Neutron star equation of state for the quark level in the light of GW170817

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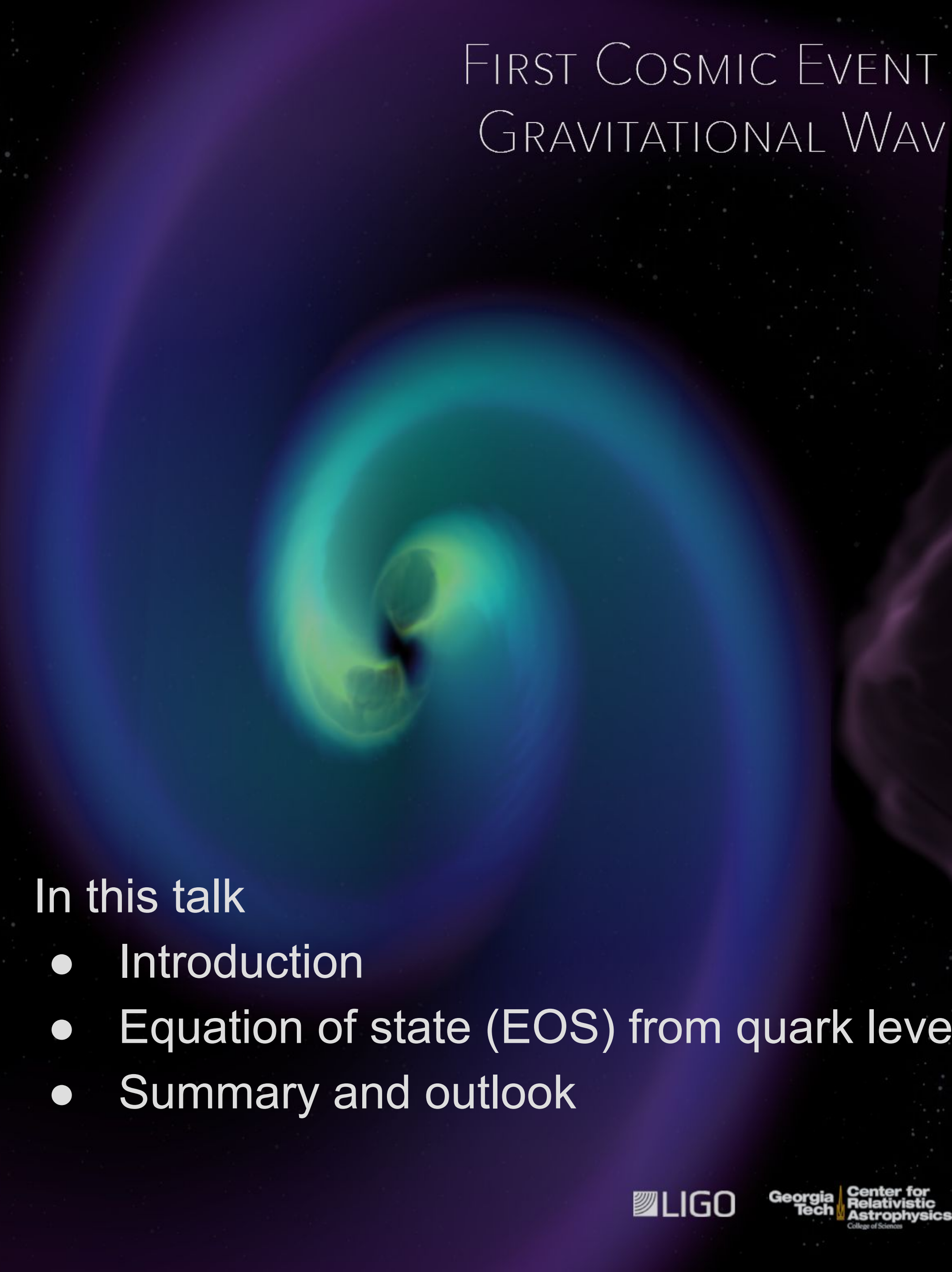
First Cosmic Event Observed in Gravitational Waves and Light



In this talk

- Introduction
- Equation of state (EOS) from quark level in the light of GW170817
- Summary and outlook

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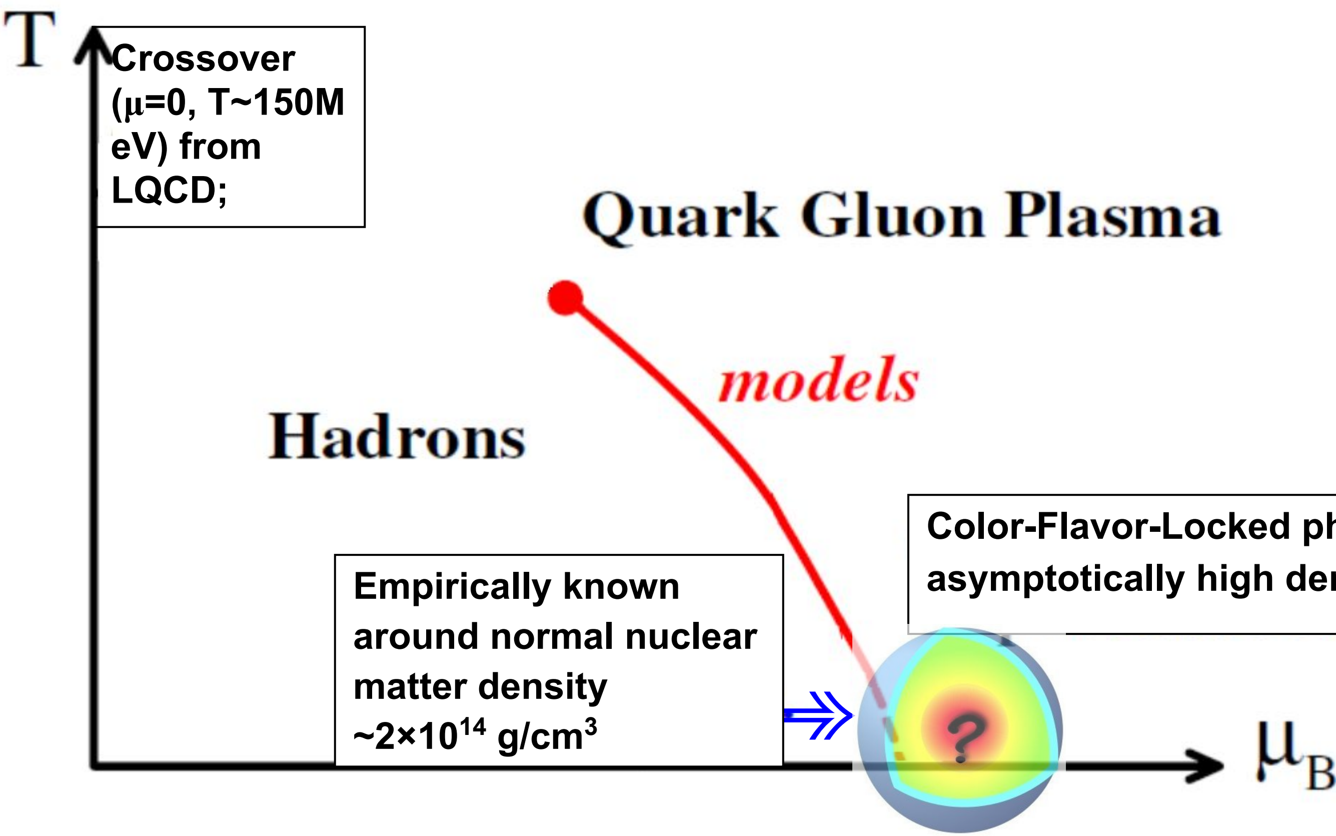
- Phase diagram at (T~0, μ≠0) is not achievable from HIC (experiment), LQCD (simulation) or pQCD (first-principle theory), but it is important for NS/QS: **Model calculations.**

- EOS uncertainty from **QCD phase uncertainty and model uncertainty**
  - Hyperon **puzzle**; Δ(1232)/hyperon/Kaon/quark **complication**
  - 1) Self-consistency from one nuclear force for core & crust; 2) High-density extrapolation



Input: EOS, mainly P(rho)
Output: M_{TOV}, M(R), Λ, etc.

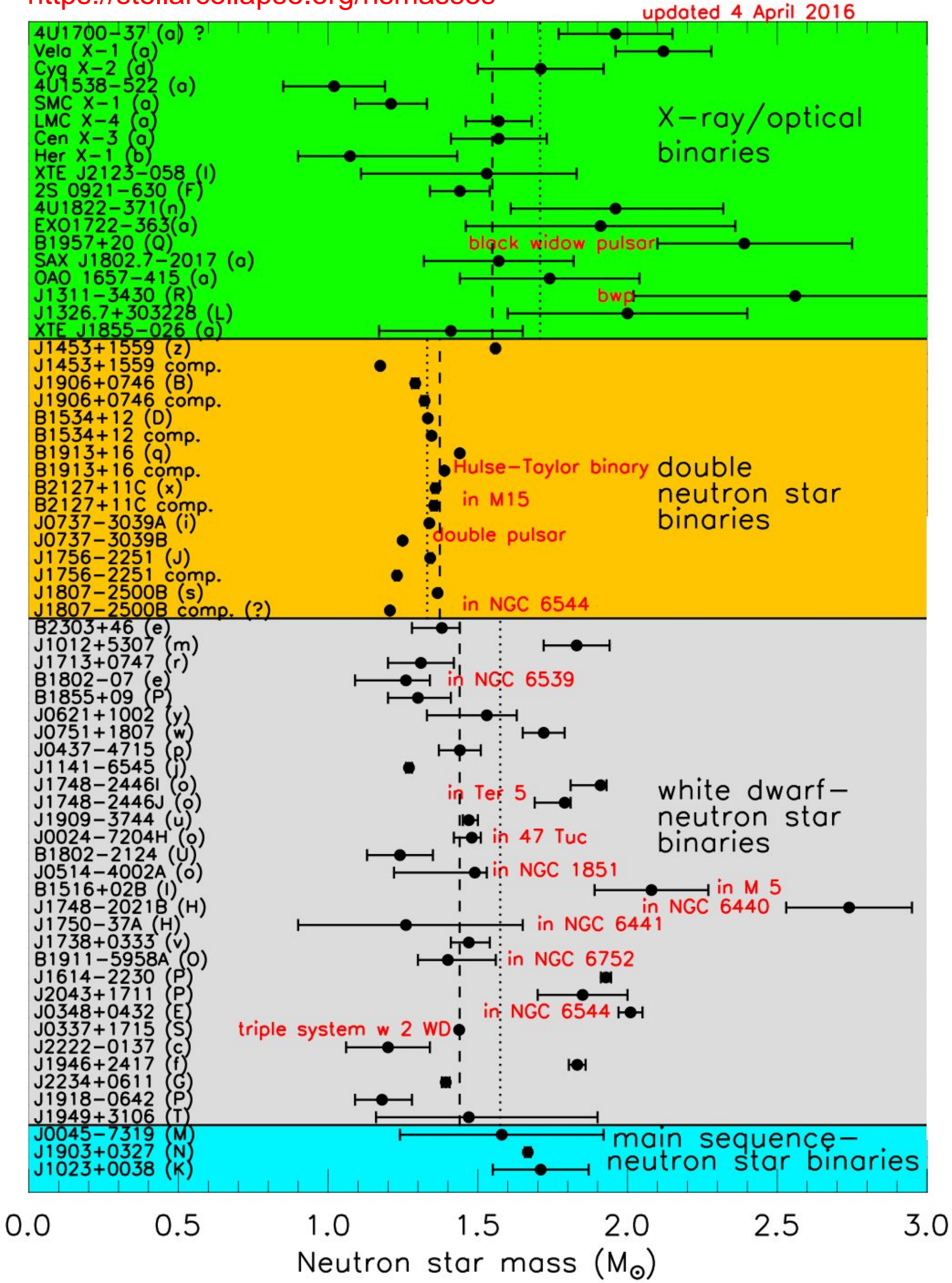
First Cosmic Event Observed in Gravitational Waves and Light

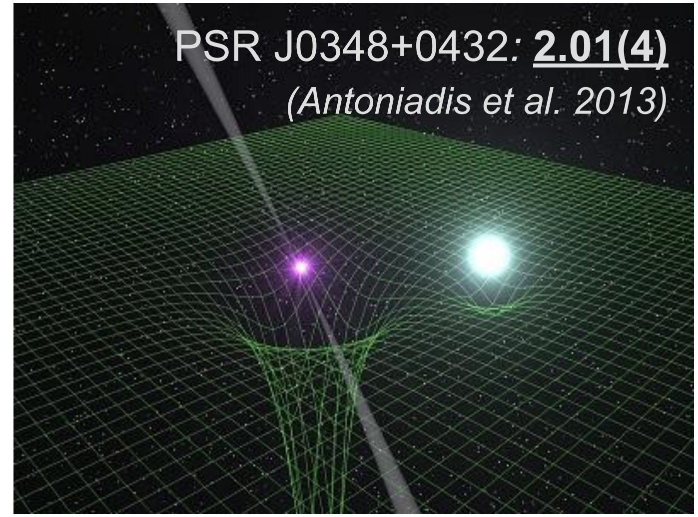
- GW

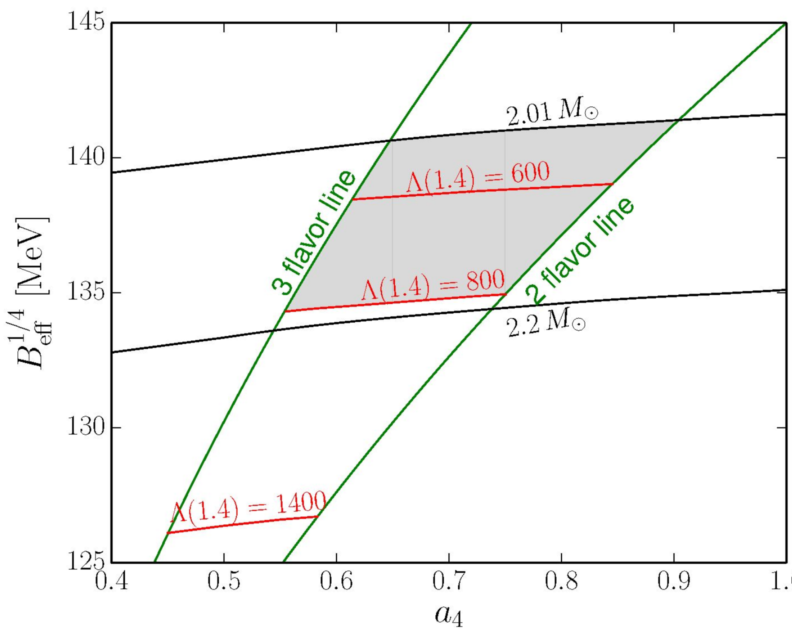
Pre-merger: Tidal deformability (≤ 800)

Postmerger: Hopefully O5 (202X) ?!

https://stellarcollapse.org/nsmasses







M_{TOV} ; $\Lambda(1.4)$ *QM stability window

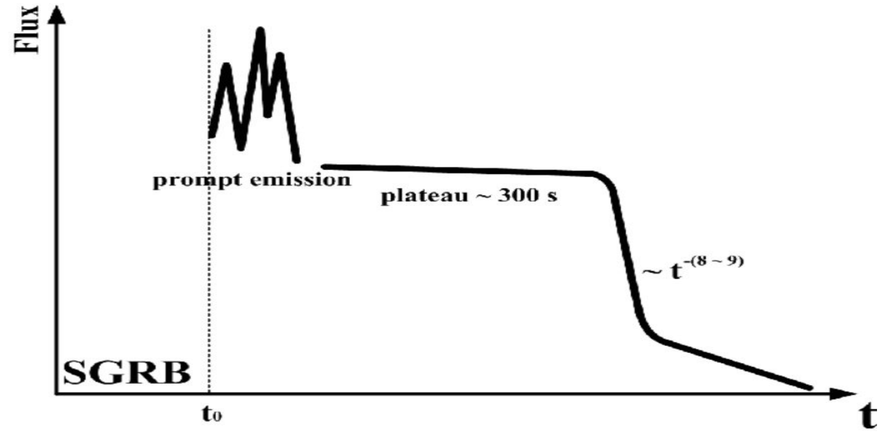
*Zhou, Zhou & **AL****, *1711.04312, PRD*

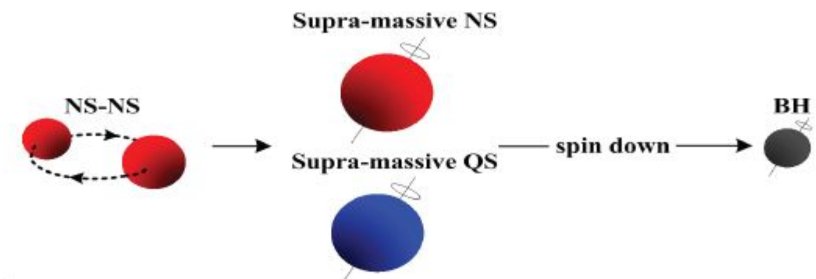
- NS/QS two-branch picture?

No hyperon puzzle for QS;

Preferred by particular group of SGRB

*(e.g., **AL** et al., 1706.04720, ApJ; 1606.02934, PRD)*

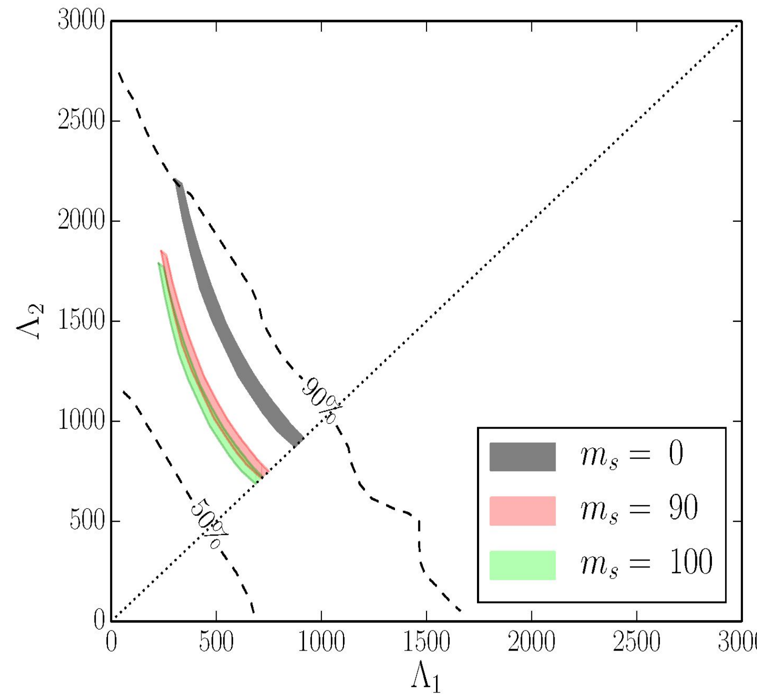




- QS merger scenario for GW demonstrated.

*(e.g., Zhou, Zhou & **AL***, 1711.04312, PRD)*

- $M_{TOV} \leq$ **2.18** (2.32 with superfluid) for QS within MIT.



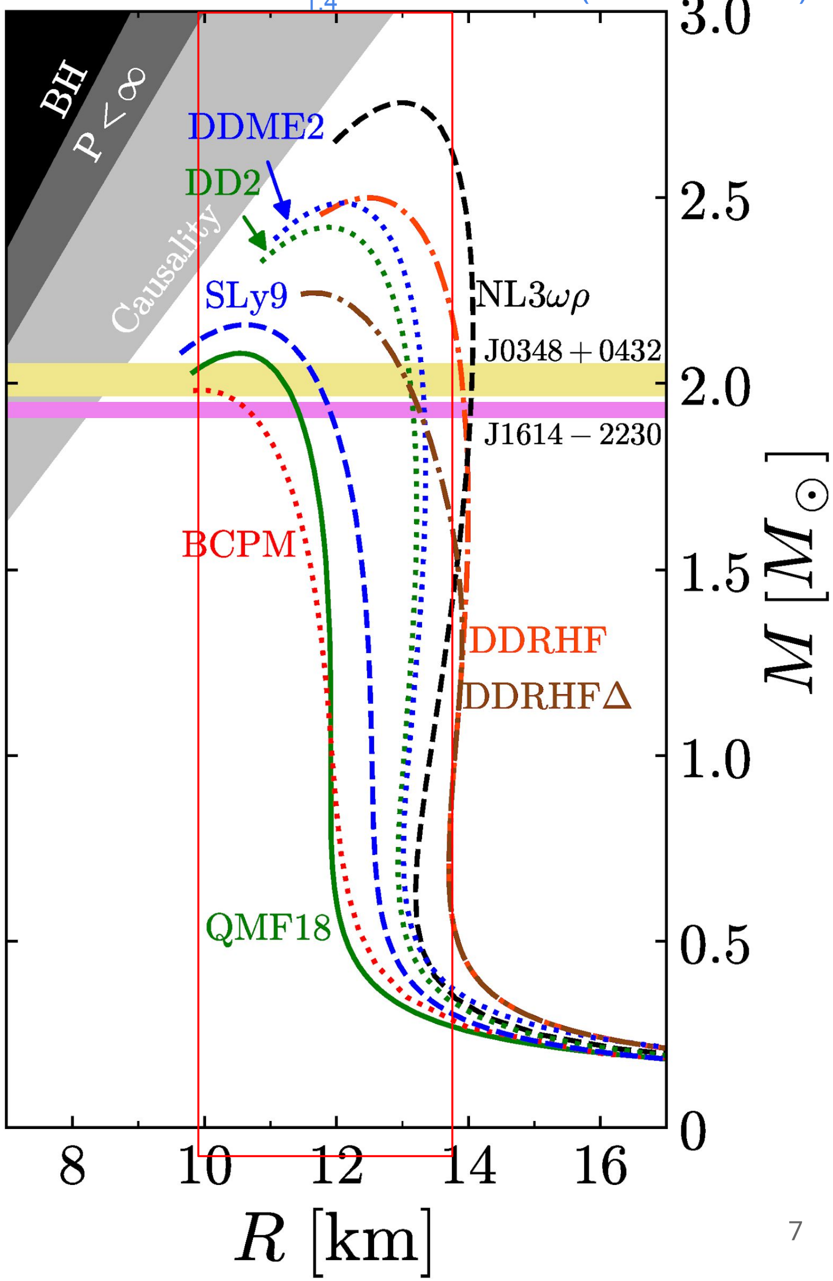
- New **'QMF18'** from the quark level

- BH: $R > 2GM/c^2$
- $P<\infty$: $R > (9/4)GM/c^2$
- Causality: $c \gtrsim v_s$ or $R \gtrsim 2.9GM/c^2$

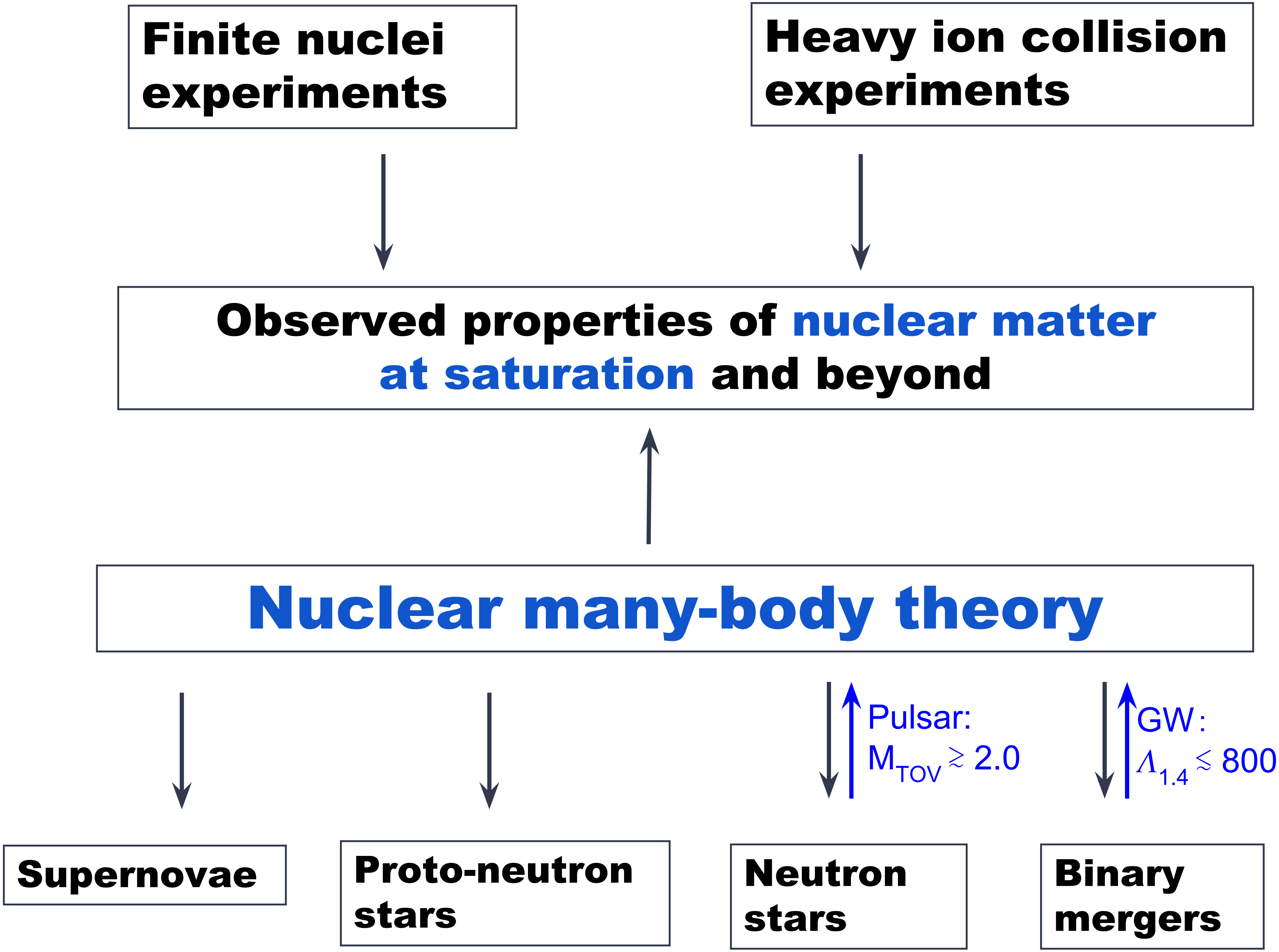
- Nucleon (m_N, r_N)
- **Nuclear saturation (rho_0, E/A, K, E_{sym}, L, M_N*)**

- Heavy pulsar mass measurements around 2 solar mass
- Clean/robust GW170817 constraint of tidal deformability

$R_{1.6} \geq 10.68$ km (Bauswein, et al)
$R_{1.6} \leq 13.25$ km (Fattoyev, et al.)
$R_{1.4} = 9.9\text{-}13.6$ km (Annala et al.)



*Zhu, Zhou & **AL*** 1802.05510, ApJ*


Finite nuclei experiments
Heavy ion collision experiments
Observed properties of nuclear matter at saturation and beyond
Nuclear many-body theory
Pulsar:
$M_{TOV} \gtrsim 2.0$
GW:
$\Lambda_{1.4} \lesssim 800$
Supernovae
Proto-neutron stars
Neutron stars
Binary mergers

- NS EOS model from the quark level within QMF (m_q~300MeV)

Step 1: Single nucleon

$$[\gamma^0(\epsilon_q - g_{\omega q}\omega - \tau_{3q} g_{\rho q}\rho) - \vec{\gamma}\cdot\vec{p} - (m_q - g_{\sigma q}\sigma) - U(r)]\psi_q(\vec{r}) = 0$$

$$U(r) = \frac{1}{2}(1+\gamma^0)(ar^2 + V_0)$$

$V_0 = -62.257187$ MeV, $a = 0.534296$ fm^{-3} ← $M_N = 939$ MeV, $r_N = 0.87$ fm.

Step 2: Nucleon many-body system

$$\mathcal{L} = \overline{\psi}\left(i\gamma_\mu\partial^\mu - M_N^* - g_{\omega N}\omega\gamma^0 - g_{\rho N}\rho\tau_3\gamma^0\right)\psi - \frac{1}{2}(\nabla\sigma)^2 - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 + \frac{1}{2}(\nabla\rho)^2 + \frac{1}{2}m_\rho^2\rho^2 + \frac{1}{2}(\nabla\omega)^2 + \frac{1}{2}m_\omega^2\omega^2 + \frac{1}{2}g_{\rho N}^2\rho^2\Lambda_v g_{\omega N}^2\omega^2,$$

- *K=**240**±20 (Colo et al. 2014)*
  *E_{sym}=**31.6**±2.66*
  *L=**58.9**±16 (Li & Han 2013)*
  *L≳**20** (Centelles et al. 2009)*
  *L≲**170** (Cozma 2013)*

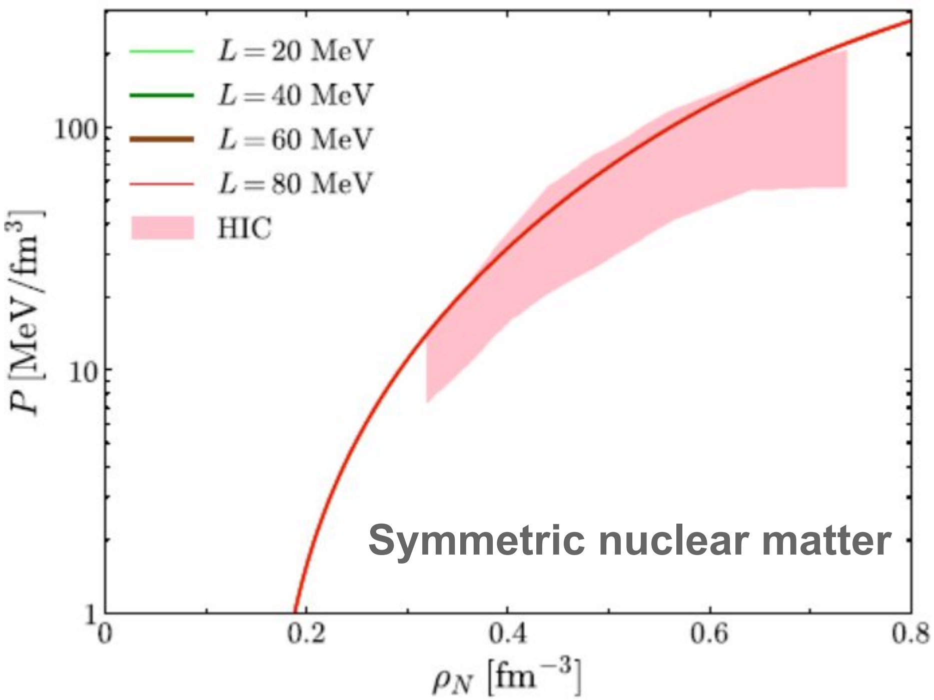
L [MeV]	$g_{\sigma q}$	$g_{\omega q}$	$g_{\rho q}$	g_2 [fm^{-1}]	g_3	Λ_v
20	3.8620366	2.9174838	6.9588083	14.6179599	-66.3442468	1.1080665
40	3.8620366	2.9174838	5.4129448	14.6179599	-66.3442468	0.7693664
60	3.8620366	2.9174838	4.5830609	14.6179599	-66.3442468	0.4306662
80	3.8620366	2.9174838	4.0459574	14.6179599	-66.3442468	0.0919661

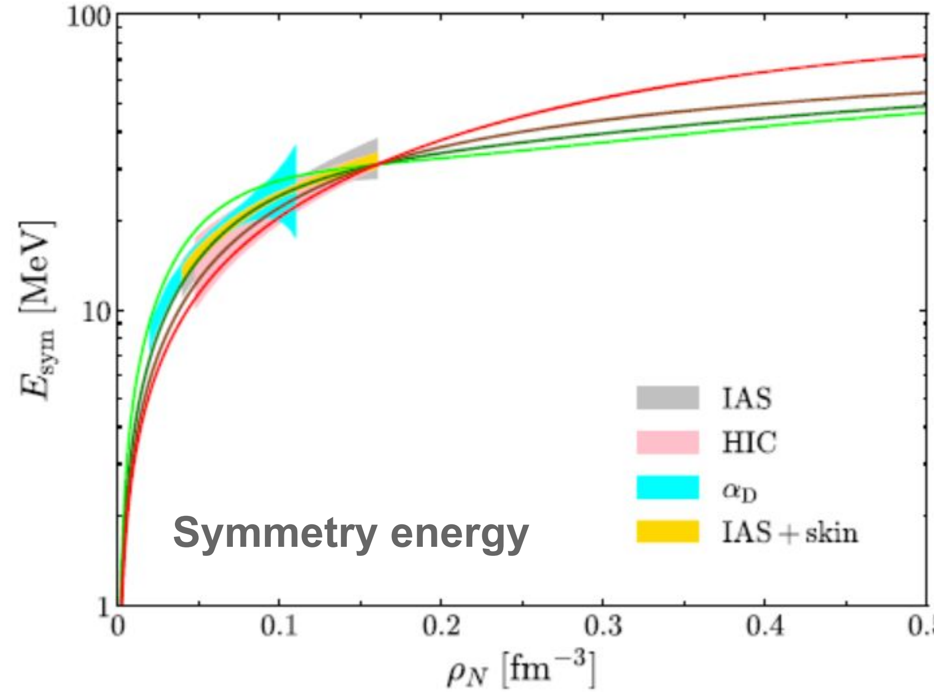
ρ_0 [fm^{-3}]	E/A [MeV]	K [MeV]	$E_{\rm sym}$ [MeV]	L [MeV]	M_N^*/M_N /
0.16	-16	240	31	20/40/60/80	0.77

- Equations of state $$E(\rho,\delta) \approx E_0(\rho) + E_{\rm sym}(\rho)\delta^2$$

Among them, the *L = 40 MeV* case comfortably inside all exp. boundaries.

*Zhu, Zhou & **AL*** 1802.05510, ApJ*

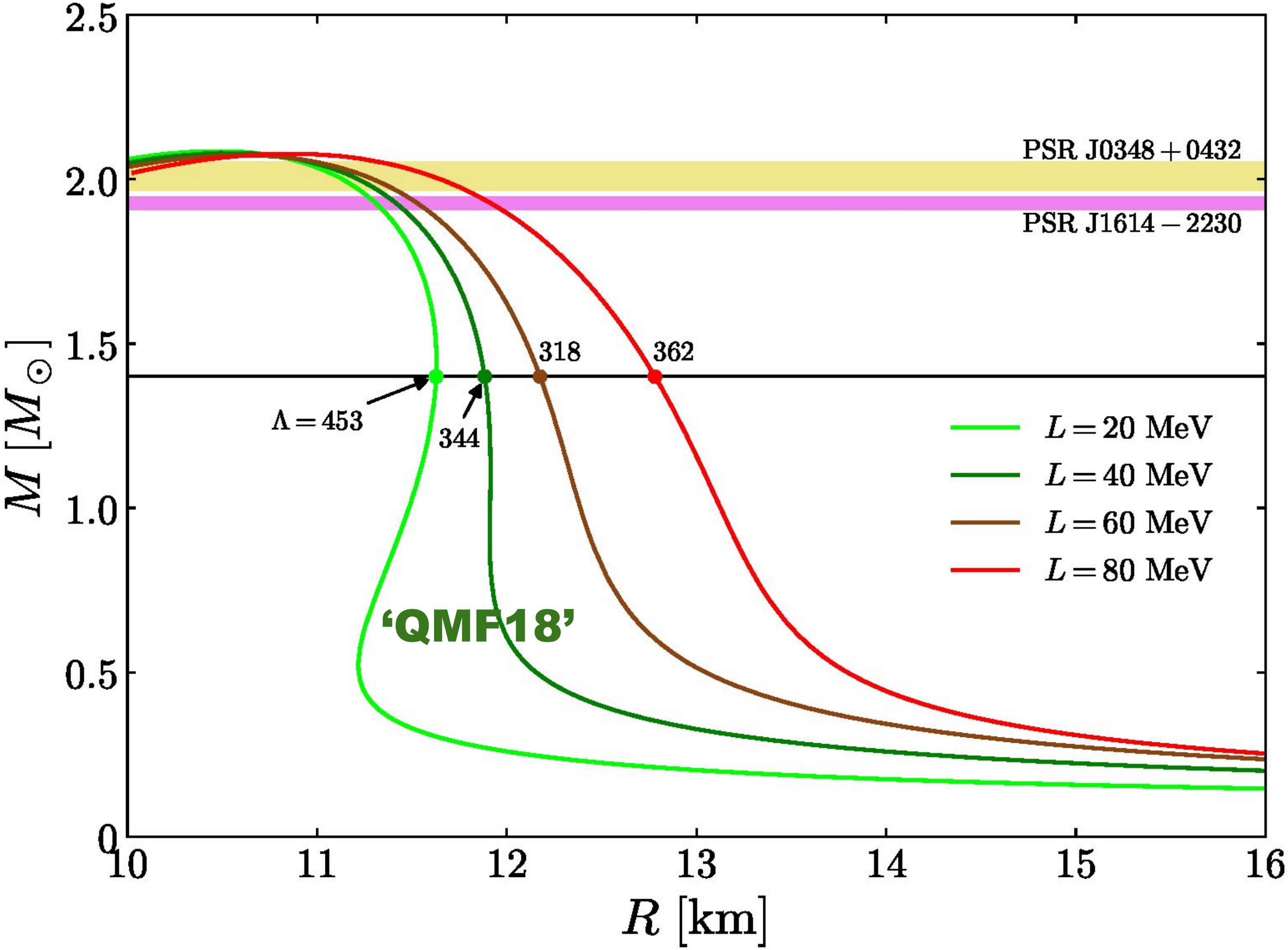




Experimental constraints (e.g.,):

Danielewicz et al. 2002
Tsang et al. 2009
Zhang & Chen 2015
Danielewicz & Lee 2014

- Mass-radius relation, $\Lambda(1.4)$



*Zhu, Zhou & **AL*** 1802.05510, ApJ*

Table 3. NS EOS for the QMF18 model newly introduced in this work.

ϵ [g cm^{-3}]	P [erg cm^{-3}]	ρ_N [fm^{-3}]
0.13855E+15	0.79586E+33	0.082
0.14365E+15	0.85234E+33	0.085
0.15216E+15	0.95144E+33	0.090
0.16920E+15	0.11706E+34	0.100
0.18626E+15	0.14226E+34	0.110
0.20336E+15	0.17145E+34	0.120
0.22047E+15	0.20433E+34	0.130
0.27203E+15	0.33950E+34	0.160
0.32393E+15	0.55426E+34	0.190
0.37631E+15	0.87679E+34	0.220
0.42926E+15	0.13315E+35	0.250
0.48293E+15	0.19385E+35	0.280
0.53741E+15	0.27149E+35	0.310
0.59282E+15	0.36752E+35	0.340
0.64927E+15	0.48329E+35	0.370
0.70686E+15	0.62008E+35	0.400
0.76568E+15	0.77912E+35	0.430
0.82583E+15	0.96151E+35	0.460
0.88738E+15	0.11682E+36	0.490
0.95043E+15	0.13999E+36	0.520
0.10150E+16	0.16569E+36	0.550
0.10813E+16	0.19389E+36	0.580
0.11492E+16	0.22449E+36	0.610
0.12189E+16	0.25733E+36	0.640
0.12904E+16	0.29223E+36	0.670
0.13636E+16	0.32903E+36	0.700
0.14896E+16	0.39423E+36	0.750
0.16207E+16	0.46399E+36	0.800
0.17568E+16	0.53809E+36	0.850
0.18978E+16	0.61645E+36	0.900
0.20438E+16	0.69900E+36	0.950
0.21948E+16	0.78573E+36	1.000
0.25116E+16	0.97160E+36	1.100
0.28480E+16	0.11739E+37	1.200
0.32039E+16	0.13926E+37	1.300

“QMF18” EOS table
Welcome to use!

*Zhu, Zhou & **AL**** *1802.05510, ApJ*

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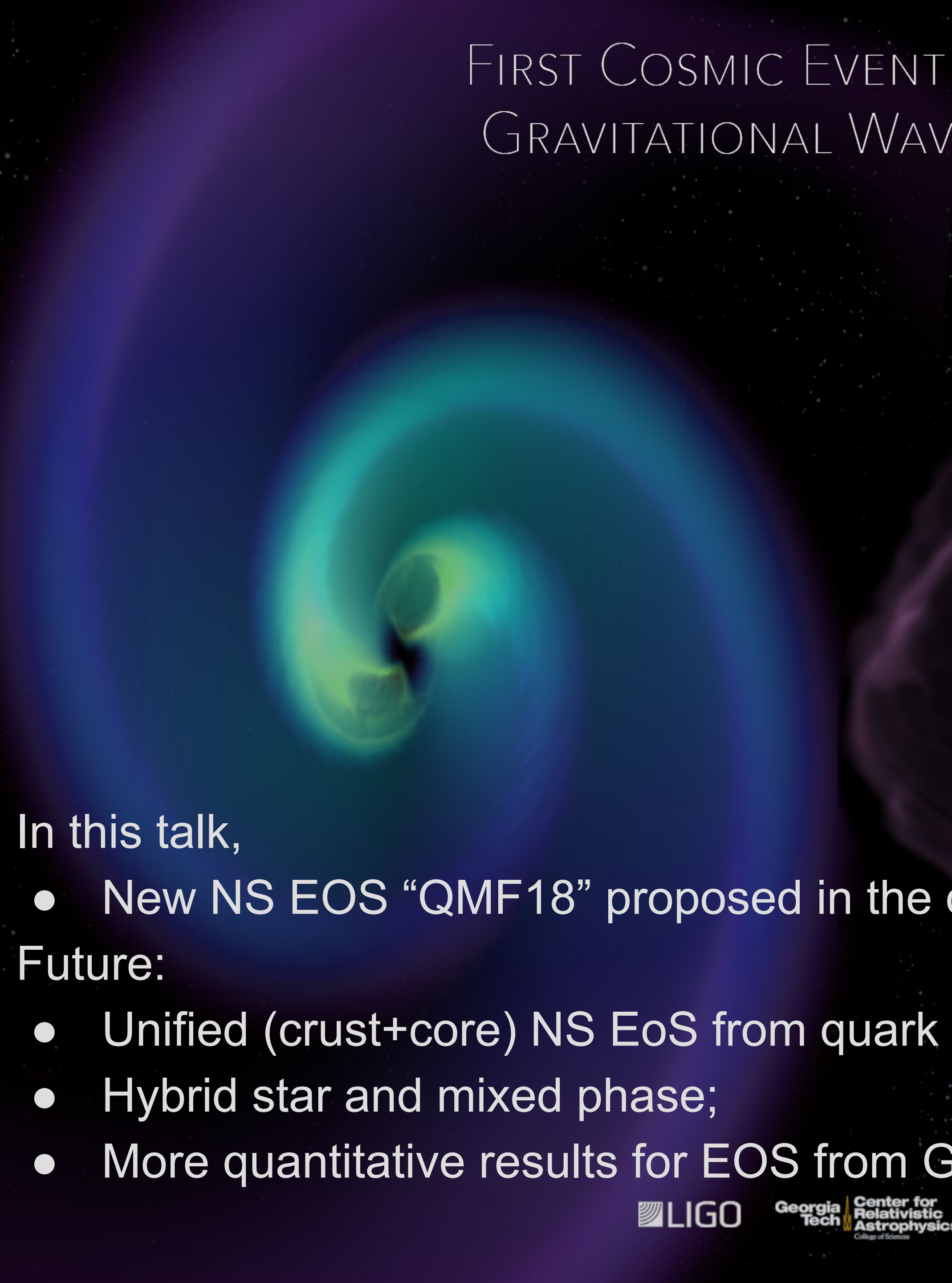

In this talk,

- New NS EOS “QMF18” proposed in the quark level in the GW era;

Future:

- Unified (crust+core) NS EoS from quark level;
- Hybrid star and mixed phase;
- More quantitative results for EOS from GW tidal results.

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▸ Unified (crust+core) NS EoS from quark level

Core (nuclear matter)

Green's Function Monte Carlo

Chiral Perturbation Theory (ChPT)

Variational Many-Body (VMB; e.g., APR)

$V_{\mathrm{low}k}$ + Renormalization Group

Brueckner-Hartree-Fock (BHF; e.g., BCPM)

Dirac-Brueckner-Hartree-Fock (DBHF)

Quark mean-field (QMF; e.g., QMF18)

Quark Meson Coupling (QMC)

Relativistic mean-field (RMF; e.g., DD2, NL3, TM1)

Skyrme energy density functional (e.g., BSk20, Sly)

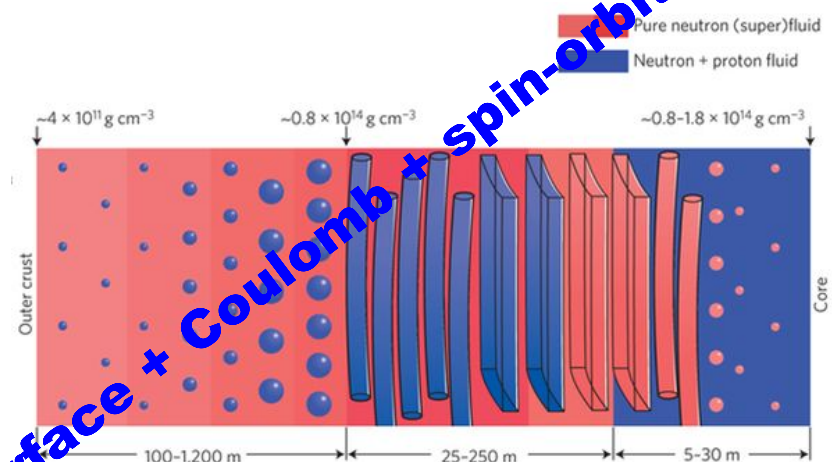
…

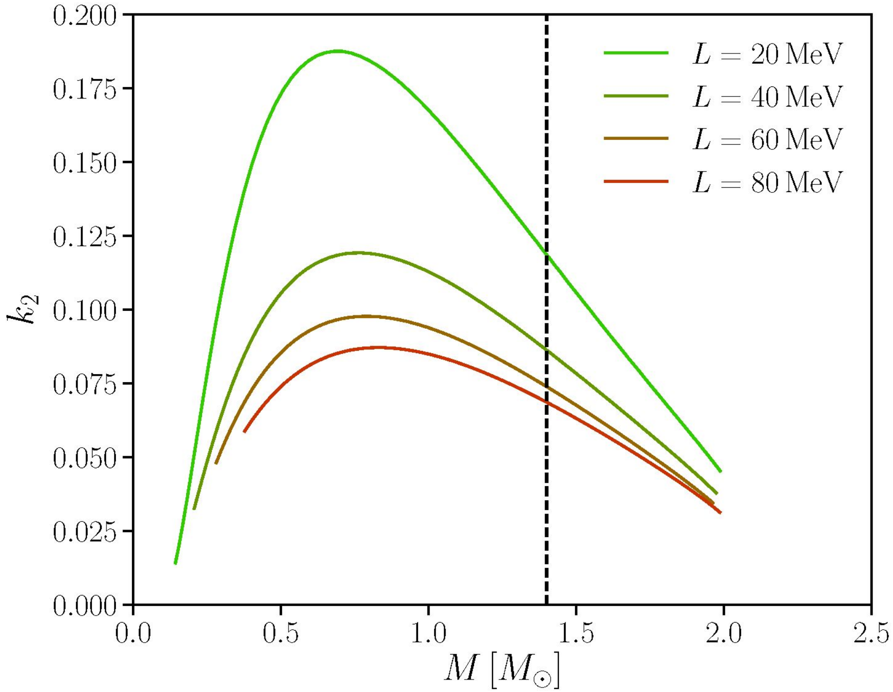
Infinite uniform nuclear matter: Bulk

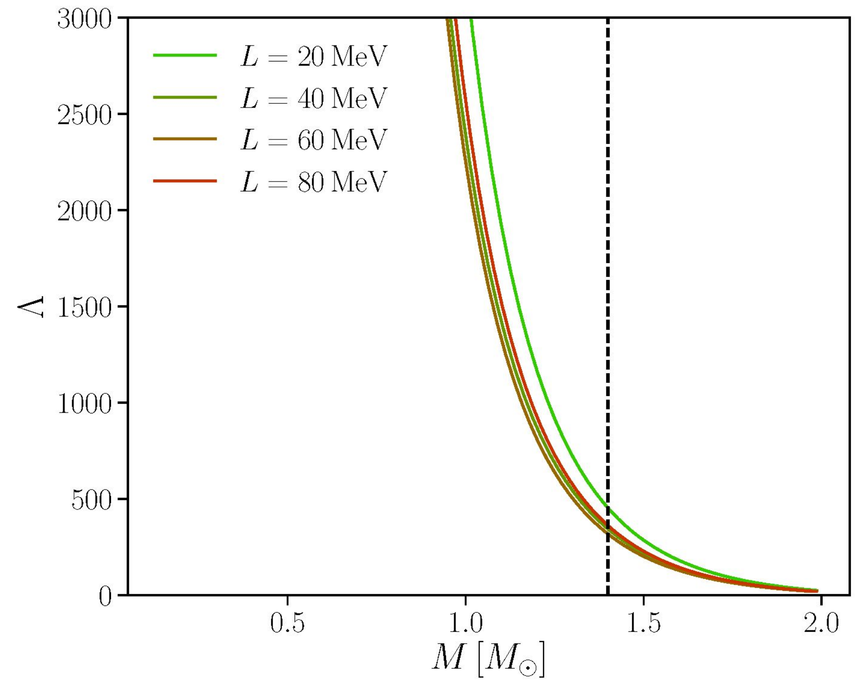
Inner crust:

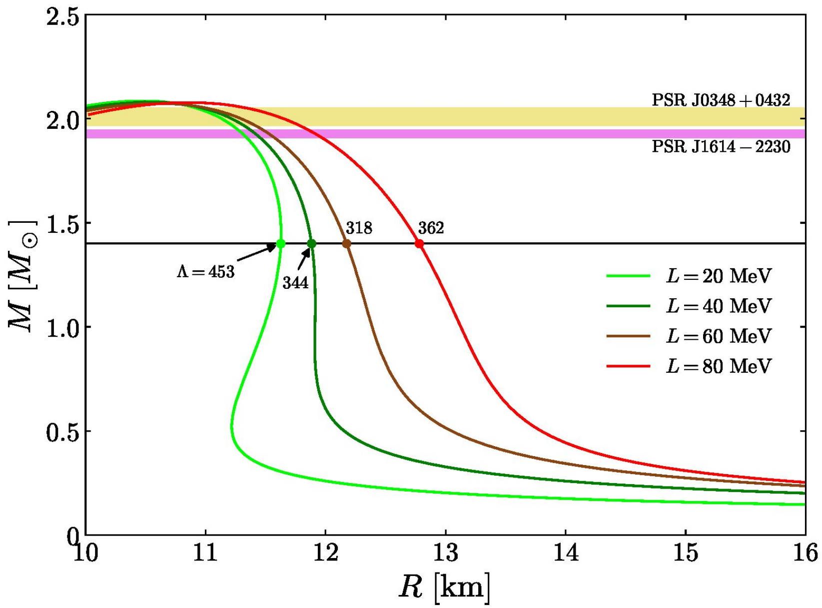
- Compressible Liquid Drop (CLDM)
- Thomas-Fermi (TF) approximation

Bulk + surface + Coulomb + spin-orbit + pairing







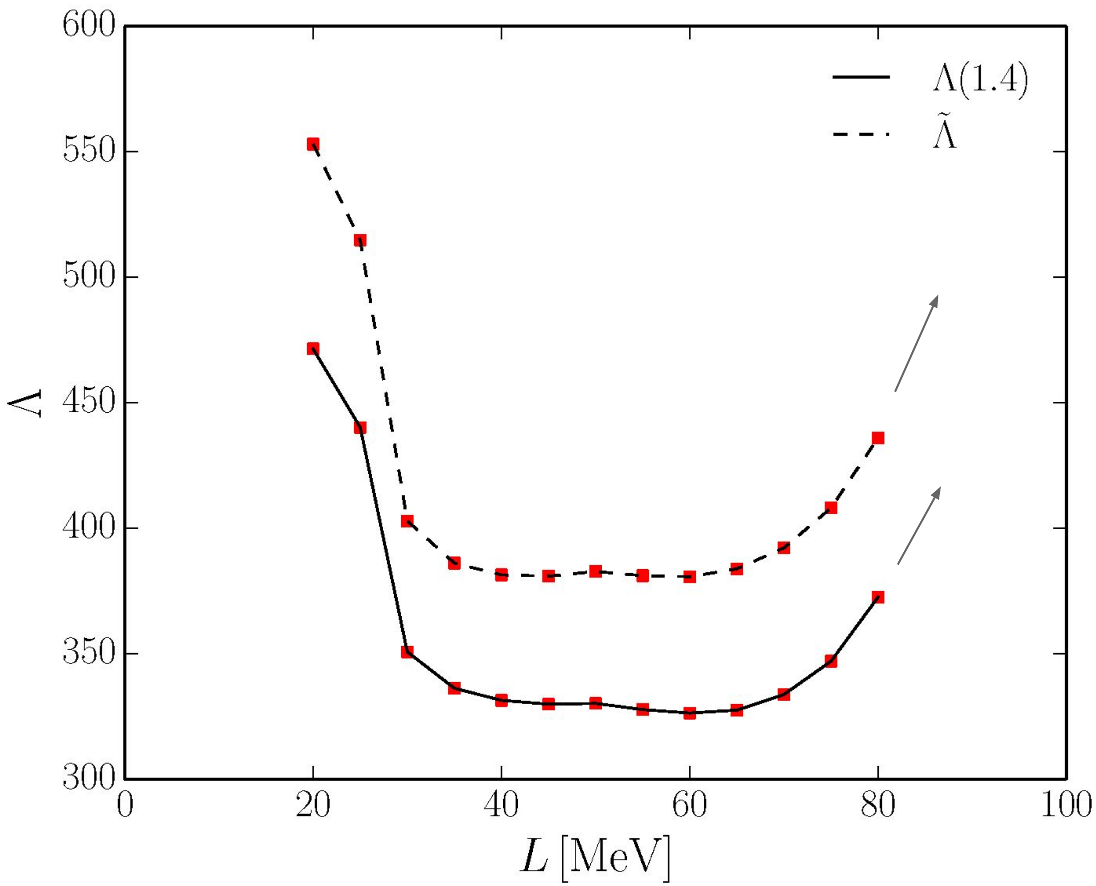


$$\Lambda = \frac{2}{3} k_2 (M/R)^{-5}$$

- Λ is normalized with a factor of R^5 , from k_2
- Differences in radius scatter the dependence on L.

*Zhu, Zhou & **AL*** 1802.05510, ApJ*

▸ **NO** L-vs-Λ correlation found, despite good L-vs-R correlation:
Λ measurements do **NOT** necessarily translate into info. on R?!



Crust effect?

Crust-core interface?

*Zhu, Zhou & **AL*** *1802.05510, ApJ*

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$

▸ From EoS (with strangeness) to Λ

	QMF18	DDRHF	DDRHFΔ	NL3ωρ	DDME2	DD2	Sly9	BCPM
$M_{\rm TOV}$ $[M_\odot]$	2.08	2.50	2.24	2.75	2.48	2.42	2.16	1.98
L [MeV]	40	82.99	82.99	55.5	51.2	55.0	54.9	52.96
$R(1.4)$ [km]	11.77	13.74	13.67	13.75	13.21	13.16	12.46	11.72
$M/R(1.4)$	0.1756	0.1505	0.1512	0.1503	0.1566	0.1571	0.1660	0.1765
$\Lambda(1.4)$	344	865	828	925	681	674	446	294
$\tilde{\Lambda}$	397.7 - 403.7	948.7 - 993.4	900.8 - 962.9	1002.9 - 1056.3	747.8 - 782.7	747.9 - 777.3	519.6 - 524.3	353.9 - 1056.3

*Zhu, Zhou & **AL*** *1802.05510, ApJ*

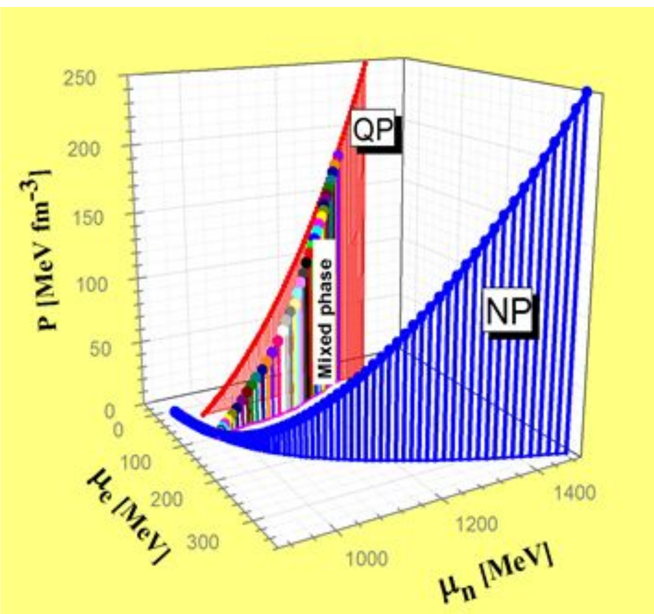
$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$

▸ Hybrid star and mixed phase

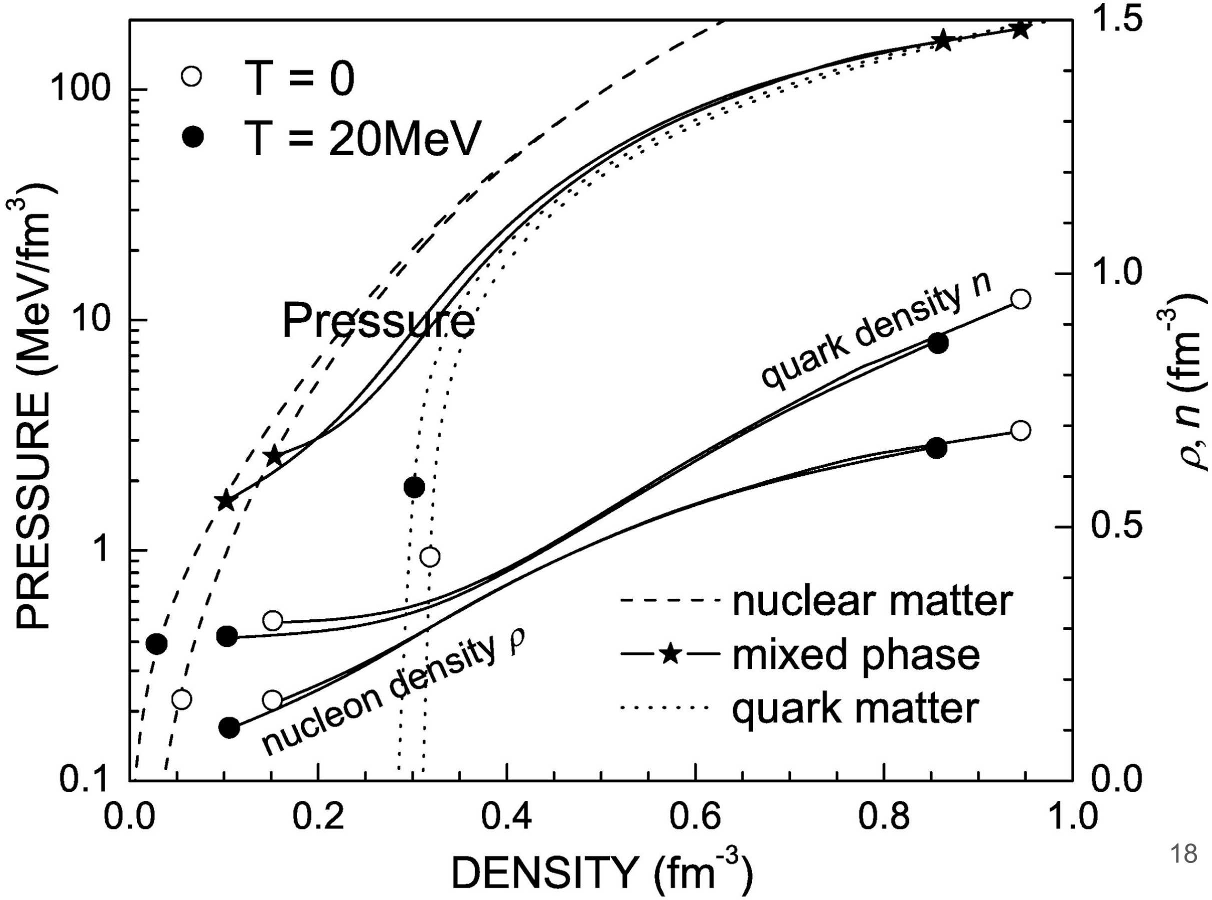
$$p \longleftrightarrow 2u + d,$$
$$n \longleftrightarrow u + 2d,$$
$$u + d \longleftrightarrow u + s,$$

$$P_N = P_q \quad \text{(mechanical)},$$
$$\mu_N = \mu_q \quad \text{(chemical)},$$
$$T_N = T_q \equiv T \quad \text{(thermodynamical)}$$

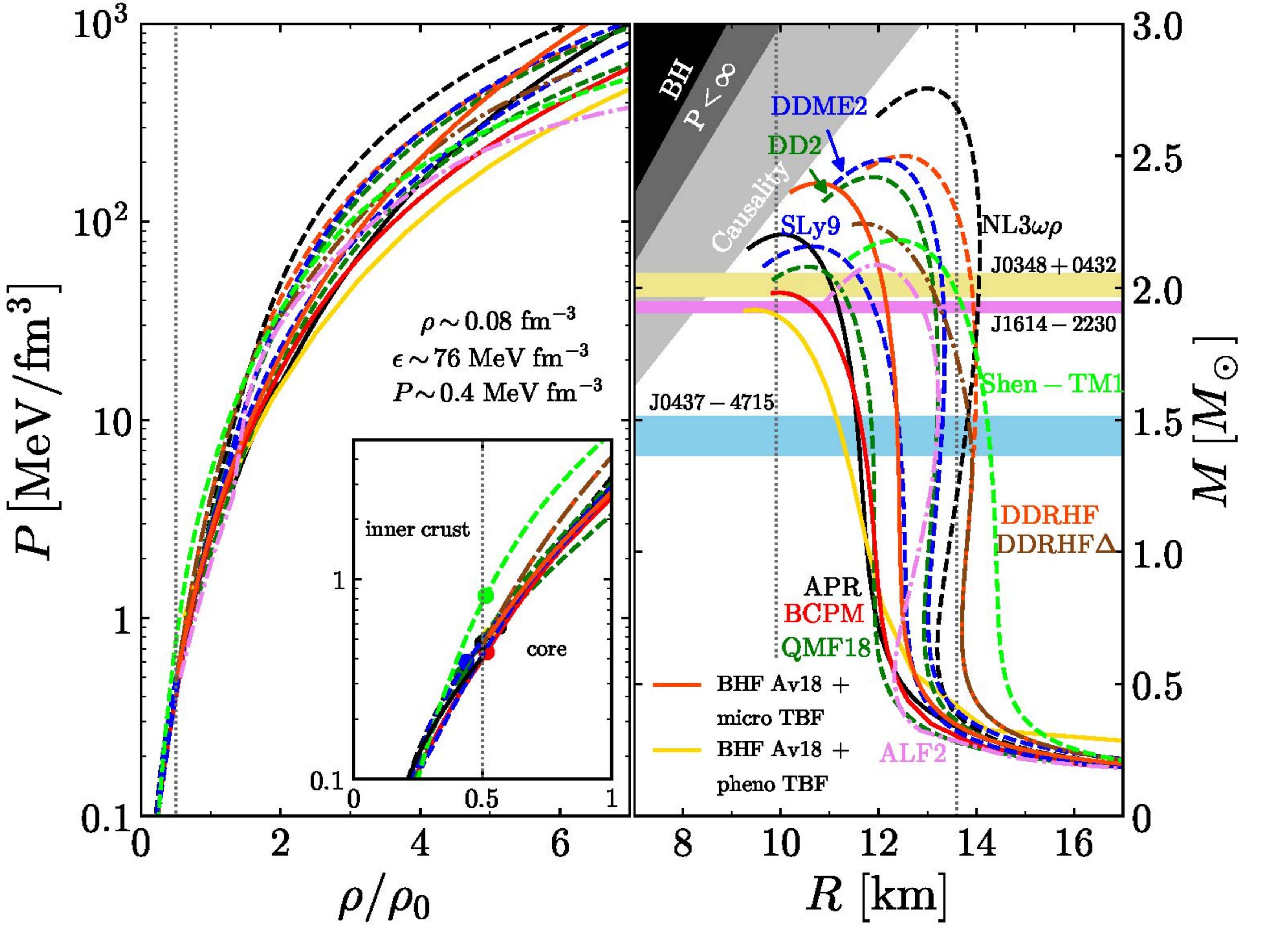
Gibbs construction



*e.g., **AL**, et al. 1503.02739, PRC*
*Peng, **AL**, Lombardo, 2008 PRC*



Thank you.



***AL**, Hu, Bao, Shen, Xu, Nucl. Phys. Rev. 2019*