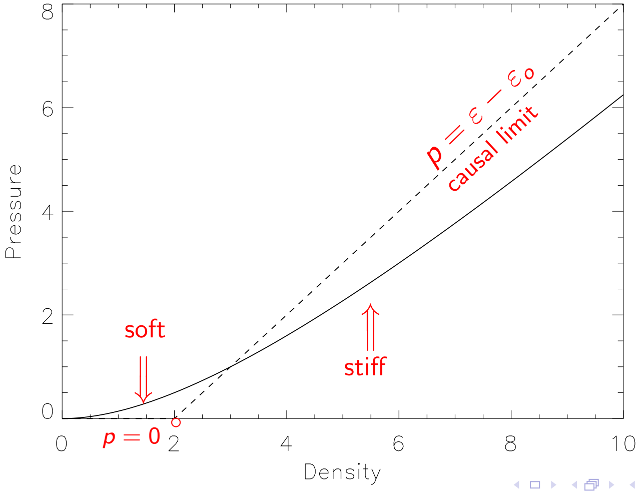
Extreme Properties of Neutron Stars

- The most compact and massive configurations occur when the low-density equation of state is "soft" and the high-density equation of state is "stiff" (Koranda, Stergioulas & Friedman 1997).



ε_0 is the only EOS parameter

The TOV solutions scale with ε_0

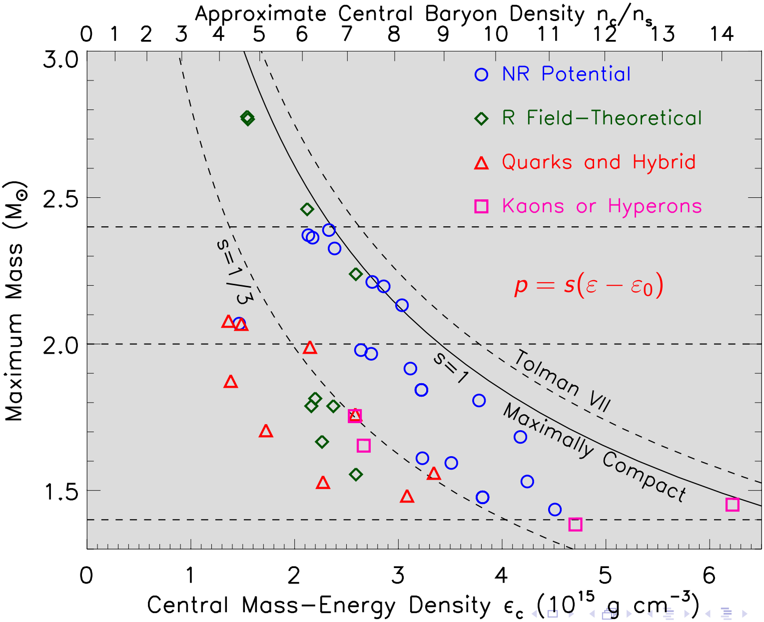
Extreme Properties of Neutron Stars

- $M_{max} = 4.1\ (\varepsilon_s/\varepsilon_0)^{1/2}\ \mathrm{M}_\odot$ (Rhoades & Ruffini 1974)
- $M_{B,max} = 5.41\ (m_B c^2/\mu_o)(\varepsilon_s/\varepsilon_0)^{1/2}\ \mathrm{M}_\odot$
- $R_{min} = 2.82\ GM/c^2 = 4.3\ (M/\mathrm{M}_\odot)\ \mathrm{km}$
- $\mu_{B,max} = 2.09$ GeV
- $\varepsilon_{c,max} = 3.034\ \varepsilon_0 \simeq 51\ (\mathrm{M}_\odot/M_{largest})^2\ \varepsilon_s$
- $p_{c,max} = 2.034\ \varepsilon_0 \simeq 34\ (\mathrm{M}_\odot/M_{largest})^2\ \varepsilon_s$
- $n_{B,max} \simeq 38\ (\mathrm{M}_\odot/M_{largest})^2\ n_s$
- $\mathrm{BE}_{max} = 0.34\ M$
- $$P_{min} = 0.74\ (\mathrm{M}_\odot/M_{sph})^{1/2}(R_{sph}/10\ \mathrm{km})^{3/2}\ \mathrm{ms} = 0.20\ (M_{sph,max}/\mathrm{M}_\odot)\ \mathrm{ms}$$

A phenomenological limit for hadronic matter (Lattimer & Prakash 2004)

- $$P_{min} \simeq 1.00\ (\mathrm{M}_\odot/M_{sph})^{1/2}(R_{sph}/10\ \mathrm{km})^{3/2}\ \mathrm{ms} = 0.27\ (M_{sph,max}/\mathrm{M}_\odot)\ \mathrm{ms}$$

Maximum Energy Density in Neutron Stars



Mass-Radius Diagram and Theoretical Constraints

GR:

$R > 2GM/c^2$

$P < \infty$:

$R > (9/4)GM/c^2$

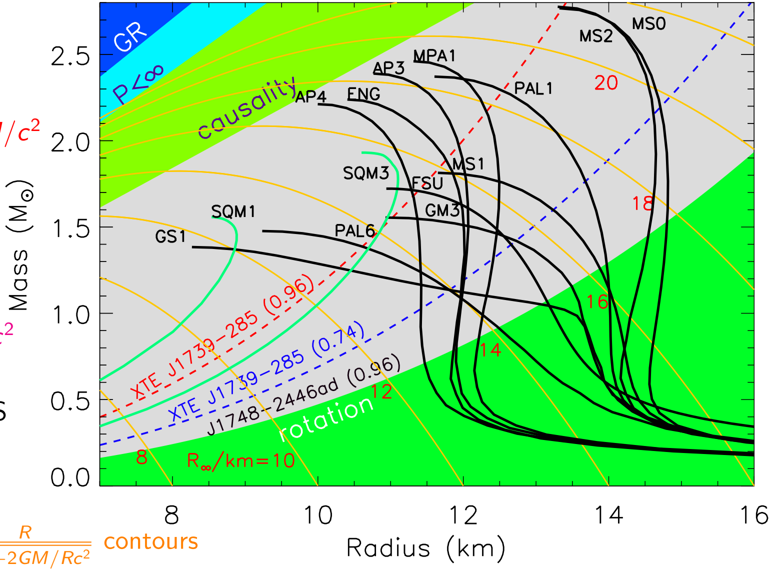
causality:

$R \gtrsim 2.9GM/c^2$

— normal NS

— SQS

— $R_\infty = \frac{R}{\sqrt{1-2GM/Rc^2}}$ contours



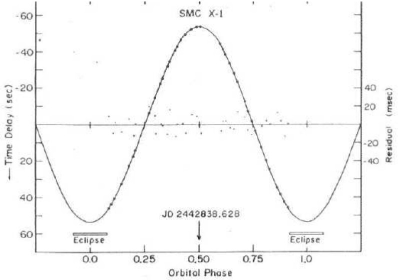
Mass Measurements In X-Ray Binaries

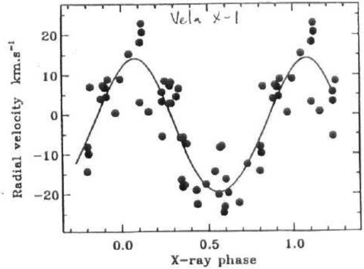
Mass function

$$f(M_1) = \frac{P(v_2 \sin i)^3}{2\pi G} = \frac{(M_1 \sin i)^3}{(M_1+M_2)^2} > M_1$$

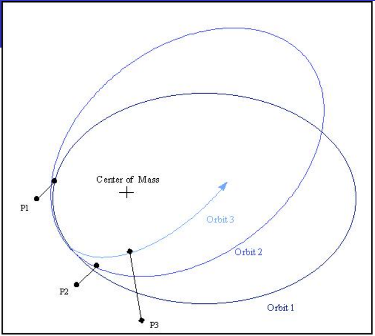
$$f(M_2) = \frac{P(v_1 \sin i)^3}{2\pi G} = \frac{(M_2 \sin i)^3}{(M_1+M_2)^2} > M_2$$

In an X-ray binary, $v_{optical}$ has the largest uncertainties. In some cases, $\sin i \sim 1$ if eclipses are observed. If eclipses are not observed, limits to i can be made based on the estimated radius of the optical star.





Pulsar Mass Measurements



Mass function for pulsar precisely obtained.
It is also possible in some cases to obtain the rate of periastron advance and the Einstein gravitational redshift + time dilation term:

$\dot\omega = 3(2\pi/P)^{5/3}(GM/c^2)^{2/3}/(1-e^2)$

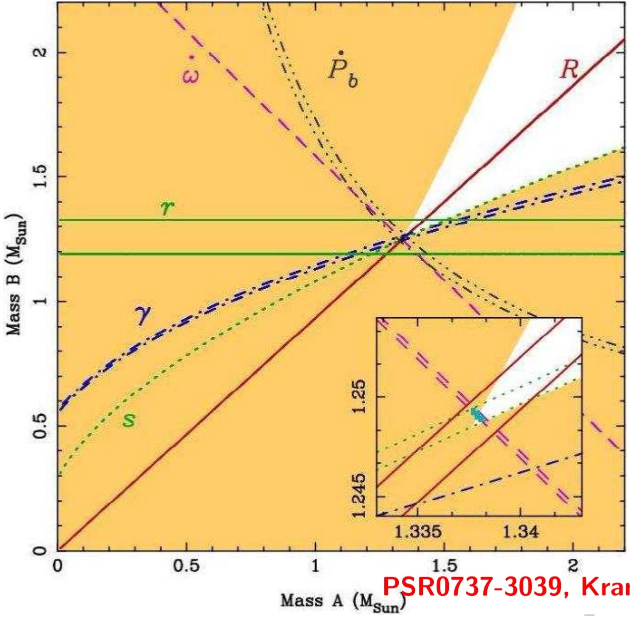
$\gamma = (P/2\pi)^{1/3} e M_2 (2M_2 + M_1)(G/M^2c^2)^{2/3}$

Gravitational radiation leads to orbit decay:

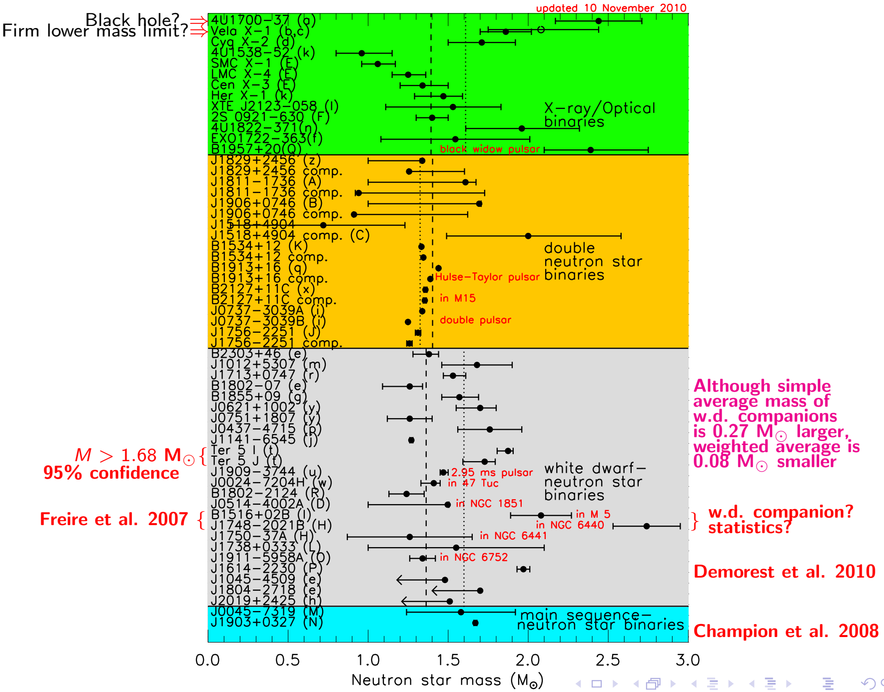
$\dot P = -\frac{192\pi}{5c^5}\left(\frac{2\pi G}{P}\right)^{5/3}(1-e^2)^{-7/2}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)\frac{M_1M_2}{M^{1/2}}$

In some cases, can constrain Shapiro time delay, r is magnitude and $s = \sin i$ is shape parameter.

The Double Pulsar Binary

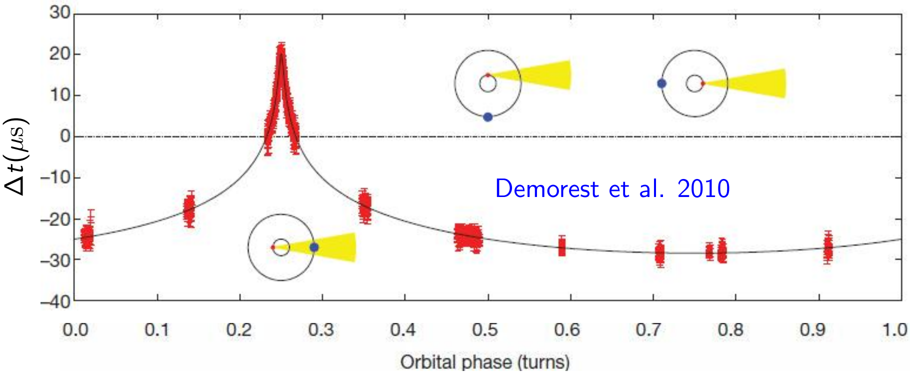


PSR0737-3039, Kramer et al. (2007)


updated 10 November 2010
Black hole?
Firm lower mass limit?
4U1700−37 (a)
Vela X−1 (b,c)
Cyg X−2 (d)
4U1538−52 (k)
SMC X−1 (E)
LMC X−4 (E)
Cen X−3 (E)
Her X−1 (k)
XTE J2123−058 (l)
2S 0921−630 (F)
4U1822−371(n)
EXO1722−363(f)
B1957+20(Q)
black widow pulsar
X−ray/Optical binaries
J1829+2456 (z)
J1829+2456 comp.
J1811−1736 (A)
J1811−1736 comp.
J1906+0746 (B)
J1906+0746 comp.
J1518+4904
J1518+4904 comp. (C)
B1534+12 (K)
B1534+12 comp.
B1913+16 (q)
B1913+16 comp.
Hulse−Taylor pulsar
B2127+11C (x)
B2127+11C comp.
in M15
J0737−3039A (i)
J0737−3039B (i)
double pulsar
J1756−2251 (J)
J1756−2251 comp.
double neutron star binaries
B2303+46 (e)
J1012+5307 (m)
J1713+0747 (r)
B1802−07 (e)
B1855+09 (g)
J0621+1002 (y)
J0751+1807 (y)
J0437−4715 (p)
J1141−6545 (j)
Ter 5 I (t)
Ter 5 J (t)
J1909−3744 (u)
2.95 ms pulsar
J0024−7204H (w)
in 47 Tuc
B1802−2124 (R)
J0514−4002A (D)
in NGC 1851
B1516+02B (I)
in M 5
J1748−2021B (H)
in NGC 6440
J1750−37A (H)
in NGC 6441
J1738+0333 (L)
J1911−5958A (O)
in NGC 6752
J1614−2230 (P)
J1045−4509 (e)
J1804−2718 (e)
J2019+2425 (h)
white dwarf−neutron star binaries
J0045−7319 (M)
J1903+0327 (N)
main sequence−neutron star binaries
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron star mass ($M_\odot$)
$M > 1.68\ M_\odot$
95% confidence
Freire et al. 2007
Although simple average mass of w.d. companions is 0.27 $M_\odot$ larger, weighted average is 0.08 $M_\odot$ smaller
w.d. companion? statistics?
Demorest et al. 2010
Champion et al. 2008

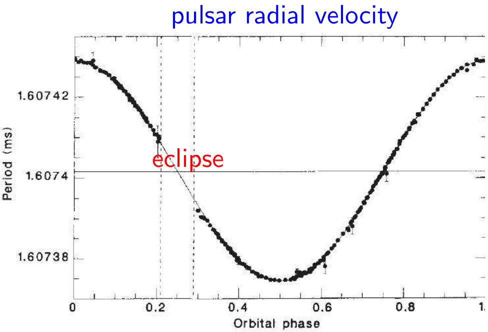
PSR J1614-2230

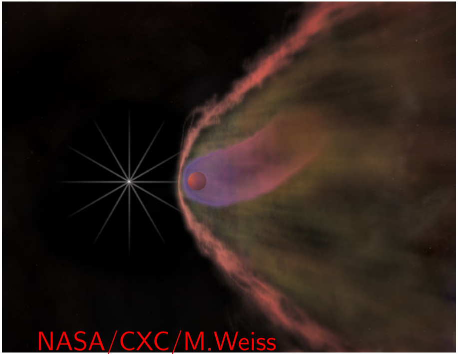
A 3.15 ms pulsar in an 8.69d orbit with an 0.5 $M_\odot$ white dwarf companion.
Shapiro delay yields edge-on inclination: $\sin i = 0.99984$
Pulsar mass is $1.97 \pm 0.04\ M_\odot$
Distance > 1 kpc, $B \simeq \times 10^8$ G



Black Widow Pulsar PSR B1957+20

1.6ms pulsar in circular 9.17h orbit with a $M_c \sim 0.03$ $M_\odot$ companion.
Pulsar is eclipsed for 50-60 minutes each orbit; eclipsing object has a volume much larger than the companion or its Roche lobe.
It is believed the companion is ablated by the pulsar leading to mass loss and an eclipsing plasma cloud. Companion nearly fills its Roche lobe.
Ablation by pulsar leads to eventual disappearance of companion.
The optical light curve does not represent the center of mass of the companion, but the motion of its irradiated hot spot.





Implications of Maximum Masses

$M_{max} > 2\ \mathrm{M}_\odot$

- Upper limits to energy density, pressure and baryon density:
  - $\varepsilon < 13.1\varepsilon_s$
  - $p < 8.8\varepsilon_s$
  - $n_B < 9.8n_s$
- Lower limit to spin period: $P > 0.56$ ms
- Lower limit to neutron star radius: $R > 8.5$ km
- Upper limits to energy density, pressure and baryon density in the case of a quark matter core:
  - $\varepsilon < 7.7\varepsilon_s$
  - $p < 2.0\varepsilon_s$
  - $n_B < 6.9n_s$

$M_{max} > 2.4\ \mathrm{M}_\odot$

- Upper limits to energy density, pressure, baryon density:
  - $\varepsilon < 8.9\varepsilon_s$
  - $p < 5.9\varepsilon_s$
  - $n_B < 6.6n_s$
- Lower limit to spin period: $P > 0.68$ ms
- Lower limit to neutron star radius: $R > 10.4$ km
- Upper limits to energy density, pressure, baryon density in the case of a quark matter core:
  - $\varepsilon < 5.2\varepsilon_s$
  - $p < 1.4\varepsilon_s$
  - $n_B < 4.6n_s$

Neutron Star Matter Pressure and the Radius

$p \simeq K n^{\gamma}$

$\gamma = d \ln p / d \ln \; n \sim 2$

$R \propto K^{1/(3\gamma-4)} M^{(\gamma-2)/(3\gamma-4)}$

$R \propto p_f^{1/2} n_f^{-1} M^0$

$(1 < n_f / n_s < 2)$

Wide variation:

$1.2 < \frac{p(n_s)}{\mathrm{MeV\ fm^{-3}}} < 7$

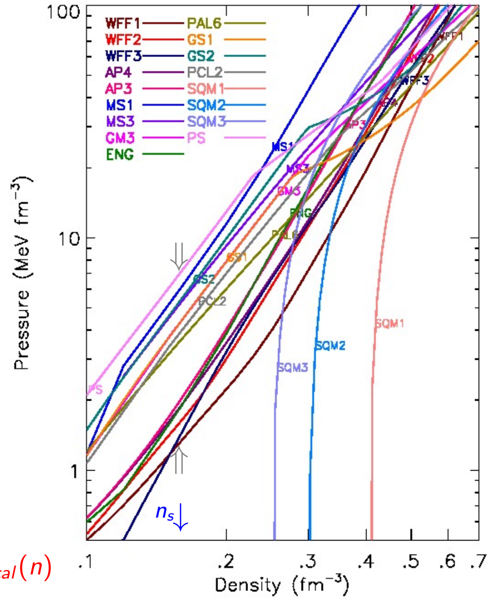
GR phenomenological result

(Lattimer & Prakash 2001)

$R \propto p_f^{1/4} n_f^{-1/2}$

$p_f = n^2 dE_{sym}/dn$

$E_{sym}(n) = E_{neutron}(n) - E_{symmetrical}(n)$

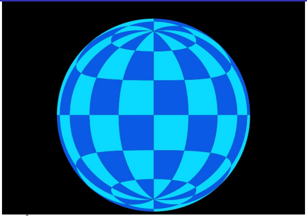


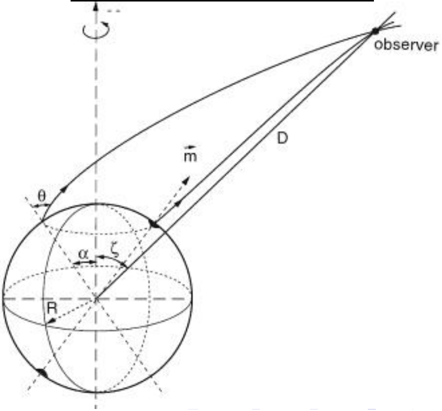
Radiation Radius

- The measurement of flux and temperature yields an apparent angular size (pseudo-BB):

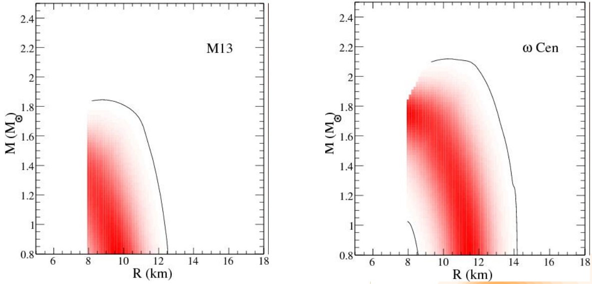
$$\frac{R_\infty}{d} = \frac{R}{d}\frac{1}{\sqrt{1-2GM/Rc^2}}$$

- Observational uncertainties include distance, interstellar H absorption (hard UV and X-rays), atmospheric composition
- Best chances for accurate radii:
  - Nearby isolated neutron stars (parallax measurable)
  - Quiescent X-ray binaries in globular clusters (reliable distances, low B H-atmosperes)

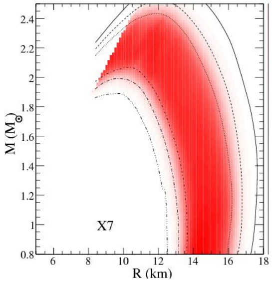


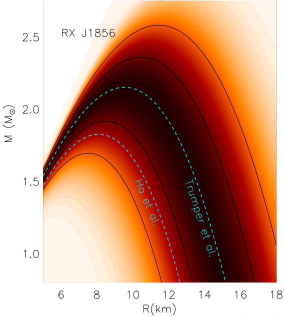


Inferred M-R Probability Estimates from Thermal Sources

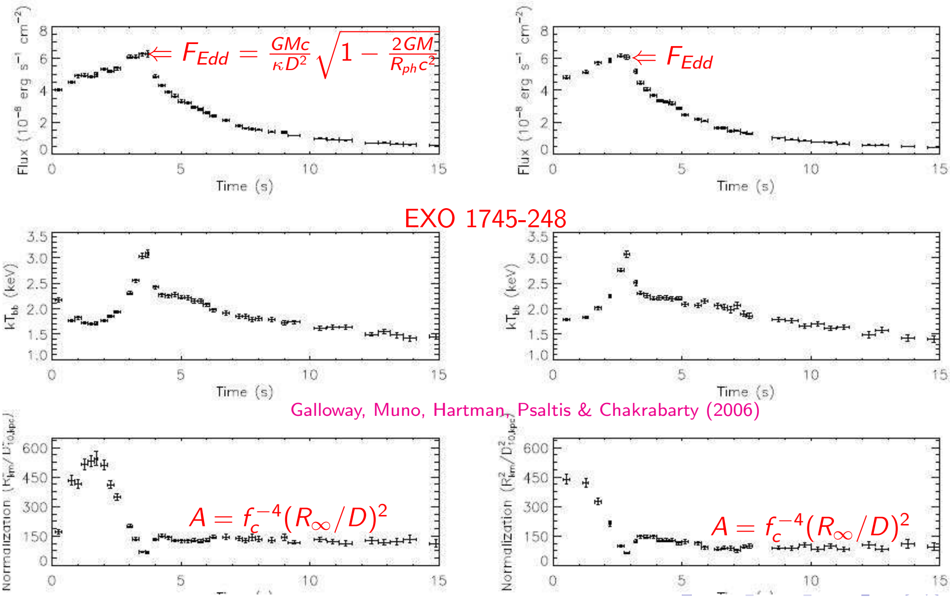


Steiner, Lattimer & Brown 2010





Photospheric Radius Expansion X-Ray Bursts

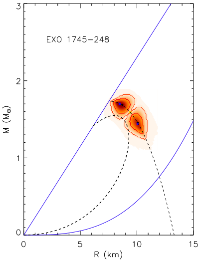


$M - R$ Probability Estimates from PRE Bursts

$R_{ph} = R$

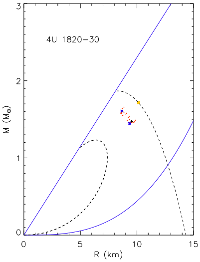
EXO 1745-248

$\alpha = 0.14 \pm 0.01$



4U 1820-30

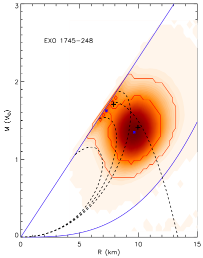
$\alpha = 0.18 \pm 0.02$



$R_{ph} > R$

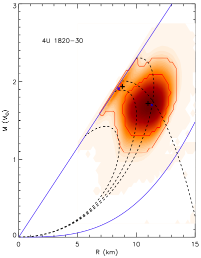
EXO 1745-248

$\alpha = 0.14 \pm 0.01$



4U 1820-30

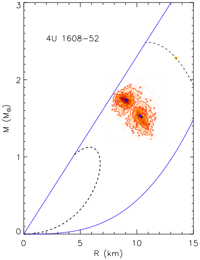
$\alpha = 0.18 \pm 0.02$



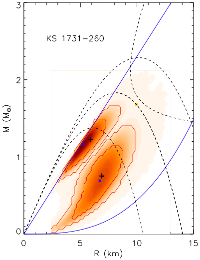
Özel et al. 2009, 2010, 2011

4U 1608-52

$\alpha = 0.26 \pm 0.10$



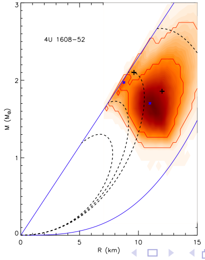
$\alpha = 0.21 \pm 0.06$



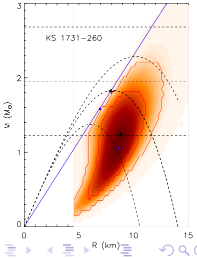
Steiner, Lattimer & Brown 2010, 2011

4U 1608-52

$\alpha = 0.26 \pm 0.10$

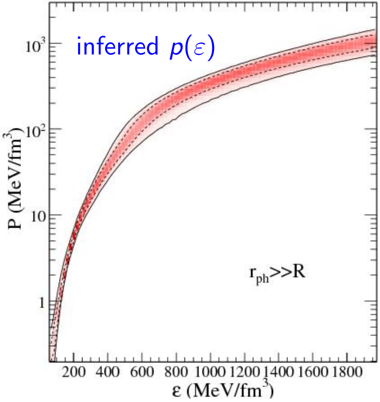


$\alpha = 0.21 \pm 0.06$

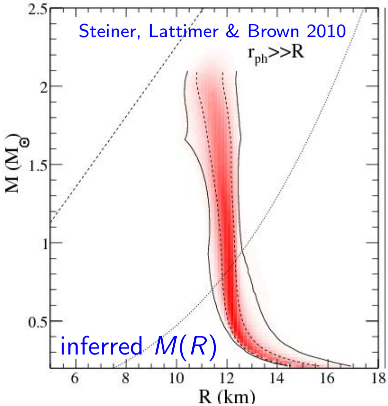


Bayesian TOV Inversion

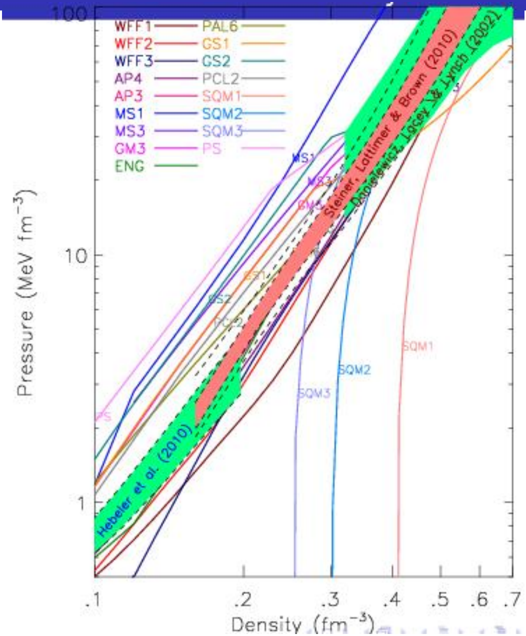
- $\varepsilon < 0.5\varepsilon_0$: Known crustal EOS
- $0.5\varepsilon_0 < \varepsilon < \varepsilon_1$: EOS parametrized by K, K', S_v, γ
- $\varepsilon_1 < \varepsilon < \varepsilon_2$: n_1; $\varepsilon > \varepsilon_2$: Polytropic EOS with n_2



- EOS parameters $(K, K', S_v, \gamma, \varepsilon_1, n_1, \varepsilon_2, n_2)$ uniformly distributed
- M and R probability distributions for 7 neutron stars treated equally.



Consistency with Neutron Matter and Heavy-Ion Collisions



Urca Processes

Gamow & Schönberg proposed the direct Urca process: nucleons at the top of the Fermi sea beta decay.
$n \to p + e^- + \nu_e$,
$p \to n + e^+ + \bar{\nu}_e$

Energy conservation guaranteed by beta equilibrium
$\mu_n - \mu_p = \mu_e$

Momentum conservation requires $|k_{Fn}| \le |k_{Fp}| + |k_{Fe}|$.

Charge neutrality requires $k_{Fp} = k_{Fe}$, therefore $|k_{Fp}| \ge 2|k_{Fn}|$.

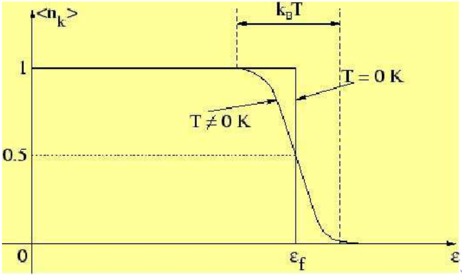
Degeneracy implies $n_i \propto k_{Fi}^3$, thus $x \ge x_{DU} = 1/9$.

With muons
$(n > 2n_s), x_{DU} = \frac{2}{2+(1+2^{1/3})^3} \simeq 0.148$

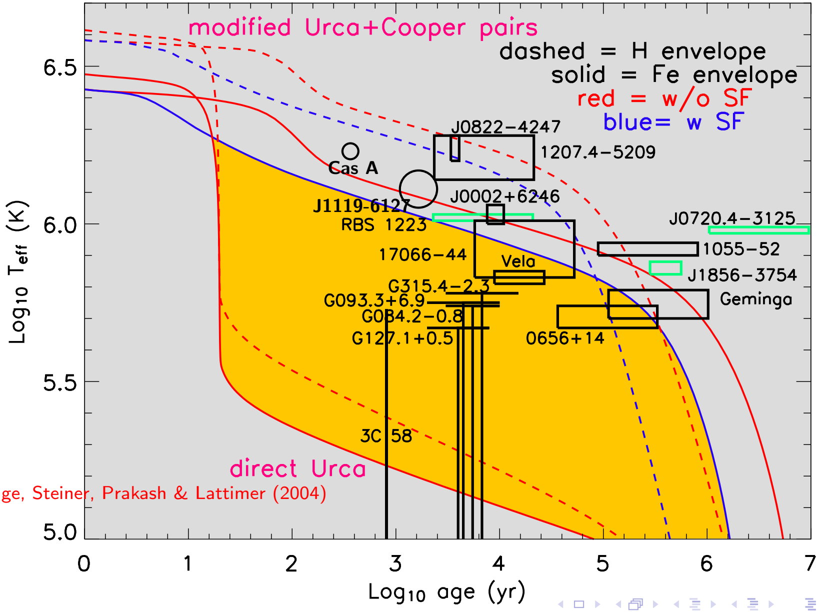
If $x < x_{DU}$, bystander nucleons needed: modified Urca process.
$(n,p) + n \to (n,p) + p + e^- + \nu_e$,
$(n,p) + p \to (n,p) + n + e^+ + \bar{\nu}_e$

Neutrino emissivities:
$\dot{\epsilon}_{MU} \simeq (T/\mu_n)^2 \dot{\epsilon}_{DU} \sim 10^{-6} \dot{\epsilon}_{DU}$.

Beta equilibrium composition:
$$x_\beta \simeq (3\pi^2 n)^{-1} (4E_{sym}/\hbar c)^3 \simeq 0.04 (n/n_s)^{0.5-2} \ .$$



Neutron Star Cooling



Transitory Rapid Cooling

MU emissivity: $\dot{\varepsilon}_{MU} \propto T^8$

PBF emissivity ($f \sim 10$):
$\dot{\varepsilon}_{PBF} \propto F(T)\ T^7 \propto T^8 \simeq f\dot{\varepsilon}_{MU}$

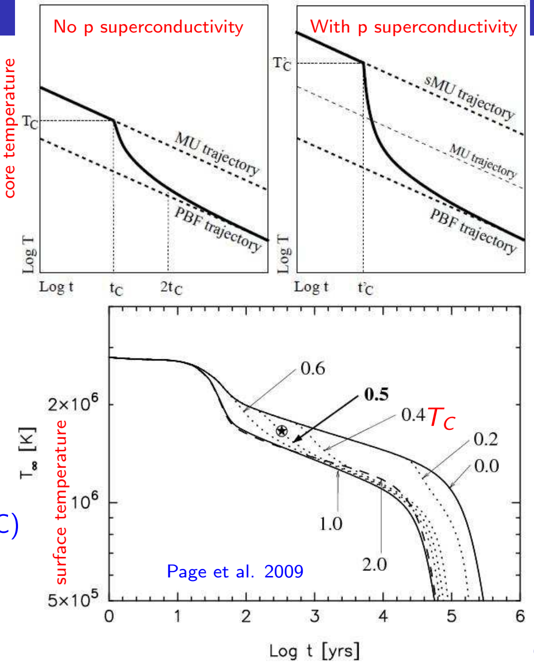
Specific heat: $C_V \propto T$

Neutrino dominated cooling:
$C_V dT/dt = -L_\nu$

$\implies T \propto (t/\tau)^{-1/6}$
$\tau_{PBF} = \tau_{MU}/f$

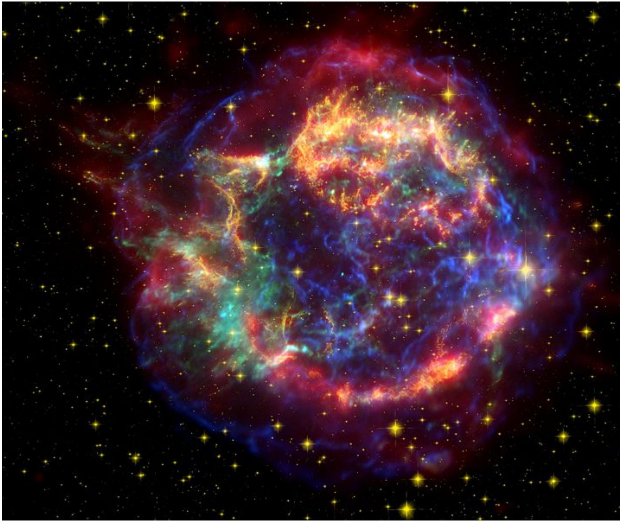
$(d\ln T/d\ln t)_{transitory}$
$\simeq (1-10)(d\ln T/d\ln t)_{MU}$
$\simeq (1-25)(d\ln T/d\ln t)_{MU}$ (p SC)

Very sensitive to n $^1S_0$ critical temperature (T_C) and existence of proton superconductivity



Cas A

- Remnant of Type IIb (gravitational collapse, no H envelope) SN in 1680 (Flamsteed).
- 3.4 kpc distance
- 3.1 pc diameter
- Strongest radio source outside solar system, discovered in 1947.
- X-ray source detected (Aerobee flight, 1965)
- X-ray point source detected (Chandra, 1999)
- 1 of 2 known CO-rich SNR (massive progenitor and neutron star?)



Spitzer, Hubble, Chandra

Cas A Superfluidity

X-ray spectrum indicates thin C atmosphere, $T_e \sim 1.7 \times 10^8$ K (Ho & Heinke 2009)

10 years of X-ray data show cooling at the rate $\frac{d \ln T_e}{d \ln t} = -1.23 \pm 0.14$ (Heinke & Ho 2010)

Modified Urca: $\left(\frac{d \ln T_e}{d \ln t}\right)_{MU} \simeq -0.08$

We infer that $T_C \simeq 5 \pm 1 \times 10^8$ K $T_C \propto (t_C L / C_V)^{-1/6}$