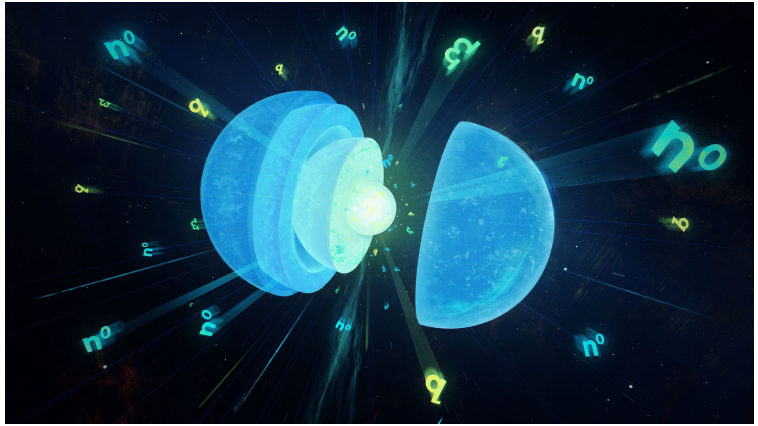
Estrellas de neutrones

¿Cómo la astrofísica nos ayuda a entender la materia más extrema?

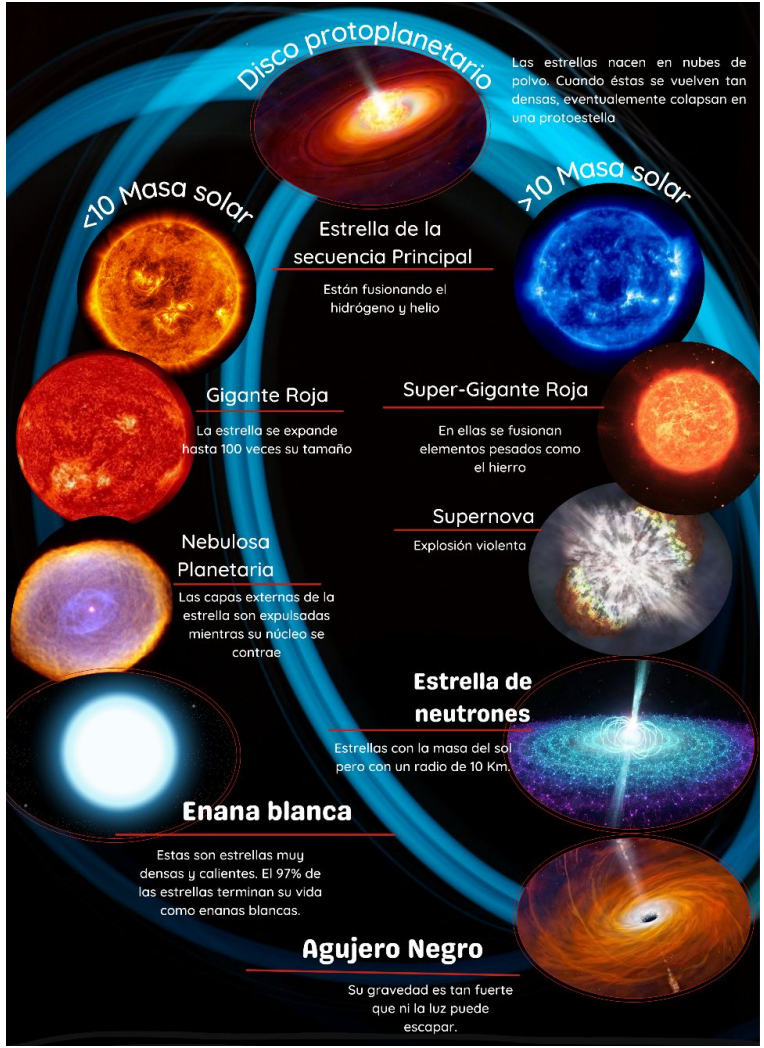


Laura Marcela Becerra B
Universidad Industrial de Santander

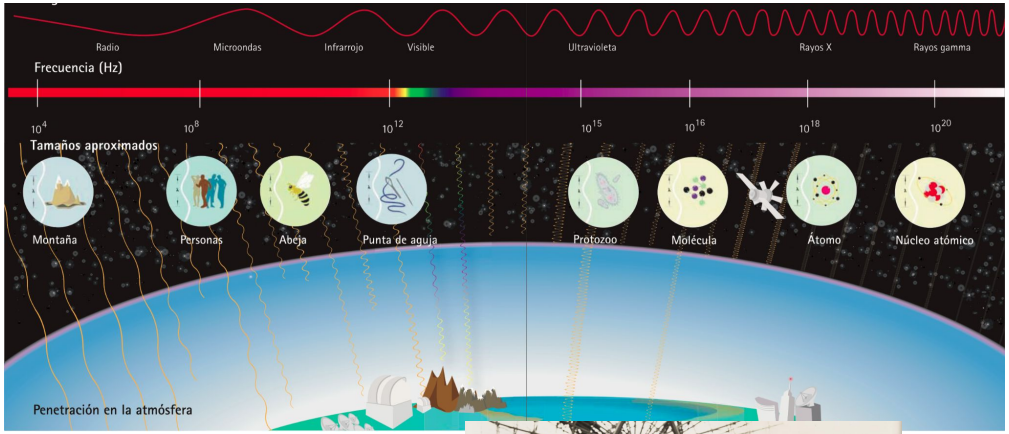
Evolución Estelar

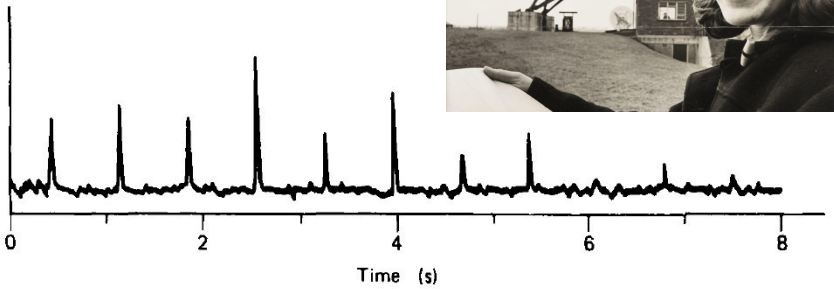
Las **estrellas de neutrones** son los objetos remanentes que resultan del **colapso gravitacional** de estrellas masivas durante un evento de **Supernova.**

- Masa: $\longrightarrow$ $1.2 - 2.0 M_{\odot}$
- Radio: $\longrightarrow$ $\sim 10\,\mathrm{Km}$
- Densidad: $\longrightarrow$ $\rho \sim M/R^3 \sim 7 \times 10^{14}\, g/cm^3$
- Gravedad: $\longrightarrow$ $GM/R \sim 2 \times 10^{14}\, cm/s^2$
- Energía Gravitacional: $\longrightarrow$ $GM^2/R \sim 10^{53}\, ergs$
- Materia rica en neutrones: $\longrightarrow$ $n_n/n_p \sim 10$
- Campos magnético grande $\longrightarrow$ $10^{15}\,\mathrm{Gauss}$



Observaciones:





- **1934:** Baade & Zwicky propusieron la formación de estrellas de neutrones en supernovas

- **1967:** Jocelyn Bell detecto fluctuaciones periodicos (1.337 s) en la señal con el radio telescope at the Mullard Radio Astronomy Observatory -> **PSR B1919+21**

- **1968:** Pacini sugirió que los púlsares son estrellas de neutrones rotantes

Crab pulsar (**PSR B0531+21**) con un periodo de 33 ms. Esto significa una velocidad para la estrella de c/4

Supernova observada por los chinos en 1054

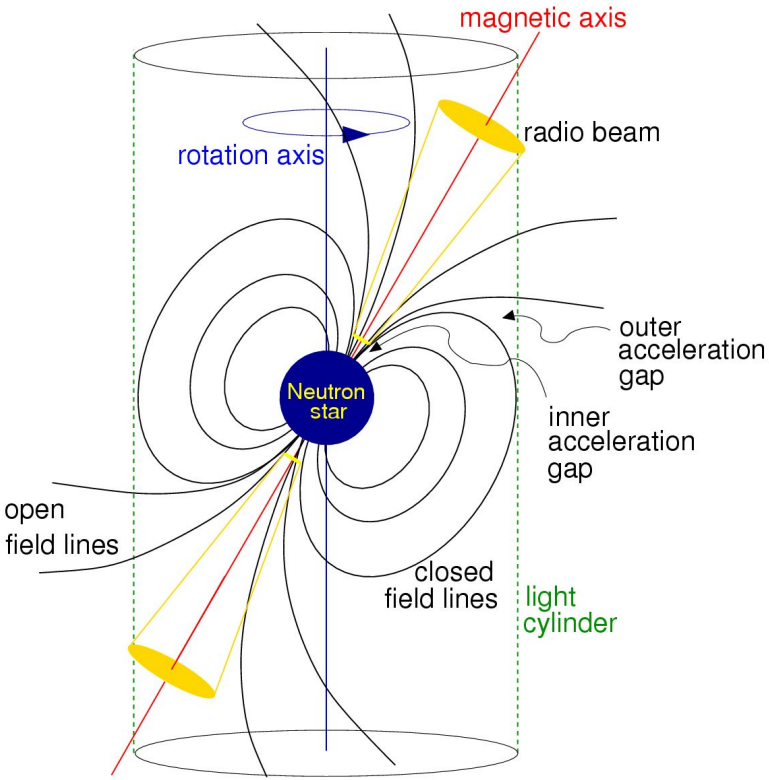
Rotación y campos magnéticos:

Energía de rotación:

$$E_{rot} = I\Omega^2 \rightarrow \dot{E}_{rot} = -2\pi I \frac{\dot{P}}{P^3}$$

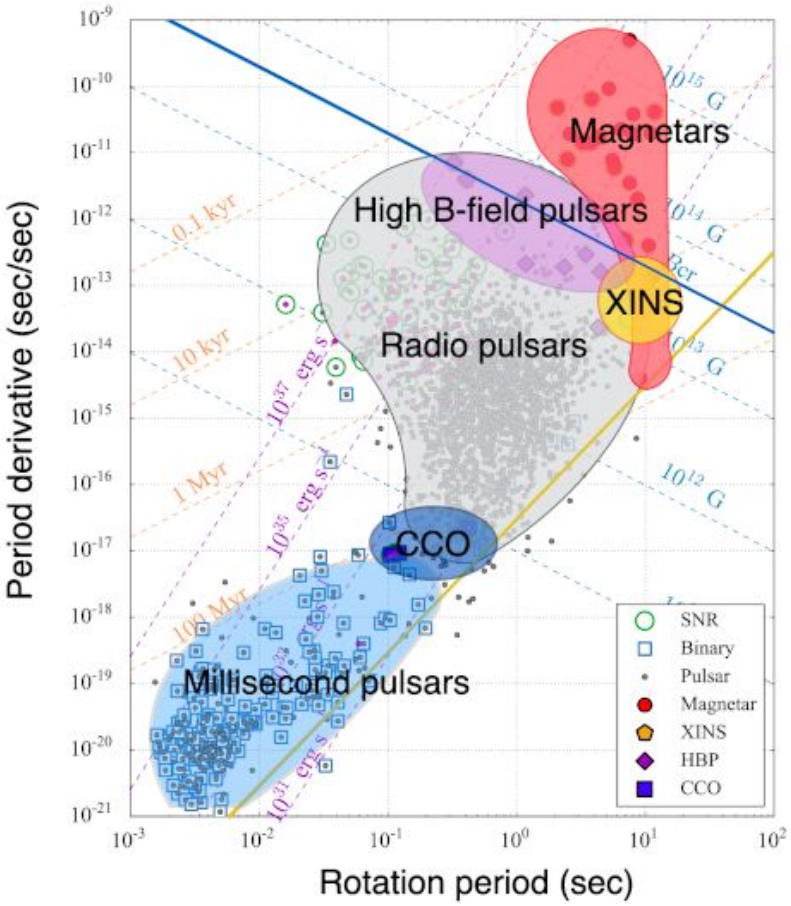
Radiación de dipolo magnético:

$$\dot{E}_{rad} = \frac{1}{6c^3} B^2 R^6 \Omega^4 \sin^2 \alpha$$

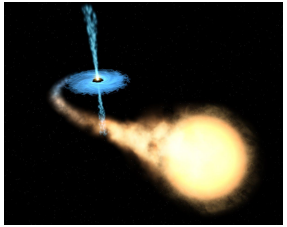


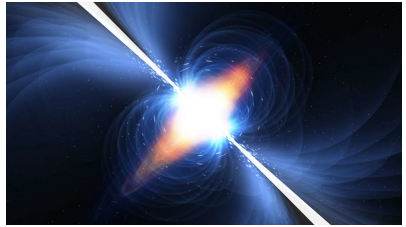
Pulsar más rápido:
PSR J1748-2446ad
1.3 ms

Objeto más lento:
1E 161348-5055
6.67 hr



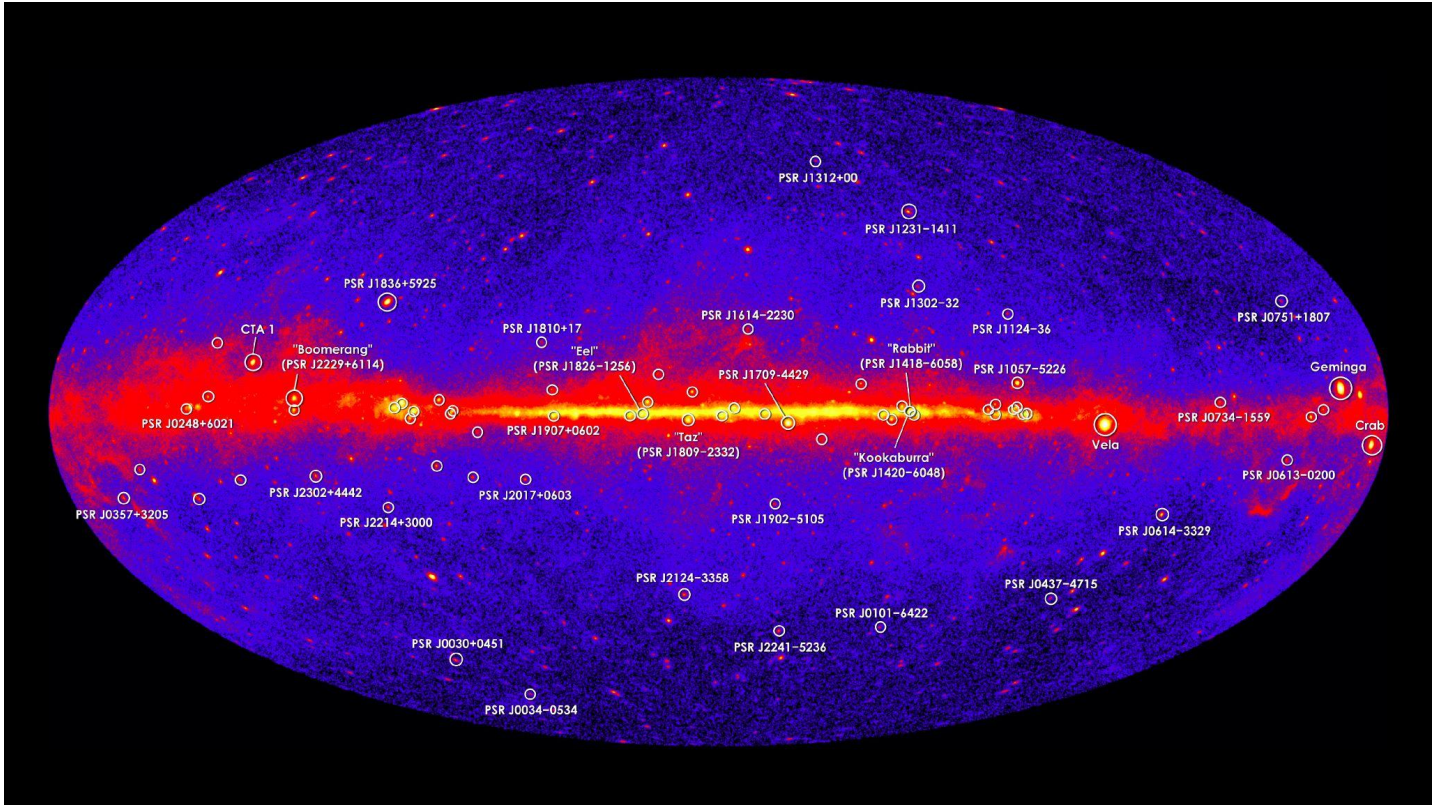
- Radio Pulsares: ~2000
- Pulsares en sistemas binarios: ~60
- Estrellas de neutrones en sistemas binarios de rayos-x: ~1000
- Estrellas de neutrones aisladas de rayos x: ~9
- Objetos compactos centrales: ~5
- Magnetares: ~20





Distribución de estrellas de neutrones en la Galaxia

Los radios-púlsares se encuentran cerca al ecuador de la galaxia, mientras los púlsares de milisegundos están dispersados en todo el cielo.



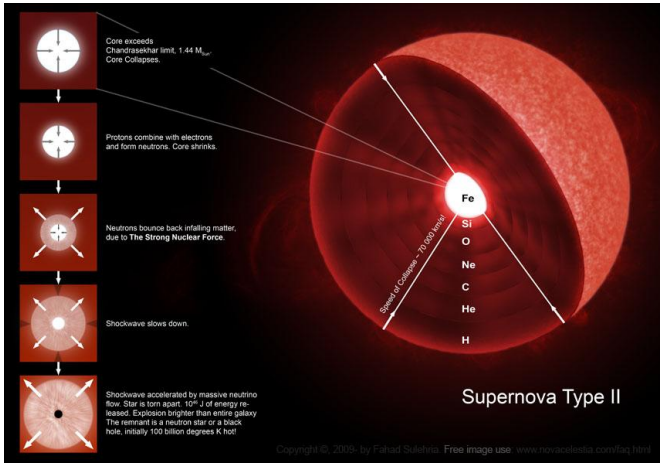
Colapso gravitacional y Supernovas

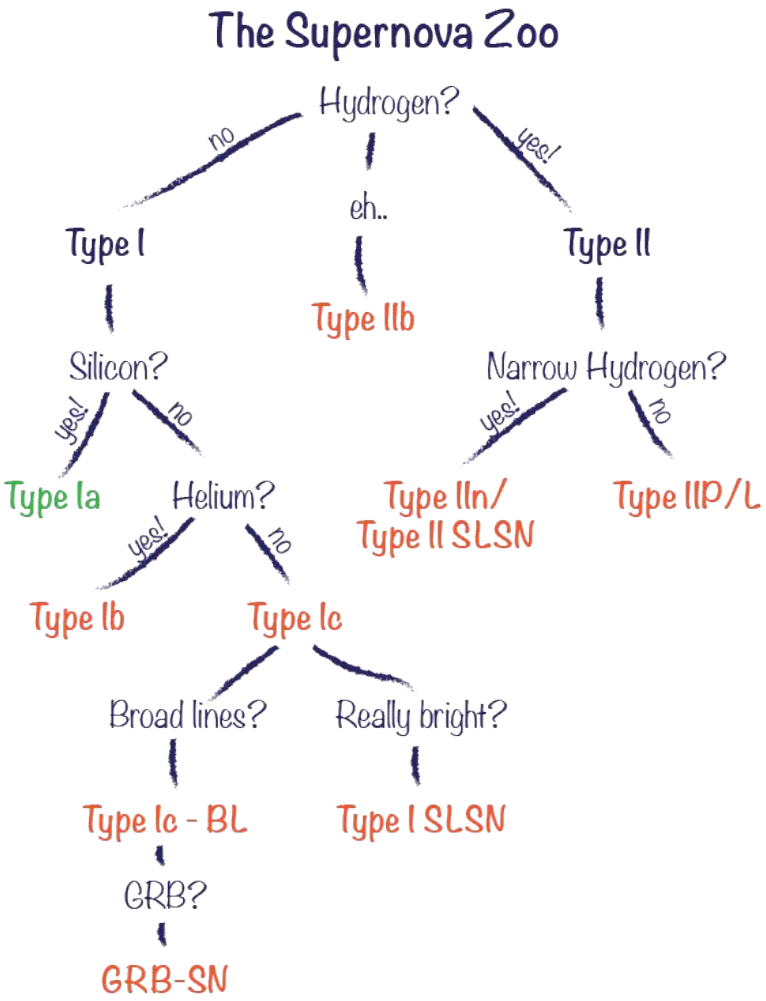
$$t_{\rm dyn} \sim \frac{1}{\sqrt{G\rho}} \sim 1{\rm s}$$

$$(1.5 M_\odot, 10^4\,{\rm Km}) \longrightarrow (1.5 M_\odot, 20\,{\rm Km})$$

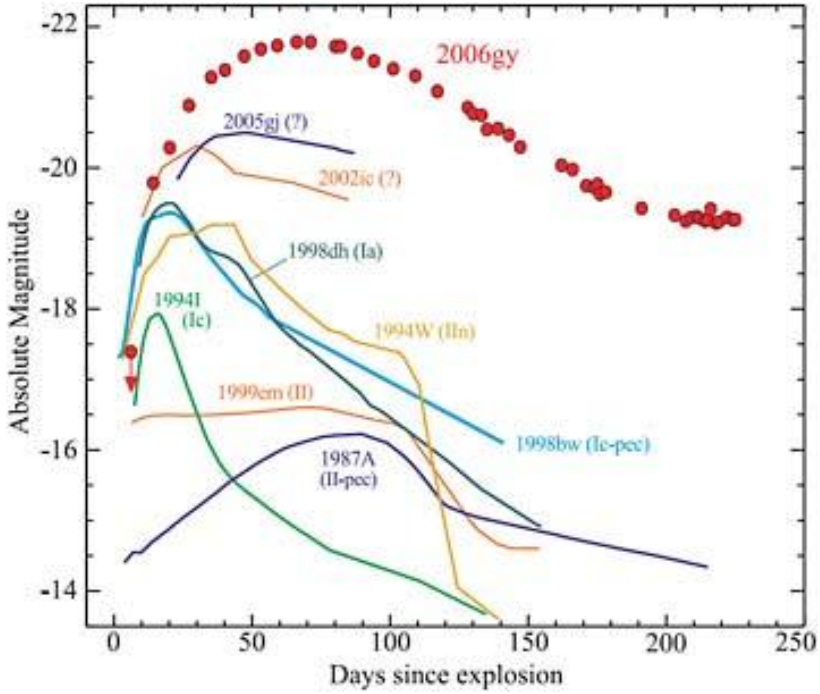
$$\boxed{\Delta E_{\rm grav} \sim G M_c^2 \left(\frac{1}{R_c} - \frac{1}{R_{ns}}\right) \sim 3\times 10^{53} ergs}$$

- Convertir protones y electrones en neutrones
- Desligar el manto
- Energía cinética
- Energía radiada
- Emisión de neutrinos





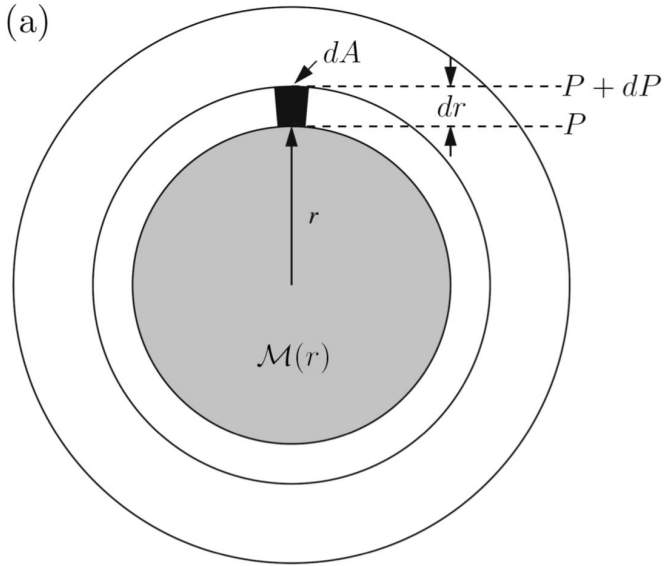
Taza de formación: 1-2 por siglo/galaxia



¿Cómo se construye una estrella de neutrones?

$$\left\{ dF_p = -dP dA \right\} \quad \left\{ dF_g = \frac{G M_r dm}{r^2} \right\}$$

Fuerza de la presión **Fuerza gravitacional**



Equilibrio hidrostático:

$$\frac{dP(r)}{dr} = -\frac{G M(r) \rho(r)}{r^2}$$

$$\frac{dM(r)}{dr} = 4\pi \rho(r) r^2$$

y en Relatividad General: Ecuaciones Tolman-Oppenheimer-Volkov

$$\frac{dP(r)}{dr} = -\frac{G}{c^2}\frac{(P(r)+e(r))(m(r)+4\pi r^3 p(r)/c^2)}{r(r-2Gm(r)/c^2)}$$

$$\frac{dm(r)}{dr} = 4\pi r^2 e(r)/c^2$$

Condiciones iniciales:

$$\left\{ \begin{array}{l} m(r=0)=0 \\ P(r=0)=P_c \end{array} \right\}$$

En el borde de la estrella

$$\left\{ \begin{array}{l} m(r=R_s)=M_s \\ P(r=R_s)=0 \end{array} \right\}$$

Ecuación de estado

$$P = P(\rho, T, \ldots)$$

Estructura de una estrella de neutrones

Un laboratorio para la física teórica

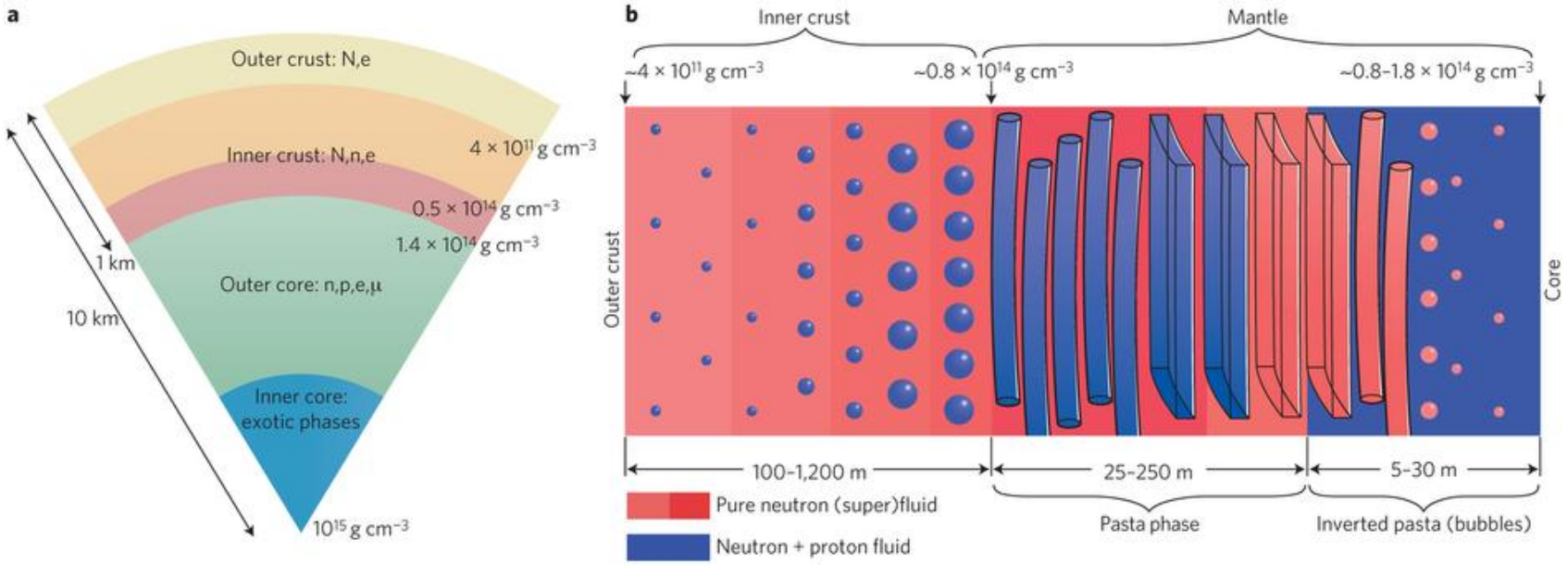
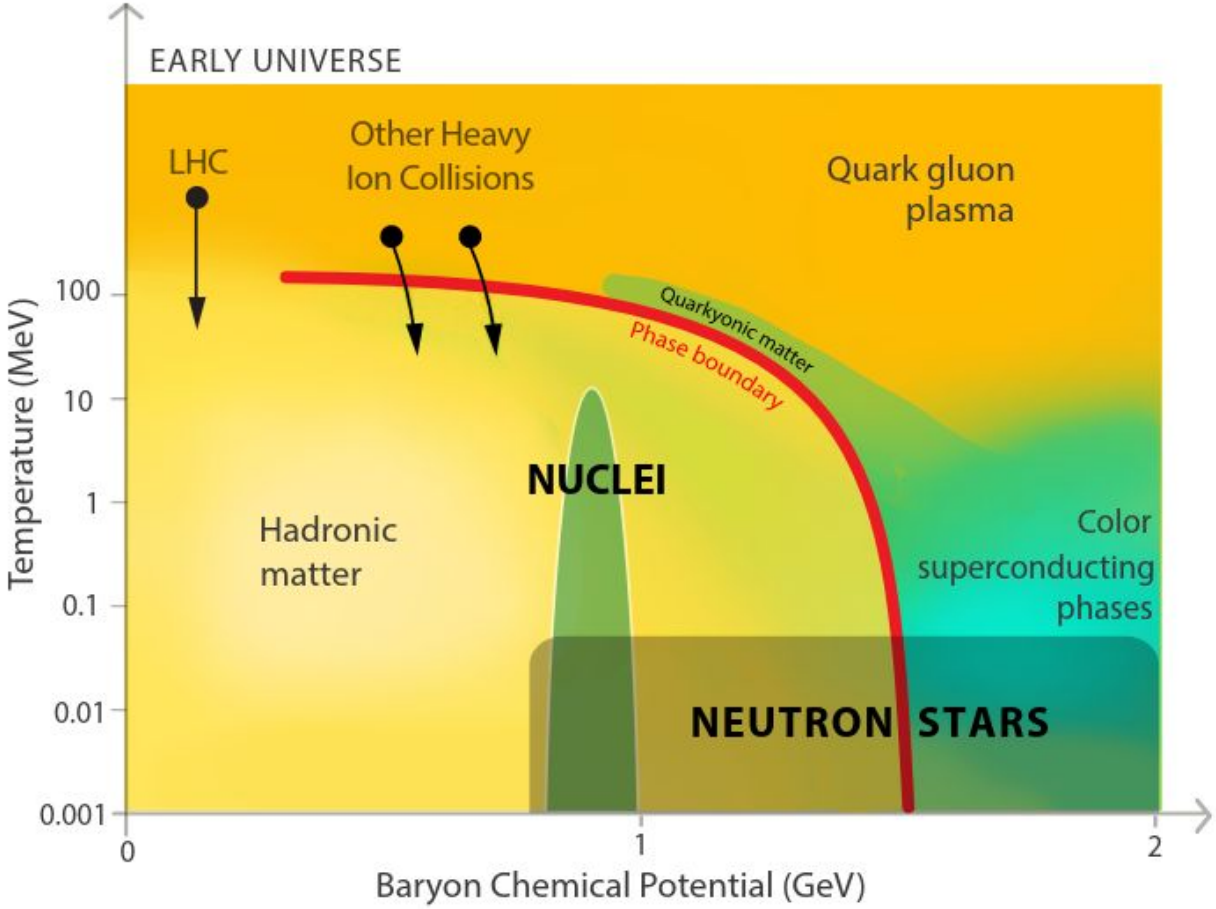
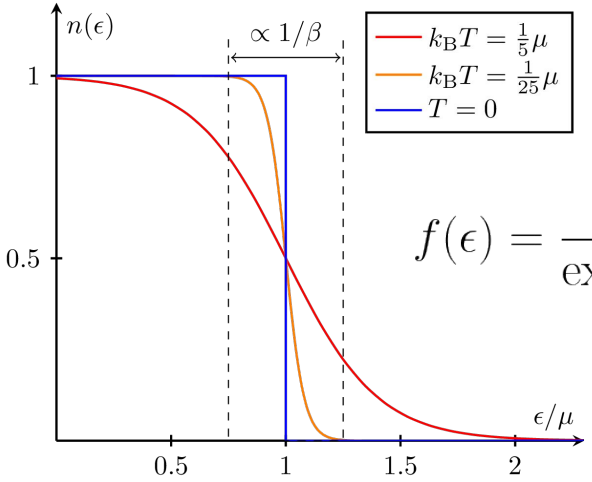


Diagrama de Fase:



Un modelo simple: gas degenerado de fermiones con T=0 K



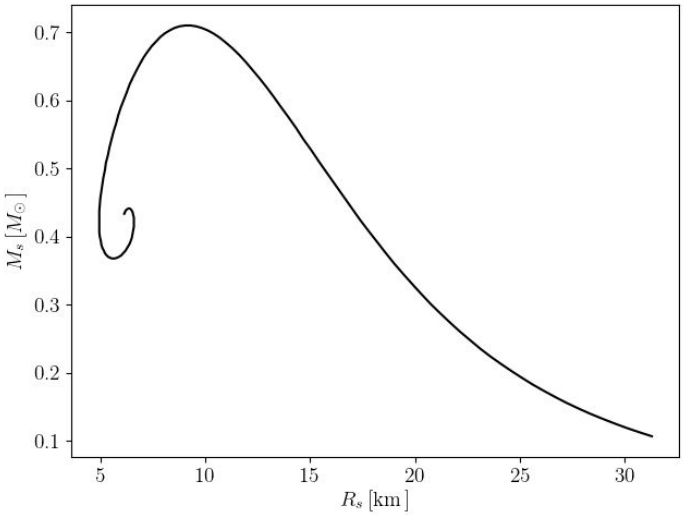
$$f(\epsilon) = \frac{1}{\exp\left[(\epsilon - \mu)/\kappa_B T\right] + 1}$$

$$n_i = \int_0^{p_F} \frac{2f(p)}{(2\pi\hbar)^3}\, d^3p = \frac{p_F^3}{3\pi^2\hbar^3}$$

$$e = \frac{2}{(2\pi\hbar)^3} \int_0^{p_F} \sqrt{(mc^2)^2 + p^2c^2}\, f(p)\, d^3p$$

$$p = n^2 \frac{d}{dn}\left(\frac{e}{n}\right)$$

$$M_{max} = 0.712 M_\odot$$
$$R_s = 9.14\,\mathrm{Km}$$



… agregando protones y electrones

$$n = n_e + n_p + n_n$$

no interactúan

- La estrella es eléctricamente neutra

$$n_e = n_p$$

- Reacciones en equilibrio químico:

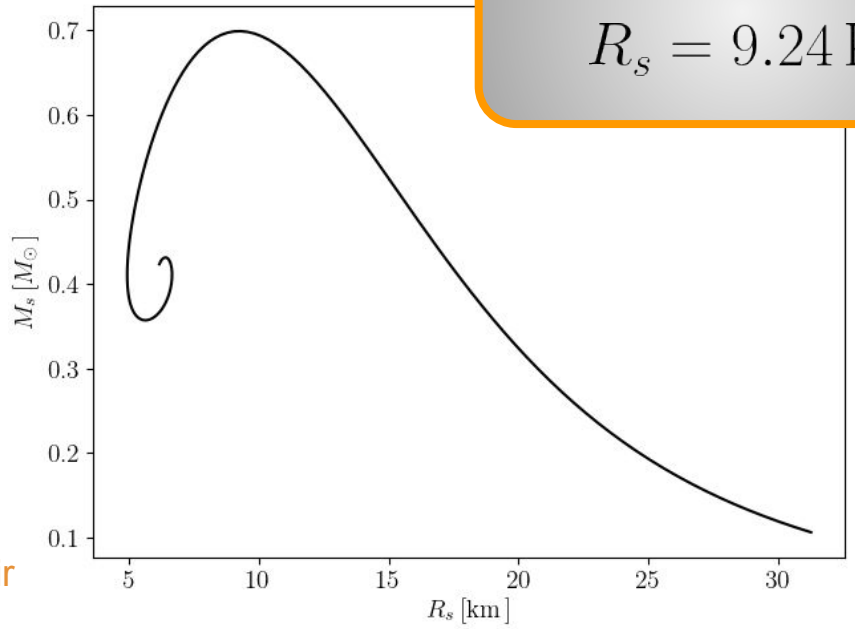
$$n \rightarrow p + e^- + \bar{\nu}_e$$

decaimiento-beta

$$\mu_n = \mu_p + \mu_e$$

$$M_s = 0.699\, M_\odot$$

$$R_s = 9.24\,\mathrm{Km}$$



La fuerza nuclear es fundamental para describir estos objetos apropiadamente.

Enfoque fenomenológico…

Reproducir las propiedades de un núcleo y los valores experimentales

Materia simétrica

$$n_n = n_p$$

$$\frac{E(n)}{n} = m_N + \langle E_0 \rangle u^{2/3} + \frac{A}{2}u + \frac{B}{\sigma + 1}u^{\sigma} \longrightarrow \langle E_0 \rangle = \frac{3}{5}\frac{k_0^2}{2m_N}$$

Condiciones:

- Densidad de partículas en equilibrio $n_o = 0.16\,\mathrm{fm}^{-3}$
- Energía de enlace promedio por nucleón: $BE = -16\mathrm{MeV}$
- Compresibilidad nuclear: $K(n_0) = 400\,\mathrm{MeV}$

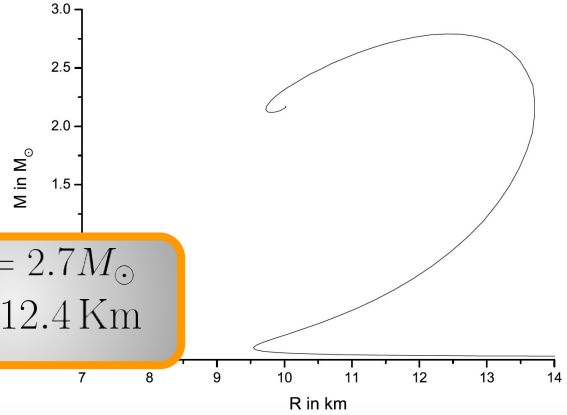
$$\left\{ \begin{array}{l} A = -118.2\,\mathrm{Mev} \\ B = 65.39\,\mathrm{Mev} \\ \sigma = 2.112 \\ \langle E_0 \rangle = 22.1 MeV. \end{array} \right\}$$

Materia no simétrica

$$\alpha = \frac{n_n + n_p}{n}$$

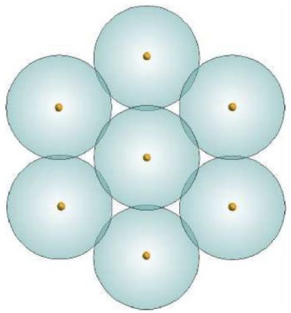
$$\boxed{\frac{E(n,\alpha)}{A} = \frac{E(n,0)}{A} + \alpha^2 S(n)}$$

- Energía de simetría $S(n_0) = 32.5\,\mathrm{MeV}$



$$M_{\max} = 2.7 M_\odot$$
$$R_s = 12.4\,\mathrm{Km}$$

Corteza exterior: BPS EoS (Baym et al. (1971)



La materia se compone por núcleos de número atómico A y carga Z.

$$E_{tot}(A, z, n_N) = n_N(W_N + W_L) + E_e(n_e)$$

Energía total por unidad de volumen

Energía total de los núcleos aislados

Energía de la red cristalina

Energía total de electrones

$$W(A, Z) = A\left[\frac{4}{3}\pi r_o^3 \epsilon_o + a_{sym}\left(\frac{N-Z}{A}\right)^2 + 4\pi r_o^2 A^{2/3}\epsilon_{surf} + \frac{3}{5}\frac{e^2 A^2}{r_o A^{1/3}}\right]$$

$$W_L = -1.819620 Z^2 e^2 \left(\frac{n_e}{2Z}\right)^{\frac{1}{3}}$$

El estado base a una presión dada está determinado por la energía de Gibbs mínima.

element	Z	N	Z/A	$\rho_{\max}$ (g cm^{-3})	μ_e (MeV)	$\Delta\rho/\rho$ (%)
^{56}Fe	26	30	0.4643	$7.96\ 10^{6}$	0.95	2.9
^{62}Ni	28	34	0.4516	$2.71\ 10^{8}$	2.61	3.1
^{64}Ni	28	36	0.4375	$1.30\ 10^{9}$	4.31	3.1
^{66}Ni	28	38	0.4242	$1.48\ 10^{9}$	4.45	2.0
^{86}Kr	36	50	0.4186	$3.12\ 10^{9}$	5.66	3.3
^{84}Se	34	50	0.4048	$1.10\ 10^{10}$	8.49	3.6
^{82}Ge	32	50	0.3902	$2.80\ 10^{10}$	11.44	3.9
^{80}Zn	30	50	0.3750	$5.44\ 10^{10}$	14.08	4.3
^{78}Ni	28	50	0.3590	$9.64\ 10^{10}$	16.78	4.0
^{126}Ru	44	82	0.3492	$1.29\ 10^{11}$	18.34	3.0
^{124}Mo	42	82	0.3387	$1.88\ 10^{11}$	20.56	3.2
^{122}Zr	40	82	0.3279	$2.67\ 10^{11}$	22.86	3.4
^{120}Sr	38	82	0.3167	$3.79\ 10^{11}$	25.38	3.6
^{118}Kr	36	82	0.3051	$(4.33\ 10^{11})$	(26.19)	

Corteza interior: BBP EoS (Baym et al. (1971))

La materia consiste en núcleos sumergidos en un mar de electrones y neutrones:

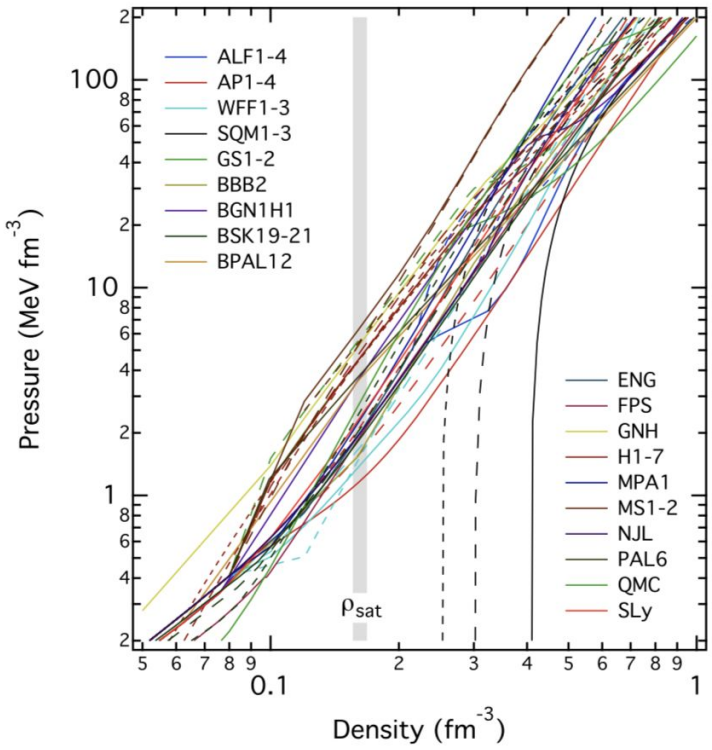
$$E_{tot} = n_N(W_N + W_L) + (1 - V_N n_N)E_n(n_n) + E_e(n_e)$$

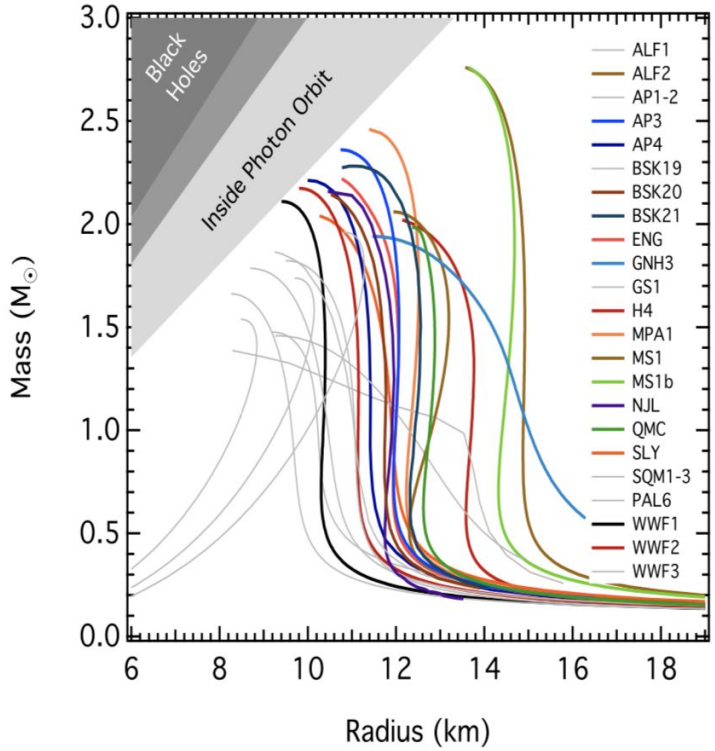
Energía de los núcleos

Energía de los neutrones

Energía de los electrones

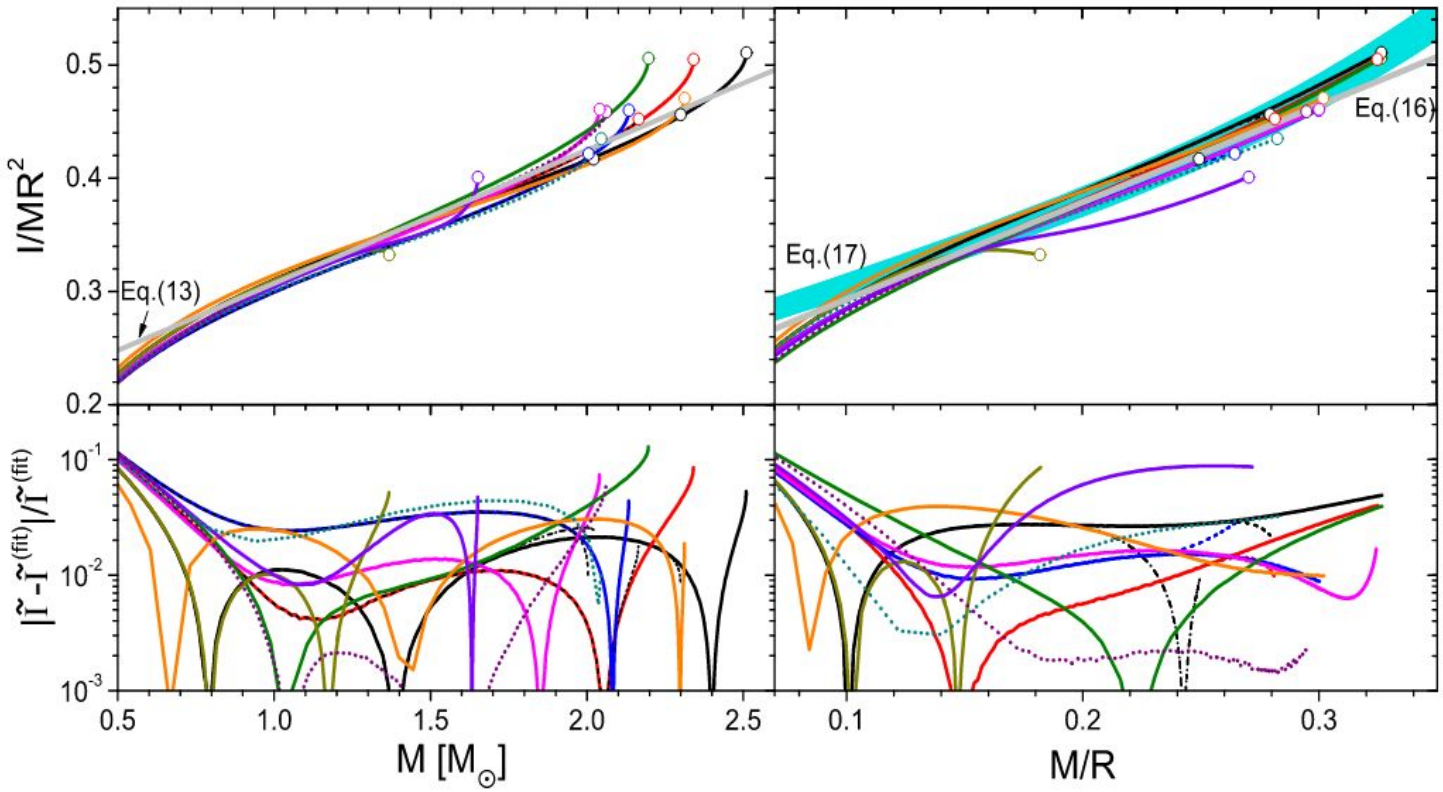
Ecuaciones de estado.





https://compose.obspm.fr

Relaciones universales



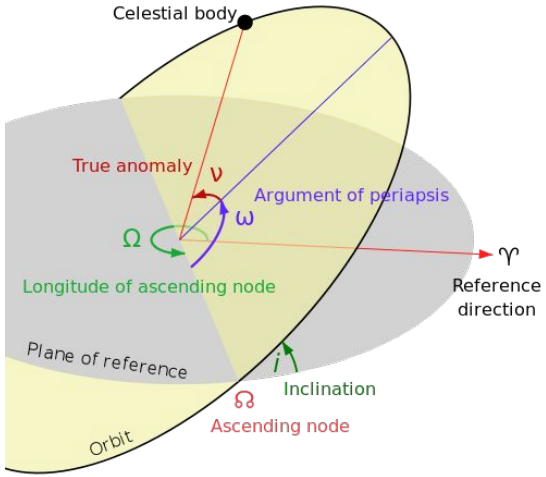
Tomada de J. B. Wei et al. 2018

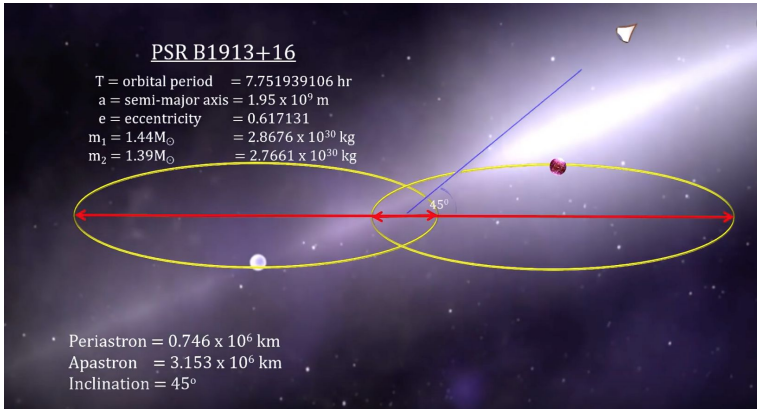
Midiendo las masas de las estrellas de neutrones:

Parámetros Keplerianos:

- Periodo binario
- Excentricidad
- Proyección del semieje mayor sobre la línea de visión
- Tiempo y longitud del periastro

$$f(M_1, M_2, i) = \frac{(M_2 \sin i)^3}{(M_1 + M_2)^2} = \frac{P_b v_1^3}{2\pi G}$$





Efectos relativistas:

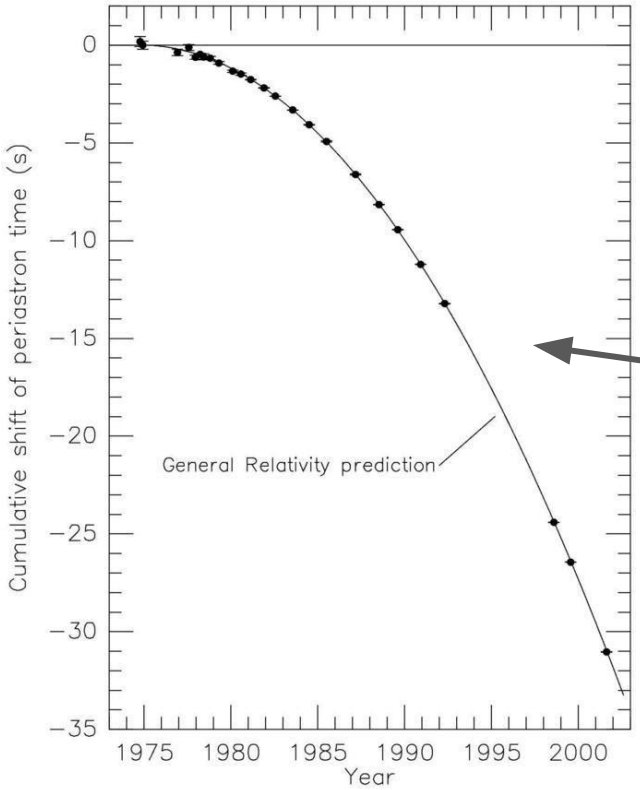
- Avance del periastro
- Efecto doppler y corregimiento al rojo gravitacional
- Decaimiento orbital
- Shapiro Time delay

Sistema binario Hulse-Taylor

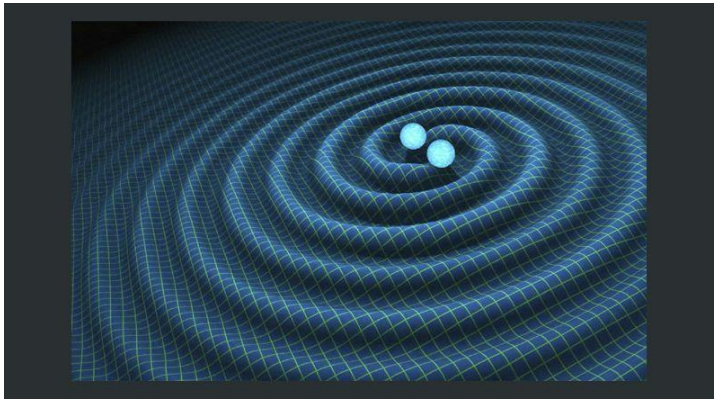
$$M_2 = 1.4408 \pm 0.00034 M_\odot$$

$$M_1 = 1.3873 \pm 0.0003 M_\odot$$

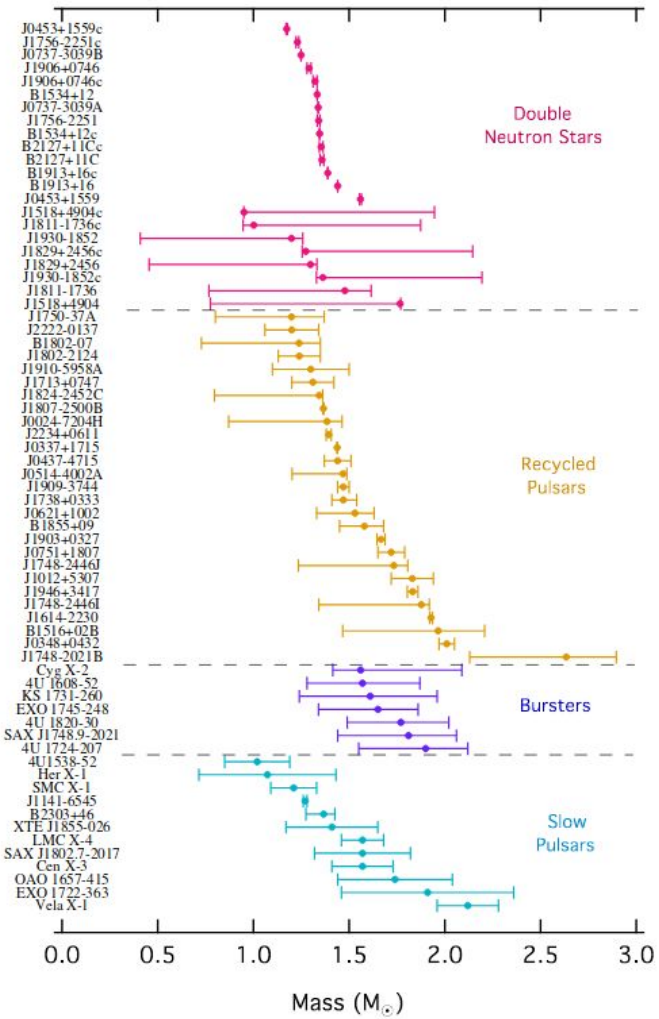
$$\frac{E_{gw}}{dt} = -\frac{32}{5} G^4 c^5 \frac{(M_1 + M_2)(M_1 M_2)^2}{r^5}$$

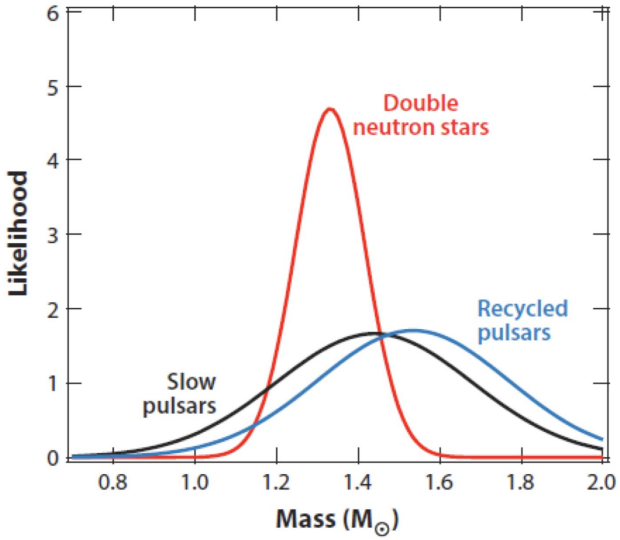


Detección indirecta de ondas gravitacionales



Masa máxima de una estrella de neutrones





PSR J0348+0432:

(Antoniadis et al. 2013)

$$2.01 \pm 0.04 M_\odot$$

PSR J1614-2230

(Demorest et al. 2010)

$$1.97 \pm 0.04 M_\odot$$

… y la masa mínima?

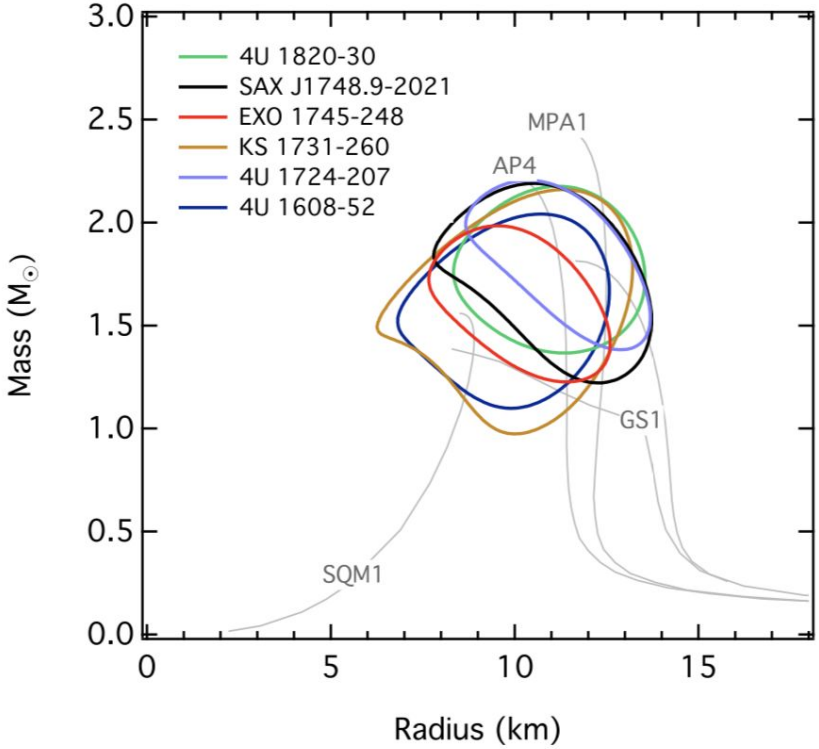
Midiendo el Radio:

Emisión térmica de binarias de rayos-x

Emisión de cuerpo negro

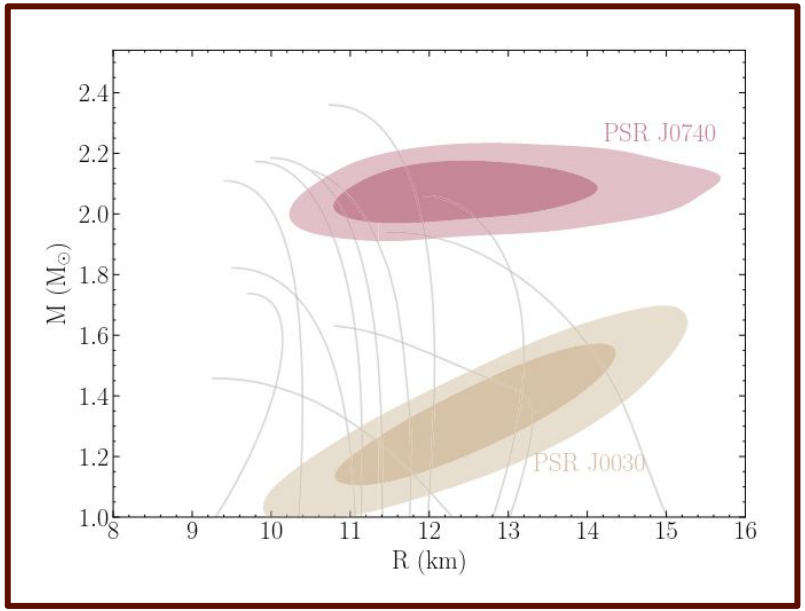
$$R_\infty = \sqrt{\frac{FD^2}{\sigma T^4}}$$

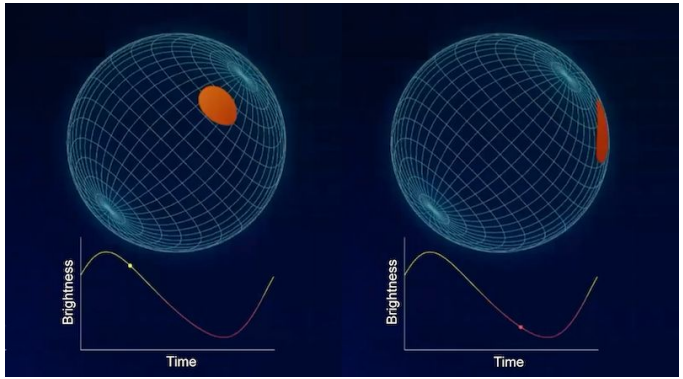
$$R = R_\infty \sqrt{1 - \frac{2GM}{c^2 R}}$$

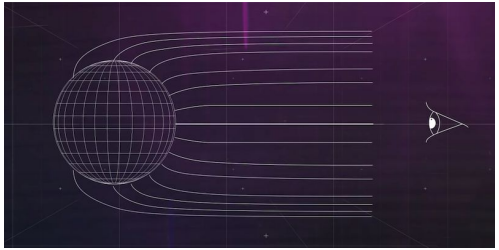


Nicer (Neutron star Interior Composition Explorer)

Fotones emitidos de las regiones calientes en la superficie de estrellas de neutrones rápidamente rotantes.



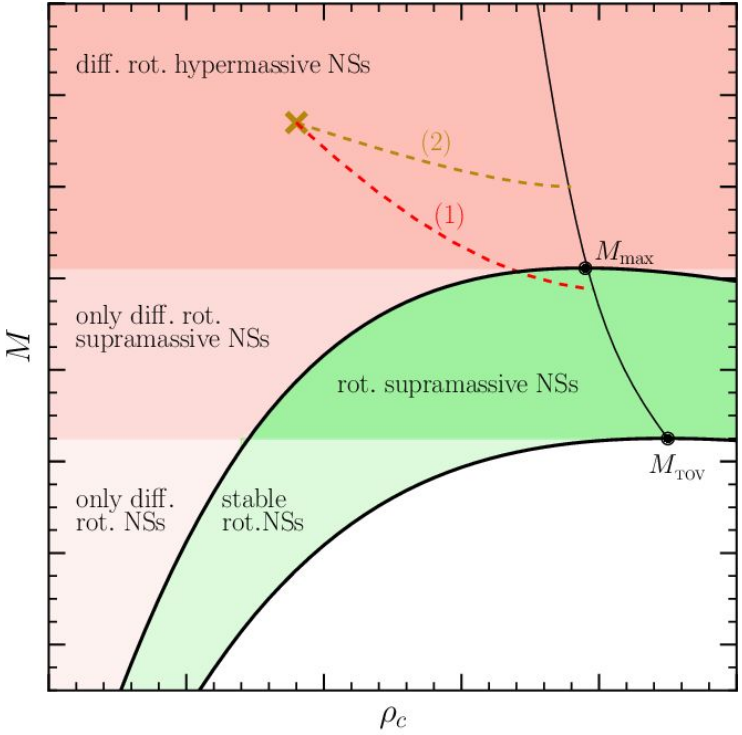


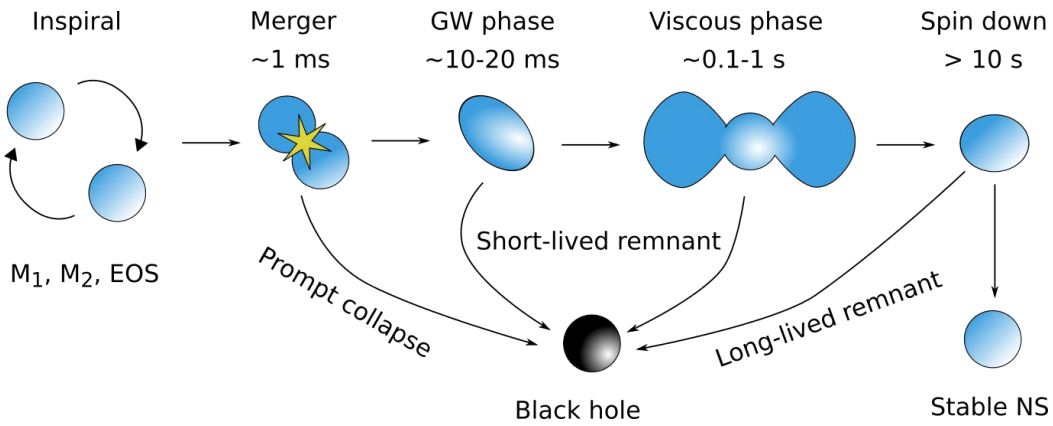


Miller et al. (2019), Riley et al. (2019), Miller et al. (2021)

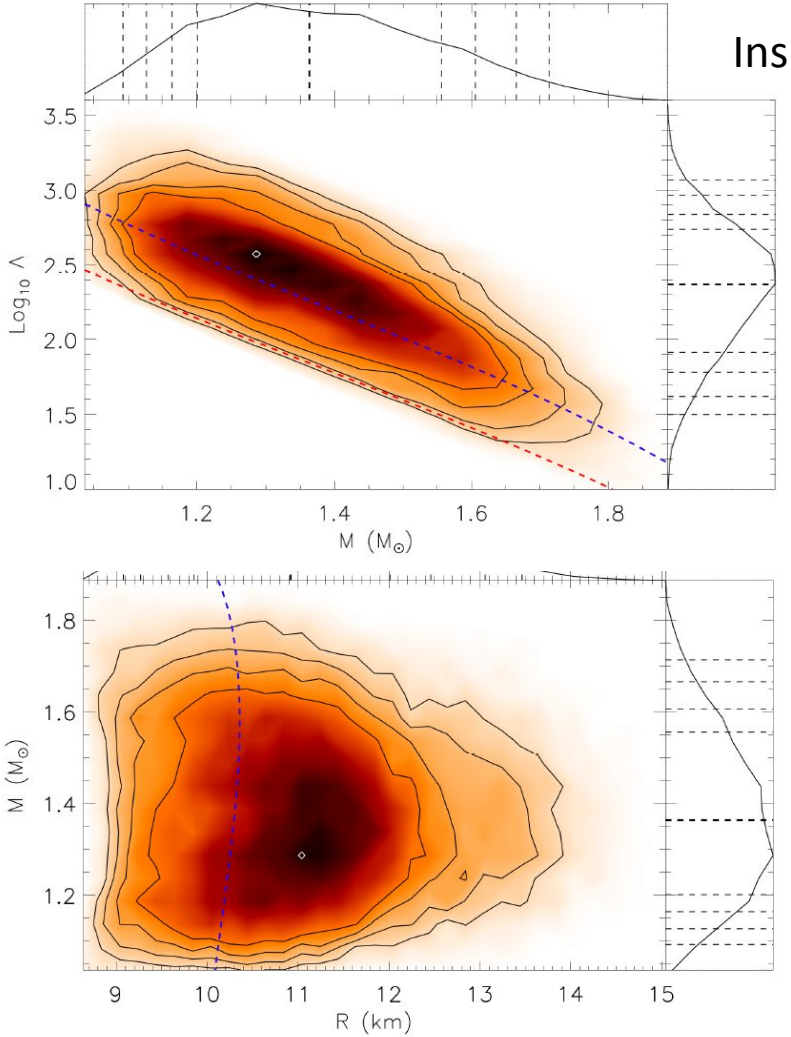
Detección de ondas gravitacionales

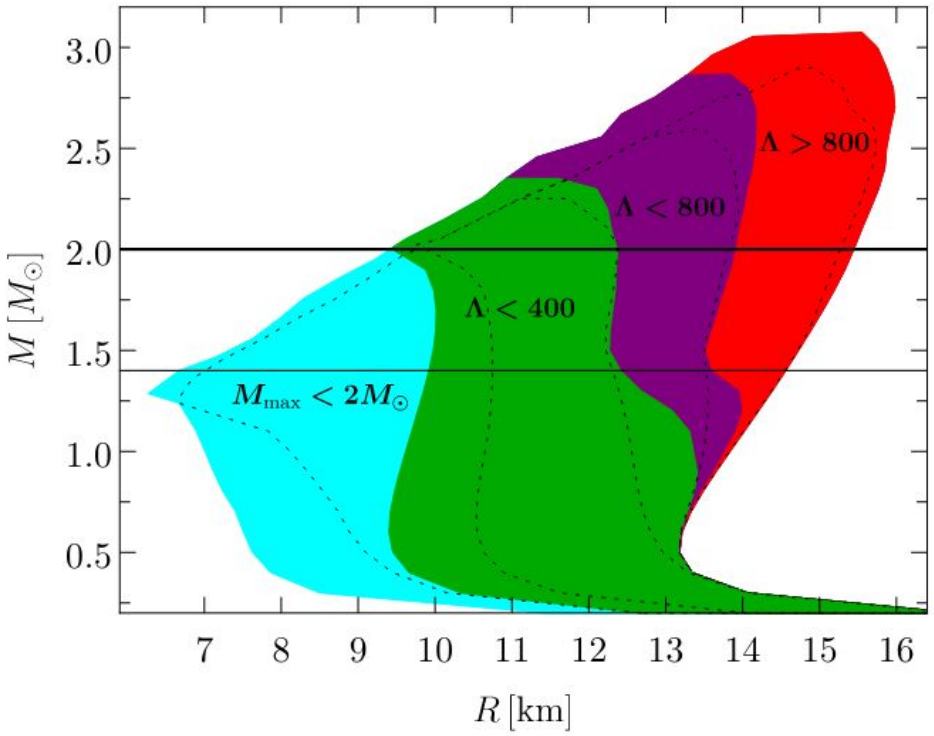
GW170817





Inspiral phase of GW170817





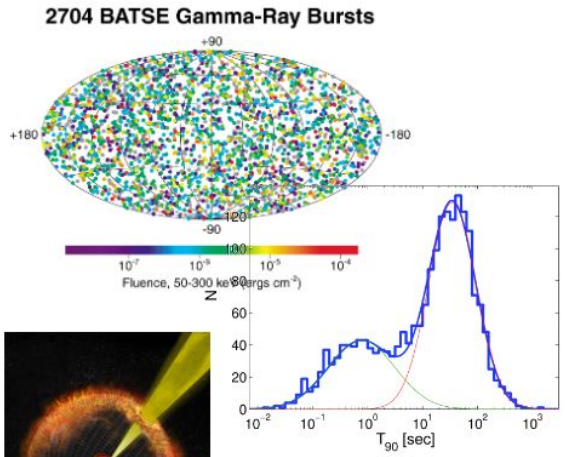
Annala et al. (2018)

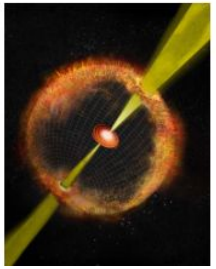
El Modelo de Colapso Gravitacional Inducido

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

Brotes de rayos gamma (BRG)

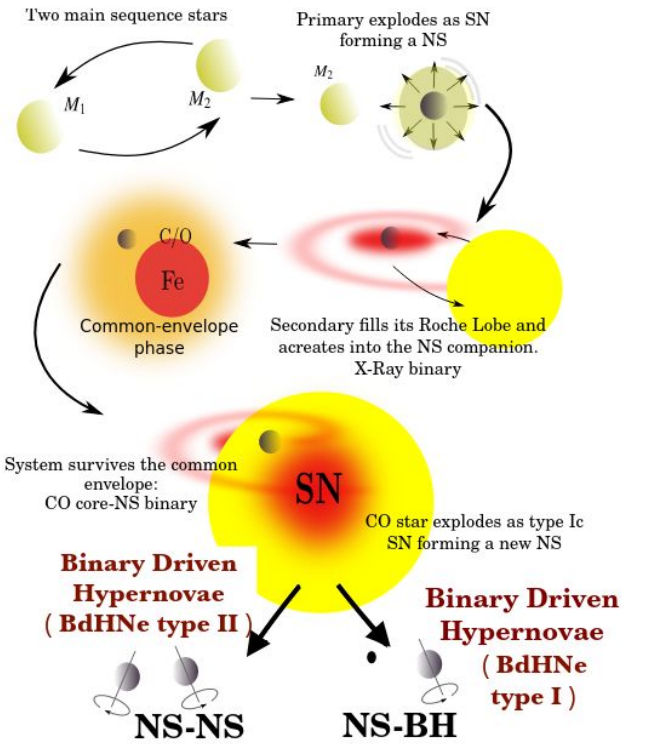
- Distribución isotropica
- Distribución bimodal
- Emisión Afterglow
- Conexión con Supernovas





Modelo de collapsar (Woosley, ApJ 1993).

Progenitor del Modelo CGI



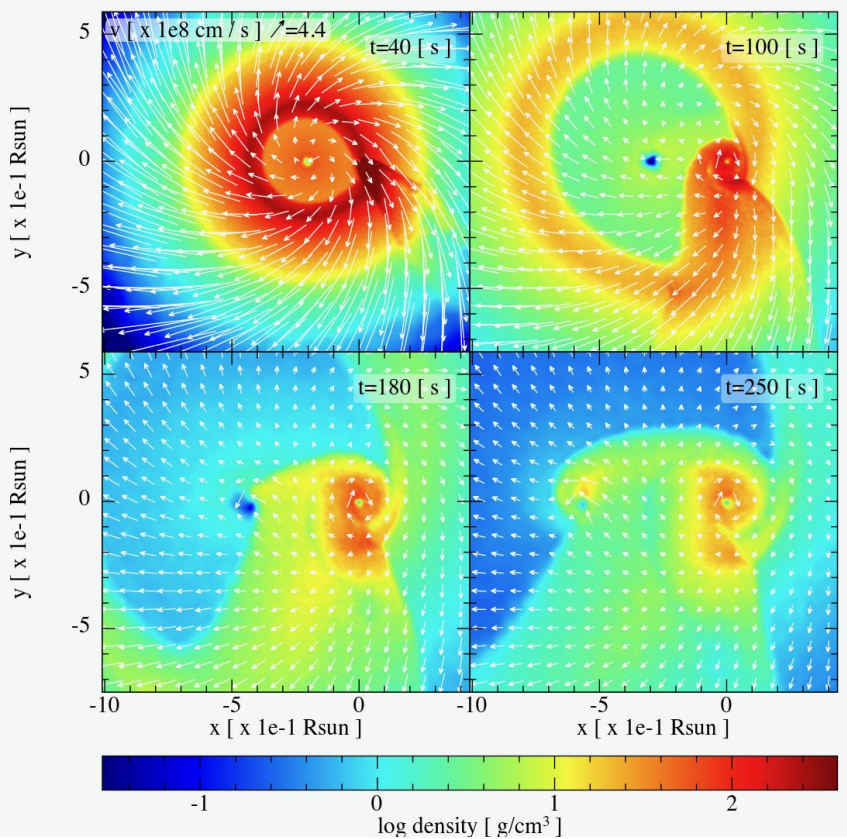
$E_{\rm iso} < 10^{52}$ ergs

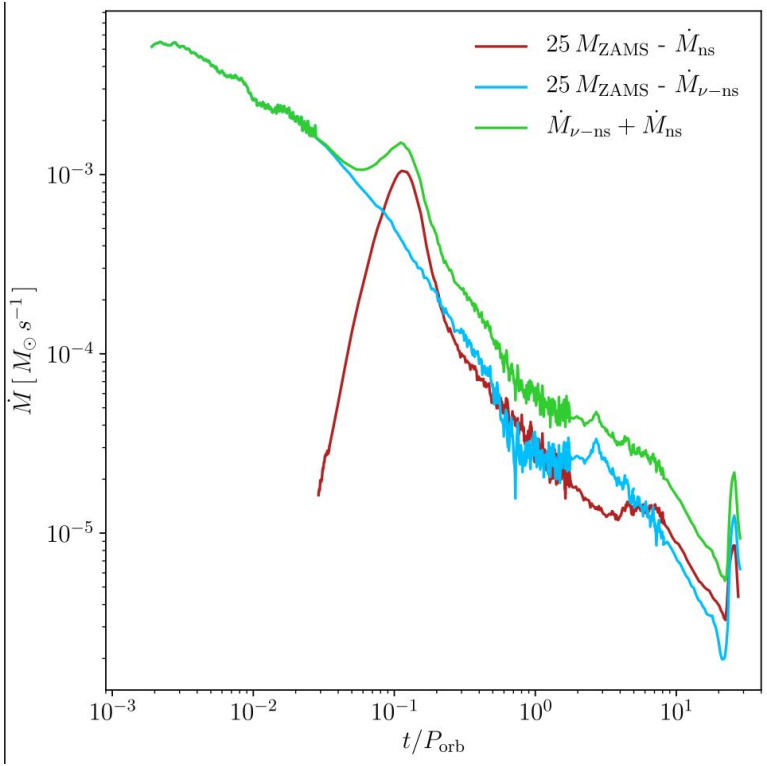
$E_{p,i} < 200$ KeV

$E_{\rm iso} > 10^{52}$ ergs

$E_{p,i} > 200$ KeV

Taza de acreción sobre la estrella de neutrones





Masa Critica de la EN y Colapso Gravitacional

Configuraciones rotantes de EN - F. Cipolletta et al, Phys. D. 2015

La evolución de la masa gravitacional y momento angular de la EN es:

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

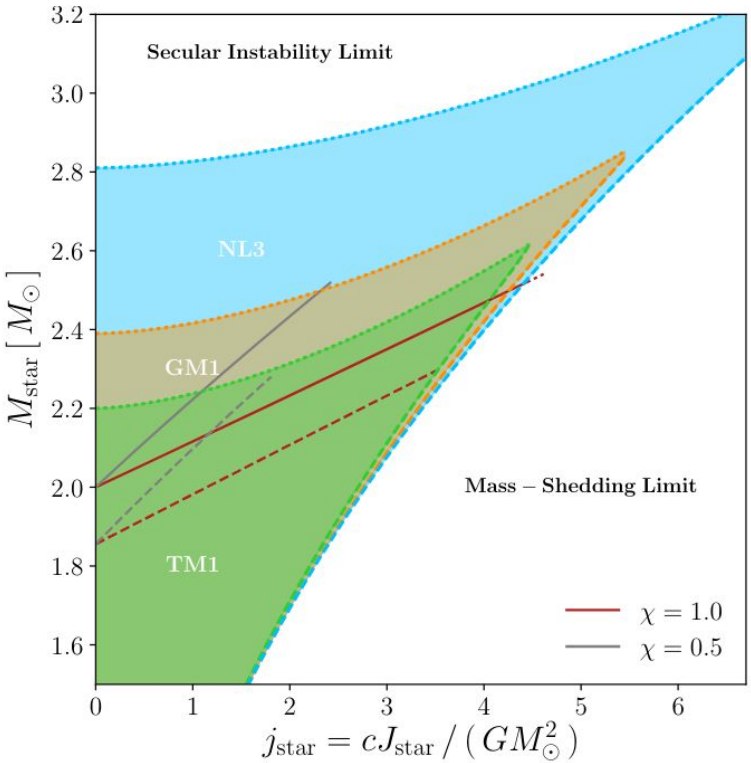
$$\frac{dJ_{\rm NS}}{dt} = \chi\, l(R_{\rm in})\frac{dM_{\rm b}}{dt} + \tau_{\rm mag} \qquad (2)$$

con $\chi < 1$, un parámetro que sigue la eficiencia de la tranferencia de momento angular.

$$\frac{M_b}{M_\odot} = \frac{M_{\rm NS}}{M_\odot} + \frac{13}{200}\left(\frac{M_{\rm NS}}{M_\odot}\right)^2\left(1 + \frac{j_{\rm NS}^{1,7}}{137}\right)$$

$$l_{\rm lso} = 2\sqrt{3}\frac{GM_{\rm NS}}{c}\left[1 - \frac{1}{10}\left(\frac{j_{\rm NS}}{M_{\rm NS}}\right)^{0,85}\right]$$

L. Becerra et al., ApJ 871, 2018



GRACIAS

¿Preguntas?