SPH Simulation of the Induced Gravitational Collapse

Laura Marcela Becerra B.
Sapienza University of Rome and Icranet

Collaborators: J. Rueda, C. Bianco, F. Cipolletta, R. Ruffini and C. Fryer

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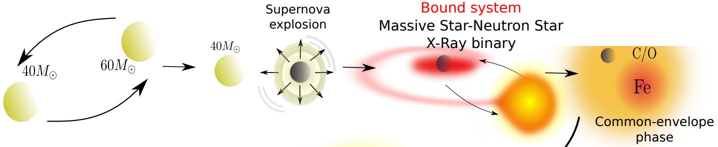
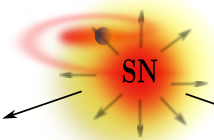
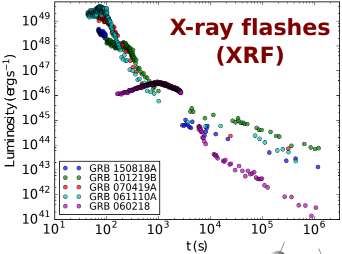
Induced Gravitational Collapse: Hypercritical Accretion

Ruffini et al, MG11,2008. Rueda and Ruffini, ApJ, 2012, Ruffini et al, 2016

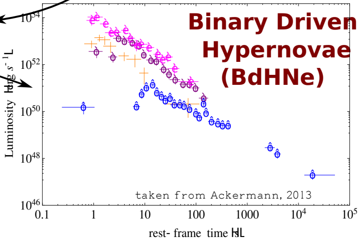
Progenitor IGC model







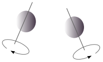
X-ray flashes (XRF)



taken from Ackermann, 2013

Binary Driven Hypernovae (BdHNe)

$$E_{\rm iso} \approx 10^{47} - 10^{52}\,{\rm erg}$$
$$E_{\rm p,i} \sim 4 - 200\,{\rm keV}$$



NS-NS

NS-BH

$$E_{\rm iso} > 10^{52}\,{\rm erg}$$
$$E_{\rm p,i} > 200\,{\rm keV}$$

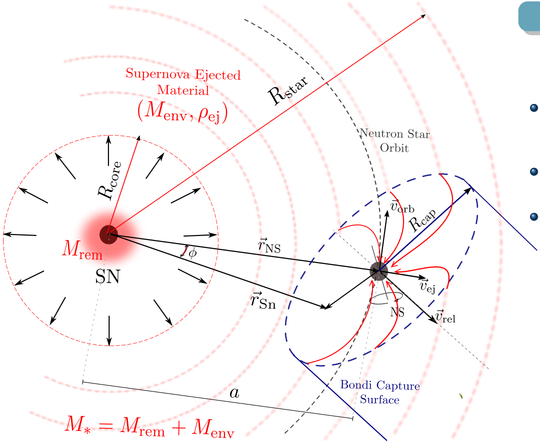
1. *Hypercritical Accretion Process and NS spin up*
   - Bondi Accretion Formalism
   - Pre-supernovae density profile and supernovae explosion
   - Neutron Star Atmosphere
   - Angular Momentum Tranfer and NS evolution

2. *XRF-Examples*

3. *SPH simulations: work in progess...*

Induced Gravitational Collapse: Hypercritical Accretion

Ruffini et al, MG11,2008. Rueda and Ruffini, ApJ, 2012



Binary system Paramaters:

- *Orbital Velocity*: $v_{\rm orb} = \sqrt{\dfrac{GM_{\rm sys}}{a}}$
- *Orbital period*: $P_{\rm orb} = 2\pi\sqrt{\dfrac{a^3}{GM_{\rm sys}}}$
- *Roche lobe position* (Eggleton, 1983):

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

with

$$q = \frac{M_*}{M_{0_{\rm NS}}}$$

$M_* \approx 5\, M_\odot$ and $R_{0_{\rm star}} \approx 3 \times 10^9$ cm

$P > 2$ min $\Longleftrightarrow a \geq 6 \times 10^9$

Induced Gravitational Collapse: Hypercritical Accretion

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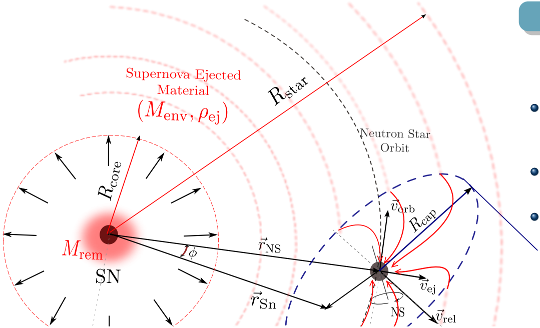

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with

Bondi-Hoyle-Lyttleton Accretion Formalism

Hoyle and Lyttleton, 1939; Bondi and Hoyle, MNRAS, 1944; Bondi, MNRAS, 1952

The rate at which the neutron star accretes mass is:

$$\dot{M}_{\rm BHL}(t) = \pi\rho_{\rm ej}R_{\rm cap}^2\sqrt{v_{\rm rel}^2 + c_{\rm s,ej}^2} \quad \text{with} \quad R_{\rm cap} = \frac{2GM_{\rm NS}}{v_{\rm rel}^2 + c_{\rm s,ej}^2}\,, \qquad (1)$$

where $\rho_{\rm ej}$, $c_{\rm s,ej}$: SN material density and sound speed and $v_{\rm rel}$: SN-material velocity of the ejecta relative to the NS.

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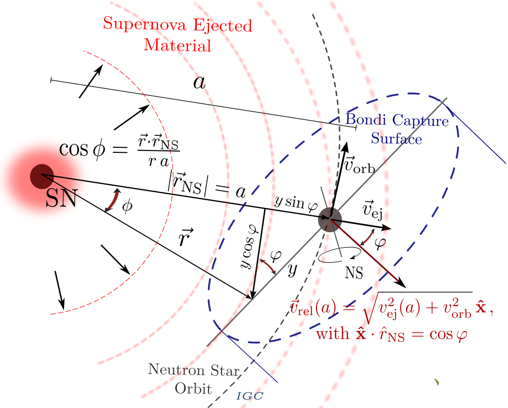

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Transport of Angular momentum by the SN-ejecta

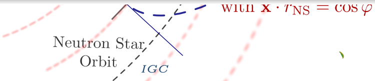
Shapiro & Lightman, ApJ, 1976 and Wang, AAP, 1981

(Angular momentum transfer in binaries systems via wind accretion)

The angular momentum per unit time that crosses the NS capture area is:

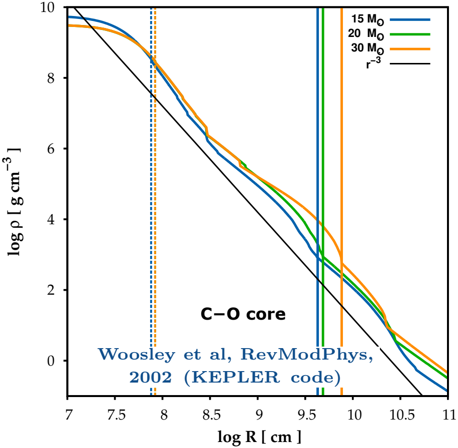
$$\dot{L}_{\rm acc}(t) = \frac{\pi}{2}\left(\frac{1}{2}\epsilon_\rho - 3\epsilon_\nu\right) \rho_{\rm ej}(a,t) v_{\rm rel}^2(a,t) R_{\rm cap}^4(a,t) \qquad (2)$$

where ϵ_ρ and ϵ_ν are the inhomogeneity parameters and depend of the ejected flow nature .



SN explosion: Homologous Expansion

Pre-Supernovae density profile: Non-Rotating progenitor



Woosley et al, RevModPhys, 2002 (KEPLER code)

Homologous expasion

- **Velocity distribution**:

$$v_{\rm ej}(r,t) = n\,\frac{r}{t} \rightarrow R_{\rm star} = R_{0_{\rm star}}\left(\frac{t}{t_0}\right)^n$$

n: *expasion parameter*

- The **density profile** for $t > t_0$ is:

$$\rho_{\rm ej}(r,t) = \rho^0_{\rm ej}\,\frac{M_{\rm env}(t)}{M_{\rm env}(t_0)}\left(\frac{R_{0_{\rm star}}}{R_{\rm star}(t)}\right)^3$$

Pre-SN density profile

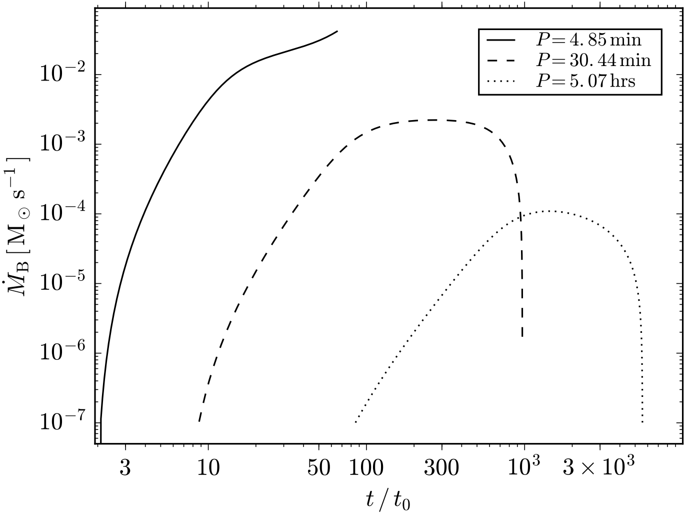
$$\rho_{\rm ej}(r,t_0) = \rho_{\rm core}\left(\frac{R_{\rm c}}{r}\right)^m$$

$M_{\rm ZAMS}$ $M_\odot$	$\rho_{\rm core}$ 10^8g cm^{-3}	$R_{\rm c}$ 10^7 cm	$M_{\rm env}$ $M_\odot$	$R_{\rm star}$ 10^9 cm^3	m
15	3.31	5.01	2.079	4.49	2.771
20	3.02	7.59	3.89	4.86	2.946
30	3.02	8.32	7.94	7.65	2.80

Hypercritical accretion onto the NS

Accretion Rate evolution

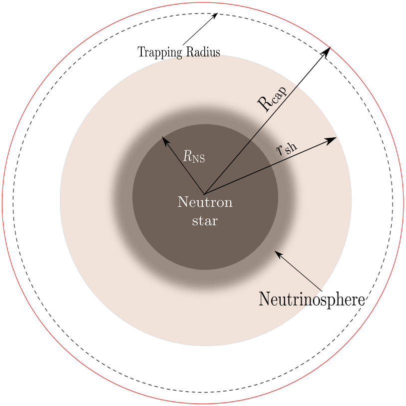
$M_{0\mathrm{env}} = 7.94\ M_\odot, \quad M_{\nu\mathrm{NS}} = 1.5\ M_\odot \quad M_{\mathrm{NS}} = 2.0\ M_\odot$

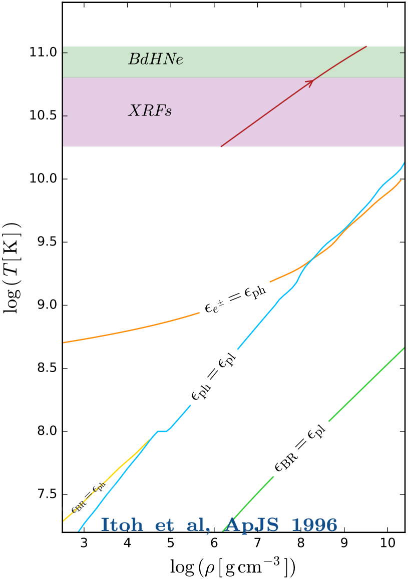


Physics Inside the Accreting Region: Accreted Atmosphere

Chevalier 1989 - Houck & Chevalier, ApJ 1991 - Fryer et al, ApJ 1996

$$\left(\frac{4\pi r_{\rm ns}^2 \Delta r_{\rm ER}}{\sqrt{1-\frac{r_s}{r_{\rm ns}}}}\right) Q_\nu \approx c^2 \dot{M}\left[\left(1-\frac{r_s}{r_{\rm ns}}\right)^{-1/2}-1\right]$$



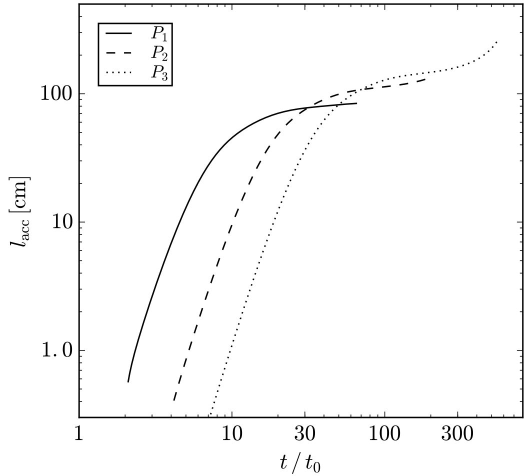


Itoh et al, ApJS 1996

Hypercritical accretion onto the NS

Angular momentum evolution

$$M_{0\rm env} = 7.94\ M_\odot, \quad M_{\nu\rm NS} = 1.5\ M_\odot \quad M_{\rm NS} = 2.0\ M_\odot$$



Hypercritical accretion onto the NS

Angular momentum evolution

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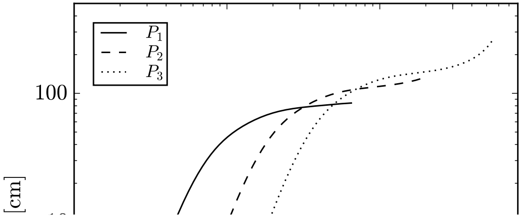


Stagnation radius

If the spacetime is described by the schwarzschild metric, the material circularizes around the NS at the radii:

$$l_{\text{acc}} = \frac{\dot{L}_{\text{acc}}}{\dot{M}_B} = \left(\frac{M_{\text{NS}} r_{\text{st}}^2}{r_{\text{st}} - 3M_{\text{NS}}} \right)^{1/2}$$

So: $r_{\text{st}}/r_{\text{mb}} \sim 10 - 10^3$

Infall Time

The viscous force that act on the disk allows the material arrive at R_{in} from r_{st} at (Chevalier, 1993):

$$t_{\text{fall}} \sim \frac{r_{\text{st}}^2}{\alpha c_{\text{s,disk}} H},$$

So: $t_{\text{fall}}/\Delta_{\text{acc}} \sim 10^{-3}$

Before being accreted, the SN material circularized around the NS for a short time forming a kind of thick disk.

NS Spin Up During the Hypercritical Accretion Process

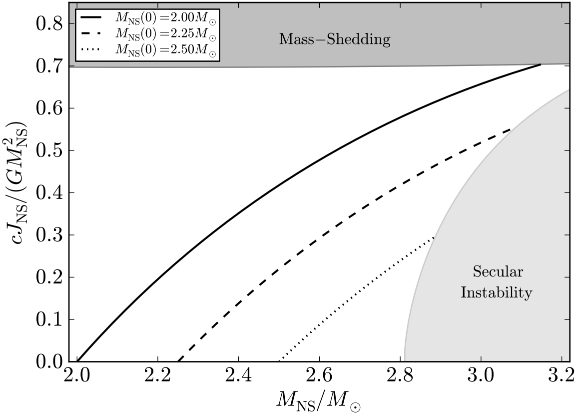
Rotating NS configurations - F. Cipolletta et al, Phys. D. 2015

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

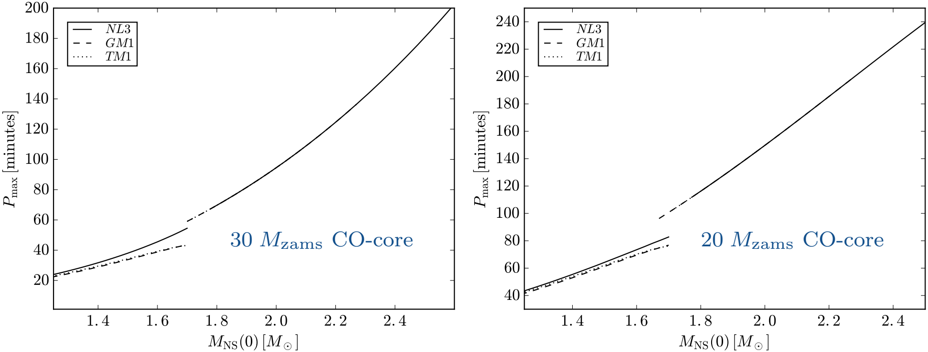
$$M_b = M_{b,0} + M_B \qquad \frac{dJ_{\rm NS}}{dt} = \xi\, l(R_{\rm in})\frac{dM_{\rm b}}{dt}$$

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

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



Induced Gravitational Collapse Of the Neutron Star



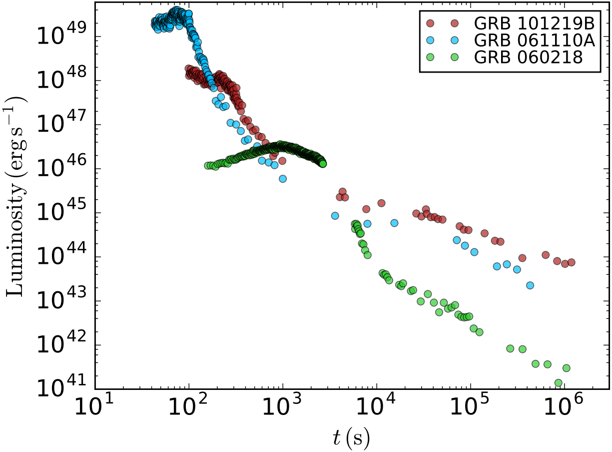
- In systems with $P \leq P_{\rm max}$ the induced gravitational collapse of the accreting NS to a BH occurs, and therefore these systems explain the BdHNe.
- Conversely, in systems with $P > P_{\rm max}$, the NS does not accrete enough matter from the supernova ejecta and the collapse to a BH does not occur. This systems produce XRF.

Accretion luminosity

XRF-Examples

The total energy released in the star in a time-interval dt during the accretion of an amount of mass dM_b, with angular momentum $l\dot{M}_b$ and energy $\epsilon\dot{M}_b$, is given by Sibgatullin& Sunyaev, 2000:

$$L_{\rm acc} = \dot{M}_b c^2 \left[\epsilon - \left(\frac{\partial M_{\rm NS}}{\partial J_{\rm NS}}\right)_{M_b} l - \left(\frac{\partial M_{\rm NS}}{\partial M_b}\right)_{J_{\rm NS}}\right]$$



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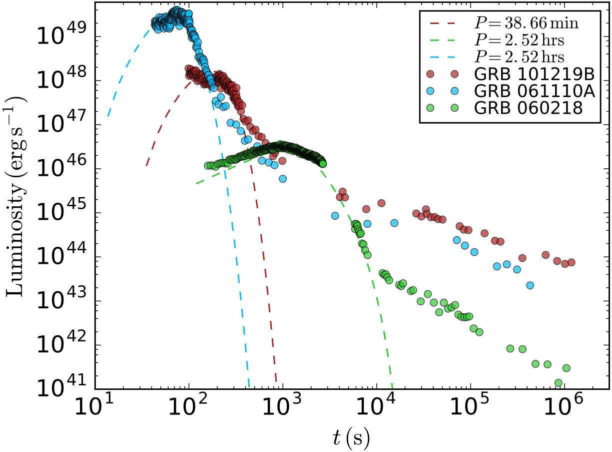
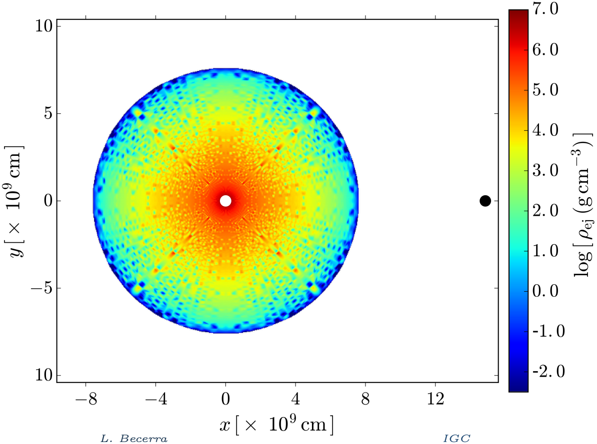


Visualizing the Supernovae

Supernovae ejecta asymmetries induced by the neutron star companion

We follow the three dimensional motion of N particles in the gravitational field of the orbiting NS:

$$\frac{d^2\vec{r}_{\rm sn}(t)}{dt^2} = -GM_{\rm NS}(t)\frac{\vec{r}_{\rm sn}(t)-\vec{r}_{\rm NS}(t)}{|\vec{r}_{\rm sn}(t)-\vec{r}_{\rm NS}(t)|^3}$$



$$M_{\rm ns} = 2.0\,M_{\odot}$$

$$P = 4.85\,{\rm min}$$

$$N = N_r \times N_\theta \times N_\phi$$

$$r = 10^x$$

$$\Delta x = \frac{1}{N_r}\log_{10}\left(\frac{R_{\rm star}}{R_{\rm core}}\right)$$

$$\Delta\,\theta = (\pi/2)/N_\theta$$

$$\Delta\,\phi = 2\pi/N_\phi$$

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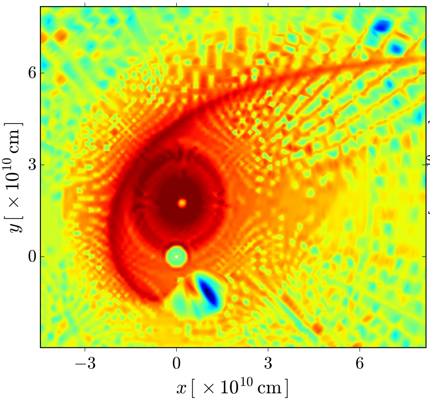
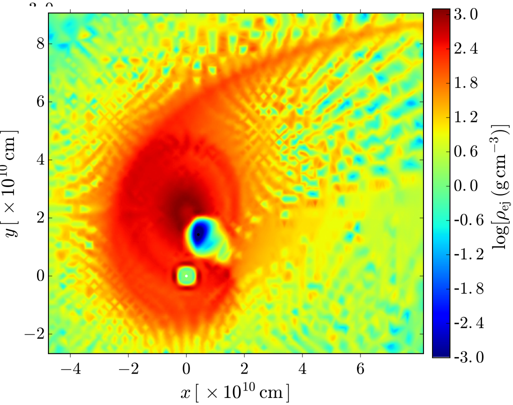
Collapse of the NS



100 seconds after the NS Collapse



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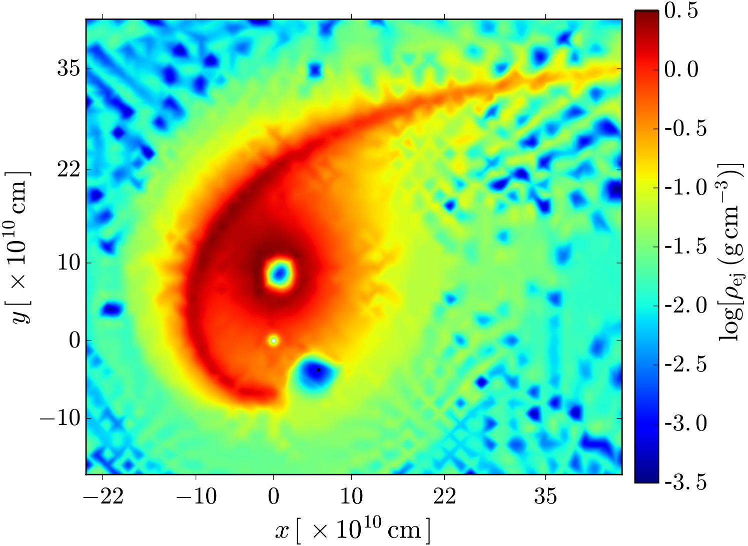
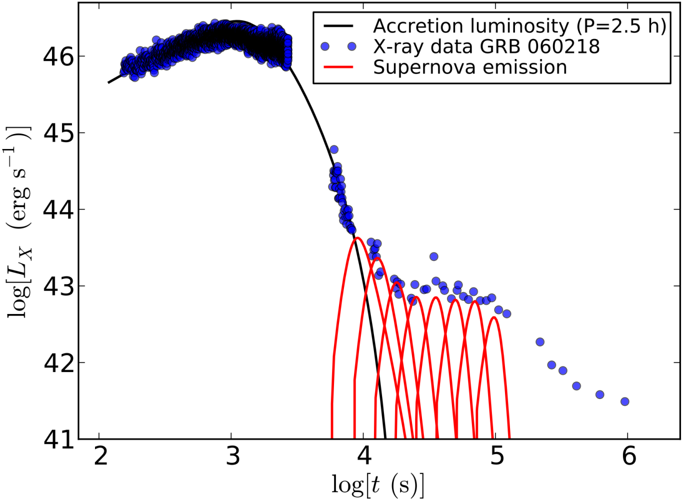
Supernovae ejecta asymmetries induced by the neutron star companion

$P = 50\,\mathrm{min}$-at half of the accretion process



Influence of the Hypercrytical Accretion on the Supernovae Emission



SPH Simulations: SNsph LANL code

Work in progress...

$$25\,M_{\rm zamns}\;-\;M_{\rm ns} = 2.0\,M_{\odot}\;-\;P_{\rm min}$$

(Loading 25Mzams.avi)

The image were made with splash Price, 2007, PASA, 24, 159-173.

SPH Simulations: SNsph LANL code

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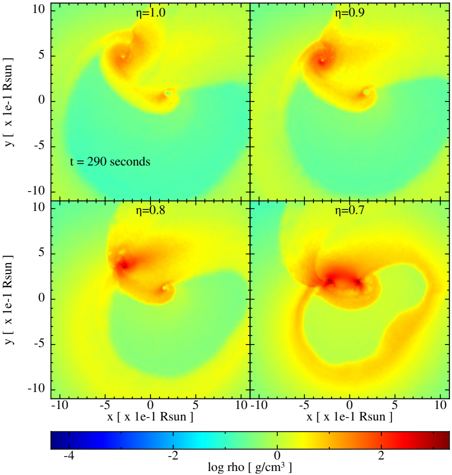

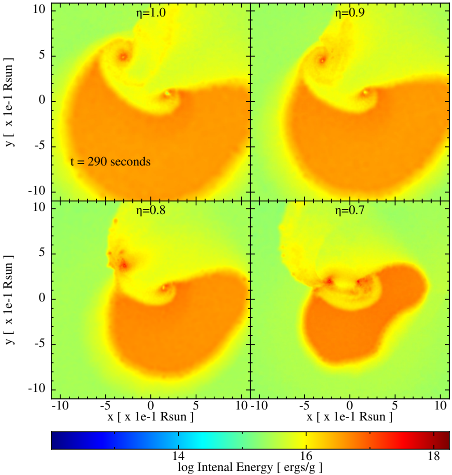

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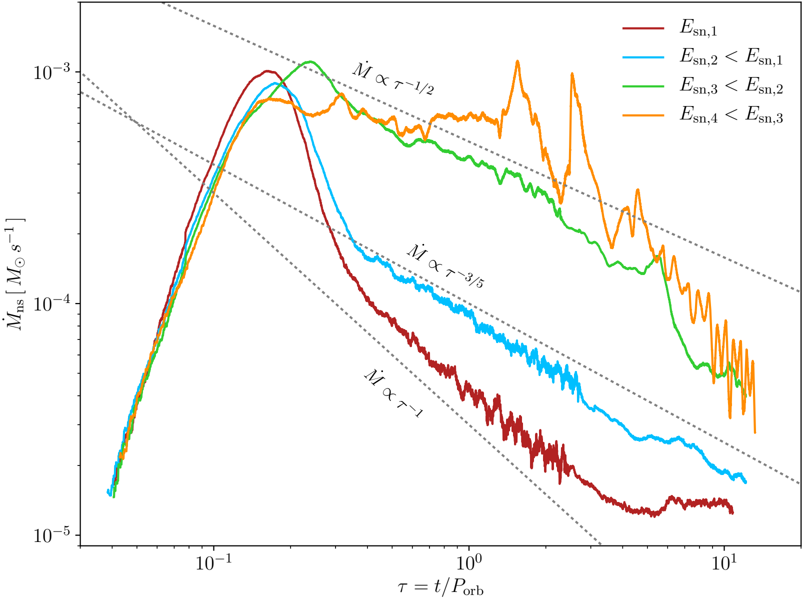

Conclusions

- Early emission of ($t < 10^3$ s) of an IGC binary is powered by the accretion luminosity.
- There is a maximum orbital period, $P_{\rm max}$, for which black hole formation is not possible because the neutron star does not acreate enough mass to collapse. These maximum orbital period is function of the neutron star initial mass and the CO core characteristics. Systems with $P < P_{\rm max}$ explain BDHNe, while system $P < P_{\rm max}$ explain the XFs.
- Neutrino emission is the main energy sink of the system, allowing the hypercritical accretion. Typical neutrino energies are in the range $1 - 15$ Mev.
- The neutron star in very compact orbit with th CO core produce large asymmetries in the supernovae ejecta around the orbital plane. These asymmetries lead to observable early X-ray emission of the supernova.
- The asymmetries caused by the neutron-star companion on the supernova ejecta density become crucial for the features of the supernova appearance in the different bands of the electromagnetic spectrum. The shocked material becomes transparent at different times with different luminosities along different directions owing to the asymmetry created in the supernova ejecta by the orbiting accreting neutron-star companion.

THANK YOU