Understanding Supernova Engines and the Properties of Compact Remnants

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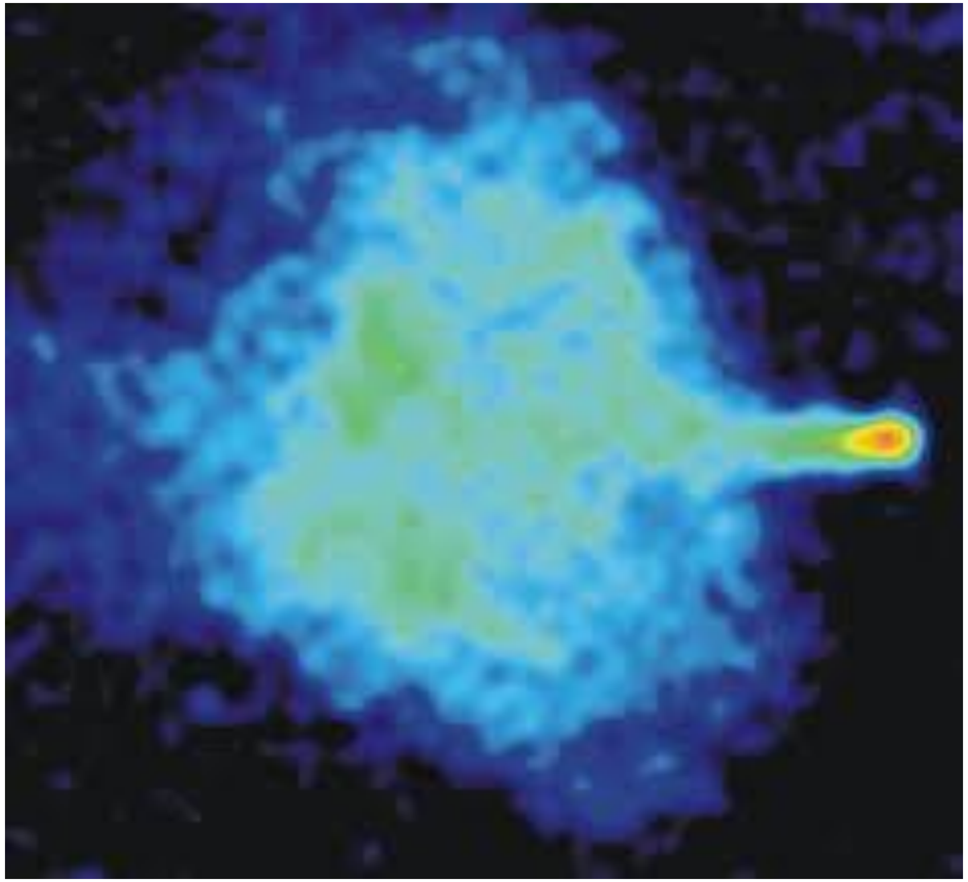


Supernova Engines

➢ **Convective Engine:**

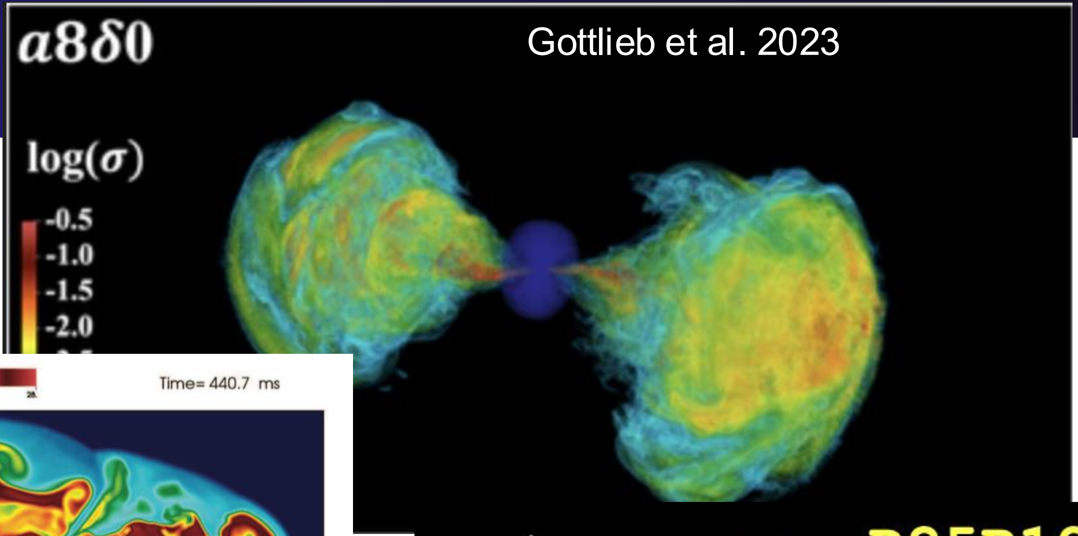
- core collapse driven by electron capture until it reaches nuclear densities
- the bounce shock leaves behind a convectively unstable region between proto-NS surface and st of shock
- convection converts energy from core/accretion t kinetic energy
- convection also removes the pressure from the infalling star

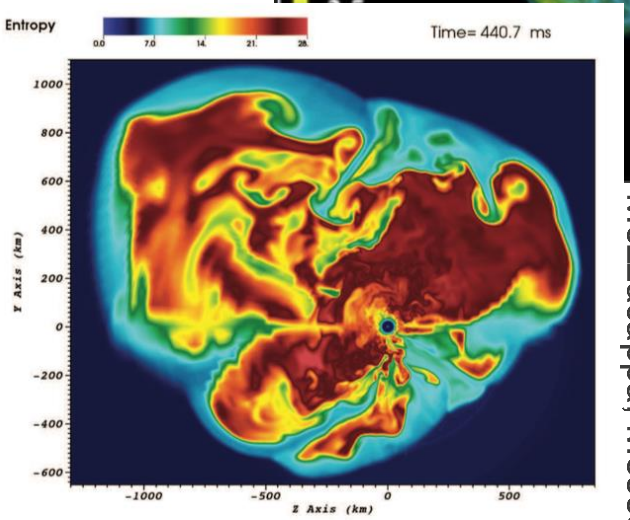
➢ **Magnetar Engine**

- requires the development of magnetic fields after NS cools
- requires high angular momenta (sub ms periods)

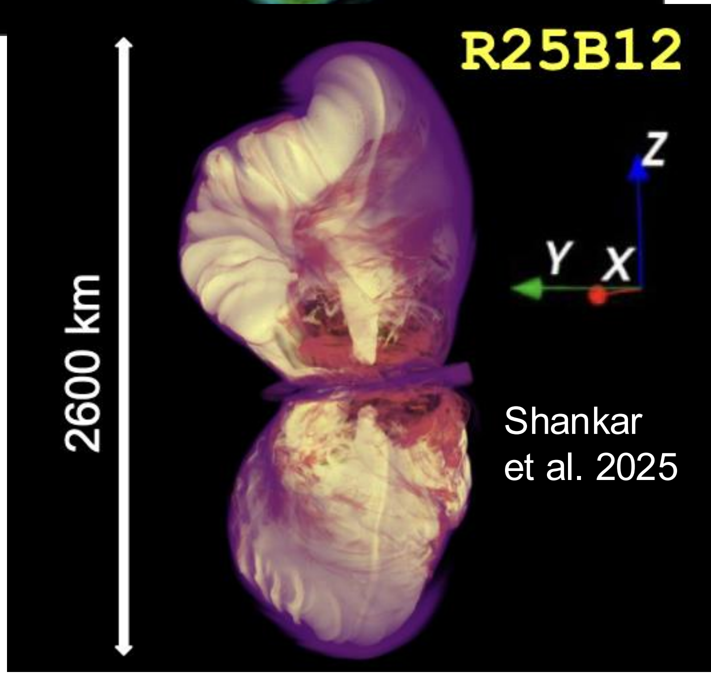
➢ **Accretion Disk Engine (NS or BH)**

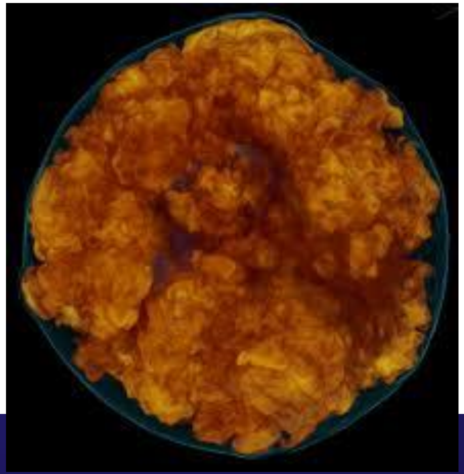
- Requires high angular momenta



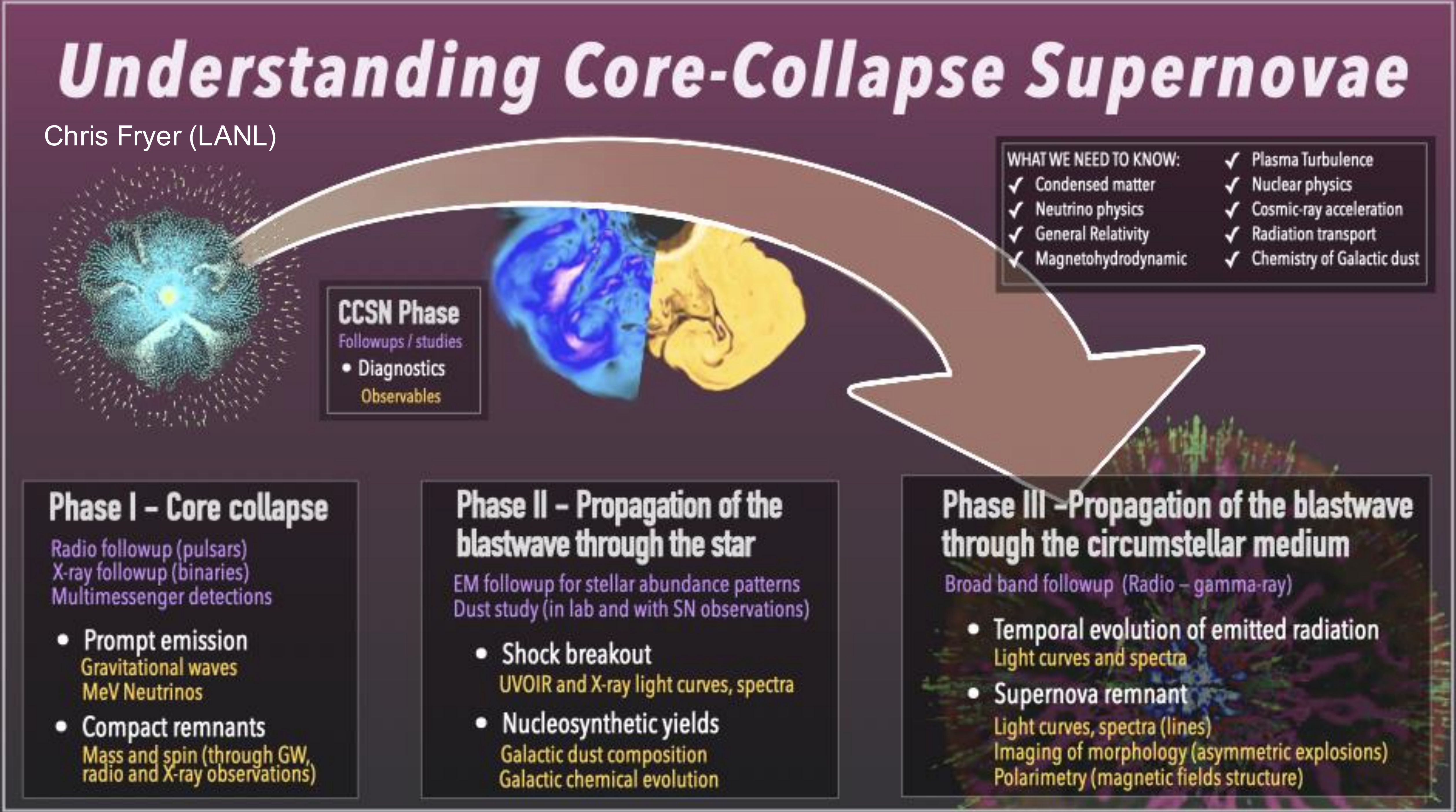


Mezzacappa, Messer, Hix





Couch, Warren, …

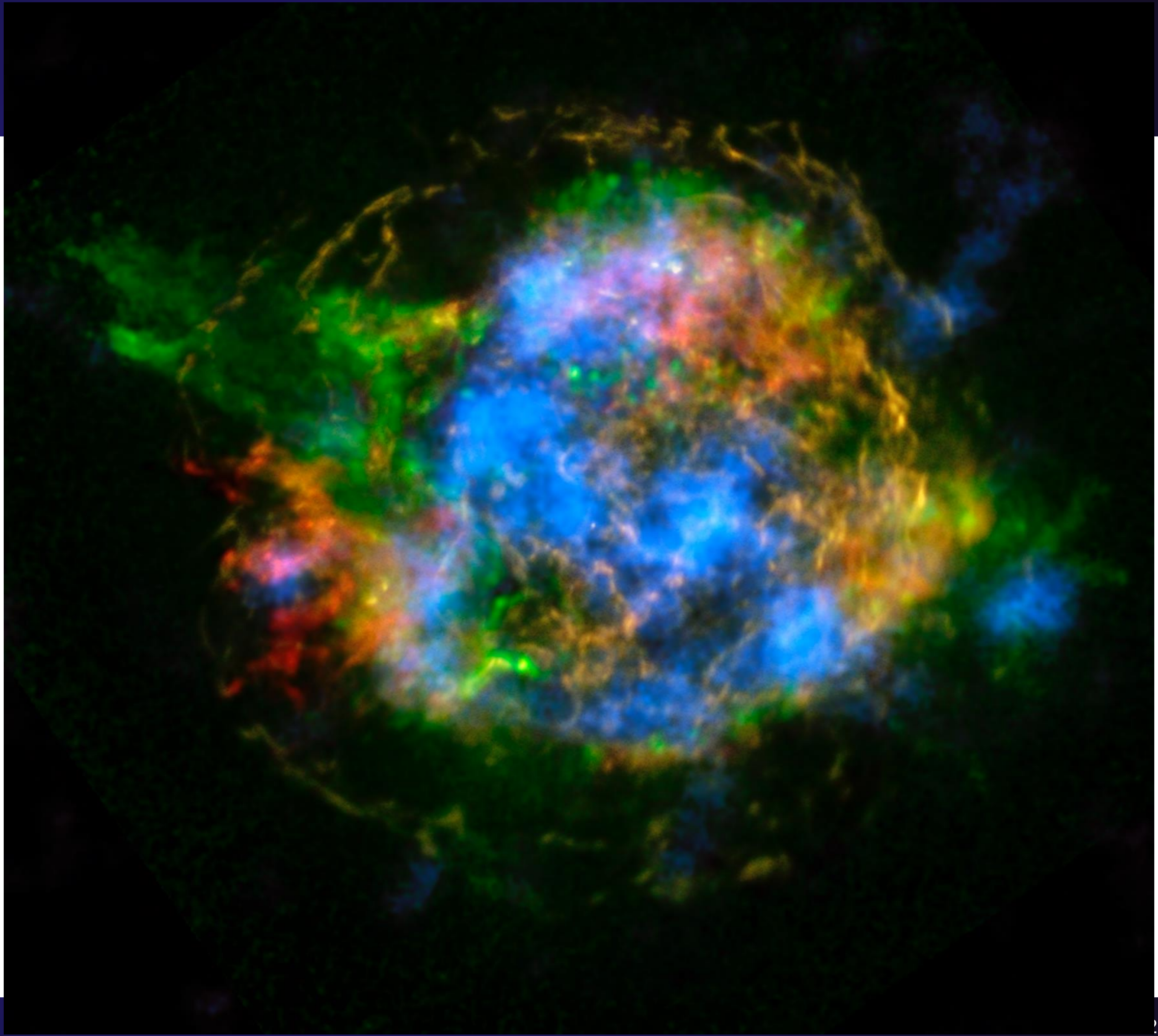


Understanding Core-Collapse Supernovae
Chris Fryer (LANL)
WHAT WE NEED TO KNOW:
✓ Condensed matter
✓ Neutrino physics
✓ General Relativity
✓ Magnetohydrodynamic
✓ Plasma Turbulence
✓ Nuclear physics
✓ Cosmic-ray acceleration
✓ Radiation transport
✓ Chemistry of Galactic dust
CCSN Phase
Followups / studies
• Diagnostics
Observables
Phase I – Core collapse
Radio followup (pulsars)
X-ray followup (binaries)
Multimessenger detections
• Prompt emission
Gravitational waves
MeV Neutrinos
• Compact remnants
Mass and spin (through GW, radio and X-ray observations)
Phase II – Propagation of the blastwave through the star
EM followup for stellar abundance patterns
Dust study (in lab and with SN observations)
• Shock breakout
UVOIR and X-ray light curves, spectra
• Nucleosynthetic yields
Galactic dust composition
Galactic chemical evolution
Phase III – Propagation of the blastwave through the circumstellar medium
Broad band followup (Radio – gamma-ray)
• Temporal evolution of emitted radiation
Light curves and spectra
• Supernova remnant
Light curves, spectra (lines)
Imaging of morphology (asymmetric explosions)
Polarimetry (magnetic fields structure)

Convection Model Confirmed (+jet???)

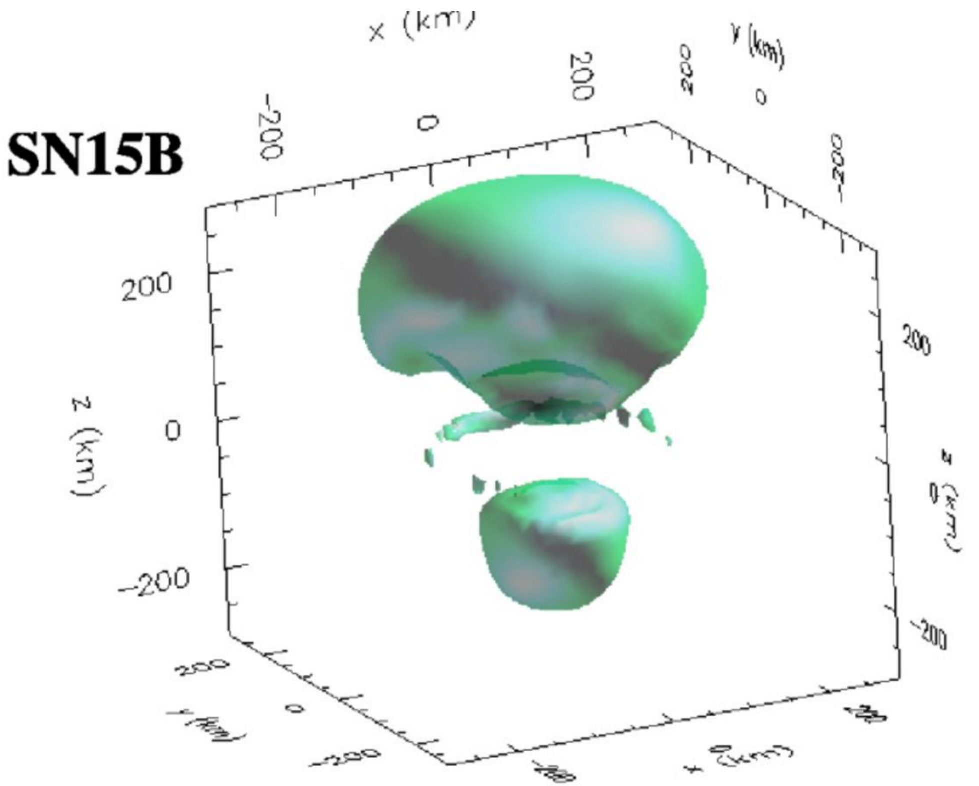
The puzzle of the Cassiopeia A Supernova remnant:

- Shock heated silicon features reminiscent of a jet (Huang et al. 2004). But this emission can be affected by the circumstellar media
- ^{44}Ti decay photons confirm the convective engine (Grefenstette et al. 2014)
- Milisavljevic is leading a JWST team to probe unshocked material (first results out – Milisavljevic et al. 2024). **Combining γ-ray and IR will solve outstanding yield questions (I hope).**



What can Compact Remnants Teach Us?

- Neutron Star and Black Hole Kicks:
  - magnitude
  - alignment with rotation axis, and hence, the axis of the binary
- NS and BH Masses: The mass distribution and mass gap probes
  - Growth Rate of Convection
  - Accretion timescales in disk models
- Rotation Rates
  - Fraction of systems driven by disks/magnetars
- Magnetic Field Emergence – role of magnetars

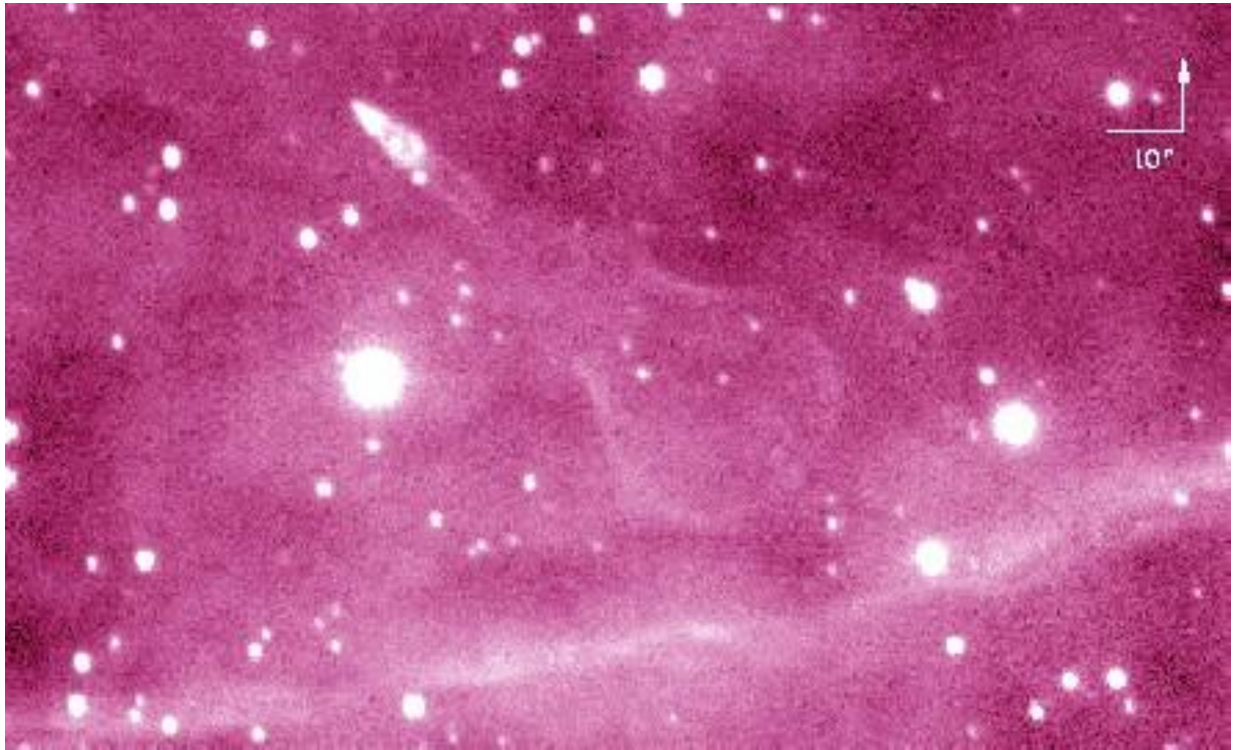


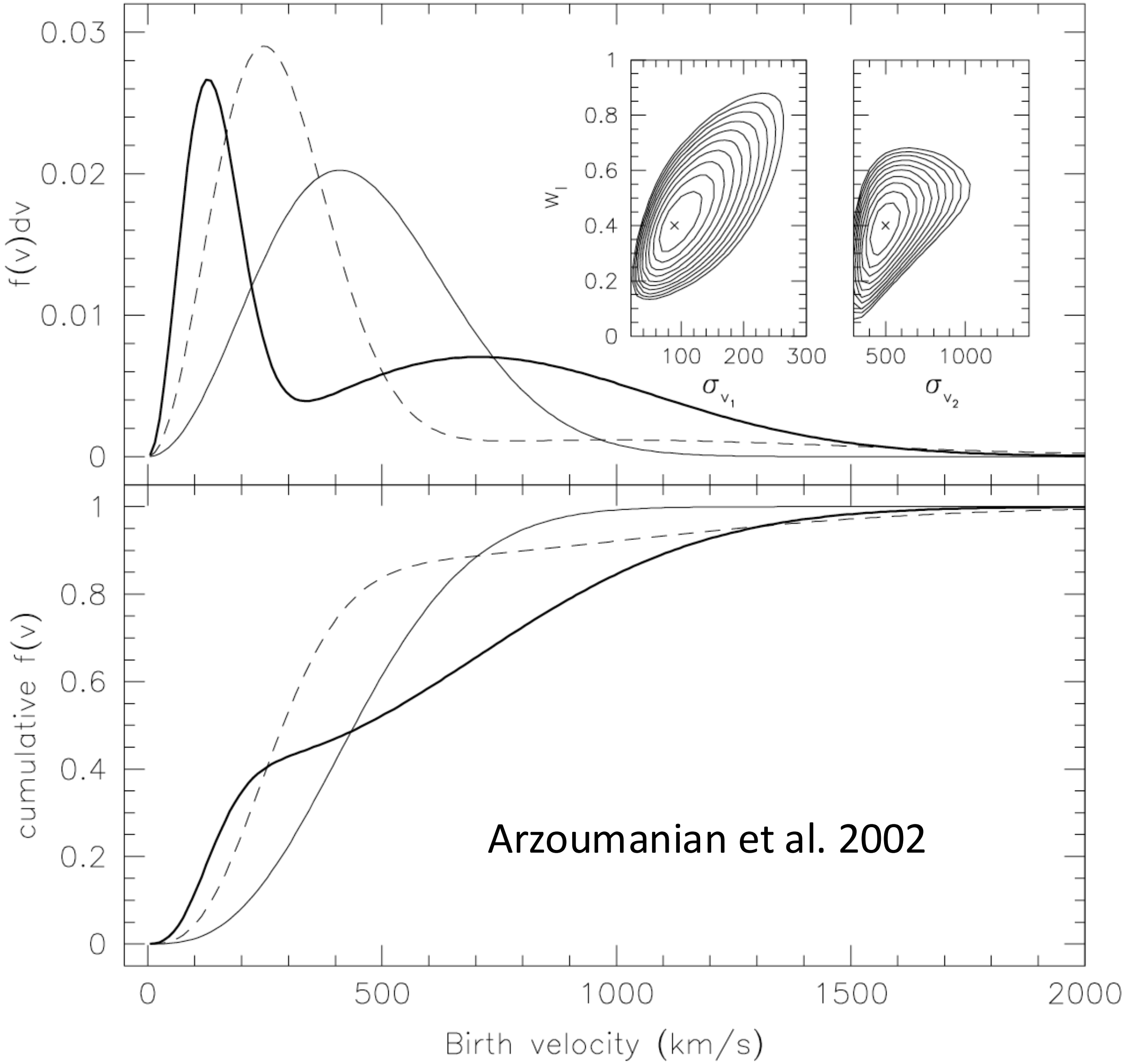
Fryer & Warren 2004

Neutron Star Velocities: Observations

Evidence for high NS velocities

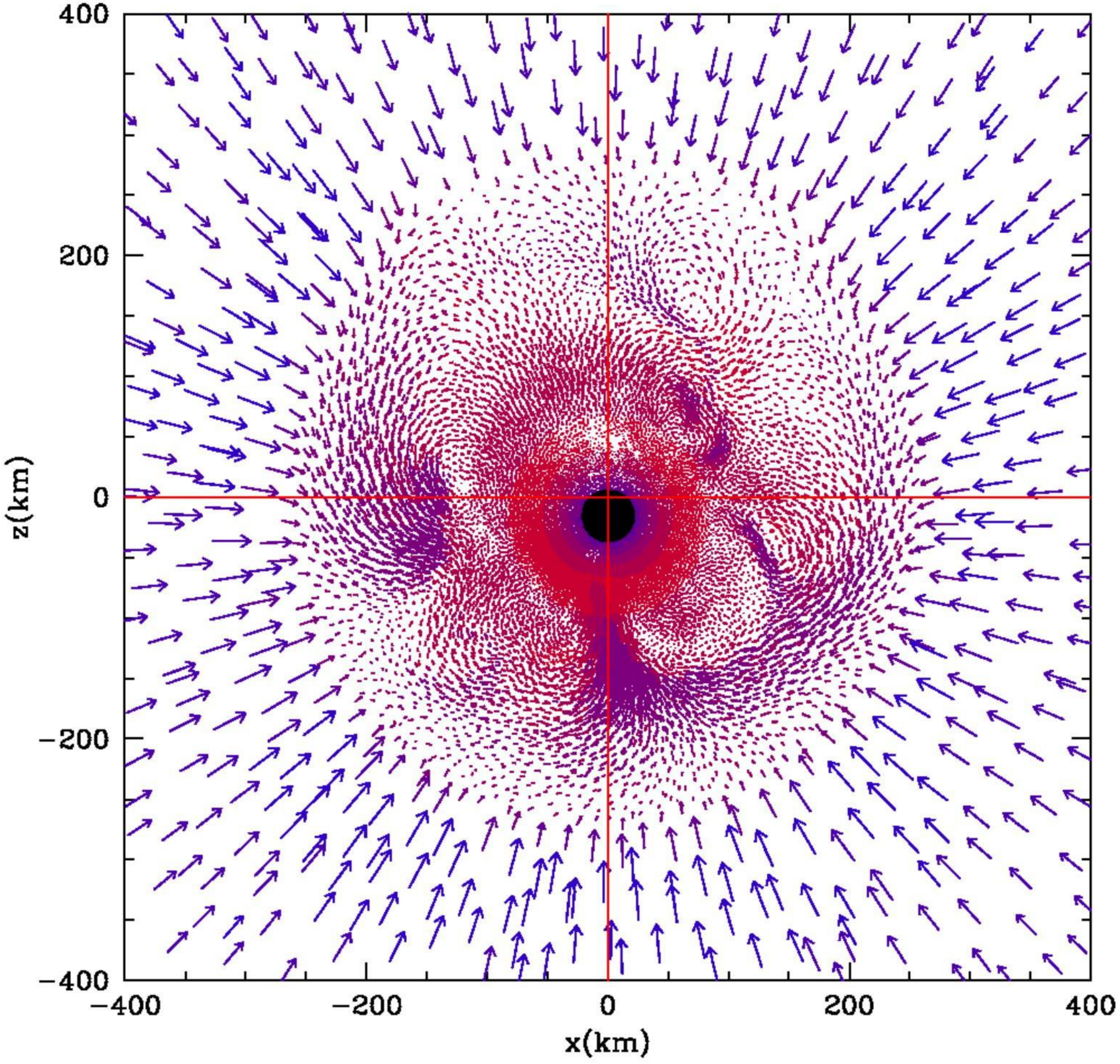
- Pulsar Velocities
- Pulsars in Remnants
- Explaining Binary Systems



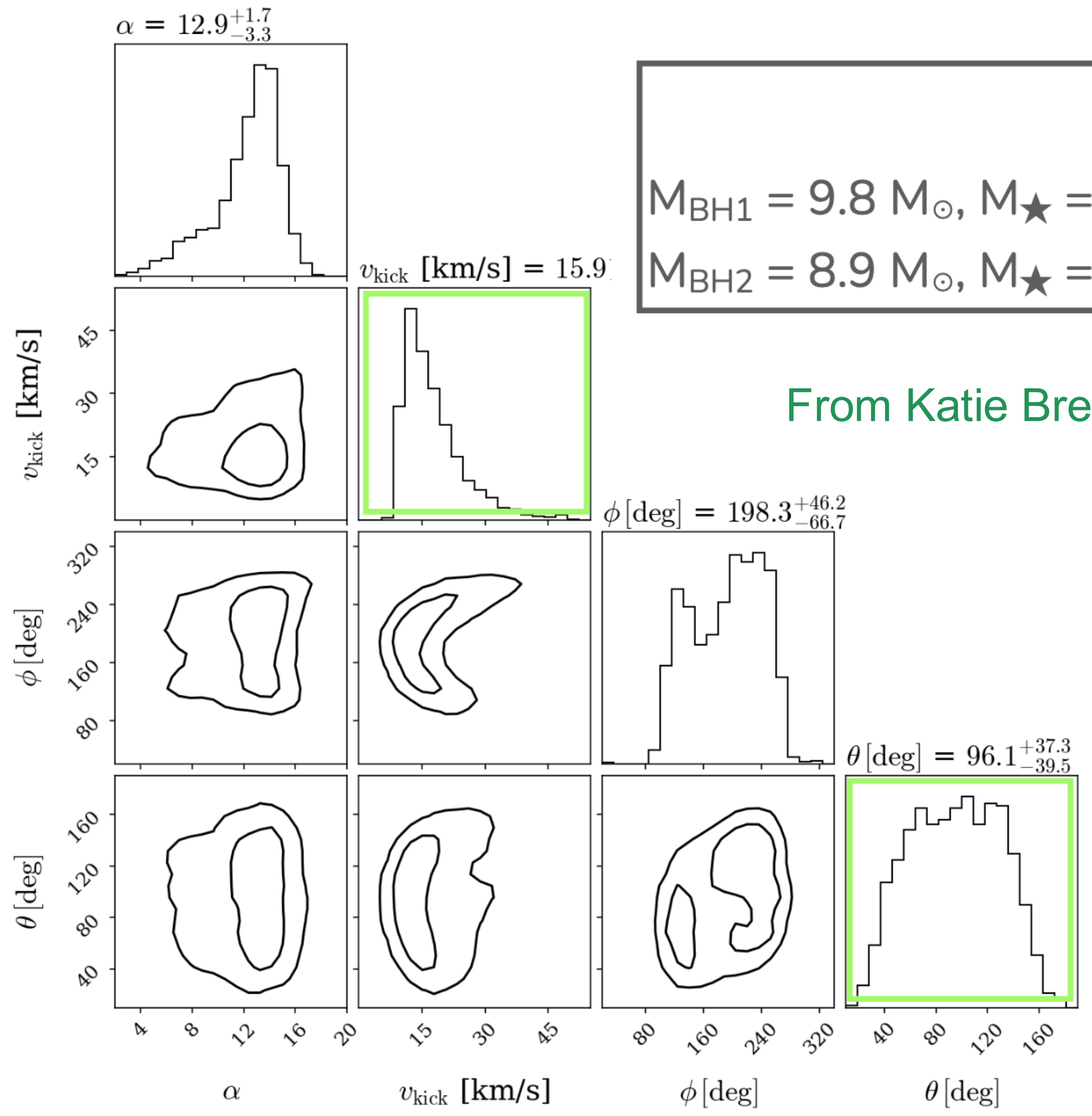


Theories behind kicks

- ➢Binaries
- ➢Propeller Effect
- ➢Ejecta Asymmetries:
- • Asymmetries in collapse (stronger in low-mass stars)
- • Asymmetries in the Engine (stronger in high-mass stars)
- • With rotation, kicks will be aligned with the rotation axis.
- ➢Neutrino Asymmetries:
- • NS interior (Kusenko)
- • Neutrino photosphere (Socrates)



Black Holes also provide clues into the kick mechanism



Gaia BH1/BH2

M_{BH1} = 9.8 $M_\odot$, $M_\star$ = 0.9 $M_\odot$, P = 185 day, e = 0.45, $Z_\star$ = 0.6 $Z_\odot$, D=460 pc

M_{BH2} = 8.9 $M_\odot$, $M_\star$ = 1.1 $M_\odot$, P = 1277 day, e = 0.52, $Z_\star$ = 0.6 $Z_\odot$, D=1.16 kpc

El-Badry+(incl KB)23a,b

From Katie Breivik

Gaia has the potential to open up new ways to probe black hole properties.

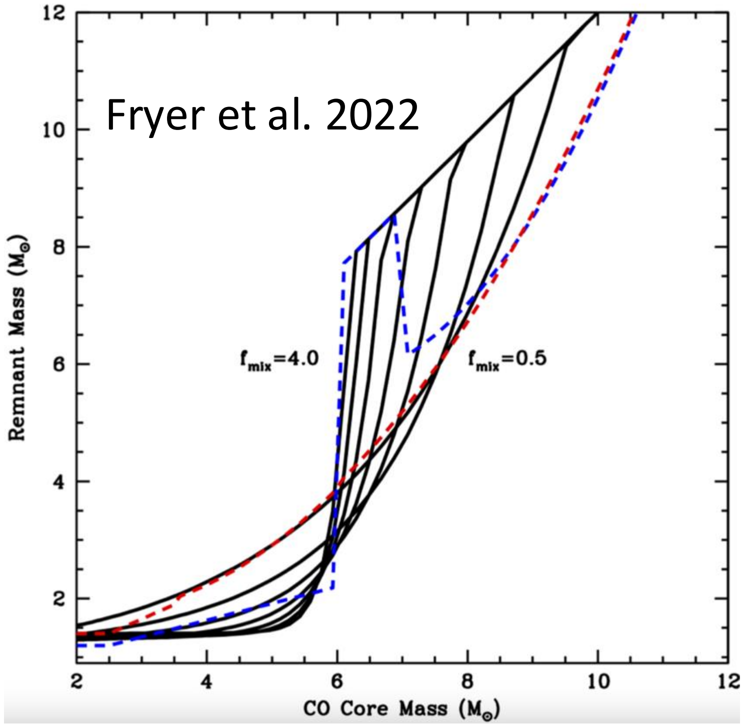
Coupled with binary star evolution, we may be able to probe kick mechanism (e.g. if the BH1 on the left is truly a field system, neutrino kicks must work and capable of making NS kicks in excess of 100km/s).

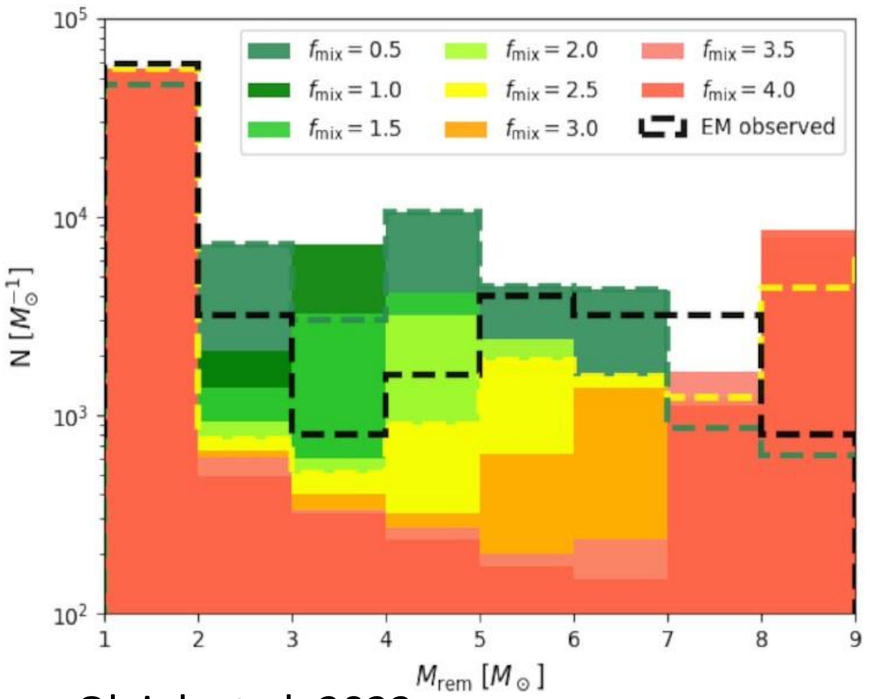
Example: Remnant Mass Distributions

Coupling Stellar Models (also constrained by SN ejecta remnants, …), Supernova Engine and Explosion calculations with physical understanding.

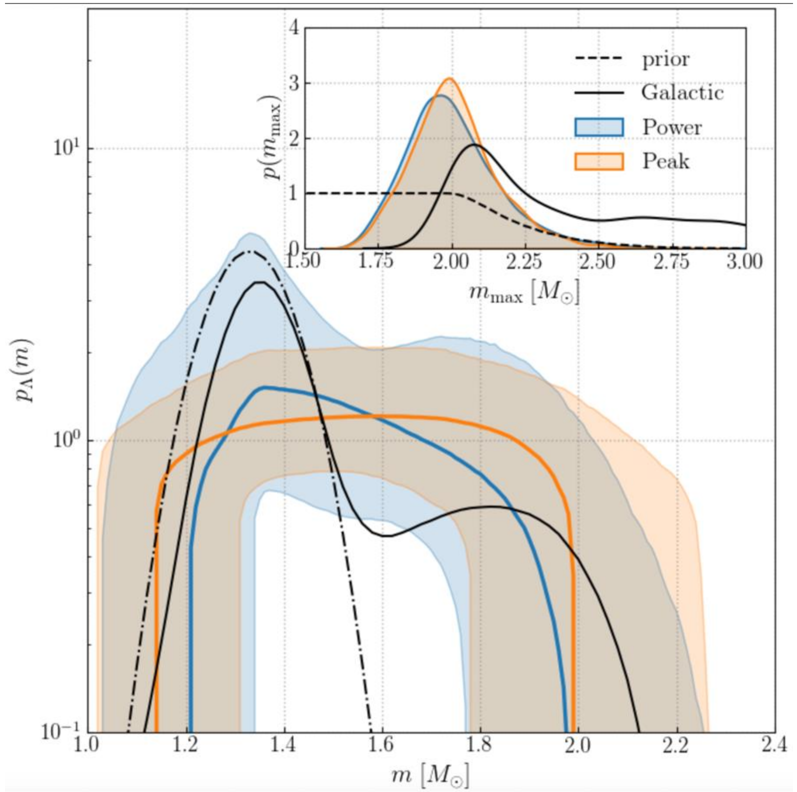
Folding our knowledge of stellar evolution and supernovae with a knowledge of Binary Stars (e.g. stellar observations), physics of binary interactions (e.g. Luminous Red Novae, …).

Comparison to data requires understanding data systematics, analysis uncertainties, …





Olejak et al. 2022



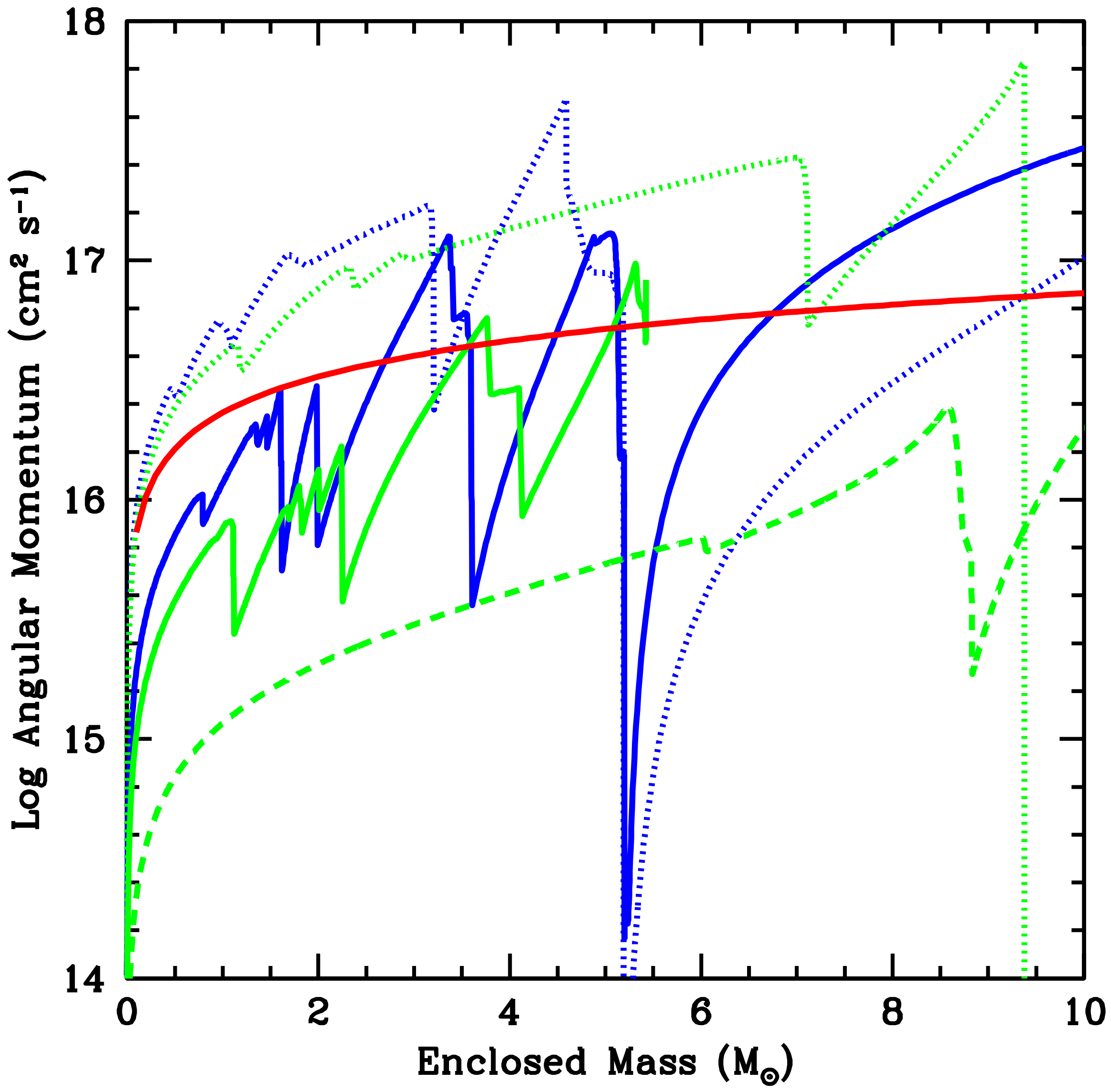
LIGO collaboration et al. 2021

Angular Momentum in Stars Depends upon Coupling

Different models produce different angular momentum profiles based on the recipe for their coupling:

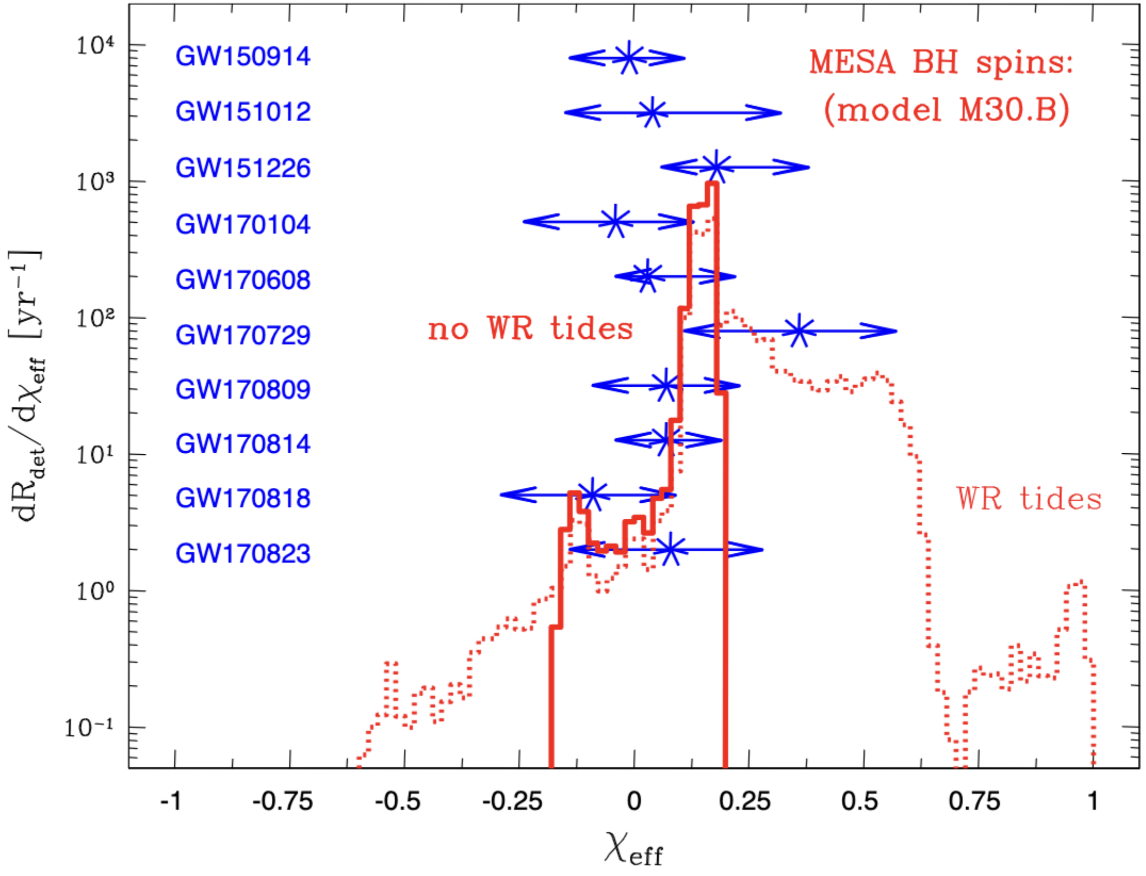
- Dotted: Meynet – no magnetic coupling
- Solid: Heger – Tayler-Spruit Dynamo
- Dashed: MESA

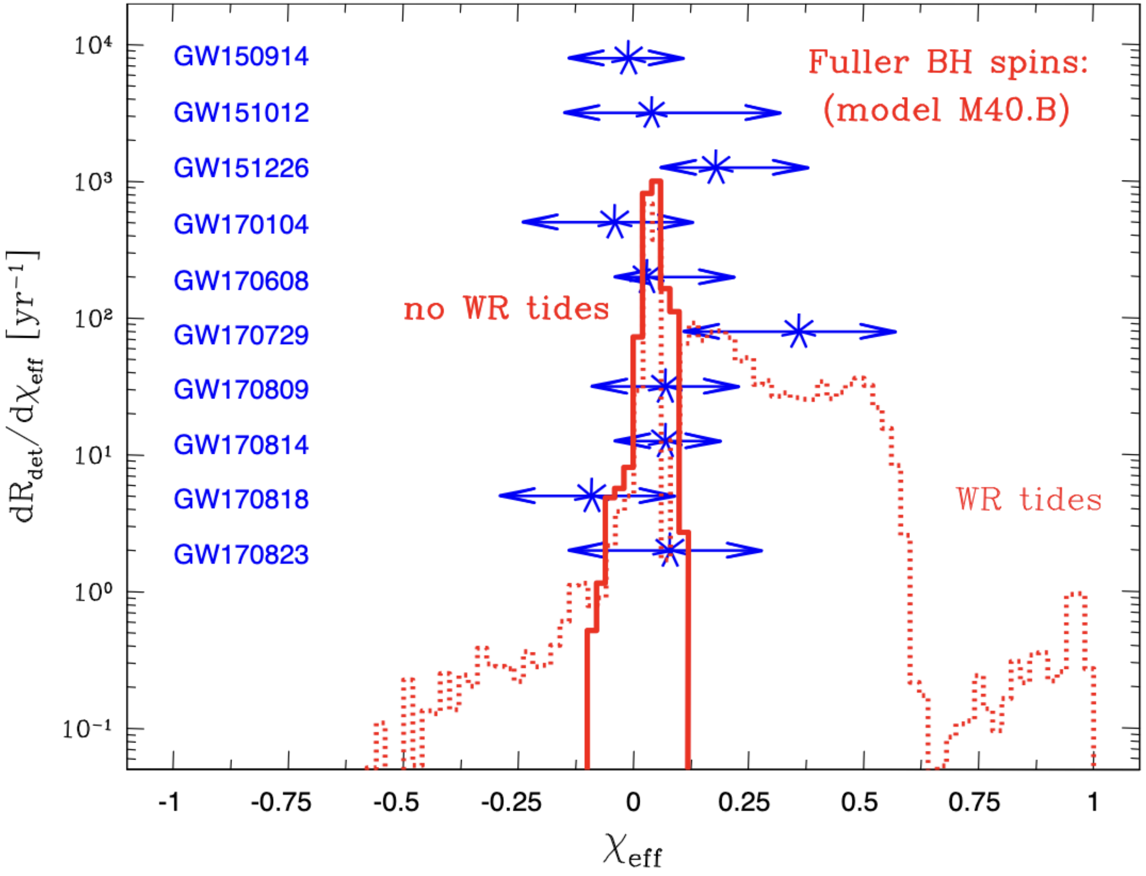
The red line shows the angular momentum required to make a 1000km disk. Strong coupling means no disk.



BH spins and GW probes of SN and GRB Engines

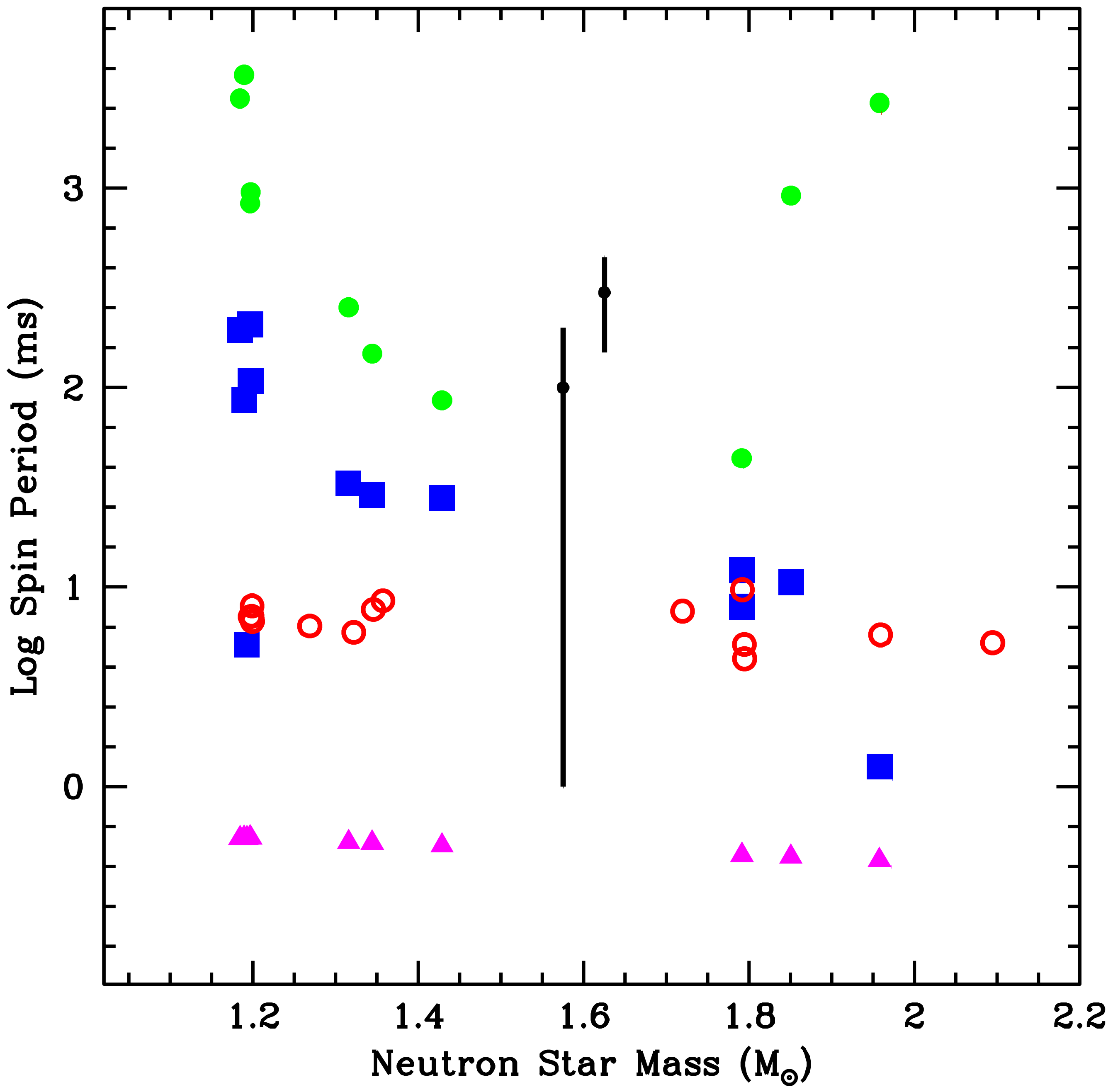
- One of the big uncertainties in stellar evolution is understanding the coupling between burning layers (with implications on BH spins, collapsar GRB models, magnetar explosions, …
- Gravitational wave data will ultimately be able to provide insight into this problem (already it suggests magnetars and NSAD engines are rare)





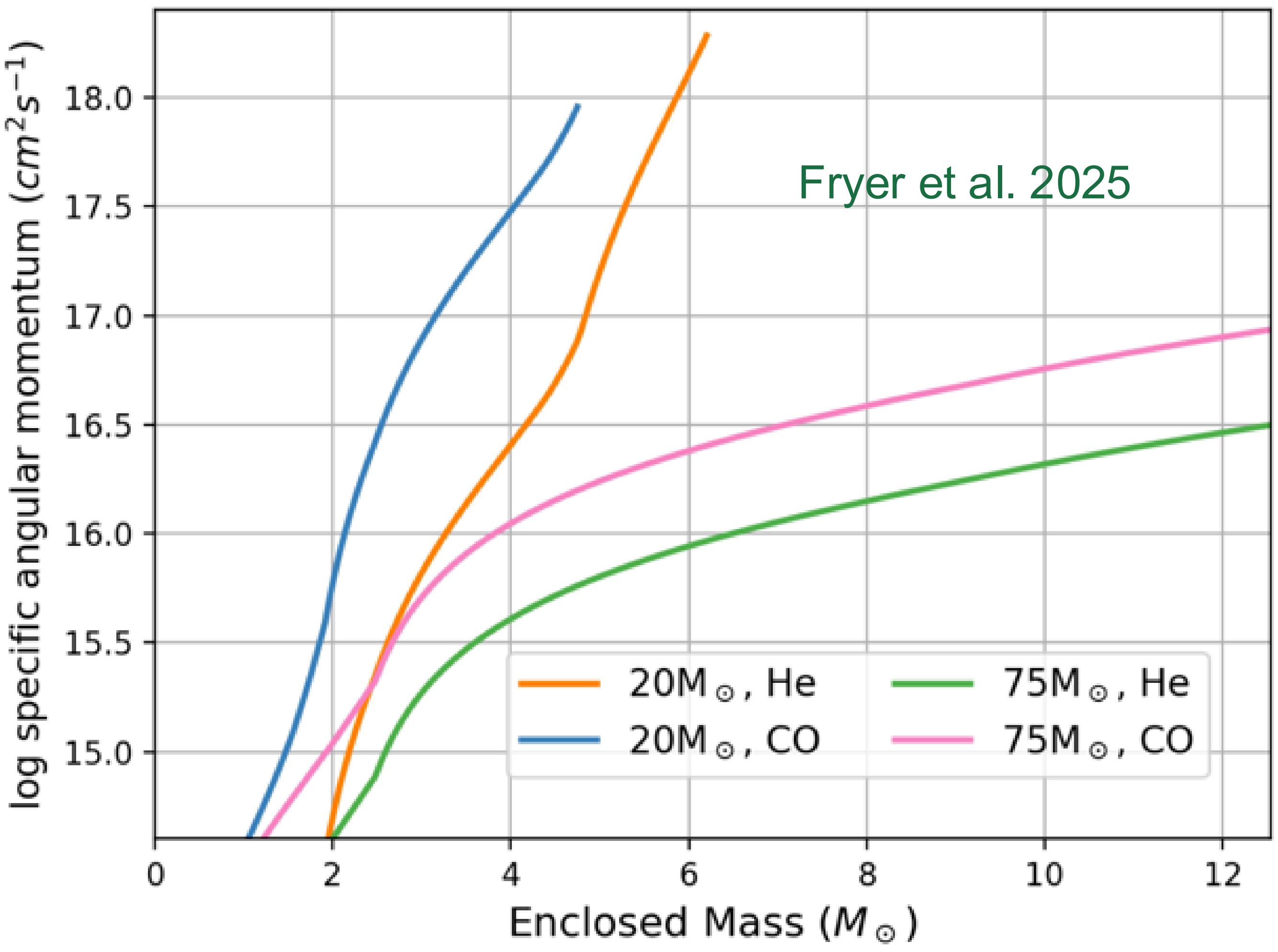
Neutron Star Spins

- From pulsar observations (plus assumptions on ages and spin-down formulae), we have rough estimates of the birth spins of neutron stars: Faucher-Giguere & Kaspi 2006, Popov & Turolla 2012, Igoshev and Popov 2013
- We can use these spins to measure the coupling between burning layers



Where are we now: Understanding Ic Supernovae, Depends on your progenitor, Tight Binary Scenario

- SN Ic are more common than our single star models predict.
- BL Ic occur even without GRBs (jets and asymmetries).
- Homogeneous mixing (e.g. Yoon and Langer???): If this mixing does require high spin rates, some fast spinning stars exist (but most of these would form BHs)
- Tight Binaries: should form a lot of rapidly spinning NS-forming systems. But why do we mostly see BL-Ic at low metallicities?
- NS jets should exist – what transients do they match?
- Lots of other progenitors to make fast rotation.



Compact Remnants and Understanding the Supernova Engine

- A number of engines for astrophysical transients have been proposed: Convection-enhanced neutrino-driven, accretion disk (NS or BH), magnetars
- It is likely that all of these work at some level. White's mandate: That which is not strictly forbidden is mandatory.
- The question is which transients are explained by which engines (most transients are classified by IR-optical emission which may depend more on the circumstellar medium than the engine)
- Compact remnant observations (proper motions, masses, angular momenta) can be strong constraints on the engine. Current results: fast rotation is rare, disk/magnetar engines are rare*.

*rare ~10% (As Ore says, this explains more than just GRBs)