# Studying the onset of deconfinement in neutron stars with multi-messenger astronomy

David.Blaschke@gmail.com

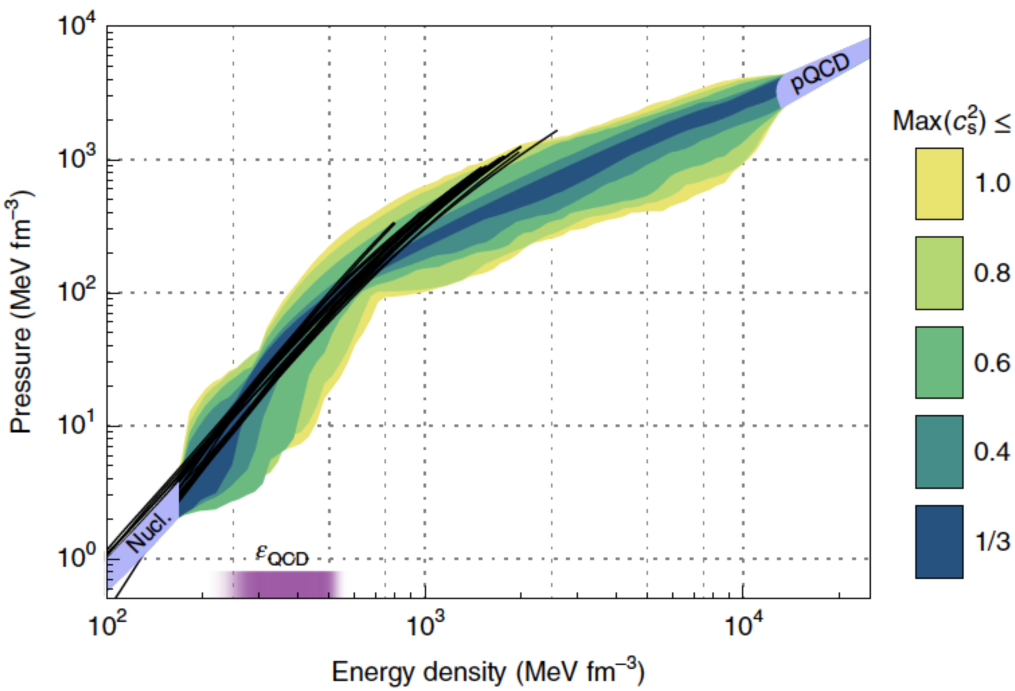
1. **Introduction: Recent relevant observations**
2. **Hybrid EoS construction from nuclear and quark matter**
3. **Hybrid stars: M(R) and Λ(M), $\Lambda_1$-$\Lambda_2$**
4. **Bayesian analysis with multimessenger data**
5. **Outlook: Supernovae & Mergers in the QCD phase diagram**

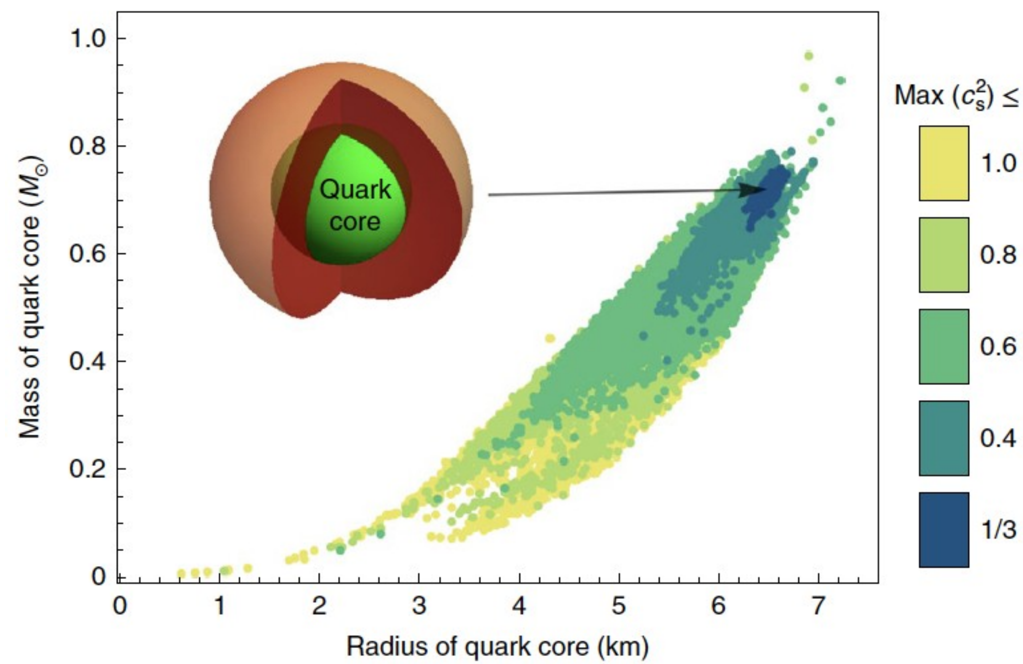
Centro de Física da Universidade de Coimbra , 22. September 2020

JINR DUBNA
MEPhI
Narodowe Centrum Nauki
Grant No. UMO 2019 / 33 / B / ST9 / 03059
RFBR
Grant No. 18-02-40137
cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY
Uniwersytet Wrocławski
RSF Russian Science Foundation
Grant No. 17-12-01427
PHAROS THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS
THOR

# Evidence for quark-matter cores in massive neutron stars

Eemeli Annala, Tyler Gorda, Aleksi Kurkela, Joonas Nättilä, Aleksi Vuorinen, Nature (2020)




A massive, 2 M_sun neutron star with 12 km radius shall have a 6.5 km quark matter core, when quark matter is defined to have a subconformal EoS (c_s^2 < 1/3) down to energy densities at a switch point to nuclear matter described by chiral effective theory (CET) which can be at 2n_0 or even lower.

Caveats: - quark matter can have c_s^2 > 1/3 (CFL phase)
- for a true (1st order) phase transition c_s^2 = 0

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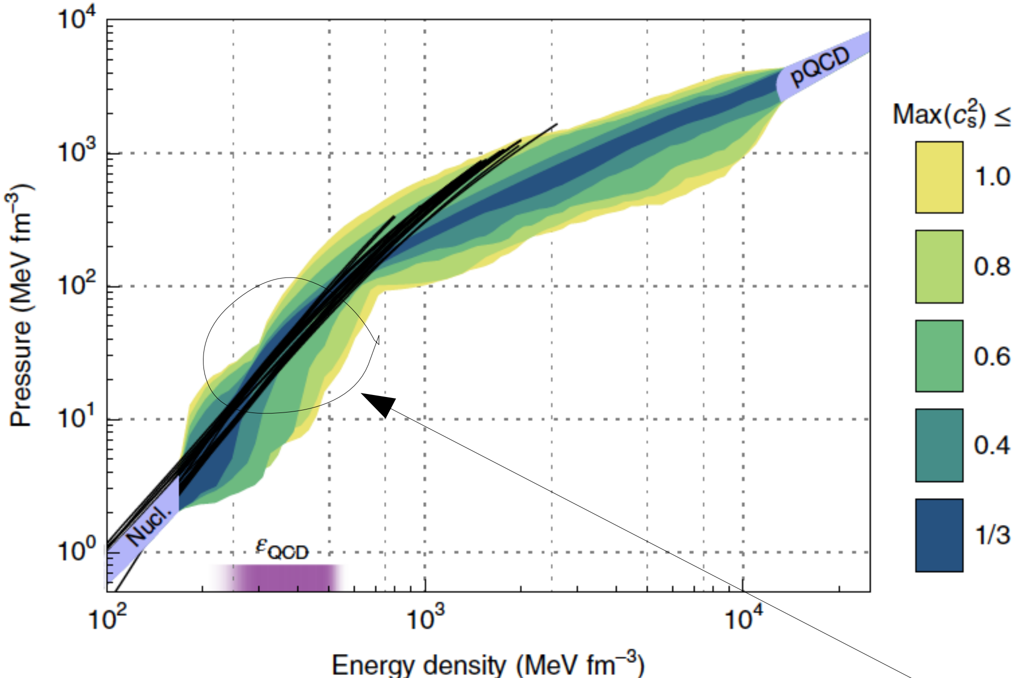


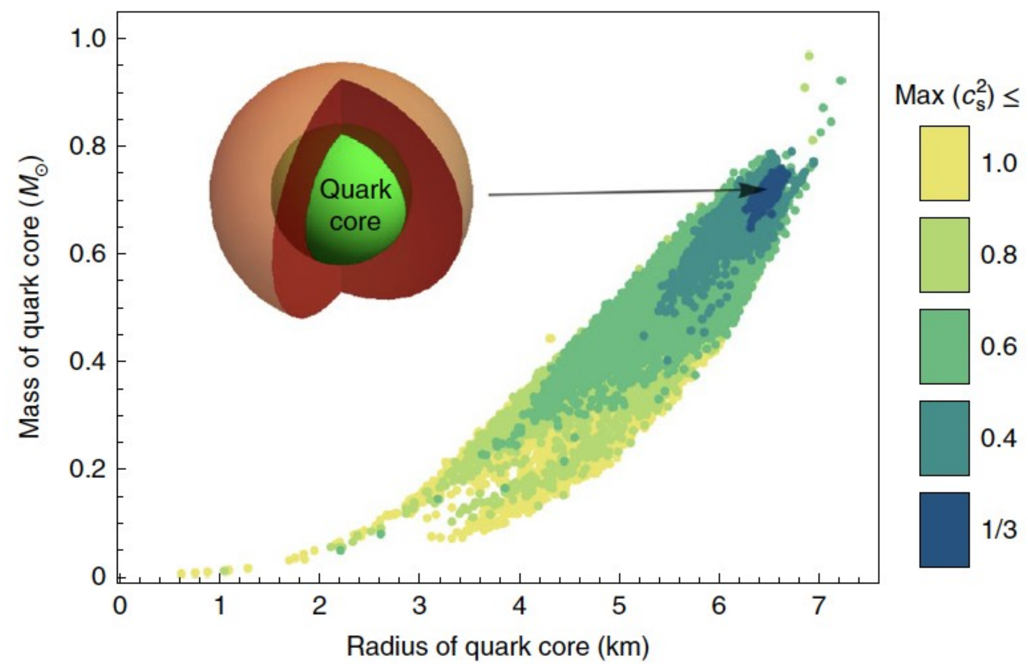


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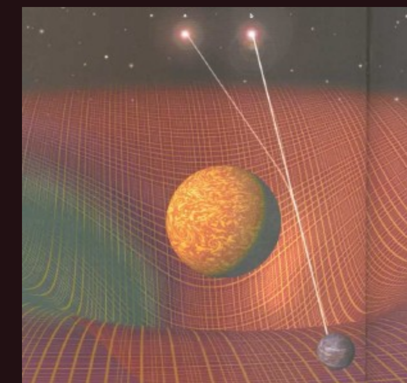
This Talk

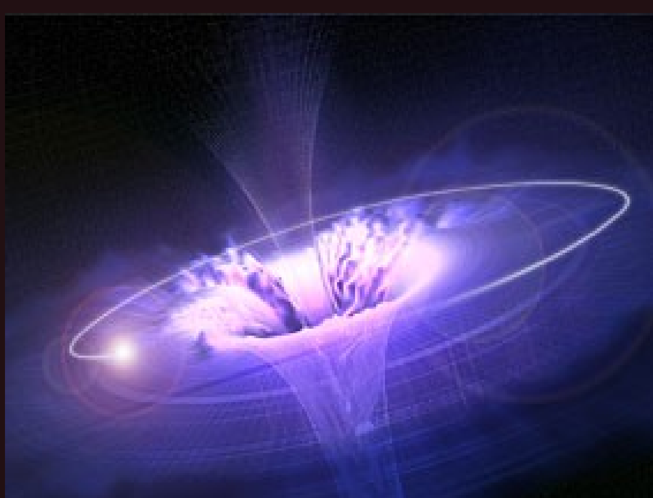
# Compact stars and black holes in Einstein's General Relativity theory

Space-Time $G_{\mu\nu} = 8\pi G \, T_{\mu\nu}$ Matter

Massive objects curve the Space-Time



Non-rotating, spherical masses → Schwarzschild Metrics



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

Einstein eqs. → Tolman-Oppenheimer-Volkoff eqs.*)
For structure and stability of compact stars

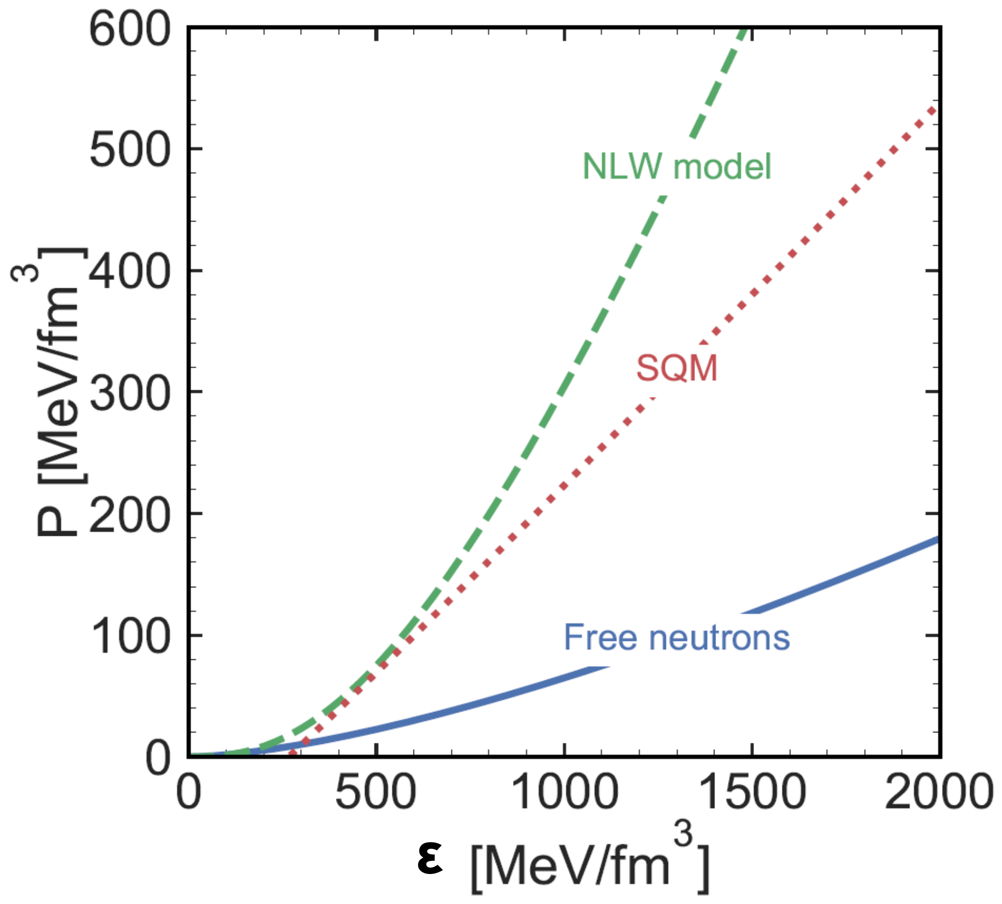
$$\frac{dP(r)}{dr} = -G\frac{m(r)\varepsilon(r)}{r^2}\left(1 + \frac{P(r)}{\varepsilon(r)}\right)\left(1 + \frac{4\pi r^3 P(r)}{m(r)}\right)\left(1 - \frac{2Gm(r)}{r}\right)^{-1}$$

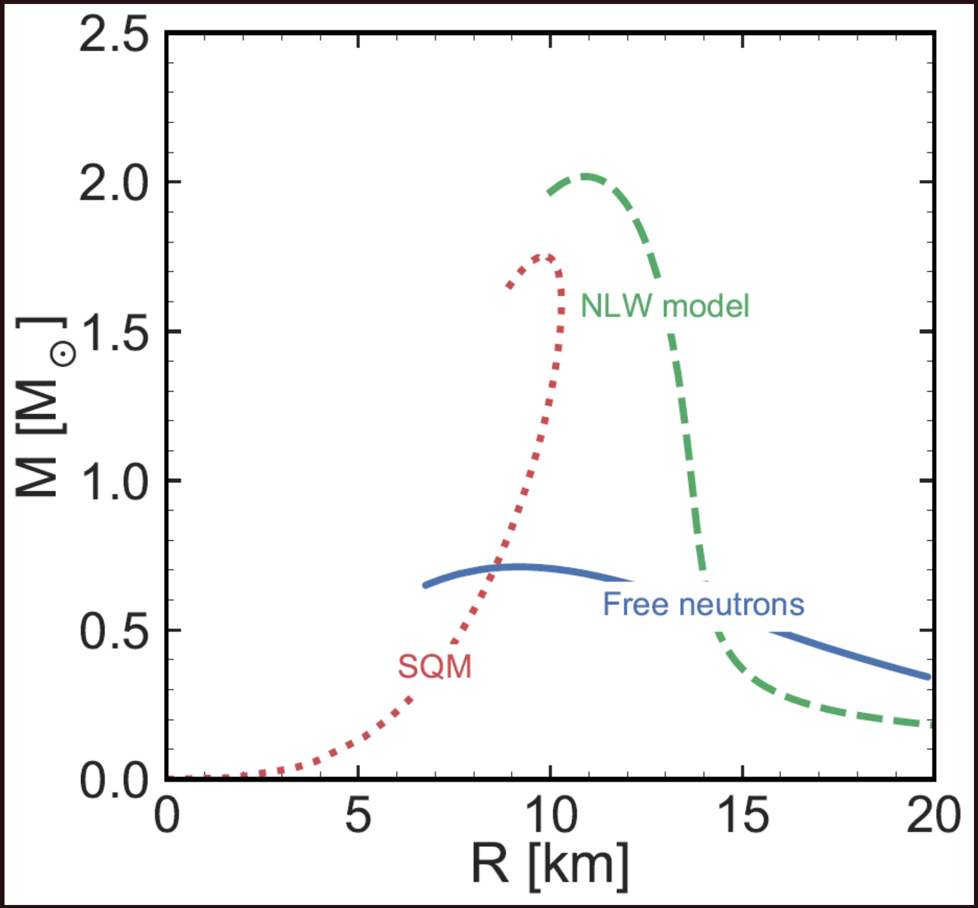
Newtonian case x GR corrections from EoS and metrics

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

# The 1:1 relation P(ε) ↔ 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

*) curtesy: Konstantin Maslov

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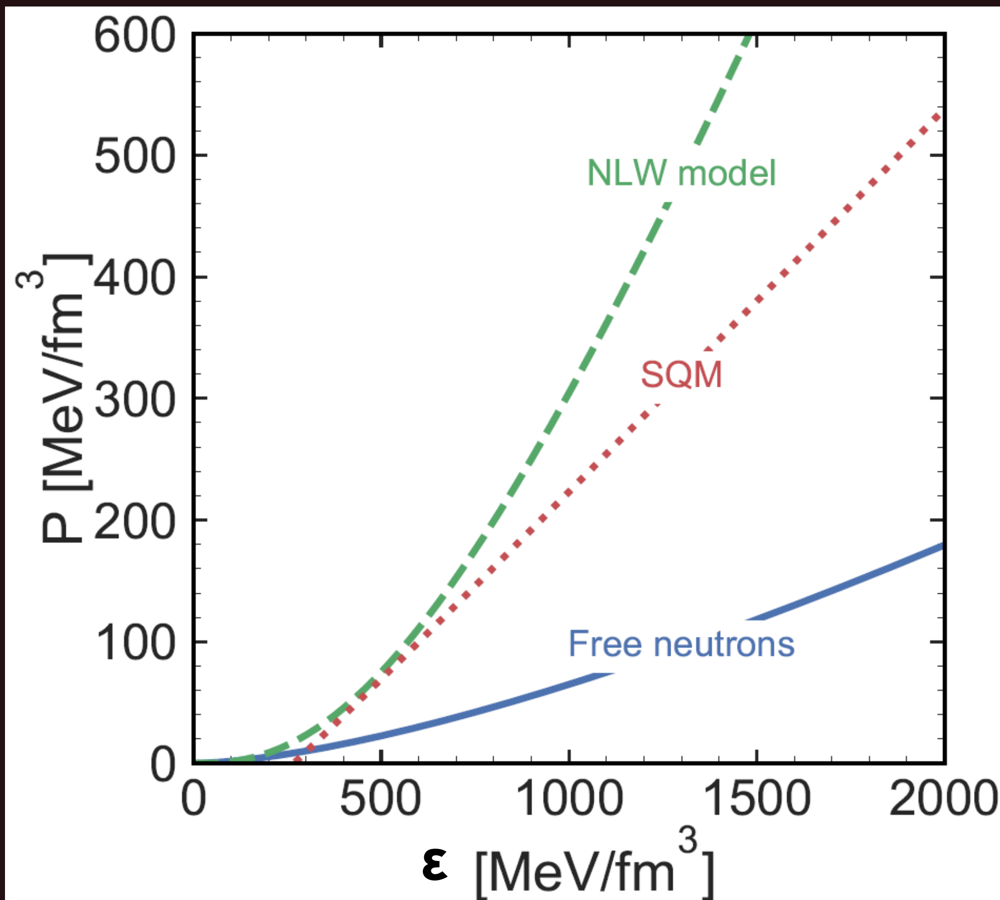


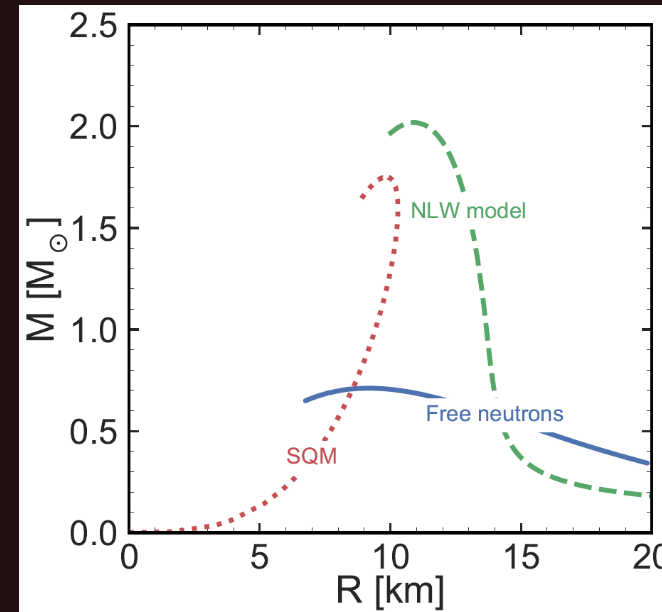


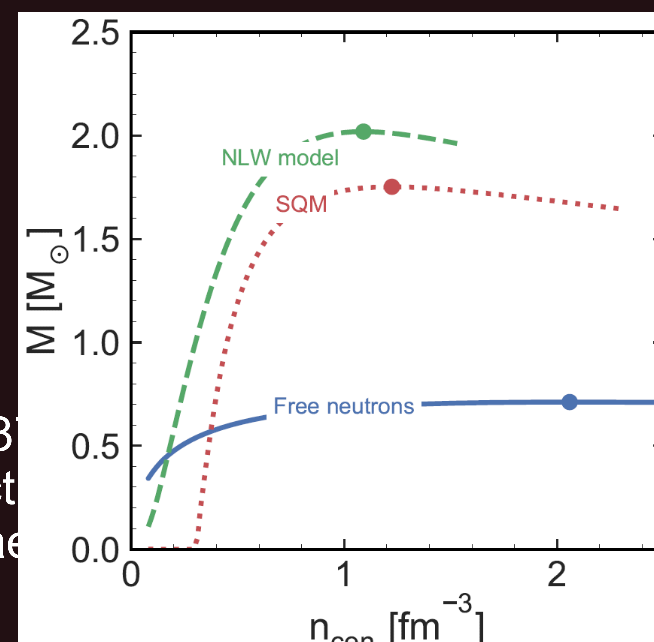


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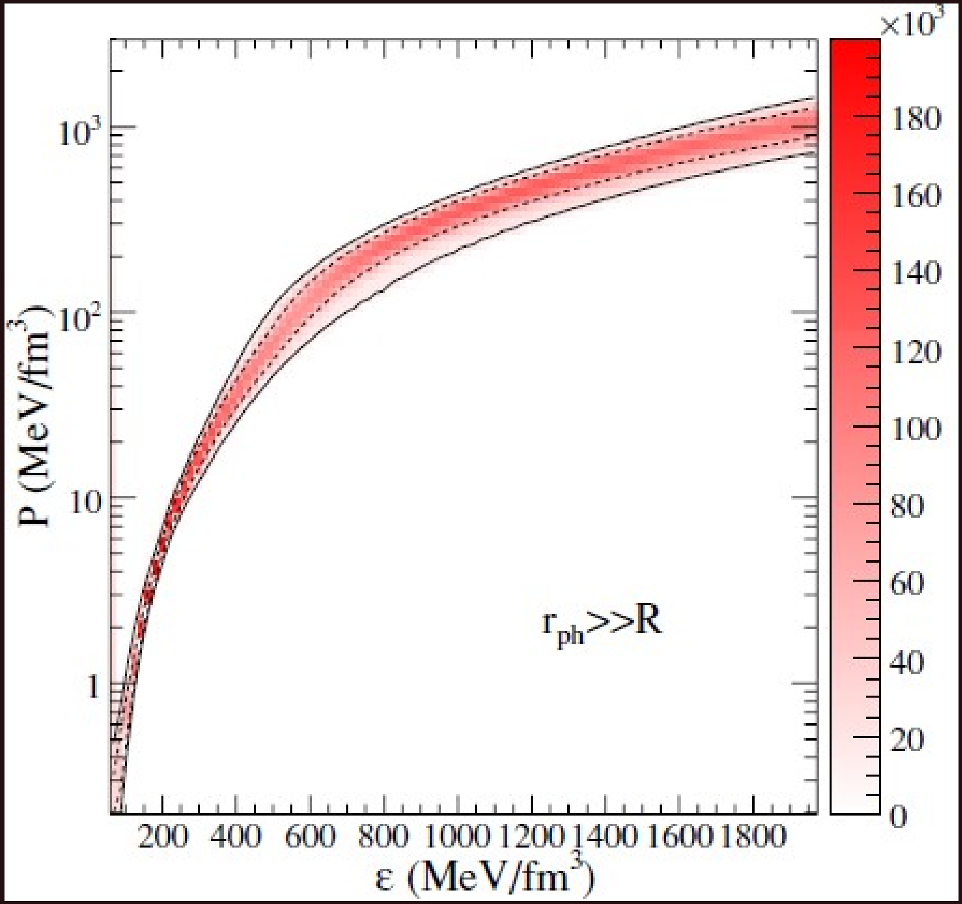
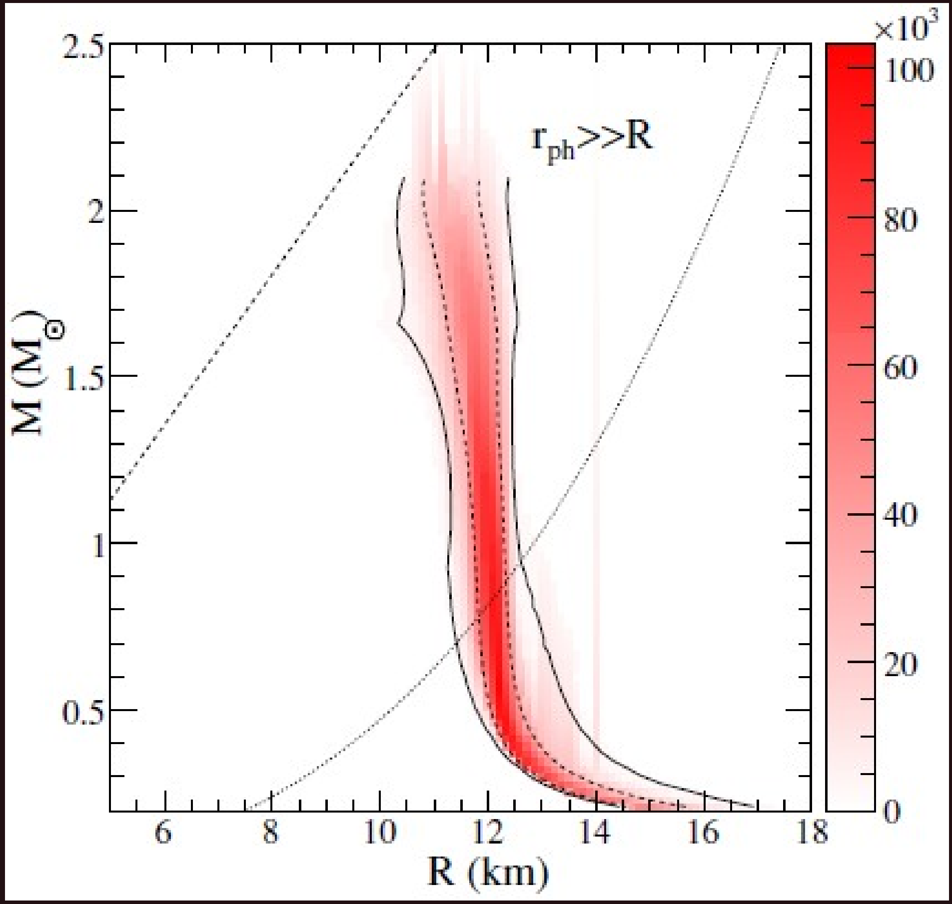
Equation of State from Mass and Radius observations *)




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

Pb = 8.68 d, e=0.00000130(4)

Inclination angle = 89.17(2) degrees !

Precise masses derived from Shapiro delay only:

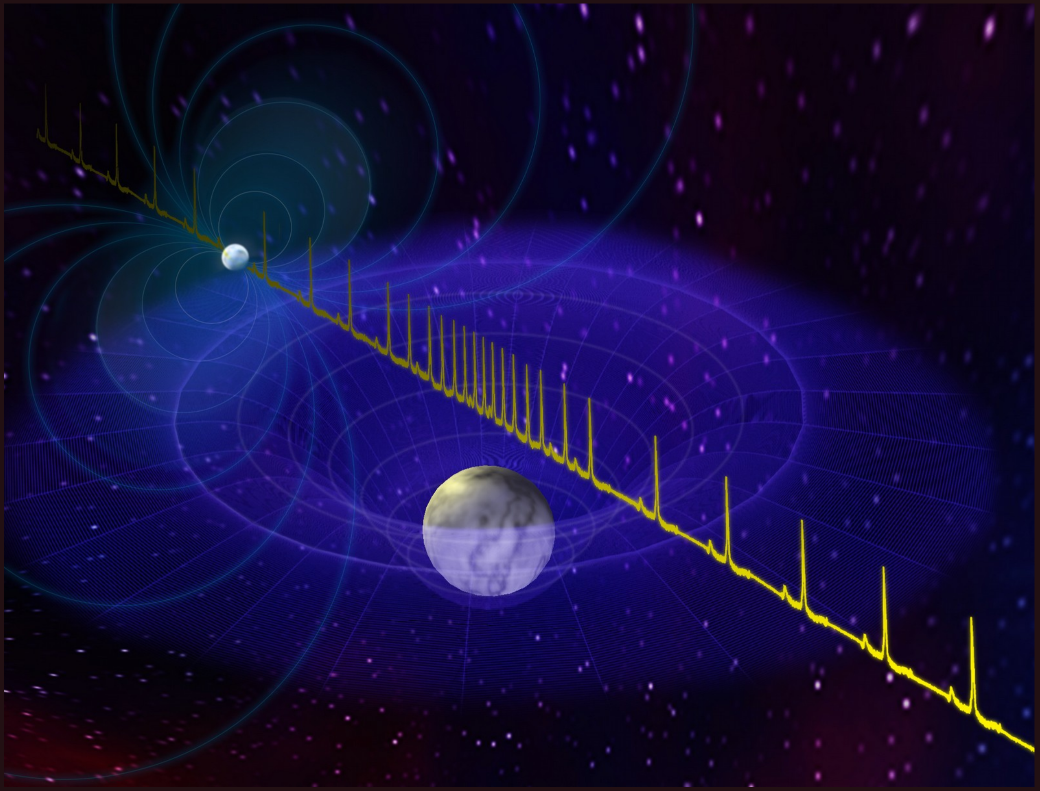
$M_p = 1.97(4)\ M_\odot$
$M_c = 0.500(6)\ M_\odot$

Update [Fonseca et al. (2016)]

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

Update [Arzoumanian et al. (2018)]
Mp = 1.908(16) Mo

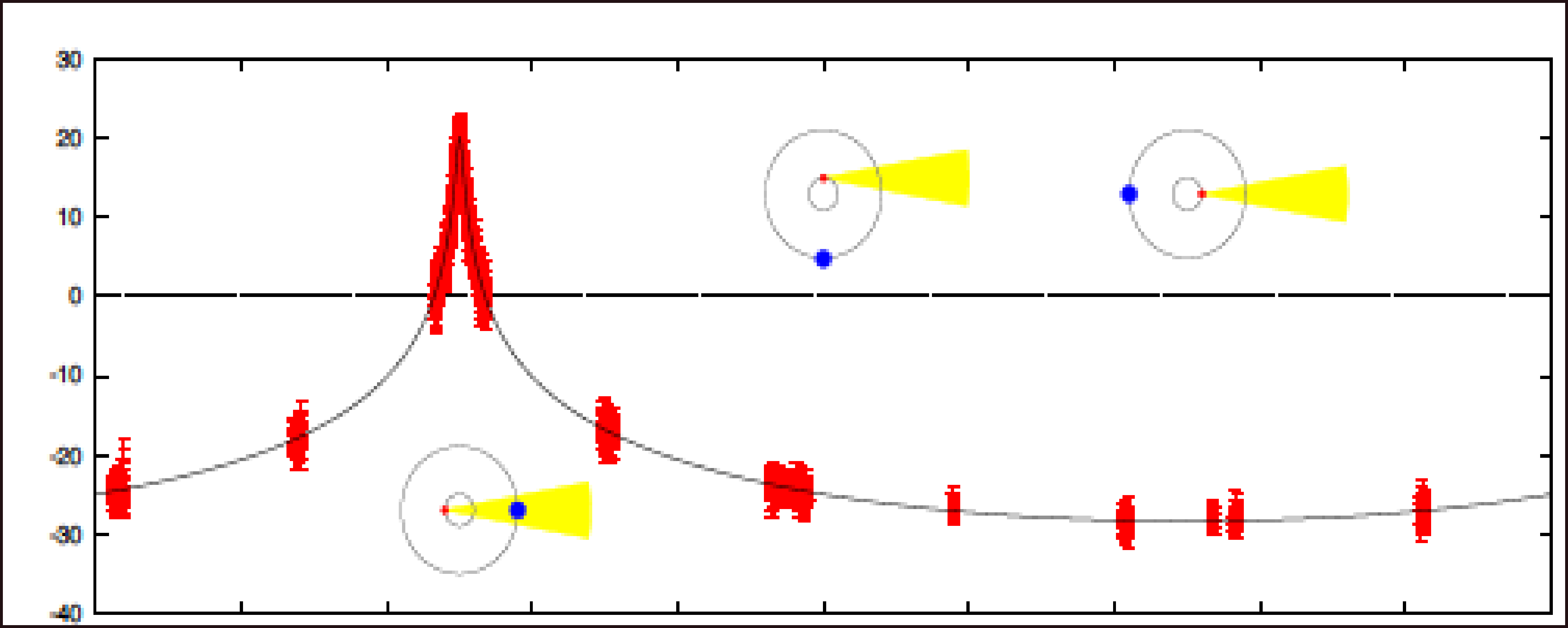
PSR J1614-2230
Demorest et al., Nature (2010)



# PSR J1614-2230

A precise AND large mass measurement

Shapiro delay:



# Neutron star mass measurements with Shapiro delay – new record

MSP with period P=2.88 ms

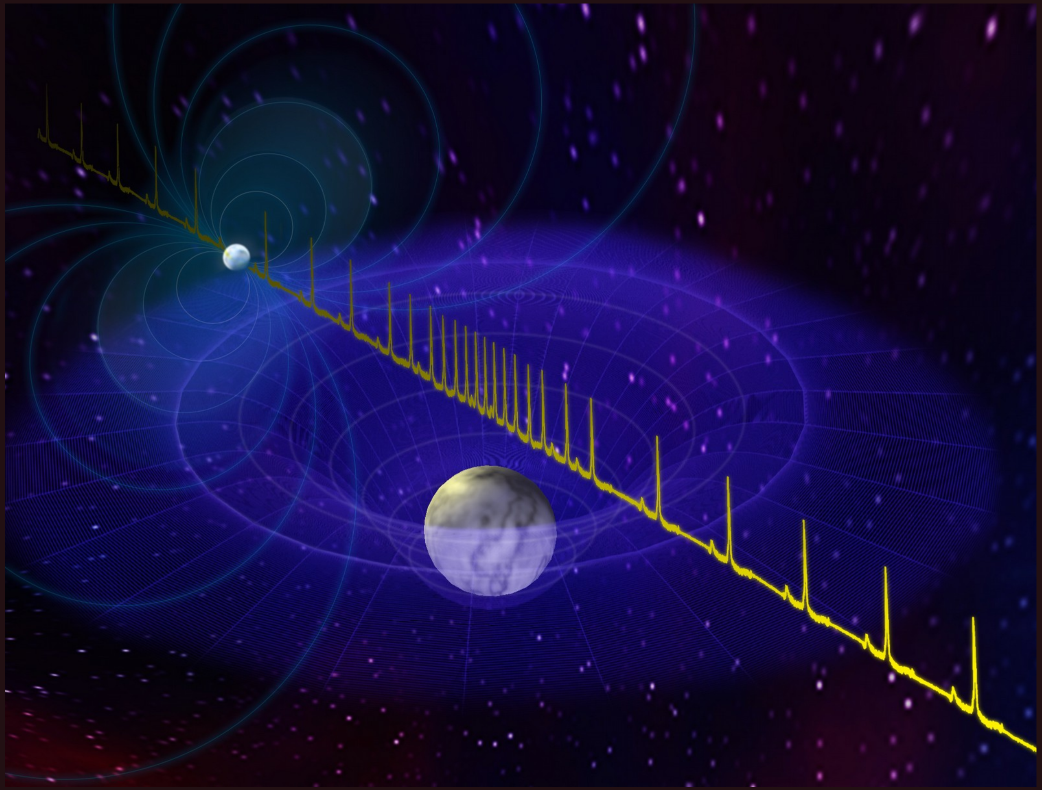
Pb = 4.7669 d, e=0.00000507(4)

Inclination angle = 87.35 degrees !

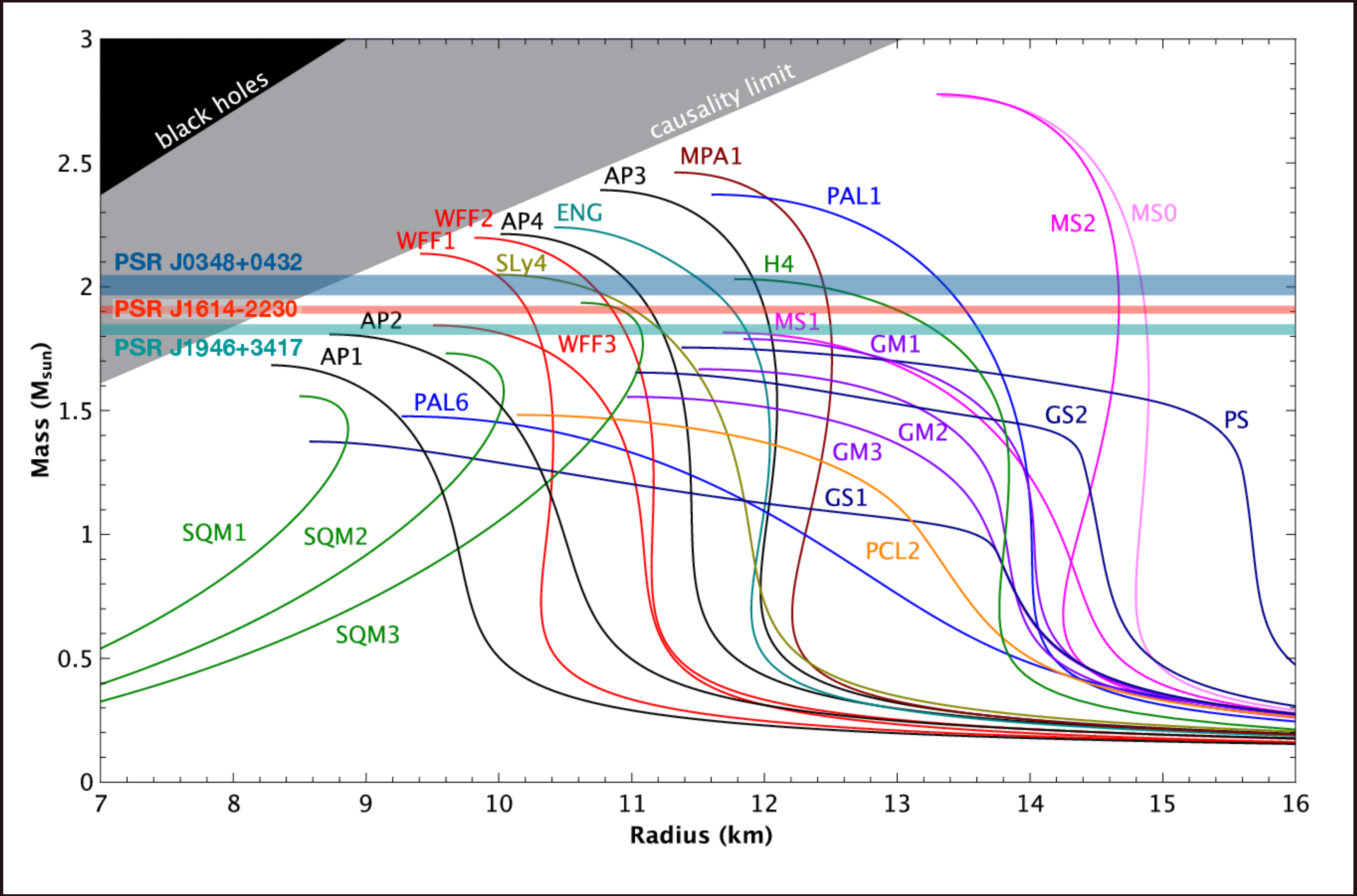
Precise mass derived from
Shapiro delay only (in M_solar):

$$2.14^{+0.10}_{-0.09}$$

PSR J0740+6620
Cromartie et al., arXiv:1904.06759
Nature Astron. 7 (2020) 72

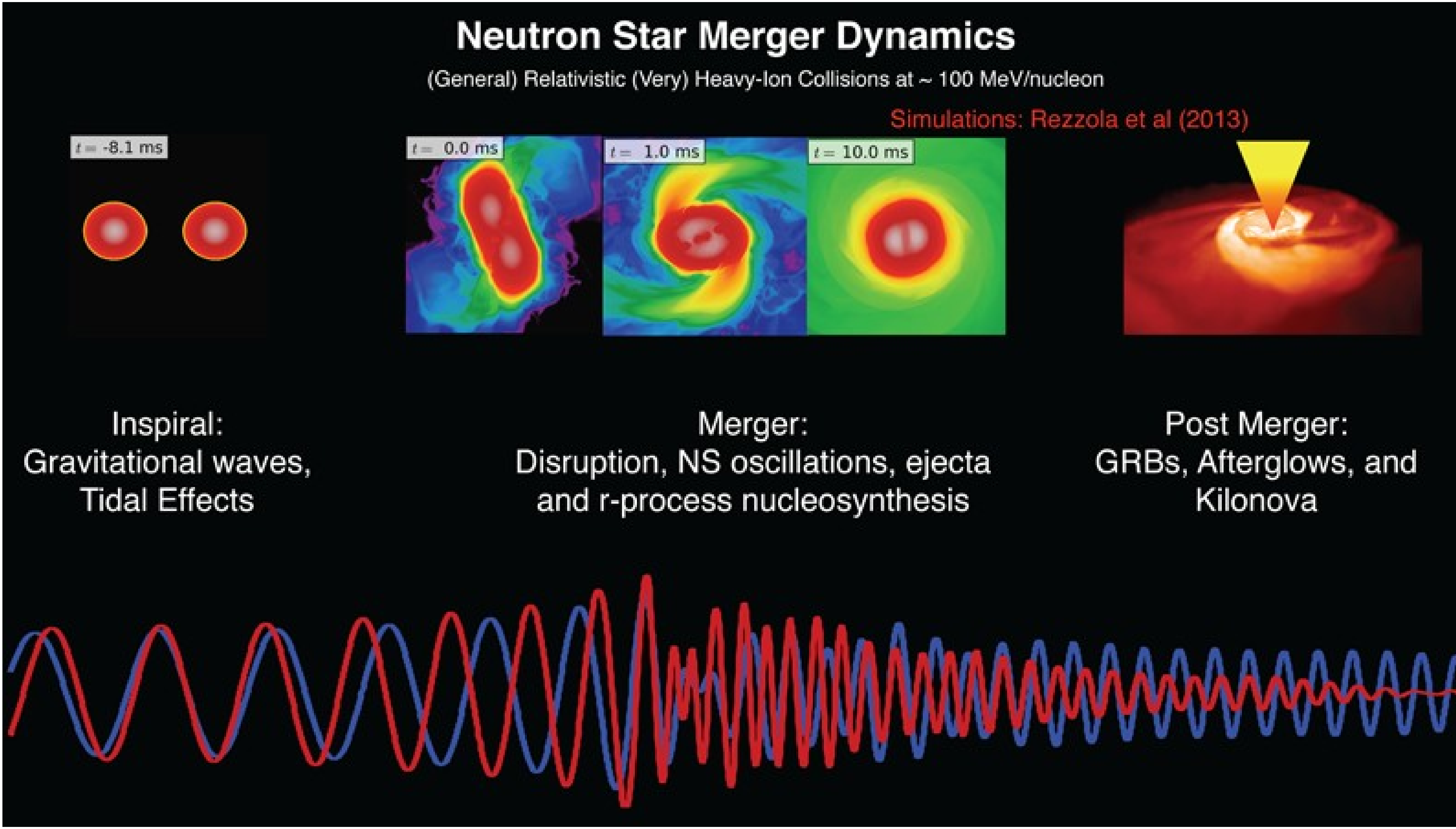


# NS Masses and Radii ↔ EoS

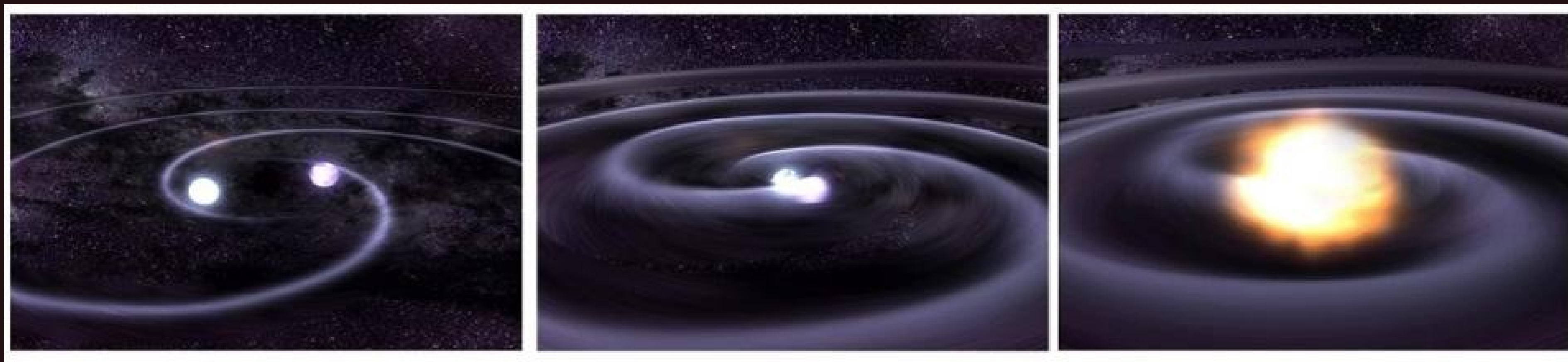


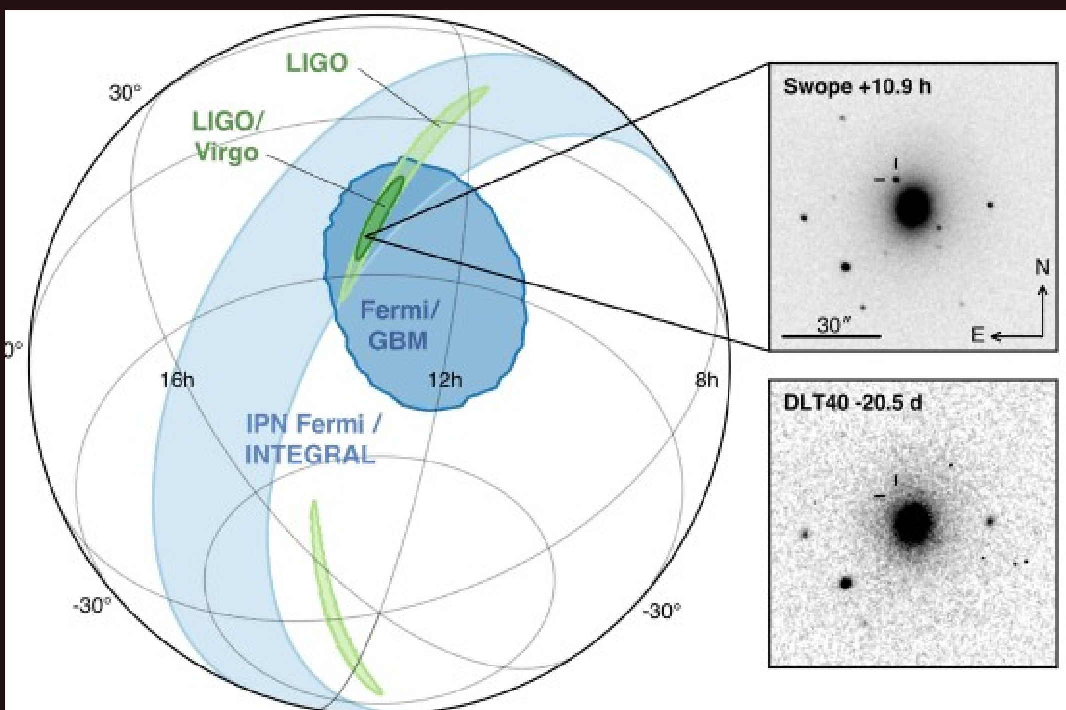

www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

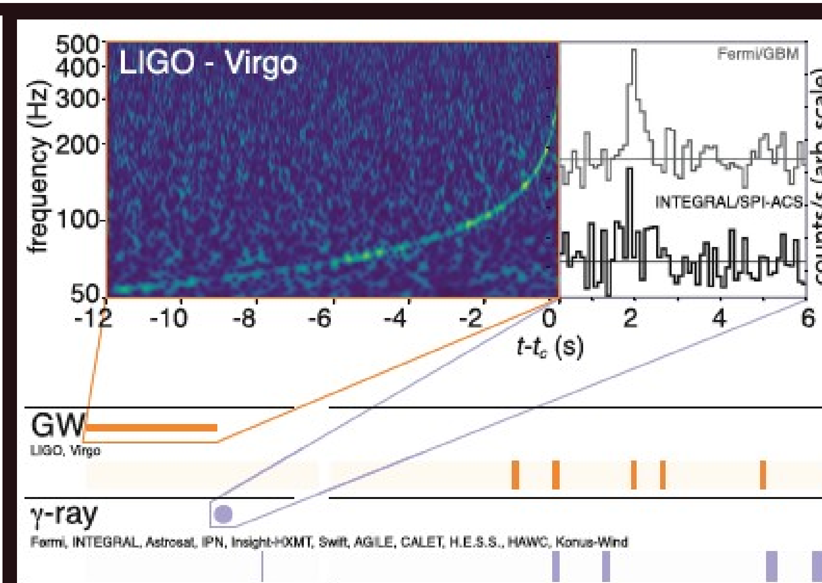
# GW170817 – a merger of two compact stars



# 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 *)

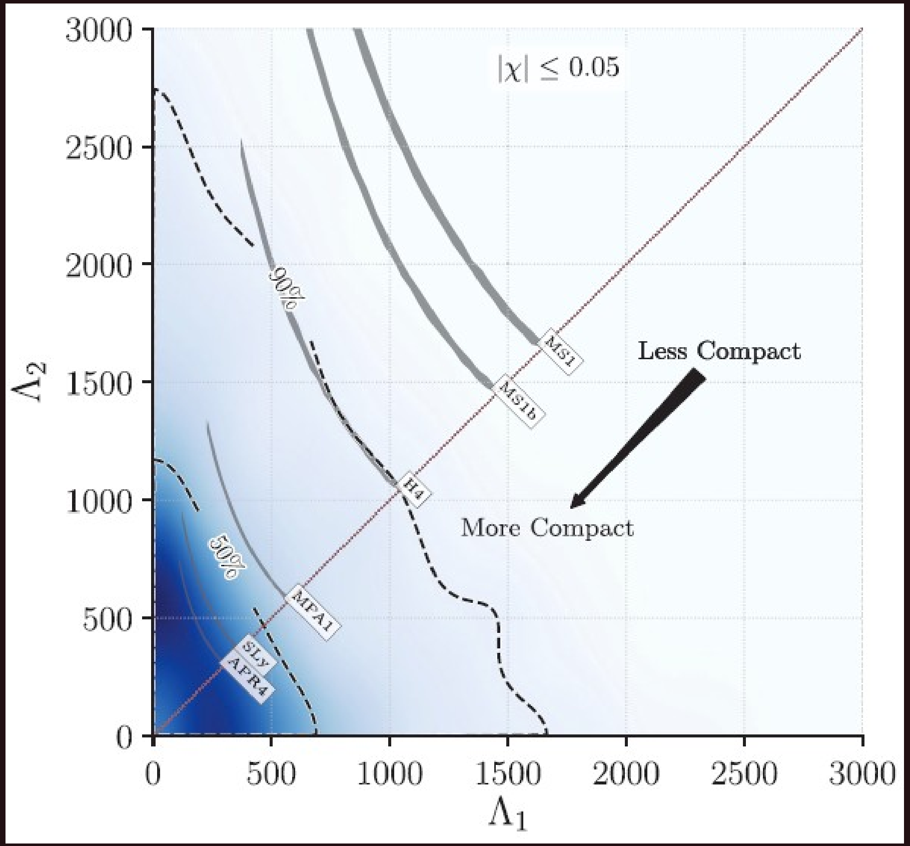
**Multi-Messenger Astrophysics !!**

| | Low-spin priors ($|\chi| \le 0.05$) |
|---|---|
| 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 $D_L$ | $40^{+8}_{-14}$ Mpc |

Constraint on neutron star maximum mass

**$M_{TOV}$ < 2.17 M_sun**

(Margalit & Metzger, arxiv:1710.05938)




Constraint on parameter  (Λ<800)

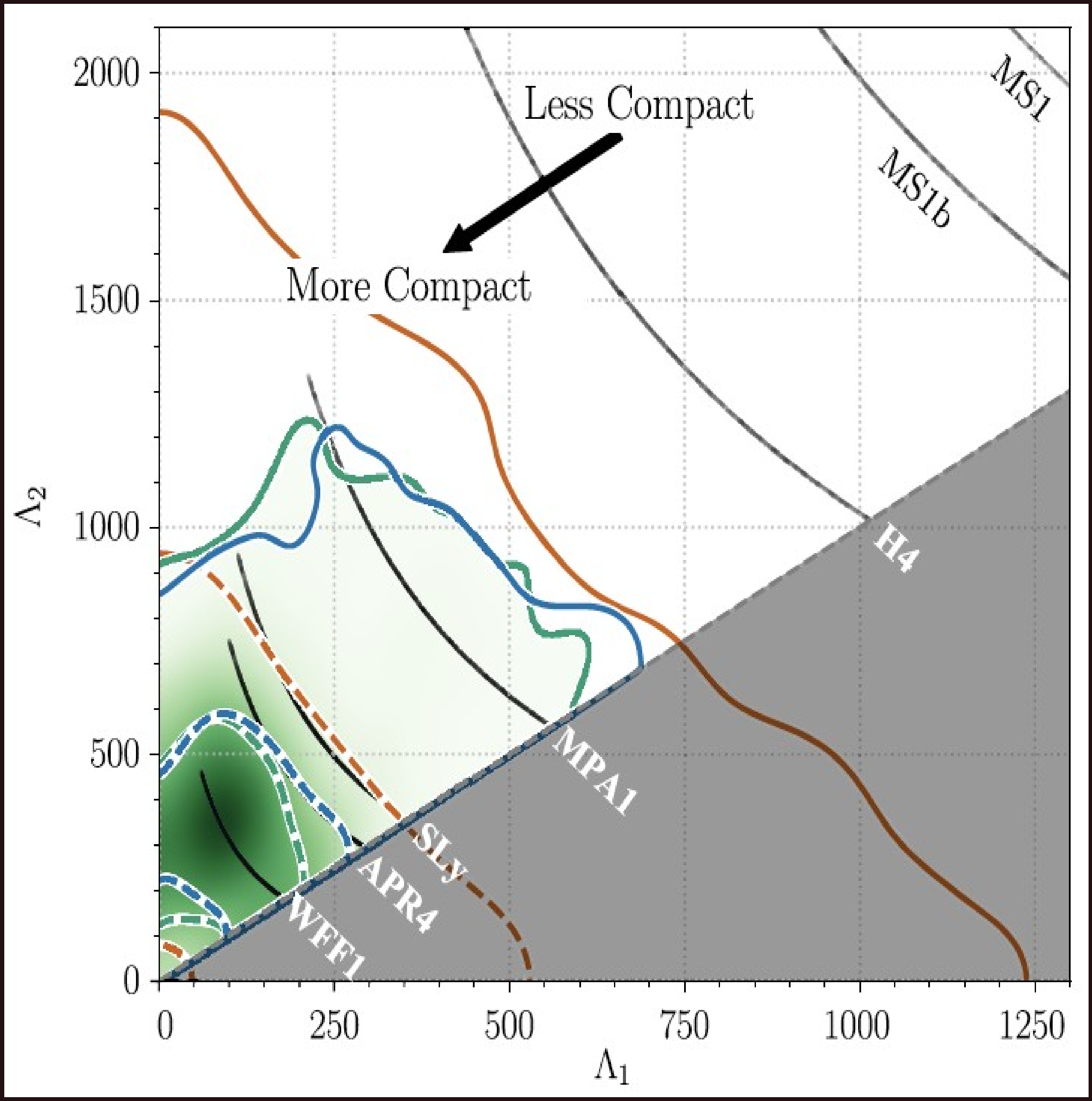
$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1+m_2)^5}$$

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)

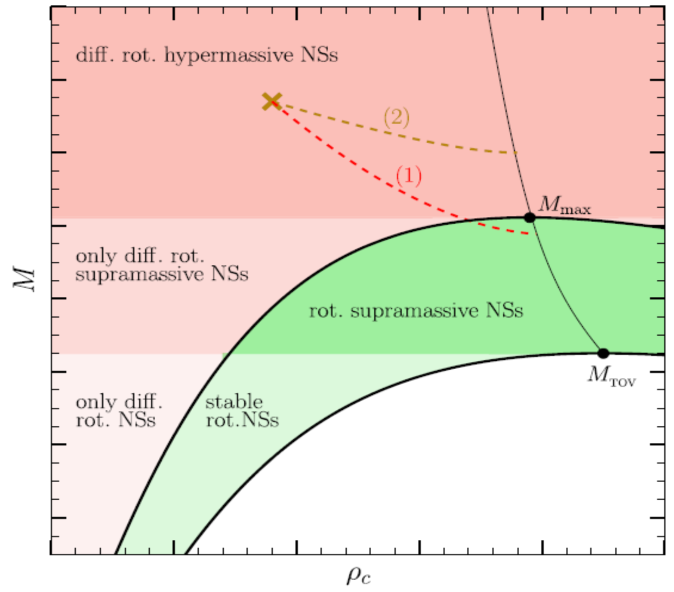
# Constraints on NS mass and radii !




Constraint on maximum mass

**2.01 < $M_{TOV}/M_O$ < 2.16**

(Rezzolla et al., arxiv:1710.05938)




LVC radius constraint

GW170817

(Abbott et al., PRL (2018))

GW190425

(Abbott et al., arxiv:2001.01761)

NICER mass -radius constraint

PSR J0030+0451

(Miller et al., ApJLett. (2019))

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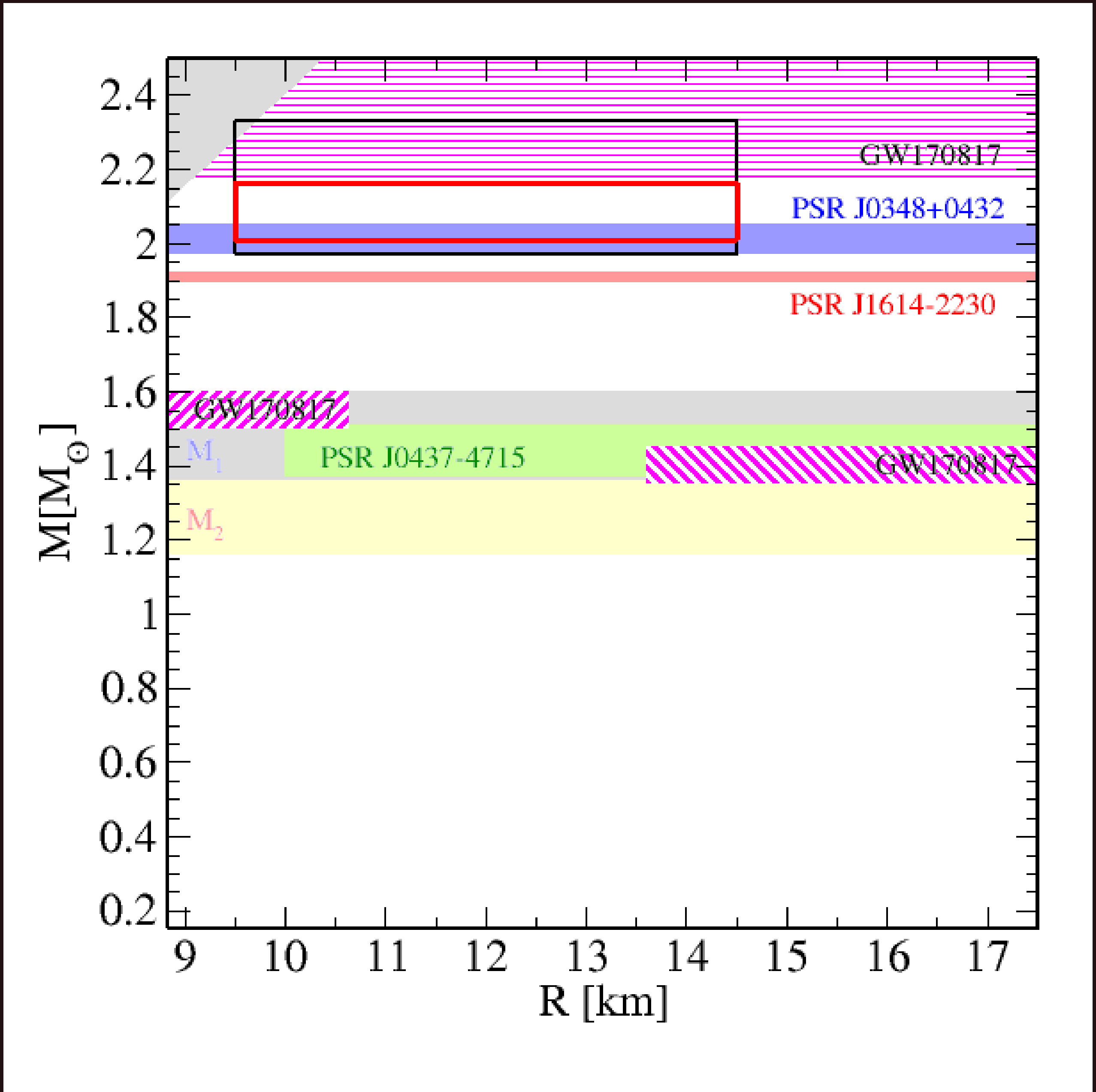


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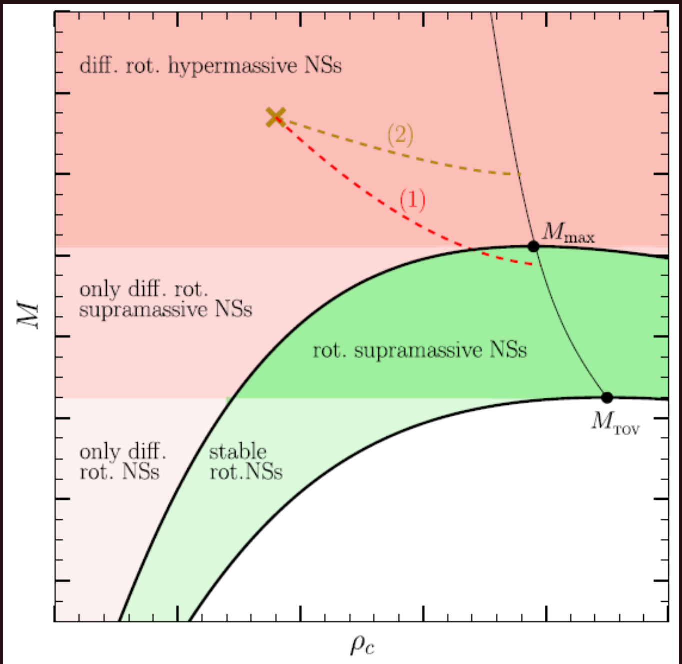



Constraint on minimal radius

**$R_{1.6} > 10.68$ km**

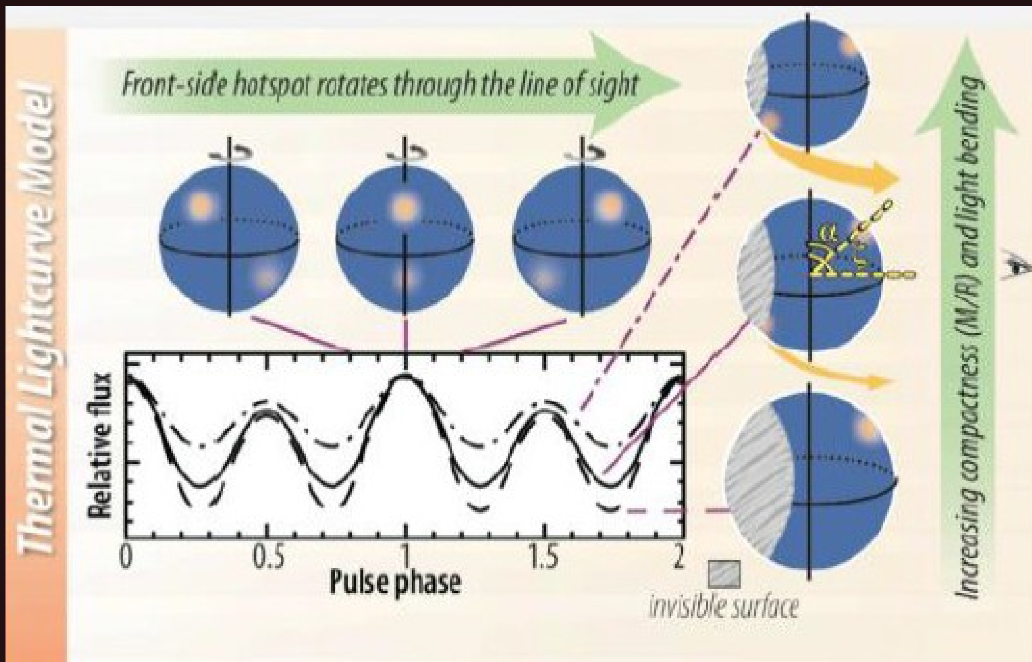
(Bauswein et al., arxiv:1710.06843)

Constraint on maximal radius

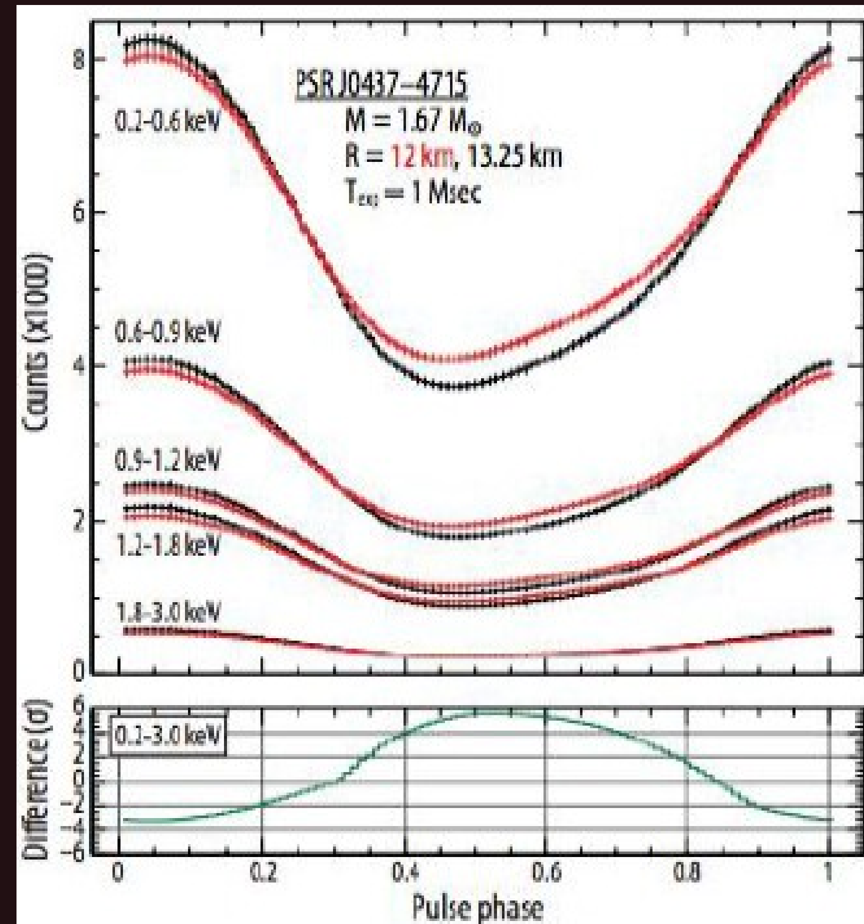
**$R_{1.4} < 13.6$ km**

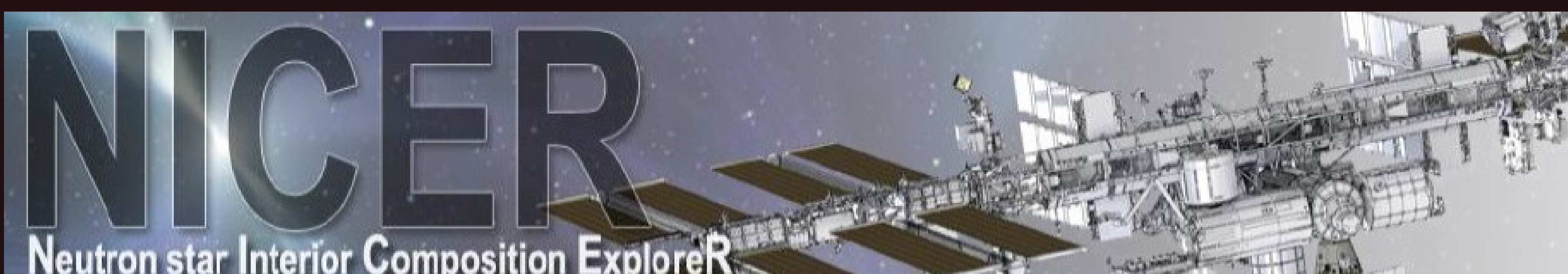
(Annala et al., arxiv:1711.02644)

# Measure NS Radii ...



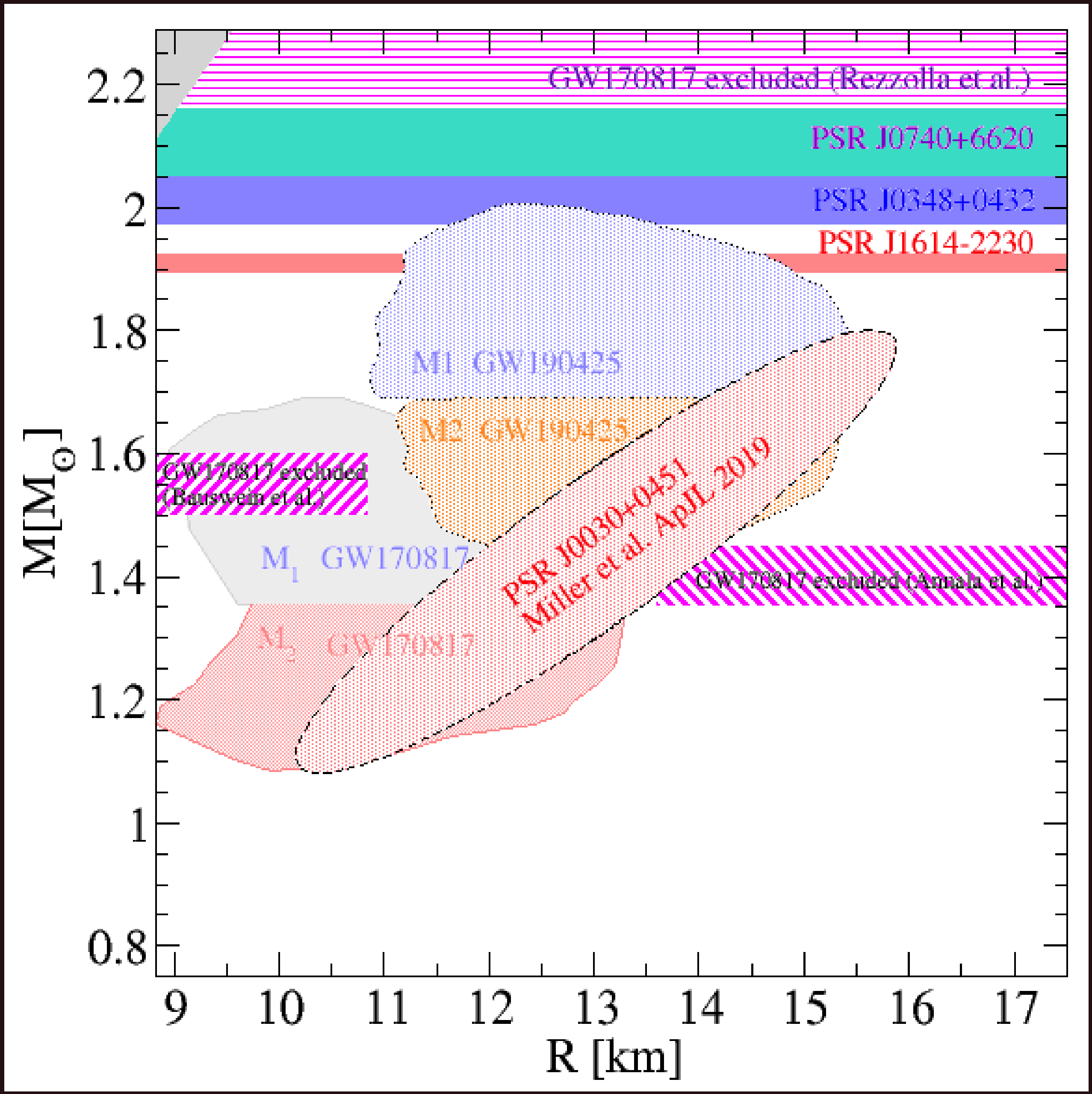

Thermal lightcurves: NS with "hot spots"




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

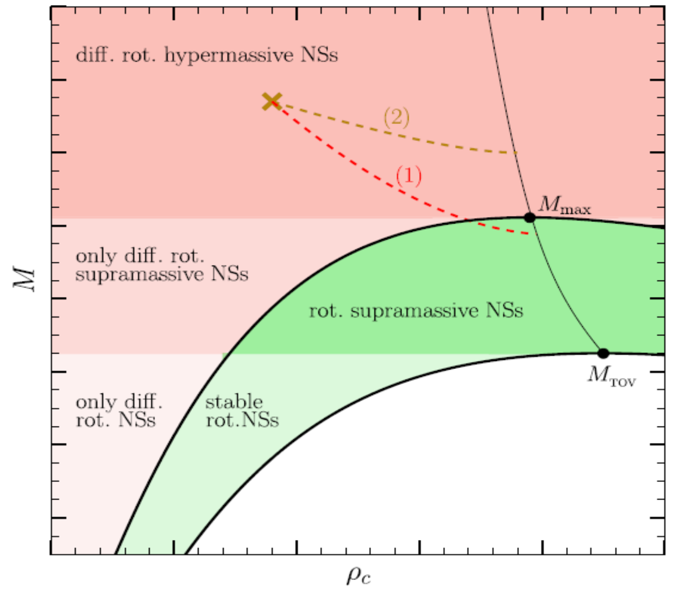
# Constraints on NS mass and radii !




Constraint on maximum mass

**$2.01 < M_{TOV}/M_{O} < 2.16$**

(Rezzolla et al., arxiv:1710.05938)




LVC radius constraint

GW170817

(Abbott et al., PRL (2018))

GW190425

(Abbott et al., arxiv:2001.01761)

NICER mass -radius constraint

PSR J0030+0451

(Miller et al., ApJLett. (2019))

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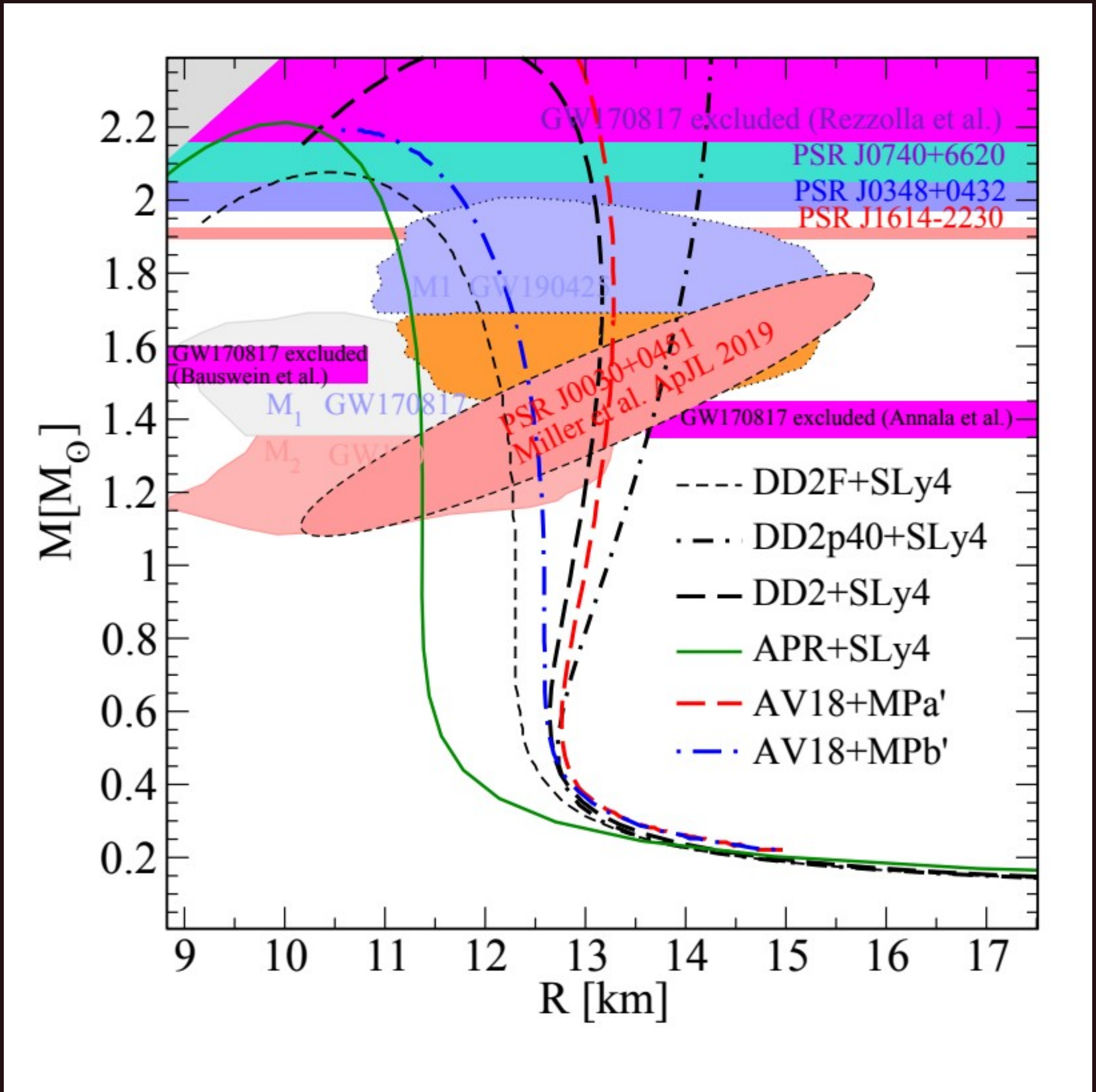


AV18*: Yamamoto, Togashi et al., Phys. Rev C 96 (2017) 065804
DD2*: Typel, Röpke, Klähn, et al., Phys. Rev. C 81 (2010) 015803

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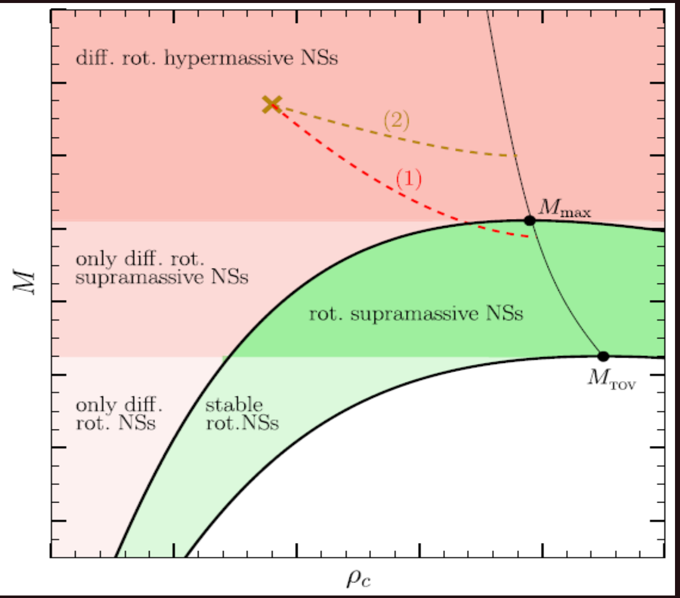


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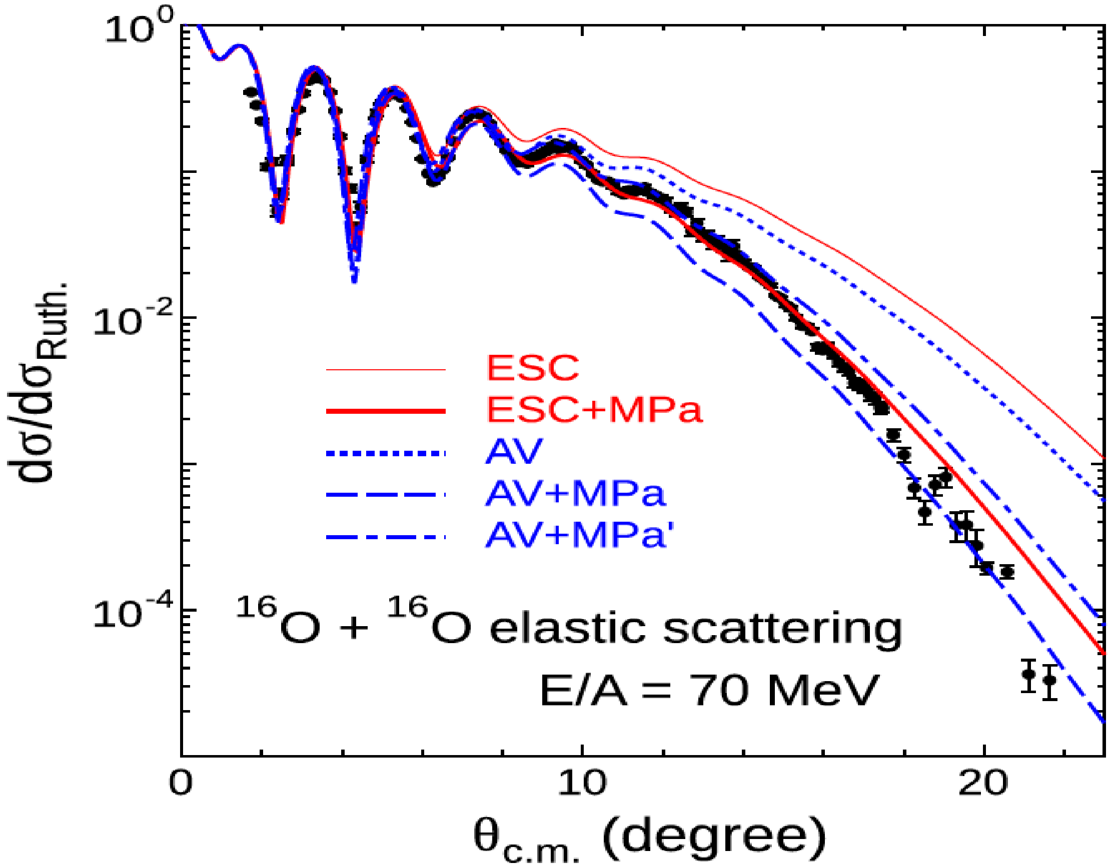
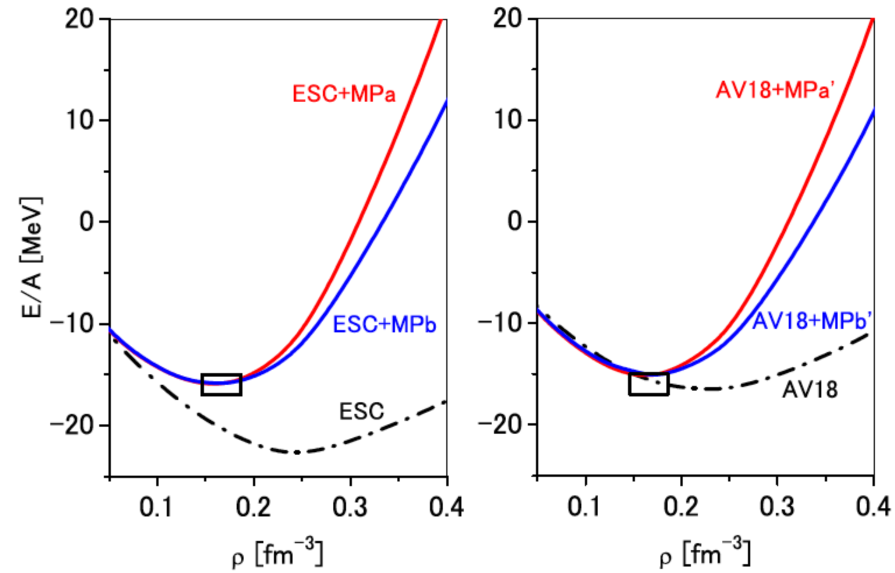
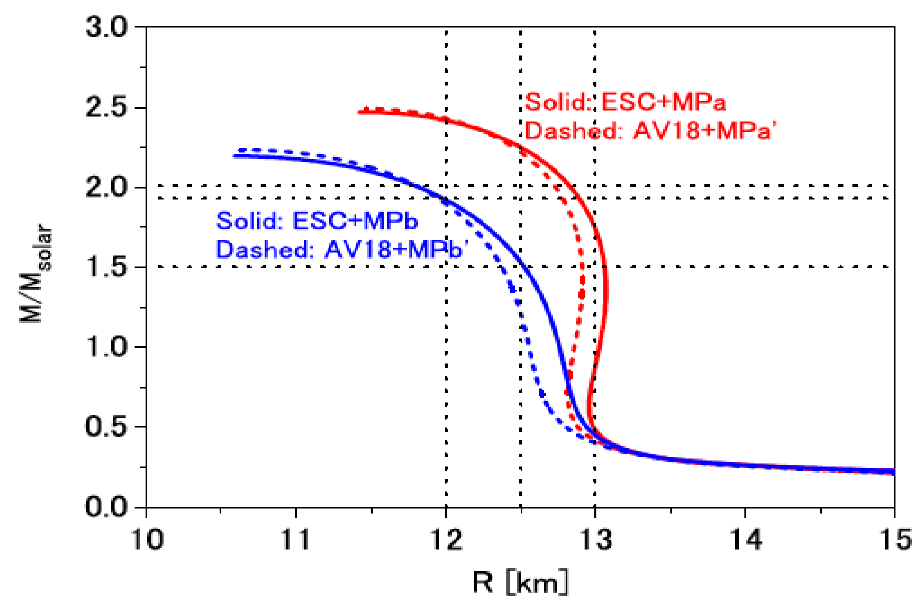
# Shall the APR EoS be abandoned?

Y. Yamamoto, H. Togashi, T. Tamagawa, T. Furumoto, N. Yasutake, T. Rijken, PRC 96 (2017)

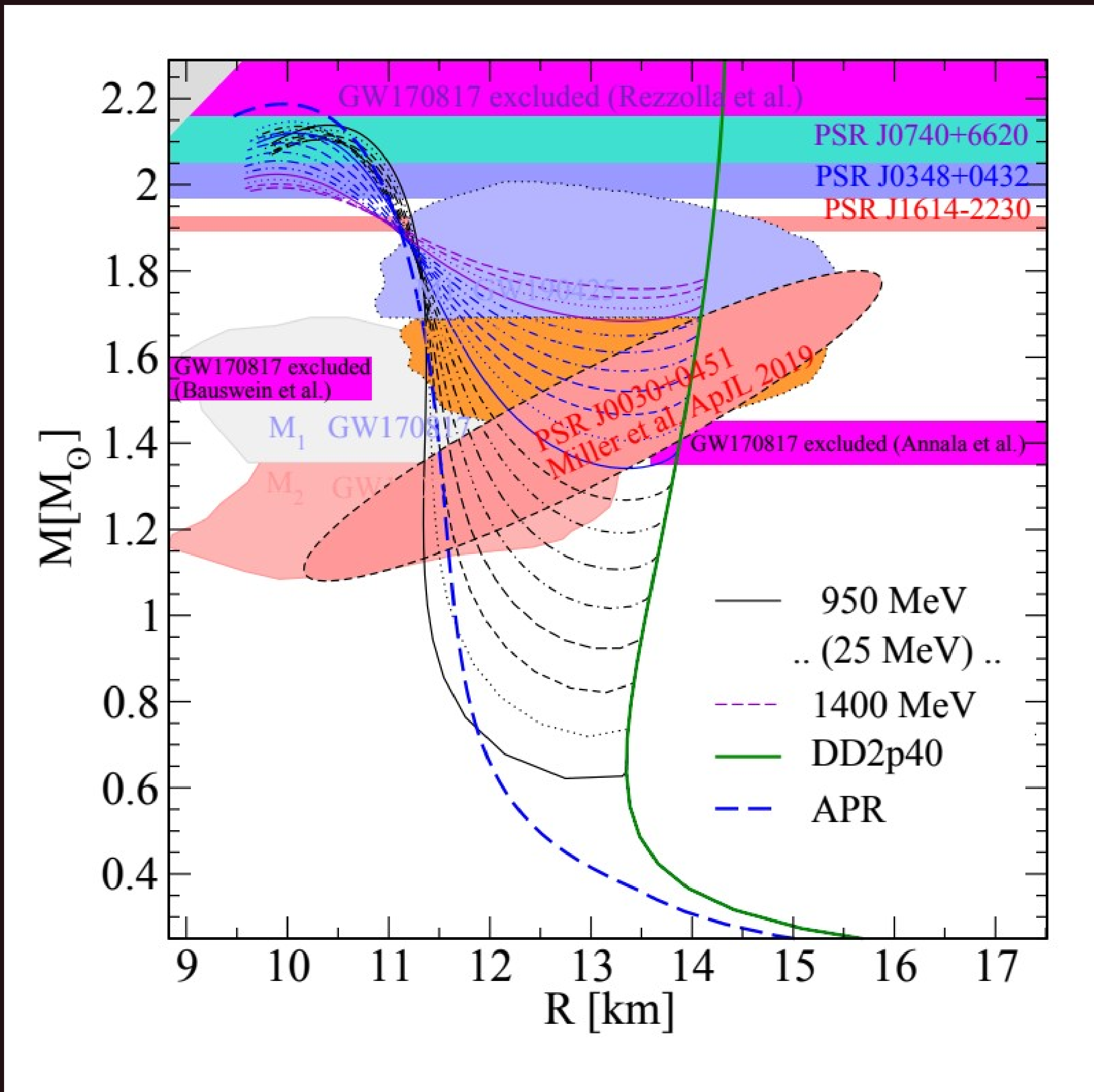



Short-range multipomeron exchange potential (MPP) added to AV18 potential gives significant improvement of large-angle scattering cross section (s.a.) and the Nuclear saturation properties, when compared to APR.
→ Neutron star radii R(M< 2 M_sun) > 12 km !!

# Constraints on NS mass and radii !




Blaschke, Ayriyan, Alvarez-Castillo et al., Universe 6 (2020) 81

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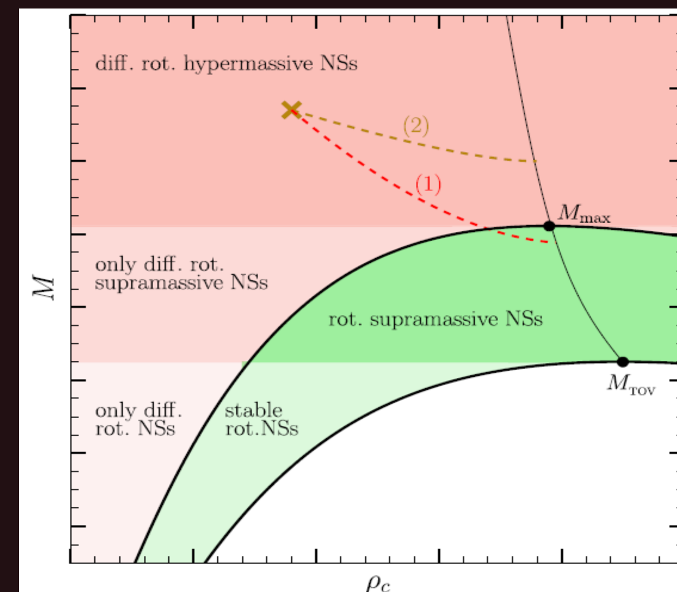


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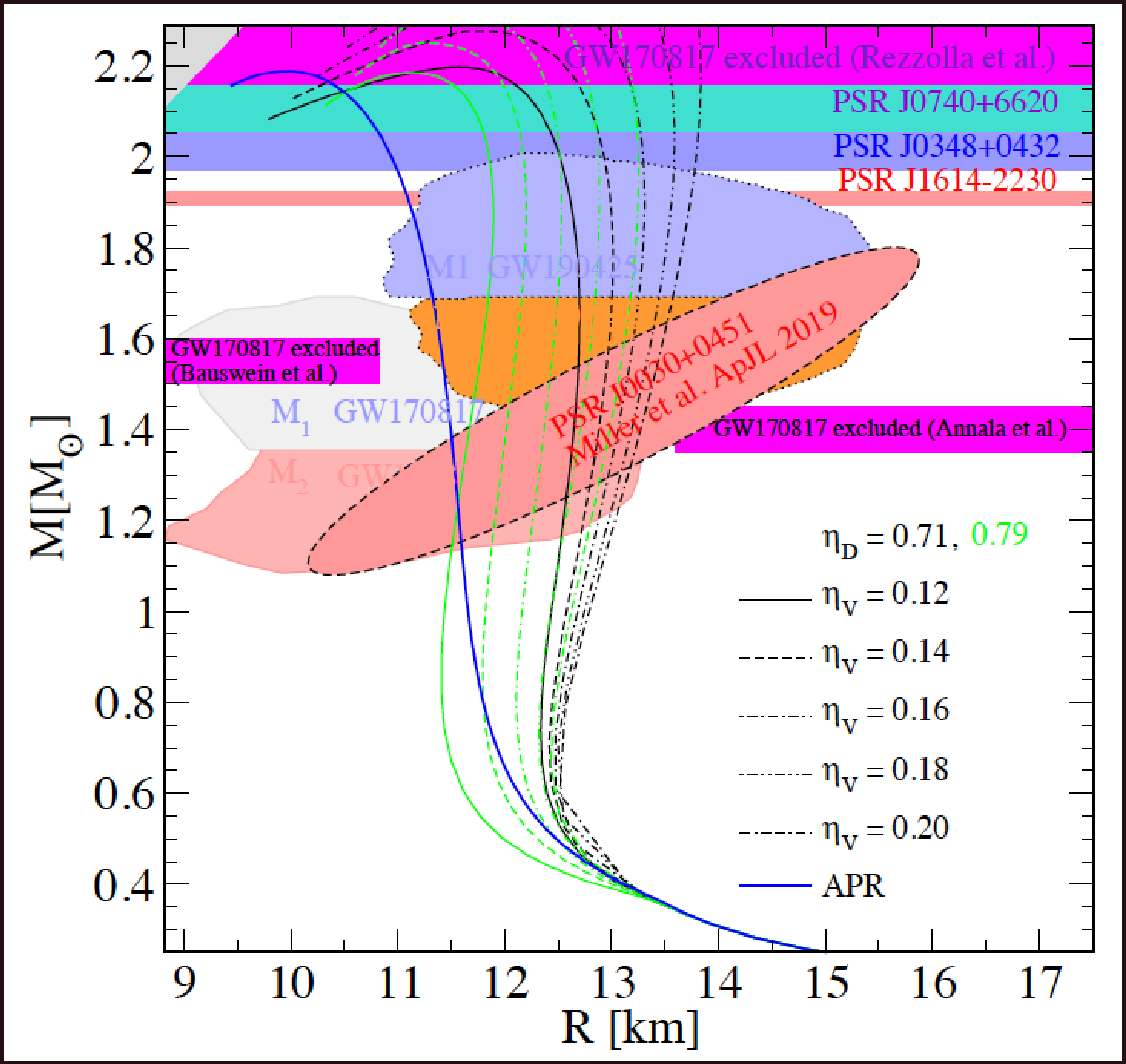


Ayriyan, Blaschke, Grunfeld, Alvarez-Castillo et al., in prep. (2020)

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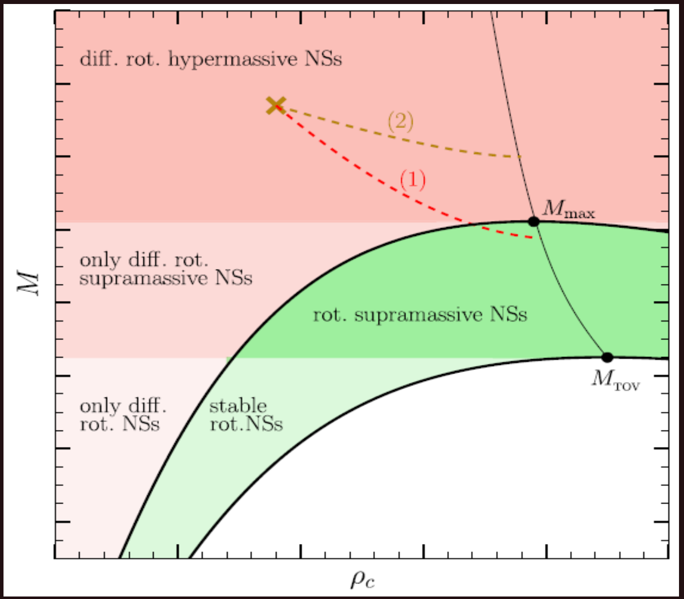


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# Relativistic density functional approach to quark matter - string-flip model (SFM)

M.A.R. Kaltenborn, N.-U.F. Bastian, D.B. Blaschke, PRD 96 (2017) 056024 [arxiv:1701.04400v3]

PHYSICAL REVIEW D VOLUME 34, NUMBER 11 1 DECEMBER 1986

# Pauli quenching effects in a simple string model of quark/nuclear matter

G. Röpke and D. Blaschke
*Department of Physics, Wilhelm-Pieck-Universtiy, 2500 Rostock, German Democratic Republic*

H. Schulz
*Central Institute for Nuclear Research, Rossendorf, 8051 Dresden, German Democratic Republic and The Niels Bohr Institute, 2100 Copenhagen, Denmark*

(Received 16 December 1985)

# Relativistic density functional approach* (I)

$$\mathcal{Z} = \int \mathcal{D}\bar{q}\mathcal{D}q \exp\left\{\int_0^\beta d\tau \int_V d^3x \left[\mathcal{L}_{\text{eff}} + \bar{q}\gamma_0\hat{\mu}q\right]\right\}\,, \quad q = \begin{pmatrix} q_u \\ q_d \end{pmatrix}, \quad \hat{\mu} = \text{diag}(\mu_u, \mu_d)$$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{free}} - \boxed{U(\bar{q}q, \bar{q}\gamma_0 q)}, \quad \mathcal{L}_{\text{free}} = \bar{q}\left(-\gamma_0\frac{\partial}{\partial\tau} + i\vec{\gamma}\cdot\vec{\nabla} - \hat{m}\right)q\,, \; \hat{m} = \text{diag}(m_u, m_d)$$

General nonlinear functional of quark density bilinears: scalar, vector, isovector, diquark ...
Expansion around the expectation values:

$$U(\bar{q}q,\, \bar{q}\gamma_0 q) = U(n_{\text{s}}, n_{\text{v}}) + (\bar{q}q - n_{\text{s}})\Sigma_{\text{s}} + (\bar{q}\gamma_0 q - n_{\text{v}})\Sigma_{\text{v}} + \ldots\,,$$

$$\langle\bar{q}q\rangle = n_{\text{s}} = \sum_{f=u,d} n_{\text{s},f} = -\sum_{f=u,d}\frac{T}{V}\frac{\partial}{\partial m_f}\ln\mathcal{Z}\,, \quad \Sigma_{\text{s}} = \left.\frac{\partial U(\bar{q}q, \bar{q}\gamma_0 q)}{\partial(\bar{q}q)}\right|_{\bar{q}q=n_{\text{s}}} = \frac{\partial U(n_{\text{s}}, n_{\text{v}})}{\partial n_{\text{s}}}\,,$$

$$\langle\bar{q}\gamma_0 q\rangle = n_{\text{v}} = \sum_{f=u,d} n_{\text{v},f} = \sum_{f=u,d}\frac{T}{V}\frac{\partial}{\partial \mu_f}\ln\mathcal{Z}\,, \quad \Sigma_{\text{v}} = \left.\frac{\partial U(\bar{q}q, \bar{q}\gamma_0 q)}{\partial(\bar{q}\gamma_0 q)}\right|_{\bar{q}\gamma_0 q=n_{\text{v}}} = \frac{\partial U(n_{\text{s}}, n_{\text{v}})}{\partial n_{\text{v}}}$$

$$\boxed{\mathcal{Z} = \int \mathcal{D}\bar{q}\mathcal{D}q \exp\left\{\mathcal{S}_{\text{quasi}}[\bar{q}, q] - \beta V\,\Theta[n_{\text{s}}, n_{\text{v}}]\right\}\,, \quad \Theta[n_{\text{s}}, n_{\text{v}}] = U(n_{\text{s}}, n_{\text{v}}) - \Sigma_{\text{s}}n_{\text{s}} - \Sigma_{\text{v}}n_{\text{v}}}$$

$$\mathcal{S}_{\text{quasi}}[\bar{q}, q] = \beta\sum_n\sum_{\vec{p}}\bar{q}\,G^{-1}(\omega_n, \vec{p})\,q\,, \quad G^{-1}(\omega_n, \vec{p}) = \gamma_0(-i\omega_n + \hat{\mu}^*) - \vec{\gamma}\cdot\vec{p} - \hat{m}^*$$

*This work was inspired by the textbook on “Thermodynamics and statistical mechanics” of the “red” series on Theoretical Physics by Walter Greiner and Coworkers.

# Relativistic density functional approach (II)

$$\mathcal{Z} = \int \mathcal{D}\bar{q}\mathcal{D}q \exp\left\{\mathcal{S}_{\rm quasi}[\bar{q},q] - \beta V \Theta[n_{\rm s},n_{\rm v}]\right\}\ , \quad \Theta[n_{\rm s},n_{\rm v}] = U(n_{\rm s},n_{\rm v}) - \Sigma_{\rm s} n_{\rm s} - \Sigma_{\rm v} n_{\rm v}$$

$$\mathcal{Z}_{\rm quasi} = \int \mathcal{D}\bar{q}\mathcal{D}q \exp\left\{\mathcal{S}_{\rm quasi}[\bar{q},q]\right\} = \det[\beta G^{-1}]\,, \qquad \ln\det A = {\rm Tr}\ln A$$

$$P_{\rm quasi} = \frac{T}{V}\ln \mathcal{Z}_{\rm quasi} = \frac{T}{V}{\rm Tr}\ln[\beta G^{-1}]$$

"no sea" approximation ...

$$= 2N_c \sum_{f=u,d}\int \frac{d^3p}{(2\pi)^3}\left\{T\ln\left[1+{\rm e}^{-\beta(E_f^*-\mu_f^*)}\right] + T\ln\left[1+{\rm e}^{-\beta(E_f^*+\mu_f^*)}\right]\right\}$$

$$P_{\rm quasi} = \sum_{f=u,d}\int \frac{dp}{\pi^2}\frac{p^4}{E_f^*}\left[f(E_f^*-\mu_f^*) + f(E_f^*+\mu_f^*)\right]$$

$$E_f^* = \sqrt{p^2 + {m_f^*}^2}$$

$$f(E) = 1/[1+\exp(\beta E)]$$

$$P = \sum_{f=u,d}\int_0^{p_{{\rm F},f}} \frac{dp}{\pi^2}\frac{p^4}{E_f^*} - \Theta[n_{\rm s},n_{\rm v}]\,, \quad p_{{\rm F},f} = \sqrt{{\mu_f^*}^2 - {m_f^*}^2}$$

$$\hat{m}^* = \hat{m} + \Sigma_{\rm s}$$
$$\hat{\mu}^* = \hat{\mu} - \Sigma_{\rm v}$$

Selfconsistent densities

$$n_{\rm s} = -\sum_{f=u,d}\frac{\partial P}{\partial m_f} = \frac{3}{\pi^2}\sum_{f=u,d}\int_0^{p_{{\rm F},f}} dp\,p^2\frac{m_f^*}{E_f^*}\,, \quad n_{\rm v} = \sum_{f=u,d}\frac{\partial P}{\partial \mu_f} = \frac{3}{\pi^2}\sum_{f=u,d}\int_0^{p_{{\rm F},f}} dp\,p^2 = \frac{p_{{\rm F},u}^3 + p_{{\rm F},d}^3}{\pi^2}\,.$$

# Relativistic density functional approach (III)

Density functional for the SFM

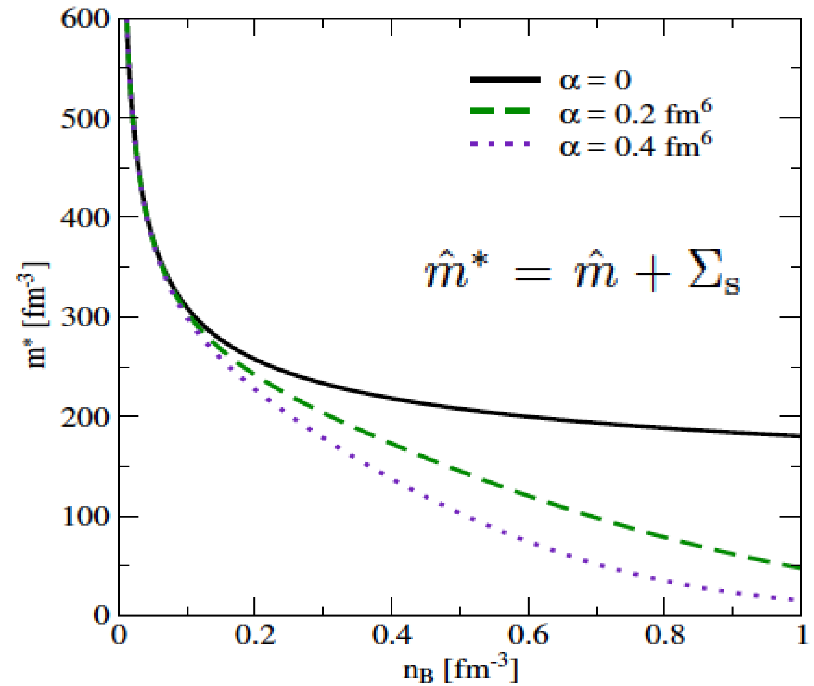
$$U(n_{\rm s}, n_{\rm v}) = D(n_{\rm v}) n_{\rm s}^{2/3} + a n_{\rm v}^2 + \frac{b n_{\rm v}^4}{1 + c n_{\rm v}^2} ,$$

Quark selfenergies

$$\Sigma_{\rm s} = \frac{2}{3} D(n_{\rm v}) n_{\rm s}^{-1/3} ,$$

Quark “confinement”

$$\Sigma_{\rm v} = 2 a n_{\rm v} + \frac{4 b n_{\rm v}^3}{1 + c n_{\rm v}^2} - \frac{2 b c n_{\rm v}^5}{(1 + c n_{\rm v}^2)^2} + \frac{\partial D(n_{\rm v})}{\partial n_{\rm v}} n_{\rm s}^{2/3}$$

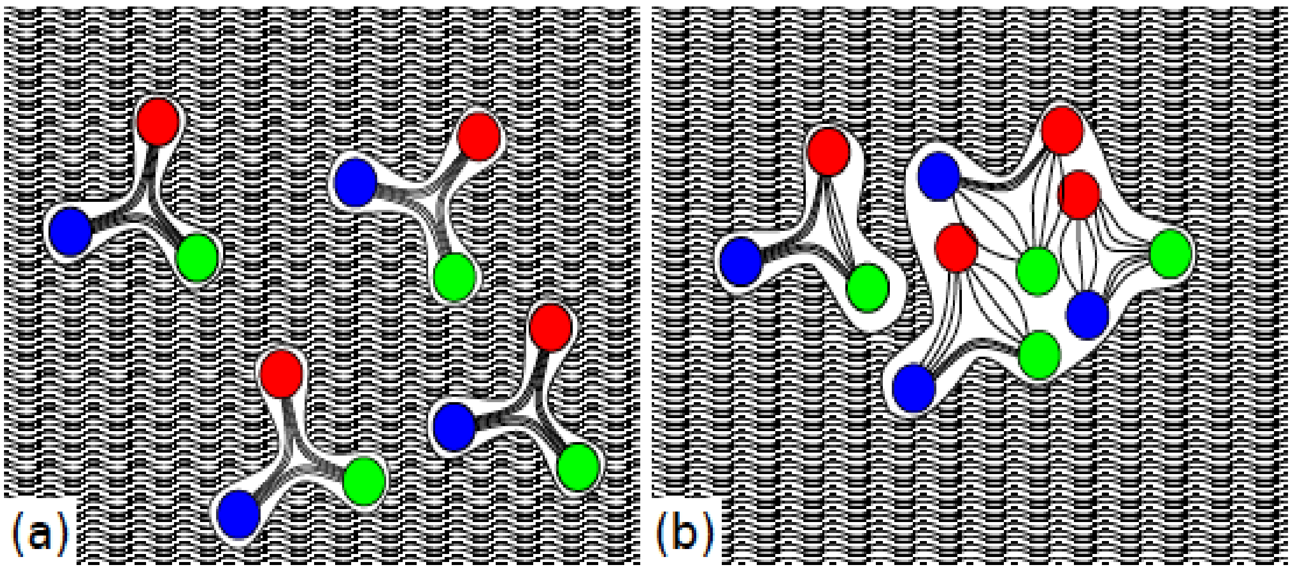



String tension & confinement due to dual Meissner effect (dual superconductor model)

$$D(n_{\rm v}) = D_0 \Phi(n_{\rm v})$$

Effective screening of the string tension in dense matter by a reduction of the available volume $\alpha = v|v|/2$

$$\Phi(n_{\rm B}) = \begin{cases} 1, & \text{if } n_{\rm B} < n_0 \\ e^{-\alpha(n_{\rm B}-n_0)^2}, & \text{if } n_{\rm B} > n_0 \end{cases}$$

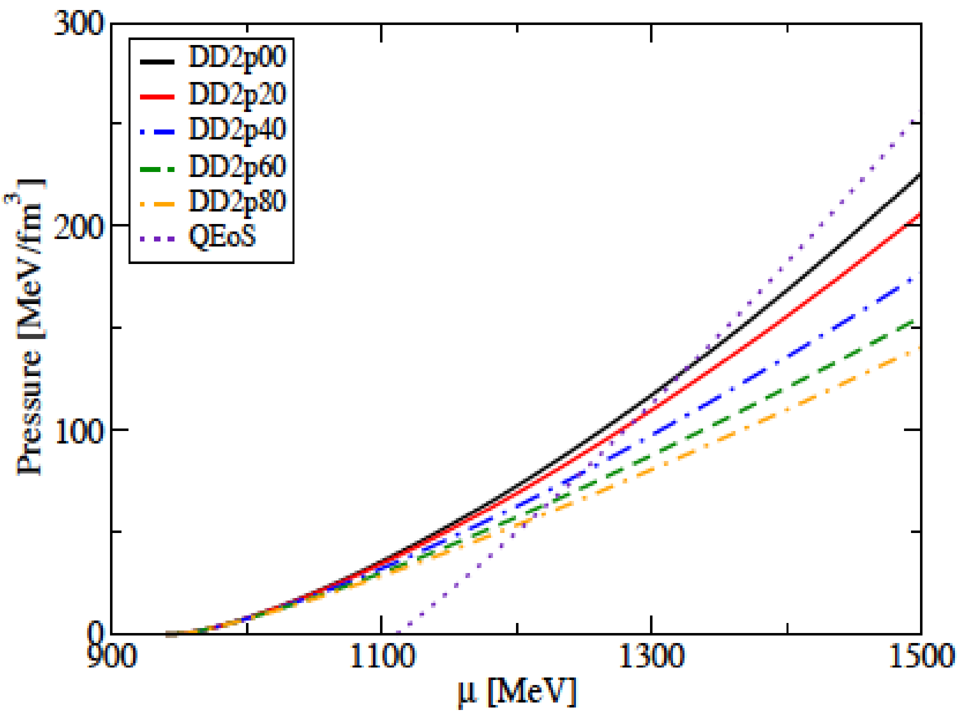


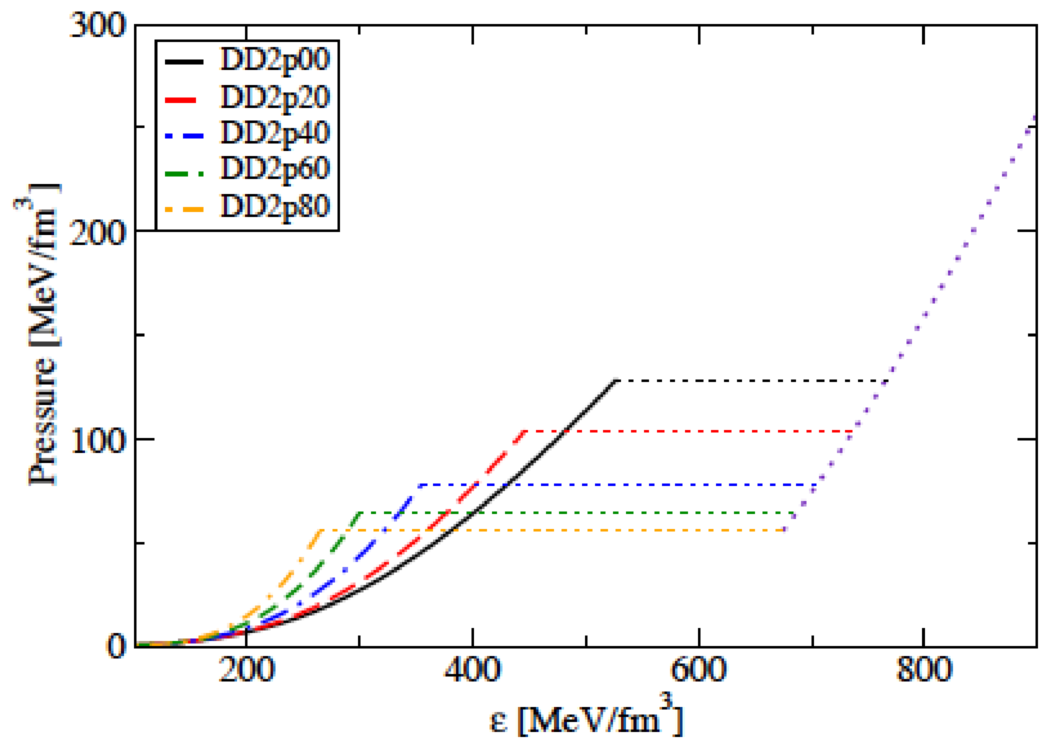
# Phase transition DD2p** to SFM quark matter

Hadronic matter: DD2 with excluded volume **[S. Typel, EPJA 52 (3) (2016)]**

$$\Phi_n = \Phi_p = \begin{cases} 1, & \text{if } n_B < n_0 \\ e^{-\frac{v|v|}{2}(n_B - n_0)^2}, & \text{if } n_B > n_0 \end{cases}$$

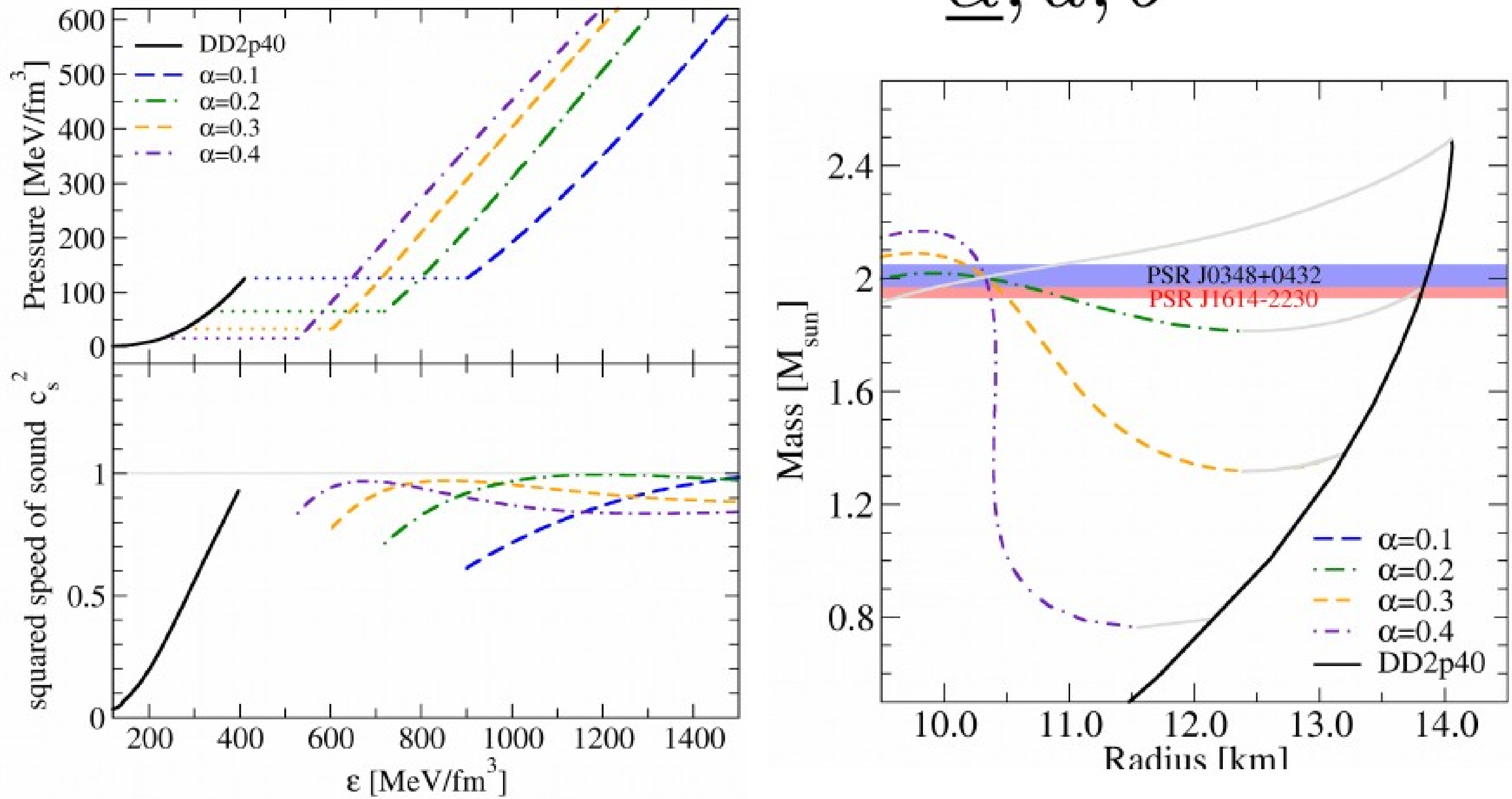
Varying the hadronic excluded volume parameter, p00 → v=0, … , p80 → v=8 fm^3



# Hybrid EOS - parameters

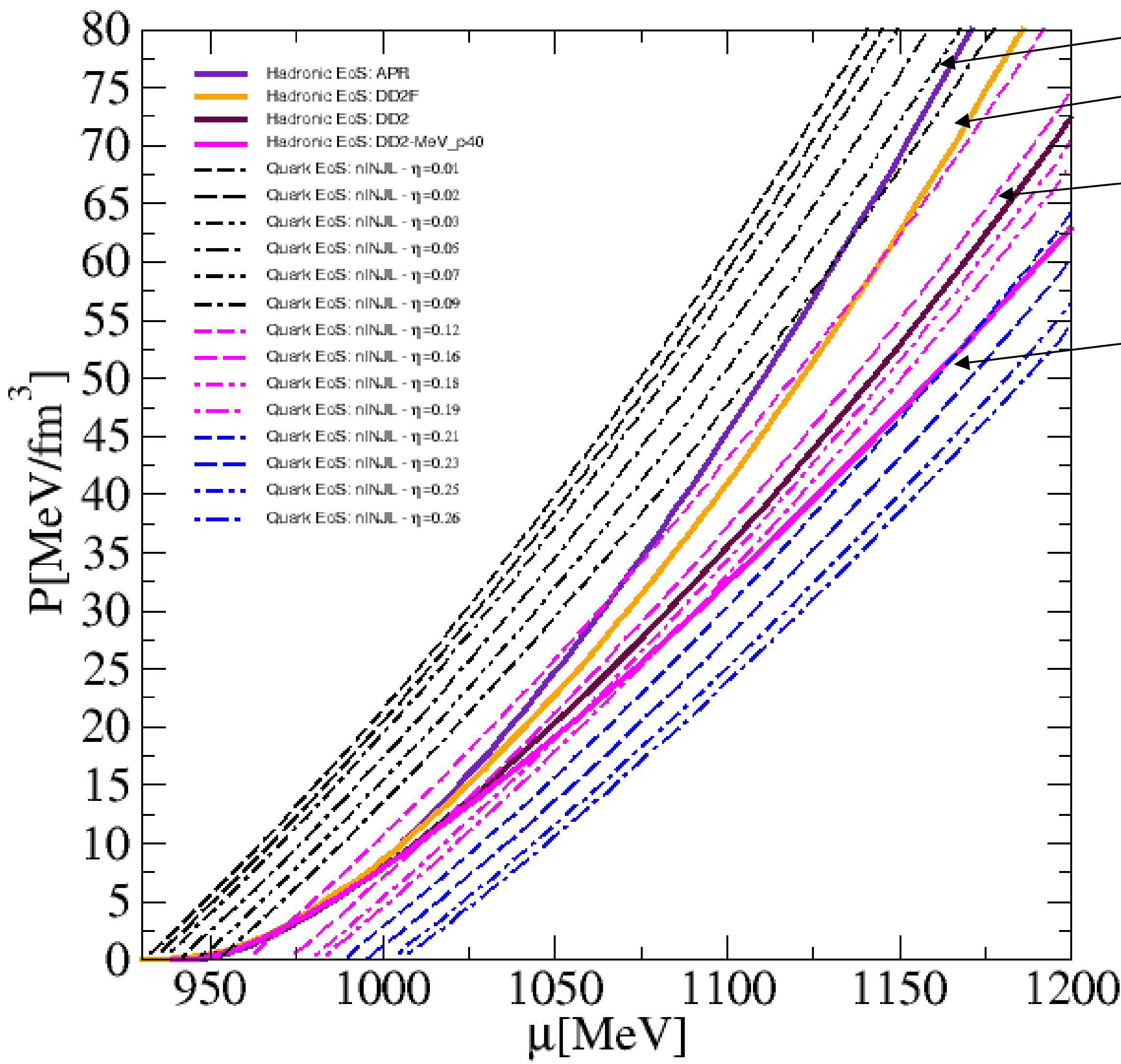
$\underline{\alpha}, a, b$




Kaltenborn, Bastian, Blaschke, arXiv:1701.04400 → Phys. Rev. D 96 (2017) 056024.

# 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:

$$S_E = \int d^4x \left\{ \bar\psi(x)\left(-i\partial\!\!\!/ + m_c\right)\psi(x) - \frac{G_S}{2} j_S^f(x) j_S^f(x) - \frac{H}{2}\left[j_D^a(x)\right]^\dagger j_D^a(x) - \frac{G_V}{2} j_V^\mu(x)\, j_V^\mu(x) \right\} .$$

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

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

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

# Nonlocal chiral quark model - generalized

$$S_E = \int d^4x \left\{ \bar\psi(x)\left(-i\partial\!\!\!/ + m_c\right)\psi(x) - \frac{G_S}{2} j_S^f(x) j_S^f(x) - \frac{H}{2}\left[j_D^a(x)\right]^\dagger j_D^a(x) - \frac{G_V}{2} j_V^\mu(x)\, j_V^\mu(x) \right\}$$

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

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

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

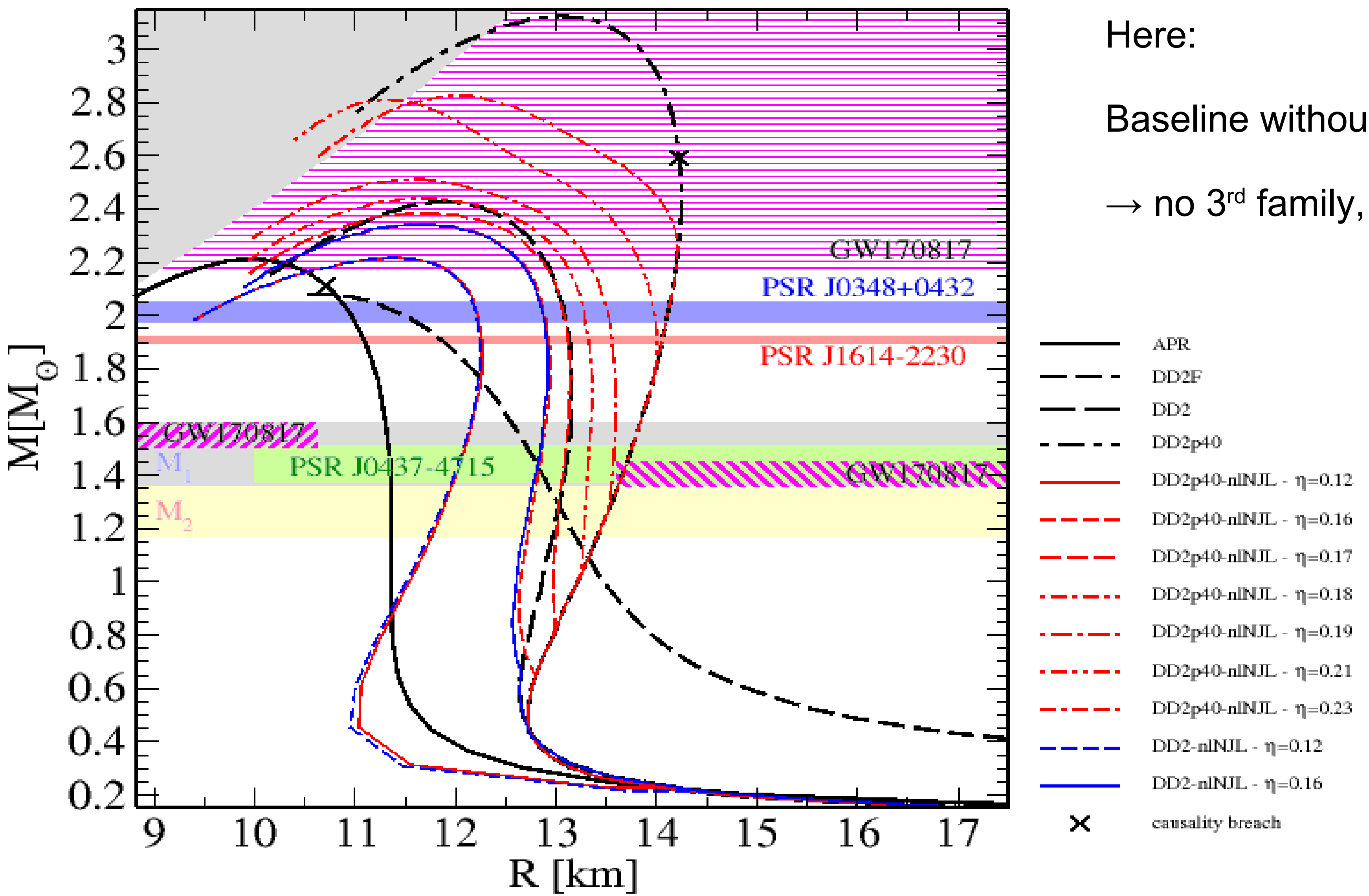
$$\Omega^{MFA} = \frac{\bar\sigma^2}{2G_S} + \frac{\bar\Delta^2}{2H} - \frac{\bar\omega^2}{2G_V} - \frac{1}{2}\int \frac{d^4p}{(2\pi)^4}\; \ln\det\left[\, S^{-1}(\bar\sigma, \bar\Delta, \bar\omega, \mu_{fc})\right]$$

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

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

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




Here:

Baseline without interpolation

→ no 3rd family, no twins!

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 $\eta_>$.

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

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

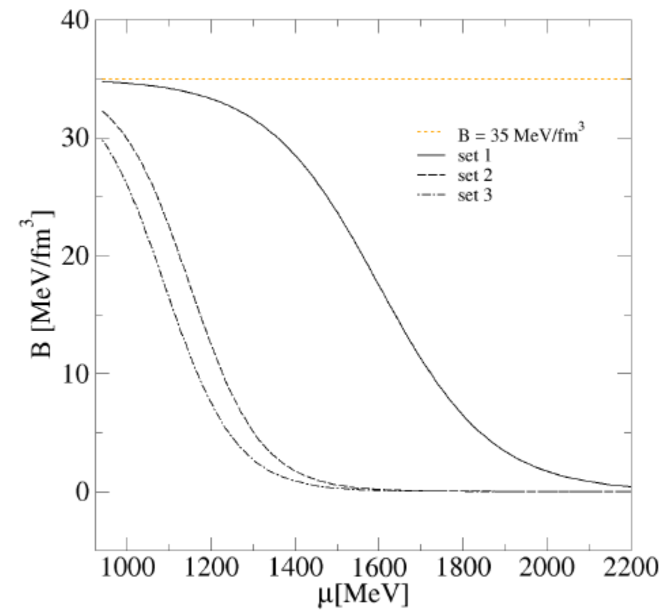
$$f_>(\mu) = 1 - f_<(\mu) \ , \quad f_\gg(\mu) = 1 - f_\ll(\mu).$$

D.E. Alvarez-Castillo, D.B., A.G. Grunfeld, V.P. Pagura, Phys. Rev. D99, 063010 (2019); [arxiv:1805.04105v3]

# Interpolation vs. medium dependence of coefficients

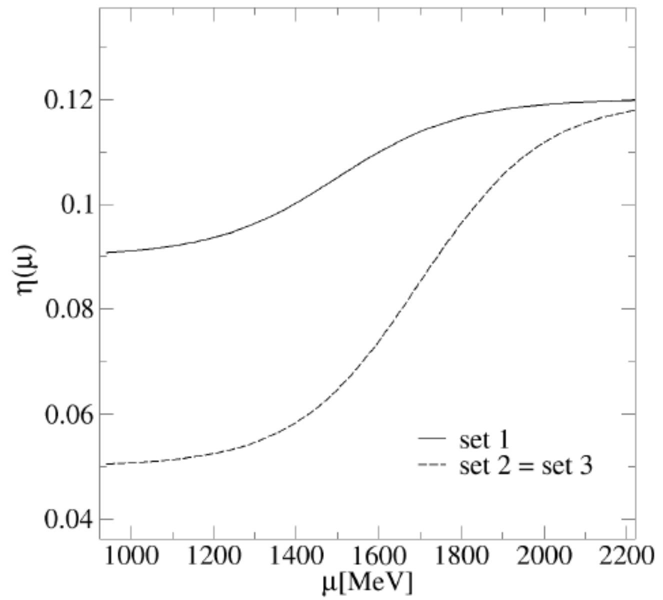
$$\begin{aligned} P(\mu) &= P(\mu;\eta,B)f_<(\mu)+P(\mu;\eta,0)f_>(\mu) \\ &= P(\mu;\eta,0)[f_<(\mu)+f_>(\mu)]-Bf_<(\mu) \\ &= P(\mu;\eta,B(\mu)), \end{aligned}$$

$B(\mu)=Bf_<(\mu)$ is the $\mu-$dependent bag pressure

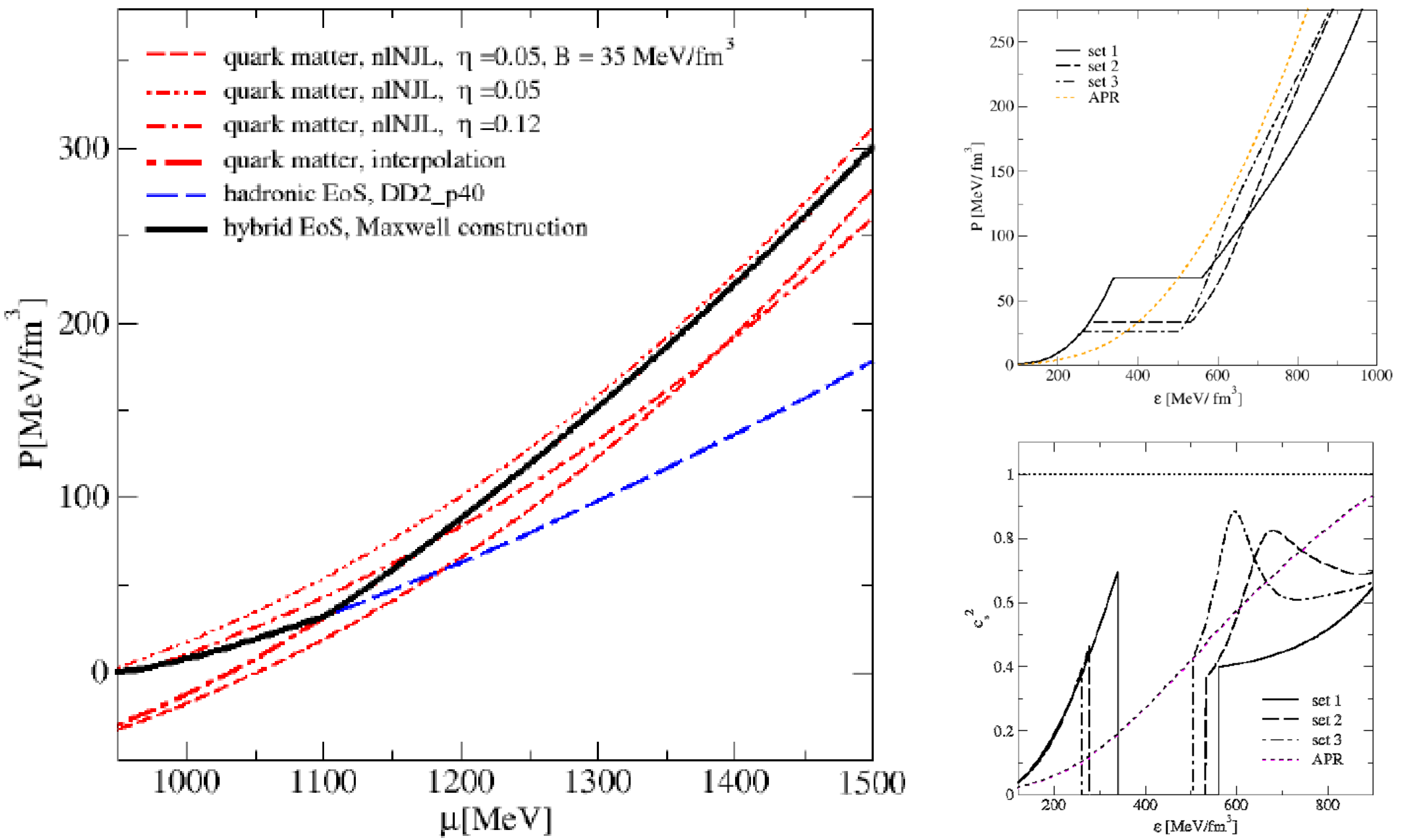



$$\begin{aligned} P(\mu) &= P(\mu;\eta_<,B)f_\ll(\mu)+P(\mu;\eta_>,B)f_\gg(\mu) \\ &= P(\mu;\eta_<,B)[f_\ll(\mu)+f_\gg(\mu)] \\ &\quad +(\eta_>-\eta_<)f_\gg(\mu)\left.\frac{dP(\mu;\eta,B)}{d\eta}\right|_{\eta=\eta_<} \\ &= P(\mu;\eta_<,B) \\ &\quad +[\eta_>f_\gg(\mu)+\eta_<f_\ll(\mu)-\eta_<]\left.\frac{dP(\mu;\eta,B)}{d\eta}\right|_{\eta=}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

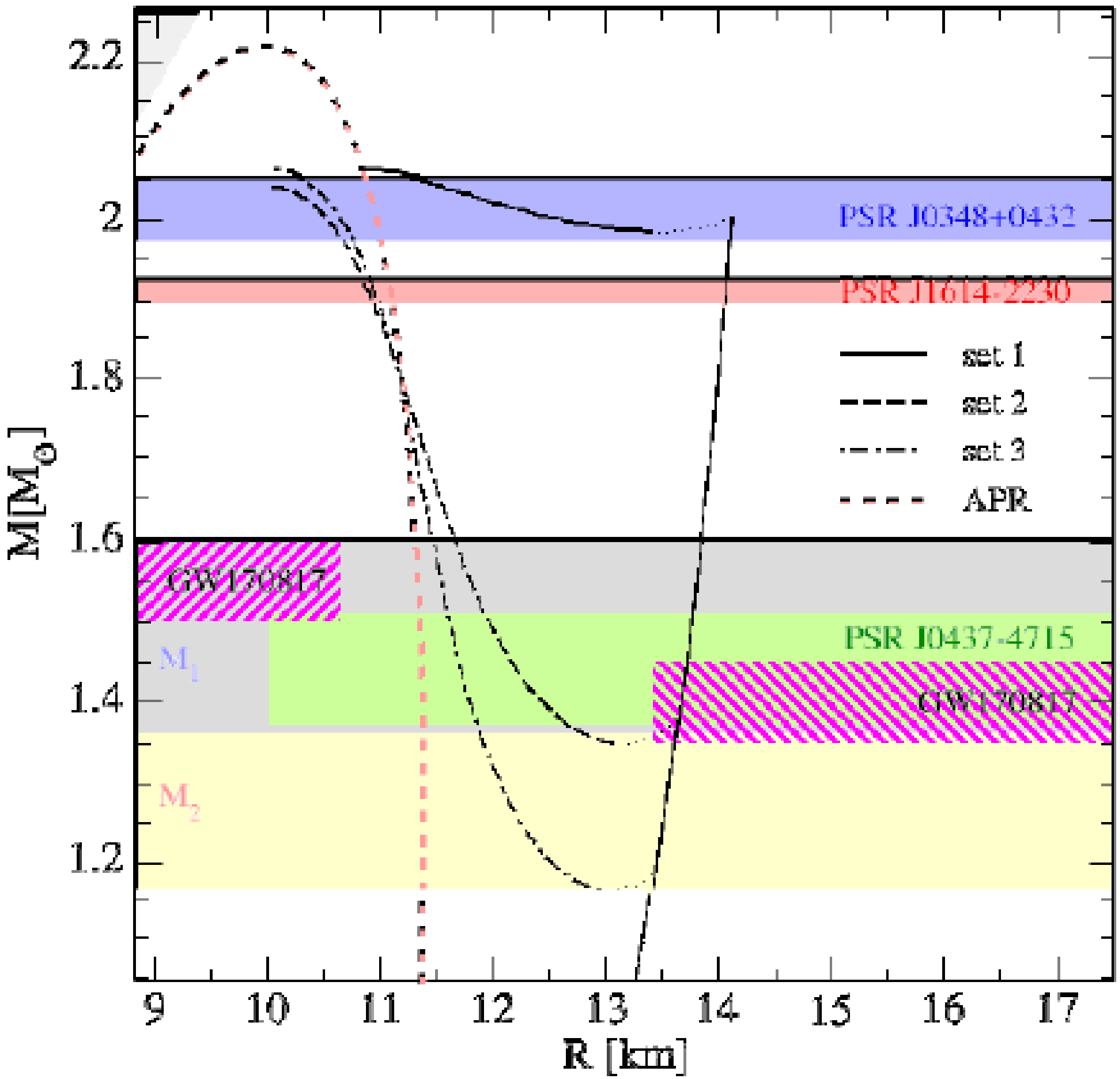
$\eta(\mu) = \eta_>f_\gg(\mu)+\eta_<f_\ll(\mu)$ is the medium-dependent vector meson coupling

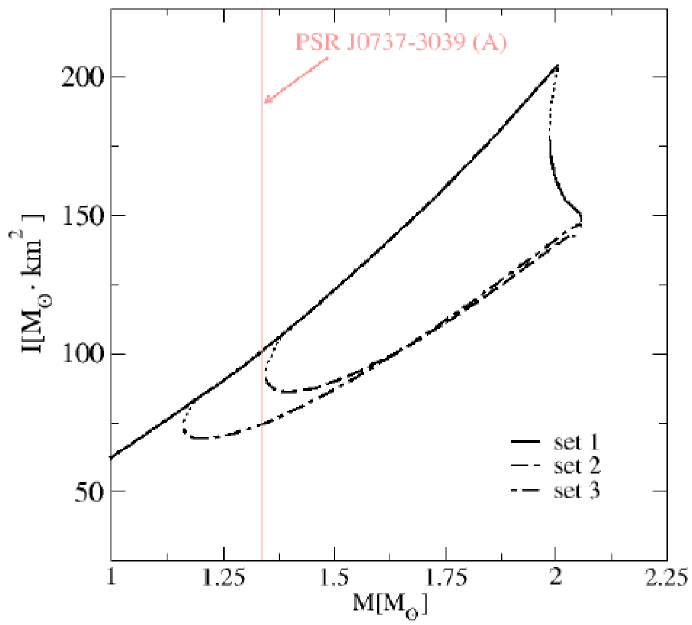


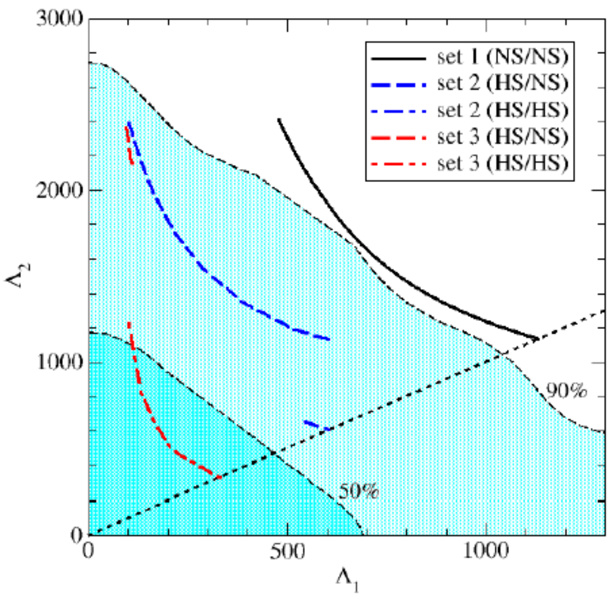
# Maxwell Construction between Hadron and Quark Phases



# Maxwell Construction between Hadron and Quark Phases




D.E. Alvarez-Castillo, et al., PRD 99 (2019) 063010

# A class of hybrid star models with early Phase transition onset & Bayesian analysis with multimessenger data

D.B., A. Ayriyan, D.E. Alvarez-Castillo, H. Grigorian, Universe 6, 81 (2020) [arxiv:2005.03926]

# Quark-hadron hybrid equations of state (normal case)

Quark matter model: Generalized nonlocal NJL model [Alvarez-Castillo et al. PRD(2019)]

$$P(\mu) = P(\mu;\eta(\mu),B(\mu)) = P_{\rm nlNJL}(\mu;\eta(\mu)) - B(\mu)\,, \quad \eta(\mu) = \eta_> f_\gg(\mu) + \eta_< f_\ll(\mu) \quad B(\mu) = B f_<(\mu) f_\ll(\mu)\,.$$

Chemical-potential-dependent vector coupling and bag function, defined by switch functions:

$$f_<(\mu) = \frac{1}{2}\left[1 - \tanh\left(\frac{\mu-\mu_<}{\Gamma_<}\right)\right], \quad f_>(\mu) = 1 - f_<(\mu)$$ , where $\mu_<$ defines onset of deconfinement.

Mixed phase construction:

$$P_M(\mu) = \alpha_2(\mu-\mu_c)^2 + \alpha_1(\mu-\mu_c) + (1+\Delta_P)P_c\,,$$

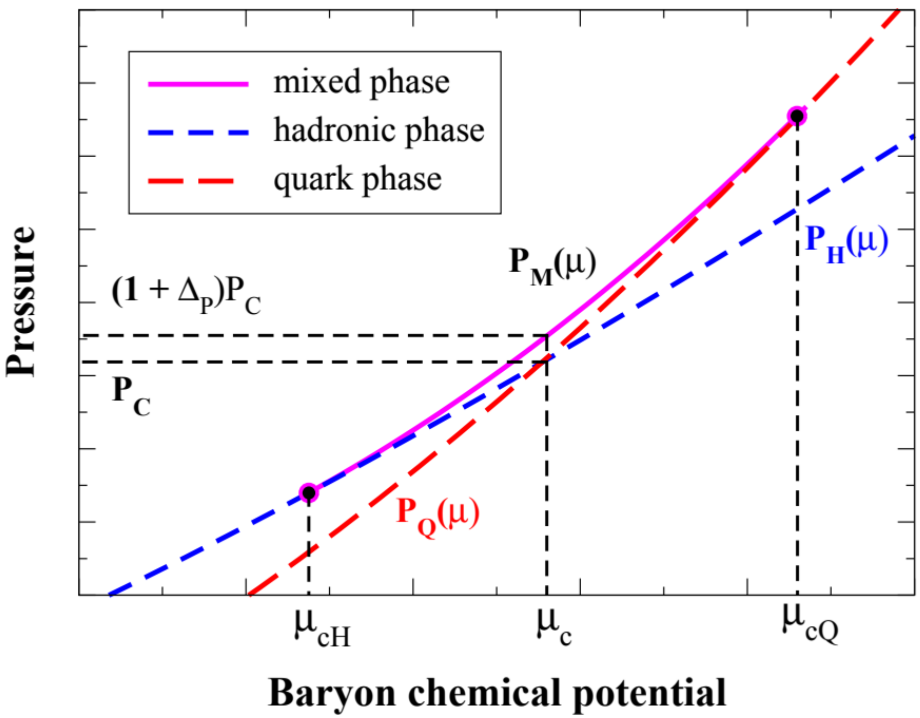
Connects three points:

$P_H(\mu_{cH})$, $P_Q(\mu_{cQ})$, $P_c(1+\Delta_P)$

Constant speed of sound extrapolation:

$$\begin{aligned} P(\mu) &= P_0 + P_1(\mu/\mu_x)^\beta, && \text{for } \mu > \mu_x, \\ \varepsilon(\mu) &= -P_0 + P_1(\beta-1)(\mu/\mu_x)^\beta, && \text{for } \mu > \mu_x, \\ n_B(\mu) &= P_1\frac{\beta}{\mu_x}(\mu/\mu_x)^{\beta-1}, && \text{for } \mu > \mu_x, \end{aligned}$$

$$c_s^2 = \frac{\partial P/\partial\mu}{\partial\varepsilon/\partial\mu} = \frac{1}{\beta-1}\,, \qquad \begin{aligned} P_0 &= [(\beta-1)P_x - \varepsilon_x]/\beta \\ P_1 &= (P_x+\varepsilon_x)/\beta\,, \end{aligned}$$




Matching point is at: $P_x = P(\mu_x)$, $\varepsilon_x = \varepsilon(\mu_x)$

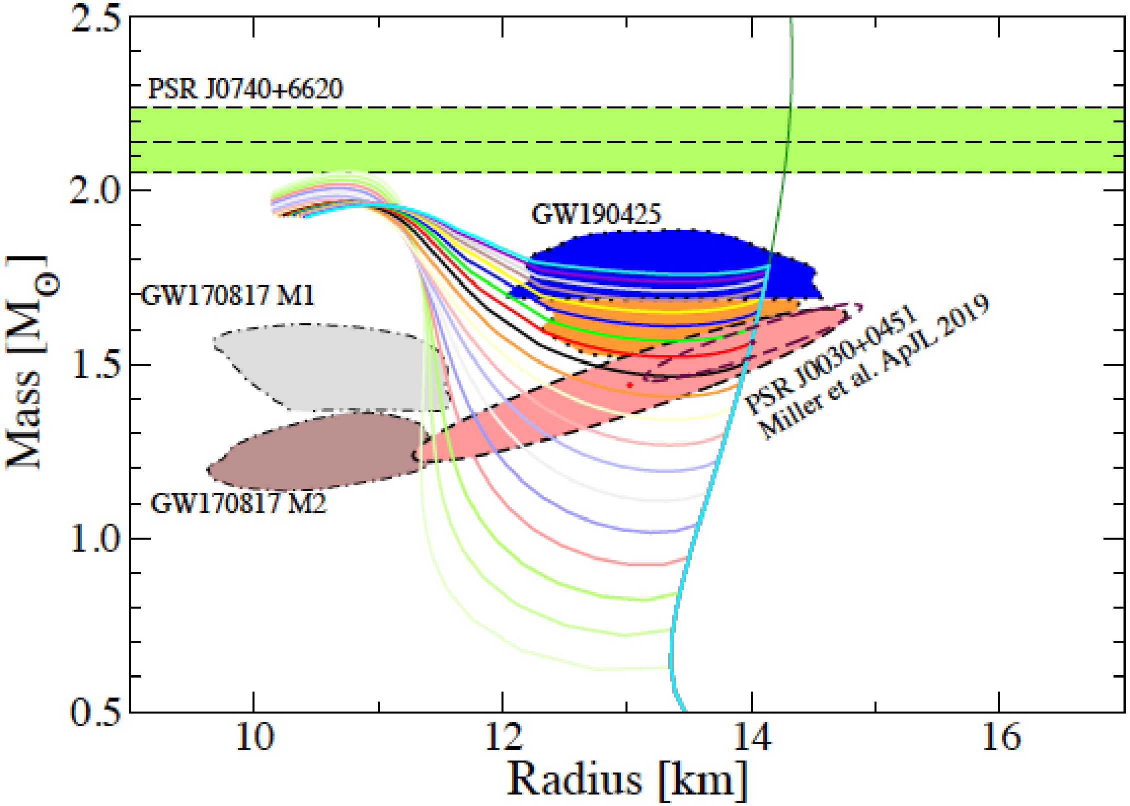
A. Ayriyan et al., PRC 97, 054802 (2018)

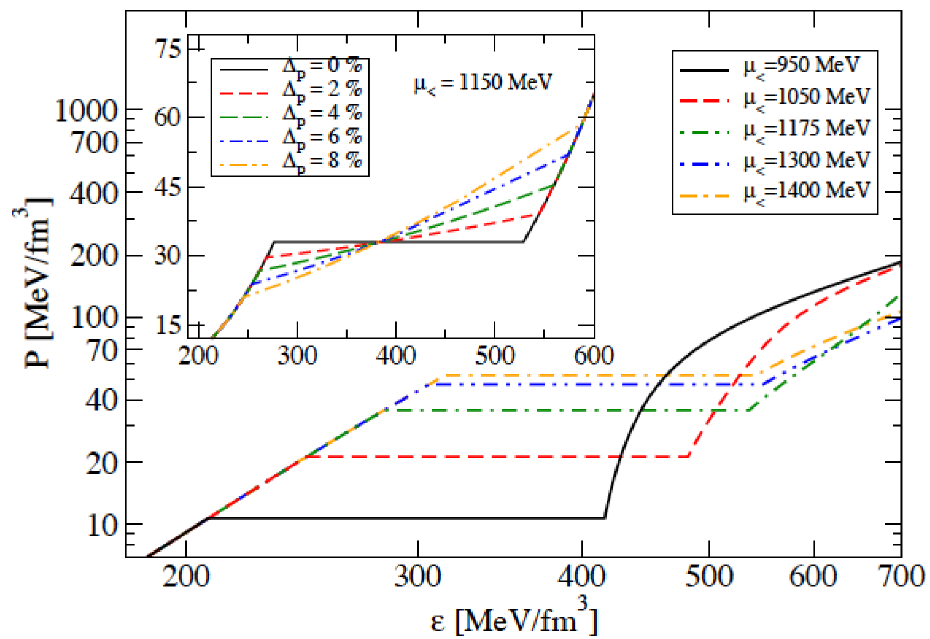
# Was GW170817 a merger of conventional neutron stars ? A Bayesian analysis for a class of hybrid equations of state

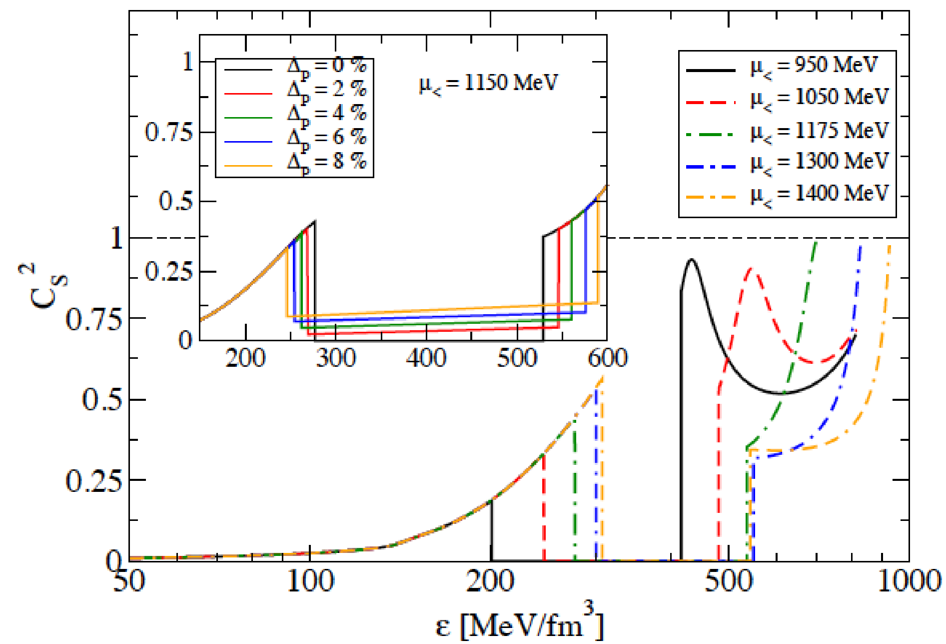
- Mass 2.14+0.10-0.09 M_sun &
- Compactness (tidal deform.) GW170817 &
- Mass+Radius NICER PSR J0030+0451

- New (fictitious) mass+radius measurement "NICER PSR J0030+0451", R→R+1.6 km Gaussian width parameter σ → σ/2

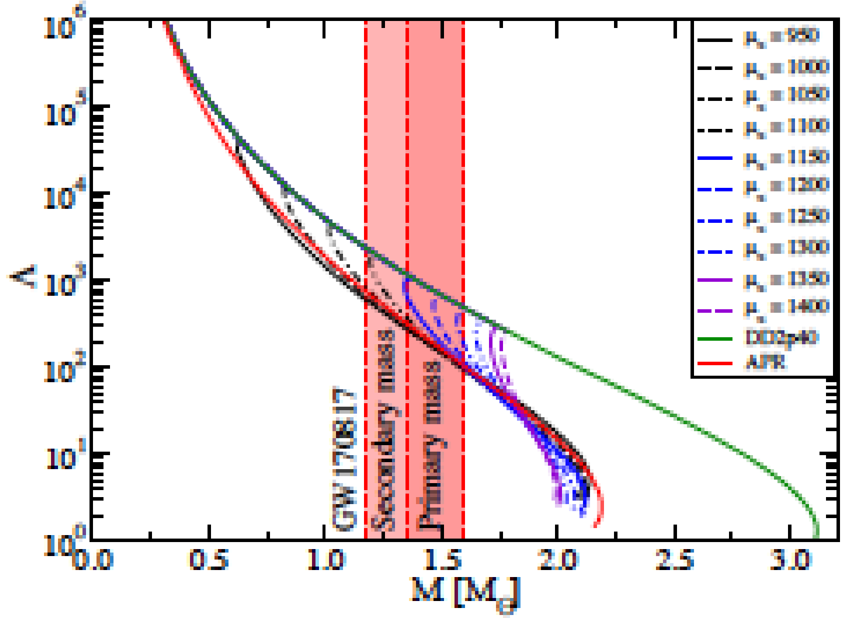
→ Two-parameter family EoS: $\mu_<$ , $\Delta_P$

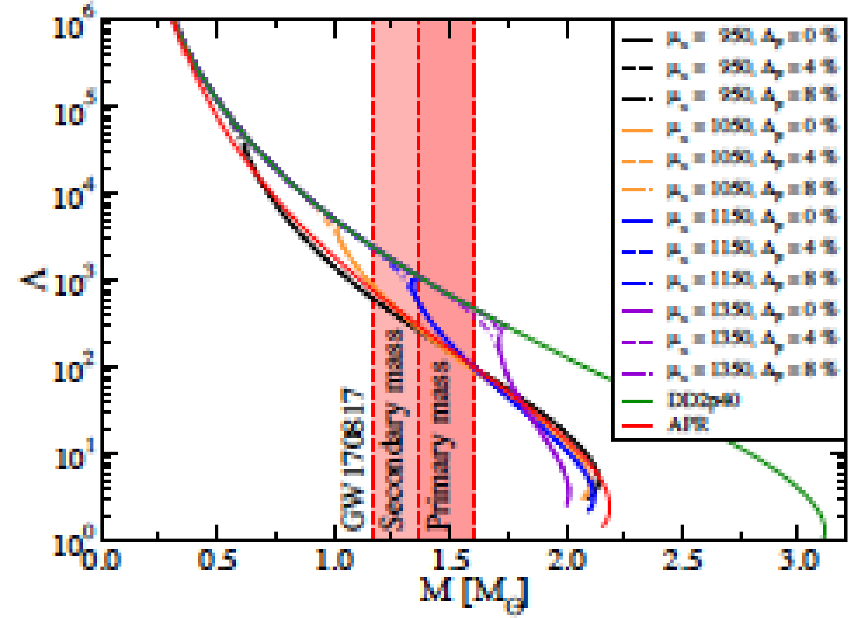


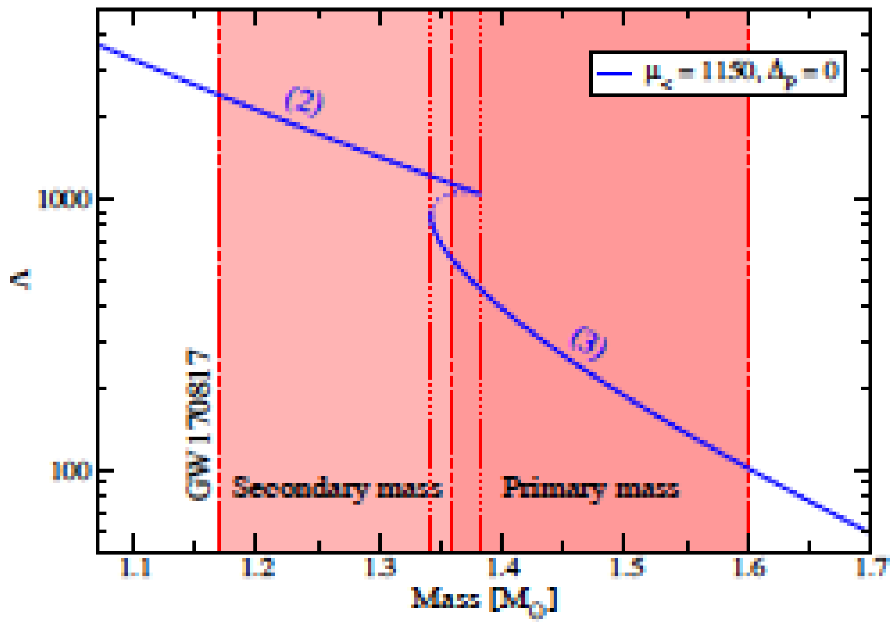



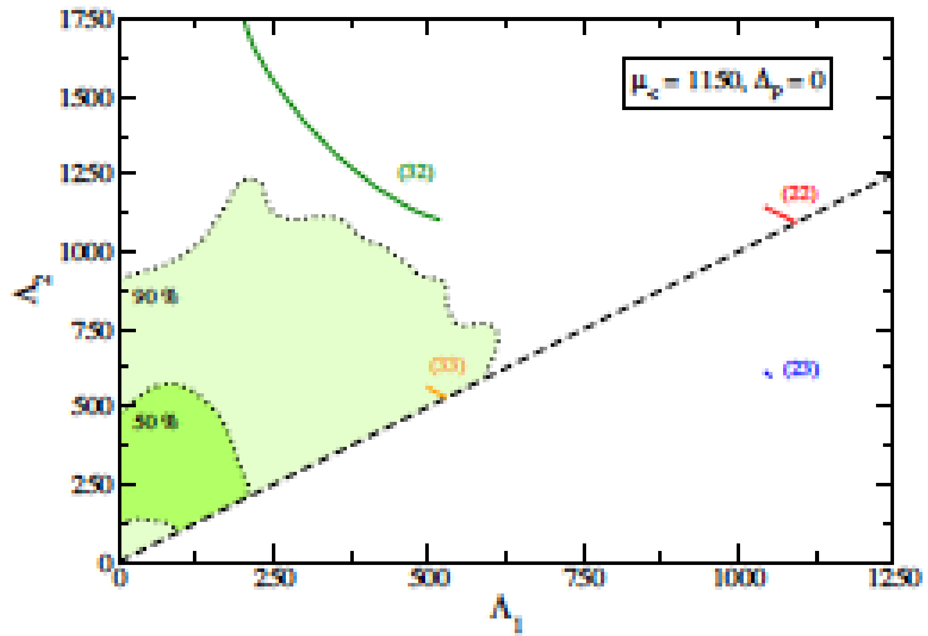



# Tidal deformabilities Λ (dimensionless)

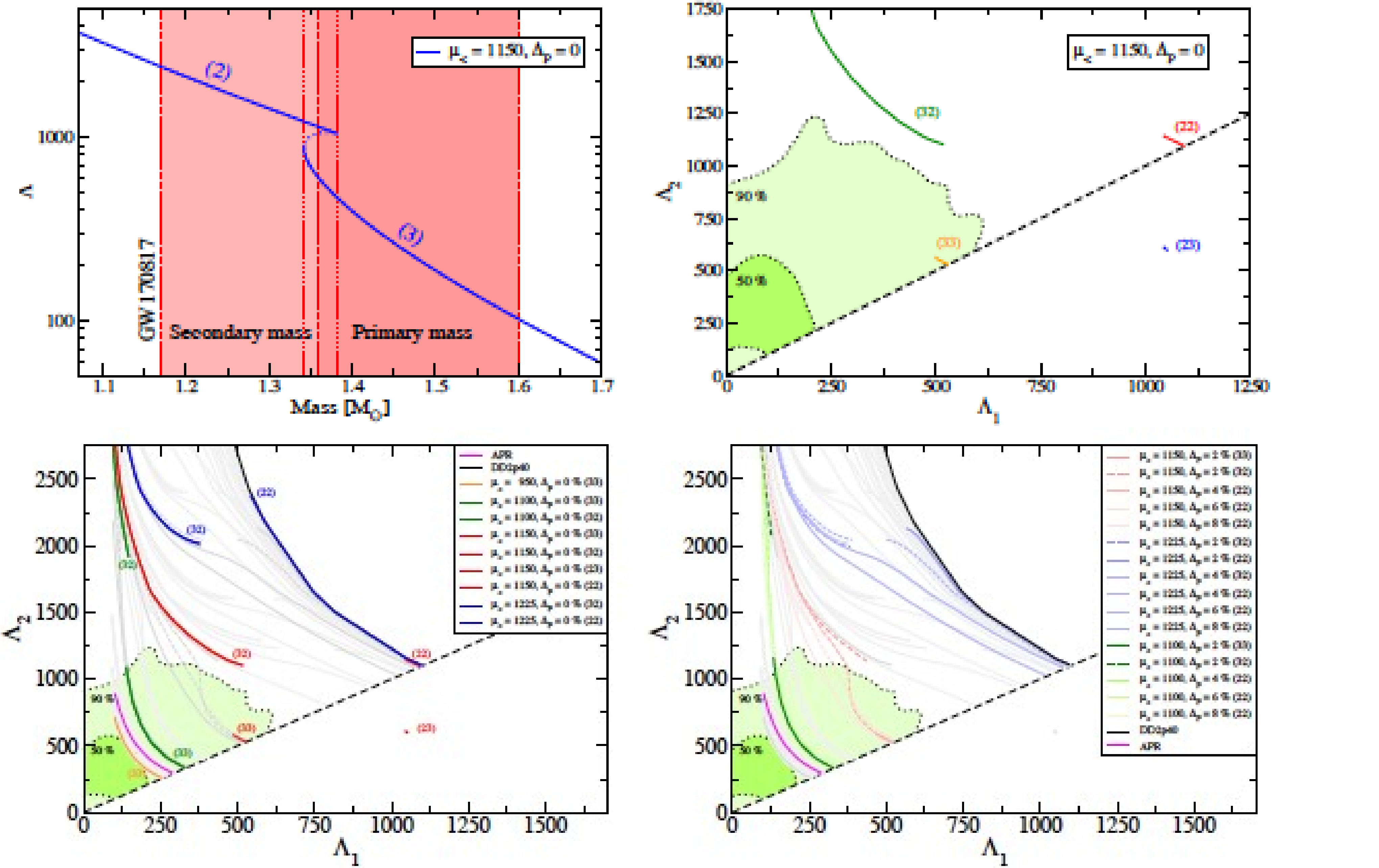


# Tidal deformabilities Λ (dimensionless)



# Bayesian inference for the EoS models

1. Vector of parameters: $\vec{\pi}_i = \left\{ \mu_{<(j)}, \Delta p_{(k)} \right\}$

2. Likelihood of a model under Λ1-Λ2 constraint from GW170817:

$$P\left(E_{GW} \,|\, \pi_i\right) = \int_{l_{22}} \beta(\Lambda_1(\tau), \Lambda_2(\tau)) d\tau + \int_{l_{23}} \beta(\Lambda_1(\tau), \Lambda_2(\tau)) d\tau + \int_{l_{32}} \beta(\Lambda_1(\tau), \Lambda_2(\tau)) d\tau + \int_{l_{33}} \beta(\Lambda_1(\tau), \Lambda_2(\tau)) d\tau,$$

3. Likelihood of a model under constraint for lower limit of the maximum mass:

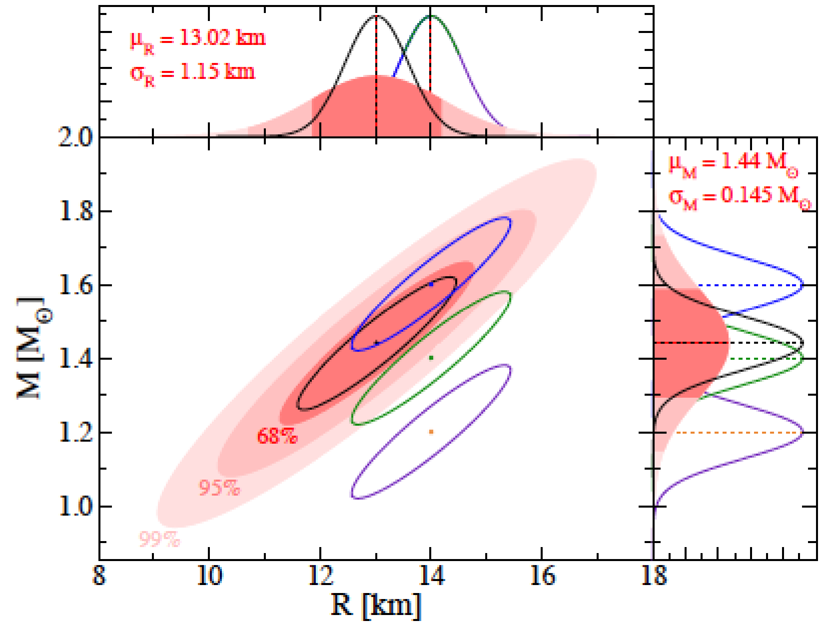
$$P\left(E_A \,|\, \pi_i\right) = \Phi(M_i, \mu_A, \sigma_A) = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{M_i - \mu_A}{\sqrt{2}\sigma_A}\right)\right]$$

4. Likelihood of a model under the combined M-R constraint of the NICER experiment:

$$\mathcal{N}(M, R; \mu_M, \sigma_M, \mu_R, \sigma_R, \rho) = \frac{1}{2\pi\sigma_M\sigma_R\sqrt{1-\rho^2}} \exp\left(-\frac{x}{2(1-\rho^2)}\right),$$

$$x = \frac{(M-\mu_M)^2}{\sigma_M^2} - 2\rho\frac{(M-\mu_M)(R-\mu_R)}{\sigma_M\sigma_R} + \frac{(R-\mu_R)^2}{\sigma_R^2},$$

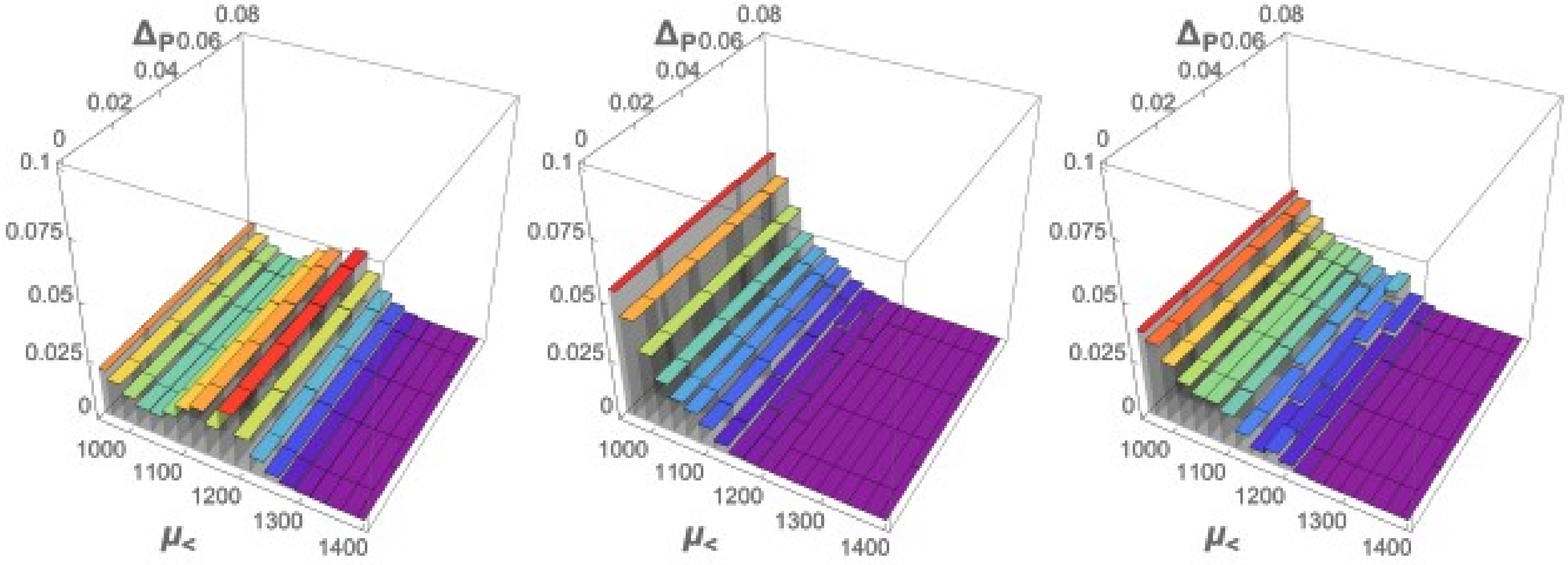
$$P\left(E_{MR} \,|\, \pi_i\right) = \int_{l_2} \mathcal{N}(\mu_R, \sigma_R, \mu_M, \sigma_M, \rho) d\tau + \int_{l_3} \mathcal{N}(\mu_R, \sigma_R, \mu_M, \sigma_M, \rho) d\tau,$$

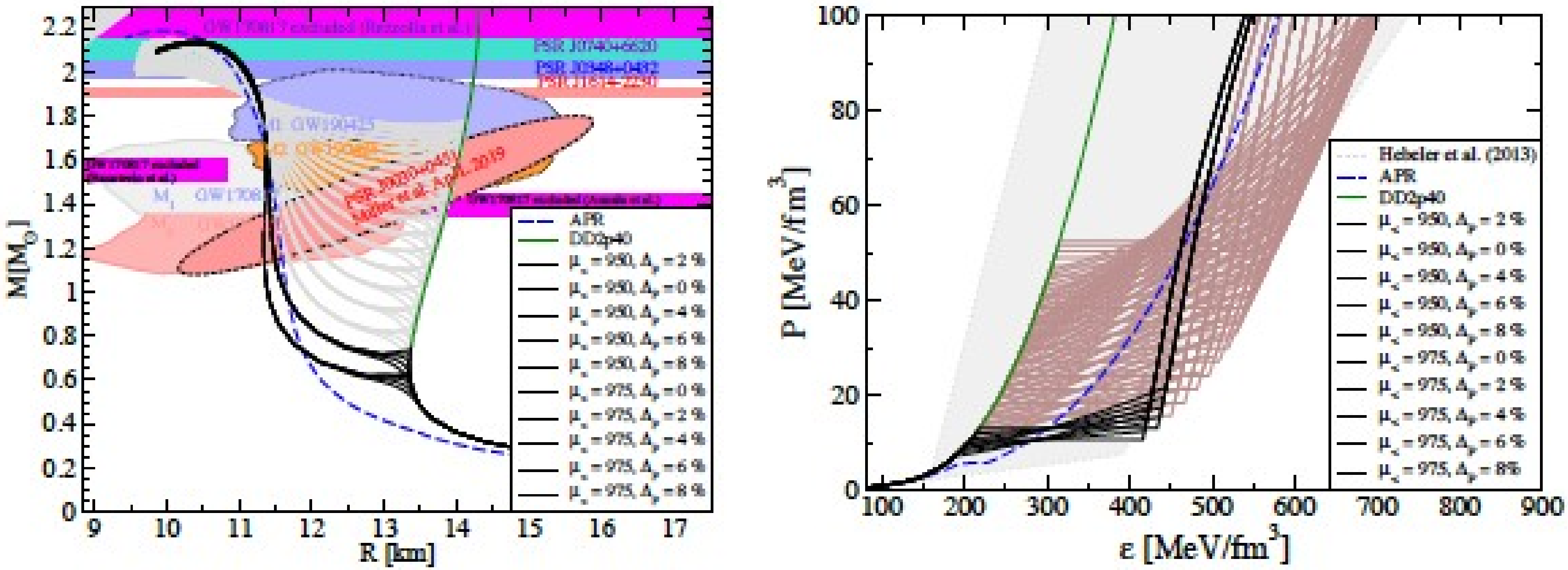



5. Fictitious M-R measurements a la NICER:

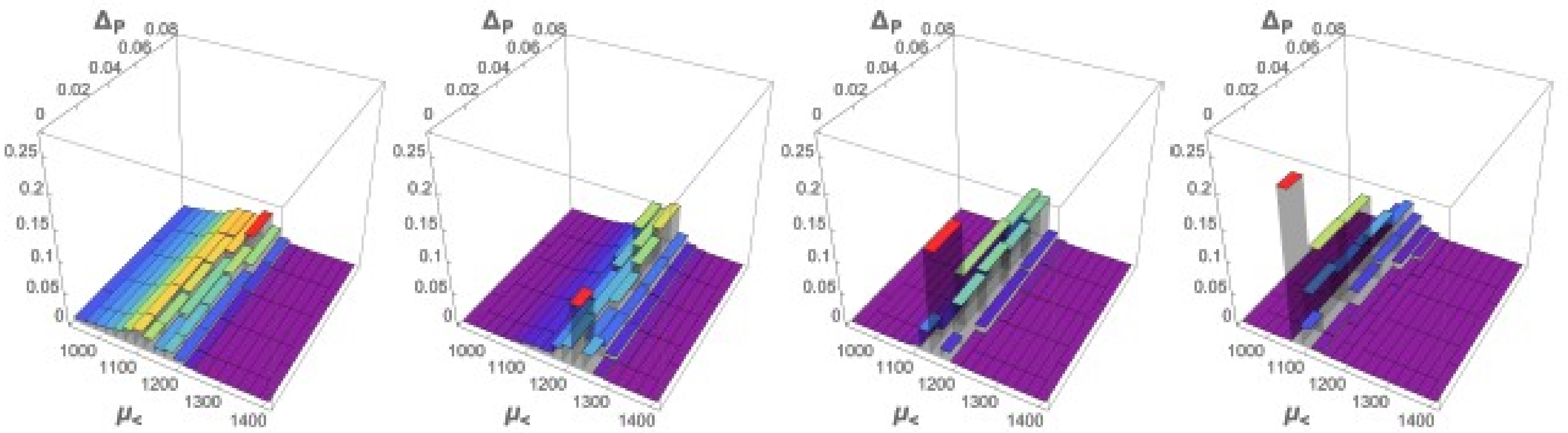
6. Posterior Distribution: $P\left(\vec{\pi}_i \,|\, E\right) = \frac{P\left(E \,|\, \vec{\pi}_i\right) P\left(\vec{\pi}_i\right)}{\sum_{j=0}^{N-1} P\left(E \,|\, \vec{\pi}_j\right) P\left(\vec{\pi}_j\right)},$

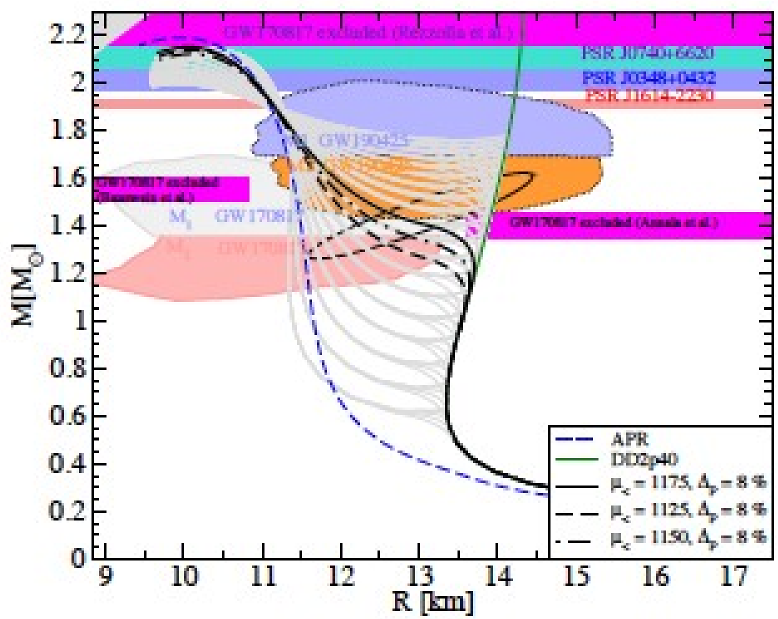
# Bayesian inference for the EoS models

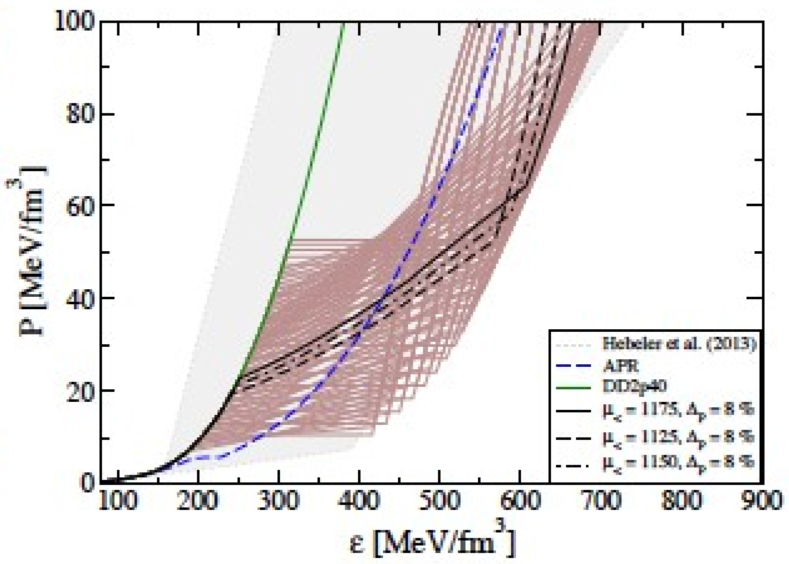


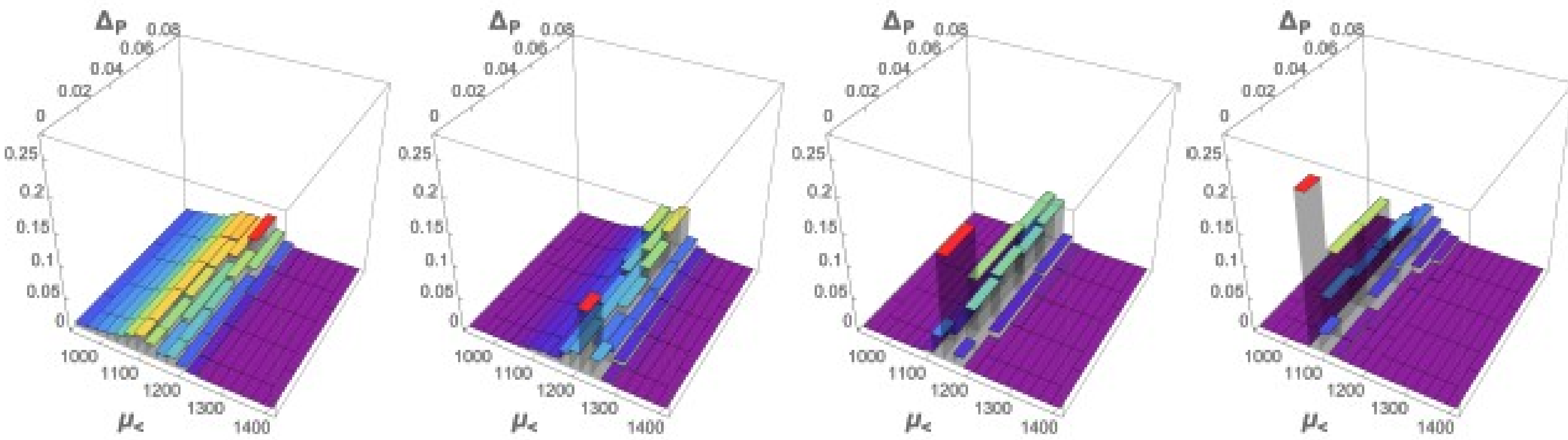
# Bayesian inference for the EoS models

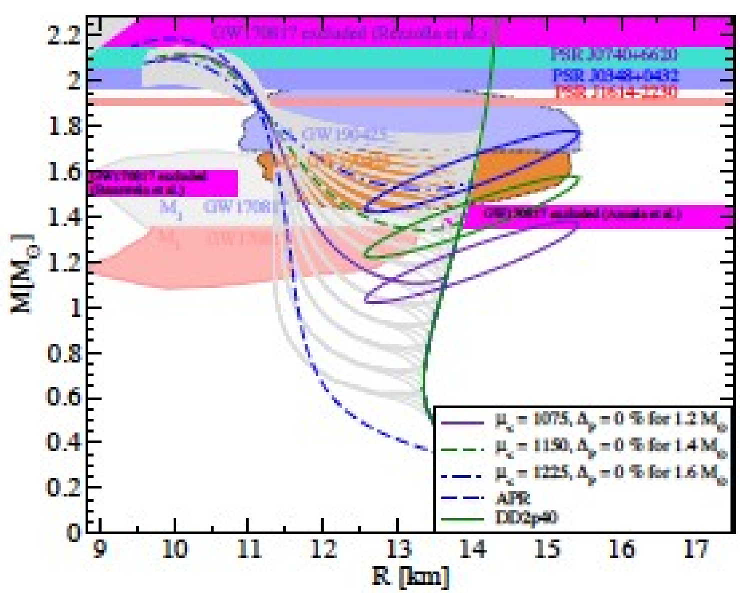


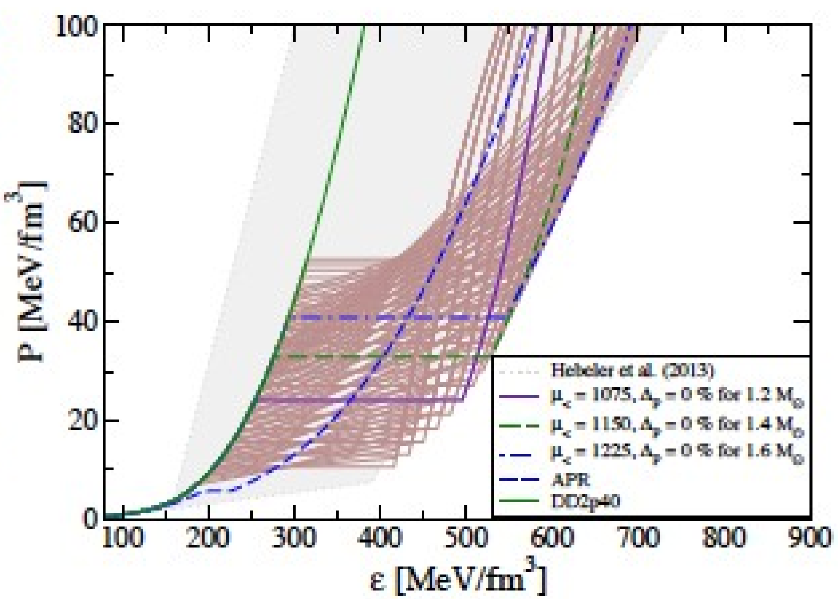



# Bayesian inference for the EoS models



# Quark-hadron hybrid equations of state (anomalous case)

<u>Quark matter model:</u> Generalized nonlocal NJL model [Alvarez-Castillo et al. PRD(2019)]

$$P(\mu) = P(\mu;\eta(\mu),B(\mu)) = P_{\rm nlNJL}(\mu;\eta(\mu)) - B(\mu)\,, \quad \eta(\mu) = \eta_> f_\gg(\mu) + \eta_< f_\ll(\mu) \quad B(\mu) = B f_<(\mu) f_\ll(\mu)\,.$$

<u>Crossover construction (interpolation):</u>

$$\begin{cases} P_\eta(\mu) = a_\eta(\mu-\mu_H)^2 + b_\eta(\mu-\mu_H) + c_\eta & \mu \le \mu_c \\ P_\rho(\mu) = a_\rho(\mu-\mu_Q)^2 + b_\rho(\mu-\mu_Q) + c_\rho & \mu \ge \mu_c \end{cases}$$

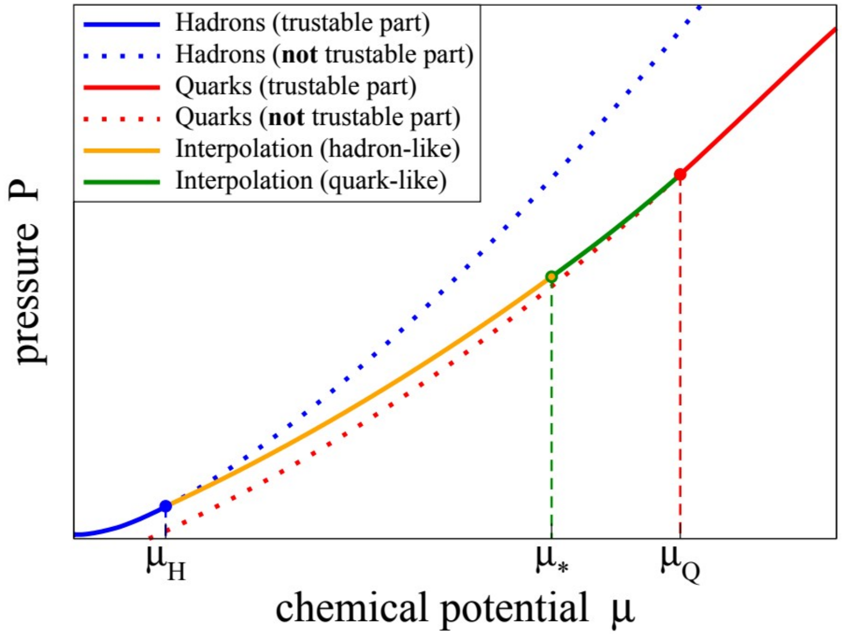
$$P_\eta(\mu_H) = P_H(\mu_H) \Rightarrow c_\eta = P_H(\mu_H)$$
$$n_\eta(\mu_H) = n_H(\mu_H) \Rightarrow b_\eta = n_H(\mu_H)$$
$$P_\rho(\mu_Q) = P_Q(\mu_Q) \Rightarrow c_\rho = P_Q(\mu_Q)$$
$$n_\rho(\mu_Q) = n_Q(\mu_Q) \Rightarrow b_\rho = n_Q(\mu_Q)$$

$$\begin{cases} P_\eta(\mu_c) = P_\rho(\mu_c) \\ n_\eta(\mu_c) = n_\rho(\mu_c) \end{cases}$$

$$\begin{cases} a_\eta(\mu_c-\mu_H)^2 - a_\rho(\mu_c-\mu_Q)^2 = \kappa_1 \\ 2a_\eta(\mu_c-\mu_H) - 2a_\rho(\mu_c-\mu_Q) = \kappa_2 \end{cases}$$

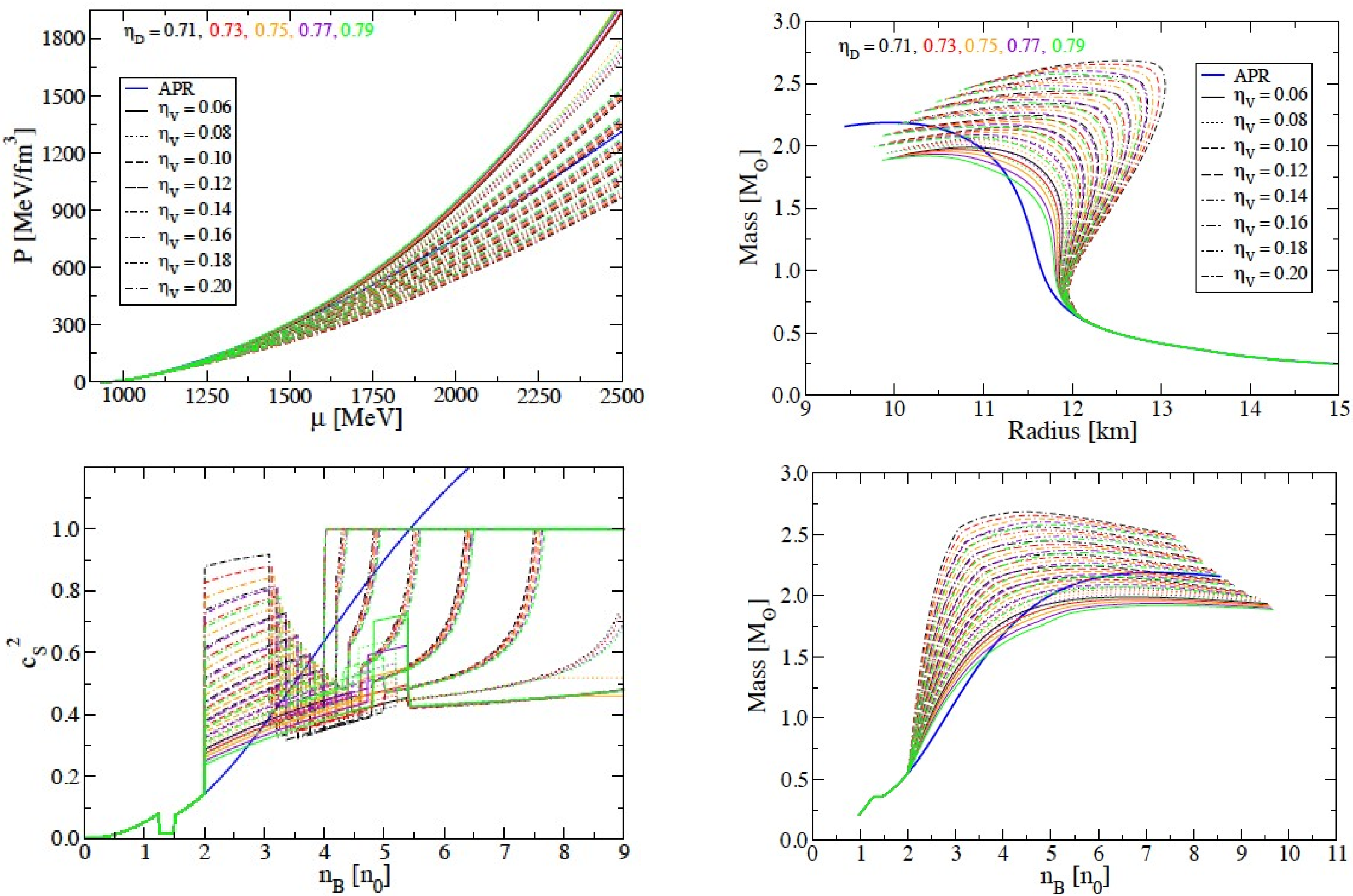
$$\begin{cases} \kappa_1 = n_Q(\mu_c-\mu_Q) - n_H(\mu_c-\mu_H) + P_Q - P_H, \\ \kappa_2 = n_Q - n_H \end{cases}$$

Solution of SLAE:
$$\begin{cases} a_\eta = \dfrac{-2\kappa_1 + \kappa_2(\mu_c-\mu_Q)}{2(\mu_c-\mu_H)(\mu_H-\mu_Q)} \\ a_\rho = \dfrac{-2\kappa_1 + \kappa_2(\mu_c-\mu_H)}{2(\mu_c-\mu_Q)(\mu_H-\mu_Q)} \end{cases}$$

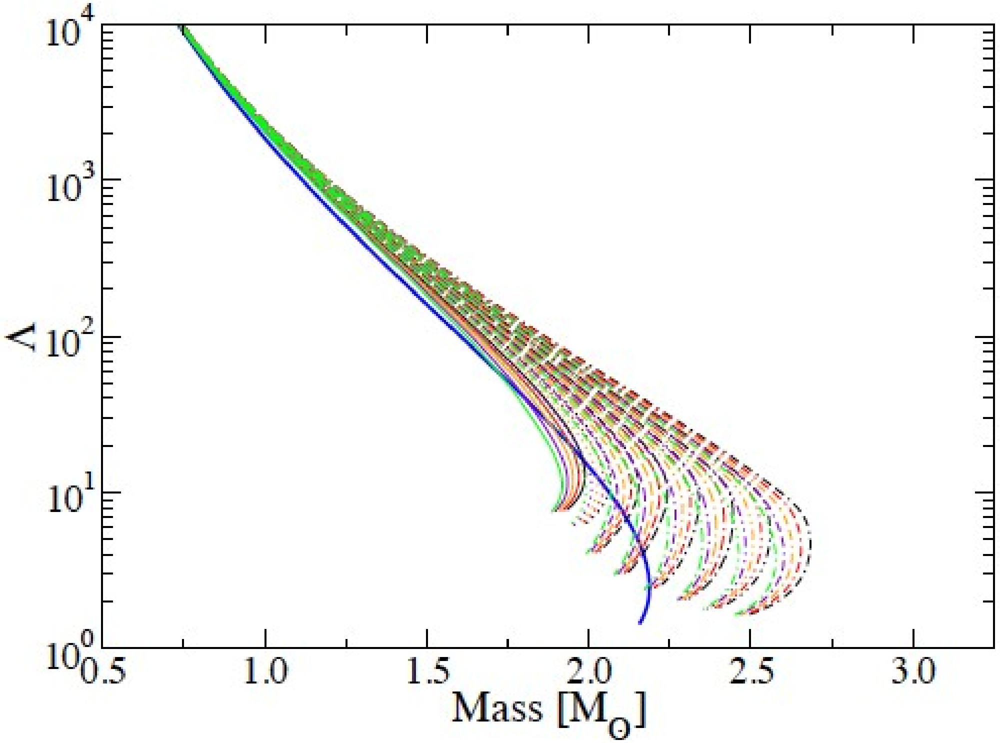


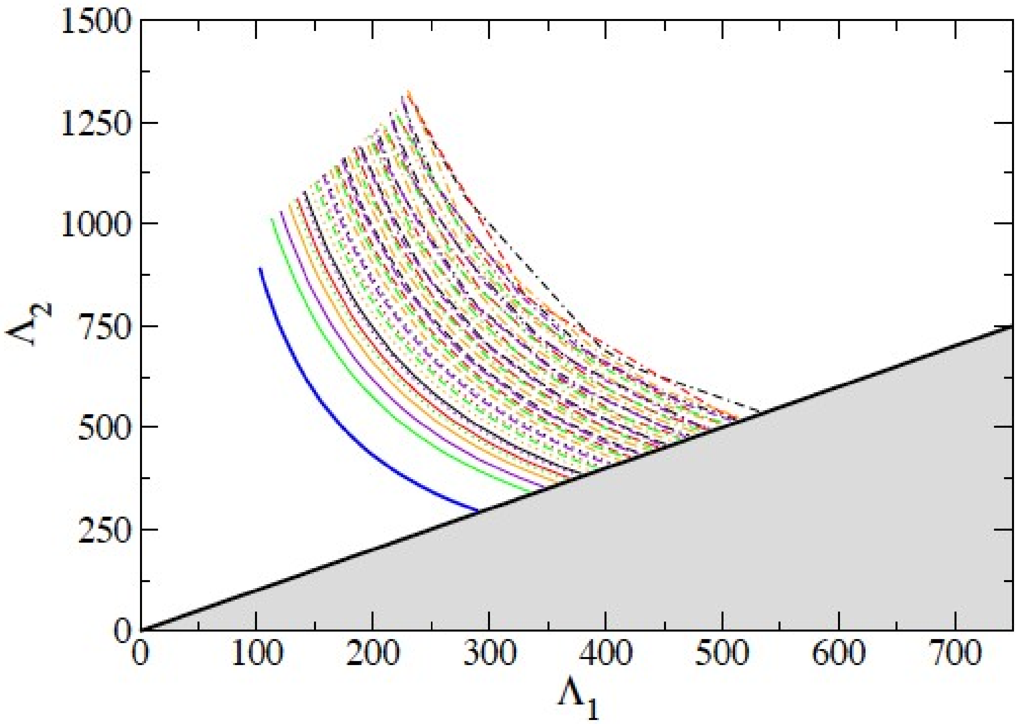

A. Ayriyan et al., in preparation (2020)

# Hybrid EoS ↔ Hybrid star configurations



# Tidal deformabilities Λ  (dimensionless)



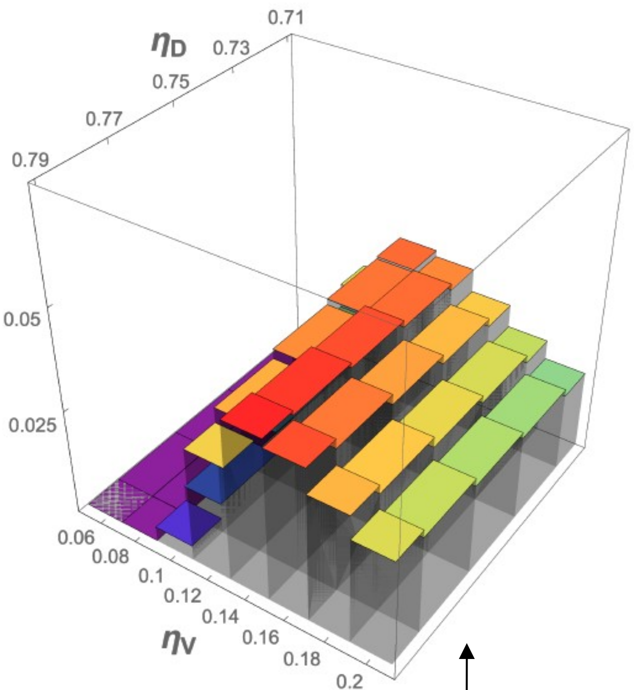

Tidal deformabilities in accordance with GW170817 → Now for a crossover interpolation

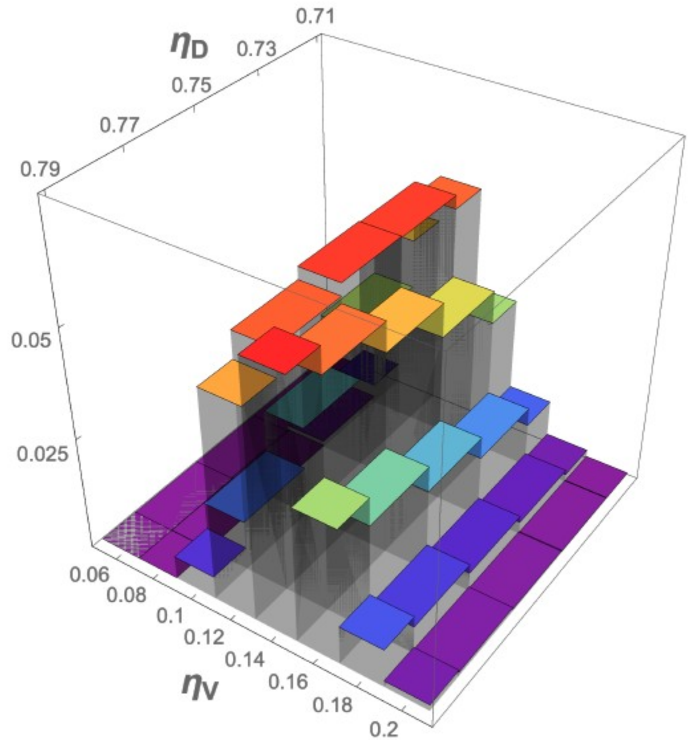
Is the early onset of the crossover an early onset of quark matter in neutron stars?

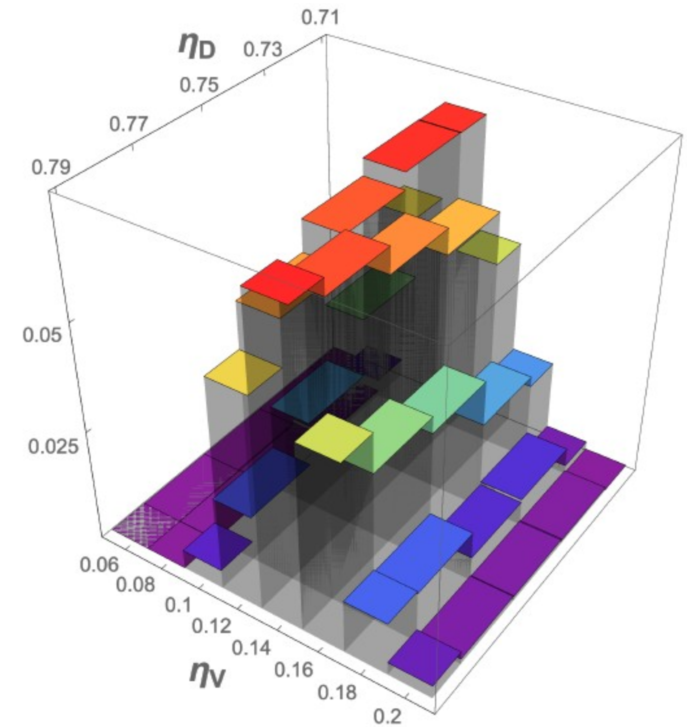
- hadronlike region: hadronic matter with parton substructure (Pauli blocking, MPP) stiffening
- quarklike region: delocalized quark matter, but strong hadronic correlations

→ Is this quarkyonic matter?  [McLerran & Reddy, PRL 122 (2019) 122701; arxiv:1811.12503]
→ Soft and hard deconfinement?  [Fukushima, Kojo, Weise, arxiv:2008.08436]

# Bayesian inference for the EoS models




Constraints:

- min(M_max) from
  PSR J0740+6620 (Cromartie et al.)

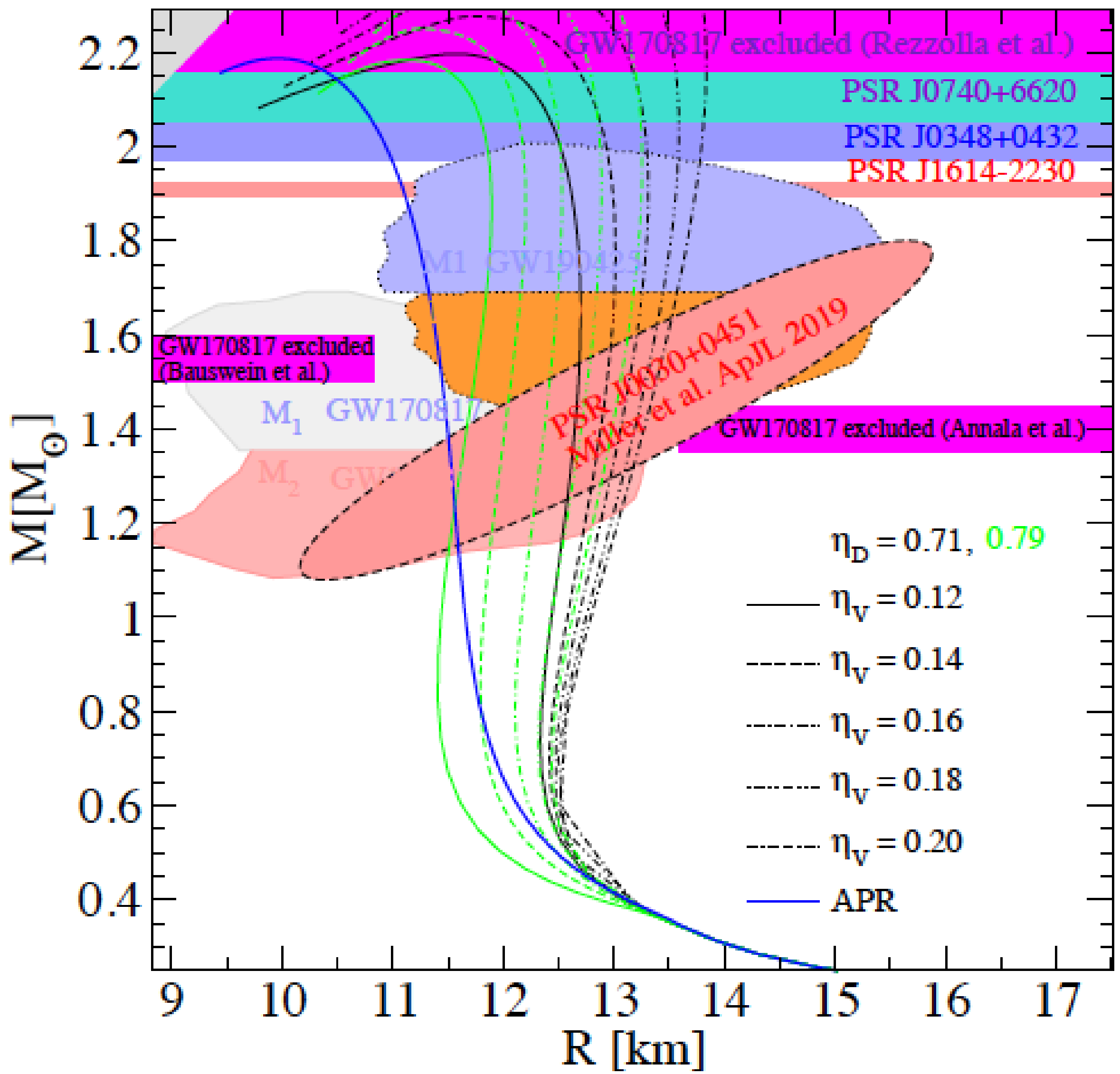
- tidal deformability from
  GW170817 (Abbott et al.)

- M-R constraint from
  PSR J0030+0451 (Miller et al.)

+ max(M_max) from
GW170817 (Rezzolla et al.)

+ error ellipse from NICER
Reduced by factor 2 (fictitious)

# Hybrid EoS ↔ Hybrid star configurations




Is the early onset of the crossover an early onset of quark matter in neutron stars?

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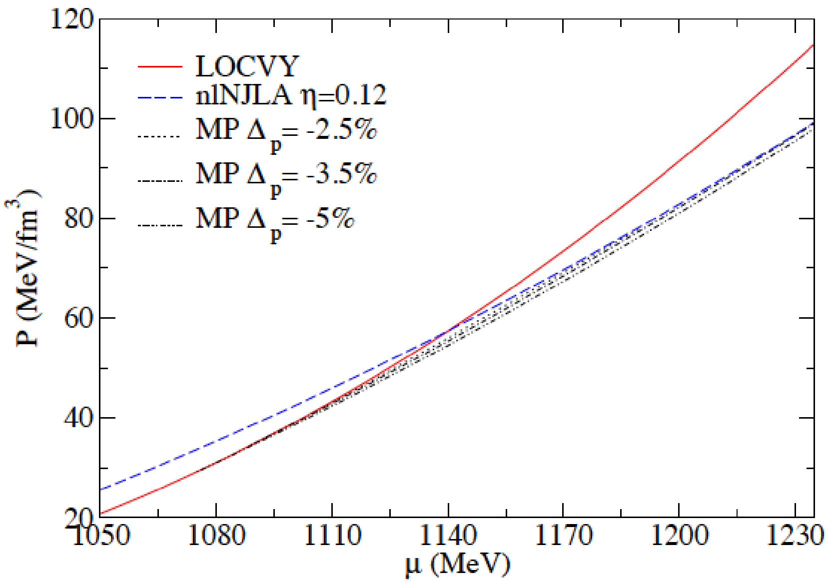
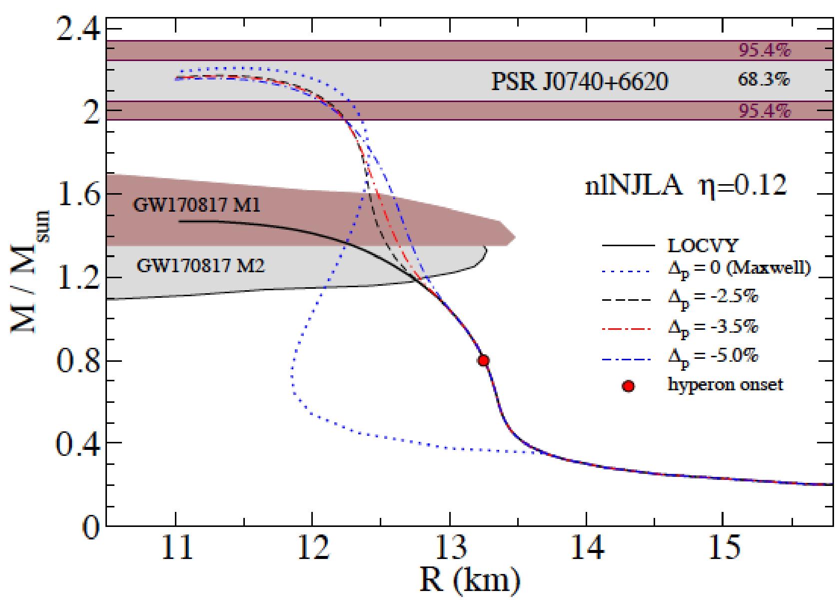
→ Soft and hard deconfinement?
[Fukushima, Kojo, Weise, arxiv:2008.08436]

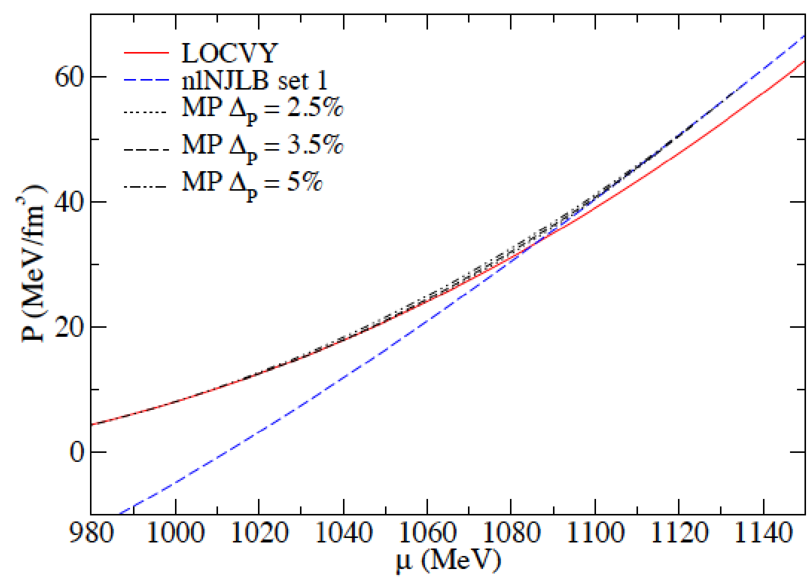
# Interpolation constructions and hyperon puzzle solution

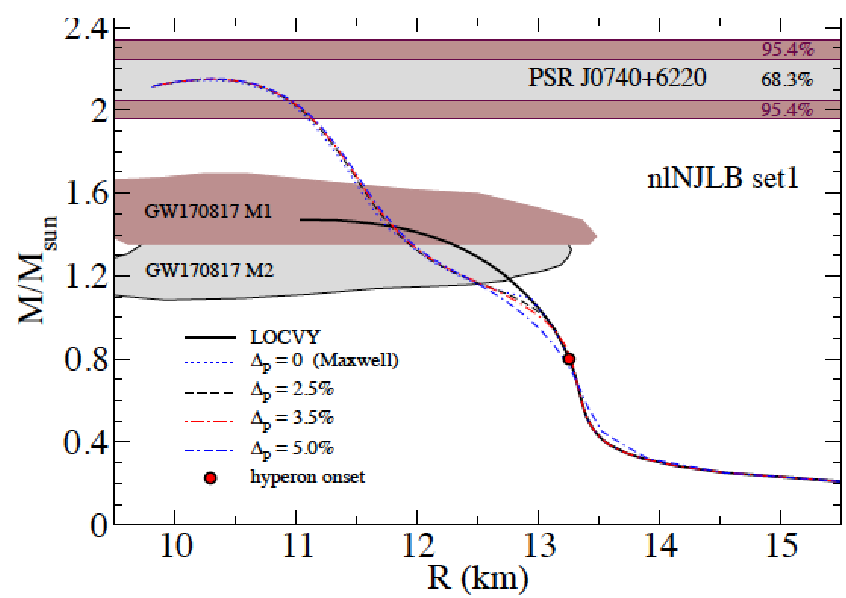
## anomalous case




## normal case

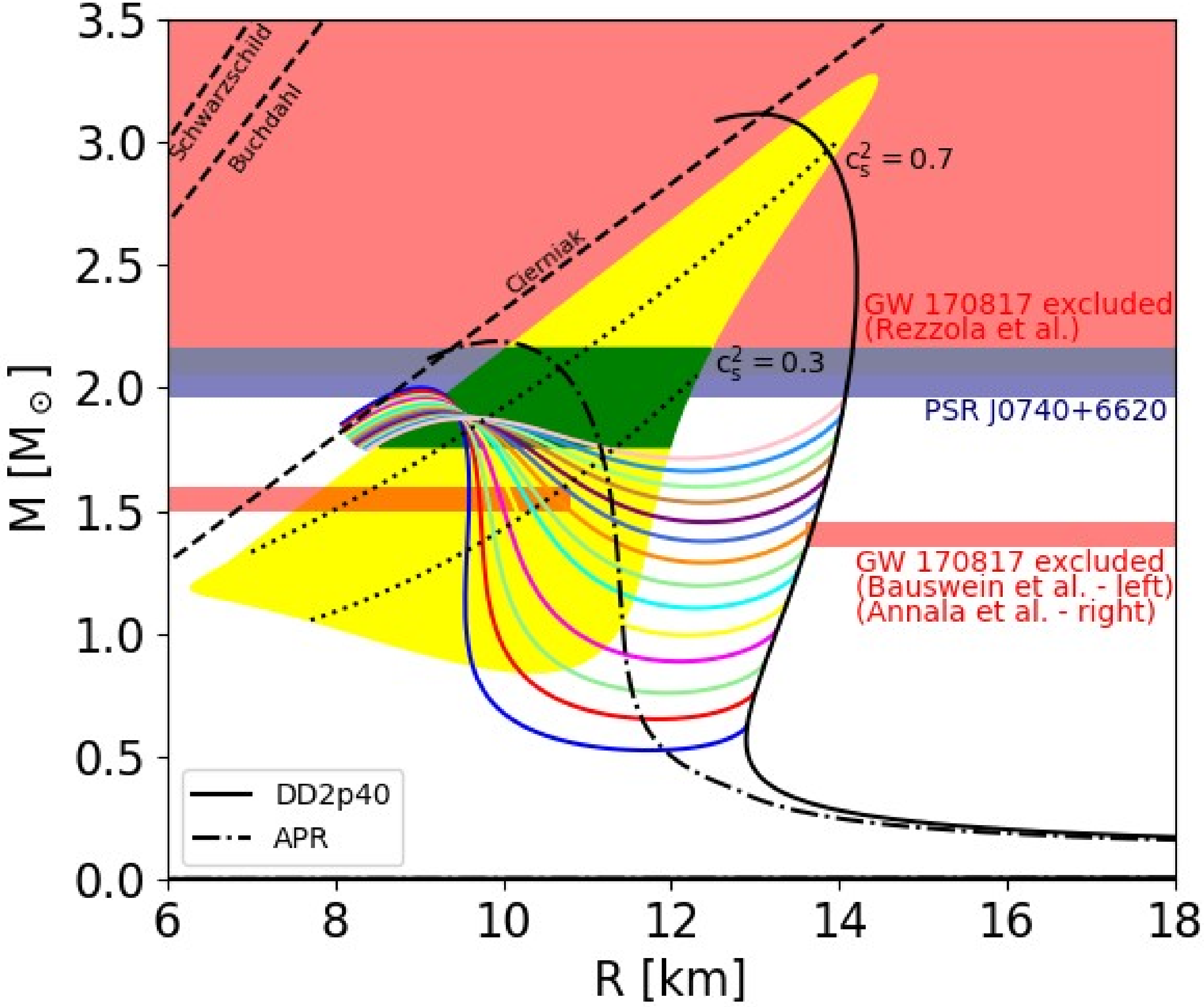



M. Shahrbaf, D. Blaschke, S. Khanmohamadi, arxiv: 2004.14377; J. Phys. G to appear (2020)

# The Special Point in the M-R Diagram for Hybrid Stars

M. Cierniak & D. Blaschke, in preparation for EPJ ST (2020)



# Outlook:
# Supernovae & Merger Simulations

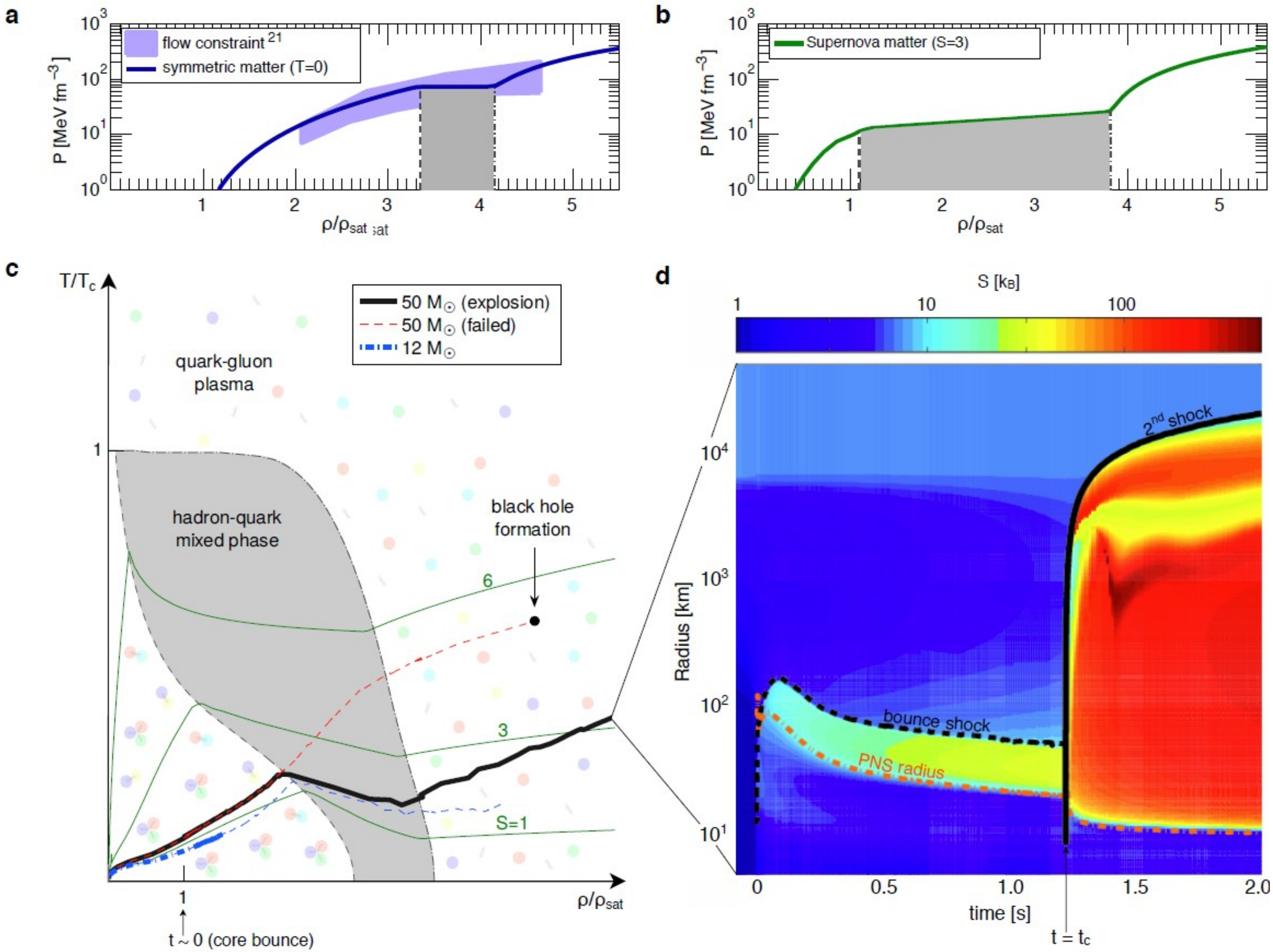
T. Fischer et al., Quark deconfinement as supernova engine of massive blue supergiant star explosions, Nature Astronomy 2 (2018) 980-986; arxiv:1712.08788

A. Bauswein et al., Identifying a first-order phase transition in neutron star mergers through gravitational waves, PRL 122 (2019) 061102

S. Blacker et al., Constraining the onset density of the hadron-quark phase transition with gravitational-wave observations, arxiv:2006.03789 [astro-ph.HE]

A Bauswein et al., Gravitational-wave signature of quark deconfinement in neutron star mergers and hybrid star mergers, EPJ ST (2020), submitted.

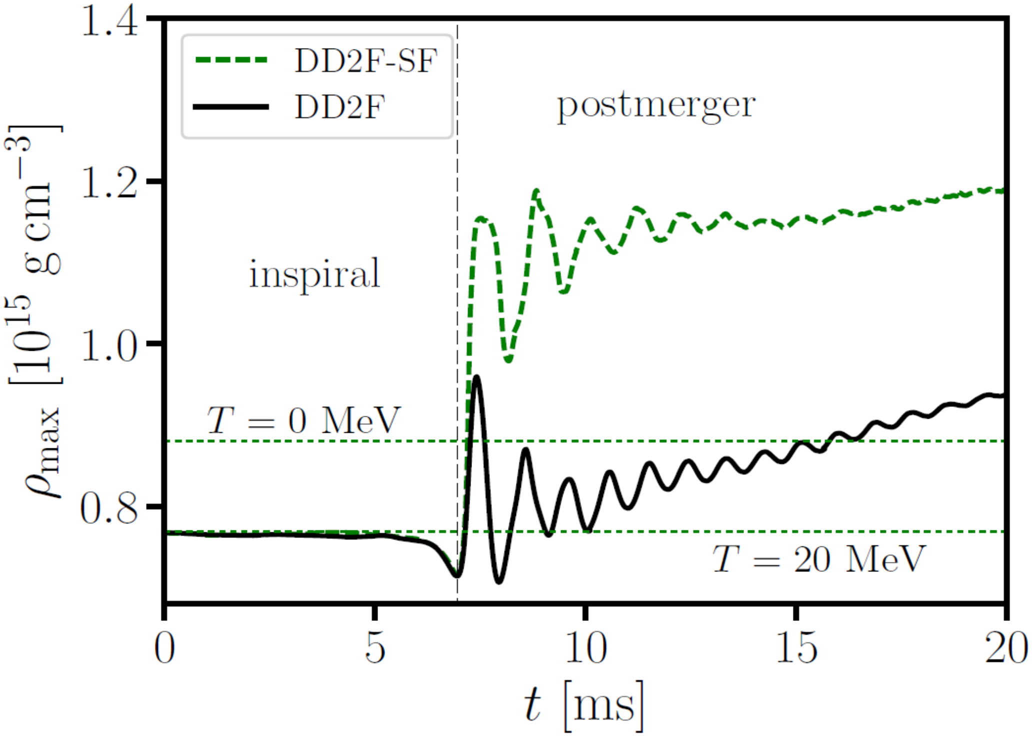
# Deconfinement transition as SN explosion mechanism



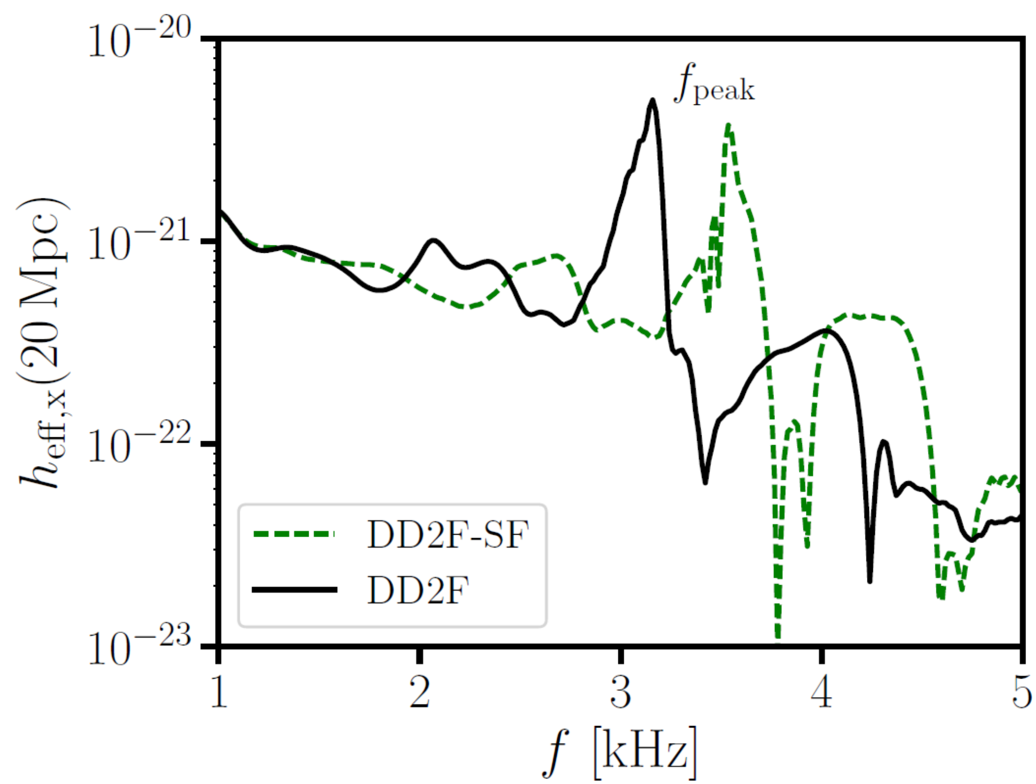

Progenitor:
$M = 50\ M_O$

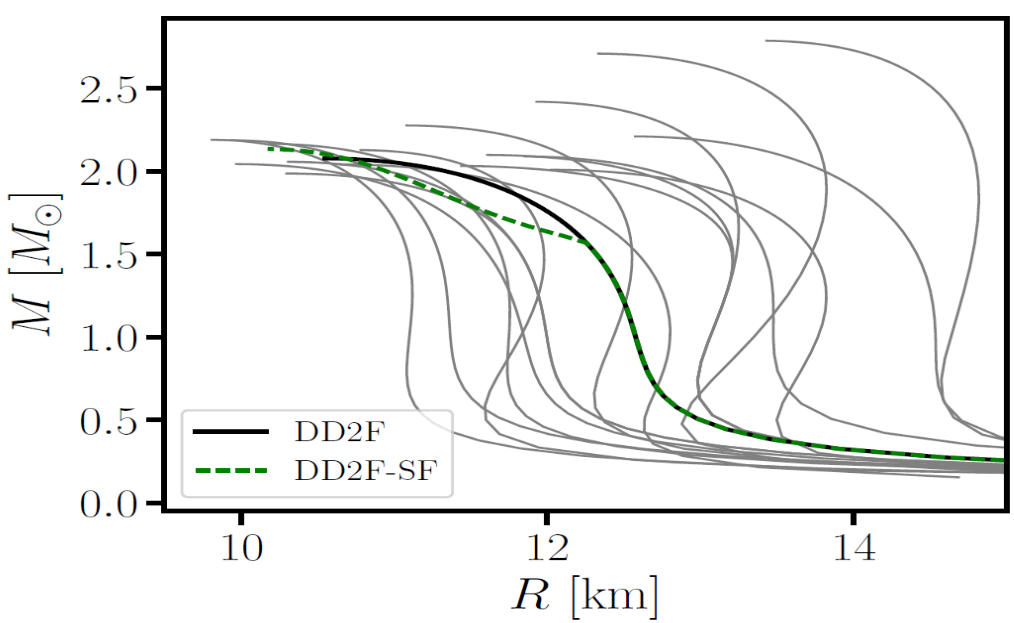
T. Fischer, N.-U. Bastian et al., Quark deconfinement as supernova engine of massive blue Supergiant star explosions, Nature Astronomy 2 (2018) 980-986; arxiv:1712.08788

# Hybrid star formation in postmerger phase




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



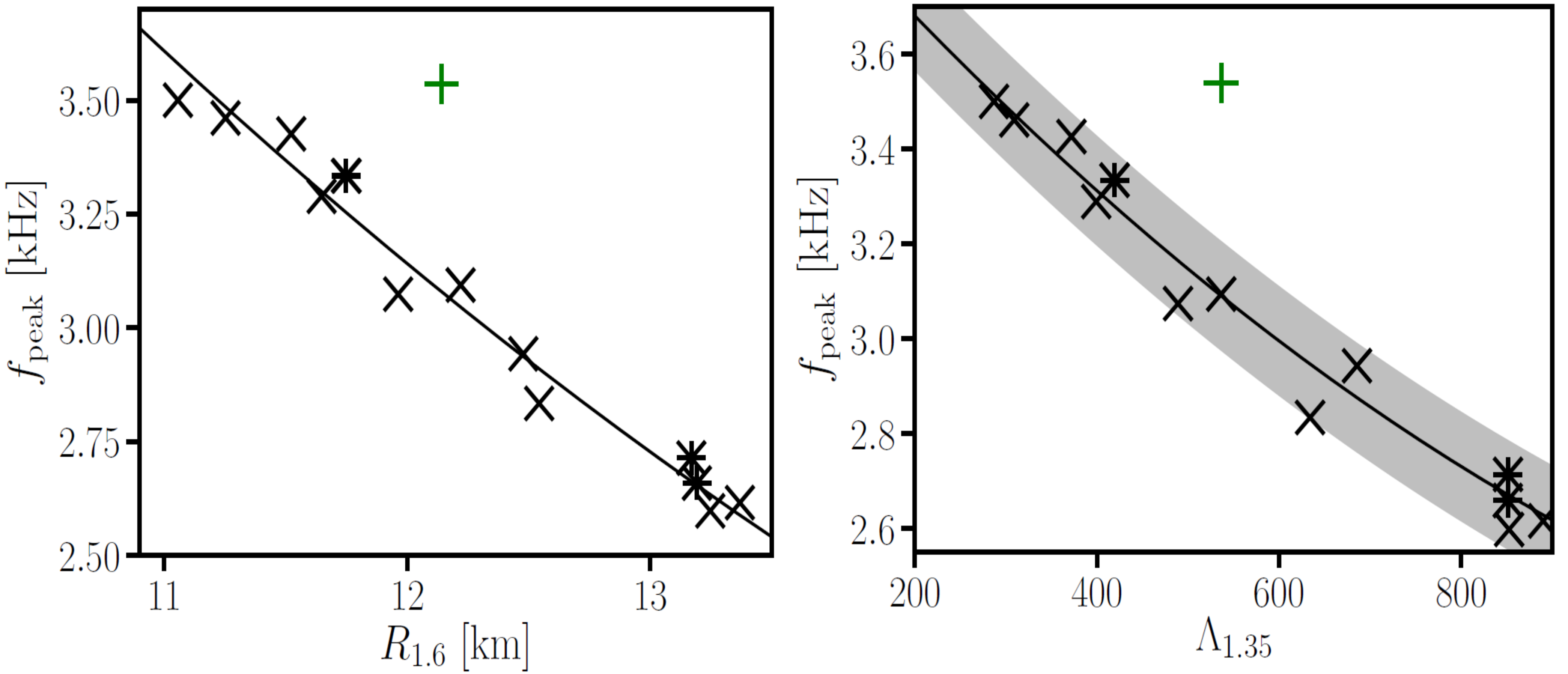




Hybrid star formation during NS merger
→ higher densities and compacter star
→ higher peak frequency of the GW

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]

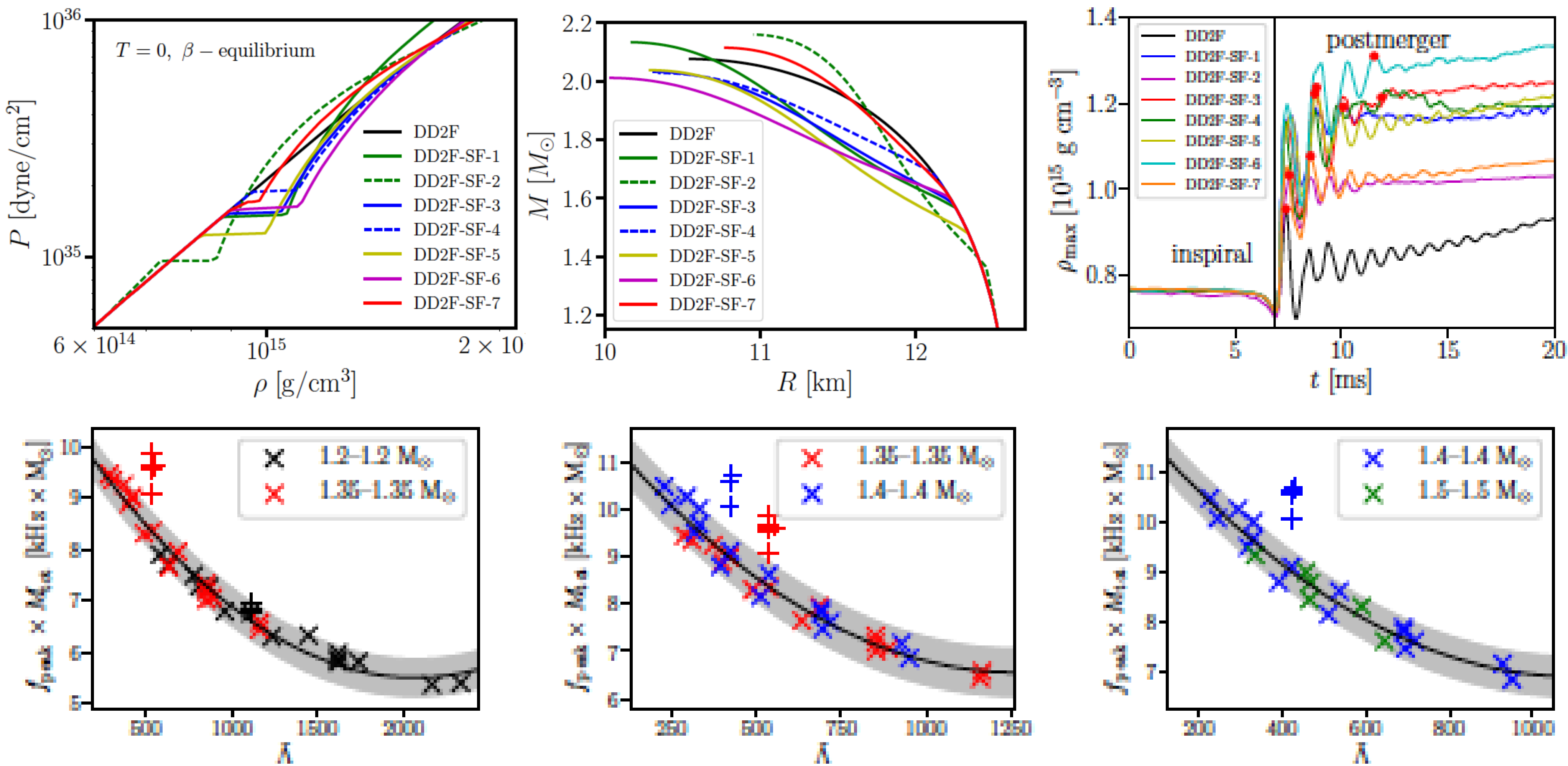



**Strong deviation** from $f_{peak}$ – $R_{1.6}$ relation signals **strong phase transition in** NS merger**!**

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

# Hybrid star formation in postmerger phase

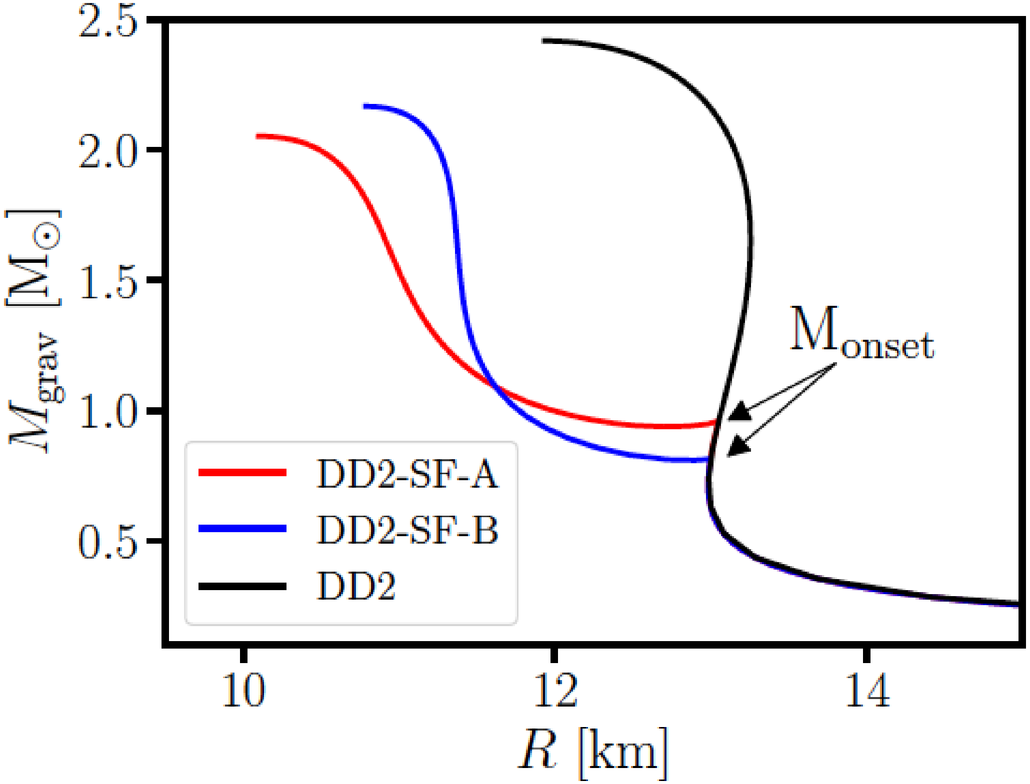
Strong phase transition in postmerger GW signal, S. Blacker et al., arxiv:2006.03789

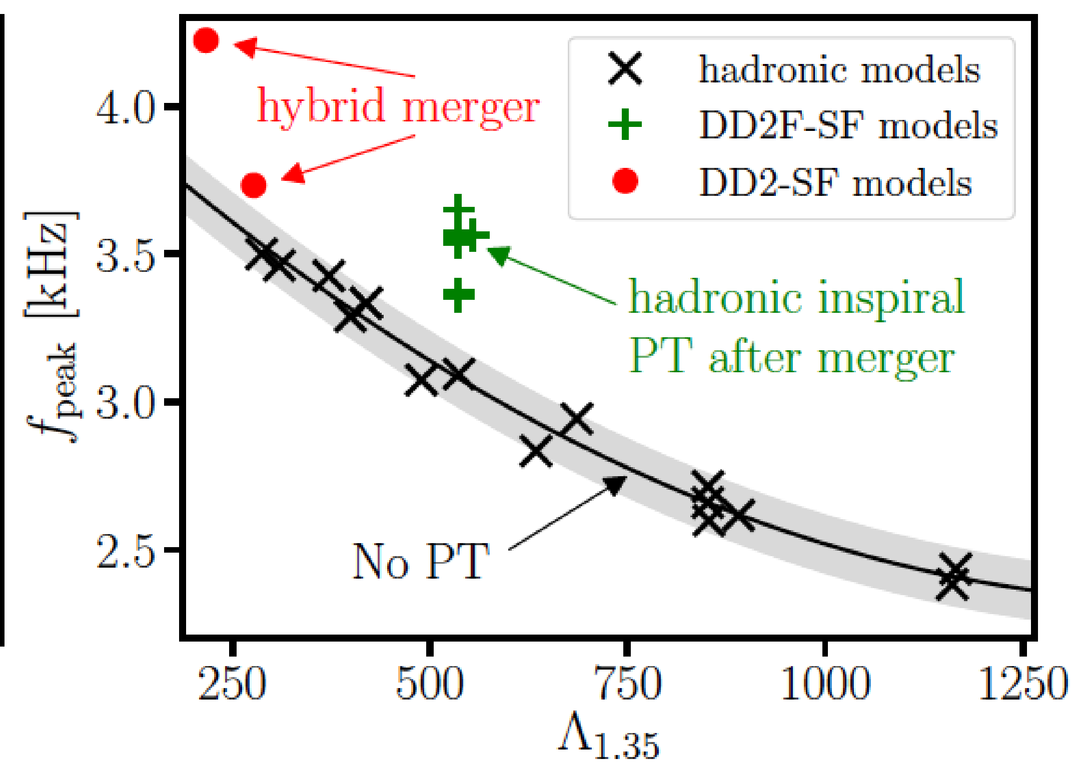



Dominant **postmerger** frequency $f_{peak}$ vs. tidal deformability $\Lambda_{1.35}$ from inspiral phase:
Results from hybrid models appear as **outliers** of the grey band (maximal deviation of purely hadronic models from a least squares fit) = signalling a **strong phase transition in** NS **!**

# GW signal of deconfinement in merger of hybrid stars

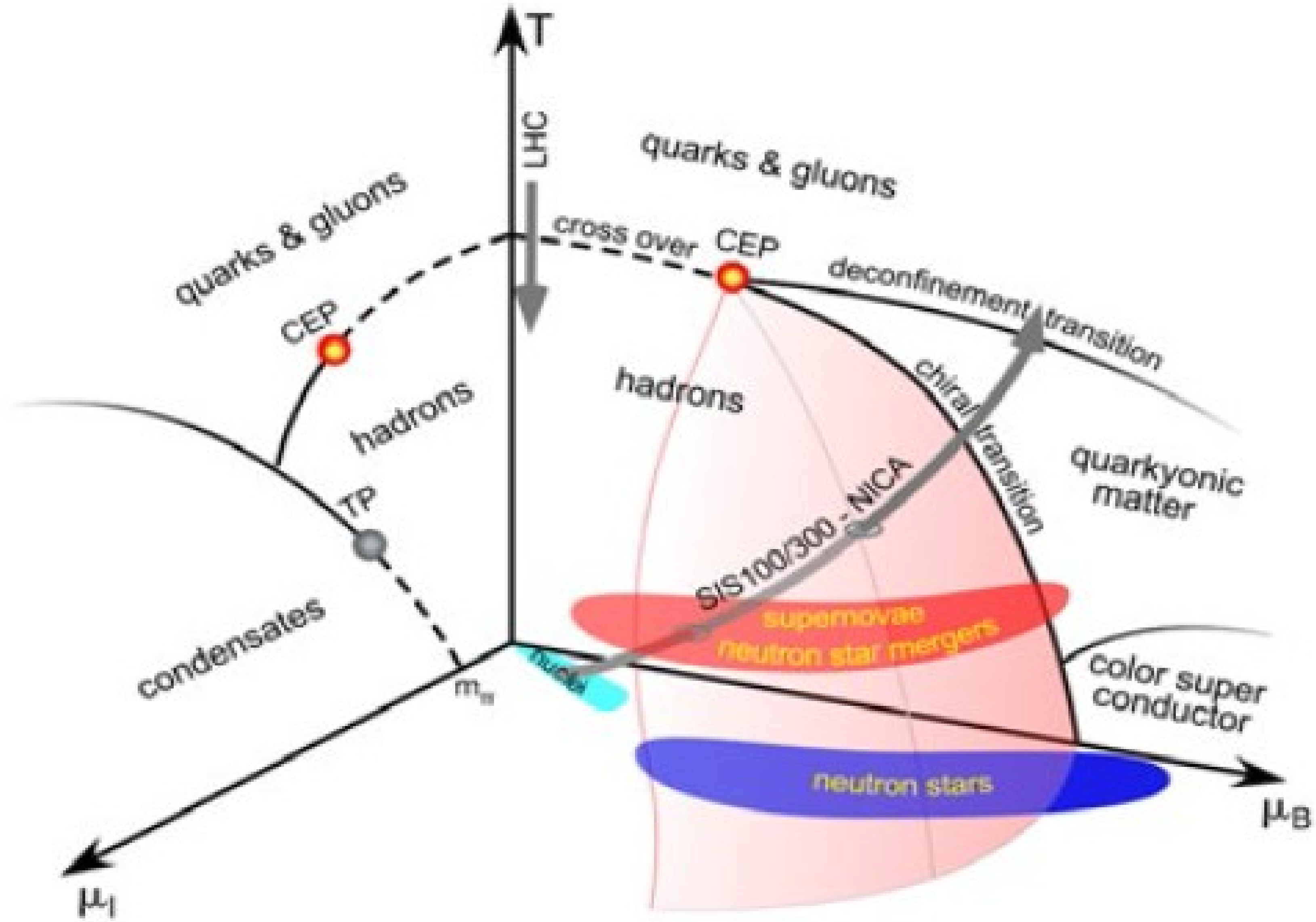
Merger of hybrid stars with early phase transition: A. Bauswein et al., EPJ ST (2020) submitted




The combination of stiff hadronic EoS (DD2) and string-flip (SF) model allows for early onset of deconfinement in low-mass neutron stars and even third-family solutions (mass twins). For these cases, the event GW170817 could have been a **merger of two hybrid stars**! Also in these cases (red dots in above figure) a **significant deviation** from the grey band of Purely hadronic star mergers without a phase transition is obtained!

# CEP in the QCD phase diagram: HIC vs. Astrophysics

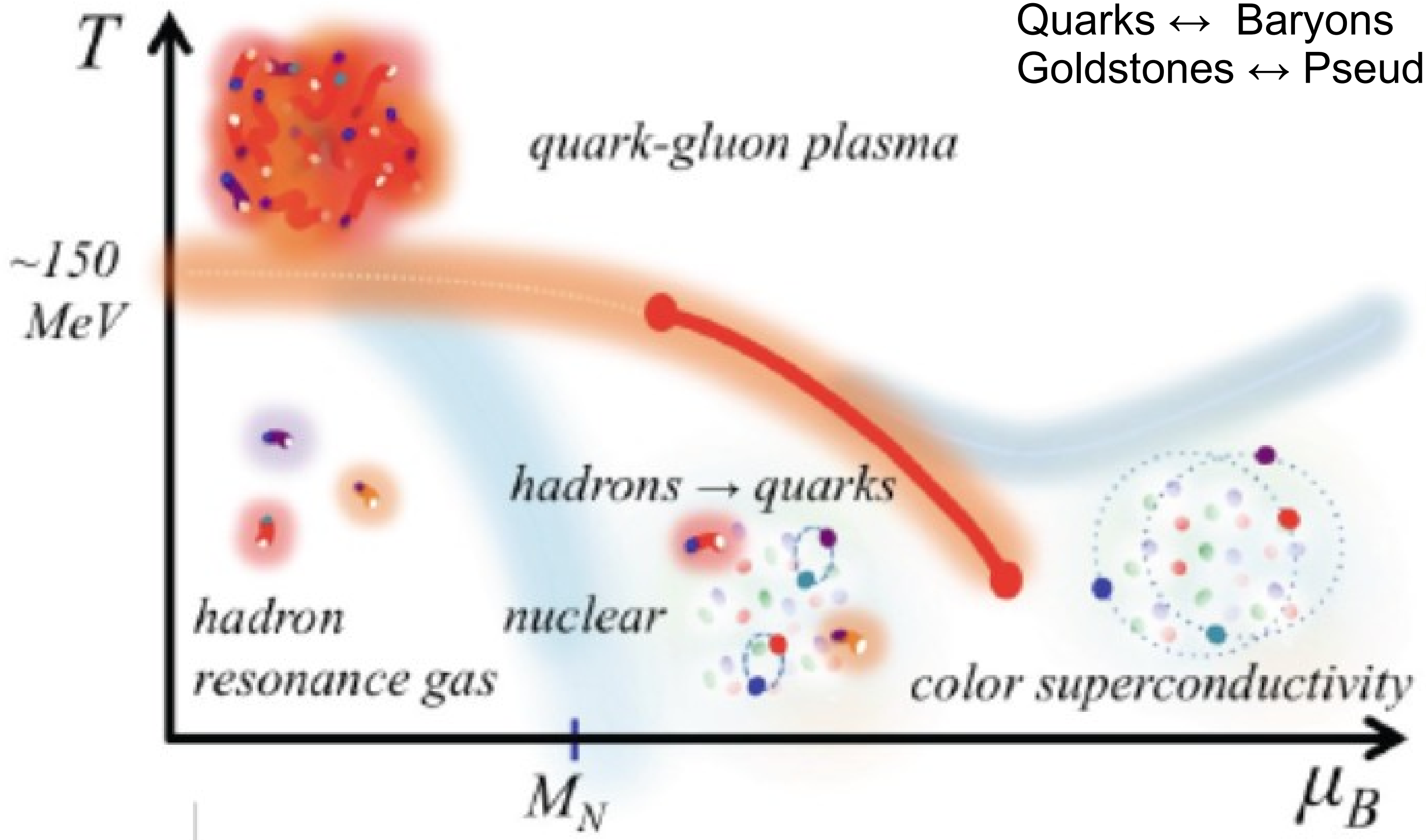



NuPECC Long Range Plan 2017; http://www.nupecc.org

A. Andronic, D. Blaschke, et al., "Hadron production ...", Nucl. Phys. A 837 (2010) 65 - 86

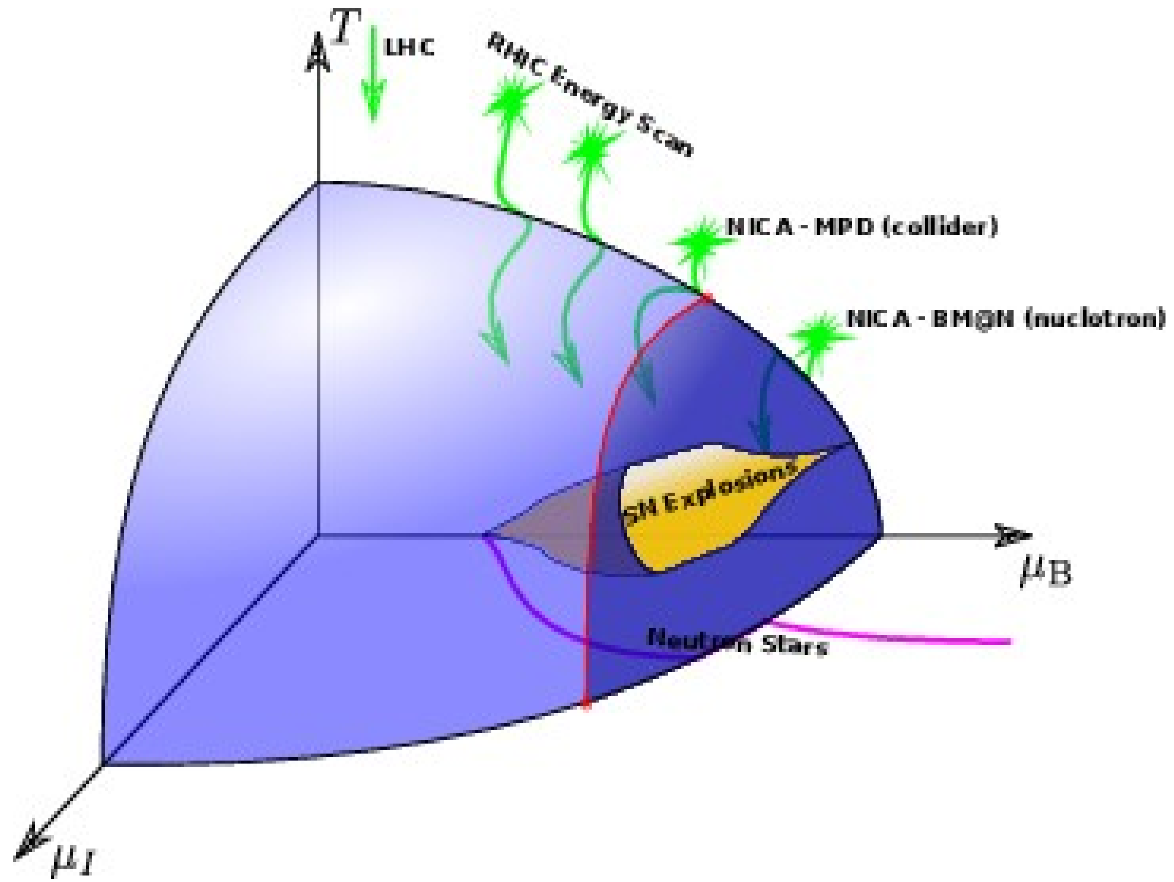
# $2^{nd}$ CEP in QCD phase diagram: Quark-Hadron Continuity?

Gluons ↔ Vector mesons
Quarks ↔ Baryons
Goldstones ↔ Pseudoscalar mesons




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

# Conclusions:



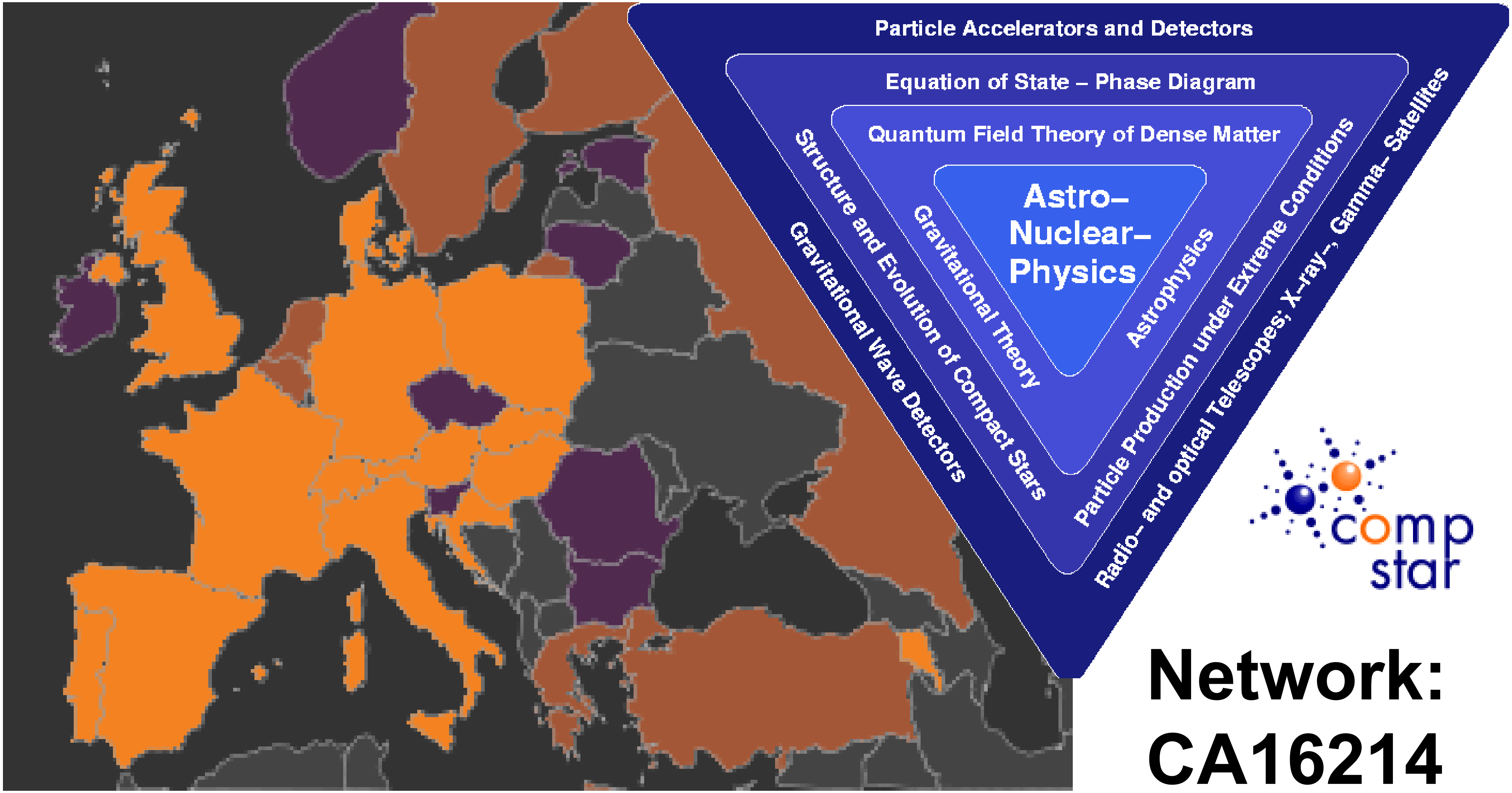

High-mass twin (HMT) and Typical-mass twin (TMT) solutions obtained within different hybrid star EoS, e.g.,
- constant speed of sound
- higher order NJL
- piecewise polytrope
- density functional

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 the inspiral of a neutron star – hybrid star binary !

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




comp star

# Network: CA16214

# Newest: PHAROS

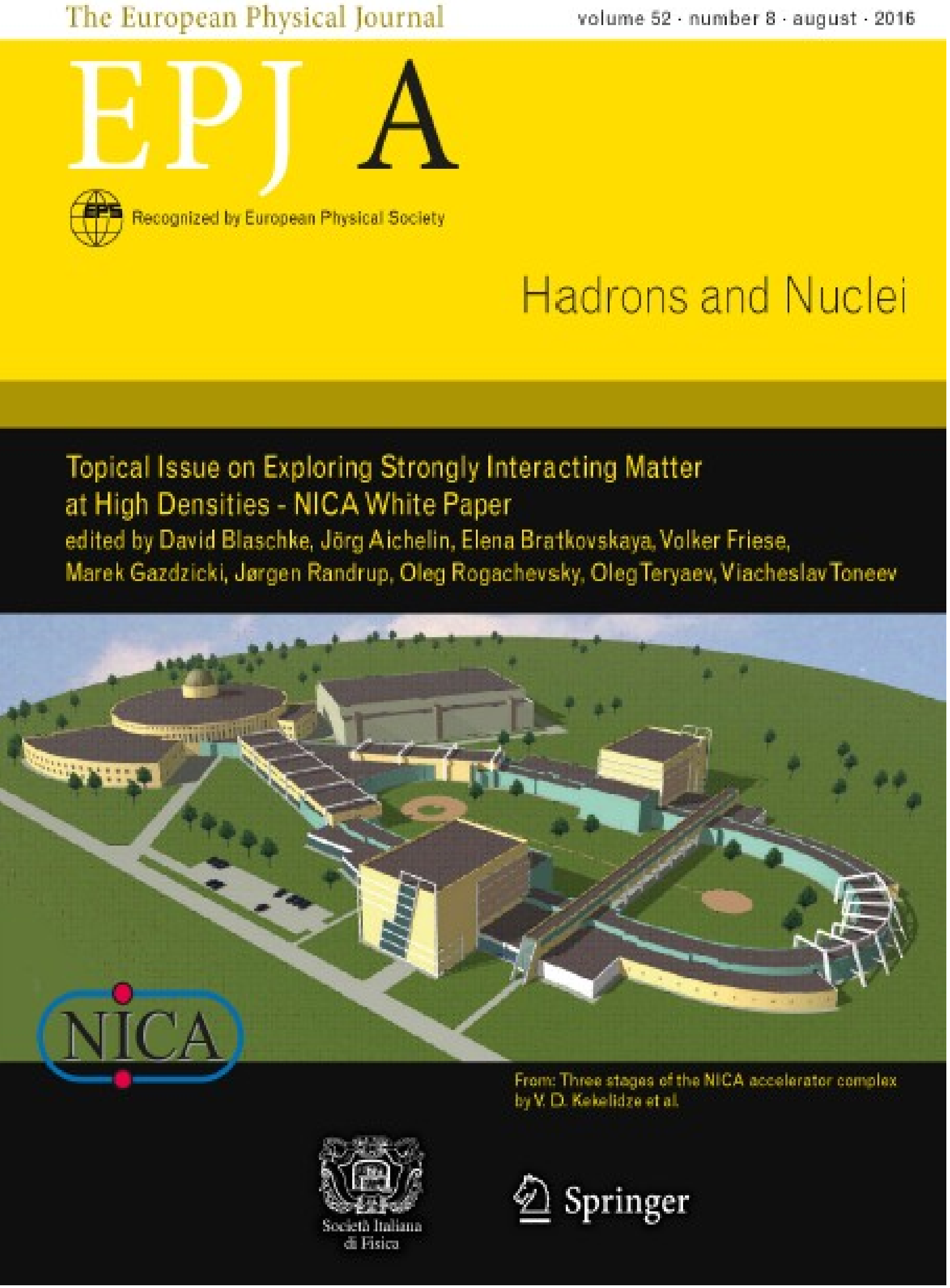
cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

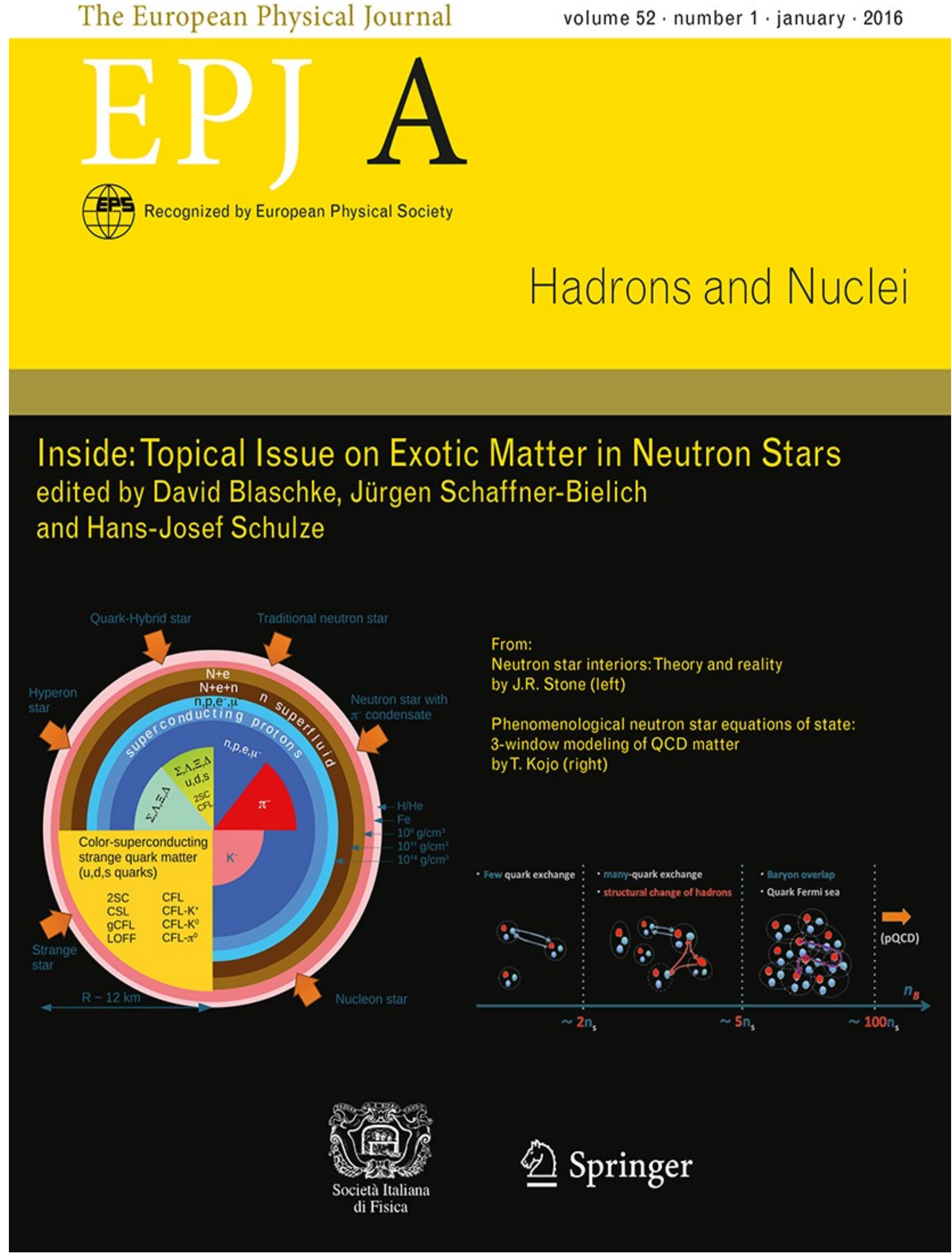
http://www.cost.eu/COST_Actions/ca/CA16214

**Kick-off: Brussels, 22**

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


Thanks to Constanca & Co.
CompStar Workshop and School 2009 in Coimbra

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