Quark star EOSs in the light of SGRB and GW170817

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Compact Stars in the QCD Phase Diagram VII

11- 15 June 2018
CUNY Advanced Science Research Center
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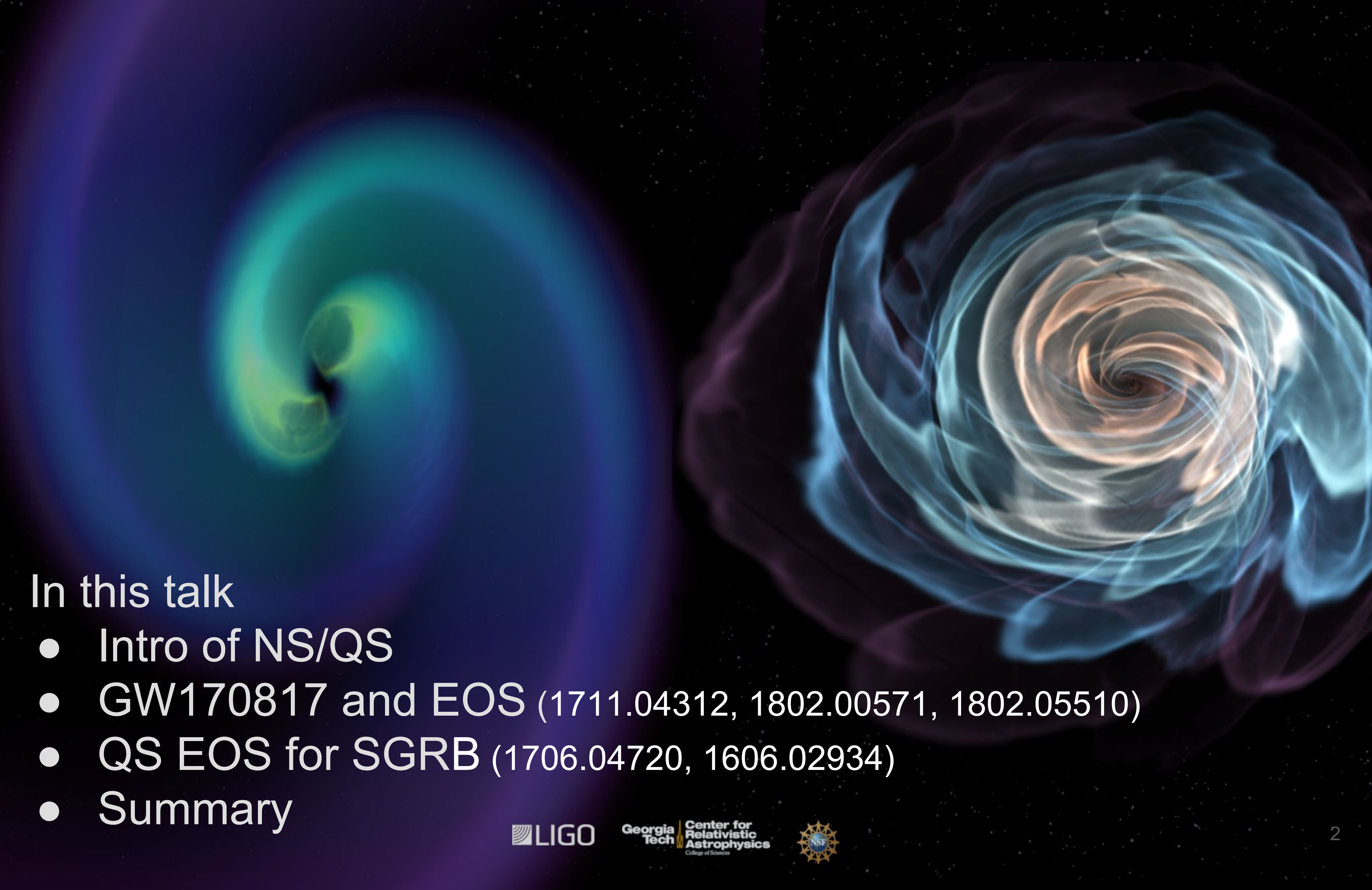
First Cosmic Event Observed in Gravitational Waves and Light



In this talk

- Intro of NS/QS
- GW170817 and EOS (1711.04312, 1802.00571, 1802.05510)
- QS EOS for SGRB (1706.04720, 1606.02934)
- Summary

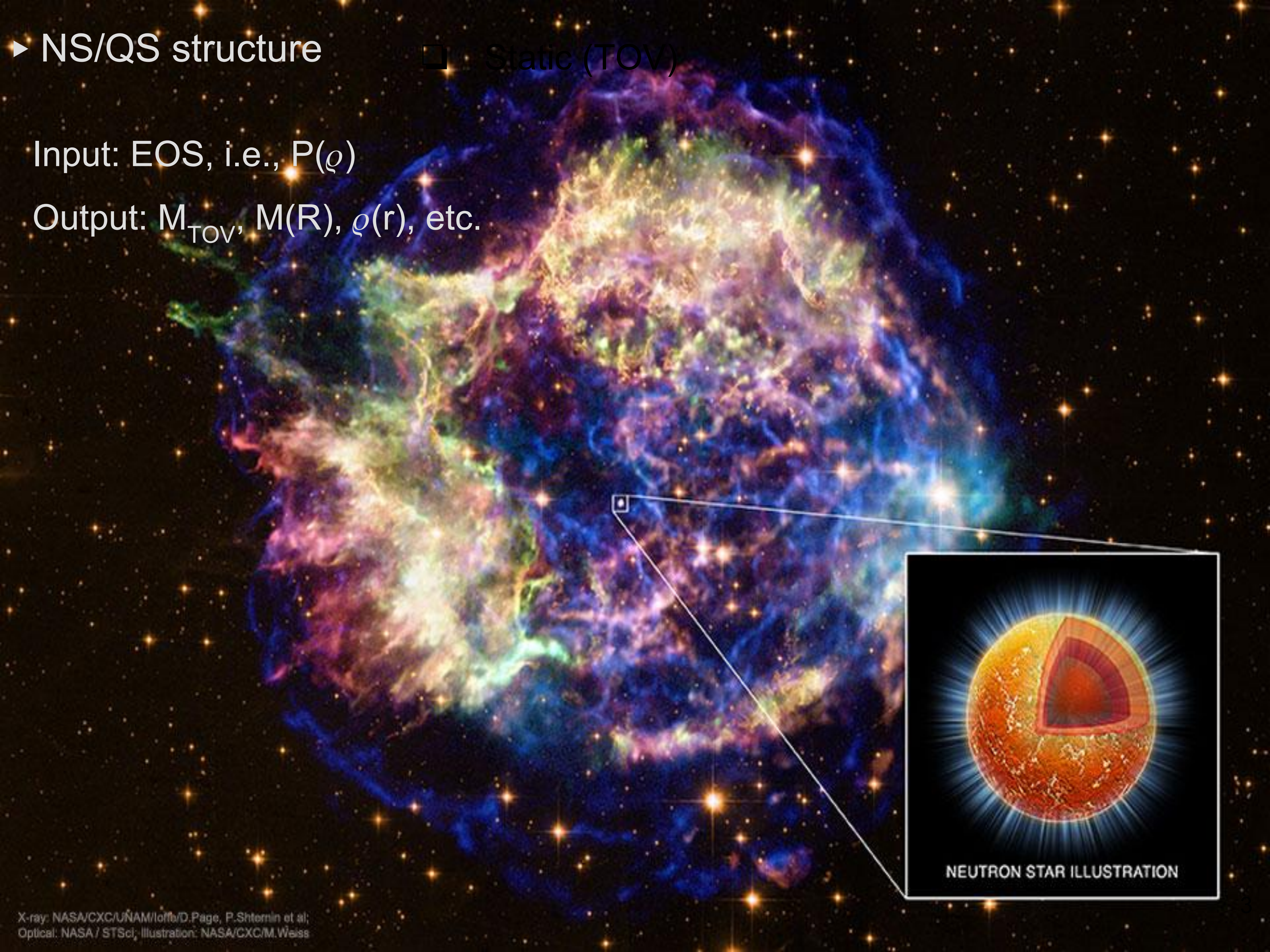
LIGO Georgia Tech Center for Relativistic Astrophysics College of Sciences NSF

- NS/QS structure

- Static (TOV)

Input: EOS, i.e., P(ϱ)

Output: M_{TOV}, M(R), ϱ(r), etc.

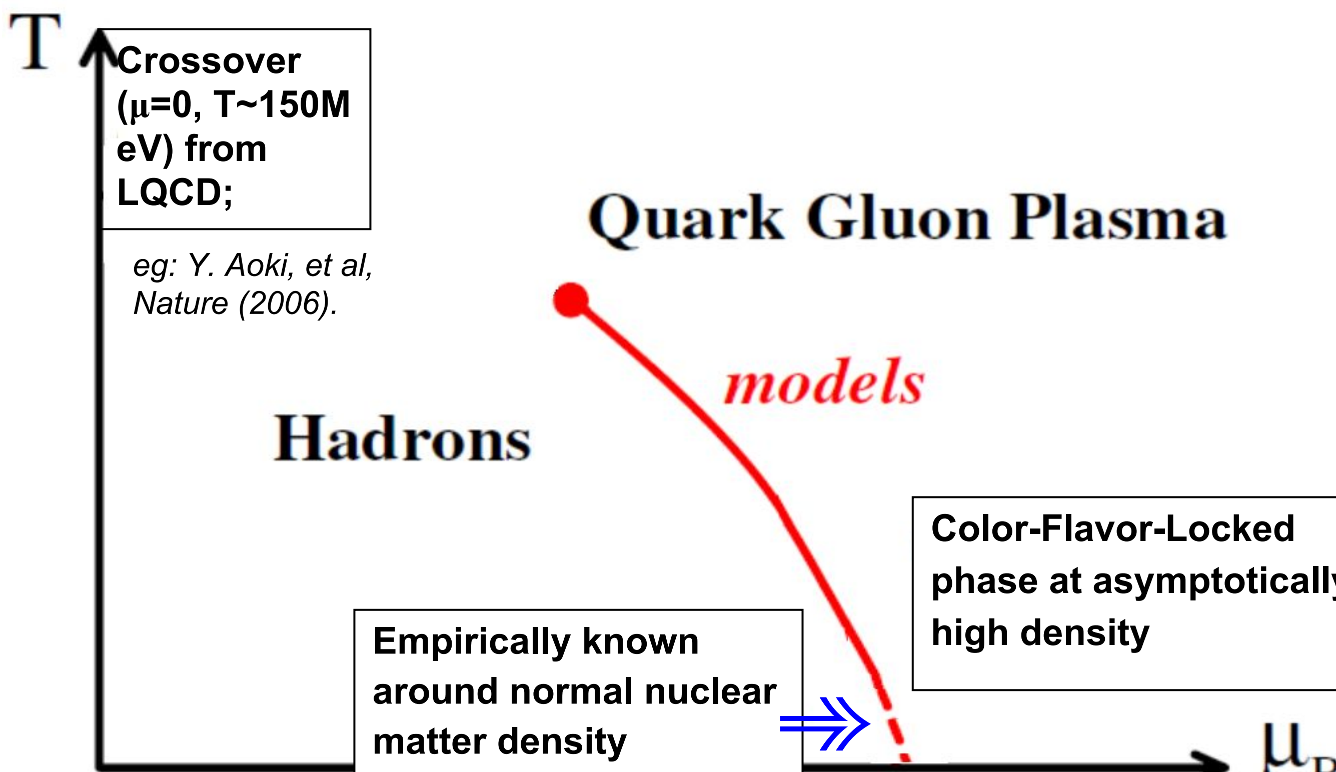


▸ Theoretical difficulties

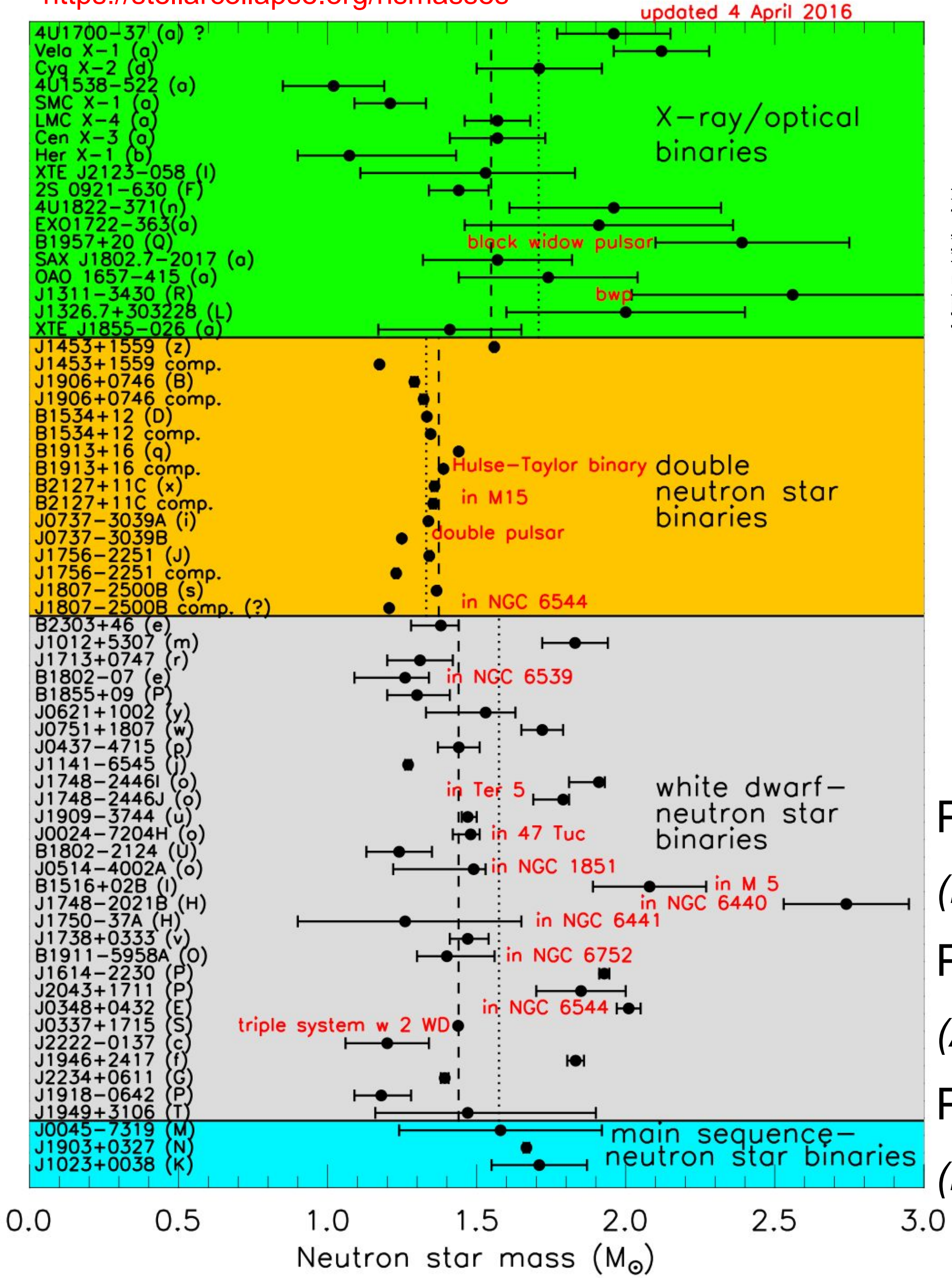
▸ Phase diagram at (T~0, μ≠0) is not achievable from HIC (experiment), LQCD (simulation) or pQCD (first-principle theory), but it is important for NS/QS: **Model calculations.**

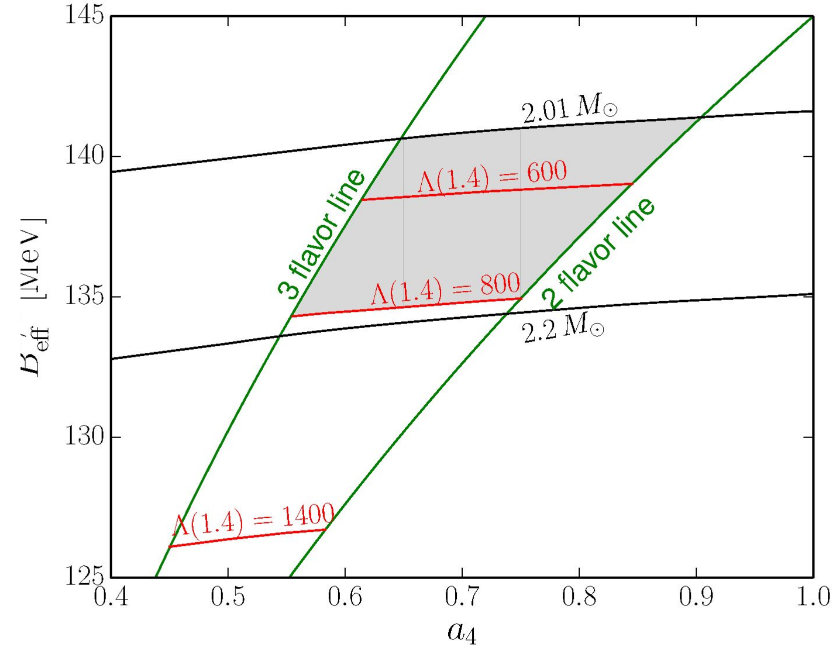
▸ EOS uncertainty from **QCD phase uncertainty and model uncertainty**

- Hyperon **puzzle**; Δ(1232)/hyperon/Kaon/quark **complication**
- 1) Self-consistency (why unified NS EOS); 2) High-density extrapolation



https://stellarcollapse.org/nsmasses





M_{TOV} ; $\Lambda(1.4)$

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

PSR J1614-2230: 1.928(17)

(Demorest et al. 2010; Fonseca et al. 2016)

PSR J0348+0432*:* **2.01(4)**

(Antoniadis et al. 2013)

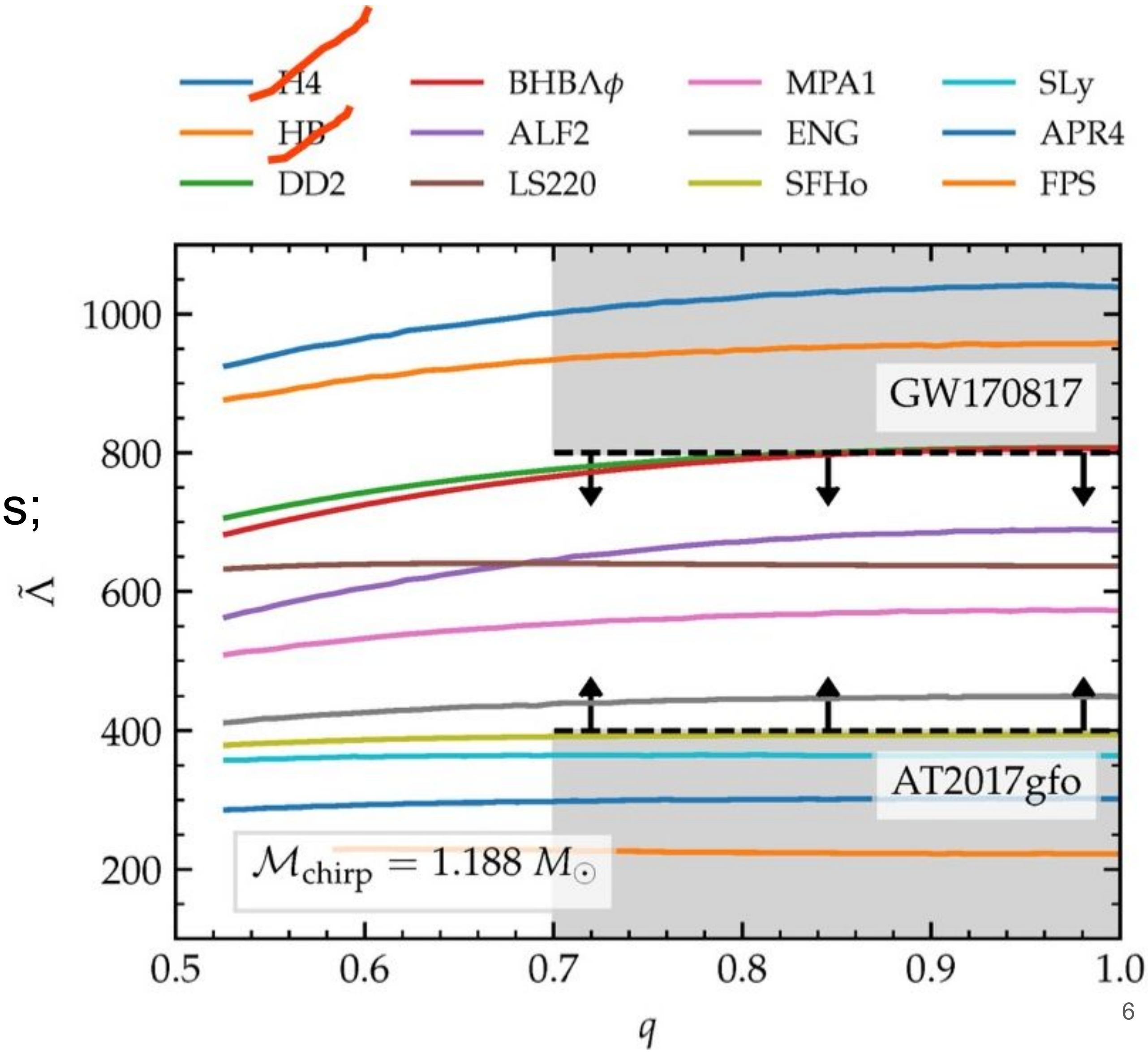
PSR J2215+5135: $2.27^{+0.17}_{-0.15}$ **?!**

(Linares et al., 1805.08799)

▸ NS EOS constraints with GW170817 (e.g.)

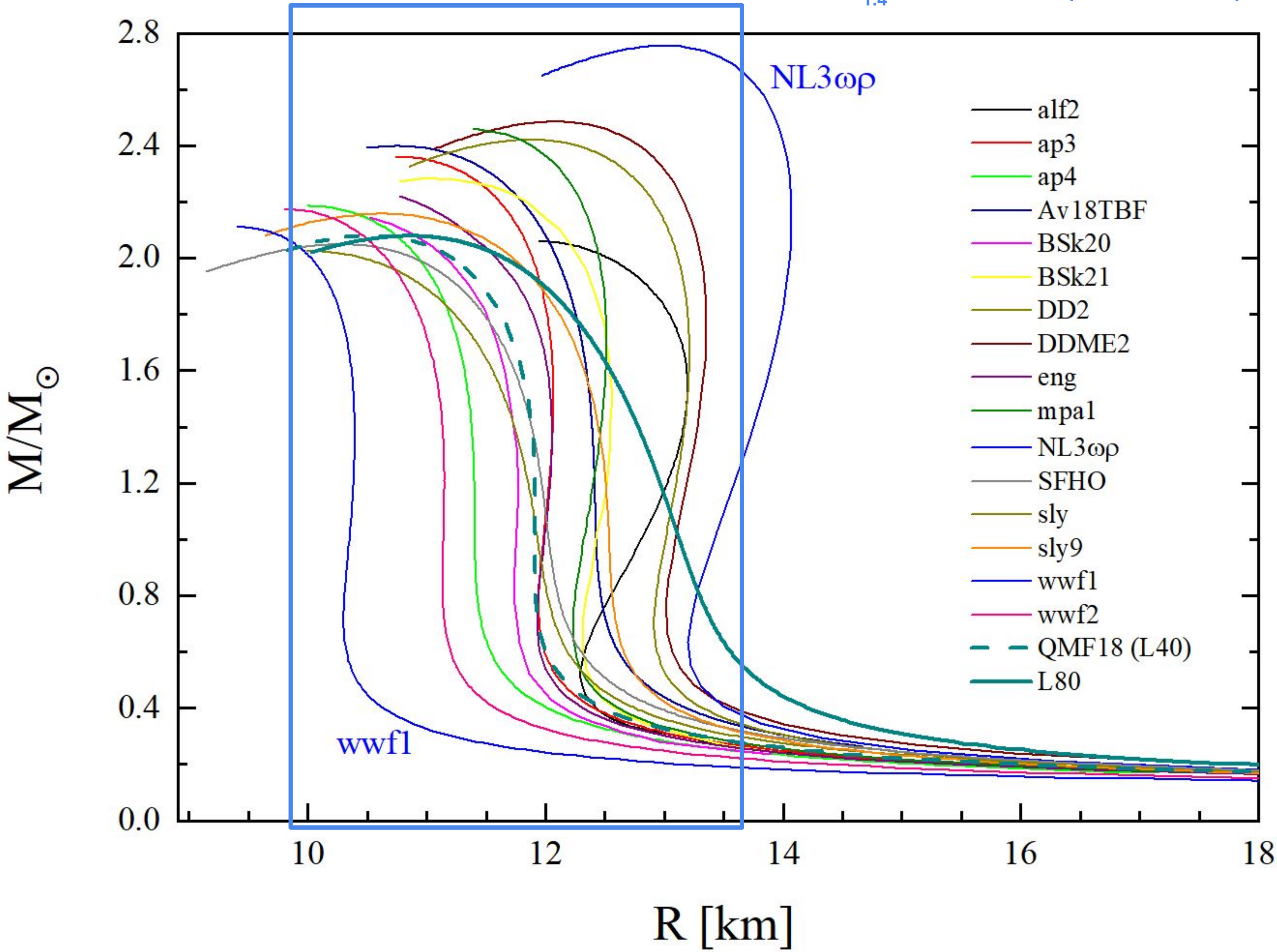
- GR hydrodynamics code WhiskyTHC;
- Assumption: UV/Optical/IR from kilonova;
- 29 merger simulations;
- 12 NS EOSs;
- Rule out extremely stiff NS EOS.

Radice et al., **1711.03647, ApJL**

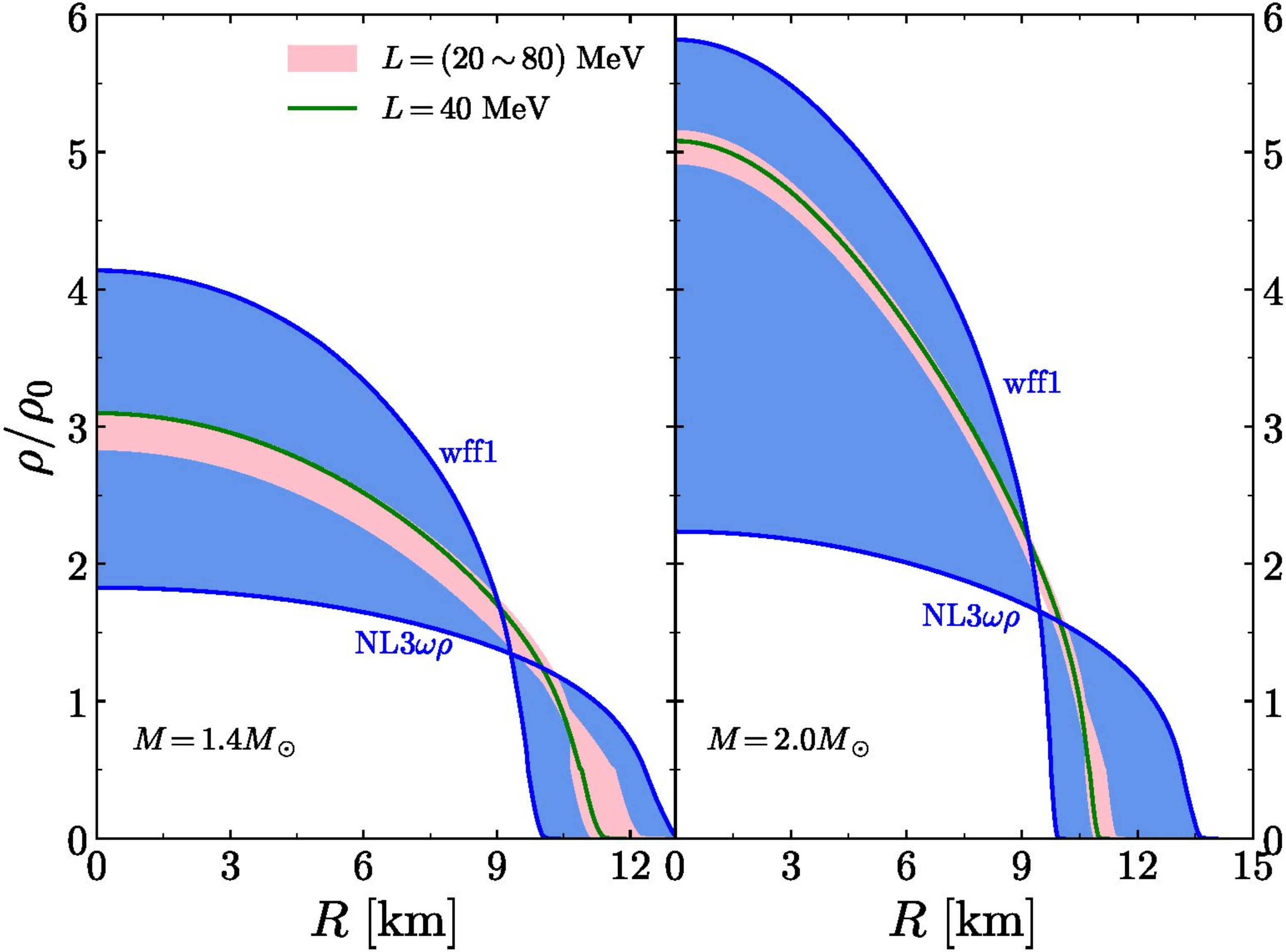


- NS EOS constraints with GW170817 (e.g.)

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

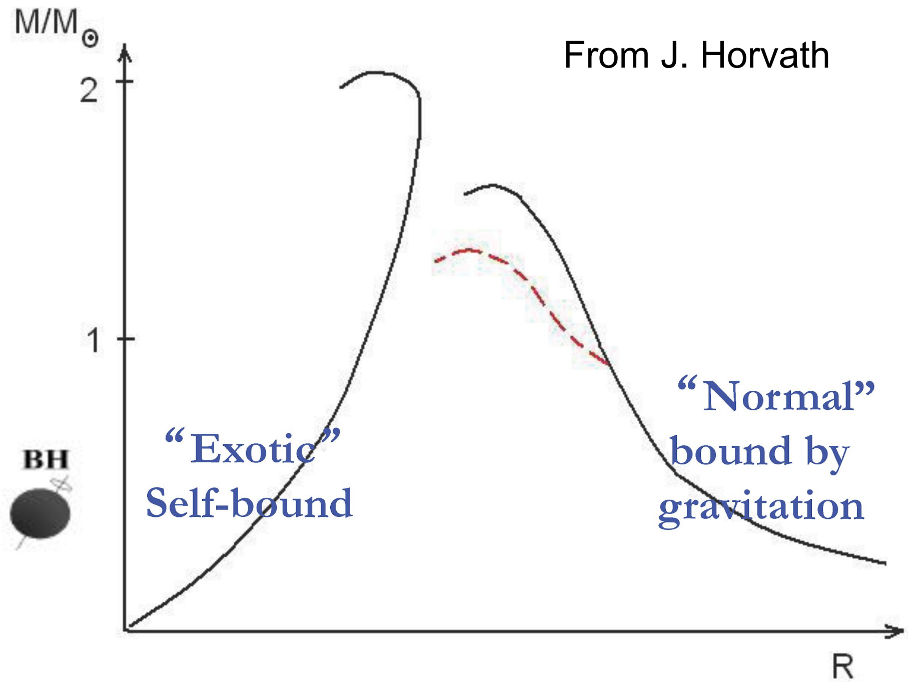


▸ NS (npeμ) structure



- NS/QS two-branch picture?

No hyperon puzzle for QS.



- **Observations maybe way out** (FAST, SKA; eXTP, NICER, Athena; LIGO/VIRGO)

#Neutron star equation of state from the quark level in the light of GW170817
Zhu, Zhou & **AL**, **1802.05510, ApJ**

#Constraints on interquark interaction parameters with GW170817 in a binary strange star scenario
Zhou, Zhou & **AL**, **1711.04312**, **PRD**

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

- New NS EOS “QMF18” proposed;
- **NO** L-vs-Λ correlation found, despite good L-vs-R correlation.

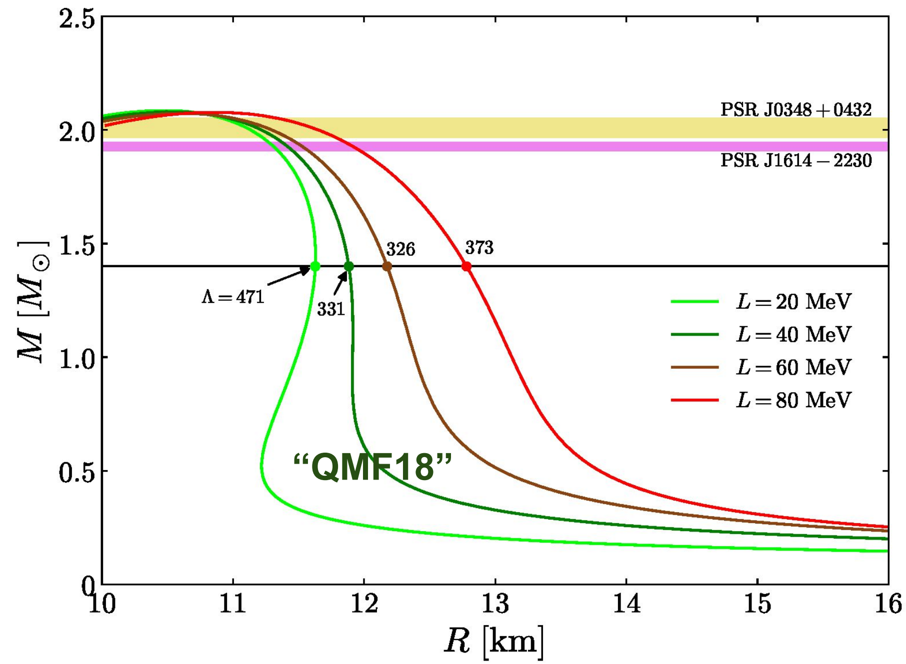
- Tidal deformability Λ:

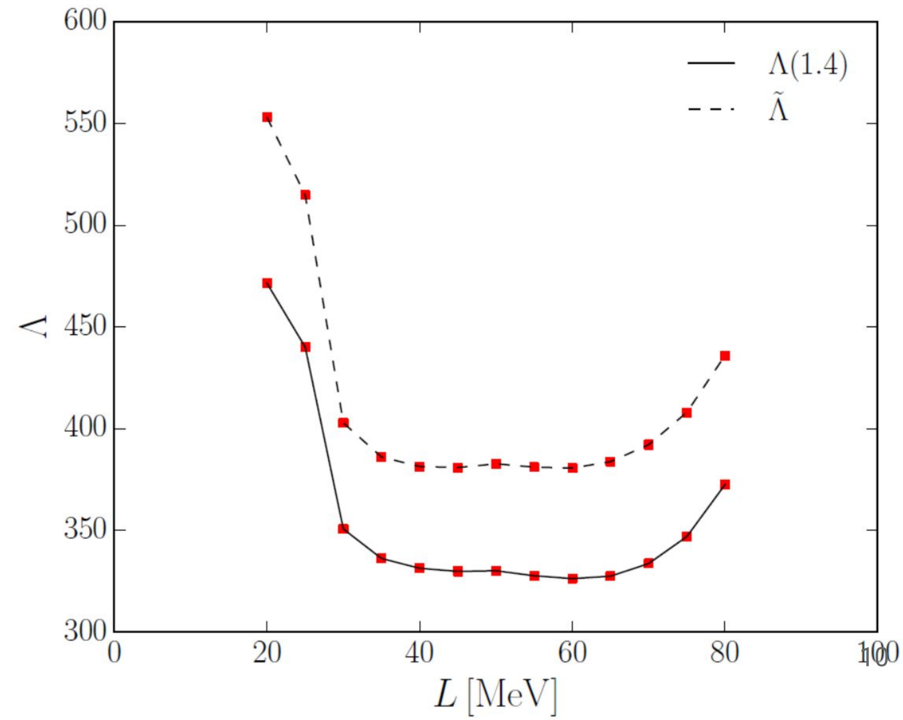
describes the amount of induced mass quadrupole moment when reacting to a certain external tidal field.

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

- **NOT** monotonic dependence of Λ.

- Λ measurements do NOT necessarily translate into info. on R.





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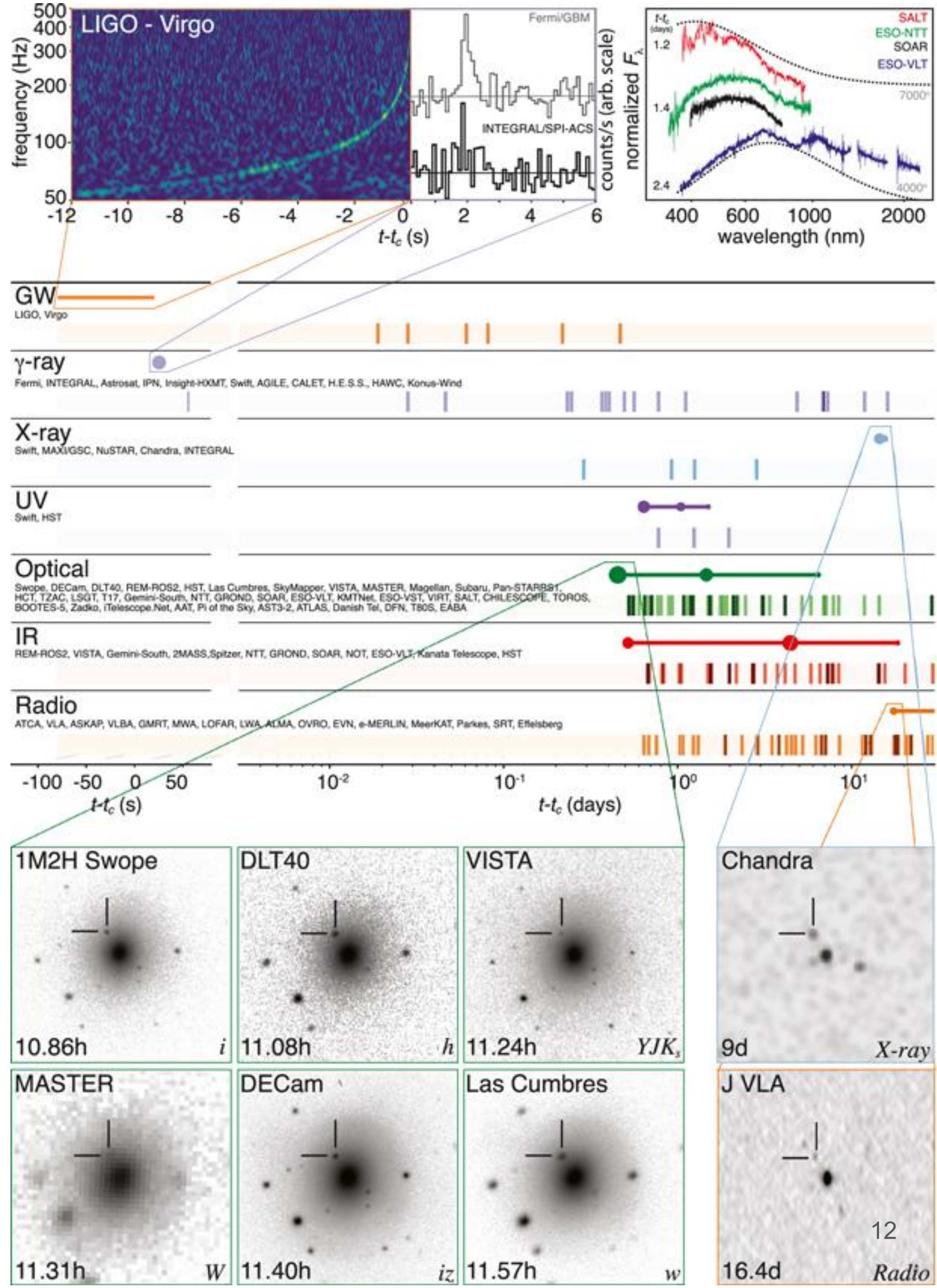
- GW
- Neutrino: none
- γ-ray: 1.7 s
- X-ray: 9 days
- UV/Optical/IR: 2 days
- Radio:16 days



Uncertain:

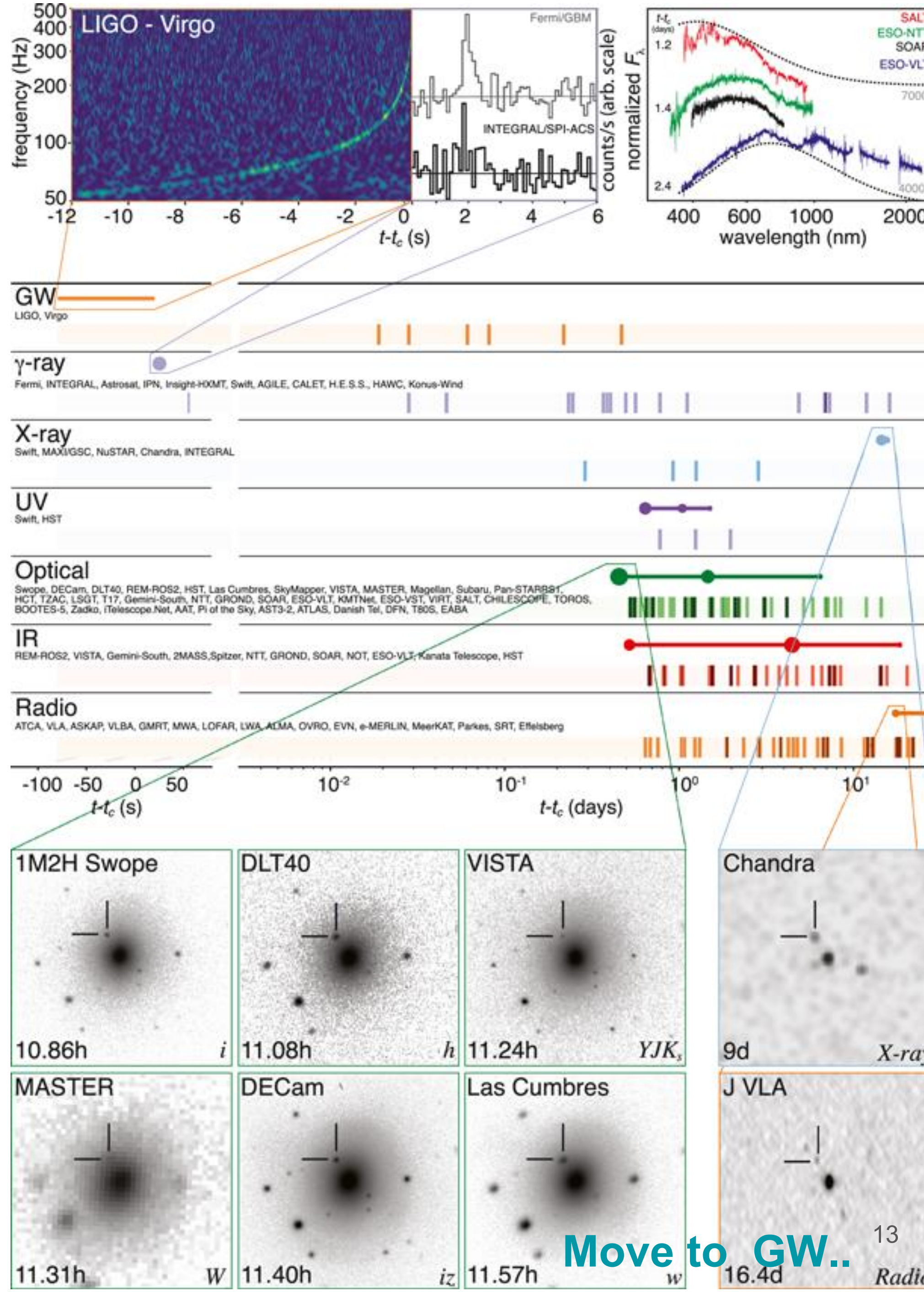
- EOS
- Ejecta mass
- Mass ratio
- Jet structure
- ...

Long-lived NS as remnant?

1. **Spin period**
2. **Magnetic field**
3. **Ellipticity**
4. **...**

Ai, Gao, Dai, Wu, ***AL*** & Zhang, **1802.00571, ApJ**

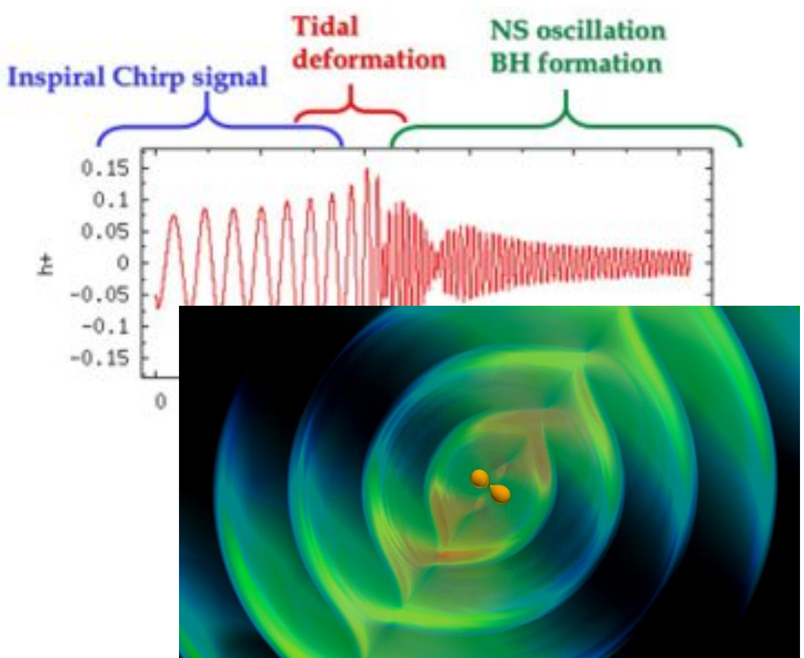
#The allowed parameter space of a long-lived neutron star as the merger remnant of GW170817

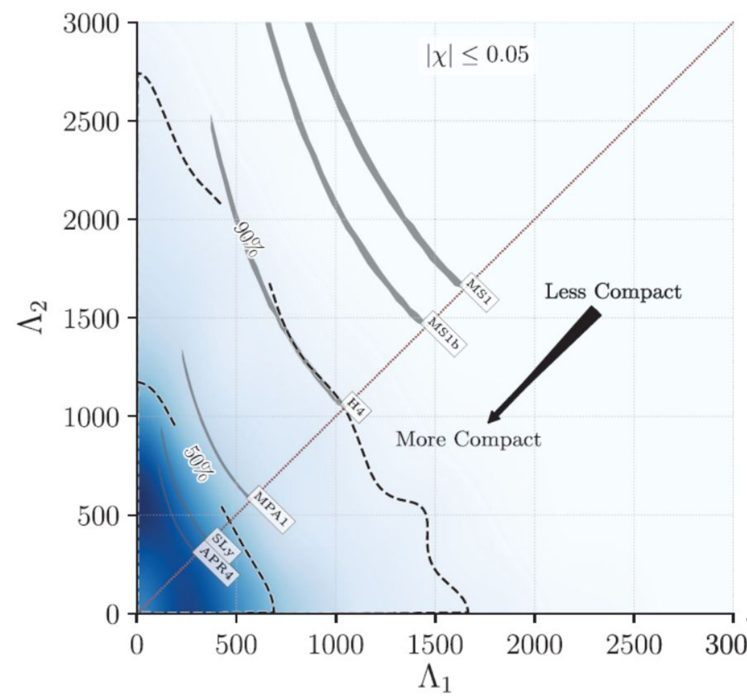


Move to GW..

TABLE I. Source properties for GW170817: we give ranges encompassing the 90% credible intervals for different assumptions of the waveform model to bound systematic uncertainty. The mass values are quoted in the frame of the source, accounting for uncertainty in the source redshift.

	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4M_\odot)$	≤ 800	≤ 1400





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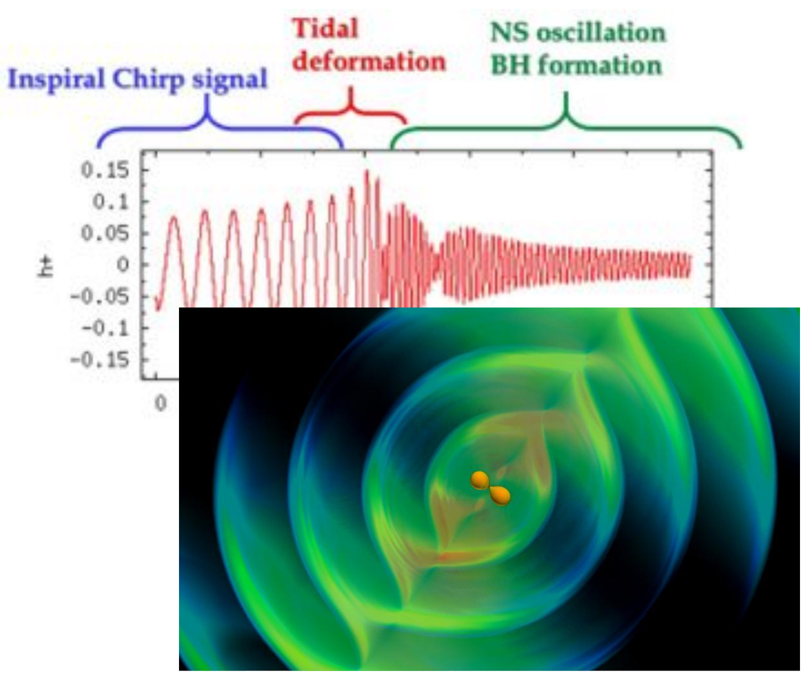
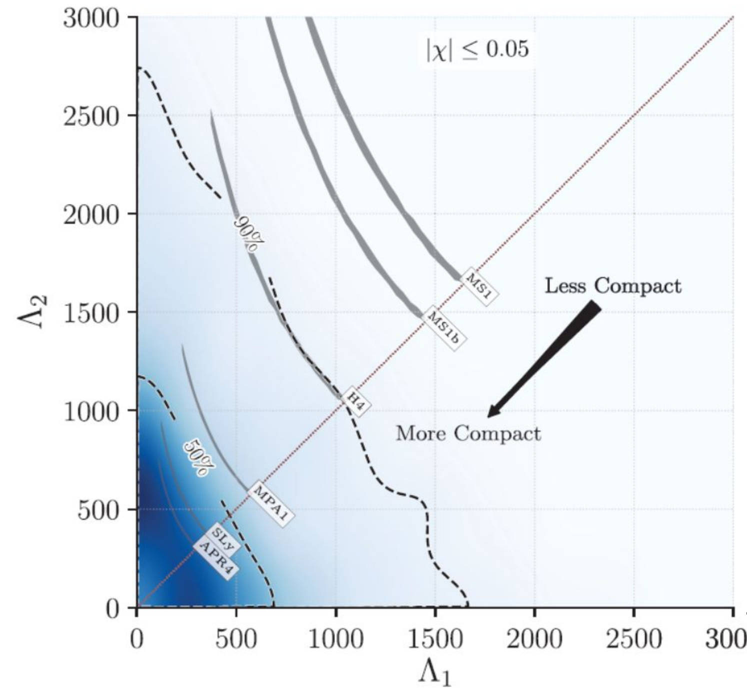
More reasonable considering magnetic braking during the binary evolution



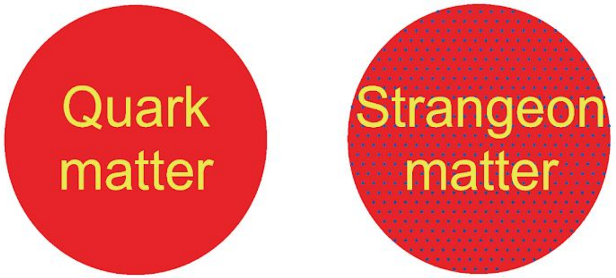


- QS from Bodmer-Witten's conjecture

Self-bound by strong interaction:

- Finite surface density;
- Fast increase of grav. mass with spin frequency (40% vs. 20%)

….



Quark star: quarks de-confined

Strangeon star: quarks localized

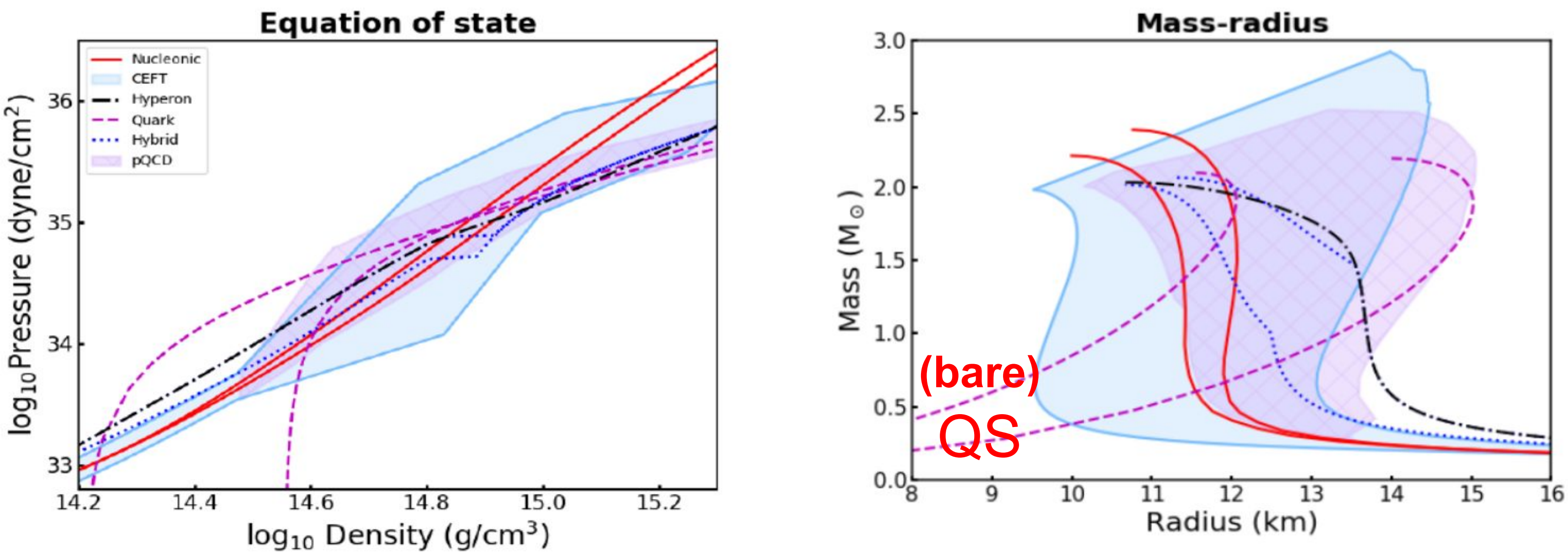


Figure 3 The pressure–density relation (EOS, left) and the corresponding M-R relation (right) for some example models with different microphysics. Nucleonic (neutrons, protons): models AP3 and AP4 from Akmal & Pandharipande (1997), also used in Lattimer & Prakash (2001). Quark (u, d, s quarks): models from Li et al. (2016) and Bhattacharyya et al. (2016). Hybrid (inner core of uds quarks, outer core of nucleonic matter): models from Zdunik & Haensel (2013). Hyperon (inner core of hyperons, outer core of nucleonic matter): Model from Bednarek et al. (2012). CEFT: range of nucleonic EOS based on Chiral Effective Field Theory (CEFT) from Hebeler et al. (2013). pQCD: range of nucleonic EOS from Kurkela et al. (2014) that interpolate from CEFT at low densities and match to perturbative QCD (pQCD) calculations at higher densities than shown in this figure. All of the EOS shown are compatible with the existence of ~ 2 $M_\odot$ NSs.

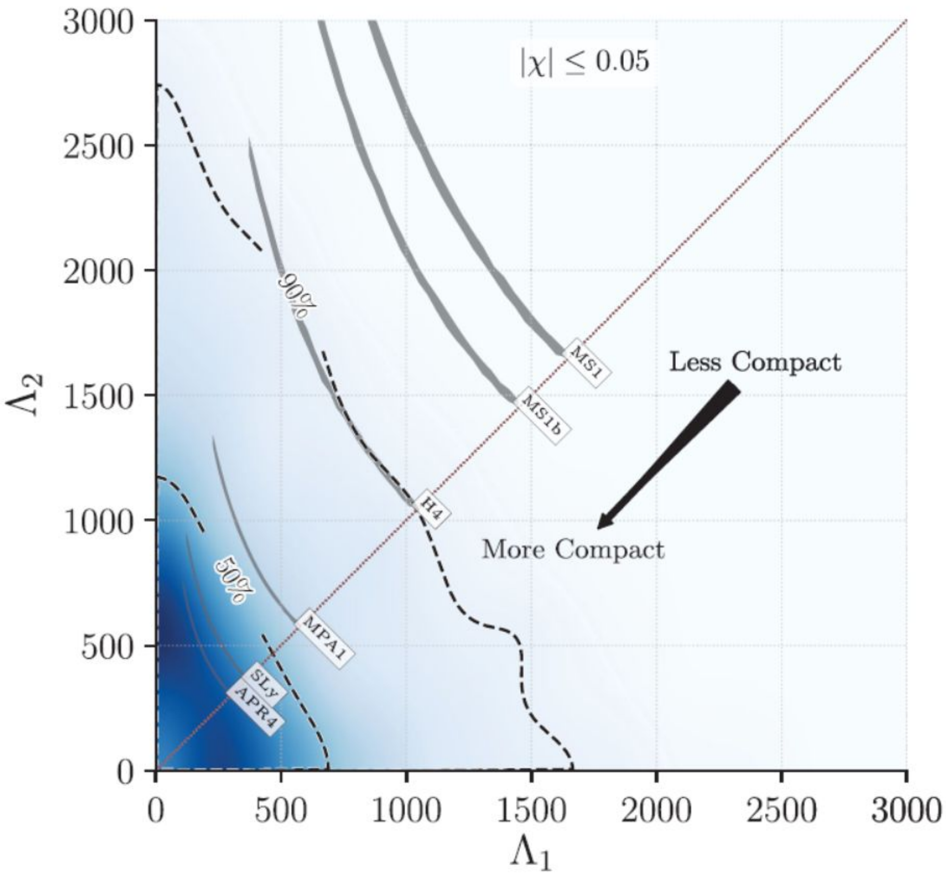
Dense matter with eXTP (White paper), Sci. China in press

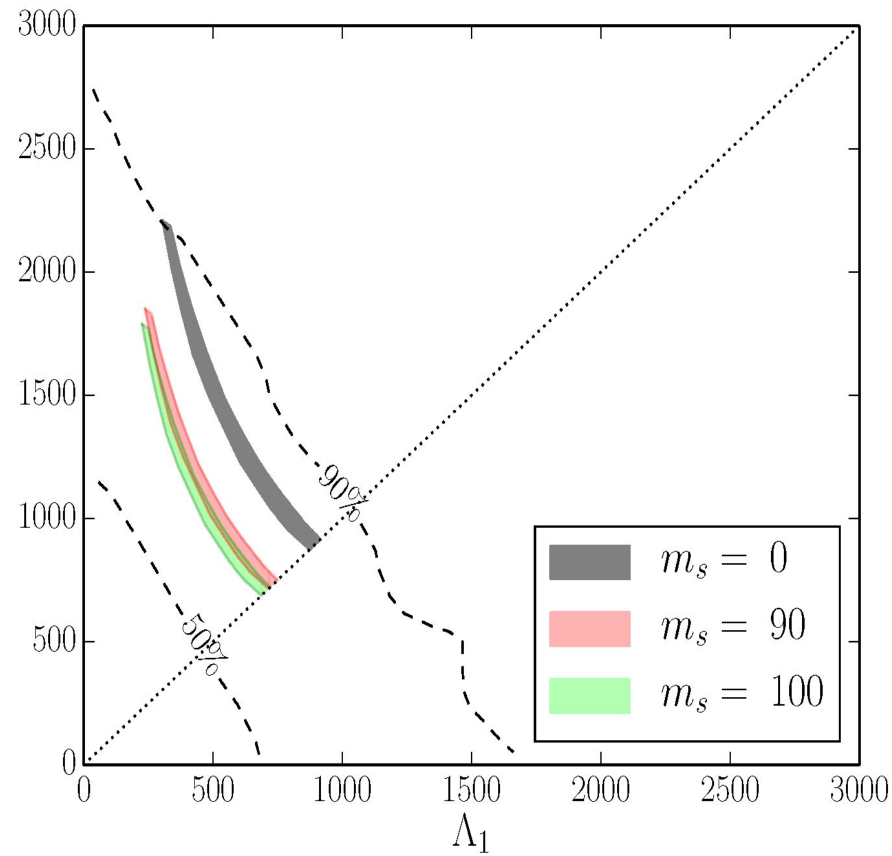
- MITα_s^2 bag model
  - interaction parameterized in ($B_{\rm eff}$, a_4)
  - superfluid parametrized in Δ

$$\Omega_{\rm free} = \sum_i \Omega_i^0 + \frac{3}{4\pi^2}(1-a_4)\left(\frac{\mu_b}{3}\right)^4 + B_{\rm eff}$$

$$\Omega_{\rm CFL} = \Omega_{\rm free} - \frac{3}{\pi^2}\Delta^2\mu_b^2$$

- Typical parameters ($B_{\rm eff}^{1/4}$, a_4)= (145, 0.61)
- **BQS merger justified**.



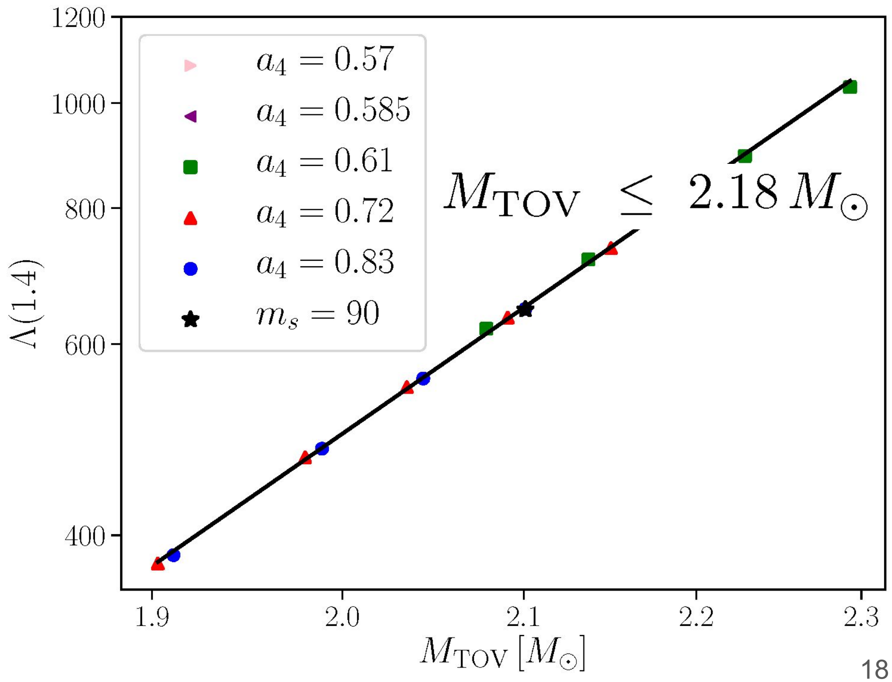


a_4	$B_{\rm eff}^{1/4}$ [MeV]	R [km]	M/R	k_2	Λ
0.61	133	12.046	0.17166	0.19973	893.4
0.61	136	11.662	0.17731	0.18865	717.7
0.61	138	11.415	0.18115	0.18133	619.7
0.72	138	11.453	0.18055	0.18262	634.5
0.83	138	11.482	0.18008	0.18367	646.6

- **Normal QS**

- Finite strange quark mass (m_s) soften EOS;
- Perturbative QCD correction (a_4) soften EOS;
- Effective bag constant ($B_{\rm eff}$) dominates the EOS stiffness;
- Strong $\Lambda(1.4)$-$M_{\rm TOV}$ correlation:

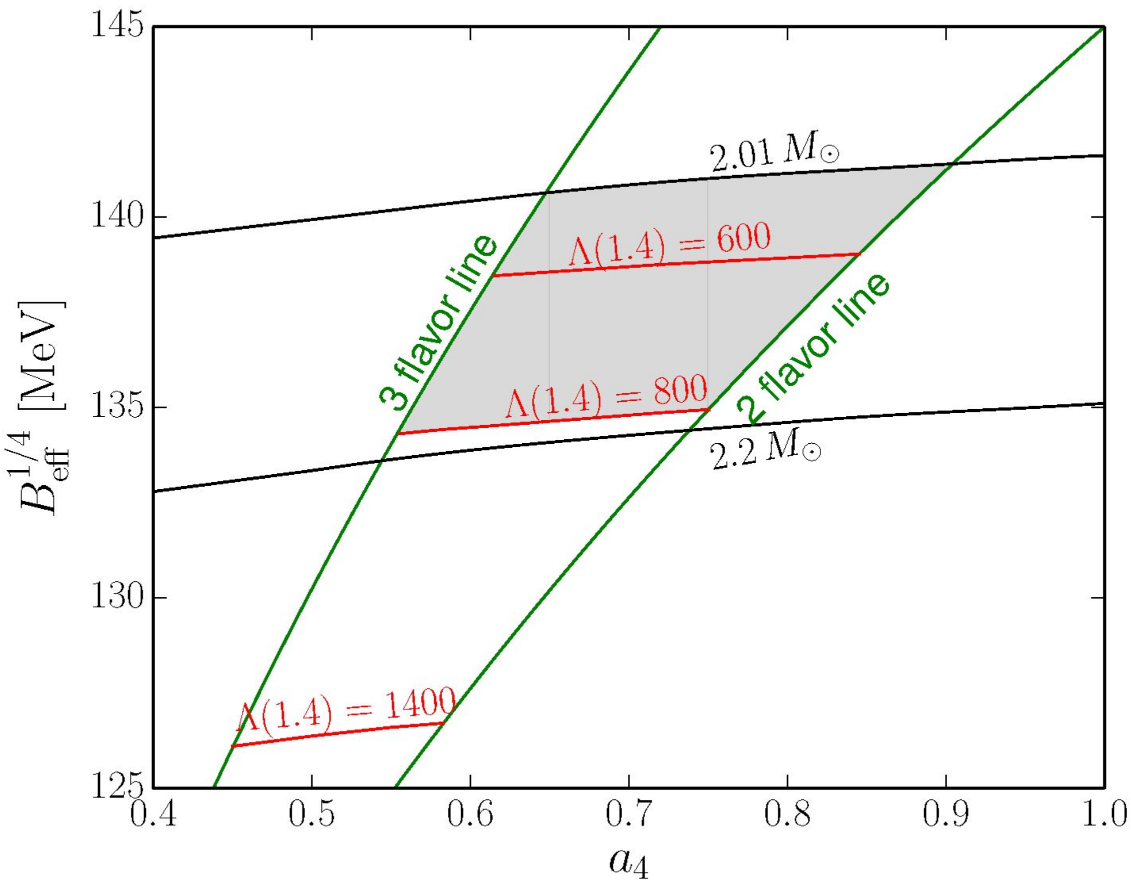
$$\Lambda(1.4) = 510.058 \times \left(\frac{M_{\rm TOV}}{2.01\, M_\odot}\right)^{5.457}$$



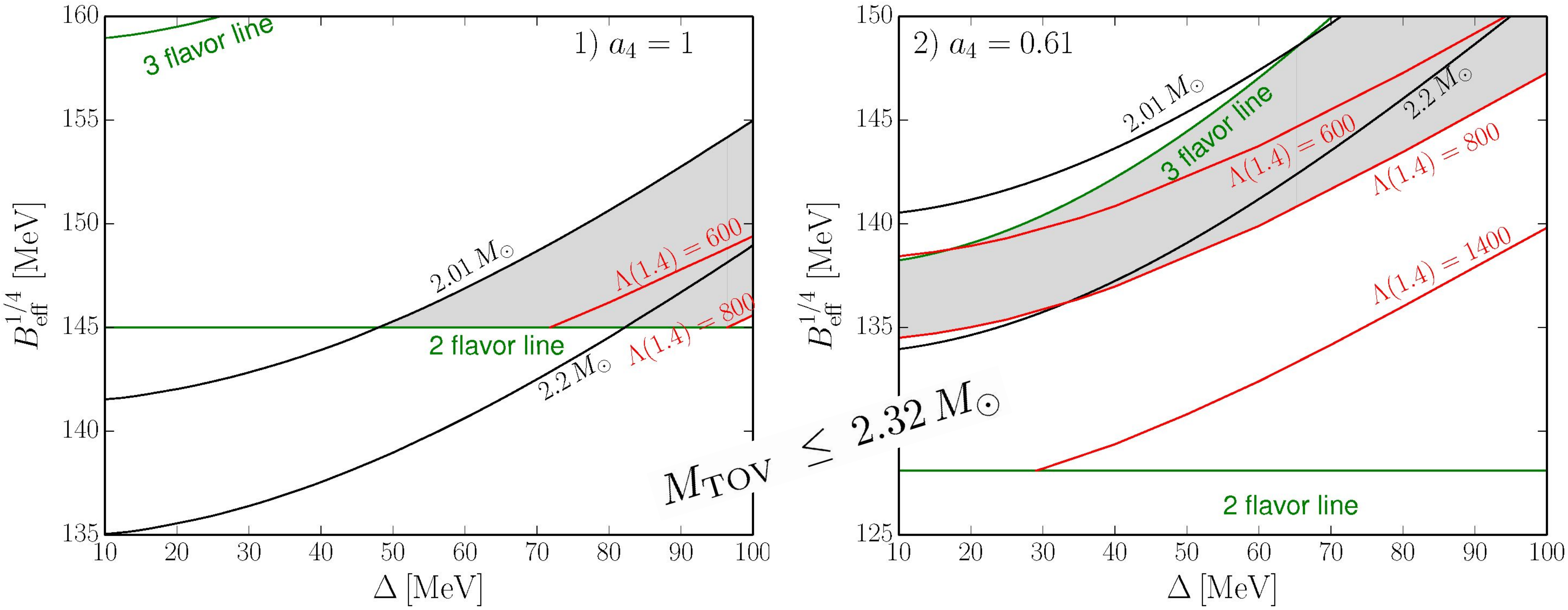
- NEW parameter ranges from GW170817: $B_{\rm eff}^{1/4} \in (134.1, 141.4)\,\mathrm{MeV}$
- Weak a_4 softening; $a_4 \in (0.56, 0.91)$
- QM stability window:
  - 2-flavor quark matter cannot be more stable than Fe nuclei;
  - 3-flavor quark matter is more stable than Fe nuclei.

Larger $B_{\rm eff}$ is required to bound the quark matter for larger a_4;

- **Possible future** observations of $\Lambda(1.4)$=600 & M_{TOV} =2.2$M_\odot$ can not reconcile in the model: **QS out?**



- **Superfluid QS**
- Gap parameter *Δ* very uncertain: (0,100/150 MeV);
- a_4=1: Two-solar mass constraint bounds the lower limit of at the order of 50 MeV;
- a_4=0.61: No new lower limit is found for both the low-spin prior and the high-spin prior.



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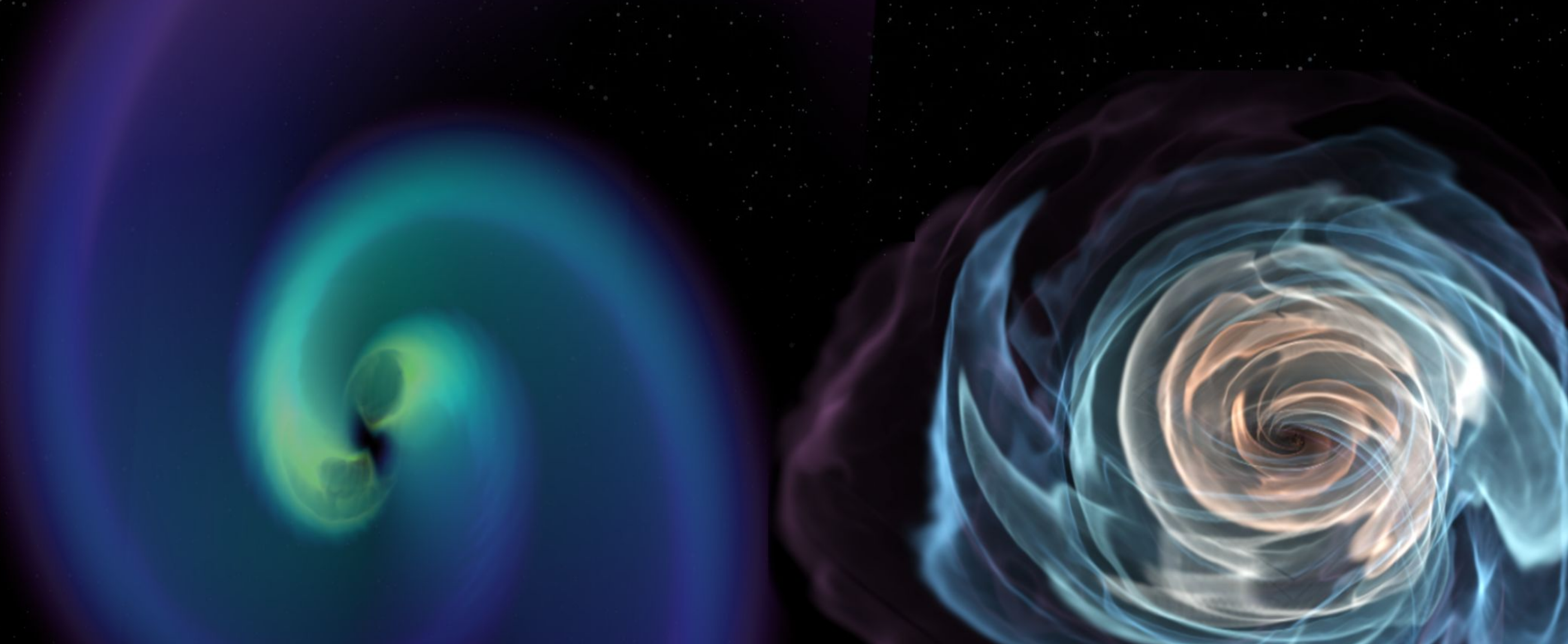

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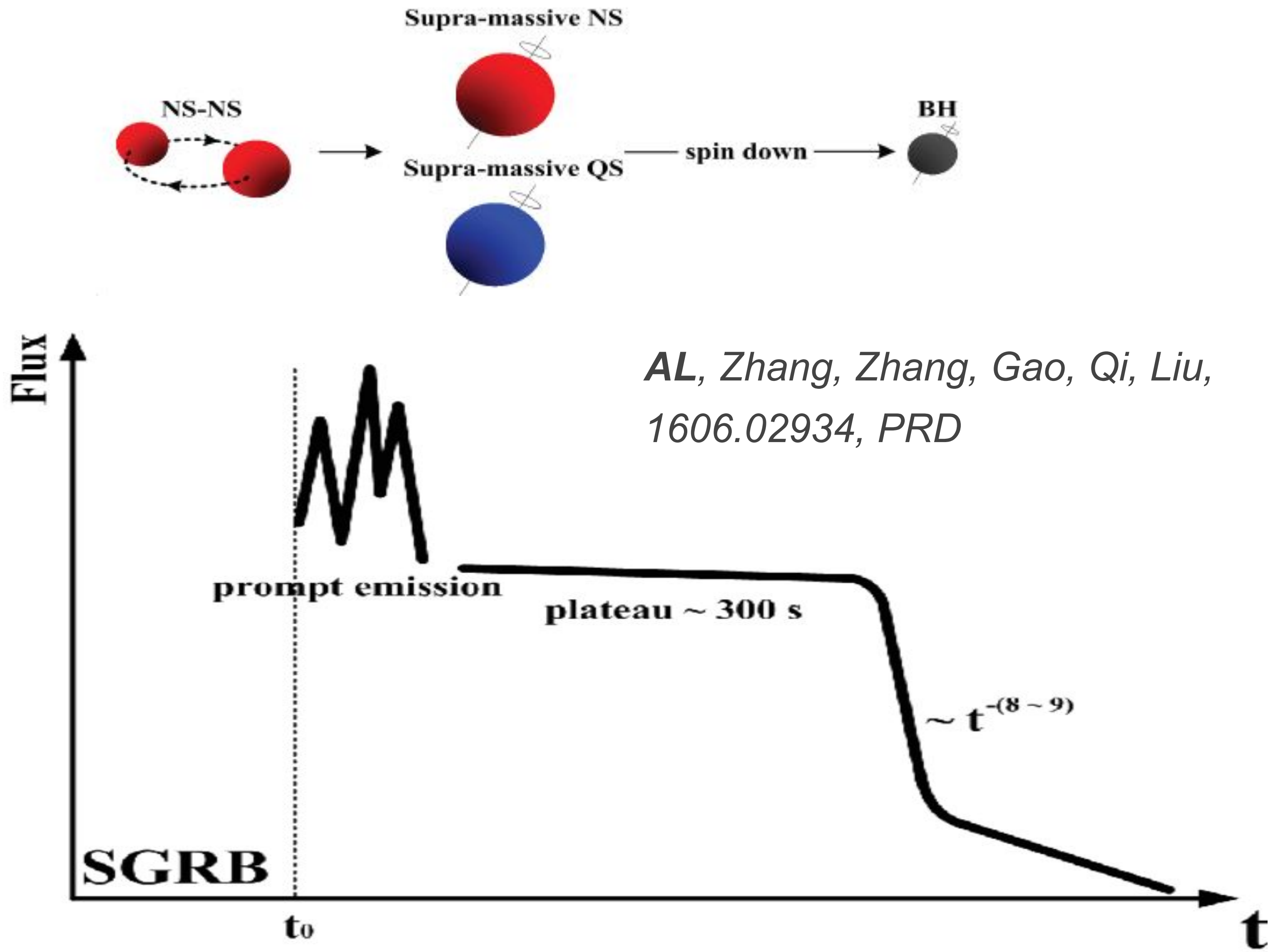
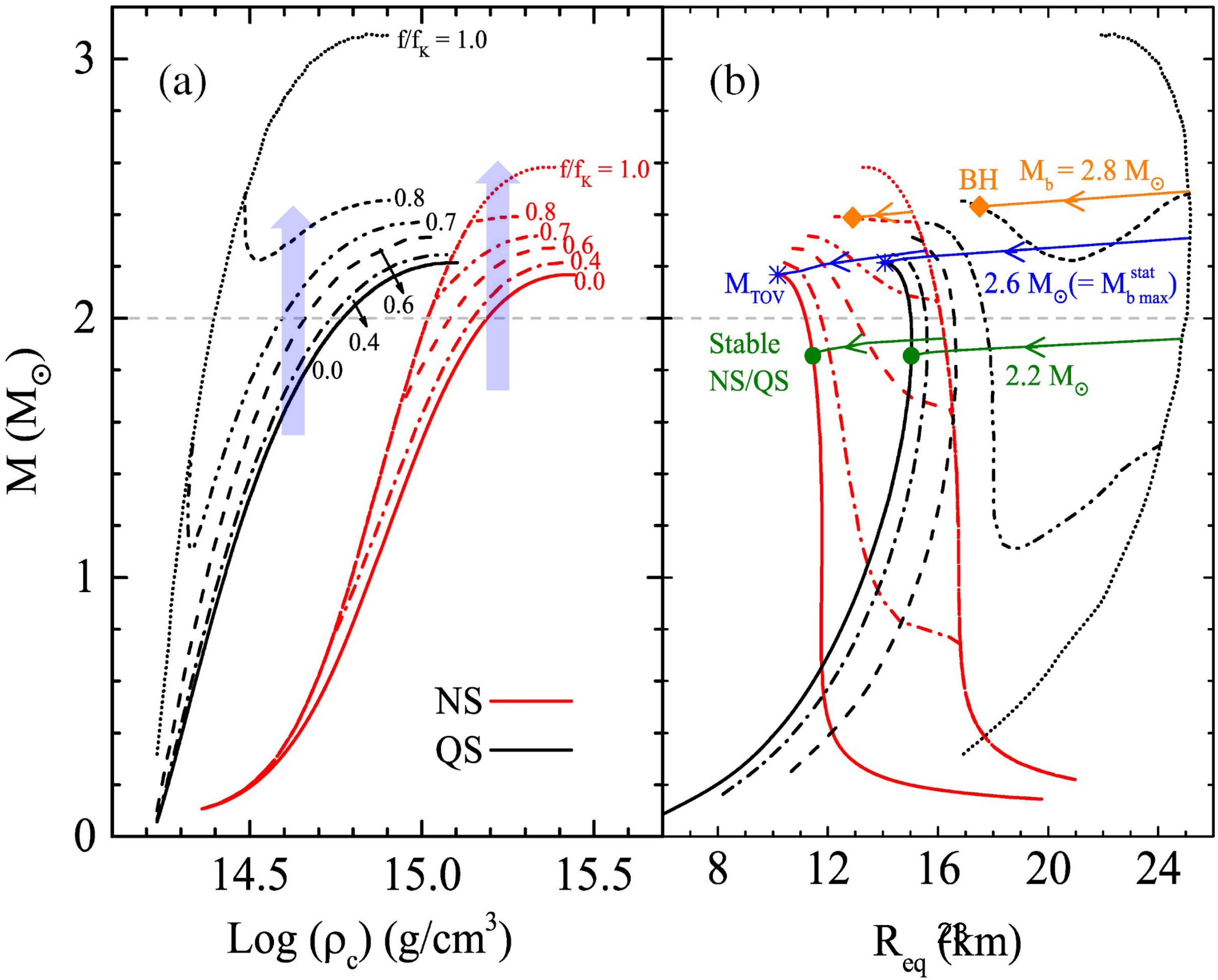
LIGO Georgia Tech Center for Relativistic Astrophysics College of Sciences NSF

- Spindown-induced collapse of a NS/QS to a BH



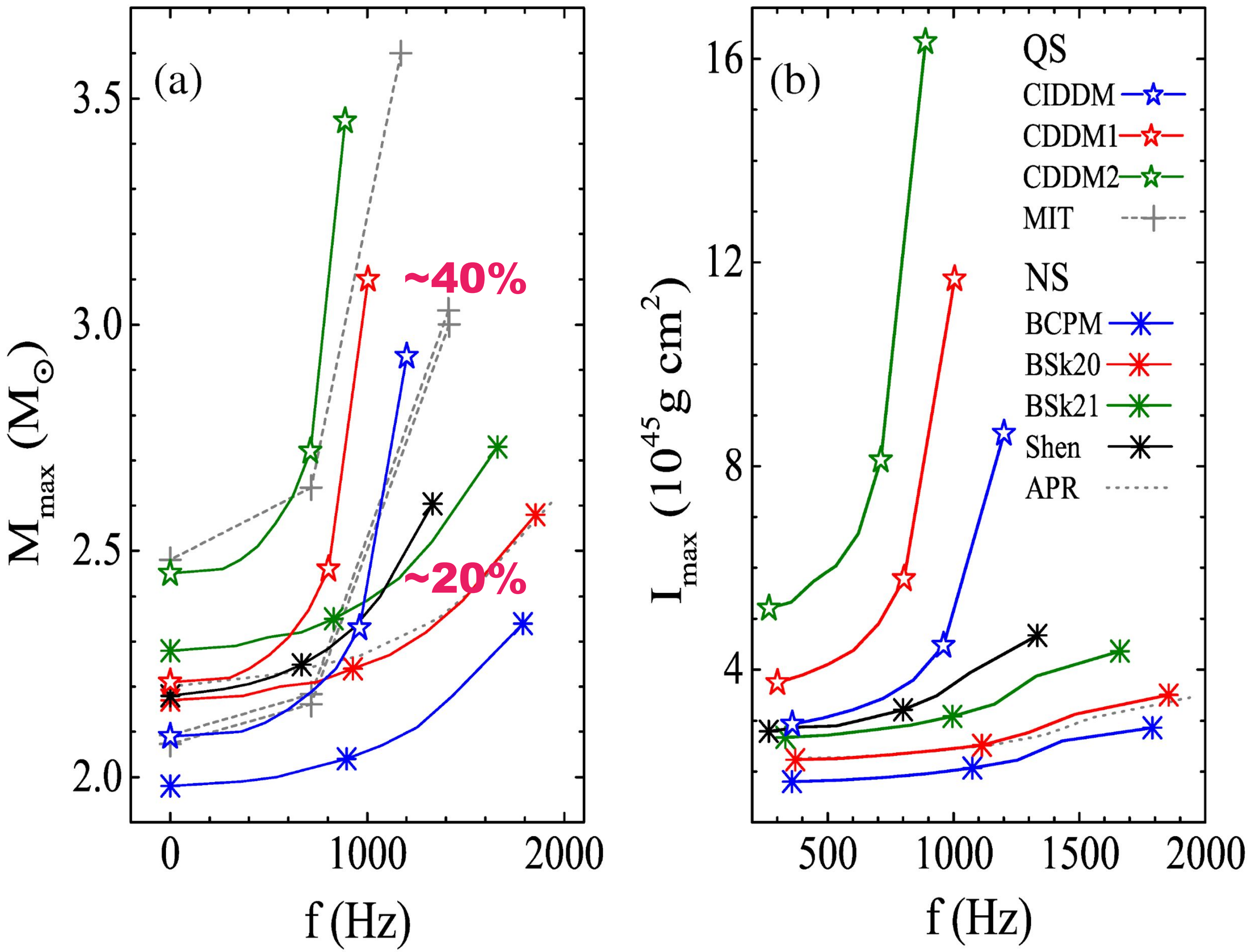
***AL**, Zhang, Zhang, Gao, Qi, Liu, 1606.02934, PRD*

▸ Supramassive NS/QS: Doomed to collapse

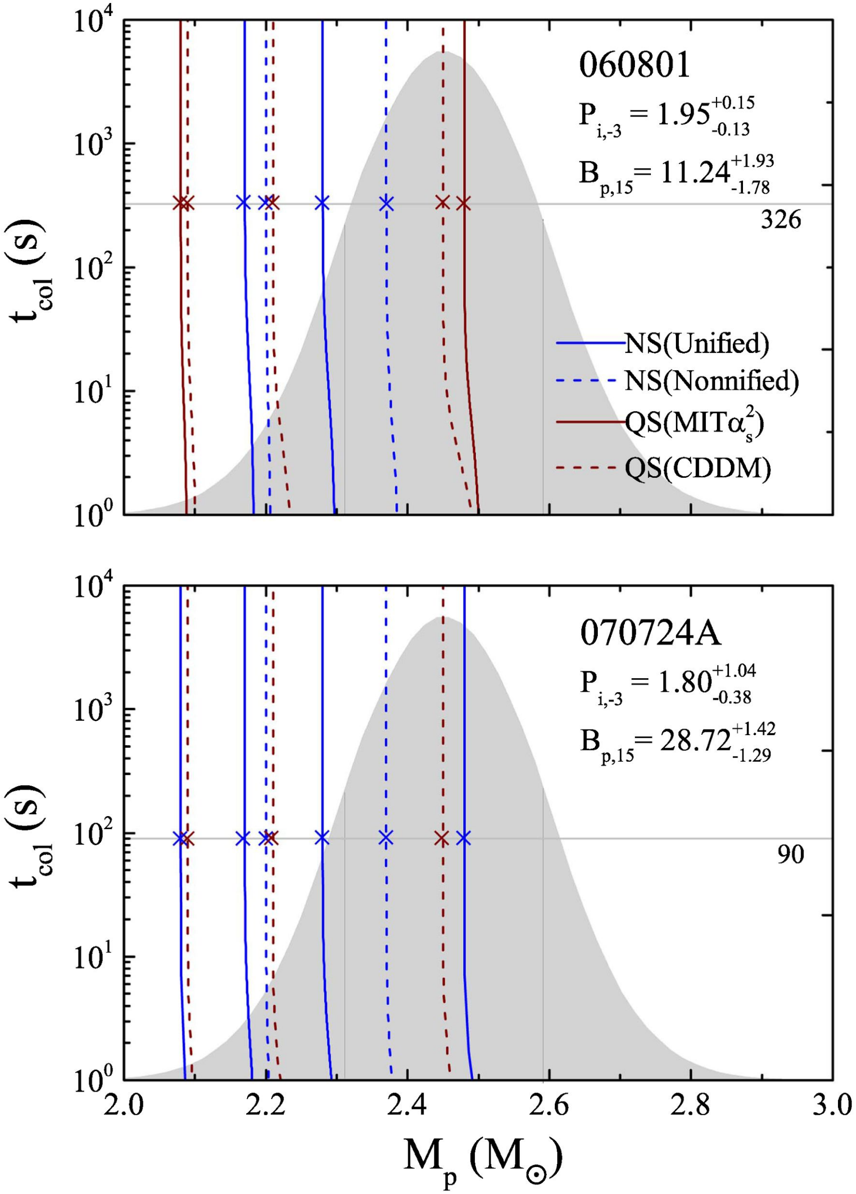


▸ Uniformly fast-rotating supramassive NS/QS

from ***rns*** code *(Komatsu, et. al. 1989, Cook et al. 1994, Stergiouslas, at al. 1995)*



- Collapse time
  - 4 NS EOS; 5 QS EOS: Largely determined by the **TOV** mass.



$$\frac{P(t)}{P_0} = \left[1 + \frac{4\pi^2 B_p^2 R^6}{3c^3 I P_i^2} t\right]^{1/2}, \quad (1)$$

$$M_{\rm max} = M_{\rm TOV}(1 + \alpha P^{\beta}). \quad (2)$$

Setting the protomagnetar mass $M_{\rm p} = M_{\rm max}$ in Equation (2), we have the collapse time $t_{\rm col}$ defined as a function of $M_{\rm p}$ for each $P = P_i$ in Equation (1):

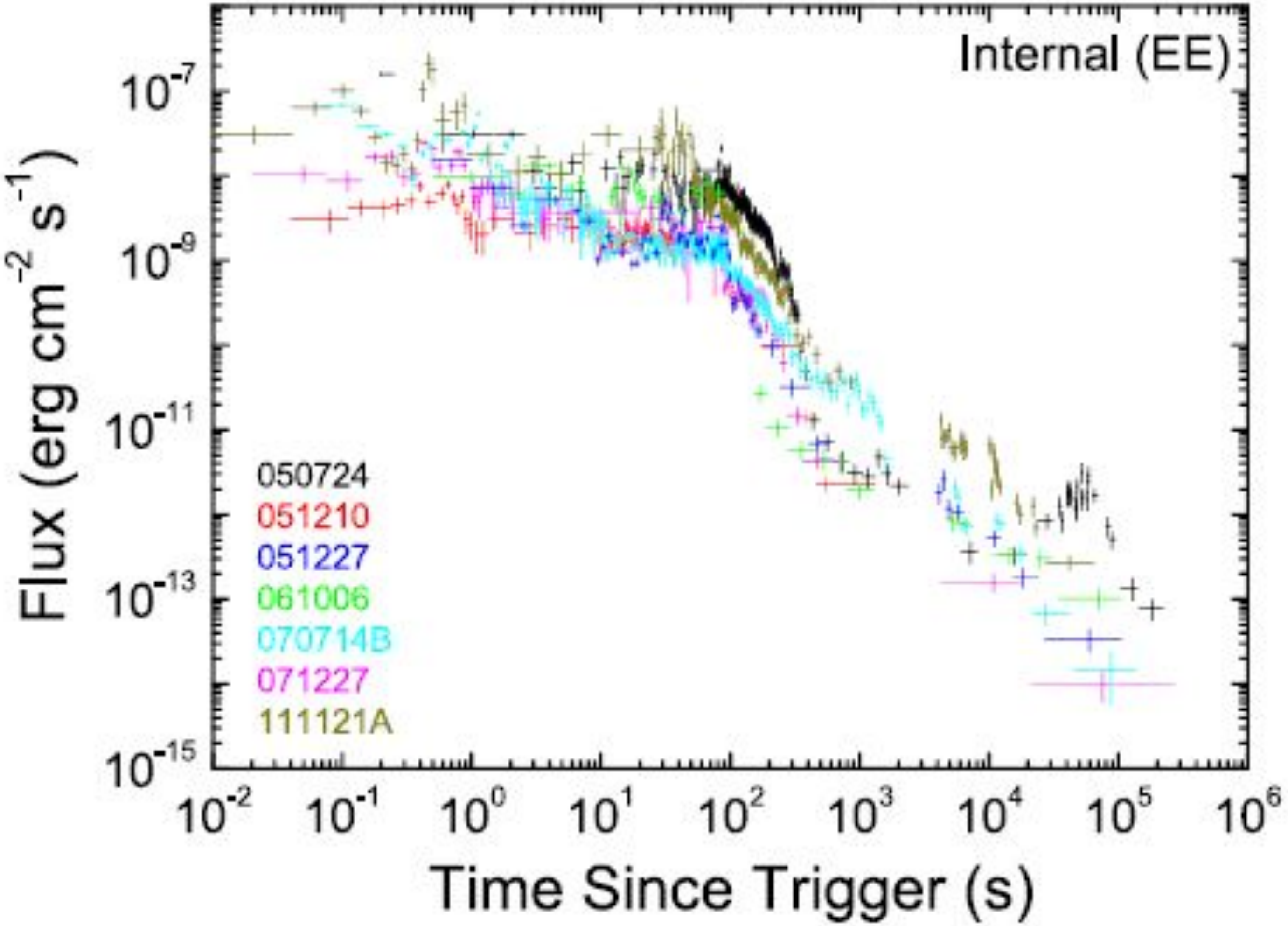
$$t_{\rm col} = \frac{3c^3 I}{4\pi^2 B_p^2 R^6}\left[\left(\frac{M_{\rm p} - M_{\rm TOV}}{\alpha M_{\rm TOV}}\right)^{2/\beta} - P_i^2\right], \quad (3)$$

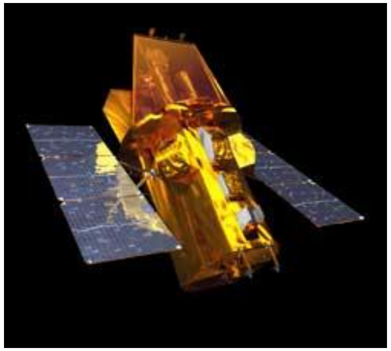
Grey region: posterior mass distribution from Galactic NS binary.

***AL**, Zhu & Zhou, 1706.04720 ApJ*

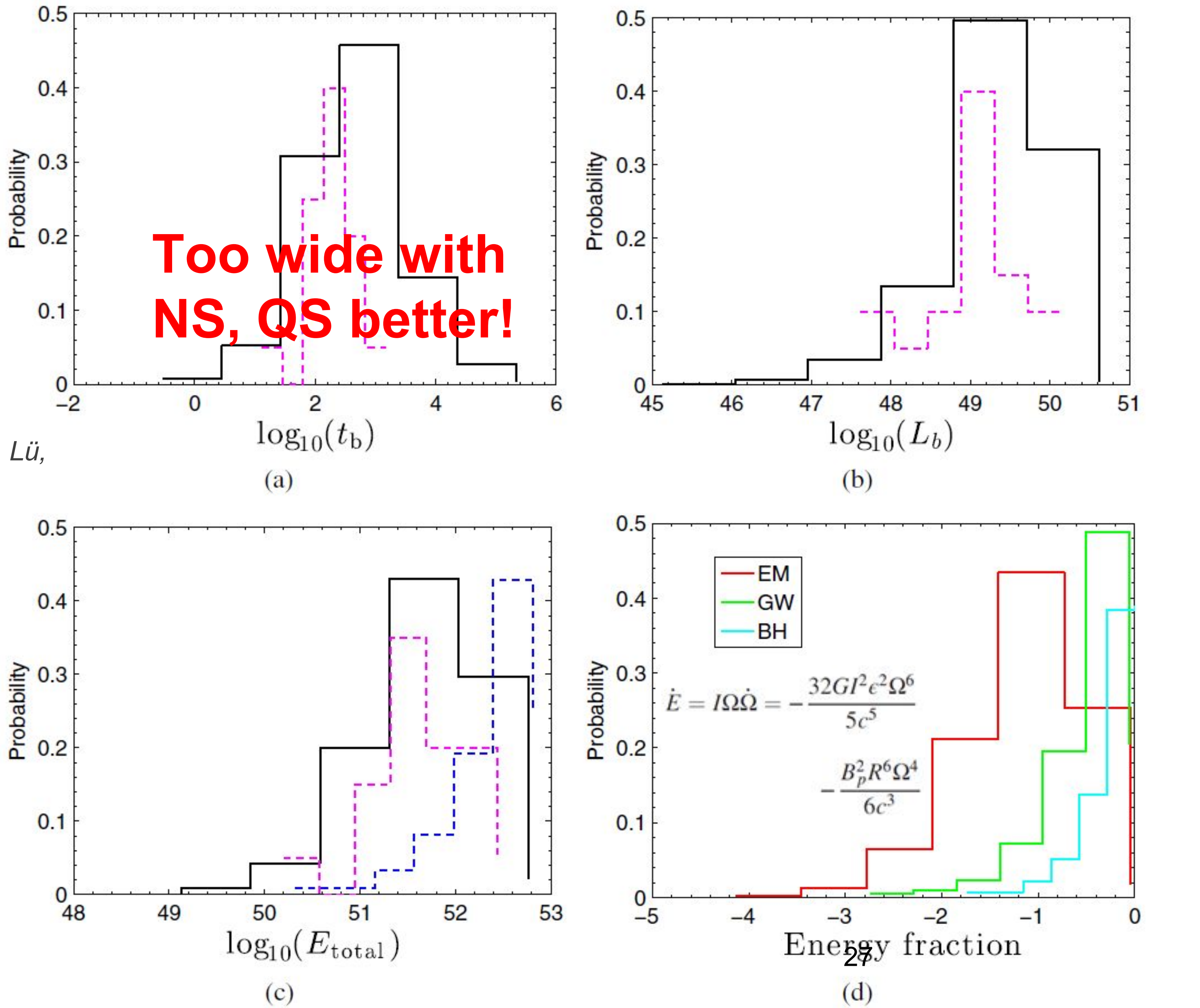
- 21 SGRB plateau sample with SWIFT (2005/01-2015/10)

(Rowlinson et al. 2010, 2013, MNRAS)





Lasky,et al. 2014, PRD



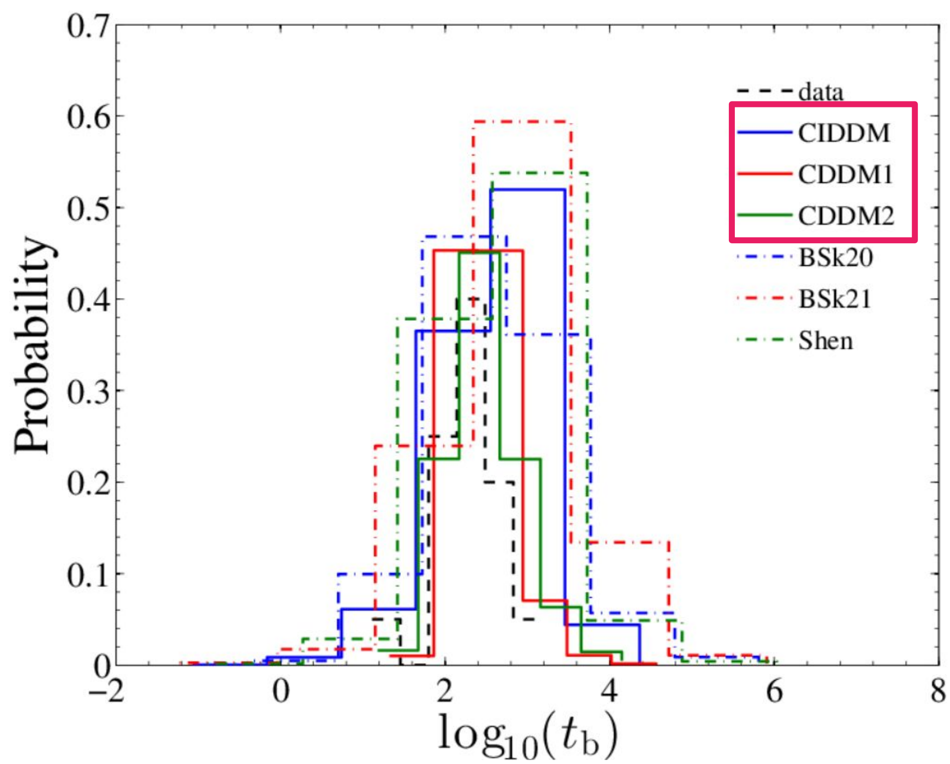
Gao, Zhang, Lü, 2016 PRD

▸ MC simulation

- ❑ Reproducing simultaneously all three observed distributions (Break time t_b, Break time luminosity L_b, Total electromagnetic energy E_{total});

  Eg., time simulation

- ❑ Including both EM and GW;
- ❑ Constraining parameter ranges of stars (Ellipticity ε, Initial spin P_i, Surface dipole magnetic field B_p);
- ❑ NS vs. QS



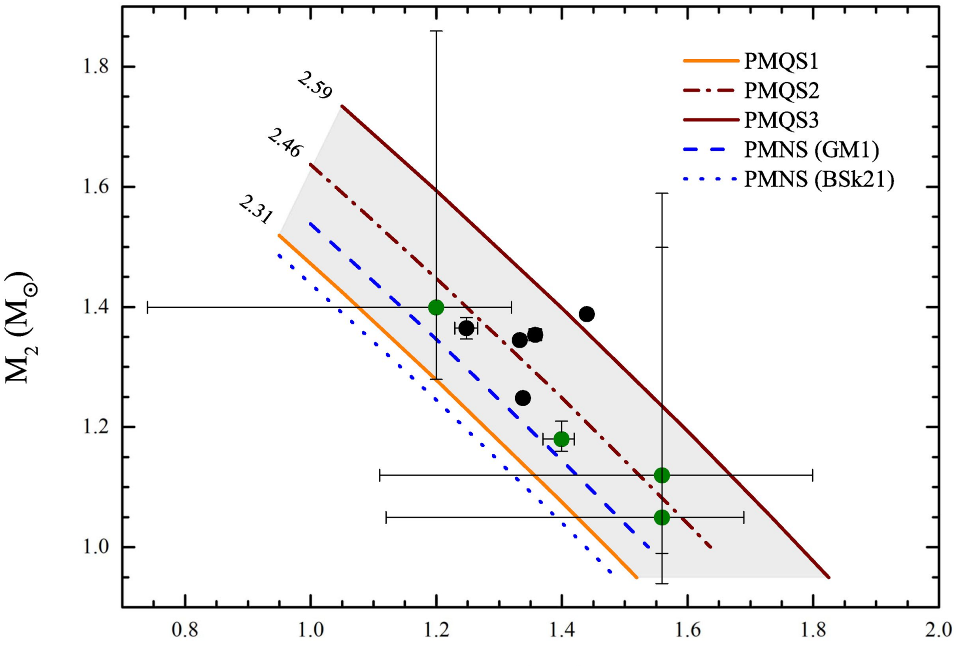
EoS	ε	P_i (ms)	$B_p(G)$	η	$P_{best}(t_b)$
BSk20	0.002	0.70–0.75 (0.75)	$N(\mu_{Bp}=10^{14.8-15.4}, \sigma_{Bp}\le 0.2)[N(\mu_{Bp}=10^{14.9}, \sigma_{Bp}=0.2)]$	0.5–1 (0.9)	0.20
BSk21	0.002	0.60–0.80 (0.70)	$N(\mu_{Bp}=10^{14.7-15.1}, \sigma_{Bp}\le 0.2)[N(\mu_{Bp}=10^{15.0}, \sigma_{Bp}=0.2)]$	0.7–1 (0.9)	0.29
Shen	0.002–0.003 (0.002)	0.70–0.90 (0.70)	$N(\mu_{Bp}=10^{14.6-15.0}, \sigma_{Bp}\le 0.2)[N(\mu_{Bp}=10^{14.6}, \sigma_{Bp}=0.2)]$	0.5–1 (0.9)	0.41
CIDDM	0.001	0.95–1.05 (0.95)	$N(\mu_{Bp}=10^{14.8-15.4}, \sigma_{Bp}\le 0.2)[N(\mu_{Bp}=10^{15.0}, \sigma_{Bp}=0.2)]$	0.5–1 (0.5)	0.44
CDDM1	0.002–0.003 (0.003)	1.00–1.40 (1.0)	$N(\mu_{Bp}=10^{14.7-15.1}, \sigma_{Bp}\le 0.3)[N(\mu_{Bp}=10^{14.7}, \sigma_{Bp}=0.2)]$	0.5–1 (1)	0.65
CDDM2	0.004–0.007 (0.005)	1.10–1.70 (1.3)	$N(\mu_{Bp}=10^{14.8-15.3}, \sigma_{Bp}\le 0.4)[N(\mu_{Bp}=10^{14.9}, \sigma_{Bp}=0.4)]$	0.5–1 (1)	0.84

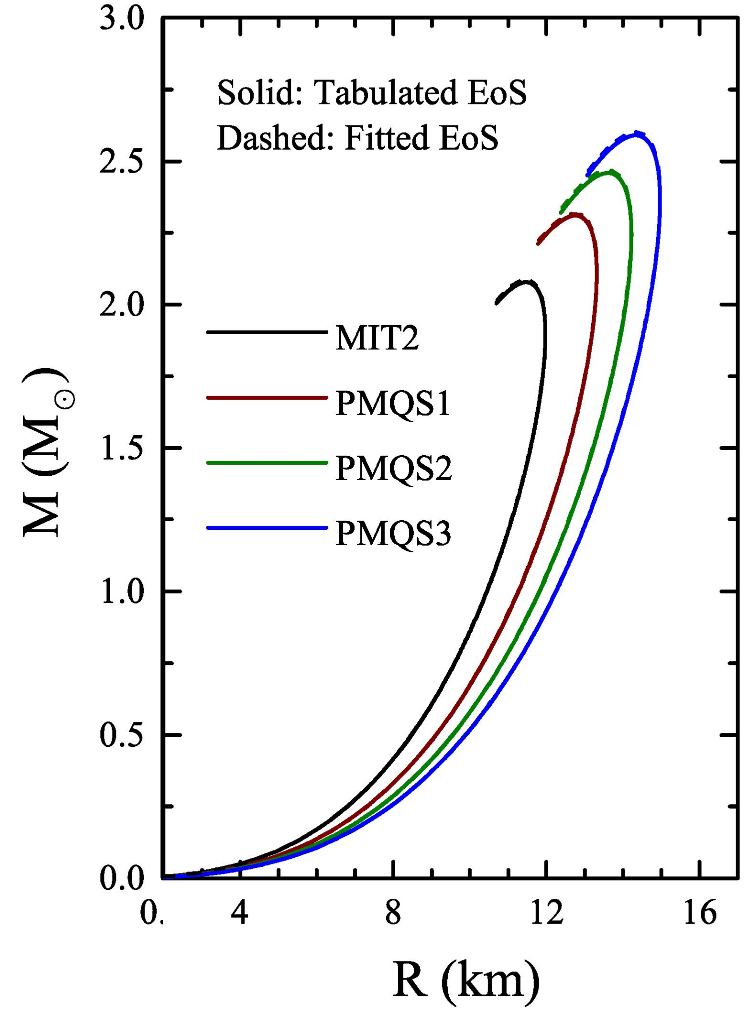
Millisecond

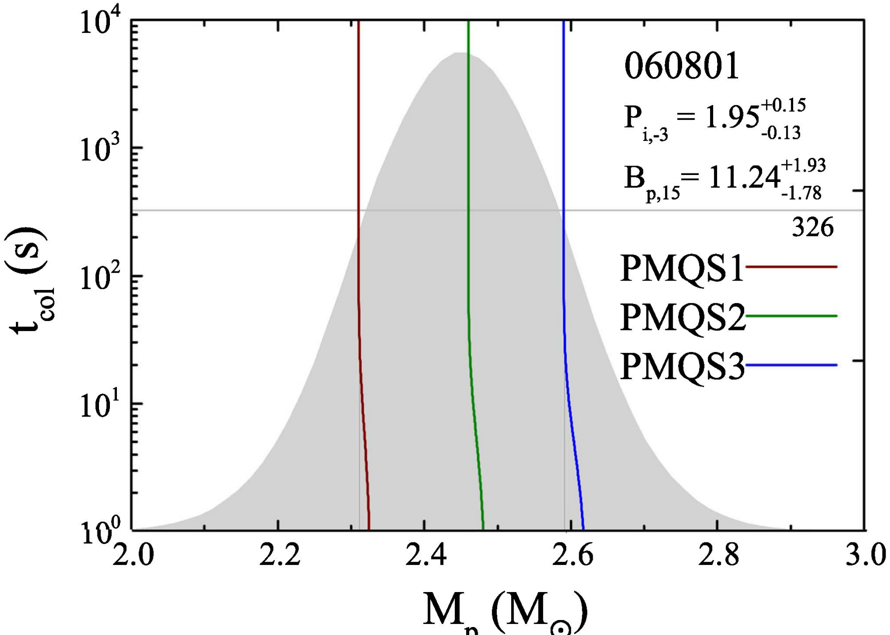
Strongly-magnetized

Efficiency related to the conversion of the dipole spin-down luminosity to the observed X-ray luminosity.

▸ New postmerger supramassive QS EOSs **proposed** and fitted: *"PMQS1-3"*







The shaded region is the $M = 2.46^{+0.13}_{-0.15}\, M_\odot$ mass distribution derived from the binary NS mass distribution $M = 1.32^{+0.11}_{-0.11}\, M_\odot$ (Kiziltan et al. 2013).

First Cosmic Event Observed in Gravitational Waves and Light

In this talk

- QS merger scenario for GW demonstrated;
- BNS → massive QS for some SGRB;
- EOS constraints with GW170817;
- QS $M_{TOV} \leq 2.18$ (2.32 with pairing).

Thank you.

- $\Lambda_{1.4} \lesssim 800$ for low-spin spior

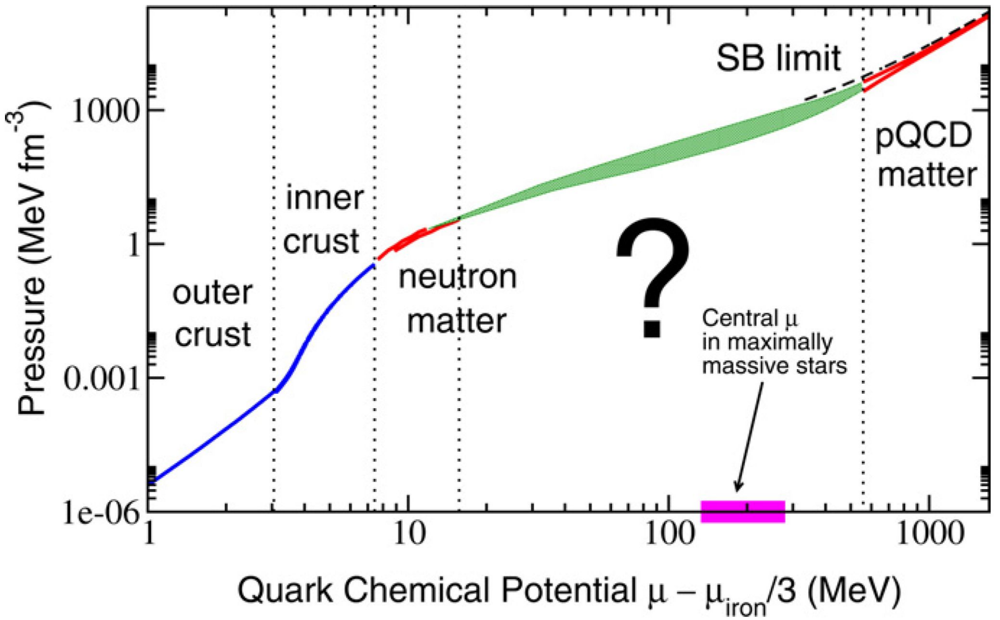
- CET(<1.1n_0)+pQCD($\gtrsim$2.6GeV)
- ±24% uncertainty@1.1n_0

Soft/hard hadronic component (0.6-1.1n_0; Hebeler et al. 2013):

$\Lambda_{1.4}$=(120/161, 1353/1504)

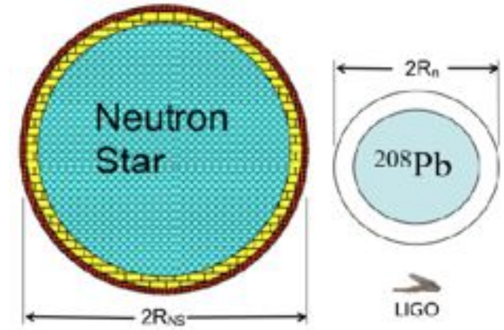
- $M_{TOV} \gtrsim$ 2.0: $R_{1.4}$ > 9.9 km
- $\Lambda_{1.4} \lesssim$ 800: $R_{1.4}$ <13.6 km

Annala et al., **1711.02644, PRL**



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

- $\Lambda_{1.4} \lesssim 800$ for low-spin spior



- 10 representative EOSs of RMF models;

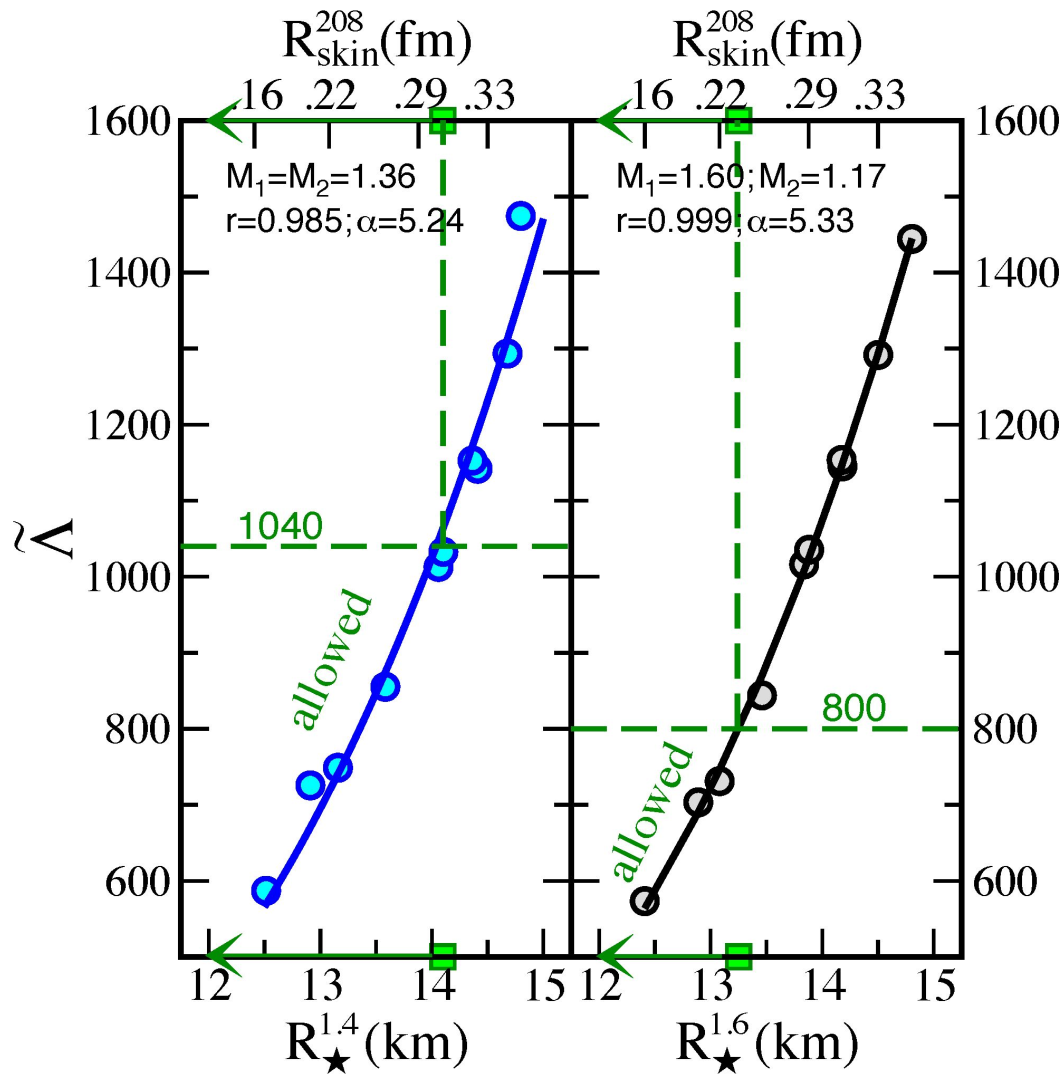
- $\Lambda_{1.4} \lesssim 800$: $R_{1.6} \leq 13.25\mathrm{km}$
  $R^{208}_{\mathrm{skin}} \leq 0.25\mathrm{fm}$

- PREX experiment:

(Abrahamyan, et al. 2012; Horowitz et al., 2012)

$$R^{208}_{\mathrm{skin}} = 0.33^{+0.16}_{-0.18}\mathrm{fm}$$

- Stiff low + Soft high: phase transition in NS interior?!



Fattoyev, et al., **1711.06615, PRL**

▸ Two-branch picture?

▸ Only with NS:

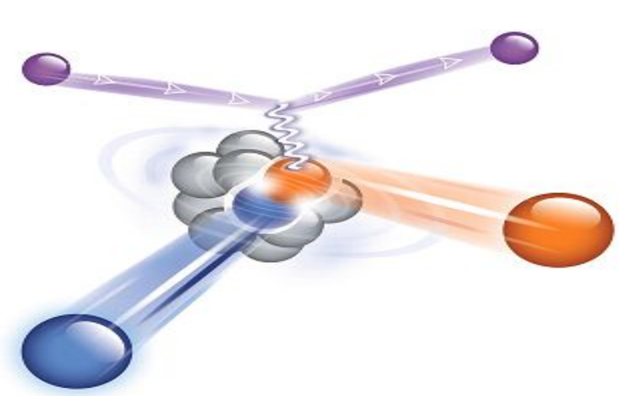
▸ Any strangeness phase transition leads to softer EOS (lower M_{TOV}) (Hyperon puzzle);

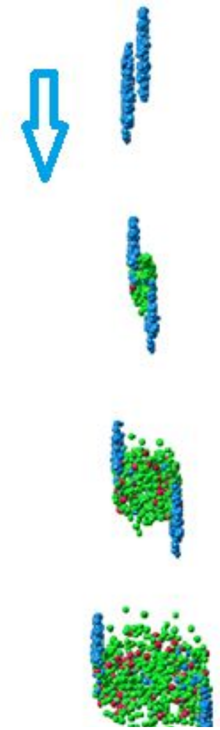
▸ Nucleonic EOS sufficiently stiff, or only weak soften (late appearance) of Delta(1232)/hyperon/Kaon/quark:

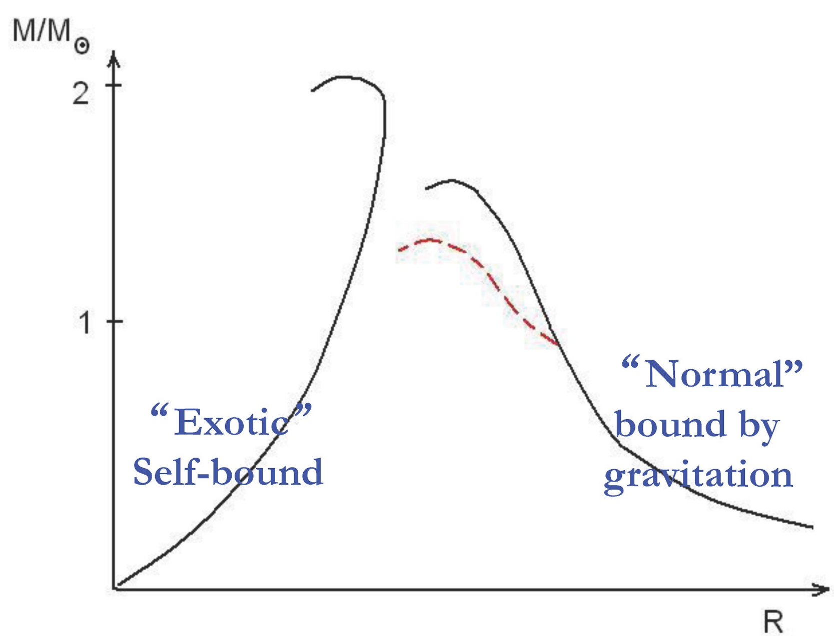
If late enough appearance for hyperons, then NO hyperons & hyperon puzzle?!

▸ Universal baryonic repulsive three-body force, or stiff quark core;

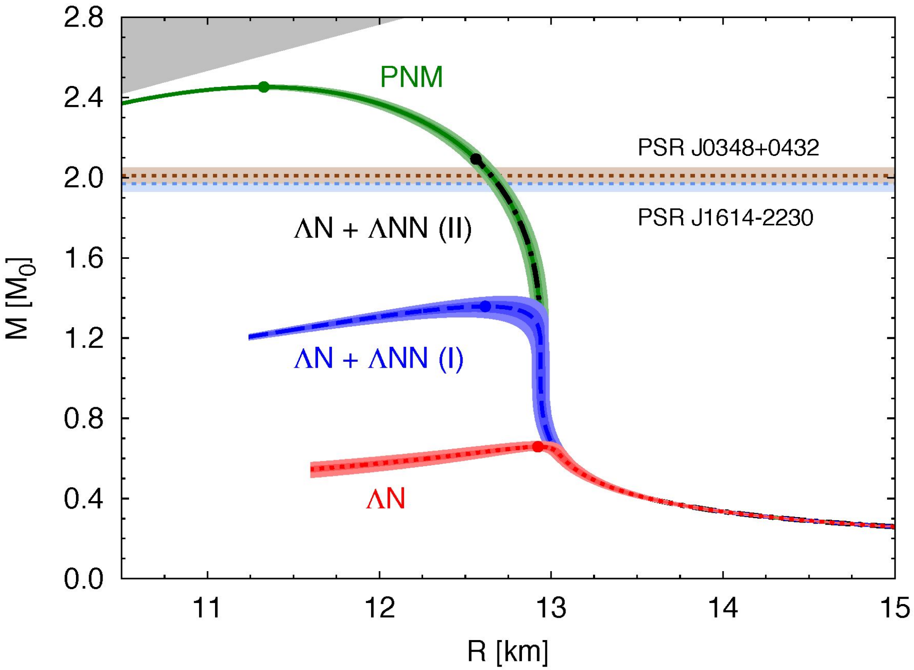
▸ Study of hyperon interaction (NY,YY,NNY,NYY,YYY) through scattering/hyperonnuclei/HIC experiments <u>VERY IMPORTANT</u>.







▸ NS theoretical difficulties: Heavy pulsars larger than $2M_\odot$ is a pain.

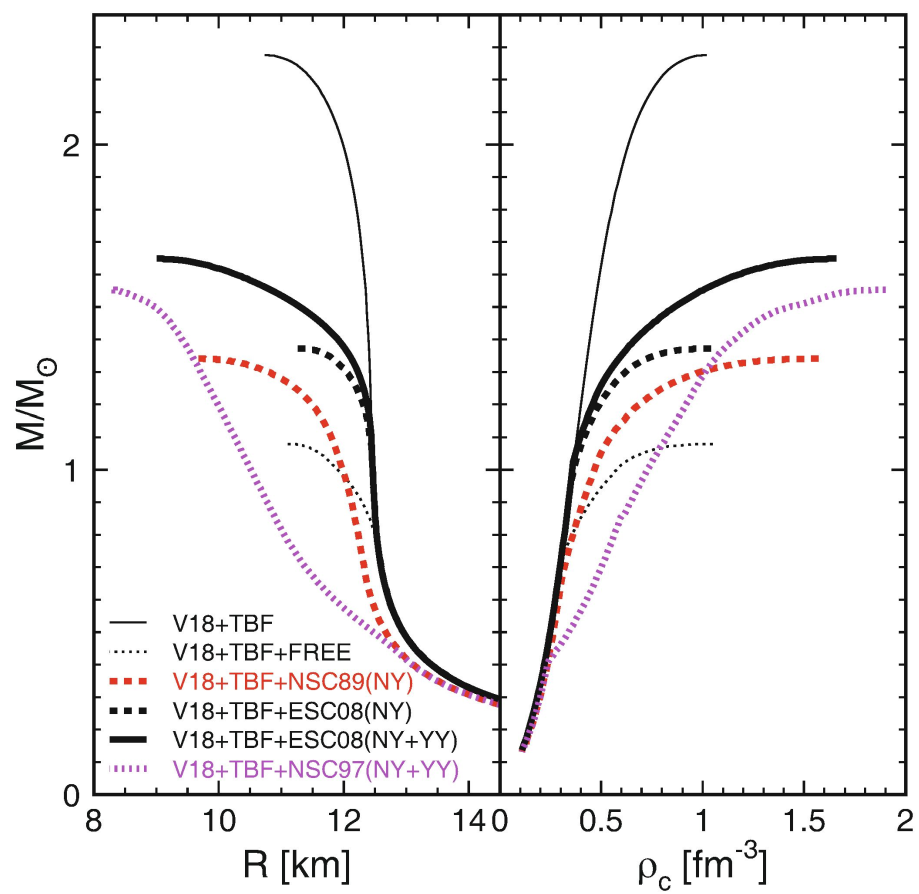


AFDMC (NN + NNN + NY + NNY)

Lonardoni et al. 2015 PRL

BHF (NN + NNN + NY)

Schulze & Rijken 2016 EPJA



- NS EOS: core + crust

- Core:

Green's Function Monte Carlo

Chiral Perturbation Theory (ChPT)

Variational Many-Body (VMB)

V_{lowk} + Renormalization Group

Brueckner-Hartree-Fock (BHF)

Dirac-Brueckner-Hartree-Fock (DBHF)

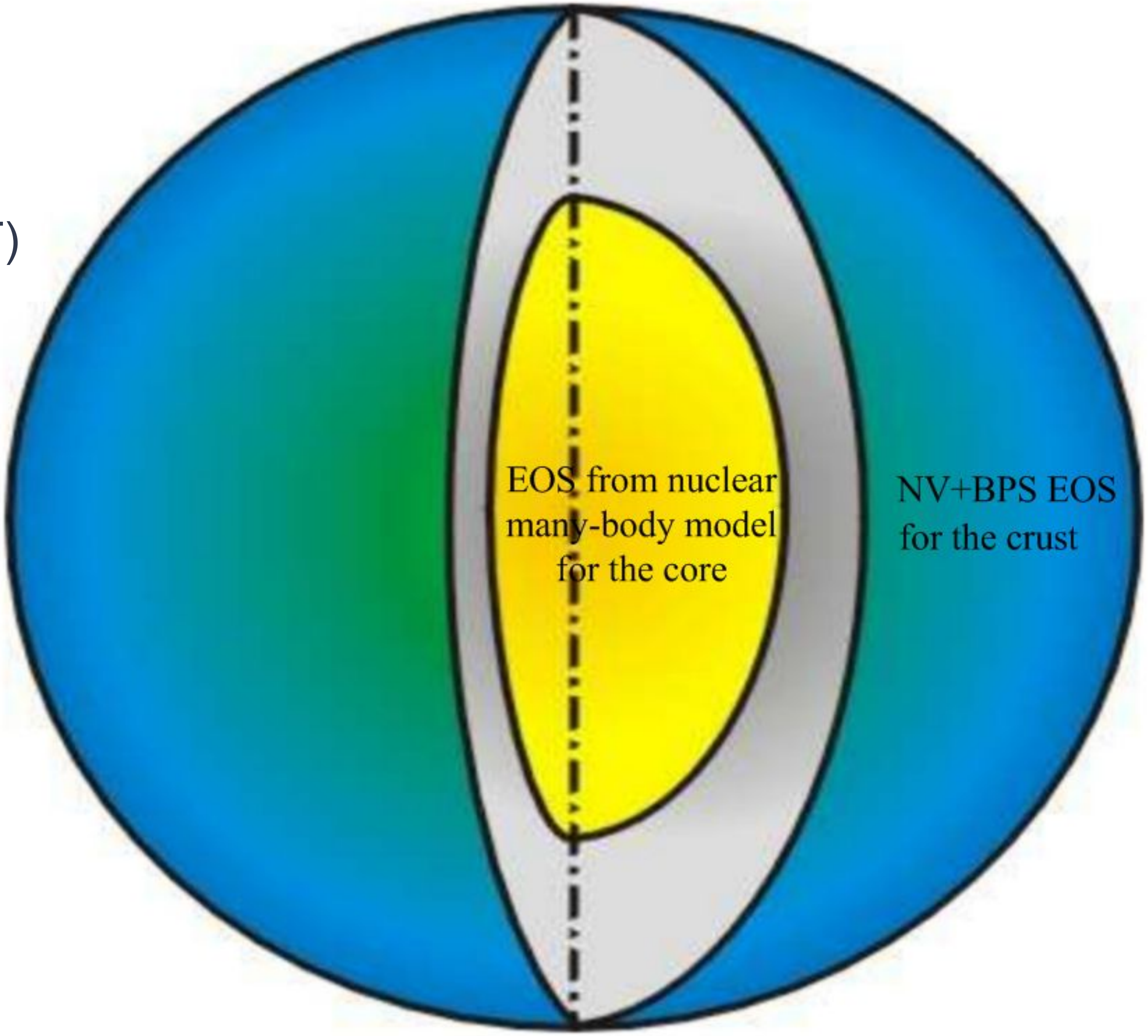
Quark mean-field (QMF)

Quark Meson Coupling (QMC)

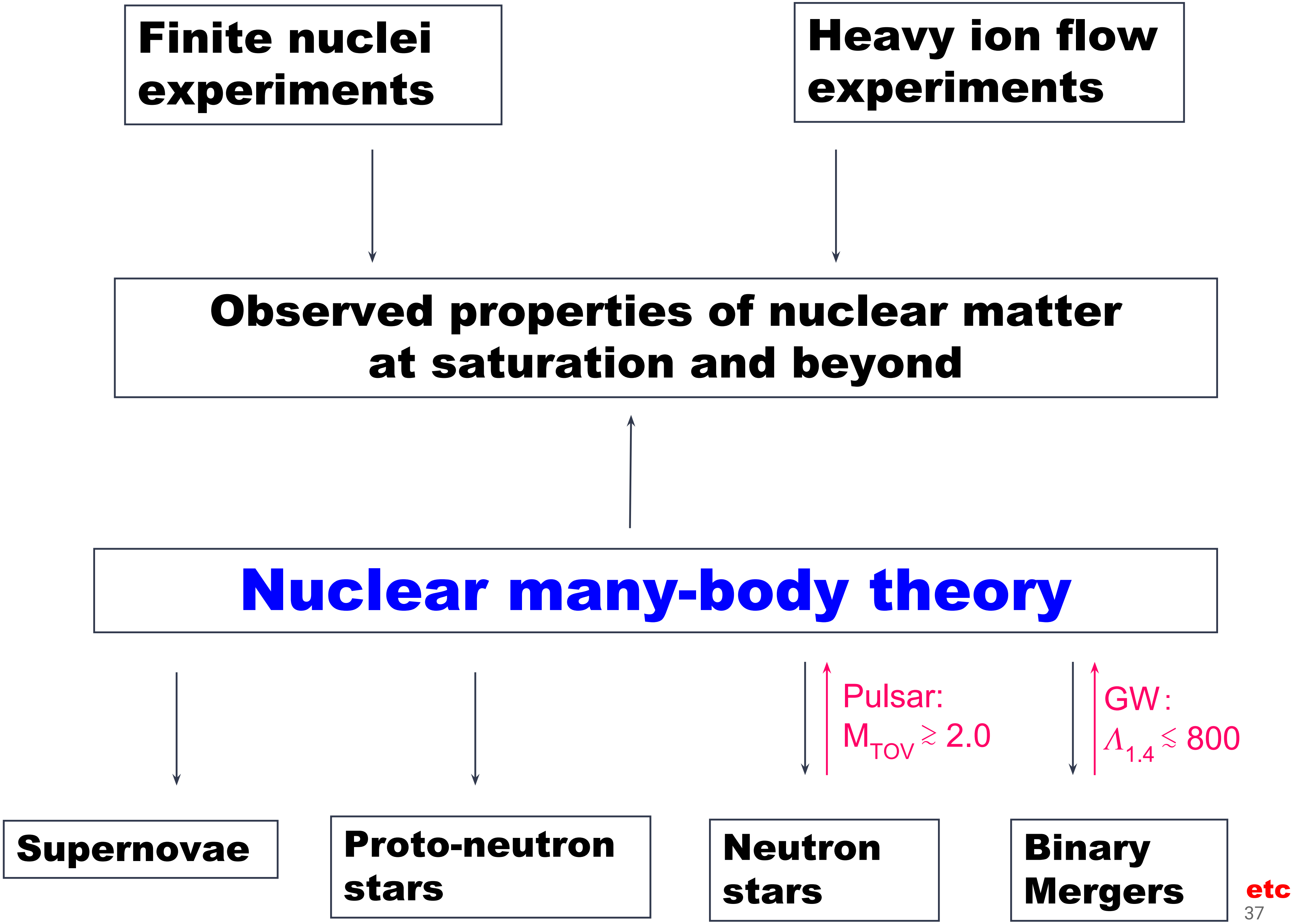
Relativistic mean-field (RMF)

Skyrme energy density functional

…



N.B. From NS model to its astro. correspondence: Thermal; Neutrino; Rotation; Magnetic field, etc


Finite nuclei experiments
Heavy ion flow 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
etc

▸ 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

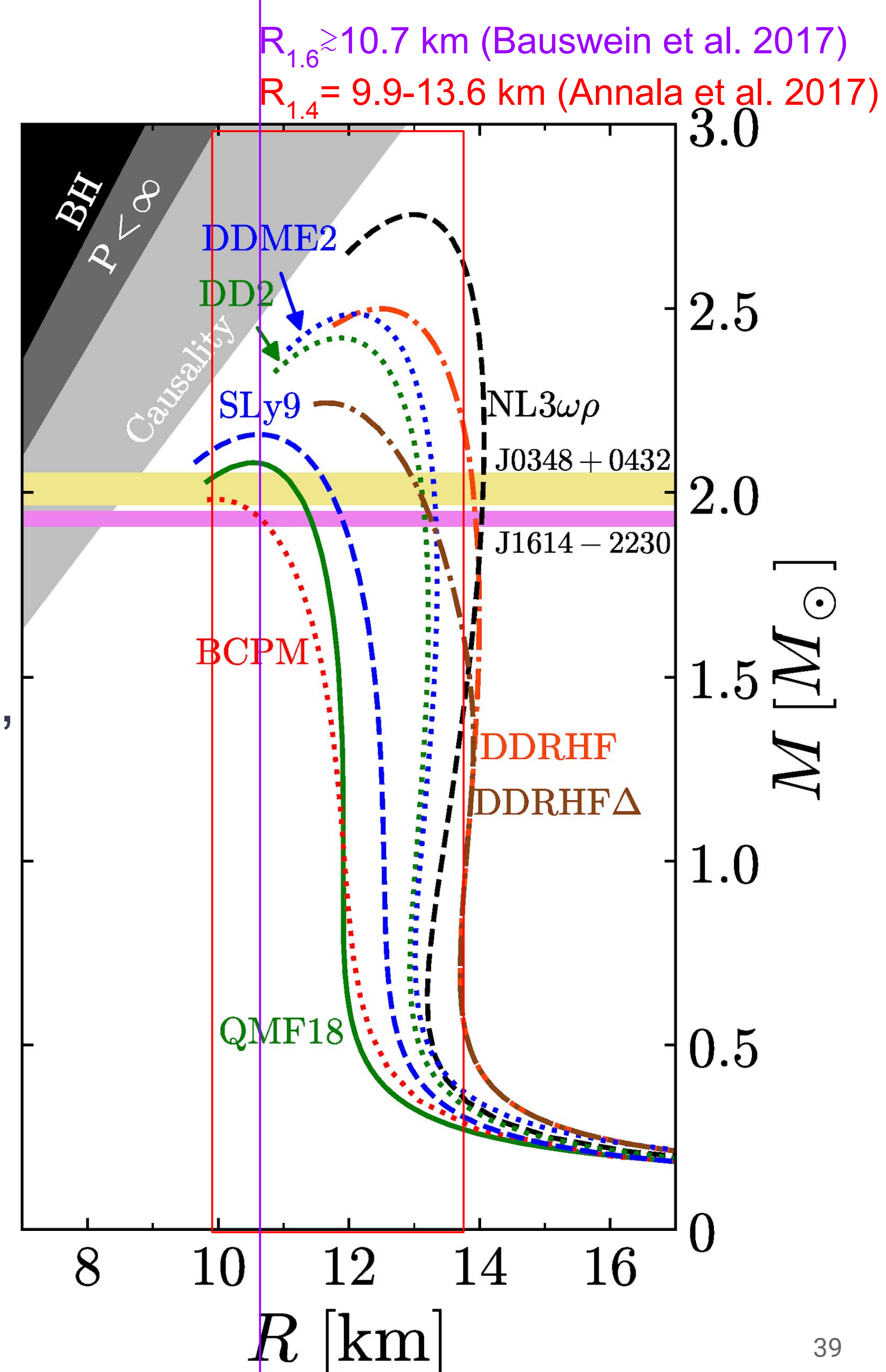
$$\mathcal{L} = \overline{\psi}\left(i\gamma_\mu\partial^\mu - M_N^* - g_{\omega N}\omega\gamma^0 - g_{\rho N}\rho\tau_3\gamma^0\right)\psi - \frac{1}{2}(\nabla\sigma)^2 - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 + \frac{1}{2}(\nabla\rho)^2 + \frac{1}{2}m_\rho^2\rho^2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

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

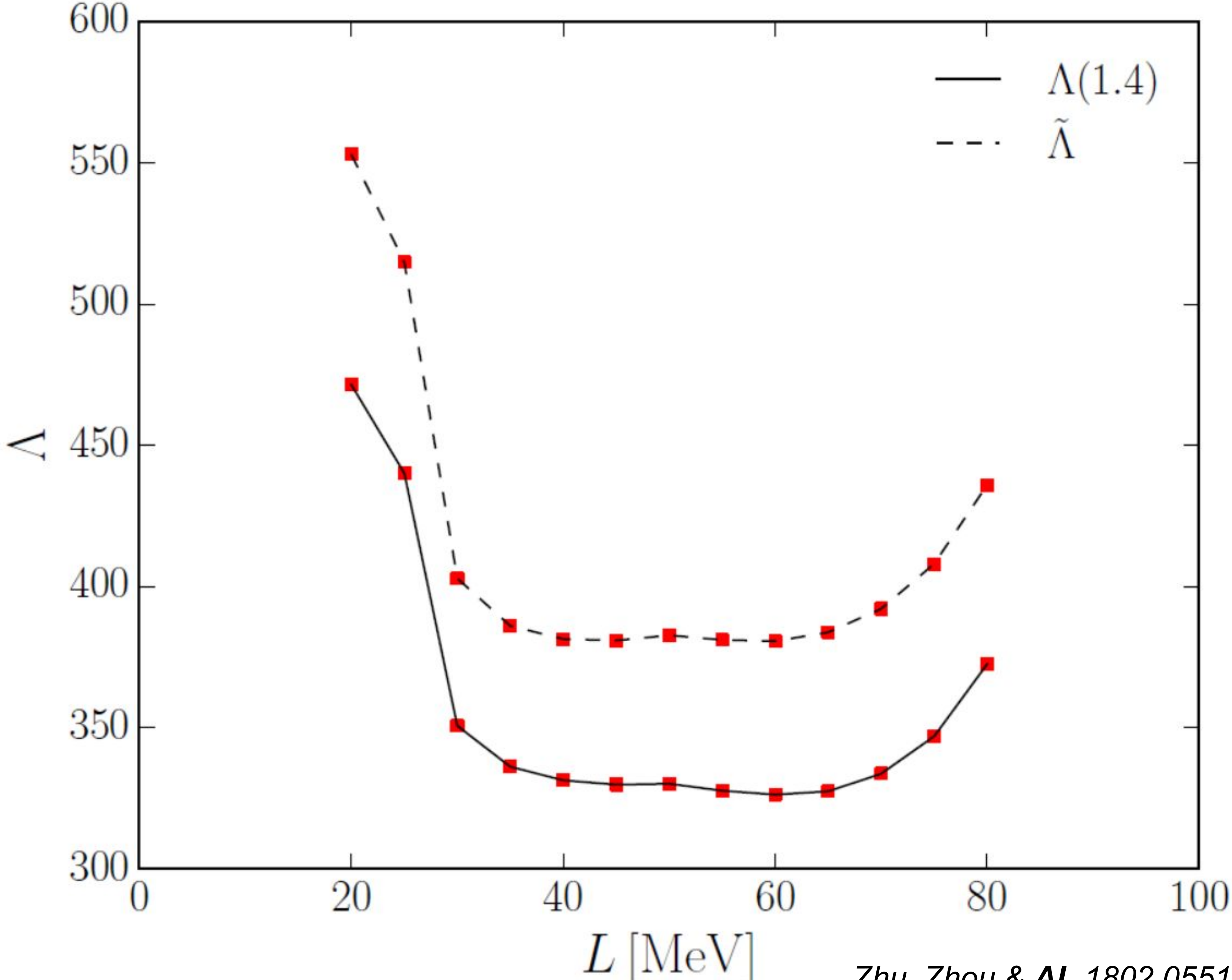
ρ_0 [fm^{-3}]	E/A [MeV]	K [MeV]	$E_{\rm sym}$ [MeV]	L [MeV]	M_N^*/M_N /
0.16	-16	240	31	20/40/60/80	0.77

- *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)*

- "QMF18" from the quark level
- GR: $R>2GM/c^2$
- $P<\infty$: $R>(9/4)GM/c^2$
- 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 GW constraint of tidal deformability



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



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

Table 4. Radius, compactness and tidal deformability for a 1.4 $M_\odot$ star are provided for various advanced NS EOSs, together with their maximum static gravitational mass $M_{\rm TOV}$ and the symmetry energy slope L. In the last line we have also shown the range of $\tilde{\Lambda}$ for a binary system with chirp mass equal to 1.188 $M_\odot$ and mass ratio in the range of $(0.7 - 1)$, which corresponds to the low spin case for GW170817. This calculation shows the consistency between the constraint in $\tilde{\Lambda}$ and $\Lambda(1.4)$. Further more, for NL3$\omega\rho$ EOS which possesses the largest value of $\Lambda(1.4)$ among all the EOSs, $\tilde{\Lambda}$ can actually be as small as 712 if the mass ratio of the system is 0.4 (which corresponds to the 90 % credible range of the mass ratio in the high spin assumption case for GW170817), hence very close to the 90 % credible upper limit for $\tilde{\Lambda}$ in the high spin case. Therefore, the possibility of this EOS wouldn't be clearly excluded if the high spin case in taken into account, as also seen in Nandi & Char (2018).

	QMF18	DDRHF	DDRHFΔ	NL3$\omega\rho$	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
$\Lambda(1.4)$	331	865	828	925	681	674	446	294
$\tilde{\Lambda}$	381.4 - 388.4	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*