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Two massive neutron stars: The role of dark matter?

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Content

- Introduction
  - Neutron star EoSs in the light of 2 solar mass neutron star
- Motivation
- Two massive neutron star: The role of dark matter?
- Summary and next plans

The place I come from…


鳄鱼屿
三担岛

5th in China

Department of Astronomy (founded 20 days ago)

4 prof.
3 associate prof. (me included)
3 assistant prof.
11 students

Research topics:

- Black hole accretion and radiation
- Gamma-ray burst
- Formation of galaxy and large-scale structure of universe
- Dark matter theory and detection
- Neutrino physics
- Compact star

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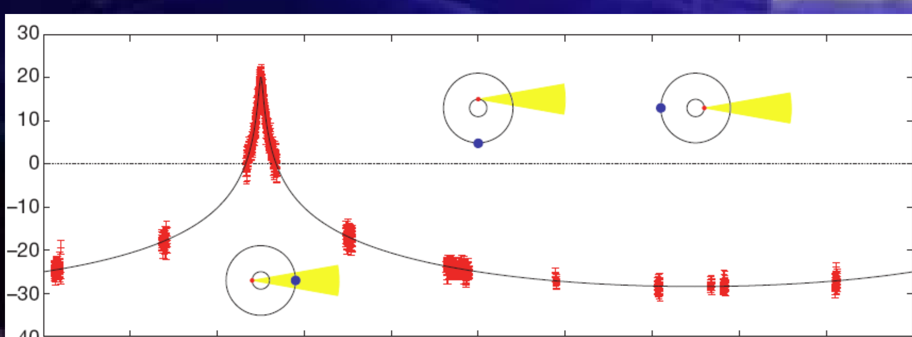
PSR J1614-2230 - A new constraint for the Compact Star EoS

- NS-WD binary in Scorpius
- NS is recycled MSP with P = 3.15 ms
- almost edge-on, inclination 89.17^o
- Shapiro delay measured!
- $M_{WD} \sim 0.5\ M_\odot$
- $M_{NS} = (1.97 \pm 0.04)\ M_\odot$



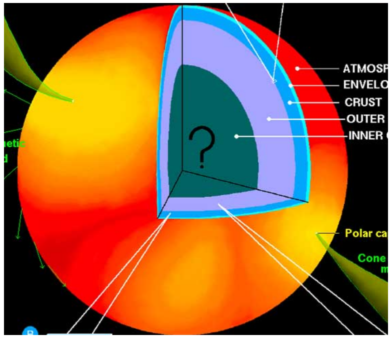
Demorest et. al, Nature, 2010

NS structure from TOV equations

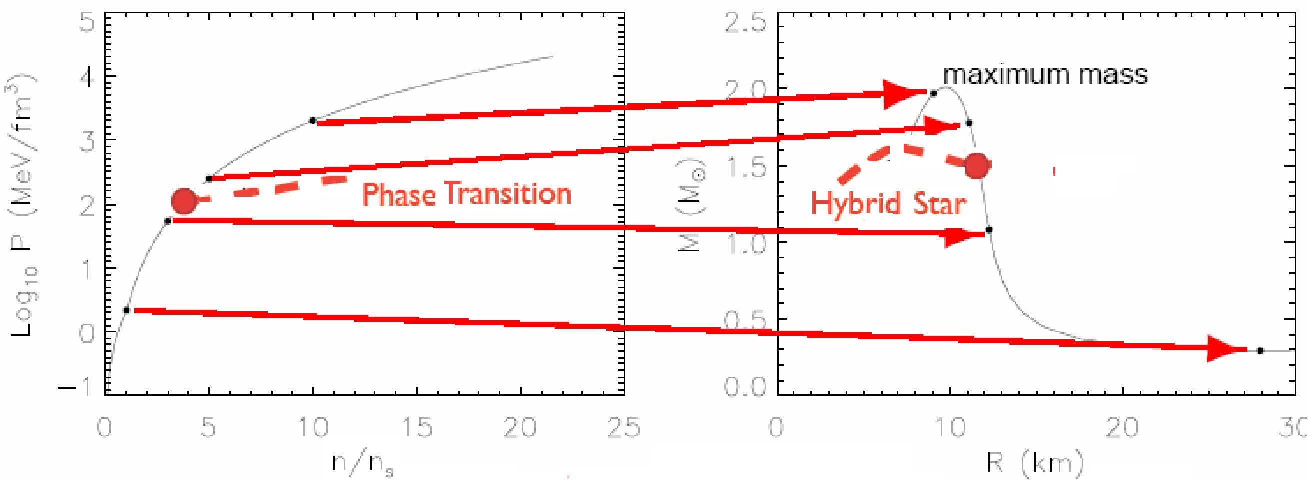
- Stable configurations from hydrostatic equilibrium TOV Eqs:

$$\frac{dp}{dr} = -\frac{[p(r)+\varepsilon(r)][M(r)+4\pi r^3 p(r)]}{r(r-2M(r))}$$

$$M(r) = 4\pi \int_0^r \varepsilon(r') r'^2 dr'$$



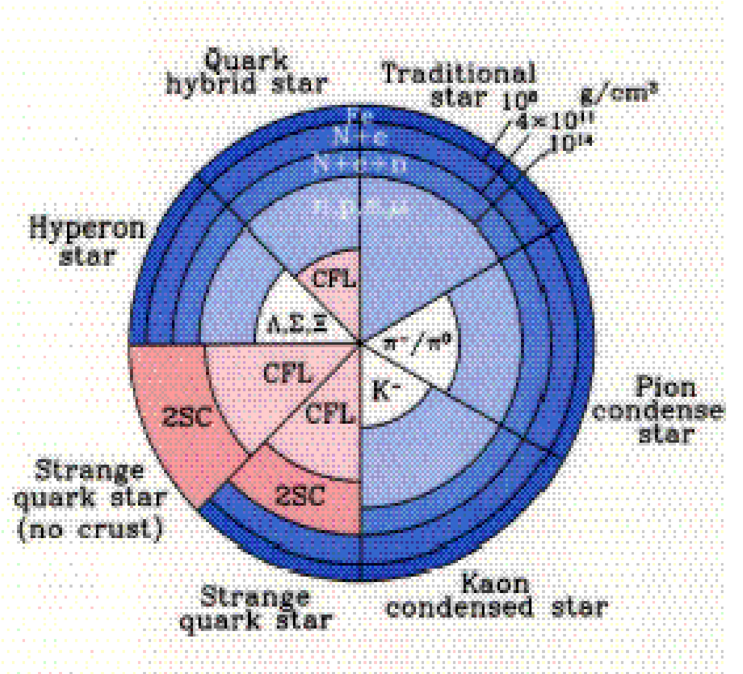
- Mass-Radius relation is unique to the underlying EoS.



- Soft EoS: low maximum mass and small radii
- Stiff EoS: high maximum mass and large radii

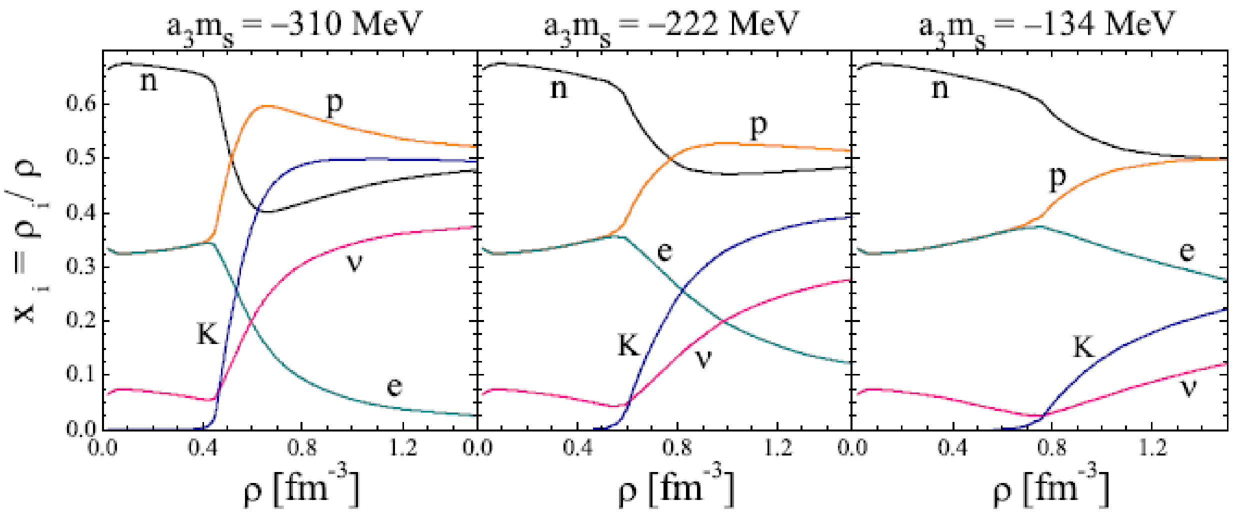
NS EoS model

- There are many;
- Mass calculation is rather independent of the details of EoS, only the stiffness matters.
- Exotic phase in NS core is unavoidable, which will soften the EoS and may make it not stiff enough to support 2 solar mass.
- Kaons? Hyperons? Quarks?



Kaons strongly disfavored

- Onset density strongly dependent on a_3m_s.



BHF + Standard chiral model for KN contribution

- a_3 corresponds to different values of the strangeness content of the proton:

$$\langle p|\bar{d}d|p\rangle \approx \langle p|\bar{u}u|p\rangle = -(a_1 + 2a_3), \quad \langle p|\bar{s}s|p\rangle = -2(a_2 + a_3)$$

The most recent lattice determination of the strangeness content of the proton indicate: **a_3m_s = -143 MeV** **(H.Ohki et al, PRD 2008).**

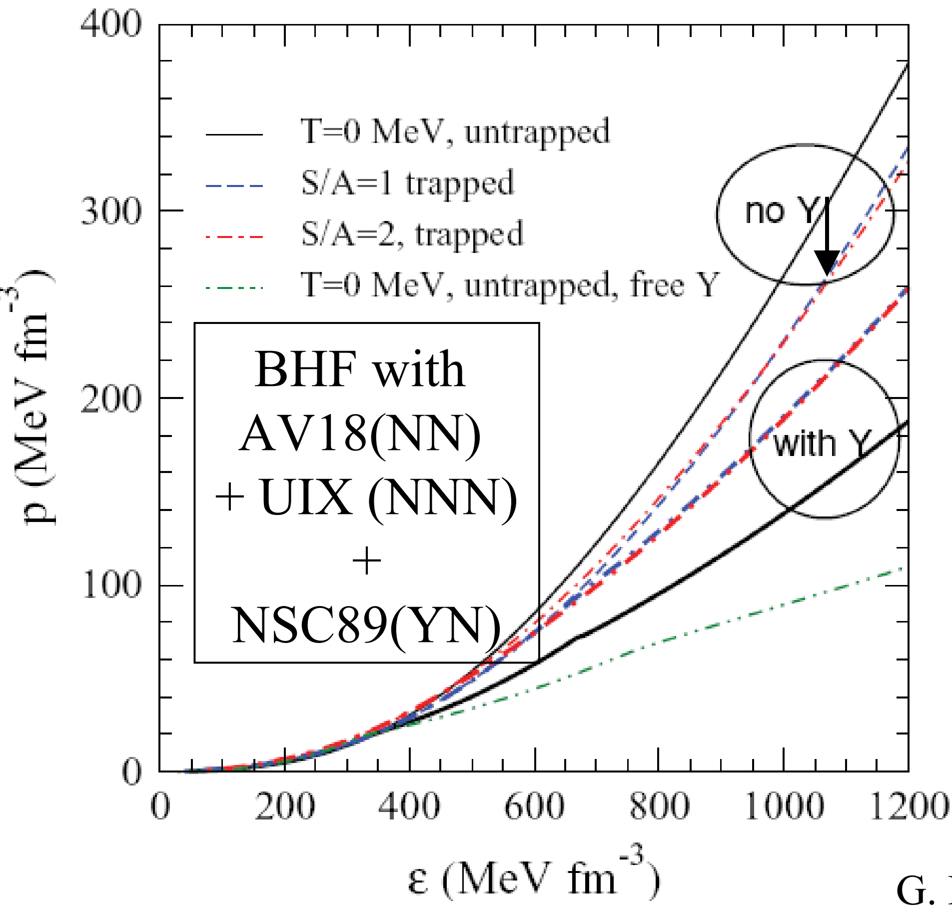
→ Fairly large onset densities; Kaons strongly disfavored!

AL, XR Zhou, F.Burgio, H.-J. Schulze, PRC2010

WZuo, AL, ZH Li, U. Lombardo, PRC2004; AL, F.Burgio, U. Lombardo, WZuo, PRC2006

NS with hyperons

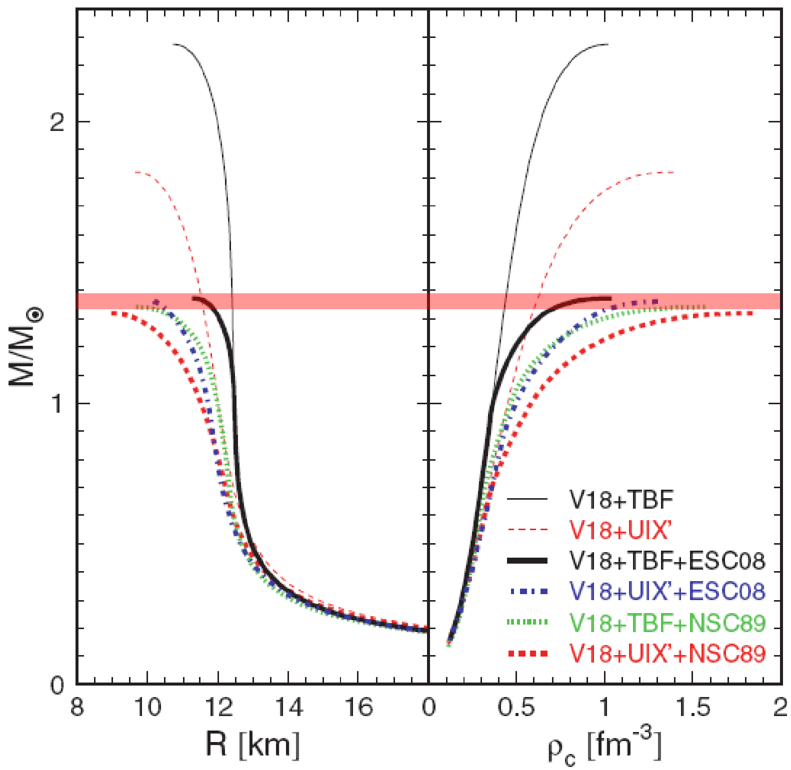
- Hyperons appear ~2ρ_0; Largerly soften the EoS.



Composition	S/A	$M/M_\odot$	R (km)	ρ_c/ρ_0
N,l	0	1.84	9.6	8.
	1	1.84	9.7	8.
	2	1.83	10.2	7.5
N,l,ν	1	1.74	9.96	8.47
	2	1.74	10.5	8.
N,Y,l	0	1.31	9.	10.8
	1	1.32	8.96	10.8
	2	1.37	9.2	10.7
N,Y,l,ν	1	1.57	10.6	8.35
	2	1.58	11.	8.

G. F. Burgio, H.-J. Schulze, AL, PRC2011

Result with the latest ESC08b hyperon interaction



< 1.4M⊙

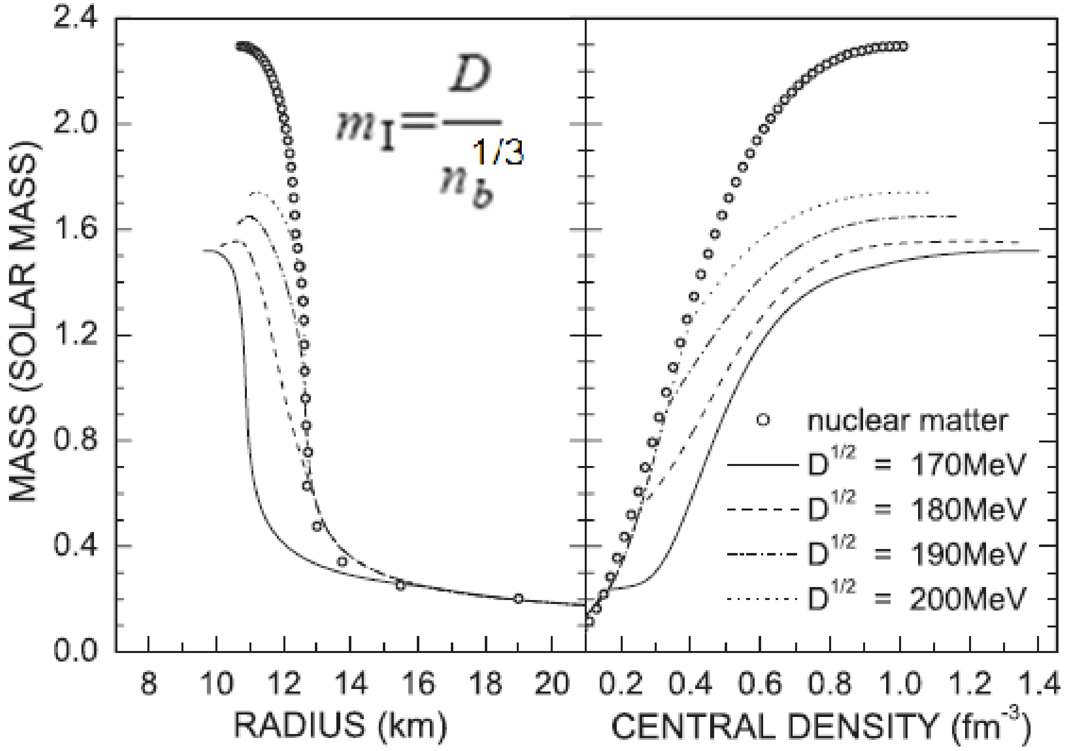
H.-J. Schulze and T. Rijken, PRC2011

- Contradiction with observed pulsar masses;
- The introduction of repulsive hyperonic TBF: ESC08c,…
- Or Massive NSs have to be hybrid stars containing a core of nonbaryonic ("quark") matter?

Hybrid star

- Only low-mass hybrid stars obtained;
- The necessity of a repulsive interaction in quark matter?
- Extend the present model to include one-glue exchange term.

BHF + Quark-mass-density-dependent (QMDD) model



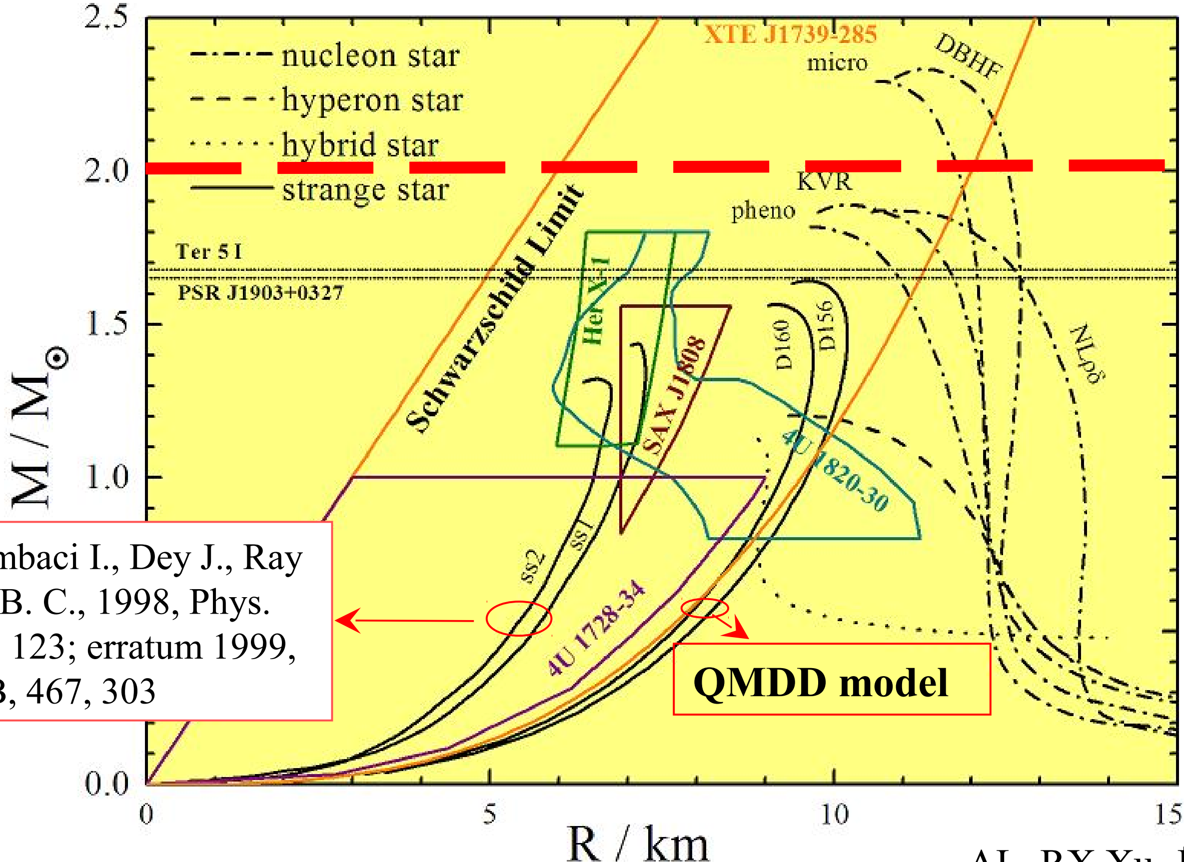
$$m_q = m_{q0} + m_I$$

$$m_I = \frac{\langle H_I \rangle}{\sum_{q=u,d,s} \left[\langle \bar{q}q \rangle_{n_b,T} - \langle \bar{q}q \rangle_0 \right]}$$

GX. Peng, AL, U. Lombardo, PRC2008

Quark star

- Rather small radius: A sign for quark star; Weber 2005
- No QS condidates supported by at least 2 models;
- In the same time fulfill the new 2 $M_{\odot}$ constrain.



Dey M., Bombaci I., Dey J., Ray S., Samanta B. C., 1998, Phys. Lett. B, 438, 123; erratum 1999, Phys. Lett. B, 467, 303

QMDD model

XTE J1739-285: The first compact star with a submillisecond spin period (*P* = 0.891ms)

Kaaret et al 2007

AL, RX Xu, JF Lu, MNRAS2010
AL, GX Peng, JF Lu, RAA 2011

A few remark

- Hyperons appear for sure, but too soft EoS;
- Need universal repulsive 3BF, or stiff quark core: Still in progress;
- One may refer to a more exotic scenario including dark matter.

Too massive neutron stars: The role of dark matter?
AL, F Huang, RX Xu, Astroparticle Physics, 2012

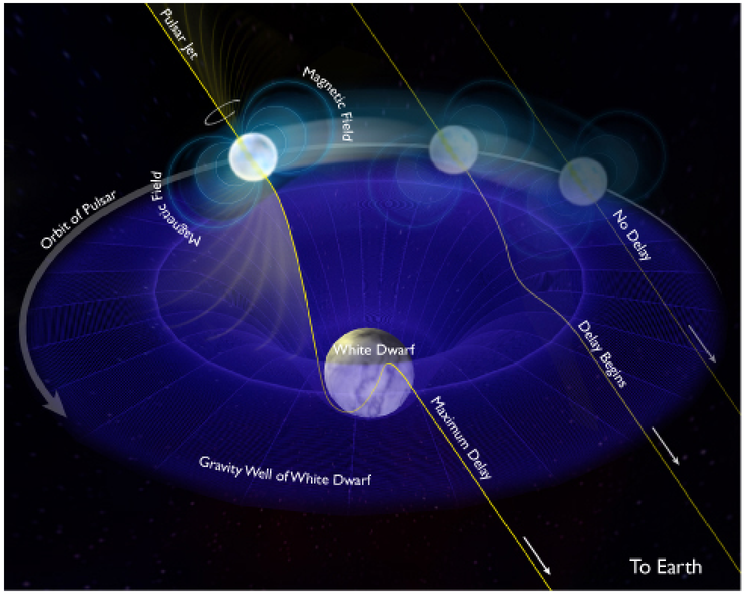
Motivation

- NS masses in NS-NS binaries are all below 1.5 solar mass;
- High-mass in NS-WD binaries may result from the supercritical accretion after NS birth;
- During accretion, DM may also accumulate inside NS;
- Through scattering with normal NS particles, DM particles lose energy and are trapped by NS.
- “DM-admixed NS”.

M.A. Perez-Garcia, J. Silk, J.R. Stone, Phys. Rev. Lett. 105 (2010) 141101.
S.-C. Leung, M.-C. Chu, L.-M. Lin, Phys. Rev. D 84 (2011) 107301.
P. Ciarcelluti, F. Sandin, Phys. Lett. B 695 (2011) 19.
I. Goldman, APPB 42 (2011) 2203.
F. Sandin, P. Ciarcelluti, Astropart. Phys. 32 (2009) 278.
G. Bertone, M. Fairbairn, Phys. Rev. D 77 (2008) 043515.
C. Kouvaris, Phys. Rev. D 77 (2008) 023006.
C. Kouvaris, P. Tinyakov, Phys. Rev. D 82 (2010) 063531.
A. de Lavallaz, M. Fairbairn, Phys. Rev. D 81 (2010) 123521.

Motivation (2)

- Radius not well-determined;
- Heavy DM particles usually do not collapse with the ordinary matter, an extended halo around the star may be formed;
- There should exist an extra general-relativistic mass effect from the halo;
- Is NS mass overestimated?



P. Demorest, T. Pennucci, S. Ransom, M. Roberts, J. Hessels, Nature 467 (2010) 1081.
G. Steigman, C.L. Sarazin, H. Quintana, J. Faulkner, ApJ 83 (1978) 1050.
W.H. Press, D.N. Spergel, ApJ 296 (1985) 679.

The role of DM inside NS

- Approximate DM inside the star as self-interacting Fermi gas.

$$P = P_N + P_\chi,\ \mathcal{E} = \mathcal{E}_N + \mathcal{E}_\chi$$

$$\mathcal{E}_\chi = \frac{m_\chi^4}{\pi^2}\int_0^{k_F/m_\chi} x^2\sqrt{1+x^2}dx + \left(\frac{1}{3\pi^2}\right)^2\frac{k_F^6}{m_I^2},$$

$$P_\chi = \frac{m_\chi^4}{3\pi^2}\int_0^{k_F/m_\chi} \frac{x^4}{\sqrt{1+x^2}}dx + \left(\frac{1}{3\pi^2}\right)^2\frac{k_F^6}{m_I^2},$$

$\boldsymbol{m_\chi}$ mass of DM particles

$\boldsymbol{k_F}$ Fermi momentum $k_F = (3\pi^2\rho)^{1/3}$

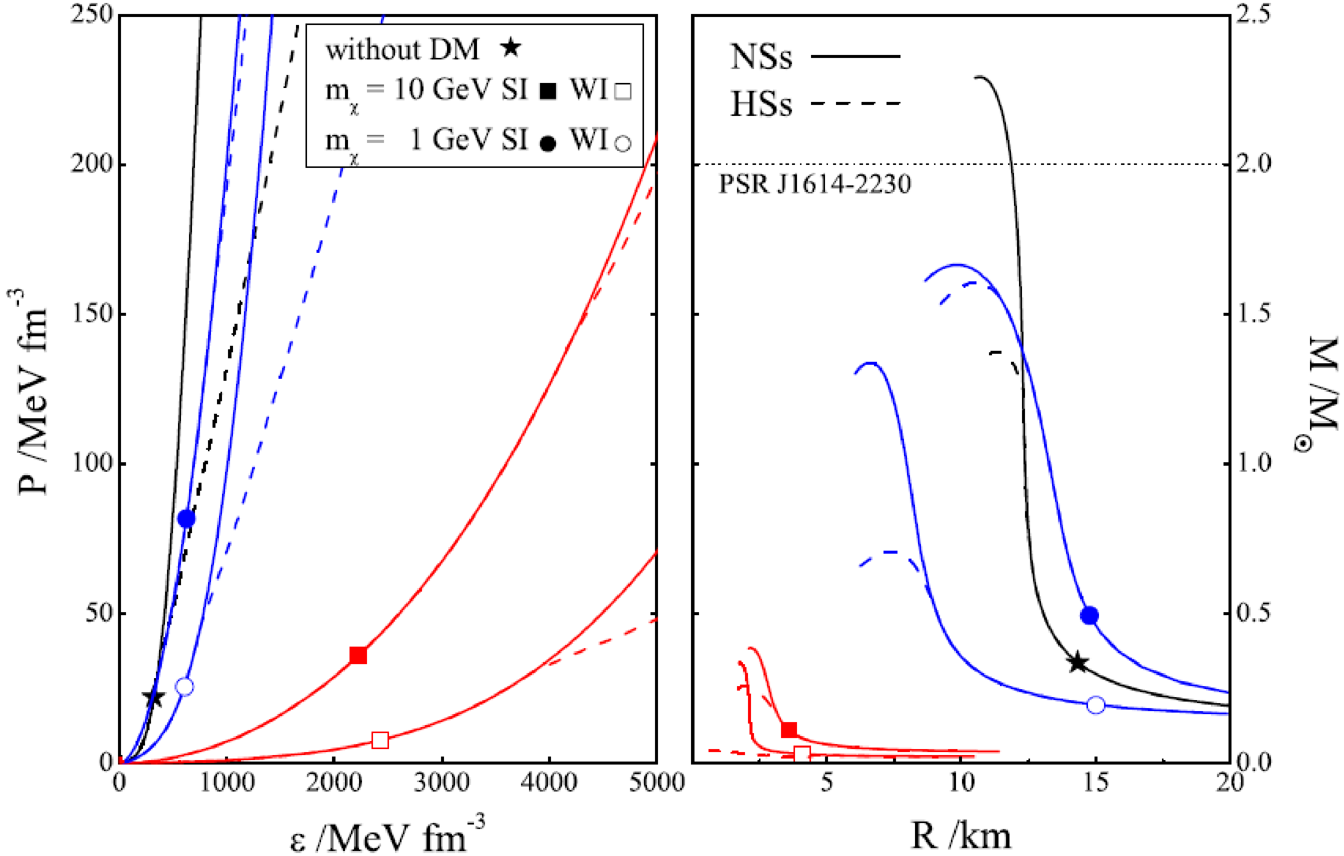
$\boldsymbol{m_I}$ Energy scale of the interaction

(SI:100MeV ~ WI: 300GeV)

G. Narain, J. Schaffner-Bielich, I.N. Mishustin, Phys. Rev. D 74 (2006) 063003.

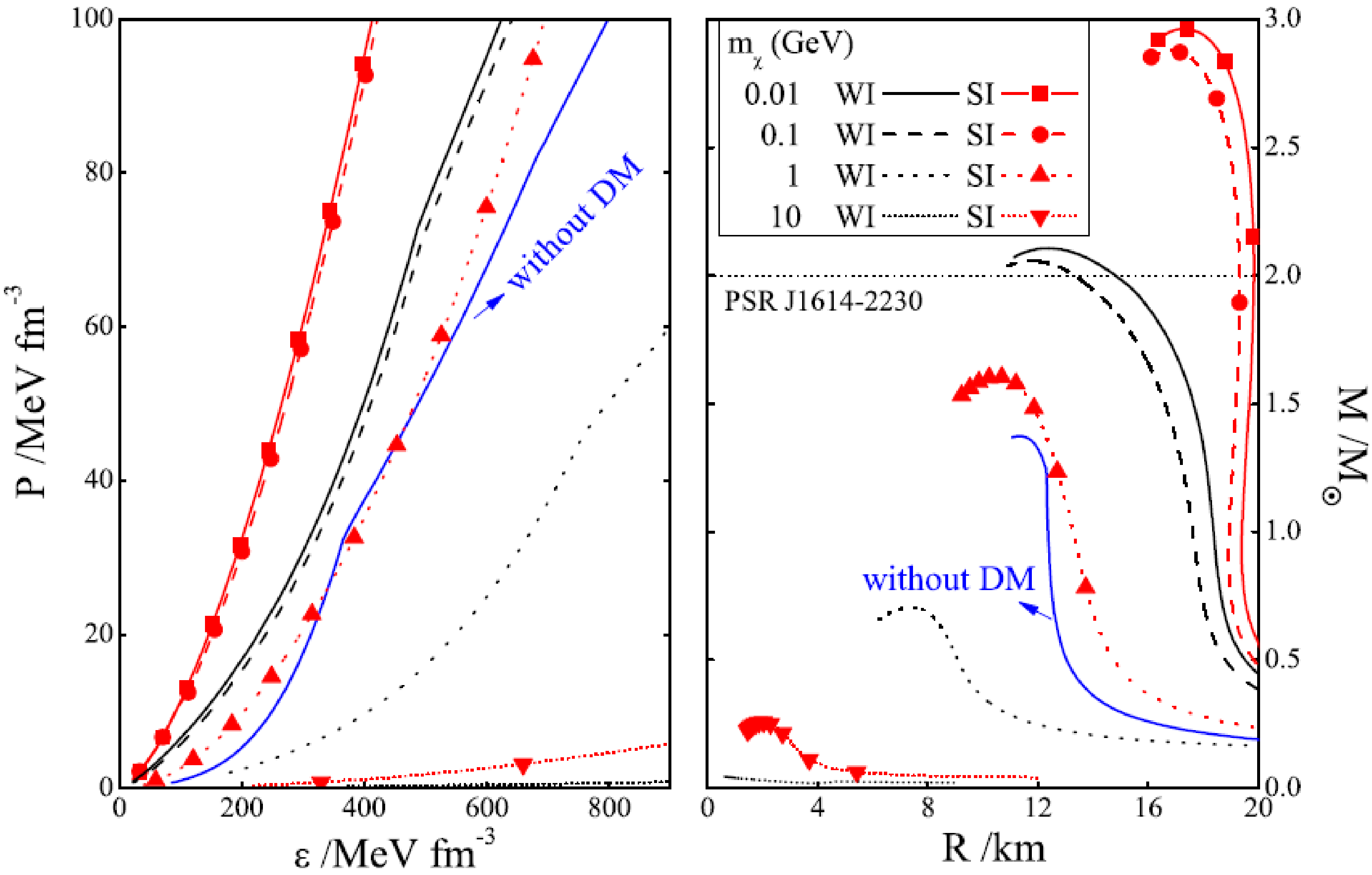
DM-admixed NS

- DM further soften EoS, as expected;
- However, NS/HS mass is sensitive to DM particle mass m_χ .



DM-admixed NS

- Achieve 2 solar mass HS with a small DM particle mass m_χ.



The role of DM halo outside for PSR J1614 2230

- We estimate the size of the halo as big as that of the possible Roche lobe of the centered NS;

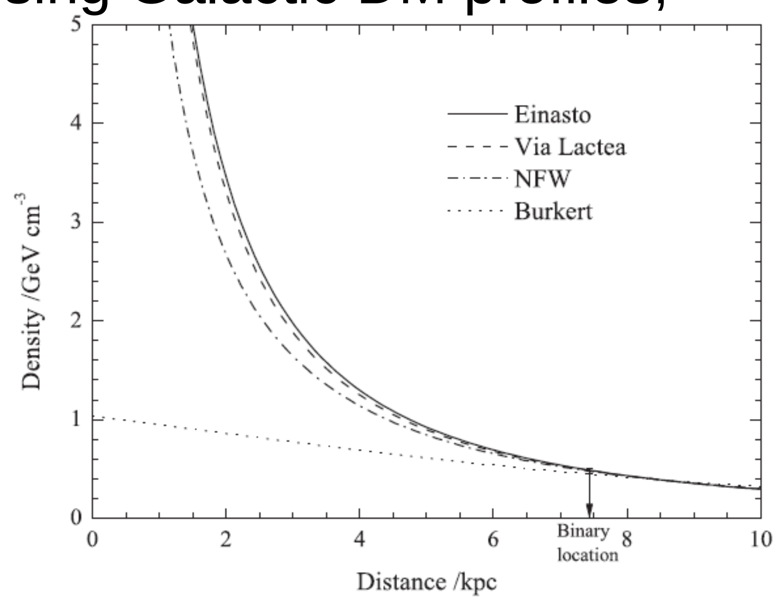
$$R = \frac{0.49(M_1/M_2)^{2/3}}{0.6(M_1/M_2)^{2/3} + ln[1 + (M_1/M_2)^{1/3}]} a.$$

P.P. Eggleton, ApJ 268 (1983) 368.

- Possible DM halo around WD has no influence;
- Estimate the local DM density using Galactic DM profiles;
- Estimate the mass contribution;

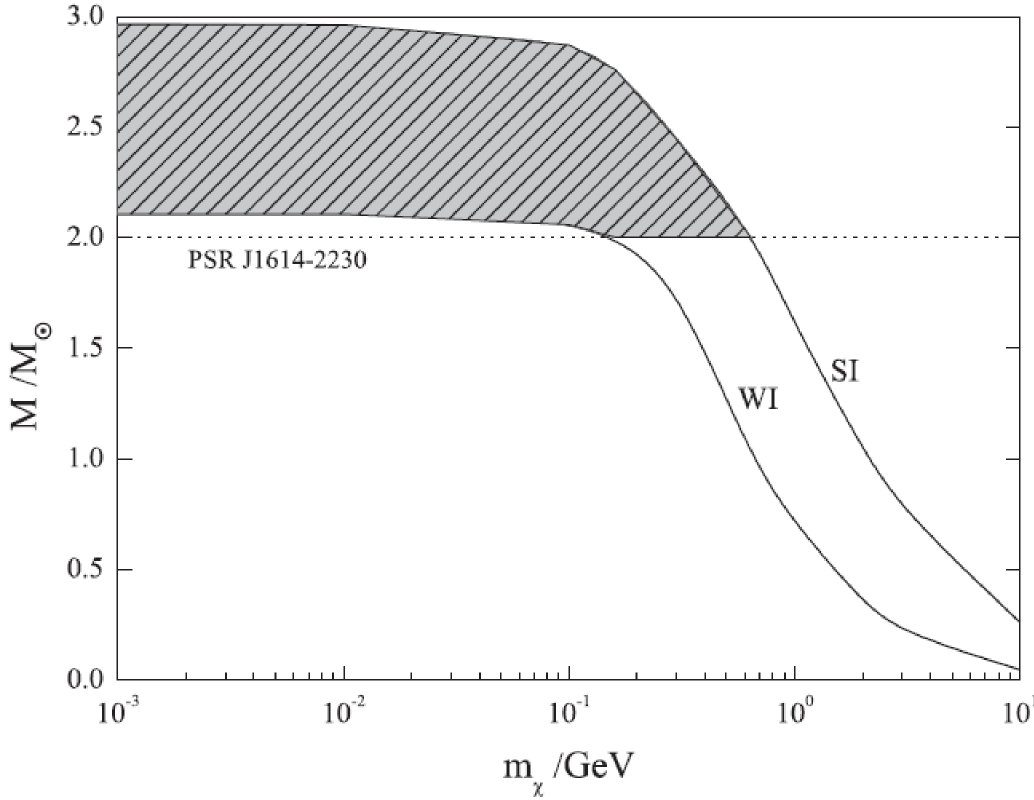
$$M_\chi = \frac{4}{3}\pi R^3 \bar{\rho}_\chi$$

- The conclusion is negative: $\sim 10^{-24} M_\odot$
- No influence of DM halo unless extremely dense DM medium.



New DM constrains from the compact-star scale

- m_χ<=0.64 GeV for non-self-annihilating DM particles;
- m_χ~ 4.5- 12GeV indicated by three recent direct detection experiments. M.R. Buckley, D. Hooper, T.M.P. Tait, PLB 702 (2011) 216.



Summary

- Including dark matter particles as ingredients of neutron stars;
- Achieve 2 solar mass hyperon star with a light dark matter mass m_χ<=0.64 GeV, as an constrain of DM particle properties from star scale;
- Possible DM halo of PSR J1614 2230 is trivial for the Shapiro delay measurement on the star mass.
- A more proper way: Using relativistic two-fluid formalism instead of TOV Eqs. for a more realistic density profile of DM.

Next plan (1)

- NSs with Quark-Mean-Field model (constituent quark model) including tunable density dependence of symmetry energy, mimicked by the isoscalar-isovector coupling

$$\Lambda_{\mathrm{v}}(g_\rho^2 \vec{\rho}_\mu \cdot \vec{\rho}^\mu)(g_\omega^2 \omega_\mu \omega^\mu)$$

At the same time to adjust the strength of the *NN*ρ coupling constant g_ρ to maintain E_{sym} L at saturation density unchanged.

cf. [1] *Compact stars within an asy-soft quark-meson-coupling model*, P.K. Panda, A.M.S. Santos, D.P. Menezes, C. Providência

[2] *Neutron star properties and the symmetry energy*, R.Cavagnoli, Debora P. Menezes, and C. Providência

H. Shen, H. Toki, NPA 707 (2002) 469

H. Shen, H. Toki, PRC 61 (2000) 045205

H. Toki, U. Meyer, A. Fassler, R. Brockmann, PRC58 (1998) 3749

Next plan (2)

- Phase transition within a chiral description

Hadron phase: Microscopic BHF calculation using chiral potential (For example, 2NF (N3LO) + 3NF(N2LO))

Chiral effective field theory and nuclear forces
R. Machleidt, D.R. Entemb, Physics Reports 503 (2011) 1-75

Quark phase: Chiral (soliton) quark model

Baryons as non-topological chiral solitons
Chr. V. Christov, A. Blotz, H.-C. Kim, P. Pobylitsa, T. Watabe, Th. Meissner, E. Ruiz Arriola, K. Goeke
PROG PART NUCL PHYS , vol. 37, pp. 91-191, 1996

The campus