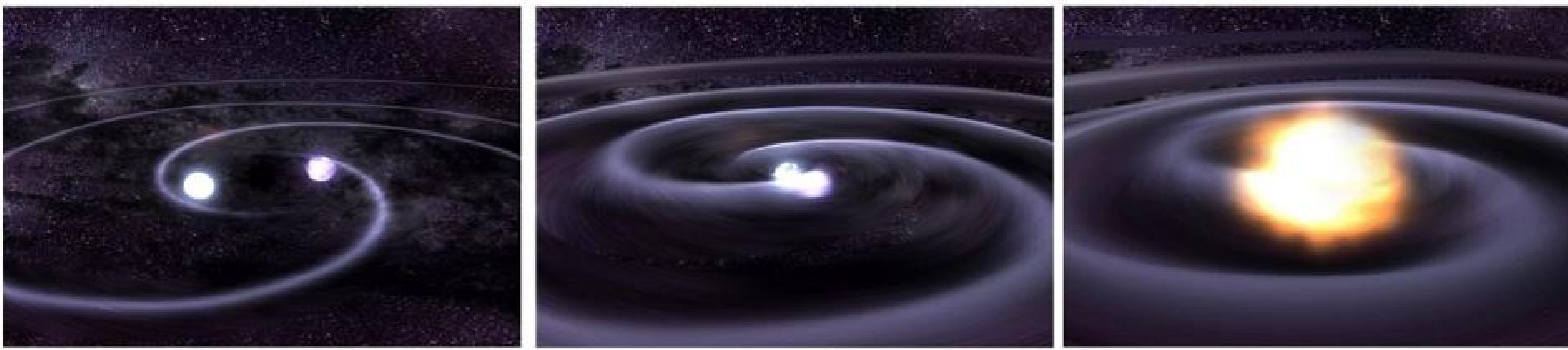
Boiling QCD in supernova explosions and binary mergers

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



4th Int. Conf. on Particle Physics and Astrophysics, 26.10.2018

JINR DUBNA
MEPhI
Narodowe Centrum Nauki
COST European Cooperation in Science and Technology
Uniwersytet Wrocławski
RSF Russian Science Foundation

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1. **Mapping: EoS ↔ Compact star sequence M(R)**
2. **Modern M-R constraints**
3. **Standard example for hybrid EoS**
4. **Third family & deconfinement**
5. **Deconfinement as engine for massive supernova explosion**
6. **Signal for strong PT in post-merger gravitational waves**

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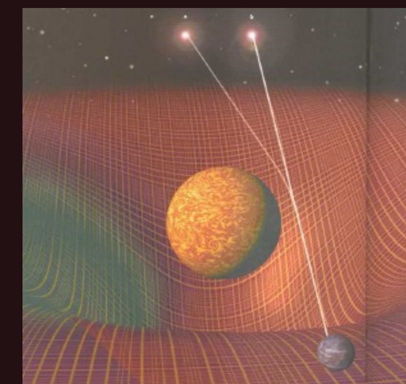
Compact stars and black holes in Einstein's General Relativity theory

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

Massive objects curve the Space-Time



Non-rotating, spherical masses → Schwarzschild Metrics

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

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

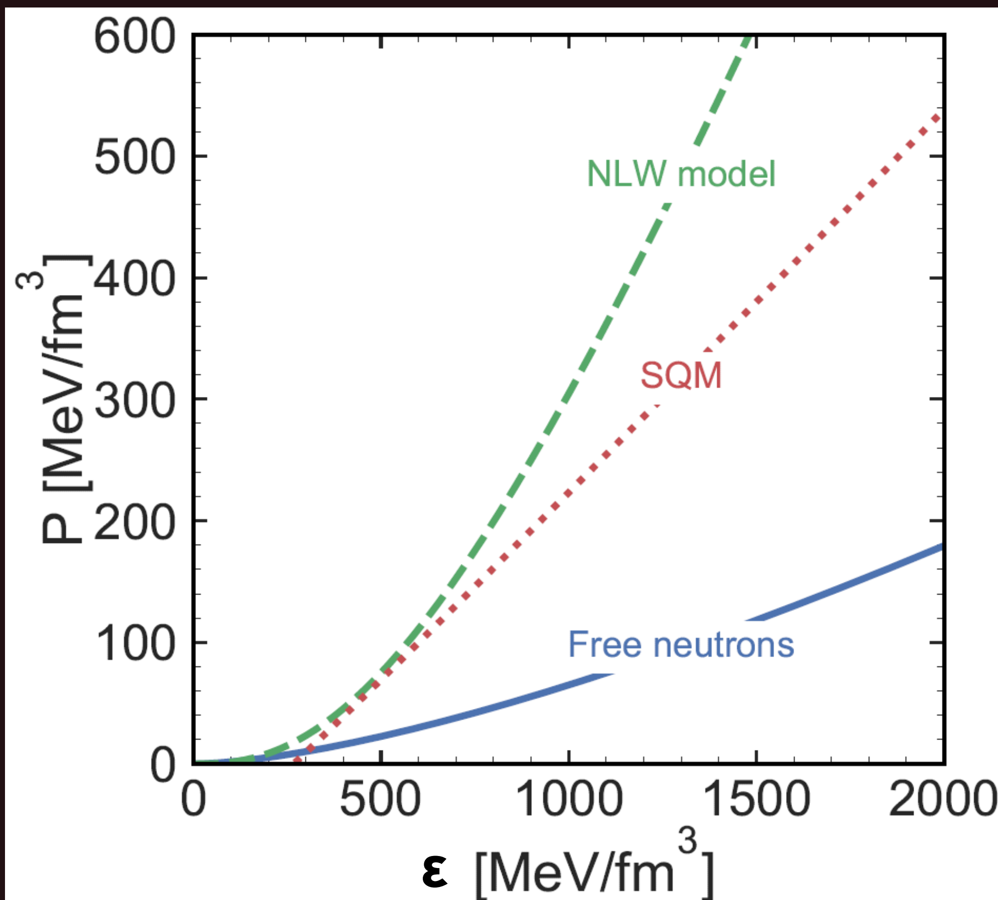
$$\frac{dP(r)}{dr} = -G\frac{m(r)\varepsilon(r)}{r^2} \left(1 + \frac{P(r)}{\varepsilon(r)}\right) \left(1 + \frac{4\pi r^3 P(r)}{m(r)}\right) \left(1 - \frac{2Gm(r)}{r}\right)^{-1}$$

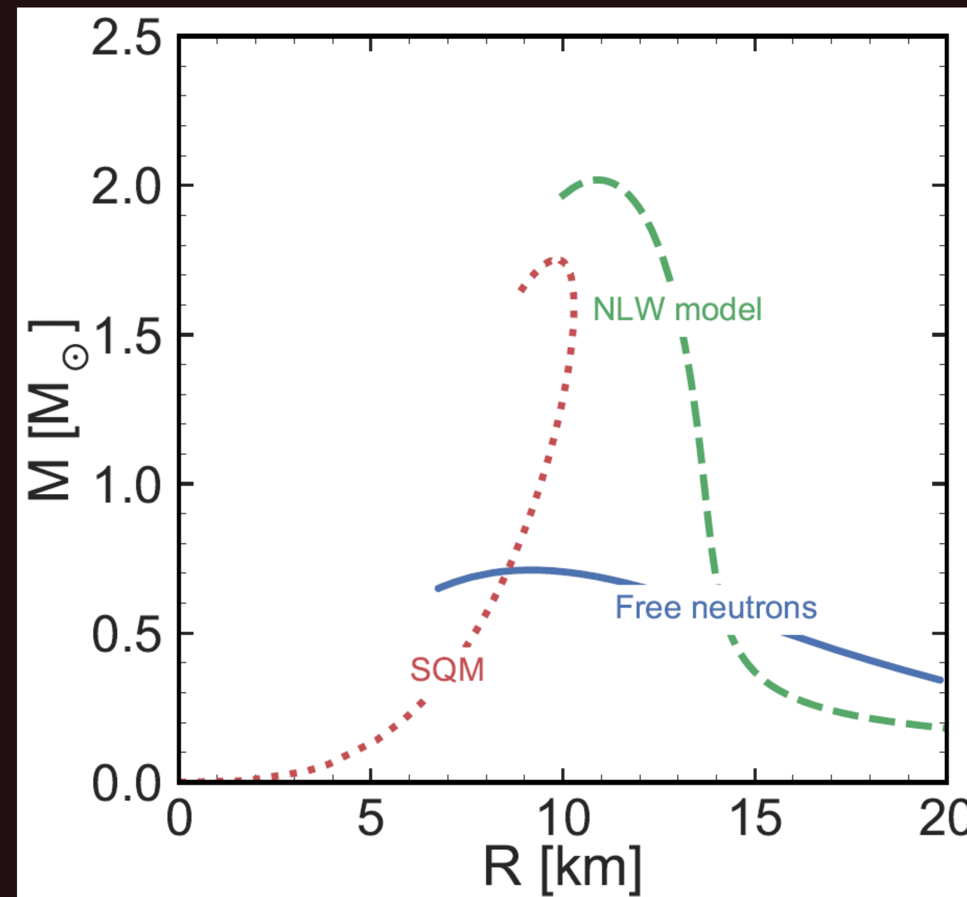
Newtonian case x GR corrections from EoS and metrics

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

The 1:1 relation P(ε) ↔ M(R) via TOV

Simple examples*)





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

*) courtesy: Konstantin Maslov

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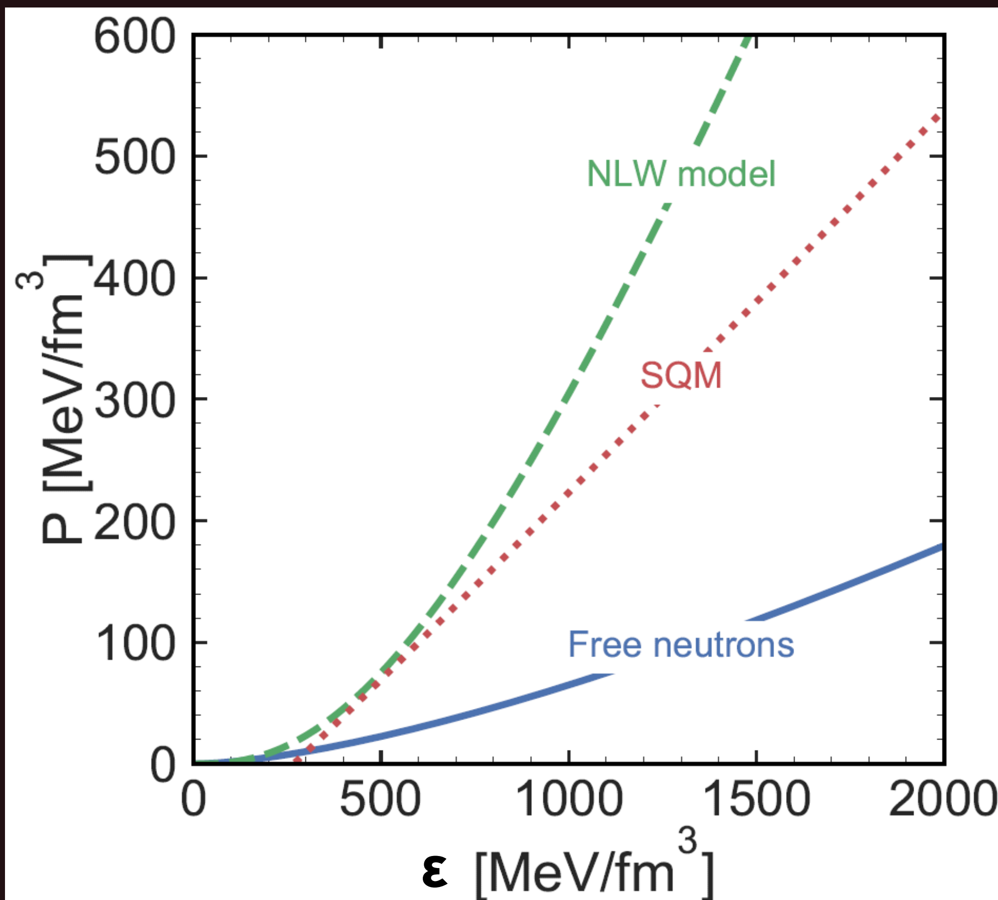

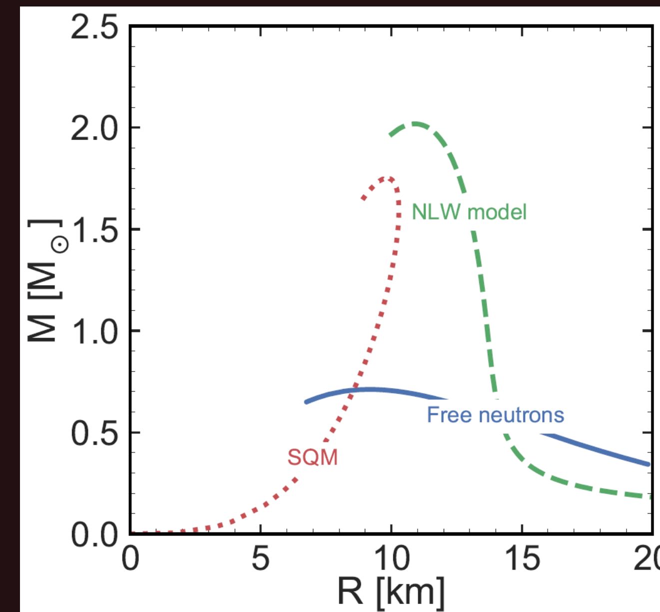

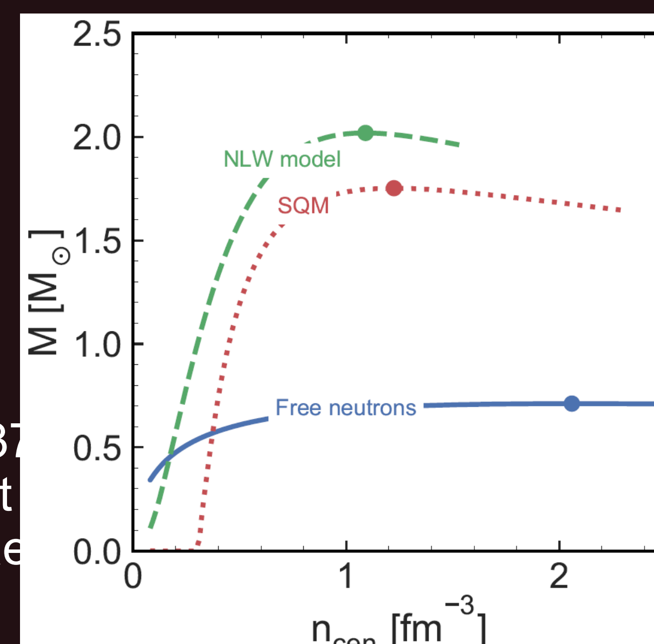

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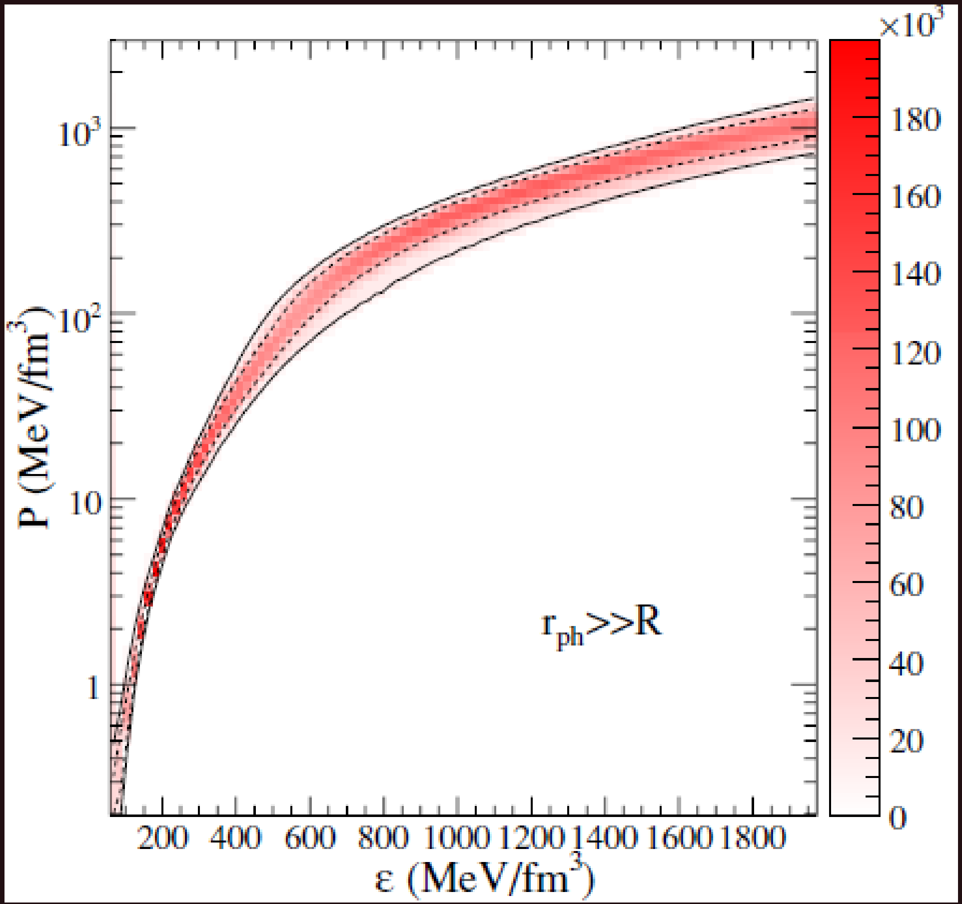
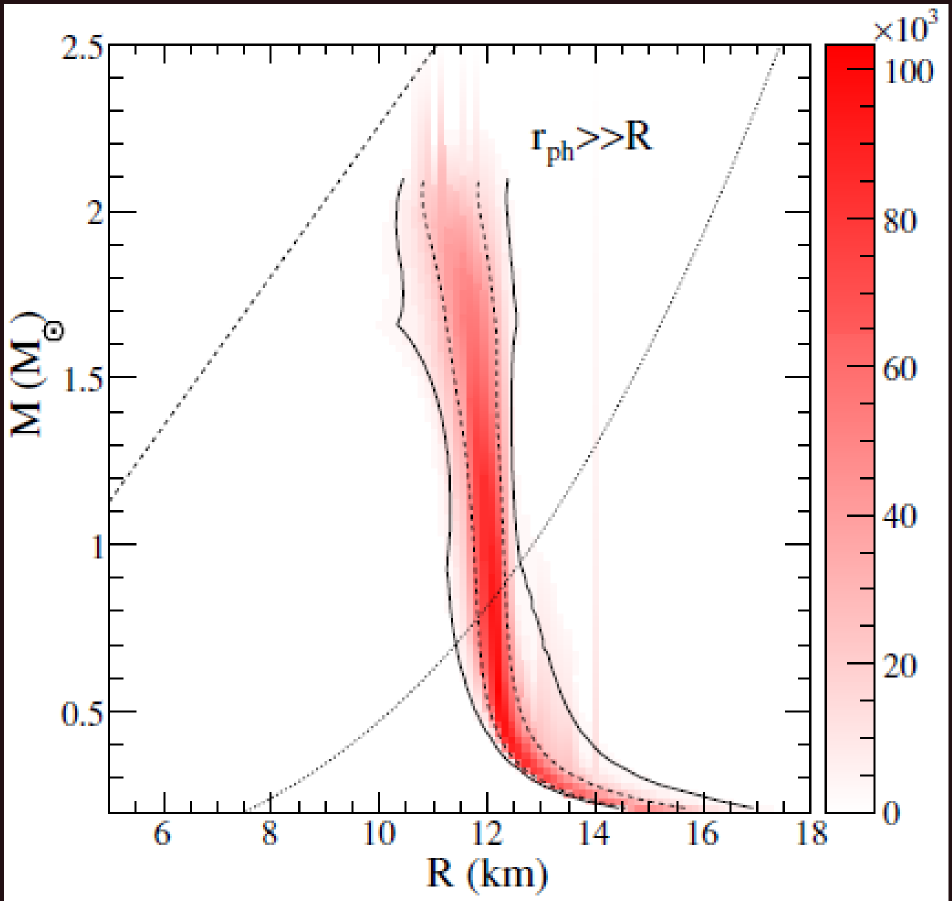
The 1:1 relation P(ε) ↔ M(R) via TOV

Equation of State from Mass and Radius observations *)





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

*) caution with radius measurements from burst sources

Neutron star mass measurements with binary radio pulsars

MSP with period P=3.15 ms

Pb = 8.68 d, e=0.00000130(4)

Inclination angle = 89.17(2) degrees !

Precise masses derived from Shapiro delay only:

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

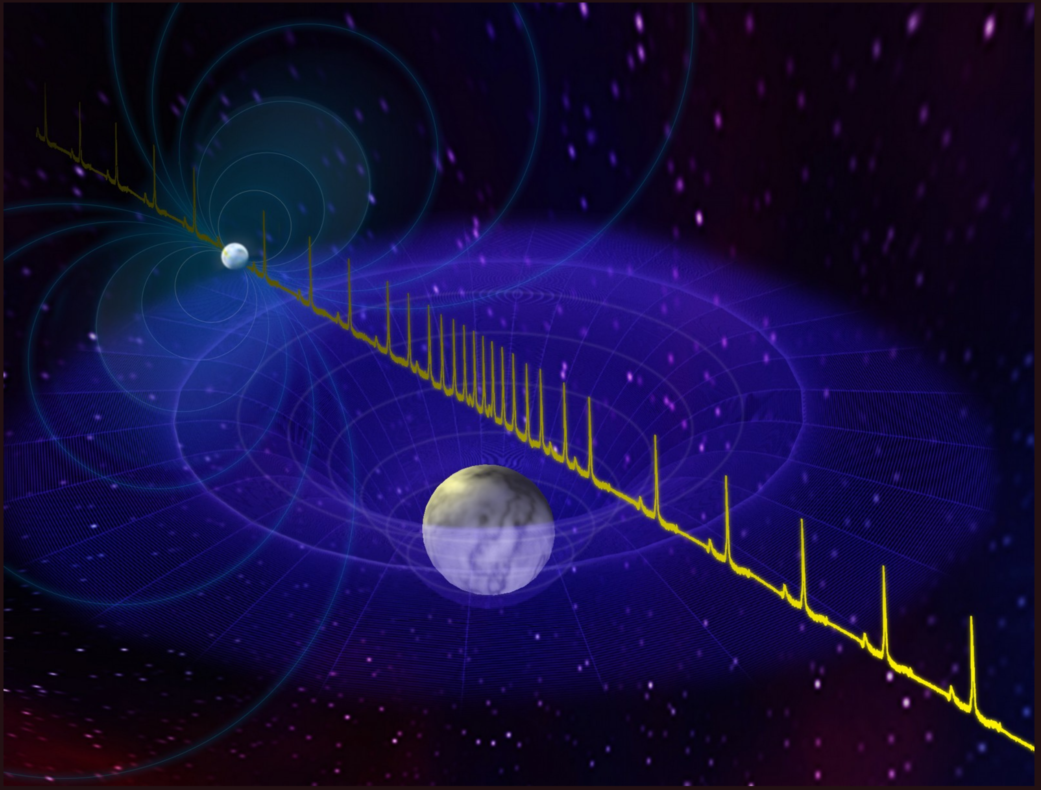
Update [Fonseca et al. (2016)]

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

Update [Arzoumanian et al. (2018)]

Mp = 1.908(16) Mo

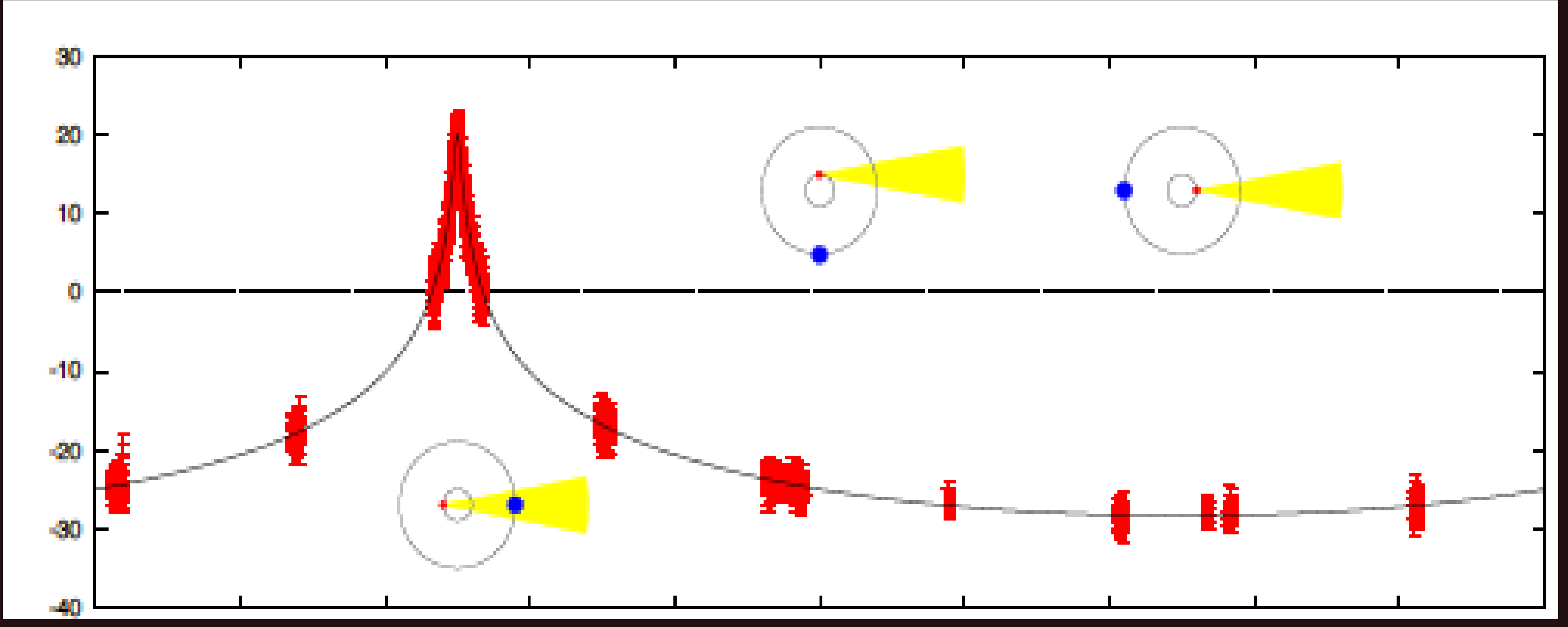
PSR J1614-2230
Demorest et al., Nature (2010)



PSR J1614-2230

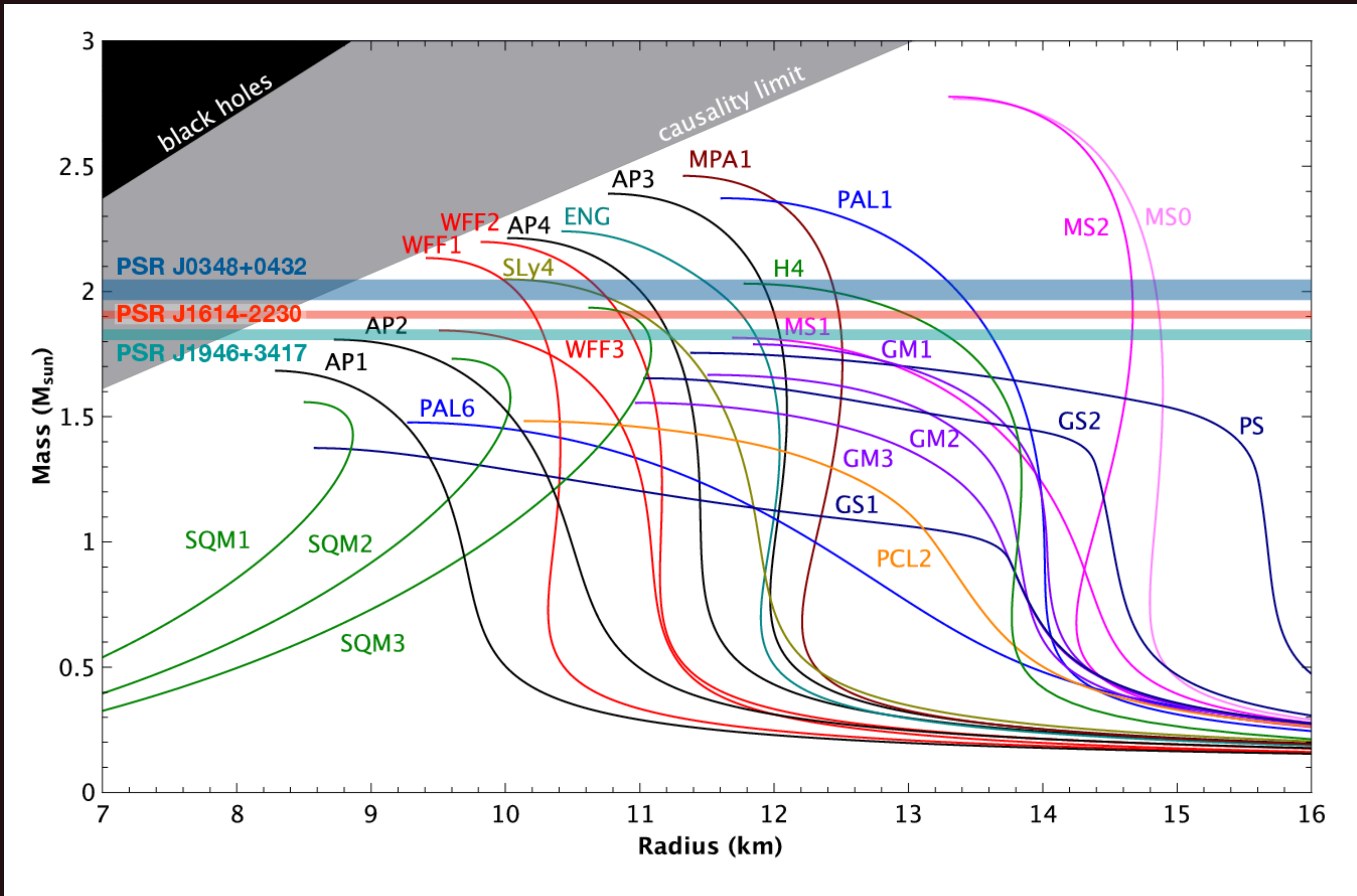
A precise AND large mass measurement

Shapiro delay:



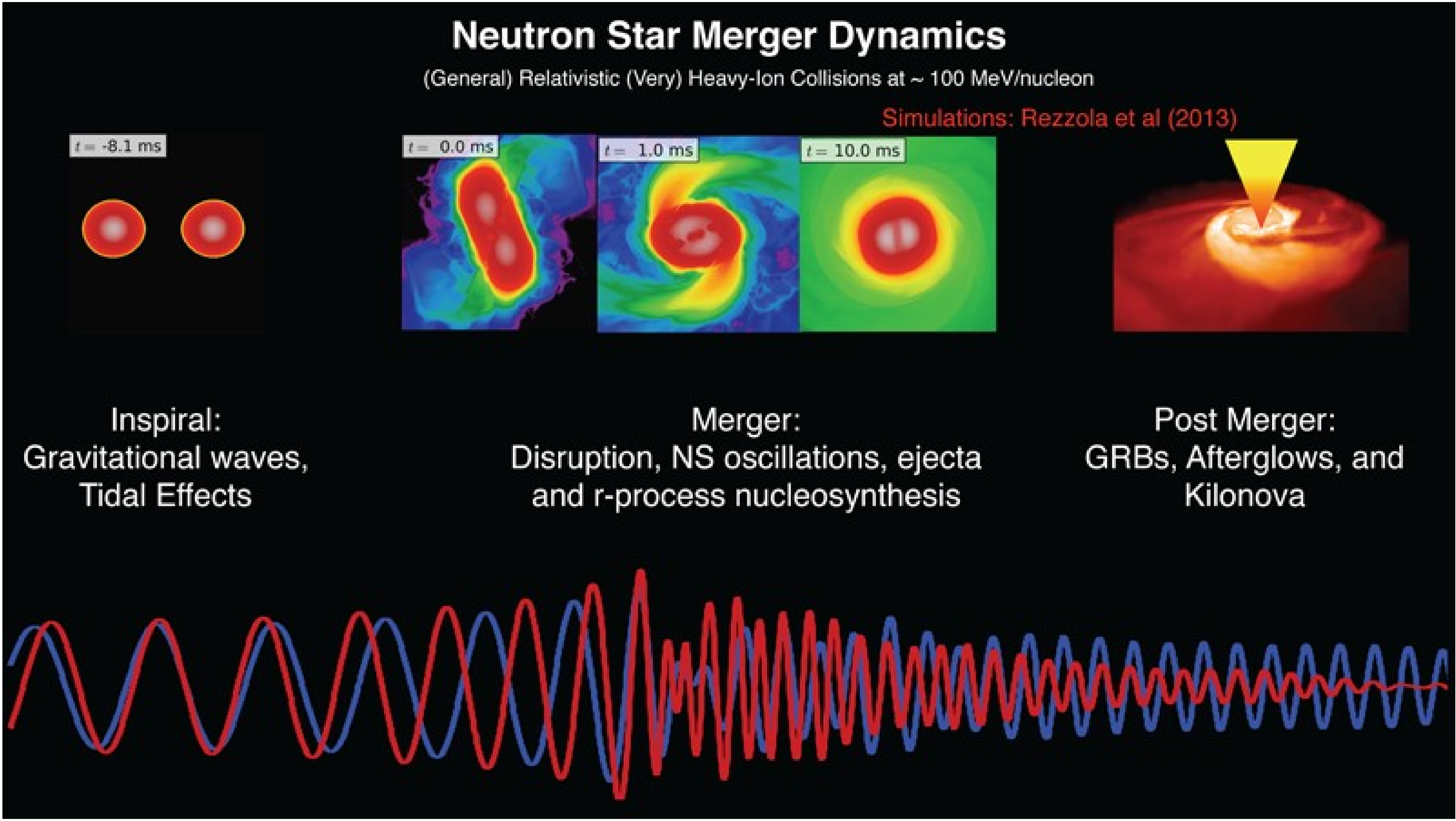
Demorest et al., Nature 467 (2010) 1081, arxiv:1010.5788

NS Masses and Radii ↔ EoS



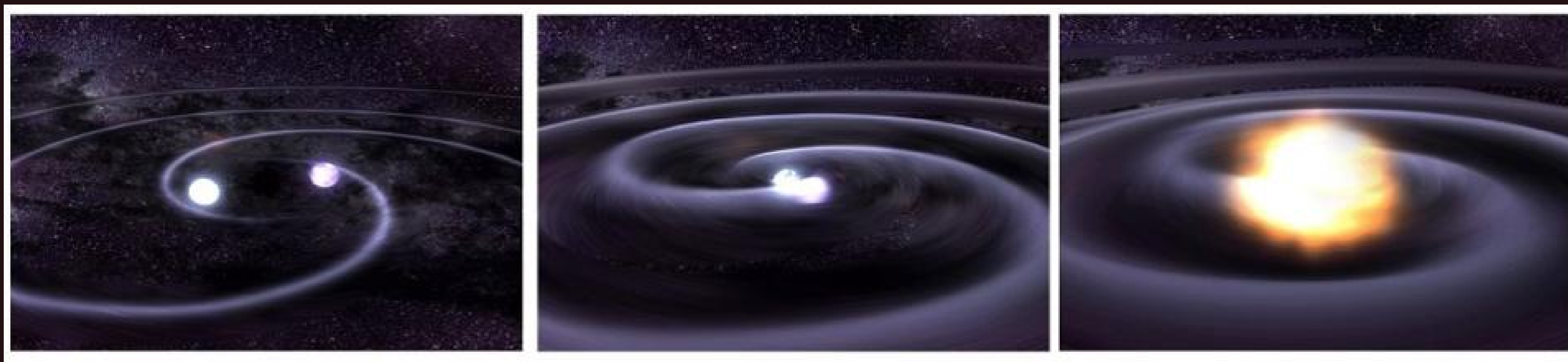
www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

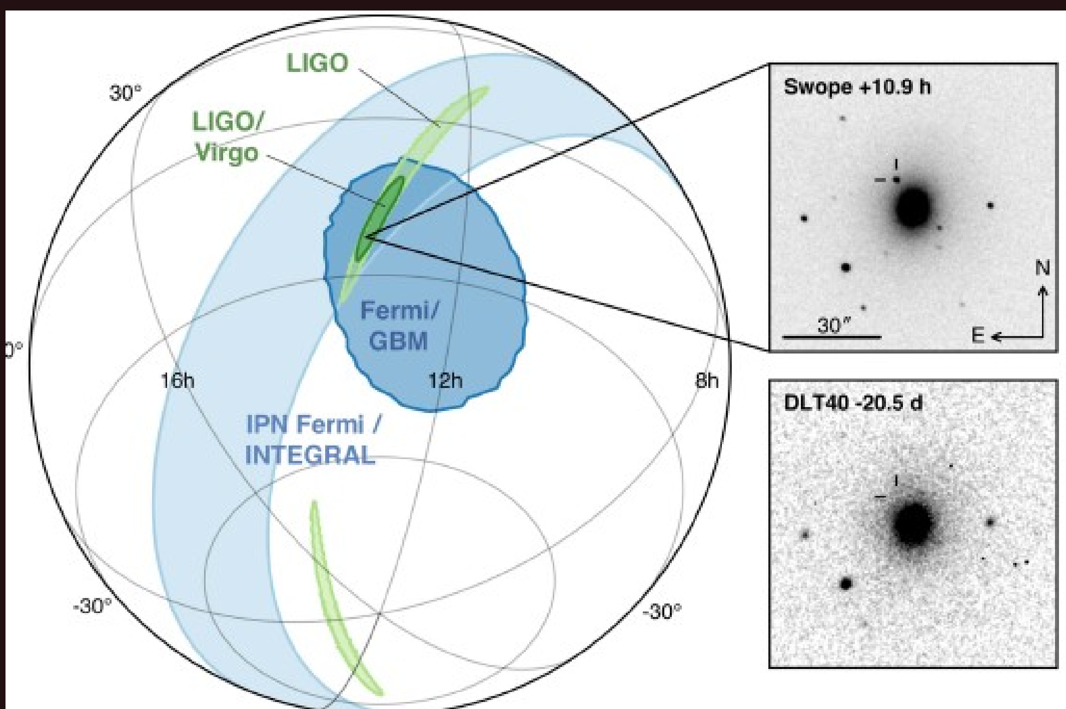
GW170817 – a merger of two compact stars

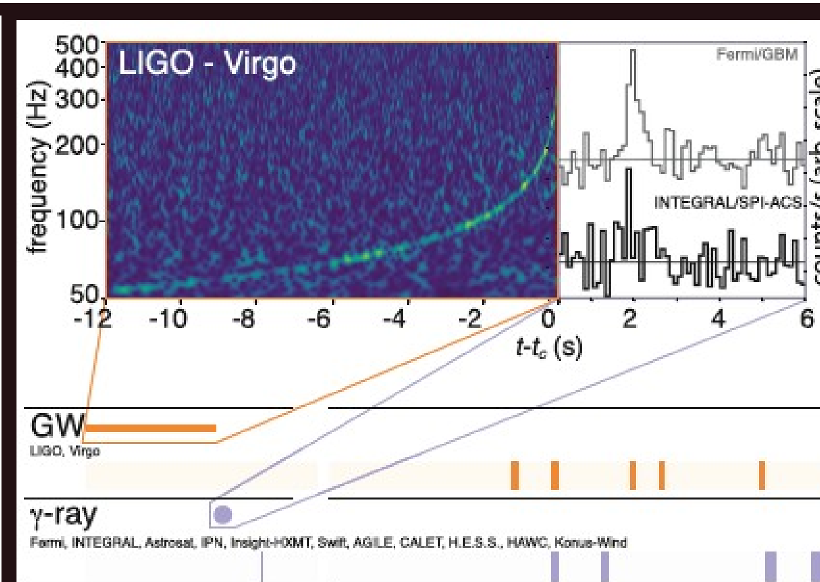


Symposium @ INT Seattle, March 2018

Discovery: neutron star merger !







GW170817A , announced 16.10.2017 *)

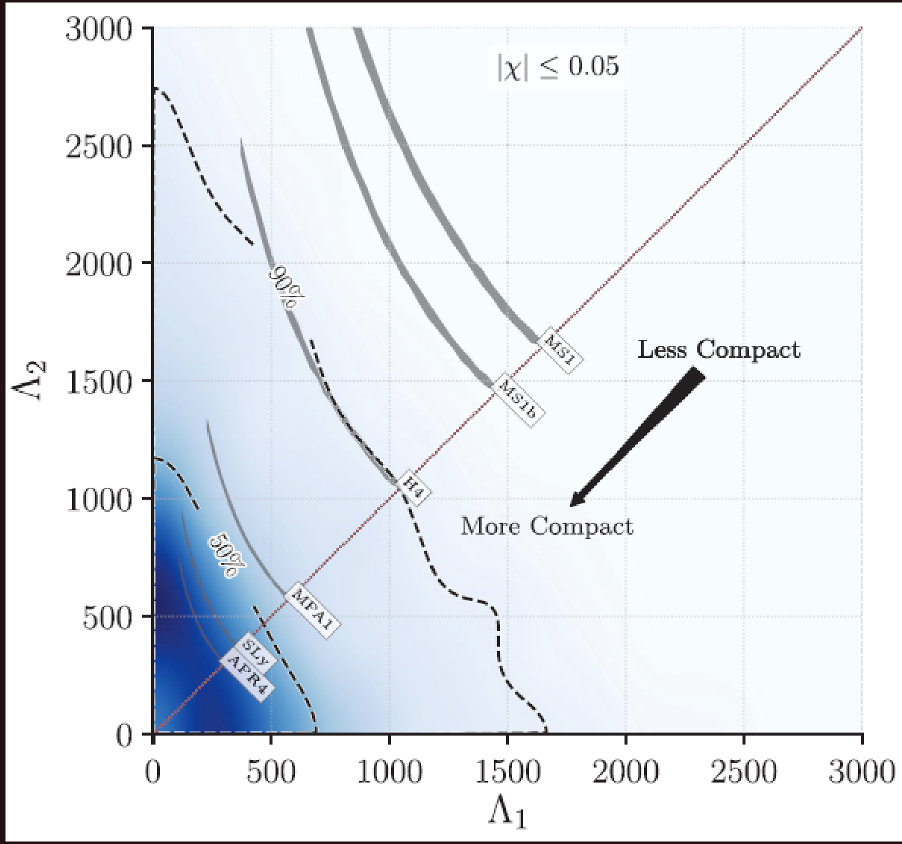
*) B.P. Abbott et al. [LIGO/Virgo Collab.], PRL 119, 161101 (2017); ApJLett 848, L12 (2017)

NS-NS merger !

GW170817A , announced 16.10.2017 *)

Multi-Messenger Astrophysics !!

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



Constraint on parameter (Λ<800)

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

Constraint on neutron star maximum mass

M_{TOV} < 2.17 M_sun

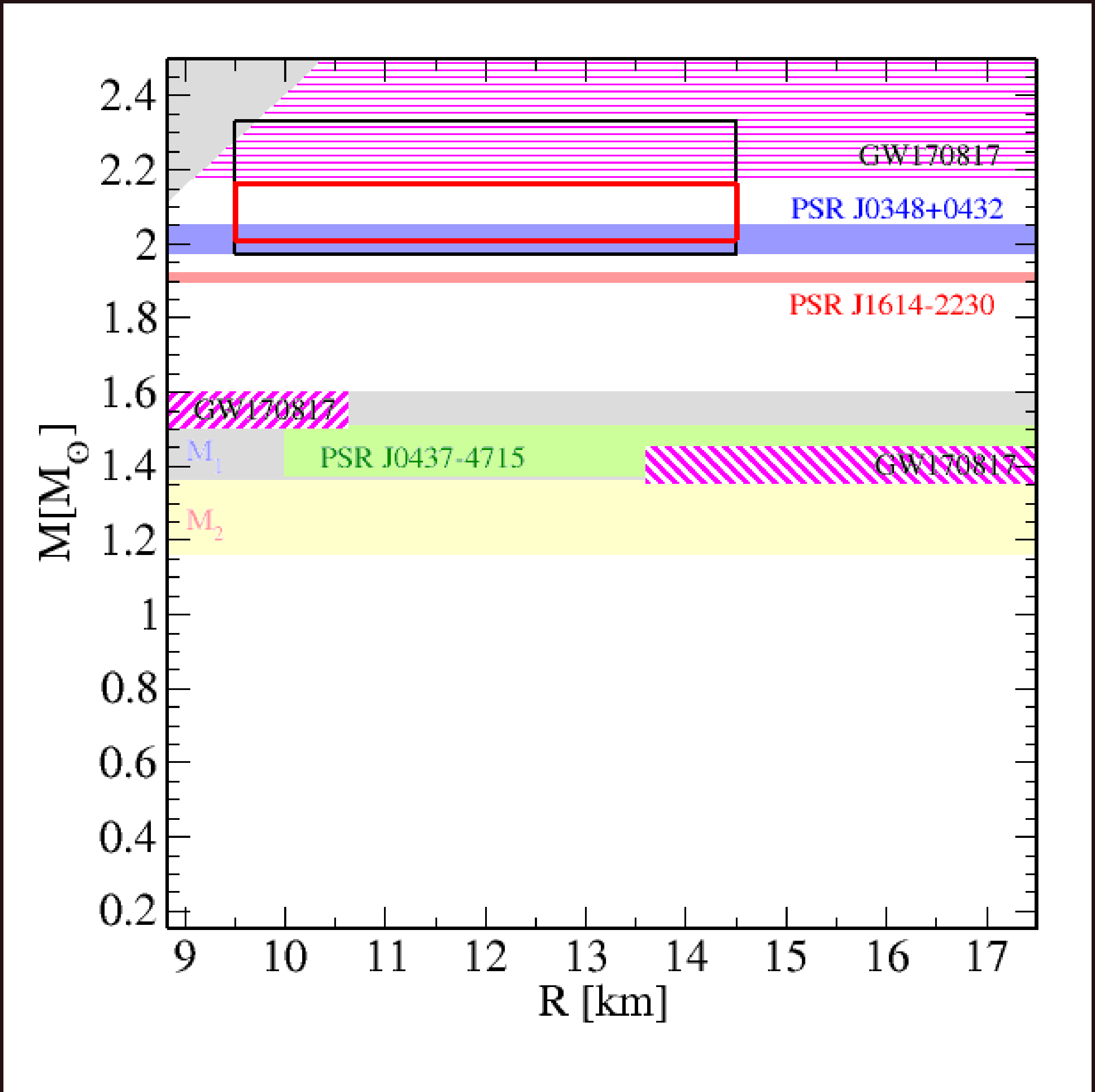
(Margalit & Metzger, arxiv:1710.05938)

Dimensionless tidal deformability

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

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

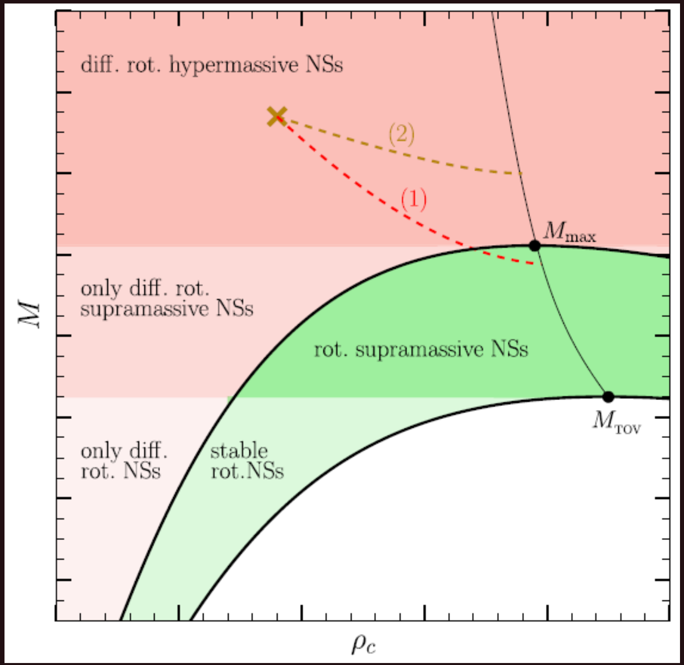
Constraints on NS mass and radii !



Constraint on maximum mass

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

(Rezzolla et al., arxiv:1710.05938)



Constraint on minimal radius

$R_{1.6} > 10.68$ km

(Bauswein et al., arxiv:1710.06843)

Constraint on maximal radius

$R_{1.4} < 13.6$ km

(Annala et al., arxiv:1711.02644)

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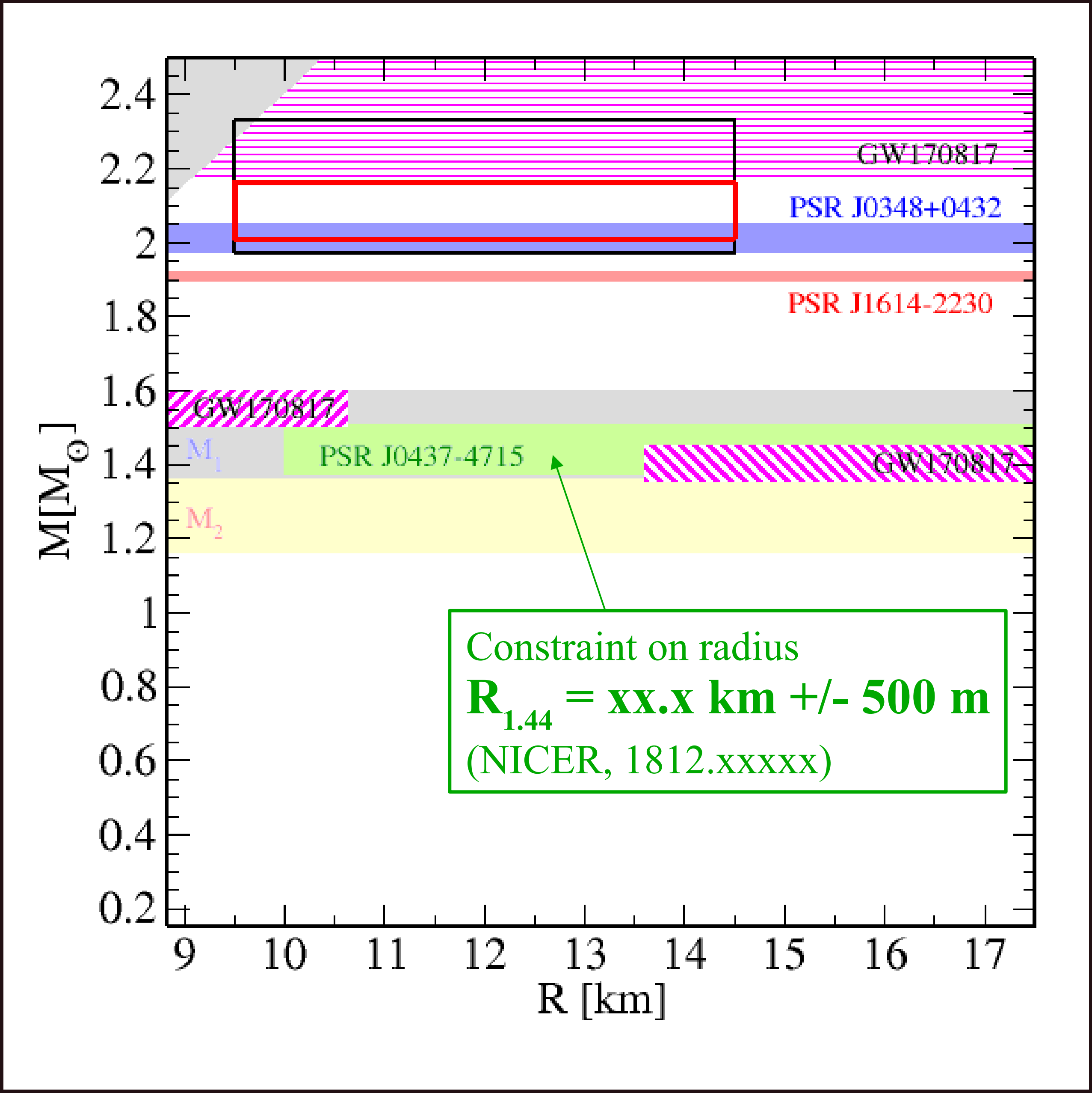

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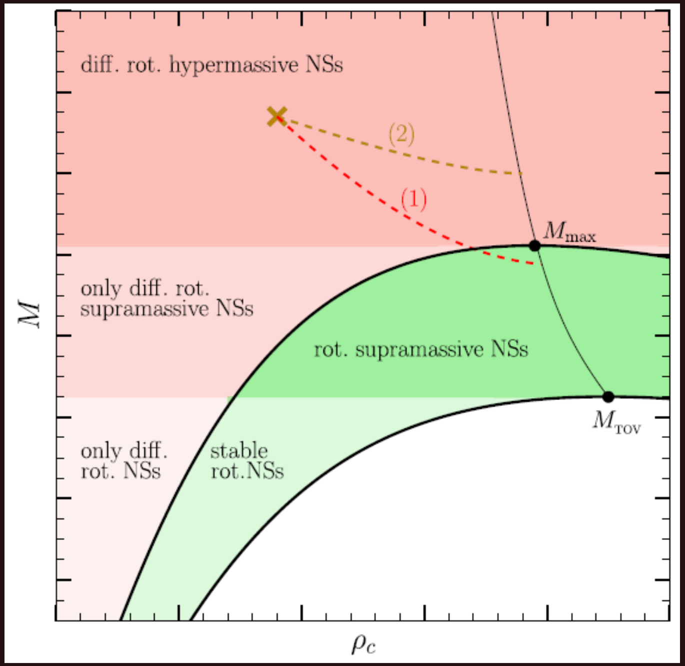

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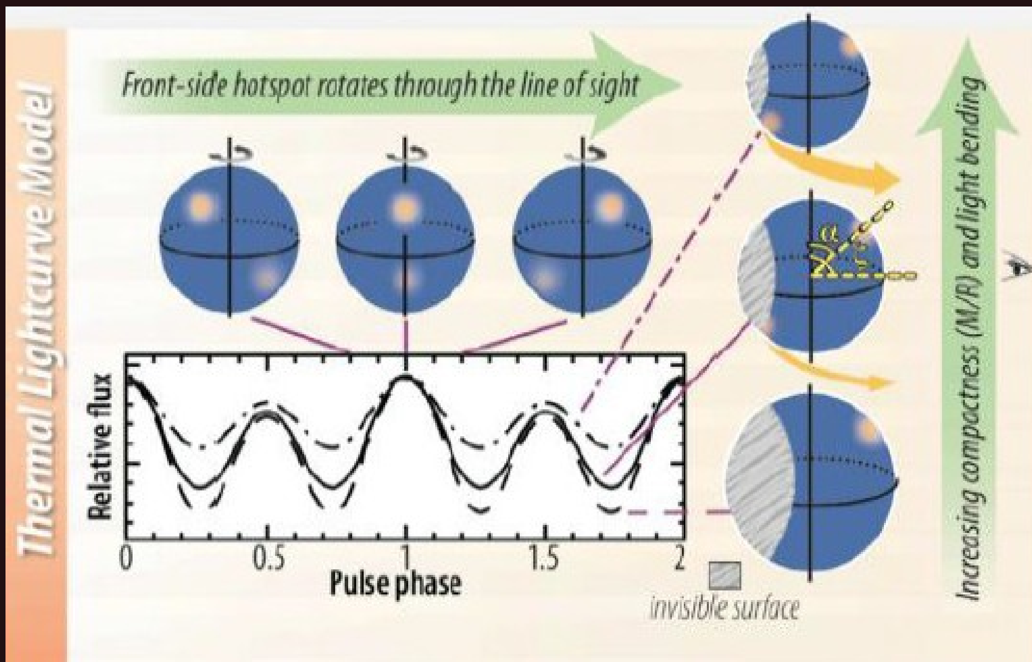
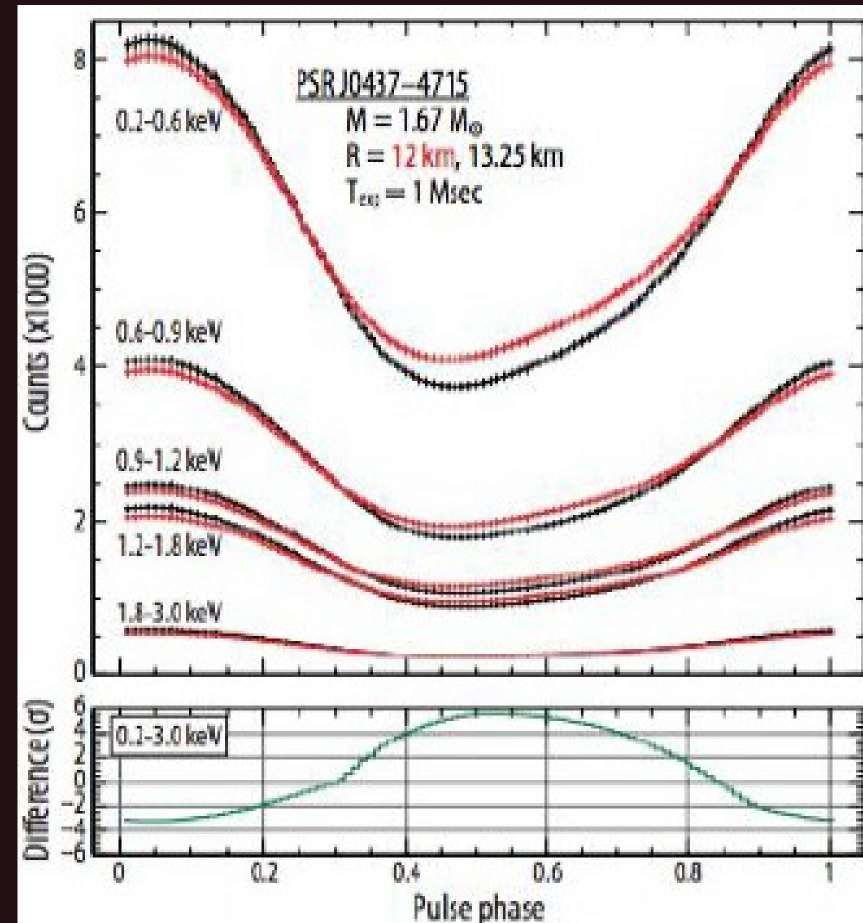
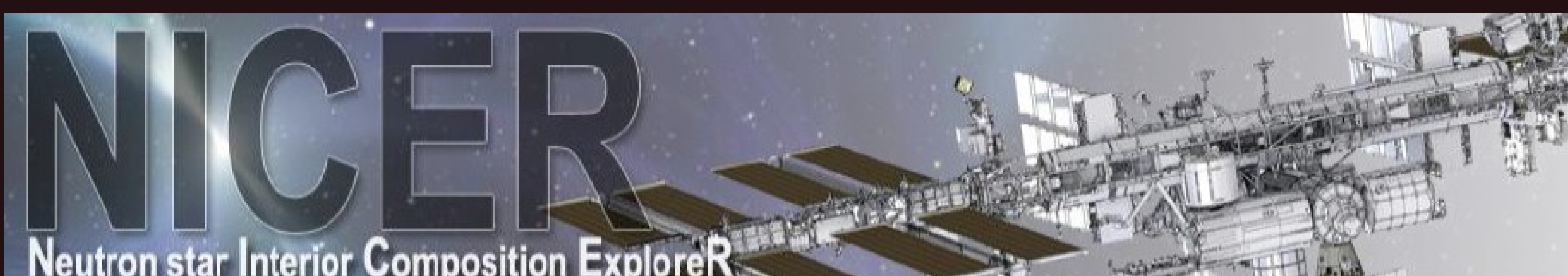
Measure NS Radii ...



Thermal lightcurves: NS with “hot spots”





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

GW170817: NS-NS Merger – Equation of State Constraints

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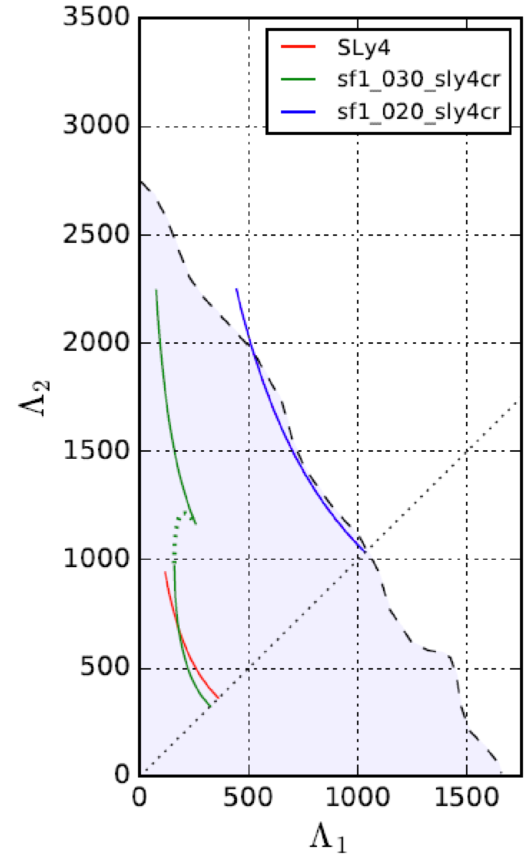
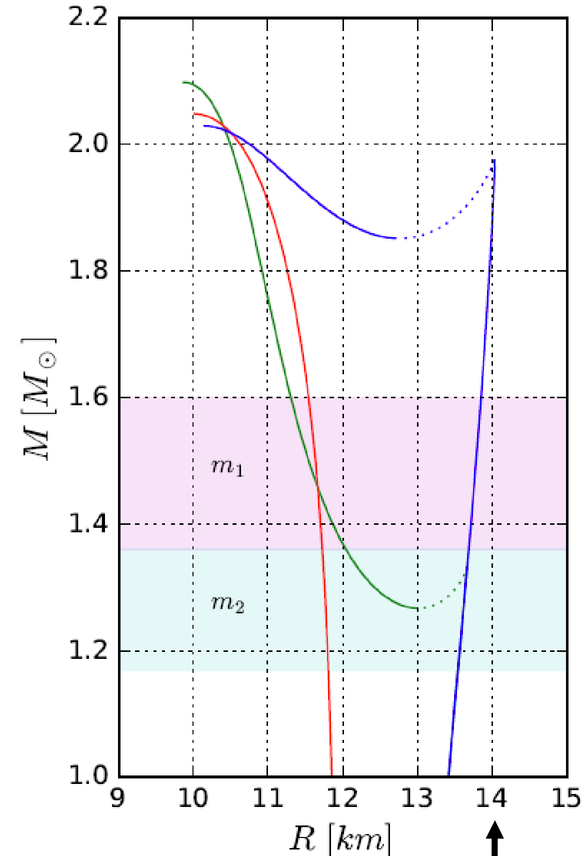
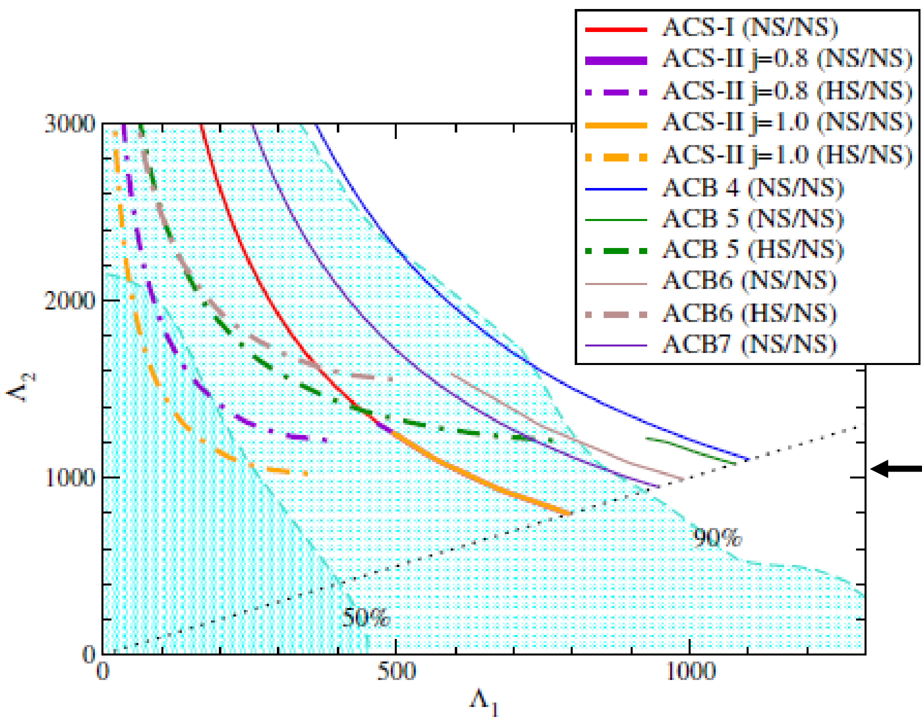






M. Bejger, D.B., et al., in preparation (2018)

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

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

History: Third family & Nonidentical Twins

PHYSICAL REVIEW VOLUME 172, NUMBER 5 25 AUGUST 1968

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

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

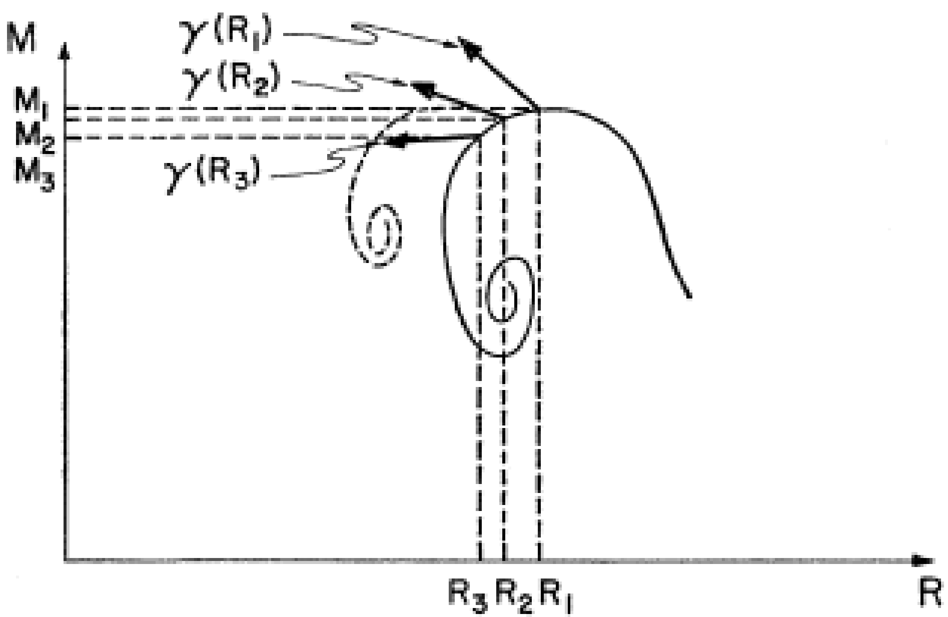
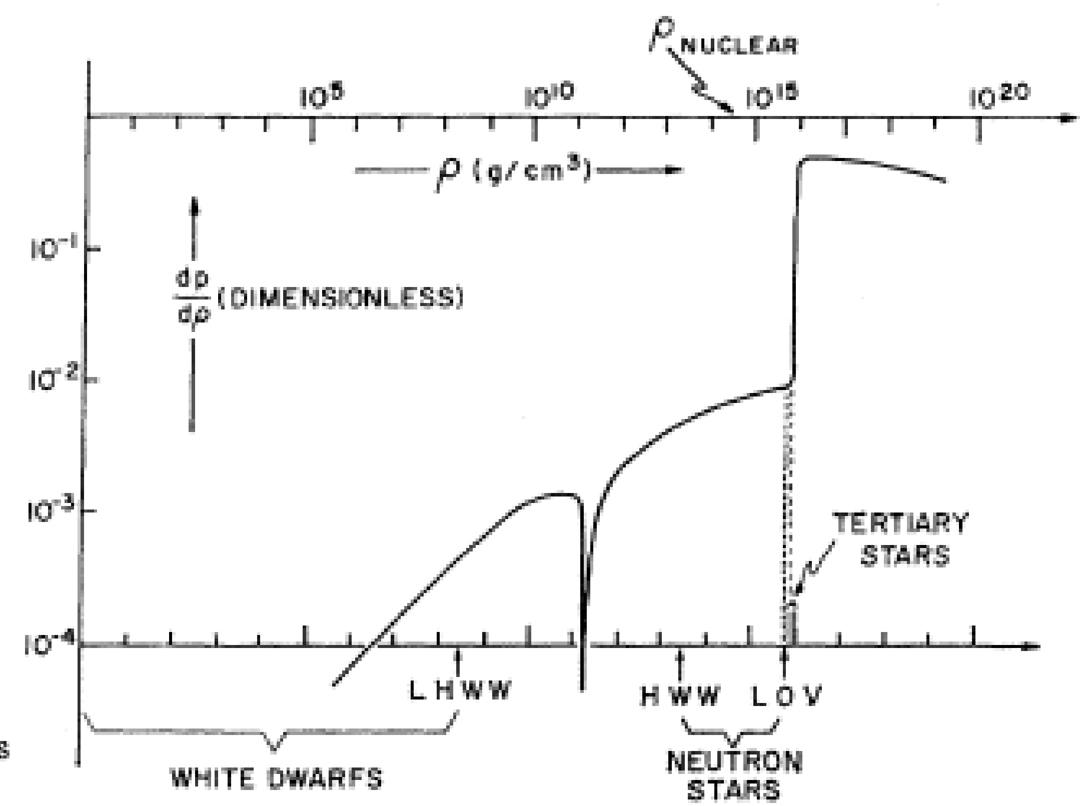


FIG. 3. A blow-up of the LOV maximum. The central densities



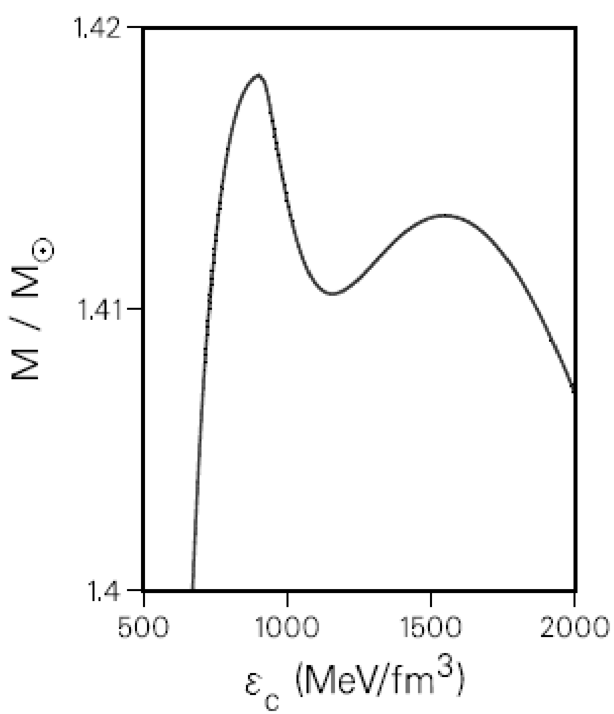
History: Third family & Nonidentical Twins

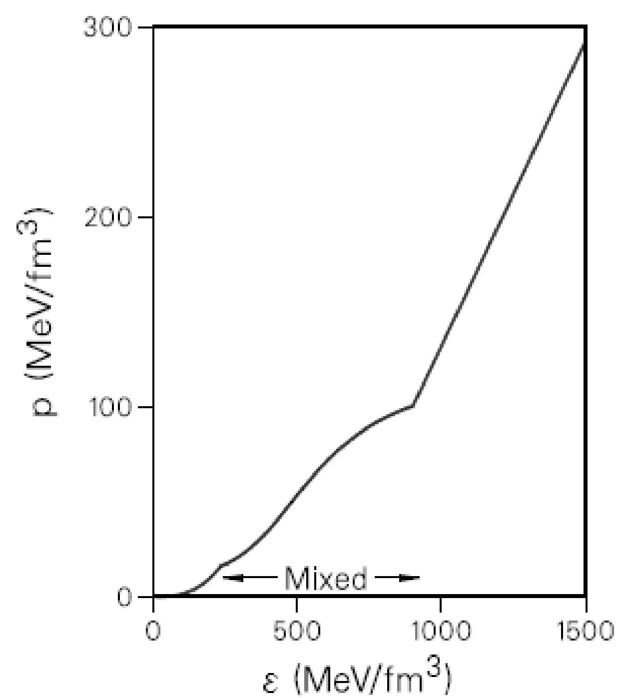
Non-Identical Neutron Star Twins

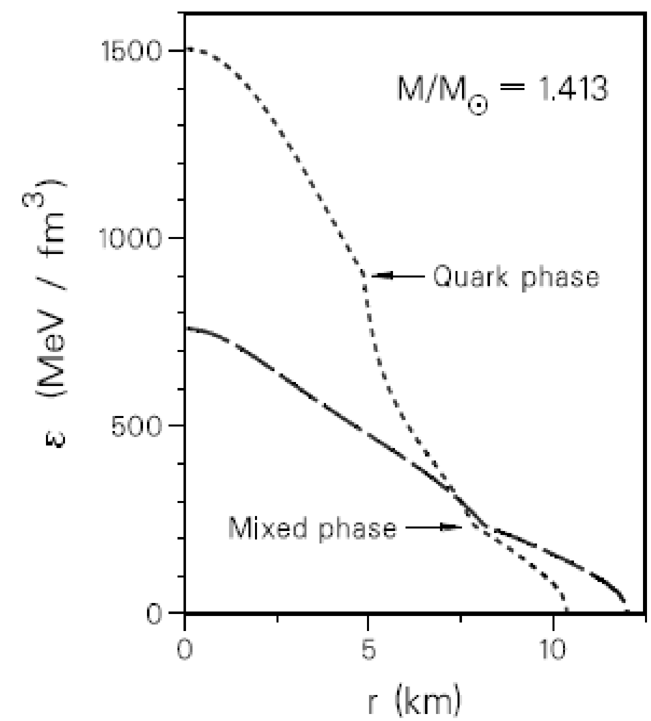
Norman K. Glendenning
Nuclear Science Division, Lawrence Berkeley National Laboratory,
University of California, Berkeley, CA 94720, USA

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

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







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

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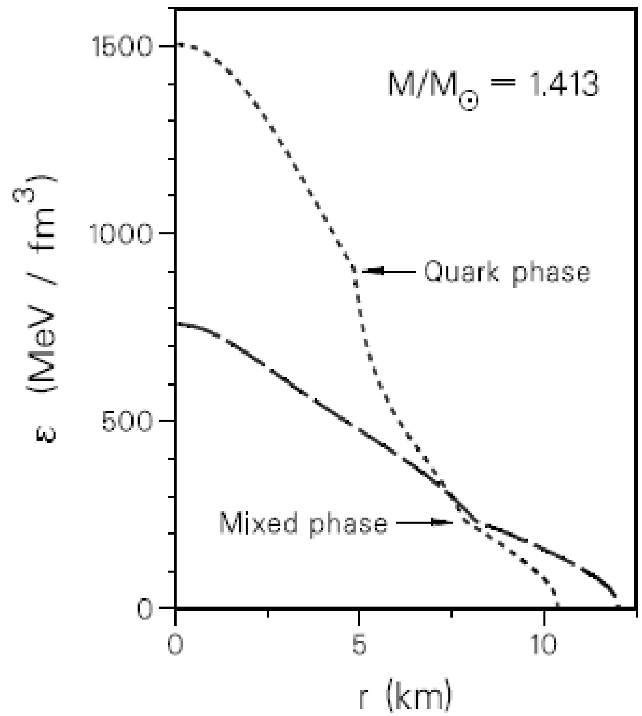
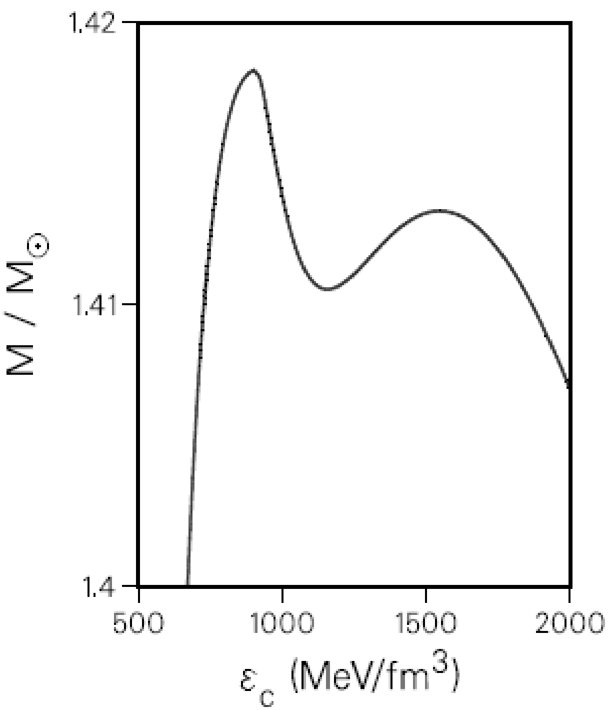
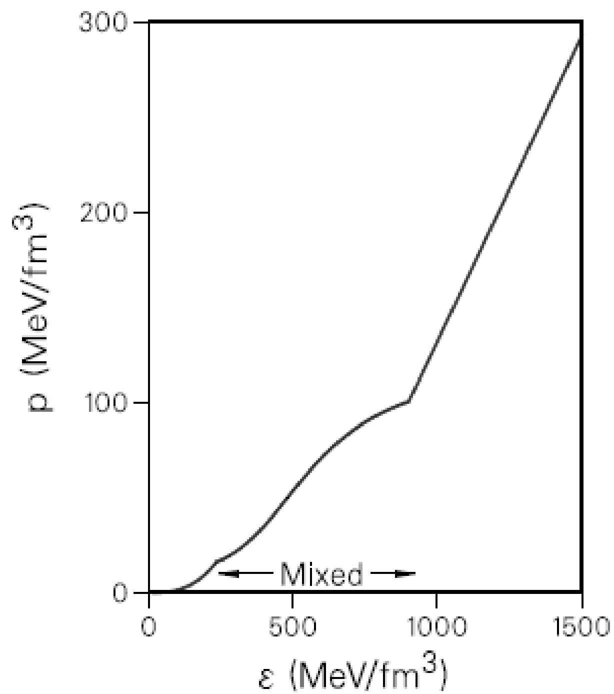


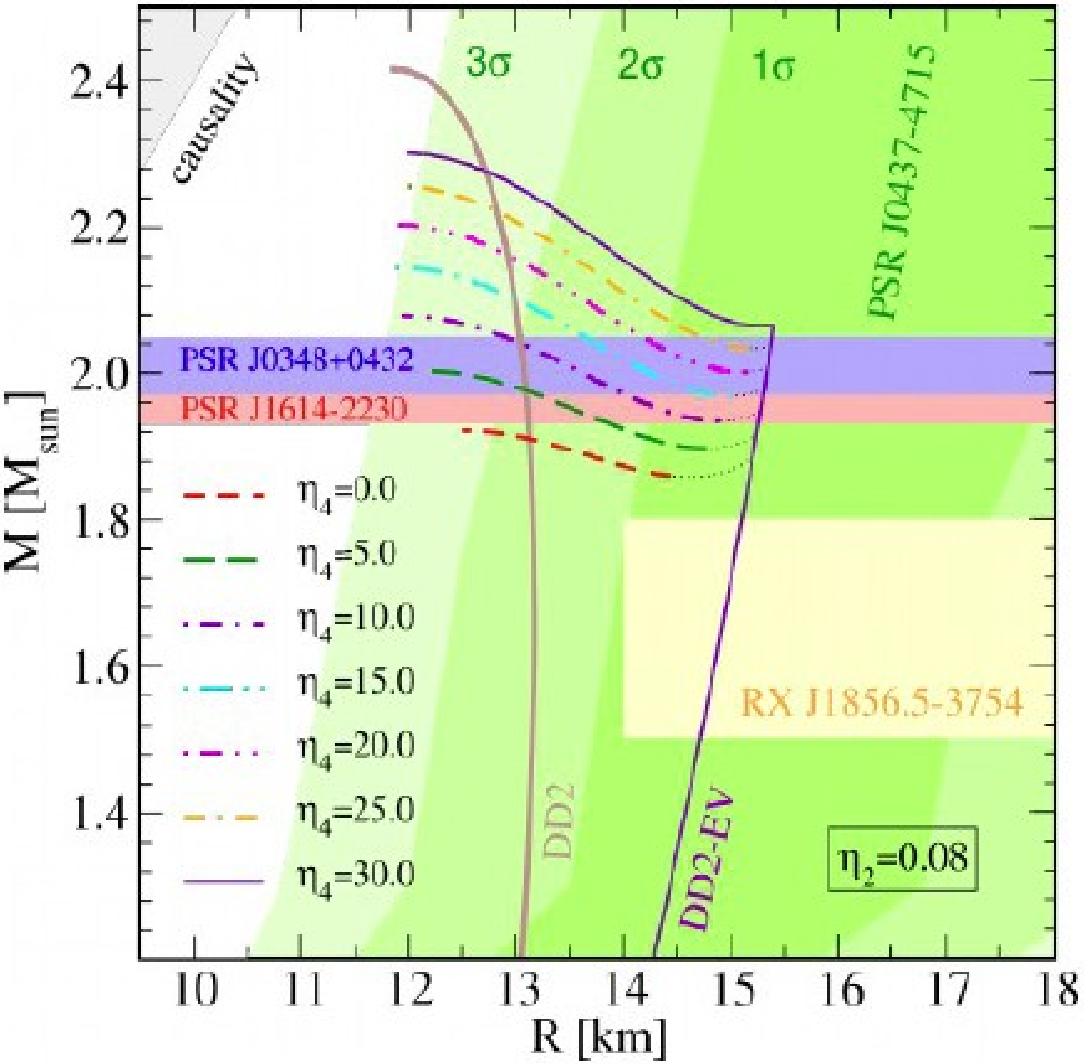




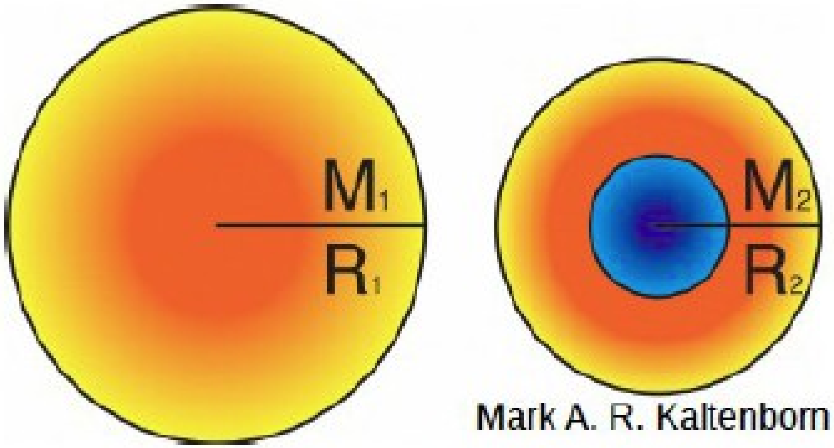
The original Twin paper uses Glendenning construction, not Maxwell one -
Surface tension zero vs. infty!
Pasta phases in-between ...

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

Neutron Star Interiors: Strong Phase Transition?



- Star configurations with same masses, but different radii

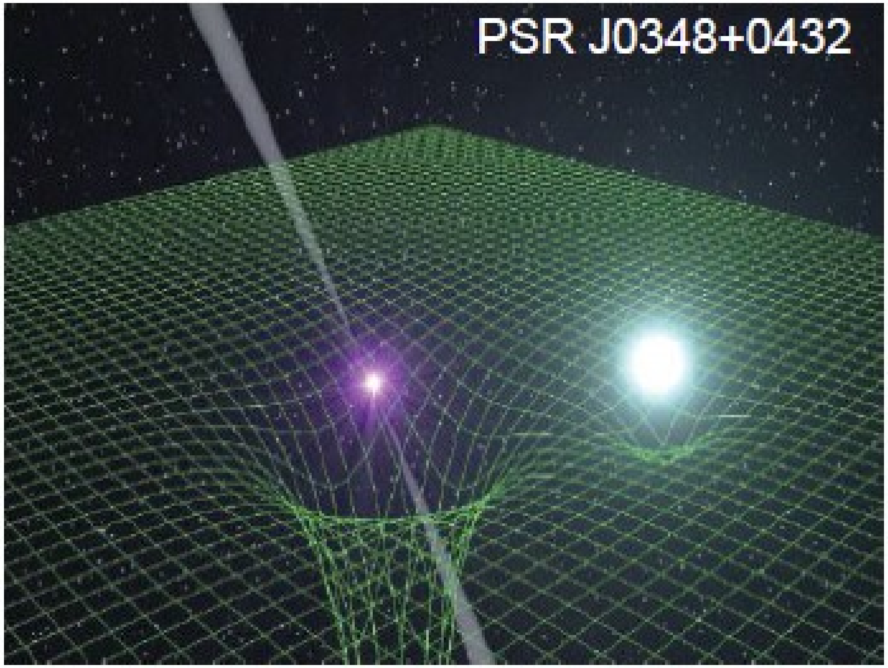


- **New class of EOS, that features high mass twins**
- NASA NICER mission: radii measurements ~ 0.5 km
- Existence of twins implies 1st order phase-transition and hence a critical point

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

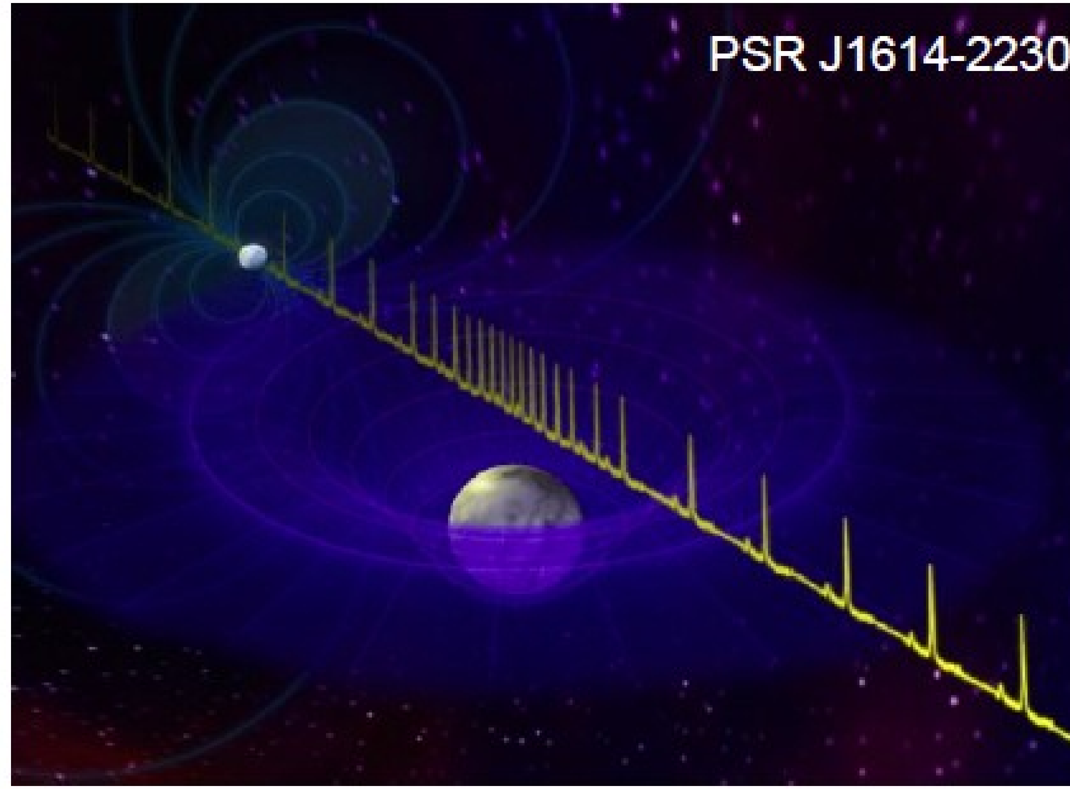
Neutron Star Interiors: Strong Phase Transition?

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

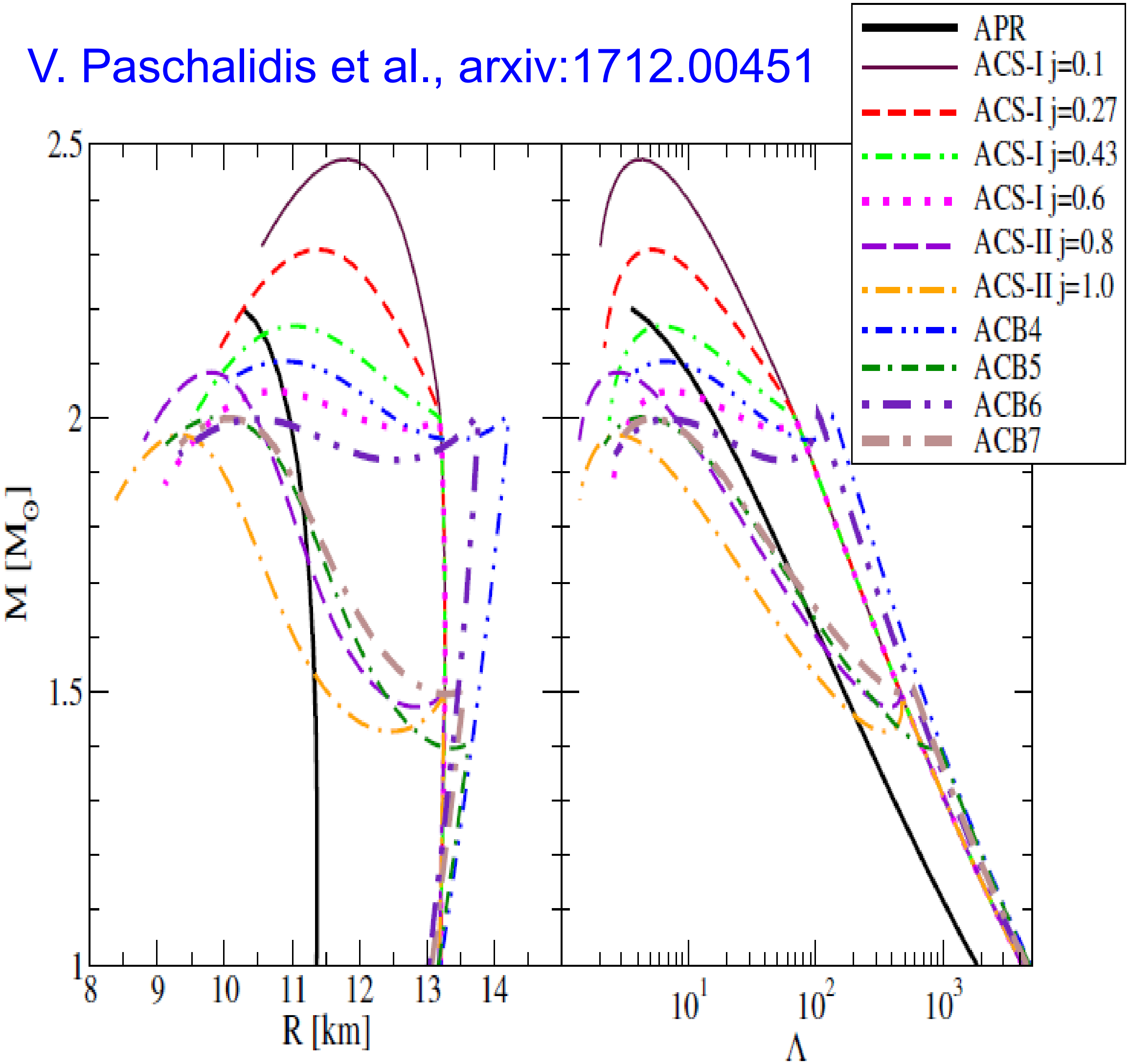


What if they were high-mass twin stars?

→ 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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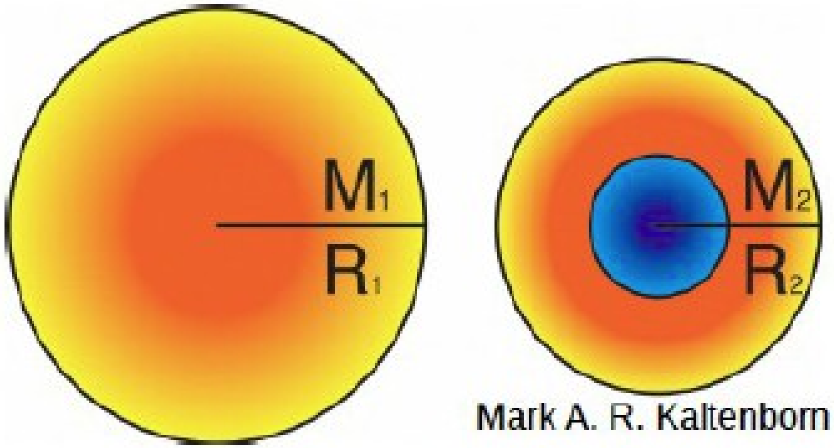

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High-mass twins (HMT) or typical-mass twins (TMT) ?

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

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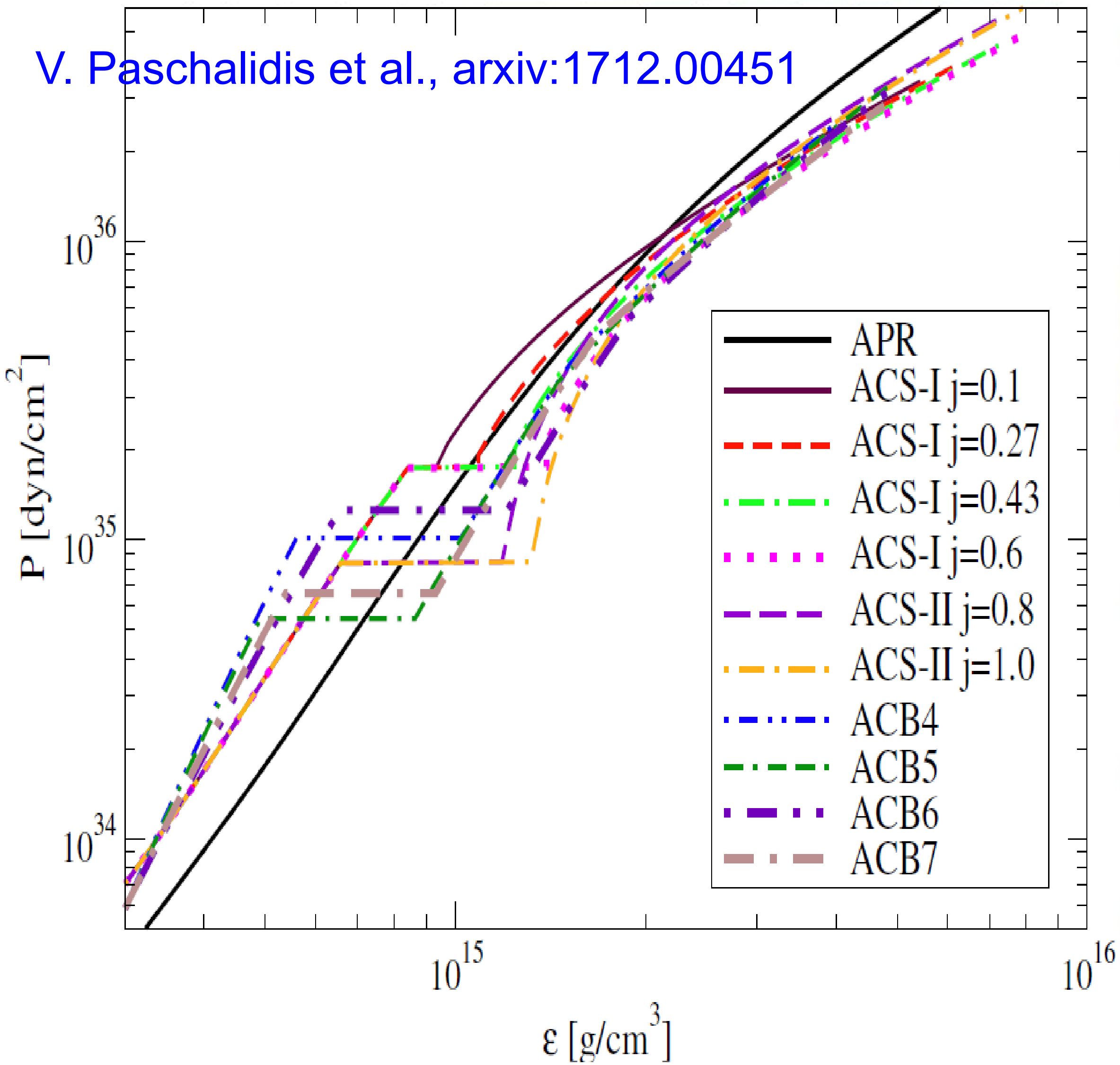

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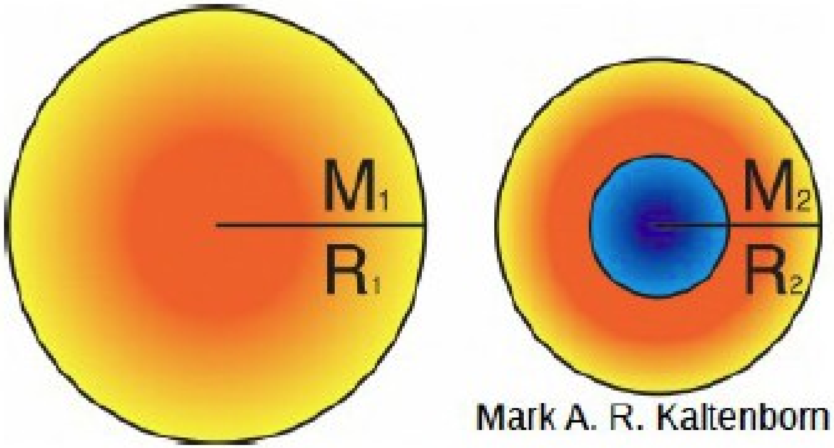

Mark A. R. Kaltenborn

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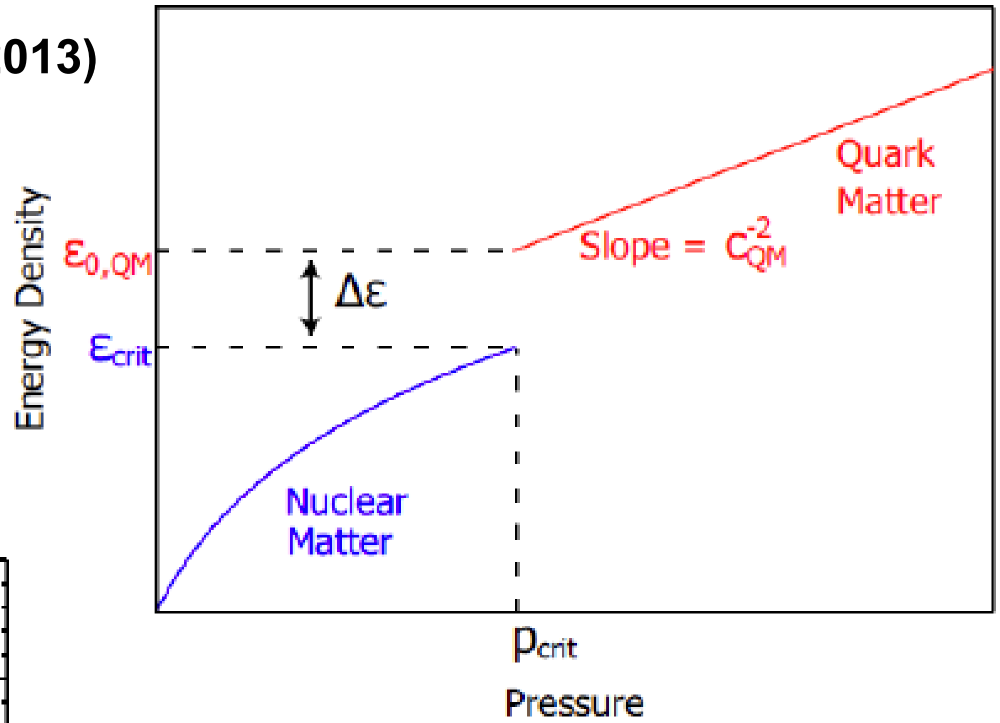
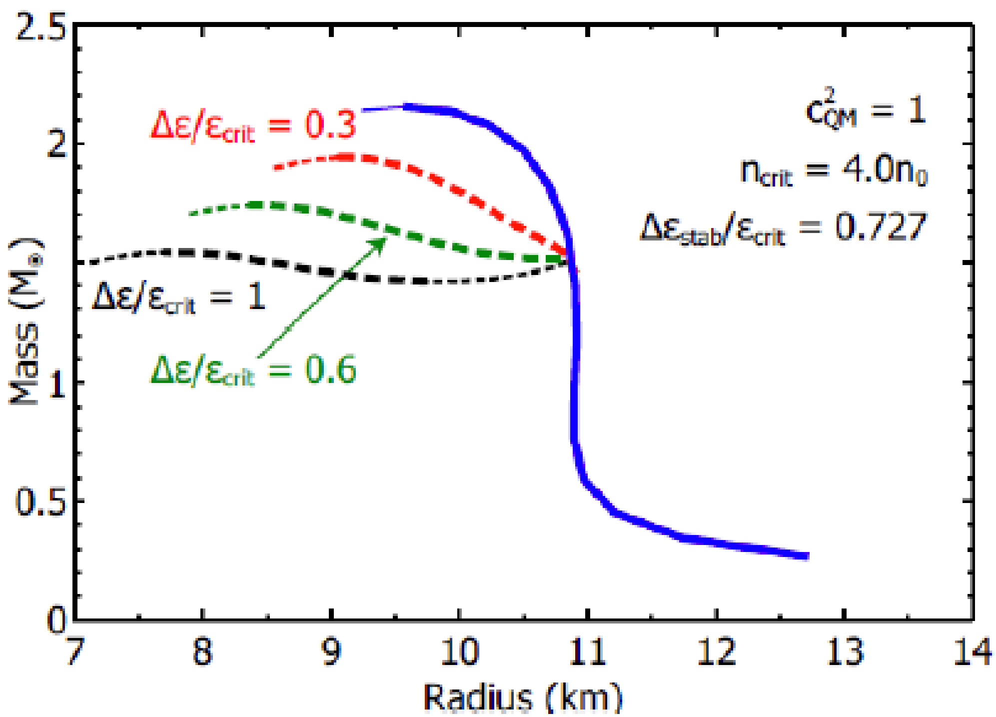
Constant Speed of Sound (CSS) Model

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

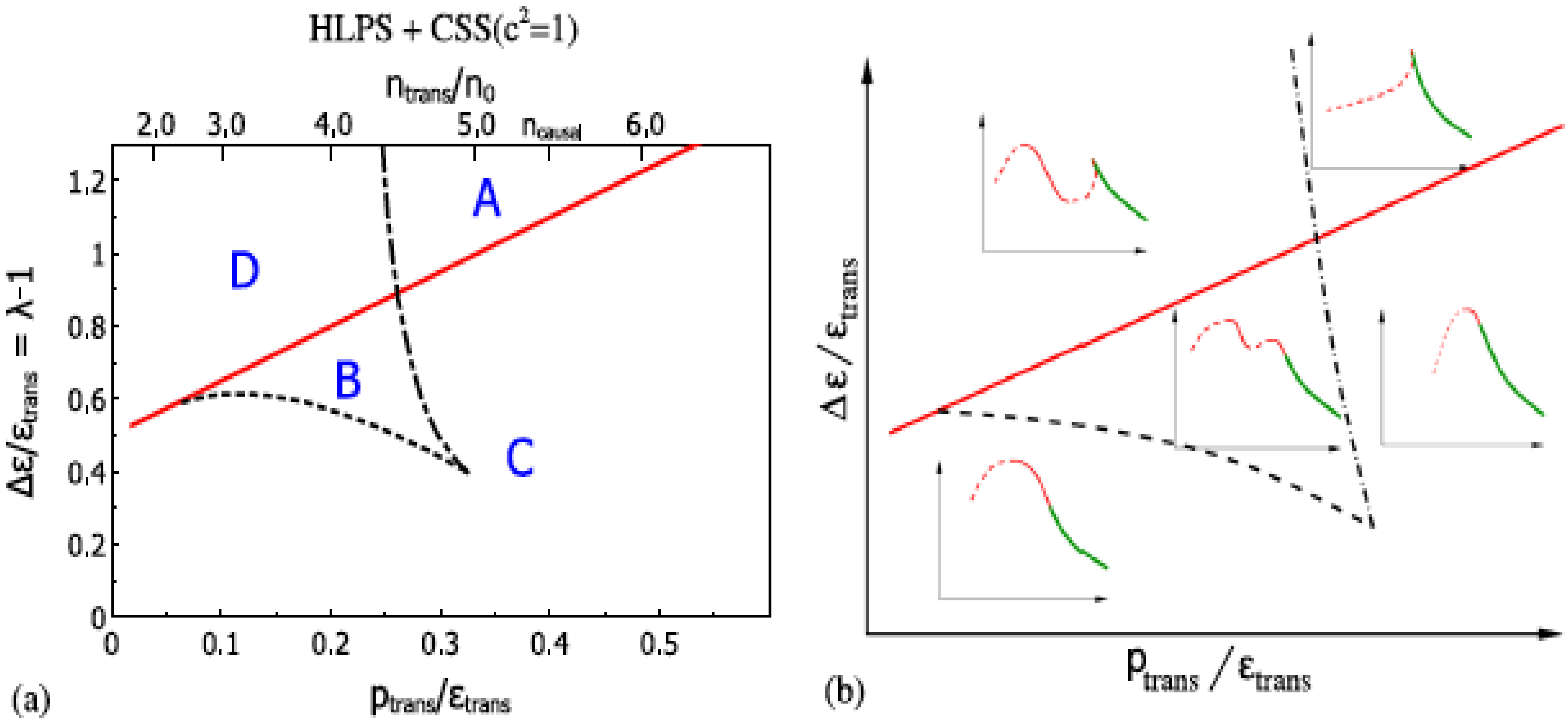
First order PT can lead to a stable branch of hybrid stars with quark matter cores which, depending on the size of the "latent heat" (jump in energy density), can even be disconnected from the hadronic one by an unstable branch → **"third family of CS"**.





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" $\leftrightarrow$ 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!

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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(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)

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

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

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

"no sea" approximation ...

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

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

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

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

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

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

Selfconsistent densities

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

Relativistic density functional approach (III)

Density functional for the SFM

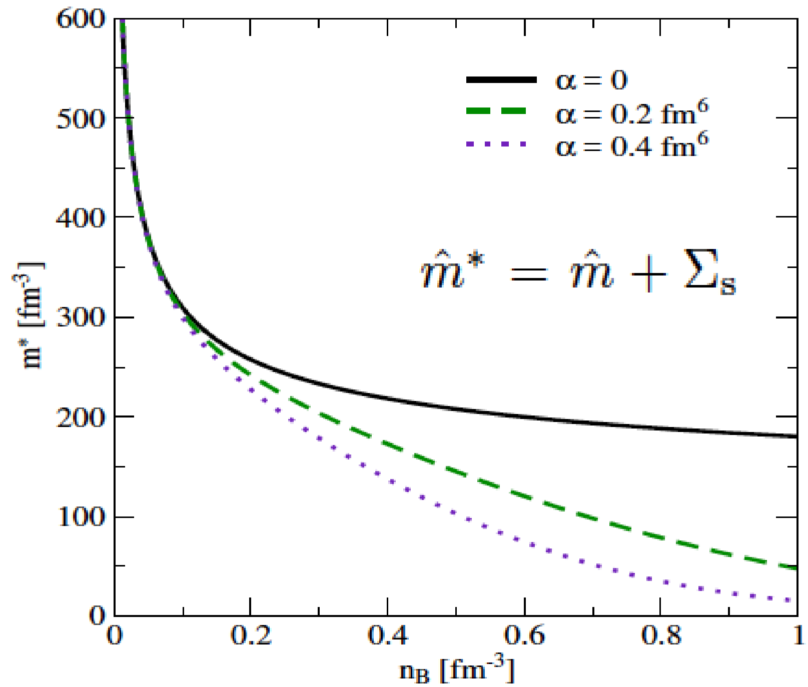
$$U(n_s, n_v) = D(n_v) n_s^{2/3} + a n_v^2 + \frac{b n_v^4}{1 + c n_v^2} ,$$

Quark selfenergies

$$\Sigma_s = \frac{2}{3} D(n_v) n_s^{-1/3} ,$$

Quark "confinement"

$$\Sigma_v = 2 a n_v + \frac{4 b n_v^3}{1 + c n_v^2} - \frac{2 b c n_v^5}{(1 + c n_v^2)^2} + \frac{\partial D(n_v)}{\partial n_v} n_s^{2/3}$$

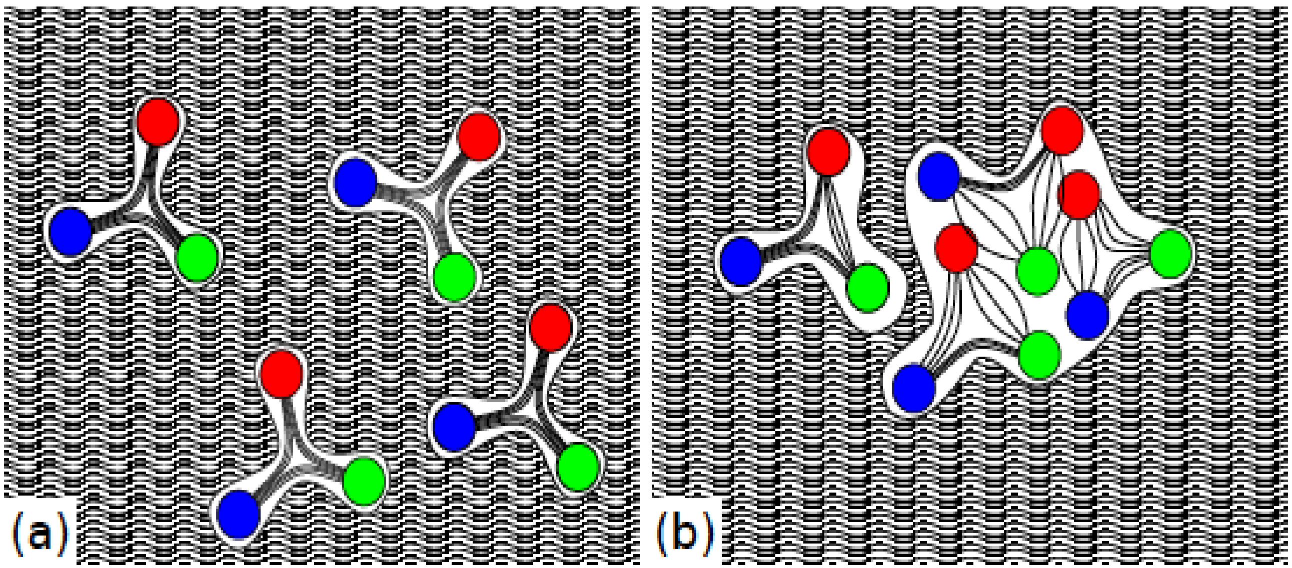


String tension & confinement due to dual Meissner effect (dual superconductor model)

$$D(n_v) = D_0 \Phi(n_v)$$

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

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

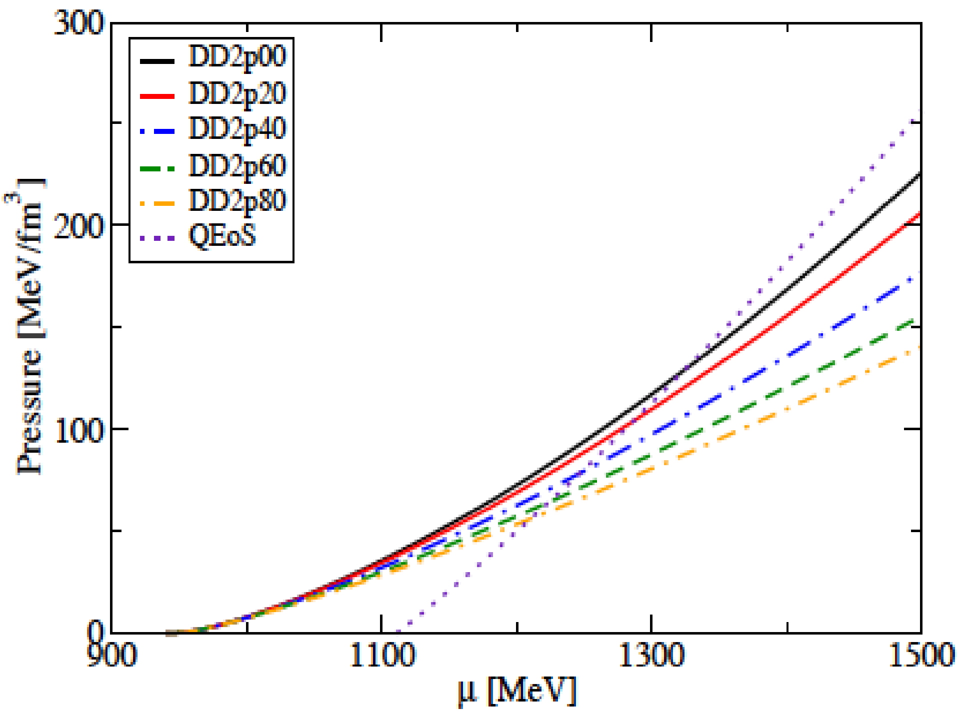


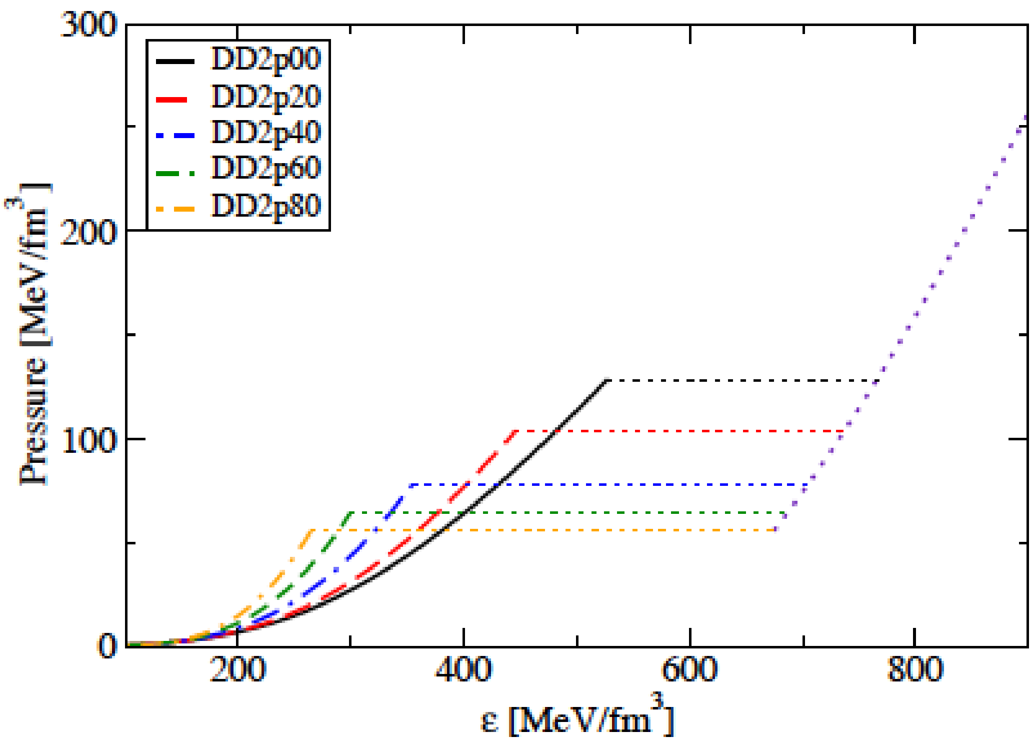
Phase transition from hadronic to SFM quark matter

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

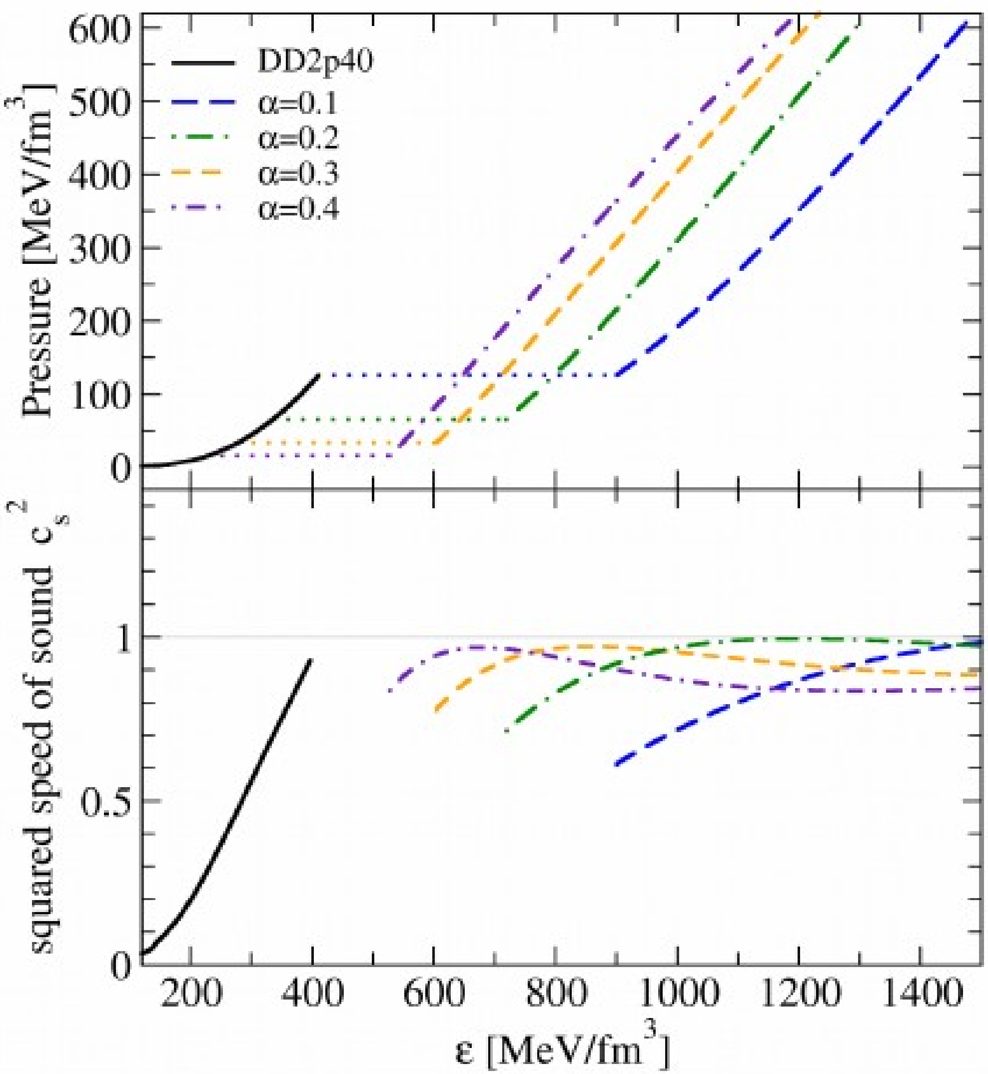
$$\Phi_n = \Phi_p = \begin{cases} 1, & \text{if } n_{\rm B} < n_0 \\ e^{-\frac{v|v|}{2}(n_{\rm B}-n_0)^2}, & \text{if } n_{\rm B} > n_0 \end{cases}$$

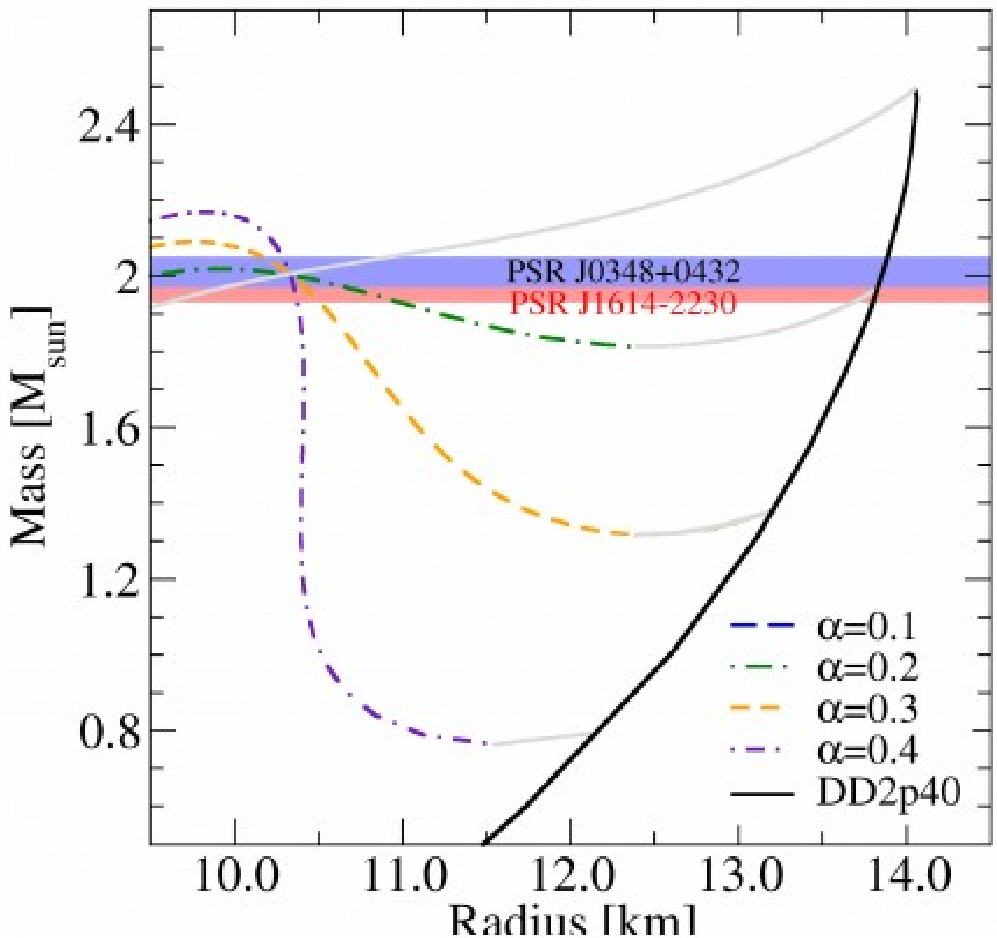
Varying the hadronic excluded volume parameter, p00 → v=0, … , p80 → v=8 fm^3





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

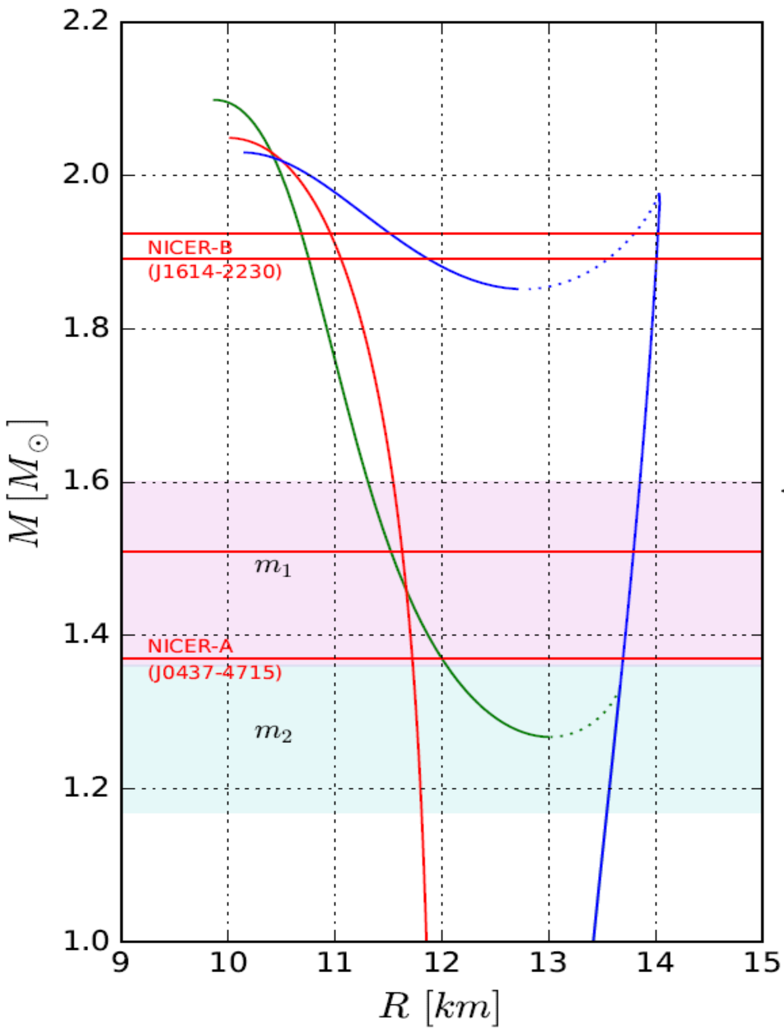


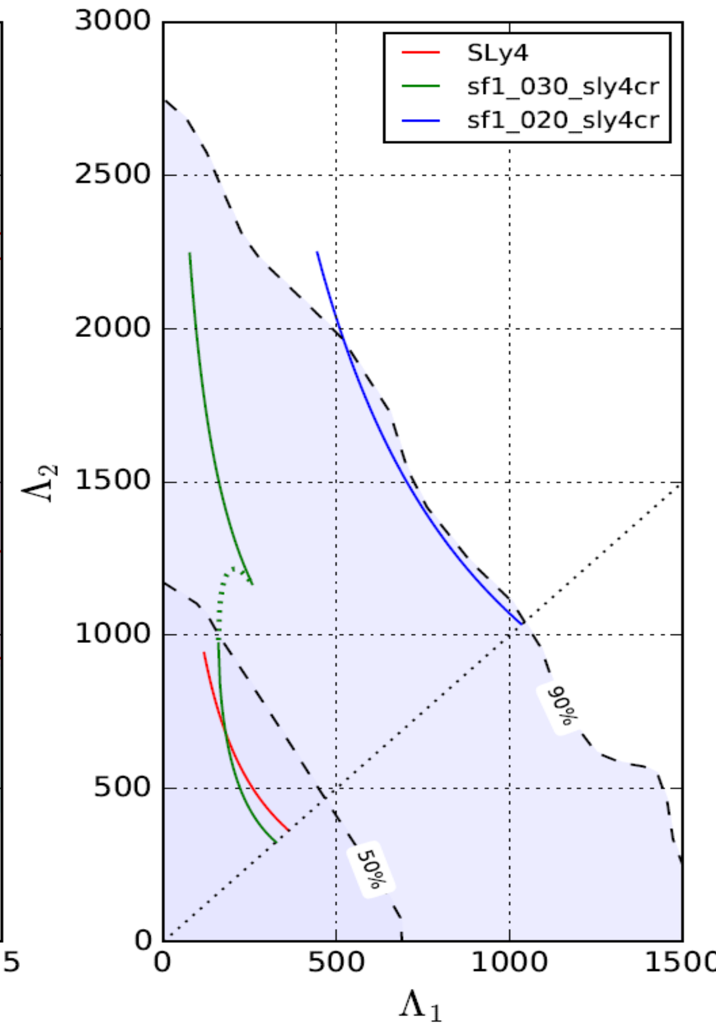


Kaltenborn, Bastian, Blaschke, arXiv:1701.04400 → Phys. Rev. D 96, 056024 (2017)

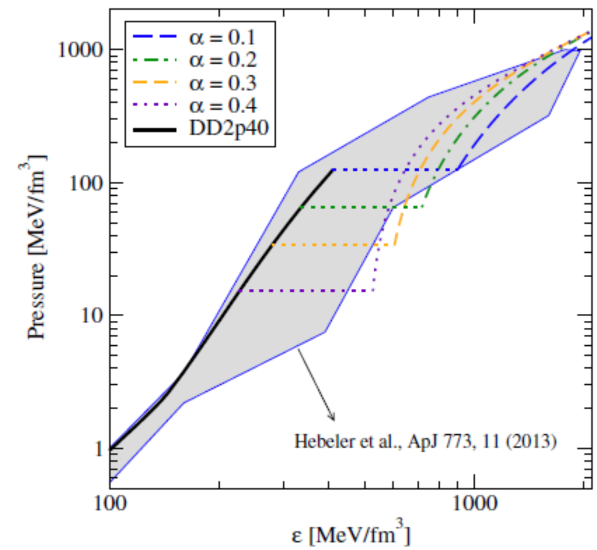
Results of Maxwell construction! Could pasta phases remove the twins (3rd family instability)?

Discover the 3rd family – NICER vs. GW170817





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



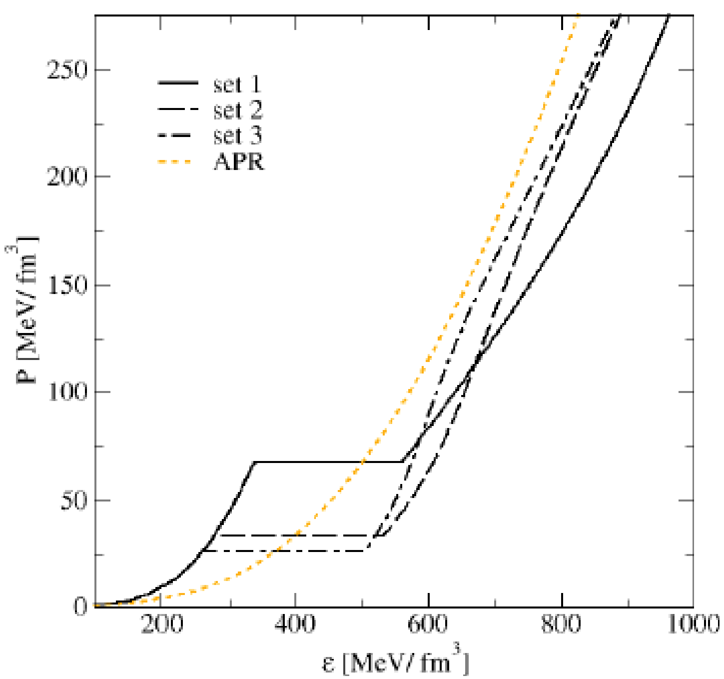
TOV / TD calculation:
M. Bejger et al.

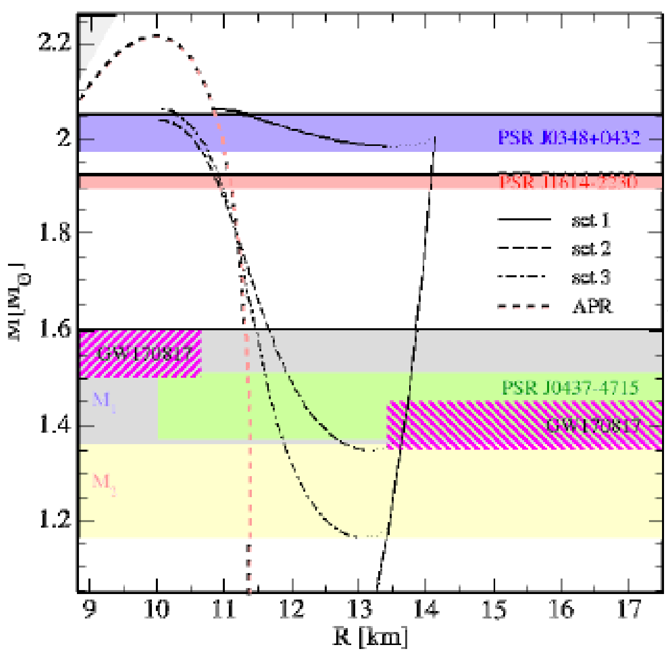
Alternative to NS merger with soft EoS → Hybrid star (HS) – HS / HS-NS merger

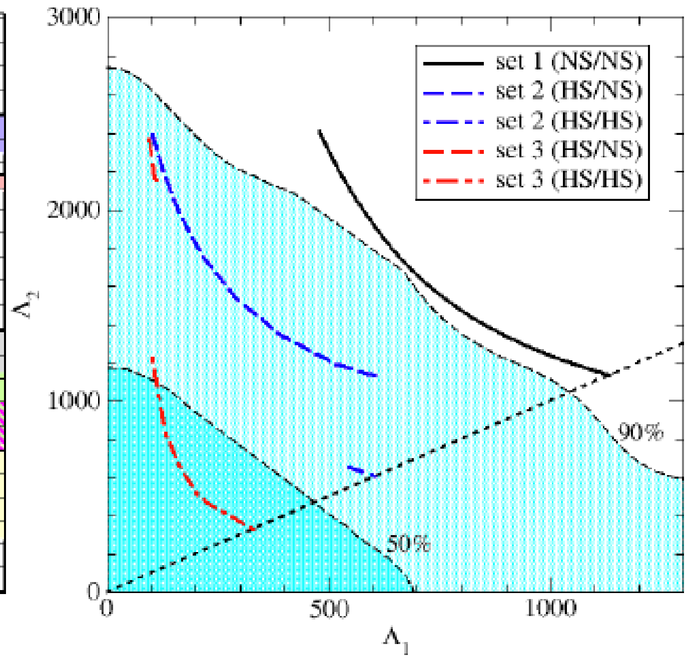
If NICER rules out soft EoS (since $R_{0437\text{-}4715}$ >13.5 km) then **Third Family is Discovered !!**

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)

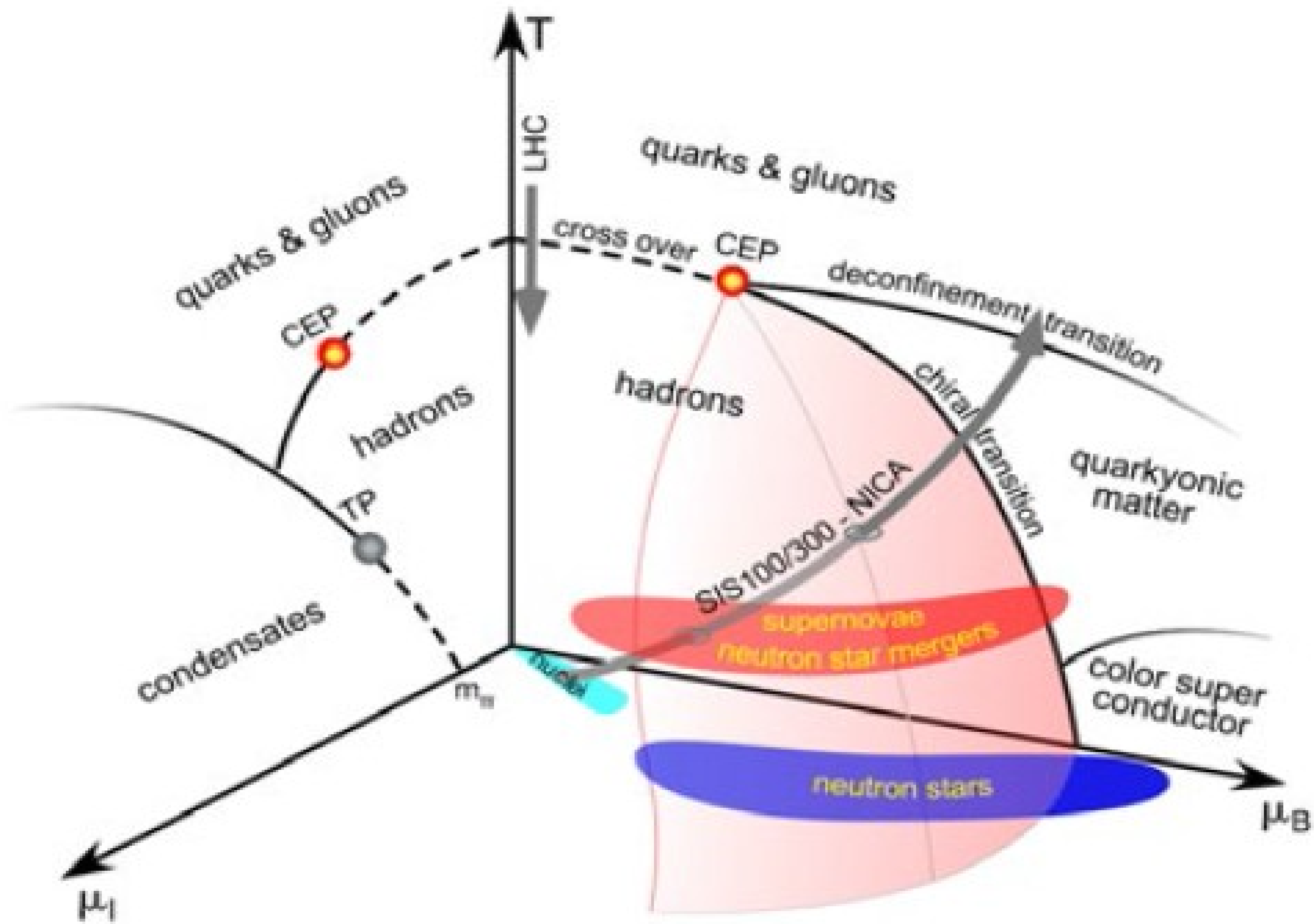
TOV / TD calculation:
2 M_sun constraint fulfilled
GW170817: R_1.4 < 13.6 km
[Annala et al., PRL (2018)]
NICER: R_1.44 > ?? (2018)

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 !!**

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

nature astronomy

ARTICLES

https://doi.org/10.1038/s41550-018-0583-0

Quark deconfinement as a supernova explosion engine for massive blue supergiant stars

Tobias Fischer[1*], Niels-Uwe F. Bastian[1], Meng-Ru Wu[2,3], Petr Baklanov[4,5], Elena Sorokina[4,6], Sergei Blinnikov[4,7], Stefan Typel[8,9], Thomas Klähn[10] and David B. Blaschke[1,5,11]

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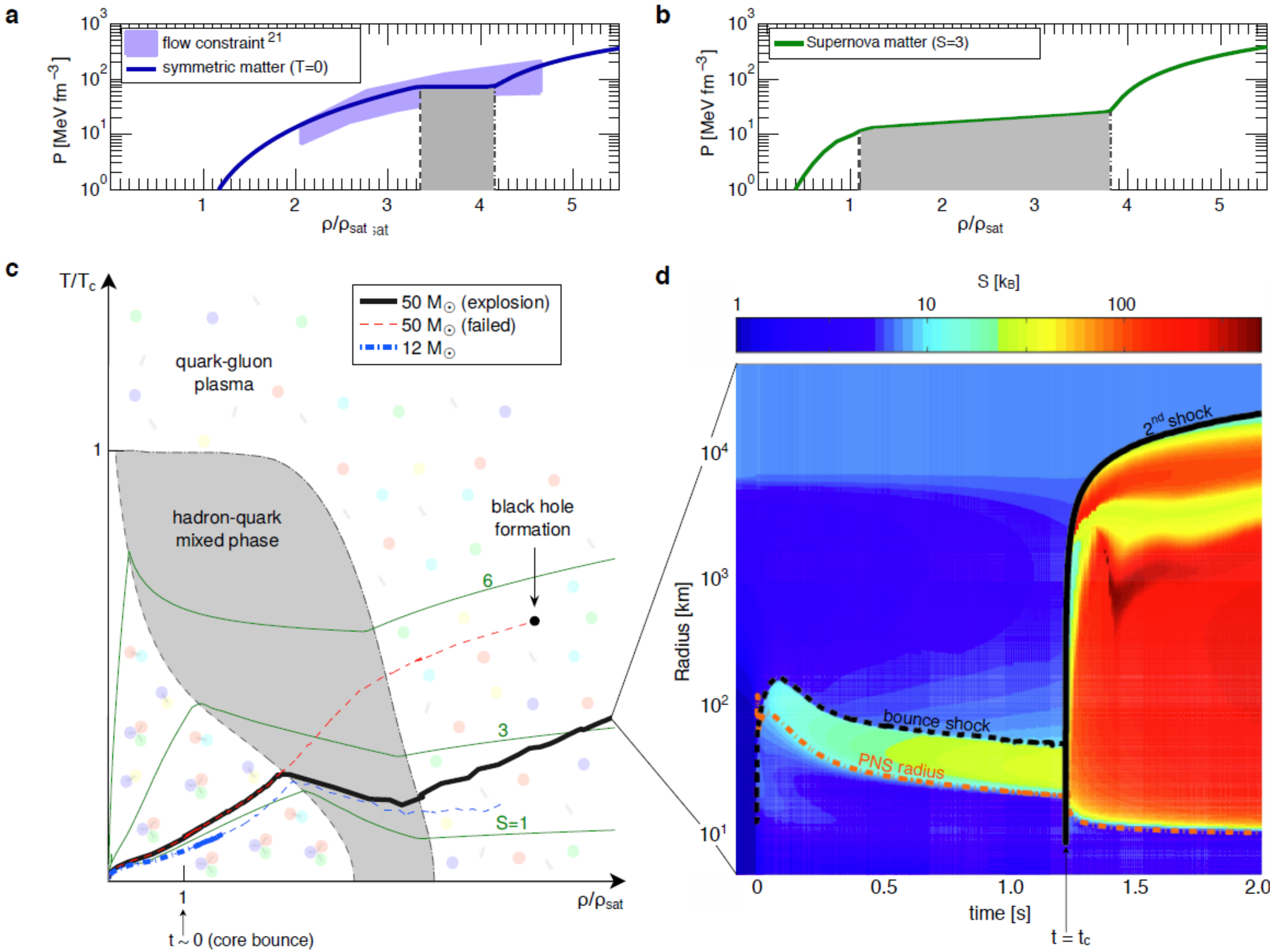
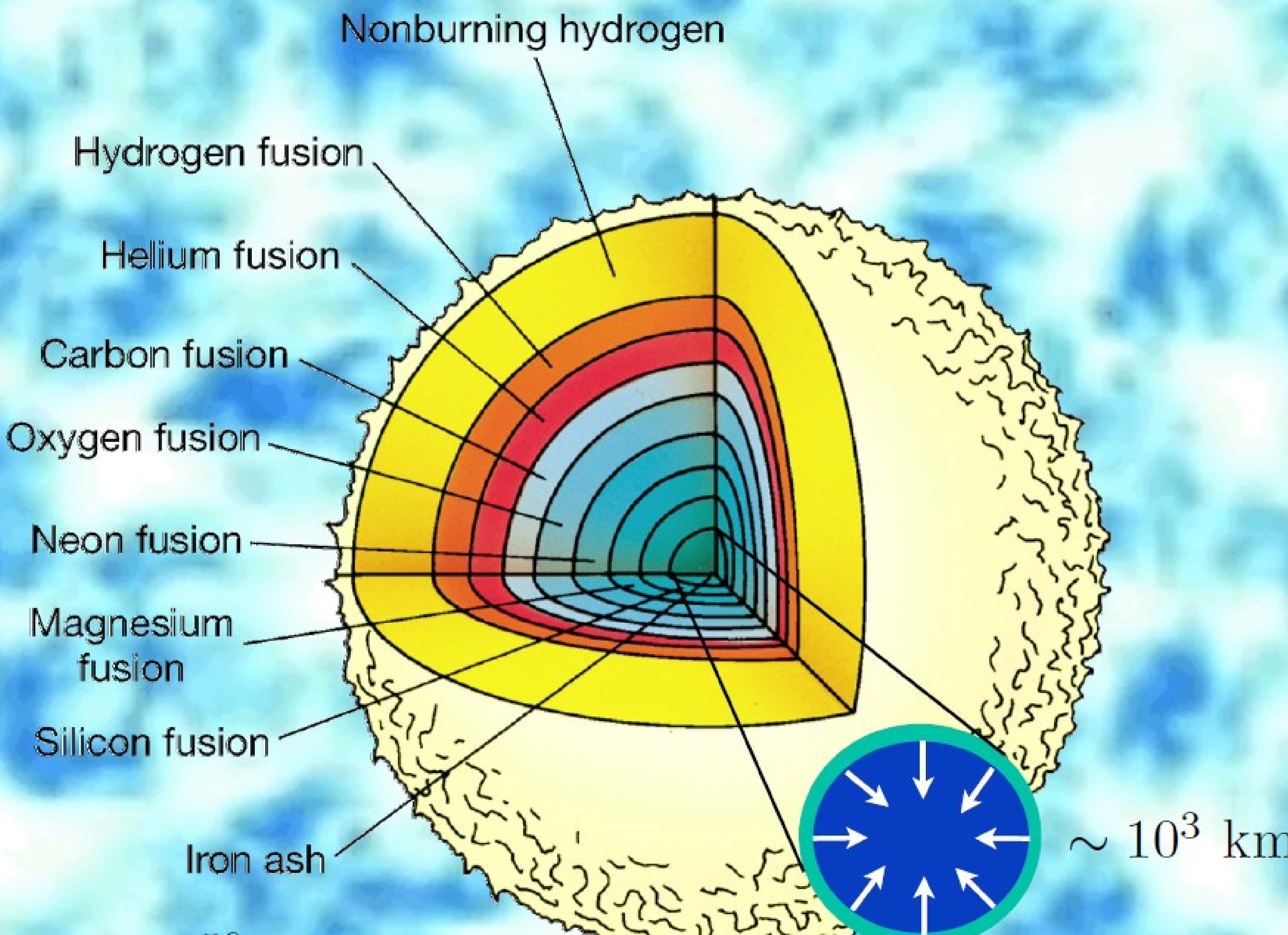
Deconfinement transition as SN explosion mechanism



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 (to appear); arxiv:1712.08788

T. Fischer, Dubna

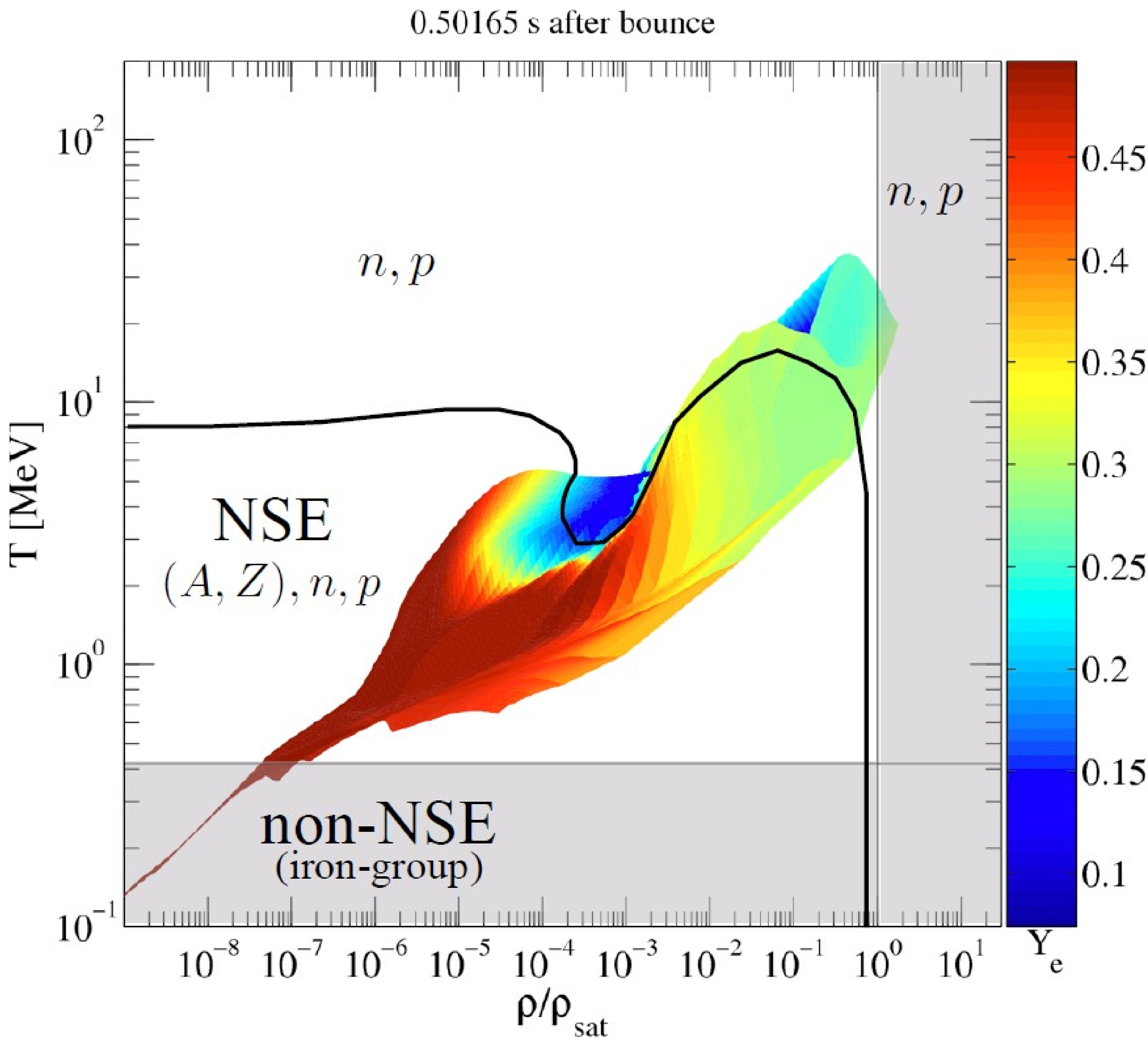


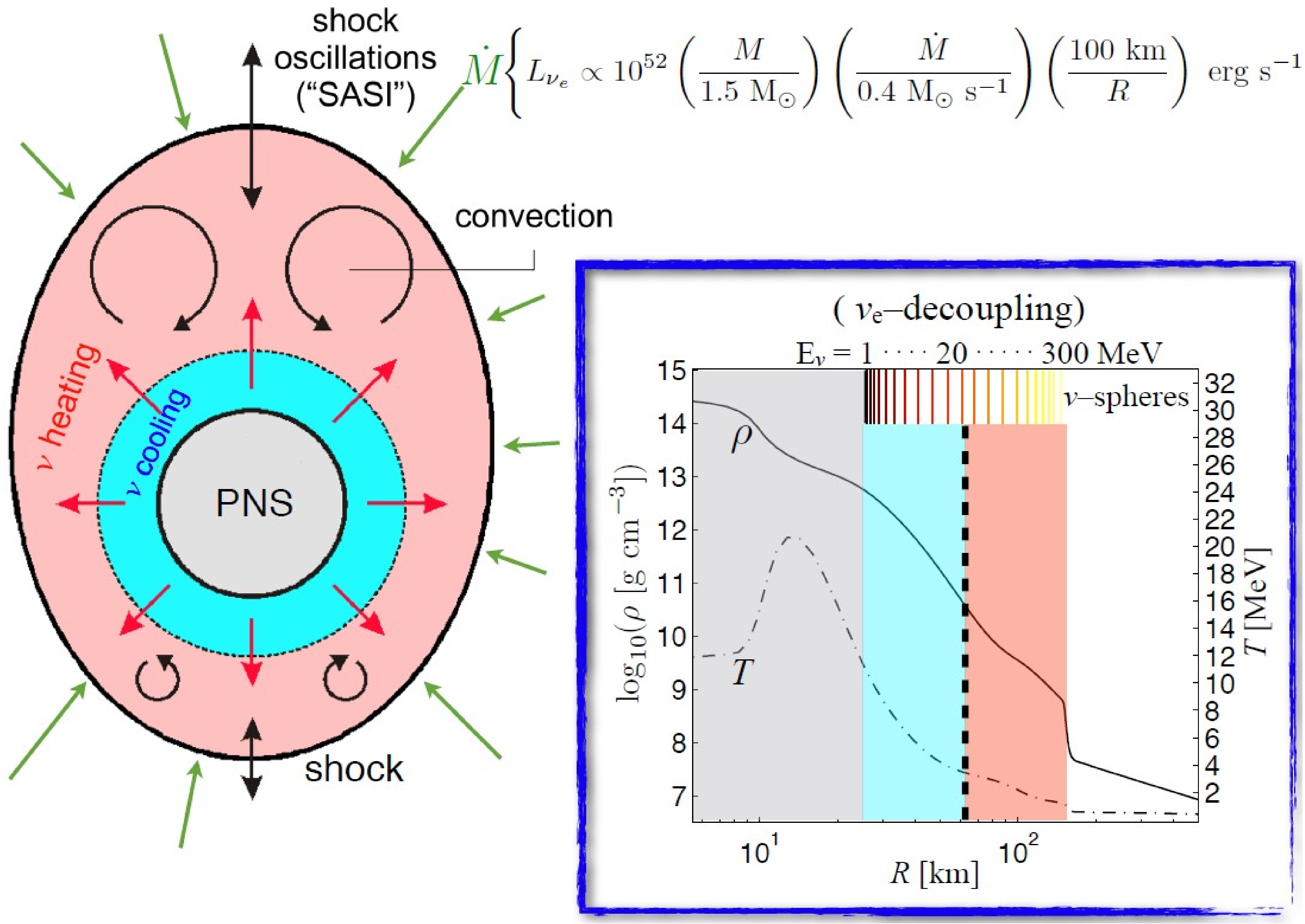
$$e^- + {}^{56}\mathrm{Mn} \longrightarrow {}^{56}\mathrm{Fe} + \nu_\mathrm{e}$$
$$e^- + {}^{56}\mathrm{Fe} \longrightarrow {}^{56}\mathrm{Co} + \nu_\mathrm{e}$$
$$e^- + {}^{56}\mathrm{Co} \longrightarrow {}^{56}\mathrm{Ni} + \nu_\mathrm{e}$$

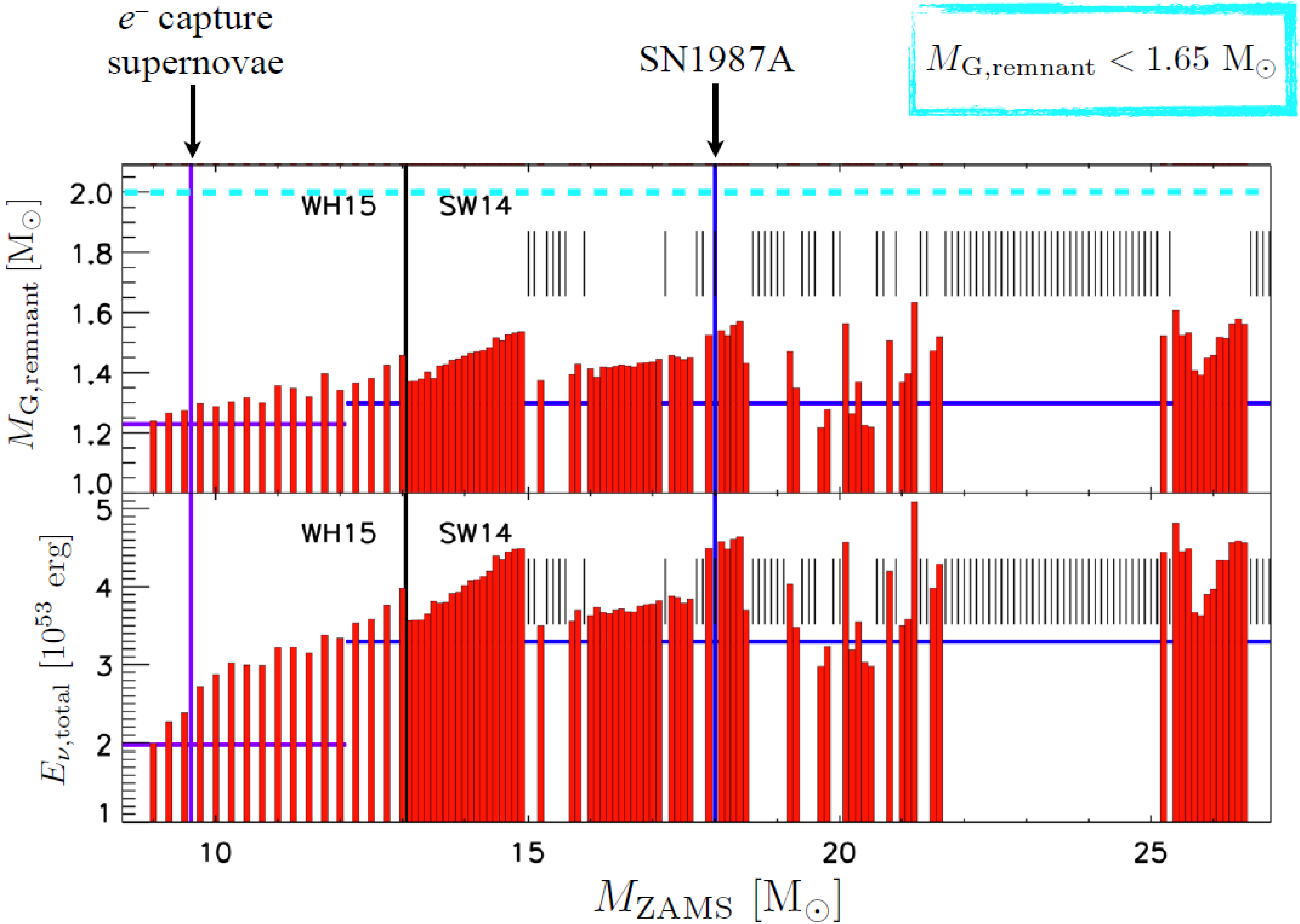
Iron core collapse

$$E_\mathrm{gain} \simeq 3 - 6 \times 10^{53}\ \mathrm{erg}$$
$$(\nu_e, \bar{\nu}_e, \nu_{\mu/\tau}, \bar{\nu}_{\mu/\tau})$$

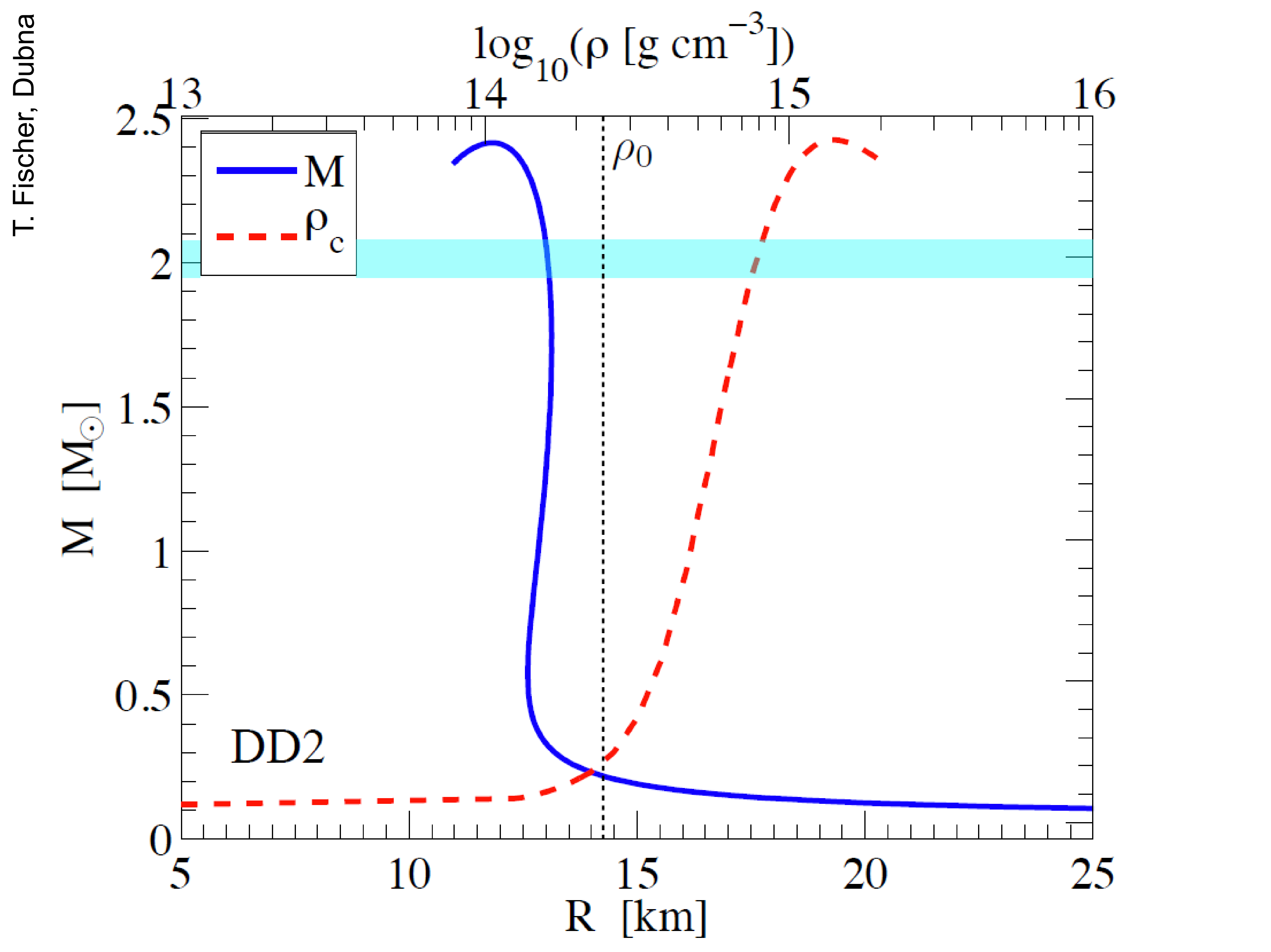
T. Fischer, Dubna

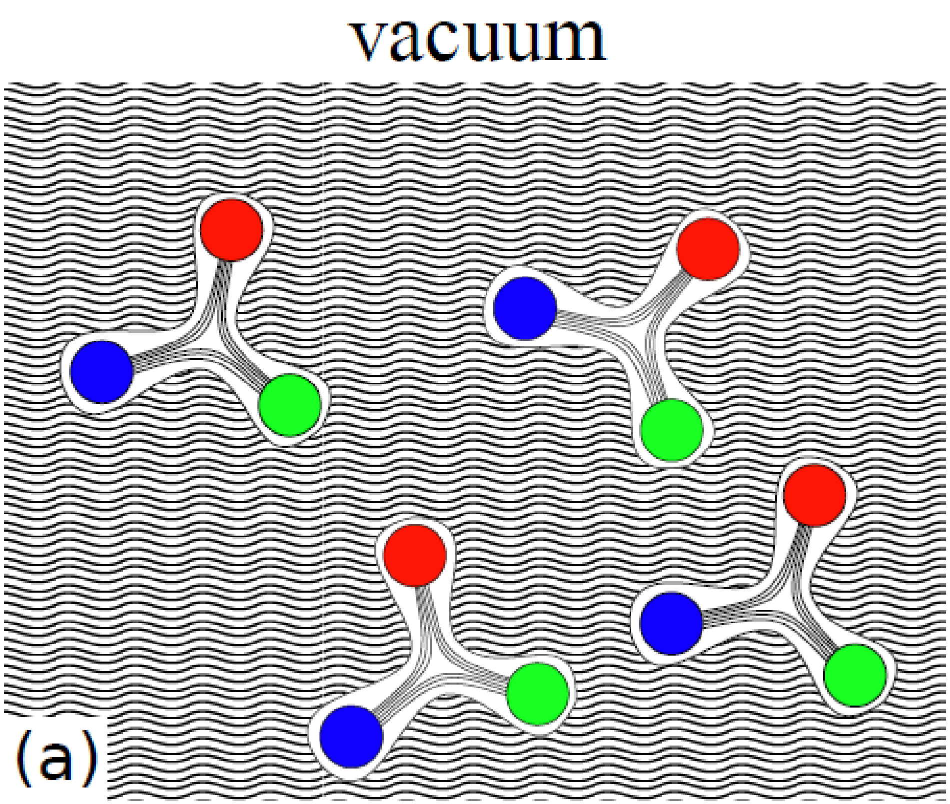



shock
oscillations
("SASI")
$\dot{M} \{ L_{\nu_e} \propto 10^{52} \left(\frac{M}{1.5\ \mathrm{M}_\odot}\right) \left(\frac{\dot{M}}{0.4\ \mathrm{M}_\odot\ \mathrm{s}^{-1}}\right) \left(\frac{100\ \mathrm{km}}{R}\right)\ \mathrm{erg\ s}^{-1}$
convection
ν heating
ν cooling
PNS
shock
(ν_e–decoupling)
E_ν = 1 · · · · 20 · · · · · 300 MeV
ν–spheres
ρ
T
$\log_{10}(\rho\ [\mathrm{g\ cm}^{-3}])$
T [MeV]
R [km]
10^1
10^2
15
14
13
12
11
10
9
8
7
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2

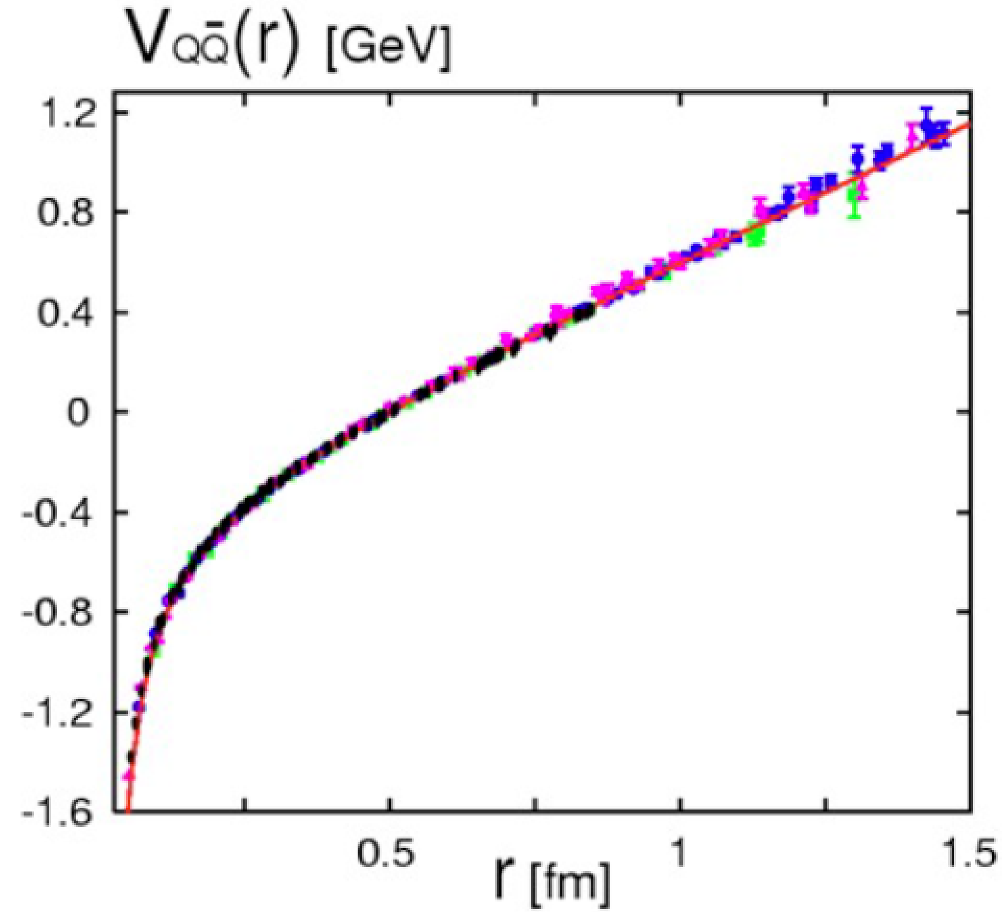


ApJ 821:38, 45 (2016)


T. Fischer, Dubna
log10(ρ [g cm−3])
13
14
15
16
2.5
2
1.5
1
0.5
0
M [M⊙]
M
ρc
ρ0
DD2
5
10
15
20
25
R [km]



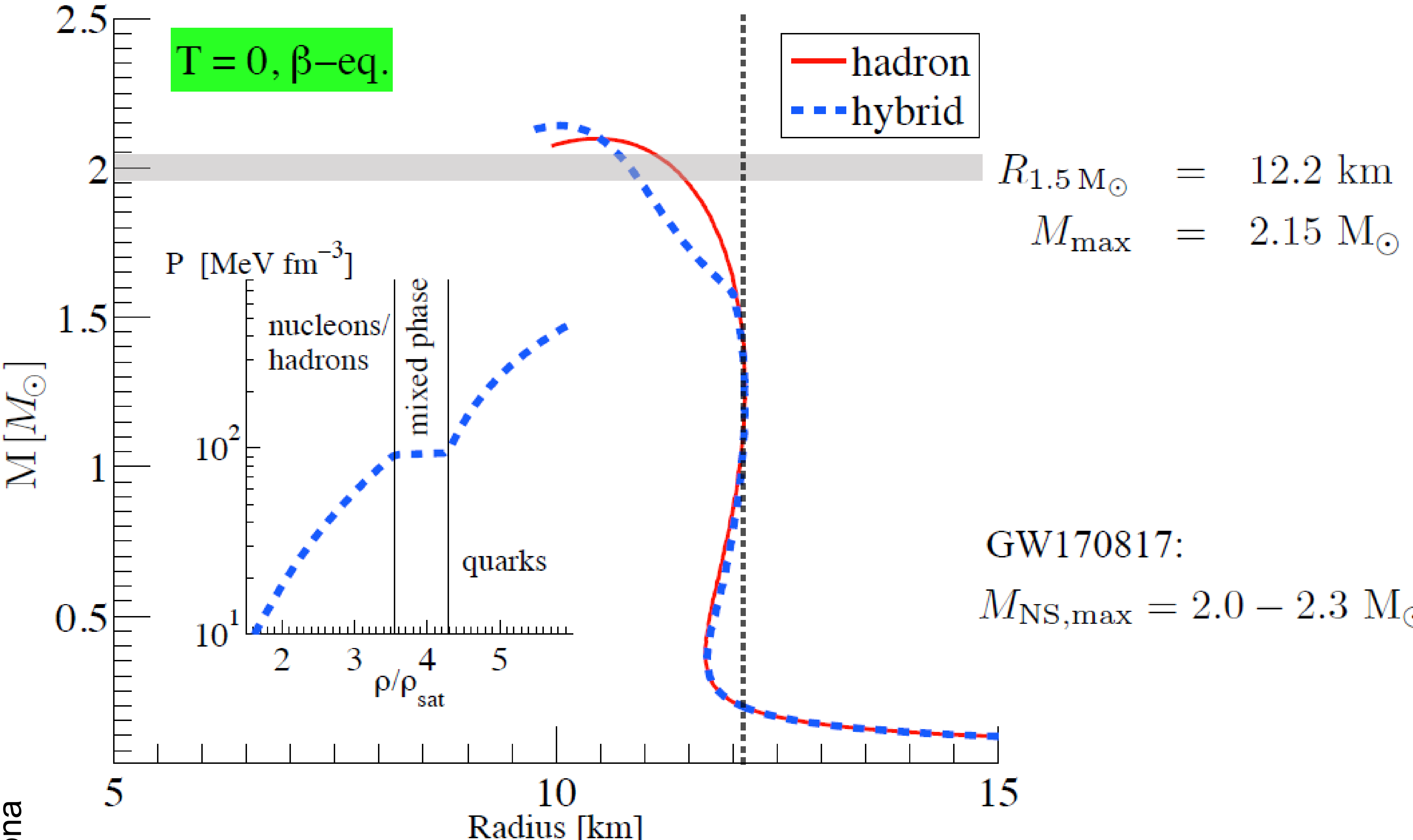
$$D = D_0$$



$$V_{QQ}(r) \propto D_0\, r - \frac{A}{r}$$

$$D_0 = 1\ \text{GeV fm}^{-1}$$

NPA 536, 669 (1992)



GW170817:

$M_{NS,max} = 2.0 - 2.3\ M_\odot$

Margalit & Metzger (2017) ApJ 850, L19
Shibata et al., (2017) PRD 96, 123012
Rezzolla et al., (2018) ApJ 852, L25
Ruiz et al., (2018) PRD 97

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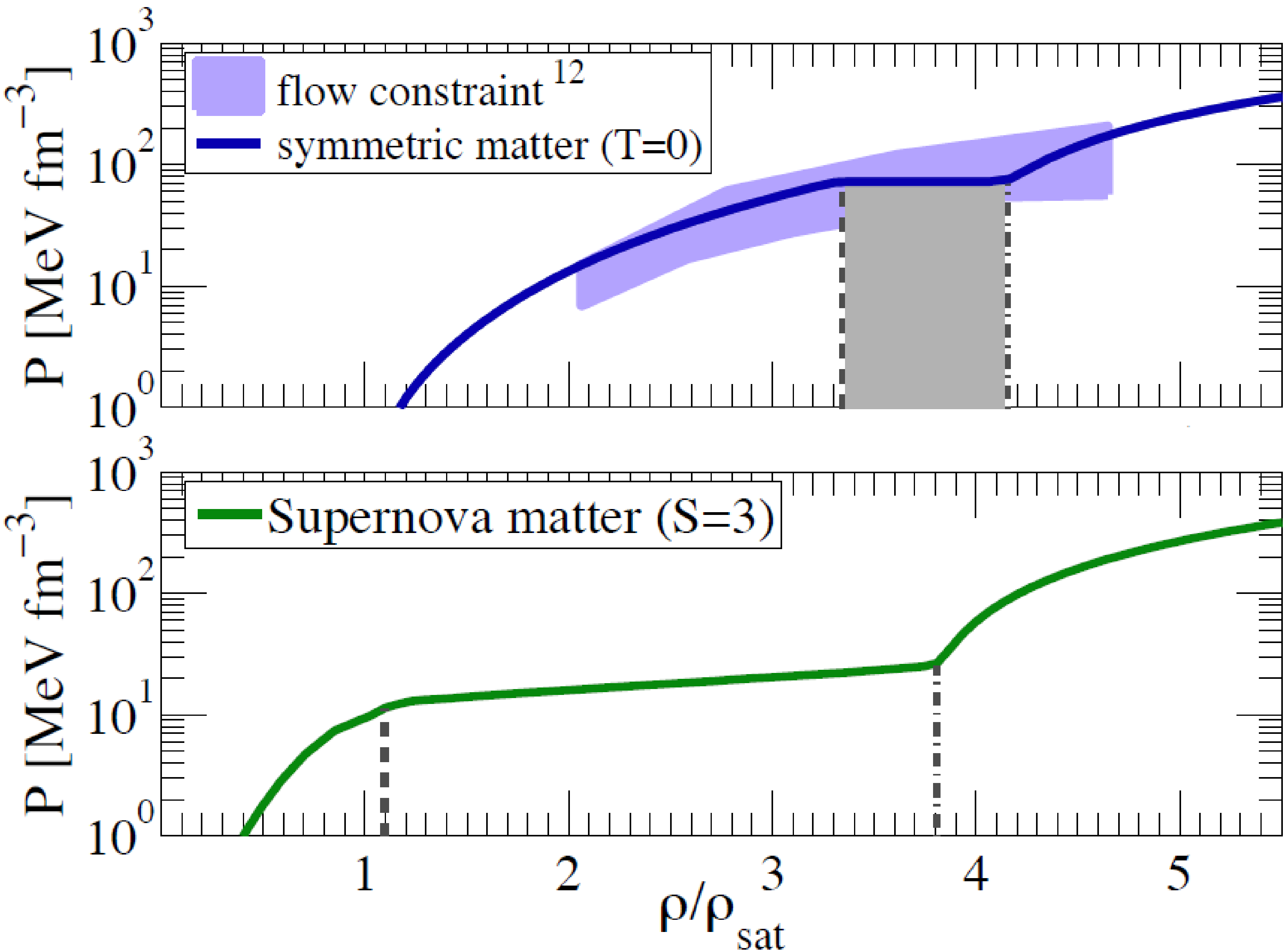
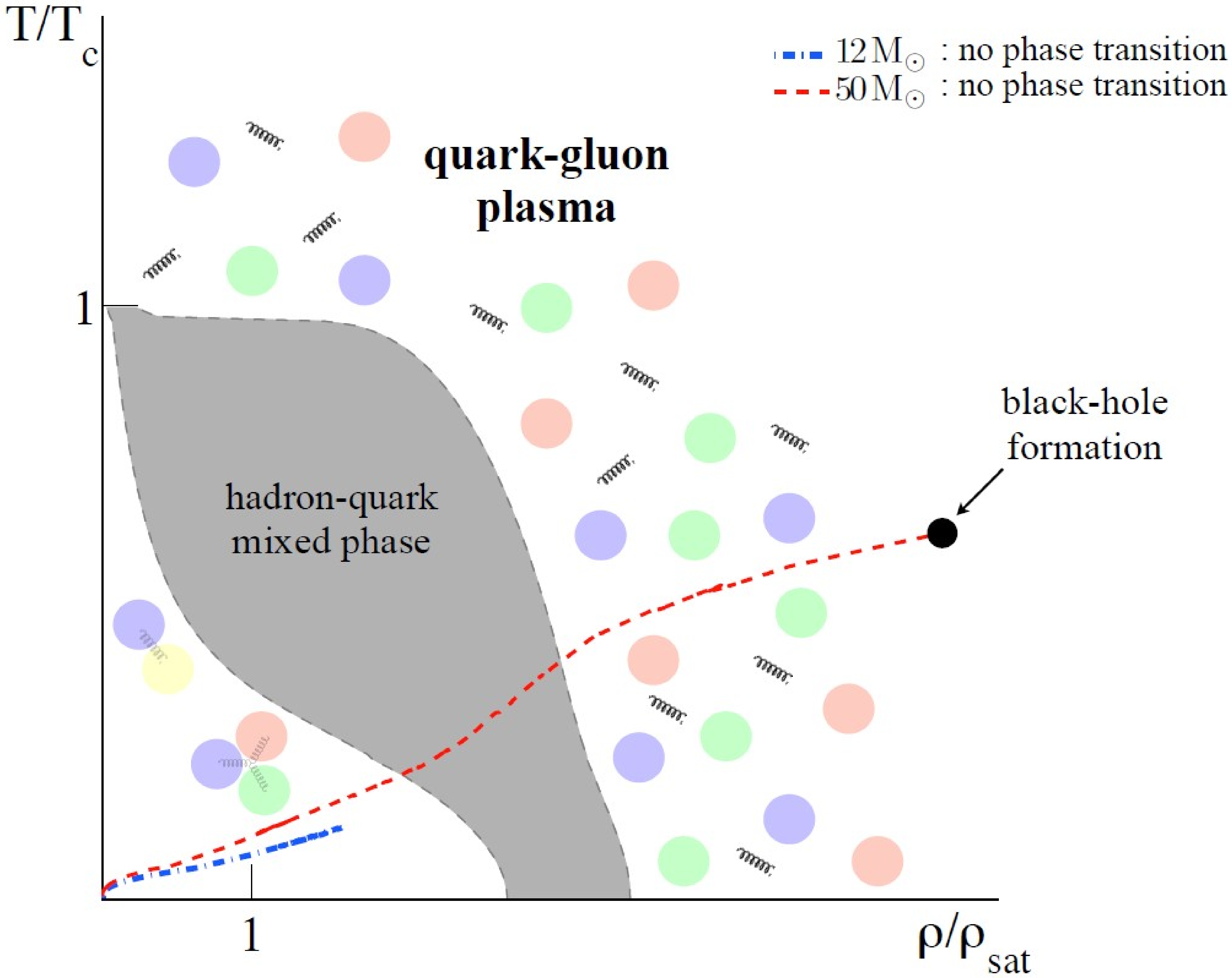


Nature Astron.2 (2018)



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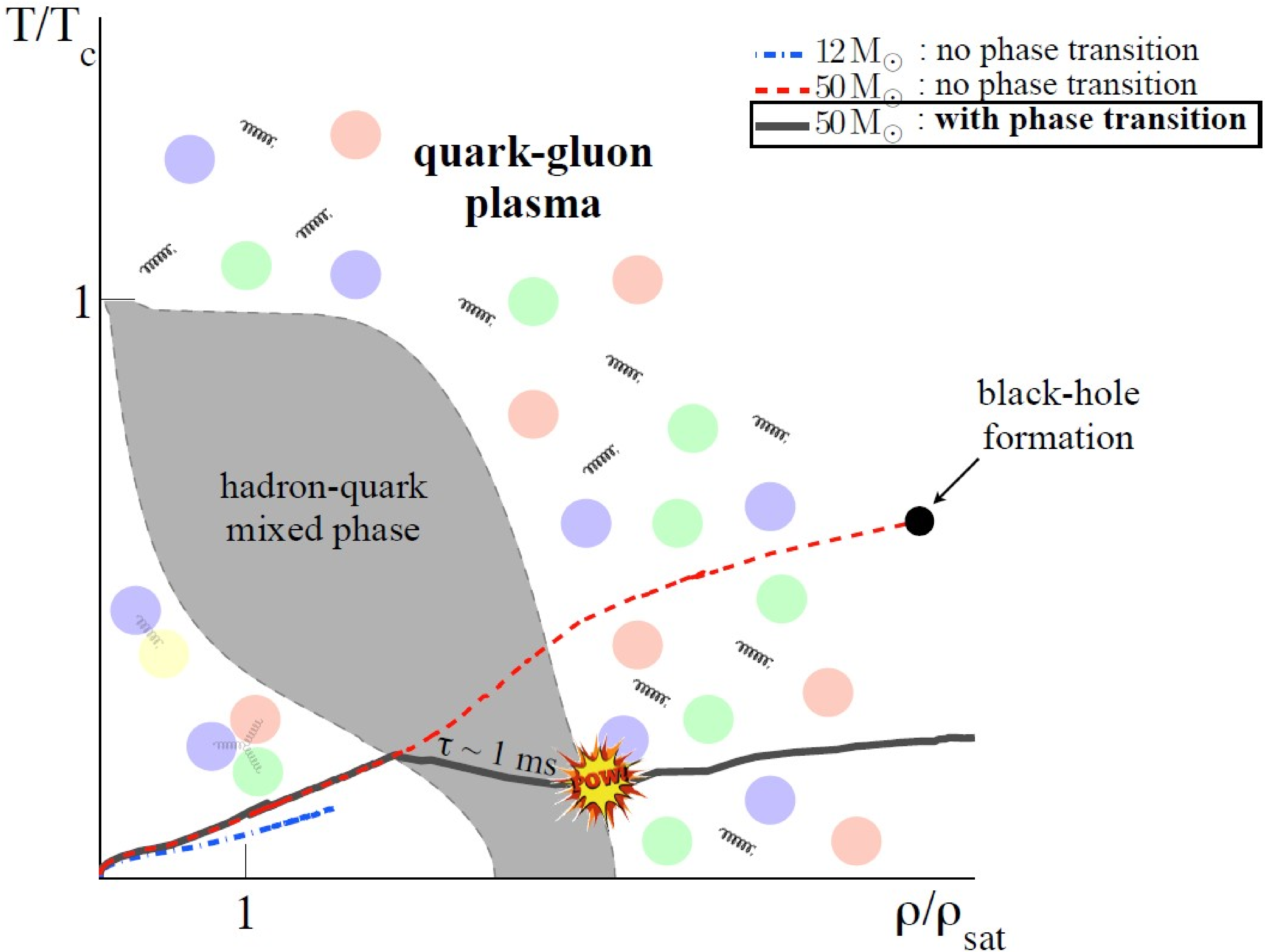

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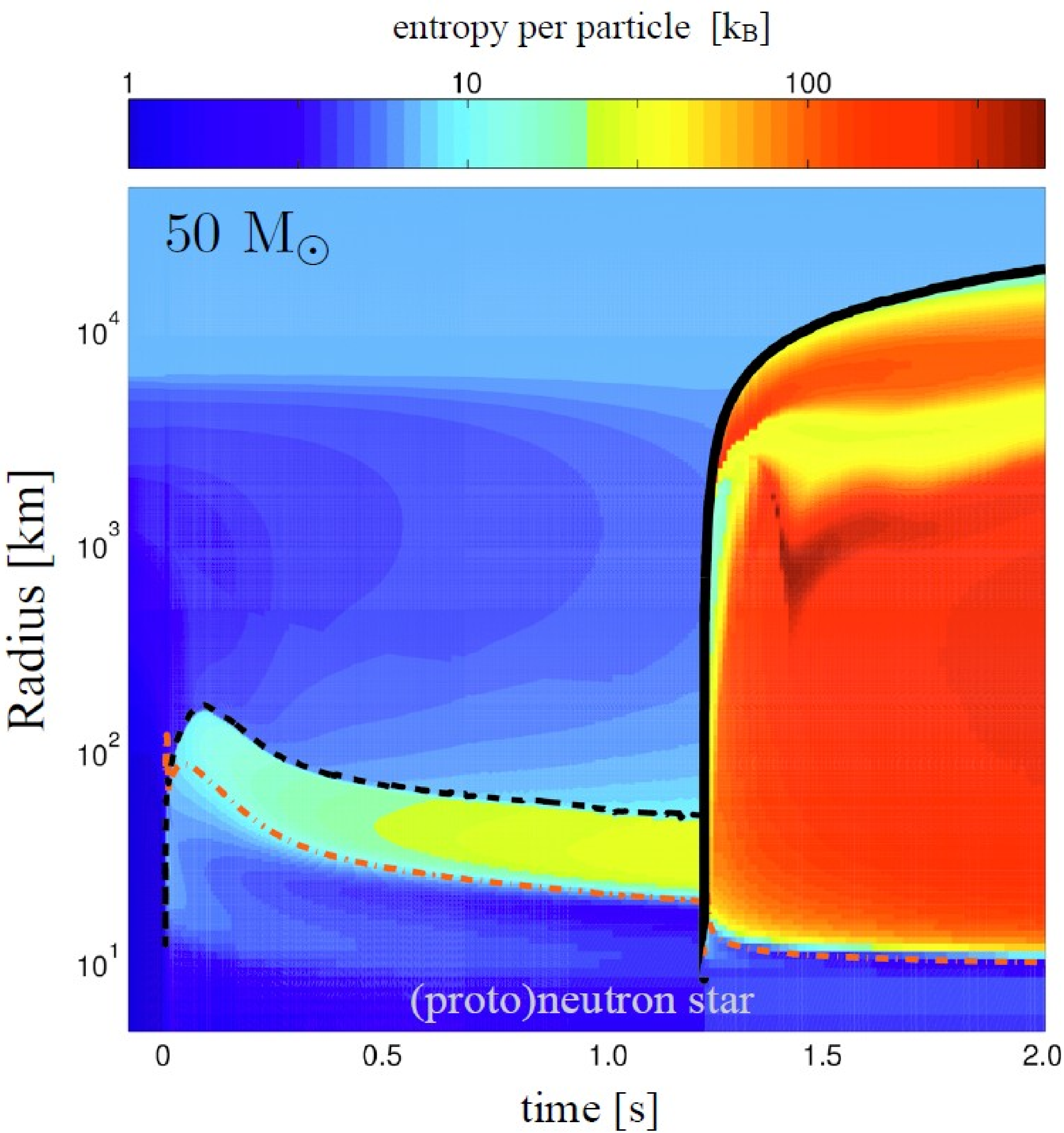
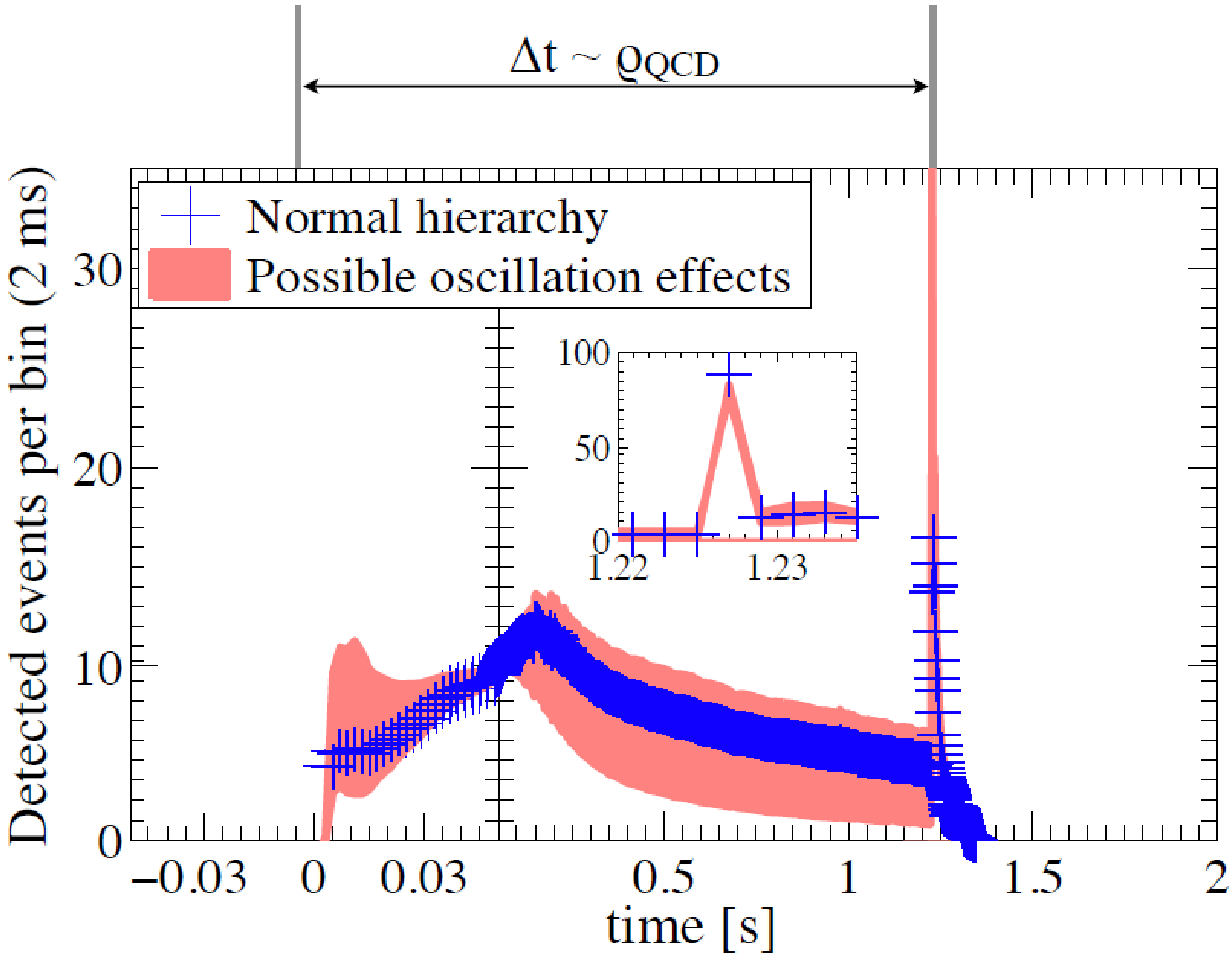


Nature Astron.2 (2018)

ν – signal @ Super-Kamiokande (d ~ 10 kpc)



Nature Astron.2 (2018)

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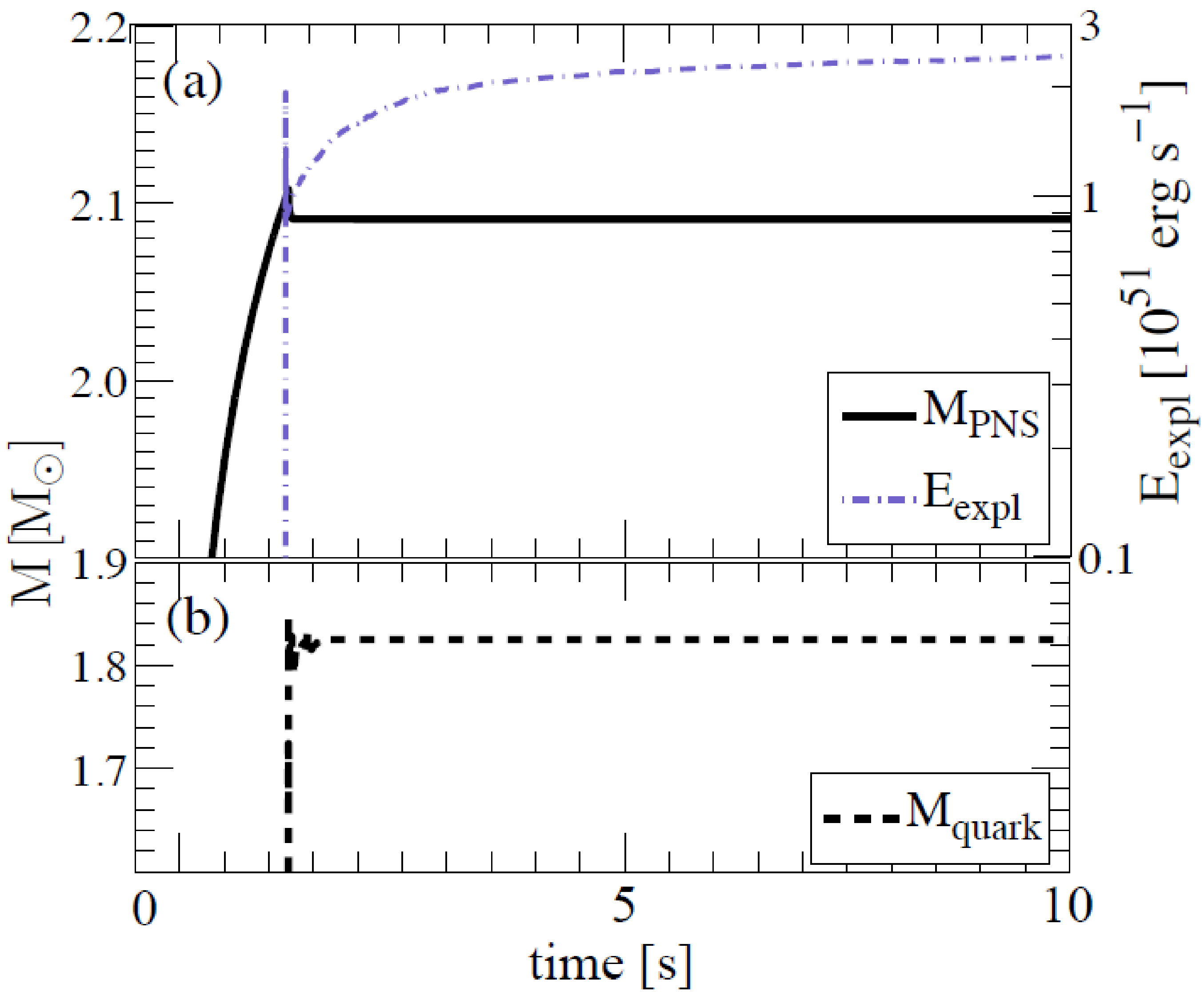
$$E_{expl} = 3 \times 10^{51} \text{ erg s}^{-1}$$
$$M_{NS} \simeq 2 \, M_\odot$$



Nature Astron.2 (2018)

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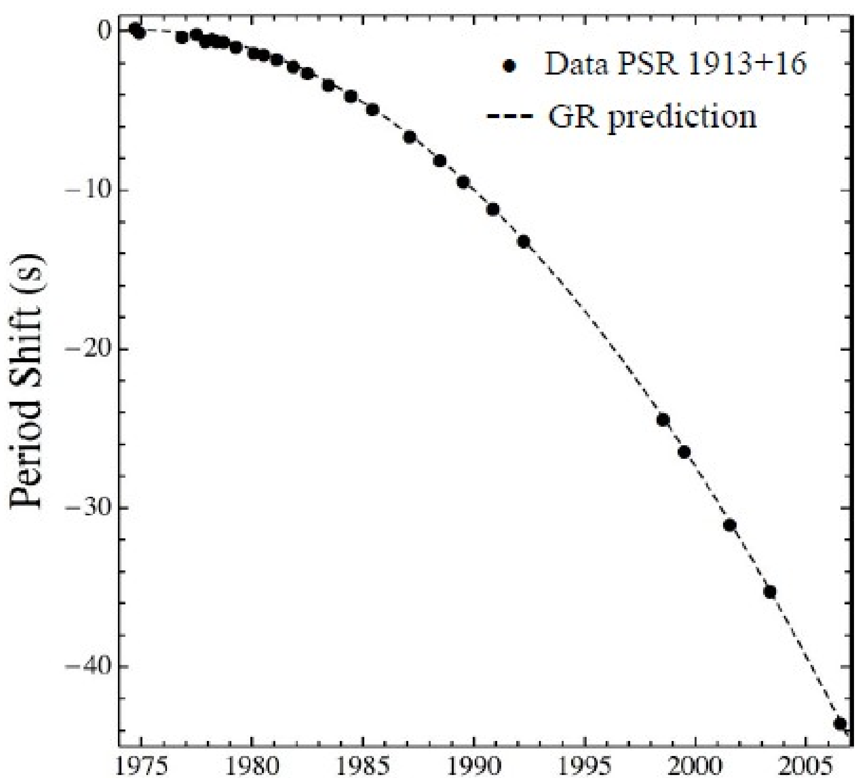
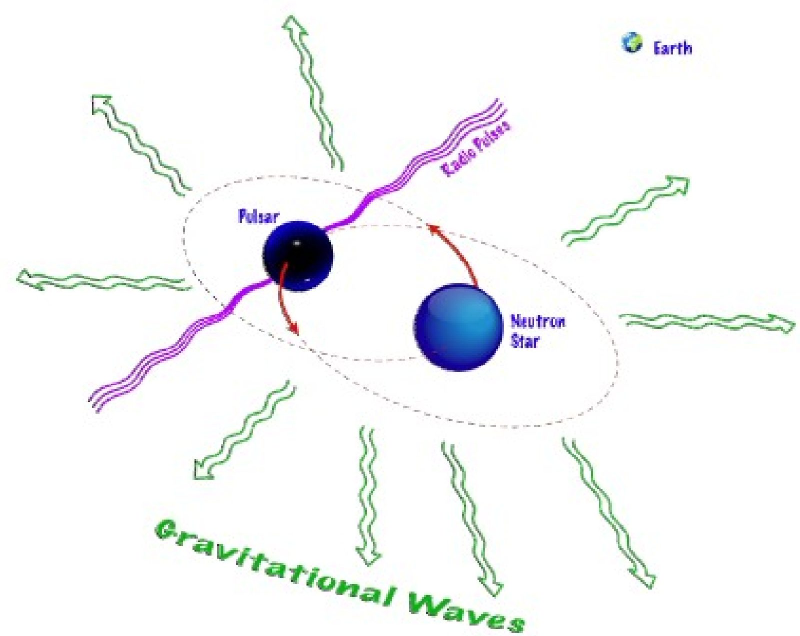
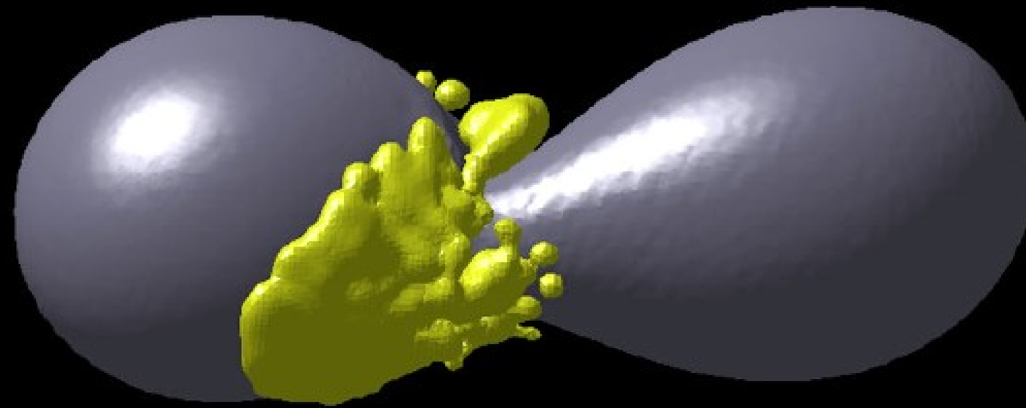
The Nobel Prize in Physics 1993

Russell A. Hulse, Joseph H. Taylor Jr.

"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"





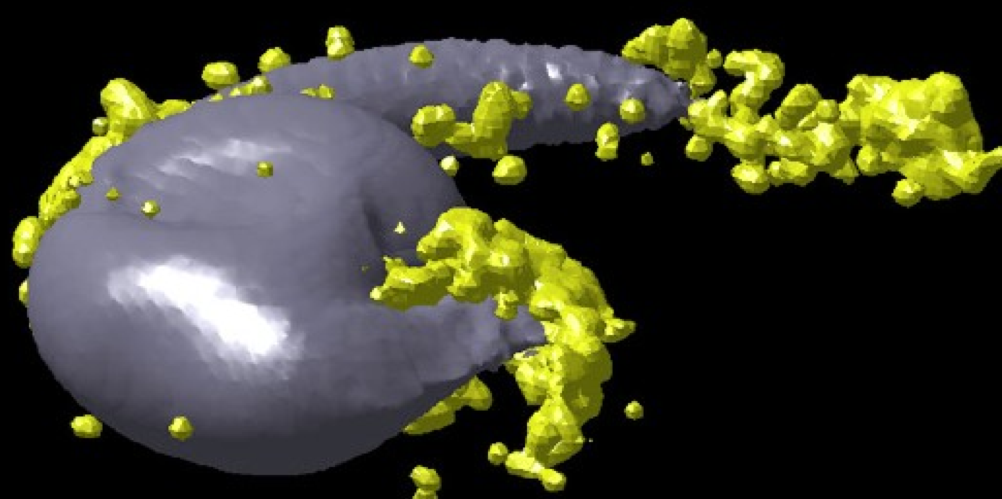


Goriely et al.,(2011) ApJ 738, L32
Bauswein & Janka (2010) PRD 82, 084043

Baiotti et al.,(2008) PRD 78, 084033
Freiburghaus et al.,(1999) ApJ 525, L121
Lattimer et al.,(1974) ApJ 192, L145

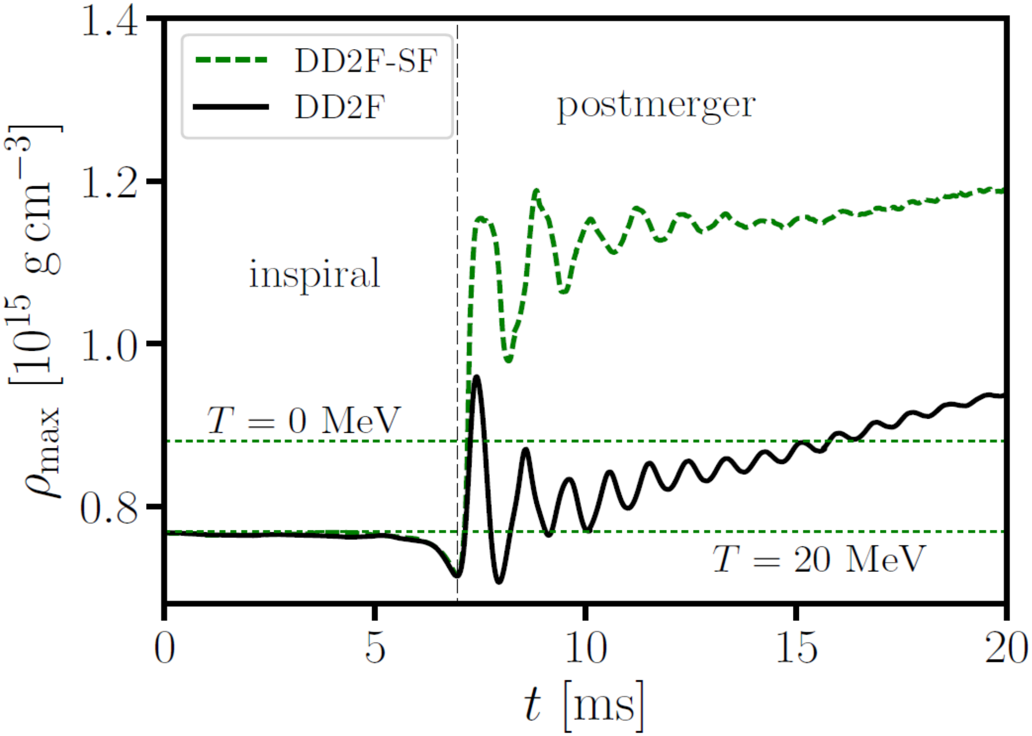
Rezzolla et al,(2016) PRD 93, 124051
Goriely et al.,(2015) MNRAS 452, 894
Bauswein et al.,(2015) PRC 92, 055805
Eichler et al.,(2015) ApJ 808, 13
Perego et al.,(2014) MNRAS 443, 3134
Korobkin et al.,(2012) MNRAS 426, 1940

1st binary neutron star merger detection: **GW170817**

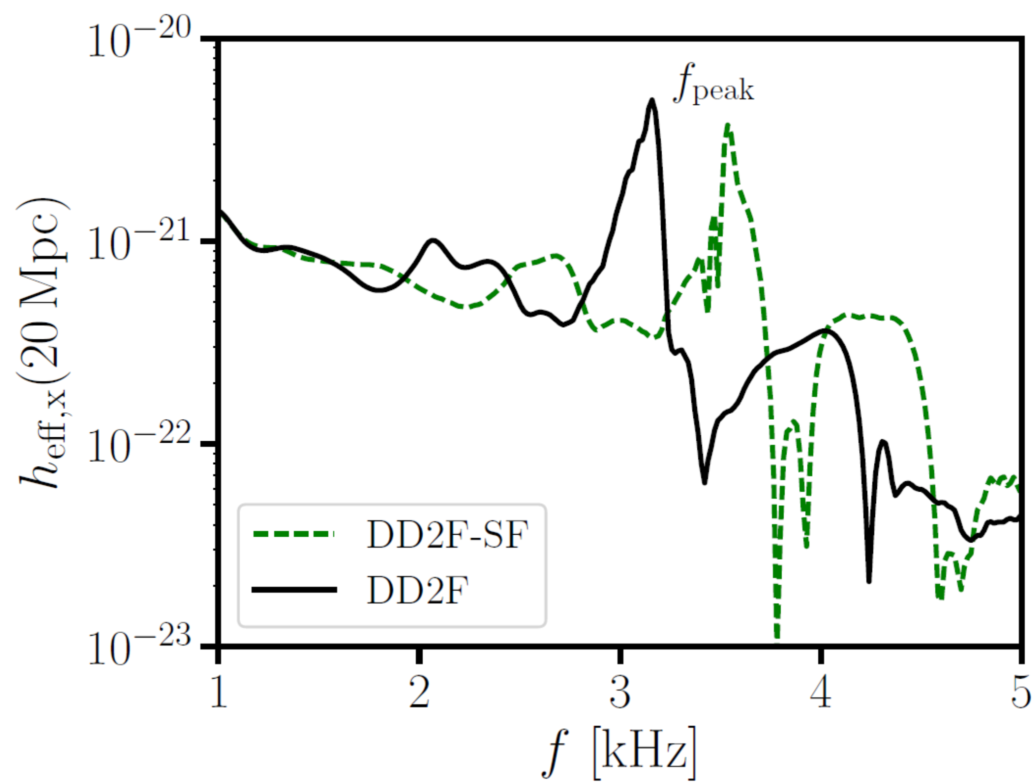


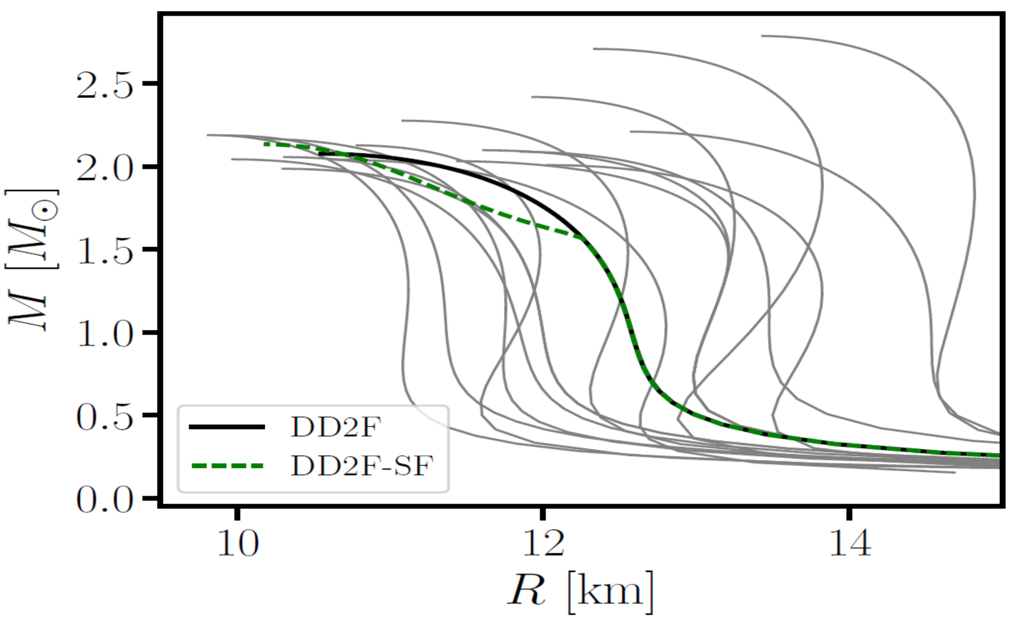
yellow regions: gold
grey: high baryon density

Hybrid star formation in postmerger phase



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



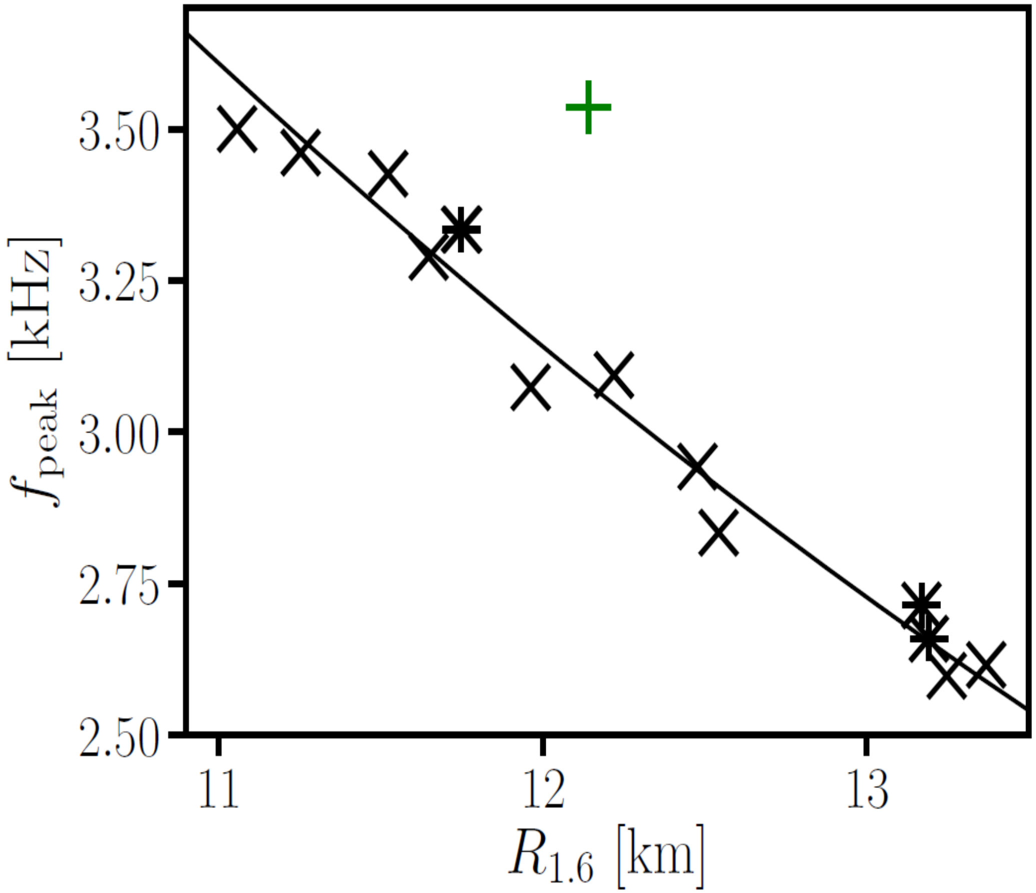


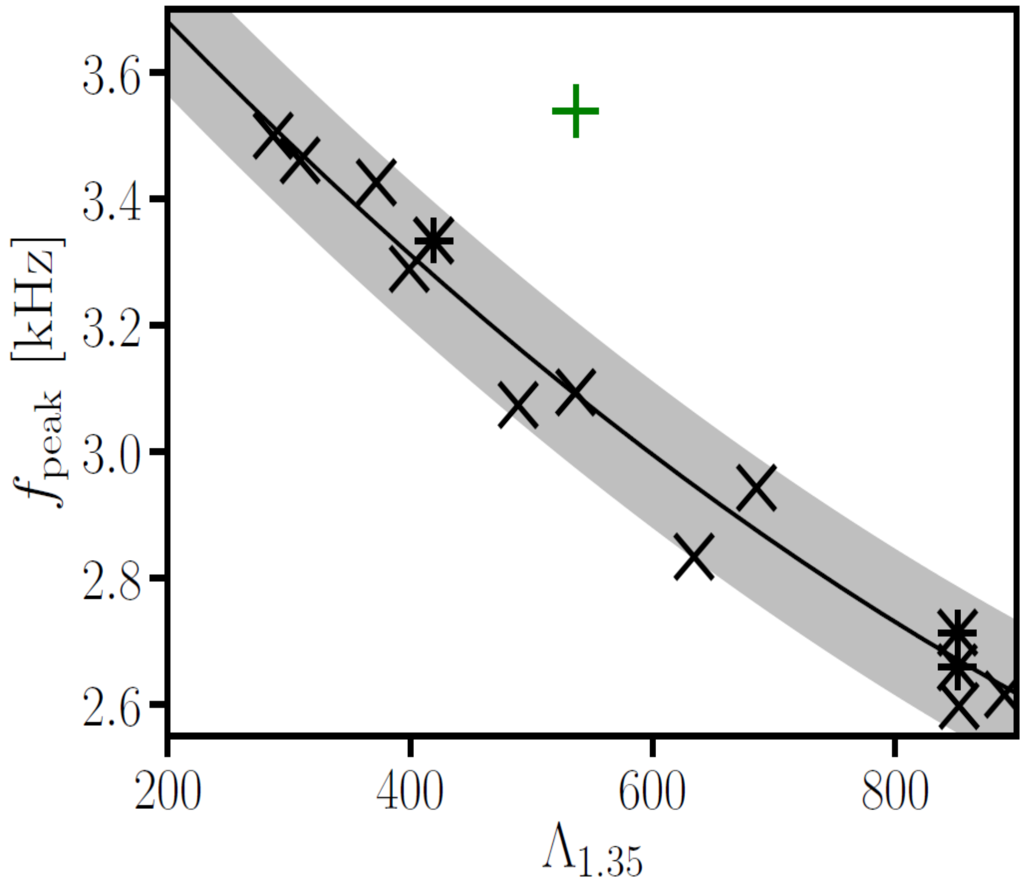
Hybrid star formaton during NS merger
→ higher densities and compacter star
→ higher peak frequency of the GW

Bauswein et al., arxiv:1809.01116

Hybrid star formation in postmerger phase

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



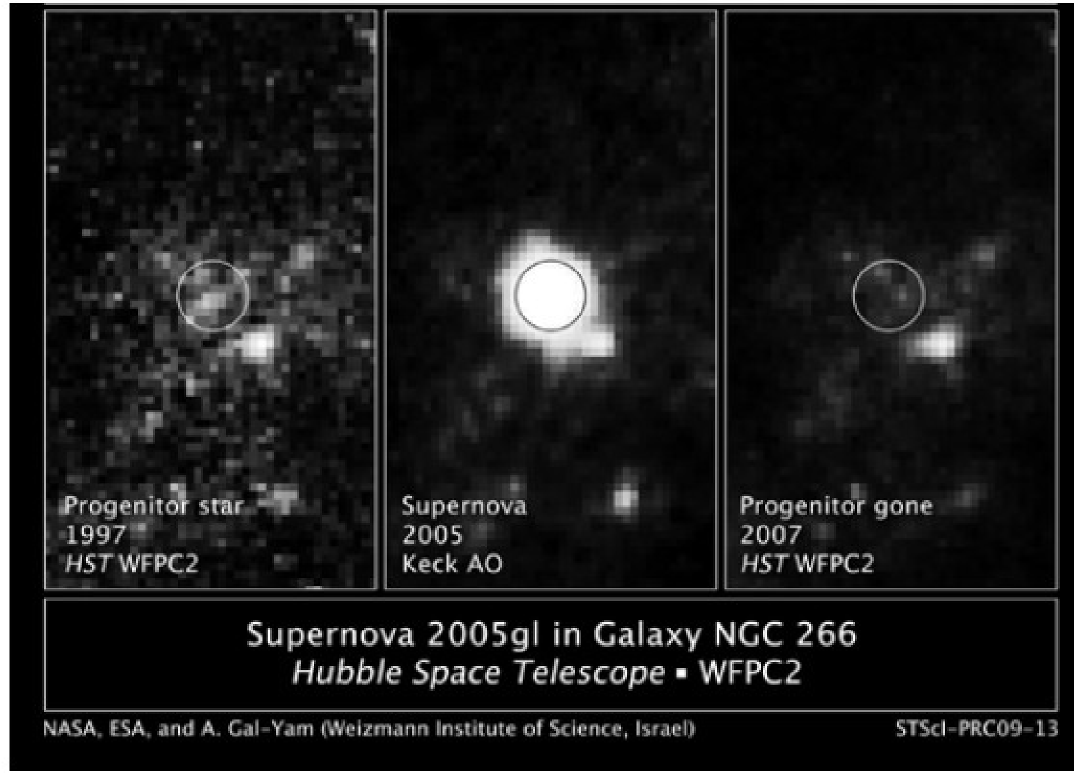


Strong deviation from **f_{peak} – $R_{1.6}$** relation signals **strong phase transition in** NS merger**!**

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

Novel road to explosions of *very* massive stars $\gtrsim 40 - 50 \ \mathrm{M}_\odot$

"The progenitor was so bright that it probably belonged to a class of stars called Luminous Blue Variables (LBVs)"



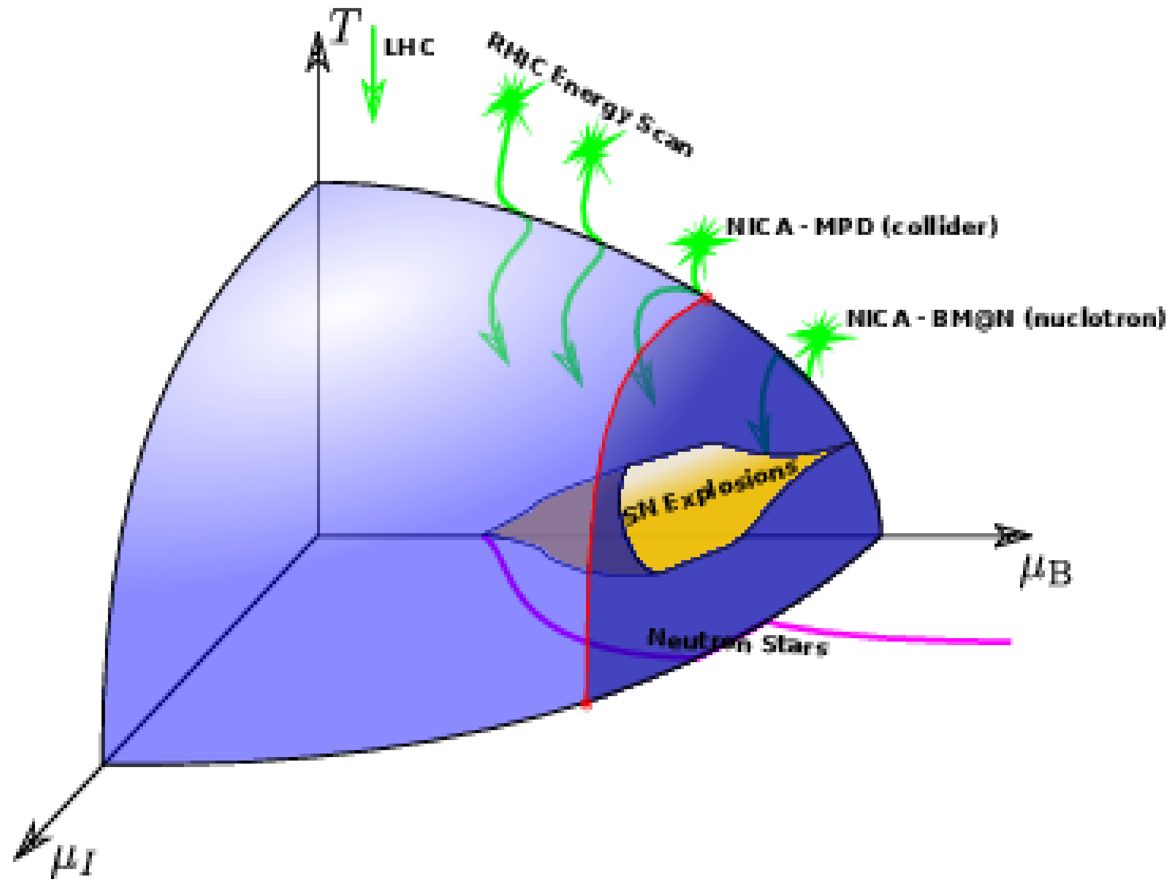
Remnants: massive neutron stars $\sim 2 \ \mathrm{M}_\odot$

Additional neutrino burst

GW-signal from neutron-star mergers

Conclusions:

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

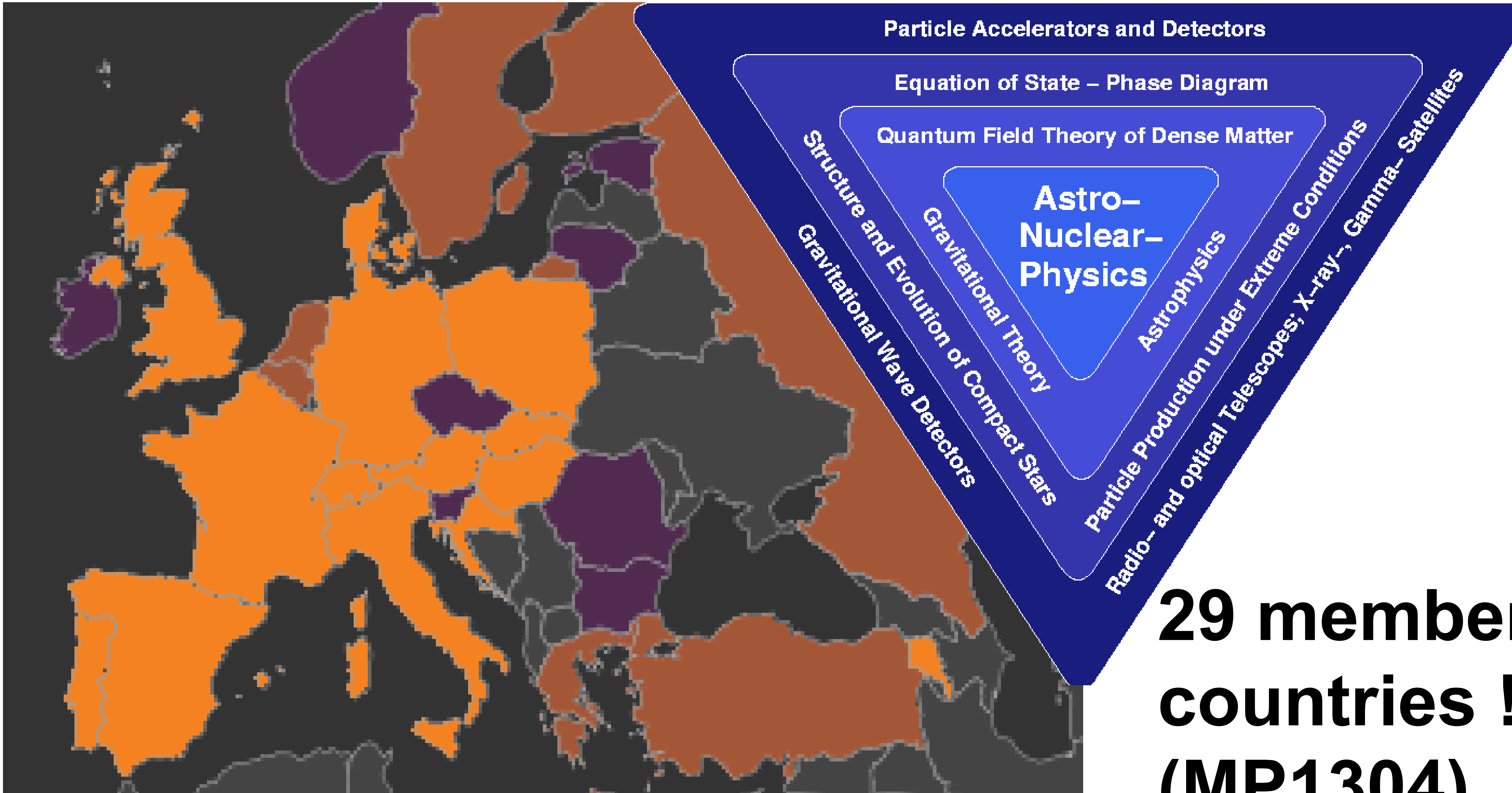


Main condition: stiff hadronic & stiff quark matter EoS with strong phase transition (PT)

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

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

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

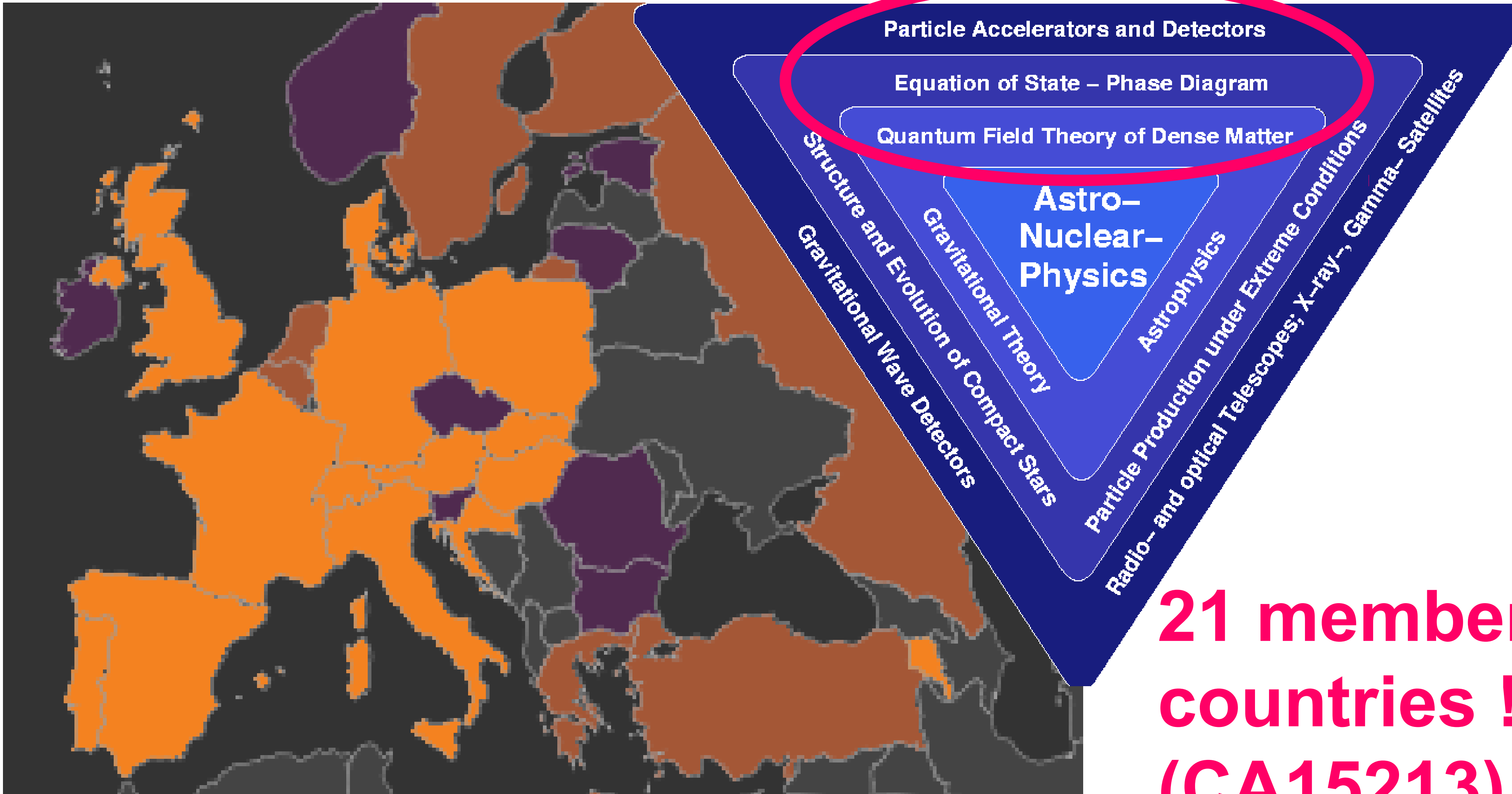


29 member countries !! (MP1304)

New compstar **!**

cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

November 2013 - November 2017



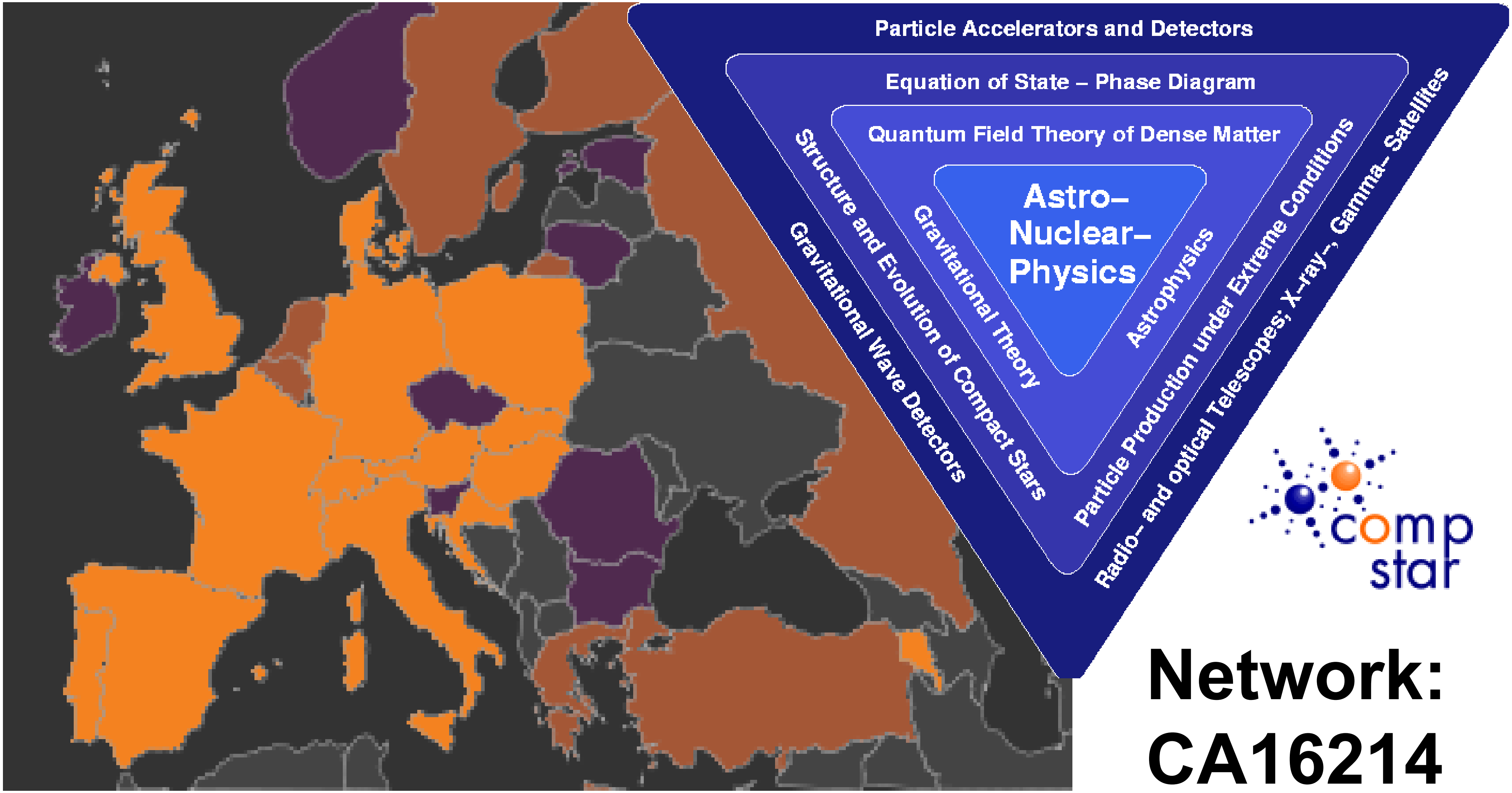
21 member countries ! (CA15213)

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

New: THOR!

cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

Kick-off: Brussels, October 17, 2016



comp star

Network: CA16214

Newest:

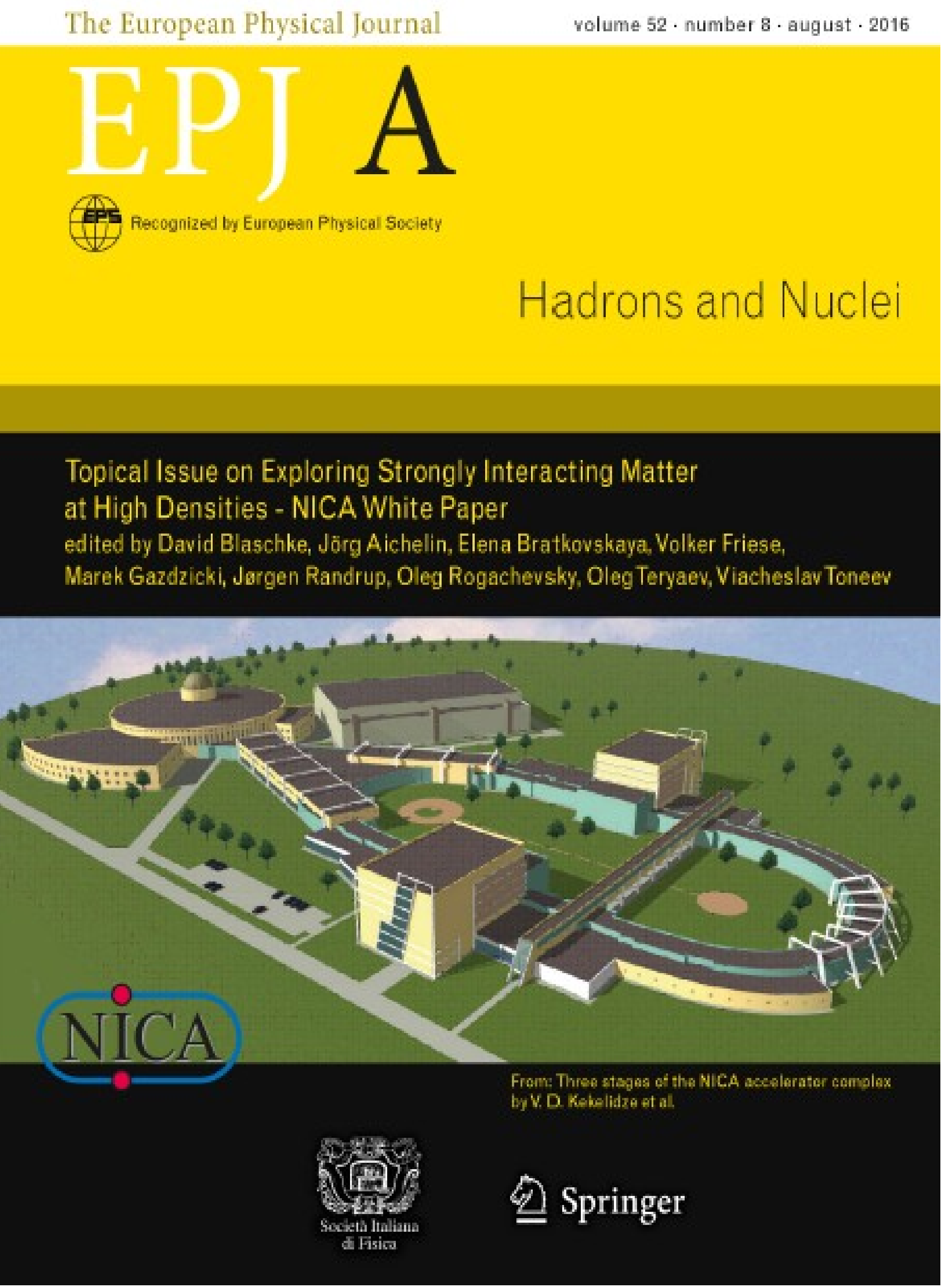
PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

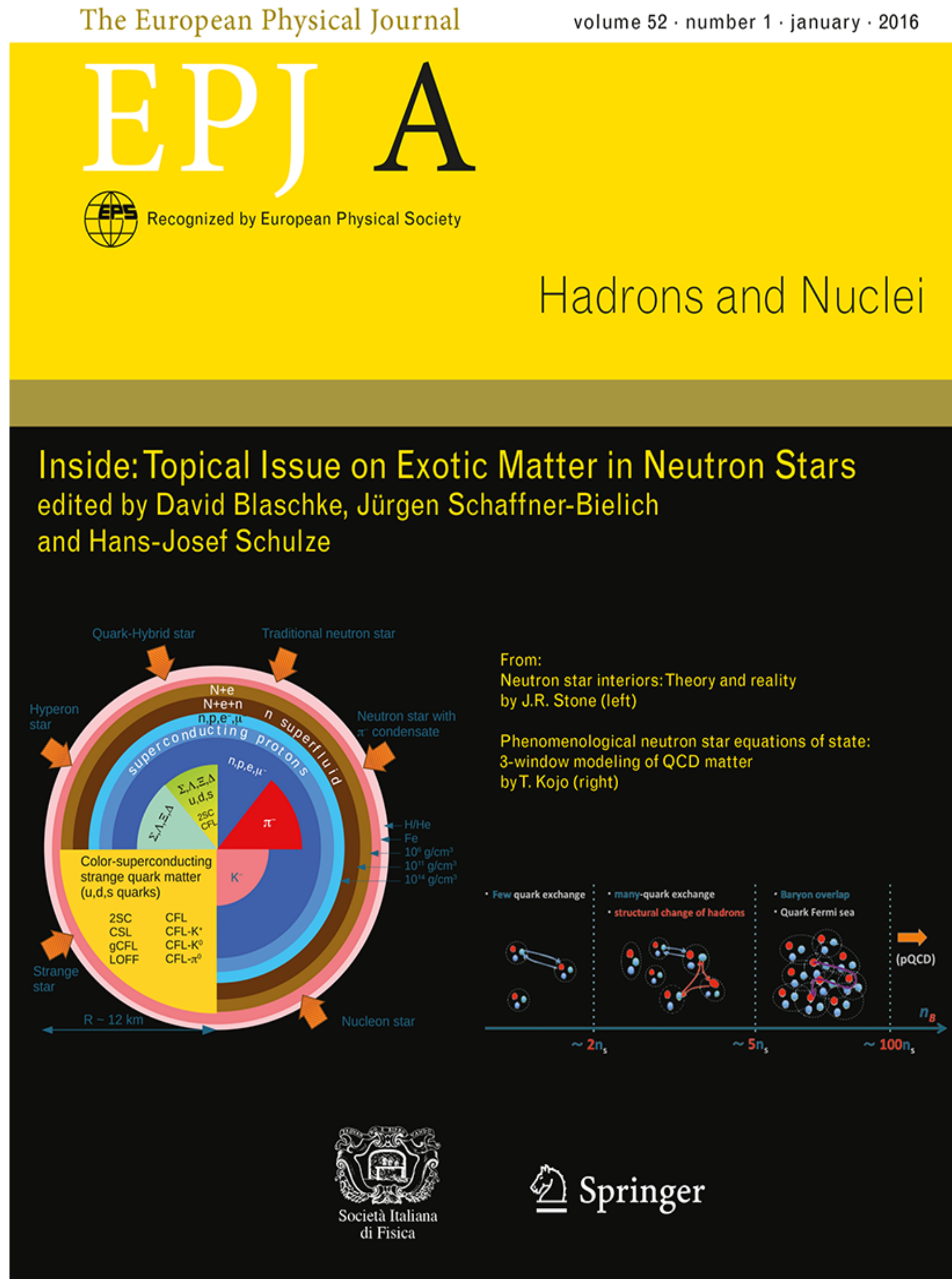
cost
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

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





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 – October 2018

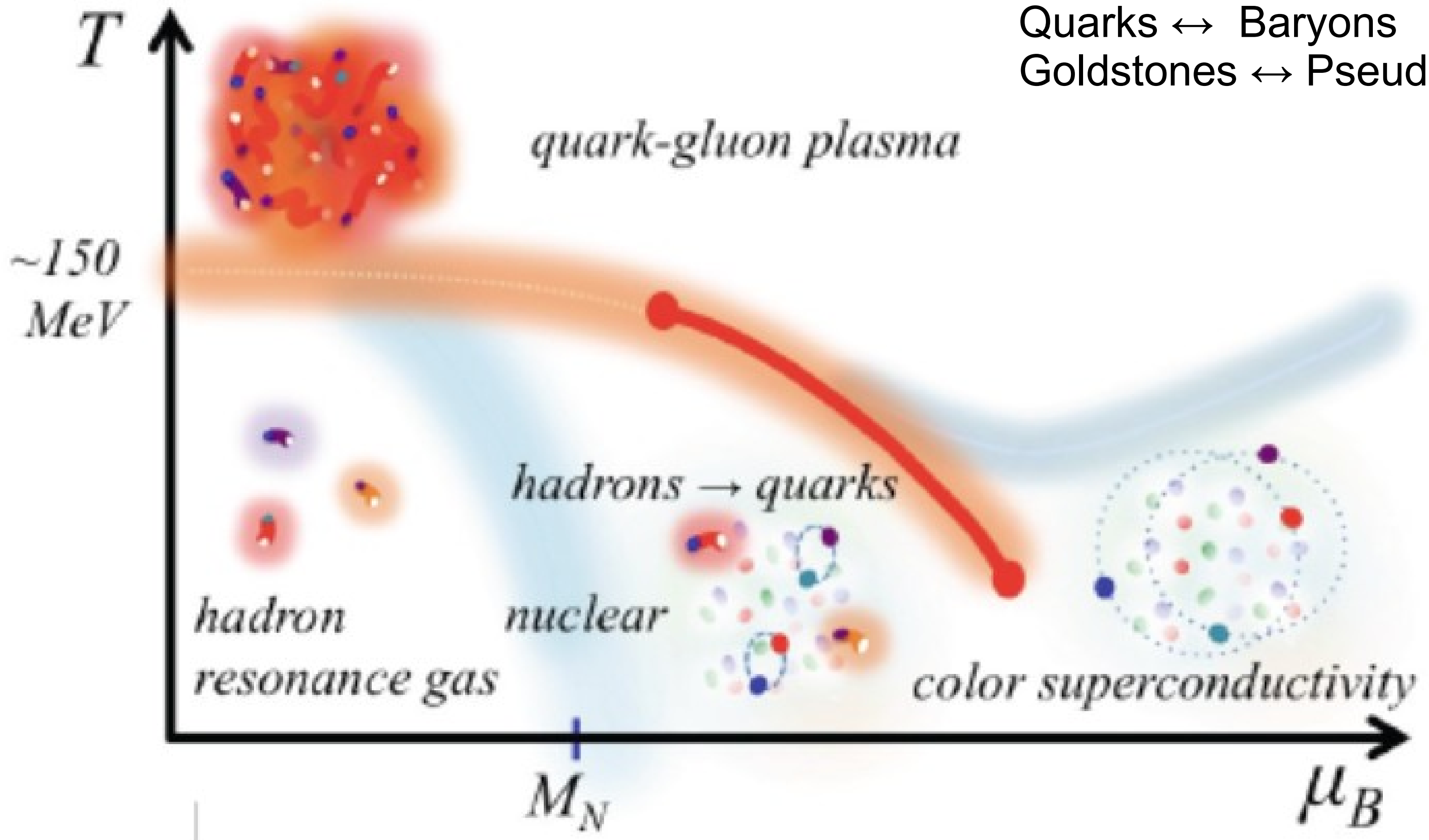
Website: https://www.epj.org/open-calls-for-papers/122-epj-a/

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

Backup slides

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

Gluons ↔ Vector mesons
Quarks ↔ Baryons
Goldstones ↔ Pseudoscalar mesons



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