Place zoom window here

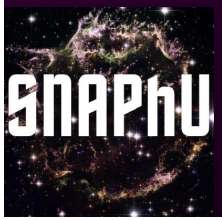
# Determining the Structure of Rotating Massive Stellar Cores with Gravitational Waves

Mike Pajkos

MacKenzie Warren, KuoChuan Pan, Evan O'Connor, Sean Couch

Pajkos+ 2021 arXiv:2011.09000

Pajkos+ 2019 arXiv:1901.09055

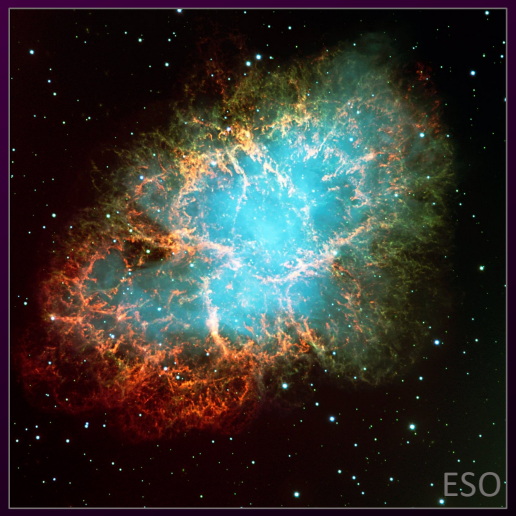



Argonne NATIONAL LABORATORY

ECP EXASCALE COMPUTING PROJECT

# Different Aspects of the Core-collapse Supernova (CCSN) Problem

Identifying physical processes



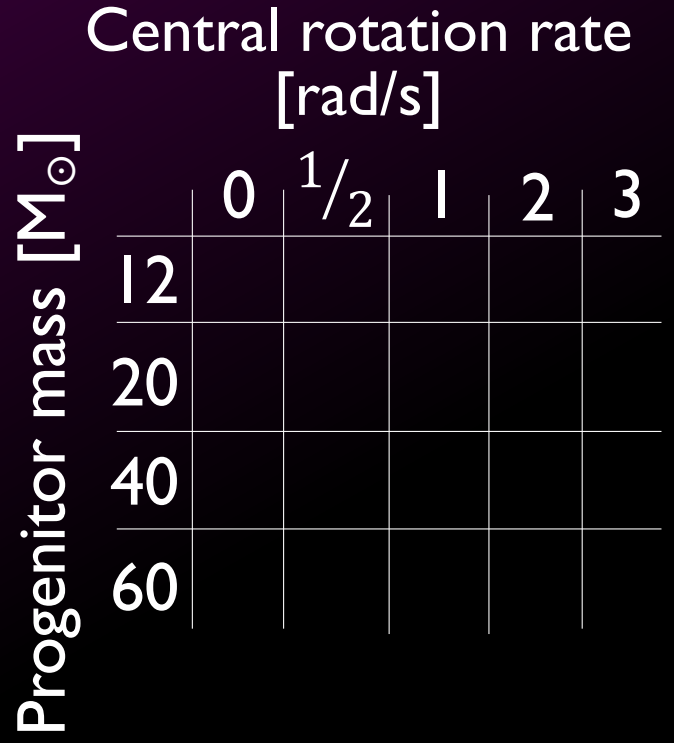

Adapting codes to advancing hardware

Predicting observables

# Latest Project Setup

- Perform 34 2D CCSN simulations (Sukhbold+ 2016)
  - 4 additional 3D simulations
- Using 3 equations of state (EOSs)
  - SFHo, SFHx, & LS220 (Steiner+ 2013, Lattimer & Swesty 1991)
- M1 neutrino treatment (Shibata+ 2011)

- What can we learn about the progenitor, based on the supernova?

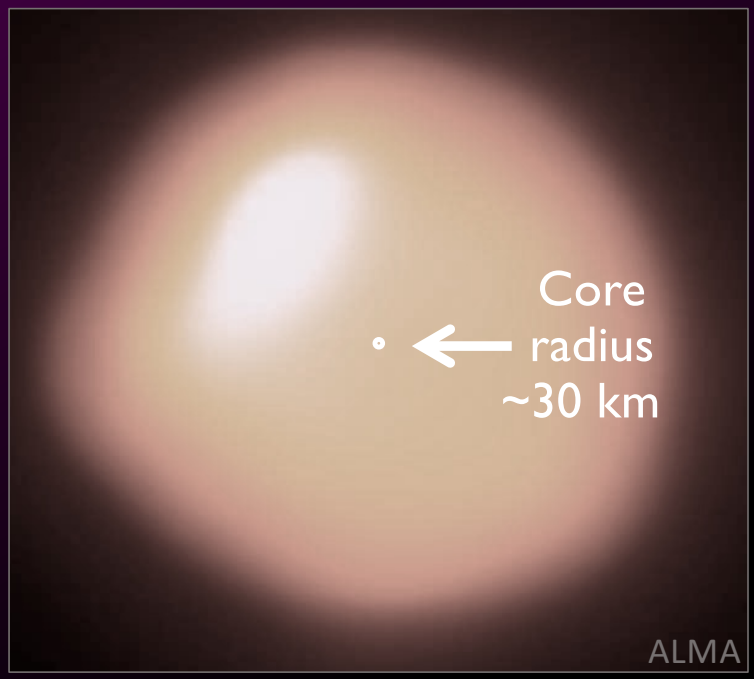


# The Collapse Phase

- High temperature in Fe core (~5 GK)
- Photodissociation & $e^-$ captures
- Bounce: collapse halts at high densities ($\rho_{core}$~2e14 g/cc)

# The Collapse Phase

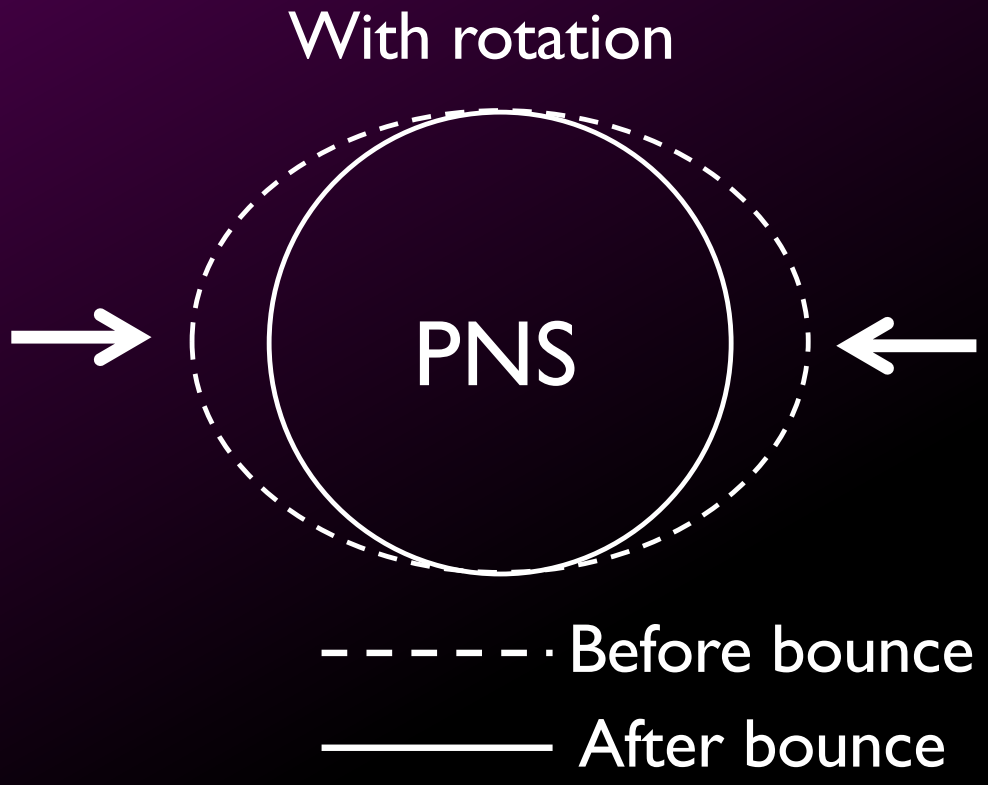
- High temperature in Fe core (~5 GK)
- Photodissociation & $e^-$ captures
- Bounce: collapse halts at high densities ($\rho_{core}$~2e14 g/cc)




*Not to scale

# Visualizing the Bounce

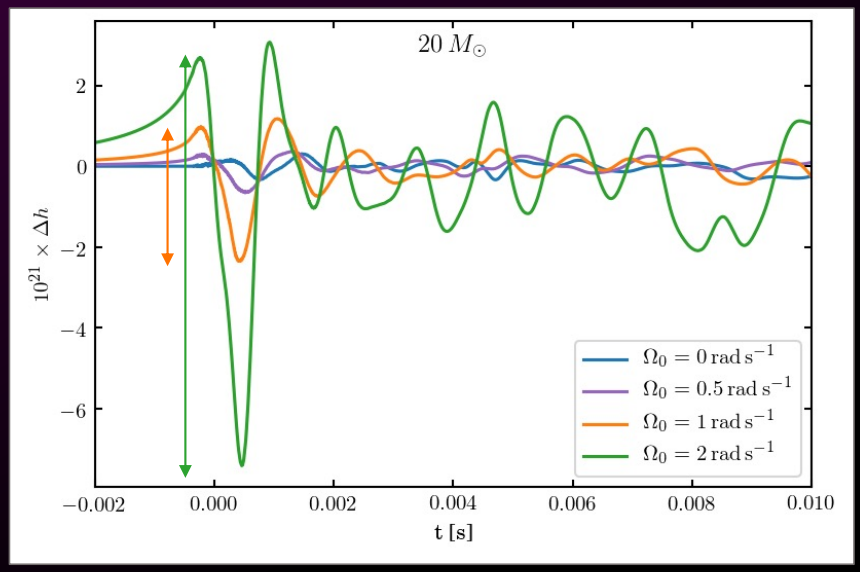
- Strong force halts collapse
- Deforms PNS
  - Accelerates mass quadrupole moment
- Creates GW 'bounce signal'



# Analyzing the Bounce Signal

- Smooth rise and fall
- Related to internal rotation (Dimmelmeier+ 2008, Abdikamalov+ 2014)
- Quantify with 'bounce height' (Δh)

GW Amplitude →



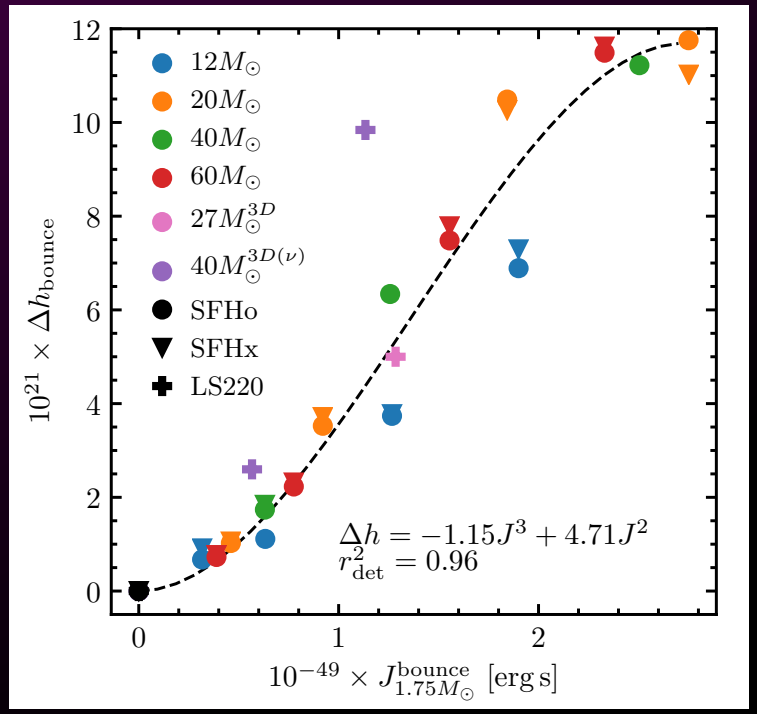

Time→

# Analyzing the Bounce Signal

- Relate Δh to angular momentum
- Equation of State independent (Richers+ 2017)
- Deleptonization on collapse effects this signal (Pajkos+ 2021)

✚ Different deleptonization on collapse

Bounce Height →



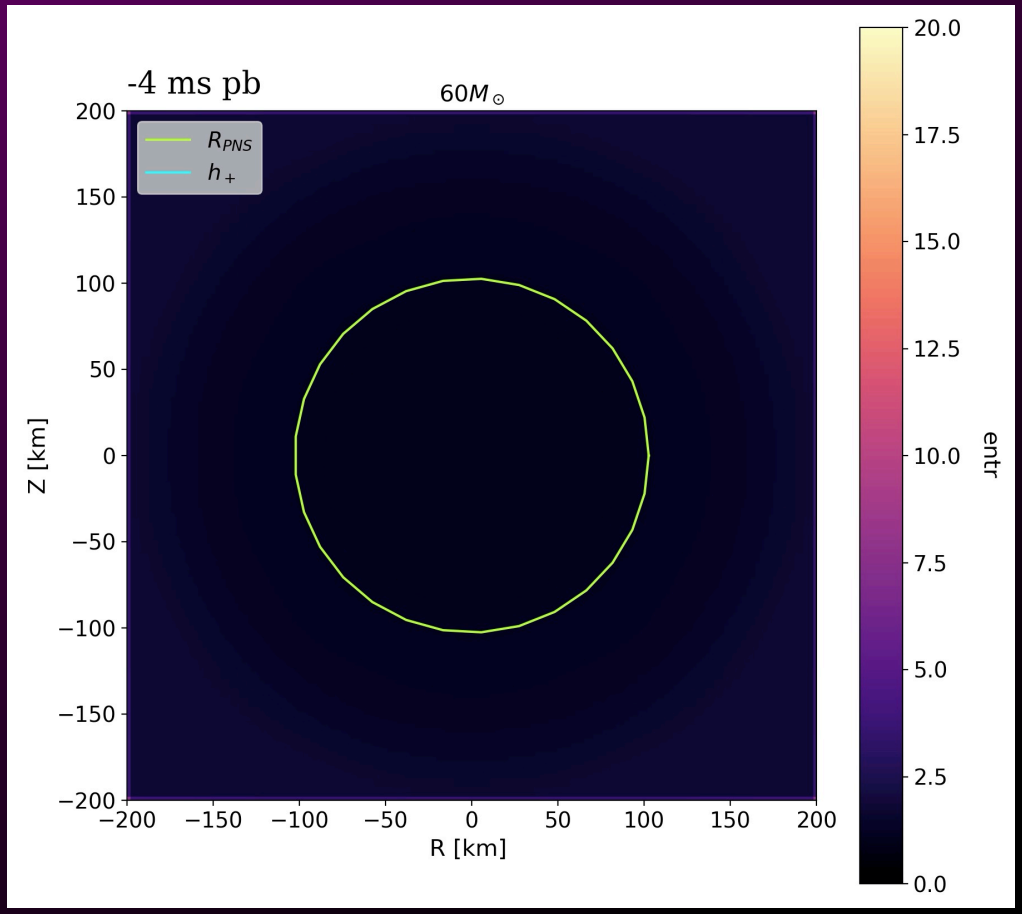

Angular Momentum →

# Accretion Phase Visualized

PNS Radius

GW Strain

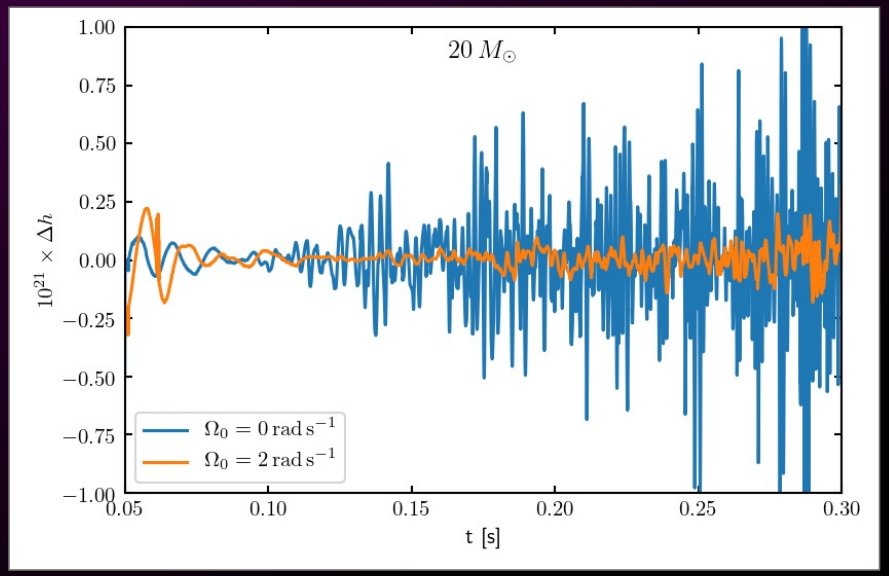
Polar Direction →



# Accretion Phase GW Signal

- PNS oscillations drive GWs
- Stochastic in the time domain
- Rotation can 'mute' the GW signal in 2D (Pajkos+ 2019)

GW Amplitude →

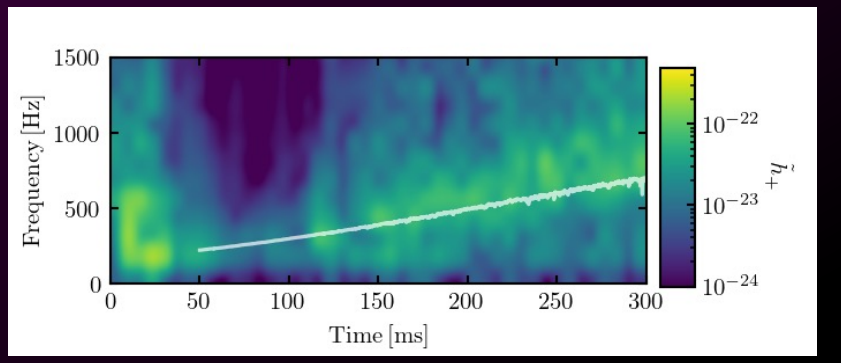



Time→

# Frequency Evolution

- Frequency increase tracks PNS cooling (Muller+ 2013)
  - Related to PNS density
- Rotation flattens frequency slope (larger PNS radius)
- *Insight:* constraining nuclear EOS (Muller+ 2012, Torres-Forne+ 2018)

Frequency →



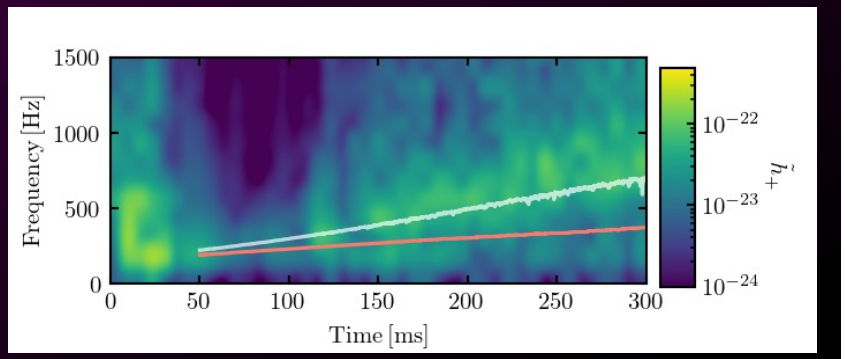

Time →

$f_{peak}$ Non-rotating ($\dot{f}_{J=0}$)

# Frequency Evolution

- Frequency increase tracks PNS cooling (Muller+ 2013)
  - Related to PNS density
- Rotation flattens frequency slope (larger PNS radius)
- *Insight:* constraining nuclear EOS (Muller+ 2012, Torres-Forne+ 2018)

Frequency →




Time →

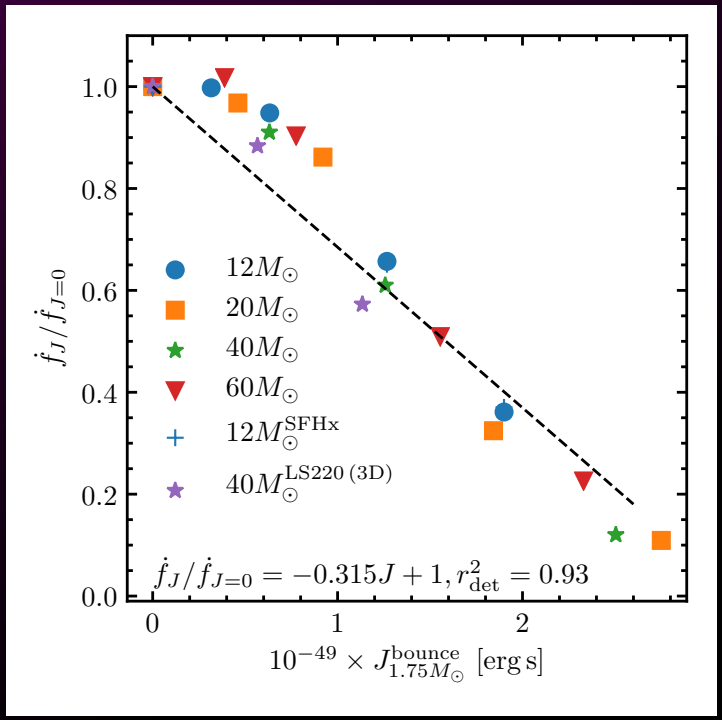
$f_{peak}$ Non-rotating ($\dot{f}_{J=0}$)

$f_{peak}$ Rapidly rotating ($\dot{f}_J$)

# Frequency Evolution

- Frequency increase tracks PNS cooling (Muller+ 2013)
  - Related to PNS density
- Rotation flattens frequency slope (larger PNS radius)
- *Insight:* constraining nuclear EOS (Muller+ 2012, Torres-Forne+ 2018)

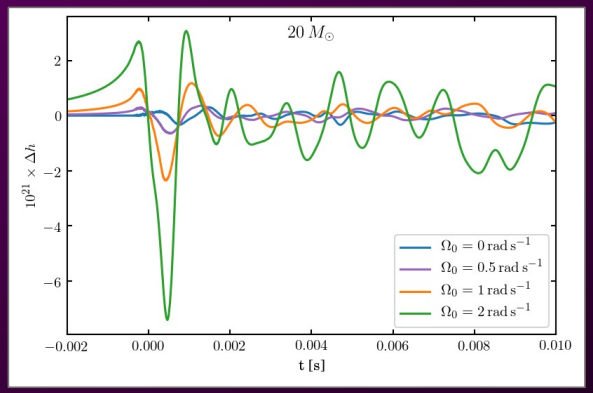
Normalized Frequency slope →



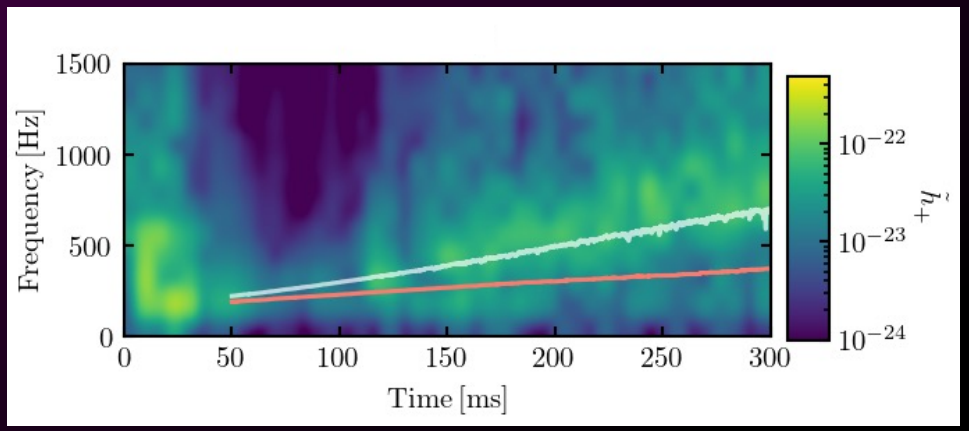

Angular momentum →

# Both signals are related to rotation…

Bounce signal (Δh)



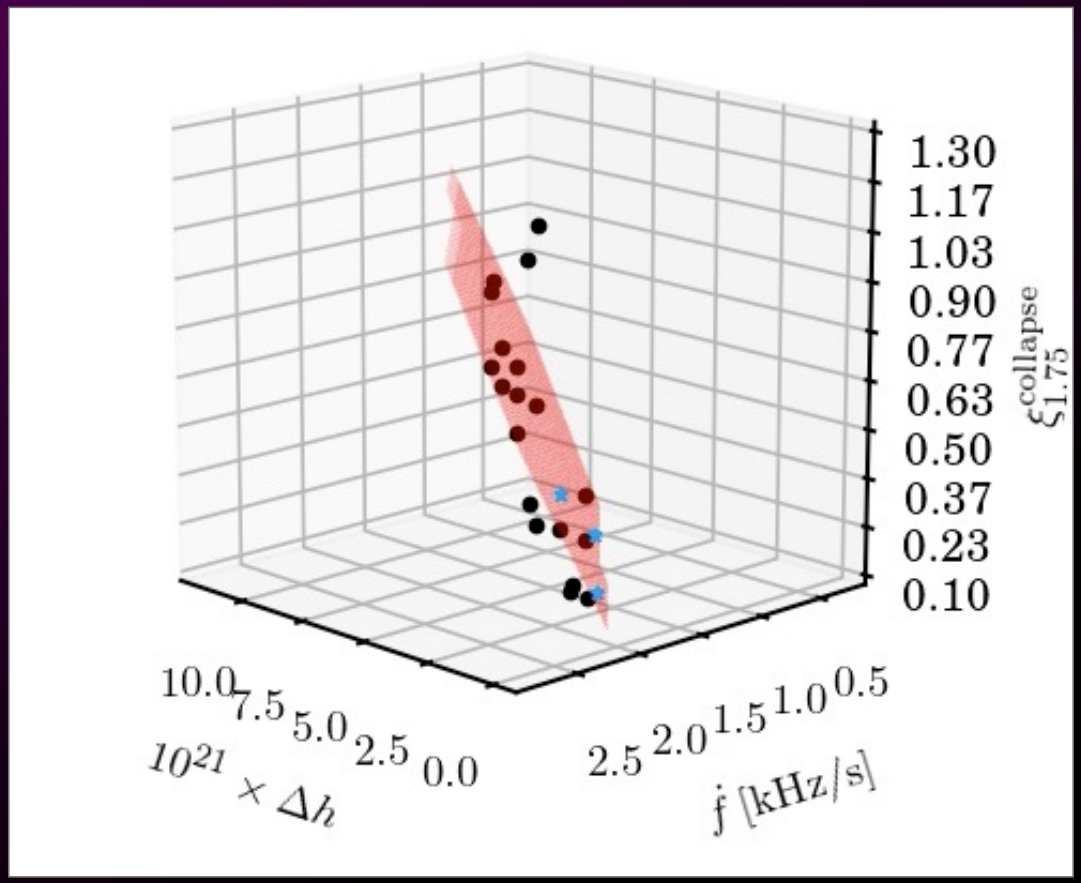

Frequency slope ($\dot{f}$)




# Can we combine multiple GW signals?

# Parameter Space

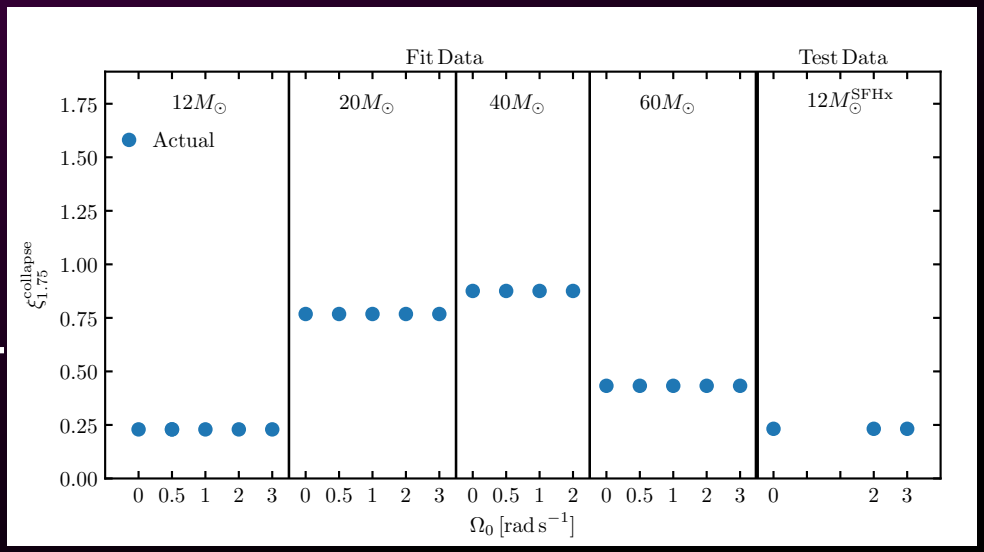
- Bounce, ramp up, M/R (ξ) should be related
- Fit with simple plane (avoid overfitting)
- Given observable bounce & ramp up → ξ of progenitor (Pajkos+ 2021)



# Testing Quality of Fit

- Input same bounce & ramp up slope using planar fit
- Assume 10% & 30% observational error
- 'Reconstruct' ξ values

Compactness →

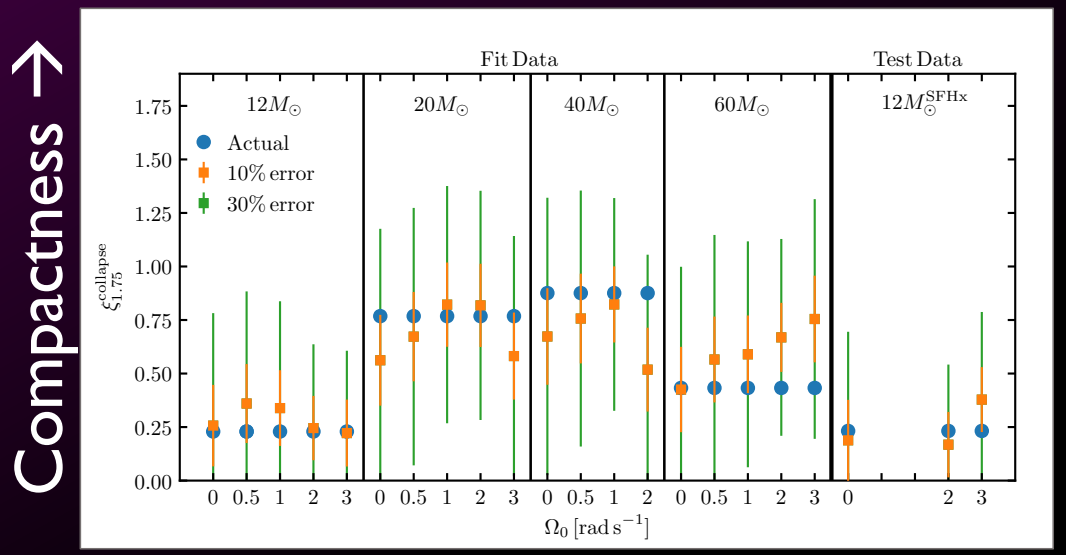



Simulations

Pajkos+ (2021)

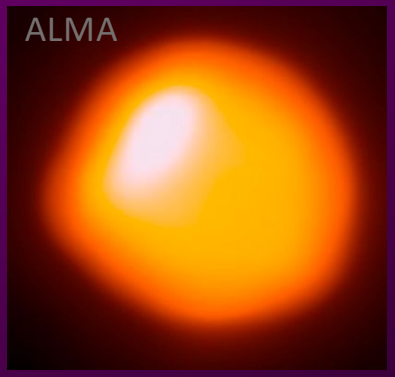
# Testing Quality of Fit

- Input same bounce & ramp up slope using planar fit
- Assume 10% & 30% observational error
- 'Reconstruct' ξ values




Pajkos+ (2021)

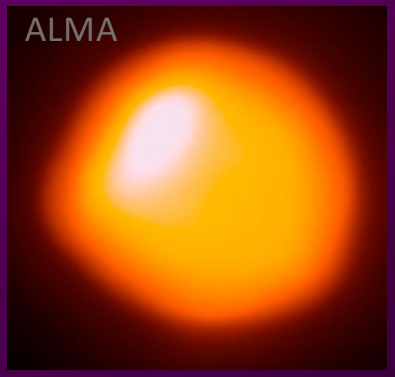
# The Supernova Timeline




RSG

Physical insight

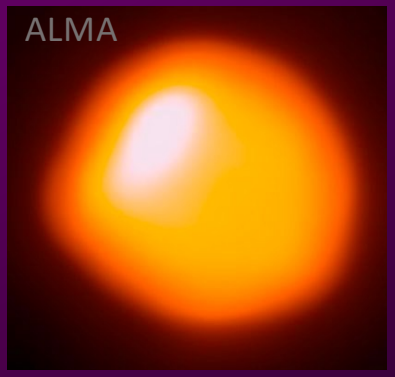
# The Supernova Timeline




RSG Bounce

Physical insight

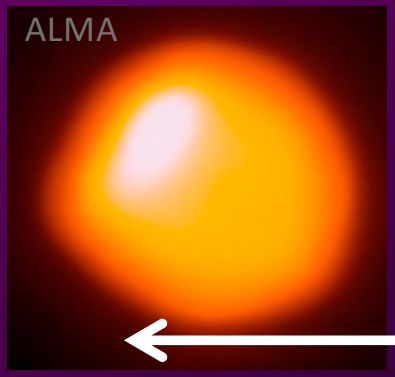
# The Supernova Timeline





Physical insight

# The Supernova Timeline




GW detections

$\xi$

~100s ms

RSG

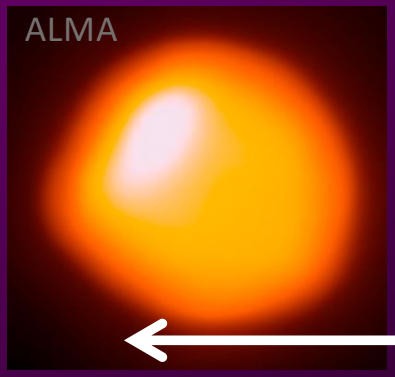
Bounce

Accretion phase ends

Physical insight

Progenitor initial conditions

# The Supernova Timeline




GW detections

ξ

~100s ms

RSG

Bounce

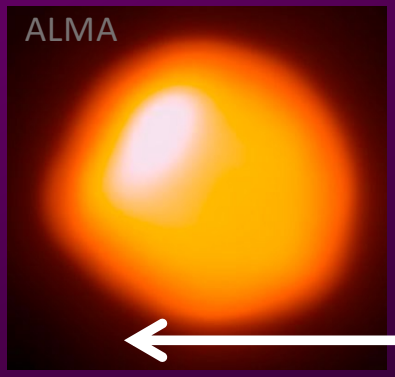
Accretion phase ends

Physical insight

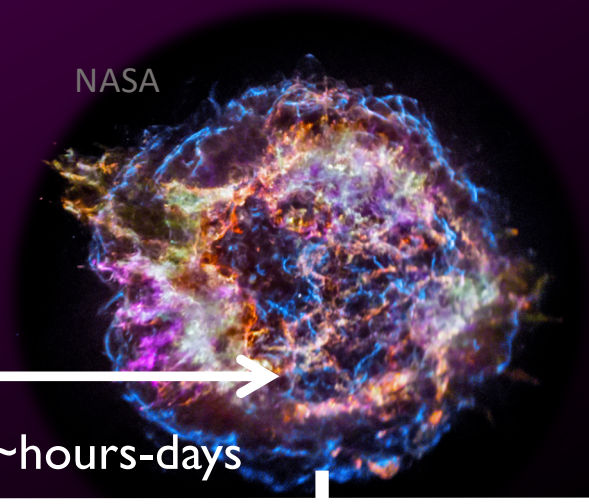
Progenitor initial conditions

Explosion & compact object properties

# The Supernova Timeline




GW detections




$\xi$

~100s ms

~hours-days

RSG

Bounce

Accretion phase ends

Explosion or failure

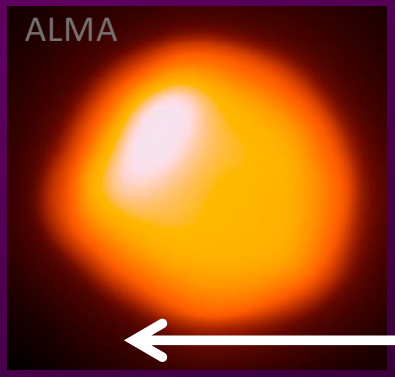
What can we learn from photons? See Barker+ (2021)

Physical insight

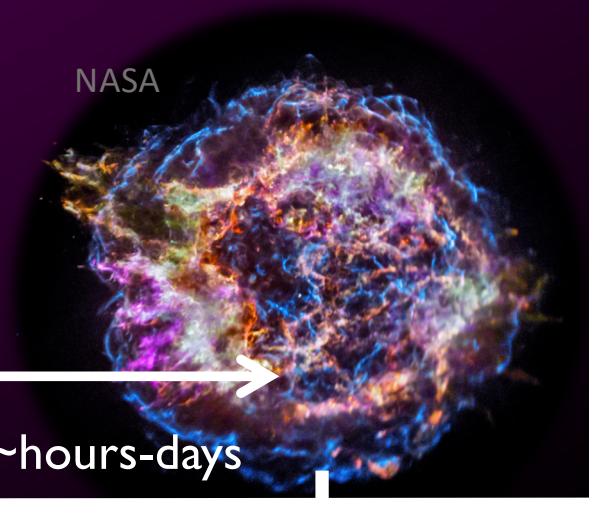
Progenitor initial conditions

Explosion & compact object properties

# The Supernova Timeline




GW detections




ξ

~100s ms

~hours-days

RSG

Bounce

Accretion phase ends

Explosion or failure

Physical insight

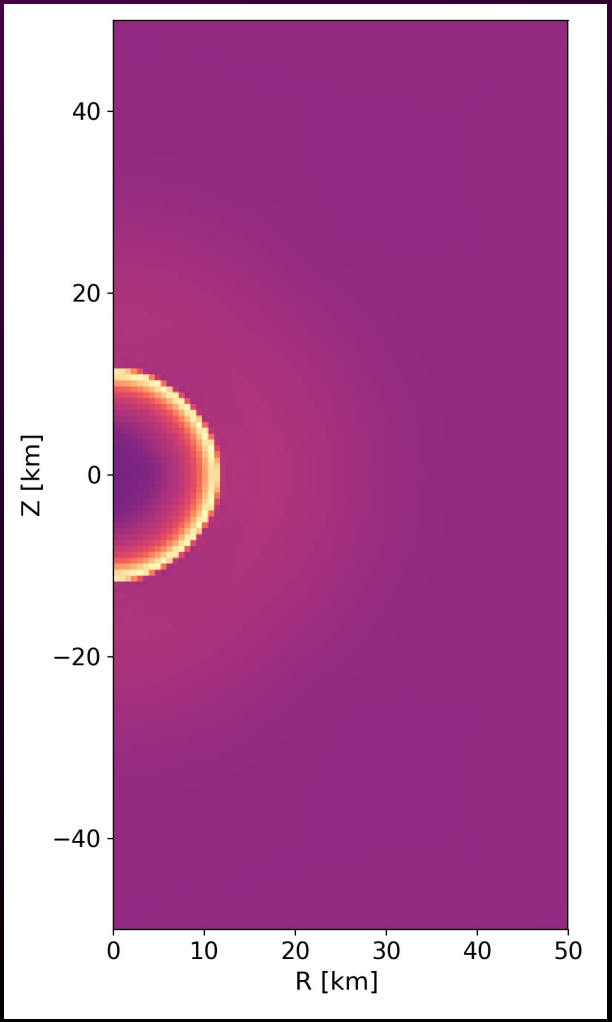
Progenitor initial conditions

How can we improve our simulation predictions?

Explosion & compact object properties

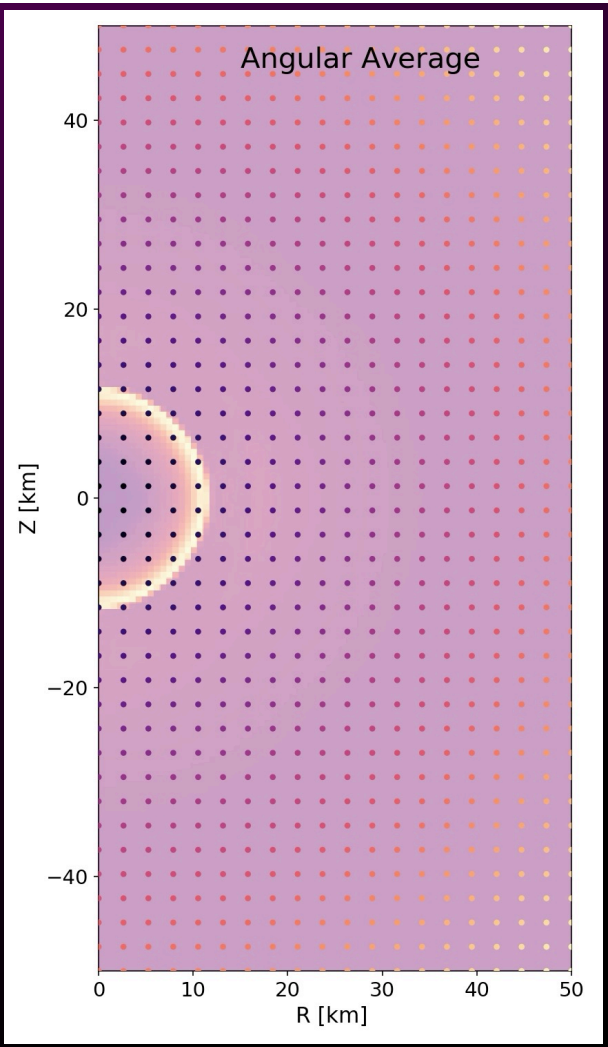
# GRMHD in FLASH

- Generalize the `GR1D` code in multi-D (O'Connor & Ott 2011)
  - Angular average of matter
  - Evolve 1D profile
  - Remap to multiple dimensions
- Couple evolving spacetime to relativistic MHD
- Passing numerical benchmarks
  - 1D Oppenheimer-Snyder collapse
  - 3D TOV Star

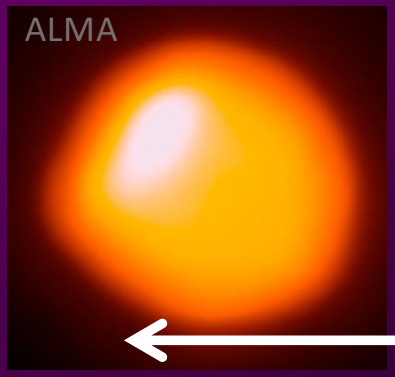


# GRMHD in FLASH

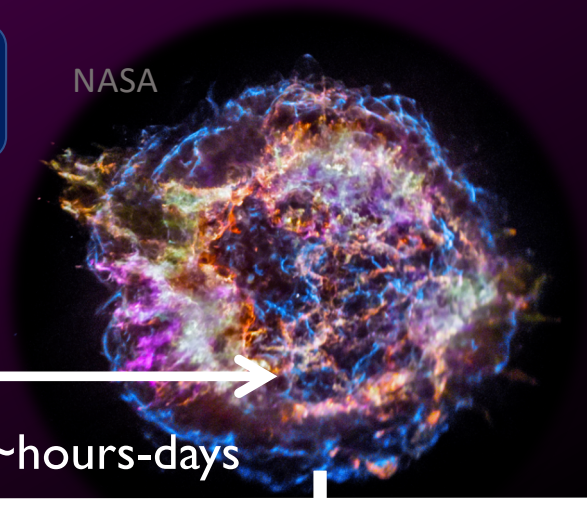
- Generalize the `GR1D` code in multi-D (O'Connor & Ott 2011)
  - Angular average of matter
  - Evolve 1D profile
  - Remap to multiple dimensions
- Couple evolving spacetime to relativistic MHD
- Passing numerical benchmarks
  - 1D Oppenheimer-Snyder collapse
  - 3D TOV Star



# The Supernova Timeline




Use FLASH to improve predictions




GW detections

ξ

~100s ms

~hours-days

RSG

Bounce

Accretion phase ends

Explosion or failure

Physical insight:

Progenitor initial conditions**

PNS rotation

Convective activity + PNS density evolution

Explosion & compact object properties**