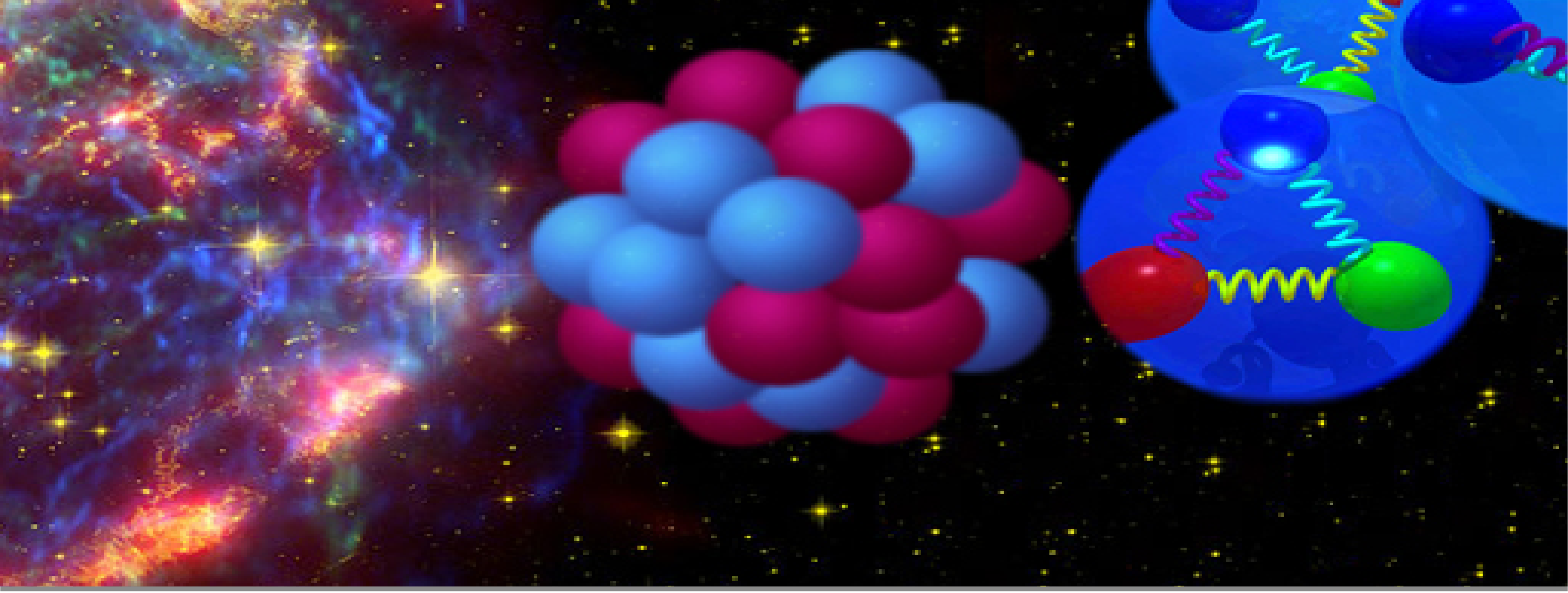

Physics and Astrophysics of Neutron Stars

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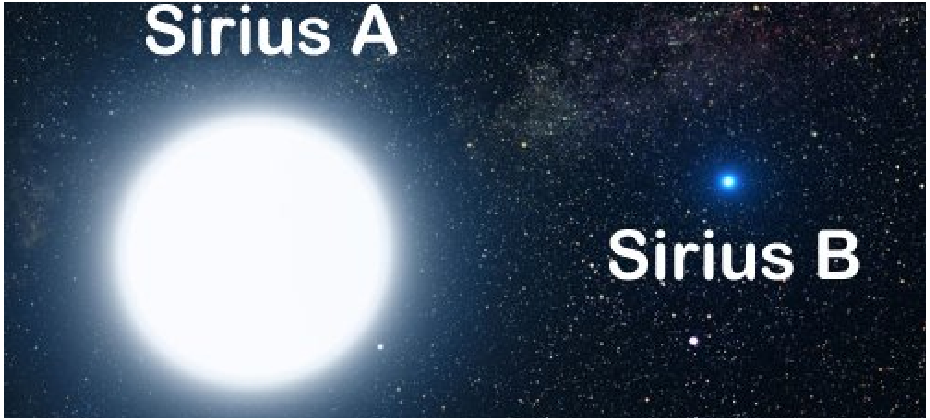
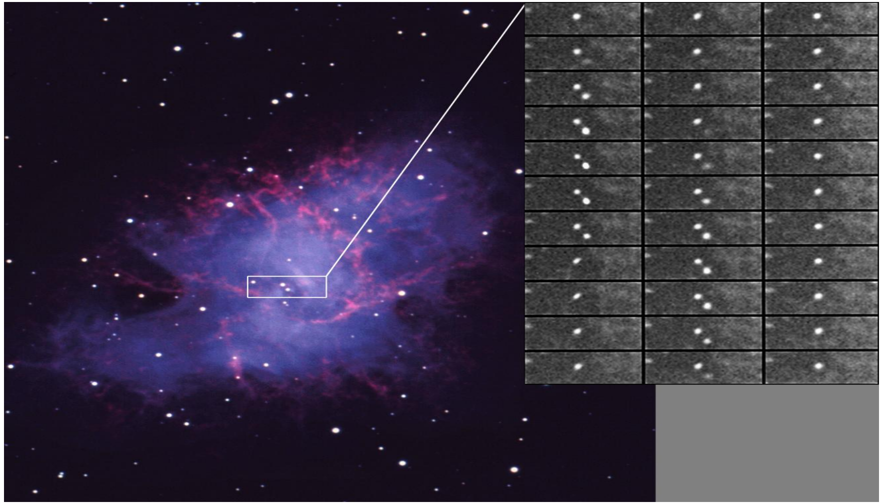
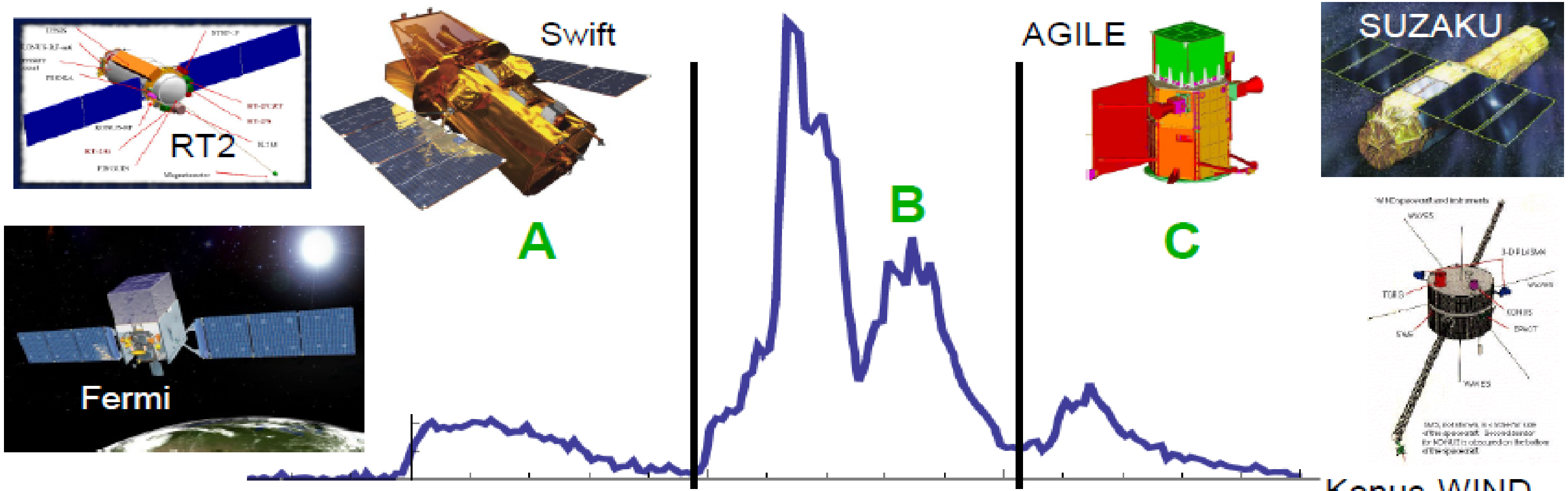
ISYA2018, Universidad Industrial de Santander, El Socorro

Introduction

White Dwarfs and Neutron Stars



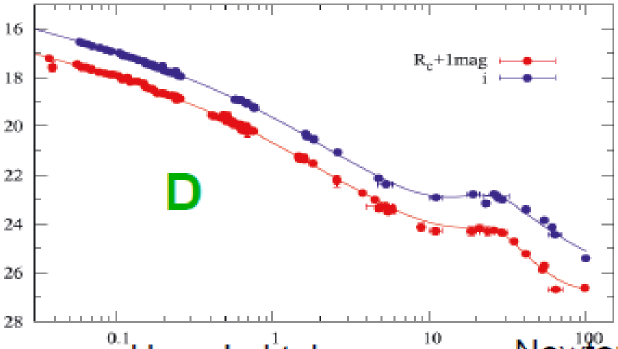




GRB 090618

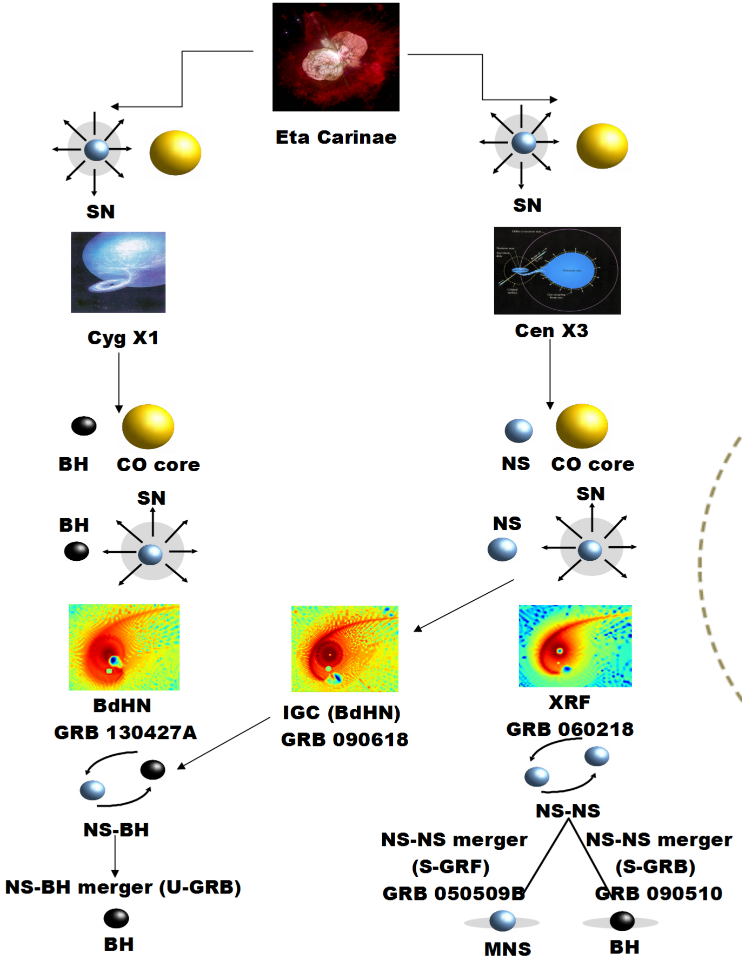
Eiso=2.8x10^{53} erg

Z=0.54

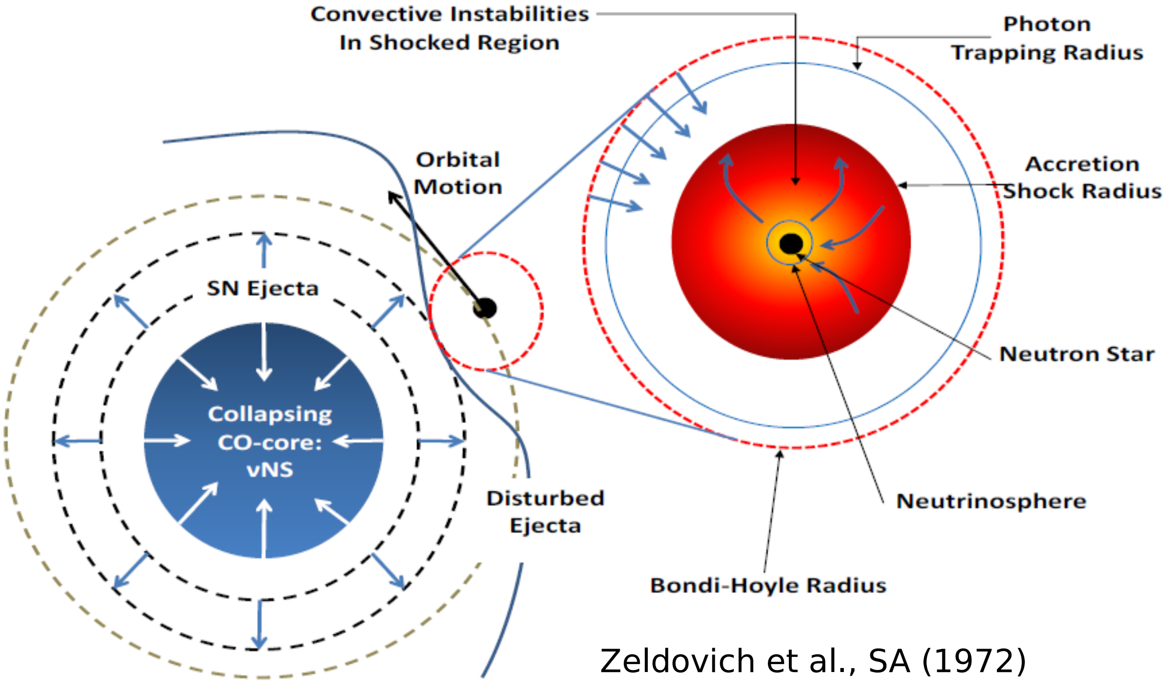


Ruffini et al. *PoS(Texas2010)*, 101 (2011)
Izzo et al., *A&A*, 543, A10 (2012)

A common evolutionary scenario for short and long GRBs

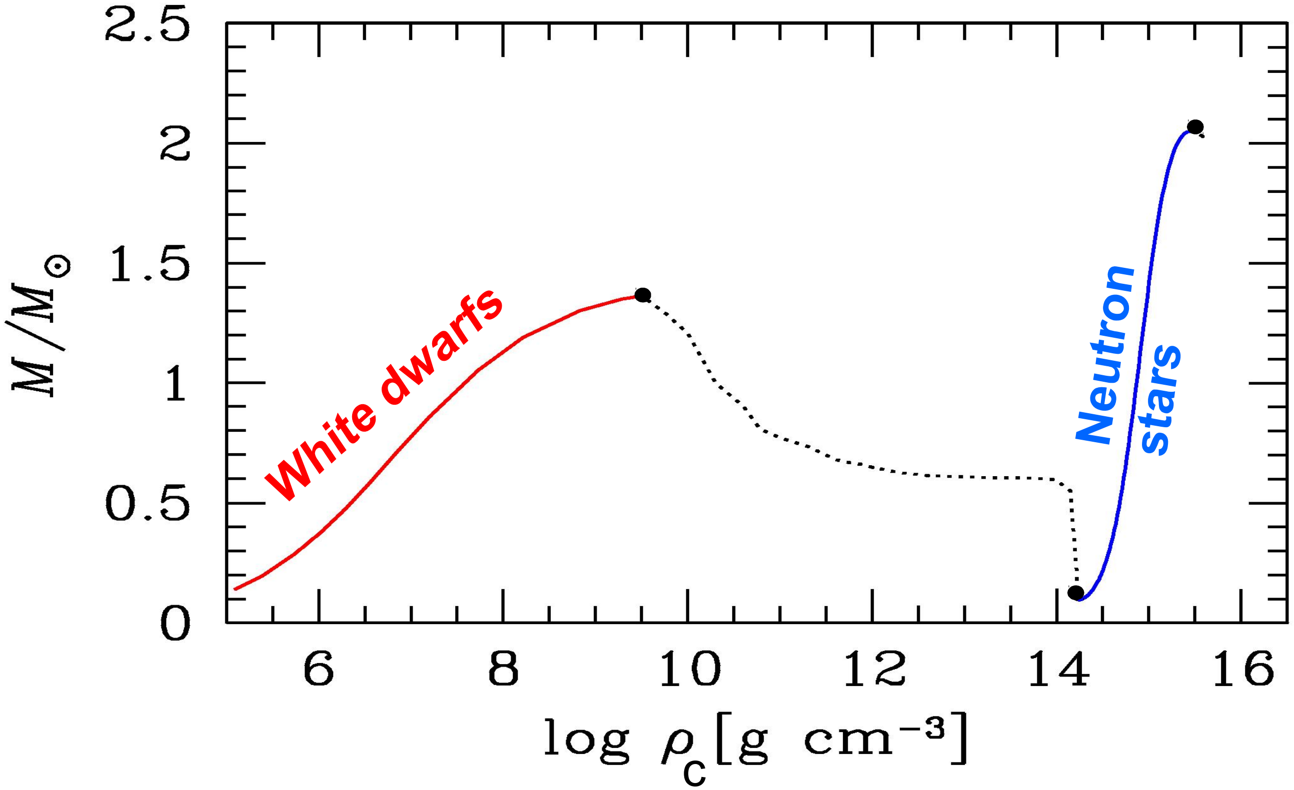


Binary-driven hypernovae (BdHNe)



Zeldovich et al., SA (1972)
Ruffini & Wilson, PRL (1973)
Rueda & Ruffini, ApJL (2012)
Fryer, Rueda, Ruffini, ApJL (2014)

Parte I:
Physics of White Dwarfs and Neutron Stars



Some properties

White Dwarfs

M= smaller than 1.4*Msun (Stoner 1929, Chandrasekhar 1931, Landau 1932)

R ~ 0.01*Rsun ~ 10^9 cm

Densityies < 10^10 g/cc

Grav. Pot.=G*M/R=10^-4*M c^2

Supported by electron degeneracy pressure

Neutron Stars

M= smaller than 3.2*Msun (Rhoades & Ruffini, 1972)

R ~ 10^-5*Rsun ~ 10^6 cm

Densities>nuclear density=2.7*10^14 g/cc

Grav. Pot.=G*M/R=10^-1*Mc^2

Supported by neutron degeneracy pressure

From a WD to a NS: from atomic to nuclear physics

The Nucleus

$Rn = r0*A^{(1/3)} = fermi = 10^{-13}$ cm

$A = N + Z < 200$

$Density = mn*A/Rn^3$
$= mn/r0^3 = 10^{15}$ g/cc

The Atom (free)

$R_{Bohr} = hbar^2/(me*e^2) = 10^{-8}$ cm $= 10^5*Rn$

$Ne = Z$

$Density = Nuclear\ density*(Rn/R_{Bohr})^3 = 1$ g/cc

Physics at work

White Dwarfs

Microphysics:

Atomic Physics, Solid State Physics, Quantum Statistics, Coulomb interactions, Nuclear Physics at experimental level

Macrophysics:

General Relativity equations of equilibrium

Neutron Stars

Microphysics:

Atomic Physics, Solid State Physics, Quantum Statistics, Coulomb interactions, Weak interactions equilibrium, Nuclear Physics at both experimental and theoretical level,

Macrophysics:

General Relativity equations of equilibrium

White dwarf physics

Equation of state (EOS) of a fermion gas

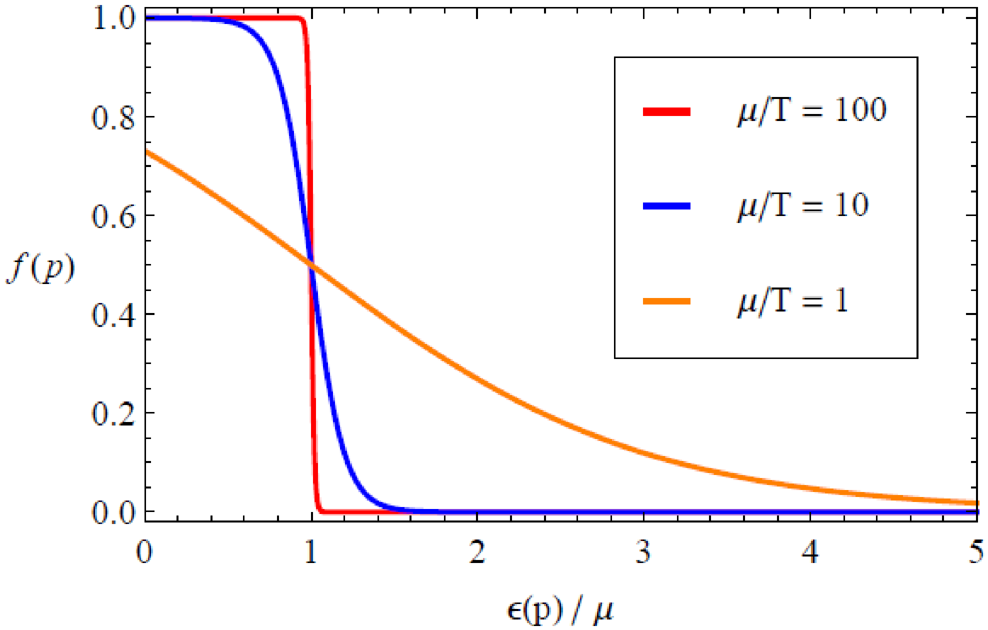
General equations

$$
\begin{aligned}
n = \frac{N}{V} &= \frac{g}{(2\pi\hbar)^3}\int_0^\infty f(p)d^3p \\
\mathcal{E} = \frac{E}{V} &= \frac{g}{(2\pi\hbar)^3}\int_0^\infty f(p)\epsilon(p)d^3p \\
P = \left(\frac{\partial E}{\partial V}\right)_S &= \frac{1}{3}\frac{g}{(2\pi\hbar)^3}\int_0^\infty f(p)\frac{p^2}{\epsilon(p)}d^3p
\end{aligned}
$$

N: number of particles | V: volume of the system
E: total energy of the system | P: total pressure
$\epsilon(p)$: particle energy | p: particle momentum

g: degeneracy of energy levels $= 2$ for fermions (spin $\uparrow$ and $\downarrow$)
$f(p)$: distribution function (or average occupation number)

EOS of a fermion gas



$$\begin{aligned} \epsilon(p) &= \text{particle energy} \\ \mu &= \text{chemical potential} \\ T &= \text{temperature} \\ \mu/T &= \text{degeneracy parameter} \end{aligned}$$

Boltzmann limit: $\mu/T << 1$

$$f(p) = \frac{1}{1 + e^{\frac{\epsilon(p)-\mu}{T}}} \approx e^{\frac{\mu-\epsilon(p)}{T}} << 1$$

$\Rightarrow$ $$P = nk_BT$$

Degenerate limit: $\mu/T >> 1$

$$f(p) = \frac{1}{1 + e^{\frac{\epsilon(p)-\mu}{T}}} \approx \begin{cases} 1 & \text{for} \quad \epsilon \leq \mu \\ 0 & \text{for} \quad \epsilon > \mu \end{cases}$$

EOS of a fermion gas

The Onset of Degeneracy: Pdeg >> Pideal

$$\boxed{\frac{(3\pi^2)^{2/3}}{5}\frac{\hbar^2}{m^{5/3}}\frac{\rho^{2/3}}{k_B T} \gg 1\,, \qquad \rho = mn}$$

Assuming T=10^5 K

$$\begin{cases} \left(\frac{(3\pi^2)^{2/3}}{5}\frac{\hbar^2}{m^{5/3}}\frac{\rho^{2/3}}{k_B T}\right)_{WD} = 10^3 \\ \left(\frac{(3\pi^2)^{2/3}}{5}\frac{\hbar^2}{m^{5/3}}\frac{\rho^{2/3}}{k_B T}\right)_{NS} = 10^8 \end{cases}$$

EOS of a fermion gas

Degenerate Case: T=0

$$n_e = \frac{(P_e^F)^3}{3\pi^2\hbar^3}$$

$$P_e^F = m_e c x_e$$

$$P_e = \frac{1}{3}\frac{2}{(2\pi\hbar)^3}\int_0^{P_e^F}\frac{c^2p^2}{\sqrt{c^2p^2+m_e^2c^4}}4\pi p^2 dp$$

$$= \frac{m_e^4c^5}{8\pi^2\hbar^3}[x_e\sqrt{1+x_e^2}(2x_e^2/3-1)+\ \operatorname{arcsinh}(x_e)]$$

Non-Relativistic Limit

$$P_e = \frac{(3\pi^2)^{2/3}}{5}\frac{\hbar^2}{m_e}n_e^{5/3}$$

Ultra-Relativistic Limit

$$P_e = \frac{(3\pi^2)^{1/3}}{4}\hbar c n_e^{4/3}$$

Self-gravitating system of degenerate fermions: non-relativistic case

Stoner's approach (1929)

$$E = E_{deg} + E_g = N\frac{P_F^2}{2m} - \frac{3}{5}\frac{GM^2}{R}$$

$$= \frac{3}{10}\left(\frac{9\pi}{4}\right)^{2/3}\frac{\hbar^2}{m}\frac{N^{5/3}}{R^2} - \frac{3}{5}\frac{Gm^2N^2}{R}$$

$$\left(\frac{\partial E}{\partial R}\right)_N = 0$$

For a given N, it is always possible to obtain an equilibrium configuration of radius:

$$R = \left(\frac{9\pi}{4}\right)^{2/3}\frac{\hbar^2}{Gm^3}\frac{1}{N^{1/3}}$$

Self-gravitating system of degenerate fermions: ultra-relativistic case

Stoner's approach (1929)

$$E = E_{deg} + E_g = NcP_F - \frac{3}{5}\frac{GM^2}{R}$$
$$= \frac{3}{4}\left(\frac{9\pi}{4}\right)^{1/3}\hbar c\frac{N^{4/3}}{R} - \frac{3}{5}\frac{Gm^2N^2}{R}$$

$$\left(\frac{\partial E}{\partial R}\right)_N = 0$$

The solution does not depend on the radius !!

$$M_{crit} = mN_{crit} = \frac{15}{16}\sqrt{5\pi}\frac{m^3_{\text{Planck}}}{m^2}$$

Relaxing the assumption of uniform density

Basic Assumptions

$$E^F = \underbrace{\sqrt{(cP^F)^2 + m^2c^4} - mc^2 - m\Phi = \text{constant} = -m\Phi(R)}_{\text{Equilibrium Condition}}$$

$$\nabla^2\Phi = -4\pi G m n\,, \qquad n = \frac{(P^F)^3}{3\pi^2\hbar^3}$$

New convenient variable

$$\Phi(r) - \Phi(R) = GmN\frac{\chi(r)}{r}$$

Poisson's equation

$$\frac{d^2\chi(\xi)}{d\xi^2} = -\frac{\chi(\xi)^{3/2}}{\xi^{1/2}}\left[1 + \left(\frac{N}{N^*}\right)^{4/3}\frac{\chi(\xi)}{\xi}\right]^{3/2}$$

$$N^* = \frac{\sqrt{3\pi}}{2}\left(\frac{m_{\text{Planck}}}{m}\right)^3$$

Boundary Conditions

$$\chi(0) = \chi(\xi_0) = 0\,, \qquad \left(\frac{d\chi}{d\xi}\right)_{\xi=0} > 0$$

$$\int_0^{\xi_0} \chi^{3/2}\xi^{1/2}d\xi = -\xi_0\left(\frac{d\chi}{d\xi}\right)_{\xi=\xi_0} = 1$$

The Chandrasekhar-Landau Mass

$$P^F >> m\,c \quad \Rightarrow \quad E_F = cP^F - m\Phi = \text{constant} = -m\Phi(R)$$

$$\frac{d^2\chi(\xi)}{d\xi^2} = -\left(\frac{N}{N^*}\right)^2 \frac{\chi(\xi)^3}{\xi^2} \quad \begin{cases} \chi(0) = \chi(\xi_0) = 0\,, \\ \int_0^{\xi_0} \chi^{3/2}\xi^{1/2} d\xi = -\xi_0 \left(\frac{d\chi}{d\xi}\right)_{\xi=\xi_0} = 1 \end{cases}$$

$$\frac{d^2\hat{\chi}}{d\hat{x}^2} = -\frac{\hat{\chi}^3}{\hat{x}^2} \quad \begin{cases} \hat{\chi}(0) = 0, \quad \hat{\chi}(\hat{x}_0) = 0, \quad \frac{N}{N^*} = -\hat{x}_0 \left(\frac{d\hat{\chi}}{d\hat{x}}\right)_{\hat{x}=\hat{x}_0} = 2.015 \end{cases}$$

n=3 (gamma=4/3) Lane-Emden Polytrope !!

The Critical Mass

$$\boxed{M_{crit} = m\,N = 2.015\,N^* = 2.015\frac{\sqrt{3\pi}}{2}\frac{m_{\text{Planck}}^3}{m^2}}$$

Approx. 20% smaller than Stoner’s value

Application to WDs and NSs

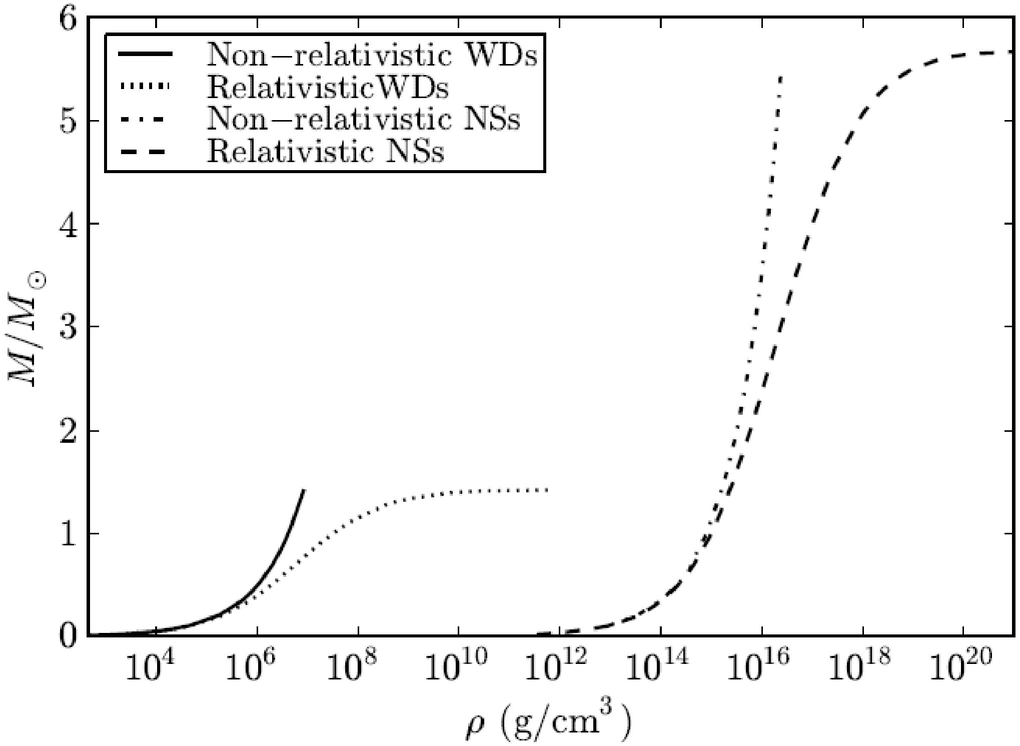
White Dwarfs

$$n_e = \frac{Z}{A_r} n_N$$

$$M_{crit} = m_n\, N = 2.015\, N^* = \frac{\sqrt{3\pi}}{2} \frac{m_{\text{Planck}}^3}{\mu^2 m_N^2} \approx 1.44 M_\odot$$

Neutron Stars

$$M_{crit} = m\, N = 2.015\, N^* = \frac{\sqrt{3\pi}}{2} \frac{m_{\text{Planck}}^3}{m_n^2} \approx 5.76 M_\odot$$



Electrostatic corrections

Chandrasekhar approximation…

Uniform Electrons

Uniform Nucleons

A/Z fixed parameter

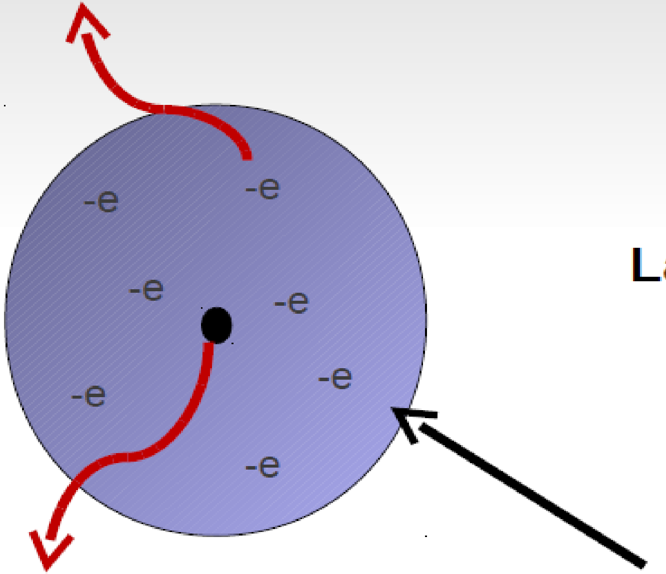
NO Electromagnetic Interactions

Relativistic degenerate gas of electrons

$$\rho = \frac{A}{Z} m_N n_e \qquad P = P_e(n_e)$$

Lattice model...

Ne = Z uniform electrons



Point-like nucleus +eZ

Wigner-Seitz cell

$$E_{WS} = E_N - \frac{9}{10}\frac{Z^2 e^2}{R_{WS}}$$

Lattice Energy (Coulomb energy)

$$P_{WS} = P_e + \frac{1}{3}\frac{E_L}{V_{WS}}$$

Effect on the critical mass

Homework:
Show that the critical mass becomes:

$$M_{crit} = M_{crit}^{Ch}\left(1 - \frac{6\alpha}{5}Z^{2/3}\right)^{3/2} < M_{crit}^{Ch}$$

Hint. Use Stoner's approximation

Electron distribution: Thomas-Fermi model

Basic Assumptions

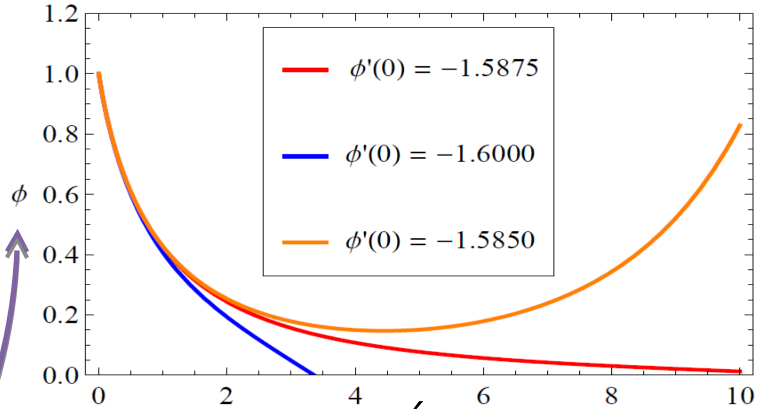
$$\underbrace{E_e^F = \frac{(P_e^F)^2}{2m_e} - eV = \text{constant}}_{\text{Equilibrium Condition}}$$

$$\nabla^2 V = 4\pi e n_e\,, \quad n_e = \frac{(P_e^F)^3}{3\pi^2\hbar^3}, \quad eV(r) + E_e^F = e^2 N_p \frac{\phi(r)}{r}$$

$$r = b\eta\,, \quad b = \frac{\sigma}{N_p^{1/3}} r_{\mathrm{Bohr}}$$

$$\frac{d^2\phi(\eta)}{d\eta^2} = \frac{\phi(\eta)^{3/2}}{\eta^{1/2}}$$

Thomas-Fermi solutions



$$\phi(0) = 1, \quad \phi'(0) < 0$$

$$N_e = \int_0^{R_0} 4\pi n_e(r) r^2 dr = N_p[1 - \phi(\eta_0) + \eta_0 \phi'(\eta_0)]$$

Number of electrons

$$N_e = \int_0^{R_0} 4\pi r^2 n_e dr = Z[1 + \phi(x_0) - x_0\phi'(x_0)]$$

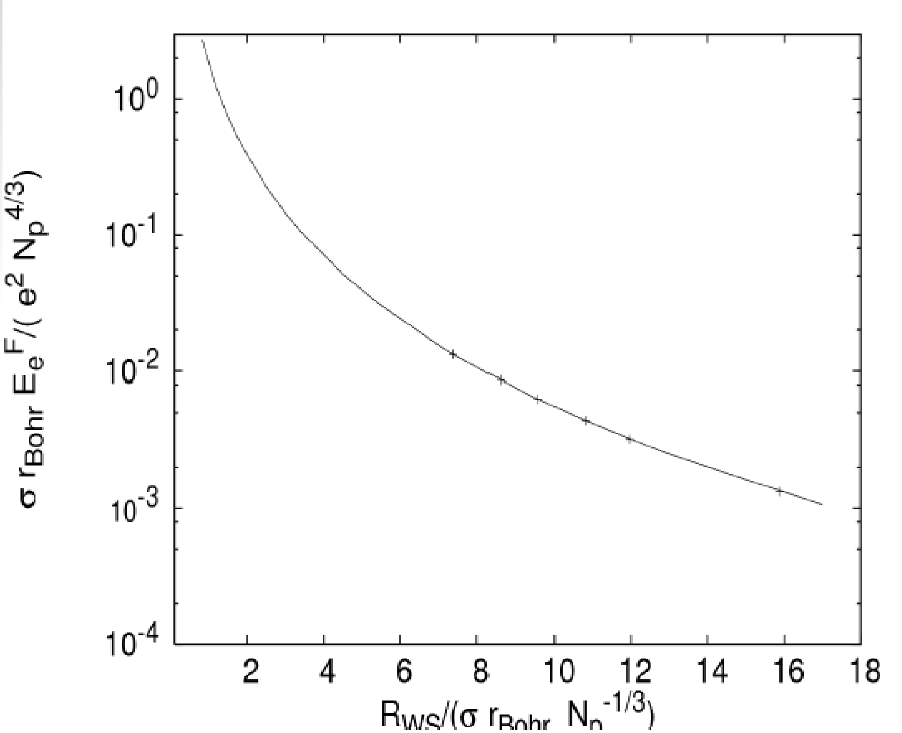
where $x_0 = R_0/b$ being R_0 the radius of the configuration.

Free and Compressed configurations

$$\text{Atom} = \begin{cases} \text{free} & \phi(x_0) = x_0\phi'(x_0)\,, \quad \phi(x_0) = 0 \Rightarrow E_e^F = 0 \\ \text{compressed} & \phi(x_0) = x_0\phi'(x_0)\,, \quad \phi(x_0) \neq 0 \Rightarrow E_e^F > 0 \end{cases}$$

Feynman, Metropolis, Teller (1949)

Compressed atoms...

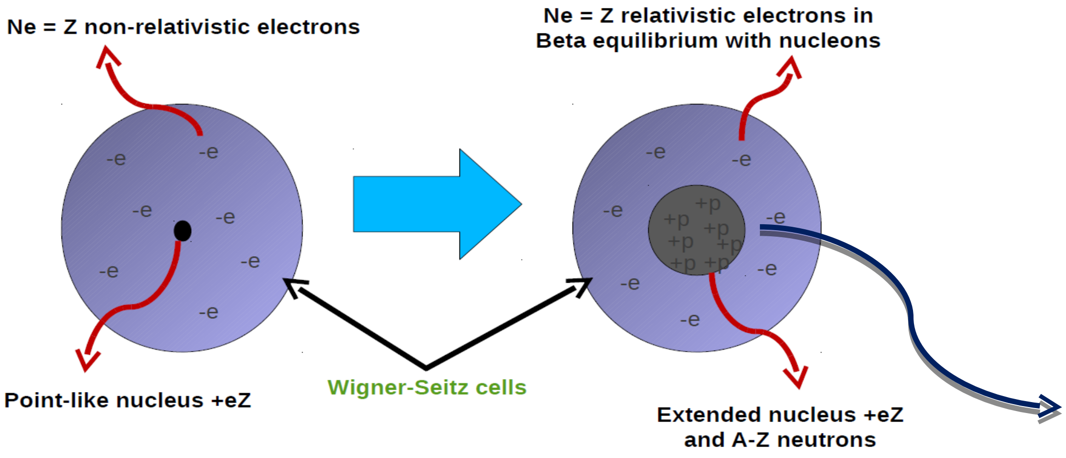


$$E^F_e = \mu_e - eV > 0$$

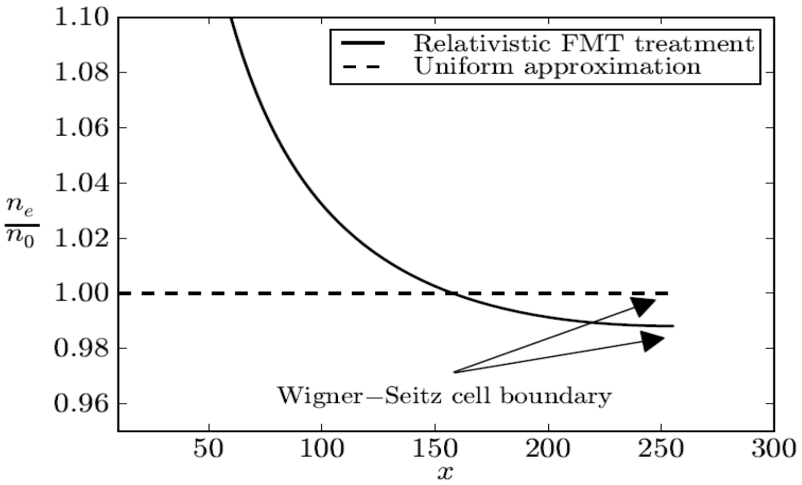
Feynman-Metropolis-Teller treatment of compressed atoms

Relativistic Feynman-Metropolis-Teller Atom

(Rotondo, Rueda, Ruffini, Xue, Phys. Rev. C 84, 045805, 2011)



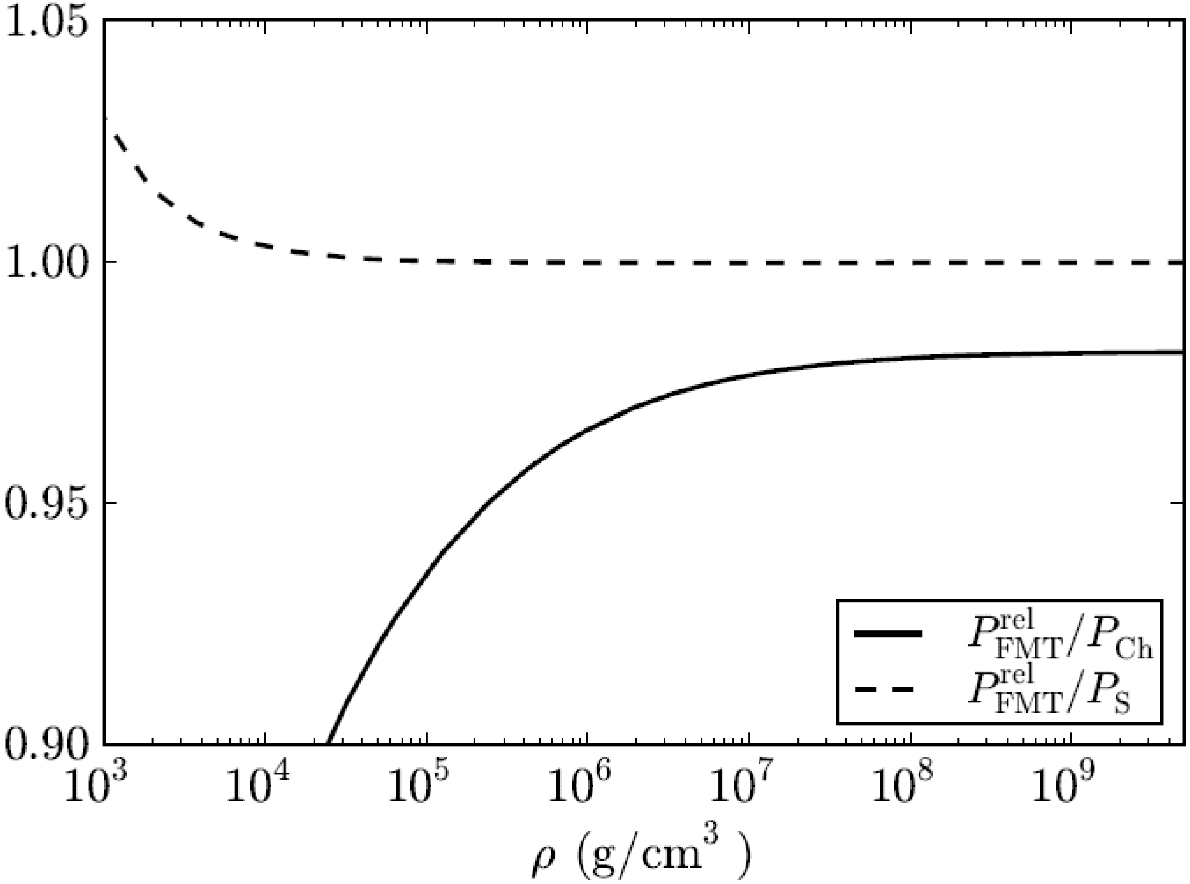
Electrons in a Wigner-Seitz Cell



$$E_e^F = \sqrt{c^2(P_e^F)^2 + m_e^2c^4} - m_e c^2 - eV(r) = \text{constant} > 0$$

$$\frac{1}{3x}\frac{d^2\chi(x)}{dx^2} = -\frac{\alpha}{\Delta^3}\theta(x_c - x) + \frac{4\alpha}{9\pi}\left[\frac{\chi^2(x)}{x^2} + 2\frac{m_e}{m_\pi}\frac{\chi(x)}{x}\right]^{3/2}$$

Effect on the EOS



WDs in GR

(Rotondo, Rueda, Ruffini, Xue, Phys. Rev. D 84, 084007, 2011)

General Relativistic Thomas-Fermi Equilibrium Condition for WDs

Decay	ϵ_Z^β	$\rho_{\rm crit}^{\beta,\rm relFMT}$	$\rho_{\rm crit}^{\beta,\rm unif}$
^{4}He $\rightarrow^3$ H + $n \rightarrow 4n$	20.596	1.39×10^{11}	1.37×10^{11}
^{12}C $\rightarrow^{12}$B $\rightarrow^{12}$Be	13.370	3.97×10^{10}	3.88×10^{10}
^{16}O $\rightarrow^{16}$N $\rightarrow^{16}$C	10.419	1.94×10^{10}	1.89×10^{10}
^{56}Fe $\rightarrow^{56}$Mn $\rightarrow^{56}$Cr	3.695	1.18×10^{9}	1.14×10^{9}

Einstein Equations

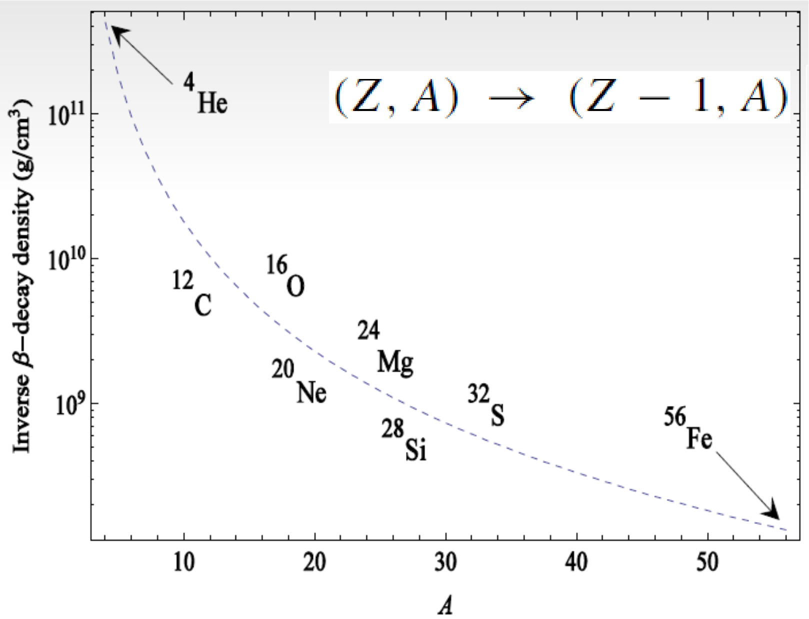
+

Relativistic FMT EOS

$$\sqrt{g_{00}}\,\mu_{WS} = \text{constant}$$

Macrophysics GR **Microphysics WS cells**

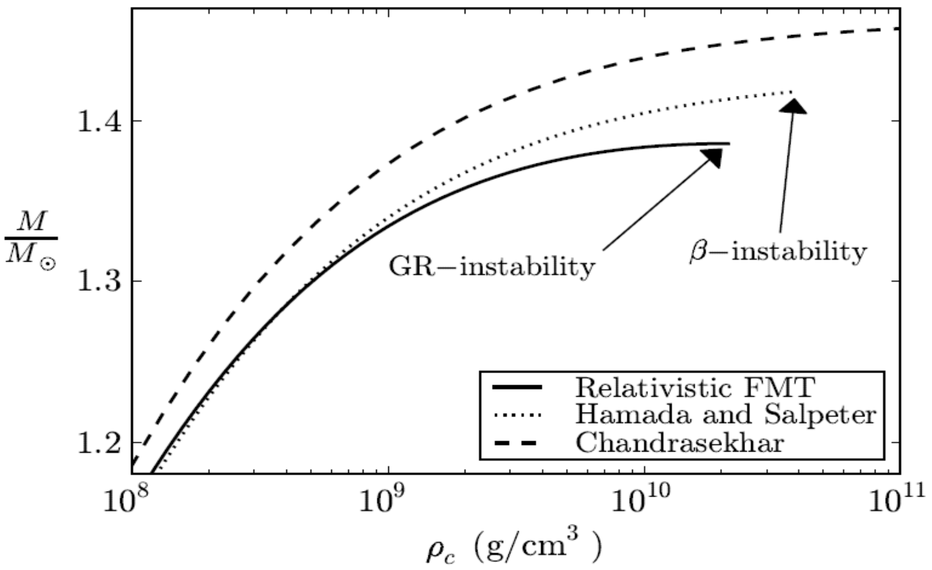
Relativistically consistent approach



WDs in GR

(Rotondo, Rueda, Ruffini, Xue, Phys. Rev. D 84, 084007, 2011)

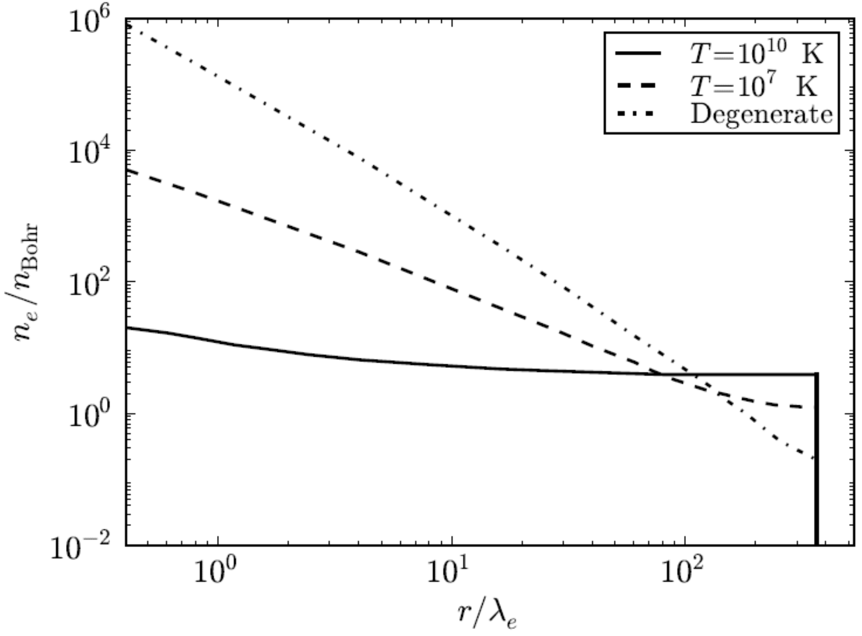
	$\rho_{\rm crit}^{\rm H\&S}$	$M_{\rm crit}^{\rm H\&S}/M_\odot$	$\rho_{\rm crit}^{\rm FMTrel}$	$M_{\rm crit}^{\rm FMTrel}/M_\odot$
^{4}He	1.37×10^{11}	1.44064	1.56×10^{10}	1.40906
^{12}C	3.88×10^{10}	1.41745	2.12×10^{10}	1.38603
^{16}O	1.89×10^{10}	1.40696	1.94×10^{10}	1.38024
^{56}Fe	1.14×10^{9}	1.11765	1.18×10^{9}	1.10618



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

Relativistic FMT at finite T

$$\frac{d^2\chi(x)}{dx^2} = -4\pi\alpha x \left\{ \frac{3}{4\pi\Delta^3}\theta(x_c - x) - \frac{\sqrt{2}}{\pi^2}\left(\frac{m_e}{m_\pi}\right)^3 \beta^{3/2}\left[F_{1/2}(\eta,\beta) + \beta F_{3/2}(\eta,\beta)\right] \right\}$$



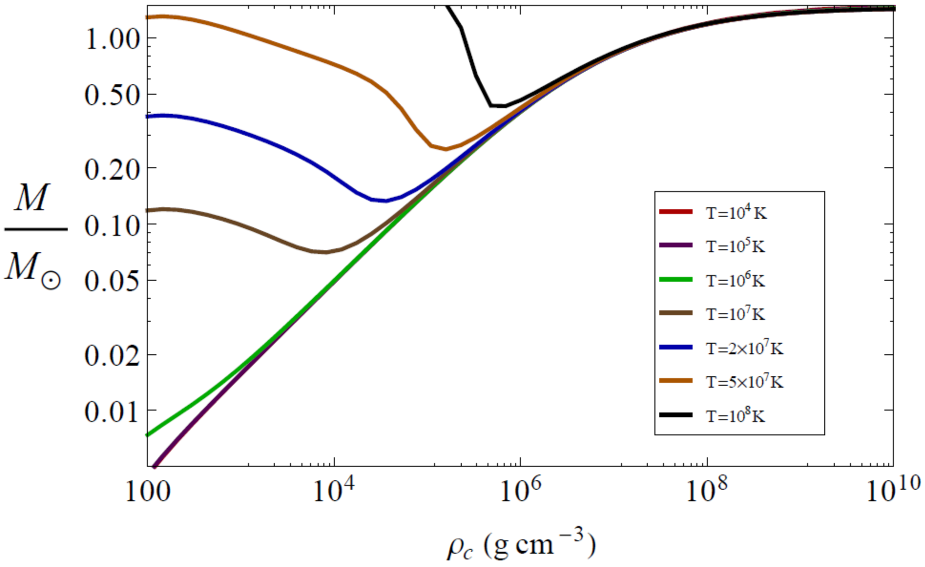
$$n_e = \frac{8\pi\sqrt{2}}{(2\pi\hbar)^3} m^3 c^3 \beta^{3/2}\left[F_{1/2}(\eta,\beta) + \beta F_{3/2}(\eta,\beta)\right]$$

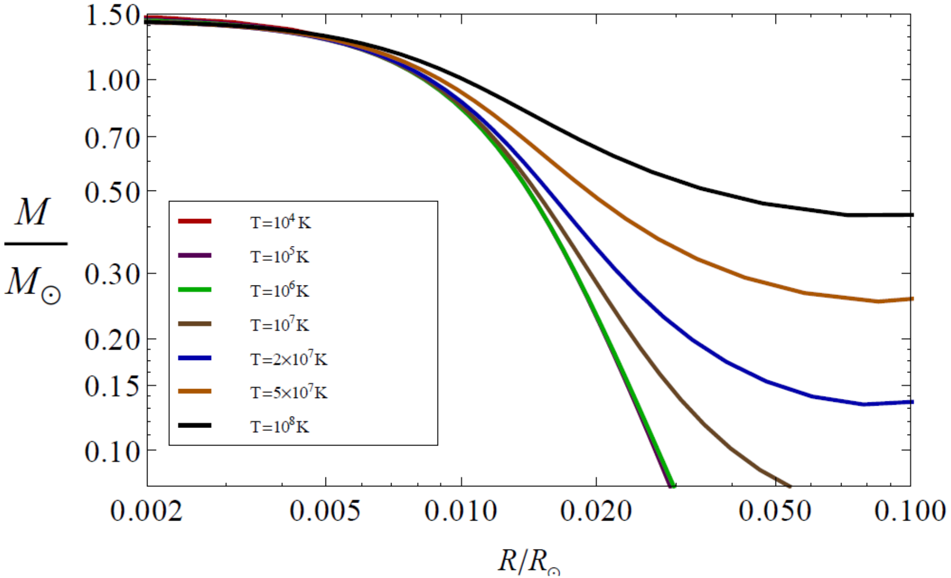
$$P_e = \frac{2^{3/2}}{3\pi^2\hbar^3} m_e^4 c^5 \beta^{5/2}\left[F_{3/2}(\eta_{\rm WS},\beta) + \frac{\beta}{2} F_{5/2}(\eta_{\rm WS},\beta)\right],$$

$$F_k(\eta,\beta) \equiv \int_0^\infty \frac{t^k\sqrt{1+(\beta/2)t}}{1+e^{t-\eta}}\, dt$$

Carvalho, Rotondo, Rueda, Ruffini, PRC 2014.

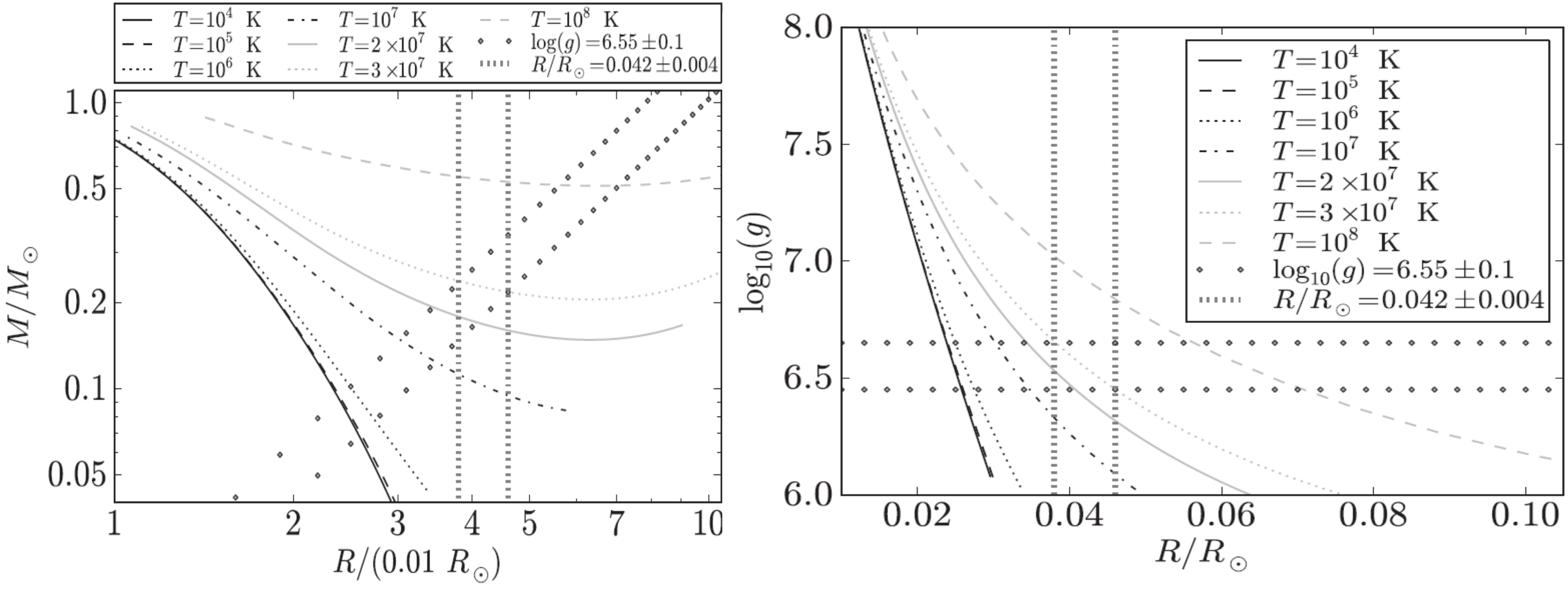
WD at finite temperature: M-R relation





Carvalho, Rotondo, Rueda, Ruffini, PRC 2014.

Testing the M-R with low-mass WD: PSR J1738+0333



Carvalho, Rotondo, Rueda, Ruffini, PRC 2014.

WDs in uniform rotation: Hartle's formalism

Boshkayev, Rueda, Ruffini, Siutsou, ApJ 762, 117 (2013)

- *Hartle, J. B., ApJ 150, 1005 (1967)*
- *Hartle, J. B. & Thorne, K. S., ApJ, 153, 807 (1968)*

$$ds^2 = e^{\nu(r)}\left[1 + 2h(r,\theta)\right]dt^2 - e^{\lambda(r)}\left[1 + \frac{2m(r,\theta)}{r - M^{J=0}(r)}\right]dr^2 - r^2\left[1 + 2k(r,\theta)\right]\left\{d\theta^2 + \sin^2\theta(d\phi - \omega dt)^2\right\}$$

where $h(r,\theta) = h_0(r) + h_2(r)P_2(\cos\theta) + \ldots$

$$m(r,\theta) = m_0(r) + m_2(r)P_2(\cos\theta) + \ldots$$

$$k(r,\theta) = k_2(r)P_2(\cos\theta) + \ldots$$

$$e^{\lambda(r)} = [1 - 2M^{J=0}(r)/r]^{-1}$$

to be obtained from Einstein equations

$\omega(r)$, proportional to Ω

h_0, h_2, m_0, m_2, k_2, proportional to Ω^2

Stability Criteria

Boshkayev, Rueda, Ruffini, Siutsou, ApJ 762, 117 (2013)

Mass-Shedding Limit

see e.g. Stergioulas, N. 2003, Living Reviews in Relativity, 6, 3

$$\Omega_{orb}(r) = \Omega_0(r)\left[1 - jF_1(r) + j^2F_2(r) + qF_3(r)\right],$$

$$j = cJ/(GM^2) \text{ and } q = c^4Q/(G^2M^3)$$

$$\Omega_0 = \frac{M^{1/2}}{r^{3/2}}, \qquad F_1 = \frac{M^{3/2}}{r^{3/2}},$$

$$F_2 = (48M^7 - 80M^6r + 4M^5r^2 - 18M^4r^3 + 40M^3r^4 + 10M^2r^5 + 15Mr^6 - 15r^7)/[16M^2r^4(r-2M)] + F,$$

$$F_3 = \frac{6M^4 - 8M^3r - 2M^2r^2 - 3Mr^3 + 3r^4}{16M^2r(r-2M)/5} - F,$$

$$F = \frac{15(r^3 - 2M^3)}{32M^3}\ln\frac{r}{r-2M}.$$

Turning Points

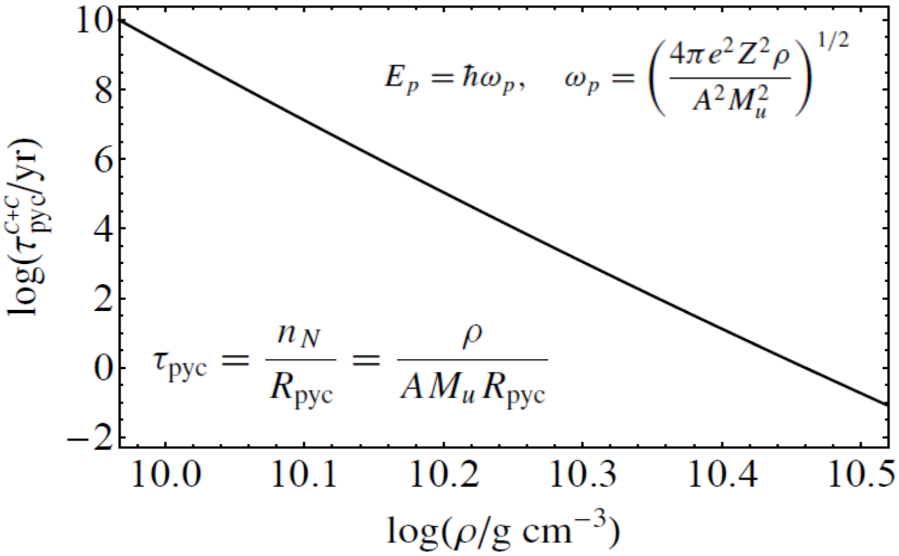
$$\left(\frac{\partial M(\rho_c, J)}{\partial \rho_c}\right)_J = 0$$

Friedman, Ipser, Sorkin, ApJ, 325, 722 (1988)

Microscopic instabilities

Boshkayev, Rueda, Ruffini, Siutsou, ApJ 762, 117 (2013)

Pycnonuclear reactions



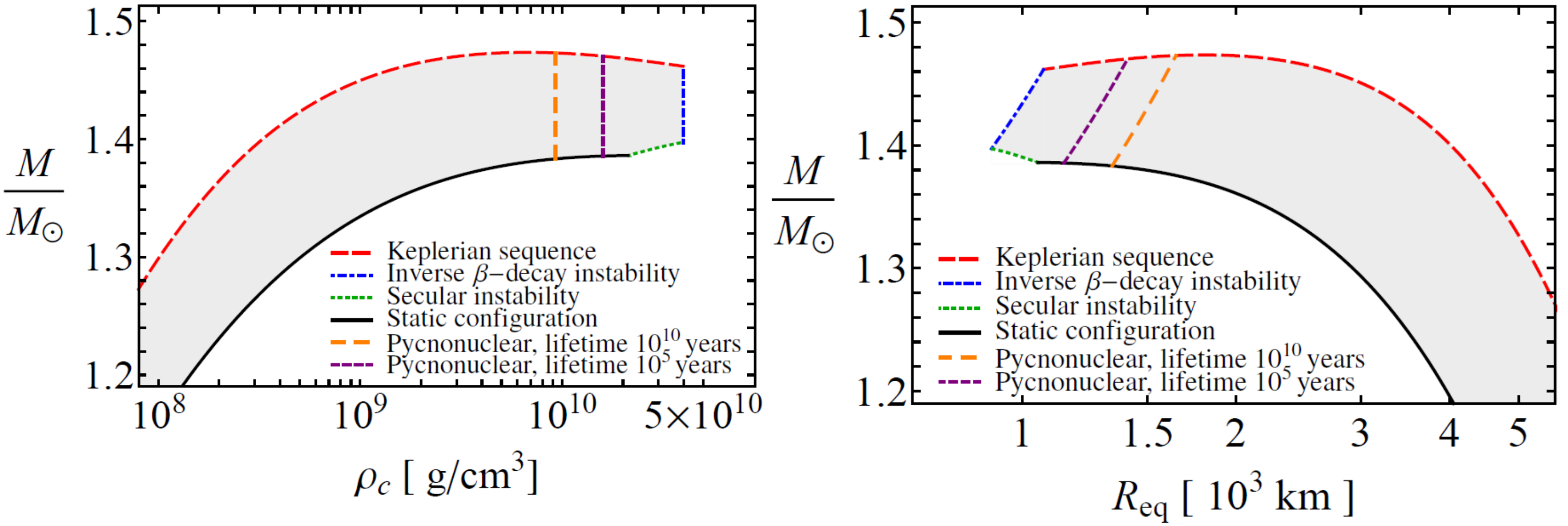
Inverse beta decay

Decay	ϵ_Z^β	$\rho_{\rm crit}^{\beta,{\rm relFMT}}$	$\rho_{\rm crit}^{\beta,{\rm unif}}$
${}^4{\rm He} \rightarrow {}^3{\rm H} + n \rightarrow 4n$	20.596	1.39×10^{11}	1.37×10^{11}
${}^{12}{\rm C} \rightarrow {}^{12}{\rm B} \rightarrow {}^{12}{\rm Be}$	13.370	3.97×10^{10}	3.88×10^{10}
${}^{16}{\rm O} \rightarrow {}^{16}{\rm N} \rightarrow {}^{16}{\rm C}$	10.419	1.94×10^{10}	1.89×10^{10}
${}^{56}{\rm Fe} \rightarrow {}^{56}{\rm Mn} \rightarrow {}^{56}{\rm Cr}$	3.695	1.18×10^{9}	1.14×10^{9}

$$R_{\rm pyc} = Z^4 A \rho S(E_p) 3.90 \times 10^{46} \lambda^{7/4} \times \exp(-2.638/\sqrt{\lambda})\ {\rm cm^{-3}\ s^{-1}}$$

$$\lambda = \frac{1}{Z^2 A^{4/3}} \left(\frac{\rho}{1.3574 \times 10^{11}\ {\rm g\ cm^{-3}}}\right)^{1/3}$$

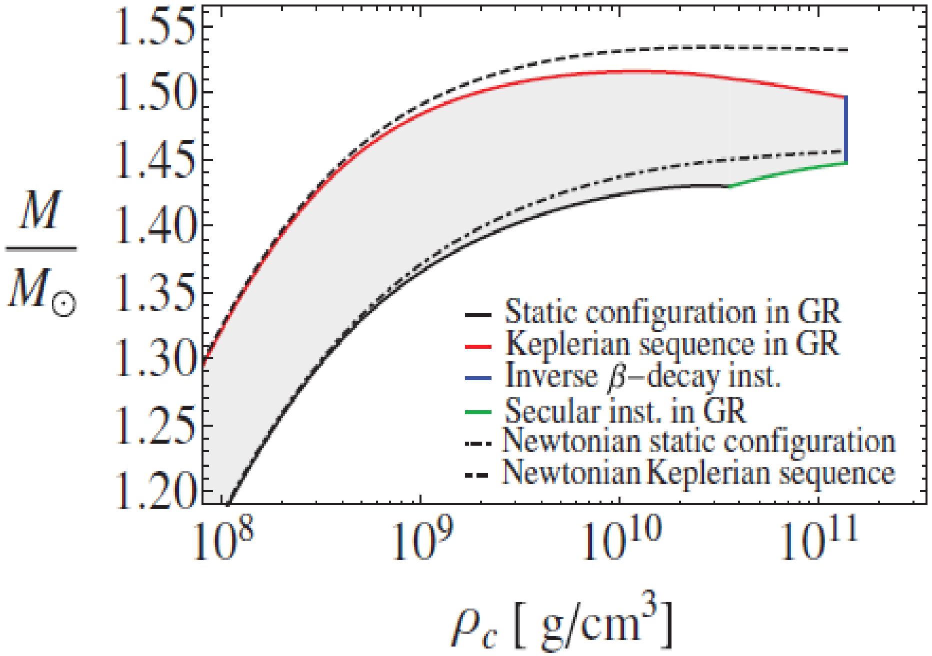
Rotating WDs

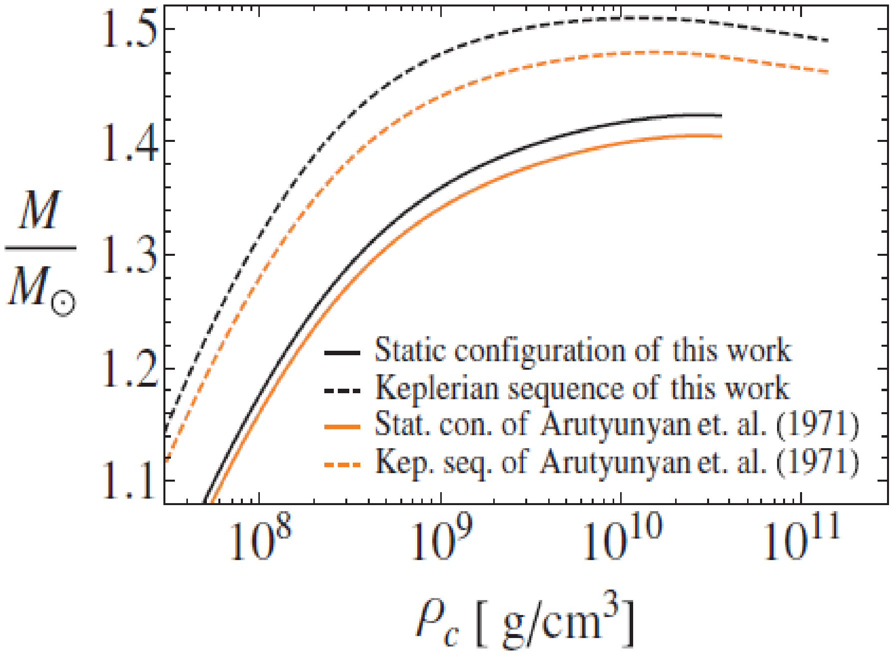


Boshkayev, Rueda, Ruffini, Siutsou, ApJ 762, 117 (2013)

Newtonian versus GR

Boshkayev, Rueda, Ruffini, Siutsou, ApJ 762, 117 (2013)



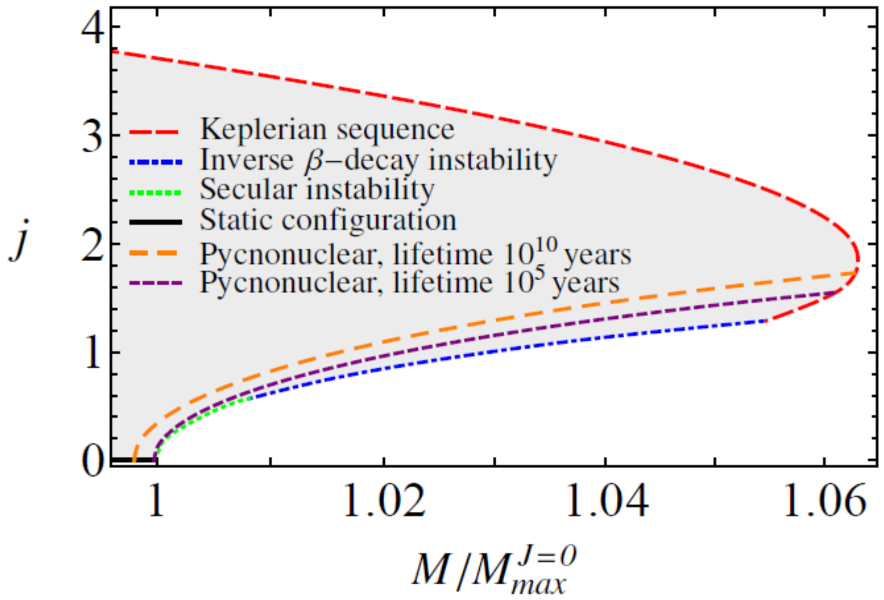


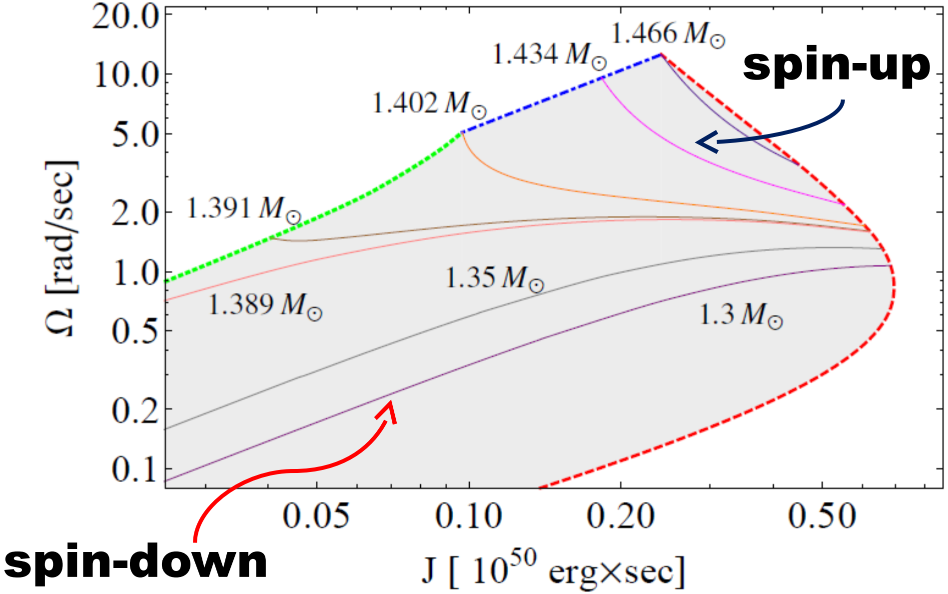
Spin-down and spin-up episodes

Boshkayev, Rueda, Ruffini, Siutsou, ApJ 762, 117 (2013)

$$\dot{\Omega} = \frac{\dot{E}}{\Omega}\left(\frac{\partial \Omega}{\partial J}\right)_{M_0,S,Z,A}$$

Equilibrium plane

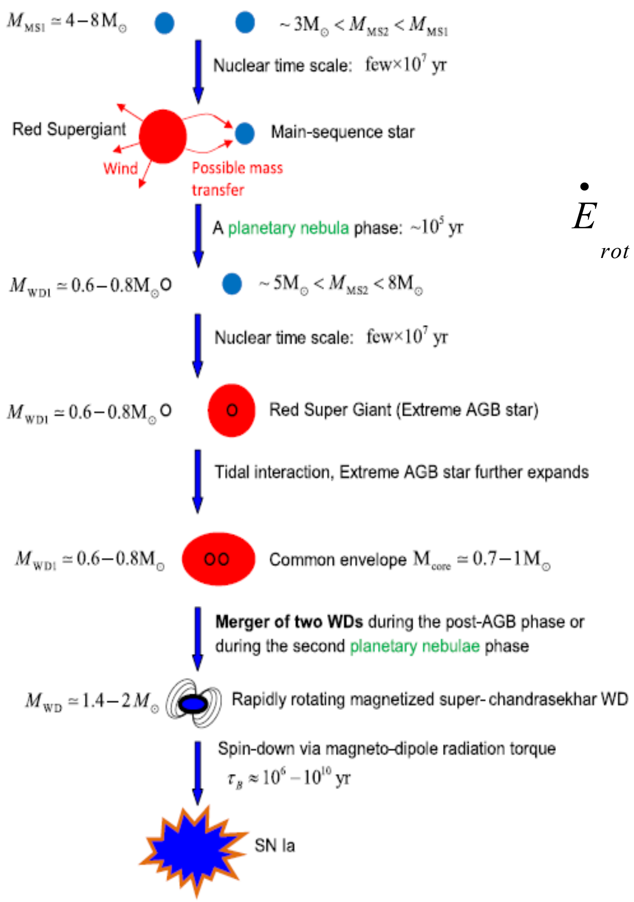




TYPE IA SUPERNOVAE FROM VERY LONG DELAYED EXPLOSION OF CORE–WD MERGER

(MNRAS 419, 1695, 2012)

Marjan Ilkov[1] and Noam Soker[1]



$$\dot{E}_{rot} = \Omega \frac{dJ}{d\Omega}\frac{d\Omega}{dt} = \Omega I \frac{d\Omega}{dt} = -4\pi^2 I \frac{\dot{P}}{P^3}$$

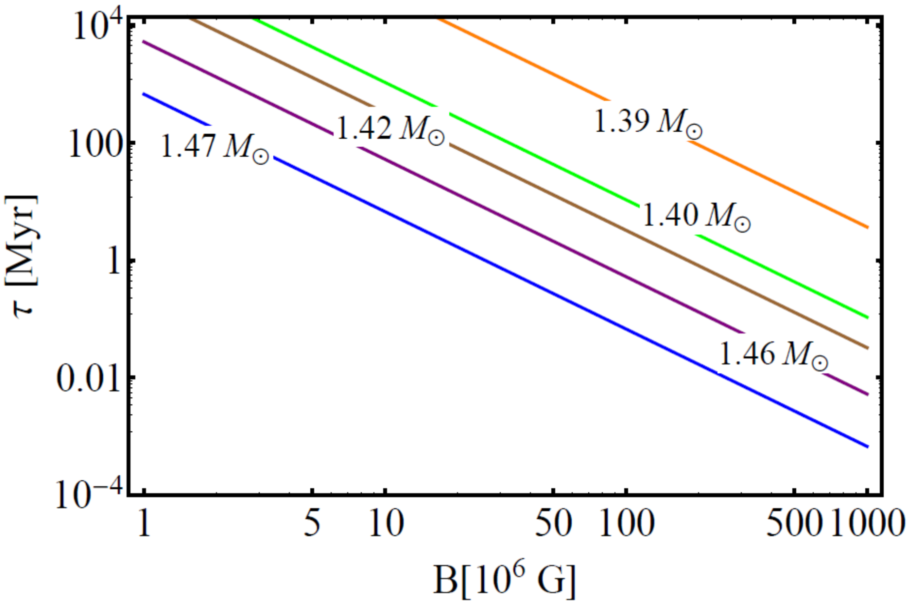
$$\dot{E}_{EM} = -\frac{2}{3}\frac{B^2 R^6}{c^3}\Omega^4 = -\frac{32\pi^4}{3}\frac{B^2}{c^3}\frac{R^6}{P^4}$$

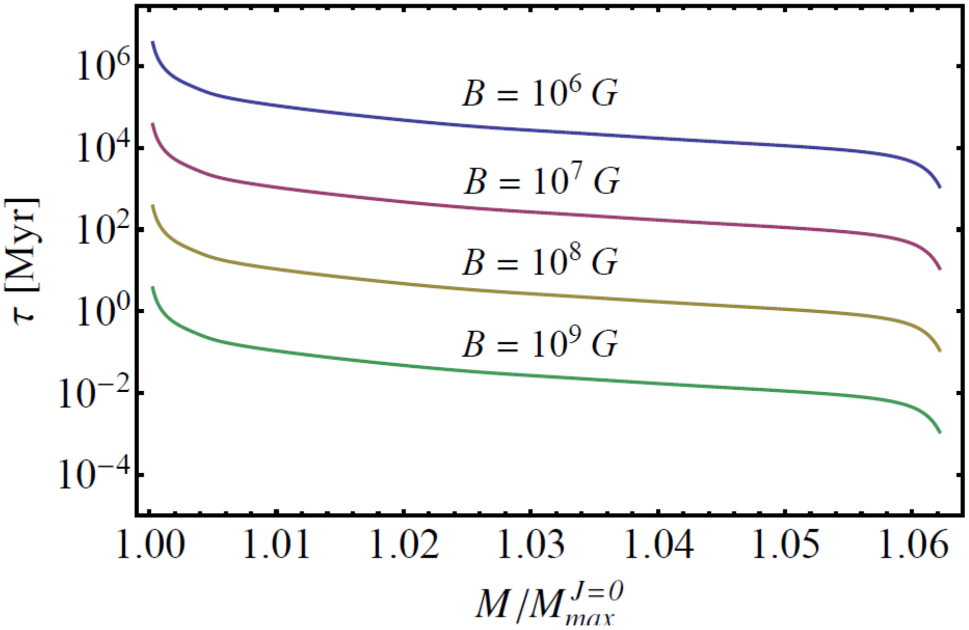
$$\tau_B \simeq \frac{Ic^3}{B^2 R^6 \Omega_c^2}\left[1-\left(\frac{\tilde{\Omega}_0}{\tilde{\Omega}_c}\right)^{-2}\right](\sin\delta)^{-2} \approx 10^8 \left(\frac{B}{10^8\ \mathrm{G}}\right)^{-2}\left(\frac{\tilde{\Omega}_c}{0.7\Omega_{\rm Kep}}\right)^{-2}$$
$$\times \left(\frac{R}{4000\ \mathrm{km}}\right)^{-1}\left(\frac{\sin\delta}{0.1}\right)^{-2}\left(\frac{\beta_I}{0.3}\right)\left[1-\left(\frac{\tilde{\Omega}_0}{\tilde{\Omega}_c}\right)^{-2}\right]\ \mathrm{yr},$$

The result...

$$10^6\ \mathrm{G} \lesssim \mathrm{B}\sin\delta \lesssim 10^8\ \mathrm{G} \quad \Rightarrow \quad 10^7 \lesssim t \lesssim 10^{10}\ \mathrm{yr}$$

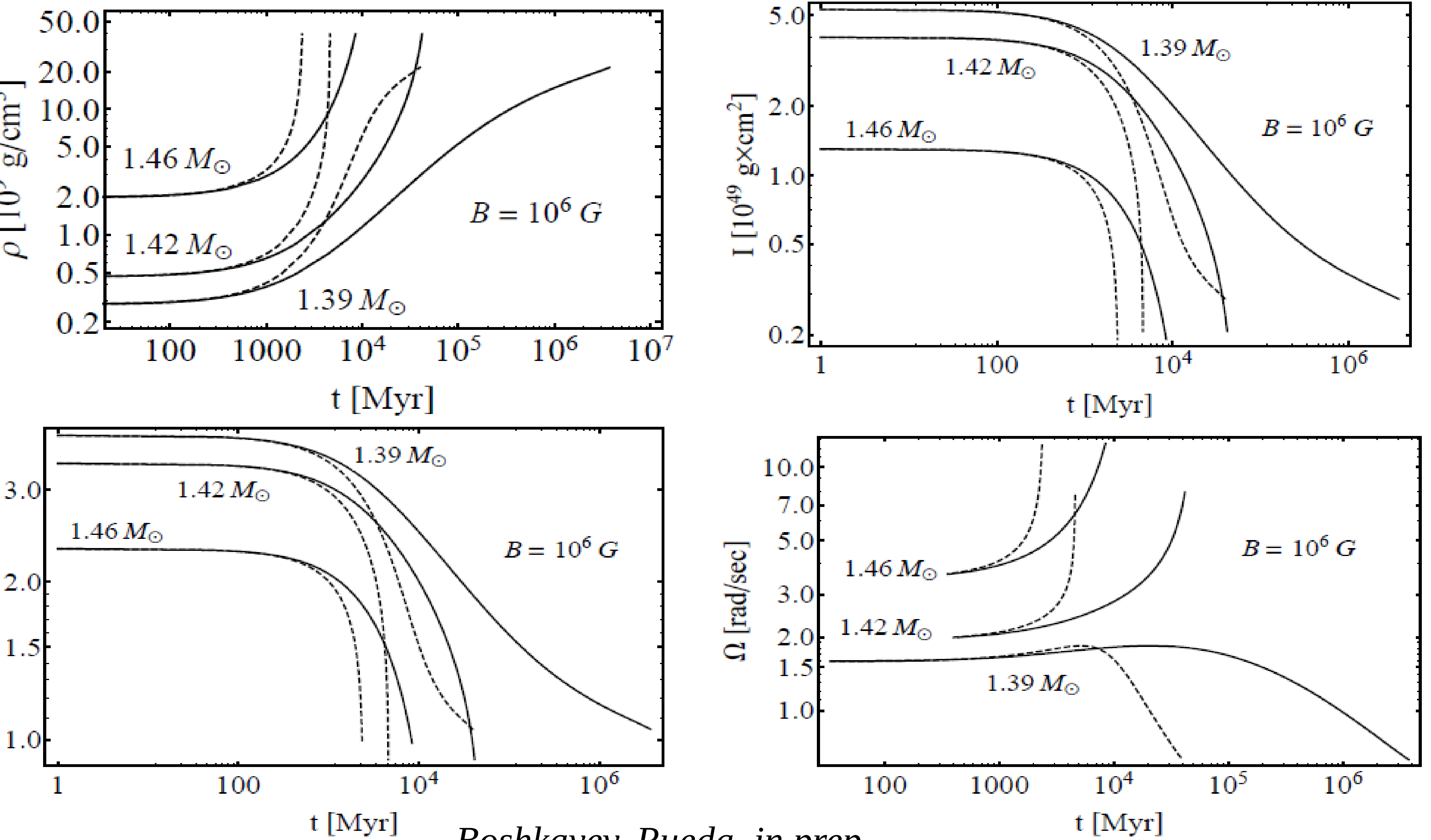
Induced compression by angular momentum loss in super-Chandrasekhar WDs





$$dt = -\frac{3}{2}\frac{c^3}{B^2}\frac{1}{\langle R\rangle^6}\frac{1}{\Omega^3}\frac{\partial J}{\partial\langle R\rangle}d\langle R\rangle$$

Boshkayev, Rueda, in preparation.



Boshkayev, Rueda, in prep.

Neutron star physics and astrophysics

Pulsars and Neutron stars rotational energy

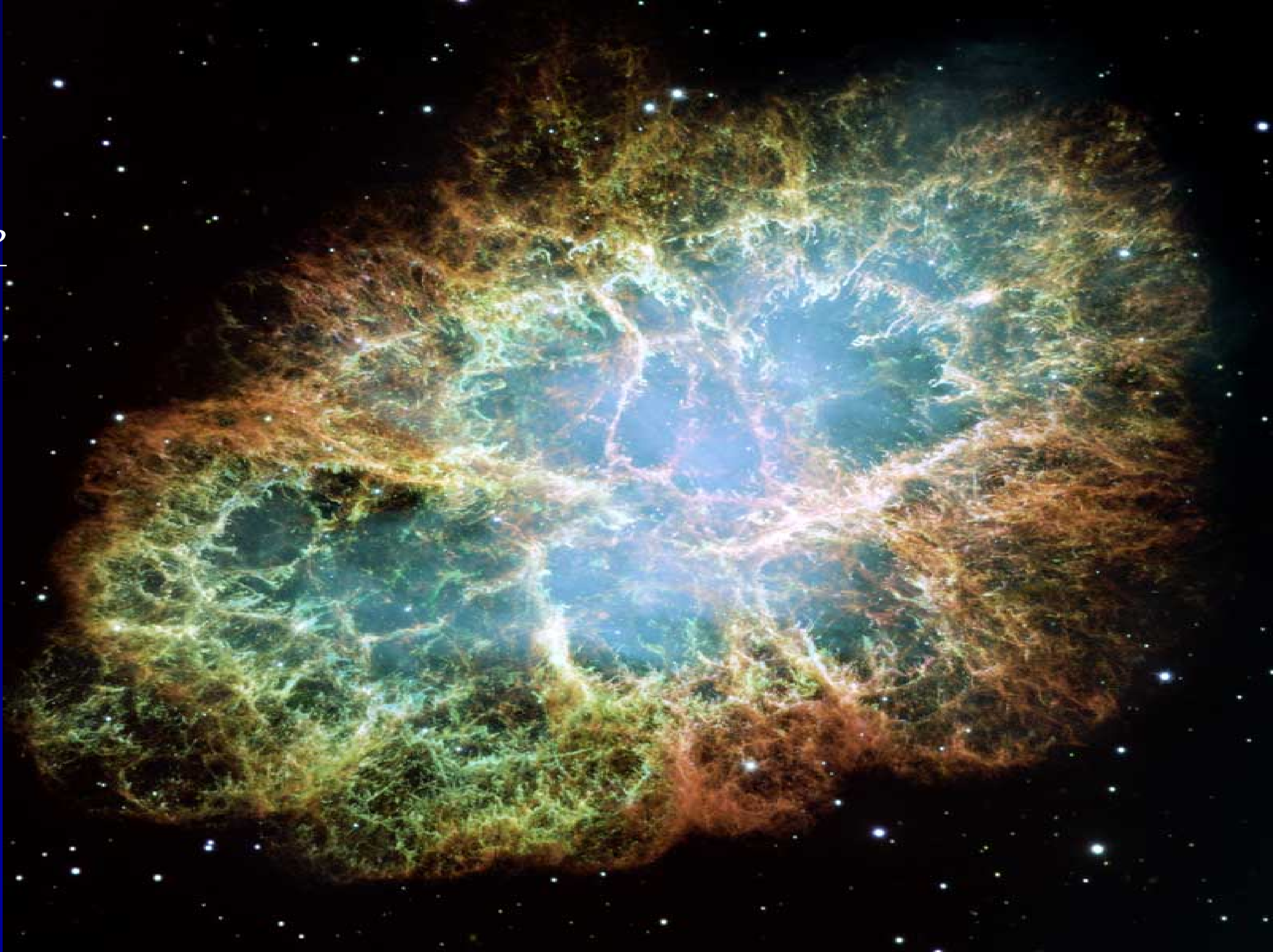
$$\left(\frac{dE}{dt}\right)_{obs} \simeq 4\pi^2 \frac{I_{NS}}{P^3}\frac{dP}{dt}$$

Chinese, Japanese, Korean astronomers

R. Oppenheimer & R. Volkoff (1939)

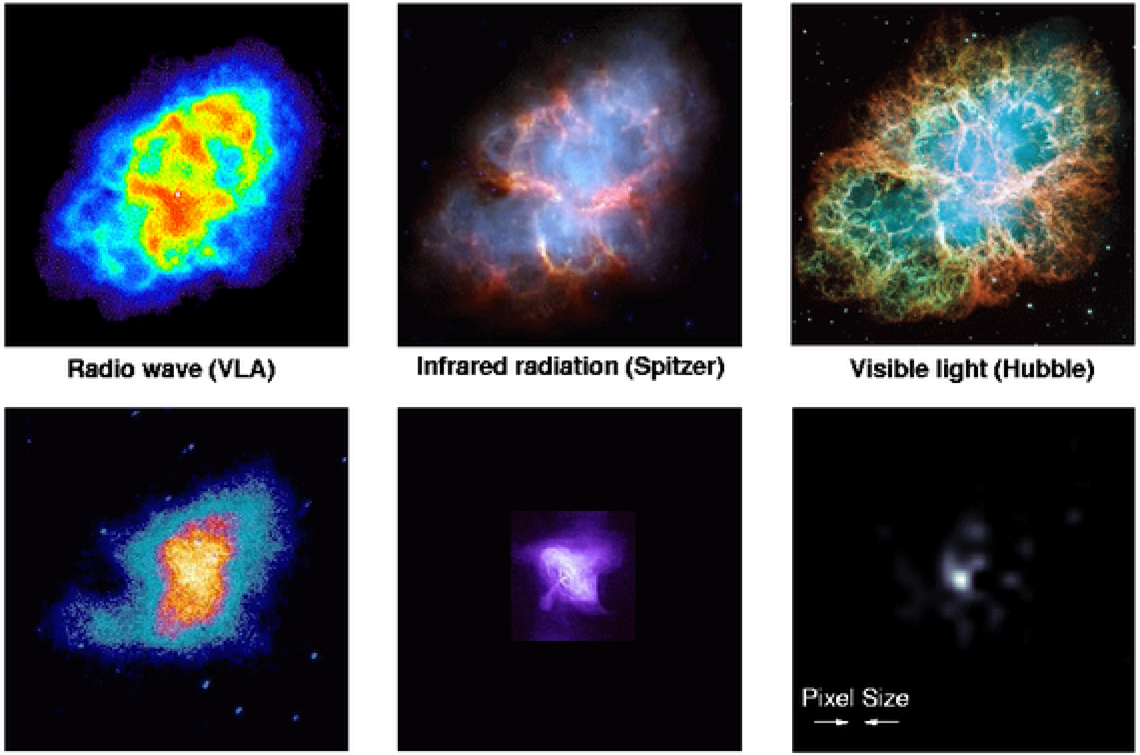
J. Bell & T. Hewish (1967)

UHECRs (2000-2011)



Multi-frequency astronomy

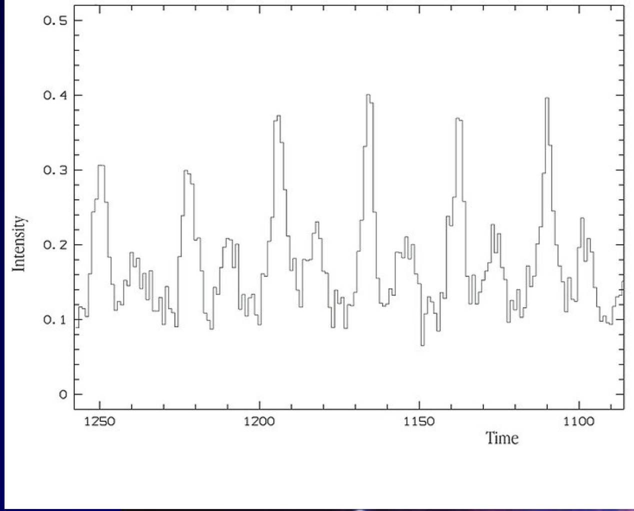
Crab Nebula: Remnant of an Exploded Star (Supernova)

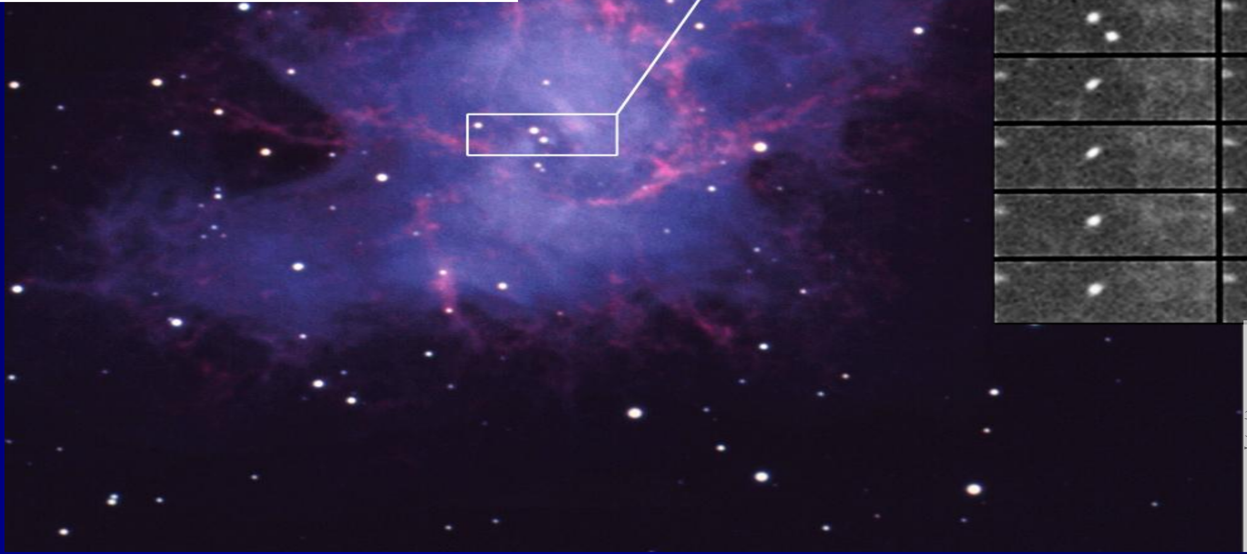


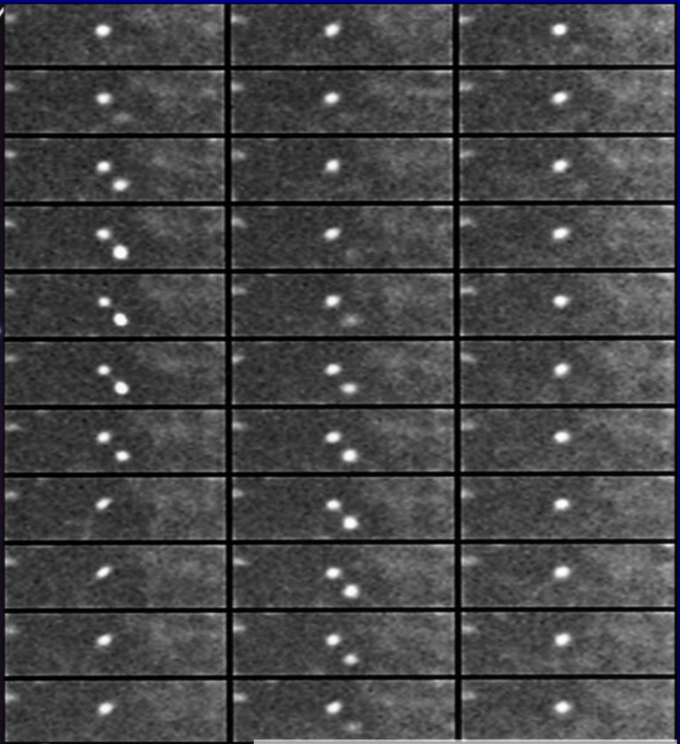
Radio wave (VLA) | Infrared radiation (Spitzer) | Visible light (Hubble)

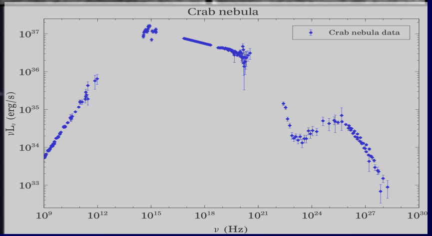
Ultraviolet radiation (Astro–1) | Low–energy X–ray (Chandra) | High–energy X–ray (HEFT) *** 15 min exposure ***

Crab Nebula and CrabPulsar

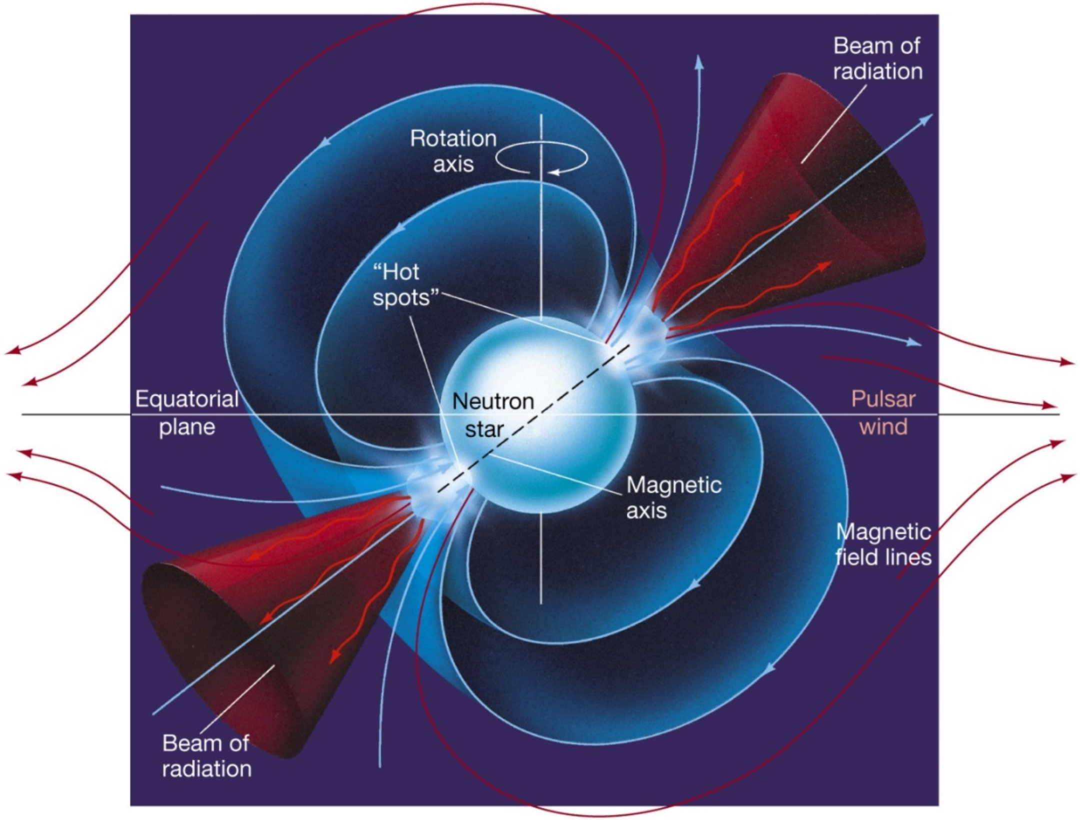








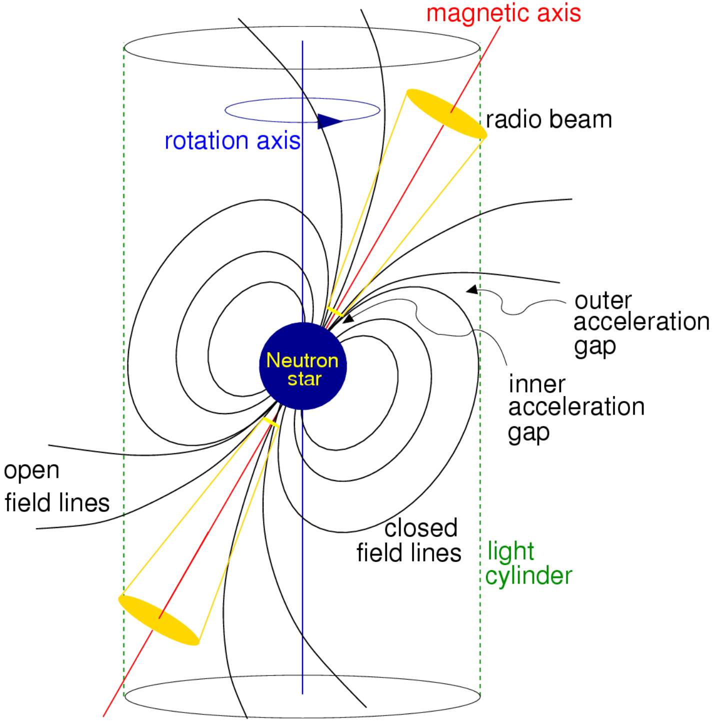
Pulsars

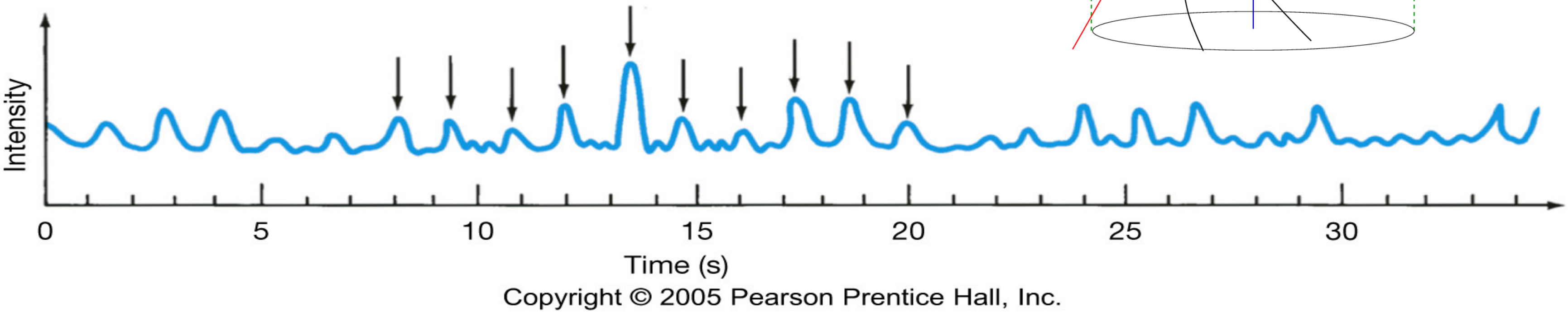


Descubiertos en 1967 por Jocelyn Bell y su profesor Anthony Hewish. Este último recibió el Premio Nobel de Física en 1974 por el descubrimiento.

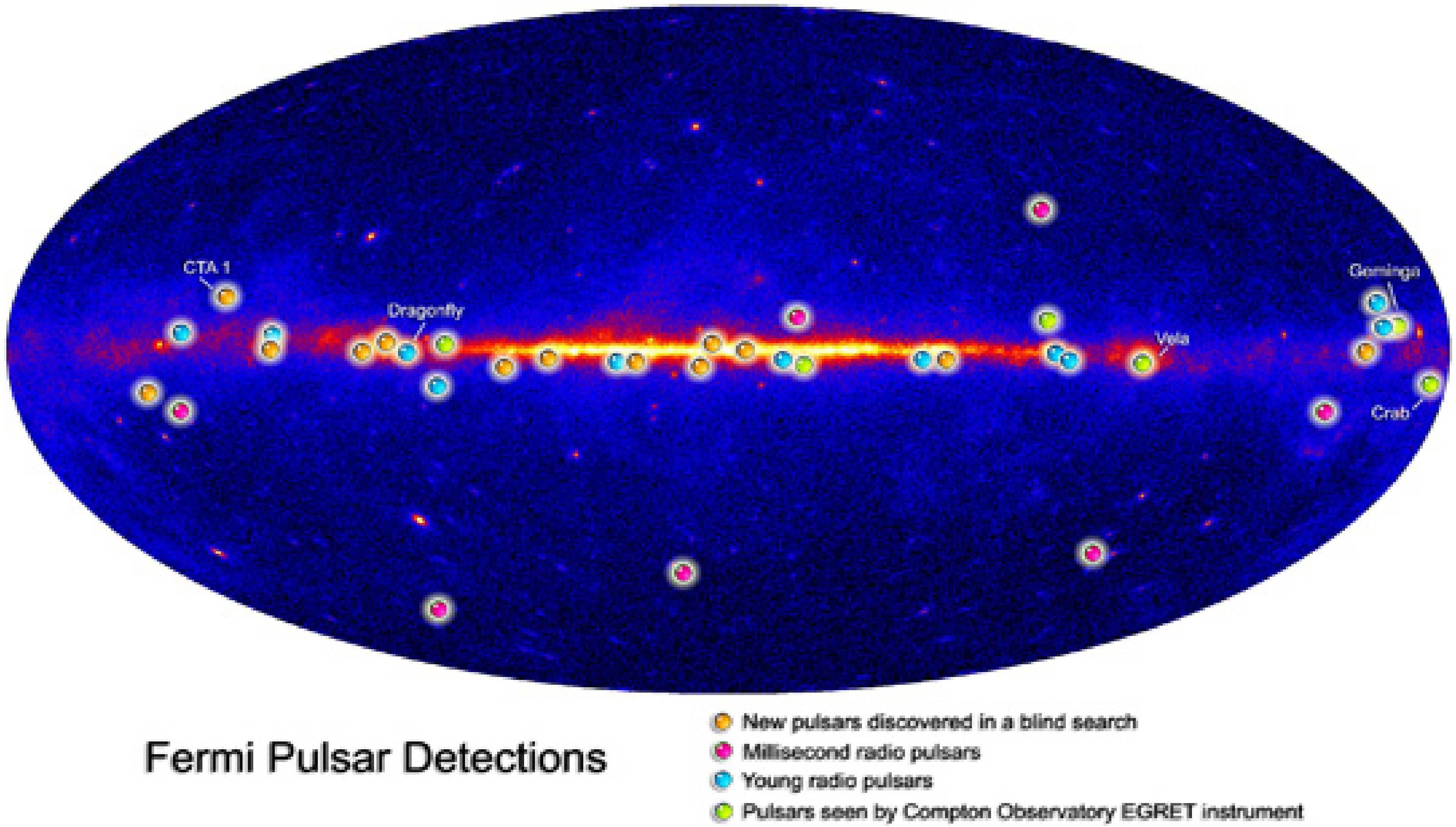
Pulsar traditional model

- NS radiating via a rotating magnetic dipole in form of a lighthouse effect
- We see a "light pulse" every time that the radiation cone is in our line of sight





Pulsars (from radio to gamma rays)



Neutron star Pdot-P diagram

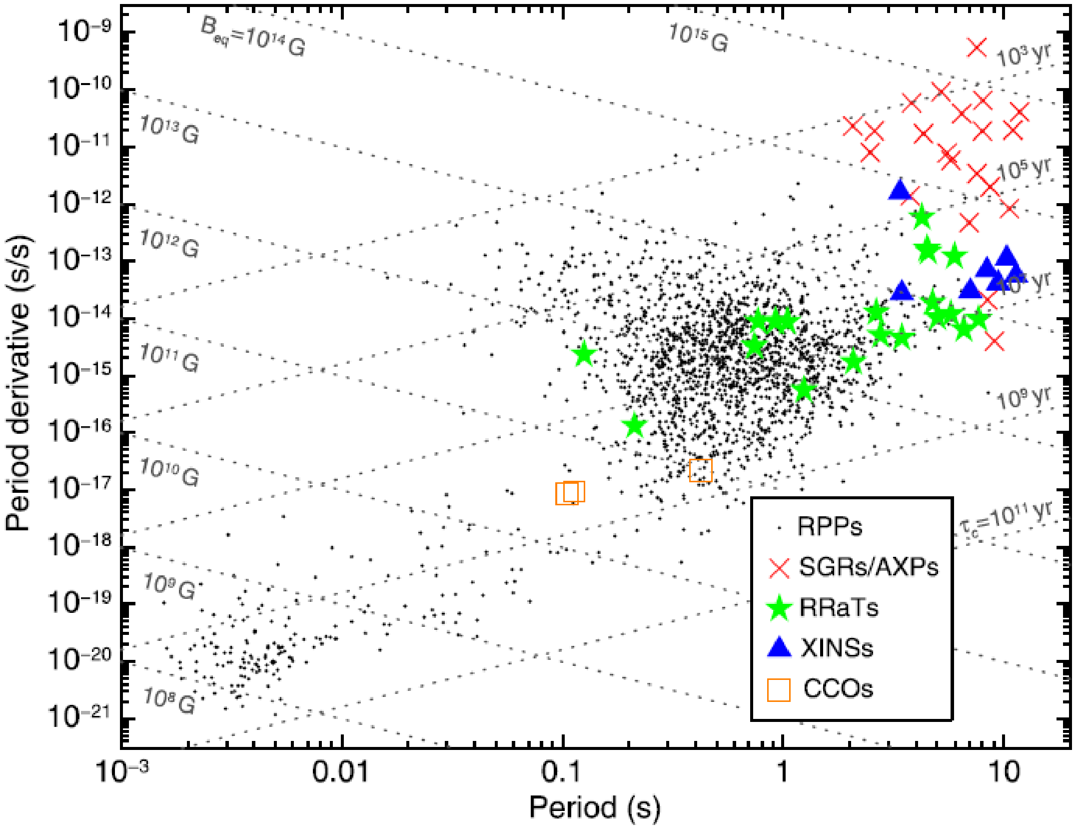
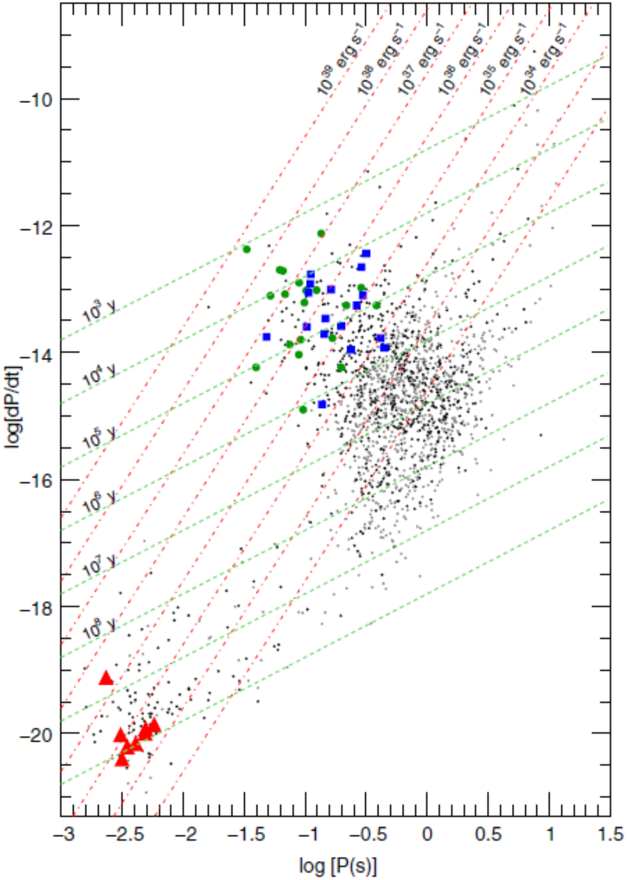
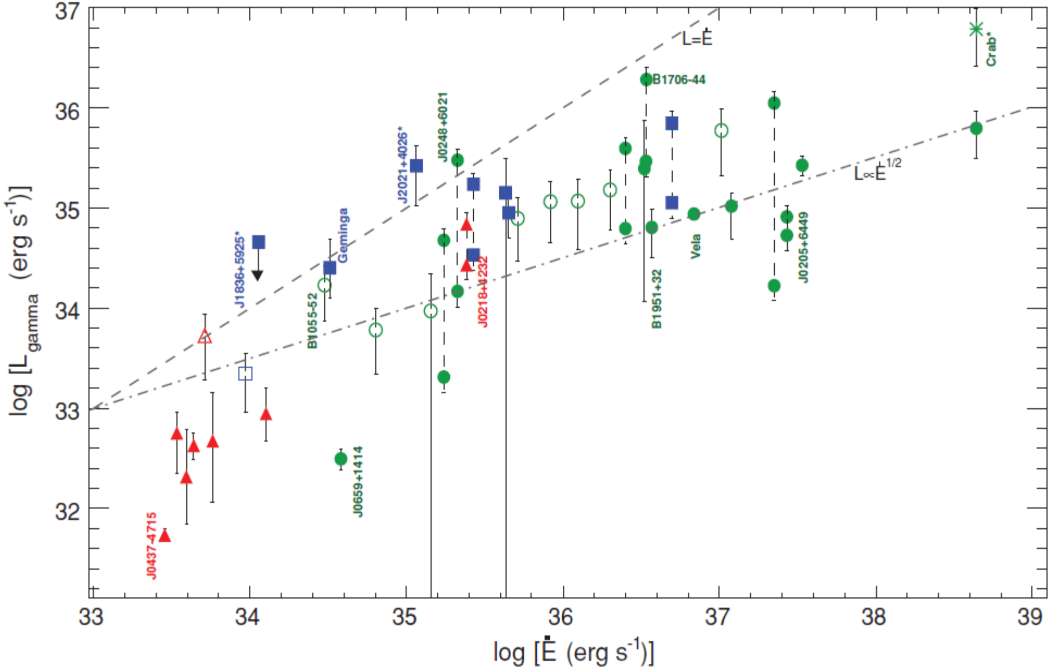


Figure from: Potekhin, De Luca, Pons, Space Sci. Rev. 2014

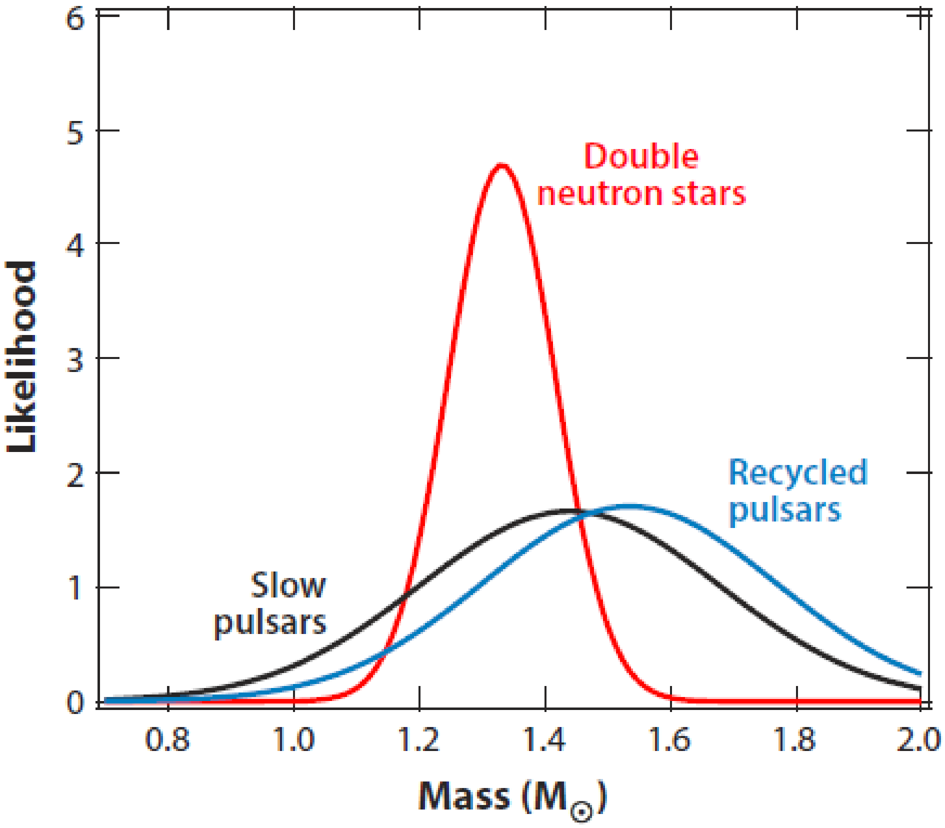
Pulsar energetics and efficiency

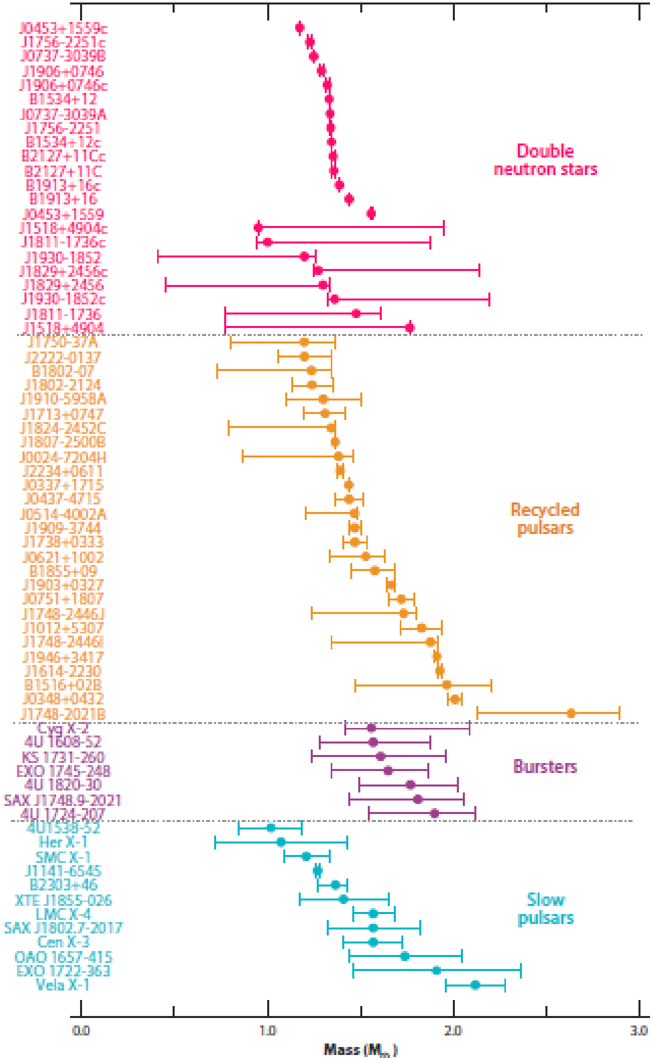
(review: Abdo et al. ApJSS187, 460 (2010))





NS measured masses





Taken from: Ozel & Freire, ARAA016

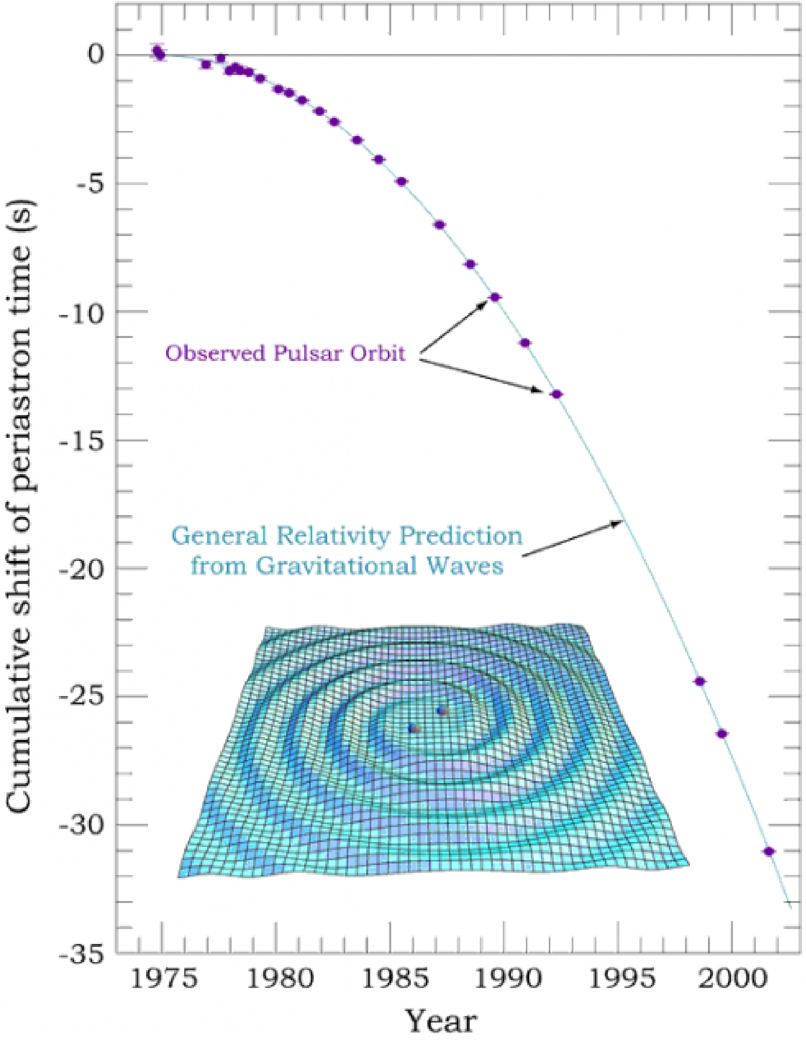
How fast can be a pulsar?

Up to 2010, the fastest OBSERVED pulsar was PSR1937+21:

P= 1.5578064688197945+/- 0.0000000000000004 ms

Currently, the fastest OBSERVED, **PSR J1748-2446ad,** has a period

P=1.39595482 ms ! (716 laps per second !!!)



The discovery of GWs

Hulse-Taylor binary:

M1 = 1.387 Msun
M1 + M2 = 2.828378(7) Msun
Periodo di rotazione pulsar = 59 ms (~17 giri/s)
Periodo orbitale: 7.751938773864 h
Separazione binaria ~ 2 milioni di km (~distanza Terra-Sole/75)
Velocità orbitale ~ 450 km/s (al periastro)
dP/dt = 76.5 microsec/anno (da/dt =3.5 metri/anno)
dE/dt (OG) ~ 7.3×10^{24} Watt ~ Lsole/200
Fusione attesa in 300 milioni di anni !

$$-\frac{dE_b}{dt} = \frac{32}{5}\frac{G^4}{c^5}\frac{(M_1+M_2)(M_1M_2)^2}{r^5}$$

$$\frac{1}{P}\frac{dP}{dt} = \frac{3}{2}\frac{1}{r}\frac{dr}{dt} = -\frac{3}{2}\frac{1}{E_b}\frac{dE_b}{dt}$$

Comparison for some compact-object binaries in the Milky Way

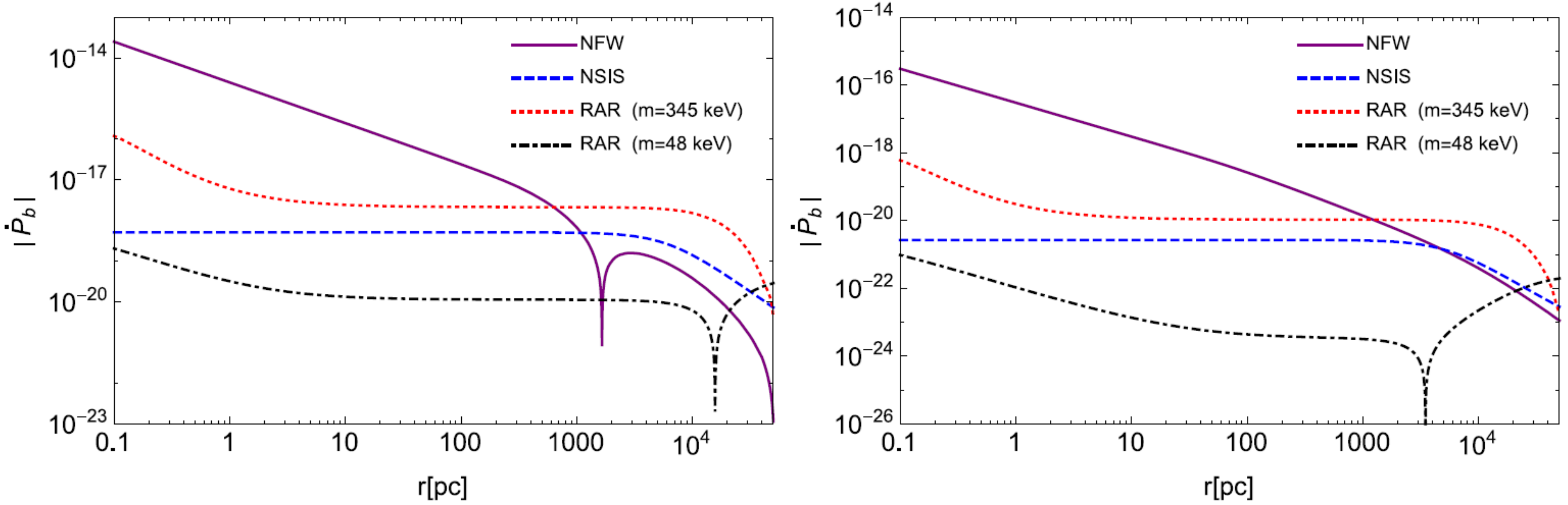
Gomez & Rueda, ArXiv: 1706.06801

Name	Type	m_p $[M_\odot]$	m_c $[M_\odot]$	P_b [days]	d [kpc]	$\dot{P}_b^{\rm int}$ $[10^{-12}]$	$\dot{P}_b^{\rm GW}$ $[10^{-12}]$	$\dot{P}_{b,NFW}^{\rm DF}$ $[10^{-21}]$	$\dot{P}_{b,\rm RAR}^{\rm DF}$ $[10^{-21}]$
J0737-3039	NS-NS	1.3381(7)	1.2489(7)	0.104	1.15(22)	-1.252(17)	-1.24787(13)	-10.498	-7.860
B1534+12	NS-NS	1.3330(4)	1.3455(4)	0.421	0.7	-0.19244(5)	-0.1366(3)	-244.166	-27.827
J1756-2251	NS-NS	1.312(17)	1.258(17)	0.321	2.5	-0.21(3)	-0.22(1)	-0.271	-20.695
J1906+0746	NS-NS	1.323(11)	1.290(11)	0.166	5.4	-0.565(6)	-0.52(2)	-2.655	-11.176
B1913+16	NS-NS	1.4398(2)	1.3886(2)	0.325	9.9	-2.396(5)	-2.402531(14)	-7.942	-17.747
B2127+11C[a]	NS-NS	1.358(10)	1.354(10)	0.333	10.3(4)	-3.961(2)	-3.95(13)	-8.083	-17.0154
J0348+0432	NS-WD	2.01(4)	0.172(3)	0.104	2.1(2)	-0.273(45)	-0.258(11)	-0.399	-1.514
J0751+1807	NS-WD	1.26(14)	0.13(2)	0.263	2.0	-0.031(14)	—	-1.022	-2.587
J1012+5307	NS-WD	1.64(22)	0.16(2)	0.60	0.836(80)	-0.15(15)	-0.11(2)	-3.404	-7.343
J1141-6545	NS-WD	1.27(1)	1.02(1)	0.20	3.7	-0.401(25)	-0.403(25)	-3.578	-11.469
J1738+0333	NS-WD	1.46(6)	0.181(7)	0.354	1.47(10)	-0.0259(32)	-0.028(2)	-2.120	-4.379
WDJ0651+2844	WD-WD	0.26(4)	0.50(4)	0.008	1	-9.8(28)	-8.2(17)	-0.014	-0.207

In relativistic (Pb small) compact-star binaries located in the Galactic halo (low DM density) the orbital evolution is largely driven by GW emission and DMDF plays no role

Dark matter effect on compact-object evolution

Gomez & Rueda, PRD 2017; ArXiv: 1706.06801



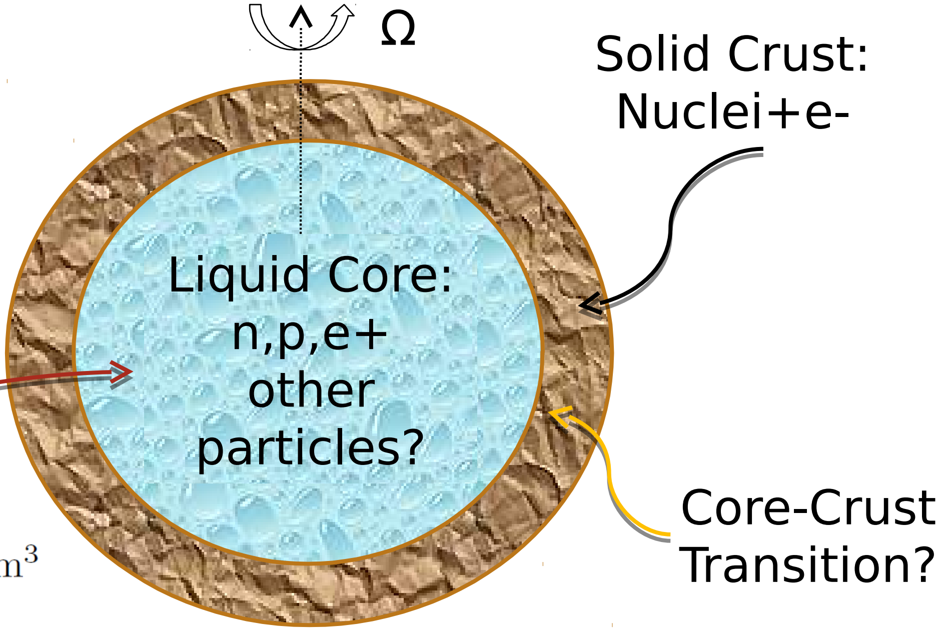
Binaries with Pb = 0.5 days. When r is large (halo; ~kpc) the DMDF is small and the orbital evolution is largely driven by GW emission. When r is small (< 1-10 pc), the DMDF can become comparable (or overcome) the GW emission

Current knowledge of the NS structure

Oppenheimer-Volkoff (1939)

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

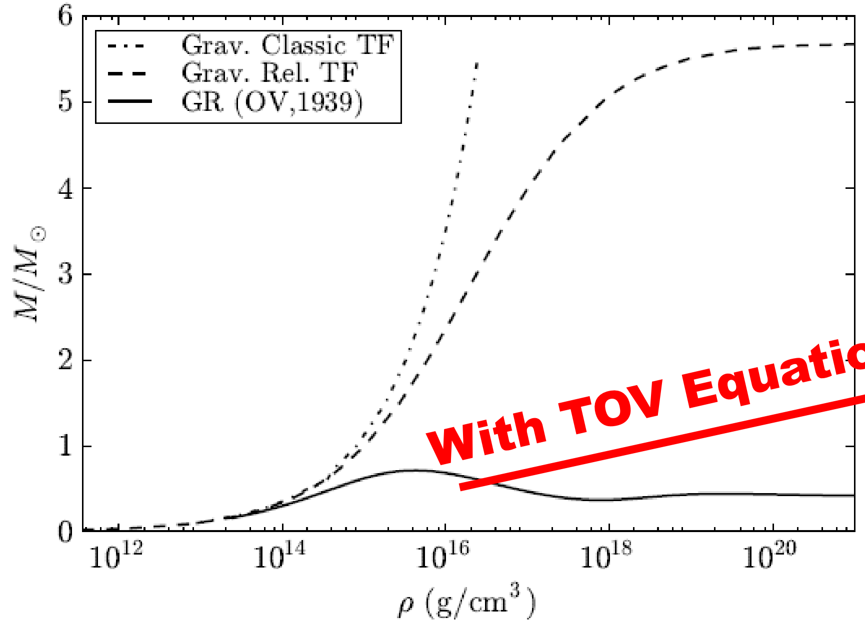
Neutron star today

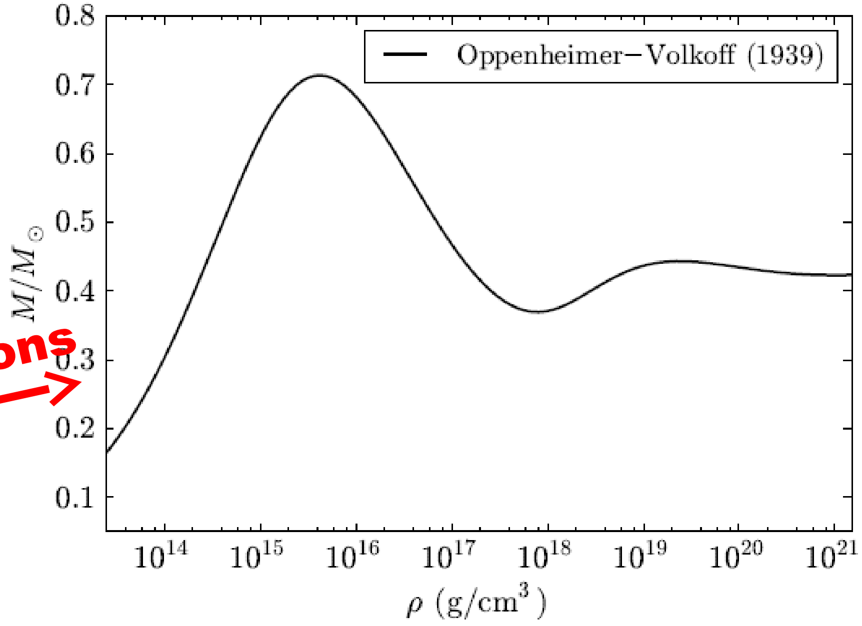


$$\rho_{\rm core} \gtrsim \rho_{\rm nuc} \sim 2.7 \times 10^{14} \ \ {\rm g/cm^3}$$

The Oppenheimer-Volkoff Neutron Star

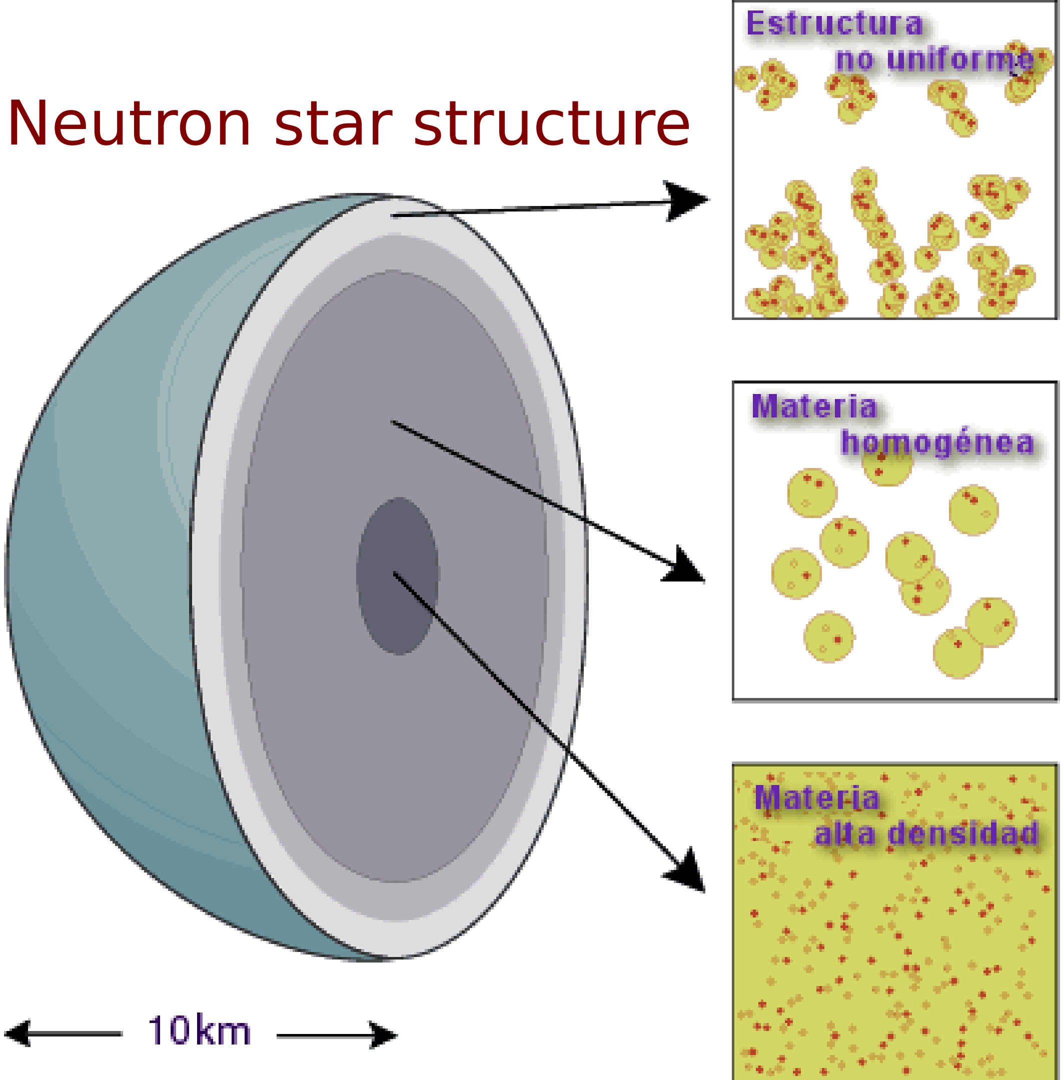
$$\frac{dM(r)}{dr} = 4\pi r^2 \rho(r)\,, \qquad \frac{dP(r)}{dr} = -\frac{G[\rho(r) + P(r)/c^2][4\pi r^3 P(r)/c^2 + M(r)]}{r^2[1 - 2GM(r)/(c^2 r)]}$$





HW: integrate GR hydrostatic eq. equations for a degenerate neutron gas

Neutron star structure



Outer crust:
nuclei+electrons

Inner crust:
nuclei+electrons+neutrons

Core:
n + p + e + other particles
but at lower fractions

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

Neutron Stars: an interplay of physics theories...

Liquid Core Physics:

Strong Interaction

Electromagnetic Interaction

Neutrons

Protons

Electrons

Weak interaction

Gravitational Interaction

Solid Crust Physics:

Solid State Physics

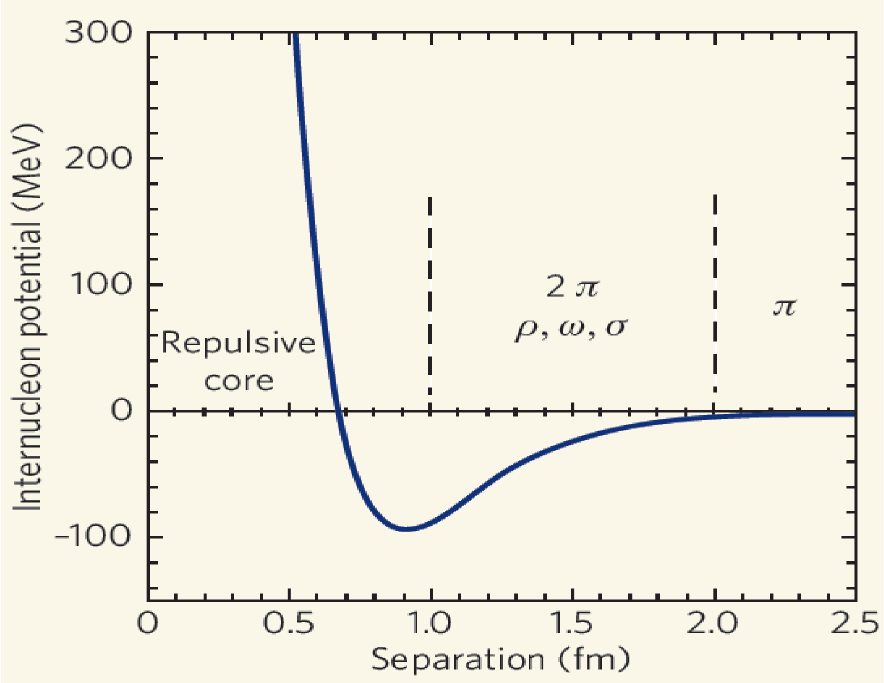
Nuclei Lattice

Electrons

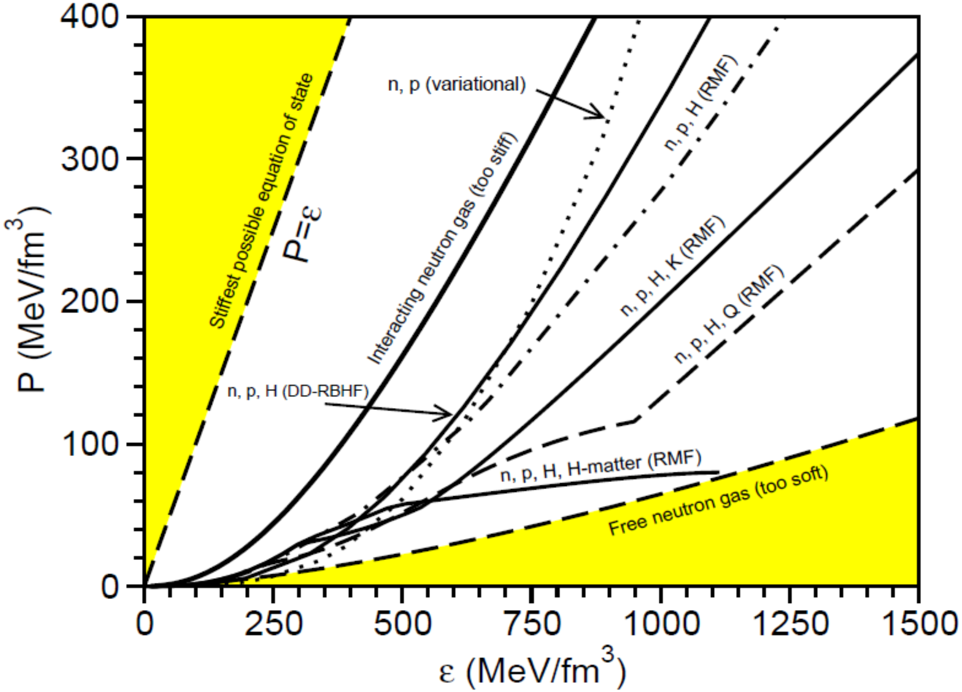
Neutrons

Nuclear Physics

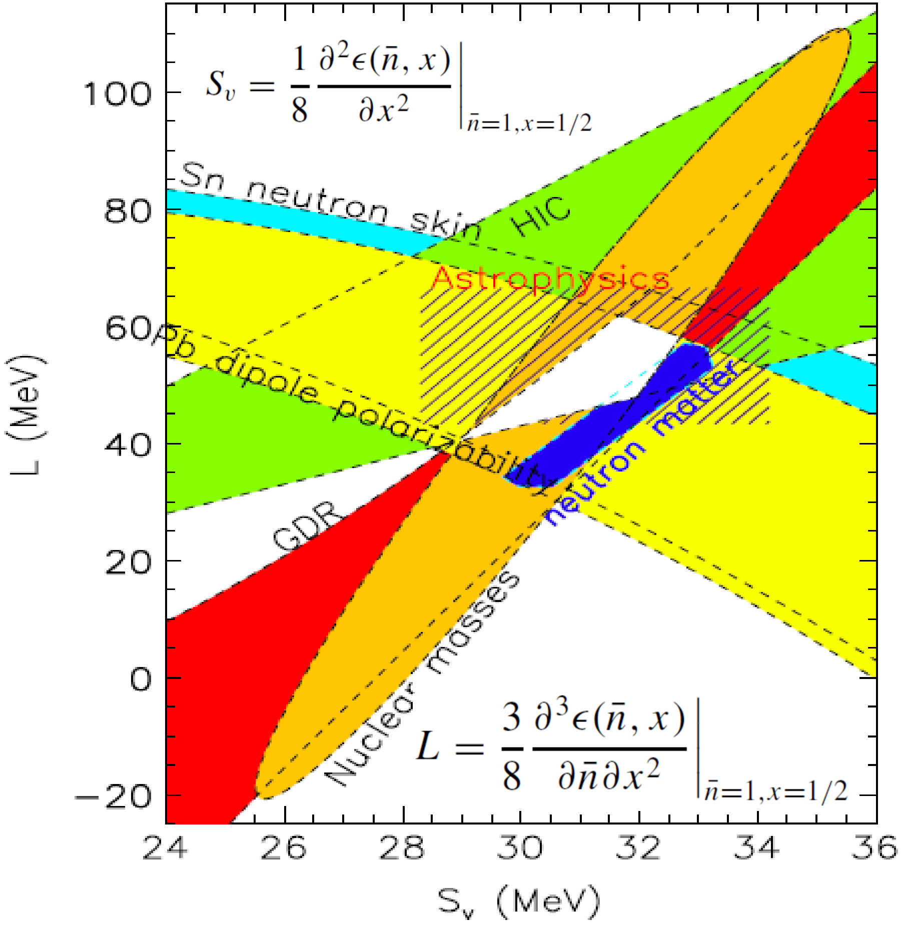
Interacciones fuertes en NS



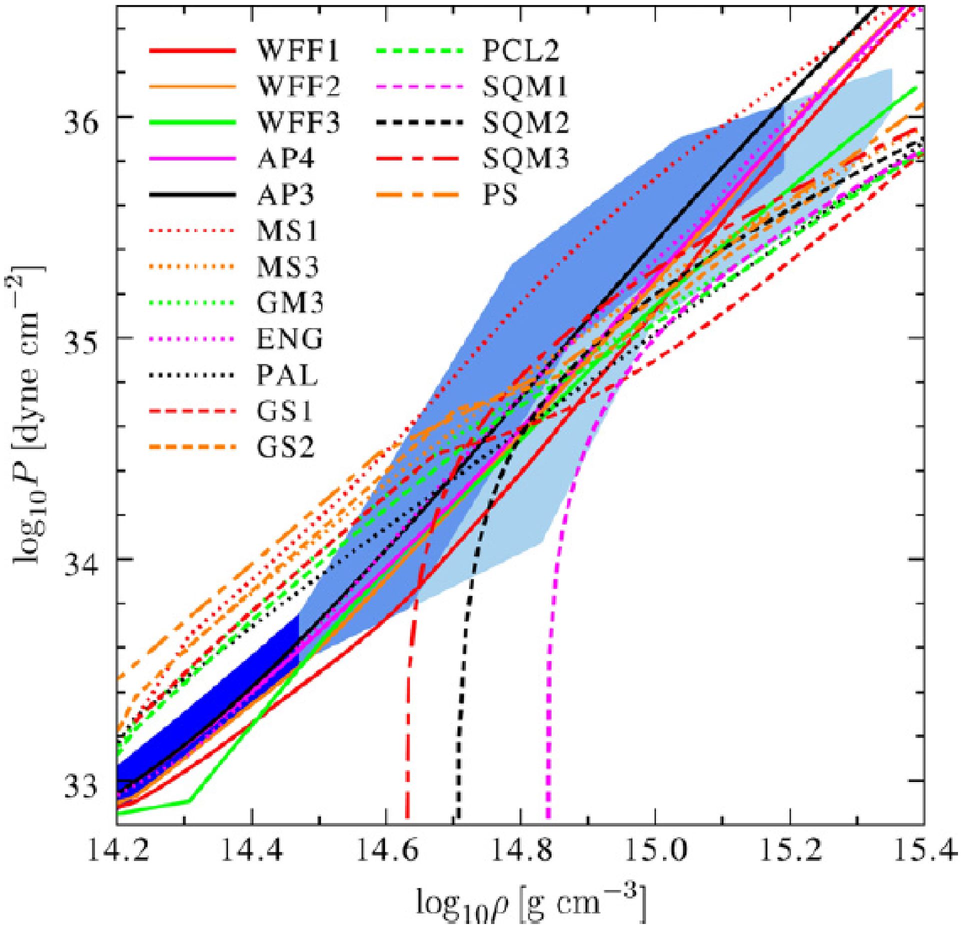
NATURE|Vol 445|11 January 2007



Fridolin, Weber, Negreiros, Rosenfield
arXiv:0705.2708v2



Lattimer & Lim, ApJ (2013)



Hebeler et al., ApJ (2013)

NS EOS (Relativistic Mean-Field Models)

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

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

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

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

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

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

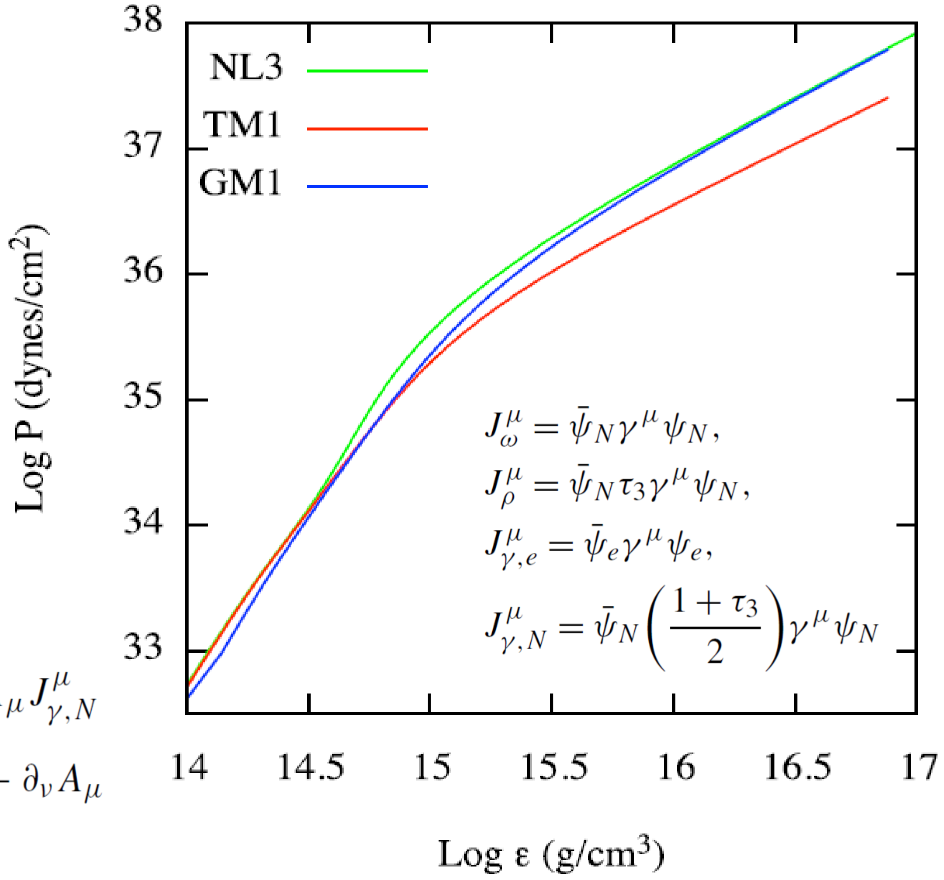
$$\mathcal{L}_\rho = -\frac{1}{4}\mathcal{R}_{\mu\nu}\mathcal{R}^{\mu\nu} + \frac{1}{2} m_\rho^2 \rho_\mu \rho^\mu,$$

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

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

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

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



Equations of motion

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

$$G_{\mu\nu} + 8\pi G T_{\mu\nu} = 0,$$

$$\nabla_\mu F^{\mu\nu} - eJ^\nu_{ch} = 0,$$

$$\nabla_\mu \Omega^{\mu\nu} + m_\omega^2 \omega^\nu - g_\omega J^\nu_\omega = 0,$$

$$\nabla_\mu \mathcal{R}^{\mu\nu} + m_\rho^2 \rho^\nu - g_\rho J^\nu_\rho = 0,$$

$$\nabla_\mu \nabla^\mu \sigma + \partial_\sigma U(\sigma) + g_s n_s = 0,$$

$$\left[\gamma_\mu \left(iD^\mu - V^\mu_N\right) - \tilde{m}_N\right] \psi_N = 0,$$

$$\left[\gamma_\mu \left(iD^\mu + eA^\mu\right) - m_e\right] \psi_e = 0,$$

$$n_s = \bar{\psi}_N \psi_N$$

$$\tilde{m}_N \equiv m_N + g_\sigma \sigma$$

$$V^\mu_N \equiv g_\omega \omega^\mu + g_\rho \tau \rho^\mu + e\left(\frac{1+\tau_3}{2}\right) A^\mu$$

Fixing the nuclear model parameters

$$n_0 = 4\int_0^{k_\mathrm{F}} \frac{d^3k}{8\pi^3} = \frac{2k_\mathrm{F}^3}{3\pi^2} \approx 0.16\ \mathrm{fm}^{-3}$$

$$E_\mathrm{BE} = \Sigma - m_\mathrm{N} \approx -16\ \mathrm{MeV} \qquad \Sigma \equiv \epsilon/n_\mathrm{b}$$

$$\tilde{m} = m_\mathrm{N} + g_\sigma \sigma \approx (0.7 \div 0.8)\ m_\mathrm{N}$$

$$a_\mathrm{sym} = \frac{1}{2}\left[\frac{\partial^2}{\partial t^2}\left(\frac{\epsilon}{n_\mathrm{b}}\right)\right]_{t=0}, \qquad t \equiv \frac{n_\mathrm{n} - n_\mathrm{p}}{n_\mathrm{b}}$$

$$\approx \ (31 \div 33)\ \mathrm{MeV}$$

$$K = \left[k^2 \frac{d^2}{dk^2}\left(\frac{\epsilon}{n_\mathrm{b}}\right)\right]_{k_\mathrm{F}} = 9\left[n_\mathrm{b}^2 \frac{d^2}{dn^2}\left(\frac{\epsilon}{n_\mathrm{b}}\right)\right]_{n_0} \approx (200 \div 300)\ \mathrm{MeV}$$

Nuclear model parameters…

$$\frac{\epsilon_0}{n_0} = \left(C_\omega n_{\mathrm{b}} + \sqrt{k_{\mathrm{F}}^2 + \tilde{m}^2}\right),$$

$$K = C_\omega \frac{6k_{\mathrm{F}}^3}{\pi^2} + \frac{3k_{\mathrm{F}}^2}{E(k_{\mathrm{F}})} - \frac{6}{\pi^2}\frac{\tilde{m}^2 C_\sigma k_{\mathrm{F}}^3}{E^2(k_{\mathrm{F}})D},$$

$$E_{\mathrm{BE}} = \Sigma - m_{\mathrm{N}},$$

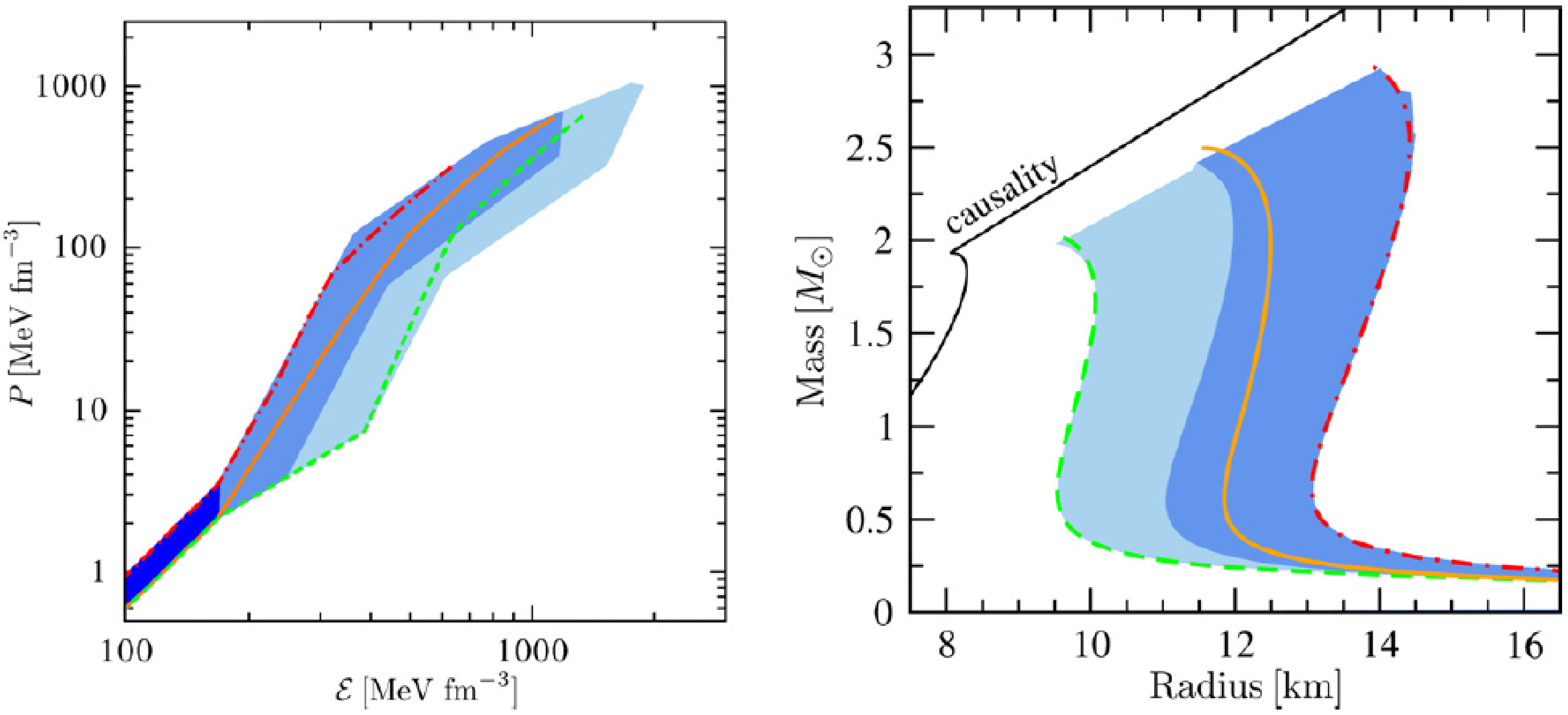
$$a_{\mathrm{sym}} = C_\rho \frac{k_{\mathrm{F}}^3}{12\pi^2} + \frac{k_{\mathrm{F}}^2}{6(k_{\mathrm{F}}^2 + \tilde{m}^2)^{1/2}}.$$

	NL3	NL–SH	TM1	TM2
m_σ (MeV)	508.194	526.059	511.198	526.443
m_ω (MeV)	782.501	783.000	783.000	783.000
m_ρ (MeV)	763.000	763.000	770.000	770.000
g_s	10.2170	10.4440	10.0289	11.4694
g_ω	12.8680	12.9450	12.6139	14.6377
g_ρ	4.4740	4.3830	4.6322	4.6783
g_2 (fm^{-1})	-10.4310	-6.9099	-7.2325	-4.4440
g_3	-28.8850	-15.8337	0.6183	4.6076
c_3	0.0000	0.0000	71.3075	84.5318

To obtain:

$$\{C_\sigma,\ C_\omega,\ C_\rho,\ g_2,\ g_3\}$$

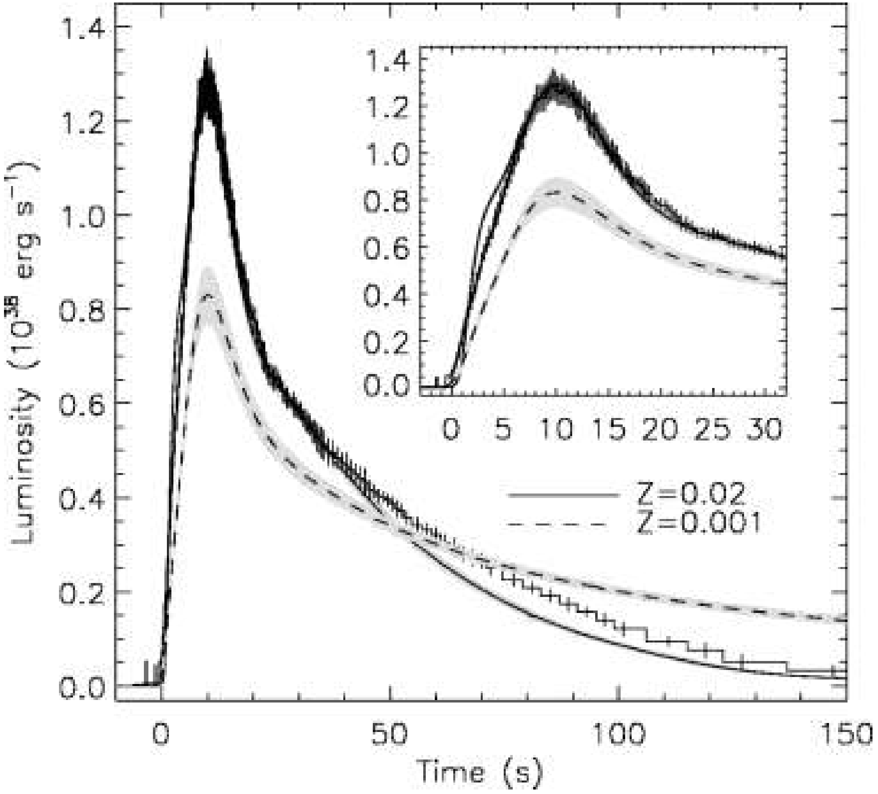
Constraining the nuclear EOS and Mass-Radius Relation

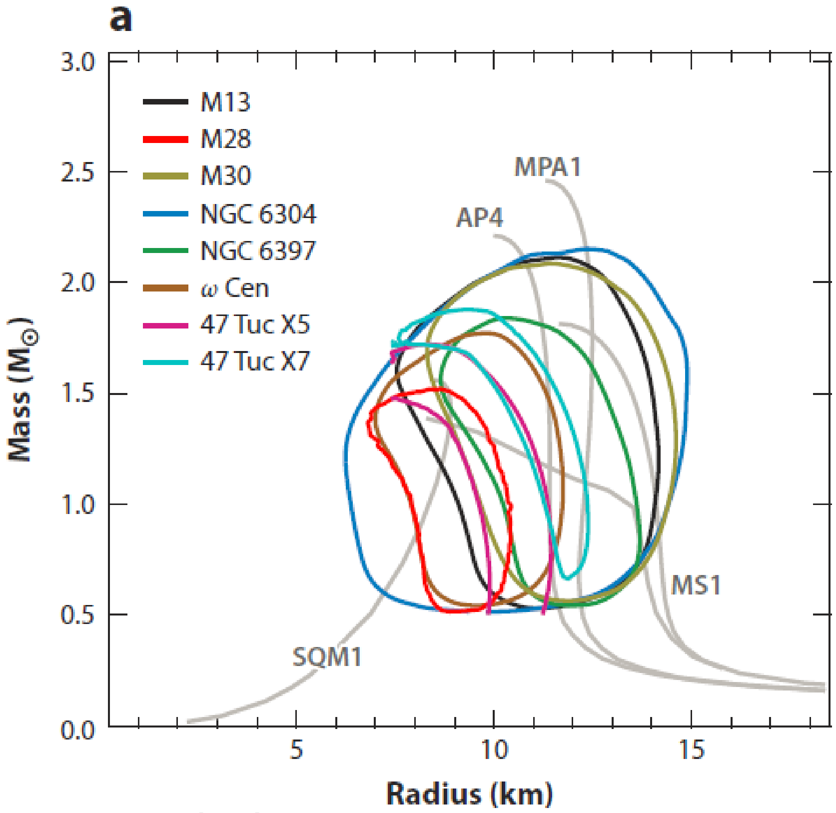


Hebeler et al., ApJ (2013)

More recent neutron star radius constraints

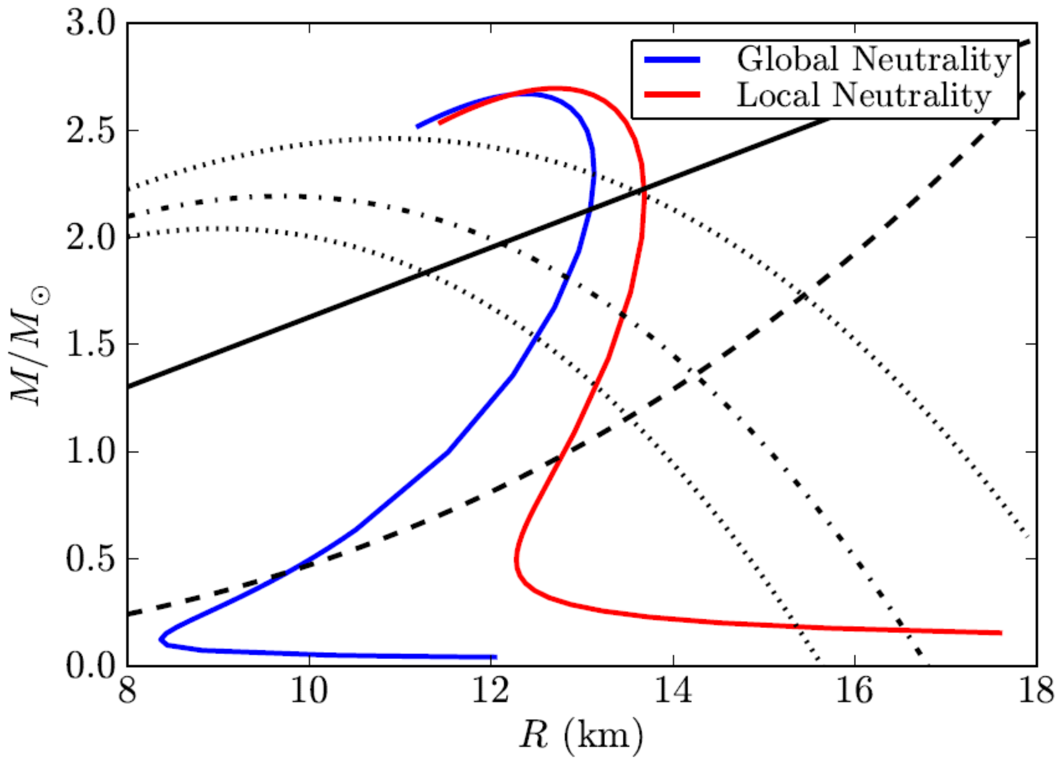
(From Ozel & Freire, ARAA 2016)





Radii often obtained from X-ray bursts or quiescent emission

Mass-radius relation



Observational Constraints

Maximum Observed Mass: 2 Msun

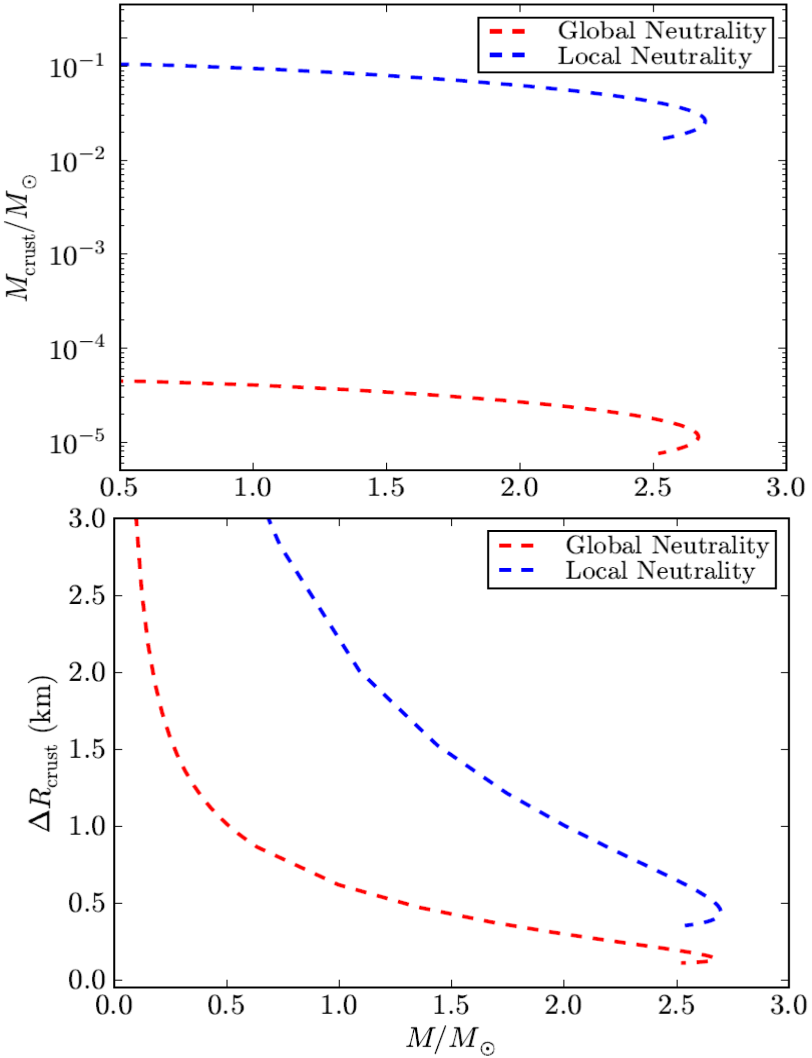
Fastest Observed Pulsar: PSR J1614-2230, 716 Hz, dashed curve

Minimum Radius of RX J1856-3754: dotted-dashed curve

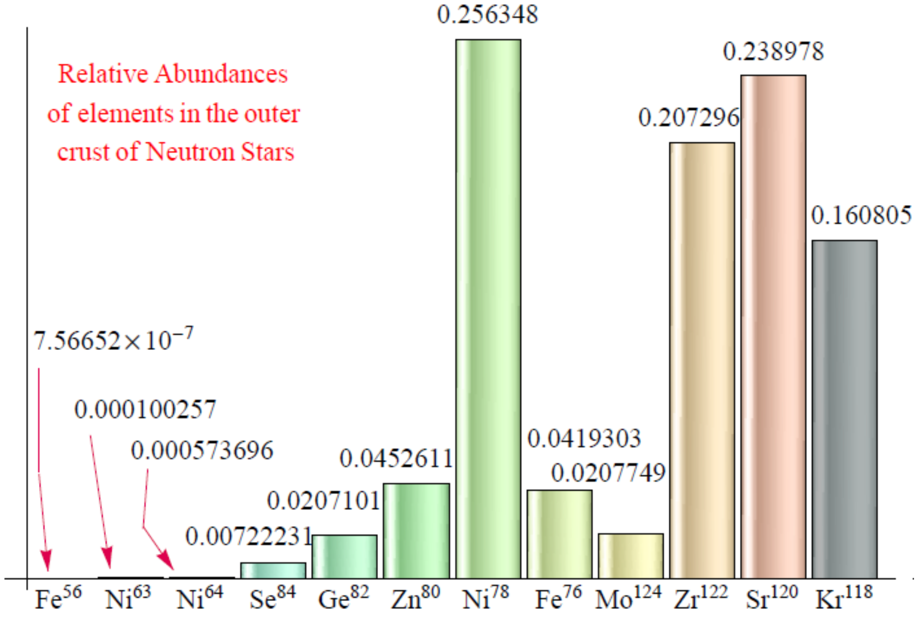
Surface gravity of X7: dotted curves

NS crust

Belvedere, Pugliese, Rueda, Ruffini, Xue, NPA 883, 1 (2012)



$$\mathrm{R.A.} = \frac{1}{M_{\rm crust}^{\rm BPS}} \int_{\Delta r} 4\pi r^2 \mathcal{E}\, dr$$



NS in full rotation in GR

(e.g. Cipolletta, Cherubini, Filippi, Rueda, Ruffini, PRD 2015)

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

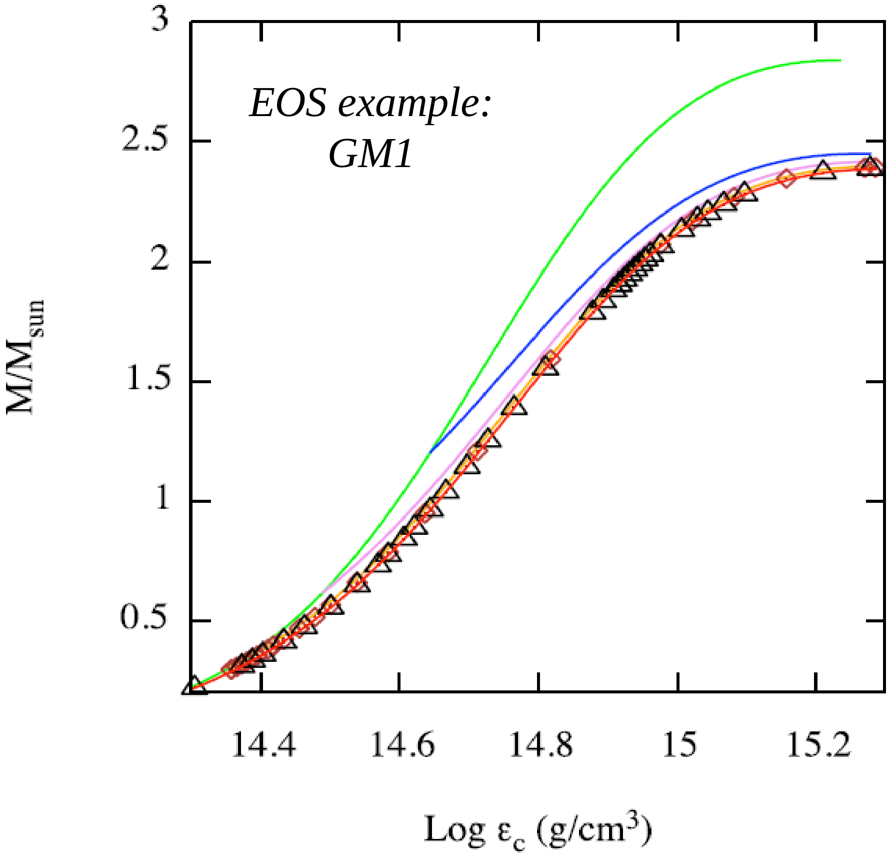
$$\nabla \cdot (B\nabla\nu) = \frac{1}{2}r^2 \sin^2\theta B^3 e^{-4\nu}\nabla\omega\cdot\nabla\omega + 4\pi B e^{2\zeta-2\nu}\left[\frac{(\varepsilon+P)(1+v^2)}{1-v^2} + 2P\right]$$

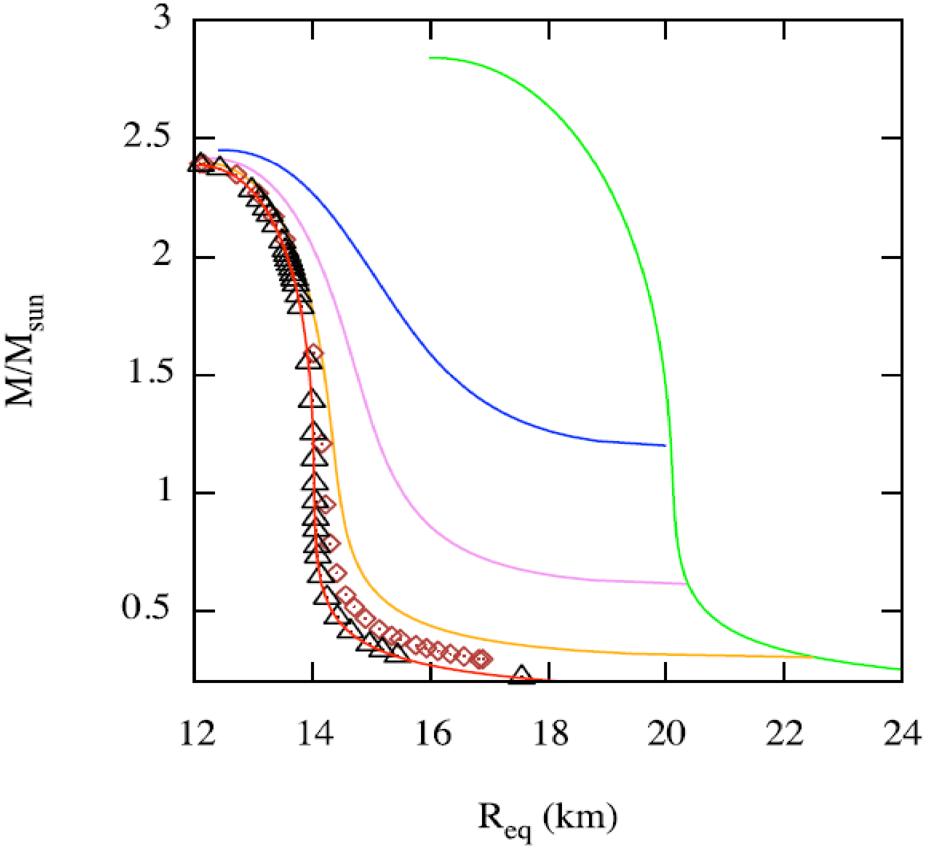
$$\nabla\cdot(r^2\sin^2\theta B^3 e^{-4\nu}\nabla\omega) = -16\pi r\sin\theta B^2\; e^{2\zeta-4\nu}\frac{(\varepsilon+P)v}{1-v^2} \qquad \nabla\cdot(r\sin(\theta)\nabla B) = 16\pi r\sin\theta B e^{2\zeta-2\nu}P,$$

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

Full rotation in GR

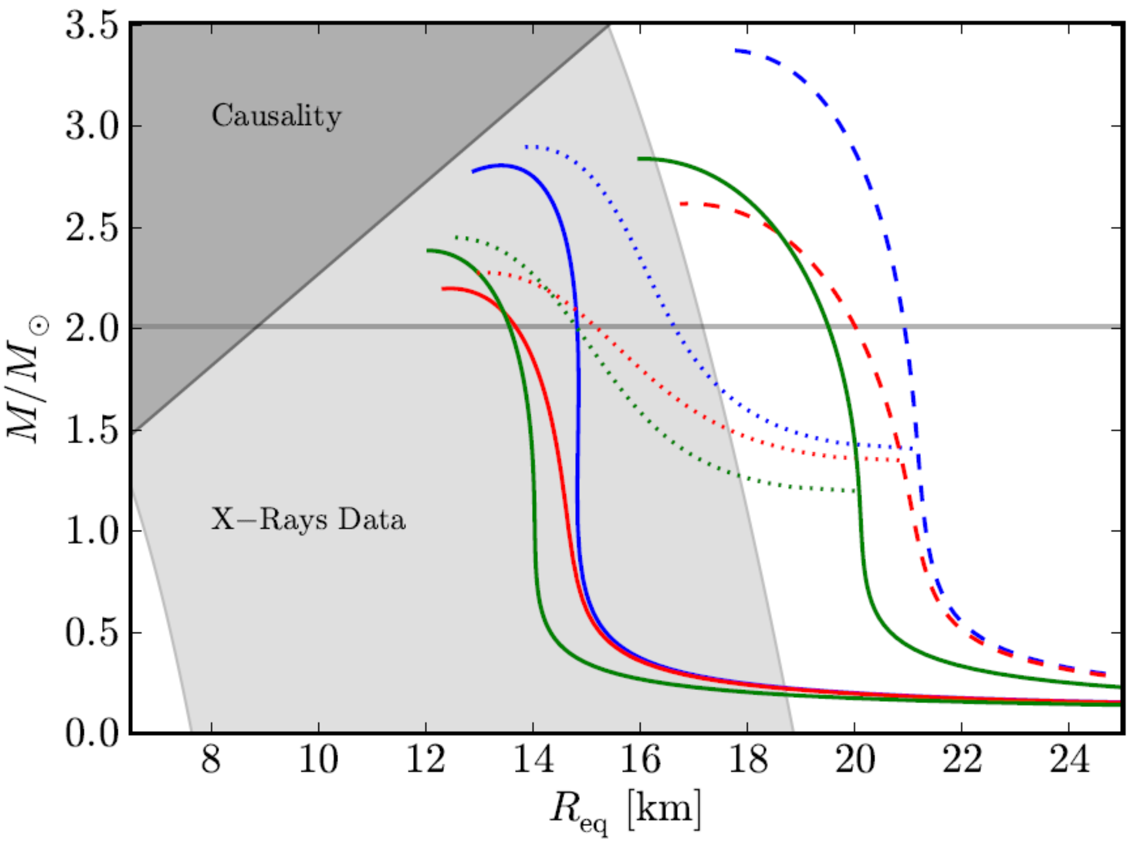
(Cipolletta, Cherubini, Filippi, Rueda, Ruffini, PRD 2015)





Full rotation in GR

(Cipolletta, Cherubini, Filippi, Rueda, Ruffini, PRD 2015)

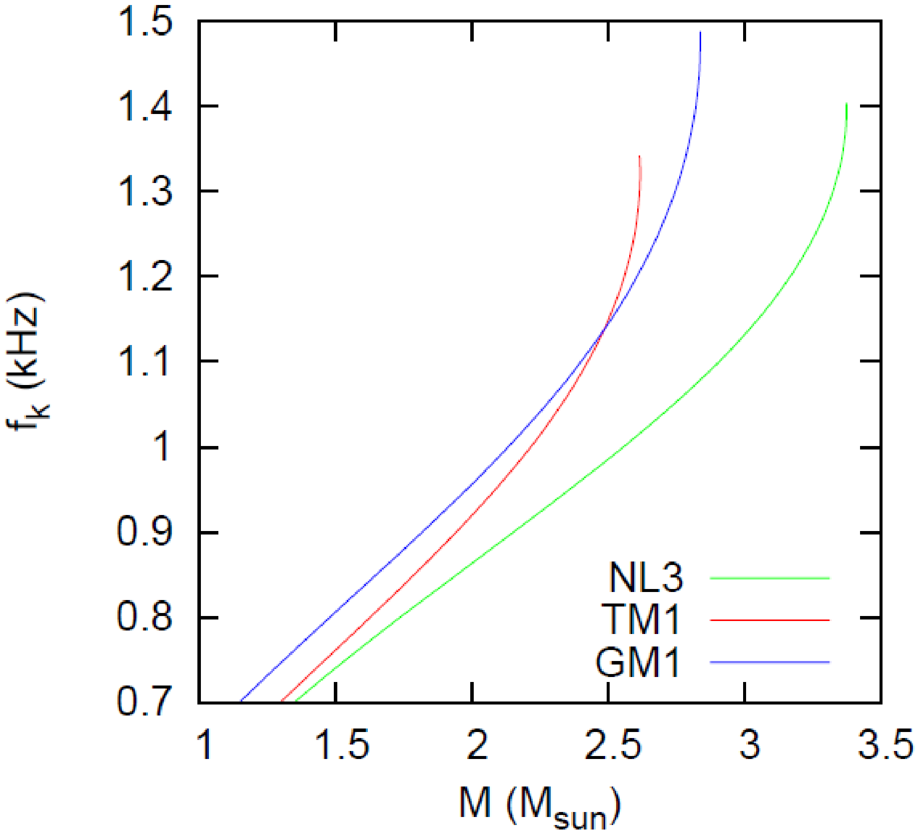


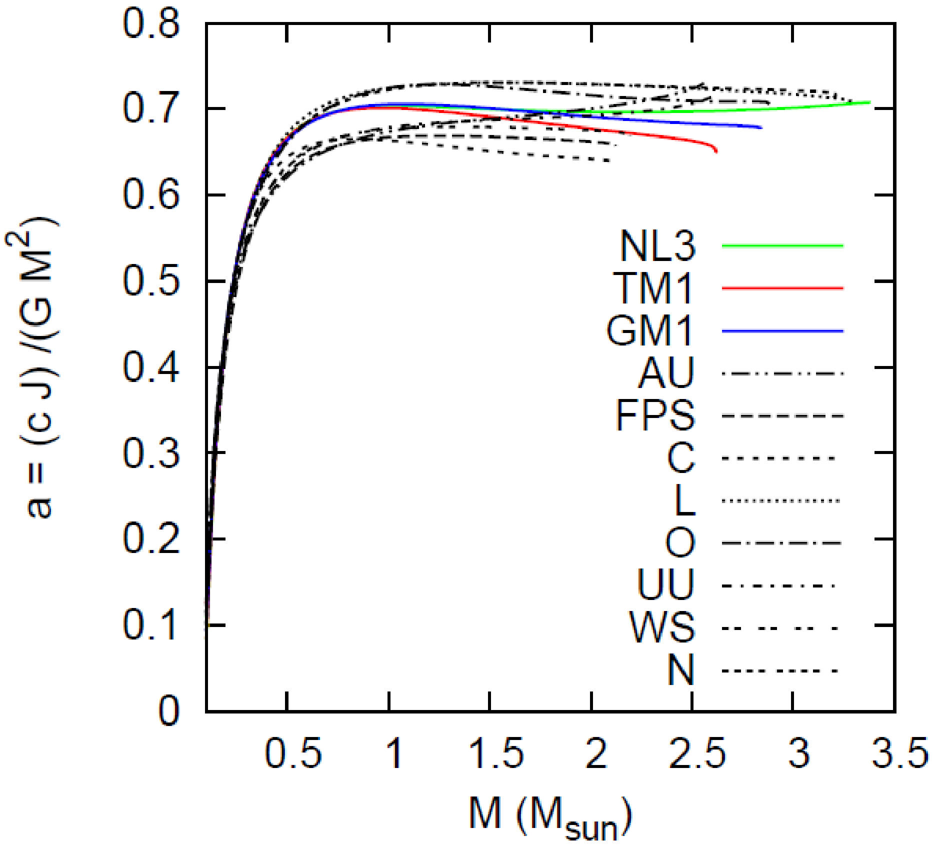
Observational Constraints:

- Maximum NS mass observed
- Fastest NS observed
- Radii measurements from X-ray emisison: mainly from low-mass X-ray binaries (LMXBs), and X-ray isolated NSs (XINSs)
- Causality: satisfied by construction in relativistic

Full rotation in GR

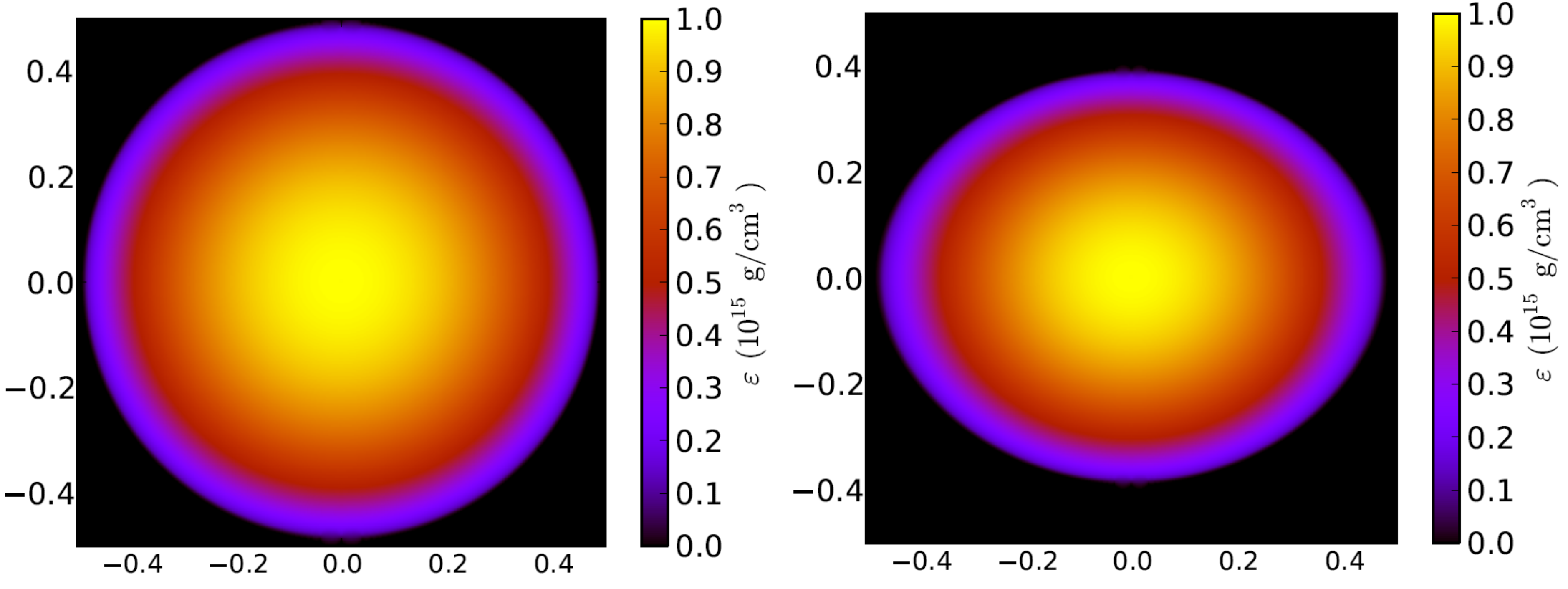
(Cipolletta, Cherubini, Filippi, Rueda, Ruffini, PRD 2015)





NS deformation by rotation

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



Full rotation in GR

(Cipolletta, Cherubini, Filippi, Rueda, Ruffini, PRD 2015)

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

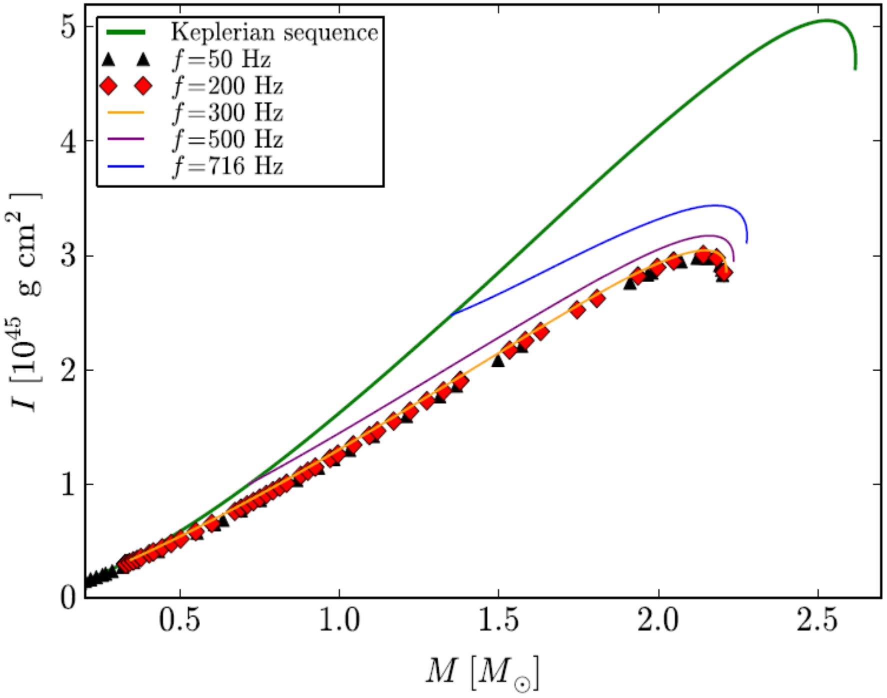
Pappas & Apostolatos, PRL 2012

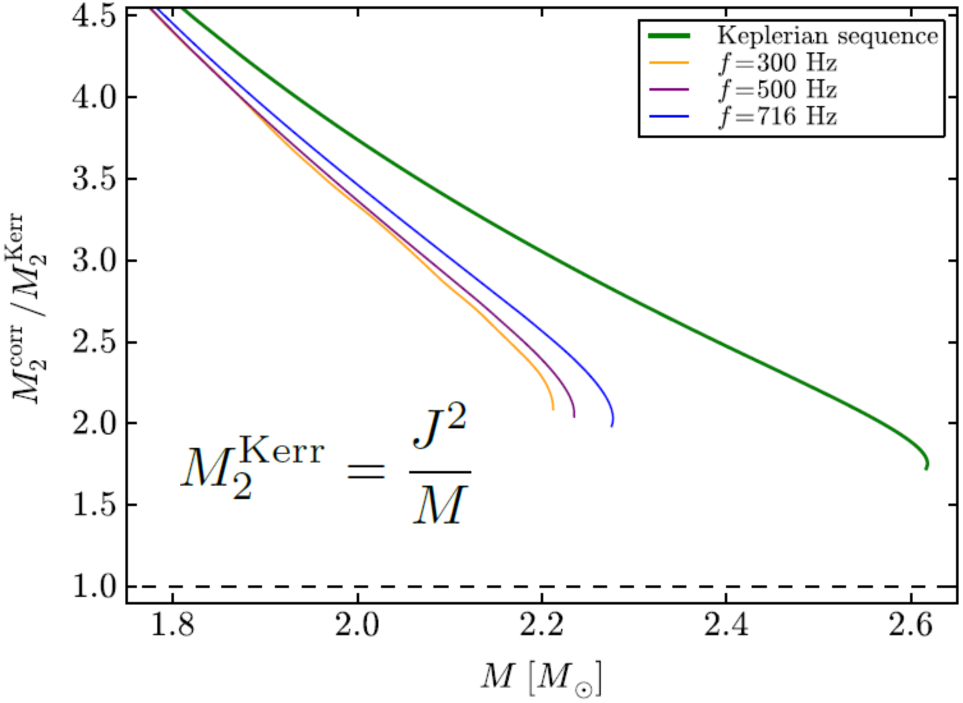
$$\begin{aligned} S_\rho(r,\mu) = \quad & e^{\frac{\gamma}{2}}\Bigg[8\pi e^{2\lambda}(\varepsilon + P)\frac{1+u^2}{1-u^2} + r^2 e^{-2\rho}\left[\omega_{,r}^2 + \frac{1}{r^2}(1-\mu^2)\omega_{,\mu}^2\right] + \frac{1}{r}\gamma_{,r} - \frac{1}{r^2}\mu\gamma_{,\mu} \\ & + \frac{\rho}{2}\left\{16\pi e^{2\lambda}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

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

NS moment of inertia and quadrupole moment

(Cipolletta, Cherubini, Filippi, Rueda, Ruffini, PRD 92, 023007, 2015)





Full rotation in GR

(Cipolletta, Cherubini, Filippi, Rueda, Ruffini, PRD 2015)

Static Configurations

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

Rotating Configurations

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

Are there stable stars denser than neutron stars ?
YES/NO

Are there astrophysical objects denser than neutron stars ? YES, BLACK HOLES

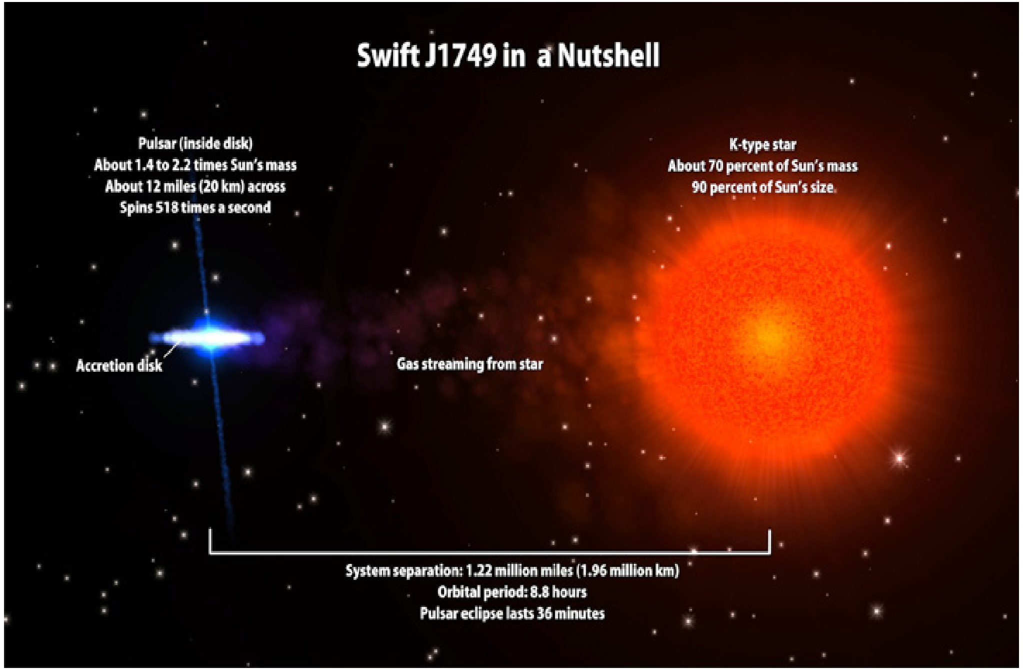
What object is formed from the gravitational collapse of a neutron star ? A BLACK HOLE

Gamma-Ray Bursts

Some energy sources in astrophysical systems

- Thermal energy: e.g. main-sequence stars
- Nuclear energy: novae, X-ray bursters, kilonovae, SNe Ia
- Accretion energy: e.g. X-ray binaries, quasars, blazars, AGN
- Gravitational energy: gravitational collapse, SN II, GRBs, …
- Rotational energy: e.g. pulsars, AGN
- Electromagnetic energy: e.g. magnetospheric processes, magnetic field decay, twisted field flares, …

X-ray binaries



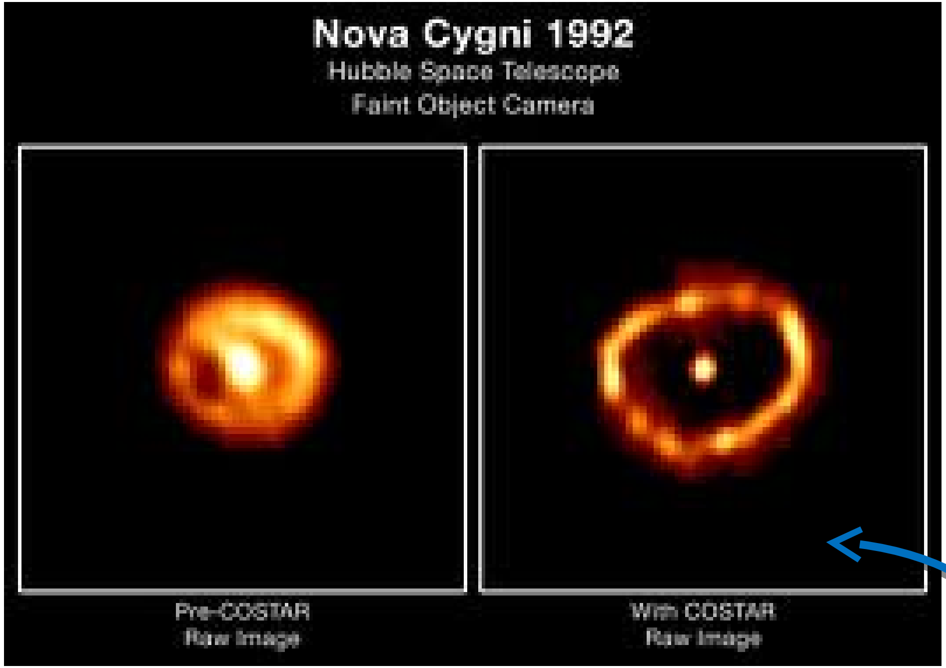
Compact object: NS or BH

Orbital periods= minutes to days

$L=10^{32}$-10^{35} erg/s

(in X-rays of course !)

Novae



Compact object: White Dwarf; donor: ordinary star: Sun-like

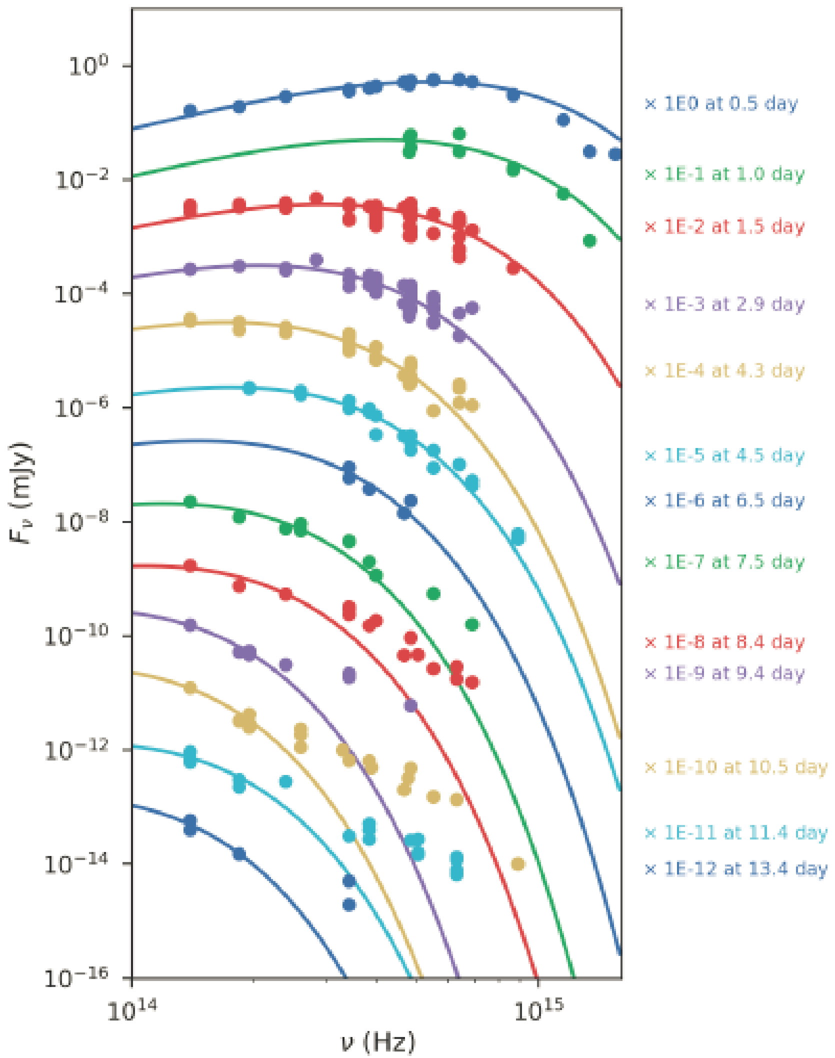
Orbital period, P = few minutes-hours

Quiescent Emission: up to X-rays, L=10^34 erg/s

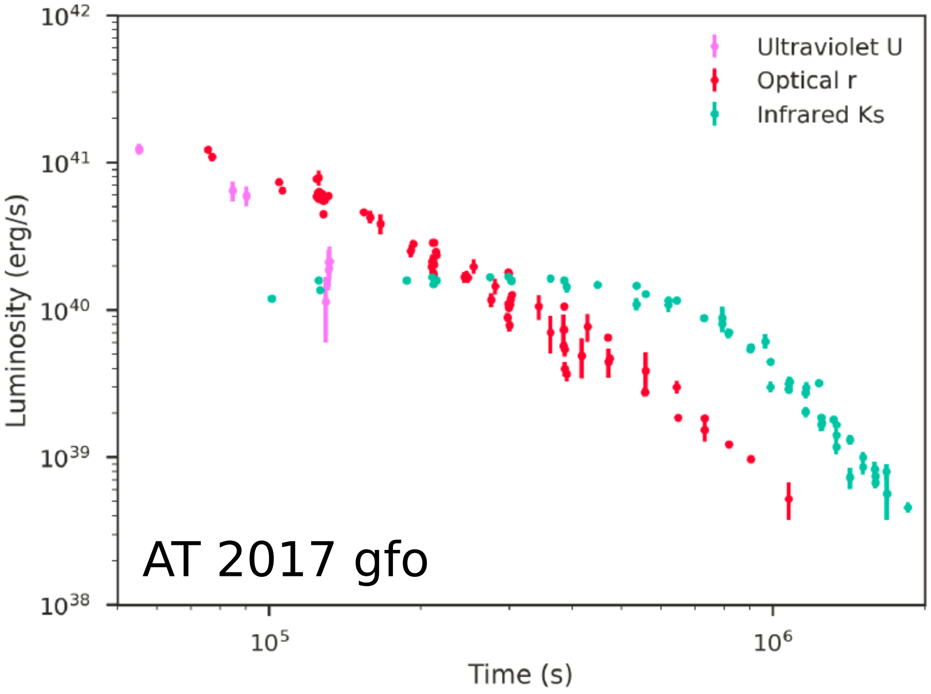
Thermonuclear explosions: brightness increases in a few days up to a factor 10^6

Nova shell expansion !!

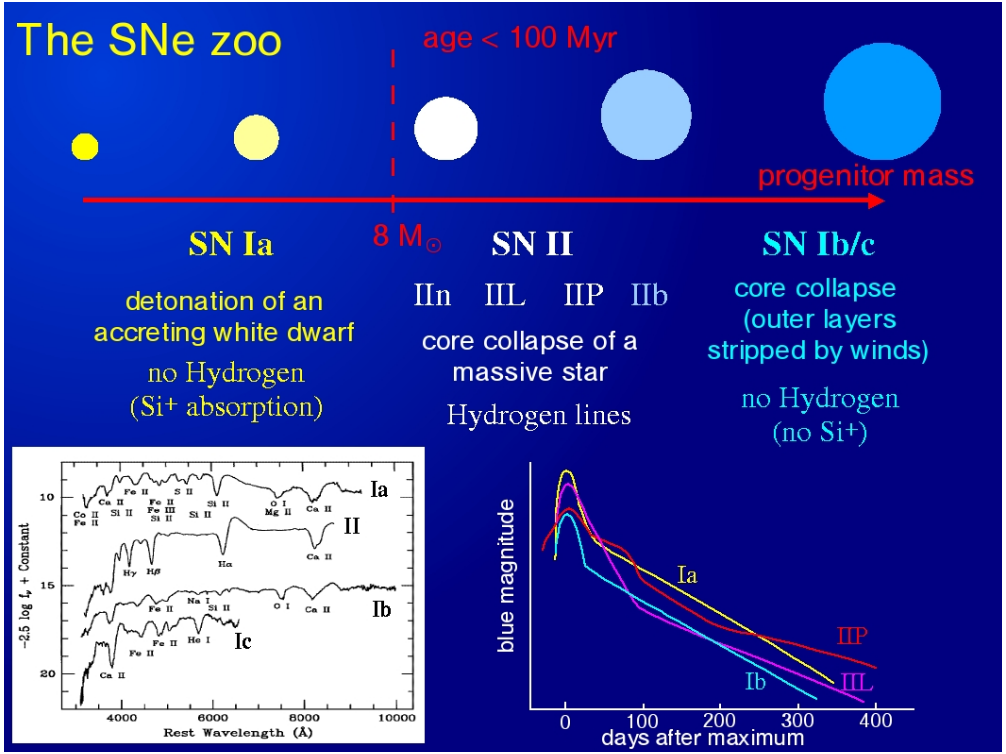
Kilonovae

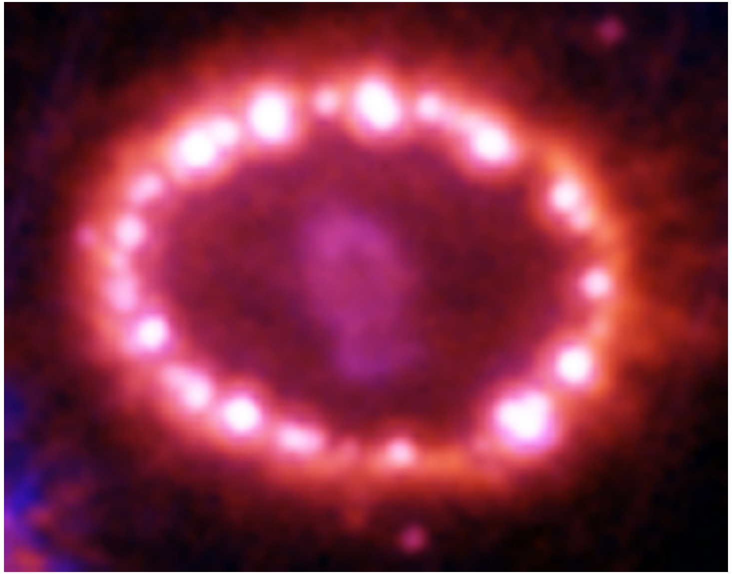


Powered by nuclear decay of heavy elements synthetized in ejecta of e.g. NS-NS mergers



Supernovae (I and II)

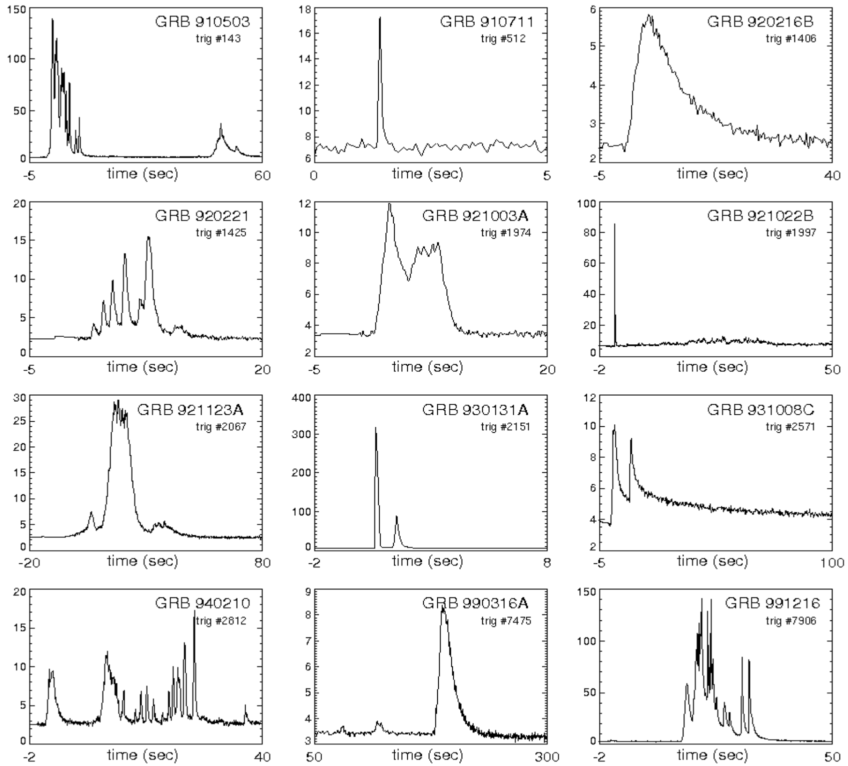




Energy release
10^{49} - 10^{51} erg

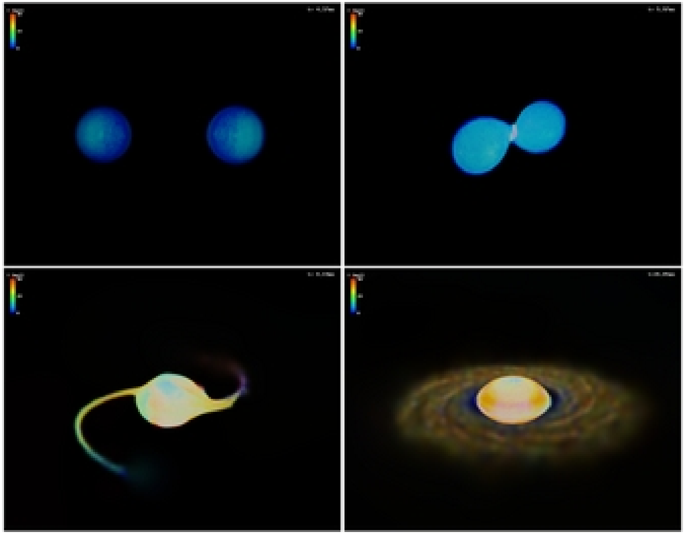
Gamma-Ray Bursts

- **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***

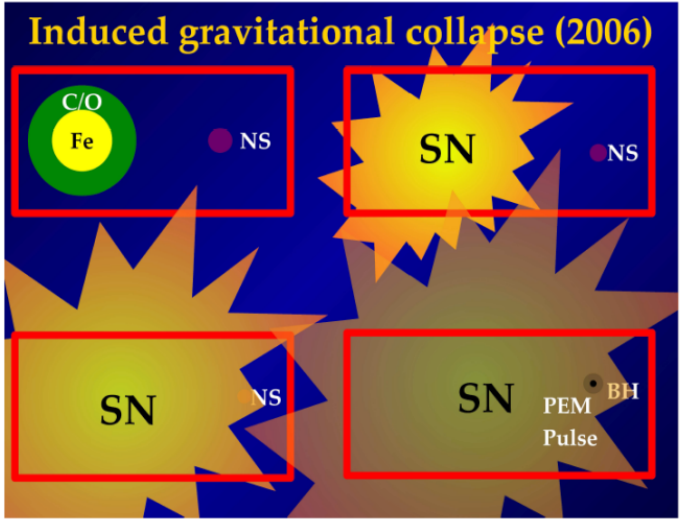


Gamma-Ray Bursts and Neutron Star Physics

Short GRBs: NS-NS and NS-BH Mergers

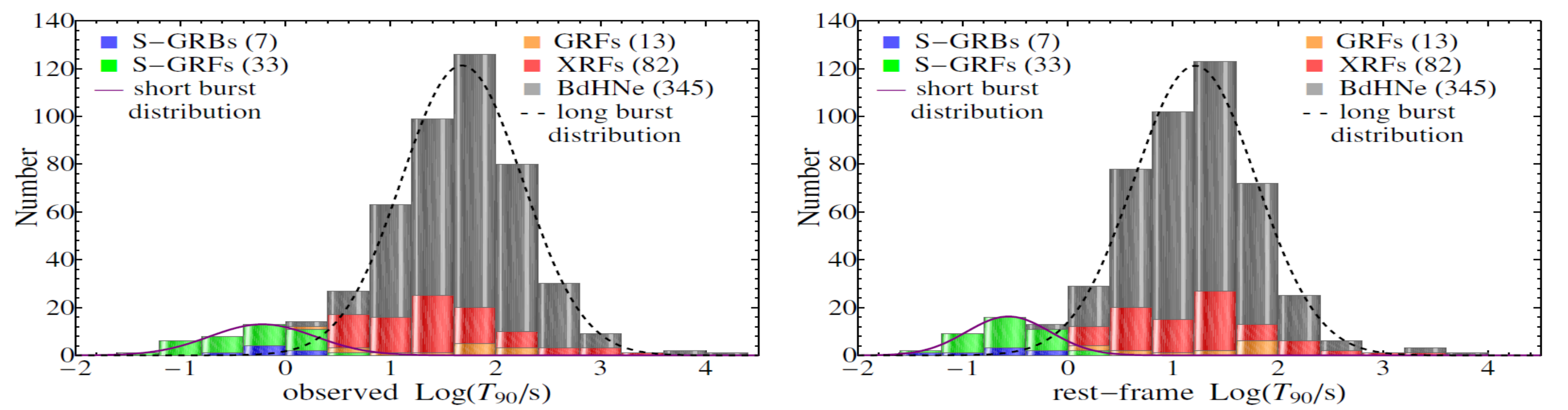


Long GRB-SN: Induced Gravitational Collapse



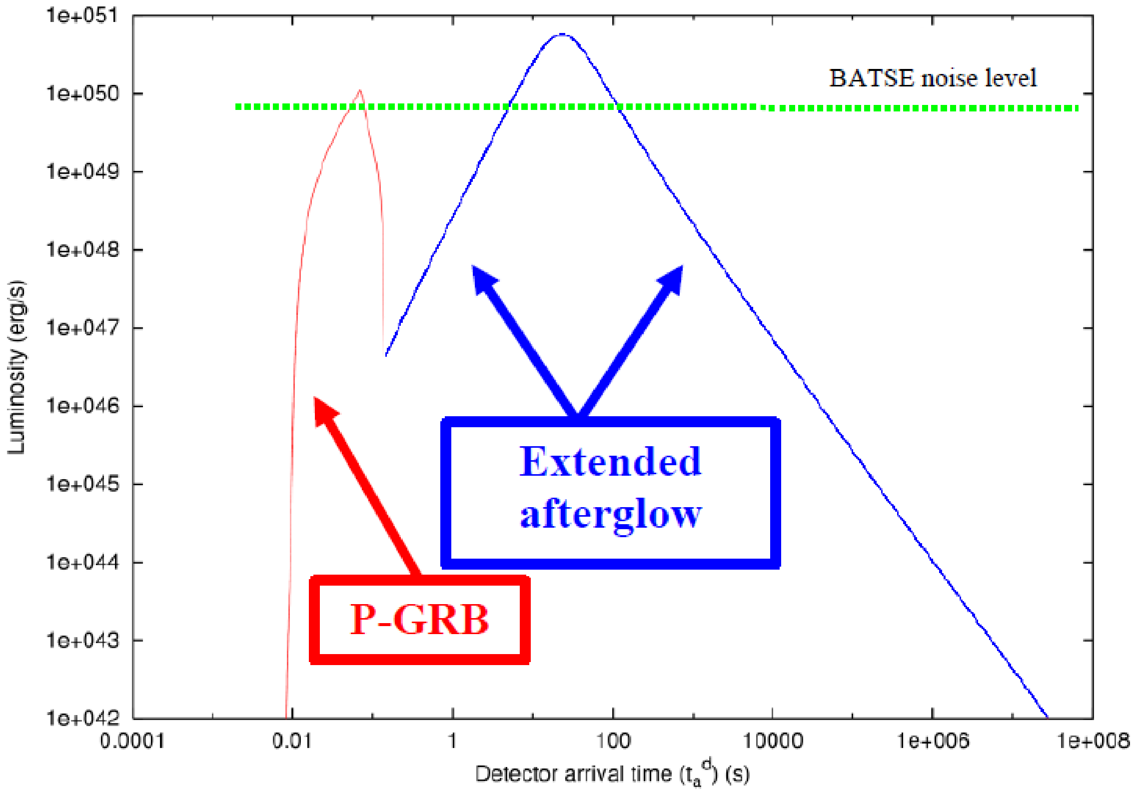
But … eight different GRB families ?

	Sub-class	Number	*In-state*	*Out-state*	$E_{p,i}$ (MeV)	E_{iso} (erg)	$E_{iso,Gev}$ (erg)
I	S-GRFs	17	NS-NS	MNS	~ 0.2–2	$\sim 10^{49}$–10^{52}	–
II	S-GRBs	6	NS-NS	BH	~ 2–8	$\sim 10^{52}$–10^{53}	$\gtrsim 10^{52}$
III	XRFs	48	CO_{core}-NS	νNS-NS	~ 0.004–0.2	$\sim 10^{48}$–10^{52}	–
IV	BdHNe	329	CO_{core}-NS	νNS-BH	~ 0.2–2	$\sim 10^{52}$–10^{54}	$\gtrsim 10^{52}$
V	BH-SN	4	CO_{core}-BH	νNS-BH	$\gtrsim 2$	$> 10^{54}$	$\gtrsim 10^{53}$
VI	U-GRBs	0	νNS-BH	BH	$\gtrsim 2$	$> 10^{52}$	–
VII	GRFs	1	NS-WD	MNS	~ 0.2–2	$\sim 10^{51}$–10^{52}	–
VIII	GR-K	1	WD-WD	MWD	~ 0.082	$\sim 10^{47}$	–

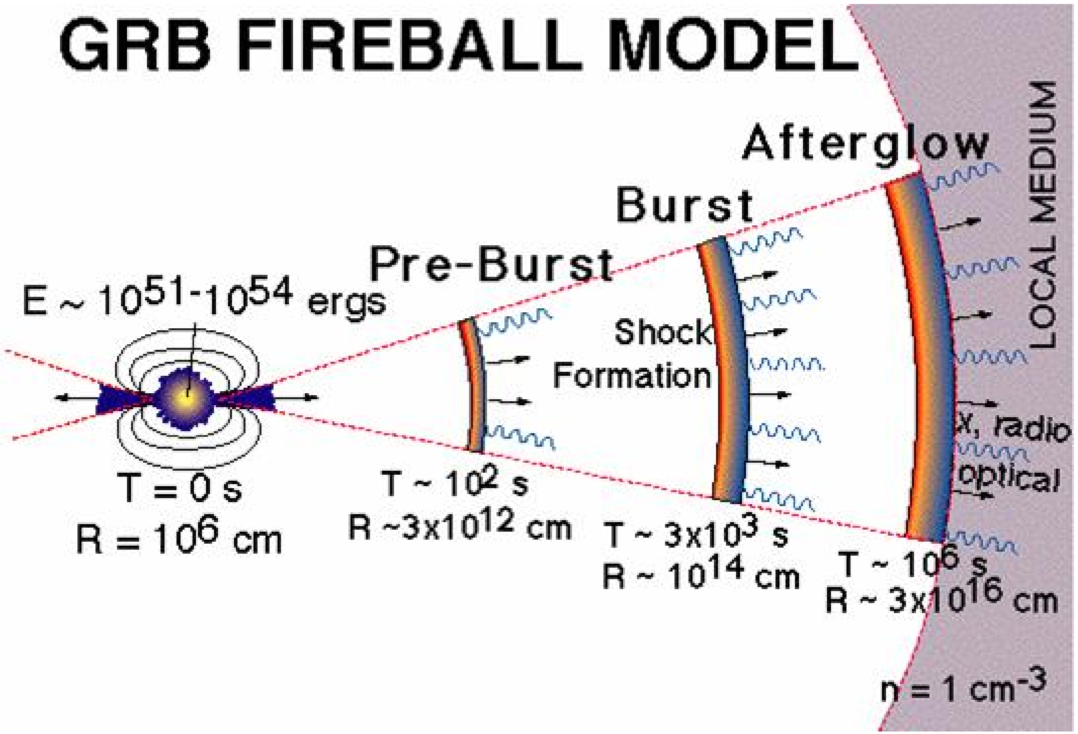


Ruffini, Rueda, et al., *ApJ*, 832 (2016) 136

The canonical GRB lightcurve



The “standard” model of GRBs



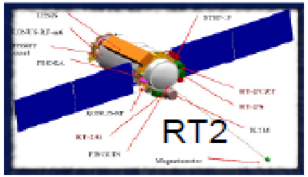
Central engine: unknown, but BH is needed (required by high energetics): most used: collapsar model, massive star formes a BH with surrounding disk

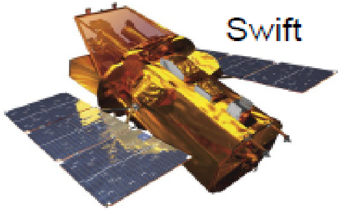
Ultrarelativistic expanding electron-positron-photon-baryon plasma

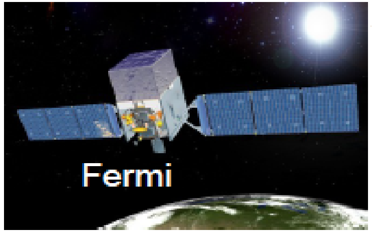
Interaction with interestellar medium (ISM)

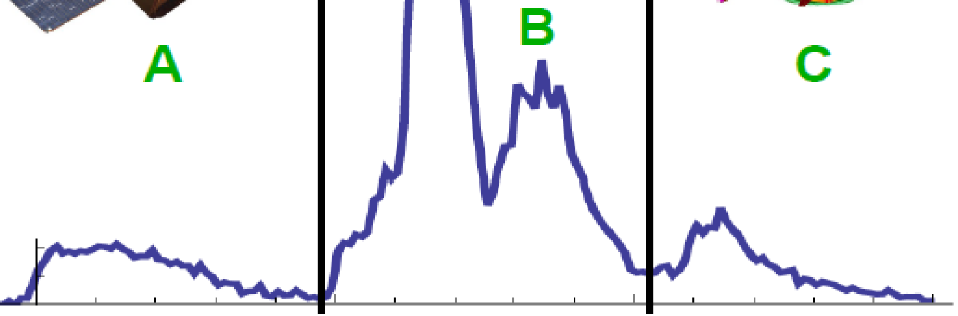
Shocks, reverse and forward

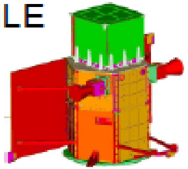
…

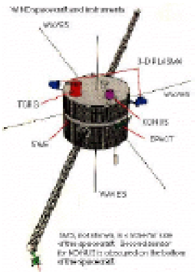












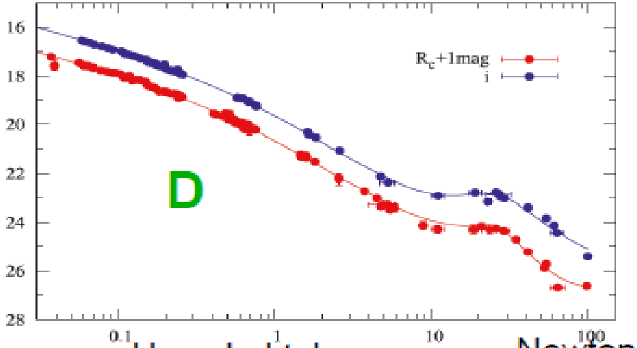
Konus-WIND

GRB 090618

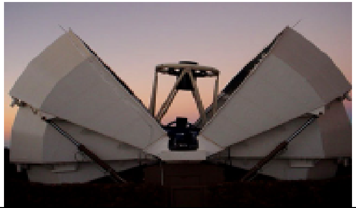
Eiso=2.8x10^{53} erg

Z=0.54

Ruffini et al. *PoS(Texas2010)*, 101 (2011)
Izzo et al., *A&A*, 543, A10 (2012)



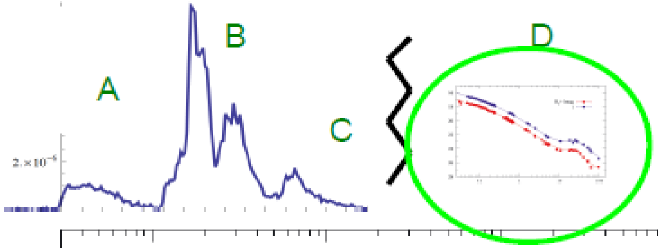
Faulkes North



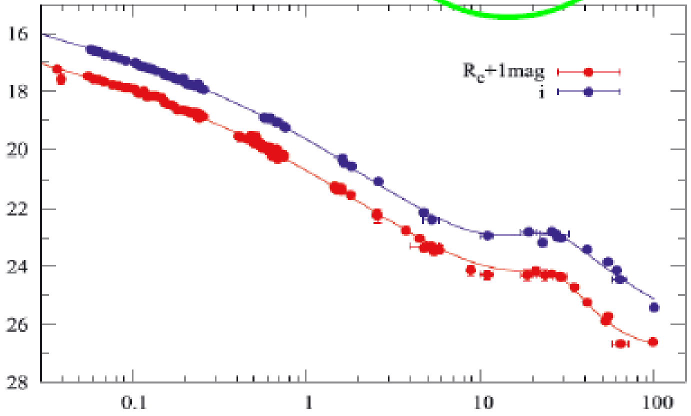
Gemini North

Herschel telescope

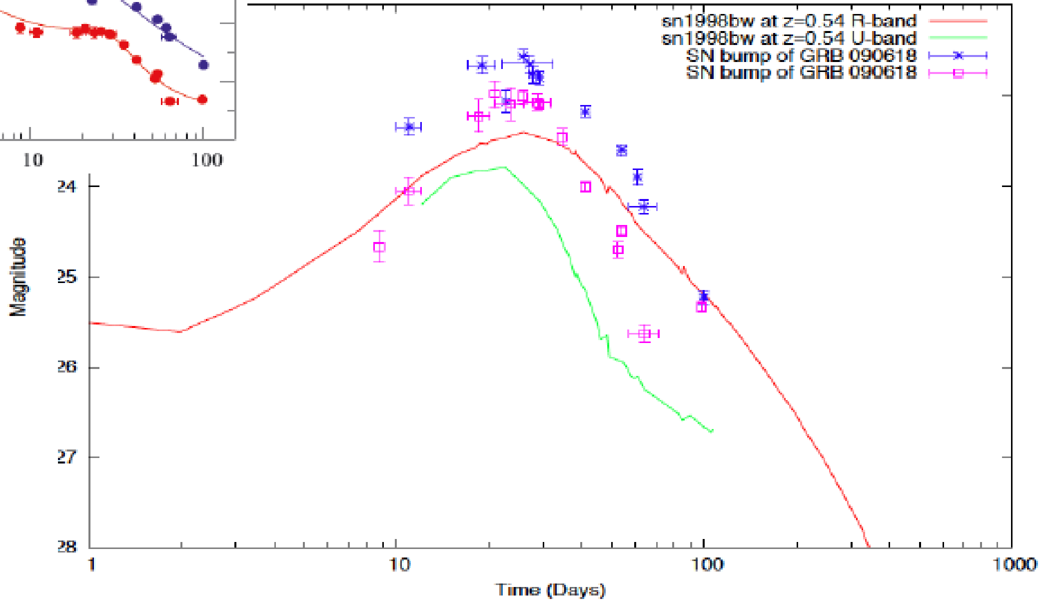
Newton telescope



The supernova emission

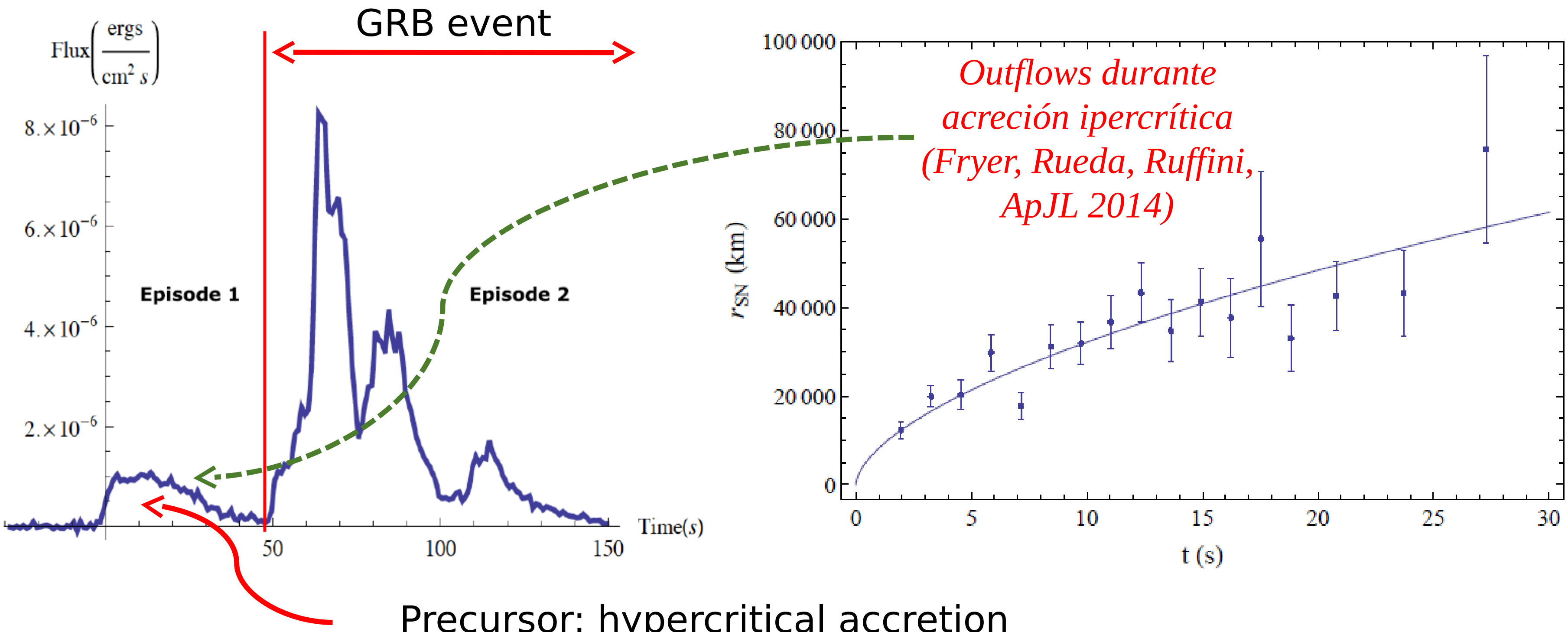


sn1998bw and “bump” in GRB 090618



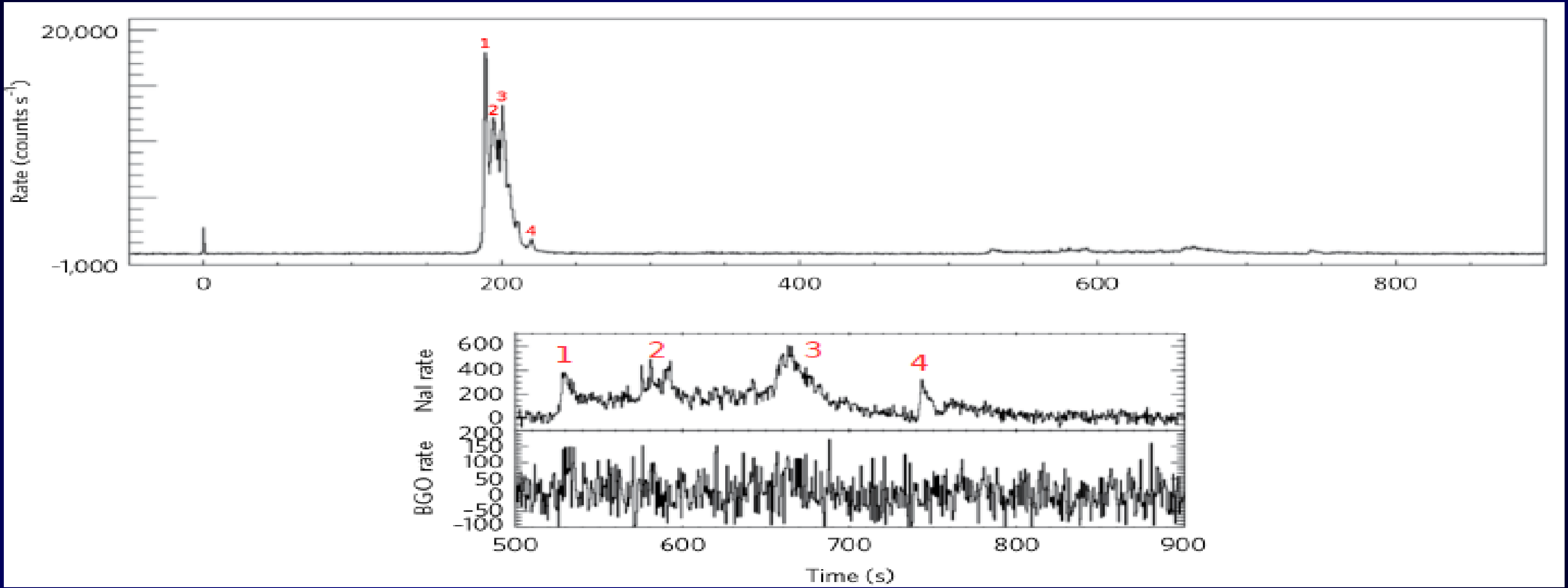
Cano et al. 2011

A historical example: GRB 090618
(Izzo, Rueda, Ruffini, A&A Lett. 2012)



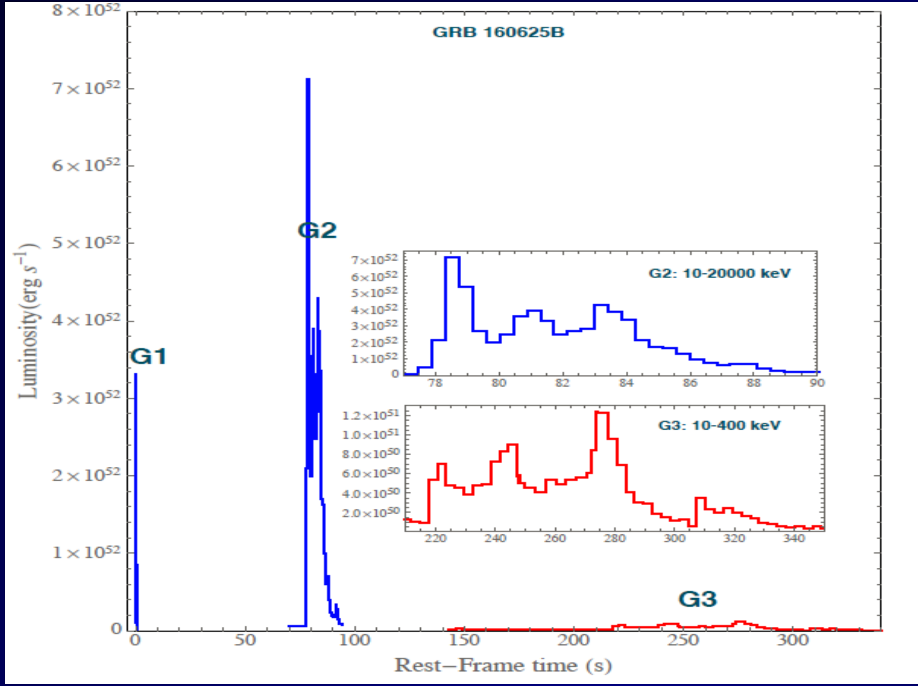
Precursor: hypercritical accretion

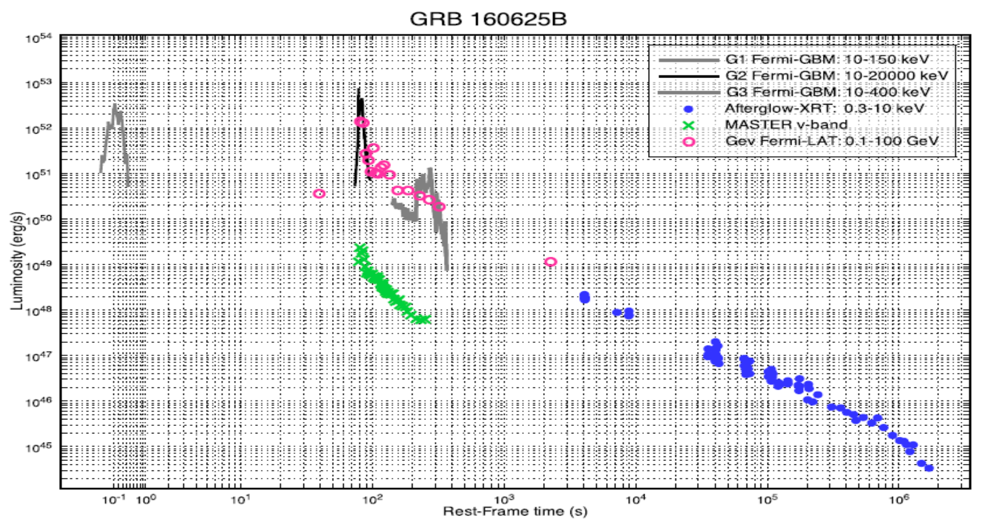
Another example: GRB 160625B



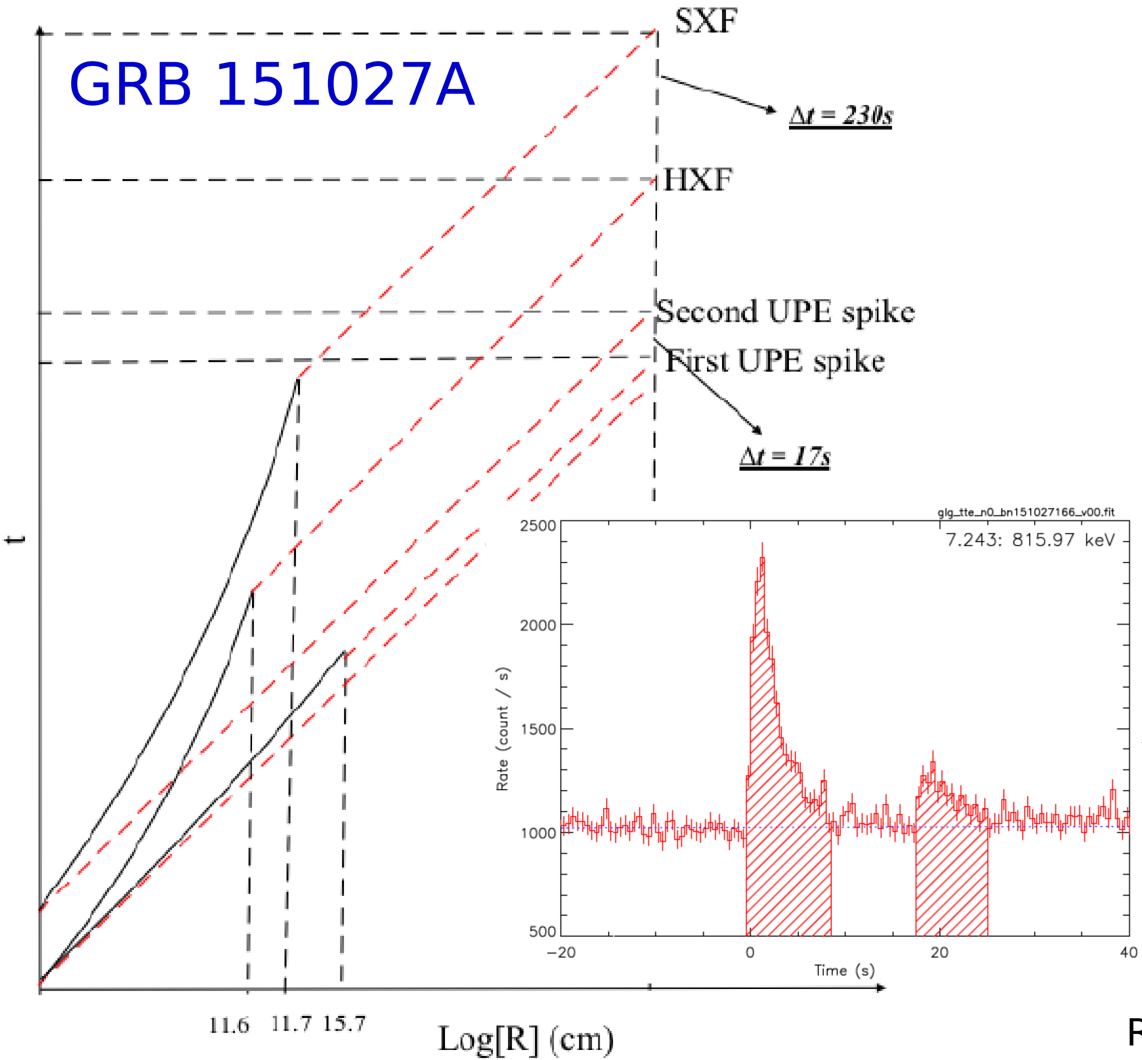
Data from B.-B. Zhang et. al., Nat. Astron. 2017

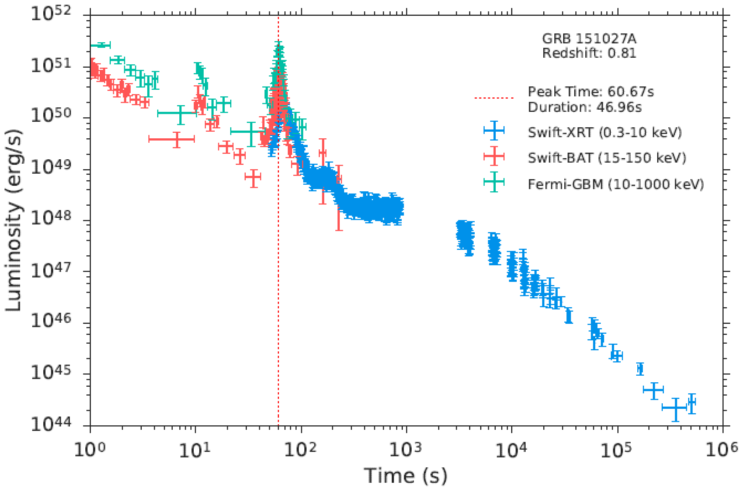
A current polar view of a BdHN

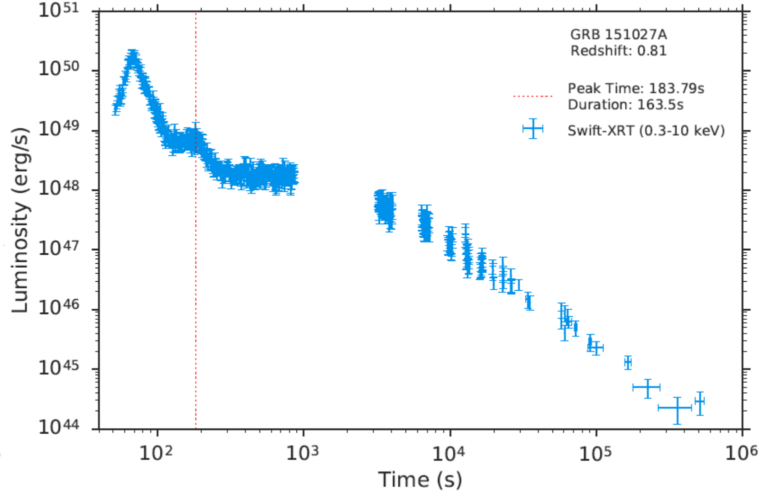




Data from B.-B. Zhang et. al., Nat. Astron. 2017

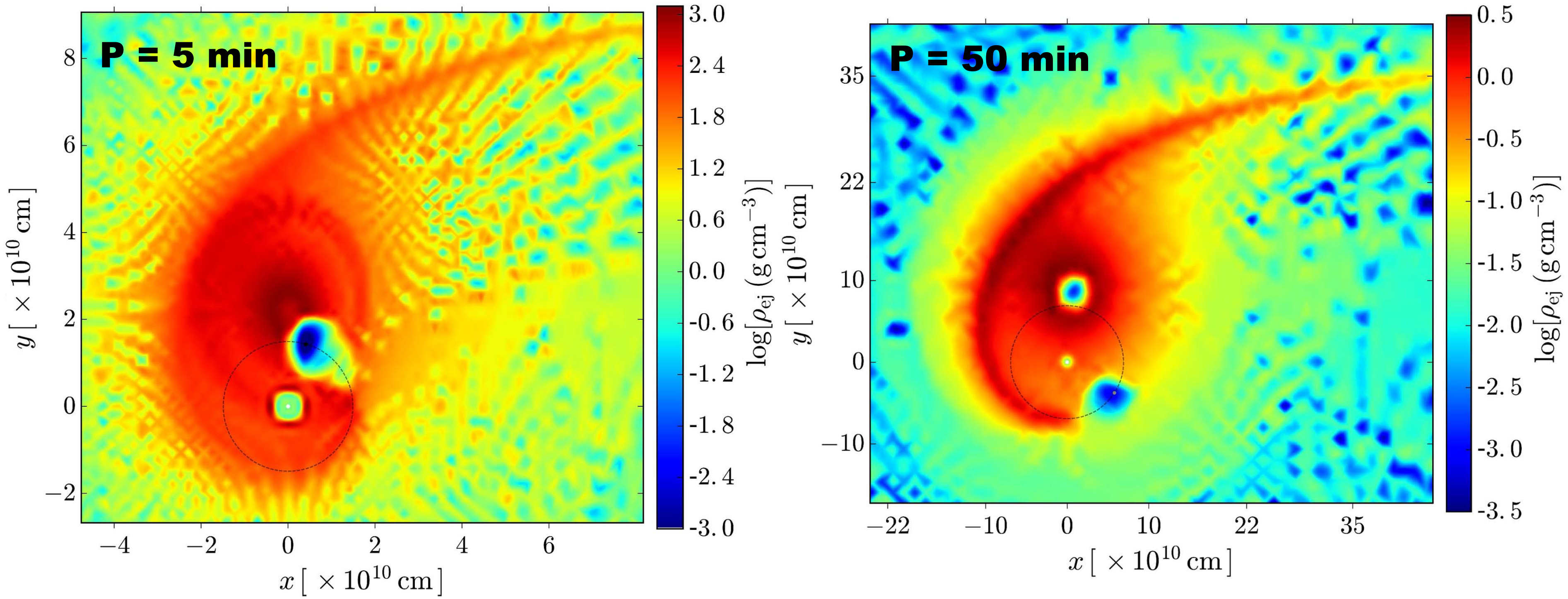






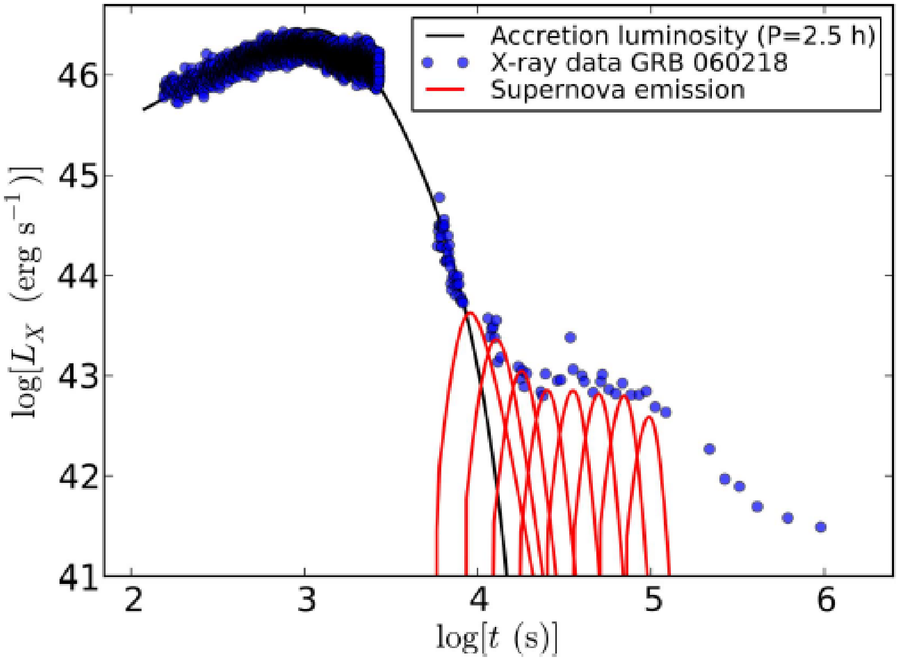
Ruffini, et al.; arXiv:1712.05001

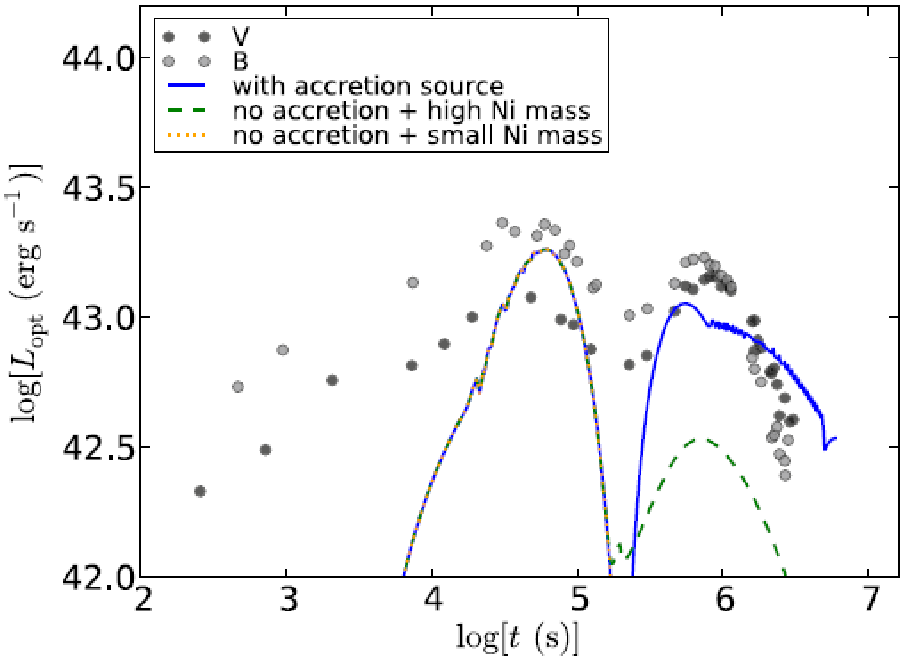
BdHNe and X-ray Flashes



Becerra, Bianco, Fryer, Rueda, Ruffini, ApJ 2016;arXiv:1606.02523

The example of GRB 060218: X-rays and optical emission





Becerra, Bianco, Fryer, Rueda, Ruffini, ApJ 2016;arXiv:1606.02523

The BdHN basic structure

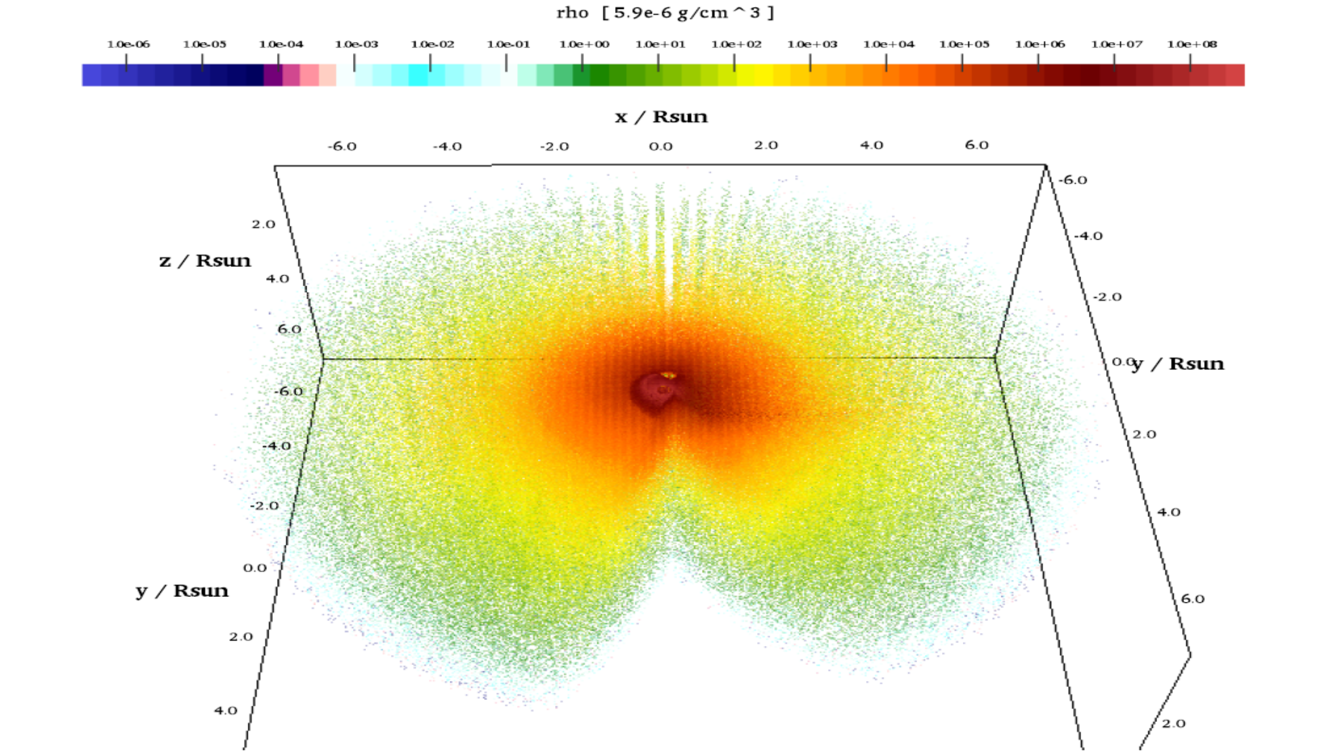


Figure 5. Three-dimensional, half hemisphere views of the density distribution of the SN ejecta at the moment of BH formation in a BdHN. The simulation is performed with a SPH code that follows the SN ejecta expansion under the influence of the NS companion gravitational field including the effects of the orbital motion and the changes in the NS gravitational mass by the hypercritical accretion process. The initial conditions of the SN ejecta are set by a homologous velocity distribution in free expansion and the mass-distribution is modeled with 16 millions point-like particles (see Becerra et al. 2016, for additional details). The binary parameters of this simulation are: the NS companion has an initial mass of 2.0 $M_\odot$; the CO_{core}, obtained from a progenitor with ZAMS mass $M_{ZAMS} = 30\ M_\odot$, leads to a total ejecta mass 7.94 $M_\odot$ and to a 1.5 $M_\odot$ νNS, the orbital period is $P \approx 5$ min (binary separation $a \approx 1.5 \times 10^{10}$ cm).

See arXiv:1803.05476

$M_{\rm ZAMS}$ ($M_\odot$)	$M_{\rm rem}$ ($M_\odot$)	$M_{\rm ej}$ ($M_\odot$)	$R_{\rm core}$ (10^8 cm)	$R_{\rm star}$ (10^9 cm)	$V_{\rm star}$ (10^8cm/s)	$E_{\rm grav}$ (10^{51} erg)	m_j ($10^{-6}\,M_\odot$)
15	1.30	1.606	8.648	5.156	9.75	0.2149	0.2 – 4.4
25	1.85	4.995	2.141	5.855	5.43	1.5797	2.2 – 11.4
30[a]	1.75	7.140	28.33	7.751	8.78	1.7916	1.9 – 58.9
30[b]	1.75	7.140	13.84	7.830	5.21	1.5131	1.9 – 58.9
40	1.85	11.50	19.47	6.529	6.58	4.4305	2.3 – 72.3

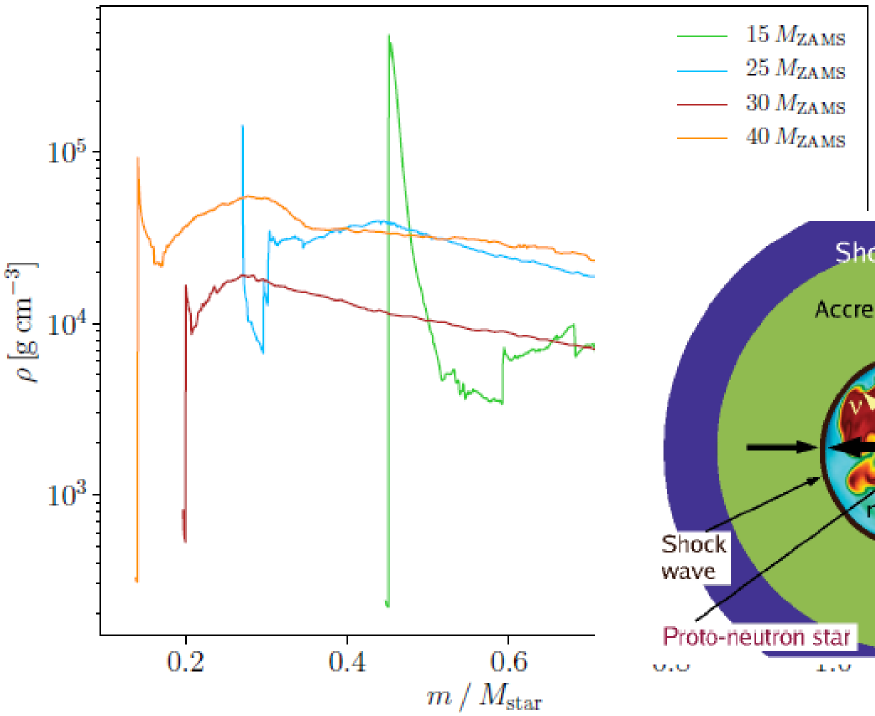
CO core-NS properties

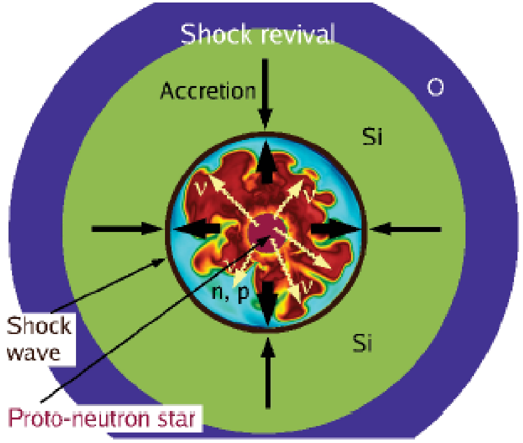
SPH Simulations I

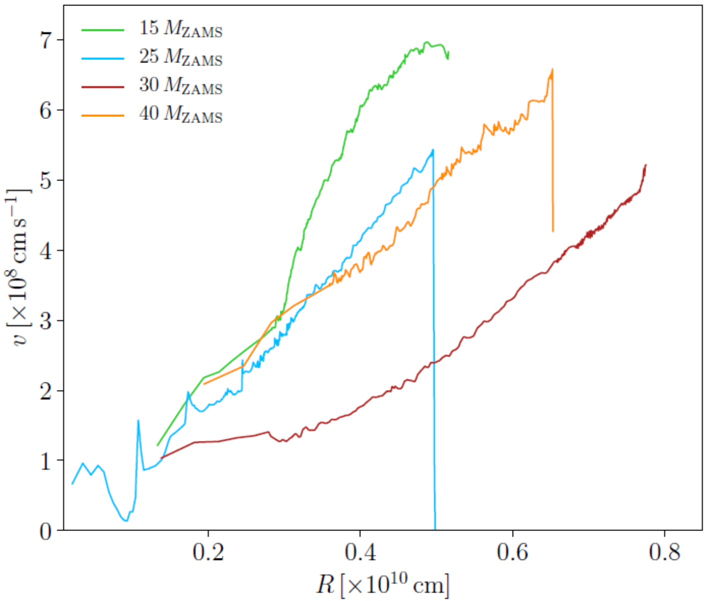
CO-Core Progenitor:	$25\,M_{zams}$
Total energy:	1.57×10^{51} ergs
Ejected Mass:	$5.0\,M_\odot$
$\nu - NS$ Mass:	$1.85\,M_\odot$
NS Mass:	$2.0\,M_\odot$
Orbital Period :	≈ 5 minutes
Orbital Separation:	1.35×10^{10} cm

Becerra, Ellinger, Fryer, Rueda, Ruffini; arXiv:1803.04356

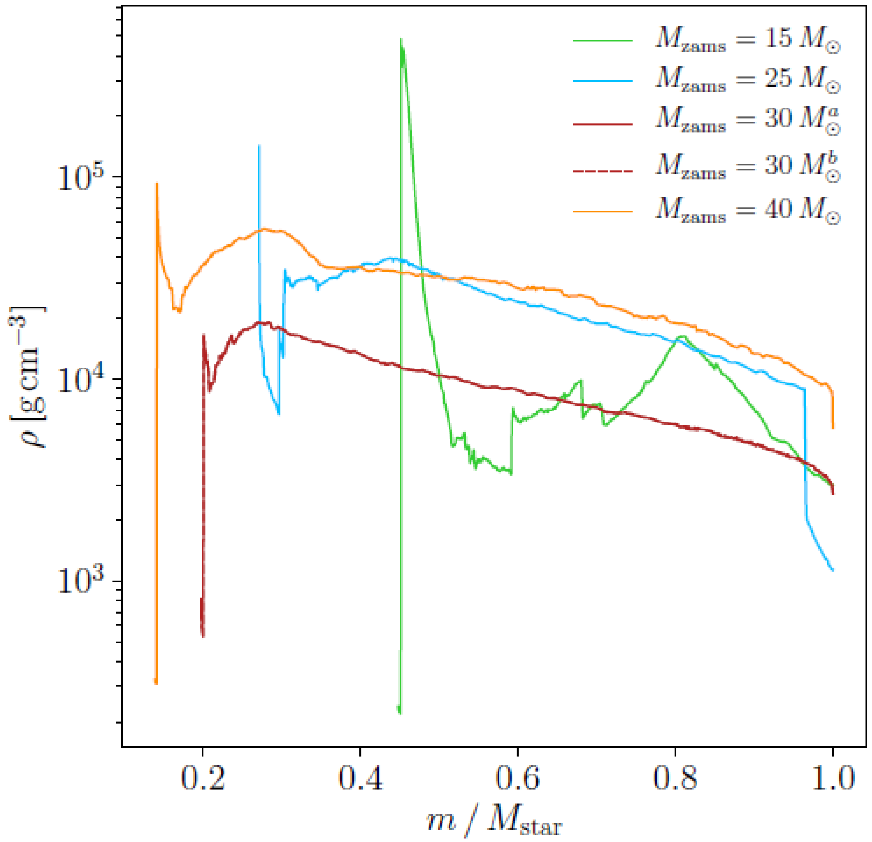
Initial Conditions: Before and After the SN explosion

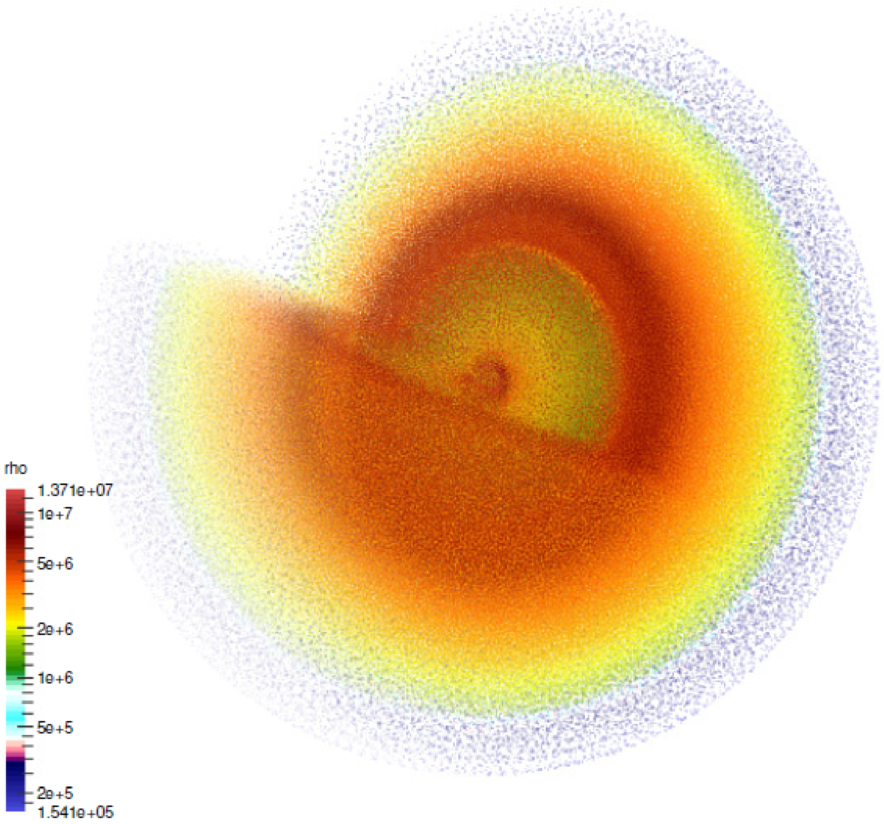






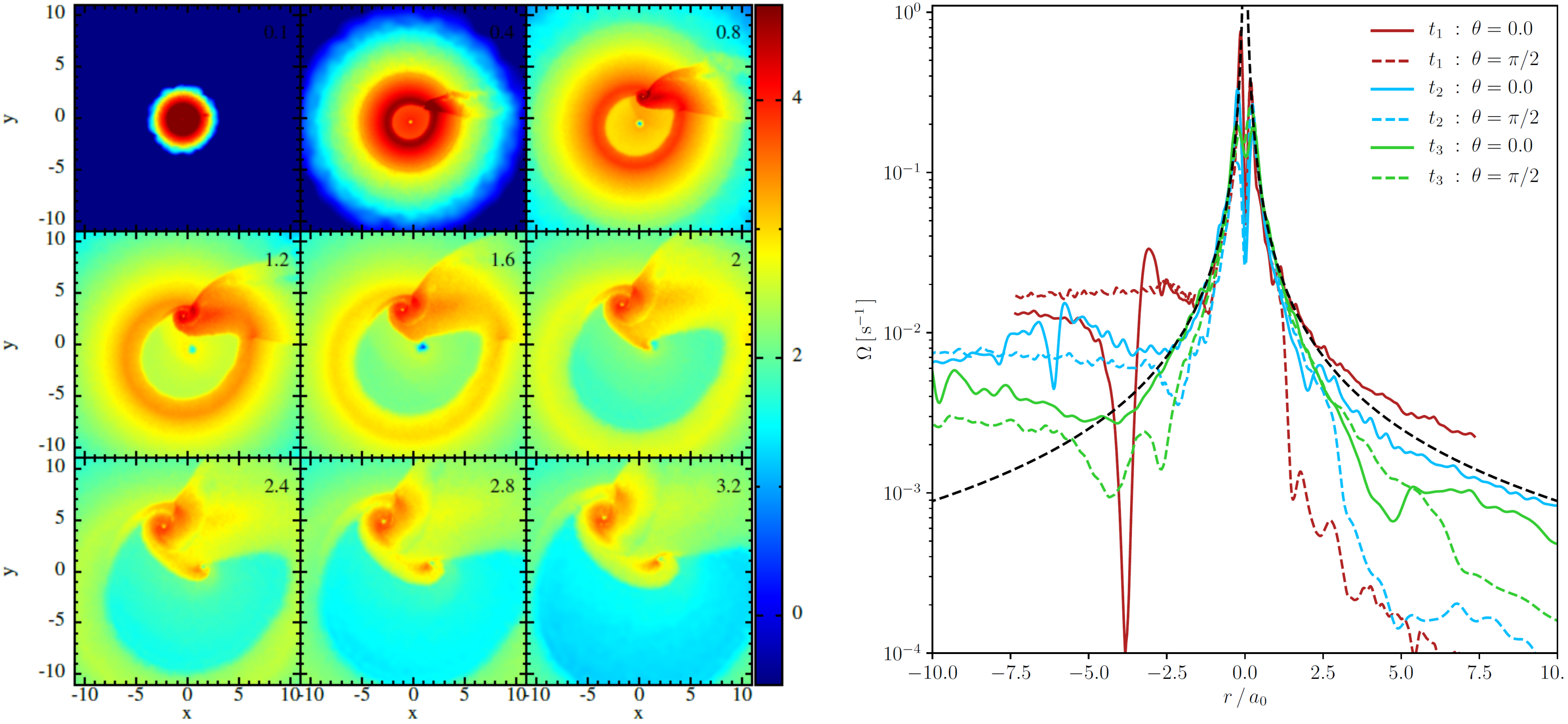
SN at t=0 (shock at CO-core surface)



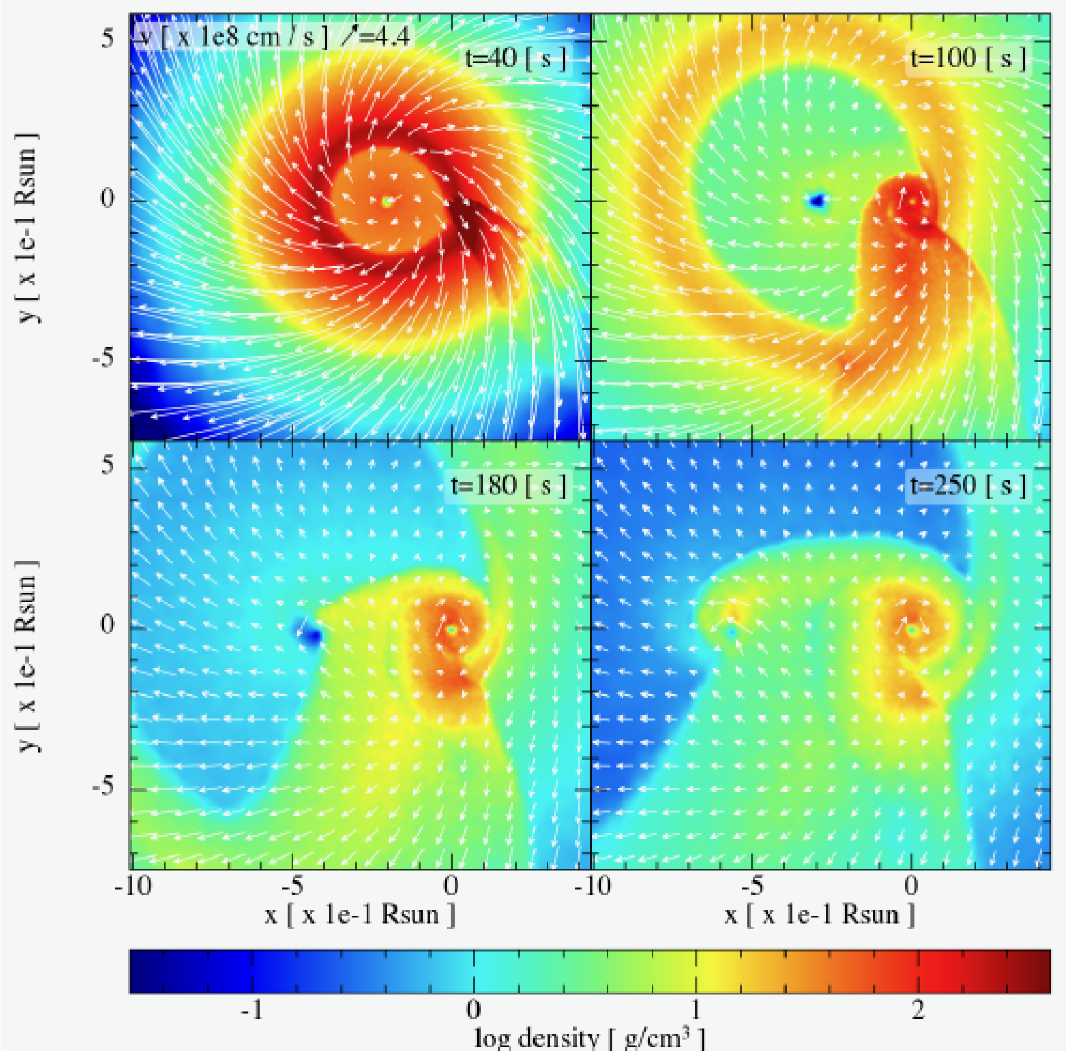


Becerra, Ellinger, Fryer, Rueda, Ruffini; arXiv:1803.04356

Binary-driven hypernova: orbital plane view



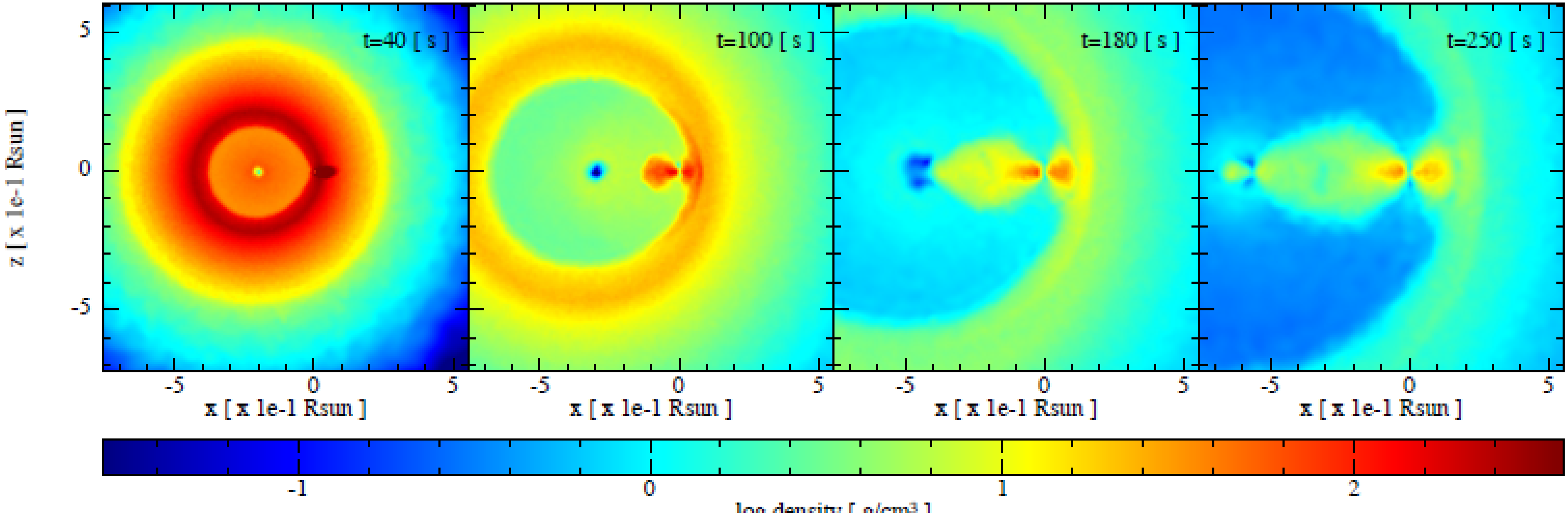
Becerra, Ellinger, Fryer, Rueda, Ruffini; arXiv:1803.04356



BdHN: orbital plane view

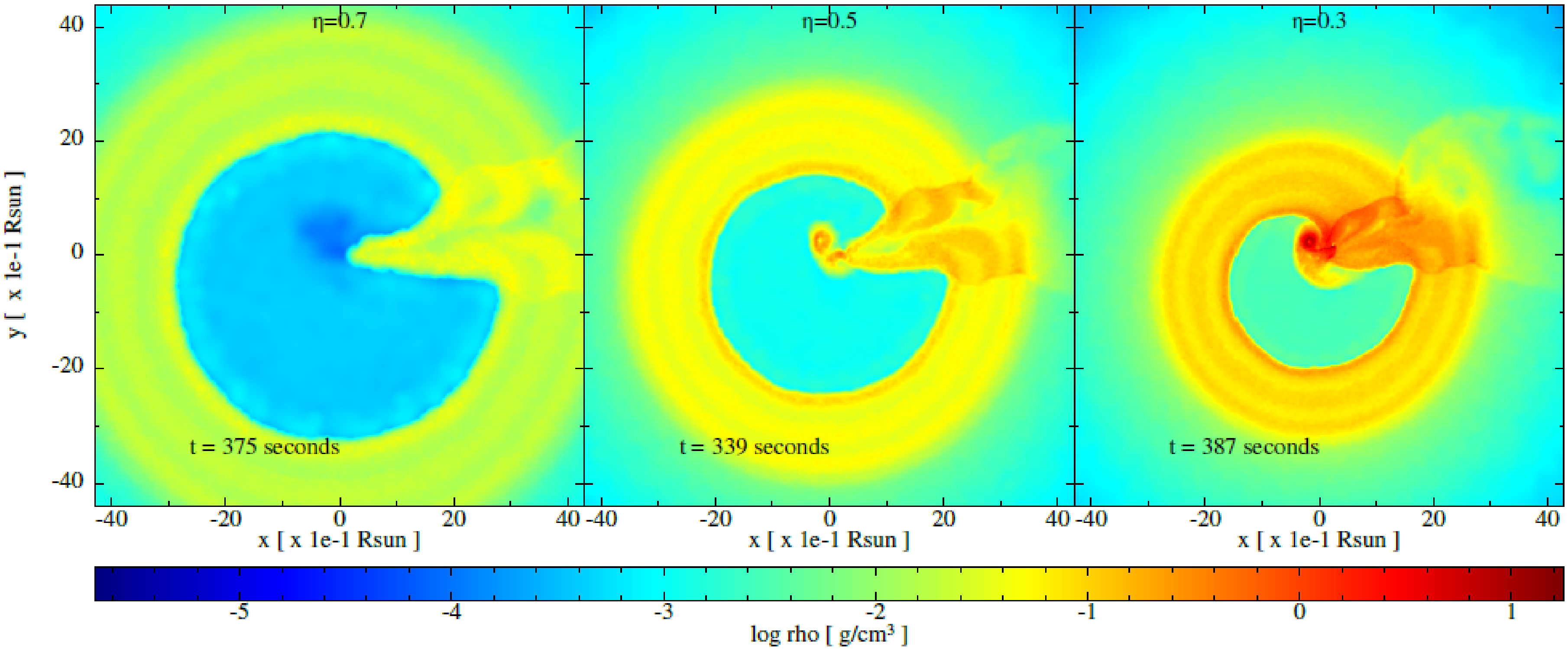
Becerra, Ellinger, Fryer, Rueda, Ruffini; arXiv:1803.04356

BdHNe: polar view and disk-like structure



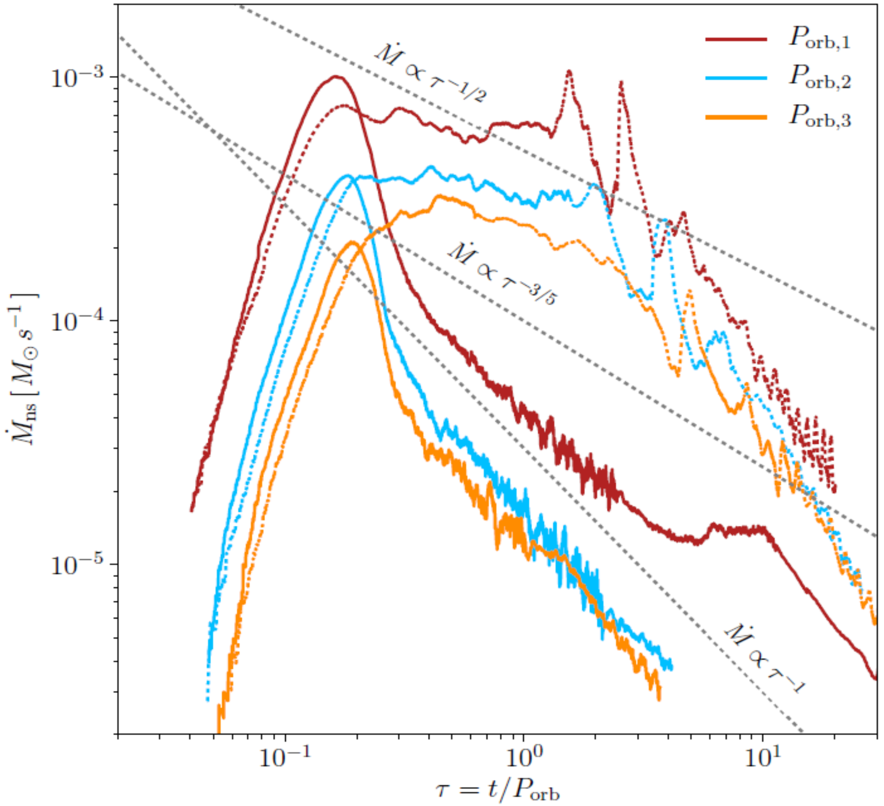
Becerra, Ellinger, Fryer, Rueda, Ruffini; arXiv:1803.04356

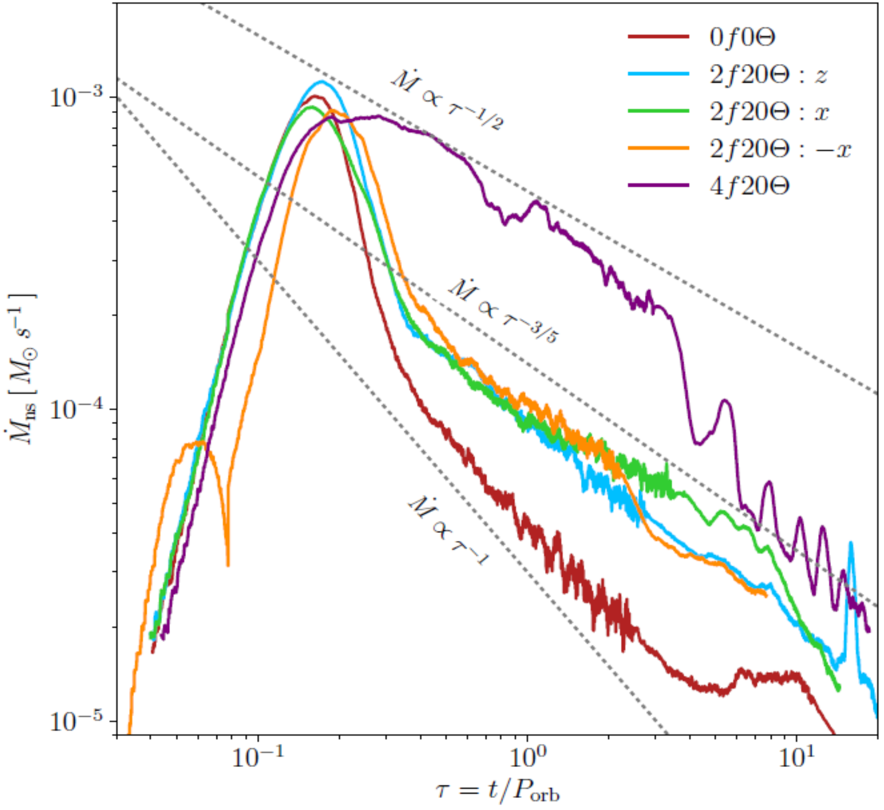
BdHNe and the orbital plane view: "fortune cookie" morphology



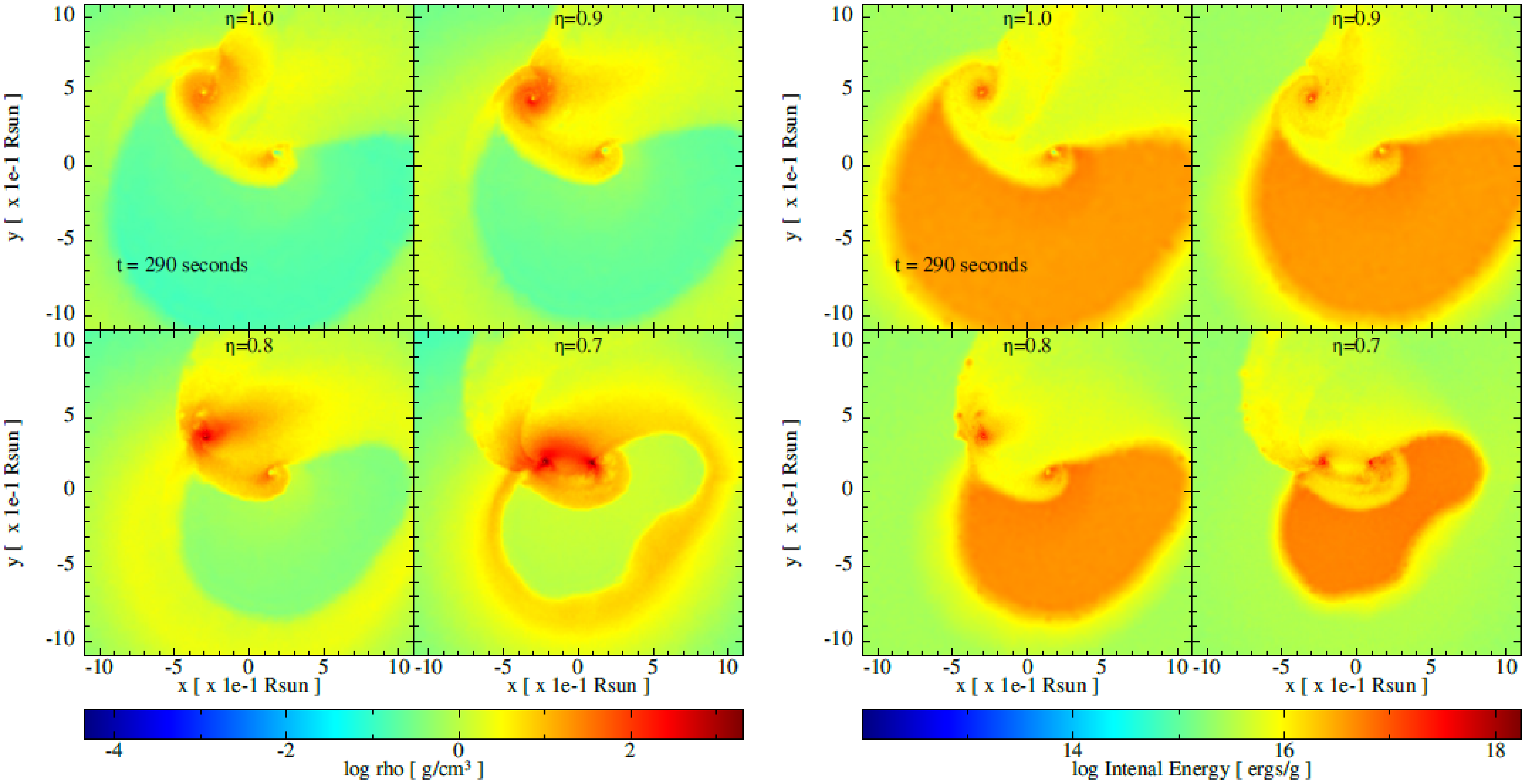
Becerra, Ellinger, Fryer, Rueda, Ruffini; arXiv:1803.04356

Scaling with the orbital period and asymmetric explosion effects



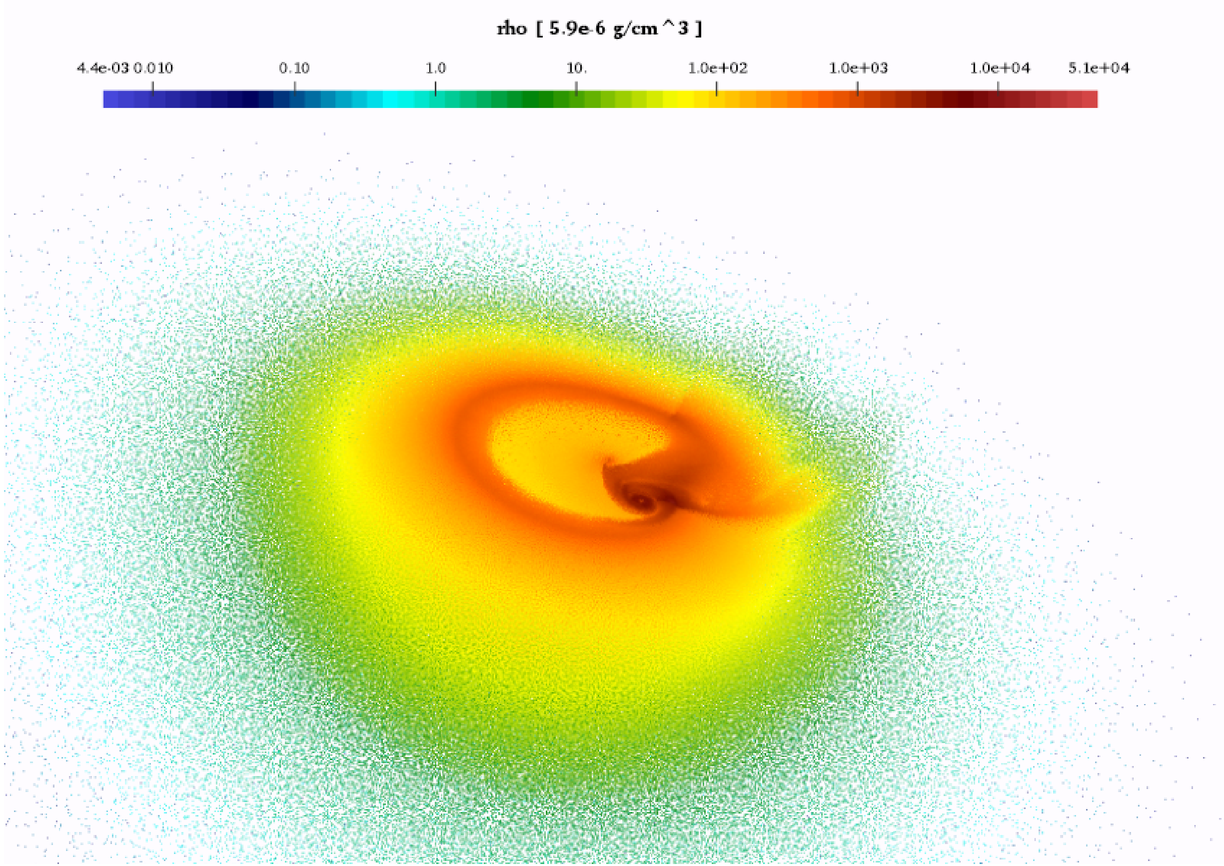


Orbital separation evolution



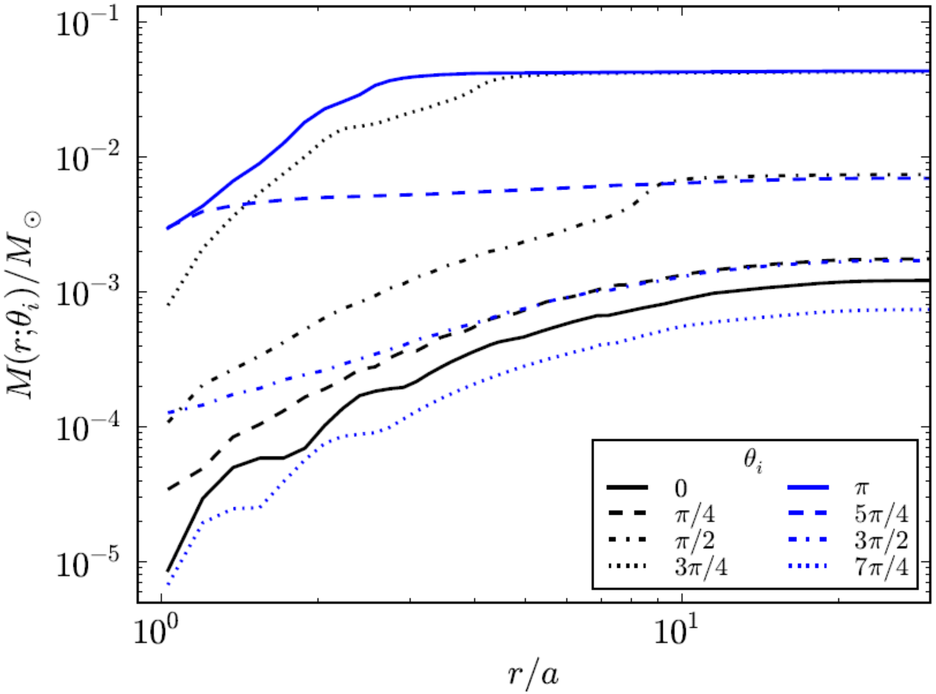
(a) Surface density (b) Surface specific internal energy

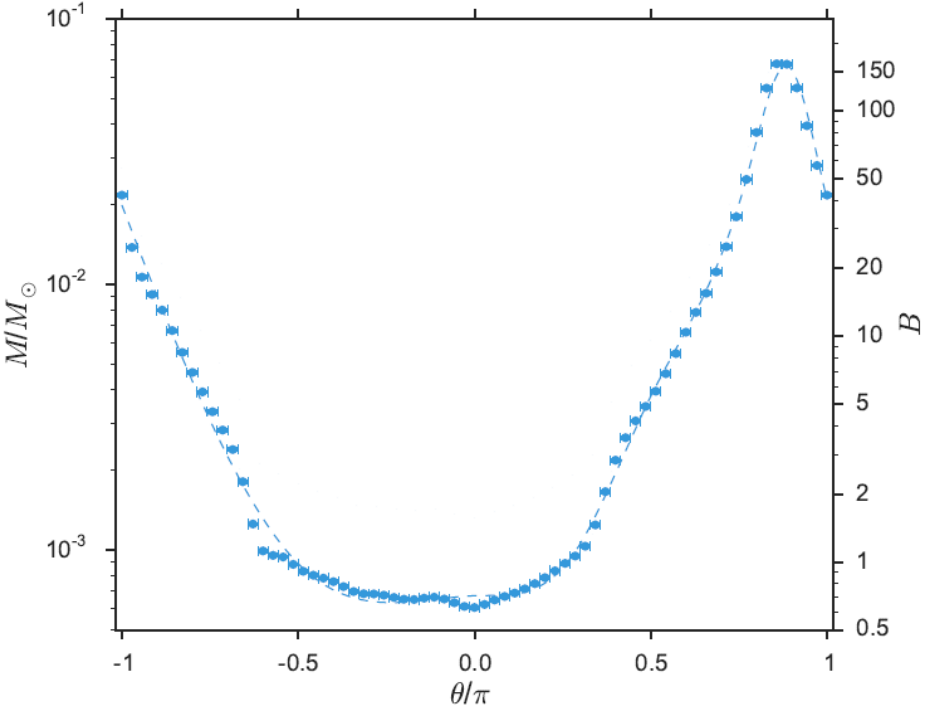
3D view of a binary-driven hypernova



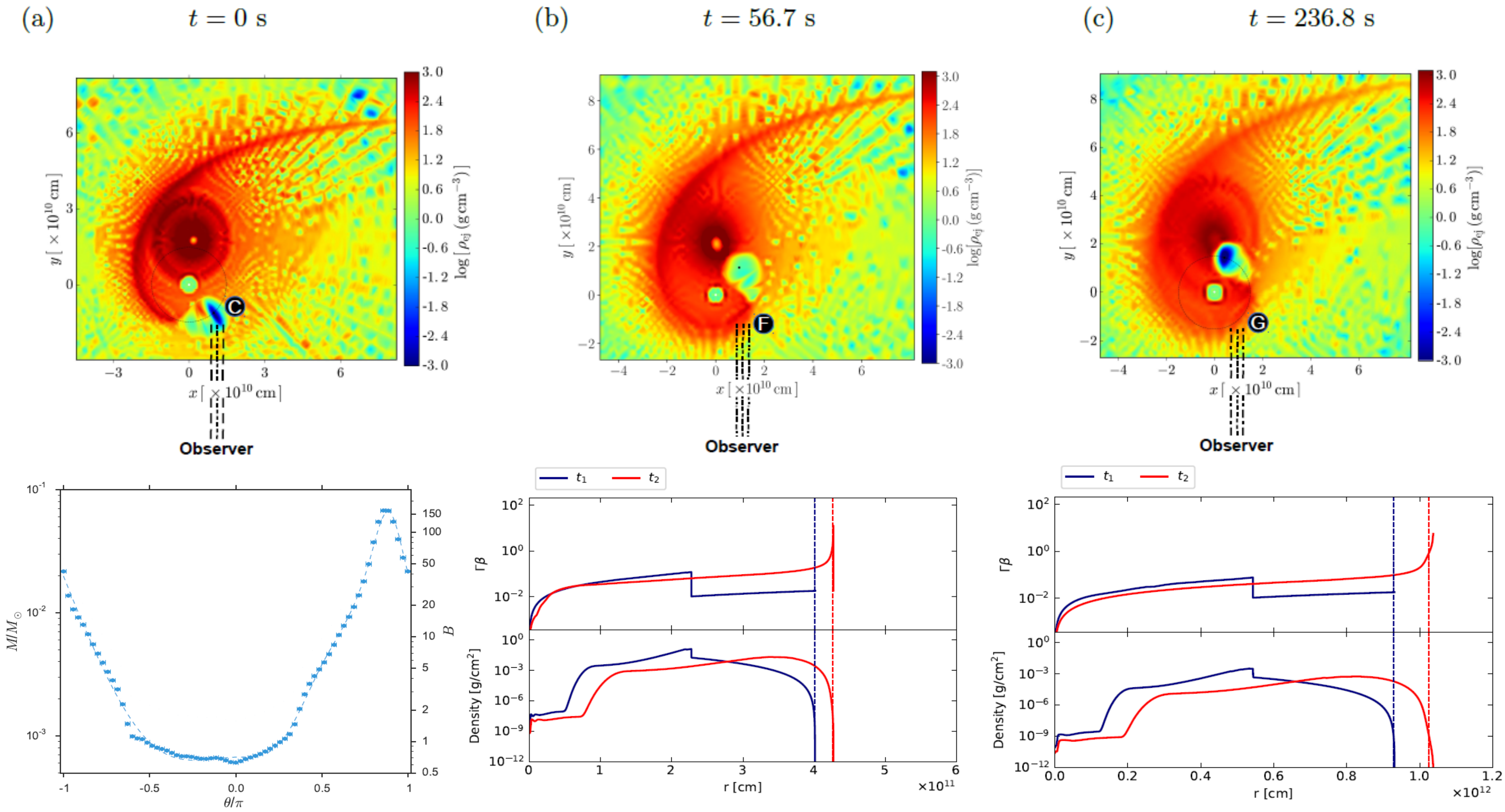
Baryon load on the orbital plane

R. Ruffini, L. Becerra, C. L. Bianco, et al.; arXiv:1712.05001; Ruffini et al. ApJ 852, 53 (2018)

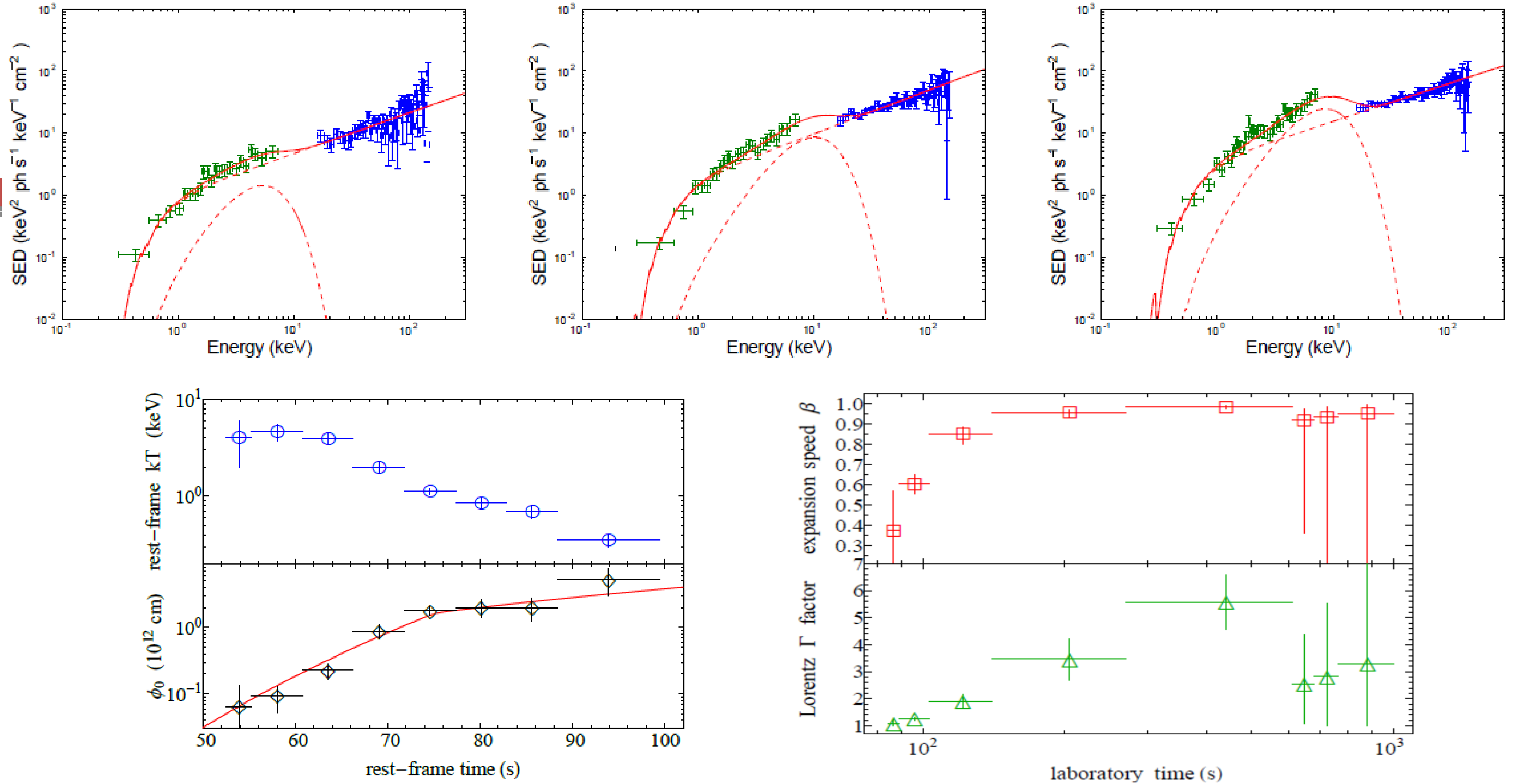




Baryon load parameter = B = plasma energy / baryon target mass-energy



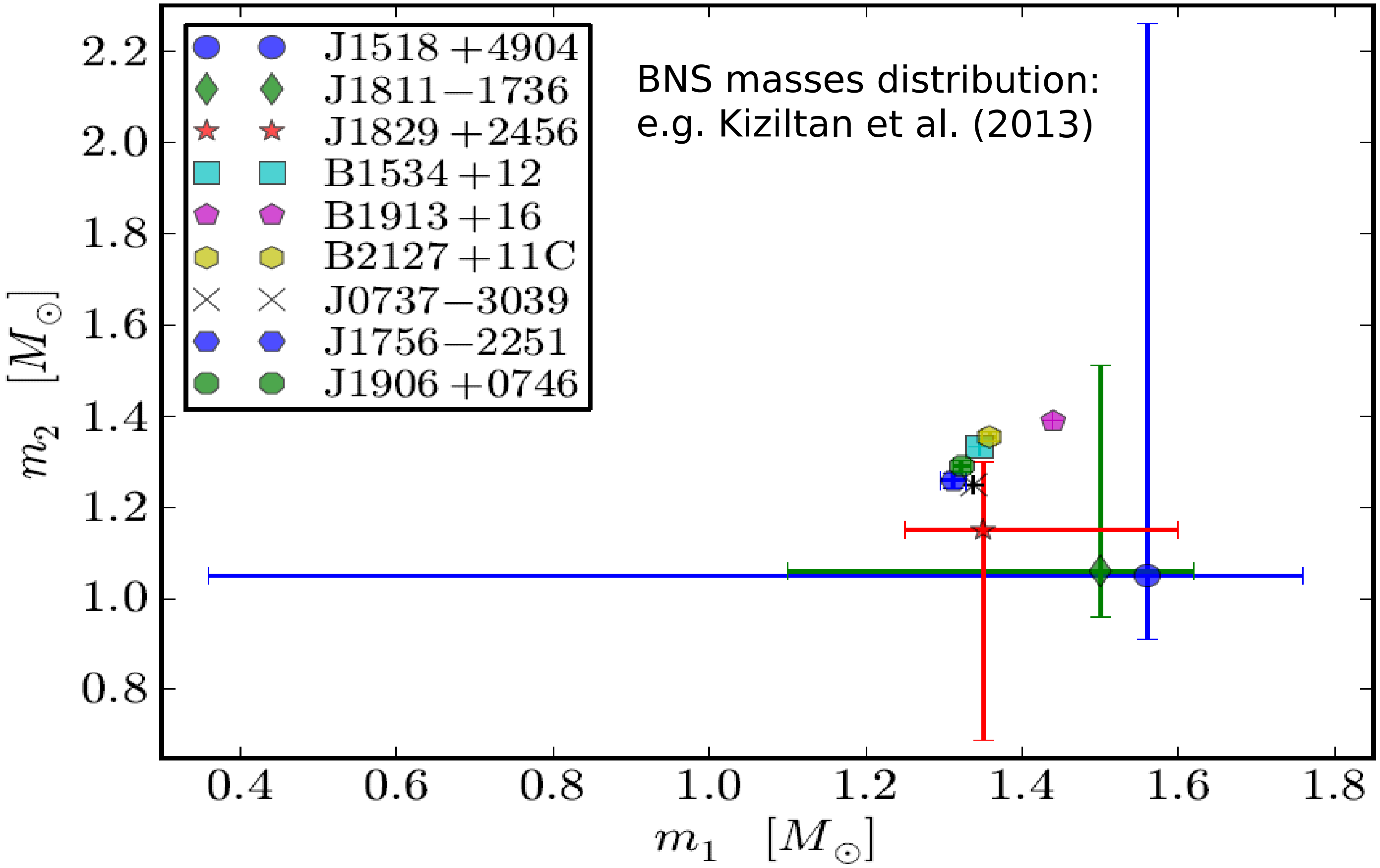
e+e- plasma within the supernova ejecta: arXiv:1712.05001



arXiv:1712.05001

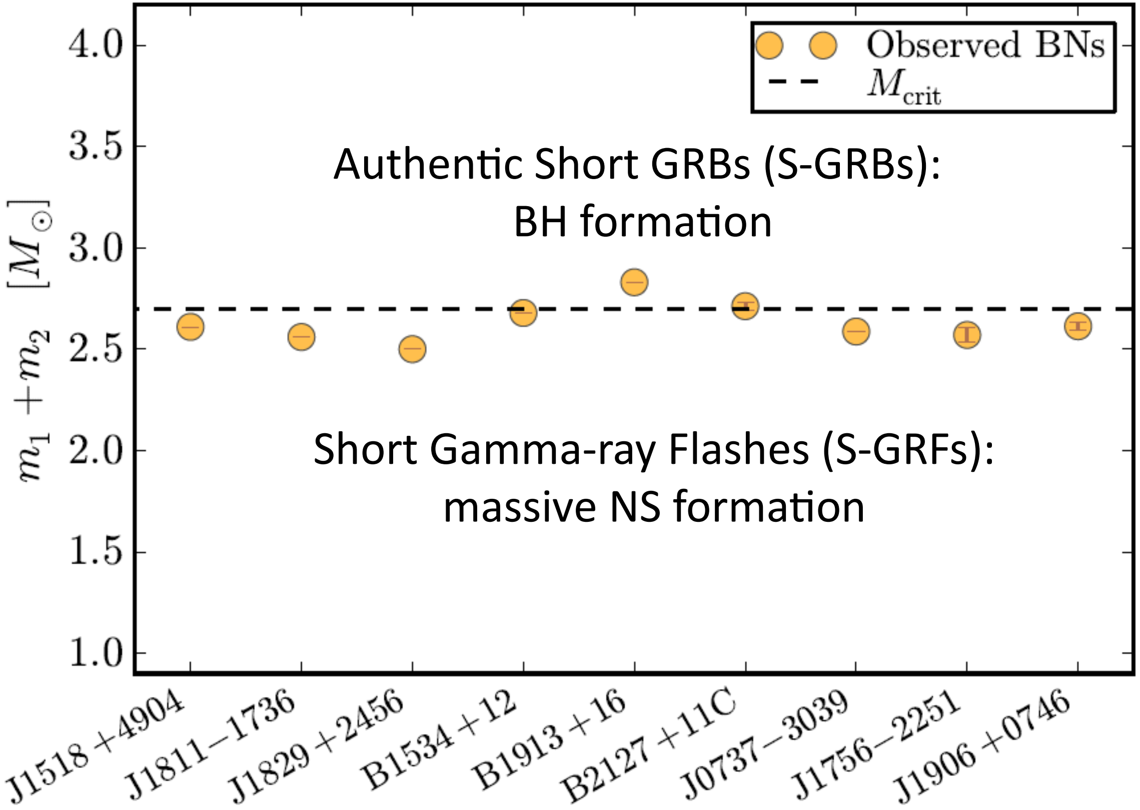
Neutron star binary mergers:
short gamma-ray burst progenitors

Galactic Binary NSs: will they form BHs?



BNS masses distribution:
e.g. Kiziltan et al. (2013)

Short GRB subclasses: S-GRFs and S-GRBs



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

(Kiziltan et al. 2013)

So:

$M_{BNS} \sim 2.64\ M_{sun}$

But this will not be the mass of the new object formed from the merger: we need to account for energy, baryon number, and angular momentum conservation

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

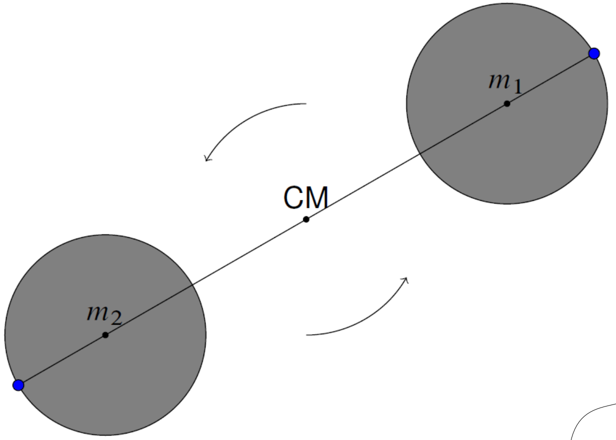
Which are the mass and angular momentum of the central remnant?

Depends on:

1) Mass-ratio of the binary (M1/M2 ~1 for the galactc BNS)
2) Degree at which baryon mass is conserved
3) Degree at which angular momentum is conserved

$(M_1,M_2) \rightarrow (M_{b1},M_{b2}) \rightarrow M_{bf}= \alpha\,(M_{b1}+M_{b2})$; $\alpha \sim 1$ (little mass is expelled)

$J_{mc} = \eta\, J_i \sim \eta\, J_{bin}$ (merger instant); $\eta < 1$



Specifically ...

$$M_b = m_{b,c} + \overbrace{m_{\rm ej} + m_d}^{\text{Baryon mass of the new central remnant}}$$

Total baryon mass of the NS-NS binary

Baryon mass of the new central remnant

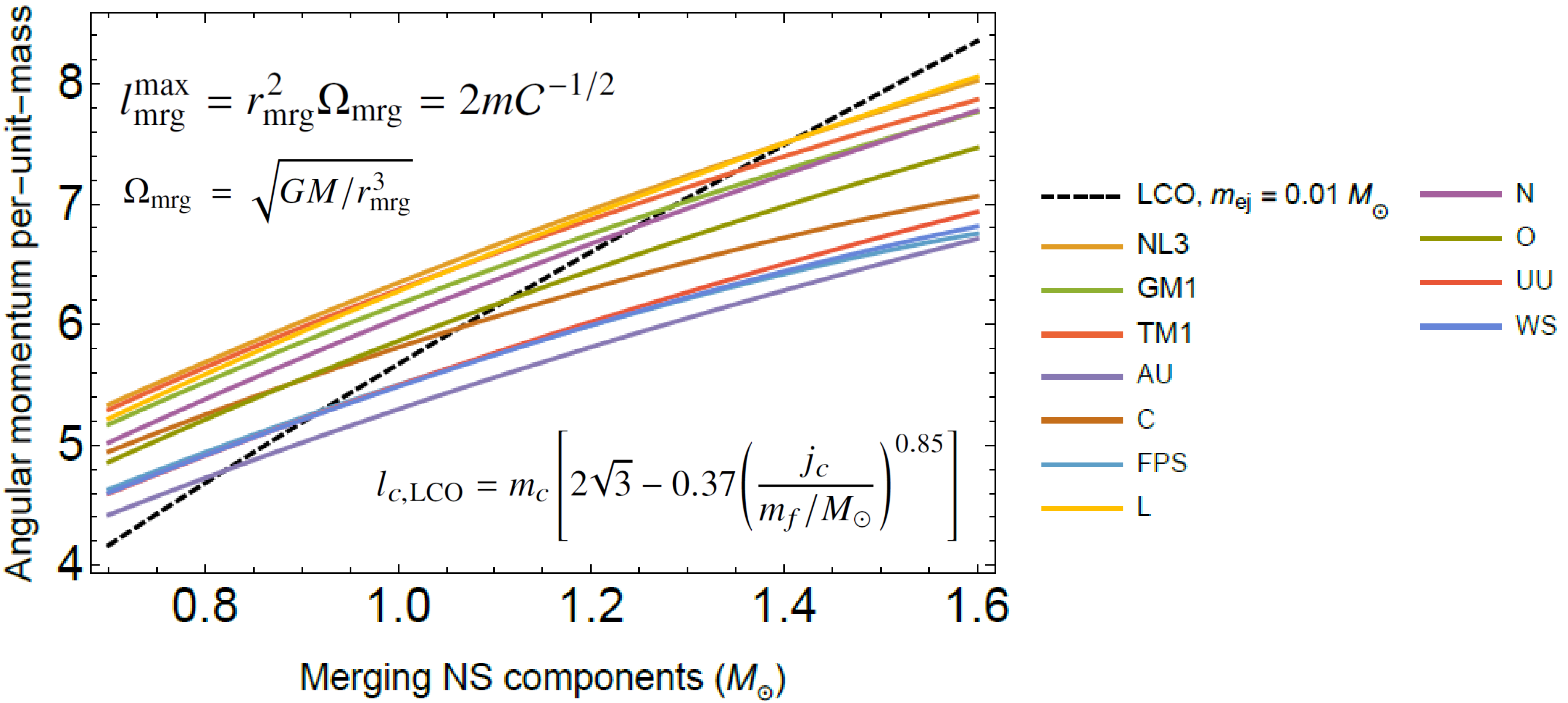
$$J = 2\left(mr^2 + \frac{2}{5}\kappa\, mR^2\right)\Omega \quad \Rightarrow \quad J_{\rm mrg} = J_{\rm contact} = \frac{G}{c}\left(1 + \frac{2}{5}\kappa\right) m^2 C^{-1/2}$$

Mass of merging NS components

Compactness of merging NS components

Specific example assuming equal-mass binary components

(On going work; preliminary)



So you can construct something like this for a specific EOS

(On going work; preliminary)