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Angular momentum imprints in the Multimessenger signals of Accretion Induced Collapse of White Dwarfs

FAPESP

erc European Research Council

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talk to
NP3M collaboration
19/10/2023

JOURNAL ARTICLE

Multimessenger emission from the accretion-induced collapse of white dwarfs

Luís Felipe Longo Micchi ✉, David Radice, Cecilia Chirenti Author Notes

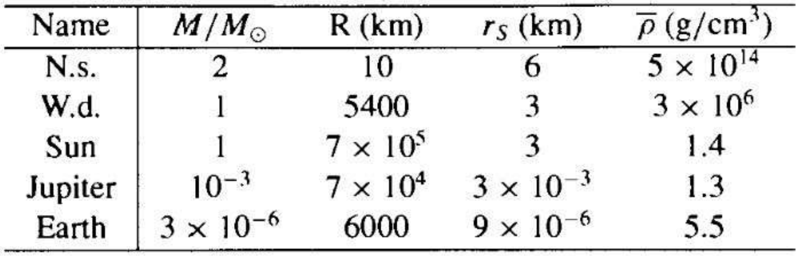
Monthly Notices of the Royal Astronomical Society, Volume 525, Issue 4, November 2023, Pages 6359–6376, https://doi.org/10.1093/mnras/stad2420

Published: 16 August 2023 **Article history** ▾

Check it for more details

What is a White Dwarf (WD)?

1. What are White Dwarfs?
    - a. Final stage of low mass MS stars
    - b. Did not burn all its fuel up to Fe
    - c. Most commonly composed by C-O or O-Ne-Mg
    - d. Main Features (order of magnitude):



Name	$M/M_\odot$	R (km)	r_S (km)	$\bar{\rho}$ (g/cm^3)
N.s.	2	10	6	5×10^{14}
W.d.	1	5400	3	3×10^{6}
Sun	1	7×10^{5}	3	1.4
Jupiter	10^{-3}	7×10^{4}	3×10^{-3}	1.3
Earth	3×10^{-6}	6000	9×10^{-6}	5.5

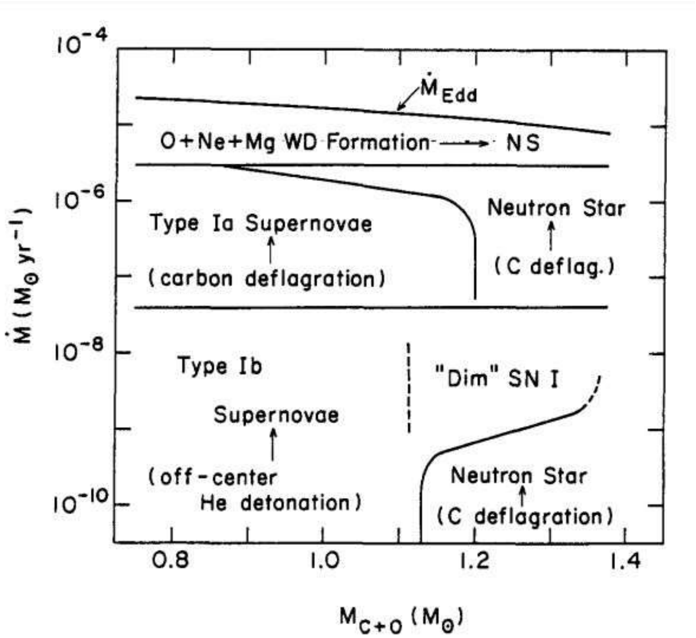
Table reproduced from Gledenning's "Compact stars" book

2. What supports White Dwarfs?
    - a. No thermonuclear burning
    - b. e$^-$-degeneracy pressure
    - c. Maximum mass:

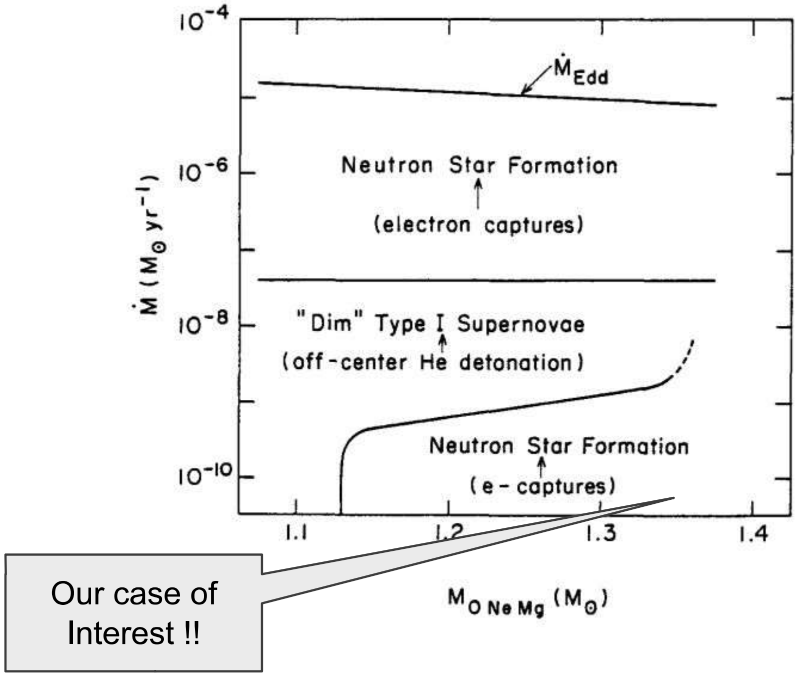
$$M_{max} \approx 5.87 \times Y_e^2 \times M_\odot, \quad \text{where} \quad Y_e \equiv \frac{n_e}{n_p + n_n}$$

    - d. Main Assumptions / Caveats:
        - I. Non-rotating WD – rotation is everywhere
        - II. Cold WD -- mergers
        - III. Isolated WD -- mergers

What is an Accretion-induced Collapse (AIC)?



1. What is its fate?
   - a. Unstable according to Chandrashekar limit
   - b. Collapse → Emits in 3 Bands of MMA
   - c. Production of exotic isotopes as: ^{62}Ni, ^{66}Zn, ^{68}Zn, ^{87}Rb, ^{88}Sr
   - d. Historically connected to: sGRB's, ms-pulsars

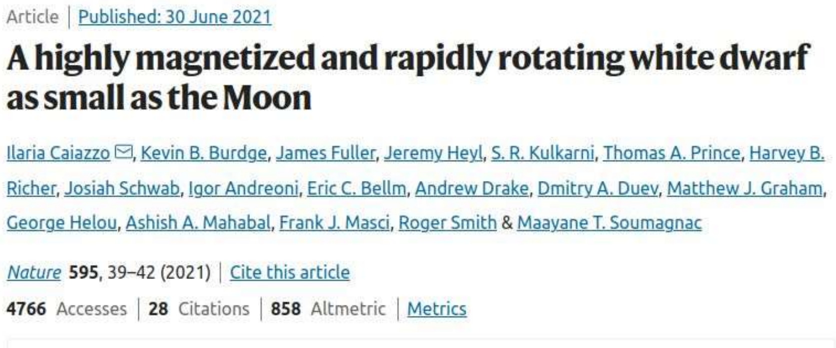


Our case of Interest !!

Images reproduced from Nomoto '86

Can it happen?
Possible Sources

I. ZTF J1901+1458



Article | Published: 30 June 2021

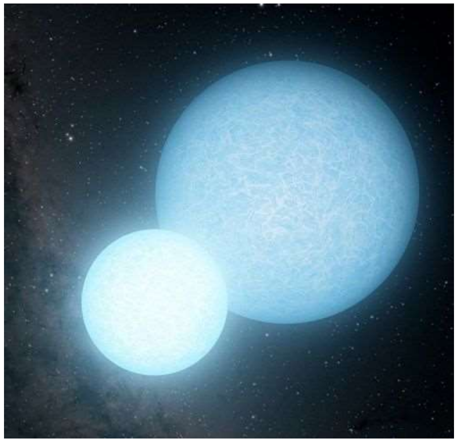
A highly magnetized and rapidly rotating white dwarf as small as the Moon

Ilaria Caiazzo, Kevin B. Burdge, James Fuller, Jeremy Heyl, S. R. Kulkarni, Thomas A. Prince, Harvey B. Richer, Josiah Schwab, Igor Andreoni, Eric C. Bellm, Andrew Drake, Dmitry A. Duev, Matthew J. Graham, George Helou, Ashish A. Mahabal, Frank J. Masci, Roger Smith & Maayane T. Soumagnac

Nature **595**, 39–42 (2021) | Cite this article

4766 Accesses | **28** Citations | **858** Altmetric | Metrics

Image reproduced from astronomy.com
Artistic comparison of a regular
and a supermassive WD



II. S Ophiuchi

a. Red Giant

$M = (0.7 - 0.8)M_{\odot}$ (E. Brandim et al.'09)

b. WD

$M = (1.2 - 1.4)M_{\odot}$ (E. Brandi et al.'09)

c. Accretion

$\dot{M} = ??$

III. T Coronae Borealis

a. Red Giant

$M = (1.12 \pm 0.23)M_{\odot}$ (J.D. Linford et al.'19)

b. WD

$M = (1.37 \pm 0.13)M_{\odot}$ (J.D. Linford et al.'19)

c. Accretion

$\dot{M} = 6.7 \times 10^{-9} M_{\odot} \mathrm{yr}^{-1}$ (G.J.M. Luna et al.'18)

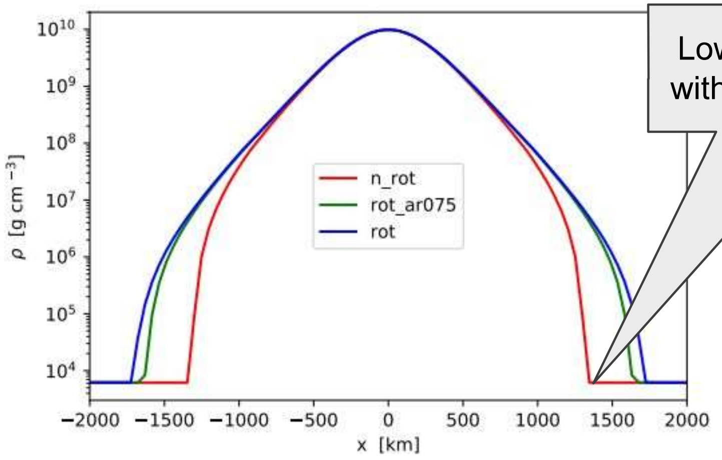
Numerical set-up & Initial data

Numerical details:

- I. Hydrodynamics: WhiskyTHC
  - (Radice et al.'12 '13 '14 '16 '18 '21)
- II. Neutrinos:
  - a. De-leptonization (Liebendörfer'05) & WhiskyTHC
- III. Einstein Toolkit (Löffer et at. '12):
  - a. Initial data: RNDS thorn (Stergioulas & Friedman '95)
  - b. Spacetime evolution: CTGamma thorn (Pollney et al. '11; Reisswig et al. '13),
  - c. AMR grid by CARPET thorn (Schnetter et al. '04)
- IV. Novelties:
  - a. 3D (mirror symmetry on rotation axis)
  - b. Full GR
- VI. Previous models are either:
  - a. 2D simulations (Abdikamalov et al. '10)
  - b. Newtonian Gravity (Dessart et al. '06 '07)

Simulation	ρ_0 [g cm^{-3}]	Temp. [MeV]	M [$M_\odot$]	$M_{\mathrm{bar.}}$ [$M_\odot$]	R [km]
`rot`	9.95×10^9	0.01	1.52	1.53	1.93×10^3
`rot_ar075`	9.95×10^9	0.01	1.51	1.53	1.71×10^3
`nrot`	9.95×10^9	0.01	1.45	1.47	1.33×10^3

Simulations	J [g cm^2 s^{-1}]	T/W	Ω [Hz]	Ω_{Kepler} [Hz]	a_r
`rot`	3.26×10^{49}	1.49×10^{-2}	5.28	5.30	0.66
`rot_ar075`	3.08×10^{49}	1.37×10^{-2}	5.09	6.38	0.75
`nrot`	0	0	0	9.03	1.00



Low density atmosphere with low energy neutrinos

Electron Fraction Dynamics

1. De-leptonization of the core
   a. Parameterized scheme by Liebendörfer'05:

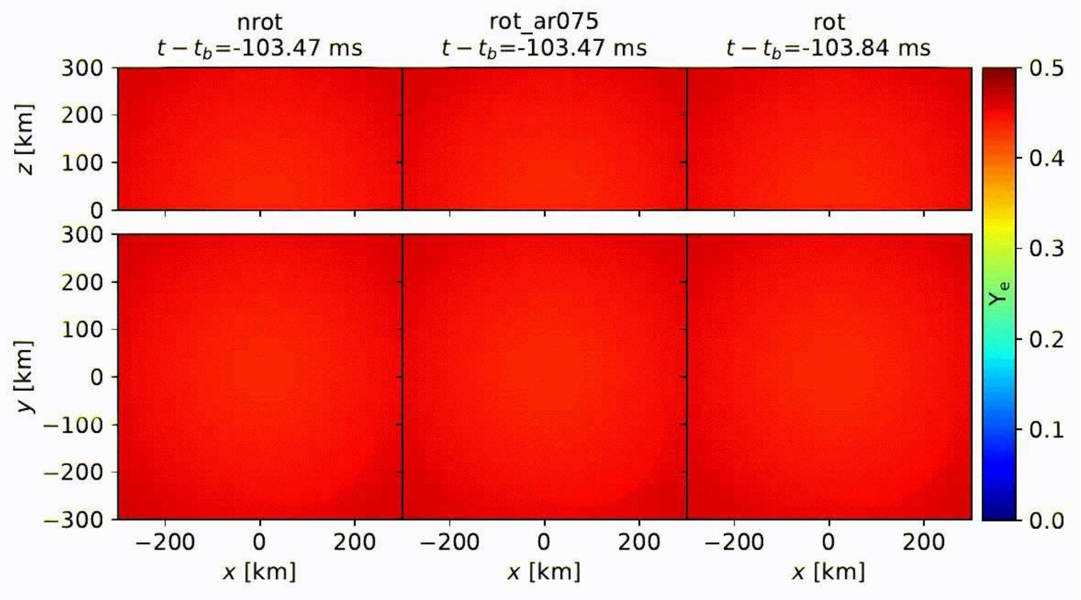
$$Y_e = Y_e(\rho)$$

   b. Diminishing the e^- density diminishes the supporting pressure

From the theory of fermionic gases

$$\epsilon \to 3p \approx \frac{1}{4\pi^2}(3\pi^2\rho)^{4/3} \quad \text{(high density, } k >> m\text{)},$$

$$\rho = \frac{k^3}{3\pi^2}$$



$$p^+ + e^- \longleftrightarrow n + \nu_e$$

$$(A,Z) + e^- \longleftrightarrow (A,Z-1) + \nu_e$$

Mass Motion

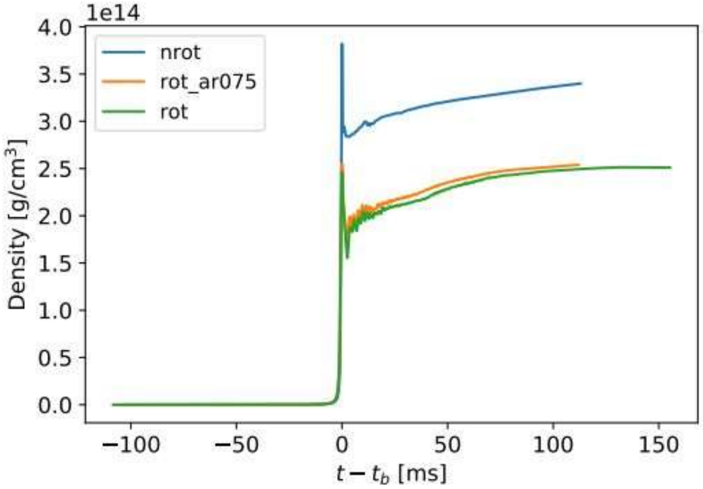
I. Initial purely outgoing motion

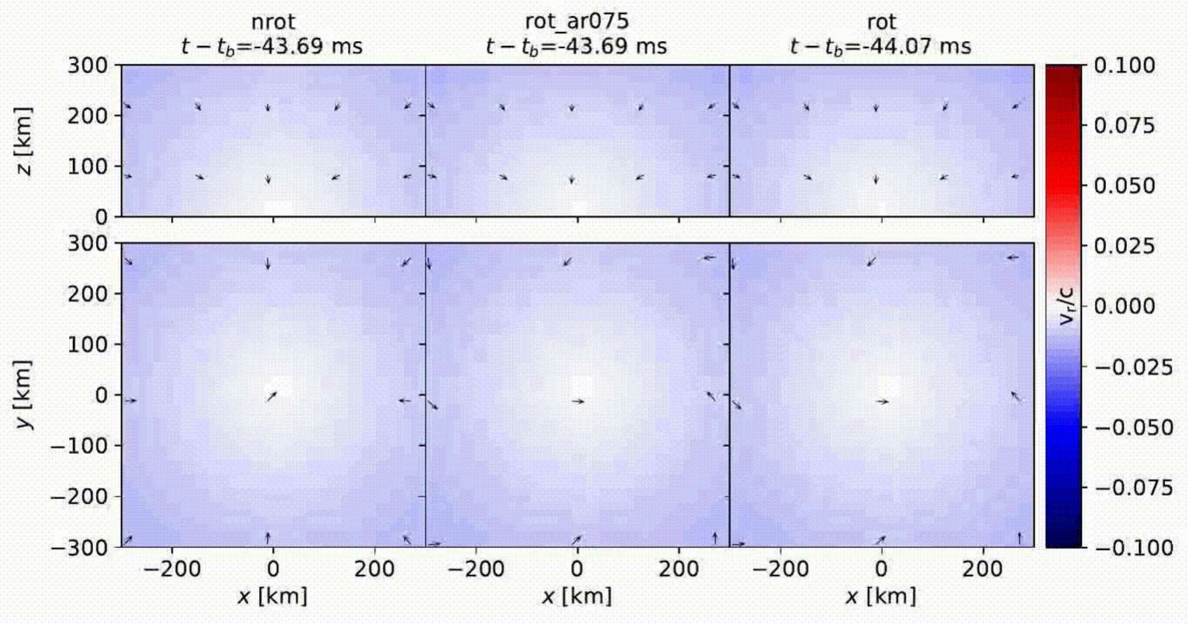
II. Core bounces:

- a. Star central density approaches

  $$\rho_{\text{nuc}} \approx 2.7 \times 10^{14} \text{g cm}^{-3}$$

- b. Core stiffens and bounce
- c. Outward motion starts





Mass Motion

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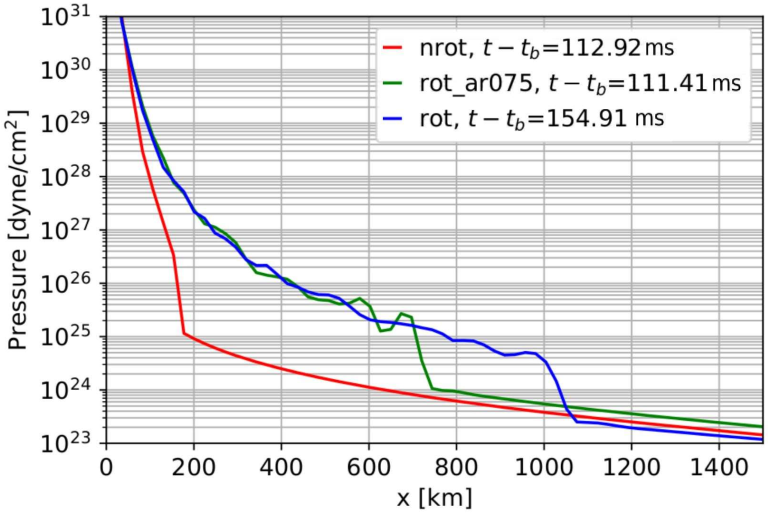
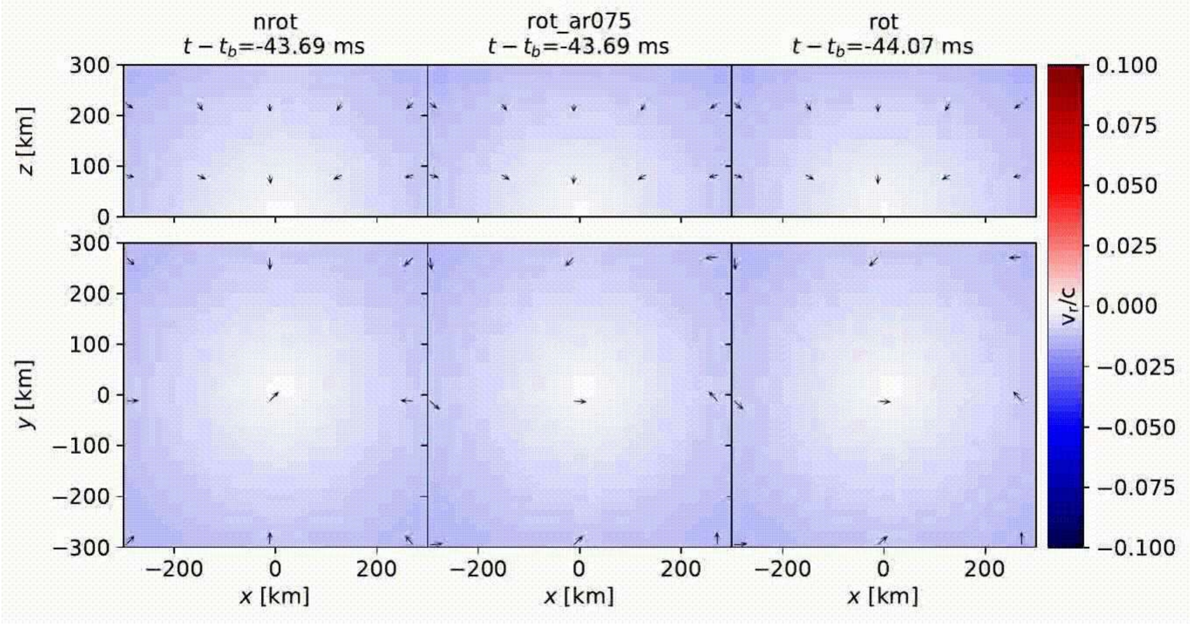
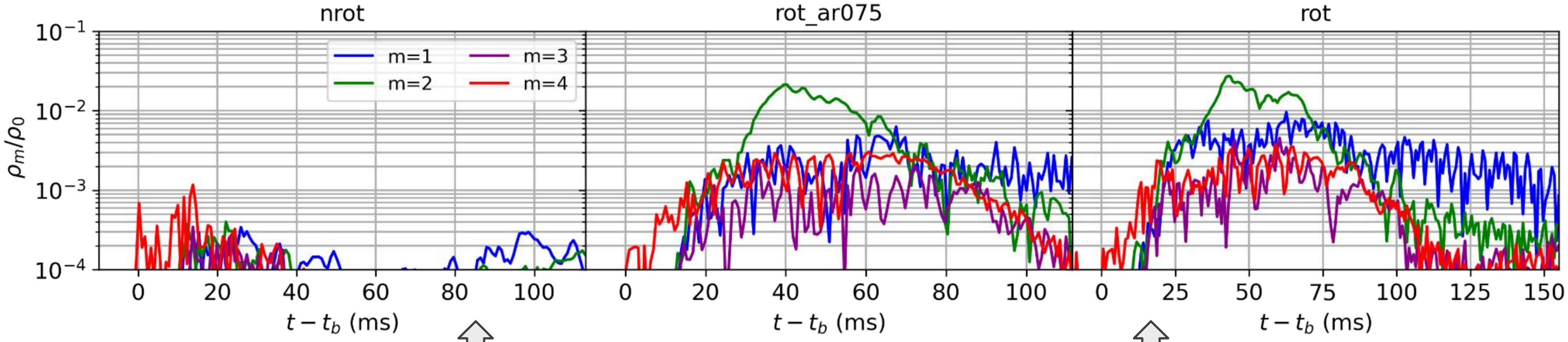
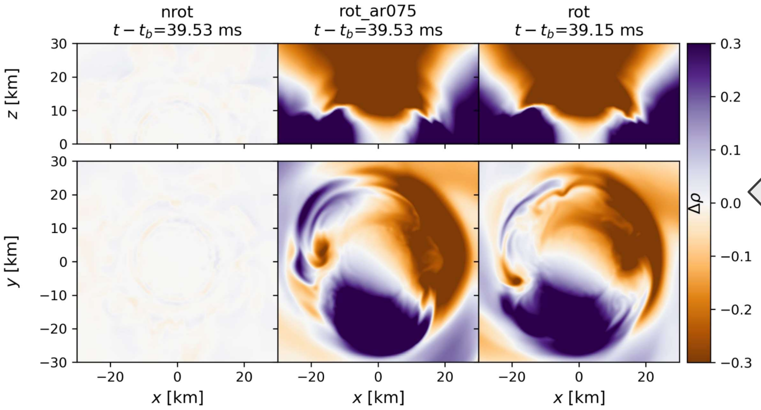




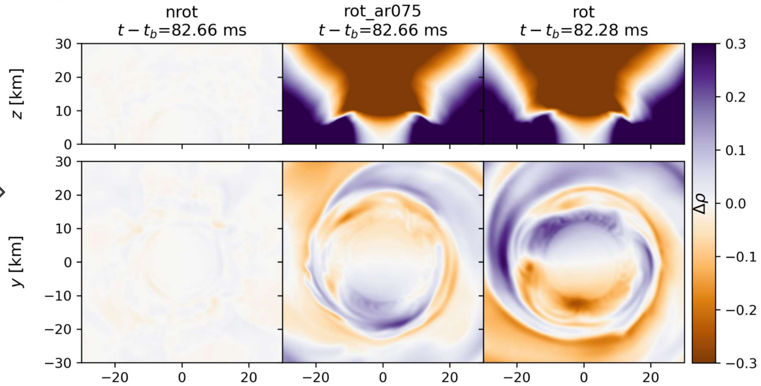
Mass Distribution: m=1 Instability



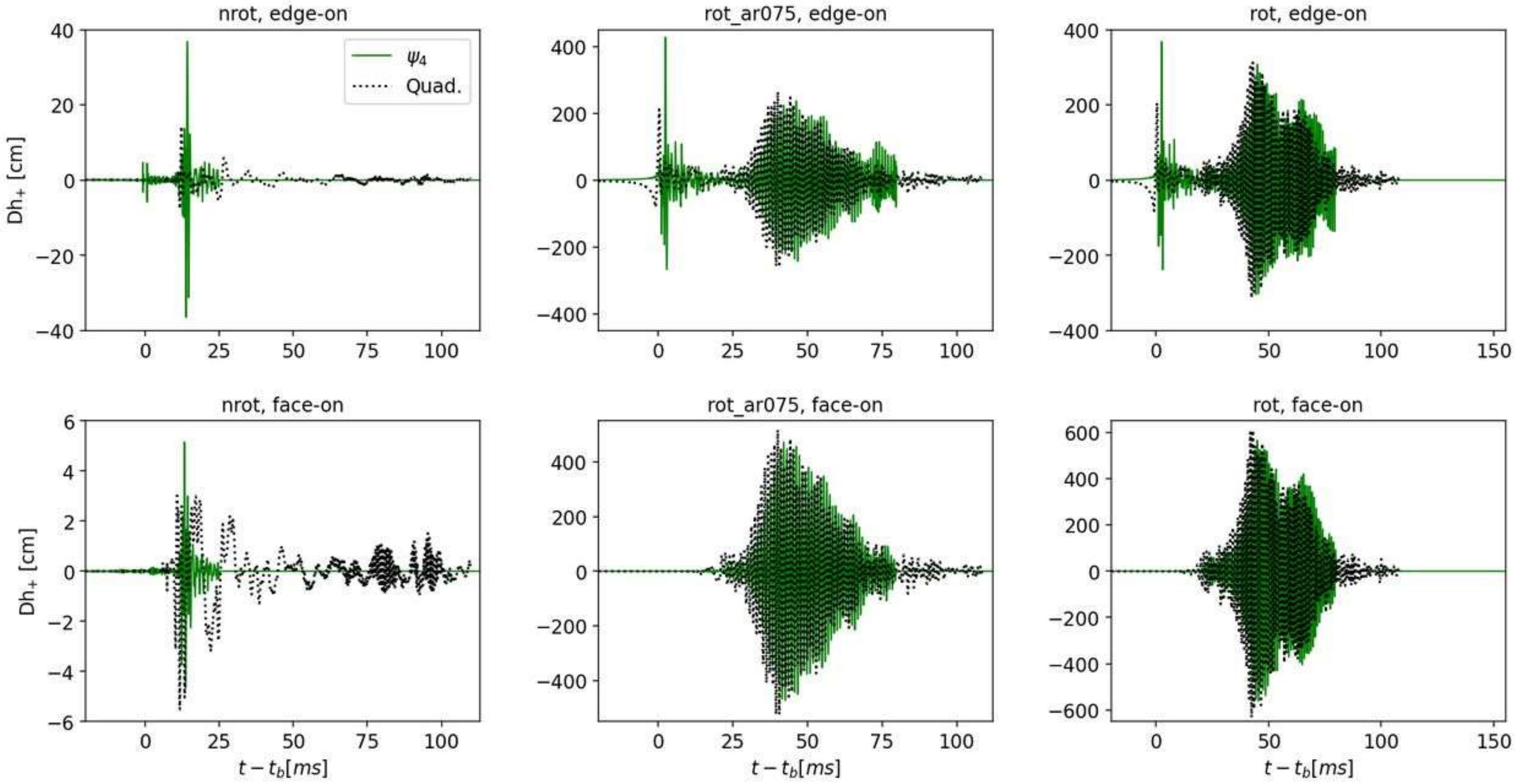
$$\rho_m \equiv \int_{z=0} \sqrt{\gamma}\,\rho\,W\,e^{-im\phi}\,dx\,dy$$



$$\Delta\rho \equiv \frac{\rho - \langle\rho\rangle|_{\phi,\theta}}{\langle\rho\rangle|_{\phi,\theta}}$$



Gravitational Waves: Time domain



Gravitational Waves: Polarization

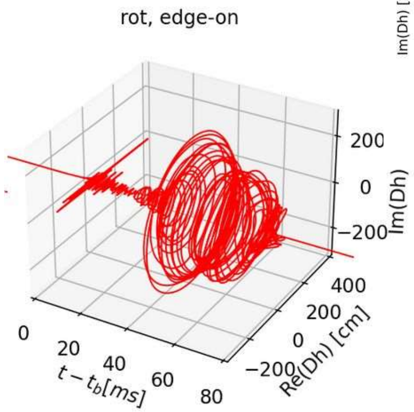
What about polarization?

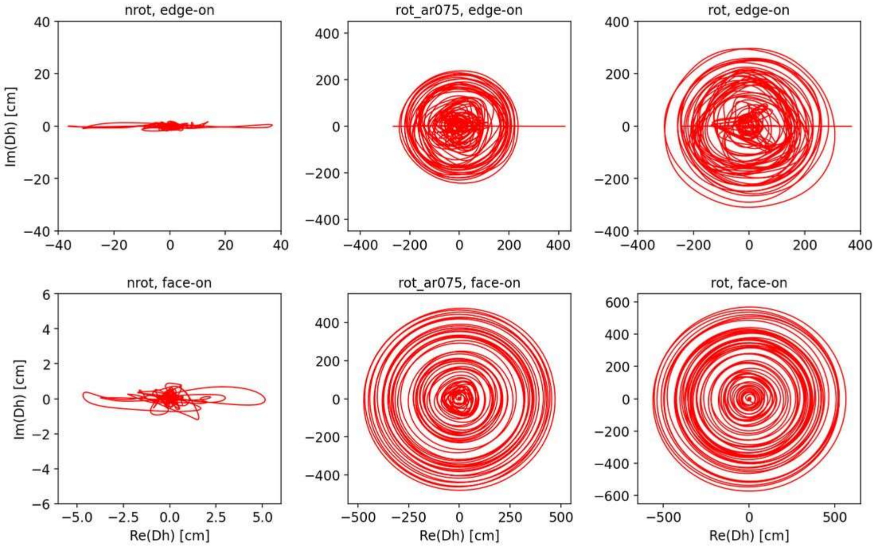
In K. Hayama et al.’18:

1. Polarization can tell us about :
    - a. EOS
    - b. Presence of SASI instability

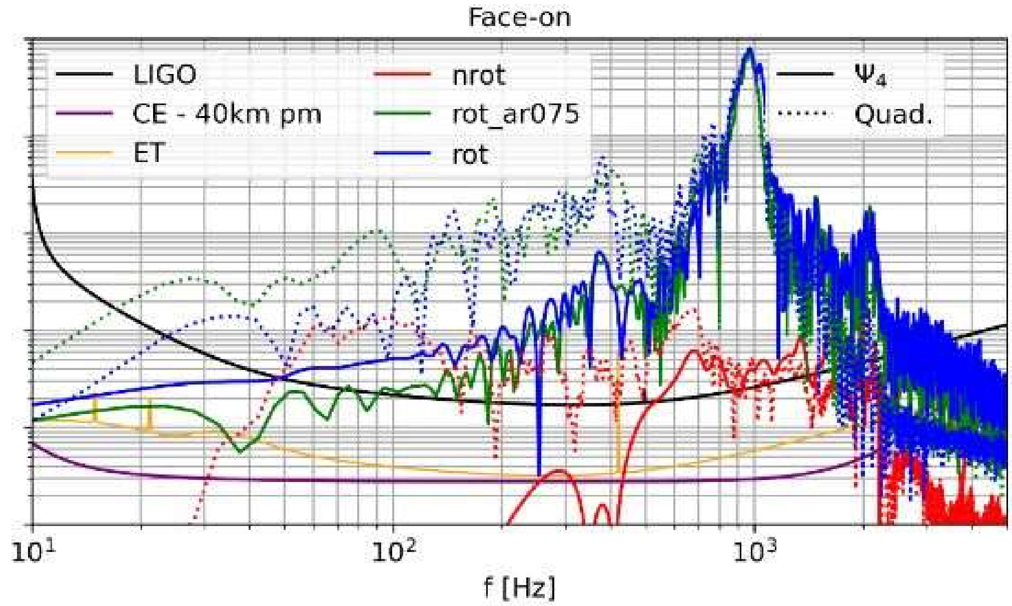
In our models:

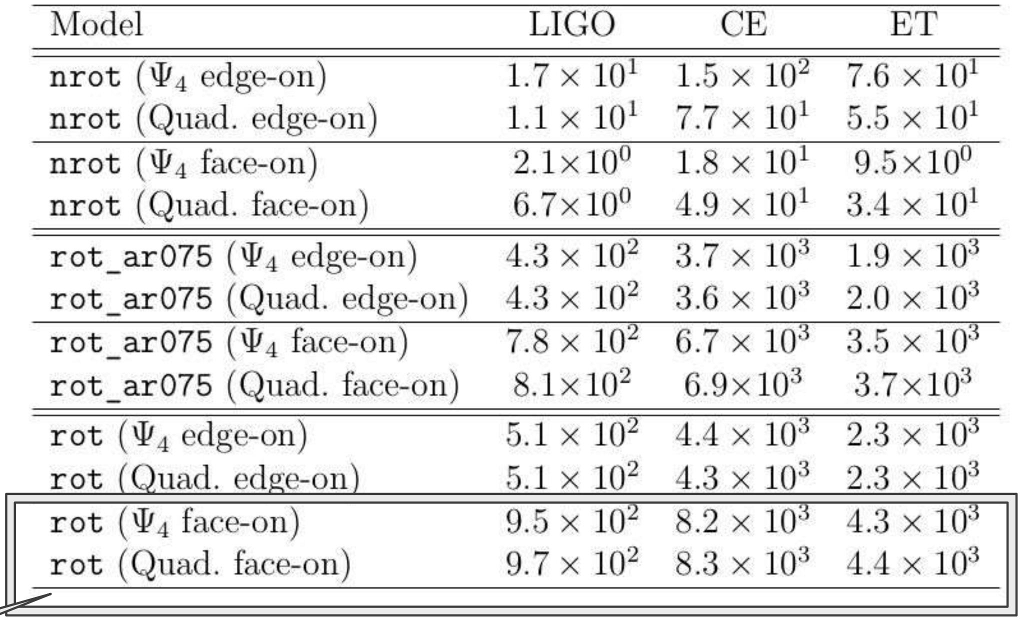
- a.m=0: linear polarization
- b. m=2: Circular polarization
- c. No sign flip of the (m=2) polarization
- d. No evidence for SASI





Gravitational Waves:
Dectectability at 10kpc

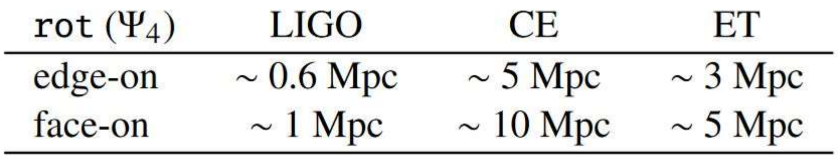




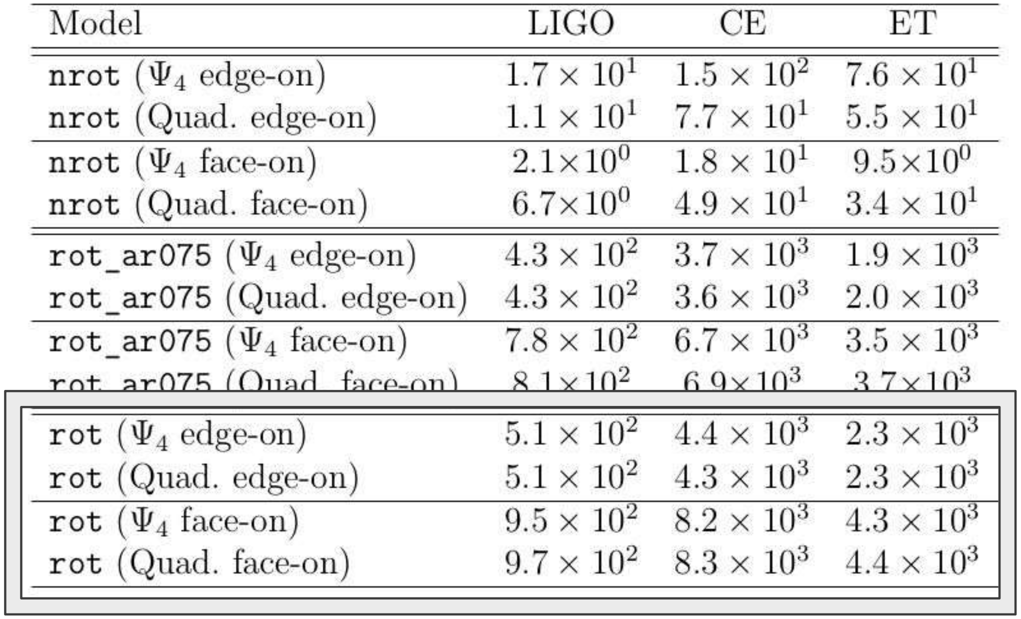
Model	LIGO	CE	ET
`nrot` (Ψ_4 edge-on)	1.7×10^1	1.5×10^2	7.6×10^1
`nrot` (Quad. edge-on)	1.1×10^1	7.7×10^1	5.5×10^1
`nrot` (Ψ_4 face-on)	2.1×10^0	1.8×10^1	9.5×10^0
`nrot` (Quad. face-on)	6.7×10^0	4.9×10^1	3.4×10^1
`rot_ar075` (Ψ_4 edge-on)	4.3×10^2	3.7×10^3	1.9×10^3
`rot_ar075` (Quad. edge-on)	4.3×10^2	3.6×10^3	2.0×10^3
`rot_ar075` (Ψ_4 face-on)	7.8×10^2	6.7×10^3	3.5×10^3
`rot_ar075` (Quad. face-on)	8.1×10^2	6.9×10^3	3.7×10^3
`rot` (Ψ_4 edge-on)	5.1×10^2	4.4×10^3	2.3×10^3
`rot` (Quad. edge-on)	5.1×10^2	4.3×10^3	2.3×10^3
`rot` (Ψ_4 face-on)	9.5×10^2	8.2×10^3	4.3×10^3
`rot` (Quad. face-on)	9.7×10^2	8.3×10^3	4.4×10^3

Best case scenario

Gravitational Waves:
Detection Horizons (SNR = 8)



`rot` (Ψ_4)	LIGO	CE	ET
edge-on	~ 0.6 Mpc	~ 5 Mpc	~ 3 Mpc
face-on	~ 1 Mpc	~ 10 Mpc	~ 5 Mpc



Model	LIGO	CE	ET
`nrot` (Ψ_4 edge-on)	1.7×10^1	1.5×10^2	7.6×10^1
`nrot` (Quad. edge-on)	1.1×10^1	7.7×10^1	5.5×10^1
`nrot` (Ψ_4 face-on)	2.1×10^0	1.8×10^1	9.5×10^0
`nrot` (Quad. face-on)	6.7×10^0	4.9×10^1	3.4×10^1
`rot_ar075` (Ψ_4 edge-on)	4.3×10^2	3.7×10^3	1.9×10^3
`rot_ar075` (Quad. edge-on)	4.3×10^2	3.6×10^3	2.0×10^3
`rot_ar075` (Ψ_4 face-on)	7.8×10^2	6.7×10^3	3.5×10^3
`rot_ar075` (Quad. face-on)	8.1×10^2	6.9×10^3	3.7×10^3
`rot` (Ψ_4 edge-on)	5.1×10^2	4.4×10^3	2.3×10^3
`rot` (Quad. edge-on)	5.1×10^2	4.3×10^3	2.3×10^3
`rot` (Ψ_4 face-on)	9.5×10^2	8.2×10^3	4.3×10^3
`rot` (Quad. face-on)	9.7×10^2	8.3×10^3	4.4×10^3

Detection Rates

Based on SNIa rates:

I. SNIa: $3\times10^{-4}\mathrm{yr}^{-1}\mathrm{Mpc}^{-3}$ (Cappellaro et al.'2015)

II. AIC:

  a. LIGO: $(x/10\%)\times2.2\times10^{-4}\,\mathrm{yr}^{-1}$

  b. CE: $(x/10\%)\times0.14\,\mathrm{yr}^{-1}$

Caviants:

I. Unknown relative fraction AIC to SNIa

Based on nucleosynthesis (Fryer et al.'99):

I. Upper limit as ~200 AIC / Myr / galaxy

II. 451 galaxies for D<10Mpc (Karachentsev et al'04)

III. AIC rate ~ $0.08\,\mathrm{yr}^{-1}$

Caviants:

I. Assuming that all galaxies contribute equally to AIC rate

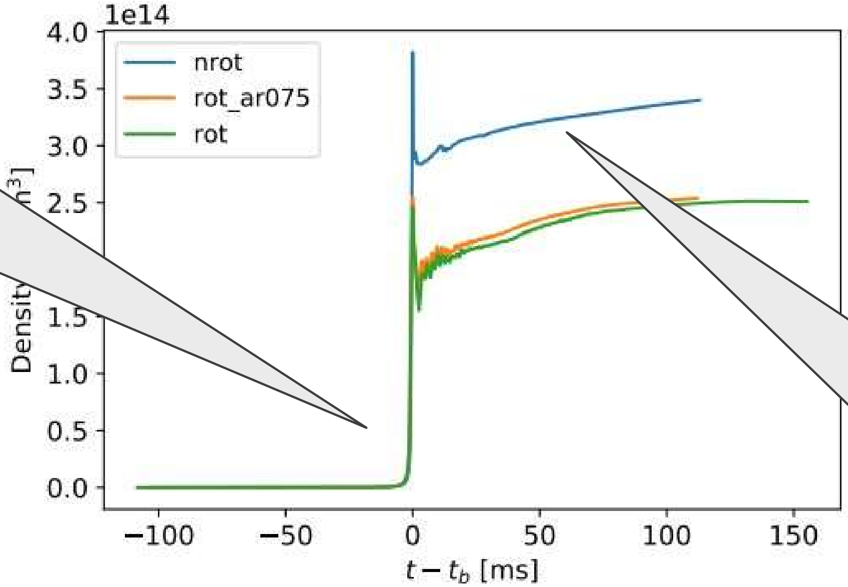
II. All exotic neutron-rich material are produced by AIC

Neutrino Treatment

Pre-bounce phase:
Liebendörfer’05
de-leptonization scheme

$$Y_e = Y_e(\rho)$$

Although it assumes the β decay
No neutrino is accounted for
WD is considered to be
transparent at this point



Post-bounce phase:
Radice et al.’21
Neutrino M1 treatment
Neutrinos opacities are numerically solved for
Includes Doppler effects at all orders
in v/c
Accounts for non-linear couplings between neutrino and matter

Chemical Potential

$\mu_\delta = \mu_n + \mu_\nu - \mu_e - \mu_p$:

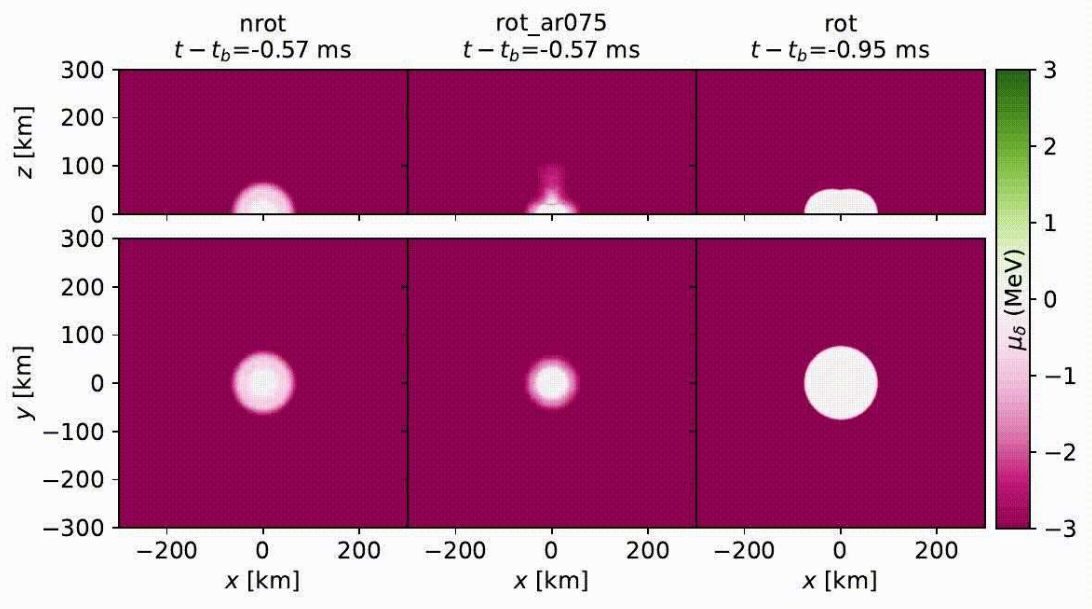
If $\mu_\delta = 0$, β- equilibrium → Neutrinos in thermal equil.

If $\mu_\delta > 0$, leptonize → Absorbs Neutrinos

If $\mu_\delta < 0$, neutronize → Neutrinos Emission

Inverse β-decay: $p^+ + e^- \longleftrightarrow n + \nu_e$

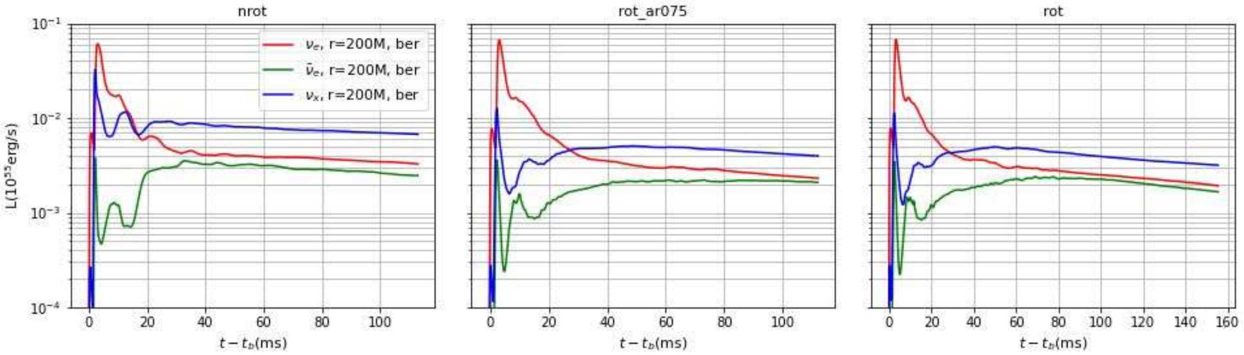
Weak reaction: $(A, Z) + e^- \longleftrightarrow (A, Z-1) + \nu_e$



Neutrino Luminosity : AIC vs CCSNe

1. AIC (at 100 ms)

   a. $L_{\nu_e} \approx 4 \times 10^{52} \mathrm{erg\,s^{-1}}$
   b. $L_{\bar{\nu}_e} \approx 3 \times 10^{52} \mathrm{erg\,s^{-1}}$
   c. $L_{\nu_x} \approx 7 \times 10^{52} \mathrm{erg\,s^{-1}}$
   d. O(1) correction due rotation



2. CCSNe at 100 ms (H. Nagakura et al.'21)

   a. $L_{\nu_e} \approx (4-8) \times 10^{52} \mathrm{erg\,s^{-1}}$
   b. $L_{\bar{\nu}_e} \approx (4-8) \times 10^{52} \mathrm{erg\,s^{-1}}$
   c. $L_{\nu_x} \approx (2.5-3.5) \times 10^{52} \mathrm{erg\,s^{-1}}$

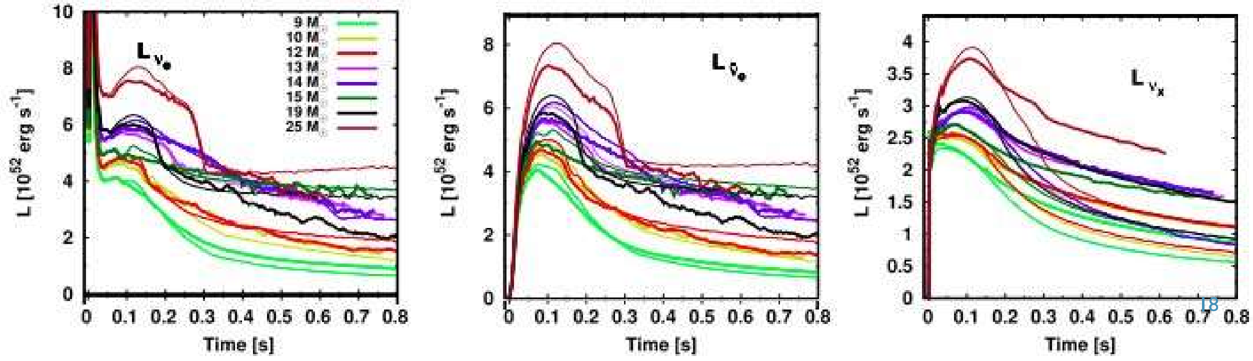
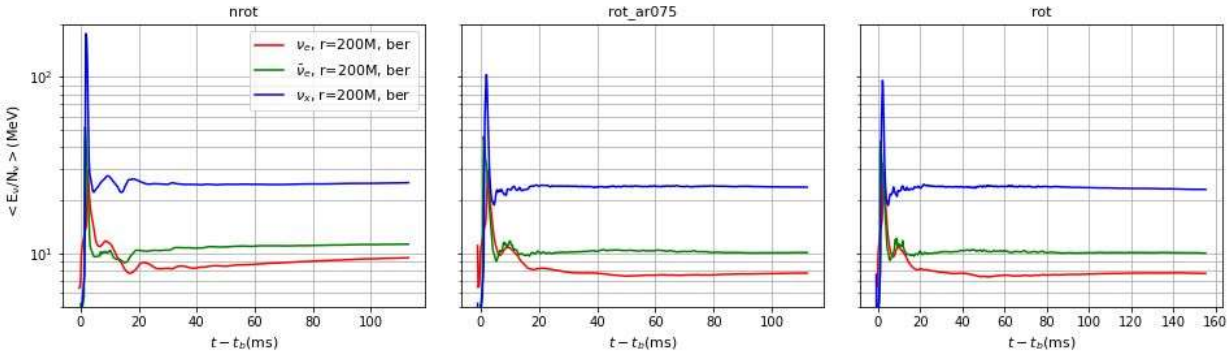


Image reproduced from H. Nagakura et al.'21

Neutrino Average Energy : AIC vs CCSNe

1. AIC (at 100 ms)
   - a. $\langle E/N \rangle_{\nu_e} \approx 9\mathrm{MeV}$
   - b. $\langle E/N \rangle_{\bar{\nu}_e} \approx 12\mathrm{MeV}$
   - c. $\langle E/N \rangle_{\nu_x} \approx 25\mathrm{MeV}$

2. CCSNe (at 100 ms)
   - a. $\langle E/N \rangle_{\nu_e} \approx 9\mathrm{Mev}$
   - b. $\langle E/N \rangle_{\bar{\nu}_e} \approx 12\mathrm{Mev}$
   - c. $\langle E/N \rangle_{\nu_x} \approx 15\mathrm{Mev}$



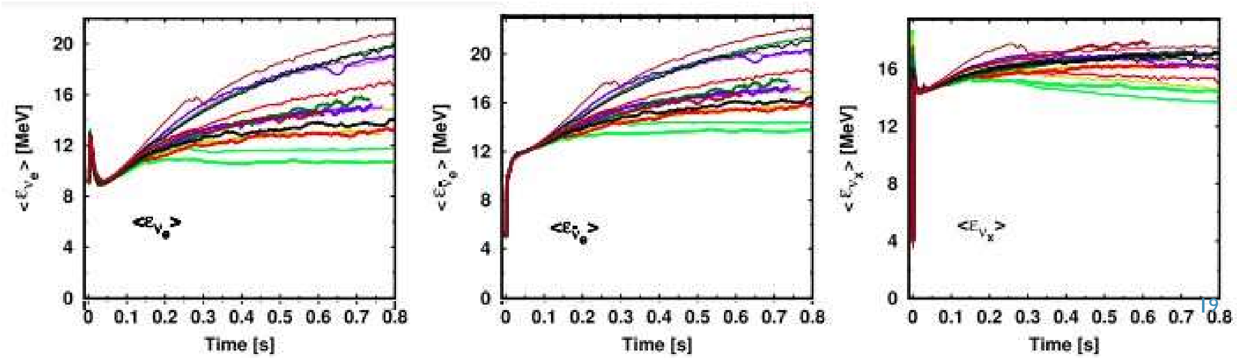
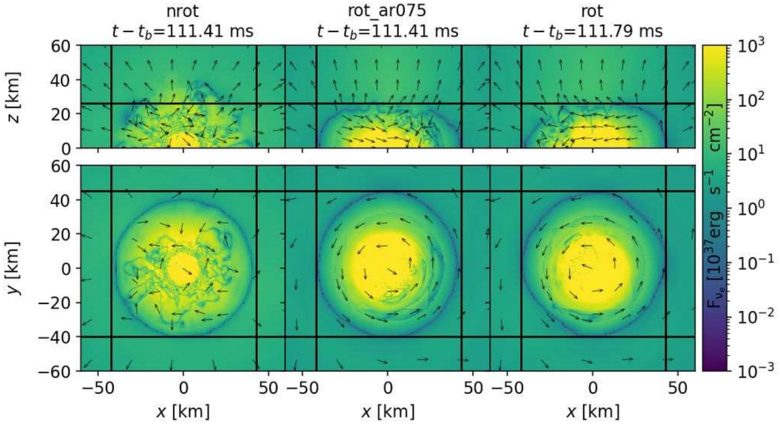


Image reproduced from H. Nagakura et al.'21

Neutrino emission

F_{ν_e}



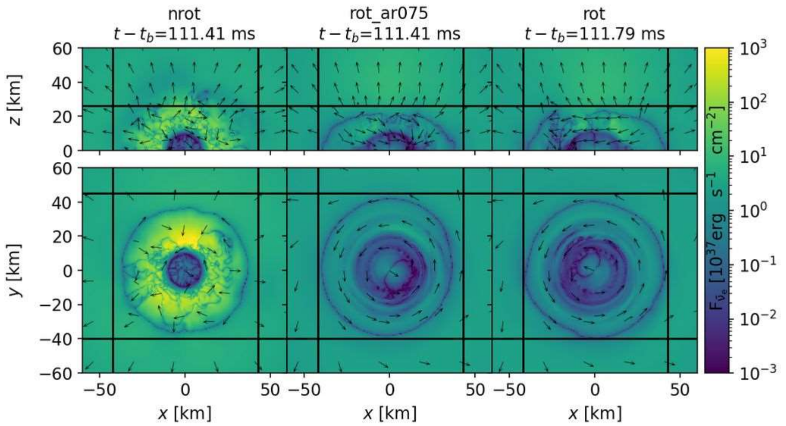
What can it tell us?

I. Flux $$F_{\nu_e} > F_{\bar{\nu}_e} > F_{\nu_x}$$

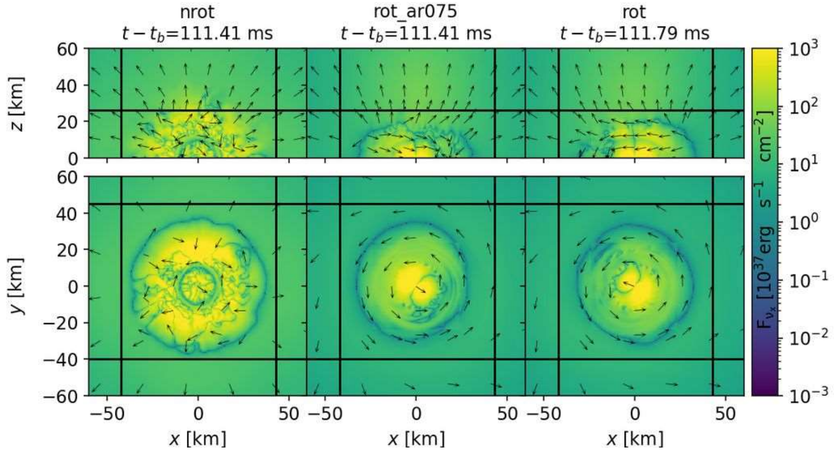
II. Thermal decoupling $$R_{\nu_e} > R_{\bar{\nu}_e} > R_{\nu_x}$$

III. Temperature $$T_{\nu_e} < T_{\bar{\nu}_e} < T_{\nu_x}$$

$F_{\bar{\nu}_e}$



F_{ν_x}



Ejecta Properties

I. Temperature:

Ejecta cools down as it expands

II. Entropy:

Roughly constant

O(1) adiabatic expansion

III. Ye:

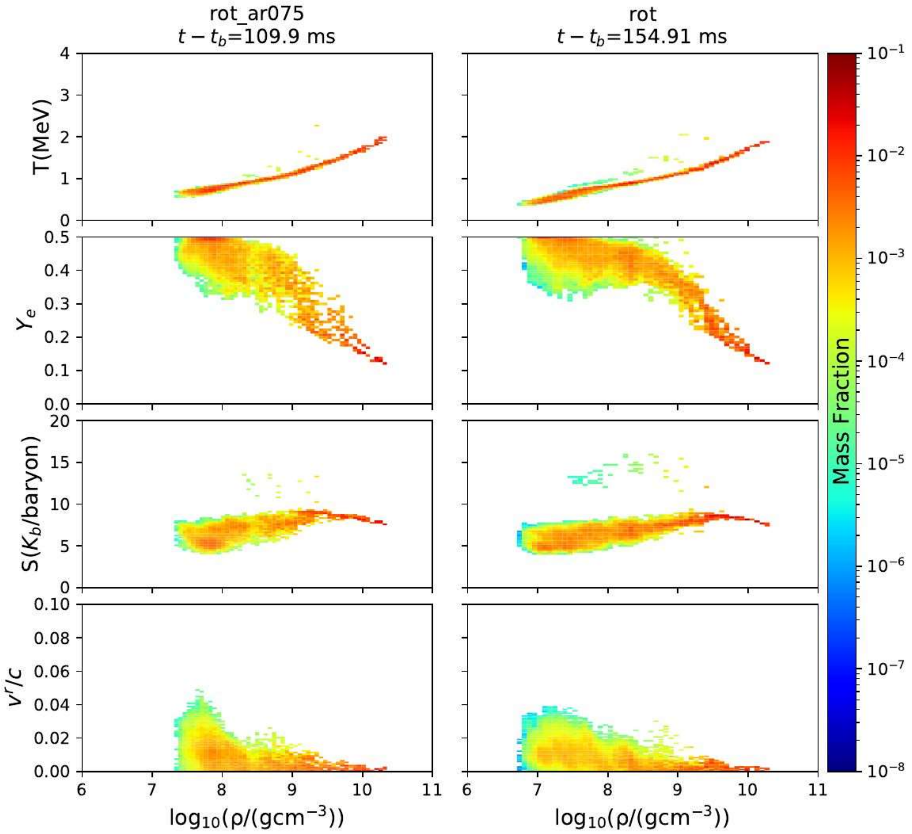
Ejecta with almost symmetric electron fraction (~0.46)

IV. Ejecta Mass:

No evidence of ejecta for the non-rotating case (stalled shock)

Around $M_{\mathrm{ej}} \approx 3 \times 10^{-2} M_{\odot}$ for both rotating models

Agreement with 1D models of Metzger et al. '09



Ejecta Energy

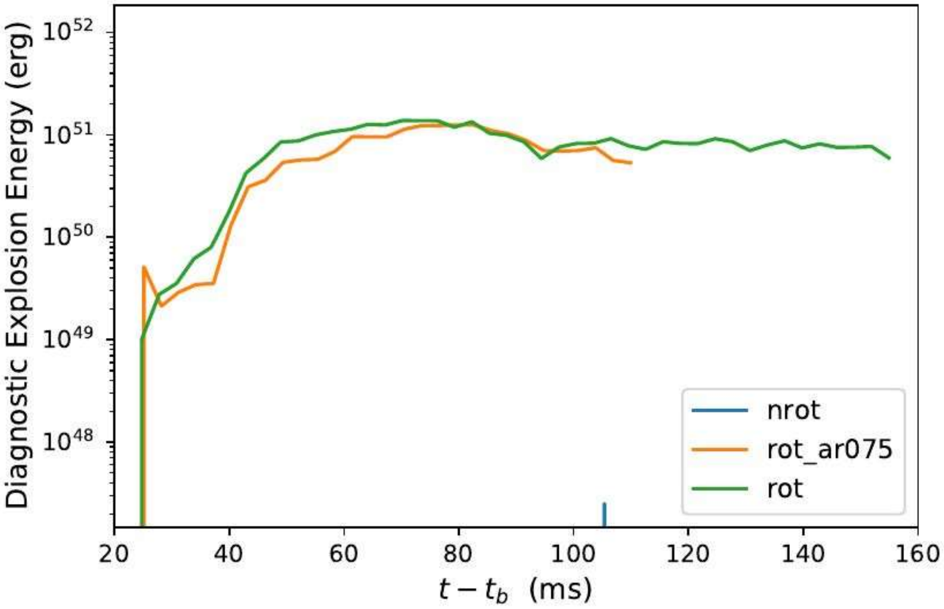
Relativistic energy :

$$E_{\mathrm{exp.}} = \int_V \left(\rho\varepsilon W^2 + \rho W(W-1) + P(W^2-1)\right)\sqrt{\gamma}dV$$

$$E_{\mathrm{exp.}} \sim 5.3 \times 10^{50} \text{ erg (rot\_ar075)}$$
$$E_{\mathrm{exp.}} \sim 5.9 \times 10^{50} \text{ erg (rot)}$$

Ejecta velocity :

$$v^r_\infty \sim (2E_{\mathrm{exp.}}/M_{\mathrm{ej.}})^{1/2}$$
$$\sim 0.14c$$



Electromagnetic Emission

Arnett's Law (Arnett'82): $L_{\mathrm{peak}} \sim \dot{Q}(t_{\mathrm{peak}})$

Peak Luminosity (Metzger '20):

$$L_{\mathrm{peak}} \approx 10^{41}\mathrm{erg\ s^{-1}}\left(\frac{\epsilon_{\mathrm{th,v}}}{0.5}\right)\left(\frac{M}{10^{-2}M_{\odot}}\right)^{0.35}\left(\frac{v}{0.1c}\,\frac{1\mathrm{cm^2g^{-1}}}{\kappa}\right)^{0.65}$$

Time of peak (Metzger '20):

$$t_{\mathrm{peak}} \approx 1.6\ \mathrm{days}\left(\frac{M}{10^{-2}M_{\odot}}\right)^{1/2}\left(\frac{v}{0.1c}\,\frac{1\mathrm{cm^2g^{-1}}}{\kappa}\right)^{-1/2}$$

Estimates for our models

$$L_{\mathrm{peak}} = 5.1\times10^{41}\ \mathrm{erg/s}\quad t_{\mathrm{peak}} = 1\ \mathrm{day}\ (\mathrm{rot\_ar075})$$

$$L_{\mathrm{peak}} = 5.5\times10^{41}\ \mathrm{erg/s}\quad t_{\mathrm{peak}} = 1.3\ \mathrm{days}\ (\mathrm{rot})$$

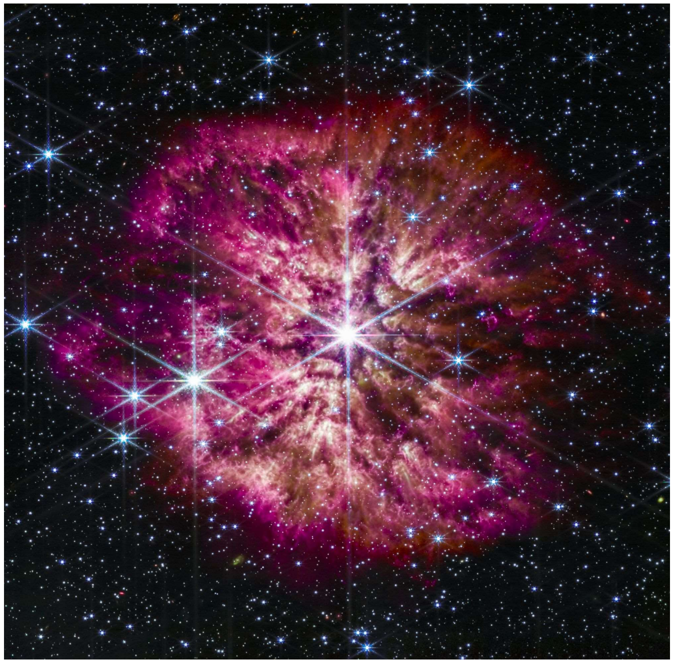


Image reproduced from www.nasa.gov
James Webb Space Telescope's image

Comparison against SNIa

$$L_{\text{ peak}} = 5.1 \times 10^{41}\ \text{erg/s} \quad t_{\text{peak}} = 1\ \text{day}\ (\text{rot\_ar075})$$

$$L_{\text{ peak}} = 5.5 \times 10^{41}\ \text{erg/s} \quad t_{\text{peak}} = 1.3\ \text{days}\ (\text{rot})$$

AIC are:

a. Faster evolving than SNIa: timescale of ~ weeks

b. Fainter than SNIa :

By 2 orders of magnitude

Mainly due a lower ejecta mass for SNIa

(K D Wilk et al.'18)

Not likely to be observed as far (but still far enough)

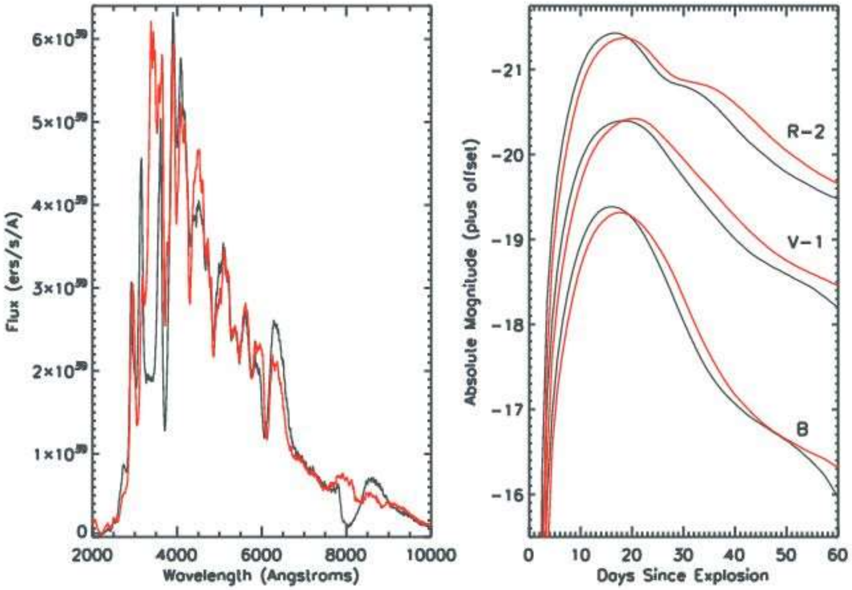


Image reproduced from Woosley et al.'07

Conclusions

Gravitational radiation:

- I. kHz band
- II. Dh ~ 500 cm
- III. Polarization
  - i. m=0 (prompt emission) linear
  - ii. m=2 (late emission) circular
- IV. Detectable up to D~10 Mpc in CE

Electromagnetic radiation:

- I. nrot ~ no ejecta mass ~ no EM emission
- II. rot_ar075 and rot:
  - i. L~5 x 10^{41} erg/s (~10^{2} x less than SNIa)
  - ii. time scale of few days (few weeks for SNIa)

Neutrino emission (~100ms after bounce):

- I. Neutrino luminosities ~ 4-7 x 10^{52} erg/s
- II. Average energy per neutrino ~9-25 Mev
- III. Slight suppression due to rotation
- IV. Comparable to CCSNe (H.Nagakura et al.'20)

UFABC

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FRIEDRICH-SCHILLER-
UNIVERSITÄT
JENA

Angular momentum imprints in the Multimessenger signals of Accretion Induced Collapse of White Dwarfs

FAPESP

erc European Research Council

THANK YOU!

Possible connection to GRBs & Future Work

Works such B. D. Metzger et al.'08 :

- I. AIC produces a protomagnetar and a disc of M ~0.1 M (t ~ 100 ms)
- II. Disc accretion, prompt EM emission (t ~ 0.1 − 1 s)
- III. Neutrino wind becomes ultra-relativistic (t~3-10s)
- IV. Protomagnetar spins down, X-ray emission (t ~ 10–100 s)

Realizable?

- I. sGRB+EE : such as GRB211211A

Future work:

- I.Inclusion of magnetic fields
- II.Jet formation (?)
- III. Light curves
- IV. Comparison against events like GRB211211A

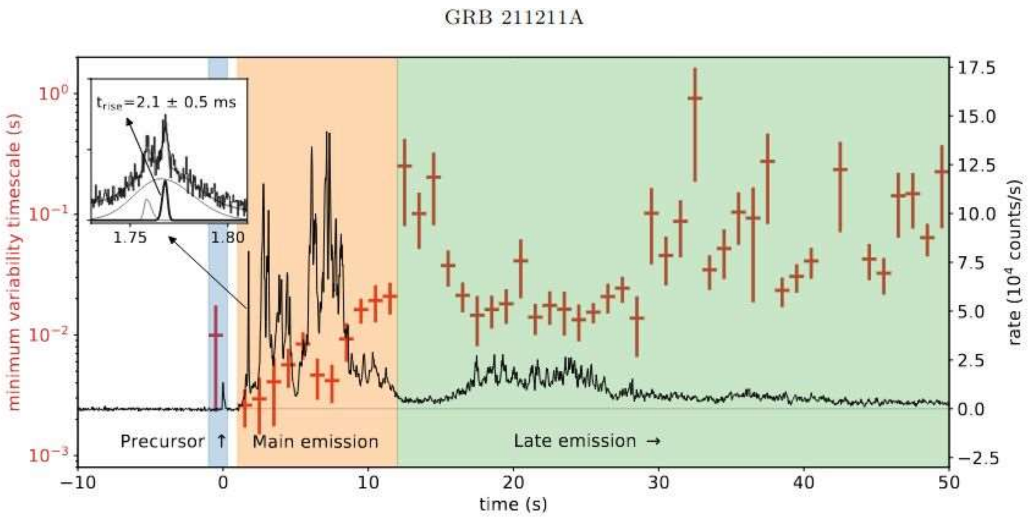
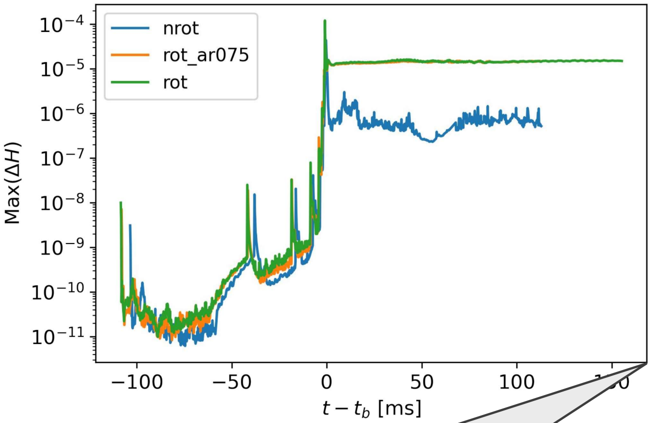


Image reproduced from
P.Veres et al 2023 ApJL 954 L5

Error Control



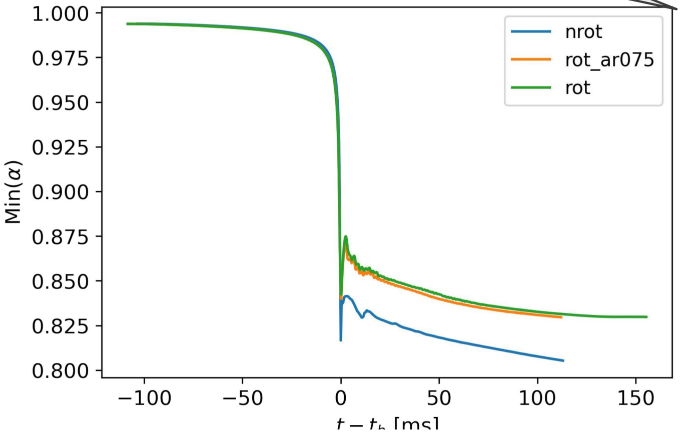
$$^{3\mathrm{D}}R + K^2 - K_{ij}K^{ij} = 16\pi E$$

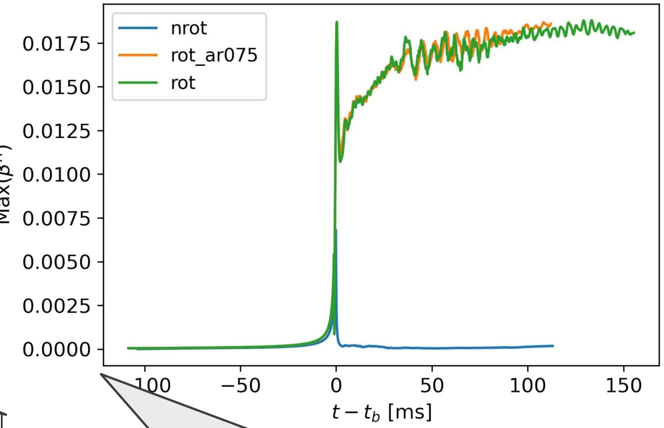
$$\Delta H = |^{3\mathrm{D}}R + K^2 - K_{ij}K^{ij} - 16\pi E|$$

$$g_{\mu\nu}dx^\mu dx^\nu = -\alpha^2 dt^2 + \gamma_{ij}(dx^i - \beta^i dt)(dx^j - \beta^j dt)$$

$$g_{\mu\nu}dx^\mu dx^\nu = -\left(1 - \frac{2GM}{c^2 r}\right)dt + \left(1 - \frac{2GM}{c^2 r}\right)^{-1}\gamma_{ij}dx^i dx^j$$

$$\alpha \sim 1 - \mathcal{O}(M/r)$$





$$g_{\mu\nu}dx^\mu dx^\nu = -\alpha^2 dt^2 + \gamma_{ij}(dx^i - \beta^i dt)(dx^j - \beta^j dt)$$

$$g_{\mu\nu}dx^\mu dx^\nu = -\left(1 - \frac{2GM}{c^2 r}\right)dt + \left(1 - \frac{2GM}{c^2 r}\right)^{-1}\gamma_{ij}dx^i dx^j$$

$$\beta^R \equiv \sqrt{(\beta^x)^2 + (\beta^y)^2 + (\beta^z)^2}$$