Stellar Mass Black Hole Formation and Multimessenger Signals from Core-Collapse Supernovae

arXiv:2010.02453

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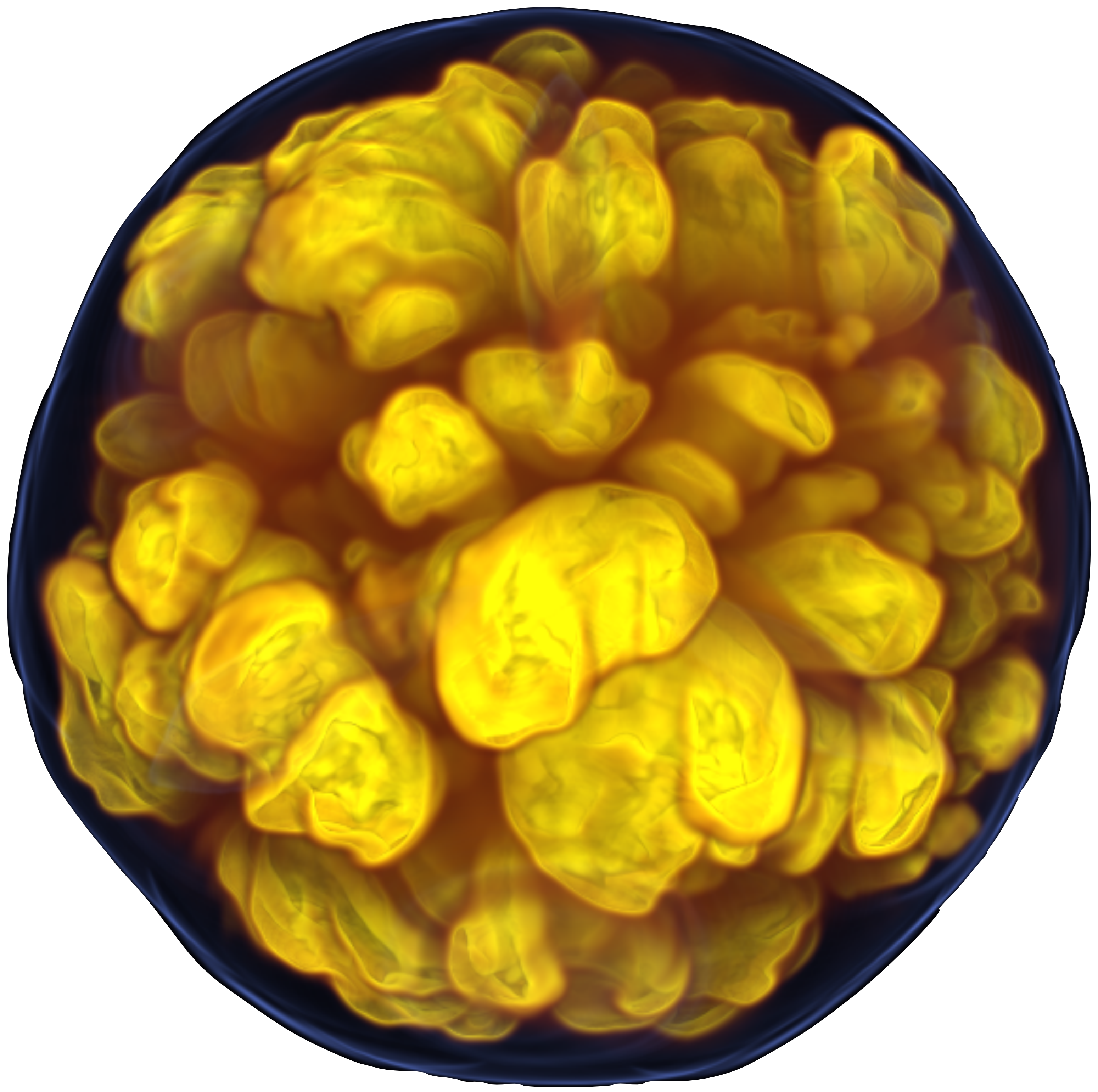
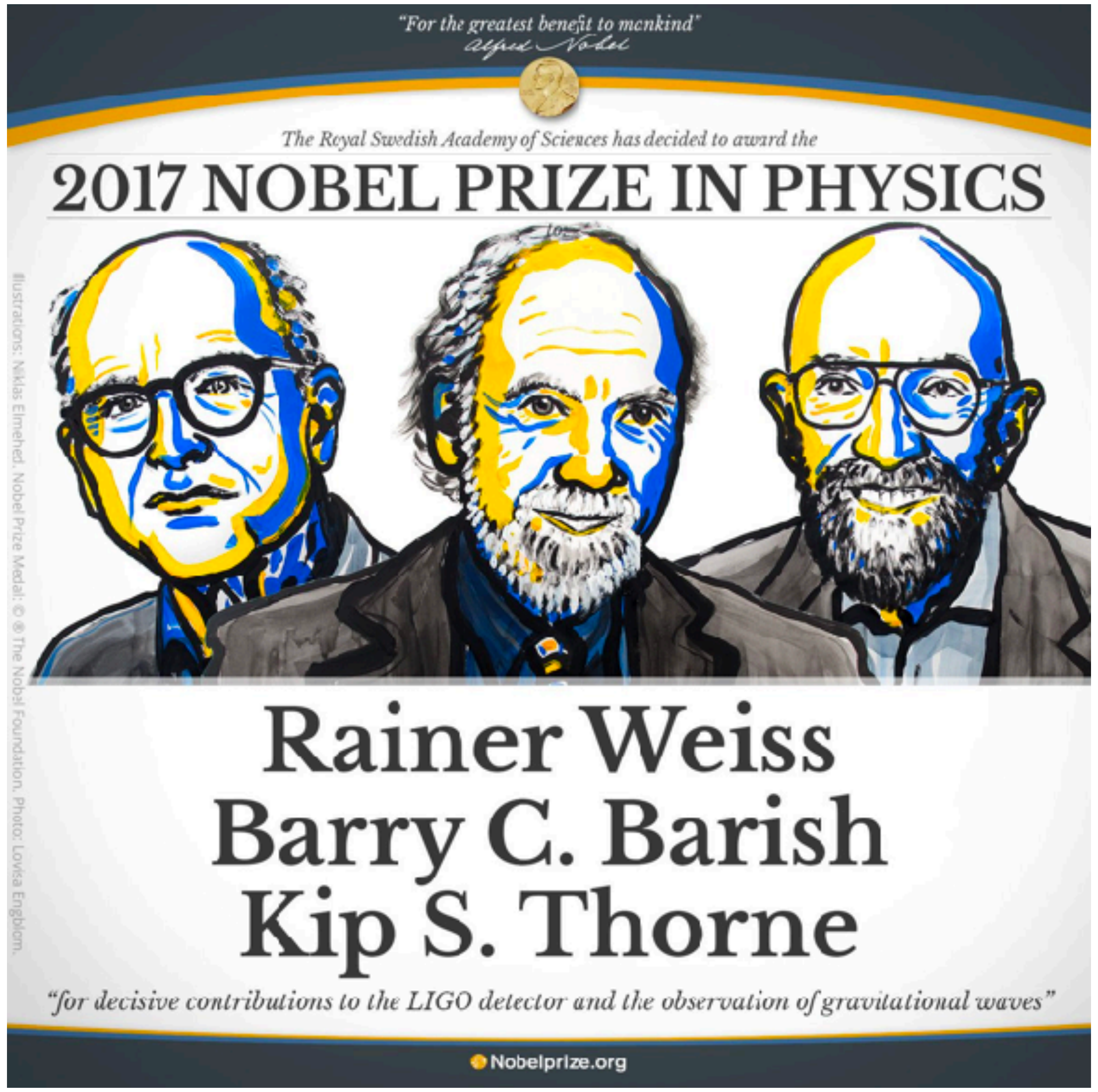
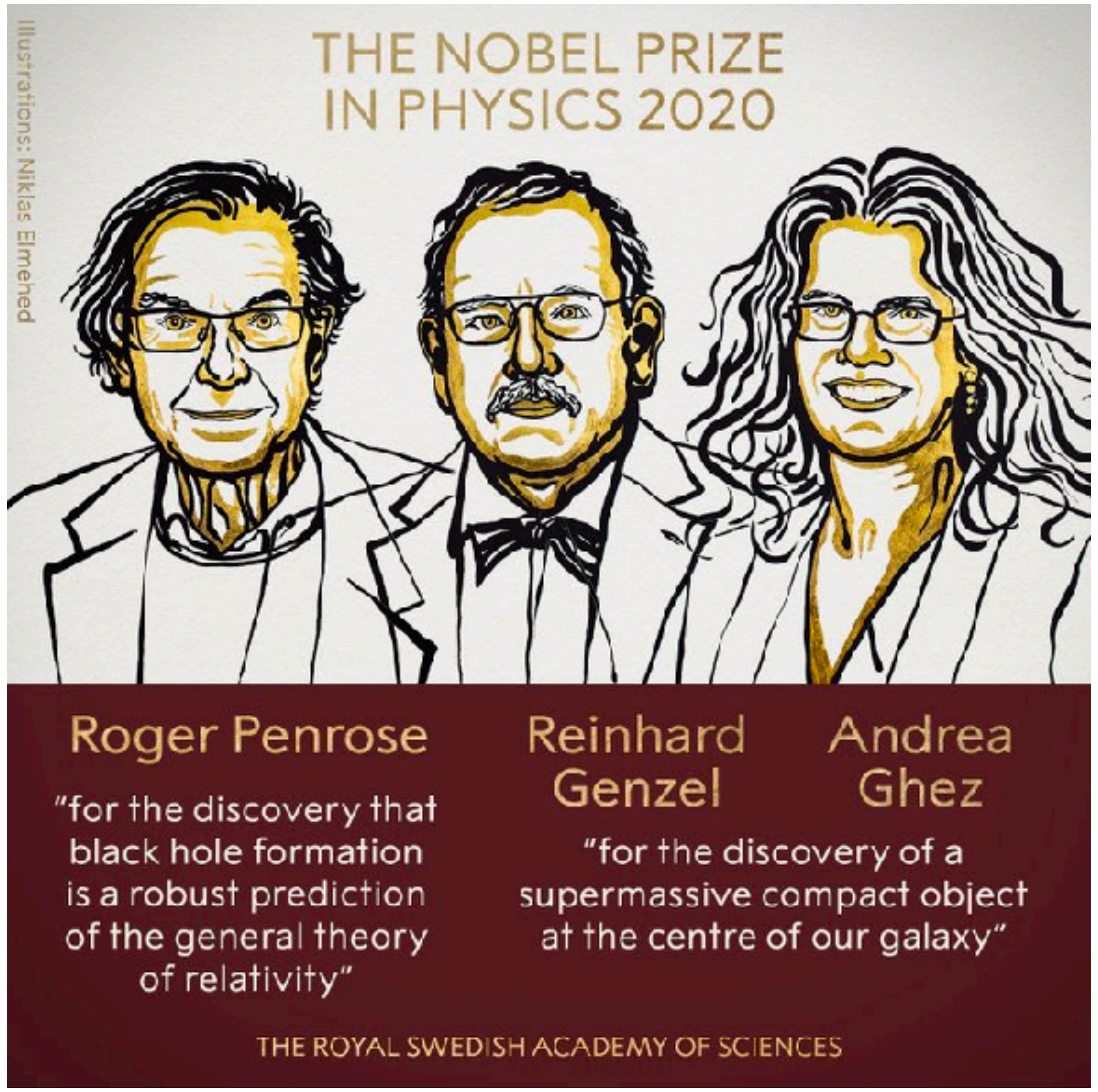
Outline

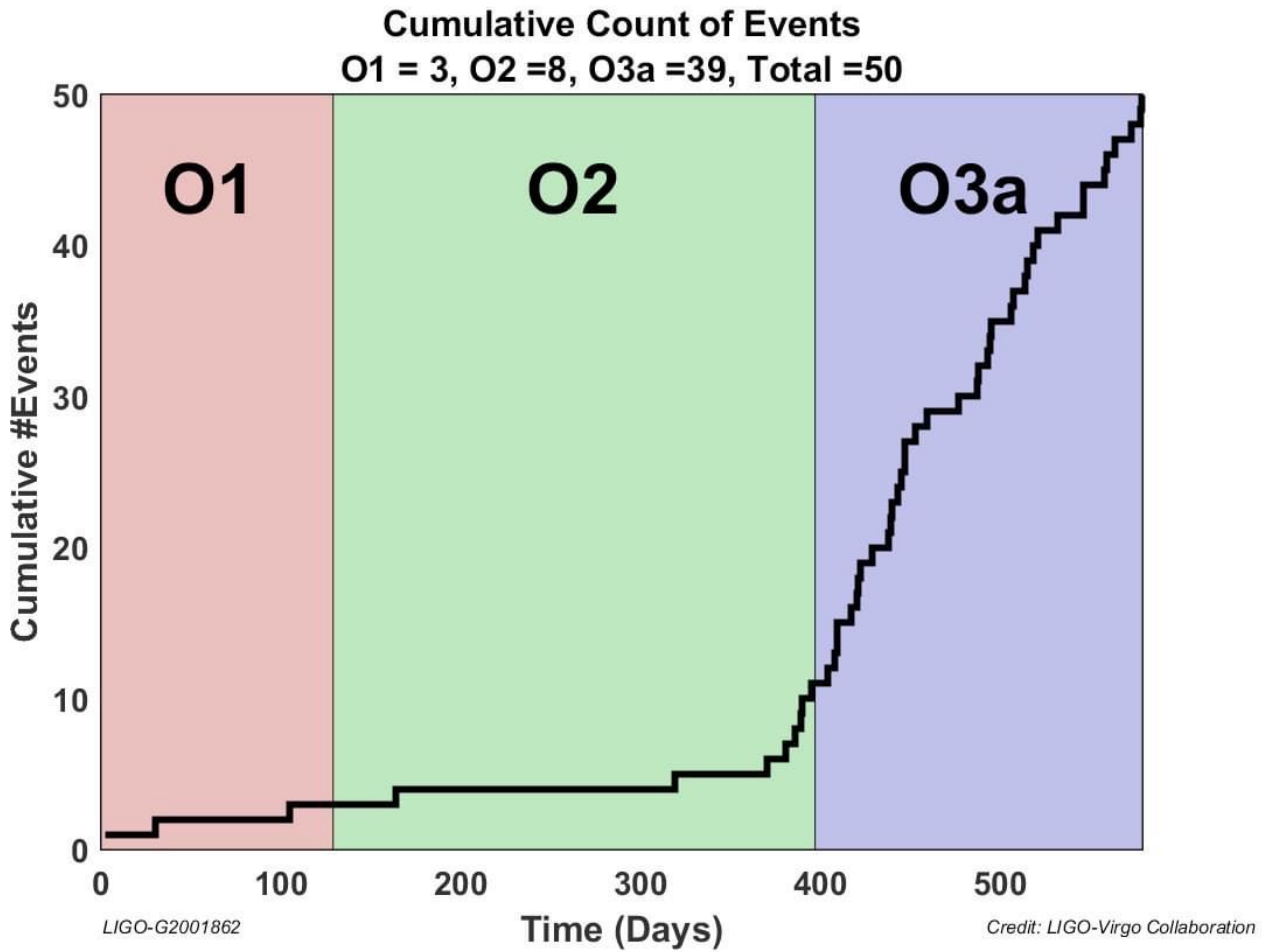
- Introduction
- Core-Collapse Supernova Engines
- Stellar Mass Black Hole Formation
- Multimessenger signatures
- Detectability of such events
- Conclusions



A New Era of Gravitational Wave Astrophysics







Cumulative Count of Events
O1 = 3, O2 =8, O3a =39, Total =50
O1
O2
O3a
Cumulative #Events
0
10
20
30
40
50
0
100
200
300
400
500
Time (Days)
LIGO-G2001862
Credit: LIGO-Virgo Collaboration

Masses in the Stellar Graveyard

2020

Gravitational Wave Astronomy

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

Multi-Messenger Astrophysics

Image credit: NASA

Core-Collapse Supernovae

Zwicky Transient Facility (ZTF)

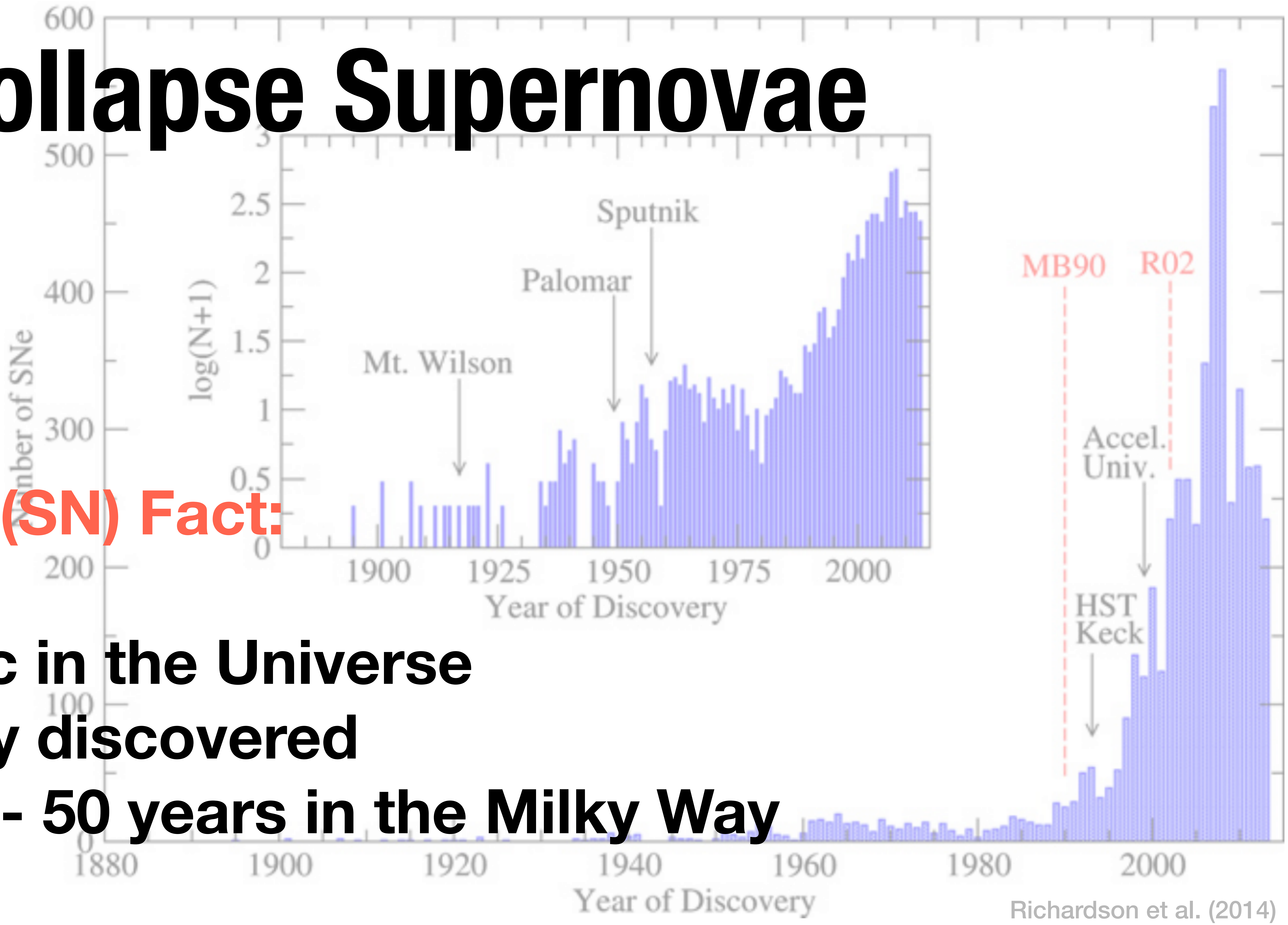
All-Sky Automated Survey For Supernovae (ASAS-SN)

Supernova (SN) Fact:

~ 1 SN / sec in the Universe

> 1 SN / day discovered

~ 1 SN / 30 - 50 years in the Milky Way



Richardson et al. (2014)

Multi-messenger Signals from CCSN

Core collapse

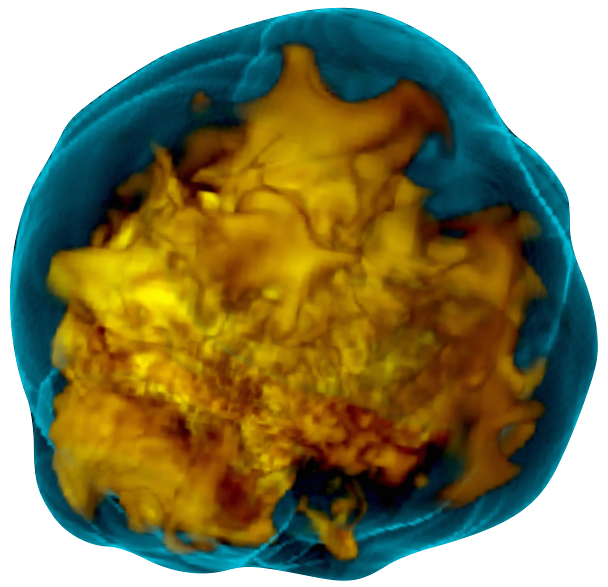
M (or ξ), z, Ω, B

Core bounce

Shock is revived

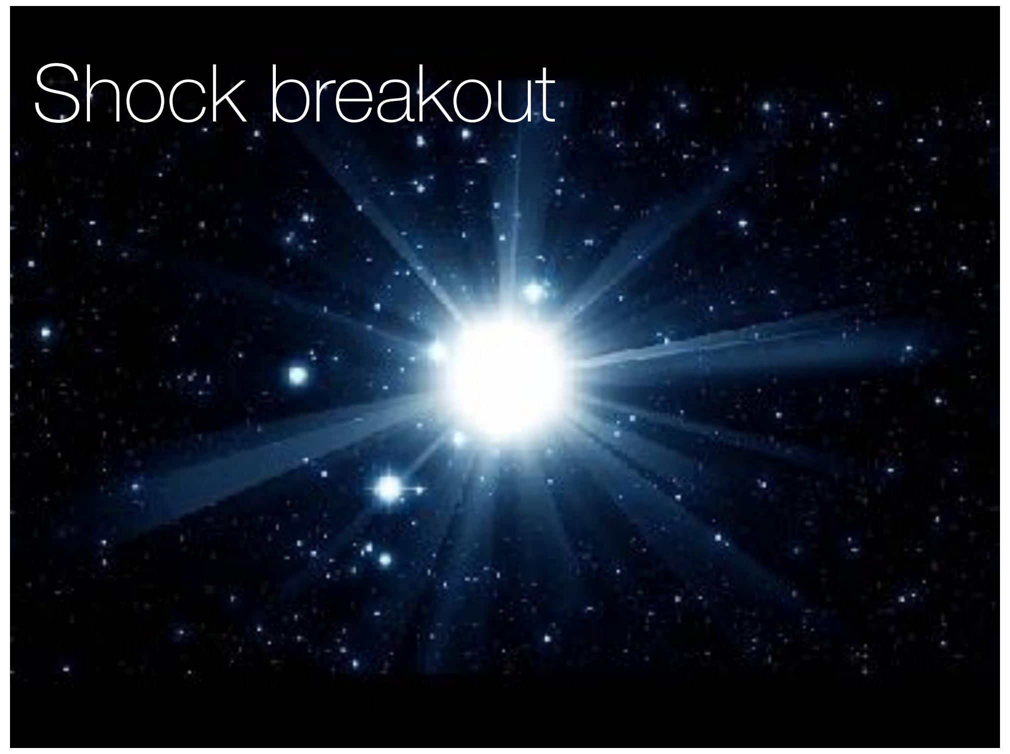
Shock is not revived

Shock revival



BH formation

SN Explosion

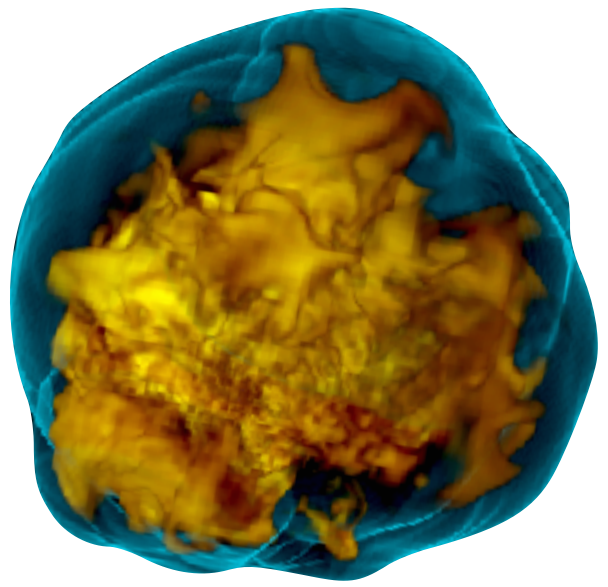


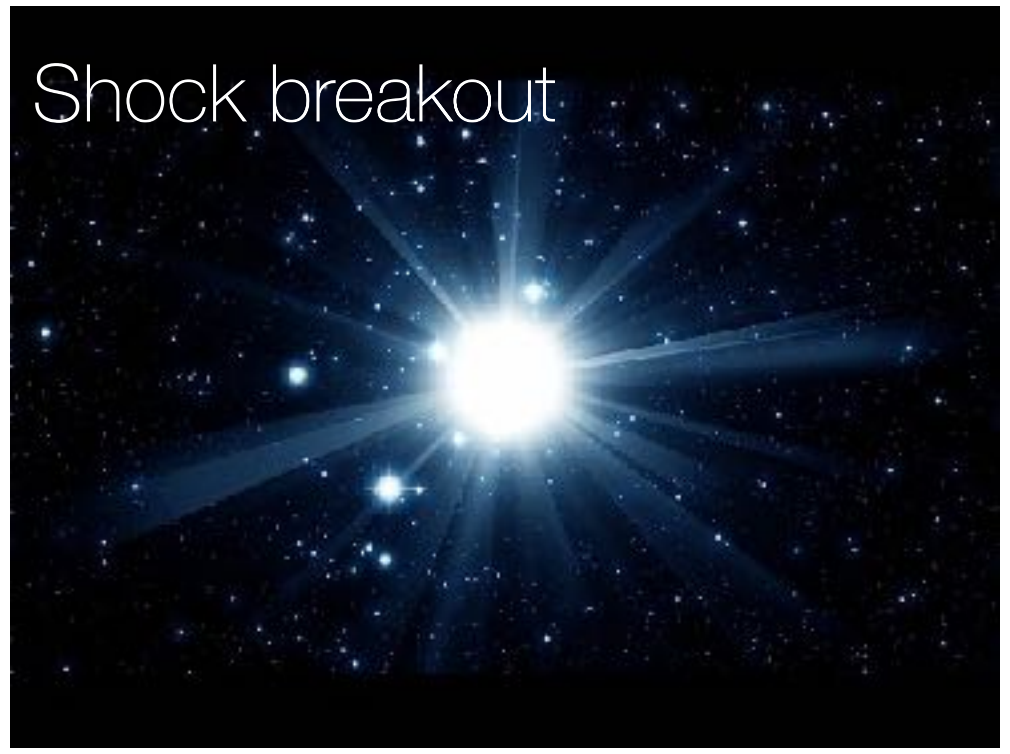
-300 ms | **0 ms** | **Time** | **1 sec** | **1 day**

Multi-messenger Signals from CCSN

Core collapse → **Core bounce**

- **Shock is revived** → **Shock revival** → **SN Explosion**
- **Shock is not revived** → **BH formation**





EM Waves

Neutrinos

Gravitational Waves

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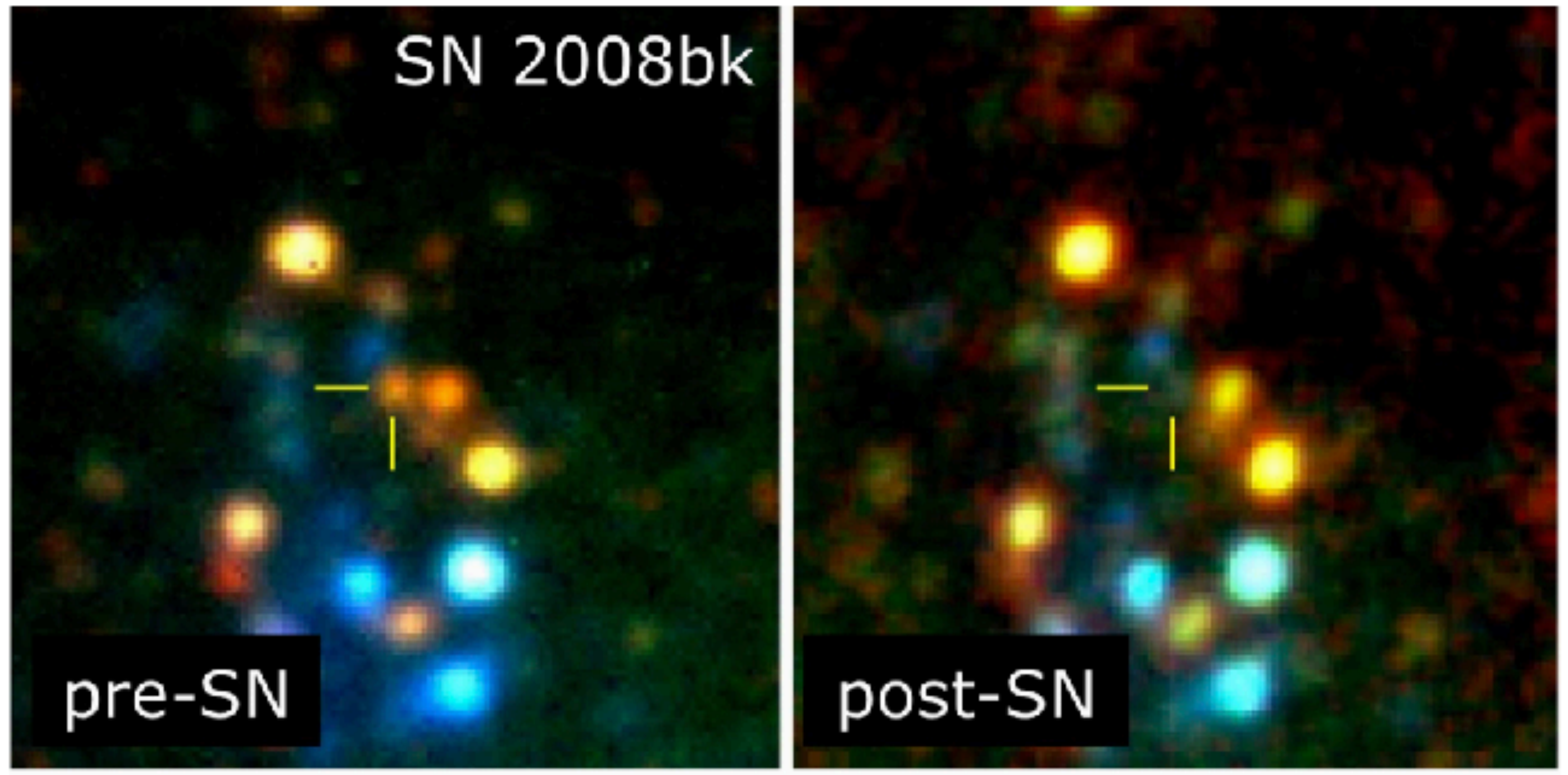
Multi-messenger Signals from CCSN

SN 2008bk, red supergiant progenitor (Mattila et al. 2



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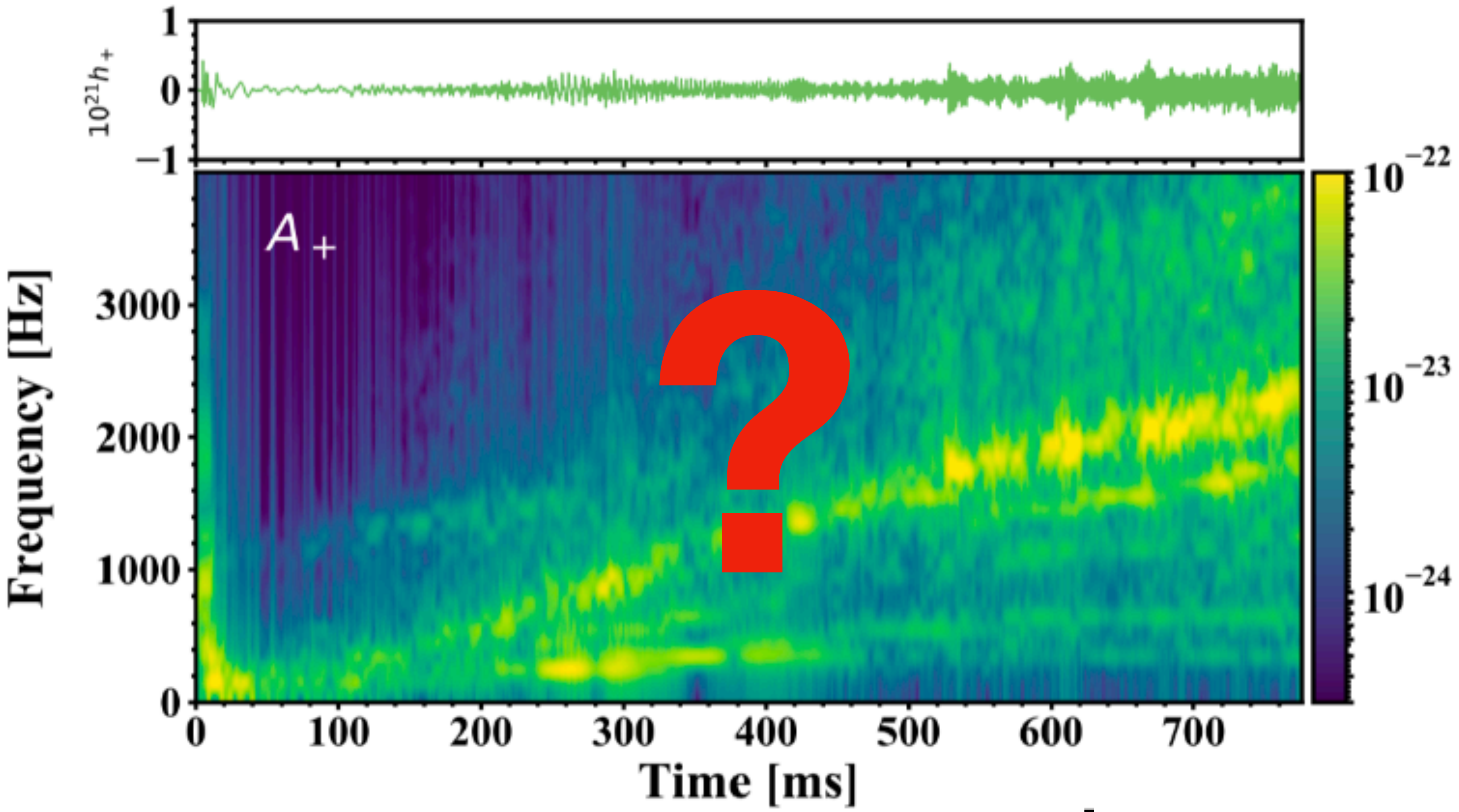
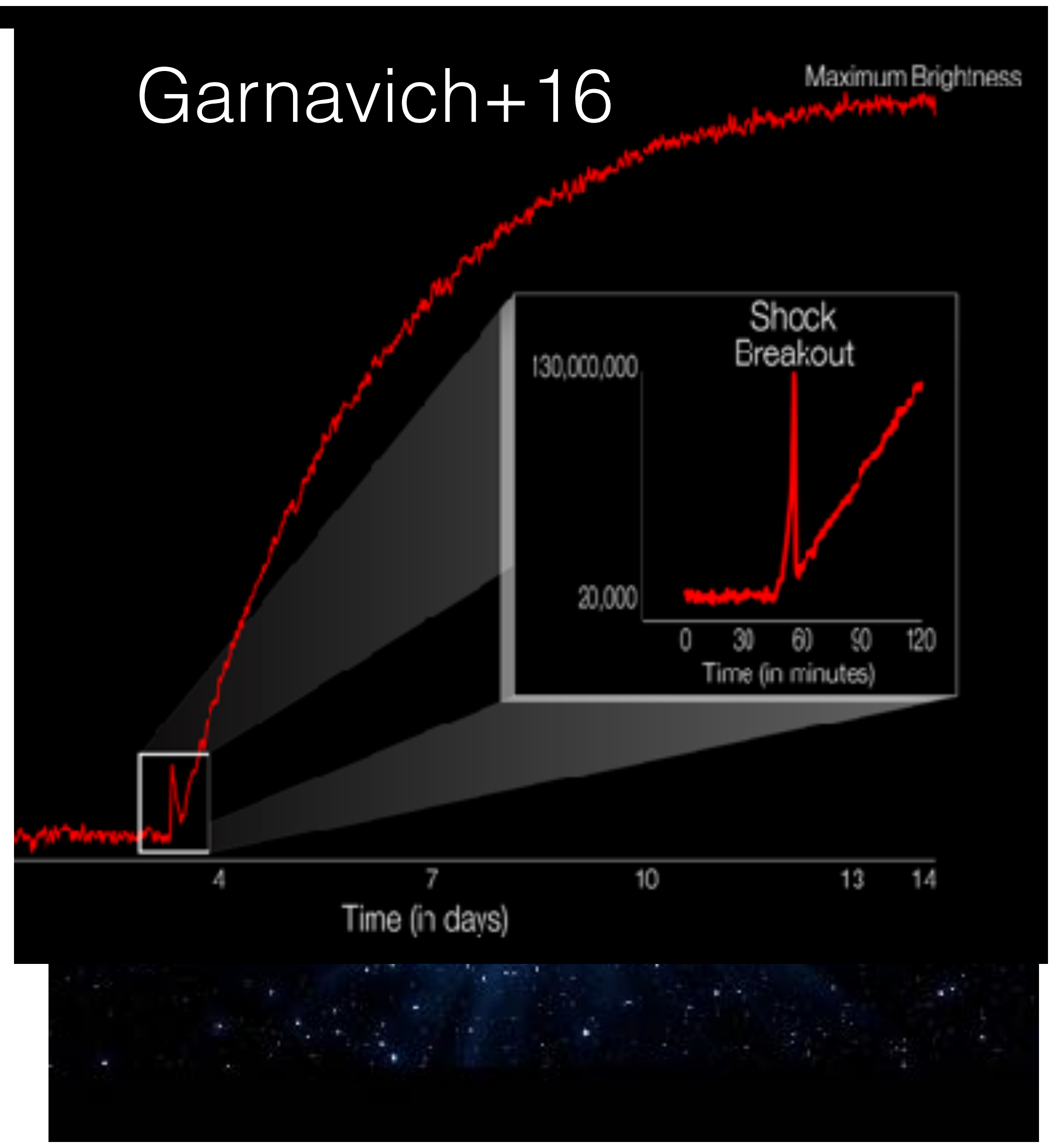
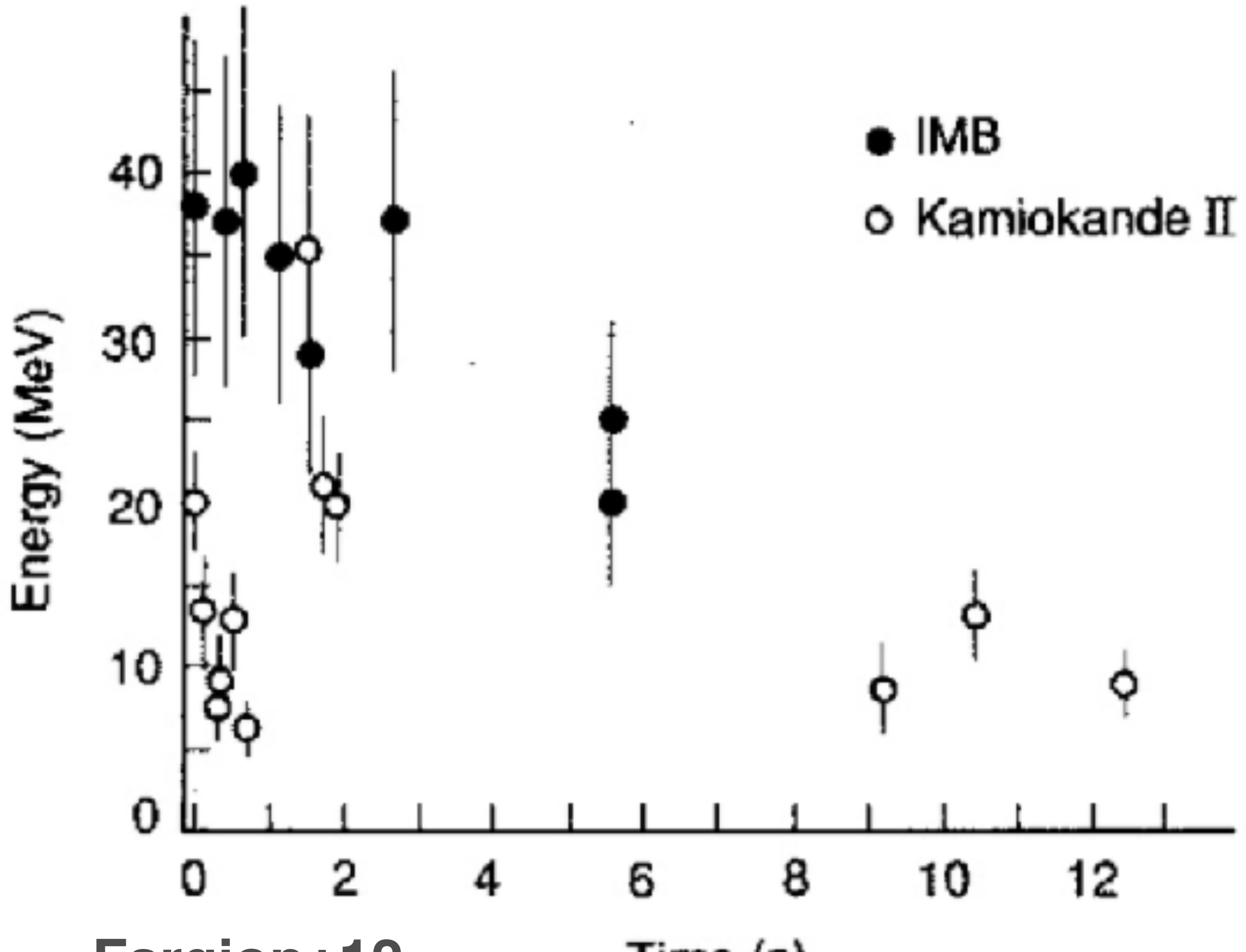
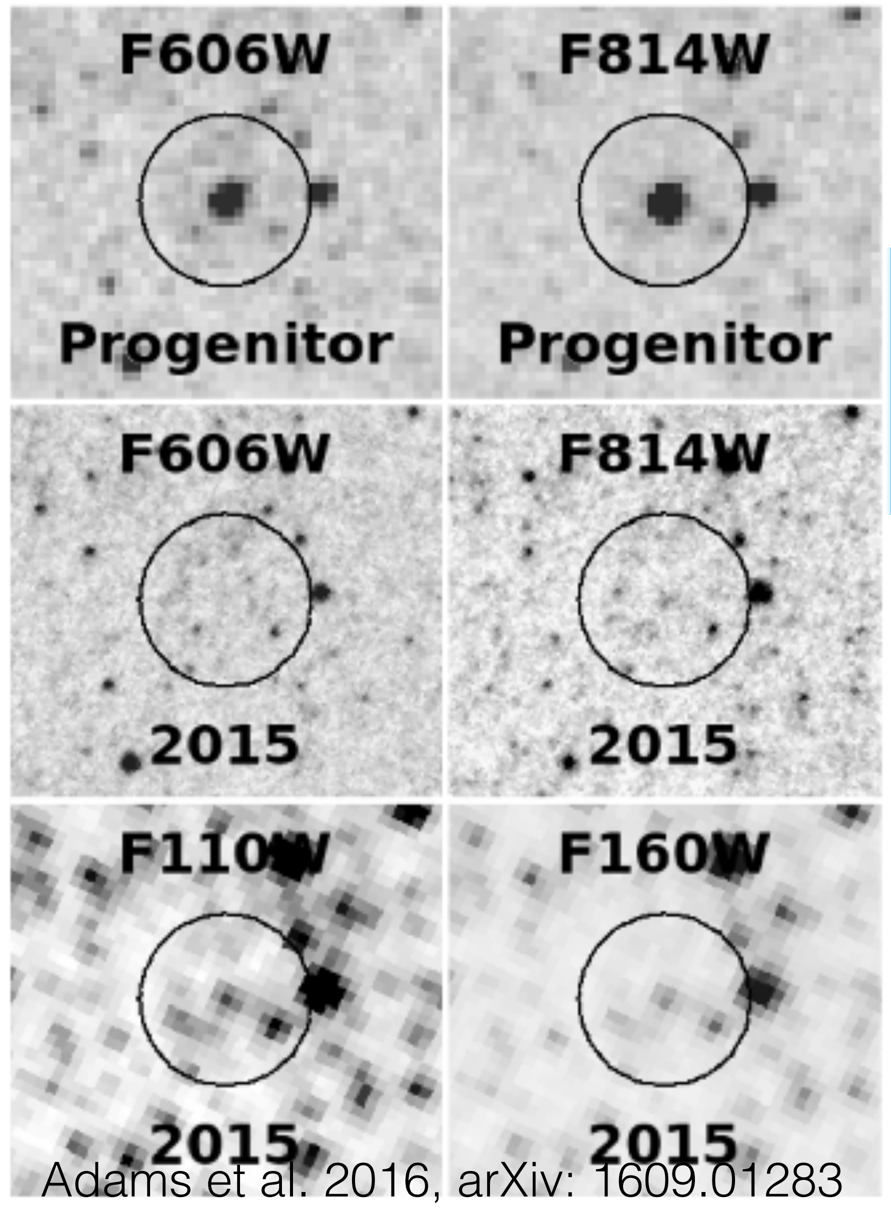






revived

BH forma



EM Waves

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Masses in the Stellar Graveyard

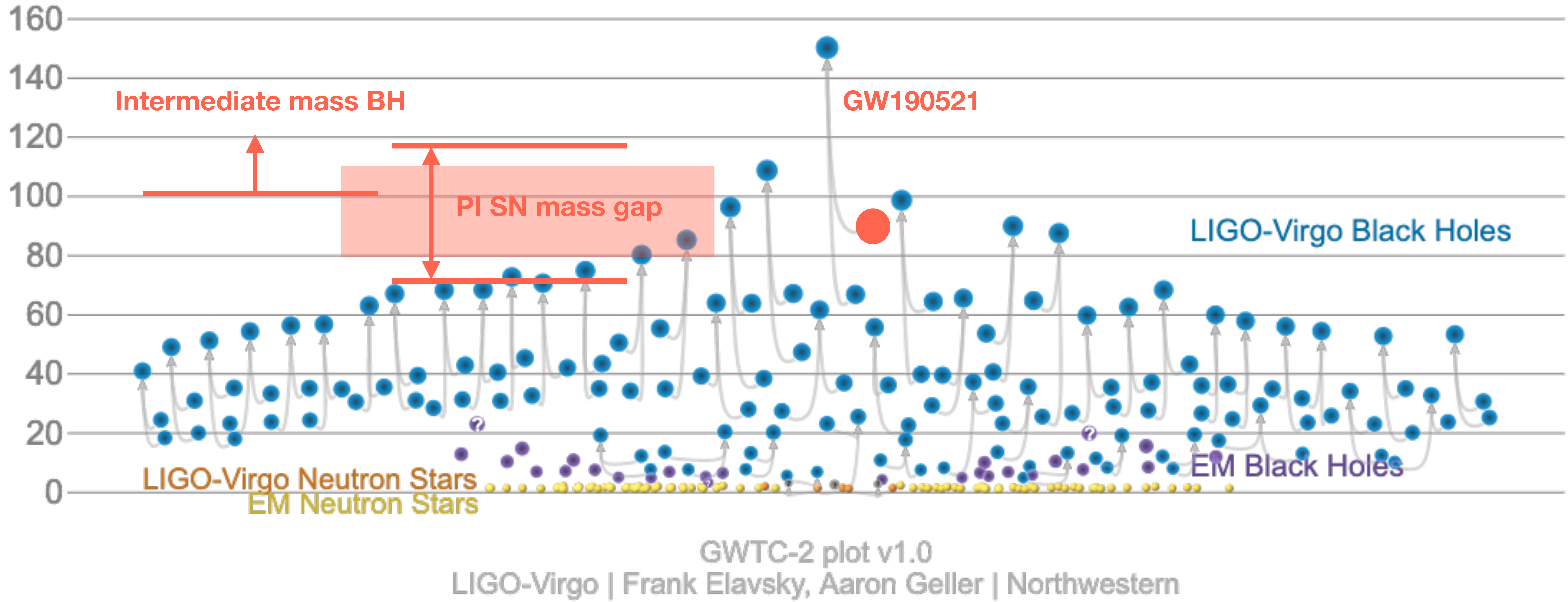
in Solar Masses

GWTC-2 plot v1.0

LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Masses in the Stellar Graveyard

in Solar Masses

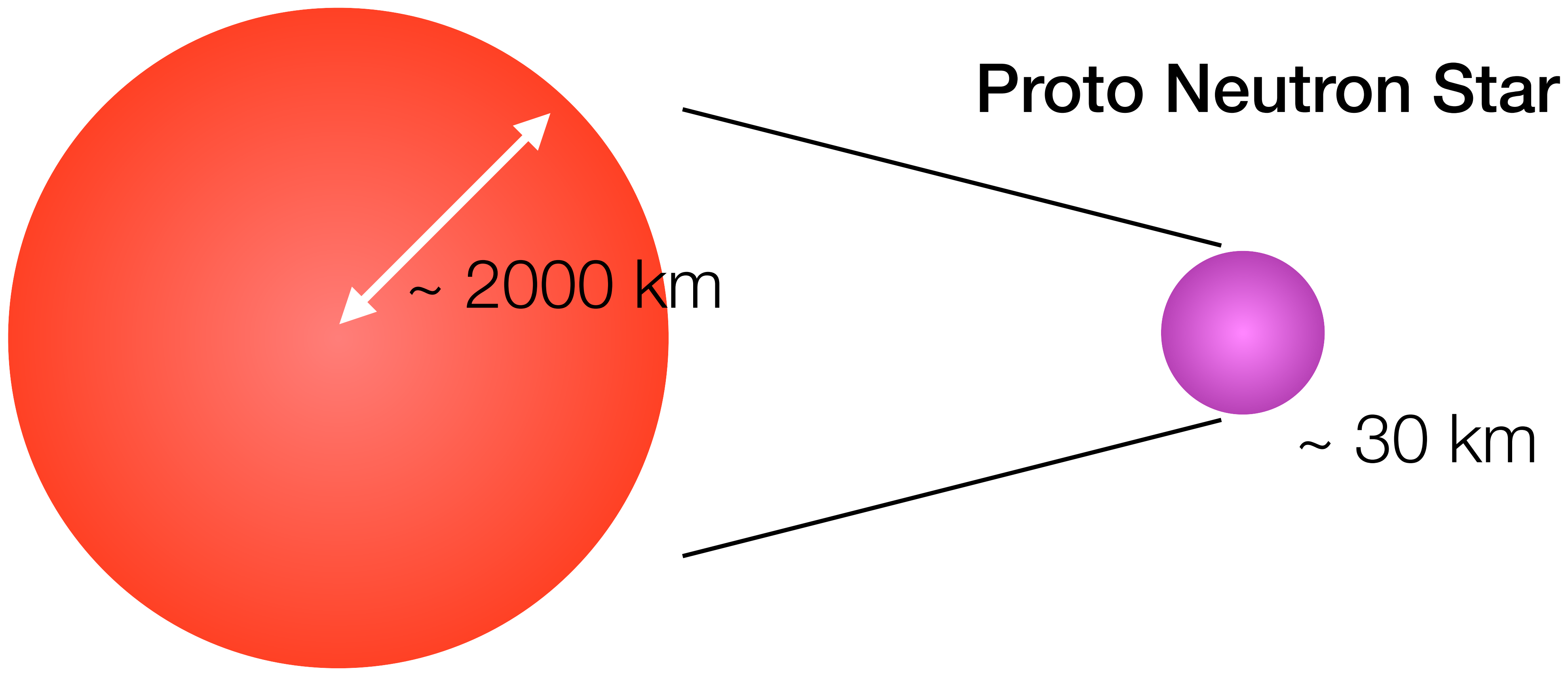


Masses in the Stellar Graveyard

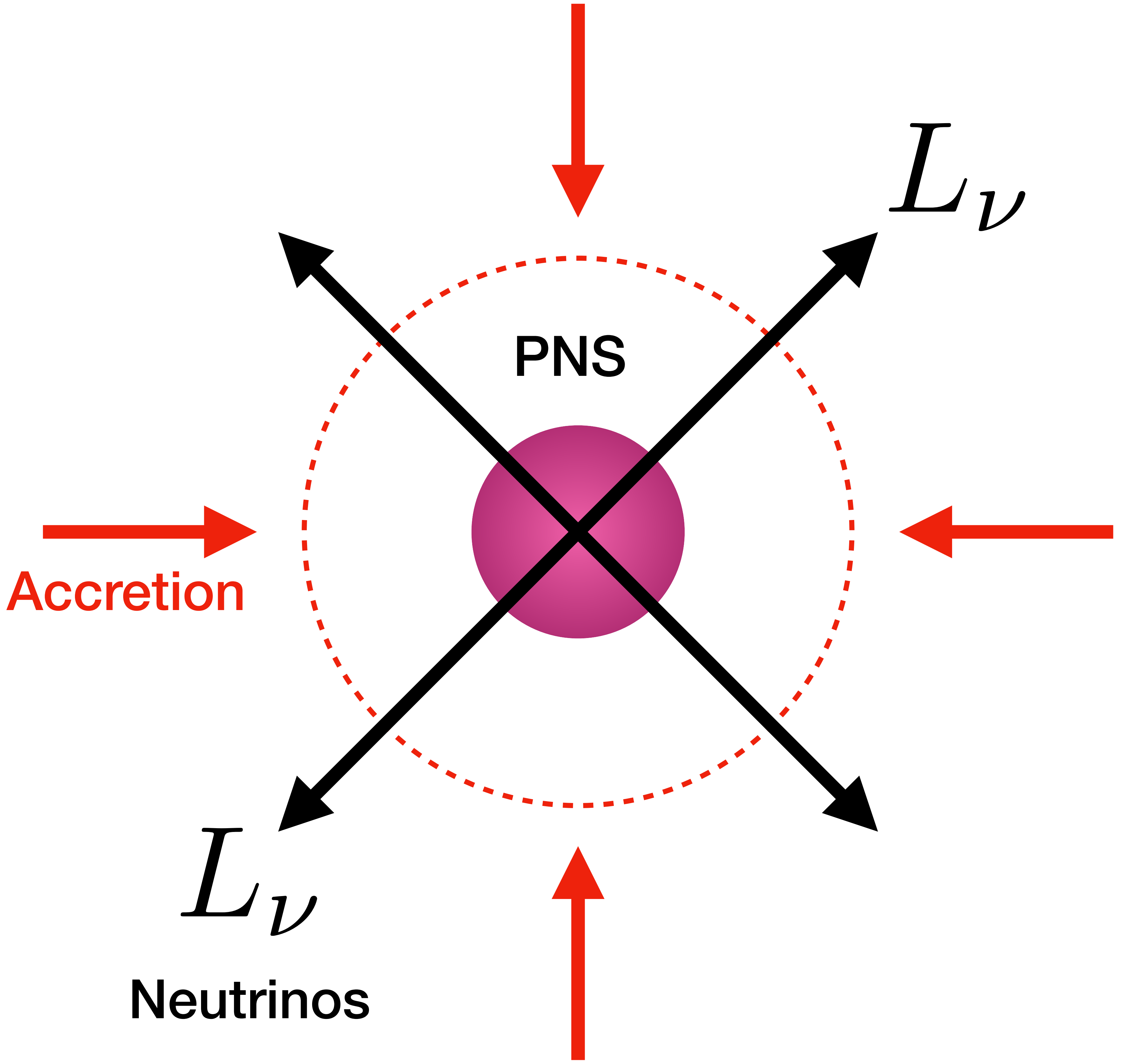
in Solar Masses

Core-Collapse Supernova Engines

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

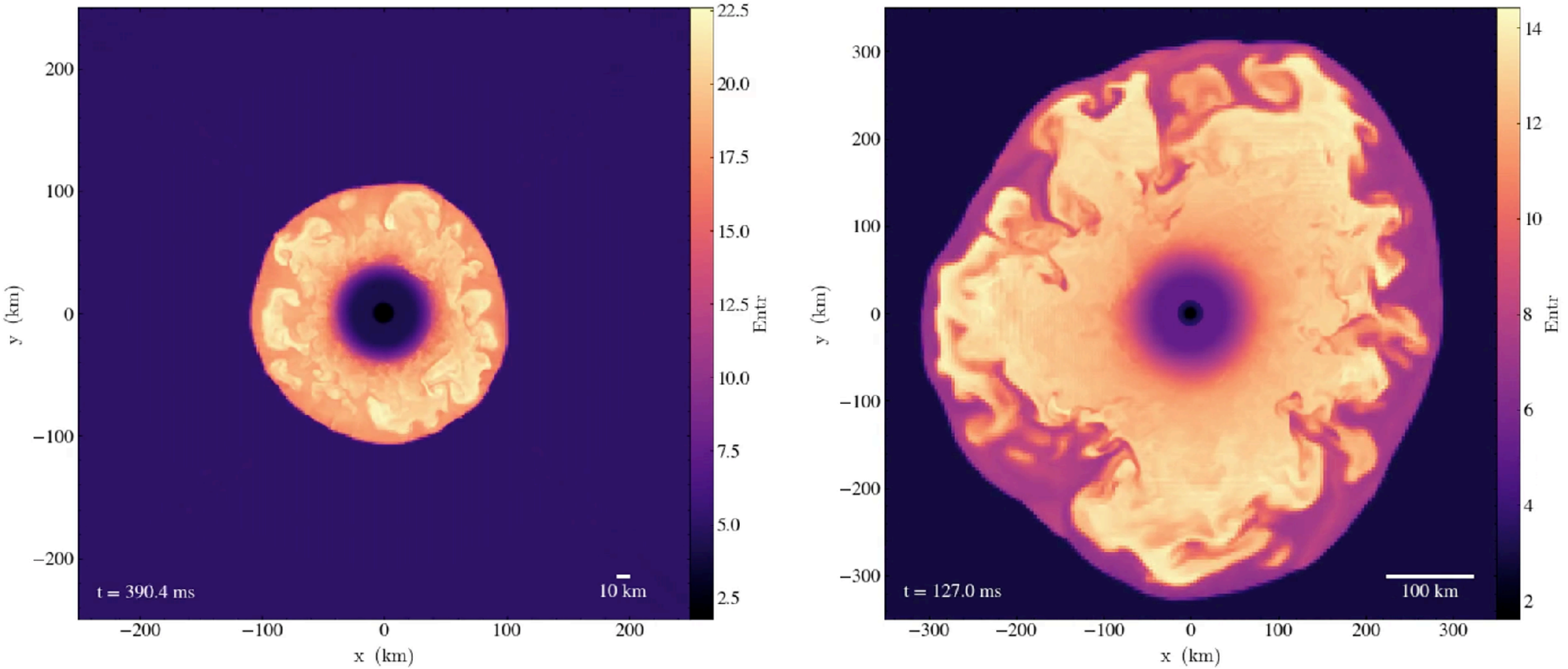
- (Magneto) hydrodynamics → (Plasma) /fluid dynamics
- General Relativity → Gravity
- Nuclear and Neutrino Physics → Nuclear EoS, nuclear reactions & neutrino interactions
- Boltzmann Transport Theory → Neutrino Transport

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. Mosta)

Shock Revival



Pan et al. in prep.

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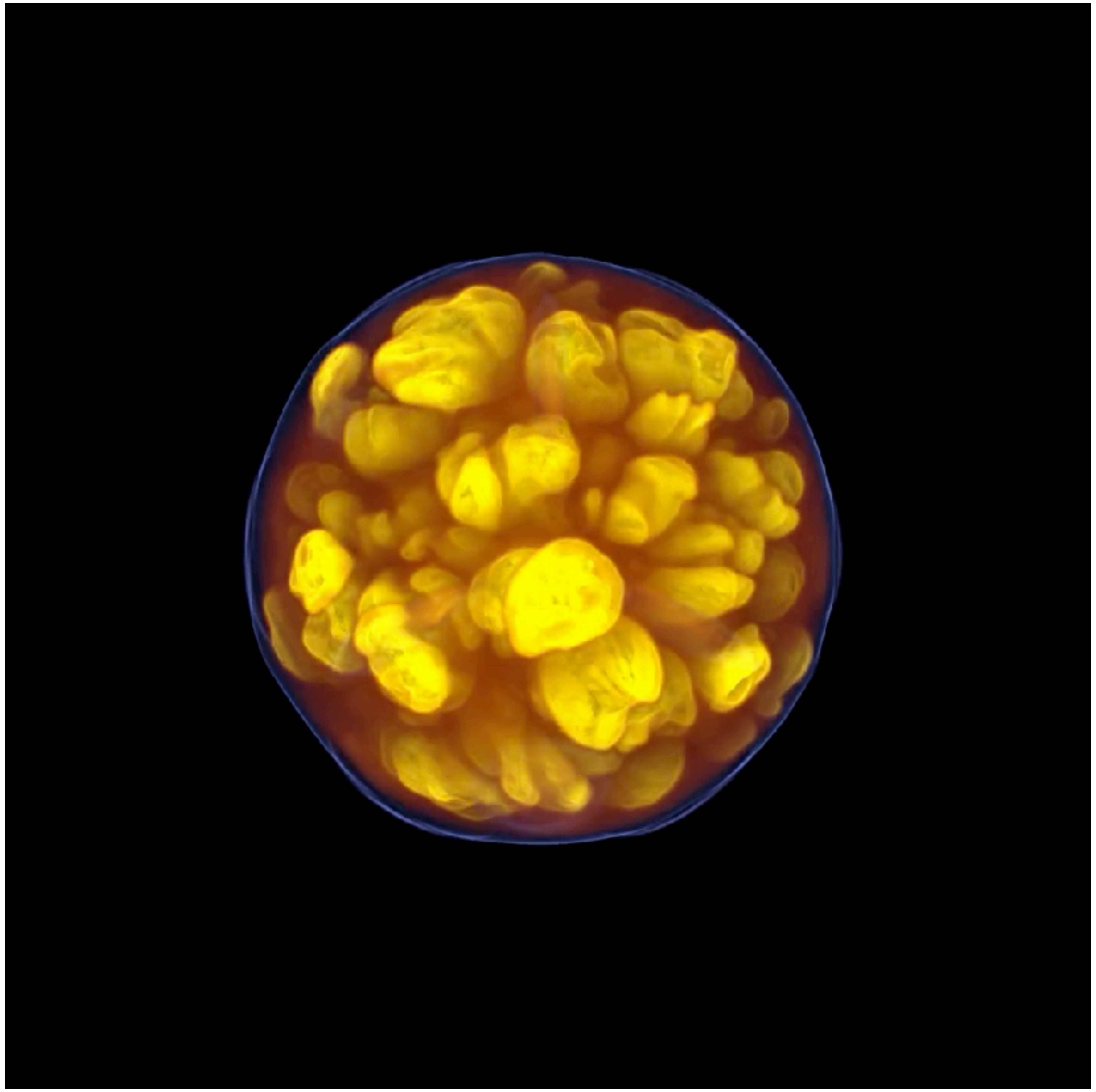
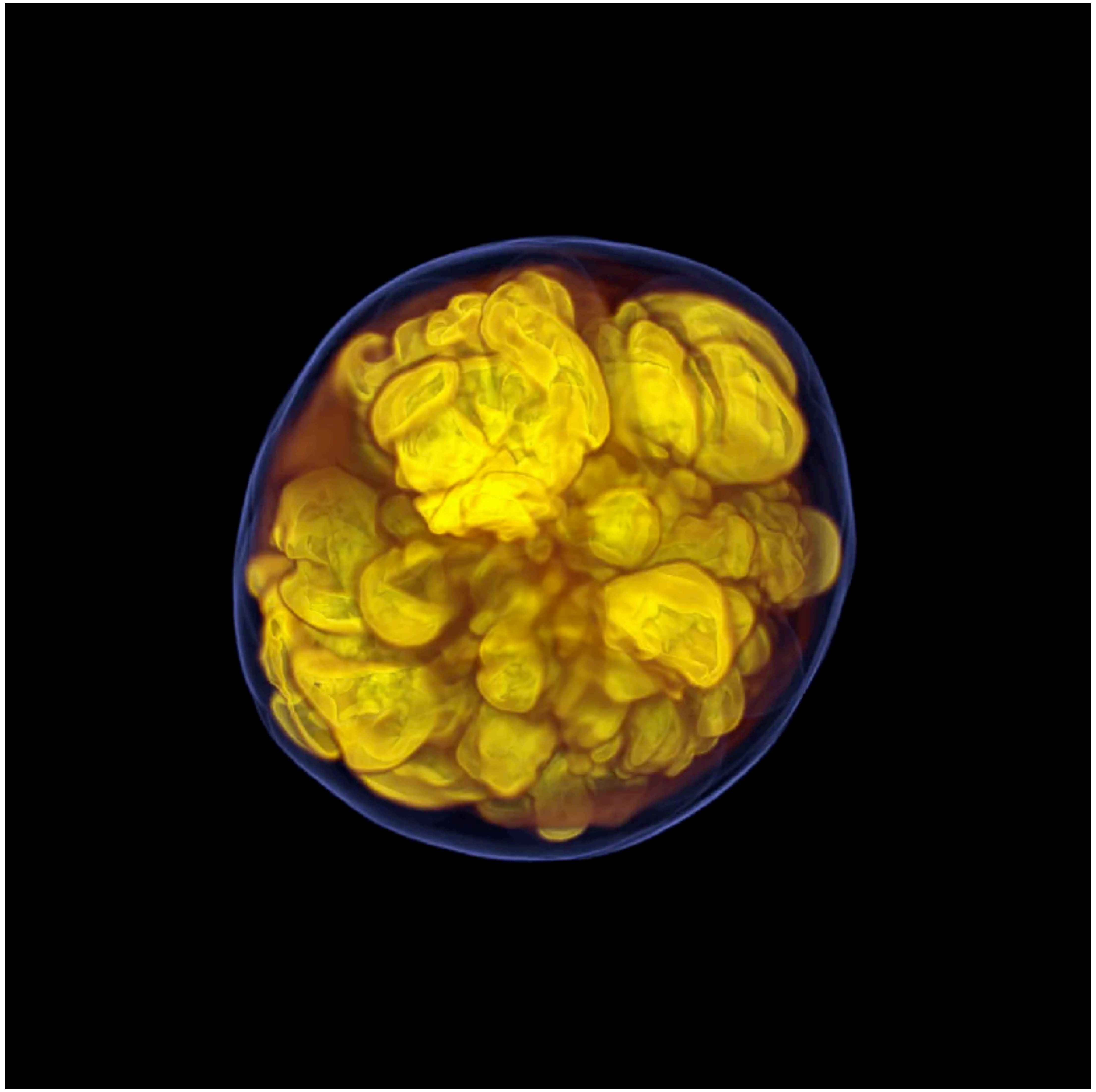
Shock Revival

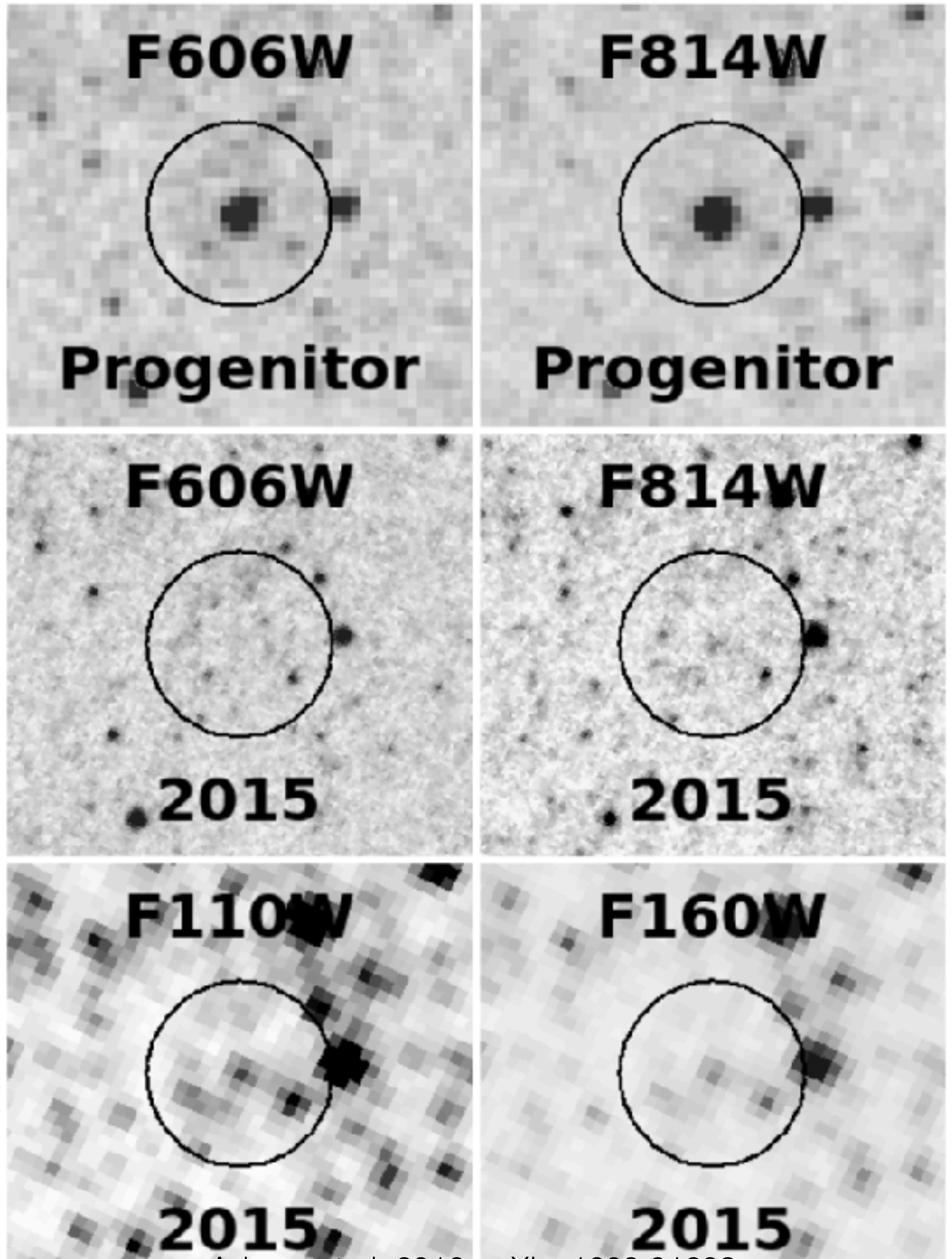




Pan et al. in prep.

Stellar Mass Black Hole Formation

Failed Supernovae



Adams et al. 2016, arXiv: 1609.01283

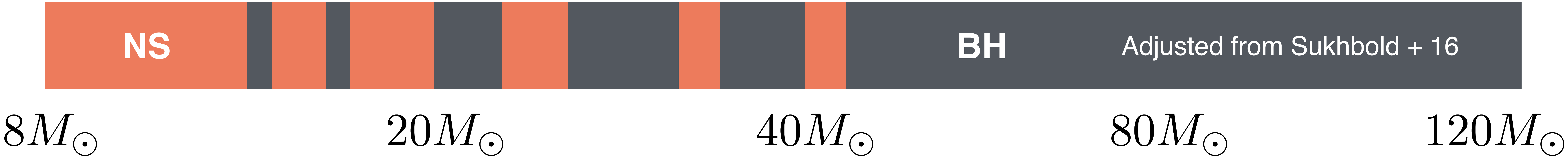
The first Candidate: N6946-BH1

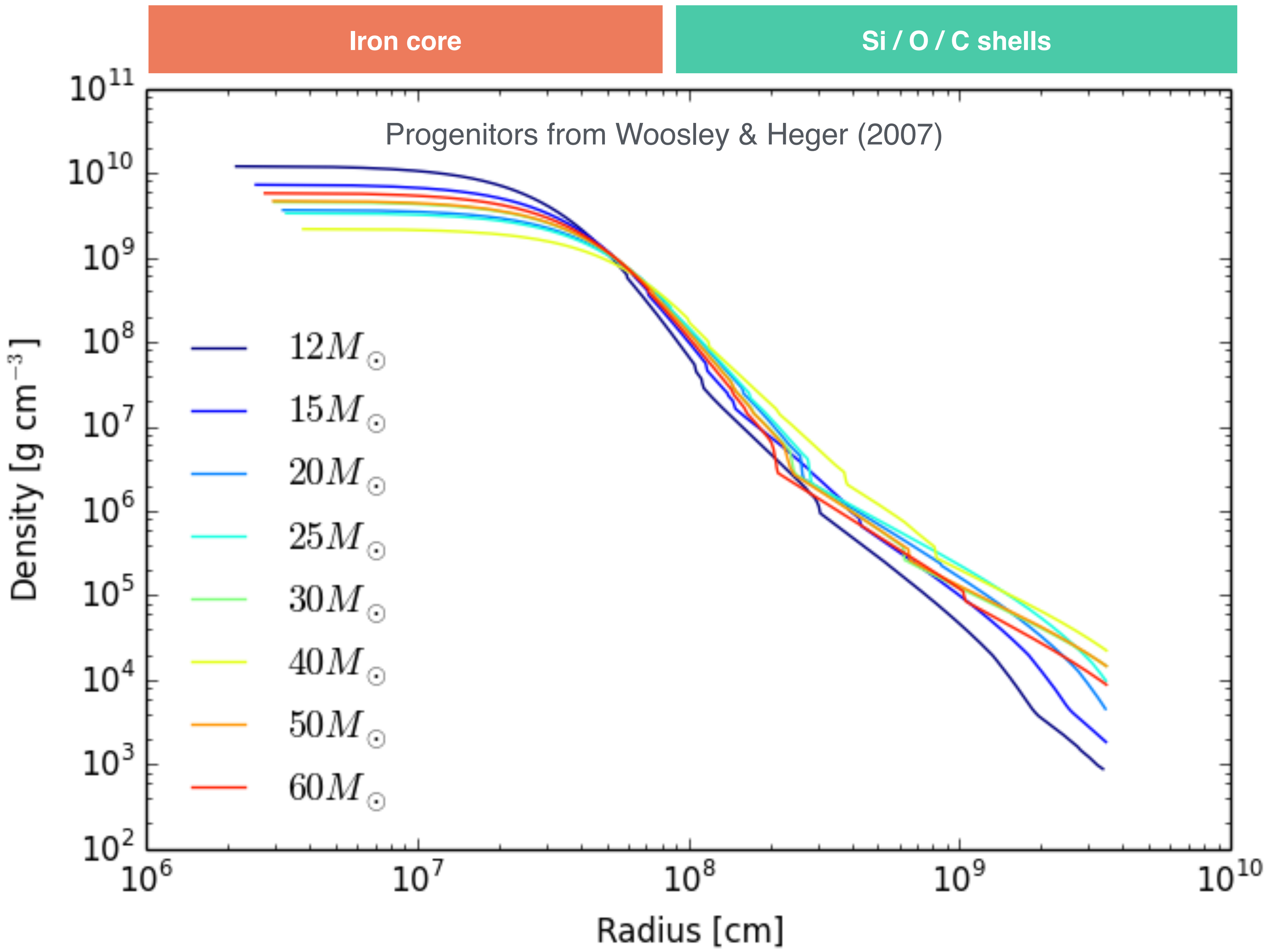
NGC6946-BH1: In NGC 6946 (5.96 Mpc) at RA 20:35:27.56 and Dec + 60:08:08.29

experienced an outburst in 2009, $L > 10^6 L_{sun}$ but than fading to $\sim 10^5 L_{sun}$ below its pre-outburst luminosity

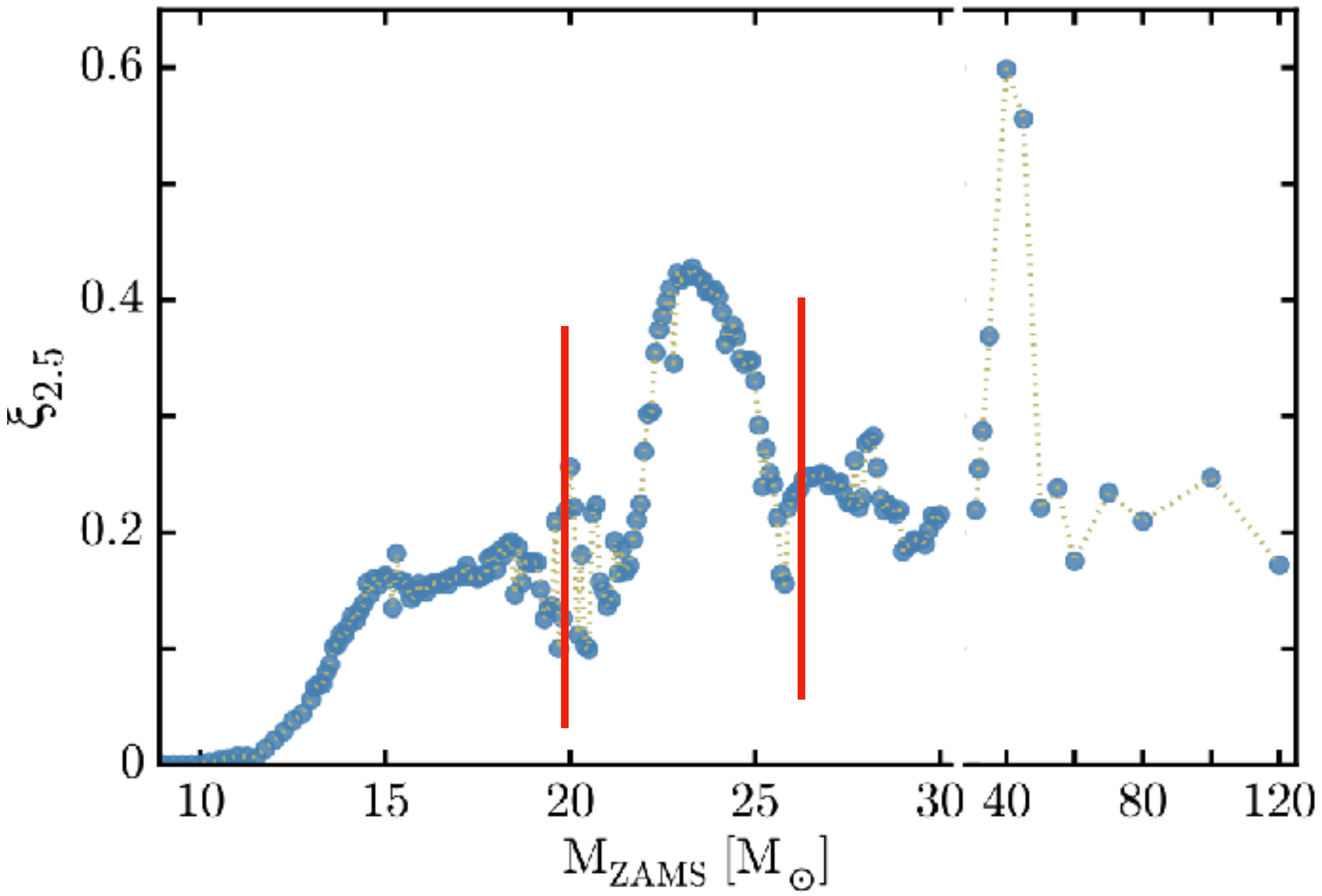
However, the surviving star could be hidden by dust —> luminous in the IR but optically obscured (Crause et al. 2003)

Supernova Progenitors





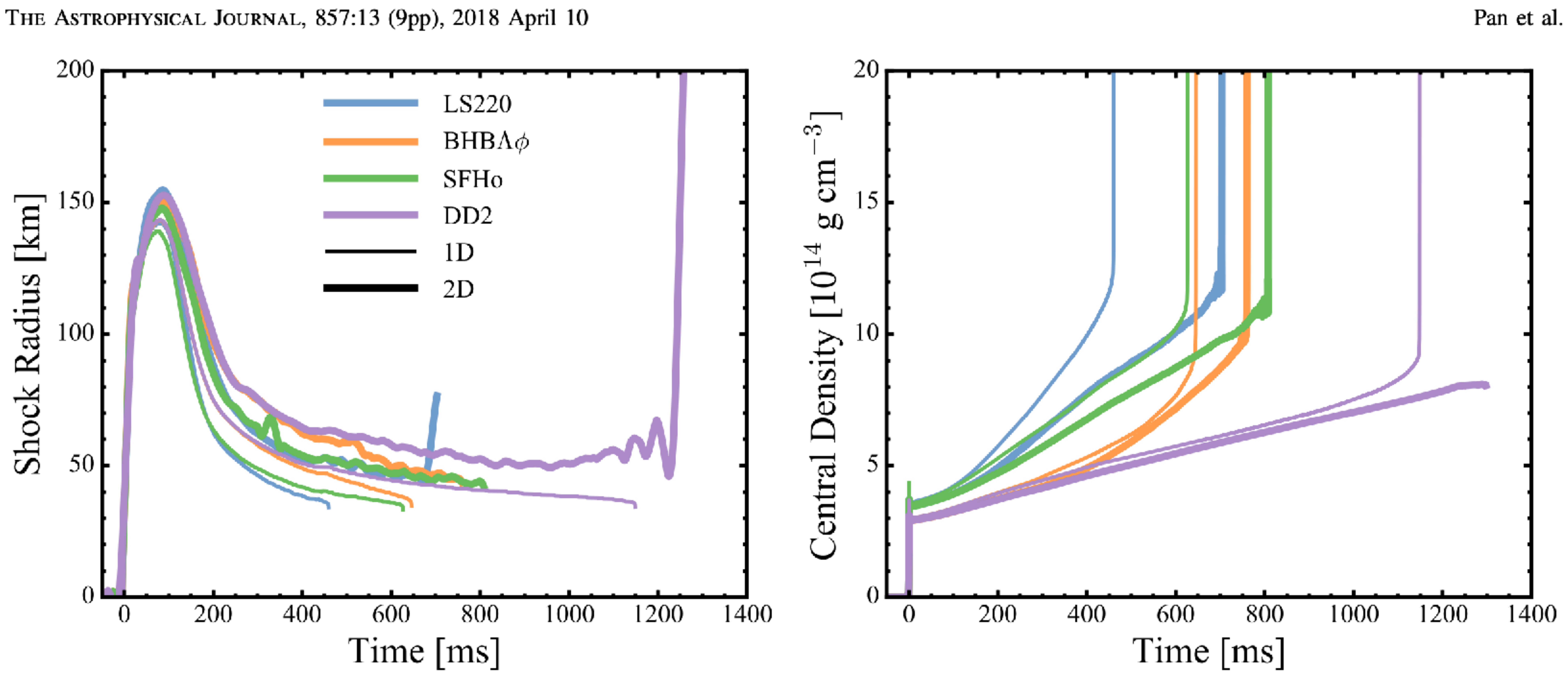
Sukhbold + 16



The Compactness Parameter:

$$\xi_M = \frac{M/\mathrm{M}_\odot}{R(M)/1000\,\mathrm{km}}\Big|_{t_\mathrm{bounce}},$$

Failed Supernovae



Pan et al. (2018)

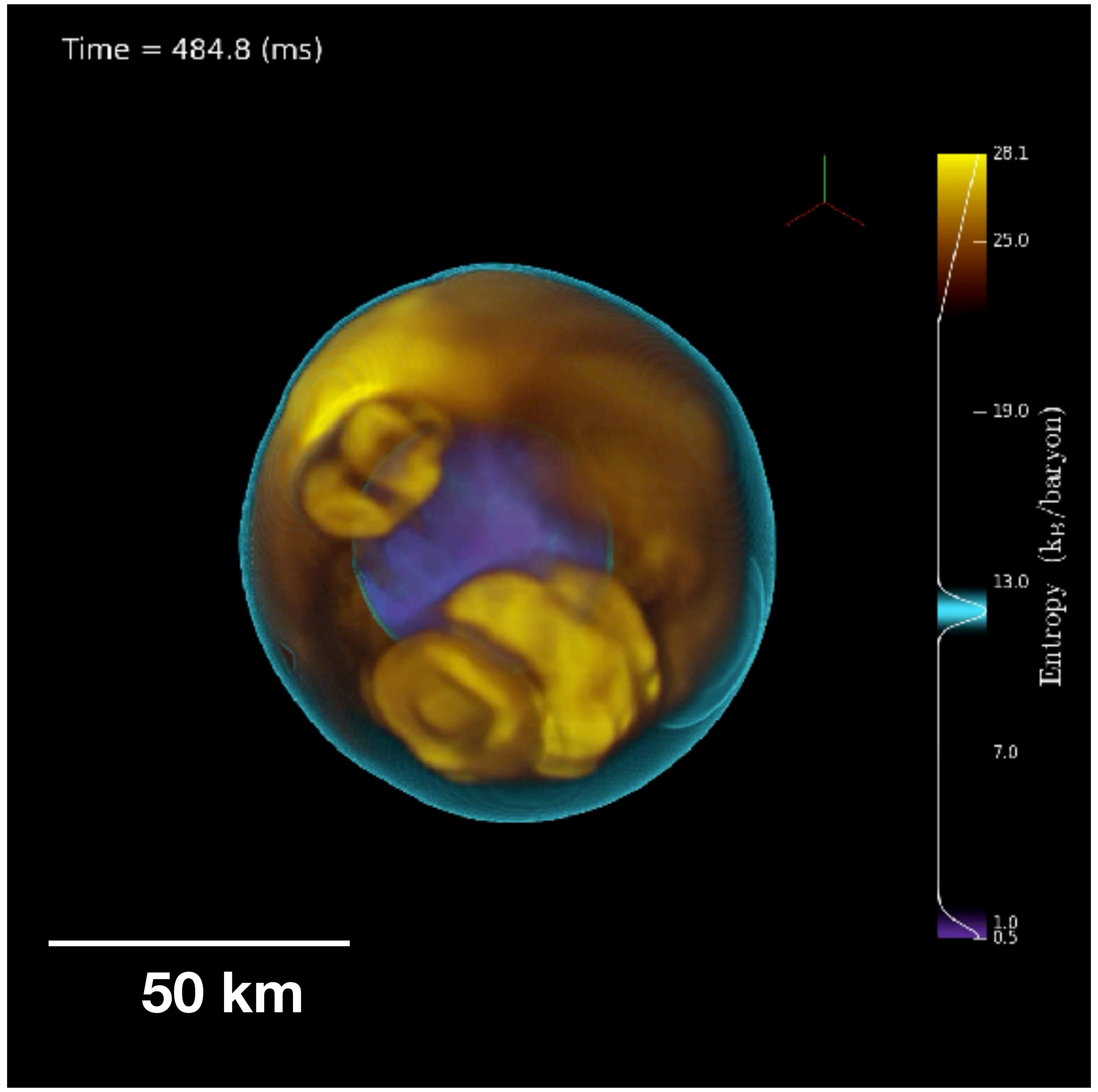
arXiv:2010.02453

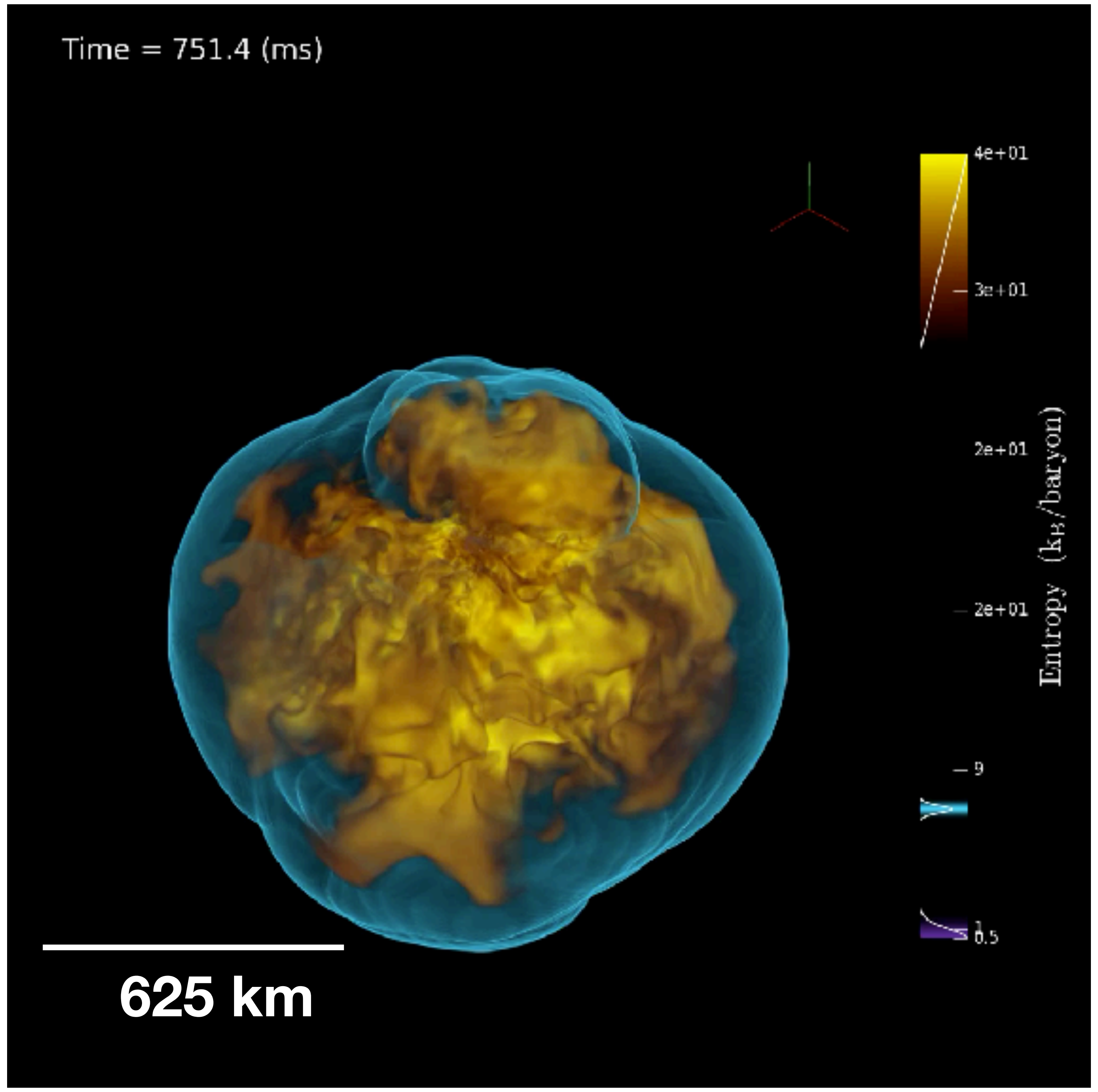
Simulations (some technical details)

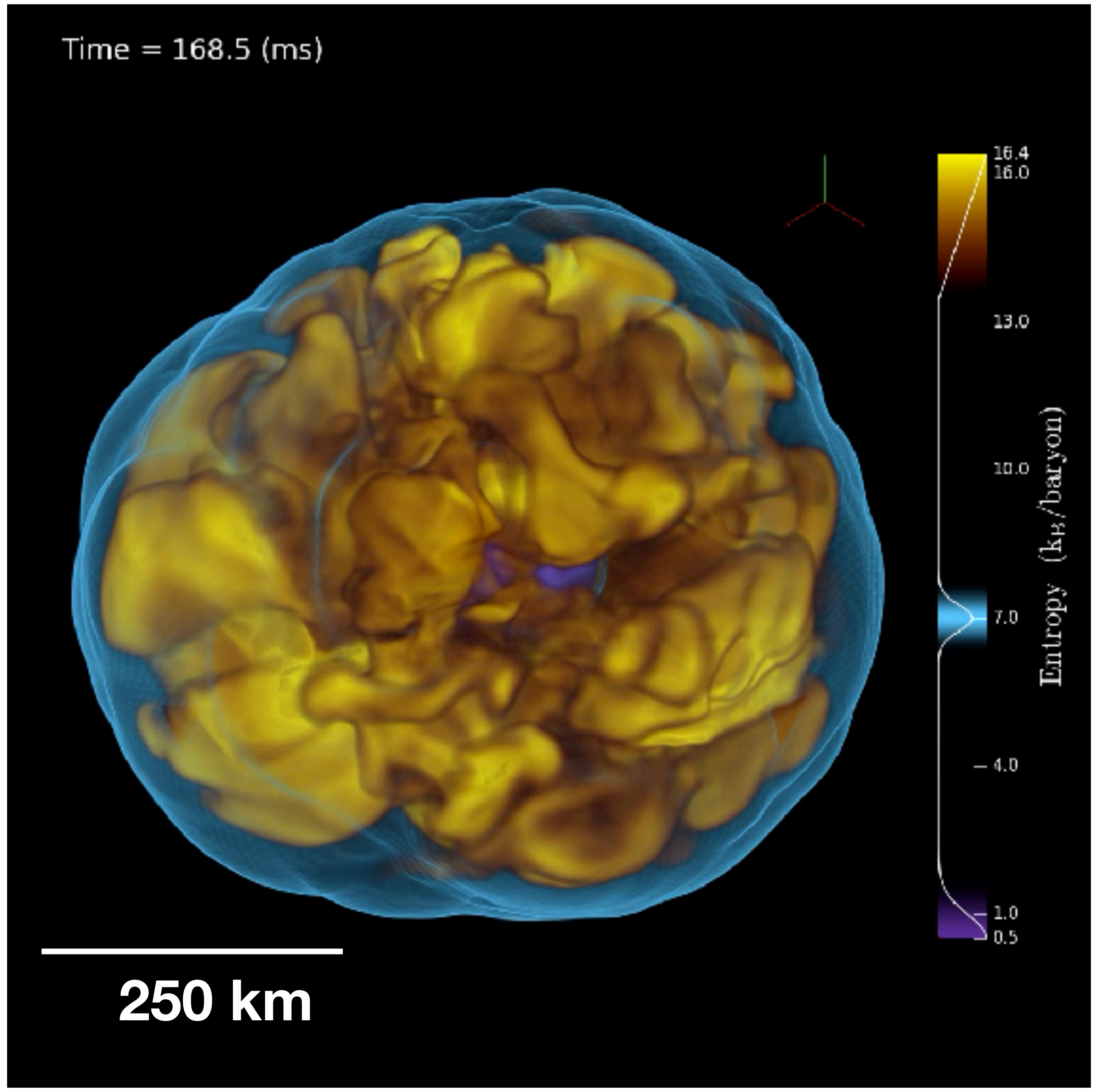
- 40 solar mass progenitor (s40) from Woosley and Heger (2007)
- v-constant rotation formula (Eriguchi & Muller 1985)
- 3D FLASH + IDSA for Neutrino transport (Pan et al. 2016, 2017, 2018)
- An Effective GR Potential (Marek et al. 2006, O'Connor & Couch 2018)
- LS220 Equation of State
- 20 neutrino energy bins from 3 MeV to 300 MeV
- Minimum cell size 488 m (1 degree angular resolution)
- GPU acceleration with OpenACC (Pan et al. 2018, 2019)
- Three 3D simulations (NR, SR, FR) and one 2D counter part (NR-2D)

Overview of simulations

$\Omega_0 = 0 \text{ rad s}^{-1}$	$\Omega_0 = 0.5 \text{ rad s}^{-1}$	$\Omega_0 = 1 \text{ rad s}^{-1}$
NR	**SR**	**FR**

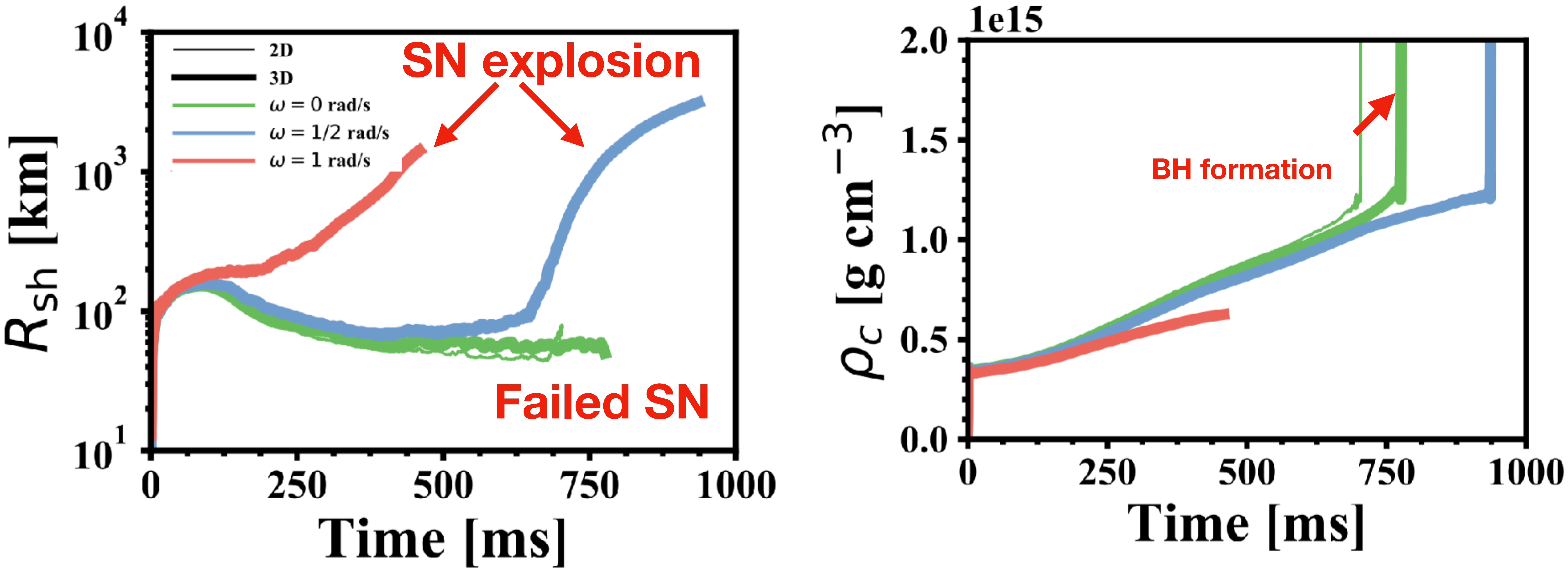






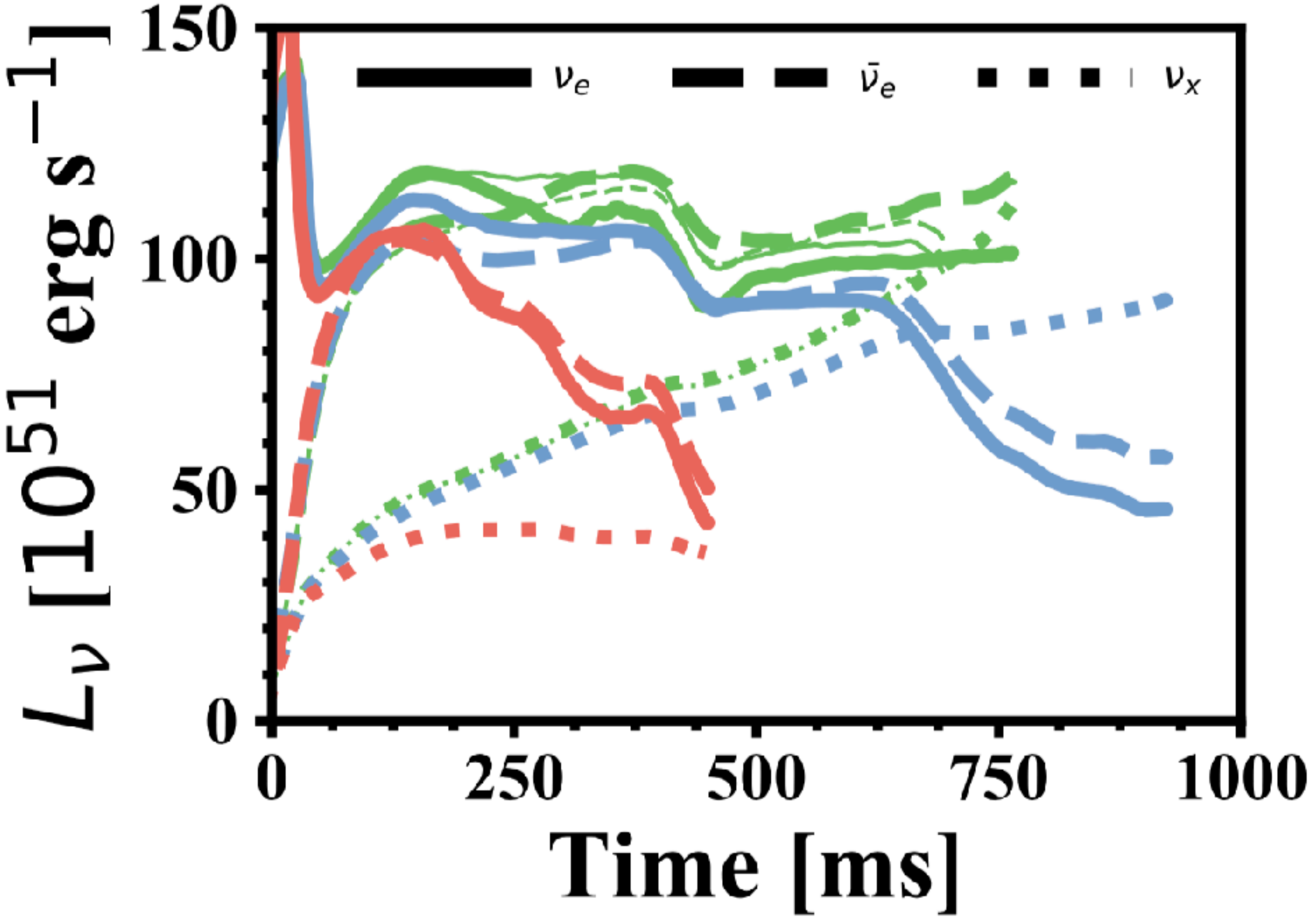
Pan et al. (2020), arXiv:2010.02453

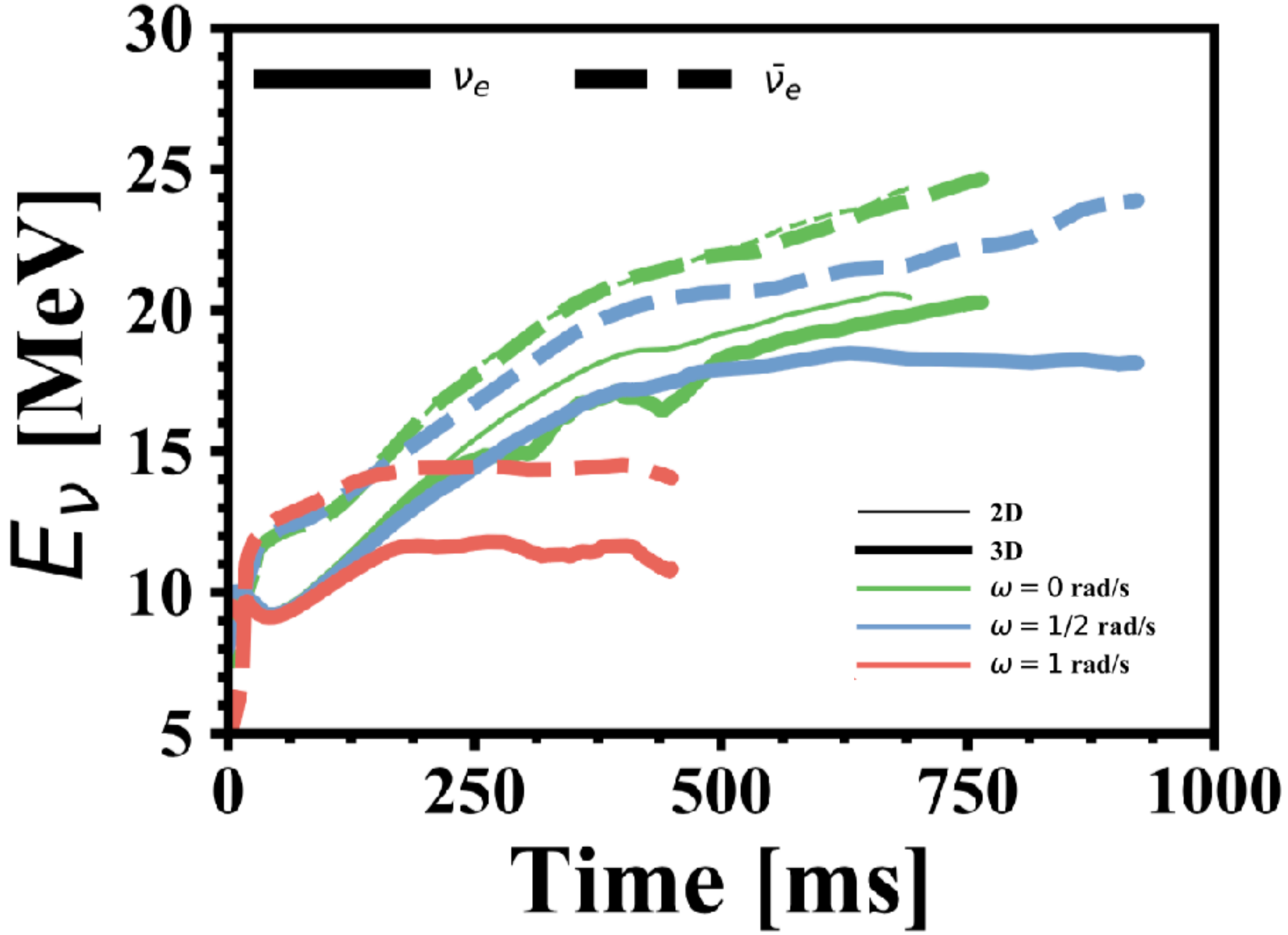
Explosion together with BH formation



Pan et al. (2020), arXiv:2010.02453

Neutrino Emissions





Pan et al. (2020), arXiv:2010.02453

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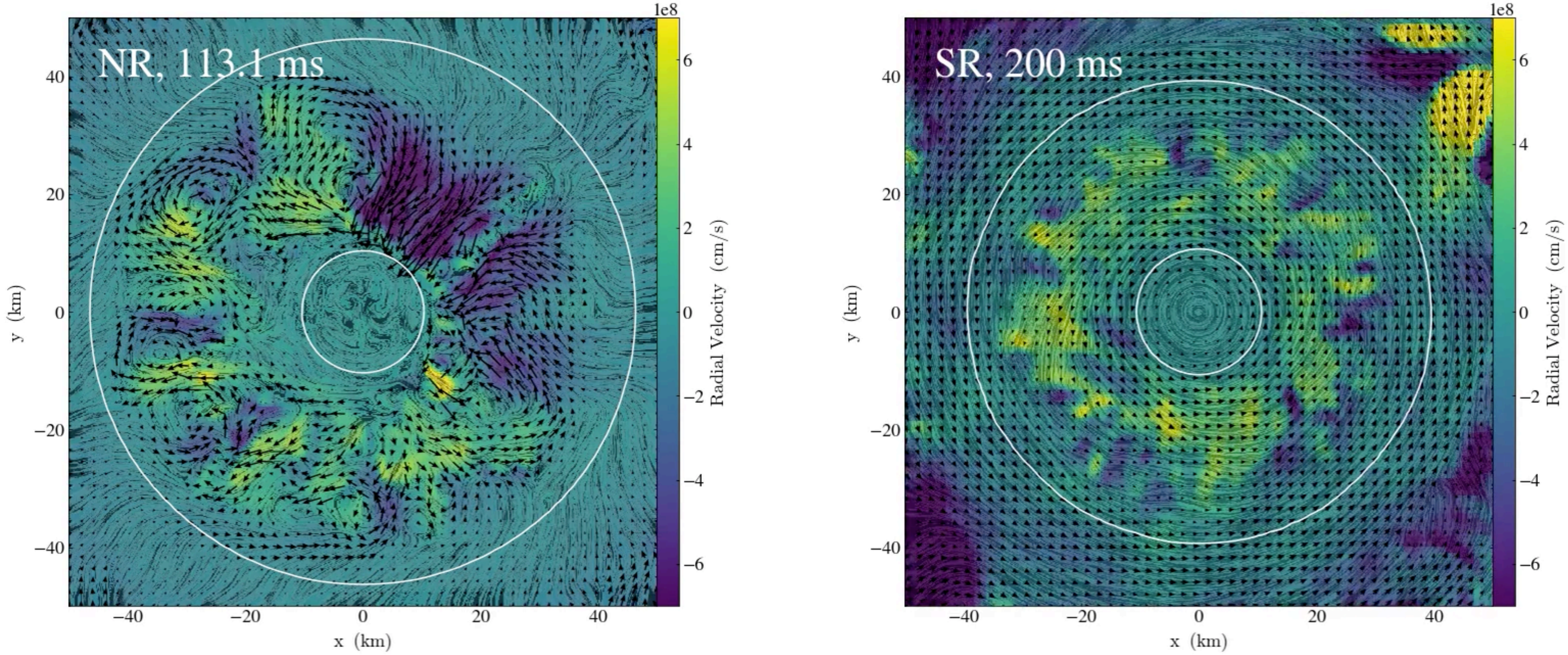
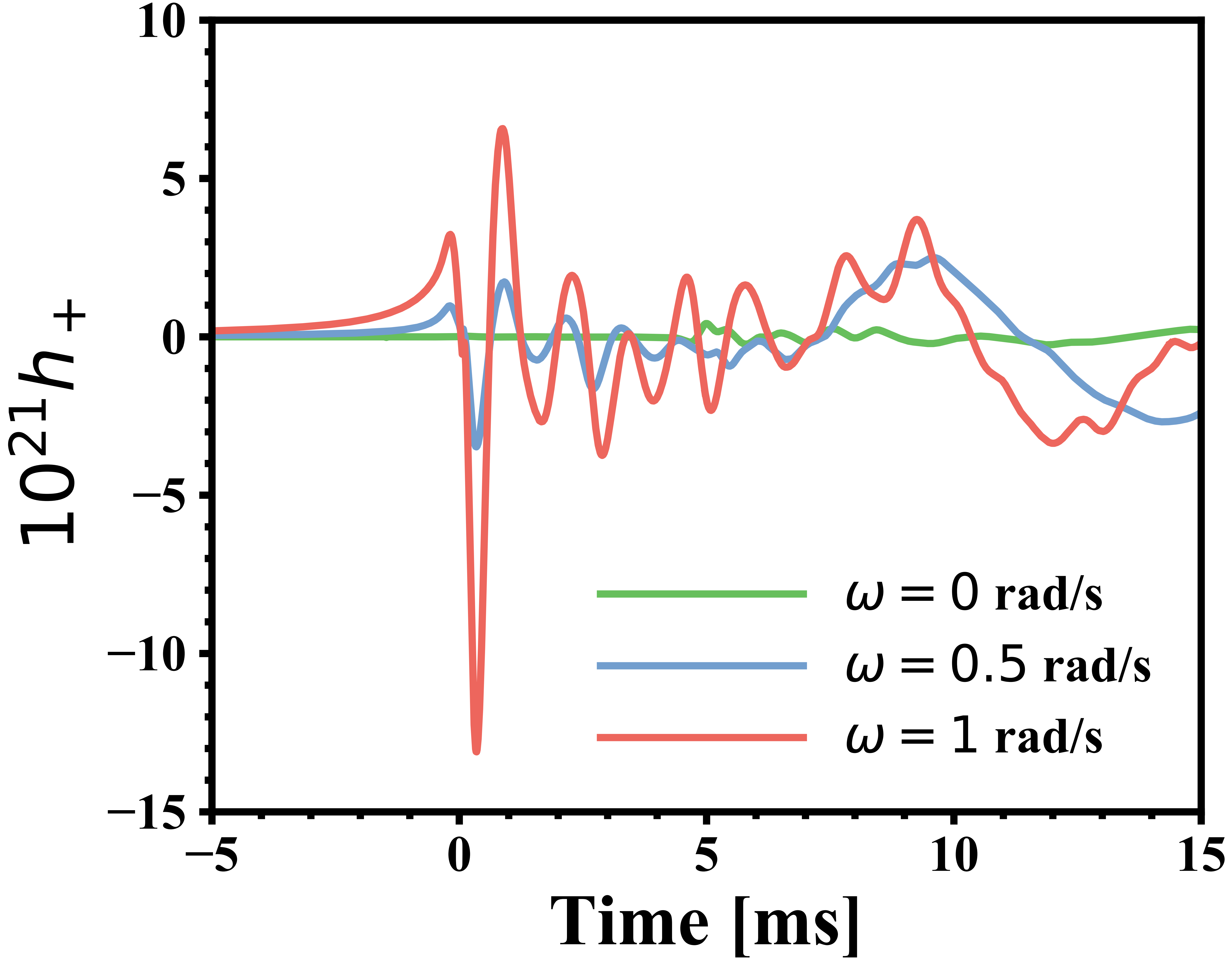
Density contours at 1e12 and 1e14 g/cm^3



Pan et al. (2020), arXiv:2010.02453

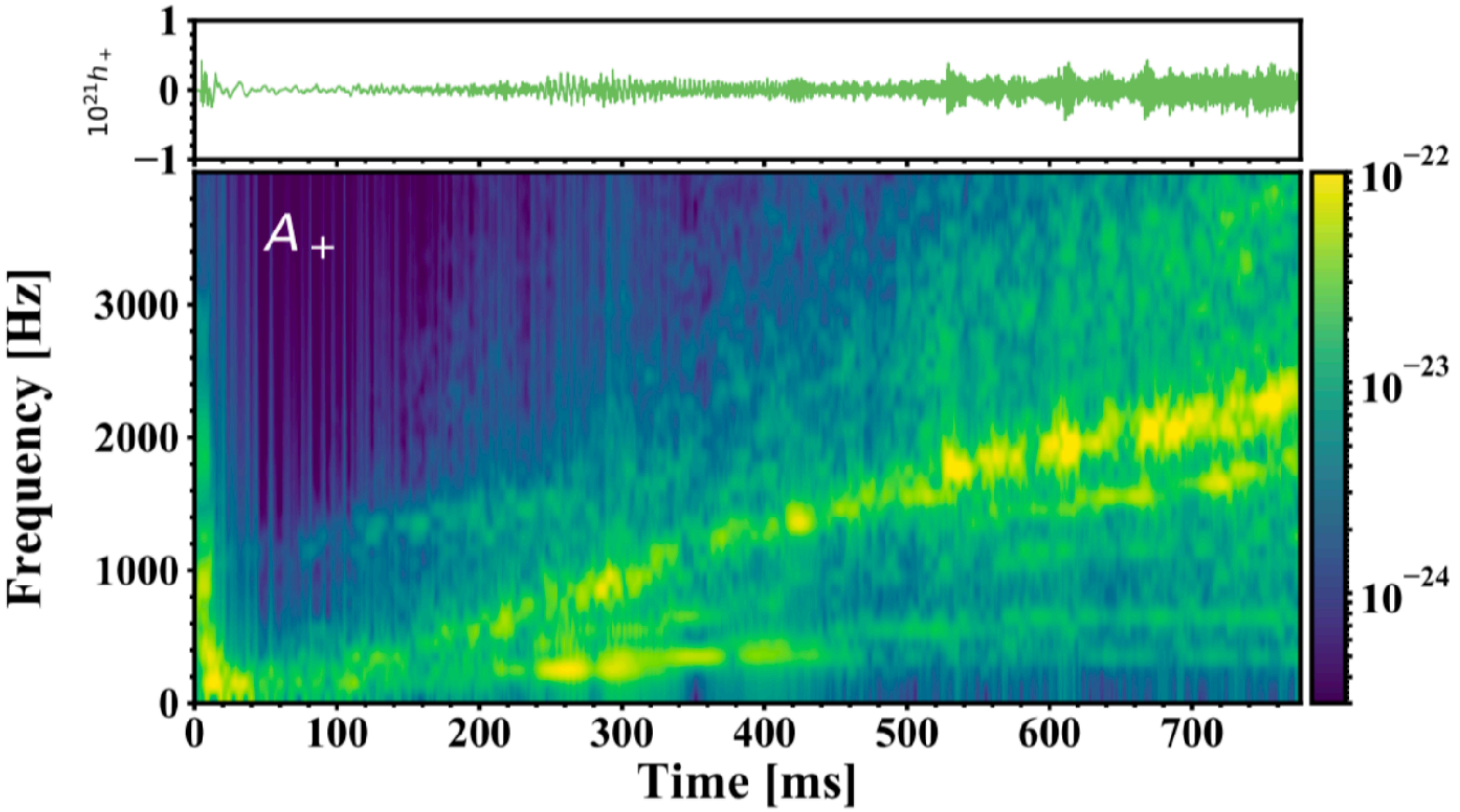
Gravitational Wave Emissions

Assuming a distance at 10 kpc



Pan et al. (2020), arXiv:2010.02453

Gravitational Wave Spectrogram



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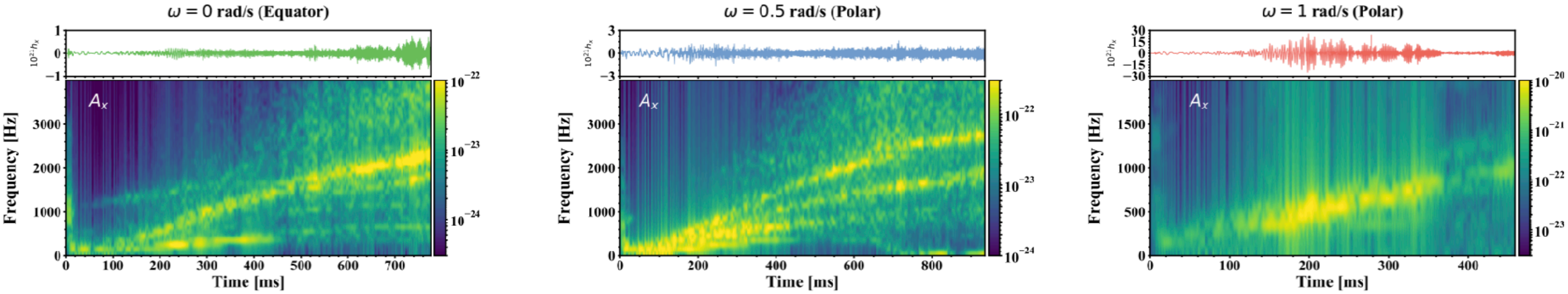
Pan et al. (2020), arXiv:2010.02453

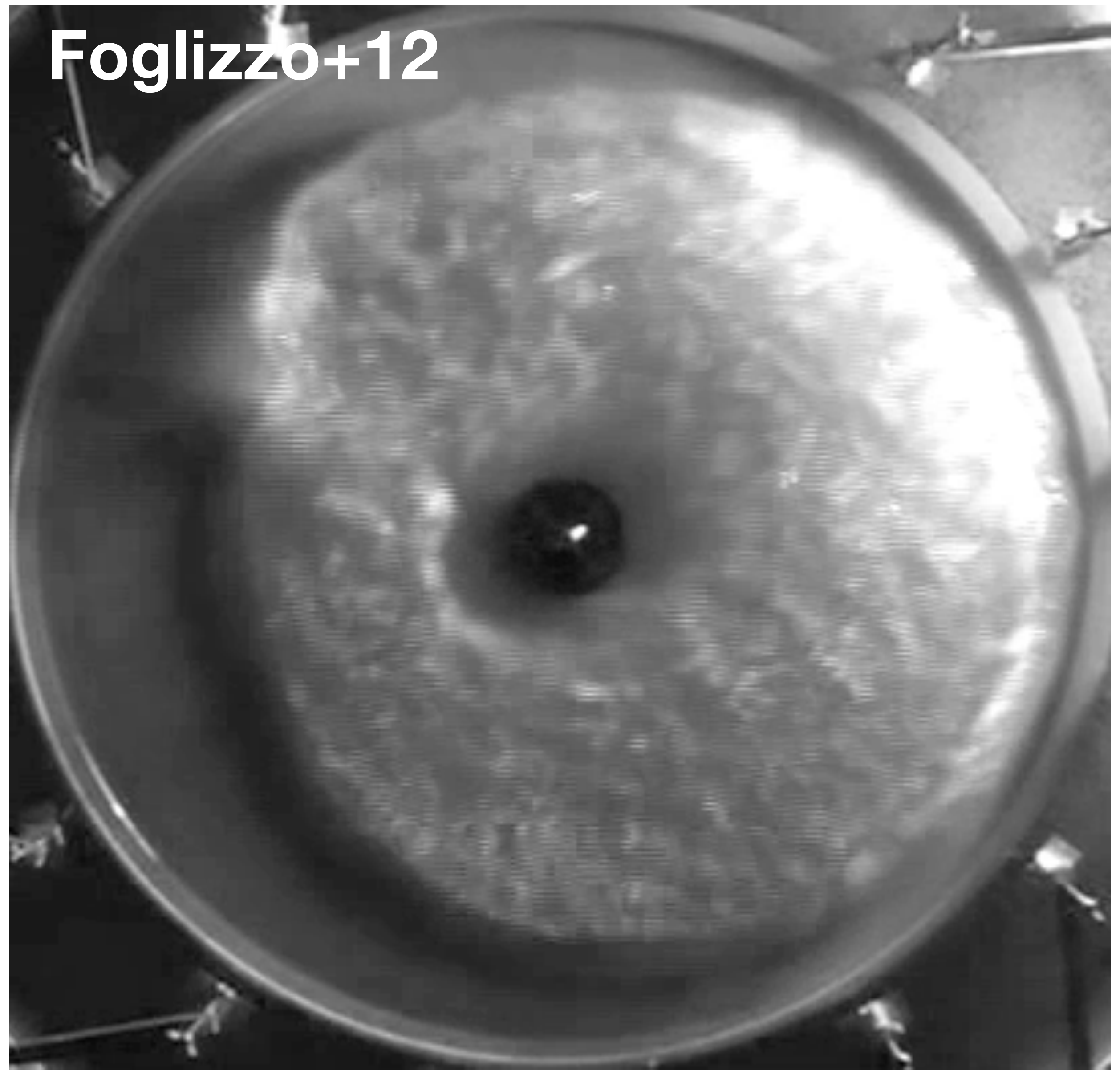
Gravitational Wave Spectrogram

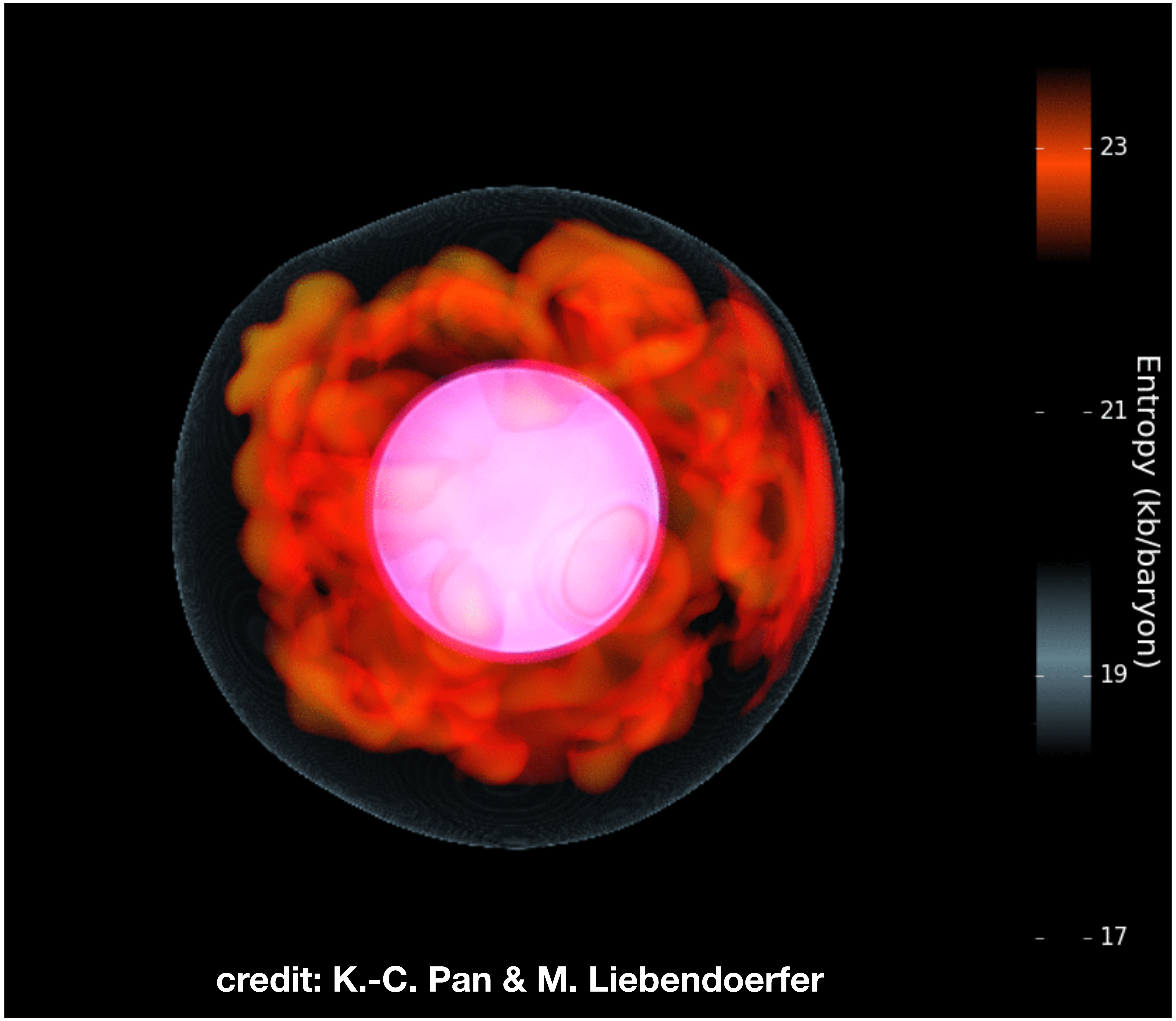
Dependence on the rotational speeds



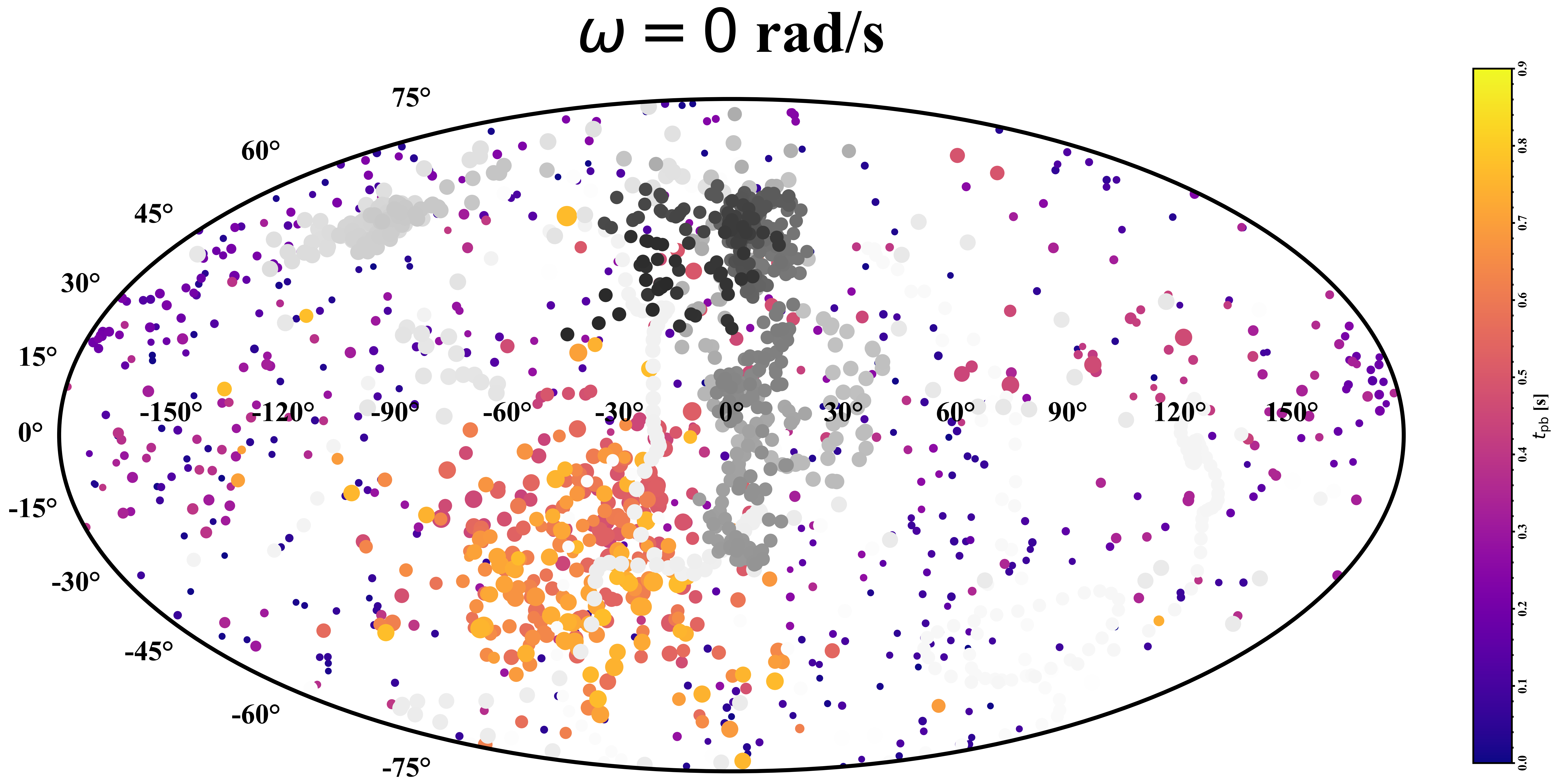
Pan et al. (2020), arXiv:2010.02453

Standing Accretion Shock Instability (SASI)



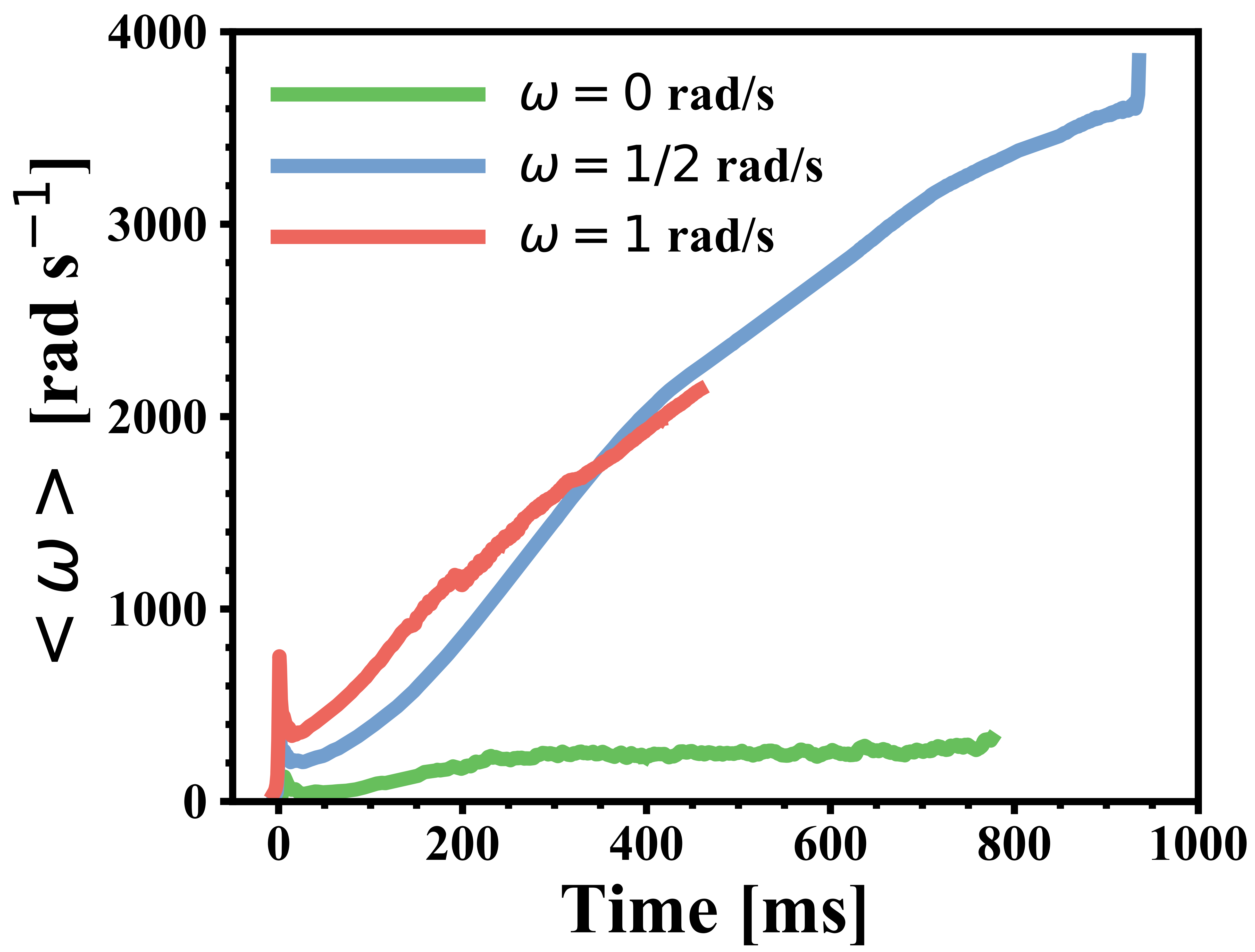


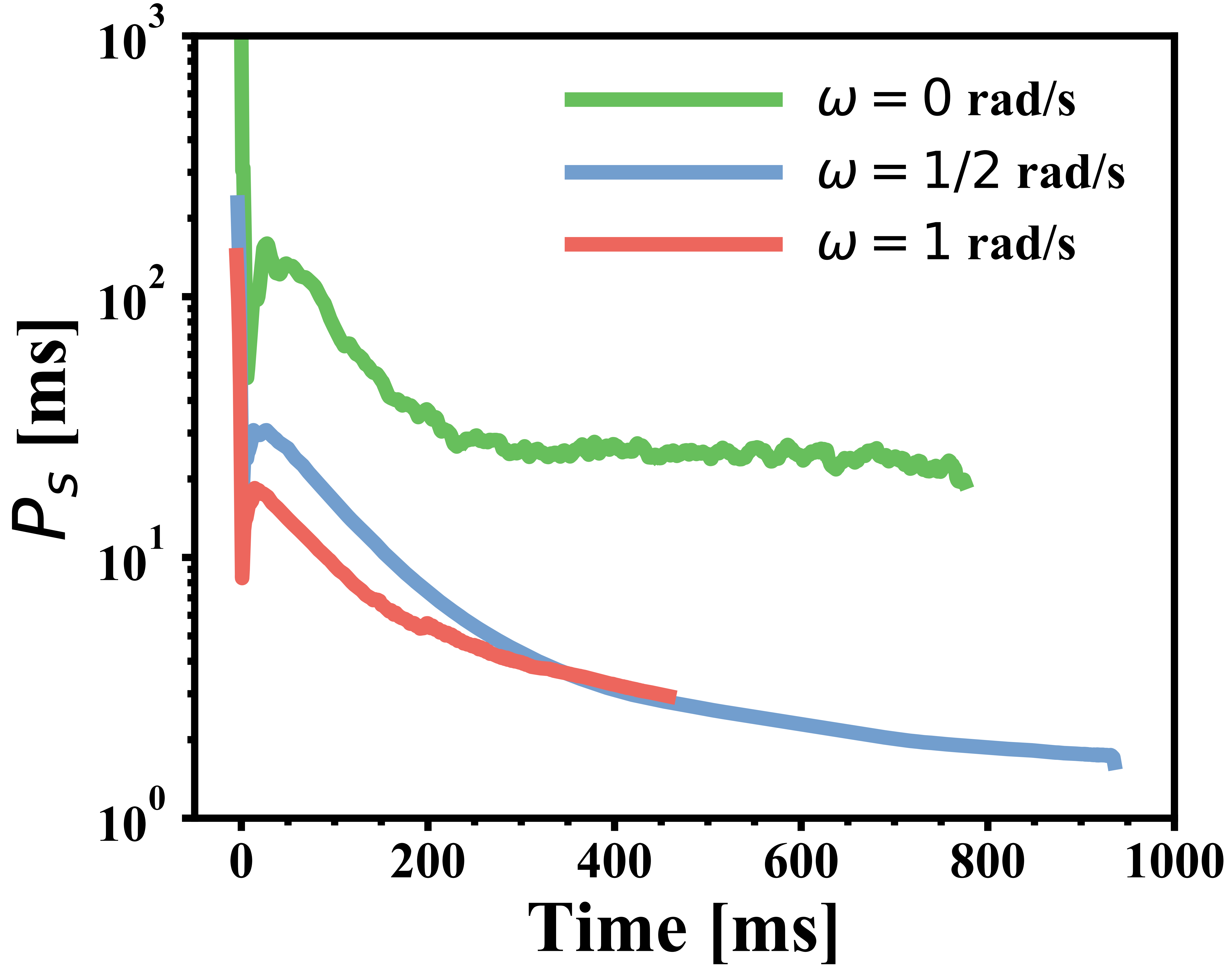
SASI induced rotation



Pan et al. (2020), arXiv:2010.02453

SASI induced rotation

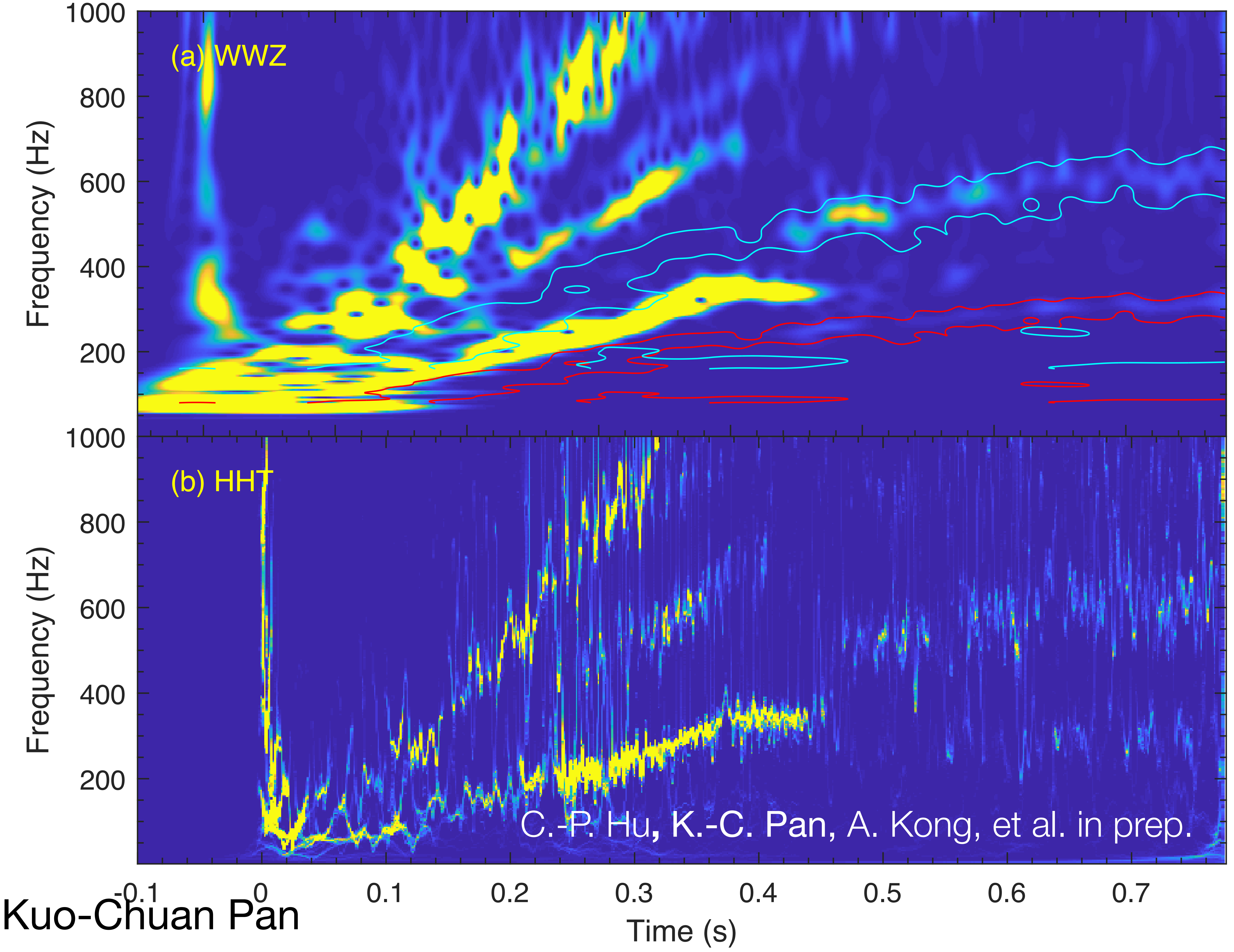


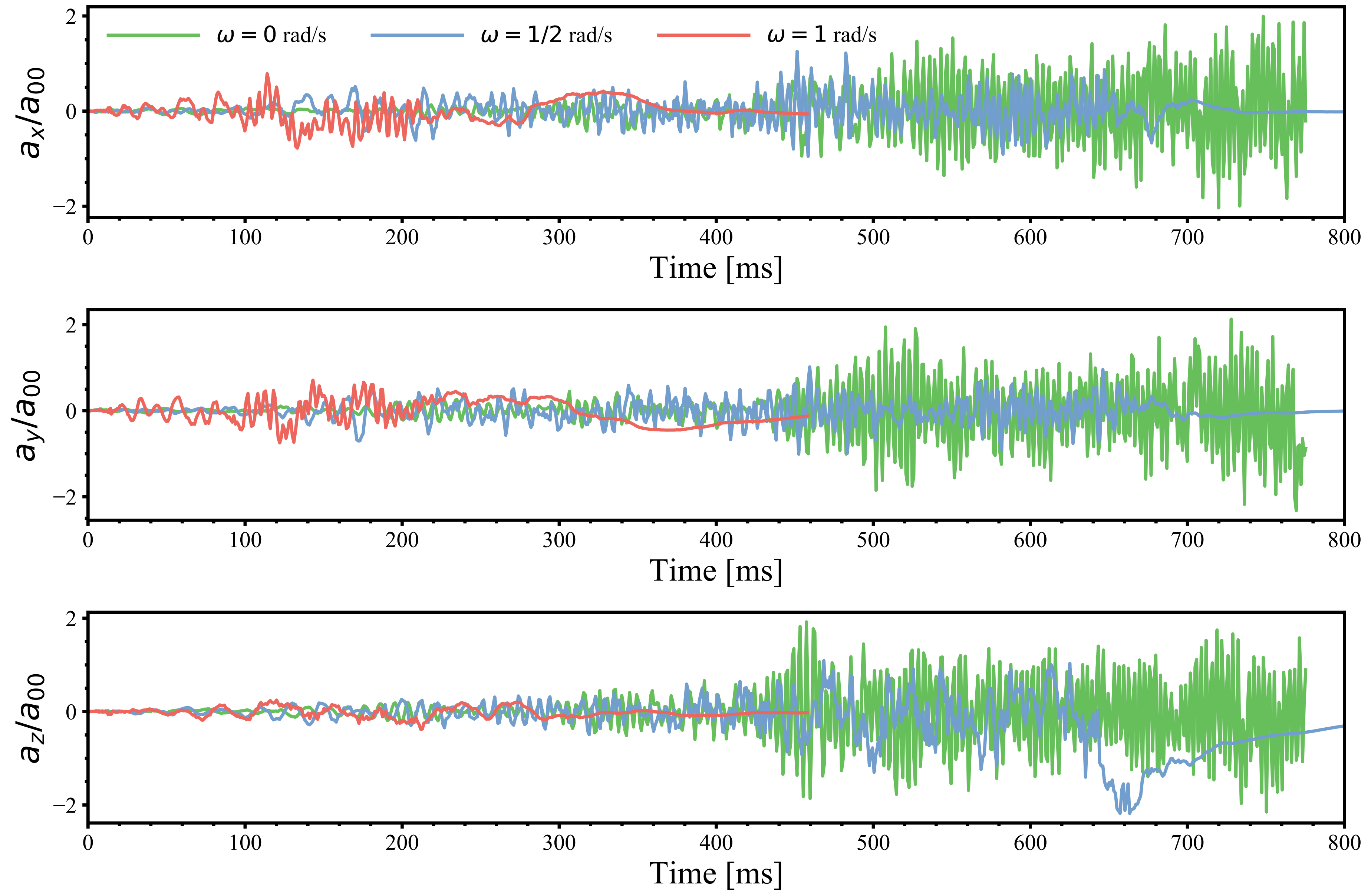


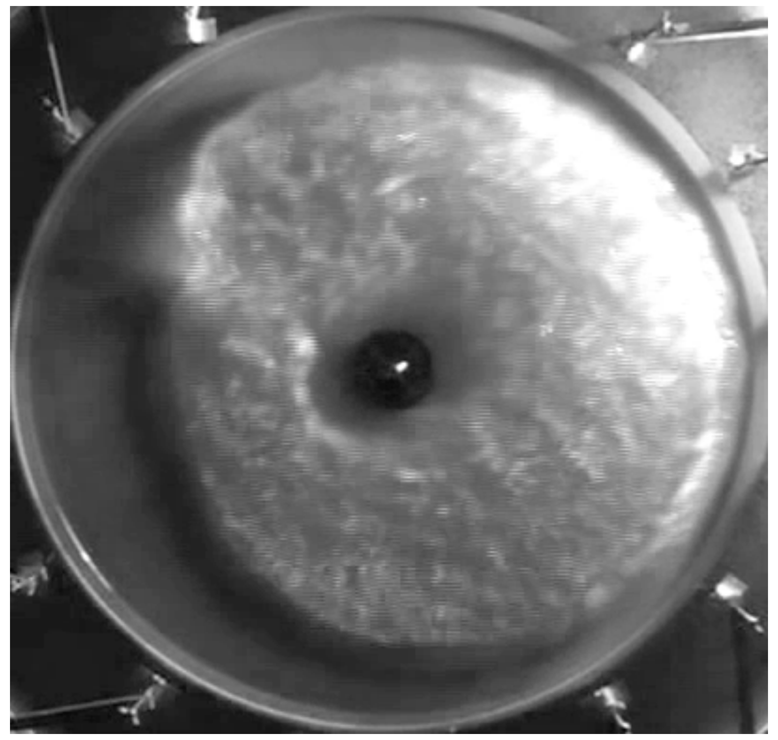
Pan et al. (2020), arXiv:2010.02453

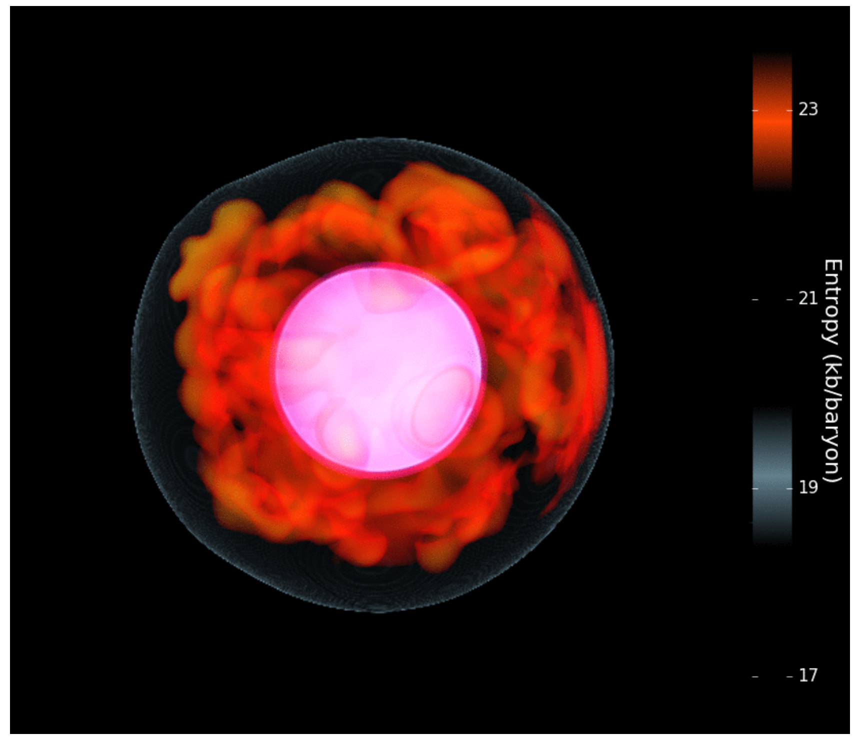
Gravitational Wave from SASI

with WWZ and HHT analysis





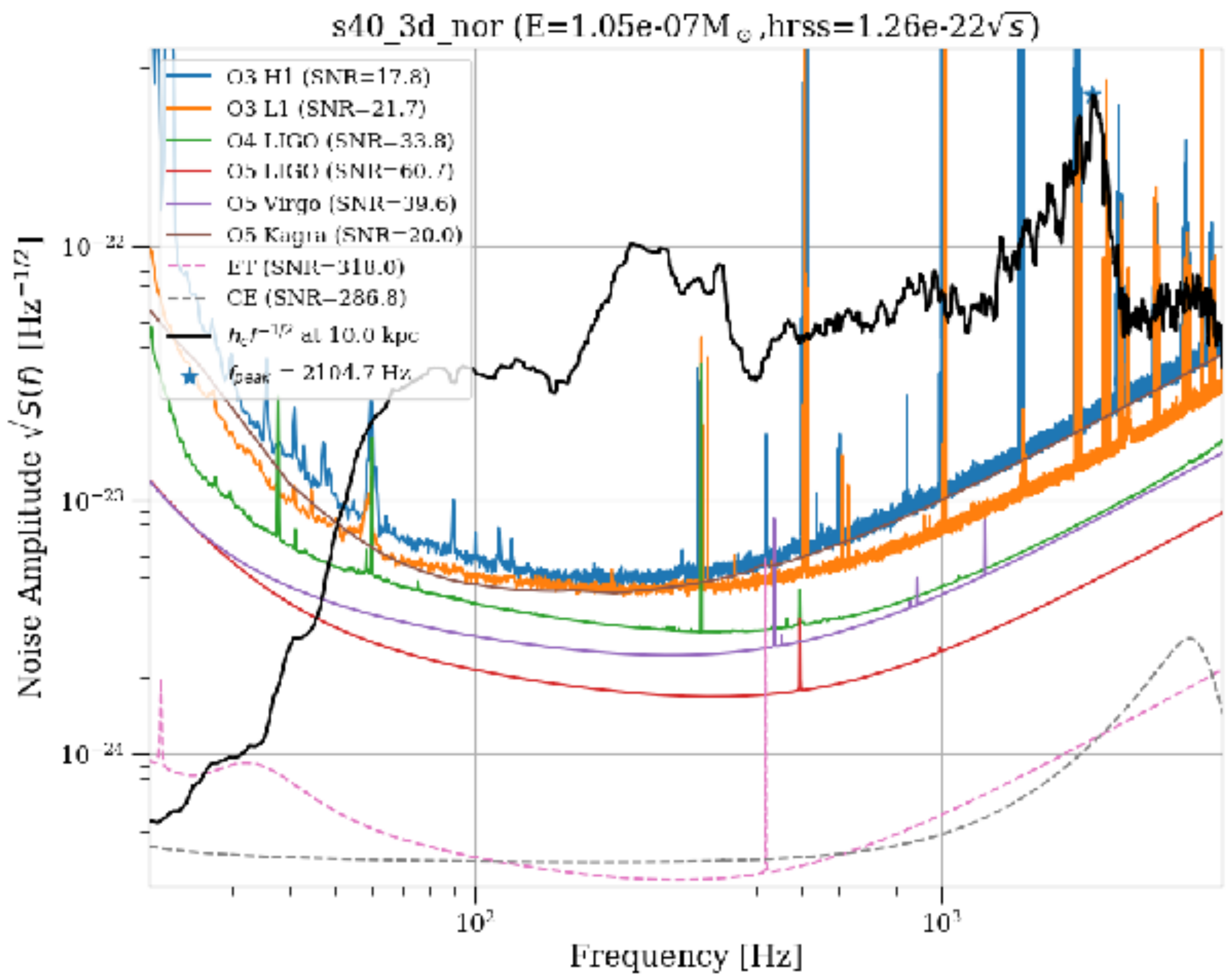




Detectability

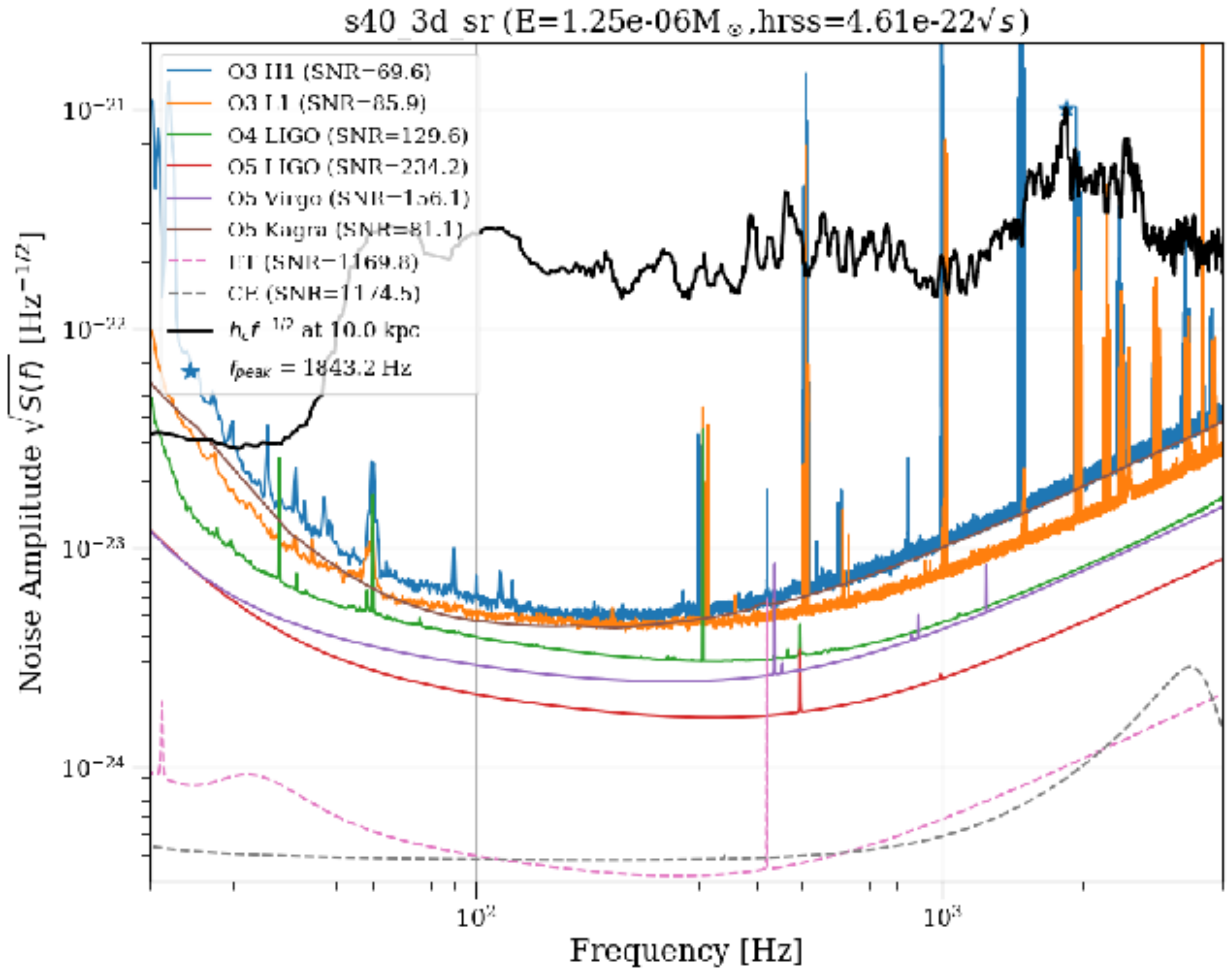
GW Spectra

NR



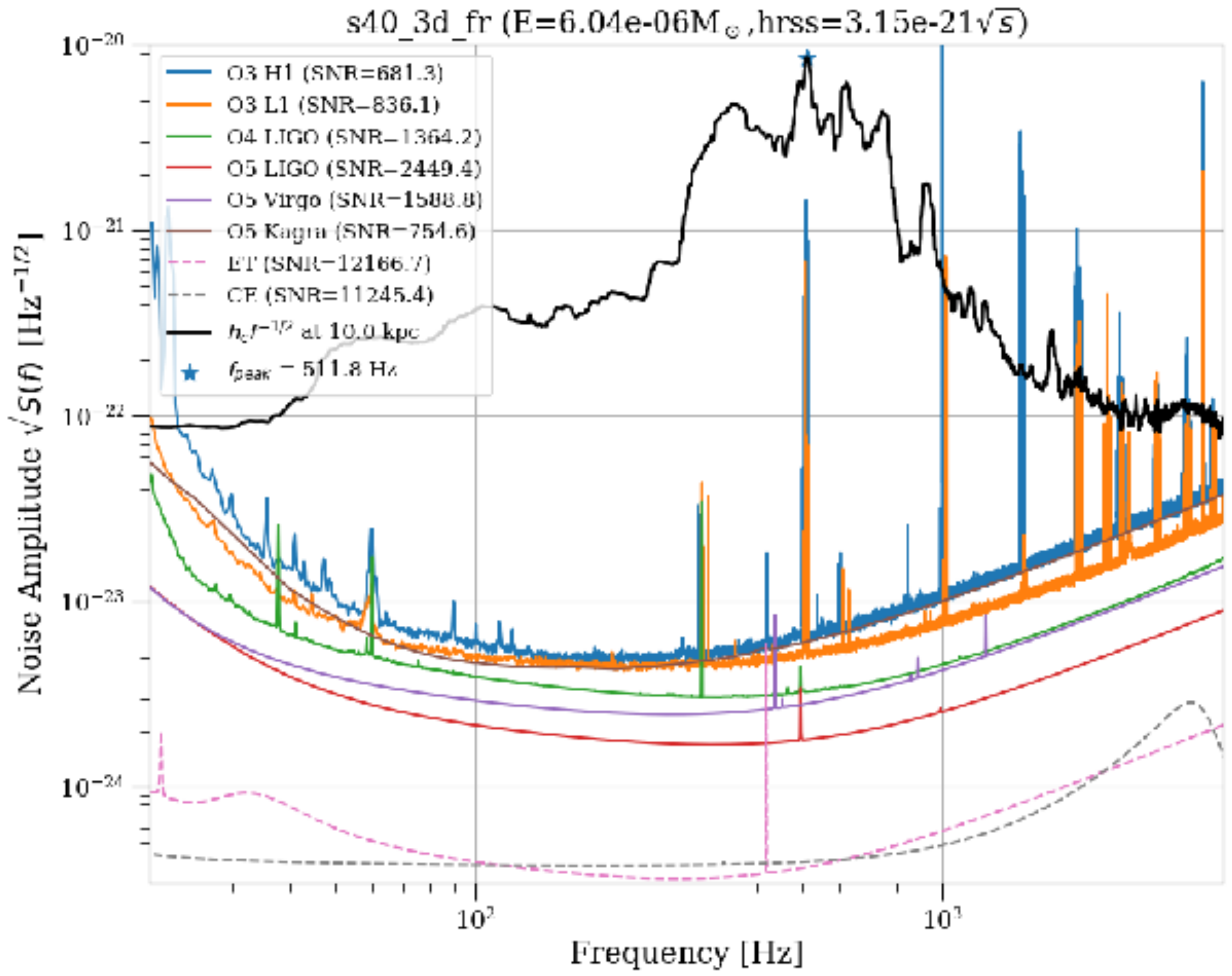
fpeak = 2104.7 Hz

SR



fpeak = 1843.2 Hz

FR



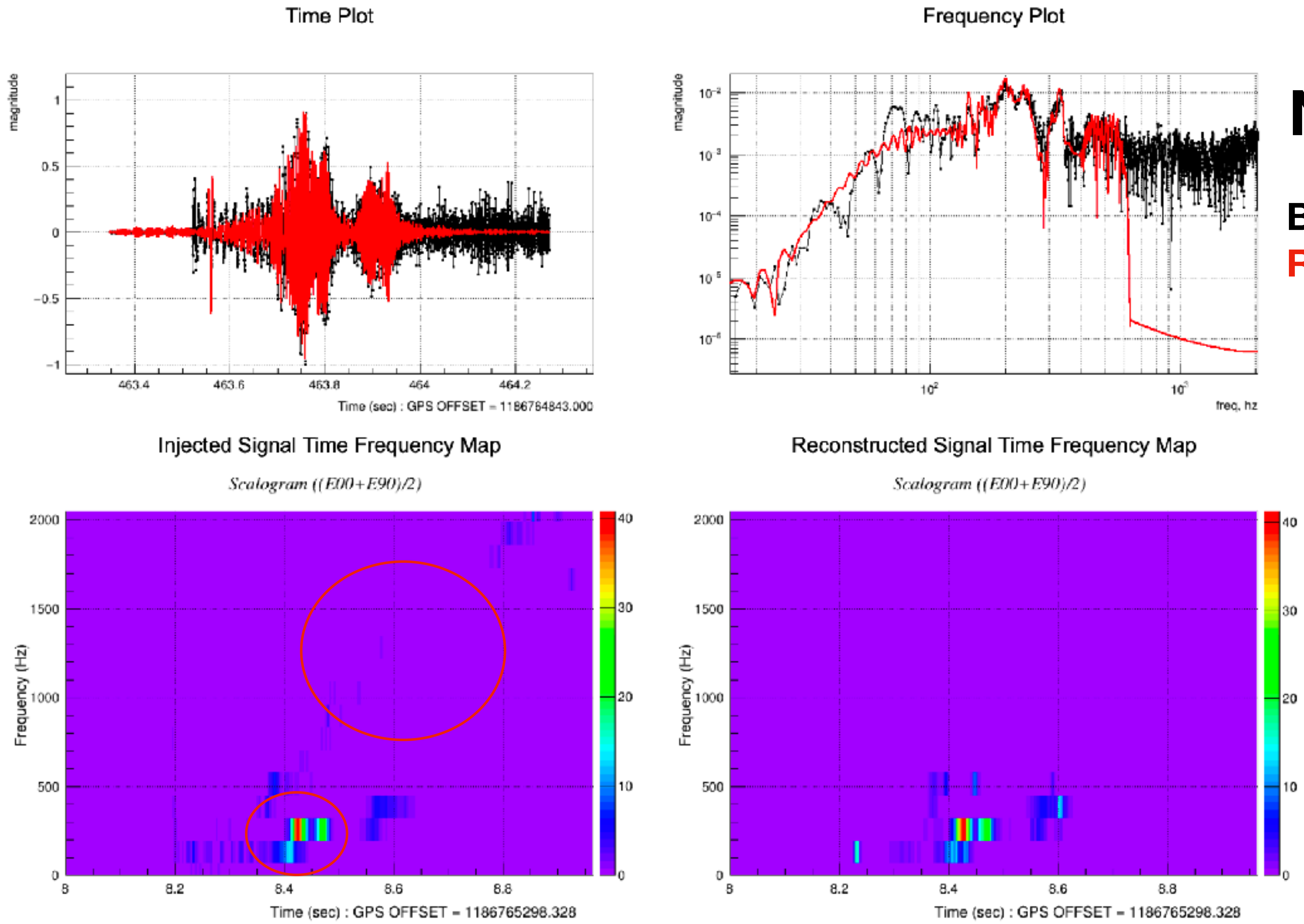
fpeak = 511.8 Hz

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

cWB Analysis

SNR 30

O2 data
Livingston-Hanford network
100 source angles and locations



NR

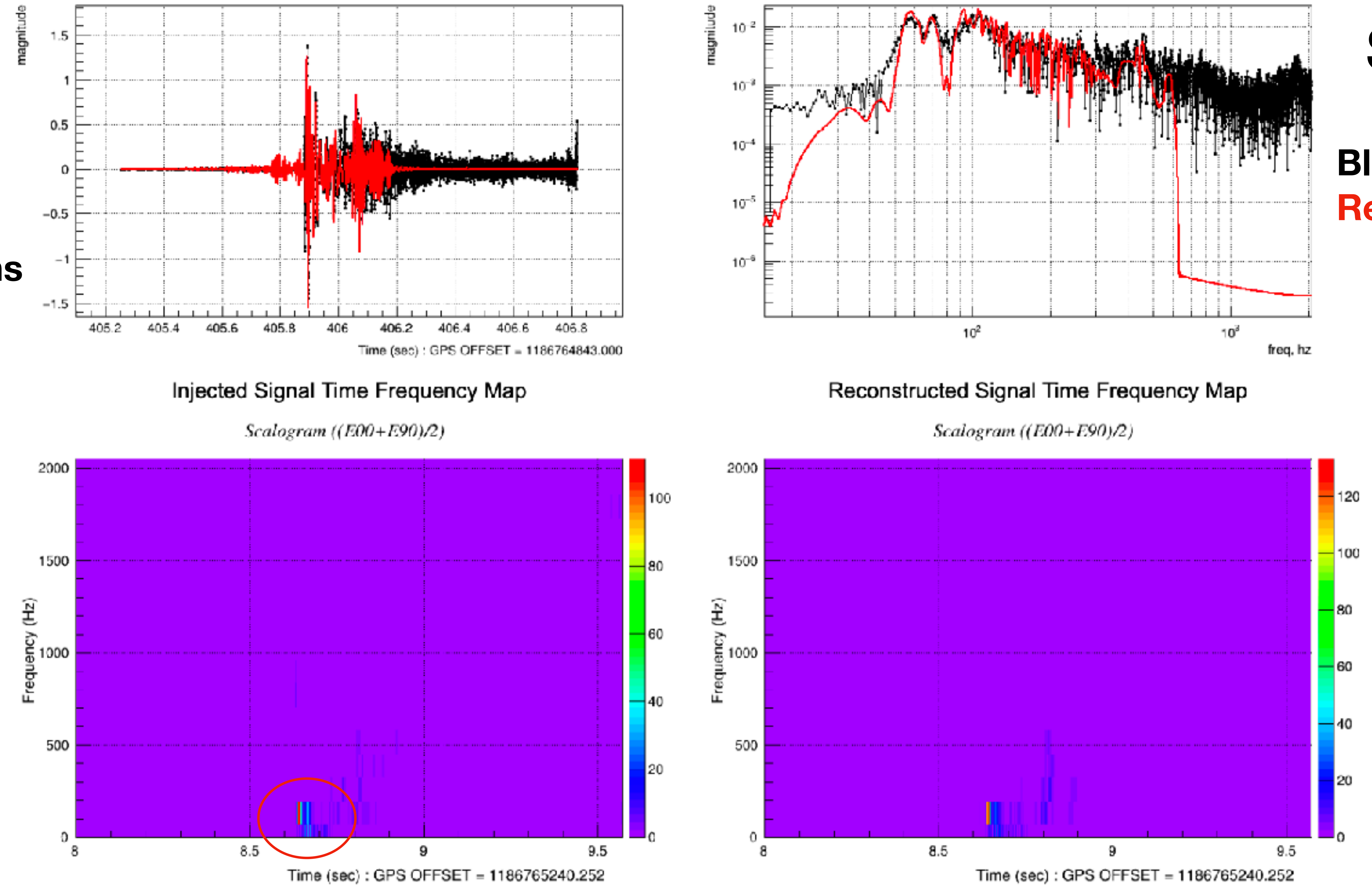
Black: injected
Red: reconstructed

Made by M. Szczepańczyk (Couch et al. 2020, in prep.)

cWB Analysis

SNR 30

O2 data
Livingston-Hanford network
100 source angles and locations



SR

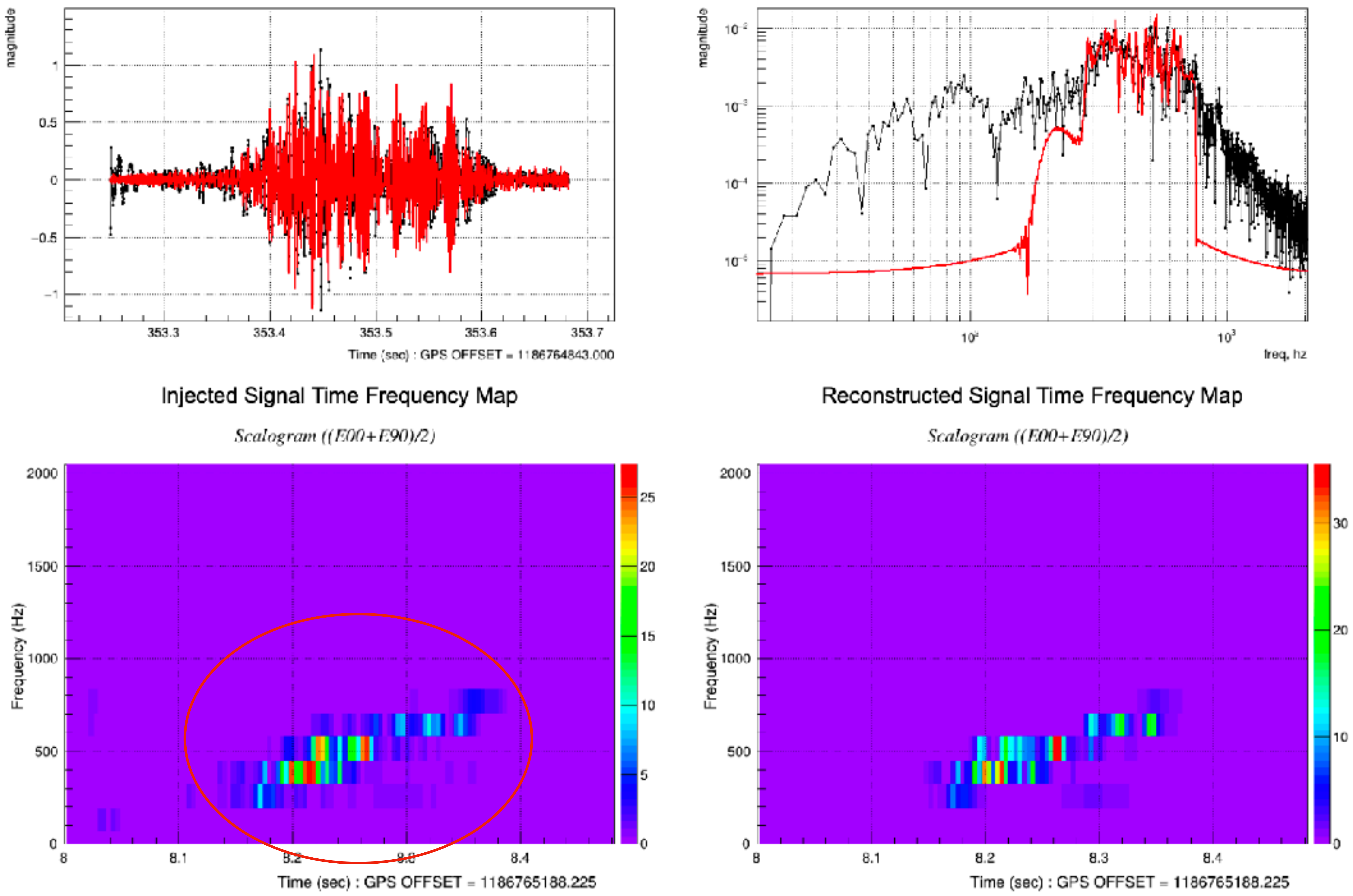
Black: injected
Red: reconstructed

Made by M. Szczepańczyk (Couch et al. 2020, in prep.)

cWB Analysis

SNR 30

O2 data
Livingston-Hanford network
100 source angles and locations

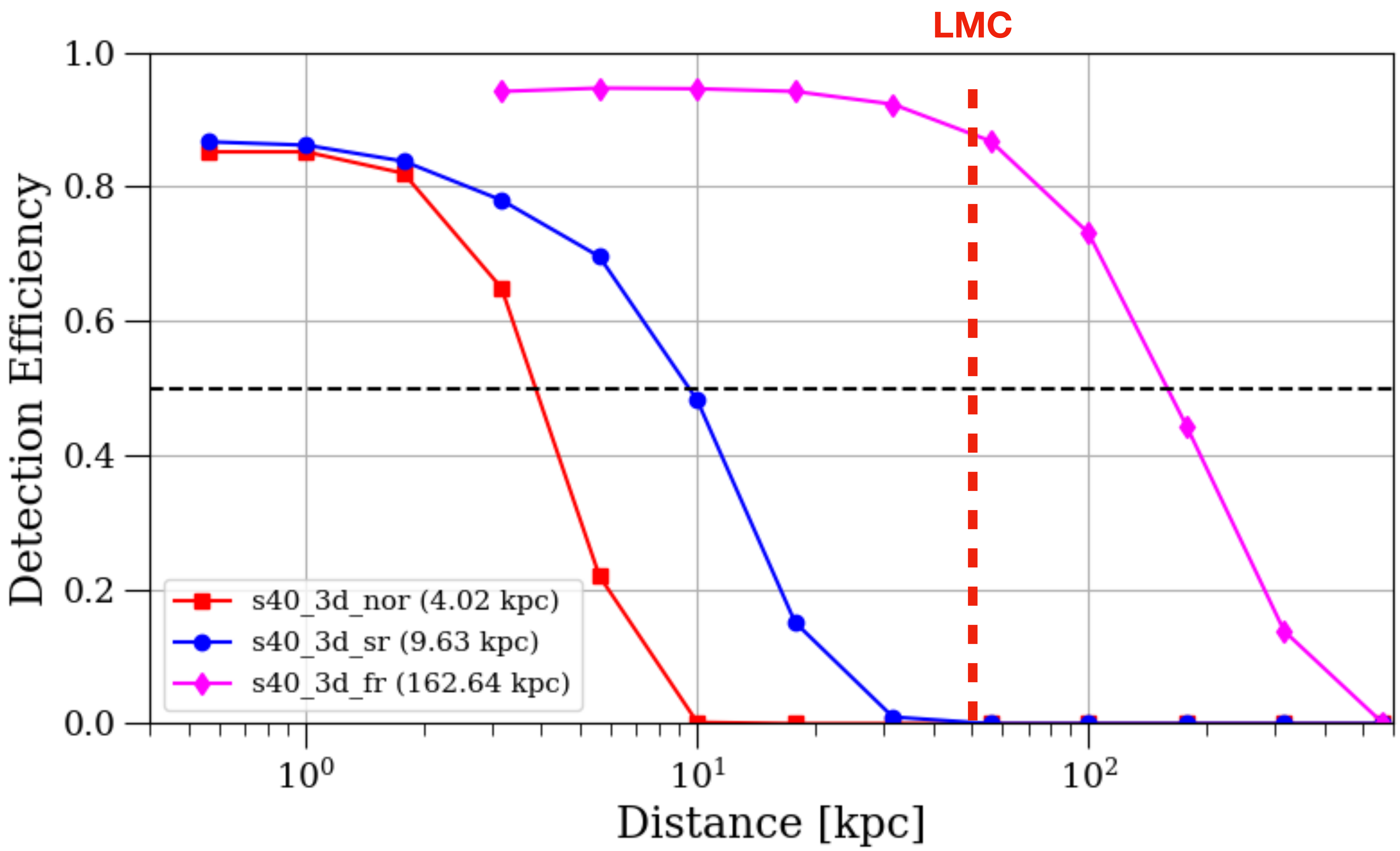


FR

Black: injected
Red: reconstructed

Made by M. Szczepańczyk (Couch et al. 2020, in prep.)

Detection Efficiency



Made by M. Szczepańczyk (Couch et al. 2020, in prep.)

Conclusions

- Neutrino and GW probe the SN explosion, progenitor star, and nuclear EoS
- NS/BH spins can be induced by spiral SASI (even in non-rotating stars).
- GW features from SASI (~100-200 Hz) is possible to be detected.
- GW from fast rotating CCSNe can be detected beyond Milky Way.
- Improve the detector sensitivity at kHz window is necessary for studying stellar mass black hole formation.