Neutron stars/pulsars with THEIA

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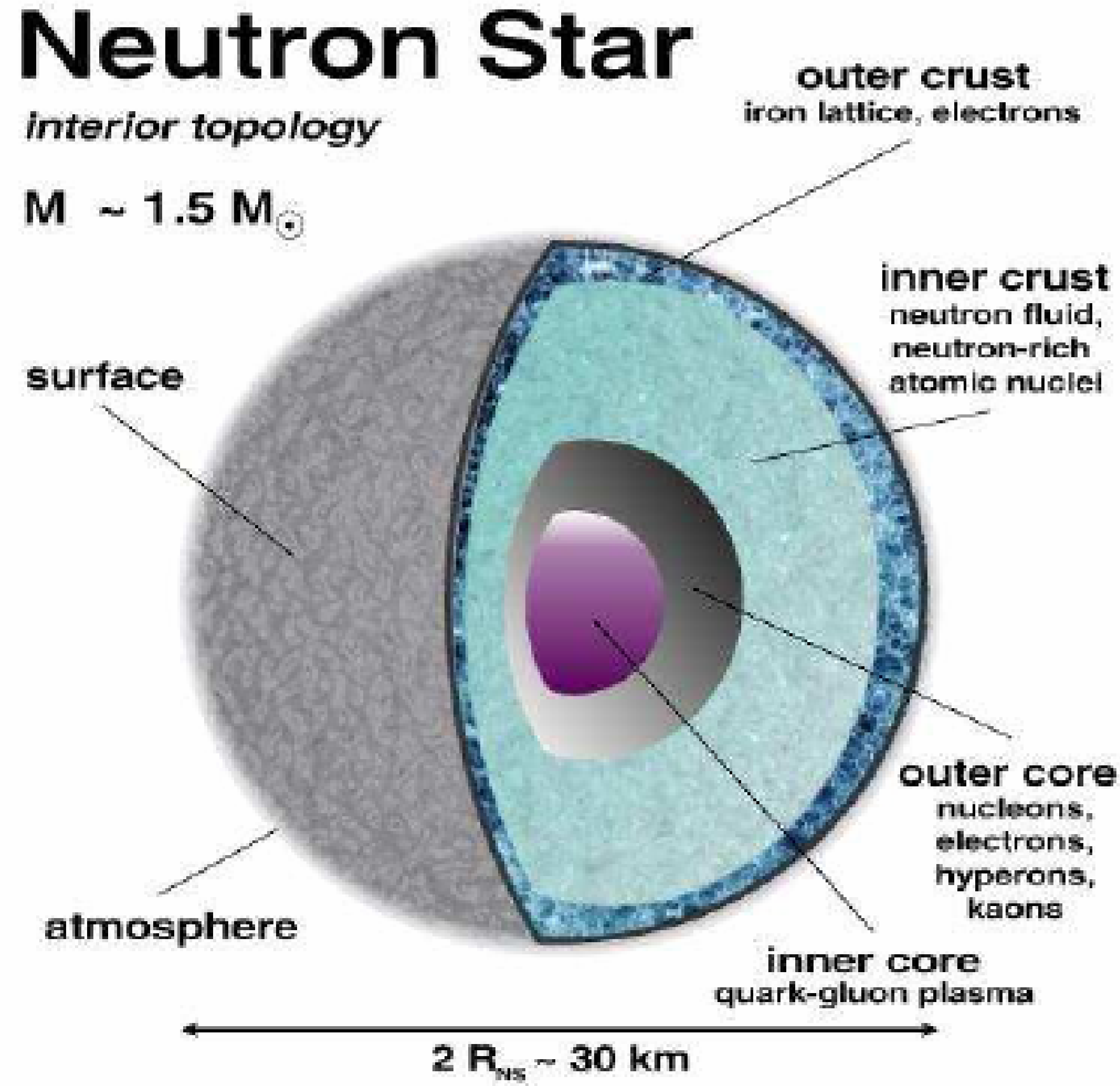


Neutron Star
interior topology
M ~ 1.5 M⊙
outer crust
iron lattice, electrons
inner crust
neutron fluid,
neutron-rich
atomic nuclei
surface
outer core
nucleons,
electrons,
hyperons,
kaons
atmosphere
inner core
quark-gluon plasma
2 R_NS ~ 30 km

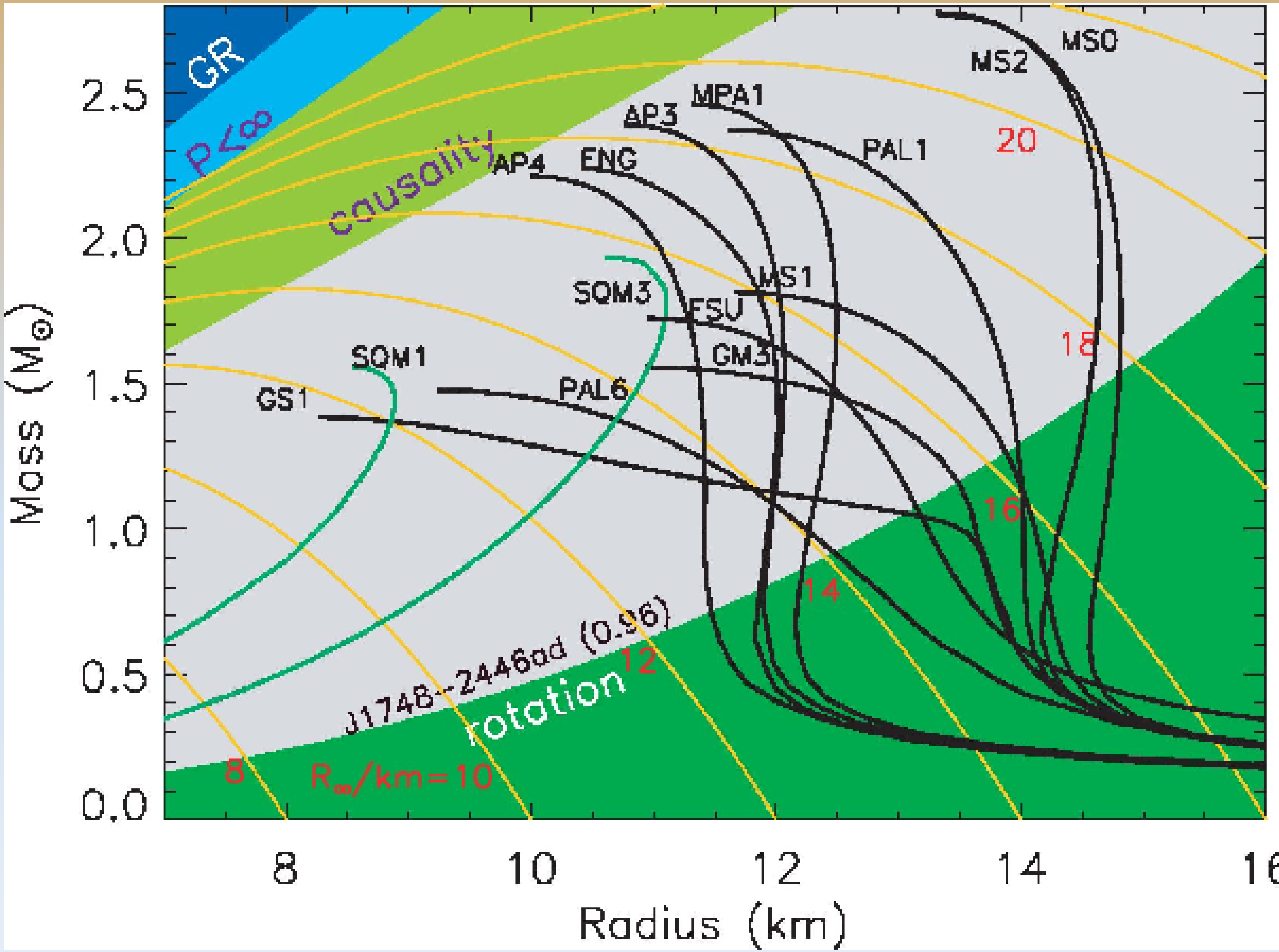
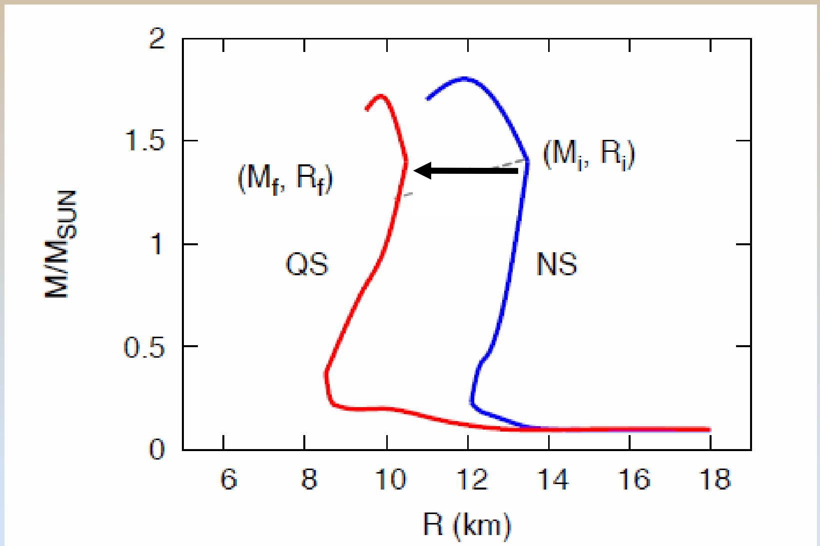
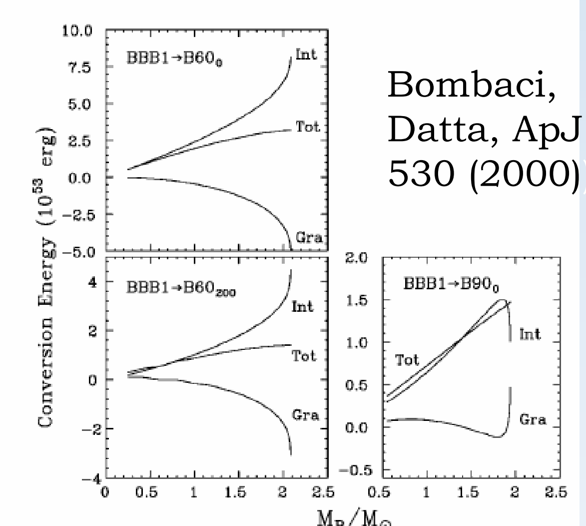


Fig courtesy of J. Lattimer

Mass and radius determination



Perez-Garcia, Daigne, Silk, ApJ (2012)



Bombaci, Datta, ApJ 530 (2000)

- Major goal:
- Simultaneous Mass and Radius determination
- I.e. Hybrid vs pure neutron stars
- Transition to partial Quark content, Perez-Garcia, Silk, Stone PRL 105, 141101 (2010)

$$\Delta E \approx G M_{NS}^2 \left(\frac{1}{R_{QS}} - \frac{1}{R_{NS}} \right) \approx 10^{53} \quad erg$$

NS vs QS

- Baryons vs deconfined quark content
- Finite strangeness content
- Energetically possible (Itoh' 1970)
- Characteristic M vs R relation (dashed curve)
- Smaller radius

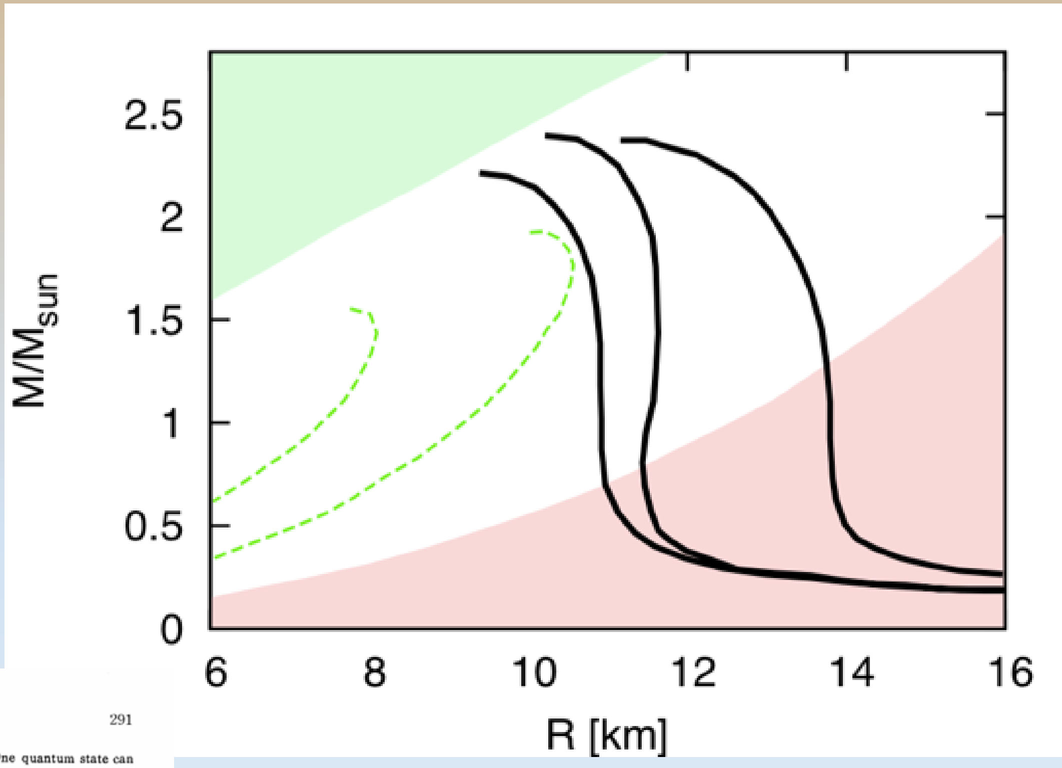
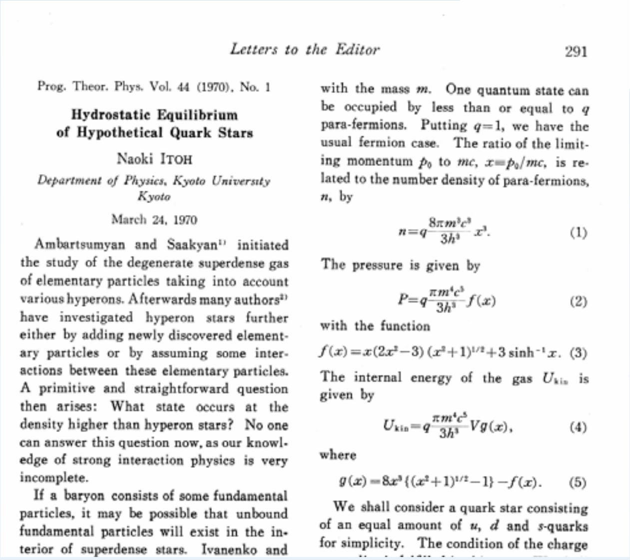


Fig 1-Previous proposal Theia



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Hydrostatic Equilibrium of Hypothetical Quark Stars

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Department of Physics, Kyoto University Kyoto

March 24, 1970

Ambartsumyan and Saakyan[1] initiated the study of the degenerate superdense gas of elementary particles taking into account various hyperons. Afterwards many authors[2] have investigated hyperon stars further either by adding newly discovered elementary particles or by assuming some interactions between these elementary particles. A primitive and straightforward question then arises: What state occurs at the density higher than hyperon stars? No one can answer this question now, as our knowledge of strong interaction physics is very incomplete.

If a baryon consists of some fundamental particles, it may be possible that unbound fundamental particles will exist in the interior of superdense stars. Ivanenko and

with the mass m. One quantum state can be occupied by less than or equal to q para-fermions. Putting $q=1$, we have the usual fermion case. The ratio of the limiting momentum p_0 to mc, $x=p_0/mc$, is related to the number density of para-fermions, n, by

$$n=q\frac{8\pi m^3c^3}{3h^3}x^3. \quad (1)$$

The pressure is given by

$$P=q\frac{\pi m^4c^5}{3h^3}f(x) \quad (2)$$

with the function

$$f(x)=x(2x^2-3)(x^2+1)^{1/2}+3\sinh^{-1}x. \quad (3)$$

The internal energy of the gas U_{kin} is given by

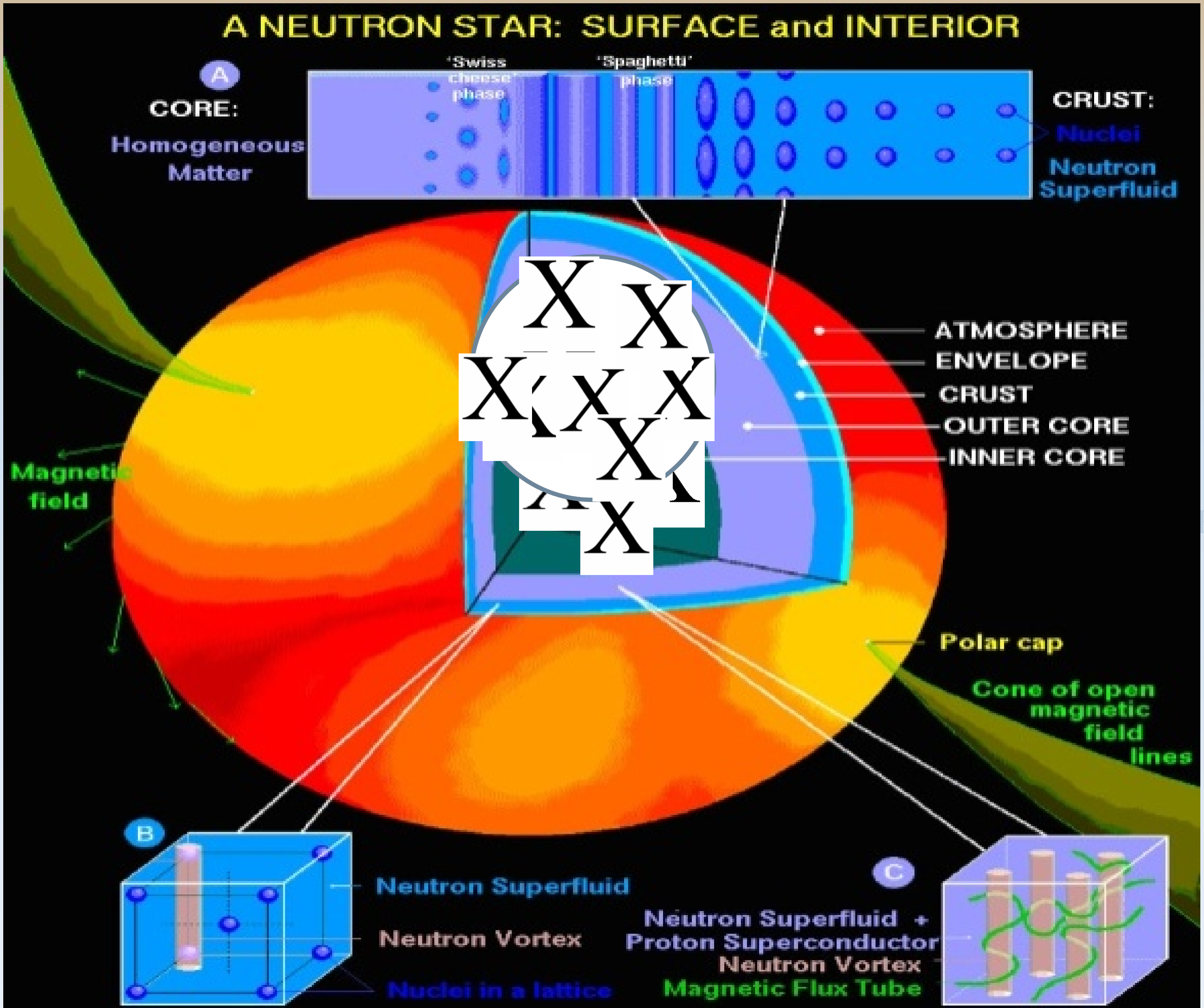
$$U_{kin}=q\frac{\pi m^4c^5}{3h^3}Vg(x), \quad (4)$$

where

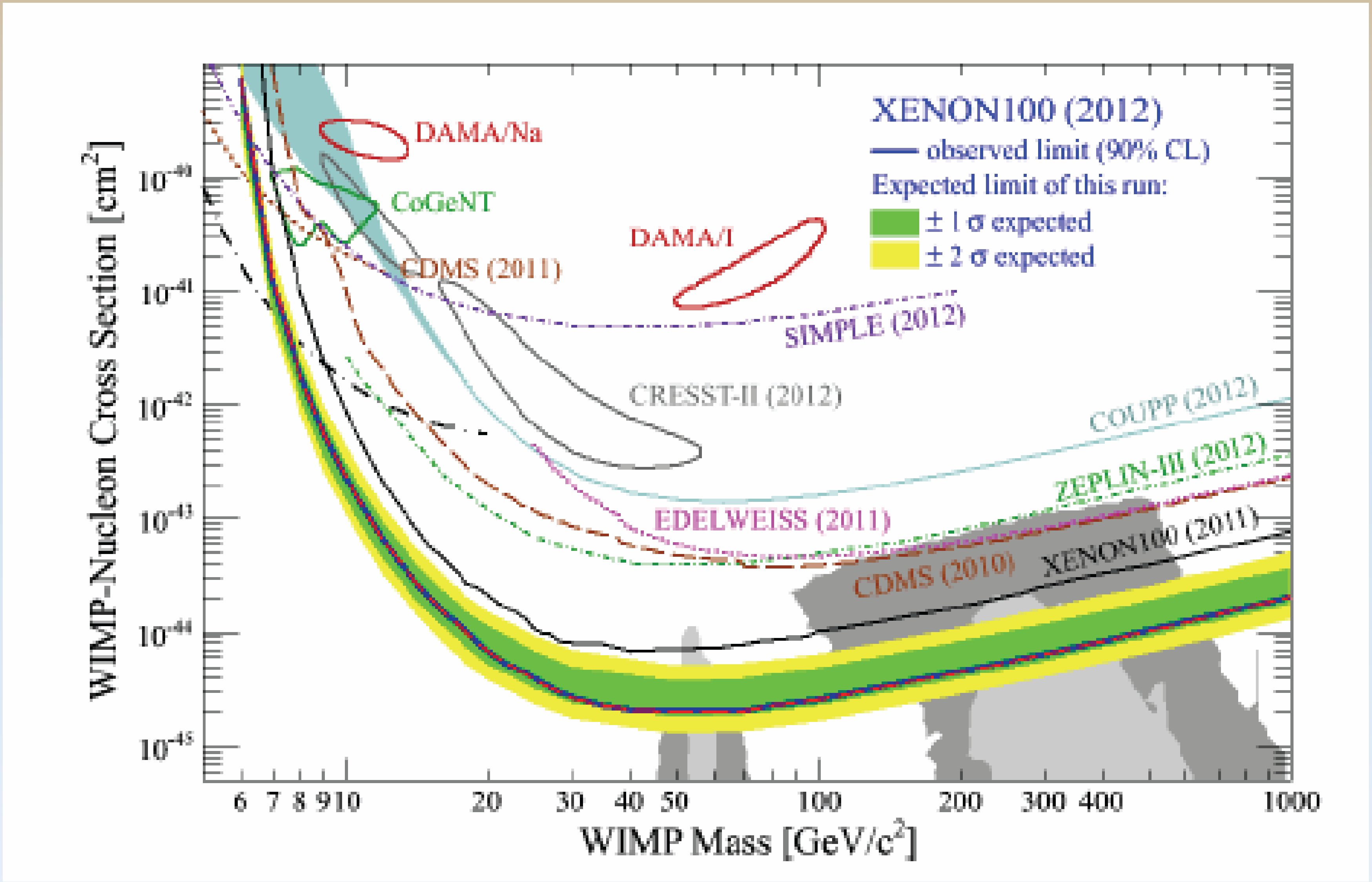
$$g(x)=8x^3\{(x^2+1)^{1/2}-1\}-f(x). \quad (5)$$

We shall consider a quark star consisting of an equal amount of u, d and s-quarks for simplicity. The condition of the charge

UCO and Dark Matter sections are related..



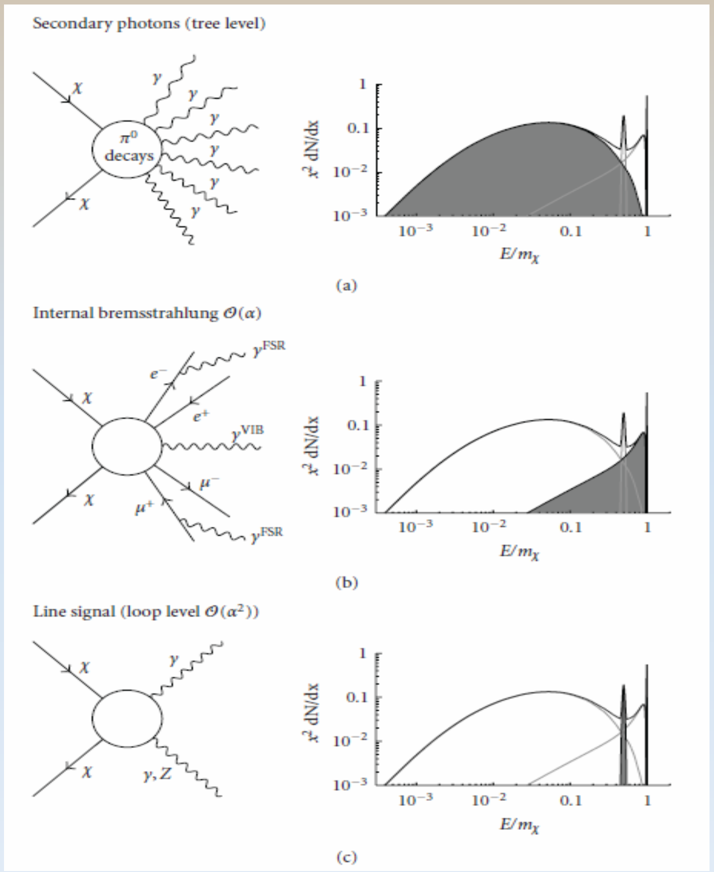
Dark matter direct search

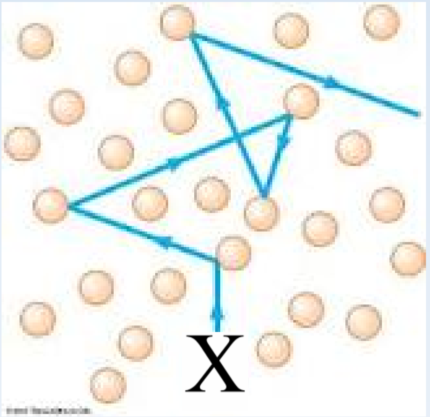


NS opaque to Dark Matter

The efficiency of NS to capture DM is much larger than for the sun since:

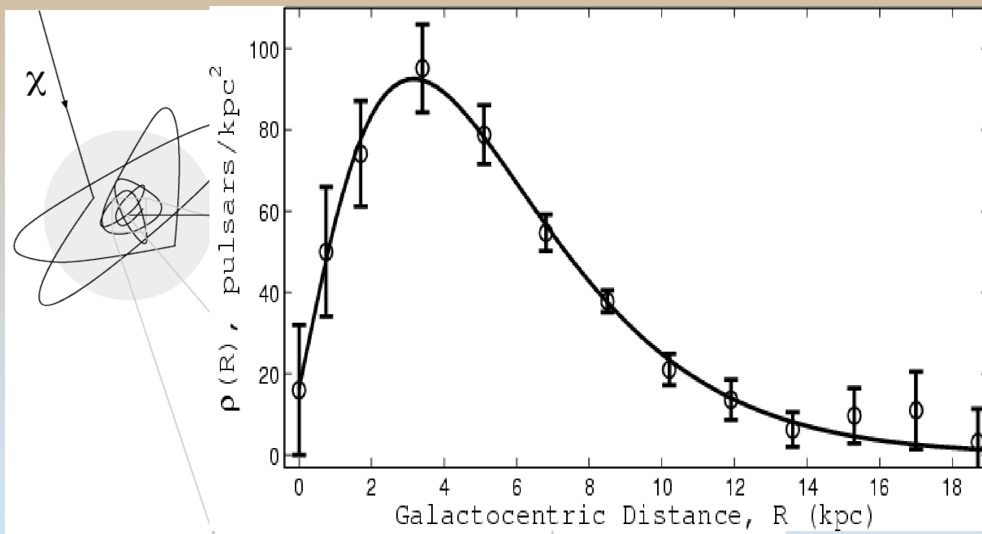
Magnitude	Sun	Neutron star
Central mass density [g/cc]	10^2	10^{14}
Mean free path [1/σn] cm	10^{14}	100
Capture rate [s^{-1}]	10^{23}	10^{25}

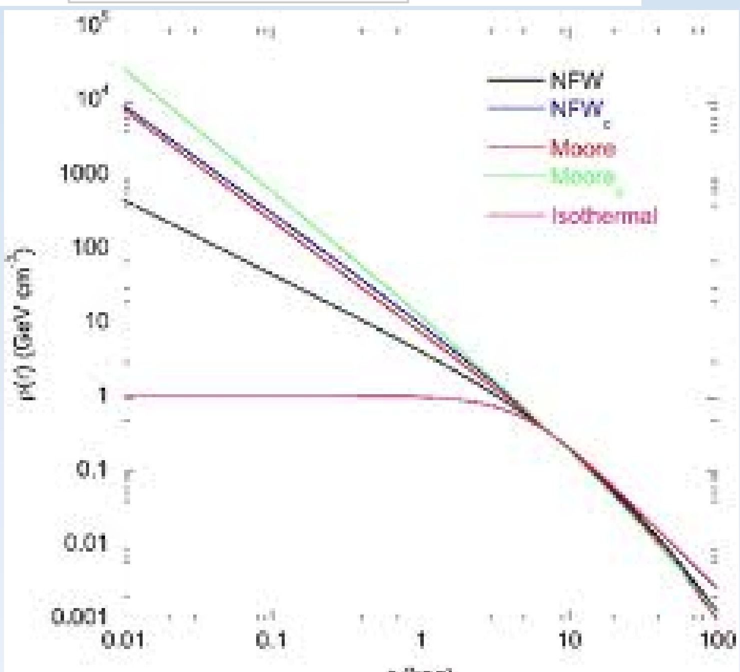




•DM can be accreted from galactic profile by many massive astrophysical objects [Goldman, Nussinov, Press, Spergel, Kouvaris, Lavallaz, Fairbairn, Silk, Stone, Bramante, Zurek, Freese, Perez-Garcia..]

Engine model: NS accretor of DM





- Pulsar profile peaks at ~3 Kpc
- DM particle could be accreted from the galactic halo
- A number of DM profiles can provide a density of local solar (~8 Kpc)

$\rho_{DM,0} \approx 0.3\ \ GeV/c^2$

$$F = \frac{3.042\ \ 10^{25}}{m_X(GeV)} \rho_{DM} \Big/ \rho_{DM,0} \ (s^{-1})$$

Theia proposal: amplitudes

A system at distance *D* made of two objects of 1 Solar mass each, one being a main sequence star and the other a compact object, the astrometric amplitude is:

$$A = 150\,\mu\text{as}\left(\frac{\text{P}}{1\,\text{yr}}\right)^{2/3}\left(\frac{\text{D}}{3\,\text{Kpc}}\right)^{-1} \qquad (1)$$

Theia previous proposal

The HMXBs usually have longer orbital periods, P: days to hundreds of days (about 1 yr).

The LMXBs are more compact, P range from tens of minutes to several hours. Y. Chou, arXiv:1408.6638v2., Q. Liu A&A 469, 807(2007)
[XMM, Chandra, INTEGRAL data]

Theia proposal: accuracy Mass

A Sun-like star at 3 Kpc has an apparent magnitude R = 17.

The uncertainty of a Theia observation, 10 visits, 4 h each (~ 0.2% of the total mission time), for a R = 17 object is 5 μas (1 σ)

signal to noise S/N = 30 measurement of the astrometric signal

3% accuracy in measurement of the mass of a compact object located 3 kpc with a 1 yr orbital period.

Minimum Mass for NS: 0.2 M sun →no min for QS

Theia proposal: accuracy Radius

At the distance of 3 kpc, the parallax of objects is 300 μas.

For a R = 17 object, the distance will be measured with a 1.5% accuracy.

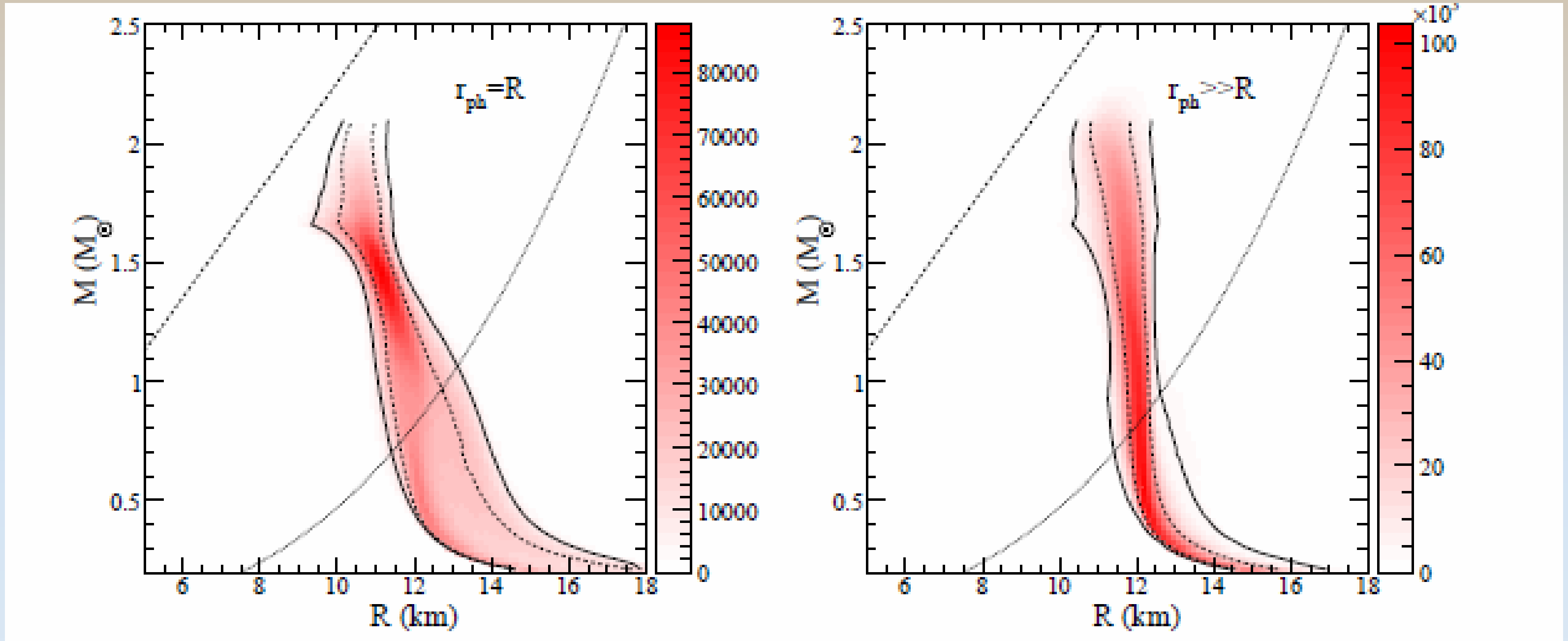
Accurate knowledge of the distance, combined with X-ray measurements of the effective temperature, T_{eff}^{∞}

T_{eff}^{∞} *is* gravitationally red-shifted.

Derived bolometric flux, *Fbol*, provides *a* measurement of the radius,

$$R^{\infty} = D \left(\frac{F_{bol}^{\infty}}{\sigma_{SB} T_{eff}^{4}} \right)^{1/2}$$

M vs R and EOS



They use three Type-I X-ray bursters with photospheric radius expansion, and three transient low-mass X-ray binaries.

Steiner et al, Astrophysical Journal 722 (2010)

M vs R and bursting/quiescent LMXBs

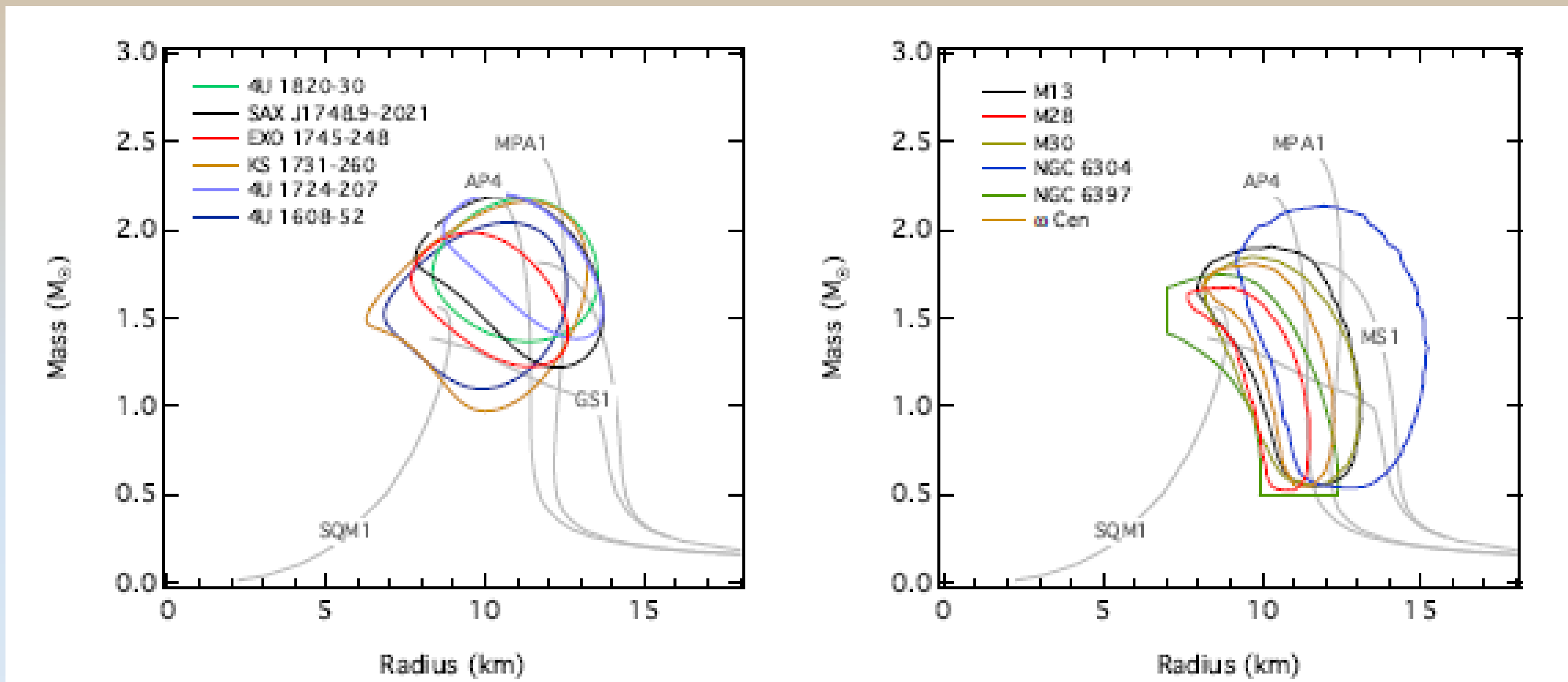


TABLE 2
PROPERTIES OF QUIESCENT LMXBs

Source	N_H[a] (10^{22} cm^{-2})	kT_{eff} (eV)	P.L. Norm.[b] (10^{-7}keV^{-1}s^{-1}cm^{-2})	Distance[c] (kpc)
M13	$0.01^{+0.08}_{-0.01}$	82^{+26}_{-10}	$3.9^{+3.8}_{-3.0p}$	7.1 ± 0.4[1]
M28	$0.25^{+0.03}_{-0.02}$	123^{+41}_{-10}	$8.3^{+4.8}_{-4.6p}$	5.5 ± 0.3[2]
M30	$0.01^{+0.03}_{-0.01}$	98^{+31}_{-12}	$8.6^{+8.2}_{-8.1p}$	9.0 ± 0.5[3,4]
ωCen	$0.13^{+0.04}_{-0.03}$	77^{+24}_{-8}	$0.9^{+1.3}_{-0.7p}$	4.59 ± 0.08[5,6]
NGC 6304	$0.38^{+0.11}_{-0.10}$	97^{+30}_{-11}	$2.5^{+2.7}_{-2.0p}$	6.22 ± 0.26[7]
NGC 6397	$0.12^{+0.01}_{-0.01}$	76^{+14}_{-7}	$4.1^{+2.0}_{-2.0}$	$2.44 - 2.58$[8]

[a] The hydrogen column density is fixed at the best-fit value when calculating confidence contours over the neutron star mass and radius, except for NGC 6397, see Heinke et al. (2014).
[b] Subscript p indicates that the posterior likelihood did not converge to zero within the hard limit of the model.
[c] References: 1. Harris et al. (1996, 2010 revision); 2. Servillat et al. (2012); 3. Carretta et al. (2000); 4. Lugger et al. (2007); 5. Watkins et al. (2013); 6. see also the discussion in Heinke et al. (2014); 7. Guillot et al. (2013) and references therein; 8. Heinke et al. (2014)

reason why the masses and radii they infer for 4U 1608−52 are very different between the bursts they consider (see their Figure 8) and their net result is marginally consistent with the independently measured distance to this source.

F. Ozel et al (2015), arXiv:1505.05155v1

Conclusions

- Theia can beat in accuracy in Mass and Radius determination with respect to GAIA.

- Typical binary systems with masses can provide mass accuracy to 3%, orbital period determination.

- Radius accuracy to 1.5%, bursting sources not necessary…but thermal emitters. X-ray missions.

- Complementary test to EOS → already important goal itself due to the difficulty of measurements.

- Best case scenario→ testing QS and Quark matter EOS by selecting "small candidates".