Title: Magnetar Formation via Accretion-Induced Collapse of White Dwarfs

Speakers: Siu Hei Cheung

Collection/Series: Magnetic Fields Around Compact Objects Workshop

Subject: Strong Gravity

Date: March 27, 2025 - 3:00 PM

URL: https://pirsa.org/25030146

Abstract:

We present the first two-dimensional axisymmetric Newtonian magnetohydrodynamic simulations of accretion-induced collapse (AIC) of rotating white dwarfs (WDs) with self-consistent initial magnetic progenitors and neutrino leakage. Our findings show that with initial surface magnetic field strength constrained by isolated WD observations, the protoneutron star can reach field strength consistent with magnetar observations. Our results suggest that single degenerate WDs can form magnetars via AIC.

Magnetar Formation via Accretion-Induced Collapse of White Dwarves

(Peter) Siu Hei CHEUNG, LM Lin, MC Chu, SC Leung, Leon Chan

Outline

- Motivation
  - Magnetars and mystery on its formation
  - Accretion-induced collapse of White Dwarf
- Methods
  - Progenitors
  - Evolution
- Results and Conclusion

Magnetar

- Neutron Stars with strong magnetic field ($\sim 10^{14}$ G)
- Found 30
- Unclear formation mechanism

Magnetar

Extreme Magnetic
Field Amplification

- Neutron Stars with strong magnetic field ($\sim 10^{14}$ G)
- Found 30

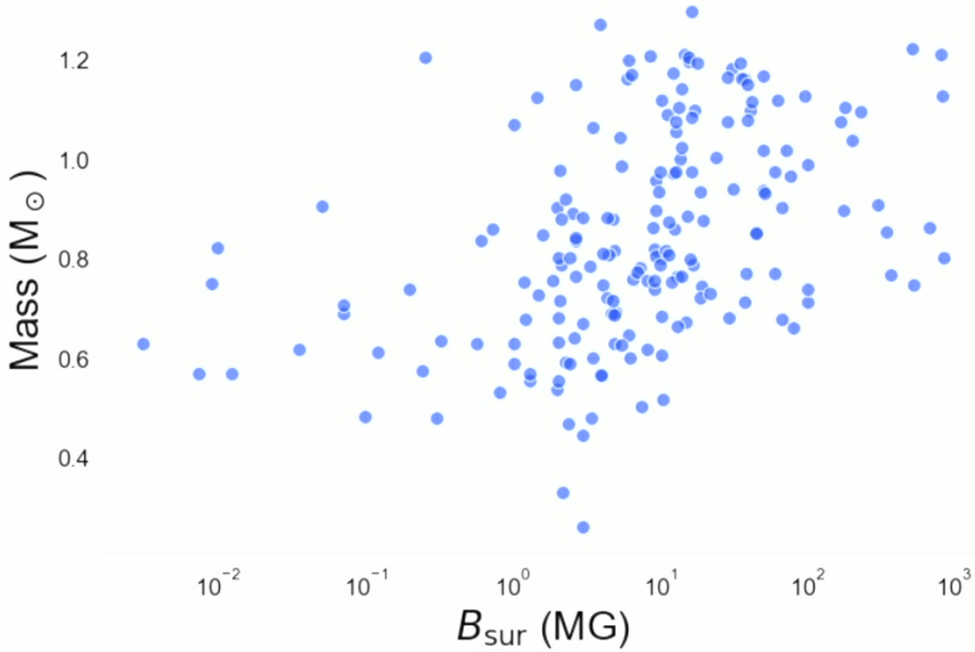
Limited observational
evidence

- Unclear formation mechanism
- Complex core collapse supernova progenitor
- Complex microphysics and instabilities

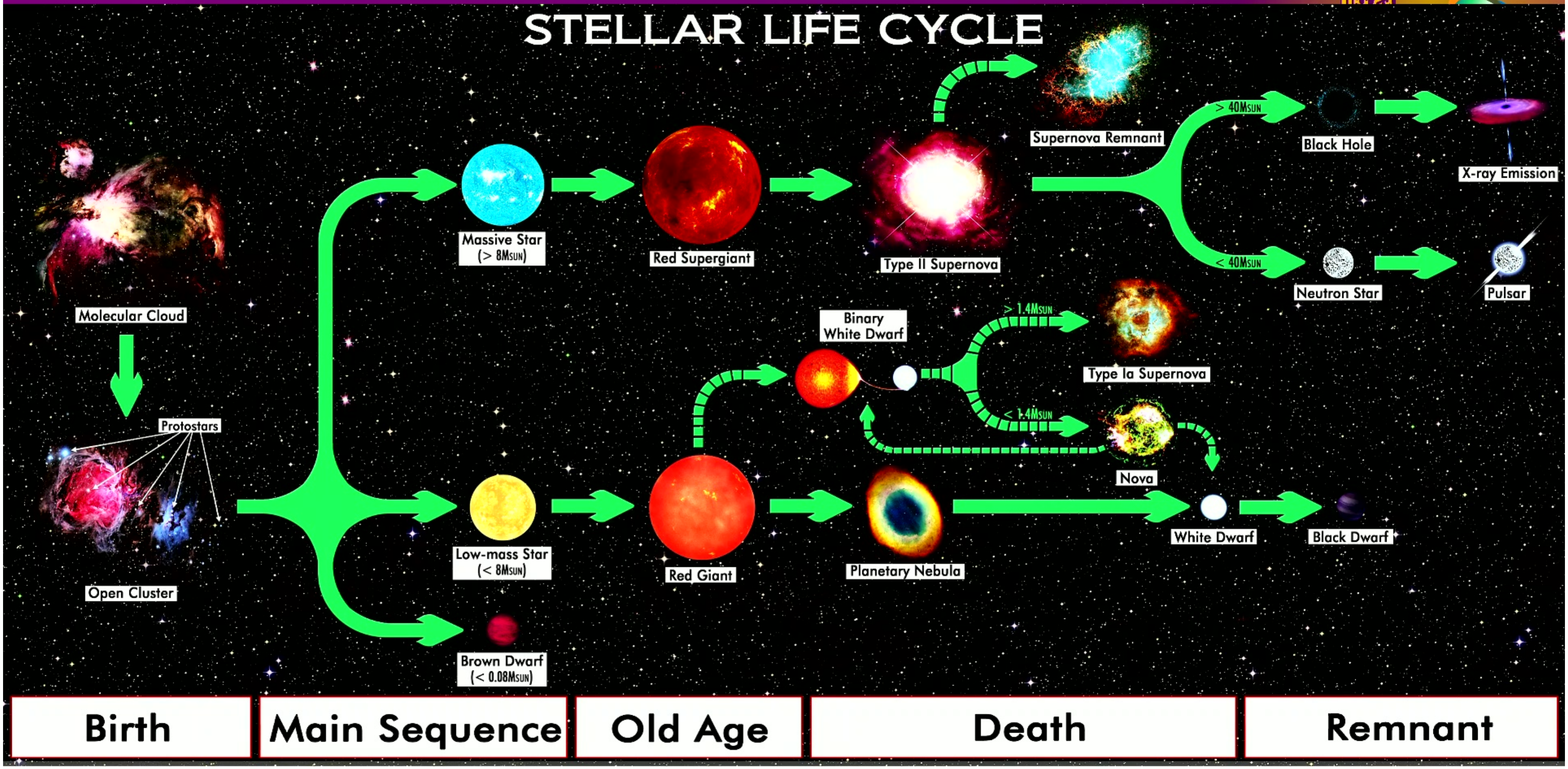
Objective

WD can carry magnetic fields

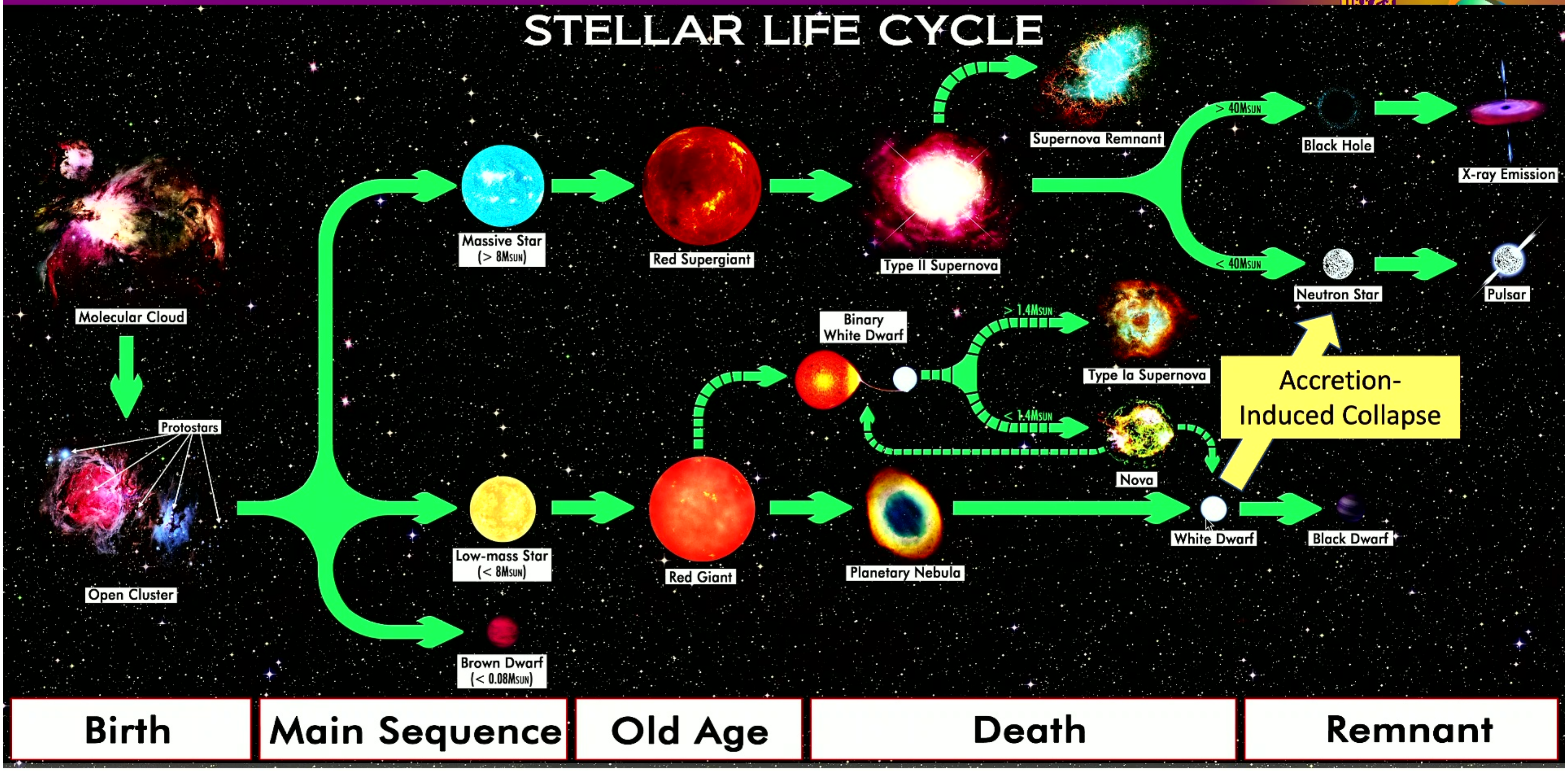
- Under what conditions can magnetized white dwarfs form a magnetar-like object?



Montreal White Dwarf Database



Credit: R.N. Bailey



Credit: R.N. Bailey

Accretion-Induced Collapse of WD

- Alternatively, theoretically possible (Nomoto 1991)
- Instead of carbon ignition or thermonuclear runaway (SN Type Ia)
- WD gains mass by accretion or merging
- Rapid electron capture at center ($\rho_c \gtrsim 10^{9.7}$ g/cc)
- Triggering collapse to form protoneutron star (PNS)

$e^- + p^+ \rightarrow n + \nu$

Electron capturing occurs in the center

Dynamically collapsed
A proto-neutron star formed

Electron pressure < gravity

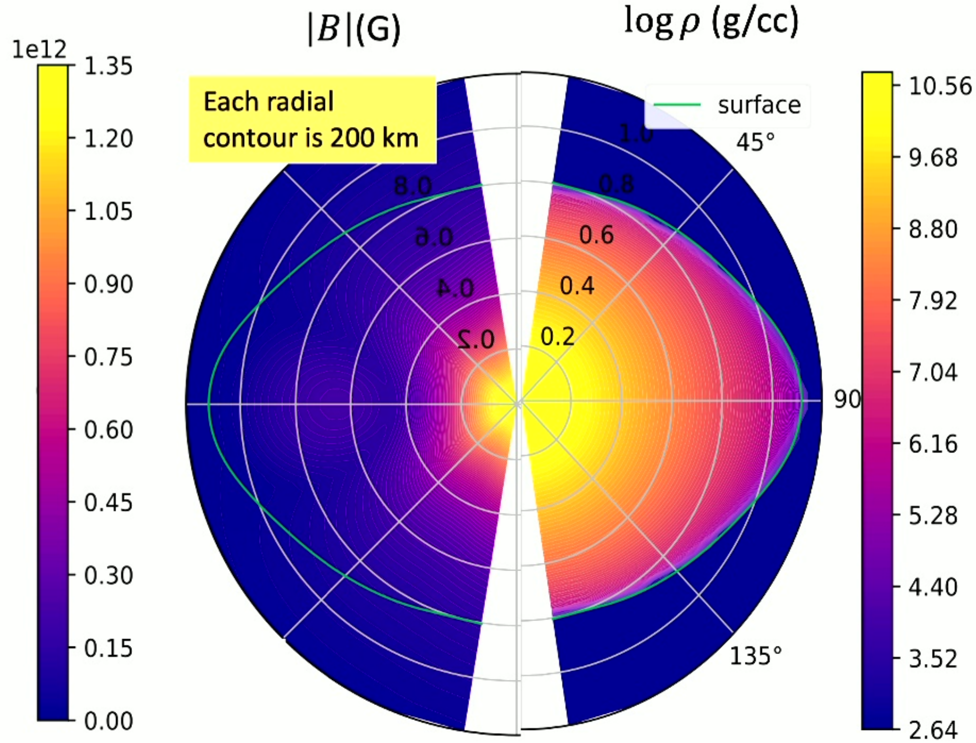
Self-consistent Initial Condition

- Solving a magneto-hydrostatic system

$$0 = -\frac{1}{\rho}\nabla P - \nabla\Phi - \Omega\times(\Omega\times r) + \frac{1}{4\pi}(j\times B)$$

$$\nabla^2\Phi = 4\pi G\rho$$

- Search for varies
  - Magnetic field strength
  - Rotational speed(Ω)

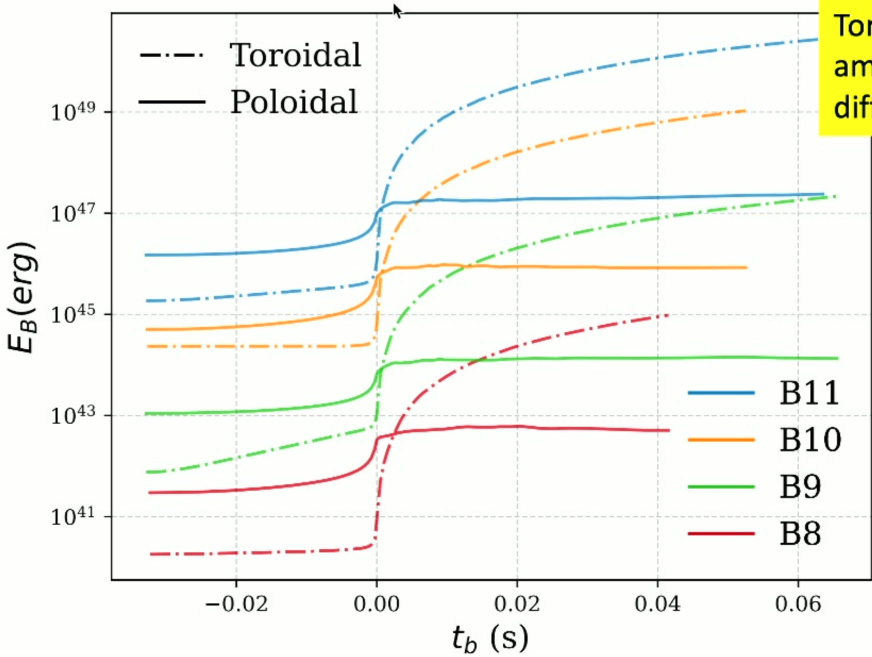


Simulation Setup

- Axisymmetric (2D), in spherical coordinate (Eastern hemisphere)
- MHD + GR-inspired modification (Marek+ 2006, Obergaulinger+ 2020)
- Nuclear EOS: STOS
- Parametrized deleptonization in the collapsing phase (Liebendorfer 2005)
- Rosswog leakage in the post bounce phase
- $N_r = 200$ (Uniform until ~30 km); $N_\theta = 60$ (Uniform θ)
- Domain: $[0, 1.1]R_{WD} \times [0, \pi]$
- OpenMP

Magnetic Energy Component

Model	M_{ini} ($M_\odot$)	t_b (ms)	$\max(B_{ini})$ (G)	$\max(B_{sur})$ (G)	Ω_{ini} (s^{-1})	T_{ini} (s)	$M_{PNS,11}$ ($M_\odot$)	$M_{PNS,10}$ ($M_\odot$)	$\max(B_{PNS})$ (G)	T_{PNS} (ms)
B11	1.484	32.86	2.00×10^{12}	1.67×10^{11}	10.847	0.58	1.216	1.385	1.49×10^{16}	1.245
B10	1.470	32.69	5.50×10^{11}	1.71×10^{10}	9.611	0.65	1.226	1.384	3.47×10^{15}	1.518
B9	1.484	32.86	4.85×10^{10}	4.69×10^{9}	10.847	0.58	1.217	1.385	4.02×10^{14}	1.288
B8	1.434	32.30	1.28×10^{10}	4.56×10^{8}	4.084	1.54	1.252	1.379	9.74×10^{13}	3.120



Toroidal energy amplified by differential shearing

No poloidal energy regeneration limited by 2D MHD

Maximum Field Strength

Model	$M_{\rm ini}$ ($M_\odot$)	t_b (ms)	$\max(B_{\rm ini})$ (G)	$\max(B_{\rm sur})$ (G)	$\Omega_{\rm ini}$ (s^{-1})	$T_{\rm ini}$ (s)	$M_{\rm PNS,11}$ ($M_\odot$)	$M_{\rm PNS,10}$ ($M_\odot$)	$\max(B_{\rm PNS})$ (G)	$T_{\rm PNS}$ (ms)
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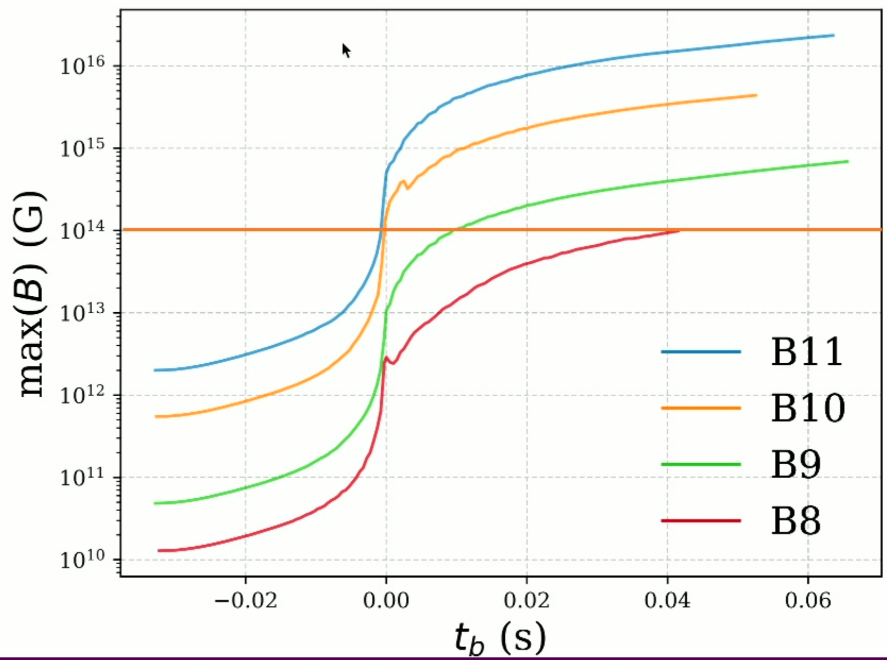

Conclusion

- *B* field amplifed as strong as observed magnetars
- Both toroidal and poloidal fields are amplified
  - Toroidal is the strongest component after bounce due to Ω-effect
- With a self-consistent initial surface maximum magnetic field constrained by White Dwarf observation, AIC is a possible pathway to form a protoneutron star with a magnetic field strength consistent with magnetar observations