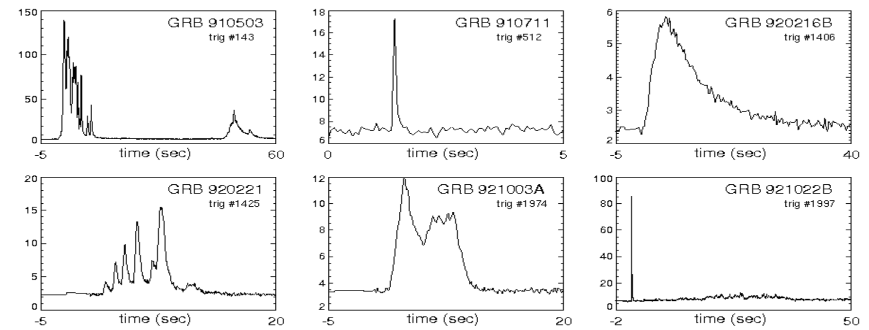


Neutron stars and relativistic astrophysics: the case of gamma-ray bursts and supernovae

Jorge Armando Rueda Hernández – ICRANet and Sapienza University of Rome

UIS-Planetario de Bogotá-UNAL, 23-27 November, Bucaramanga-Bogotá, Colombia 2015

Gamma-Ray Bursts

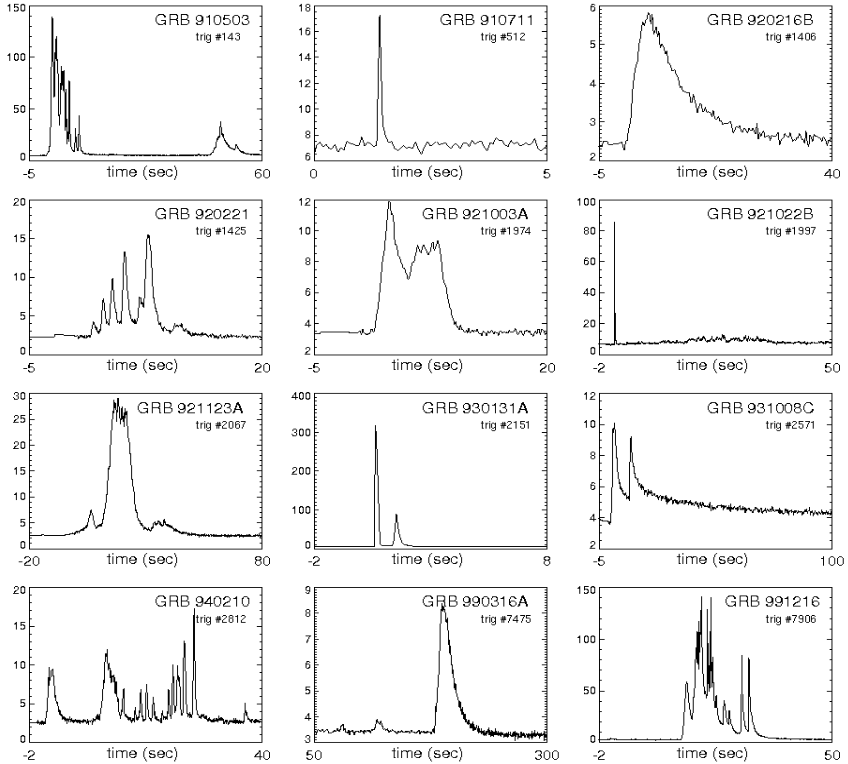
- **GRBs are cosmological explosions (observed up to z=9.4 GRB 090429B)**

- **Most energetic objects (up to a few *10^{54} erg* of *isotropic energy*)**

- **Complex light-curves but in general characterized by a prompt and an extended afterglow emission**

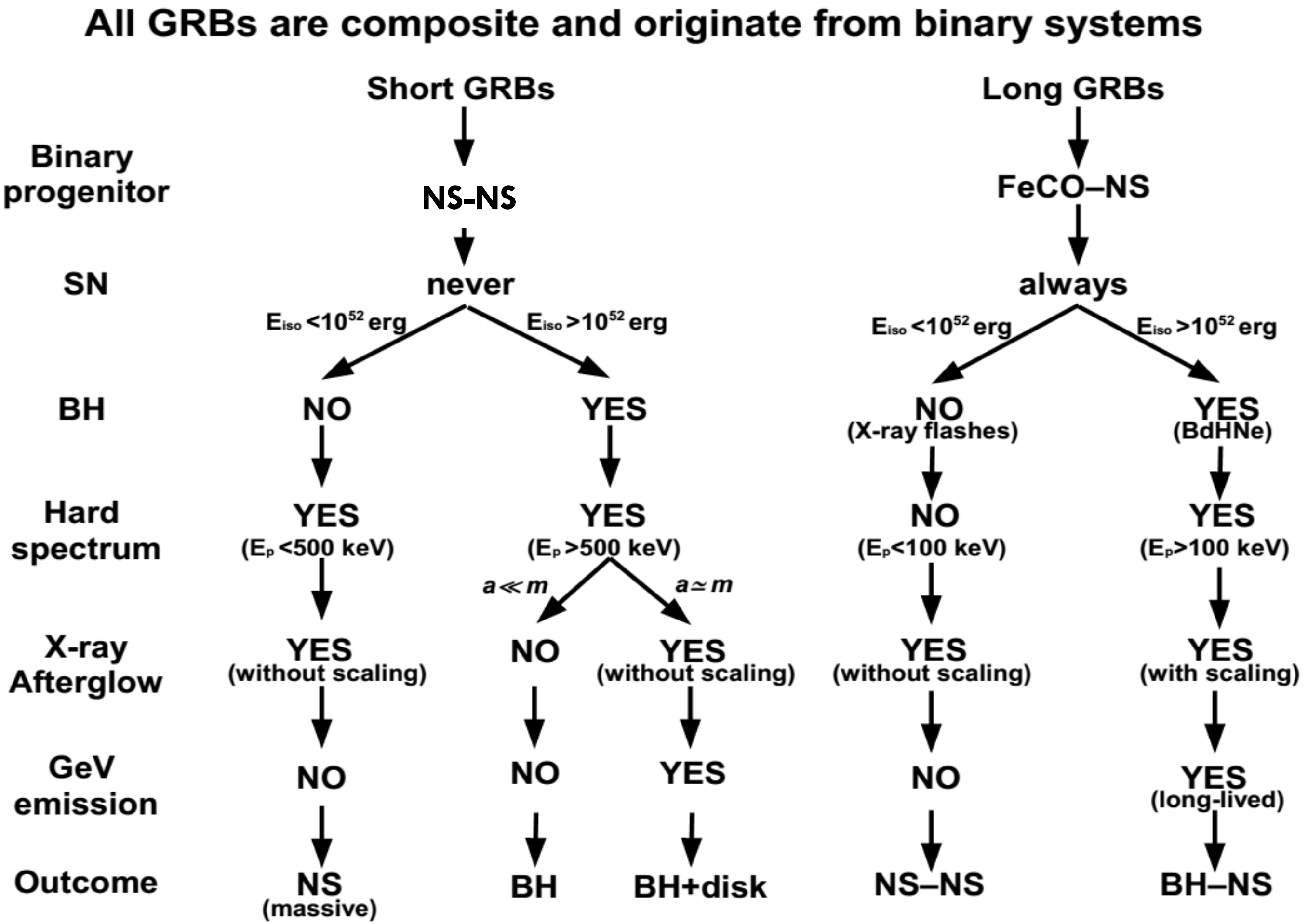
- **Duration: "Short" GRBs <2 seconds and "Long" GRBs >2 seconds**

- **Probe the Physics of *Gravitational Collapse and Black Hole formation***



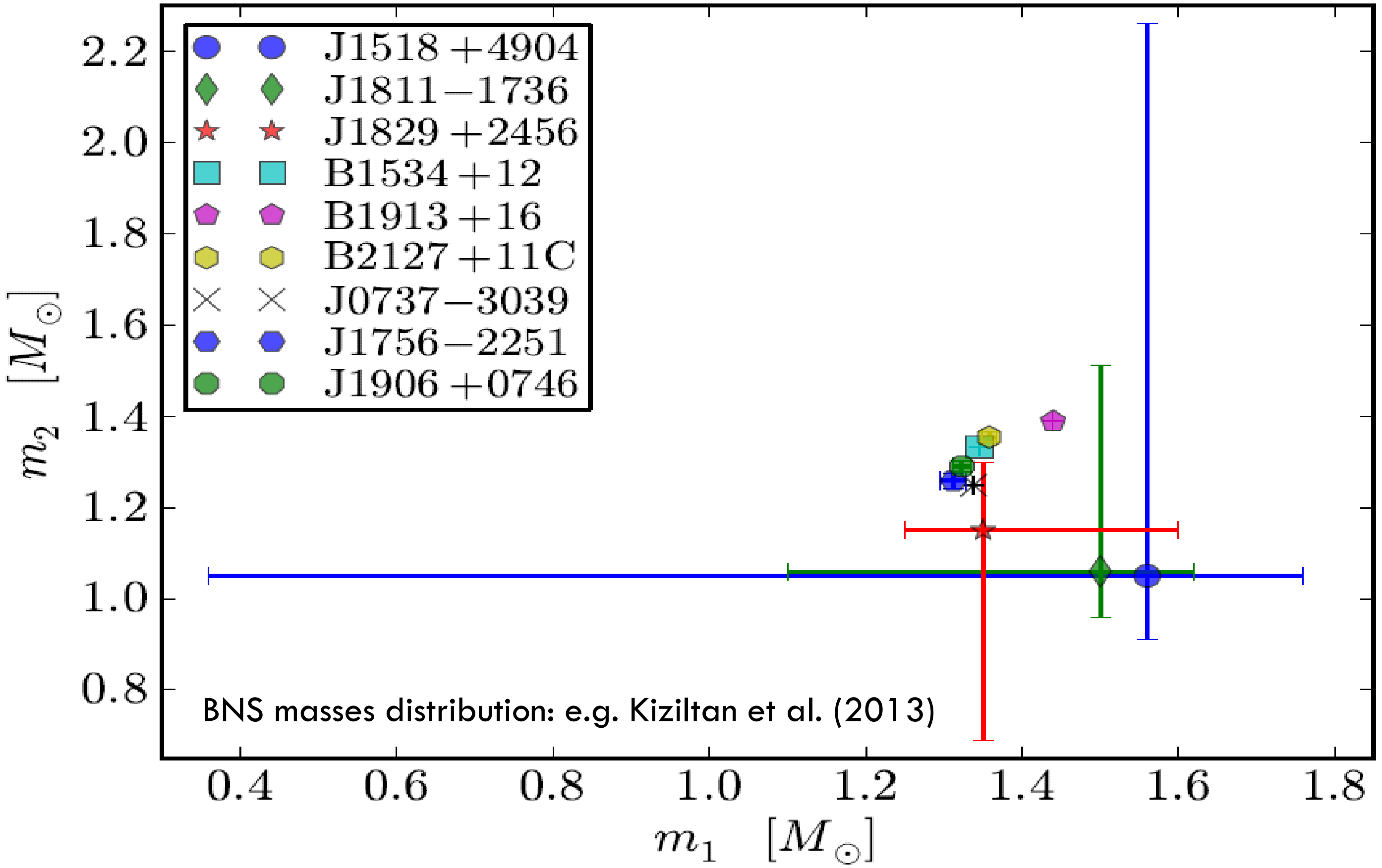
Short and Long GRB Families

Ruffini et al., ApJ (2015); arXiv: 1412.1018v4
Ruffini et al. ApJ (2015); arXiv:1405.5723

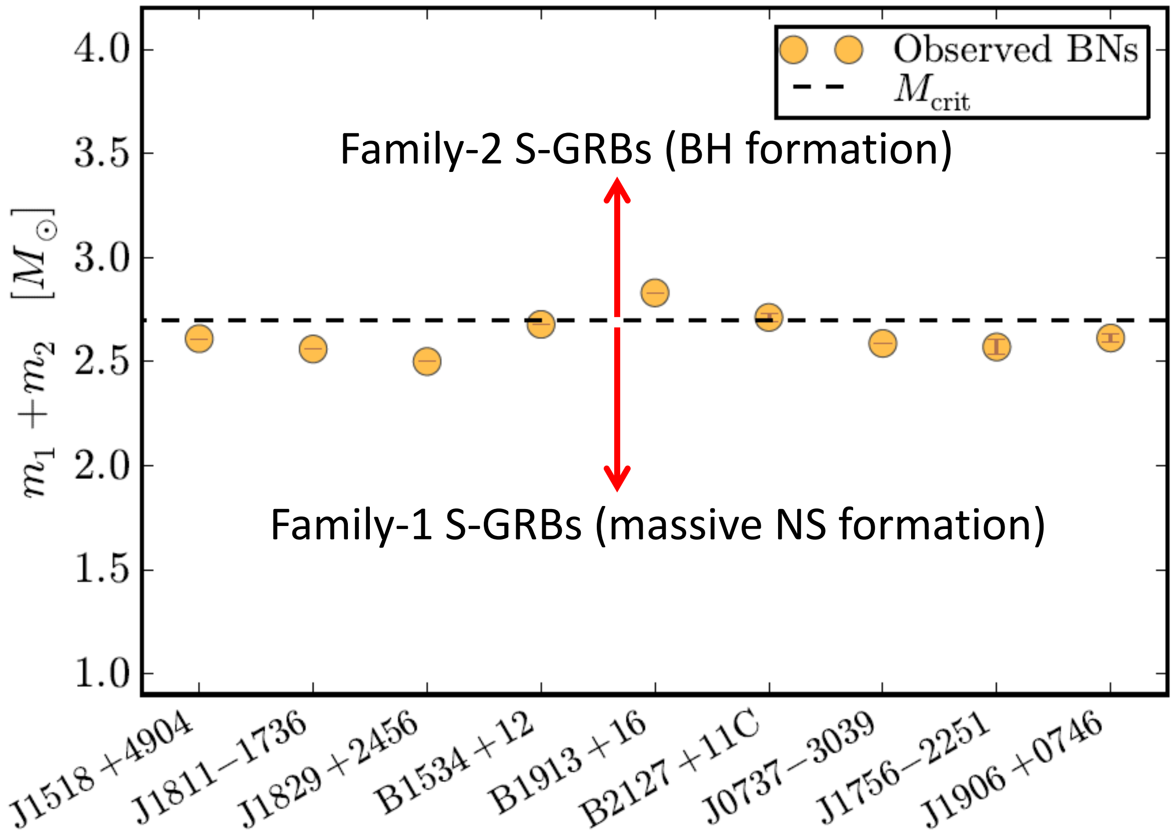


Let’s start with short GRBs

Galactic Binary NSs: will they form BHs?



Families of Short GRBs



NS mass distribution in BNS peaks at 1.32 M_{sun}

(Kiziltan et al. 2013)

So:

M_{BNS} ~ 2.64 M_{sun}

(neglecting NS binding energy and angular momentum)

Ruffini et al., ApJ (2015); arXiv: 1412.1018v4

Which are the mass and angular momentum of the merged core?

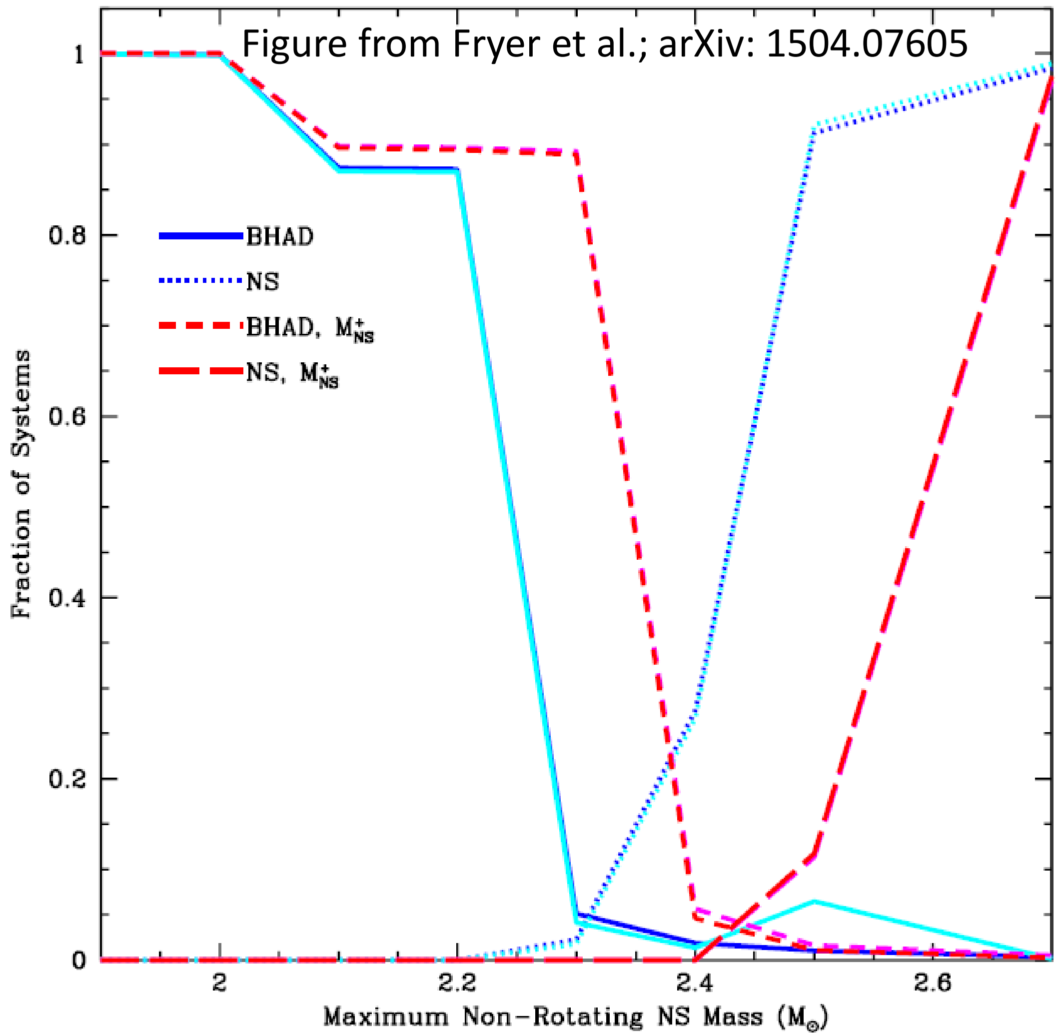
Depends on:

1) Mass-ratio of the binary (M1/M2 ~1 for the galactc BNS)

2) Degree at which baryon and angular momentum are conserved (mass and angular momentum loss, mass and angular momentum of a surrounding disk):

$$(M_1,M_2) \rightarrow (M_{b1},M_{b2}) \rightarrow M_{bf}= \alpha\,(M_{b1}+M_{b2}); \quad \text{where} \quad \alpha <=1$$

$$J_{mc} = \eta\, J_i \sim \eta\, J_{bin}\ (\text{contact}); \quad \text{where}\ \eta <=1$$



Fate of the Merged Core?

F-1S-GRB Rate: (1-10) Gpc^-3 y^-1

see, e.g., E. Berger, ARAA 52, 43 (2014)

F-2 S-GRB Rate: (0.2-6.2)x10^{-4} Gpc^-3 y^-1

Ruffini et al., ApJ (2015); arXiv: 1412.1018v4

Galactic BNS rate: (10-10000) Gpc^-3 y^-1

Abadie et al.; arXiv: 1003.2480

The relative rates:

F1SGRB/GBNS = 10^{-4} - 1

F2SGRB/GBNS = 2x10^{-9} – 6.2x10^{-5}

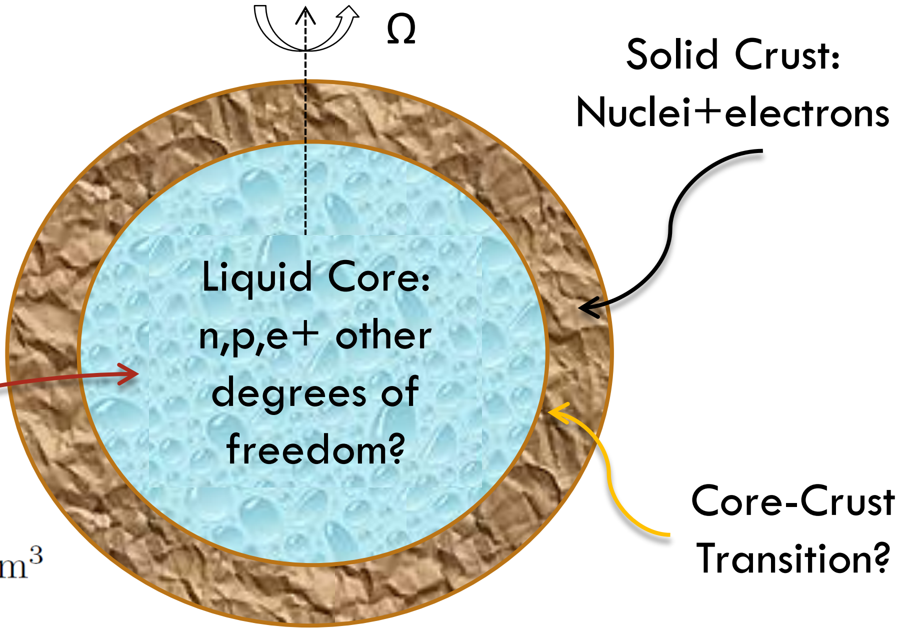
suggests quite large critical NS mass!

Oppenheimer & Volkoff (1939) versus Today Neutron Stars

Oppenheimer-Volkoff

- Degenerate fluid of neutrons
- Non-strongly interacting neutrons
- Non-rotating

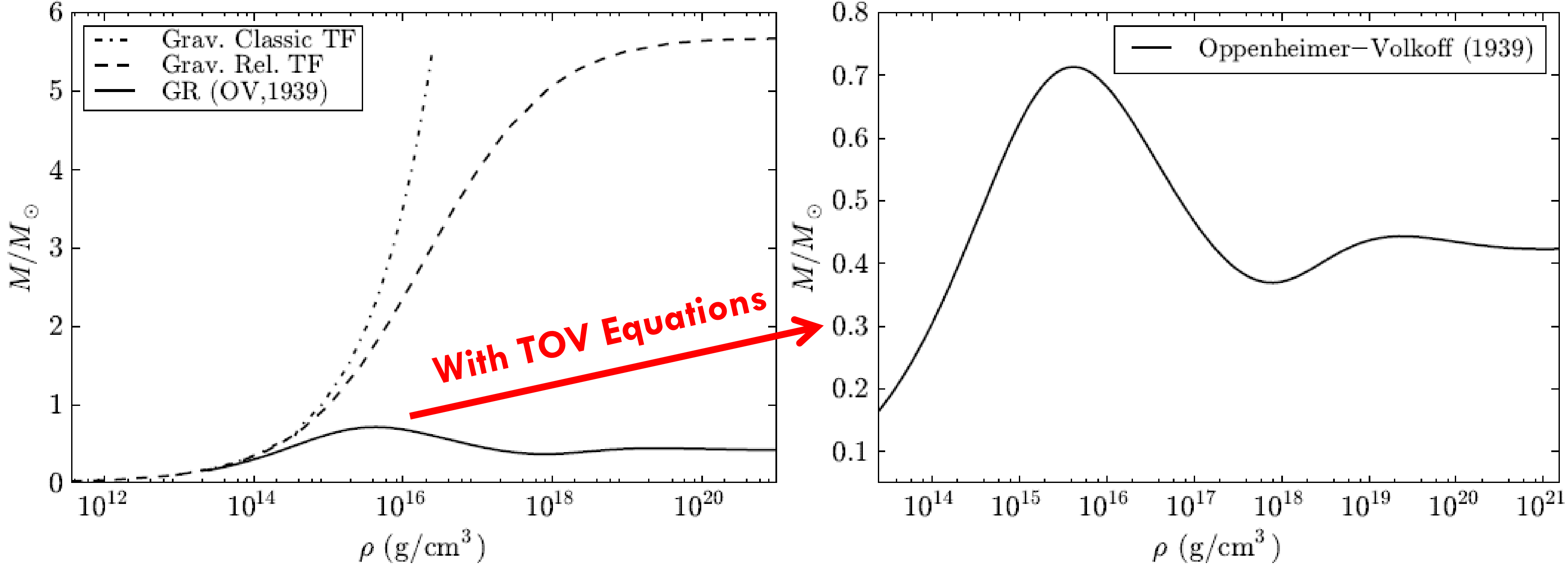
Realistic Neutron Stars

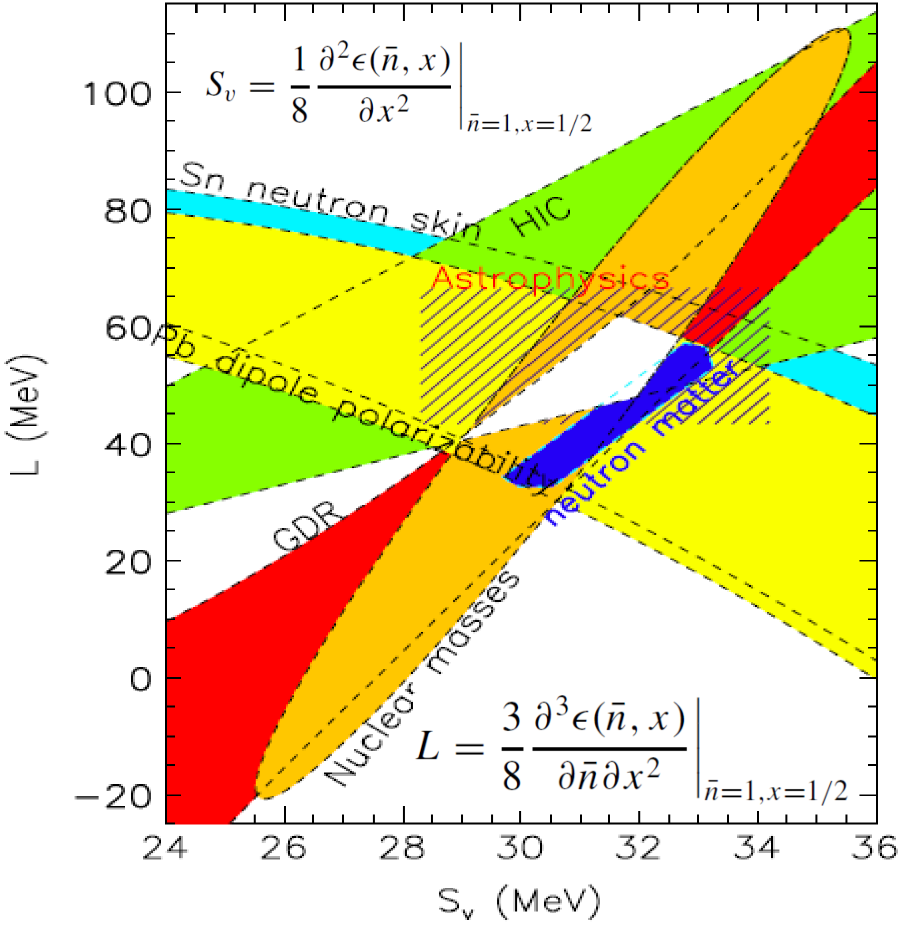


$$\rho_{\rm core} \gtrsim \rho_{\rm nuc} \sim 2.7 \times 10^{14} \ \ {\rm g/cm^3}$$

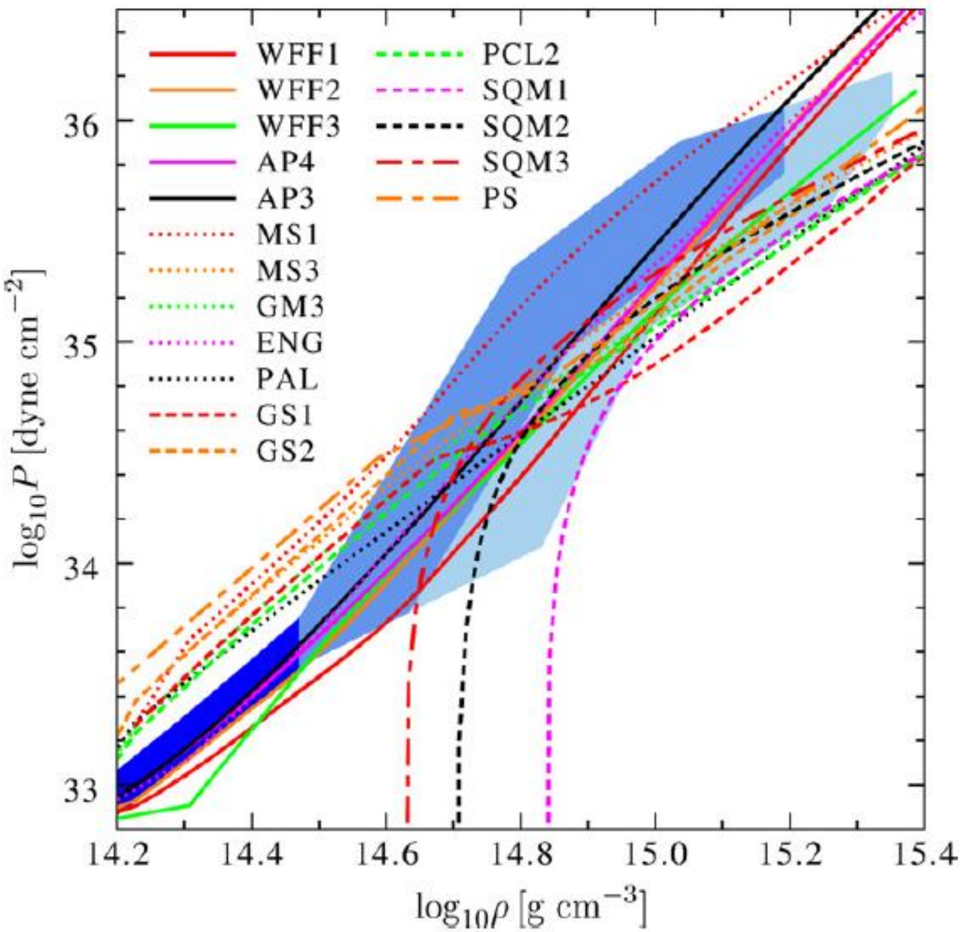
The Oppenheimer-Volkoff Neutron Star

$$\frac{dM(r)}{dr} = 4\pi r^2 \rho(r)\,, \qquad \frac{dP(r)}{dr} = -\frac{G[\rho(r) + P(r)/c^2][4\pi r^3 P(r)/c^2 + M(r)]}{r^2[1 - 2GM(r)/(c^2 r)]}$$



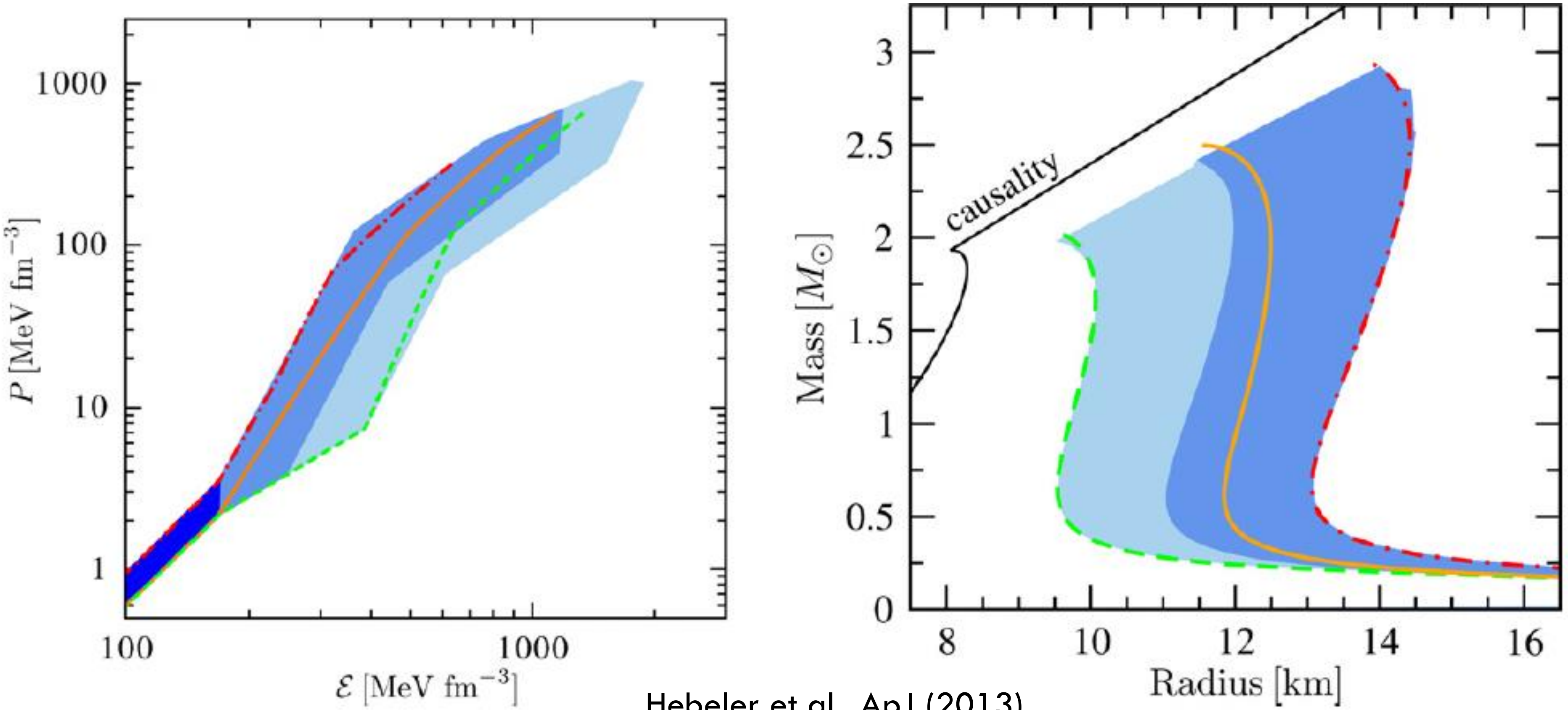


Lattimer & Lim, ApJ (2013)



Hebeler et al., ApJ (2013)

Constraining the nuclear EOS and Mass-Radius Relation



Hebeler et al., ApJ (2013)

NS EOS (Relativistic Mean-Field-RMF- Models)

(Rueda, Ruffini, Xue, Nucl. Phys. A 872, 286, 2011)

$$\mathcal{L} = \mathcal{L}_g + \mathcal{L}_f + \mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\rho + \mathcal{L}_\gamma + \mathcal{L}_{\rm int}$$

$$\mathcal{L}_g = -\frac{R}{16\pi G},$$

$$\mathcal{L}_\gamma = -\frac{1}{16\pi} F_{\mu\nu} F^{\mu\nu},$$

$$\mathcal{L}_\sigma = \frac{1}{2}\nabla_\mu \sigma \nabla^\mu \sigma - U(\sigma), \quad U(\sigma) = U_0 + U(\sigma, 4)$$

$$\mathcal{L}_\omega = -\frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu,$$

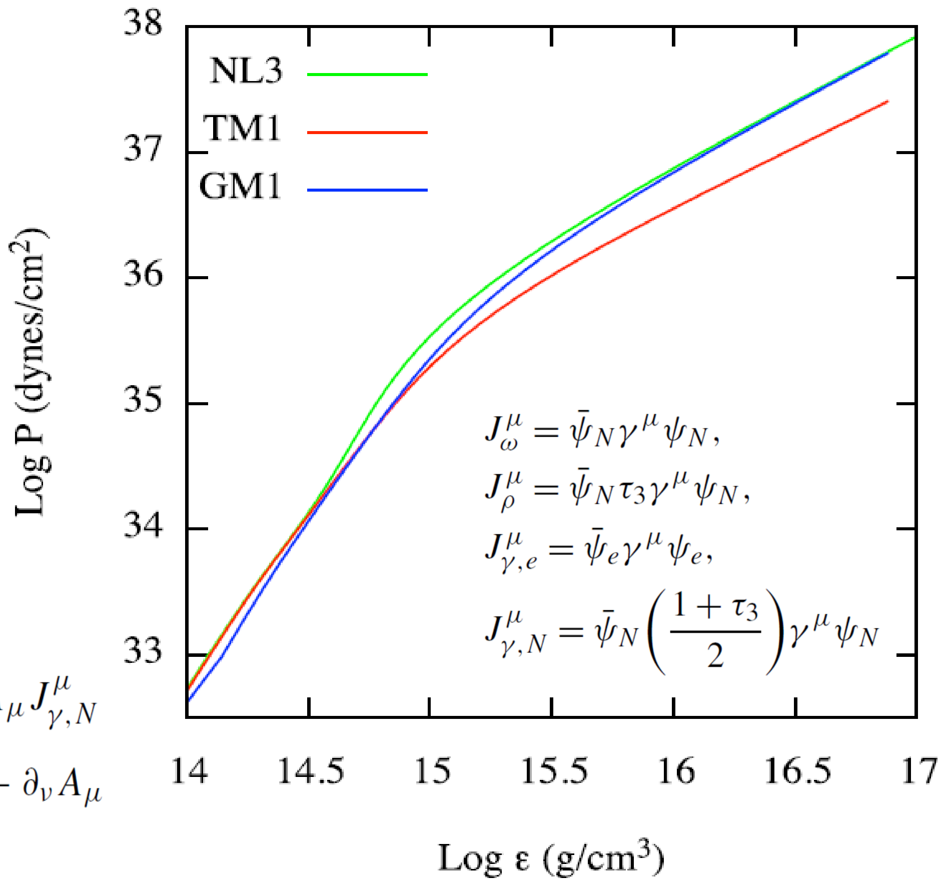
$$\mathcal{L}_\rho = -\frac{1}{4}\mathcal{R}_{\mu\nu}\mathcal{R}^{\mu\nu} + \frac{1}{2} m_\rho^2 \rho_\mu \rho^\mu,$$

$$\mathcal{L}_{\rm int} = -g_\sigma \sigma \bar{\psi}_N \psi_N - g_\omega \omega_\mu J_\omega^\mu - g_\rho \rho_\mu J_\rho^\mu + e A_\mu J_{\gamma,e}^\mu - e A_\mu J_{\gamma,N}^\mu$$

$$\Omega_{\mu\nu} \equiv \partial_\mu \omega_\nu - \partial_\nu \omega_\mu, \ \mathcal{R}_{\mu\nu} \equiv \partial_\mu \rho_\nu - \partial_\nu \rho_\mu, \ F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$U_0 \equiv \frac{1}{2} m_\sigma^2 \sigma^2,$$

$$U(\sigma, 4) \equiv \tfrac{1}{3} g_2 \sigma^3 + \tfrac{1}{4} g_3 \sigma^4$$



Rotating NS configurations: full rotation in GR

(Cipolletta, Cherubini, Filippi, Rueda, Ruffini, PRD 92, 023007 (2015); arXiv: 1506.05926)

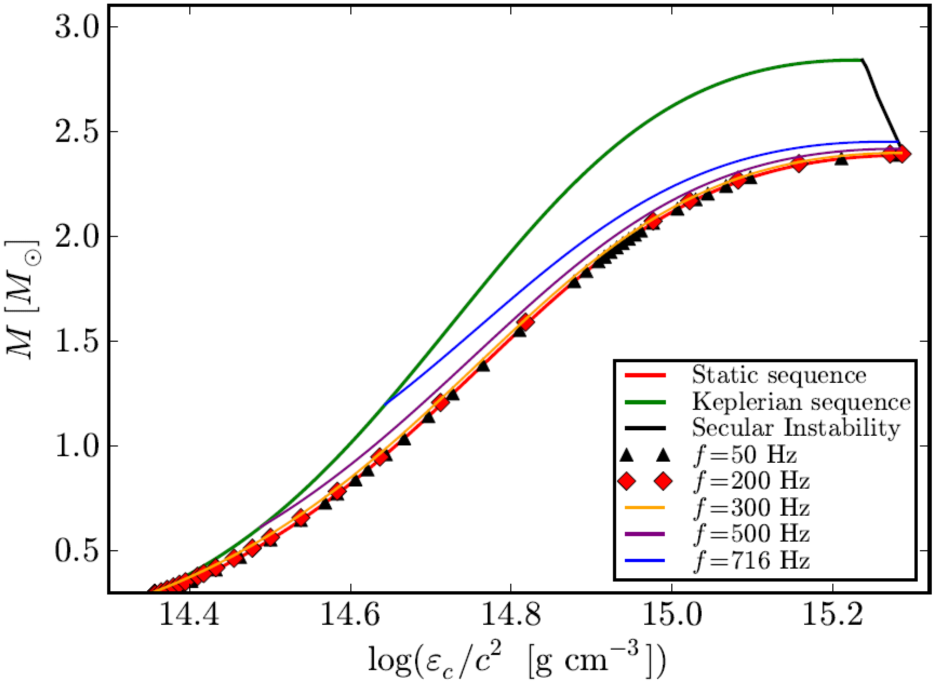
$$ds^2 = -e^{2\nu}dt^2 + e^{2\psi}(d\phi - \omega dt)^2 + e^{2\lambda}(dr^2 + r^2 d\theta^2) \qquad T^{\alpha\beta} = (\varepsilon + P)u^\alpha u^\beta + P g^{\alpha\beta}$$

$$\nabla \cdot (B\nabla\nu) = \frac{1}{2}r^2 \sin^2\theta B^3 e^{-4\nu}\nabla\omega \cdot \nabla\omega + 4\pi B e^{2\zeta - 2\nu}\left[\frac{(\varepsilon + P)(1 + v^2)}{1 - v^2} + 2P\right]$$

$$\nabla \cdot (r^2 \sin^2\theta B^3 e^{-4\nu}\nabla\omega) = -16\pi r \sin\theta B^2\ e^{2\zeta - 4\nu}\frac{(\varepsilon + P)v}{1 - v^2} \qquad \nabla \cdot (r\sin(\theta)\nabla B) = 16\pi r \sin\theta B e^{2\zeta - 2\nu}P$$

$$\begin{aligned}
\zeta_{,\mu} = &-\left\{(1-\mu^2)\left(1 + r\frac{B_{,r}}{B}\right)^2 + \left[\mu - (1-\mu^2)\frac{B_{,r}}{B}\right]^2\right\}^{-1}\left[\frac{1}{2}B^{-1}\left\{r^2 B_{,rr} - \left[(1-\mu^2)B_{,\mu}\right]_{,\mu} - 2\mu B_{,\mu}\right\}\right.\\
&\times\left\{-\mu + (1-\mu^2)\frac{B_{,\mu}}{B}\right\} + r\frac{B_{,r}}{B}\left[\frac{1}{2}\mu + \mu r\frac{B_{,r}}{B} + \frac{1}{2}(1-\mu^2)\frac{B_{,\mu}}{B}\right] + \frac{3}{2}\frac{B_{,\mu}}{B}\left[-\mu^2 + \mu(1-\mu^2)\frac{B_{,\mu}}{B}\right]\\
&- (1-\mu^2)r\frac{B_{,\mu r}}{B}\left(1 + r\frac{B_{,r}}{B}\right) - \mu r^2(\nu_{,r})^2 - 2(1-\mu^2)r\nu_{,\mu}\nu_{,r} + \mu(1-\mu^2)(\nu_{,\mu})^2 - 2(1-\mu^2)r^2 B^{-1}B_{,r}\nu_{,\mu}\nu_{,r}\\
&+ (1-\mu^2)B^{-1}B_{,\mu}\left[r^2(\nu_{,r})^2 - (1-\mu^2)(\nu_{,\mu})^2\right] + (1-\mu^2)B^2 e^{-4\nu}\left\{\frac{1}{4}\mu r^4(\omega_{,r})^2 + \frac{1}{2}(1-\mu^2)r^3\omega_{,\mu}\omega_{,r}\right.\\
&\left.\left.- \frac{1}{4}\mu(1-\mu^2)r^2(\omega_{,\mu})^2 + \frac{1}{2}(1-\mu^2)r^4 B^{-1}B_{,r}\omega_{,\mu}\omega_{,r} - \frac{1}{4}(1-\mu^2)r^2 B^{-1}B_{,\mu}\left[r^2(\omega_{,r})^2 - (\mu^2)(\omega_{,\mu})^2\right]\right\}\right]
\end{aligned}$$

Rotating NS configurations: secular instability line

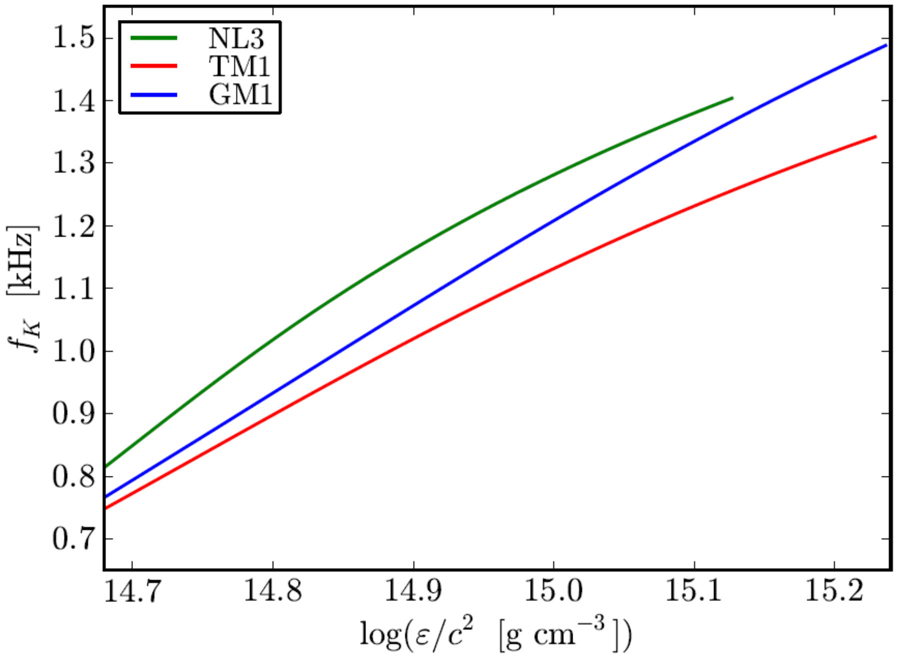


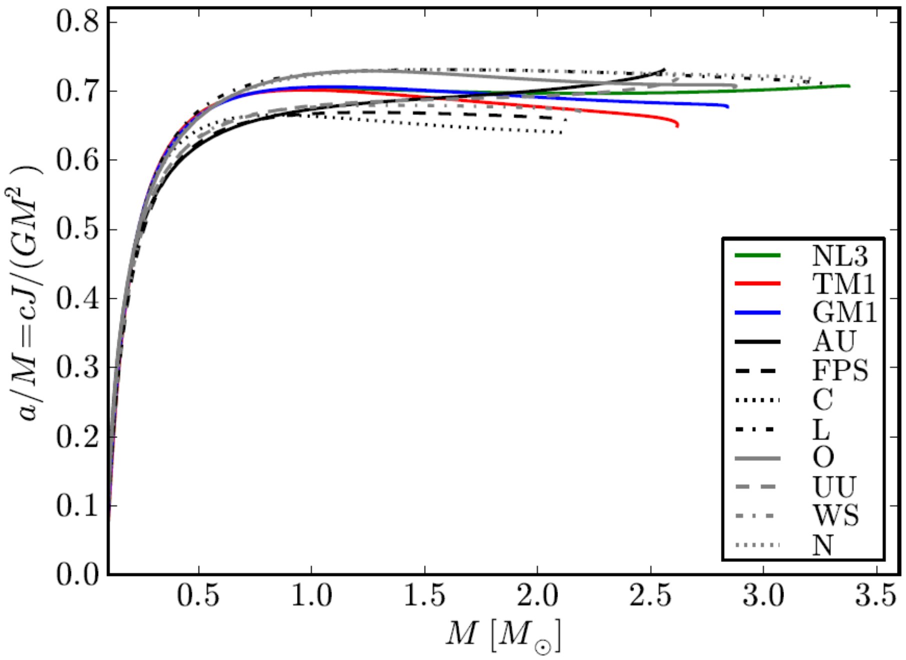
$$M_{NS}^{crit} = M_{NS}^{J=0}(1 + k j_{NS}^{p})$$

	$M_{crit}^{J=0}$ $M_\odot$	$R_{crit}^{J=0}$ km	$M_{max}^{J\neq0}$ $M_\odot$	$R_{max}^{J\neq0}$ km	f_K kHz	p	k
NL3	2.81	13.49	3.38	17.35	1.34	1.68	0.006
GM1	2.39	12.56	2.84	16.12	1.49	1.69	0.011
TM1	2.20	12.07	2.62	15.98	1.40	1.61	0.017

Taken from Cipolletta, et al. PRD 92, 023007 (2015)
arXiv: 1506.05926

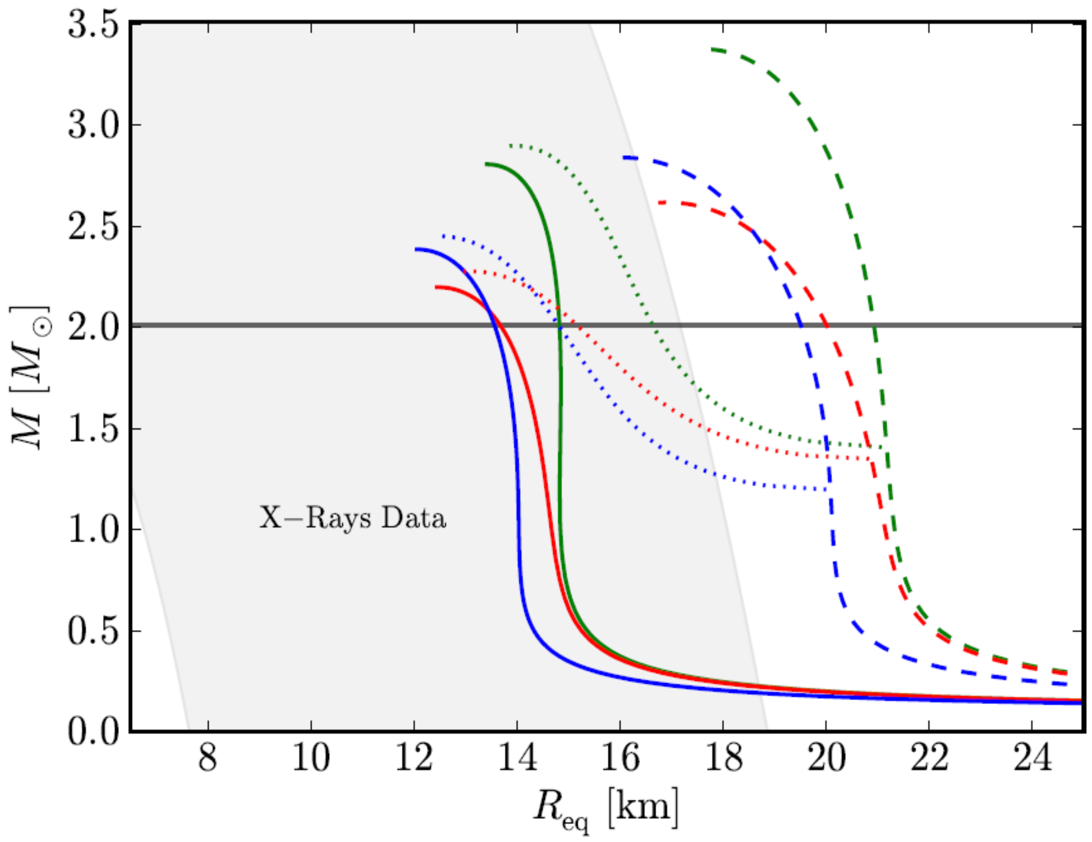
Rotating NS configurations: full rotation in GR





Figures from Cipolletta, et al. PRD 92, 023007 (2015); arXiv: 1506.05926

NS Mass-Radius Relation: Observational Constraints



- Maximum NS mass observed: 2 Msun

  (Antoniadis et al., Science (2013)

- Fastest NS observed: f=716 Hz

  (Demorest et al., Science (2006)

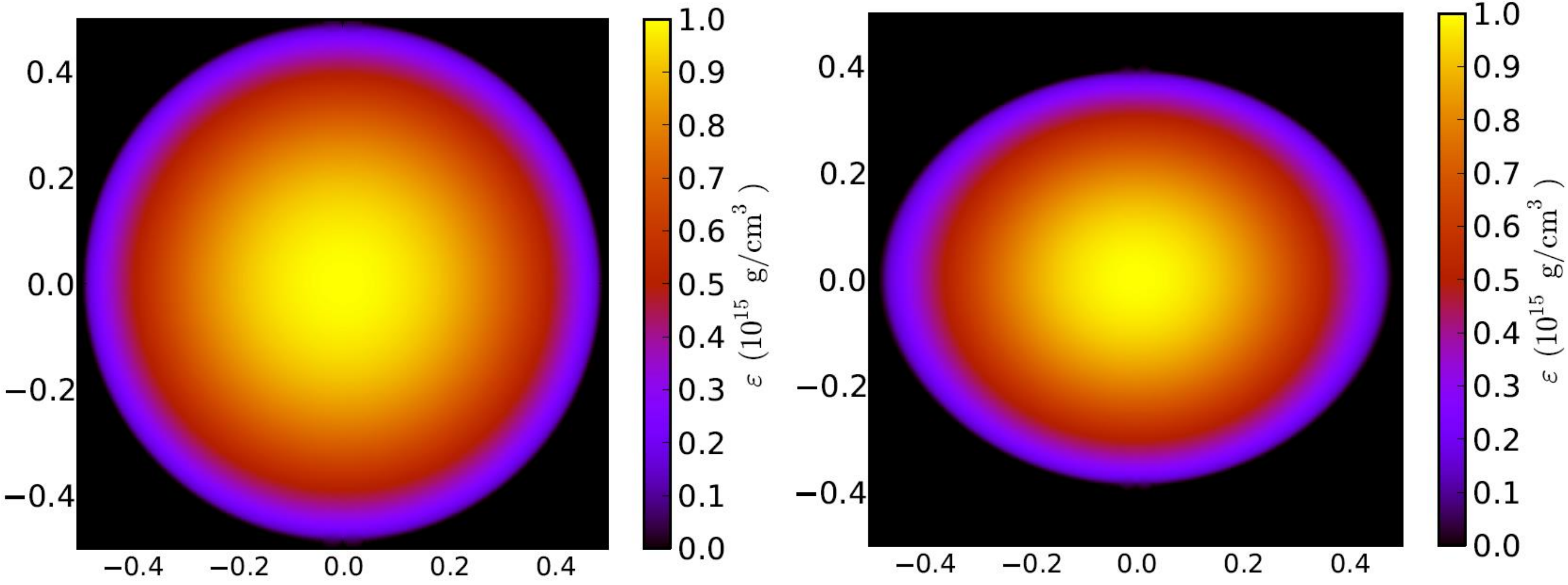
- Radii from X-ray emisison: mainly from low-mass X-ray binaries (LMXBs), and X-ray isolated NSs (XINSs): shaded area

  (Lattimer & Steiner, EPJ (2014)

Figure from Cipolletta, et al. PRD 92, 023007 (2015); arXiv: 1506.05926

Rotating NS: Deformation

(Cipolletta, Cherubini, Filippi, Rueda, Ruffini, PRD 92, 023007 (2015); arXiv: 1506.05926)



Rotating NS configurations: quadrupole moment

(Cipolletta, Cherubini, Filippi, Rueda, Ruffini, PRD 2015; arXiv: 1506.05926)

$$M_2^{\rm corr} = M_2 - \frac{4}{3}\left(\frac{1}{4} + b_0\right) M^3, \quad M_2 = \frac{1}{2} {r_{eq}}^3 \int_0^1 \frac{{s'}^2 ds'}{(1-s')^4} \int_0^1 P_2(\mu') \tilde{S}_\rho(s',\mu') d\mu'$$

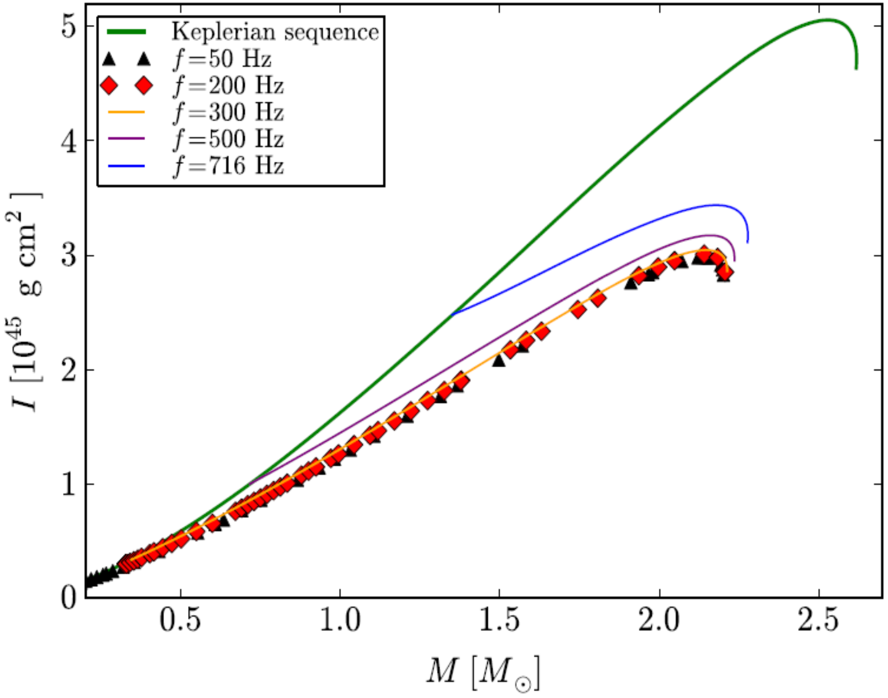
Pappas & Apostolatos, PRL 2012

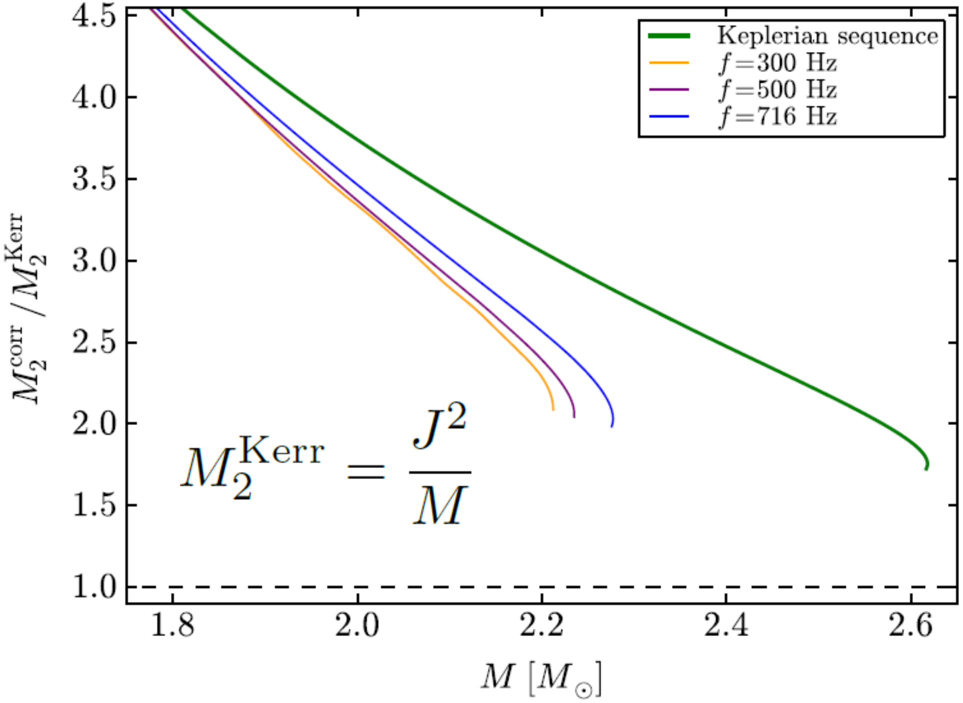
$$S_\rho(r,\mu) = e^{\frac{\gamma}{2}} \left[8\pi e^{2\lambda}(\varepsilon + P)\frac{1+u^2}{1-u^2} + r^2 e^{-2\rho}\left[\omega_{,r}^2 + \frac{1}{r^2}(1-\mu^2)\omega_{,\mu}^2\right] + \frac{1}{r}\gamma_{,r} - \frac{1}{r^2}\mu\gamma_{,\mu} + \frac{\rho}{2}\left\{16\pi e^{2\lambda} - \gamma_{,r}\left(\frac{1}{2}\gamma_{,r} + \frac{1}{r}\right) \frac{1}{r^2}\gamma_{,\mu}\left[\frac{1}{2}\gamma_{,\mu}(1-\mu^2) - \mu\right]\right\}\right],$$

$$b_0 = -\frac{16\sqrt{2\pi}{r_{eq}}^4}{M^2} \int_0^{\frac{1}{2}} \frac{{s'}^3 ds'}{(1-s')^5} \int_0^1 d\mu' \sqrt{1-{\mu'}^2} P(s',\mu') e^{\gamma+2\lambda} T_0^{\frac{1}{2}}(\mu')$$

NS moment of inertia and quadrupole moment

(Cipolletta, Cherubini, Filippi, Rueda, Ruffini, PRD 92, 023007 (2015); arXiv: 1506.05926)





Neutron Star Binding Energy

(Cipolletta, Cherubini, Filippi, Rueda, Ruffini, PRD 2015; arXiv: 1506.05926)

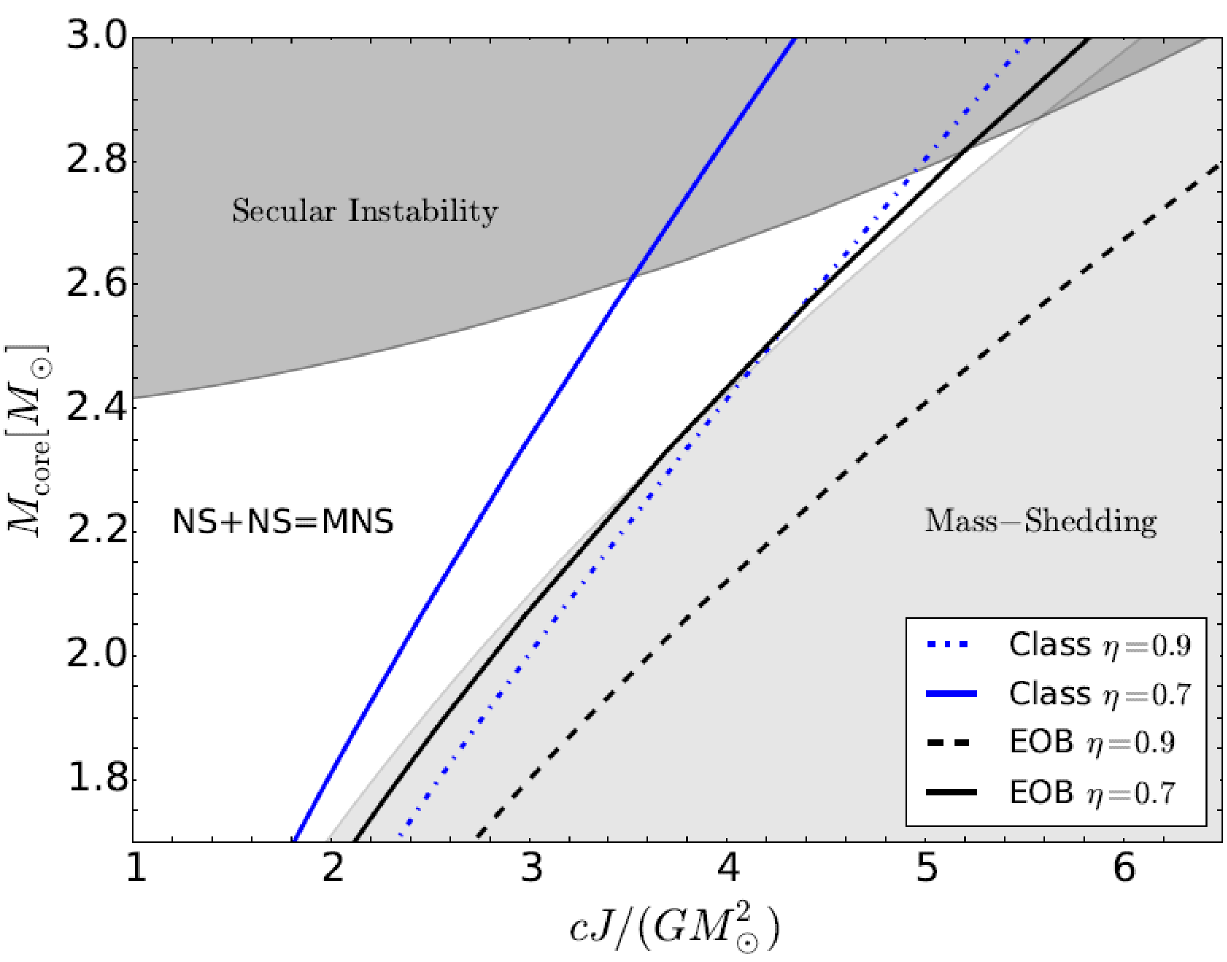
Static Configurations

$$\frac{M_b}{M_\odot} \approx \frac{M}{M_\odot} + \frac{13}{200}\left(\frac{M}{M_\odot}\right)^2$$

Rotating Configurations

$$\frac{M_b}{M_\odot} = \frac{M}{M_\odot} + \frac{13}{200}\left(\frac{M}{M_\odot}\right)^2\left(1 - \frac{1}{130} j^{1.7}\right)$$

c J/(G M^2_{sun})



The starting question was: Fate of the merged core?

In this example:

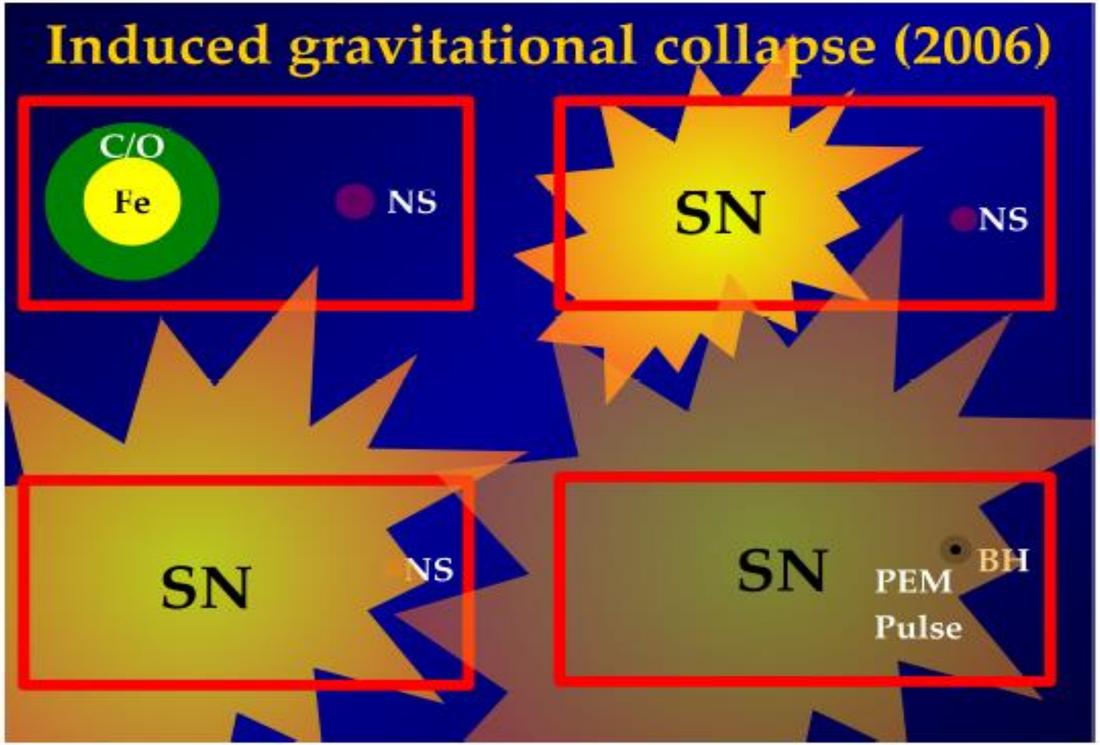
- EOS: GM1

- 70-90% of the angular momentum at the merger assumed to be kept by the new compact core

- 1.0 Msun < M1=M2 < 2.0 Msun

Now let’s turn to long GRBs

Induced Gravitational Collapse (IGC) Paradigm



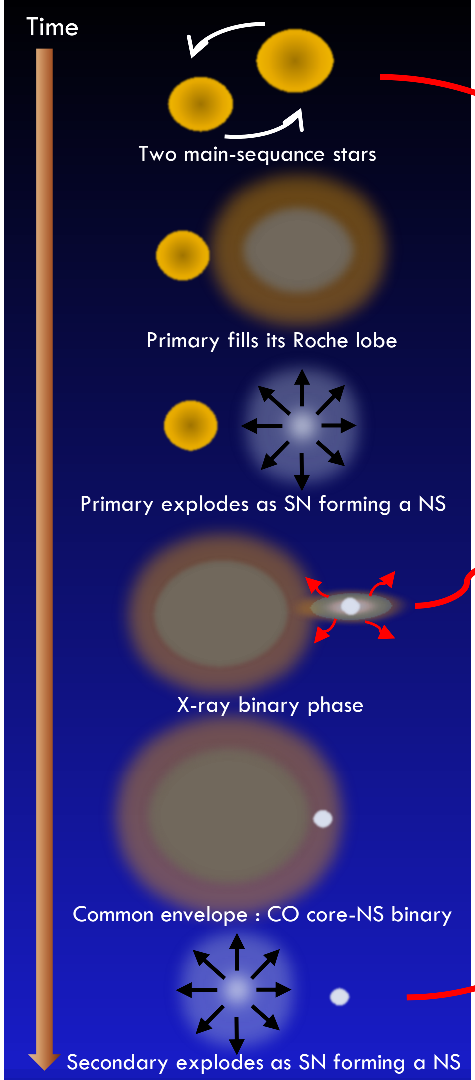
Ruffini et al. MG11-Berlin (2006)

The Induced Gravitational Collapse

Nomoto et al. 1994

Iwamoto et al. 1994

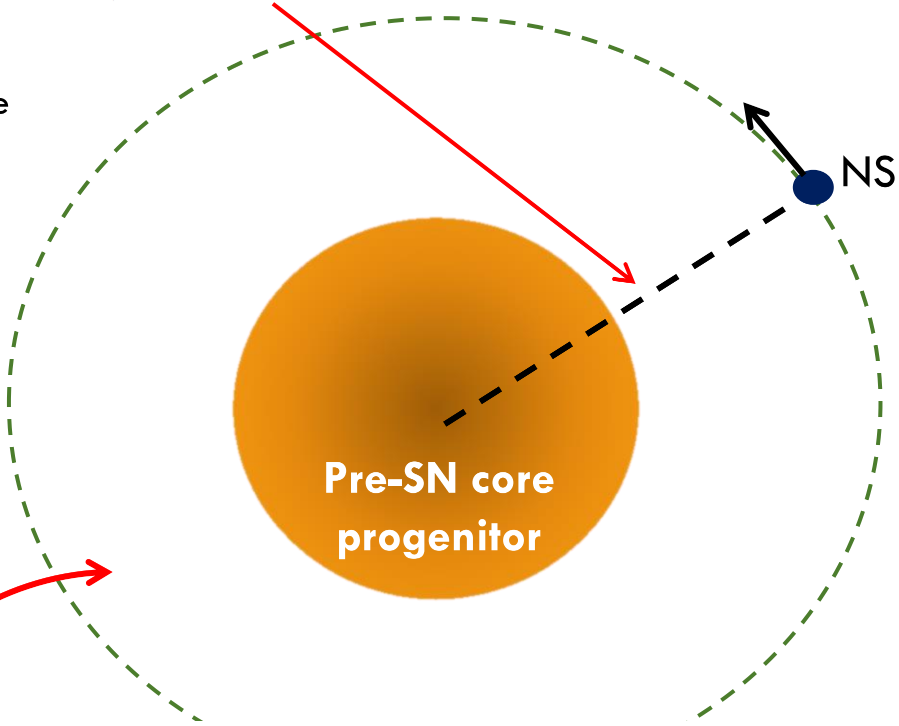
Nomoto et al. 1995



Eta Carinae

Cen X-3

$$v_{\rm orb} = \sqrt{\frac{G(M_{\rm SN-prog} + M_{\rm NS})}{a}} = 1.15 \times 10^8 \left(\frac{M_{\rm SN-prog} + M_{\rm NS}}{M_\odot}\right)^{1/2} \ {\rm cm\,s^{-1}}$$



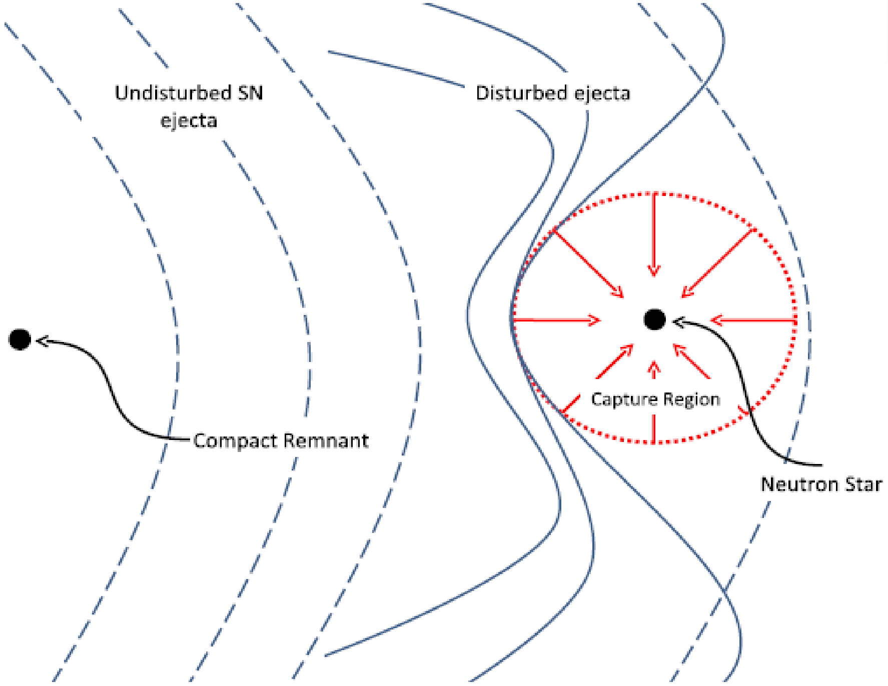
$$P = \sqrt{\frac{4\pi^2 a^3}{G(M_{\rm SN-prog} + M_{\rm NS})}} = 545 \left(\frac{M_{\rm SN-prog} + M_{\rm NS}}{M_\odot}\right)^{-1/2} \ {\rm s}$$

Rueda & Ruffini, ApJL (2012)   Izzo, Rueda, Ruffini, A&AL (2012)

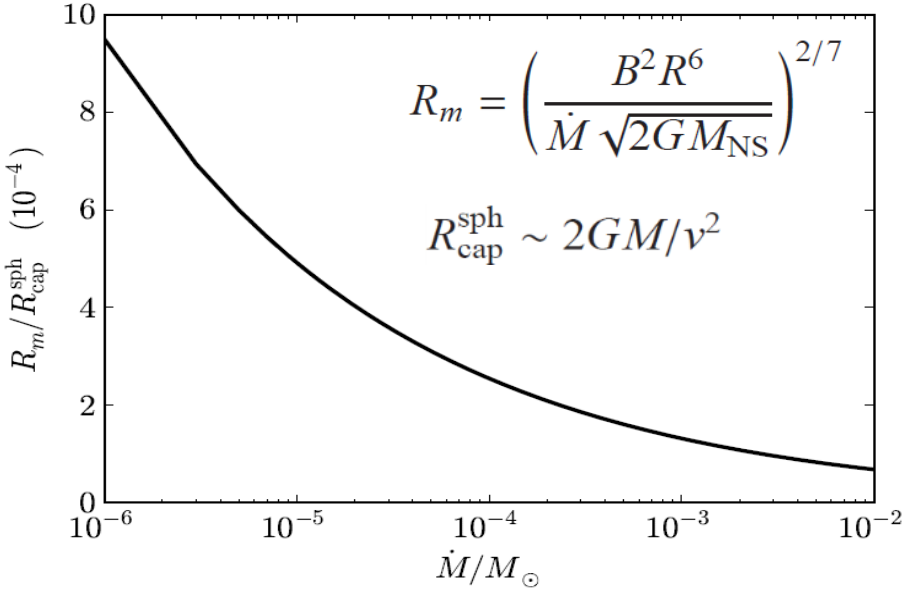
First estimates of the accretion process

Rueda &Ruffini, ApJ Lett. 758, L7 (2012)
Izzo, Rueda, Ruffini, A&A Lett. 548, L5 (2012)

$$R_{\rm cap} = \frac{2GM_{\rm NS}}{v_{\rm rel,ej}^2}, \qquad v_{\rm rel,ej} = \sqrt{v_{\rm orb}^2 + v_{\rm ej}^2}, \qquad r_{\rm ej} = \sigma t^n$$



The relative importance of the magnetosphere



See also Toropina, Romanova, Lovelace, MNRAS 420, 810 (2012)

How long is the accretion process?
Does the neutron star reach maximum mass?

Which is the initial mass of the neutron star?

Which is the maximum stable mass of a neutron star?

Improvements to the First IGC Scenario

- SN core density and SN initial velocity profiles from numerical simulations
- SN core and NS masses from binary evolution codes
- Hydrodynamics inside the Bondi accretion region: photon trapping radius, neutrino emission
- Characteristic emission from the accretion process
- ...

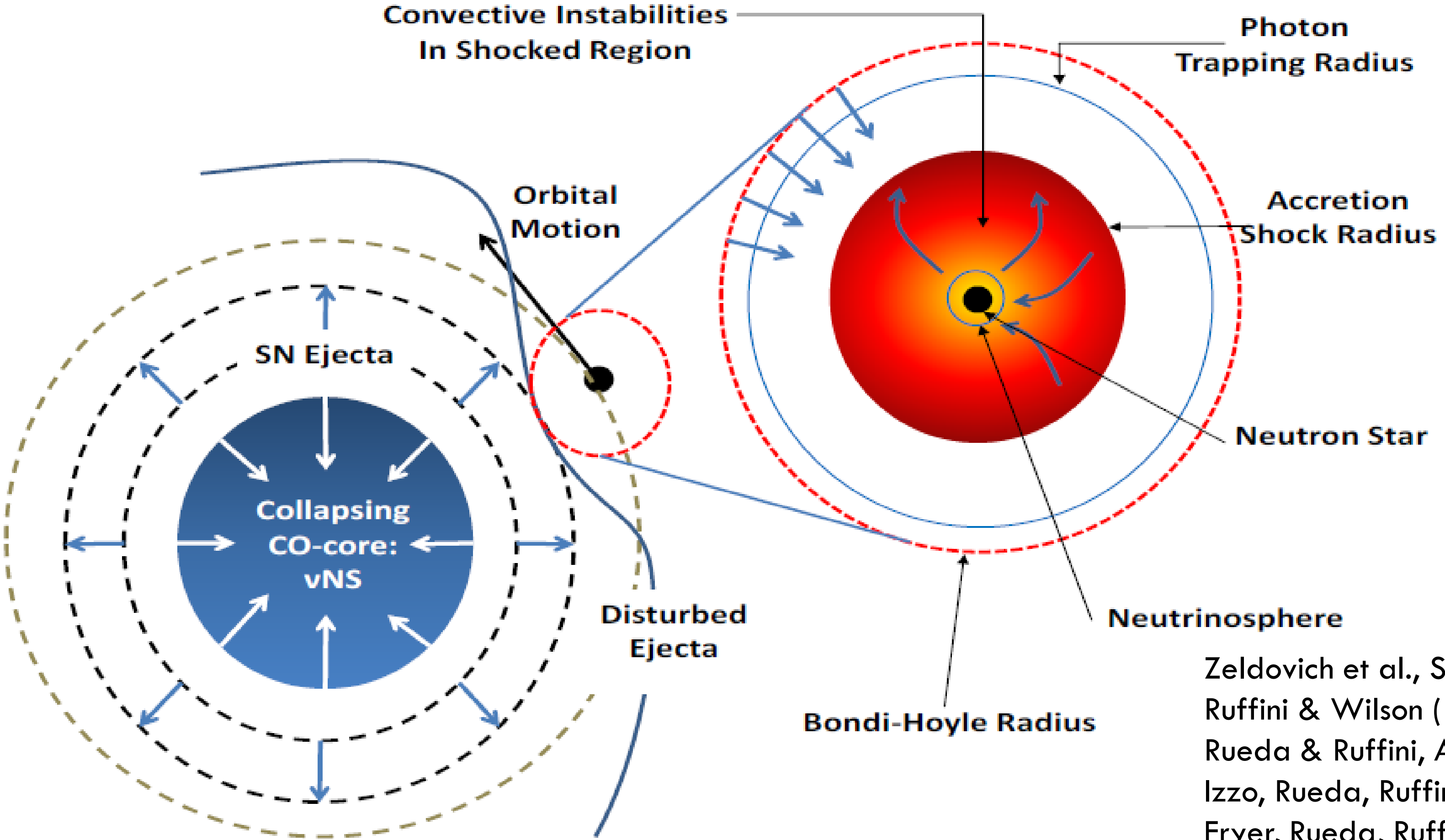
Hypercritical Accretion

Conditions for Eddington limited accretion:

- Potential energy is released in the form of photons
- Inflowing material and outflowing radiation are spherically symmetric
- Photons can flow and deposit momentum to the inflowing material
- Opacity is dominated by electron scattering

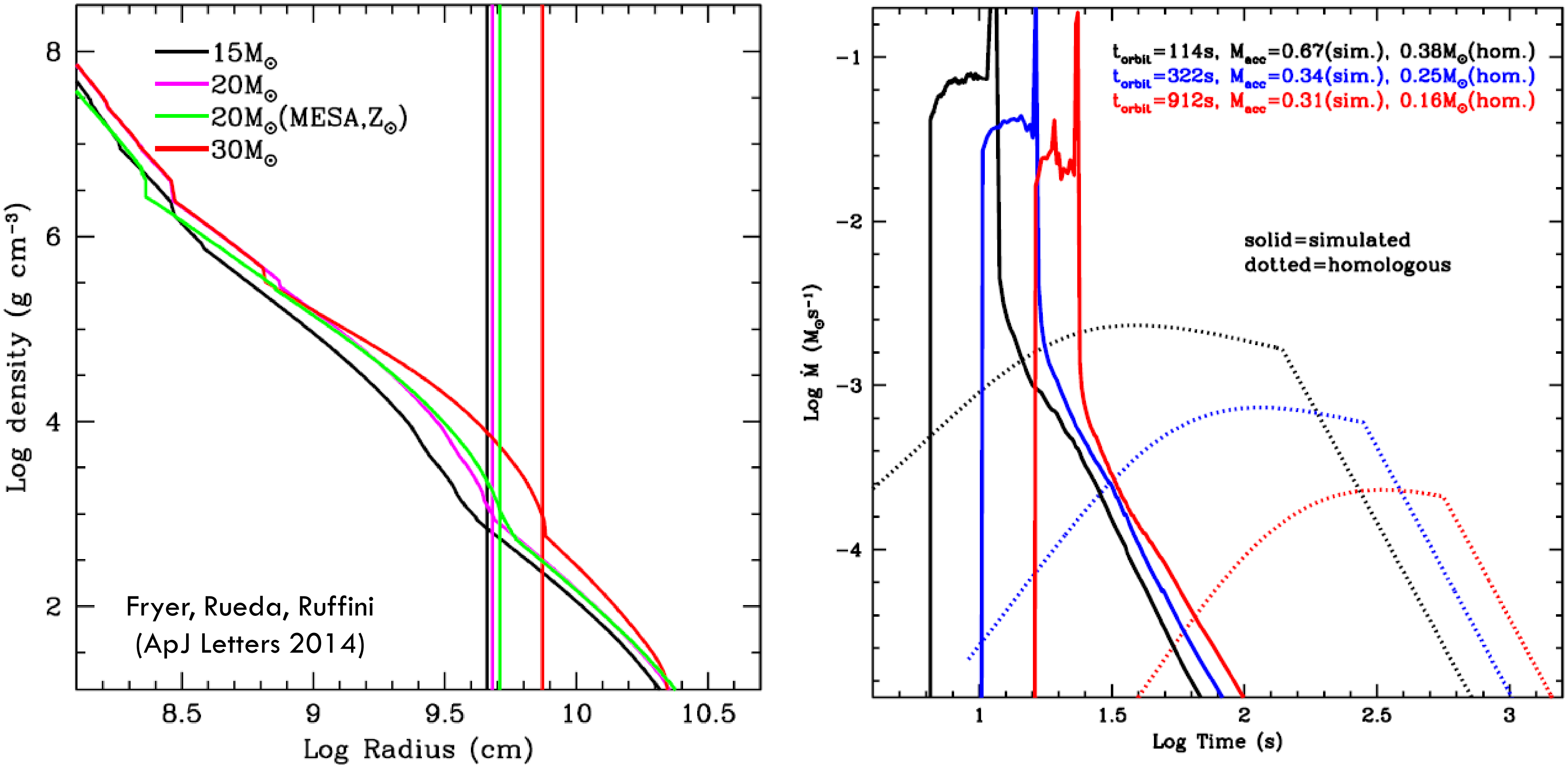
NONE OF THE ABOVE CONDITIONS IS SATISFIED IN THE IGC BINARY SYSTEM !!!

Binary Driven Hypercritical Accretion in the IGC



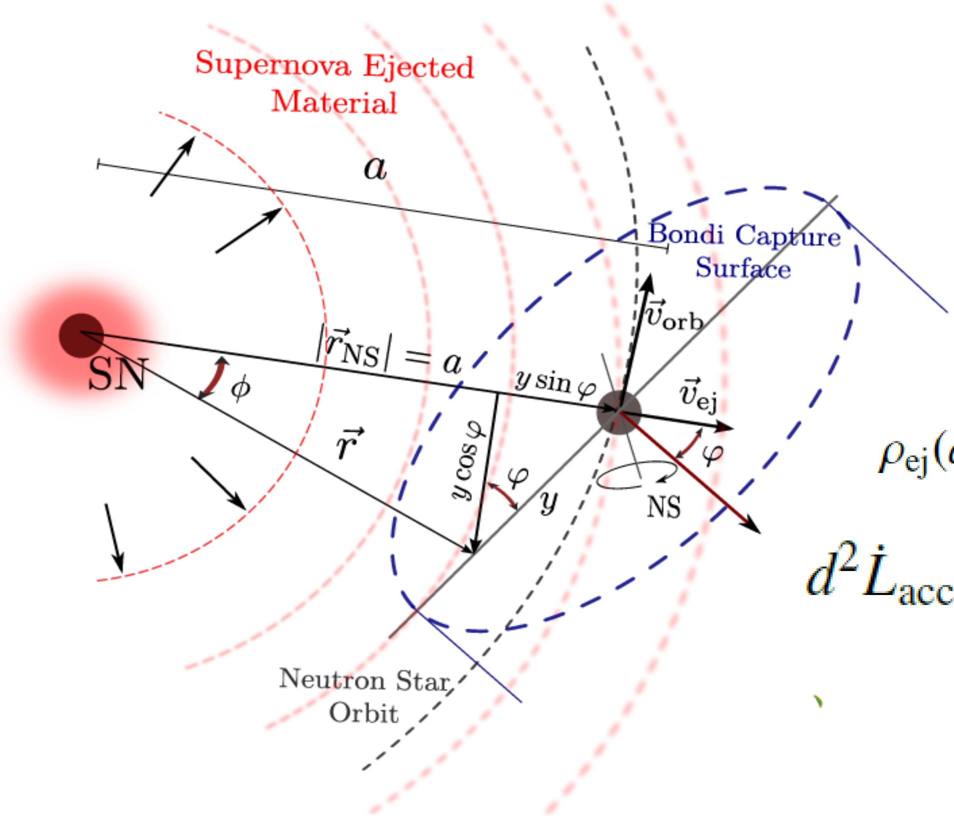
Zeldovich et al., Sov. Astron. (1972)
Ruffini & Wilson (1973)
Rueda & Ruffini, ApJL (2012)
Izzo, Rueda, Ruffini, A&AL (2012)
Fryer, Rueda, Ruffini, ApJL (2014)

$$\dot{M}_{\rm BHL} = 4\pi r_{\rm BHL}^2 \rho (v^2 + c_s^2)^{1/2} \qquad r_{\rm BHL} = \frac{G M_{\rm NS}}{v^2 + c_s^2} \qquad r_{\rm trapping} = min[(\dot{M}_{\rm BHL}\kappa)/(4\pi c), r_{\rm BHL}]$$



On the role of angular momentum in BdHNe

(Becerra, Cipolletta, Fryer, Rueda, Ruffini, ApJ 2015; arXiv: 1505.07580)



$$\dot{M}_B(t) = \pi \rho_{\rm ej} R_{\rm cap}^2 \sqrt{v_{\rm rel}^2 + c_{\rm s,ej}^2}$$

$$R_{\rm cap}(t) = \frac{2GM_{\rm NS}(t)}{v_{\rm rel}^2 + c_{\rm s,ej}^2}$$

$$\rho_{\rm ej}(a) \simeq \rho_{\rm ej}(a)(1+\epsilon_\rho y) \;\; \text{and} \;\; v_{\rm rel}(a) \simeq v_{\rm rel}(a)(1+\epsilon_v y)$$

$$d^2\dot{L}_{\rm acc} = \rho_{\rm ej}(a) v_{\rm rel}^2(a) \left[y + (\epsilon_\rho + 2\epsilon_v) y^2 \right] dy dz$$

$$y^2 + z^2 = R_{\rm cap}^2 = \left(\frac{2GM_{\rm NS}}{v_{\rm rel}^2(a,t)} \right)^2 (1 - 4\epsilon_v y)$$

On the role of angular momentum in BdHNe

(Becerra, Cipolletta, Fryer, Rueda, Ruffini, ApJ 2015; arXiv:1505.07580)

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

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

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

$$\rho_{\rm ej}(r,t) \approx \rho_{\rm ej}(a,t)\left(1 + \frac{1}{\rho_{ej}(a,t)}\left.\frac{\partial\rho_{\rm ej}}{\partial r}\right|_{(a,t)}\delta r\right)$$

$$v_{\rm ej}(r,t) \approx v_{\rm ej}(a,t)\left(1 + \frac{1}{v_{\rm ej}(a,t)}\left.\frac{\partial v_{\rm ej}}{\partial r}\right|_{(a,t)}\delta r\right)$$

$$\dot{L}_{\rm acc} = 8\pi\rho_{\rm core}\left(\frac{R_{\rm core}}{a}\right)^m\frac{GM_{\rm NS}(t_0)a^2}{(1+q)^3}H(y)$$

$$H(y) = y^{n(m-3)}\left(\frac{M_{\rm G}(M_b)}{M_{\rm NS}(t_0)}\right)^4(1-\chi\mu_B)\left(1+\frac{\eta}{y^2}\right)^{-7/2}\left(\frac{m}{2}+\frac{6\eta}{y^2+\eta}\right)$$

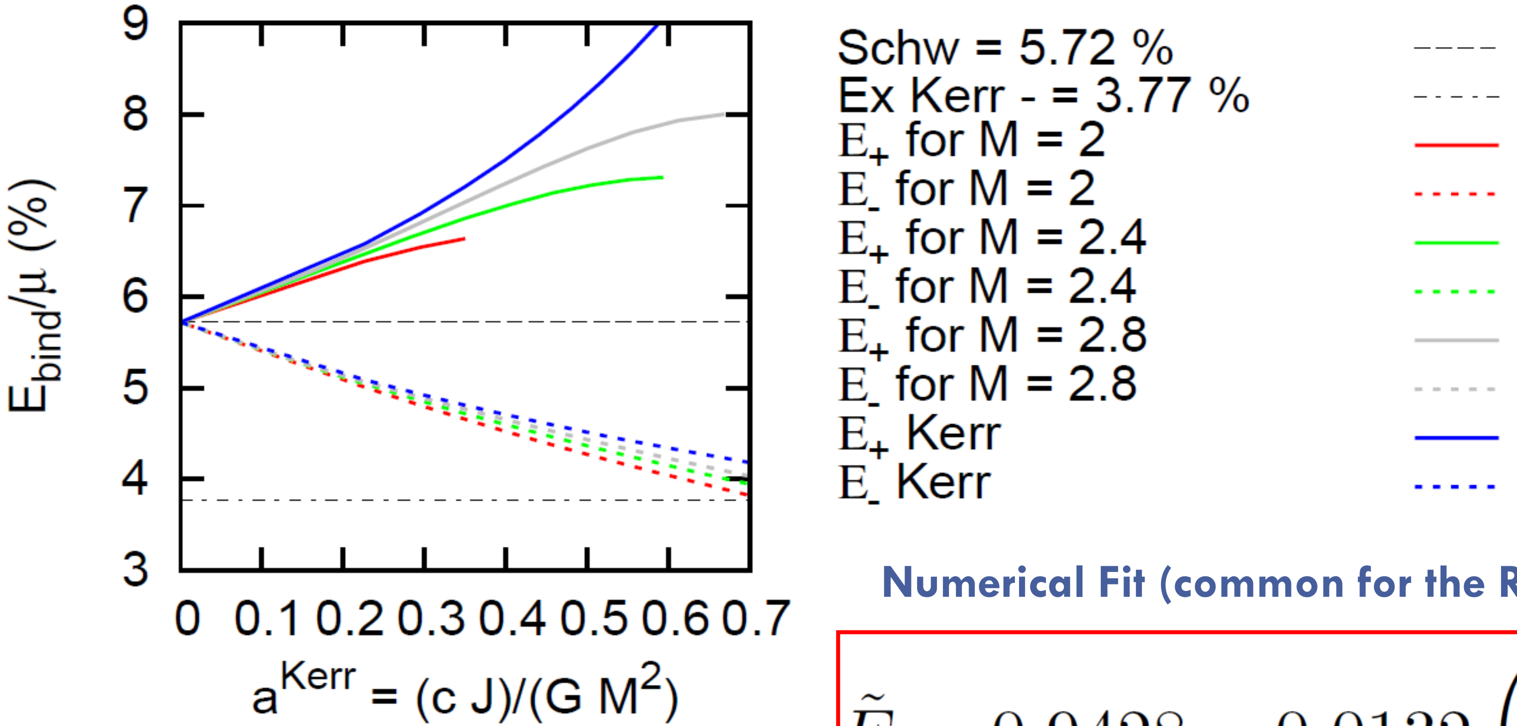
$$\frac{\dot{\mu}_B}{(1-\chi\mu_B)M_{\rm G}(M_b)^2} = \frac{t_0}{\tau_B}\frac{y^{n(m-3)}}{\hat{r}^m}\left[1+\eta\left(\frac{\hat{r}}{y}\right)^2\right]^{-3/2}$$

$$y \equiv \frac{t}{t_0}, \qquad \mu_B \equiv \frac{M_B(y)}{M_{\rm NS}(t_0)}, \qquad \hat{r} \equiv 1 - \frac{R_B}{a}$$

$$\tau_B \equiv \frac{M_{\rm NS}(t_0)v_{\rm orb}^3}{4\pi G^2\rho_{\rm ej}(a,t_0)}, \qquad \chi \equiv \frac{M_{0_{\rm NS}}}{M_{\rm env}(t_0)}, \qquad \eta \equiv \left(\frac{n}{t_0}\frac{a}{v_{\rm orb}}\right)^2$$

Mostly bound circular orbit around rotating NSs

(Cipolletta, Rueda, Ruffini, PRD, submitted)

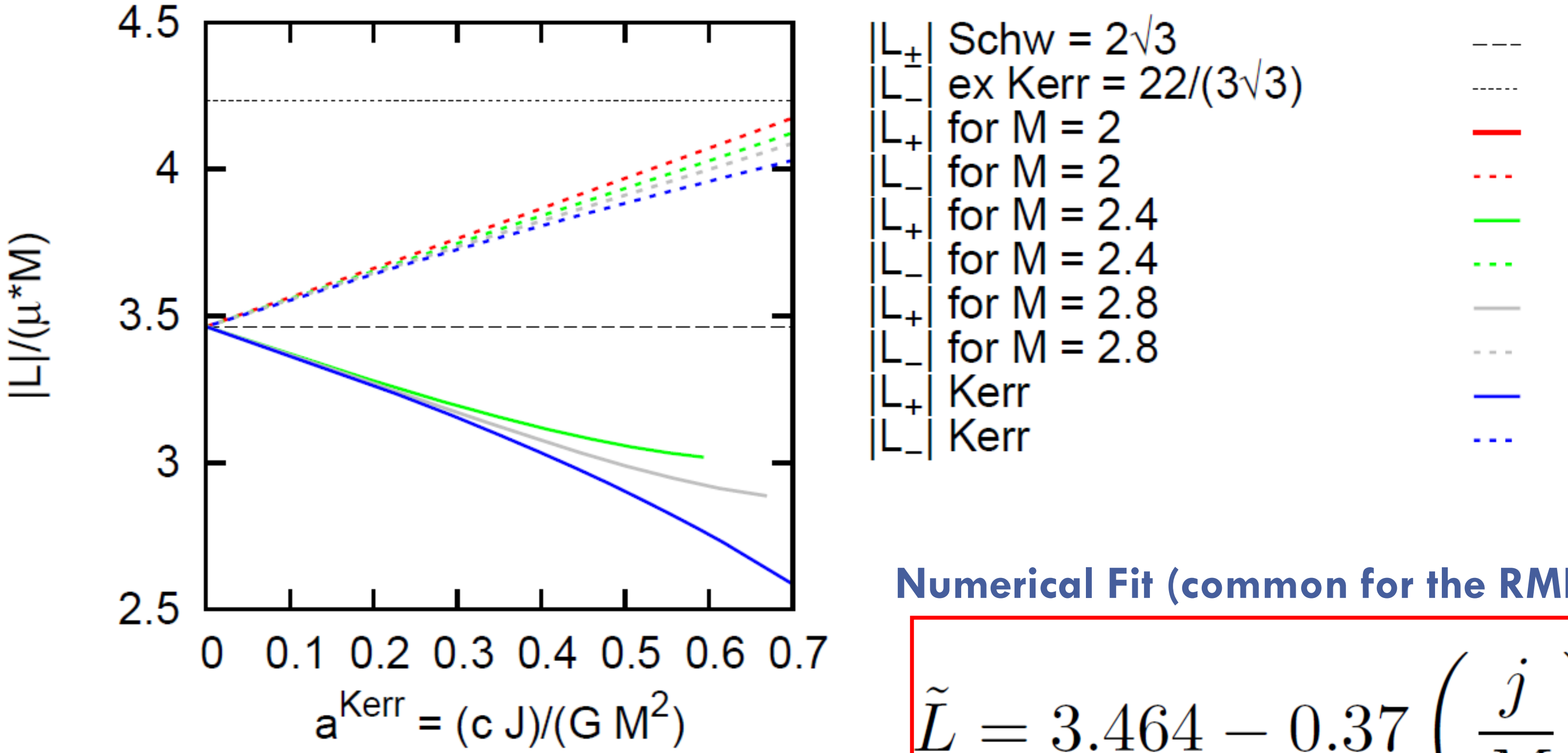


Numerical Fit (common for the RMF EOS !):

$$\tilde{E} = 0.9428 - 0.0132 \left(\frac{j}{M} \right)^{0.85}$$

Mostly bound circular orbit around rotating NSs

(Cipolletta, Rueda, Ruffini, PRD, submitted)

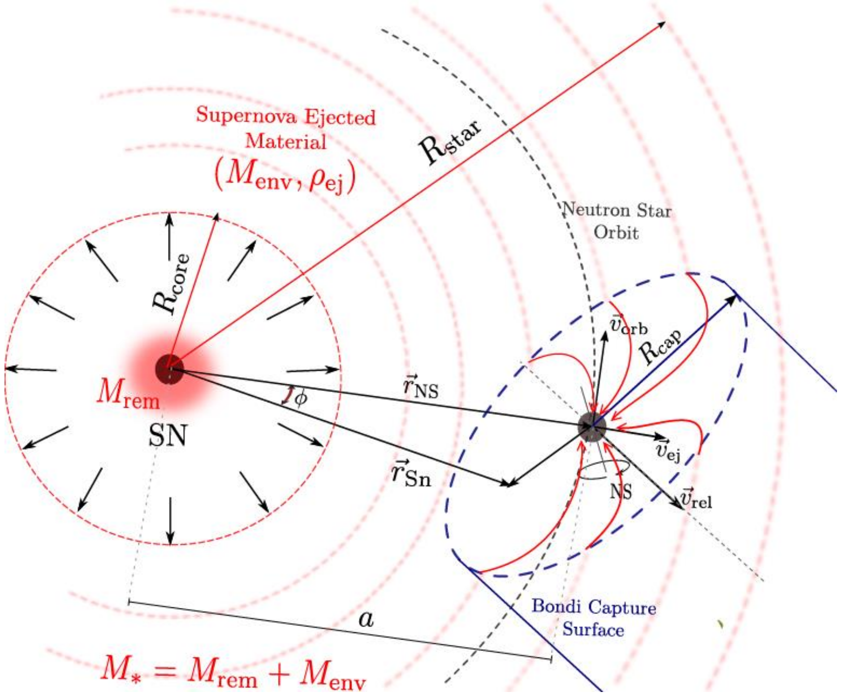


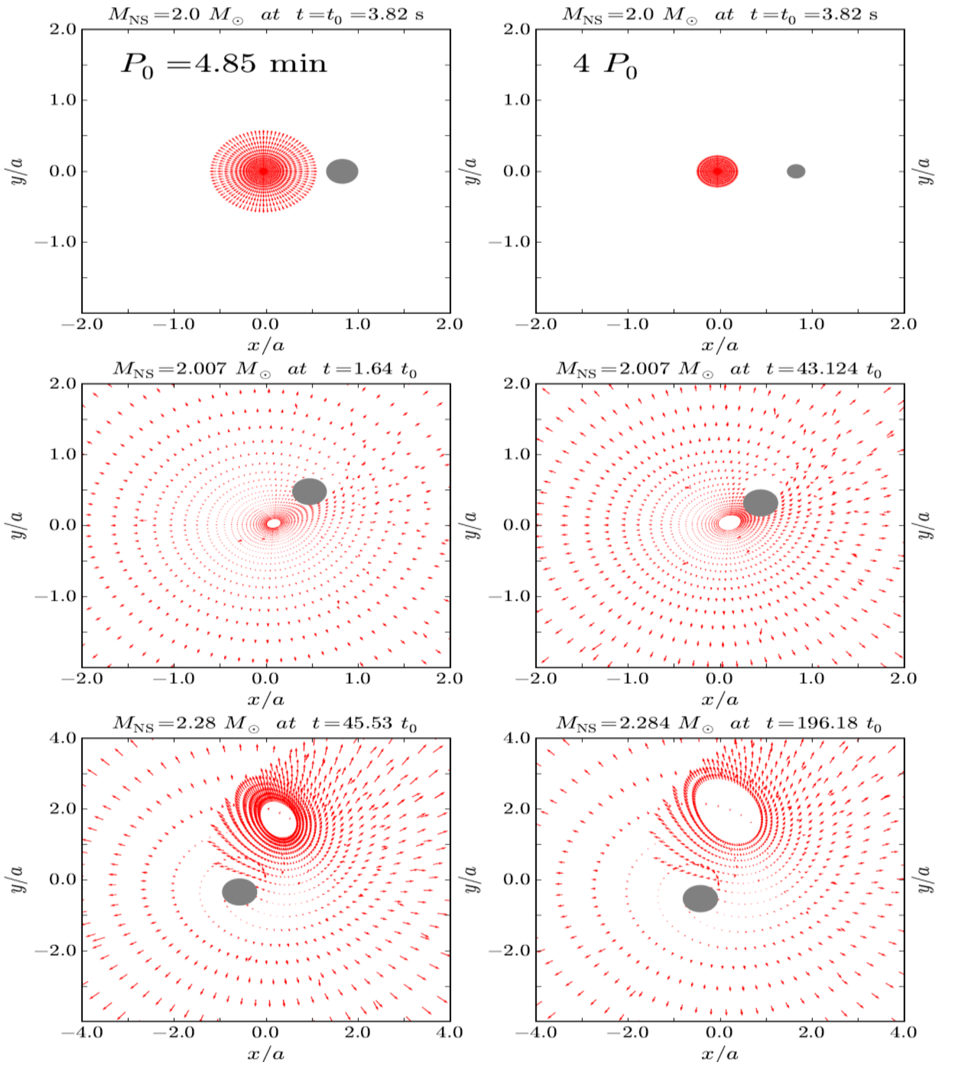
Numerical Fit (common for the RMF EOS !):

$$\tilde{L} = 3.464 - 0.37 \left(\frac{j}{M} \right)^{0.85}$$

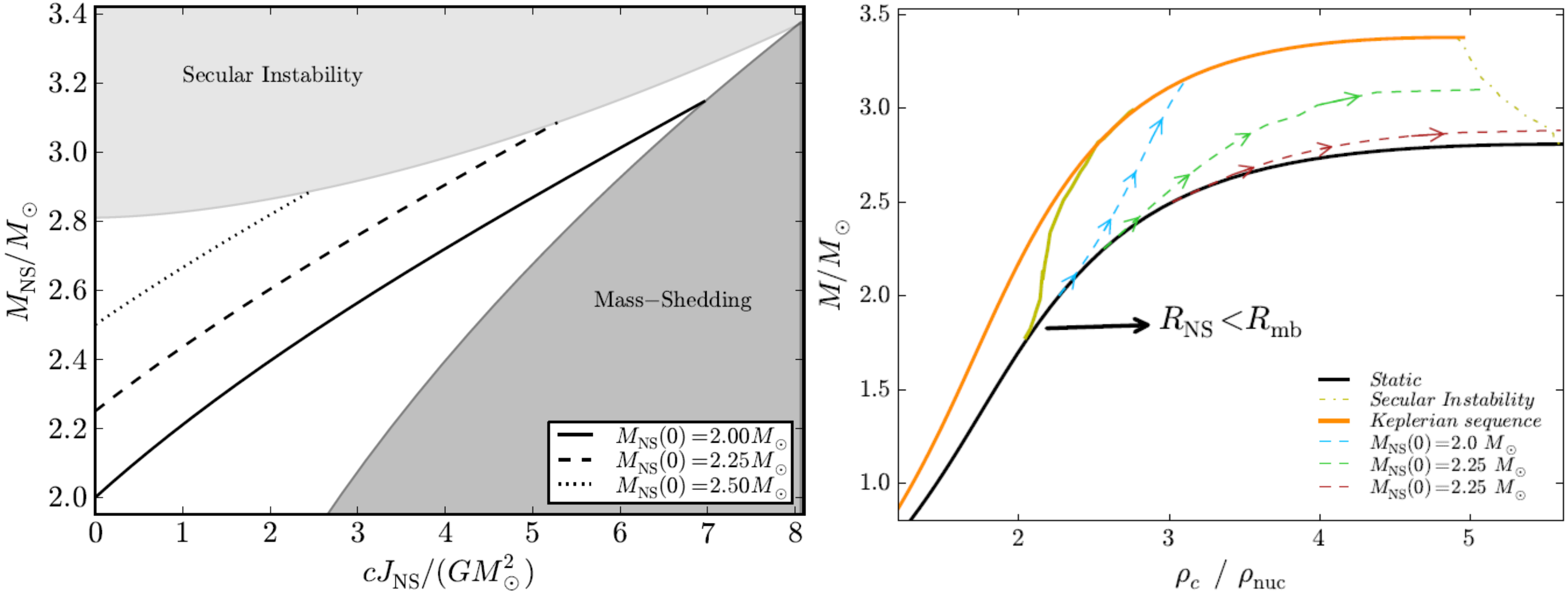
NS evolution during hypercritical accretion

Becerra, Cipolletta, Fryer, Rueda, Ruffini, ApJ 2015:
arXiv:1505.07580





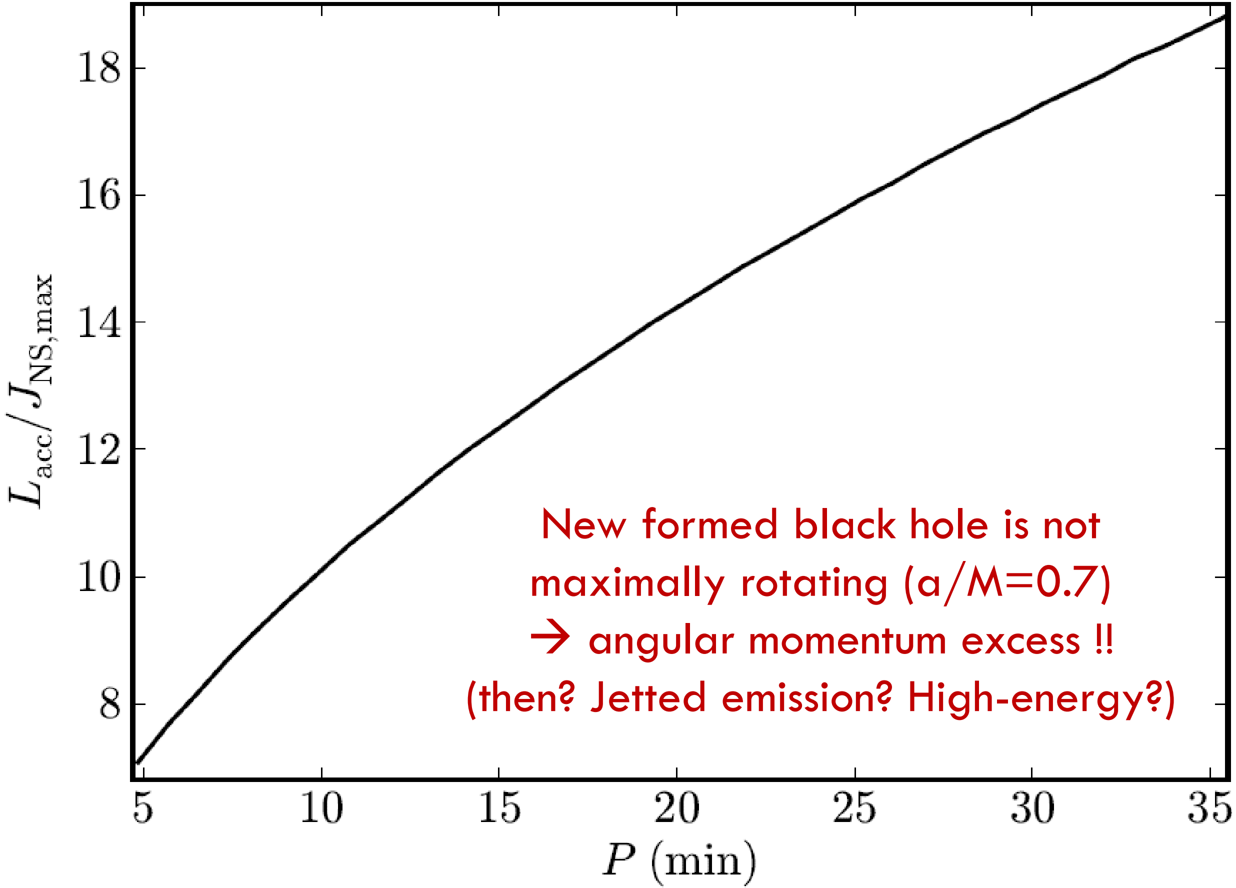
NS evolution up to the instability point



Becerra, Cipolletta, Fryer, Rueda, Ruffini, ApJ 2015; arXiv: 1505.07580

On the role of angular momentum in BdHNe

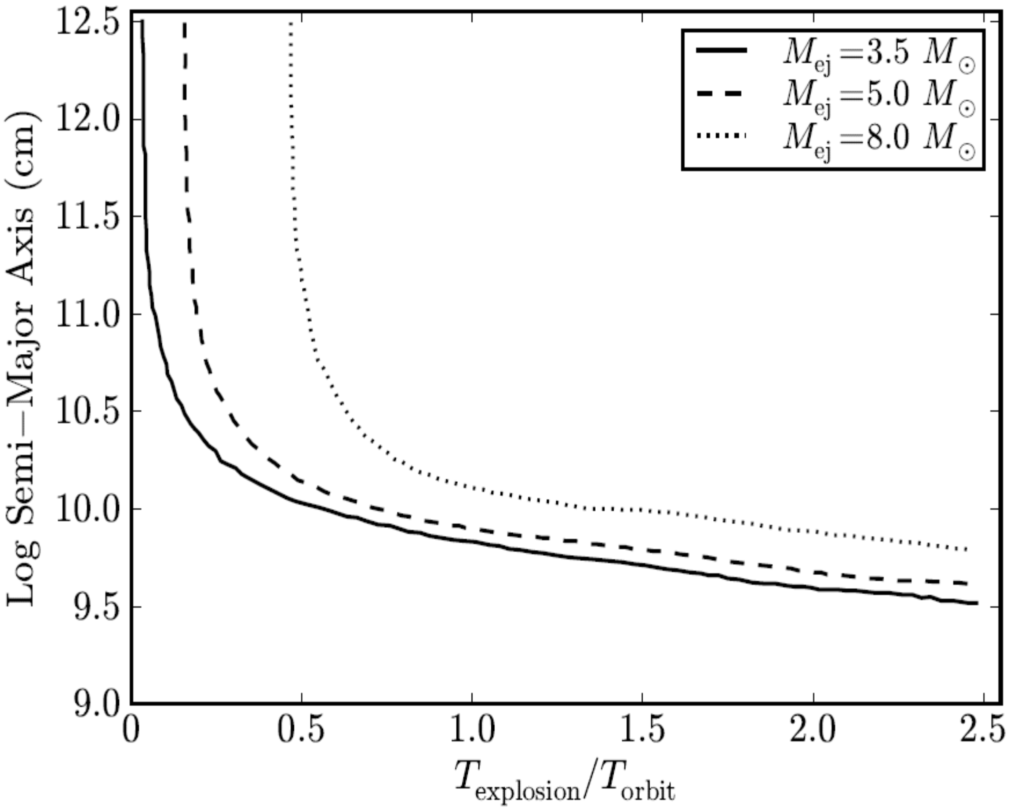
(Becerra, Cipolletta, Fryer, Rueda, Ruffini, ApJ 2015; arXiv: 1505.07580)

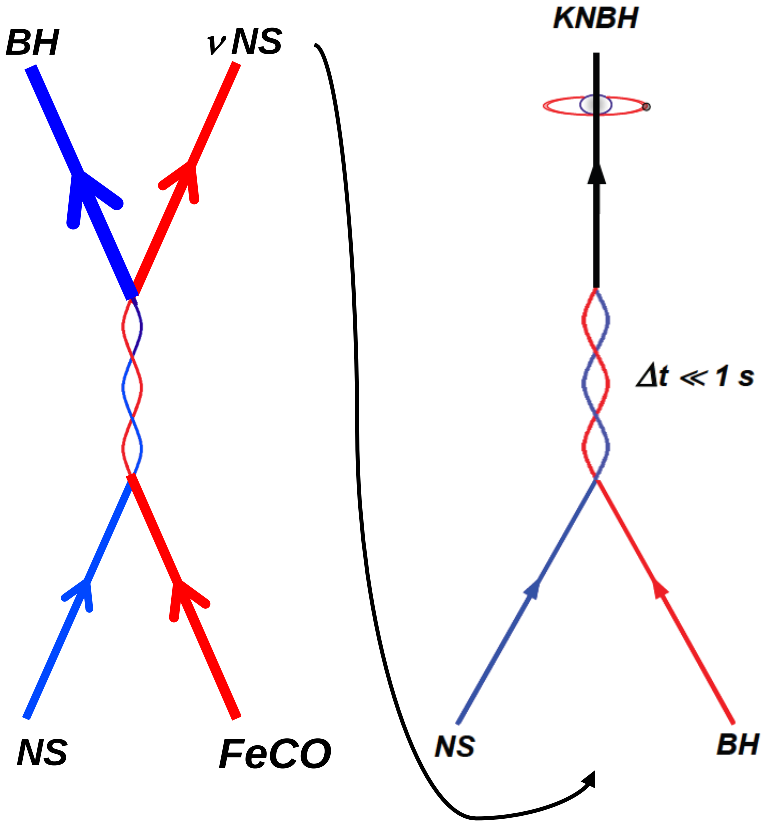


New formed black hole is not maximally rotating (a/M=0.7)
→ angular momentum excess !!
(then? Jetted emission? High-energy?)

What's next?
On the NS-BH binaries produced by BdHNe

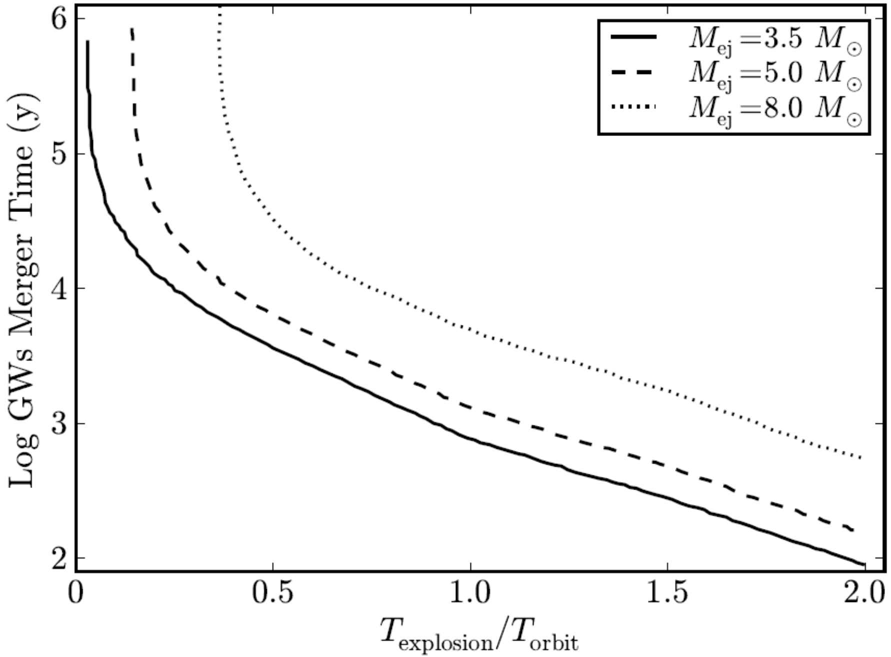
(Fryer, Oliveira, Rueda, Ruffini, Phys. Rev. Lett., in press)

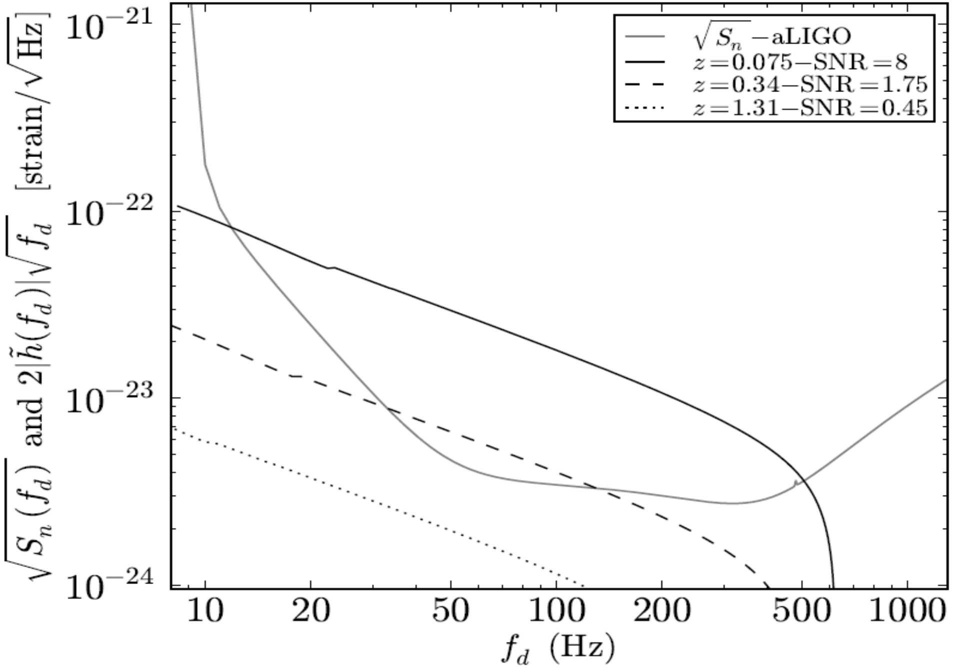




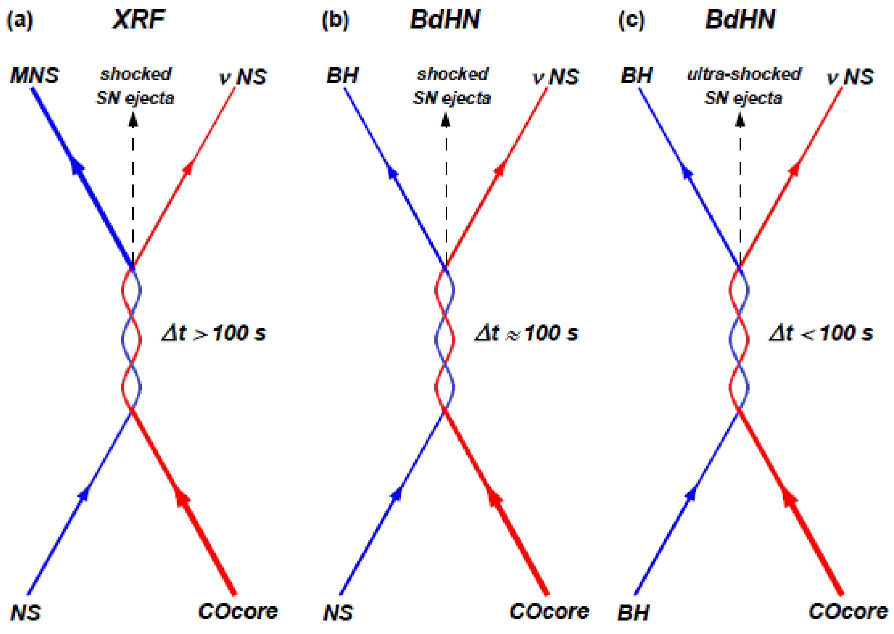
What's next?
On the NS-BH binaries produced by BdHNe

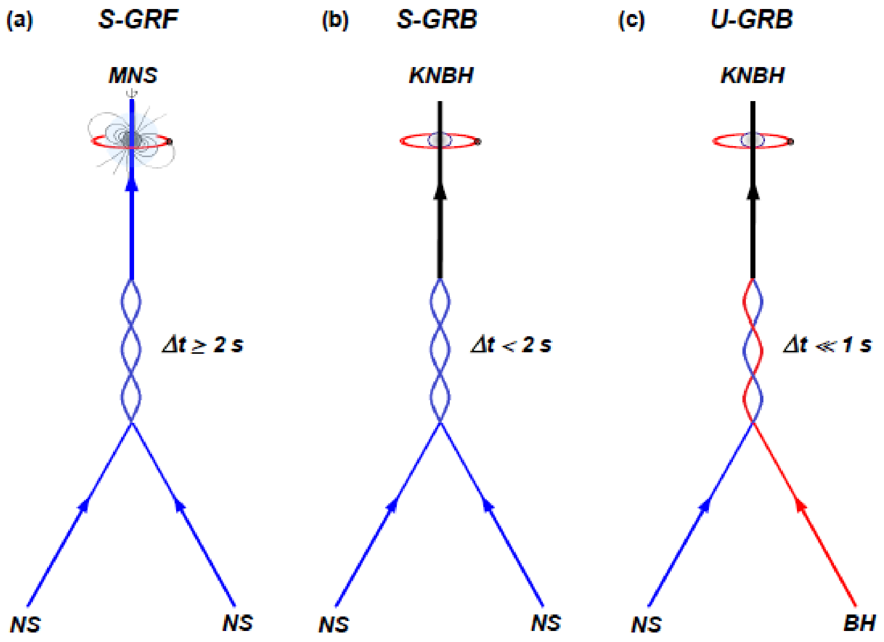
(Fryer, Oliveira, Rueda, Ruffini, Phys. Rev. Lett., in press)





CONCLUSION


(a) XRF
MNS
shocked SN ejecta
ν NS
Δt > 100 s
NS
COcore
(b) BdHN
BH
shocked SN ejecta
ν NS
Δt ≈ 100 s
NS
COcore
(c) BdHN
BH
ultra-shocked SN ejecta
ν NS
Δt < 100 s
BH
COcore


(a) S-GRF
MNS
Δt ≥ 2 s
NS
NS
(b) S-GRB
KNBH
Δt < 2 s
NS
NS
(c) U-GRB
KNBH
Δt ≪ 1 s
NS
BH