GW170817-like events: binary neutron stars or binary strange stars?

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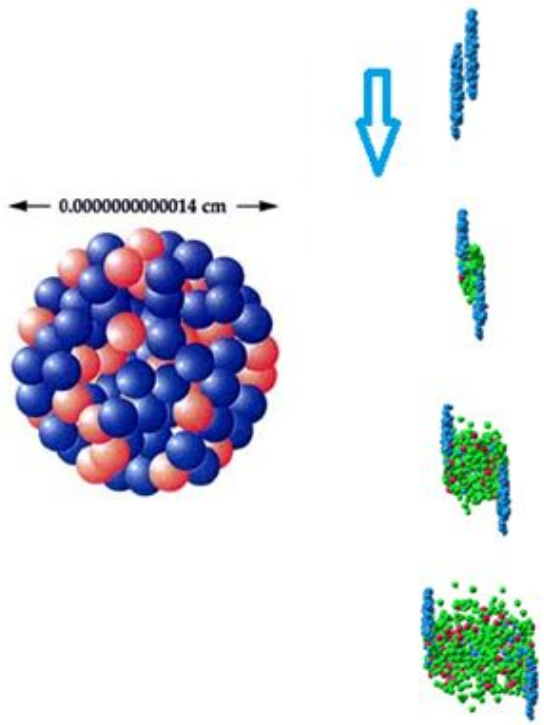
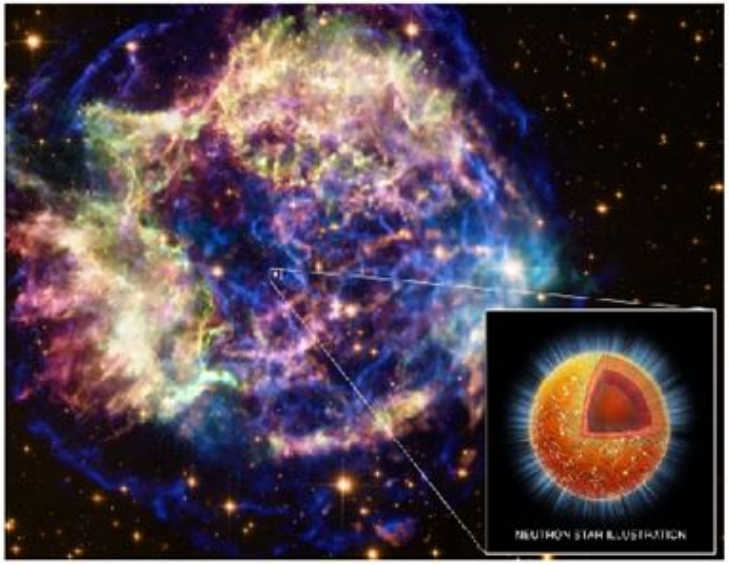
Content

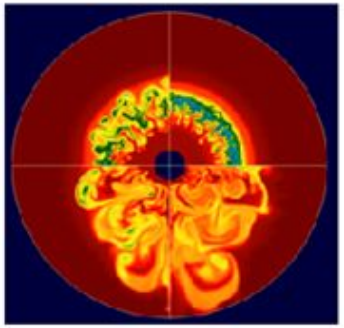
- Introduction of compact star in GW era
- Binary neutron star/strange star merger scenario for GW170817
- Future plans

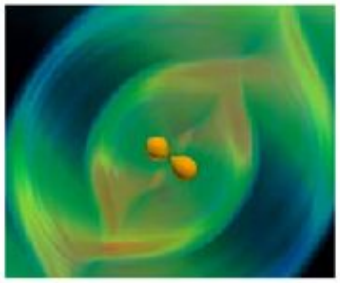
Neutron star in multi-messenger/multi-scale era

- Finite nuclei (e.g., neutron skin width/isovector excitation/dipole polarizability)
- ❖ HIC (e.g., collective flow/transport/meson production);



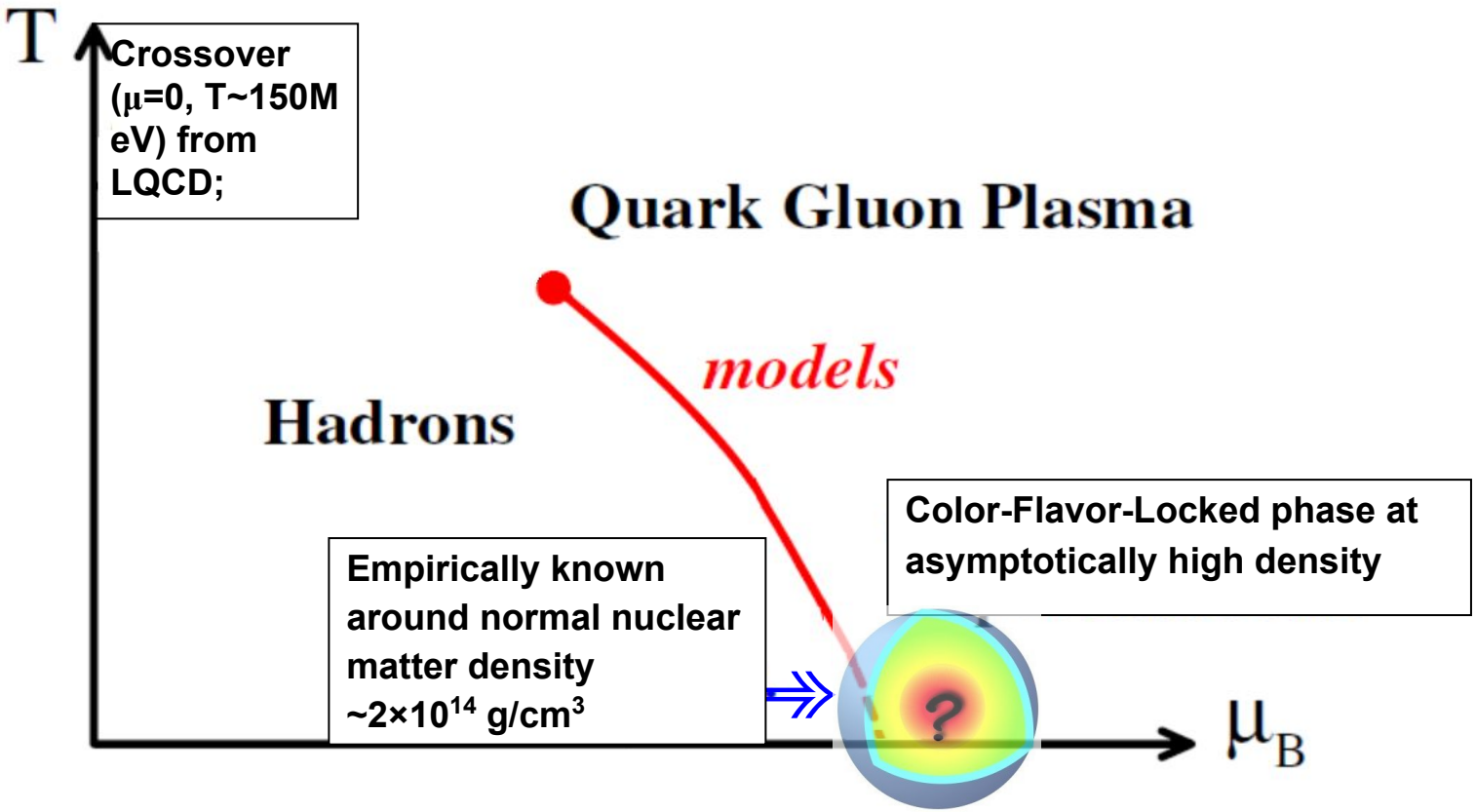






- ★ PSR J1614-2230 *(Demorest et al. 2010; Fonseca et al. 2016)*;
- ★ PSR J0348+0432 *(Antoniadis et al. 2013)*;
- ★ MSP J0740+6620 *(Cromartie et al. 2019);*
- ❑ BH accretion disk, core-collapse SN, neutron star binary, etc

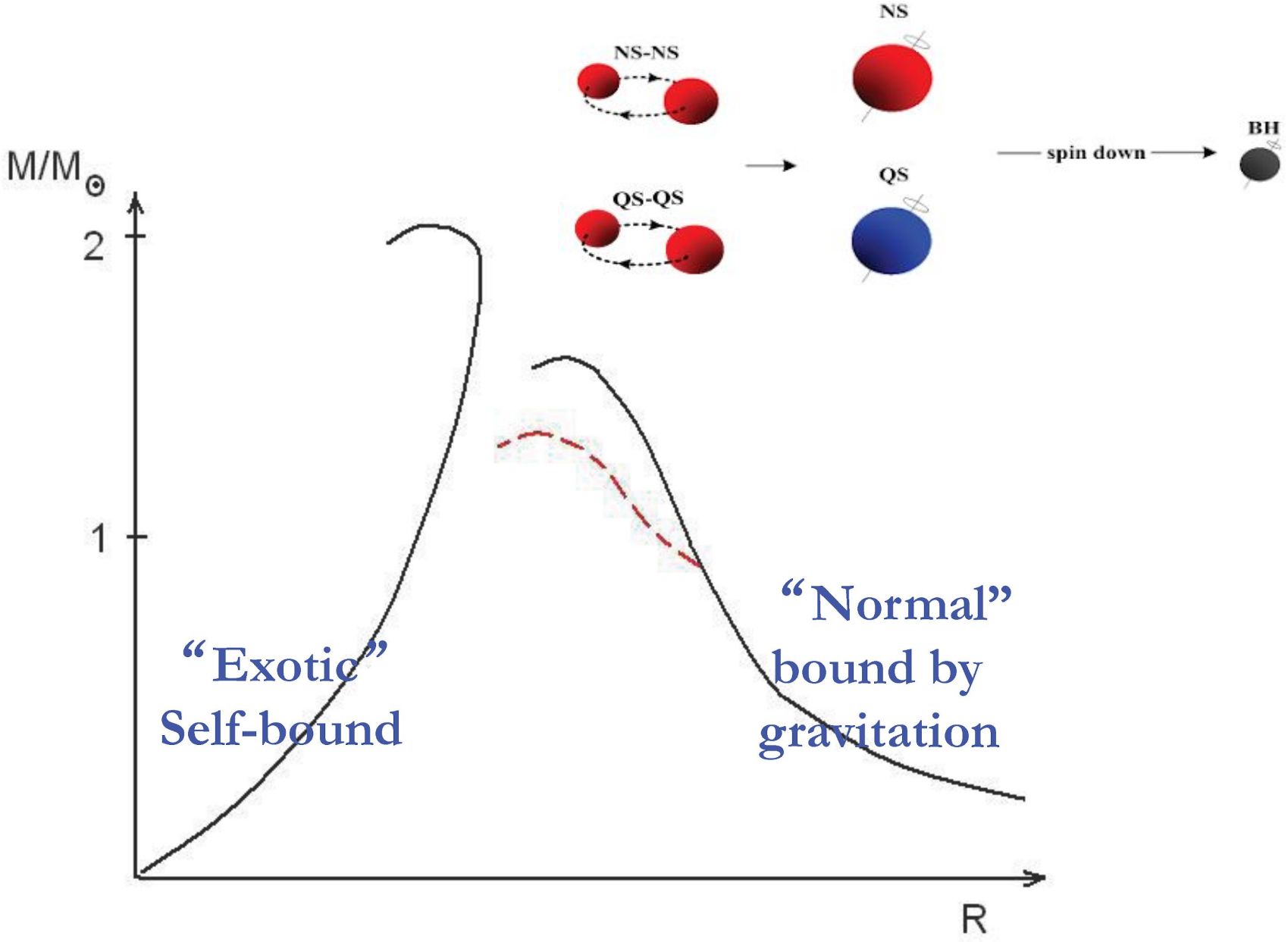
- Phase diagram at (T~0, $\mu \neq 0$) is not achievable from HIC (experiment), LQCD (simulation) or pQCD (first-principle theory), but it is important for NS/QS: **Model calculations.**
- EOS uncertainty from **QCD phase uncertainty and model uncertainty**
  - Hyperon **puzzle**; Δ(1232)/hyperon/Kaon/quark **complication**
  - 1) Self-consistency from one nuclear force for core & crust; 2) High-density extrapolation



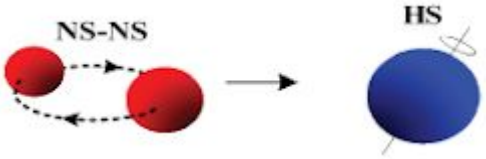
Input: EOS, mainly P(rho)

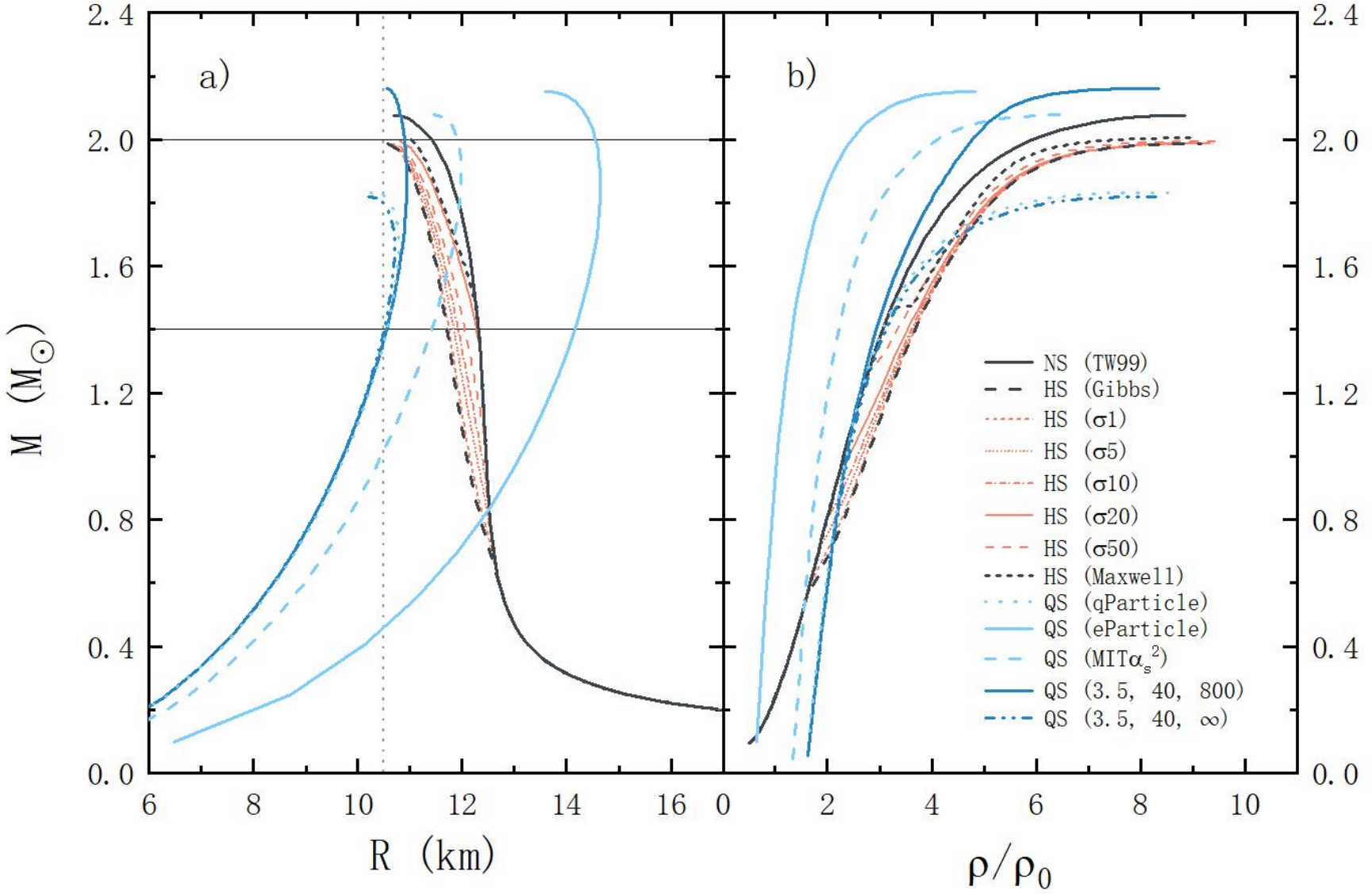
Output: M_{TOV}, M(R), Λ, etc.

NS/QS two-branch picture?



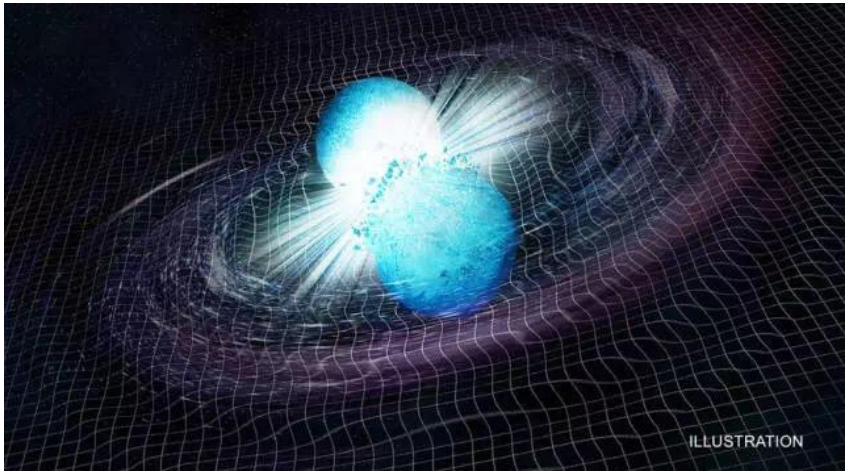
Hybrid star?



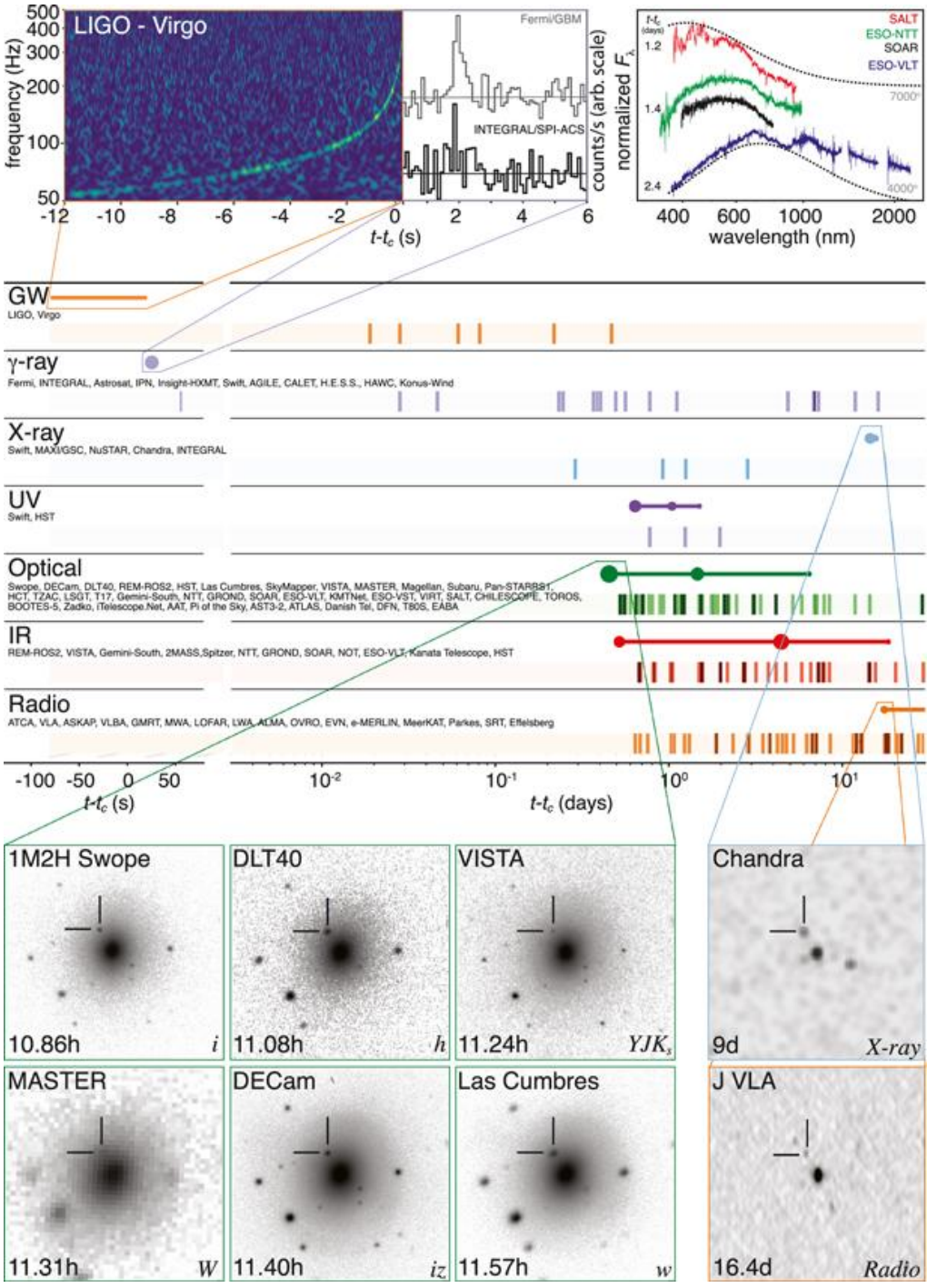


*Xia, Zhu, Zhou, **AL*** , to be submitted*

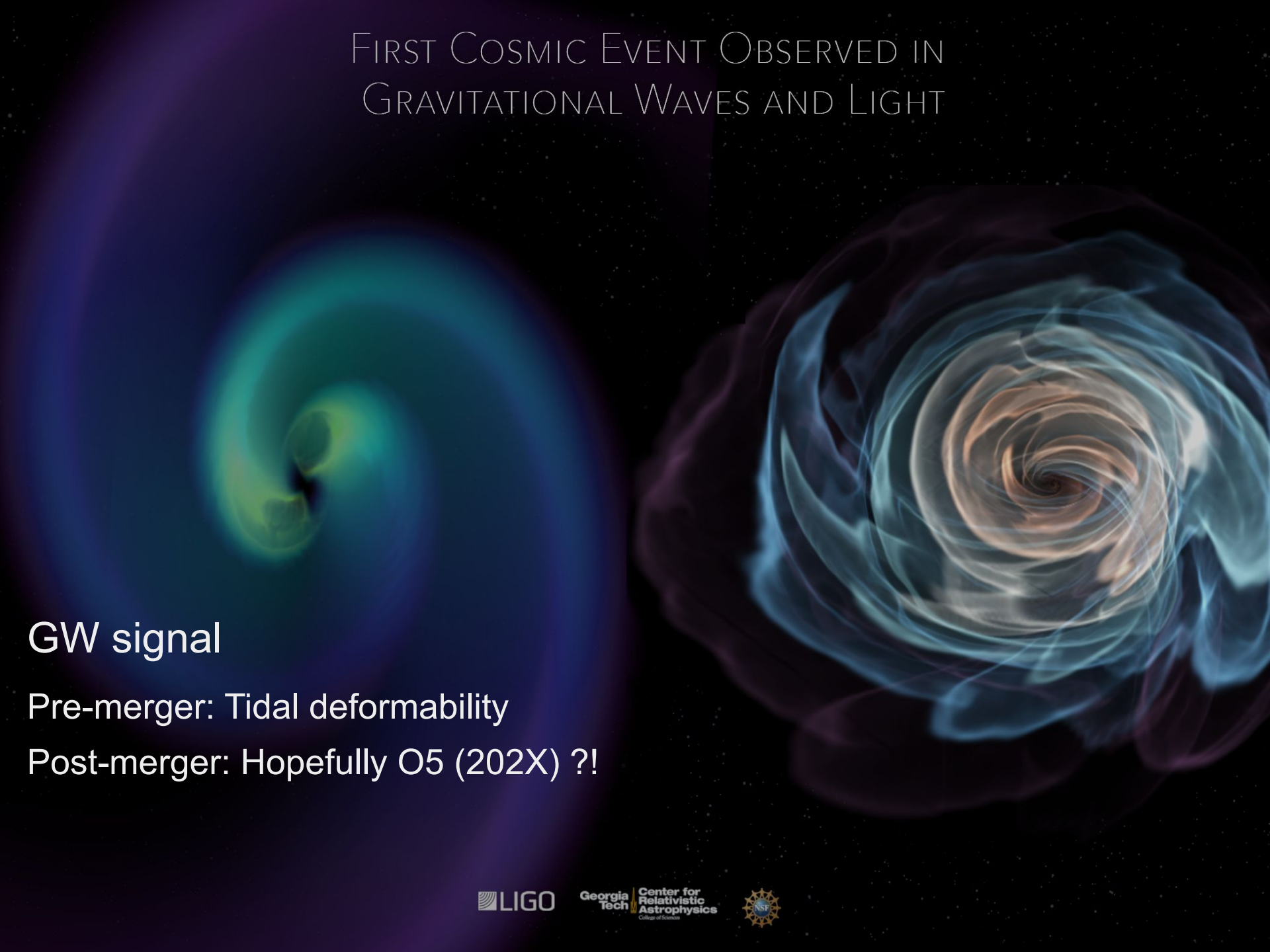
GW170817



- GW
- Neutrino: none
- ***γ***-ray: 1.7 s
- X-ray: 9 days +155 days?
- UV/Optical/IR (kilonova): 2 days
- Radio:16 days



First Cosmic Event Observed in Gravitational Waves and Light



GW signal

Pre-merger: Tidal deformability

Post-merger: Hopefully O5 (202X) ?!

LIGO Georgia Tech Center for Relativistic Astrophysics College of Sciences NSF

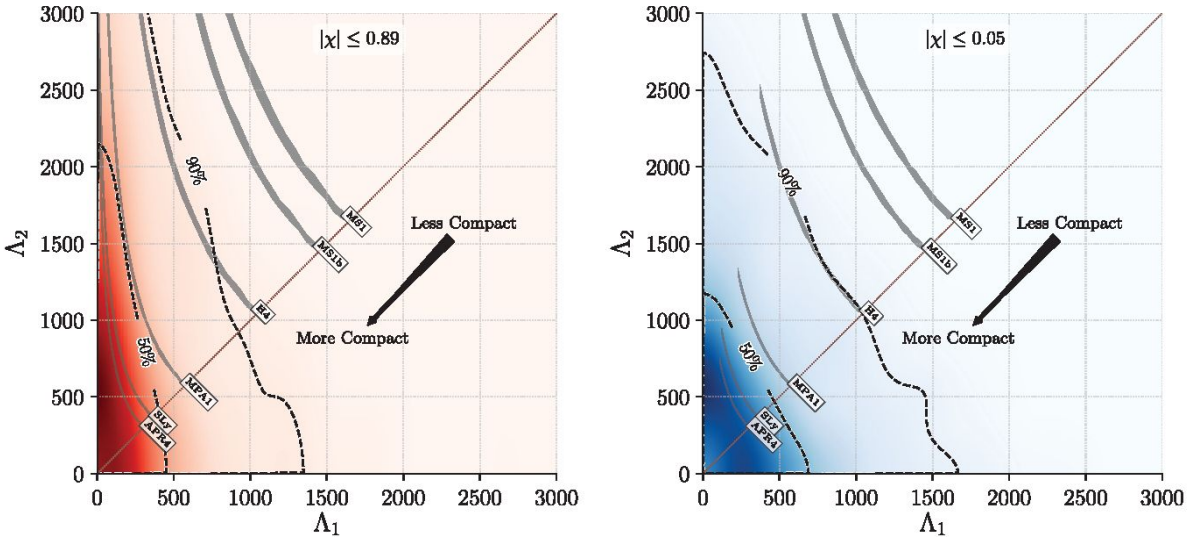
GW170817: GW signal

Finite size effects of NSs will alter the late inspiral GW signal;

- Dimensionless tidal deformability of each star, $\Lambda = \frac{2}{3} k_2 (\frac{R}{M})^5$

Under different spin priors, assuming $\Lambda_{1,2}$ vary independently:

Favor softer EoS;



- A combination of the tidal deformability for each star,

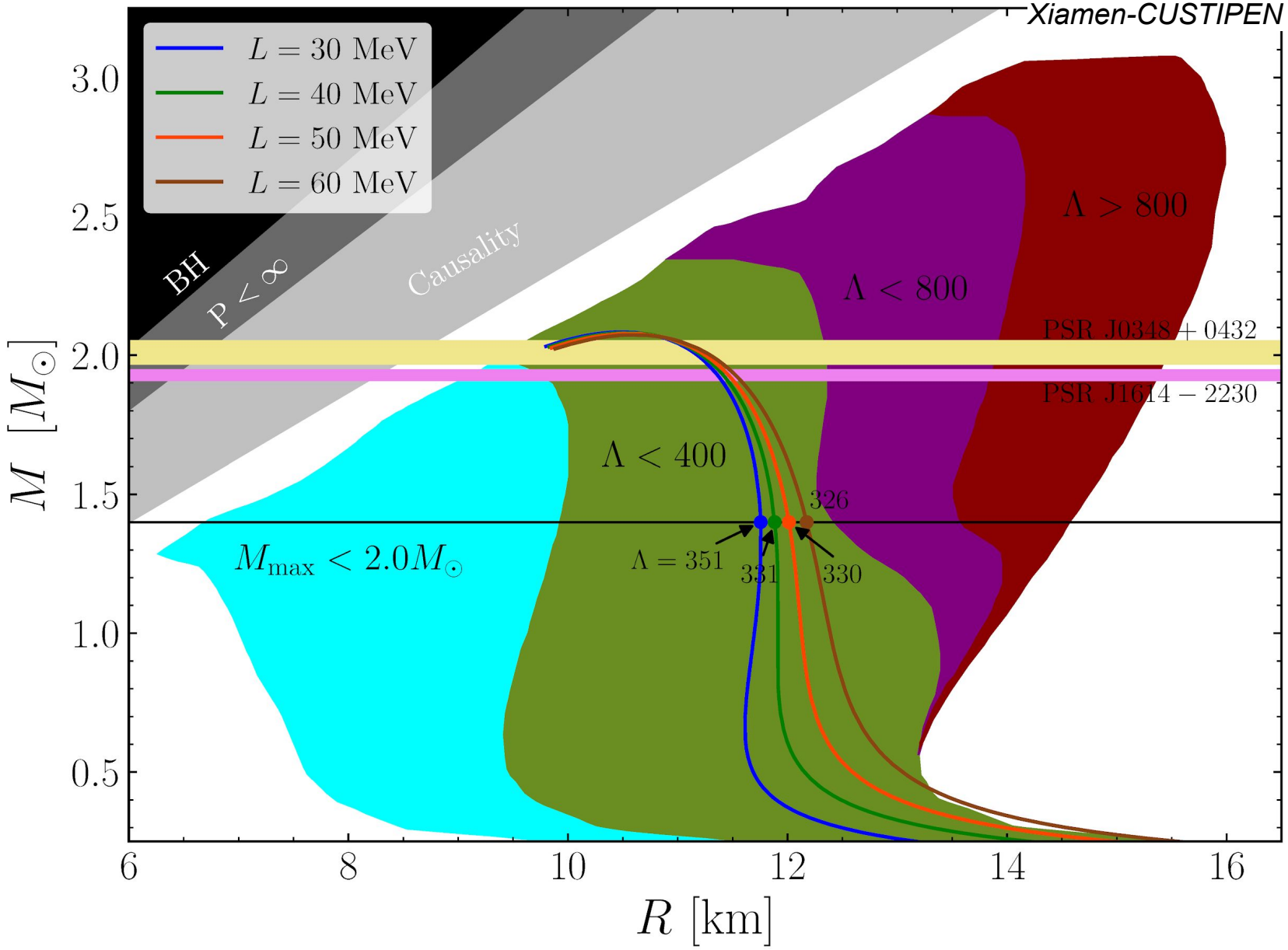
Assuming a uniform prior, $\tilde{\Lambda} = \frac{16}{13} \frac{(12q+1)\Lambda_1 + (12+q)q^4\Lambda_2}{(1+q)^5}$ ⩽ 800 (low-spin case)

$\Lambda(1.4) \leq 800$ (low-spin case) $\quad 190^{+390}_{-120}$

LVC group, 2018 PRL

NS EOS in the light of GW170817: Systematic studies

AL & Zhu, 1903.01280,*
Xiamen-CUSTIPEN Workshop



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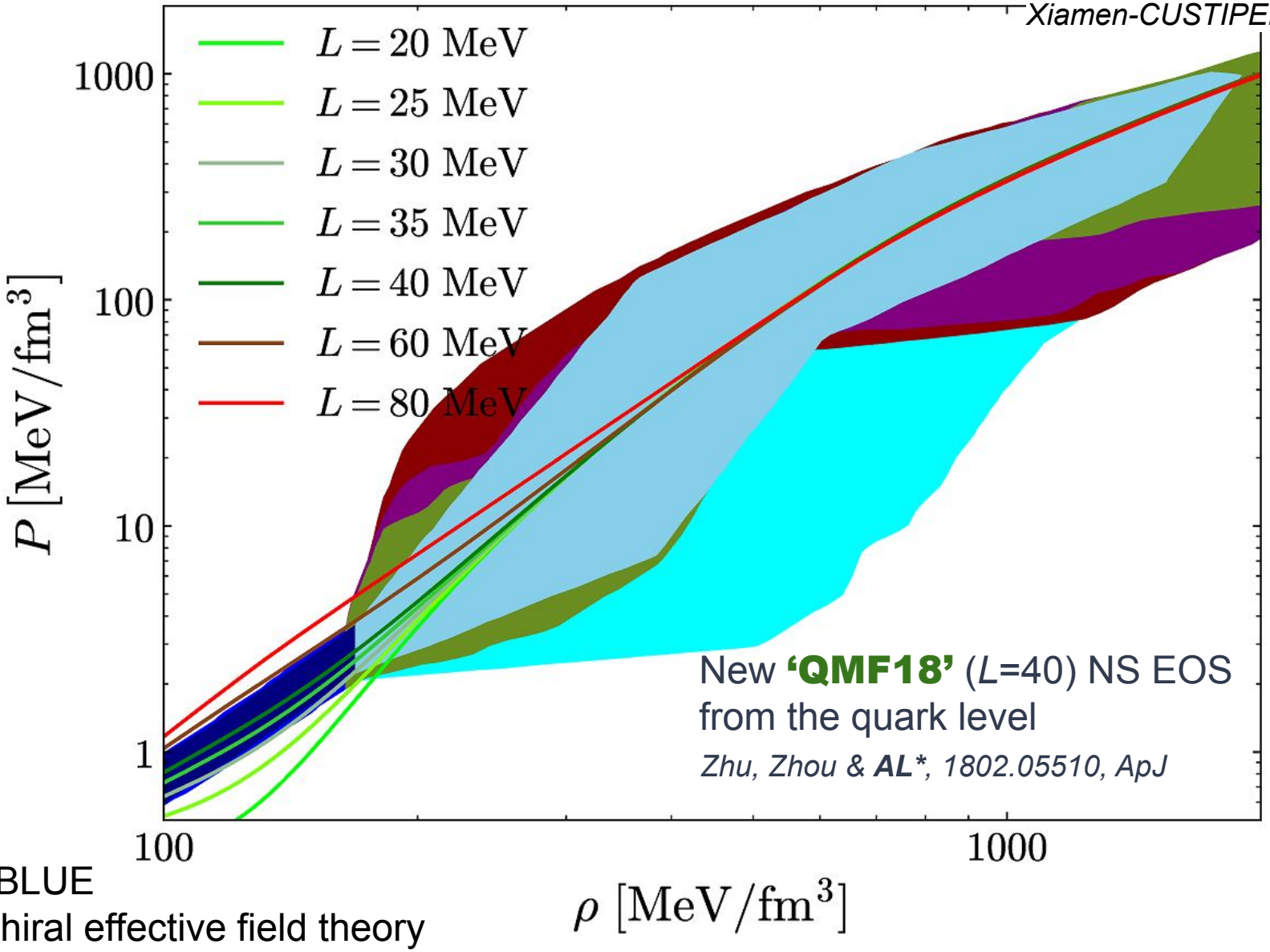
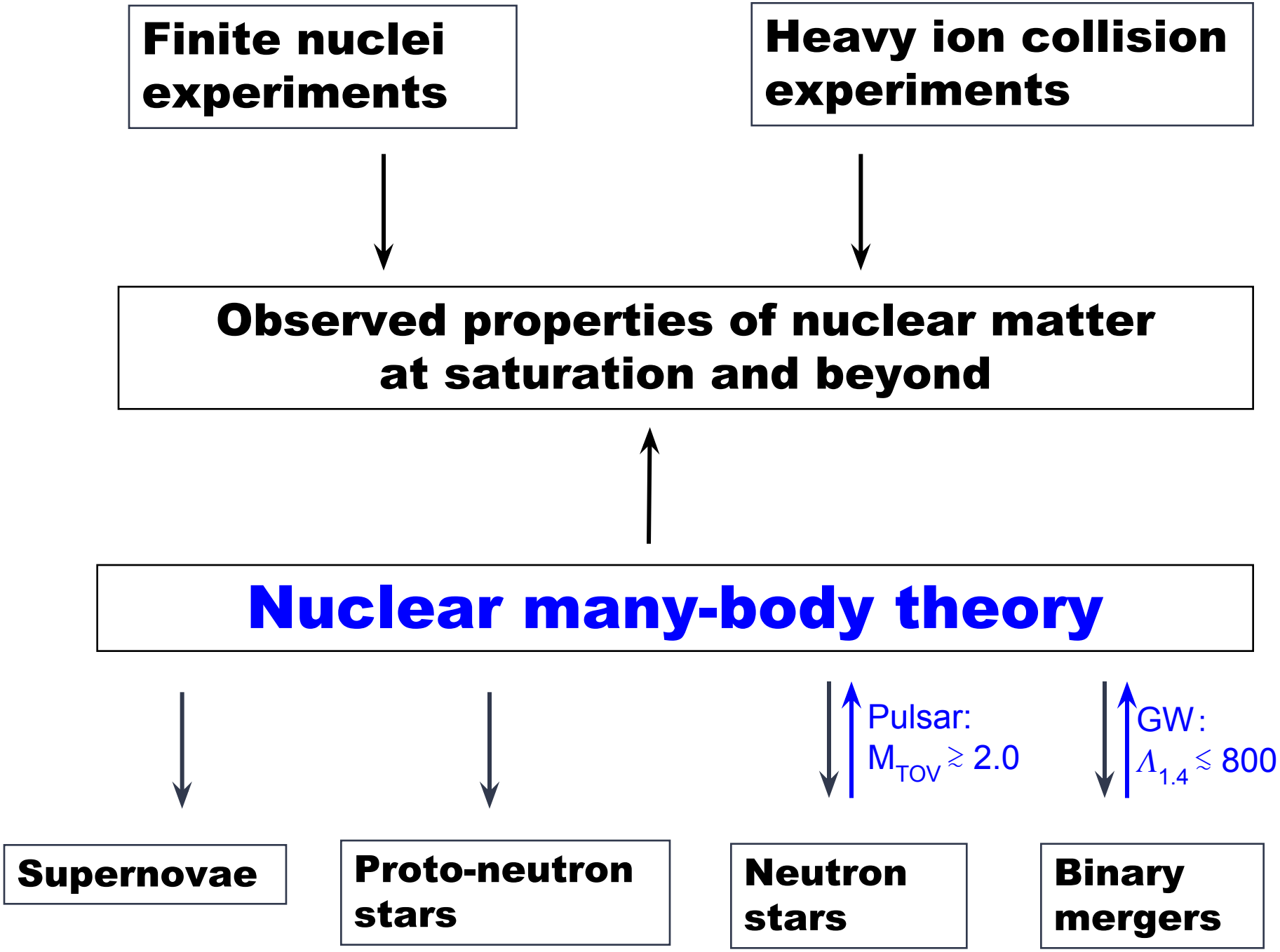


#BLUE
Chiral effective field theory
Hebeler et al. 2013


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~300 MeV)

Step 1: Single nucleon

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

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

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

$$V_0 = -62.257187 \text{ MeV}, \quad a = 0.534296 \text{ fm}^{-3} \longleftarrow M_N = 939 \text{ MeV}, \; r_N = 0.87 \text{ fm}.$$

Step 2: Nucleon many-body system

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

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

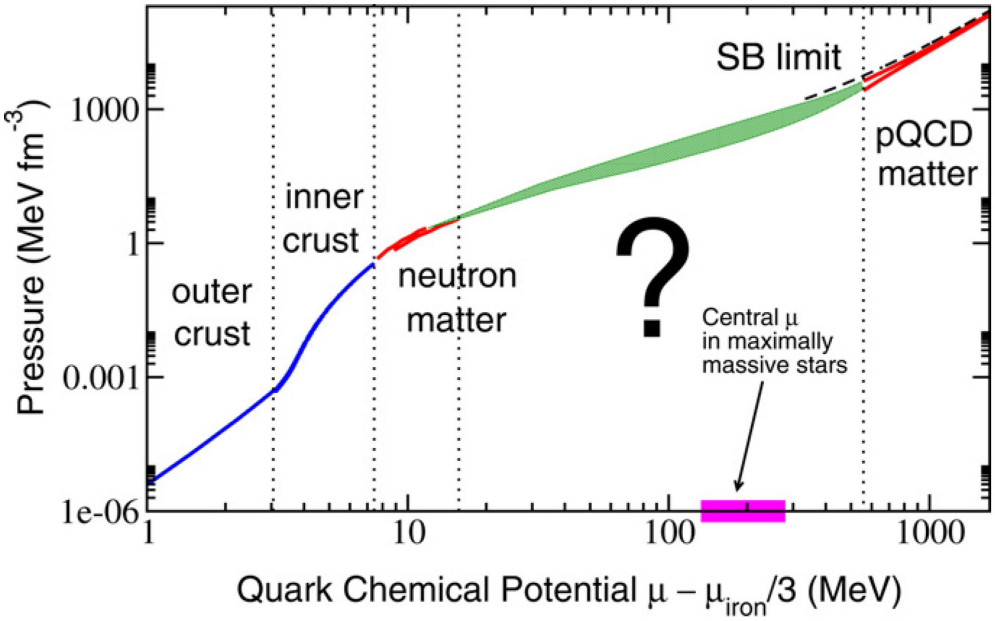
*K=**240**±20*
(Colo et al. 2014)
*E_{sym}=**31.6**±2.66*
*L=**58.9**±16*
(Li & Han 2013)
*L≳**20** (Centelles et al. 2009)*
*L≲**170** (Cozma 2013)*

NS EOS in the light of GW170817: Systematic studies

- CET(<1.1n_0)+pQCD(≳2.6GeV) ±24% uncertainty@1.1n_0

- Soft/hard hadronic component (0.6-1.1n_0; Hebeler et al. 2013): $\Lambda_{1.4}$=(120/161, 1353/1504)

- $M_{TOV} \gtrsim 2.0$: $R_{1.4}$ > 9.9 km
  $\Lambda_{1.4} \lesssim 800$: $R_{1.4}$ <13.6 km

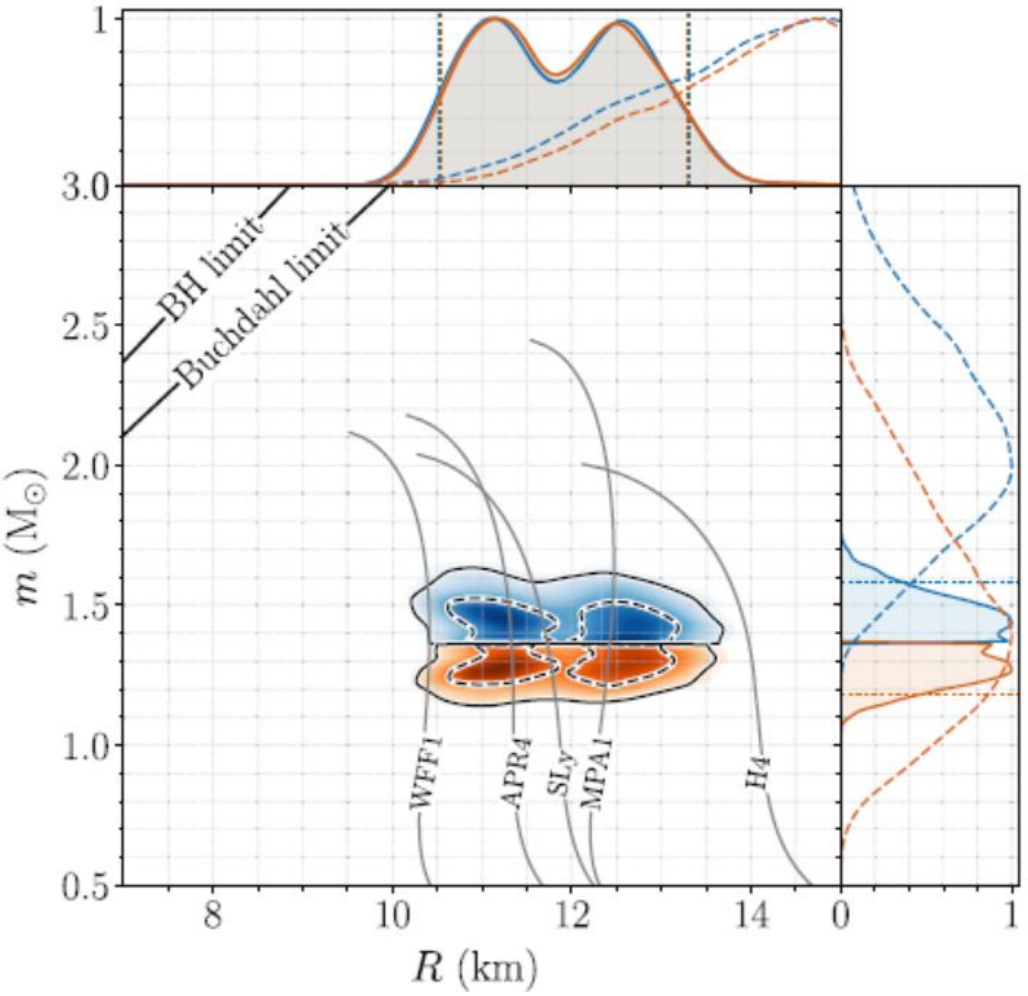


3-tropes	All EoSs	$2M_\odot$	$\Lambda < 800$
γ_1	0.2-8.5	0.7-8.5	0.7-6.6
$M_{\max}[M_\odot]$	<0.5-3.0	2.0-3.0	2.0-2.7
$R(1.4M_\odot)$[km]	7.1-14.6	10.7-14.6	10.7-13.6
4-tropes	**All EoSs**	$2M_\odot$	$\Lambda < 800$
γ_1	0.05-8.5	0.6-8.5	0.6-6.7
$M_{\max}[M_\odot]$	<0.5-3.2	2.0-3.2	2.0-3.0
$R(1.4M_\odot)$[km]	6.6-14.6	9.9-14.6	9.9-13.6

Annala et al., 1711.02644, PRL

NS EOS in the light of GW170817: Systematic studies

Logarithm of the adiabatic index of the EoSs are treated as a polynomial of the pressure for the high density EoS,



$$R_1 = 11.9^{+1.4}_{-1.4}\ \text{km}$$

$$R_2 = 11.9^{+1.4}_{-1.4}\ \text{km}$$

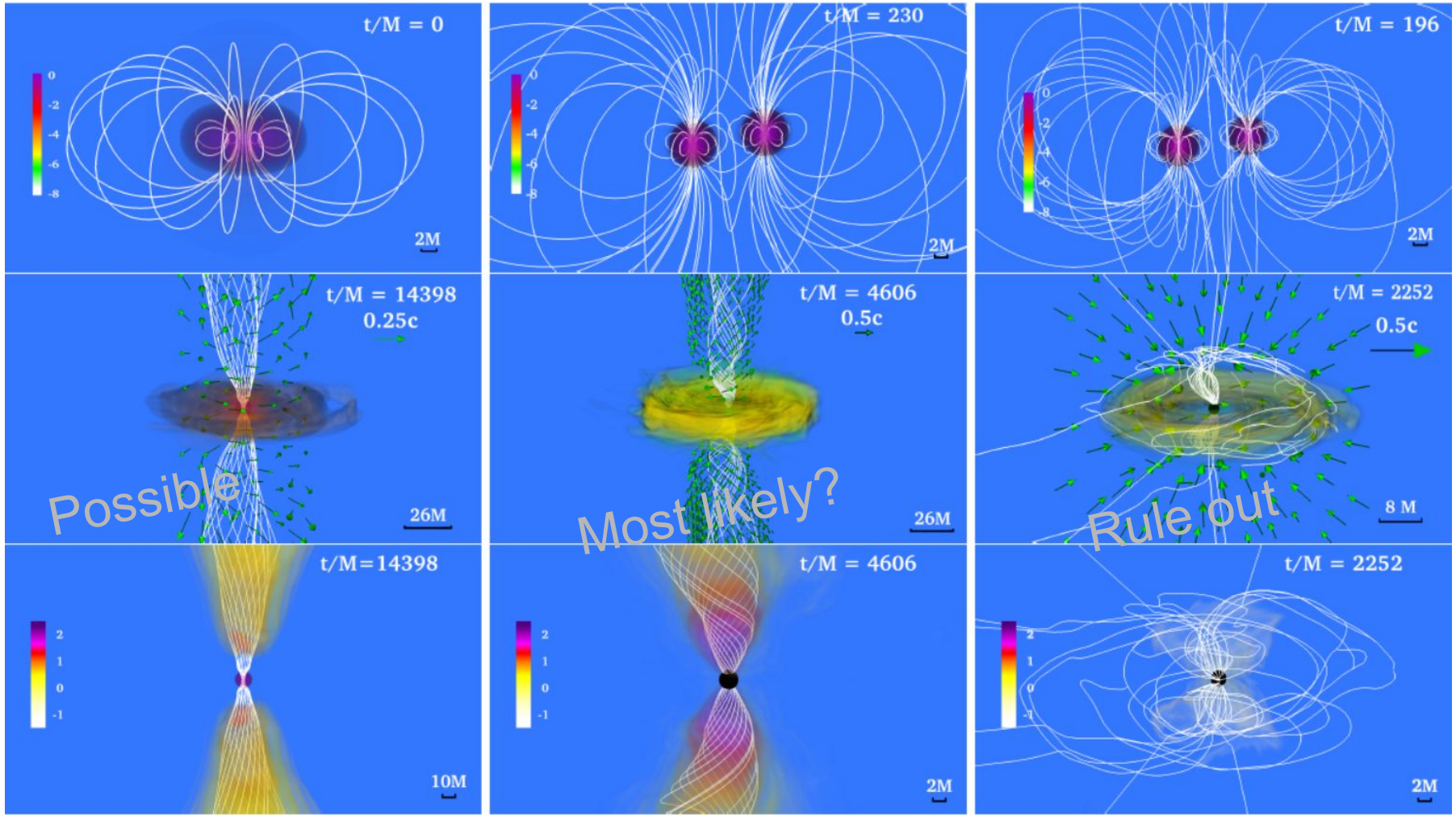
Note: With prior considering phase transition, results less constrained.

LVC group, 2018 PRL

GW170817: SGRB GRB170817A (1.7 s)

M_{TOV} ~2.2, the maximum
(or the minimum?)

i)Long-lived supramassive NS **ii)Short-lived hypermassive NS** **iii)Prompt collapse hypermassive NS**

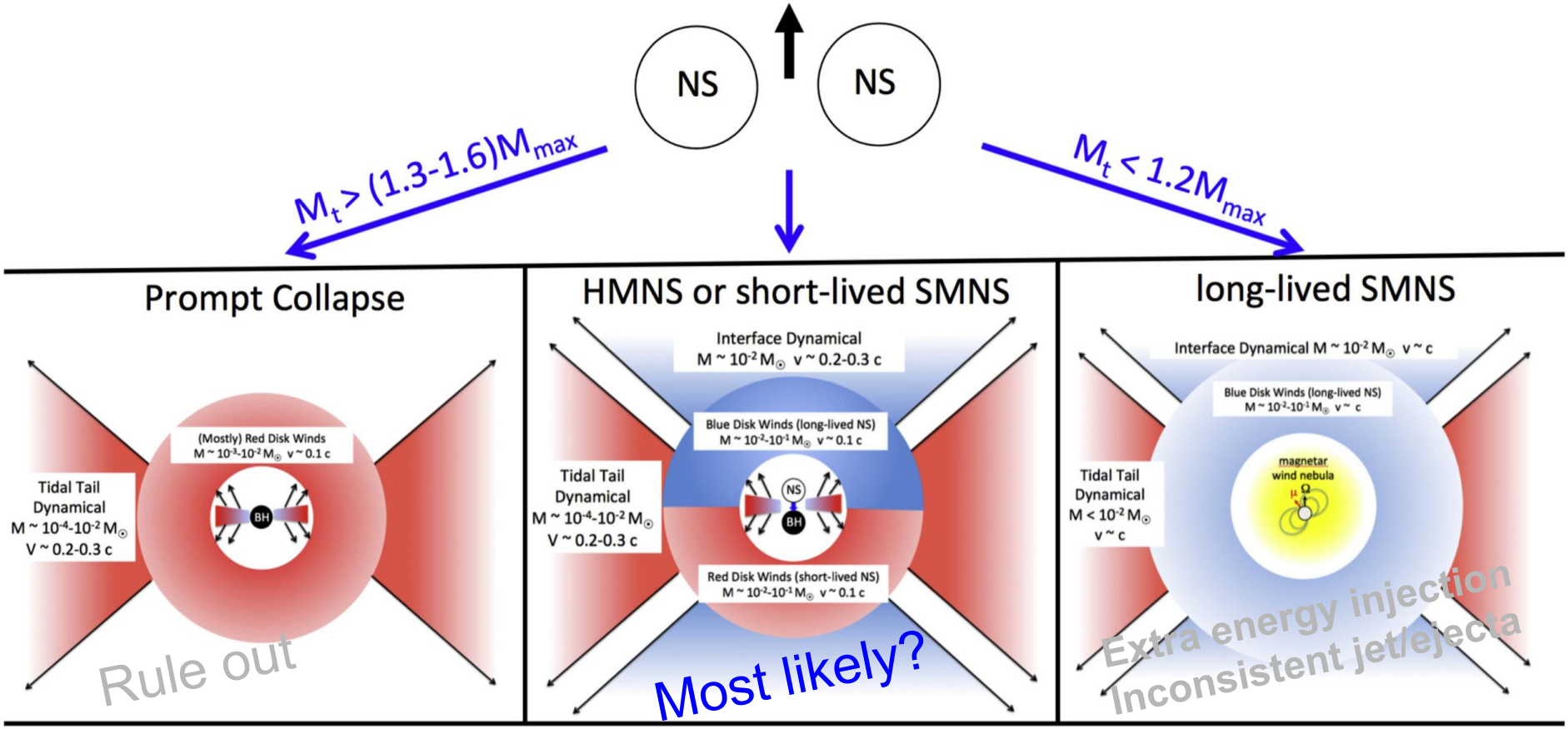


If originating from a BH central engine
(See Gao's talk for the case of magnetar central engine)

Ruiz, Shapiro & Tsokaros, 1711.00473, PRD

GW170817: kilonova AT2017gfo

M_{TOV} ~2.2, the maximum
(or the minimum?)

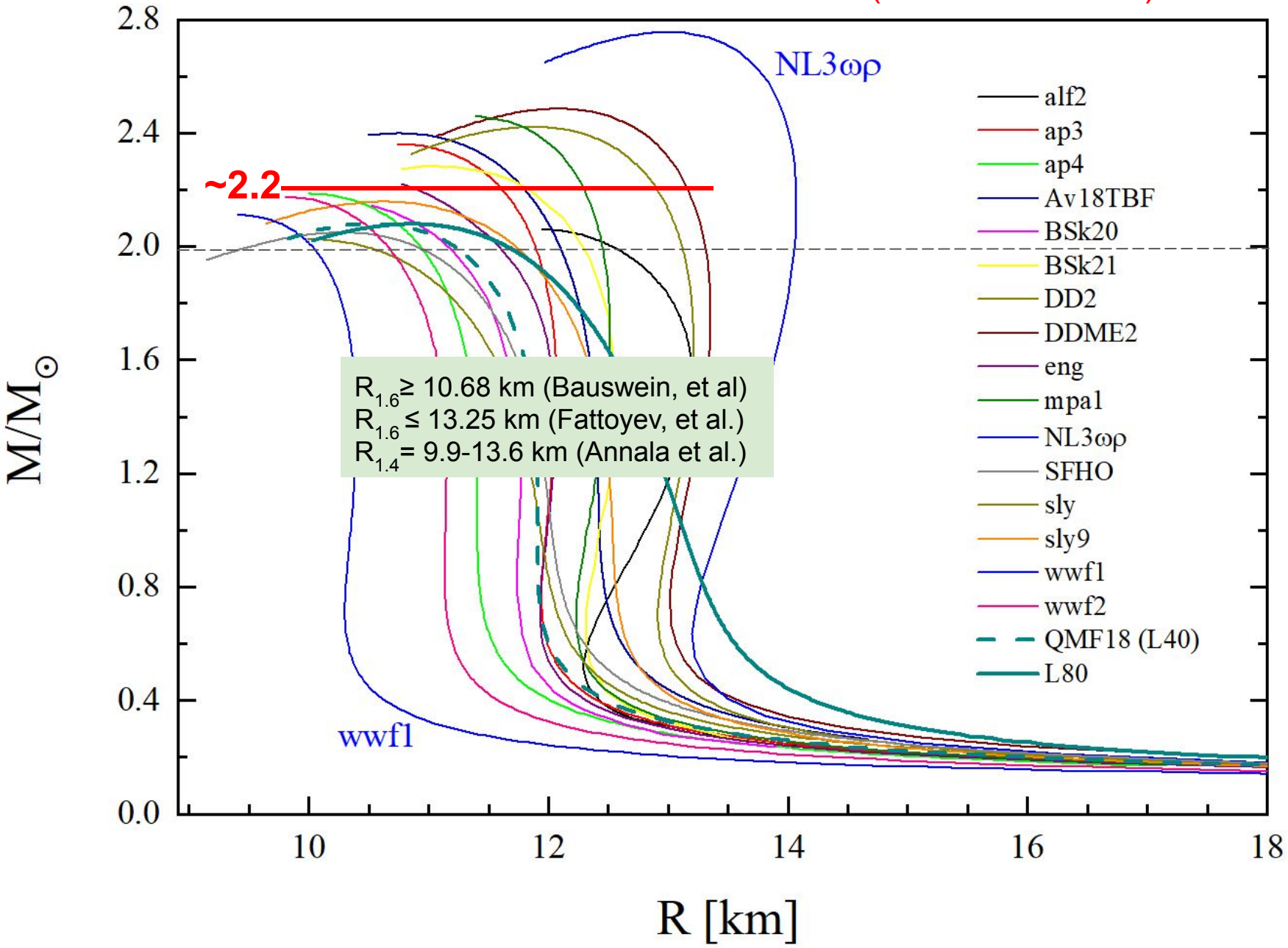


Margalit & Metzger, 1710.05938, ApJL

If originating from a BH central engine
(See Gao's talk for the case of magnetar central engine)

GW170817: SGRB (1.7 s)

M_{TOV} ~2.2, the maximum
(or the minimum?)



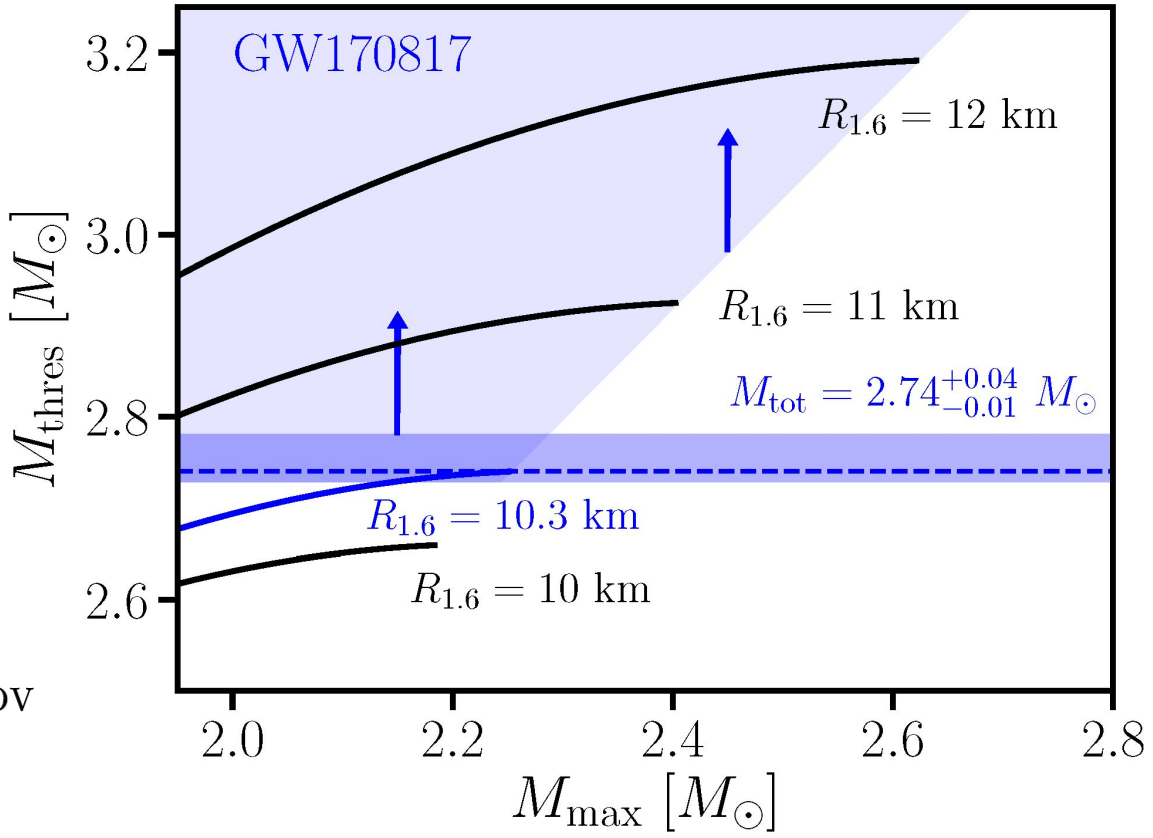
GW170817: EM

- 3D relativistic smoothed particle hydrodynamics (SPH) code;
- Assuming no prompt collapse;
- A previous fitted formula for threshold binary mass:

$$M_{\rm thres} = (-3.606 \frac{M_{\rm TOV}}{R_{1.6}} + 2.38) \times M_{\rm TOV}$$

- Conclusion:

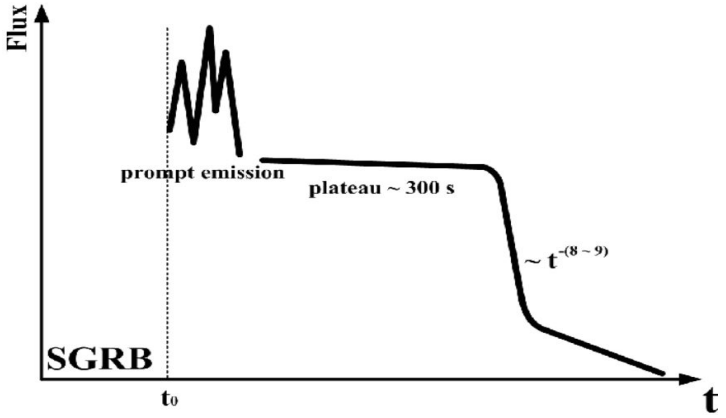
$$R_{1.6} \geq 10.68^{+0.15}_{-0.04} \rm km$$



Bauswein et al., 1710.06843, ApJL

NS/QS two-branch picture?

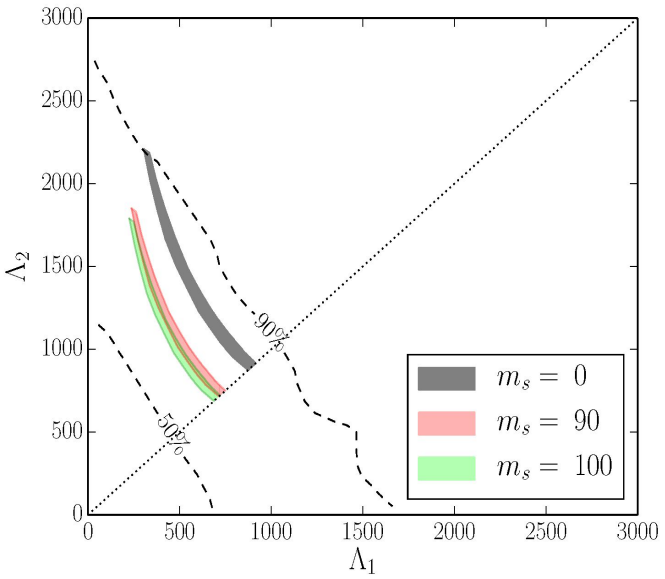
- No hyperon puzzle for QS;
  Preferred by particular group of SGRB
  *(e.g., **AL** et al., 1706.04720, ApJ; 1606.02934, PRD)*



- QS merger scenario for GW170817

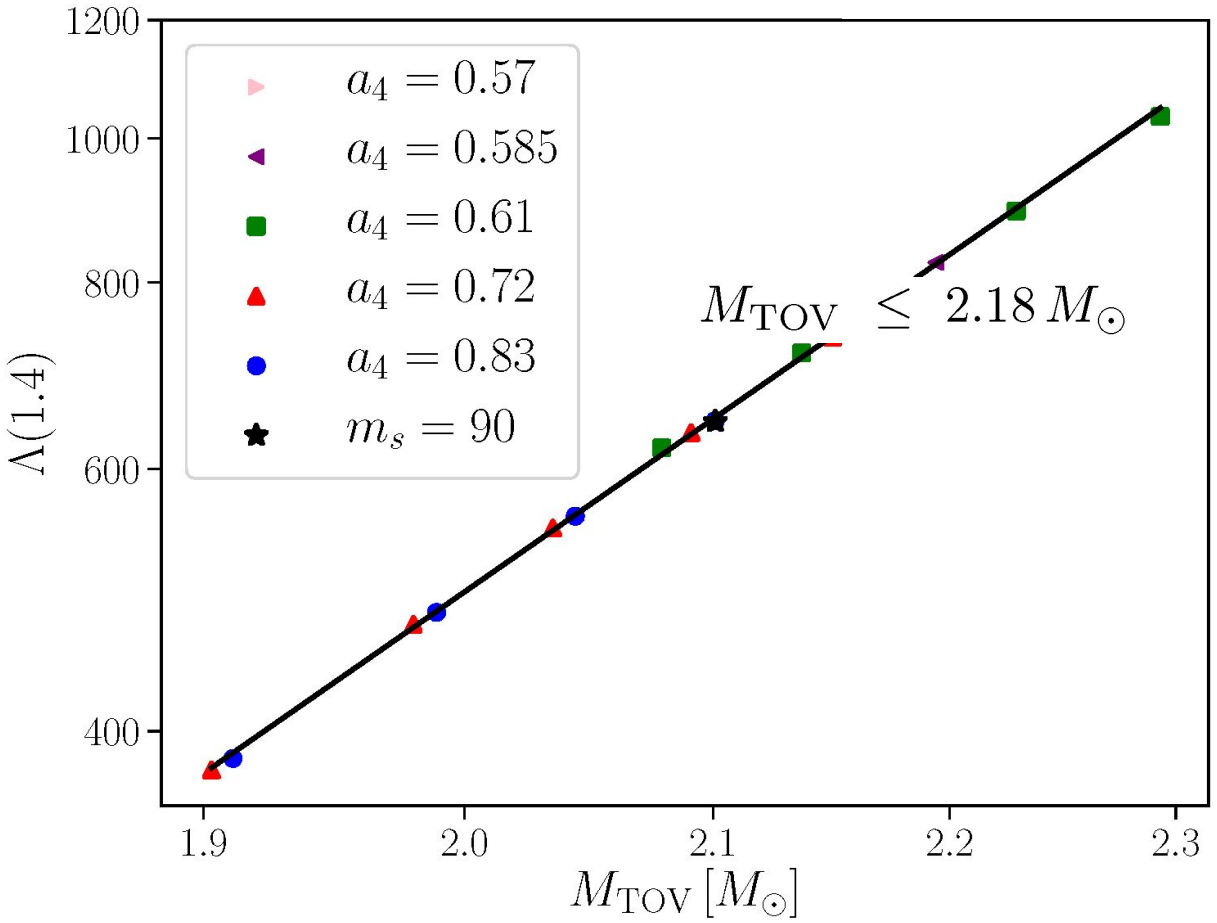
  *(e.g., Zhou, Zhou & **AL***, 1711.04312, PRD)*

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



Strong $M_{\rm TOV}$-vs-$\Lambda(1.4)$ correlation

$$\Lambda(1.4) = 510.058 \times \left(\frac{M_{\rm TOV}}{2.01\, M_\odot} \right)^{5.457}$$



Stiffer EOS

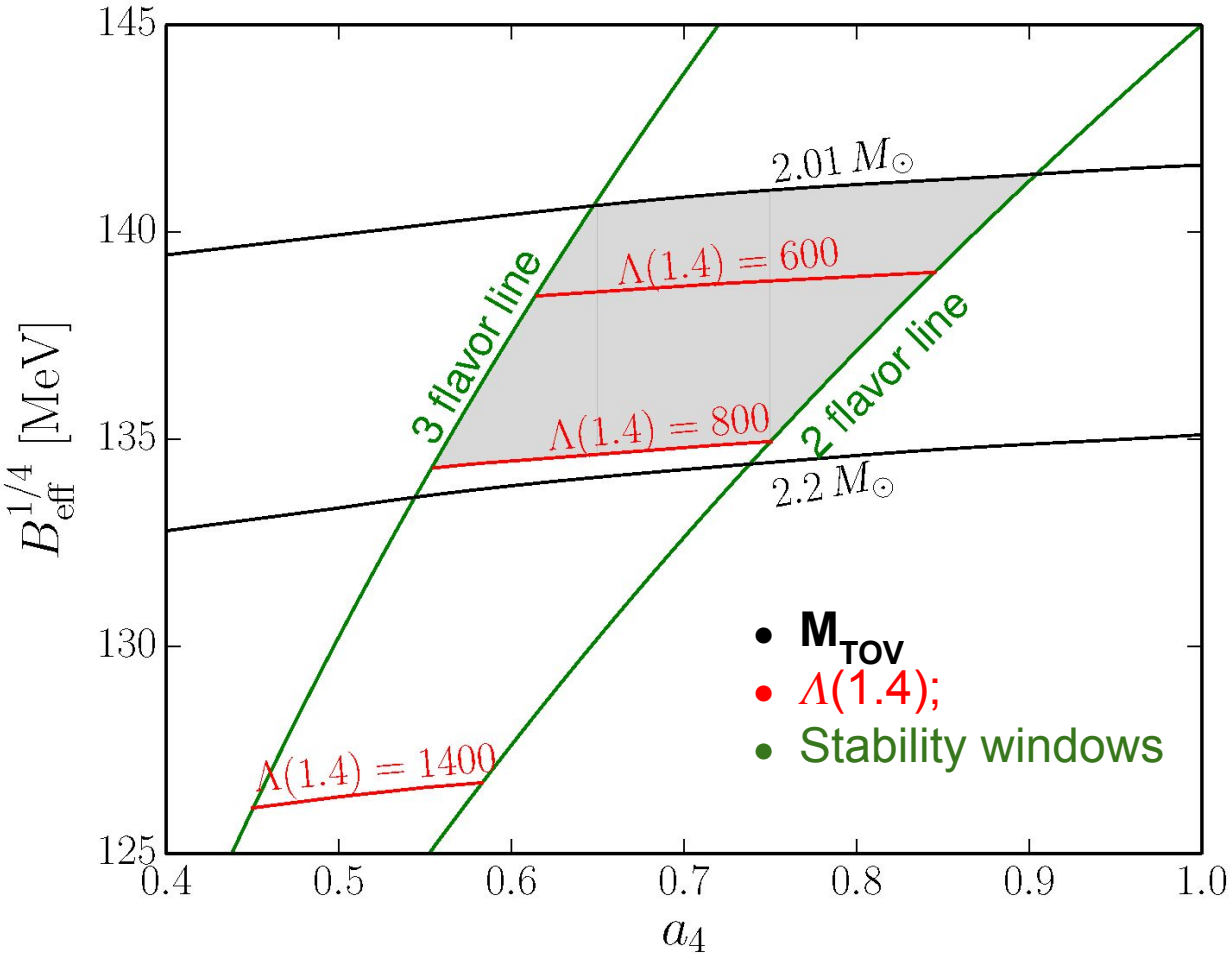
Larger $M_{\rm TOV}$

Larger $\Lambda(1.4)$

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

QS merger scenario for GW170817

Tidal deformability constraint of GW170817: Interquark interaction



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

QS merger scenario for GW170817

Short summary: One event of GW170817, small tidal upper limit (not too stiff), long-lived (stiff)? Ejecta (?)

- Post-merger remnant: long-lived/short lived?
- SGRB central engine: The minimum/maximum of M_{TOV} ~2.2?
- Post-merger GW signals/better EM signals
- Minimum: Two branch/Soften of phase transition (hyperon puzzle)? Identify QS from SGRB/GW/...? Phase transition?
- Maximum: Heavy pulsars? QS? Phase transition?

First Cosmic Event Observed in Gravitational Waves and Light

In this talk,

- One event of GW170817, possibly from binary NS/QS/HS;

In the near future,

- More GW170817-like events;
- Post-merger GW signals/better EM signals.

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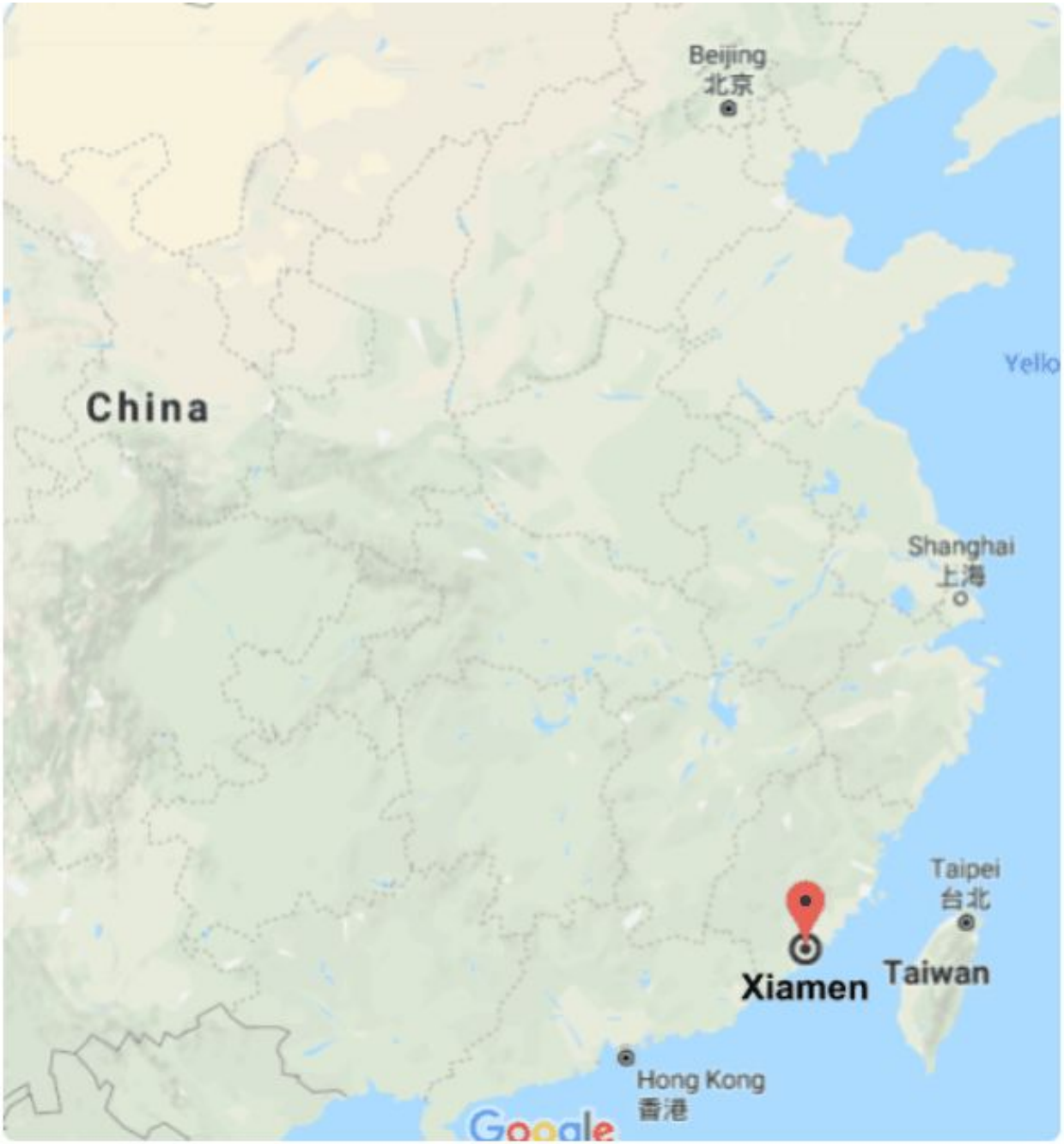
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Thank you.