Higher-order symmetry energy parameters and neutron star properties

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in collaboraton with
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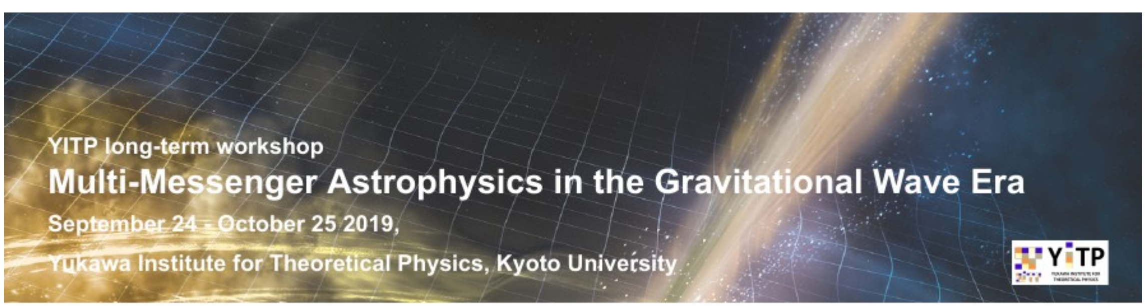
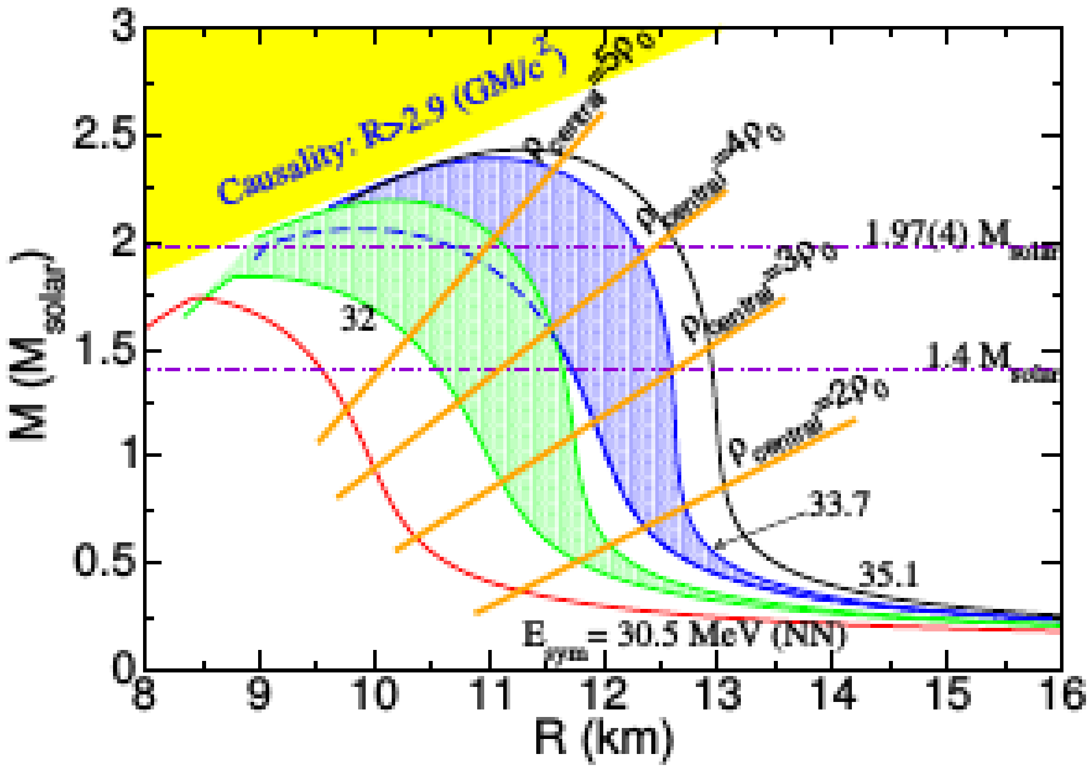
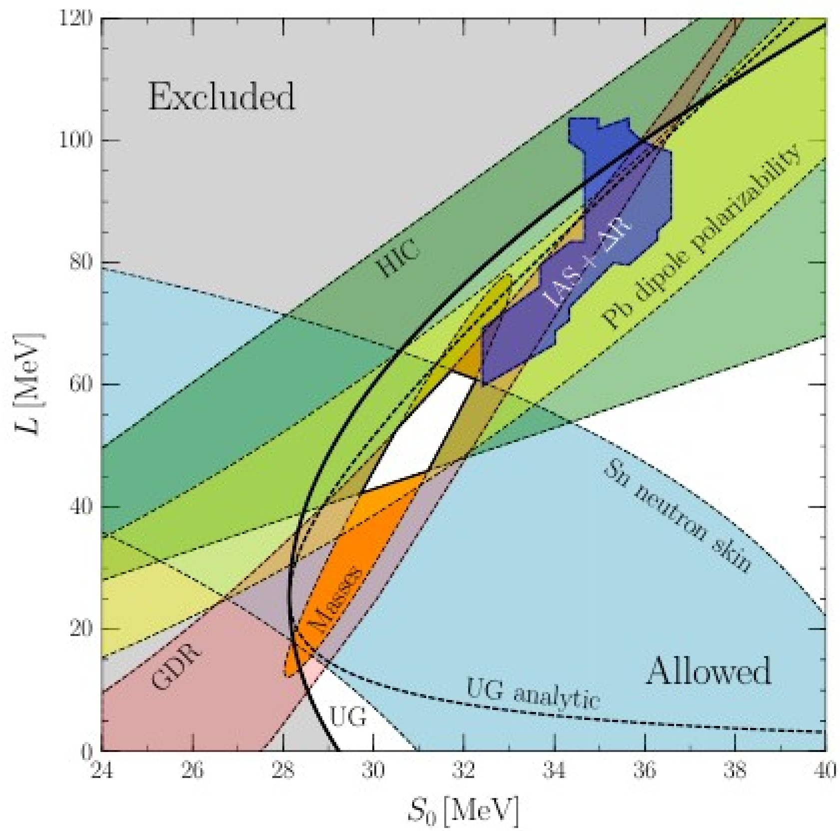
YITP long-term workshop on
Multi-Messenger Astrophysics in the Gravitational Wave Era
Sep. 24 – Oct. 25 2019, Kyoto, Japan



Symmetry Energy and Neutron Star Radius



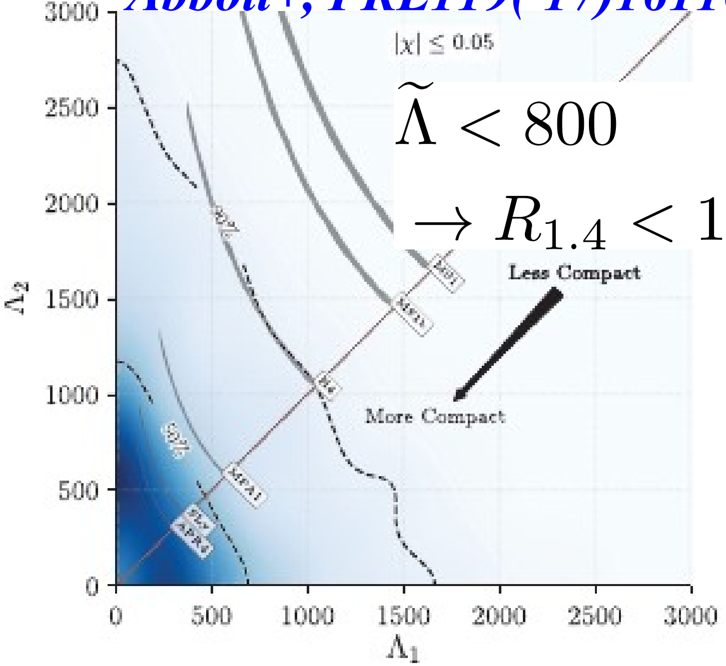


S.Gandolfi, J.Carlson, S.Reddy, PRC85('12) 032801

I. Tews, J.M.Lattimer, AO, E.E.Kolometisev (TLOK), ApJ 848 ('17)105

Constraints on EOS from GW170817

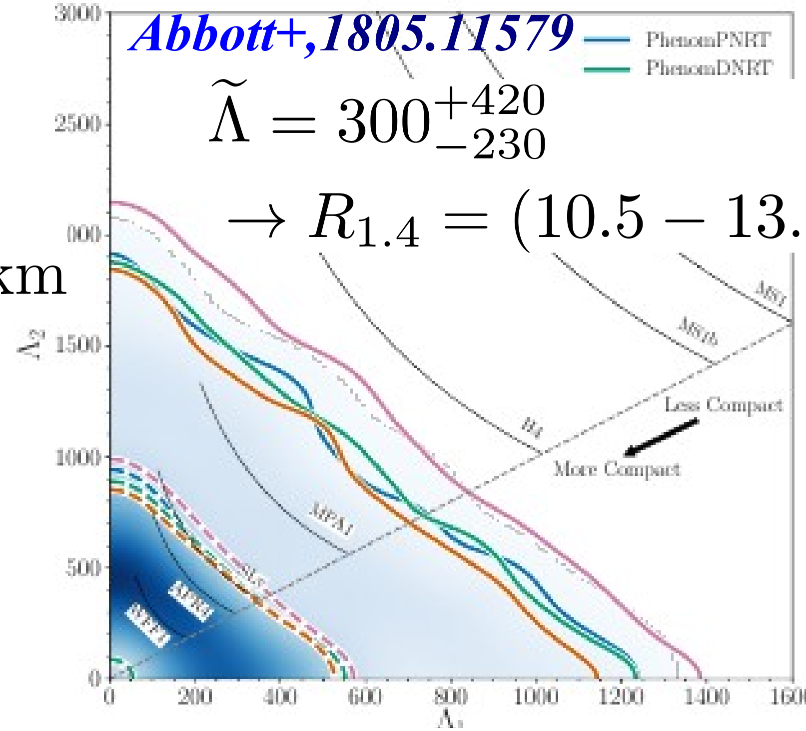
Abbott+, PRL119('17)161101



$\widetilde{\Lambda} < 800$

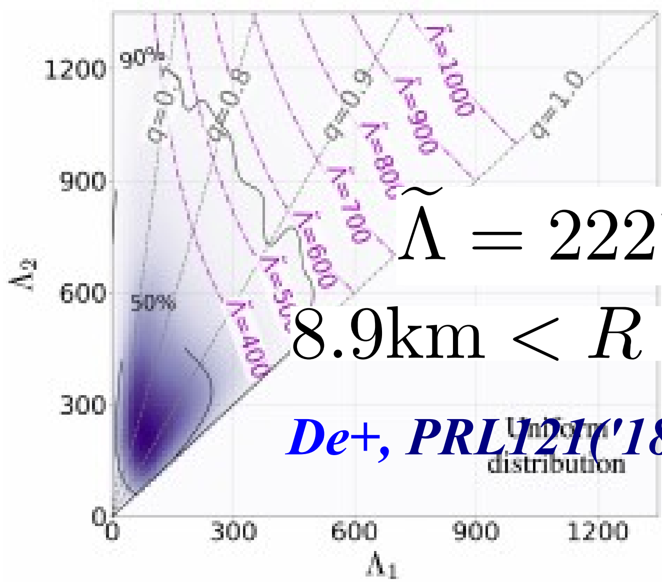
$\rightarrow R_{1.4} < 13.6$ km

Abbott+,1805.11579



$\widetilde{\Lambda} = 300^{+420}_{-230}$

$\rightarrow R_{1.4} = (10.5 - 13.3)$ km

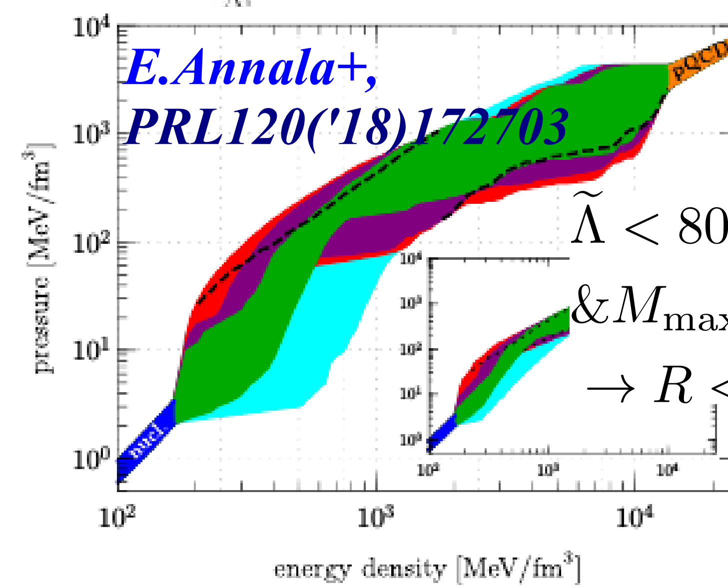


$\widetilde{\Lambda} = 222^{+420}_{-138}$

$8.9\text{km} < R < 13.2\text{km}$

De+, PRL121('18)091102

E.Annala+, PRL120('18)172703

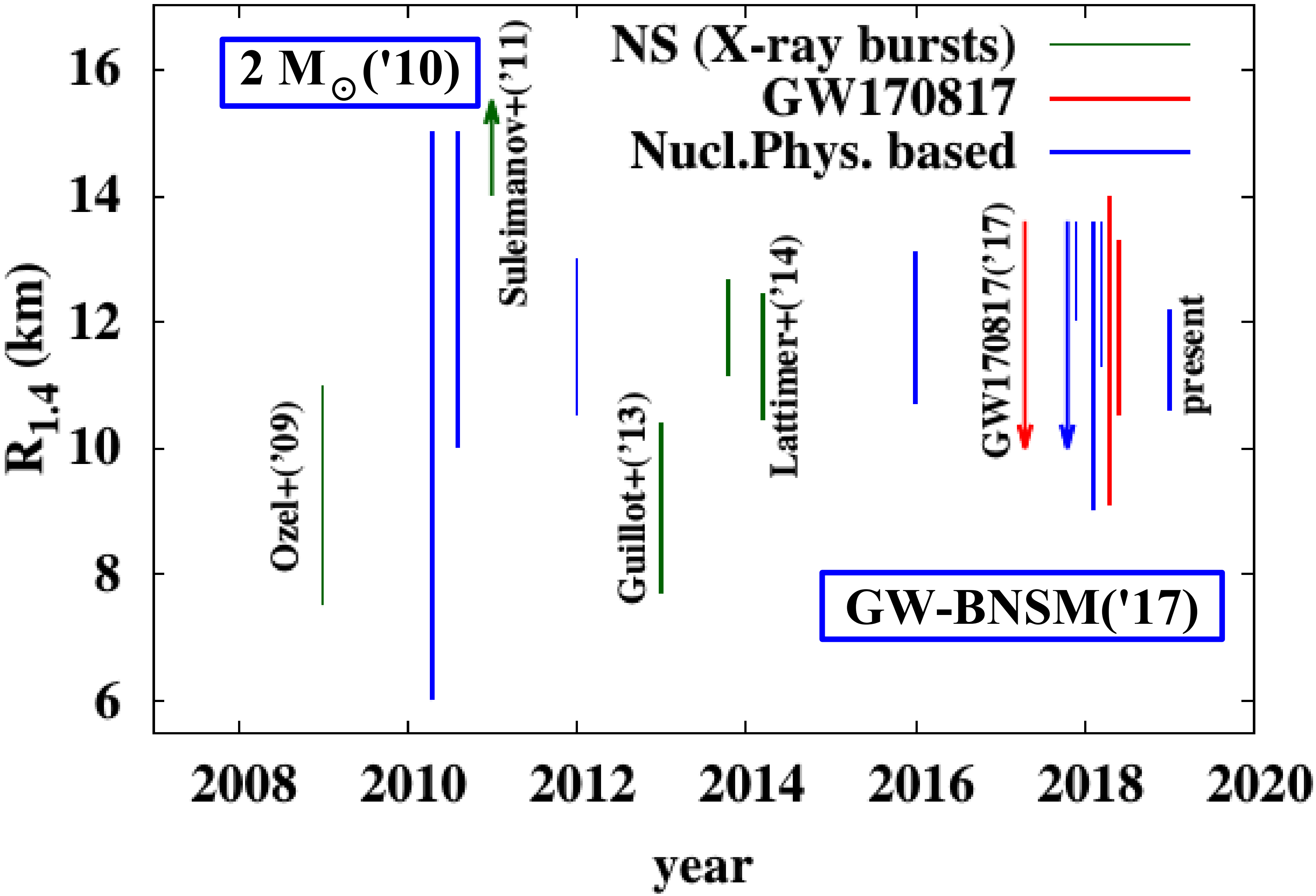


$\widetilde{\Lambda} < 800$

$\& M_{\max} > 2M_\odot$

$\rightarrow R < 13.6$km

Time dependence of Neutron Star Radius ($R_{1.4}$)



Symmetry Energy Parameters (S_0 , L) affect Neutron Star Radius

S_0 =(32-35) MeV → R = (9-14) km

Now GW observation suggests R = 11 ± 1 km,

and 30<S_0<32 MeV and 40<L<60 MeV

are favored by nucl. phys. experiments

How about higher-order parameters ?

Outline

- Introduction
- Symmetry energy parameters and Neutron Star Radius
  - Constructing EOS using symmetry energy parameters
  - Higher-order symmetry energy parameters
  - Neutron star radius
- Quarkyonic QCD Phase Transition and Neutron Star Properties
  - What is quarkyonic matter ?
  - Density dependence of sound velocity
  - M-R curve with quarkyonic matter
- Summary

Symmetry Energy Parameters and Neutron Star Radius

Sym. E. Parameters → EOS

TLOK

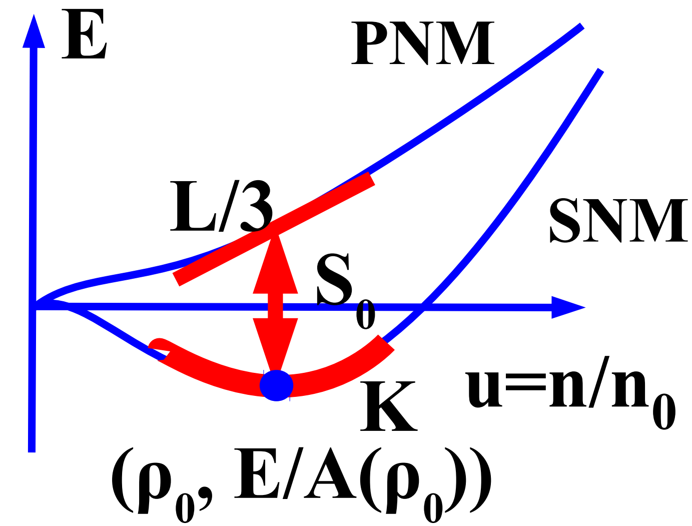
- **Saturation & Symmetry Energy Parameters**

$$E_{\rm NM}(u,\alpha) = E_{\rm SNM}(u) + \alpha^2\, S(u)$$

$$E_{\rm SNM}(u) \simeq E_0 + \frac{K_0}{18}(u-1)^2 + \frac{Q_0}{162}(u-1)^3$$

$$S(u) \simeq S_0 + \frac{L}{3}(u-1) + \frac{K_s}{18}(u-1)^2 + \frac{Q_s}{162}(u-1)^3$$

$$(u = n/n_0, \alpha = (n_n - n_p)/n)$$



Energy does not approach zero at n → 0.

- **Fermi momentum expansion (~ Skyrme type EDF)**
  - **Generated many-body force is given by** $k_F \propto u^{1/3}$

m*

$$E_{\rm SNM}(u) \simeq \boxed{T_0\, u^{2/3}} + \underline{a_0 u} + \underline{b_0 u^{4/3}} + \underline{c_0 u^{5/3}} + \underline{d_0 u^2}$$

$$S(u) \simeq \boxed{T_s u^{2/3}} + \underline{a_s u} + \underline{b_s u^{4/3}} + \underline{c_s u^{5/3}} + \underline{d_s u^2}$$

Kin. E. Two-body Density-dep. pot.

Expansion Coefficients

- **Coefficients (a,b,c,d) are represented by Saturation and Symmetry Energy Parameters**

TLOK

$$
\begin{aligned}
a_0 &= -\,4T_0 && +20E_0 && +\,K_0 && -Q_0/6 \\
b_0 &= \;\;6T_0 && -45E_0 && -5K_0/2 && +Q_0/2 \\
c_0 &= -\,4T_0 && +36E_0 && +2K_0 && -Q_0/2 \\
d_0 &= \;\;\;\;T_0 && -10E_0 && -\,K_0/2 && +Q_0/6
\end{aligned}
$$

$$
\begin{aligned}
a_s &= -\,4T_s && +20S_0 - 19L/3 && +\,K_s && -Q_s/6 \\
b_s &= \;\;6T_s && -45S_0 + 15L && -5K_s/2 && +Q_s/2 \\
c_s &= -\,4T_s && +36S_0 - 12L && +2K_s && -Q_s/2 \\
d_s &= \;\;\;\;T_s && -10S_0 + 10L/3 && -\,K_s/2 && +Q_s/6
\end{aligned}
$$

$$
\left(T_0 = \frac{3}{5}\frac{\hbar^2 k_F(n_0)^2}{2m},\quad T_s = T_0(2^{1/3}-1)\right)
$$

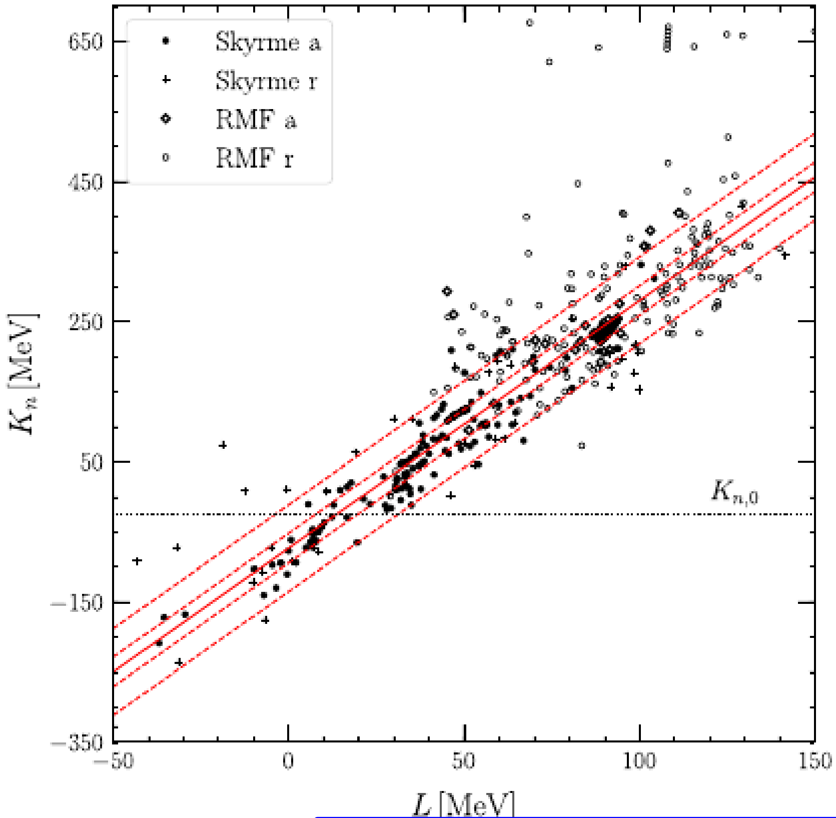
Tedious but straightforward calc.

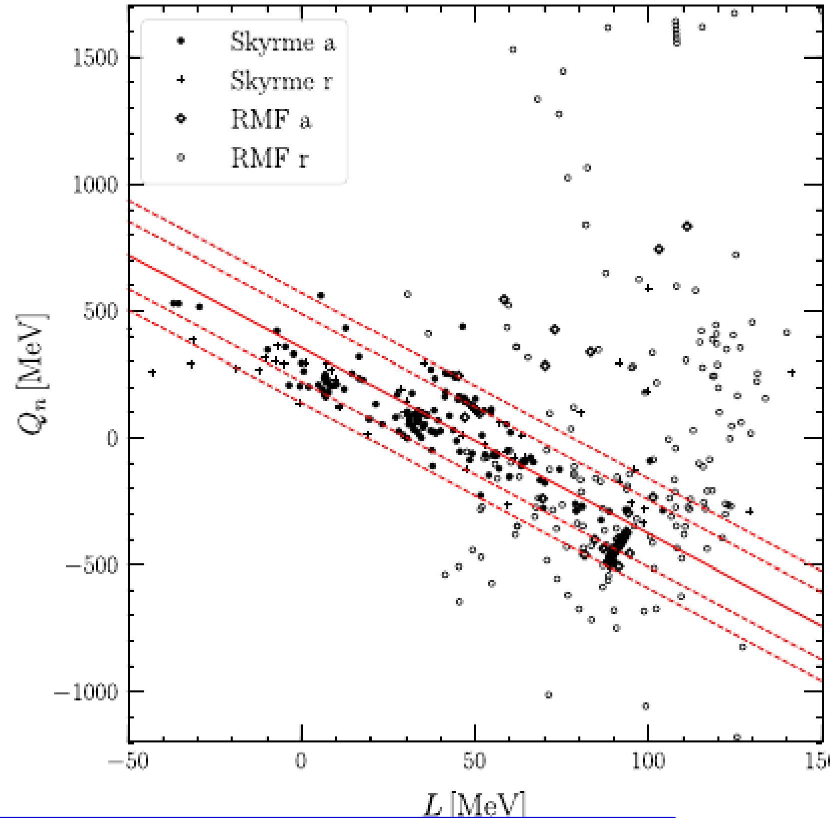
Further Constraints on Higher-Order Sym. E. parameters

- **K_n and Q_n are correlated with L in "Good" theoretical models.**

$$K_n = 3.534L - (74.02 \pm 21.17)\mathrm{MeV}$$

$$Q_n = -7.313L + (354.03 \pm 133.16)\mathrm{MeV}$$



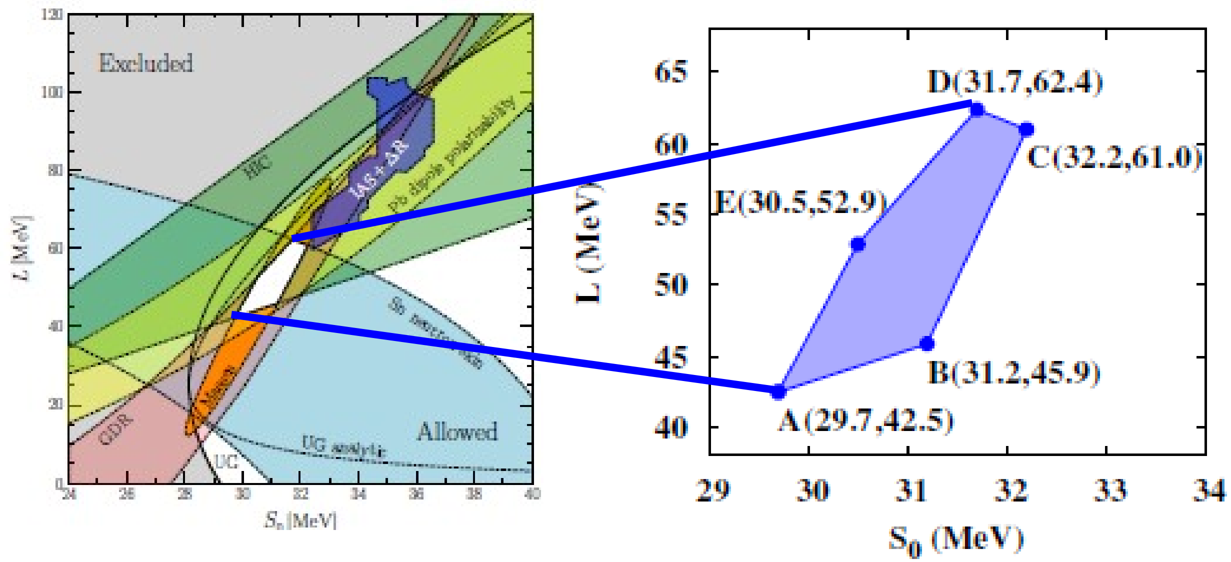


Regard theoretical models as data !

I. Tews, J.M.Lattimer, AO, E.E.Kolomeitsev (TLOK), ApJ 848 ('17)105

TLOK+2$M_\odot$ constraints

- **TLOK constraints**
  - **(S_0, L) is in Pentagon.**
  - **(K_n, Q_n) are from TLOK constraint.**
  - **K_0=(190-270) MeV**
  - **(n_0,E_0) is fixed**
    n_0=0.164 fm^{-3}, E_0=-15.9 MeV (small uncertainties)
  - **Q_0 is taken to kill d_0 parameter**
    (Coef. of u^2. Sym. N. M. is not very stiff at high-density)

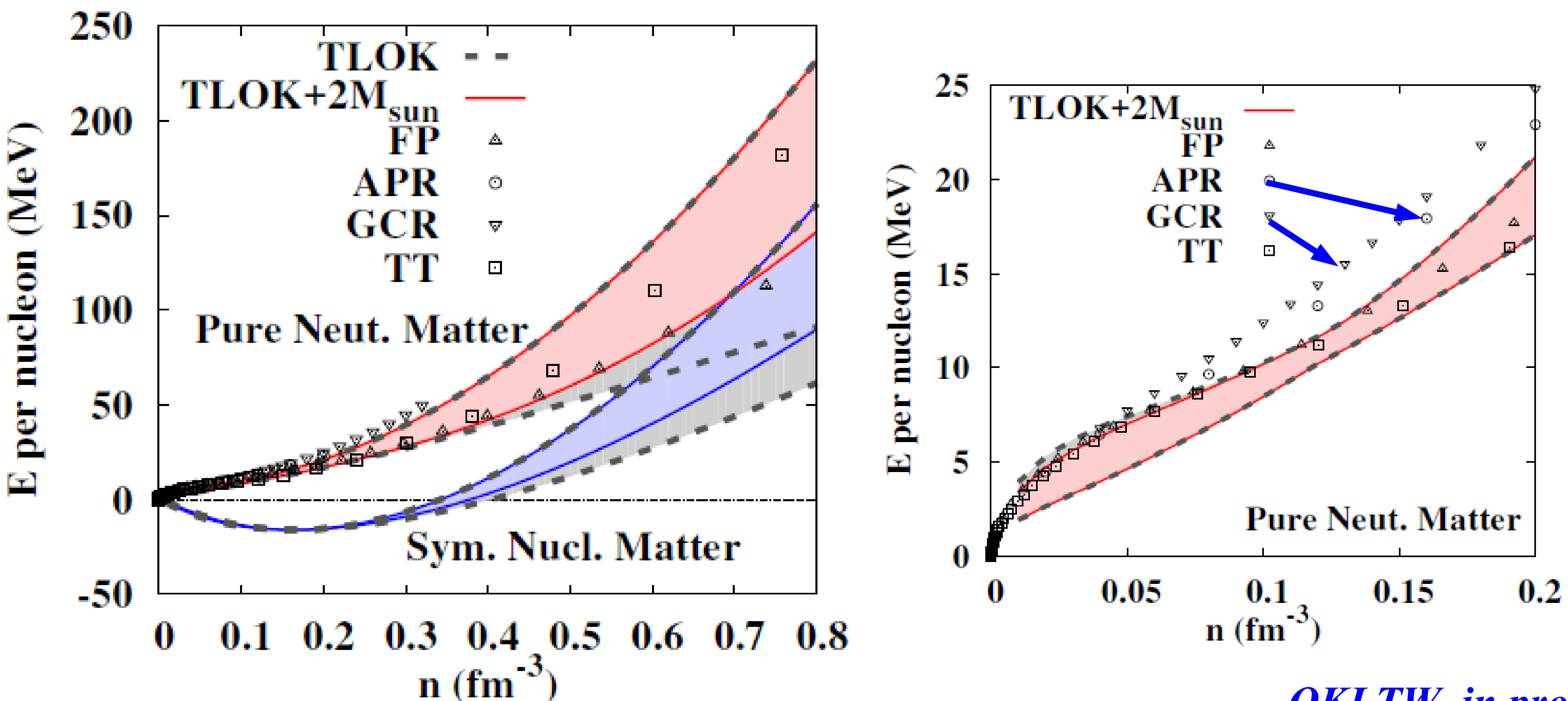


- **2 $M_\odot$ constraint**
  - **EOS should support 2 $M_\odot$ neutron stars.**

AO, Kolomeitsev, Lattimer, Tews, Wu (OKLTW), in prog.

TLOK+2M$_\odot$ constraints on EOS

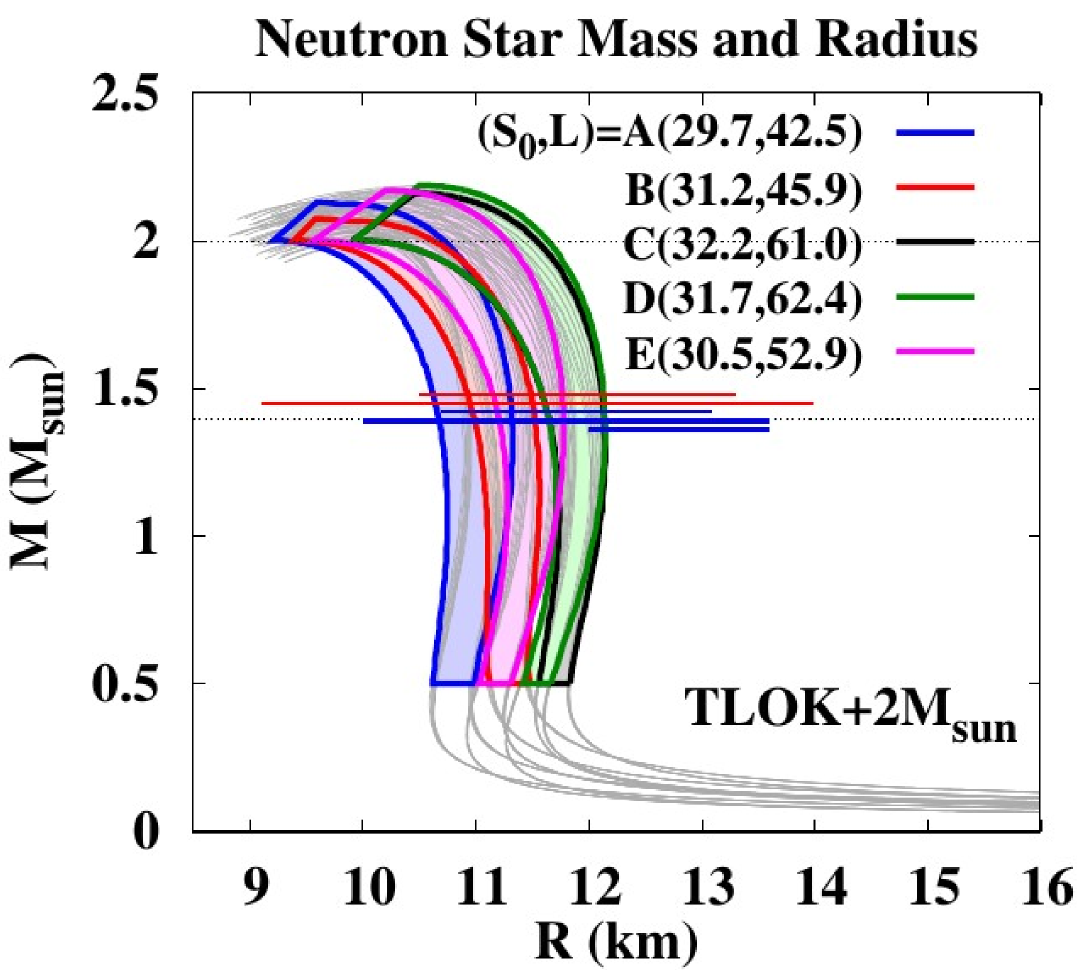
- 2M$_\odot$ constraint narrows the range of EOS.
- Consistent with FP and TT(Togashi-Takano) EOSs.
- APR and GCR(Gandolfi-Carlson-Reddy) EOSs seems to have larger S_0 values.



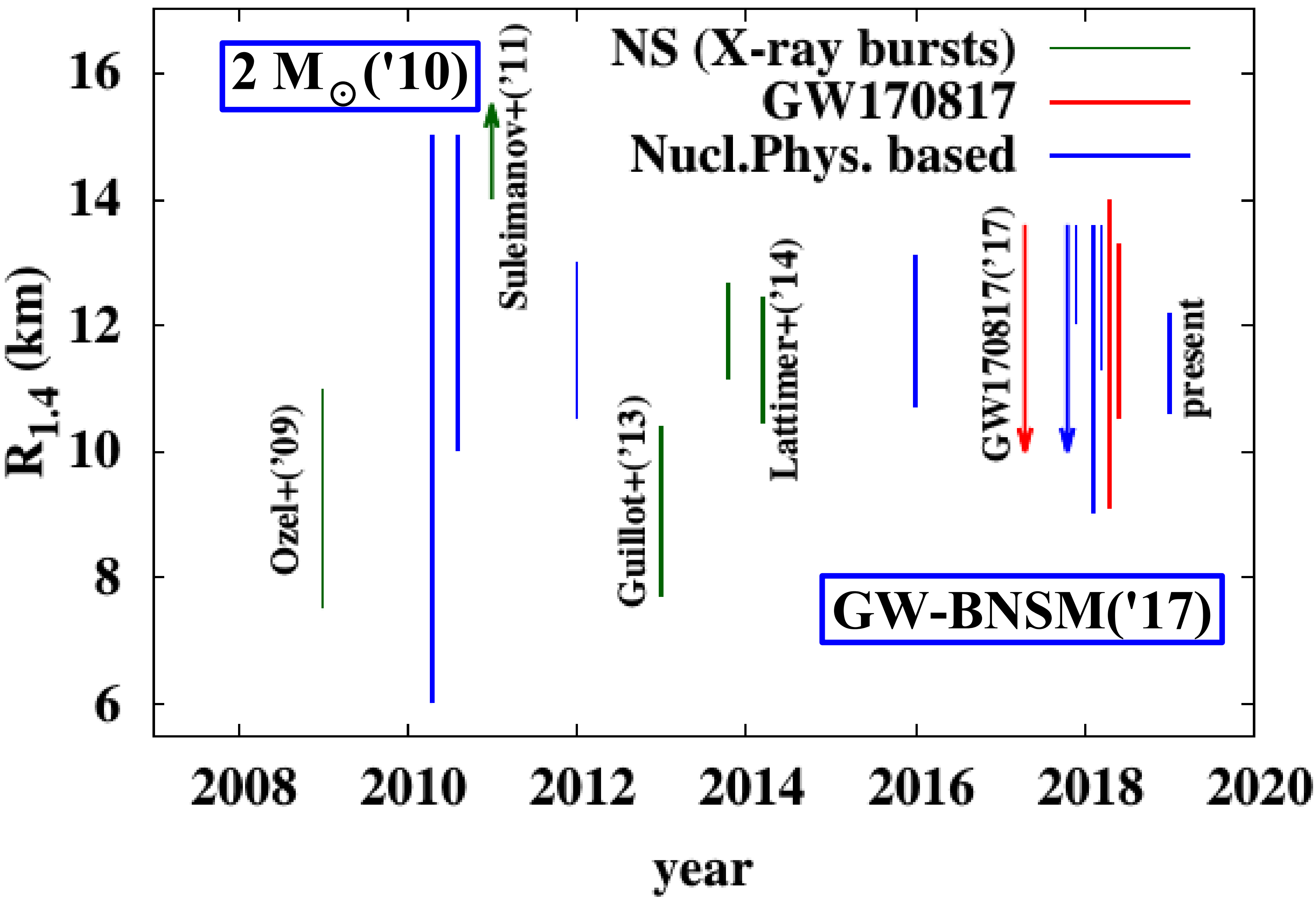
OKLTW, in prog.

Neutron Star MR curve

- **TLOK + 2 $M_\odot$ constraints → $R_{1.4}$=(10.6-12.2) km** *OKLTW, in prog.*
  - **E and P are linear fn. of Sat. & Sym. E. parameters → Min./Max. appears at the corners of pentagon (ABCDE).**
  - **For a given (S_0, L), unc. of $R_{1.4}$ ~ 0.5 km = unc. from higher-order parameters**
  - **Unc. from (S_0, L) ~ 1.1 km → We still need to fix (S_0, L) more precisely.**



Time dependence of Neutron Star Radius ($R_{1.4}$)



Astrophysics Observation
and Estimate based on Nuclear Physics
are consistent.

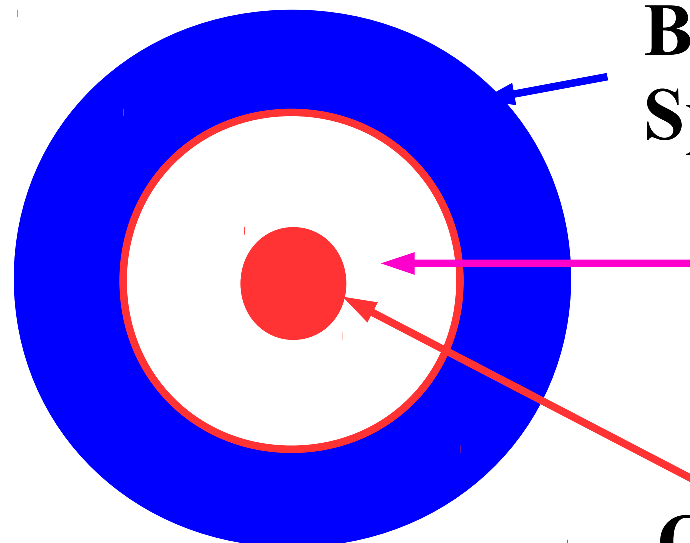
But there are several problems !

Non.-Rel. EOS violates causality !
Effects of QCD phase transition exists at high density ?
Crust modifies NS radius !

Quarkyonic QCD Phase Transition and Neutron Star Properties

Quarkyonic Transition

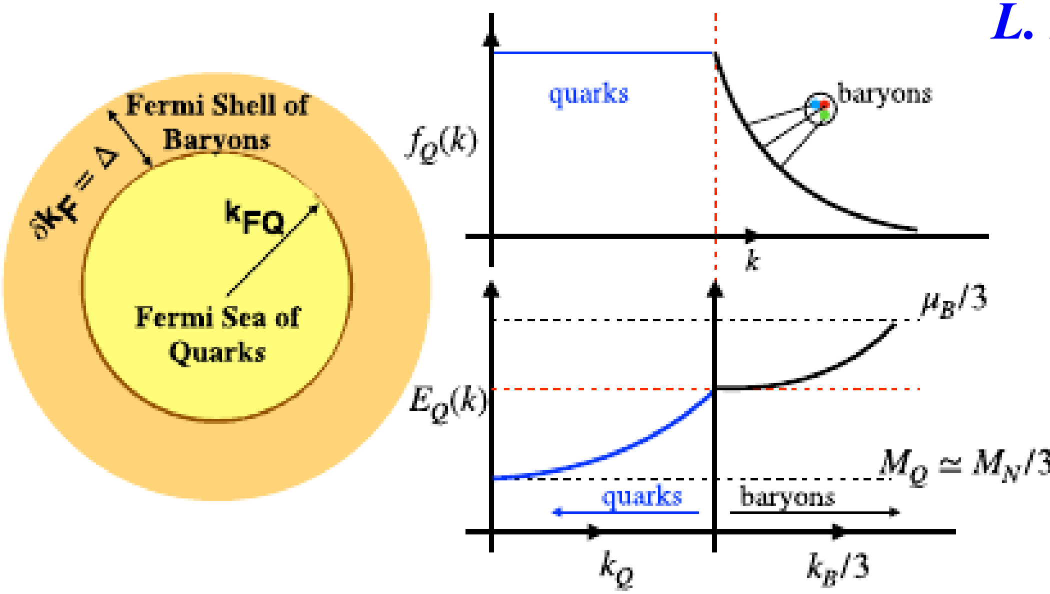
- **Quarkyonic (Quark+(Bar)yon+ic) Matter**
  L. McLerran, R. D. Pisarski, NPA796 ('07) 83.
  - **Quark Fermi Sphere + Baryonic Excitation**
  - **Low momentum baryons are blocked by quarks**
  - **Excitations is dominated by baryons**

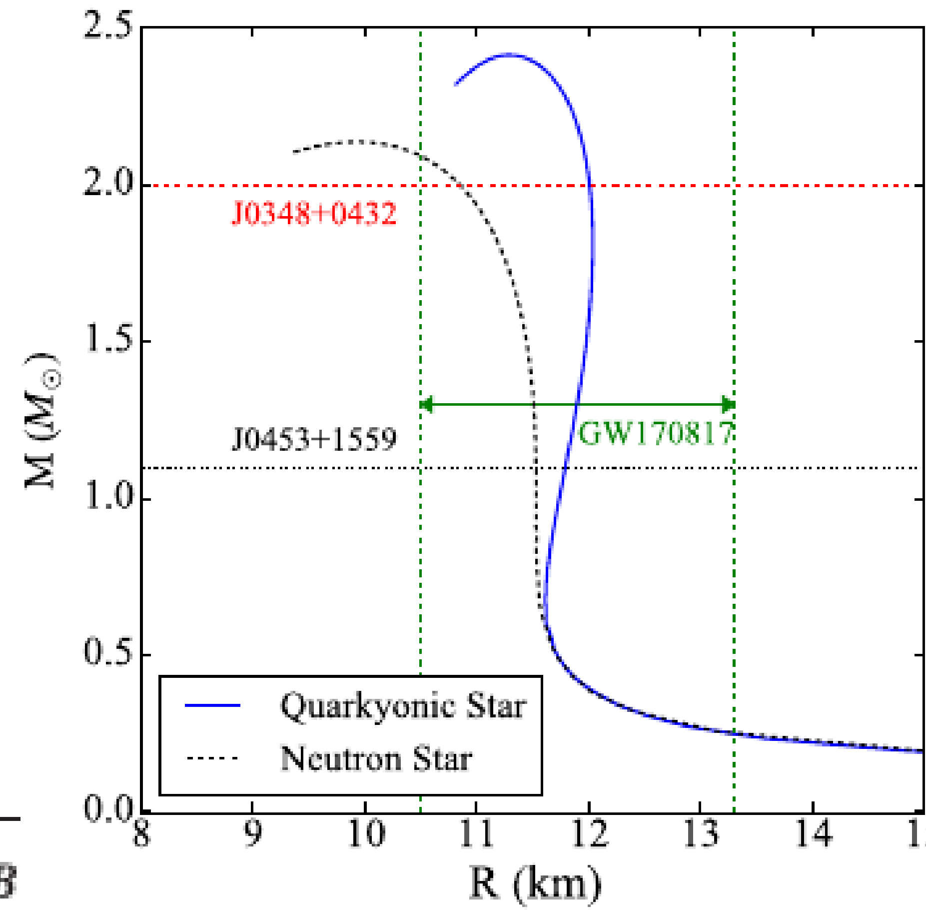


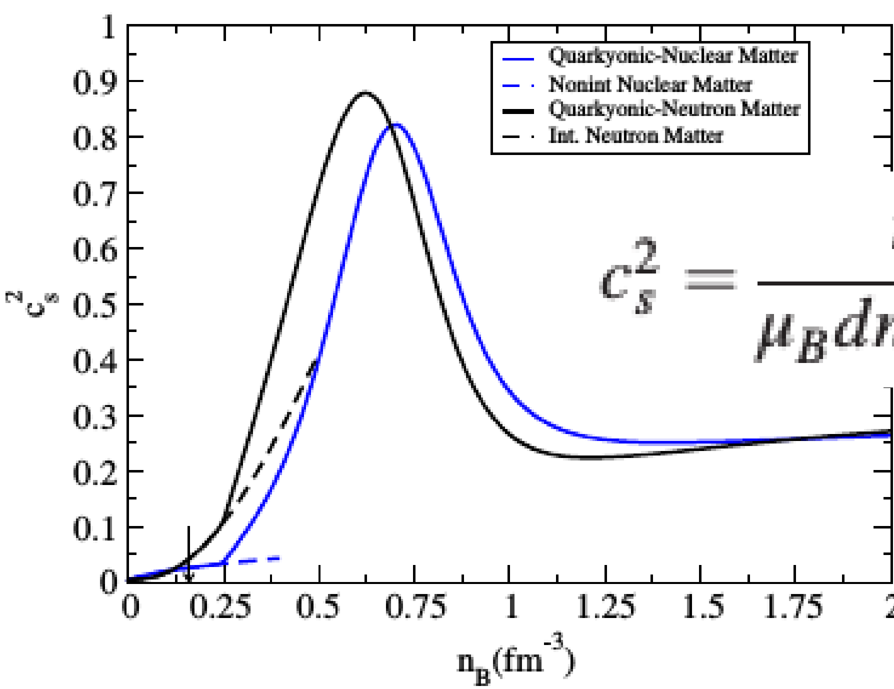
- **Quarkyonic Transition**
  L. McLerran, S. Reddy, PRL122 ('19)122701.
  - **Suppressed baryon density for a given k_B → Quick rise and down of sound velocity**
  - **Supports massive NS without increasing R much.**

Quarkyonic Transition

L. McLerran, S. Reddy, PRL122 ('19)122701.

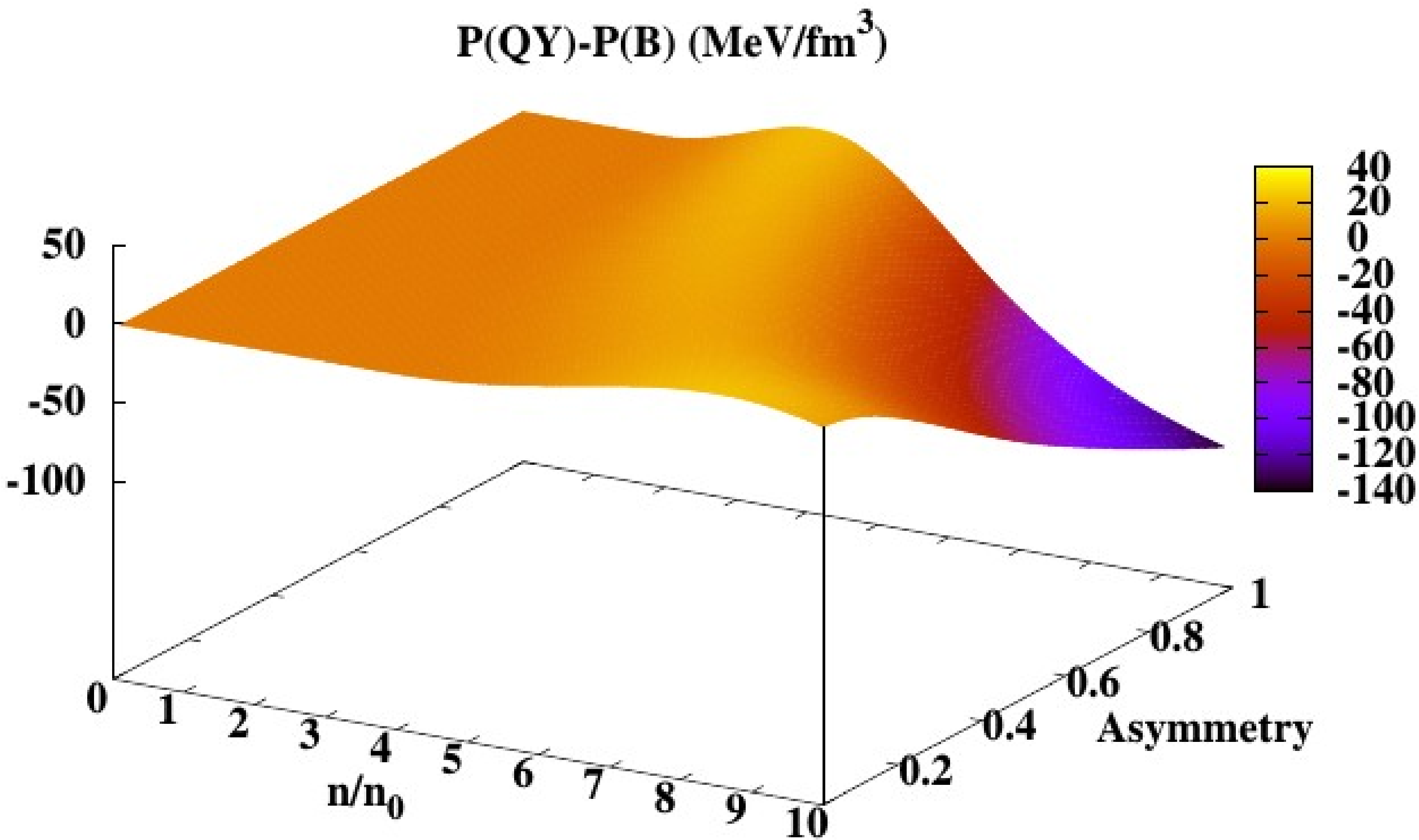






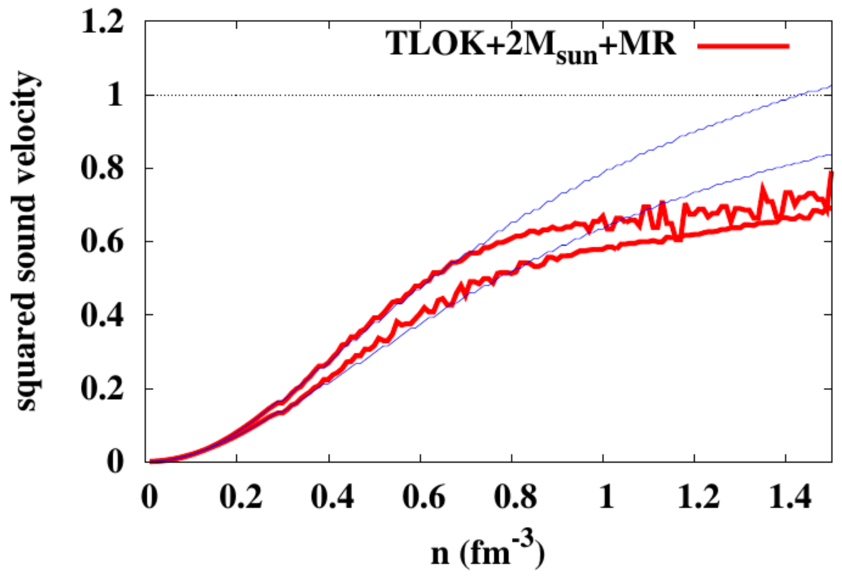
$$c_s^2 = \frac{n_B}{\mu_B dn_B/d\mu_B}$$

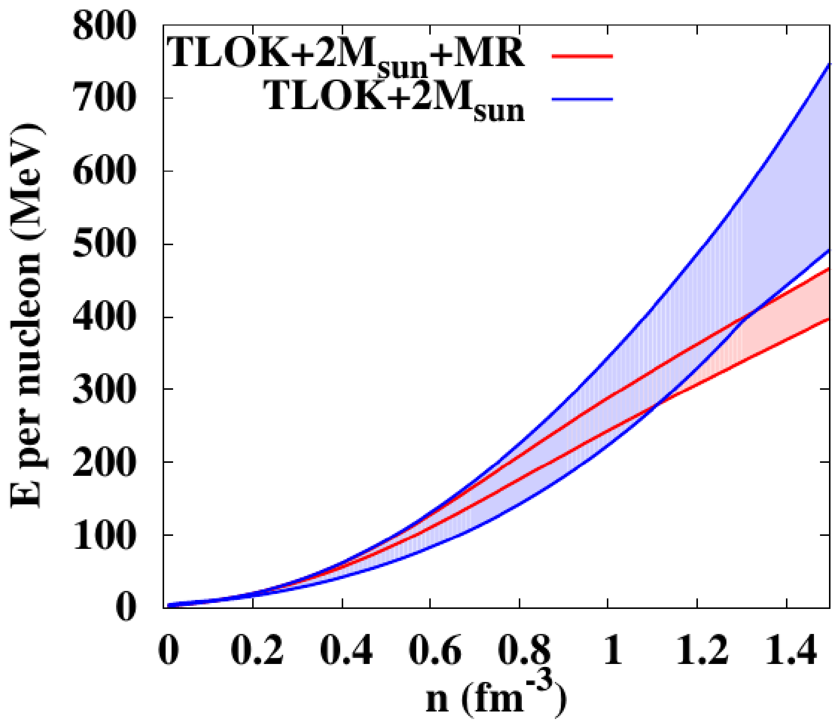
Pressure difference



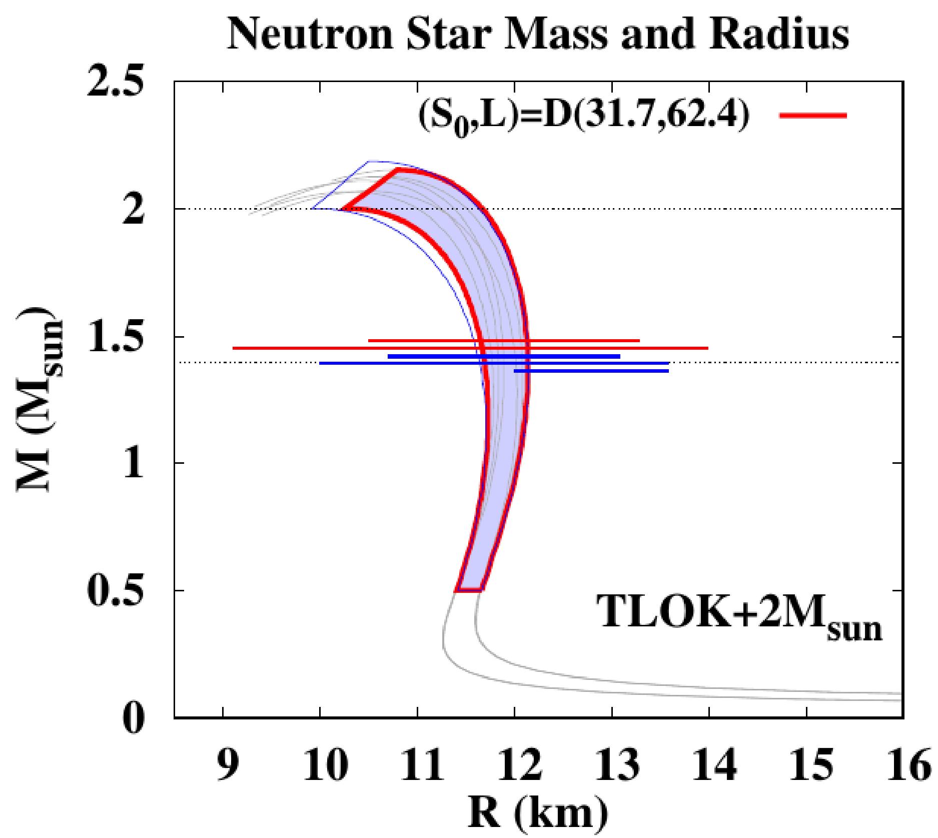
Kinetic Energy Only

Example of Application to TLOK EOS

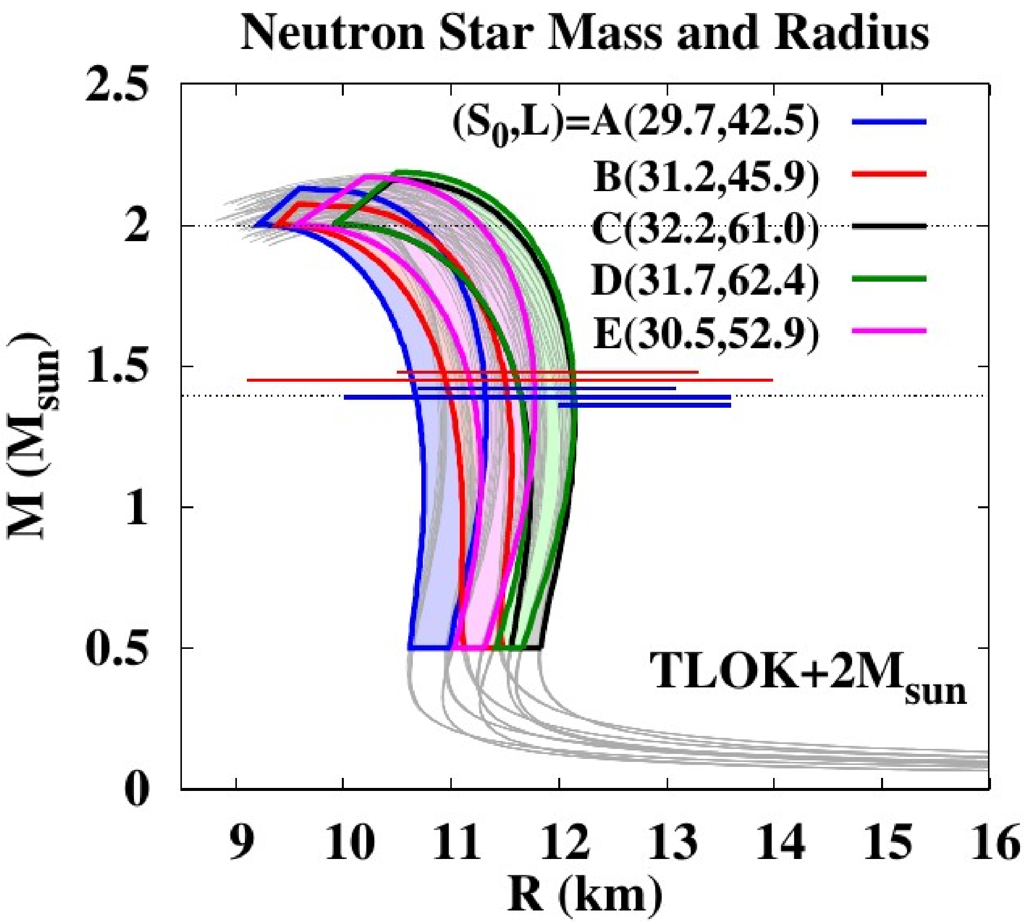


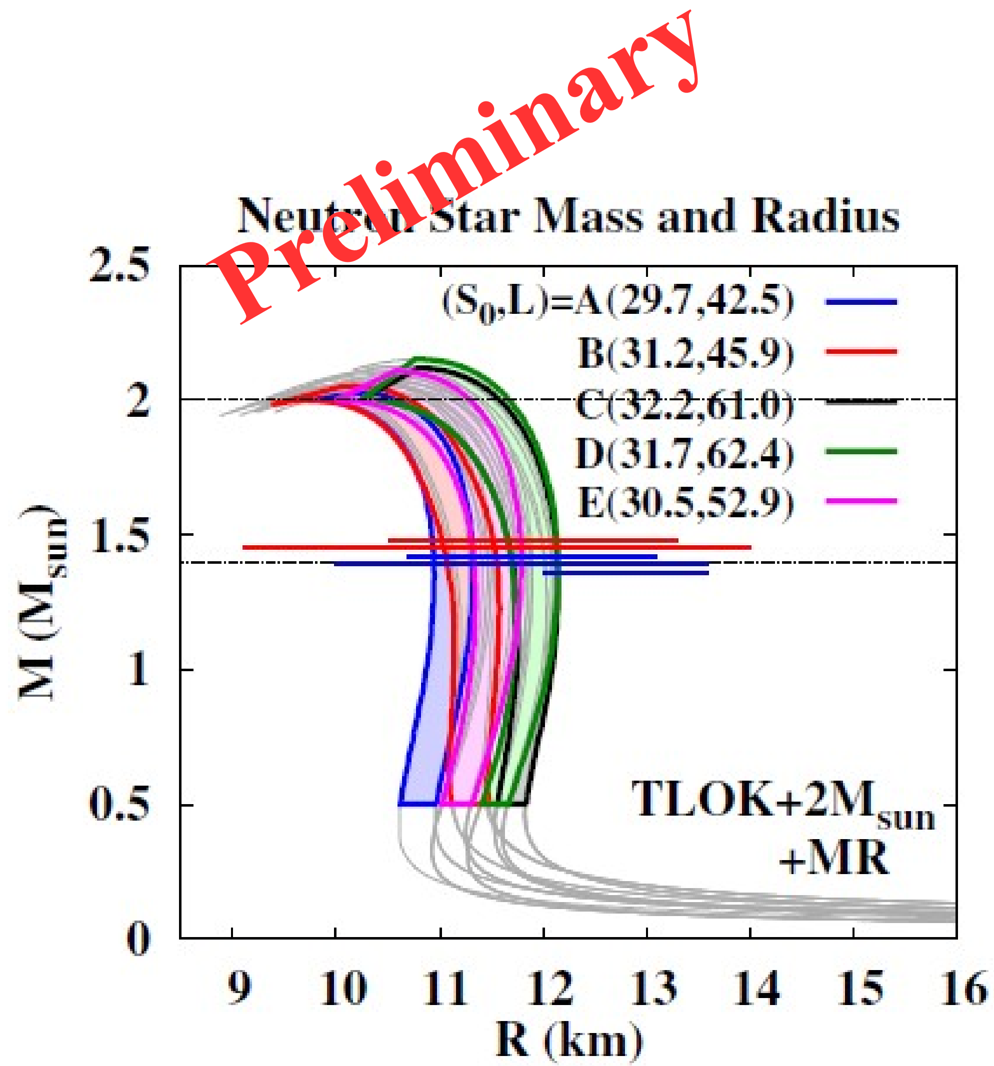


Preliminary



TLOK+2M$_\odot$+MR (McLerran-Reddy)





Summary

- **Tews-Lattimer-AO-Kolomeitsev ('17) constraints (S0, L, K_n, Q_n) and 2 $M_\odot$ constraint with the aid of Fermi momentum (k_F) expansion lead to the costraint on 1.4 $M_\odot$ neutron star radius of (10.6-12.2) km.**
  - **Consistent with many of other constraint.**
- **Quarkyonic transition picture seems to be promising.**
  - **Sudden rise and down of sound velocity is helpful to support massive NS without changing R(1.4) much.**
  - **We can respect both of causality at high densities and symmetry energy parameters at low densities. (c.f. Polytrope)**
  - **Interactions in quark matter should be considered.**
- **Soft (<$2n_0$) – Stiff ($2n_0$<n<$5n_0$) – Soft (>$5n_0$) EOS agrees with the implication from heavy-ion collision data.**

MR (McLerran-Reddy) model

- **Baryon shell thickness**

$$\Delta_B = \frac{\Lambda^3}{k_B^2} + \frac{\kappa\Lambda}{N_c^2}$$

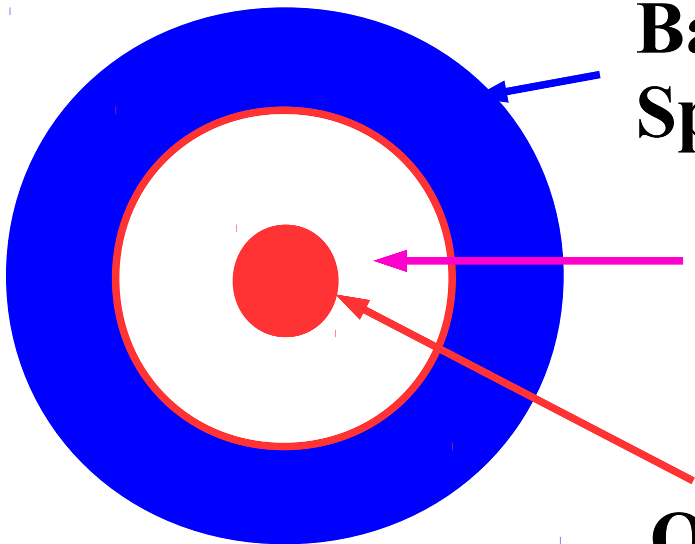
- **Quark Fermi sphere**
  - **Symmetric Matter**

$$k_q = \frac{k_B - \Delta_B}{N_c}$$

  - **Asymmetric Matter**

$$k_u^3 = \frac{1}{N_c^3}\left(\frac{2(k_p - \Delta_p)^3}{3} + \frac{(k_n - \Delta_n)^3}{3}\right)$$

$$k_d^3 = \frac{1}{N_c^3}\left(\frac{(k_p - \Delta_p)^3}{3} + \frac{2(k_n - \Delta_n)^3}{3}\right)$$

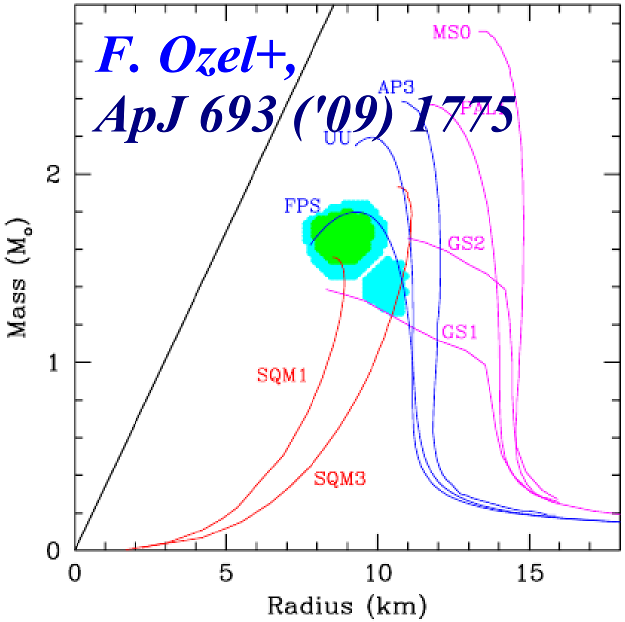


$$\Lambda = (380 - 400)\ \mathrm{MeV}/c,\ \ \kappa \simeq 0.8$$

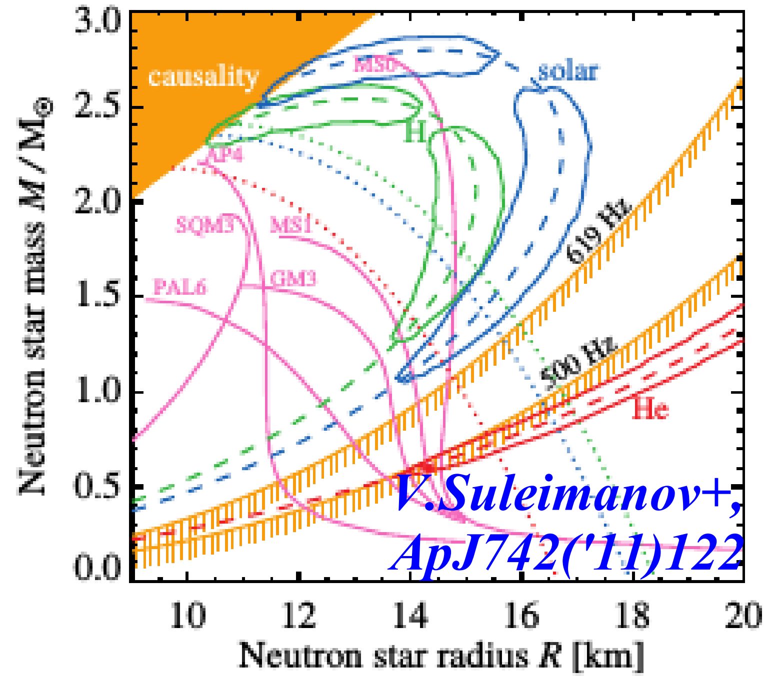
$$\mathrm{MR}:\ \Lambda = 300\ \mathrm{MeV}/c,\ \ \kappa = 0.3$$

Thank you for your attention !

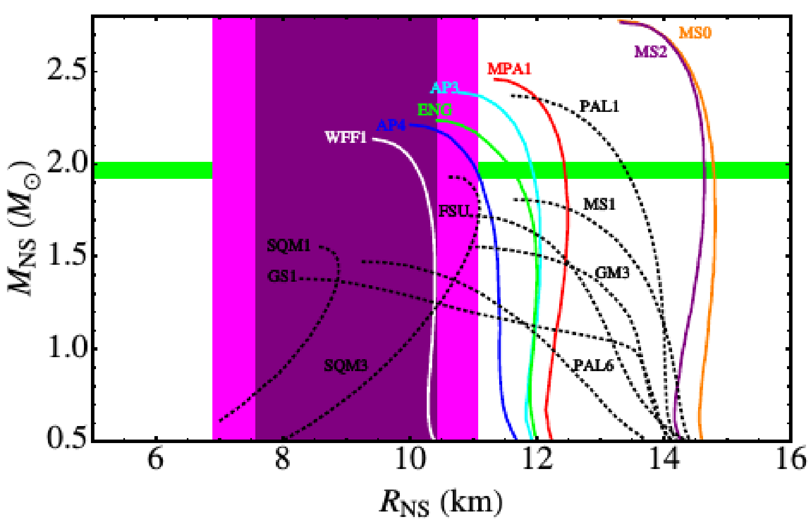
MR curve from X-ray burst



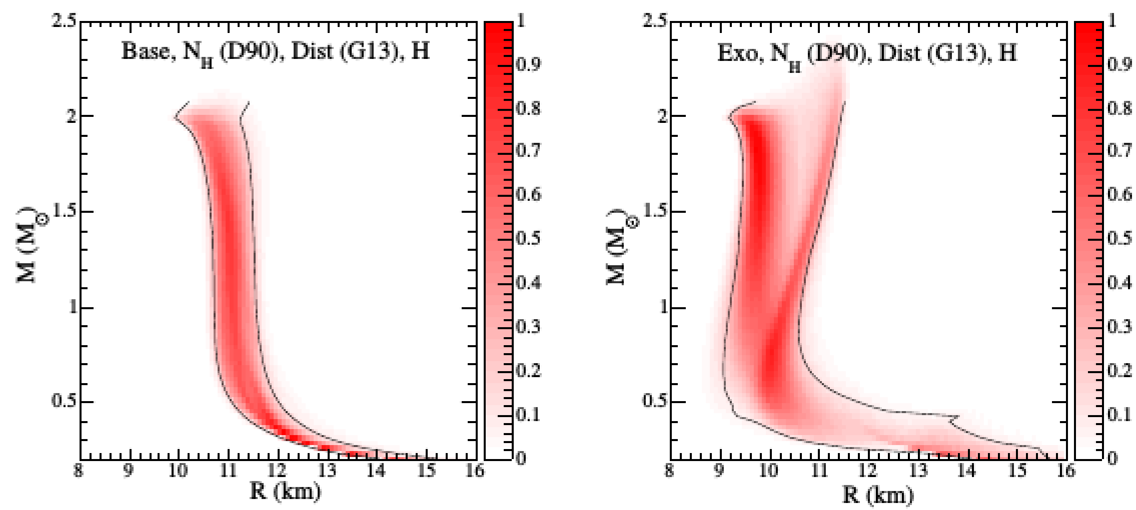
F. Ozel+, ApJ 693 ('09) 1775



V.Suleimanov+, ApJ742('11)122



S. Guillot+, ApJ772('13)7

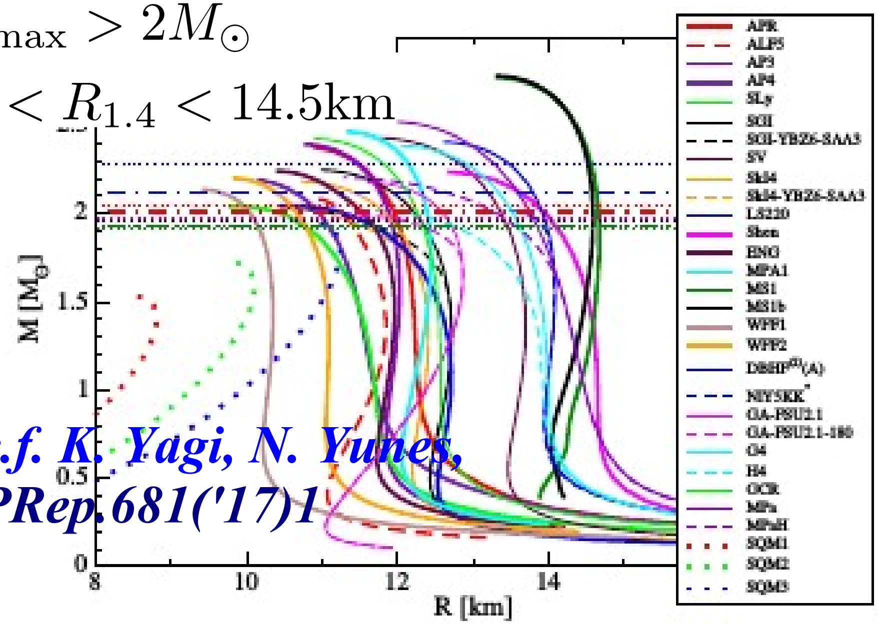


J.M.Lattimer, A.W.Steiner, ApJ784('14)123

Constraints from Nuclear Physics (+α)

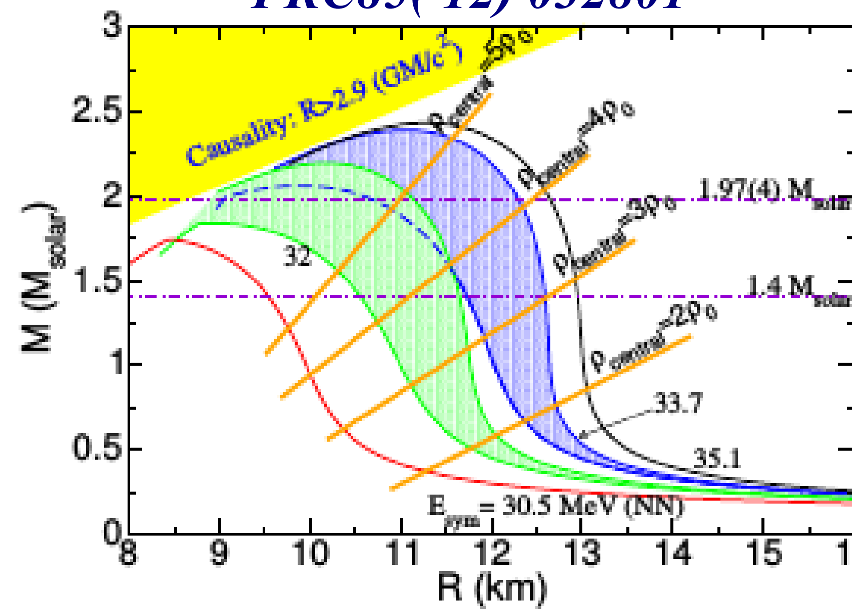
$M_{\max} > 2M_\odot$

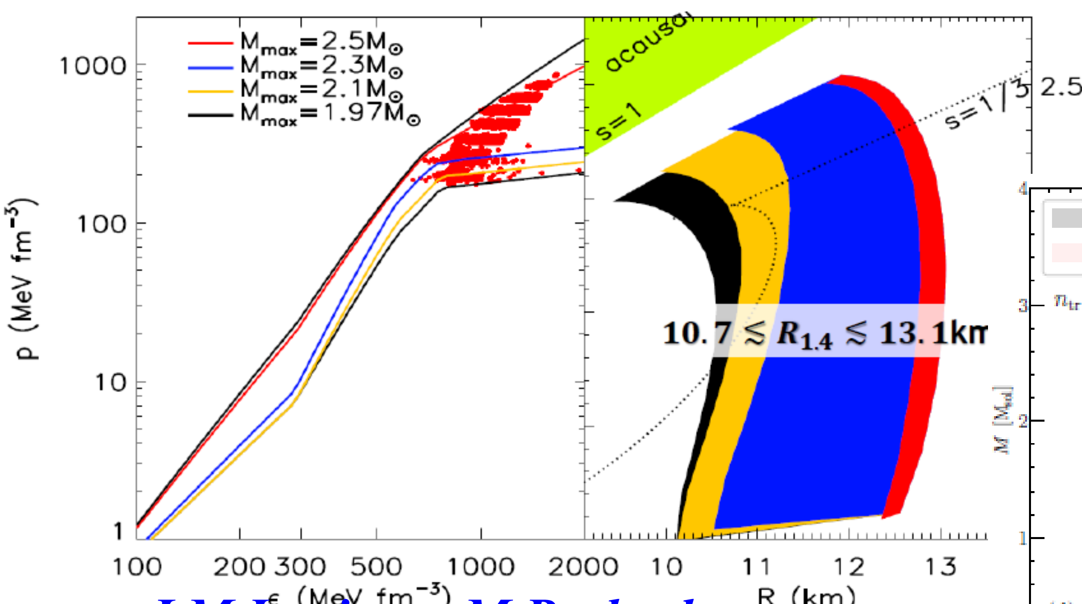
$10 < R_{1.4} < 14.5\mathrm{km}$



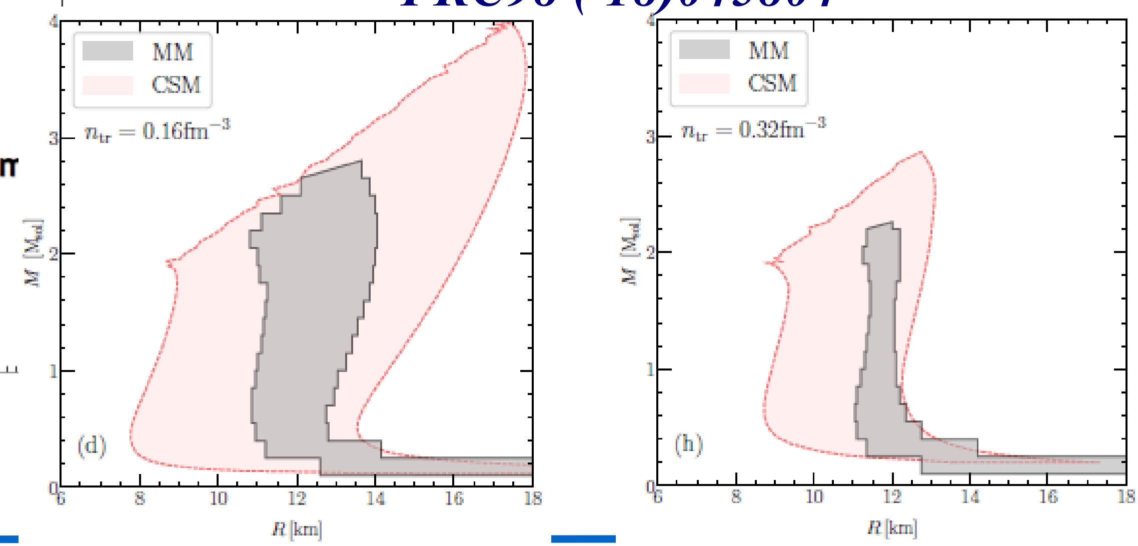
c.f. K. Yagi, N. Yunes, PRep.681('17)1

S.Gandolfi, J.Carlson, S.Reddy, PRC85('12) 032801



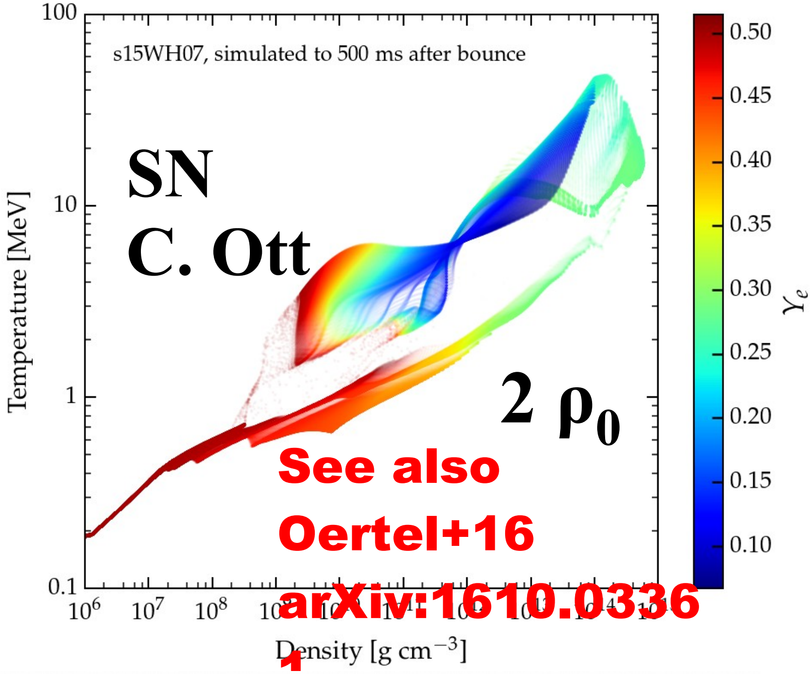


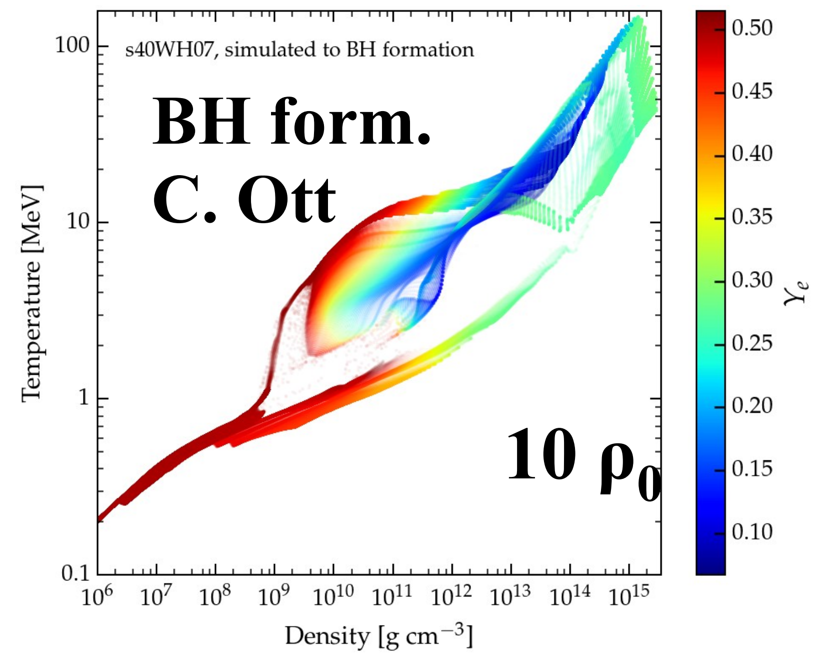
I. Tews, J. Margueron, S. Reddy, PRC98 ('18)045804

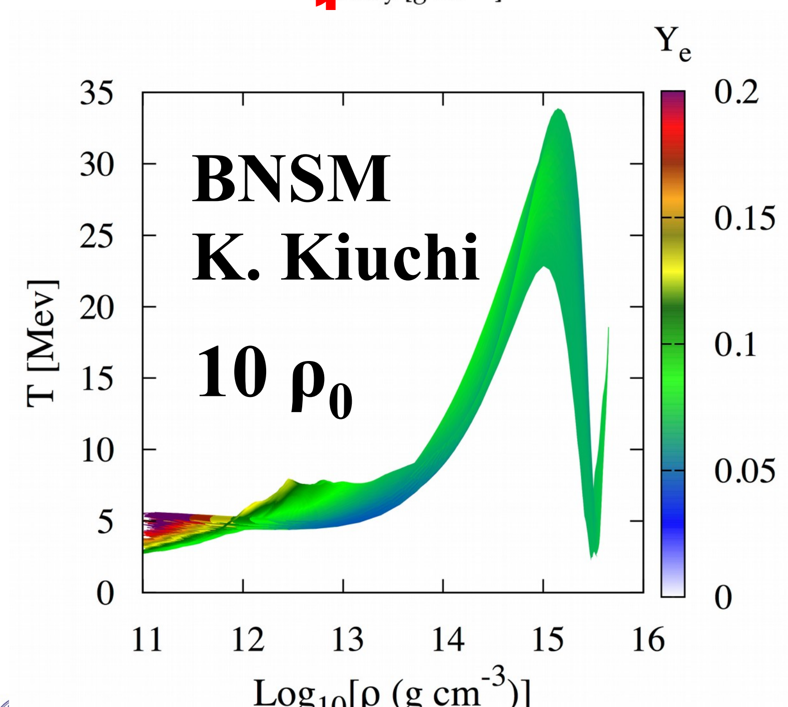


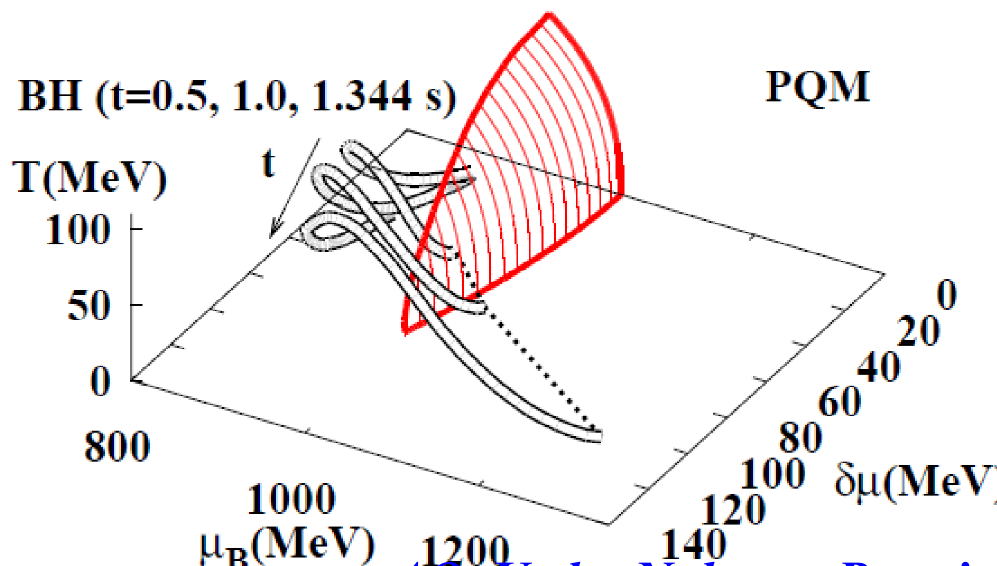
J.M.Lattimer, M.Prakash, PRep.621('16)127

(ρ, T, Y_e) during SN, BH formation, BNSM





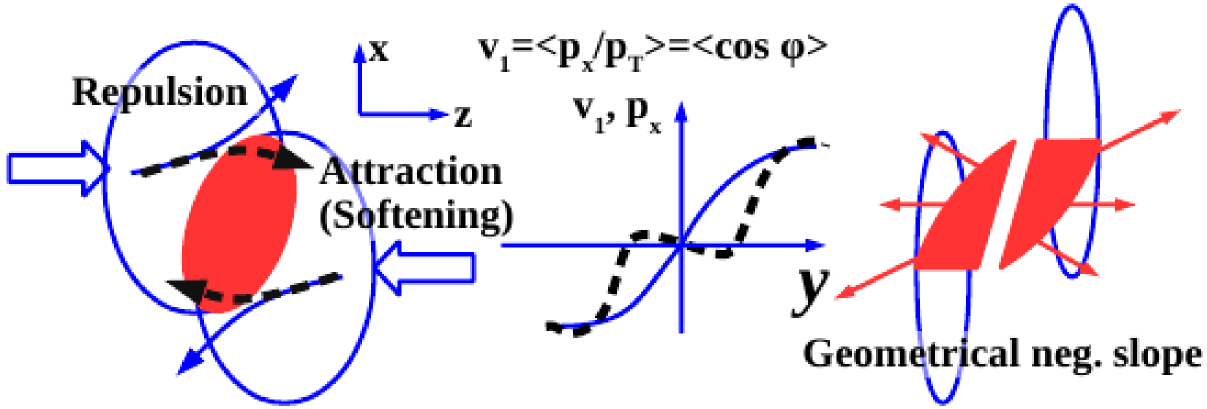




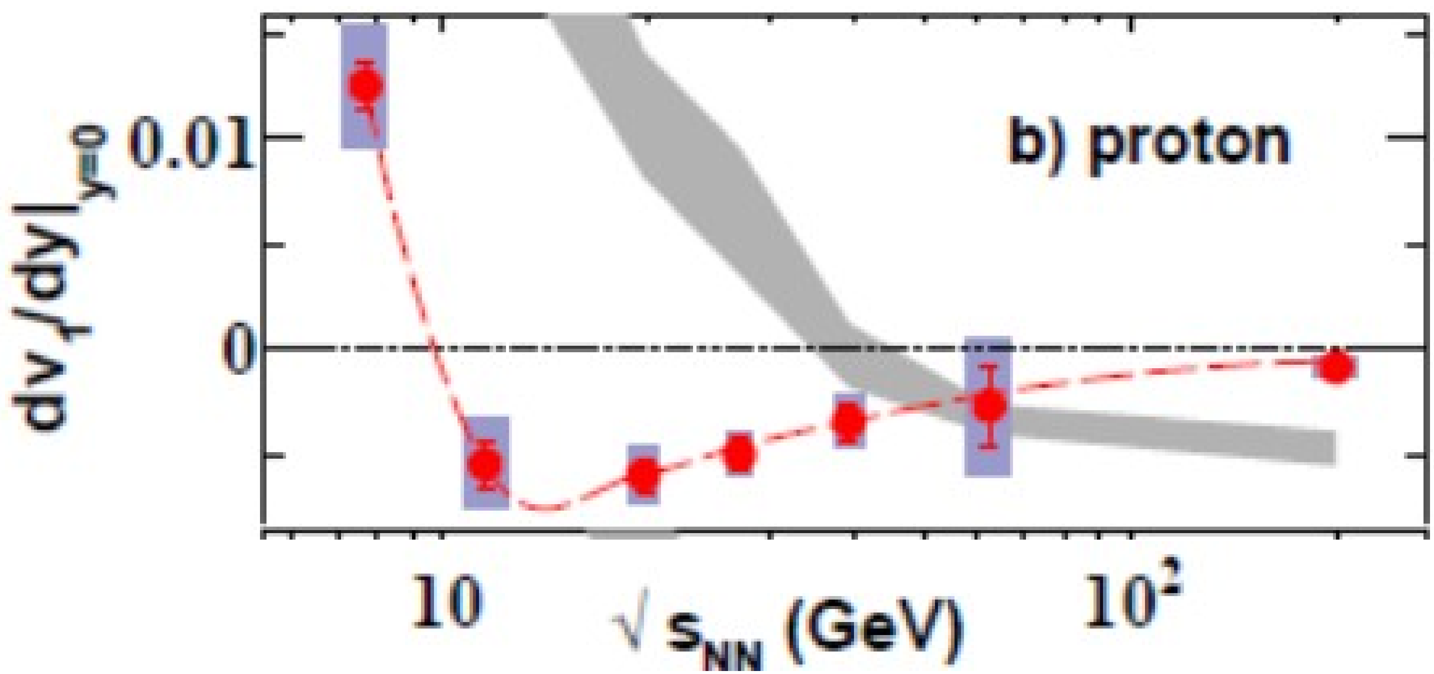
AO, Ueda, Nakano, Ruggieri, Sumiyoshi, PLB704('11),284

Negative Directed Flow

- **Directed Flow** $v_1 = \langle \cos\phi \rangle = \langle p_x/p_T \rangle$, $\text{Slope} = dv_1/dy$



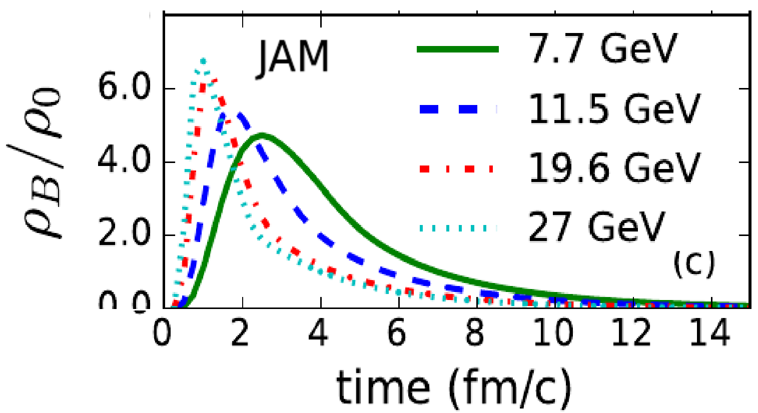
- **Negative Flow in Heavy-Ion Collisions**

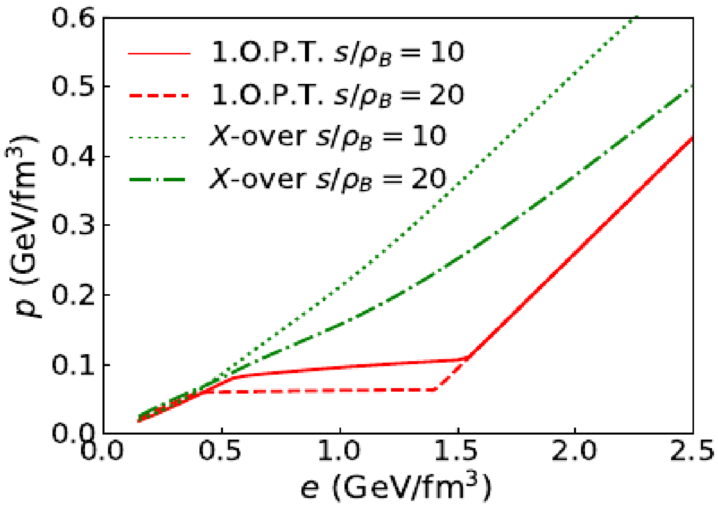


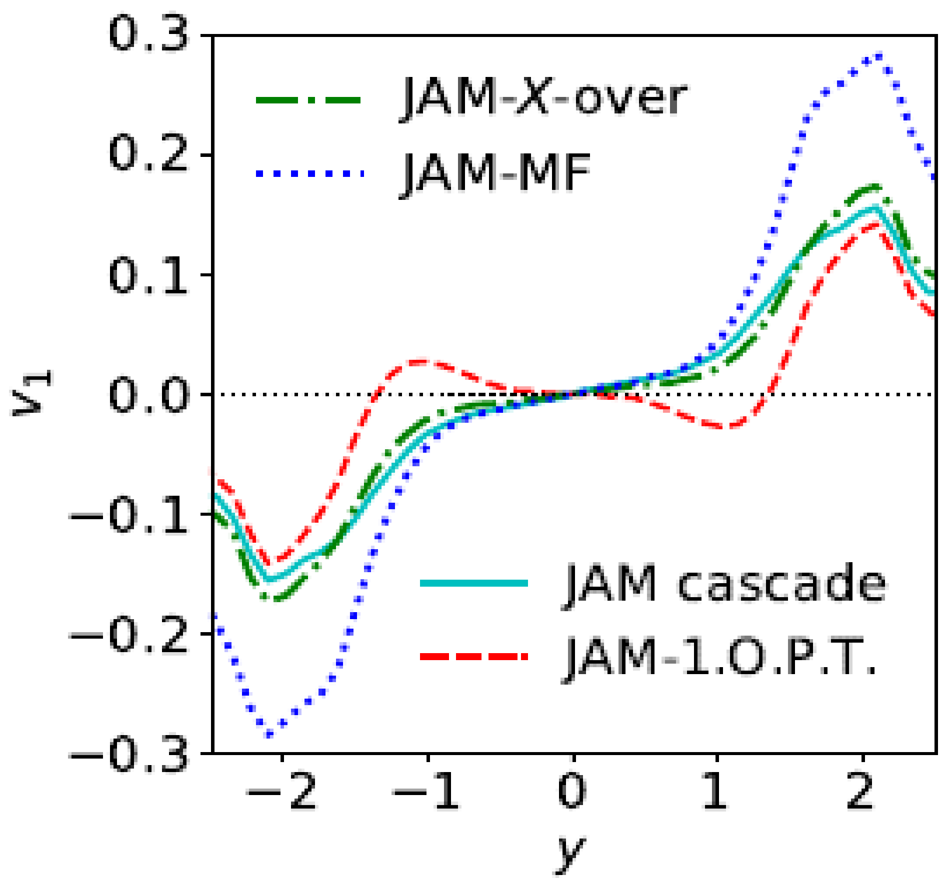
STAR Collab. (L. Adamczyk et al.), Phys.Rev.Lett. 112 ('14), 162301

Negative Directed Flow

- **Negative Directed Flow slope at $\sqrt{s_{NN}}$= 11.5 GeV (STAR ('14))**
  → Strong softening of EOS is necessary at n > (5-10) n_0







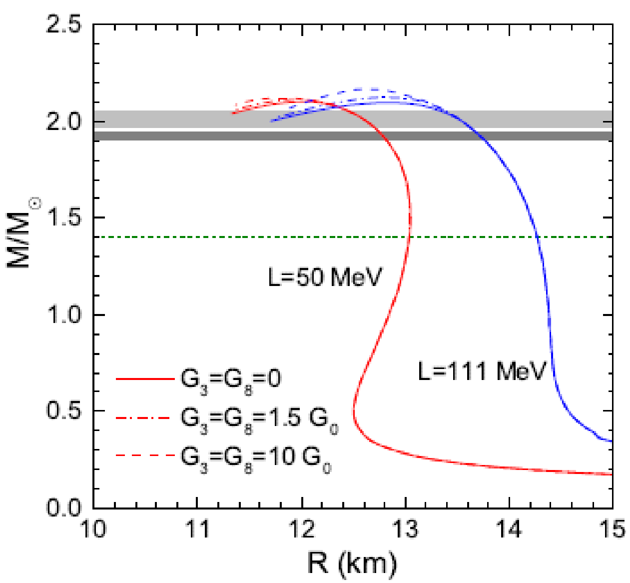
Y.Nara, H.Niemi, AO, H.Stoecker, PRC94('16)034906.
Y. Nara, H. Niemi, AO, J. Steinheimer, X.-F. Luo, H. Stoecker, EPJA 54 ('18)18

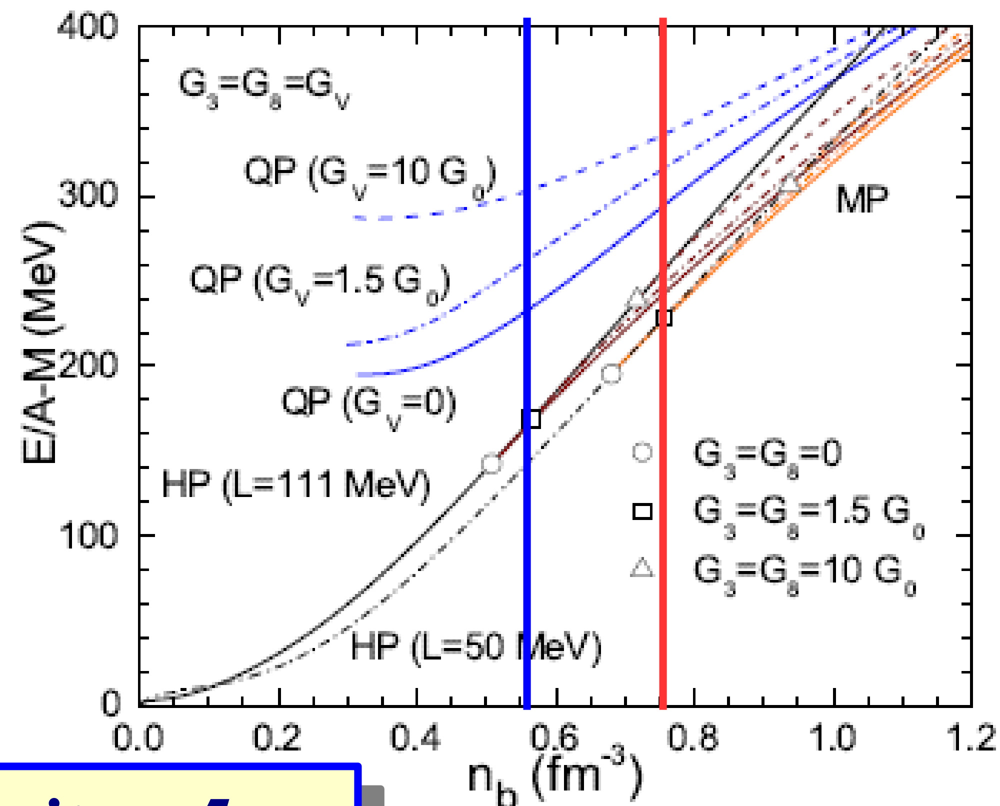
Isospin & Hypercharge Sym. E in quark matter

- **Two types of vector int. in NJL → Isospin & Hypercharge Sym. E**
  X.Wu, AO, H.Shen, PRC to appear (arXiv:1806.03760)

$$\mathcal{L}_v = -G_0(\bar{q}\gamma_\mu q)^2 - G_v \sum_i \left[(\bar{q}\gamma_\mu\lambda_i q)^2 + (\bar{q}i\gamma_5\gamma_\mu\lambda_i q)^2\right]$$

$$E = \alpha^2 S(n) + \alpha_Y^2 S_Y(n)\ ,\ \alpha = -2\langle T_z\rangle/B\ ,\ \alpha_Y = \langle B+S\rangle/B$$





L= 50 MeV → transition density ~ 5 n_0

Neutron Star MR curve

- **Our constraint is consistent with many of previous ones.**
  - $R_{1.4}$=(10.6-12.2) km *Present work (TLOK + 2 $M_{\odot}$) OKLTW, in prog.*
  - LIGO-Virgo (Tidal deformability Λ from BNSM)
    (10.5-13.3) km *Abbott+('18b)*
    (9.1-14.0) km *De+('18) (Λ)*
  - Theoretical Estimates
    (10.7-13.1) km
    Lattimer, Prakash('16)
    (10.0-13.6) km
    Annala+('18) (χEFT+pQCD)
    (10-13.6) km
    Tews+('18)(χEFT+ c_s)
    (12.0-13.6) km
    Fattoyev+('18) (PREX)
    12.7 ± 0.4 km
    Margueron+('18) (n expansion)