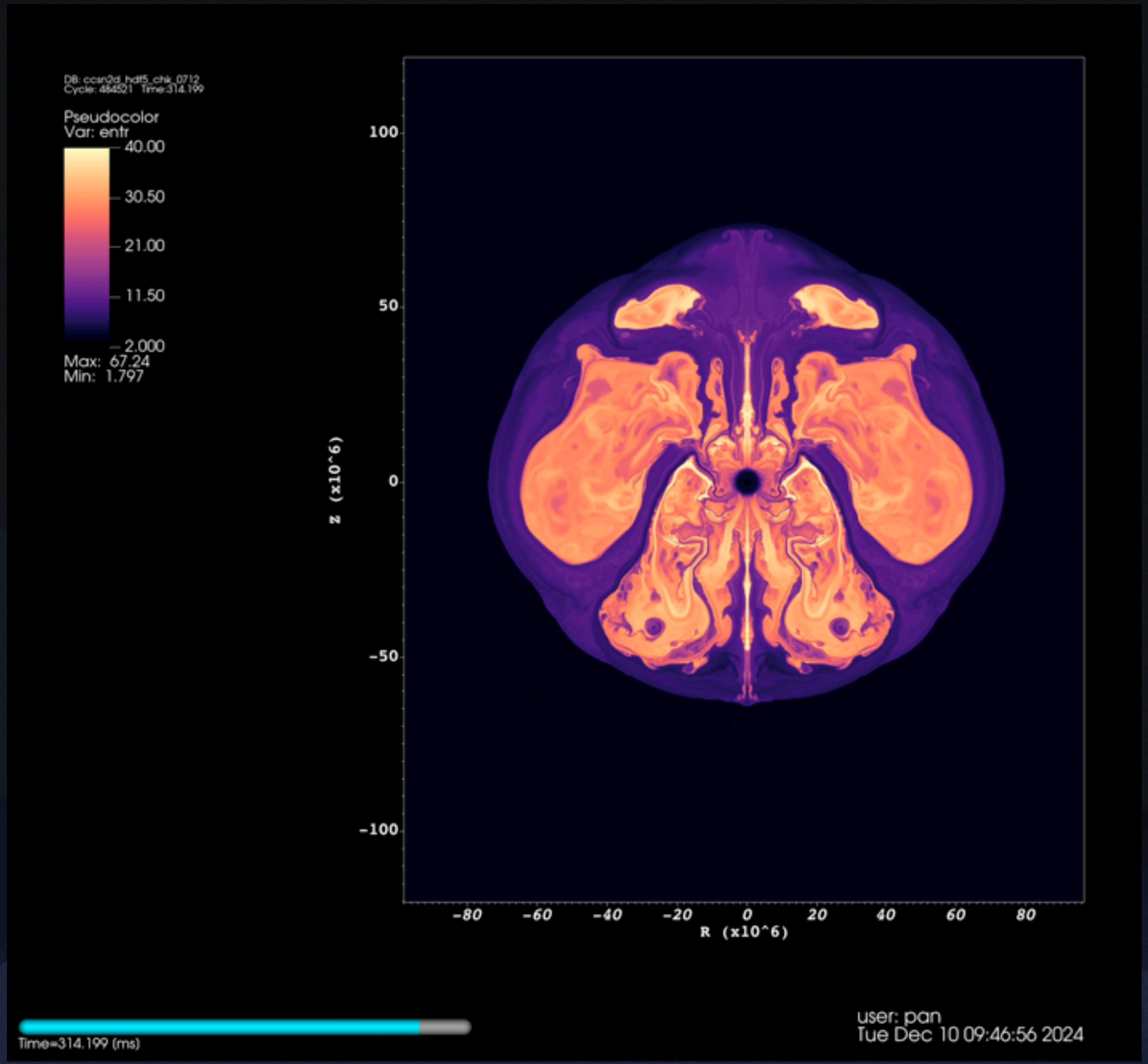
NCTS
National Center for Theoretical Sciences

KAGRA

Magnetized CCSN

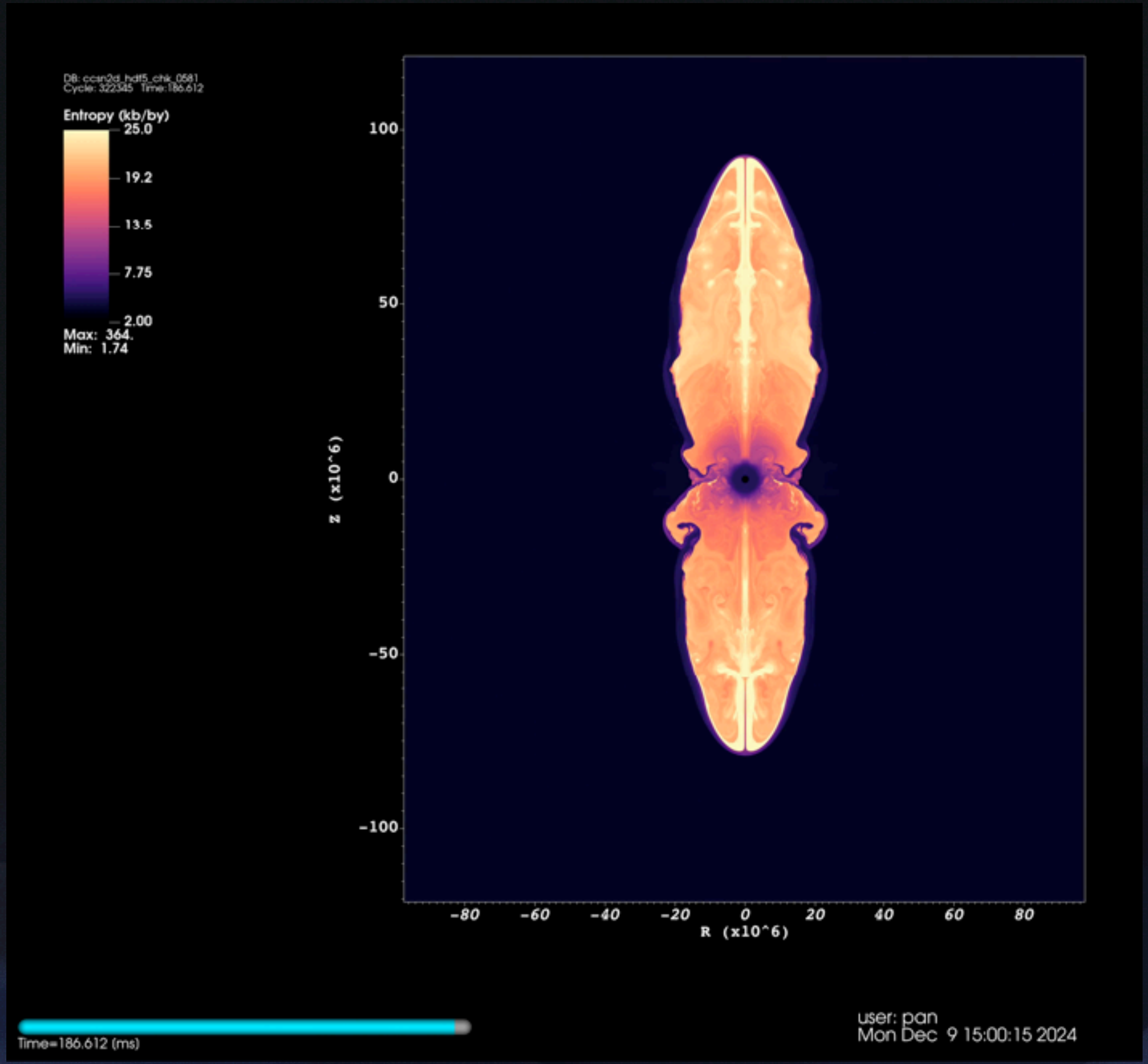


Failed supernovae

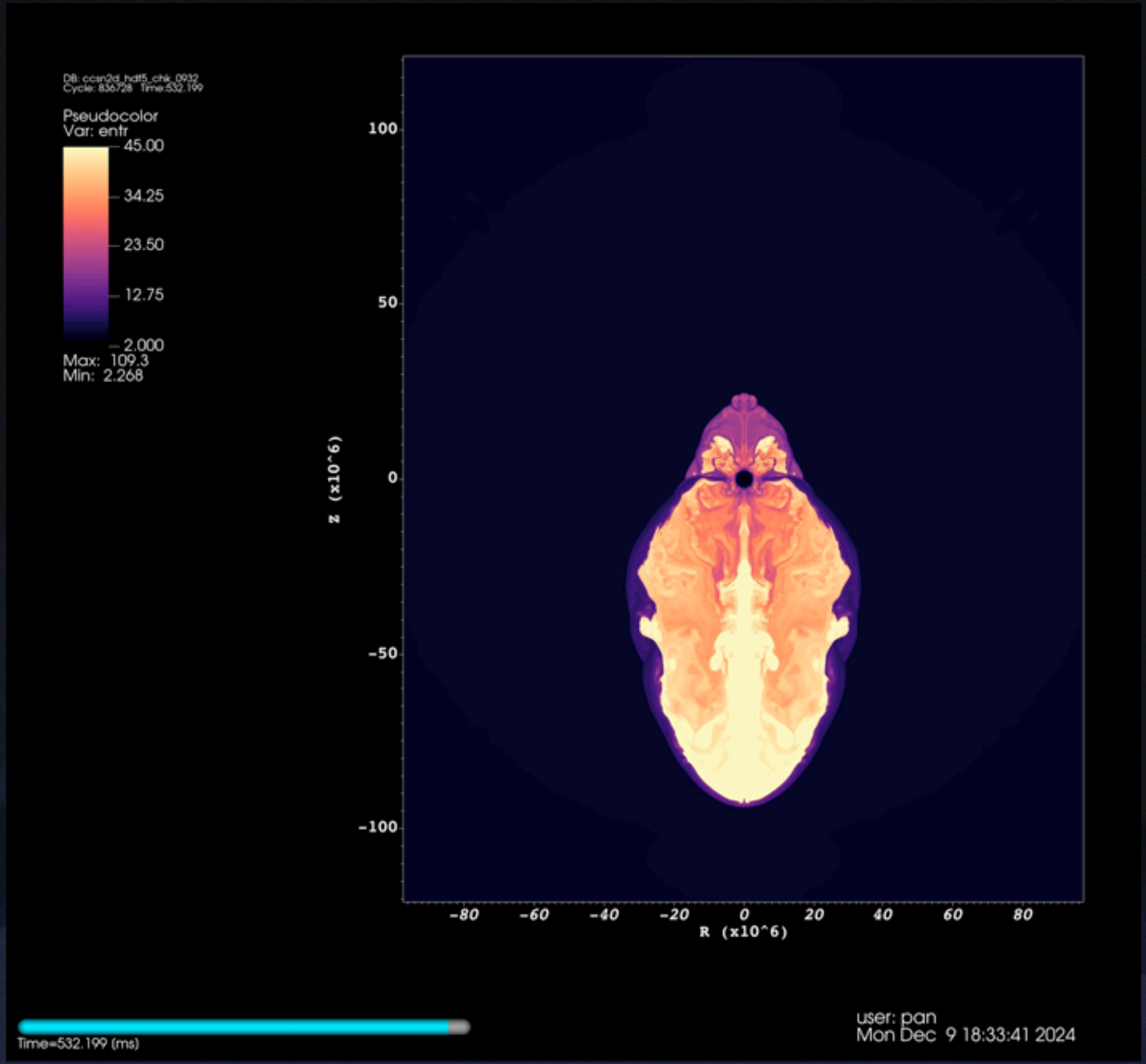


Butterfly-pattern neutrino-driven explosion

Magnetized CCSN



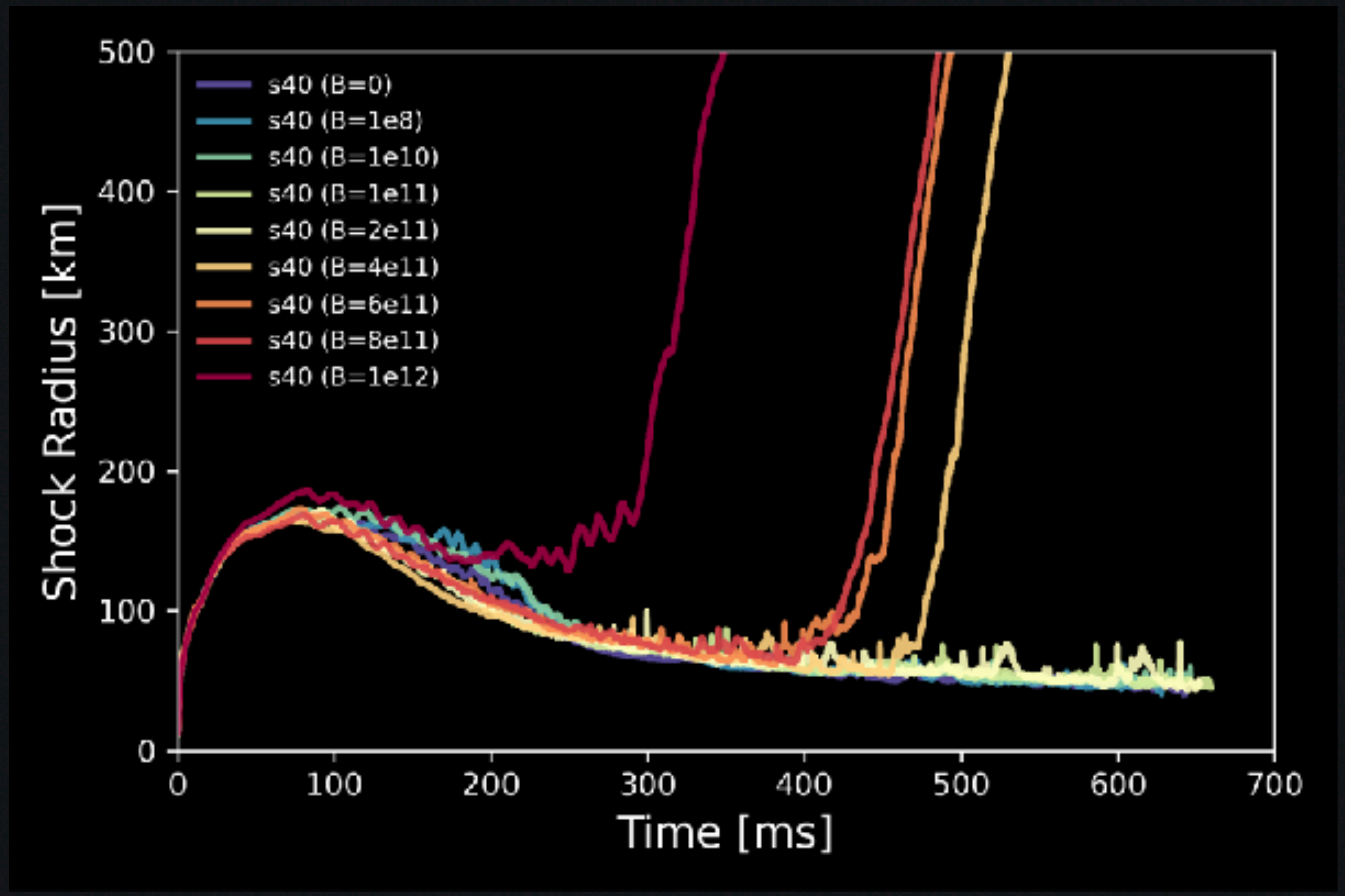
Bipolar explosion

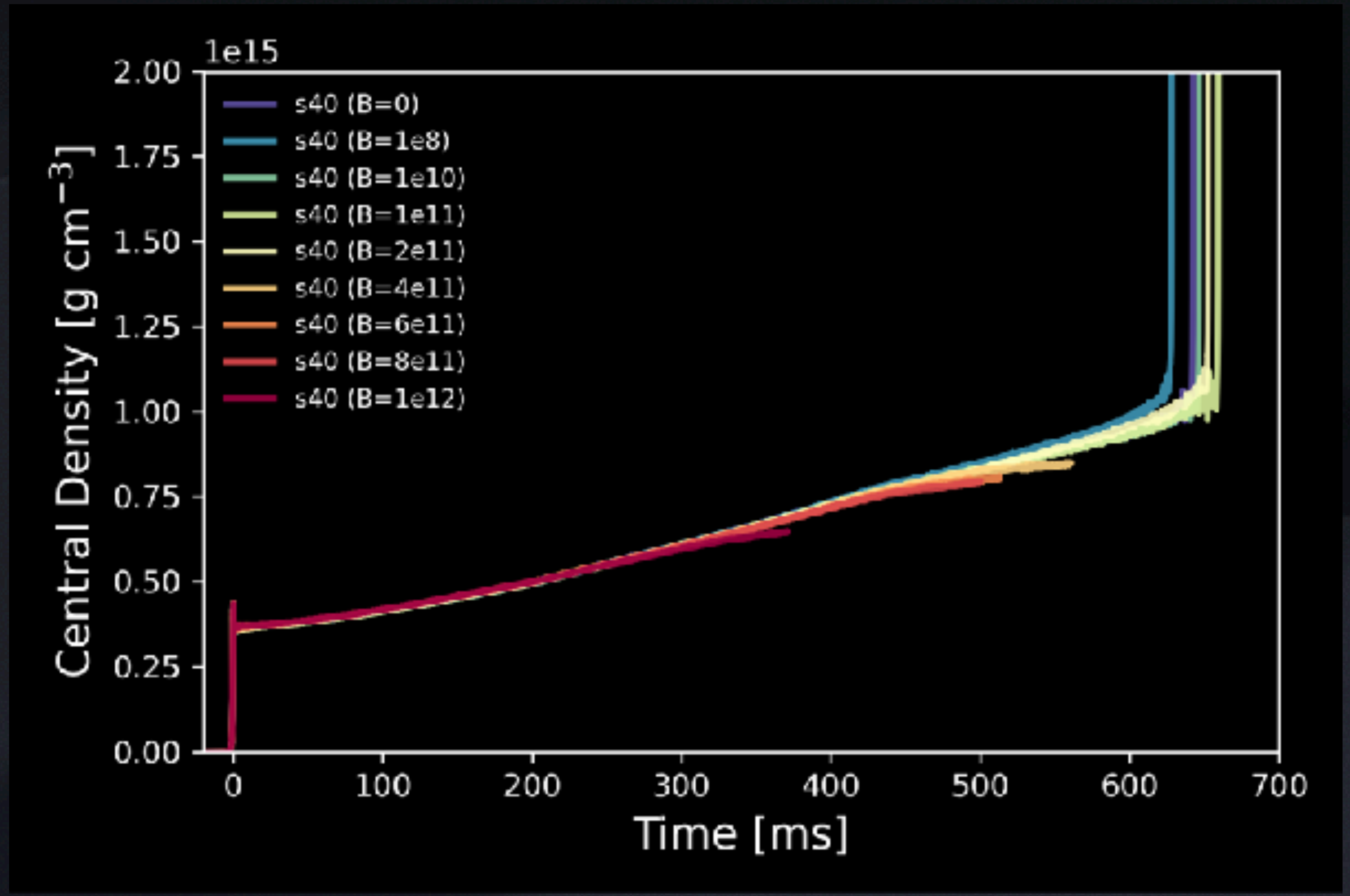


Monopolar explosion

Shock dynamics (non-rotating models)

- Non-magnetized models and weak fields models form BH at the end of simulations
- Magnetic fields assist in explosion
- Once a model explodes, BH formation will be delayed due to less accretion





Li et al. (including K.C Pan), in prep.

Shock dynamics (rotating models)

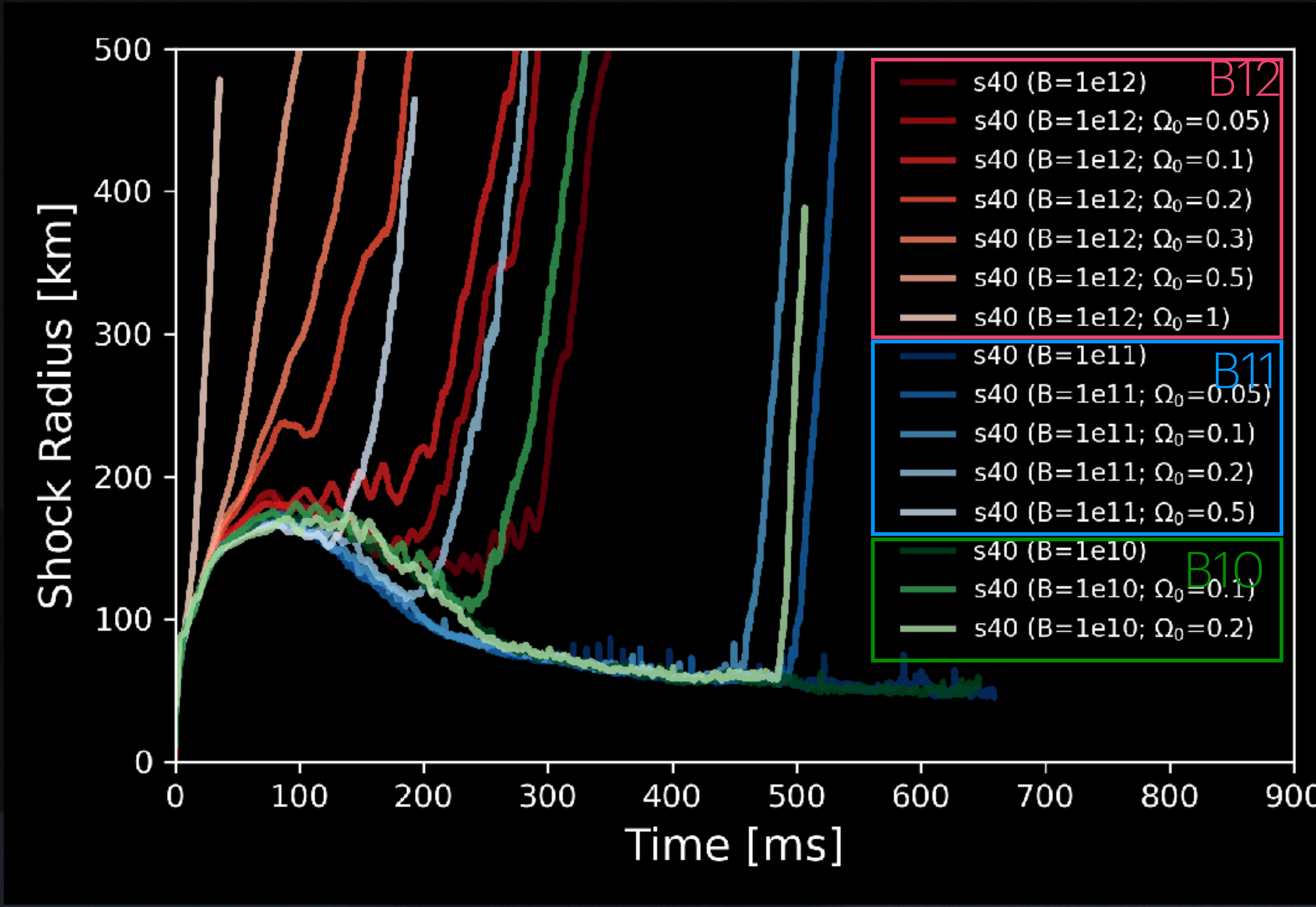
- Without magnetic fields, rotation tends to suppress explosion (Pajkos et al. 2019)

- If magnetic fields are present, rotation could assist in the explosion! (**opposite**)

- The threshold is under investigation

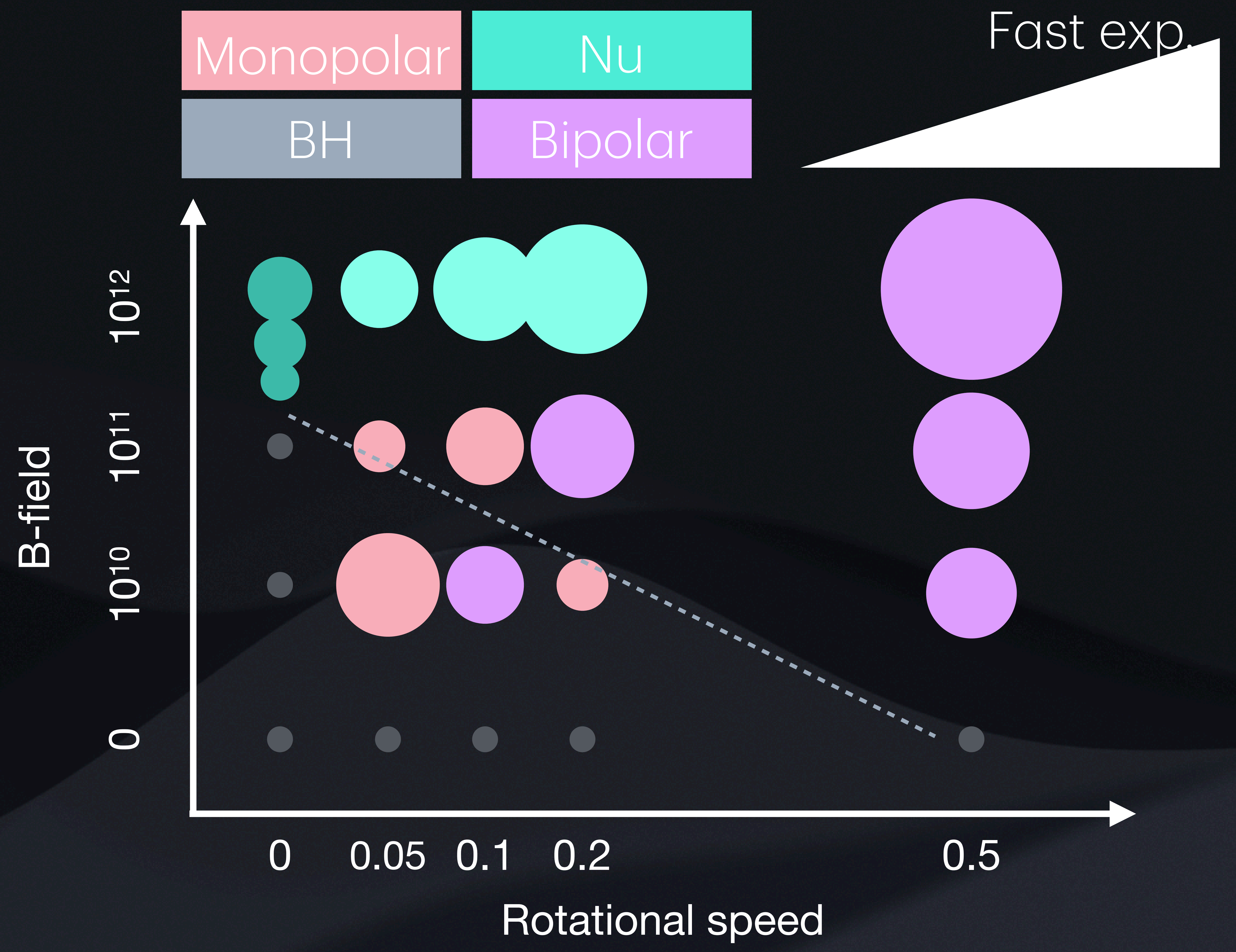
- Jets could be launched in exploding models

Li et al. (including K.C Pan), in prep.



Explosion time vs. morphology

- Neutrino-driven explosion models are less sensitive to explosion times
- Bipolar jet models have shorter explosion times
- Monopolar jet models tend to have slightly longer explosion times



Preliminary