Formación de sistemas binarios compactos en el modelo de hipernova impulsada por binarias (BdHN).

Laura Marcela Becerra B.

Universidad Industrial de Santander (UIS)

Colaboración ICRANet (International Center for Relativistic Astrophysics Network)

Y. Aimuratov, C. L. Bianco, C. Fryer, M. Karlica, D. Melon, R. Moradi, D. Primorac, J. F. Rodriguez, J. A. Rueda, R. Ruffini, N. Sahakyan, J. D. Uribe, Y. Wang

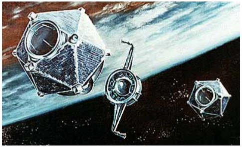
Seminarios GIRG

Colombia

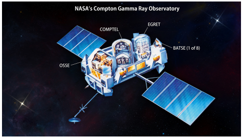
February 26, 2024

Gamma Ray Burst (GRBs)

The most energetic events



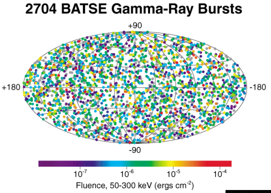
1960s: Vela Satellite

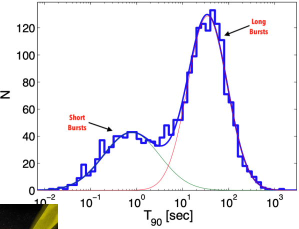


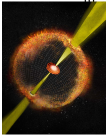
1991: Compton Gamma Rays Observatory (CGRO)

1996: Beppo-Sax

- Isotropic distribution
- Bimodal distribution
- Afterglow emission
- GRB-SNe Ic connection (The SNe show similar properties independent of the GRB)







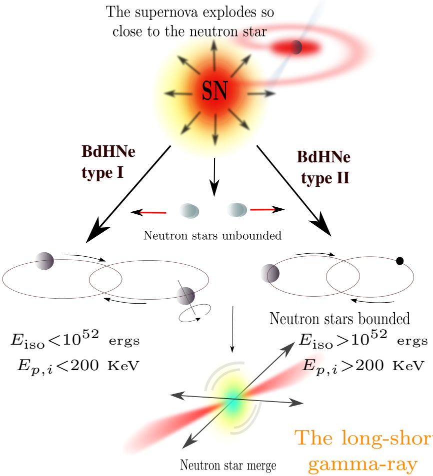
Collapsar Model

Core-collapse of a single, massive, fast-rotating star

The Induced Gravitational Collapse (IGC)

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

Progenitor



The long-short gamma-ray burst connection

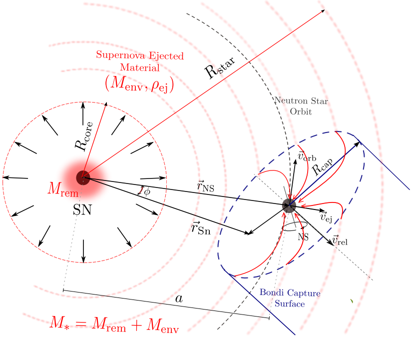
- GRB-SN events are related to massive star explosions, and most massive stars belong to binaries
- The models of SNe Ic show they are more plausibly explained via binary interactions to aid the pre-SN hydrogen and helium layers ejection.
- Direct formation of a BH may occur only in the evolved cores of zero-age main-sequence (ZAMS) stars above $25M_\odot$, and without an SN.

Smooth particle hydrodynamic (SPH) of the IGC scenario

SNSPH–Fryer et. al., ApJ 2006

What we want to simulate?
Schematic Initial Conditions

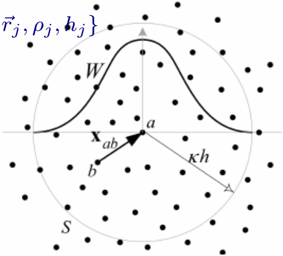
L. Becerra, et. al., ApJ 2015,
L. Becerra et. al., ApJ 2016



Parameter space:
(CO, $E_{\rm sn}$, $M_{\rm ns}$, $P_{\rm orb}$)

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

$\{m_j, \vec{r}_j, \rho_j, h_j\}$



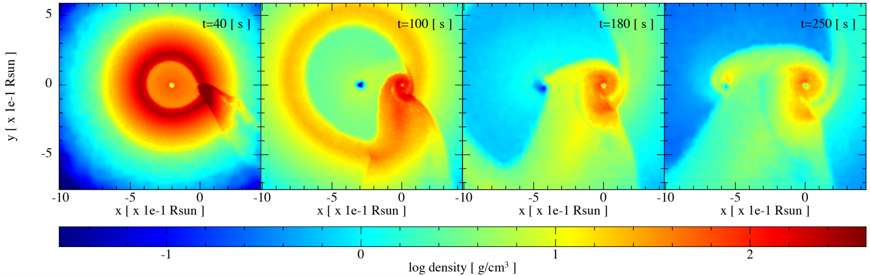
Accretion algorithm:

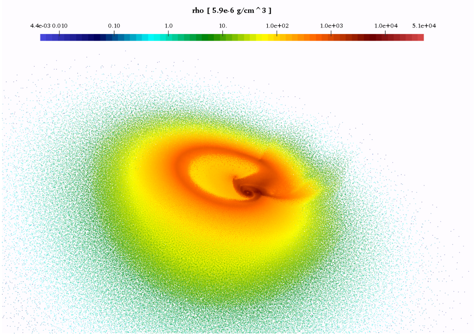
A particle is accreted by a point mass, if:

- It is inside the star accretion radius
- It is gravitational bounded to the star
- It isn't circularizing.

Smooth particle hydrodynamic (SPH) of the IGC scenario

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





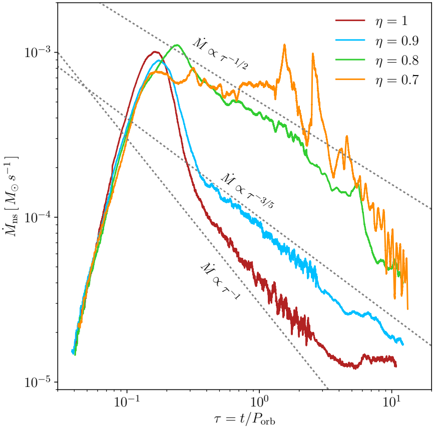
Canonical Simulation

CO Progenitor ($M_{\rm zams}$):	$25\,M_\odot$
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

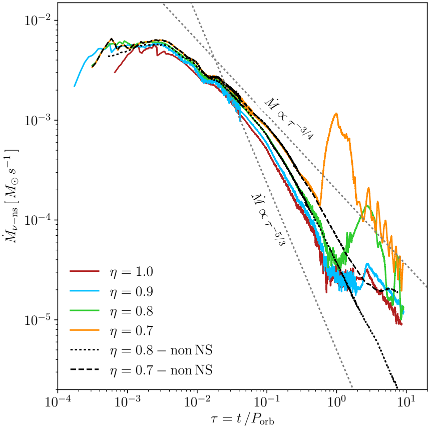
Mass Accretion Rate on the νNS and the NS companion

SN Energy and Initial Binary Period (L. Becerra et al, ApJ 871,2019)

NS-companion



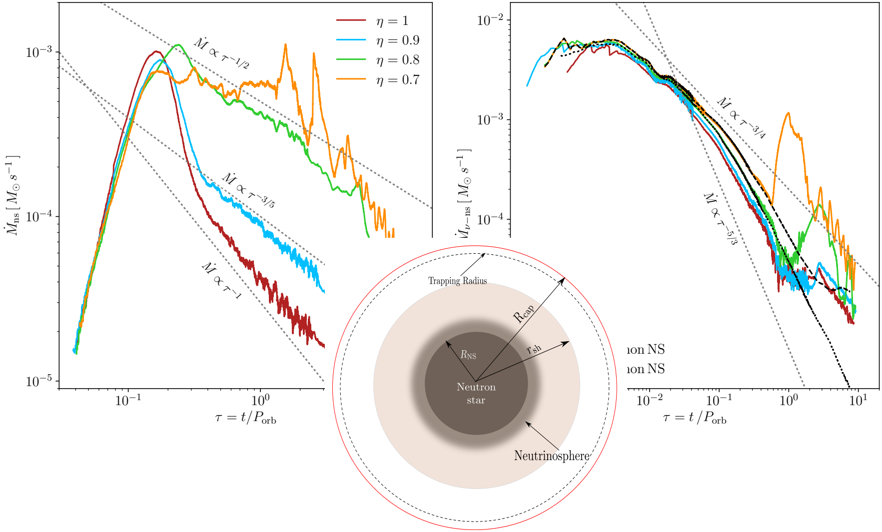
νNS



Mass Accretion Rate on the νNS and the NS companion

SN Energy and Initial Binary Period (L. Becerra et al, ApJ 871,2019)

NS-companion | **νNS**



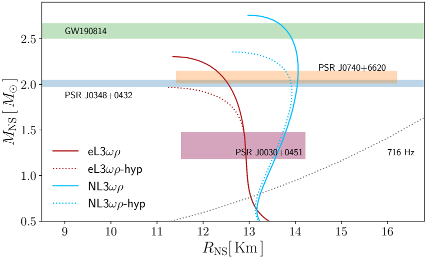
NS critical mass and gravitational collapse

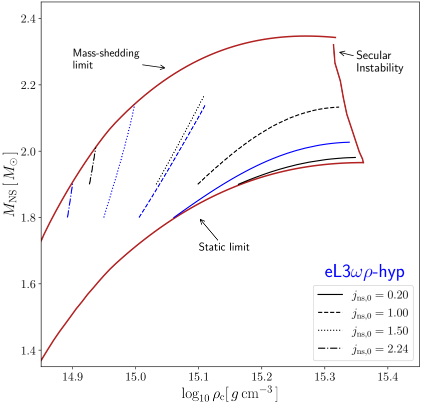
Rotating NS configurations - RNS Code (L. Becerra et al., ApJ 871, 2018, L. Becerra et al., in prep.)

The evolution of the NS gravitational mass and angular momentum is:

$$\frac{dJ_{\rm NS}}{dt} = \chi\, l(R_{\rm in}) \frac{dM_{\rm b}}{dt} + \tau_{\rm mag} \qquad (1)$$

$$l = \begin{cases} l_{\rm isco}, & \text{if } R_{\rm in} \geq R_{\rm ns} \\ \Omega\, R_{\rm ns}^2, & \text{if } R_{\rm in} < R_{\rm ns} \end{cases} \qquad (2)$$





The NSs could have different fates.

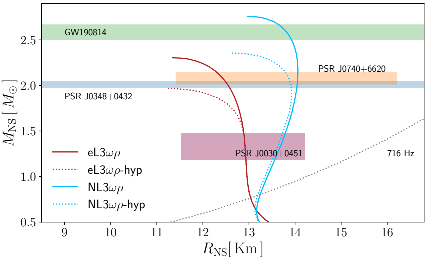
NS critical mass and gravitational collapse

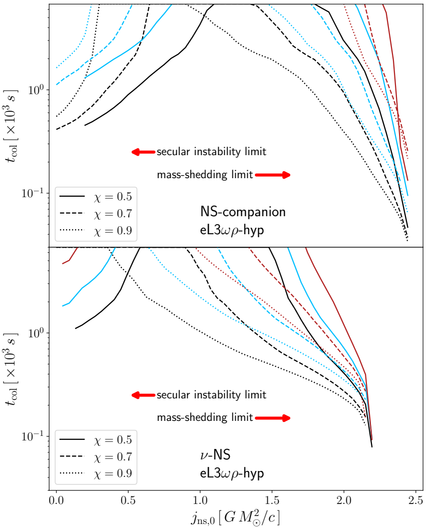
Rotating NS configurations - RNS Code (L. Becerra et al., ApJ 871, 2018, L. Becerra et al., in prep.)

The evolution of the NS gravitational mass and angular momentum is:

$$\frac{dJ_{\rm NS}}{dt} = \chi\, l(R_{\rm in})\frac{dM_{\rm b}}{dt} + \tau_{\rm mag} \qquad (1)$$

$$l = \begin{cases} l_{\rm isco}, & \text{if } R_{\rm in} \geq R_{\rm ns} \\ \Omega\, R_{\rm ns}^2, & \text{if } R_{\rm in} < R_{\rm ns} \end{cases} \qquad (2)$$





Observables in the GRB data

Y. Wang, et al 2019, R. Morandi et. al. 2021, Rueda, et. al. 2022,L. Becerra et al., 2022

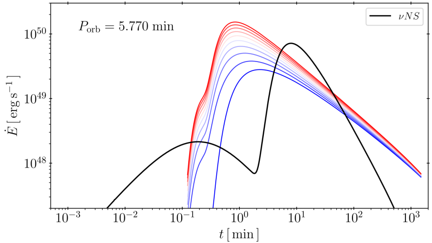
Physical phenomenon	BdHN type	GRB observable				
		νNS-rise (soft-hard X-rays)	UPE (MeV)	GeV emission	SXFs HXFs	Afterglow (X/optical/radio)
Early SN emission	I, II, III	⊗				
Hypercritical accretion onto νNS	I, II, III	⊗				
Hypercritical accretion onto NS	I, II	⊗				
BH formation from NS collapse	I			⊗		
Transparency of e^+e^- (from vacuum polarization) with low baryon load region	I		⊗			
Synchrotron radiation *inner engine*: BH + B-field+SN ejecta	I			⊗		
Transparency of e^+e^- (from vacuum polarization) with high baryon load	I				⊗	
Synchrotron emission from SN ejecta with energy injection from νNS	I, II, III					⊗
Pulsar-like emission from νNS	I, II, III					⊗

Observables in the GRB data

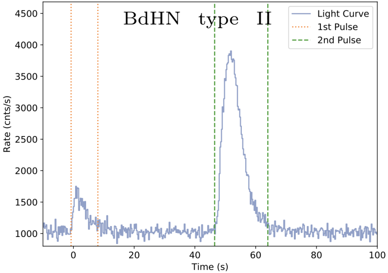
Y. Wang, et al 2019, R. Morandi et. al. 2021, Rueda, et. al. 2022,L. Becerra et al., 2022

Physical phenomenon	BdHN type	GRB observable				
		νNS-rise (soft-hard X-rays)	UPE (MeV)	GeV emission	SXFs HXFs	Afterglow (X/optical/radio)
Early SN emission	I, II, III	$\otimes$				
Hypercritical accretion onto νNS	I, II, III	$\otimes$				
Hypercritical accretion onto NS	I, II	$\otimes$				
BH formation from NS collapse	I			$\otimes$		
Transparency of e^+e^- (from vacuum polarization) with low baryon load region	I		$\otimes$			
Synchrotron radiation *inner engine*: BH + B-field+SN ejecta	I			$\otimes$		
Transparency of e^+e^- (from vacuum polarization) with high baryon load	I				$\otimes$	
Synchrotron emission from SN ejecta with energy injection from νNS	I, II, III					$\otimes$
Pulsar-like emission from νNS	I, II, III					$\otimes$

Accretion: $\dot{E} = \Omega \dot{J}$



GRB 190829A

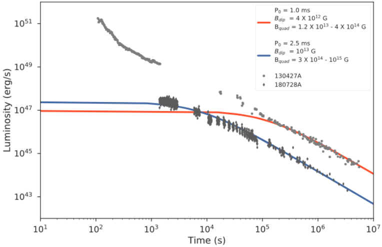


Observables in the GRB data

Y. Wang, et al 2019, R. Morandi et. al. 2021, Rueda, et. al. 2022,L. Becerra et al., 2022

Physical phenomenon	BdHN type	GRB observable				
		νNS-rise (soft-hard X-rays)	UPE (MeV)	GeV emission	SXFs HXFs	Afterglow (X/optical/radio)
Early SN emission	I, II, III	$\otimes$				
Hypercritical accretion onto νNS	I, II, III	$\otimes$				
Hypercritical accretion onto NS	I, II	$\otimes$				
BH formation from NS collapse	I			$\otimes$		
Transparency of e^+e^- (from vacuum polarization) with low baryon load region	I		$\otimes$			
Synchrotron radiation *inner engine*: BH + B-field+SN ejecta	I			$\otimes$		
Transparency of e^+e^- (from vacuum polarization) with high baryon load	I				$\otimes$	
Synchrotron emission from SN ejecta with energy injection from νNS	I, II, III					$\otimes$
Pulsar-like emission from νNS	I, II, III					$\otimes$

Afterglow



Pulsar-like emision:

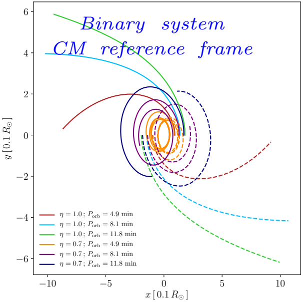
$$Lx = -\dot{E}_{\rm rot} = I\Omega\dot{\Omega}$$

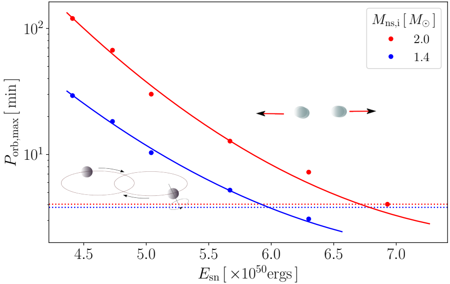
$$Lx = -\frac{2}{3c^3}\Omega^4 B^2 R^2 \sin^2\chi \left(1 + \eta^2 \frac{16}{45}\frac{R^2\Omega^2}{c^2}\right)$$

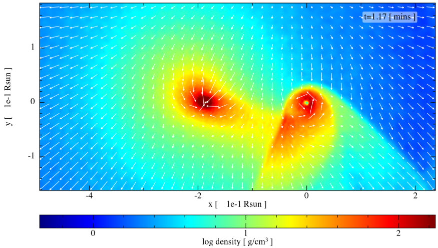
$$J_{\rm CO} = J_{\nu\rm NS} \qquad \rightarrow \qquad \frac{P_{II}}{P_I} = 2.5$$

Binary System fate: the long and short GRB connection

Motion of the binary stars (L. Becerra et al, Universe 9 2023, L. Becerra et al, arXiv:2401.15702)







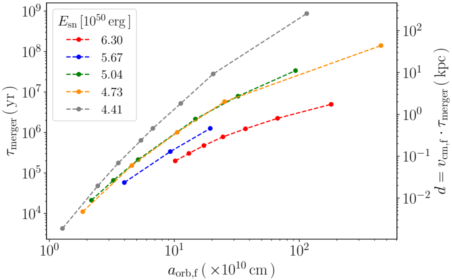
Binary System fate: the long and short GRB connection

Density rates and projected offsets (L. Becerra et al, in prep)

Subclass	Pre-BdHN	Post-BdHN	$\mathcal{R}$ (Gpc^{-3}yr^{-1})
BdHN I	CO-NS	NS-BH	$0.77^{+0.09}_{-0.08}$
BdHN II+III	CO-NS	NS-NS	100^{+45}_{-34}
S-GRF	NS-NS	NS	$3.6^{+1.4}_{-1.0}$
S-GRB	NS-NS	BH	$\left(1.9^{+1.8}_{-1.1}\right) \times 10^{-3}$
U-GRB	NS-BH	BH	$\lesssim \mathcal{R}_{\rm I}$

$\mathcal{R}_{\rm long} > \mathcal{R}_{\rm short}$

SN event disrupts a non-negligible fraction of binaries.



- Fong et al, 2022 finds offsets ranging from a fraction of kpc to 60 kpc, with a median offset value 5–8 kpc
- 90% of long GRB offsets are < 5 kpc, with a median value ~ 1 kpc.

Summary

- The results of 3D-numerical simulations of the IGC model have allowed for the opening of new lines of research on the interpretation of long BRG data

- BdHNe events can result in BH-BH, BH-NS, and NS-NS binaries. Collapse times can be as short as 10 s for rapidly rotating initial stars reaching the mass-shedding limit or as short as 50 s for slowly rotating initial stars reaching the secular instability limit and modeled by a soft EOS.

- Rotational energy acquired by the νNS and the NS companion, along with accretion power, can result in early emissions preceding the main prompt emission. This suggests the potential for detecting precursors with a double-peak structure in X-ray and/or gamma-ray observations.

- BdHN I and II systems remain bound after the GRB-SN event, the corresponding systems, driven by GW radiation, will merge and lead to short GRBs. The relative rates of BdHNe I and II offer vital insights into the nuclear EOS of NSs and CO-NS parameters. This data also offers clues about the stellar evolution leading to CO-NS binaries in the BdHN scenario.

Thanks!