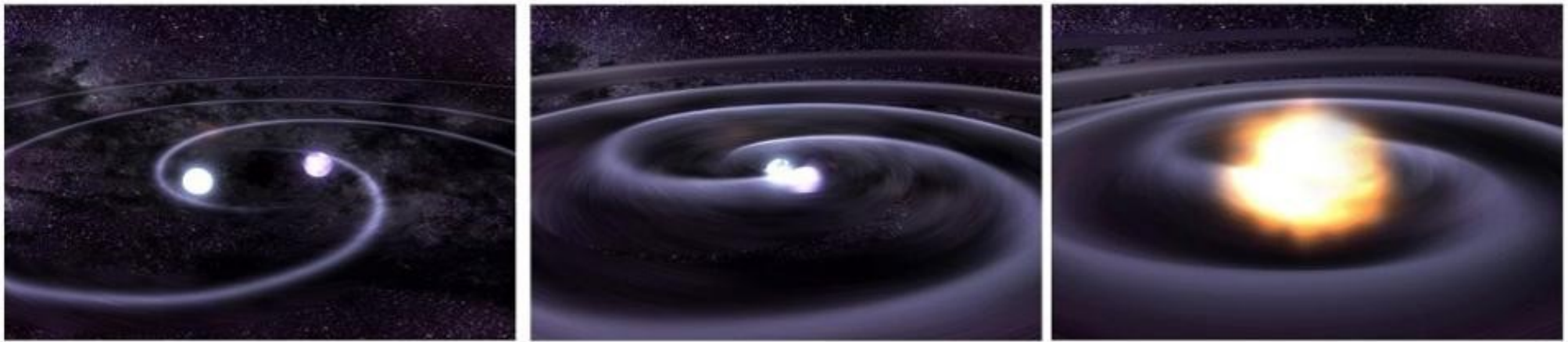


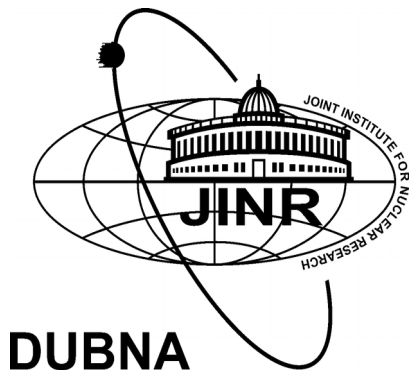
Exotic Matter in Neutron Stars

David.Blaschke@gmail.com

University of Wroclaw, Poland & JINR Dubna & MEPhI Moscow, Russia



III. EMMI Workshop on Exotics in HIC, Wroclaw, 2.-6.12.2019



Russian
Science
Foundation

Grant No. 17-12-01427



Grant No. 18-02-40137

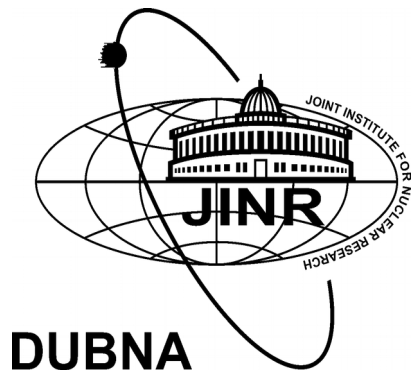
EoS Constraints from Compact Star Astrophysics & Light Fragment Production at Low Energies

David.Blaschke@gmail.com

University of Wroclaw, Poland & JINR Dubna & MEPhI Moscow, Russia

1. Introduction: The QCD Phase Diagram
2. EoS $\leftrightarrow$ Compact star sequences; Modern M-R constraints
3. Massive supernova explodability & postmerger GW signal
4. Hyperon puzzle – an update
5. Sexaquarks in Compact stars?
6. Conclusions

III. EMMI Workshop on Exotics in HIC, Wroclaw, 2.-6.12.2019



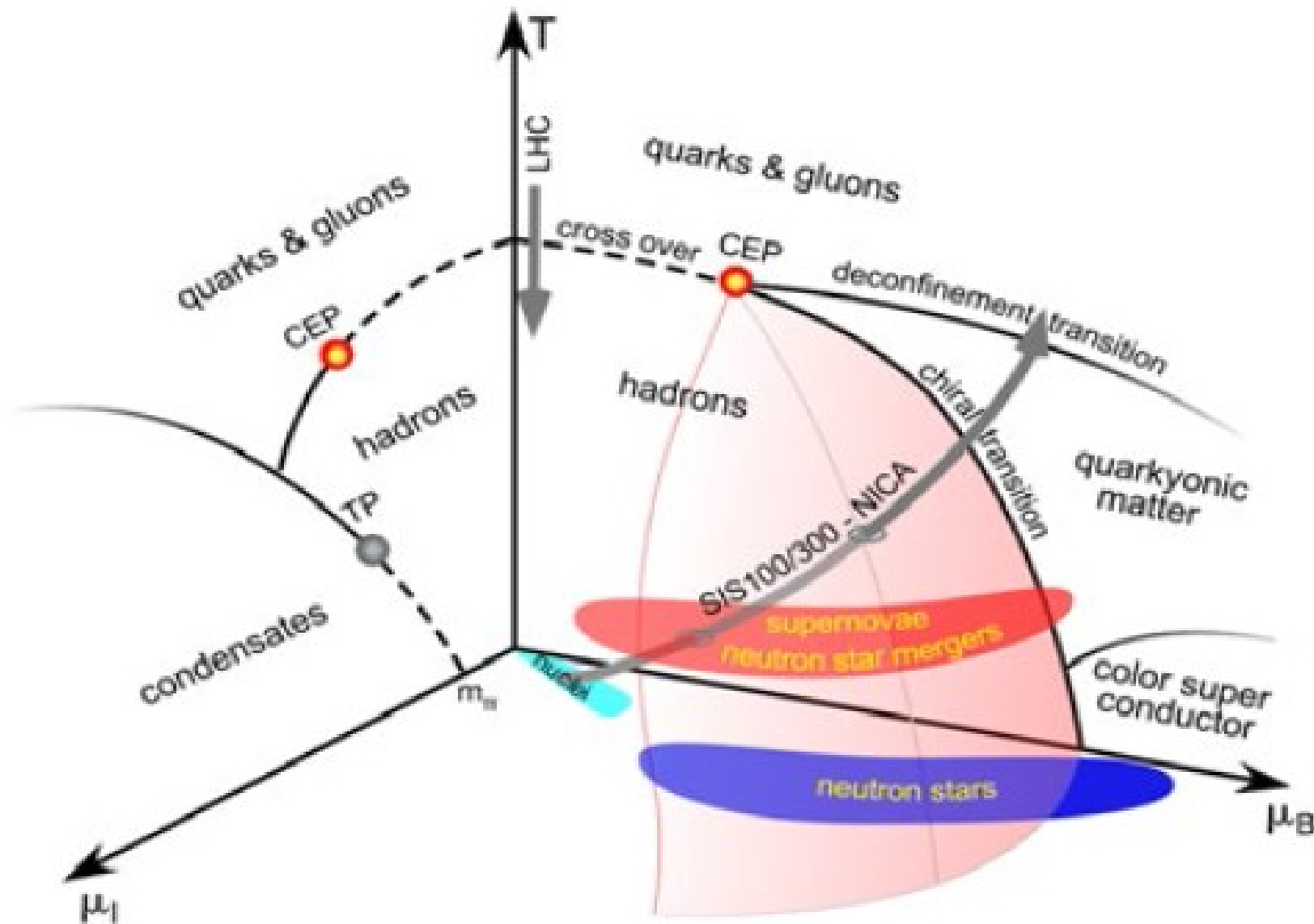
Russian
Science
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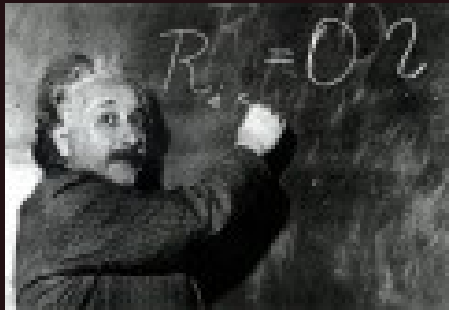


Grant No. 18-02-40137

CEP in the QCD phase diagram: HIC vs. Astrophysics



Compact stars and black holes in Einstein's General Relativity theory

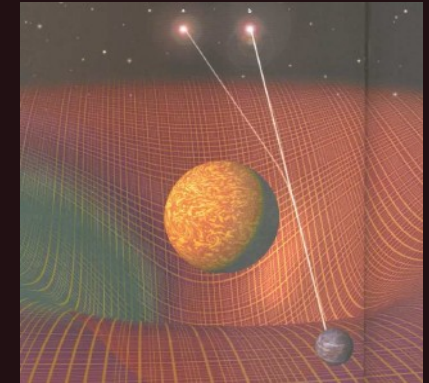


Space-Time

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Matter

Massive objects curve the Space-Time

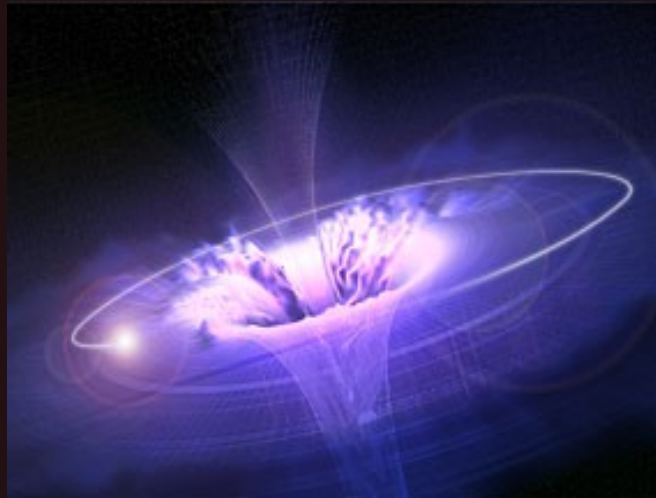


Non-rotating, spherical masses $\rightarrow$ Schwarzschild Metrics

$$ds^2 = -\left(1 - \frac{2M}{r}\right)dt^2 + \left(1 - \frac{2M}{r}\right)^{-1}dr^2 + r^2d\Omega^2$$

Einstein eqs. $\rightarrow$ Tolman-Oppenheimer-Volkoff eqs.*)

For structure and stability of compact stars



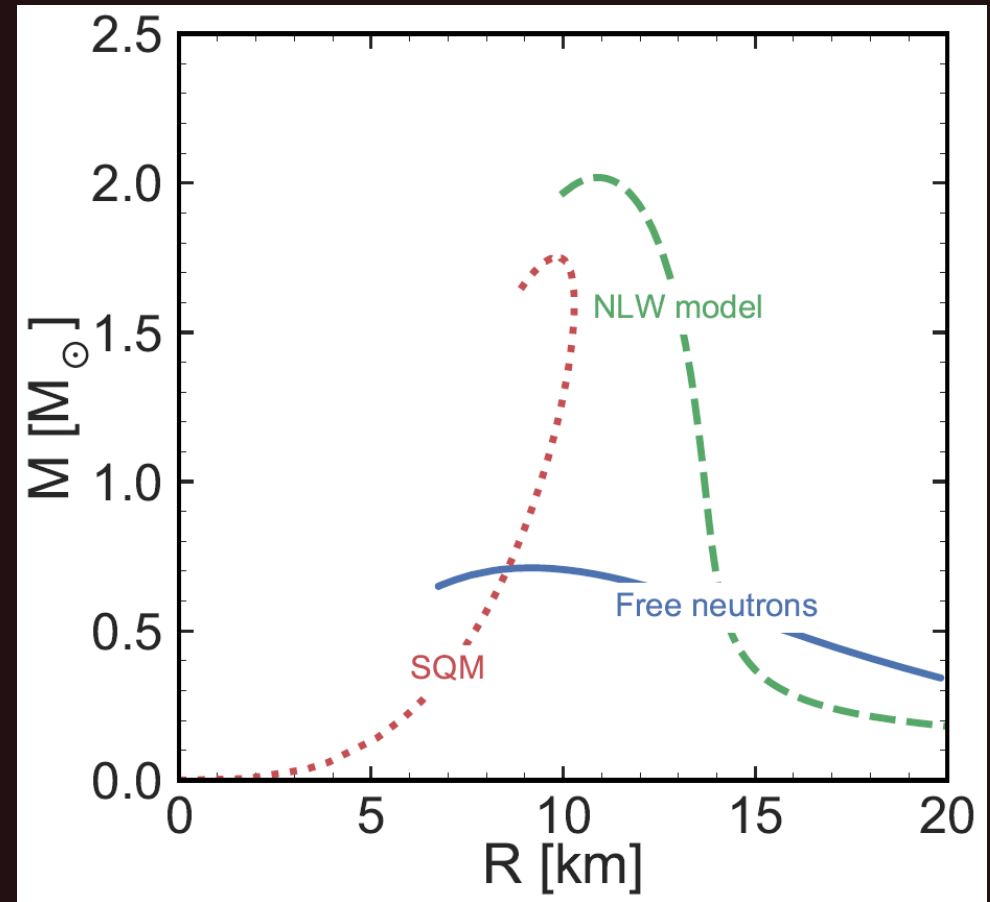
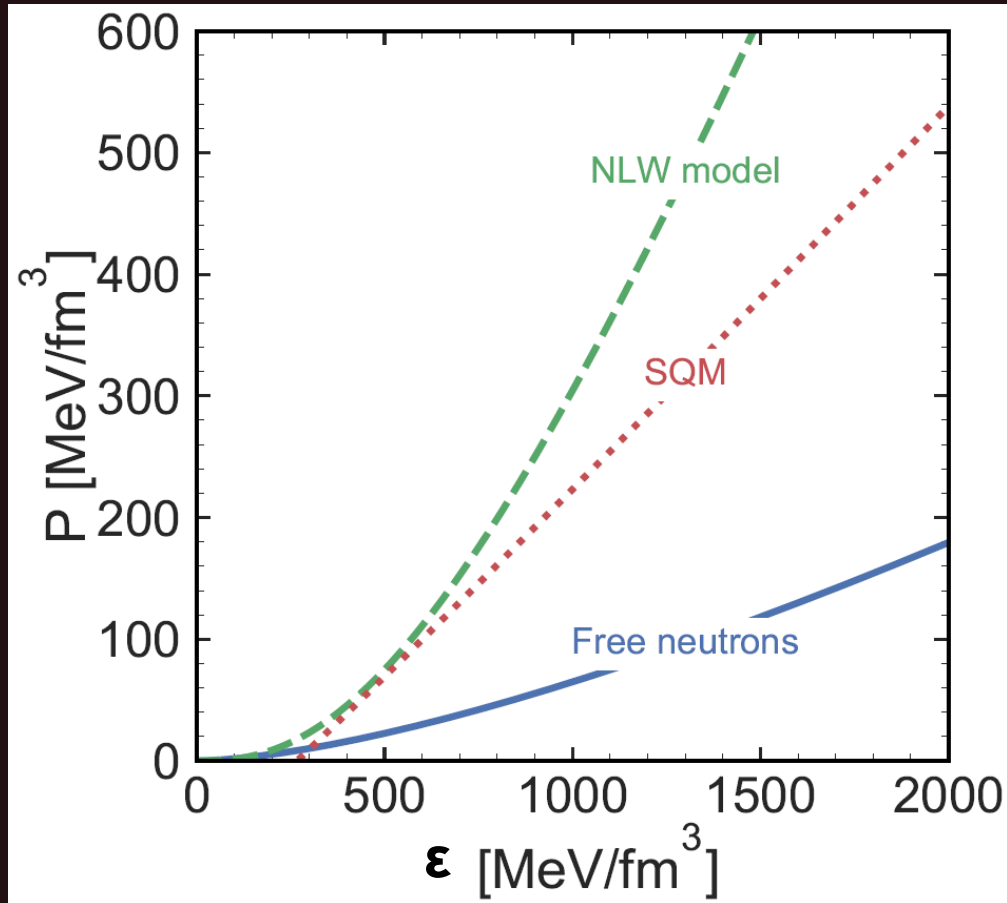
$$\frac{dP(r)}{dr} = -G \frac{m(r)\varepsilon(r)}{r^2} \left(1 + \frac{P(r)}{\varepsilon(r)}\right) \left(1 + \frac{4\pi r^3 P(r)}{m(r)}\right) \left(1 - \frac{2Gm(r)}{r}\right)^{-1}$$

Newtonian case x GR corrections from EoS and metrics

*) R. C. Tolman, Phys. Rev. 55 (1939) 364 ; J. R. Oppenheimer, G. M. Volkoff, ibid., 374

The 1:1 relation $P(\epsilon) \leftrightarrow M(R)$ via TOV

Simple examples*)



Free neutrons: Oppenheimer & Volkoff, Phys. Rev. 55 (1939) 374

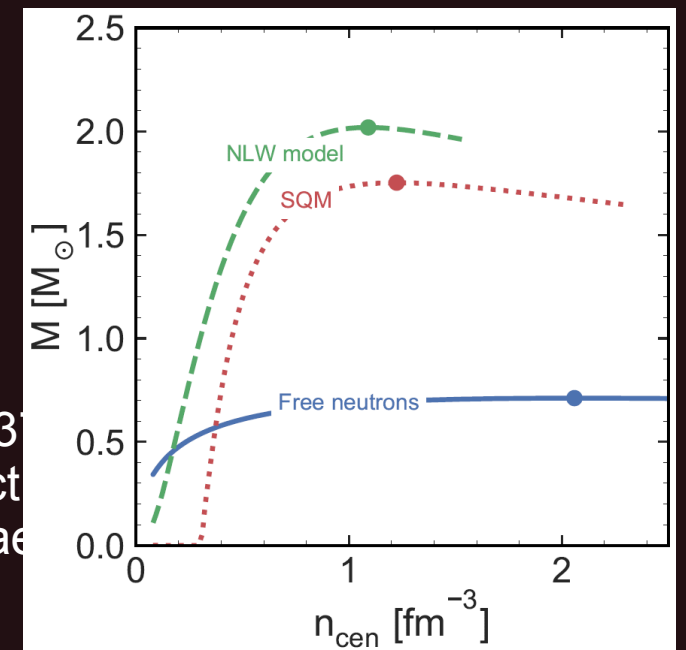
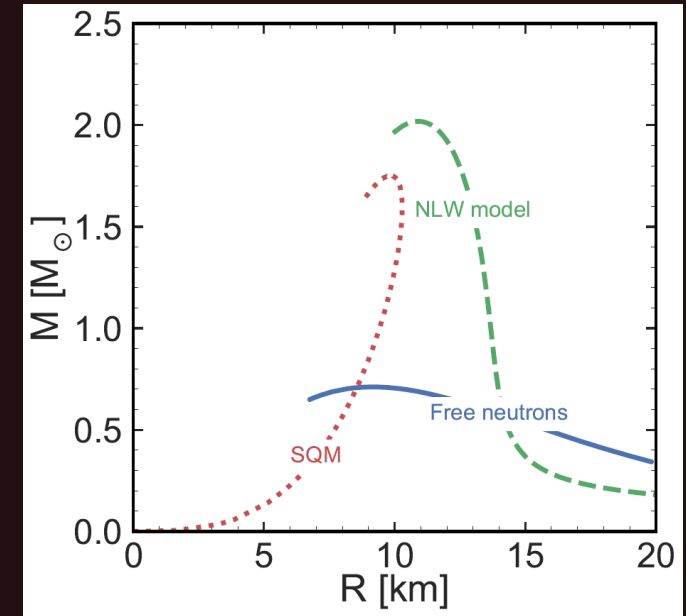
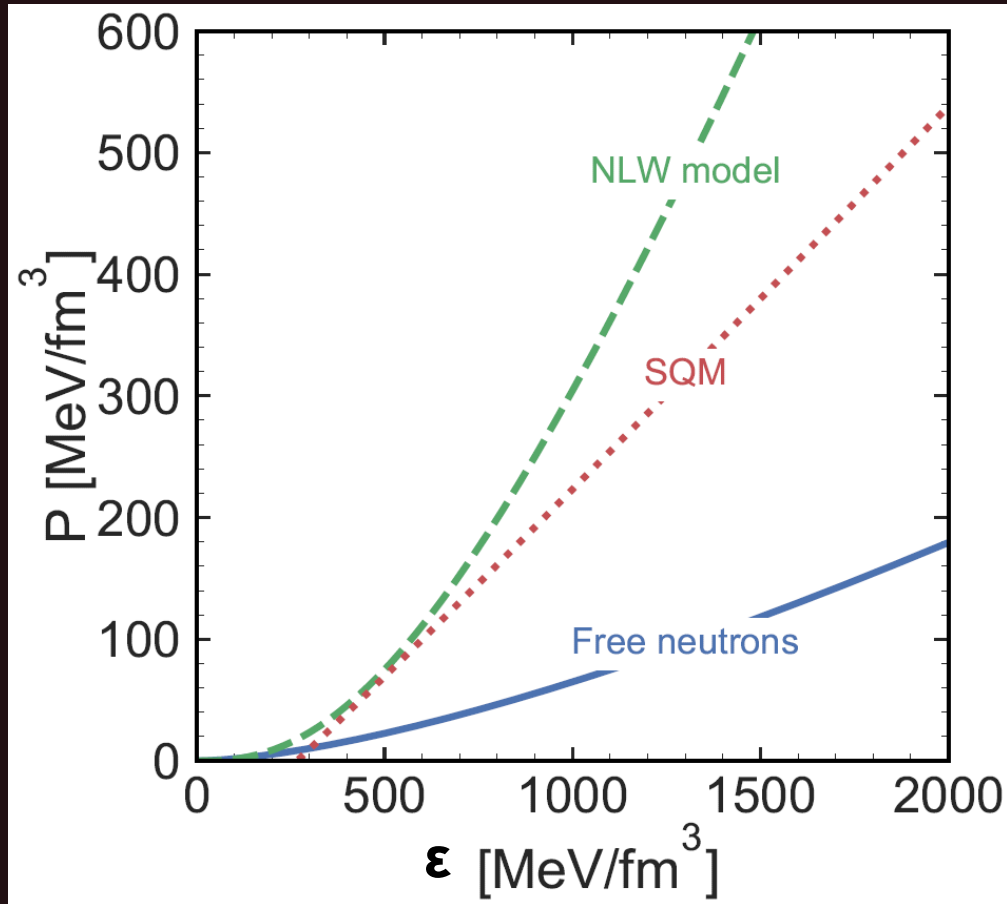
NLW (nonlinear Walecka) model: N. K. Glendenning, Compact Stars (Springer, 2000)

SQM (strange quark matter): P. Haensel, J. L. Zdunik, R. Schaeffer, A&A 160 (1986) 121

*) courtesy: Konstantin Maslov

The 1:1 relation $P(\varepsilon) \leftrightarrow M(R)$ via TOV

Simple examples*)

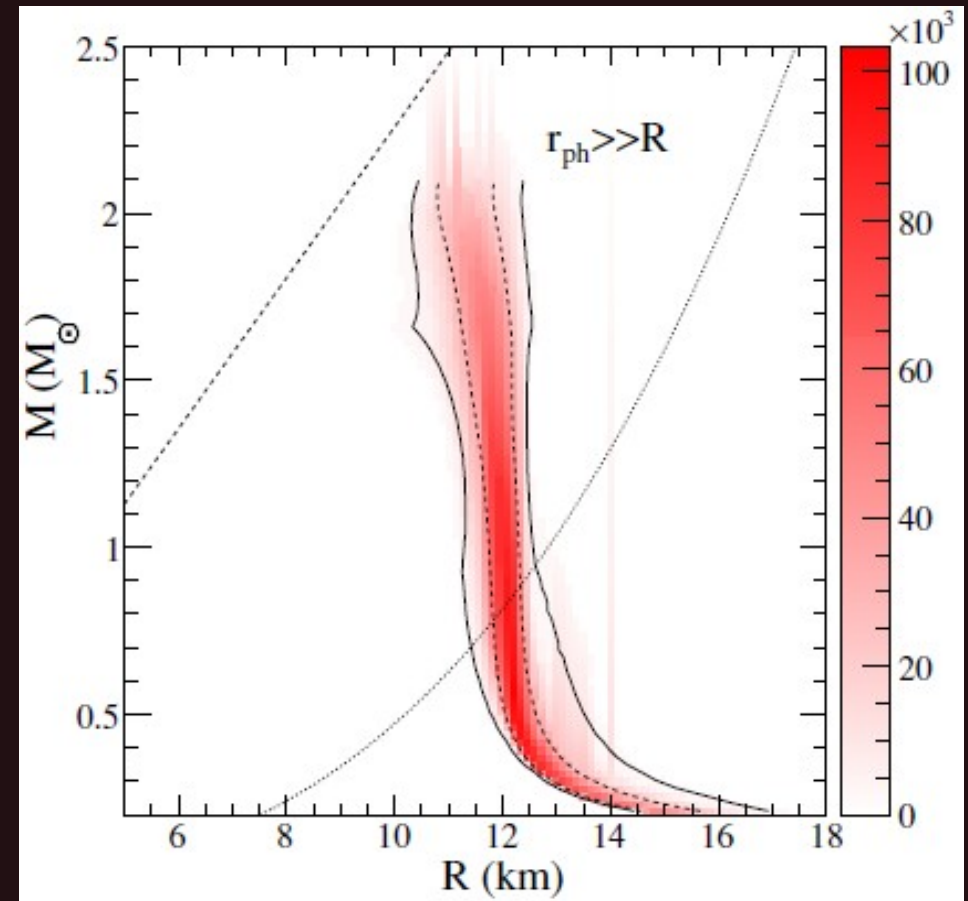
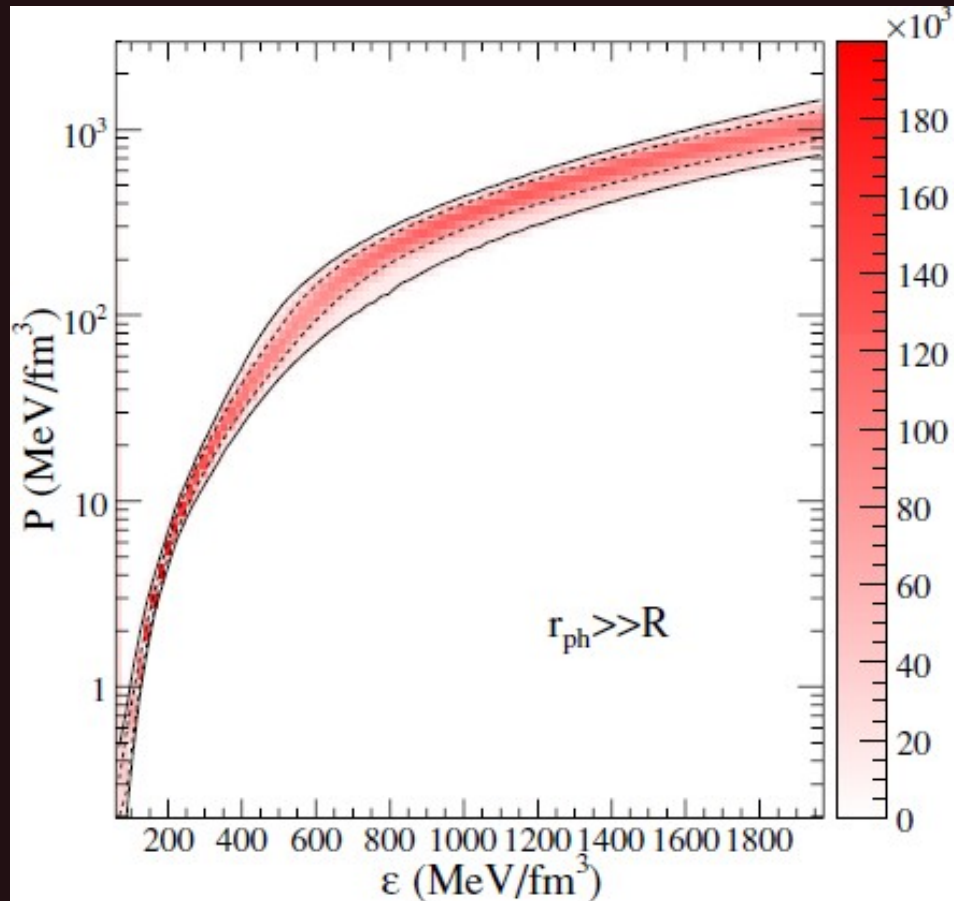


Free neutrons: Oppenheimer & Volkoff, Phys. Rev. 55 (1939) 371
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*) courtesy: Konstantin Maslov

The 1:1 relation $P(\epsilon) \leftrightarrow M(R)$ via TOV

Equation of State from Mass and Radius observations *)



A. W. Steiner, J. M. Lattimer, E. F. Brown, *Astrophys. J.* 722 (2010) 33

*) caution with radius measurements from burst sources

Neutron star mass measurements with binary radio pulsars

MSP with period $P=3.15$ ms

$P_b = 8.68$ d, $e=0.00000130(4)$

Inclination angle = $89.17(2)$ degrees !

Precise masses derived from Shapiro delay only:

$$M_p = 1.97(4) M_\odot$$
$$M_c = 0.500(6) M_\odot$$

Update [Fonseca et al. (2016)]

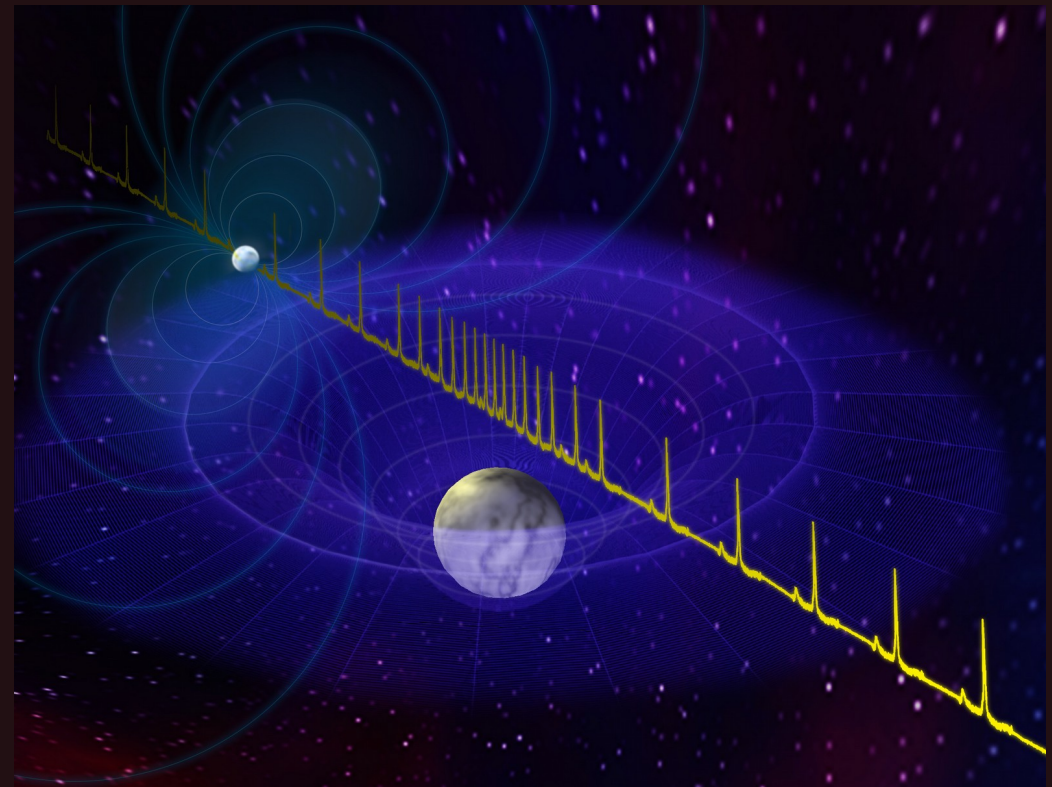
$$M_p = 1.928(17) M_\odot$$

Update [Arzoumanian et al. (2018)]

$$M_p = 1.908(16) M_\odot$$

PSR J1614-2230

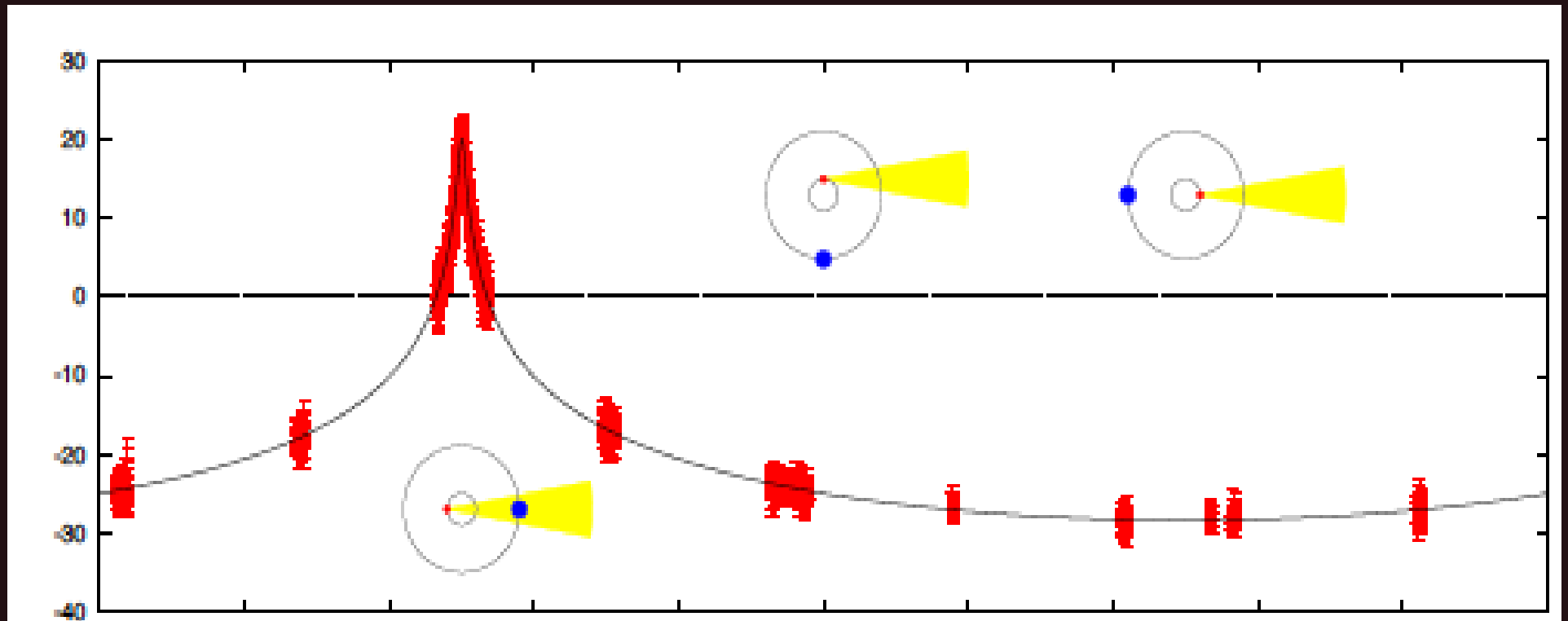
Demorest et al., Nature (2010)



PSR J1614-2230

A precise AND large mass measurement

Shapiro delay:



Demorest et al., Nature 467 (2010) 1081, arxiv:1010.5788

Neutron star mass measurements with Shapiro delay – new record

MSP with period $P=2.88$ ms

$P_b = 4.7669$ d, $e=0.00000507(4)$

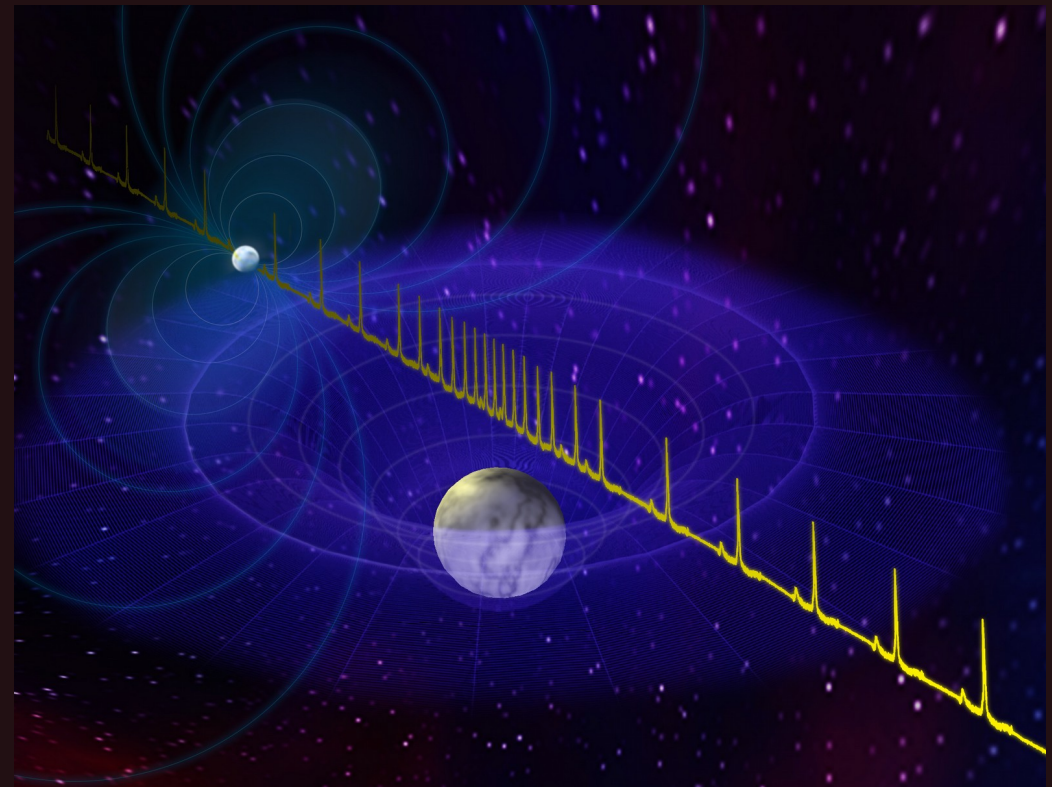
Inclination angle = 87.35 degrees !

Precise mass derived from
Shapiro delay only:

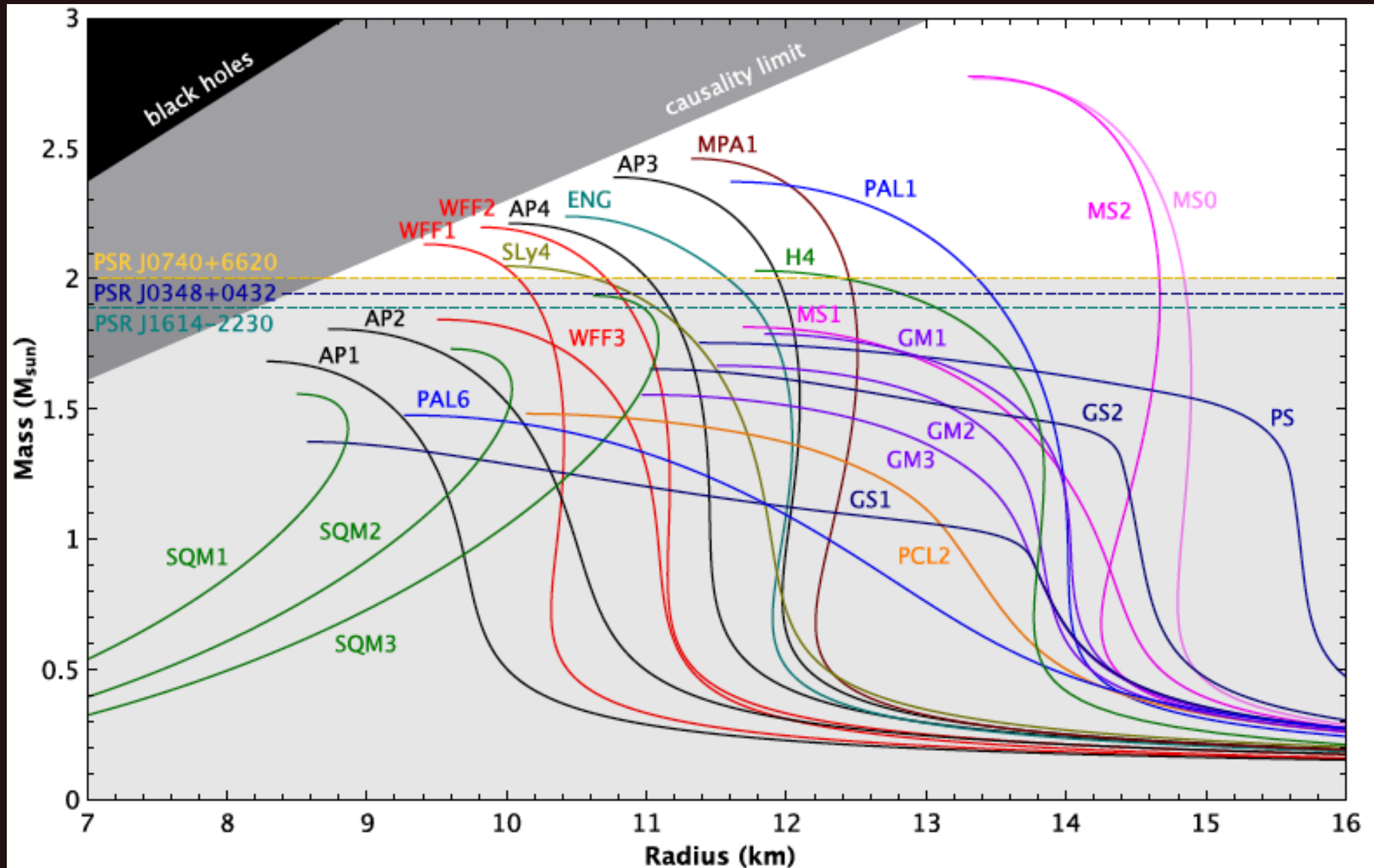
$$2.17^{+0.11}_{-0.10} M_{\odot}$$

PSR J0740+6620

Cromartie et al., arXiv:1904.06759 (2019)



NS Masses and Radii $\leftrightarrow$ EoS



GW170817 – a merger of two compact stars

Neutron Star Merger Dynamics

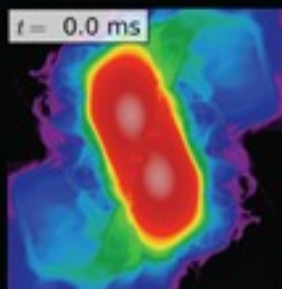
(General) Relativistic (Very) Heavy-Ion Collisions at ~ 100 MeV/nucleon

Simulations: Rezzola et al (2013)

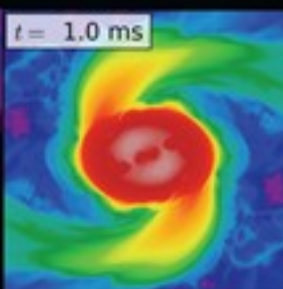
$t = -8.1$ ms



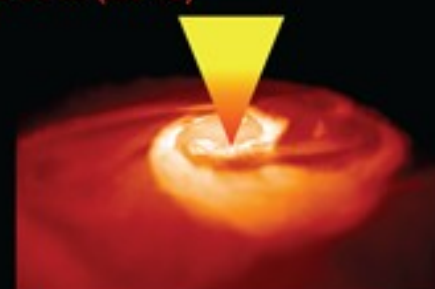
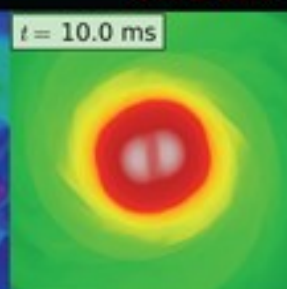
$t = 0.0$ ms



$t = 1.0$ ms



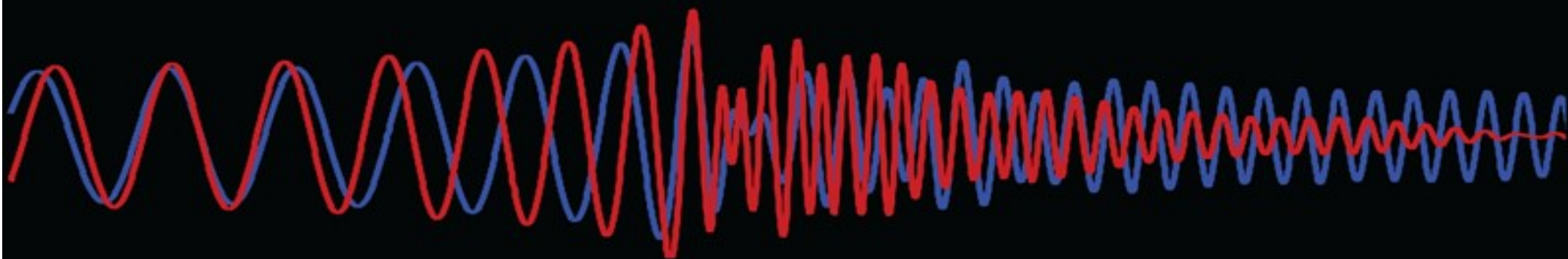
$t = 10.0$ ms



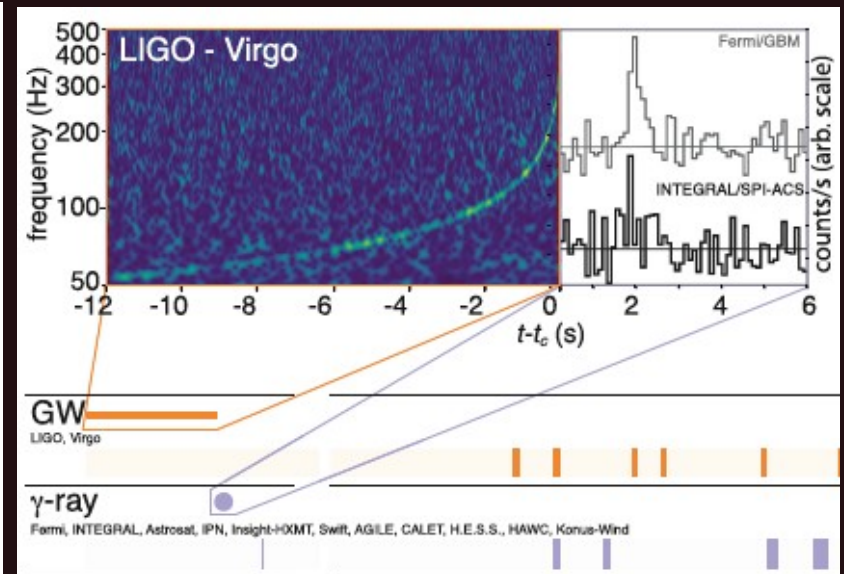
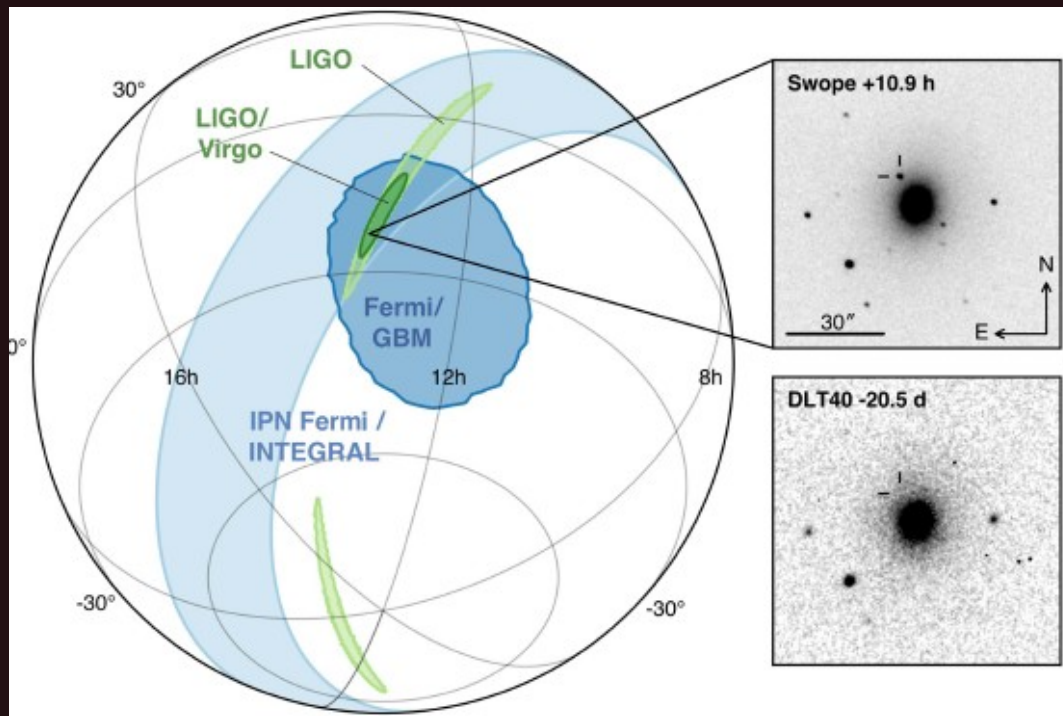
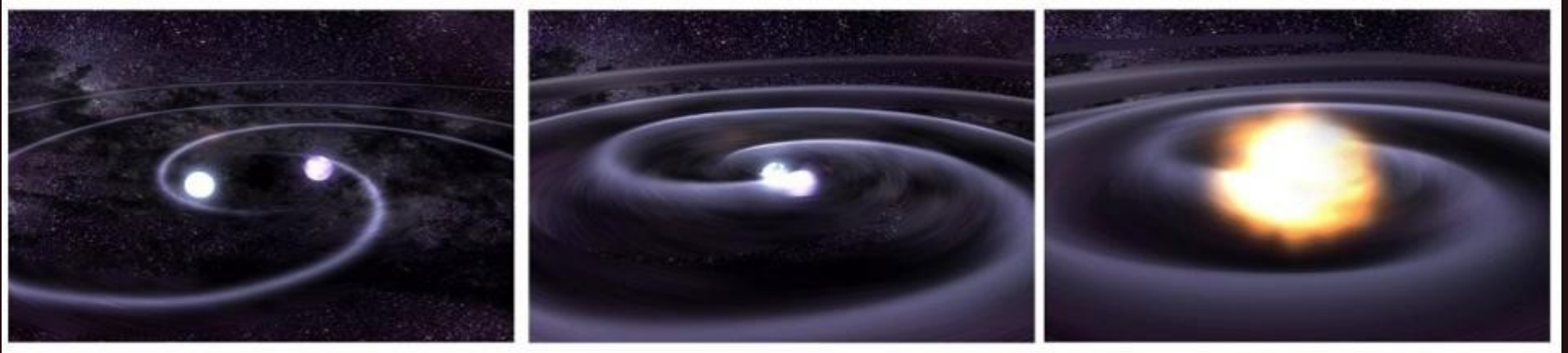
Inspiral:
Gravitational waves,
Tidal Effects

Merger:
Disruption, NS oscillations, ejecta
and r-process nucleosynthesis

Post Merger:
GRBs, Afterglows, and
Kilonova



Discovery: neutron star merger !



GW170817A , announced 16.10.2017 *)

*) B.P. Abbott et al. [LIGO/Virgo Collab.], PRL 119, 161101 (2017); ApJLett 848, L12 (2017)

NS-NS merger !

GW170817A , announced 16.10.2017 *)

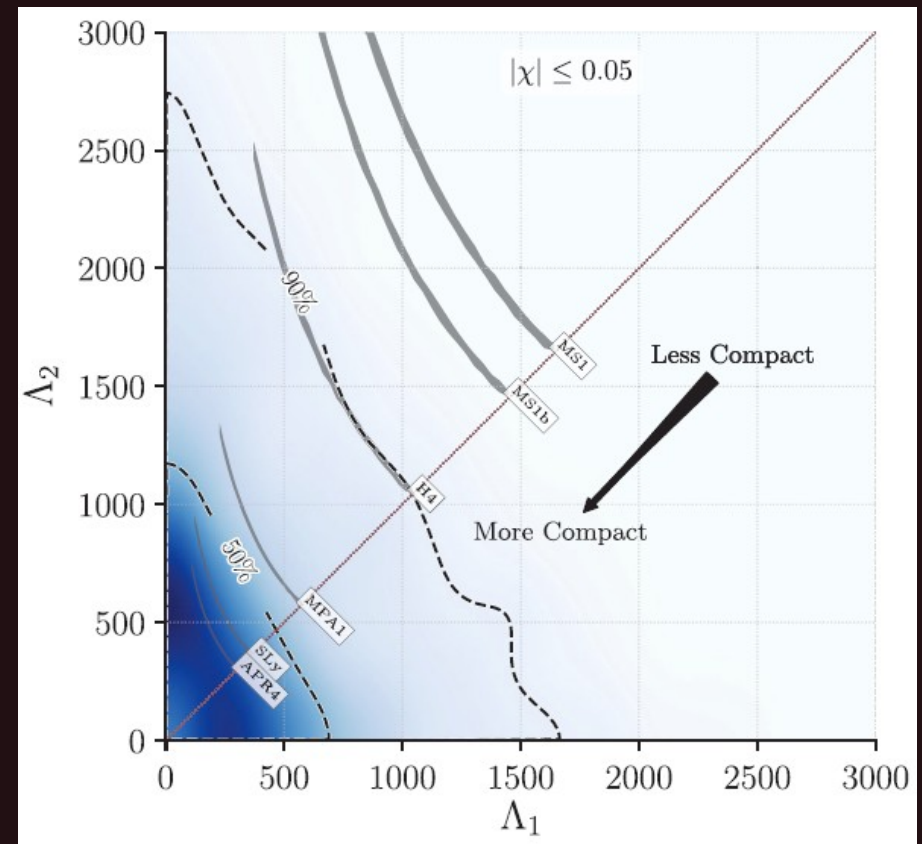
Multi-Messenger Astrophysics !!

	Low-spin priors ($ \chi \leq 0.05$)
Primary mass m_1	$1.36\text{--}1.60 M_\odot$
Secondary mass m_2	$1.17\text{--}1.36 M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	$0.7\text{--}1.0$
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$
Luminosity distance D_L	$40^{+8}_{-14} \text{ Mpc}$

Constraint on neutron star maximum mass

$$M_{\text{TOV}} < 2.17 M_{\text{sun}}$$

(Margalit & Metzger, arxiv:1710.05938)



Constraint on parameter ($\Lambda < 800$)

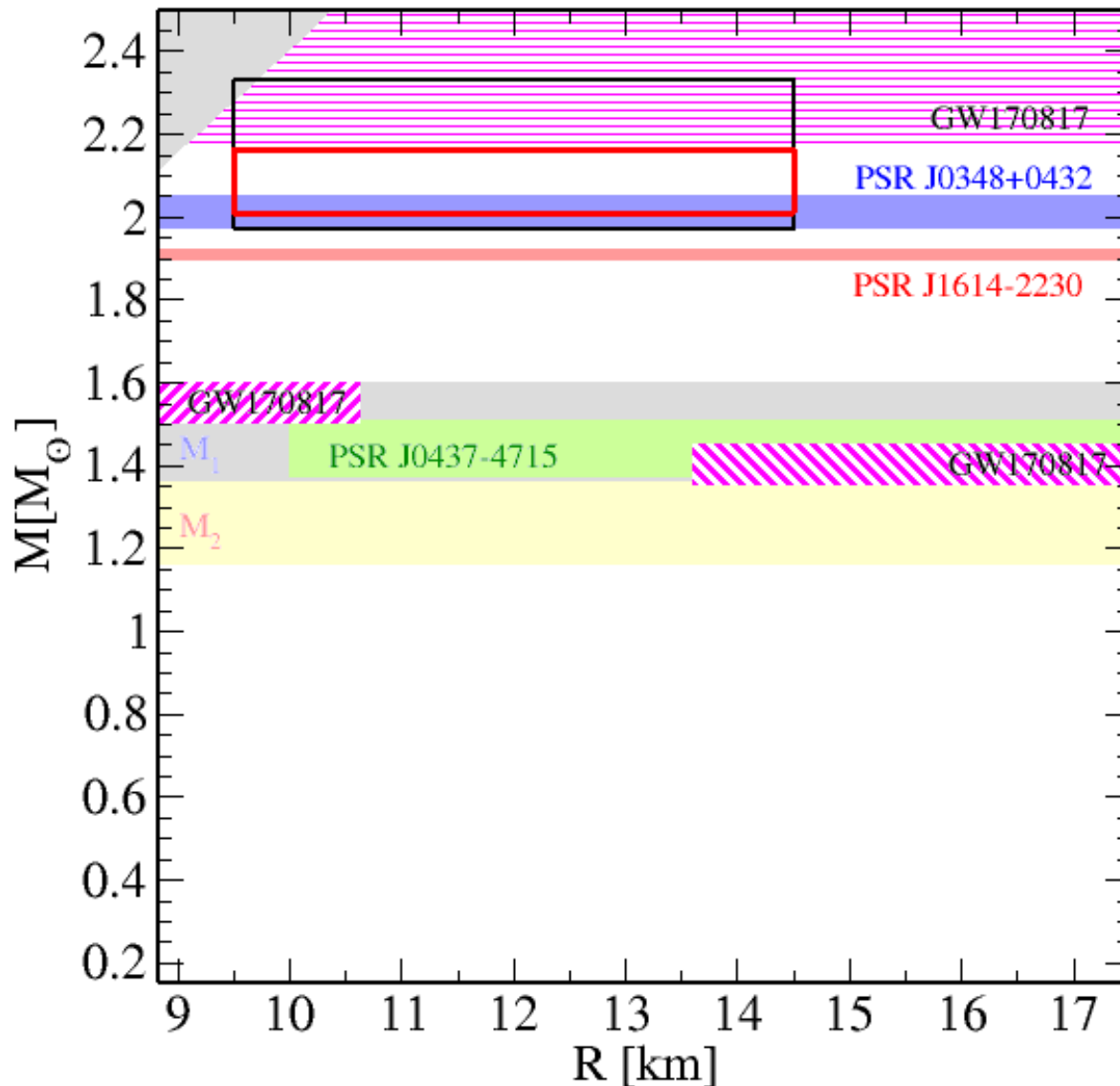
$$\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$

Dimensionless tidal deformability

$$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$$

*) B.P. Abbott et al. [LIGO/Virgo Collab.], PRL 119, 161101 (2017); ApJLett 848, L12 (2017)

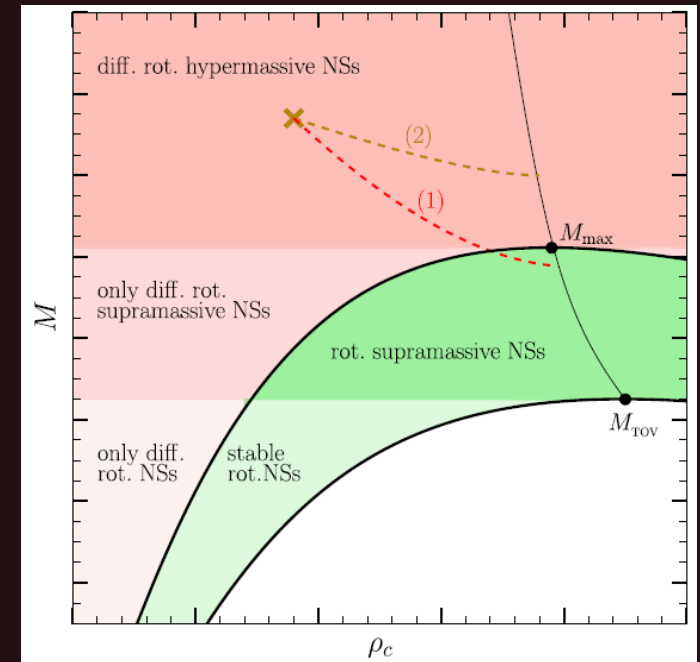
Constraints on NS mass and radii !



Constraint on maximum mass

$$2.01 < M_{\text{TOV}}/M_{\odot} < 2.16$$

(Rezzolla et al., arxiv:1710.05938)



Constraint on minimal radius

$$R_{1.6} > 10.68 \text{ km}$$

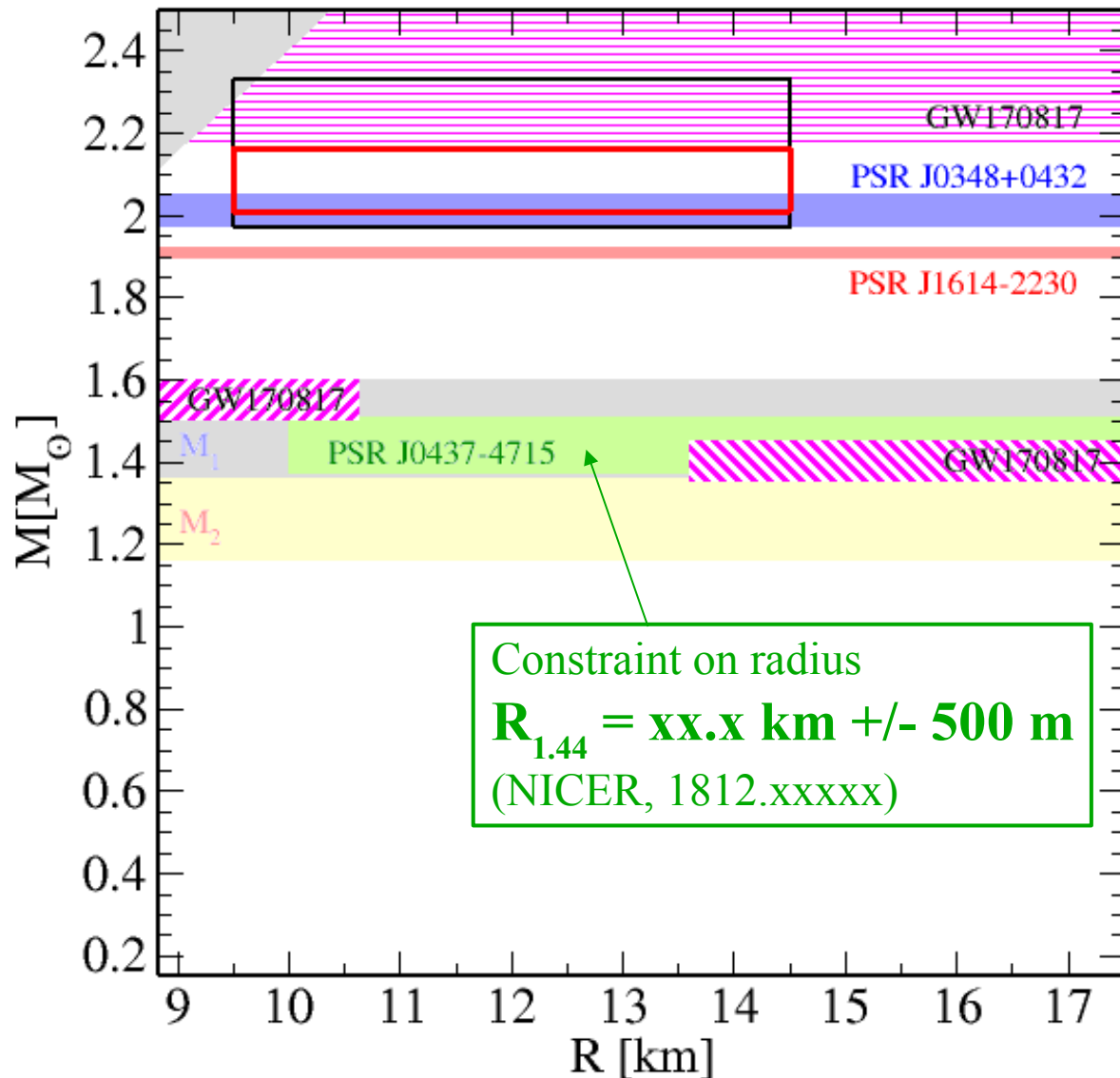
(Bauswein et al., arxiv:1710.06843)

Constraint on maximal radius

$$R_{1.4} < 13.6 \text{ km}$$

(Annala et al., arxiv:1711.02644)

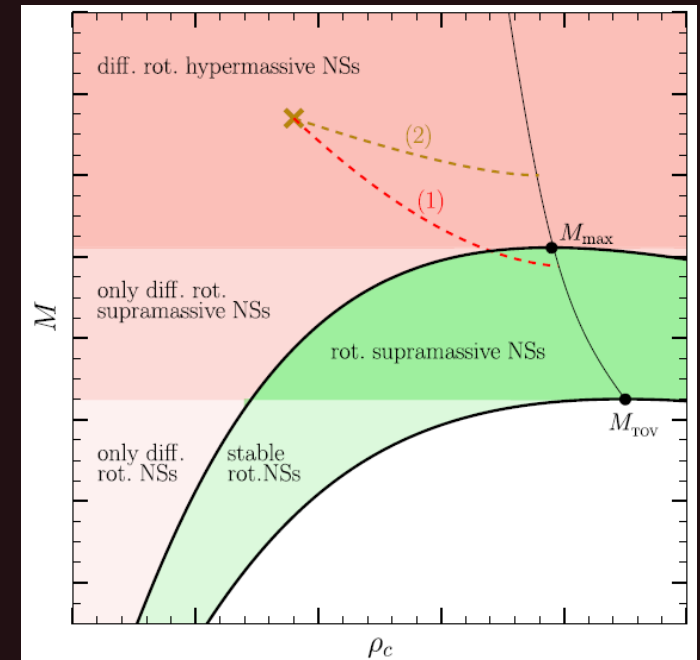
Constraints on NS mass and radii !



Constraint on maximum mass

$$2.01 < M_{\text{TOV}}/M_{\odot} < 2.16$$

(Rezzolla et al., arxiv:1710.05938)



Constraint on minimal radius

$$R_{1.6} > 10.68 \text{ km}$$

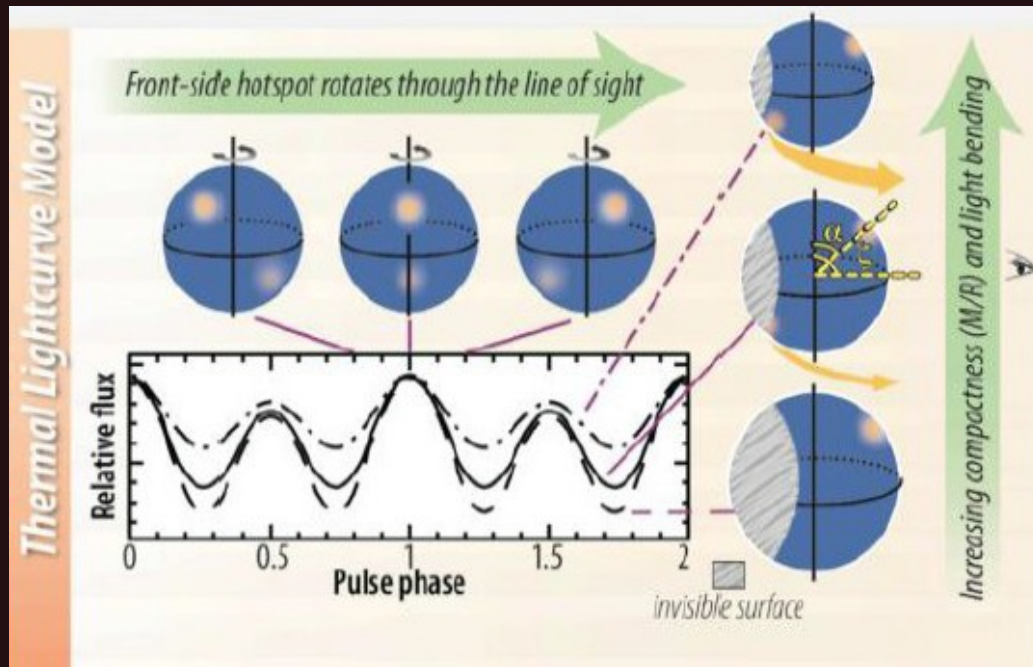
(Bauswein et al., arxiv:1710.06843)

Constraint on maximal radius

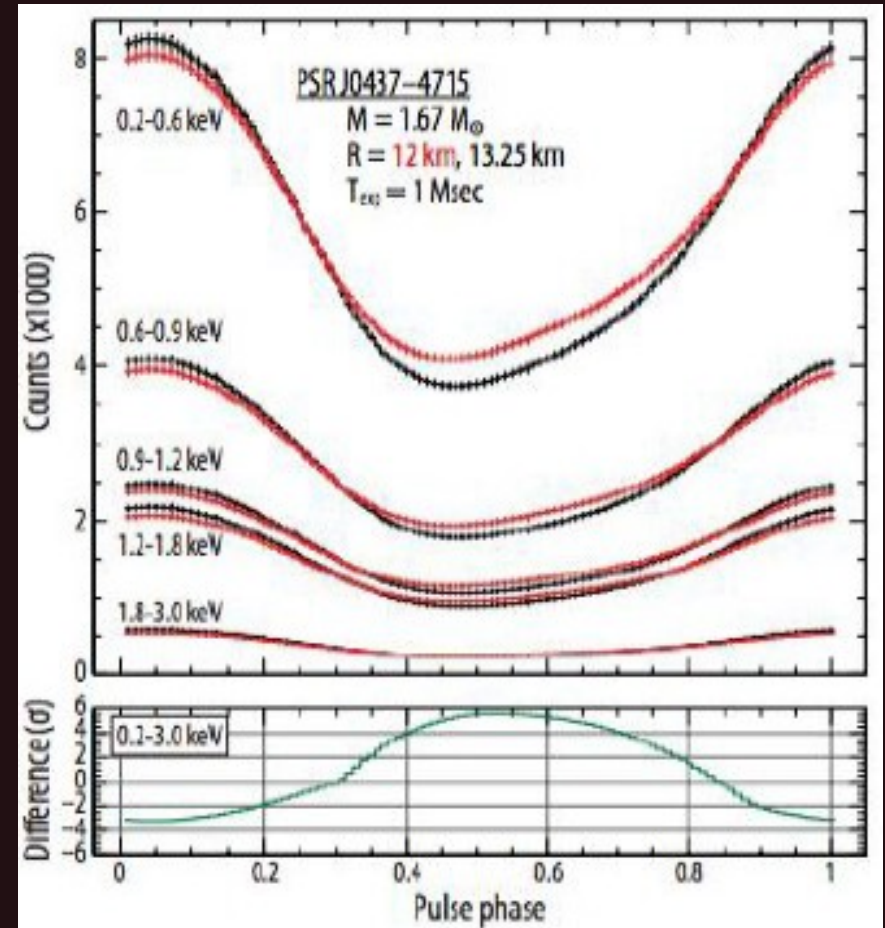
$$R_{1.4} < 13.6 \text{ km}$$

(Annala et al., arxiv:1711.02644)

Measure NS Radii ...

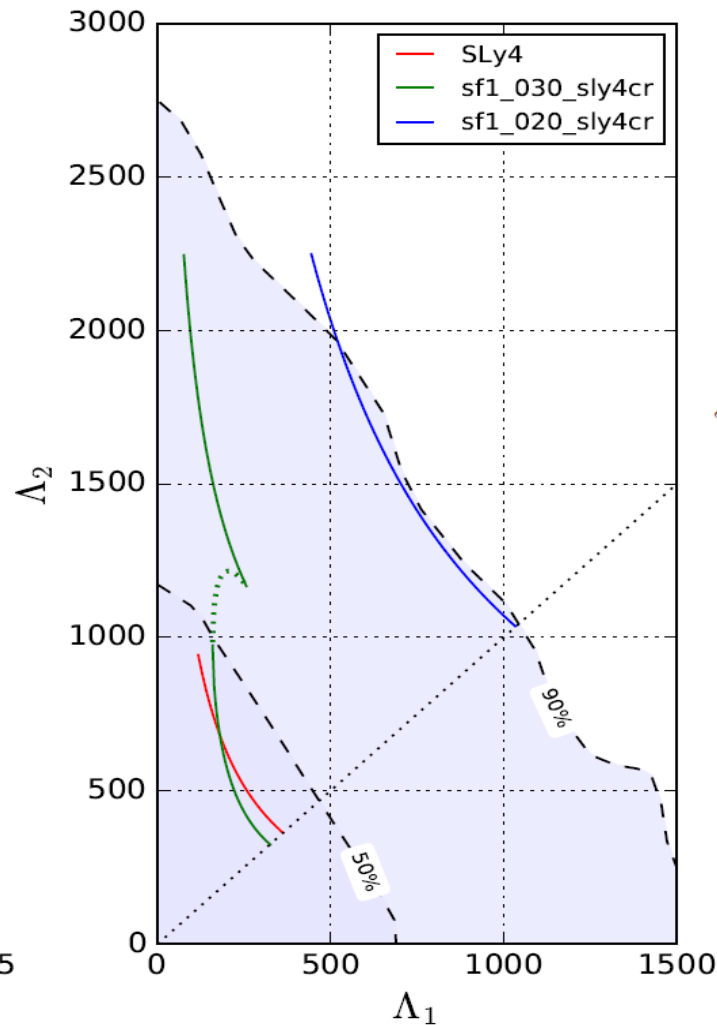
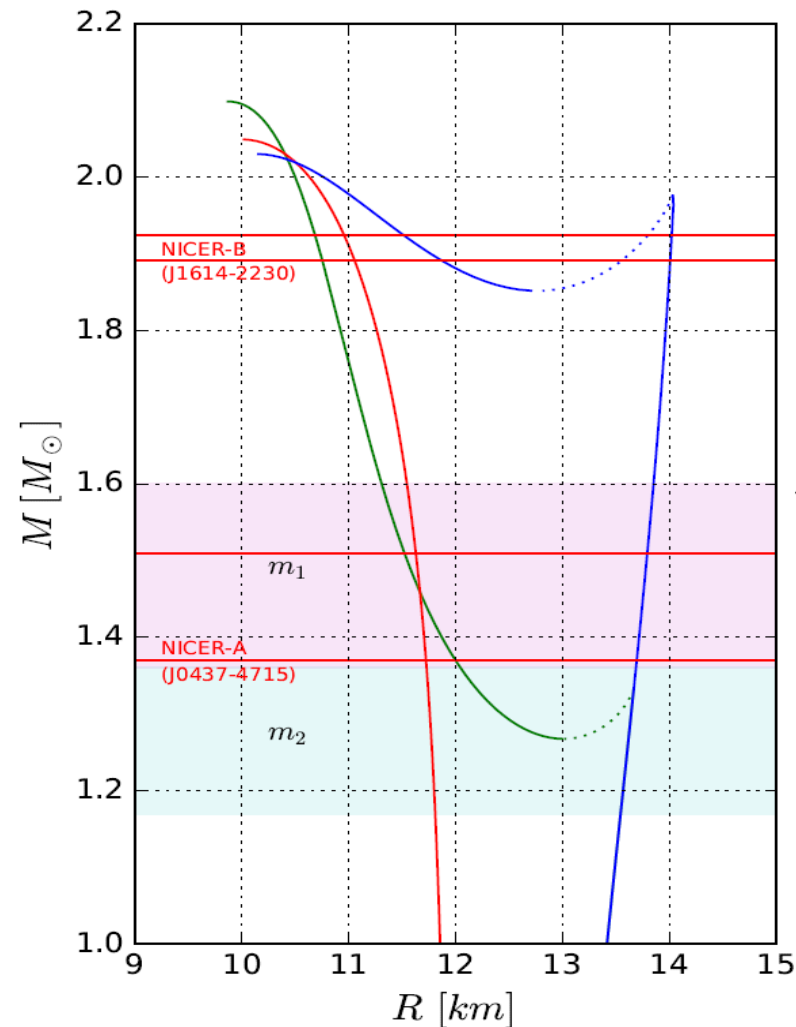


Thermal lightcurves: NS with “hot spots”

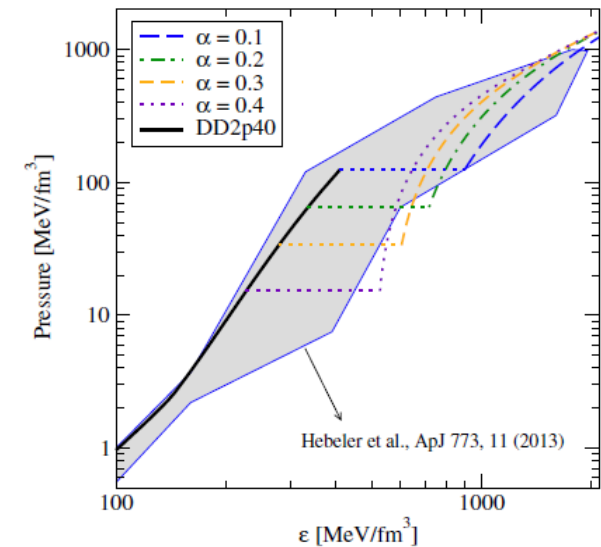


K.C. Gendreau et al., Proc. SPIE 8443 (2012) 844313 – first results end of 2019 !!

Discover the 3rd family – NICER vs. GW170817



EoS:
 DD2_P40 – SFM_α=0.3
 M. Kaltenborn et al.
 PRD 96 (2017) 056024



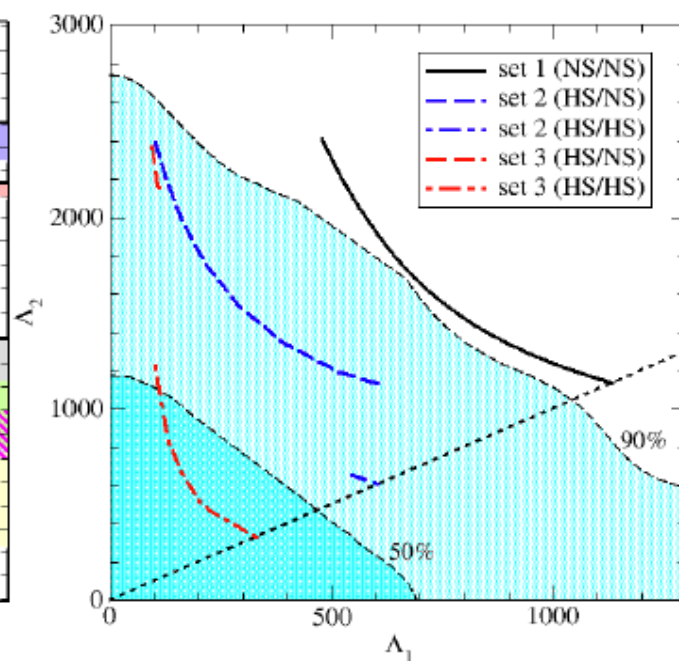
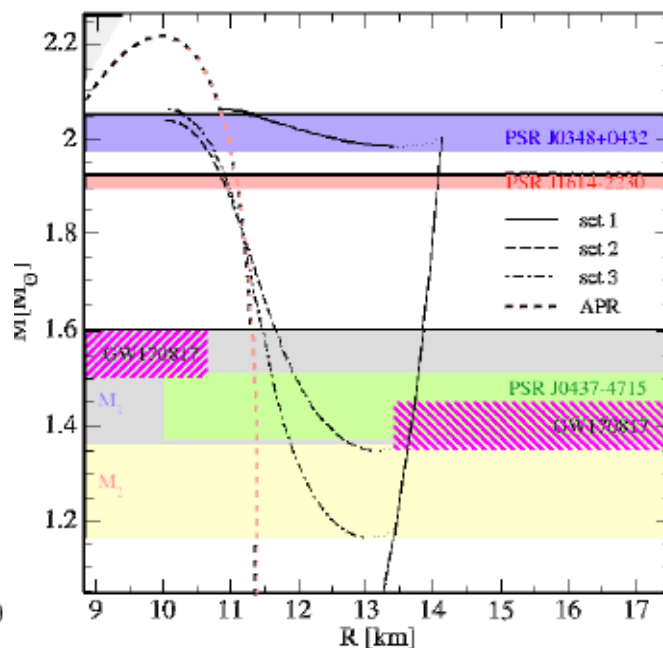
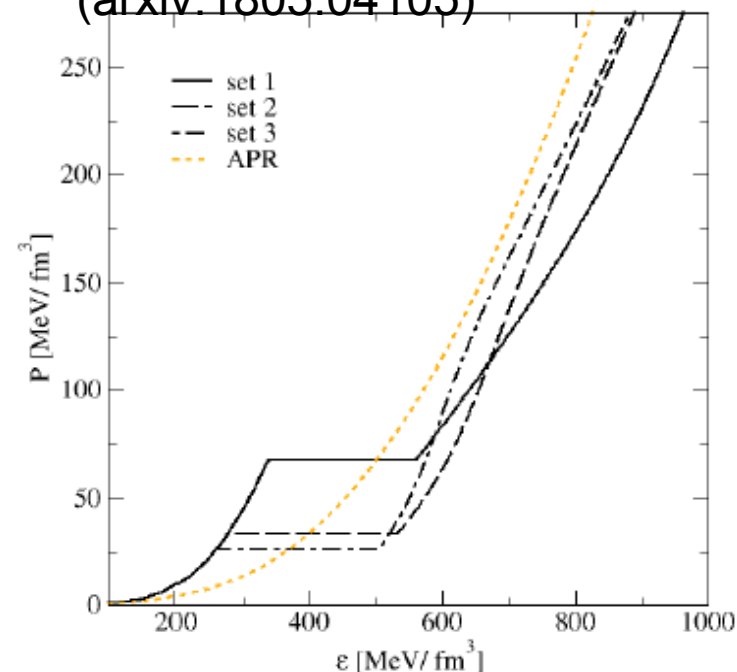
TOV / TD calculation:
 M. Bejger et al.

Alternative to NS merger with soft EoS → Hybrid star (HS) – HS / HS-NS merger

If NICER rules out soft EoS (since $R_{0437-4715} > 13.5$ km) then Third Family is Discovered !!

Discover the 3rd family – NICER vs. GW170817

Nonlocal NJL model (with interpolation), D. Alvarez-Castillo et al.
(arxiv:1805.04105)



EoS based on:

Nonlocal chiral QM with 2SC
Blaschke et al. PRC 75 (2007);
Pasta phase ext. (w/o 2SC):
Yasutake et al. PRC 89 (2014)

TOV / TD calculation:

2 $M_{\odot}$ constraint fulfilled
GW170817: $R_{1.4} < 13.6$ km
[Annala et al., PRL (2018)]
NICER: $R_{1.44} > ??$ (2018)

Pasta calculation:

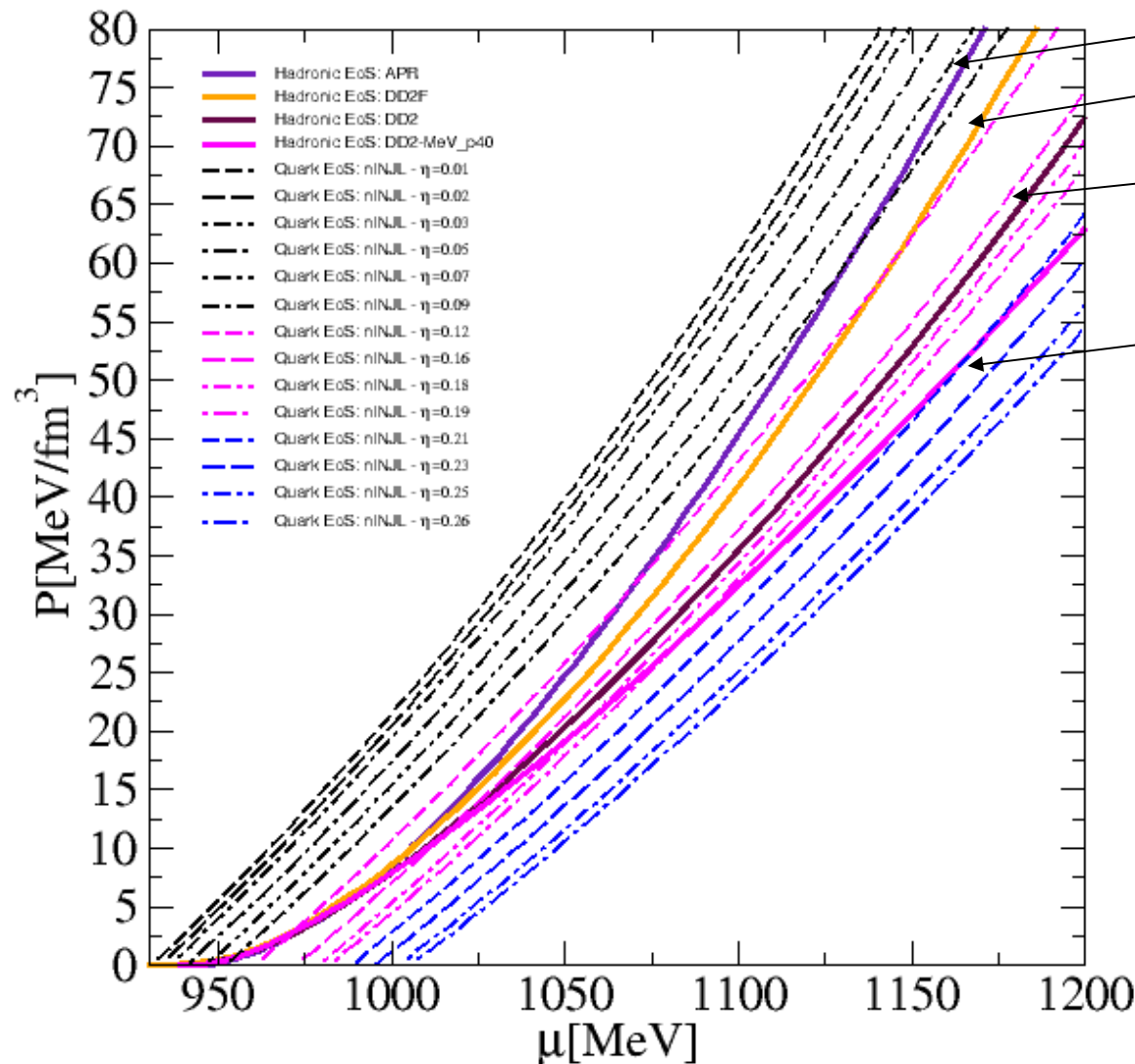
Does not spoil twin
scenario of NS-HS or
HS-HS merger!
Yasutake et al. (2018)

Alternative to NS merger with soft EoS → Hybrid star (HS) – HS / HS-NS merger

If NICER rules out soft EoS (since $R_{0437-4715} > 13.6$ km) then Evidence for Third Family !!

Maxwell Construction between Hadron and Quark Phases

D.E. Alvarez-Castillo, D.B., A.G. Grunfeld, V.P. Pagura, PRD 99 (2019); arxiv:1805.04105v3



APR
DD2F

No Maxwell construction
→ Kojo interpolation

DD2

Masquerade with nonlocal
NJLsc for eta=0.17

DD2_p40

Normal Maxwell construction

The nonlocal covariant sc quark model:

$$S_E = \int d^4x \left\{ \bar{\psi}(x) (-i\not{\partial} + m_c) \psi(x) - \frac{G_S}{2} j_S^f(x) j_S^f(x) - \frac{H}{2} [j_D^a(x)]^\dagger j_D^a(x) - \frac{G_V}{2} j_V^\mu(x) j_V^\mu(x) \right\}.$$

$$j_S^f(x) = \int d^4z g(z) \bar{\psi}(x + \frac{z}{2}) \Gamma_f \psi(x - \frac{z}{2}),$$

$$j_D^a(x) = \int d^4z g(z) \bar{\psi}_C(x + \frac{z}{2}) \Gamma_D \psi(x - \frac{z}{2})$$

$$j_V^\mu(x) = \int d^4z g(z) \bar{\psi}(x + \frac{z}{2}) i\gamma^\mu \psi(x - \frac{z}{2}).$$

Nonlocal chiral quark model - generalized

$$S_E = \int d^4x \left\{ \bar{\psi}(x) (-i\not{\partial} + m_c) \psi(x) - \frac{G_S}{2} j_S^f(x) j_S^f(x) - \frac{H}{2} [j_D^a(x)]^\dagger j_D^a(x) - \frac{G_V}{2} j_V^\mu(x) j_V^\mu(x) \right\}$$

$$j_S^f(x) = \int d^4z g(z) \bar{\psi}(x + \frac{z}{2}) \Gamma_f \psi(x - \frac{z}{2}),$$

$$j_D^a(x) = \int d^4z g(z) \bar{\psi}_C(x + \frac{z}{2}) \Gamma_D \psi(x - \frac{z}{2})$$

$$j_V^\mu(x) = \int d^4z g(z) \bar{\psi}(x + \frac{z}{2}) i\gamma^\mu \psi(x - \frac{z}{2}).$$

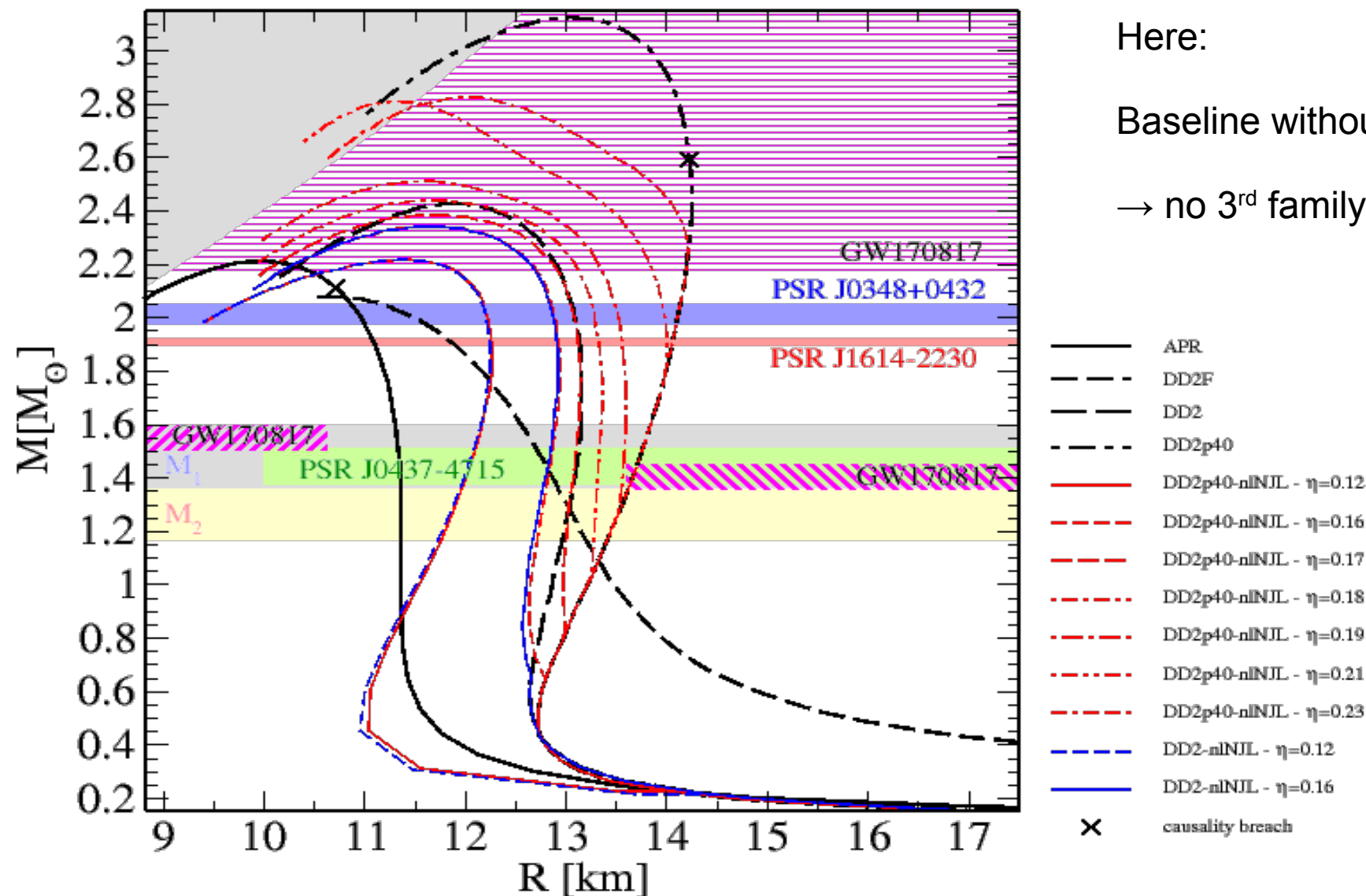
$$\Omega^{MFA} = \frac{\bar{\sigma}^2}{2G_S} + \frac{\bar{\Delta}^2}{2H} - \frac{\bar{\omega}^2}{2G_V} - \frac{1}{2} \int \frac{d^4p}{(2\pi)^4} \ln \det [S^{-1}(\bar{\sigma}, \bar{\Delta}, \bar{\omega}, \mu_{fc})]$$

$$\frac{d\Omega^{MFA}}{d\bar{\Delta}} = 0, \quad \frac{d\Omega^{MFA}}{d\bar{\sigma}} = 0, \quad \frac{d\Omega^{MFA}}{d\bar{\omega}} = 0.$$

$$P(\mu; \eta, B) = -\Omega^{MFA} - B$$

D.B., D. Gomez-Dumm, A.G. Grunfeld, T. Klaehn, N.N. Scoccola,
 “Hybrid stars within a covariant, nonlocal chiral quark model”,
 Phys. Rev. C 75, 065804 (2007)

Maxwell Construction between Hadron and Quark Phases



Violation of upper limit on maximum mass from GW170817 – does it matter?

Interpolating between Quark Phase Parametrizations

Twofold interpolation method:

1. to model the unknown density dependence of the confining mechanism by interpolating a bag pressure contribution between zero and a finite value B at low densities in the vicinity of the hadron-to-quark matter transition, and
2. to model a density dependent stiffening of the quark matter EoS at high density by interpolating between EoS for two values of the vector coupling strength, $\eta_<$ and $\eta_>$.

$$P(\mu) = [f_<(\mu)(P(\mu; \eta_<) - B) + f_>(\mu)P(\mu; \eta_<)]f_{\ll}(\mu) + f_{\gg}(\mu)P(\mu; \eta_>)$$

$$f_<(\mu) = \frac{1}{2} \left[1 - \tanh \left(\frac{\mu - \mu_<}{\Gamma_<} \right) \right], \quad f_{\ll}(\mu) = \frac{1}{2} \left[1 - \tanh \left(\frac{\mu - \mu_{\ll}}{\Gamma_{\ll}} \right) \right],$$

$$f_>(\mu) = 1 - f_<(\mu), \quad f_{\gg}(\mu) = 1 - f_{\ll}(\mu).$$

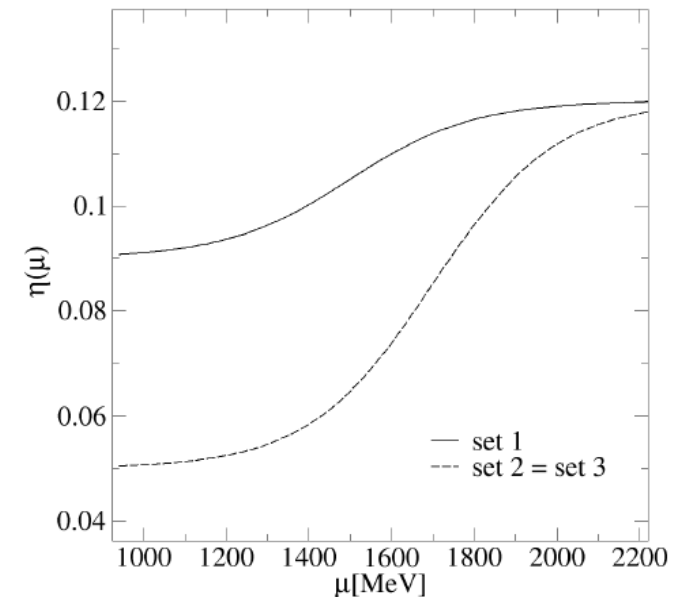
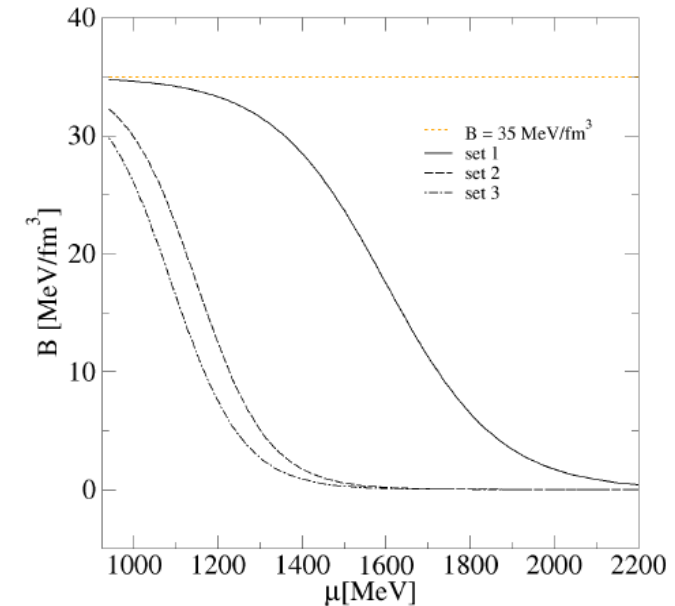
Interpolation vs. medium dependence of coefficients

$$\begin{aligned}
 P(\mu) &= P(\mu; \eta, B) f_{<}(\mu) + P(\mu; \eta, 0) f_{>}(\mu) \\
 &= P(\mu; \eta, 0) [f_{<}(\mu) + f_{>}(\mu)] - B f_{<}(\mu) \\
 &= P(\mu; \eta, B(\mu)),
 \end{aligned}$$

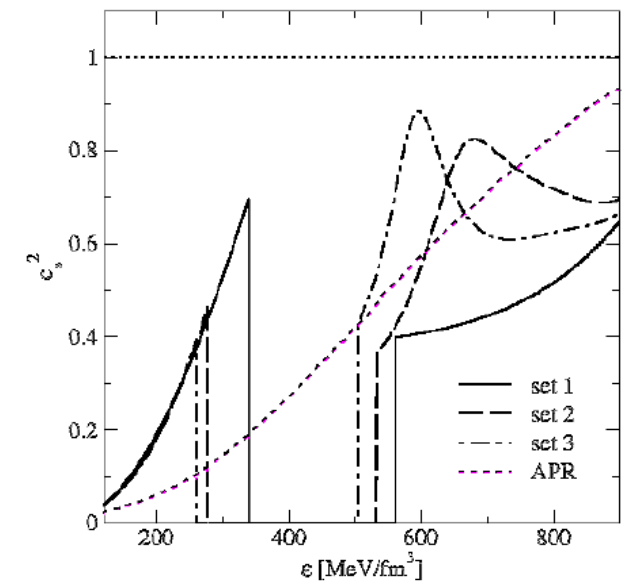
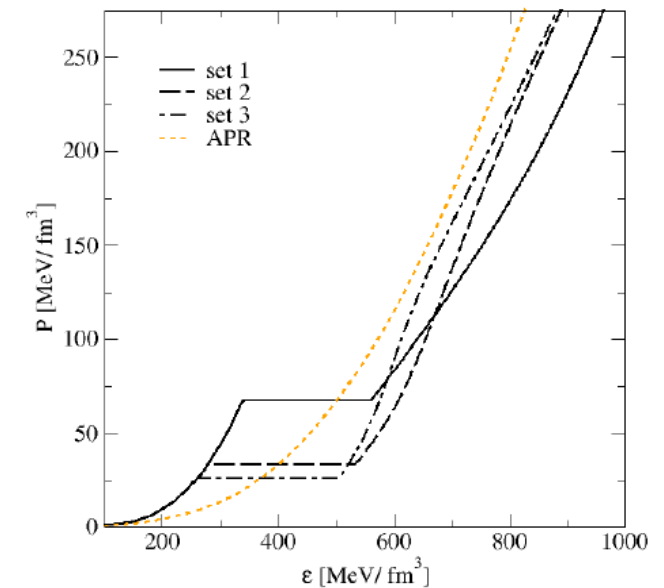
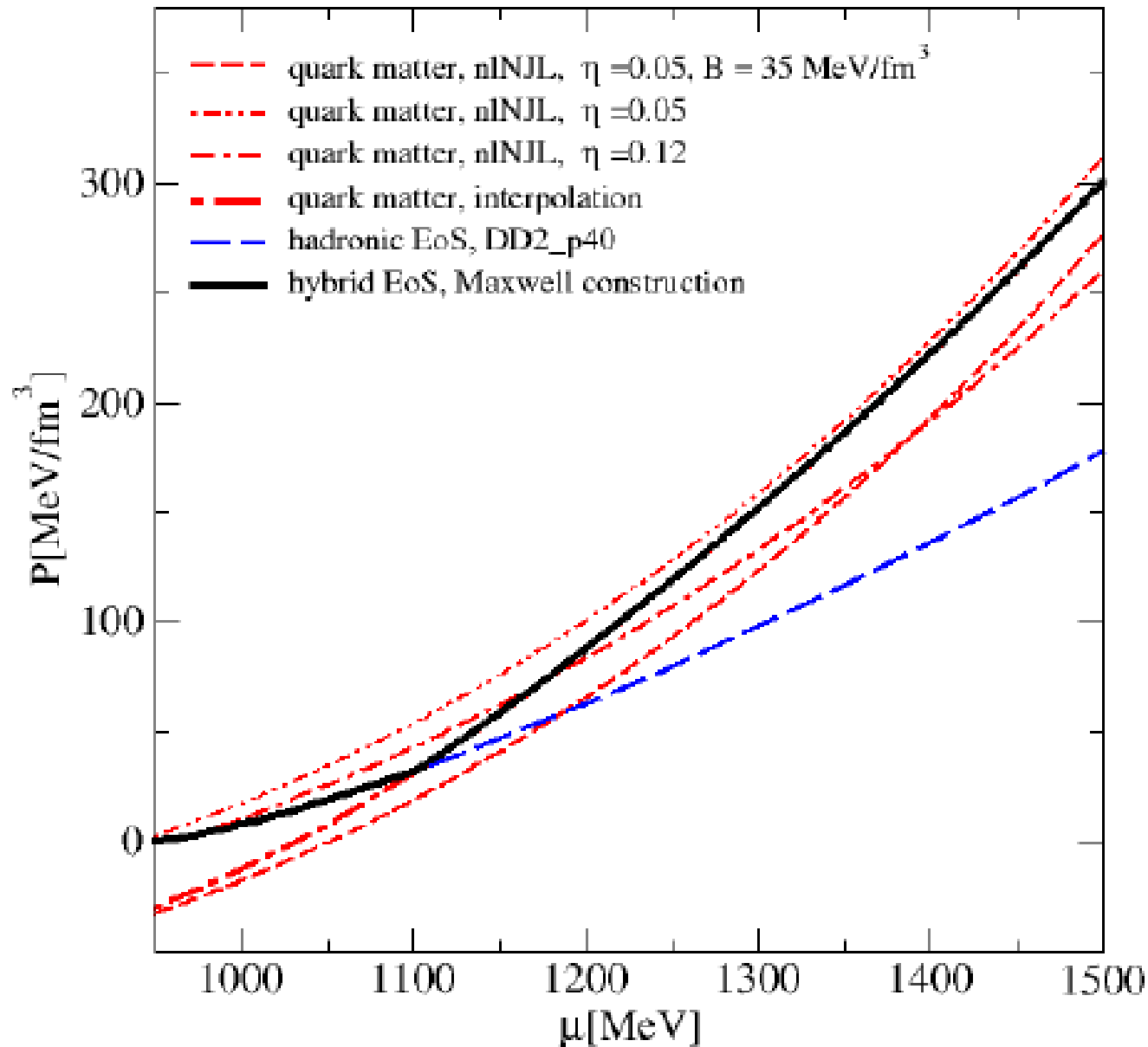
$B(\mu) = B f_{<}(\mu)$ is the μ -dependent bag pressure

$$\begin{aligned}
 P(\mu) &= P(\mu; \eta_{<}, B) f_{\ll}(\mu) + P(\mu; \eta_{>}, B) f_{\gg}(\mu) \\
 &= P(\mu; \eta_{<}, B) [f_{\ll}(\mu) + f_{\gg}(\mu)] \\
 &\quad + (\eta_{>} - \eta_{<}) f_{\gg}(\mu) \left. \frac{dP(\mu; \eta, B)}{d\eta} \right|_{\eta=\eta_{<}} \\
 &= P(\mu; \eta_{<}, B) \\
 &\quad + [\eta_{>} f_{\gg}(\mu) + \eta_{<} f_{\ll}(\mu) - \eta_{<}] \left. \frac{dP(\mu; \eta, B)}{d\eta} \right|_{\eta=} \\
 &= P(\mu; \eta(\mu), B),
 \end{aligned}$$

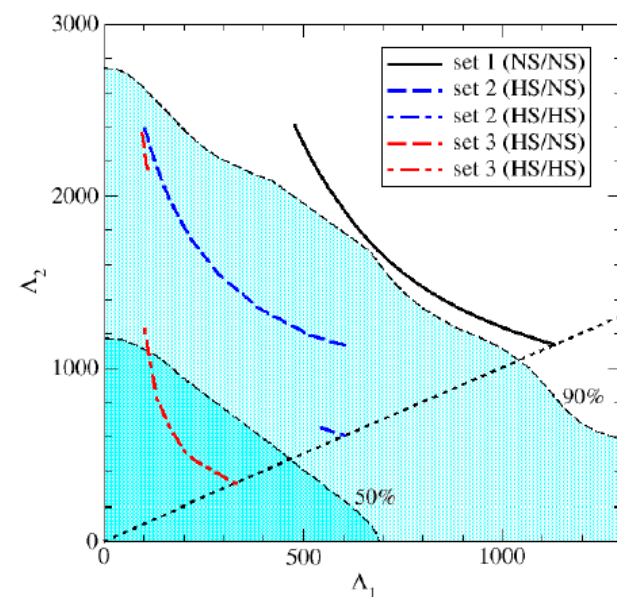
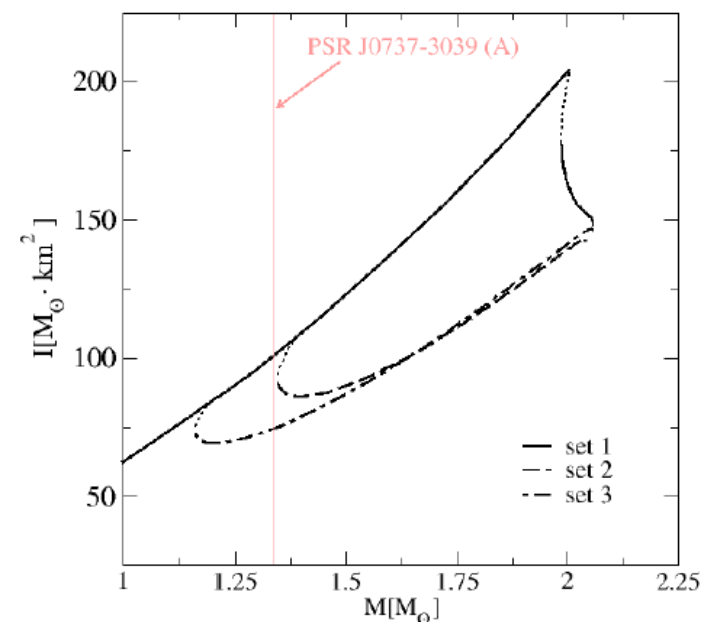
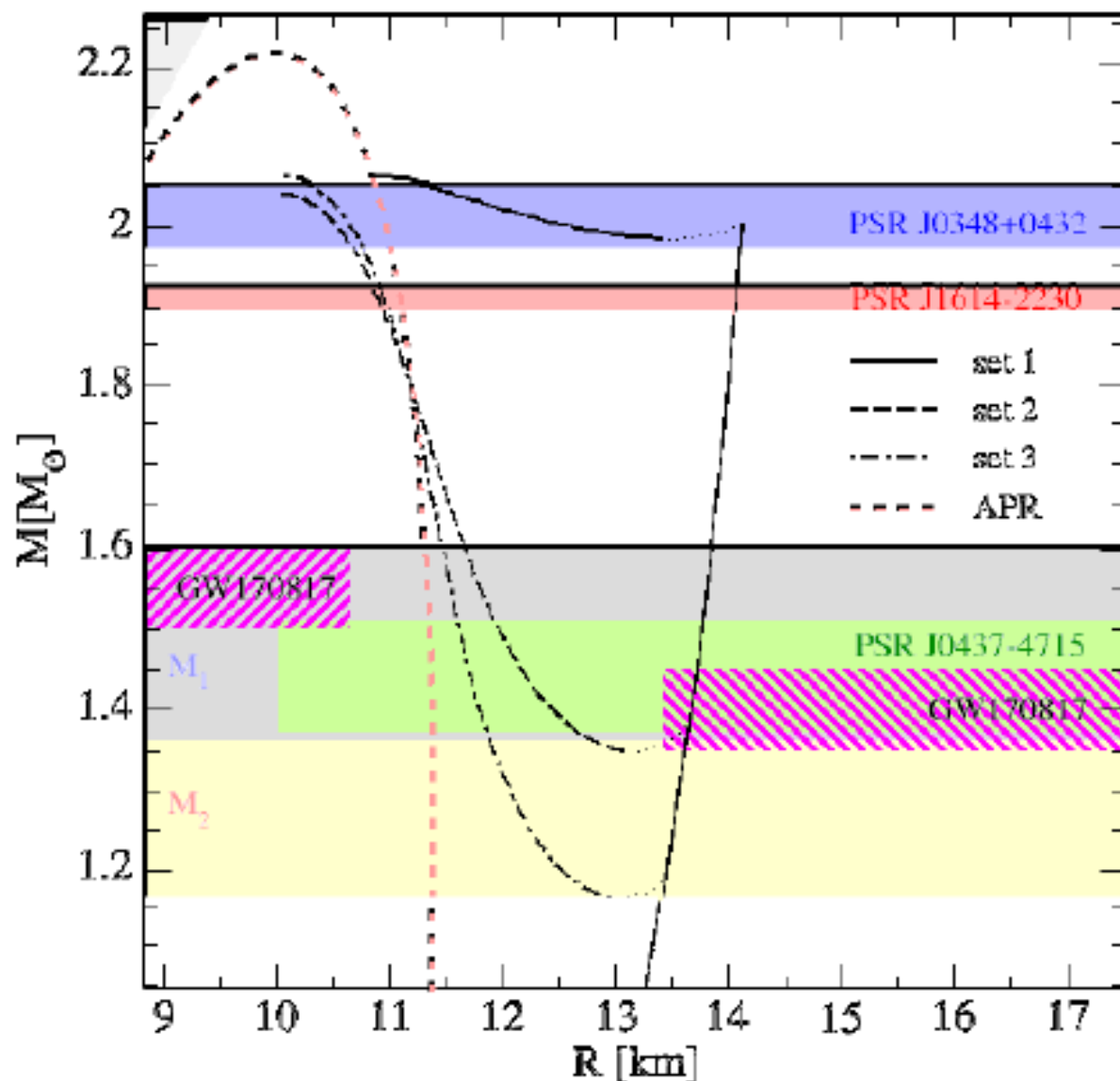
$\eta(\mu) = \eta_{>} f_{\gg}(\mu) + \eta_{<} f_{\ll}(\mu)$ is the medium-dependent vector meson coupling



Maxwell Construction between Hadron and Quark Phases



Maxwell Construction between Hadron and Quark Phases

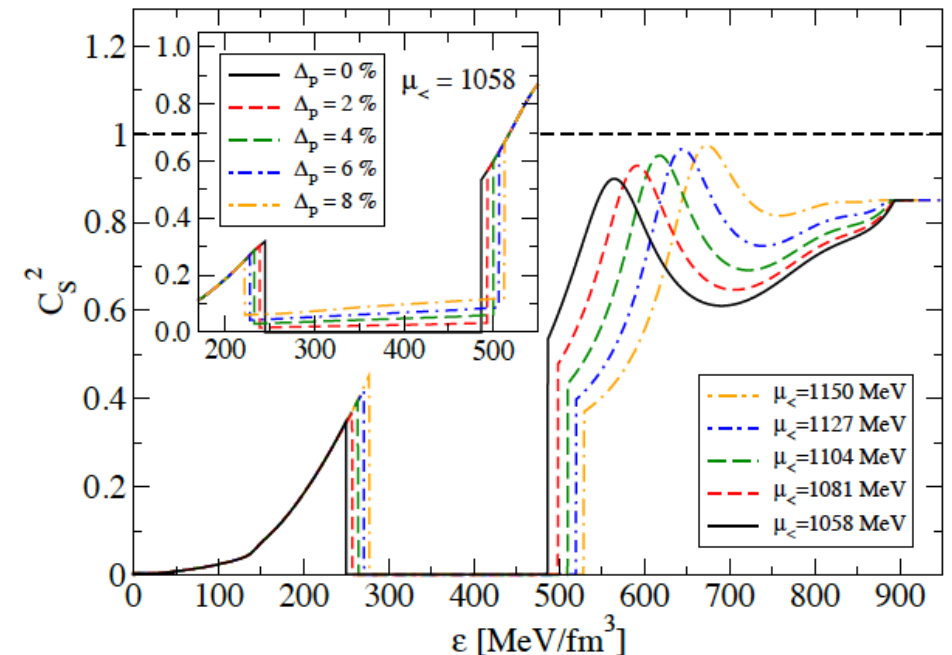
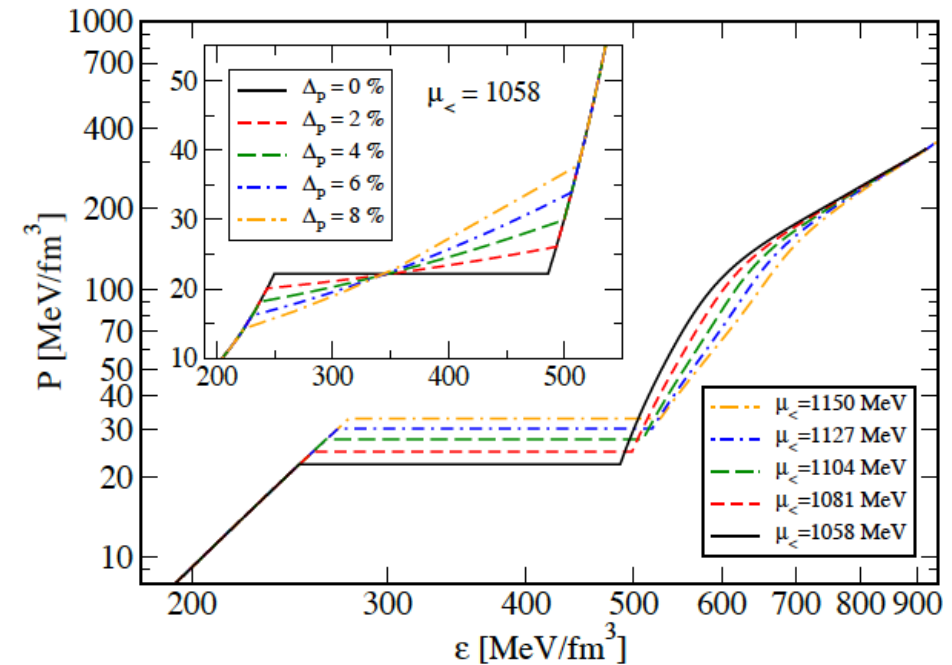
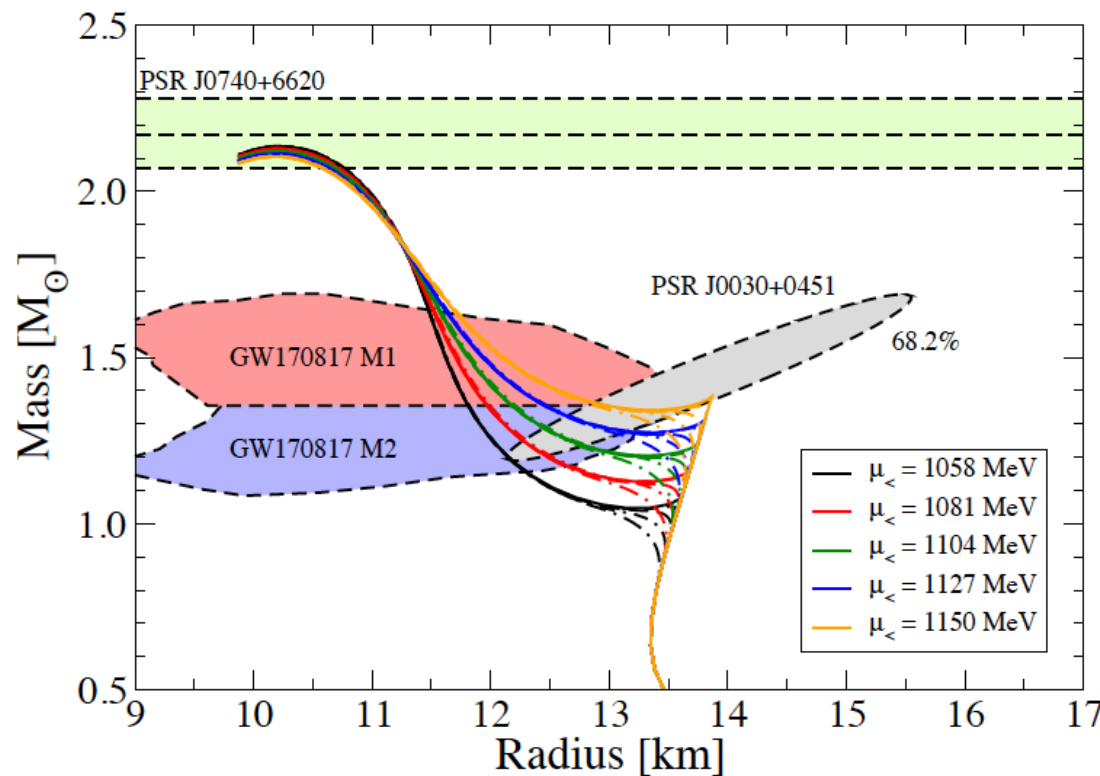


Was GW170817 indeed a binary Neutron Star Merger ?

A Bayesian Analysis for Hybrid Equations of State

- Mass $2.17^{+0.11}_{-0.10} M_{\text{sun}}$ &
- Compactness (tidal deform.) GW170817
- Additional (fictitious) radius measurement (NICER preliminary, PSR J0030+0451)

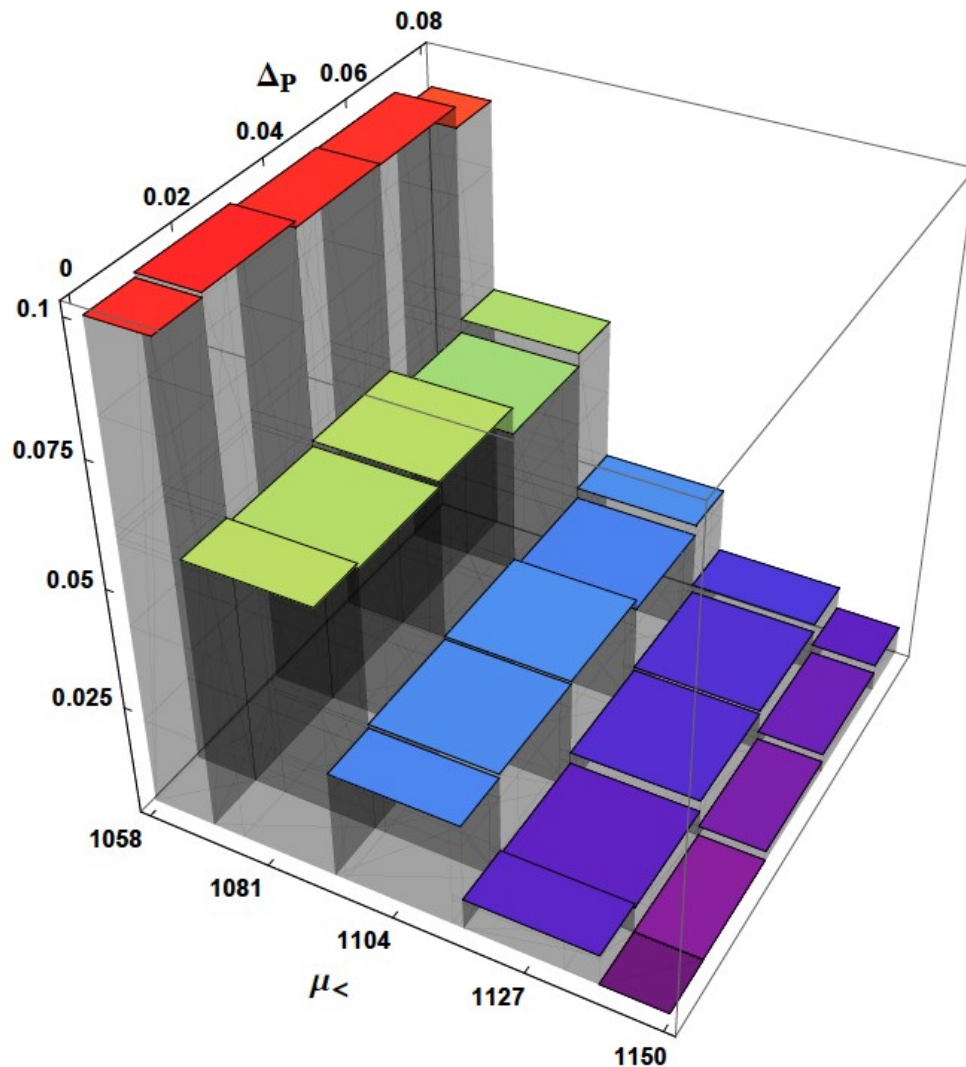
→ Two-parameter family EoS: $\mu_{\leq}$, Δ_P



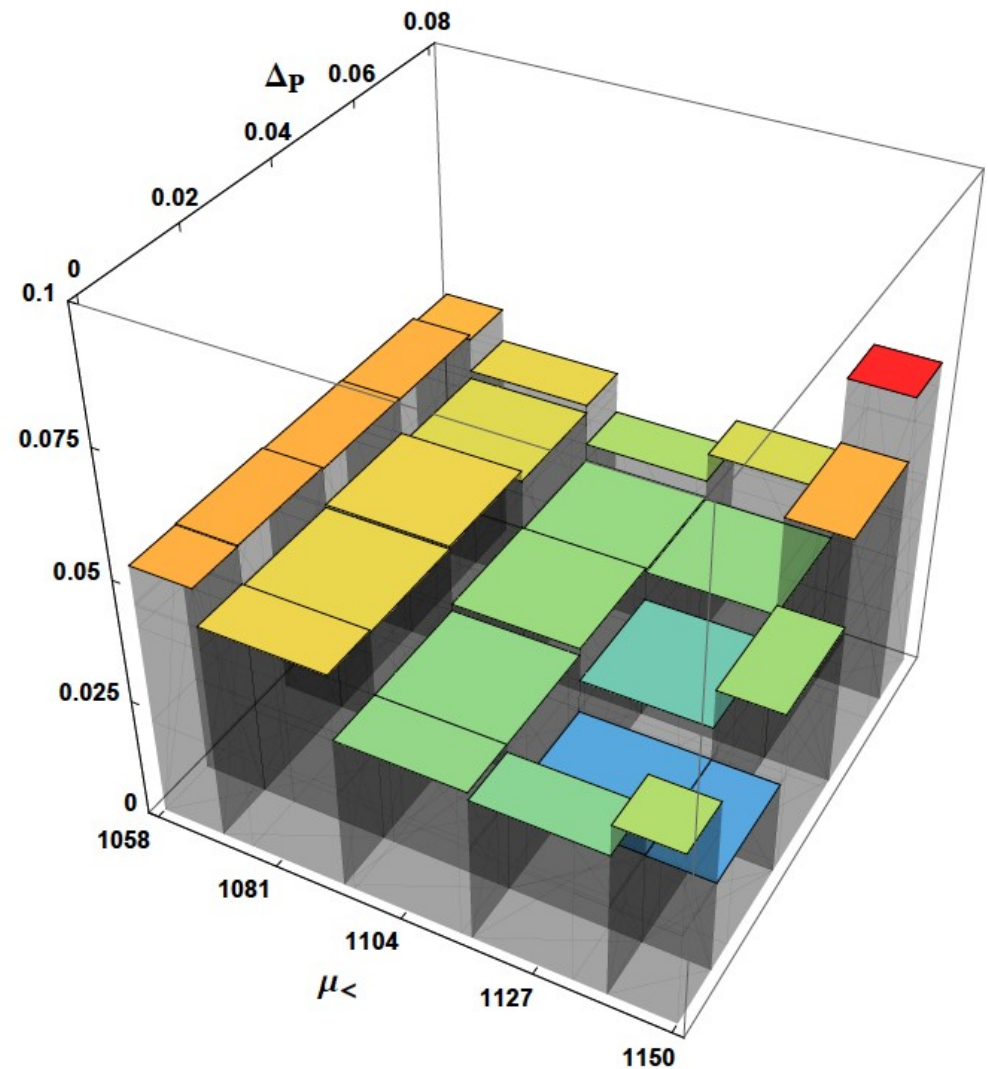
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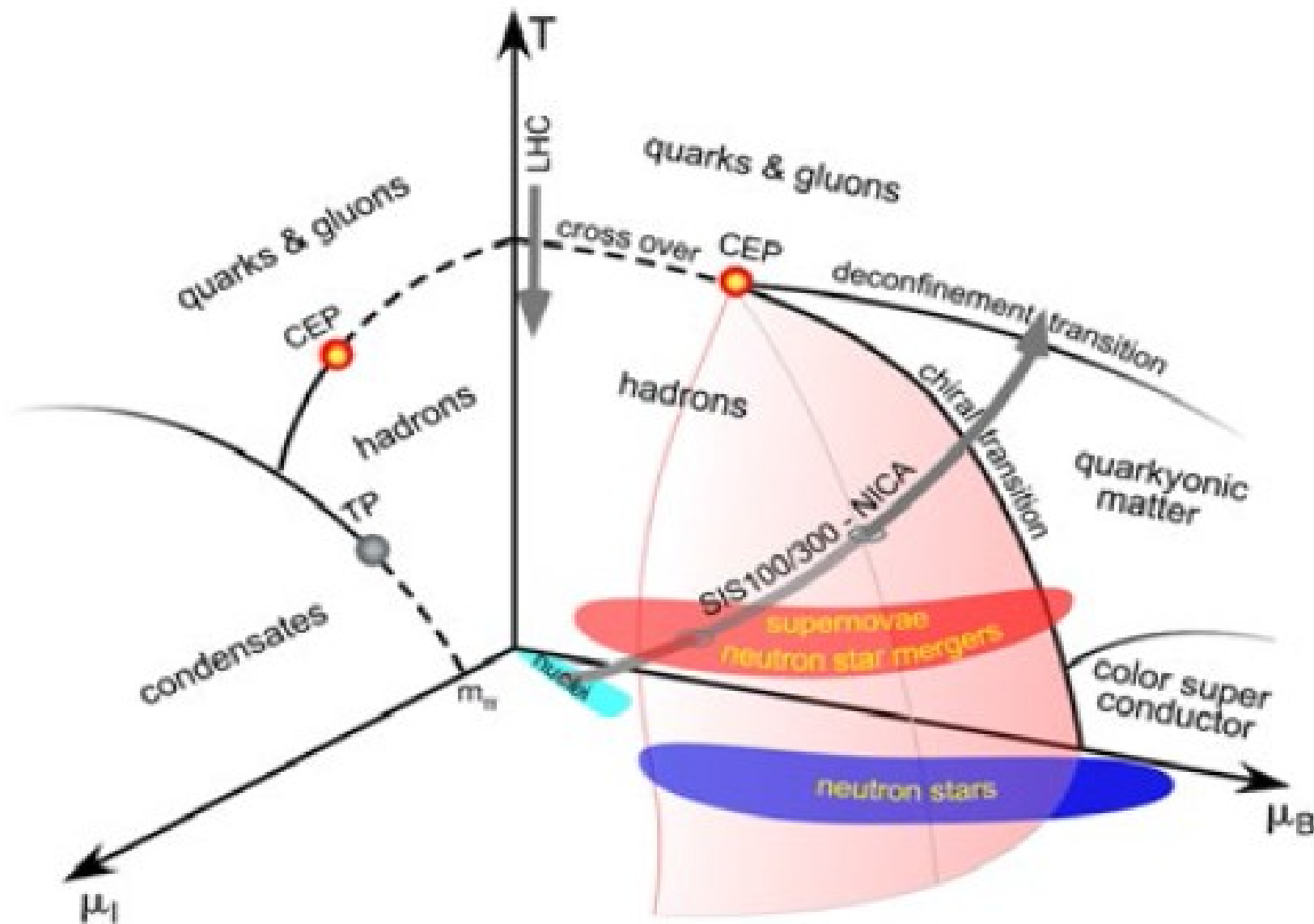
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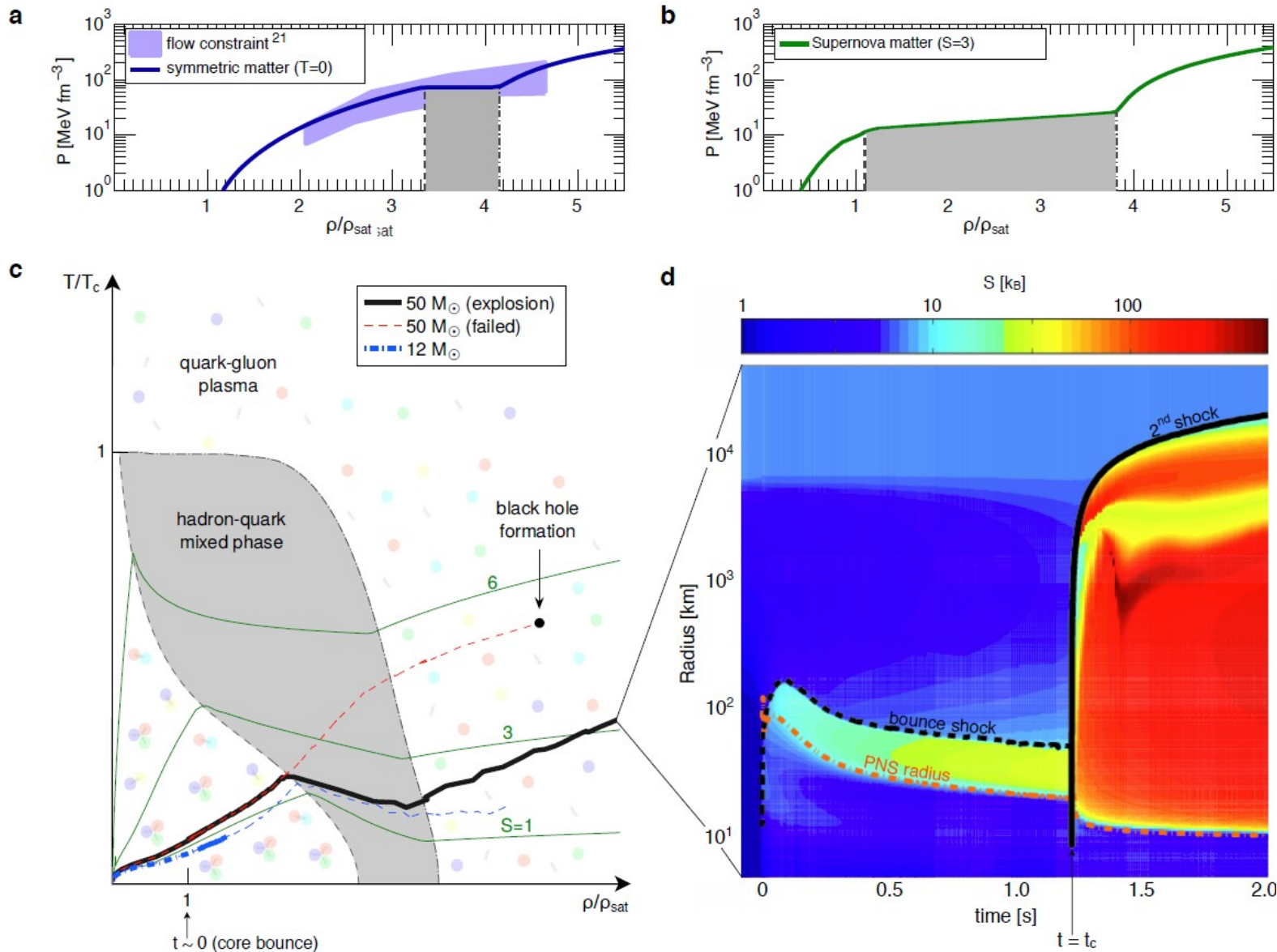
Additional (fictitious) radius measurement
(NICER preliminary, PSR J0030+0451)



CEP in the QCD phase diagram: HIC vs. Astrophysics



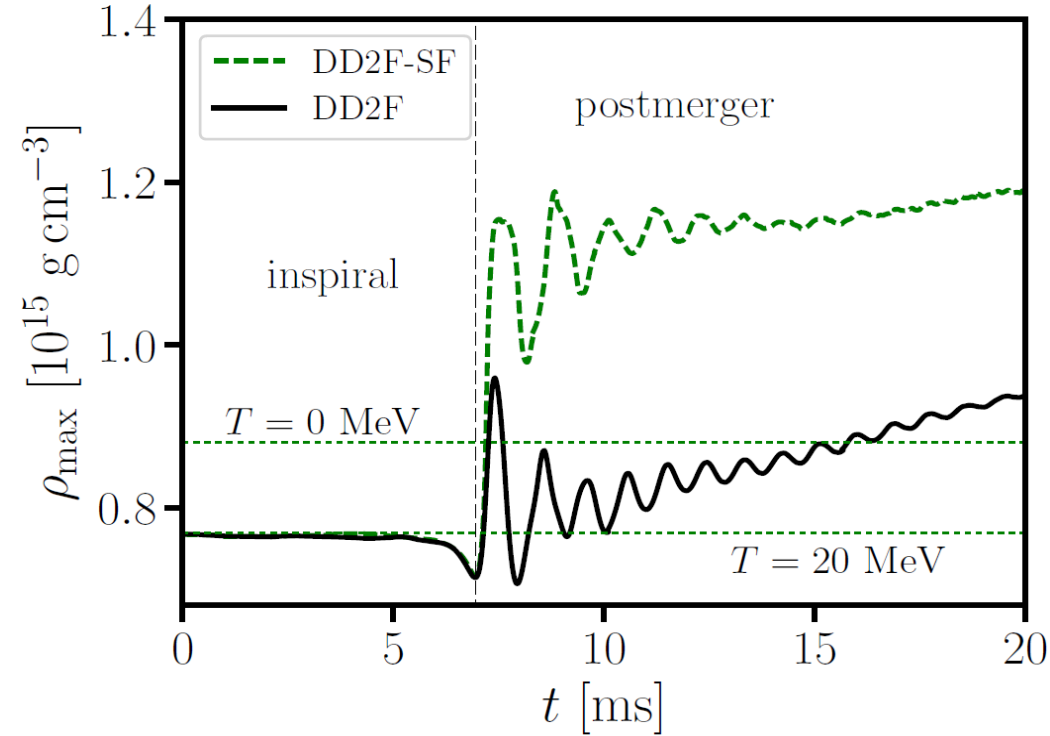
Deconfinement transition as SN explosion mechanism



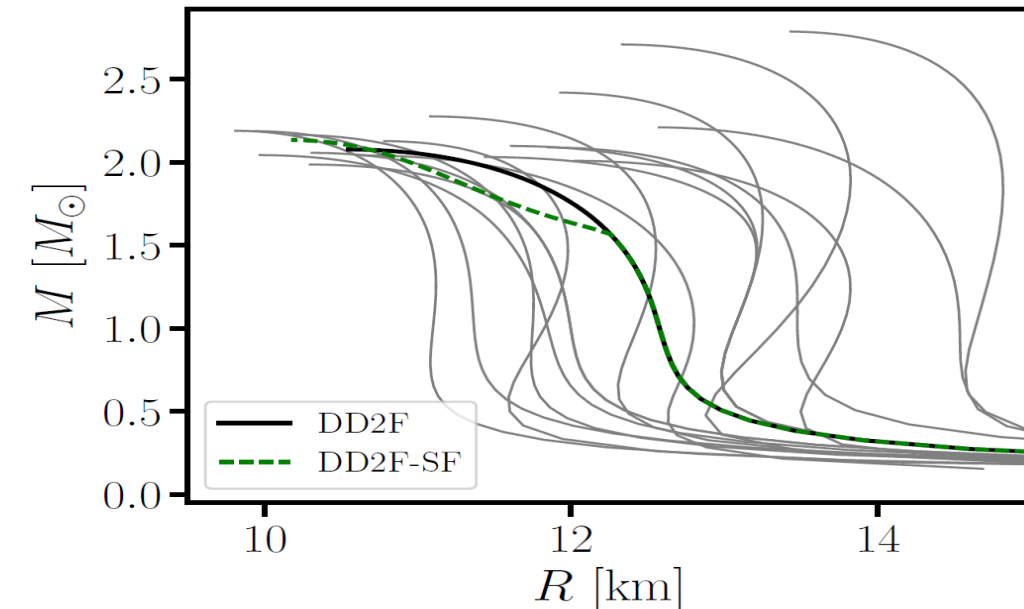
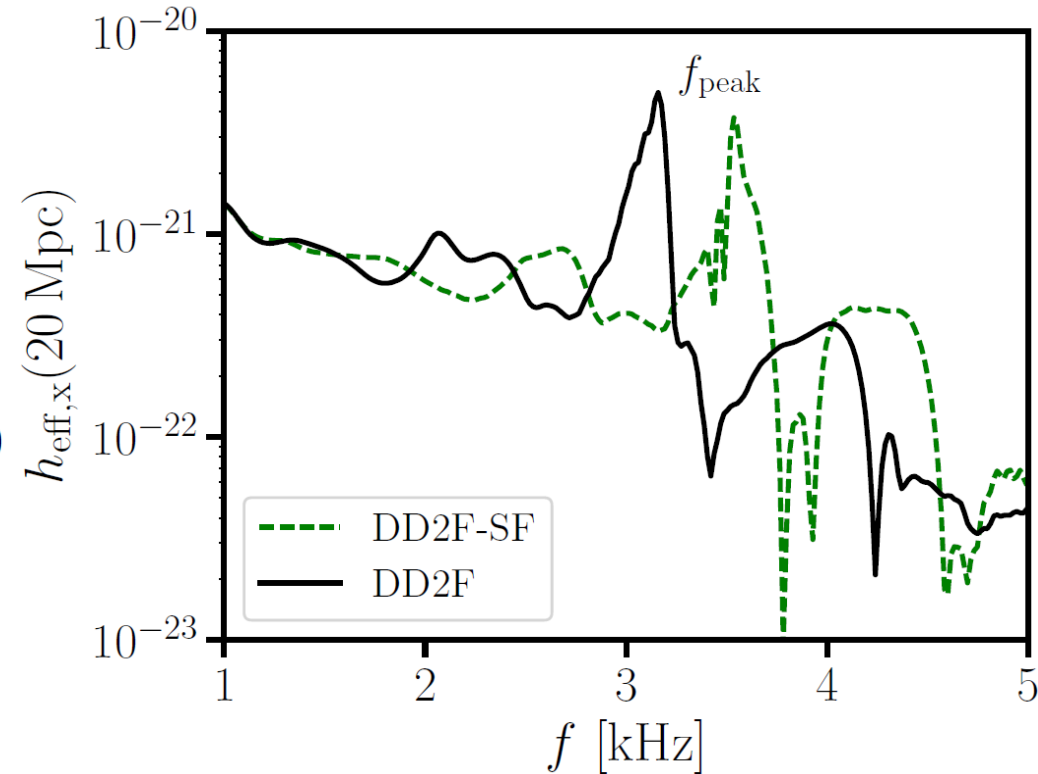
Progenitor:
 $M = 50 M_{\odot}$

T. Fischer, N.-U. Bastian et al., Quark deconfinement as supernova engine of massive blue Supergiant star explosions, *Nature Astronomy* 2 (2018) 980-986; arxiv:1712.08788

Hybrid star formation in postmerger phase



Strong phase transition in postmerger GW,
A. Bauswein et al. arxiv:1809.01116

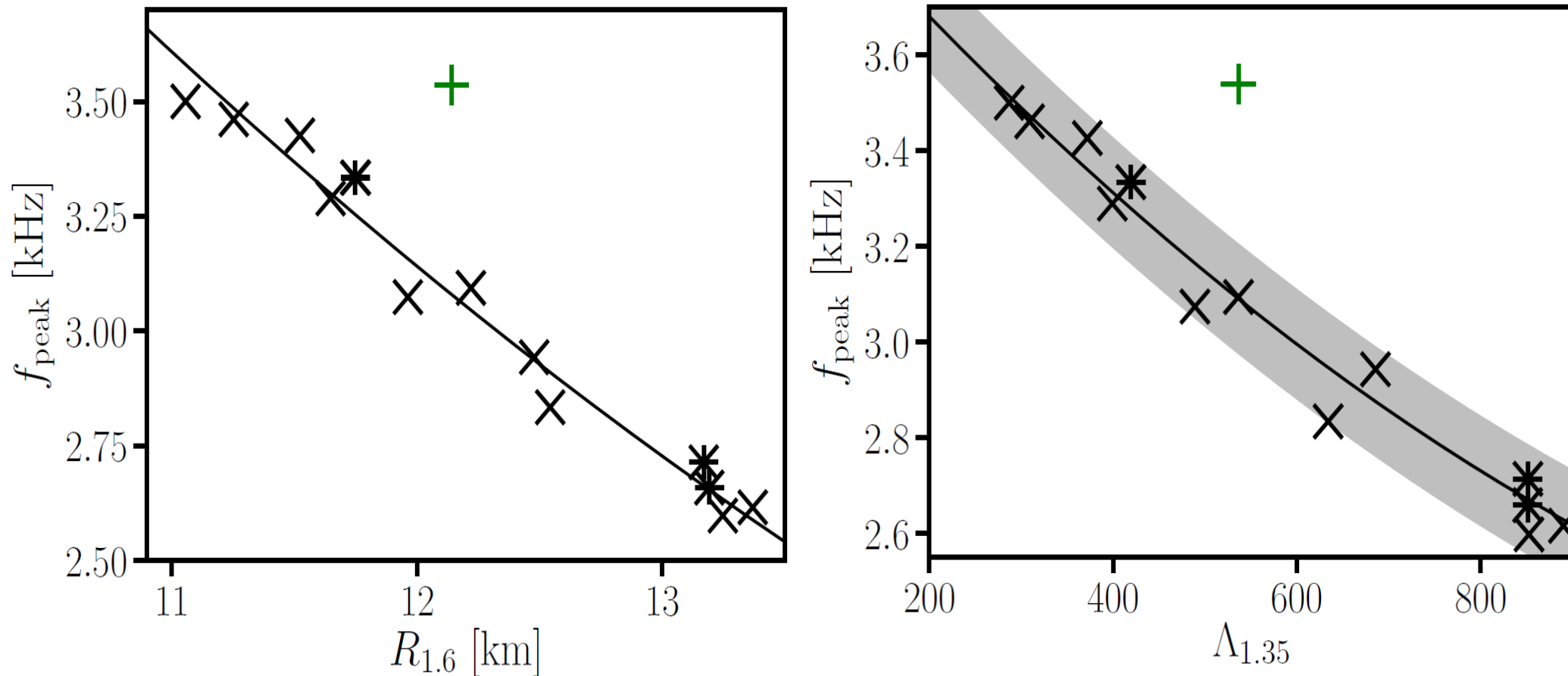


Hybrid star formation during NS merger
→ higher densities and compacter star
→ higher peak frequency of the GW

A. Bauswein et al., PRL 122 (2019) 061102

Hybrid star formation in postmerger phase

Strong phase transition in postmerger GW signal,
A. Bauswein et al., PRL 122 (2019) 061102; [arxiv:1809.01116]

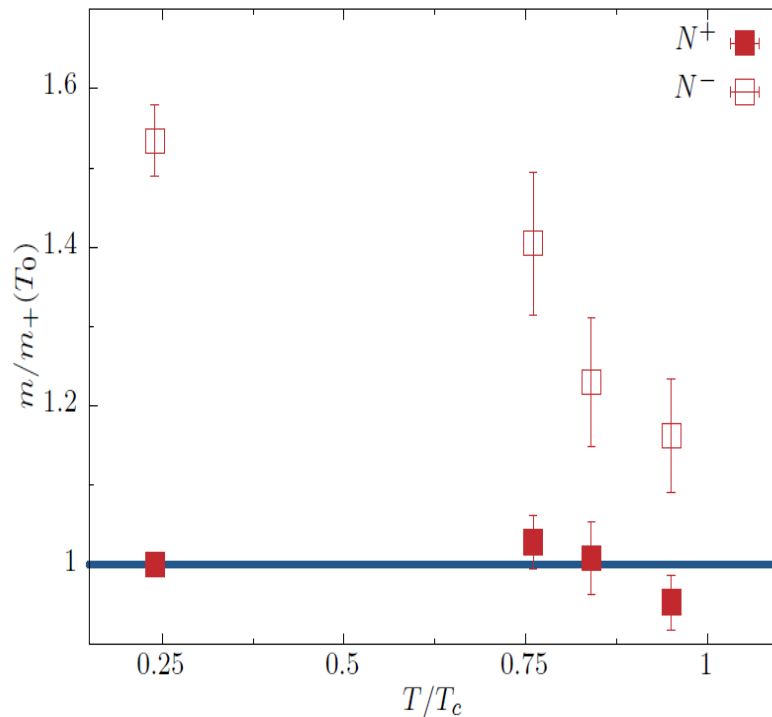


Strong deviation from $f_{\text{peak}} - R_{1.6}$ relation signals **strong phase transition** in NS merger!

Complementarity of f_{peak} from **postmerger** with tidal deformability $\Lambda_{1.35}$ from **inspiral phase**.

Caveat: Strong transition may not be deconfinement !

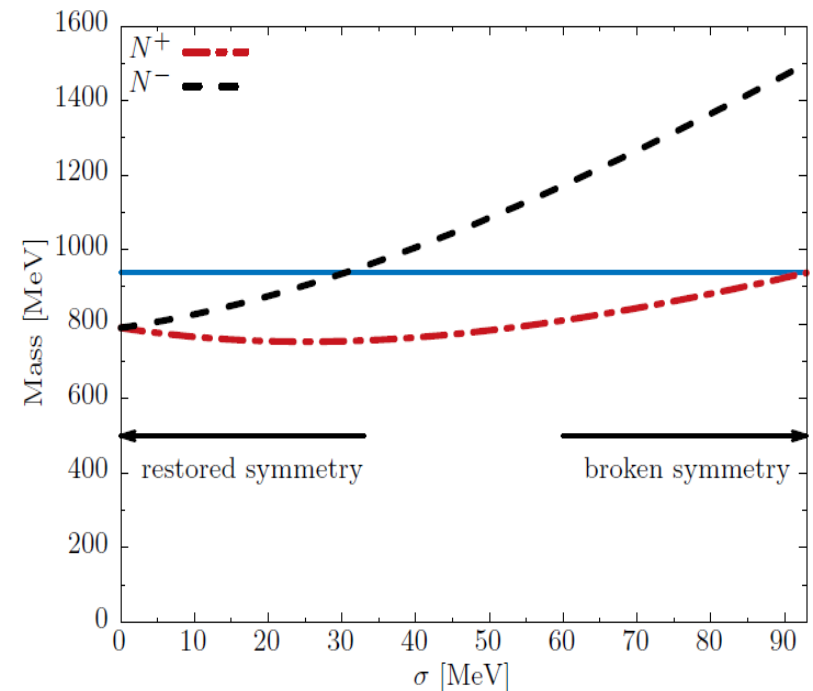
Parity doubling in lattice QCD Aarts et al, JHEP 1706, 034 (2017)



- Imprint of chiral symmetry restoration in the baryonic sector
- Expected to occur at low temperature

Parity doubling in SU(2) chiral models DeTar, Kunihiro PRD 39 2805 (1989)

$$m^\pm = \frac{1}{2} \left[\sqrt{(g_1 + g_2)^2 \sigma^2 + 4m_0^2} \mp (g_1 - g_2) \sigma \right] \xrightarrow{\sigma \rightarrow 0} m_0$$

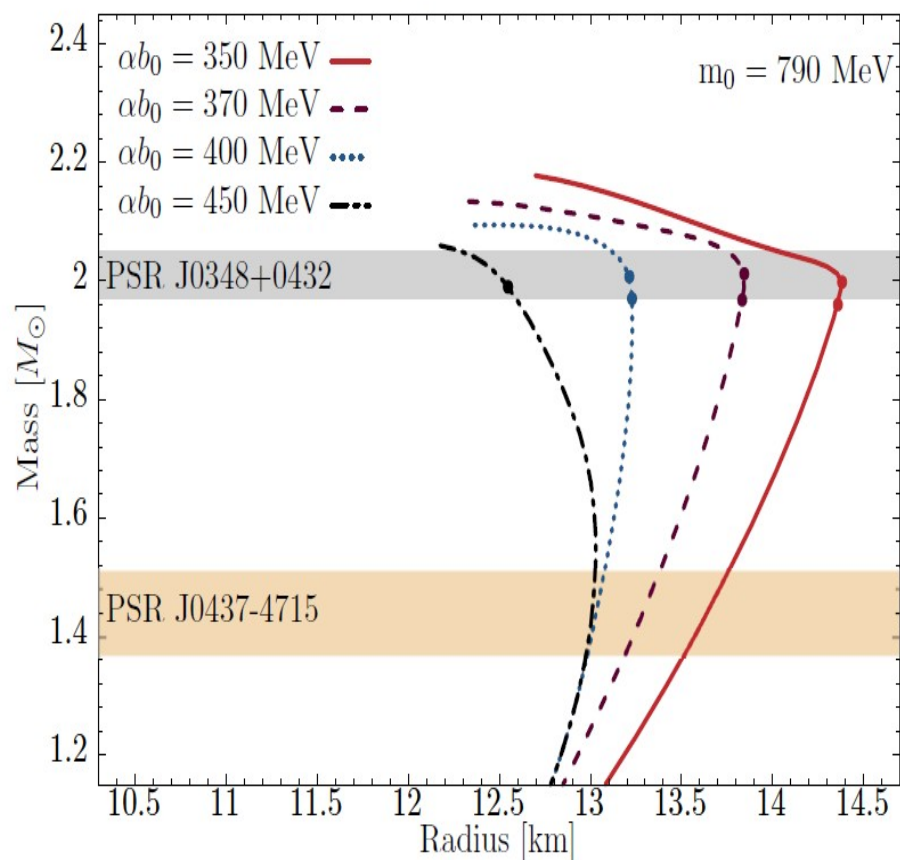


M. Marczenko, D.B., C. Sasaki, K. Redlich, Chiral symmetry restoration by parity doubling and structure of neutron stars, Phys. Rev. D98 (2018) 103021; [arxiv:1805.06886]

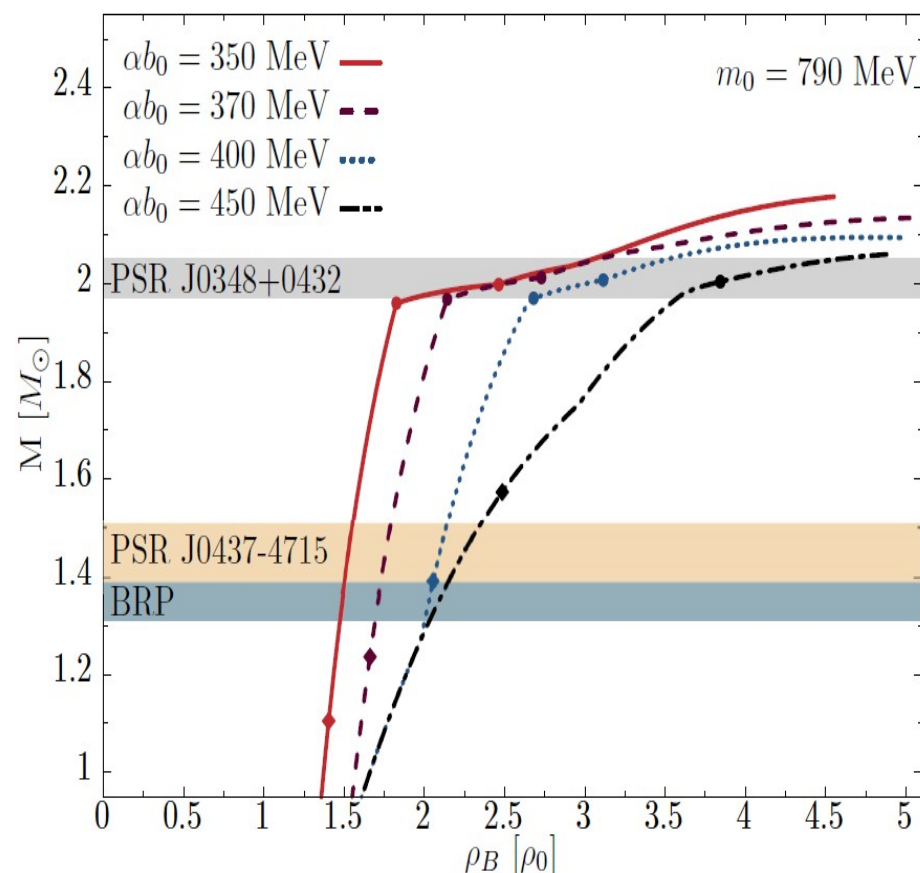
Caveat: Strong transition may not be deconfinement !

Mass-radius relation

- chiral transition in high-mass part of the sequence
- $2M_{\odot}$ with chirally restored and confined core
- deconfinement above $2M_{\odot}$



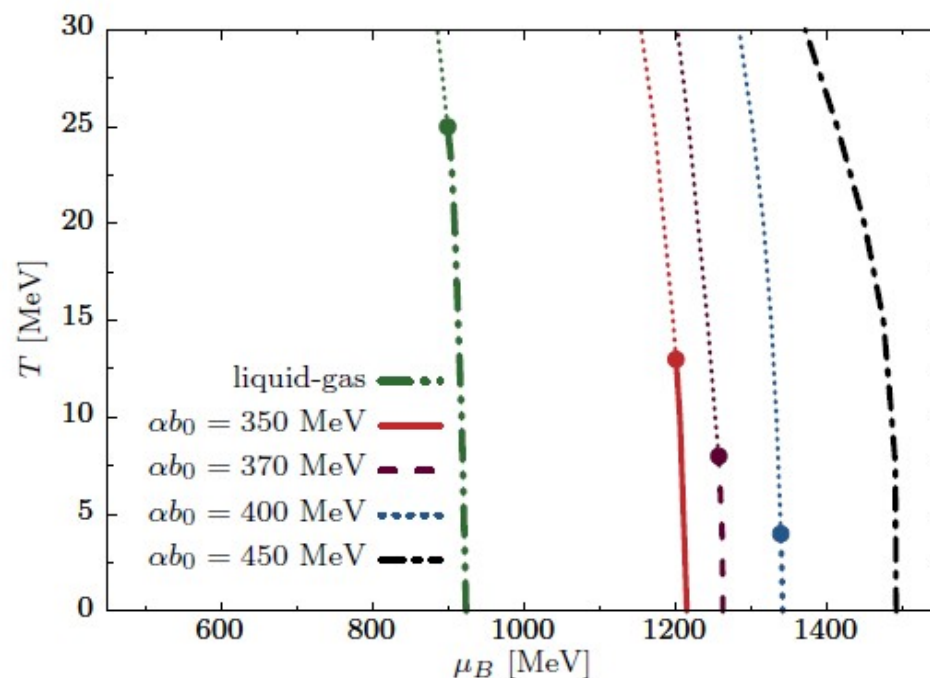
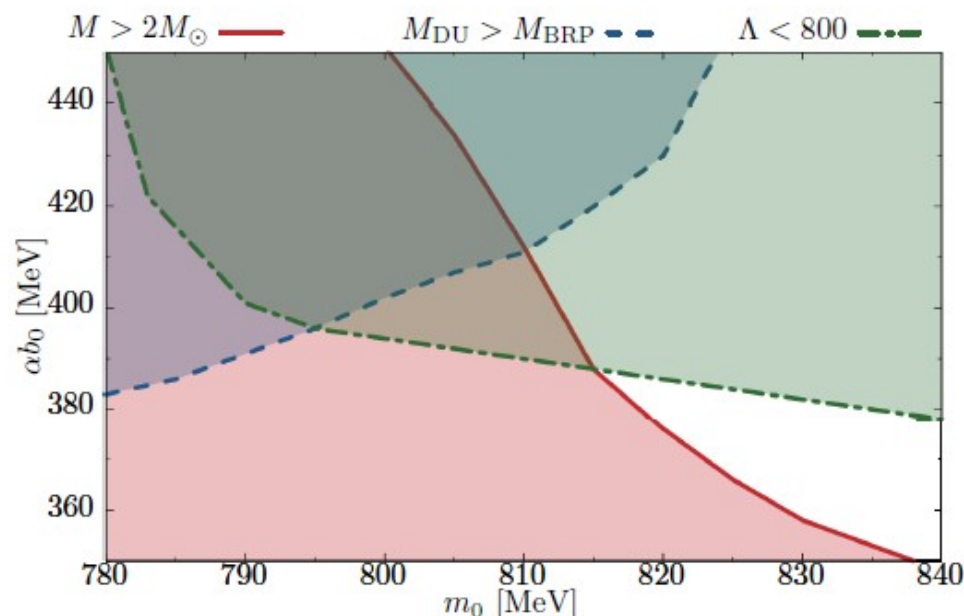
mass-density



M. Marczenko, D.B., C. Sasaki, K. Redlich, Chiral symmetry restoration by parity doubling and structure of neutron stars, Phys. Rev. D98 (2018) 103021; [arxiv:1805.06886]

Caveat: Strong transition may not be deconfinement !

Back to symmetric-matter QCD Phase Diagram



■ $2M_\odot \rightarrow$ stiff EoS

■ DU $\rightarrow$ soft EoS

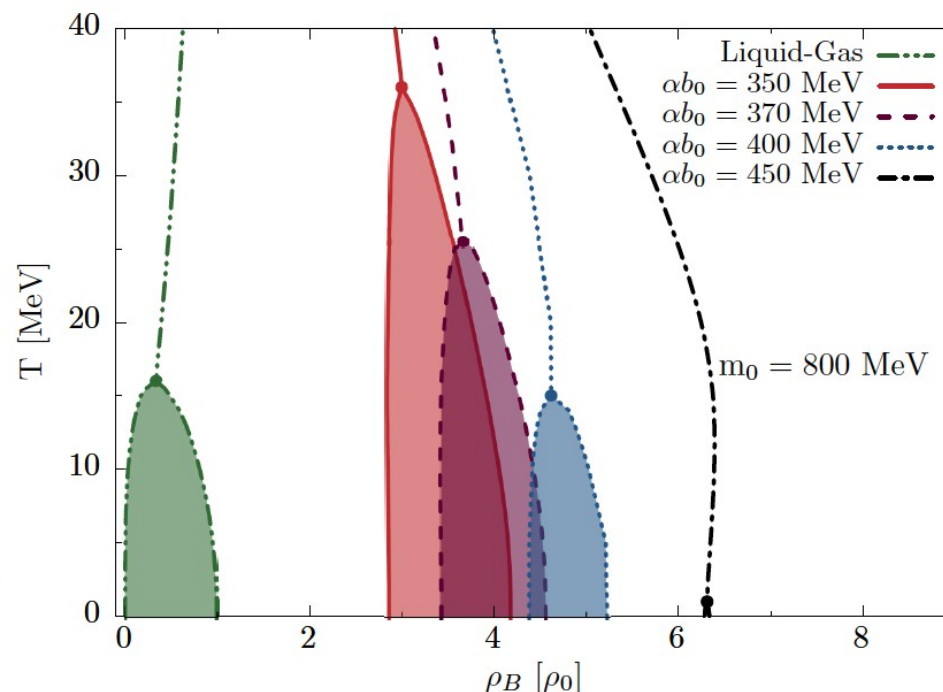
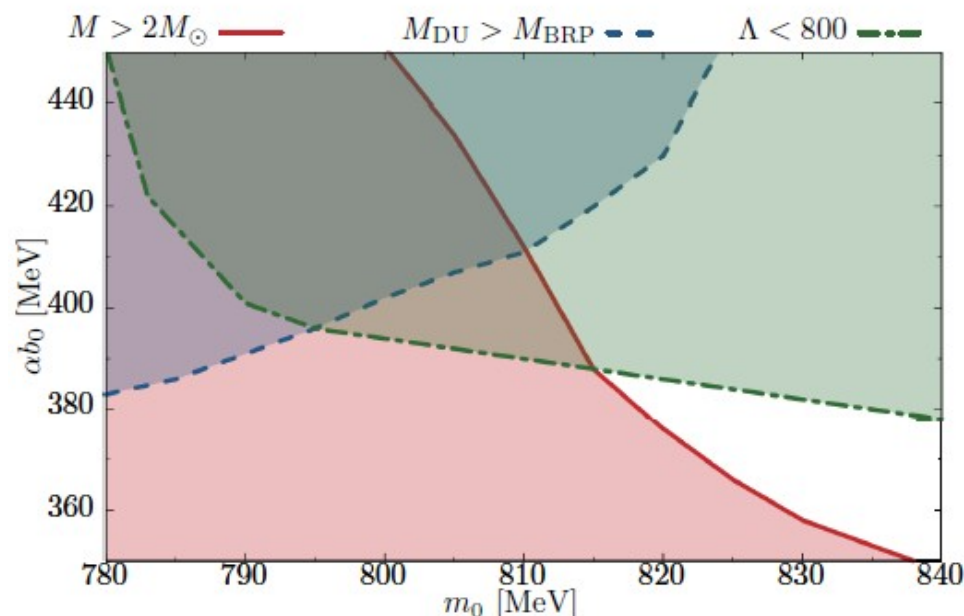
■ TD $\rightarrow$ soft EoS

■ CEP at low T or even absent!

M. Marczenko, D.B., C. Sasaki, K. Redlich, Chiral symmetry restoration by parity doubling and structure of neutron stars, Phys. Rev. D98 (2018) 103021; [arxiv:1805.06886]

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Back to symmetric-matter QCD Phase Diagram



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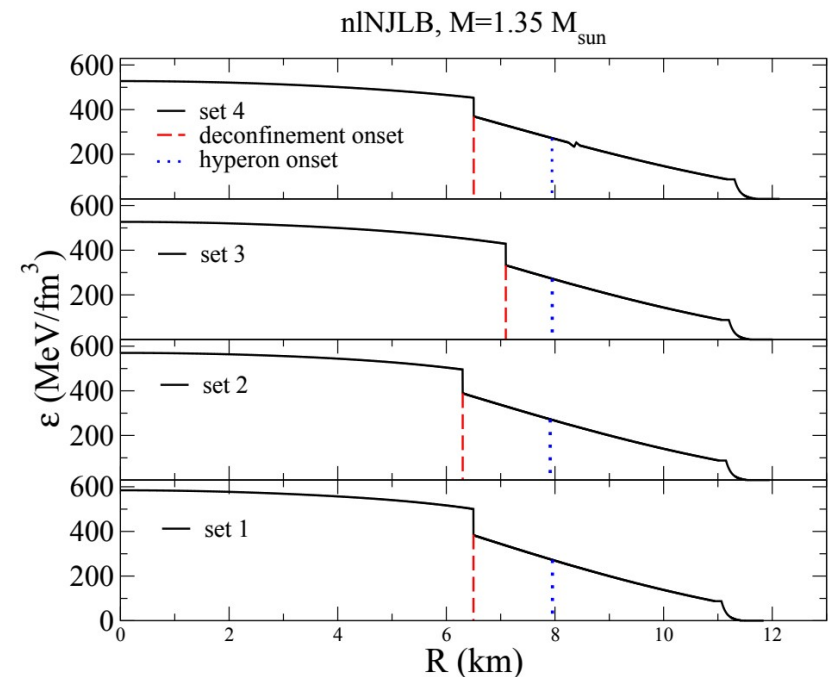
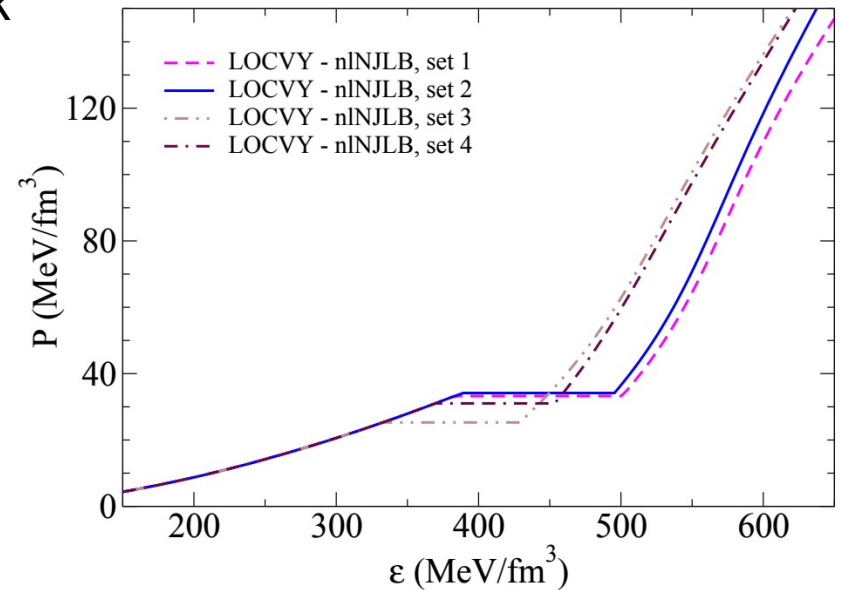
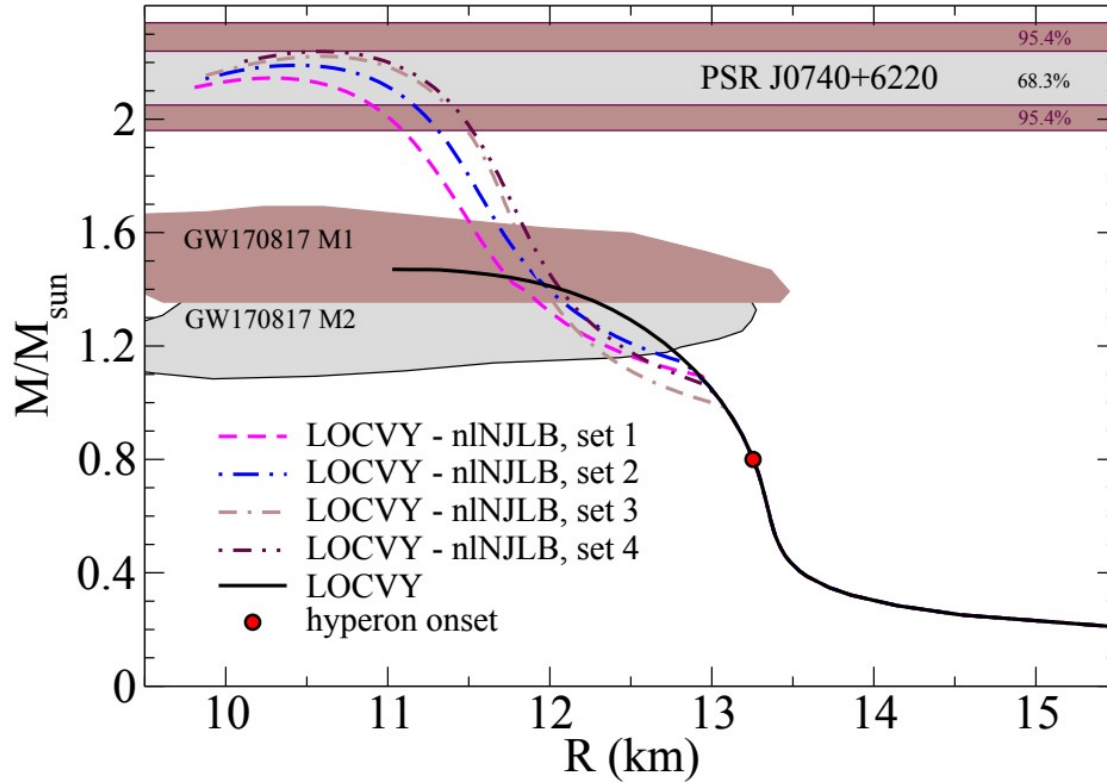
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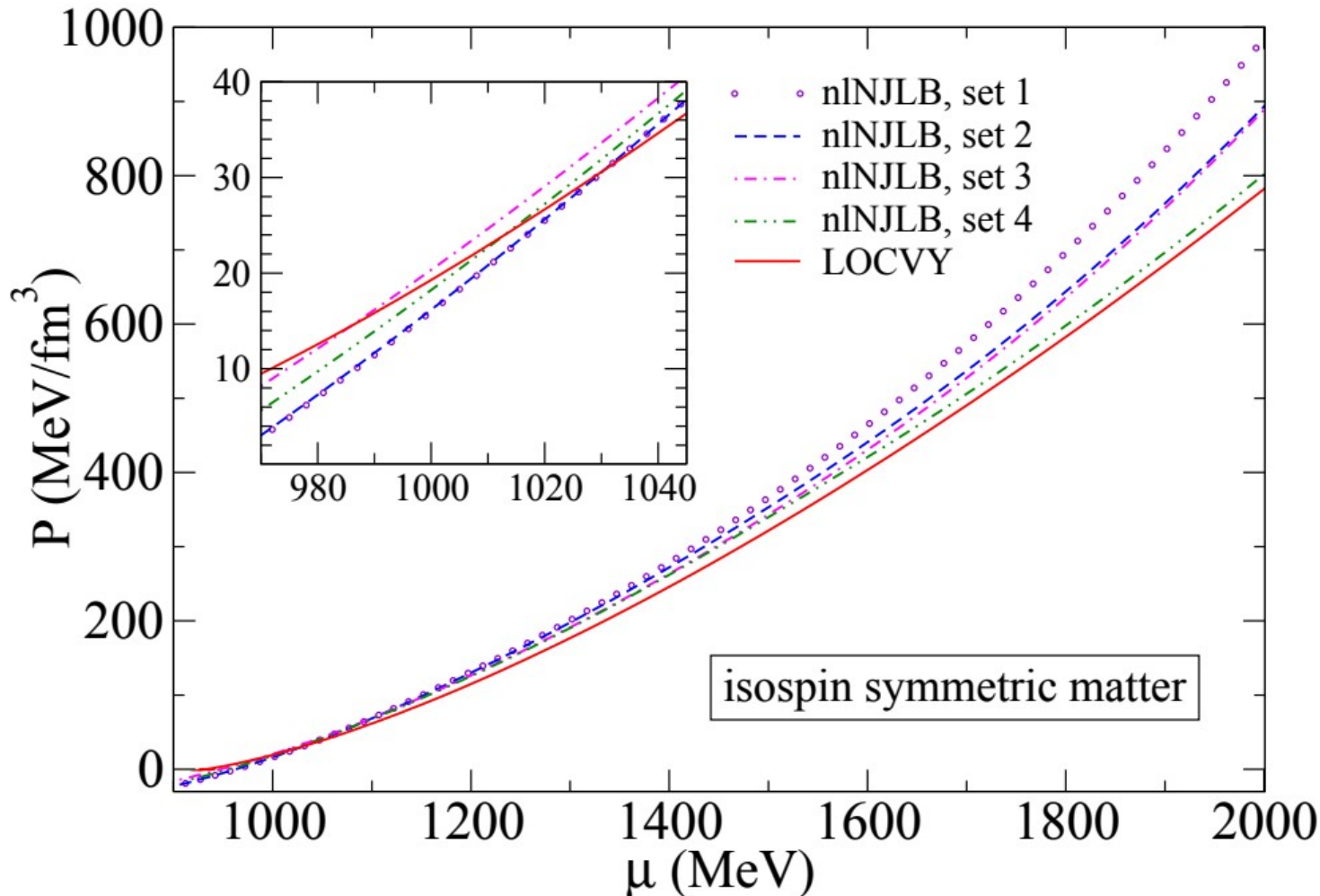
Hyperon puzzle: an update due to 2 M_{sun} constraint

Nonlocal NJL model for color superconducting quark
Matter with density-dependent coefficients



M. Shahrbafe, D.B., A.G. Grunfeld, H.R. Moshfegh,
First-order phase transition from hypernuclear
matter to deconfined quark matter obeying new
constraints from compact star observations,
Dubna Report No. E2-2019-41; [arxiv:1908.04740]

Hyperon puzzle: deconfinement solution; symmetric matter



Nonlocal NJL model for color superconducting quark matter with density-dependent coefficients

Apply hybrid star model parametrizations for symmetric matter case:

Deconfinement transition for $T=0$ predicted in range

$$2.2 < n_{\text{crit}}/n_0 < 2.7$$

M. Shahrbafe, D.B., A.G. Grunfeld, H.R. Moshfegh, First-order phase transition from hypernuclear matter to deconfined quark matter obeying new constraints from compact star observations, Dubna Report No. E2-2019-41; [arxiv:1908.04740]

Sexaquarks in CS matter?

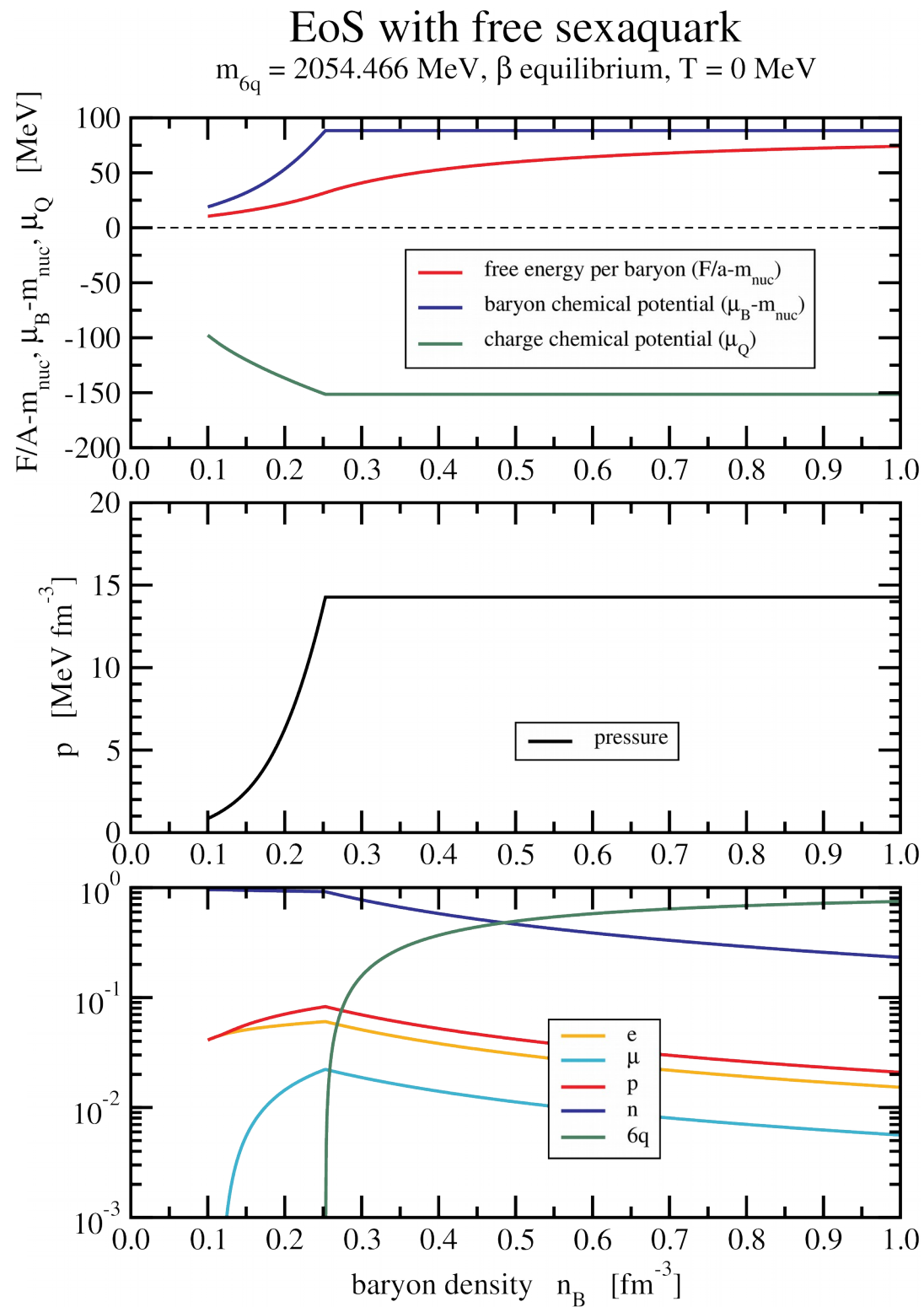
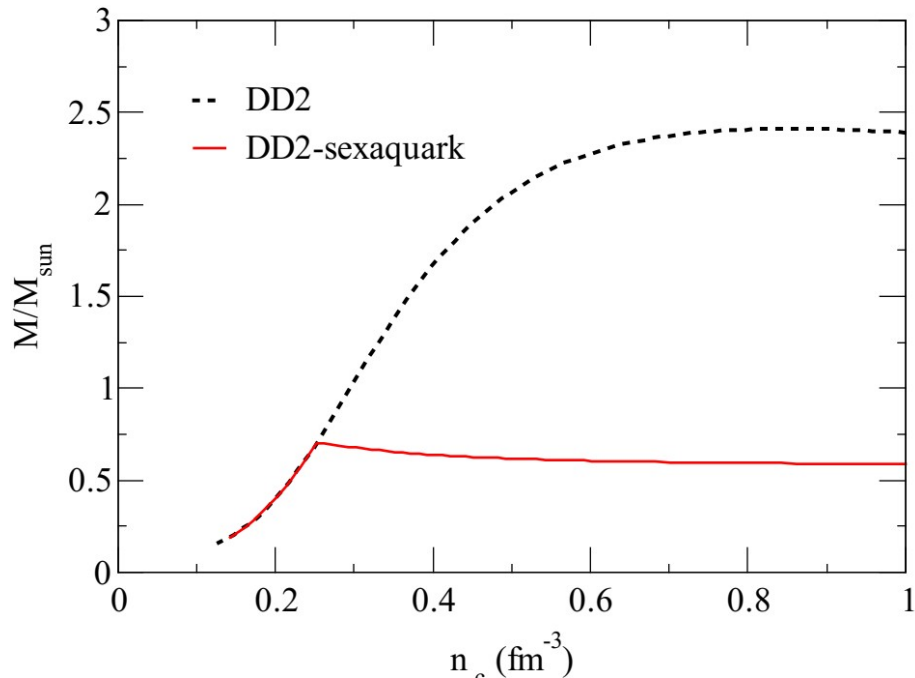
Sexaquarks form Bose condensate at

$$\mu = m_{6q}/2 = 1027 \text{ MeV}$$

Corresponding to a baryon density of

$$n_{\text{onset}} = 0.25 \text{ fm}^{-3} = 1.7 n_0$$

DD2 EoS: S. Typel et al., PRC (2010)



Sexaquark puzzle !

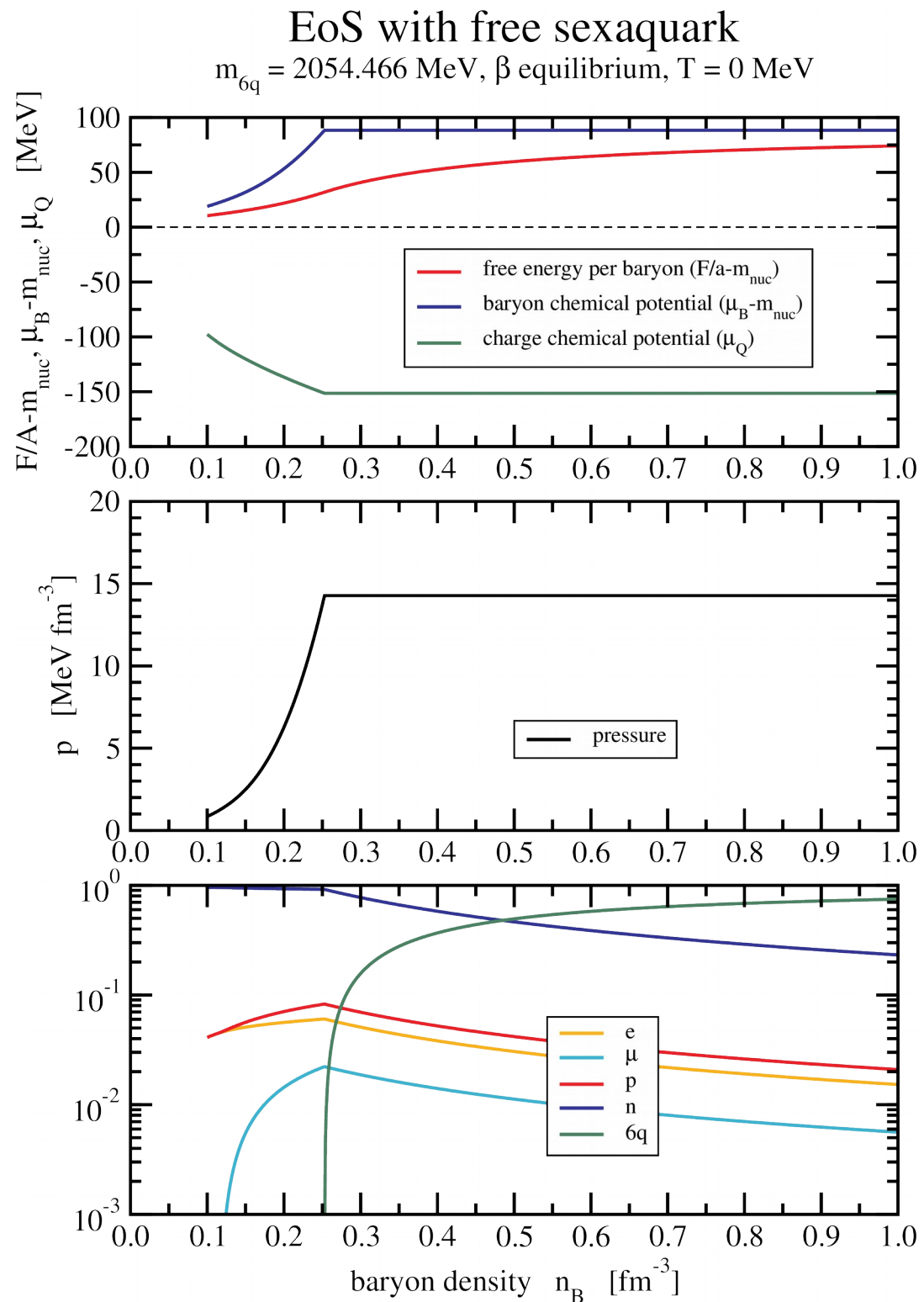
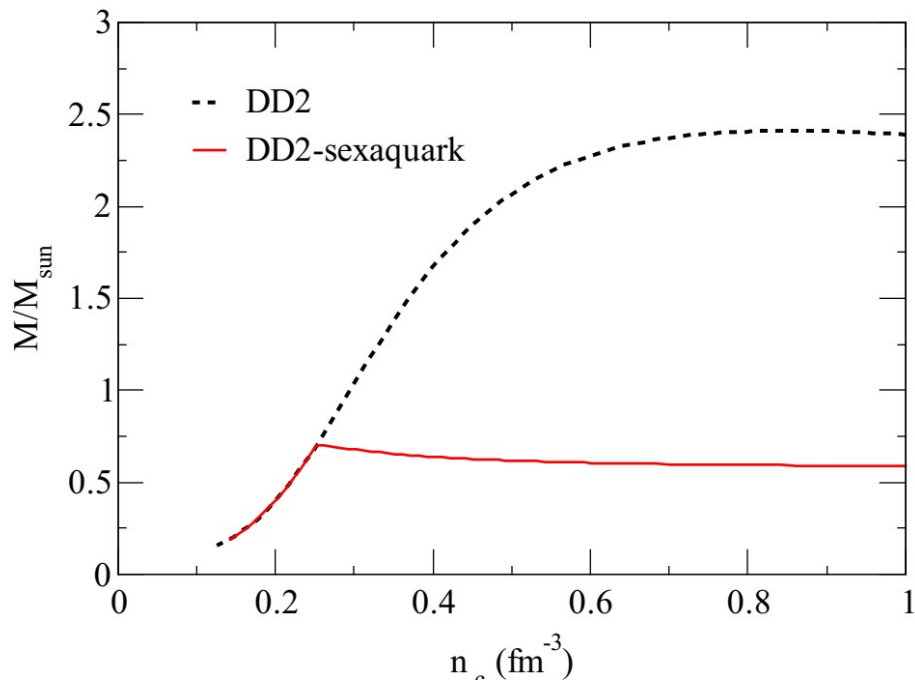
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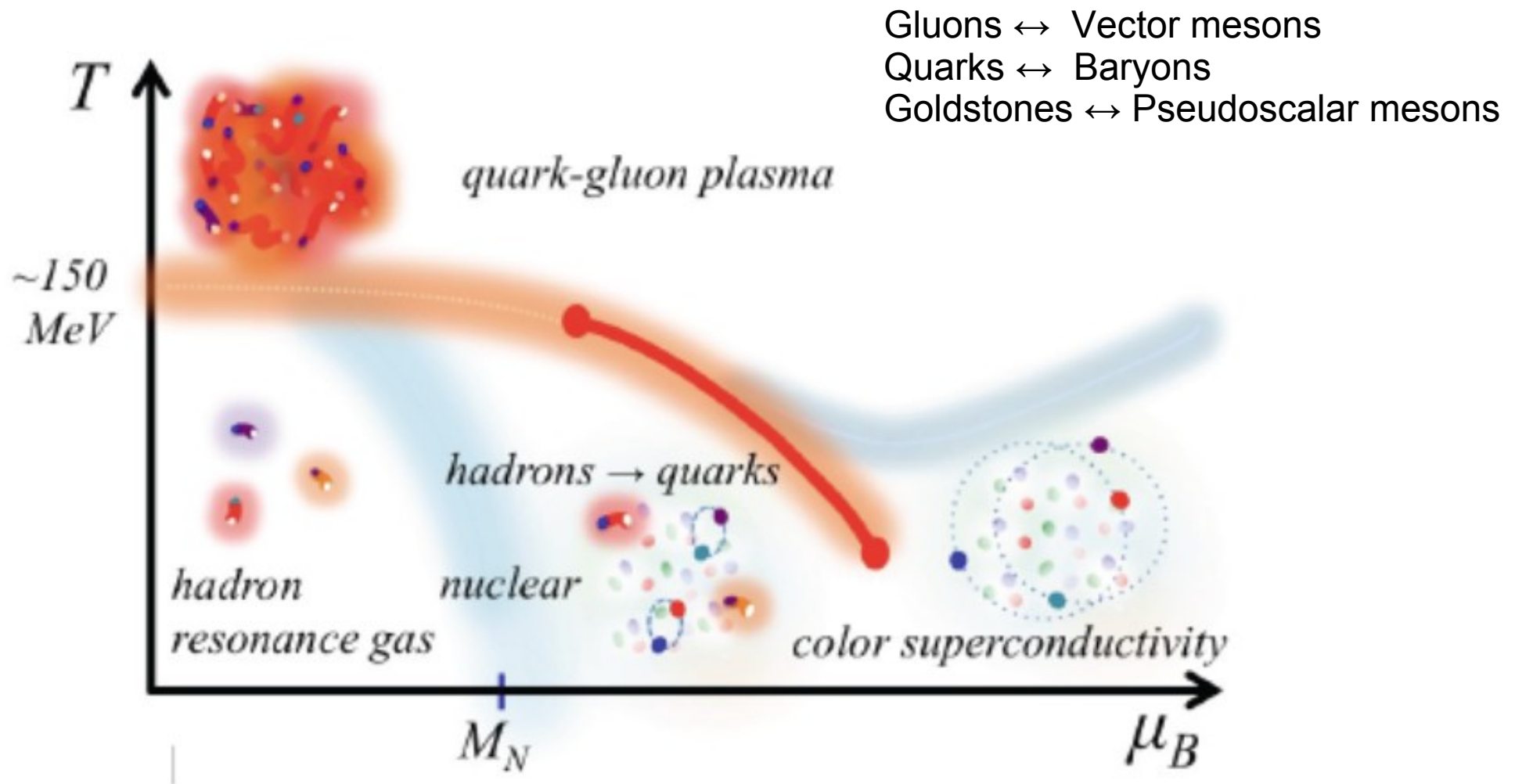
Corresponding to a baryon density of

$$n_{\text{onset}} = 0.25 \text{ fm}^{-3} = 1.7 n_0$$

This induces a gravitational collapse !
For DD2 hadronic EoS at $M \sim 0.7 M_{\text{sun}}$



2nd CEP in QCD phase diagram: Quark-Hadron Continuity?



T. Schaefer & F. Wilczek, Phys. Rev. Lett. 82 (1999) 3956

C. Wetterich, Phys. Lett. B 462 (1999) 164

T. Hatsuda, M. Tachibana, T. Yamamoto & G. Baym, Phys. Rev. Lett. 97 (2006) 122001

Solution: sexaquark dissociation into CFL quark matter

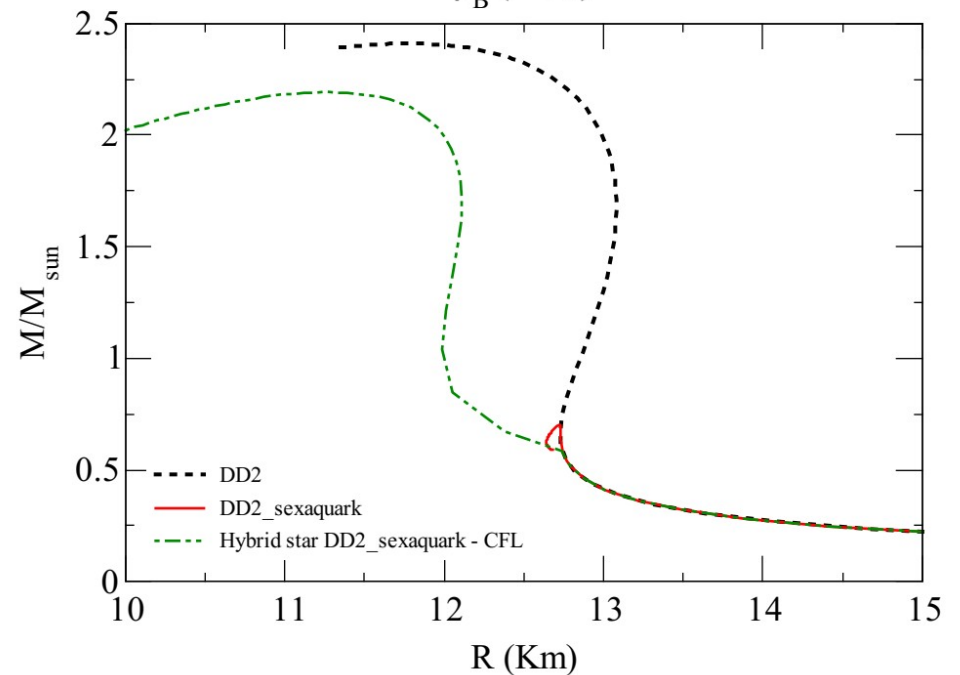
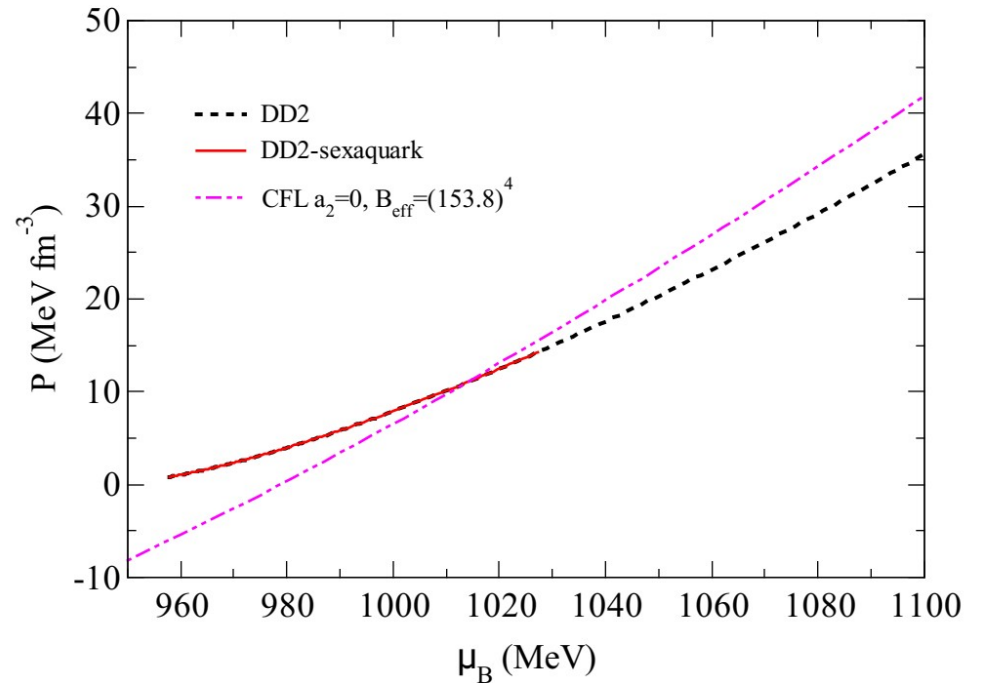
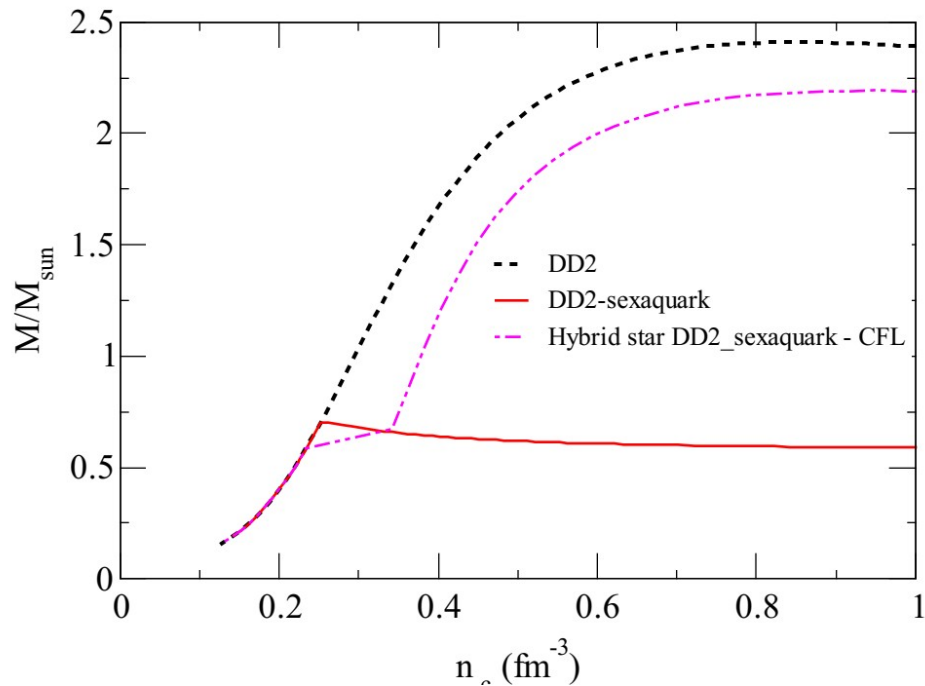
CFL quark matter: Alford et al., ApJ (2005)

$$\Omega_{\text{QM}} = -\frac{3}{4\pi^2} a_4 \mu^4 + \frac{3}{4\pi^2} a_2 \mu^2 + B_{\text{eff}},$$

$$a_4 \equiv 1 - c, \quad c = 0.3$$

$$a_2 = m_s^2 - 4\Delta^2$$

D.B., M. Shahrbafe, S. Typel, D. Alvarez,
In preparation (2019)

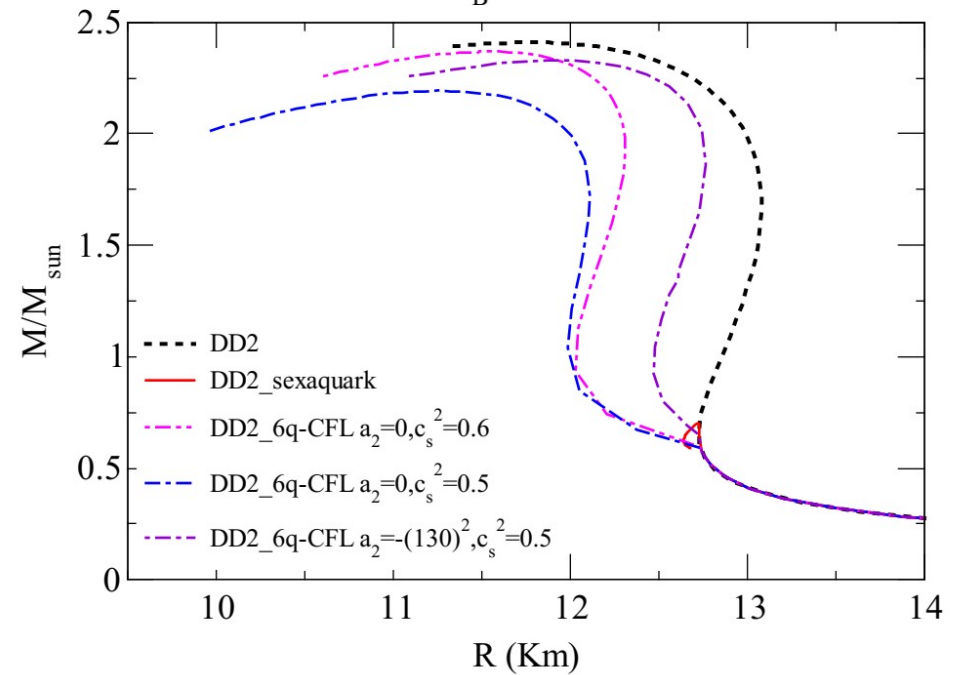
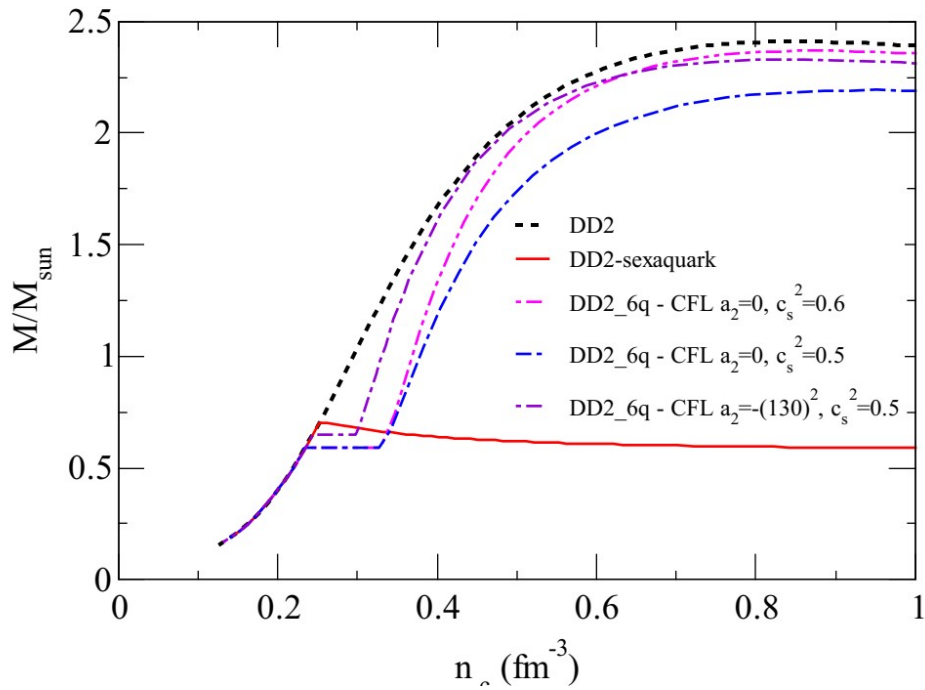
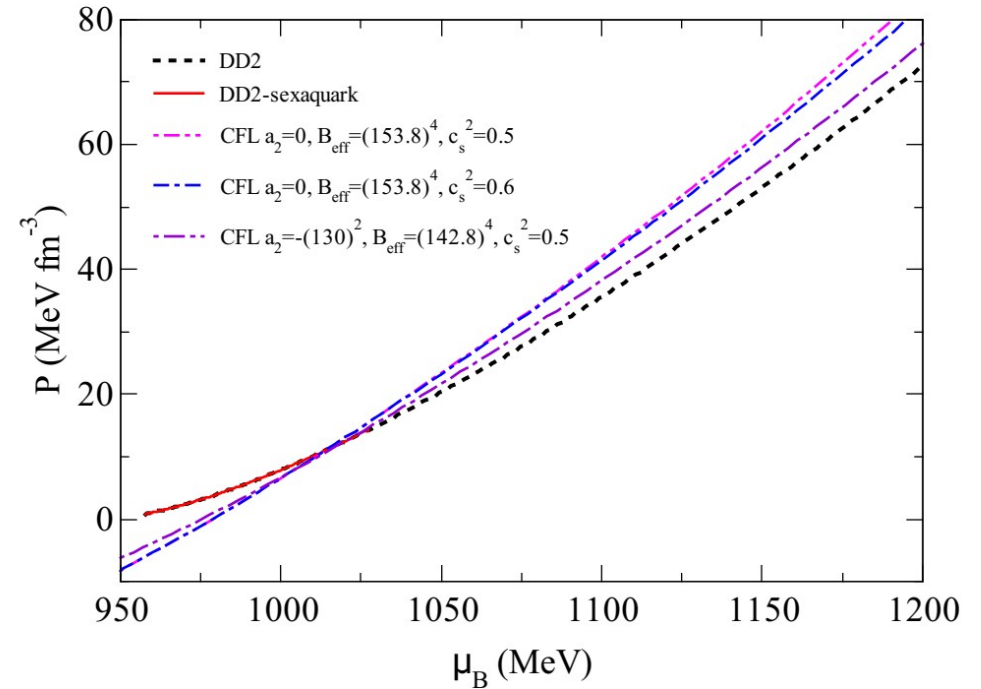


Solution: sexaquark dissociation into CFL quark matter (II)

More solutions are possible which fulfill
The $2 M_{\text{sun}}$ constraint for the maximum
Mass of the hybrid star sequence ...

Additional constraint: GW170817 inspiral

D.B., M. Shahrbafe, S. Typel, D. Alvarez,
In preparation (2019)

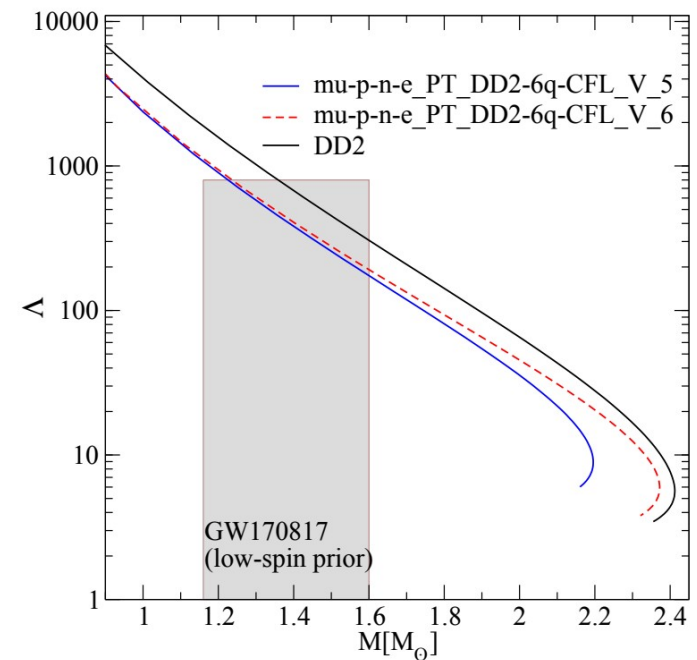
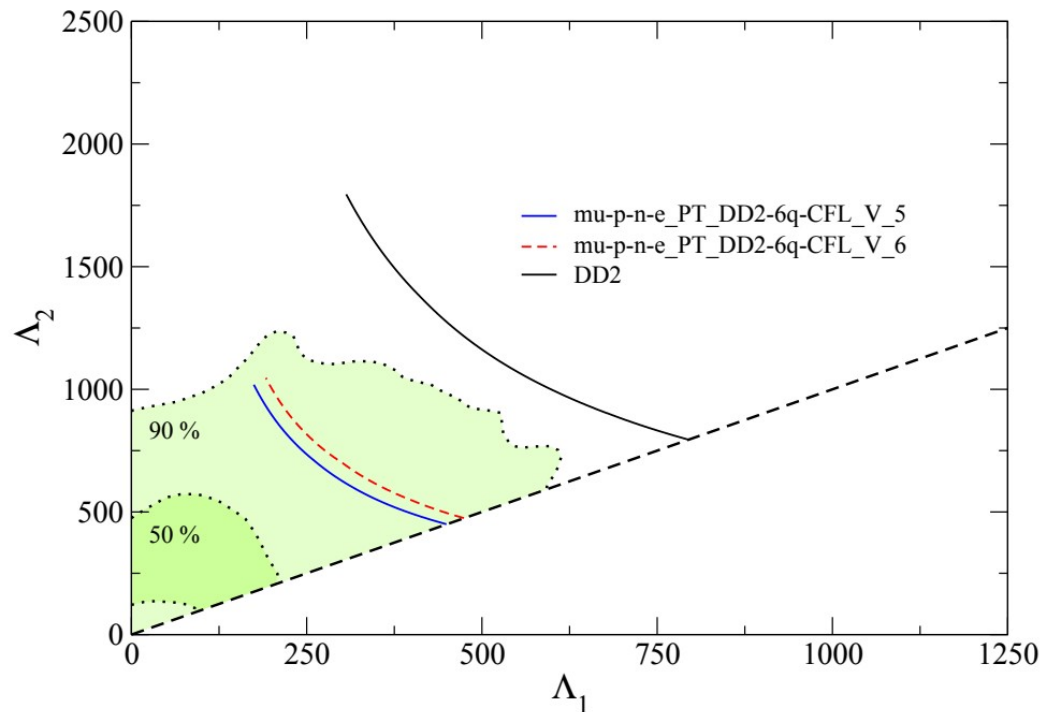
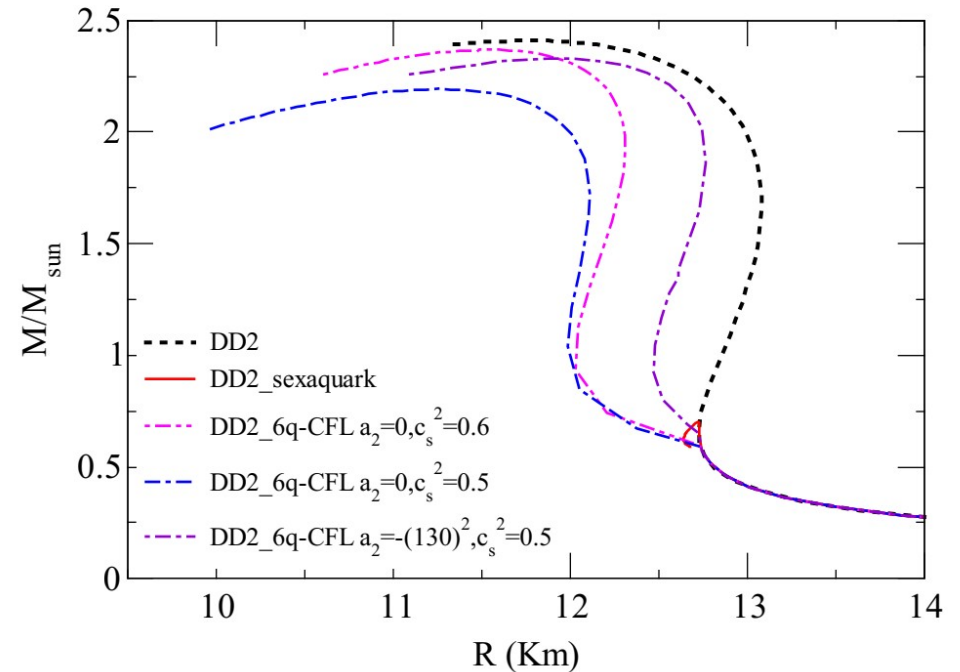


Solution: sexaquark dissociation into CFL quark matter (III)

More solutions are possible which fulfill
The $2 M_{\text{sun}}$ constraint for the maximum
Mass of the hybrid star sequence ...

Additional constraint: GW170817 inspiral
Grav. waves LIGO (Abbott et al. PRL (2018))

D.B., M. Shahrhaf, S. Typel, D. Alvarez,
In preparation (2019)



Conclusions:

High-mass twin (HMT) and Typical-mass twin (TMT) solutions can be obtained within different hybrid star EoS, e.g.,

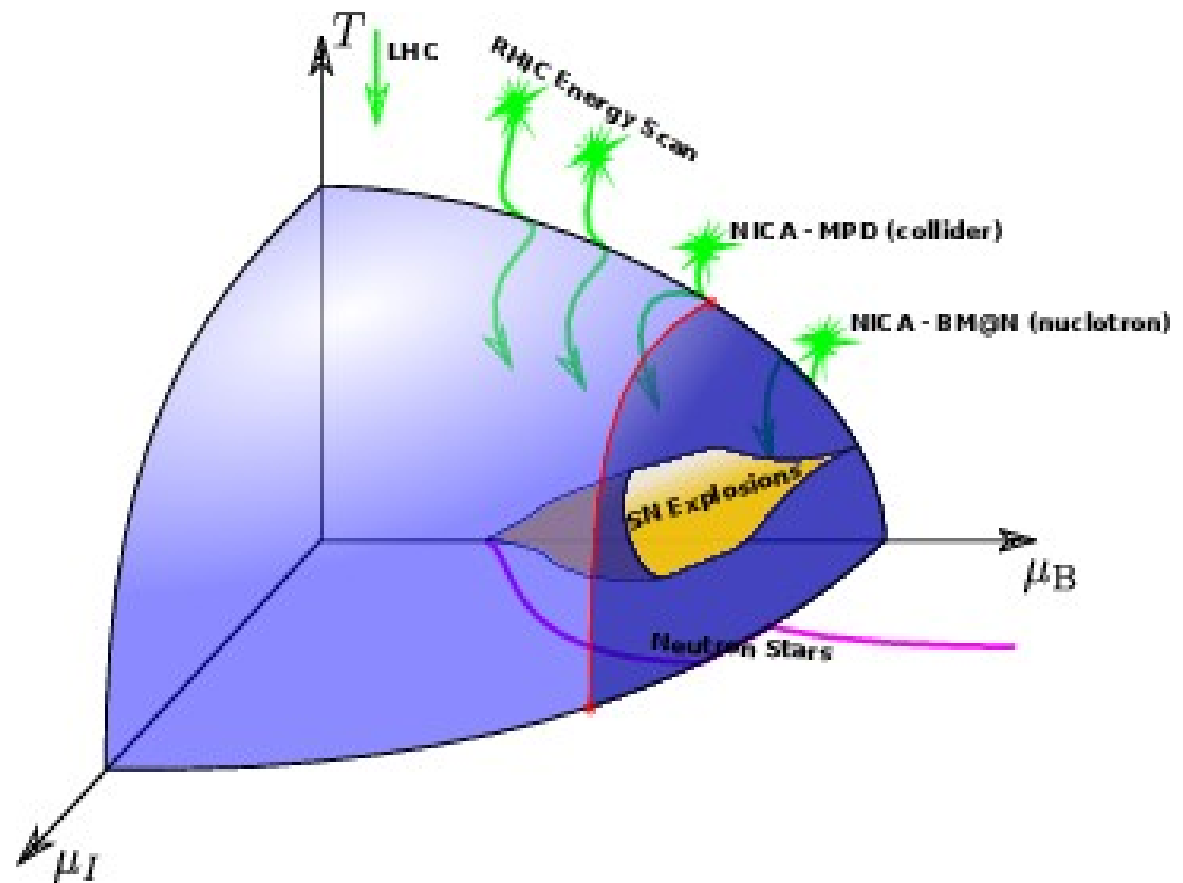
- constant speed of sound
- higher order/nonlocal NJL
- piecewise polytrope
- density functional

Main condition: stiff hadronic & stiff quark matter EoS with strong phase transition (PT)

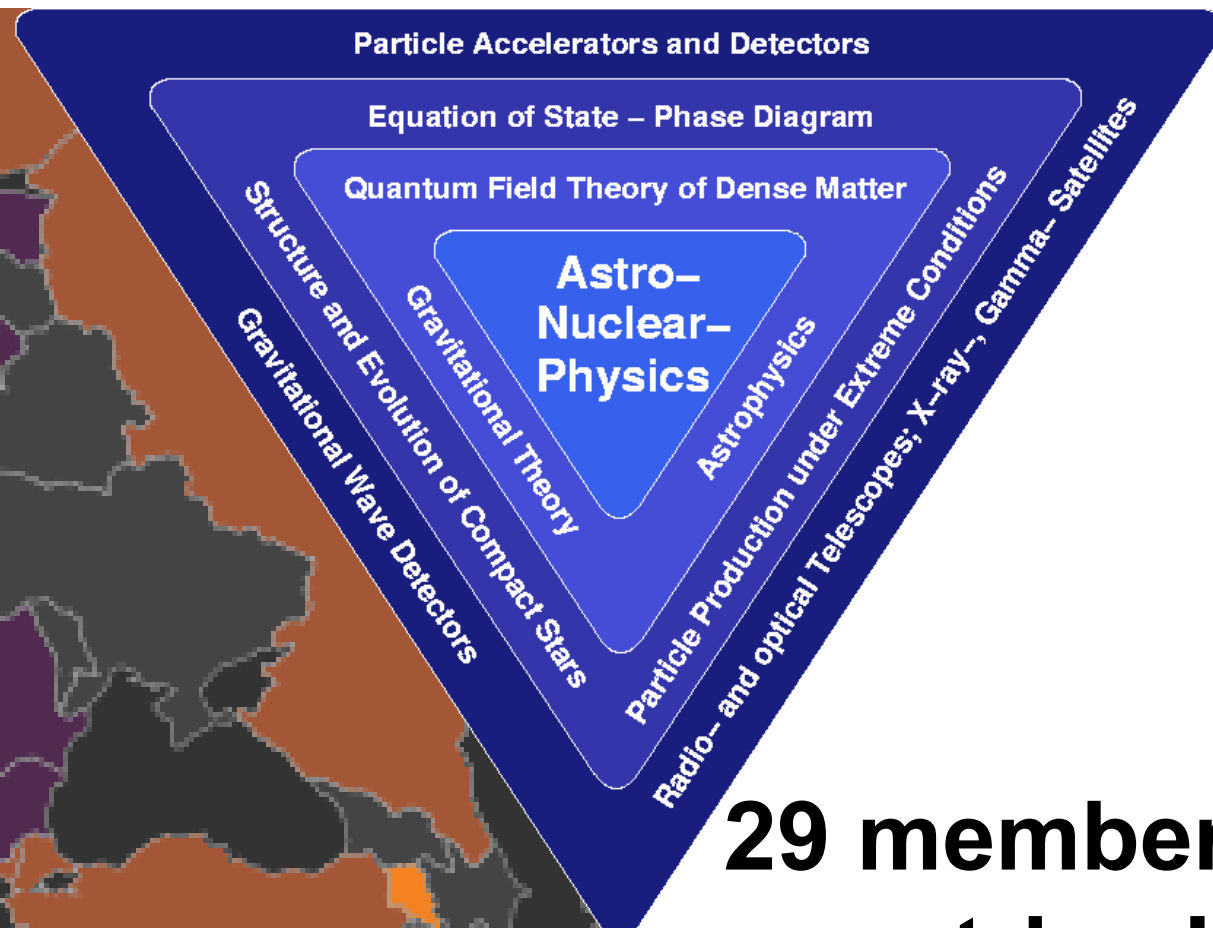
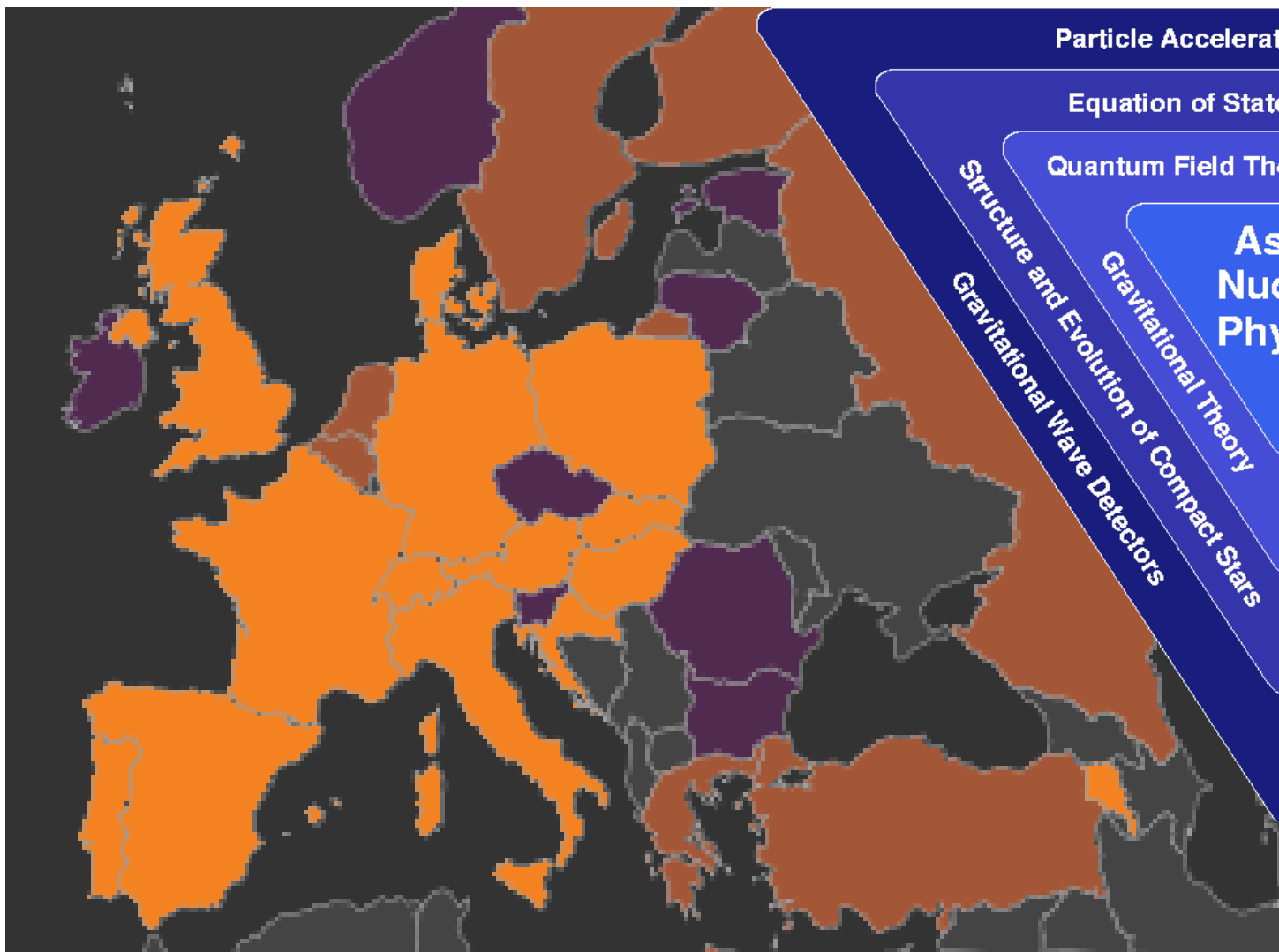
Existence of HMTs & TMTs can be verified, e.g., by precise pulsar mass and radius measurements (and good luck) → Indicator for strong PT !!

Extremely interesting scenarios possible for dynamical evolution of isolated (spin-down and accretion) and binary (NS-NS merger) compact stars; GW170817 could be inspiral of NS – hybrid star (HS) or HS - HS binary !

Critical endpoint search in the QCD phase diagram with Heavy-Ion Collisions goes well together with Compact Star Astrophysics



Extra Slides

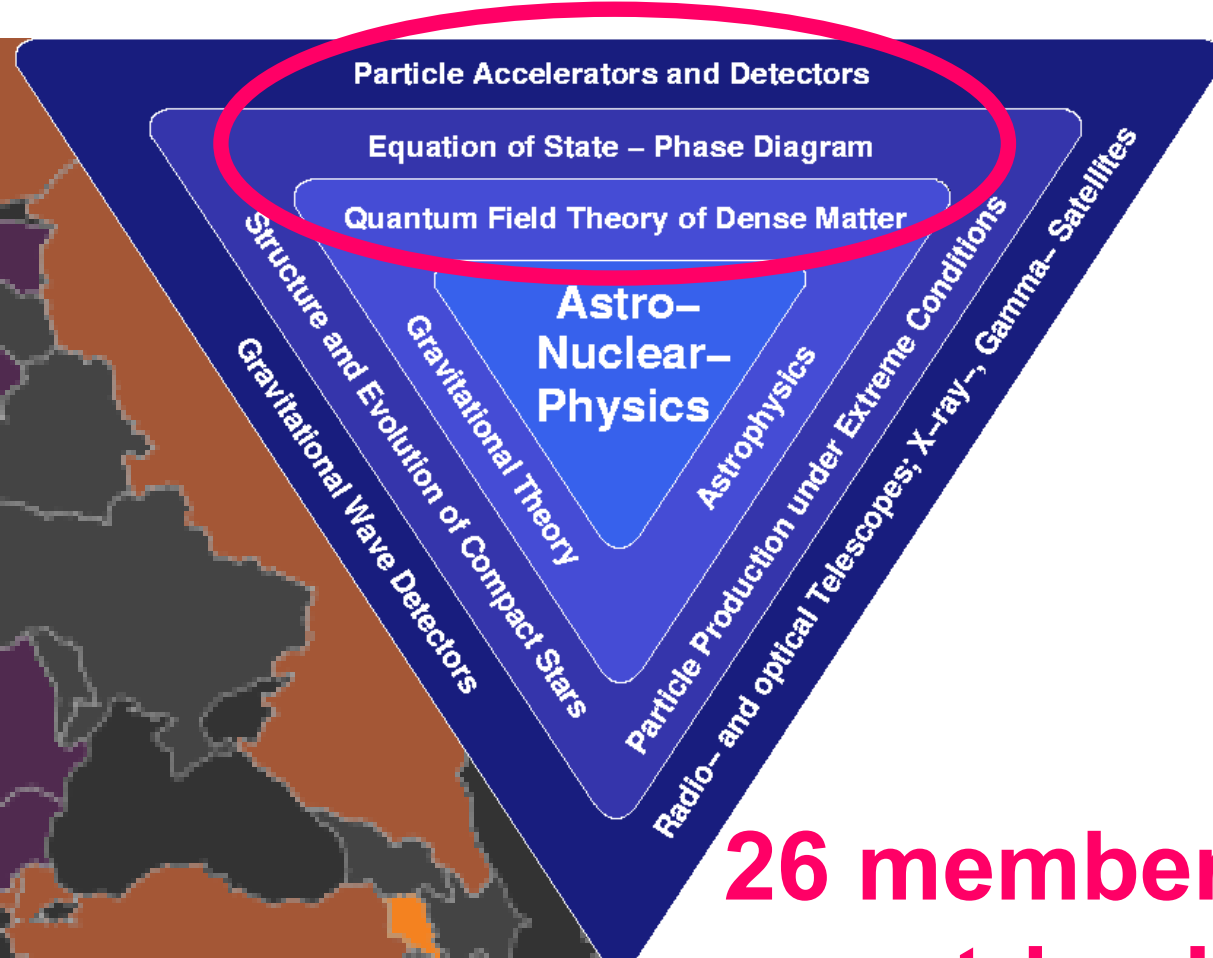
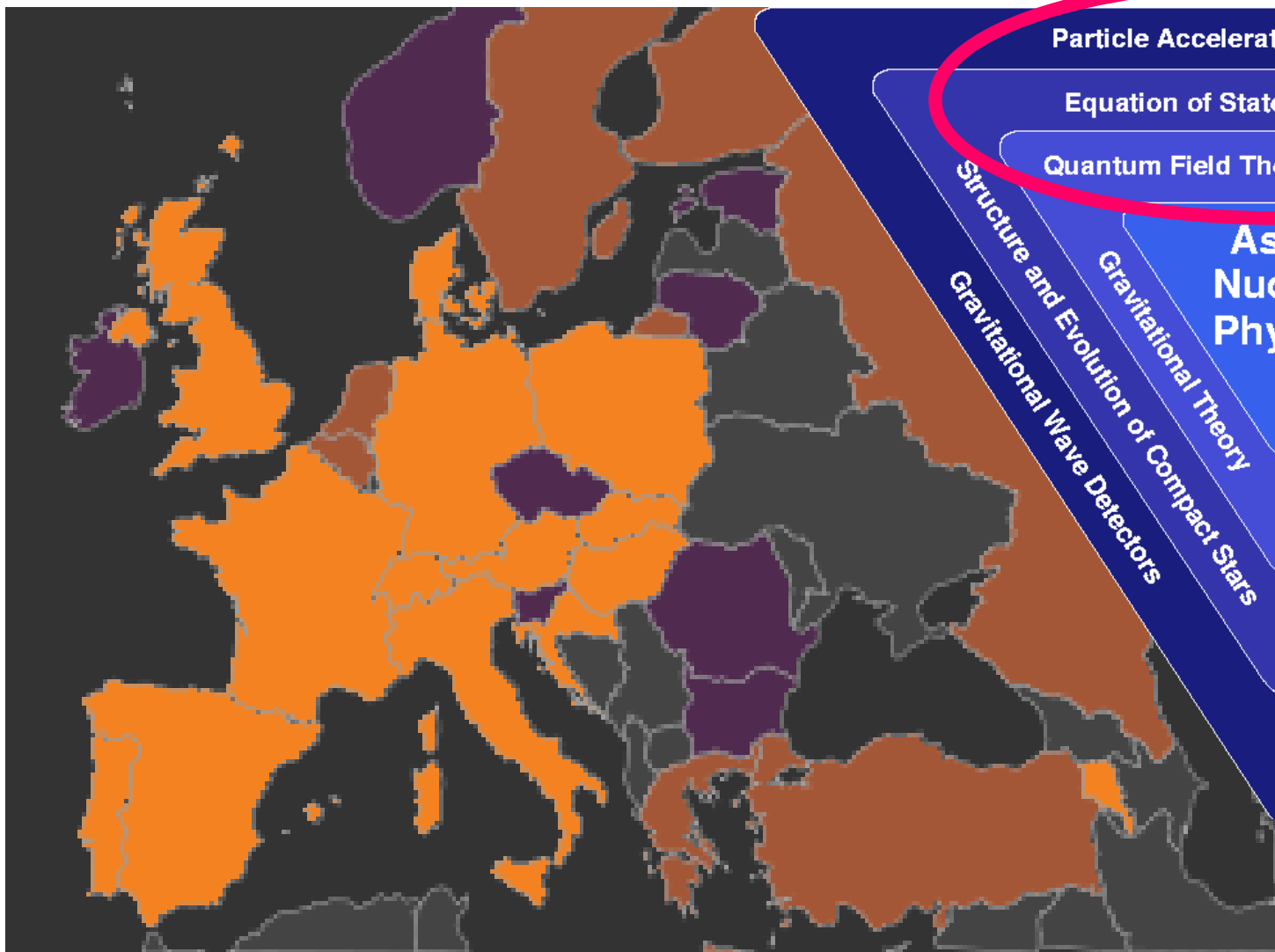


**29 member
countries !!
(MP1304)**

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<https://www.cost.eu/actions/MP1304>



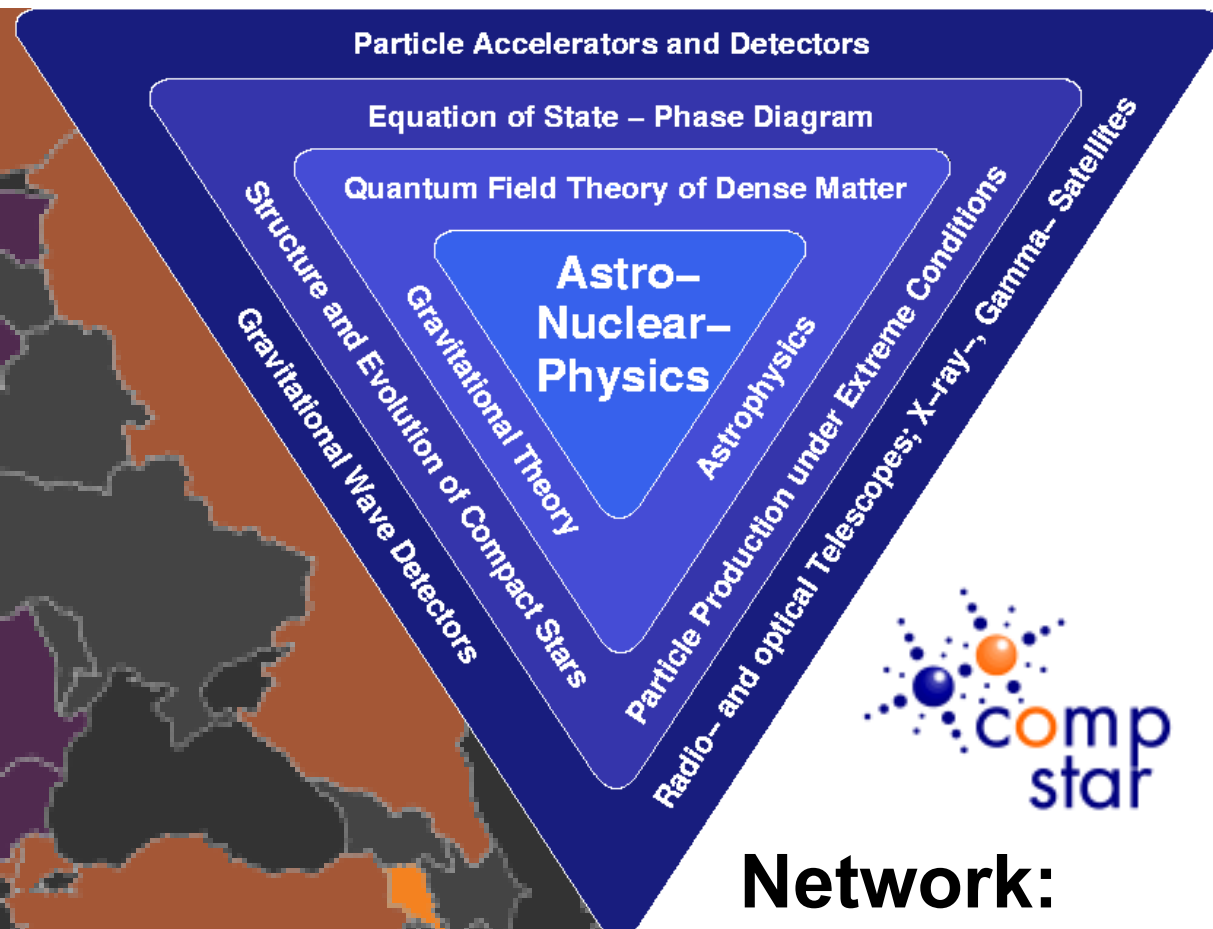
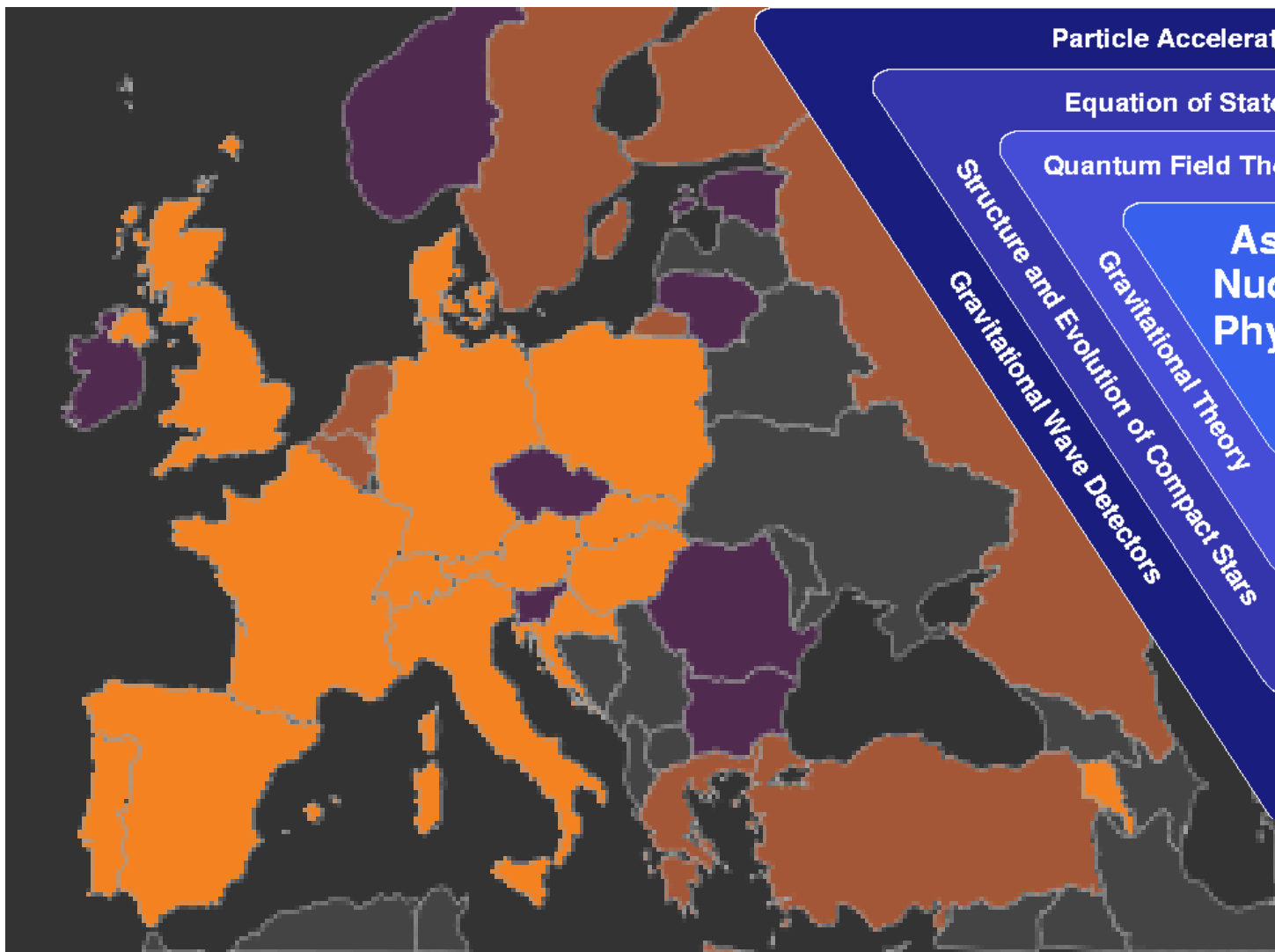
**26 member
countries !
(CA15213)**

“**T**heory of **H**ot Matter in **R**elativistic Heavy-Ion Collisions”

New: THOR!



Kick-off: Brussels, October 17, 2016



Network:
CA16214
30 countries

Newest:



http://www.cost.eu/COST_Actions/ca/CA16214

Kick-off: Brussels, 22.11. 2017



International Conference “Critical Point and Onset of Deconfinement”
University of Wroclaw, May 29 – June 4, 2016



Topical Issue on Exploring Strongly Interacting Matter

at High Densities - NICA White Paper

edited by David Blaschke, Jörg Aichelin, Elena Bratkovskaya, Volker Fries, Marek Gazdzicki, Jørgen Randrup, Oleg Rogachevsky, Oleg Teryaev, Viacheslav Toneev



NICA

From: Three stages of the NICA accelerator complex
by V. D. Kekelidze et al.

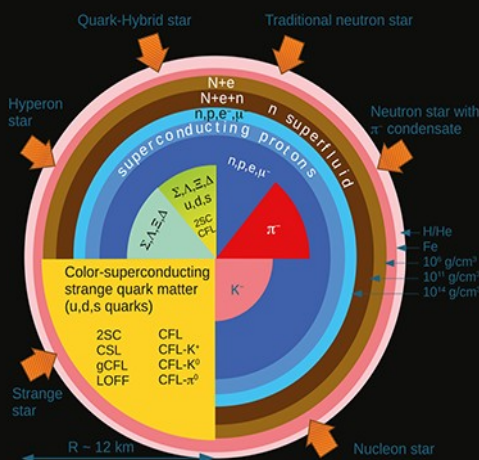


Springer



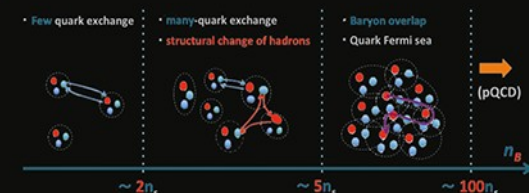
Inside: Topical Issue on Exotic Matter in Neutron Stars

edited by David Blaschke, Jürgen Schaffner-Bielich and Hans-Josef Schulze



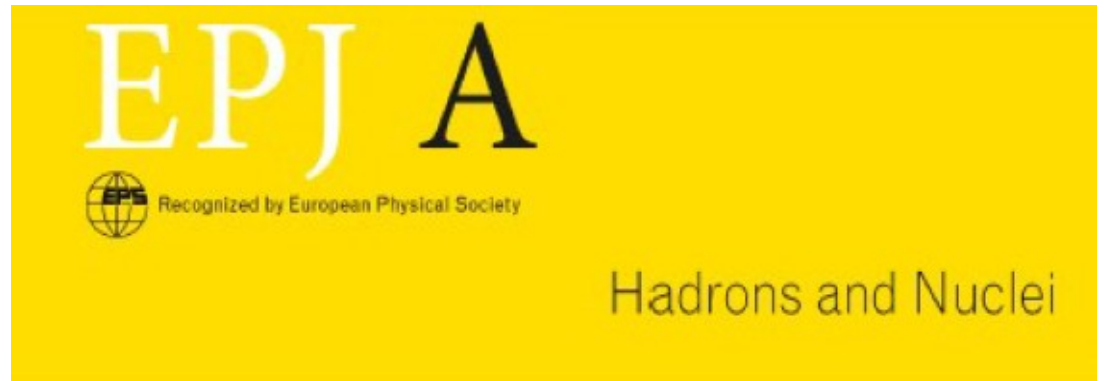
From:
Neutron star interiors: Theory and reality
by J.R. Stone (left)

Phenomenological neutron star equations of state:
3-window modeling of QCD matter
by T. Kojo (right)



Springer

New Topical Issue:



The first observation of a neutron star merger and its implications for nuclear physics

Editors: D. Blaschke (EPJA), M. Colpi, C. Horowitz, D. Radice

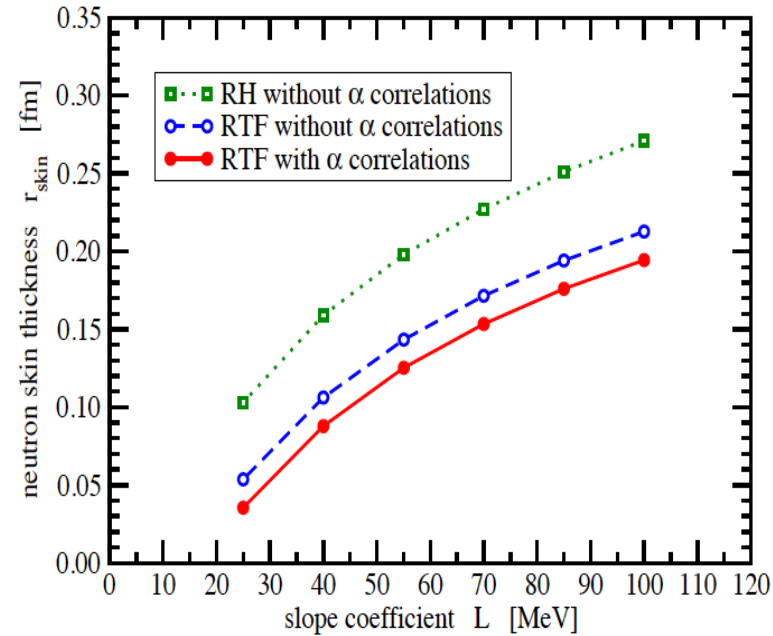
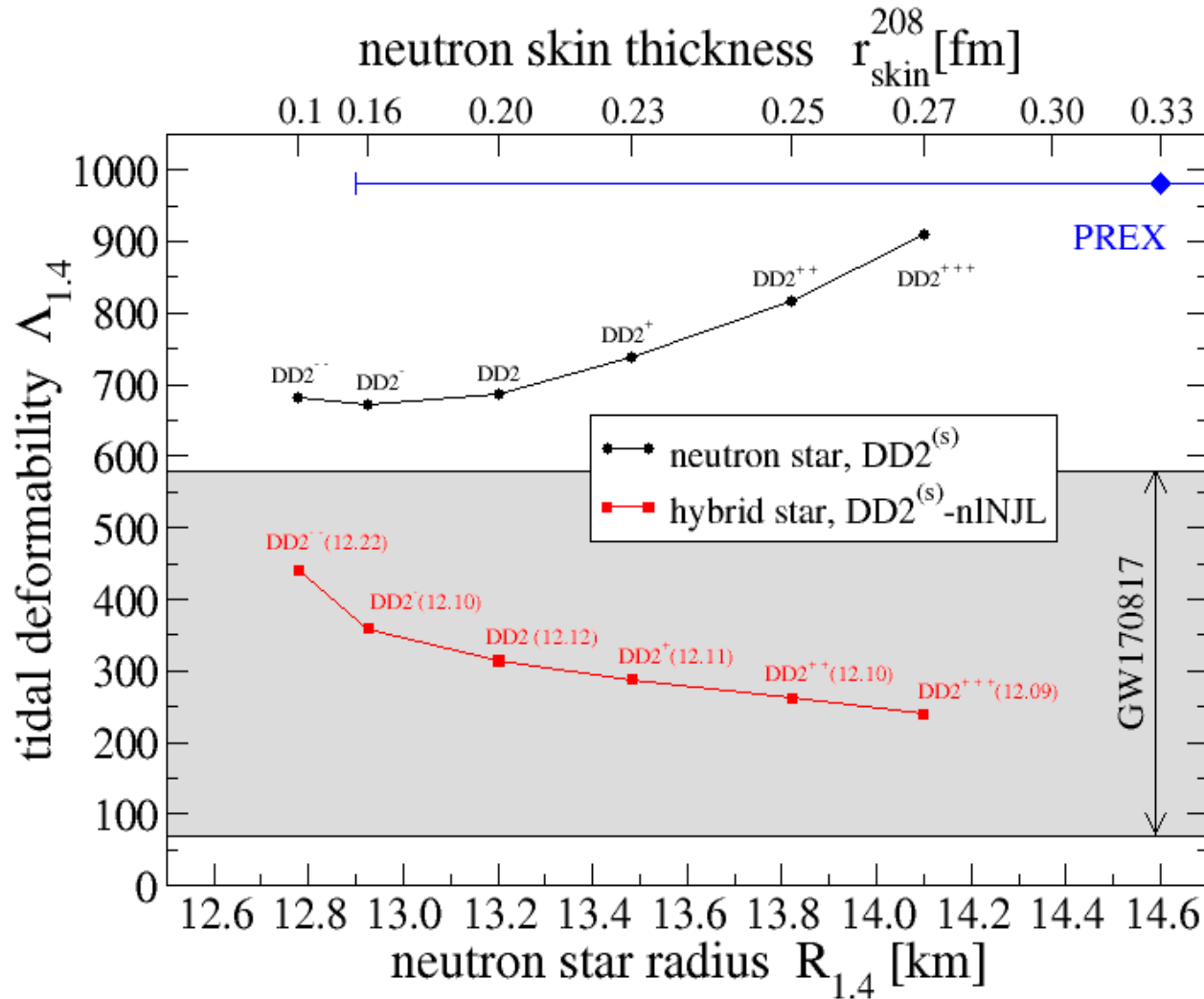
Open call for contributions

Deadline – End of 2019

Website: <https://www.epj.org/open-calls-for-papers/122-epj-a/>

Email: david.blaschke@gmail.com epja.bologna@sif.it

Is there tension between neutron skin thickness from PRex & tidal deformability constraints from GW170817 ?



parametrization	symmetry energy	slope coefficient
	J [MeV]	L [MeV]
DD2 ⁺⁺⁺	35.34	100.00
DD2 ⁺⁺	34.12	85.00
DD2 ⁺	32.98	70.00
DD2	31.67	55.04
DD2 ⁻	30.09	40.00
DD2 ⁻⁻⁻	28.22	25.00