Symmetry Parameter Constraints from a Lower Bound on the Neutron-Matter Energy (and Its Relevance to Neutron Star Physics)

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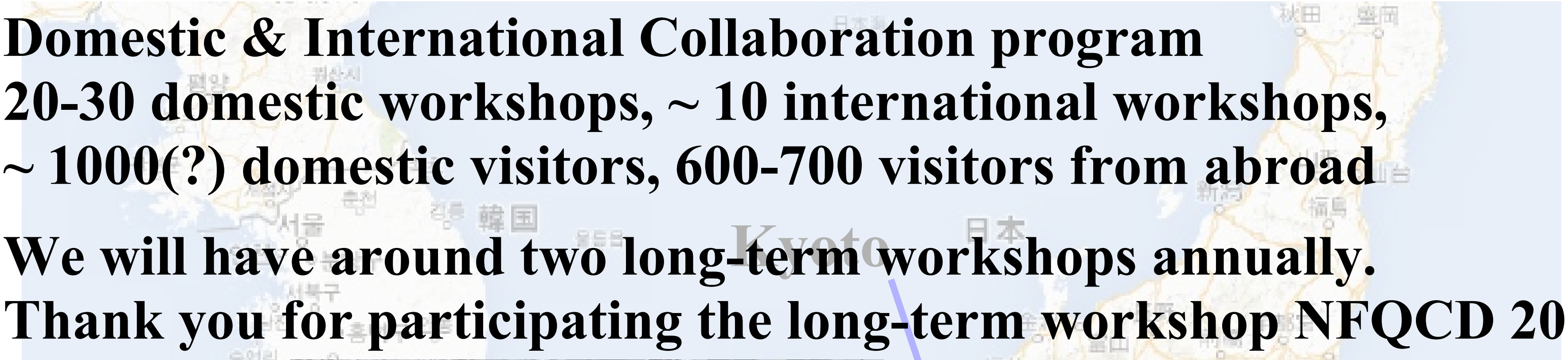
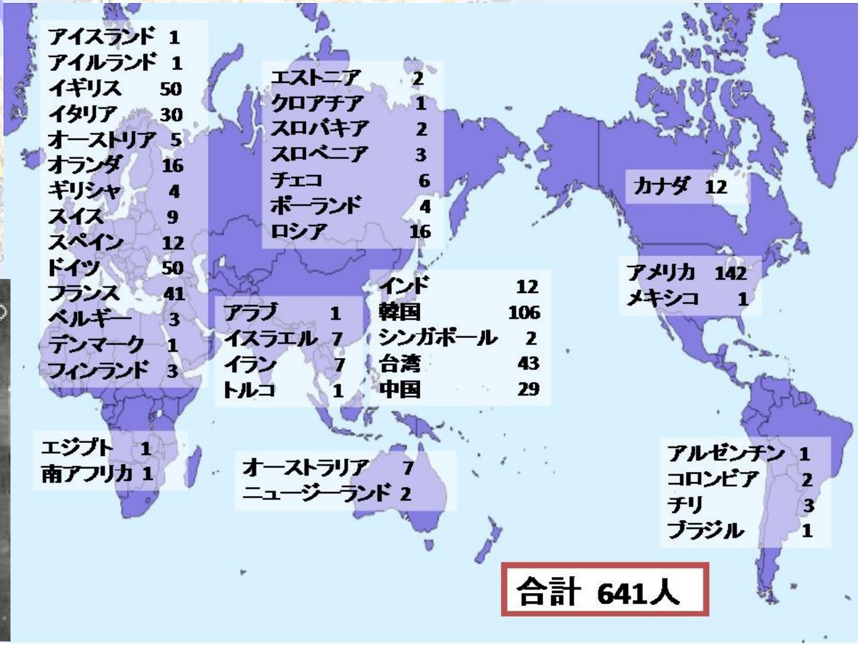
名古屋大学談話会 (2018/12/4)

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

Do you know Yukawa Institute ?

- **Yukawa Institute for Theoretical Physics, Kyoto University**
  - **Founded in 1953 to memorize Yukawa's Nobel prize (first winner in Japan).**
  - **Domestic & International Collaboration program 20-30 domestic workshops, ~ 10 international workshops, ~ 1000(?) domestic visitors, 600-700 visitors from abroad**
  - **We will have around two long-term workshops annually. Thank you for participating the long-term workshop NFQCD 2018.**





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Introduction

Impact of GW from binary neutron star merger

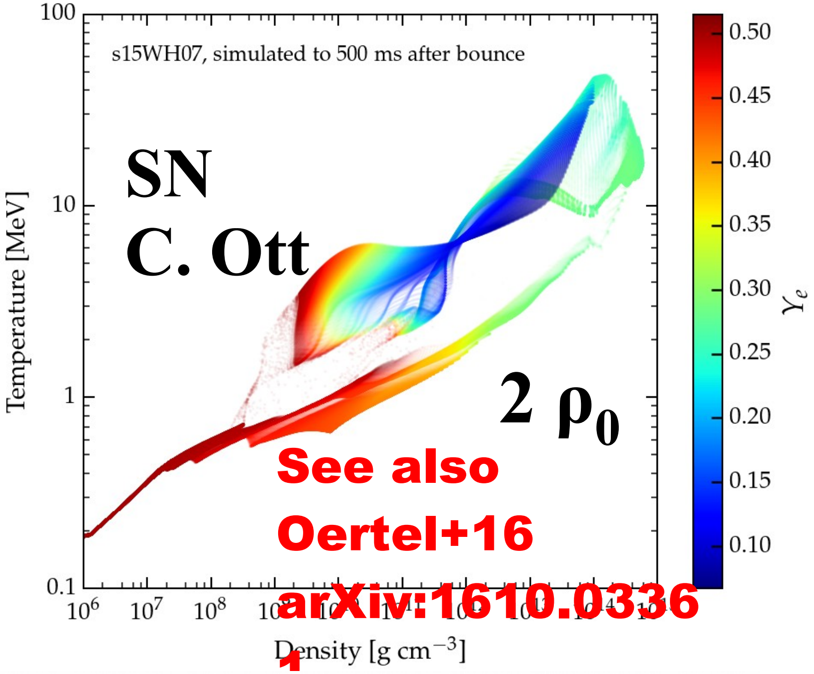
- **GW170817 from NS-NS → Multi messenger astrophysics**
  B.P.Abbott+ [LIGO Sci. and Virgo Collab.], PRL119('17)161101

- **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 !**

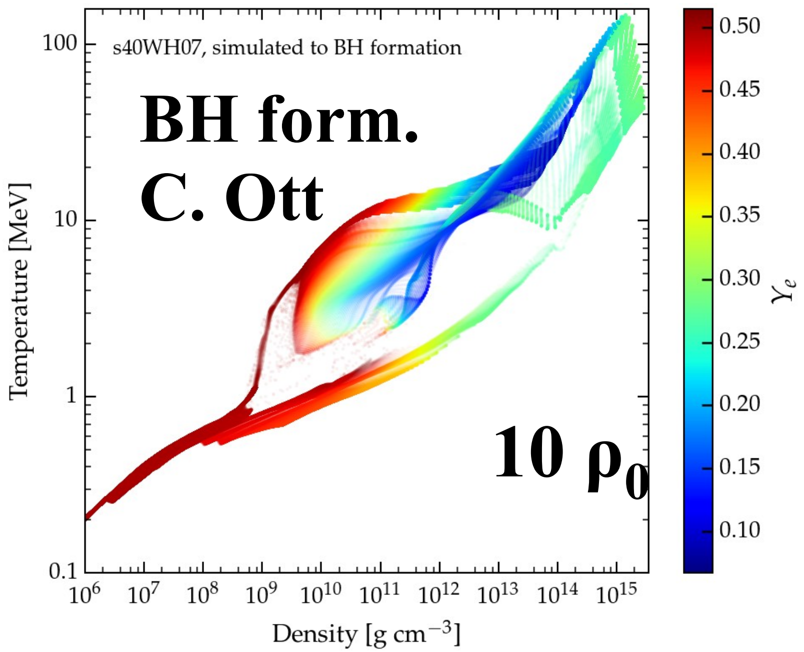
- **Central Engine of (Short) Gamma-Ray Bursts**
- **GW as standard siren (Hubble constant)**

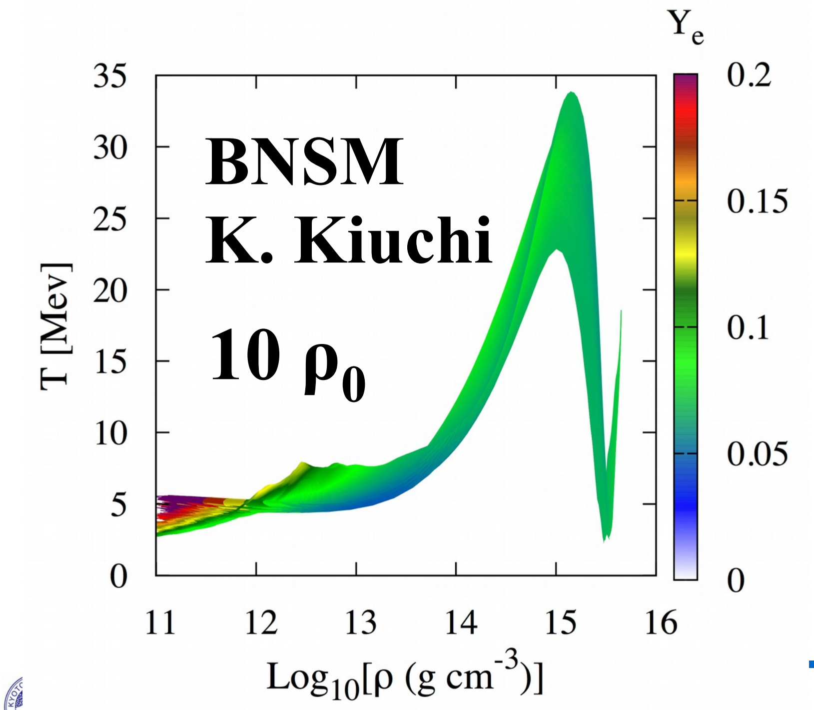
Courtesy of Y. Sekiguchi @ YKIS2018b

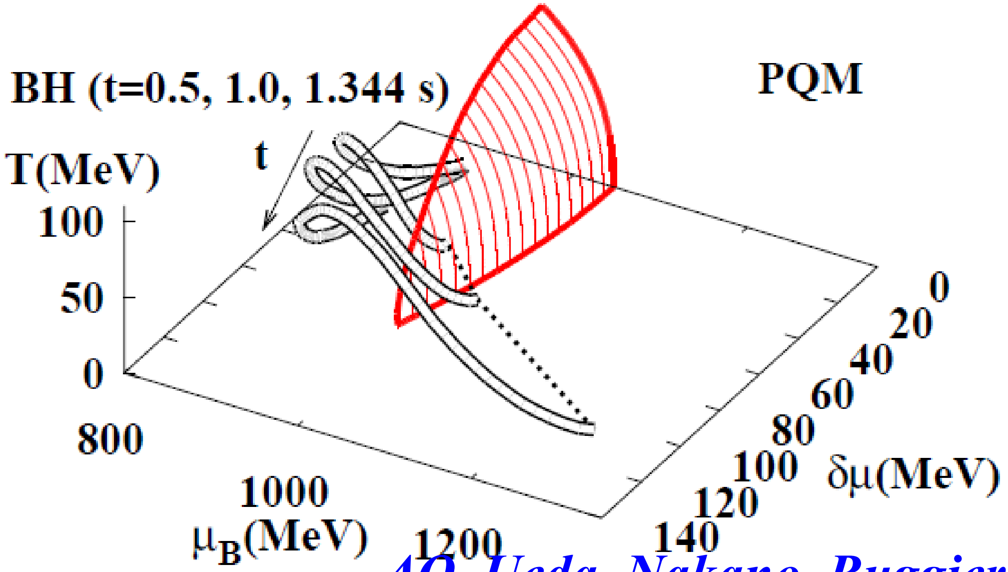
(ρ, T, Y_e) during SN, BH formation, BNSM



See also Oertel+16 arXiv:1610.0336

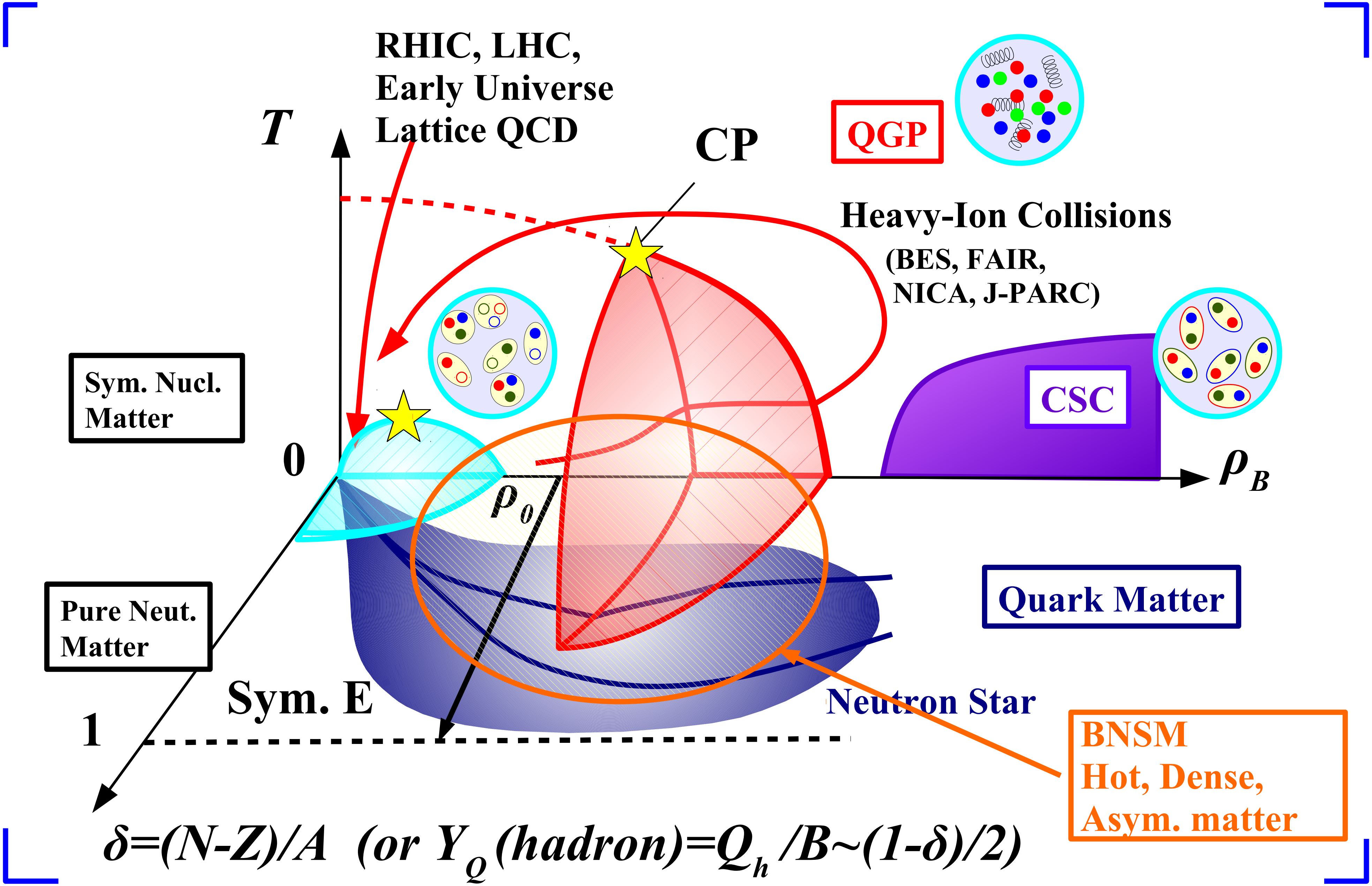






AO, Ueda, Nakano, Ruggieri, Sumiyoshi, PLB704('11),284

QCD Phase Diagram

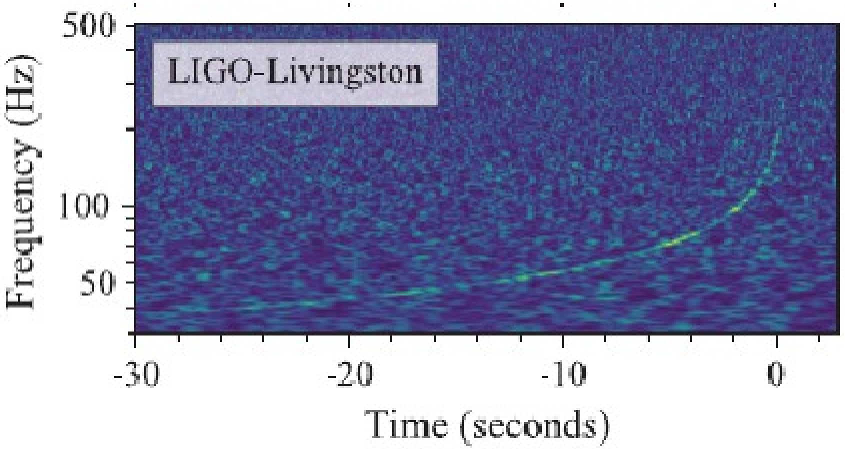


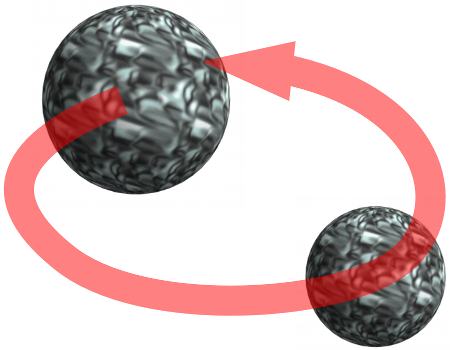
$\delta=(N-Z)/A$ (or $Y_Q(\text{hadron})=Q_h/B\sim(1-\delta)/2$)

AO, JPS Conf. Proc. 20 (2018), 011035

連星中性子星合体

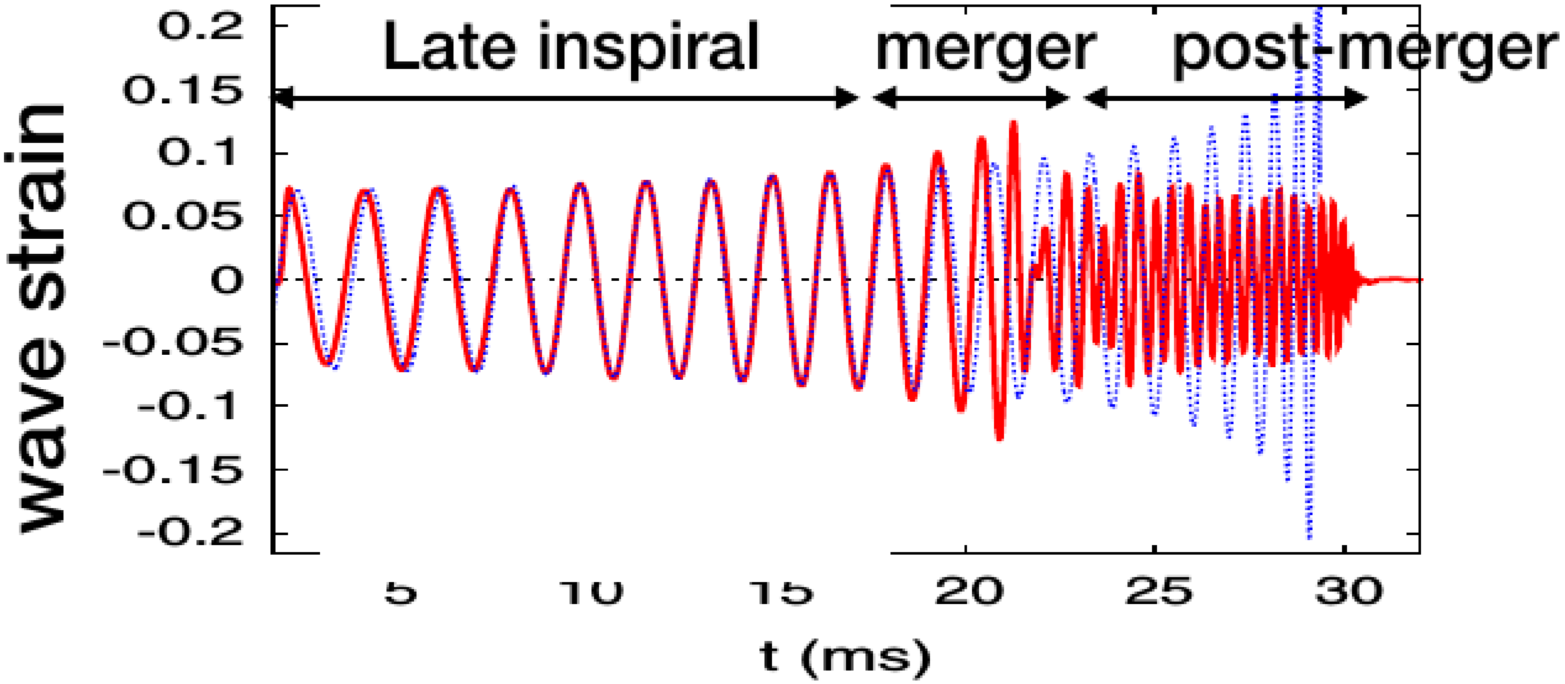
- **GW170817**
  B. P. Abbott et al. (LIGO and Virgo)
  PRL 119, 161101 (2017)
  - **質量和 $M = 2.74^{+0.04}_{-0.01}\ M_\odot$**
  - **それぞれの質量 1.17-1.60 $M_\odot$**
    → 連星中性子星合体
    (Binary Neutron Star Merger)
  - **Gamma Ray Burst (GRB170717A) が 1.7 s 後に起こる。**
    → GRB の起源 (の一つ) を特定
  - **inspiral (徐々に近づいていく段階) における振動数変化を観測**
    → 中性子星半径を制限
  - **放出された物質の速度から中性子星の最大質量を制限**
    M. Shibata et al., 1710.07579
    $M_{max} = (2.15\text{-}2.25)\ M_\odot$





Gravitational Wave in the Inspiral Phase

- **重力波の波形**
  - **Inspiral, merger, post-merger (hypermassive neutron star)**
- **Inspiral phase での重力波の波形**
  - **質点からの重力波にくらべて、位相が進む**
    → Tidal Deformation (潮汐変形) 効果



Hotokezaka

Tidal Deformability (潮汐変形度)

- **Tidal deformability λ (無次元化　Λ)**
  = 潮汐力　Eij　に対する変形　Qij　の起こりやすさ

$$Q_{ij} = -\lambda E_{ij}\ ,\quad \lambda = \frac{\Lambda}{G}(GM/c^2)^5 = \frac{\Lambda}{G}(CR)^5$$

$$C = GM/c^2R\ (\mathrm{Compactness})$$

Inspiral phase　での位相の進みは
tidal deformability　によって
ほぼ決まる。

- **大きな半径　(硬い EOS)**
  →　変形しやすい → 大きな Λ

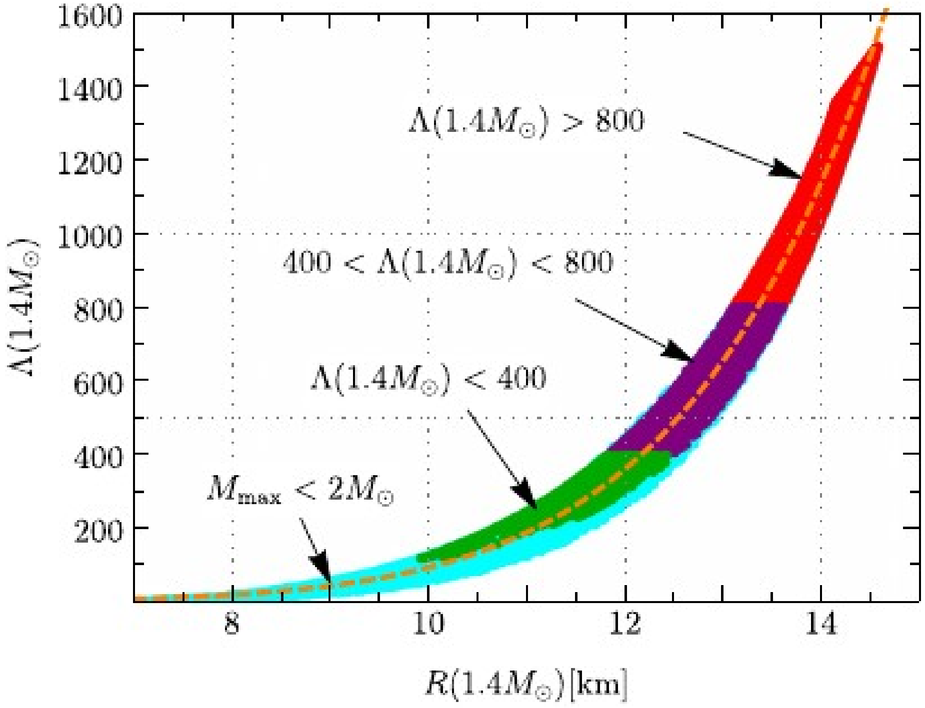
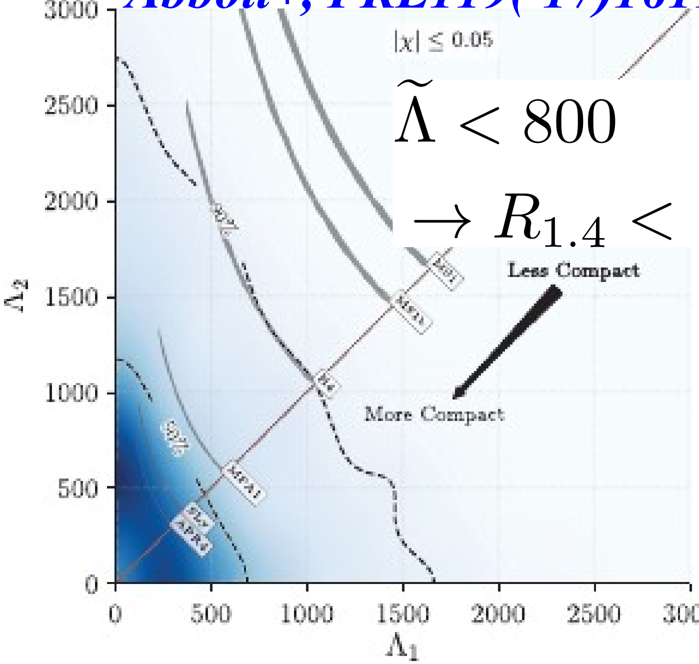


FIG. 2.　The Λ values for stars with $M = 1.4\ M_\odot$ as functions of the corresponding radius. The color coding follows Fig. 1, while the orange dashed line $\Lambda = 2.88 \times 10^{-6}(R/\mathrm{km})^{7.5}$ has been included just to guide the eye.

T.Hinderer, B.D.Lackey, R.N.Lang, J.S.Read,
PRD81 ('10)123016
(Λ) B.D. Lackey, L.Wade, PRC91('15)043002
(R-Λ) E.Annala+, PRL120('18)172703

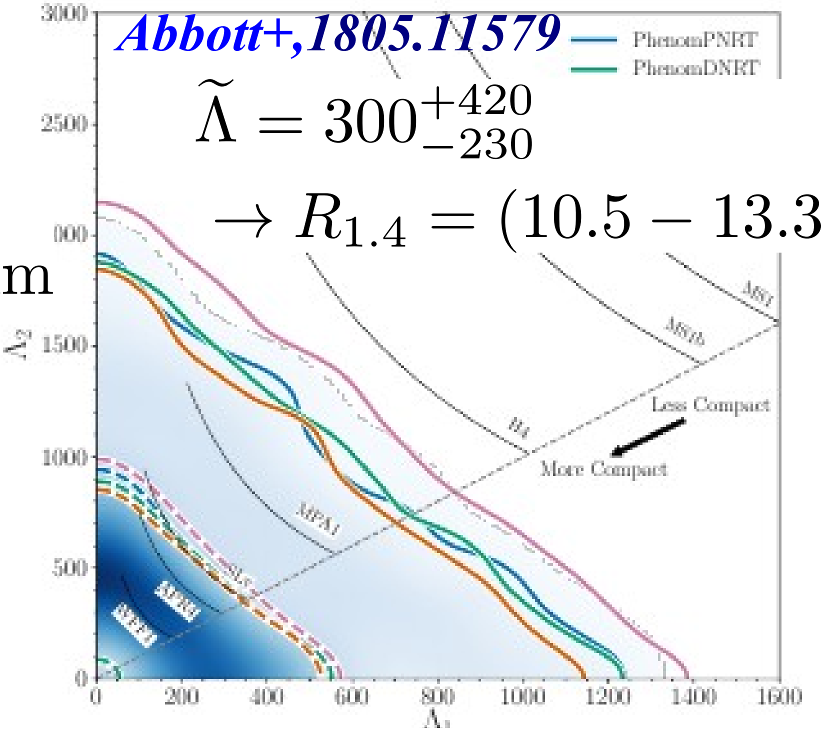
Constraints on EOS from GW170817



Abbott+, PRL119('17)161101

$\widetilde{\Lambda} < 800$

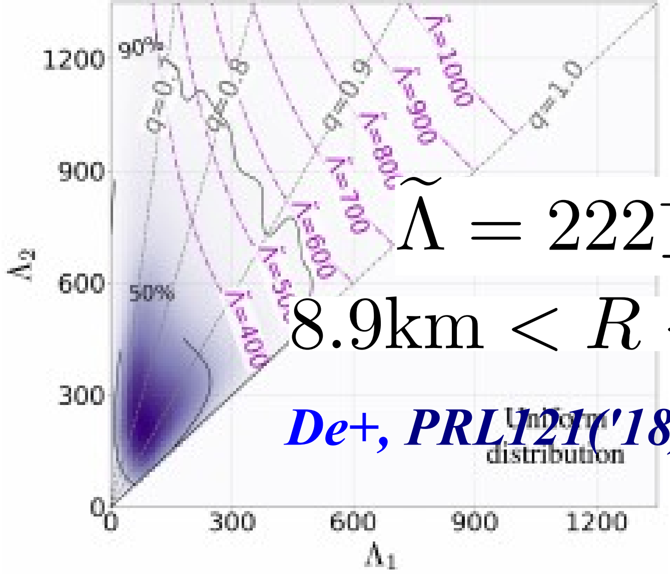
$\rightarrow R_{1.4} < 13.6$ km



Abbott+,1805.11579

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

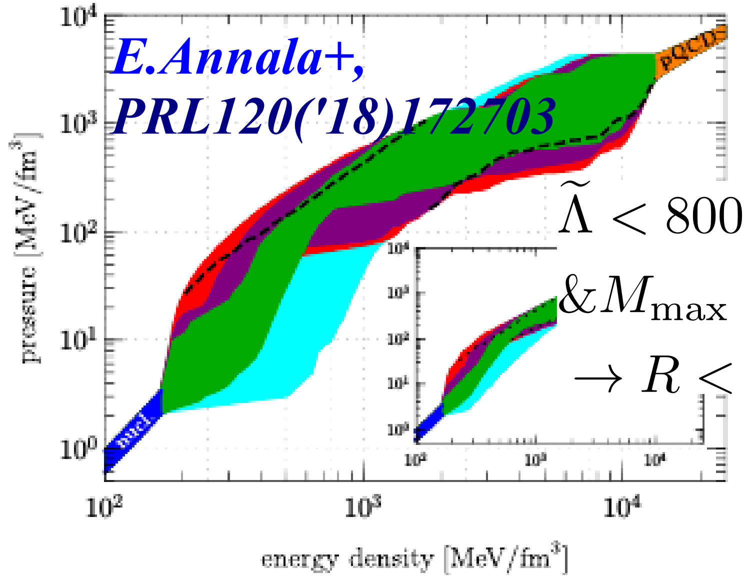
$\rightarrow R_{1.4} = (10.5 - 13.3)$ km



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

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

De+, PRL121('18)091102



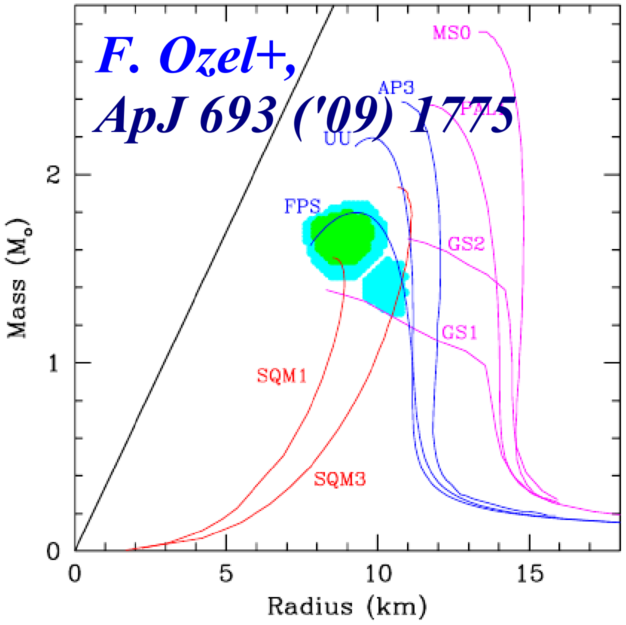
E.Annala+, PRL120('18)172703

$\widetilde{\Lambda} < 800$

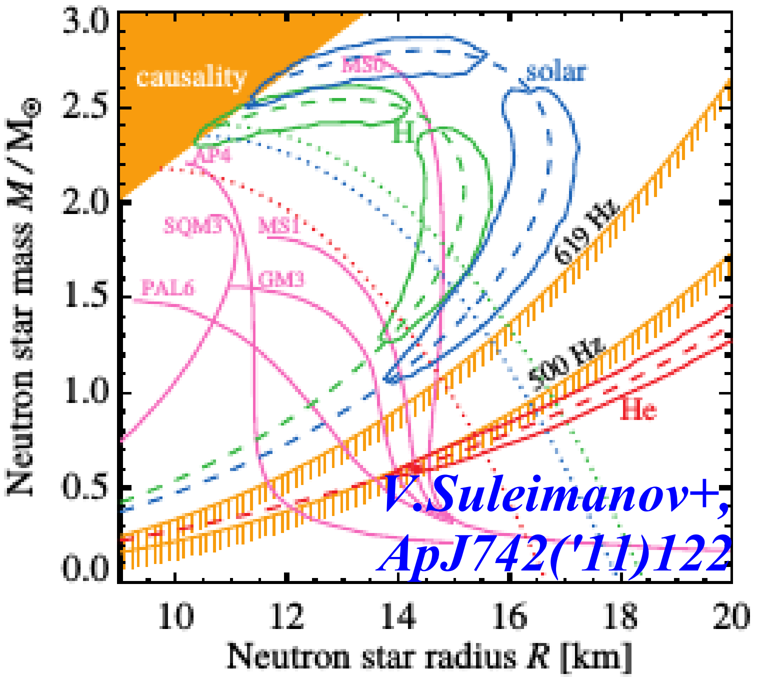
$\& M_{\max} > 2M_\odot$

$\rightarrow R < 13.6$km

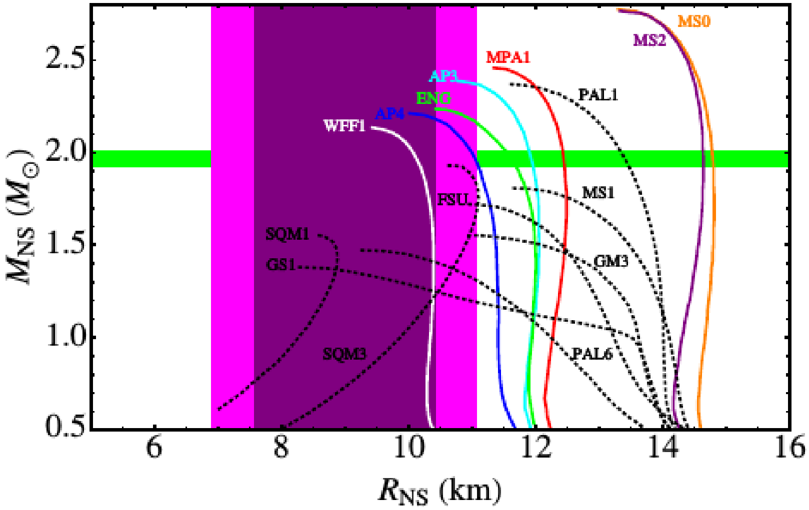
MR curve from X-ray burst



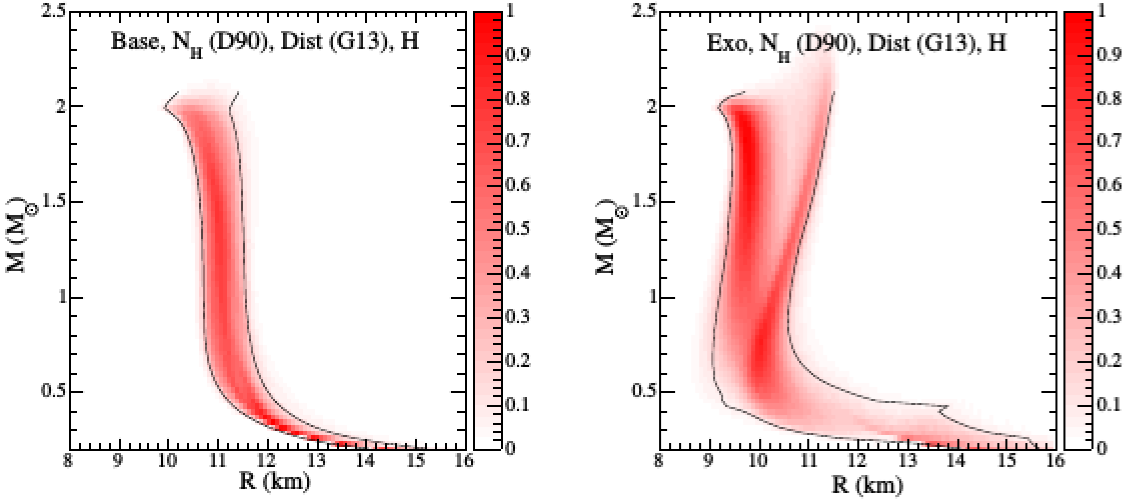
F. Ozel+,
ApJ 693 ('09) 1775



V.Suleimanov+,
ApJ742('11)122



S. Guillot+, ApJ772('13)7

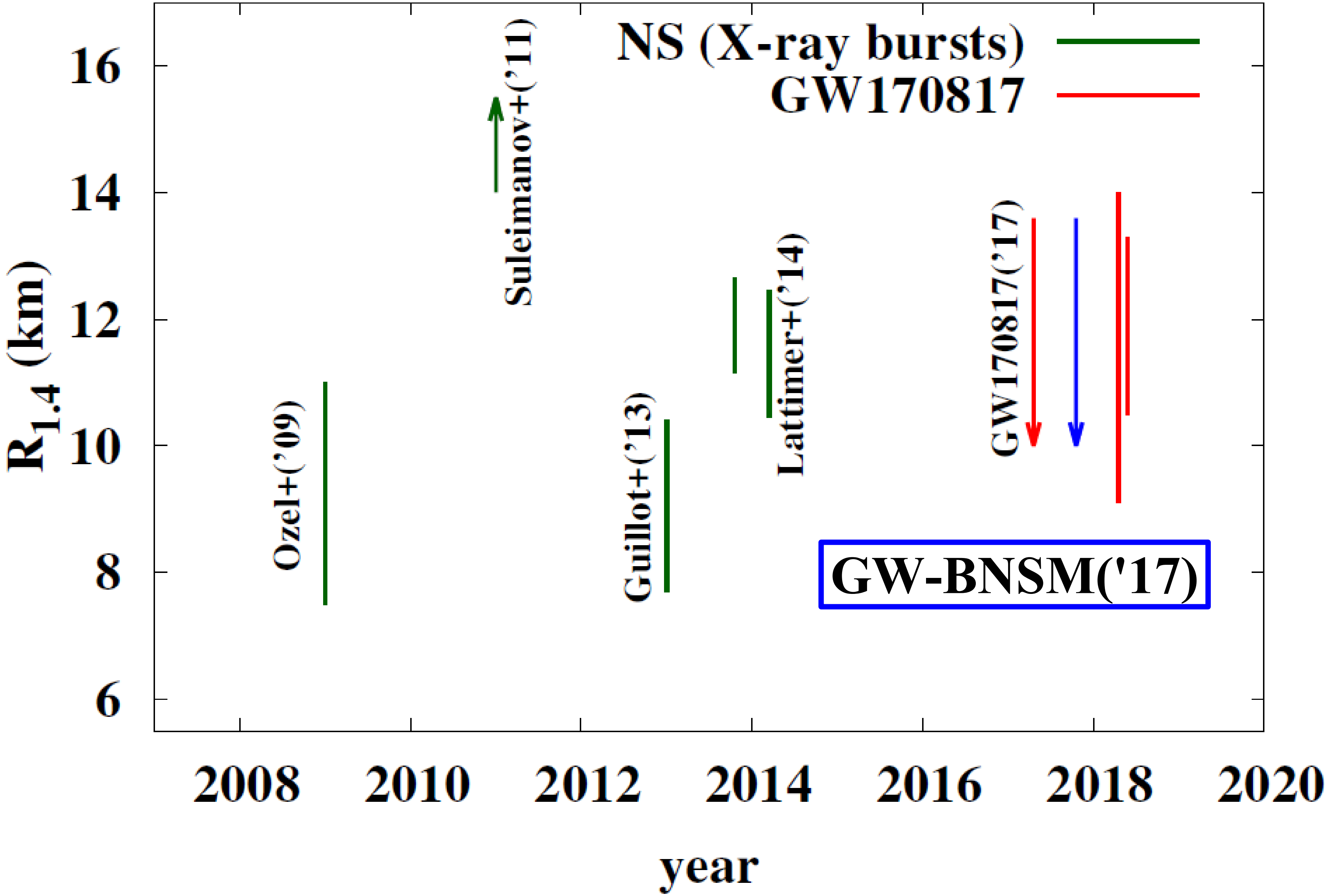


J.M.Lattimer, A.W.Steiner, ApJ784('14)123

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*

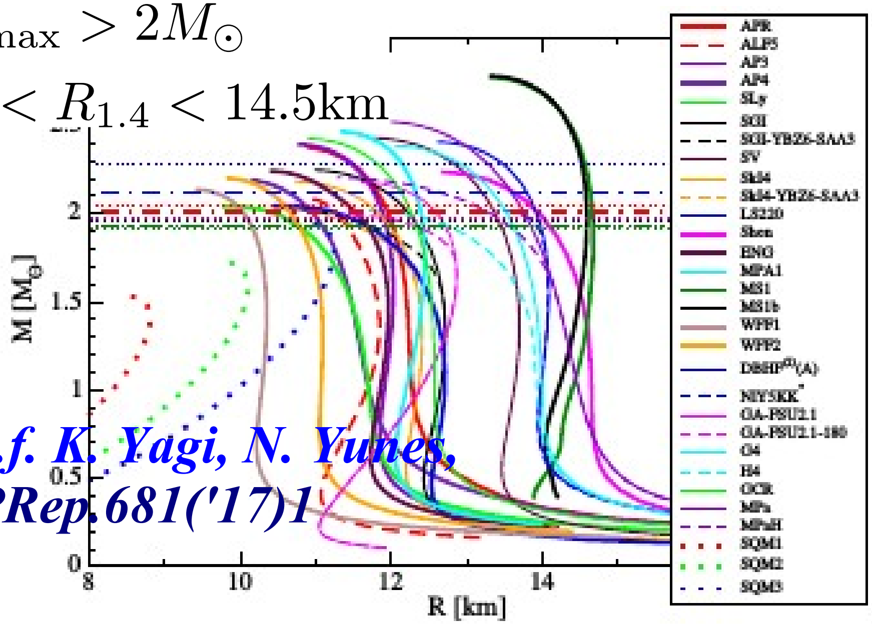
Time dependence of Neutron Star Radius ($R_{1.4}$)



Constraints from Nuclear Physics (+α)

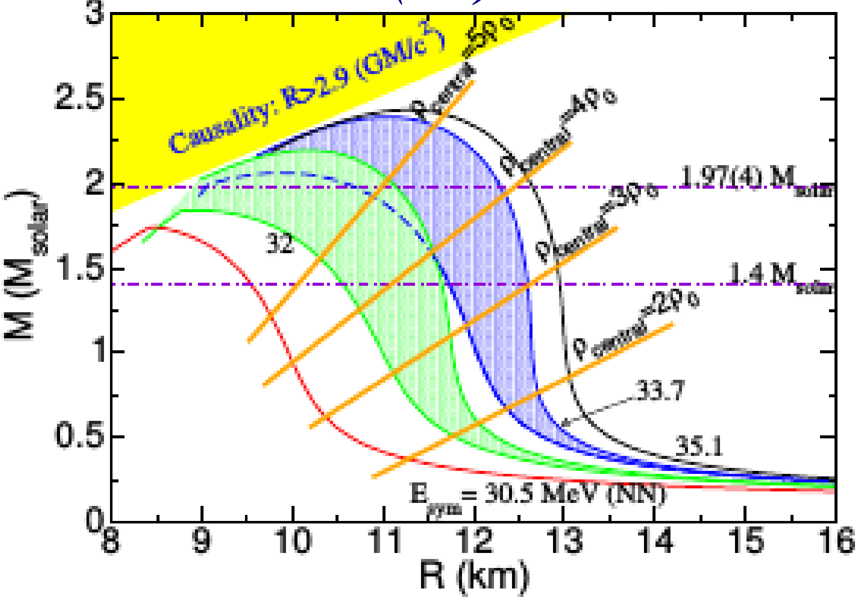
$M_{\max} > 2M_\odot$

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

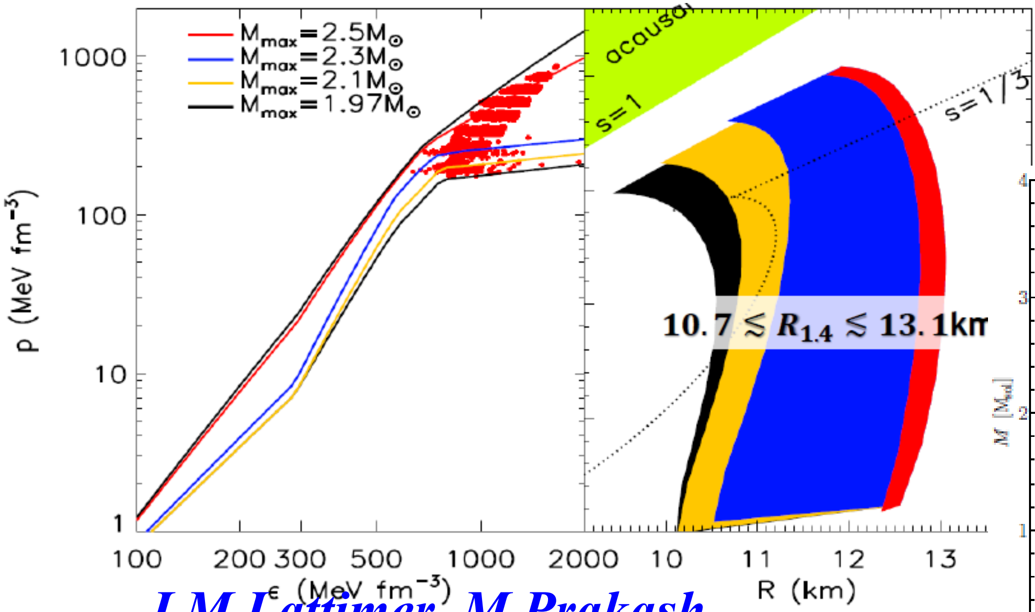


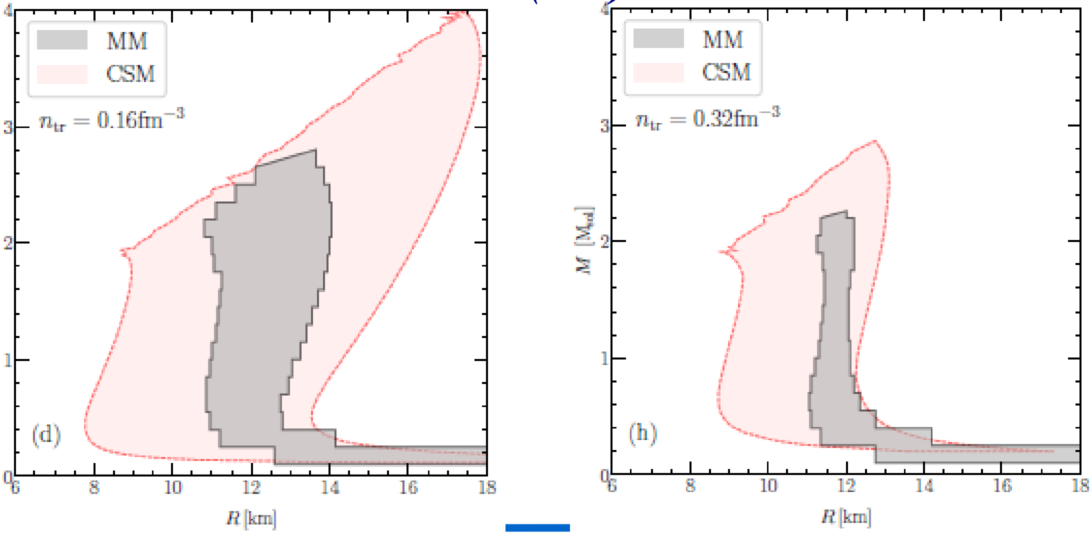
c.f. K. Yagi, N. Yunes, PRep.681('17)1

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

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*

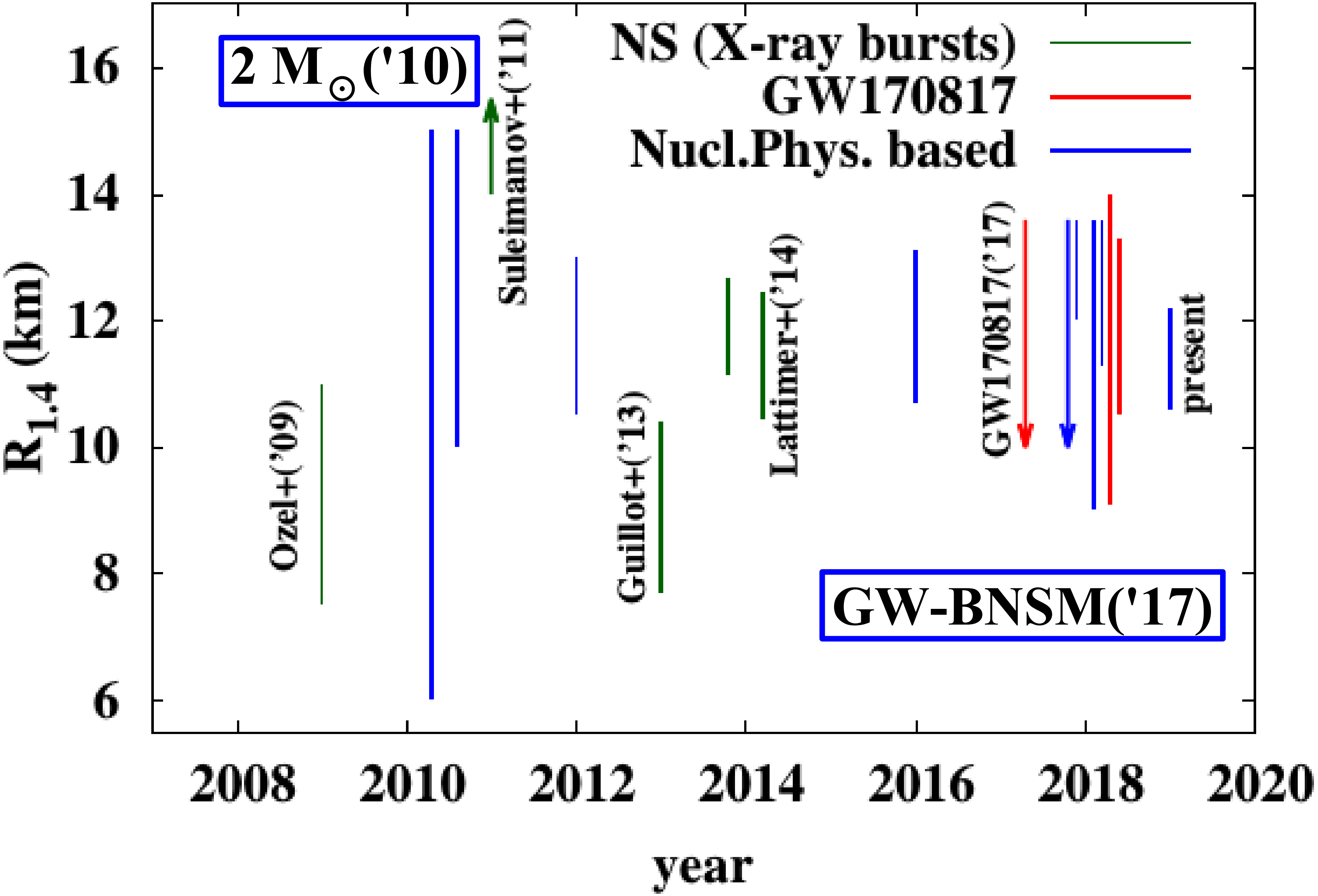
- **Chiral Effective Field Theory (Chiral EFT)**
  - **χEFT+pQCD+GW → R=(10.0-13.6) km**

    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 ($R_{1.4}$)



A. Ohnishi @ Nagoya U., Dec.4-6, 2018

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

How can we constrain (S_0 , L) ?
How about higher-order parameters ?

Unitary Gas Constraint on Symmetry Energy Parameters

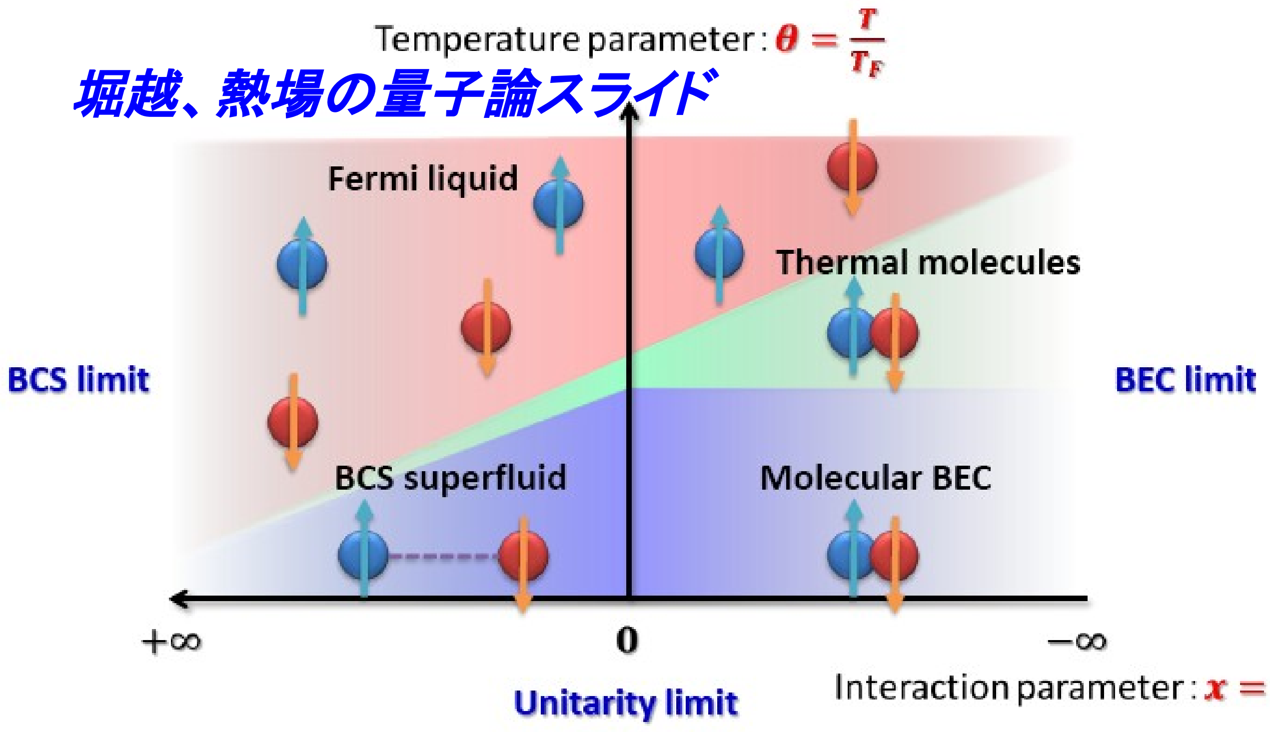
現実的な中性子物質EOS構築へ向けて

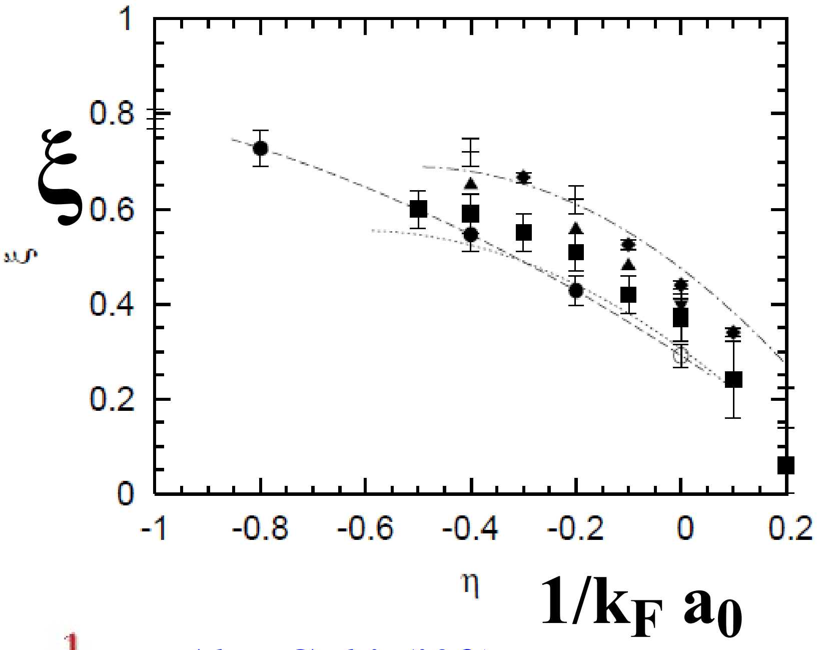
- **中性子過剰物質物質のキーワード**
  ＝ 対称エネルギー･微視的相互作用･普遍性
  - **低密度純中性子物質：第一原理計算が可能** (e.g. Abe, Seki ('09); Takano)
  - **大きな散乱長** ($a_0 \sim -16$ fm) → **中性子物質 ～ ユニタリーガス**

$$E^{Unitary} = \xi E^{Free} \qquad \xi \simeq 0.4 (\text{Bertsch parameter})$$

→ 理論計算手法のテスト、finite a_0, r_{eff} を含む普遍的関数の探索

堀越、熱場の量子論スライド

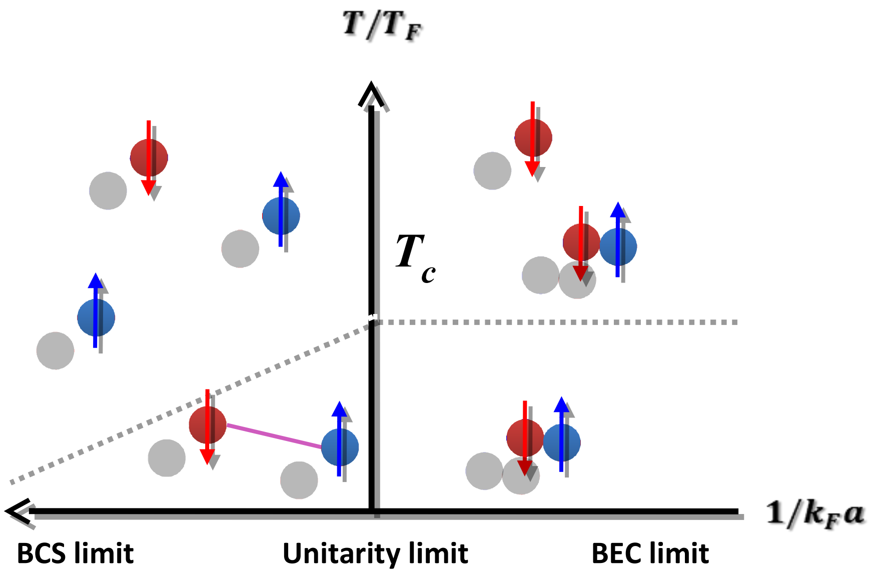


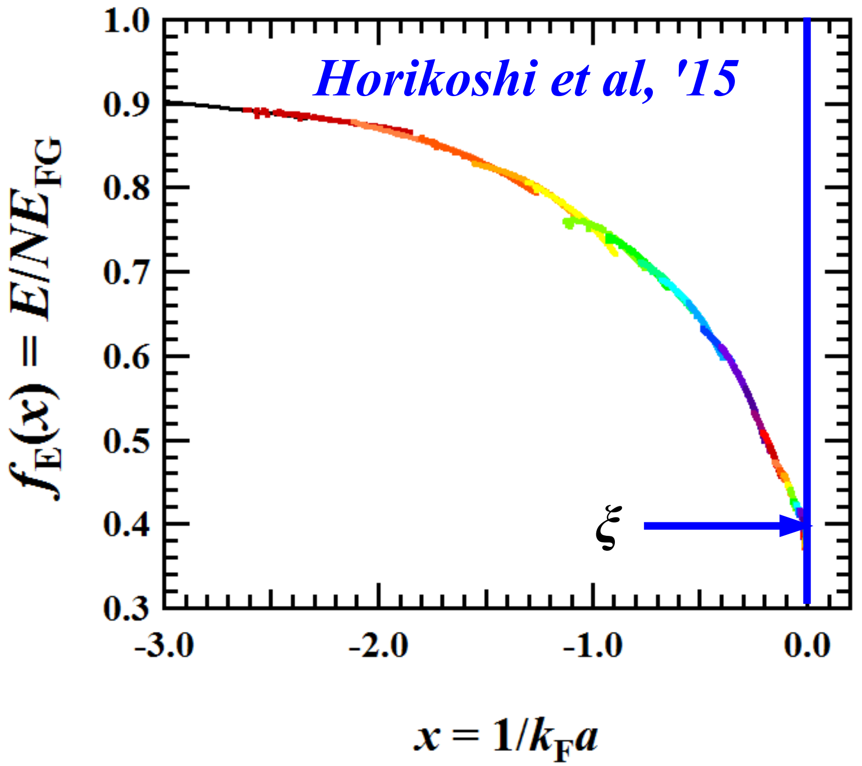


Abe, Seki ('09)

Cold Atom EOS

- **$E=\xi E_{FG}$ ($\xi \sim 0.4$) in the unitary limit ($1/k_Fa_0 \to 0$, $k_Fr_{eff}=0$)**
  - **ξ: Bertsch parameter (INT workshop)**
- **EOS measurement off unitary limit**
  Horikoshi et al., 2016
- **How can we use the cold atom EOS in the context of NS matter ?**





Comparison with Pure Neutron Matter EOS

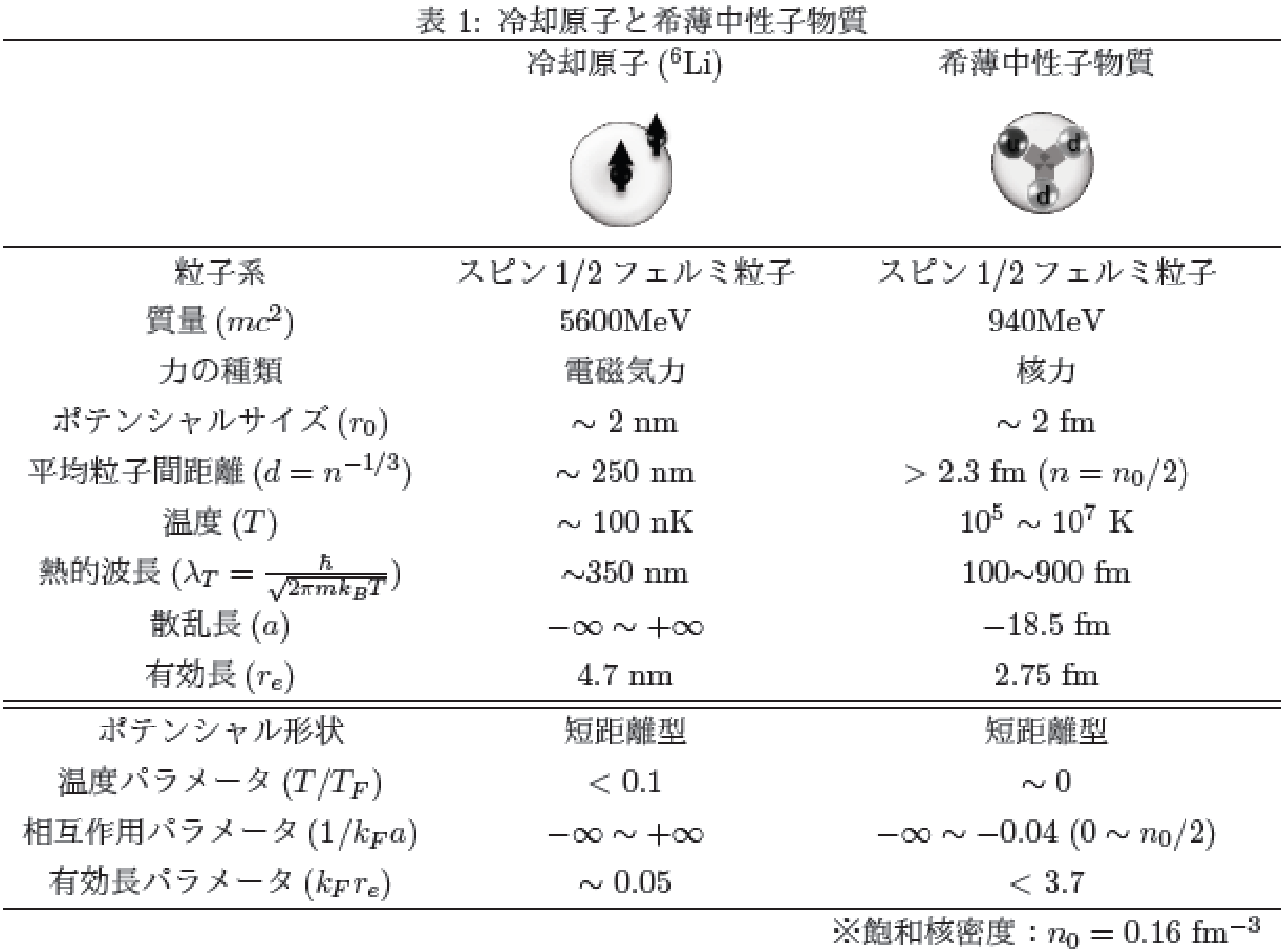


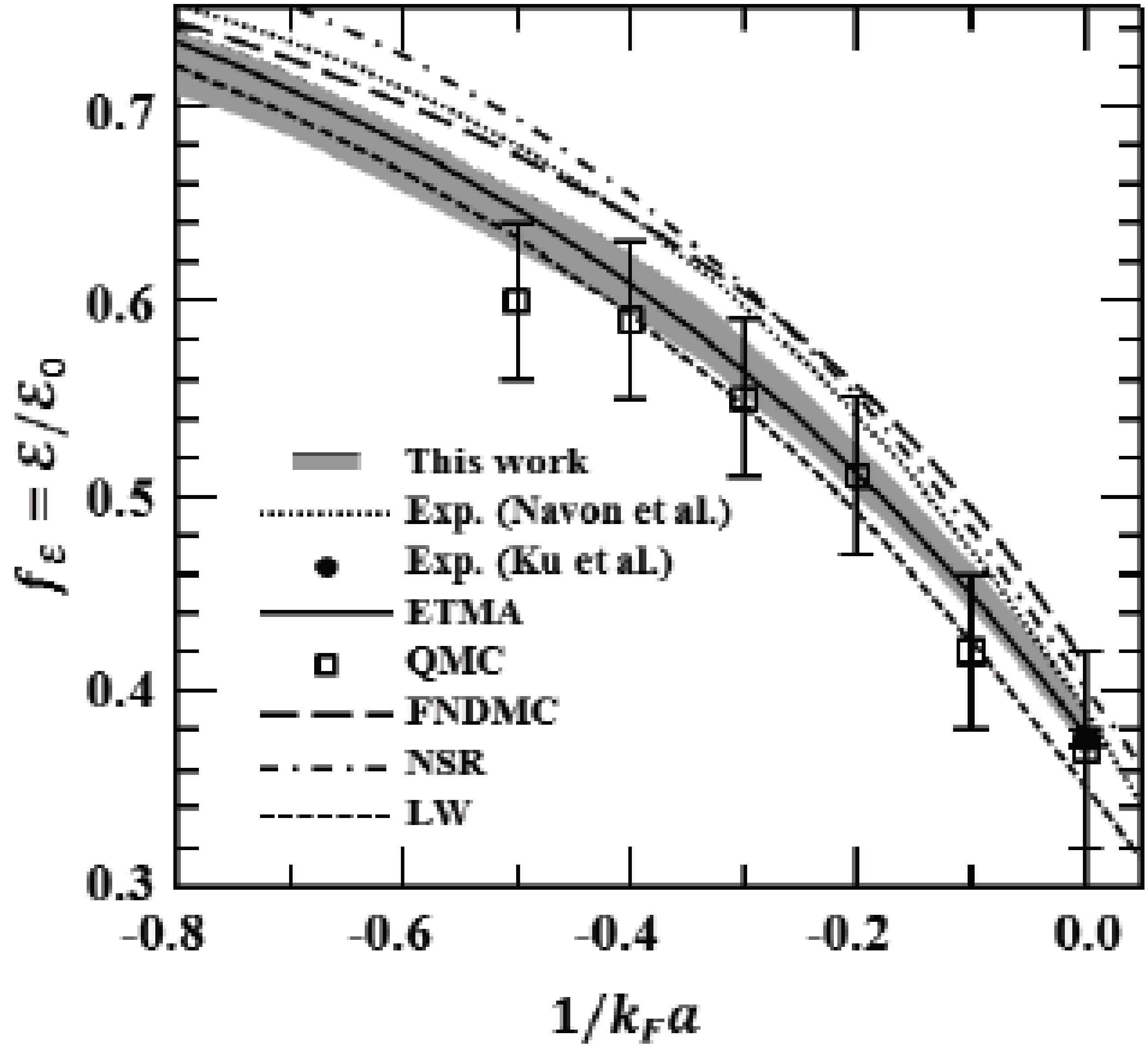
表 1: 冷却原子と希薄中性子物質

	冷却原子 (^{6}Li)	希薄中性子物質
粒子系	スピン 1/2 フェルミ粒子	スピン 1/2 フェルミ粒子
質量 (mc^2)	5600MeV	940MeV
力の種類	電磁気力	核力
ポテンシャルサイズ (r_0)	$\sim$ 2 nm	$\sim$ 2 fm
平均粒子間距離 ($d = n^{-1/3}$)	$\sim$ 250 nm	$>$ 2.3 fm ($n = n_0/2$)
温度 (T)	$\sim$ 100 nK	$10^5 \sim 10^7$ K
熱的波長 ($\lambda_T = \frac{\hbar}{\sqrt{2\pi m k_B T}}$)	~350 nm	100~900 fm
散乱長 (a)	$-\infty \sim +\infty$	-18.5 fm
有効長 (r_e)	4.7 nm	2.75 fm
ポテンシャル形状	短距離型	短距離型
温度パラメータ (T/T_F)	< 0.1	~ 0
相互作用パラメータ ($1/k_F a$)	$-\infty \sim +\infty$	$-\infty \sim -0.04$ ($0 \sim n_0/2$)
有効長パラメータ ($k_F r_e$)	~ 0.05	< 3.7

※飽和核密度：$n_0 = 0.16$ fm^{-3}

大橋 et al. ('16)[原子核研究]

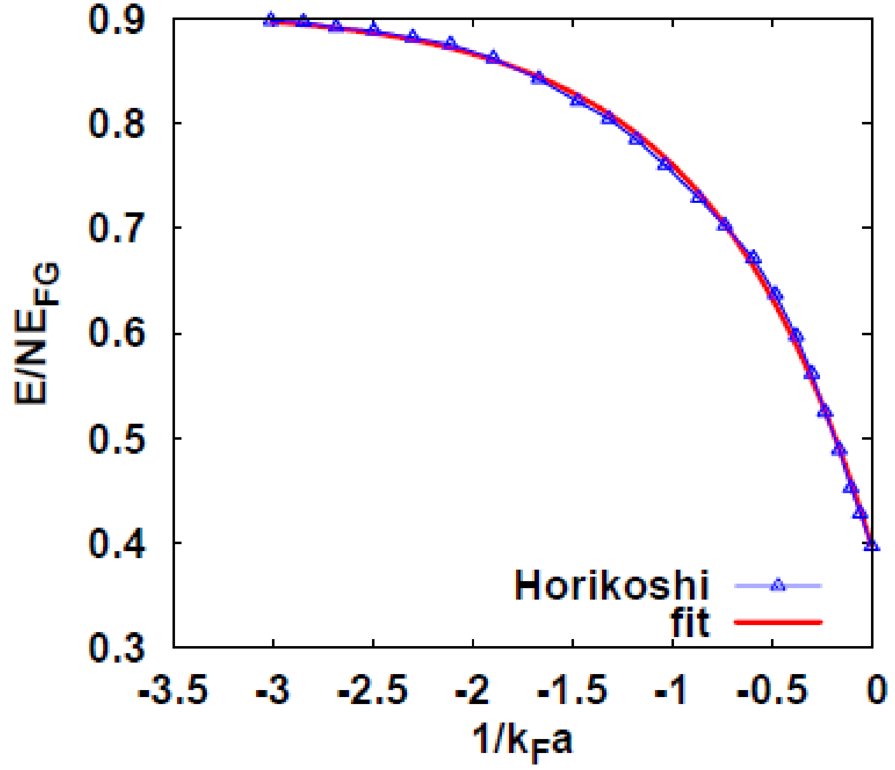
Cold Atom EOS

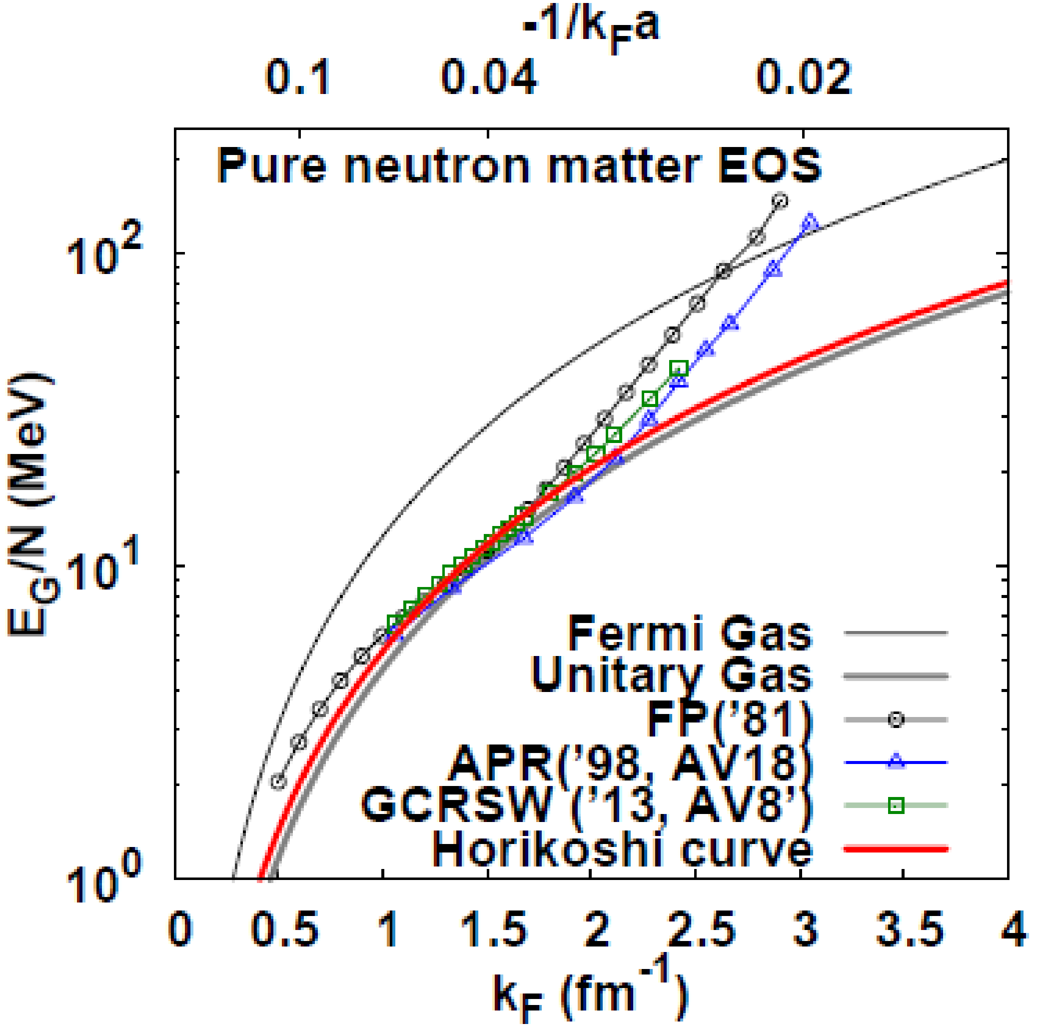


大橋 *et al.* ('16)[原子核研究]

Comparison with Pure Neutron Matter EOS

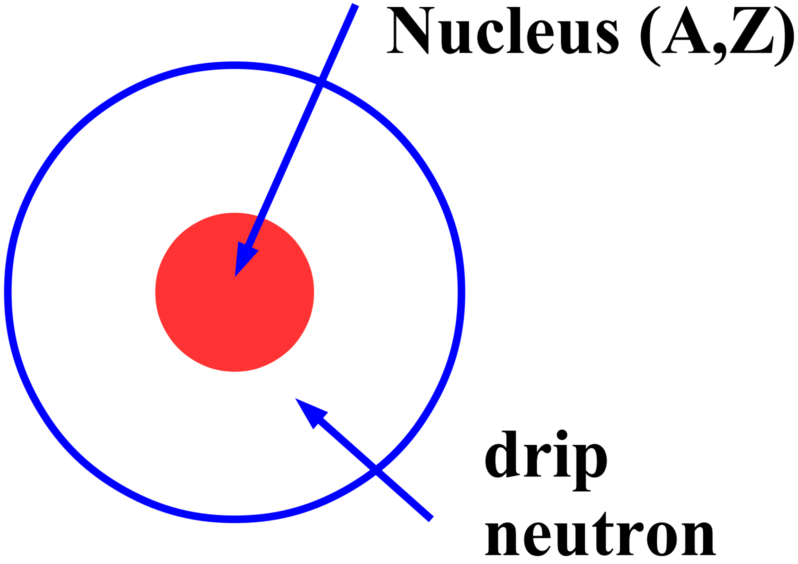
- **Cold Atom EOS is consistent with MC result.**
- **How can we evaluate the effective range correction ?**
- **Does it have other impacts in neutron star physics ?**





Low Density Neutron Star Matter EOS

- Nuclei & electron ($\rho < 4 \times 10^{11}$ g/cc)
- Nuclei, drip neutron, electron
  (4×10^{11} g/cc $< \rho < 2.5 \times 10^{14}$ g/cc)
  → pure neutron matter EOS
- Uniform nuclear matter
  ($\rho > 2.5 \times 10^{14}$ g/cc)
  → nuclear matter EOS at $Z \ll N$



- "Standard" (low density) NS matter EOS
  G. Baym, H.A. Bethe, C. J. Pethick, NPA175('71),225.
  Bulk pure neutron matter EOS

$$\underset{\substack{\uparrow\\\text{Fermi mom.}}}{W(k},0) \approx \underbrace{19.74k^2}_{\text{kin. E}} - \underset{\substack{\uparrow\\\propto\ \rho}}{k^3}\frac{(40.4-1.088k^3)}{(1+2.545k)}$$

Another way to use Cold Atom EOS

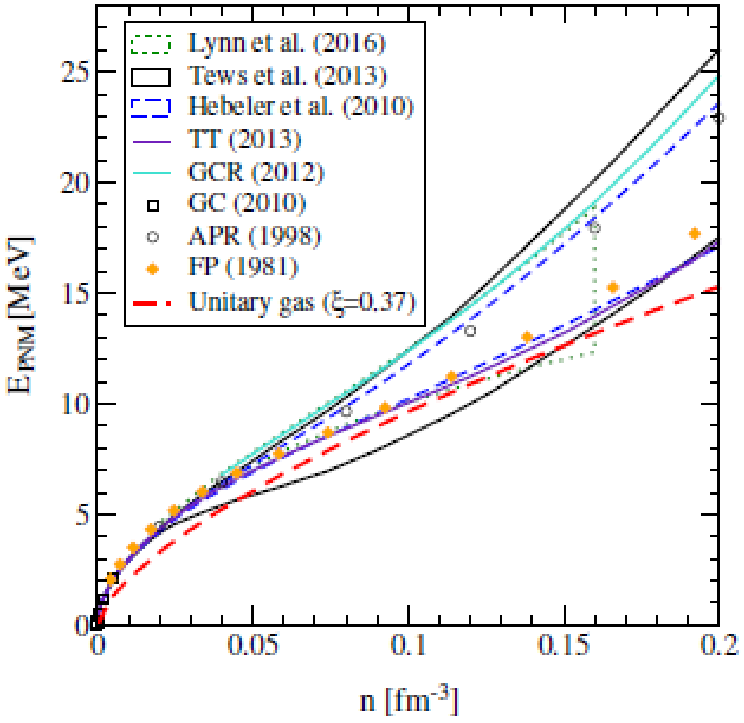
- Unitary gas EOS は ab initio pure neutron matter EOS の lower bound を与えているように見える。(Conjecture)

$$E_{\rm PNM}(n) \geq E_{\rm UG}(n)$$

$$E_{\rm UG}(u) = \frac{3}{5} E_{\rm F}(n)\,\xi = \frac{3\hbar^2 k_{\rm F}^2}{10 m_n}\,\xi = E_{\rm UG}^0\, u^{2/3}$$

($\xi \sim 0.37$, $u=n/n_0$)

- これが正しいなら、
  対称エネルギーへの制限が
  与えられるのでは？



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

Unitary Gas Constraint on Symmetry Energy

- **対称エネルギー＝**
  純中性子物質エネルギー − 対称核物質エネルギー

$$S(u) = E_{\rm PNM}(u) - E_{\rm SNM}(u)$$

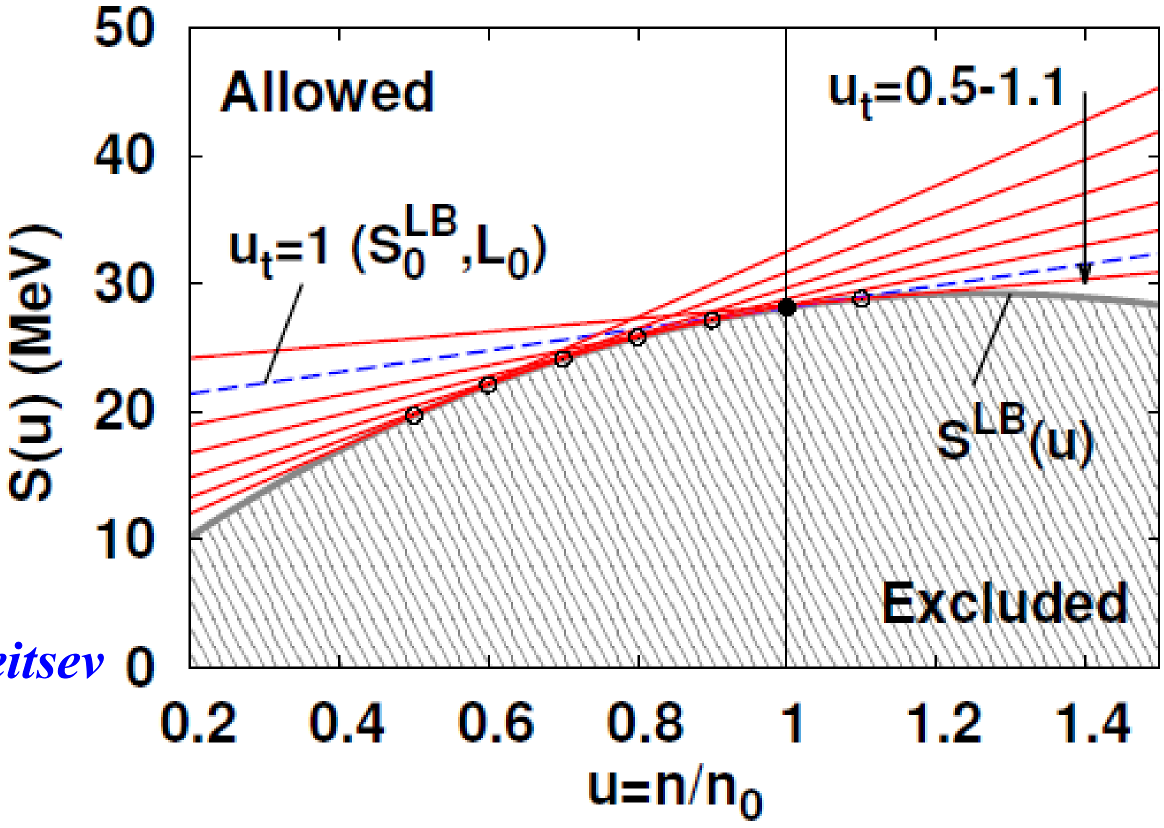
$$E_{\rm SNM}(u) = E_0 + K\,(u-1)^2/18 + \mathcal{O}[(u-1)^3]$$

$$S(u) \geq E^0_{\rm UG} u^{2/3} - \left[E_0 + \frac{K}{18}(u-1)^2\right] \equiv S^{\rm LB}(u)$$

- **S_0 への制限**

$$S_0 \geq E^0_{\rm UG} - E_0 \equiv S^{\rm LB}_0$$

- **$S_0 > S_0^{\rm LB}$ では、**
  L への制限



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

Unitary Gas Constraint on Symmetry Energy Parameters

- **Symmetry Energy Parameters (S_0, L) への制限**

$$S_0 + \frac{L}{3}(u-1) \geq E^0_{\mathrm{UG}} u^{2/3} - \left[E_0 + \frac{K_n}{18}(u-1)^2 \right]$$

- **接線条件 → L の領域**

$$S_0 = \frac{E^0_{\mathrm{UG}}}{3u_t^{1/3}}(u_t+2) + \frac{K_n}{18}(u_t-1)^2 - E_0$$

$$L = \frac{2E^0_{\mathrm{UG}}}{u_t^{1/3}} - \frac{K_n}{3}(u_t-1)$$

- **$(u-1)^3$ を無視しているので、不等式が成り立つには E_{SNM} を大きく、E_{UG} を小さく見積もる必要あり。**

  E_0=-15.9 ± 0.4 MeV, n_0=0.164 ± 0.007 fm^{-3},

  K=230 ± 40 MeV, ξ=0.370 ± 0.005

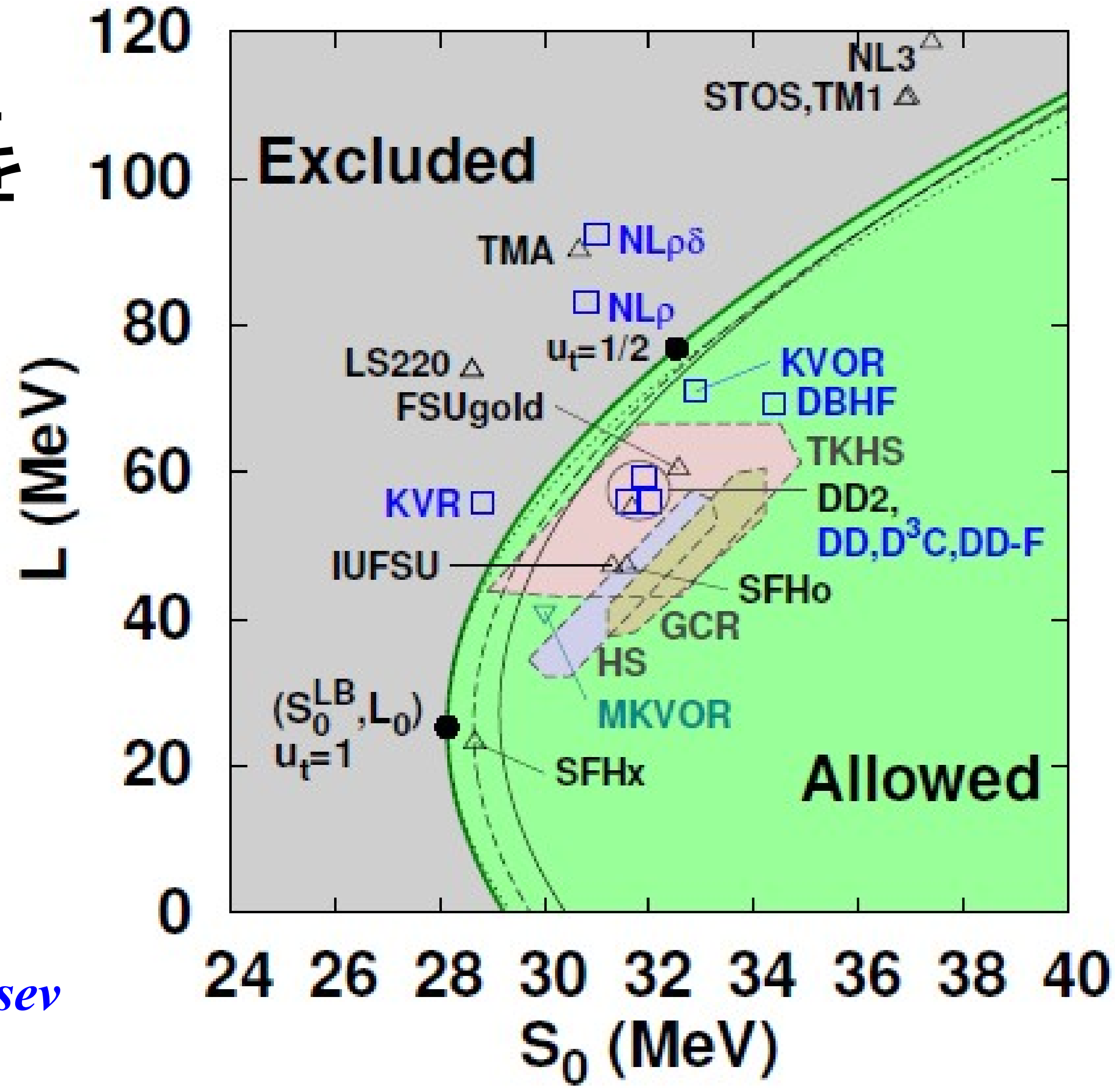
Unitary Gas Constraint on Symmetry Energy Parameters

- **最も conservative なパラメータ**

  E_0=-15.5 MeV, n_0=0.157 fm^{-3}, K=270 MeV, ξ=0.365

- **Unitary Gas からの制限は、コンパクト天体現象の計算に用いられている多くの EOS を rule out**

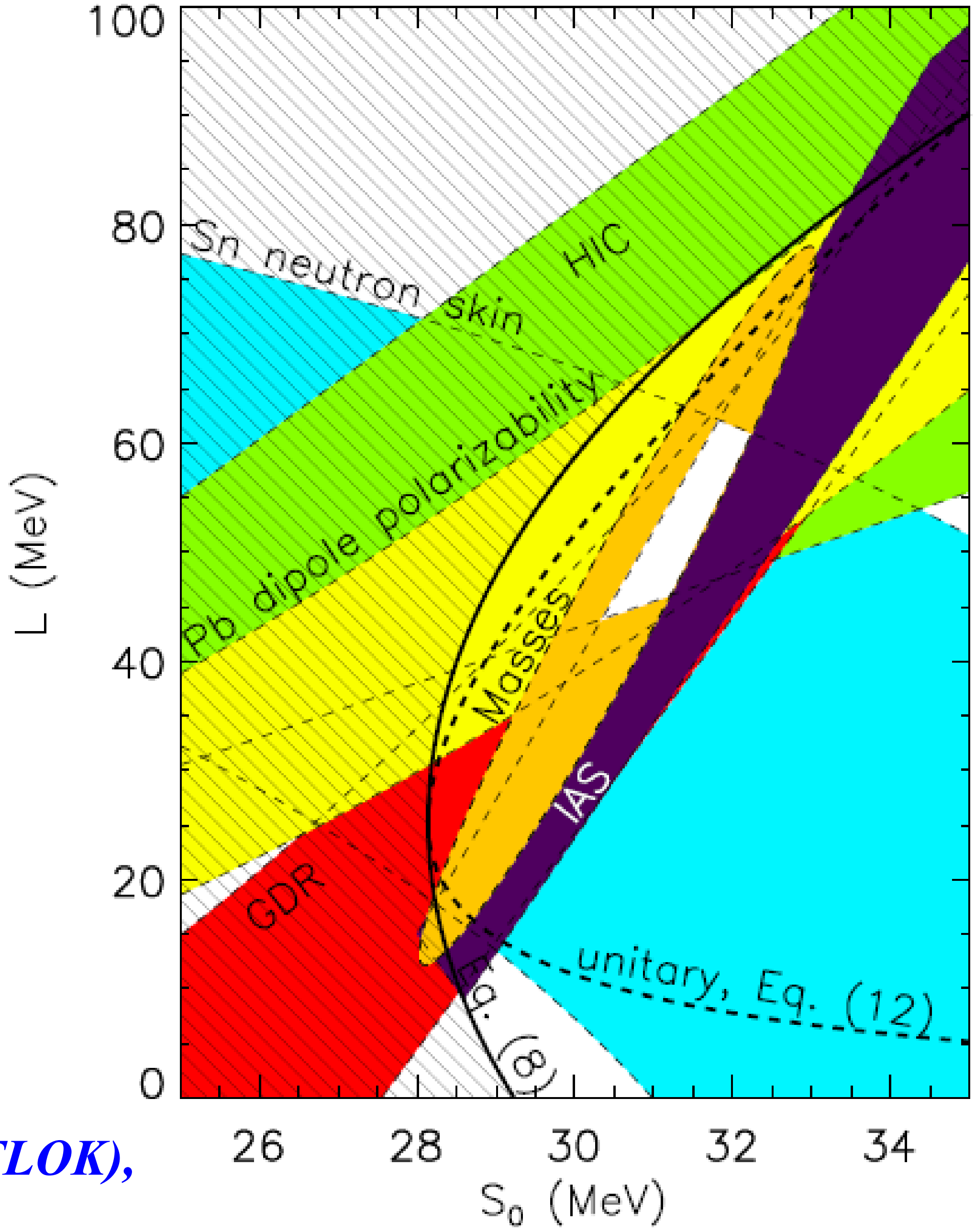
  Fisher et al.('14),
  Klahn et al.('06)



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

Unitary Gas Constraint vs Experimental Constraints

- **Unitary gas constraint と 実験による制限は consistent**



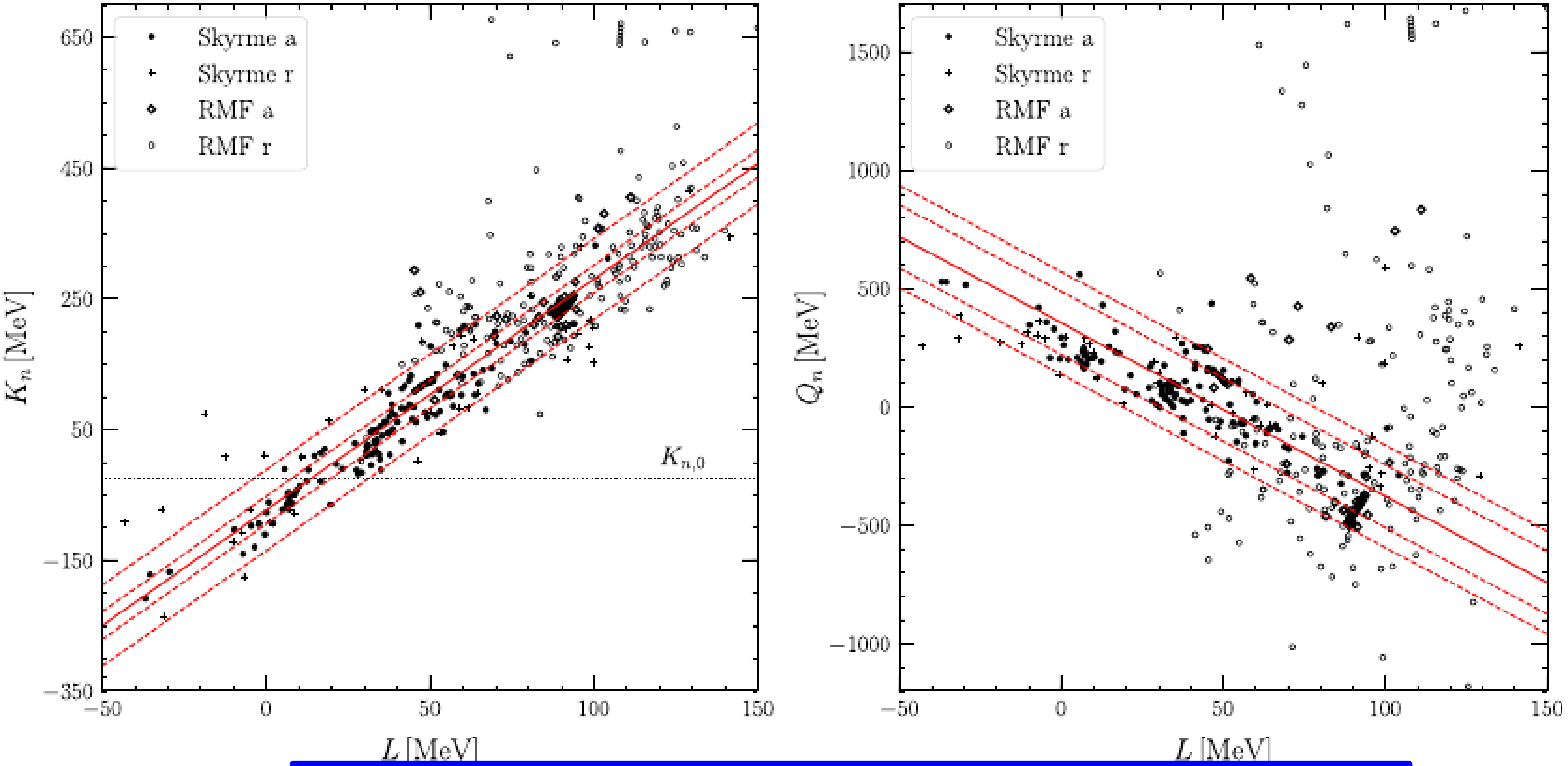
I. Tews, J.M.Lattimer, AO, E.E.Kolomeitsev (TLOK), ApJ 848 ('17)105

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

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

Fermi momentum (k_F) expansion

TLOK

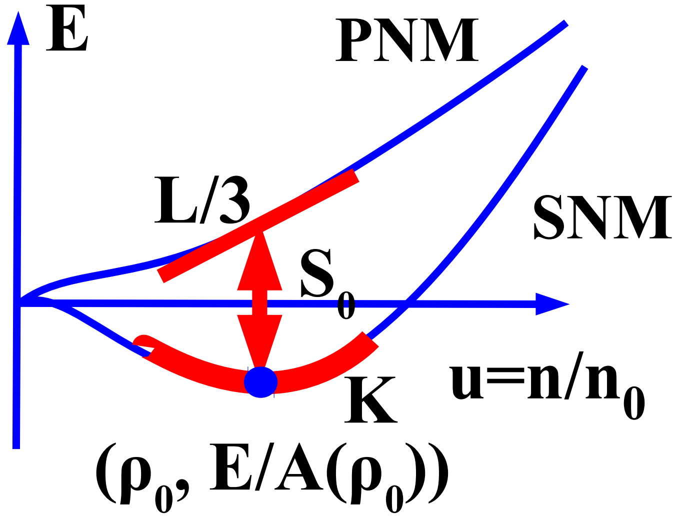
- **Saturation & Symmetry Energy Parameters**

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

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

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

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



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

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

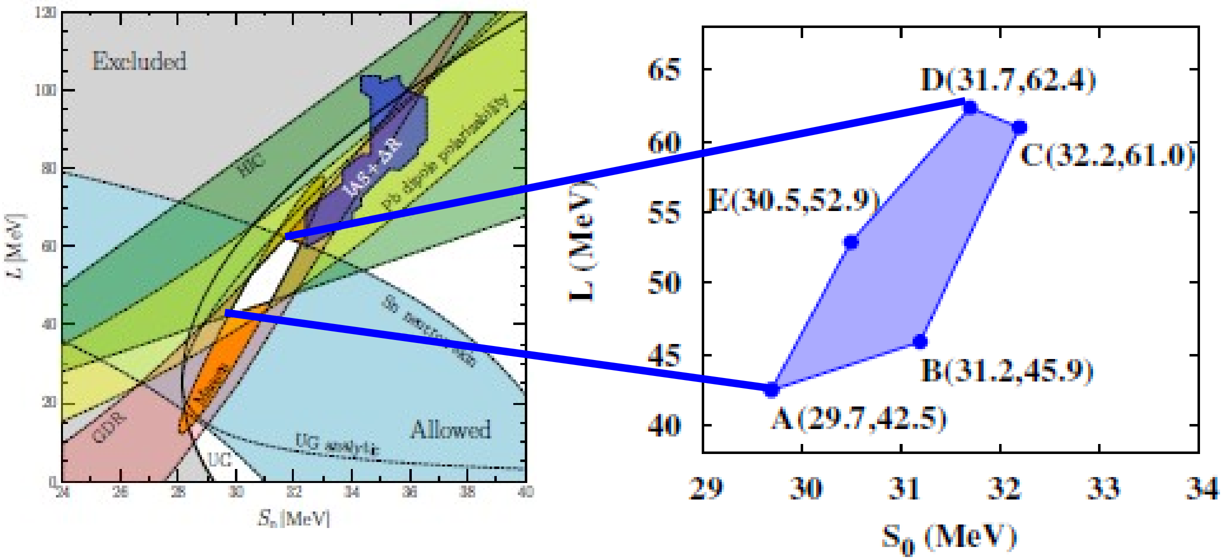
$$
\begin{aligned}
a_s &= -4T_s && +20S_0 - 19L/3 && +K_s && -Q_s/6 \\
b_s &= 6T_s && -45S_0 + 15L && -5K_s/2 && +Q_s/2 \\
c_s &= -4T_s && +36S_0 - 12L && +2K_s && -Q_s/2 \\
d_s &= T_s && -10S_0 + 10L/3 && -K_s/2 && +Q_s/6
\end{aligned}
$$

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

Tedious but straightforward calc.

TLOK+2M$_\odot$ 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)

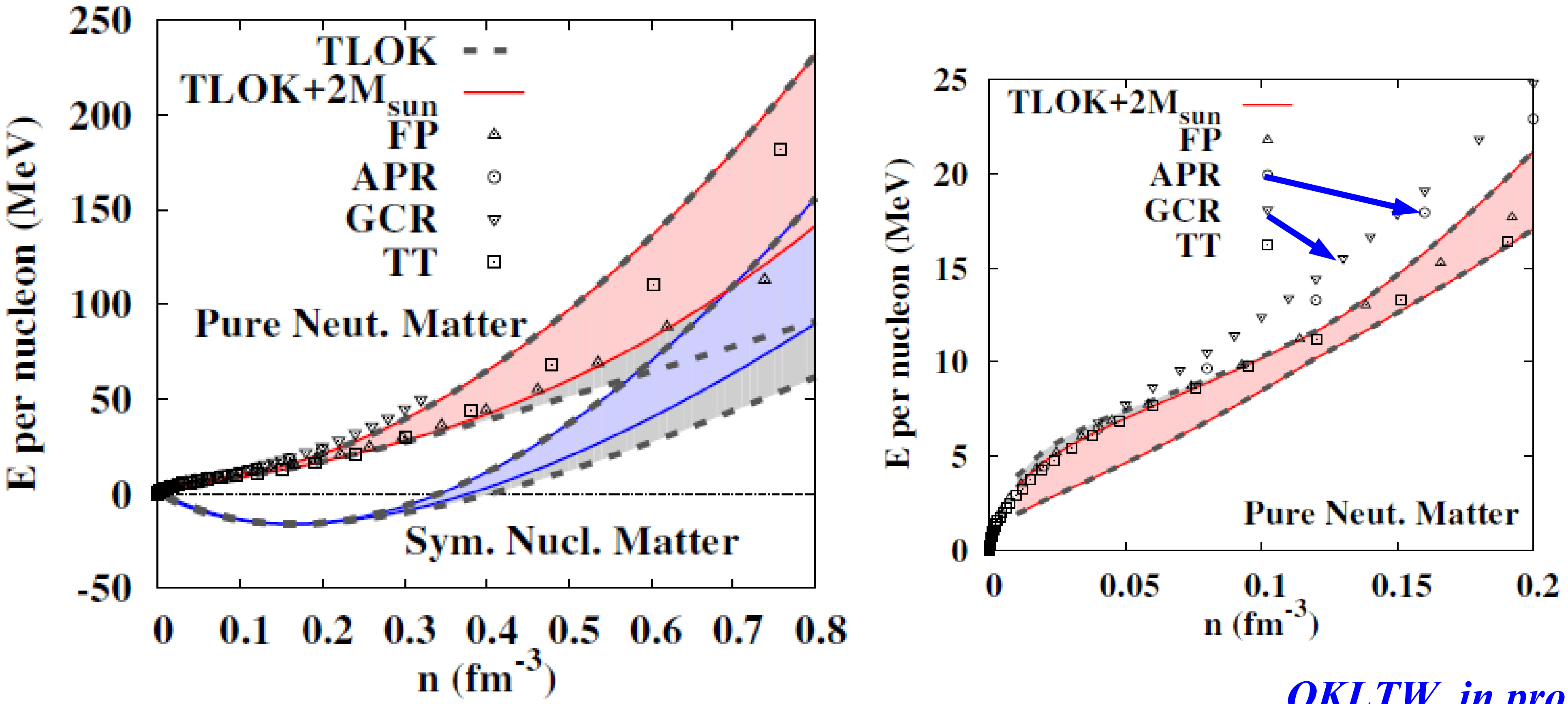


- **2 M$_\odot$ constraint**
  - **EOS should support 2 M$_\odot$ neutron stars.**

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.

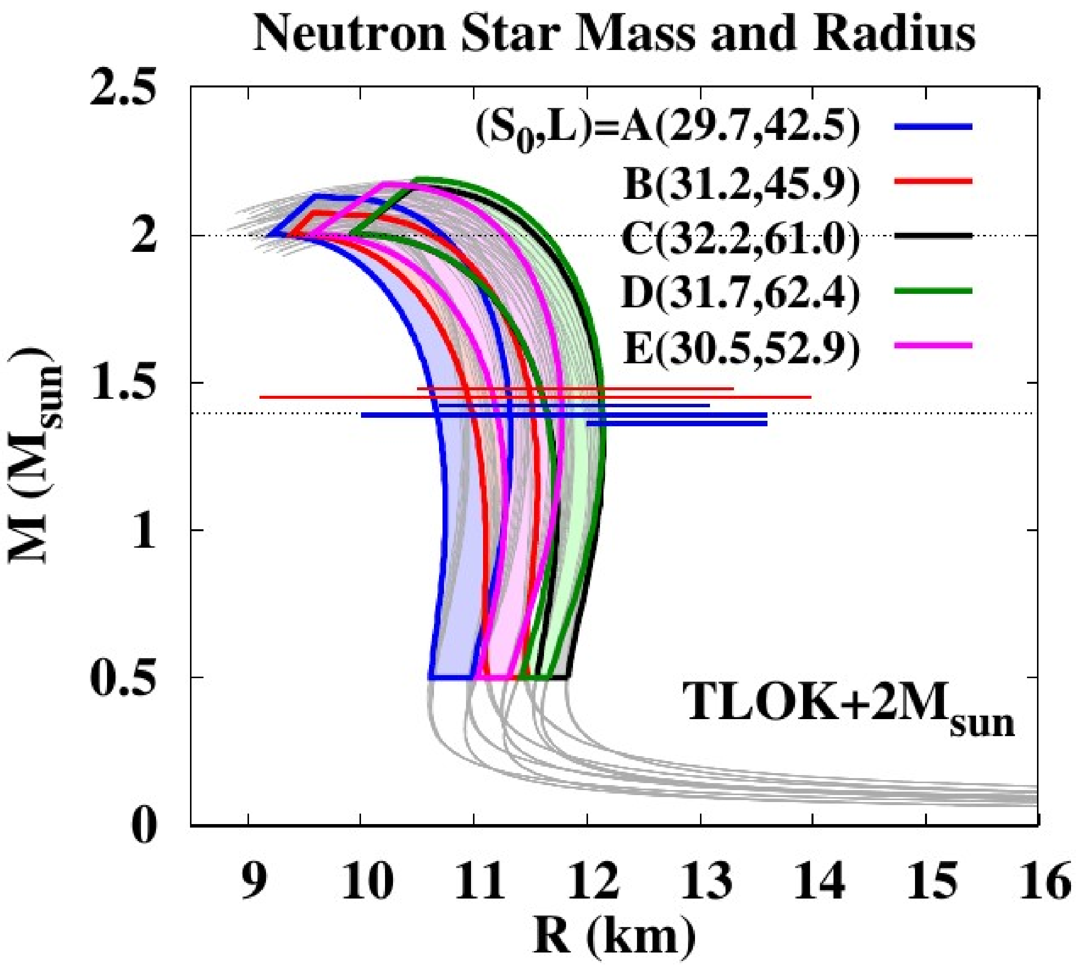


OKLTW, in prog.

Neutron Star MR curve

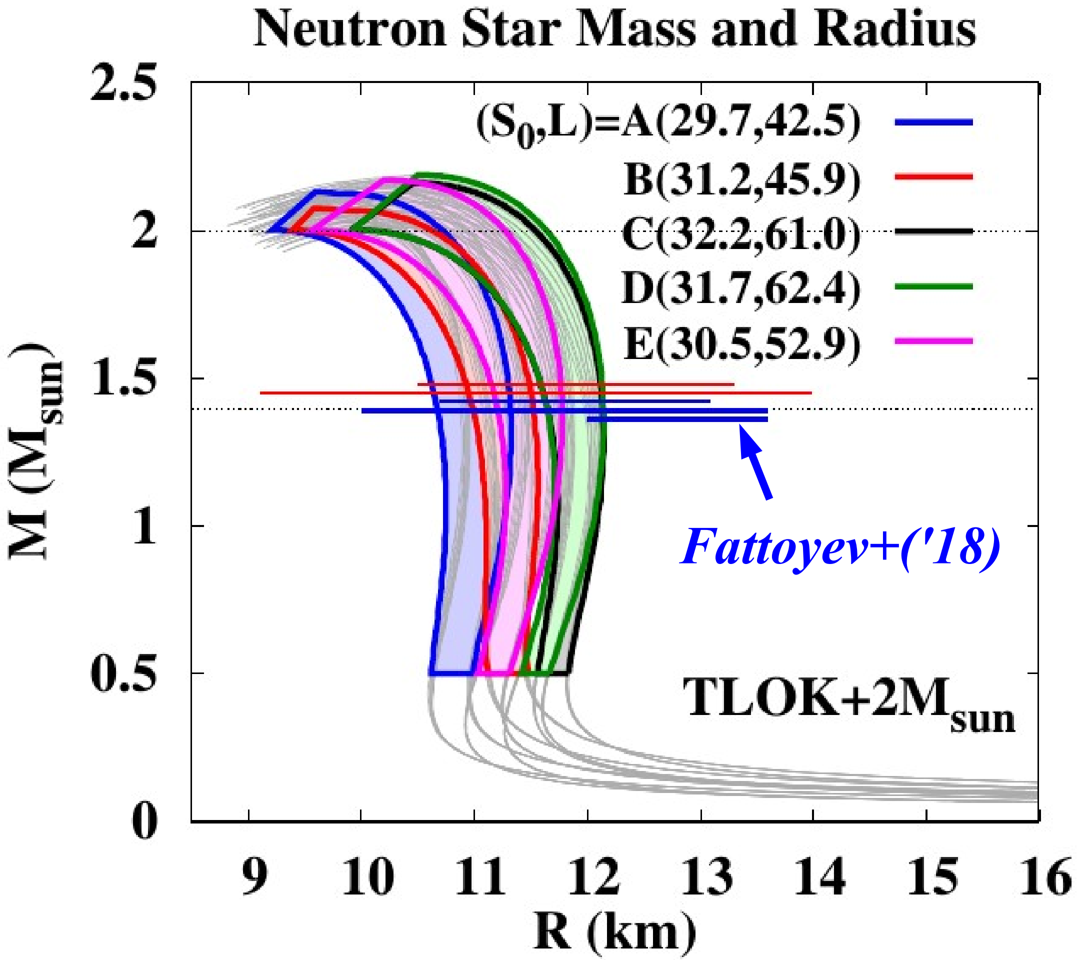
OKLTW, in prog.

- **TLOK + 2 $M_\odot$ constraints → $R_{1.4}$=(10.6-12.2) km**
  - **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.**

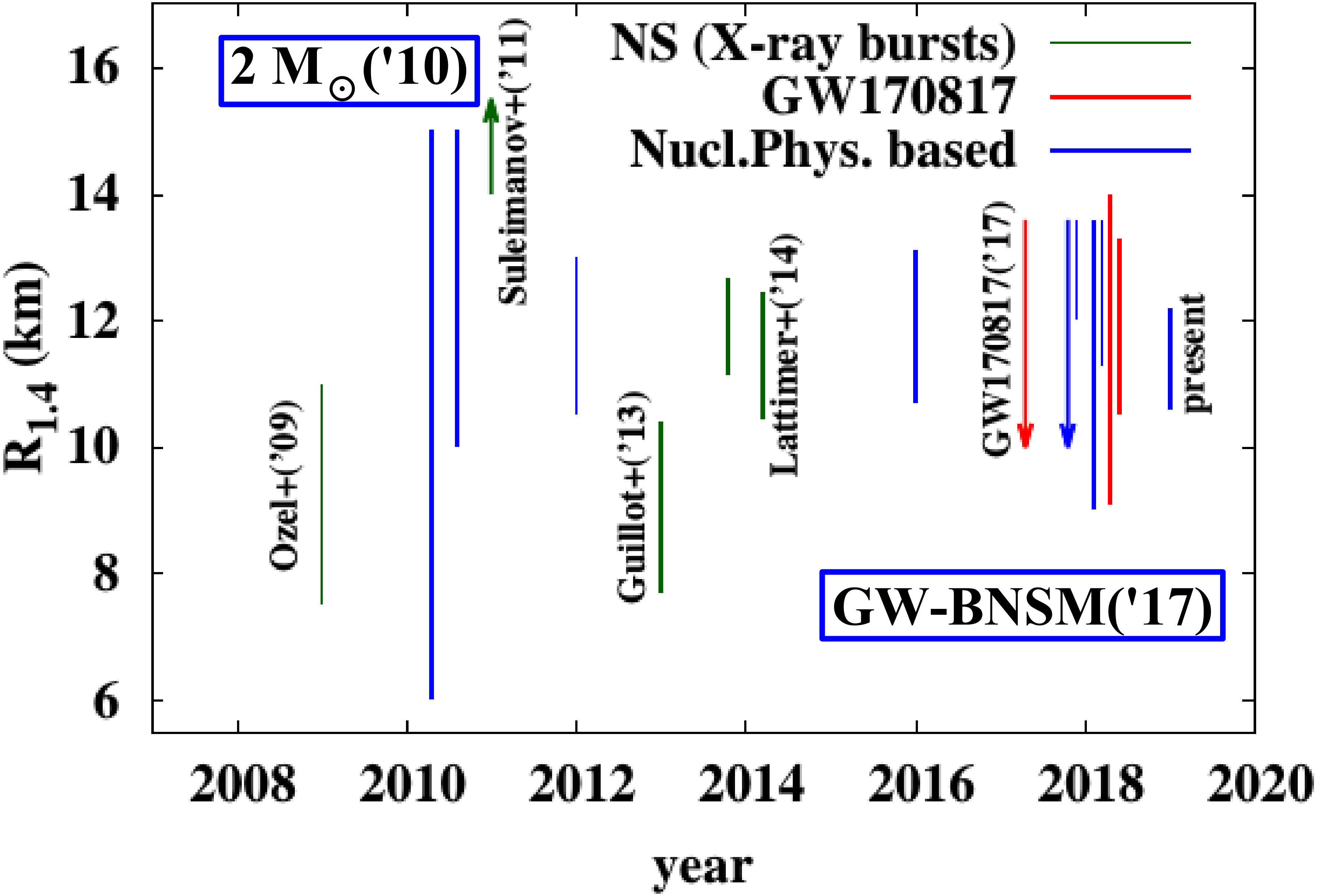


Neutron Star MR curve

- **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 ($R_{1.4}$)



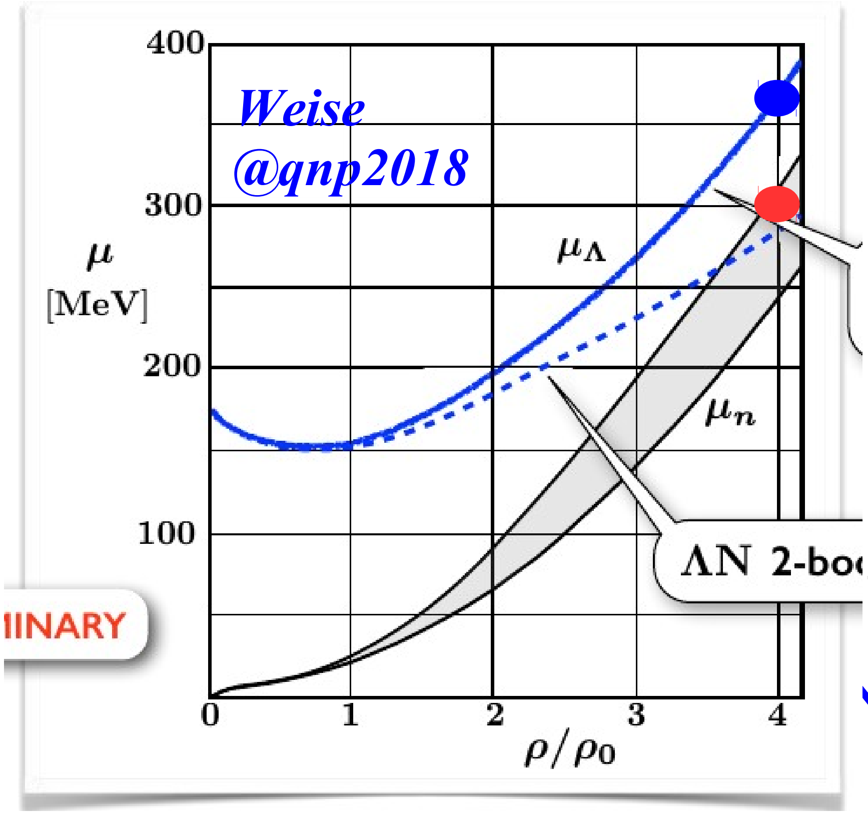
Implications to quark-hadron physics in cold dense matter

Questions !

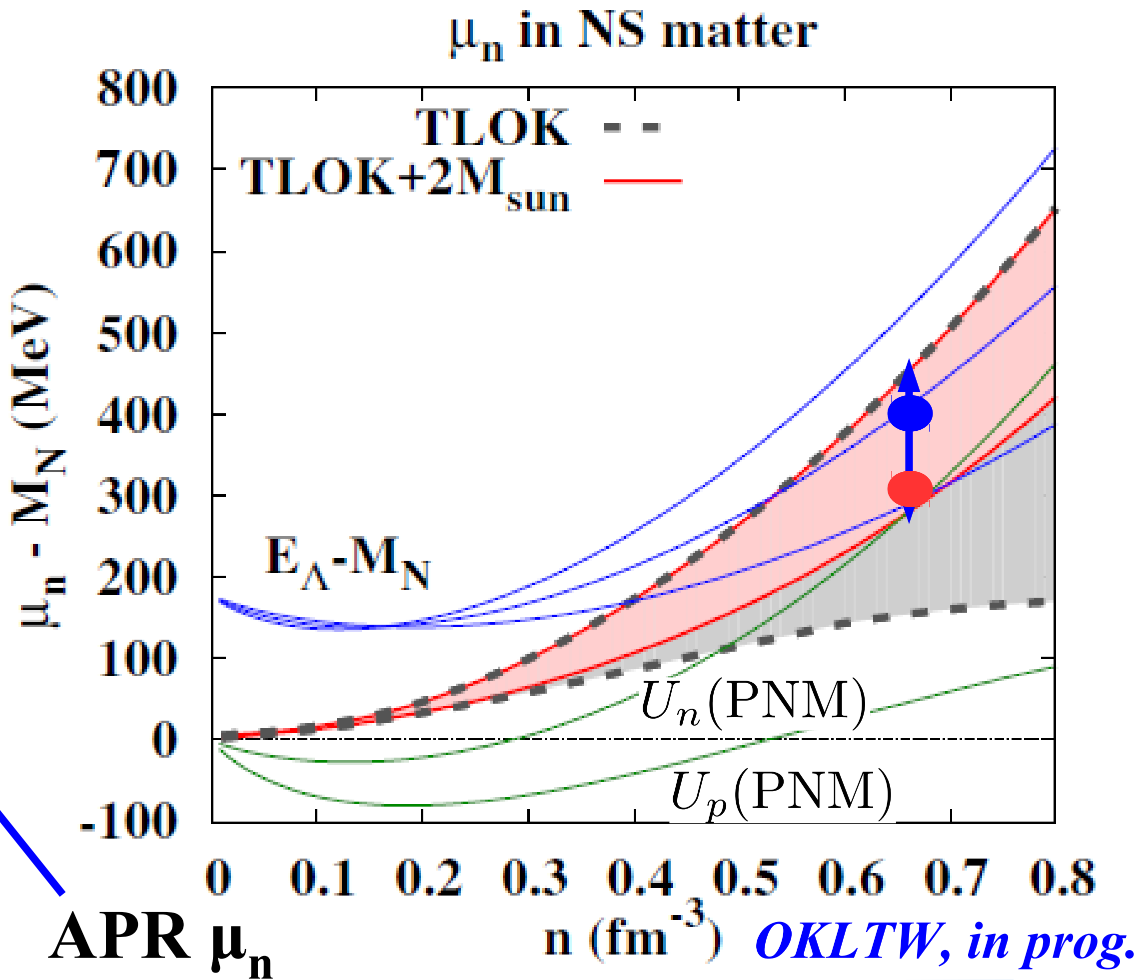
- Hyperon puzzle
  - At what density do hyperons appear ? → $U_\Lambda = \mu_n$
  - In STANDARD EOS with hyperons with $U_\Lambda(n_0)$=-30 MeV, Λ appears at $n=(2\text{-}3)n_0$
  - Density dep. of U_Λ is essential.
  - Neutron chemical potential strongly depends on sym. E.
- QCD phase transition in 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**

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

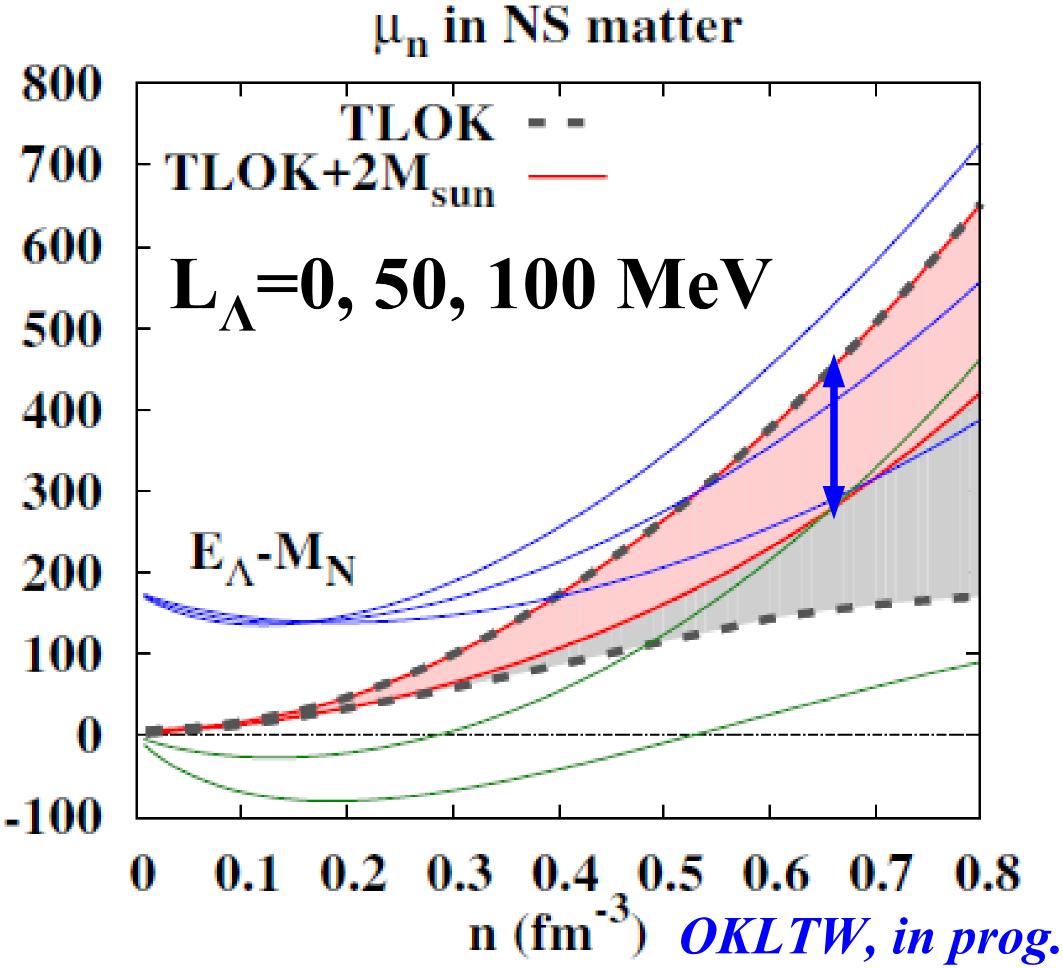
$$\simeq U_{0\Lambda} + \frac{L_\Lambda}{3}(u-1)$$

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

$$L_\Lambda = ???$$

(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)



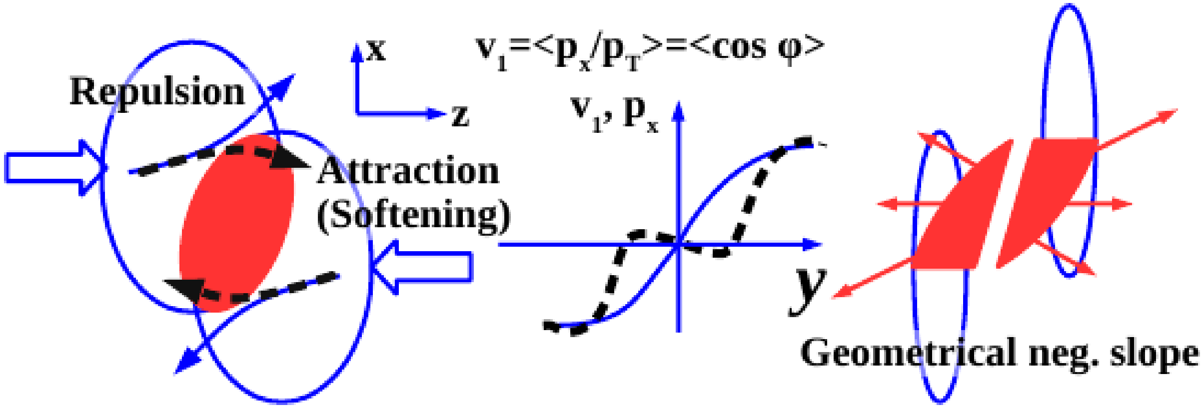
OKLTW, in prog.

QCD phase transition in cold dense matter

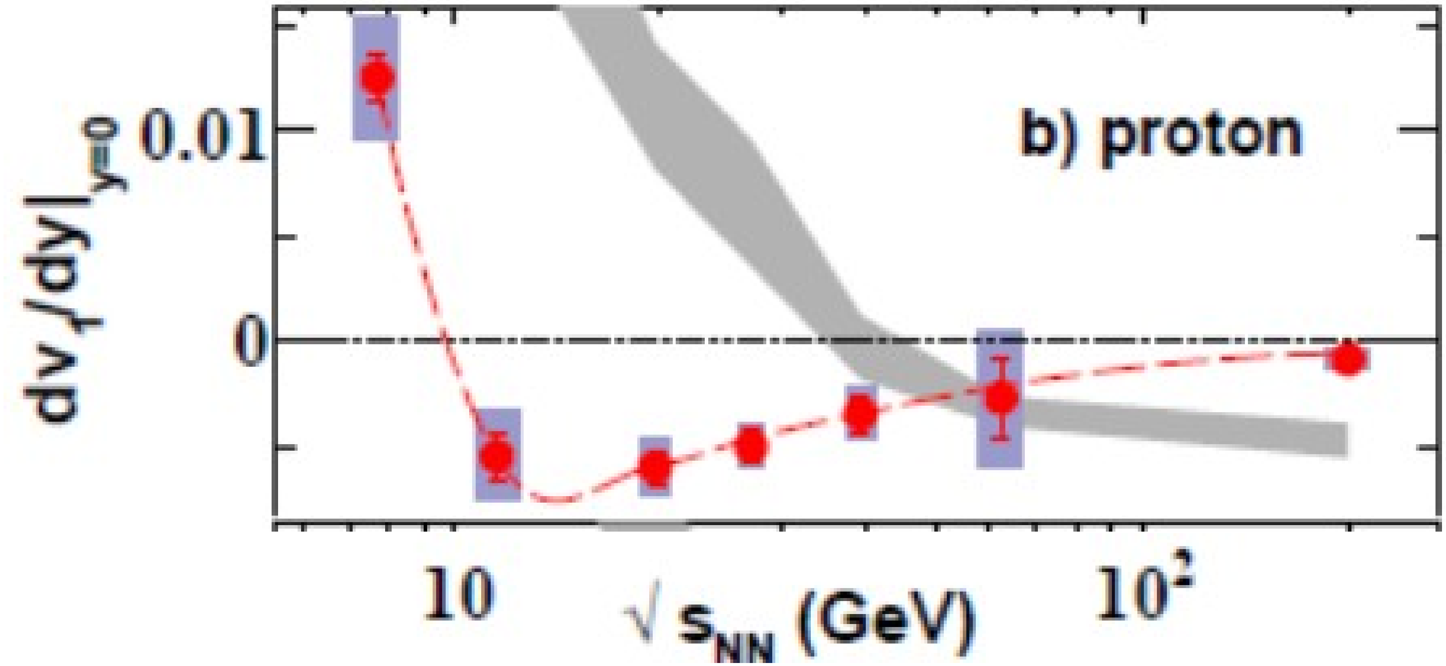
- **Transition to quark matter in cold-dense matter**
  1st order or crossover ?
- **Crossover: Masuda, Hatsuda, Takatsuka, Kojo, Baym, ...**
- **1st order p.t.**
  - **Many effective models predict, e.g. Asakawa-Yazaki CP**
  - **Recent phenomenological support: Negative Directed Flow in HIC**
    Y.Nara, 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 $= dv_1/dy$



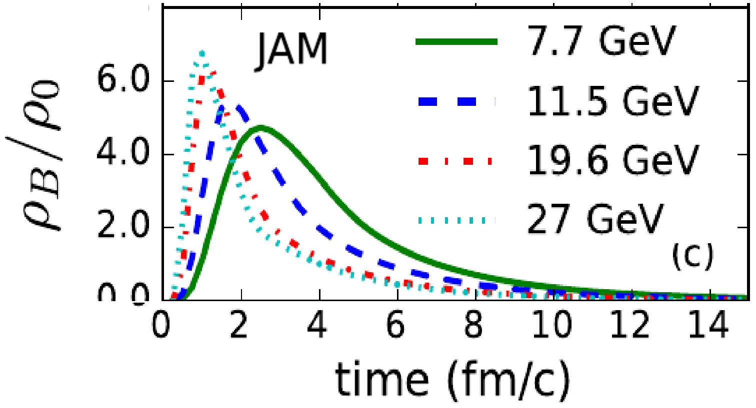
- **Negative Flow in Heavy-Ion Collisions**

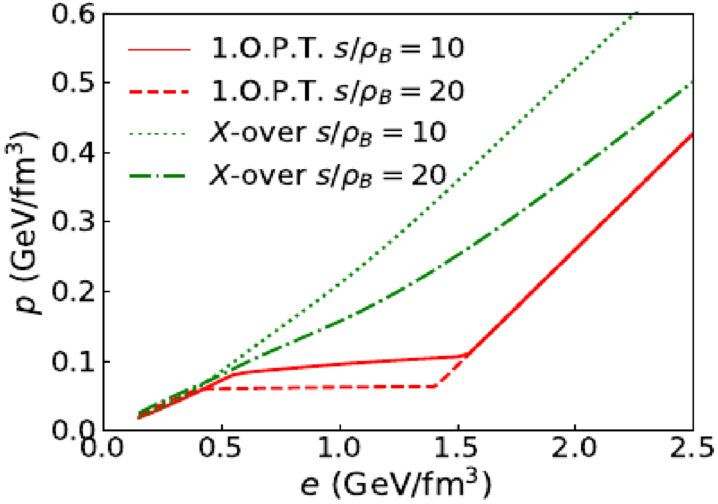


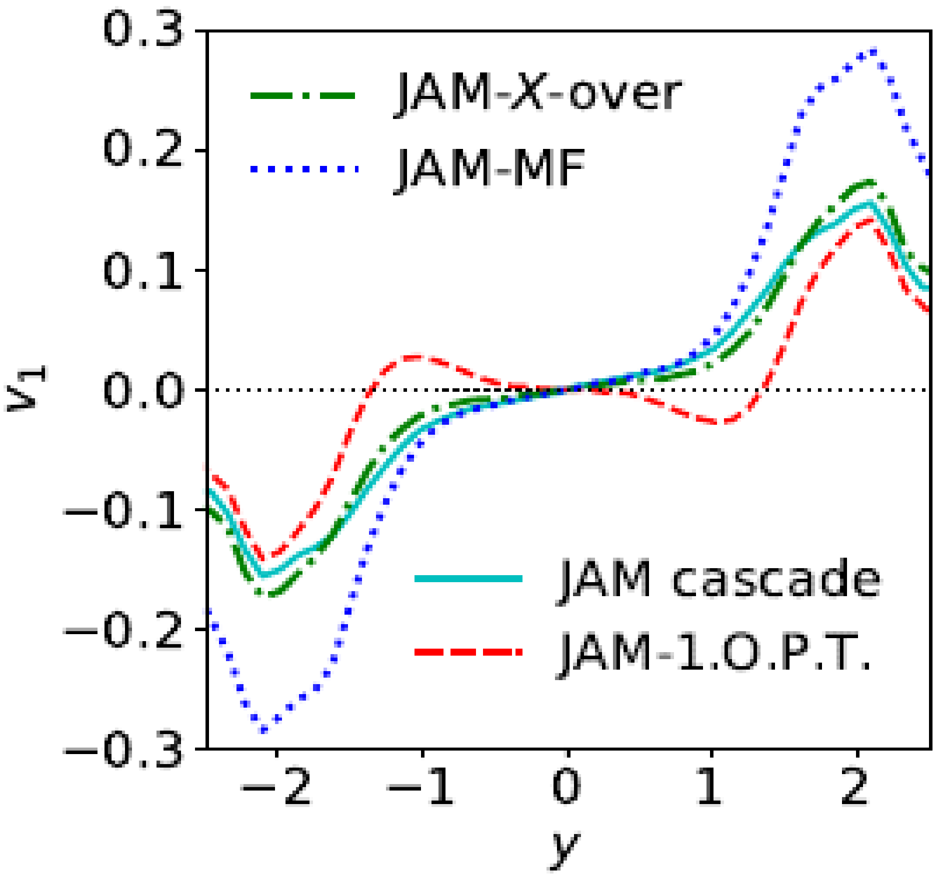
STAR Collab. (L. Adamczyk et al.), Phys.Rev.Lett. 112 ('14), 162301

Negative Directed Flow

- **Negative Directed Flow slope at $\sqrt{s_{NN}}$= 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

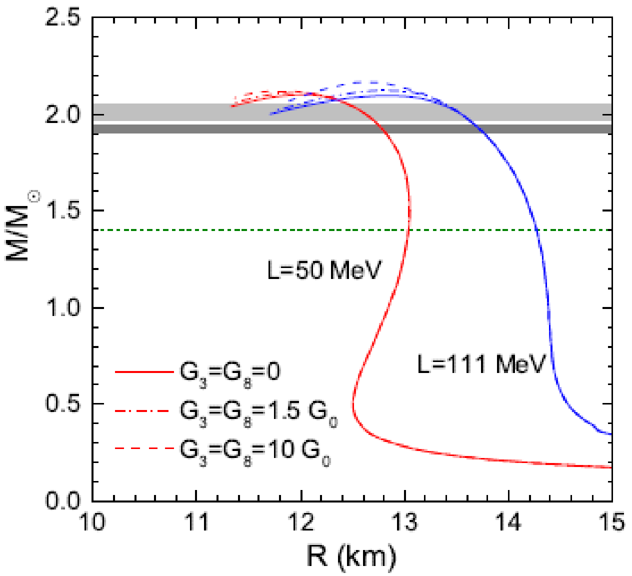
Isospin & Hypercharge Sym. E in quark matter

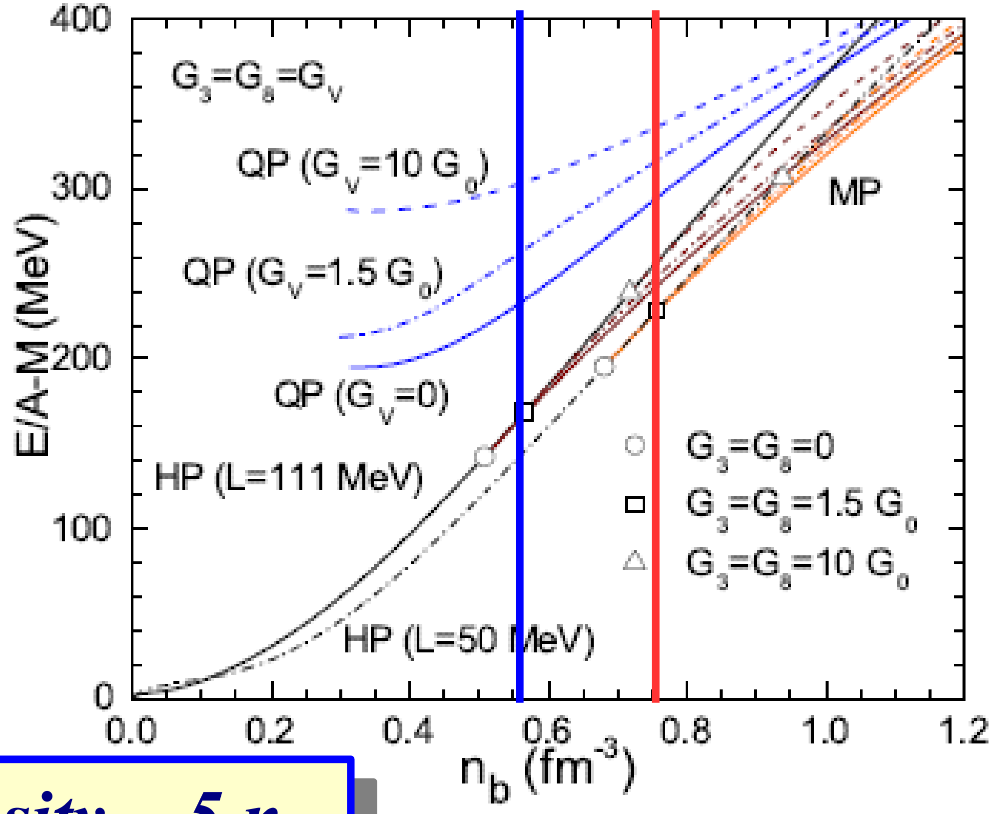
- **Two types of vector int. in NJL → Isospin & Hypercharge Sym. E**

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

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

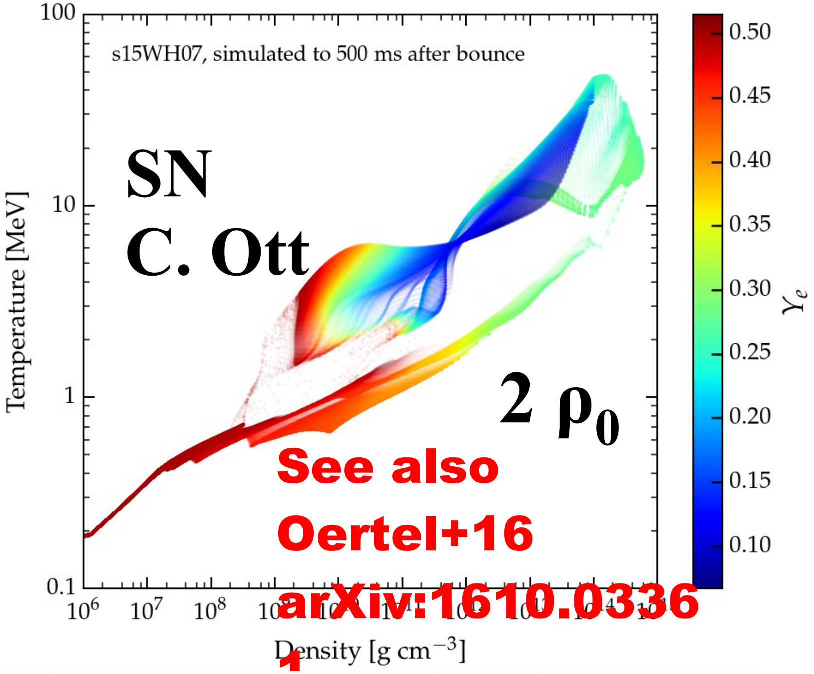
$$E = \alpha^2 S(n) + \alpha_Y^2 S_Y(n)\ ,\ \alpha = -2\langle T_z\rangle/B\ ,\ \alpha_Y = \langle B+S\rangle/B$$



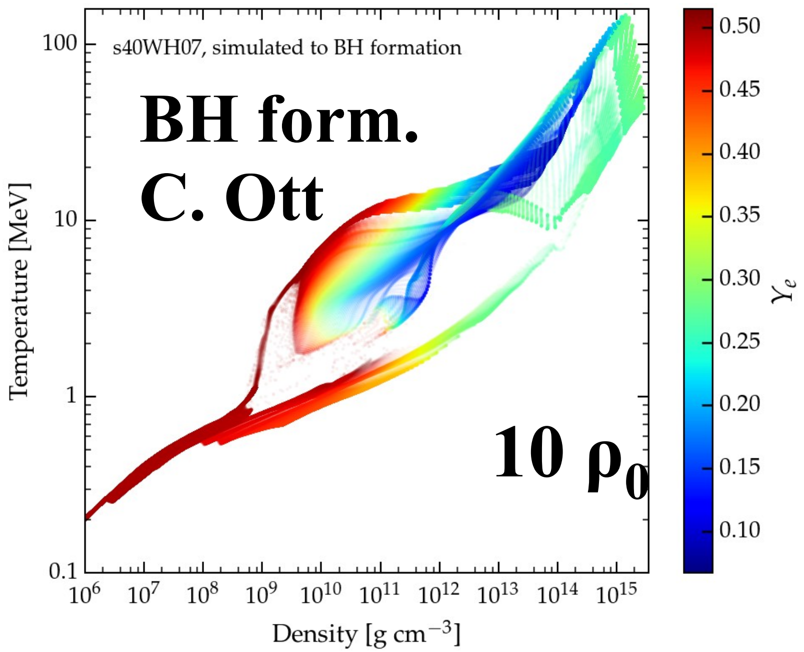


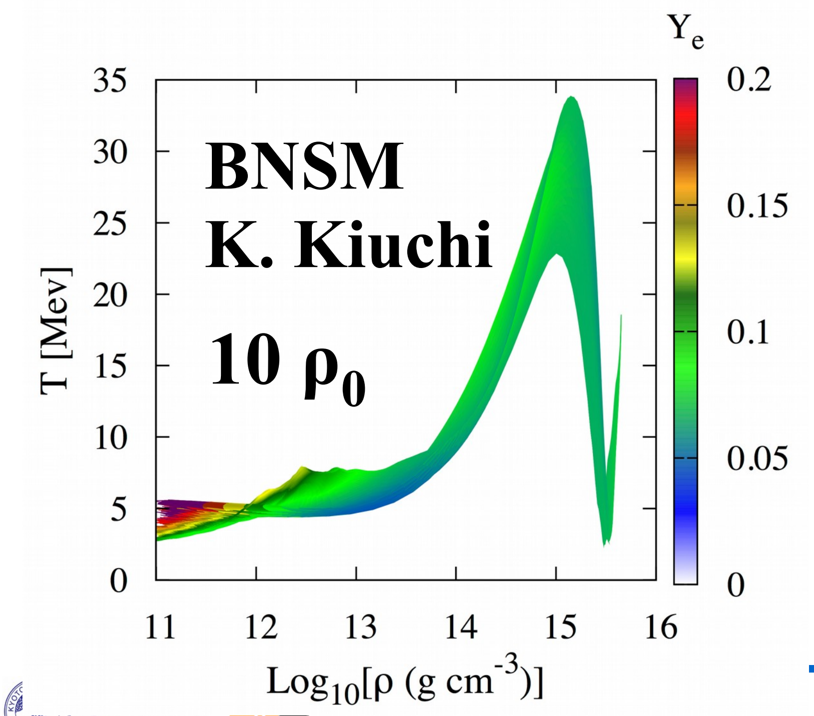
L= 50 MeV → transition density ~ 5 n_0

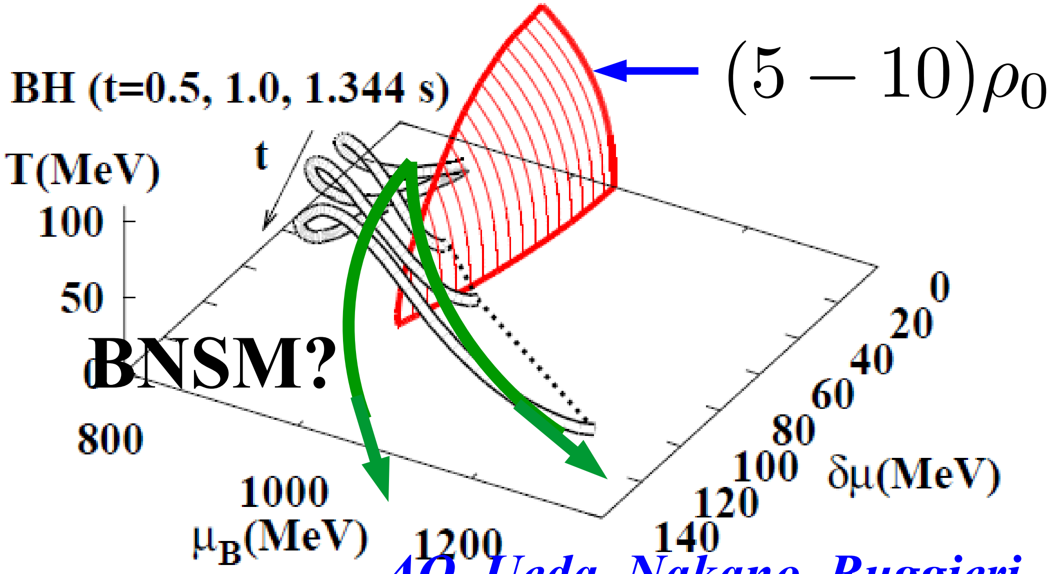
(ρ, T, Y_e) during SN, BH formation, BNSM



See also Oertel+16 arXiv:1610.0336







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

Summary

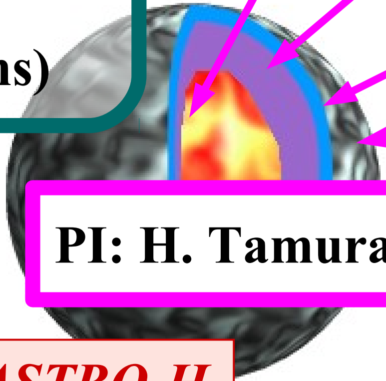
- Constraint on symmetry energy parameters (S_0, L, K_n, Q_n) together with 2 $M_\odot$ constraint gives the 1.4 $M_\odot$ neutron star radius in the range of (10.6-12.2) km.
  - Consistent with constraint from GW, e.g. (10.5-13.3) km by LIGO
  - Fermi momentum (k_F) expansion is invoked.
    Smooth extrapolation to (2-3) 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 $n=(5-10)n_0$ in almost sym. n.m. from heavy-ion data.
  - GW data from HMNS would clarify 3D phase diagram structure.

Thank you for your attention !

新学術領域「中性子星核物質」(2012-2017)

High ρ (Group A)
head: Tamura, Takahashi

Hypernuclei, Kaonic nuclei
YN & YY int.,
Eff. Interaction
(Heavy-ion collisions)



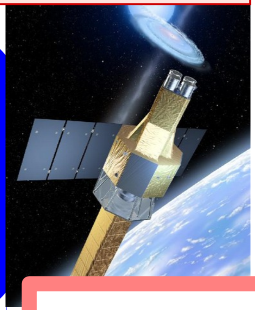
PI: H. Tamura

Low ρ (Group B)
head: Murakami,
Nakamura, Horikoshi

Sym. E, Pairing gap,
BEC-BEC cross over,
Cold atom, Unitary gas

NS Obs. (Group C)
head: Takahashi

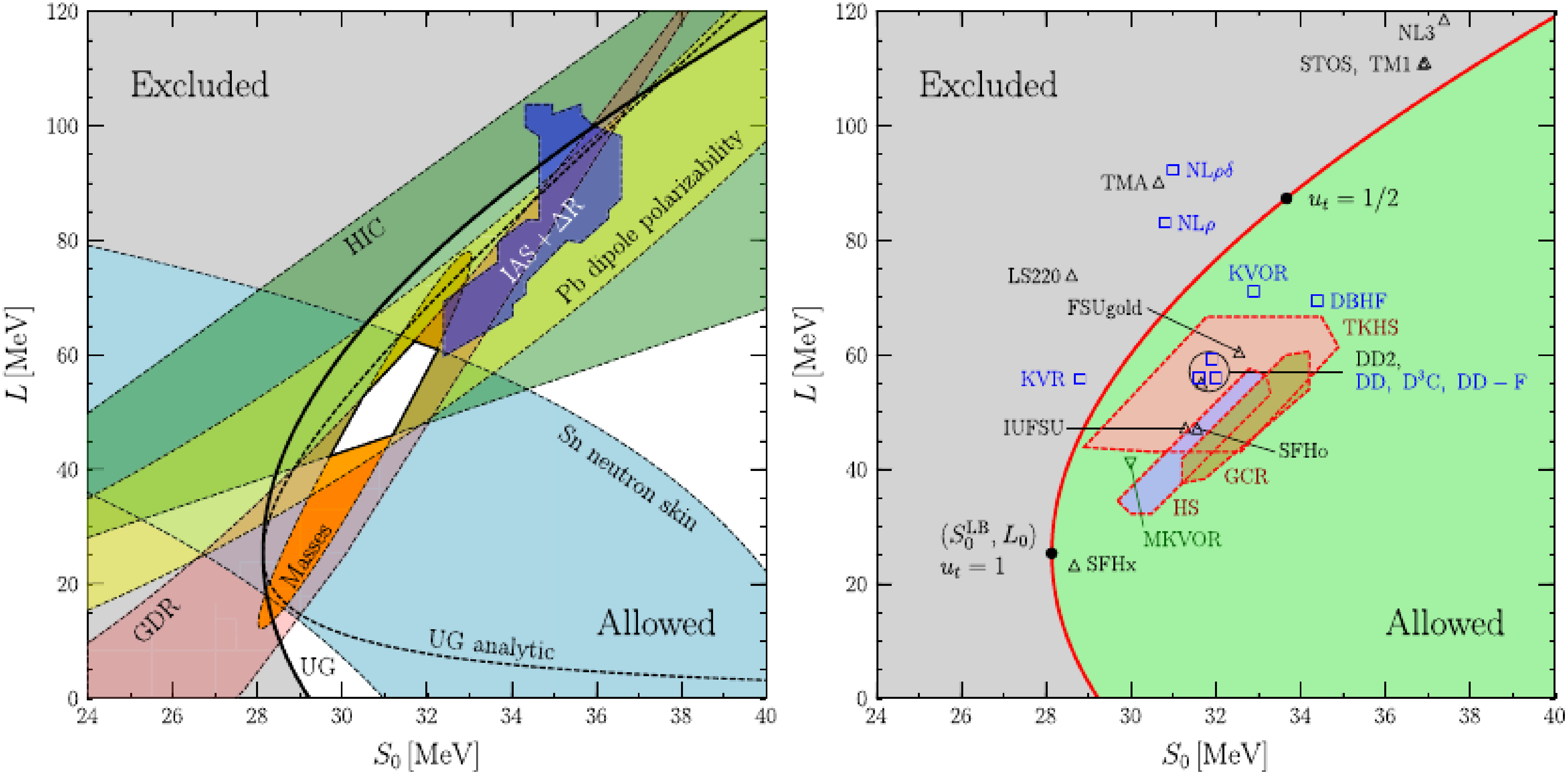
Radius, Mass,
Temp. (Cooling),
Star quake, Pasta



Theory (Group D)
head: Ohnishi

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

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.

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

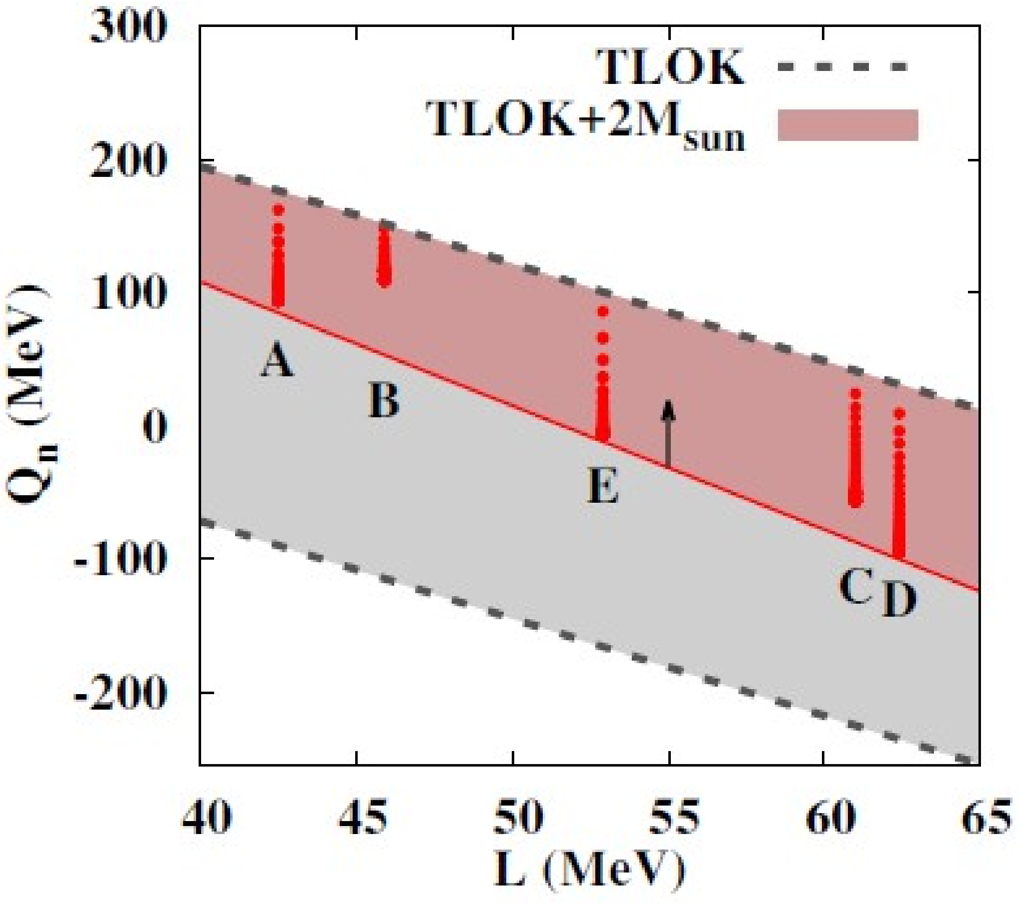
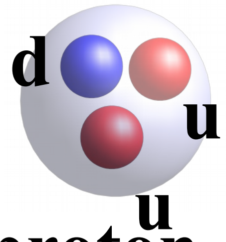


FIG. 4. Constraint on Q_n

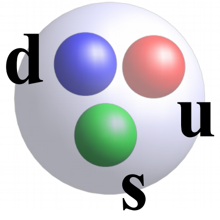
AO, Kolomeitsev, Lattimer, Tews, Wu (OKLTW), in prog.

Neutron star – Is it made of neutrons ?

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

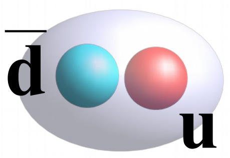


proton

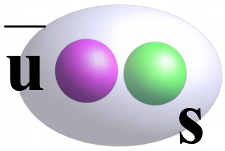


Λ hyperon

  - **Meson condensate (K, π)**

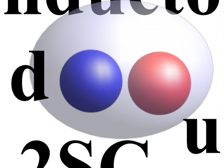


π

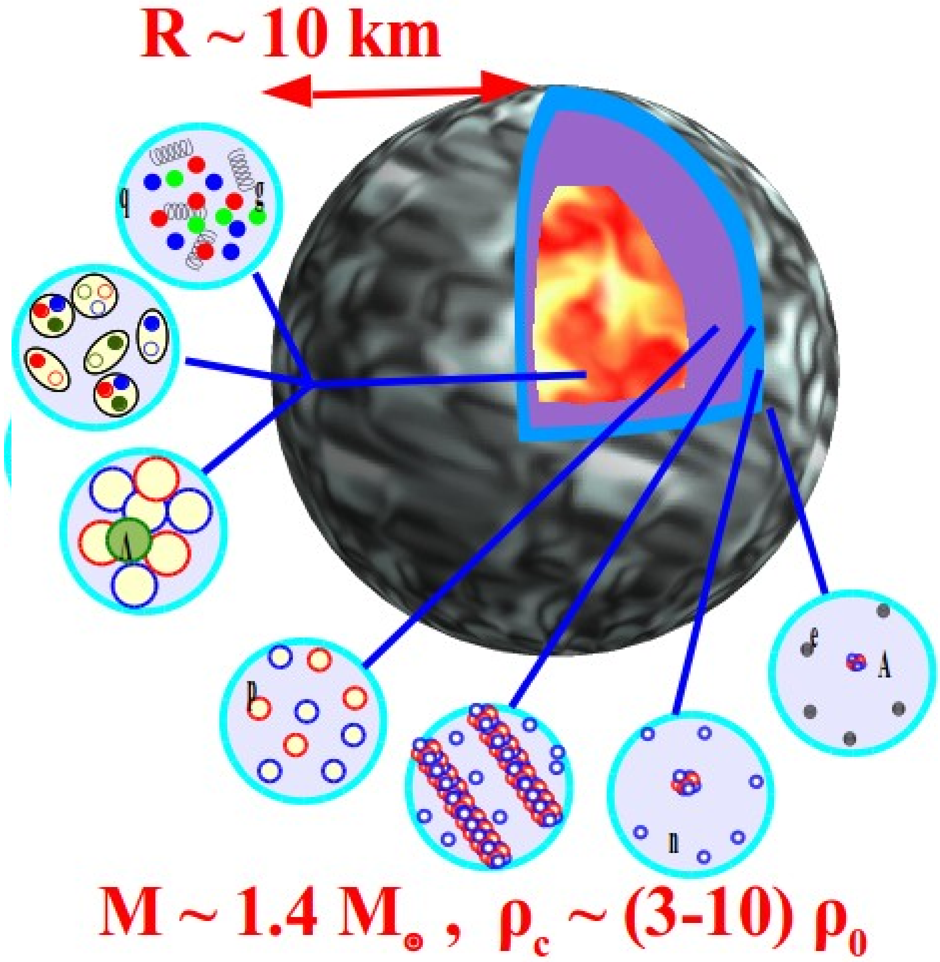


anti kaon

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

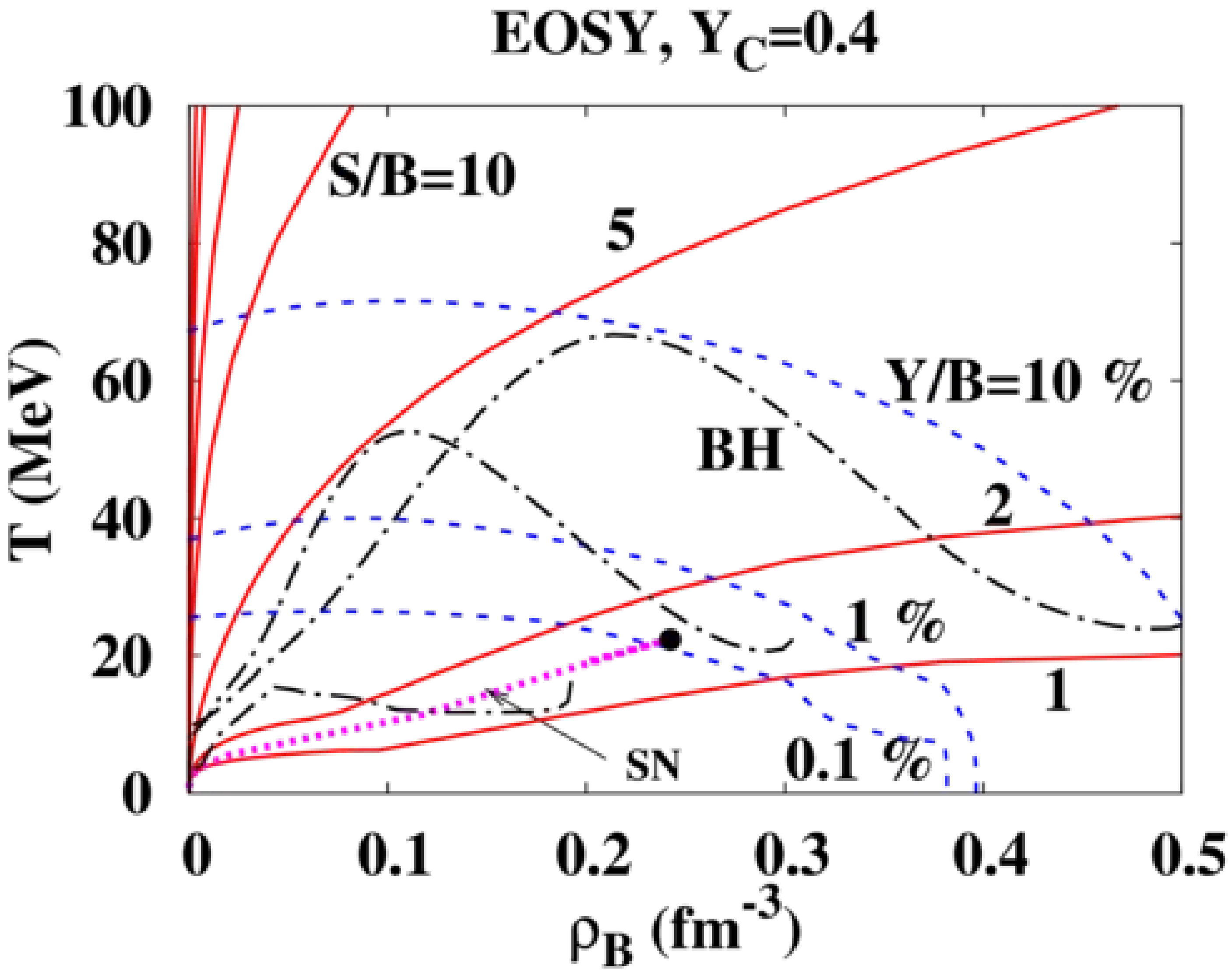


2SC



NS core = Densest stable matter existing in our universe.

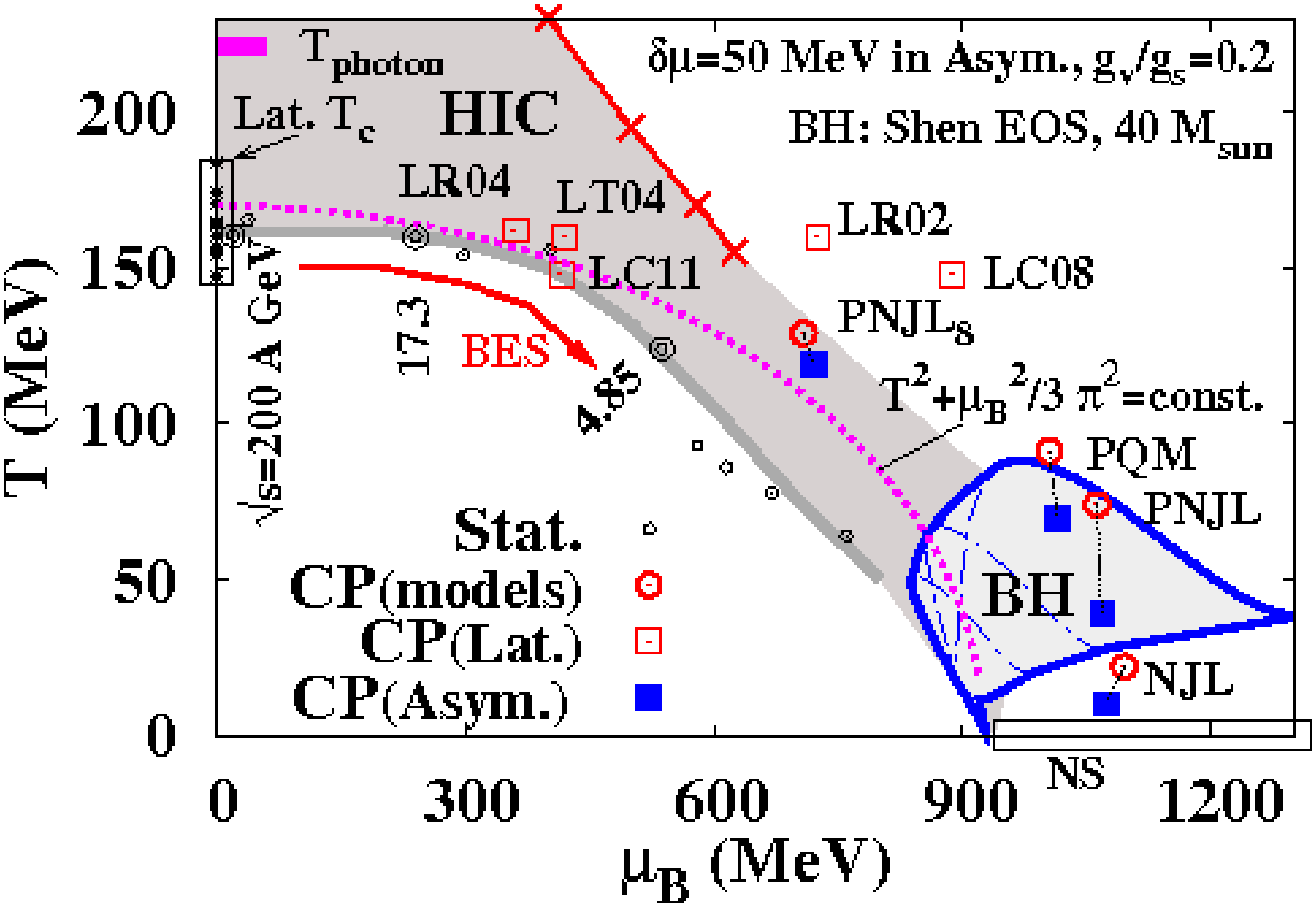
(ρ, T) during SN & BH formation



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.

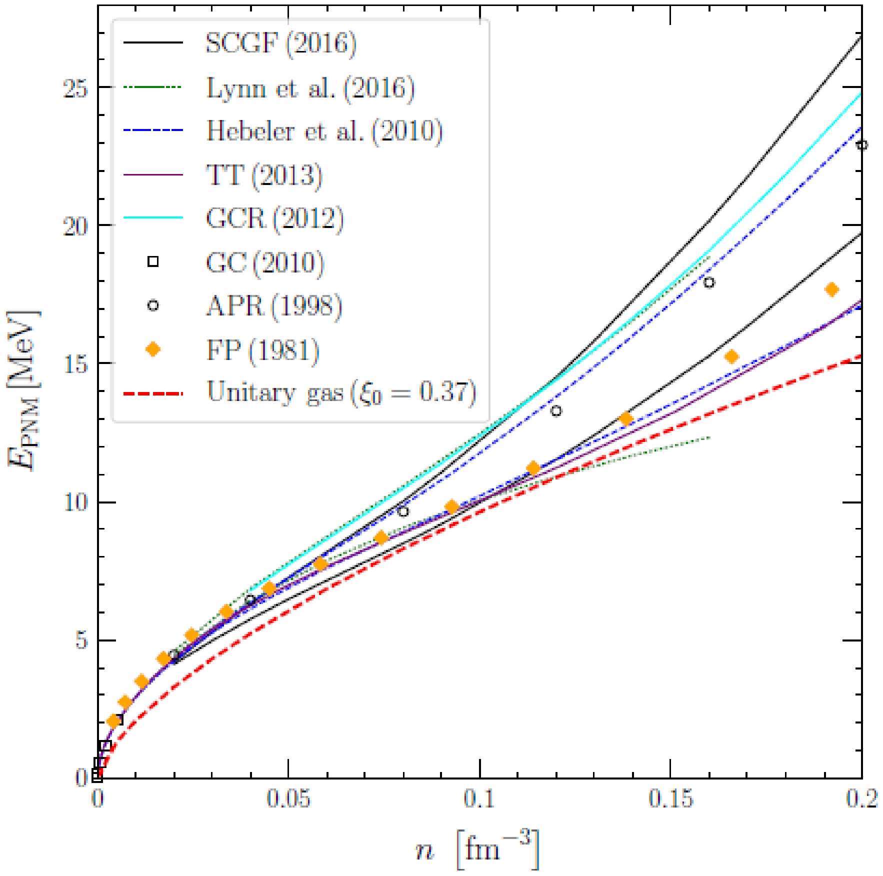
$$S(n) = E_{\mathrm{PNM}} - E_{\mathrm{SNM}} \geq E_{\mathrm{UG}} - E_{\mathrm{SNM}}$$

Sym. Nucl. Matter EOS is relatively well known.

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

- **$a_0 = \infty$ 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**

$$U_i = \frac{\partial \mathcal{V}}{n_i} = \sum_j n_j v_{ij}(n) + \sum_{jk} n_j n_k \frac{\partial v_{jk}(n)}{\partial n_i}$$

$$= U_{0i} + \frac{L_i}{3}(u-1) + \mathcal{O}((u-1)^2)$$

$$\simeq au + bu^{4/3}$$

rearrangement term

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