Pro and con quark matter in Neutron stars

David Blaschke (HZDR/CASUS & IFT UWr)

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Stories to be told ...

Historic Introduction to Pro and Con

Terra Incognita: Agnostic Bayesian Analysis vs. Interpolation

Berlin Wall constraint

Confining Density Functionals for Quark Matter

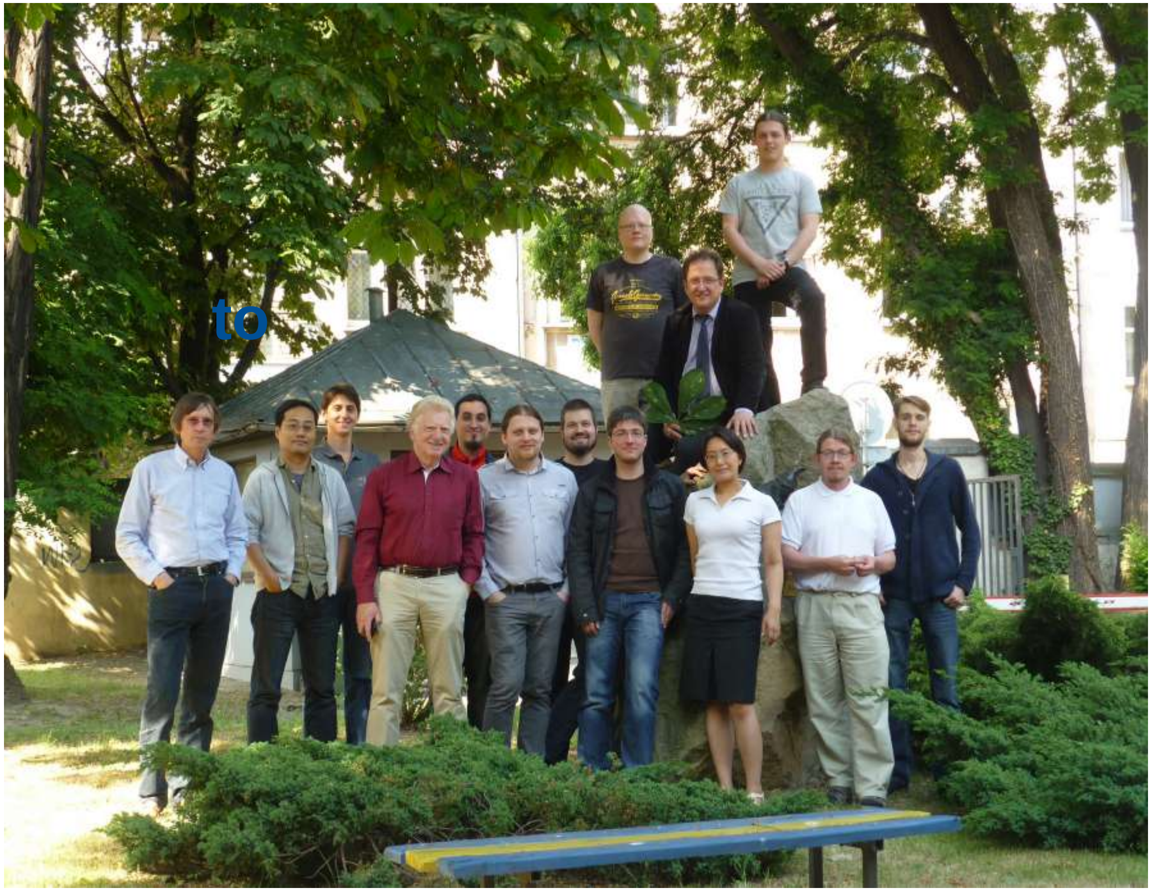
Special Points

Twins and Eccentric Binaries: Discover the 3rd Family !

Outlook: German Centre for Astrophysics (DZA)

Thanks to my collaborators:

T. Fischer, G. Röpke, A. Bauswein, O. Ivanytskyi, N. Bastian,
M. Cierniak, U. Shukla, S. Liebing, K. Maslov, A. Ayriyan,
H. Grigorian,
D.N. Voskresensky,
M. Kaltenborn,
G. Grunfeld,
D. Alvarez-Castillo,
B. Dönigus, D. Ohse,
S. Chanlaridis,
J. Antoniadis ...



Wroclaw Group ...

Pro and con quark matter in neutron stars

The early days: 1973 – asymptotic freedom of QCD

VOLUME 34, NUMBER 21 PHYSICAL REVIEW LETTERS 26 MAY 1975

Superdense Matter: Neutrons or Asymptotically Free Quarks?

Pro

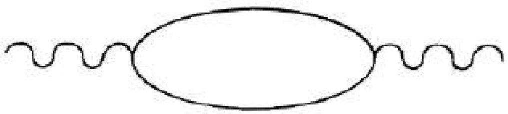
J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, England
(Received 6 January 1975)

We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.

$$B/V = \tfrac{1}{3}N/V = \tfrac{1}{18}d\textstyle\sum_i p_{\mathrm{F}i}{}^3/\pi^2, \quad (8)$$

$$P = \tfrac{1}{24}d\textstyle\sum_i p_{\mathrm{F}i}{}^4/\pi^2, \quad (9)$$

$$\rho = E/V = \tfrac{1}{8}d\textstyle\sum_i p_{\mathrm{F}i}{}^4/\pi^2, \quad (10)$$



$$E/N = BV/N + D(N/V)^{1/3} ,$$

with $D \equiv \frac{3}{4}\pi^2(1 + g_c^2/6\pi^2)\, \Sigma_i f_i^{4/3}$.

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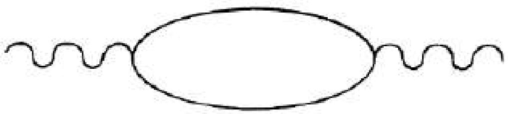

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Volume 62B, number 2 PHYSICS LETTERS 24 May 1976

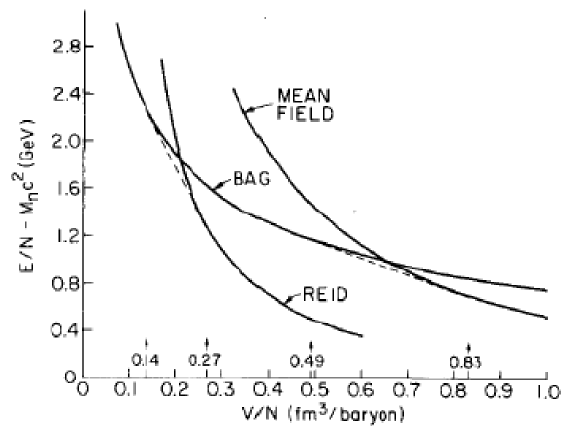
CAN A NEUTRON STAR BE A GIANT MIT BAG?*

Con

G. BAYM and S.A. CHIN
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA

Received 30 March 1976

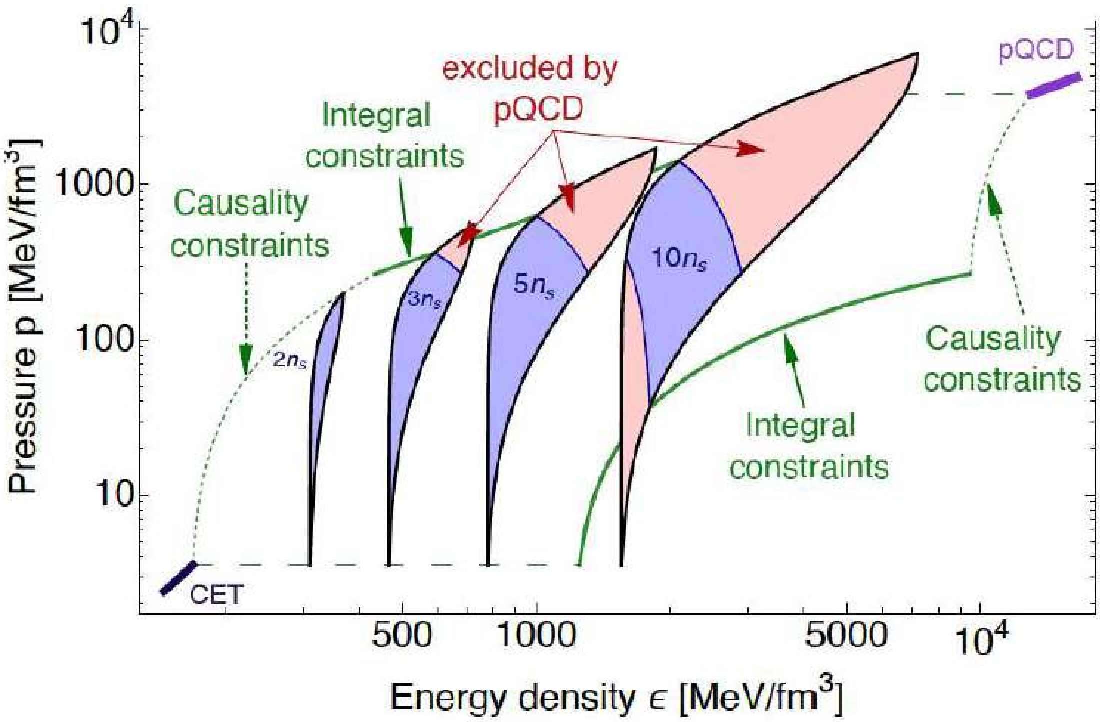
We show, on the basis of the M.I.T. bag model of hadrons, that a neutron matter-quark matter phase transition is energetically favorable at densities around ten to twenty times nuclear matter density. It is unlikely, however, that quark matter can be found within stable neutron stars, or that it may form a third family of dense stellar objects.



Pro and con quark matter in neutron stars

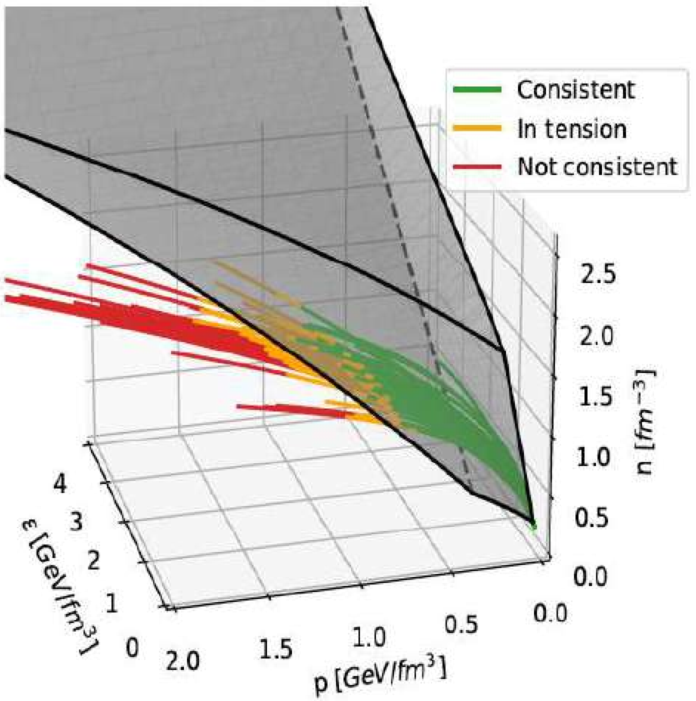
Nowadays:

Neutron star EoS constraint from pQCD



O. Komoltsev and A. Kurkela, Phys. Rev. D 128 (2022) 202701

Consistency check for neutron star EoS from the CompOSE library



Result: Not all EoS fulfill the consistency check with pQCD asymptotics! pQCD important for NS!

QCD Phase Diagram

Landscape of our investigations

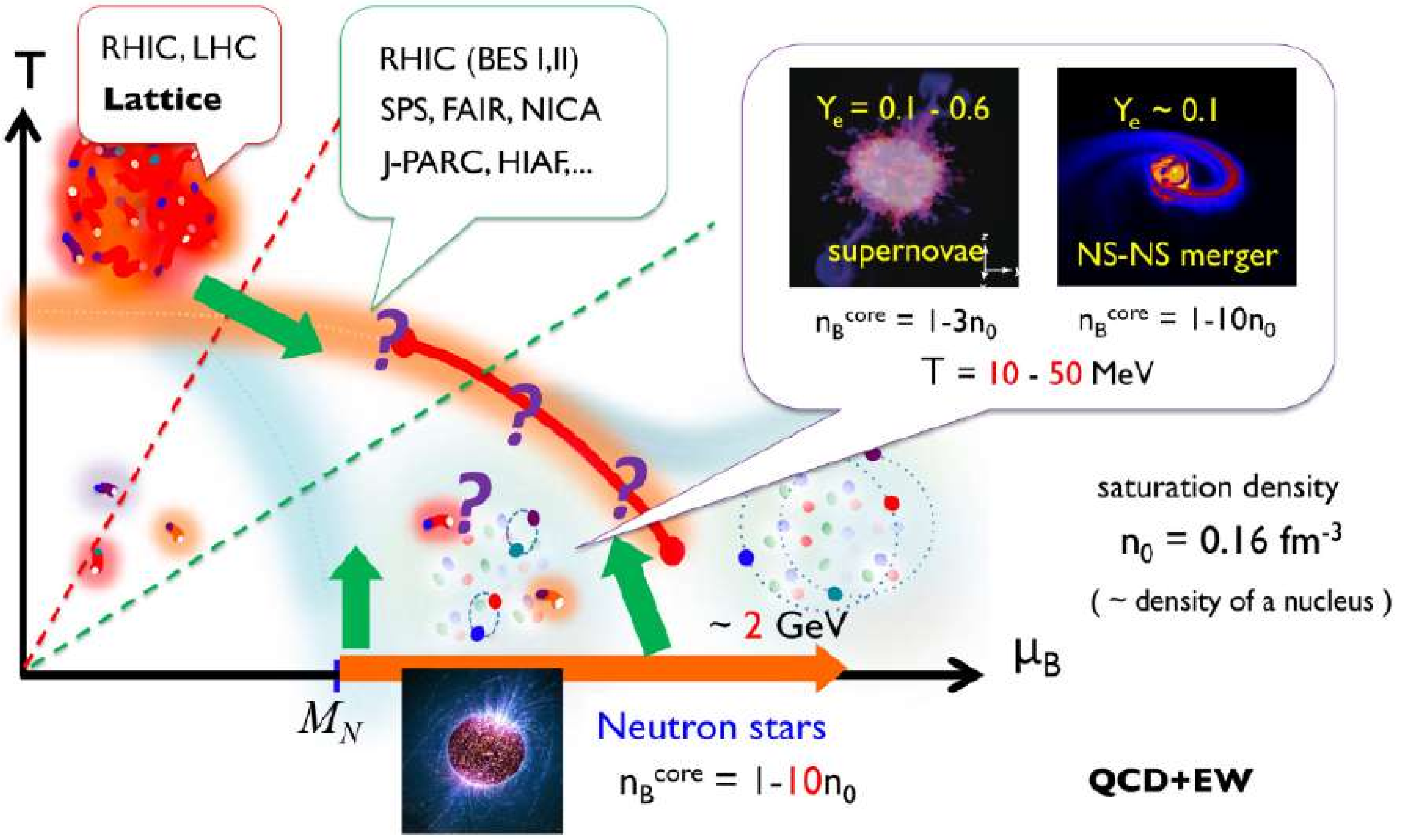
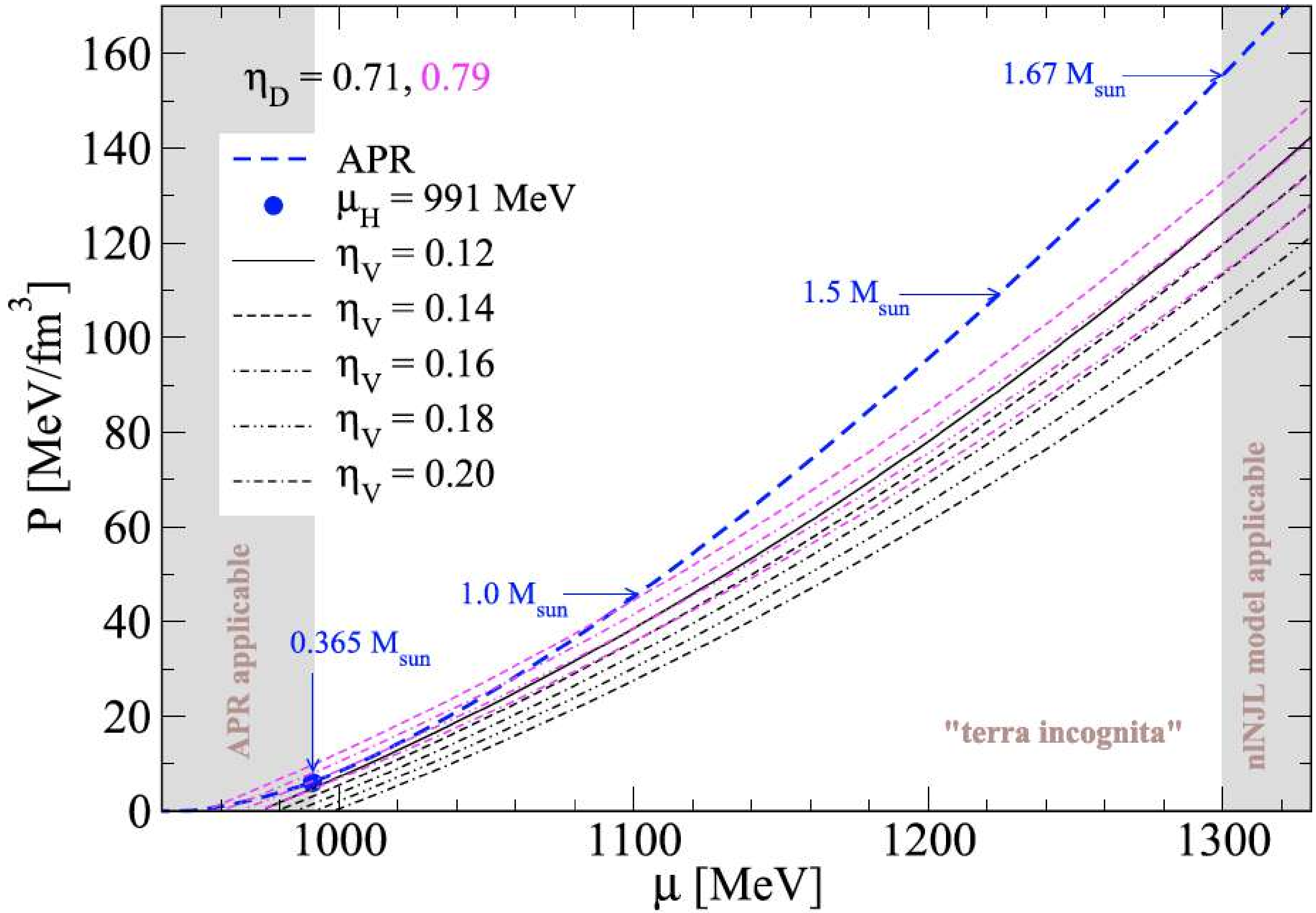


Figure from T. Kojo arXiv:1912.05326 [nucl-th]

Pro and con quark matter in neutron stars

Where is deconfinement in “terra incognita” ?



A. Ayriyan, D.B., A.G. Grunfeld, et al.

Eur. Phys. J. A (2021) 57:318
https://doi.org/10.1140/epja/s10050-021-00619-0

Neutron star EOS from multimessenger data

Bayesian analysis, nontrivial $c_s(p)$, Gaussian process

D. Mroczek, M.C. Miller, et al., Nontrivial features in cs inside neutron stars, arXiv:2309.02345

The method of (modified) Gaussian process based on cs(p)

Auxiliary function:

$$\phi \equiv \ln(d\varepsilon/dp - 1) = \ln(1/c_s^2 - 1)$$

Gaussian process:

$$\phi(\log_{10} p_i) = \mathcal{N}\left[\mu_i(\log_{10} p_i), \Sigma_{ij}\right]$$

Quadrature:

$$\varepsilon = \int \frac{dp}{c_s^2(p)} \longrightarrow p(\varepsilon)$$

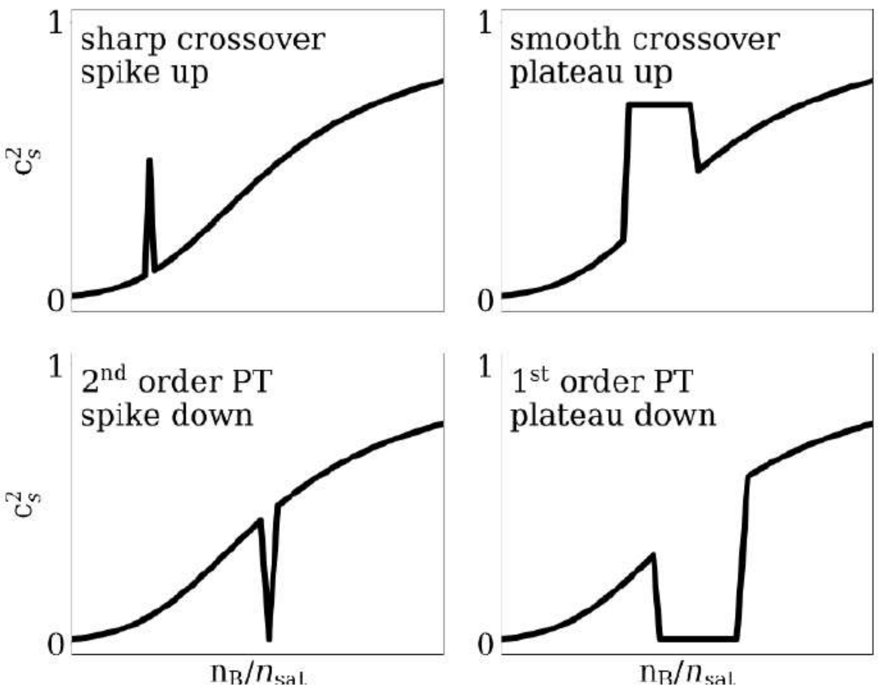
First law of thermodynamics

$$\frac{dn_B}{d\varepsilon} = \frac{n_B}{\varepsilon + p(\varepsilon)}$$

Result: EOS sample from GP as a set

$$\left\{\phi(p), c_s^2(n_B), p(\varepsilon)\right\}$$

Cartoon of physical features in $c_s^2(n_B)$



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Grey:
160 forms of cs2 from GP

CMF:
chiral mean field EOS

QHC19:
Baym, Furusawa, Hatsuda, Kojo, Togashi, ApJ 885, 42 (2019)

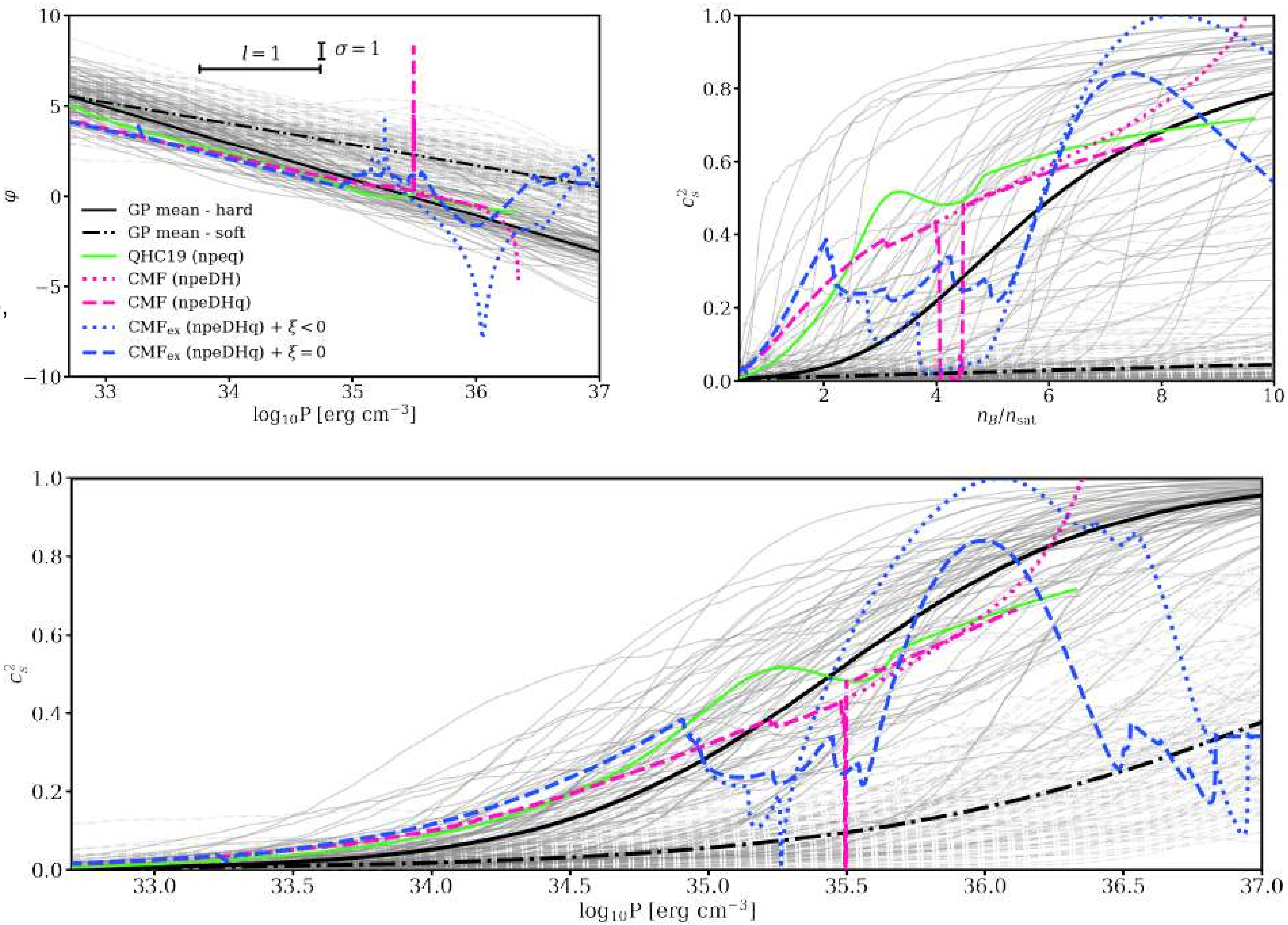

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TABLE I. Connection between phase transitions of different orders/crossover to corresponding physical processes in terms of the effect on the speed of sound *in equilibrium* and modifications in the mGP framework. Note that a first-order phase transition has a jump in baryon density across Δn_B.

Transition type	Physical Process	Representation in c_s^2	Modification
sharp crossover	quarkyonic matter [23, 41–43, 118], percolation to quark matter [38, 44], quark-meson coupling [34, 119] heavy resonances [92–98], hyperons [46, 92], chiral-superfluid transition [120]	for $\delta \ll 1$, if $n_B = \tilde{n}_B \pm \delta$, then $\left(c_s^2\right)' = \pm\delta^{-1}$ if $n_B = \tilde{n}_B$, then $\left(c_s^2\right)' = 0$	spike up, $c_s^2 \neq 0$
smooth crossover		for $\delta > 0$, if $n_B = \tilde{n}_B \pm \delta$, then $\left(c_s^2\right)' = \pm\delta^{-1}$ if $n_B \sim \tilde{n}_B$, then $\left(c_s^2\right)' \sim 0$	plateau up, $c_s^2 = 0$
n^{th}-order PT, $n > 2$		if $n_B = n_{crit}$, then $d^n p/d\mu_B^n \to \infty$	spike or plateau down, $c_s^2 \neq 0$
2nd order PT	critical point due to exotic quark phases	$c_s^2(n_{\text{crit.}}) = 0$	spike down toward $c_s^2 \approx 0$
1st order PT	quark deconfinement [92, 94], color-superconductivity, colorflavor-locking [25]	$c_s^2(n_\text{B}) = 0$ with $n_\text{B} \in [n_\text{B}^*, n_\text{B}^* + \Delta n_\text{B}]$	plateau down at $c_s^2 \approx 0$

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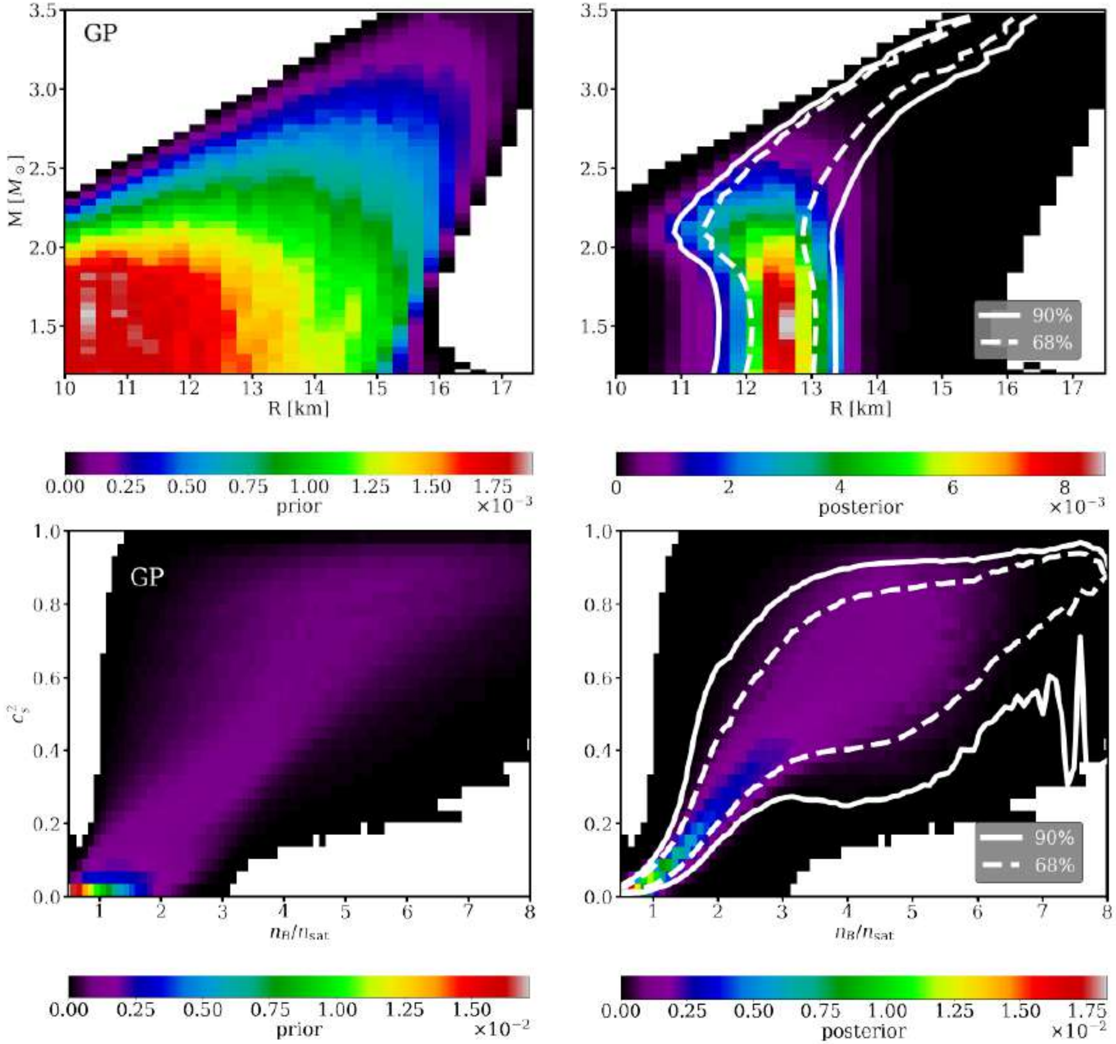

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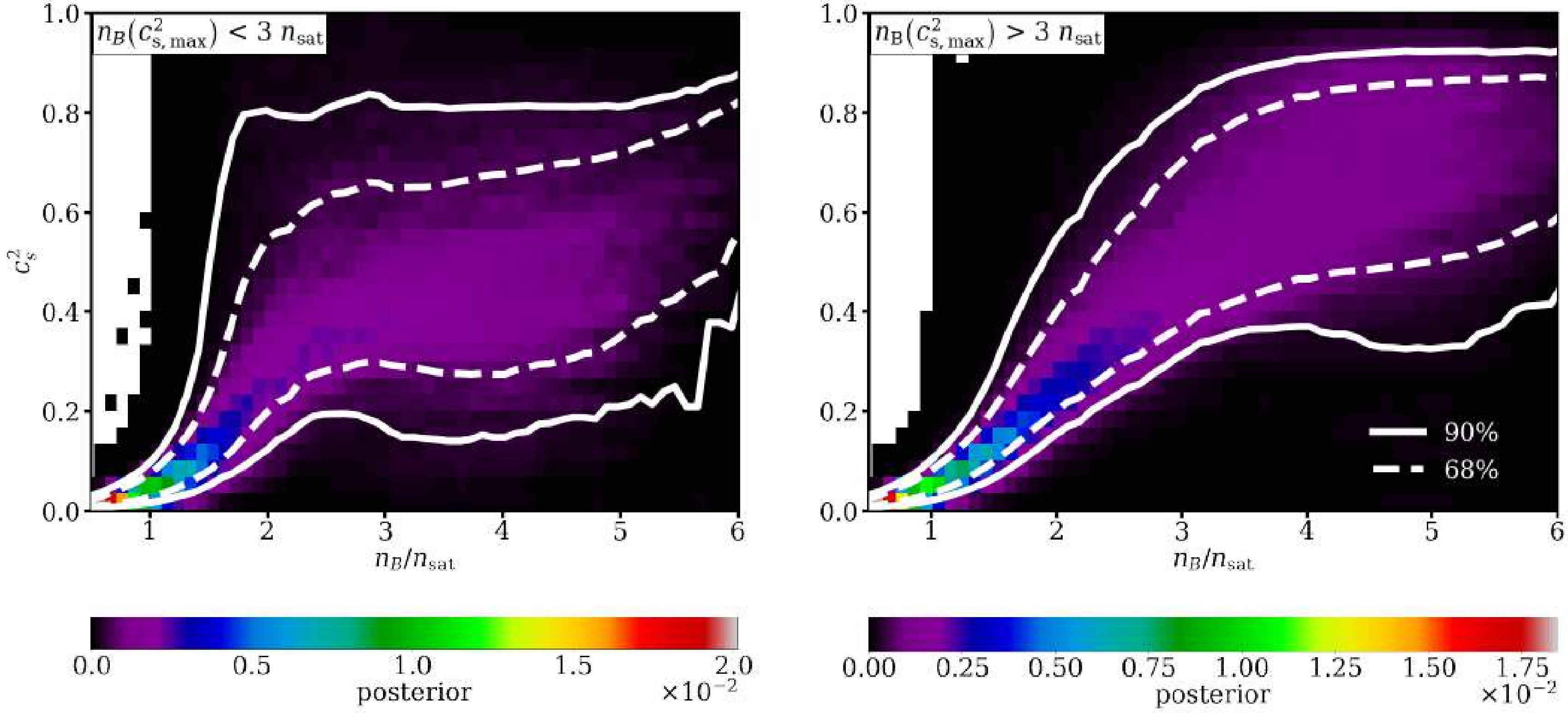


- EOS posterior probabilities when a global maximum in cs2 is present below (left) and above (right) 3 n_sat
- Posterior probability that central density for max. massive star is greater than 6 n_sat is negligible

- Global maximum (indicating softening, perhaps PT) is consistent with, but not required by, current constraints

Neutron star EOS from multimessenger data

Bayesian analysis based on $c_s(p)$

L. Brandes, W. Weise, N. Kaiser,
Evidence **against** strong 1st order PT in NS cores,
arXiv:2306.06218

Data and constraints		
Previous	PSR J1614–2230	$M = 1.908 \pm 0.016\, M_\odot$ [3]
	PSR J0348+0432	$M = 2.01 \pm 0.04\, M_\odot$ [4]
	PSR J0030+0451	$M = 1.34^{+0.15}_{-0.16}\, M_\odot$
		$R = 12.71^{+1.14}_{-1.19}$ km [7]
	PSR J0740+6620	$M = 2.072^{+0.067}_{-0.066}\, M_\odot$
		$R = 12.39^{+1.30}_{-0.98}$ km [8]
	GW170817	$\tilde{\Lambda} = 320^{+420}_{-230}$ [12]
	GW190425	$\tilde{\Lambda} \leq 600$ [13]
	ChEFT	[34, 35]
	pQCD	[36–38]
BW	PSR J0952-060	$M = 2.35 \pm 0.17\, M_\odot$ [39]
HESS	HESS J1731-347	$M = 0.77^{+0.20}_{-0.17}\, M_\odot$
		$R = 10.4^{+0.86}_{-0.78}$ km [40]

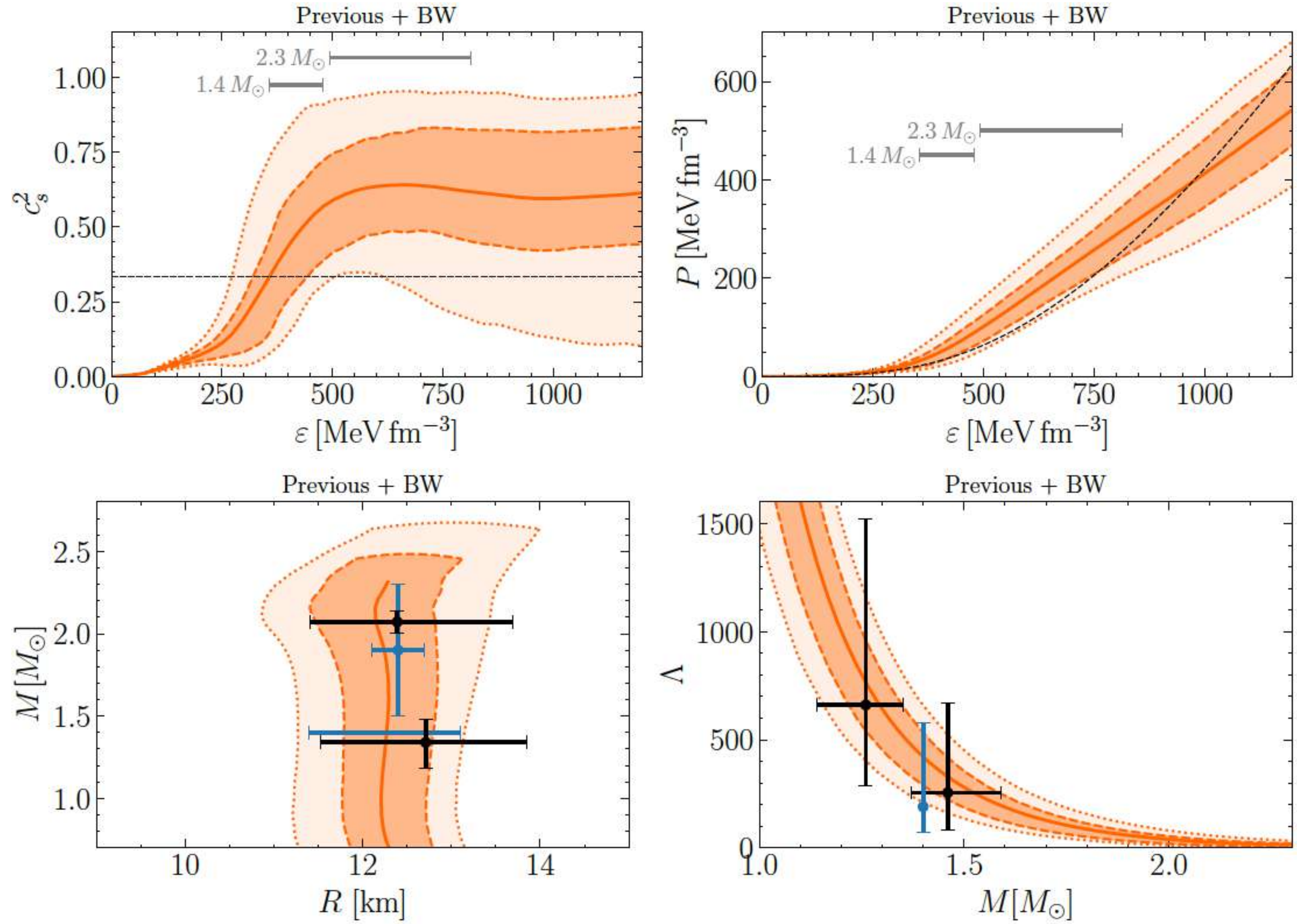
		Previous		Previous + BW	
		95%	68 %	95%	68 %
$1.4\, M_\odot$	n_c/n_0	$2.8^{+0.8}_{-0.7}$	± 0.4	2.6 ± 0.7	$^{+0.3}_{-0.4}$
	ε_c [MeV fm^{-3}]	451^{+133}_{-123}	$^{+62}_{-71}$	423^{+118}_{-116}	$^{+56}_{-67}$
	P_c [MeV fm^{-3}]	64^{+30}_{-23}	$^{+12}_{-16}$	60^{+28}_{-20}	$^{+11}_{-14}$
	R [km]	$12.2^{+0.9}_{-1.0}$	± 0.5	$12.3^{+0.8}_{-1.0}$	± 0.5
	Λ	396^{+226}_{-197}	$^{+107}_{-127}$	421^{+236}_{-200}	$^{+114}_{-124}$
$2.1\, M_\odot$	n_c/n_0	$4.1^{+1.9}_{-1.5}$	$^{+0.8}_{-0.9}$	$3.6^{+1.6}_{-1.3}$	± 0.7
	ε_c [MeV fm^{-3}]	716^{+416}_{-326}	$^{+162}_{-213}$	628^{+357}_{-251}	$^{+149}_{-146}$
	P_c [MeV fm^{-3}]	225^{+239}_{-134}	$^{+62}_{-110}$	186^{+184}_{-104}	$^{+52}_{-80}$
	R [km]	11.9 ± 1.3	± 0.7	$12.1^{+1.3}_{-1.2}$	$^{+0.6}_{-0.8}$
	Λ	21^{+30}_{-15}	$^{+9}_{-13}$	26^{+30}_{-20}	$^{+10}_{-14}$

		Previous + BW	
		95%	68 %
$2.3\, M_\odot$	n_c/n_0	$3.8^{+1.6}_{-1.3}$	$^{+0.7}_{-0.8}$
	ε_c [MeV fm^{-3}]	673^{+363}_{-268}	$^{+140}_{-180}$
	P_c [MeV fm^{-3}]	237^{+226}_{-134}	$^{+69}_{-104}$
	R [km]	12.3 ± 1.2	$^{+0.7}_{-0.6}$
	Λ	14^{+17}_{-10}	$^{+4}_{-9}$

Neutron star EOS from multimessenger data

Bayesian analysis, nontrivial $c_s(p)$, Gaussian process

L. Brandes, W. Weise, N. Kaiser, Evidence **against** strong 1st order PT in NS cores, arXiv:2306.06218



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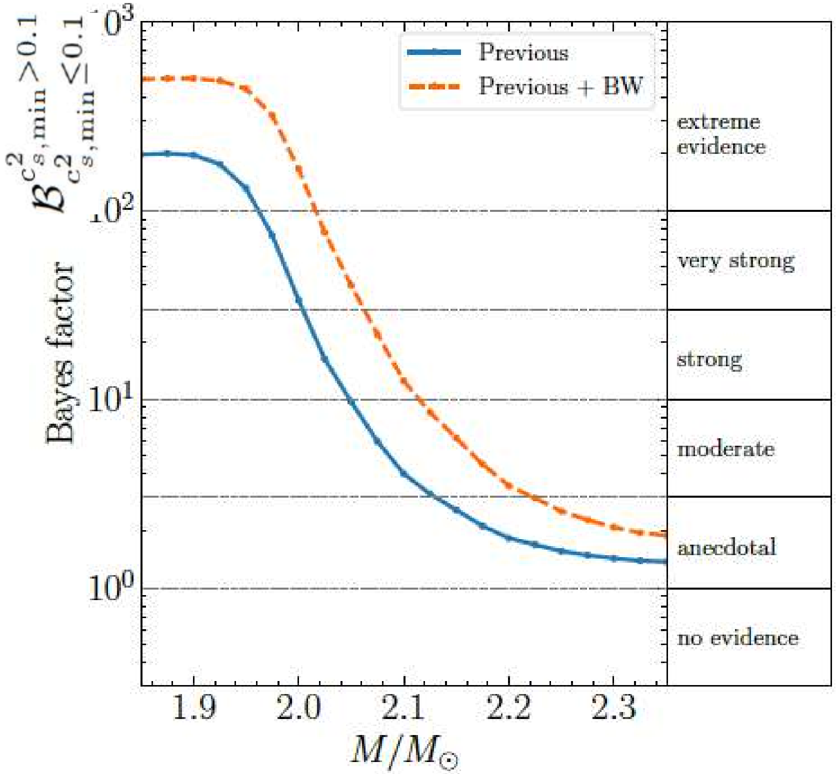

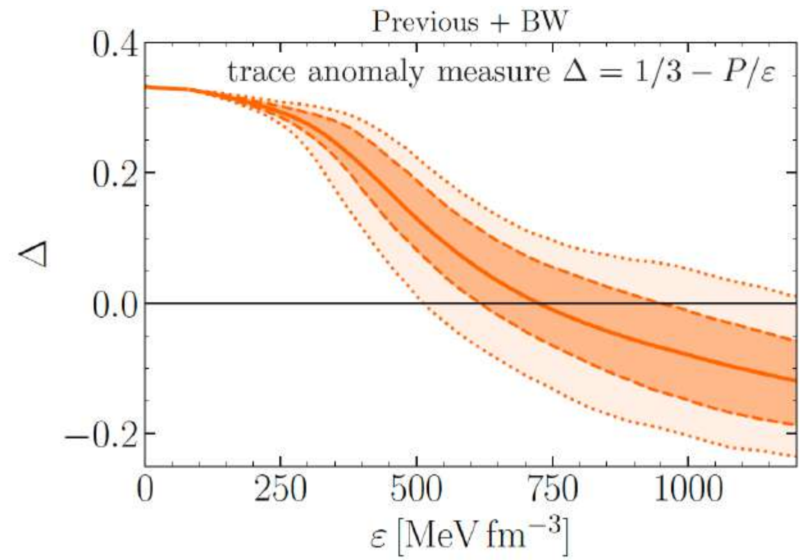

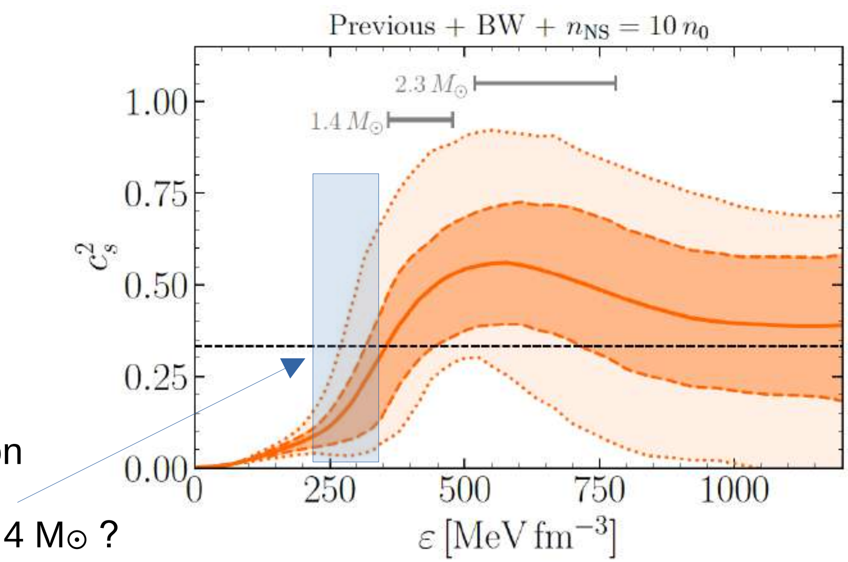

… excluding a strong 1st order PT with Maxwell construction

BUT: What if the PT occurred already in light NS, **below** 1.4 M⊙ ?

Pro and con quark matter in neutron stars

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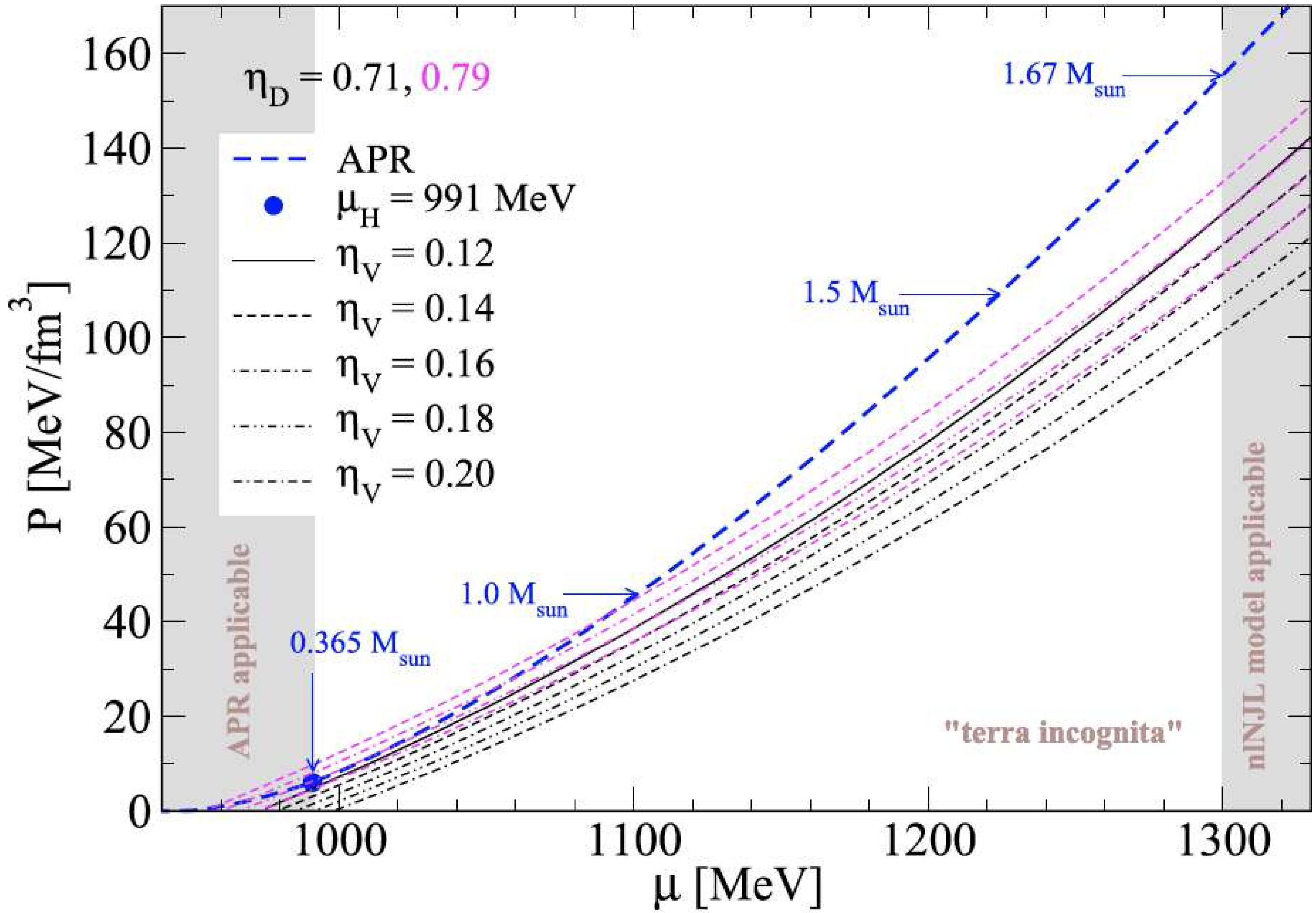

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Eur. Phys. J. A (2021) 57:318

https://doi.org/10.1140/epja/s10050-021-00619-0

Pro and con quark matter in neutron stars

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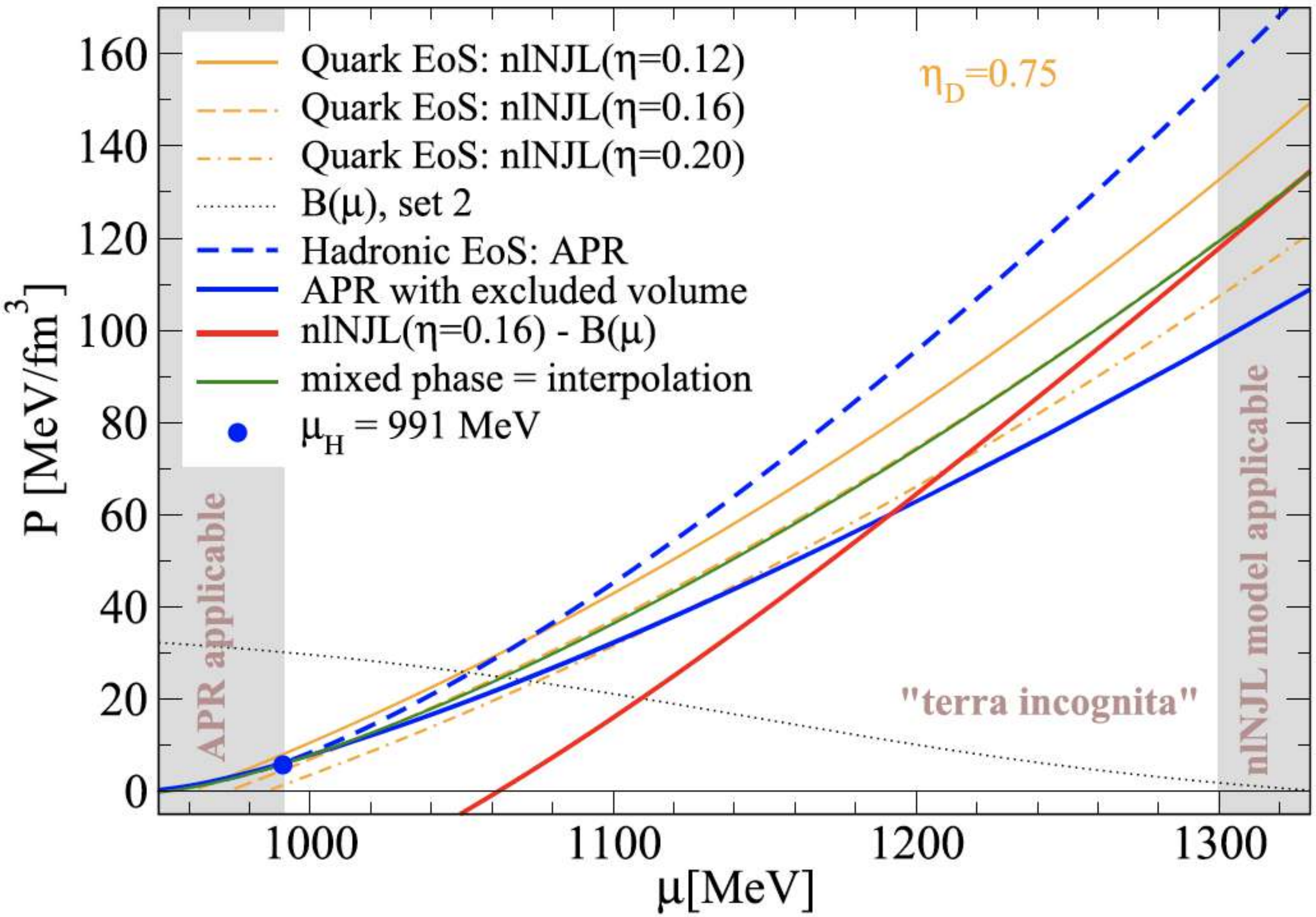
Strong 1st order PT masquerades as „crossover” via pasta phases



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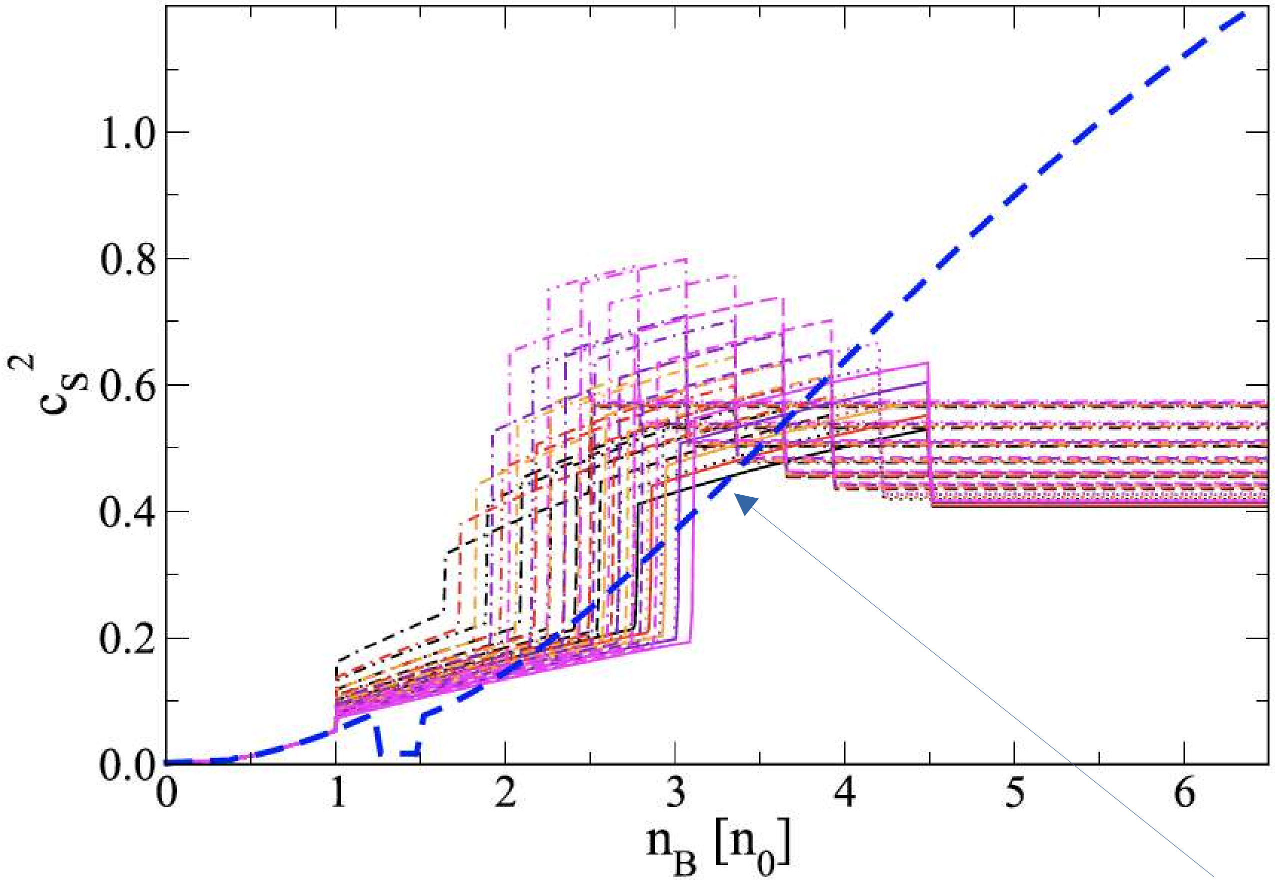

Two-zone interpolation scheme (TZIS) with crossover boundary condition → stiffening, analogous to “quarkyonic” matter behavior

A. Ayriyan, D.B., A.G. Grunfeld, et al.

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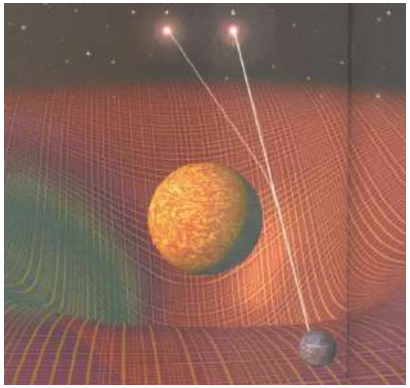
https://doi.org/10.1140/epja/s10050-021-00619-0

Neutron star phenomenology from TOV eqns.

There is a 1:1 correspondence EOS ↔ M(R)



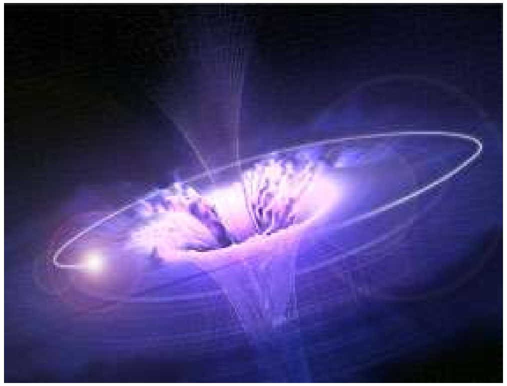
Tolman-Oppenheimer-Volkoff (TOV) equations

Einstein equations

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

Non-rotating, spherical masses → Schwarzschild Metrics

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



Tolman-Oppenheimer-Volkoff eqs.*) for structure and stability of spherical compact stars

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

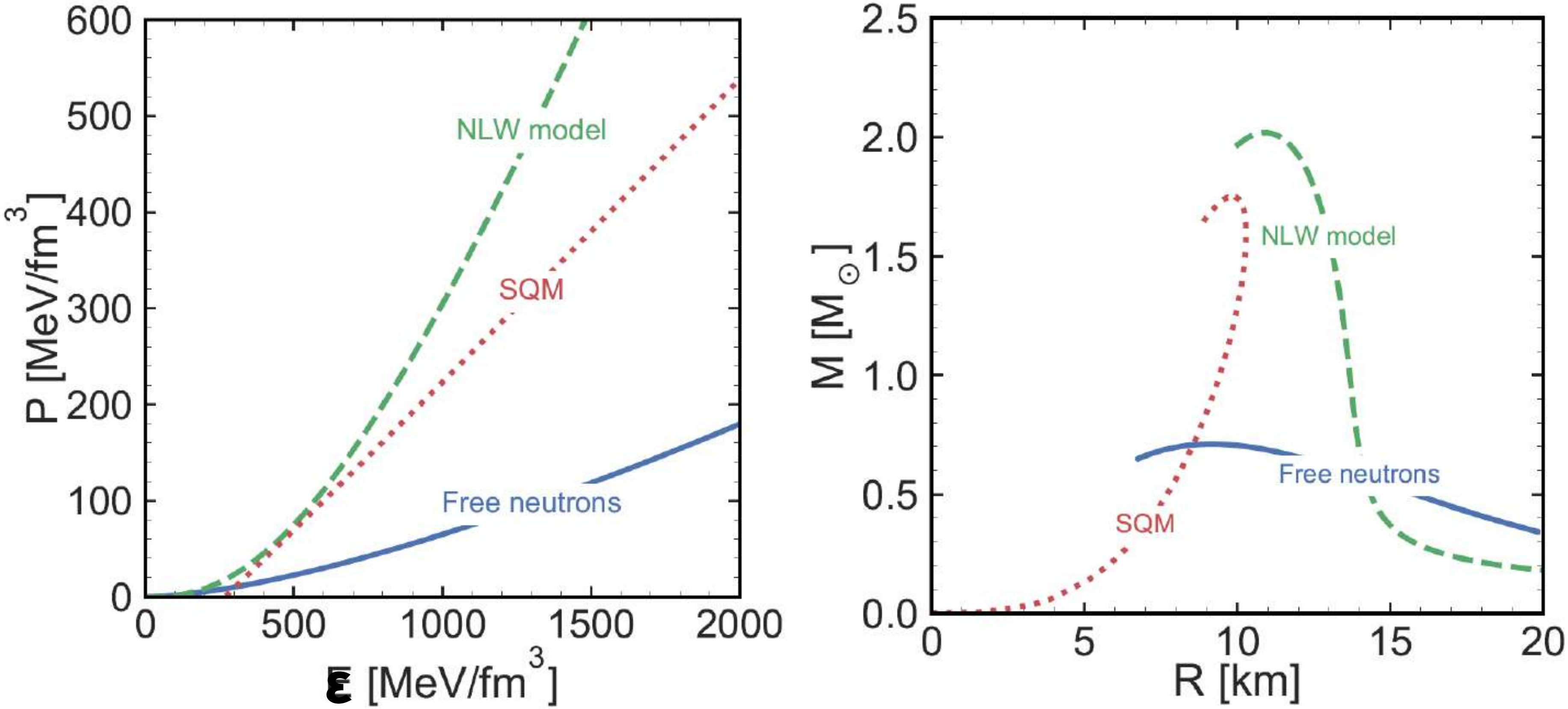
Newtonian case GR corrections from EoS and metrics

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

Neutron star phenomenology from TOV eqns.

There is a 1:1 correspondence EOS $P(\varepsilon) \leftrightarrow M(R)$

Tolman-Oppenheimer-Volkoff (TOV) equations - solutions



Stiffer equation of state → larger radius and larger maximum mass

“Berlin Wall” constraint for neutron stars?

Mass-radius diagram for purely hadronic EOS

Appearance of hyperons softens the EOS → Limitation for the maximum mass

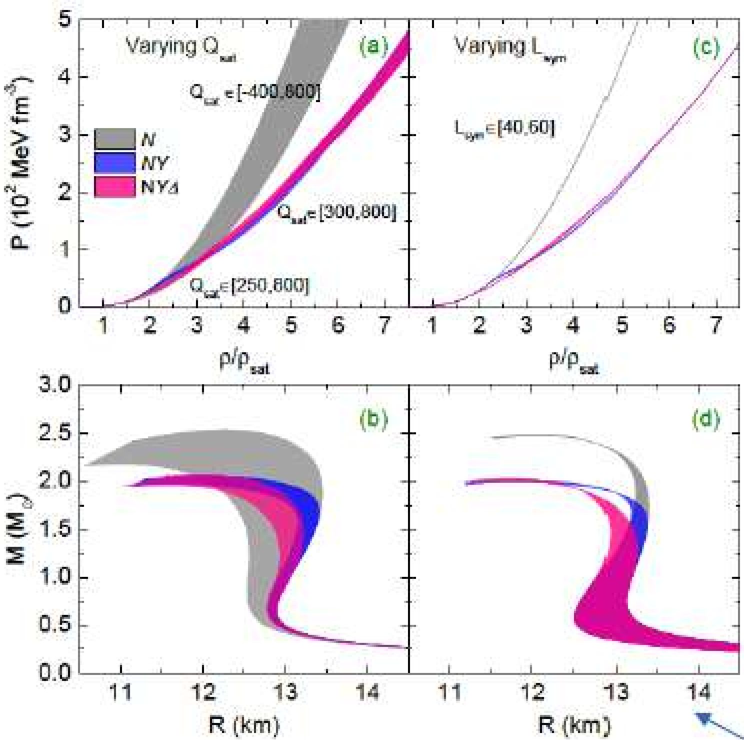


FIG. 4. EoS models and MR relations for N, NY, and $NY\Delta$ compositions of stellar matter. The bands are generated by varying the parameters Q_{sat} [MeV] (a, b) and L_{sym} [MeV] (c, d). The ranges of Q_{sat} and L_{sym} allowed by χEFT and maximum mass constraints are indicated in the figures.

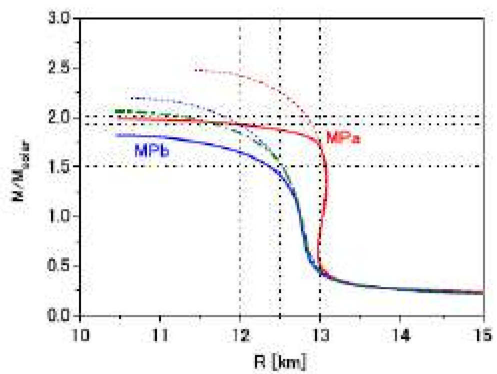


FIG. 7. Neutron-star masses as a function of the radius R. Solid (dashed) curves are with (without) hyperon (Λ and Σ^-) mixing for ESC+MPa and ESC+MPb. The dot-dashed curve for MPb is with Λ mixing only. Also see the caption of Fig. 3.

Yamamoto et al., Phys.Rev.C 96 (2017) 06580; arXiv:1708.06163 [nucl-th]

Yamamoto et al., Eur. Phys. J. A 52 (2016) 19; arXiv:1510.06099 [nucl-th]

Ji & Sedrakian, Phys. Rev. C 100 (2019) 015809; arXiv:1903.06057 [astro-ph.HE]

Examples for realistic hadronic EoS which suggest a Berlin Wall is inferior to the line M = 2.0 M_sun

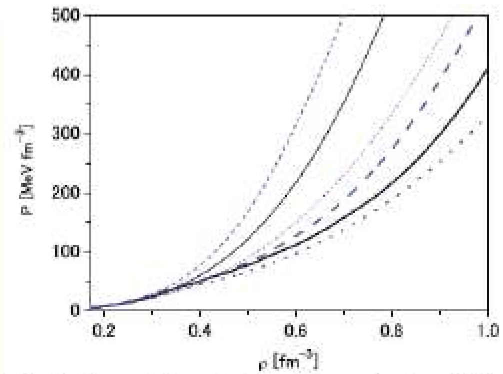


Fig. 8. Pressure P as a function of baryon density ρ. Thick (thin) curves are with (without) hyperon mixing. Solid, dashed and dotted curves are for MPa, MPa$^+$ and MPb.

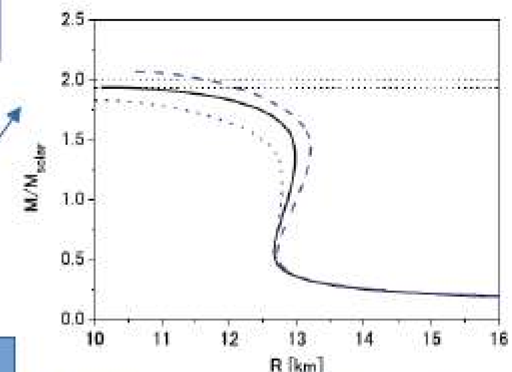
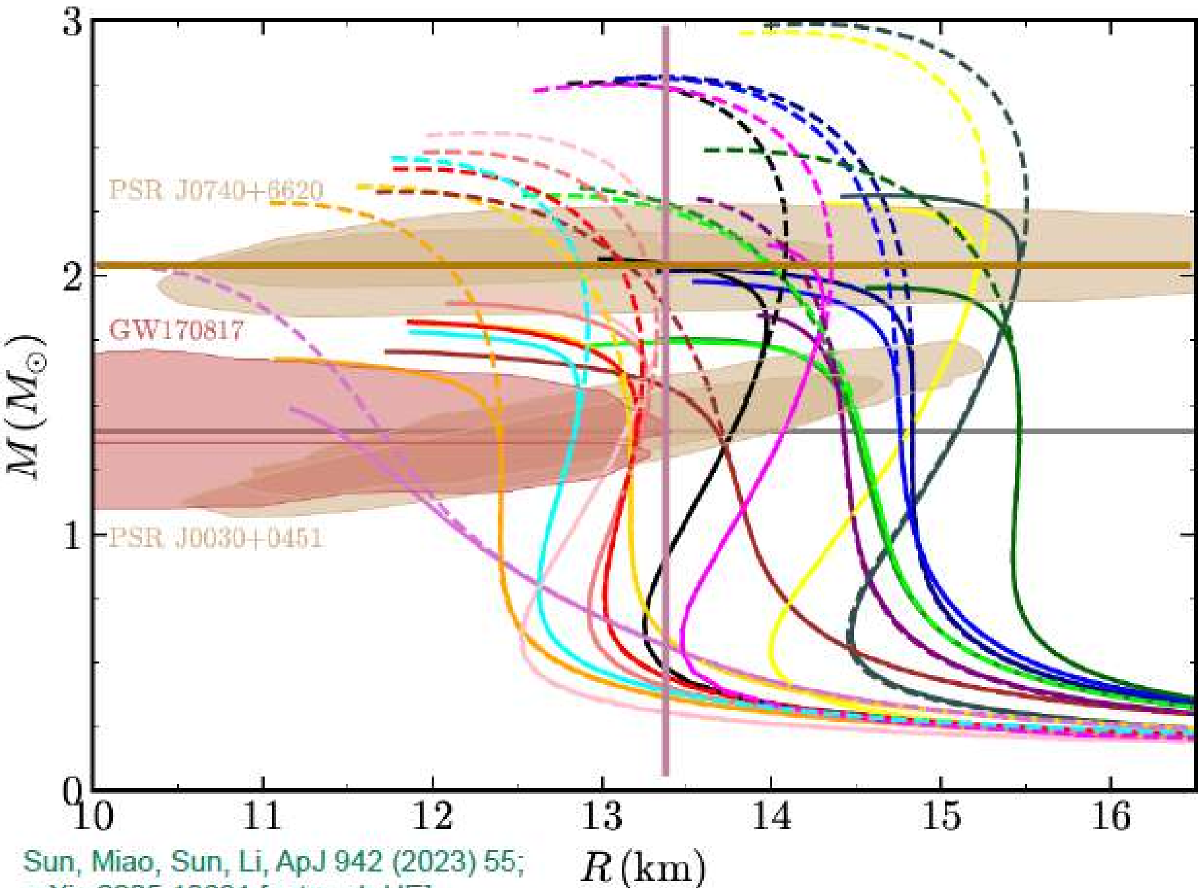


Fig. 9. Neutron-star masses as a function of the radius R. Solid, dashed and dotted curves are for MPa, MPa$^+$ and MPb. Two dotted lines show the observed mass ($1.97 \pm 0.04)M_\odot$ of J1614-2230.

“Berlin wall” constraint for neutron stars

Realistic hadronic EOS (with strange baryons)

Tension with modern multi-messenger observations by LVC and NICER



Sun, Miao, Sun, Li, ApJ 942 (2023) 55;
arXiv:2205.10631 [astro-ph.HE]

Examples for hadronic EoS without (dashed lines) and with (solid lines) strange baryons. EoS which fulfill the observational constraints should be left of the vertical line at 1.4 Msun and should cross the horizontal line for the minimal maximum mass at 2.01 Msun. There is no EoS of this sample which fulfills both constraints !!

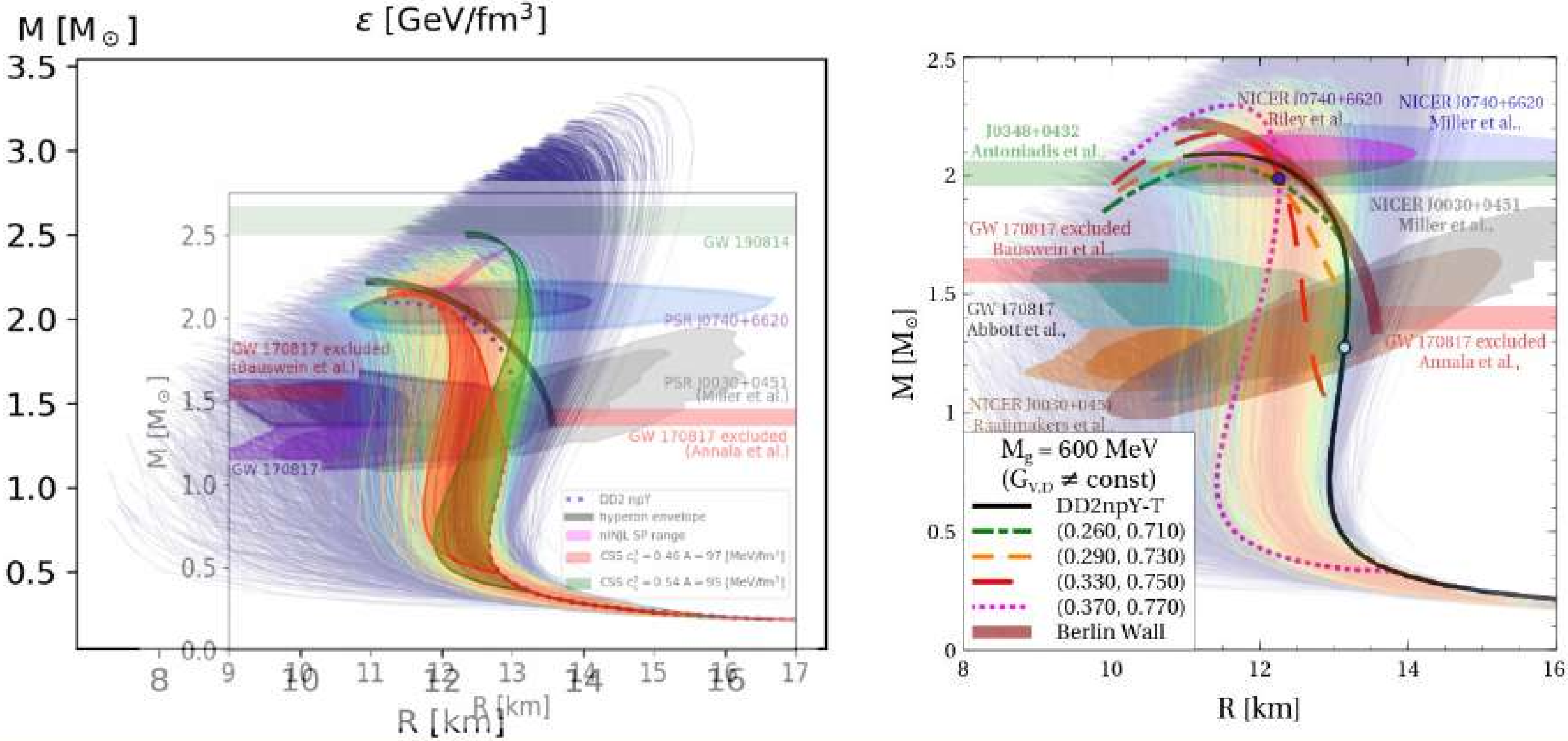
From Tab. 2 select EoS which fulfill (w. Y) 70 < Λ_1.4 < 580 and check their M_max

EoS	M_max	EoS	M_max
NL3ωρ	1.974	DD2	1.935
DDLZ1	1.989	PKDD	1.781
DD-ME2	1.971	HC	1.828
OMEG	1.862		

Breaking the “Berlin wall” constraint

With Bayesian analyses and hybrid EOS

M(R) curves generated by causality, thermodynamic stability and pQCD limit



The conjectured “Berlin Wall” overlaid to the Fig. 2 from Gorda, Komoltsev & Kurkela [2204.11877 [nucl-th]] and hybrid EoS with quark matter described by a CSS model (left) and a confining relativistic density functional (right).

Relativistic density functionals for QCD

String-flip model for quark matter confinement

Röpke, Blaschke, Schulz, PRD34 (1986) 3499

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

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

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

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

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

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

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

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

Relativistic density functionals for QCD

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

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

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

"no sea" approximation ...

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

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

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

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

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

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

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 functionals for QCD

String-flip model for quark matter

Density functional for the SFM

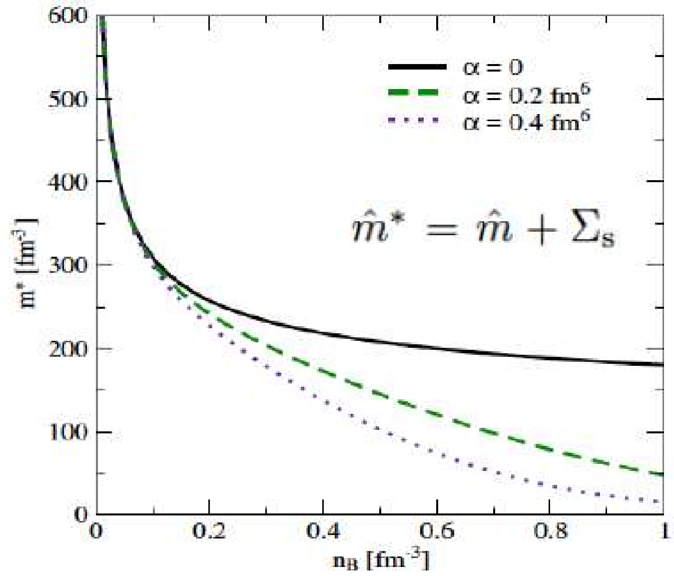
$$U(n_s, n_v) = D(n_v) n_s^{2/3} + a n_v^2 + \frac{b n_v^4}{1 + c n_v^2} ,$$

Quark selfenergies

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

Quark "confinement"

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

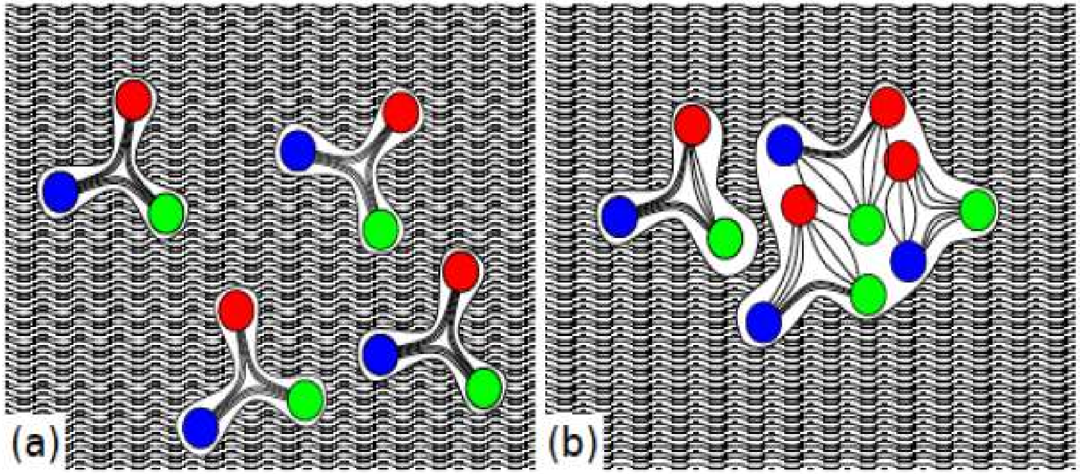


String tension & confinement due to dual Meissner effect (dual superconductor model)

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

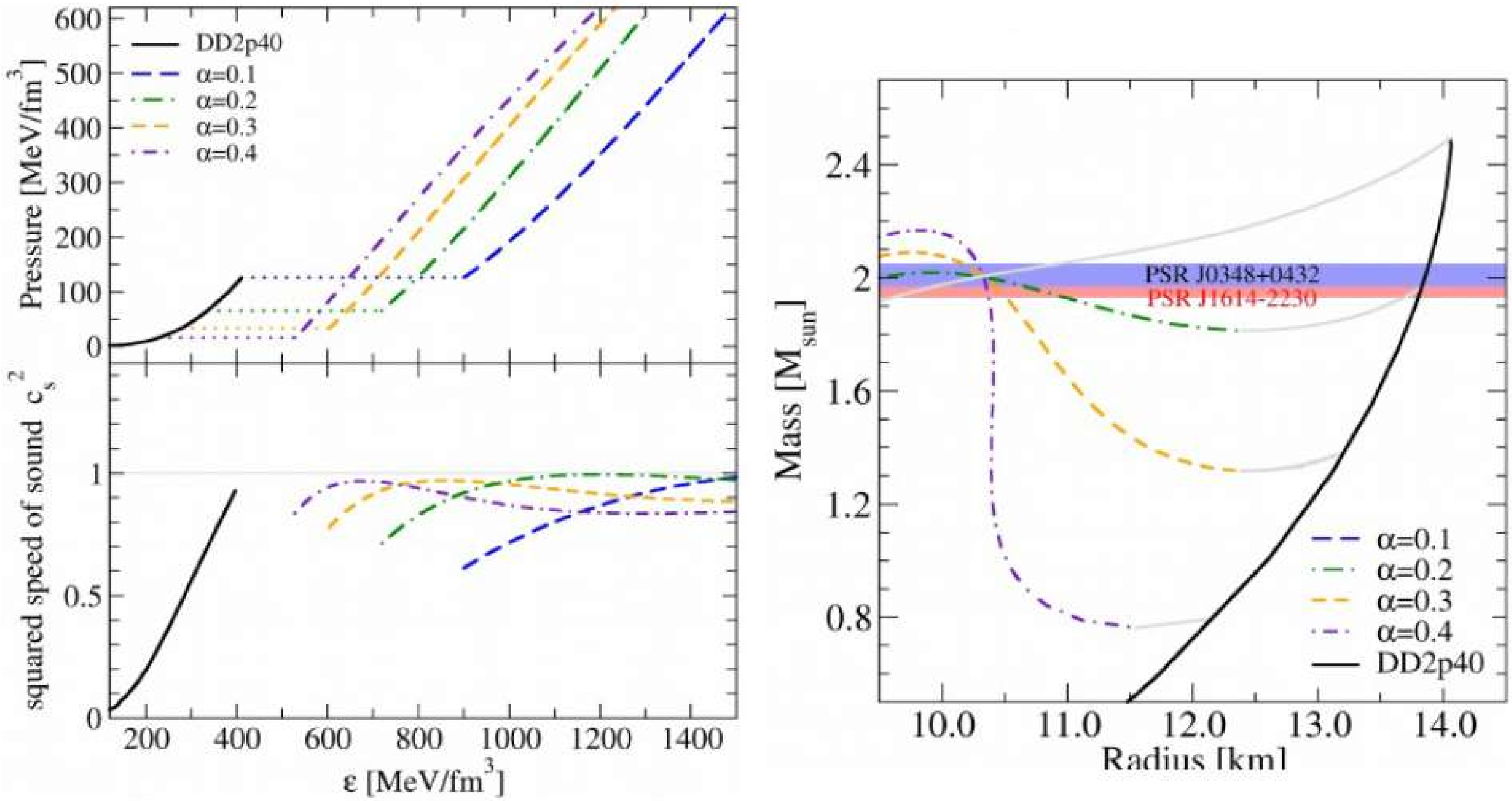
Effective screening of the string tension in dense matter by a reduction of the available volume $\alpha = v|v|/2$

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



Relativistic density functionals for QCD
String-flip model for quark matter

Results for 1st order phase transition by Maxwell construction with DD2p40



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

QCD Phase Diagram

Landscape of our investigations

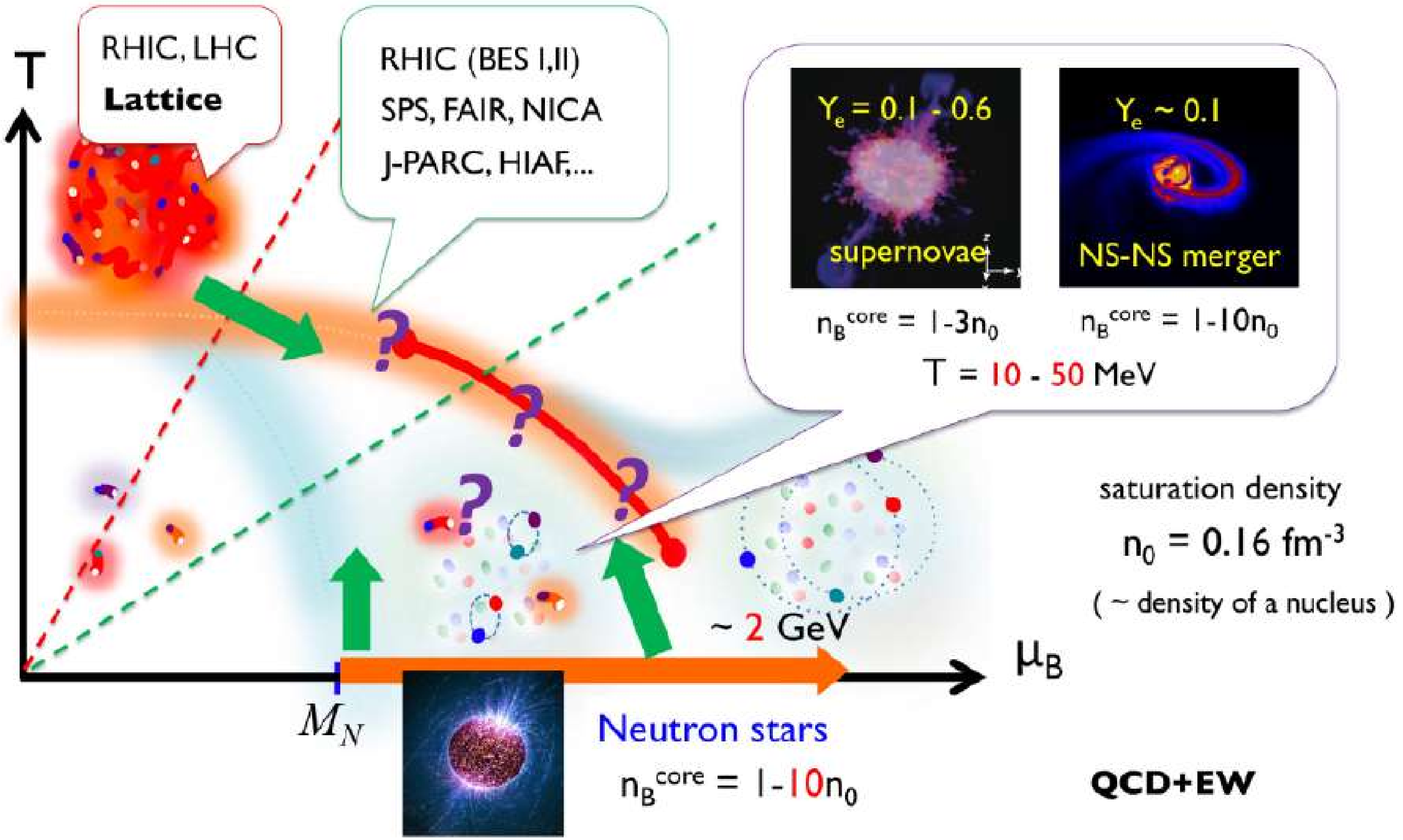
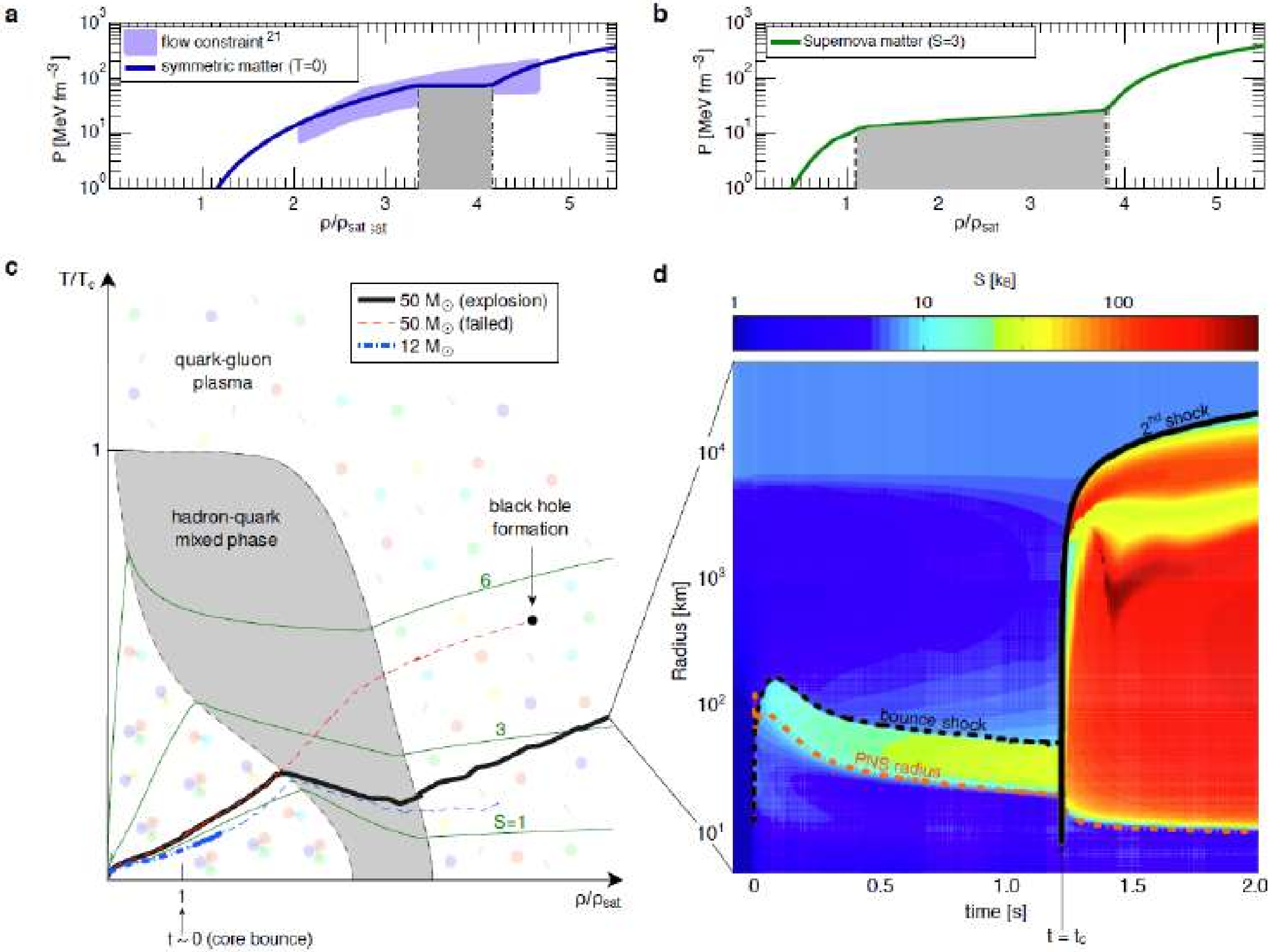


Figure from T. Kojo arXiv:1912.05326 [nucl-th]

Deconfinement as supernova engine

Of massive blue supergiant star explosions

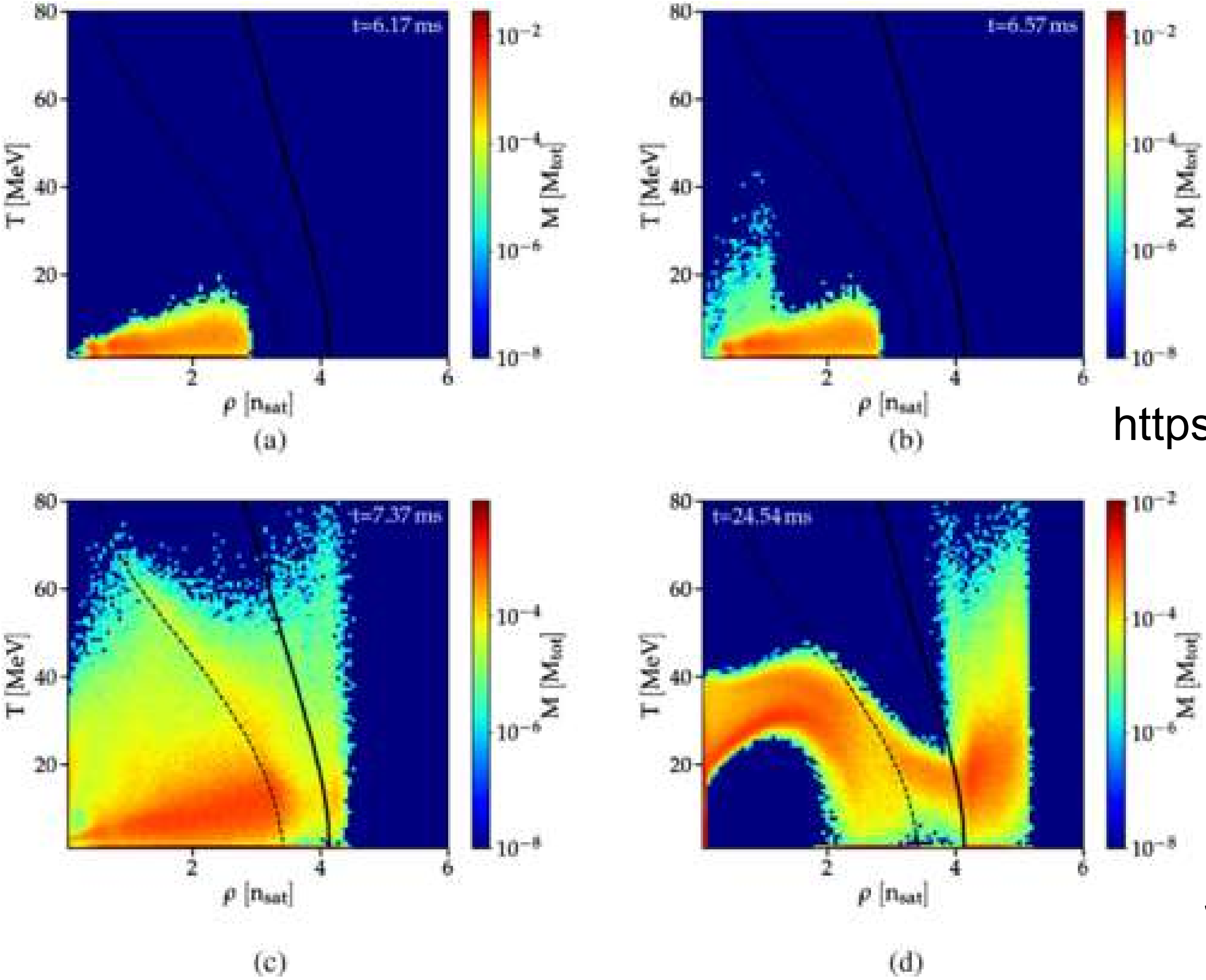


Progenitor:
$M = 50\ M_{O}$

T. Fischer et al., Nature Astronomy 2, 960 (2018)

Ultra-heavy Nucleus-Nucleus Collisions !

Population of the QCD phase diagram in a merger



1.35 M_sun + 1.35 M_sun

EoS for supernova and merger simulations:

CompOSE

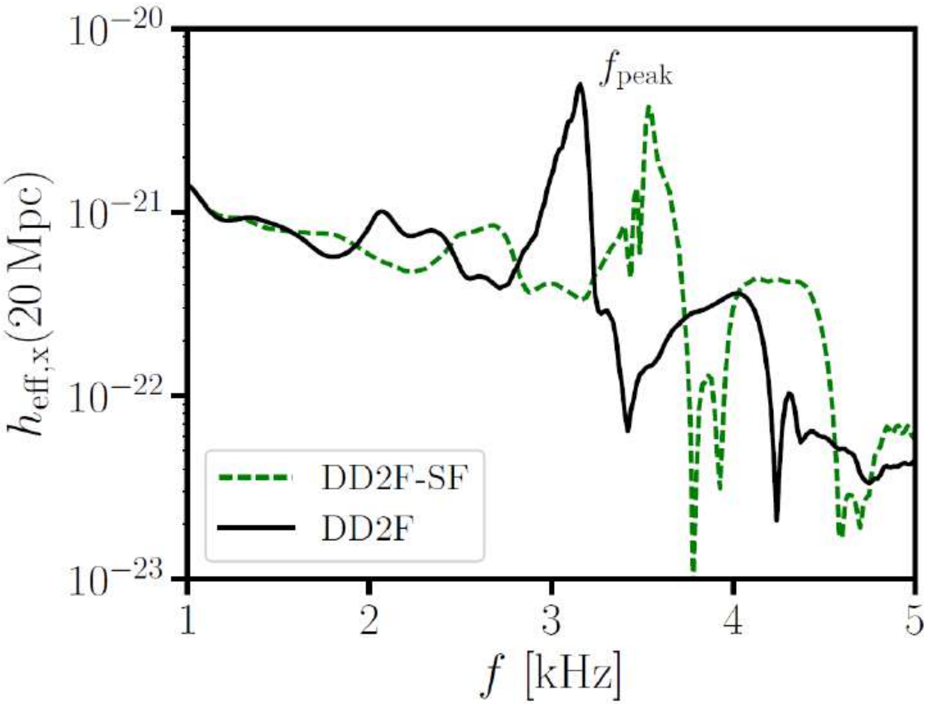
With deconfinement:

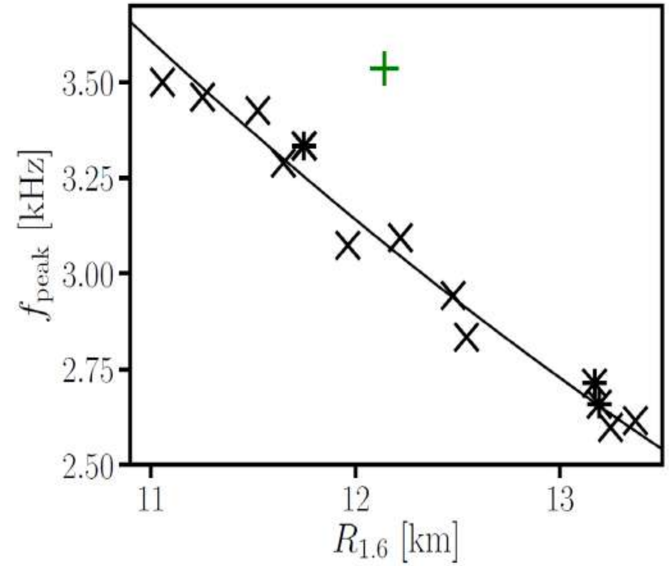
https://compose.obspm.fr/eos/166

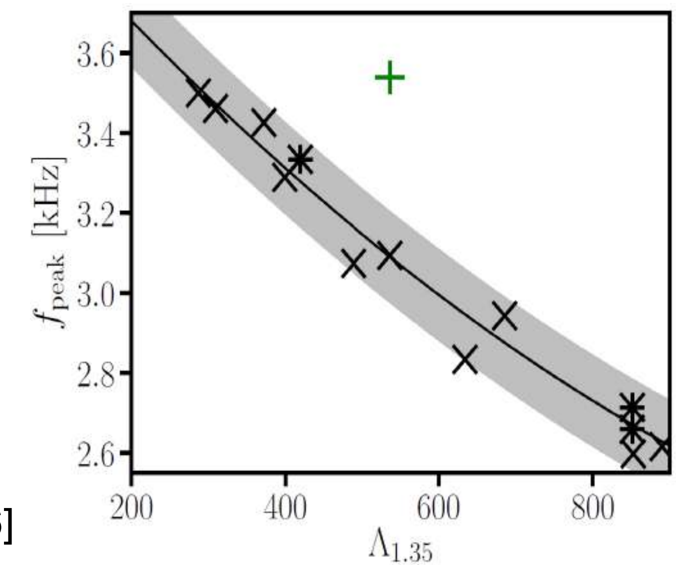
S. Blacker, A. Bauswein, et al., Phys. Rev. D 102 (2020) 123023

Ultra-heavy Nucleus-Nucleus Collisions !

Signal of a deconfinement transition







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.

A. Bauswein et al., PRL 122 (2019) 061102; [arxiv:1809.01116]

Relativistic density functional for quark matter

With chiral symmetry, color SC & confinement

Lagrangian $\mathcal{L} = \overline{q}(i\partial\!\!\!/ - \hat{m})q - \mathcal{U} + \mathcal{L}_V + \mathcal{L}_I + \mathcal{L}_D$

- **Scalar & pseudoscalar interaction channels**

$$\mathcal{U} = G_0 \left[(1+\alpha)\langle\overline{q}q\rangle_0^2 - (\overline{q}q)^2 - (\overline{q}i\vec{\tau}\gamma_5 q)^2\right]^{\frac{1}{3}}$$

(motivated by String Flip Model, χ-dynamics, quark "confinement")

- **Vector-isoscalar interaction channel**

$$\mathcal{L}_V = -G_V(\overline{q}\gamma_\mu q)^2$$

(motivated by gluon exchange, stiff EoS needed to reach $2M_\odot$)

- **Vector-isovector interaction channel**

$$\mathcal{L}_I = -G_I(\overline{q}\gamma_\mu\vec{\tau}q)^2$$

(motivated by gluon exchange, isospin sensitive interaction)

- **Diquark interaction channel**

$$\mathcal{L}_D = G_D \sum_{A=2,5,7} (\overline{q}i\gamma_5\tau_2\lambda_A q^c)(\overline{q}^c i\gamma_5\tau_2\lambda_A q)$$

(motivated by Cooper theorem, color superconductivity)

Relativistic density functional for quark matter

What is new?

O. Ivanytskyi & D.B., Phys. Rev. D 105 (2022) 114042

Interaction $\mathcal{U} = D_0 \left[(1+\alpha)\langle\overline{q}q\rangle_0^2 - (\overline{q}q)^2 - (\overline{q}i\vec{\tau}\gamma_5 q)^2\right]^{\varkappa}$

- **Parameters**

  D_0 - dimensionfull coupling, controls interaction strength

  α - dimensionless constant, controls vacuum quark mass

  $\langle\overline{q}q\rangle_0$ - χ-condensate in vacuum (introduced for the sake of convenience)

$\varkappa = 1/3$ $\Downarrow$ motivated by String Flip model

$\varkappa = 1$ $\Downarrow$ Nambu–Jona-Lasinio model

$$\mathcal{U}_{SFM} \propto \langle q^+ q\rangle^{2/3}$$

$$\Sigma_{SFM} = \frac{\partial \mathcal{U}_{SFM}}{\partial\langle q^+ q\rangle} \propto \langle q^+ q\rangle^{-1/3} \propto separation$$

- **Dimensionality**

$$[\mathcal{U}] = energy^4, \quad [\overline{q}q] = energy^3 \quad \Rightarrow \quad [D_0]_{\varkappa=1/3} = energy^2 = [string\ tension]$$

self energy = string tension × separation $\Rightarrow$ **confinement**

Relativistic density functional for quark matter

Expansion around mean fields

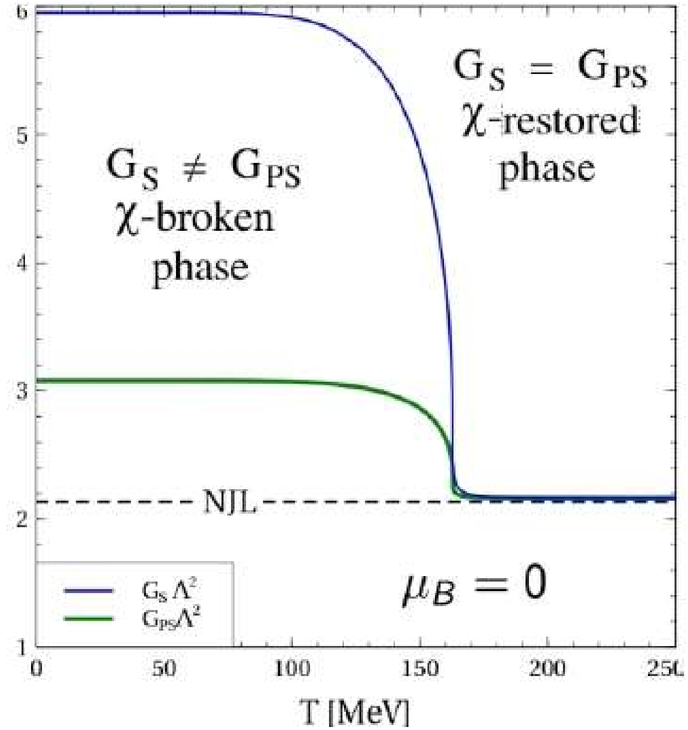
$$\mathcal{U} = \underbrace{\mathcal{U}_{MF}}_{0^{\text{th}}\ \text{order}} + \underbrace{(\overline{q}q - \langle\overline{q}q\rangle)\,\Sigma_S}_{1^{\text{st}}\ \text{order}} - \underbrace{G_S\,(\overline{q}q - \langle\overline{q}q\rangle)^2 - G_{PS}\,(\overline{q}i\vec{\tau}\gamma_5 q)^2}_{2^{\text{nd}}\ \text{order}} + \ldots$$

- **Mean-field scalar self-energy**

$$\Sigma_S = \frac{\partial \mathcal{U}_{MF}}{\partial \langle\overline{q}q\rangle}$$

- **Effective medium dependent couplings**

$$G_S = -\frac{1}{2}\frac{\partial^2 \mathcal{U}_{MF}}{\partial\langle\overline{q}q\rangle^2}, \qquad G_{PS} = -\frac{1}{6}\frac{\partial^2 \mathcal{U}_{MF}}{\partial\langle\overline{q}i\vec{\tau}\gamma_5 q\rangle^2}$$



Relativistic density functional for quark matter

Comparison to Nambu—Jona-Lasinio model

$$\mathcal{L} = \overline{q}(i\partial\!\!\!/ - \underbrace{(m + \Sigma_S)}_{\text{effective mass } m^*})q + G_S(\overline{q}q)^2 + G_{PS}(\overline{q}i\vec{\tau}\gamma_5 q)^2 + \cdots + \mathcal{L}_V + \mathcal{L}_D$$

- **Similarities:**
  - current-current interaction
  - (pseudo)scalar, vector, diquark, ... channels
- **Differences:**
  - high m^* at low T, $\mu \Rightarrow$ **"confinement"**

$$\langle\overline{q}q\rangle = \langle\overline{q}q\rangle_0 \;\Rightarrow\; m^* = m - \frac{2G_0}{3\alpha^{2/3}\langle\overline{q}q\rangle_0^{1/3}}$$

$$\Downarrow$$

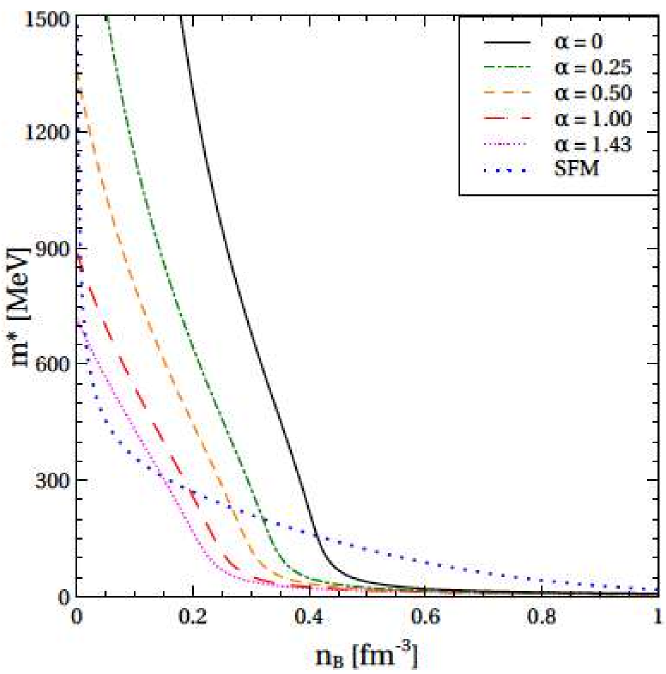
$$m^* \to \infty \text{ at } \alpha \to 0$$

  - medium dependent couplings:

low T, μ, $\Rightarrow$ $G_S \neq G_{PS}$ $\Rightarrow$ χ-broken

high T, μ, $\Rightarrow$ $G_S = G_{PS}$ $\Rightarrow$ χ-symmetric

$\mathbf{T = 0}$

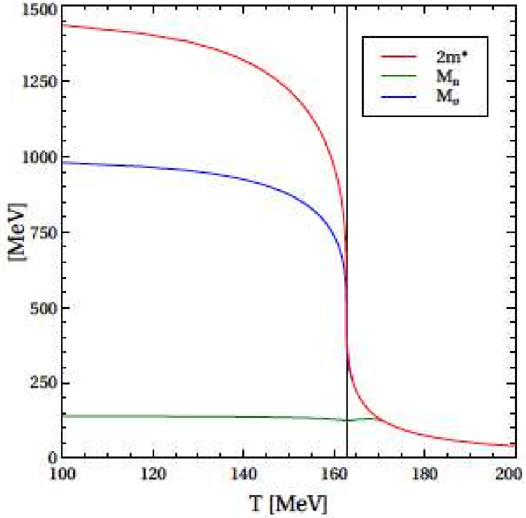


Relativistic density functional for quark matter

Model setup – parameter fixing with observables

- **(Pseudo)scalar interaction channels (chiral condensate & π, σ mesons)**

m [MeV]	Λ [MeV]	α	$D_0\Lambda^{-2}$
4.2	573	1.43	1.39
M_π [MeV]	F_π [MeV]	M_σ [MeV]	$\langle \bar{l}l \rangle_0^{1/3}$ [MeV]
140	92	980	-267



Pseudocritical temperature

$$T_c = 163 \text{ MeV}$$

- low T: $2m_{quark} > M_\pi, M_\sigma$
  (stable mesons, confined quarks)
- high T: $2m_{quark} < M_\pi, M_\sigma$
  (unstable mesons, deconfined quarks)

- **Vector-isoscalar & vector-isovector channels (ω, ρ mesons)**

$$M_\omega = 783 \text{ MeV} \Rightarrow \eta_V \equiv \frac{G_{V0}}{G_{S0}} = 0.452, \quad M_\rho = 775 \text{ MeV} \Rightarrow \eta_I \equiv \frac{G_{I0}}{G_{S0}} = 0.454$$

- **Diquark pairing channel (Fierz transformation)** $\eta_D \equiv \frac{G_{D0}}{G_{S0}} = 1.5\eta_V = 0.678$

Relativistic density functional for quark matter

Onset of color superconductivity

- **Single quark energy and distribution**

$$E_f^{\pm} = sgn(E_f \mp \mu_f)\sqrt{(E_f \mp \mu_f)^2 + \Delta^2}$$

$$f_f^{\pm} = [\exp(E_f^{\pm}/T) + 1]^{-1}$$

- **Gap equation**

$$\frac{\partial \Omega}{\partial \Delta} = \frac{\Delta}{2G_D} - 2\Delta \sum_{f,a=\pm} \int \frac{d\mathbf{k}}{(2\pi)^3} \frac{1 - 2f_f^a}{E_f^a} = 0$$

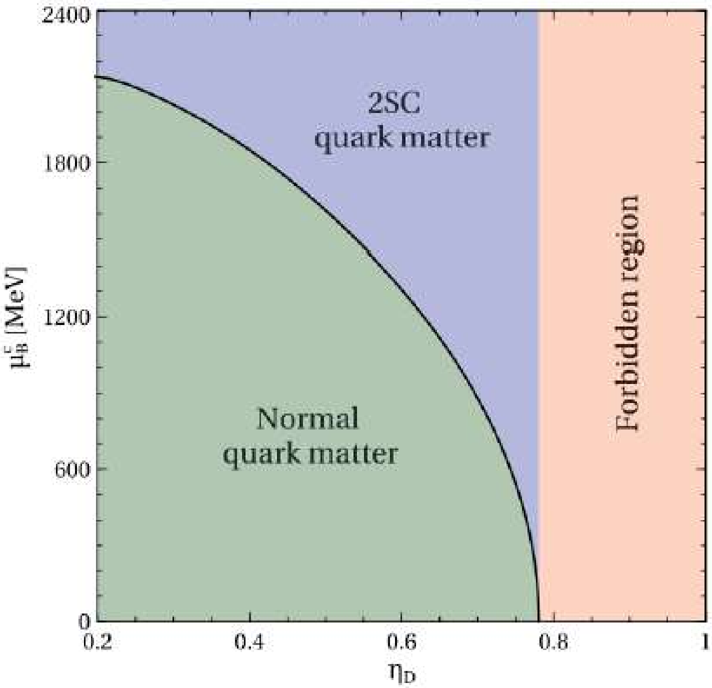
$$\Downarrow$$

two solutions : $\Delta = 0$ **or** $\Delta \neq 0$

- **Two solutions coincide $\Rightarrow$ SC onset**

$$\left.\frac{\partial^2 \Omega}{\partial \Delta^2}\right|_{\Delta=0} = 0 \quad \Rightarrow \quad \mu_B = \mu_B(G_D)$$

$\boldsymbol{T = 0}$



No vacuum superconductivity

$$\Downarrow$$

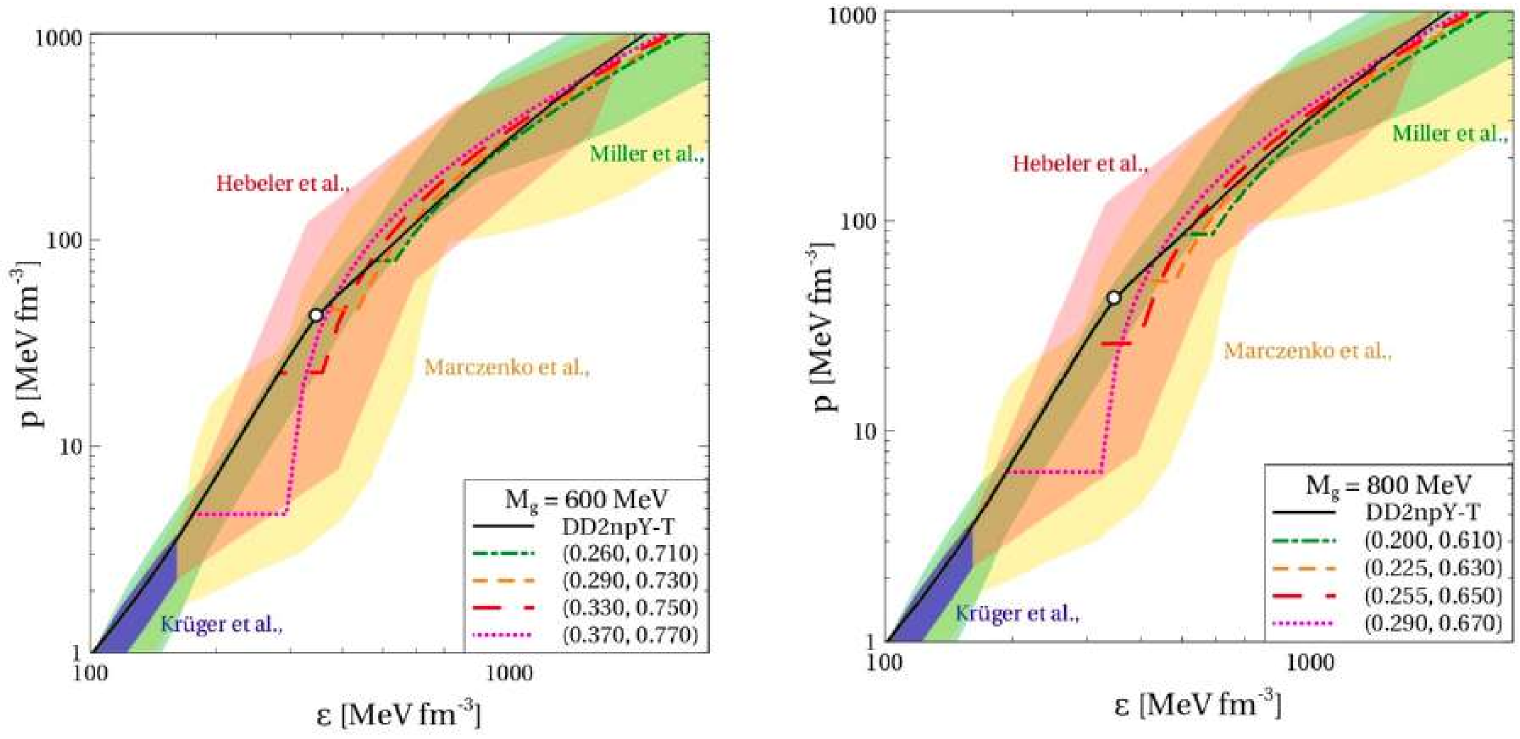
$$\eta_D \lesssim 0.78$$

(agrees with the Fierz value)

Relativistic density functional for quark matter

Asymptotically conformal EOS for neutron stars

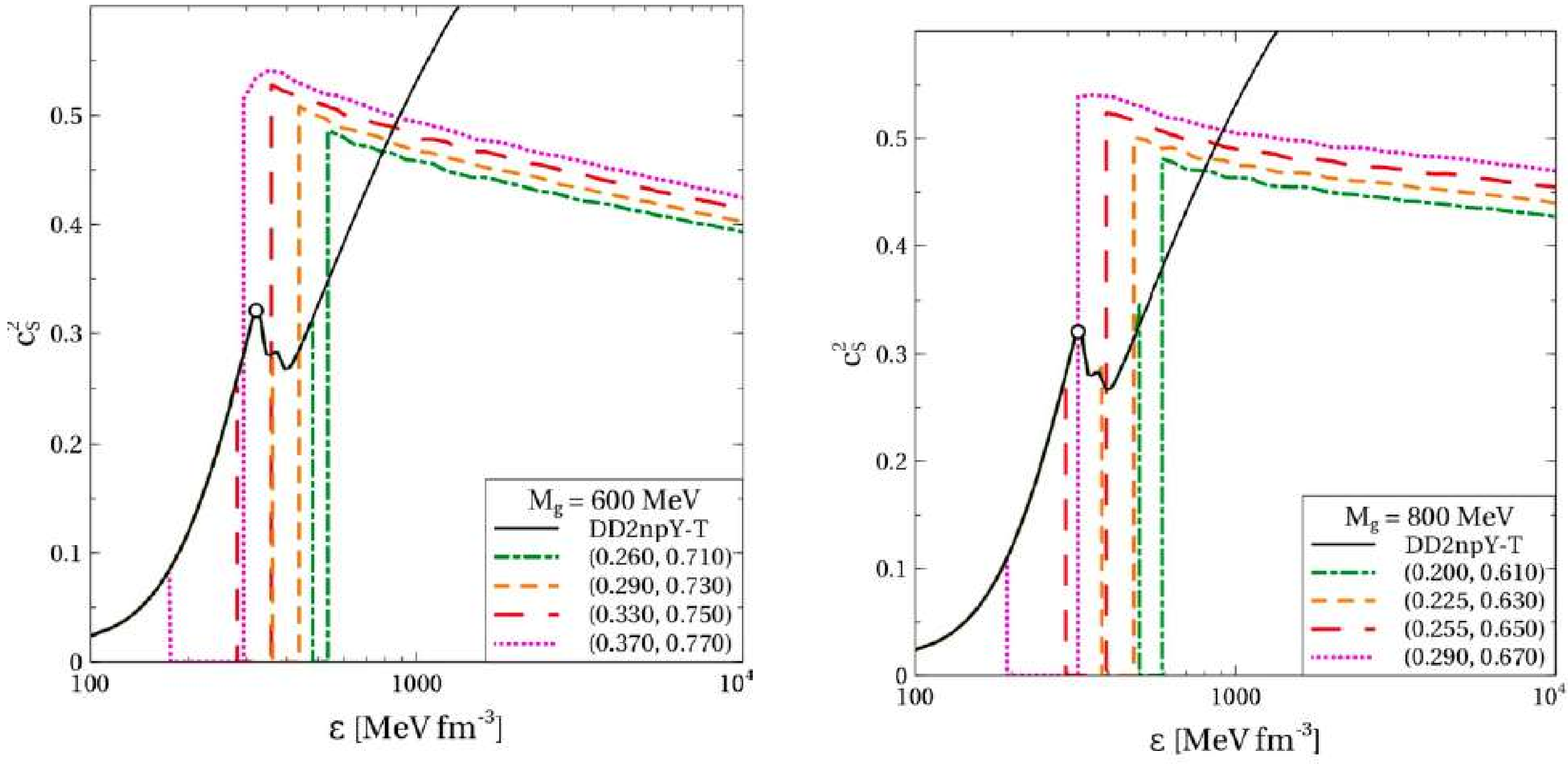
- **Setup:** electric neutrality, β-equilibrium, Maxwell construction with DD2 EoS
- **Scanning over η_V and η_D at $M_{gD} = M_{gV}$**



The ω-meson value of η_V and the Fierz value of η_D prefer early deconfinement?

Relativistic density functional for quark matter

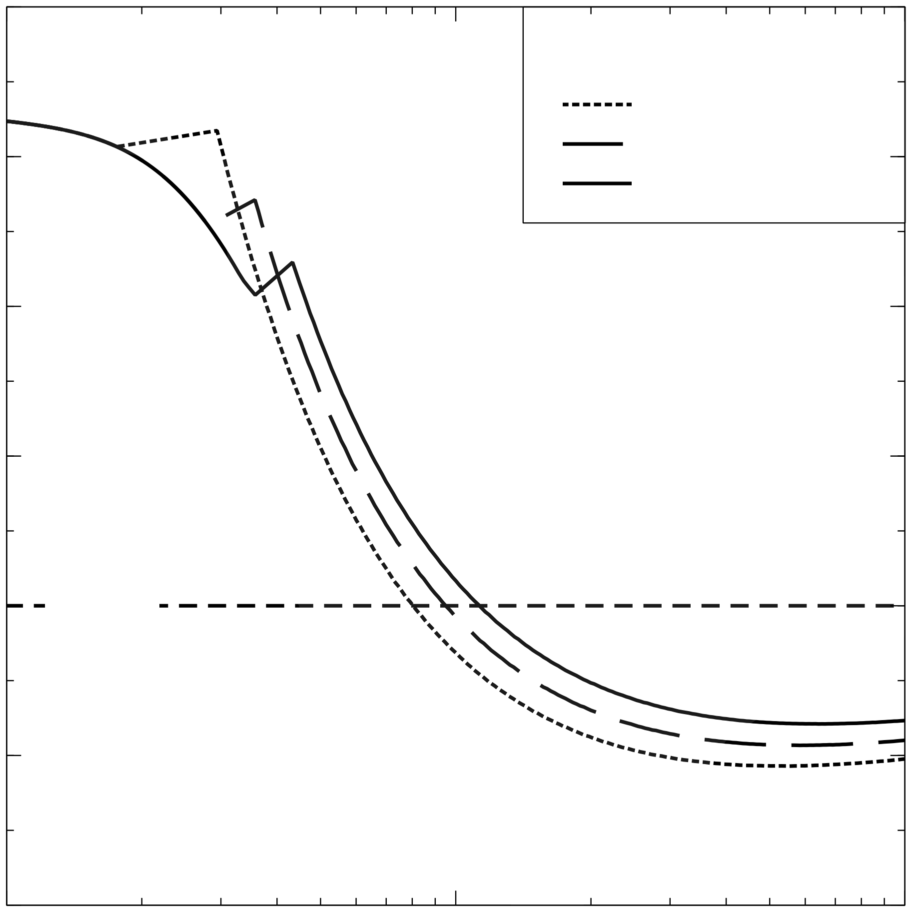
Speed of sound



O. Ivanytskyi and D. Blaschke, Particles 5 (2022) 514 - 534

Relativistic density functional for quark matter

Conformality measure $\Delta = 1/3 - P/\varepsilon$



Courtesy:

O. Ivanytskyi, derived from

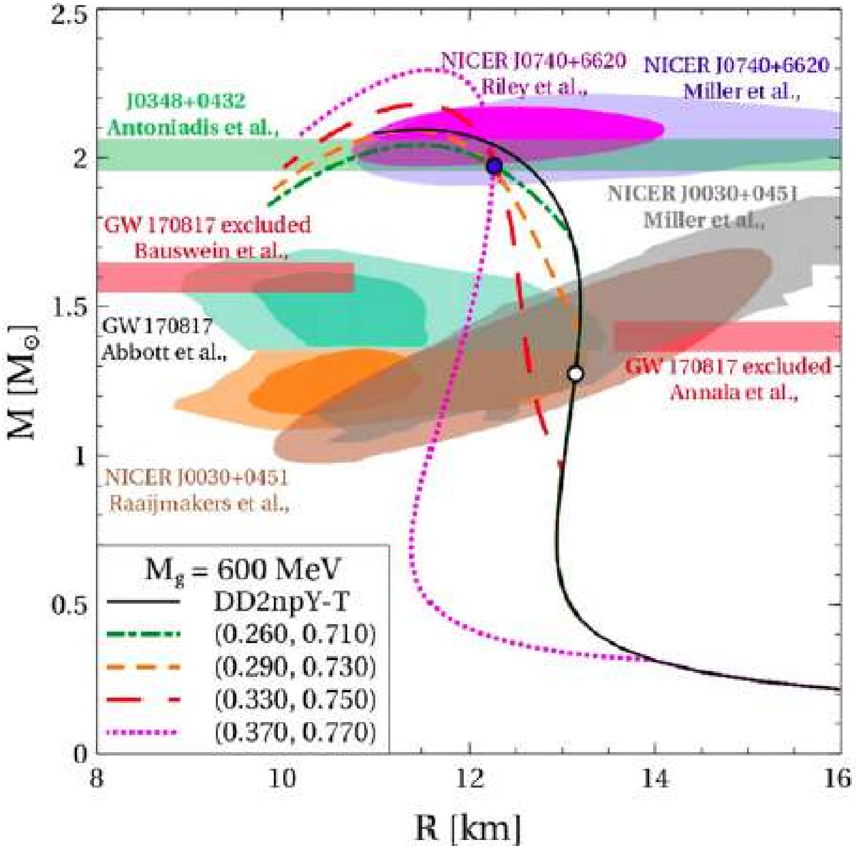
Particles 5 (2022) 514 and

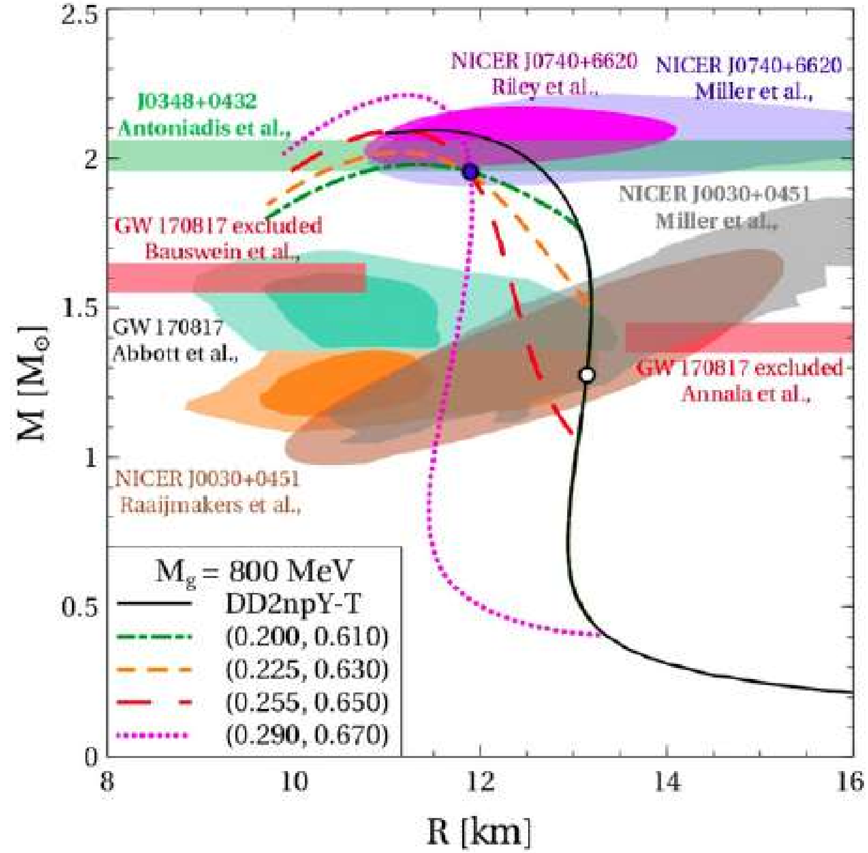
M. Marczenko et al.,

Phys. Rev. C 107 (2023) 025802

Relativistic density functional for quark matter

Mass-radius diagram for hybrid neutron stars

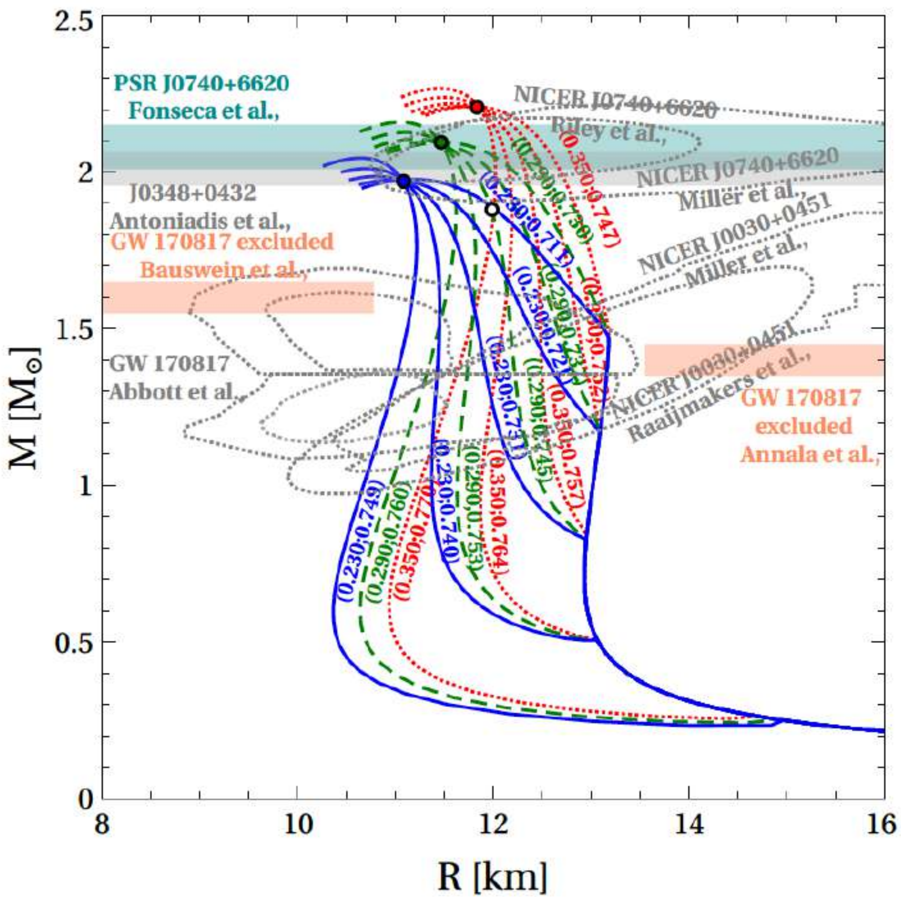


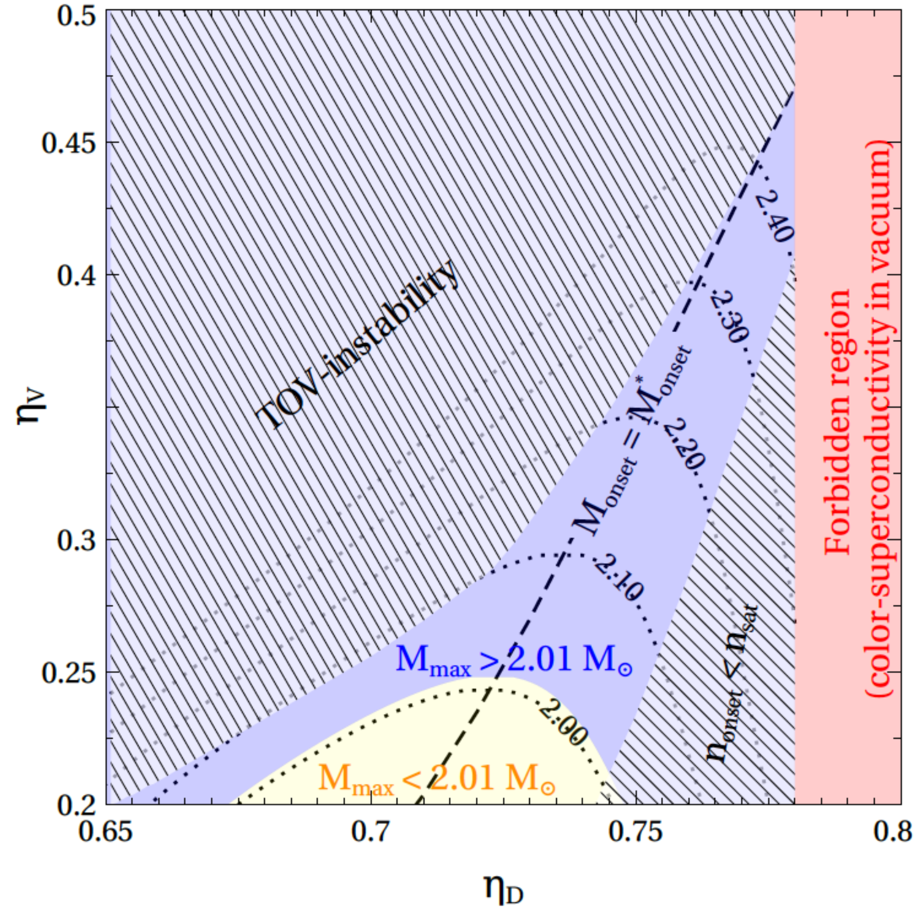


Observational data prefer early deconfinement?

Relativistic density functional for quark matter

Mass-radius diagram for hybrid neutron stars





$$M_{max} = M_{SP} + \delta\,|M^*_{onset} - M_{onset}|^{\kappa}$$

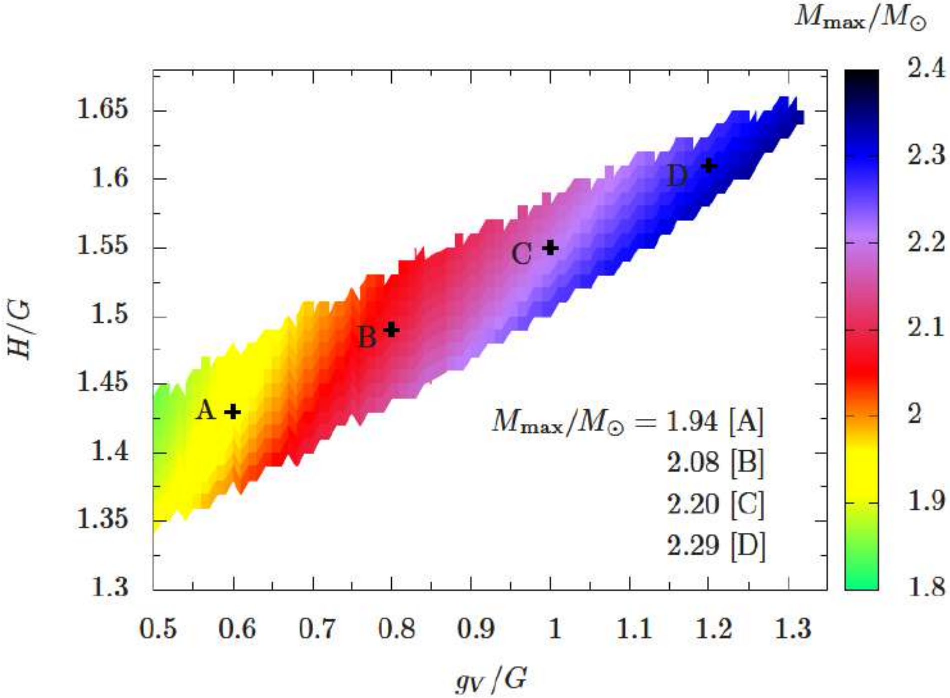
$$M_{SP} = k_{M_{SP}}\eta_V + b_{M_{SP}}\,; \quad \delta = k_\delta \eta_V + b_\delta\,; \quad M^*_{onset} = 1.254\ M_\odot$$

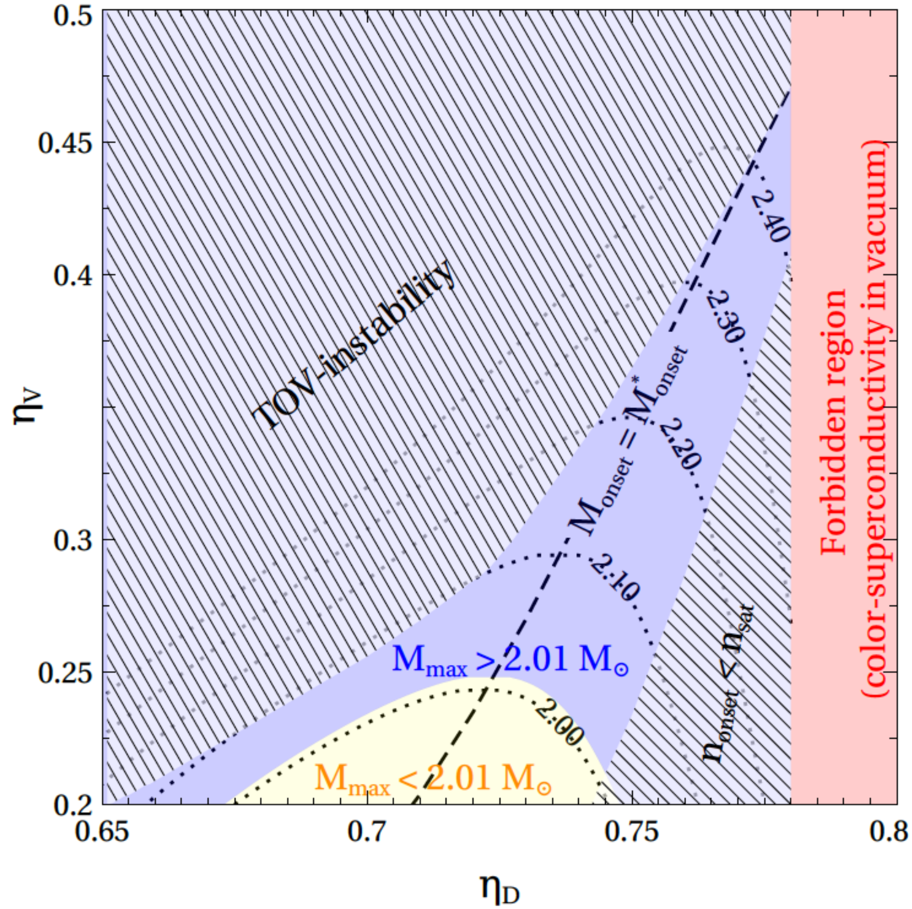
C. Gärtlein et al., arXiv:2301.10765v2 ; For more details, see talk by **Oleksii Ivanytskyi**

Relativistic density functional for quark matter

Mass-radius diagram for hybrid neutron stars

Compare to:
G. Baym, S. Furusawa, T. Hatsuda, T. Kojo,
H. Togashi, ApJ 885, 42 (2019)





$$M_{\rm max} = M_{\rm SP} + \delta\,|M^*_{\rm onset} - M_{\rm onset}|^\kappa$$

$M_{\rm SP} = k_{M_{\rm SP}}\eta_V + b_{M_{\rm SP}}$; $\delta = k_\delta \eta_V + b_\delta$; $M^*_{\rm onset} = 1.254\ M_\odot$

C. Gärtlein et al., arXiv:2301.10765v2 ; For more details, see talk by **Oleksii Ivanytskyi**

Relativistic density functional for quark matter

Phase diagram with two-zone interpolation

- **Normal quark matter**

  2 spin × 2 flavor × 3 color =12

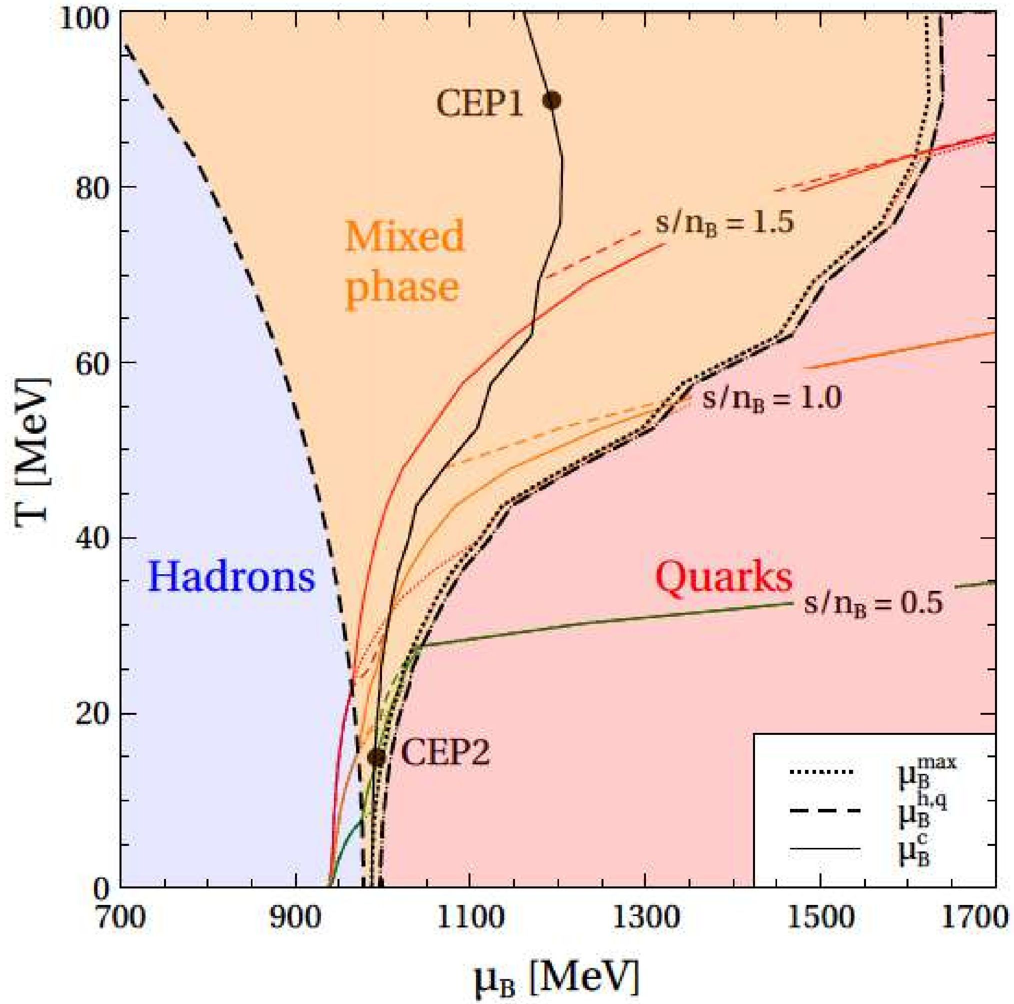
- **2SC quark matter**

  2 spin × 2 flavor × 1 color+1=5

Quark pairing reduces number of quark states

⇓

requires higher T along adiabat



→ **EOS tables are prepared for simulation of supernovae and NS mergers**

Relativistic density functional for quark matter

Phase diagram with two-zone interpolation

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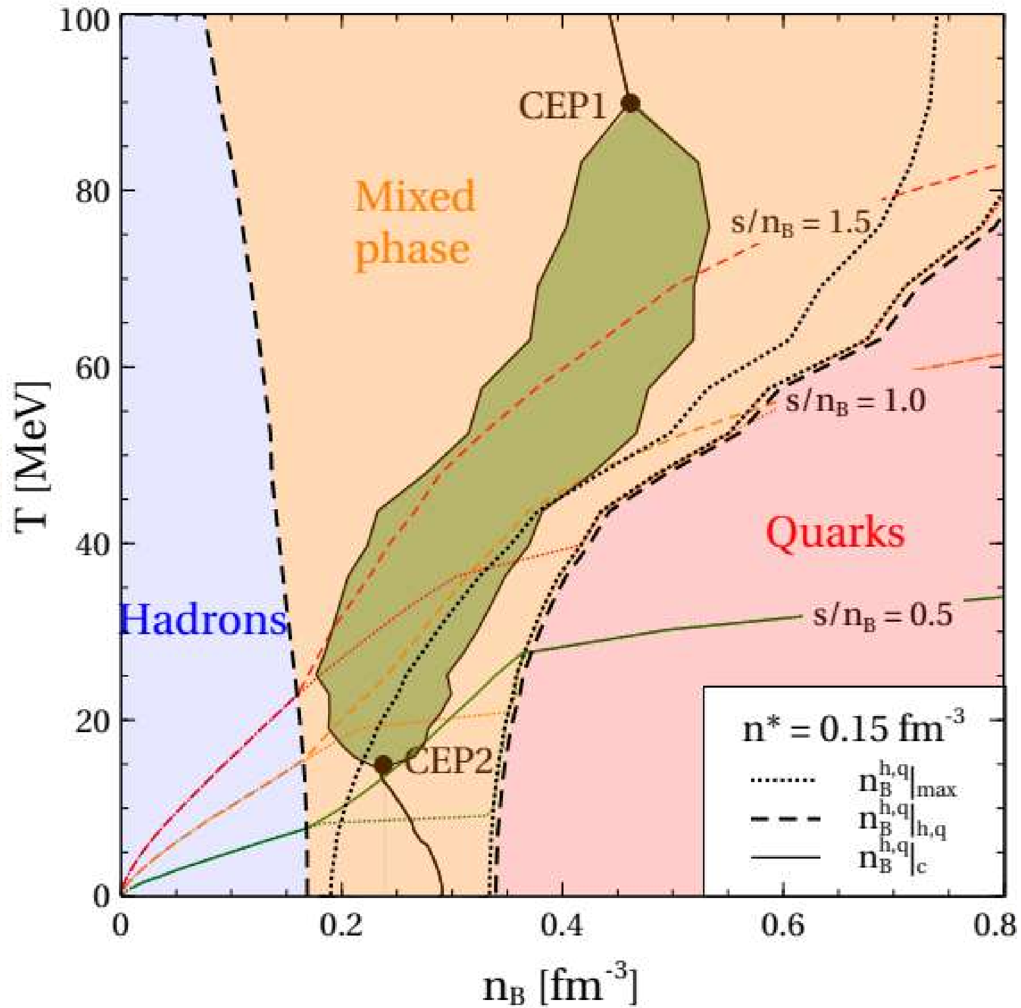
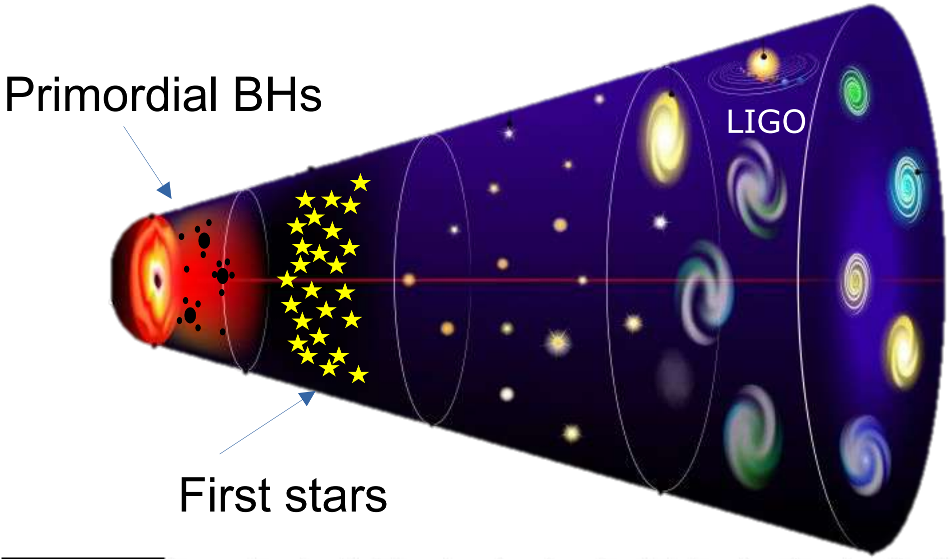
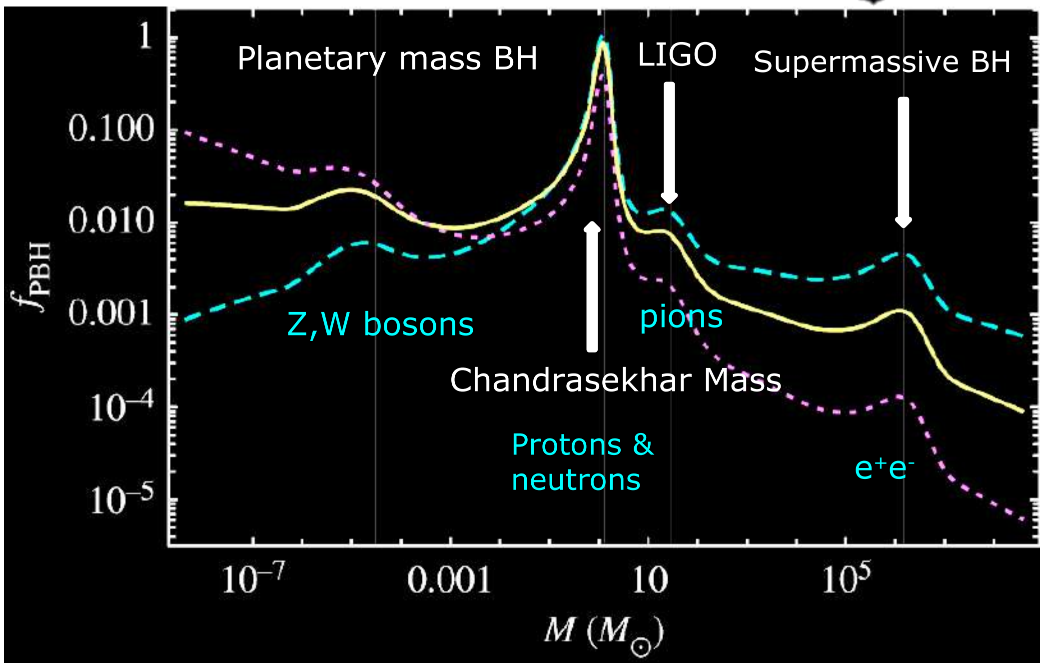


→ **EOS tables are prepared for simulation of supernovae and NS mergers**

JWST results – primordial black holes !





Talk at University of Wroclaw by Günther Hasinger, Founding director of the German Centre for Astrophysics In Görlitz:

Key role plays the QCD hadronization transition !

Different peaks correspond to different particles created at the early universe phase transitions and the corresponding reduction in the sound velocity.

BH mass corresponds to the horizon size at each time.

Only requirement is enough fluctuation power in a volume fraction of 10^{-9} of the early Universe.

Carr, Clesse, García-Bellido 2019

Let us discover the 3rd family of compact stars!

(Title of a talk I gave 5 years ago at MPIfR Bonn)

Let us discover the 3rd family of compact stars!

Prehistory … 55 years ago: Gerlach coined „3rd family“

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

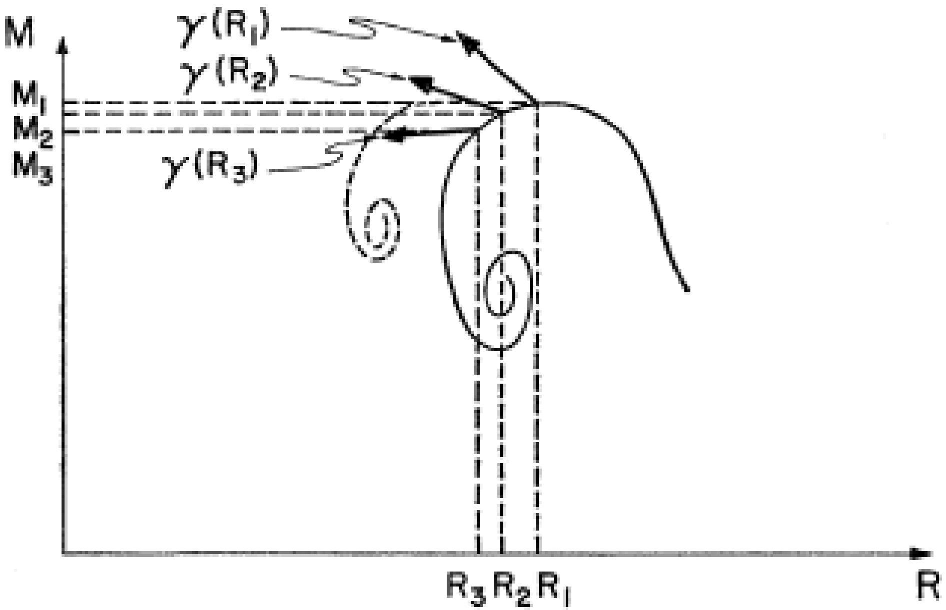
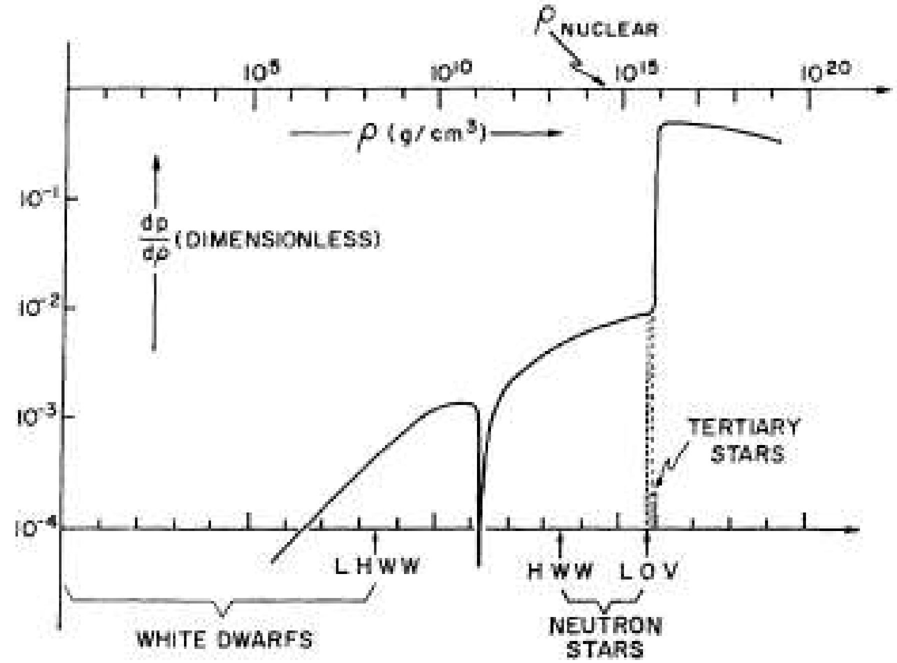
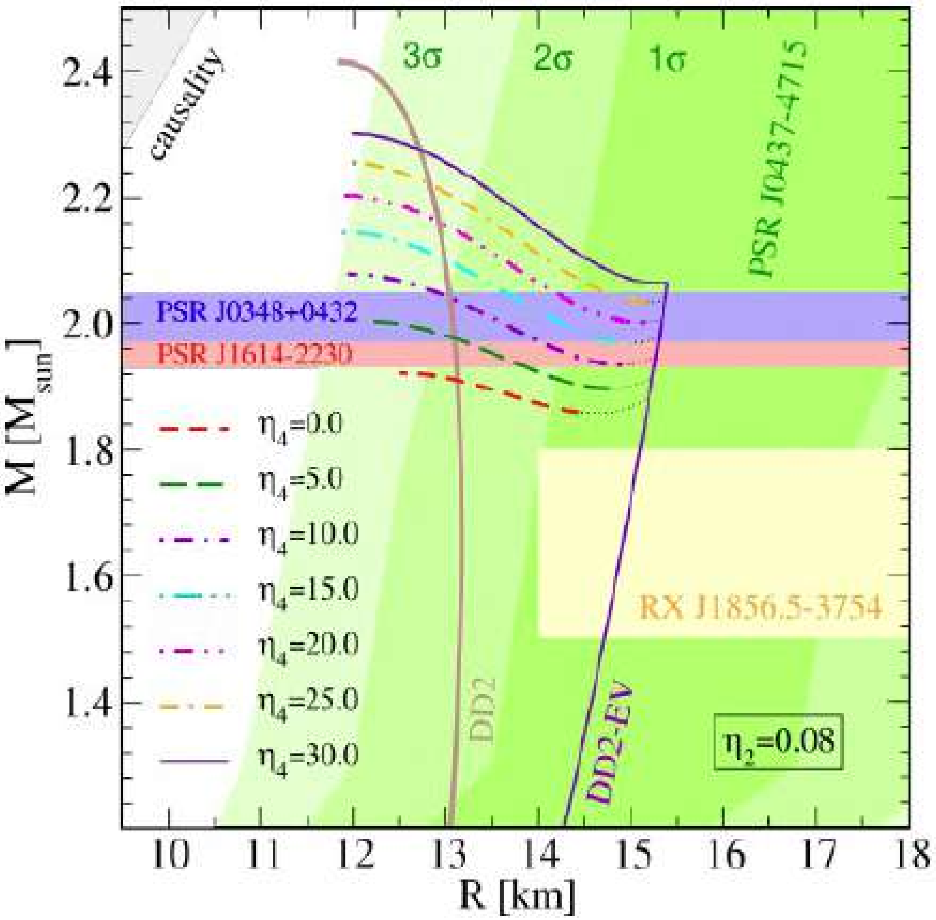


FIG. 3. A blow-up of the LOV maximum. The central densities

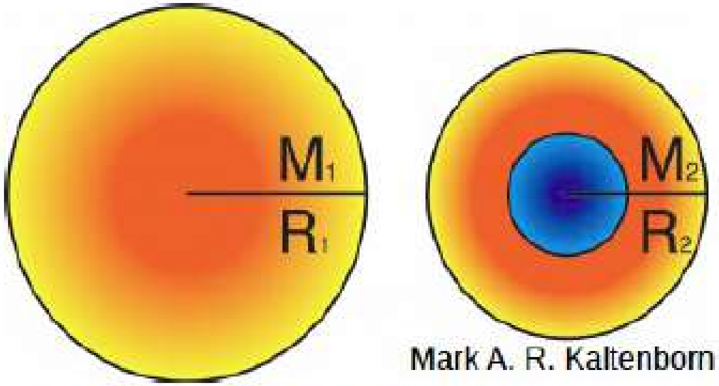


Let us discover the 3rd family of compact stars!

Prehistory … 10 years ago (2013) we revived the idea



- 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)

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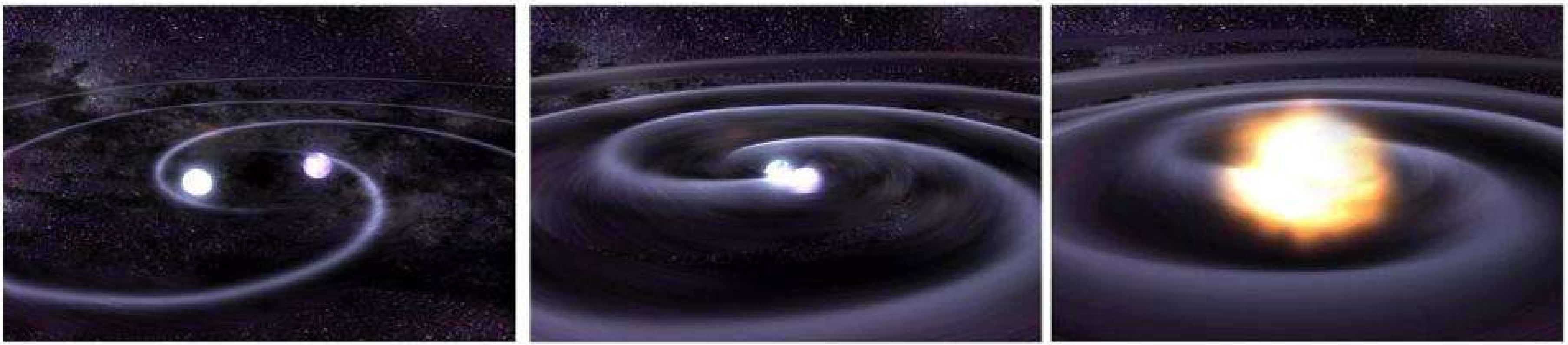
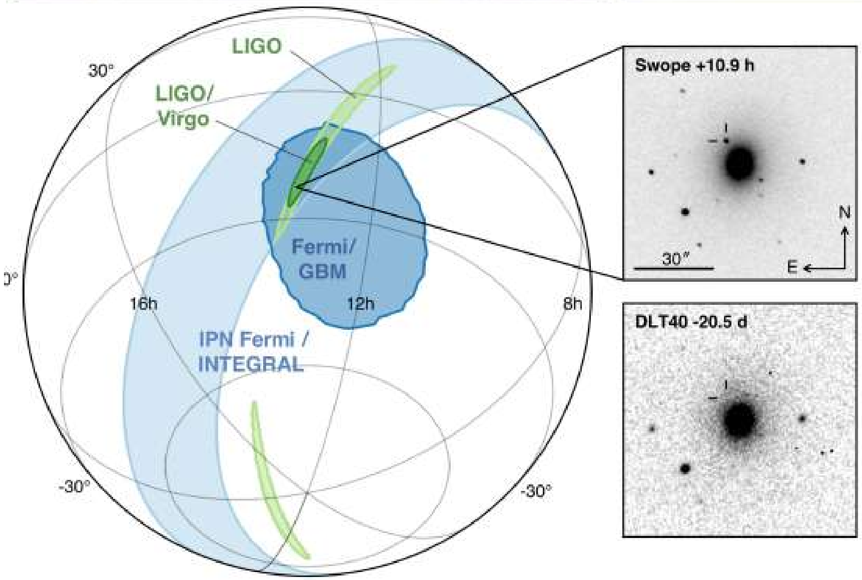
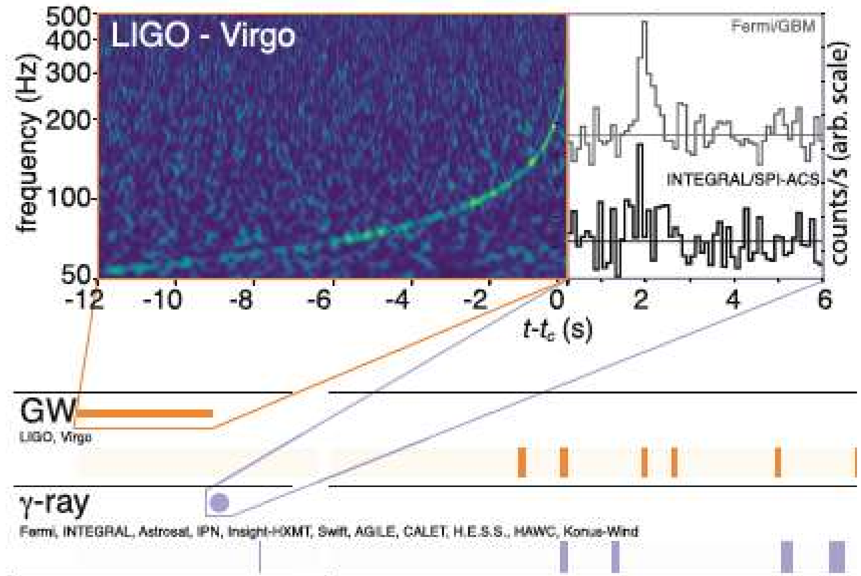
Prehistory … GW170817 happened!







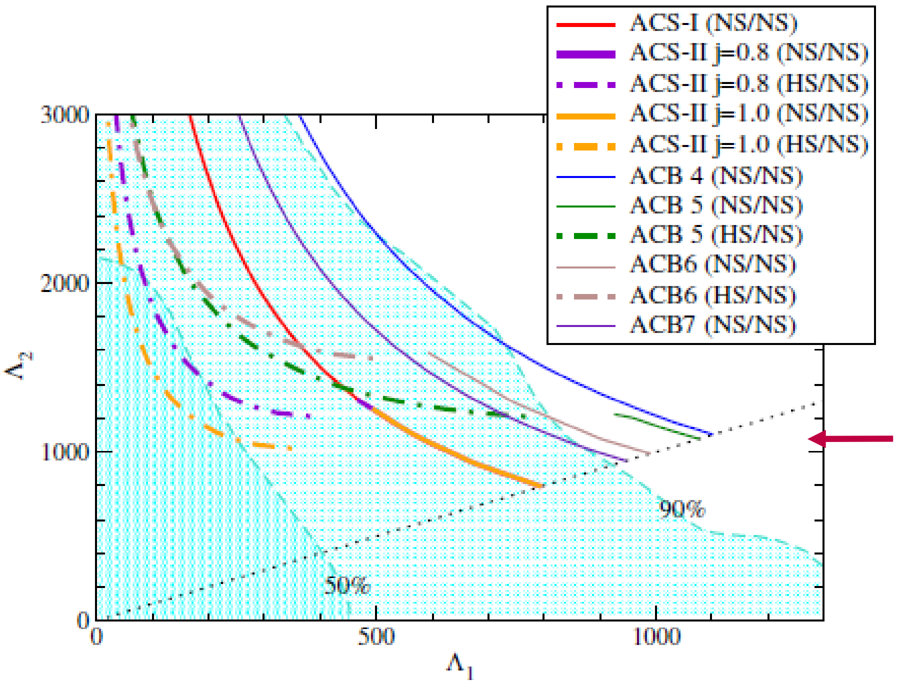
GW170817, announced on 16.10.2017

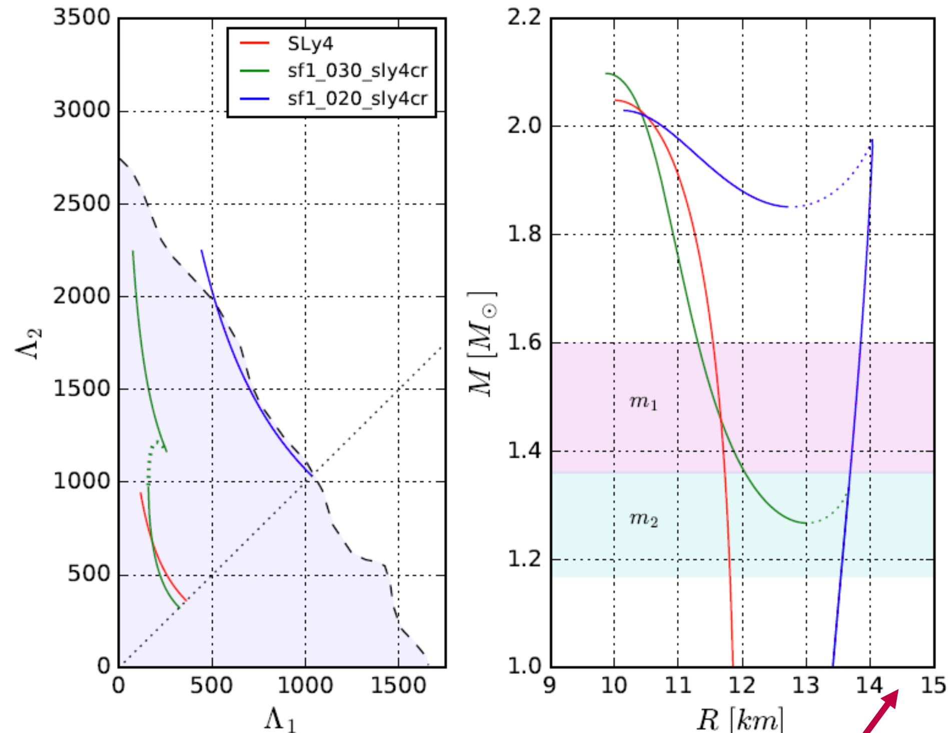
B.P. Abbott et al. [LIGO/Virgo Collab.], PRL 119, 161101 (2017); ApJLett 848, L12 (2017)

Let us discover the 3rd family of compact stars!

Prehistory ...

	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_{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., A&A 600 (2017) A39

V. Paschalidis, K. Yagi, D. Alvarez-Castillo, D.B., A. Sedrakian, arxiv:1712.00451 Phys. Rev. D97 (2018) 084038

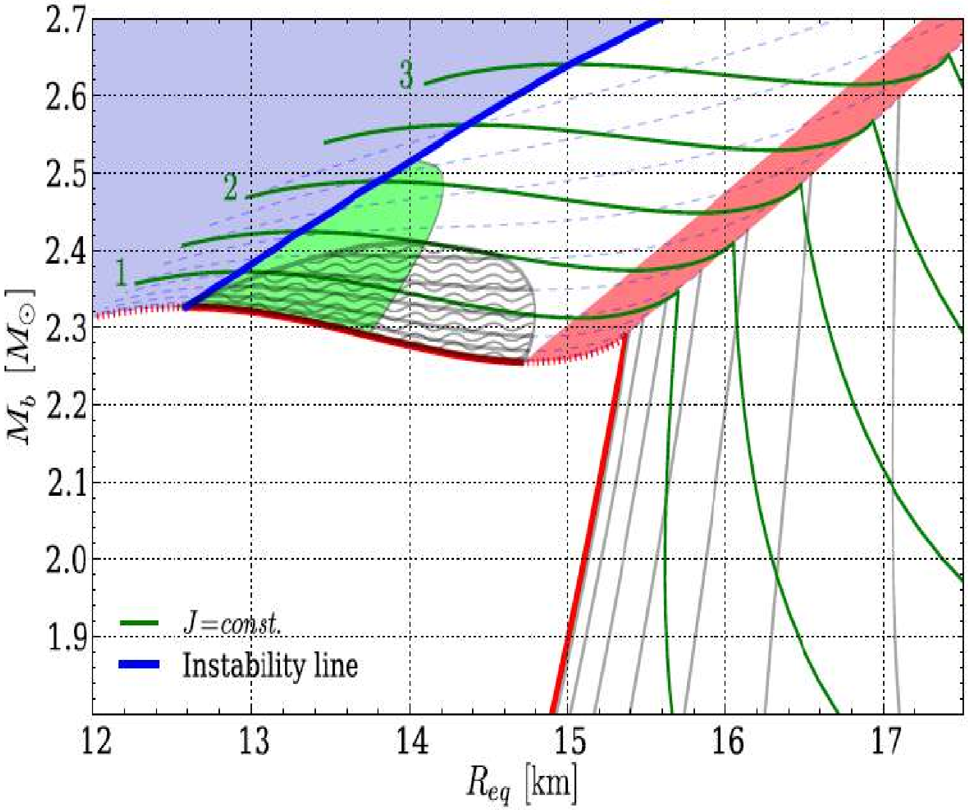
Suggestion: The heavier NS be a hybrid star (HS) with a quark core, evtl. member of a “third family”!

Let us discover the 3rd family of compact stars!

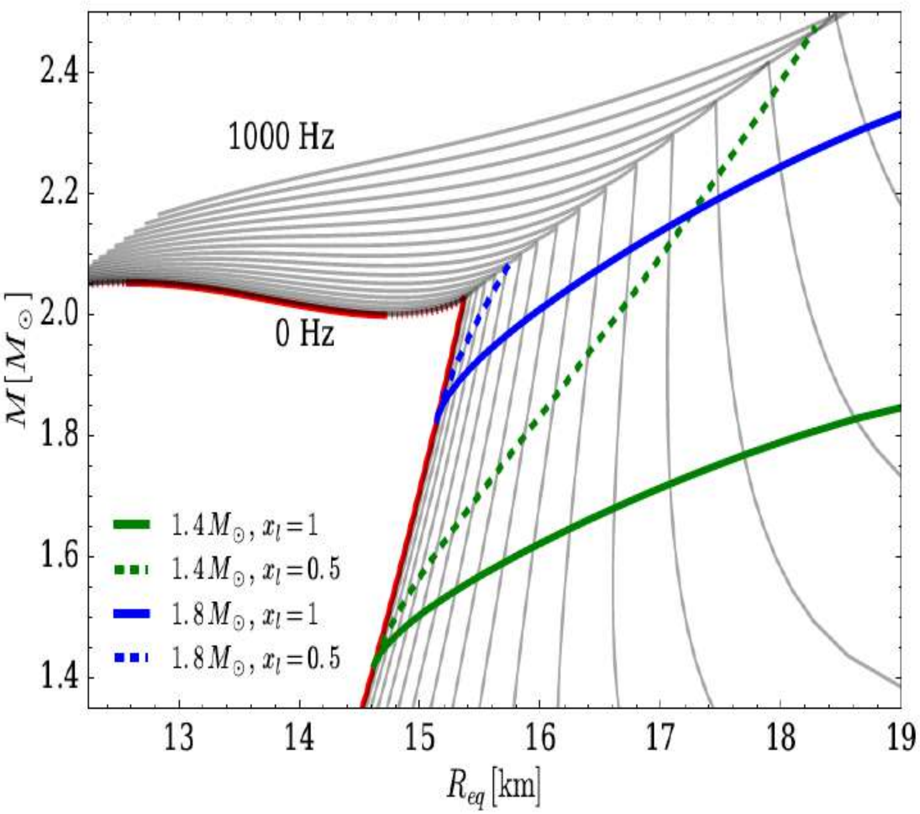
Observation:

With a strong PT (mass twins), a sudden transition NS → HS is possible,

Triggered by accretion, under simultaneous conservation of Mb and J



M. Bejger, D.B., et al., A&A 600 (2017) A39



Evolutionary tracks for disc accretion of mass with Efficiency xl=1(0.5) of angular momentum transfer

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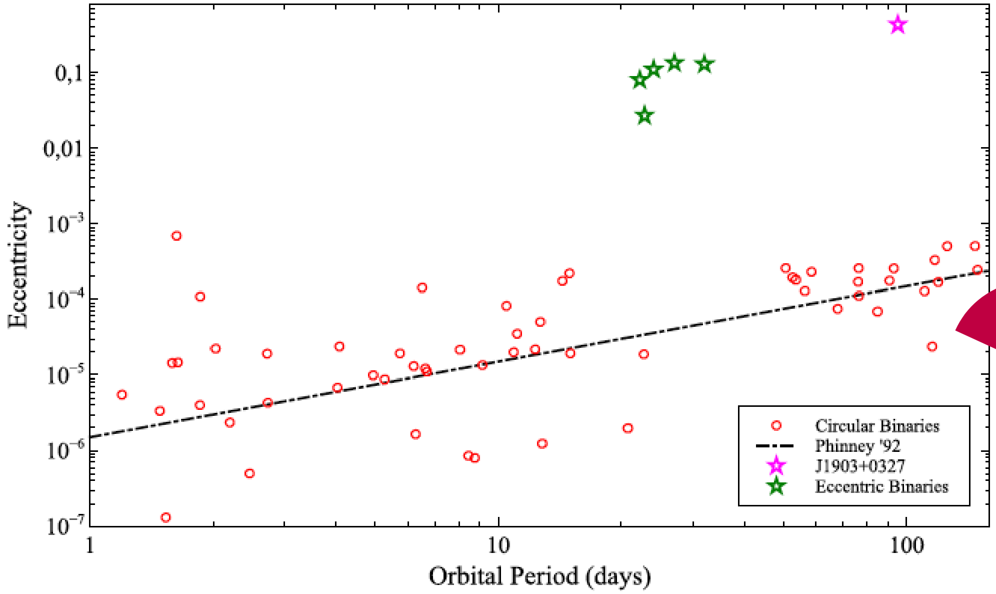
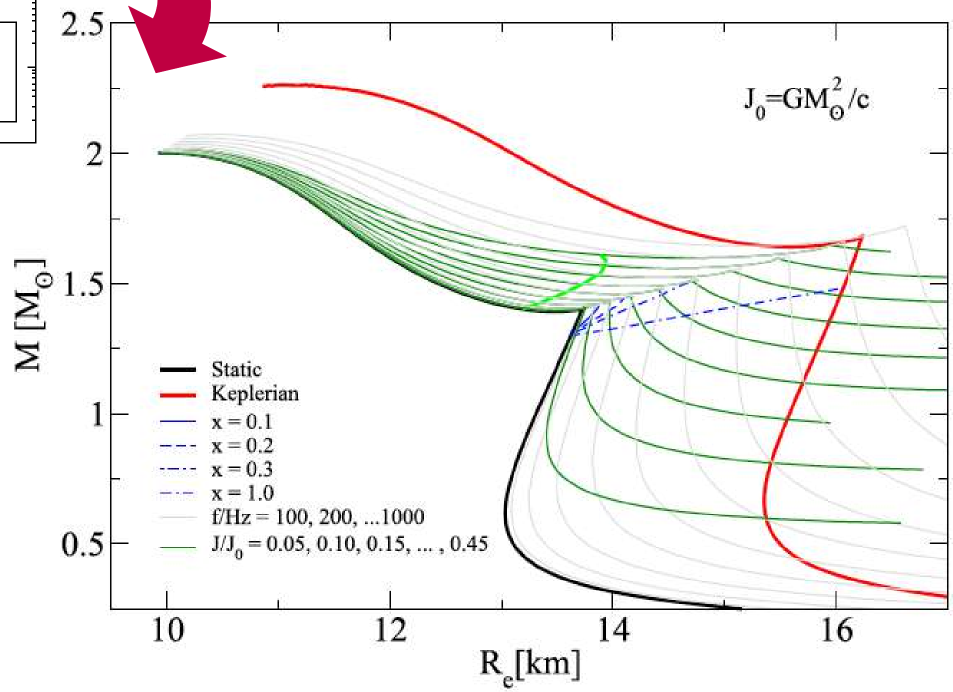
Antoniadis-puzzle



J. Antoniadis, ApJ Lett. 797, L24 (2014)

K. Stovall, P.C.C. Freire, J. Antoniadis, ApJ 870(2), 74 (2019)

How to relate this ?



D.E. Alvarez.Castillo, J. Antoniadis, A. Ayriyan, D. B., V. Danchev, H. Grigorian, N. Khosravi Largani, F. Weber,

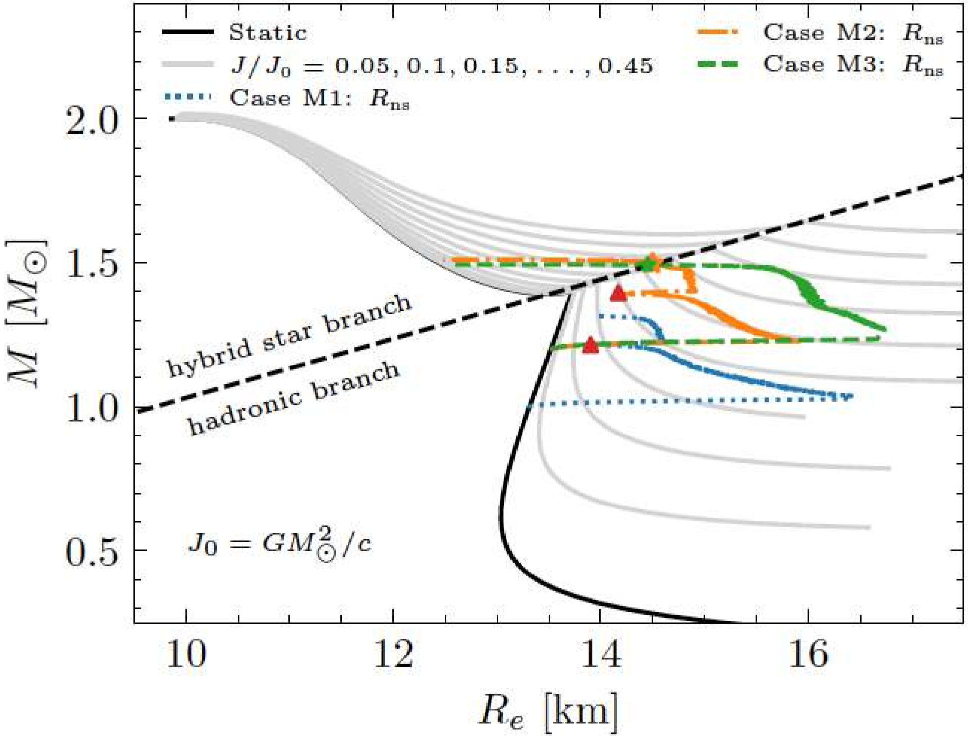
Accretion-induced collapse to third family compact stars as trigger for eccentric orbits of Millisecond pulsars in binaries,

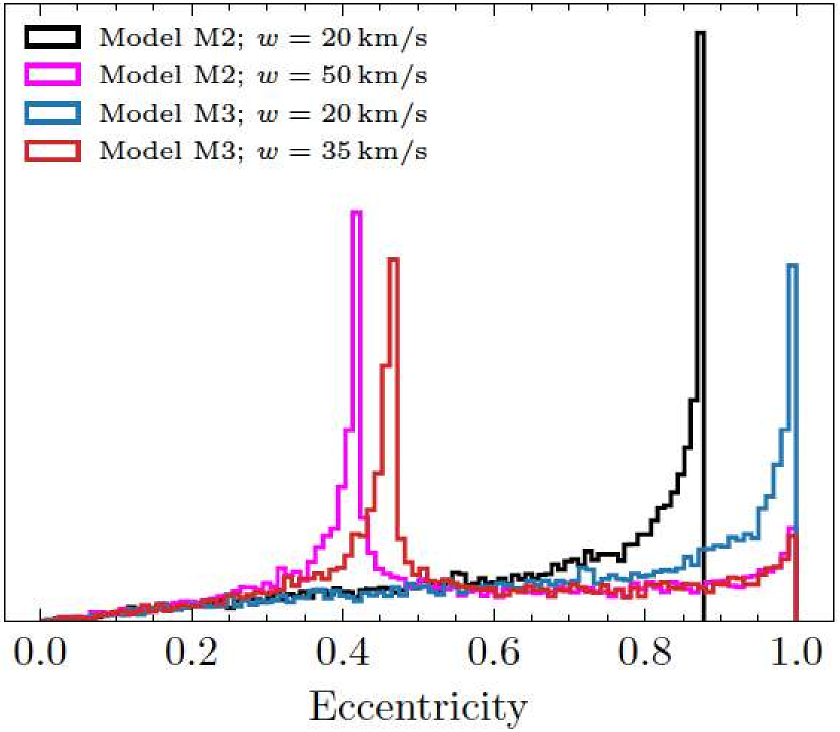
Astron. Nachr. 340 (2019) 878;
ArXiv:1912.08782 [astro-ph.HE]

Let us discover the 3rd family of compact stars!

Work in preparation ...

S. Chanlaridis, D. Ohse, A. Aspradakis, J. Antoniadis, D. Blaschke, D.E. Alvarez-Castillo,
V. Danchev and N. Langer

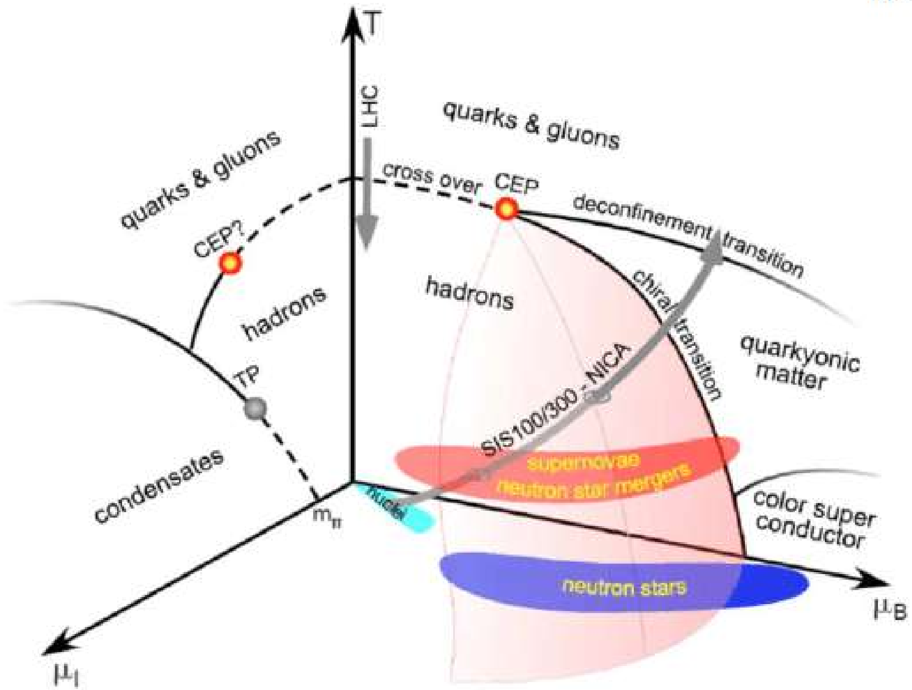




Prescription for transition-triggered kicks adapted from supernova case following:
J.G. Hills, ApJ 267, 322 (1983) and T.M. Tauris et al., ApJ 846, 170 (2017)

Conclusion

Density functional methods solve obstacles in neutron star astrophysics



From: NuPECC Long Range Plan 2017

Prominent contributions to deconfinement in modern multimessenger Astrophysics:

- Quark deconfinement transition triggers the supernova explosion of a very massive ($M = 50 M_\odot$) blue supergiant progenitor star
  T. Fischer et al., Nature Astron. 2 (2018) 960
- Unambiguous signal of a strong phase transition in the postmerger GW from a binary NS merger predicted
  A. Bauswein et al., Phys. Rev. Lett. 122 (2019) 061102
- Strong deconfinement phase transition in NS can be detected by observing the mass twin star phenomenon
  D. B. et al., Universe 6 (2020) 81

See also: Agnieszka Sorensen et al., Dense nuclear matter EOS from HIC, arXiv:2301.13253

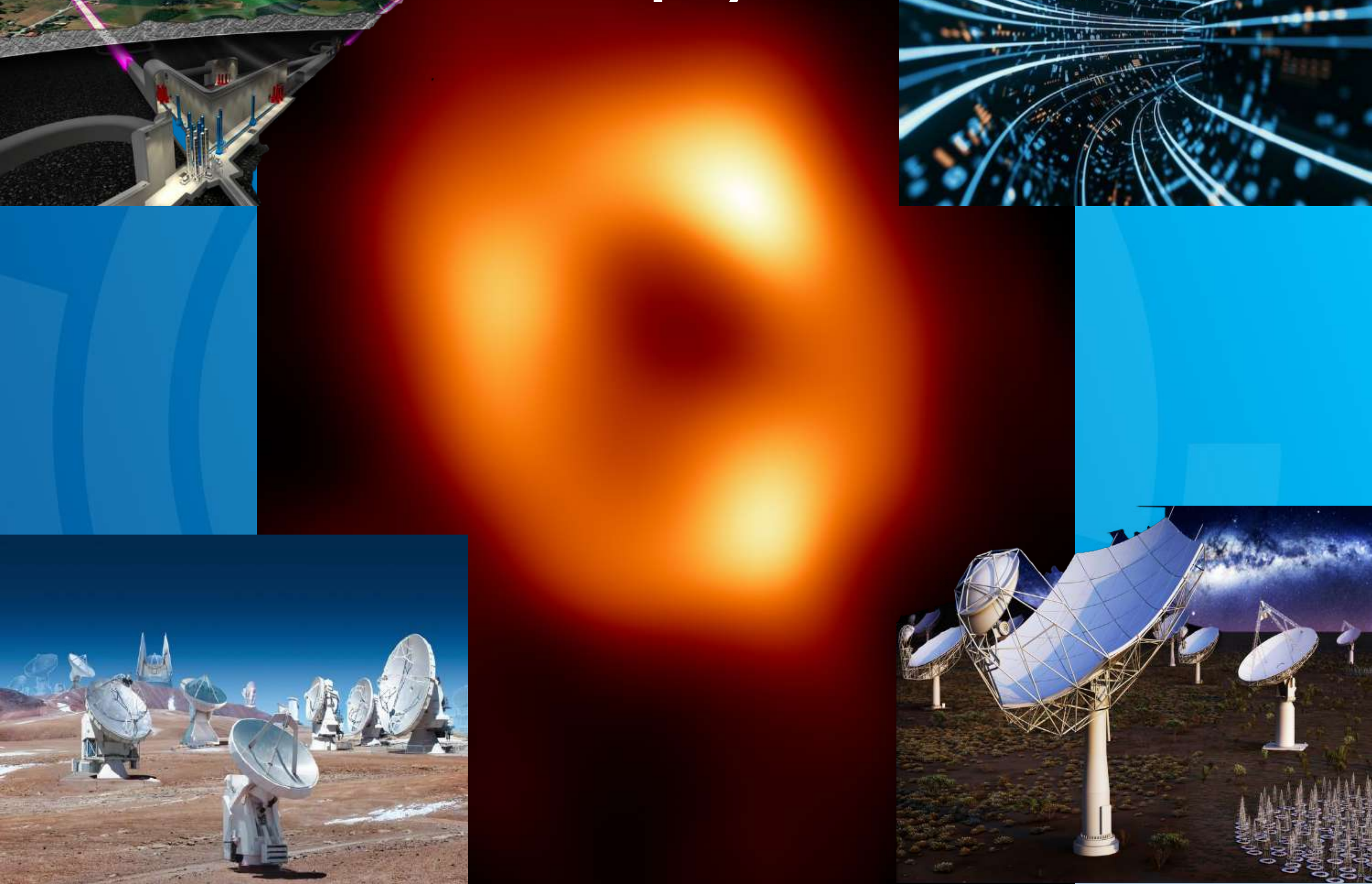
Outlook: The German Centre for Astrophysics (DZA)

Research
Technology
Digitization

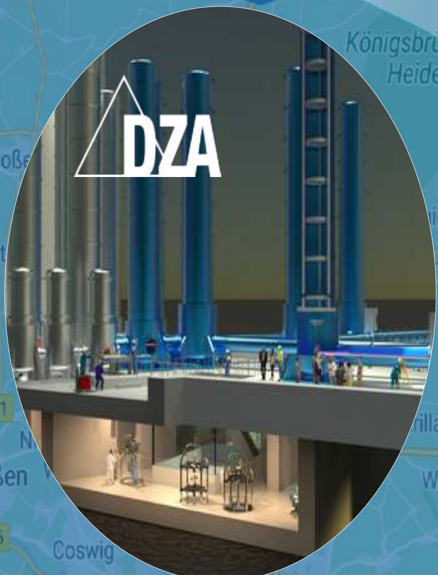
„Science Creating Prospects for the Region!"

Scientific Commission: 13. July 2022
Structural and Transfer-Commission: 30. August 2022
Final decision (Approval): 29. September 2022

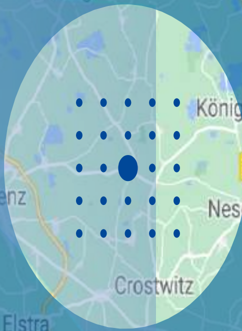
Fascination and inspiration of astrophysics



Why in Saxony? Lusatia is a unique region for Astrophysics, Technology and Digitization



Location for the Low Seismic Lab



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