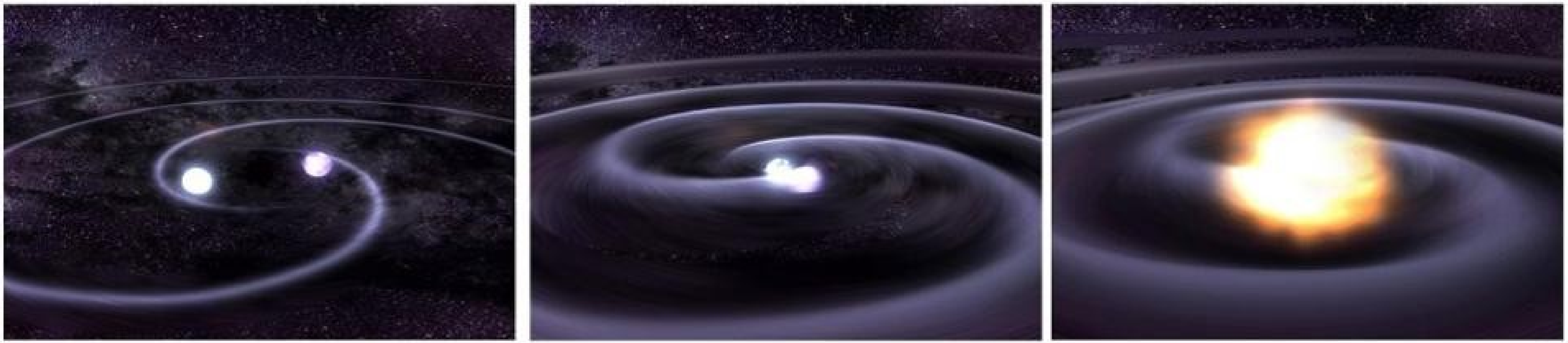
From Strongly interacting **Fields to Heavy Quark** matter systems in Astrophysics

David.Blaschke@gmail.com
University of Wroclaw, Poland & JINR Dubna & MEPhI Moscow, Russia



Helmholtz Int. Summer School "QFT@Limits", Dubna, 02.08.2019

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1. **Mapping: EoS ↔ Compact star sequence M(R)**
2. **Modern M-R constraints**
3. **Standard example for hybrid EoS**
4. **Third family & deconfinement**
5. **Maxwell, Gibbs und Pasta phase transition**
6. **Deconfinement in massive supernova explosion & merger ...**

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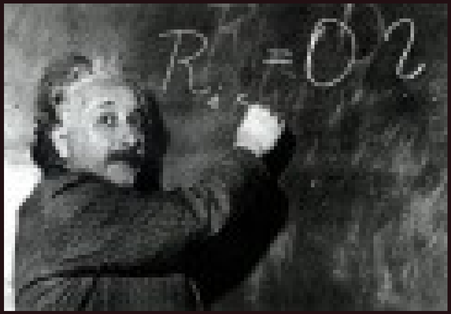
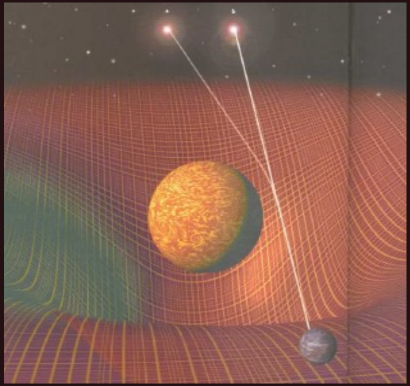
Compact stars and black holes in Einstein's General Relativity theory

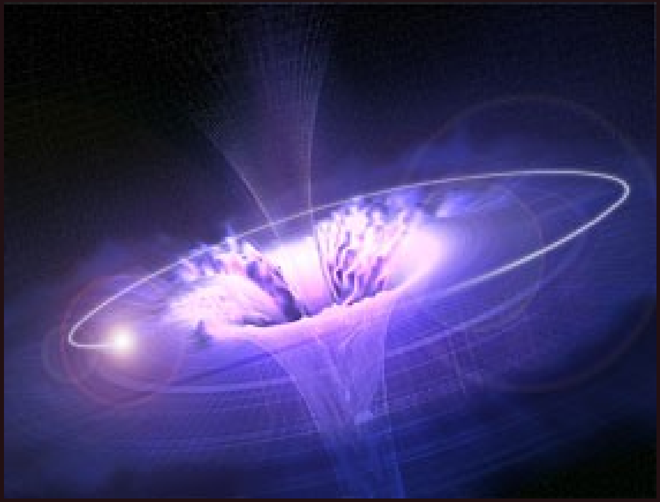


Space-Time $G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$ Matter

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

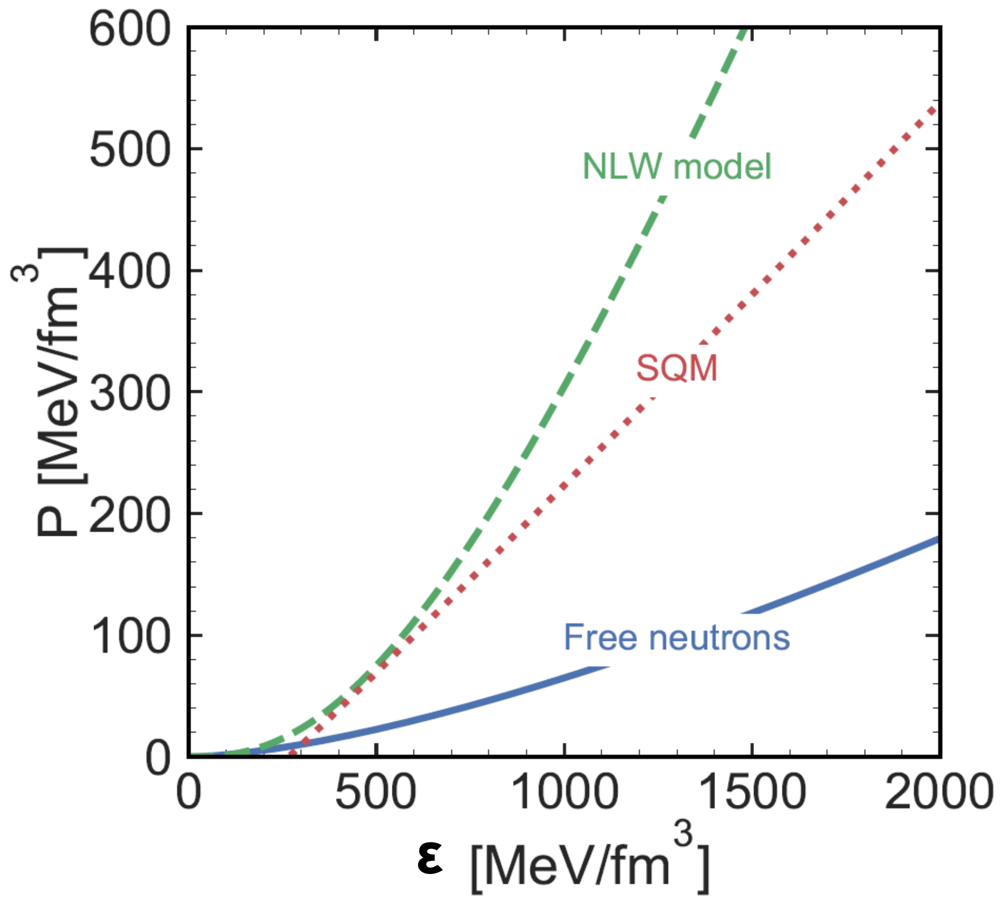
$$\frac{dP(r)}{dr} = -G\frac{m(r)\varepsilon(r)}{r^2}\left(1 + \frac{P(r)}{\varepsilon(r)}\right)\left(1 + \frac{4\pi r^3 P(r)}{m(r)}\right)\left(1 - \frac{2Gm(r)}{r}\right)^{-1}$$

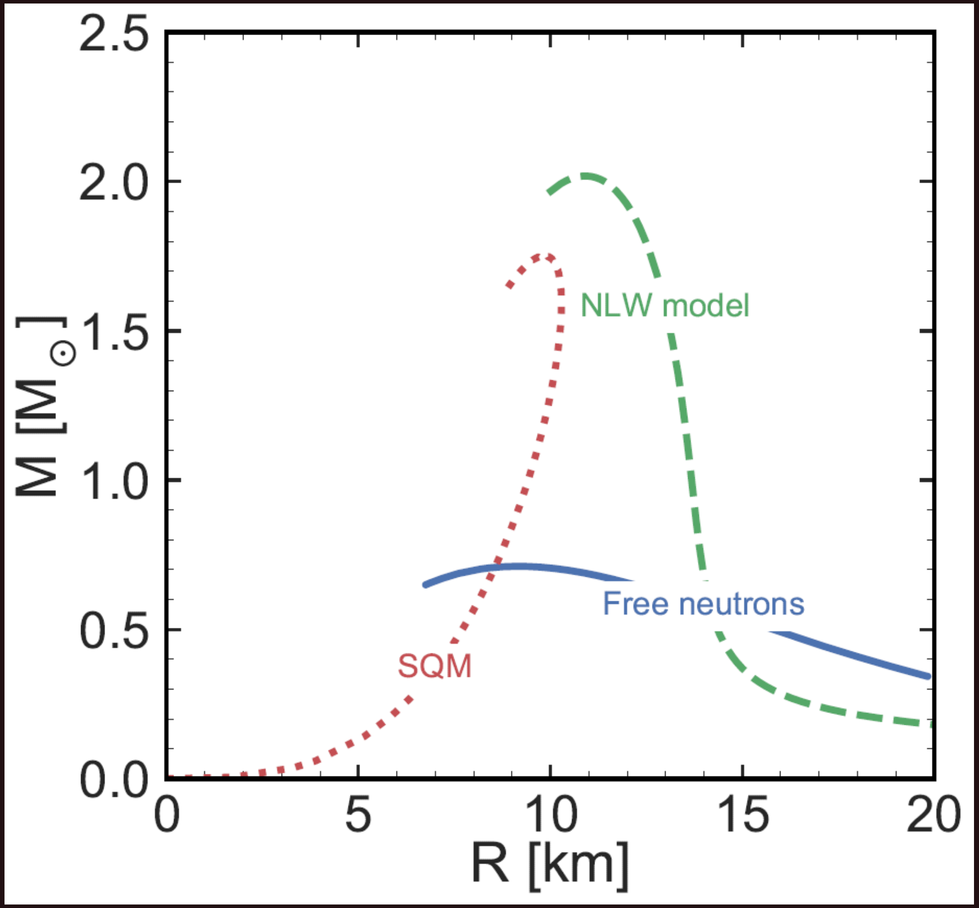
Newtonian case x GR corrections from EoS and metrics

*) 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*)



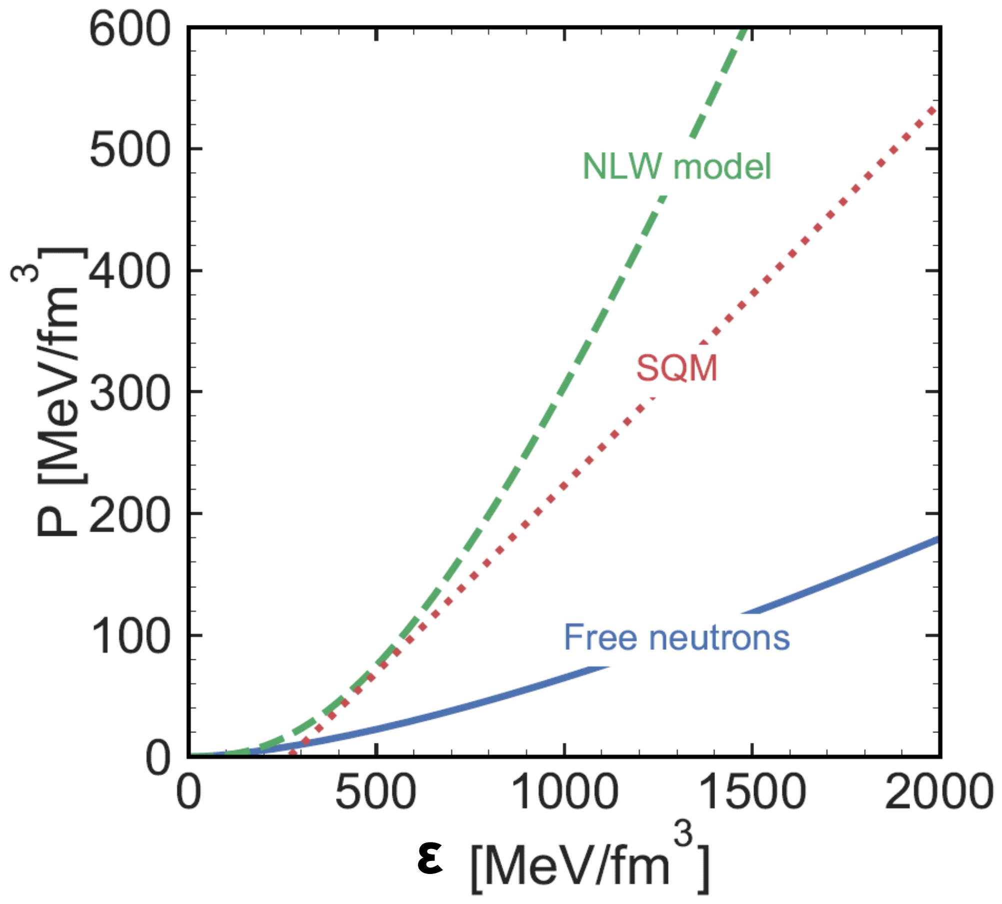


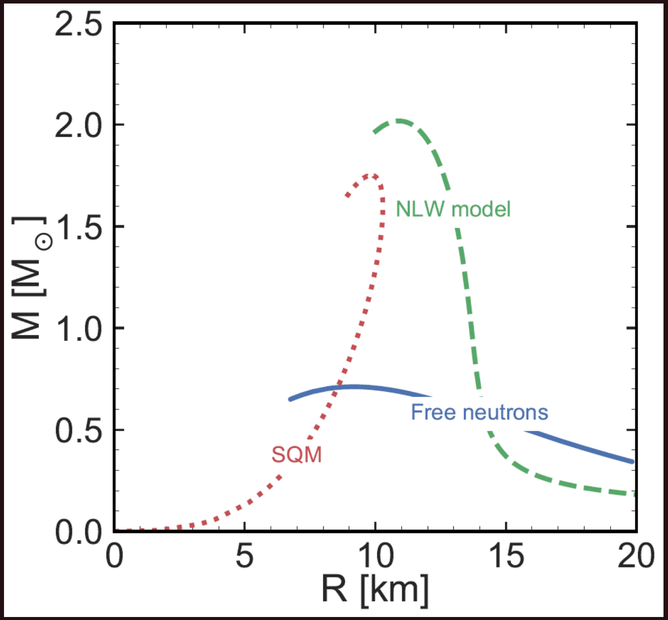
Free neutrons: Oppenheimer & Volkoff, Phys. Rev. 55 (1939) 374
NLW (nonlinear Walecka) model: N. K. Glendenning, Compact Stars (Springer, 2000)
SQM (strange quark matter): P. Haensel, J. L. Zdunik, R. Schaeffer, A&A 160 (1986) 121

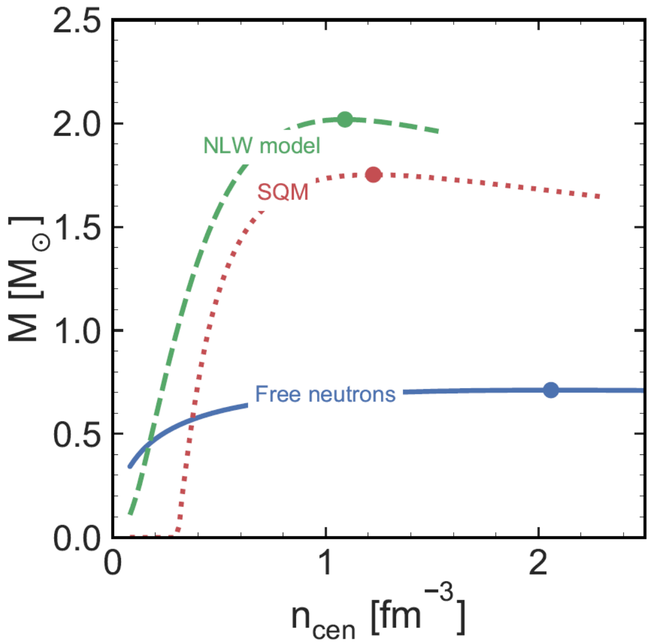
*) courtesy: Konstantin Maslov

The 1:1 relation P(ε) ↔ M(R) via TOV

Simple examples*)







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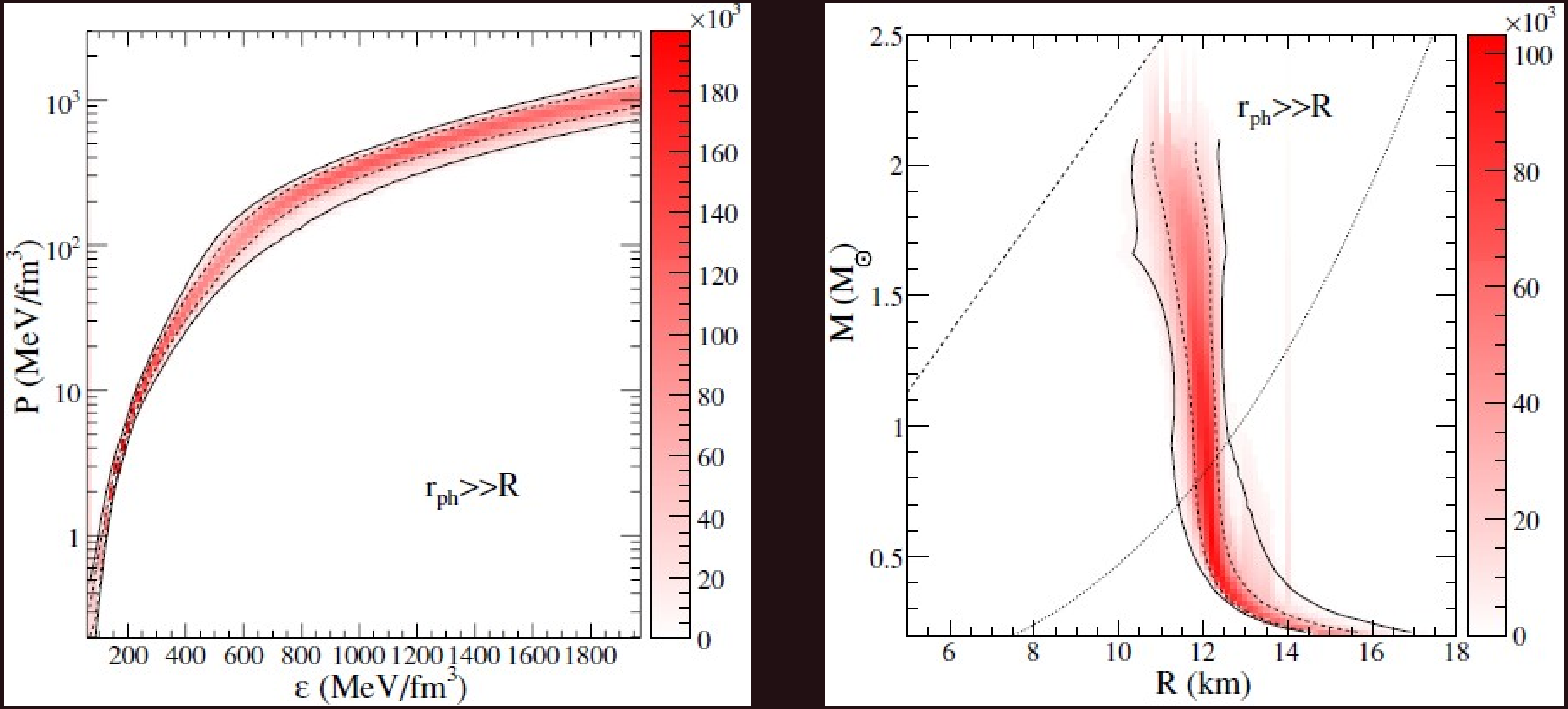
The 1:1 relation P(ε) ↔ M(R) via TOV

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

Pb = 8.68 d, e=0.00000130(4)

Inclination angle = 89.17(2) degrees !

Precise masses derived from
Shapiro delay only:

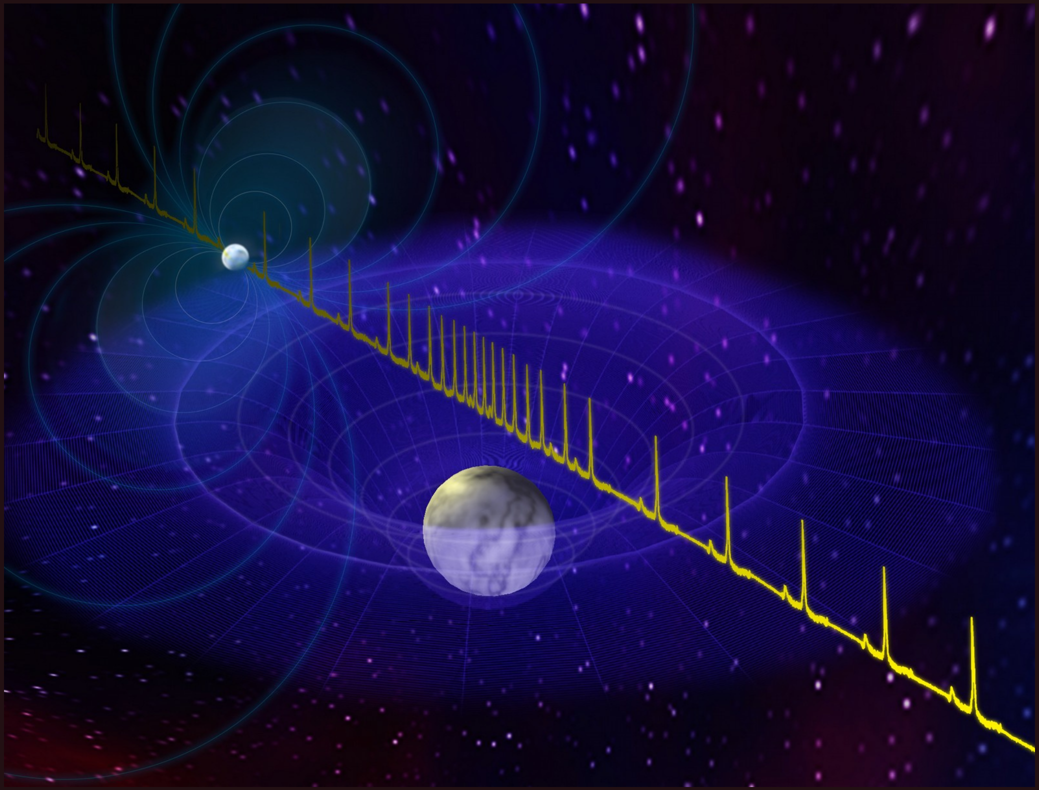
$$M_p = 1.97(4)\ M_\odot$$
$$M_c = 0.500(6)\ M_\odot$$

Update [Fonseca et al. (2016)]

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

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

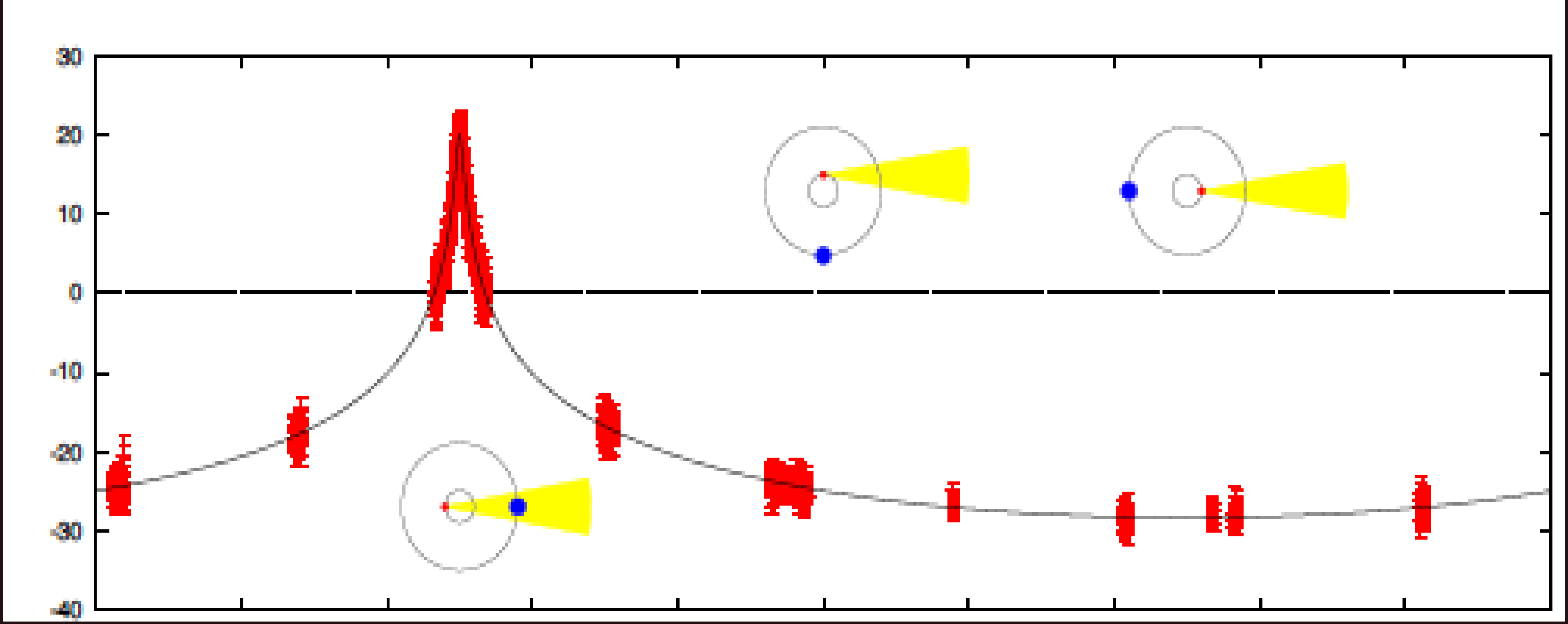
PSR J1614-2230
Demorest et al., Nature (2010)



PSR J1614-2230

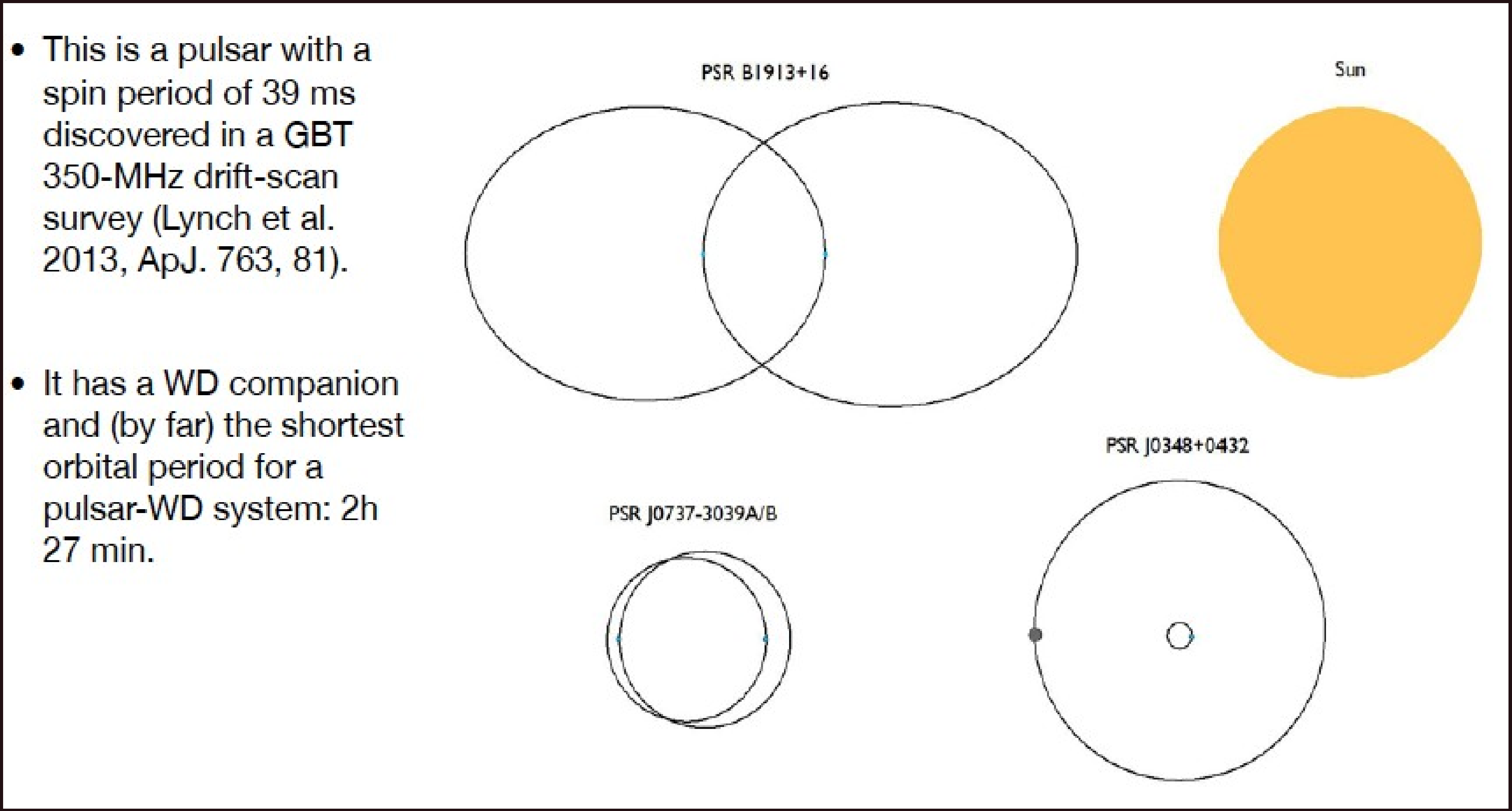
A precise AND large mass measurement

Shapiro delay:



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

The big one: PSR J0348+0432

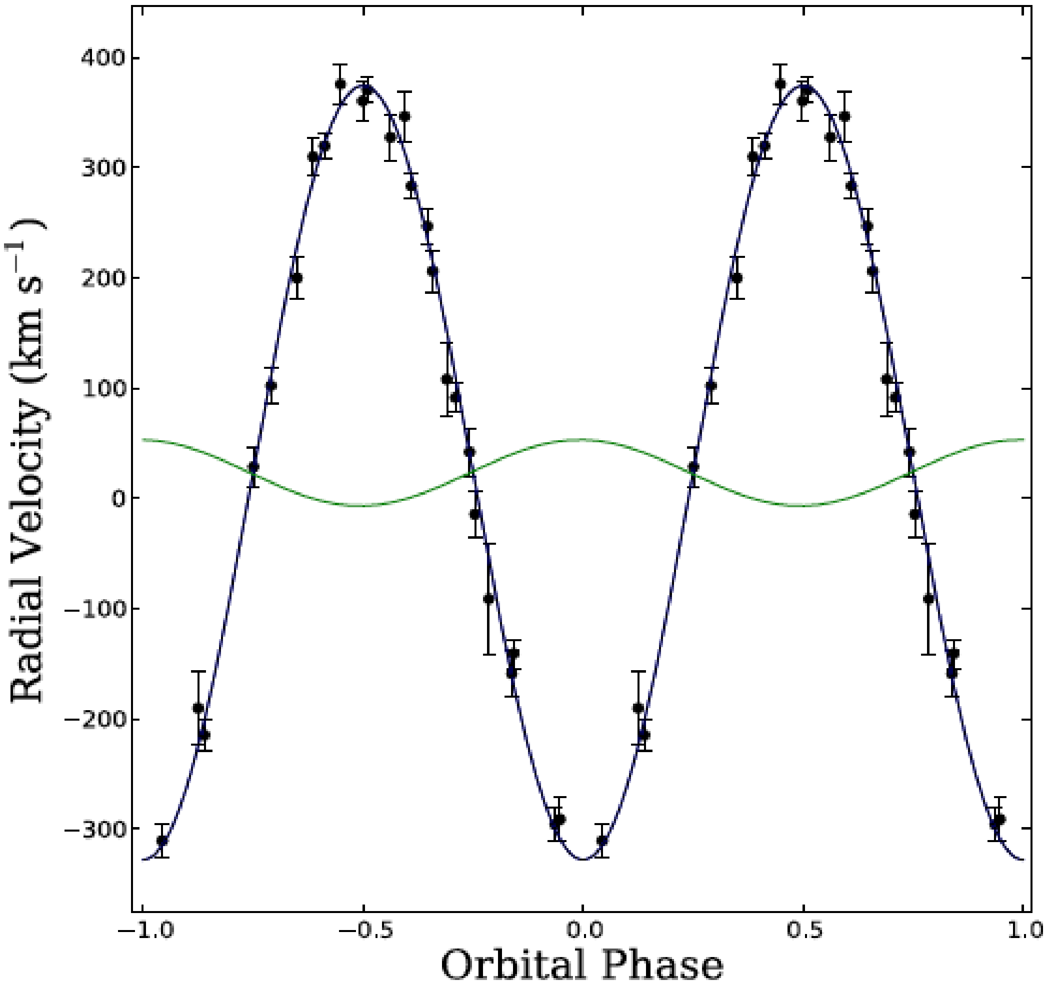


- This is a pulsar with a spin period of 39 ms discovered in a GBT 350-MHz drift-scan survey (Lynch et al. 2013, ApJ. 763, 81).

- It has a WD companion and (by far) the shortest orbital period for a pulsar-WD system: 2h 27 min.

courtesy: Paolo Freire (Hirschegg 2017)

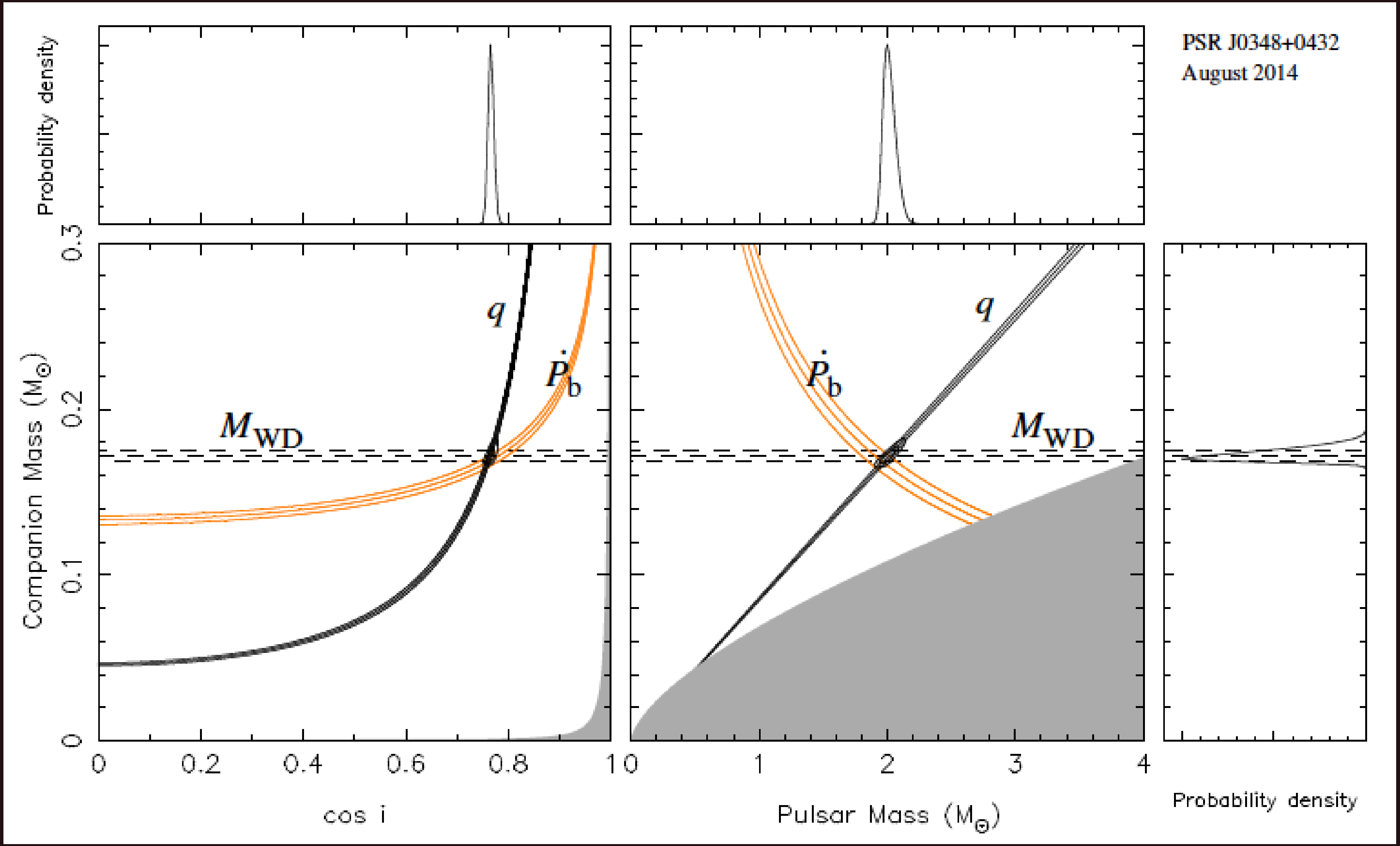
PSR J0348+0432



- Recent optical measurements at the VLT find a WD mass of 0.172 ± 0.003 M and **a pulsar mass of 2.01 ± 0.04 M** (Antoniadis et al. 2013, Science, 340, n. 6131).
- Most massive NS with a precise mass measurement.
- Confirms that such massive NSs exist using a different method than that used for J1614−2230. It also shows that these massive NSs are not rare.
- Allows, for the first time, tests of general relativity with such massive NSs! Prediction for orbital decay: −8.1 μs /year!

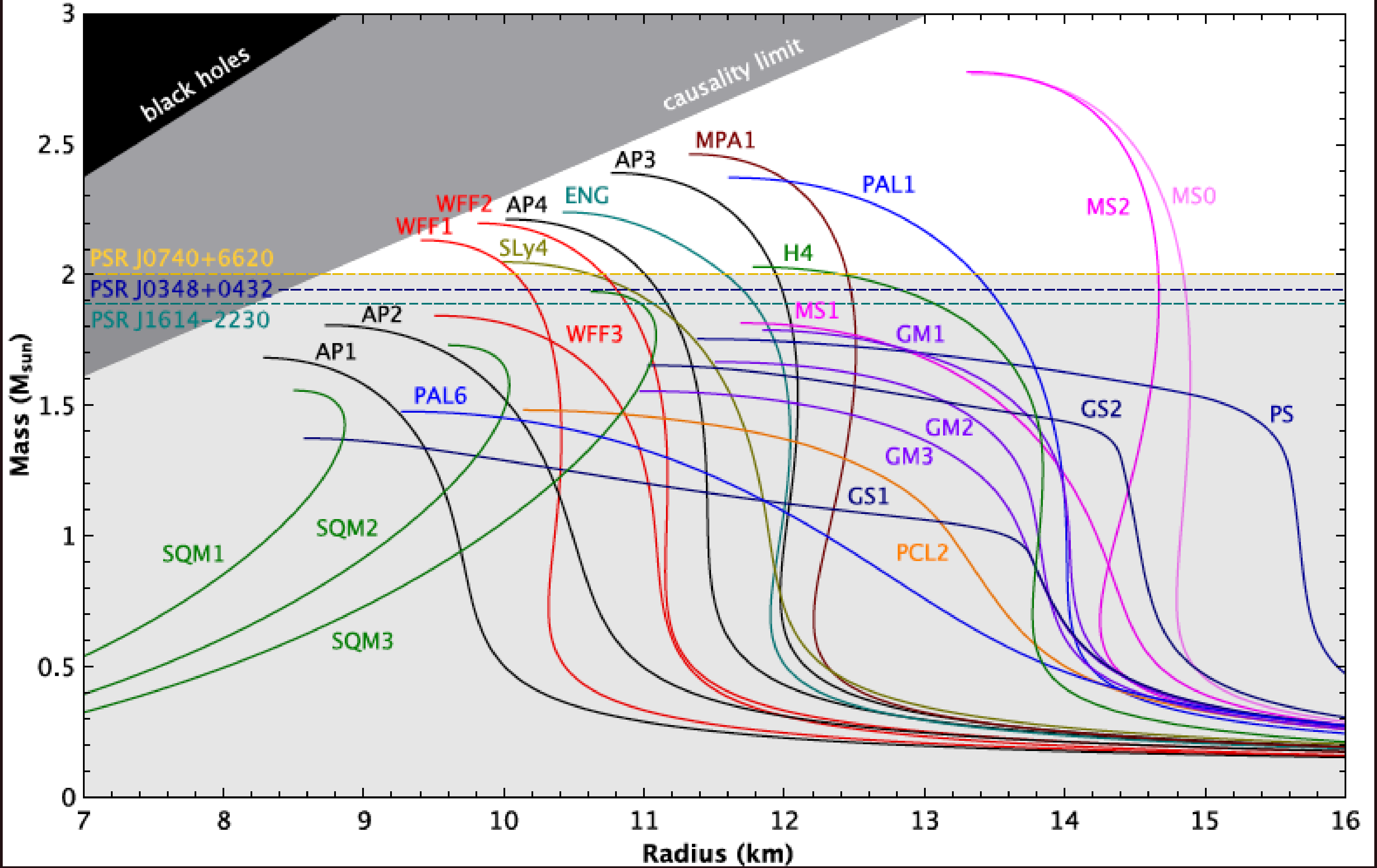
courtesy: Paolo Freire (Hirschegg 2017)

GR test / better mass measurement



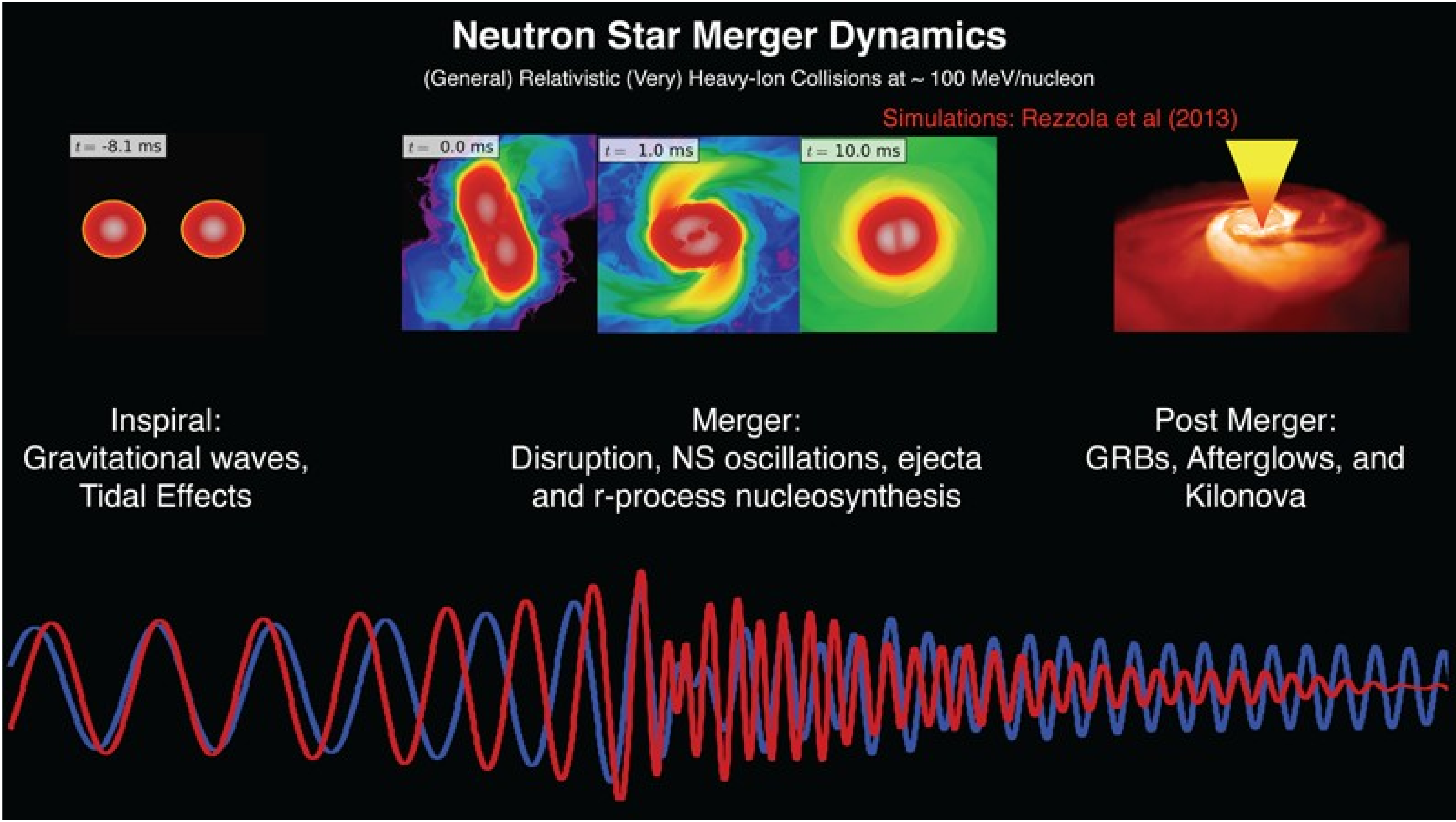
courtesy: Paolo Freire (Hirschegg 2017)

NS Masses and Radii ↔ EoS



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

GW170817 – a merger of two compact stars



Neutron Star Merger Dynamics

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

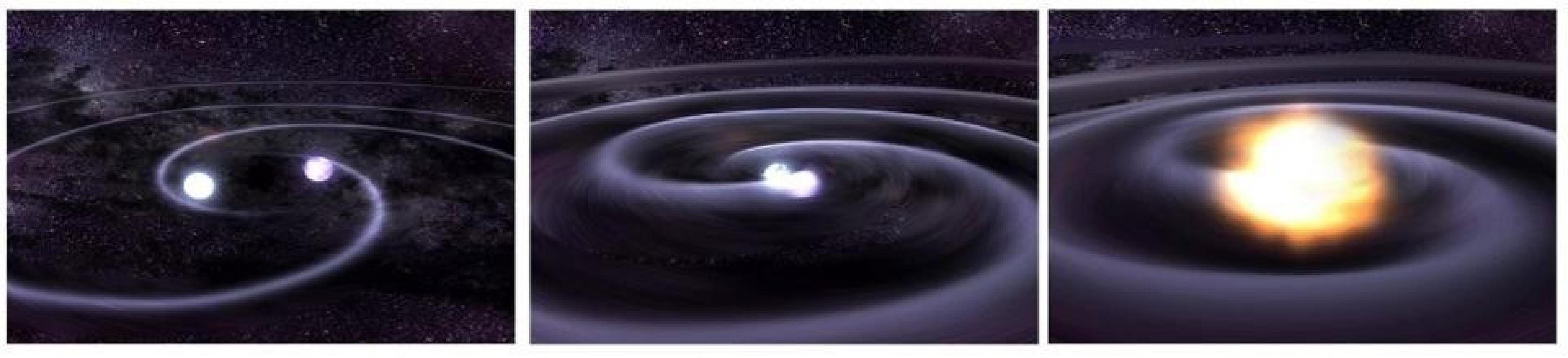
Simulations: Rezzola et al (2013)

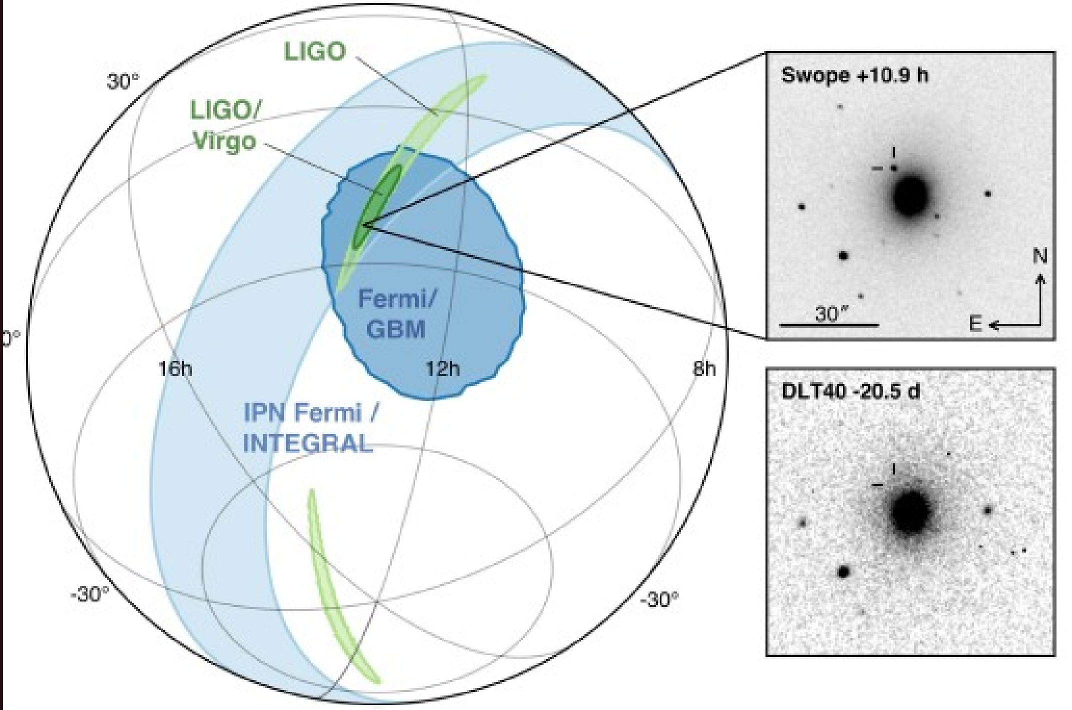
Inspiral:
Gravitational waves,
Tidal Effects

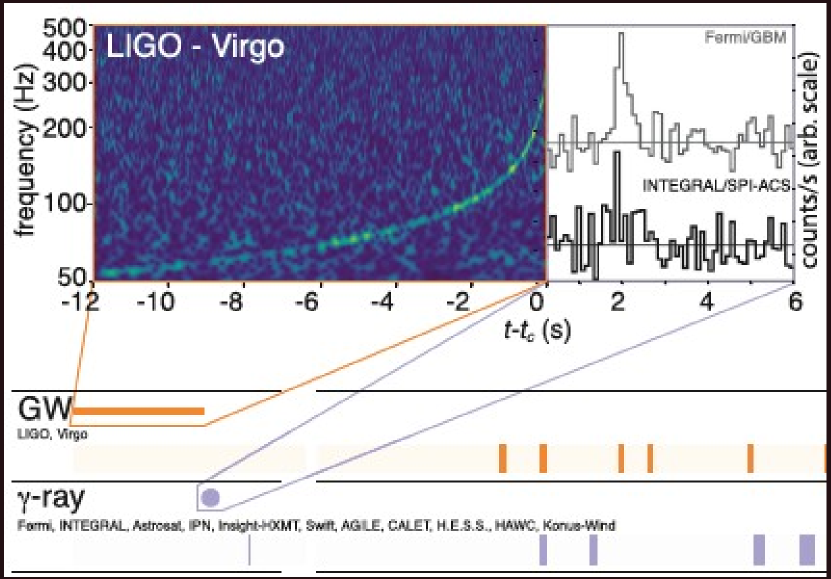
Merger:
Disruption, NS oscillations, ejecta
and r-process nucleosynthesis

Post Merger:
GRBs, Afterglows, and
Kilonova

Discovery: neutron star merger !







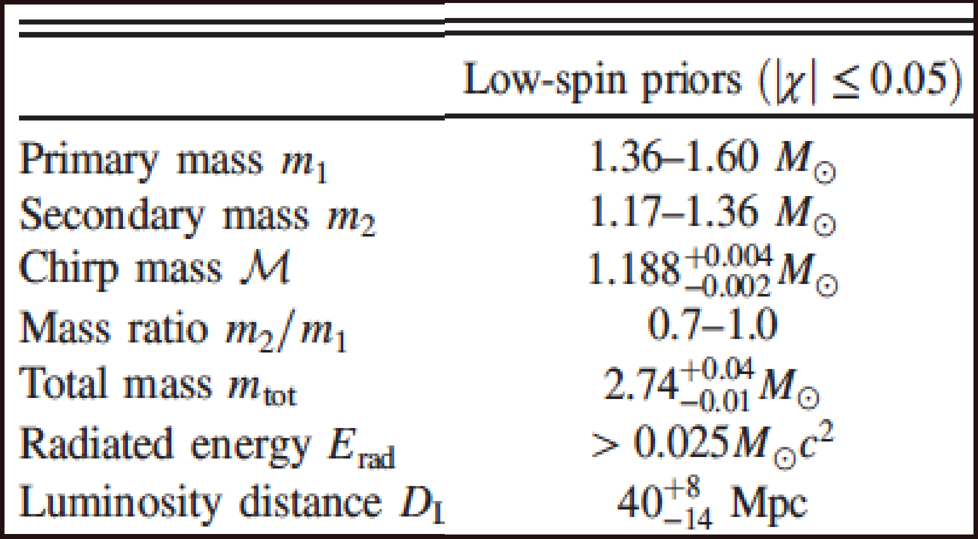
GW170817A , announced 16.10.2017 *)

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

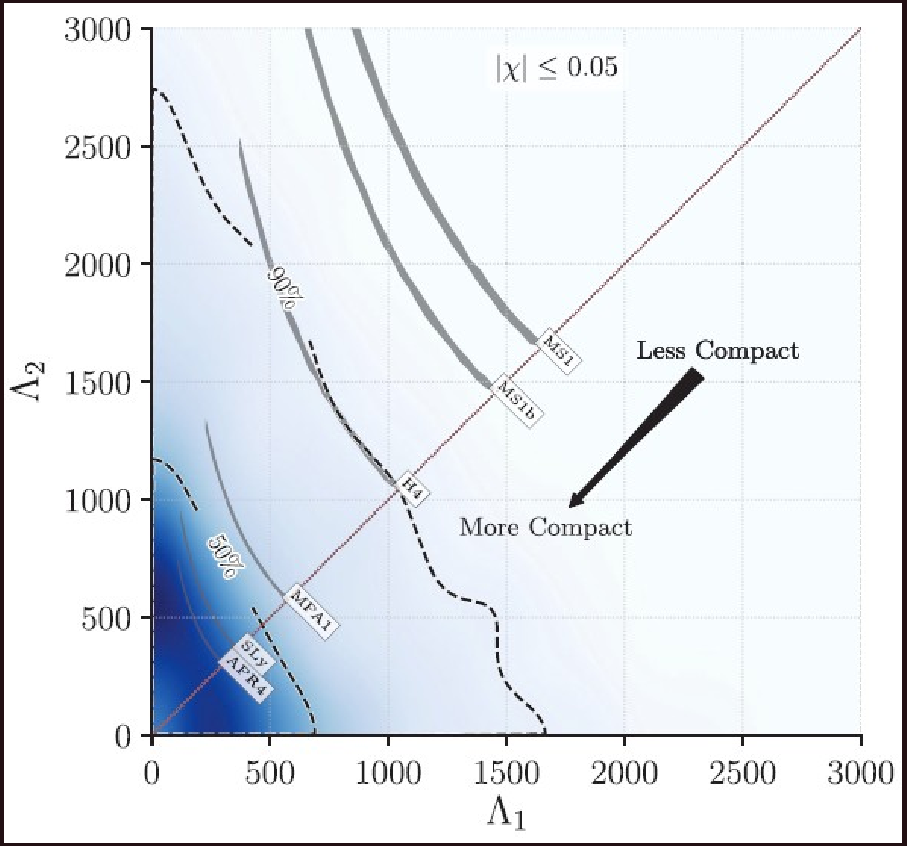
NS-NS merger !

GW170817A , announced 16.10.2017 *)

Multi-Messenger Astrophysics !!



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



Constraint on parameter (Λ<800)

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

Constraint on neutron star maximum mass

M_{TOV} < 2.17 M_sun

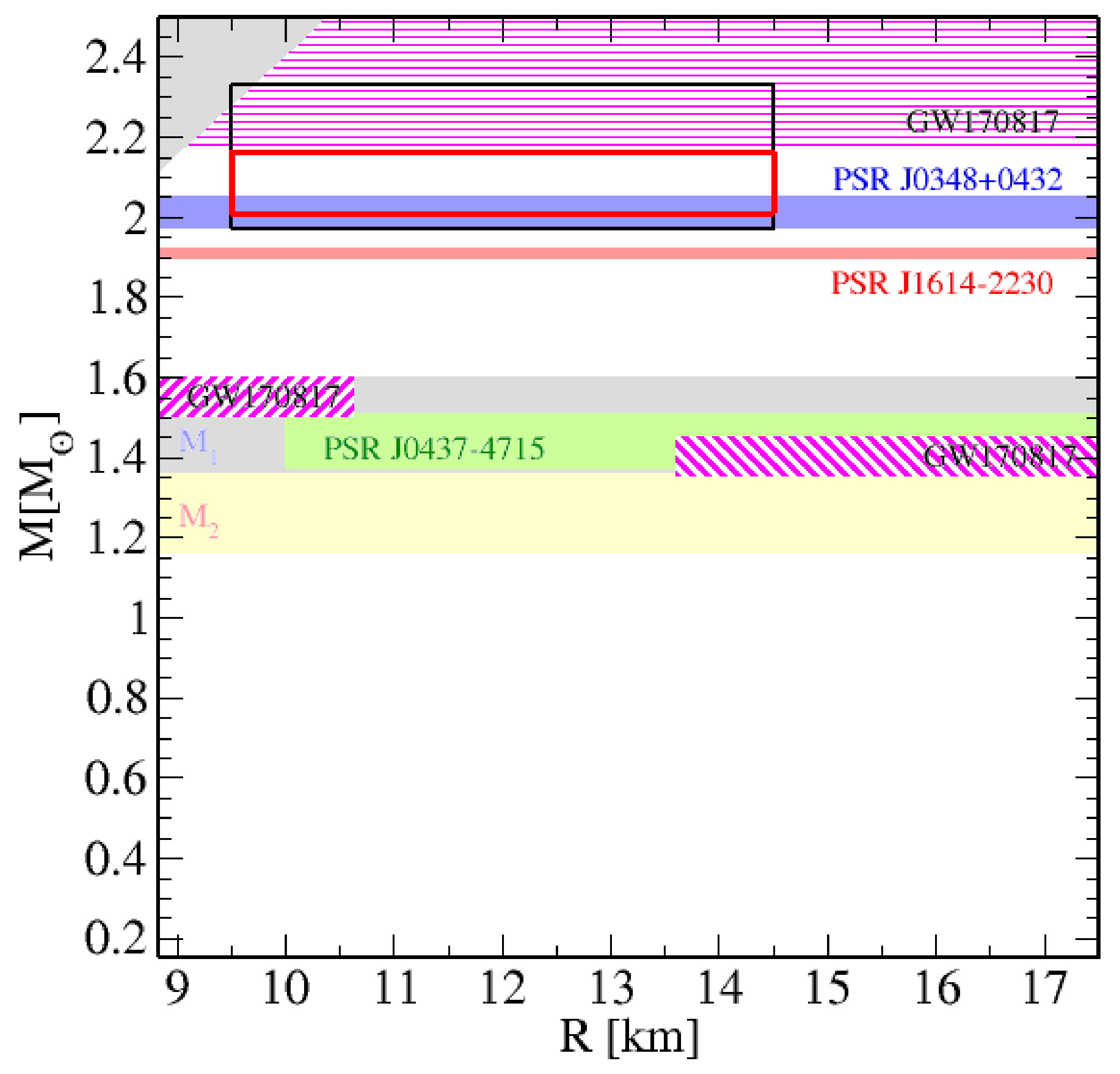
(Margalit & Metzger, arxiv:1710.05938)

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)

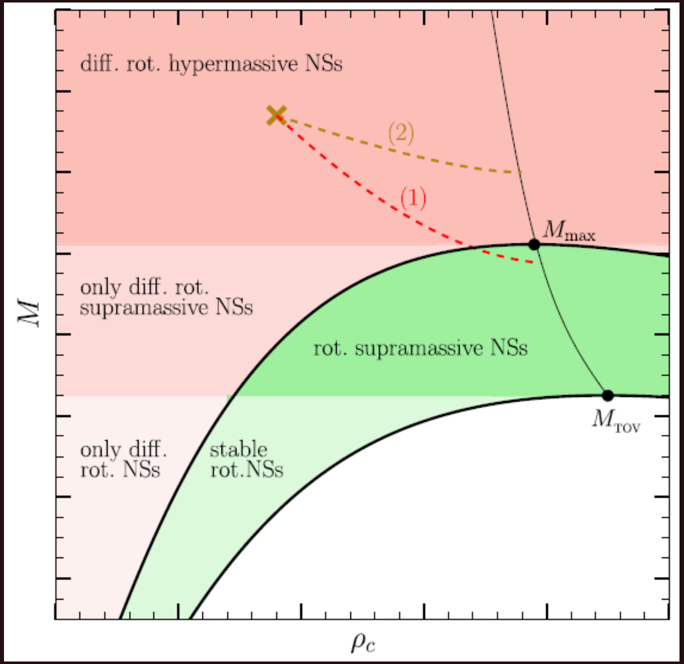
Constraints on NS mass and radii !



Constraint on maximum mass

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

(Rezzolla et al., arxiv:1710.05938)



Constraint on minimal radius

$R_{1.6} > 10.68$ km

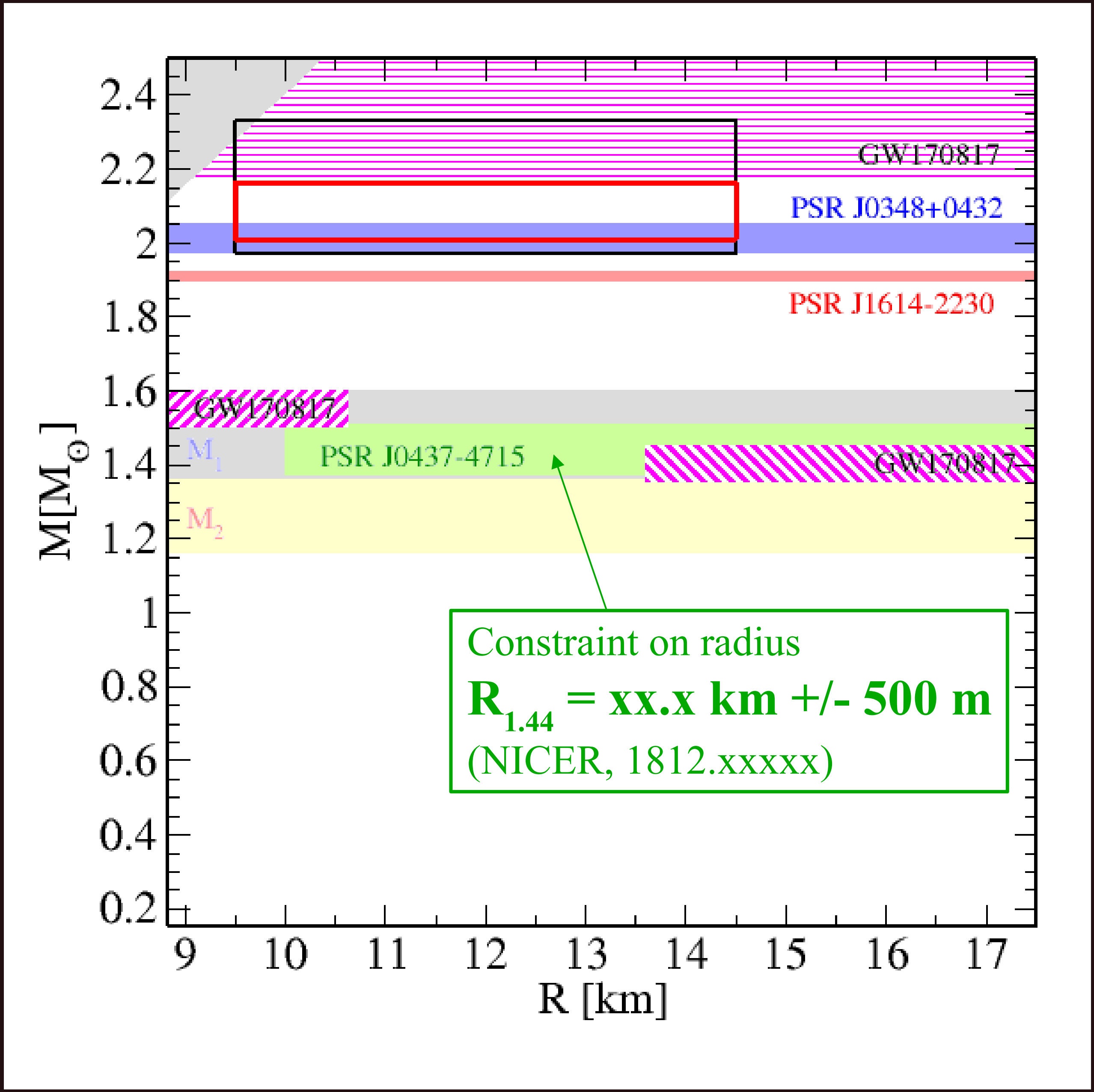
(Bauswein et al., arxiv:1710.06843)

Constraint on maximal radius

$R_{1.4} < 13.6$ km

(Annala et al., arxiv:1711.02644)

Constraints on NS mass and radii !



Constraint on radius

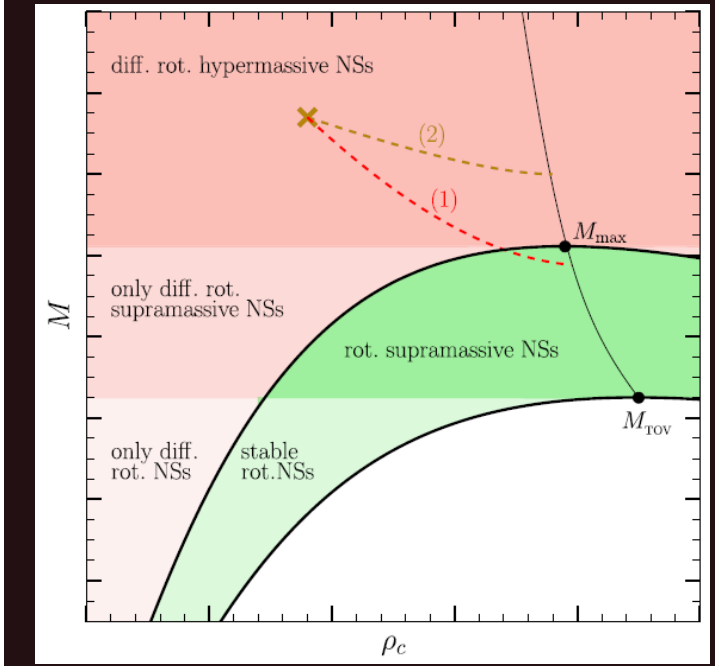
$R_{1.44}$ = xx.x km +/- 500 m

(NICER, 1812.xxxxx)

Constraint on maximum mass

$2.01 < M_{TOV}/M_o < 2.16$

(Rezzolla et al., arxiv:1710.05938)



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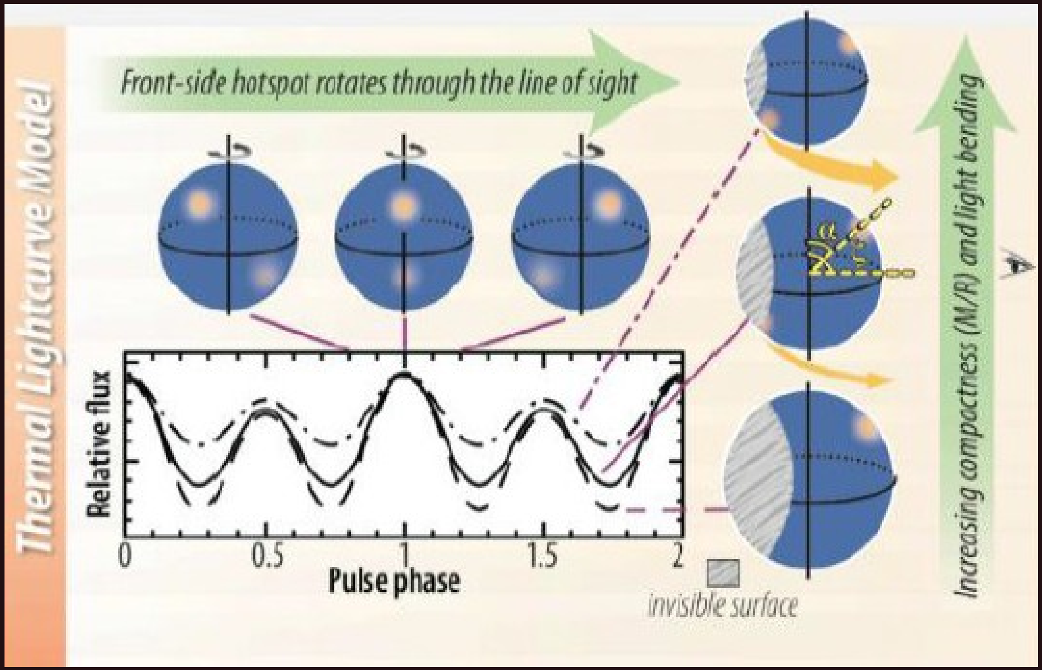
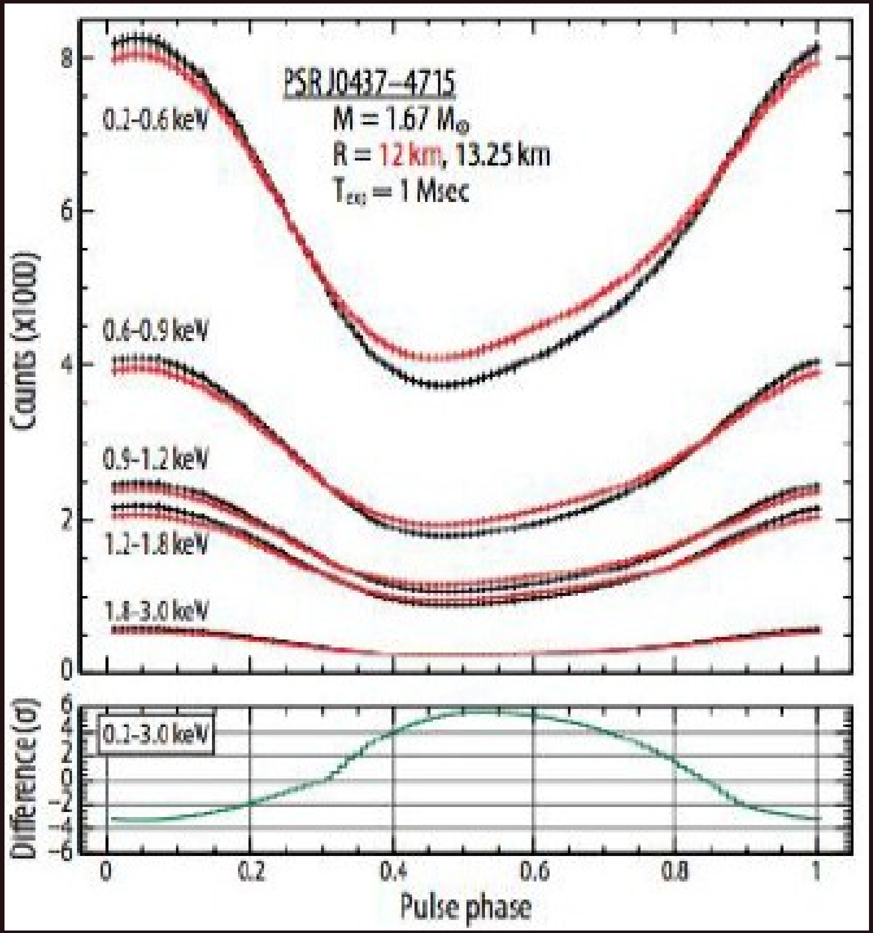
Measure NS Radii ...

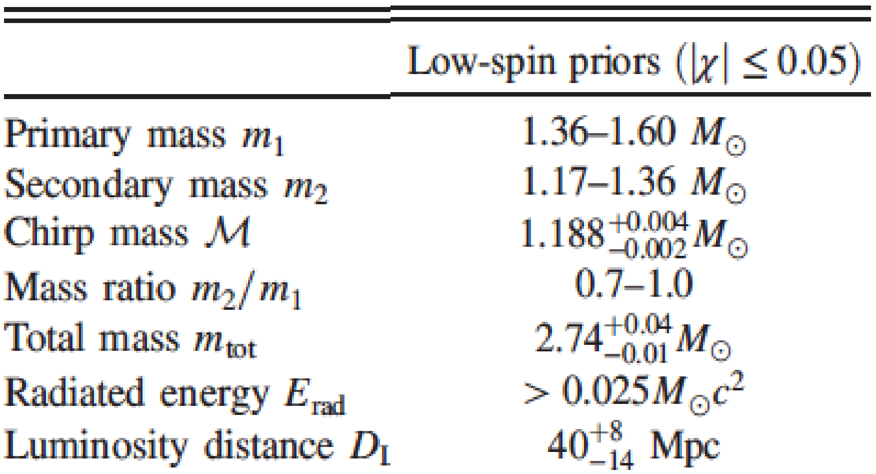


Thermal lightcurves: NS with "hot spots"



K.C. Gendreau et al., Proc. SPIE 8443 (2012) 844313 – first result end of 2018 !!

GW170817: NS-NS Merger – Equation of State Constraints



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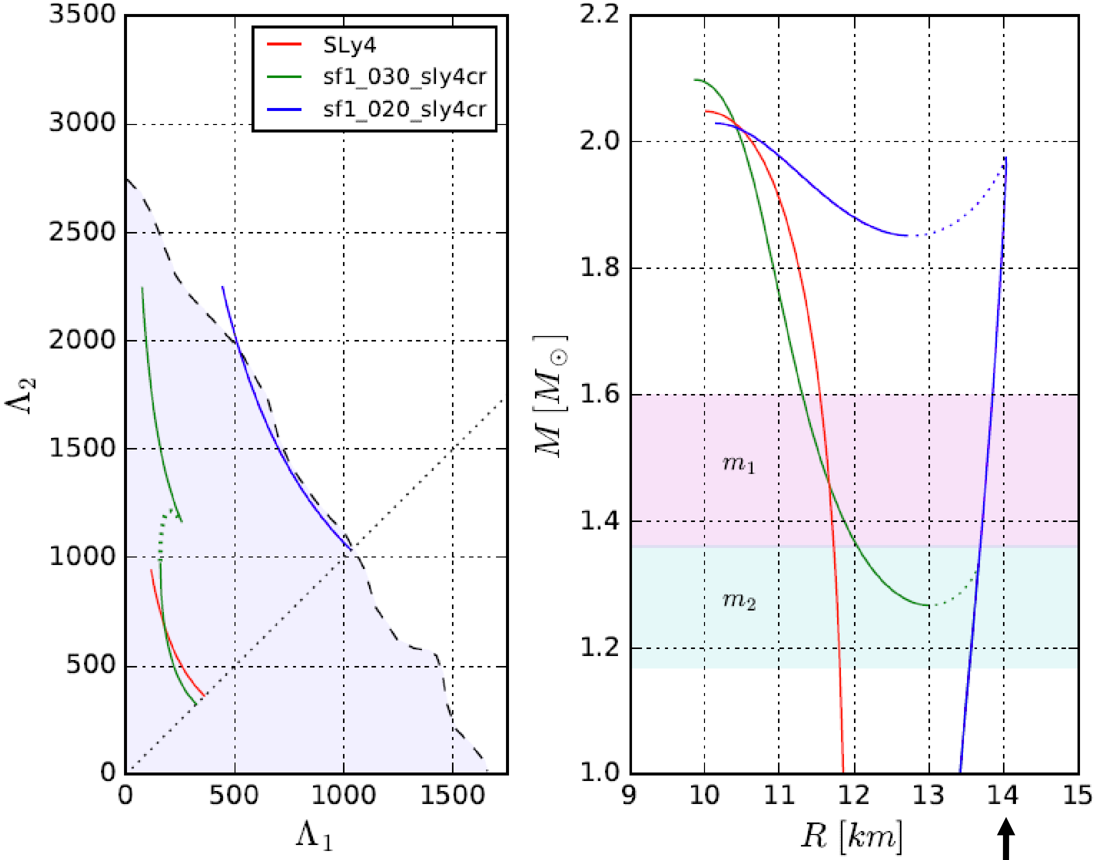
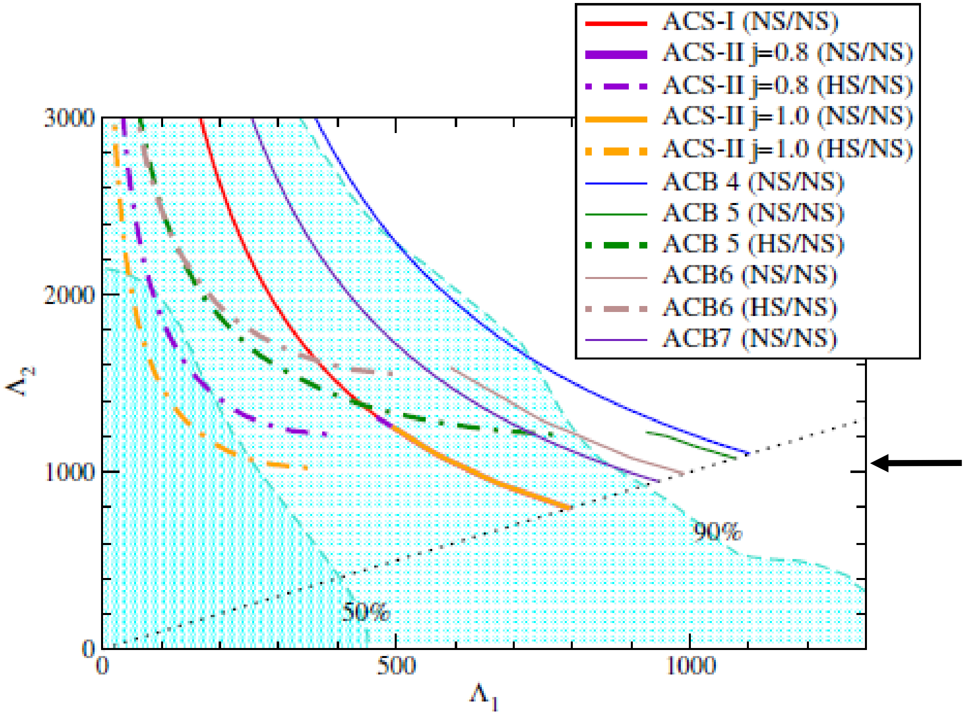


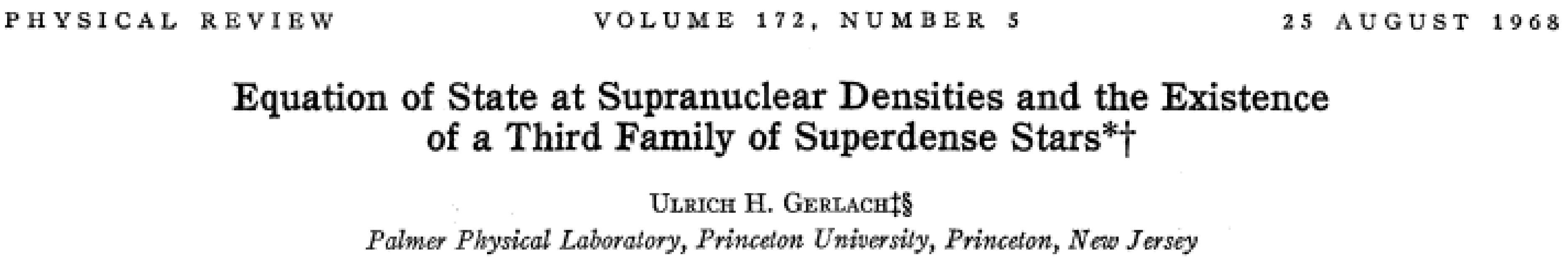
M. Bejger, D.B., et al., in preparation (2018)



V. Paschalidis, K. Yagi, D. Alvarez-Castillo, D.B., A. Sedrakian, arxiv:1712.00451
Phys. Rev. D96 (2018) to appear April 24

Suggestion: The heavier NS be a hybrid star (HS) with a quark core, evtl. member of a “third family”!

History: Third family & Nonidentical Twins



PHYSICAL REVIEW VOLUME 172, NUMBER 5 25 AUGUST 1968

Equation of State at Supranuclear Densities and the Existence of a Third Family of Superdense Stars*†

ULRICH H. GERLACH‡§
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

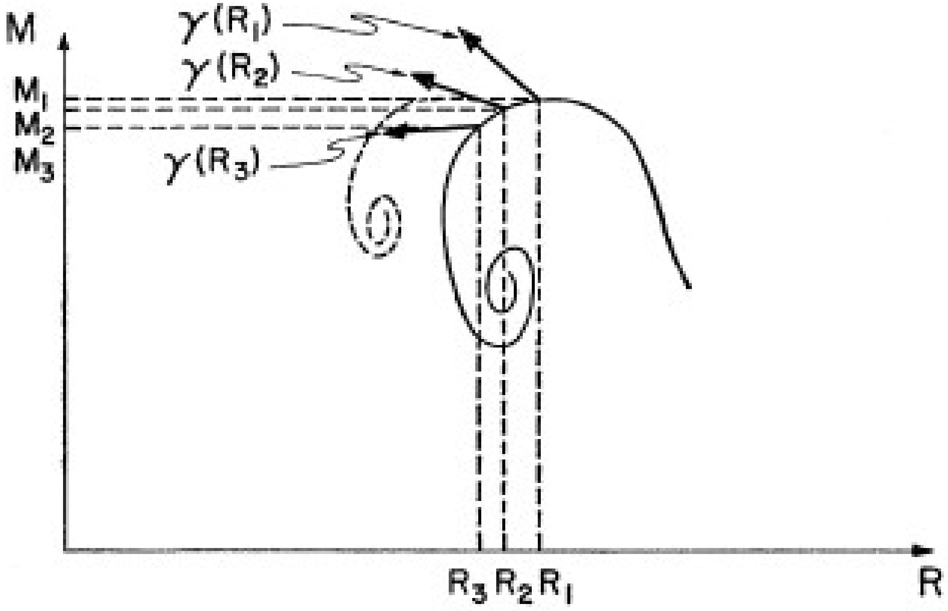
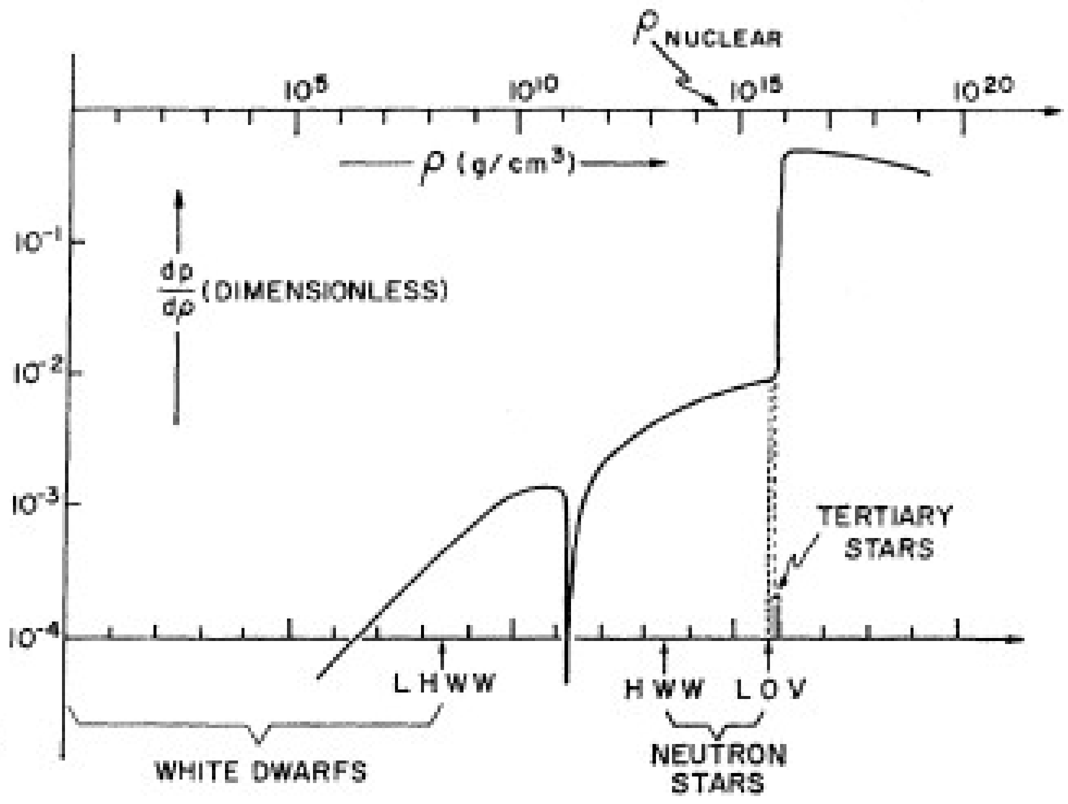
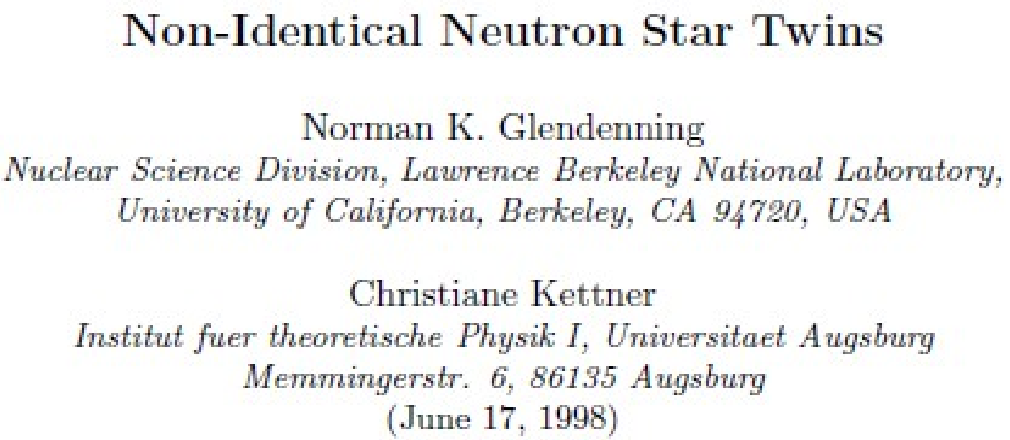


FIG. 3. A blow-up of the LOV maximum. The central densities



History: Third family & Nonidentical Twins

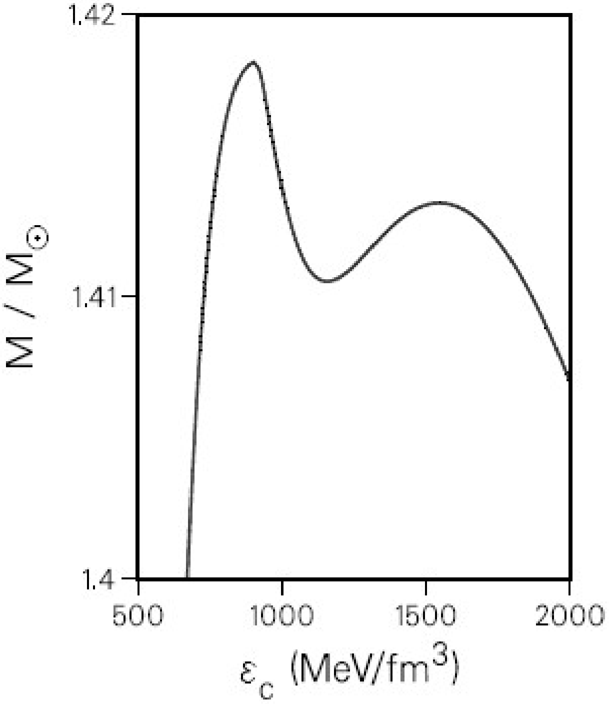


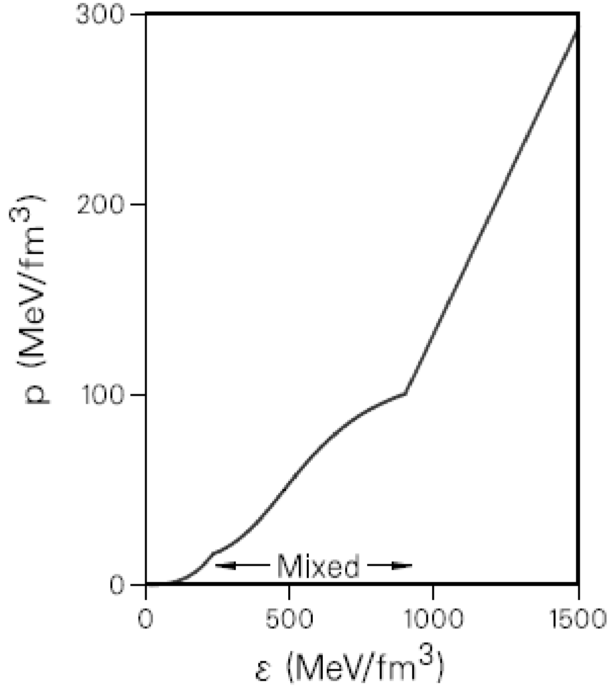
Non-Identical Neutron Star Twins

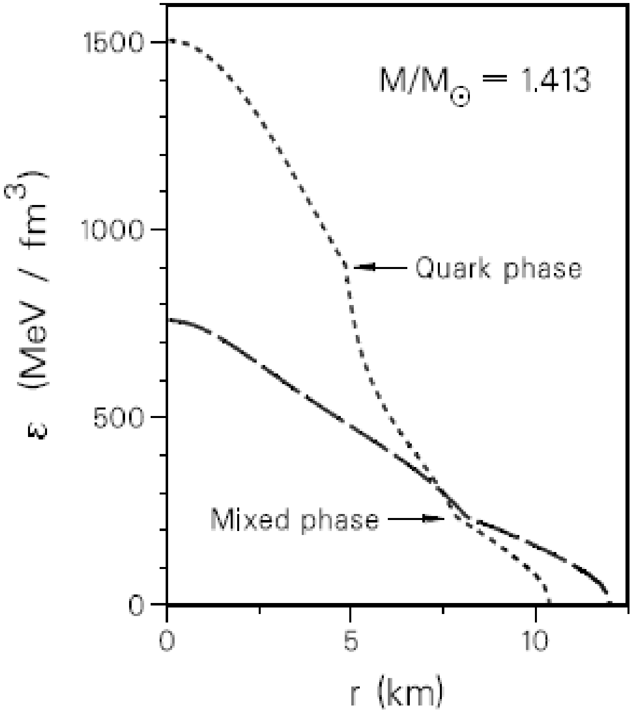
Norman K. Glendenning
Nuclear Science Division, Lawrence Berkeley National Laboratory,
University of California, Berkeley, CA 94720, USA

Christiane Kettner
Institut fuer theoretische Physik I, Universitaet Augsburg
Memmingerstr. 6, 86135 Augsburg
(June 17, 1998)

astro-ph/9807155; A&A (2000) L9

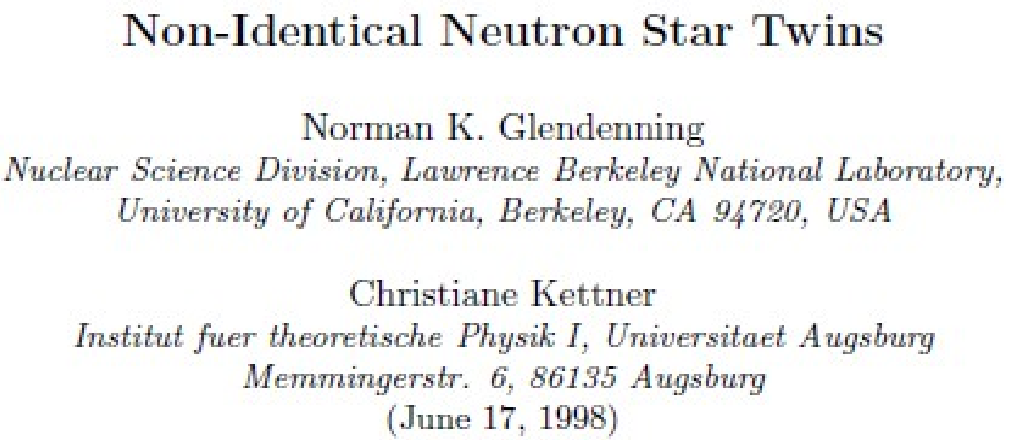






The original Twin paper uses Glendenning construction, not Maxwell one -
Surface tension zero vs. infty!
Pasta phases in-between ...

History: Third family & Nonidentical Twins



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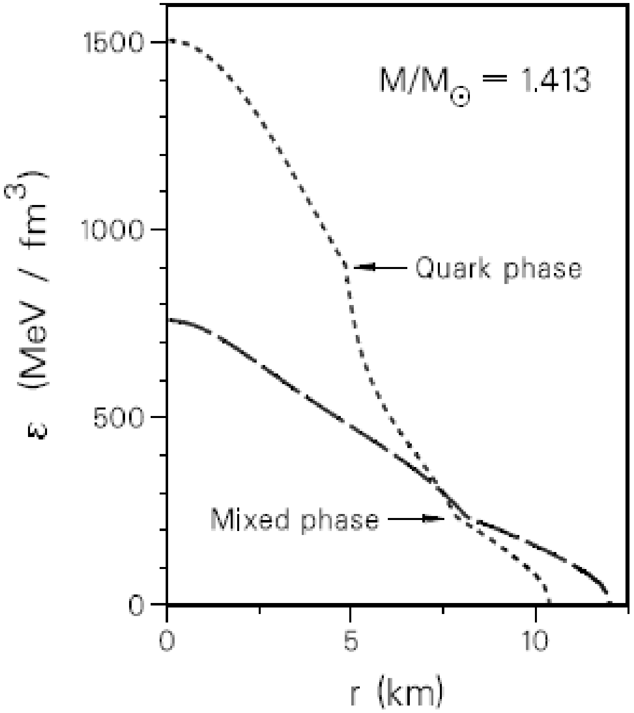
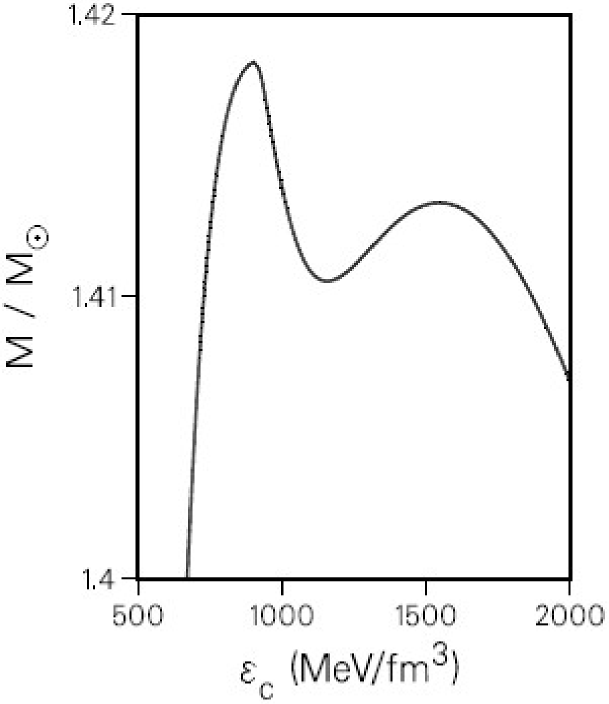
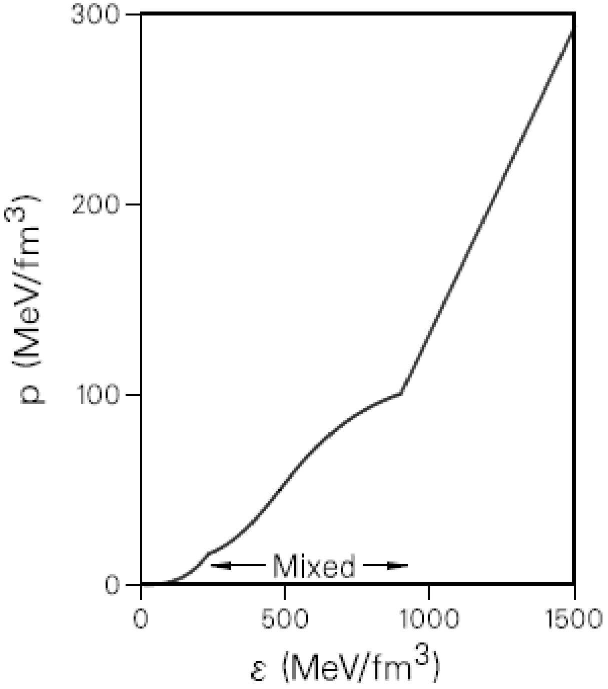


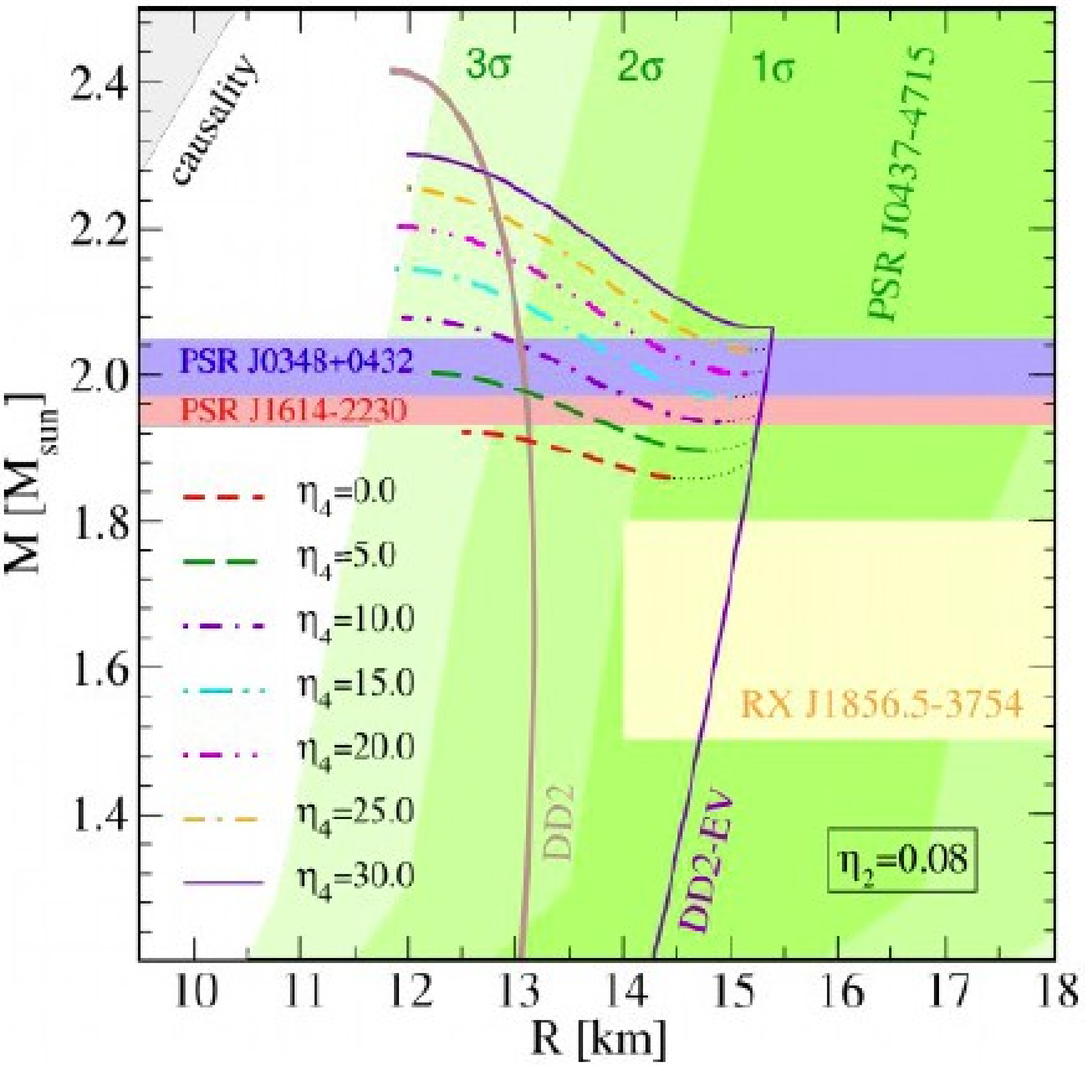




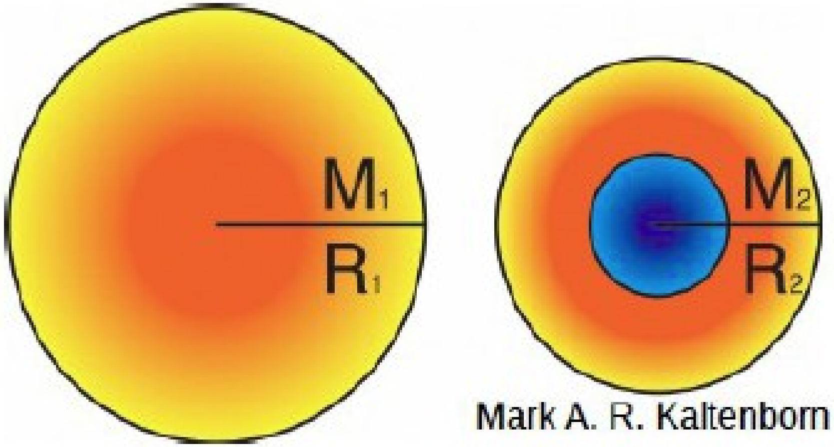
The original Twin paper uses Glendenning construction, not Maxwell one -
Surface tension zero vs. infty!
Pasta phases in-between ...

→ does not fulfill 2Msun constraint ! … Like all follow-up papers until ~2010 (B.K. Agrawal)

Neutron Star Interiors: Strong Phase Transition?



- Star configurations with same masses, but different radii



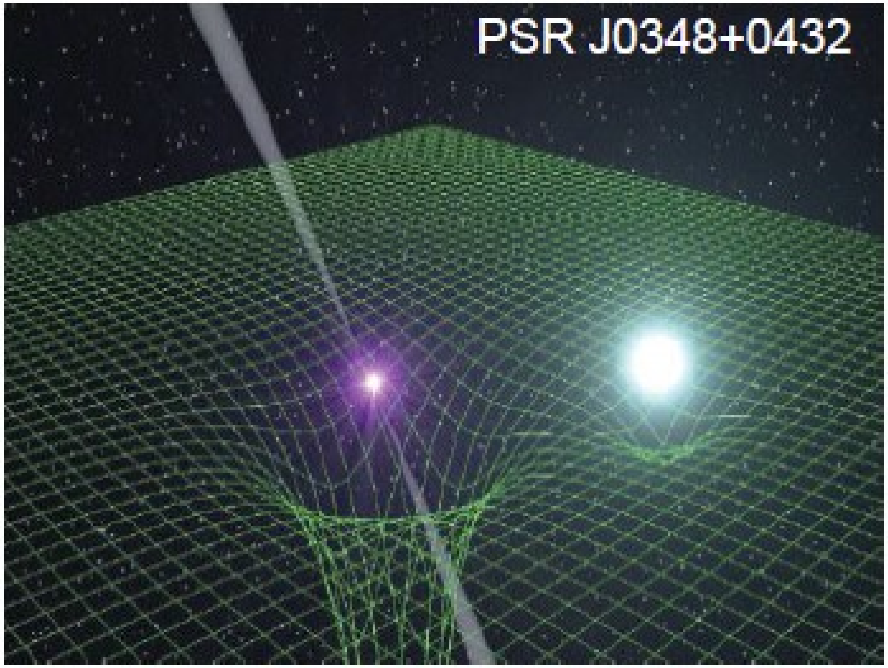
Mark A. R. Kaltenborn

- **New class of EOS, that features high mass twins**
- NASA NICER mission: radii measurements ~ 0.5 km
- Existence of twins implies 1st order phase-transition and hence a critical point

Benic, Blaschke, Alvarez-Castillo, Fischer, Typel, A&A 577, A40 (2015)

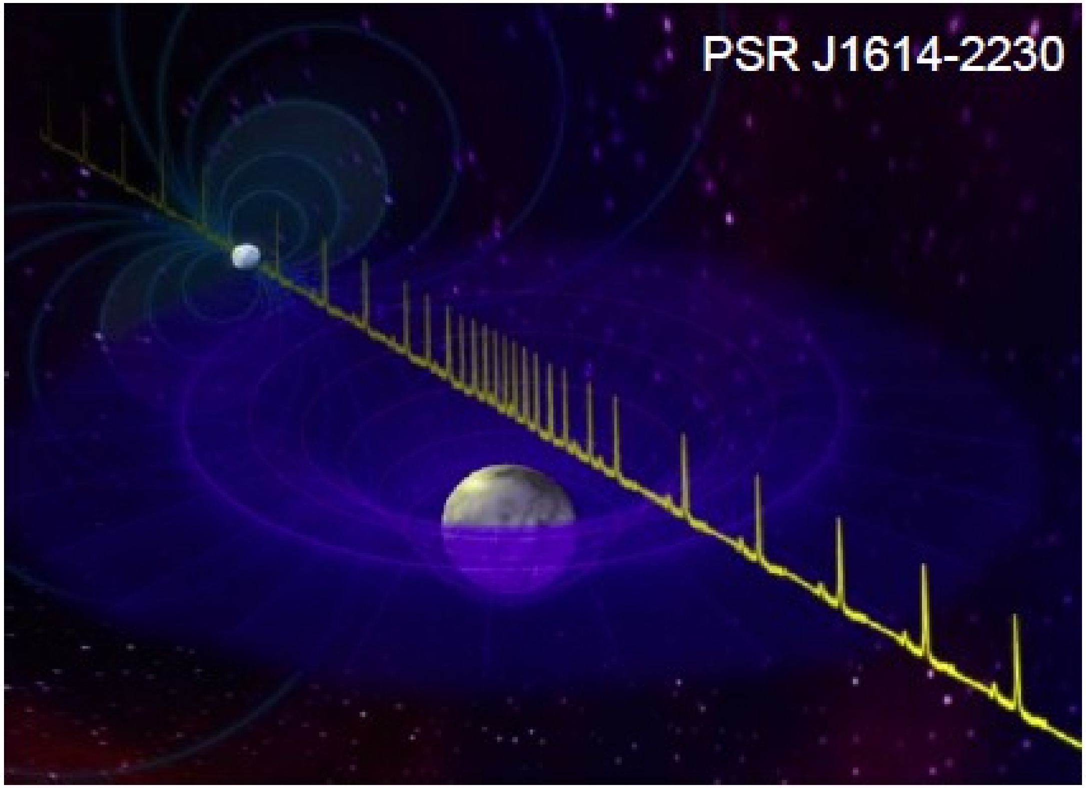
Neutron Star Interiors: Strong Phase Transition?

M=2.01 +/- 0.04 Msun



Antoniadis et al., Science 340 (2013) 448
Demorest et al., Nature 467 (2010) 1081
Fonseca et al., arxiv:1603.00545

M=1.928 +/- 0.017 Msun

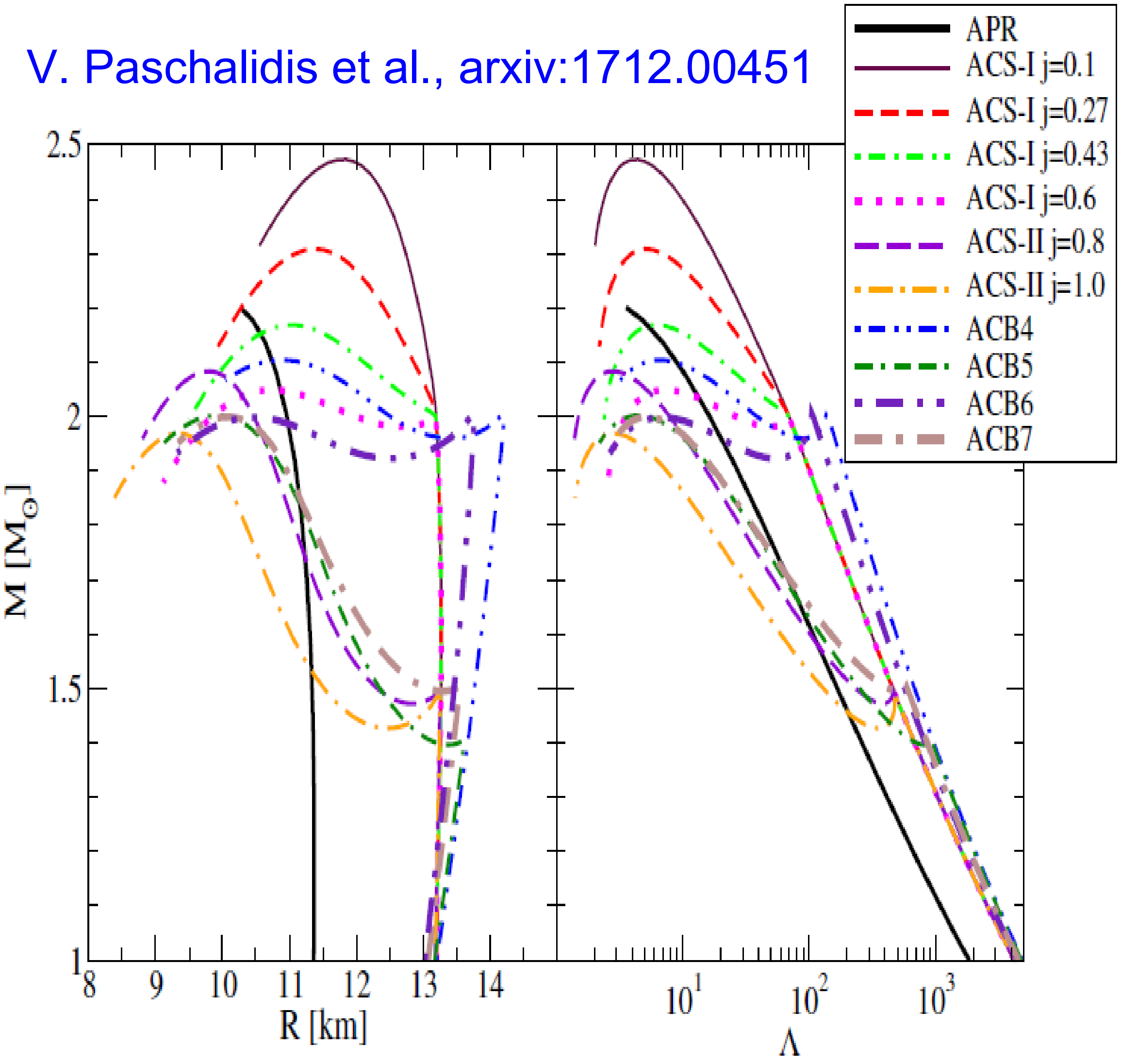


What if they were high-mass twin stars?

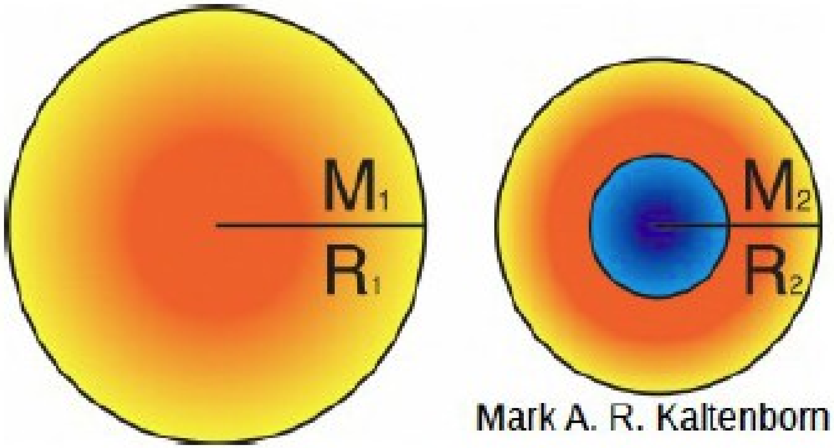
→ radius measurement required ! → NICER (2018/19)

Neutron Star Interiors: Strong Phase Transition? M-R Relation!

V. Paschalidis et al., arxiv:1712.00451



- Star configurations with same masses, but different radii



Mark A. R. Kaltenborn

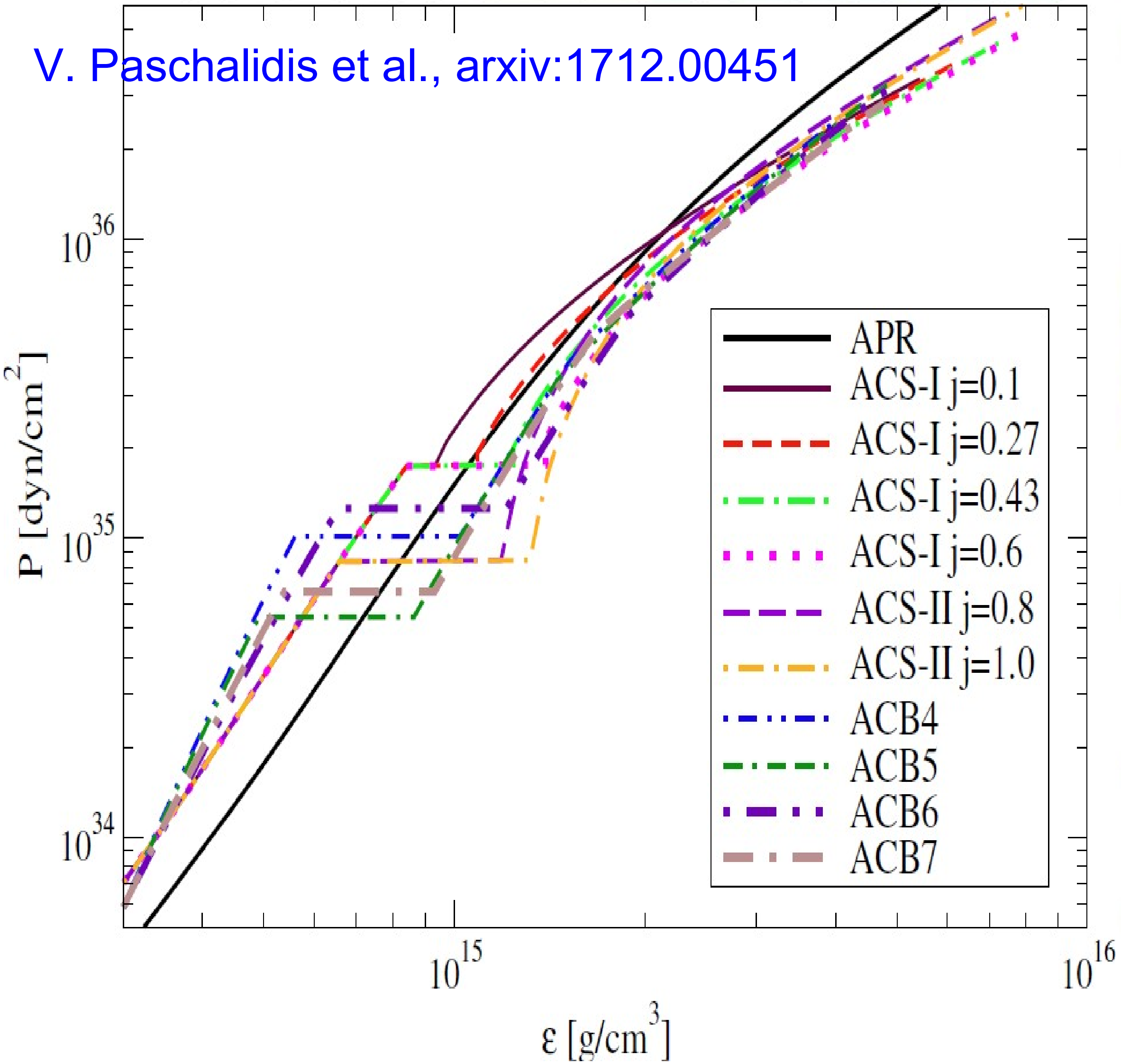
- **New class of EOS, that features high mass twins**
- NASA NICER mission: radii measurements ~ 0.5 km
- Existence of twins implies 1st order phase-transition and hence a critical point

High-mass twins (HMT) or typical-mass twins (TMT) ?

For a classification see: J.-E. Christian, A. Zacchi, J. Schaffner-Bielich, arxiv:1707.07524

Neutron Star Interiors: Strong Phase Transition? M-R Relation!

V. Paschalidis et al., arxiv:1712.00451



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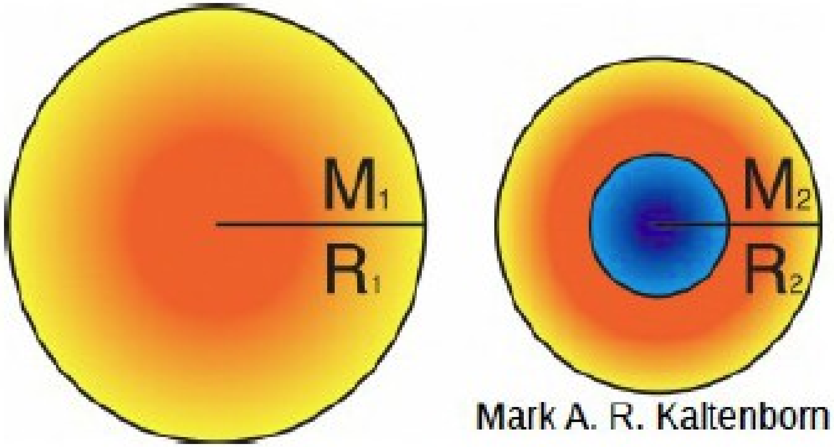

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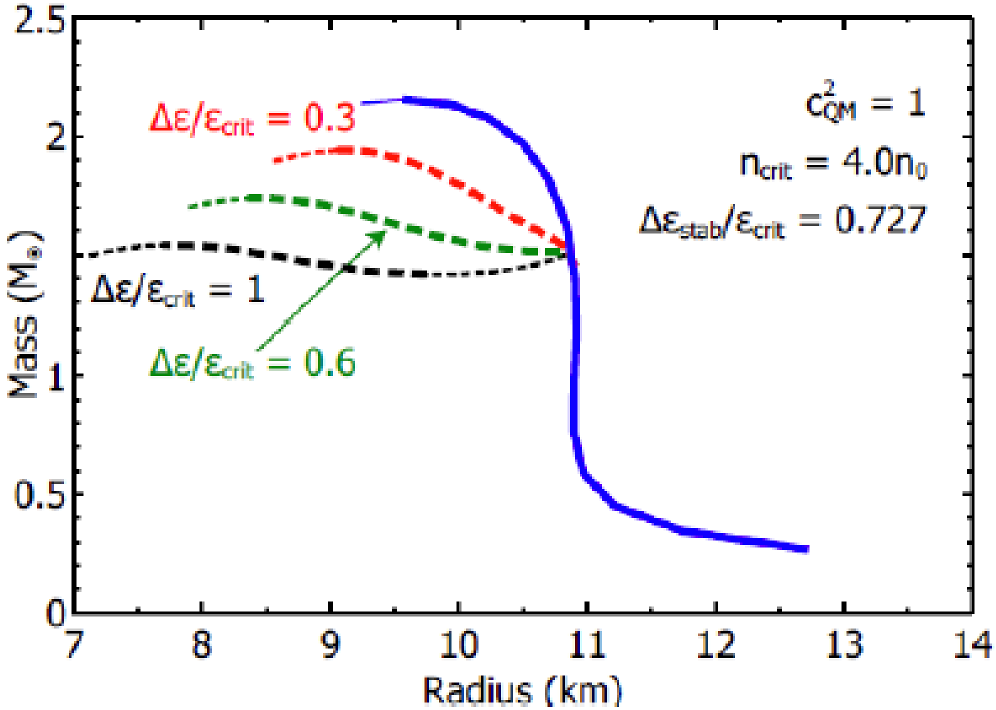
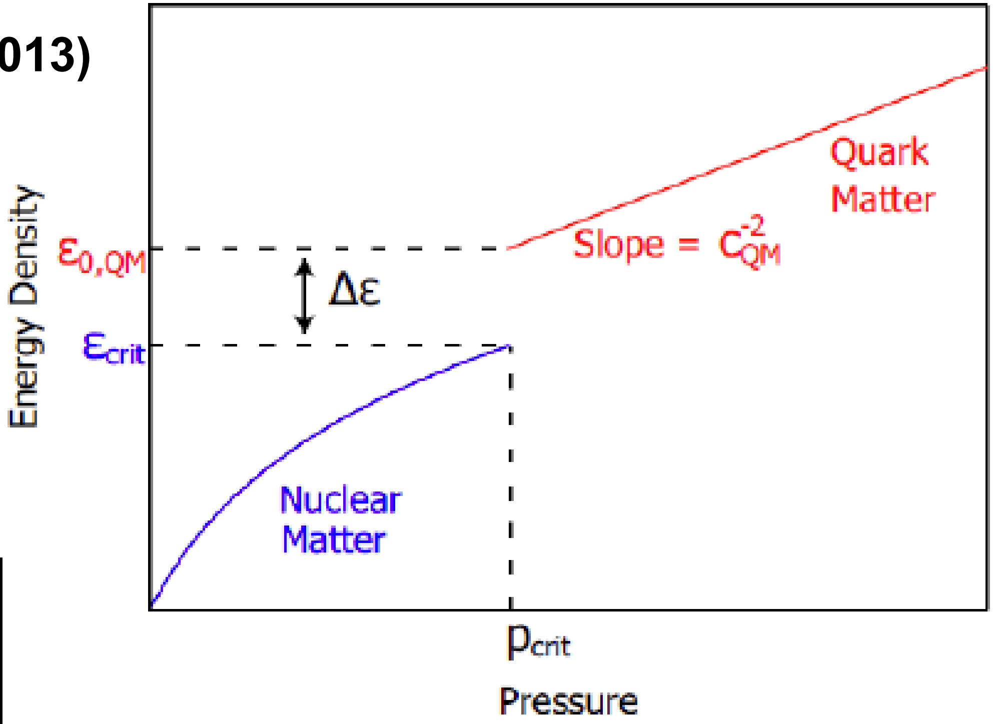
Constant Speed of Sound (CSS) Model

Alford, Han, Prakash, PRD88, 013083 (2013)

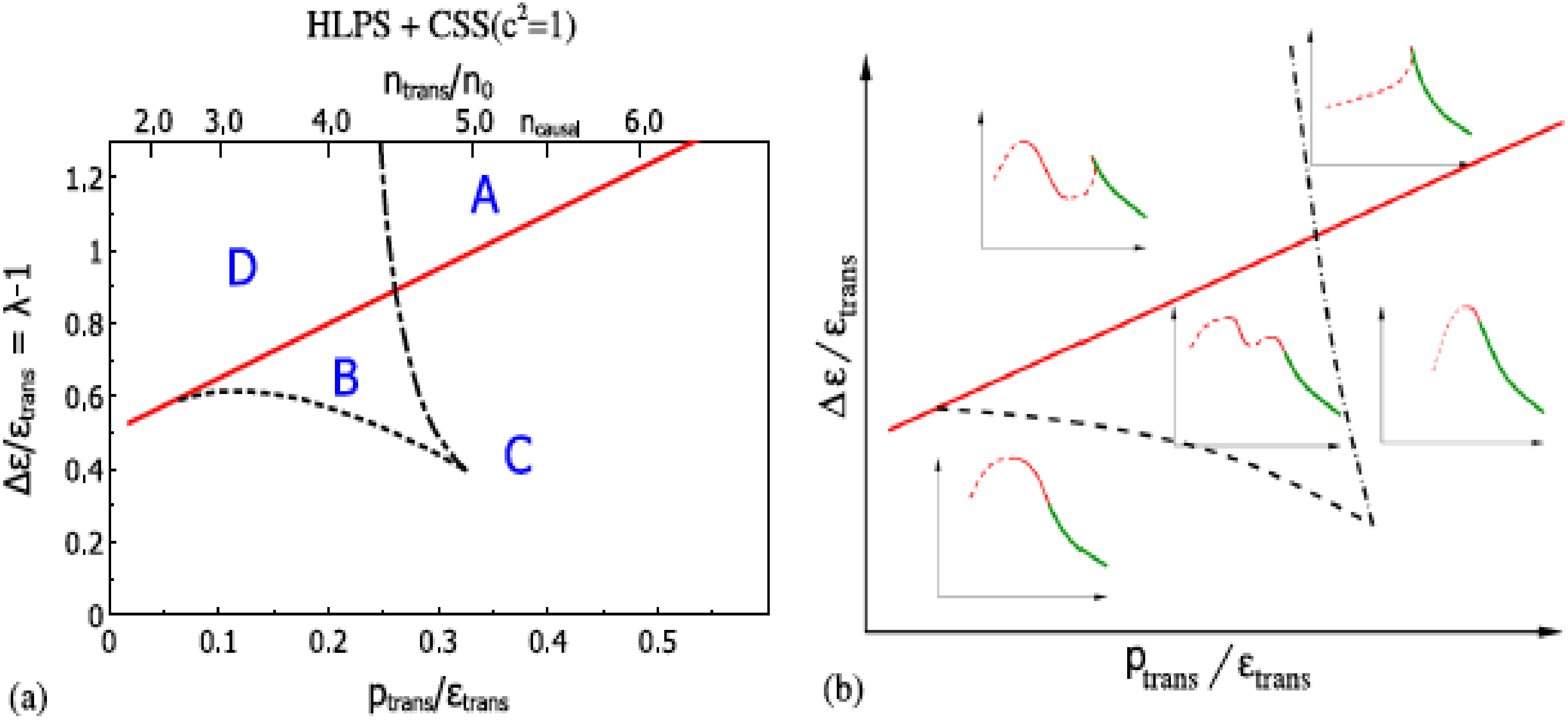
First order PT can lead to a stable branch of hybrid stars with quark matter cores which, depending on the size of the "latent heat" (jump in energy density), can even be disconnected from the hadronic one by an unstable branch → **"third family of CS"**.





Measuring two **disconnected populations** of compact stars in the M-R diagram would be the **detection of a first order phase transition** in compact star matter and thus the indirect proof for the existence of a **critical endpoint (CEP) in the QCD phase diagram**!

Key fact: Mass “twins” ↔ 1st order PT



Systematic Classification [Alford, Han, Prakash: PRD88, 083013 (2013)]

EoS P(ε) <--> Compact star phenomenology M(R)

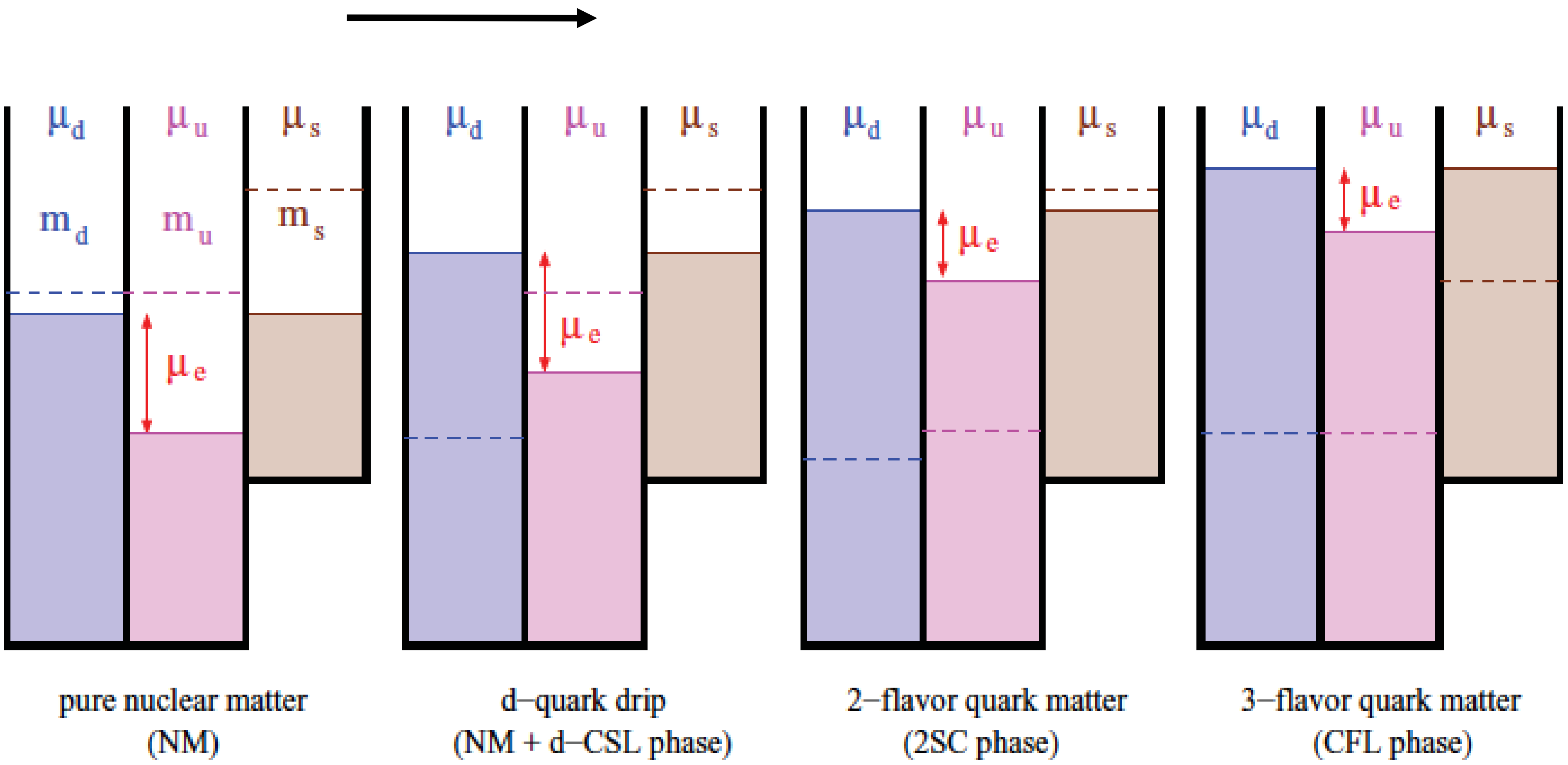
Most interesting and clear-cut cases: (D)isconnected and (B)oth – high-mass twins!

Neutron Star Interiors: Sequential Phase Transitions?

How likely is it that s-quarks (and no s-bar) exist and survive in neutron stars in a QGP or in hyperons. How large is then the ratio s/(u+d) in neutron stars and in the Universe?

There could also be single flavor quark matter, mixed with nuclear matter (d-quark dripline)

Increasing density



D.B., F. Sandin, T. Klaehn, J. Berdermann, PRC 80 (2009) 065807

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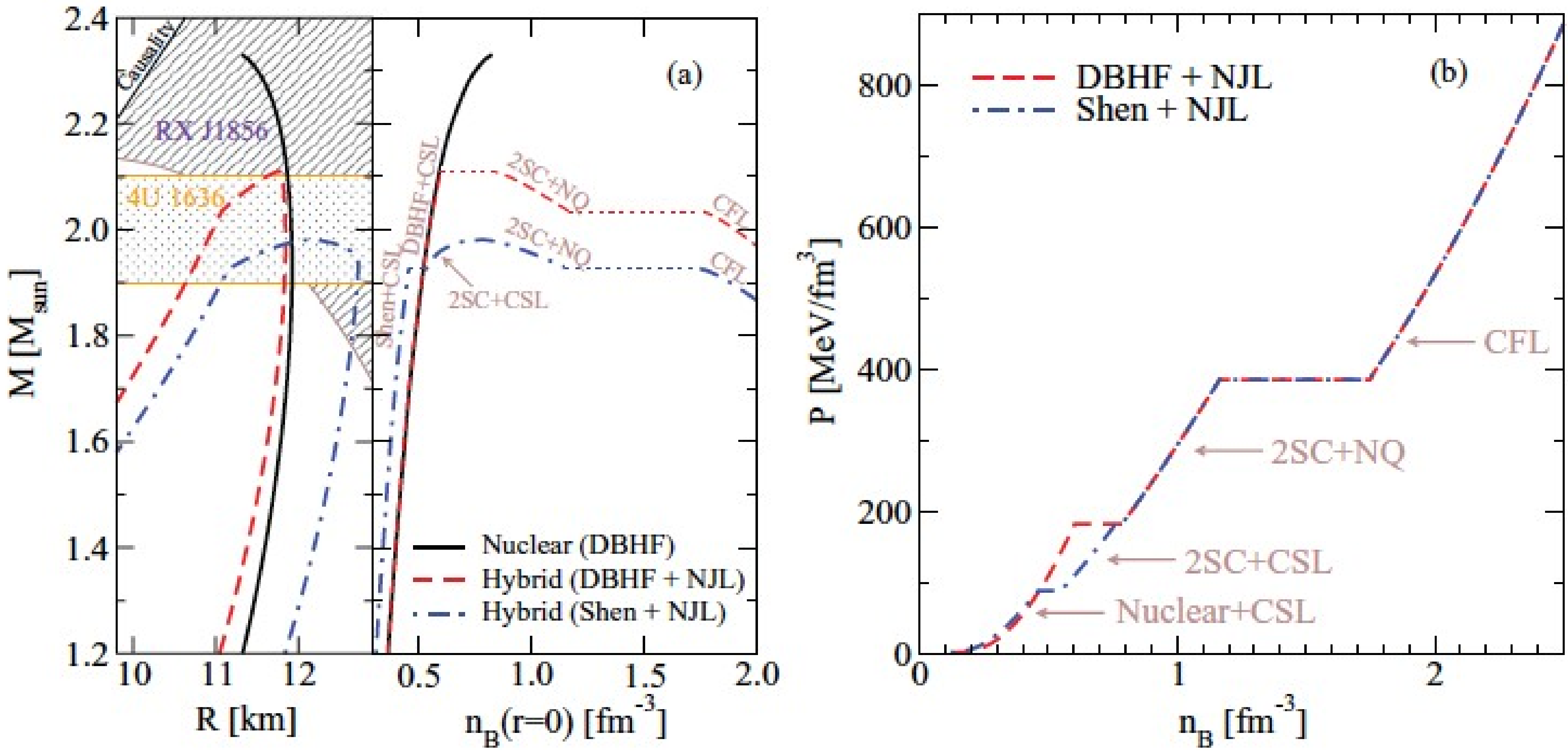
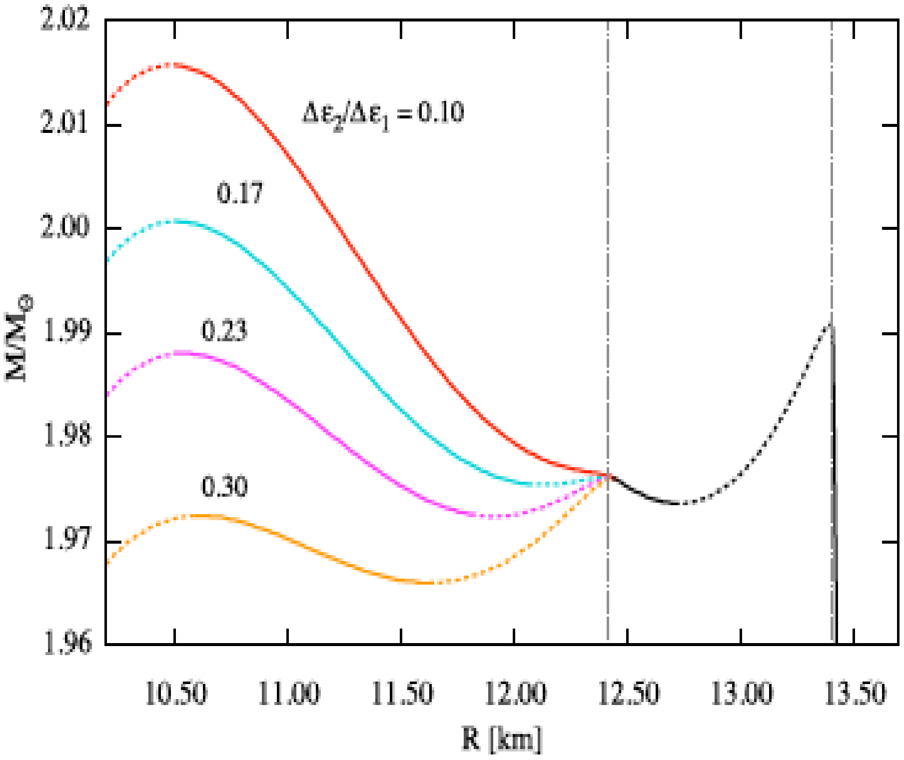
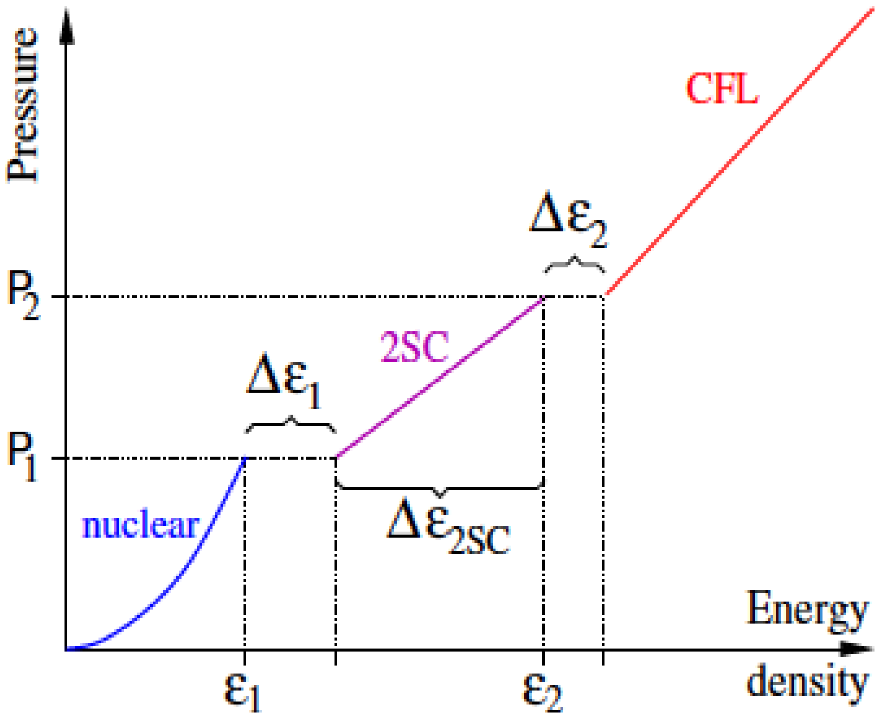


D.B., F. Sandin, T. Klaehn, J. Berdermann, PRC 80 (2009) 065807

Neutron Star Interiors: Sequential Phase Transitions?

Measuring Mass vs. Radius ↔ Equation of state



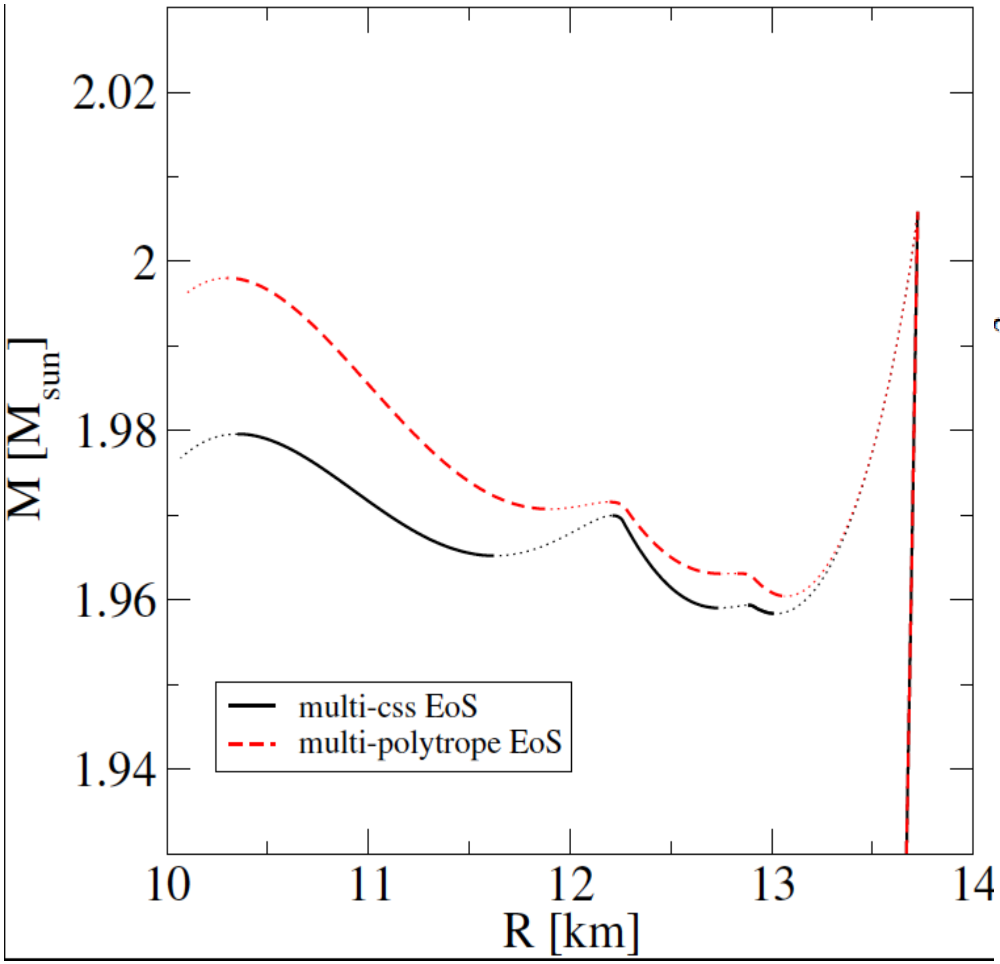


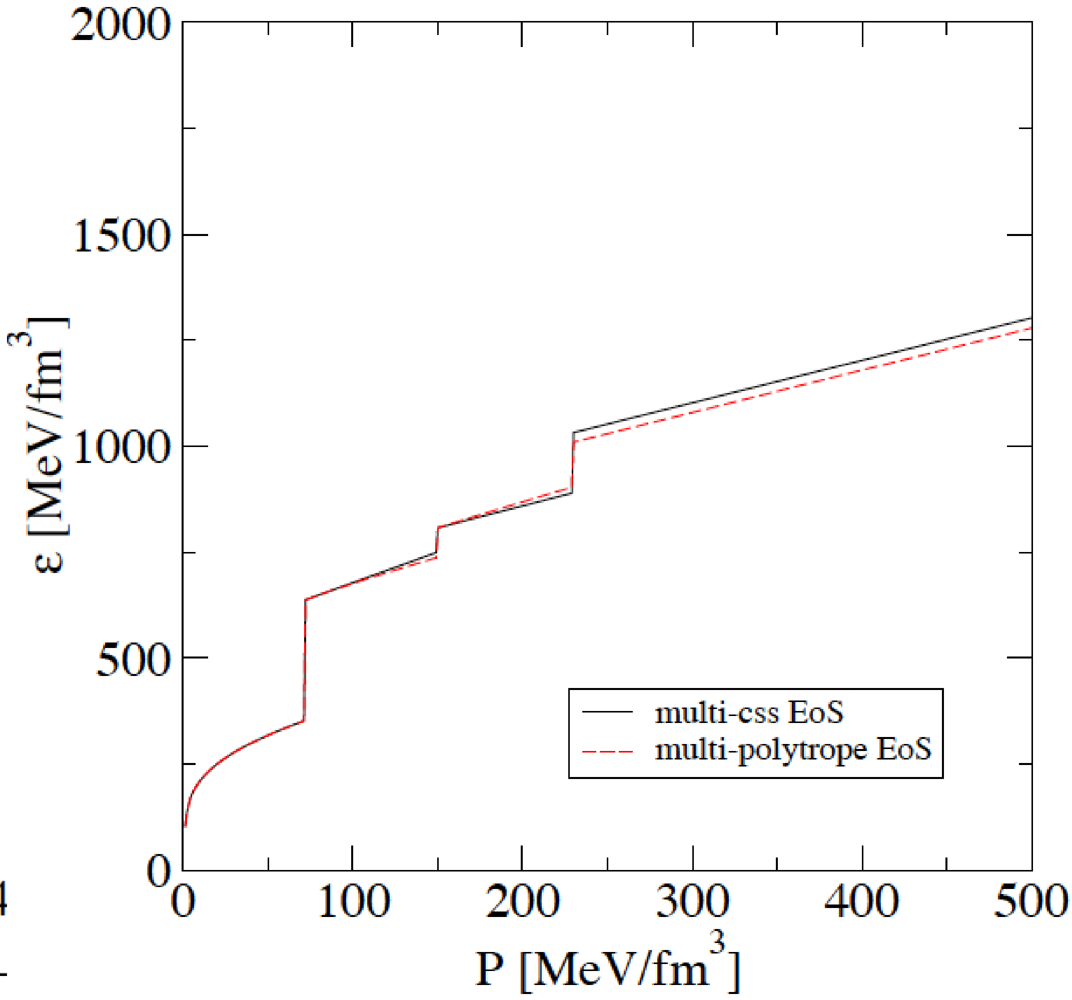
High-mass twins:
D. Blaschke et al., PoS CPOD 2013
S. Benic et al., A&A 577 (2015) A50

High-mass triples and fourth family:
M. Alford and A. Sedrakian, arxiv:1706.01592
PRL 119 (2017)

Neutron Star Interiors: Sequential Phase Transitions?

Measuring Mass vs. Radius ⟷ Equation of state





High-mass twins:
D. Blaschke et al., PoS CPOD 2013
S. Benic et al., A&A 577 (2015) A50

High-mass triples and fifth family:
A. Ayriyan, D.B., H. Grigorian, in preparation (2018)

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

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

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)

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

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

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

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

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

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

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

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

*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)

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

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

$$\begin{aligned} P_{\rm quasi} &= \frac{T}{V}\ln \mathcal{Z}_{\rm quasi} = \frac{T}{V}\mathrm{Tr}\ln[\beta G^{-1}] \\ &= 2N_c \sum_{f=u,d}\int \frac{d^3p}{(2\pi)^3}\left\{T\ln\left[1+\mathrm{e}^{-\beta(E_f^*-\mu_f^*)}\right] + T\ln\left[1+\mathrm{e}^{-\beta(E_f^*+\mu_f^*)}\right]\right\} \end{aligned}$$

“no sea” approximation ...

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

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

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

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

$$\boxed{\begin{aligned} \hat{m}^* &= \hat{m} + \Sigma_{\rm s} \\ \hat{\mu}^* &= \hat{\mu} - \Sigma_{\rm v} \end{aligned}}$$

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

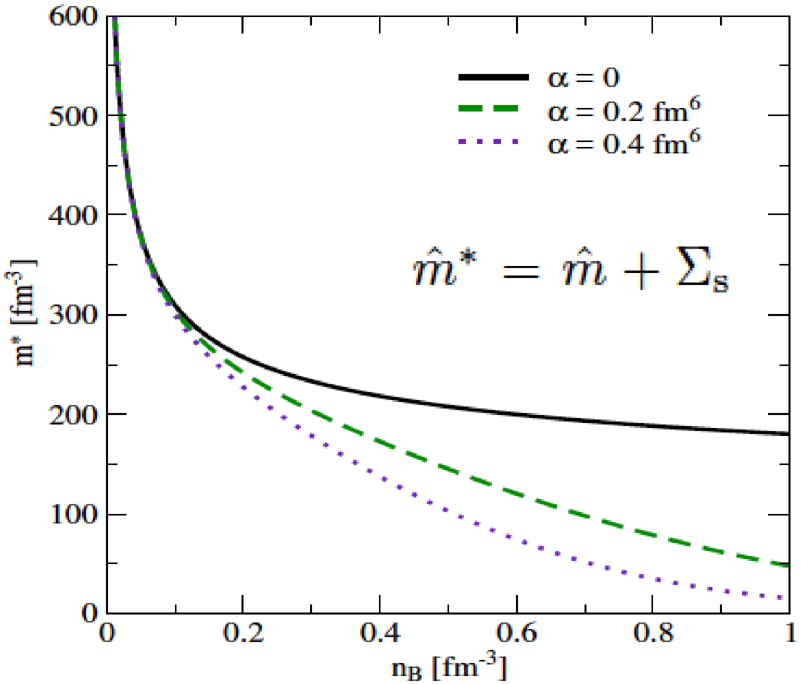
$$U(n_{\mathrm{s}},n_{\mathrm{v}}) = D(n_{\mathrm{v}})n_{\mathrm{s}}^{2/3} + an_{\mathrm{v}}^2 + \frac{bn_{\mathrm{v}}^4}{1+cn_{\mathrm{v}}^2} \ ,$$

Quark selfenergies

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

Quark "confinement"

$$\Sigma_{\mathrm{v}} = 2an_{\mathrm{v}} + \frac{4bn_{\mathrm{v}}^3}{1+cn_{\mathrm{v}}^2} - \frac{2bcn_{\mathrm{v}}^5}{(1+cn_{\mathrm{v}}^2)^2} + \frac{\partial D(n_{\mathrm{v}})}{\partial n_{\mathrm{v}}} n_s^{2/3}$$

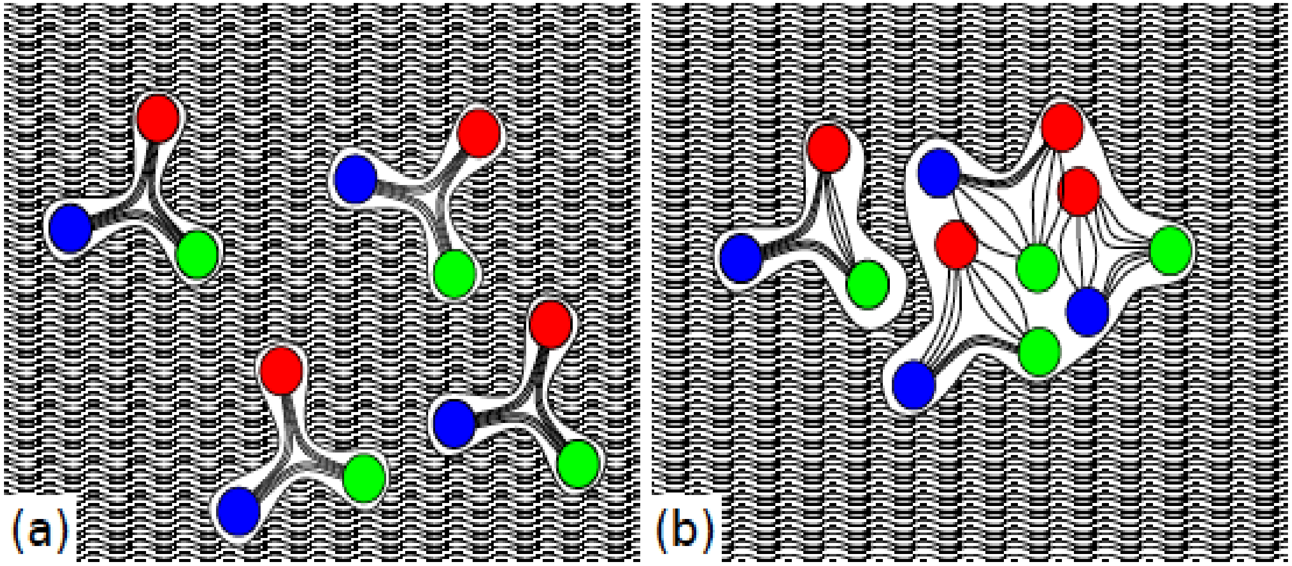


String tension & confinement due to dual Meissner effect (dual superconductor model)

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

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

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

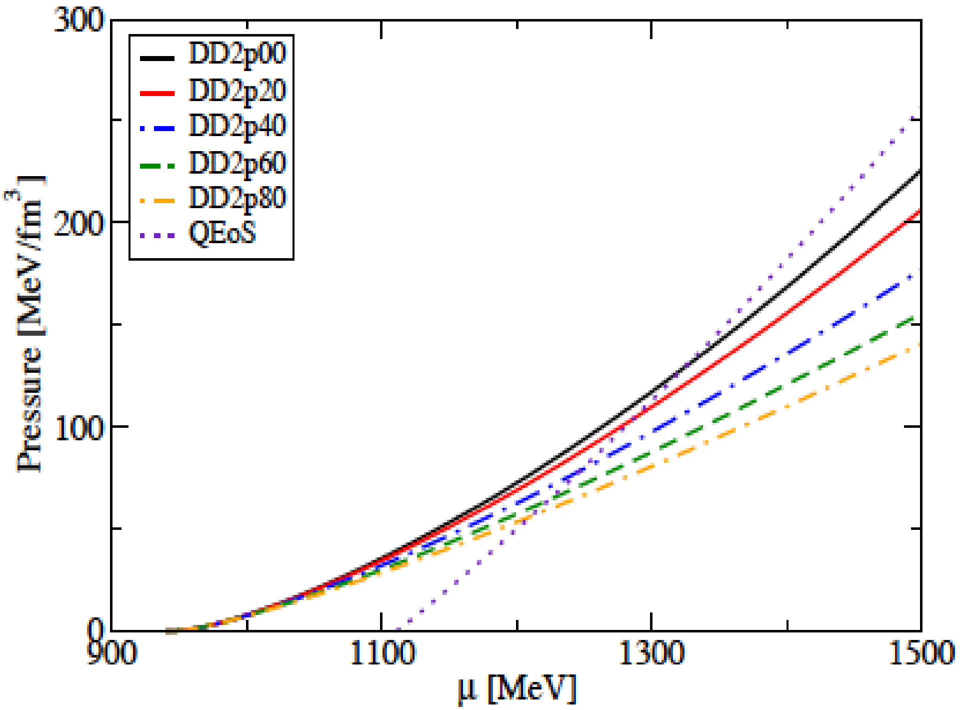


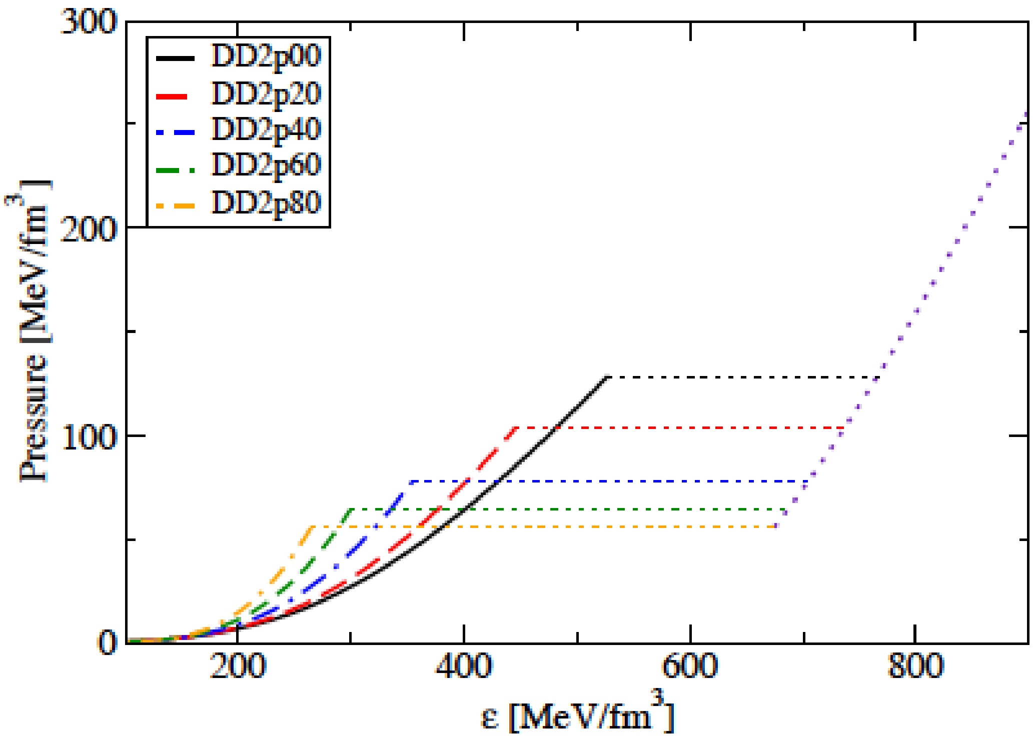
Phase transition from hadronic to SFM quark matter

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

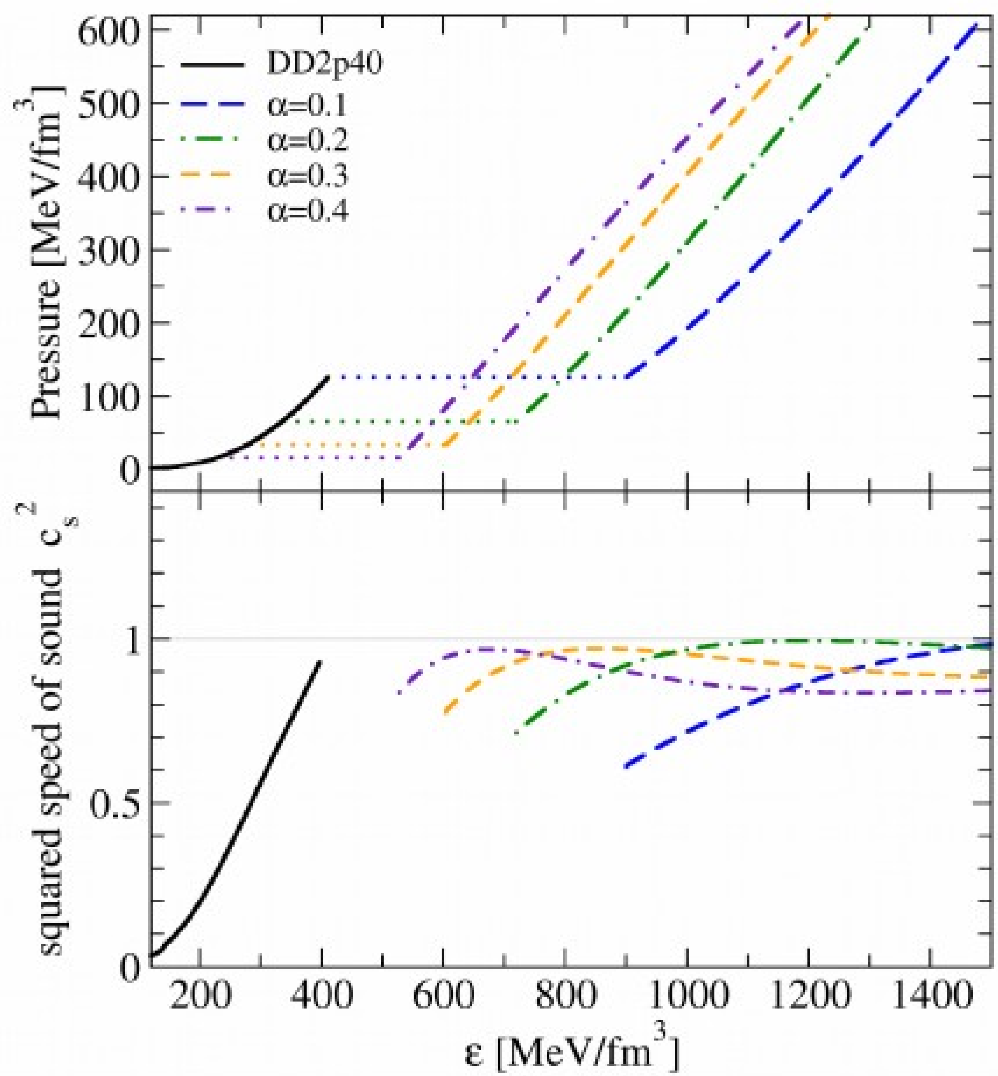
$$\Phi_n = \Phi_p = \begin{cases} 1, & \text{if } n_B < n_0 \\ e^{-\frac{v|v|}{2}(n_B - n_0)^2}, & \text{if } n_B > n_0 \end{cases}$$

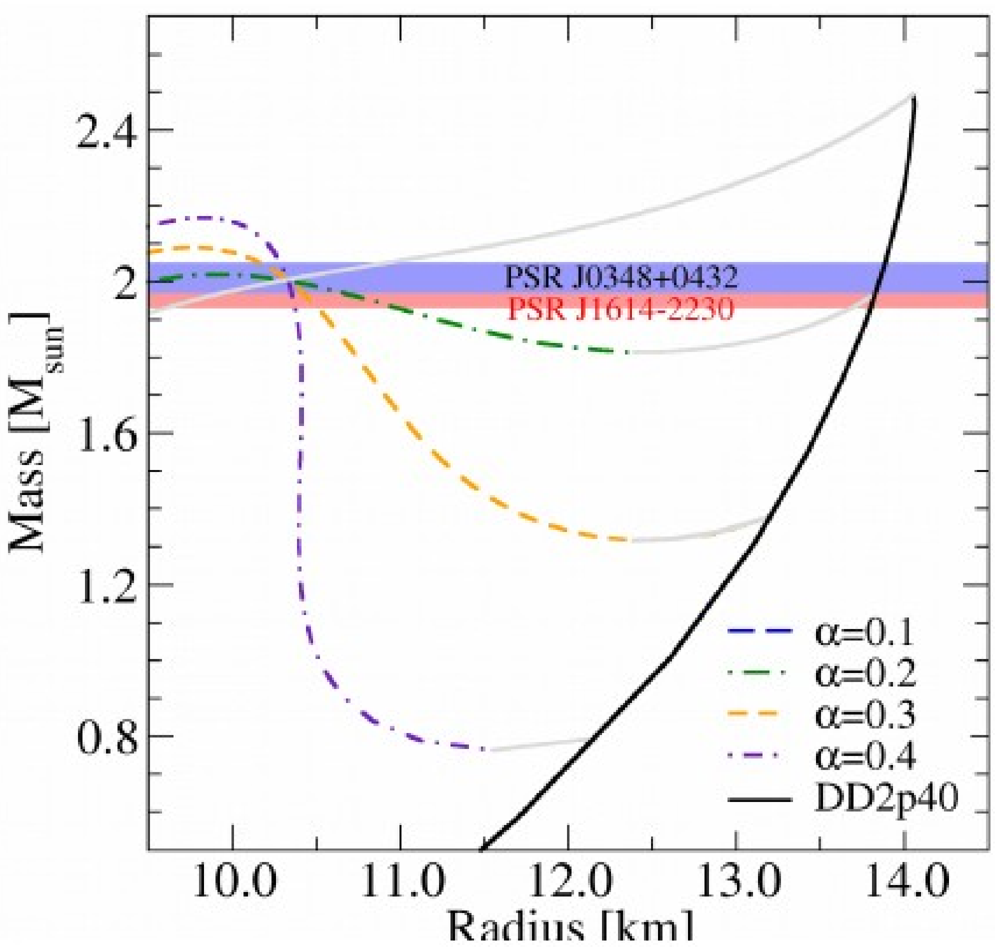
Varying the hadronic excluded volume parameter, p00 → v=0, … , p80 → v=8 fm^3





Hybrid EoS: high-mass and low-mass twins (3rd family) !





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

Results of Maxwell construction! Could pasta phases remove the twins (3rd family instability)?

Pasta phases – robustness of 3rd family?

Tatsumi-san,
Voskresensky-san,
Nara (2000)

A. Ayriyan, N.-U.Bastian, D.B., H. Grigorian, K. Maslov, D. Voskresensky;
Phys. Rev. C97, 045802 (2018); [arxiv:1711.03926]

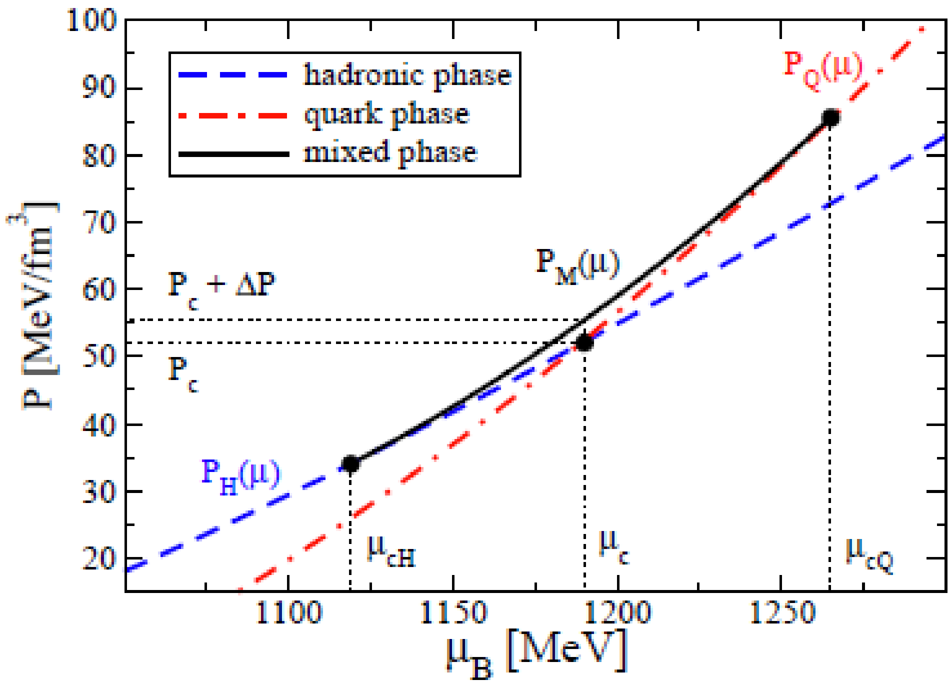
K. Maslov, N. Yasutake, A. Ayriyan, D.B., H. Grigorian, T. Maruyama, T. Tatsumi,
D. Voskresensky; Phys. Rev. C, in press (2019); [arxiv:1812.11889]

Robustness of Twins against Pasta Phase Effects

PHYSICAL REVIEW C **97**, 045802 (2018)

Robustness of third family solutions for hybrid stars against mixed phase effects

A. Ayriyan,[1,*] N.-U. Bastian,[2,†] D. Blaschke,[2,3,4,‡] H. Grigorian,[1,§] K. Maslov,[3,4,‖] and D. N. Voskresensky[3,4,¶]
[1]*Laboratory for Information Technologies, Joint Institute for Nuclear Research, Joliot-Curie Street 6, 141980 Dubna, Russia*
[2]*Institute of Theoretical Physics, University of Wroclaw, Max Born Place 9, 50-204 Wroclaw, Poland*
[3]*Bogoliubov Laboratory for Theoretical Physics, Joint Institute for Nuclear Research, Joliot-Curie Street 6, 141980 Dubna, Russia*
[4]*National Research Nuclear University (MEPhI), Kashirskoe Shosse 31, 115409 Moscow, Russia*



Strong 1st order transition (large density jump)
→ surface tension large → structures (pasta phases)

Simple interpolation ansatz (Ayriyan et al.(2017)):

$$\boxed{P_M(\mu) = a(\mu - \mu_c)^2 + b(\mu - \mu_c) + P_c + \Delta P.}$$

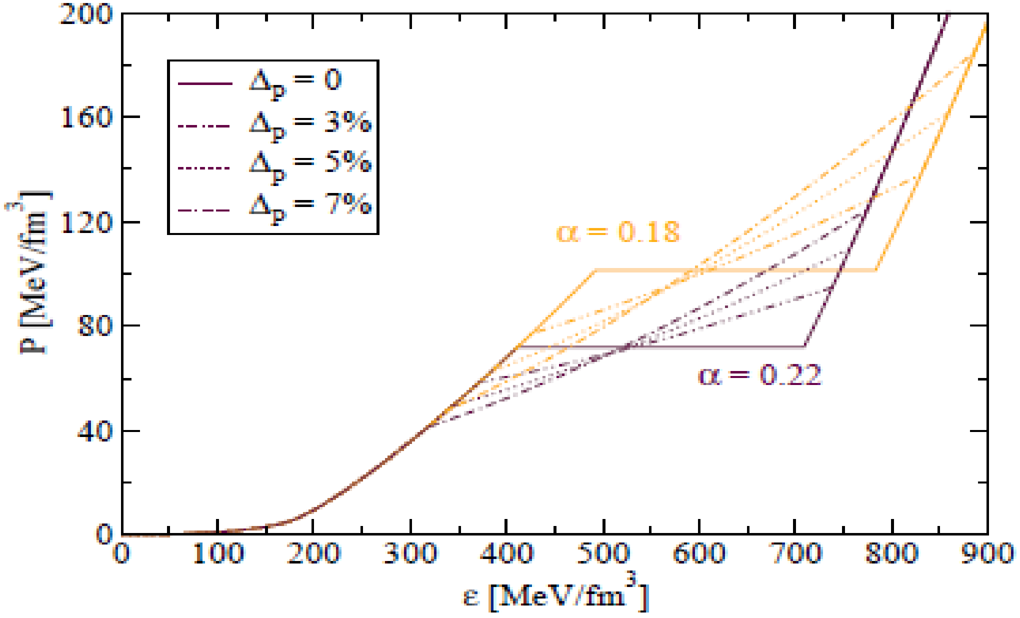
Continuity of pressure: $P_M(\mu_{cH}) = P_H(\mu_{cH}) = P_H$

$$P_M(\mu_{cQ}) = P_Q(\mu_{cQ}) = P_Q,$$

and density: $n_M(\mu_{cH}) = n_H(\mu_{cH})$

$$n_M(\mu_{cQ}) = n_Q(\mu_{cQ})$$

Robustness of Twins against Pasta Phase Effects

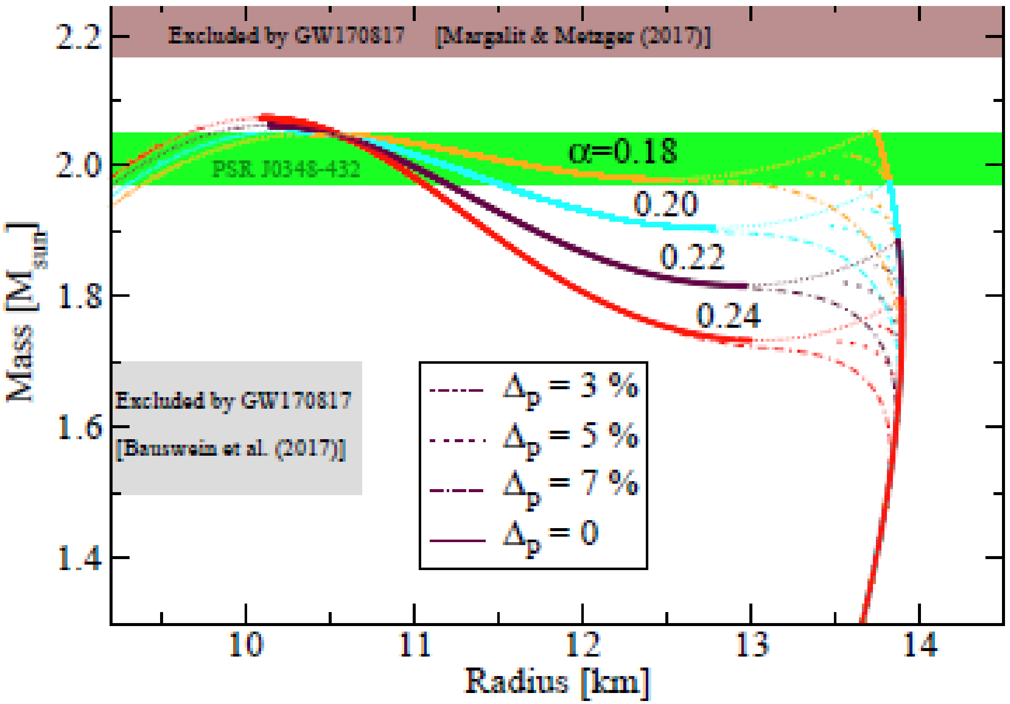


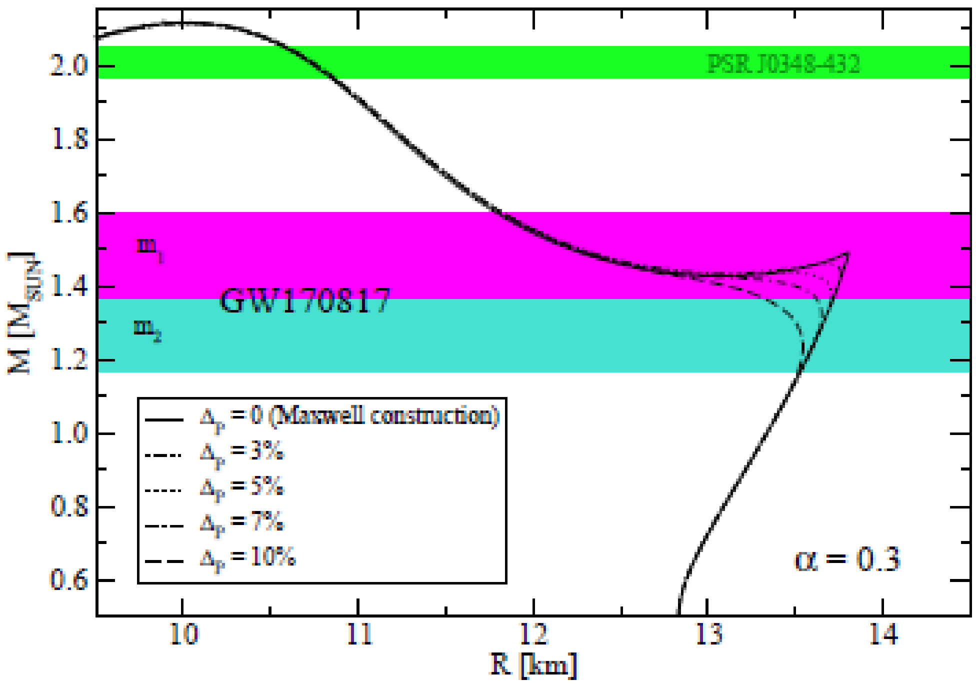
Result:

3rd family solutions (i.e. also the mass twins) are robust against pasta phase effects (mimicked by interpolation) for $\Delta_P < 5\%$

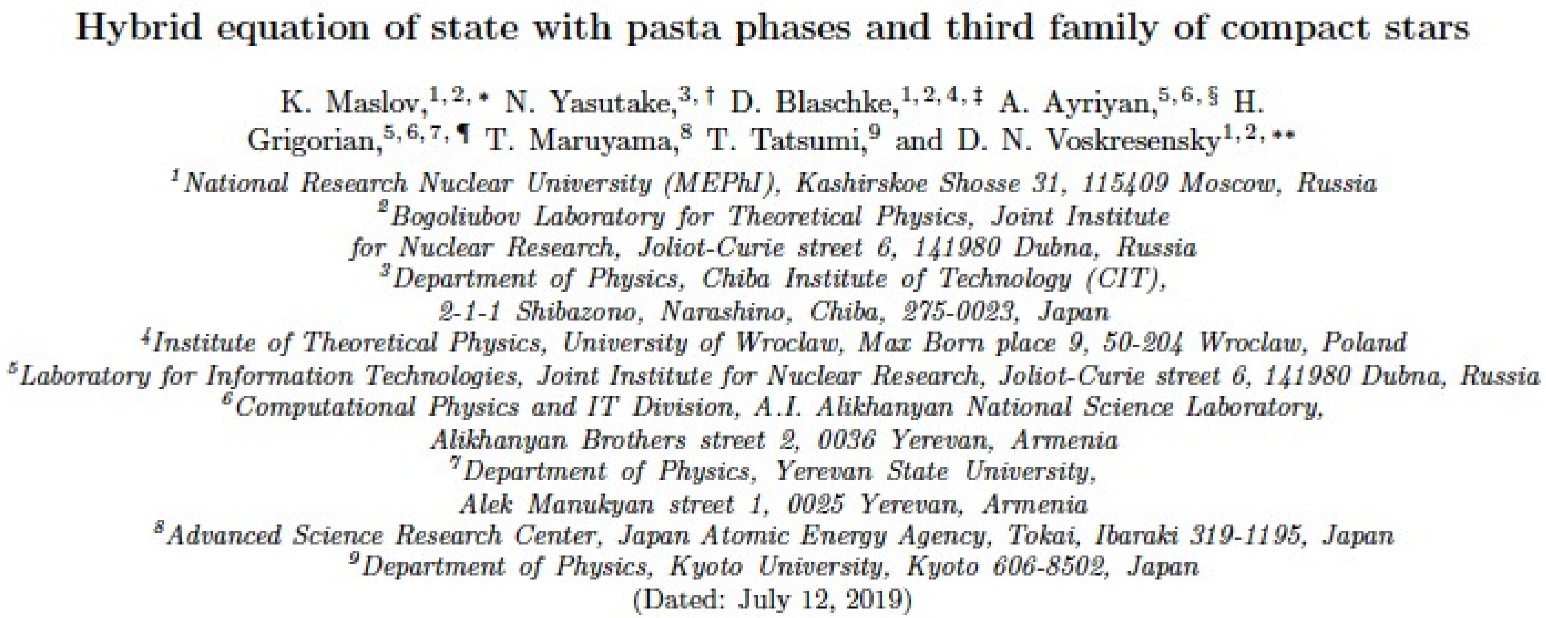
GW170817 could have been a HS-NS or even A HS-HS merger rather than NS-NS merger !!

Ayriyan et al., PRD96, 045802 (2018) [arxiv:1711.03926]





Robustness of Twins against Pasta Phase Effects



Hybrid equation of state with pasta phases and third family of compact stars

K. Maslov,[1,2,*] N. Yasutake,[3,†] D. Blaschke,[1,2,4,‡] A. Ayriyan,[5,6,§] H. Grigorian,[5,6,7,¶] T. Maruyama,[8] T. Tatsumi,[9] and D. N. Voskresensky[1,2,**]
[1] *National Research Nuclear University (MEPhI), Kashirskoe Shosse 31, 115409 Moscow, Russia*
[2] *Bogoliubov Laboratory for Theoretical Physics, Joint Institute for Nuclear Research, Joliot-Curie street 6, 141980 Dubna, Russia*
[3] *Department of Physics, Chiba Institute of Technology (CIT), 2-1-1 Shibazono, Narashino, Chiba, 275-0023, Japan*
[4] *Institute of Theoretical Physics, University of Wroclaw, Max Born place 9, 50-204 Wroclaw, Poland*
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[7] *Department of Physics, Yerevan State University, Alek Manukyan street 1, 0025 Yerevan, Armenia*
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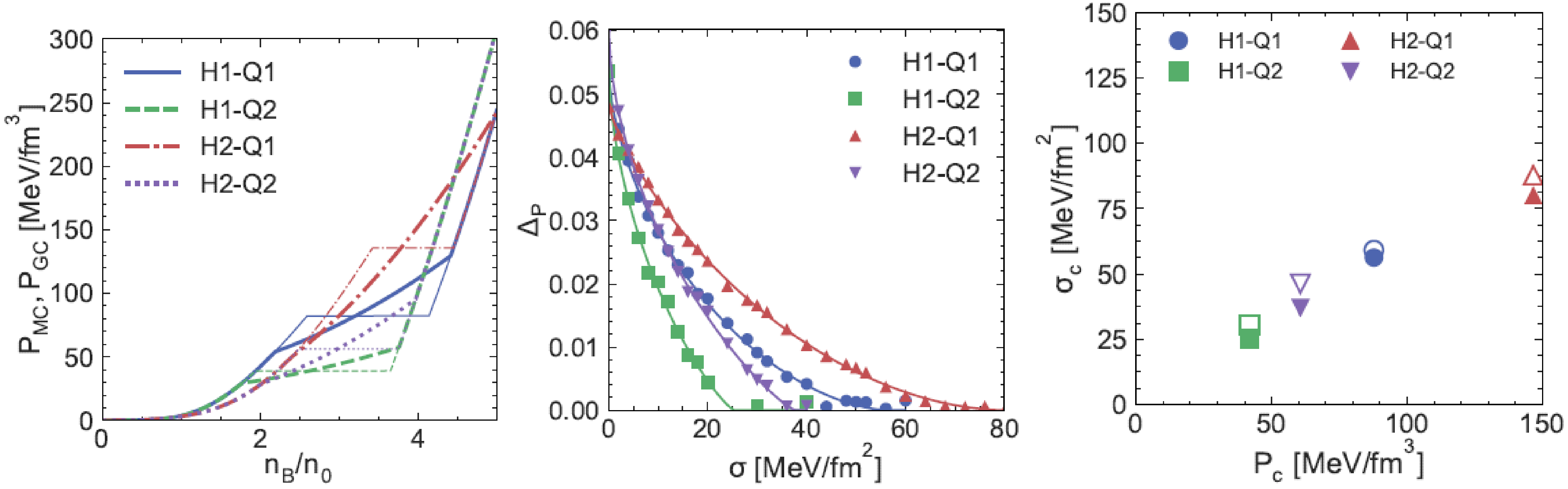
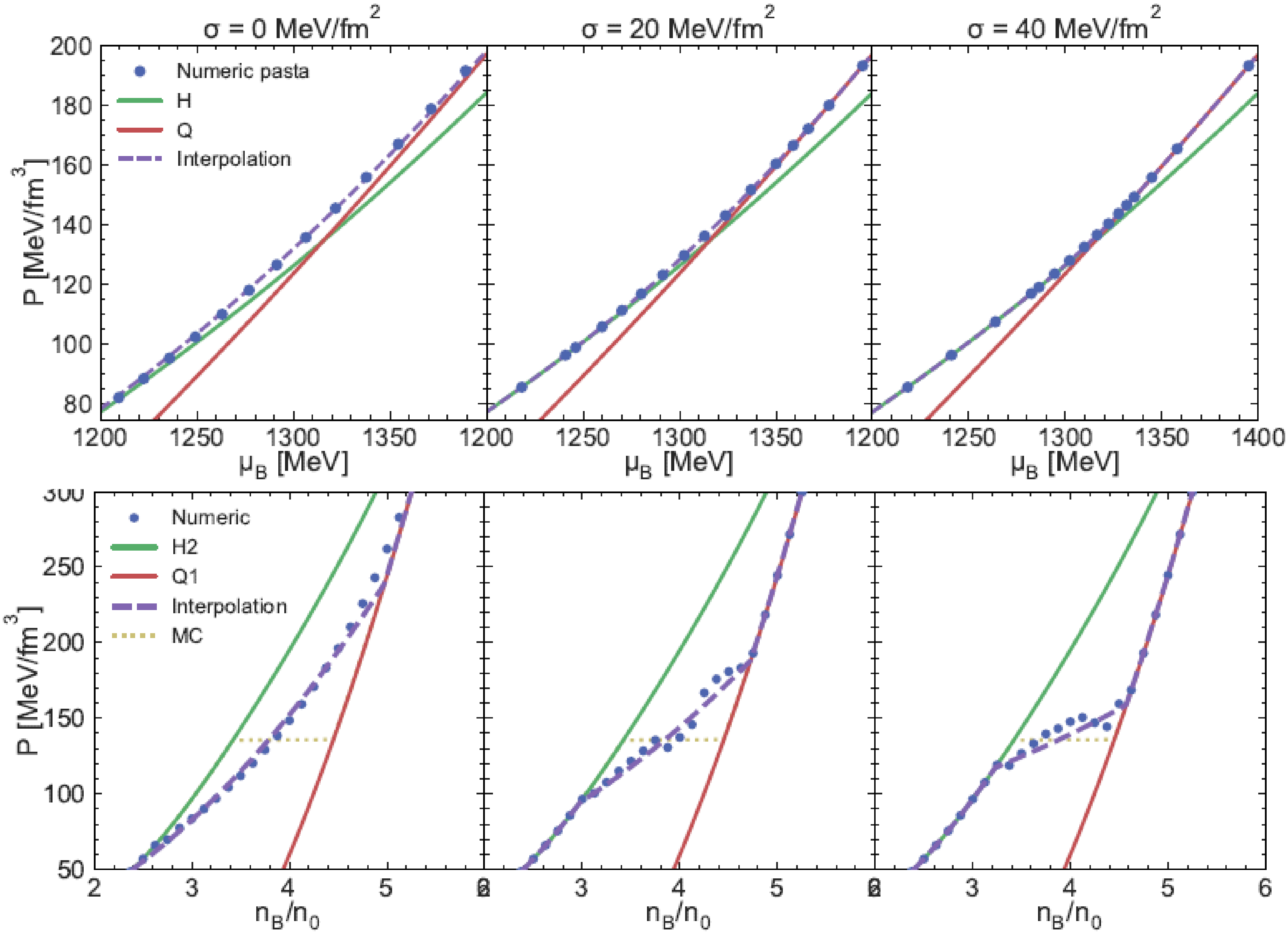
[9] *Department of Physics, Kyoto University, Kyoto 606-8502, Japan*

(Dated: July 12, 2019)

Q: Can real pasta calculations be approximated by the interpolation? **A:** Yes! And Δ_P< 5% ...



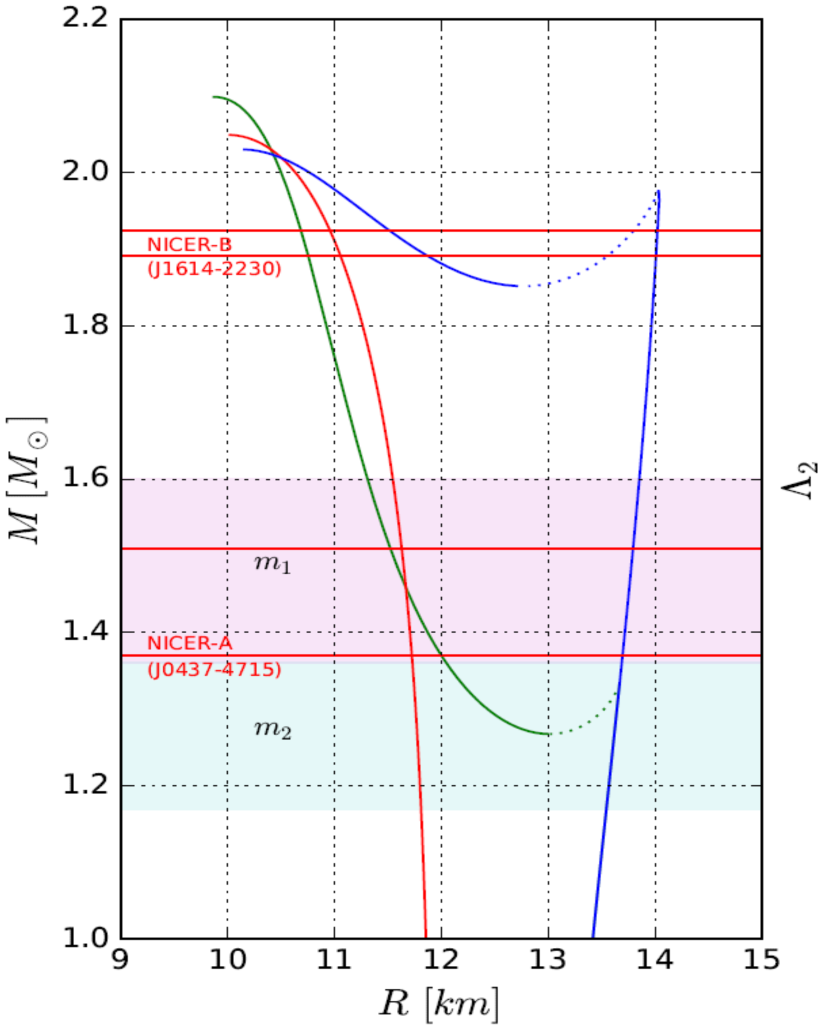
Robustness of Twins against Pasta Phase Effects

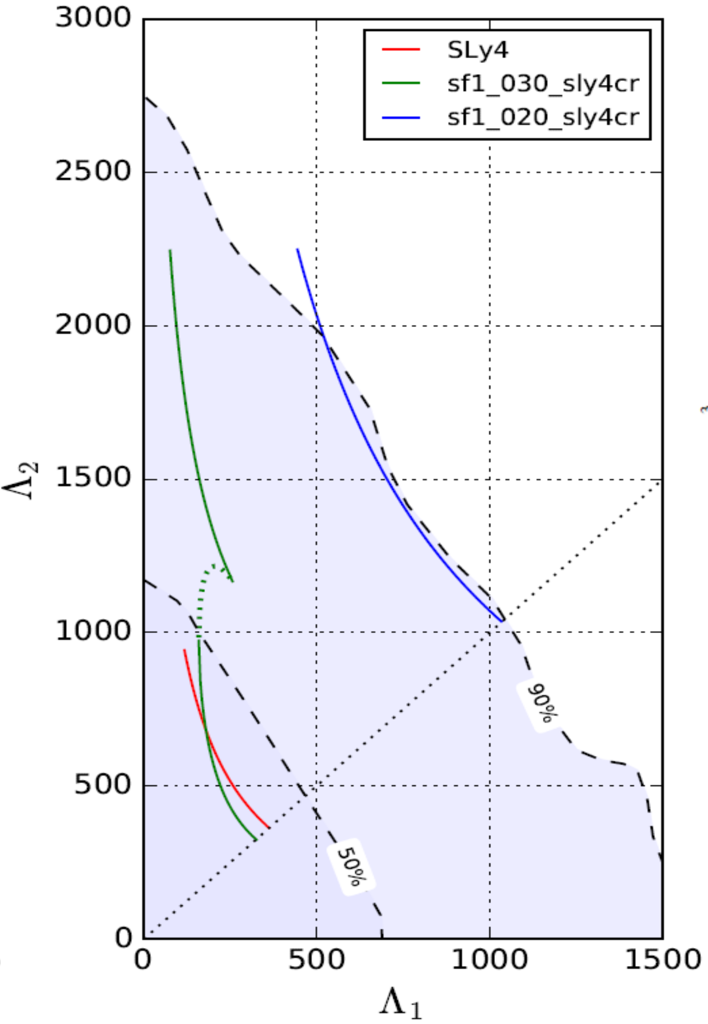


Robustness of Twins against Pasta Phase Effects

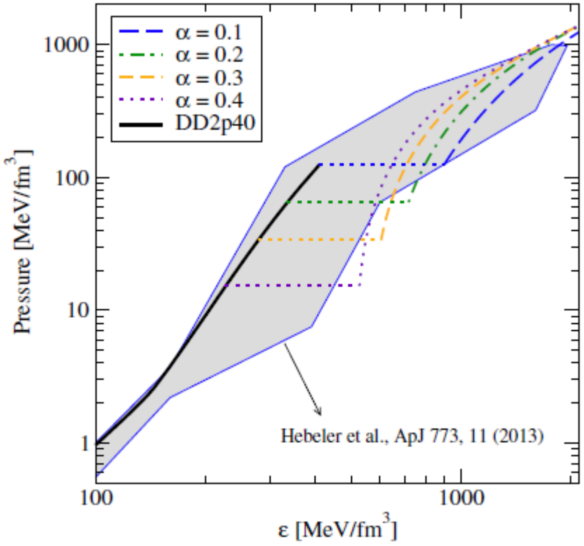
Thanks to the collaborators !

Discover the 3rd family – NICER vs. GW170817





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



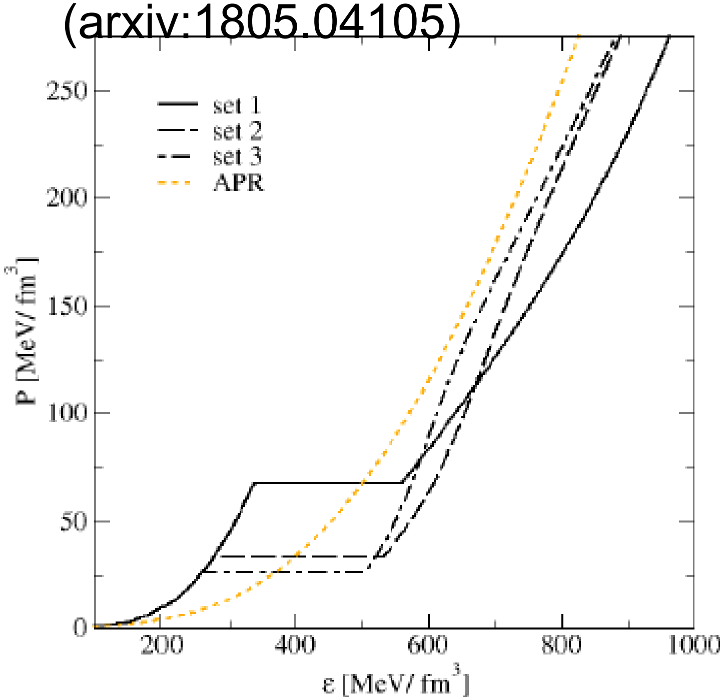
TOV / TD calculation:
M. Bejger et al.

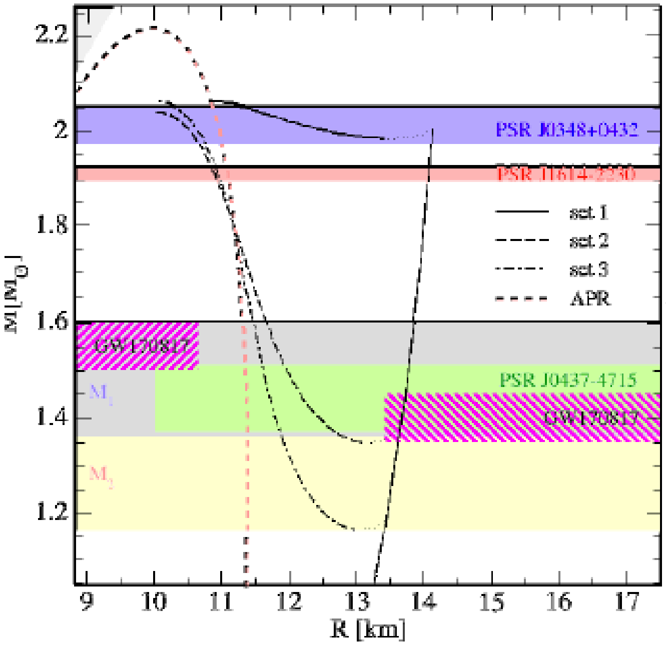
Alternative to NS merger with soft EoS → Hybrid star (HS) – HS / HS-NS merger

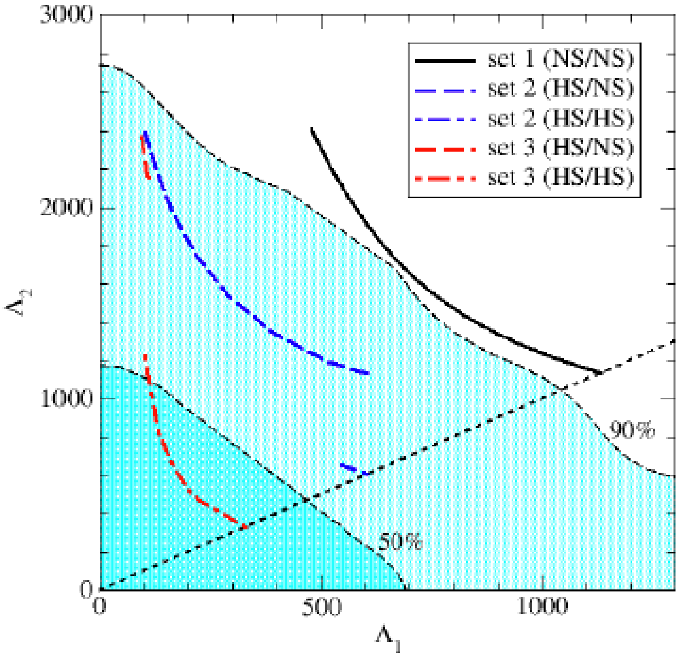
If NICER rules out soft EoS (since $R_{0437\text{-}4715}$ >13.5 km) then **Third Family is Discovered !!**

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_sun constraint fulfilled
GW170817: R_1.4 < 13.6 km
[Annala et al., PRL (2018)]
NICER: R_1.44 > ?? (2018)

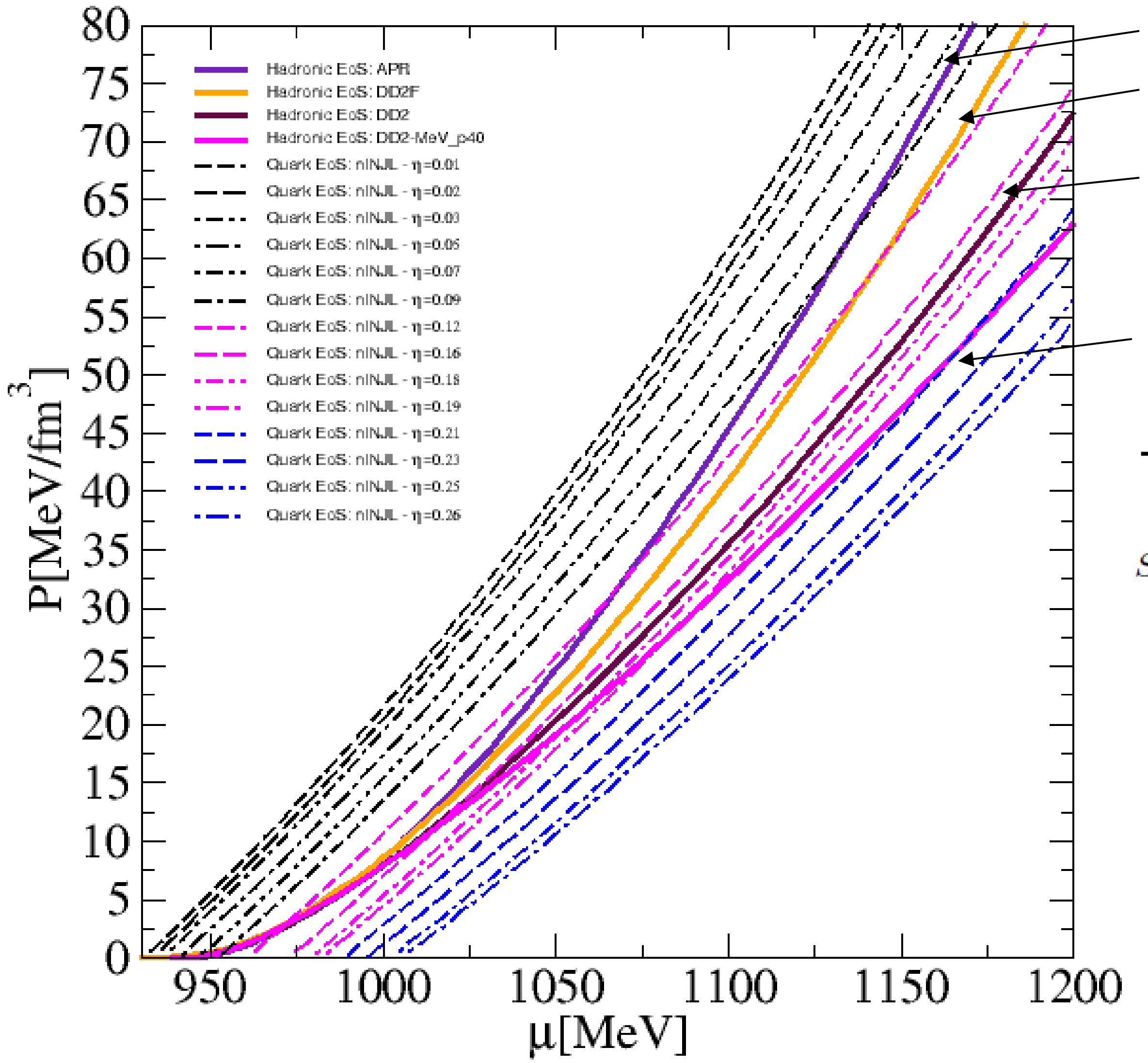
Pasta calculation:
Does not spoil twin scenario of NS-HS or HS-HS merger!
Yasutake et al. (2018)

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

If NICER rules out soft EoS (since $R_{0437\text{-}4715}$ >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:

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

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

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

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

Nonlocal chiral quark model - generalized

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

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

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

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

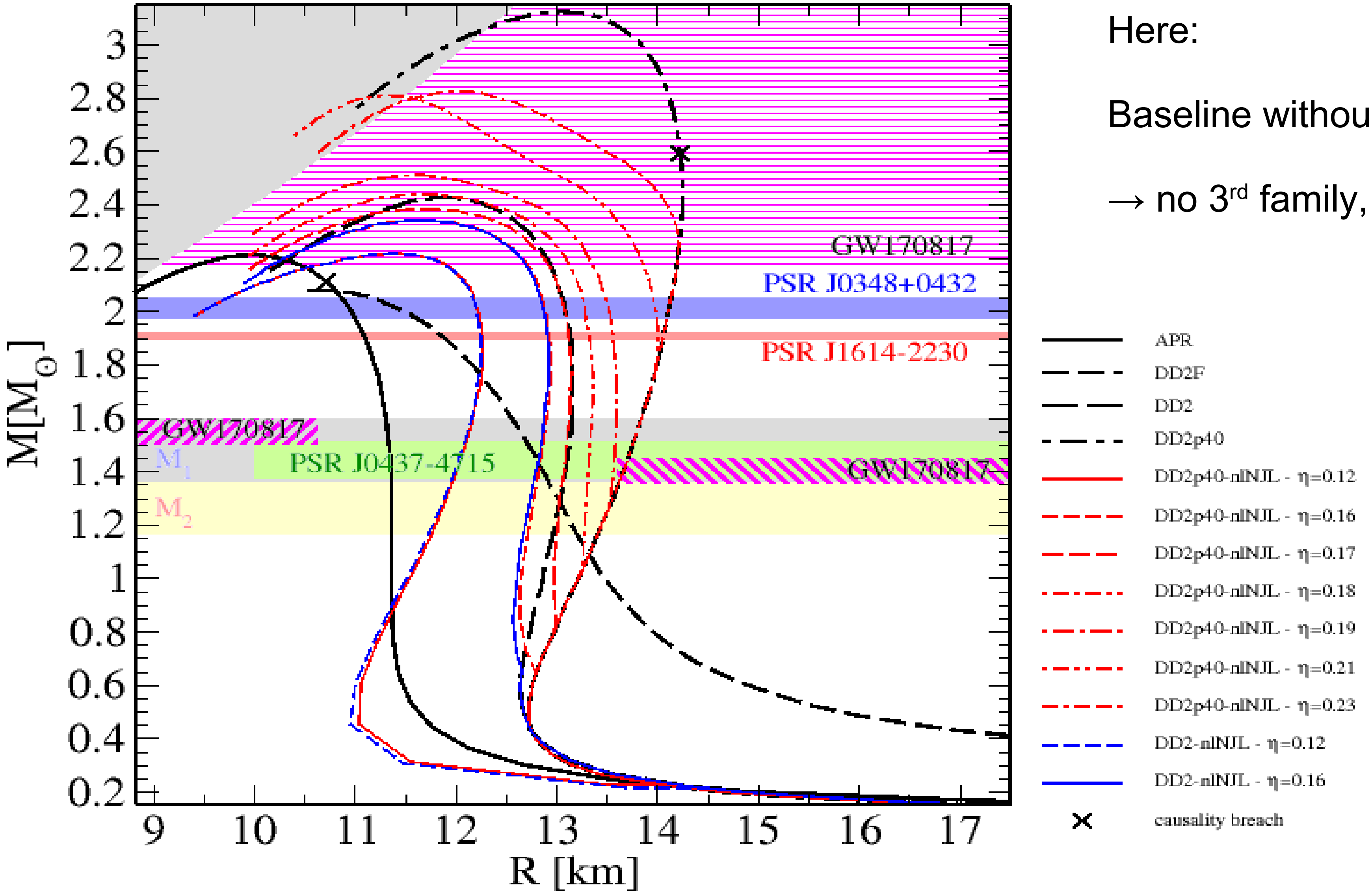
$$\Omega^{MFA} = \frac{\bar{\sigma}^2}{2G_S} + \frac{\bar{\Delta}^2}{2H} - \frac{\bar{\omega}^2}{2G_V} - \frac{1}{2}\int \frac{d^4p}{(2\pi)^4}\; \ln\det\left[\, S^{-1}(\bar{\sigma}, \bar{\Delta}, \bar{\omega}, \mu_{fc})\right]$$

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

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

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]

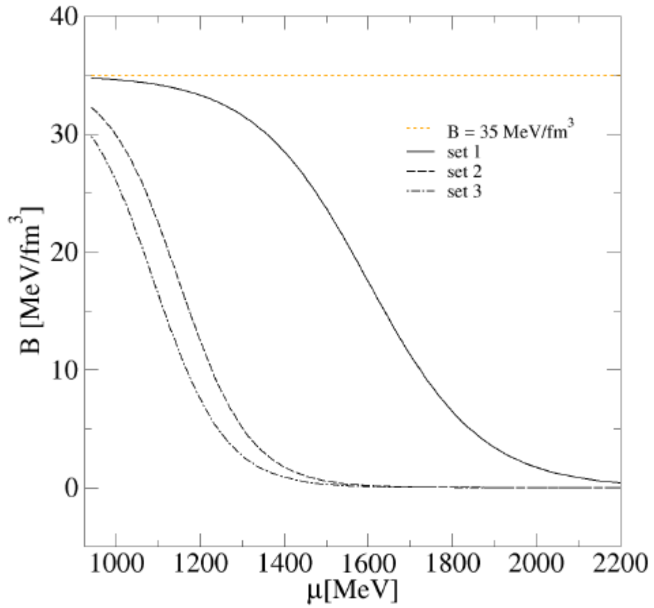
Interpolation vs. medium dependence of coefficients

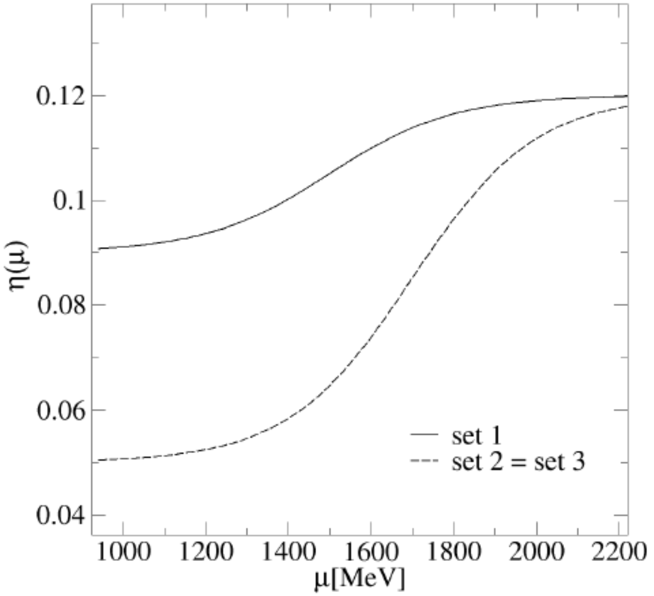
$$\begin{aligned} P(\mu) &= P(\mu;\eta,B)f_<(\mu) + P(\mu;\eta,0)f_>(\mu) \\ &= P(\mu;\eta,0)[f_<(\mu)+f_>(\mu)] - Bf_<(\mu) \\ &= P(\mu;\eta,B(\mu)), \end{aligned}$$

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

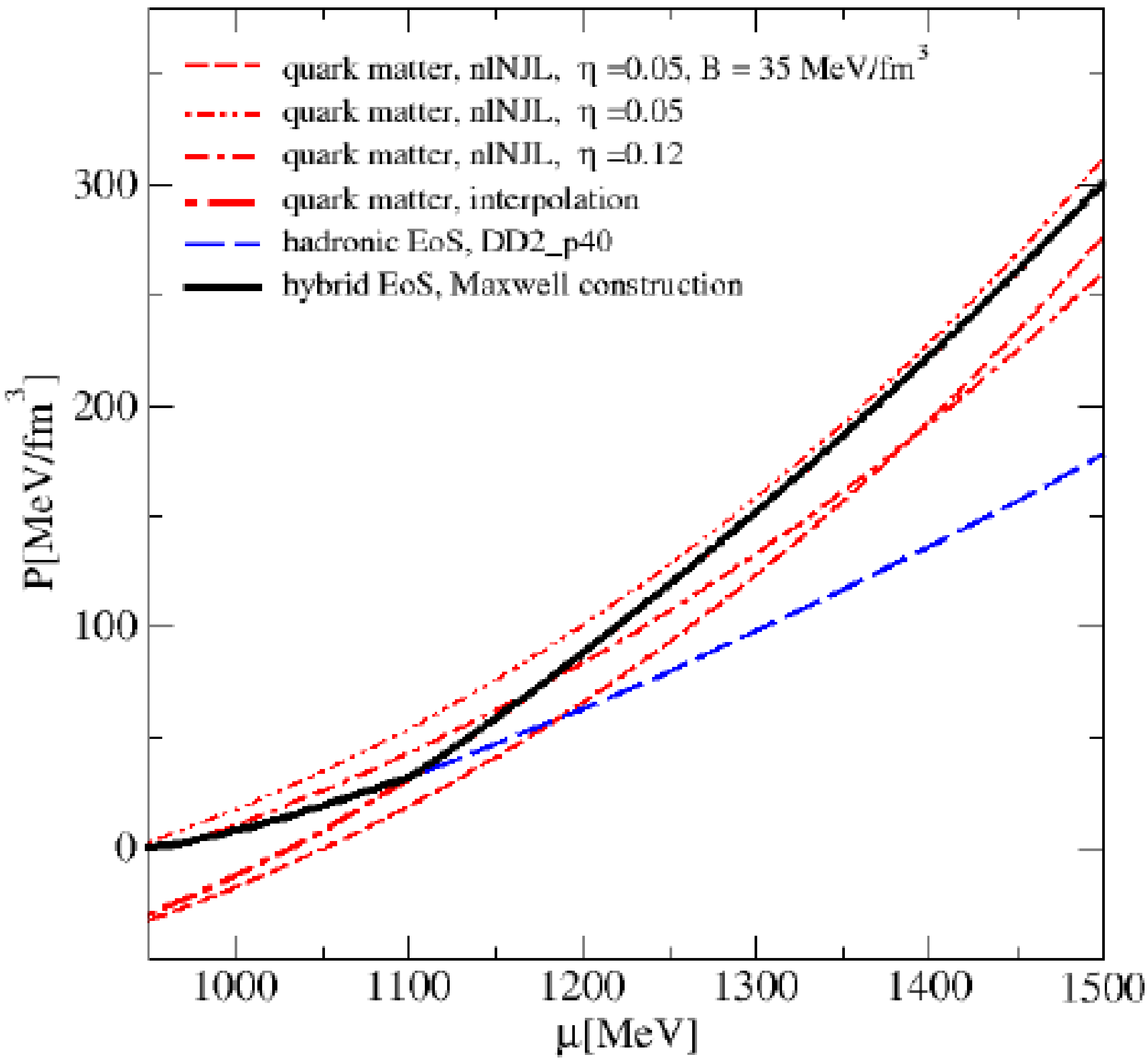
$$\begin{aligned} P(\mu) &= P(\mu;\eta_<,B)f_\ll(\mu) + P(\mu;\eta_>,B)f_\gg(\mu) \\ &= P(\mu;\eta_<,B)[f_\ll(\mu)+f_\gg(\mu)] \\ &\quad +(\eta_> - \eta_<)f_\gg(\mu)\left.\frac{dP(\mu;\eta,B)}{d\eta}\right|_{\eta=\eta_<} \\ &= P(\mu;\eta_<,B) \\ &\quad +[\eta_> f_\gg(\mu) + \eta_< f_\ll(\mu) - \eta_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

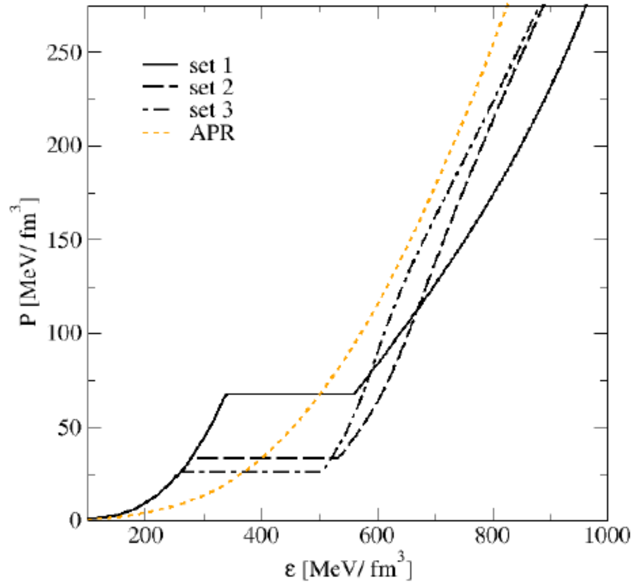
$\eta(\mu) = \eta_> f_\gg(\mu) + \eta_< f_\ll(\mu)$ is the medium-dependent vector meson coupling

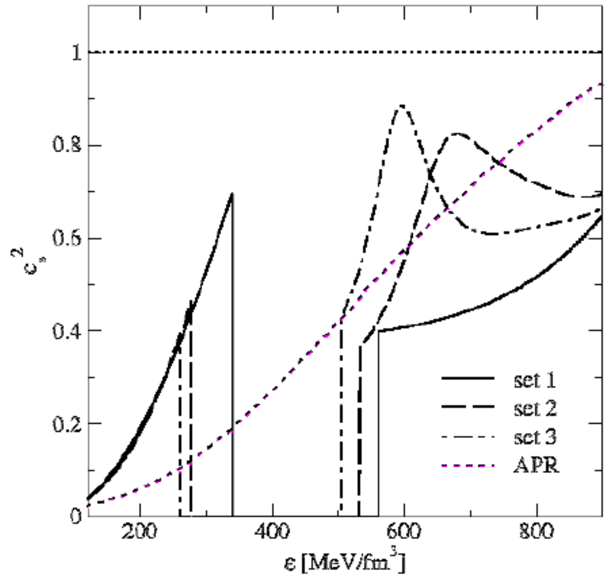




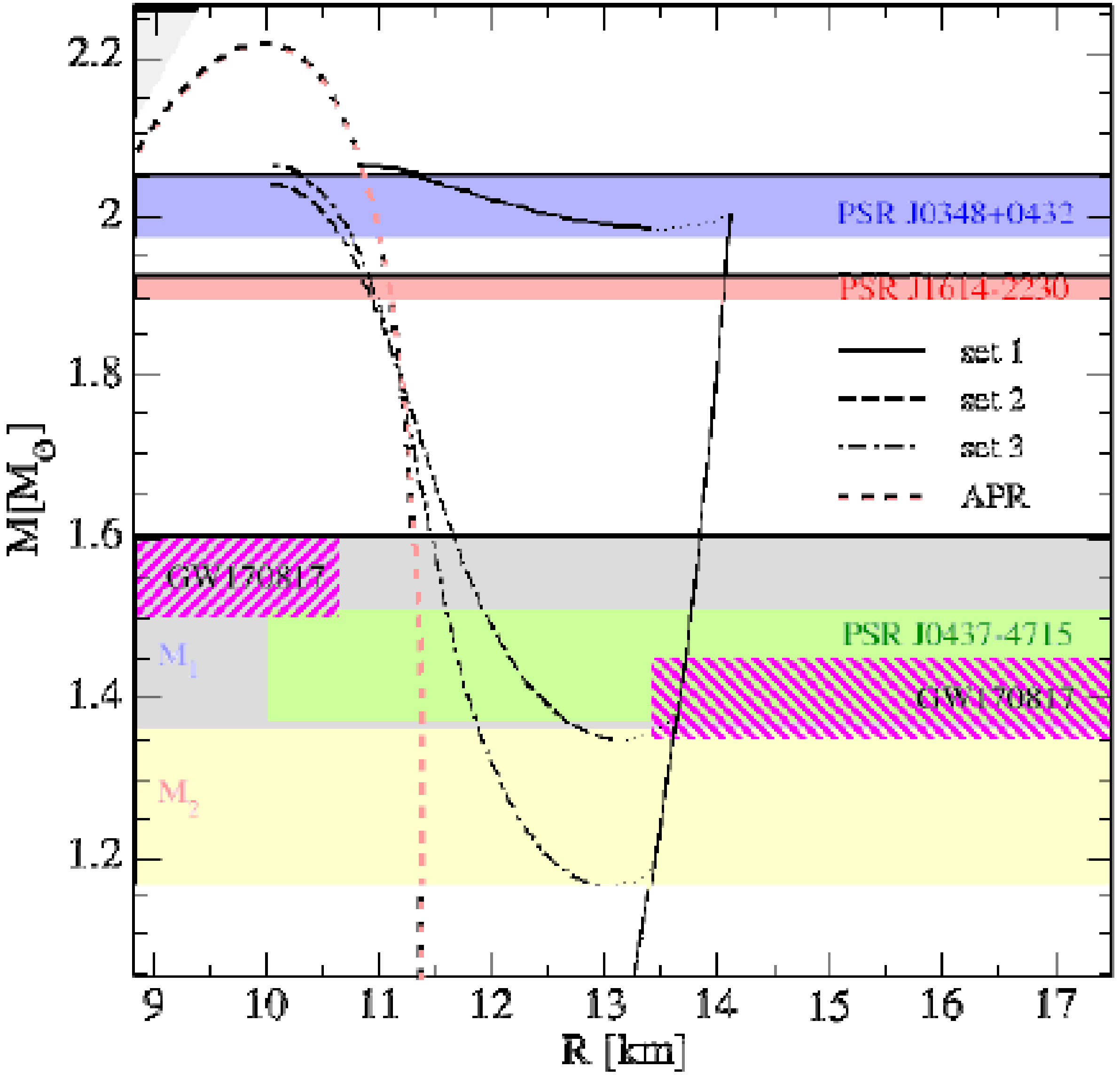
Maxwell Construction between Hadron and Quark Phases

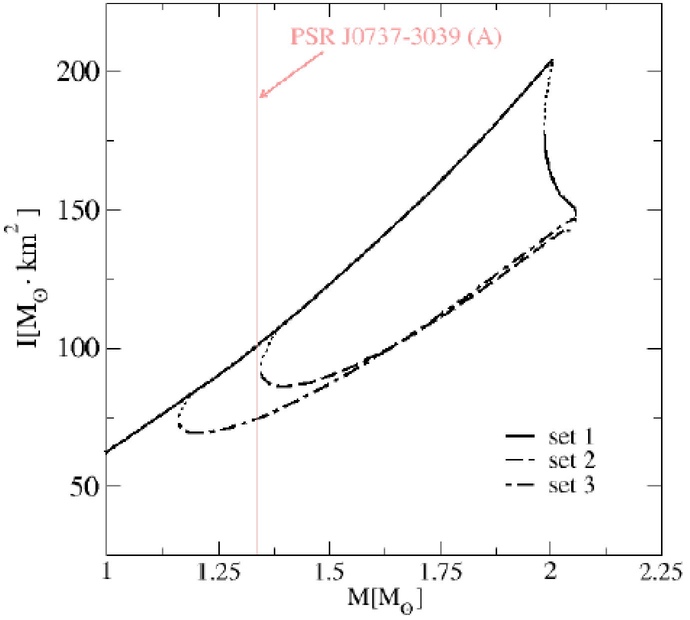


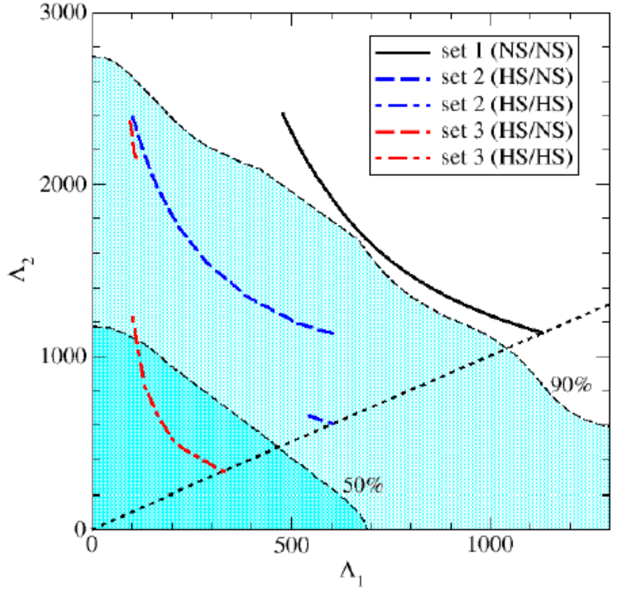




Maxwell Construction between Hadron and Quark Phases







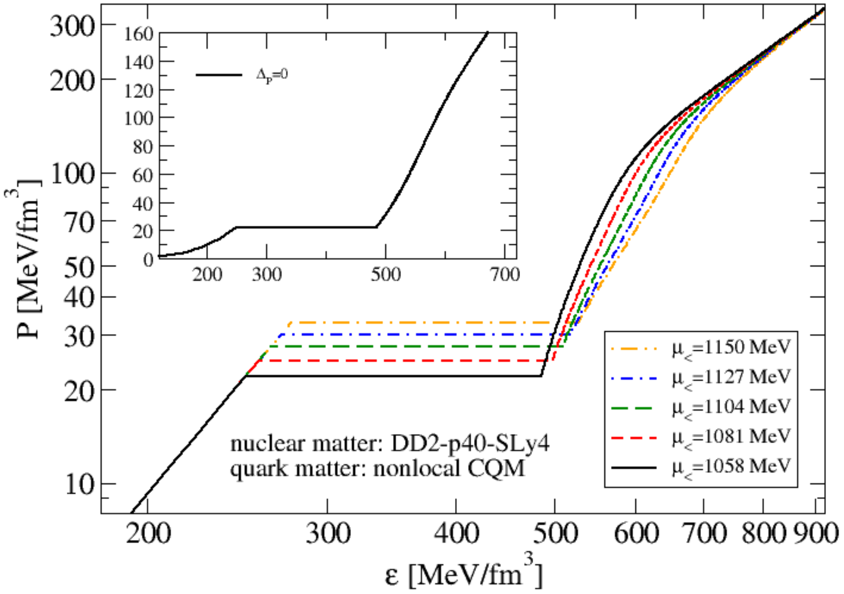
D.E. Alvarez-Castillo, et al., PRD 99 (2019) 063010

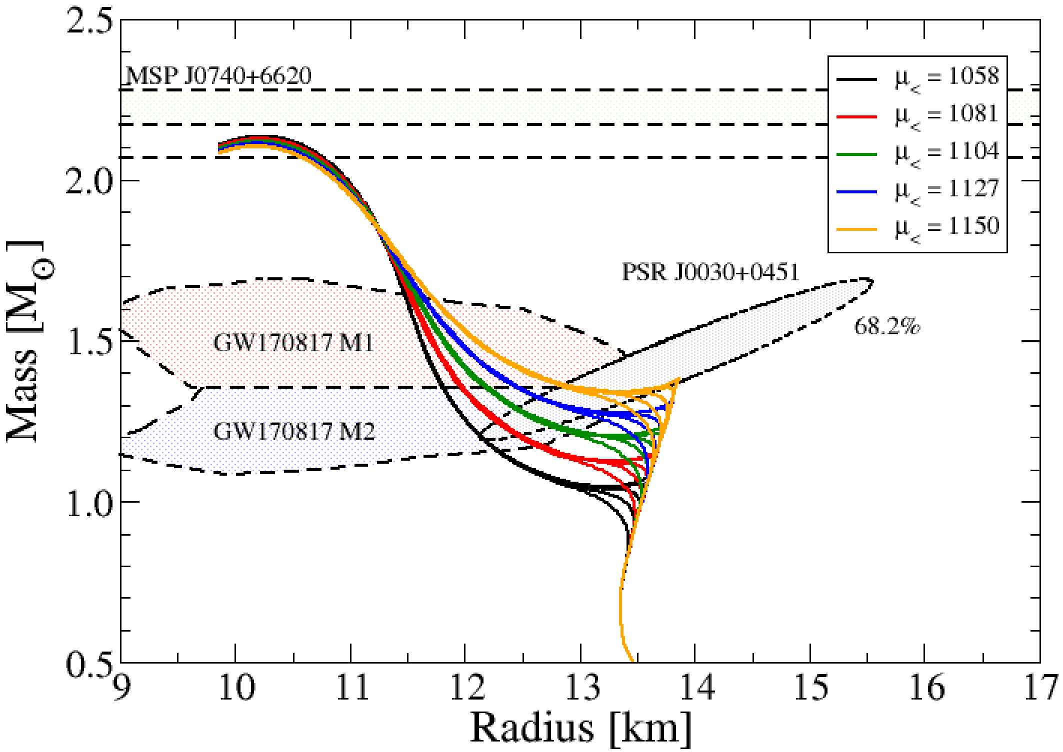
Was GW170817 indeed a binary Neutron Star Merger ? A Bayesian Analysis for Hybrid Equations of State

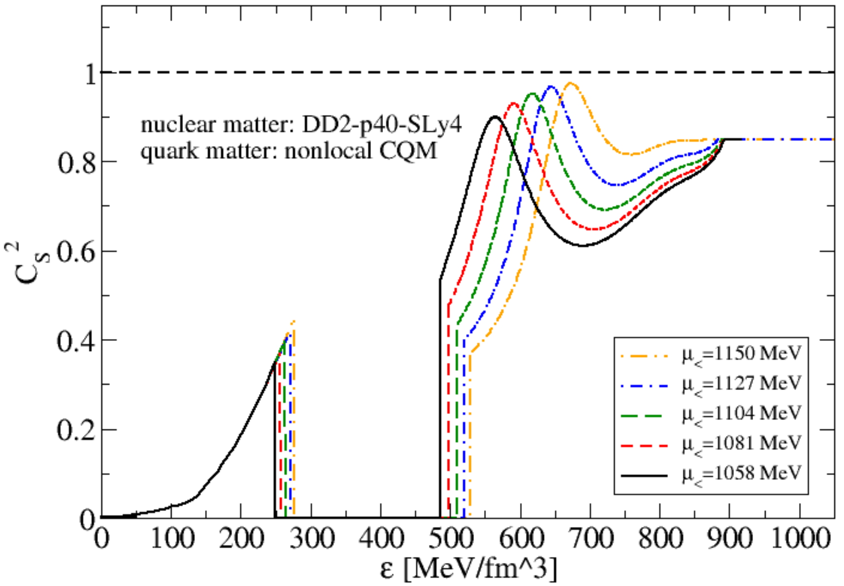
- Mass 2.17+0.11-0.10 M_sun &
- Compactness (tidal deform.) GW170817

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

→ Two-parameter family EoS: mu_< , Delta_P







Was GW170817 indeed a binary Neutron Star Merger ?
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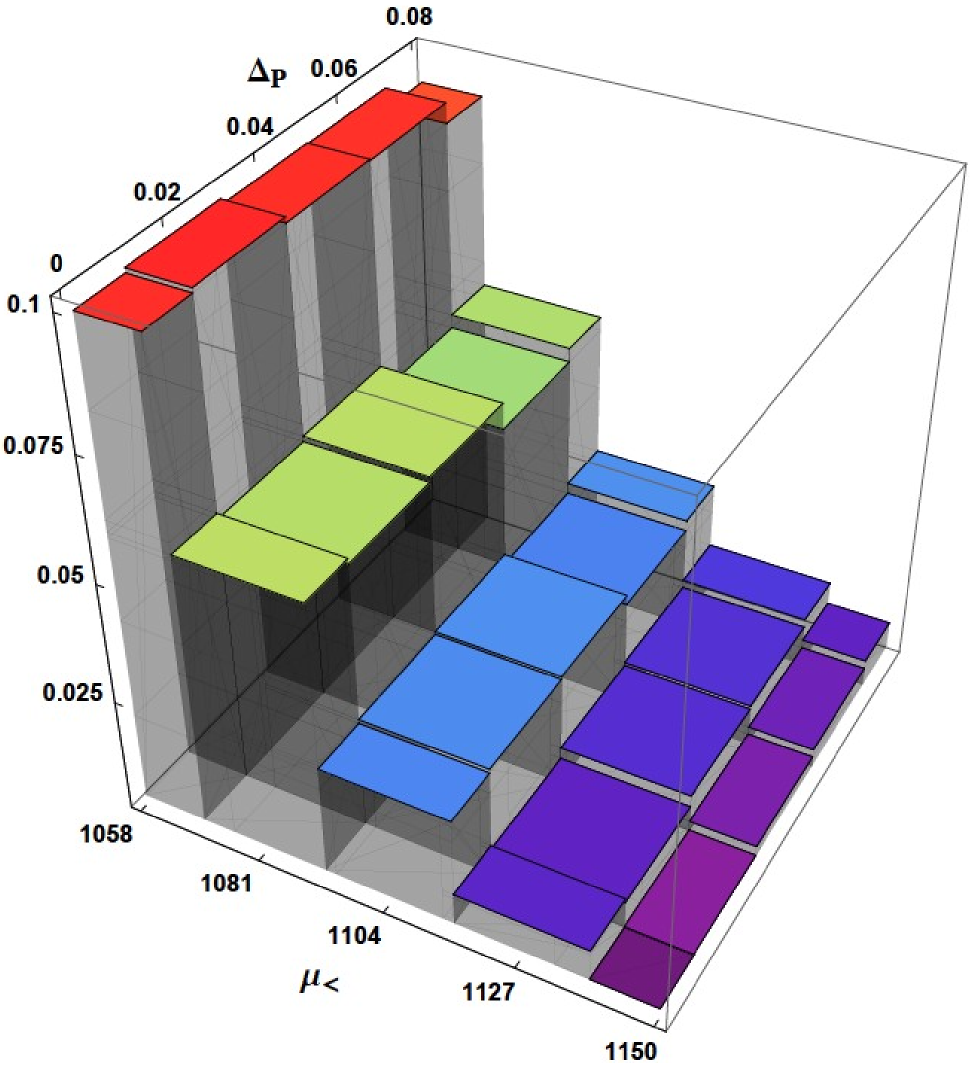

Additional (fictitious) radius measurement
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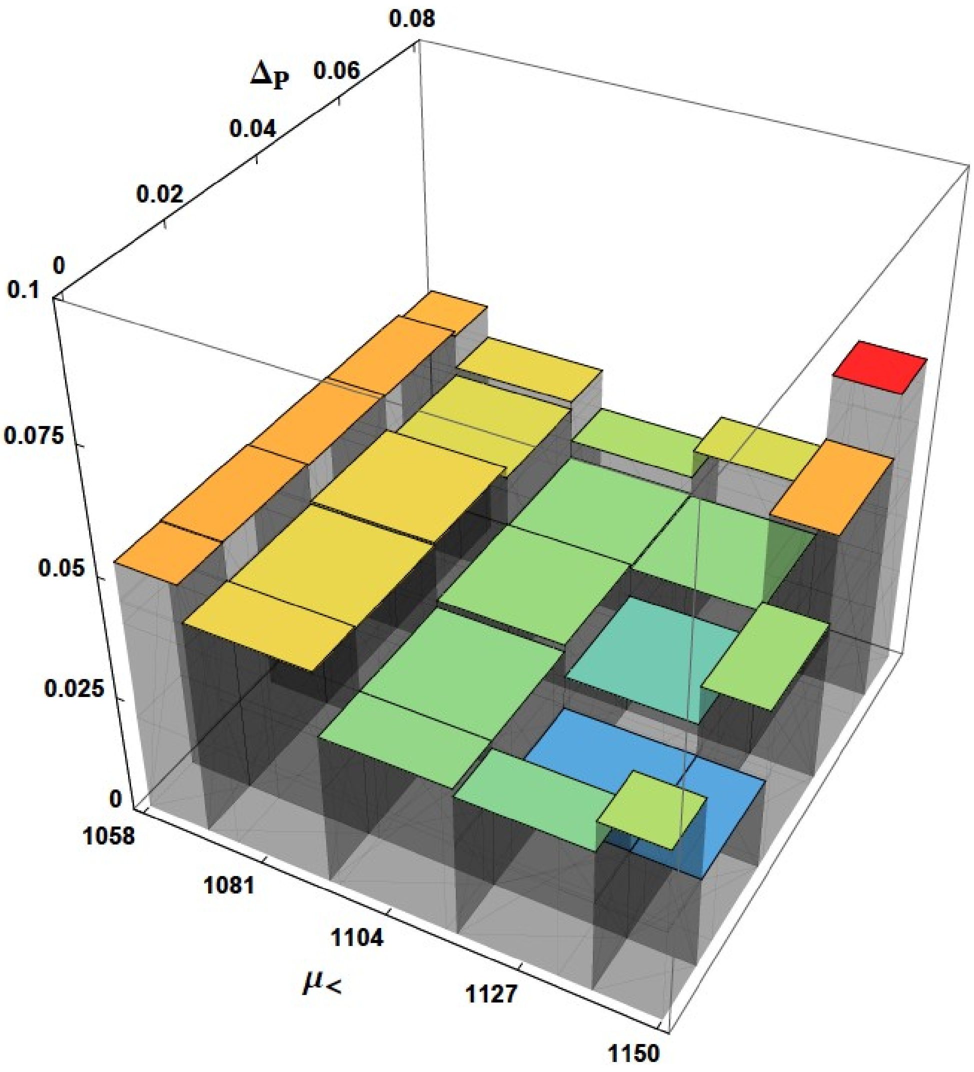
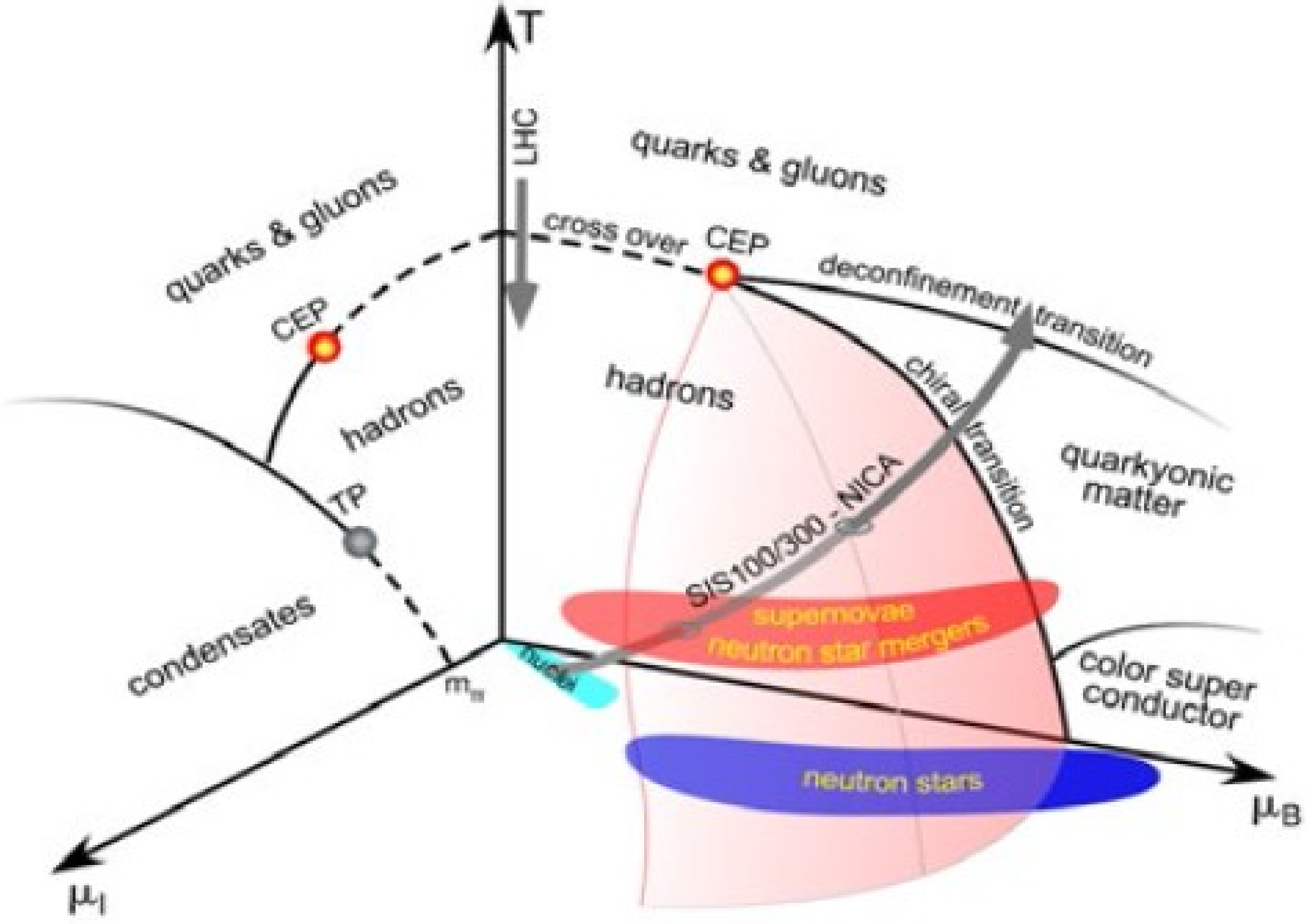


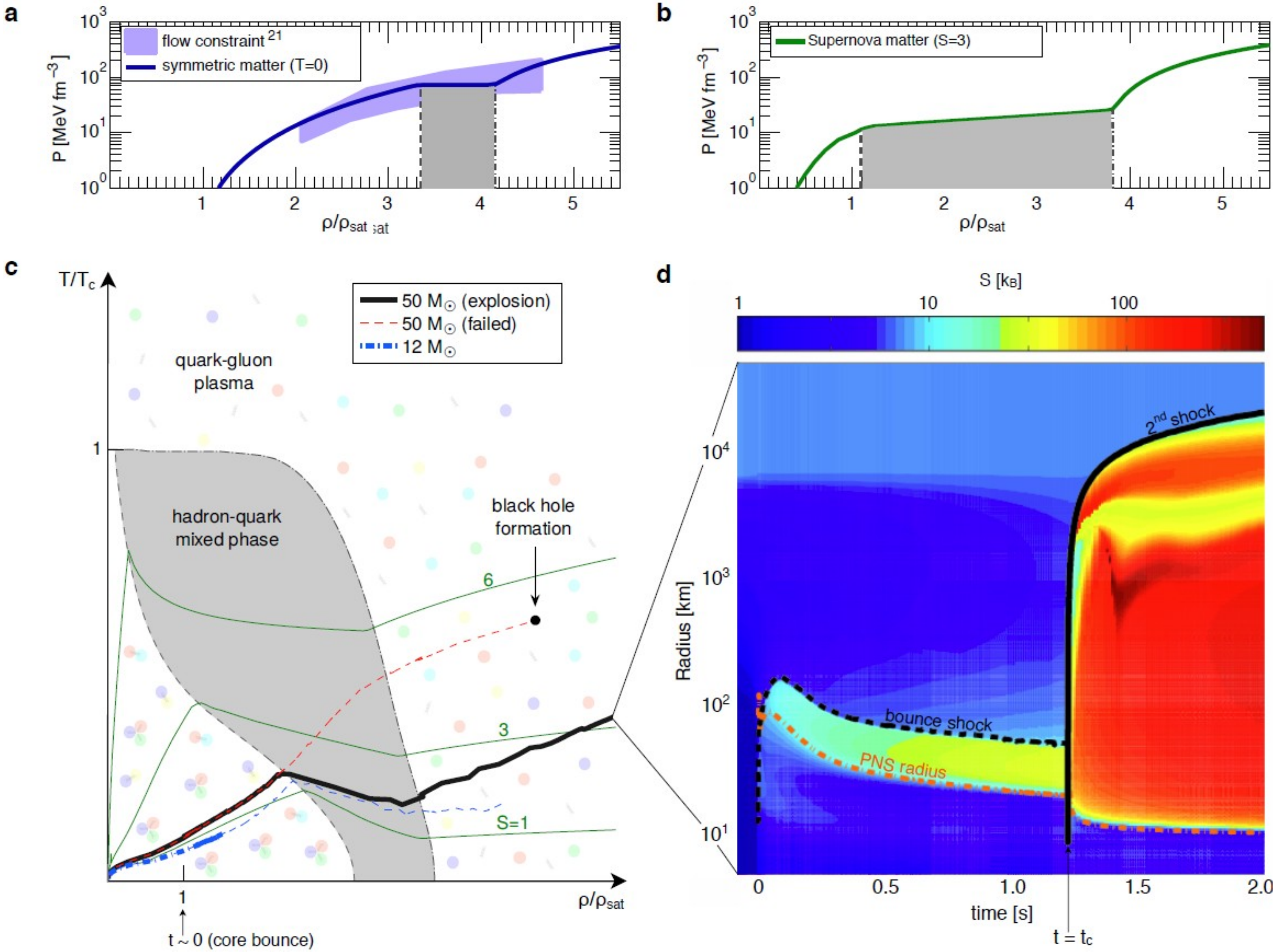
CEP in the QCD phase diagram: HIC vs. Astrophysics



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

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

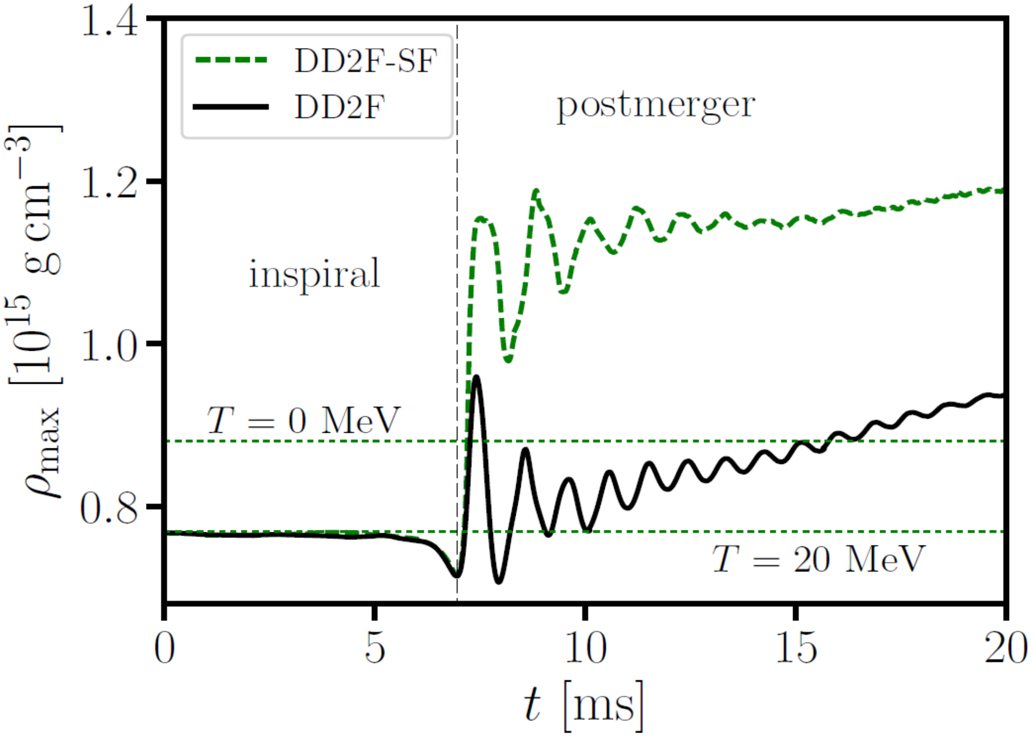
Deconfinement transition as SN explosion mechanism



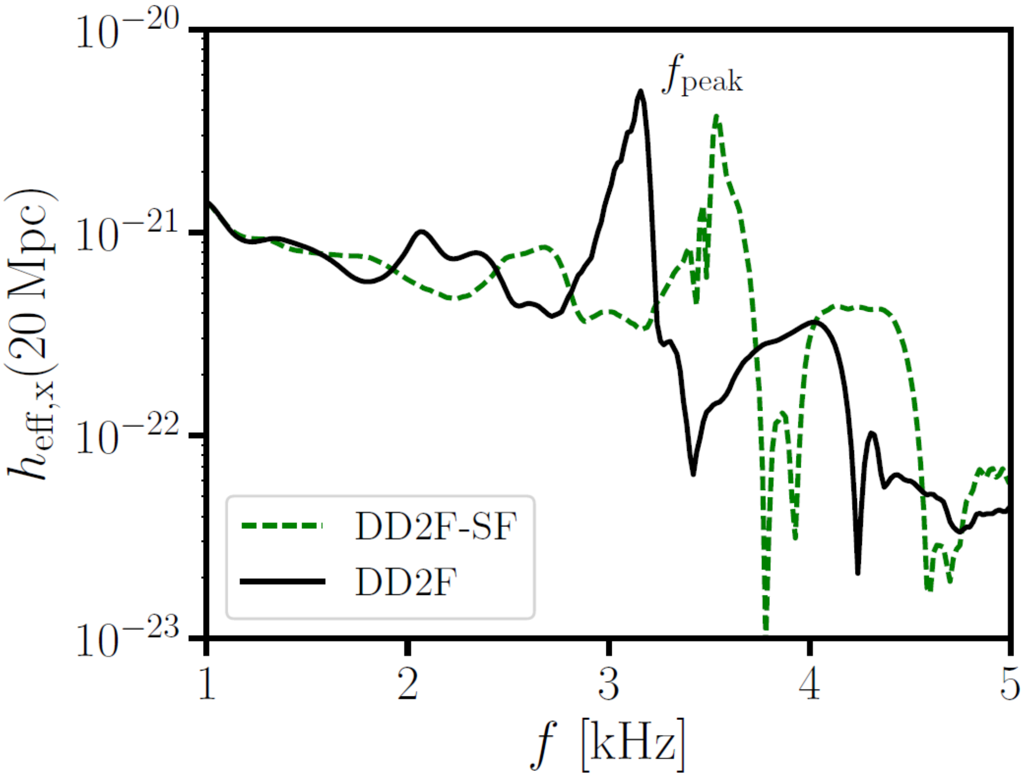
Progenitor:
M = 50 M_O

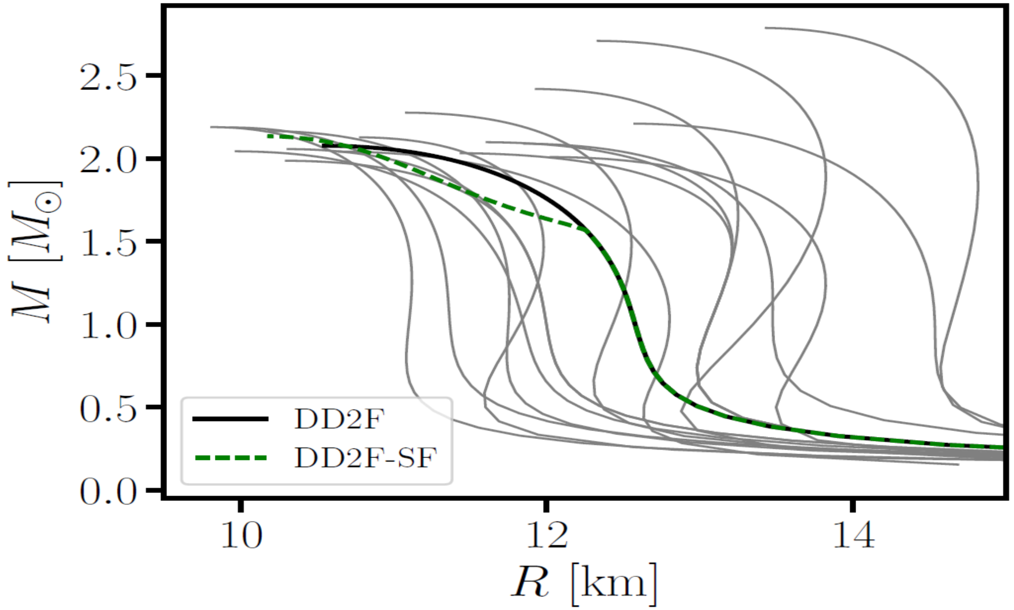
T. Fischer, N.-U. Bastian et al., Quark deconfinement as supernova engine of massive blue Supergiant star explosions, Nature Astronomy 2 (2018) 980-986; arxiv:1712.08788

Hybrid star formation in postmerger phase



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



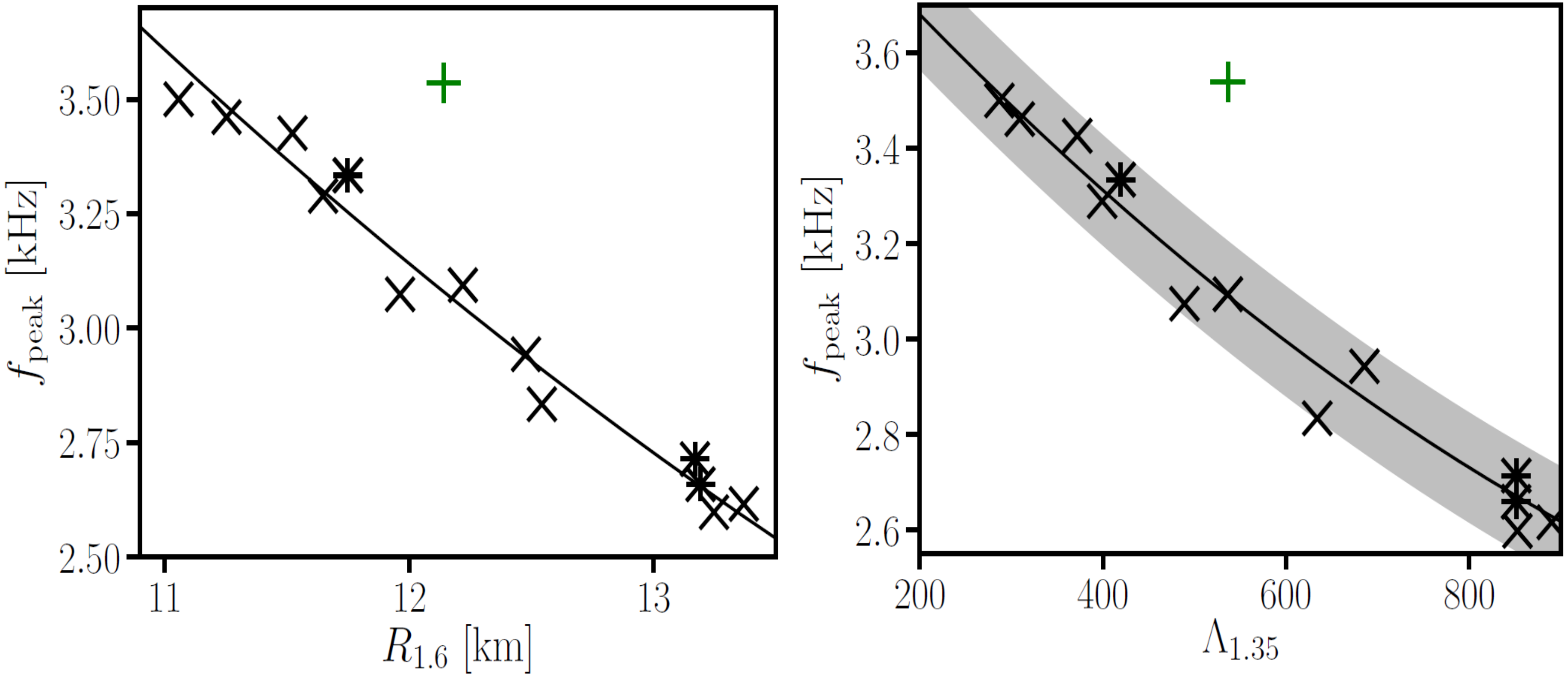


Hybrid star formaton during NS merger
→ higher densities and compacter star
→ higher peak frequency of the GW

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]

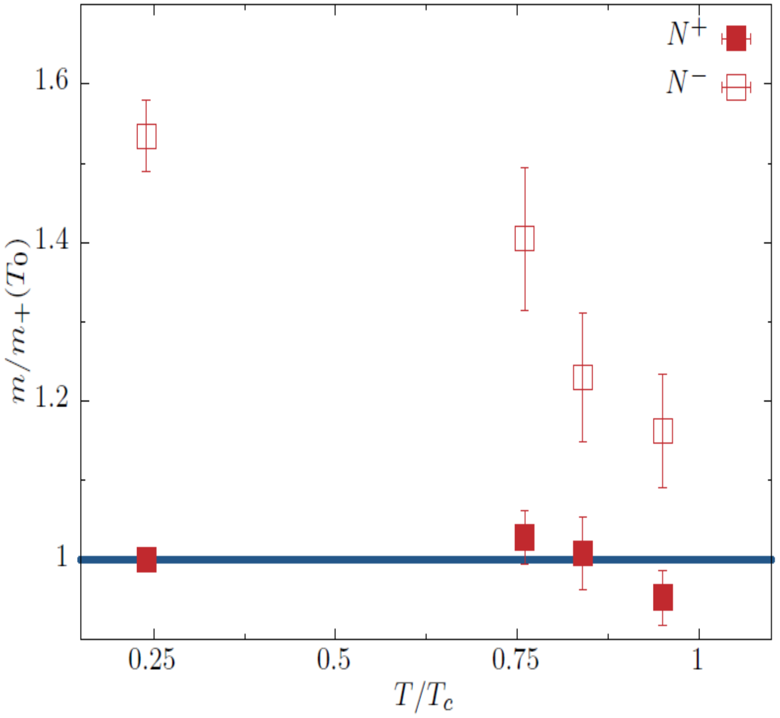


Strong deviation from **f_{peak} – $R_{1.6}$** relation signals **strong phase transition in** NS merger**!**

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

Caveat: Strong transition may not be deconfinement !

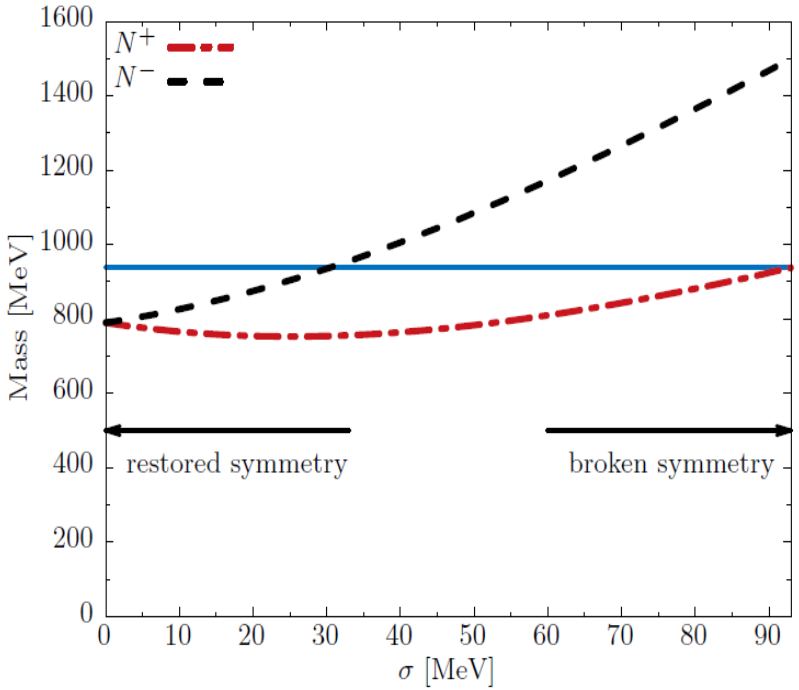
Parity doubling in lattice QCD Aarts *et al*, JHEP **1706**, 034 (2017)



- 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)

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

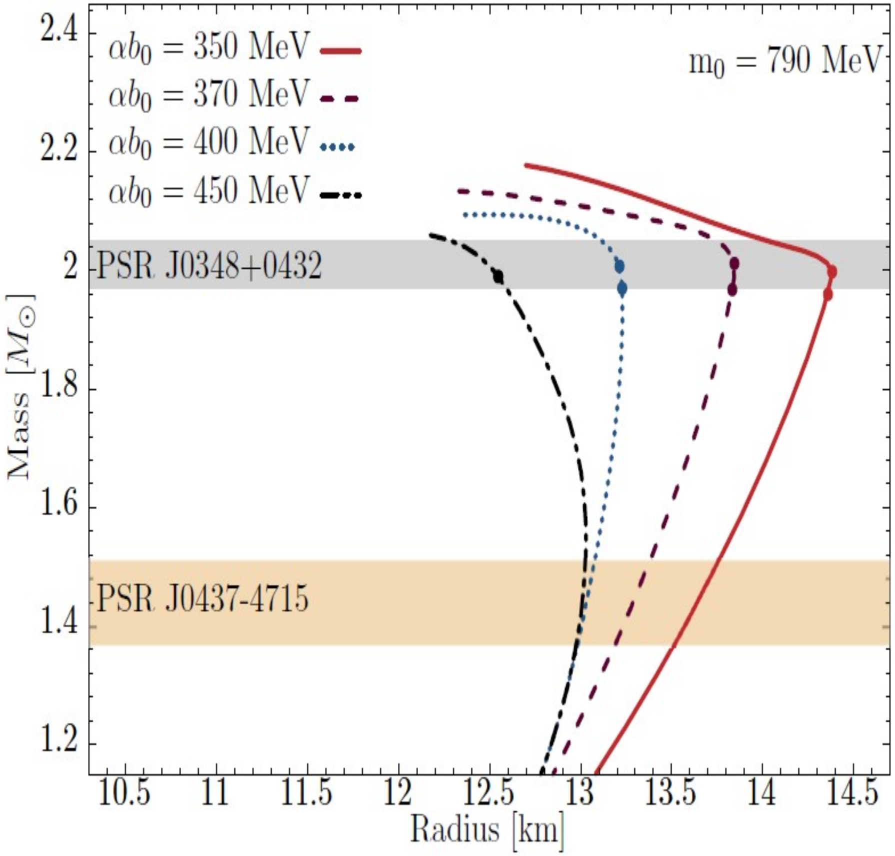


M. Marczenko, D.B., C. Sasaki, K. Redlich, Chiral symmetry restoration by parity doubling and structure of neutron stars, Phys. Rev. D98 (2018) 103021; [arxiv:1805.06886]

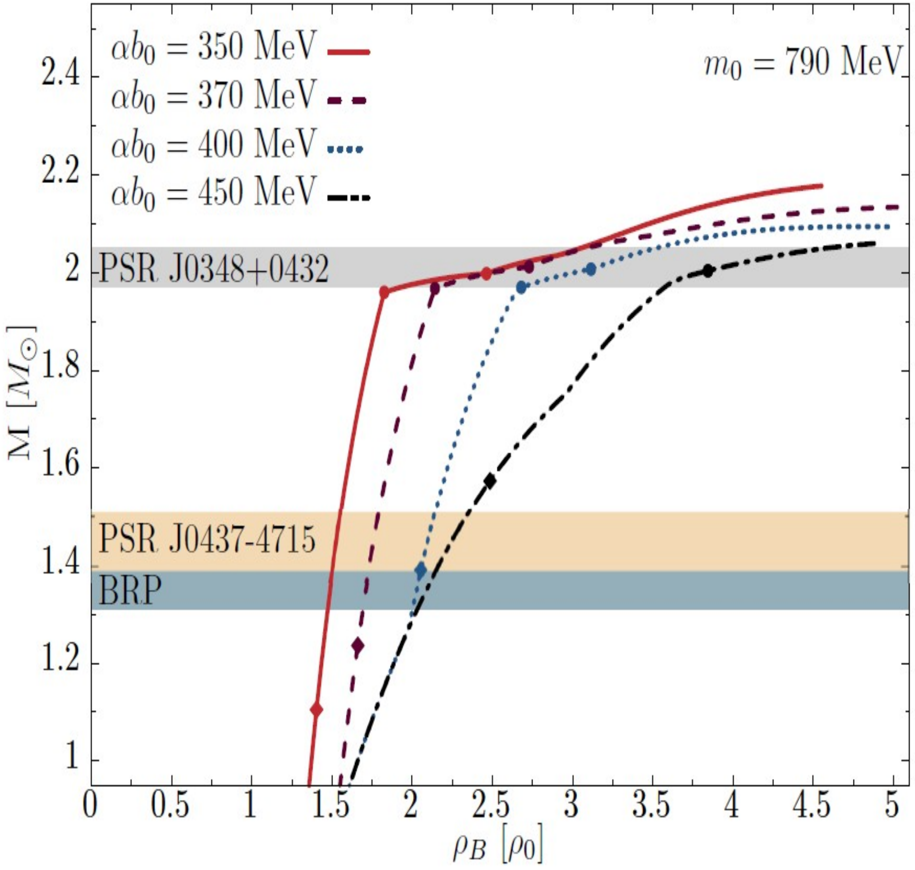
Caveat: Strong transition may not be deconfinement !

Mass-radius relation

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



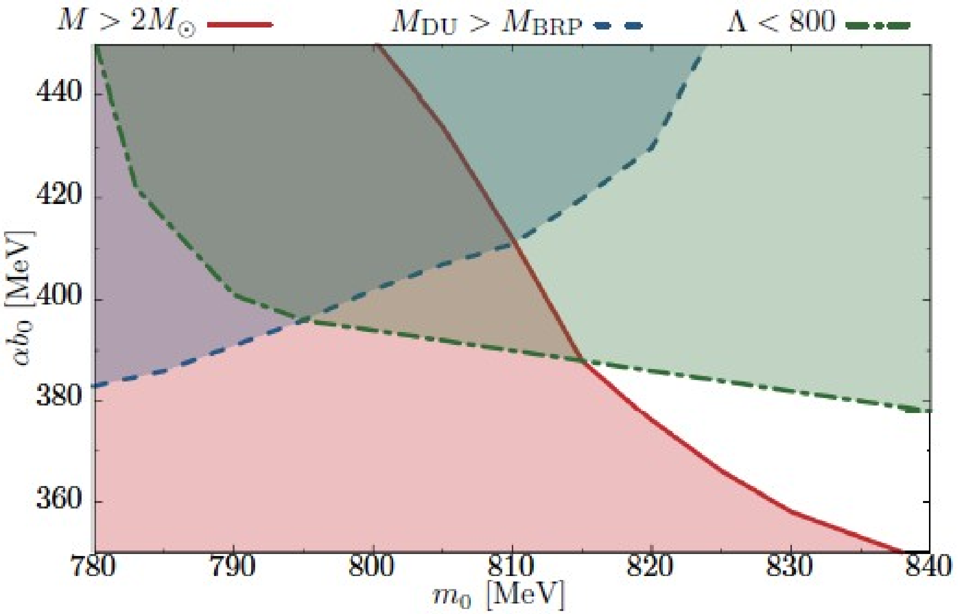
mass-density

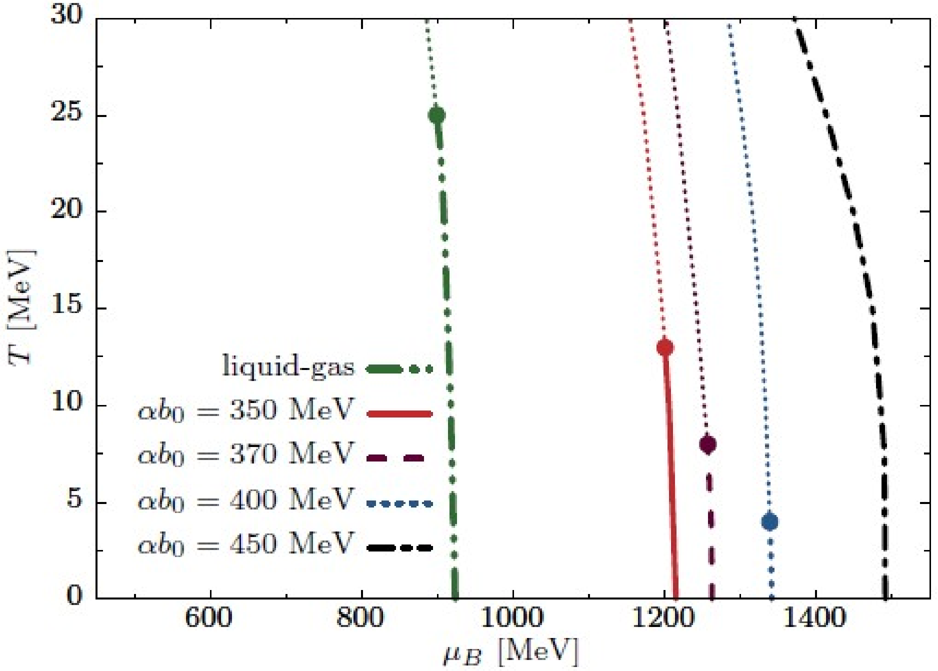


M. Marczenko, D.B., C. Sasaki, K. Redlich, Chiral symmetry restoration by parity doubling and structure of neutron stars, Phys. Rev. D98 (2018) 103021; [arxiv:1805.06886]

Caveat: Strong transition may not be deconfinement !

Back to symmetric-matter QCD Phase Diagram





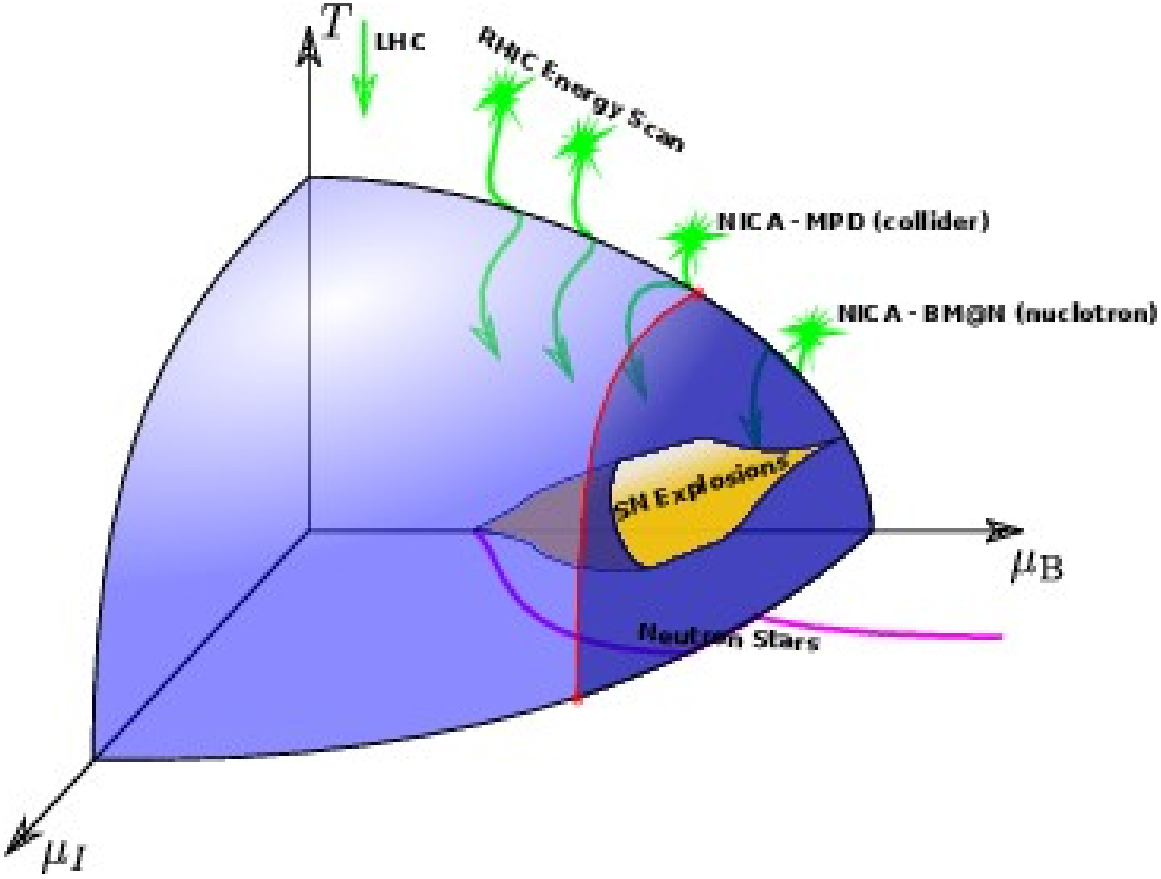
- $2M_\odot$ → stiff EoS
- DU → soft EoS
- TD → soft EoS

- 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]

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

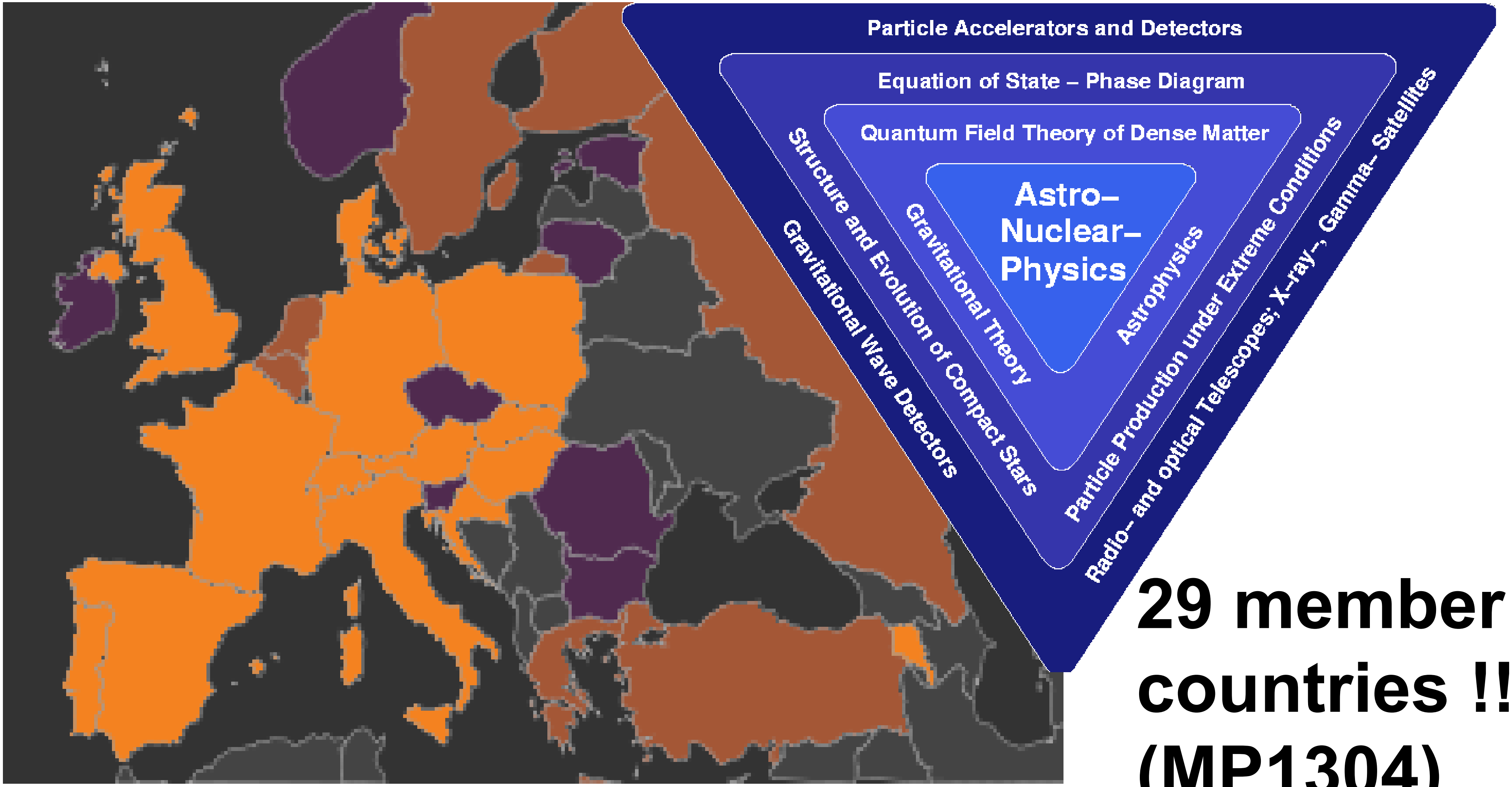


Main condition: stiff hadronic & stiff quark matter EoS with strong phase transition (PT)

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 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



Particle Accelerators and Detectors

Equation of State – Phase Diagram

Quantum Field Theory of Dense Matter

Astro–Nuclear–Physics

Gravitational Theory

Astrophysics

Structure and Evolution of Compact Stars

Particle Production under Extreme Conditions

Gravitational Wave Detectors

Radio– and optical Telescopes; X–ray–, Gamma– Satellites

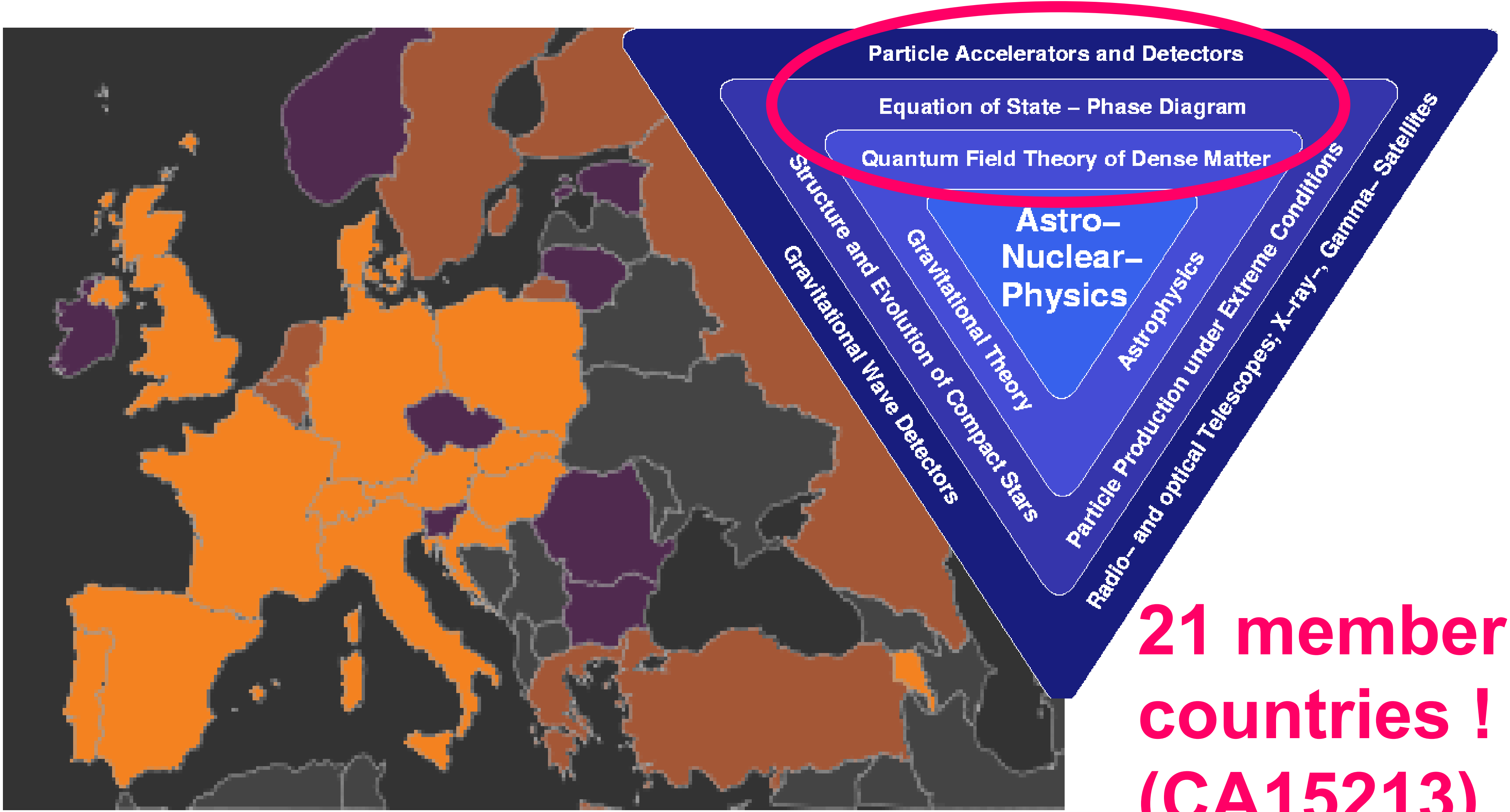
29 member countries !! (MP1304)

New compstar **!**

cost

EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

Kick-off: Brussels, November 25, 2013



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21 member countries ! (CA15213)

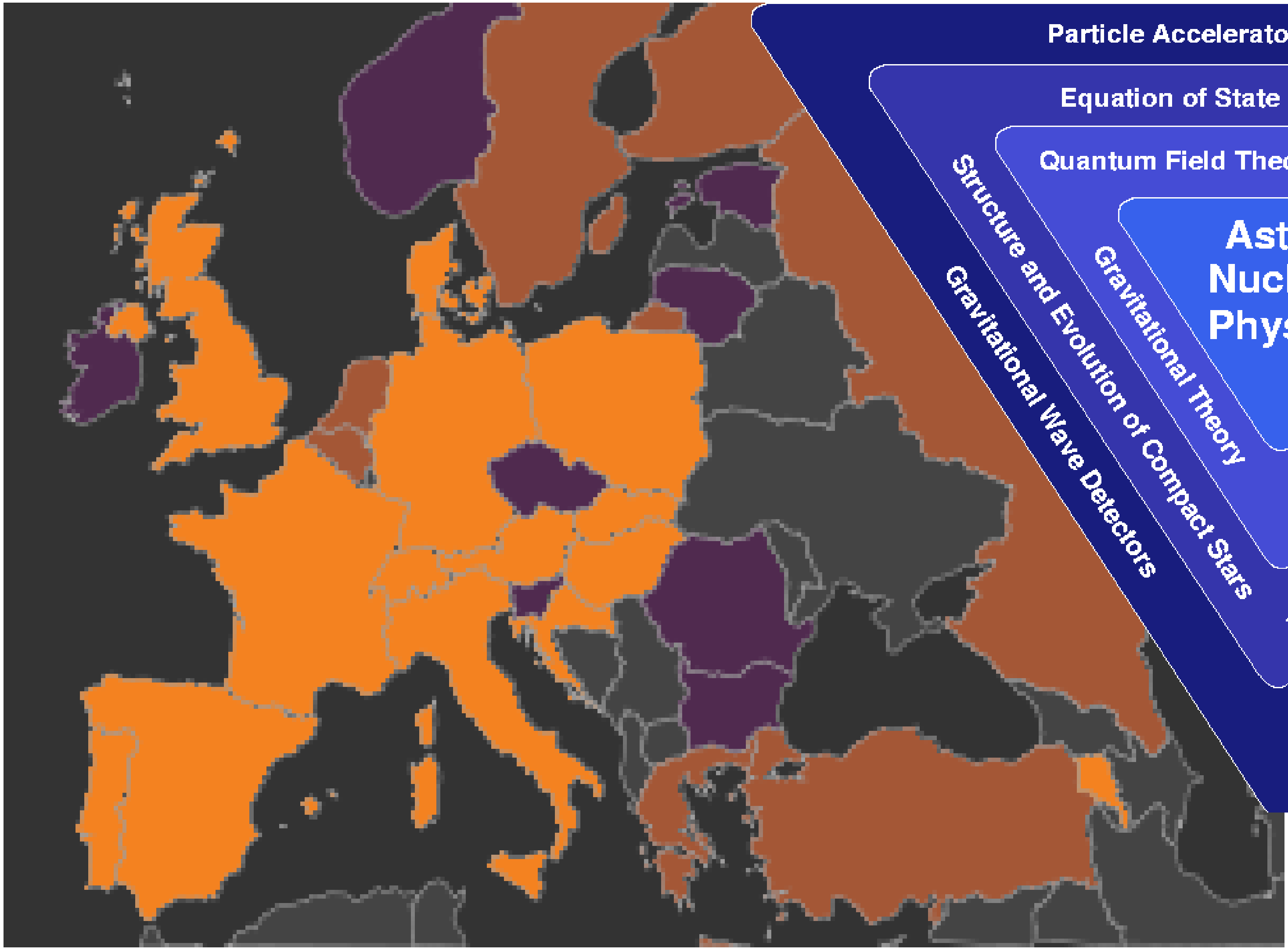
"**T**heory of **HO**t Matter in **R**elativistic Heavy-Ion Collisions"

New: THOR!

cost

EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

Kick-off: Brussels, October 17, 2016



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Gravitational Wave Detectors

Radio– and optical Telescopes; X–ray–, Gamma– Satellites

comp star

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Newest:

PHAROS

THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

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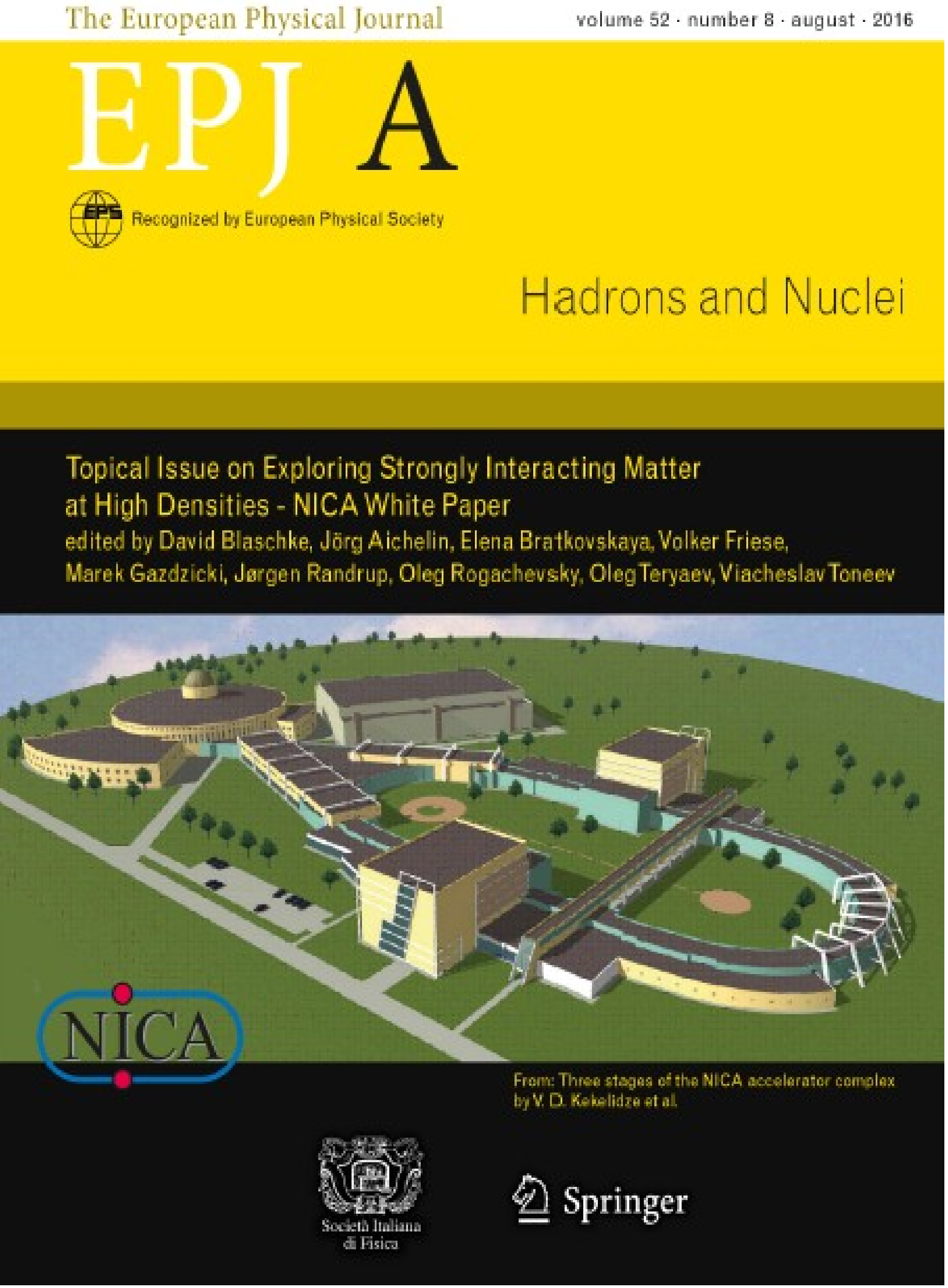
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

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


The European Physical Journal volume 52 · number 8 · august · 2016

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Hadrons and Nuclei

Topical Issue on Exploring Strongly Interacting Matter at High Densities - NICA White Paper
edited by David Blaschke, Jörg Aichelin, Elena Bratkovskaya, Volker Friese, Marek Gazdzicki, Jørgen Randrup, Oleg Rogachevsky, Oleg Teryaev, Viacheslav Toneev

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

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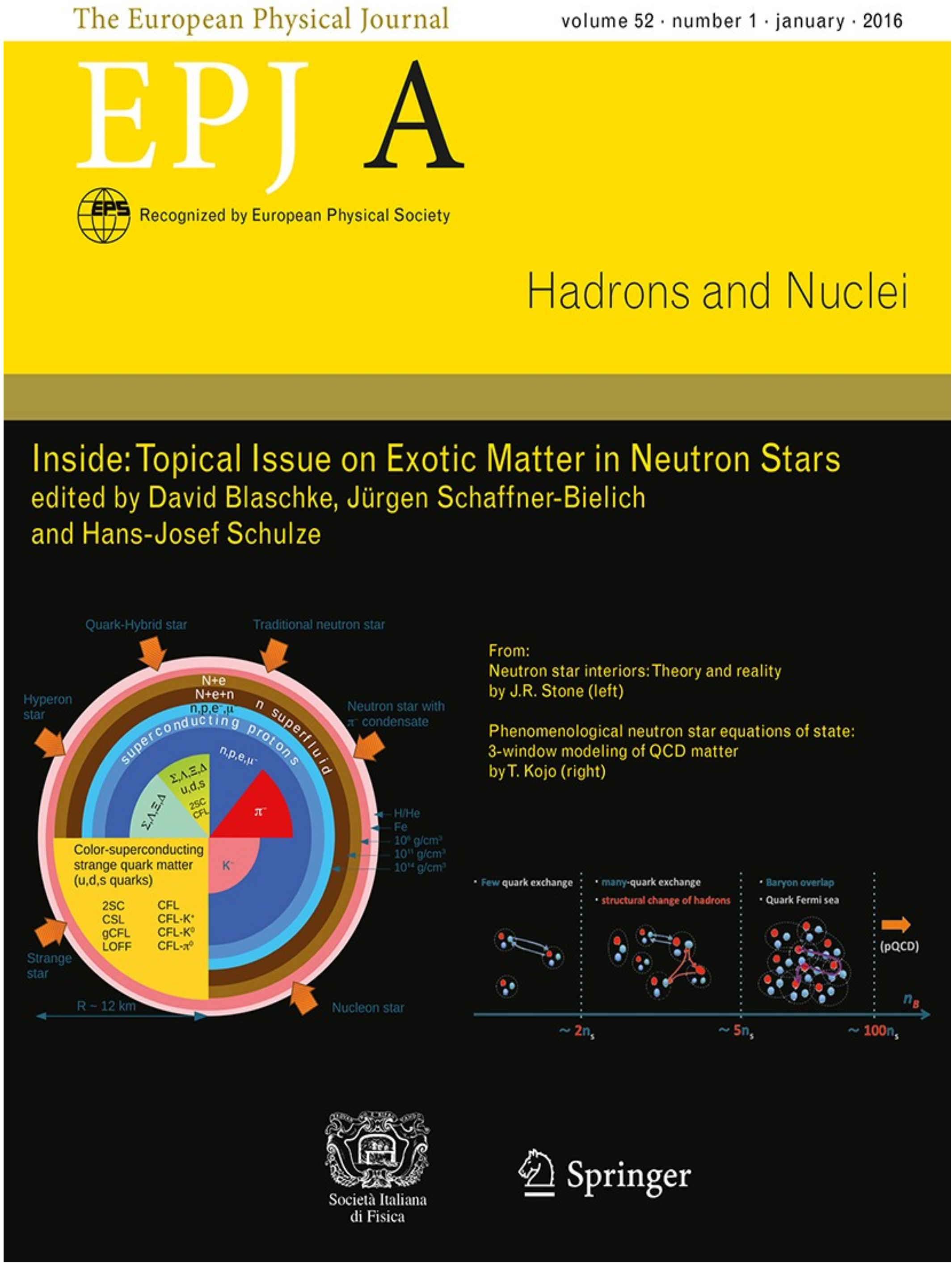
The European Physical Journal volume 52 · number 1 · january · 2016

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Hadrons and Nuclei

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edited by David Blaschke, Jürgen Schaffner-Bielich
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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)

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New Topical Issue:

EPJ A
Recognized by European Physical Society
Hadrons and Nuclei

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 – October 2019

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

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Invitation: ECT* Trento, 14.-18.10.2019 ….

The first compact star merger event – Implications for nuclear and particle physics

From Monday, 14 October, 2019 - 08:00 to Friday, 18 October, 2019 - 14:00

Location: ECT* meeting room

Abstract:
Multimessenger observation of compact stars (CSs) mergers have the potential to revolutionize nuclear astrophysics. Data from the first detection, now called GW170817, has already provided strong hints that heavy elements are produced in CS mergers and first constrains the properties of dense matter. It is expected that the Advanced LIGO & Virgo detector network will discover several new events in the first months of the new observing run, which should start in the early 2019 after a series of upgrades to the detectors that should boost their sensitivities by a factor ~3. A vibrant collaborative efforts involving nuclear physicists, computational astrophysicists, and GW and EM observers will be key for the interpretation of past and future observations. This workshop will bring together prominent members of these communities with the aim of maximizing the scientific impact of CS merger observations in nuclear astrophysics.

Registration period: 29 Jul 2019 to 23 Sep 2019

SECRETARIAT

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Organizers

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David Radice	Princeton University	dradice@astro.princeton.edu

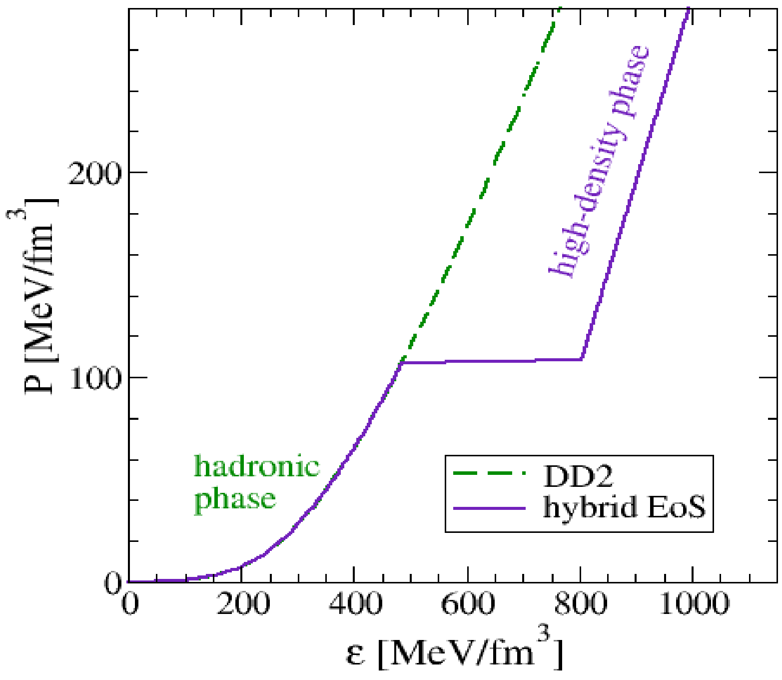
Backup slides

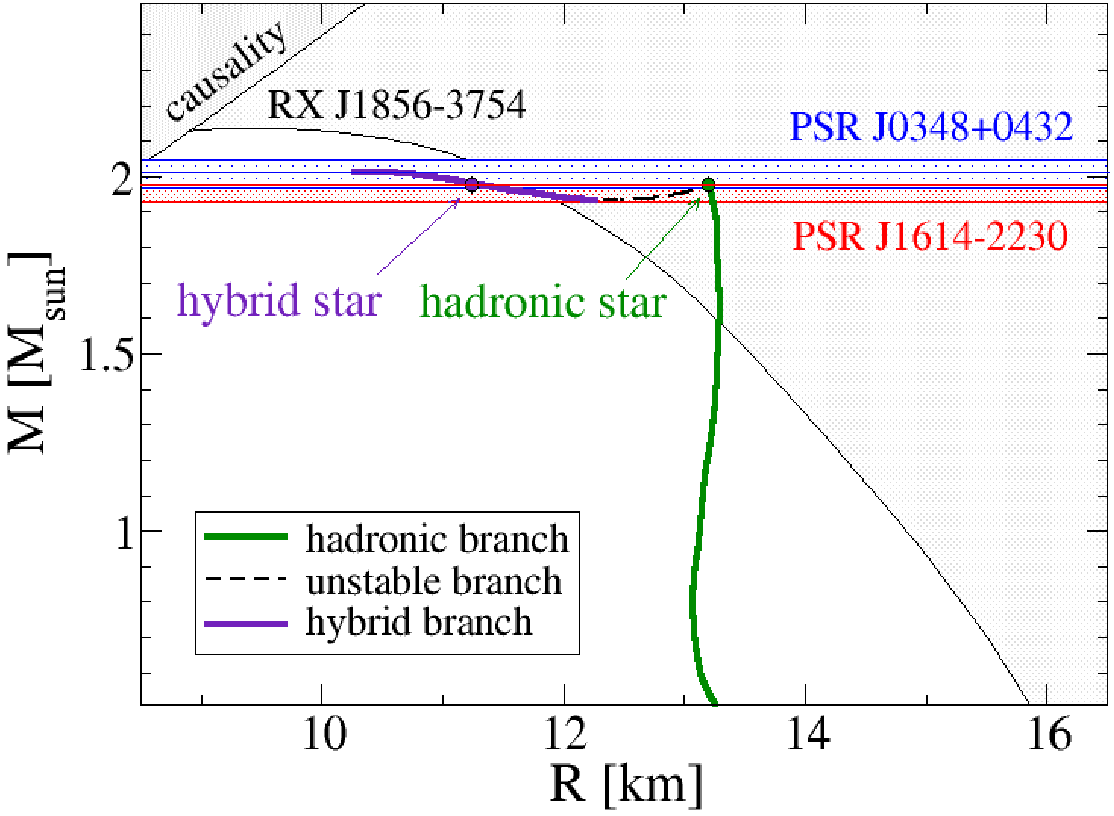
“Holy Grail” - High-Mass Twin Stars

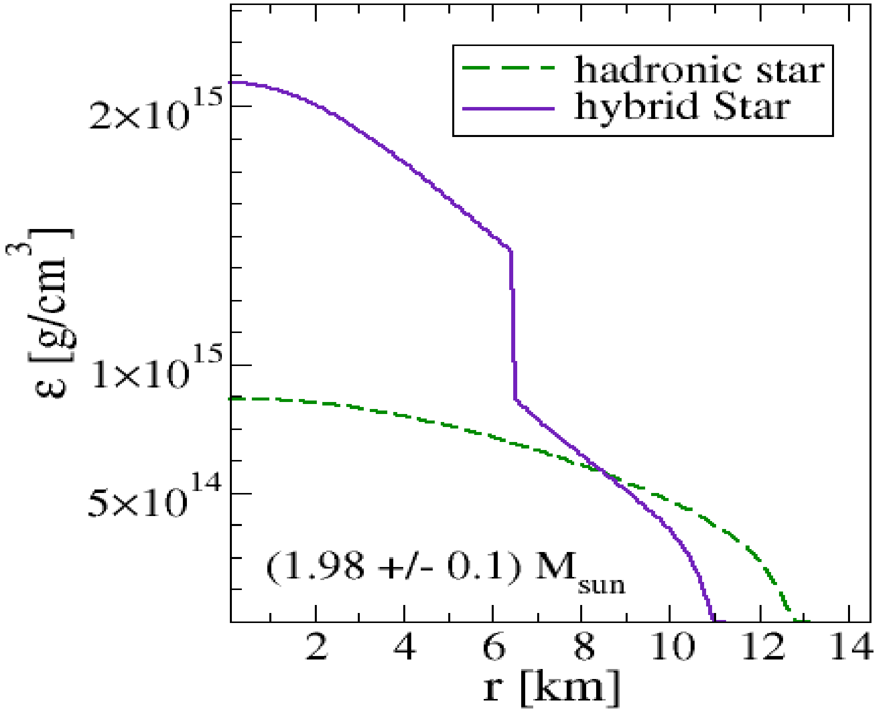
Twins prove exitence of **disconnected populations** (third family) in the M-R diagram

Consequence of a **first order phase transition**

Question: Do twins prove the 1st order phase trans.?







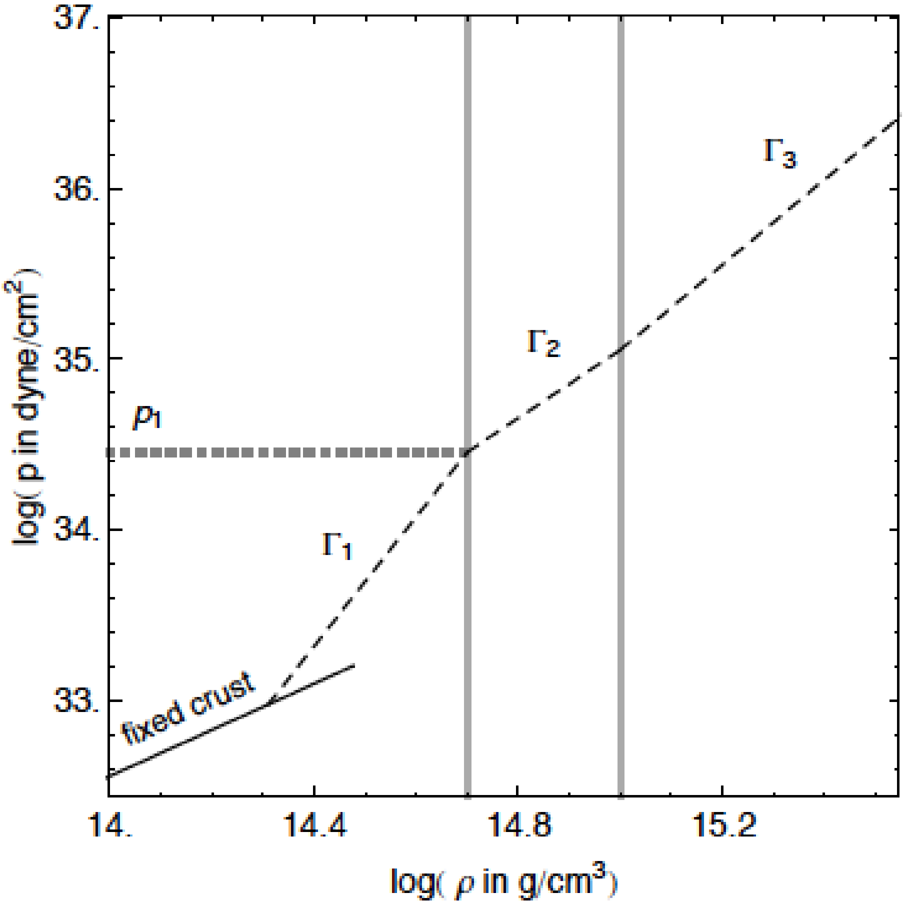
Alvarez & Blaschke, arxiv:1304.7758

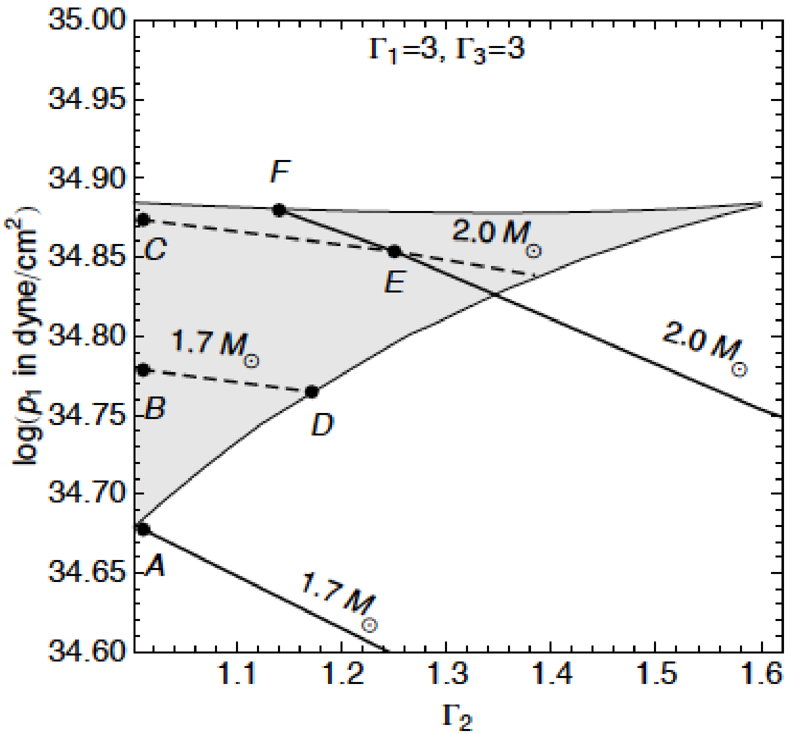
3. Piecewise polytrope EoS – high mass twins (HMT)?

J. Read et al., PRD 79, 124032 (2009)

$$\boxed{P_i(n) = \kappa_i n^{\Gamma_i}}$$

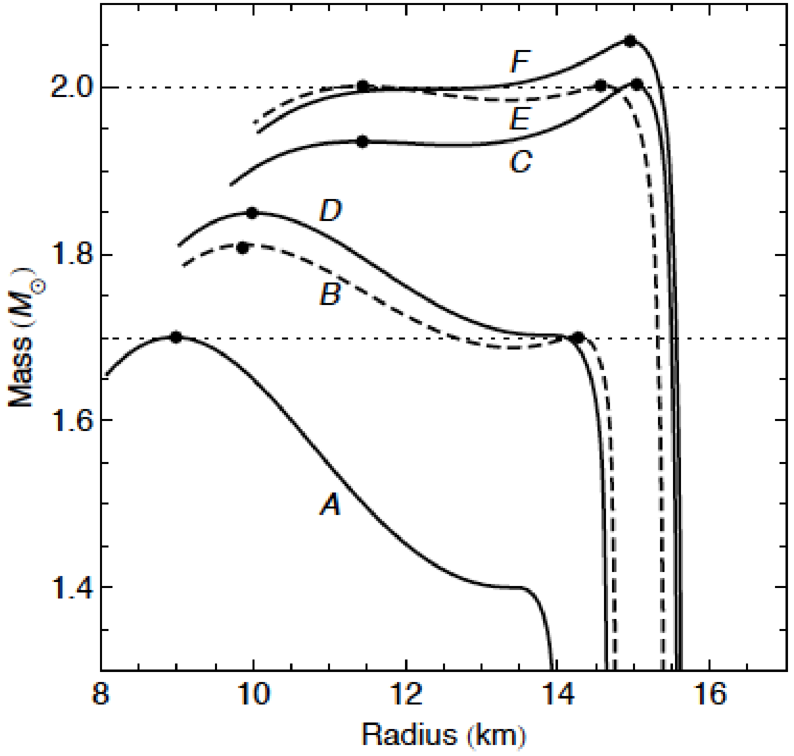
$$\begin{aligned} i = 1 &: n_1 \leq n \leq n_{12} \\ i = 2 &: n_{12} \leq n \leq n_{23} \\ i = 3 &: n \geq n_{23} \ , \end{aligned}$$





Case E:

HMT @ 2 M_{sun}



3. Piecewise polytrope EoS – high mass twins?

Hebeler et al., ApJ 773, 11 (2013)

$$P_i(n) = \kappa_i n^{\Gamma_i}$$

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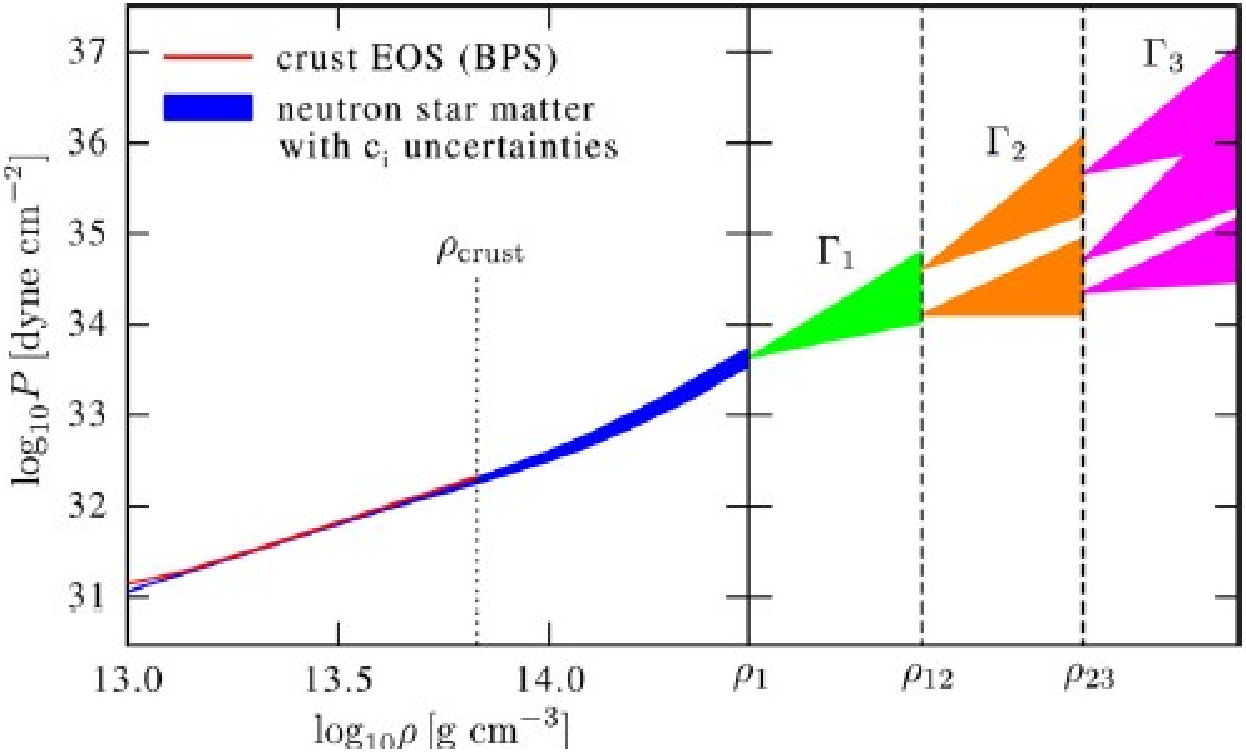

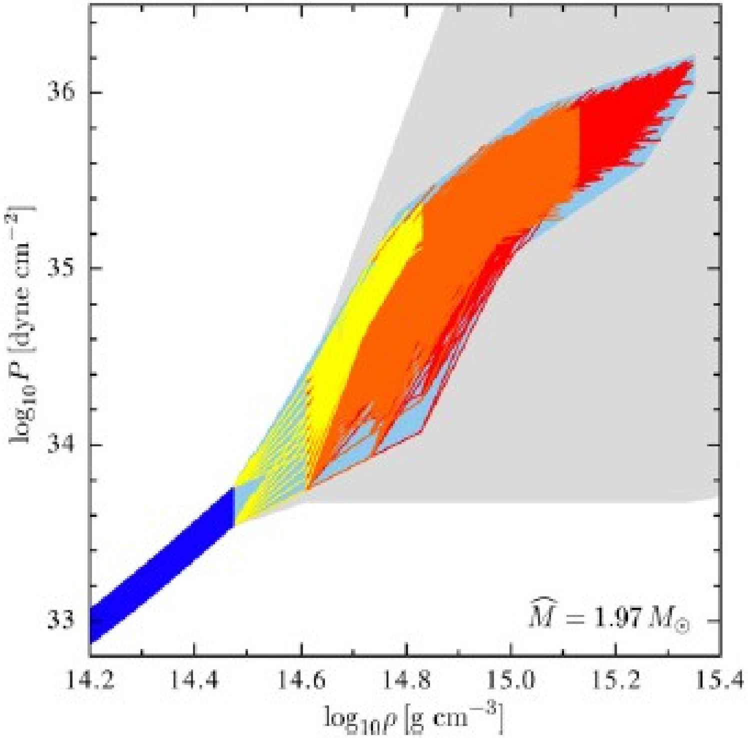

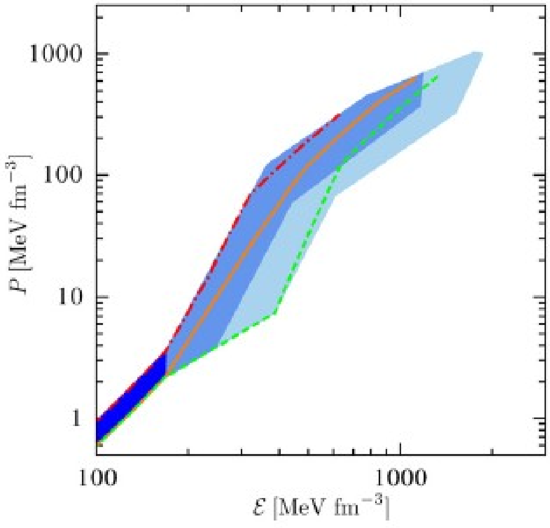

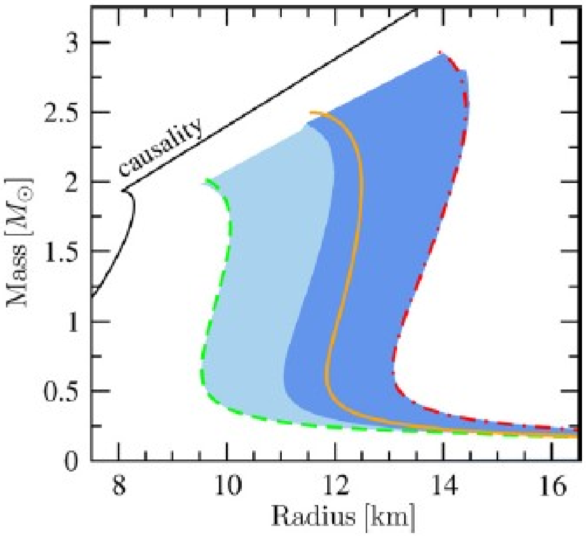

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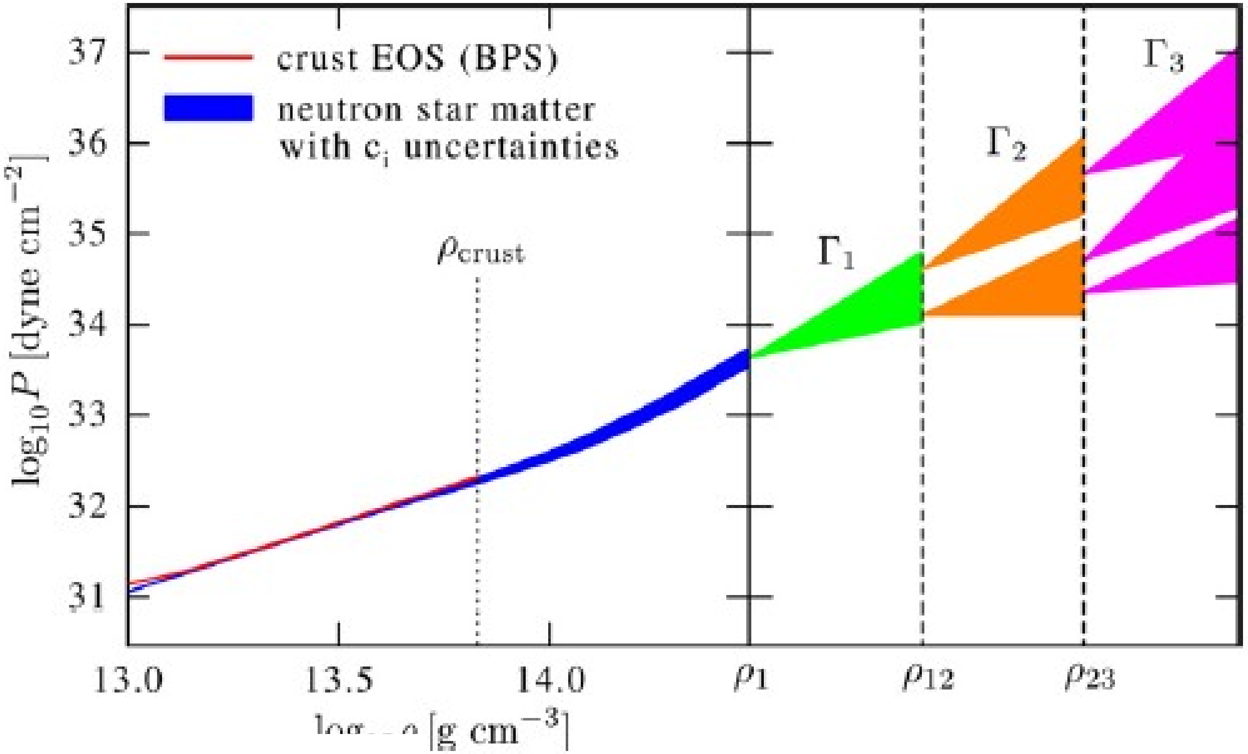

Here, 1st order PT in region 2:

$$\Gamma_2 = 0 \text{ and } P_2 = \kappa_2 = P_{\rm crit}$$

$$\begin{aligned} P(n) &= n^2 \frac{d(\varepsilon(n)/n)}{dn}, \\ \varepsilon(n)/n &= \int dn \, \frac{P(n)}{n^2} = \int dn \, \kappa n^{\Gamma-2} = \frac{\kappa \, n^{\Gamma-1}}{\Gamma - 1} + C, \\ \mu(n) &= \frac{P(n) + \varepsilon(n)}{n} = \frac{\kappa \Gamma}{\Gamma - 1} n^{\Gamma-1} + m_0, \end{aligned}$$

$$\begin{aligned} n(\mu) &= \left[(\mu - m_0) \frac{\Gamma - 1}{\kappa \Gamma} \right]^{1/(\Gamma-1)} \\ P(\mu) &= \kappa \left[(\mu - m_0) \frac{\Gamma - 1}{\kappa \Gamma} \right]^{\Gamma/(\Gamma-1)} \end{aligned}$$

Maxwell construction:

$$\begin{aligned} P_1(\mu_{\rm crit}) &= P_3(\mu_{\rm crit}) = P_{\rm crit} \\ \mu_{\rm crit} &= \mu_1(n_{12}) = \mu_3(n_{23}) \end{aligned}$$

Seidov criterion for instability: $$\frac{\Delta\varepsilon}{\varepsilon_{\rm crit}} \geq \frac{1}{2} + \frac{3}{3} \frac{P_{\rm crit}}{\varepsilon_{\rm crit}}$$

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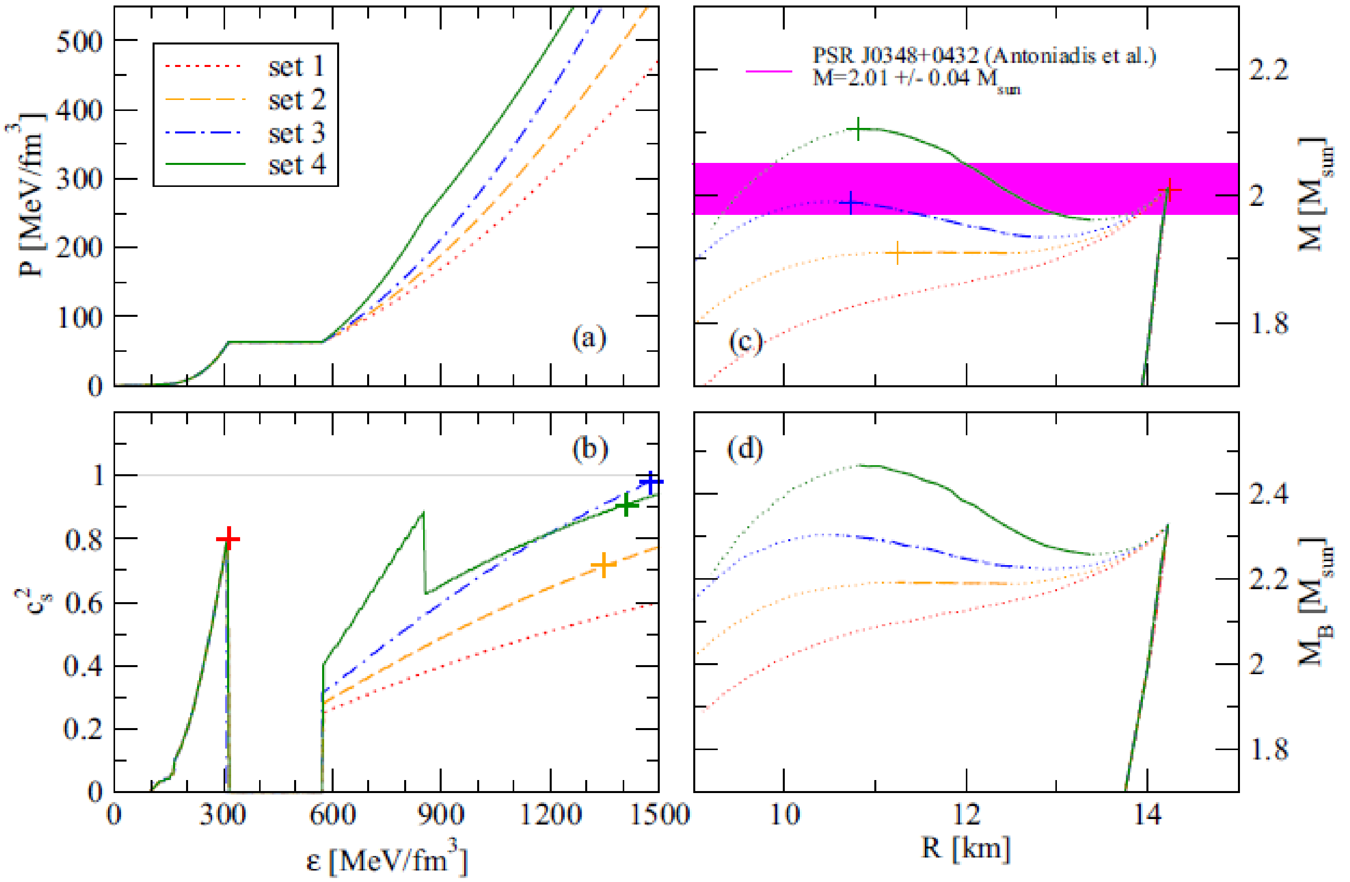
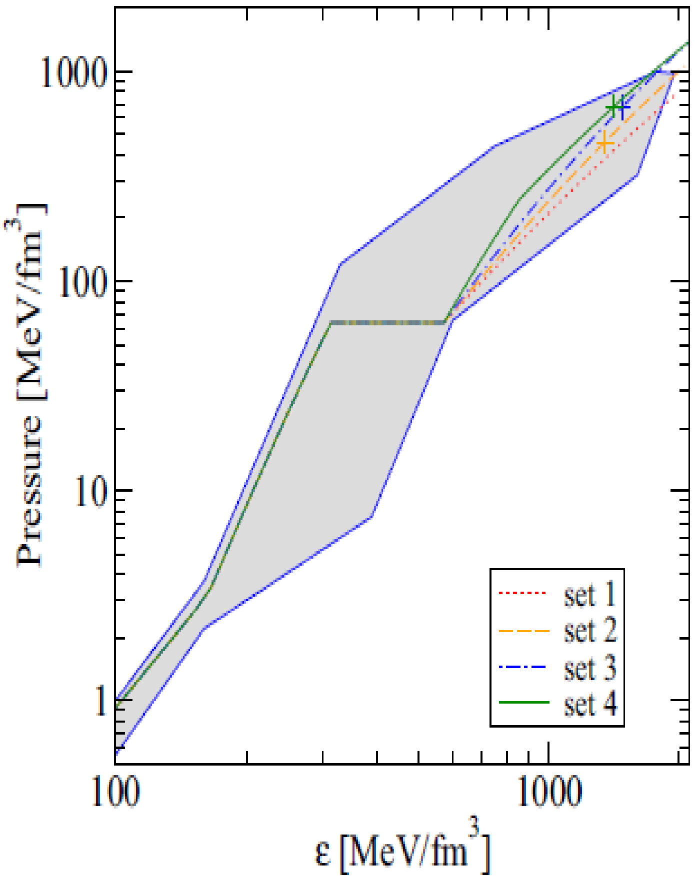




	Γ_3	κ_3 [MeV fm$^{3(\Gamma_3-1)}$]	$m_{0,3}$ [MeV]	$M^{NS}_{\max}$ [$M_\odot$]	$M^{HS}_{\max}$ [$M_\odot$]	$M^{HS}_{\min}$ [$M_\odot$]
set 1	2.50	302.56	991.75	2.01	–	–
set 2	2.80	365.12	1004.88	2.01	1.910	1.909
set 3	3.12	447.16	1014.87	2.01	1.991	1.934
set 4a	4.00	774.375	1031.815			
set 4b	2.80	548.309	958.553	2.01	2.106	1.961

All sets with same onset of phase transition; P_{crit} = 63.2 MeV/fm^3, ε_{crit} = 318.3 MeV/fm^3 and same jump in energy density $\Delta\varepsilon$ = 253.9 MeV/fm^3; varying Γ_3

Third family solutions found at 2 Msol (HMT), 4-tropes favored; match with Hebeler et al.!

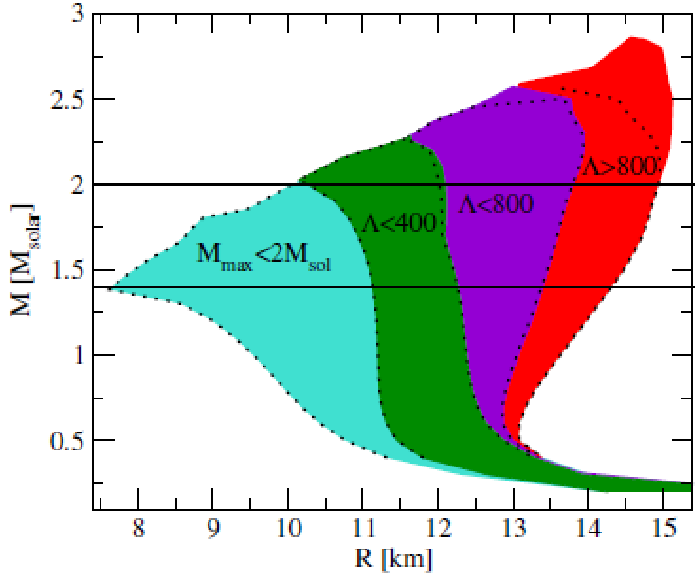
[D. Alvarez & D.B. PRC 96 (2017) 045809]

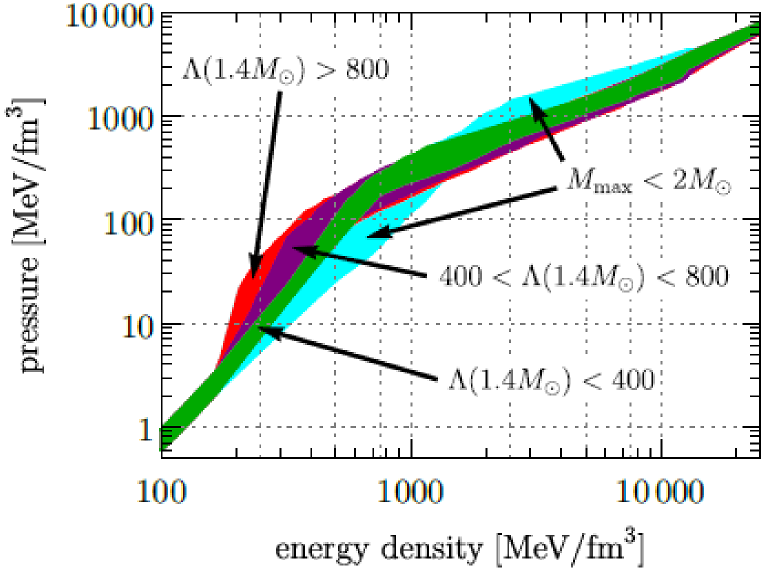
arxiv:1711.02644 [astro-ph.HE]

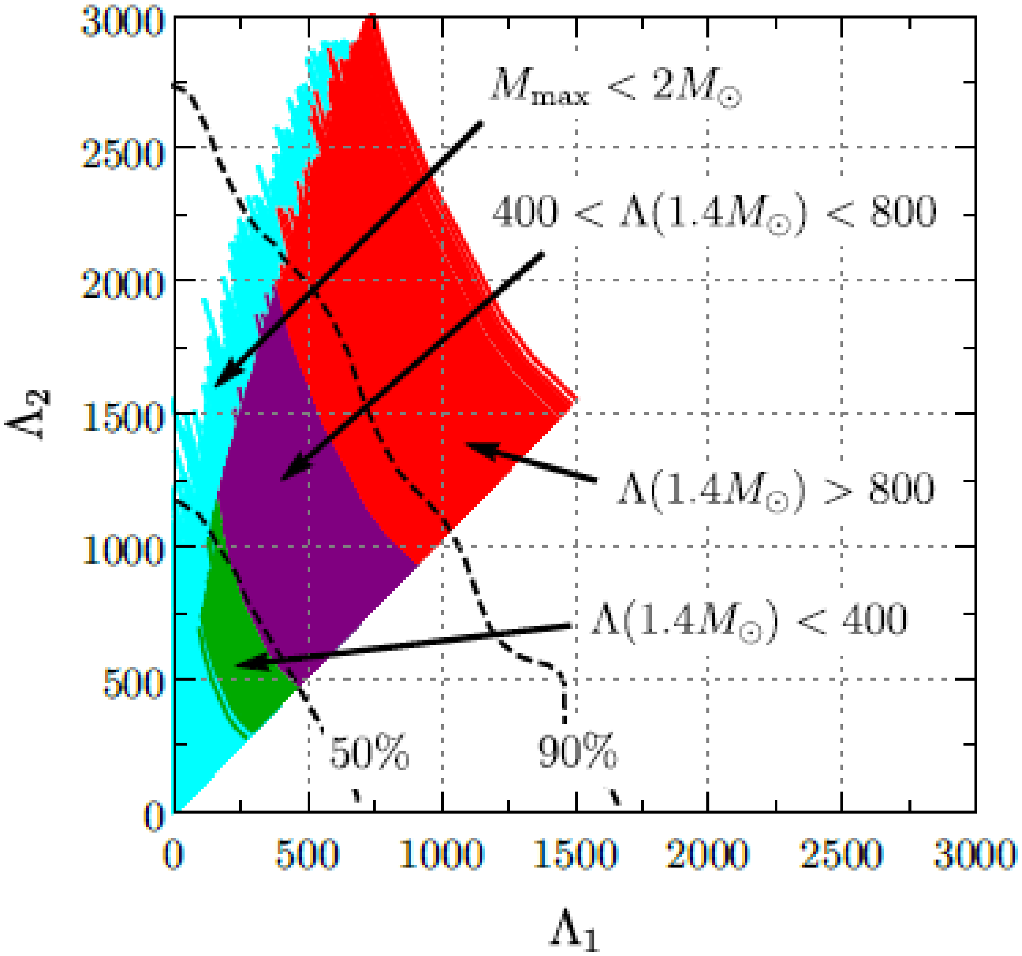
CERN-TH-2017-236, HIP-2017-30/TH

Gravitational-wave constraints on the neutron-star-matter Equation of State

Eemeli Annala,[1] Tyler Gorda,[1] Aleksi Kurkela,[2] and Aleksi Vuorinen[1]





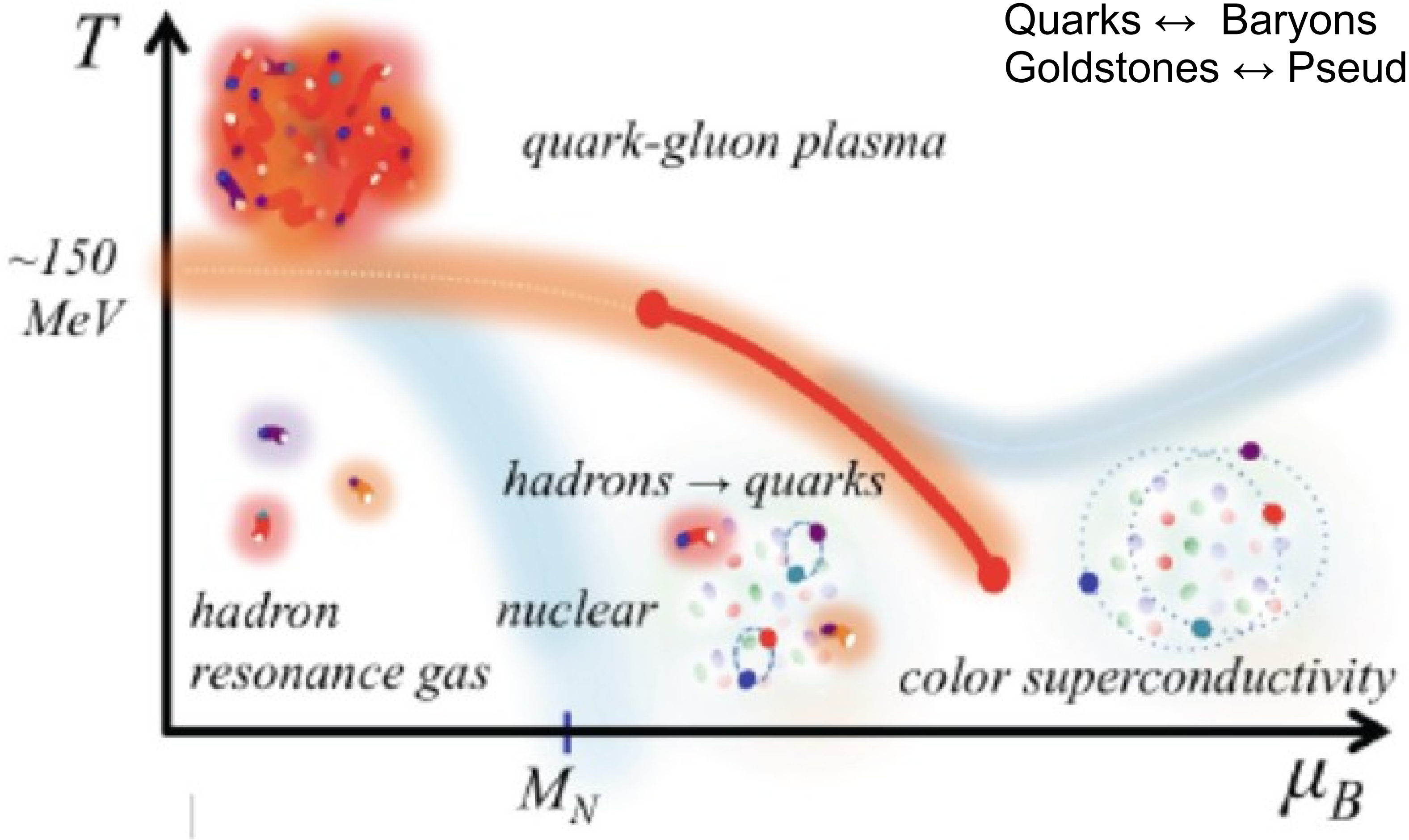


Unfortunately, twins and third family forgotten !!!
For this aim, 2- and 3-tropes not sufficient, 4-tropes!

Refined calculation (with twins) is under way (A.V.)

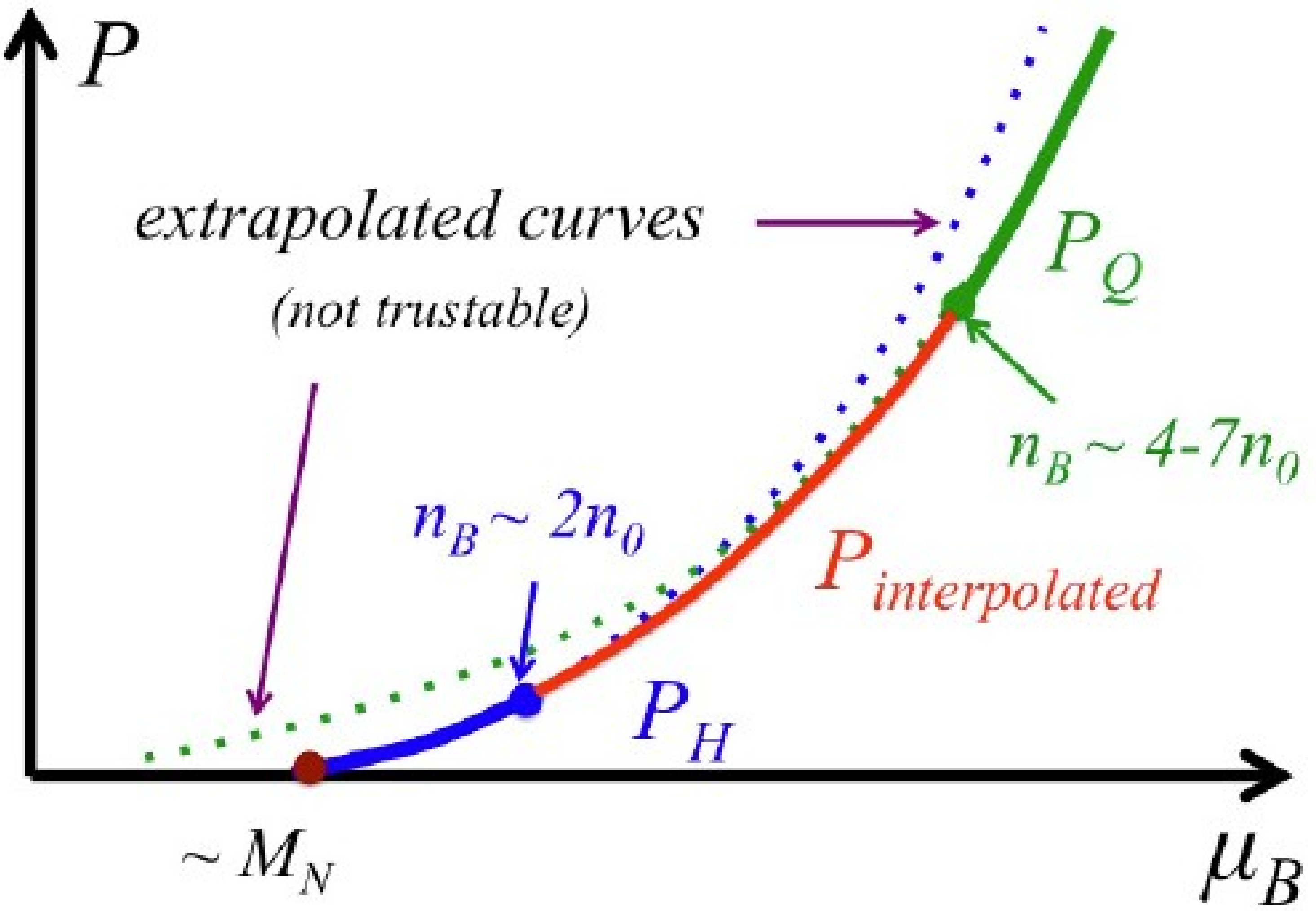
2nd CEP in QCD phase diagram: Quark-Hadron Continuity?

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

Interpolating between Hadron and Quark Phases



Note:

Here, a usual
Maxwell construction
Makes no sense!

Replaced by
“Kojo interpolation”

From: T. Kojo, P.D. Powell, Y. Song and G. Baym, PRD 91, 045003 (2015)
See also discussion in: D.B. and N. Chamel, arxiv:1803.01836

All is possible with EoS??

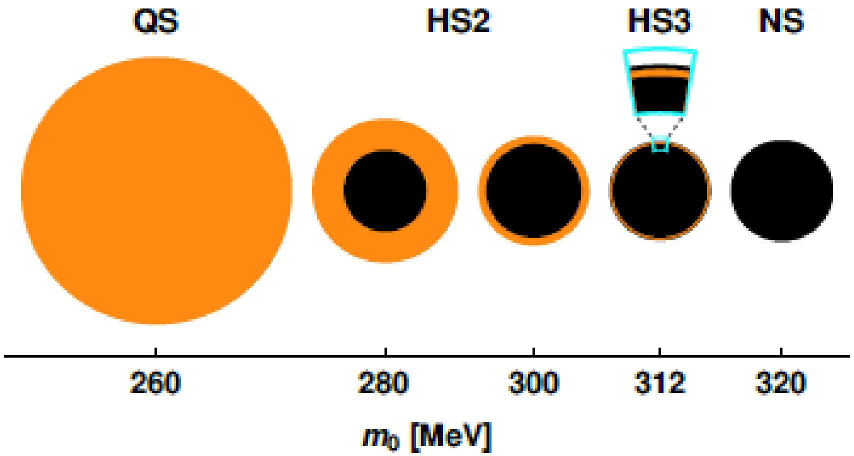
No!!

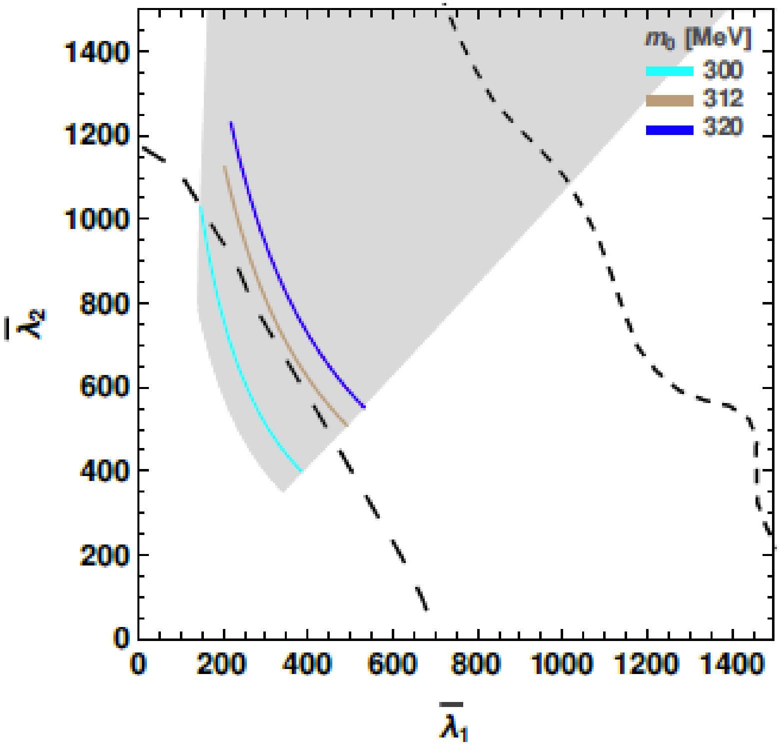
Alternative facts: New hybrid star solutions!

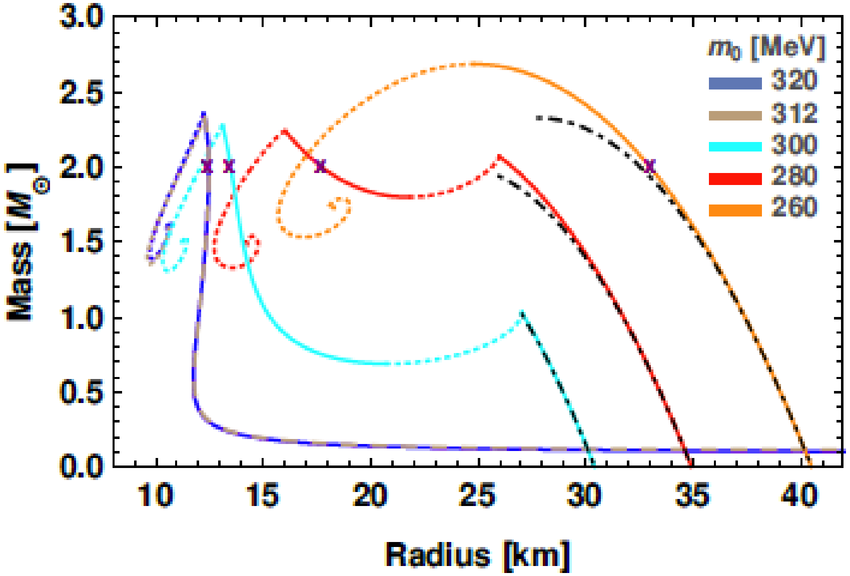
arxiv:1711.06244v1, 1611.2017

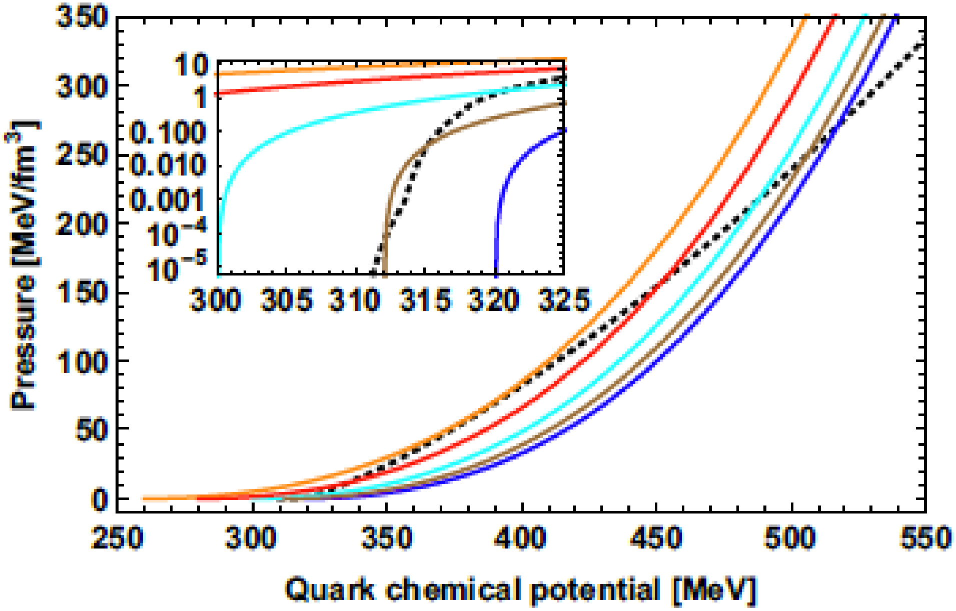
Holographic compact stars meet gravitational wave constraints

Eemeli Annala,[1,*] Christian Ecker,[2,†] Carlos Hoyos,[3,‡] Niko Jokela,[1,§]
David Rodríguez Fernández,[3,4,¶] and Aleksi Vuorinen[1,**]









Alternative facts of the day: New hybrid star solutions!

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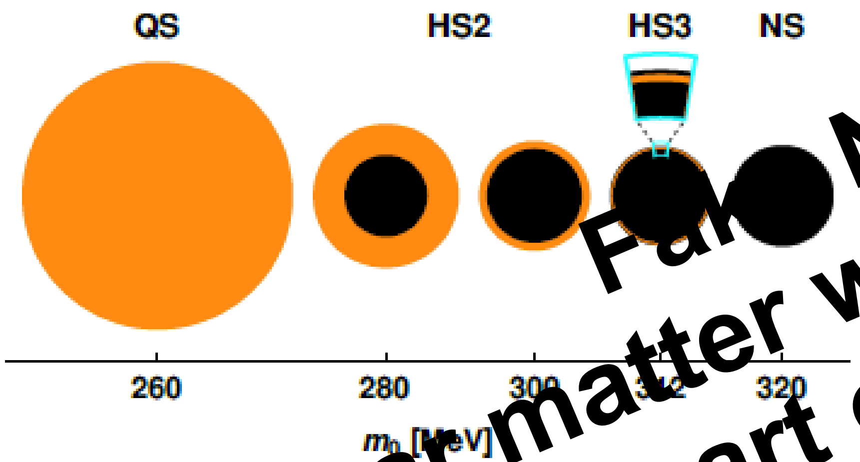

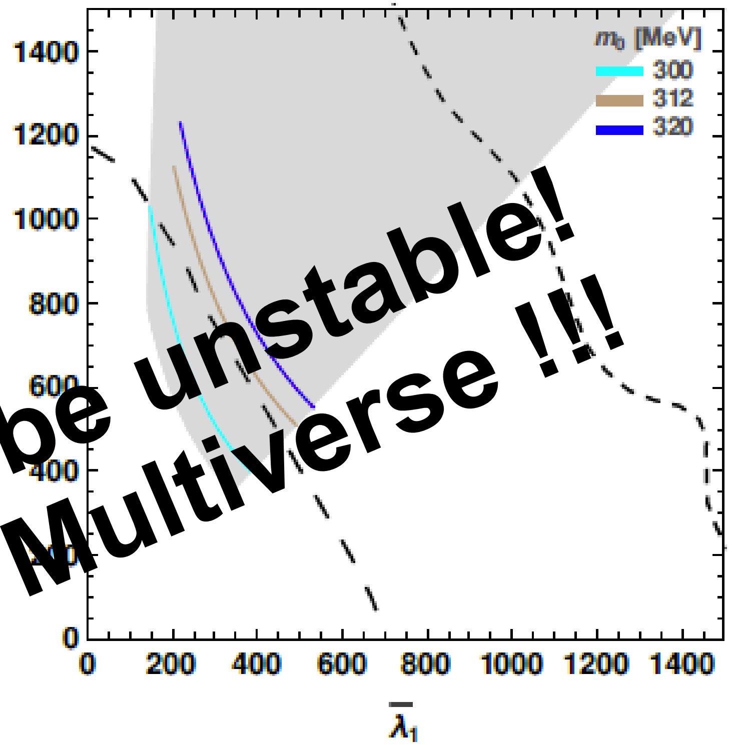

Fake News:
Nuclear matter would be unstable!
Not in our part of the Multiverse !!!