Nuclear matter symmetry energy and neutron star properties --- Neutron star radius from gravitational wave vs nuclear experiments --

Akira Ohnishi
(Yukawa Inst. for Theor. Phys., Kyoto U.)
in collaboraton with
E. E. Kolomeitsev (Matej Bel U.), James M. Lattimer (Stony Brook), Ingo Tews (LANL), Xuhao Wu (Nankai U./YITP)

Gravitational wave physics and astronomy: Genesis,
2nd annual area symposium, Nov.26-28, 2018, Kyoto, Japan

- *I. Tews, J. M. Lattimer, AO, E.E.Kolomeitsev, ApJ 848('17) 105 [arXiv:1611.07133]*
- *AO, Kolomeitsev, Lattimer, Tews, X.Wu, in prog.*

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Introduction

Impact of GW from binary neutron star merger

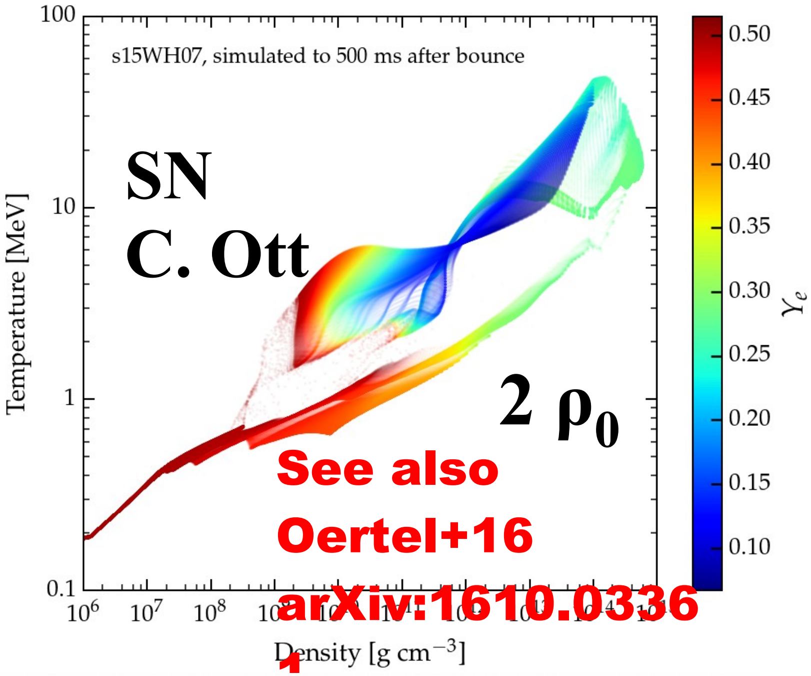
- **GW170817 from NS-NS → Multi messenger astrophysics**

  B.P.Abbott+ [LIGO Sci. and Virgo Collab.], PRL119('17)161101

- **Neutron Star Maximum Mass**
  - **No prompt collapse, No GW signal from Hyper Massive NS**
    → Mmax(T=0,ω=0) < Mmax(T=0,ω) < M < Mmax(T,ω)
- **Neutron Star Radius**
  - **Inspiral region → Tidal deformability (Λ) → NS radius (e.g. R1.4)**
- **Nucleosynthesis site of r-process nuclei**
  - **kilonova/macronova from decay energy of the synthesized elements**
  - **r-process nucleosynthesis seems to occur in BNSM !**
- **Central Engine of (Short) Gamma-Ray Bursts**
- **GW as standard siren (Hubble constant)**

Courtesy of Y. Sekiguchi @ YKIS2018b

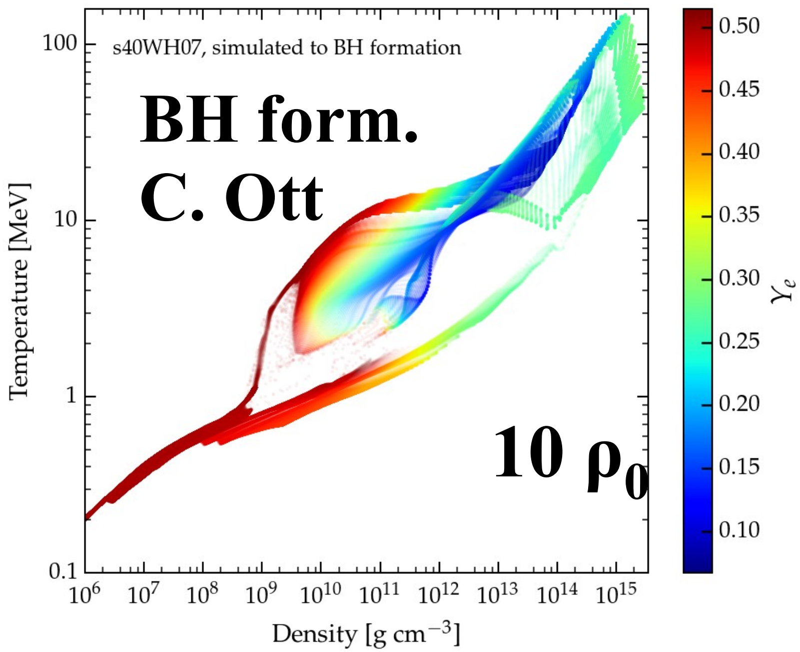
(ρ, T, Y_e) during SN, BH formation, BNSM



SN
C. Ott

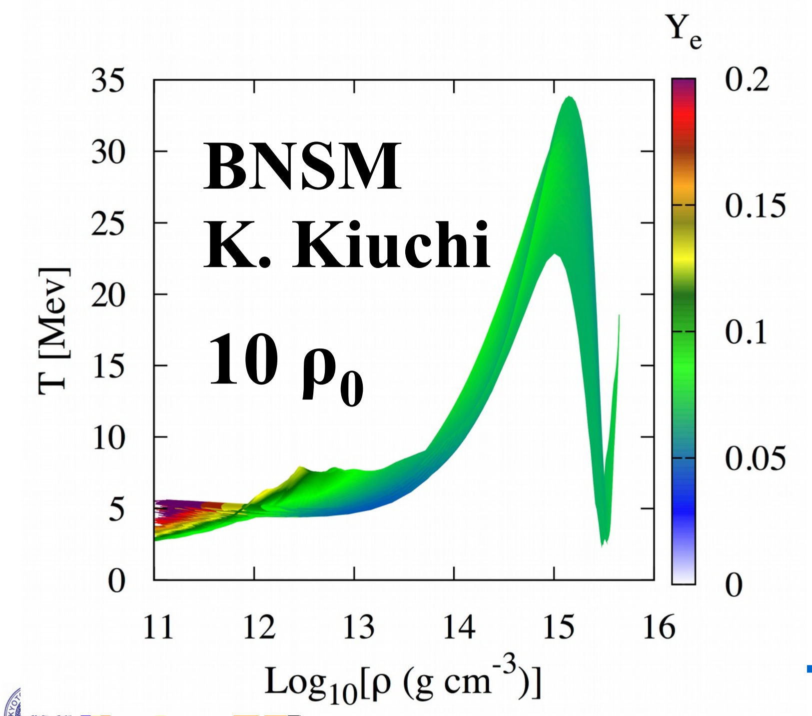
$2\ \rho_0$

See also
Oertel+16
arXiv:1610.03364



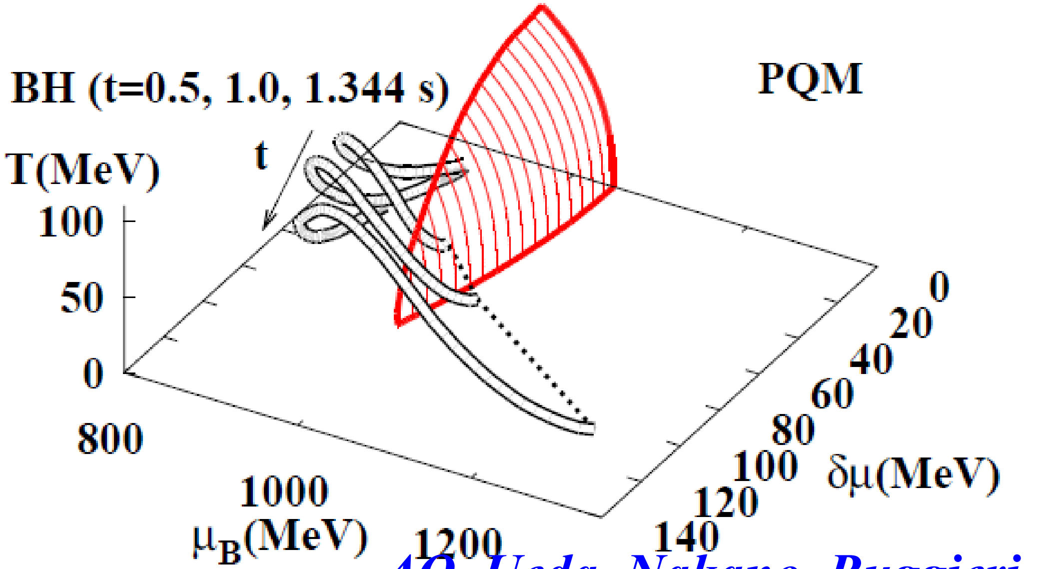
BH form.
C. Ott

$10\ \rho_0$



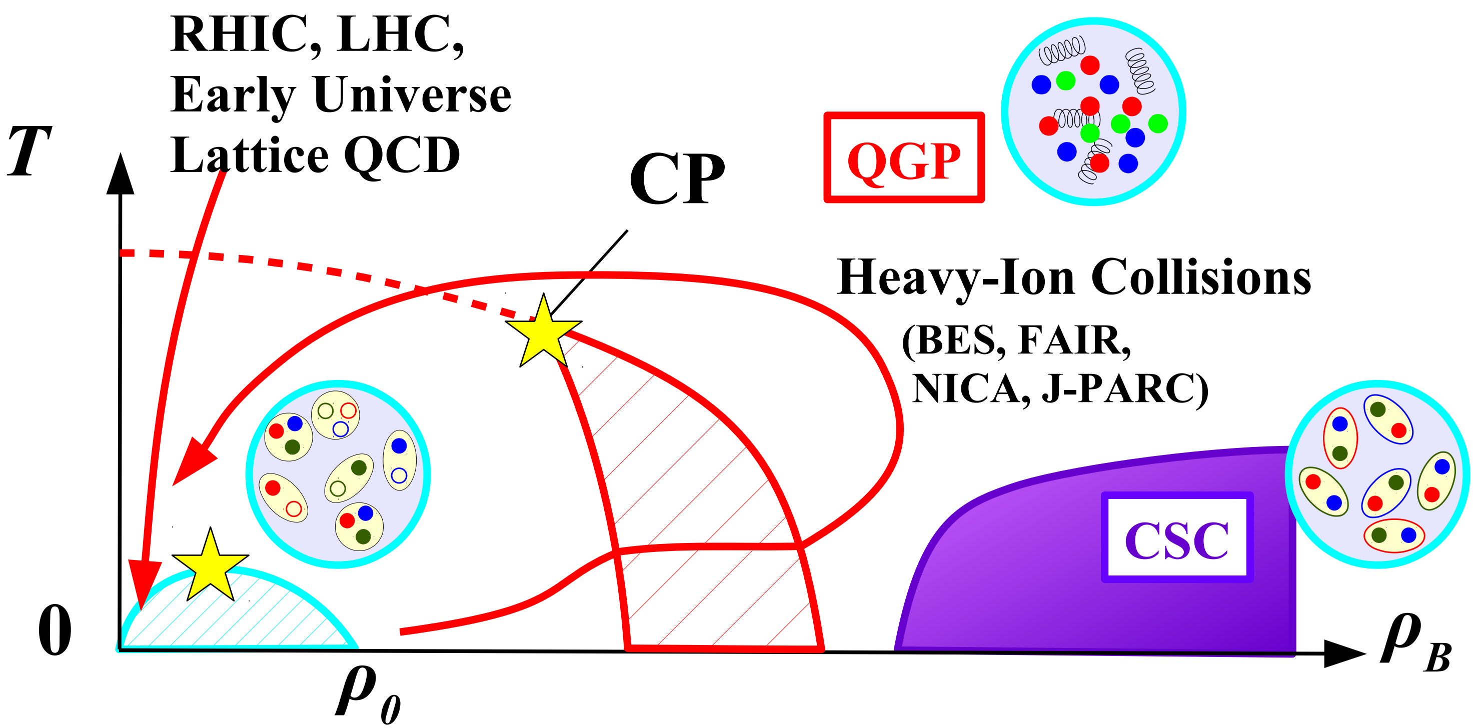
BNSM
K. Kiuchi

$10\ \rho_0$

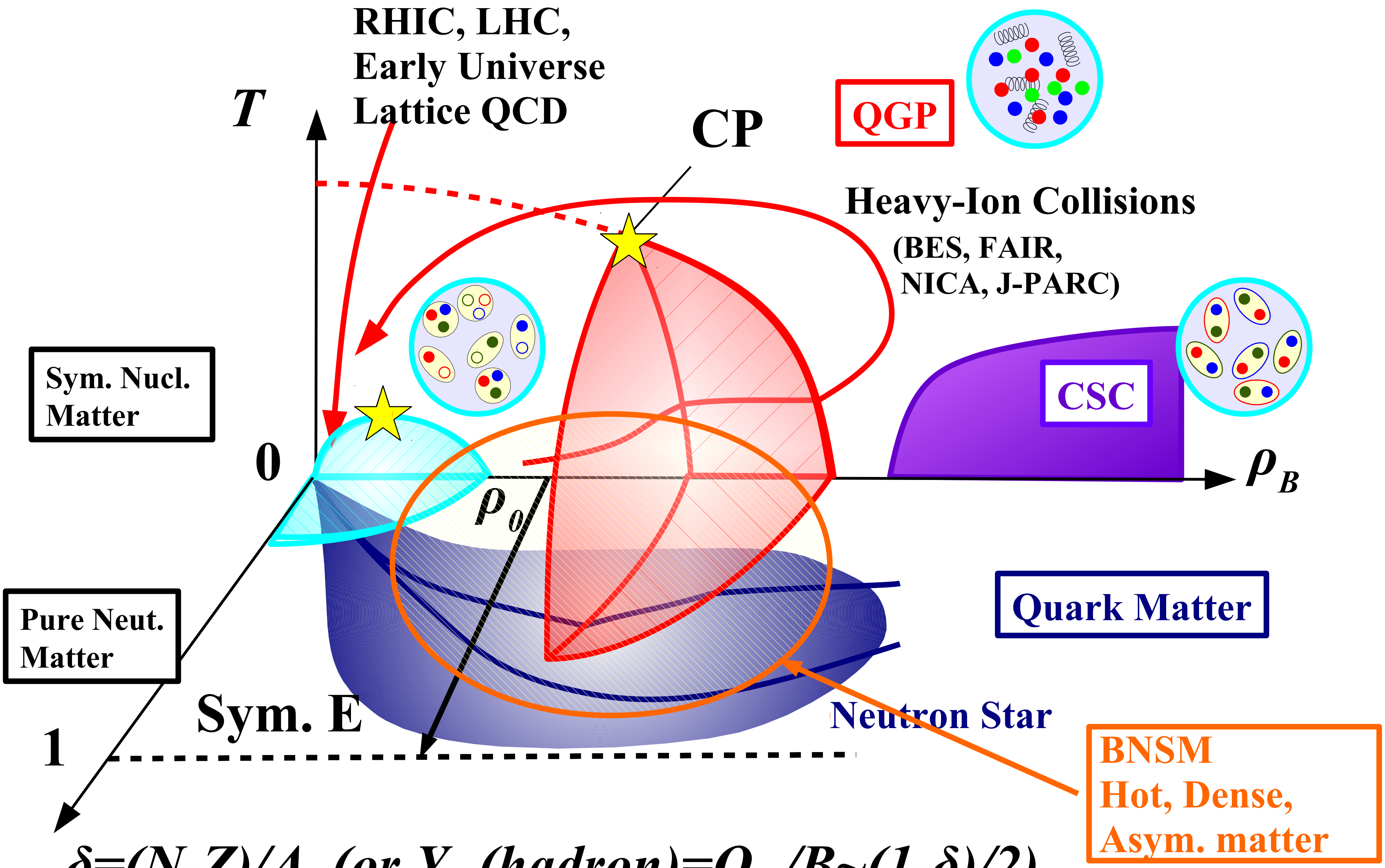


AO, Ueda, Nakano, Ruggieri, Sumiyoshi, PLB704('11),284

QCD Phase Diagram



QCD Phase Diagram



RHIC, LHC,
Early Universe
Lattice QCD

T

CP

QGP

Heavy-Ion Collisions
(BES, FAIR,
NICA, J-PARC)

Sym. Nucl.
Matter

0

ρ_0

CSC

ρ_B

Pure Neut.
Matter

Quark Matter

Sym. E

1

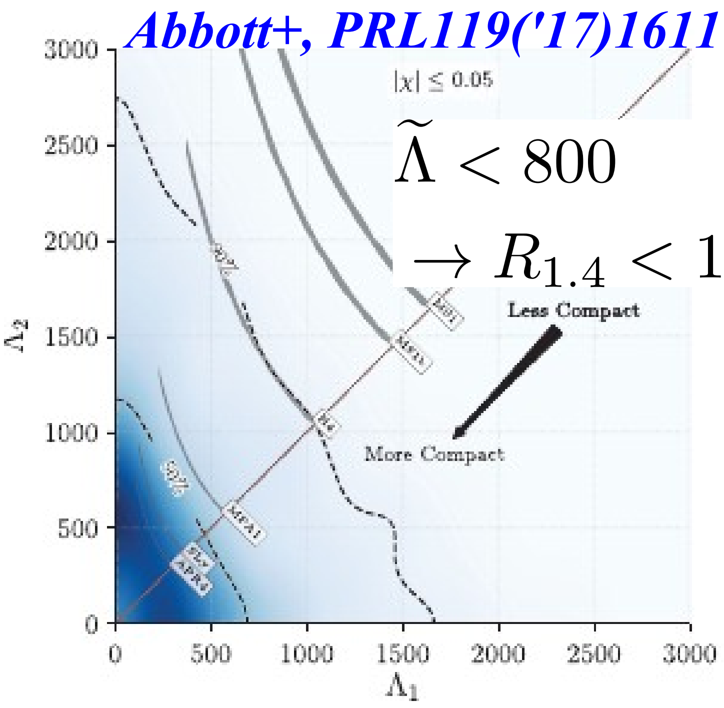
Neutron Star

BNSM
Hot, Dense,
Asym. matter

$$\delta=(N-Z)/A \quad (\text{or } Y_Q(\text{hadron})=Q_h/B\sim(1-\delta)/2)$$

AO, arXiv:1712.01088

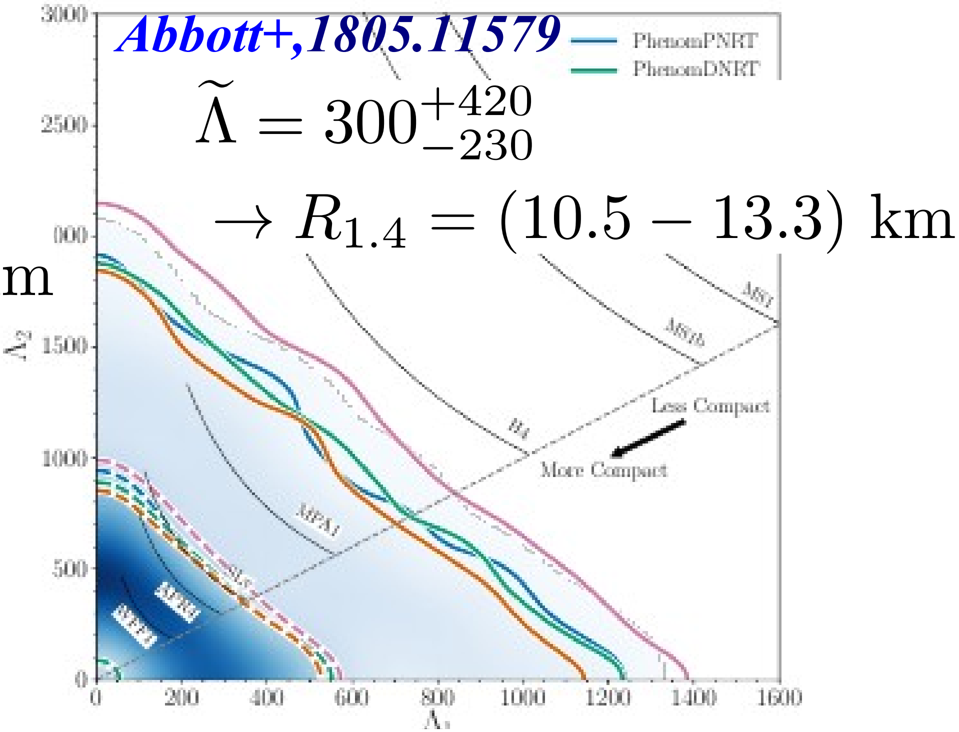
Constraints on EOS from GW170817



Abbott+, PRL119('17)161101

$\tilde{\Lambda} < 800$

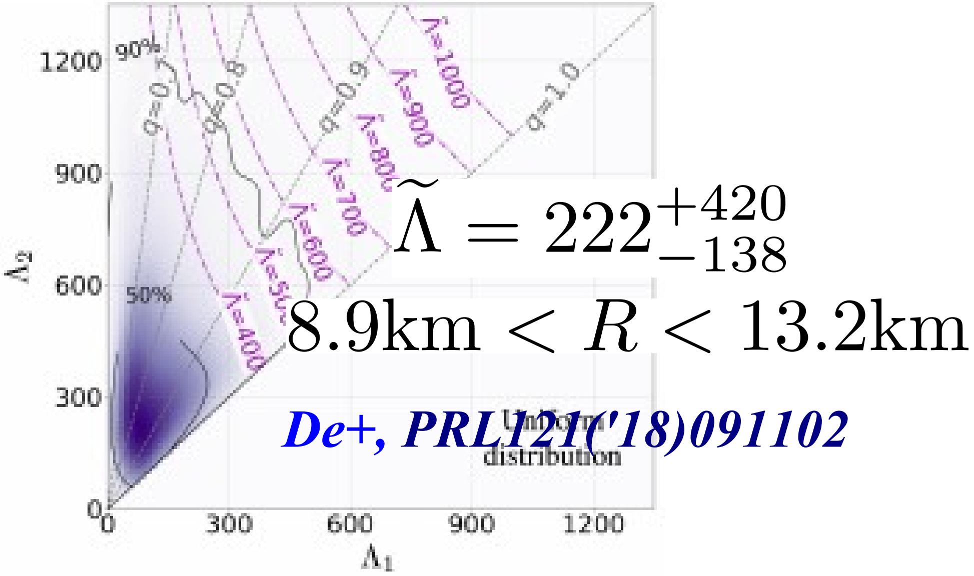
$\rightarrow R_{1.4} < 13.6$ km



Abbott+,1805.11579

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

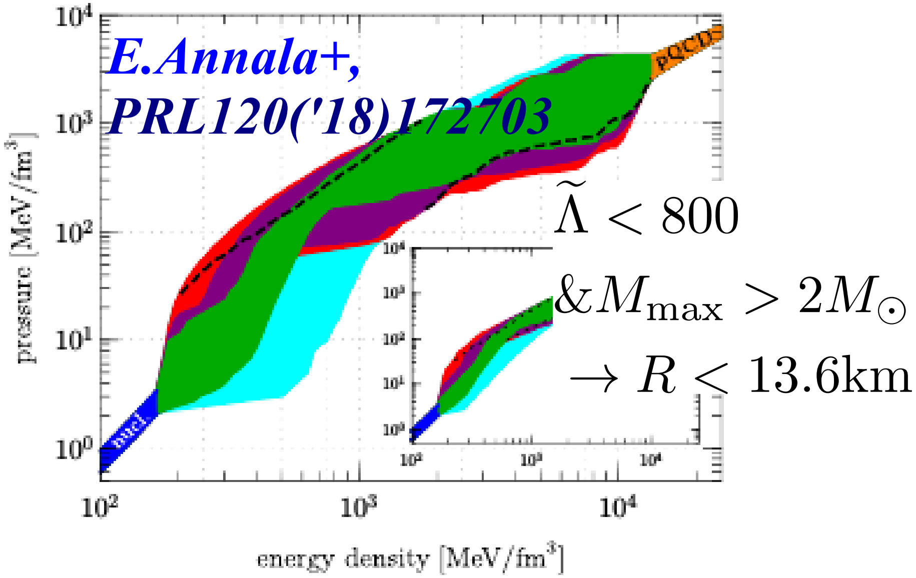
$\rightarrow R_{1.4} = (10.5 - 13.3)$ km



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

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

De+, PRL121('18)091102



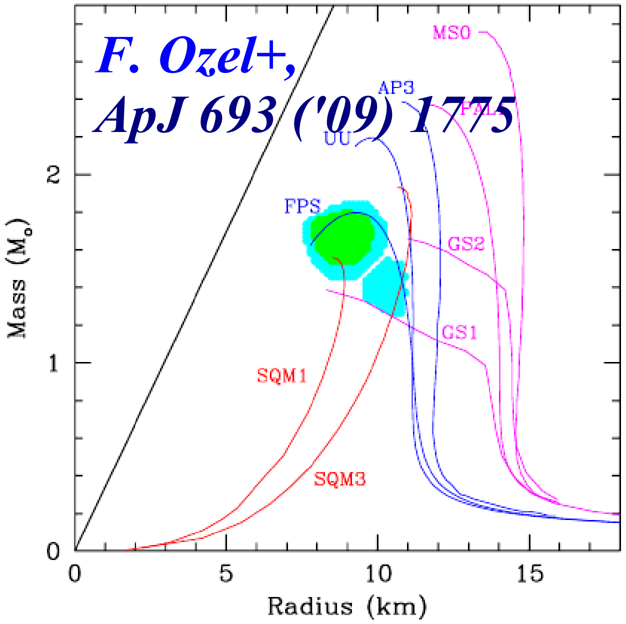
E.Annala+, PRL120('18)172703

$\tilde{\Lambda} < 800$

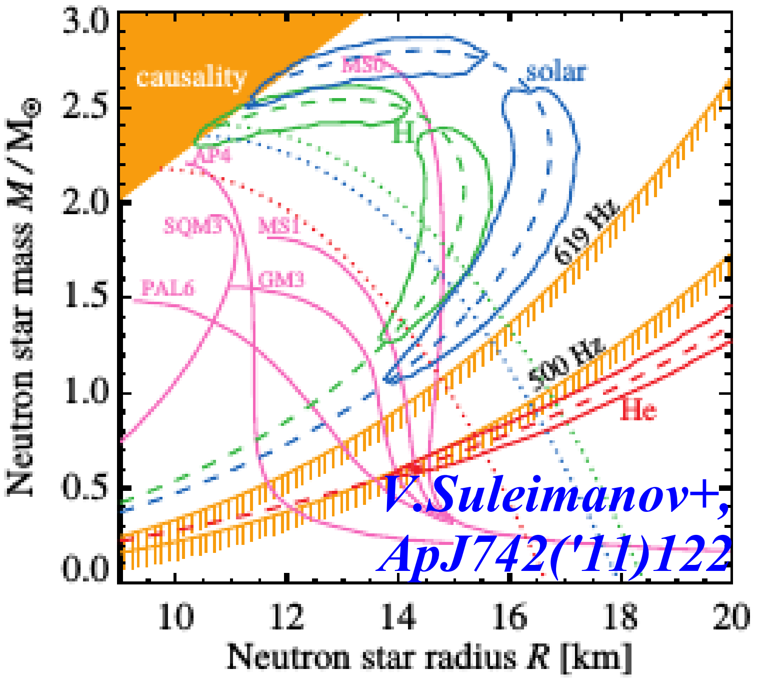
$\& M_{\max} > 2M_{\odot}$

$\rightarrow R < 13.6\text{km}$

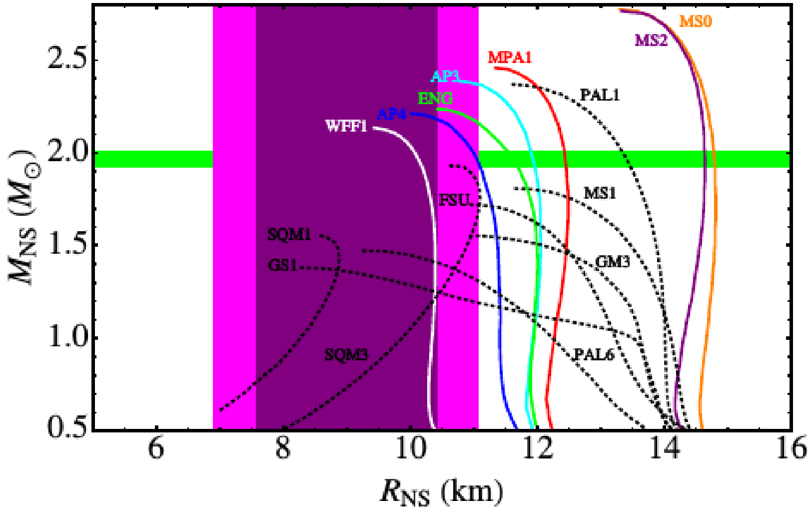
MR curve from X-ray burst



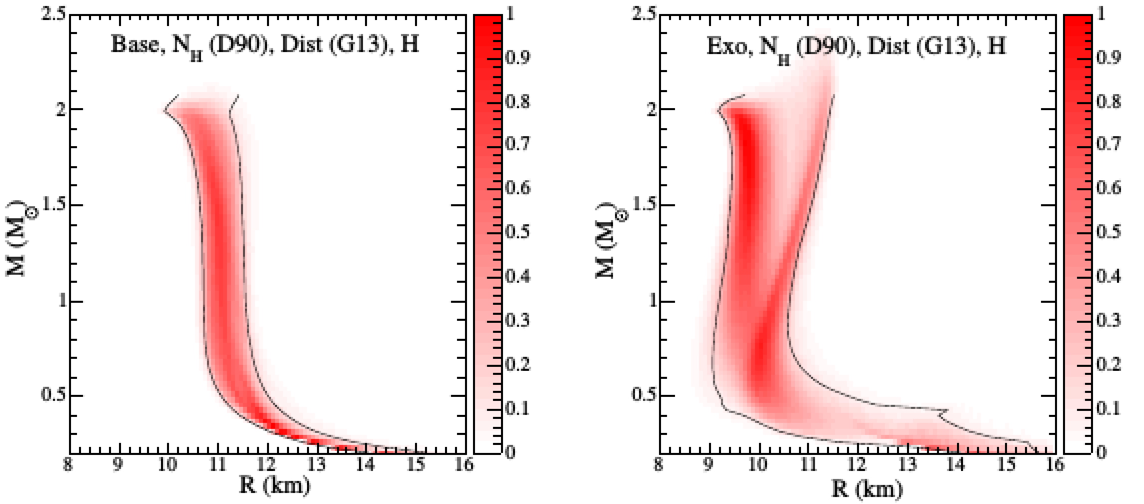
F. Ozel+, ApJ 693 ('09) 1775



V.Suleimanov+, ApJ742('11)122



S. Guillot+, ApJ772('13)7

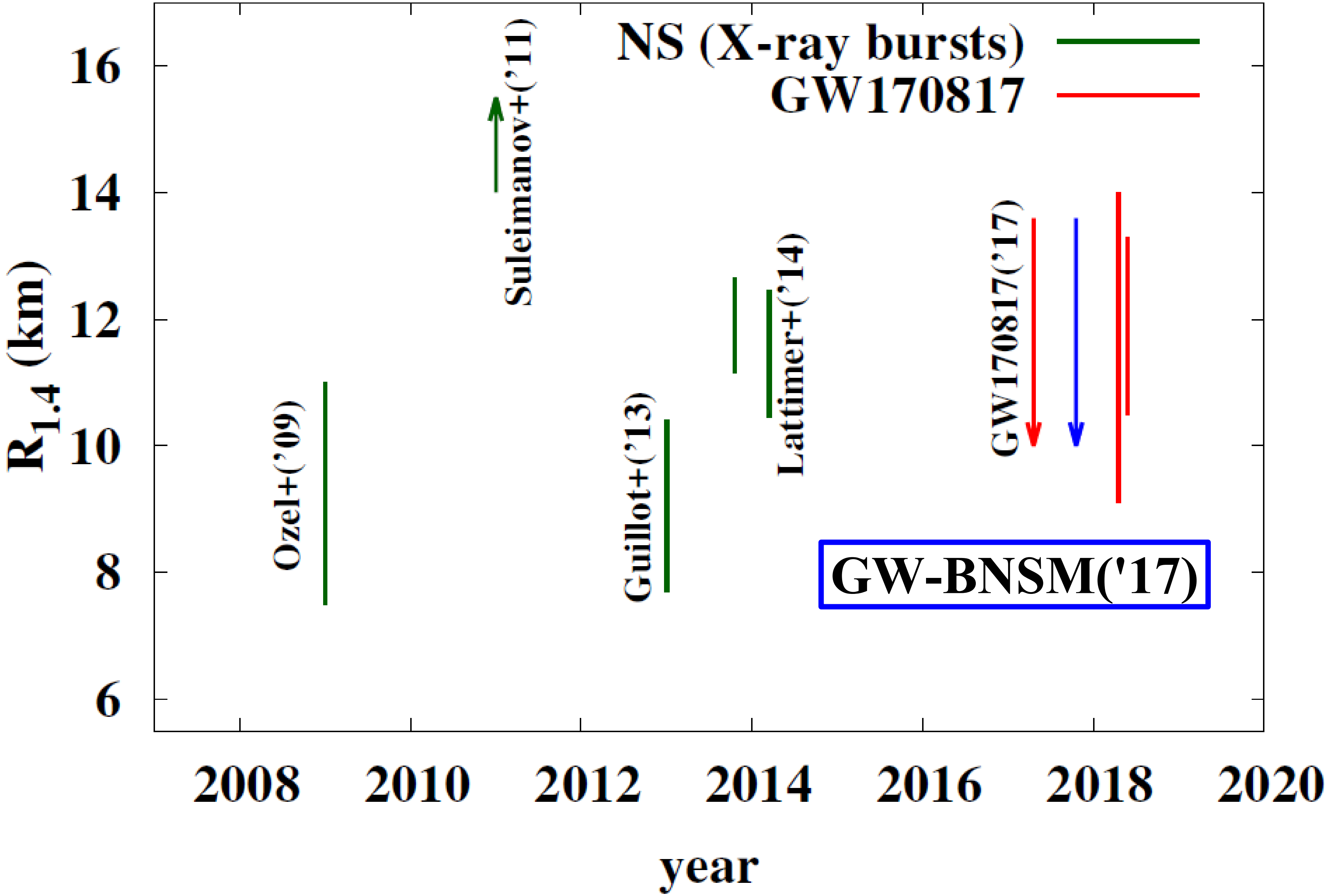


J.M.Lattimer, A.W.Steiner, ApJ784('14)123

Neutron Star Radius from Astronomical Observations

- **From X-ray bursts**
  - **R=9 or 11 km (7.5-11 km)** *F. Özel+, ApJ693('09)1775*
    [touch down = Eddington limit?]
  - **R> 14 km** *V.Suleimanov+, ApJ742('11)122*
    [color correcton factor ?]
  - **$R=9.1^{+1.3}_{-1.4}$ km** *S.Guillot+, ApJ772('13)7*
    [Common R ?; Denied later by the authors in ApJ 796('14)L3 (1409.4306)]
  - **R=10.4-12.7 km** *J.M.Lattimer, A.W.Steiner, ApJ784('14)123*
    (R=(11.15-12.66) km (normal EOS), R=(10.45-12.45) km (Exo EOS))
- **Gravitational Waves**
  - **$\bar{\Lambda}< 800$** *B.P.Abbott+,PRL119('17)161101* **→ R < 13.6 km**
  - **$\bar{\Lambda}=300^{+420}_{-230}$ → R=(10.5-13.3) km** *B.P.Abbott+ (LIGO-Virgo), 1805.11579*
  - **$\bar{\Lambda}=222^{+420}_{-138}$ → R=(9.1-14.0) km** *S.De+, PRL121('18)091102*
  - **$\bar{\Lambda}<800$ & $M_{\max}>2\,M_\odot$ → R < 13.6 km** *E.Annala+, PRL120('18)172703*

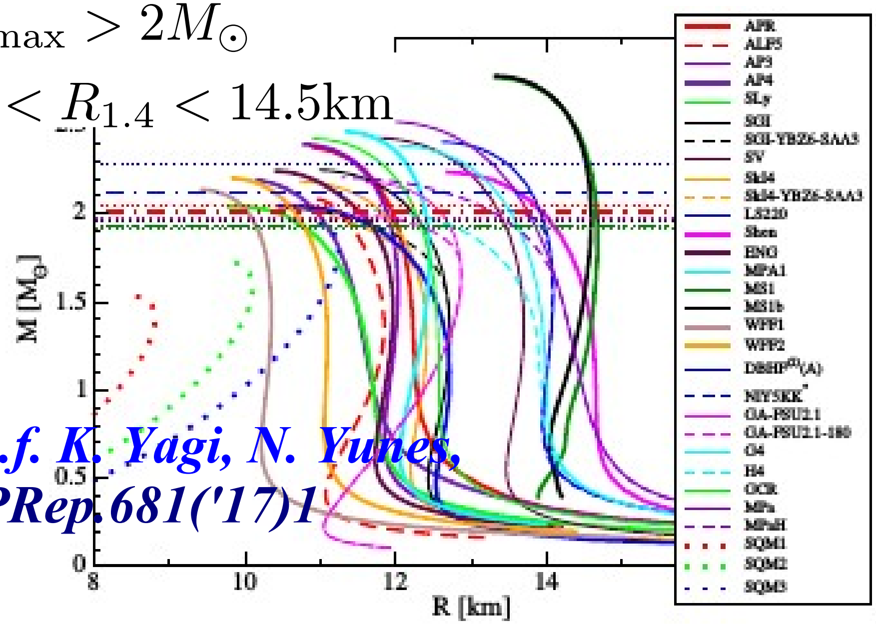
Time dependence of Neutron Star Radius ($R_{1.4}$)



Constraints from Nuclear Physics (+α)

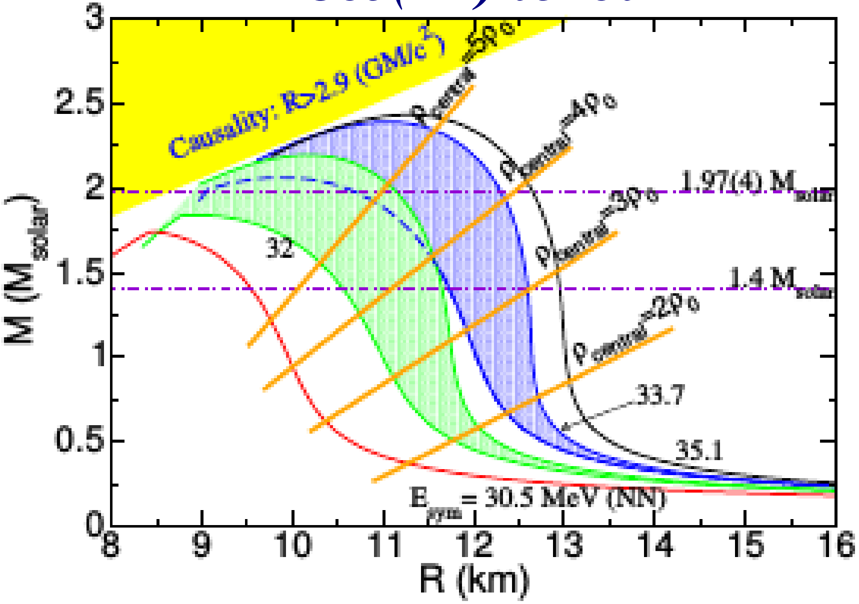
$M_{\rm max} > 2M_\odot$

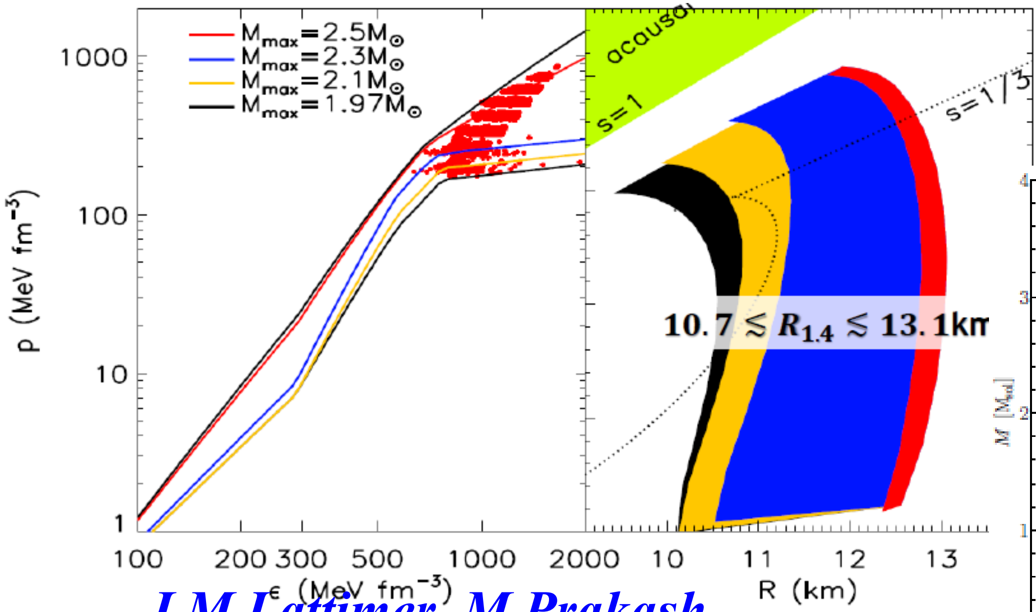
$10 < R_{1.4} < 14.5{\rm km}$



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

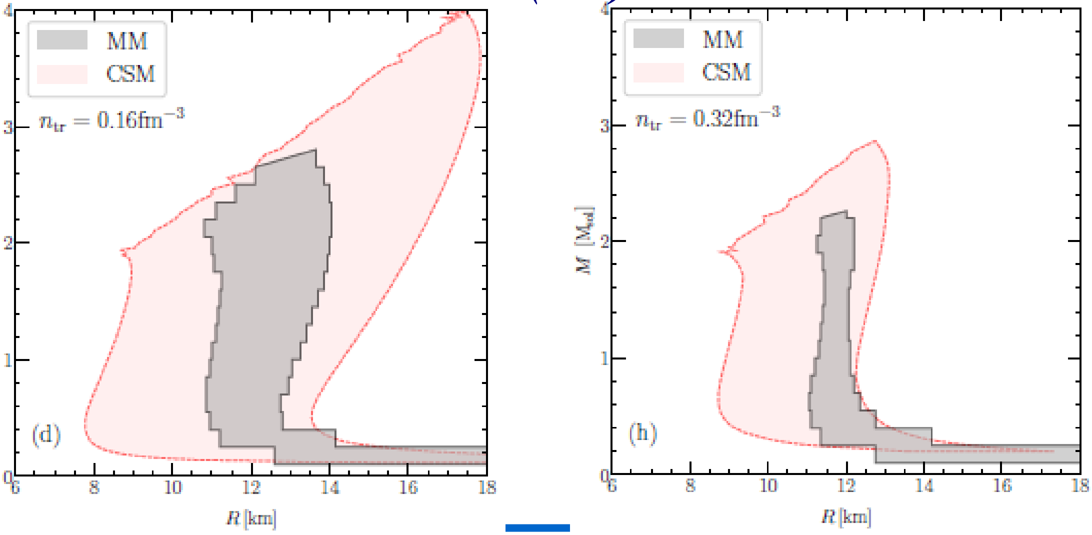
S.Gandolfi, J.Carlson, S.Reddy, PRC85('12) 032801





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

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



Neutron Star Radius from Nuclear Physics (+α)

- **Impact of 2 $M_\odot$ neutron star**

  P.Demorest+, Nature 467('10)1081 (1010.5788),
  J.Antoniadis+, Science340('13)6131(1304.6875)

  - **R=(6-15) km (before 2010) → R=(10-15) km (with 2 $M_\odot$)**

- **Impact of symmetry energy parameters**
  - **S_0 → R=(10.5-13) km** *S.Gandolfi, J.Carlson, S.Reddy, PRC85('12)032801*
  - **(S_0,L) → R=(10.7-13.1) km** *J.M.Lattimer,M.Prakash, PRep.621('16)127*

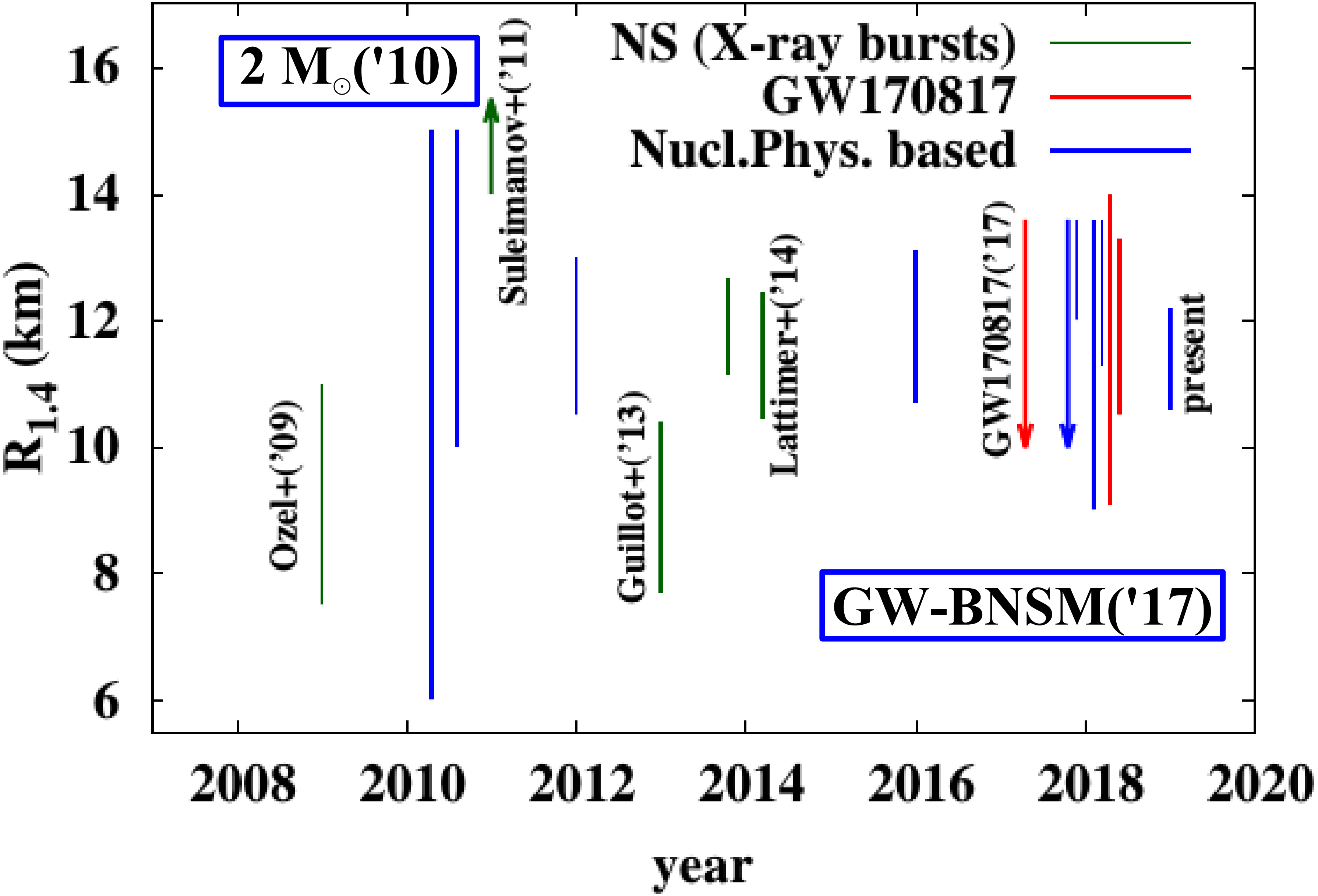
- **Chiral Effective Field Theory (Chiral EFT)**
  - **χEFT+pQCD+GW → R=(10.0-13.6) km**

    E.Annala, T.Gorda, A.Kurkela, A.Vuorinen, PRL120('18)172703
  - **χEFT+c_s^2 → R=(9.0-13.6) km [min. model R=(11.3-13.6) km]**

    I. Tews, J. Margueron, S. Reddy, PRC98 ('18)045804
  - **Neutron skin thickness from ν scatt. (PREX) → R=(12.0-13.6) km**

    F.J. Fattoyev, J. Piekarewicz, C.J. Horowicz, PRL120 ('18)172702

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



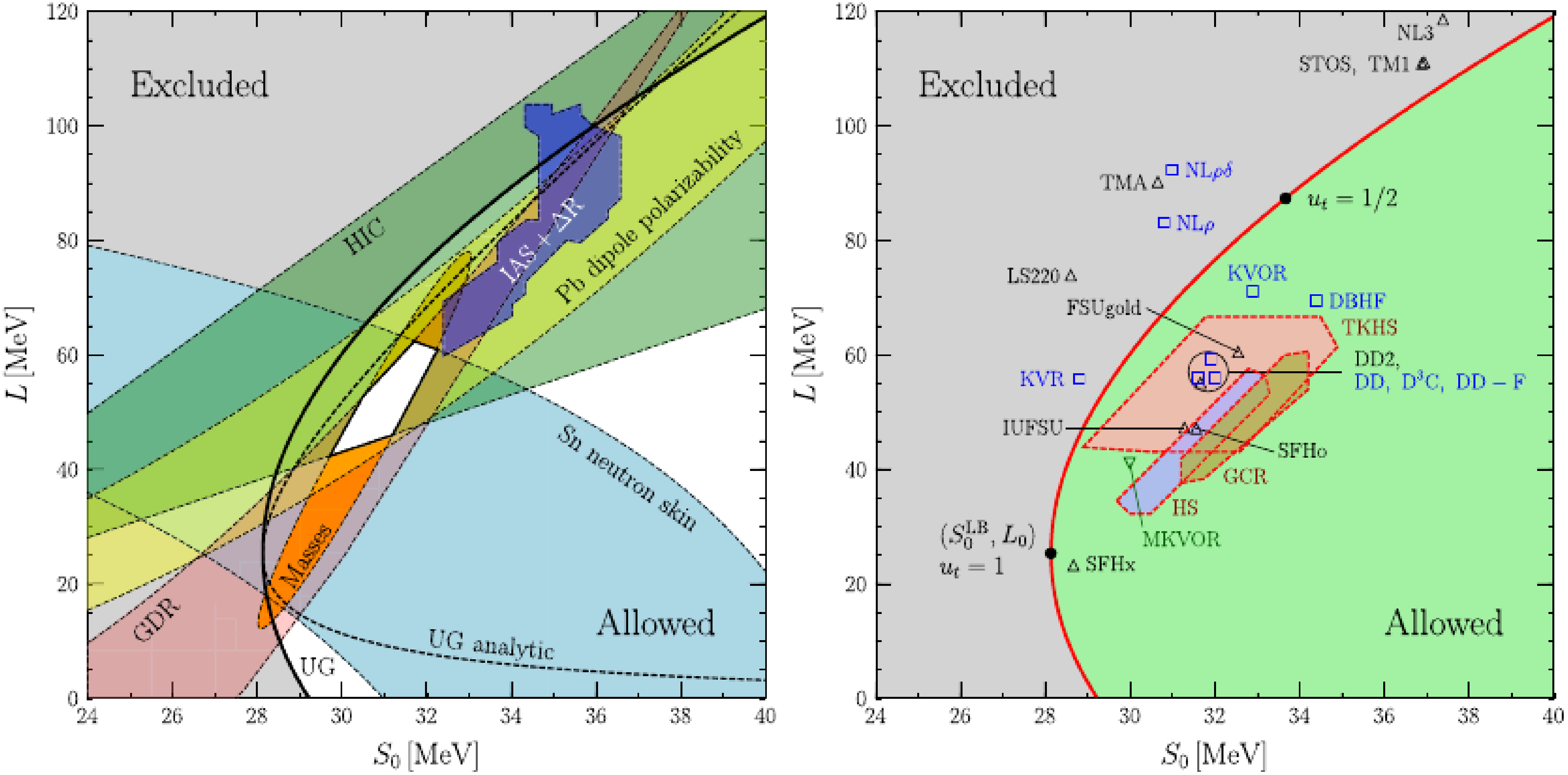
Symmetry Energy Parameters (S_0 , L) affect Neutron Star Radius.

How about higher-order parameters ?

Symmetry Energy Parameters, Nuclear Matter EOS, and Neutron Star Radius

Constraint on (S_0, L) from Lower Bound of PNM Energy

- **Unitary gas ($E_{PNM} > E_{UG}$) + 2 $M_\odot$ constraints rule out 5 EOSs (incl. LS220, Shen) out of 10 numerically tabulated ones.**



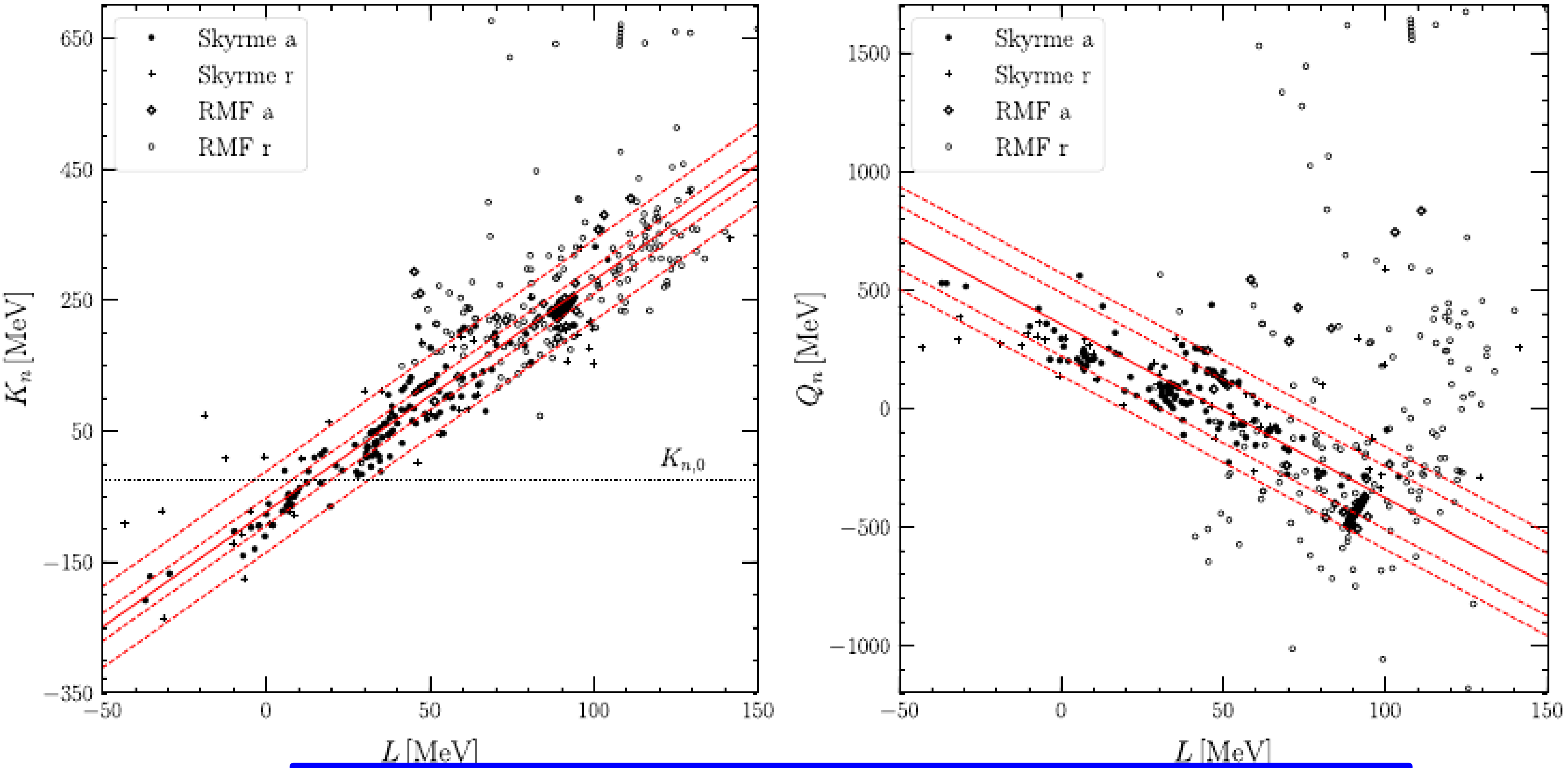
I. Tews, J.M.Lattimer, AO, E.E.Kolomeitsev (TLOK), ApJ 848 ('17)105

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

Fermi momentum (k_F) expansion

TLOK

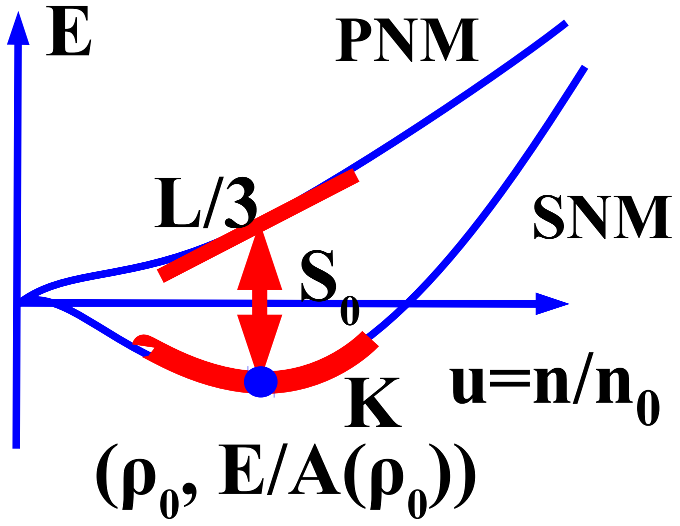
- **Saturation & Symmetry Energy Parameters**

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

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

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

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



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*

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

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

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

Expansion Coefficients

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

TLOK

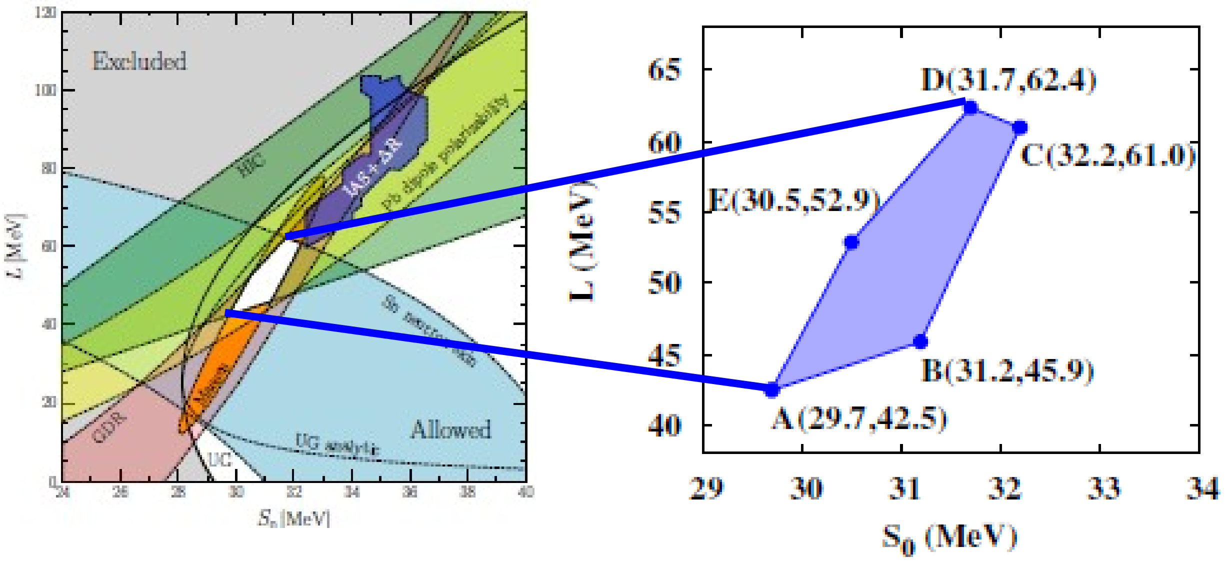
$$\begin{array}{llll}
a_0 = -4T_0 & +20E_0 & +K_0 & -Q_0/6 \\
b_0 = 6T_0 & -45E_0 & -5K_0/2 & +Q_0/2 \\
c_0 = -4T_0 & +36E_0 & +2K_0 & -Q_0/2 \\
d_0 = T_0 & -10E_0 & -K_0/2 & +Q_0/6 \\
 & & & \\
a_s = -4T_s & +20S_0 - 19L/3 & +K_s & -Q_s/6 \\
b_s = 6T_s & -45S_0 + 15L & -5K_s/2 & +Q_s/2 \\
c_s = -4T_s & +36S_0 - 12L & +2K_s & -Q_s/2 \\
d_s = T_s & -10S_0 + 10L/3 & -K_s/2 & +Q_s/6
\end{array}$$

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

Tedious but straightforward calc.

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)

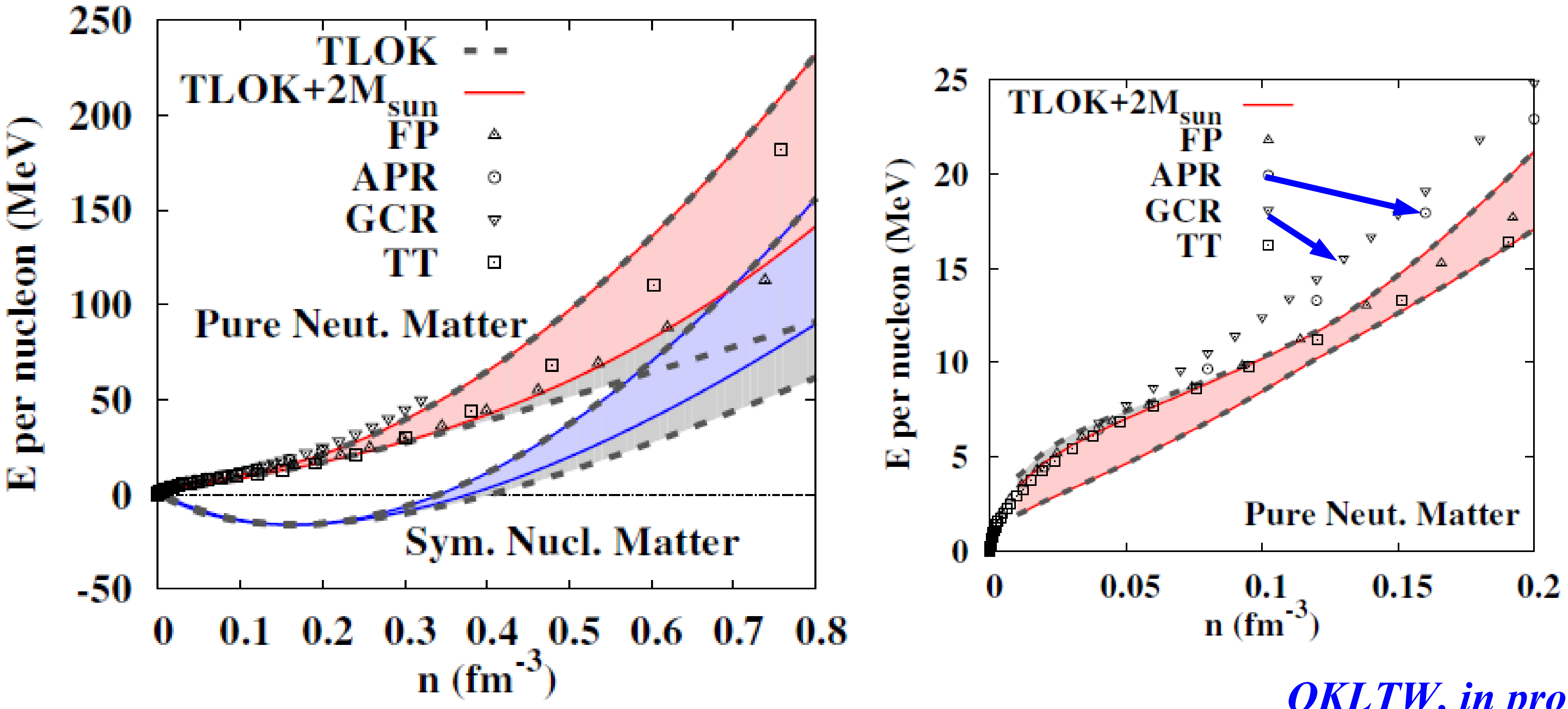


- **2 $M_\odot$ constraint**
  - **EOS should support 2 $M_\odot$ neutron stars.**

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

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

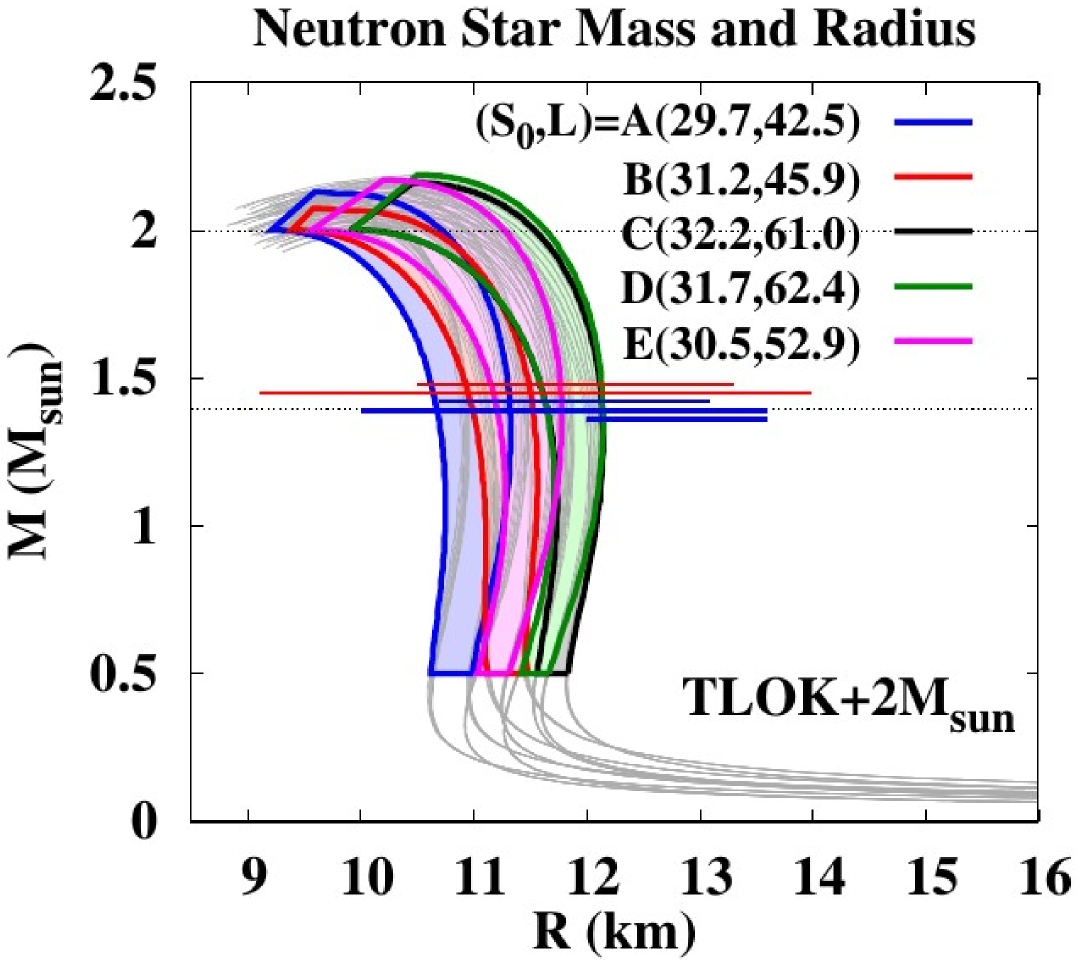
- **2M$_\odot$ constraint narrows the range of EOS.**
- **Consistent with FP and TT(Togashi-Takano) EOSs.**
- **APR and GCR(Gandolfi-Carlson-Reddy) EOSs seems to have larger S_0 values.**



OKLTW, in prog.

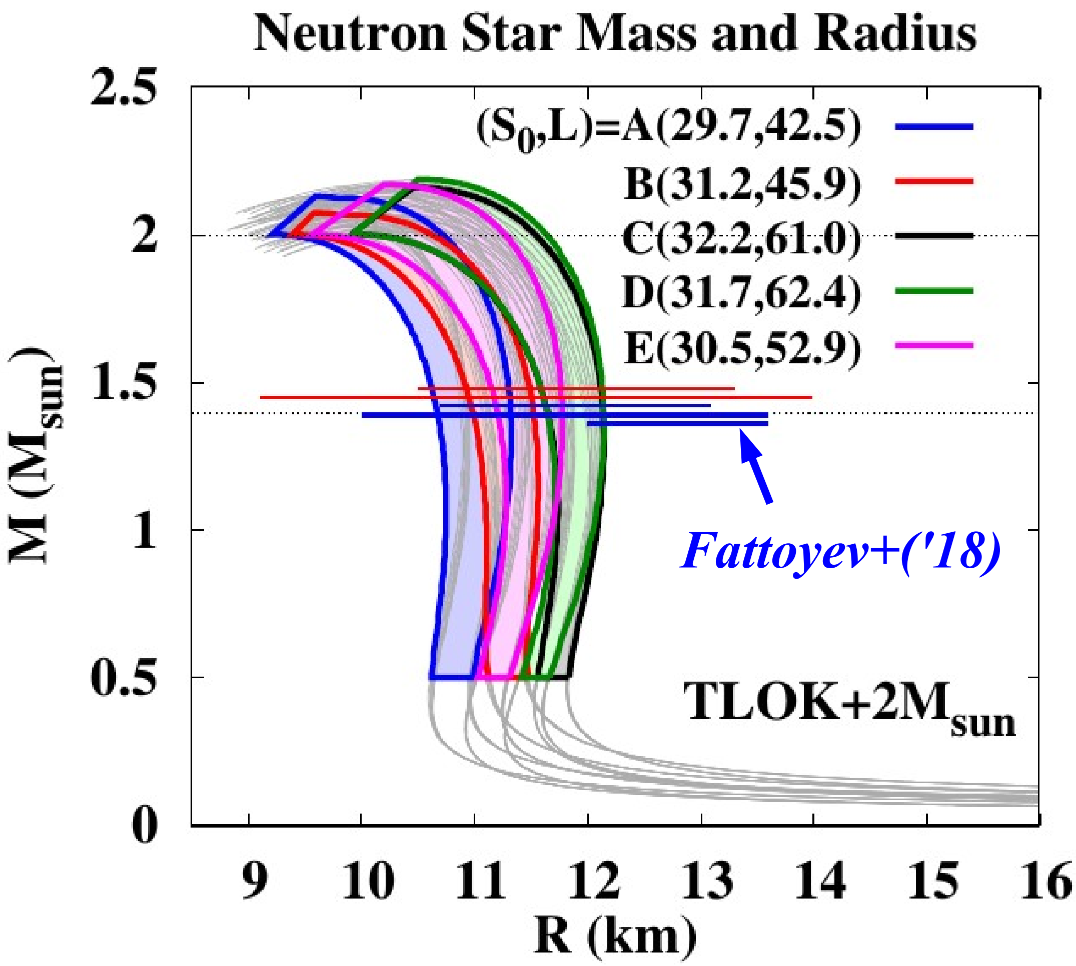
Neutron Star MR curve

- 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.

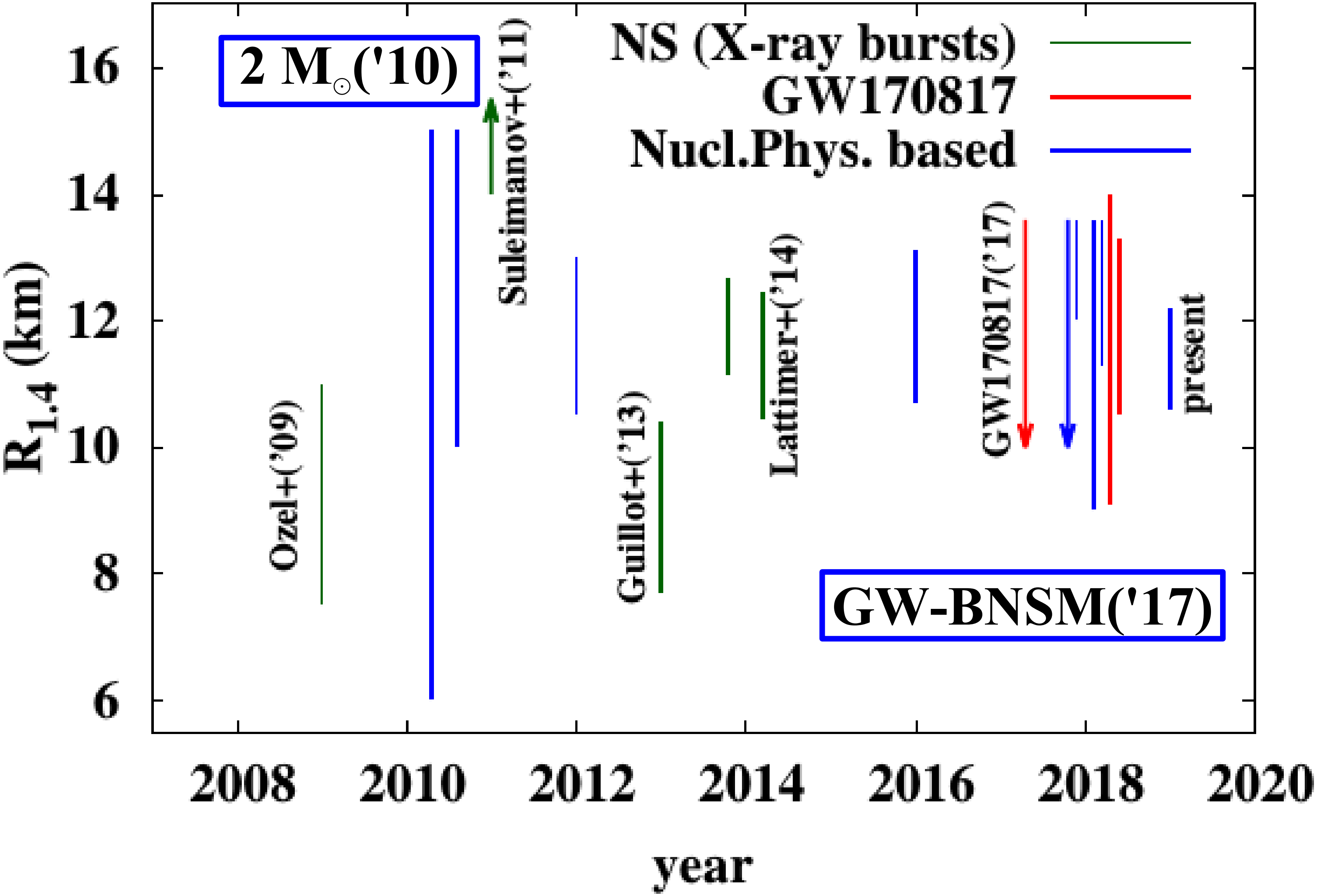


Neutron Star MR curve

- **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+, PRep.621('16)127
    (10.0-13.6) km
    Annala+,PRL120('18)172703
    (9-13.6) km
    Tews+, PRC98 ('18)045804
    (12.0-13.6) km
    F.J.Fattoyev+(PREX), PRL120 ('18)172702



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



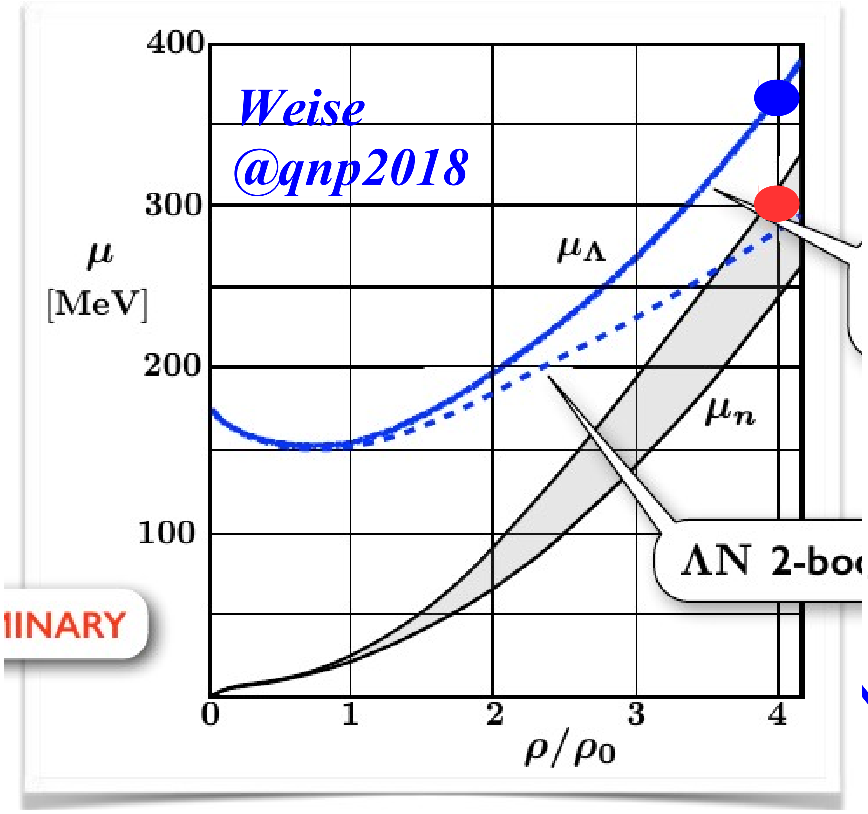
Implications to quark-hadron physics in cold dense matter

Questions !

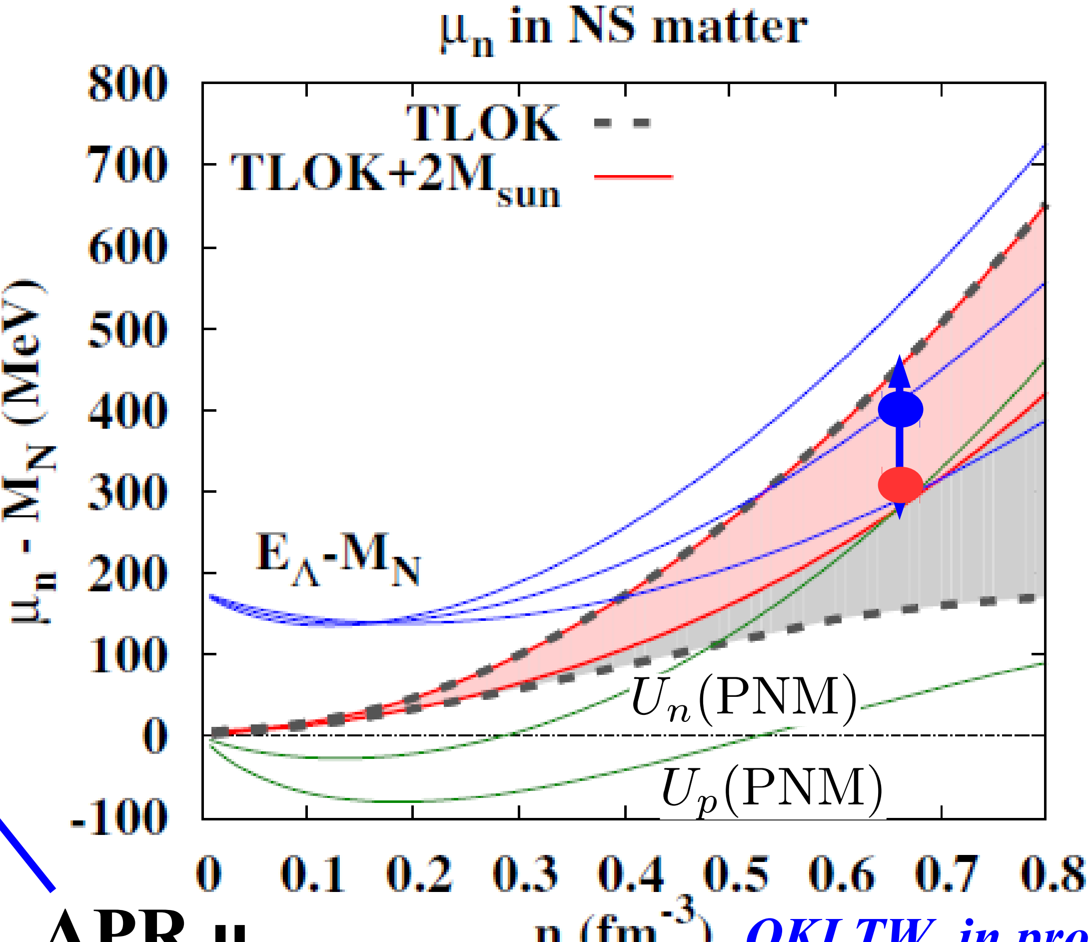
- Hyperon puzzle
  - At what density do hyperons appear ? → $U_\Lambda = \mu_n$
  - In STANDARD EOS with hyperons with $U_\Lambda(n_0)$=-30 MeV, Λ appears at $n=(2\text{-}3)n_0$
  - Density dep. of U_Λ is essential.
  - Neutron chemical potential strongly depends on sym. E.
- QCD phase transition in cold dense matter
  - Do we have the first order phase transition in cold dense matter ? If yes, at which density ?
  - Recent high-energy heavy-ion collision data suggest strong softening of EOS at $n=(5\text{-}10)\ n_0$.
  - With hadronic matter EOS with L=50 MeV and NJL model, mixed phase would appear at $n=(5\text{-}10)\ n_0$ in neutron stars.

Neutron Chemical Potential in NS

- **Λ appears in neutron stars if E_Λ (p=0) = $M_\Lambda + U_\Lambda < \mu_n$**
- **U_Λ in χEFT (2+3 body) is stiff.**
- **But μ_n is larger with TLOK+2$M_\odot$ constraints**



W. Weise, NFQCD2018 (2018.06); Gerstung, Kaiser, Weise, in prog.



APR μ_n

OKLTW, in prog.

Neutron Chemical Potential in NS

- **Neutron Chemical Potential**

$$\mu_n + M_N = \frac{\partial(nE)}{\partial n_n} = E + u\frac{\partial E}{\partial u} + 2\alpha(1-\alpha)S(u)$$

- **Single particle potential**

$$U_\Lambda(u) = \frac{\partial(nV)}{\partial n_\Lambda}$$

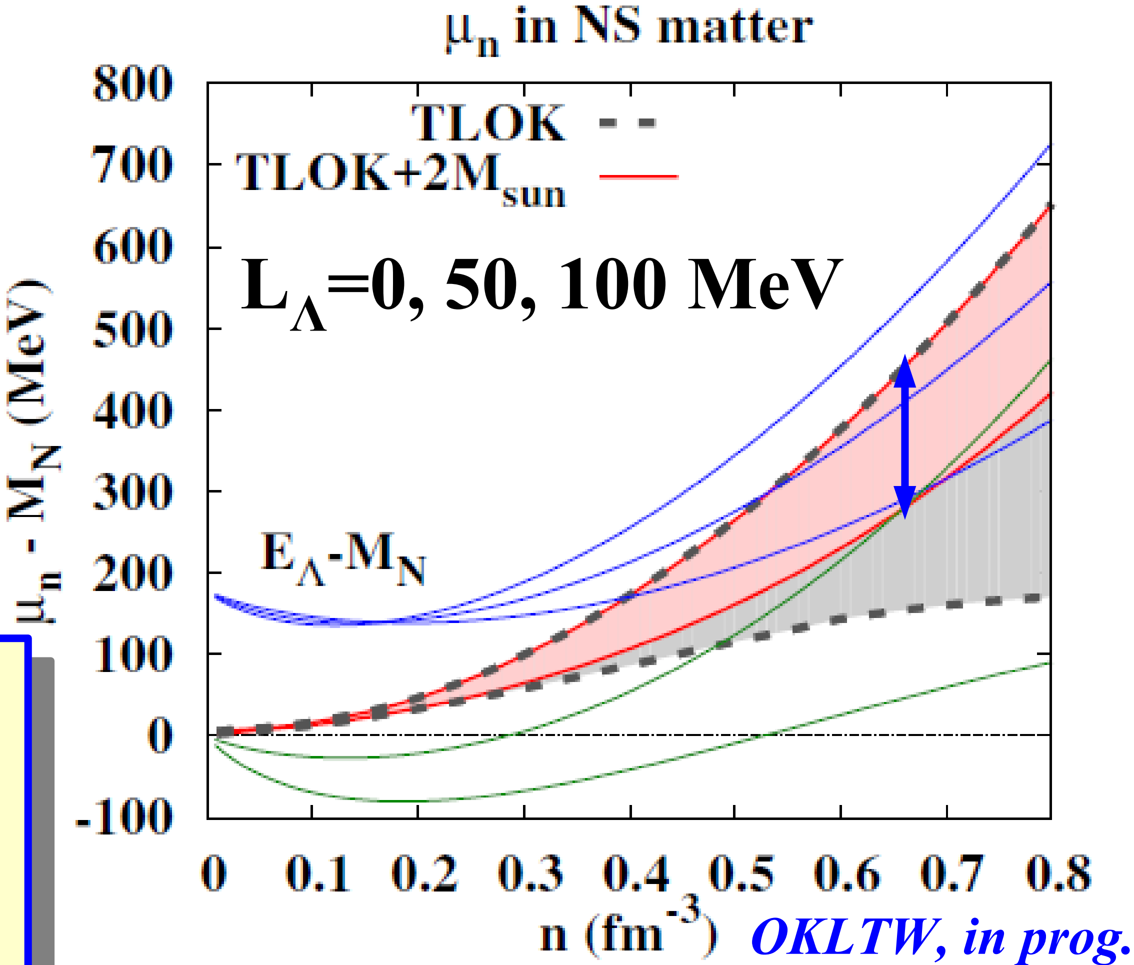
$$\simeq U_{0\Lambda} + \frac{L_\Lambda}{3}(u-1)$$

$$U_{0\Lambda} \simeq -30 \text{ MeV}$$

$$L_\Lambda = ???$$

(L_Λ<0 in most of RMF before 2010)

Sym. E. and L_Λ determine the onset density of Λ. (Already mentioned in Millener,Dover,Gal paper)



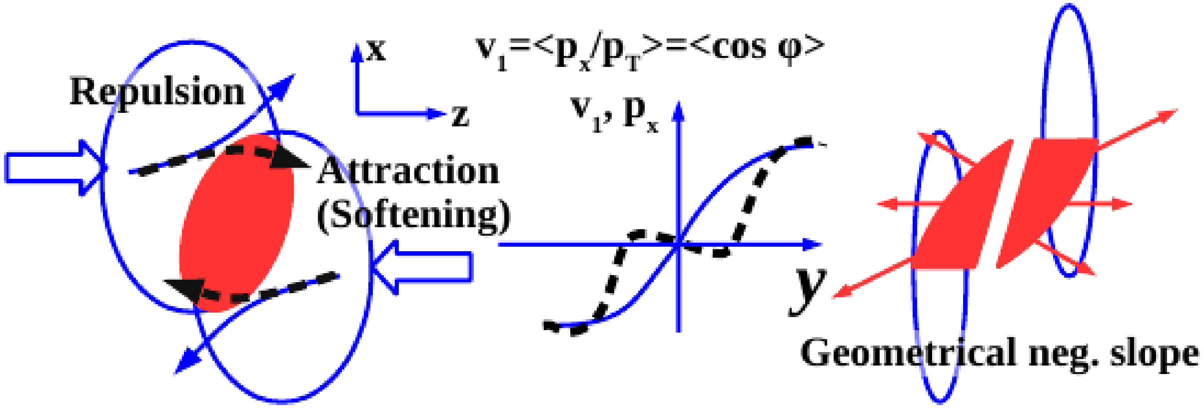
OKLTW, in prog.

QCD phase transition in cold dense matter

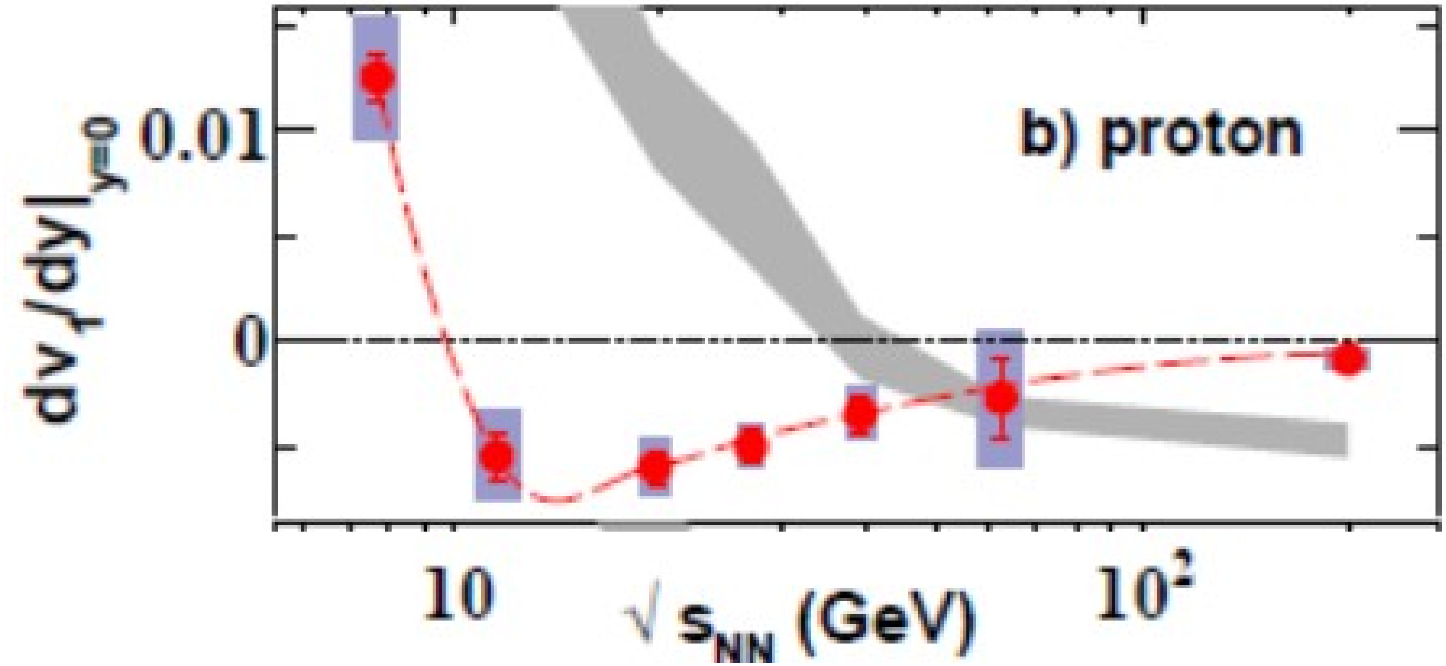
- **Transition to quark matter in cold-dense matter**
  1st order or crossover ?
- **Crossover: Masuda, Hatsuda, Takatsuka, Kojo, Baym, ...**
- **1st order p.t.**
  - **Many effective models predict, e.g. Asakawa-Yazaki CP**
  - **Recent phenomenological support: Negative Directed Flow in HIC**
    Y.Nara, H.Niemi, AO, H.Stoecker, PRC94('16)034906.
    Y. Nara, H. Niemi, AO, J. Steinheimer, X.-F. Luo, H. Stoecker, EPJA 54 ('18)18
  - **The phase transition density may be above NS central density**
    X.Wu, AO, H.Shen, PRC to appear (arXiv:1806.03760)

Negative Directed Flow

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



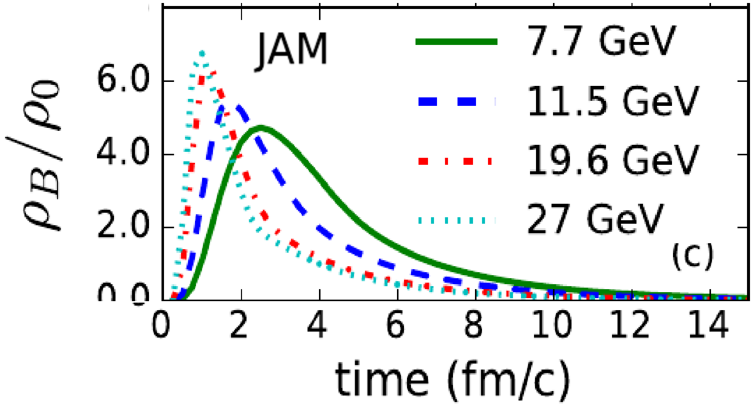
- **Negative Flow in Heavy-Ion Collisions**

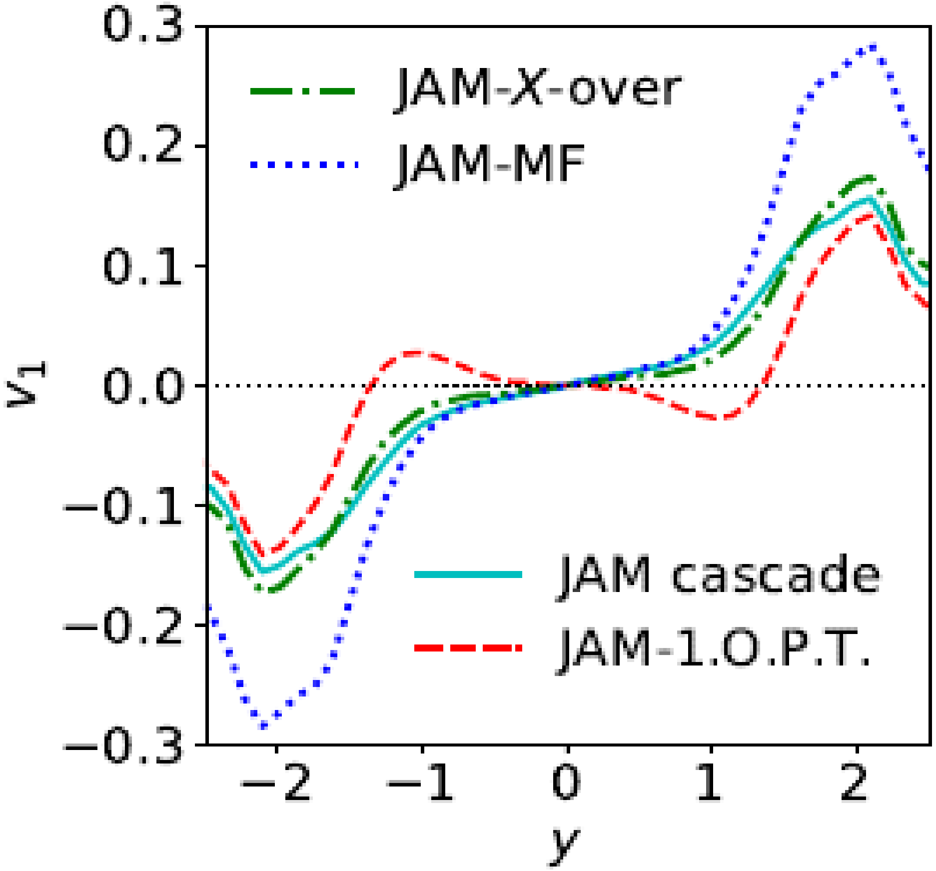


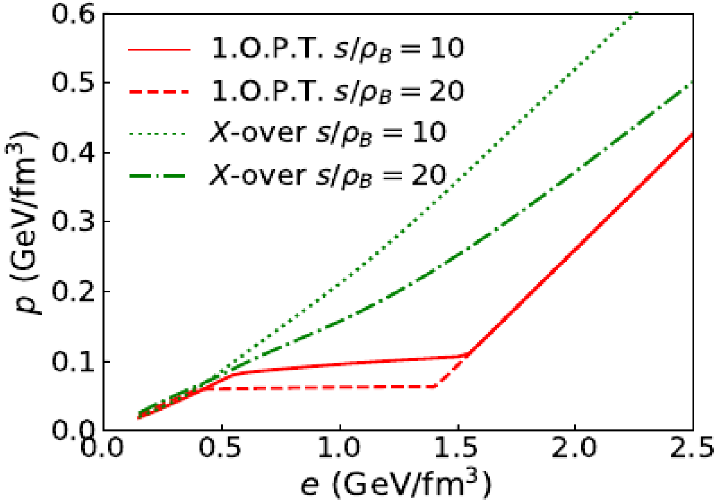
STAR Collab. (L. Adamczyk et al.), Phys.Rev.Lett. 112 ('14), 162301

Negative Directed Flow

- **Negative Directed Flow slope at √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

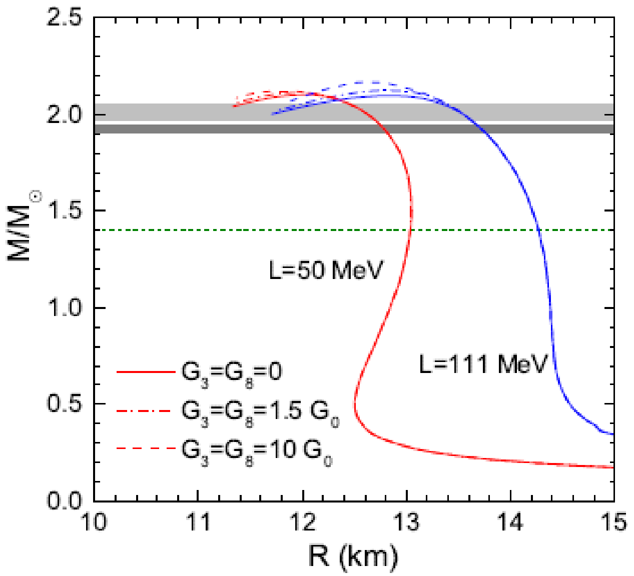
Isospin & Hypercharge Sym. E in quark matter

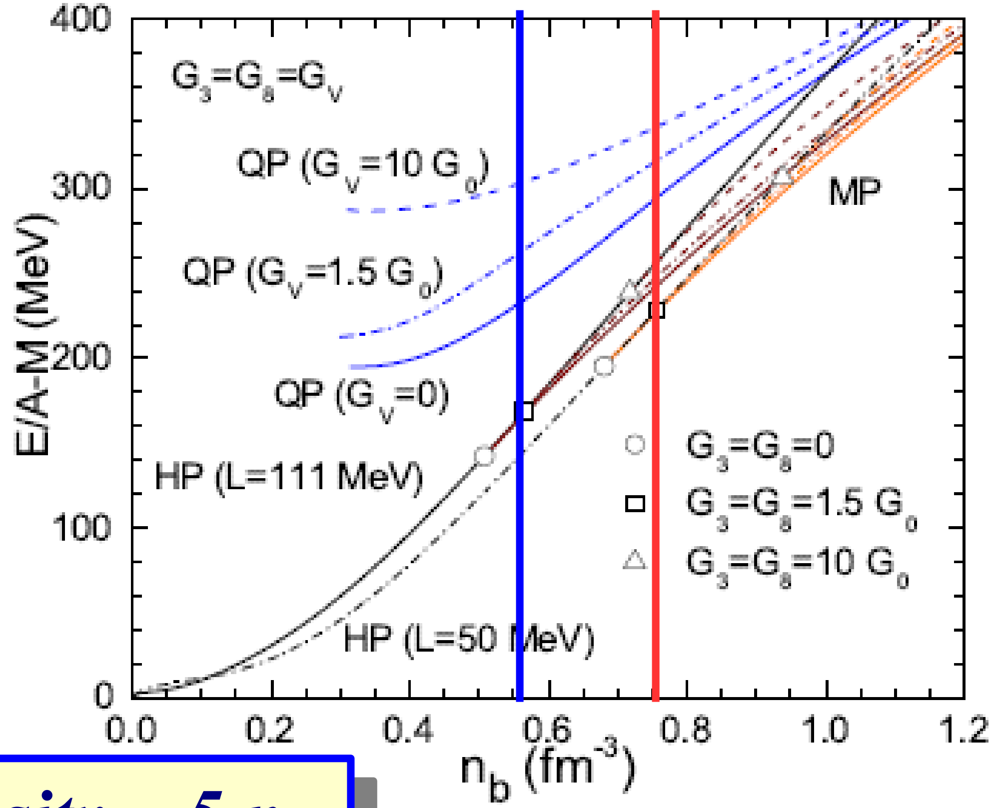
- **Two types of vector int. in NJL → Isospin & Hypercharge Sym. E**

  X.Wu, AO, H.Shen, PRC to appear (arXiv:1806.03760)

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

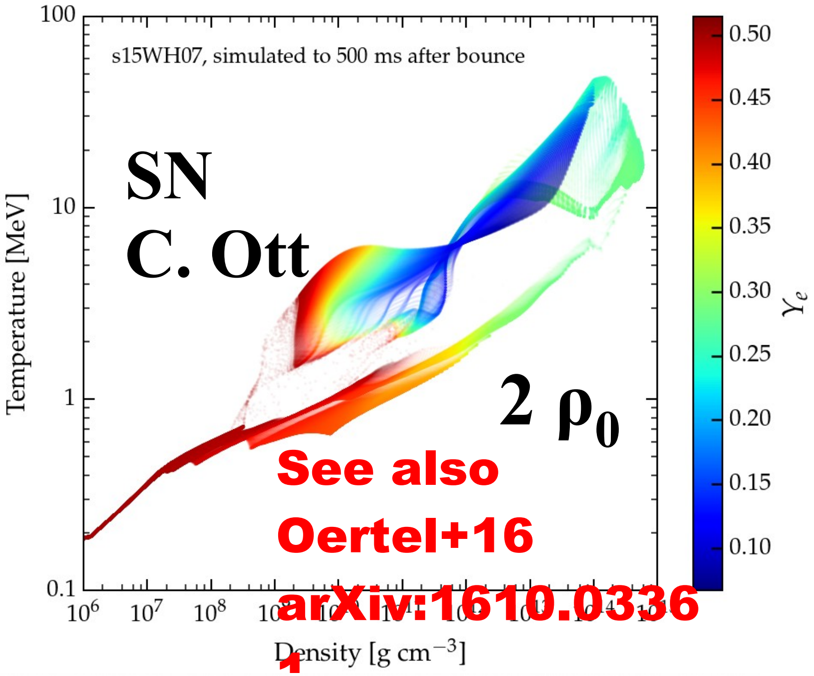
$$E = \alpha^2 S(n) + \alpha_Y^2 S_Y(n)\ ,\ \alpha = -2\langle T_z\rangle/B\ ,\ \alpha_Y = \langle B+S\rangle/B$$



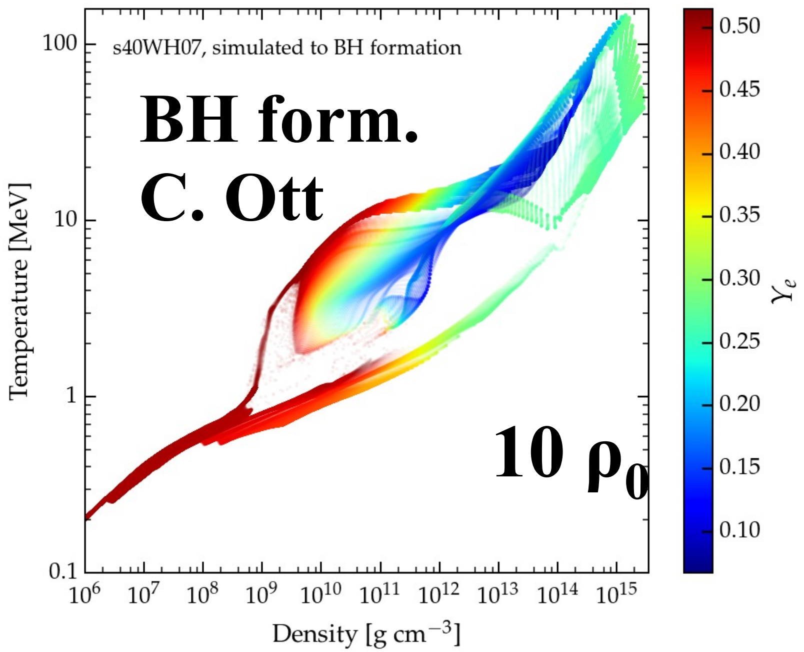


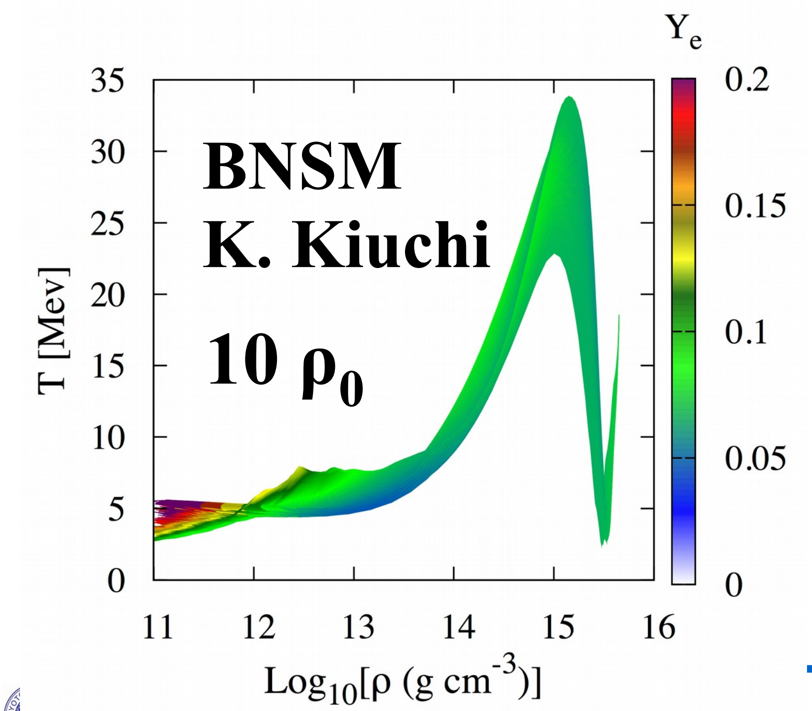
L= 50 MeV → transition density ~ 5 n_0

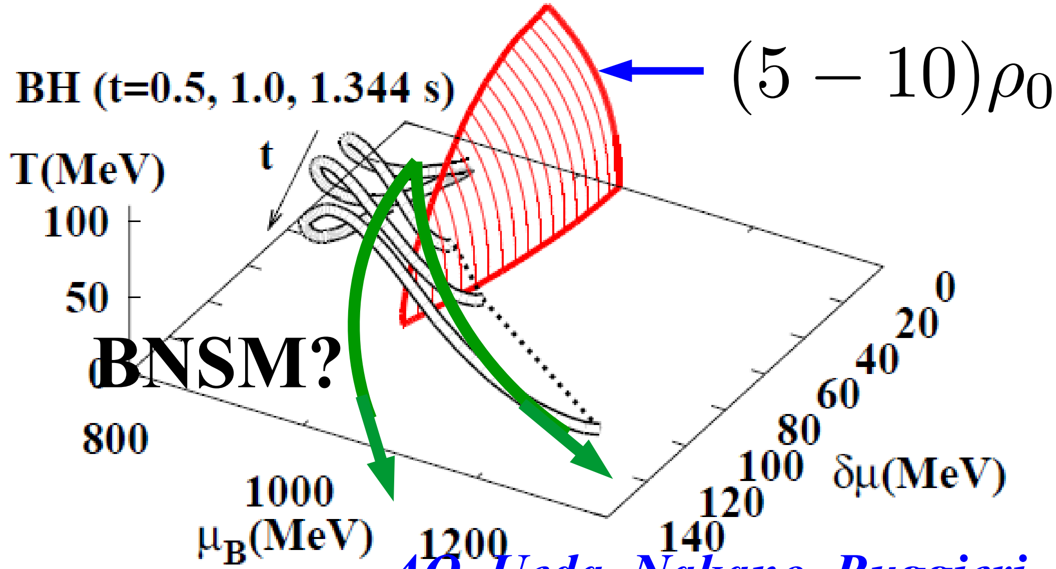
(ρ, T, Y_e) during SN, BH formation, BNSM



See also Oertel+16 arXiv:1610.0336







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

Summary

- Constraint on symmetry energy parameters (S_0, L, K_n, Q_n) together with 2 $M_\odot$ constraint gives the 1.4 $M_\odot$ neutron star radius in the range of (10.6-12.2) km.
  - Consistent with the constraint from GW.
  - Fermi momentum (k_F) expansion is invoked.
    Smooth extrapolation to 2 n_0 seems to work.
  - Let's wait for the NICER data and next NS-NS merger event.
- Onset density of hyperons may be sensitive to the symmetry energy in addition to potential parameters, (U_{0B}, L_B).
  - We need to know the slope of potential in addition to the depth.
- QCD phase transition with strong EOS softening is expected at $n=(5\text{-}10)n_0$ in almost sym. n.m. from heavy-ion data.
  - GW data from HMNS would clarify 3D phase diagram structure.

Thank you for your attention !

Reservations and Prospects

Reservations

- Only massless electrons are considered and Crust EOS is ignored.
  - With μ, chemical potential may be reduced a little.
- Non-relativistic kinetic energy is used.
  - With rel. K.E., E per nucleon is modified by 0.03 MeV @ 10 n_0 as long as Sat. and Sym. E parameters are fixed.
- Function form is limited to k_F expansion with $u^{k/3}$ (k=2-6).
  - $R_{1.4}$ range becomes narrower with k=2-5.
  - Density expansion gives EOSs very sensitive to parametrs.
- Smooth E(u) (= No phase transition) is assumed.
  - We expect QCD phase transition at (5-10) n0 from recent BES data of directed flow *Nara, Niemi, AO, Stoecker ('16)*
  - Transition to quark matter may not soften EOS drastically.
- Causality is violated at high densities, n > (4-6) n_0.

To Do (or Prospect)

- **Baryons other than nucleons Λ, Δ, Ξ, Σ, …**
- **Connecting to Hadron Resonance Gas (HRG) EOS**
  - **HRG EOS**
    mass and kinetic E of hadrons with M<2 GeV + simple potential E

    $$\varepsilon_{\mathrm{HRG}} = \mathcal{T} + cn^2$$

    or Lattice EOS in HIC(No saturation, No constraint from NS).
  - **We need to guess the potential energy density more seriously for consistent understanding of HIC, Nuclear, and NS physics.**

    $$\varepsilon = \mathcal{T} + \boxed{\mathcal{V}} \longleftarrow \textbf{Nuclear and NS physics}$$
- **Connecting to Quark(-Gluon) matter EOS**
  - **Embed model-H singularities** ***E.g. Nonaka, Asakawa ('04)***
  - **“Interpolation” of nuclear and quark matter EOS**

Further Constraint on Q_n

- **2 $M_\odot$ requirement constrains Qn further.**

$$Q_n > -9.3L + 480\,\mathrm{MeV}$$

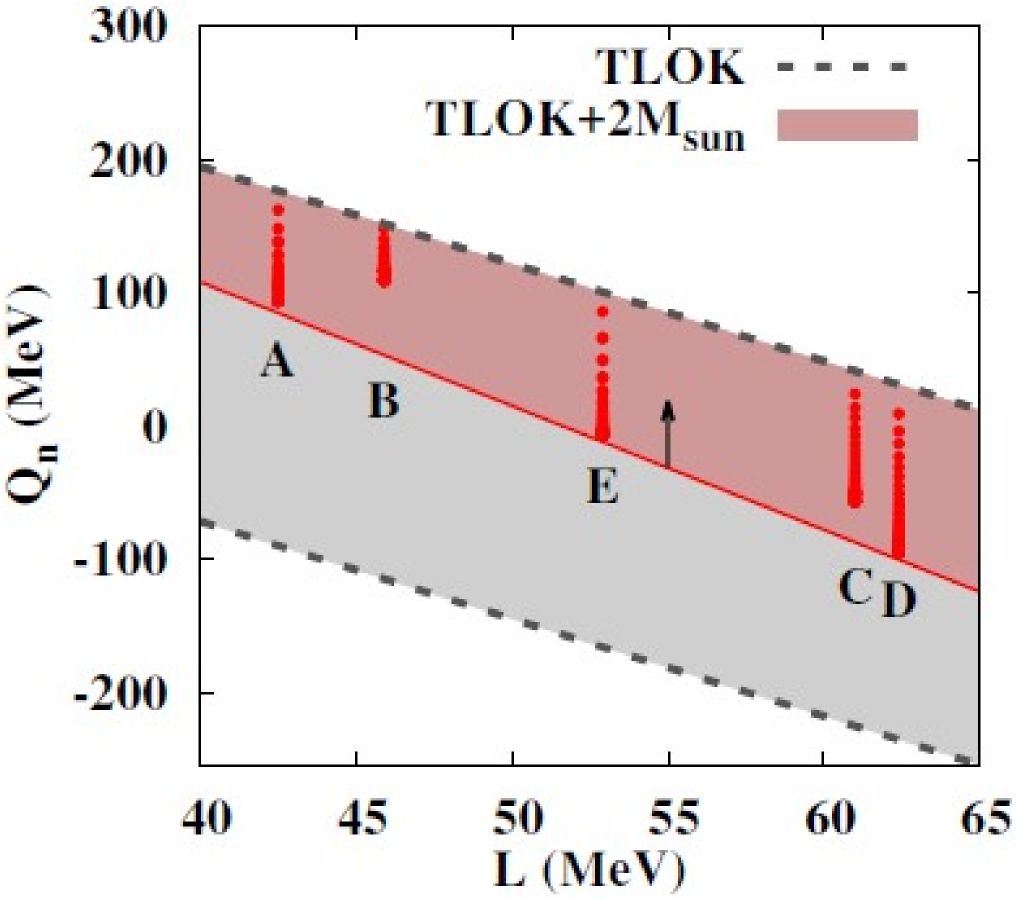
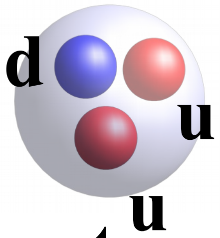


FIG. 4. Constraint on Q_n

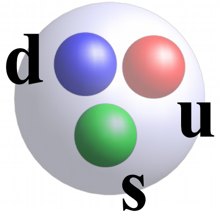
AO, Kolomeitsev, Lattimer, Tews, Wu (OKLTW), in prog.

Neutron star – Is it made of neutrons ?

- **Possibilities of various constituents in neutron star core**
  - **Strange Hadrons**

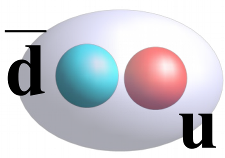


proton

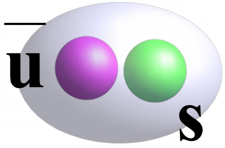


Λ hyperon

  - **Meson condensate (K, π)**

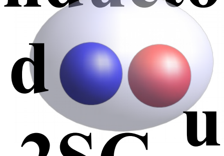


π

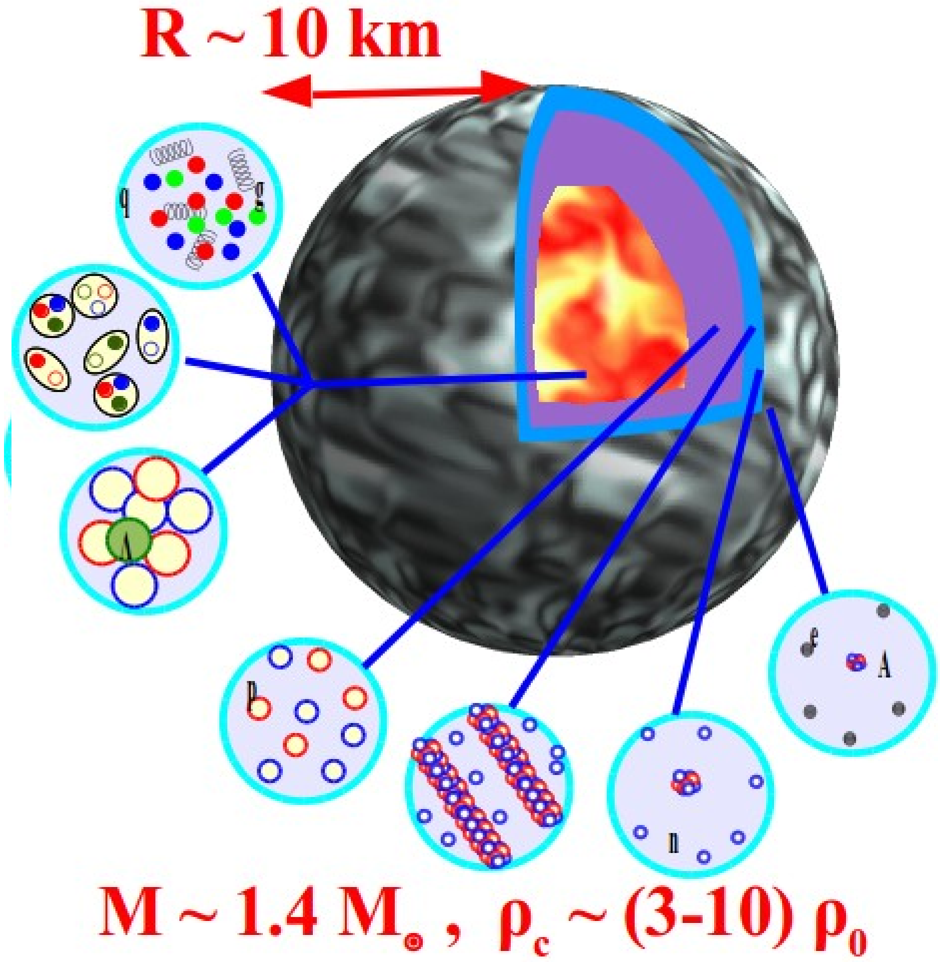


anti kaon

  - **Quark matter**
  - **Quark pair condensate (Color superconductor)**

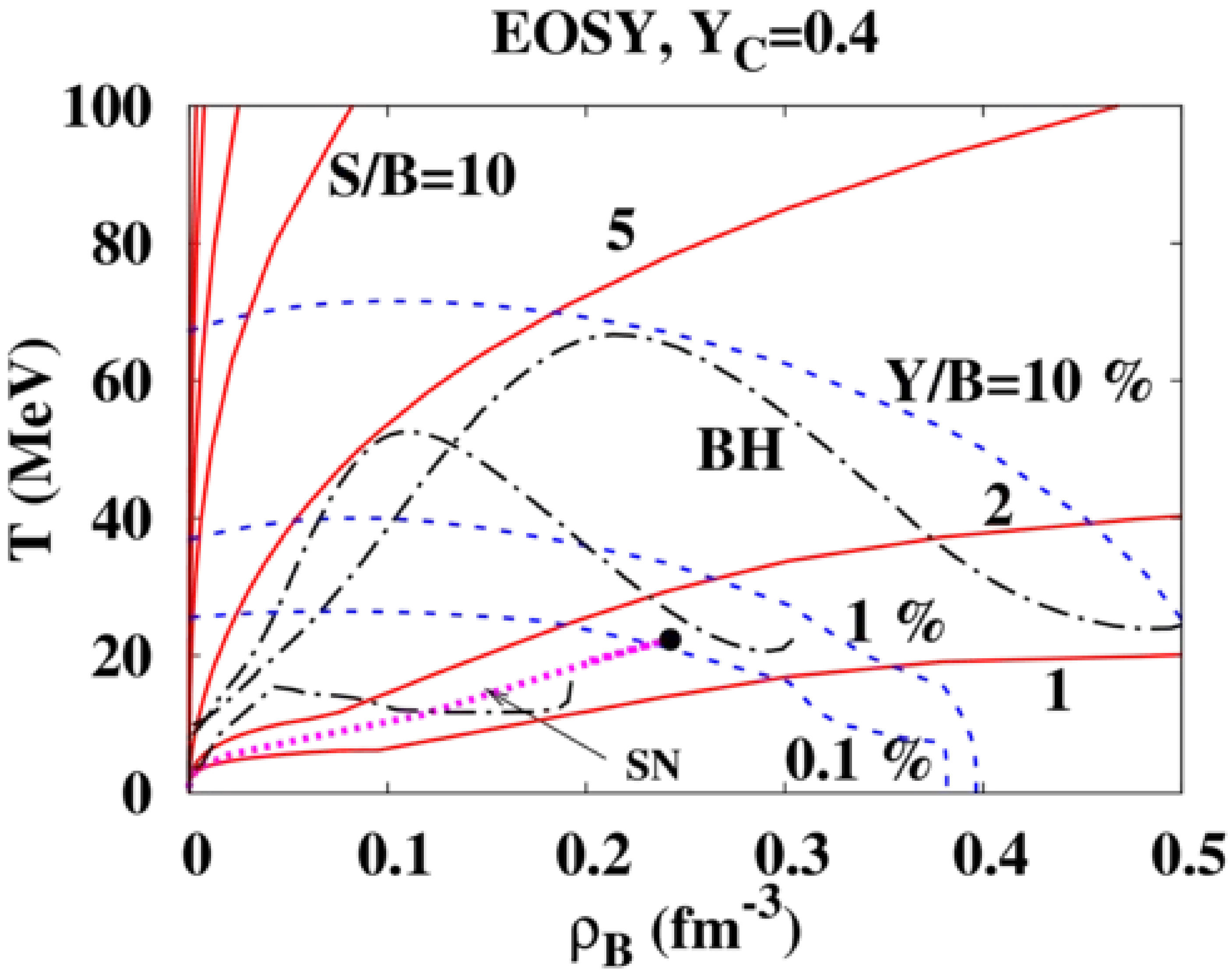


2SC



NS core = Densest stable matter existing in our universe.

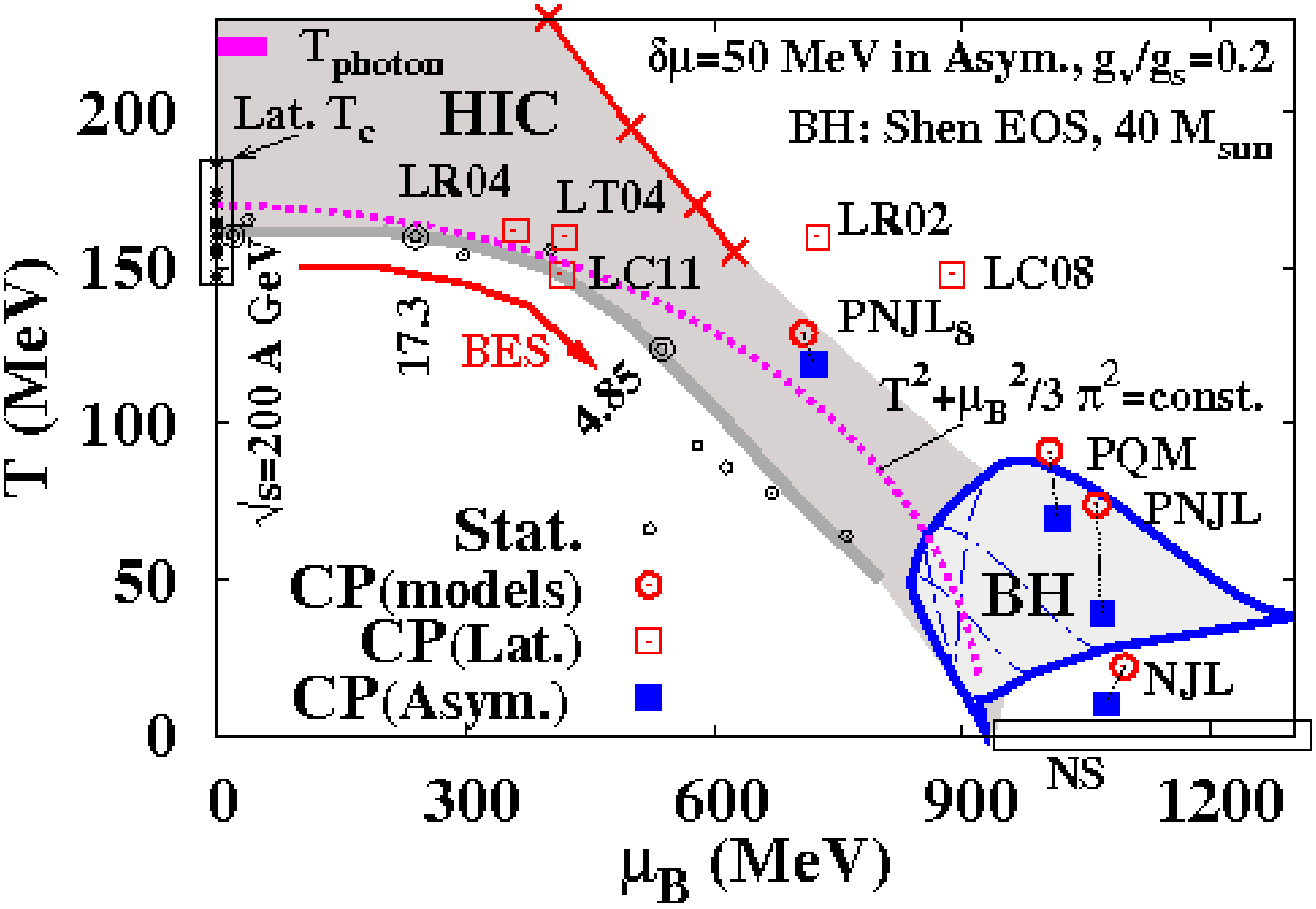
(ρ, T) during SN & BH formation



Shen EOS
+ hyperons

Ishizuka,AO, Tsubakihara, Sumiyoshi, Yamada, JPG 35('08) 085201; AO et al., NPA 835('10) 374.

QCD phase diagram (Exp. & Theor. Studies)



QCD phase transition is not only an academic problem,
but also a subject which would be measured
in HIC or Compact Stars

AO, PTPS 193('12)1

Unitary Gas Constraint

Tews, Lattimer, AO, Kolomeitsev (TLOK), ApJ ('17)

- **Conjecture:**
  Unitary gas gives the lower bound of neutron matter energy.

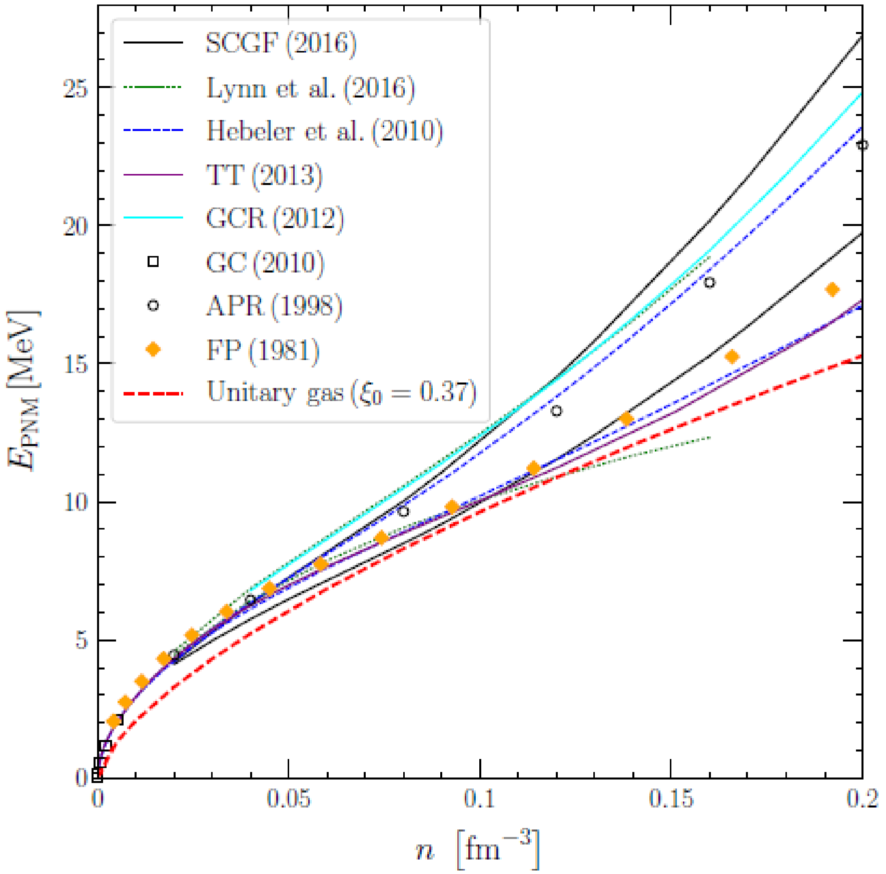
$$S(n) = E_{\rm PNM} - E_{\rm SNM} \geq E_{\rm UG} - E_{\rm SNM}$$

Sym. Nucl. Matter EOS is relatively well known.

$$E_{\rm UG} = \xi E_{\rm FG} \ (\xi \simeq 0.38)$$

- **$a_0 = \infty$ in unitary gas**
  → lower bound energy
  of $a_0 < 0$ systems
  (w/o two-body b.s.) ?

- **Supported by (most of) ab initio calc.**



Potential Energy Density

- **Potential Energy Density in the Fermi momentum expansion**

$$\mathcal{V} = nV = \sum_{i,j\in B} n_i n_j v_{ij}(n)$$

Density-dependent NN interactions vij (i, j=p or n) are known.

- **Single particle potential**

$$\begin{aligned}U_i =& \frac{\partial \mathcal{V}}{n_i} = \sum_j n_j v_{ij}(n) + \sum_{jk} n_j n_k \frac{\partial v_{jk}(n)}{\partial n_i} \\ =& U_{0i} + \frac{L_i}{3}(u-1) + \mathcal{O}((u-1)^2) \\ \simeq& au + bu^{4/3}\end{aligned}$$

rearrangement term

Again, a and b are given as a linear function of U_{0i} and L_i.