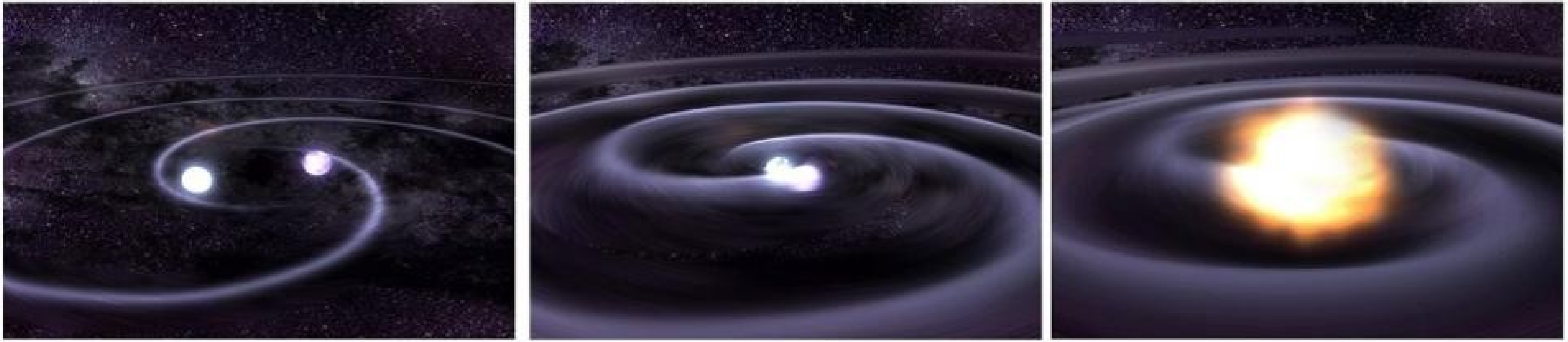
QCD Phase Diagram @ NICA energies - K+/π+ horn effect & light clusters in THESEUS

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



NICA Days & 4th MPD Collaboration Meeting, Warsaw, 21.10.2019

JINR DUBNA

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RSF Russian Science Foundation

RFBR

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1. **Introduction:**
   - **QCD Phase Diagram**
   - **3FH Model (THESEUS)**
2. **Light fragments at chemical freezeout, E~50 AMeV…30 AGeV**
3. **K^+/π^+ horn effect from anomalous K^+ mode in the BSE**
6. **Conclusions**

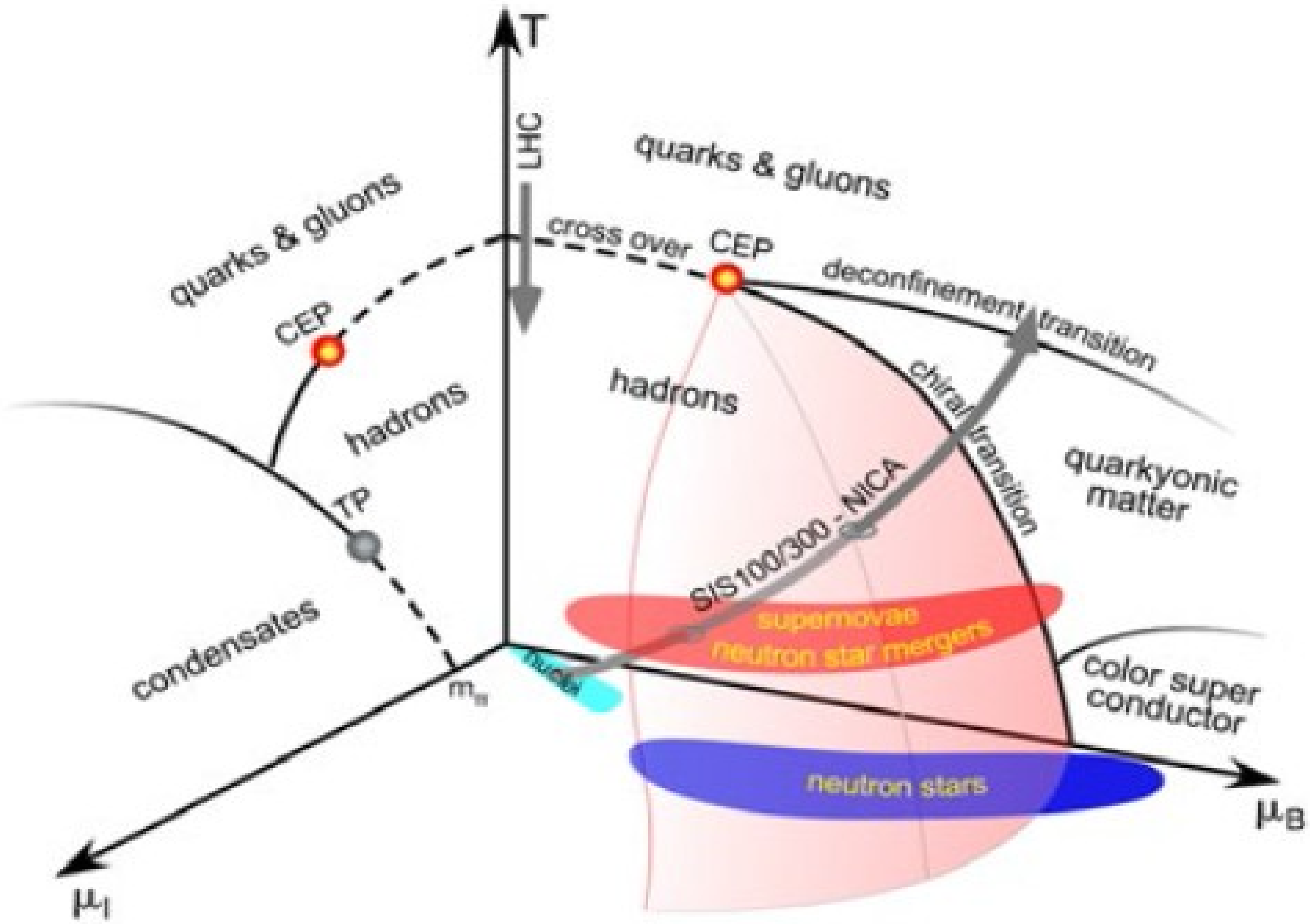
NICA Days & 4th MPD Collaboration Meeting, Warsaw, 21.10.2019

DUBNA

Grant No. 17-12-01427

Grant No. 18-02-40137

CEP in the QCD phase diagram: HIC vs. Astrophysics

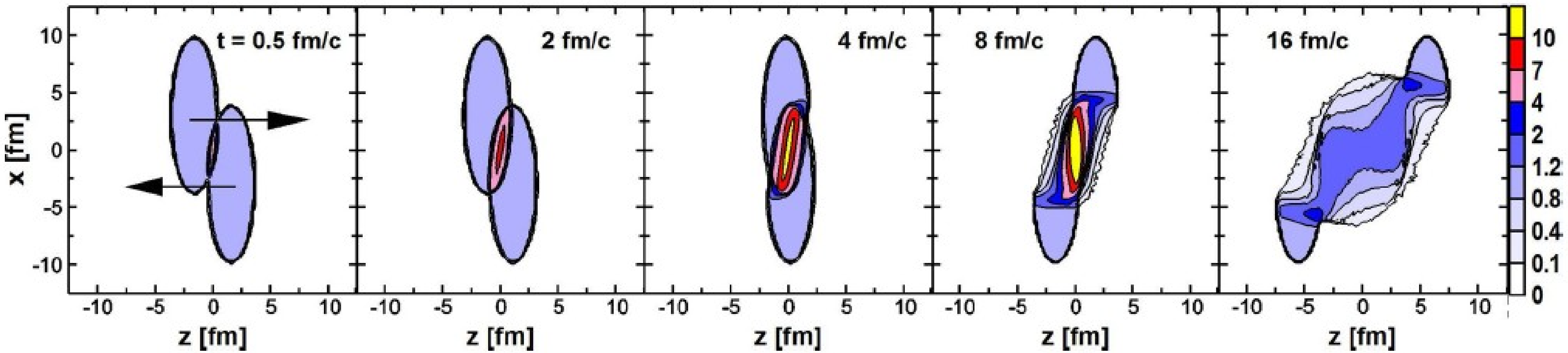


NuPECC Long Range Plan 2017; http://www.nupecc.org

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

Three-fluid hydrodynamics model of heavy-ion collisions

baryon density (n_B/n_0) in reaction plane of Au+Au collision at $\sqrt{s_{NN}}$ = 6.4 GeV, b = 6 fm



Initial state → hydrodynamic evolution → particlization → hadronic cascade → detector response

3-fluid hydro,
(Yu. Ivanov)

adapt the procedure
from existing hybrid model
(Iu. Karpenko)

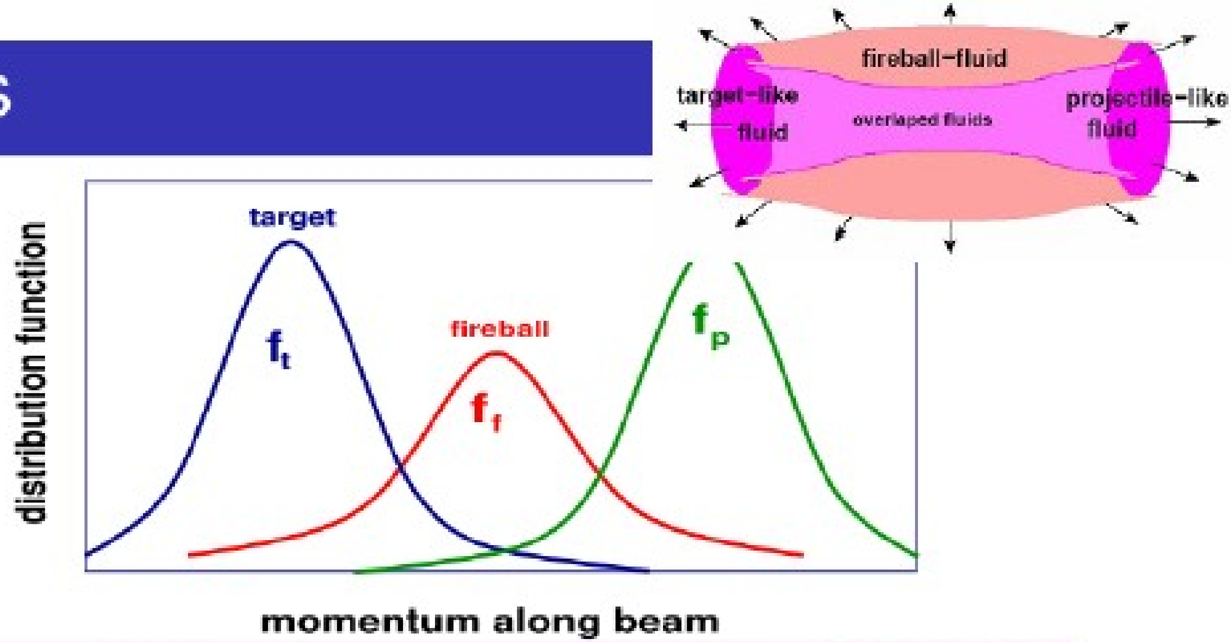
(optionally) UrQMD, etc
(Iu. Karpenko,
H. Elfner)

GEANT
MPD, BM @N
(O. Rogachevsky,
P. Batyuk,
S. Merts, et al.)

P. Batyuk et al., Phys. Rev. C 94, 044917 (2016) [THESEUS project]

3-Fluid Dynamics

Produced particles populate mid-rapidity
⇒ fireball fluid



Target-like fluid: $\partial_\mu J^\mu_t = 0$ $\quad \partial_\mu T^{\mu\nu}_t = -F^\nu_{tp} + F^\nu_{ft}$

Leading particles carry bar. charge exchange/emission

Projectile-like fluid: $\partial_\mu J^\mu_p = 0,$ $\quad \partial_\mu T^{\mu\nu}_p = -F^\nu_{pt} + F^\nu_{fp}$

Fireball fluid: $J^\mu_f = 0,$ $\quad \partial_\mu T^{\mu\nu}_f = F^\nu_{pt} + F^\nu_{tp} - F^\nu_{fp} - F^\nu_{ft}$

Baryon-free fluid Source term Exchange

The source term is delayed due to a formation time $\tau \sim 1$ fm/c

Total energy-momentum conservation:

$$\partial_\mu (T^{\mu\nu}_p + T^{\mu\nu}_t + T^{\mu\nu}_f) = 0$$

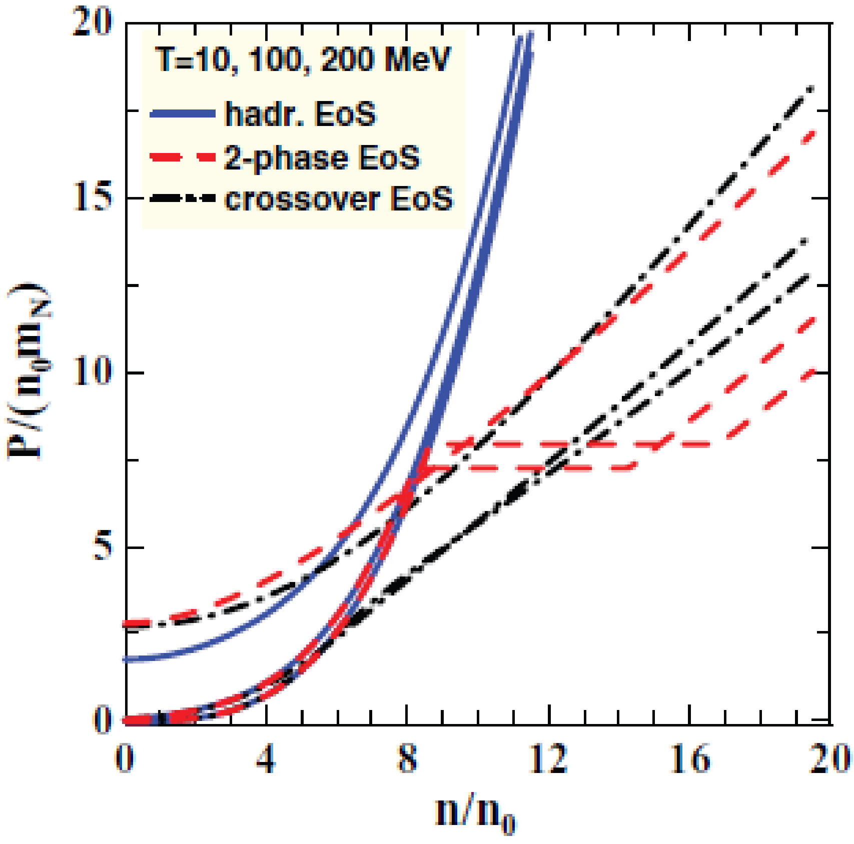
http://mfd.jinr.ru

Yu.B. Ivanov, V.N. Russkikh and V.D. Toneev, Phys. Rev. C73, 044904 (2006)

Three-fluid hydrodynamics: Equation of state inputs

- Three types of EoS for the 3FH simulation:
- Hadronic EoS: Hadron resonance gas model
- 2-phase EoS: Maxwell construction with density-functional approach to quark-gluon plasma
- Crossover EoS: Smooth interpolation between HRG and QGP

New hybrid EoS motivated by Astrophysics (CS merger, massive Supernova explosion mechanism) - under development (Wroclaw-Dubna)



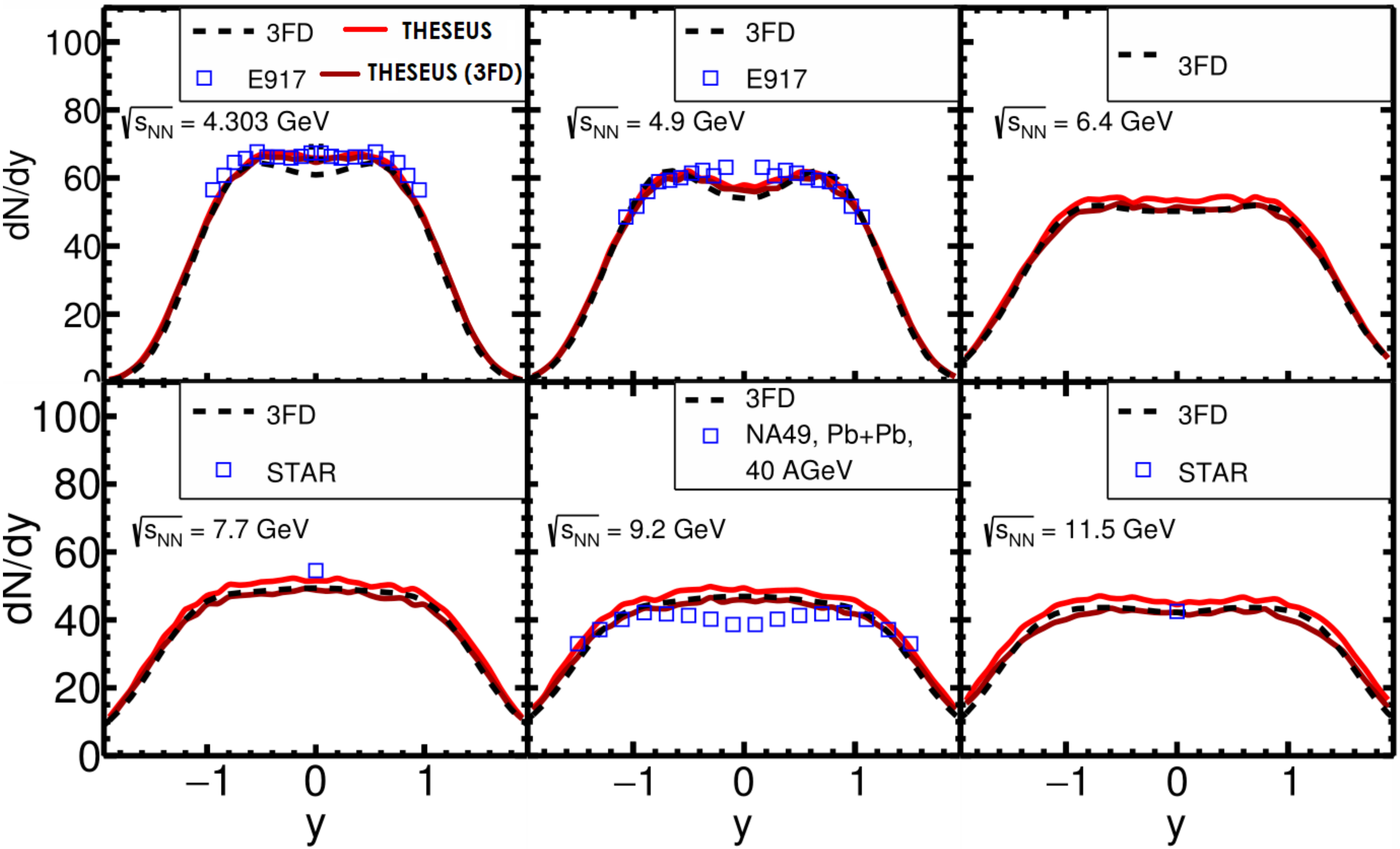
A. Khvorostukhin, V.V. Skokov, V.D. Toneev, K. Redlich, EPJ C48, 531 (2006)
Yu. B. Ivanov, D. Blaschke, PRC 92, 024916 (2015)
T. Fischer et al., Nature Astronomy 2, 980 (2018)
A. Bauswein et al., Phys. Rev. Lett. 122, 061102 (2019)

Baryon stopping signal of deconfinement - robustness

Yu. B. Ivanov, D. Blaschke, PRC 92, 024916 (2015); V. Voronyuk, et al., in preparation

Now with detector simulation!

Net-protons at NICA energies, b=2 fm, with UrQMD



Light Fragment (LF) Production at Low Energies

Chemical picture:

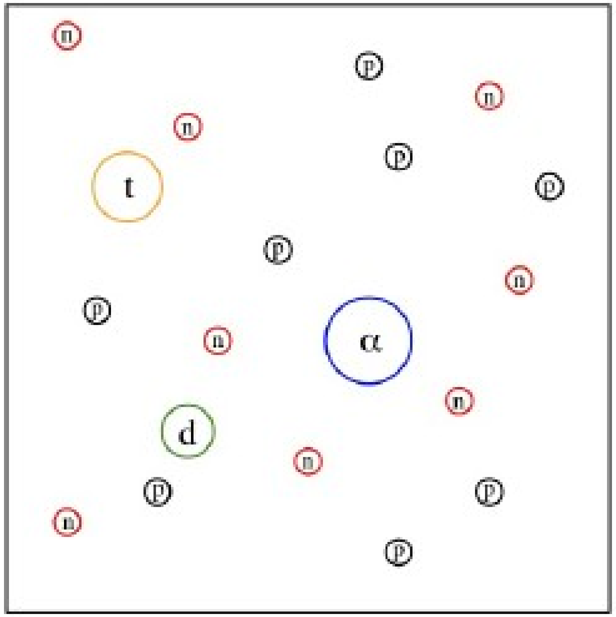
Ideal mixture of reacting components

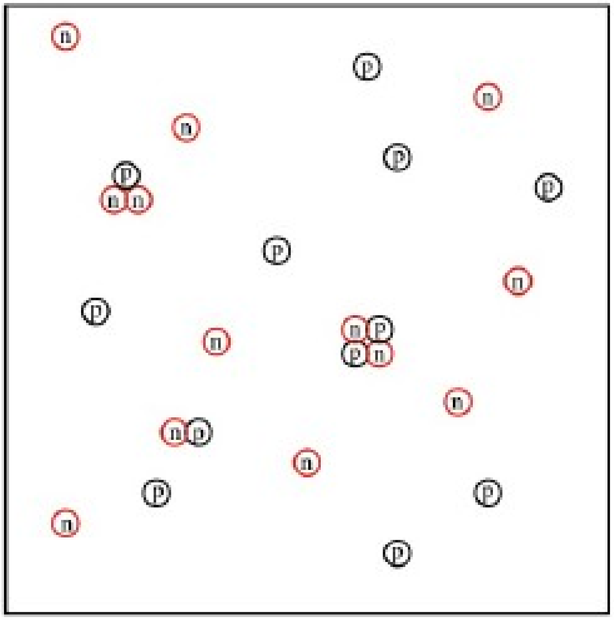
Mass action law

Physical picture:

"elementary" constituents

and their interaction





Interaction between the components

internal structure: Pauli principle

Quantum statistical (QS) approach,

quasiparticle concept, virial expansion

Light Fragment (LF) Production at Low Energies

Effective wave equation for deuterons in nuclear matter

In-medium two-particle wave equation in mean-field approximation

$$\left(\frac{p_1^2}{2m_1}+\Delta_1+\frac{p_2^2}{2m_2}+\Delta_2\right)\Psi_{d,P}(p_1,p_2)+\sum_{p_1',p_2'}(1-f_{p_1}-f_{p_2})V(p_1,p_2;p_1',p_2')\Psi_{d,P}(p_1',p_2')$$

$$= E_{d,P}\Psi_{d,P}(p_1,p_2)$$

Add self-energy

Pauli-blocking

Fermi distribution function

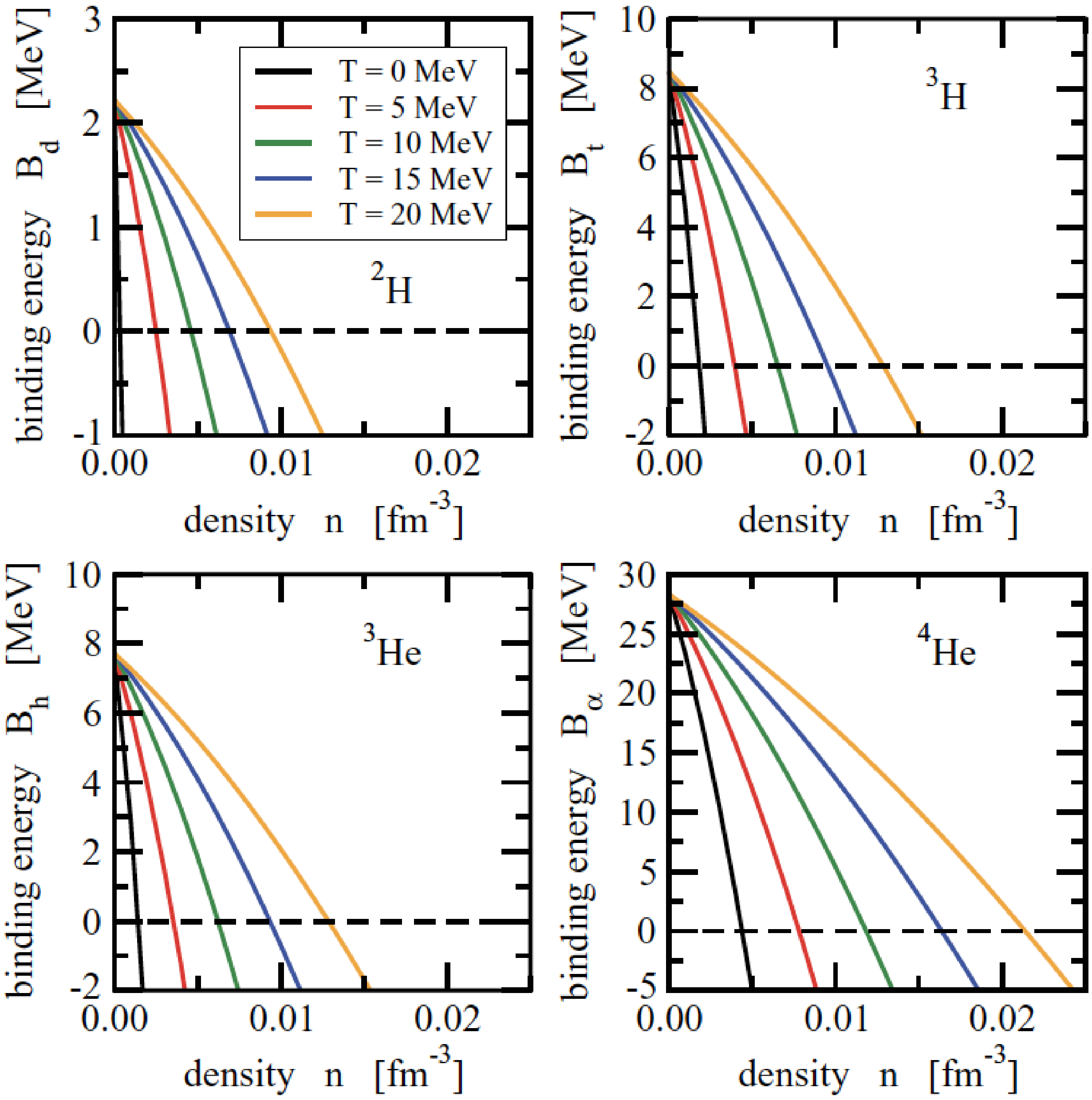
$$f_p=\left[e^{(p^2/2m-\mu)/k_BT}+1\right]^{-1}$$

Thouless criterion

$$E_d(T,\mu)=2\mu$$

BEC-BCS crossover:
Alm et al.,1993

Light Fragment (LF) Production at Low Energies



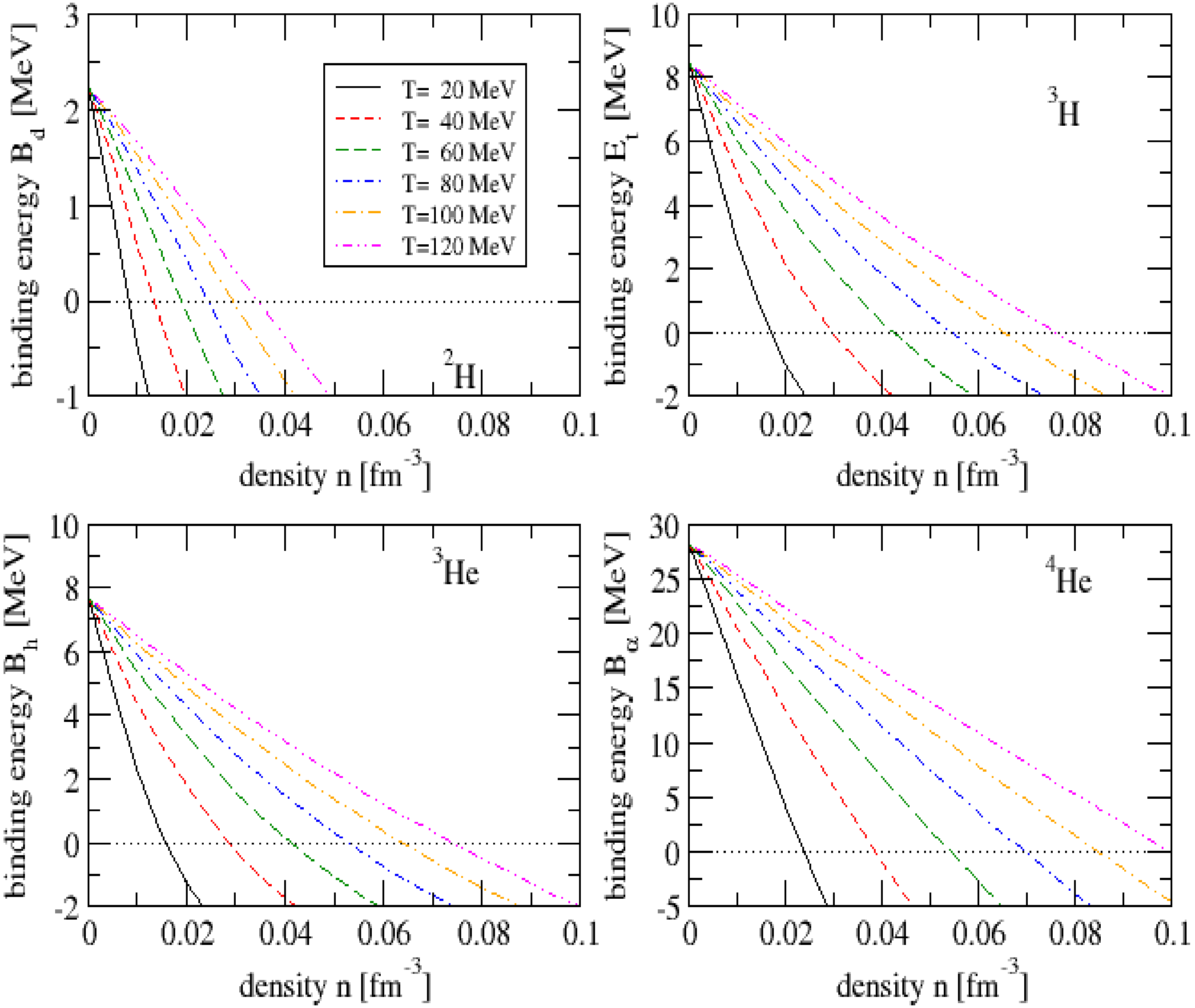
Vanishing binding energies
Indicate Mott effect for the
Light clusters!

Mott-lines in the T-μ plane
can be extracted, where the
Binding energy vanishes

Here lower temperatures:
0 < T[MeV] < 20

S. Typel et al., PRC 81, 015803 (2010)

Light Fragment (LF) Production at Low Energies



Mott-lines in the T-μ plane can be extracted, where The binding energy vanishes

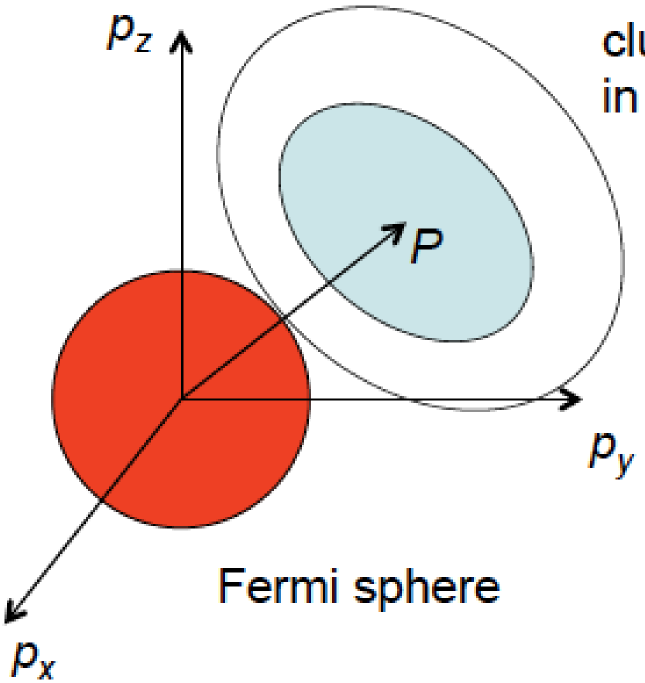
Here higher temperatures:

20 < T[MeV] < 120

Courtesy: G. Roepke

Light Fragment (LF) Production at Low Energies

Pauli blocking – phase space occupation



cluster wave function (deuteron, alpha,…)
in momentum space

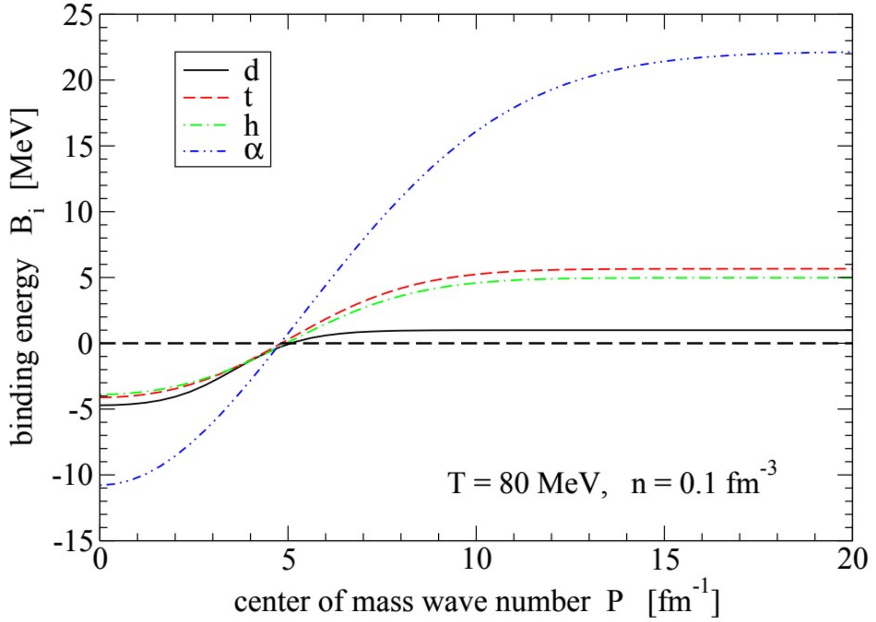
P - center of mass momentum

The Fermi sphere is forbidden,
deformation of the cluster wave function
in dependence on the c.o.m. momentum P

momentum space

The deformation is maximal at $P = 0$.
It leads to the weakening of the interaction
(disintegration of the bound state).

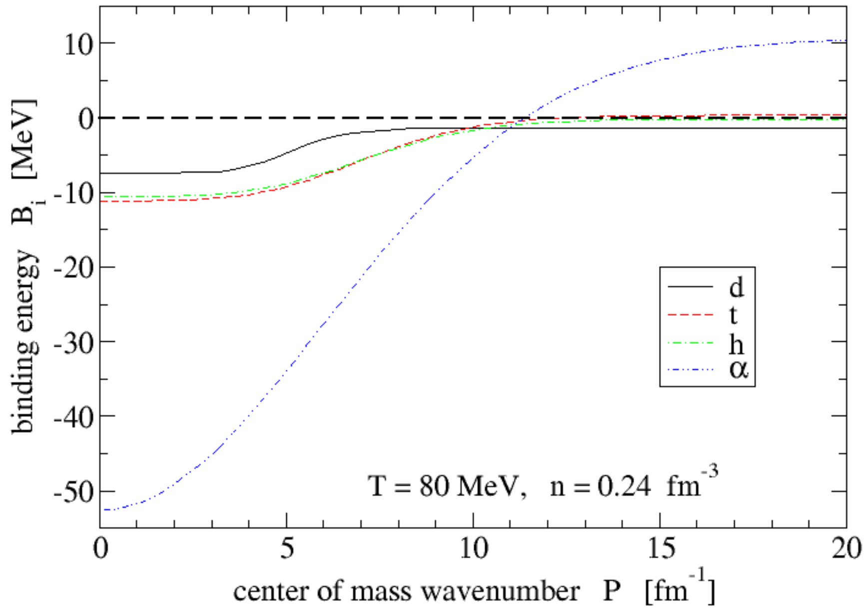
Light Fragment (LF) Production at Low Energies

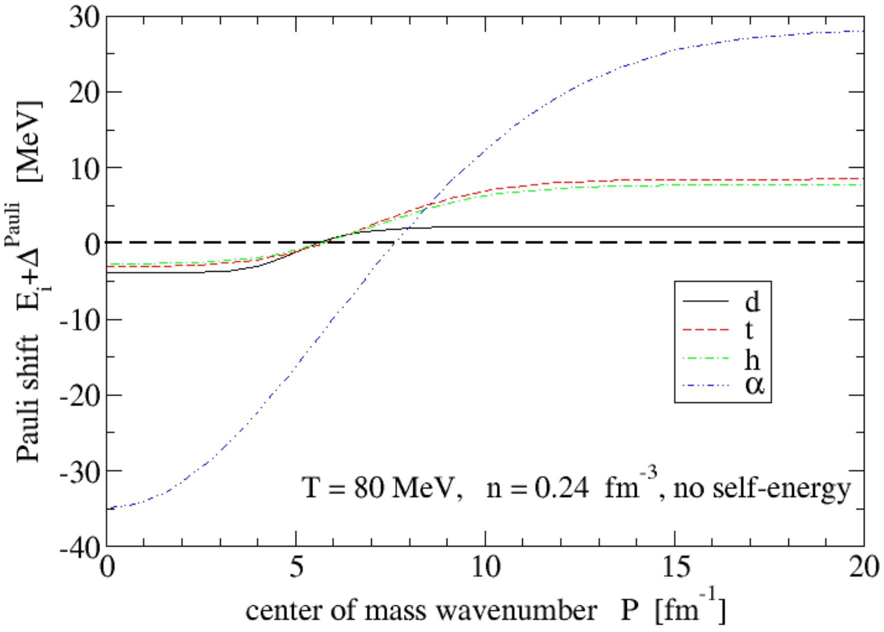


The light clusters that underwent a Mott Dissociation for low momenta become “resurrected” at high momenta relative to the medium !

The minimal momentum where this Occurs is called “Mott momentum”;
It depends on temperature and density

Binding energies without selfenergy shift,
Only Pauli blocking shift accounted for

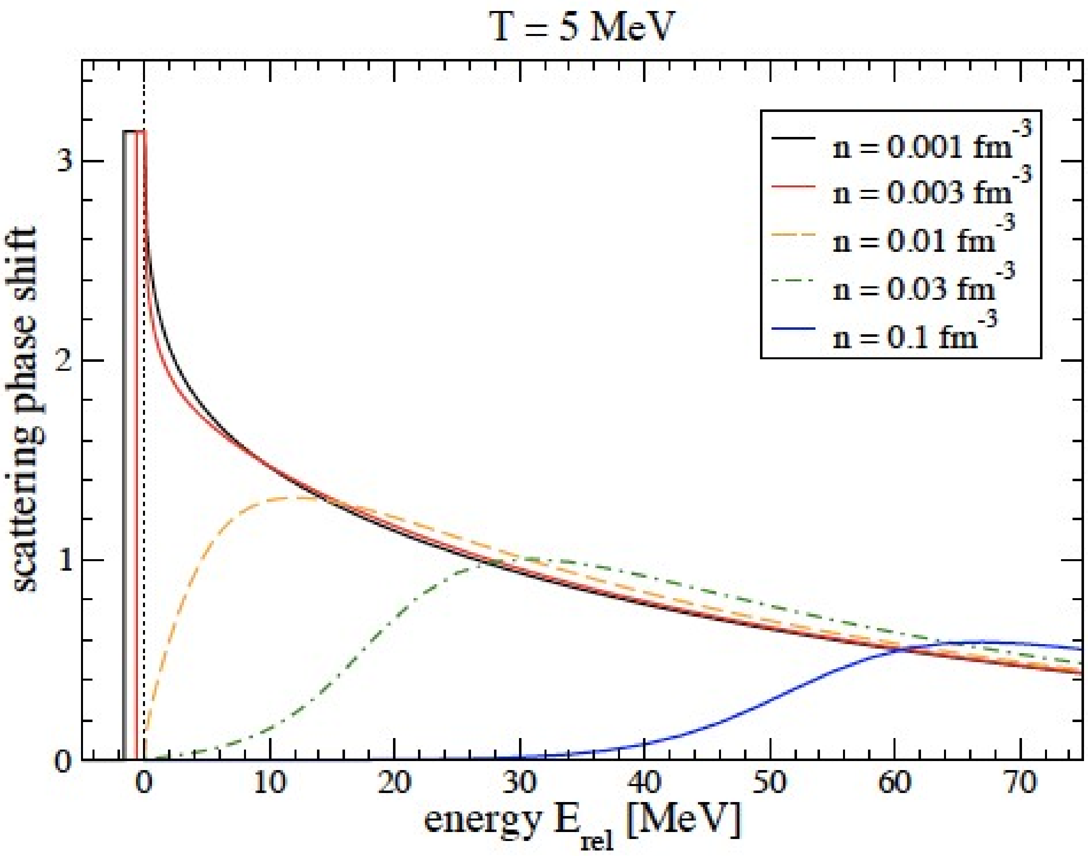




Light Fragment (LF) Production at Low Energies

Deuteron-like scattering phase shifts

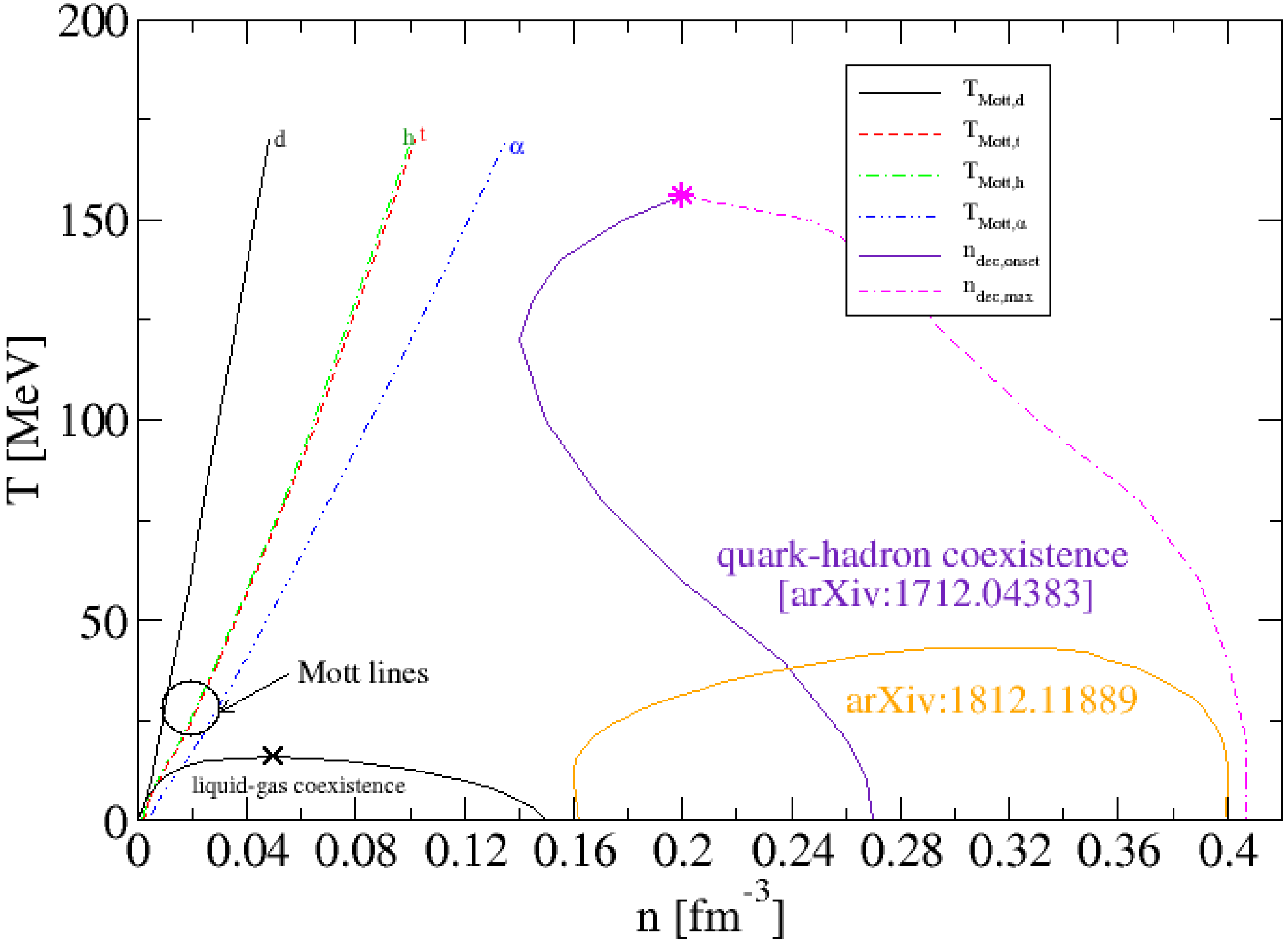
Virial coeff. $\propto e^{-E_d^0/T} - 1 + \frac{1}{\pi T}\int_0^\infty dE\, e^{-E/T}\left\{\delta_c(E) - \frac{1}{2}\sin[2\delta_c(E)]\right\}$



deuteron bound state -2.2 MeV

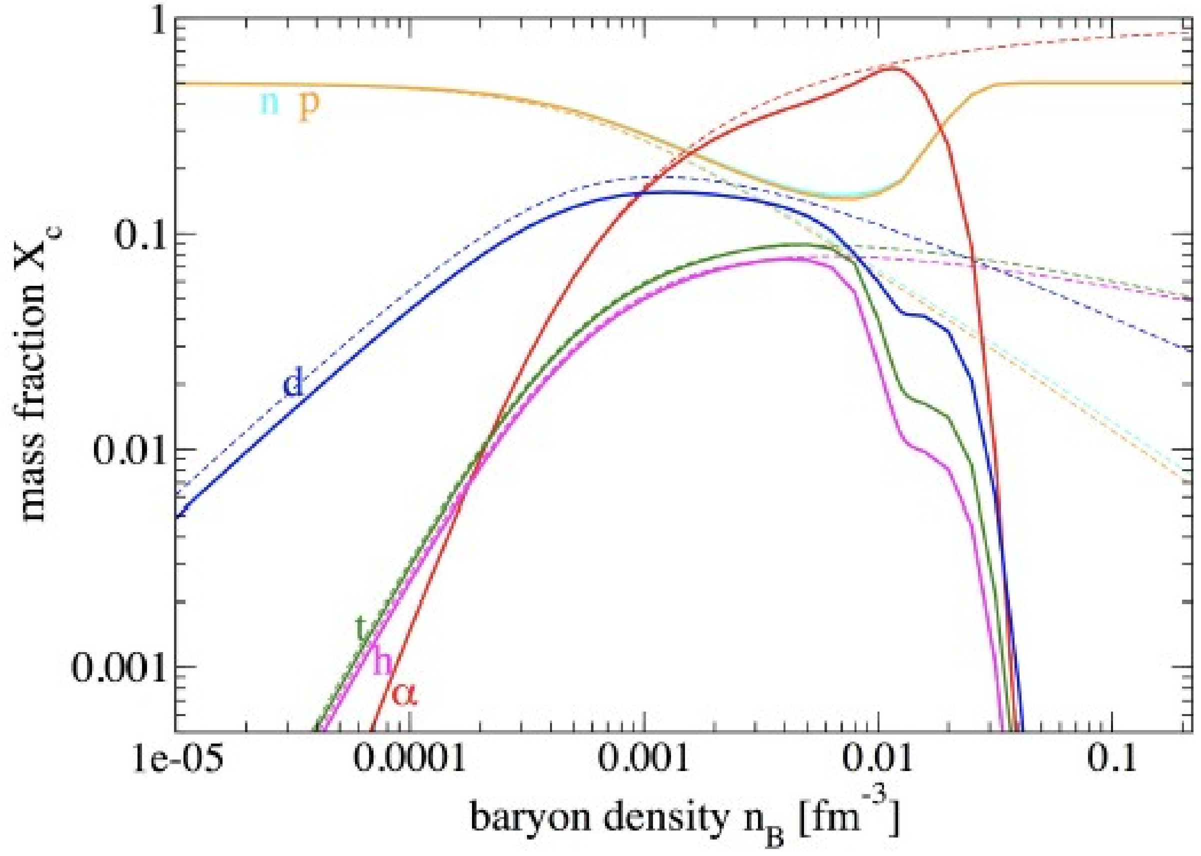
G. Roepke, J. Phys.: Conf. Series 569, 012031 (2014).

Light Fragment (LF) Production at Low Energies



Light Fragment (LF) Production at Low Energies

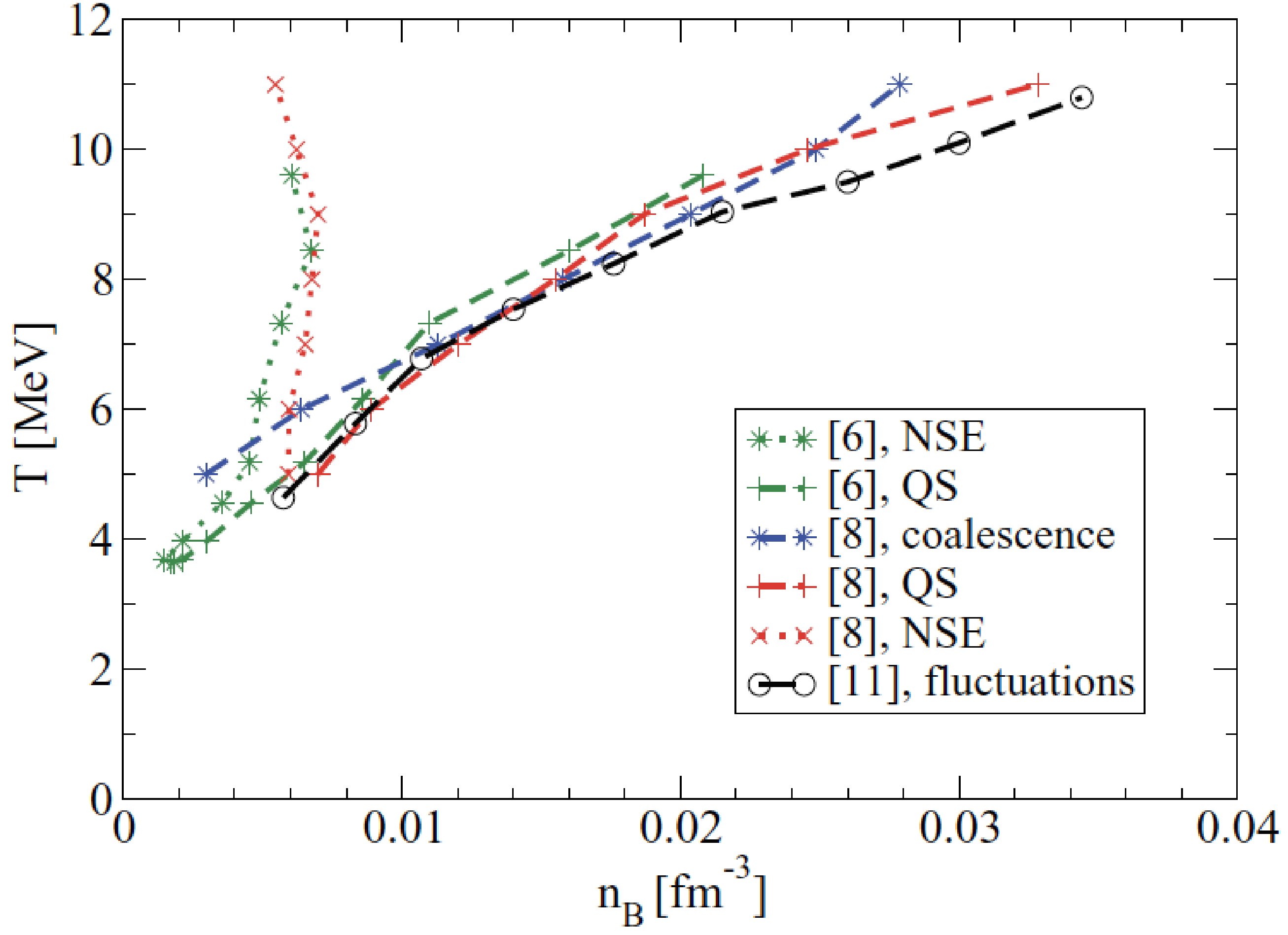
Light Cluster Abundances

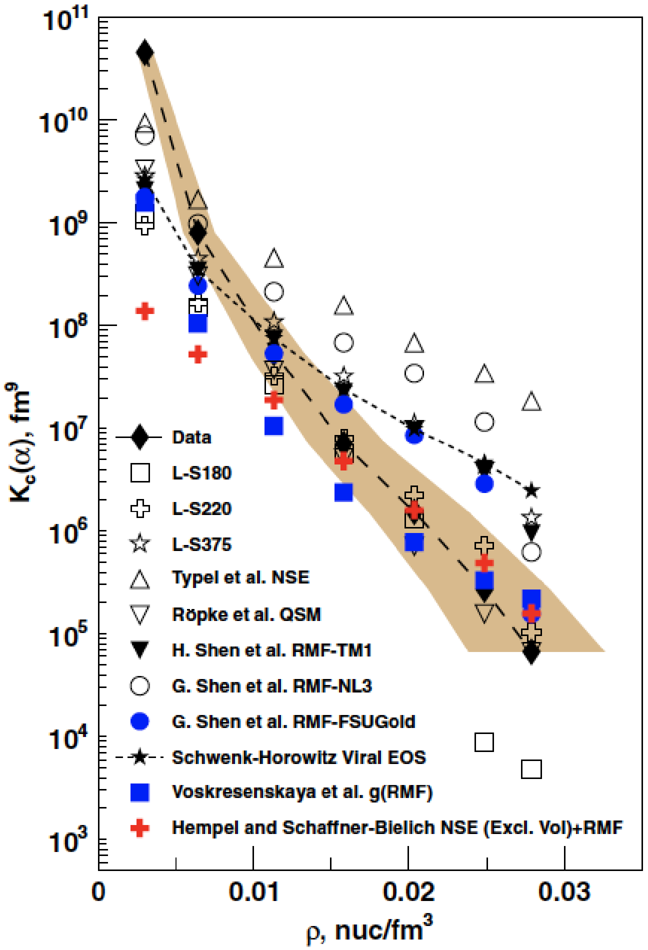


Composition of symmetric matter in dependence on the baryon density n_B, T = 5 MeV. Quantum statistical calculation (full) compared with NSE (dotted).

G. Roepke, Phys. Rev. C 92, 054001 (2015)

Light Fragment (LF) Production at Low Energies



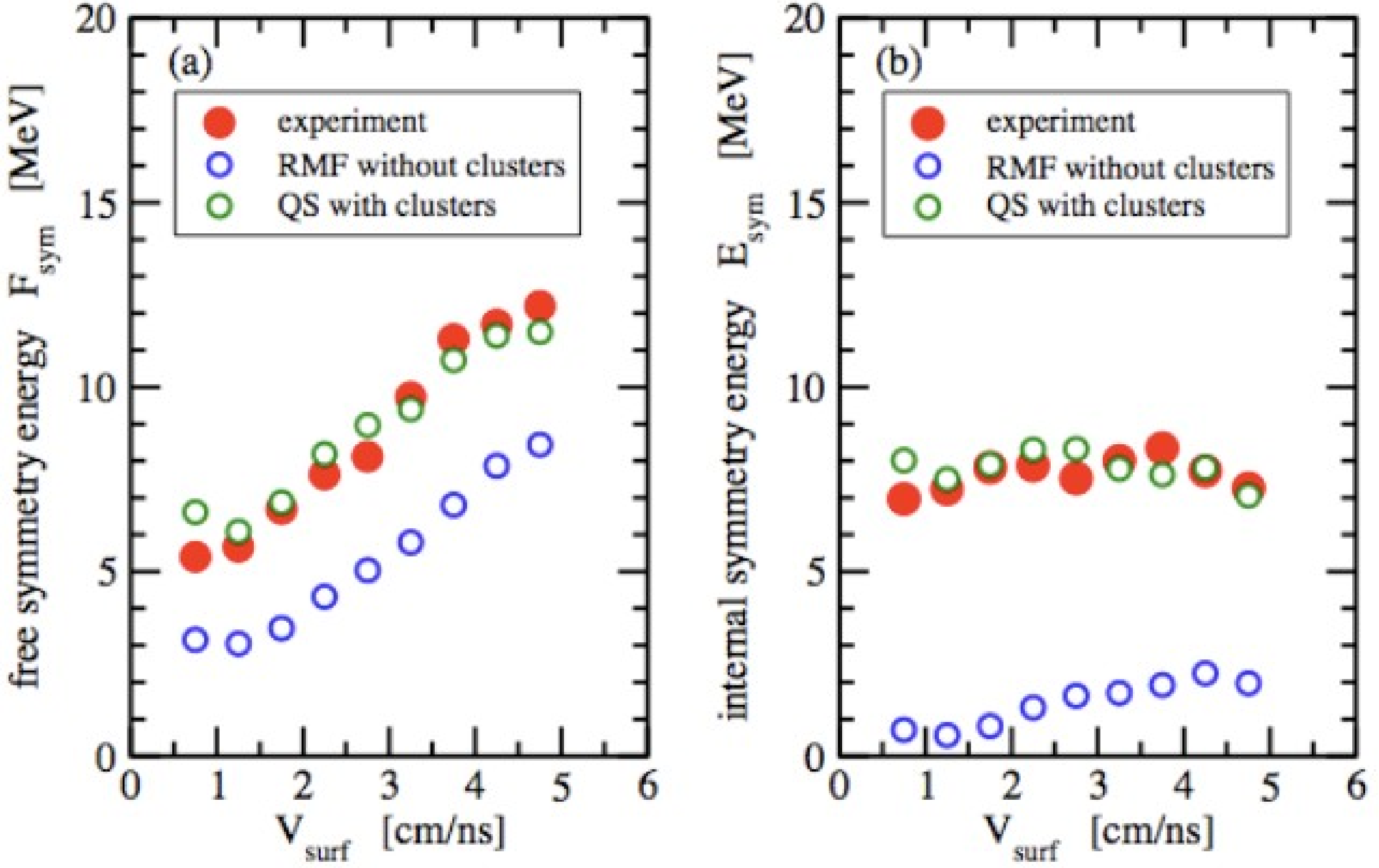


Baryon density derived from yields of light elements.
Data according to refs. [6,8,11] are compared with results of the analysis of yields using NSE and QS calculations for the chemical equilibrium constant of alpha particles Kα
From G. Roepke et al., Phys. Rev. C88, 024609 (2013).

$$K_c(A,Z) = \frac{n_{A,Z}}{n_p^Z n_n^{(A-Z)}}$$

Light Fragment (LF) Production at Low Energies

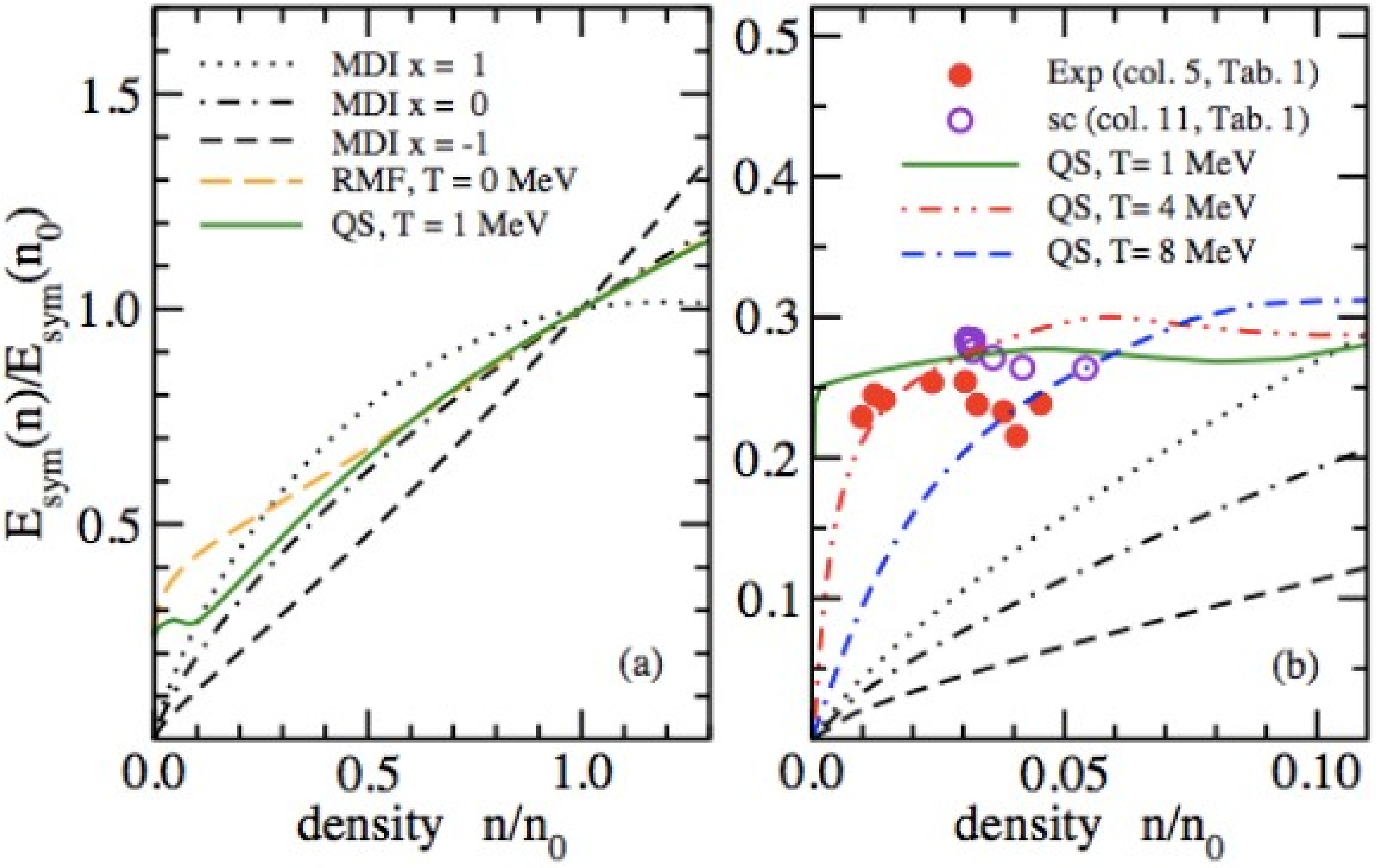
Symmetry energy, comparison experiment with theories



J. Natowitz et al., Phys. Rev. Lett. 104, 202501 (2010)

Light Fragment (LF) Production at Low Energies

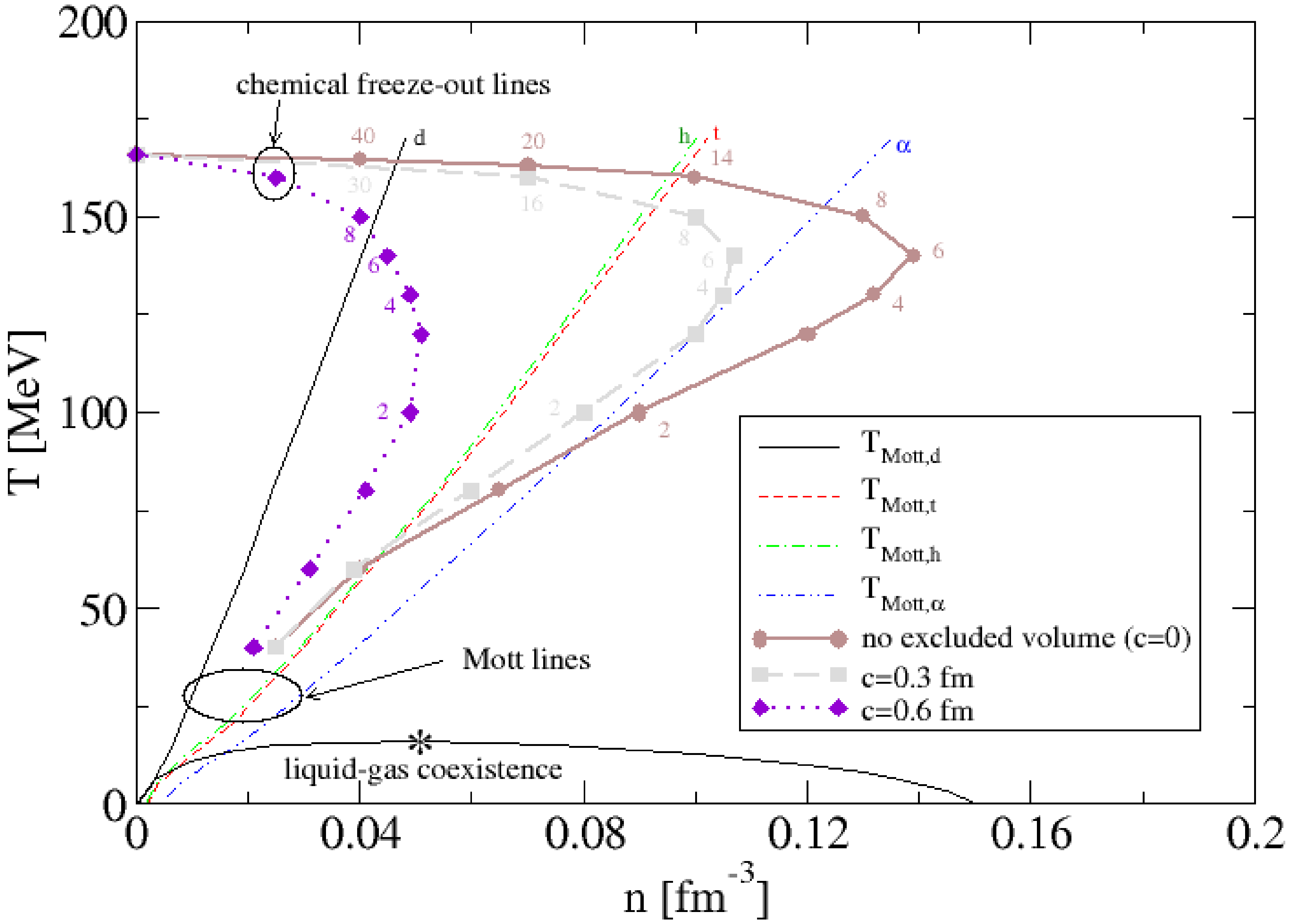
Symmetry Energy



Scaled internal symmetry energy as a function of the scaled total density.
MDI: Chen et al., QS: quantum statistical, Exp: experiment at TAMU

J. Natowitz et al., Phys. Rev. Lett. 104, 202501 (2010)

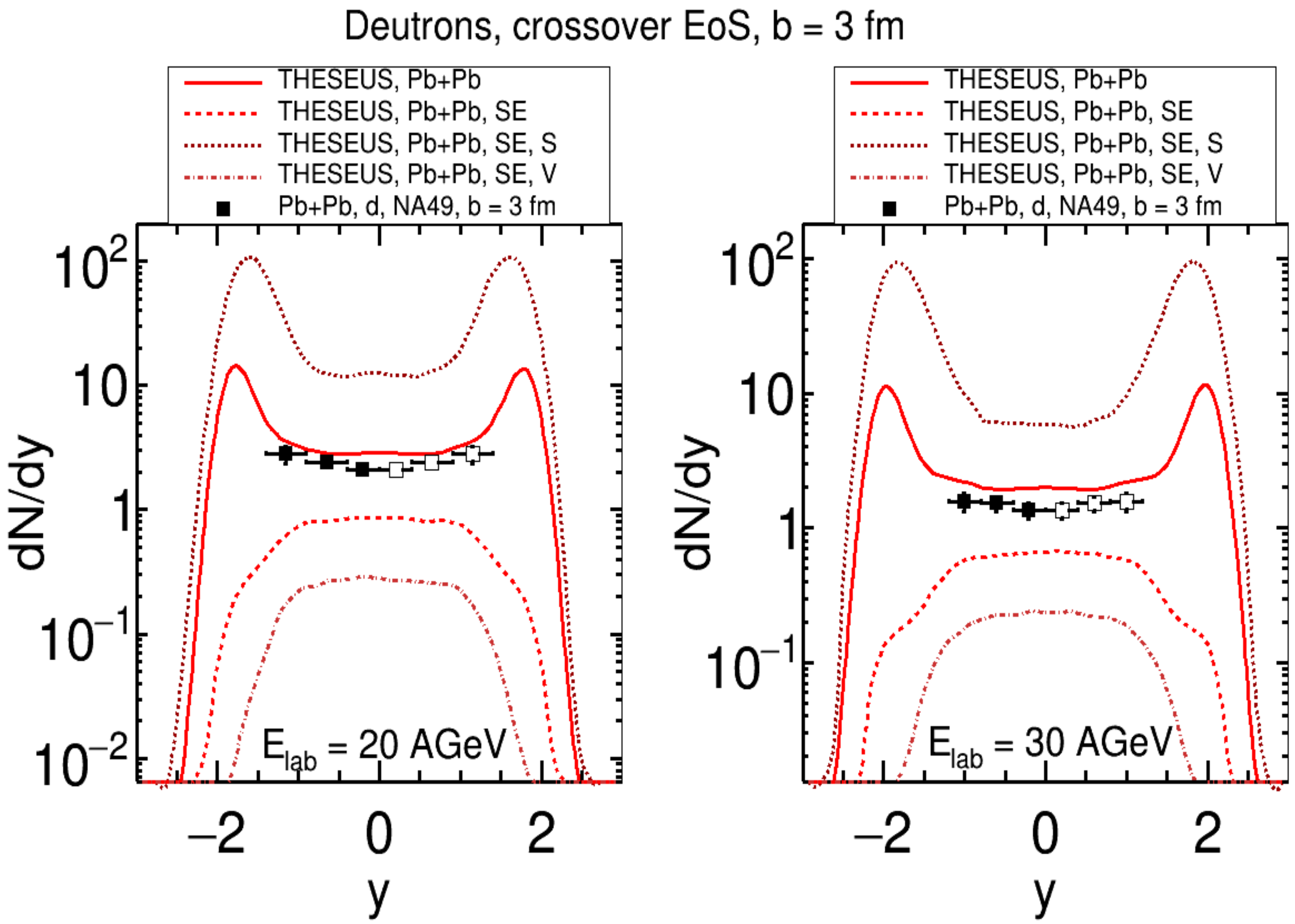
Light Fragment (LF) Production at Low Energies



Light Fragment (LF) Production at Low Energies

Rapidity distributions for deuterons in Pb+Pb collisions at energies 20 AGeV and 30 AGeV, b = 3 fm

- The scalar (S) and vector (V) self energies (SE) corrections to the mass and chemical potential are included as rough estimations.
- S-correction is positive and increases the clusters production, V is negative and reduces clusters production
- No Pauli blocking yet
- Comparison with experimental data: NA49

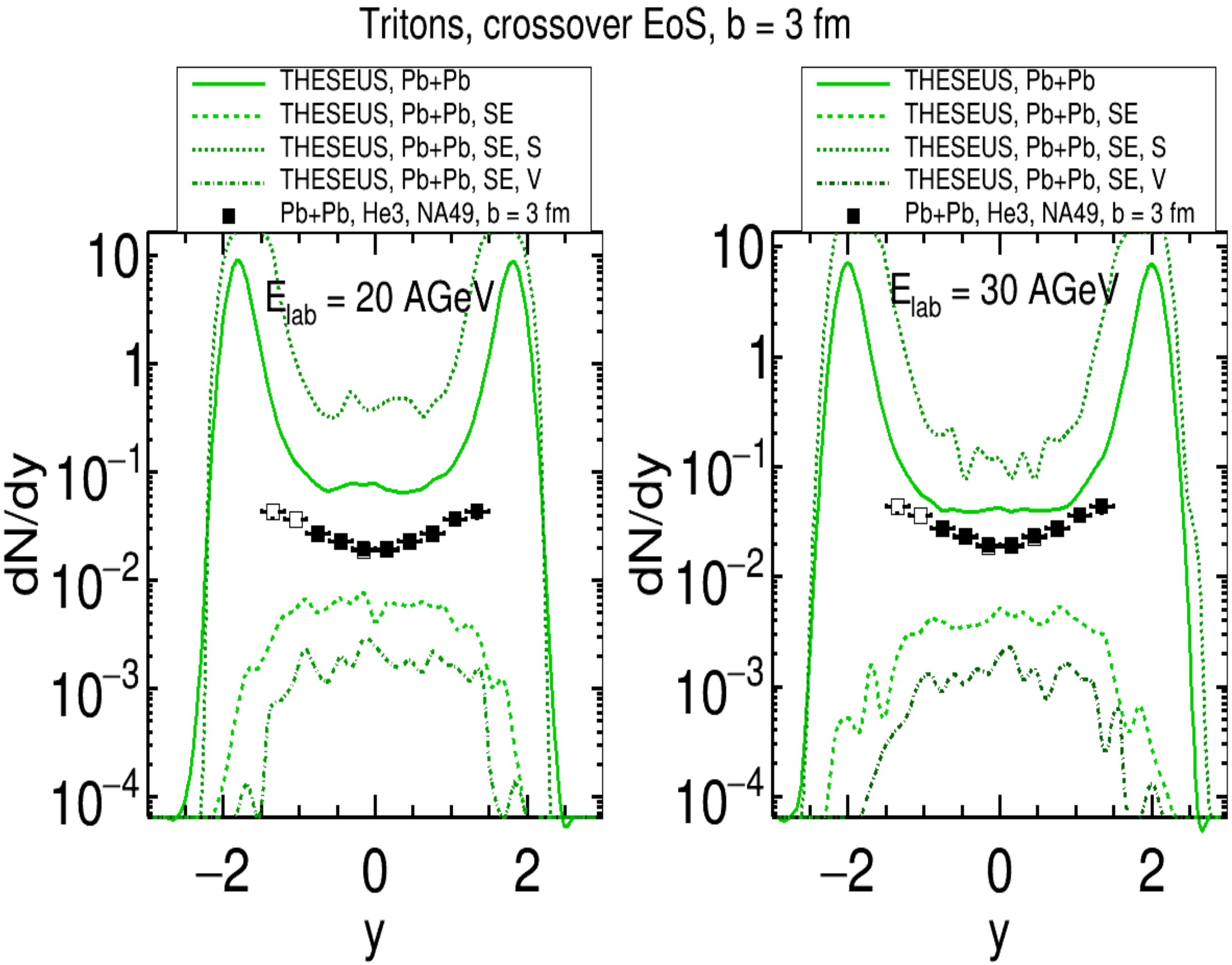


Lesson: Selfenergy and Pauli blocking effects play no role for cluster production at energies above ~20 AGeV

Light Fragment (LF) Production at Low Energies

Rapidity distributions for tritons in Pb+Pb collisions at energies 20 AGeV and 30 AGeV, b = 3 fm

- The scalar (S) and vector (V) self energies (SE) corrections to the mass and chemical potential are included as rough estimations.
- S-correction is positive and increases the clusters production, V is negative and reduces clusters production
- Comparison with experimental data for He3: NA49



Light Fragment (LF) Production at Low Energies

Comparison of THESEUS (in coalescence mode) with preliminary HADES data,

- THESEUS: 1.23 AGeV, b = 4 fm [V.N. Russkikh et al., Nucl. Phys. A572 (1994) 749]
- HADES: 1.23 AGeV, b = 5 fm [preliminary data]

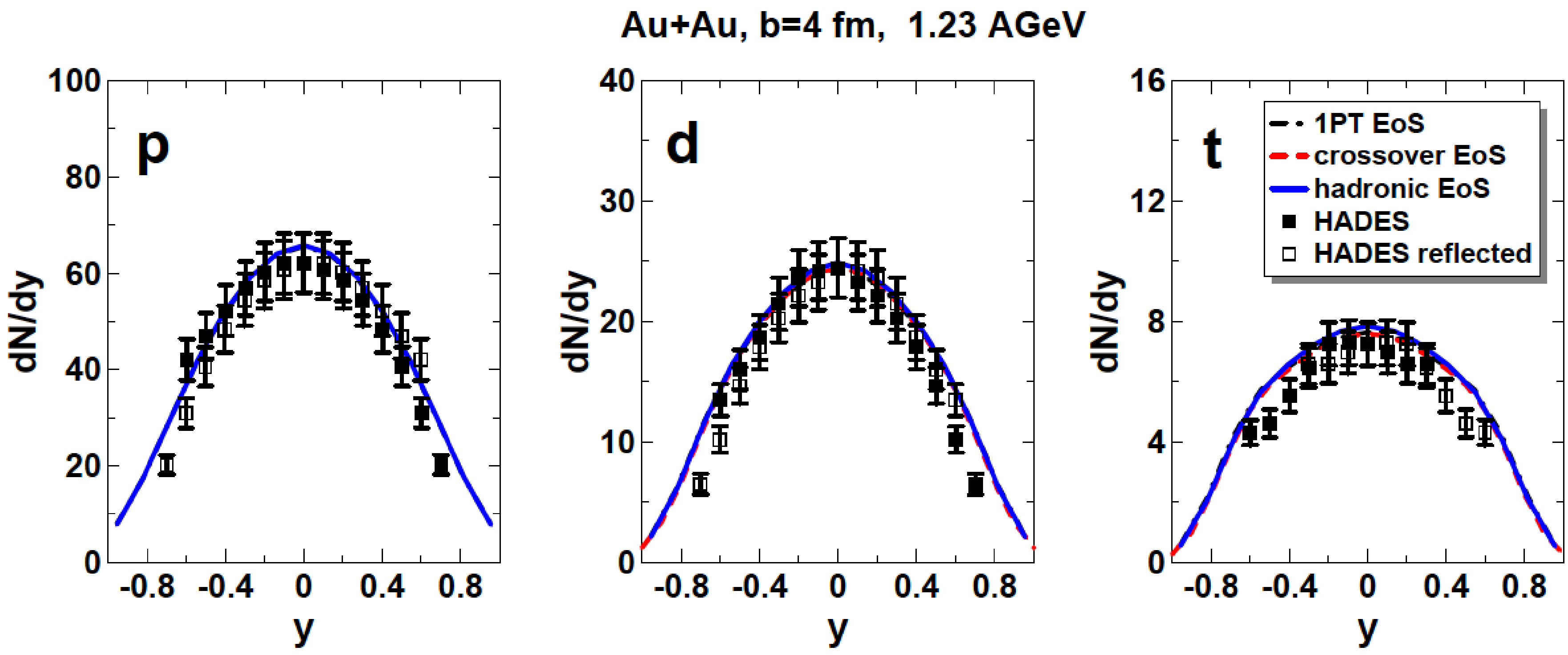


Figure courtesy: Yuri Ivanov

Lesson: Coalescence factors fitted to experiment; therefore no discussion of medium effects!

Light Fragment (LF) Production at Low Energies

Comparison of THESEUS (in sudden chemical freezeout mode) with preliminary HADES data,

- THESEUS: 1.23 AGeV, b = 4 fm, mixed-phase EoS
- HADES: 1.23 AGeV, b = 5 fm

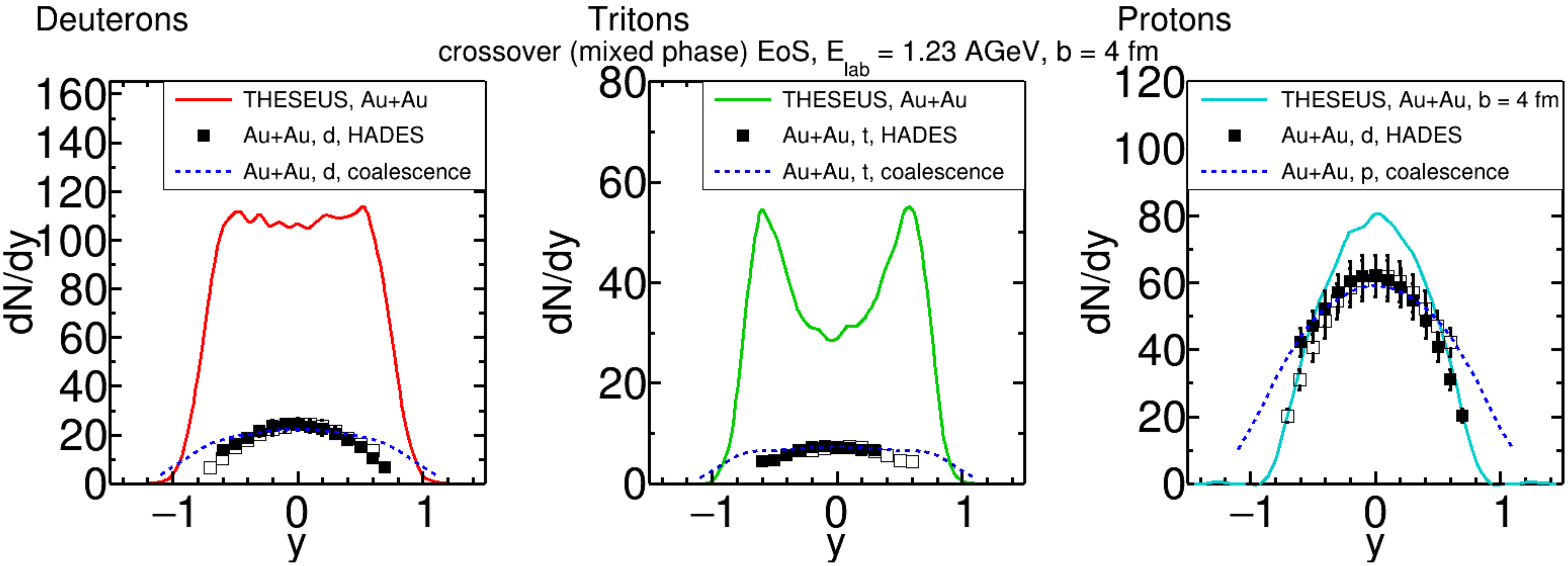
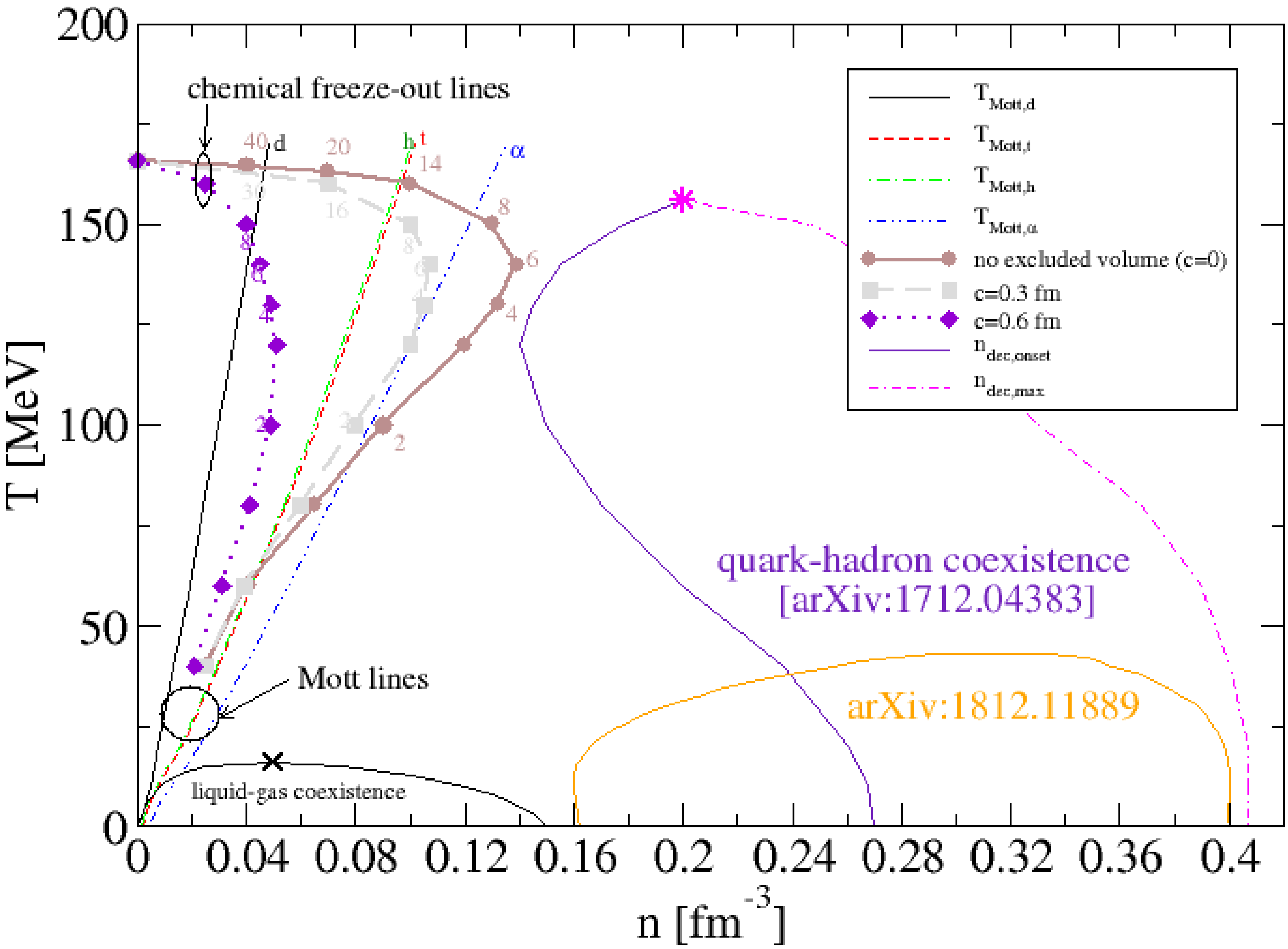


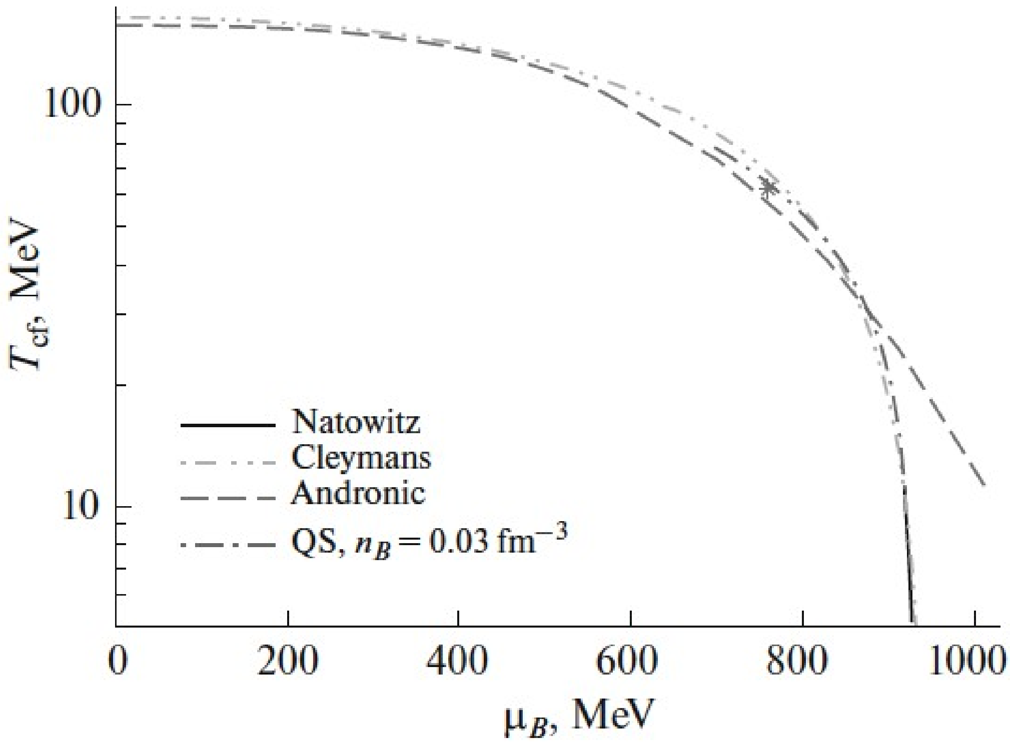
Figure courtesy: Marina Kozhevnikova

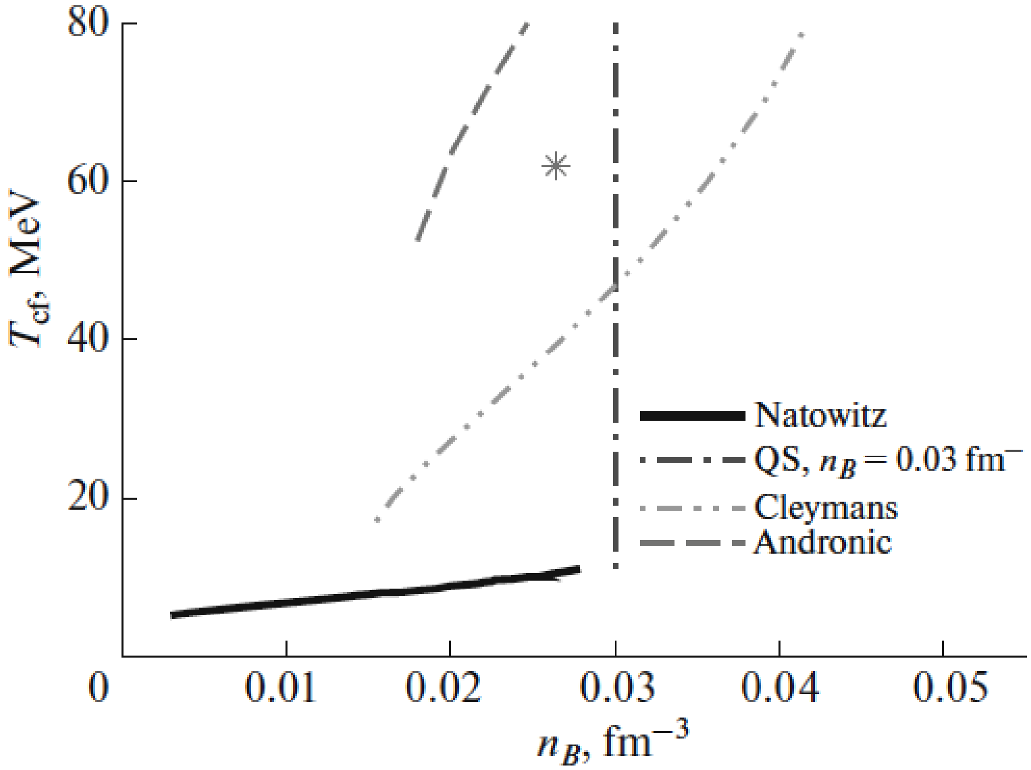
Lesson: At lower NICA energies the neglect of selfenergy and Pauli-blocking is not justified!

Light Fragment (LF) Production at Low Energies



Light Fragment (LF) Production at Low Energies

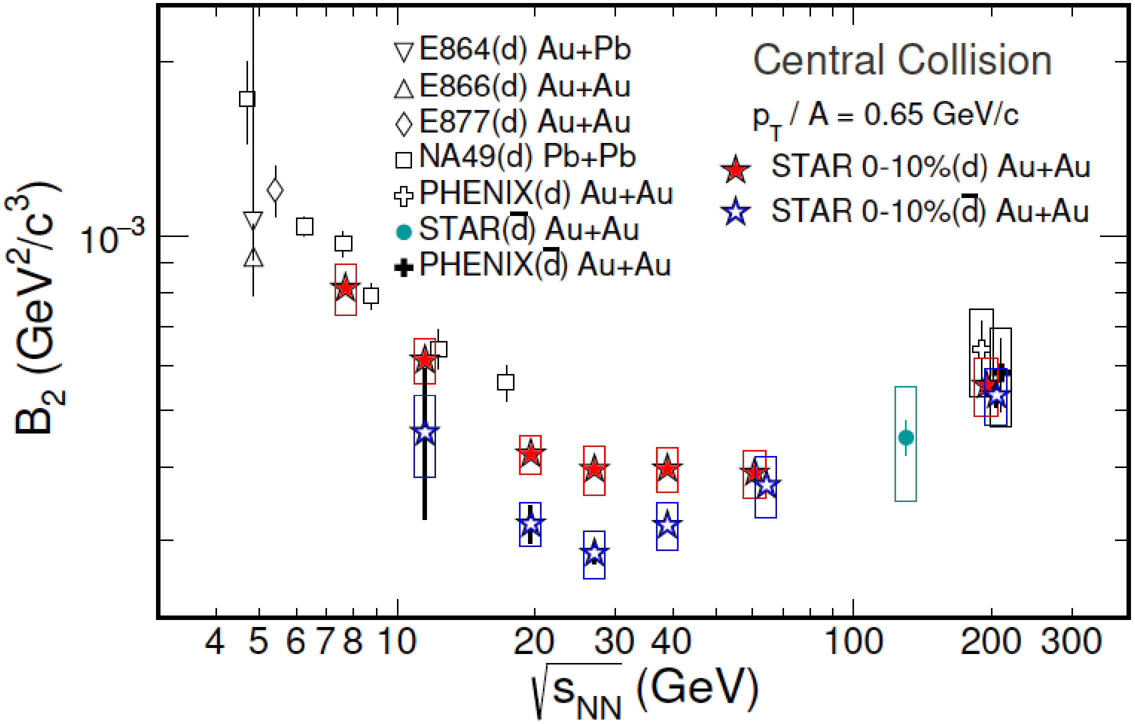




G. Roepke, D. B., Yu. Ivanov, Iu. Karpenko, O. Rogachevsky, H. Wolter,
Phys. Part. Nucl. Lett. 15 (3), 225 (2018)

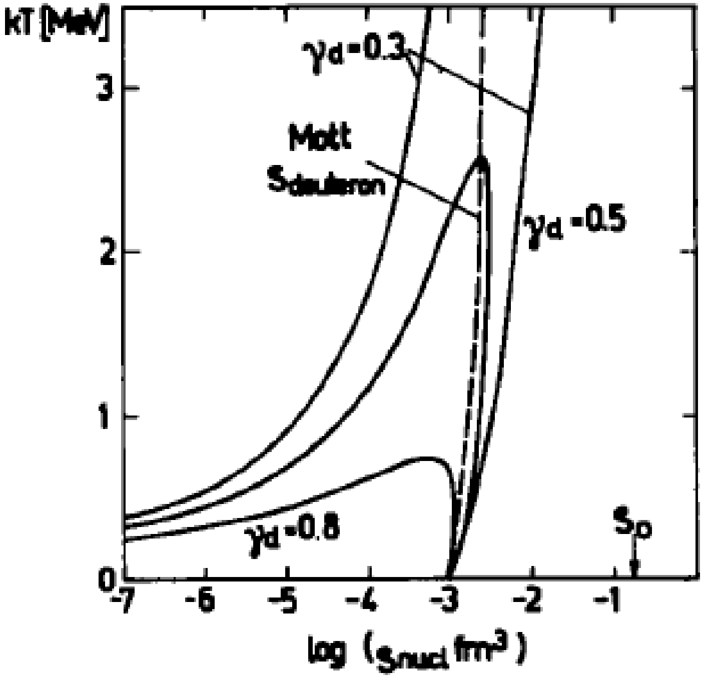
Natowitz et al.: 47 AMeV asymmetric ion collisions at Texas A&M Univ.

Light Fragment (LF) Production at Low Energies

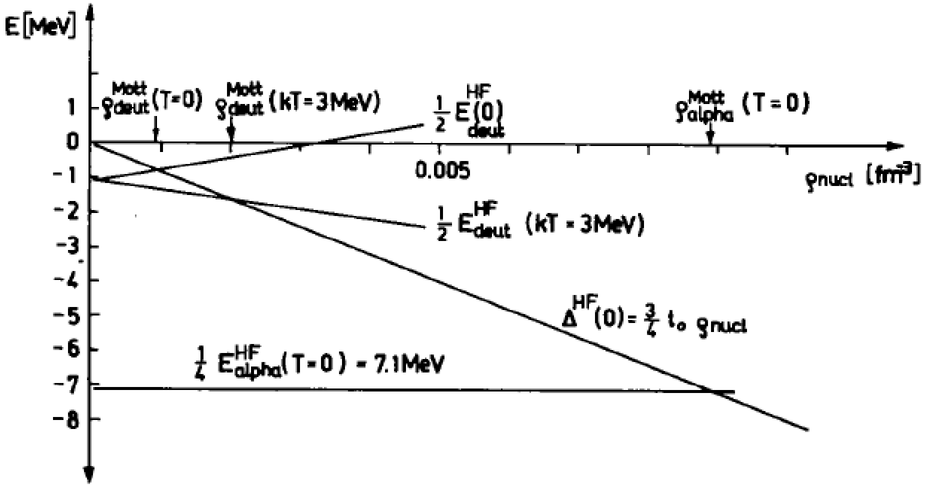


Energy dependence of coalescence parameter $B_2(d)$

J. Adam et al. (STAR Collab), arXiv:1903.11778



Association degree $\gamma_d = 2\rho_d/\rho_n$



Minimum:
Nonmonotonous behaviour of association degree (coalescence factor) along the freeze-out line ?

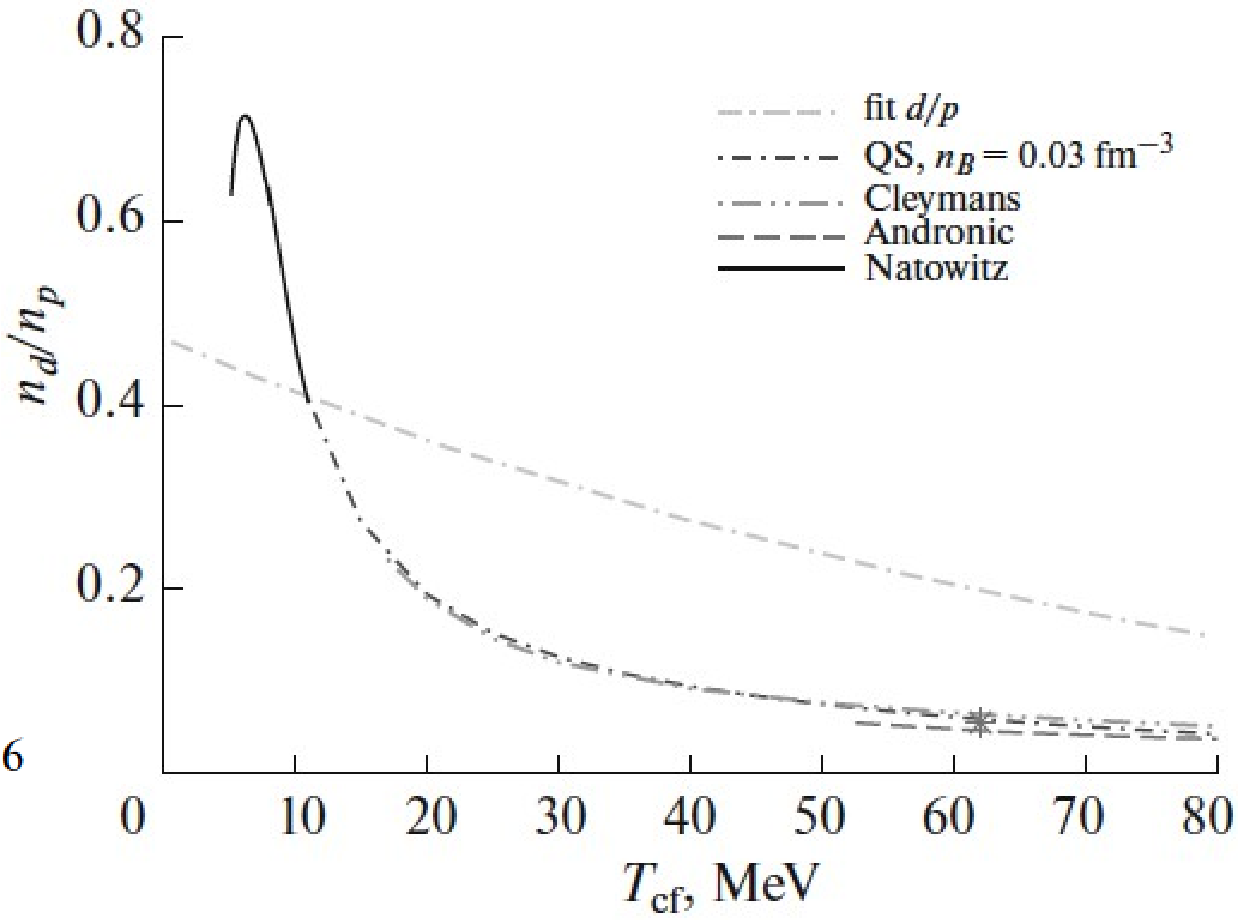
G. Roepke et al., Nucl. Phys. A379, 536 (1982)

Light Fragment (LF) Production at Low Energies

Deuteron-to-proton ratio
at freeze-out Temperature.

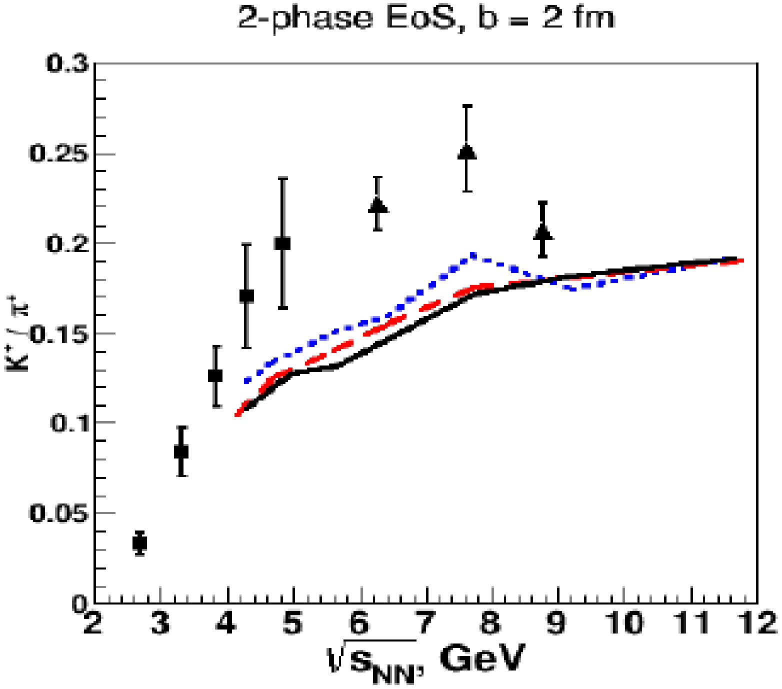
The fit formula is from
[Feckova et al.,
PRC 92 (2015) 064908]

$$d/p = 0.8\left[\sqrt{s_{NN}}/\mathrm{GeV}\right]^{-1.55} + 0.0036$$



G. Roepke et al., Medium Effects on Freeze-out of Light Clusters at NICA Energies,
Phys. Elem. Part. At. Nucl. 15, 225 (2018)

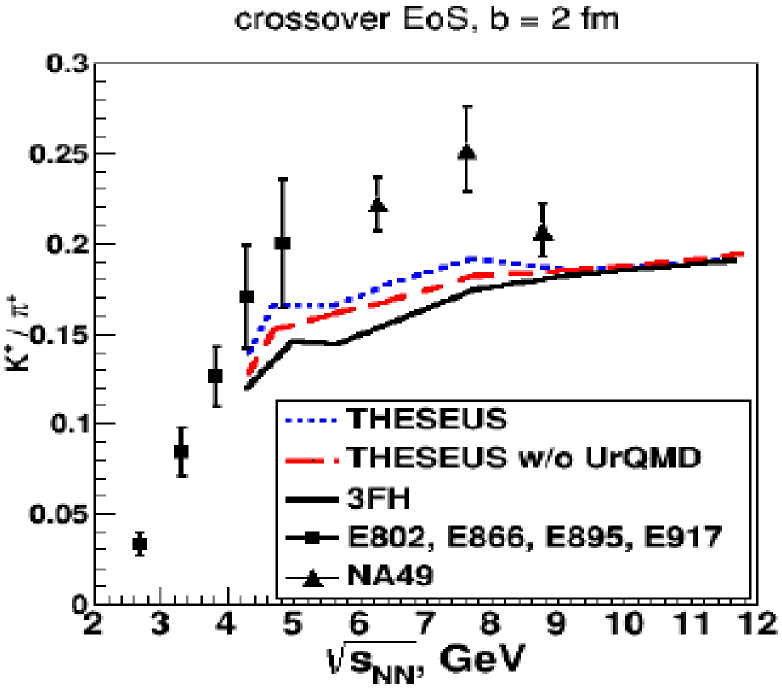
What about K^+/π^+ (Marek's horn) in THESEUS ?



THESEUS simulation reproduces 3FH result,
Thus it has the same discrepancy with experiment

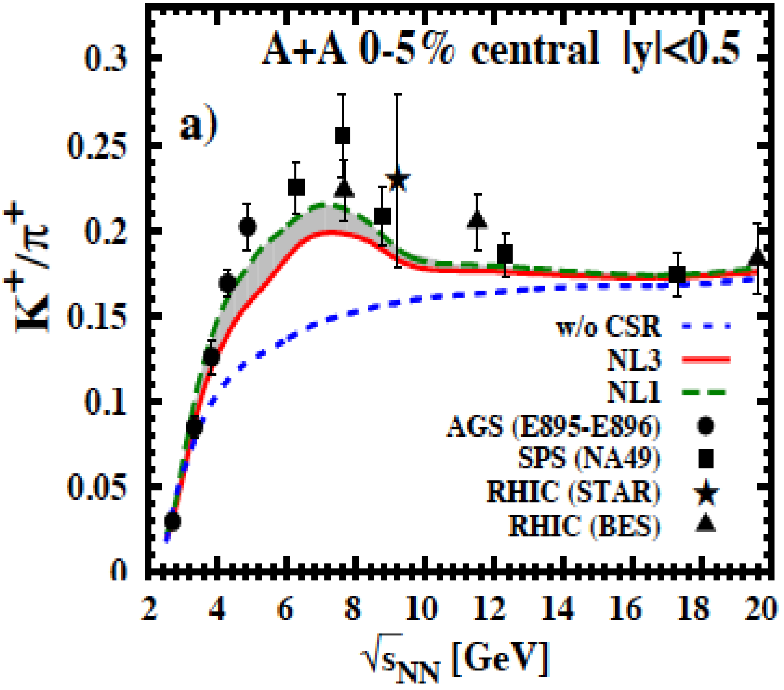
--> some key element still missing in the program

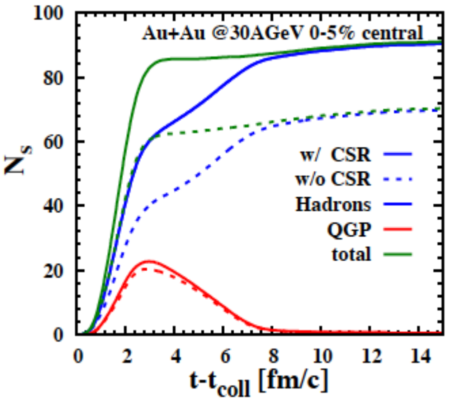
Batyuk, D.B., Bleicher, et al., PRC 94 (2016) 044917



Recent new development in PHSD

Chiral symmetry restoration in HIC at intermediate ...”
A. Palmese et al., PRC 94 (2016) 044912





Strange particle number increase by CSR

Mott dissociation of π and K in hot, dense quark matter

D. Blaschke, A. Dubinin, A. Radzhabov, A. Wergieluk, PRD 96 (2017) 094008; arxiv:1608.05383

Andrey Radzhabov in front of the University of Wroclaw

PNJL model for N_f=2+1 quark matter with π and K

$$\mathcal{L} = \bar{q}\left(i\gamma^\mu D_\mu + \hat{m}_0\right)q + G_S \sum_{a=0}^{8}\left[\left(\bar{q}\lambda^a q\right)^2 + \left(\bar{q}i\gamma_5\lambda^a q\right)^2\right] - \mathcal{U}\left(\Phi[A],\bar{\Phi}[A];T\right)$$

$$\Pi^{M^a}_{ff'}(q_0,\mathbf{q}) = 2N_c T\sum_n \int \frac{d^3p}{(2\pi)^3}\mathrm{tr}_D\left[S_f(p_n,\mathbf{p})\Gamma^{M^a}_{ff'}S_{f'}(p_n+q_0,\mathbf{p}+\mathbf{q})\Gamma^{M^a}_{ff'}\right]$$

$$\Gamma^{P^a}_{ff'} = i\gamma_5\, T^a_{ff'}\ , \quad \Gamma^{S^a}_{ff'} = T^a_{ff'}\ , \quad T^a_{ff'} = \begin{cases} (\lambda_3)_{ff'}, \\ (\lambda_1 \pm i\lambda_2)_{ff'}/\sqrt{2}, \\ (\lambda_4 \pm i\lambda_5)_{ff'}/\sqrt{2}, \\ (\lambda_6 \pm i\lambda_7)_{ff'}/\sqrt{2}, \end{cases}$$

$$P^a = \pi^0, \pi^\pm, K^\pm, K^0, \bar{K}^0$$

$$\Pi^{P^a,S^a}_{ff'}(q_0+i\eta,\mathbf{0}) = 4\left\{I_1^f(T,\mu_f) + I_1^{f'}(T,\mu_{f'}) \mp \left[(q_0+\mu_{ff'})^2 - (m_f \mp m_{f'})^2\right] I_2^{ff'}(z,T,\mu_{ff'})\right\}$$

$$I_1^f(T,\mu_f) = \frac{N_c}{4\pi^2}\int_0^\Lambda \frac{dp\,p^2}{E_f}\left(n_f^- - n_f^+\right),$$

$$I_2^{ff'}(z,T,\mu_{ff'}) = \frac{N_c}{4\pi^2}\int_0^\Lambda \frac{dp\,p^2}{E_f E_{f'}}\left[\frac{E_{f'}}{(z-E_f-\mu_{ff'})^2 - E_{f'}^2}\,n_f^- \right.$$

$$\left. - \frac{E_{f'}}{(z+E_f-\mu_{ff'})^2 - E_{f'}^2}\,n_f^+ + \frac{E_f}{(z+E_{f'}-\mu_{ff'})^2 - E_f^2}\,n_{f'}^- - \frac{E_f}{(z-E_{f'}-\mu_{ff'})^2 - E_f^2}\,n_{f'}^+\right]$$

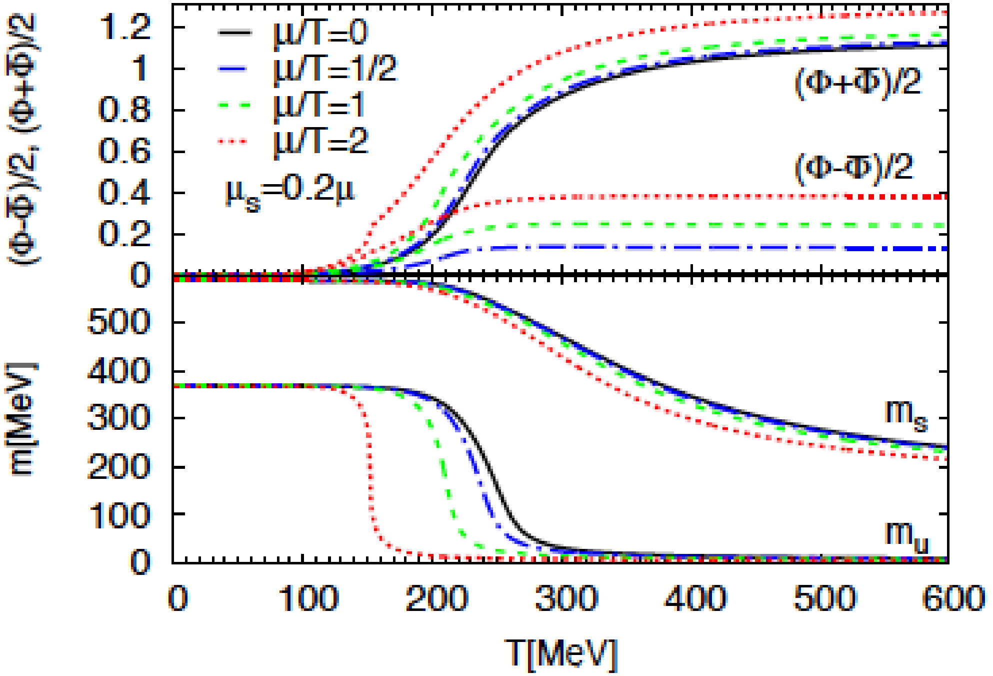
PNJL model for N_f=2+1 quark matter with π and K

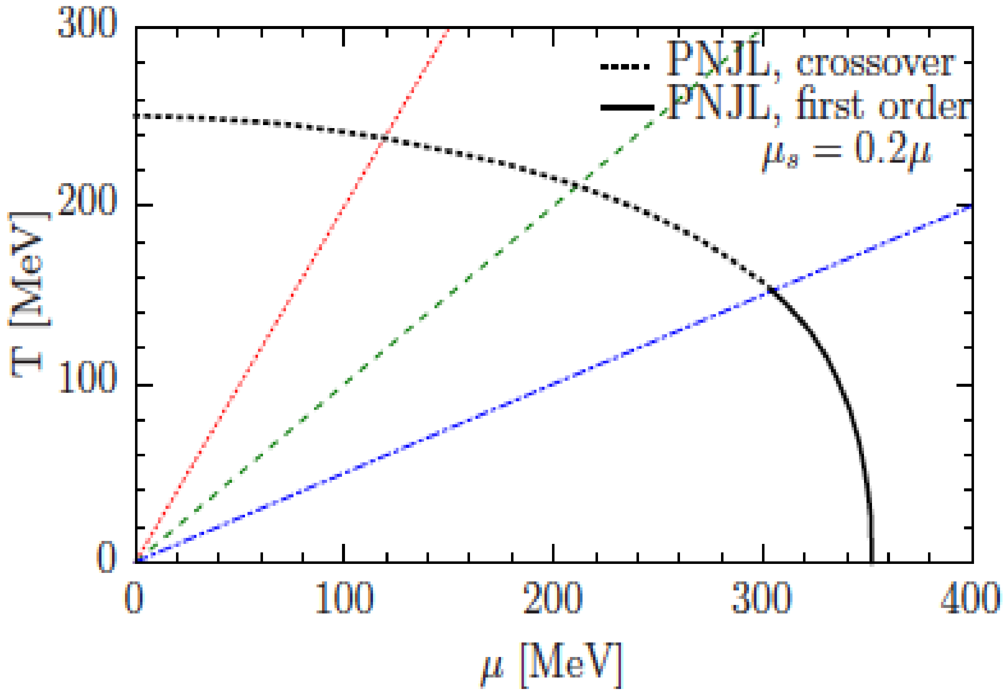
$$m_f = m_{0,f} + 16\, m_f G_S I_1^f(T,\mu), \quad \mathcal{P}^{M^a}_{ff'}(M_{M^a}+i\eta,\mathbf{0}) = 1 - 2G_S\Pi^{M^a}_{ff'}(M_{M^a}+i\eta,\mathbf{0}) = 0.$$

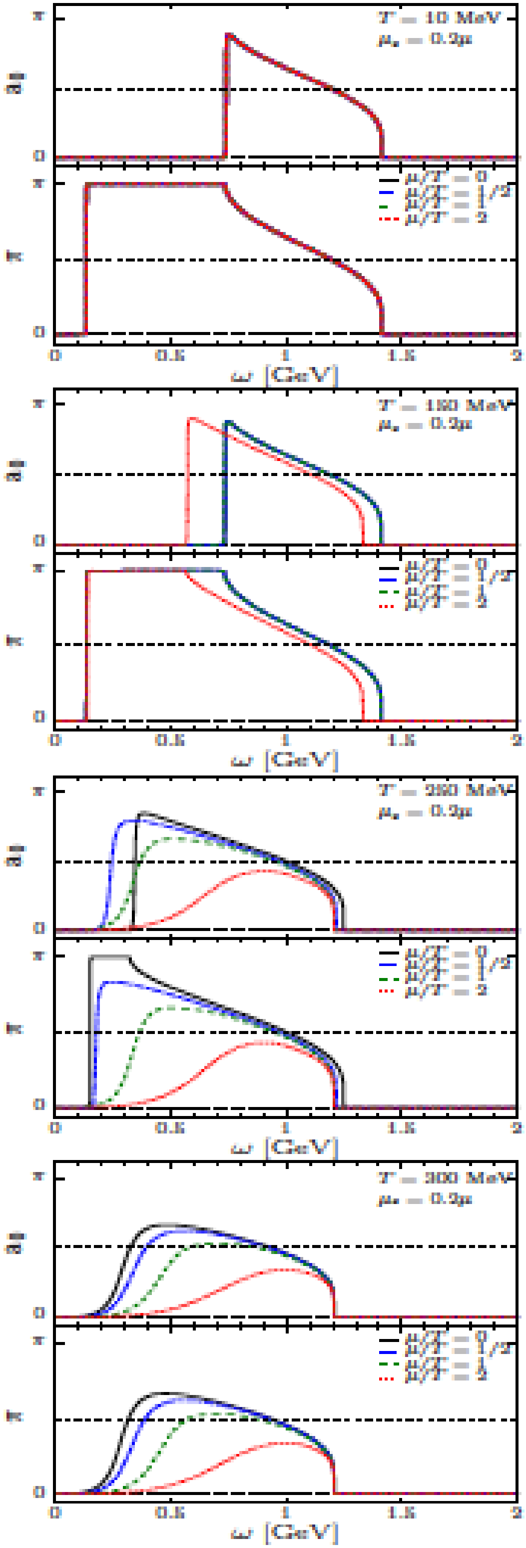
$$P_f = -\frac{(m_f-m_{0,f})^2}{8G} + \frac{N_c}{\pi^2}\int_0^\Lambda dp\,p^2\,E_f + \frac{N_c}{3\pi^2}\int_0^\infty \frac{dp\,p^4}{E_f}\left[f^+_\Phi(E_f)+f^-_\Phi(E_f)\right]$$

$$P_M = d_\mathrm{M}\int \frac{\mathrm{d}^3q}{(2\pi)^3}\int_0^\infty \frac{\mathrm{d}\omega}{2\pi}\left\{g(\omega-\mu_\mathrm{M})+g(\omega+\mu_\mathrm{M})\right\}\delta_\mathrm{M}(\omega,\mathbf{q})$$

$$\delta_\mathrm{M}(\omega,\mathbf{q}) = -\arctan\left\{\frac{\mathrm{Im}\left(\mathcal{P}^M_{ff'}(\omega-i\eta,\mathbf{q})\right)}{\mathrm{Re}\left(\mathcal{P}^M_{ff'}(\omega+i\eta,\mathbf{q})\right)}\right\}$$







3. Mott dissociation of pions and kaons in the Beth-Uhlenbeck approach ...

D.B., A. Dubinin, A. Radzhabov, A. Wergieluk, PRD 96 (2017) 094008
D.B., M. Buballa, A. Dubinin, G. Ropke, D. Zablocki, Ann. Phys. (2014)

Thermodynamics of resonances (M) via phase shifts

$$P_M = d_M \int \frac{d^3q}{(2\pi)^3} \int_0^\infty \frac{ds}{4\pi} \frac{1}{\sqrt{s+q^2}} \left\{ g(\sqrt{s+q^2} - \mu_M) \right\} \delta_M(\sqrt{s};T,\mu)$$

Polyakov-loop Nambu – Jona-Lasinio modell

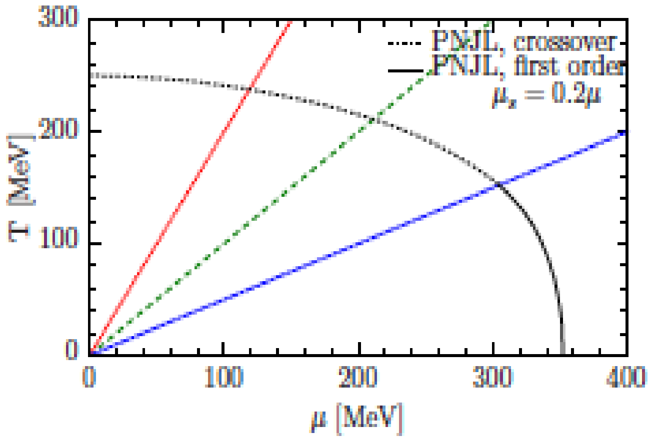
$$\Pi_{ff'}^{M^*}(q_0,\mathbf{q}) = 2N_cT\sum_n \int \frac{d^3p}{(2\pi)^3} \mathrm{tr}_D \left[S_f(p_n,\mathbf{p})\Gamma_{ff'}^{M^*} S_{f'}(p_n+q_0,\mathbf{p}+\mathbf{q})\Gamma_{ff'}^{M^*} \right],$$

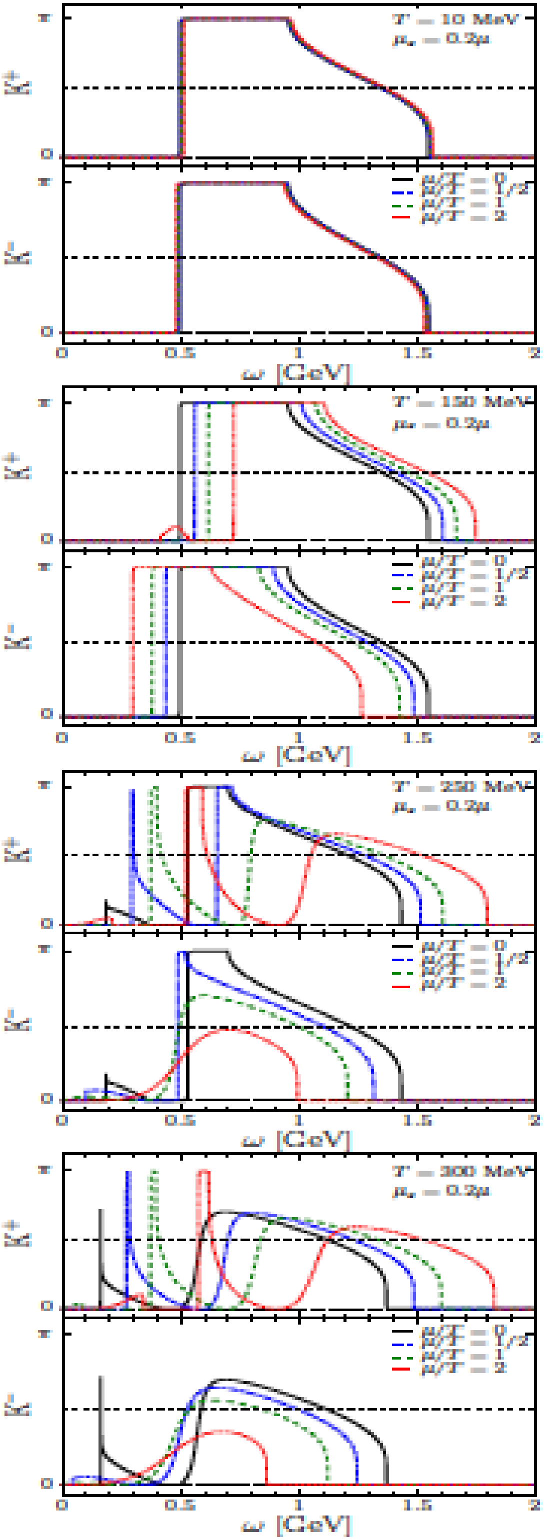
$$\mathcal{P}_{ff'}^{M^*}(M_{M^*}+i\eta,0) = 1 - 2G_S\Pi_{ff'}^{M^*}(M_{M^*}+i\eta,0)$$

$$\delta_M(\omega,\mathbf{q}) = -\arctan\left\{ \frac{\mathrm{Im}\left(\mathcal{P}_{ff'}^{M}(\omega-i\eta,\mathbf{q})\right)}{\mathrm{Re}\left(\mathcal{P}_{ff'}^{M}(\omega+i\eta,\mathbf{q})\right)} \right\}$$

Evaluation along trajectories
μ/T=const in the phase diagram:

- Pion and a0 as partner states,
- Chiral symmetry restoration,
- Mott dissociation of bound states,
- Levinson theorem





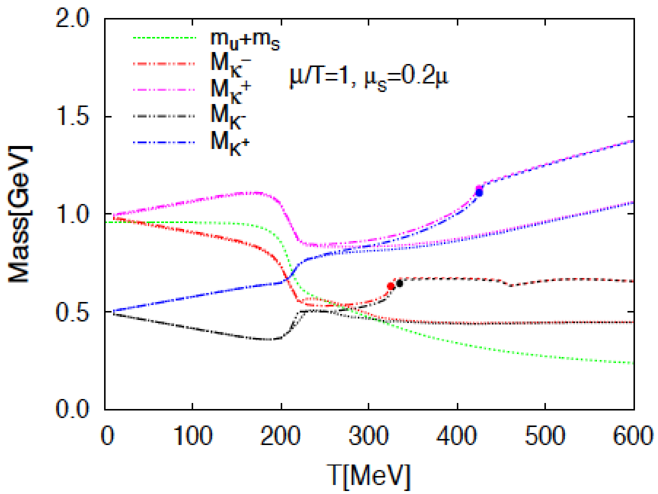
3. Mott dissociation of pions and kaons in the Beth-Uhlenbeck approach ...

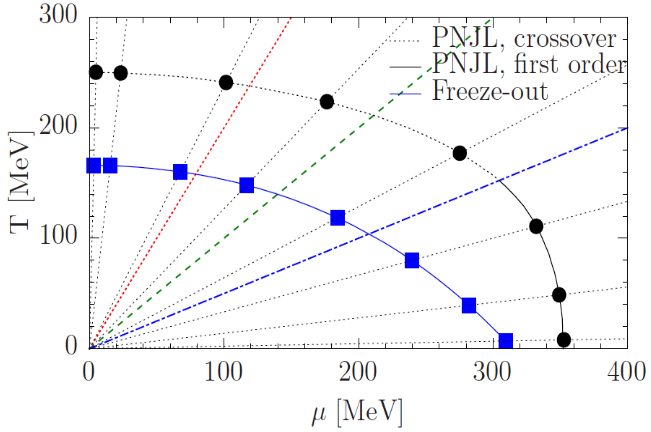
D.B., A. Dubinin, A. Radzhabov, A. Wergieluk, PRD 96 (2017) 094008

Polarization loop in Polyakov-loop Nambu – Jona-Lasinio model

$$\Pi^{P^a,S^a}_{ff'}(q_0+i\eta,\mathbf{0}) = 4\{I_1^f(T,\mu_f)+I_1^{f'}(T,\mu_{f'}) \mp \left[(q_0+\mu_{ff'})^2-(m_f\mp m_{f'})^2\right] I_2^{ff'}(z,T,\mu_{ff'})\}$$

$$\begin{aligned} I_1^f(T,\mu_f) &= \frac{N_c}{4\pi^2}\int_0^\Lambda \frac{dp\,p^2}{E_f}\left(n_f^- - n_f^+\right), \\ I_2^{ff'}(z,T,\mu_{ff'}) &= \frac{N_c}{4\pi^2}\int_0^\Lambda \frac{dp\,p^2}{E_f E_{f'}} \\ &\left[\frac{E_{f'}}{(z-E_f-\mu_{ff'})^2-E_{f'}^2}\,n_f^- \right. \\ &-\frac{E_{f'}}{(z+E_f-\mu_{ff'})^2-E_{f'}^2}\,n_f^+ \\ &+\frac{E_f}{(z+E_{f'}-\mu_{ff'})^2-E_f^2}\,n_{f'}^- \\ &\left.-\frac{E_f}{(z-E_{f'}-\mu_{ff'})^2-E_f^2}\,n_{f'}^+\right] \end{aligned}$$



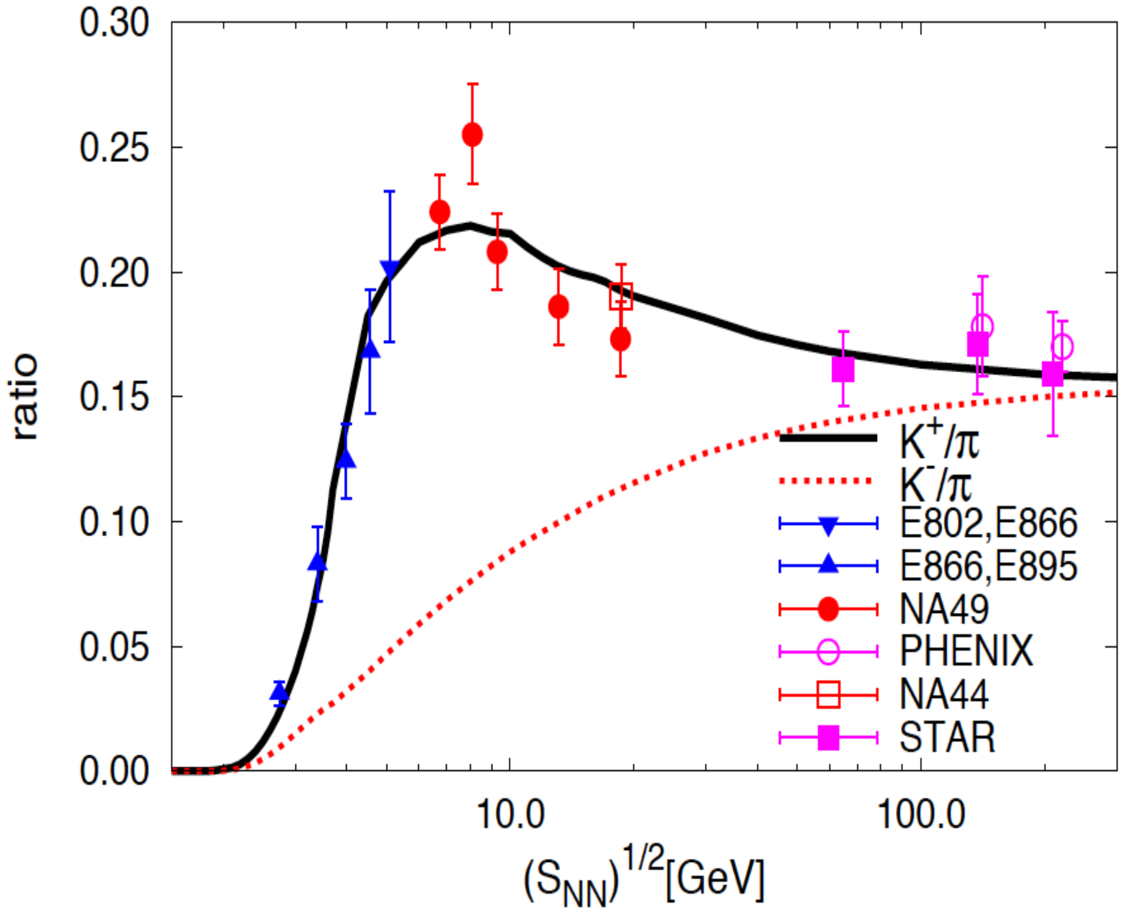


Anomalous low-mass mode for K+ in the dense medium !!

3. Mott dissociation of pions and kaons in Beth-Uhlenbeck: Explanation of the “horn” effect for K+/π+ in HIC?

Ratio of yields in BU approach
defined via phase shifts:

$$\frac{n_{K^\pm}}{n_{\pi^\pm}} = \frac{\int dM \int d^3p \; (M/E) g_{K^\pm}(E)[1+g_{K^\pm}(E)]\delta_{K^\pm}(M)}{\int dM \int d^3p \; (M/E) g_{\pi^\pm}(E)[1+g_{\pi^\pm}(E)]\delta_{\pi^\pm}(M)}$$



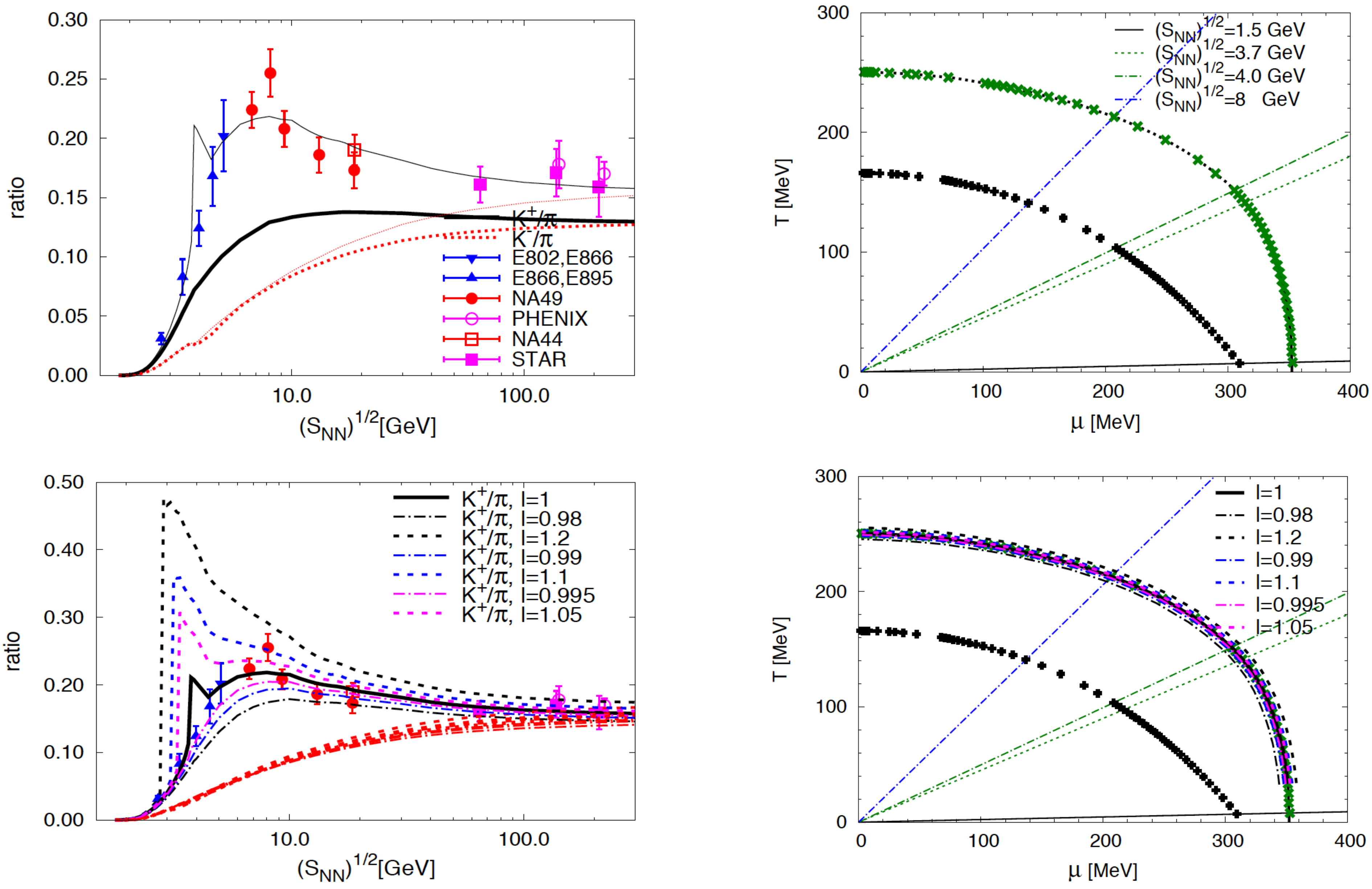
Evaluation along the freeze-out
Curve parametrized by Cleymans et al.

- enhancement for K+ due to anomalous in-medium bound state mode
- no such enhancement for K- or pions

- explore the effect in thermal statistical models and in THESEUS ...

D.B., A. Dubinin, A. Radzhabov, A. Wergieluk,
PRD 96 (2017) 094008; arxiv:1608.05383

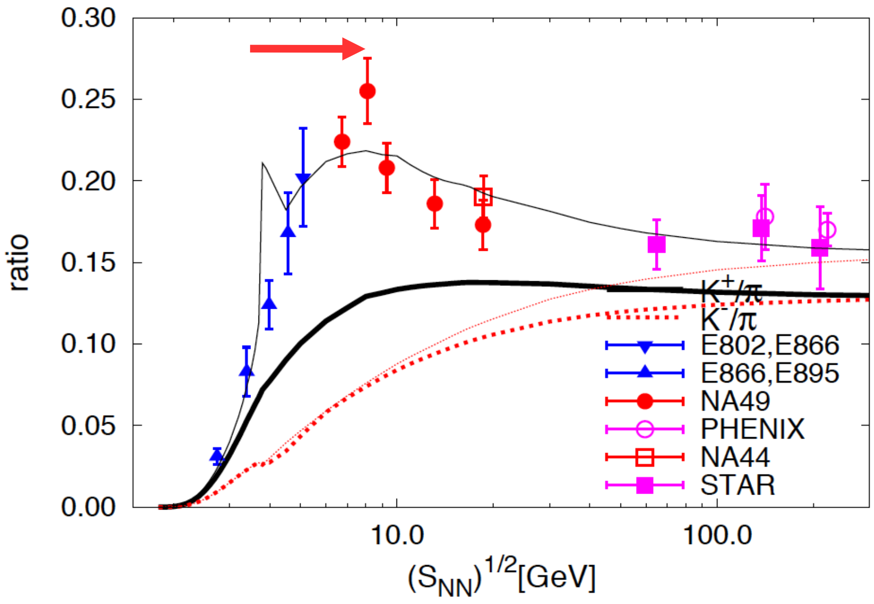
3. “Tooth” on the “horn” due to anomalous K+; sign of CEP?

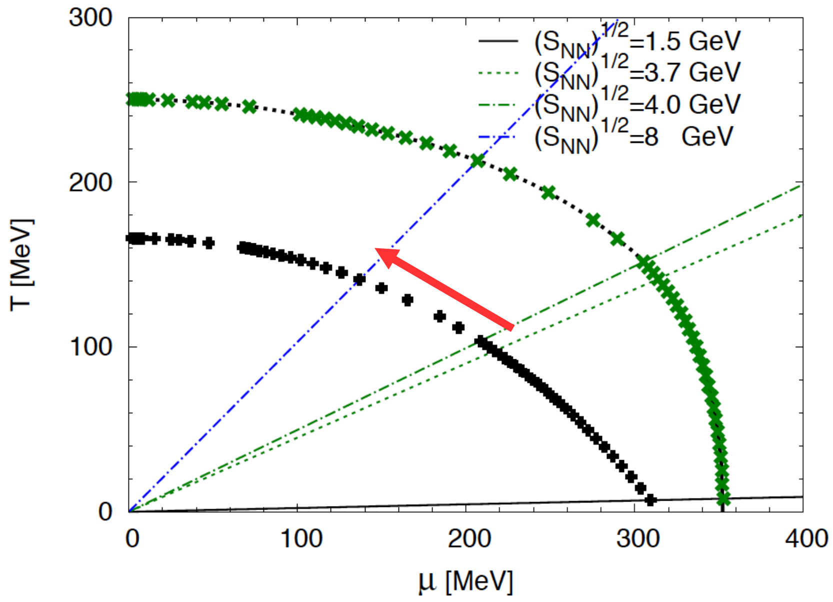


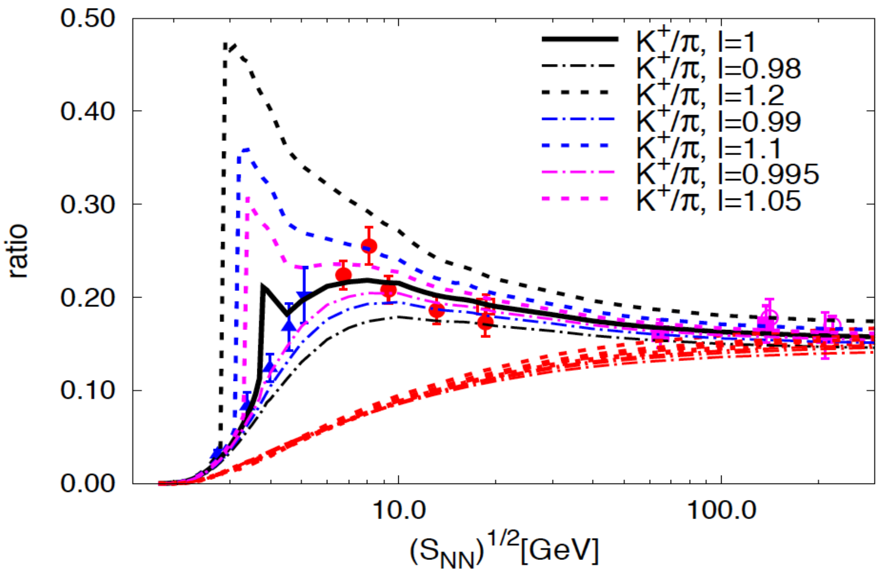
- enhancement for K+ due to anomalous in-medium bound state mode

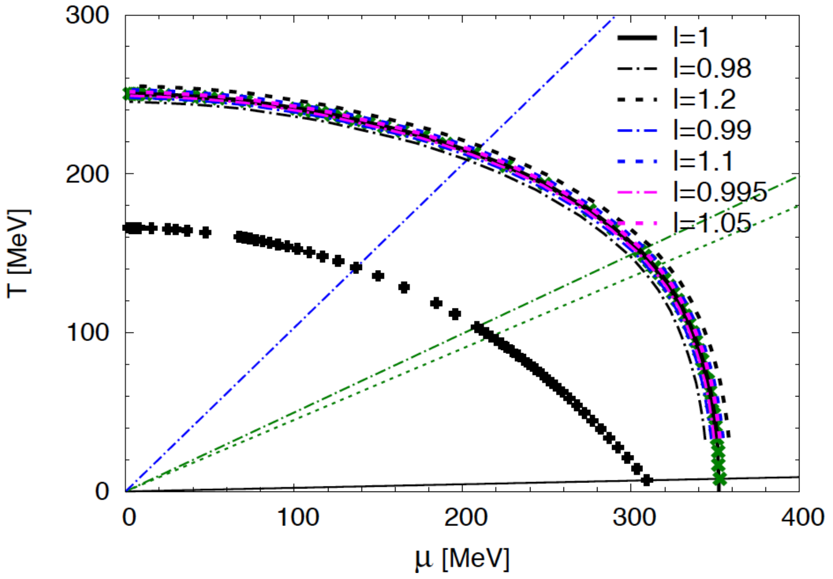
D.B., A. Radzhabov, in prep. (2019)

3. “Tooth” on the “horn” due to anomalous K+; sign of CEP?





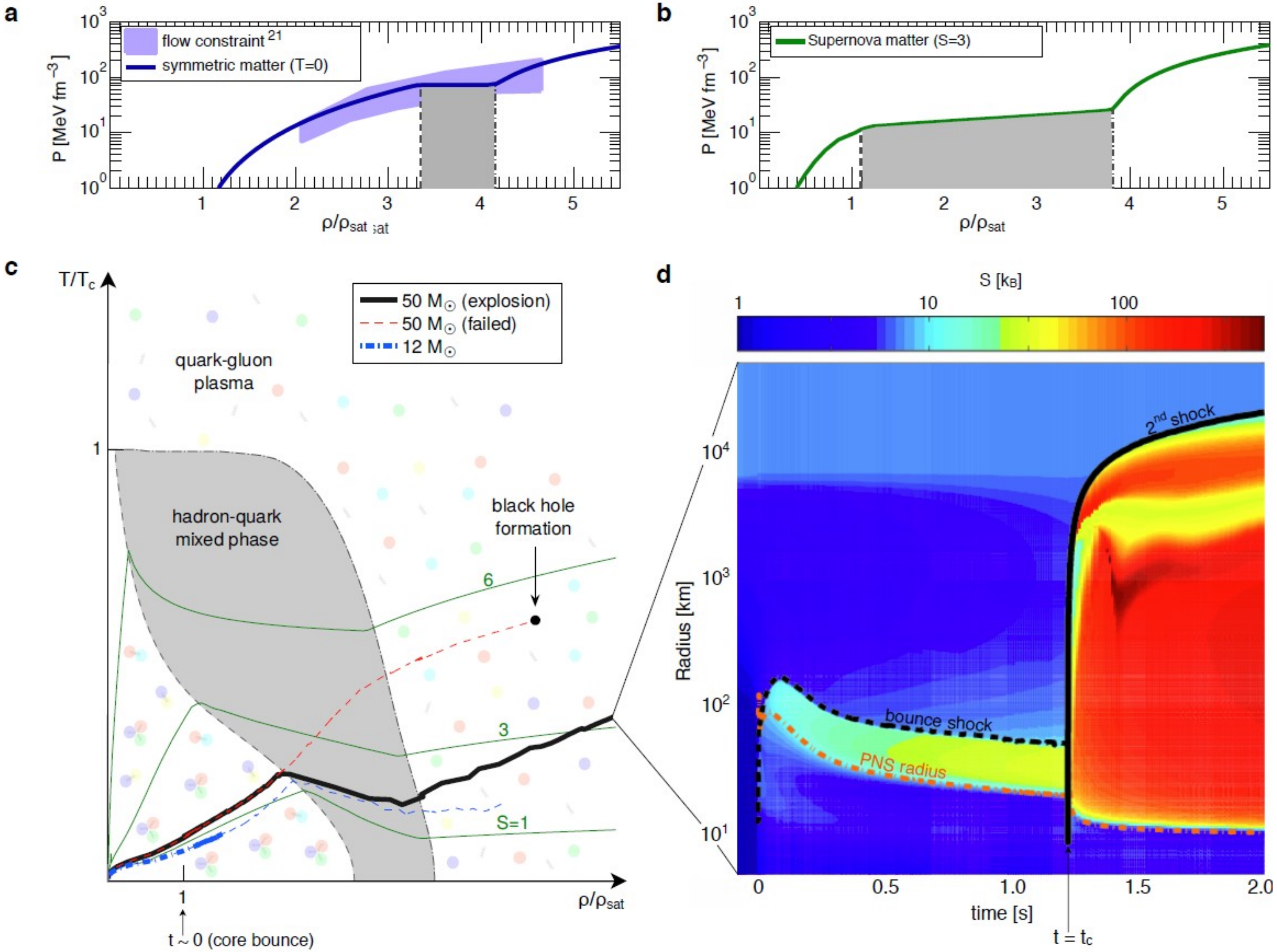




- “tooth” correlated to the CEP → indicator for CEP !!

D.B., A. Radzhabov, in prep. (2019)

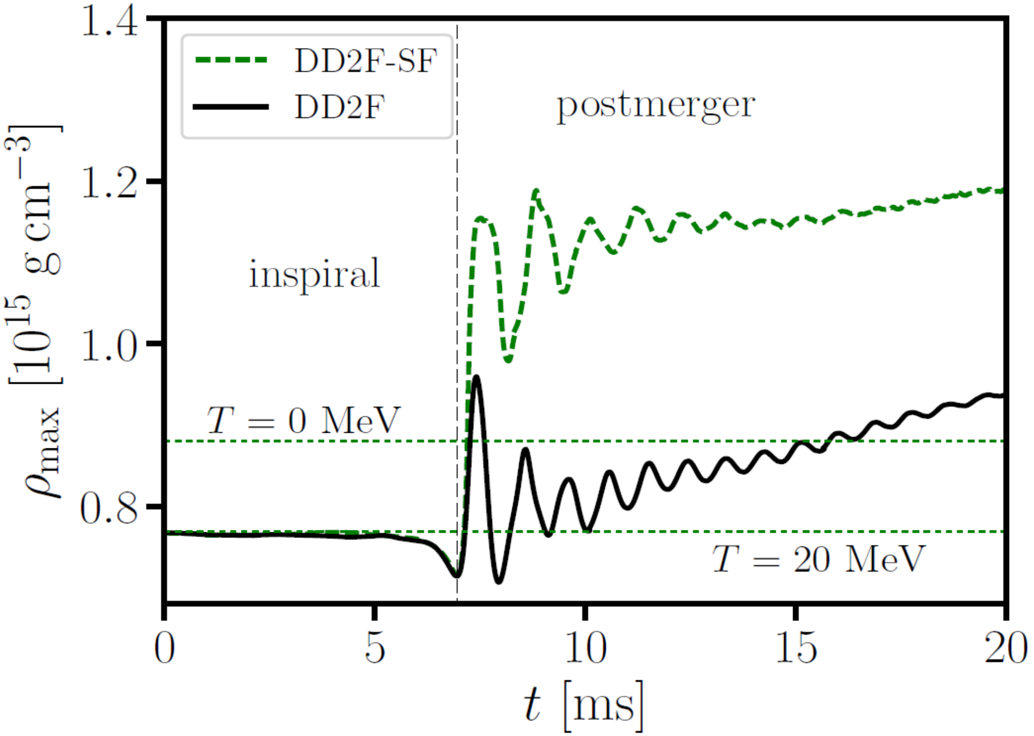
Deconfinement transition as SN explosion mechanism



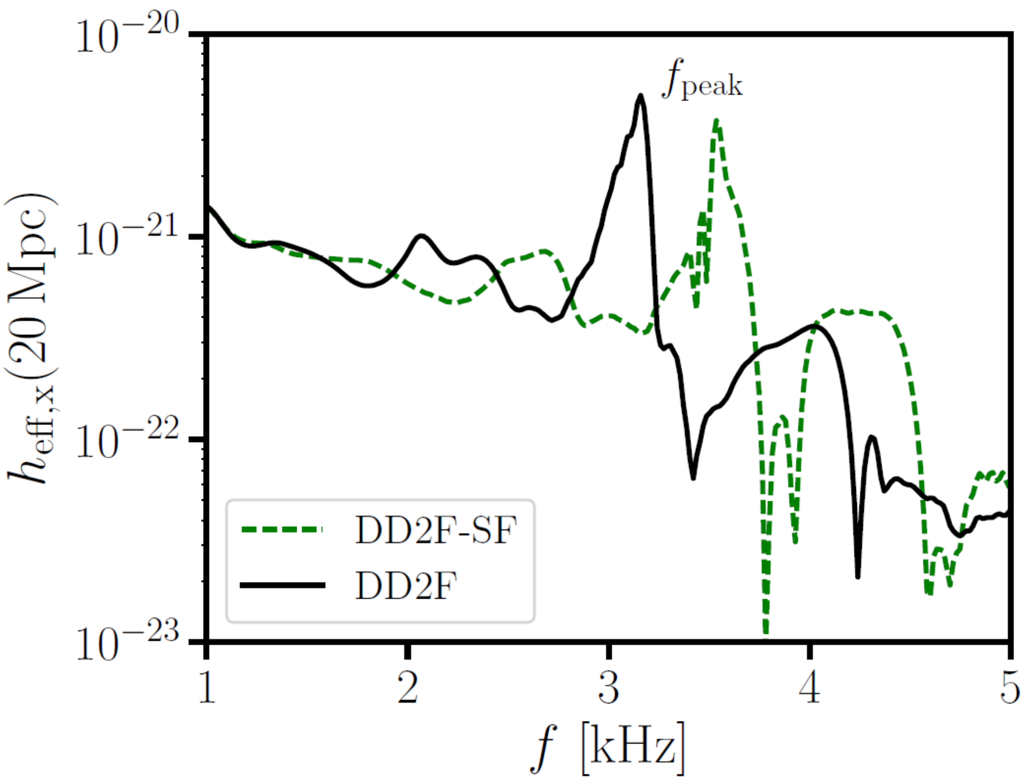
Progenitor:
M = 50 M_O

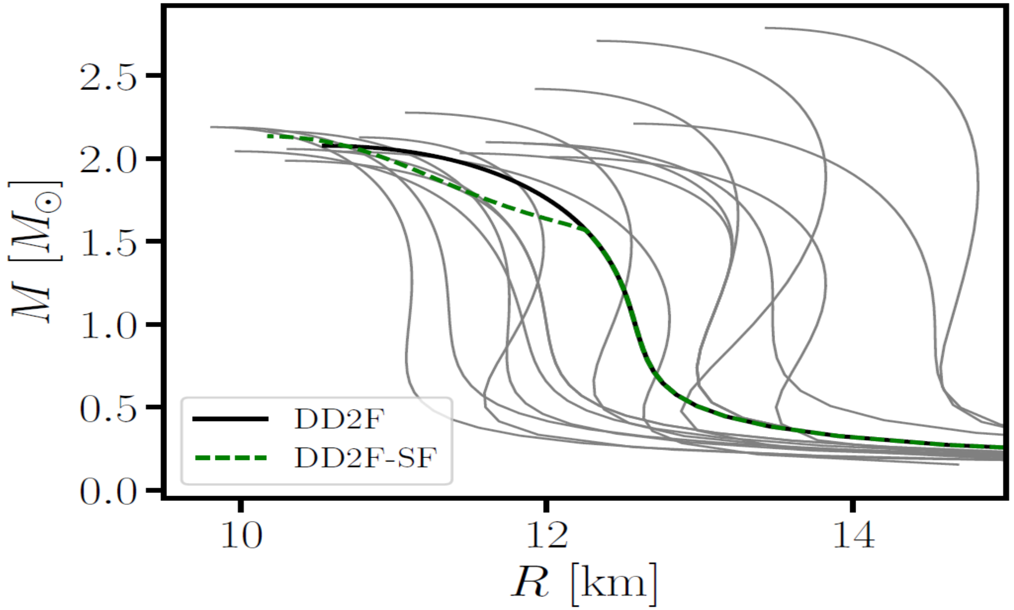
T. Fischer, N.-U. Bastian et al., Quark deconfinement as supernova engine of massive blue Supergiant star explosions, Nature Astronomy 2 (2018) 980-986; arxiv:1712.08788

Hybrid star formation in postmerger phase



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



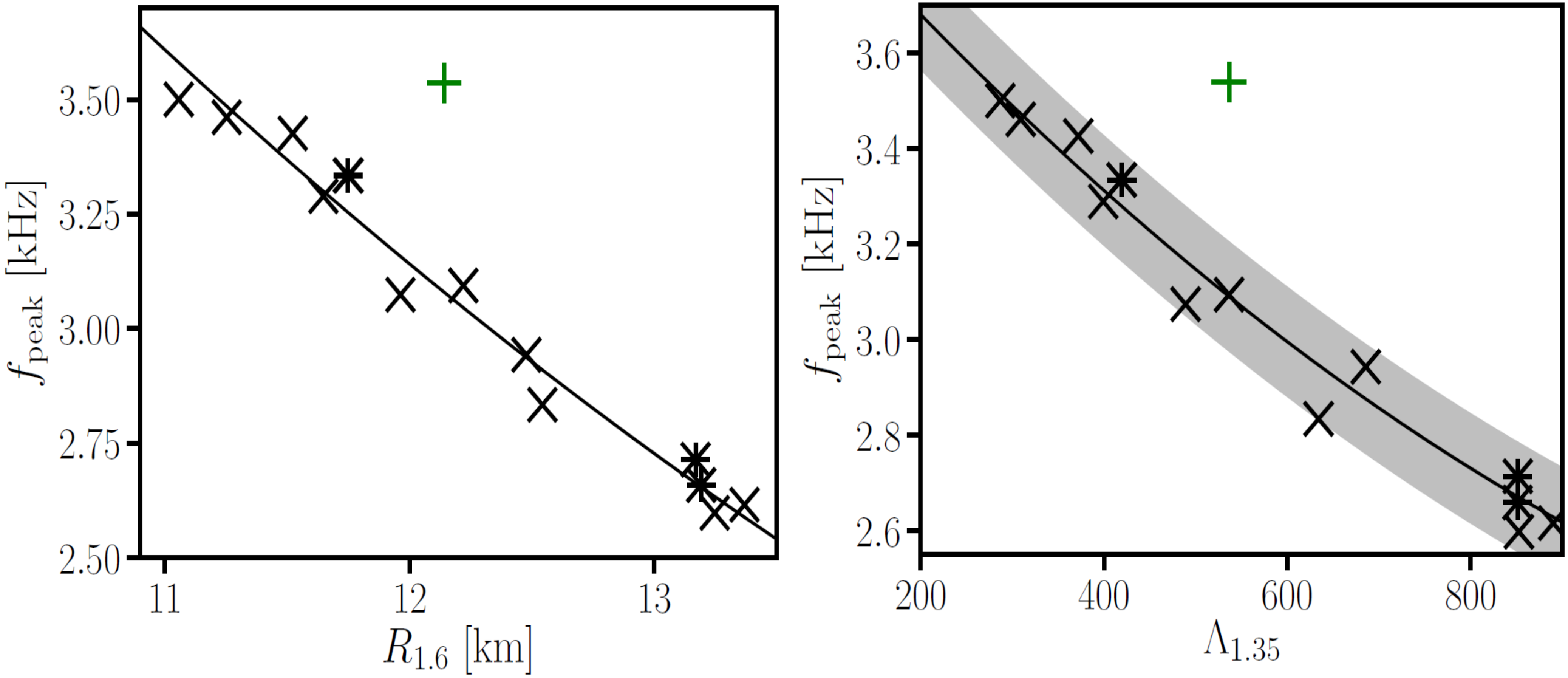


Hybrid star formaton during NS merger
→ higher densities and compacter star
→ higher peak frequency of the GW

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]



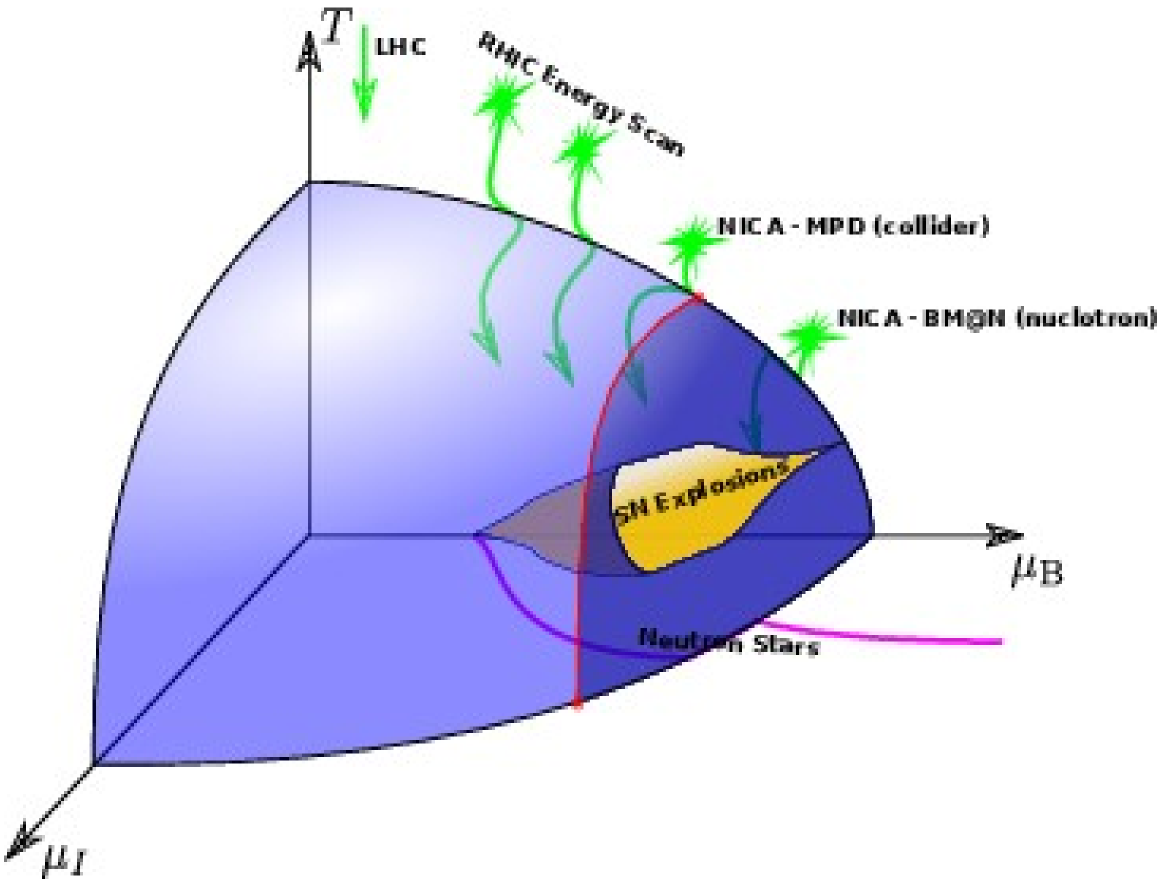
Strong deviation from **f_{peak} – $R_{1.6}$** relation signals **strong phase transition in** NS merger**!**

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

Conclusions:

Three-fluid hydrodynamical Event simulation is a tool for Investigating EoS effects in HIC observables at NICA

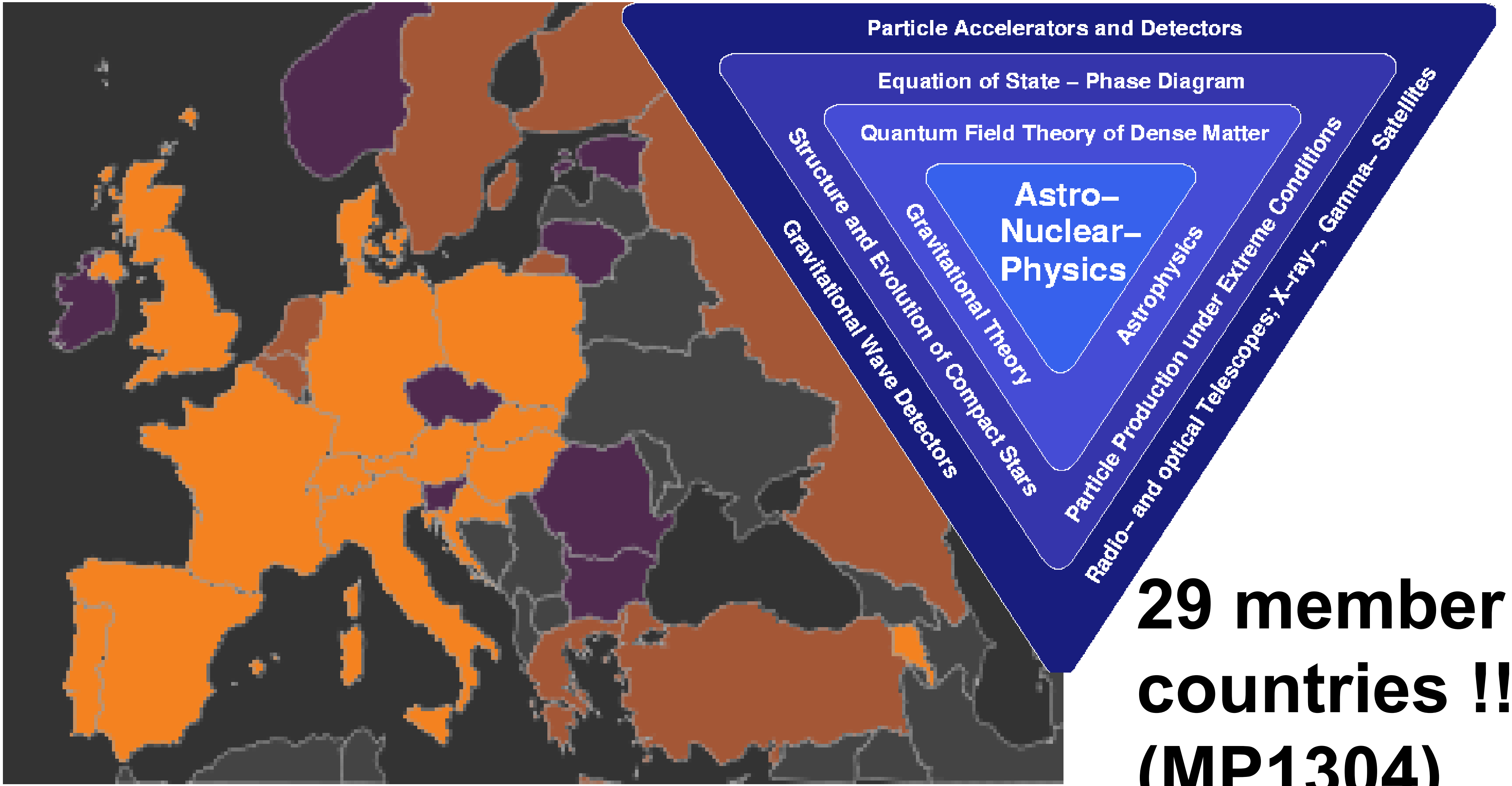
Here we demonstrated that medium effects on light nuclear cluster production become important at lower NICA energies → bridge to nuclear fragmentation experiments.



Marek’s horn may be due to an anomalous mode of the K+ meson at finite baryon densities and temperatures. The CEP may produce an additional structure (tooth) that can be used to calibrate the CEP position!

Extremely interesting to explore compatibility of EoS in HIC and Astrophysics! Massive supernova explodability and postmerger gravitational wave signal!

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 Wave Detectors

Structure and Evolution of Compact Stars

Gravitational Theory

Astrophysics

Particle Production under Extreme Conditions

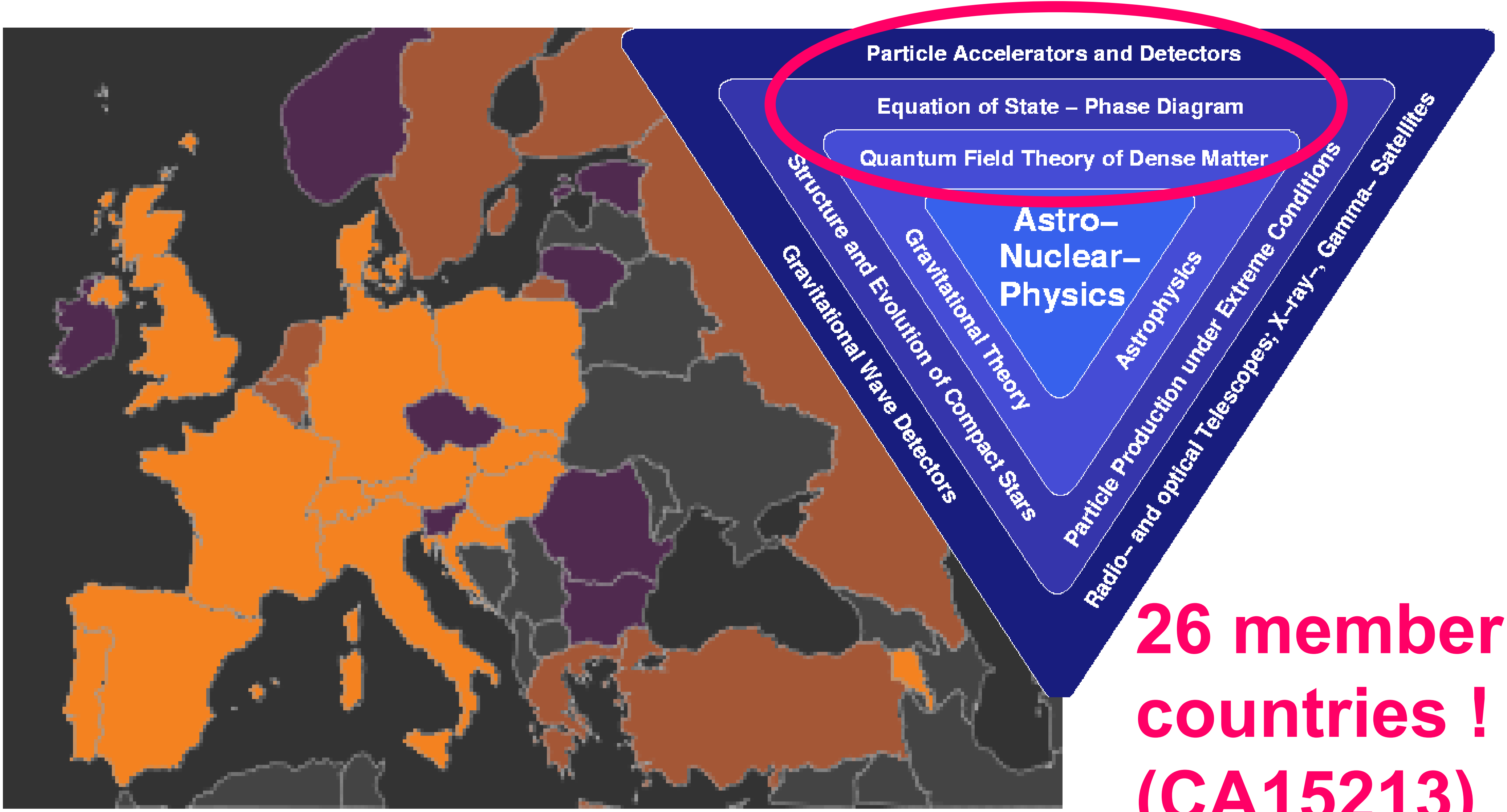
Radio- and optical Telescopes; X-ray-, Gamma- Satellites

29 member countries !! (MP1304)

New compstar **!**

cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

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



26 member countries ! (CA15213)

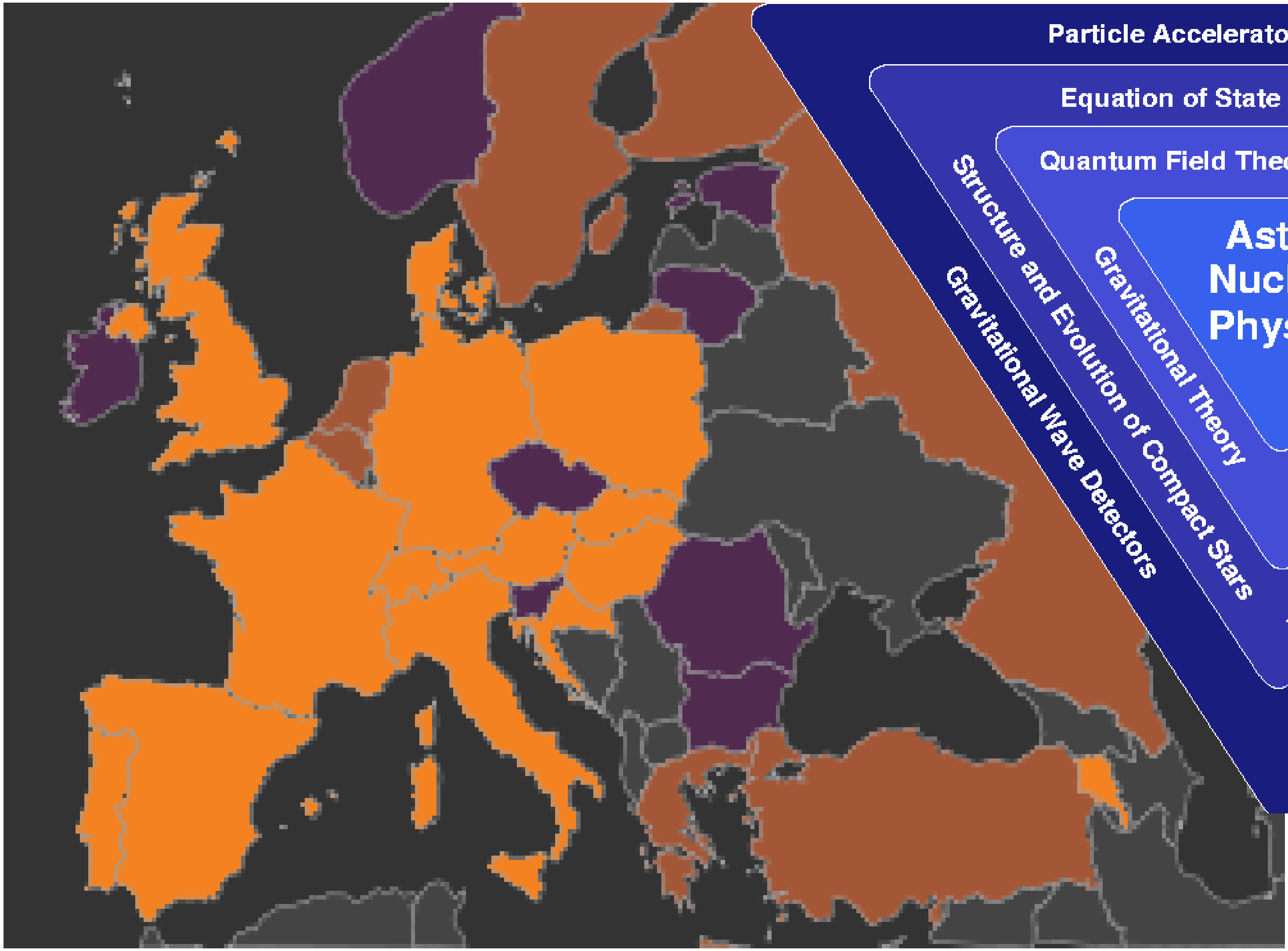
"Theory of HOt Matter in Relativistic Heavy-Ion Collisions"

New: THOR !

cost

EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

Kick-off: Brussels, October 17, 2016



Particle Accelerators and Detectors

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

comp
star

Network:
CA16214
30 countries

Newest:

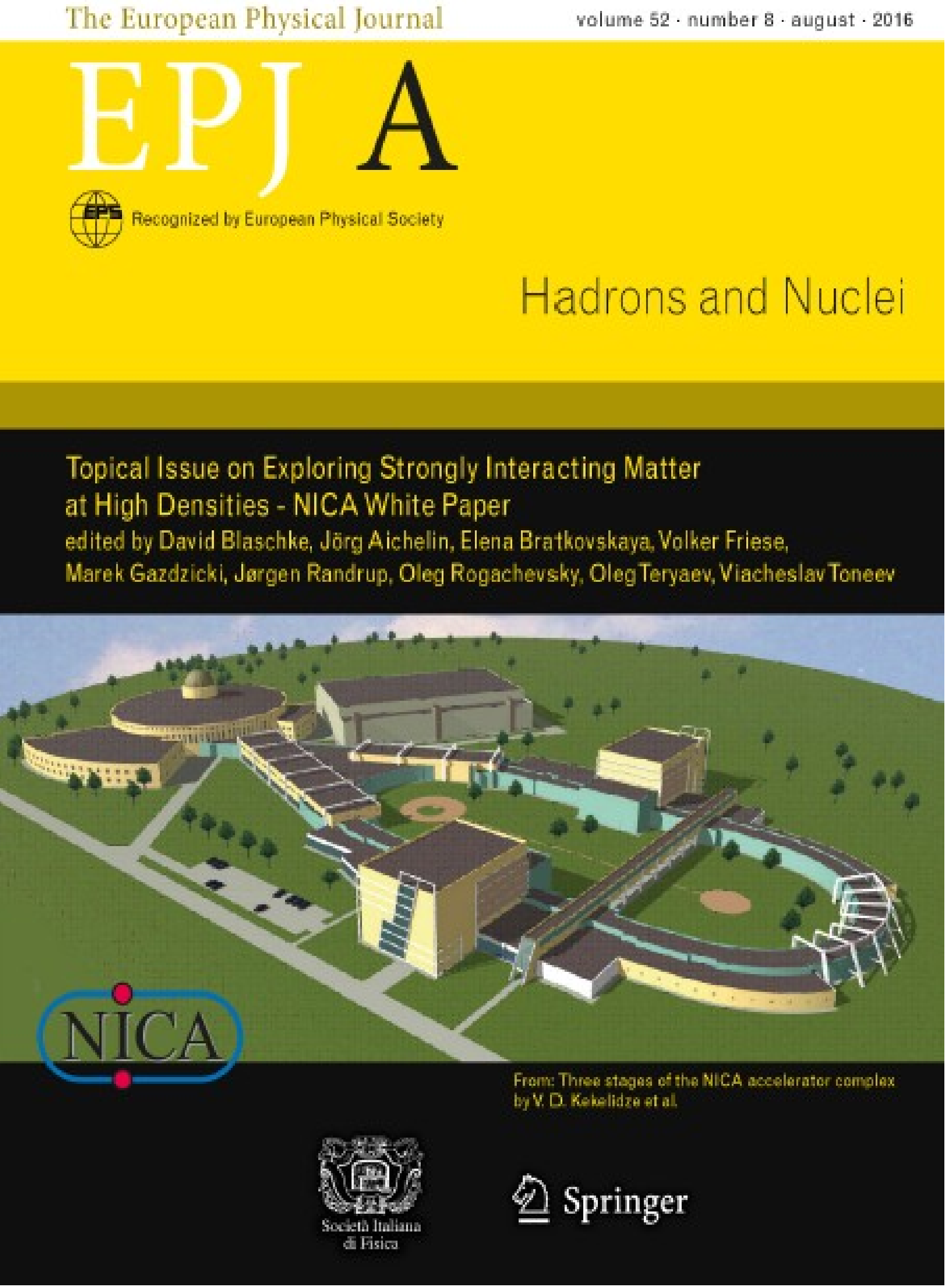
PHAROS
THE MULTI-MESSENGER
PHYSICS AND ASTROPHYSICS
OF NEUTRON STARS

cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

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

Kick-off: Brussels, 22.11. 2017

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



The European Physical Journal

volume 52 · number 8 · august · 2016

EPJ A

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Hadrons and Nuclei

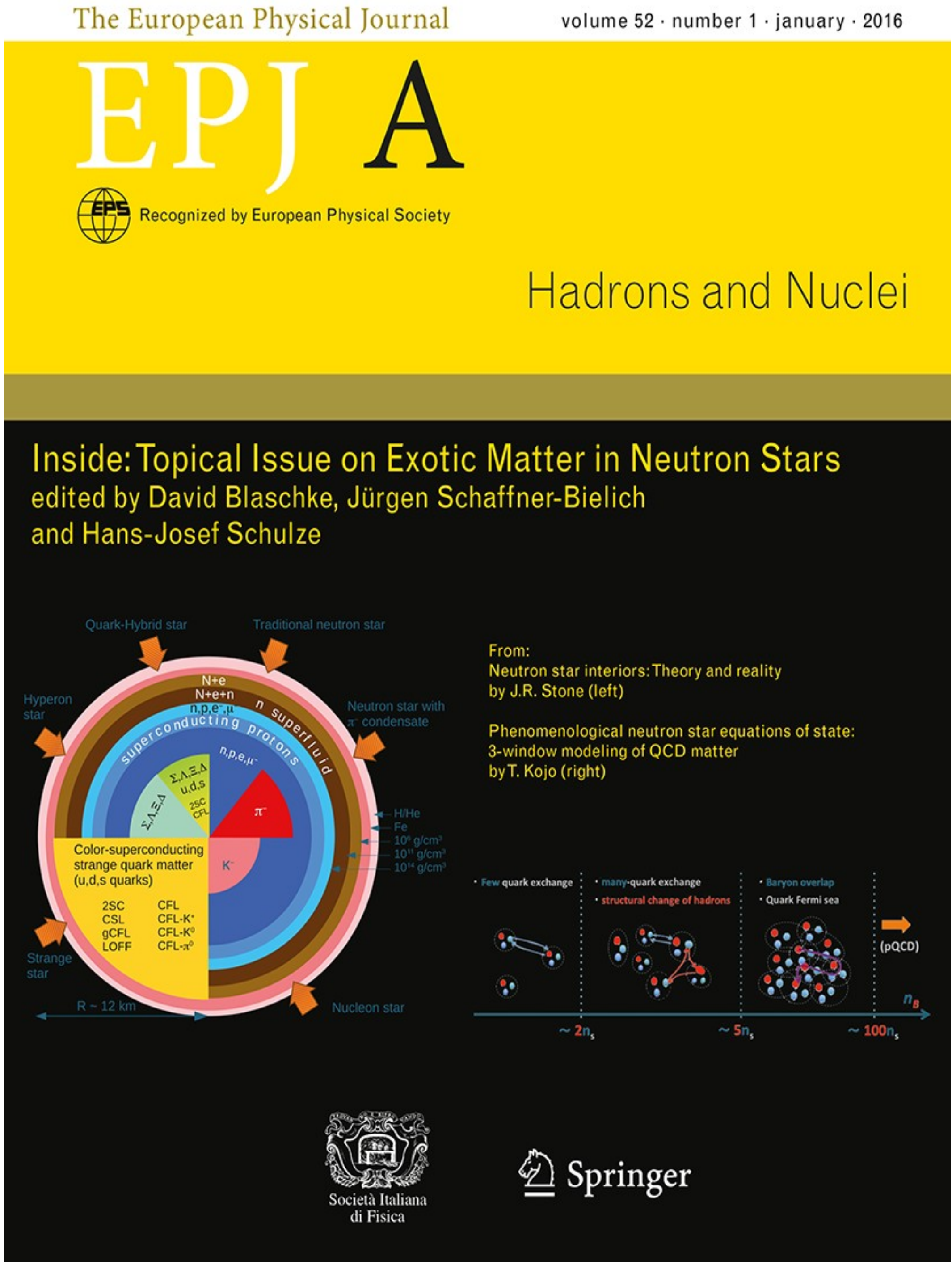
Topical Issue on Exploring Strongly Interacting Matter at High Densities - NICA White Paper

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.

Società Italiana di Fisica

Springer



The European Physical Journal

volume 52 · number 1 · january · 2016

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Hadrons and Nuclei

Inside: Topical Issue on Exotic Matter in Neutron Stars

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

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

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

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Springer

EPJA Topical Issues can be found at → http://epja.epj.org/component/list/?task=topic

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

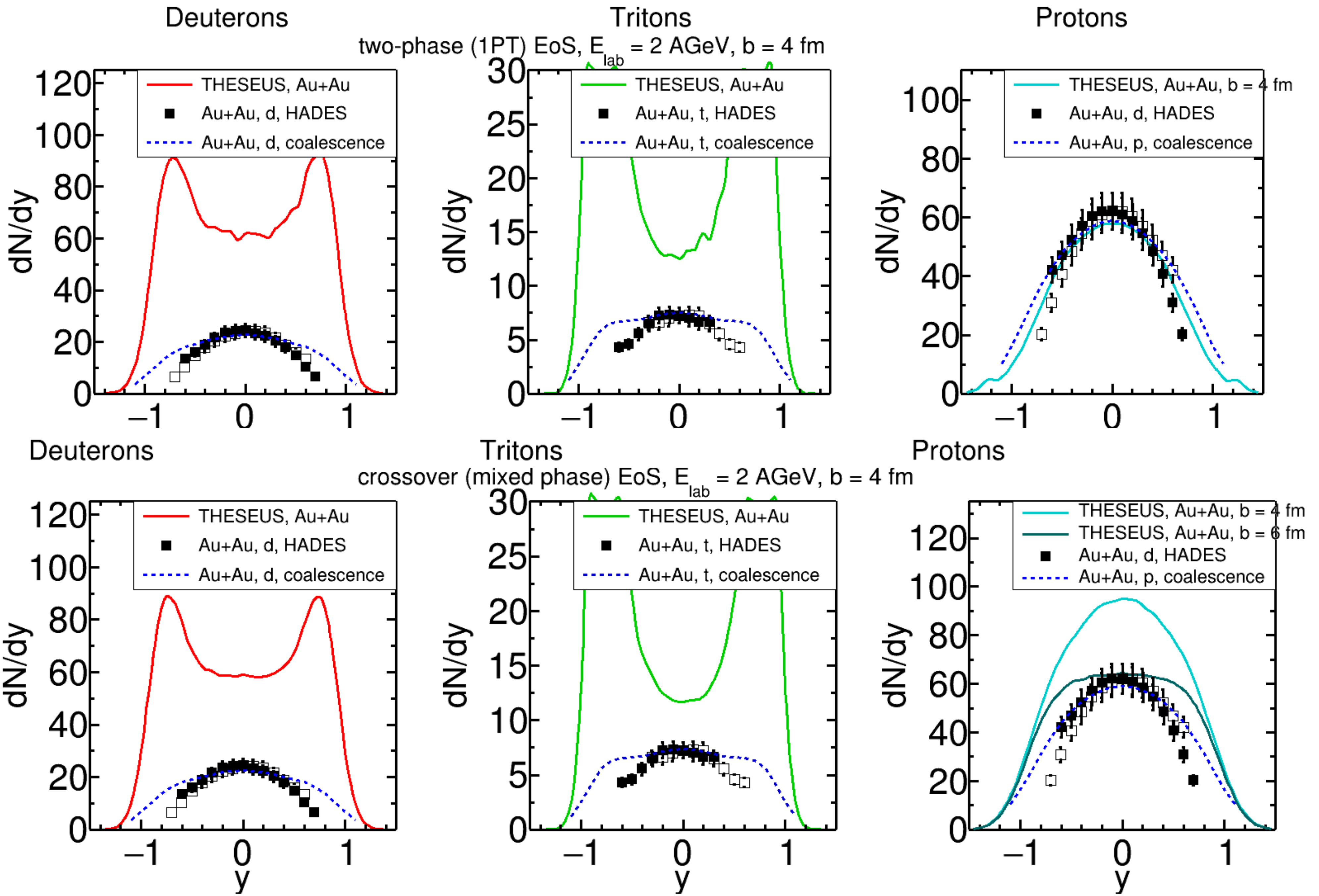
Open call for contributions
Deadline – 2019

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

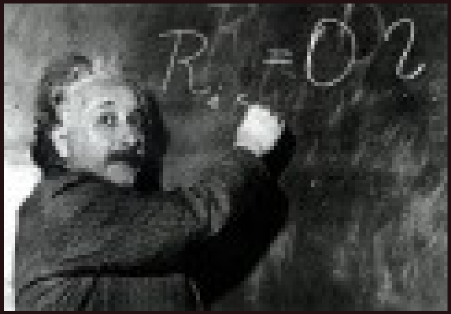
Email: david.blaschke@gmail.com epja.bologna@sif.it

Backup slides

Light Fragment (LF) Production at Low Energies

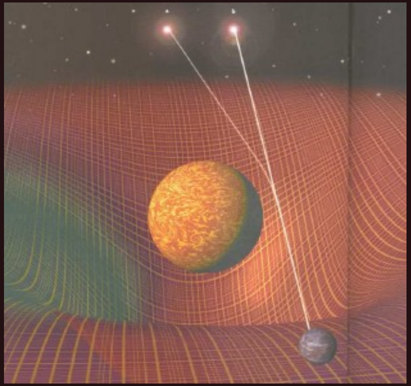


Compact stars and black holes in Einstein's General Relativity theory

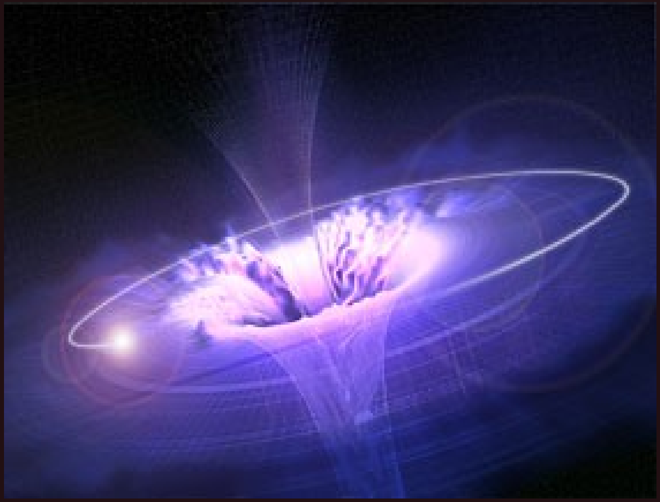


Space-Time $G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$ Matter

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

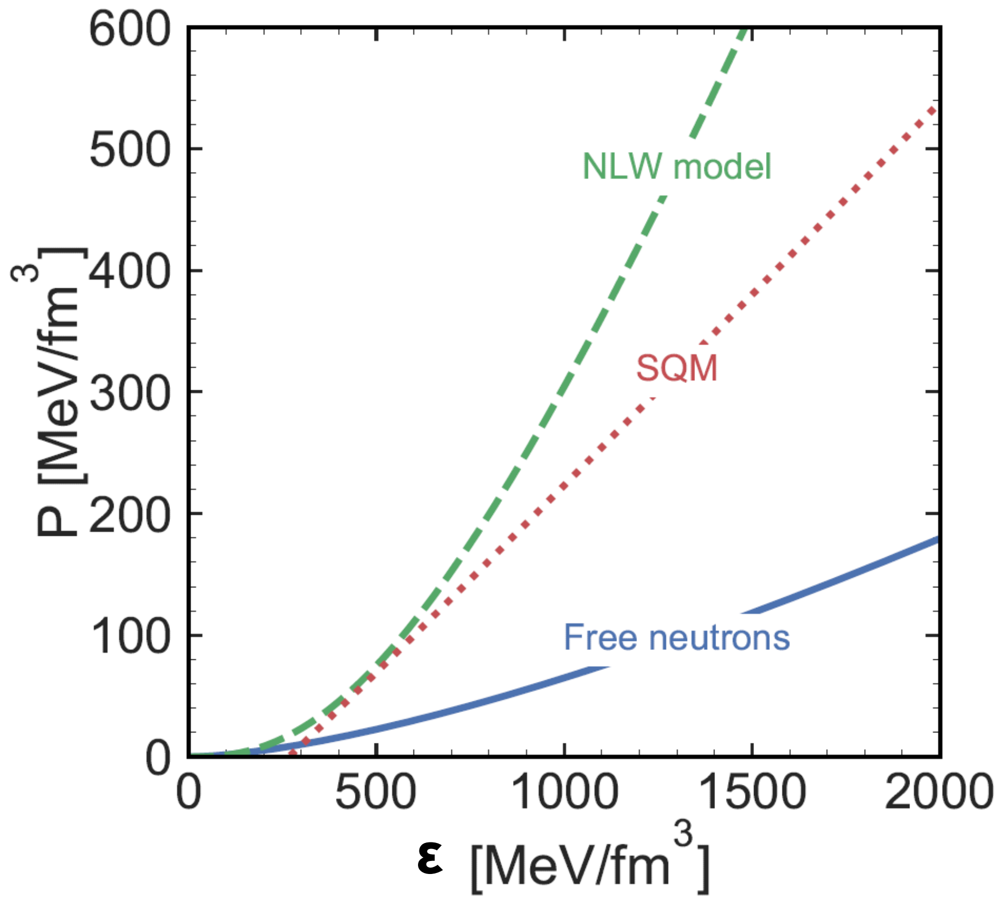
$$\frac{dP(r)}{dr} = -G\frac{m(r)\varepsilon(r)}{r^2}\left(1 + \frac{P(r)}{\varepsilon(r)}\right)\left(1 + \frac{4\pi r^3 P(r)}{m(r)}\right)\left(1 - \frac{2Gm(r)}{r}\right)^{-1}$$

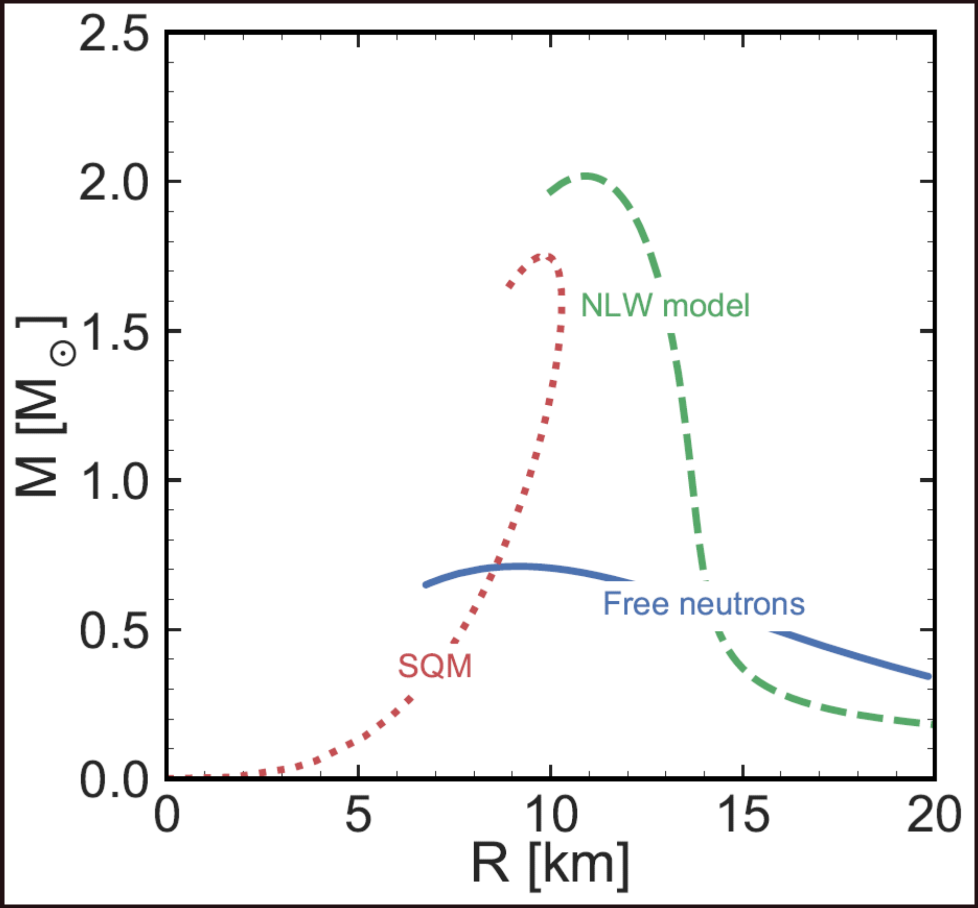
Newtonian case x GR corrections from EoS and metrics

*) 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

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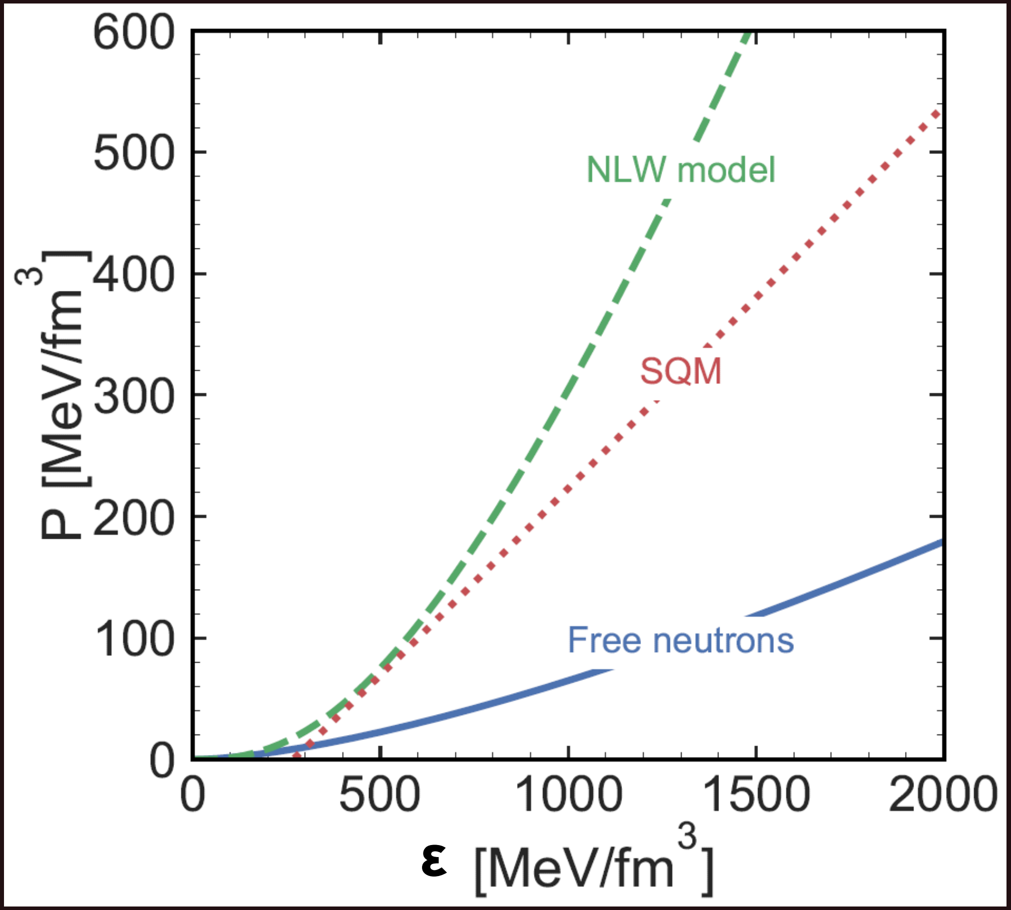

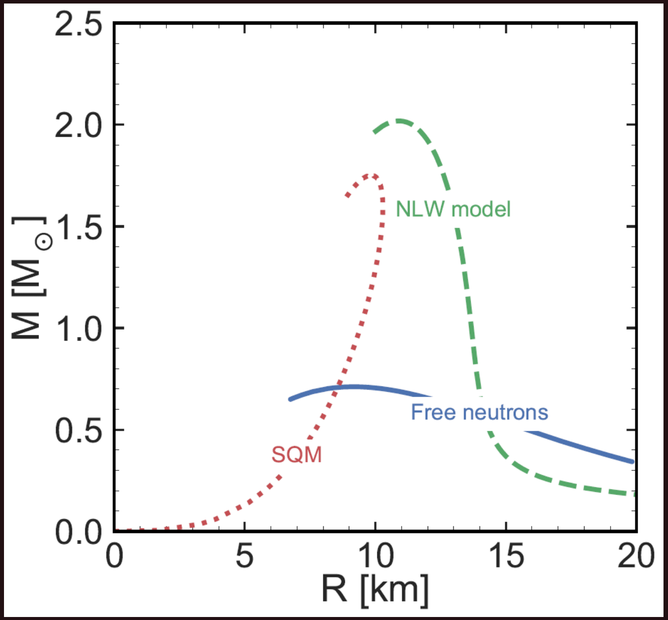

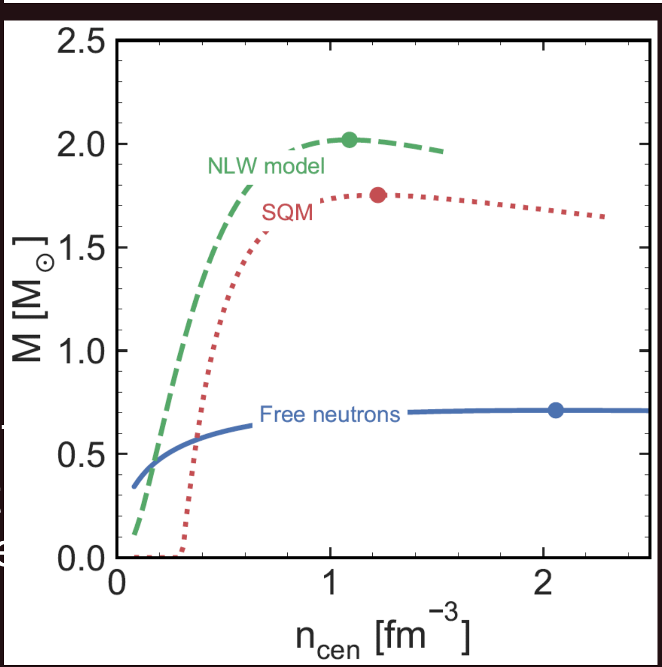

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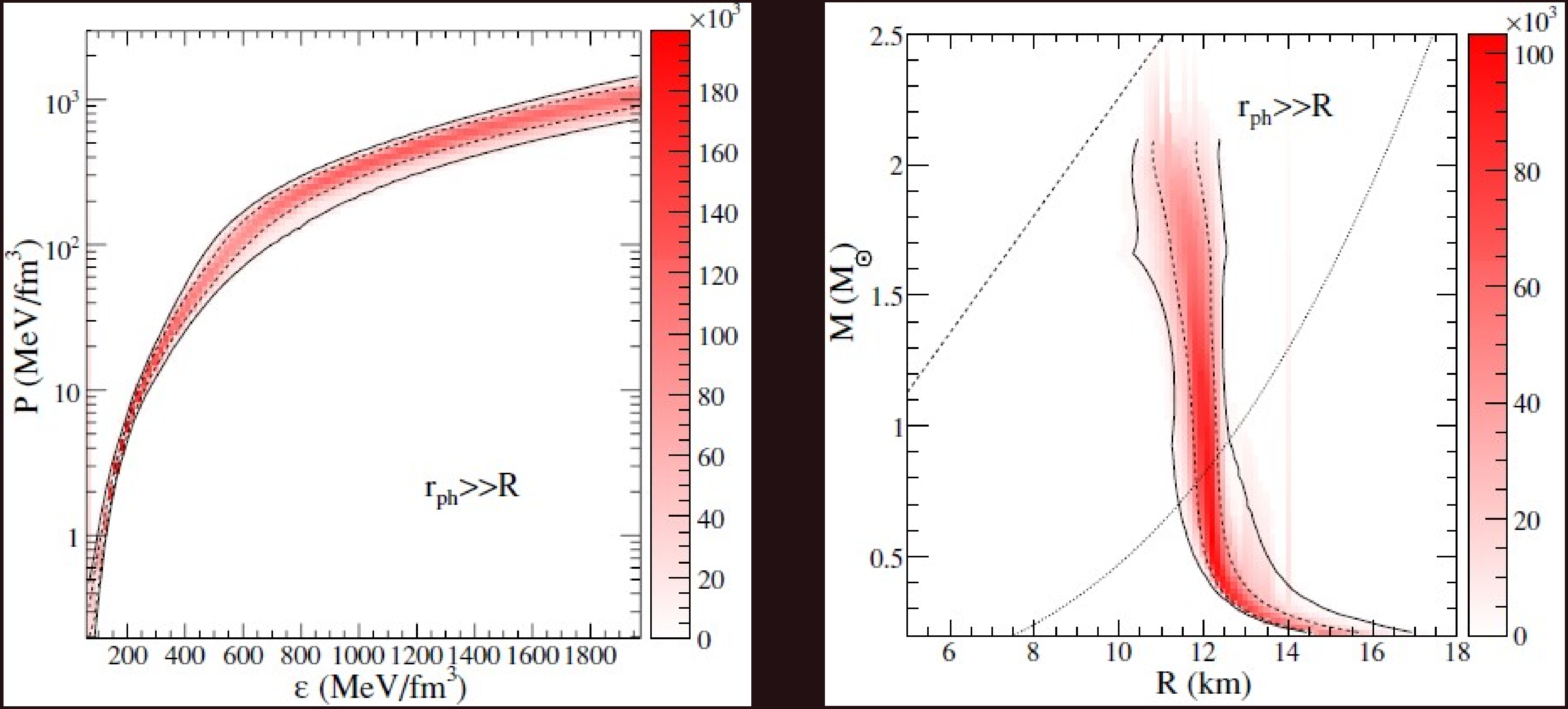
*) courtesy: Konstantin Maslov

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

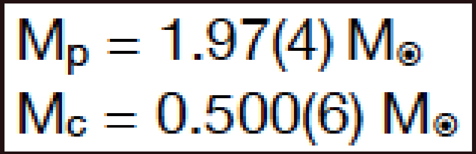
PSR J1614-2230
Demorest et al., Nature (2010)

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:

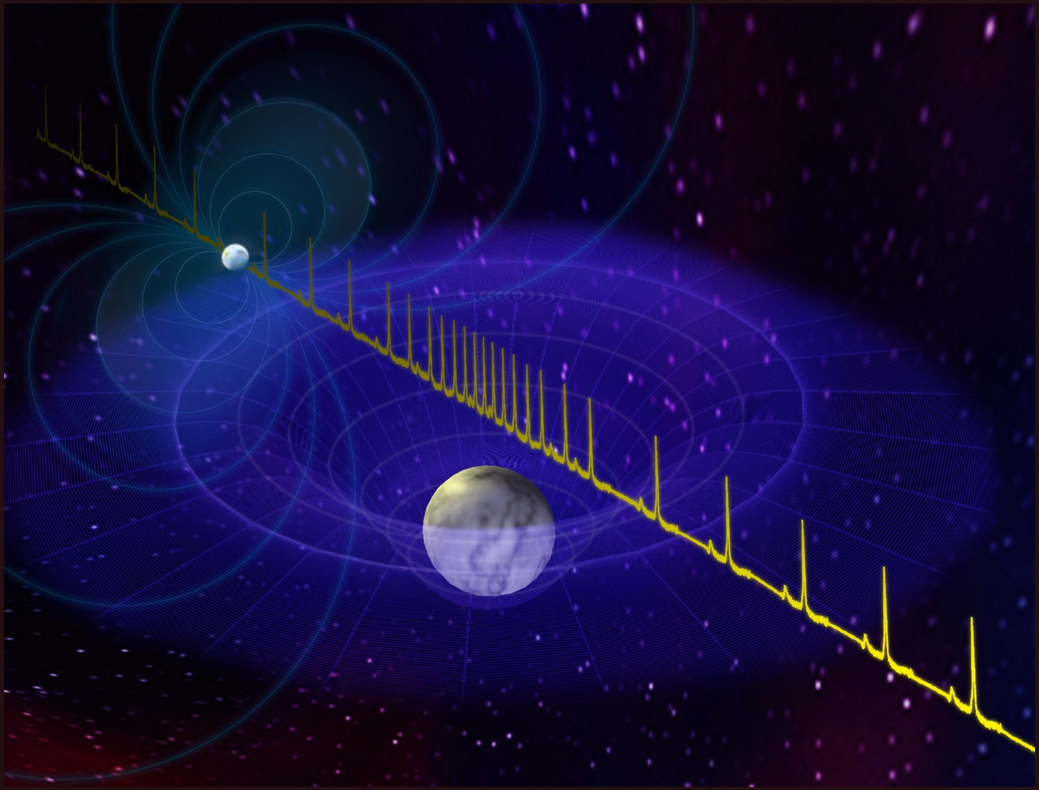


$M_p = 1.97(4)\ M_\odot$
$M_c = 0.500(6)\ M_\odot$

Update [Fonseca et al. (2016)]

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

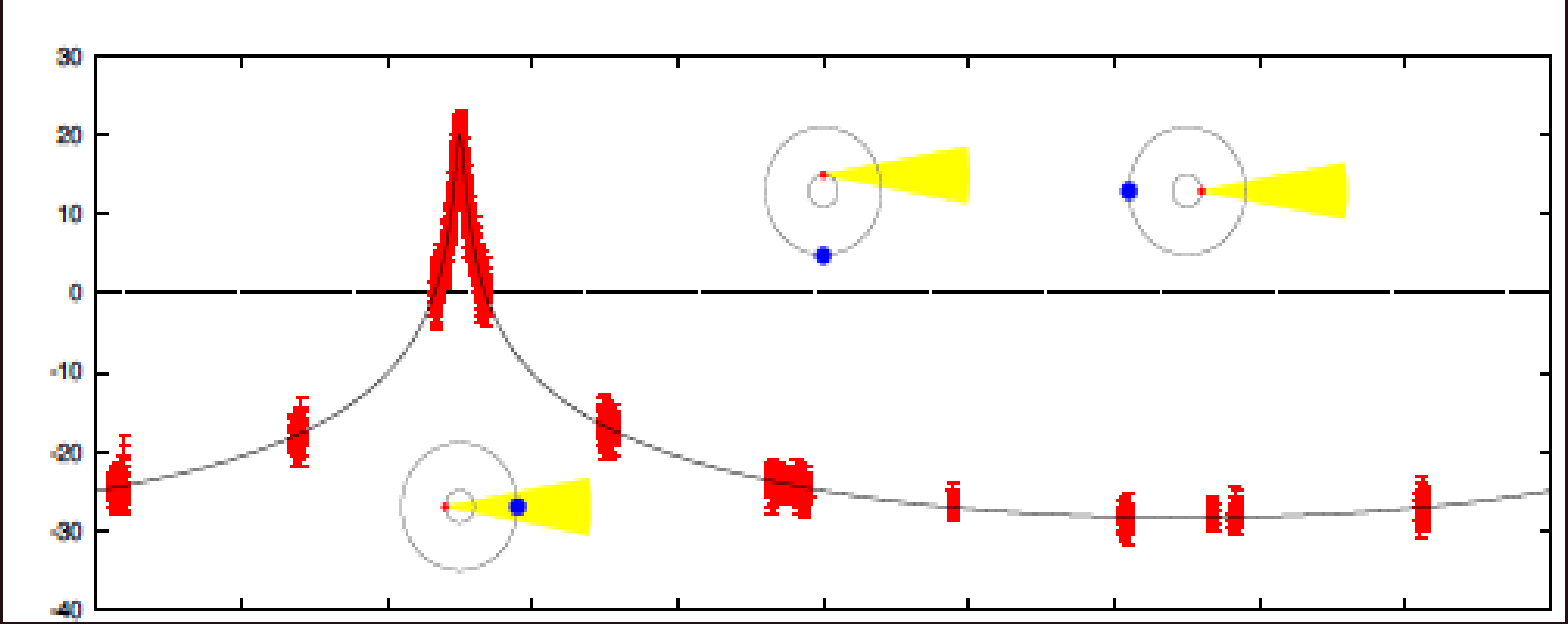
Update [Arzoumanian et al. (2018)]
Mp = 1.908(16) Mo



PSR J1614-2230

A precise AND large mass measurement

Shapiro delay:



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

Neutron star mass measurements with Shapiro delay – new record

MSP with period P=2.88 ms

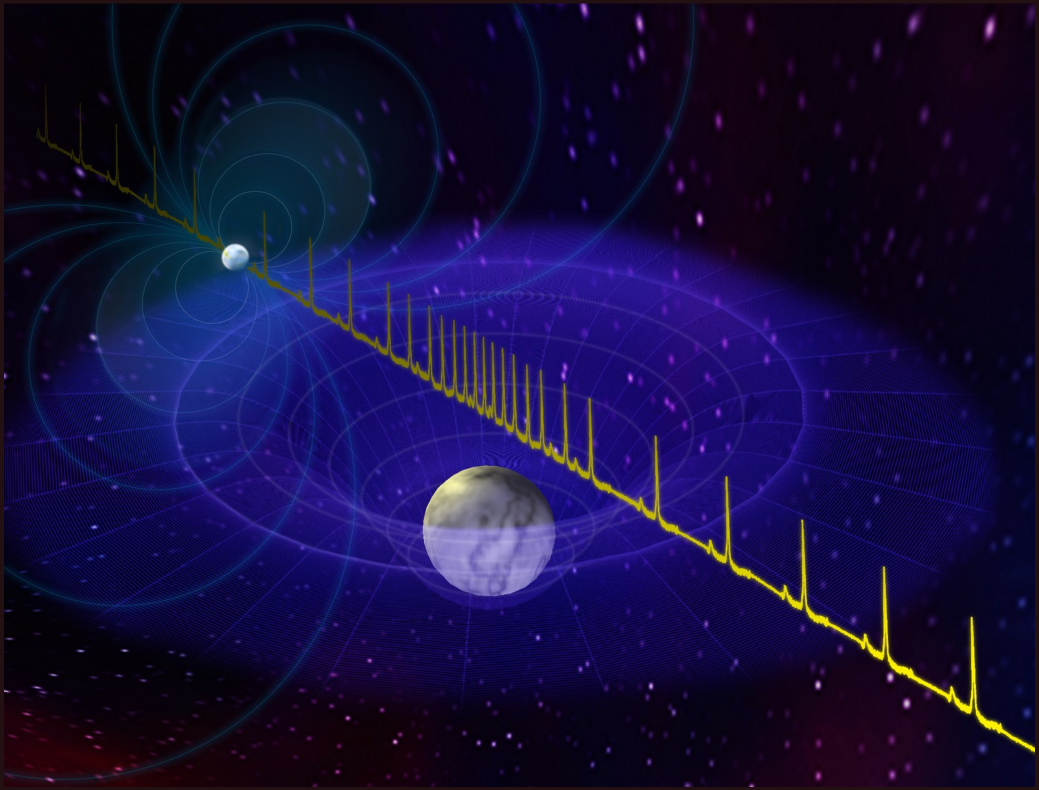
Pb = 4.7669 d, e=0.00000507(4)

Inclination angle = 87.35 degrees !

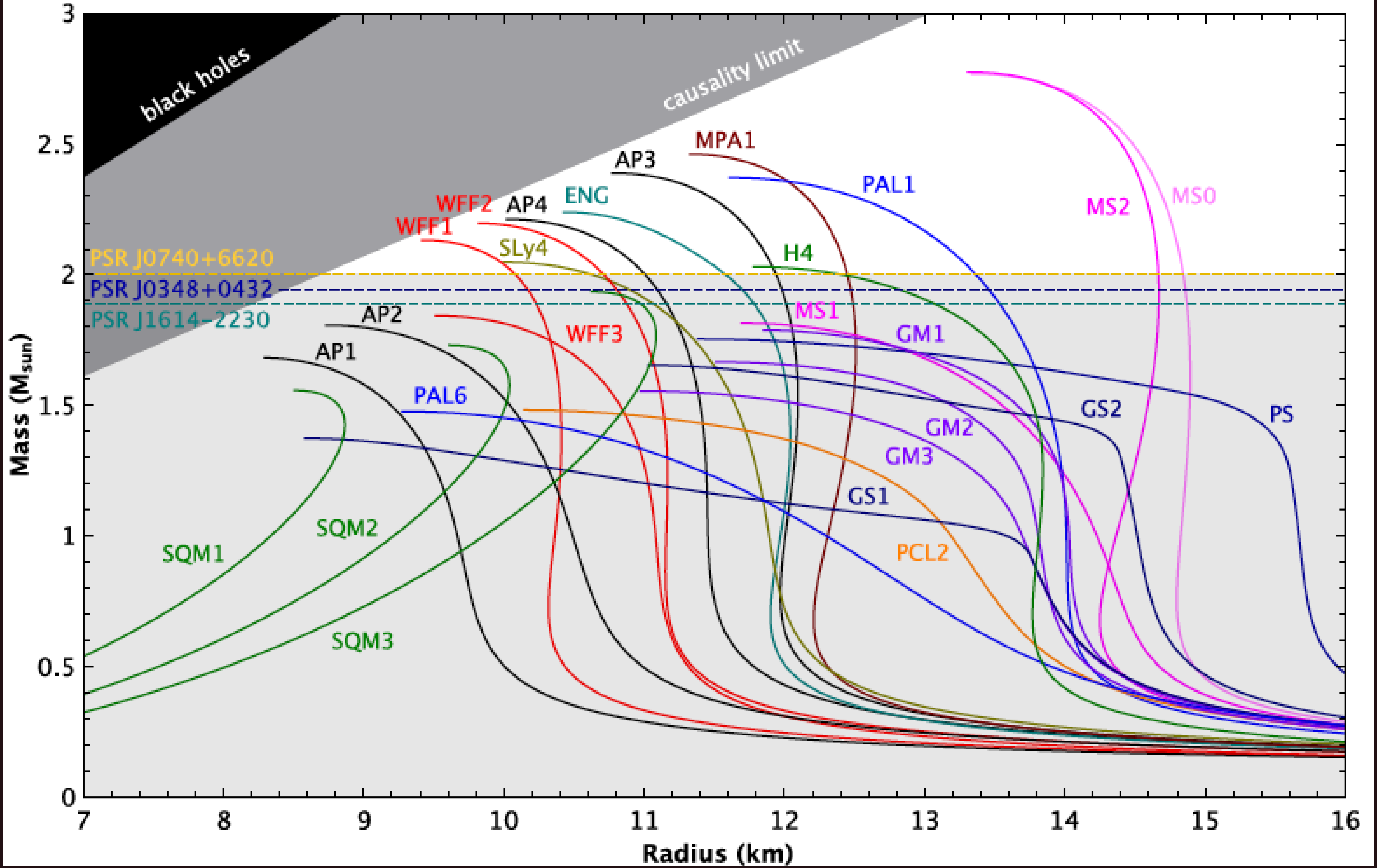
Precise mass derived from Shapiro delay only:

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

PSR J0740+6620
Cromartie et al., arXiv:1904.06759 (2019)

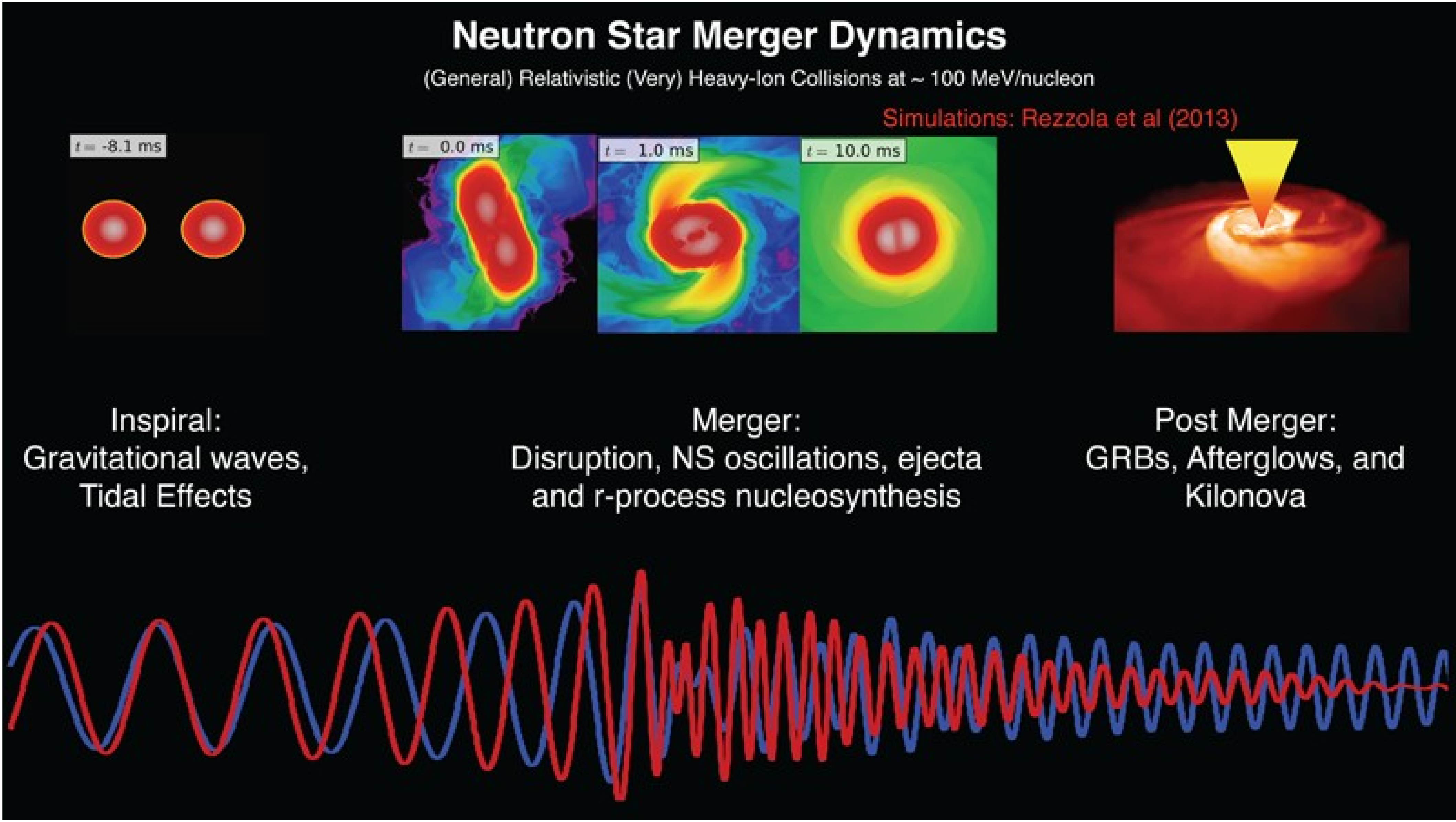


NS Masses and Radii ↔ EoS



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

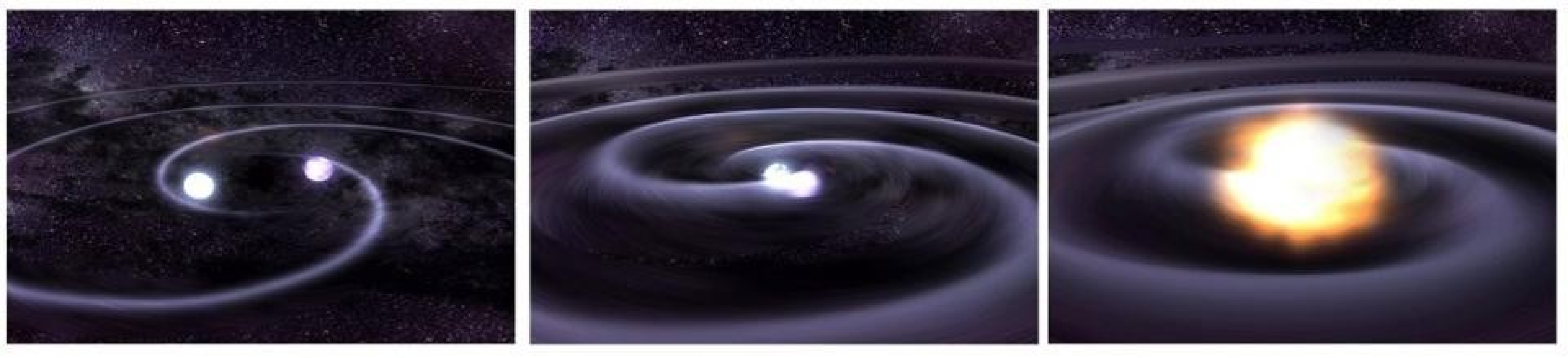
Simulations: Rezzola et al (2013)

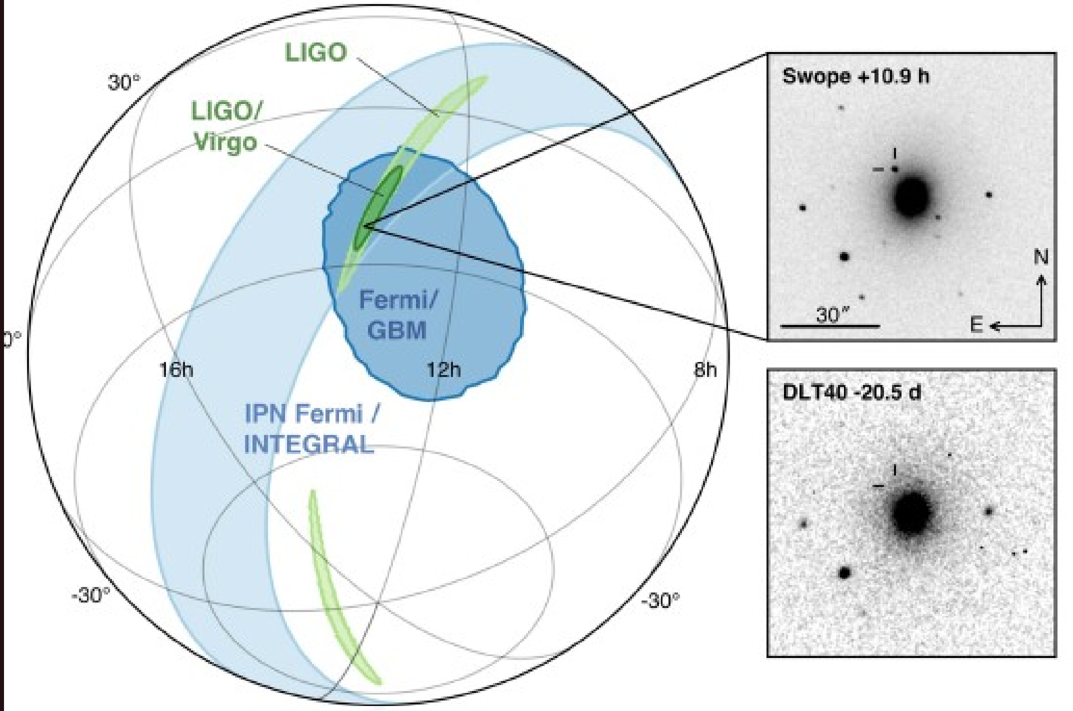
Inspiral:
Gravitational waves,
Tidal Effects

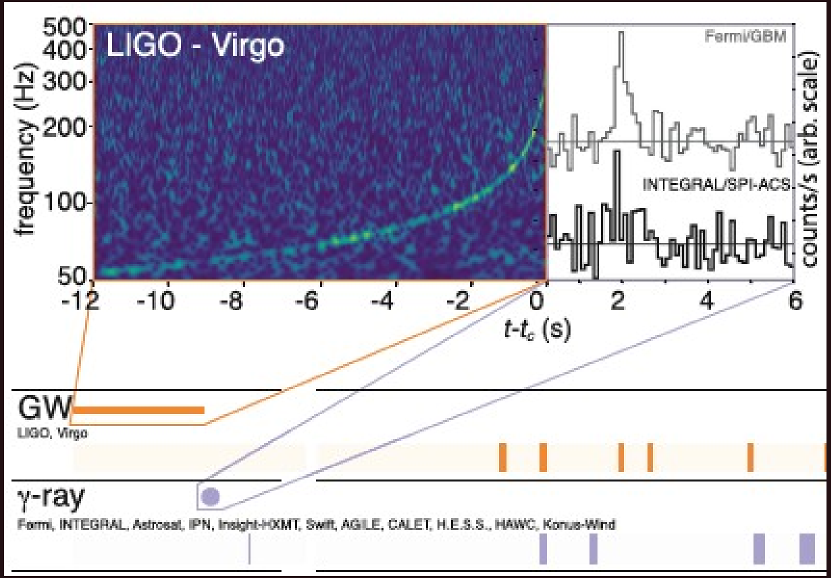
Merger:
Disruption, NS oscillations, ejecta
and r-process nucleosynthesis

Post Merger:
GRBs, Afterglows, and
Kilonova

Discovery: neutron star merger !







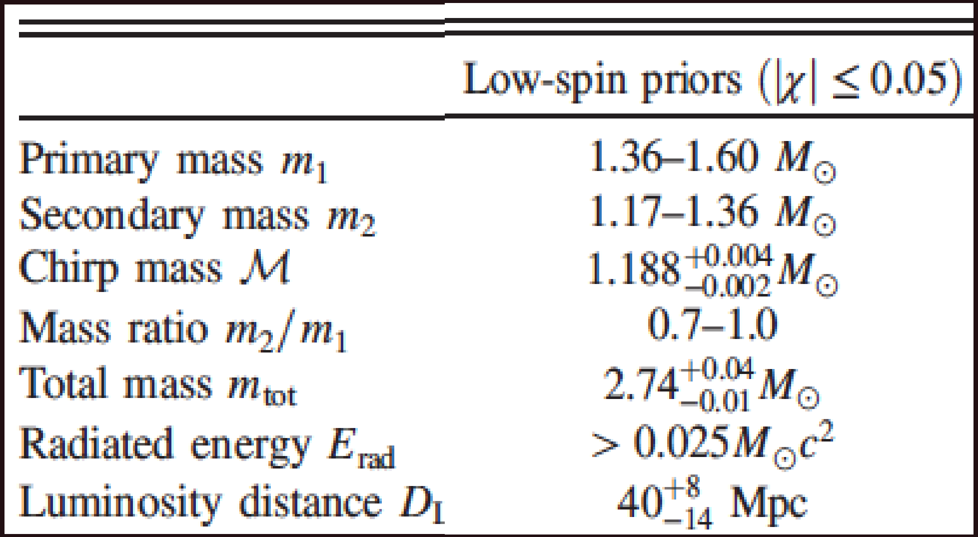
GW170817A , announced 16.10.2017 *)

*) 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 !!

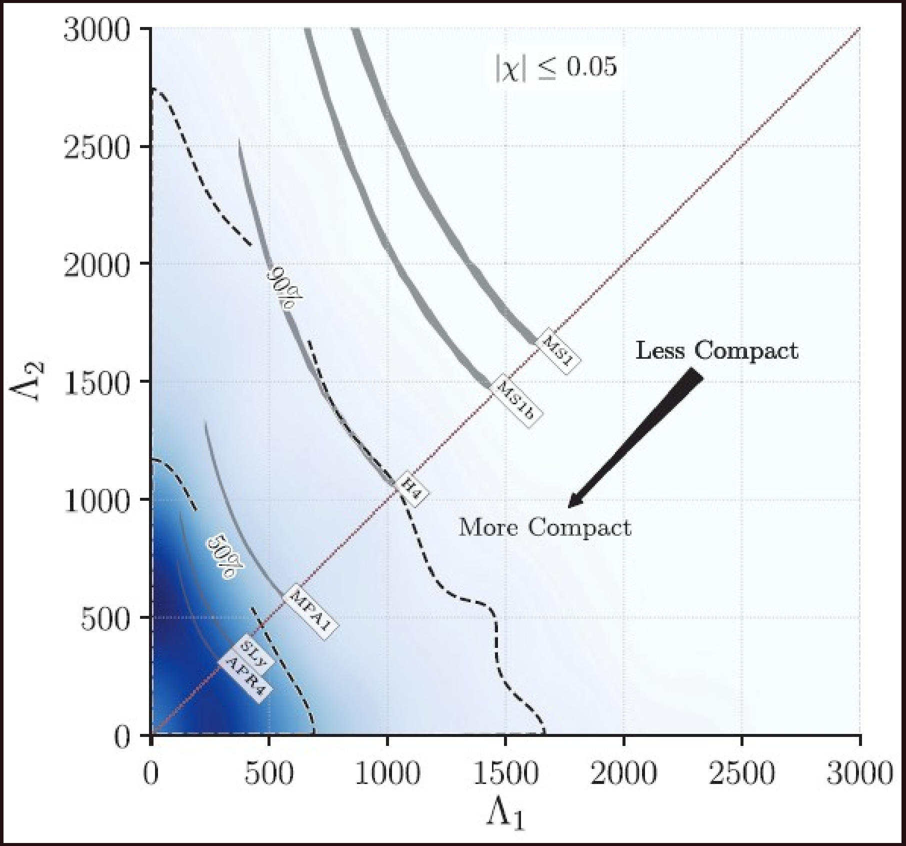


	Low-spin priors ($\vert\chi\vert \leq 0.05$)
Primary mass m_1	1.36–$1.60\ M_\odot$
Secondary mass m_2	1.17–$1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025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

Constraint on neutron star maximum mass

M_{TOV} < 2.17 M_sun

(Margalit & Metzger, arxiv:1710.05938)



Constraint on parameter (Λ<800)

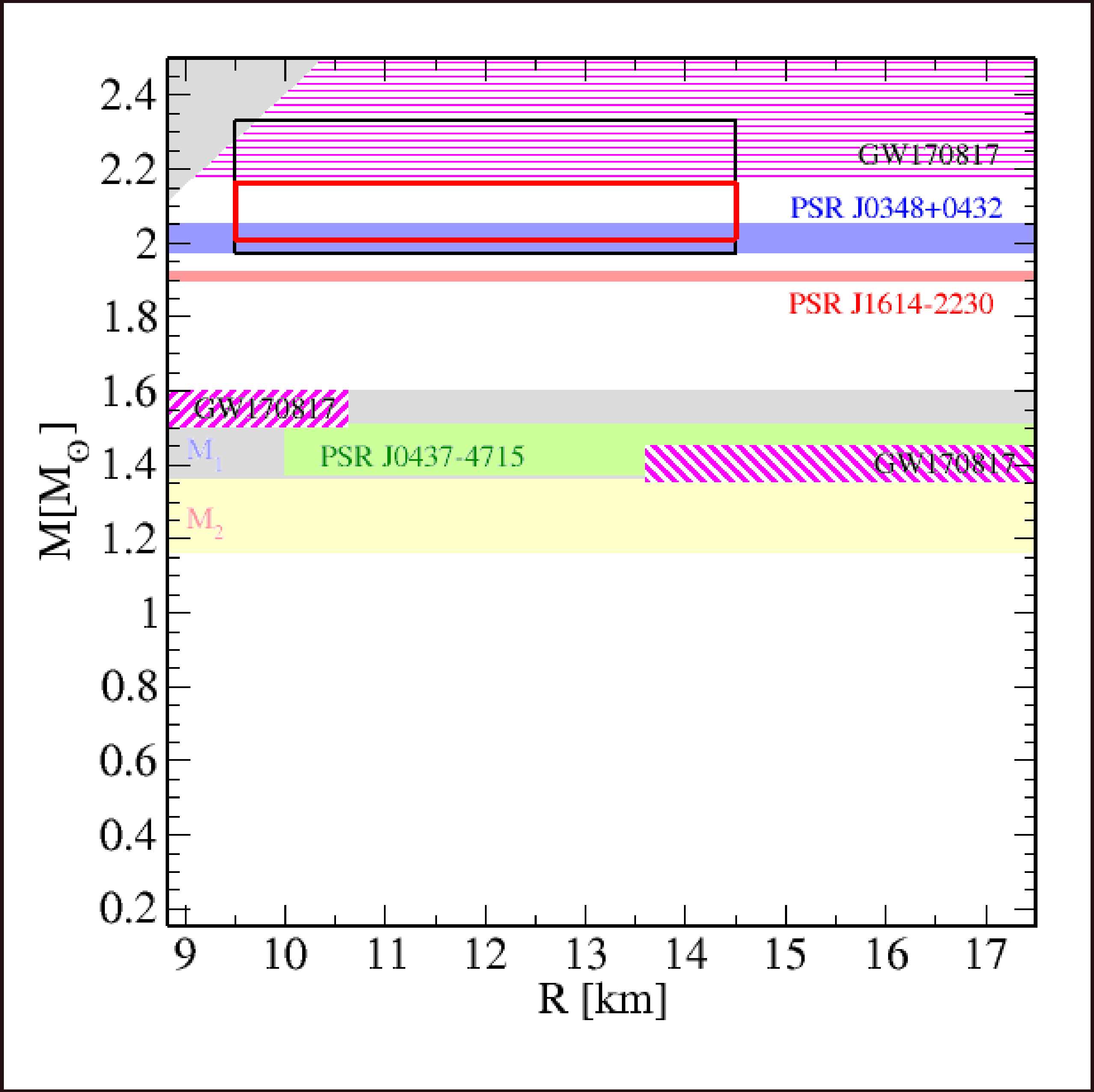
$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$

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)

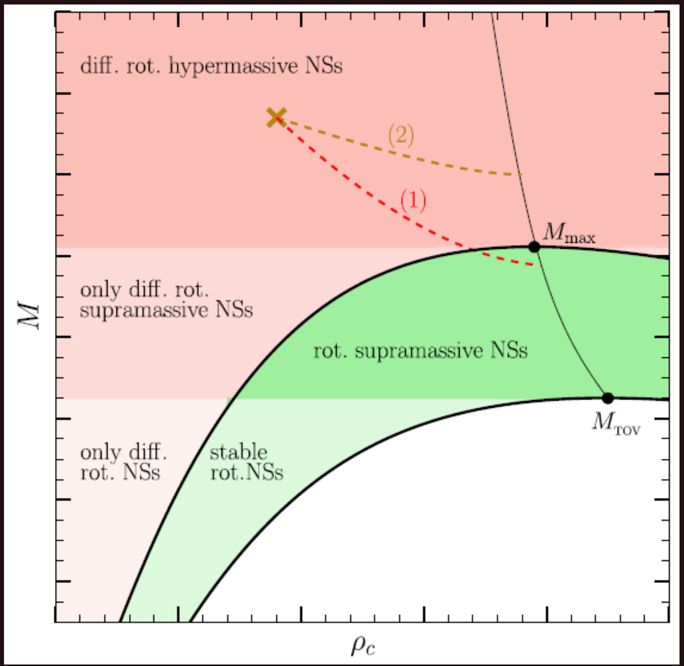
Constraints on NS mass and radii !



Constraint on maximum mass

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

(Rezzolla et al., arxiv:1710.05938)



Constraint on minimal radius

$R_{1.6} > 10.68$ km

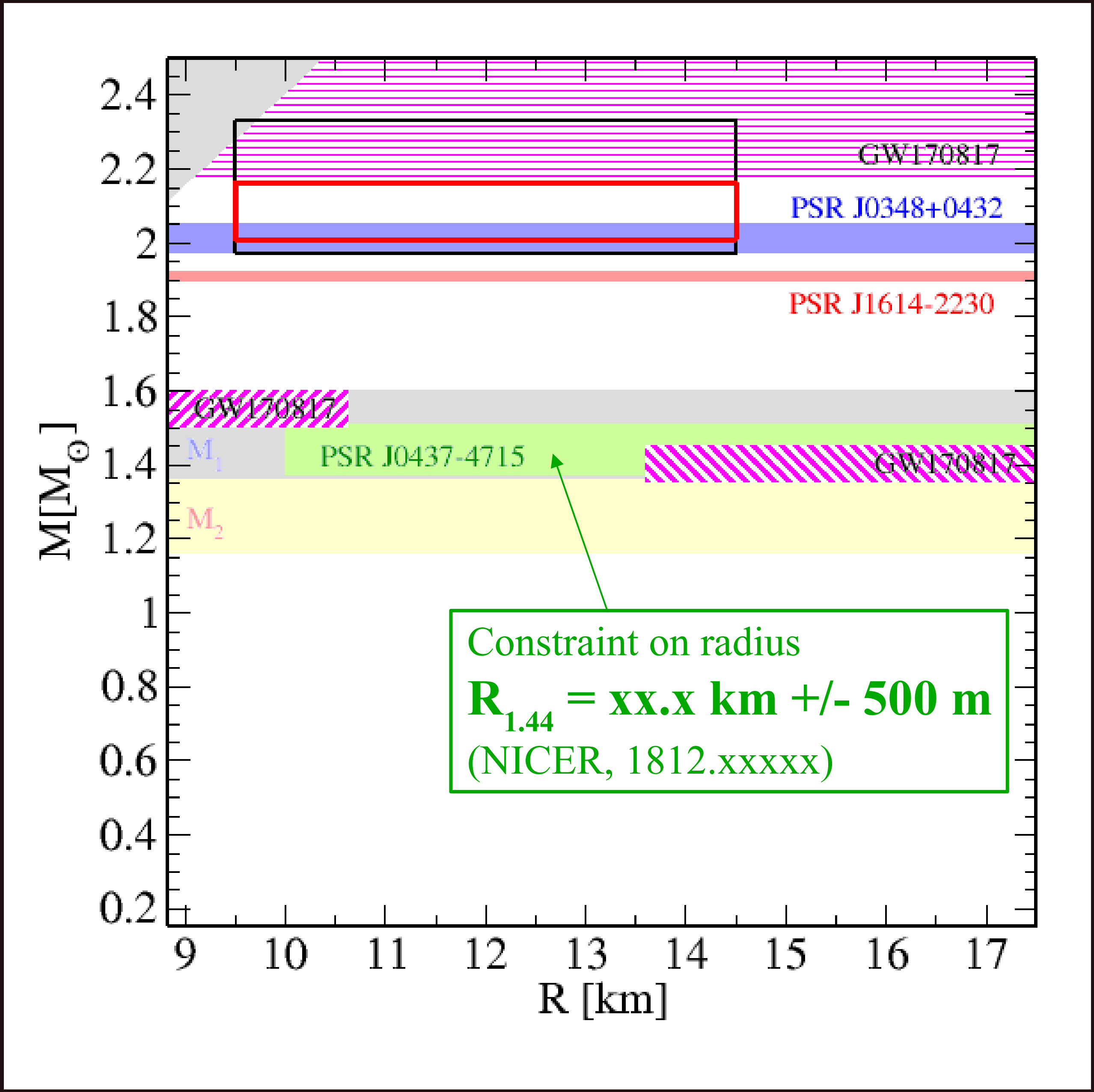
(Bauswein et al., arxiv:1710.06843)

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

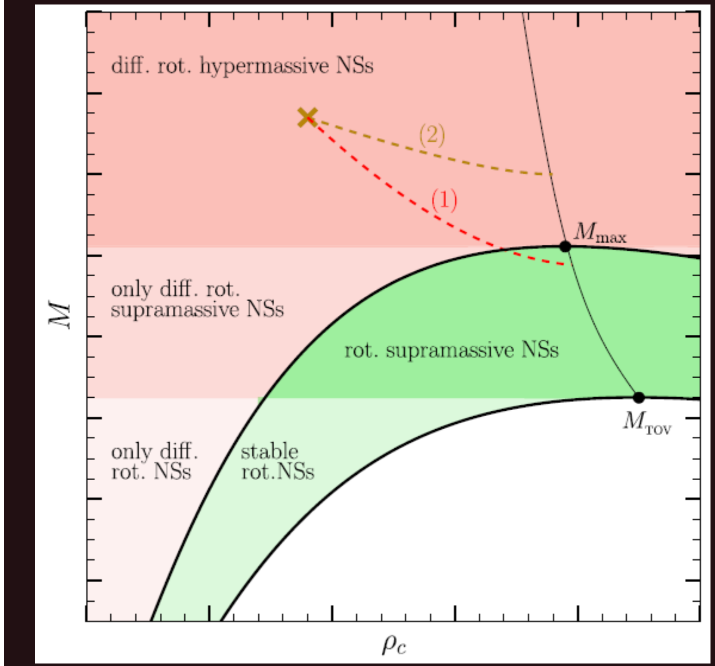
$R_{1.44}$ = xx.x km +/- 500 m

(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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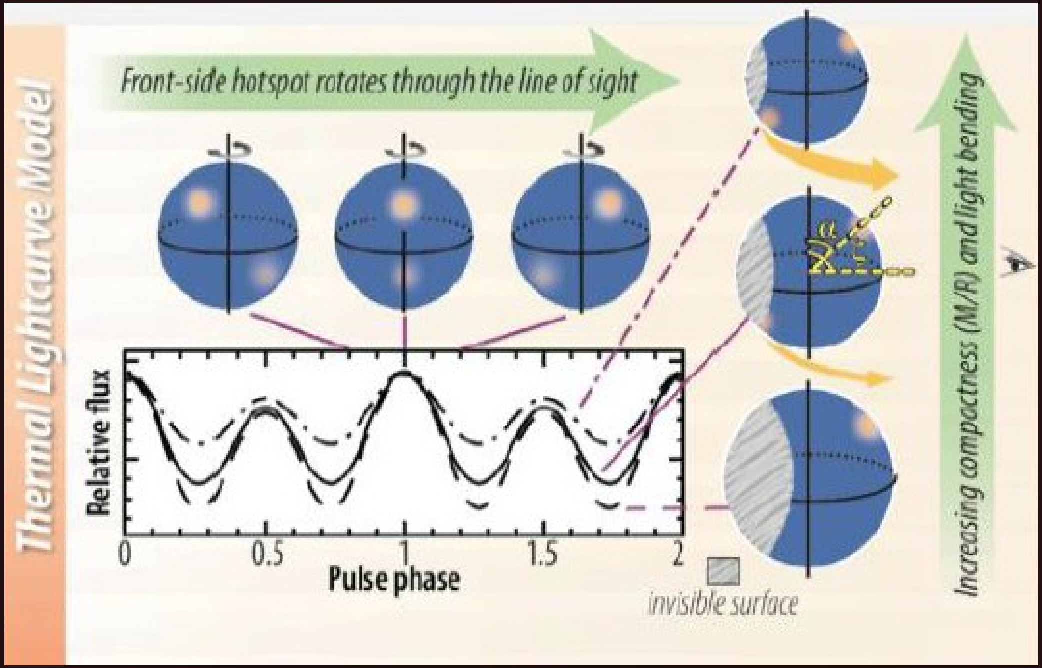
Constraint on maximal radius

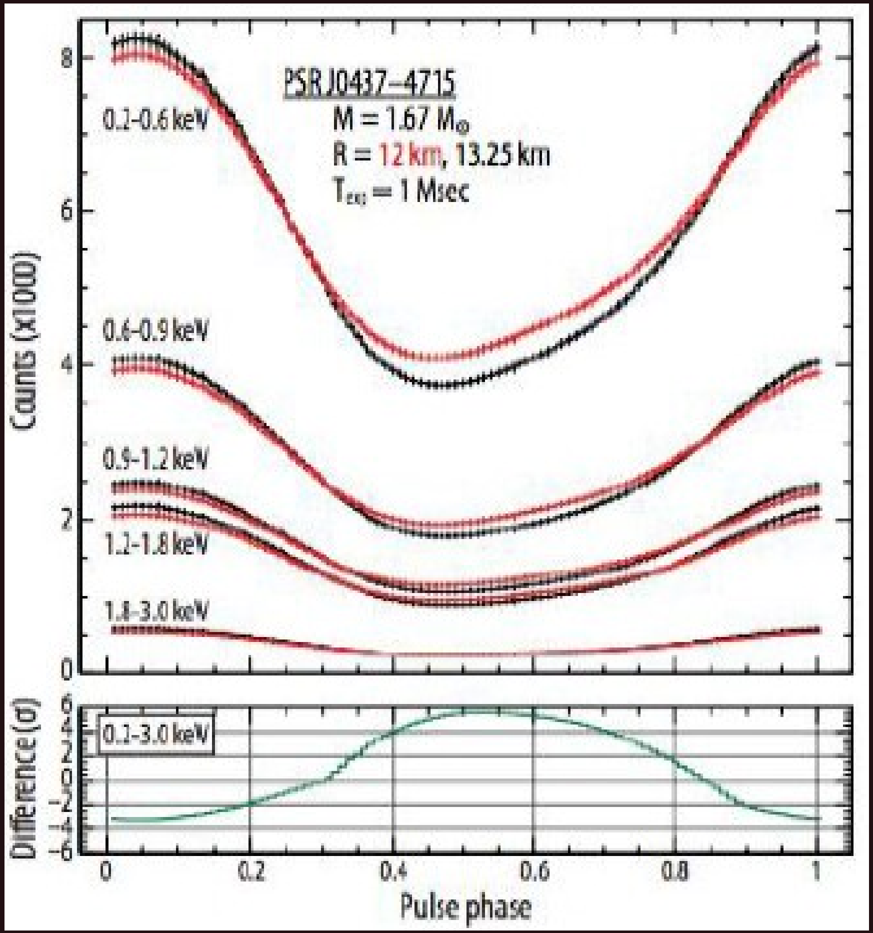
$R_{1.4} < 13.6$ km

(Annala et al., arxiv:1711.02644)

Measure NS Radii ...

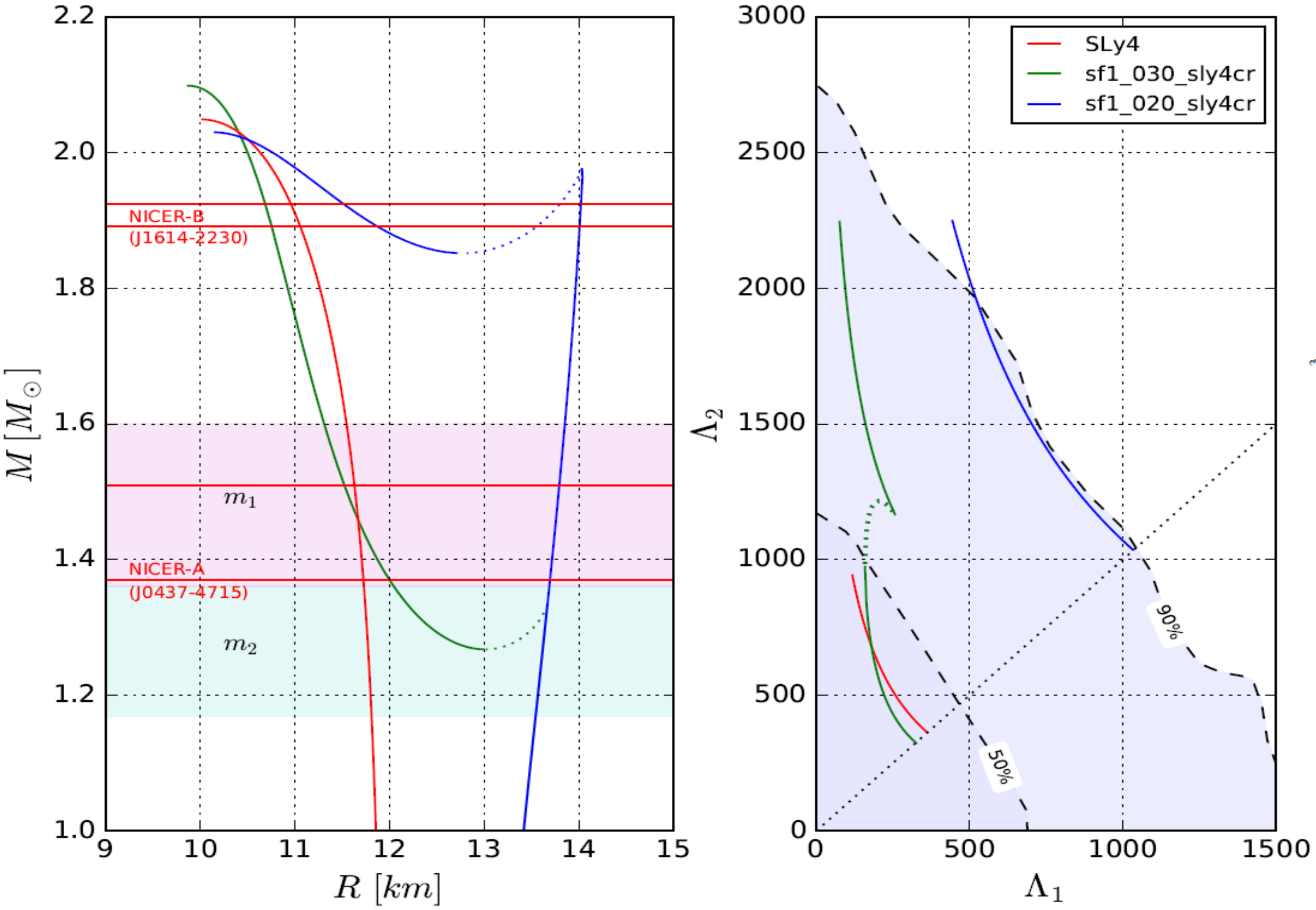


Thermal lightcurves: NS with “hot spots”

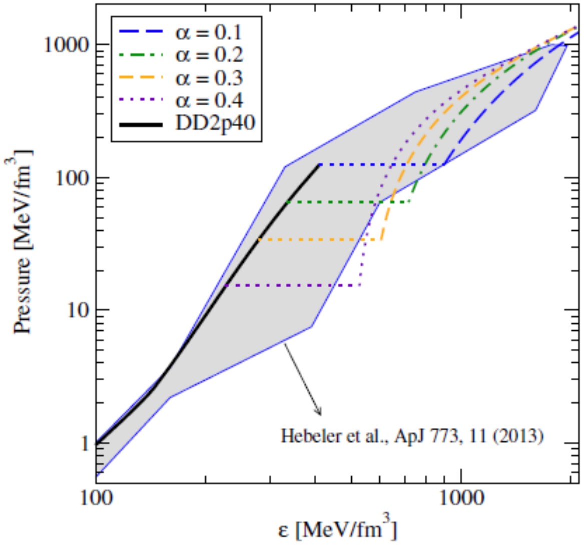


K.C. Gendreau et al., Proc. SPIE 8443 (2012) 844313 – first results end of 2019 !!

Discover the 3rd family – NICER vs. GW170817



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



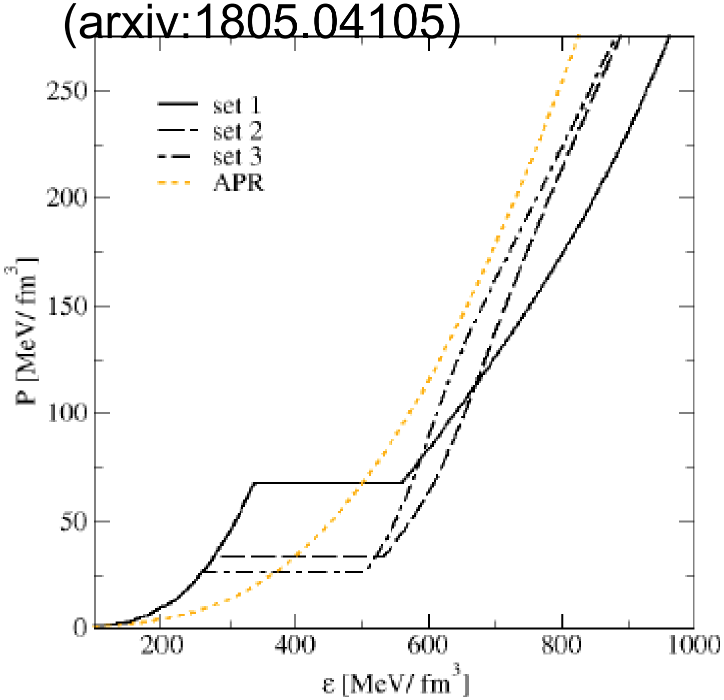
TOV / TD calculation:
M. Bejger et al.

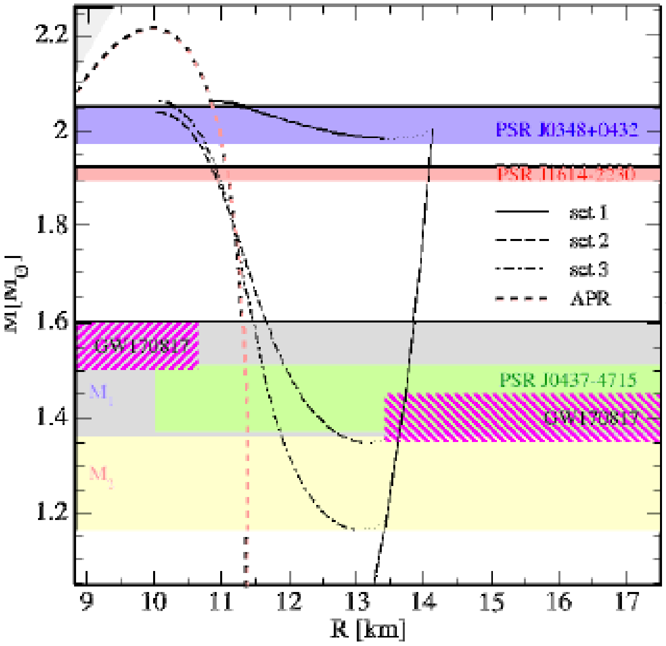
Alternative to NS merger with soft EoS → Hybrid star (HS) – HS / HS-NS merger

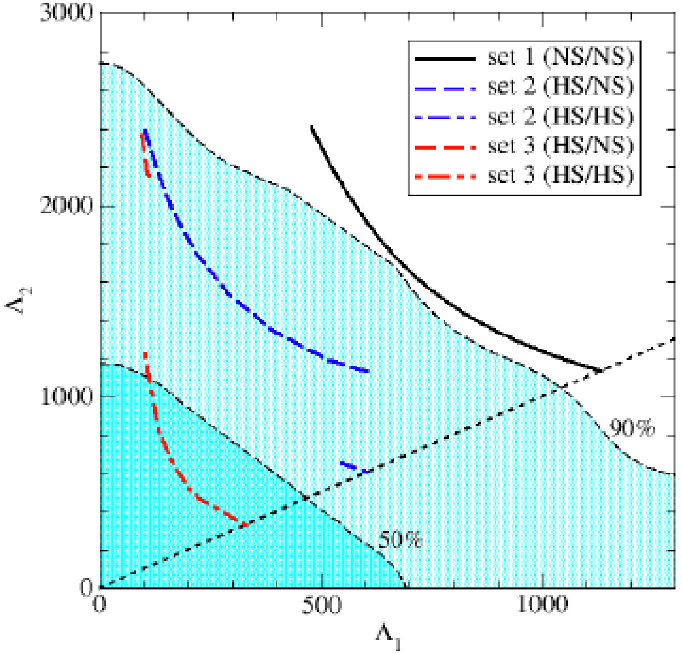
If NICER rules out soft EoS (since $R_{0437\text{-}4715}$ >13.5 km) then **Third Family is Discovered !!**

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)

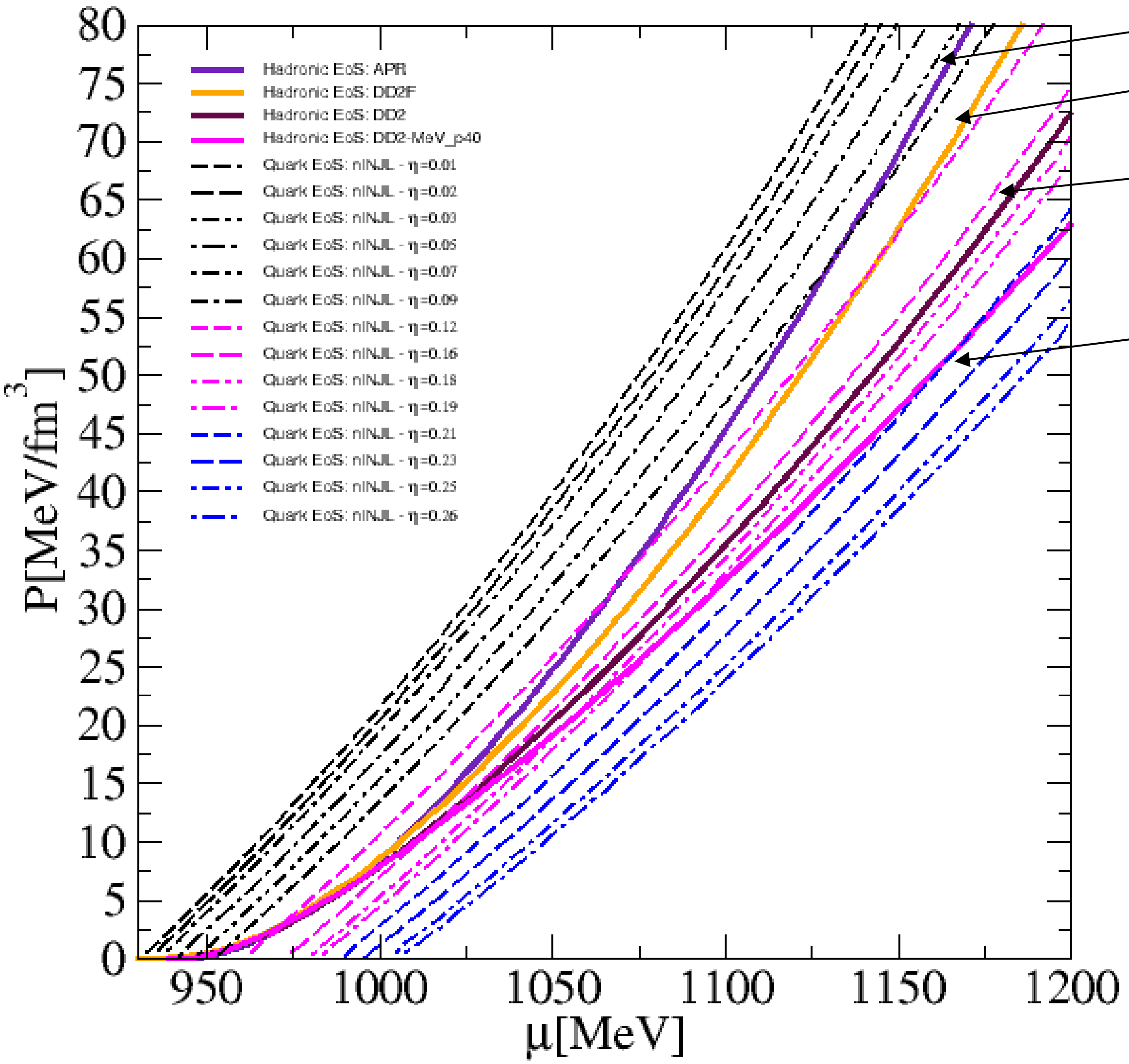
Pasta calculation:
Does not spoil twin
scenario of NS-HS or
HS-HS merger!
Yasutake et al. (2018)

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

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

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

$$\begin{aligned} j_S^f(x) &= \int d^4z\; g(z)\; \bar{\psi}(x+\frac{z}{2})\;\Gamma_f\,\psi(x-\frac{z}{2})\,, \\ j_D^a(x) &= \int d^4z\; g(z)\; \bar{\psi}_C(x+\frac{z}{2})\;\Gamma_D\;\psi(x-\frac{z}{2}) \\ j_V^\mu(x) &= \int d^4z\; g(z)\; \bar{\psi}(x+\frac{z}{2})\; i\gamma^\mu\;\psi(x-\frac{z}{2}). \end{aligned}$$

Nonlocal chiral quark model - generalized

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

$$\begin{aligned} j_S^f(x) &= \int d^4z\; g(z)\; \bar{\psi}(x+\frac{z}{2})\; \Gamma_f\, \psi(x-\frac{z}{2}), \\ j_D^a(x) &= \int d^4z\; g(z)\; \bar{\psi}_C(x+\frac{z}{2})\; \Gamma_D\; \psi(x-\frac{z}{2}) \\ j_V^\mu(x) &= \int d^4z\; g(z)\; \bar{\psi}(x+\frac{z}{2})\; i\gamma^\mu\; \psi(x-\frac{z}{2}). \end{aligned}$$

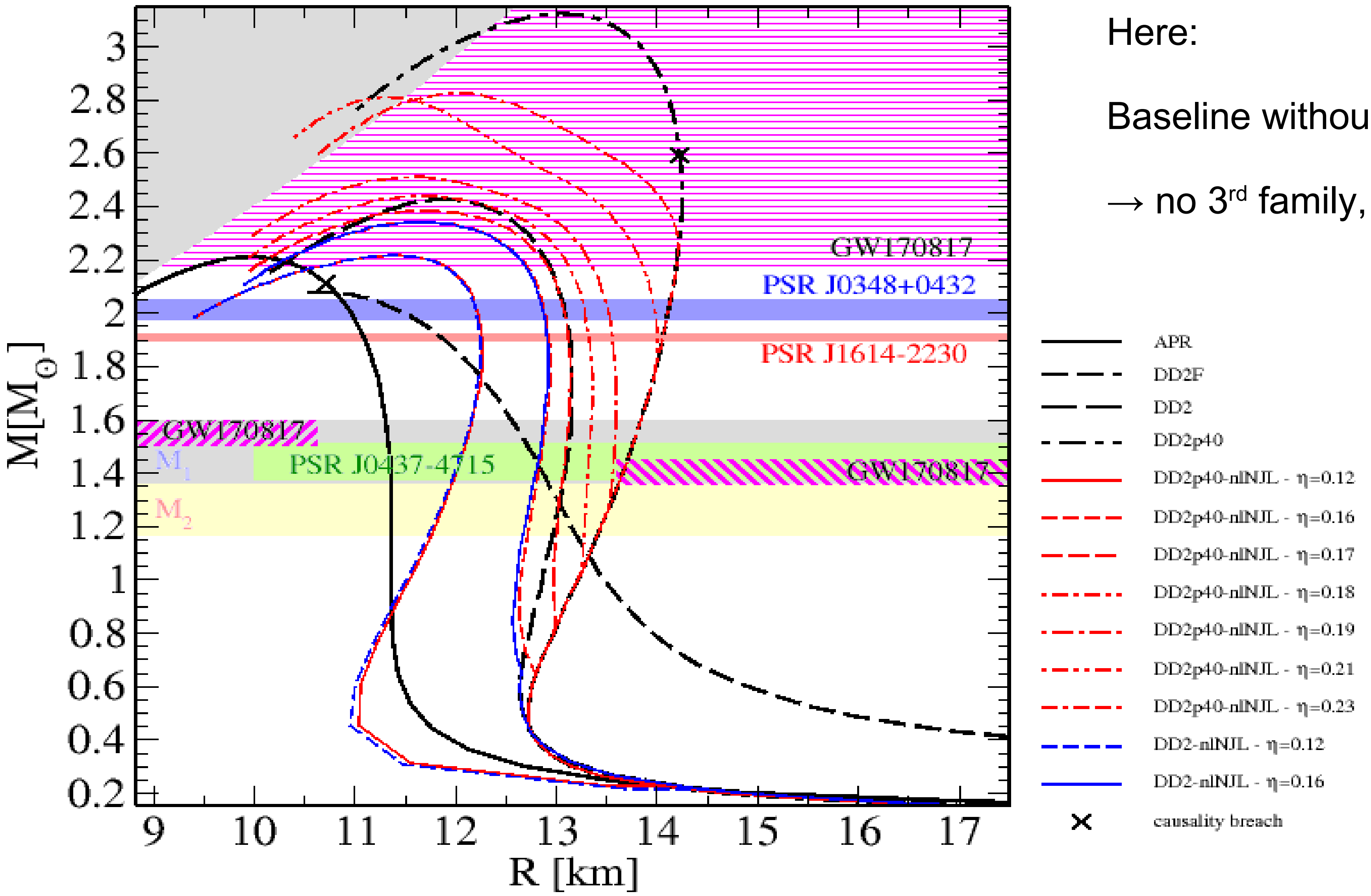
$$\Omega^{MFA} = \frac{\bar{\sigma}^2}{2G_S} + \frac{\bar{\Delta}^2}{2H} - \frac{\bar{\omega}^2}{2G_V} - \frac{1}{2}\int \frac{d^4p}{(2\pi)^4}\; \ln\det\left[\, S^{-1}(\bar{\sigma}, \bar{\Delta}, \bar{\omega}, \mu_{fc})\right]$$

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

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

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 $\eta_>$.

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

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

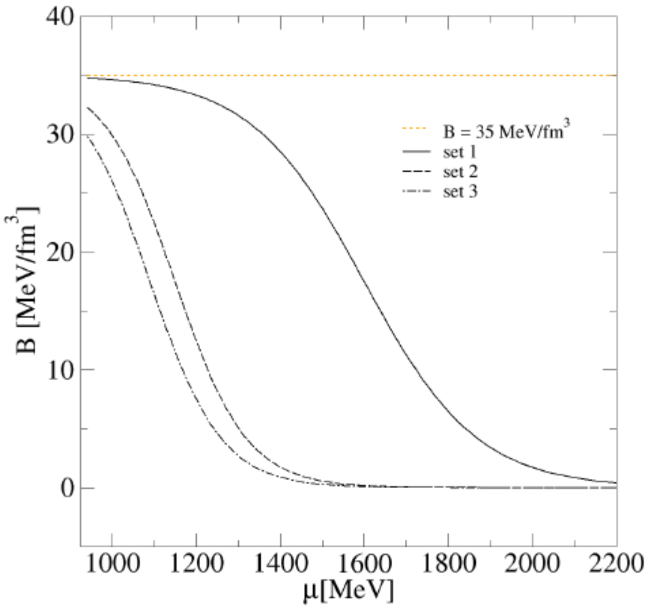
$$f_>(\mu) = 1 - f_<(\mu)\;, \quad f_\gg(\mu) = 1 - f_\ll(\mu).$$

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

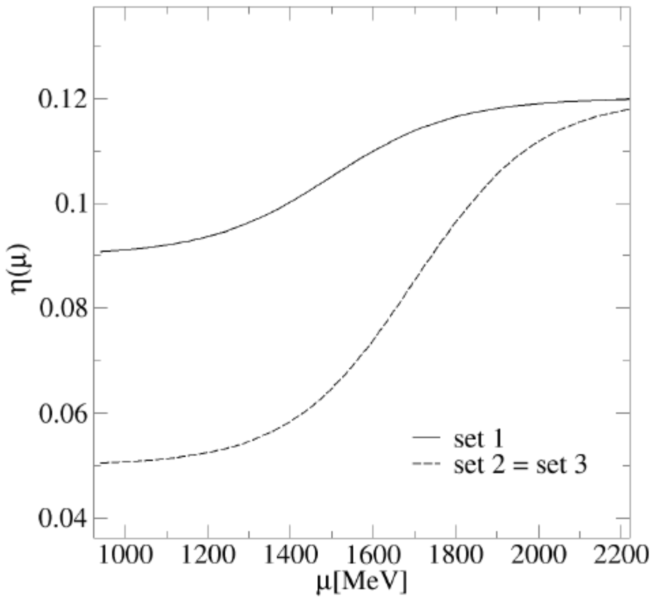
$$\begin{aligned} P(\mu) &= P(\mu;\eta,B)f_<(\mu) + P(\mu;\eta,0)f_>(\mu) \\ &= P(\mu;\eta,0)[f_<(\mu)+f_>(\mu)] - Bf_<(\mu) \\ &= P(\mu;\eta,B(\mu)), \end{aligned}$$

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

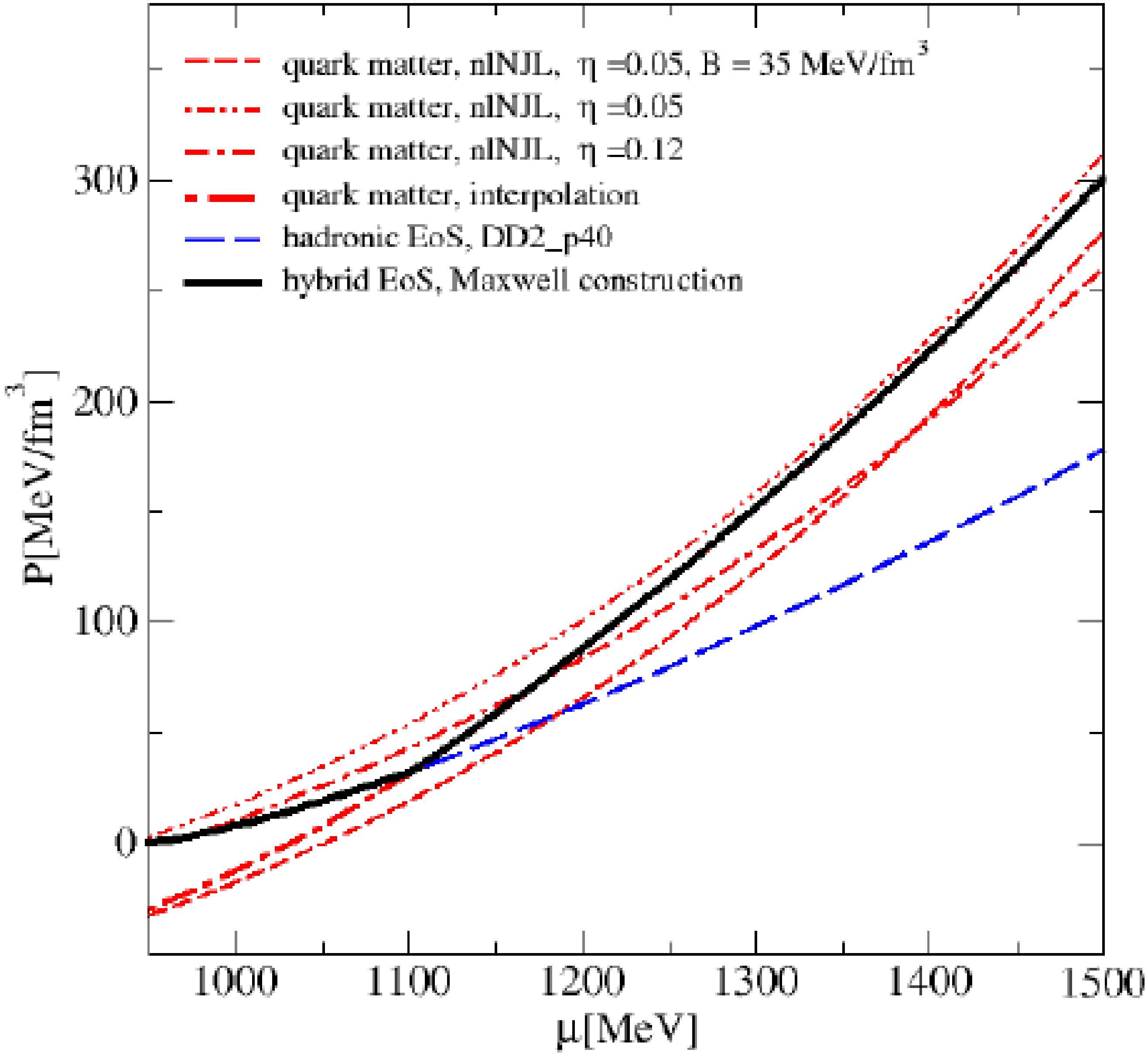


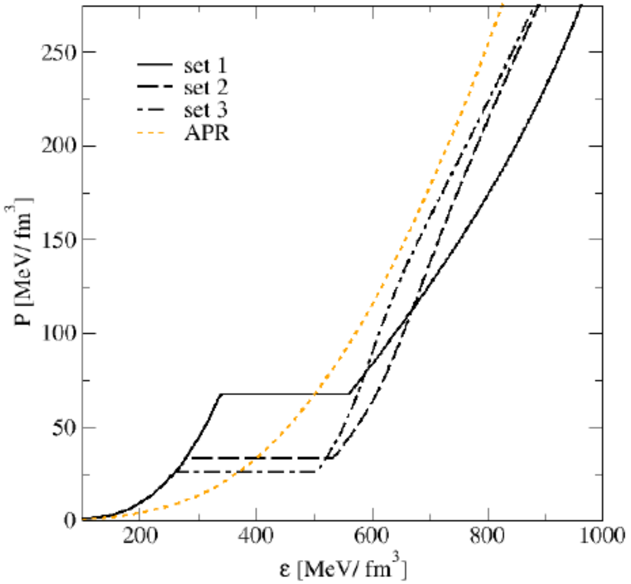
$$\begin{aligned} P(\mu) &= P(\mu;\eta_<,B)f_\ll(\mu) + P(\mu;\eta_>,B)f_\gg(\mu) \\ &= P(\mu;\eta_<,B)[f_\ll(\mu)+f_\gg(\mu)] \\ &\quad +(\eta_> - \eta_<)f_\gg(\mu)\left.\frac{dP(\mu;\eta,B)}{d\eta}\right|_{\eta=\eta_<} \\ &= P(\mu;\eta_<,B) \\ &\quad +[\eta_> f_\gg(\mu) + \eta_< f_\ll(\mu) - \eta_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

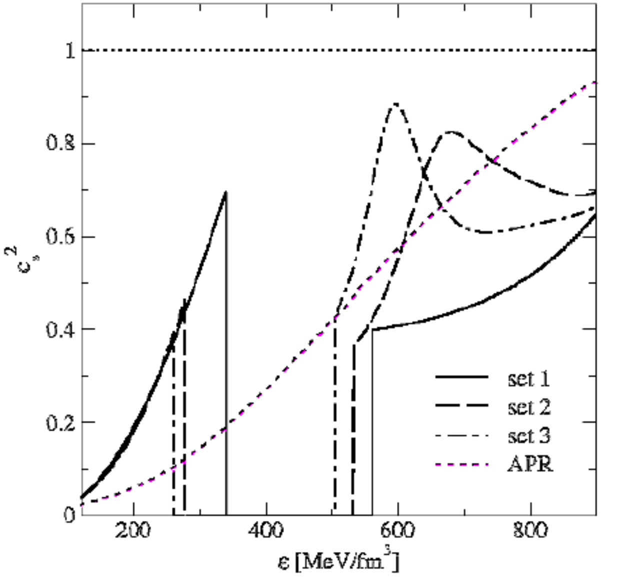
$\eta(\mu) = \eta_> f_\gg(\mu) + \eta_< f_\ll(\mu)$ is the medium-dependent vector meson coupling



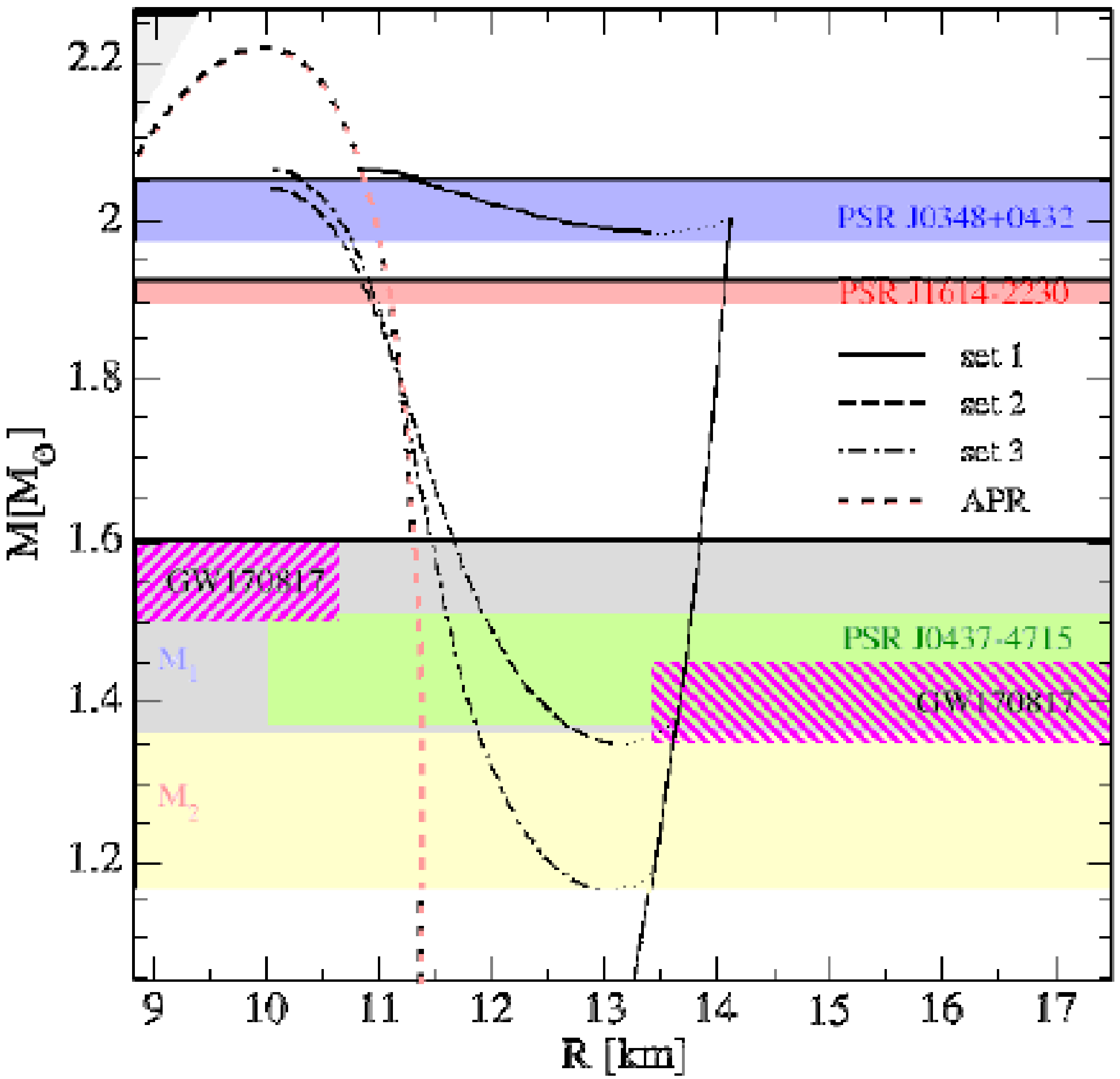
Maxwell Construction between Hadron and Quark Phases

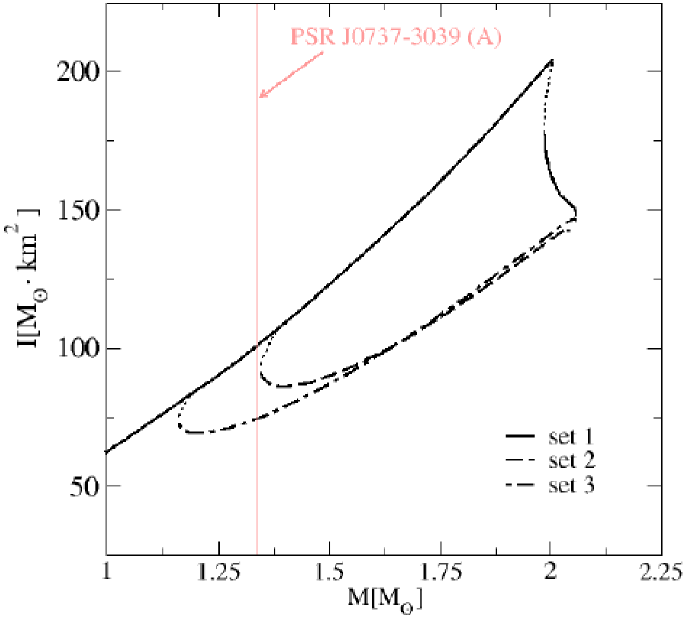


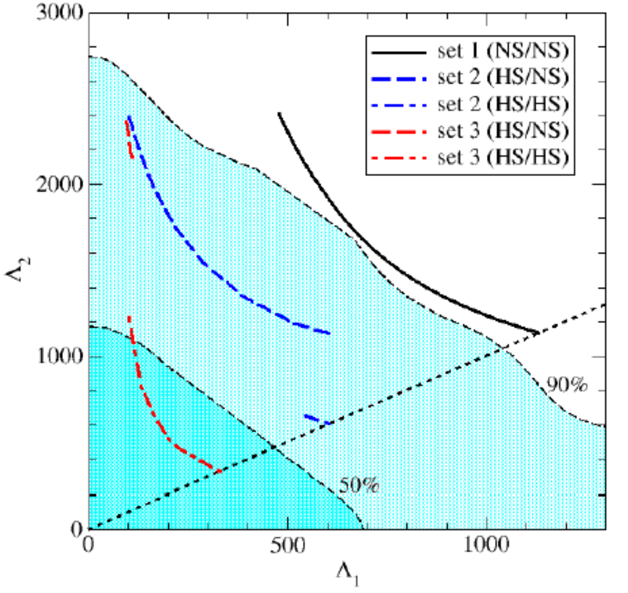




Maxwell Construction between Hadron and Quark Phases







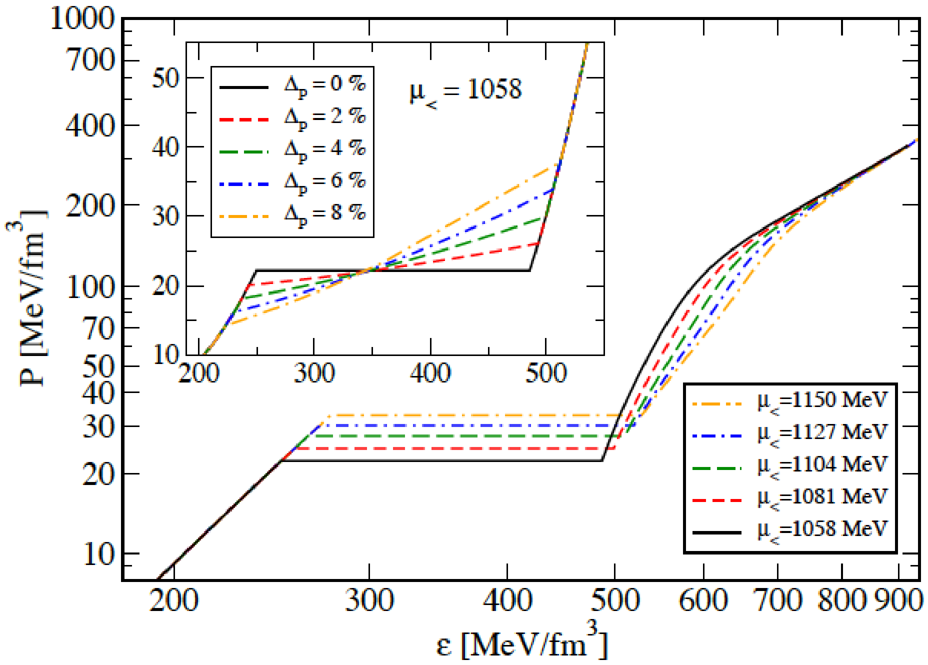
D.E. Alvarez-Castillo, et al., PRD 99 (2019) 063010

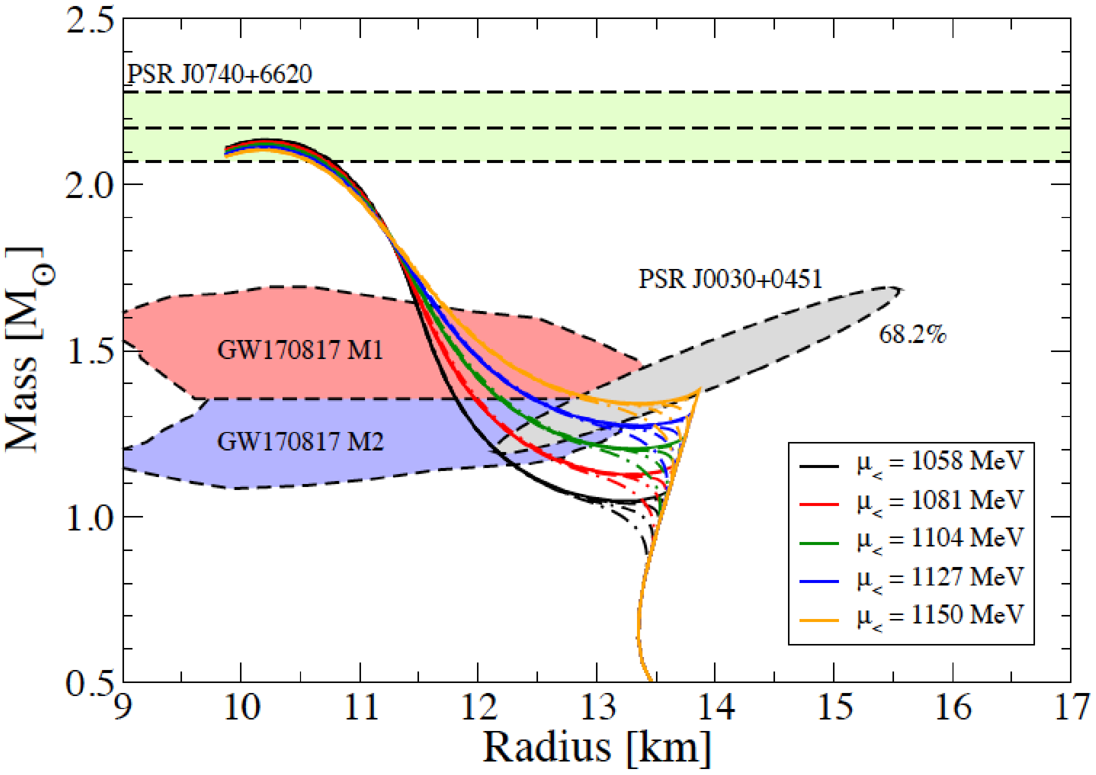
Was GW170817 indeed a binary Neutron Star Merger ?
A Bayesian Analysis for Hybrid Equations of State

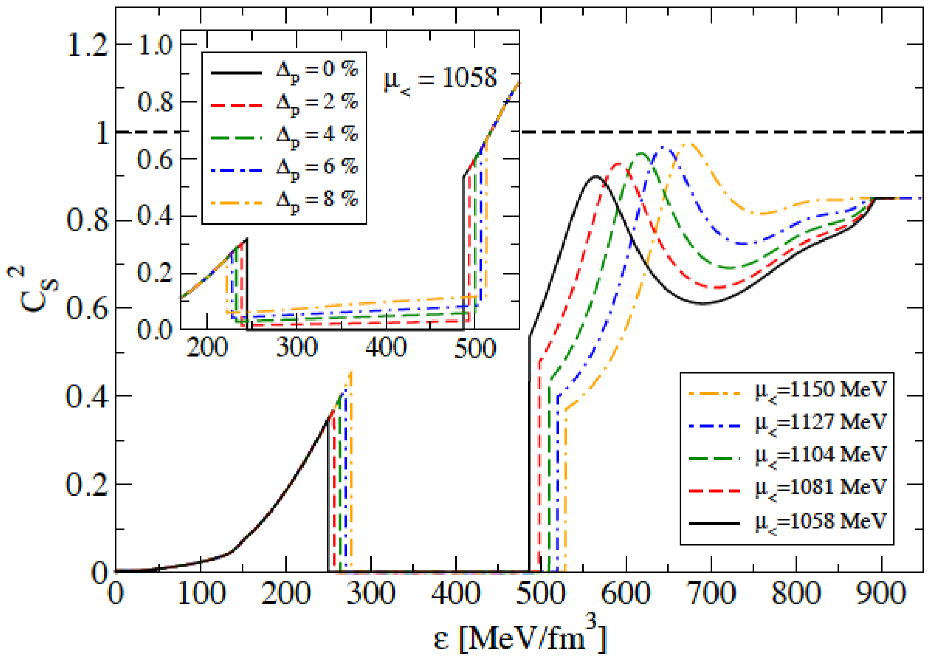
- Mass 2.17+0.11-0.10 M_sun &
- Compactness (tidal deform.) GW170817

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

→ Two-parameter family EoS: mu_< , Delta_P







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

Mass 2.17+0.11-0.10 M_sun &
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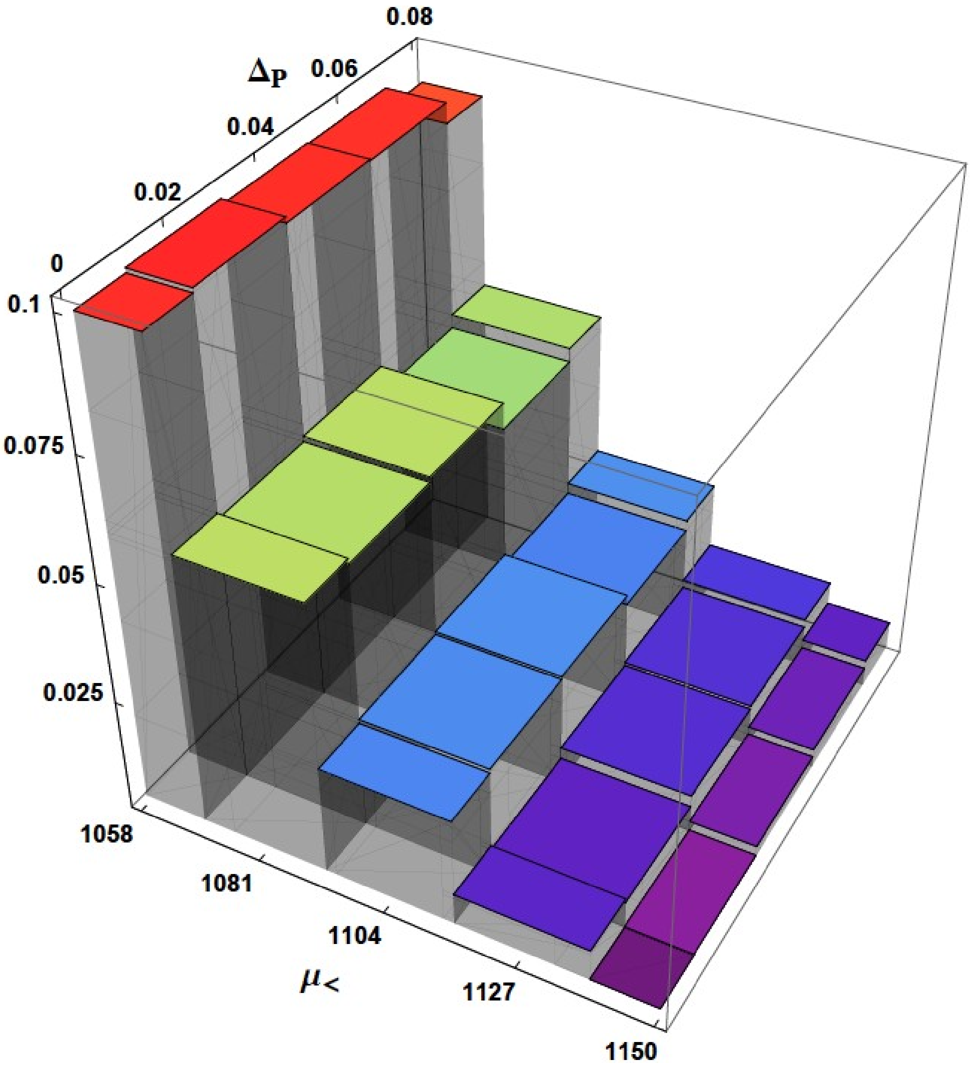
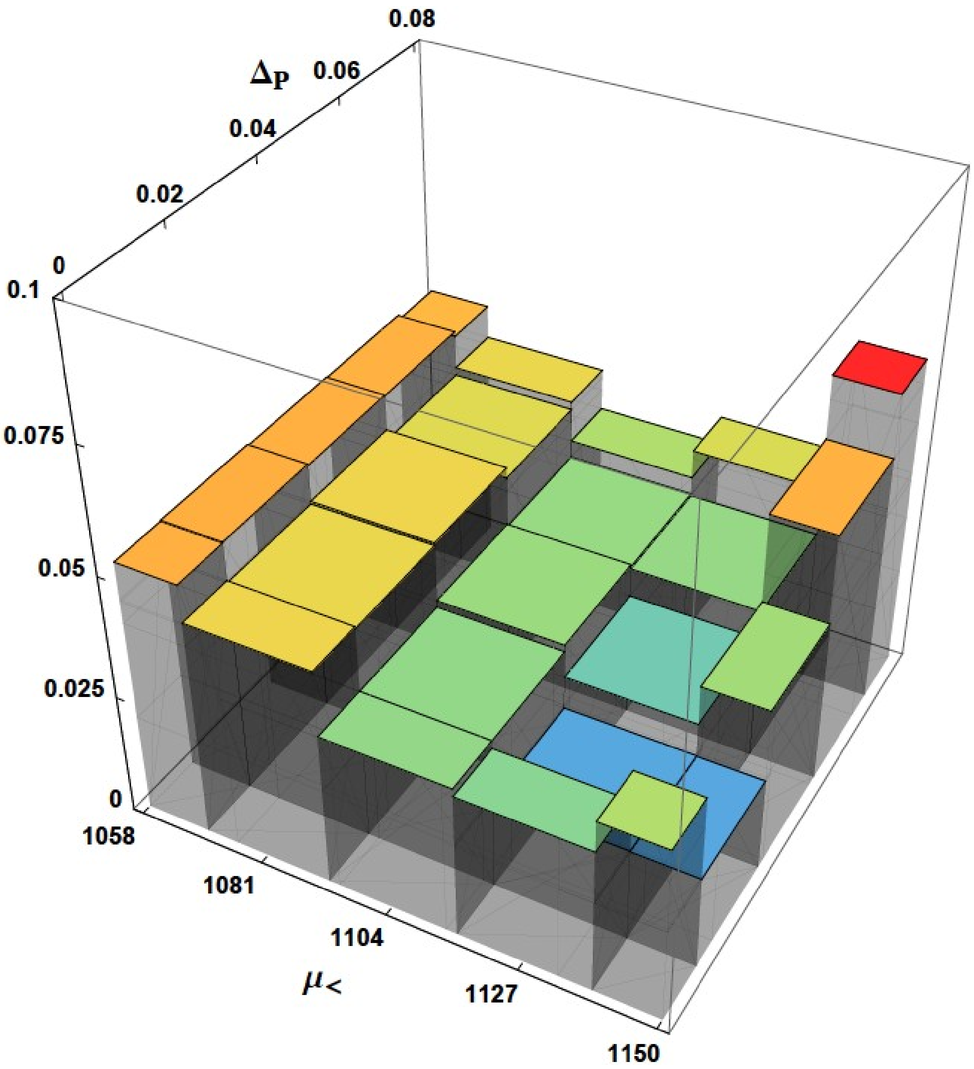
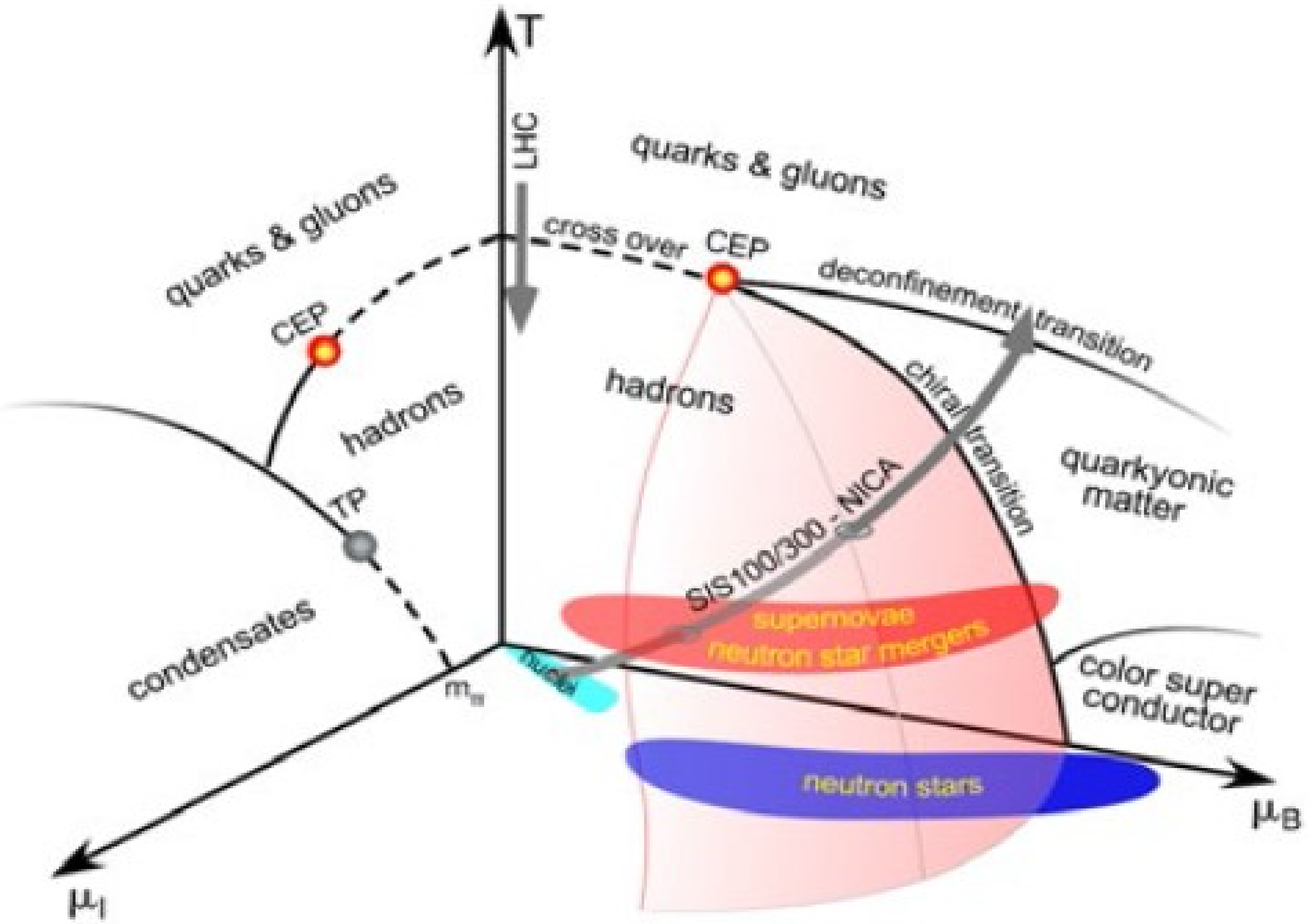


Additional (fictitious) radius measurement
(NICER preliminary, PSR J0030+0451)



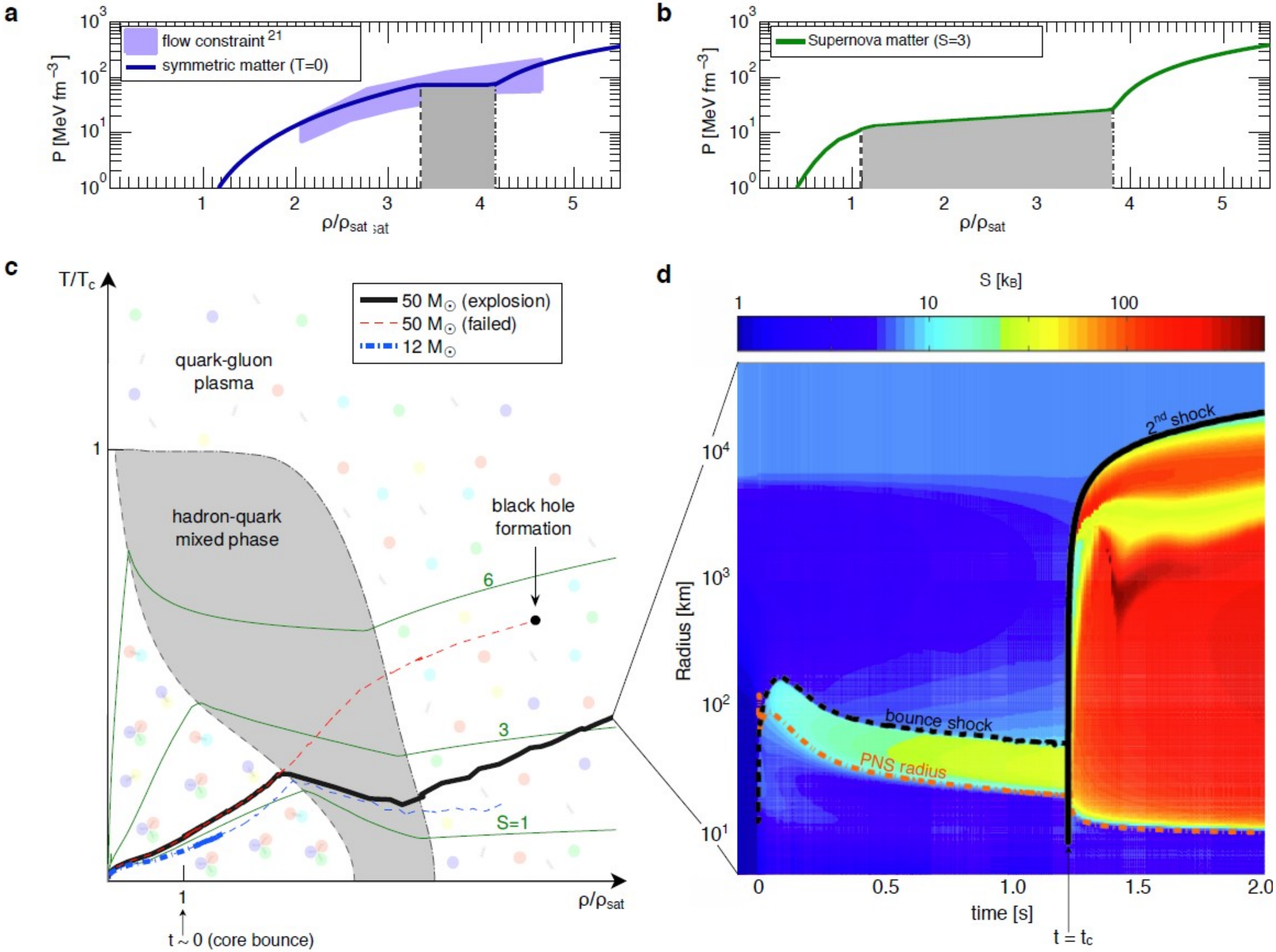
CEP in the QCD phase diagram: HIC vs. Astrophysics



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

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

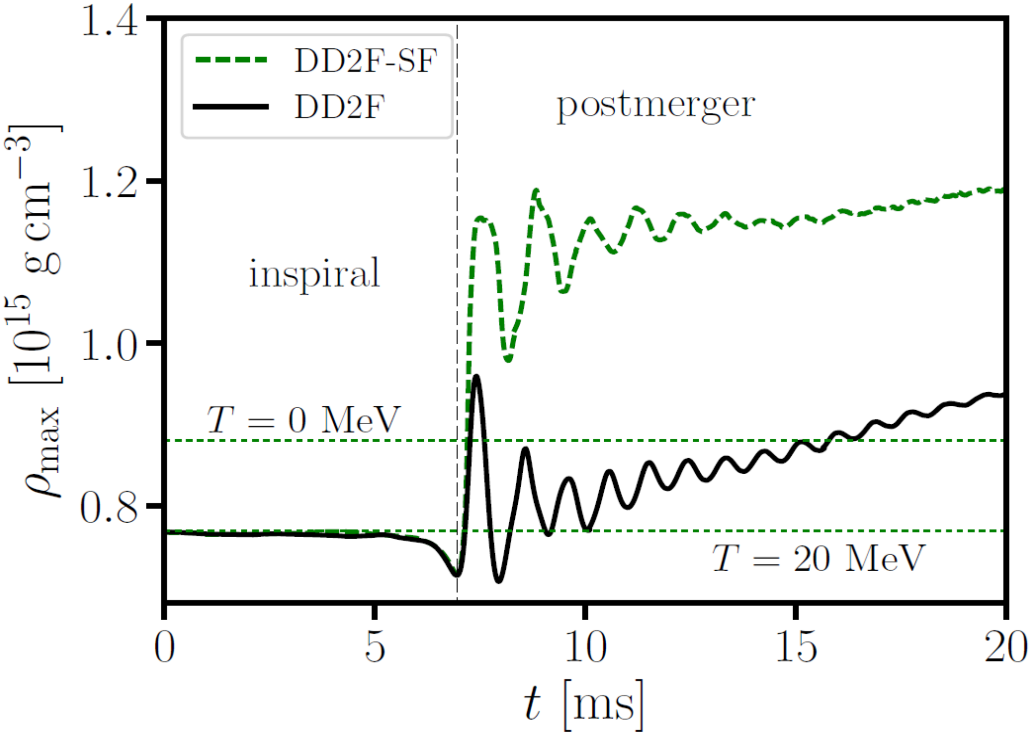
Deconfinement transition as SN explosion mechanism



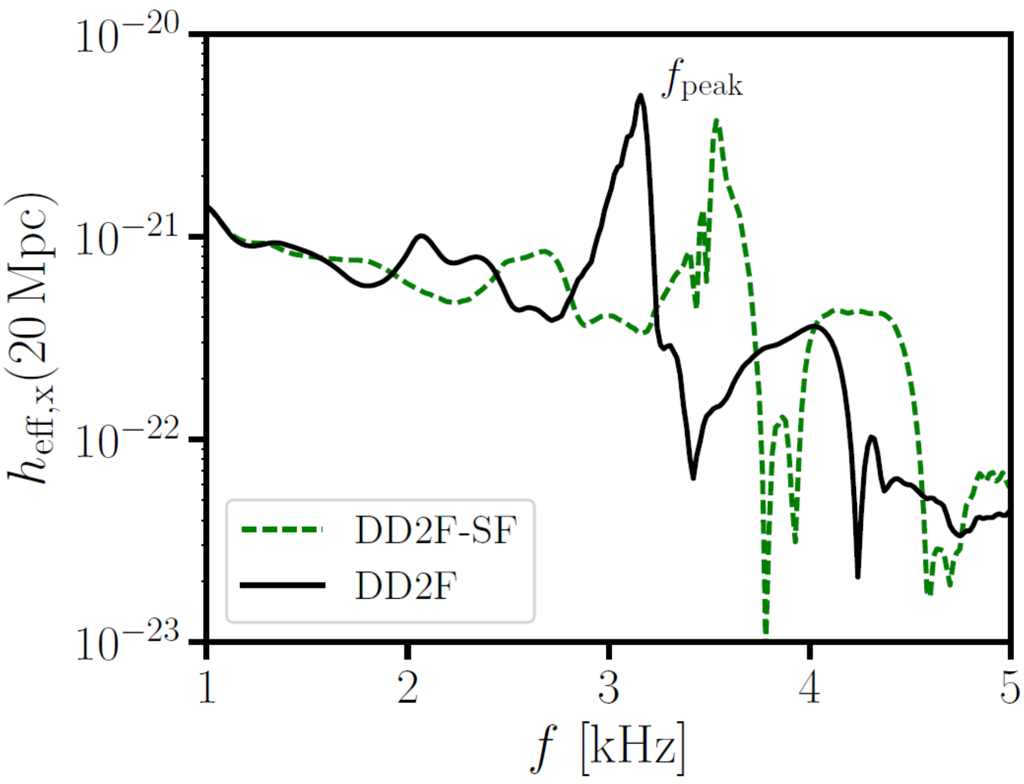
Progenitor:
M = 50 M$_O$

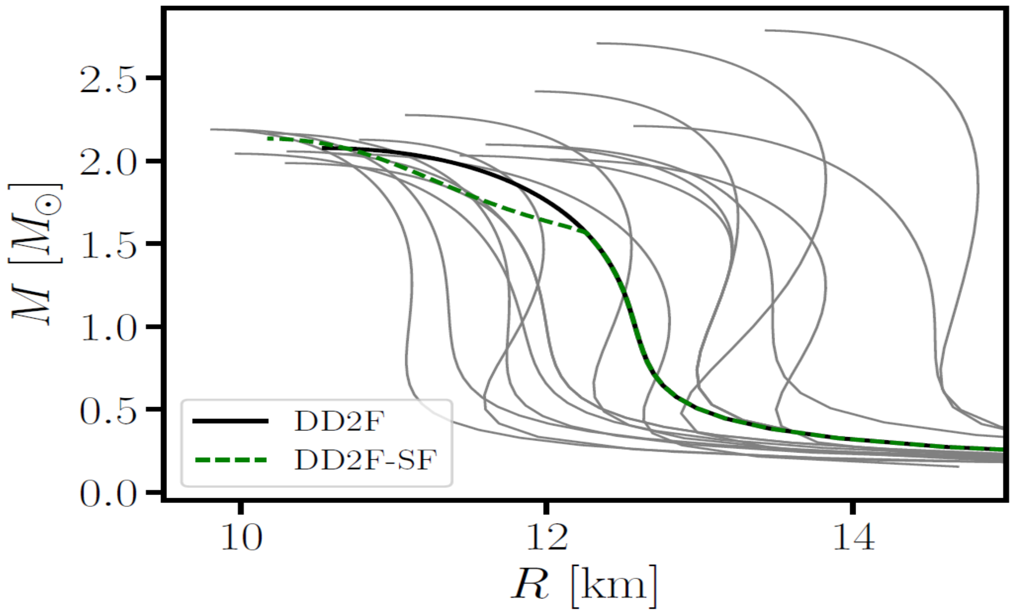
T. Fischer, N.-U. Bastian et al., Quark deconfinement as supernova engine of massive blue Supergiant star explosions, Nature Astronomy 2 (2018) 980-986; arxiv:1712.08788

Hybrid star formation in postmerger phase



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



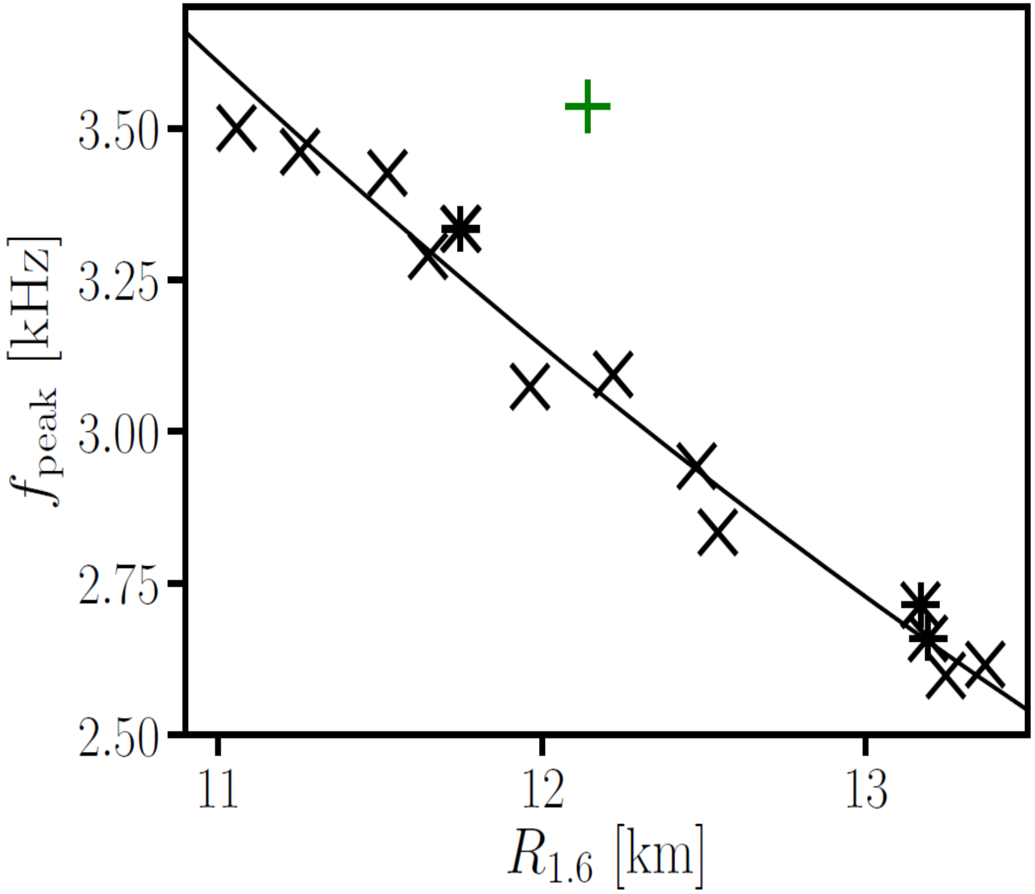


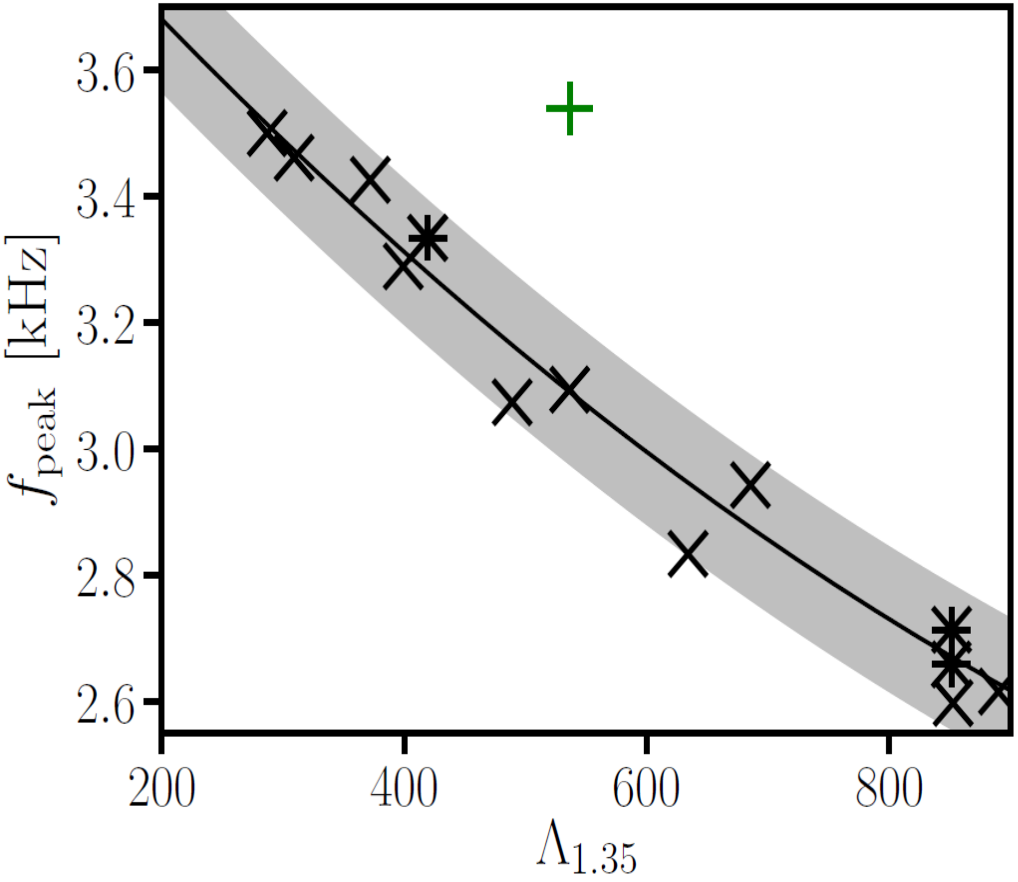
Hybrid star formaton during NS merger
→ higher densities and compacter star
→ higher peak frequency of the GW

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]



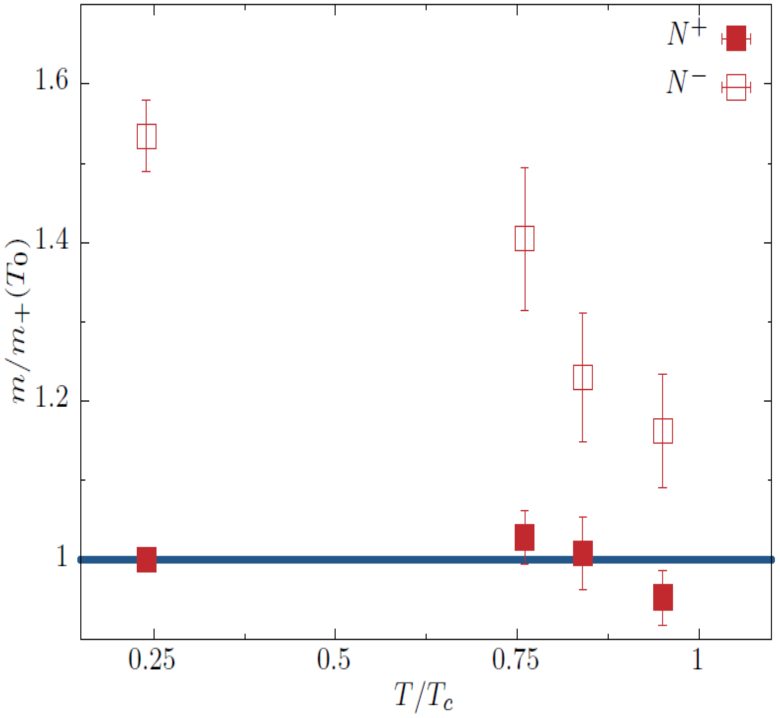


Strong deviation from **f_{peak} – $R_{1.6}$** relation signals **strong phase transition in** NS merger**!**

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

Caveat: Strong transition may not be deconfinement !

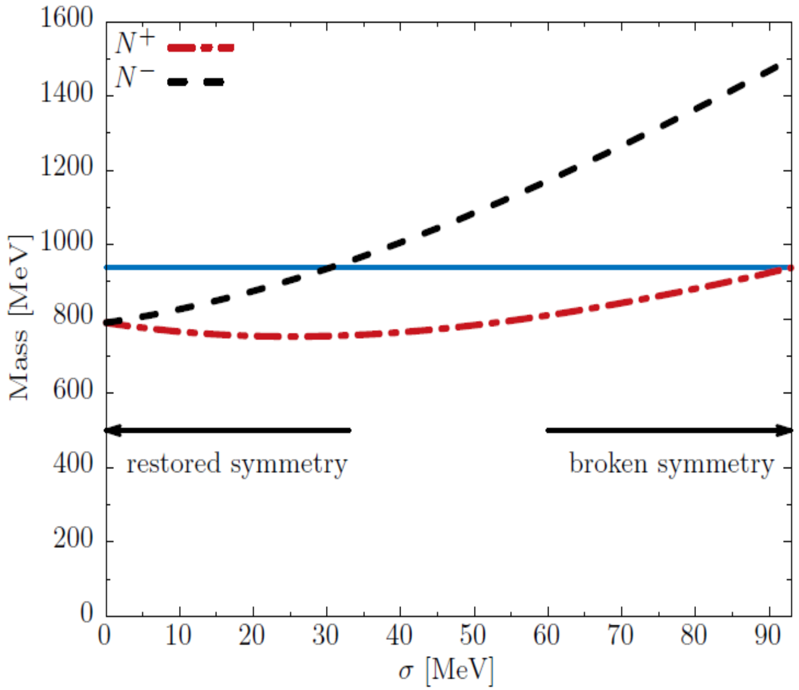
Parity doubling in lattice QCD Aarts *et al*, JHEP **1706**, 034 (2017)



- 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)

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

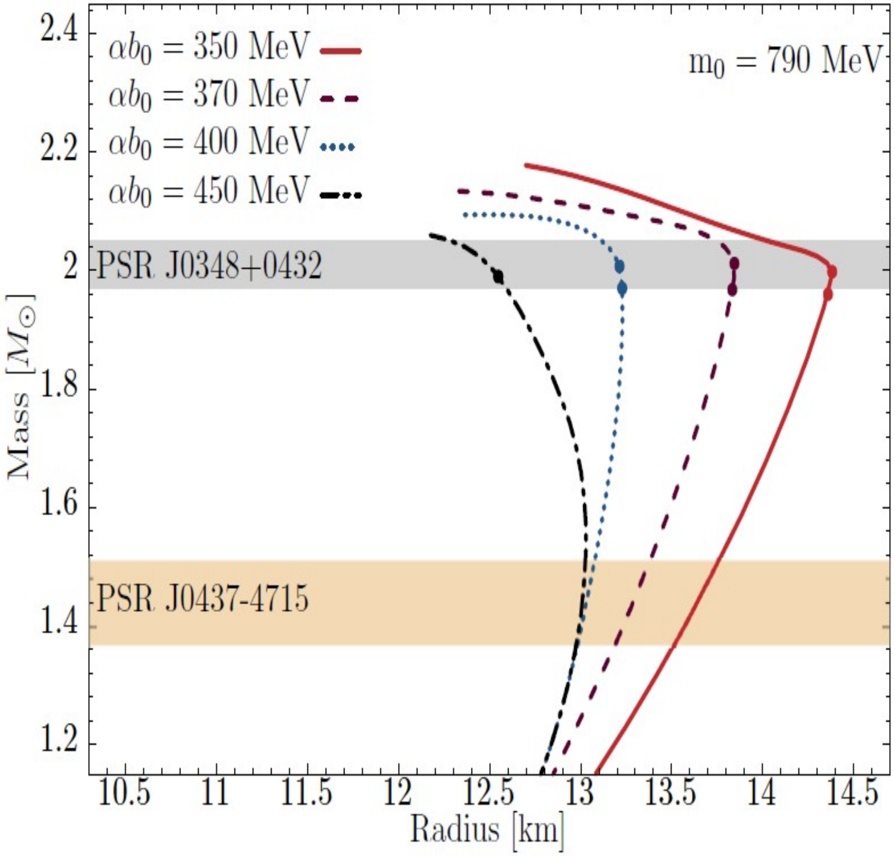


M. Marczenko, D.B., C. Sasaki, K. Redlich, Chiral symmetry restoration by parity doubling and structure of neutron stars, Phys. Rev. D98 (2018) 103021; [arxiv:1805.06886]

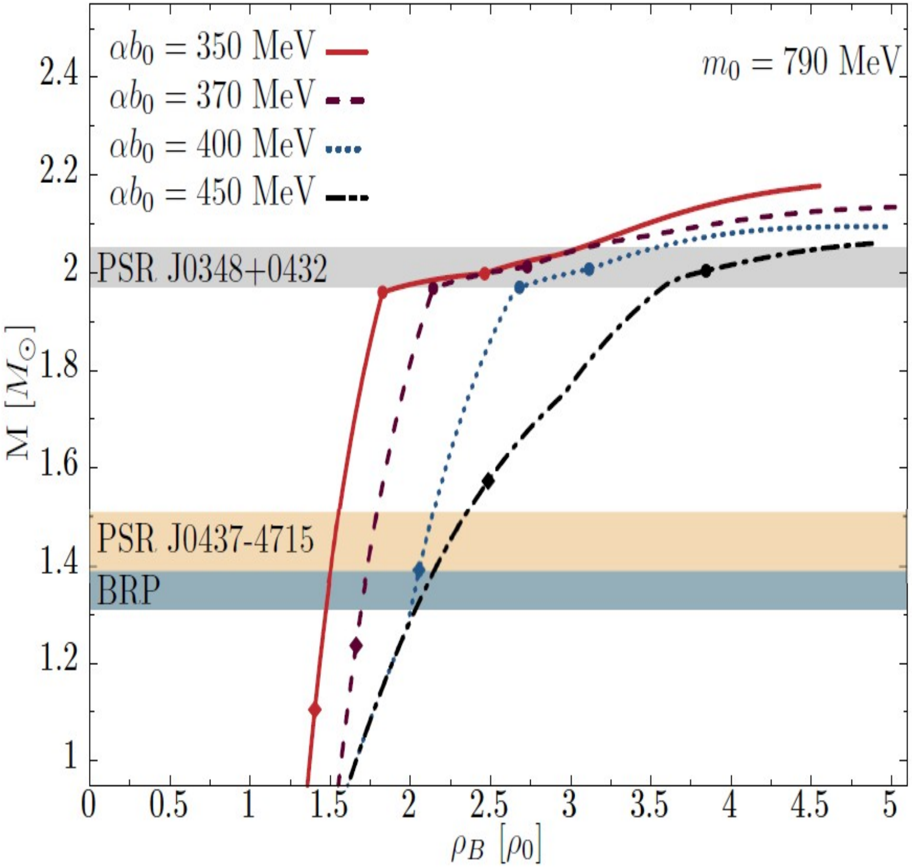
Caveat: Strong transition may not be deconfinement !

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



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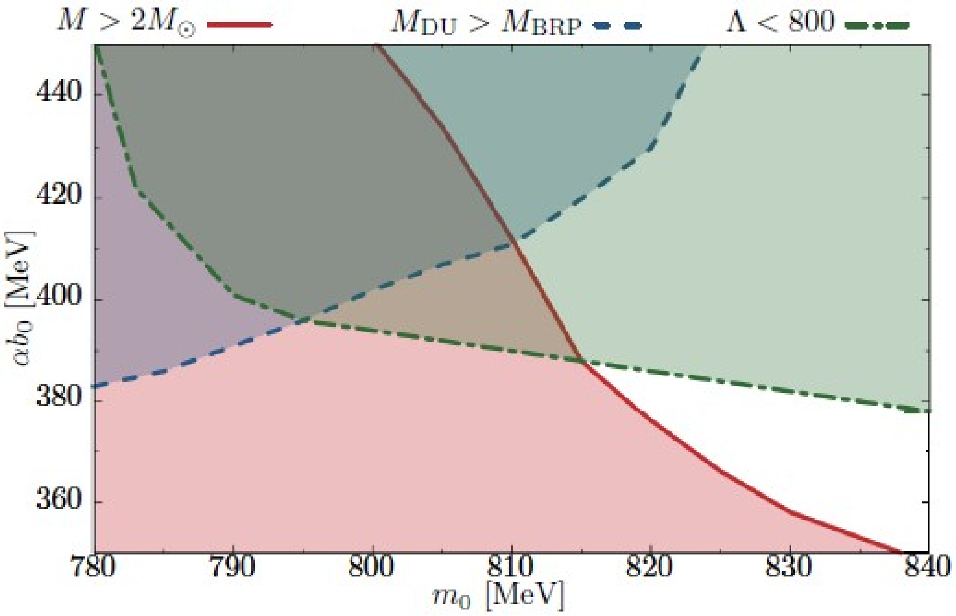
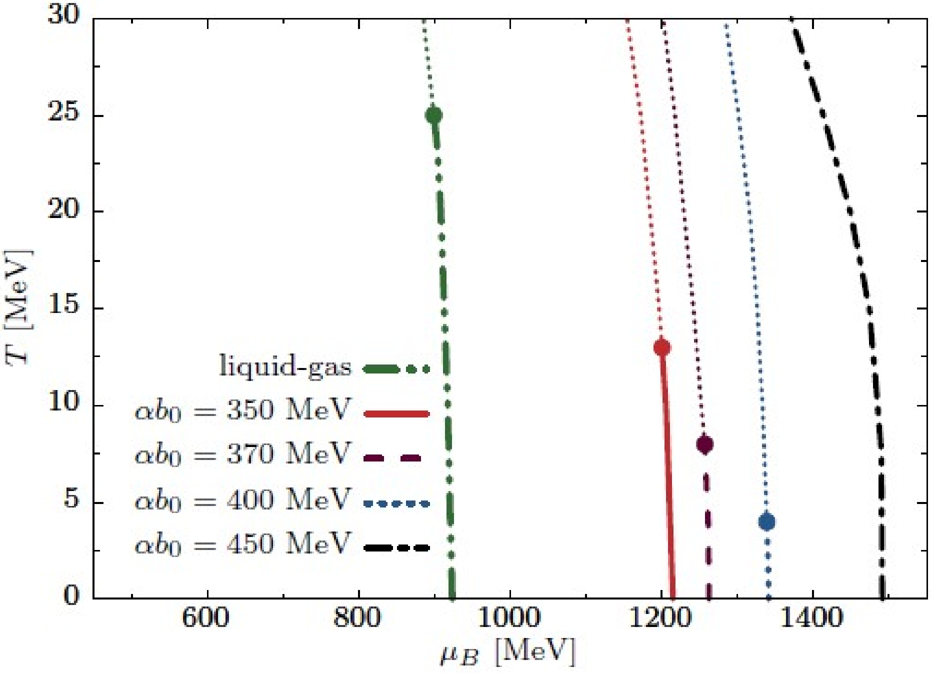
Caveat: Strong transition may not be deconfinement !

Back to symmetric-matter QCD Phase Diagram





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

- CEP at low T or even absent!

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

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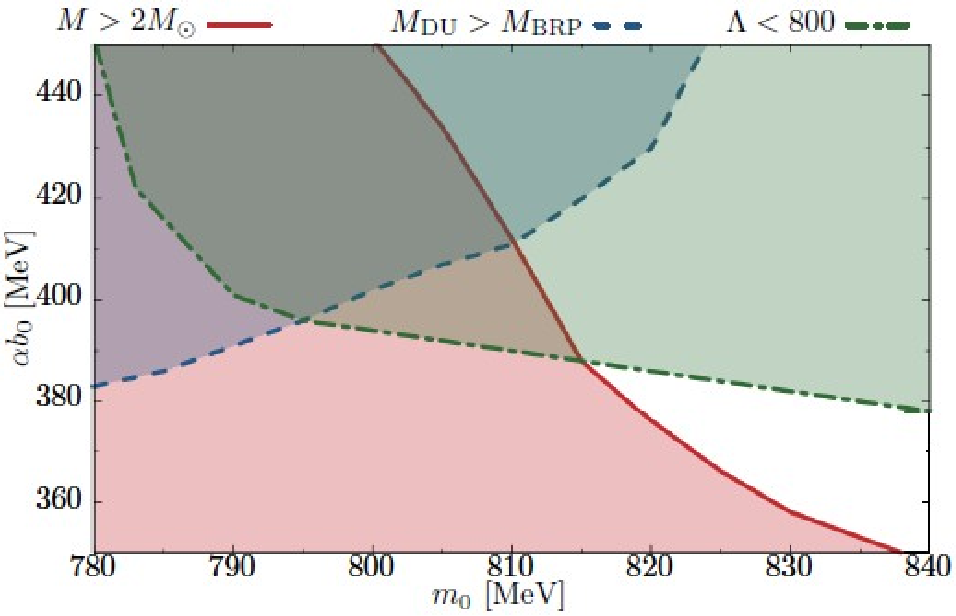

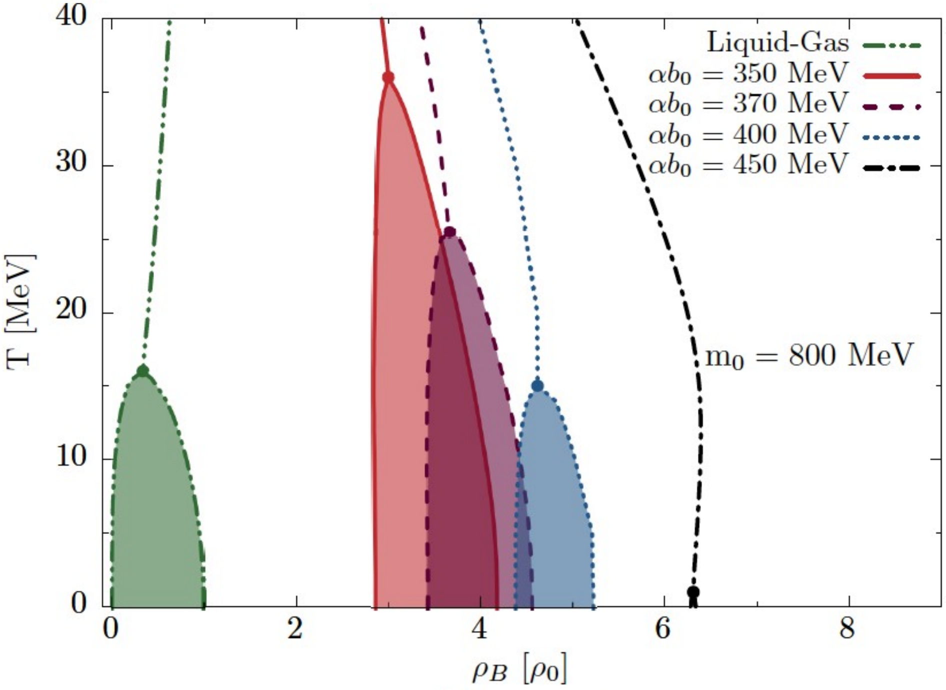

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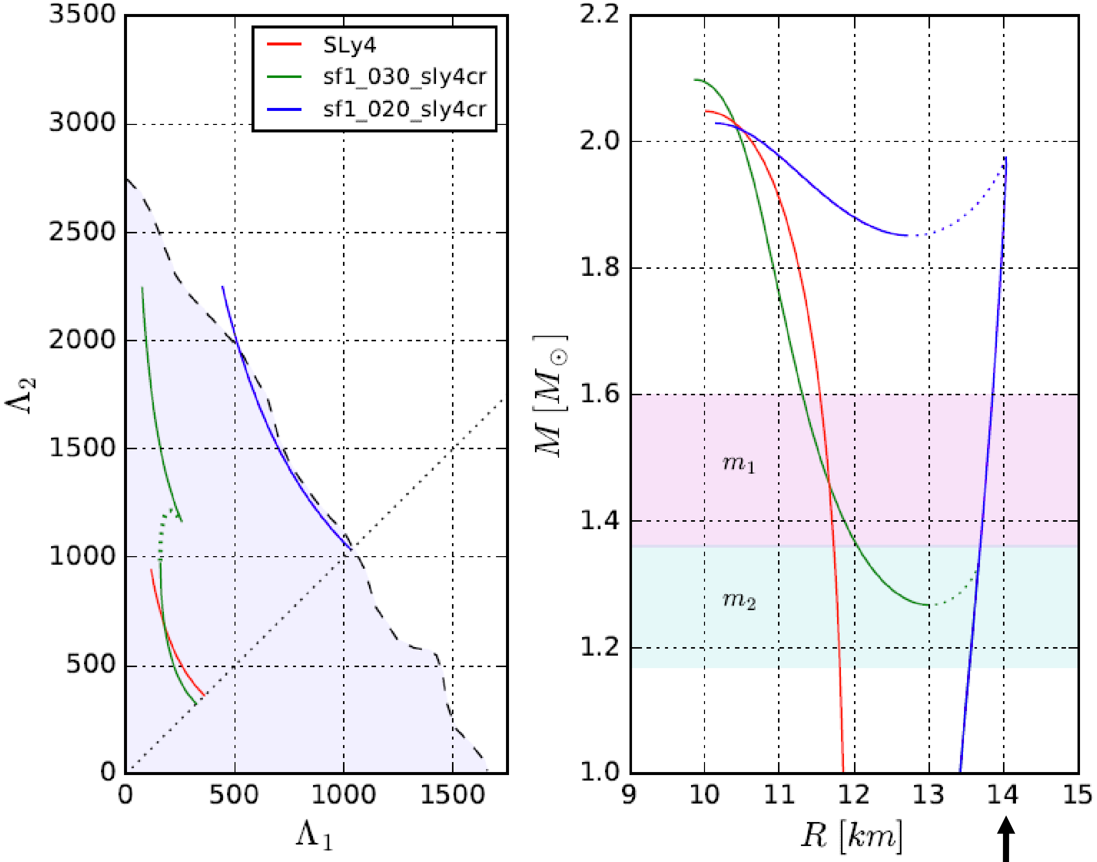
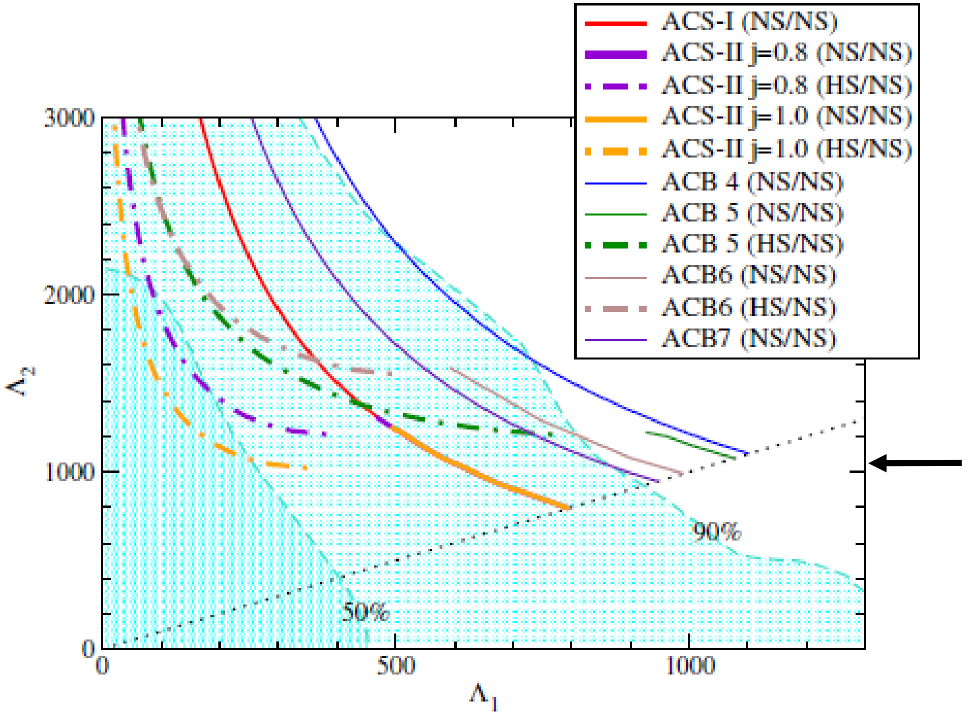
GW170817: NS-NS Merger – Equation of State Constraints

	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_{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



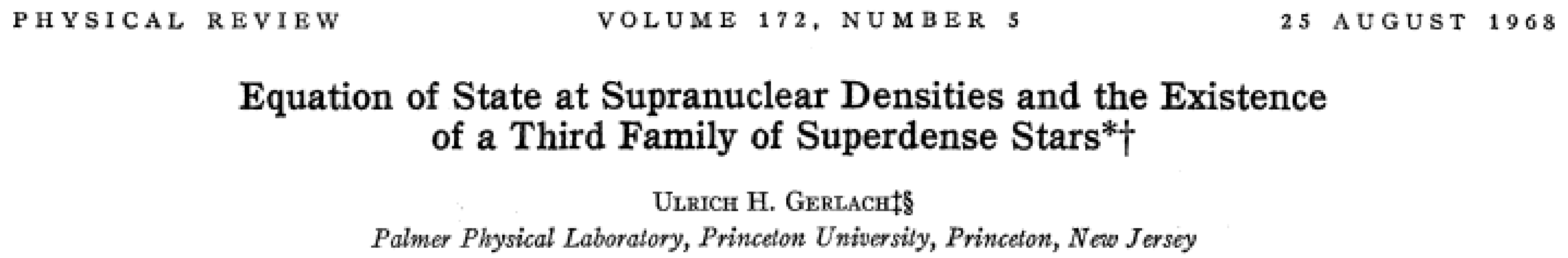
M. Bejger, D.B., et al., in preparation (2019)



V. Paschalidis, K. Yagi, D. Alvarez-Castillo, D.B., A. Sedrakian, arxiv:1712.00451 Phys. Rev. D 96 (2018)

Suggestion: CS in binary may be 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

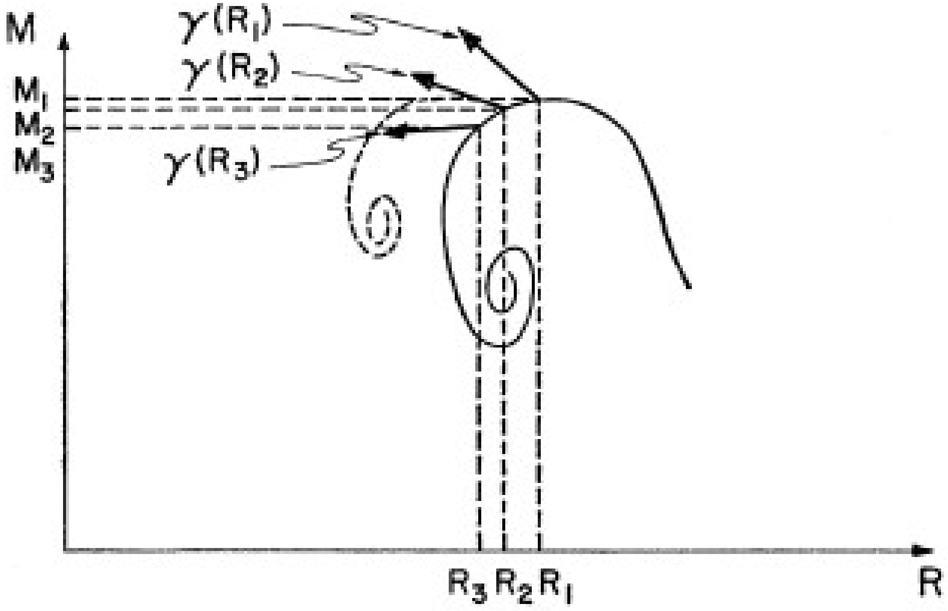
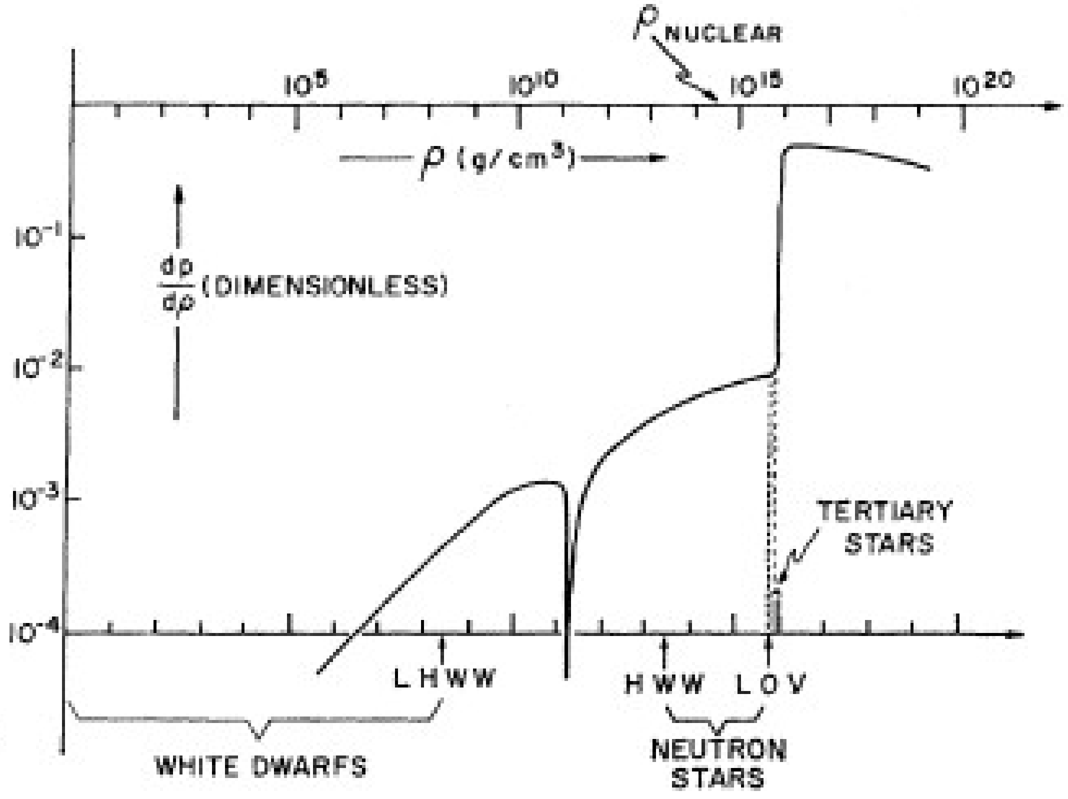


FIG. 3. A blow-up of the LOV maximum. The central densities



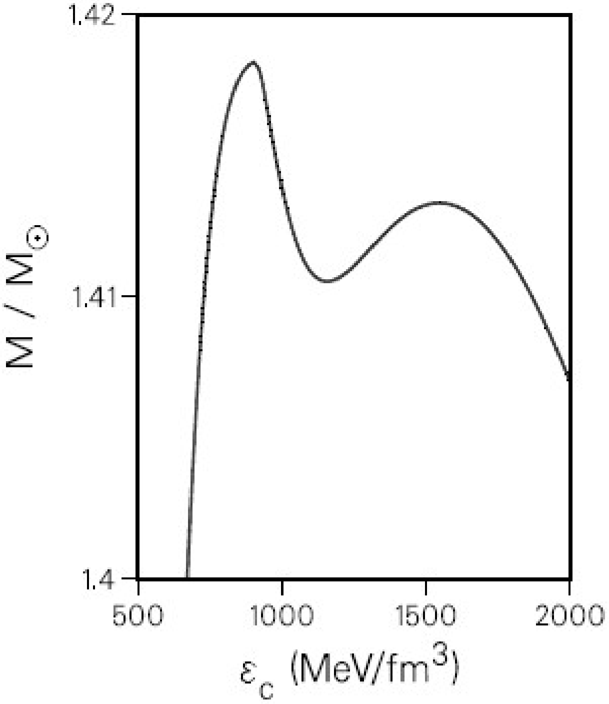
History: Third family & Nonidentical Twins

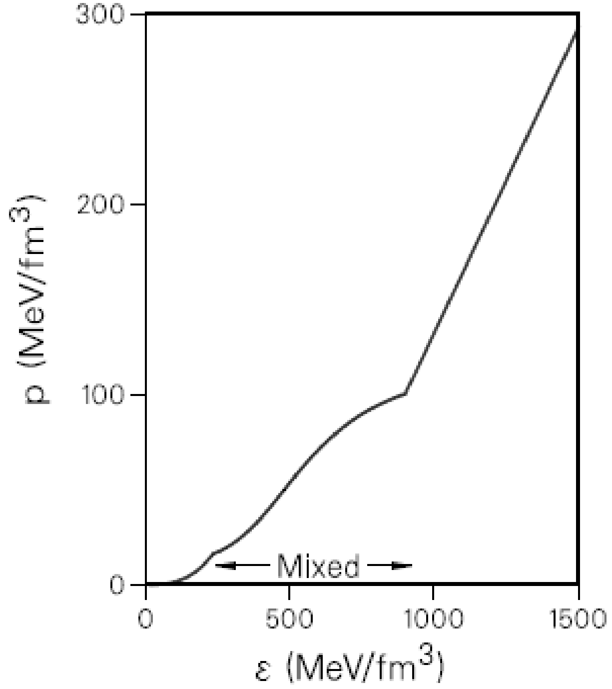
Non-Identical Neutron Star Twins

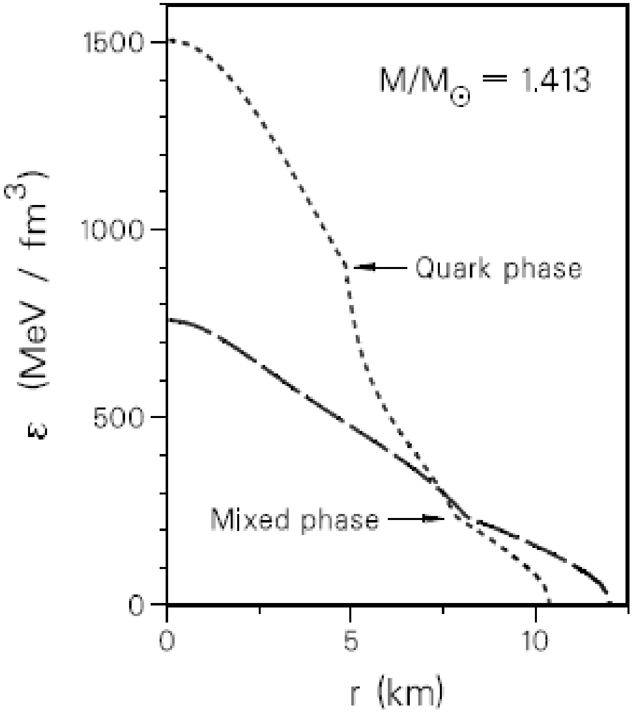
astro-ph/9807155; A&A (2000) L9

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)







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

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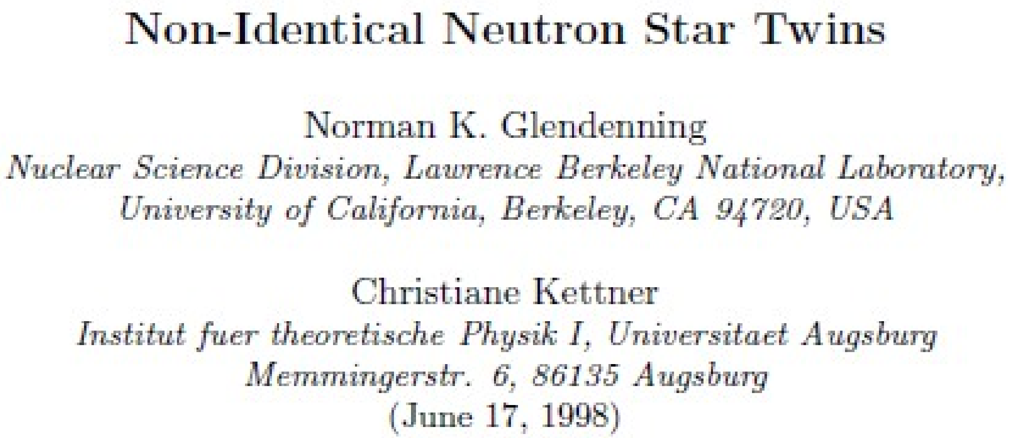

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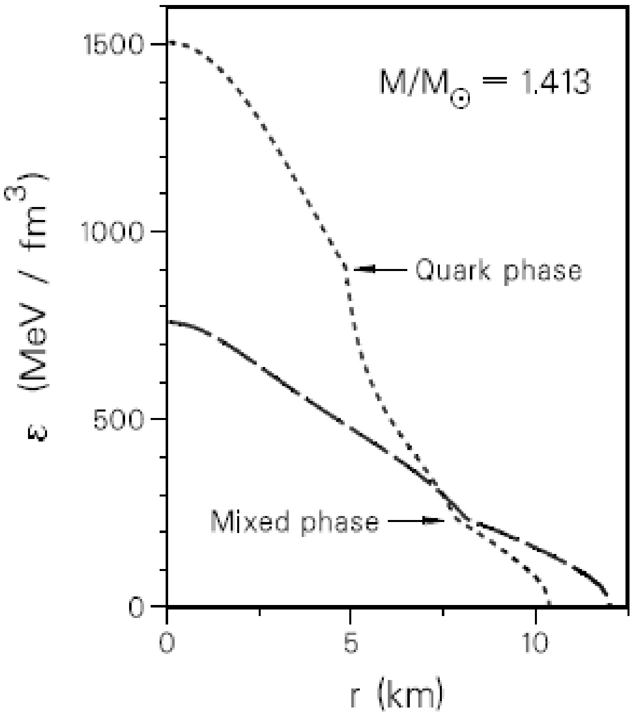

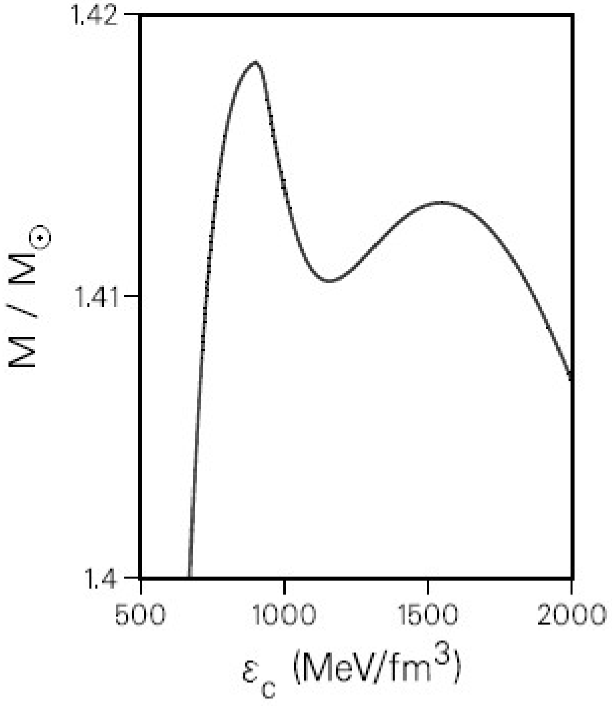

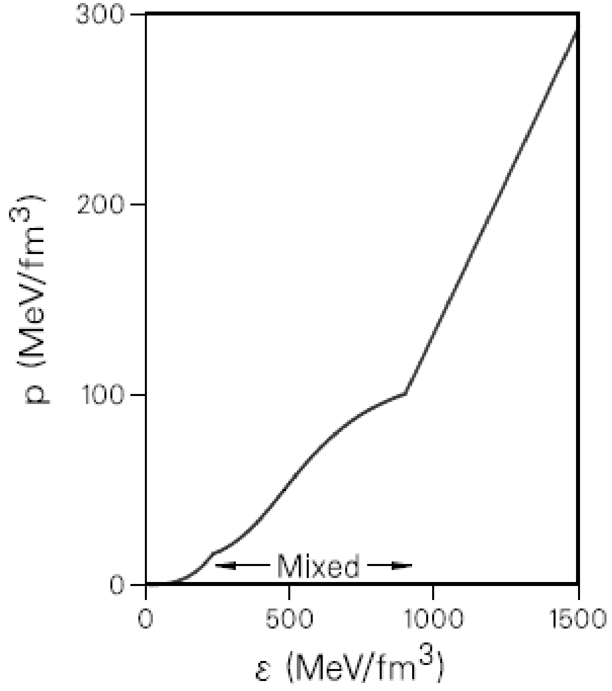

The original Twin paper uses Glendenning construction, not Maxwell one -
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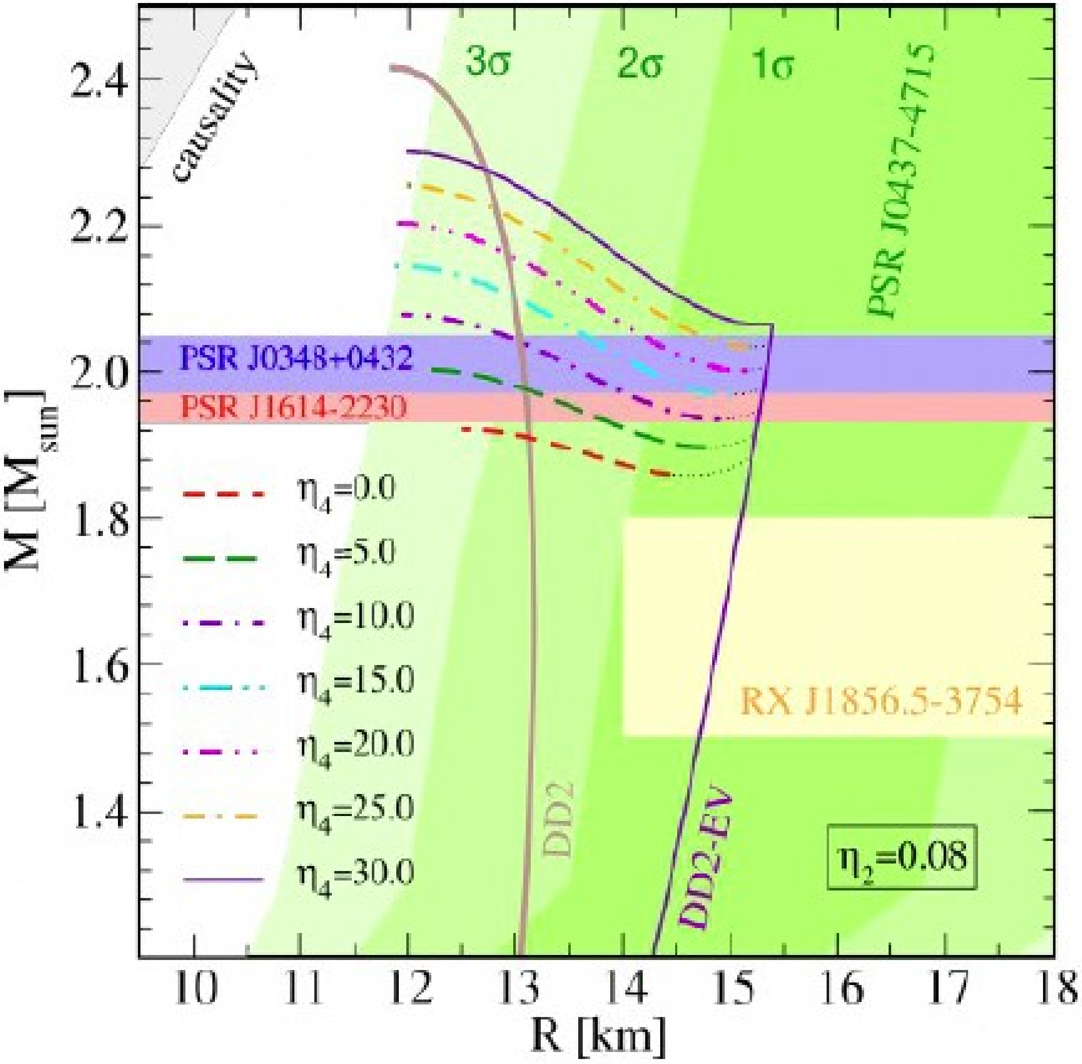
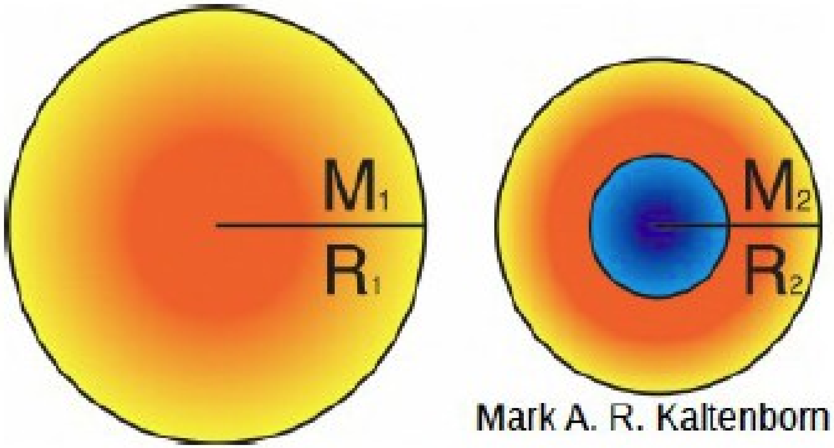
Pasta phases in-between ...

→ 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



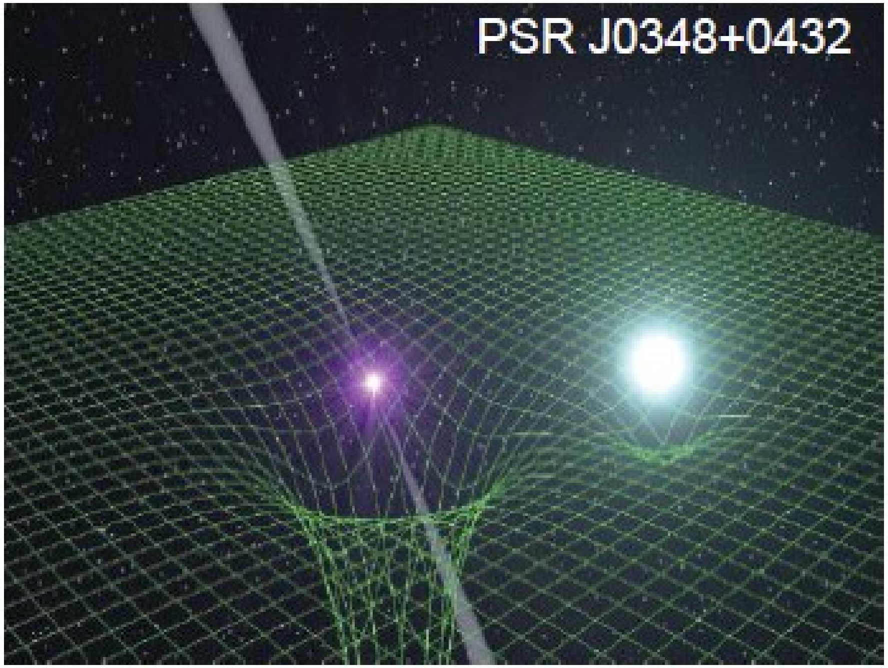
Mark A. R. Kaltenborn

- **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)

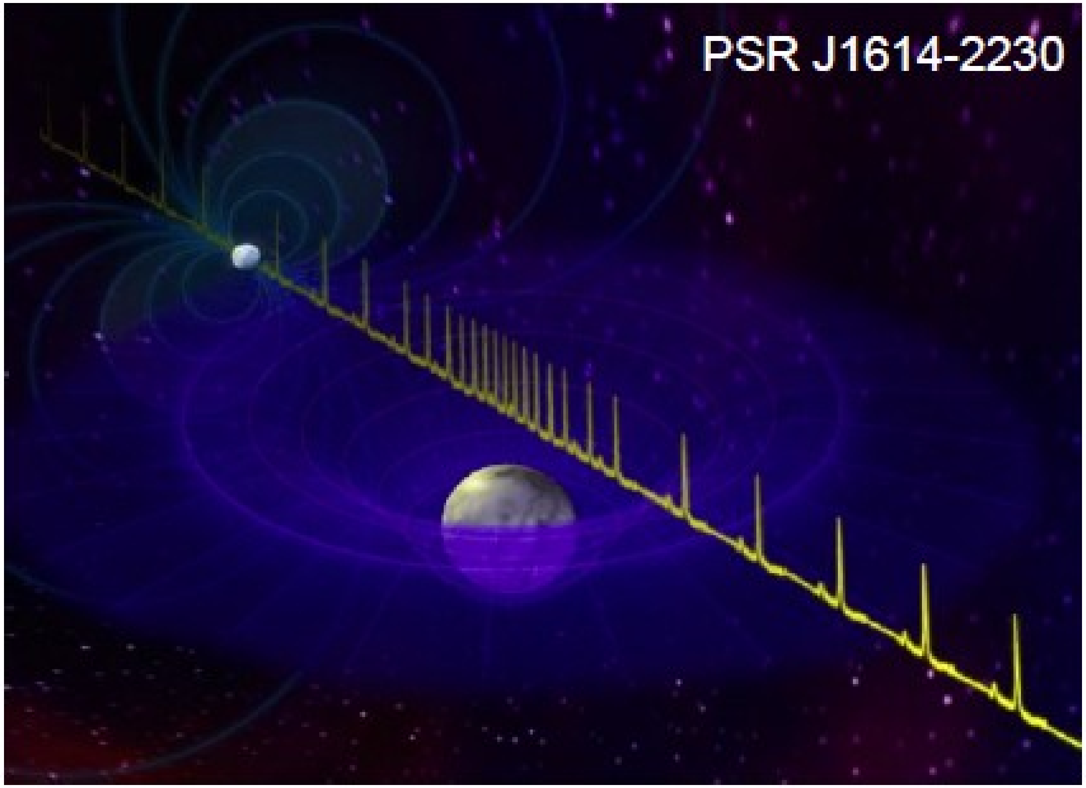
Neutron Star Interiors: Strong Phase Transition?

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

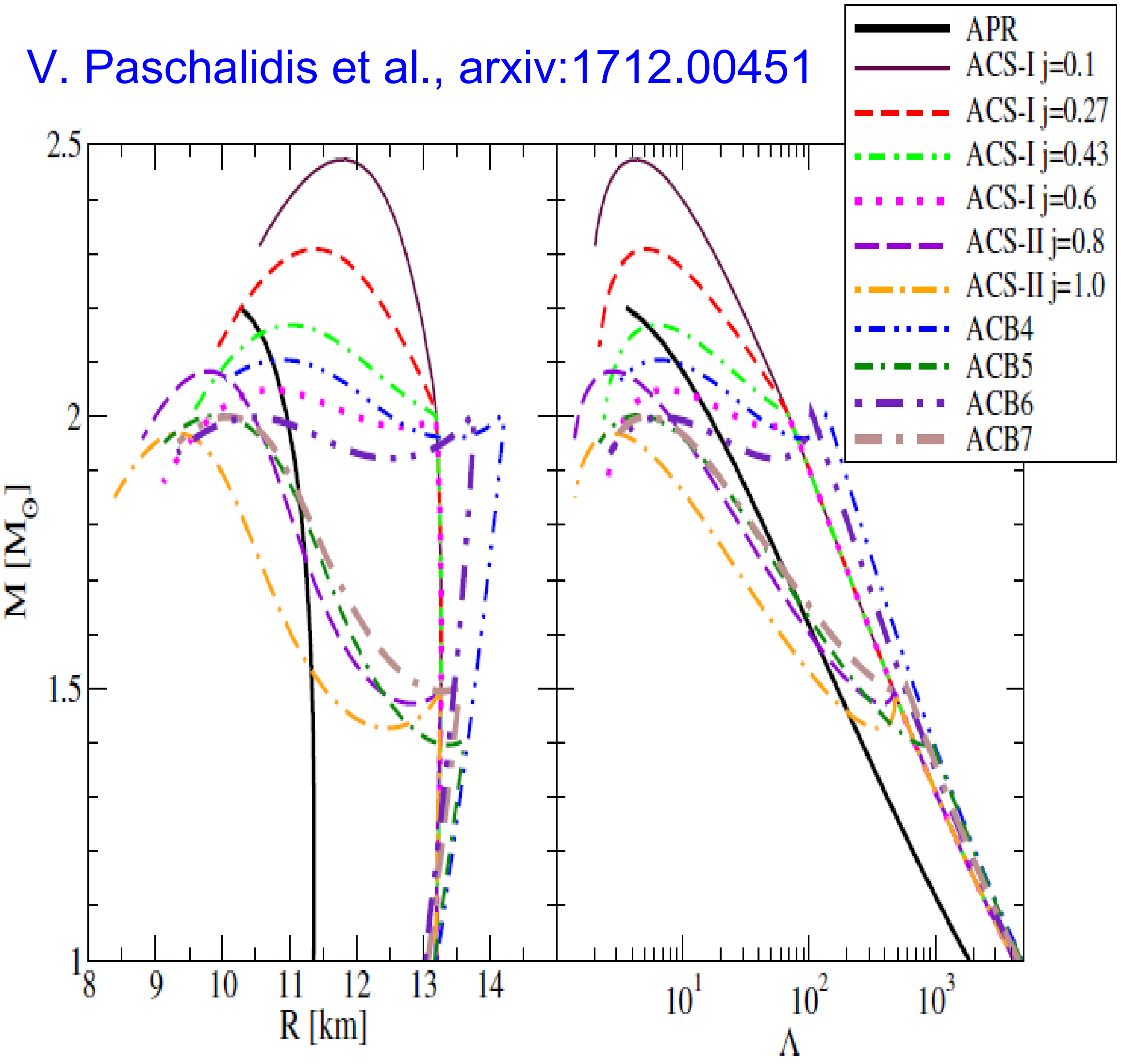


What if they were high-mass twin stars?

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

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

V. Paschalidis et al., arxiv:1712.00451



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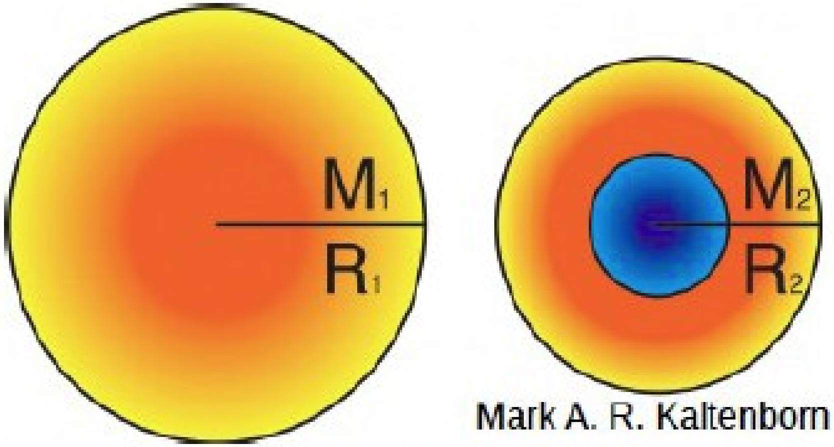

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High-mass twins (HMT) or typical-mass twins (TMT) ?

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

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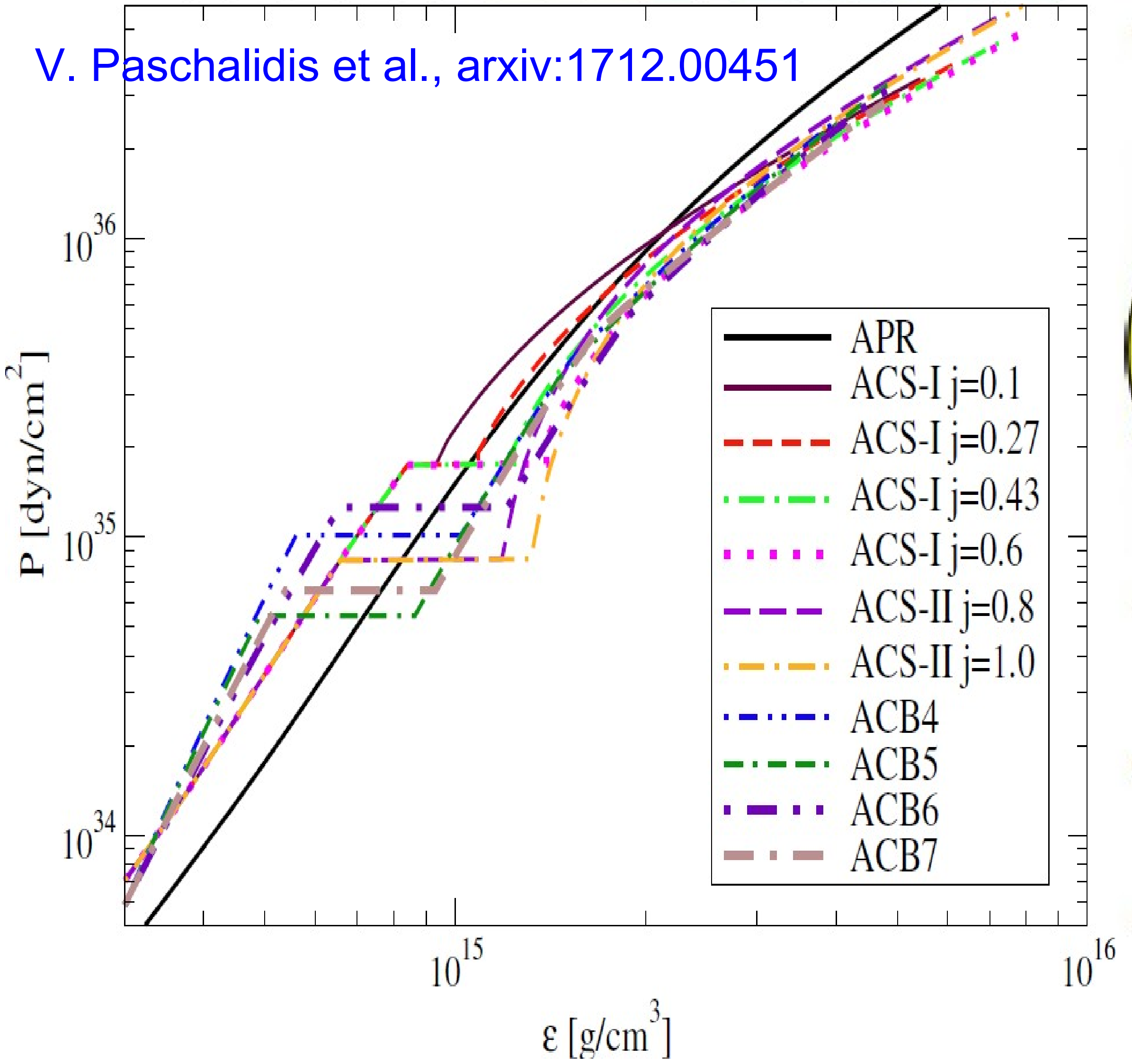

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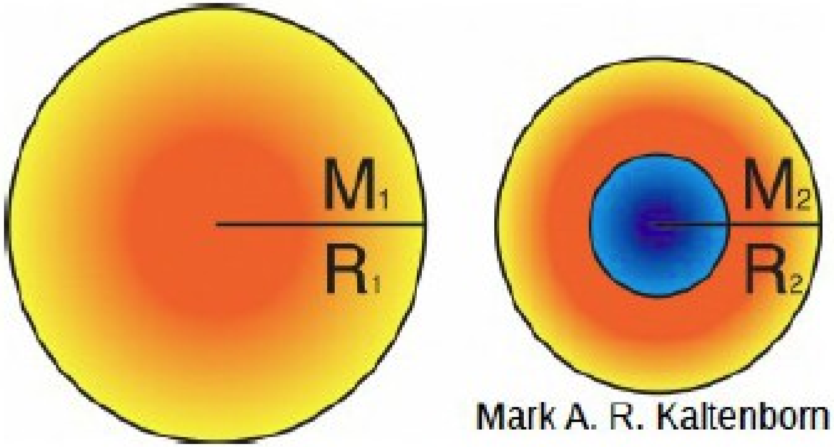

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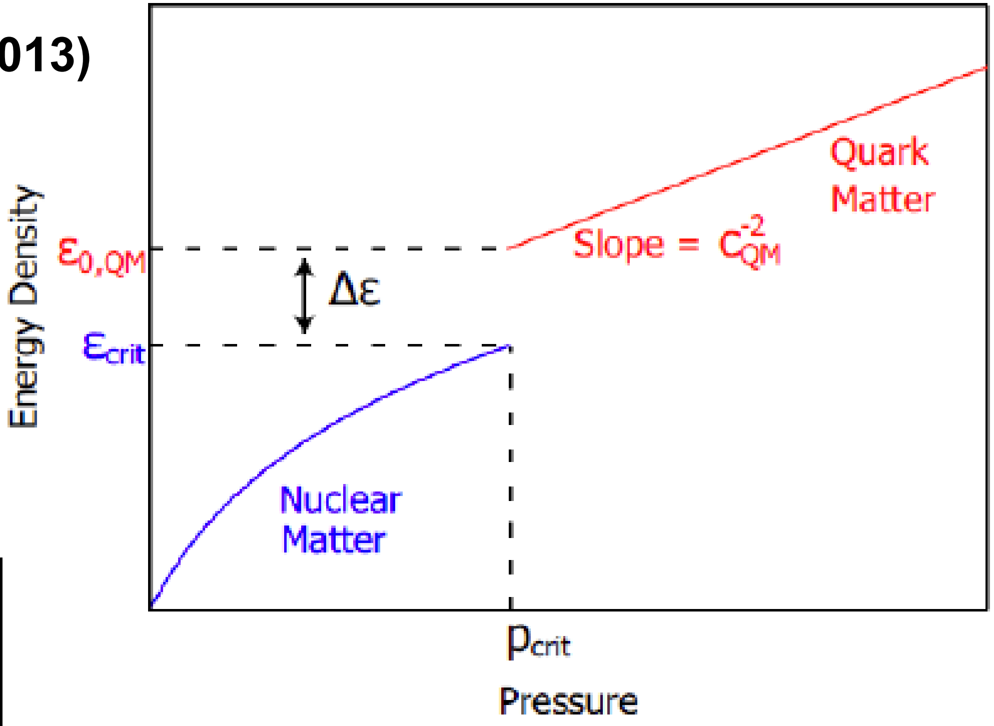
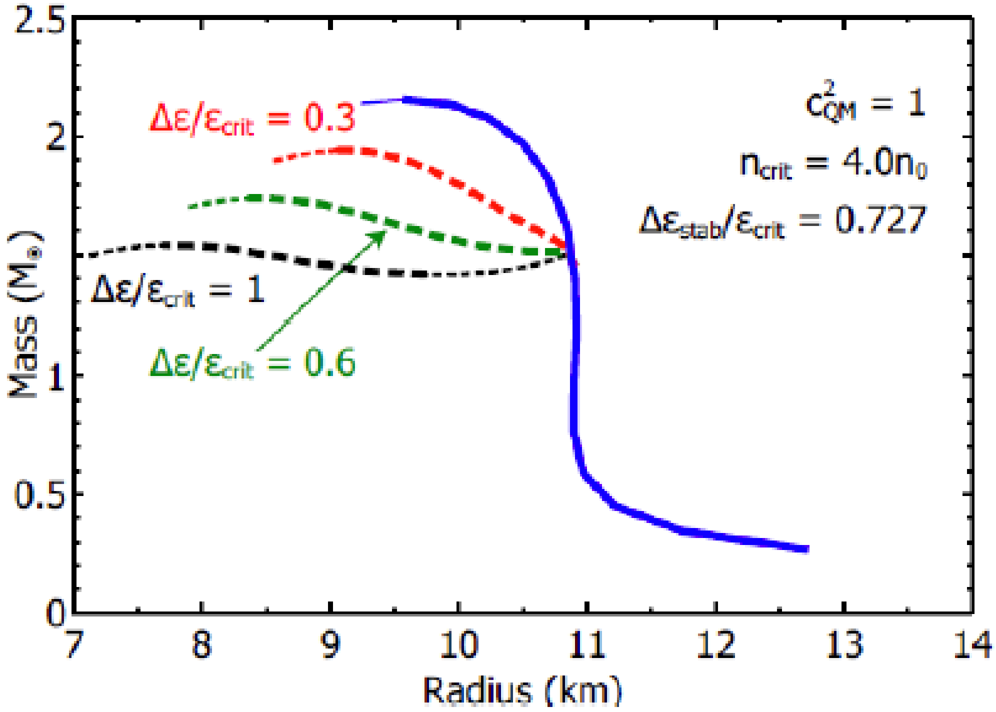
Constant Speed of Sound (CSS) Model

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

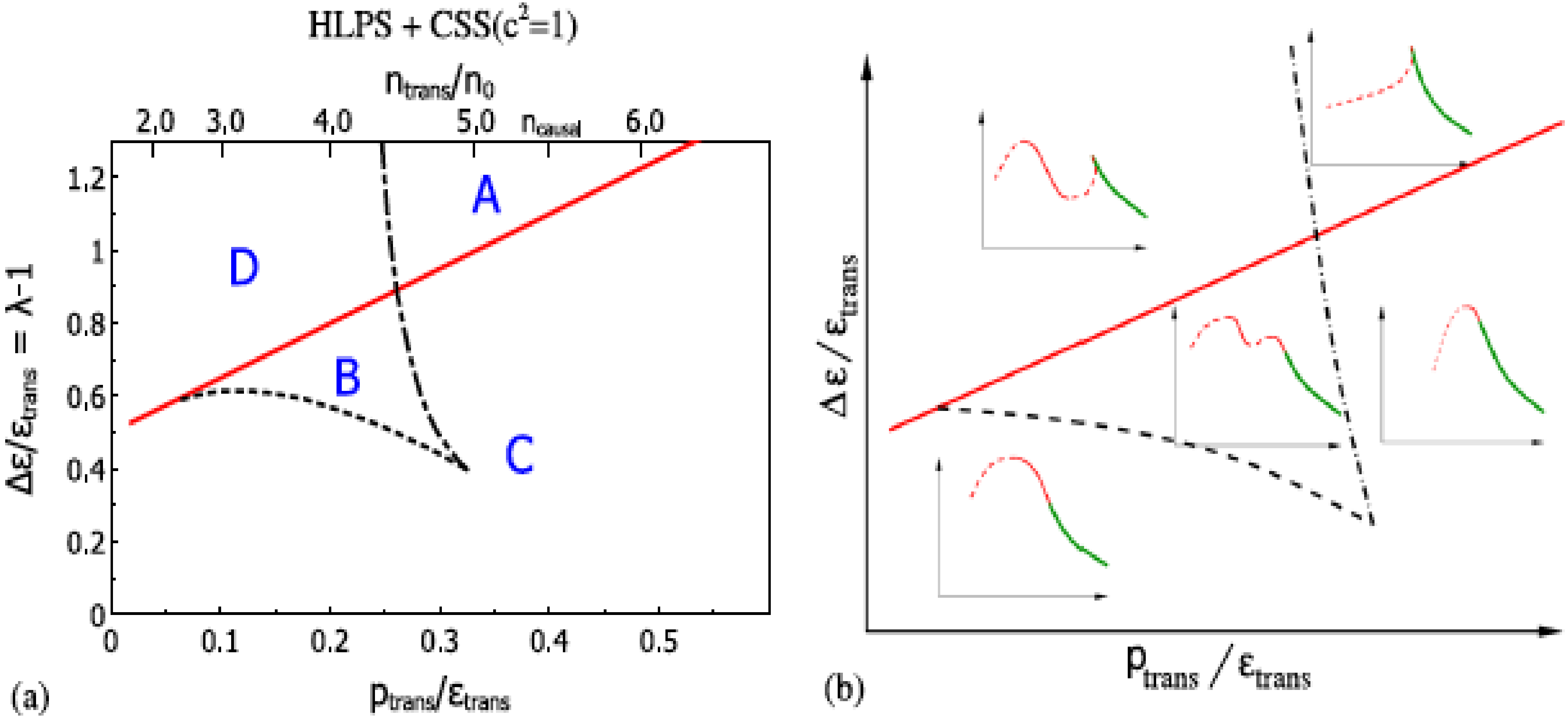
First order PT can lead to a stable branch of hybrid stars with quark matter cores which, depending on the size of the "latent heat" (jump in energy density), can even be disconnected from the hadronic one by an unstable branch → **"third family of CS"**.





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)

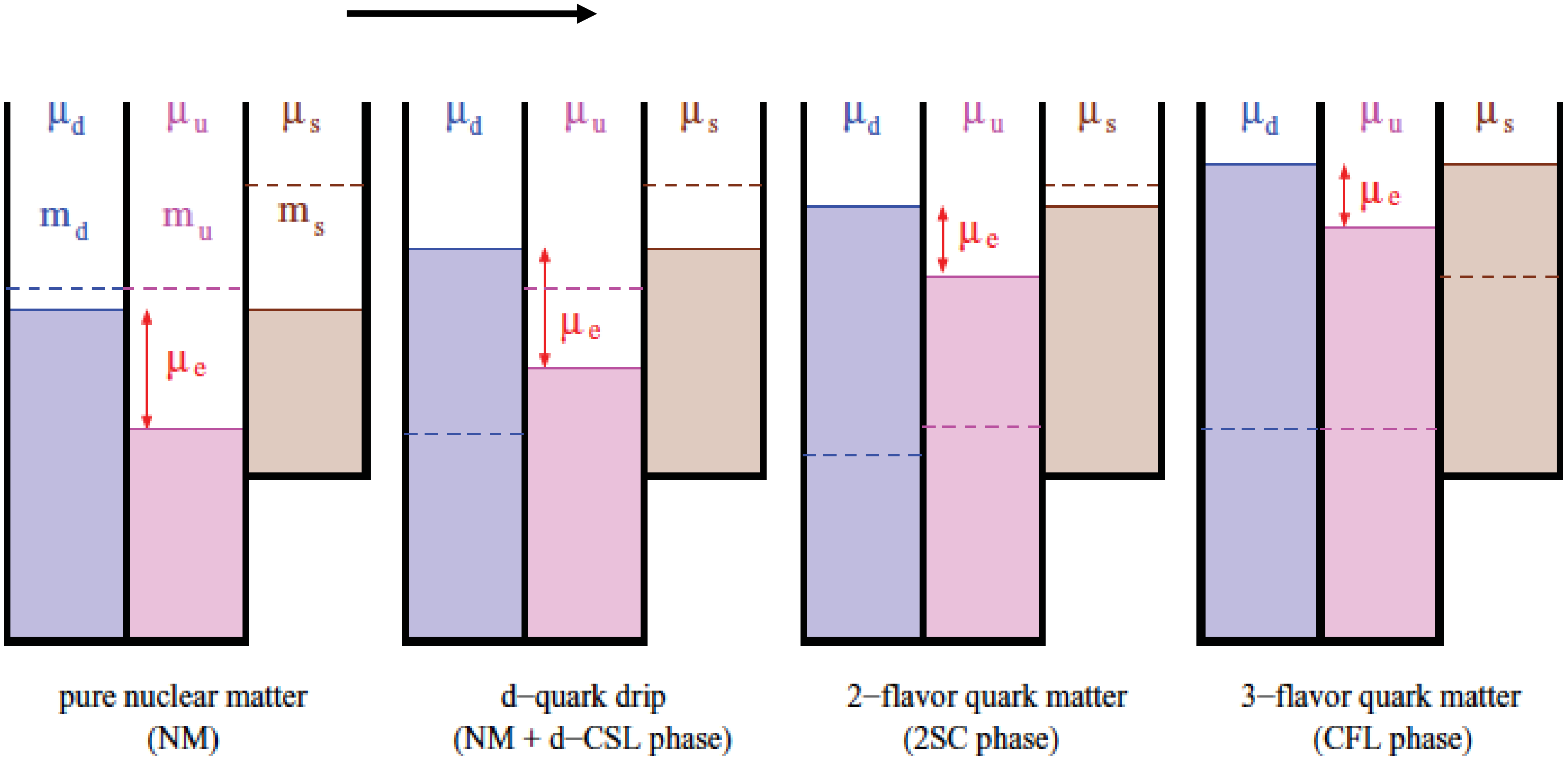
Most interesting and clear-cut cases: (D)isconnected and (B)oth – high-mass twins!

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



pure nuclear matter (NM)

d–quark drip (NM + d–CSL phase)

2–flavor quark matter (2SC phase)

3–flavor quark matter (CFL phase)

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

Neutron Star Interiors: Sequential Phase Transitions?

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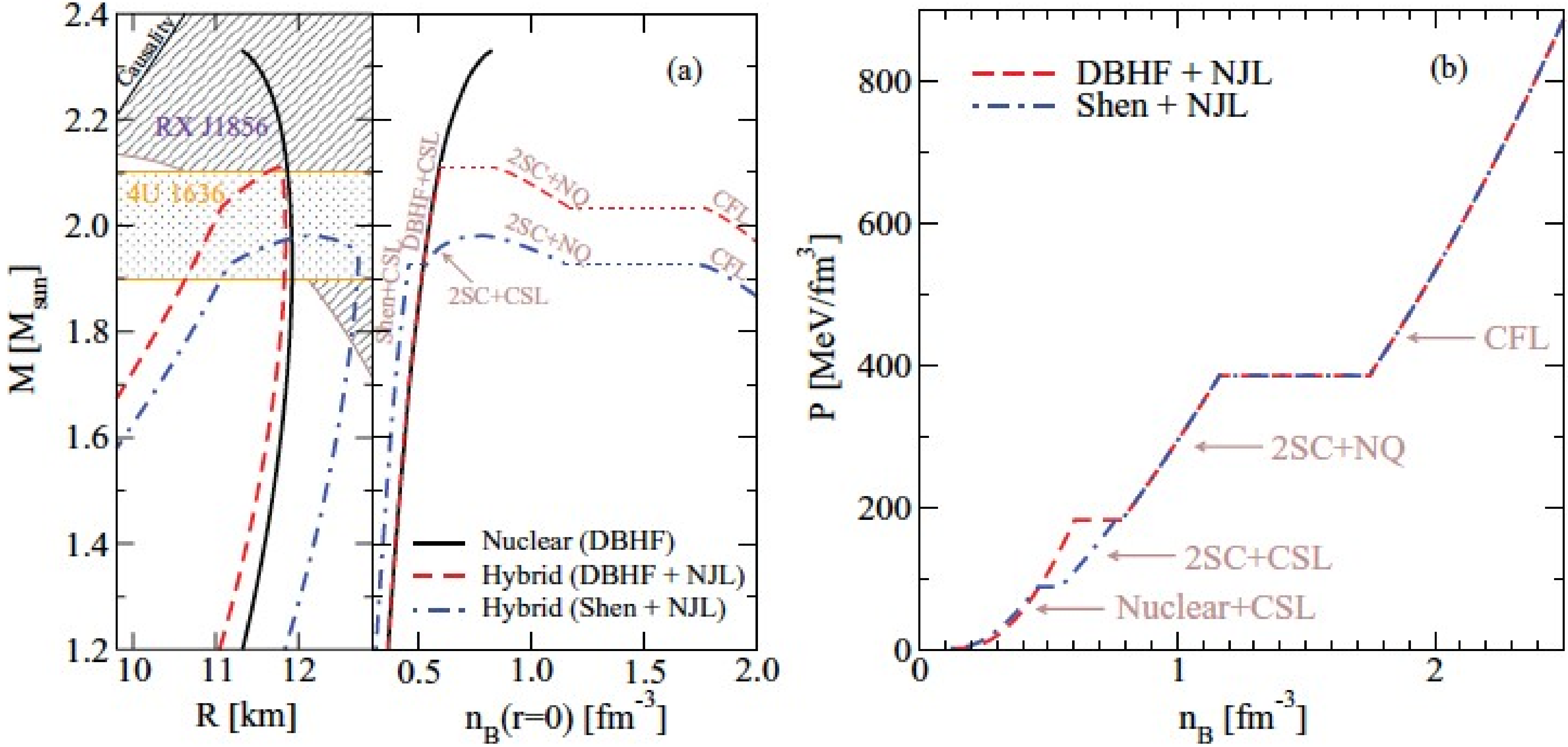
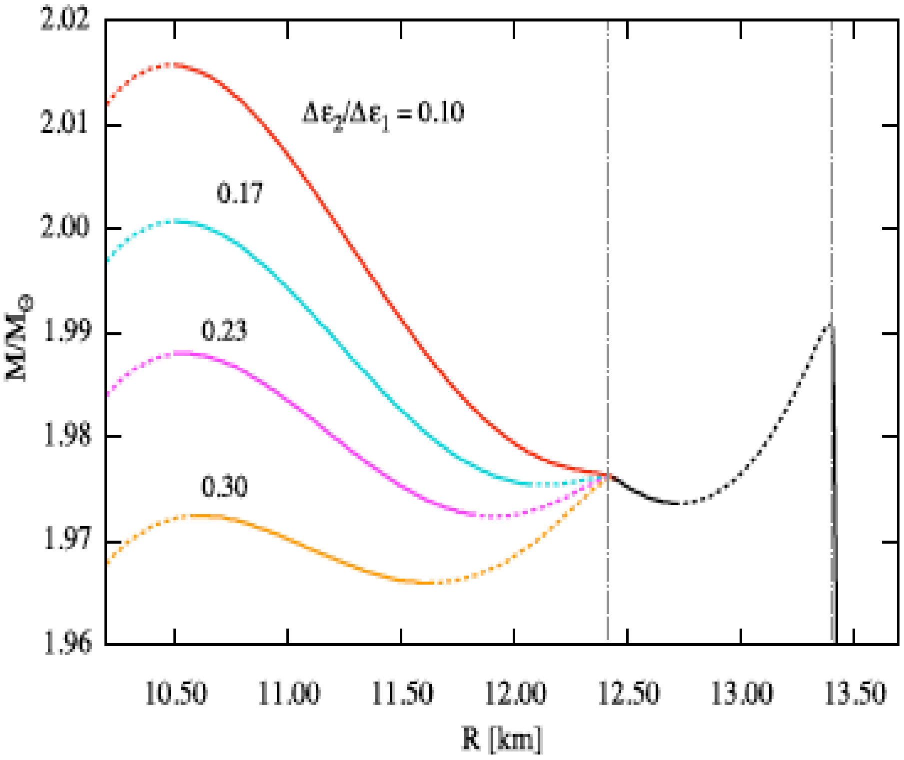
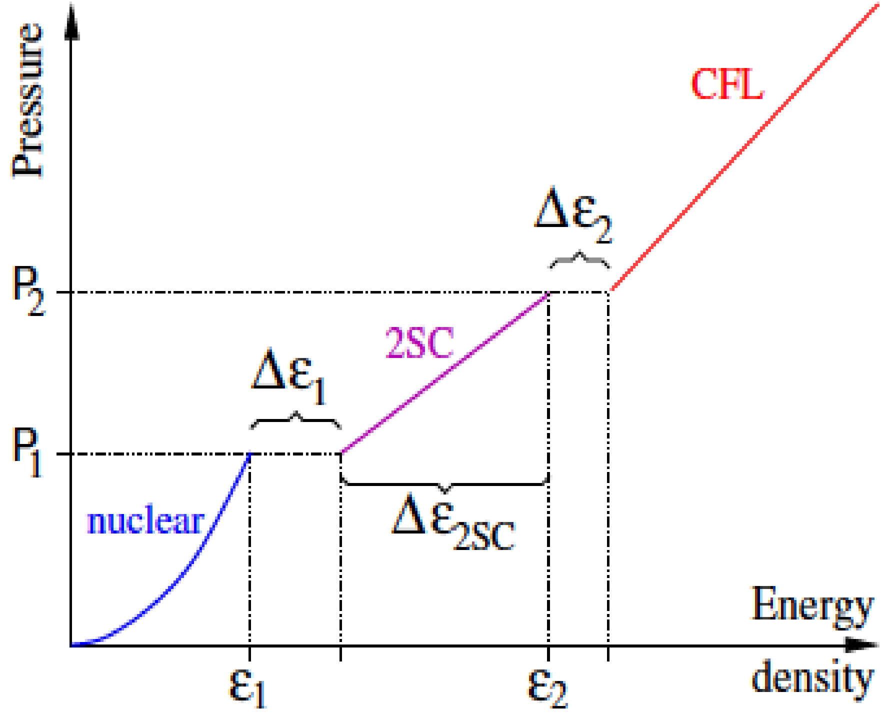


D.B., F. Sandin, T. Klaehn, J. Berdermann, PRC 80 (2009) 065807

Neutron Star Interiors: Sequential Phase Transitions?

Measuring Mass vs. Radius ↔ Equation of state



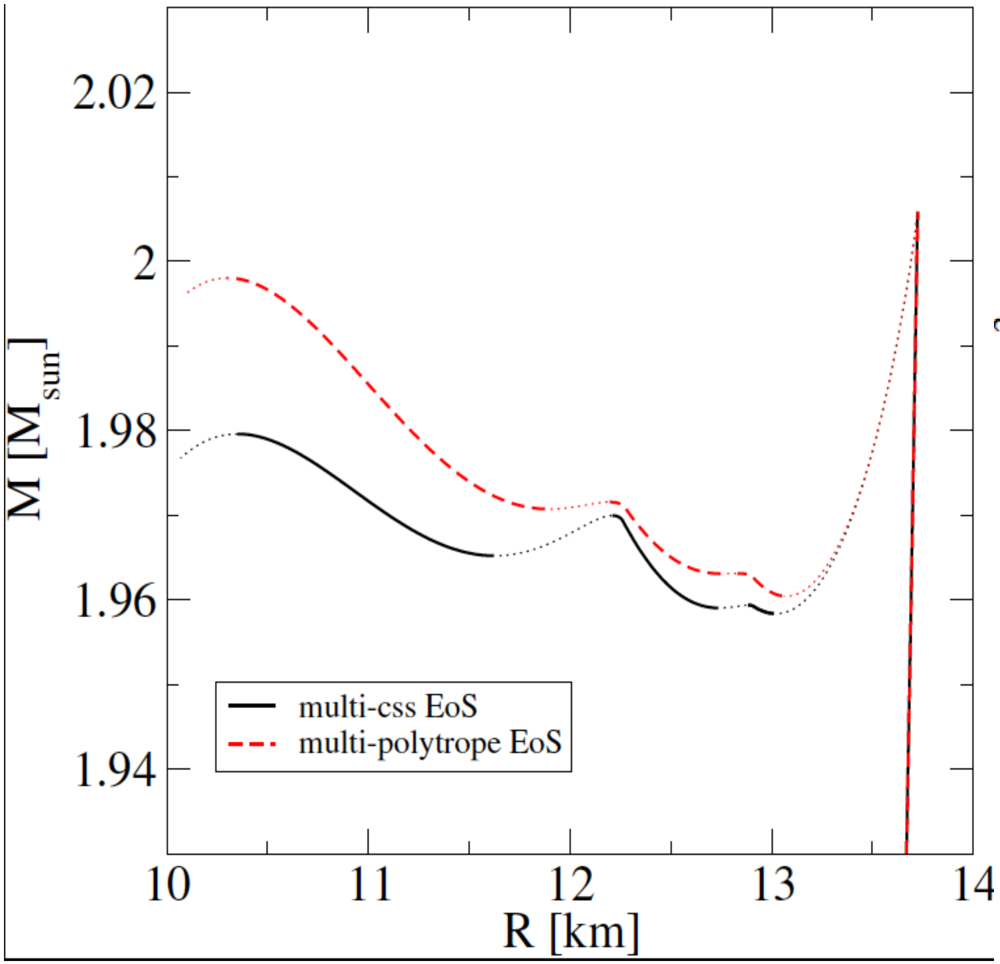


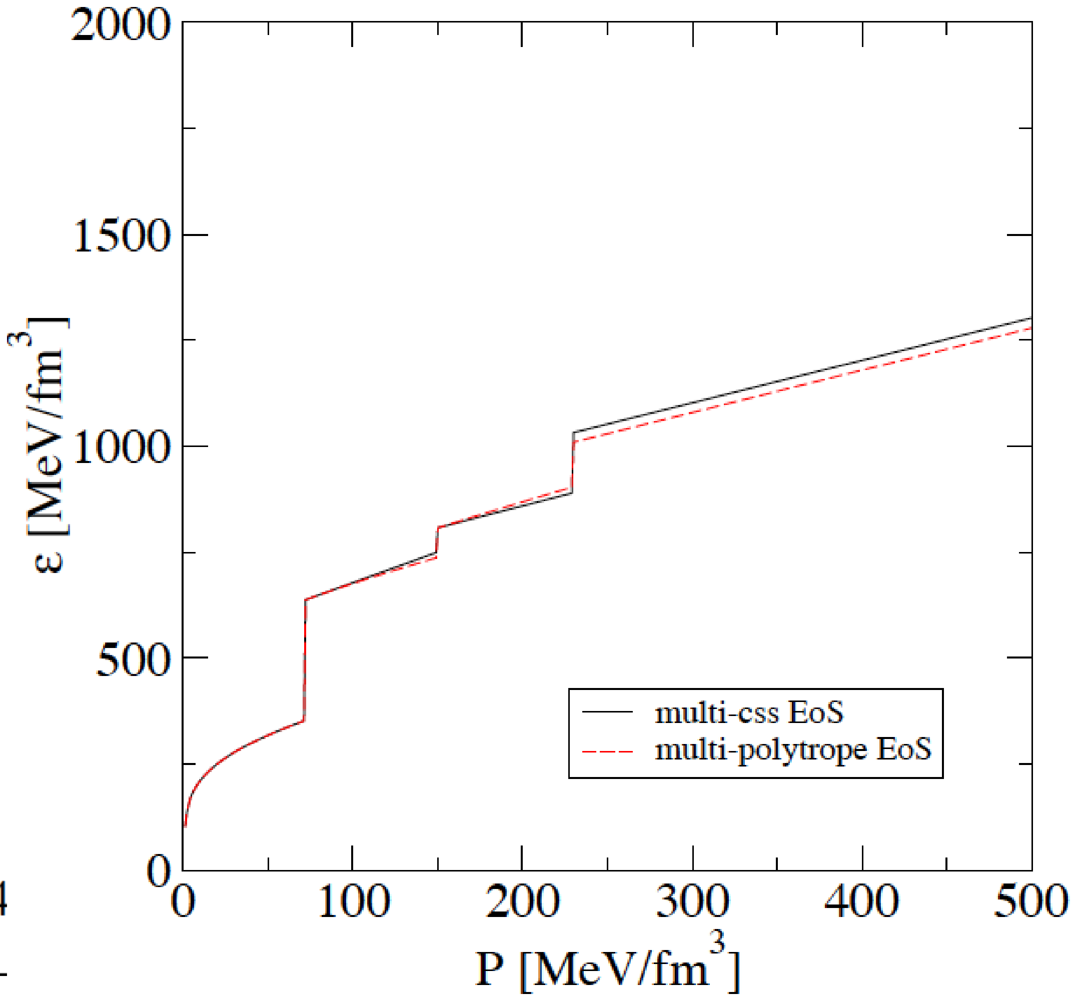
High-mass twins:
D. Blaschke et al., PoS CPOD 2013
S. Benic et al., A&A 577 (2015) A50

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





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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

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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)

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

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

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)

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

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

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

“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

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

New collaboration (Kasym – Zhandos – David) started in Dubna, July 2019

Relativistic density functional approach (III)

Density functional for the SFM

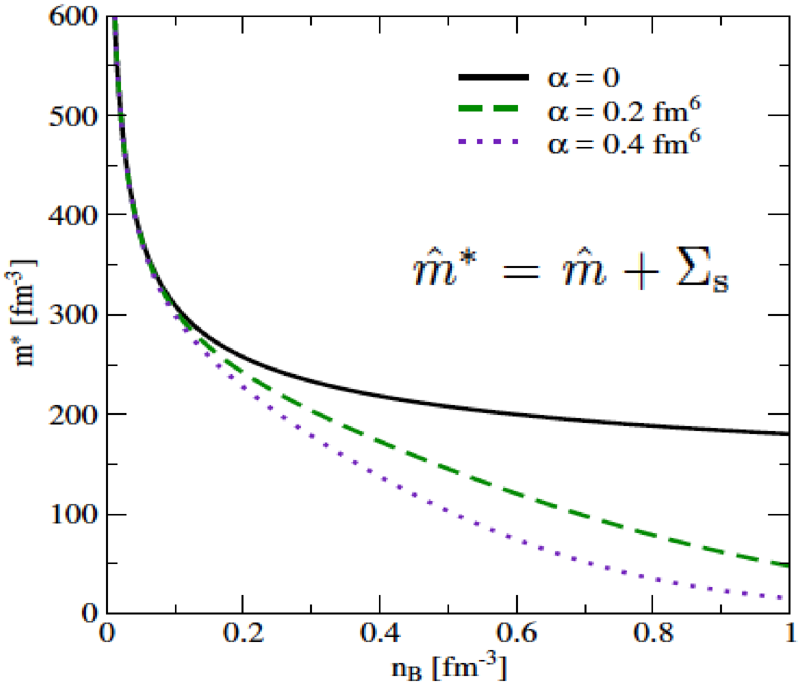
$$U(n_{\rm s}, n_{\rm v}) = D(n_{\rm v}) n_{\rm s}^{2/3} + a n_{\rm v}^2 + \frac{b n_{\rm v}^4}{1 + c n_{\rm v}^2} ,$$

Quark selfenergies

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

Quark “confinement”

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

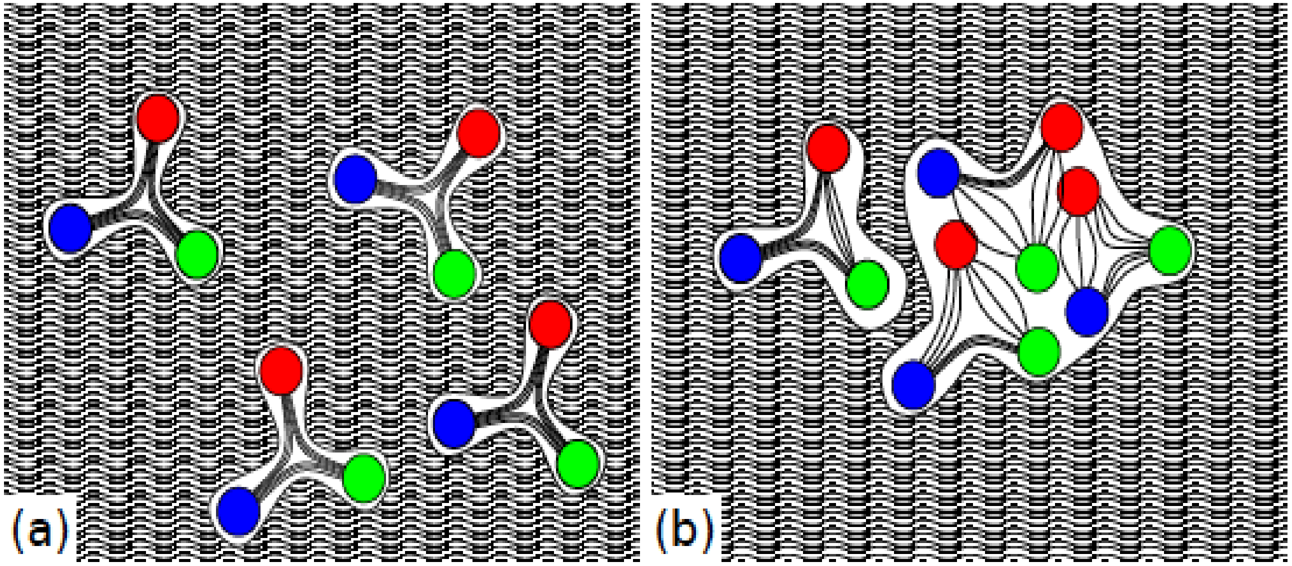


String tension & confinement due to dual Meissner effect (dual superconductor model)

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

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

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

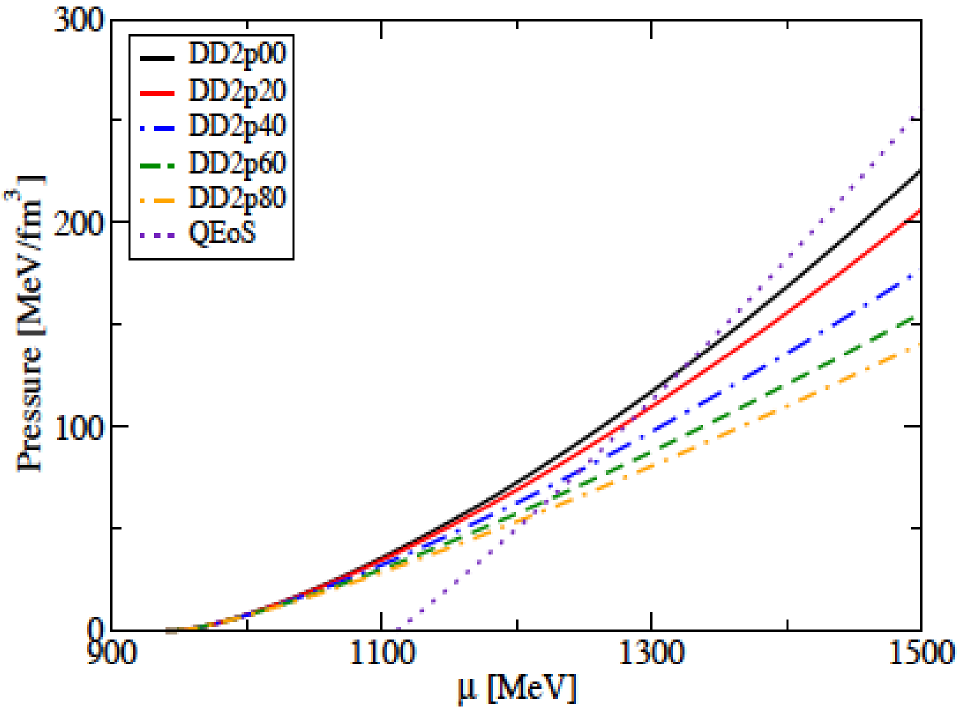


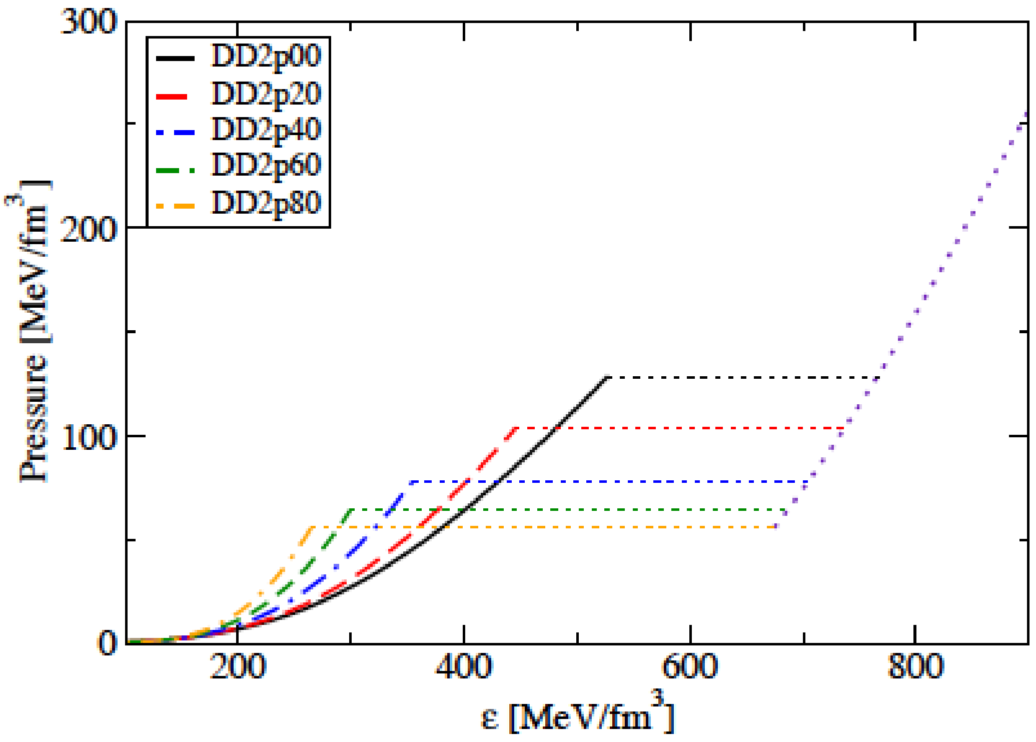
Phase transition from hadronic to SFM quark matter

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

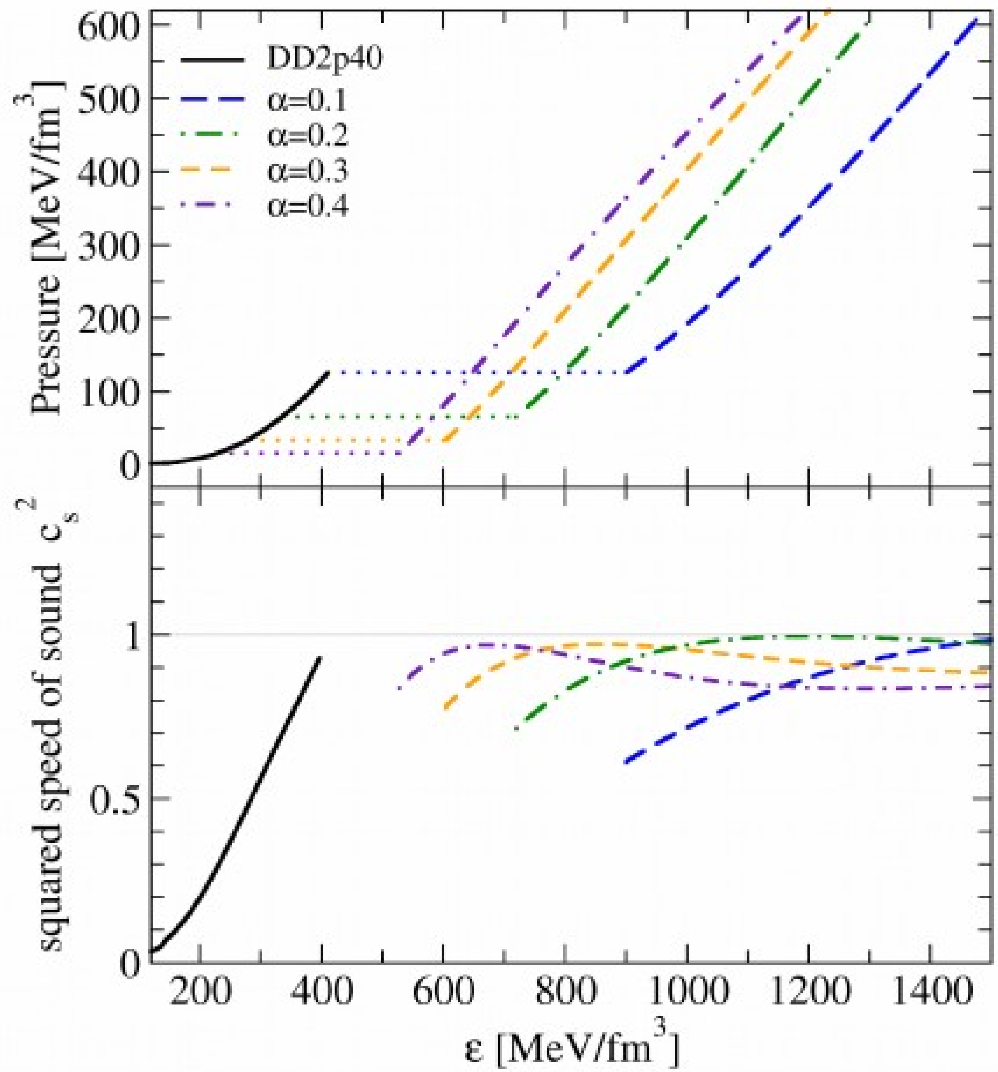
$$\Phi_n = \Phi_p = \begin{cases} 1, & \text{if } n_{\mathrm{B}} < n_0 \\ e^{-\frac{v|v|}{2}(n_{\mathrm{B}}-n_0)^2}, & \text{if } n_{\mathrm{B}} > n_0 \end{cases}$$

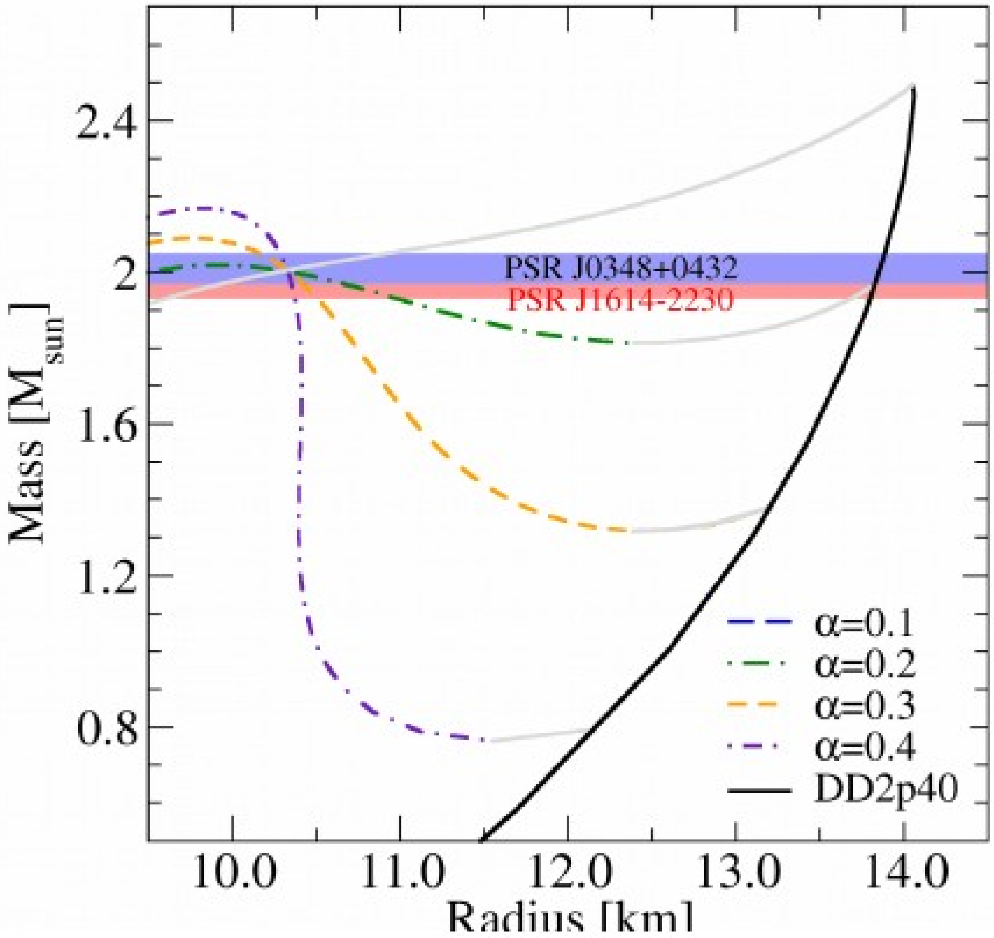
Varying the hadronic excluded volume parameter, p00 → v=0, … , p80 → v=8 fm^3





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





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

Results of Maxwell construction! Could pasta phases remove the twins (3^{rd} 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]

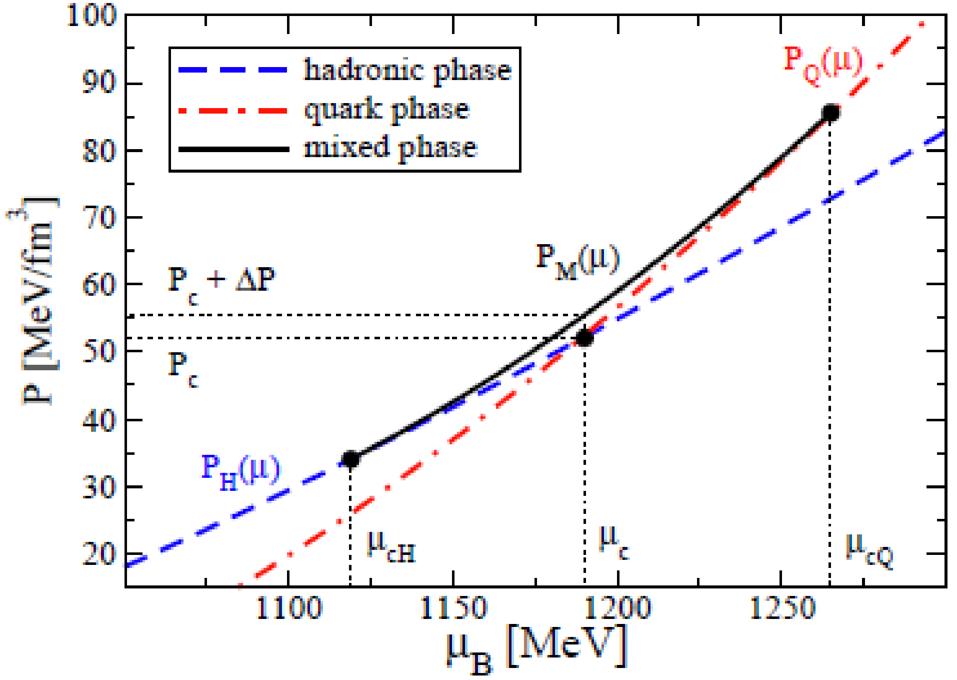
K. Maslov, N. Yasutake, A. Ayriyan, D.B., H. Grigorian, T. Maruyama, T. Tatsumi,
D. Voskresensky; Phys. Rev. C, in press (2019); [arxiv:1812.11889]

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:

$$P_M(\mu_{cH}) = P_H(\mu_{cH}) = P_H$$

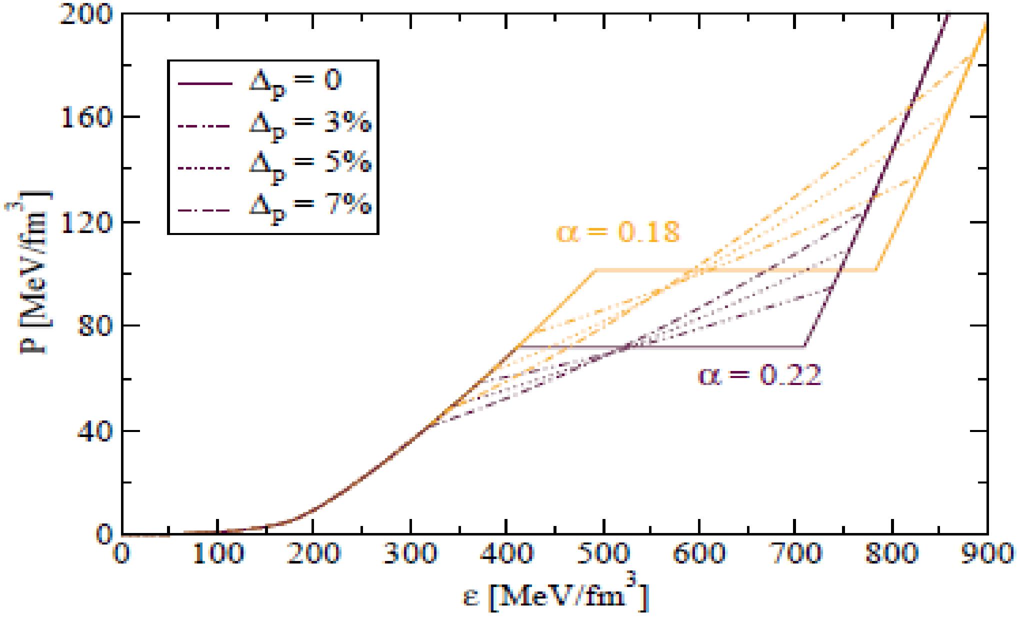
$$P_M(\mu_{cQ}) = P_Q(\mu_{cQ}) = P_Q,$$

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

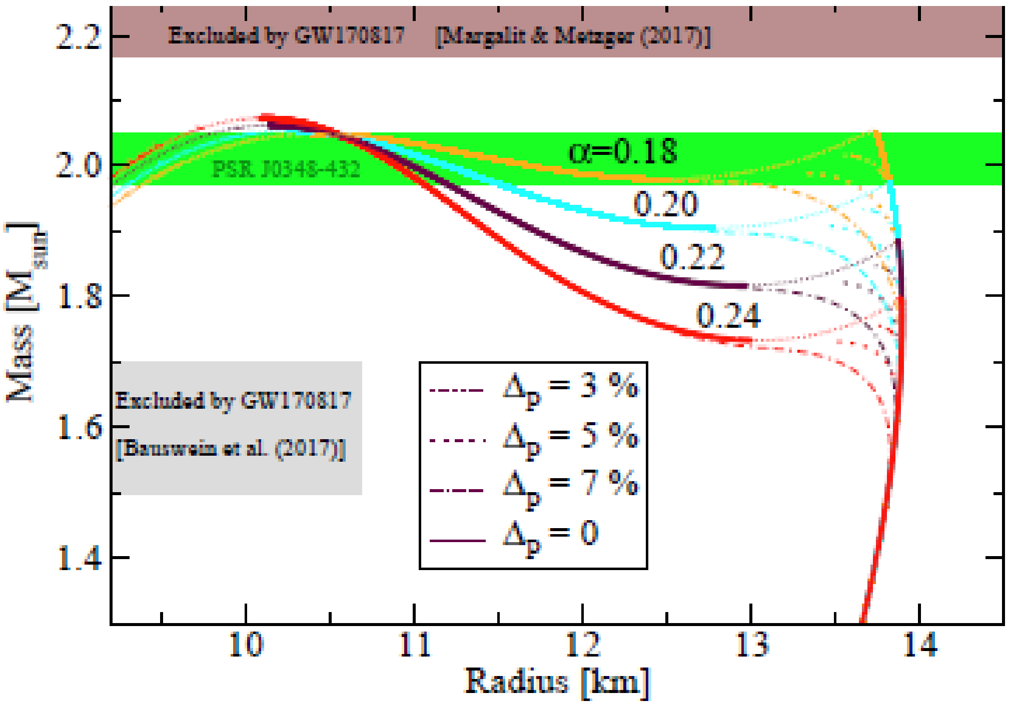


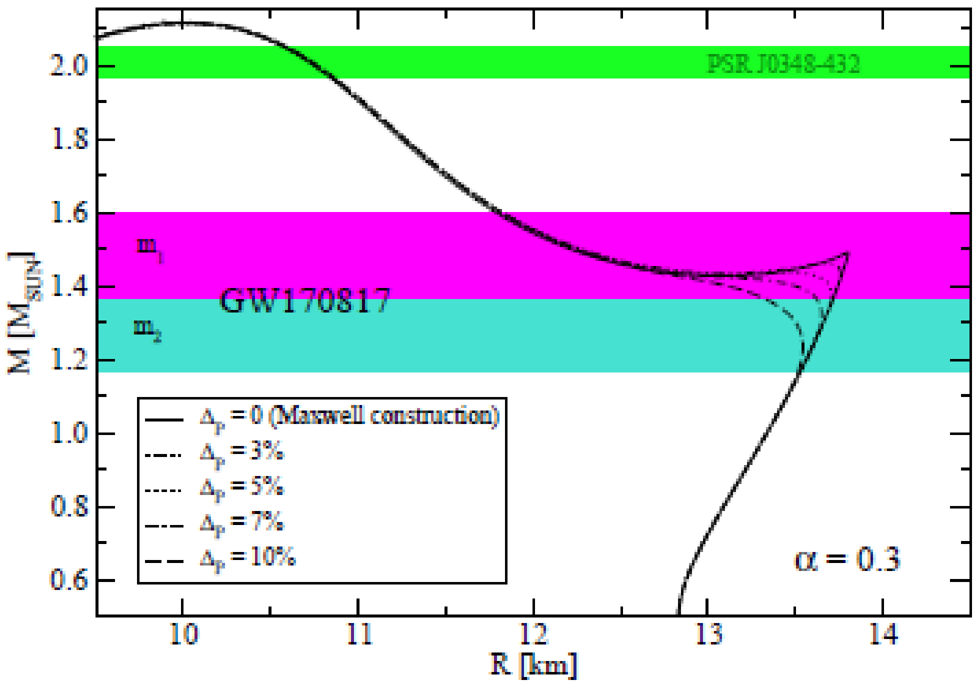
Result:

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

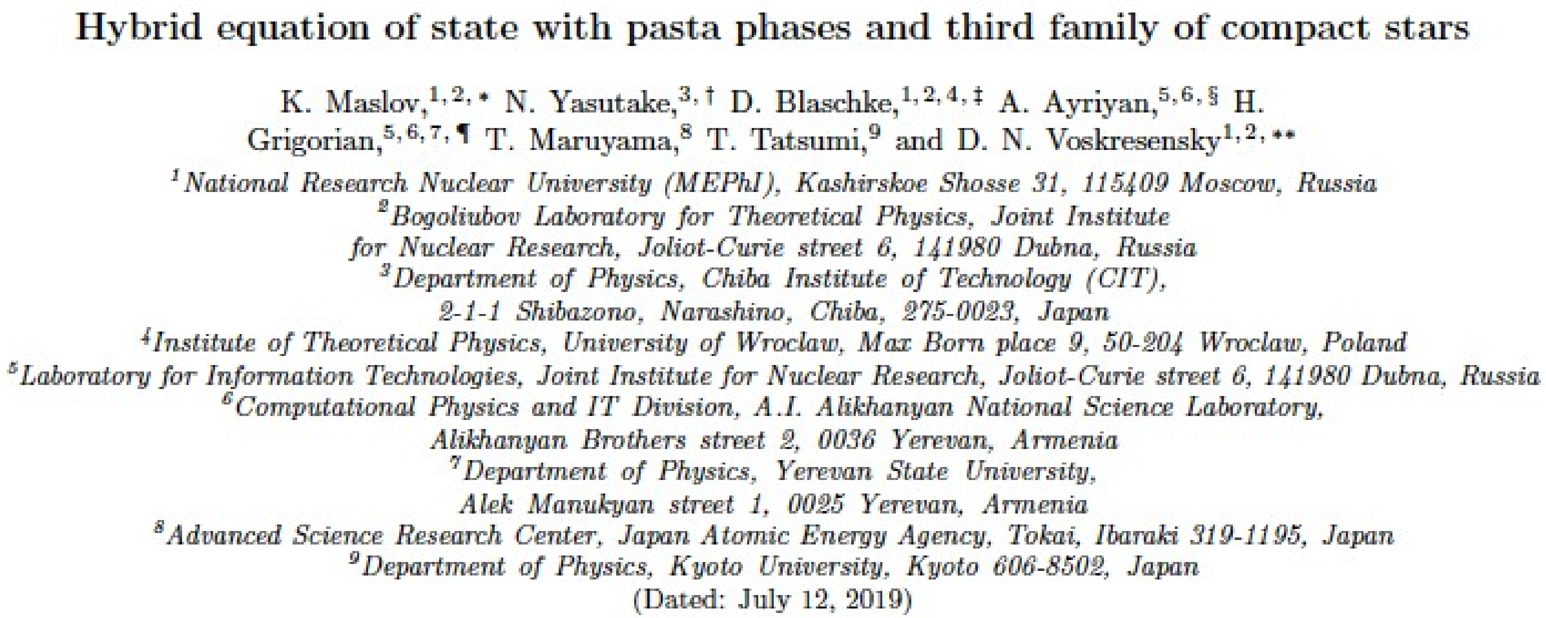
GW170817 could have been a HS-NS or even A HS-HS merger rather than NS-NS merger !!

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





Robustness of Twins against Pasta Phase Effects



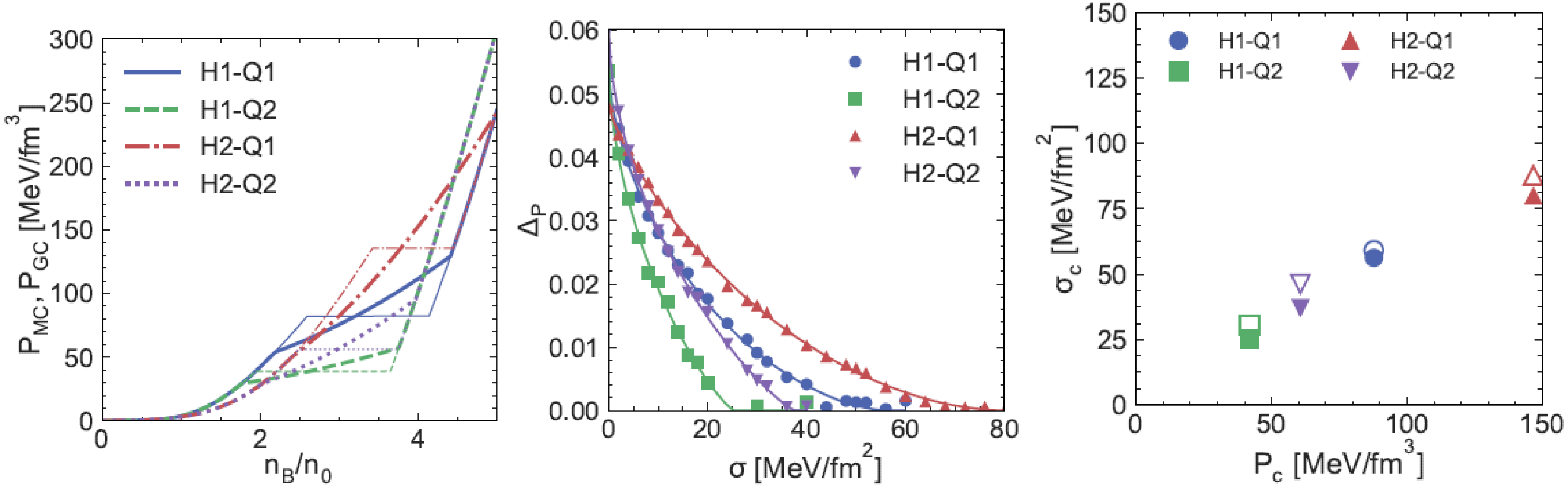
Hybrid equation of state with pasta phases and third family of compact stars

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,**]

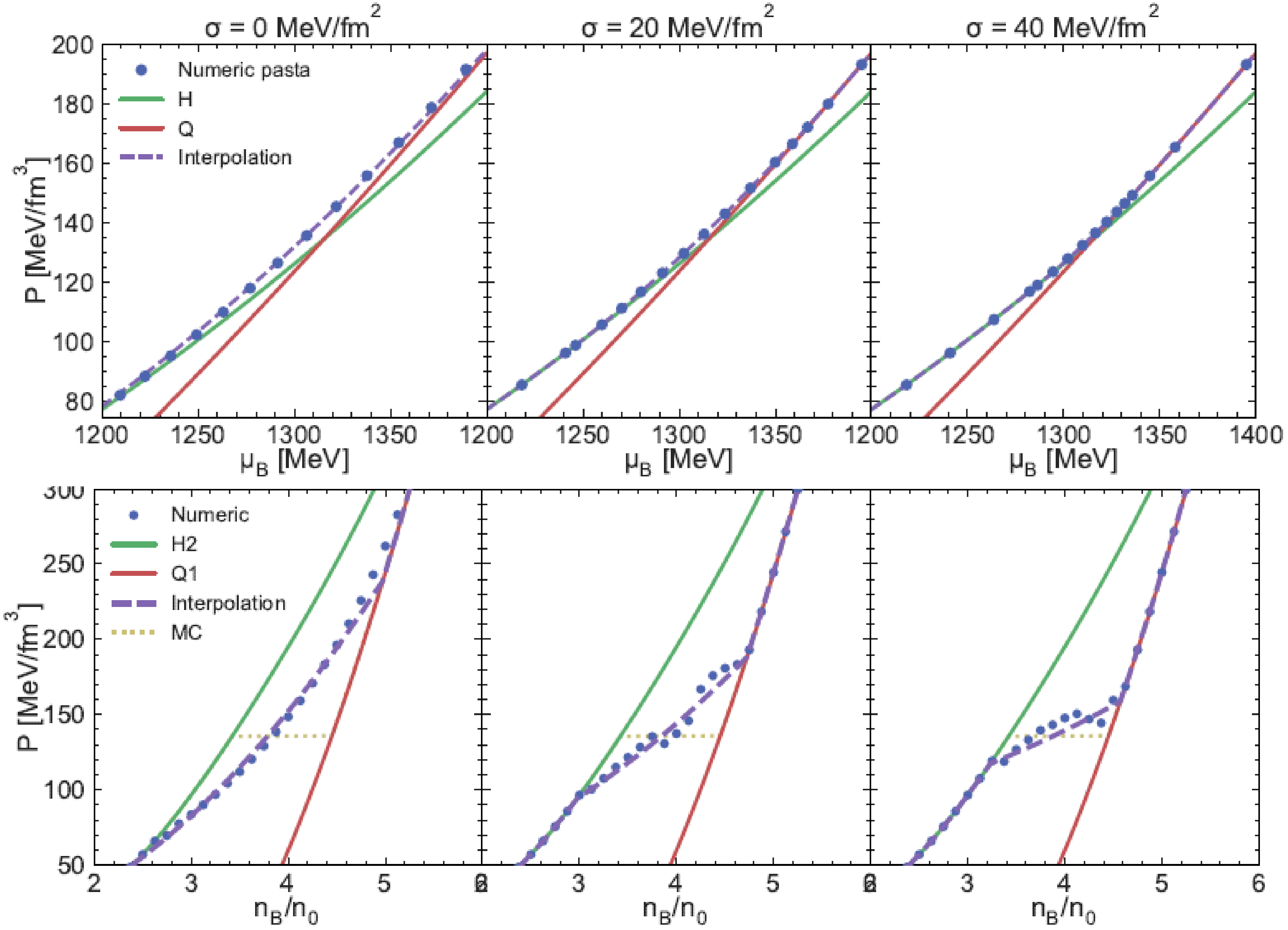
[1]*National Research Nuclear University (MEPhI), Kashirskoe Shosse 31, 115409 Moscow, Russia*
[2]*Bogoliubov Laboratory for Theoretical Physics, Joint Institute for Nuclear Research, Joliot-Curie street 6, 141980 Dubna, Russia*
[3]*Department of Physics, Chiba Institute of Technology (CIT), 2-1-1 Shibazono, Narashino, Chiba, 275-0023, Japan*
[4]*Institute of Theoretical Physics, University of Wroclaw, Max Born place 9, 50-204 Wroclaw, Poland*
[5]*Laboratory for Information Technologies, Joint Institute for Nuclear Research, Joliot-Curie street 6, 141980 Dubna, Russia*
[6]*Computational Physics and IT Division, A.I. Alikhanyan National Science Laboratory, Alikhanyan Brothers street 2, 0036 Yerevan, Armenia*
[7]*Department of Physics, Yerevan State University, Alek Manukyan street 1, 0025 Yerevan, Armenia*
[8]*Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*
[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 $\Delta_P < 5\%$ ...



Robustness of Twins against Pasta Phase Effects



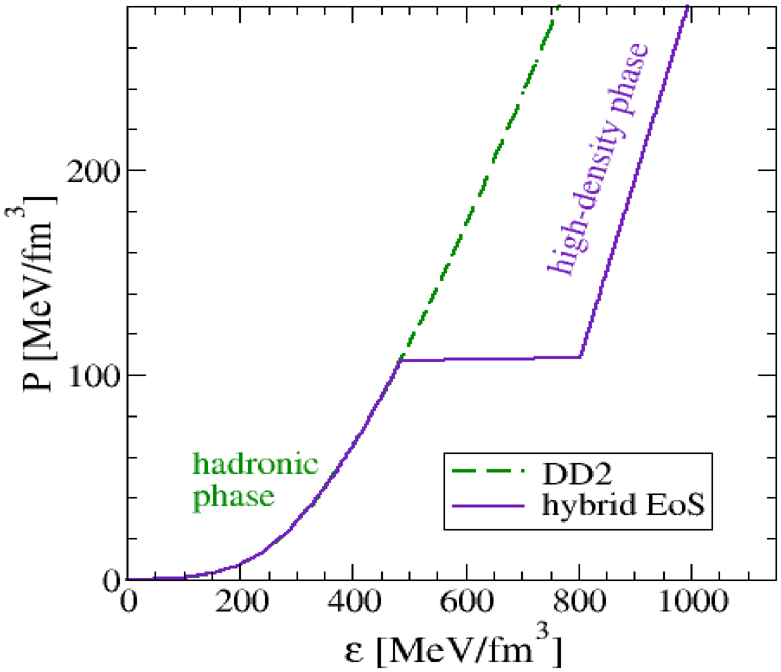
Maslov et al., Phys. Rev. C 100, 025802 (2019)

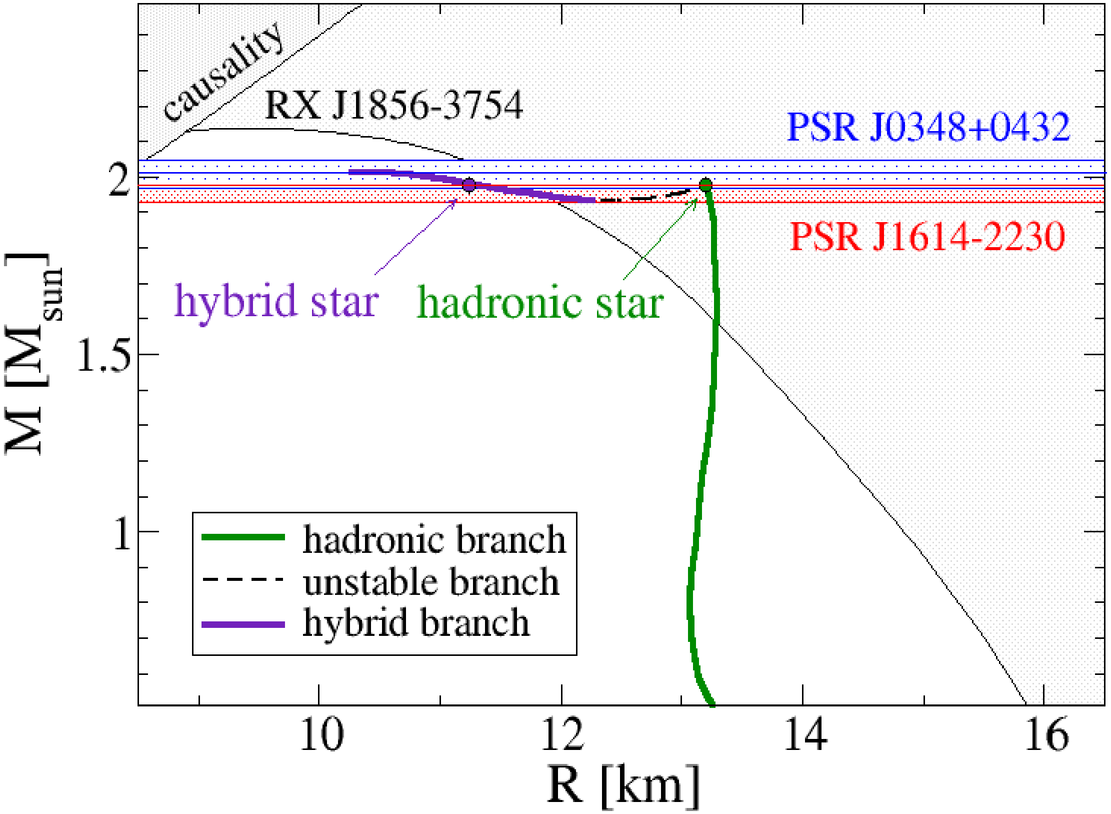
Robustness of Twins against Pasta Phase Effects

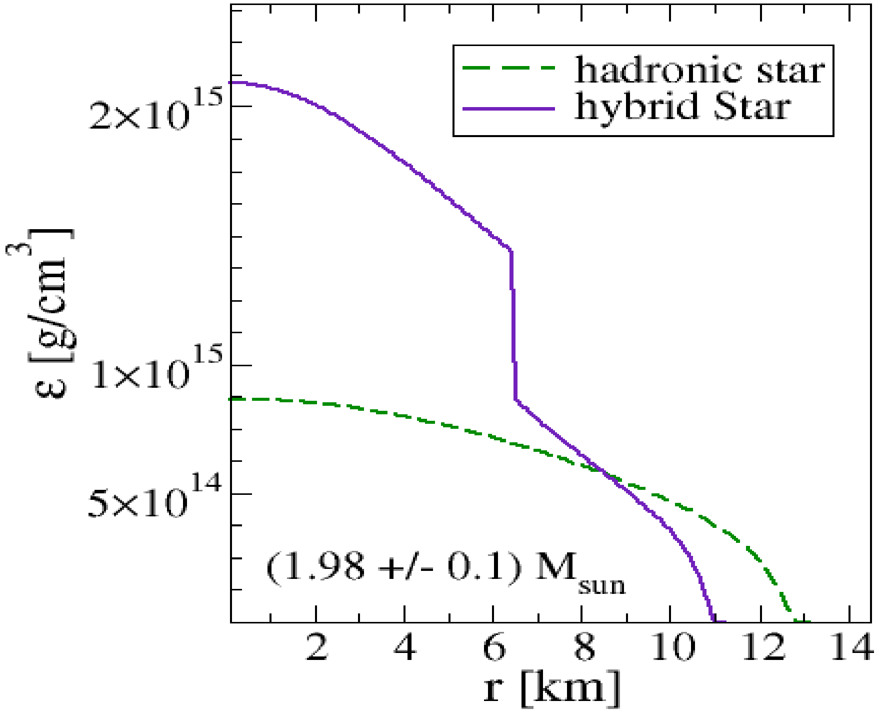
Thanks to the collaborators !

“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.?







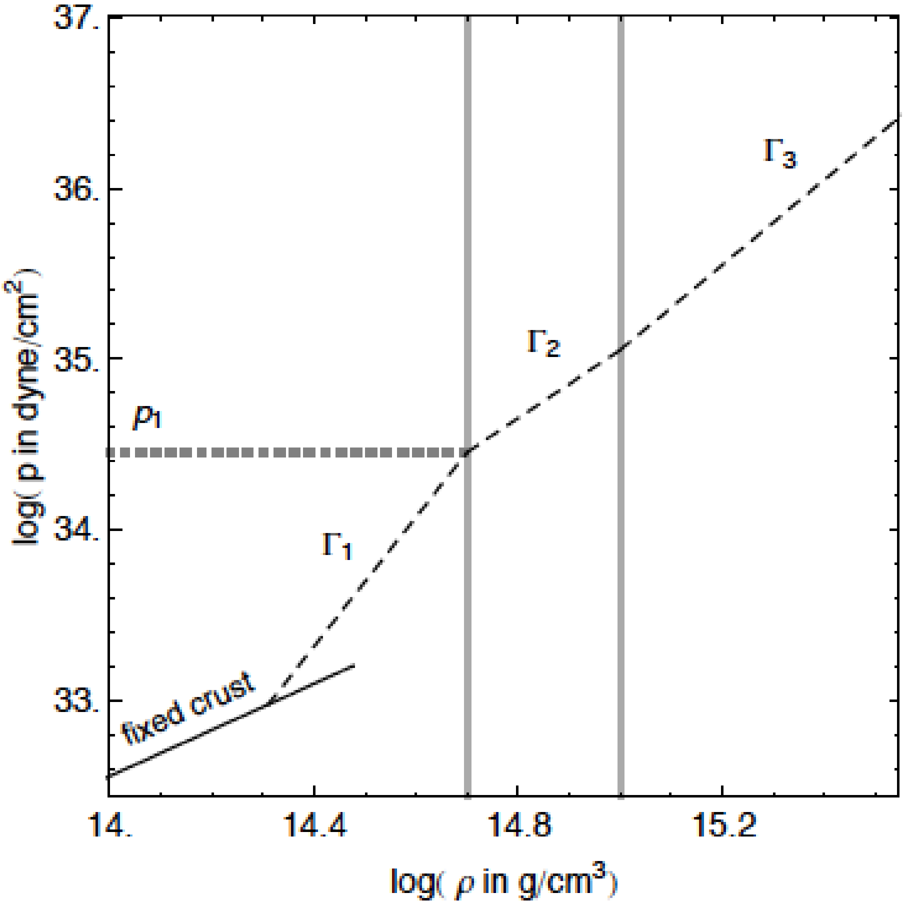
Alvarez & Blaschke, arxiv:1304.7758

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

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

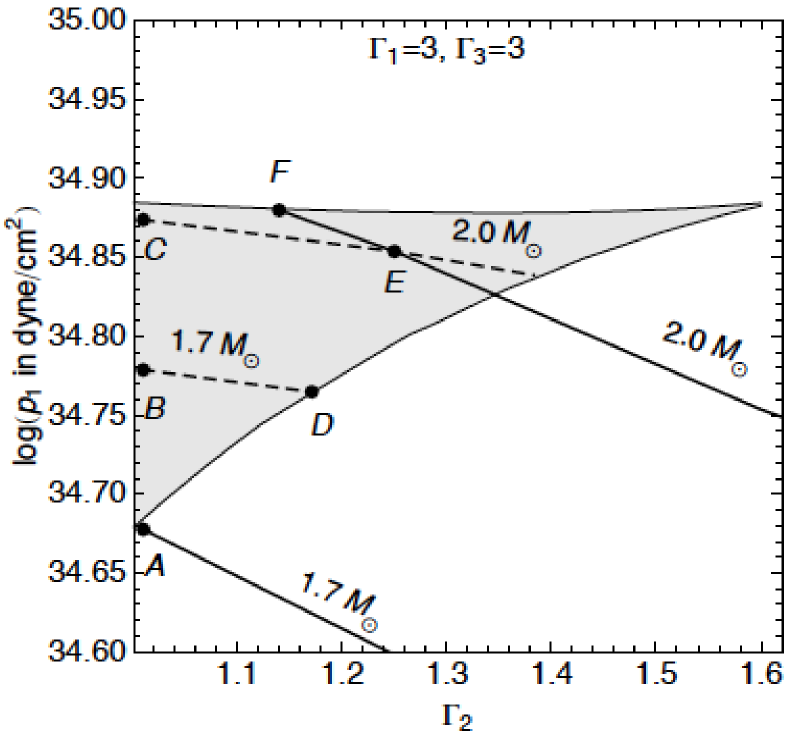
$$\boxed{P_i(n) = \kappa_i n^{\Gamma_i}}$$

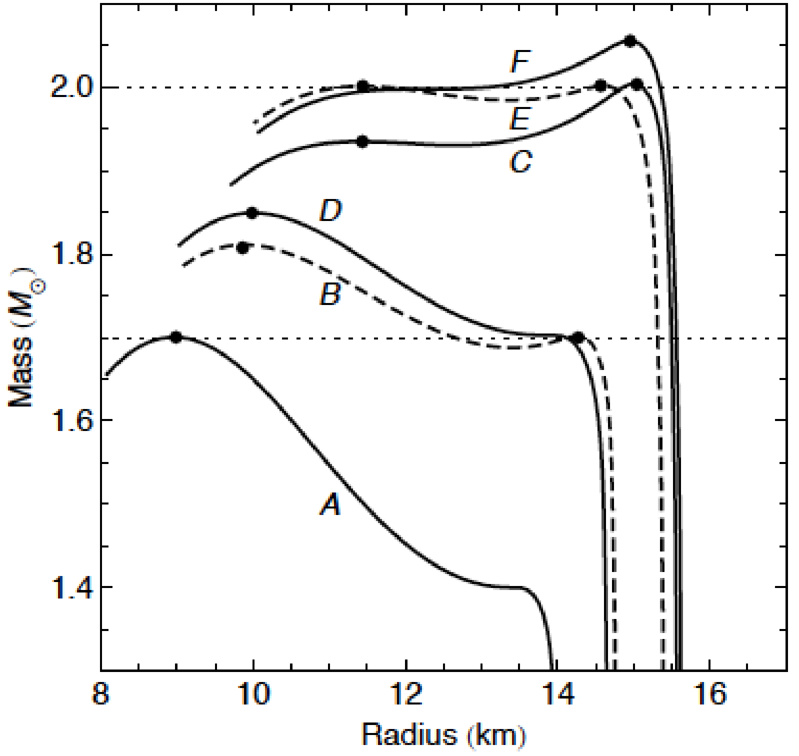
$$\begin{aligned} i = 1 &: n_1 \leq n \leq n_{12} \\ i = 2 &: n_{12} \leq n \leq n_{23} \\ i = 3 &: n \geq n_{23} \ , \end{aligned}$$



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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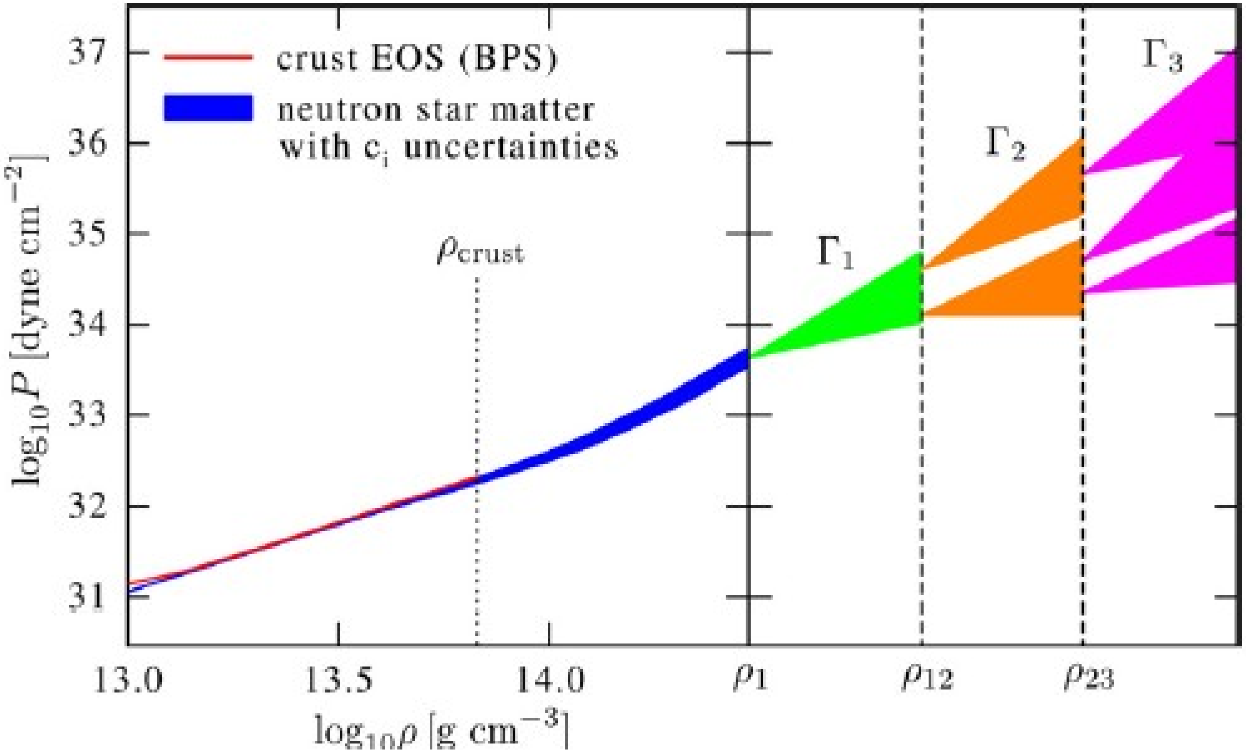
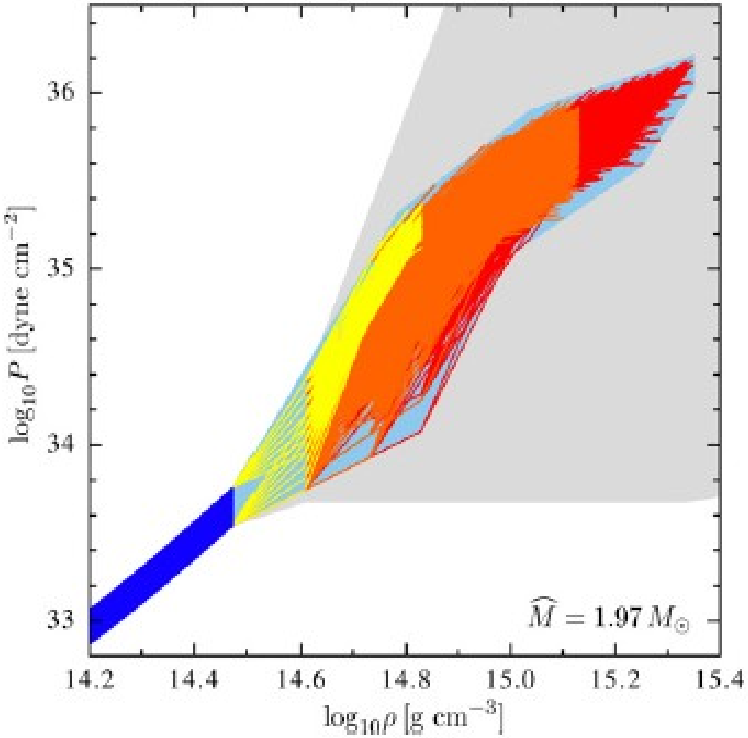
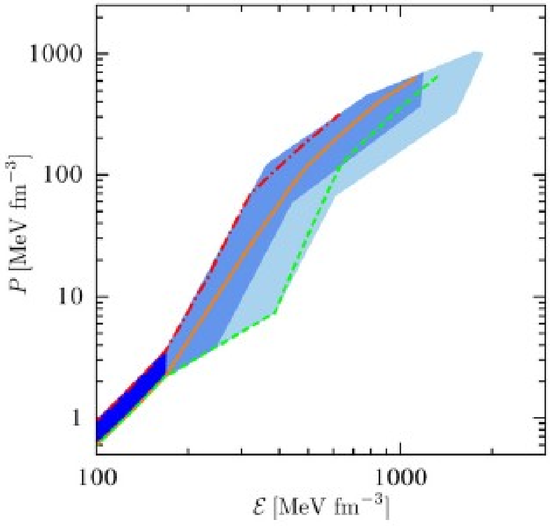
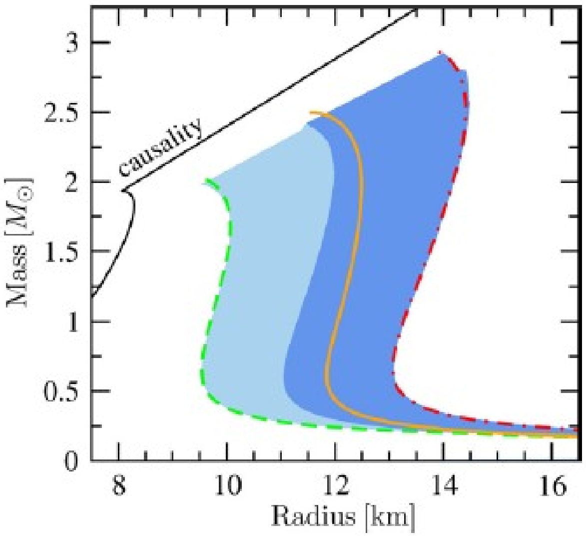


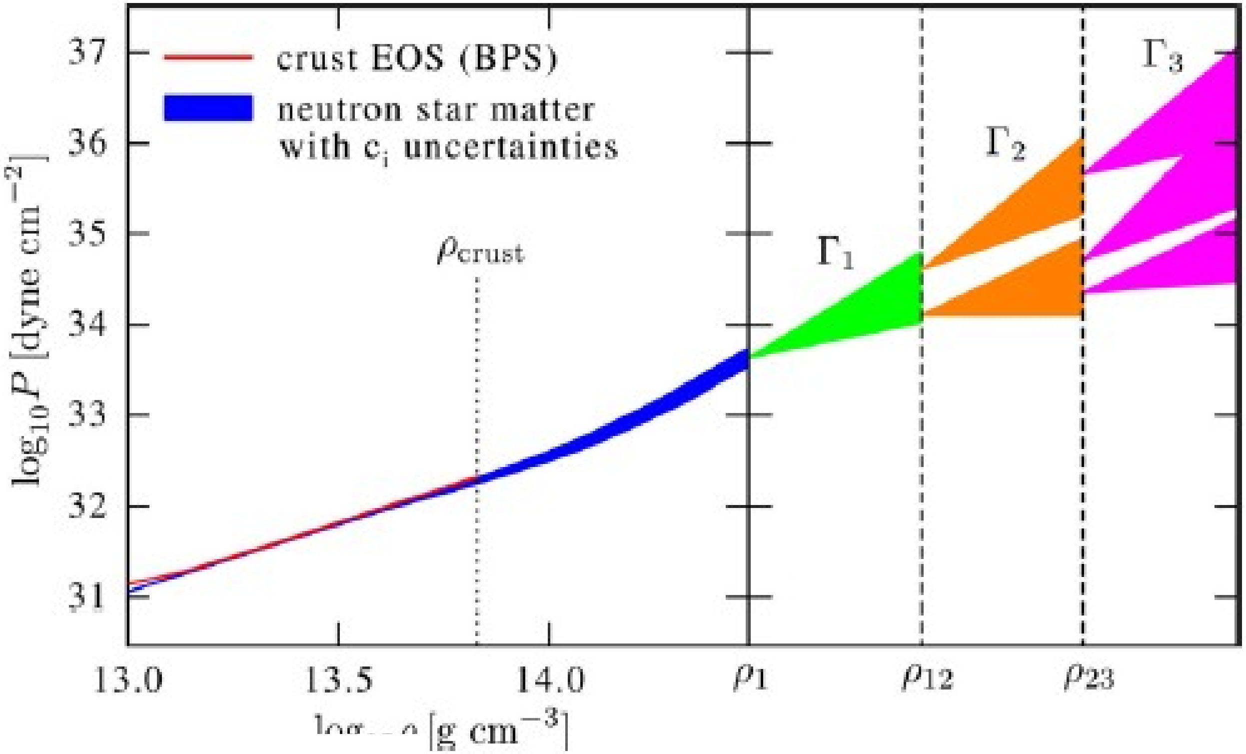






3. Piecewise polytrope EoS – high mass twins?

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



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

$$i = 1 \;:\; n_1 \leq n \leq n_{12}$$
$$i = 2 \;:\; n_{12} \leq n \leq n_{23}$$
$$i = 3 \;:\; n \geq n_{23} \;,$$

Here, 1st order PT in region 2:

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

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

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

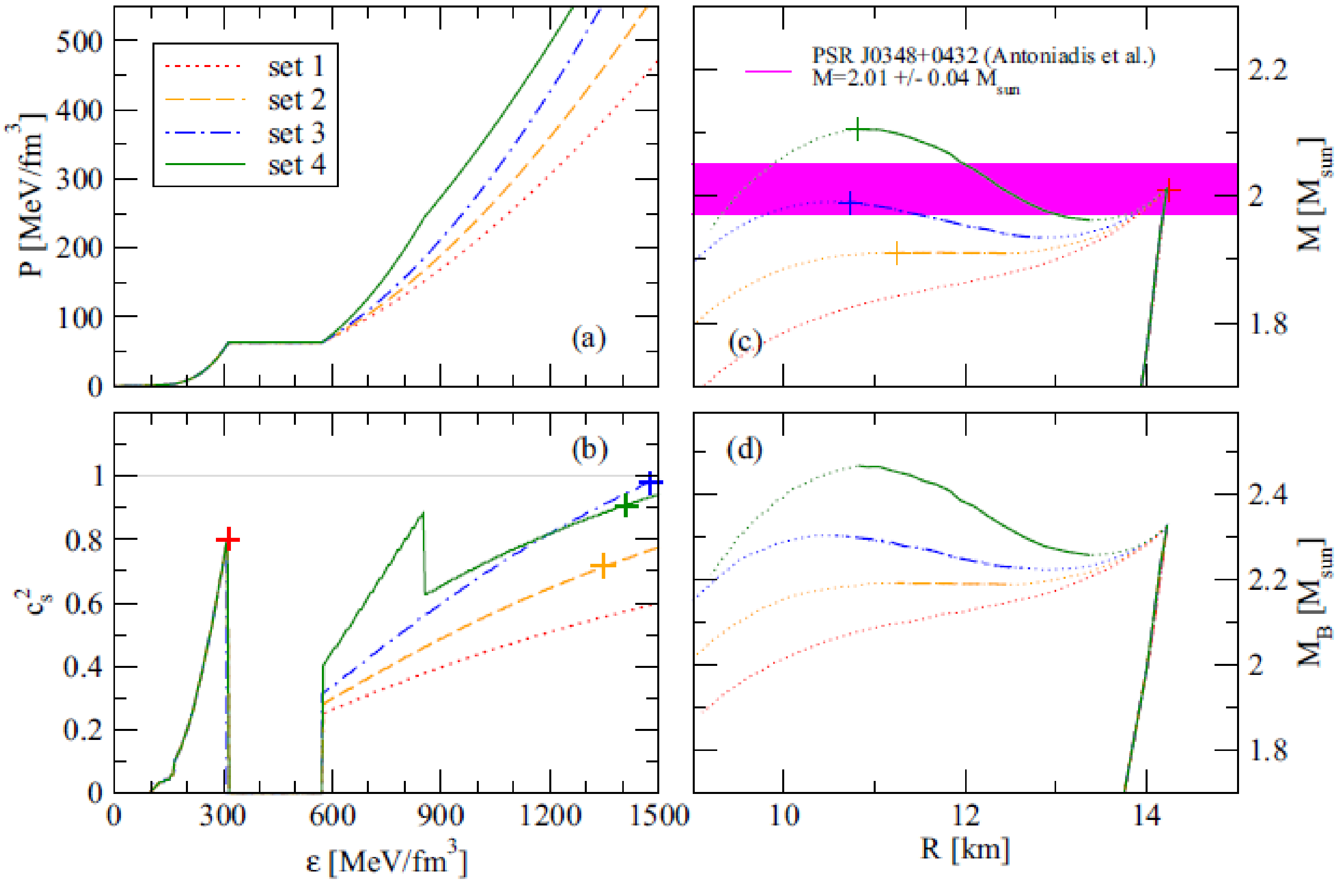
Maxwell construction:

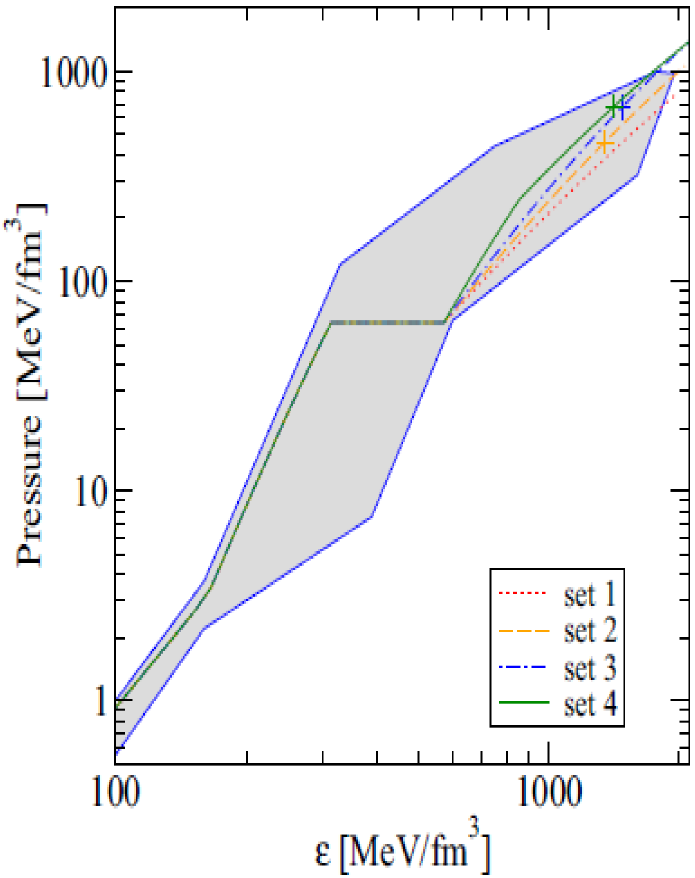
$$P_1(\mu_{\rm crit}) \;=\; P_3(\mu_{\rm crit}) = P_{\rm crit}$$
$$\mu_{\rm crit} \;=\; \mu_1(n_{12}) = \mu_3(n_{23})$$

Seidov criterion for instability:

$$\frac{\Delta\varepsilon}{\varepsilon_{\rm crit}} \geq \frac{1}{2} + \frac{3}{3}\frac{P_{\rm crit}}{\varepsilon_{\rm crit}}$$

3. Piecewise polytrope EoS – high mass twins?





	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.!

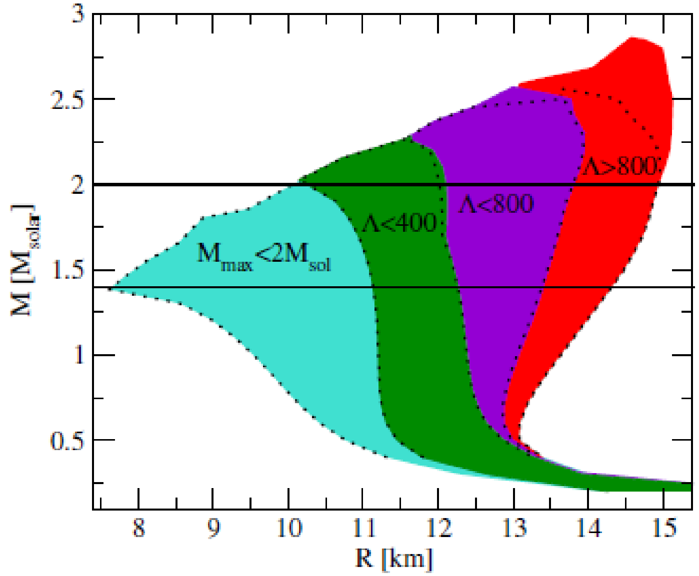
[D. Alvarez & D.B. PRC 96 (2017) 045809]

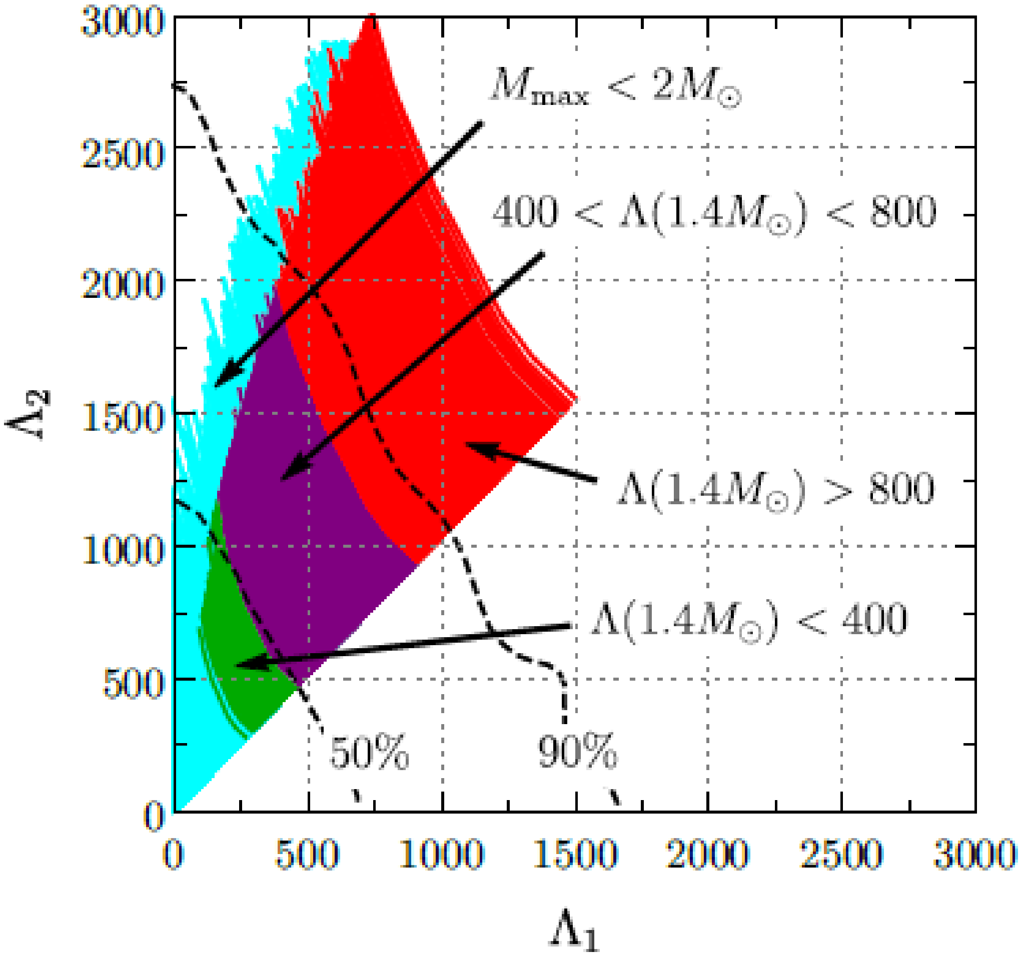
arxiv:1711.02644 [astro-ph.HE]

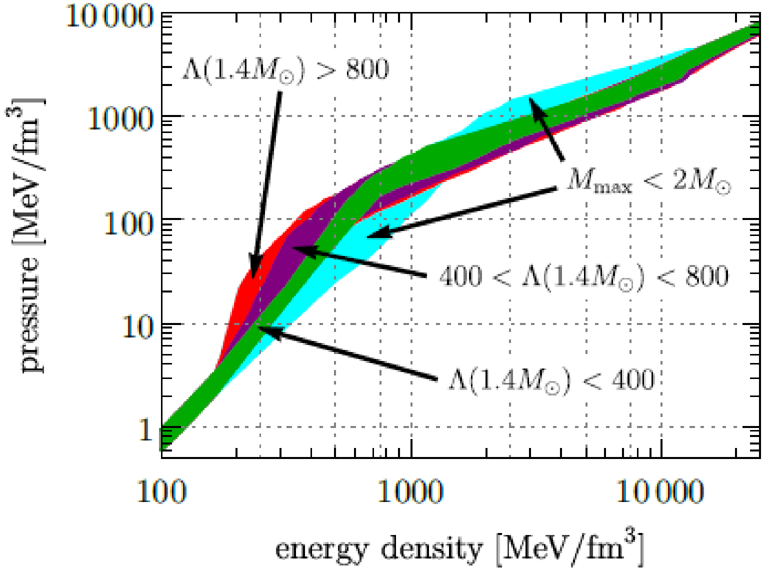
CERN-TH-2017-236, HIP-2017-30/TH

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

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





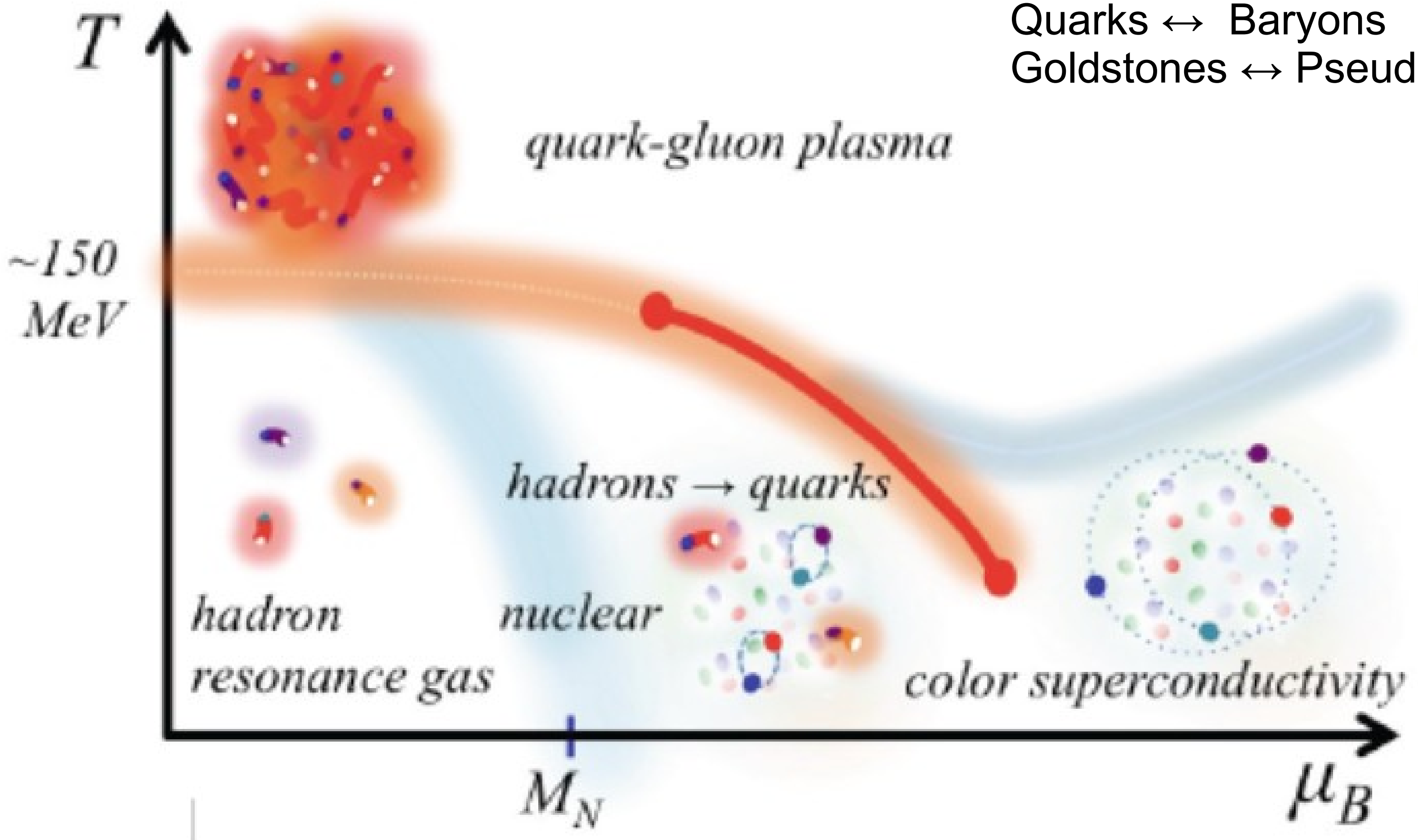


Unfortunately, twins and third family forgotten !!!
For this aim, 2- and 3-tropes not sufficient, 4-tropes!

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

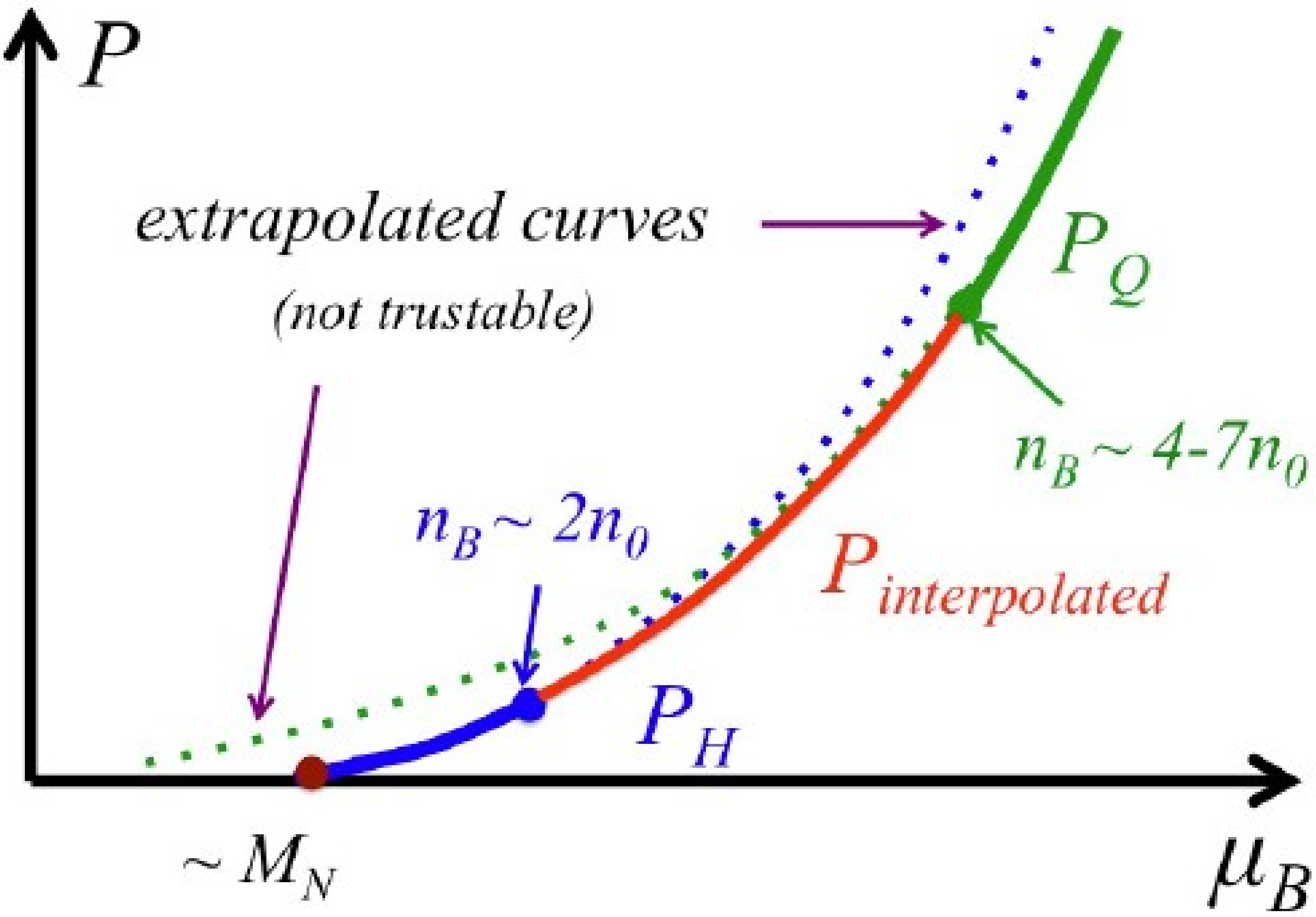
2^{nd} CEP in QCD phase diagram: Quark-Hadron Continuity?

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

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??

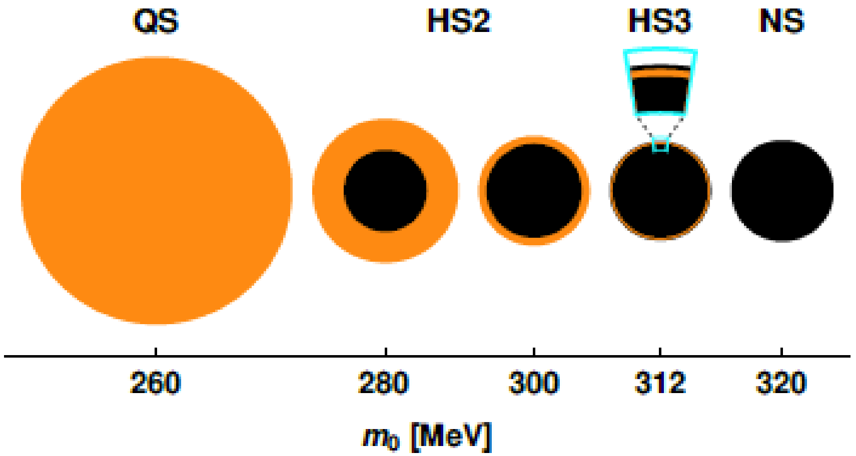
No!!

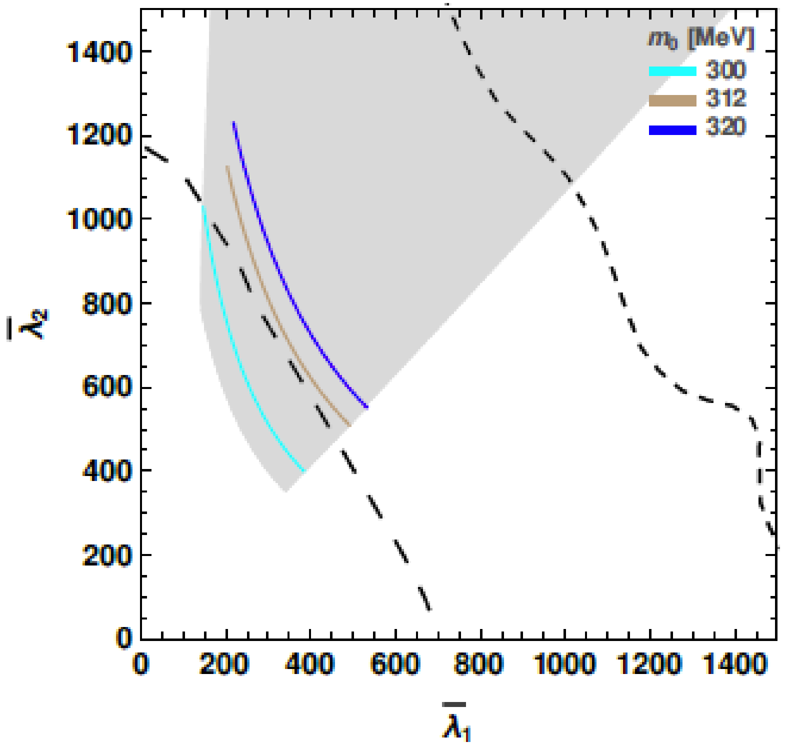
Alternative facts: New hybrid star solutions!

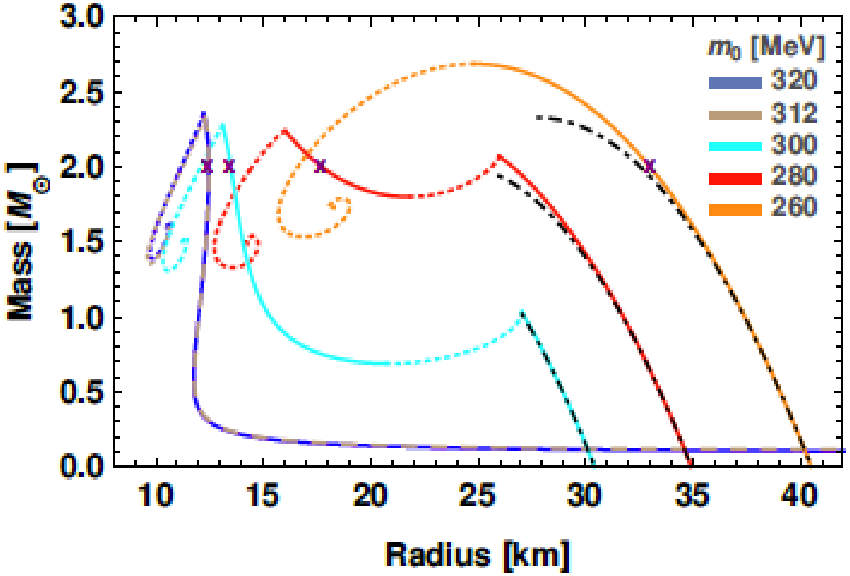
arxiv:1711.06244v1, 1611.2017

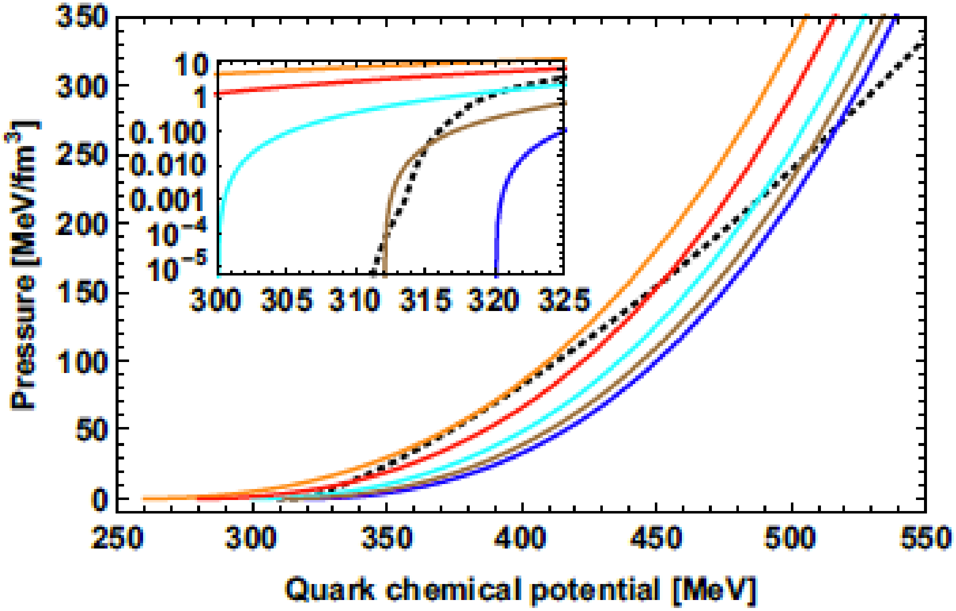
Holographic compact stars meet gravitational wave constraints

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!

arxiv:1711.06244v1, 1611.2017

Holographic compact stars meet gravitational wave constraints

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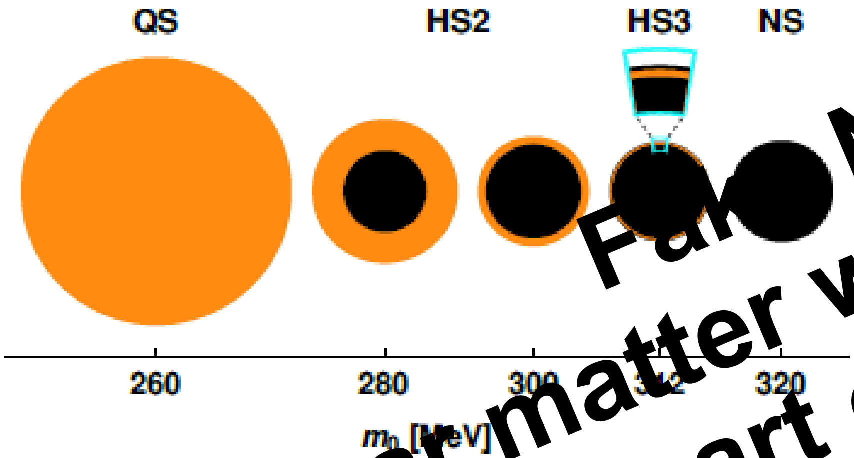
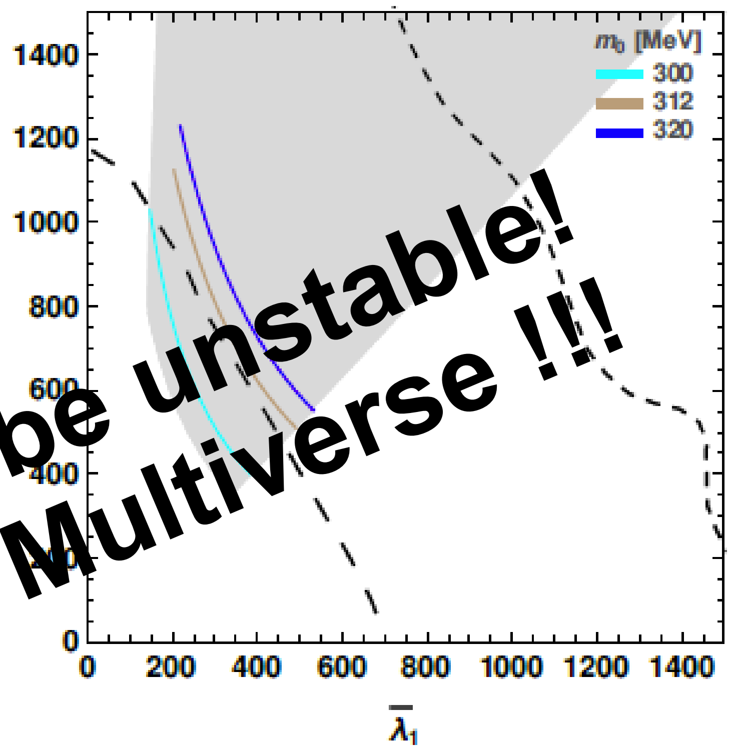
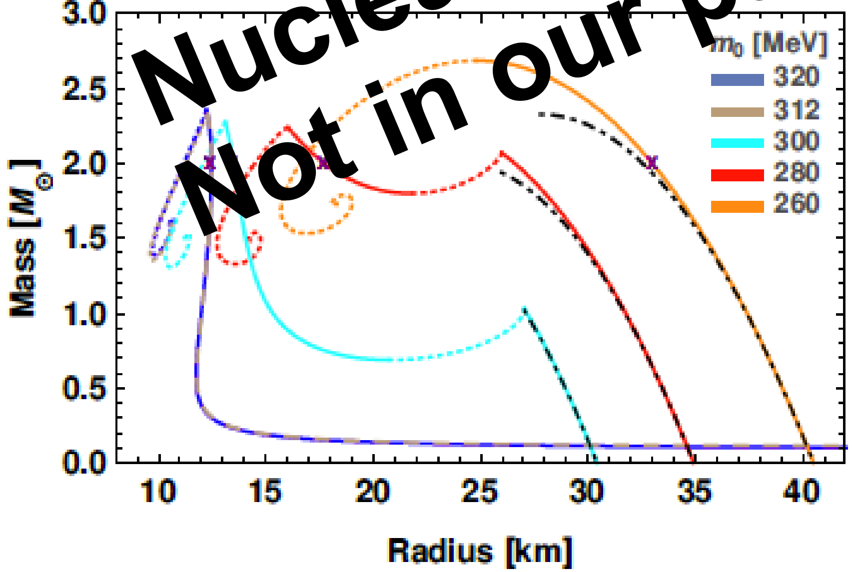


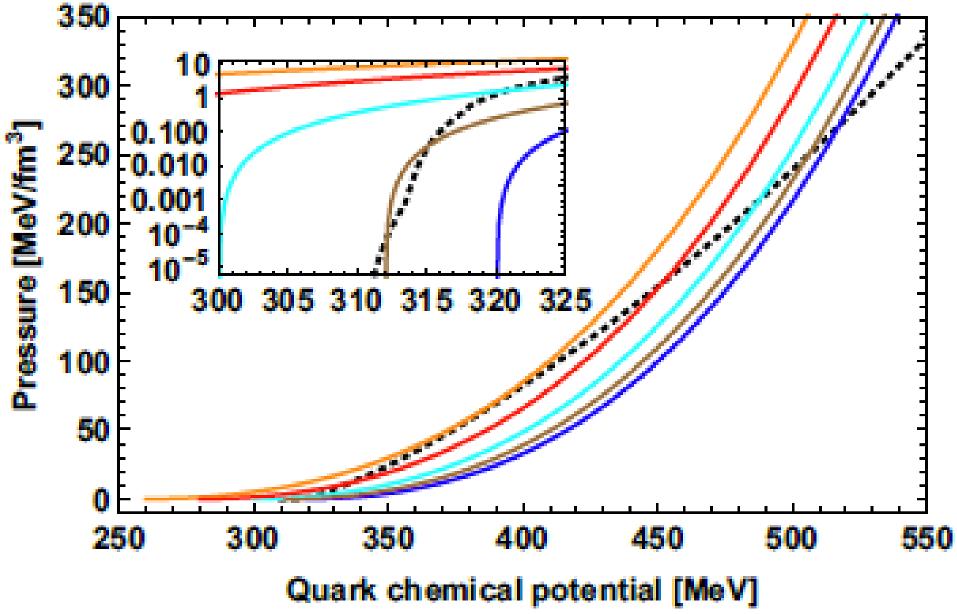


Fake News:

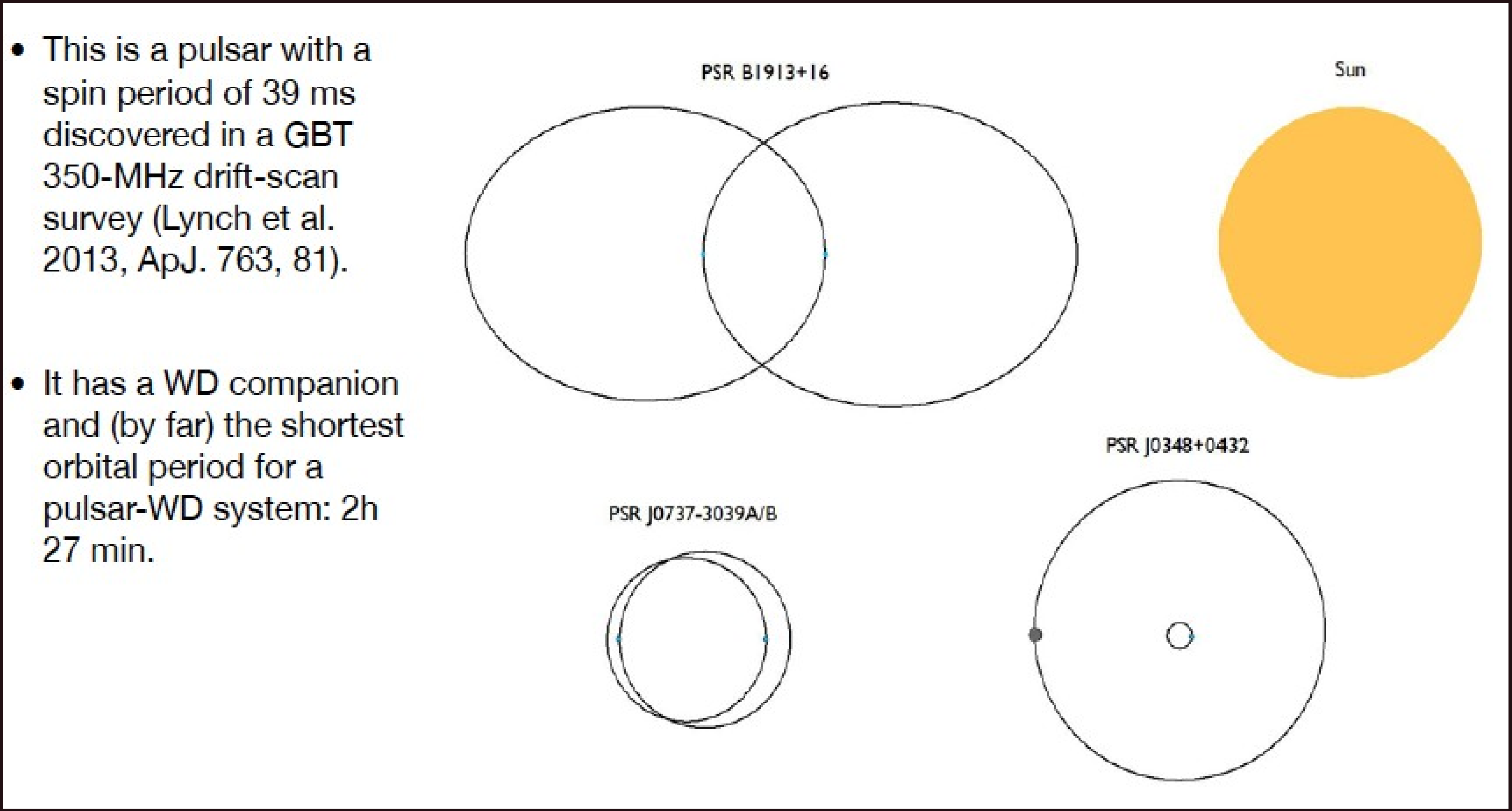
Nuclear matter would be unstable!

Not in our part of the Multiverse !!!





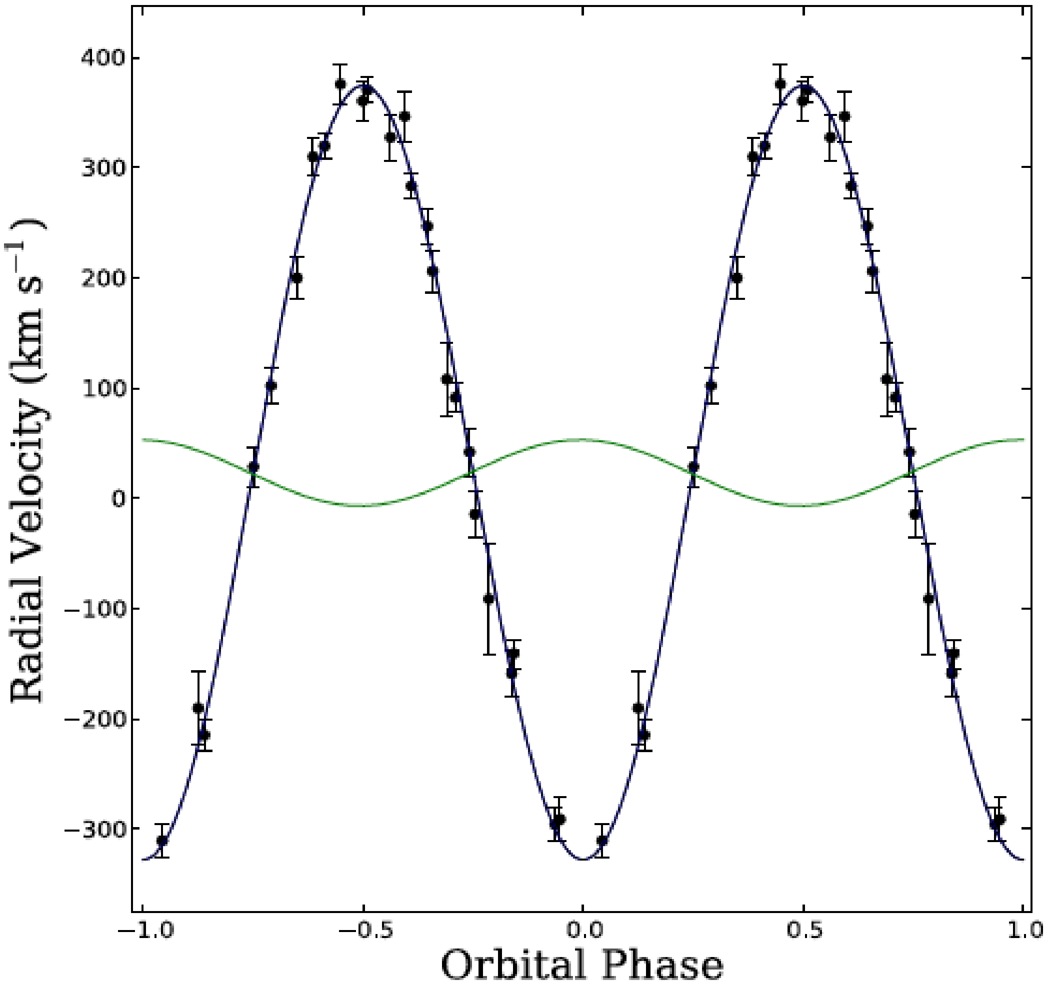
The big one: PSR J0348+0432



- 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)

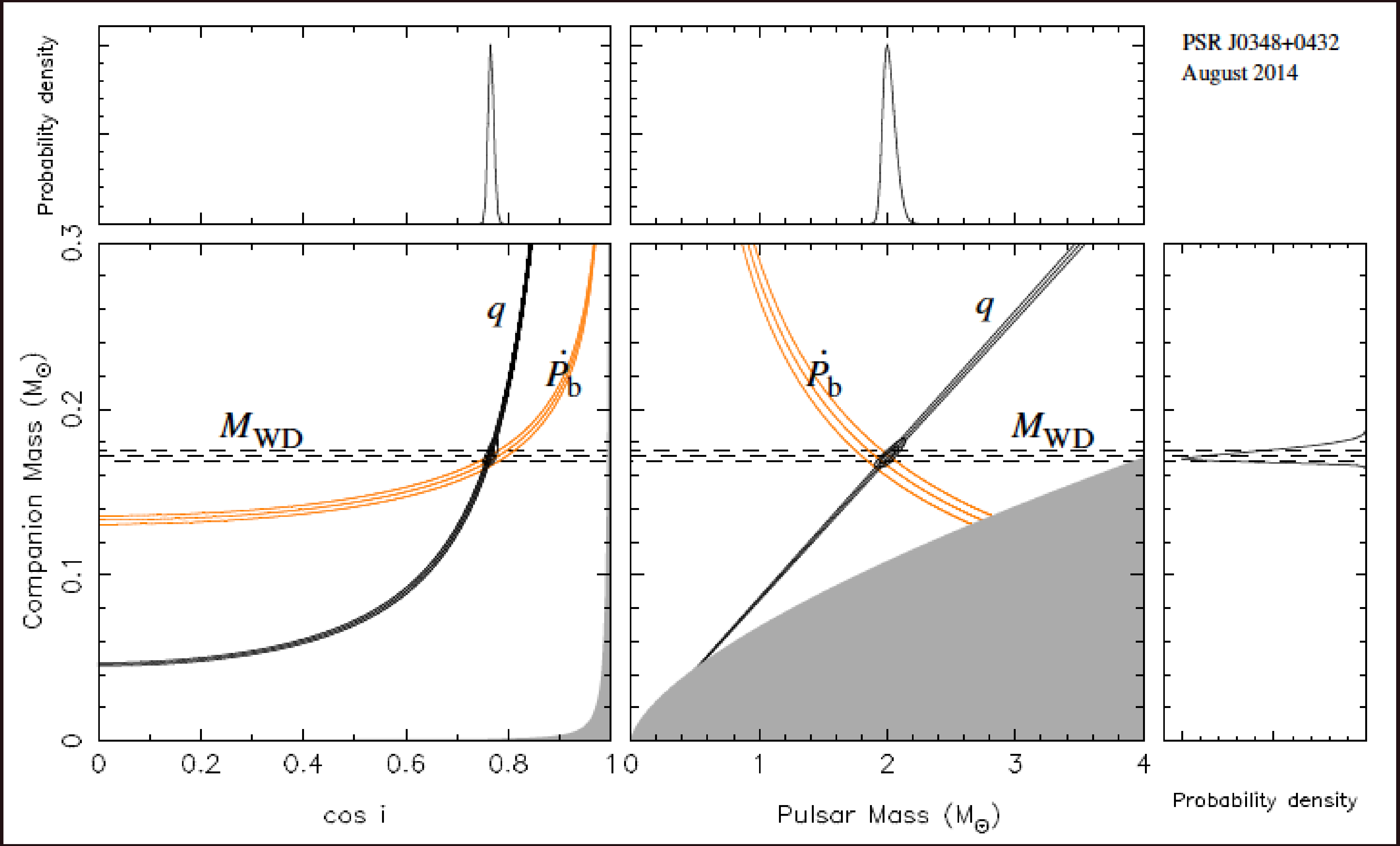
PSR J0348+0432



- 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)