SPH simulations of the Induced Gravitational Collapse

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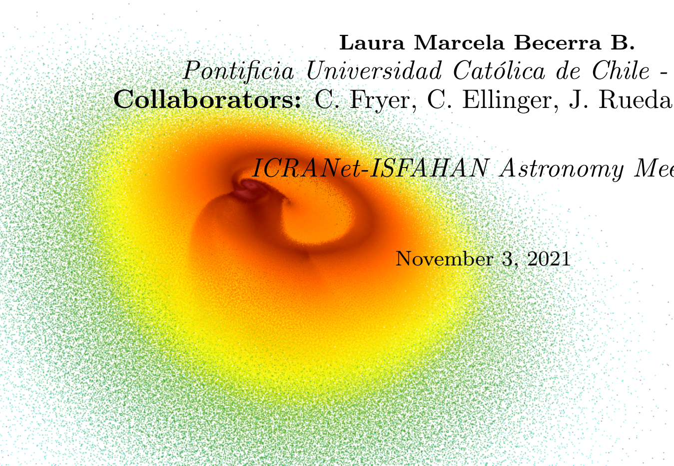
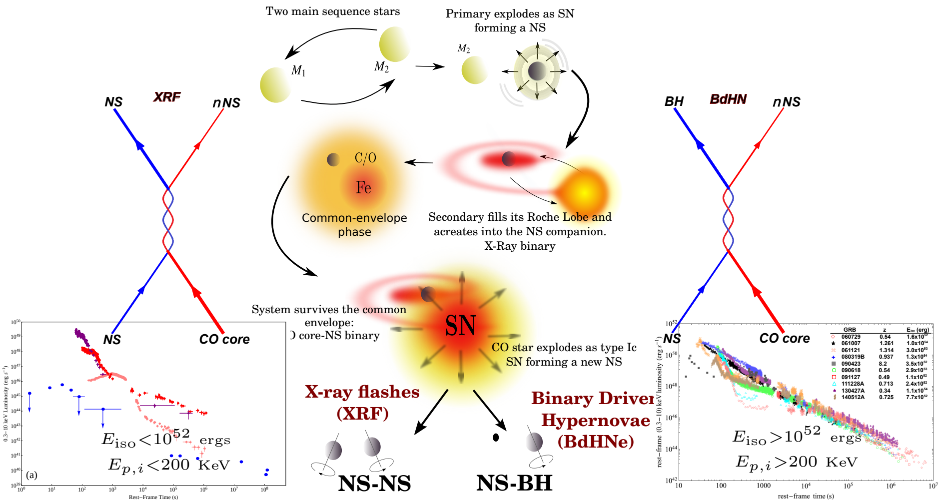


November 3, 2021

The Induced Gravitational Collapse (IGC)

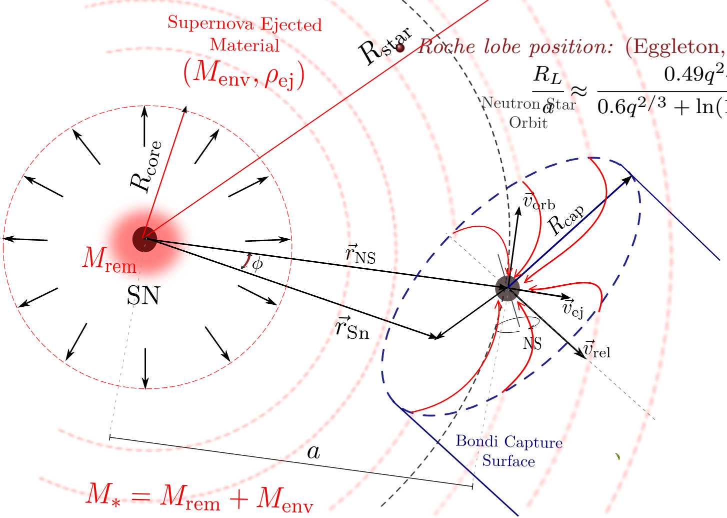
Ruffini, et. al, ApJ 2001, Rueda & Ruffini, ApJ 2012, Ruffini et al, ApJ 2016

Progenitor IGC model



Induced Gravitational Collapse IGC paradigm

What we want to simulate? Schematic Initial Conditions



- *Roche lobe position:* (Eggleton, 1983):

$$\frac{R_L}{a} \approx \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}$$

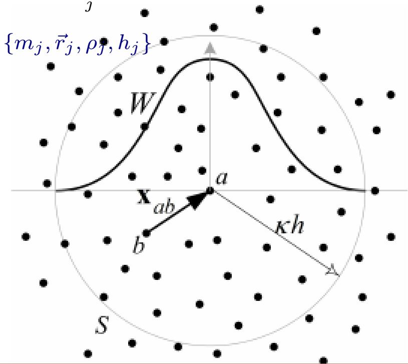
- *Orbital Velocity:* $v_{\rm orb} = \sqrt{\frac{GM_{\rm sys}}{a}}$

- *Binary Period:* $P_{\rm orb} = 2\pi\sqrt{\frac{a^3}{GM_{\rm sys}}}$

Smooth particle hydrodynamic (SPH) of the IGC scenario

SNSPH–Fryer et. al., ApJ 2006

$$\rho(r) = \sum_j^N m_j W(|\vec{r}_i - \vec{r}_j|, h_{ij})$$



Accretion algorithm:

The particle is accreted if:

- It is inside the star accretion radius:

$$|\vec{r}_j - \vec{r}_s| < R_{\rm j,acc} = \min\left(\xi \frac{2GM_s}{v_{js}^2 + c_j^2}\,,\, h_j\right)$$

- It is gravitational bounded to the star:

$$\frac{GM_s m_j}{|\vec{r}_j - \vec{r}_s|} > \frac{1}{2} m_j |\vec{v}_j - \vec{v}_s|^2$$

- It isn't circularizing:

$$|(\vec{r}_j - \vec{r}_s) \times (\vec{v}_j - \vec{v}_s)| < \sqrt{GM_s R_{\rm j,acc}}$$

$$\frac{d\vec{v}_i}{dt} = -\sum_{j=1}^N m_j \left(\frac{P_i}{\rho_i^2} + \frac{P_j}{\rho_j^2} + \Pi_{ij}\right) \vec{\nabla}_i W(r, h_{ij})$$

$$\frac{du_i}{dt} = \sum_{j=1}^N m_j \left(\frac{P_i}{\rho_i^2} + \frac{1}{2}\Pi_{ij}\right) (\vec{v}_i - \vec{v}_j) \vec{\nabla} W(r, h_{ij})$$

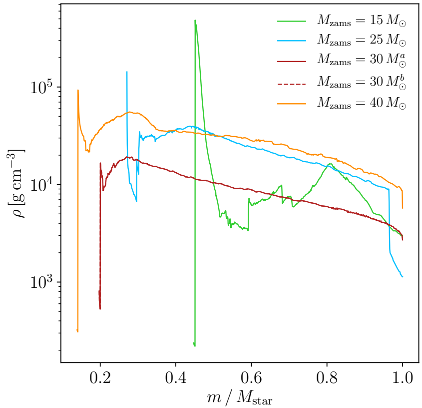
$$M_{\rm s,new} = M_{\rm s} + \sum_j m_j$$

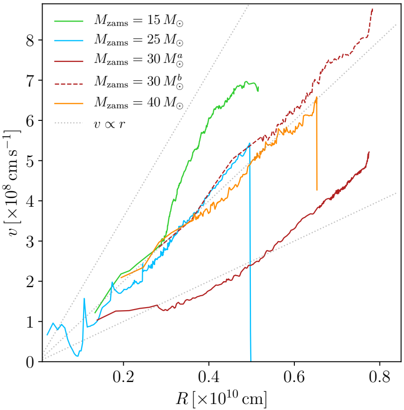
$$\vec{p}_{\rm s,new} = M_s \vec{v}_s + \sum_j m_j \vec{v}_j$$

$$\frac{L_{\rm s,new}}{M_{\rm s,new}} = \frac{L_s \vec{v}_s + \sum_j m_j (\vec{r}_{s,j} \times \vec{v}_{s,j})}{M_{\rm s}}$$

SPH-Initial set up

1D core-collapse code: Fryer et. al ,ApJ 1999

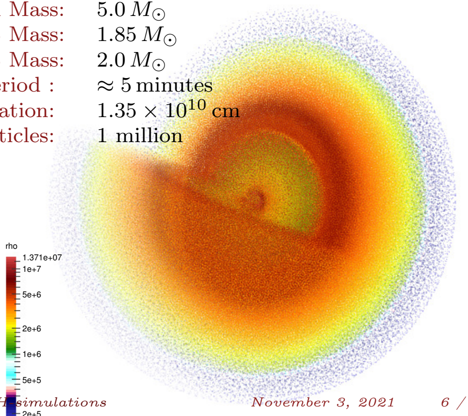




$M_{\rm ZAMS}$ $M_\odot$	$M_{\rm rem}$ $M_\odot$	$M_{\rm ej}$ $M_\odot$	$R_{\rm core}$ 10^8 cm	$R_{\rm star}$ 10^9 cm	$E_{\rm grav}$ 10^{51} erg	m_j $10^{-6}\,M_\odot$
15	1.30	1.606	8.648	5.156	0.2149	0.2 – 4.4
25	1.85	4.995	2.141	5.855	1.5797	2.2 – 11.4
30^a	1.75	7.140	28.33	7.751	1.7916	1.9 – 58.9
30^b	1.75	7.140	13.84	7.830	1.5131	1.9 – 58.9
40	1.85	11.50	19.47	6.529	4.4305	2.3 – 72.3

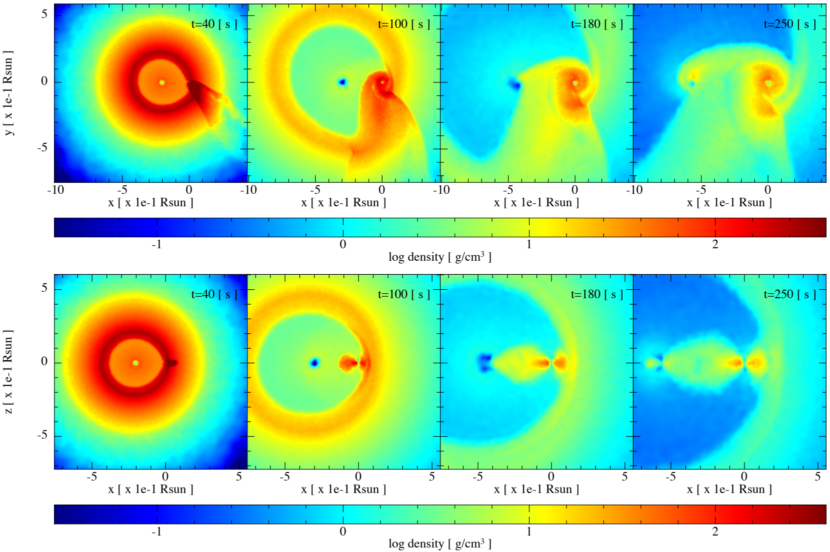
SPH Simulations I

CO_{core} Progenitor (M_{zams}):	$25\,M_\odot$
Total energy:	1.57×10^{51} ergs
Ejected Mass:	$5.0\,M_\odot$
ν-NS Mass:	$1.85\,M_\odot$
NS Mass:	$2.0\,M_\odot$
Orbital Period :	≈ 5 minutes
Orbital Separation:	1.35×10^{10} cm
Number of particles:	1 million



Snapshots IGC scenario

L. Becerra, C. Ellinger, C. Fryer, R. Rueda and R. Ruffini, ApJ 871, 2019



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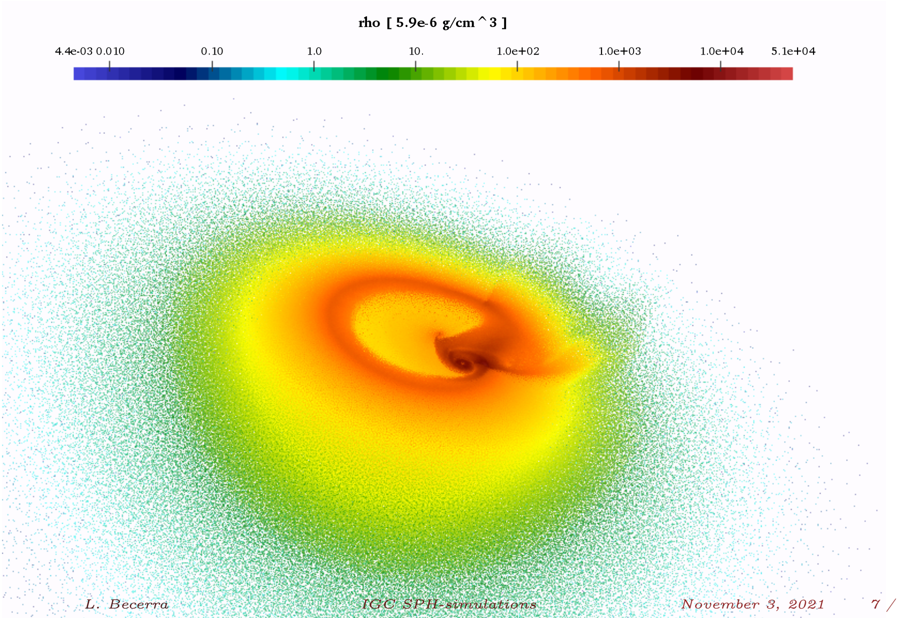

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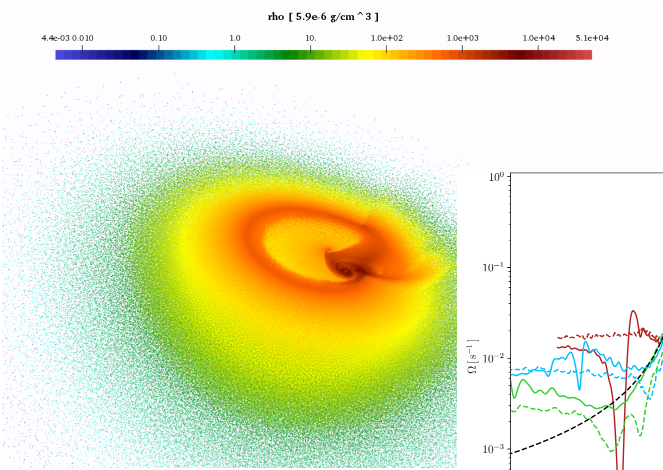
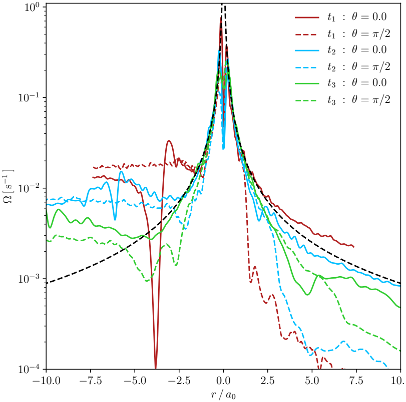
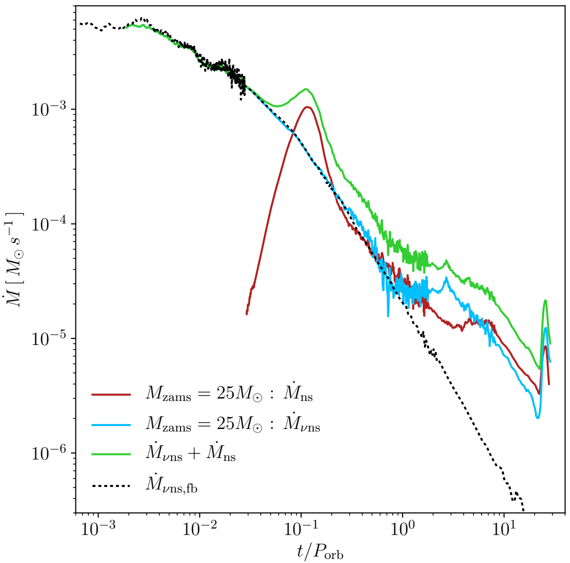




Mass Accretion Rate on the ν-NS and the NS companion



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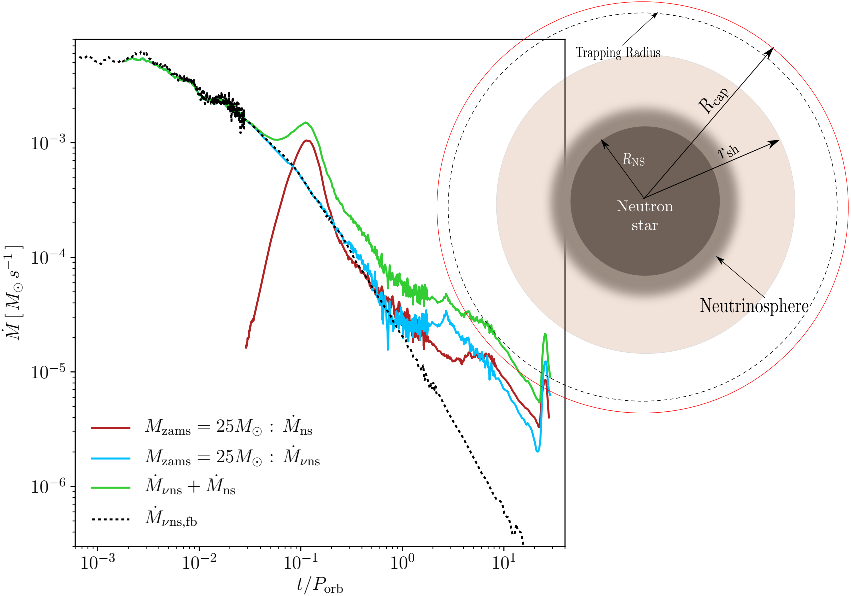
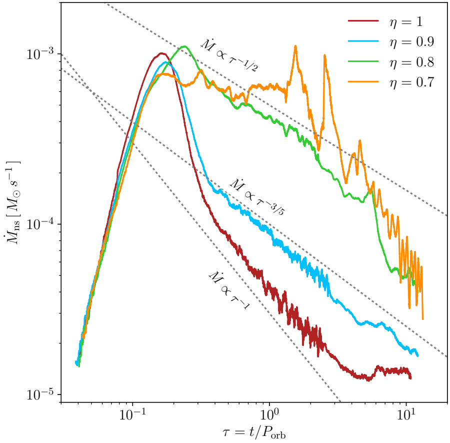


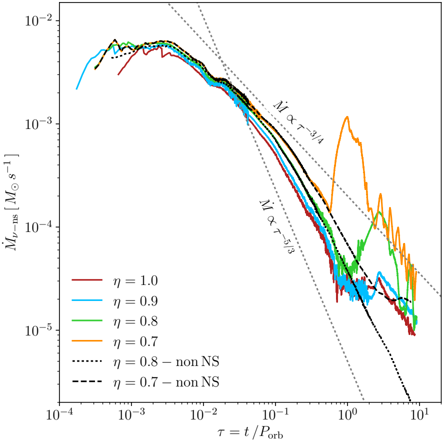
Changing the SN energy

L. Becerra et al, ApJ 871,2019

NS companion
mass accration rate



ν-NS
Mass accration rate



Changing the SN energy

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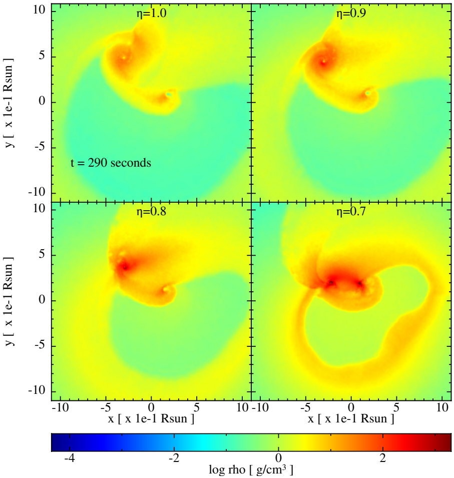
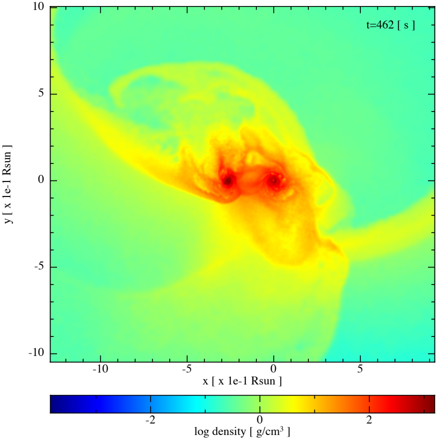
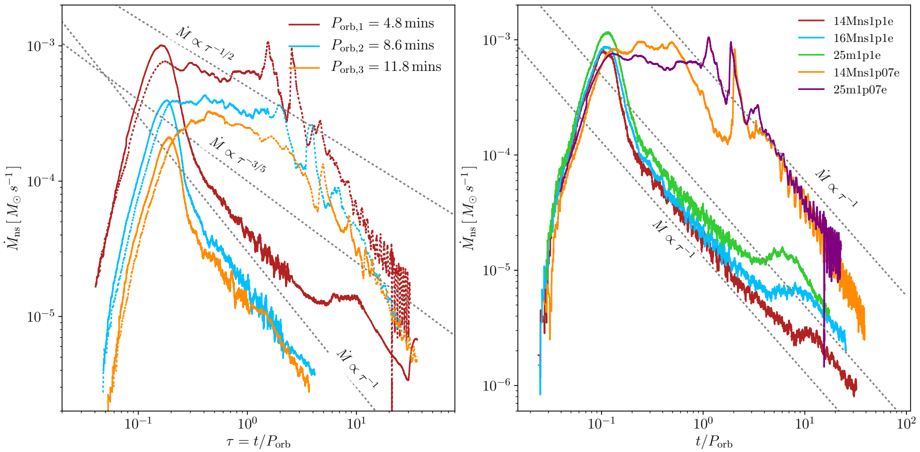




Changing the Orbital Period and NS initial mass

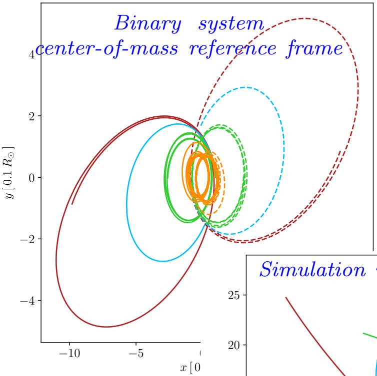
Mass Accretion rate

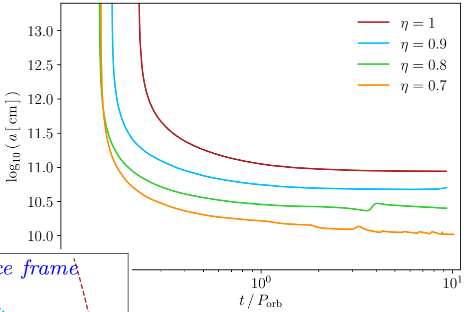


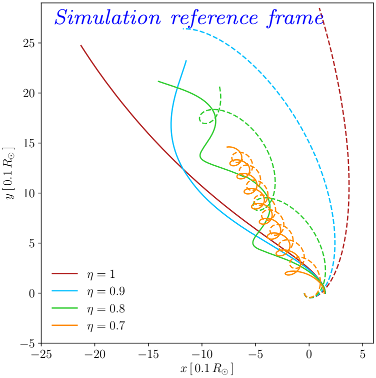
L. Becerra et al, ApJ 2019

Binary System fate

Motion of the binary stars (L. Becerra et al, ApJ 871, 2018)







If the mass is lost instantaneously (Hills, 1983):

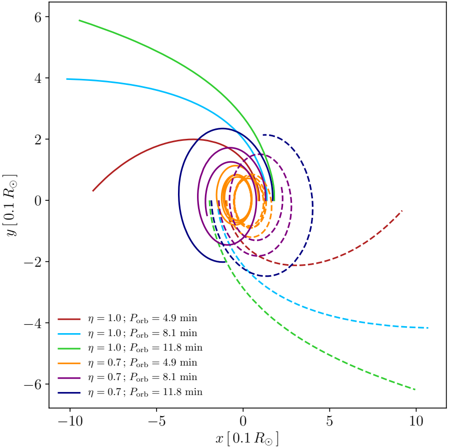
$$\frac{a}{a_0} = \frac{M_0 - \Delta M}{M_0 - 2a_0\Delta M/r}$$

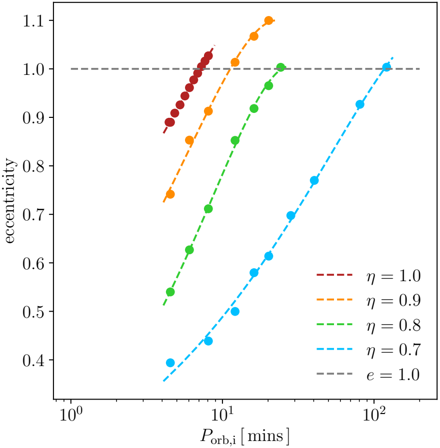
M_0: total mass
ΔM: mass ejected

Binary System fate

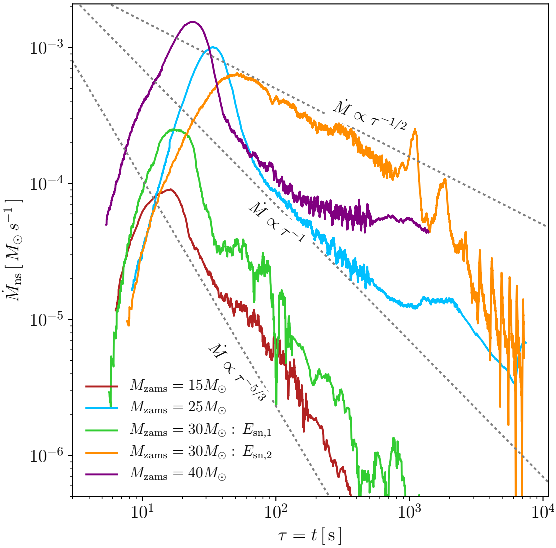
Motion of the binary stars (L. Becerra et al, ApJ 871, 2018)

Binary system center-of-mass reference frame

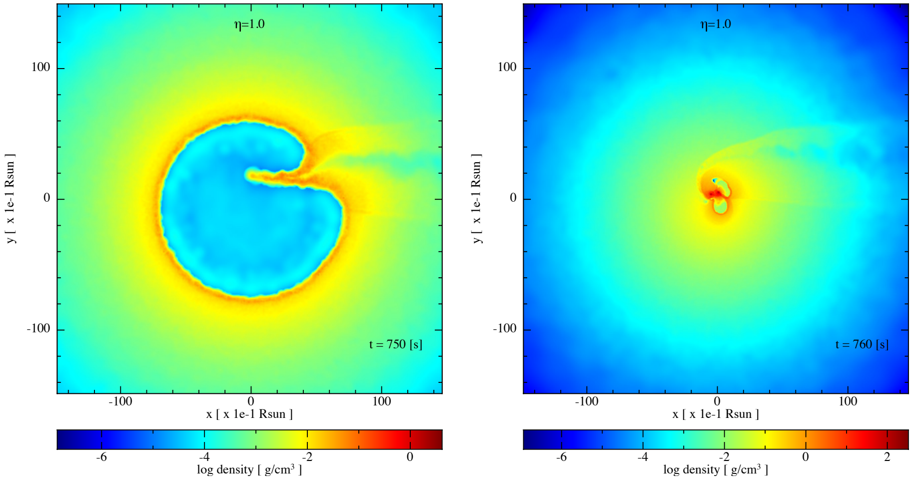




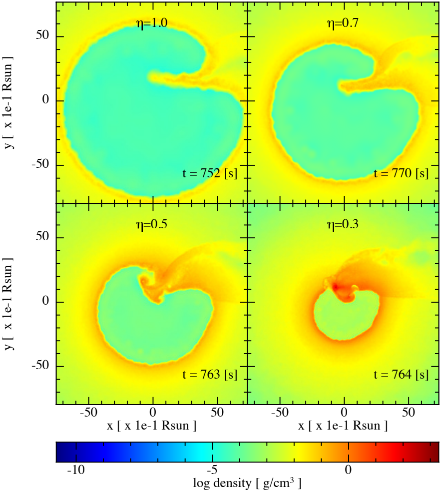
Changing the $CO_{\rm core}$ progenitor

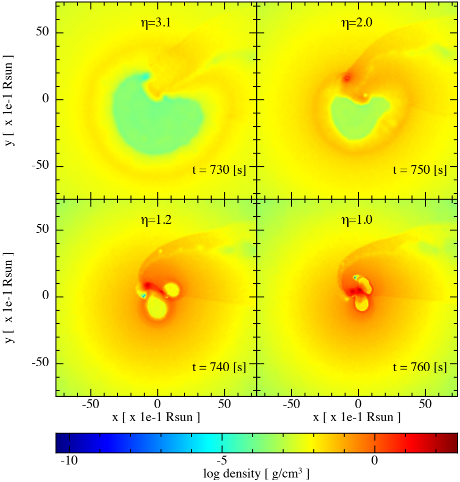


Snapshots surface density: CO$_{\rm core}$ *with* $M_{\rm zams} = 30\, M_\odot$



Snapshots surface density: CO_{core} *with* $M_{\text{zams}} = 30\, M_\odot$





NS critical mass and gravitational collapse

Rotating NS configurations - F. Cipolletta et al, Phys. D. 2015

The evolution of the NS gravitational mass is given by:

$$\dot{M}_{\rm NS} = \frac{\partial M_{\rm NS}}{\partial M_b}\dot{M}_B + \frac{\partial M_{\rm NS}}{\partial J_{\rm NS}}\dot{J}_{\rm NS} \qquad (1)$$

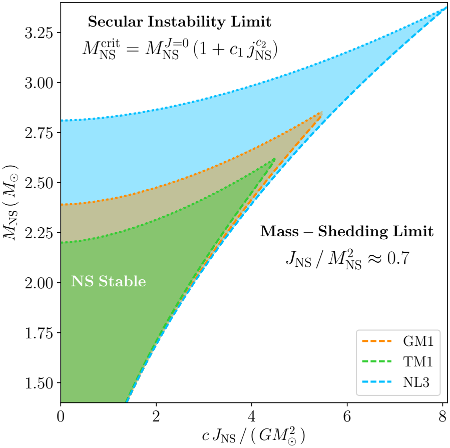
$$\frac{M_b}{M_\odot} = \frac{M_{\rm NS}}{M_\odot} + \frac{13}{200}\left(\frac{M_{\rm NS}}{M_\odot}\right)^2\left(1 + \frac{j_{\rm NS}^{1.7}}{137}\right)$$

$$l_{\rm lso} = 2\sqrt{3}\frac{GM_{\rm NS}}{c}\left[1 - \frac{1}{10}\left(\frac{j_{\rm NS}}{M_{\rm NS}}\right)^{0.85}\right]$$

We assume:

$$\frac{dJ_{\rm NS}}{dt} = \xi\, l(R_{\rm in})\frac{dM_{\rm b}}{dt}$$

where $\xi < 1$ is a parameter that accounts for the efficiency of the angular momentum transfer.



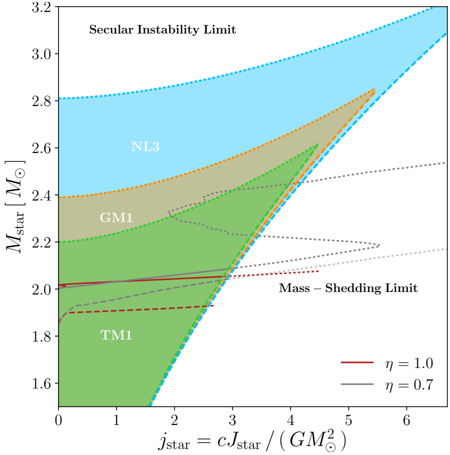
NS critical mass and gravitational collapse

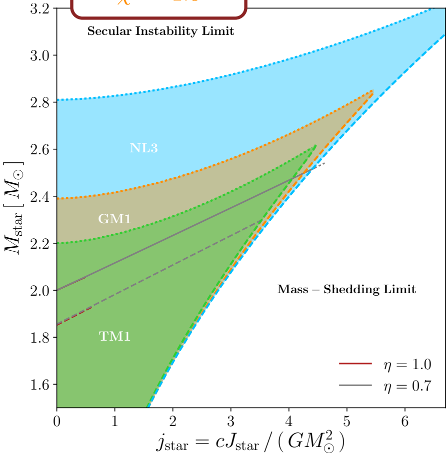
L. Becerra et al., ApJ 871, 2018

$$\dot{M}_{\rm NS} = \frac{\partial M_{\rm NS}}{\partial M_b}\dot{M}_B + \frac{\partial M_{\rm NS}}{\partial J_{\rm NS}}\dot{J}_{\rm NS}$$

$$\frac{dJ_{\rm NS}}{dt} = \chi\, l(R_{\rm in})\frac{dM_{\rm b}}{dt}$$

$\chi = 1.0$

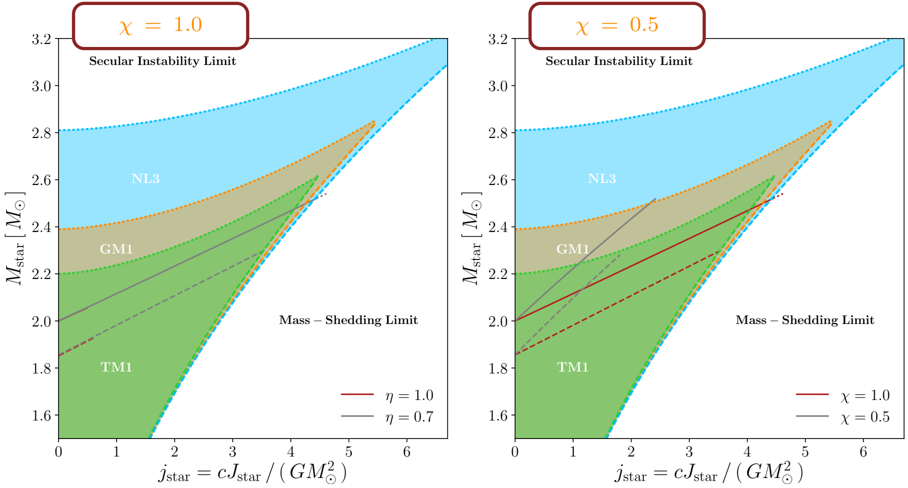




NS critical mass and gravitational collapse

L. Becerra et al., ApJ 871, 2018

$$\frac{dJ_{\rm NS}}{dt} = \chi\, l(R_{\rm in}) \frac{dM_{\rm b}}{dt}$$



NS critical mass and gravitational collapse

L. Becerra et al., ApJ 871, 2018

$$\frac{dJ_{\rm NS}}{dt} = \chi\, l(R_{\rm in}) \frac{dM_{\rm b}}{dt}$$

$\chi = 1.0$

$\chi = 0.5$

				νNS					
				$\chi = 0.5$			$\chi = 1.0$		
$CO_{\rm core}$	η	$P_{\rm orb}$	$L_{\rm tot}$ $c/(GM_\odot^2)$	$M_{\nu{\rm NS}}$ $M_\odot$	$j_{\nu{\rm NS}}$ $c/(GM_\odot^2)$	Fate	$M_{\nu{\rm NS}}$ $M_\odot$	$j_{\nu{\rm NS}}$ $c/(GM_\odot^2)$	Fate
$25M_\odot$	1.0	1.0	3.469	1.931	0.321	Stb	1.933	0.627	Stb
	1.0	2.0	1.779	1.912	0.242	Stb	1.914	0.472	Stb
	1.0	3.0	1.085	1.912	0.229	Stb	1.912	0.399	Stb
	0.9	1.0	6.243	1.982	0.513	Stb	1.983	1.010	Stb
	0.8	1.0	7.331	2.038	1.449	Stb	2.031	1.365	Stb
	0.7	1.0	18.146	2.284	1.826	Stb	2.289	3.434	Stb
	0.7	1.0	19.51	2.250	1.663	Stb	2.265	3.215	Stb
	0.7	1.0	21.34	2.214	1.476	Stb	2.226	2.812	Stb

NS critical mass and gravitational collapse

L. Becerra et al., ApJ 871, 2018

$$\frac{dJ_{\rm NS}}{dt} = \chi\, l(R_{\rm in}) \frac{dM_{\rm b}}{dt}$$

$\chi = 1.0$ $\chi = 0.5$

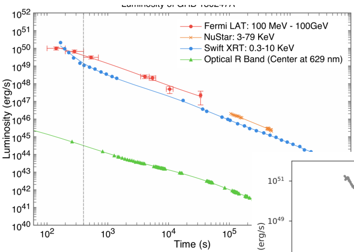
				NS					
				$\chi = 0.5$			$\chi = 1.0$		
$CO_{\rm core}$	η	$P_{\rm orb}$	$L_{\rm tot}$ $c/(GM_\odot^2)$	$M_{\rm NS}$ $M_\odot$	$j_{\rm NS}$ $c/(GM_\odot^2)$	Fate	$M_{\rm NS}$ $M_\odot$	$j_{\rm NS}$ $c/(GM_\odot^2)$	Fate
$25M_\odot$	1.0	1.0	4.746	2.055	0.247	Stb	2.056	0.497	Stb
	1.0	2.0	1.927	2.022	0.099	Stb	2.022	0.198	Stb
	1.0	3.0	1.944	2.018	0.0813	Stb	2.019	0.1639	Stb
	0.9	1.0	6.538	2.127	0.584	Stb	2.129	1.187	Stb
	0.8	1.0	9.870	2.258	1.242	**Sc-in**	2.348	3.576	Stb
	0.7	1.0	8.491	2.246	1.105	**Sc-in**	2.528	4.506	**M-sh**
	0.7	2.0	9.908	2.252	1.135	**Sc-in**	2.426	3.648	Stb
	0.7	3.0	17.292	2.004	2.246	**Sc-in**	2.425	3.638	Stb

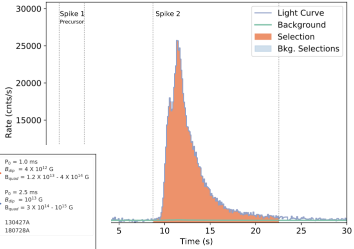
Consequences on GRB analysis

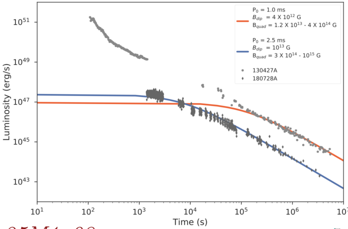
Y. Wang, J. Rueda, et al, ApJ 874, 2019

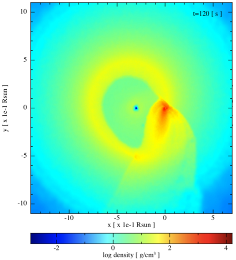
GRB 180728A/SN 2018fip

GRB 130427A/SN 2013cq







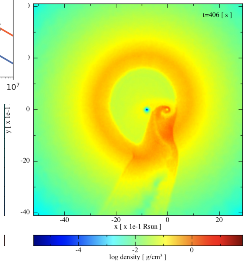


25M1p08e

$P_{\rm orb} = 4.8$ min

25M3p1e

$P_{\rm orb} = 11.8$ min



THANK YOU