Nonideal quark plasma in compact star astrophysics and at NICA/FAIR heavy-ion coll.

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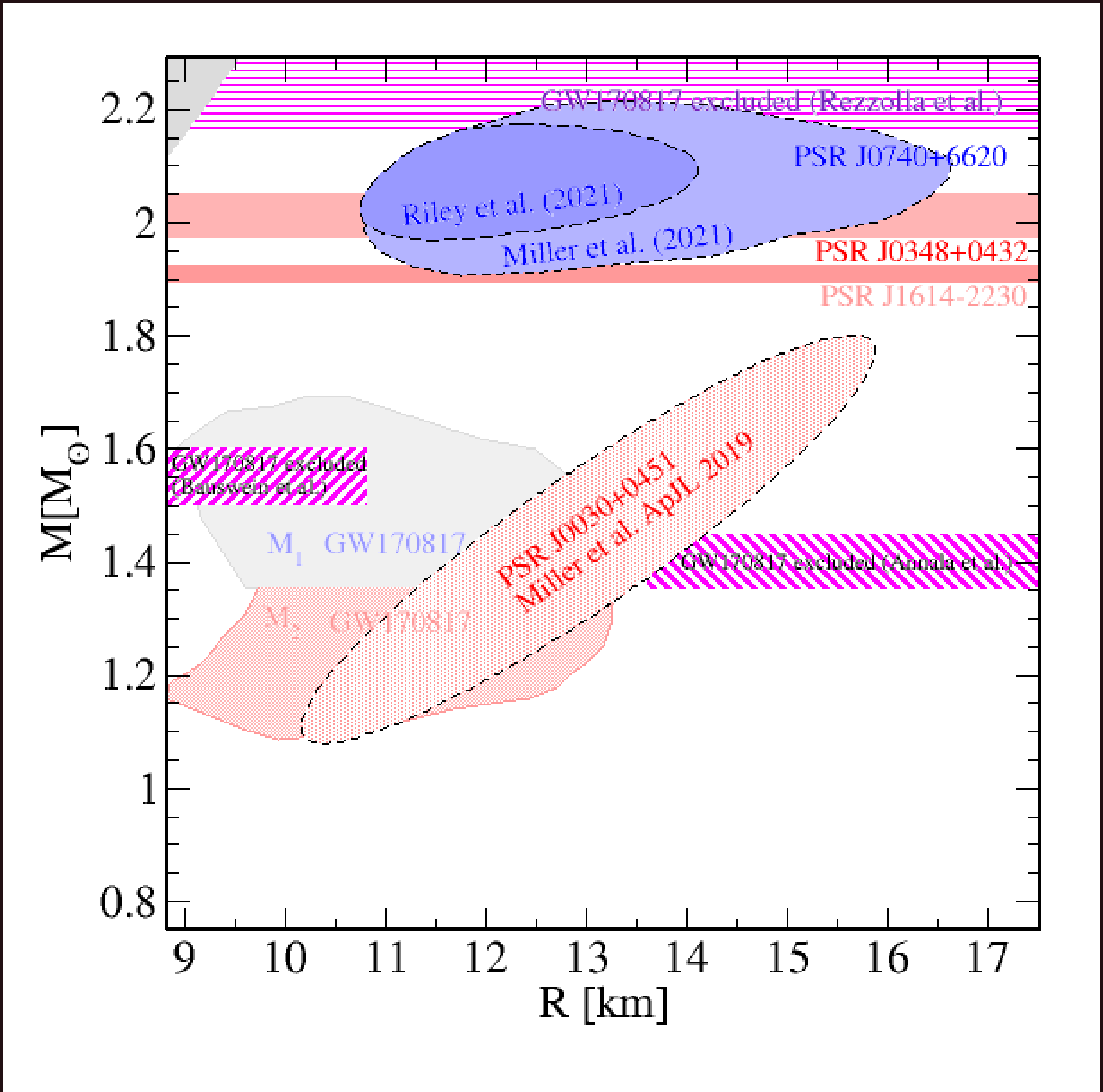
a – University Wroclaw, b - JINR Dubna, c – NRNU (MEPhI) Moscow, d – GSI Darmstadt

1. **Introduction: Recent relevant multi-messenger observations**
2. **New paradigm: Only hybrid stars fulfill new M-R constraints**
3. **Outlook: Supernovae & Mergers in the QCD phase diagram**
   → Constraints for the Onset of Deconfinement?

NPP 2021 Scientific Coordination Workshop, 9. December 2021

JINR DUBNA
MEPhI
STRONG-2020
RFBR
COST EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY
Uniwersytet Wrocławski
NARODOWE CENTRUM NAUKI
Grant No. UMO 2019 / 33 / B / ST9 / 03059
Grant No. 18-02-40137
PHAROS THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS
THOR

New constraints on NS mass and radii !



New NICER mass-radius data

PSR J0740+6620

(Riley et al., arxiv:2105.06980
Miller et al., arxiv:2105.06979)

Hypernuclear EoS out ?!

→ stiff hypernuclear matter

→ early onset of deconfinement
(M_onset < 1.5 M_sun)

New quark matter paradigm:

→ deconfinement to stiff QM EoS

→ hybrid stars larger, higher M_{max}

LVC radius constraint
GW170817
(Abbott et al., PRL (2018))

NICER mass -radius constraint
PSR J0030+0451
(Miller et al., ApJLett. (2019))
PSR J0740+6620
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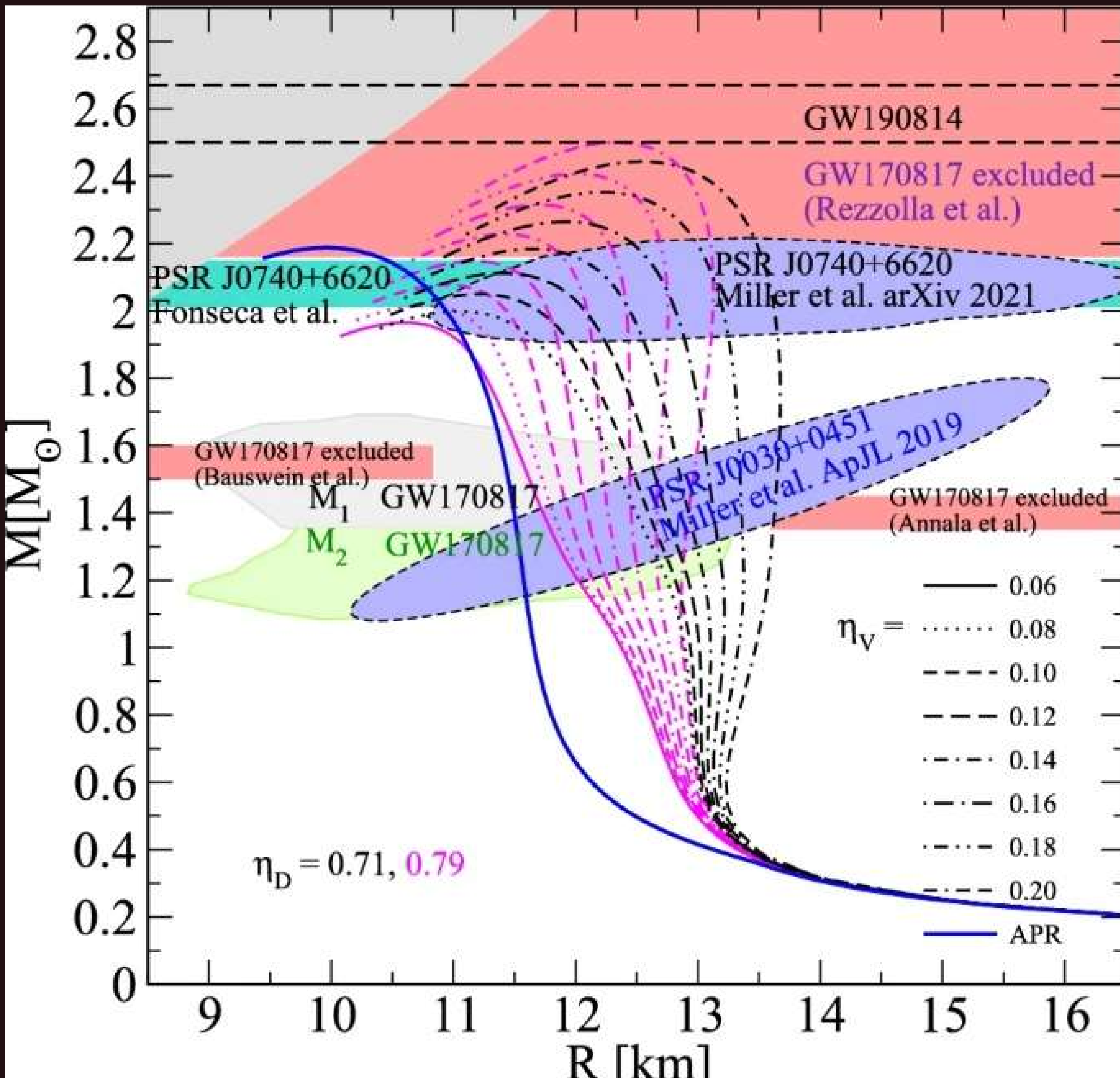
New constraints on NS mass and radii !



Ayriyan, Blaschke, Alvarez-Castillo et al., arXiv:2102.13485v2

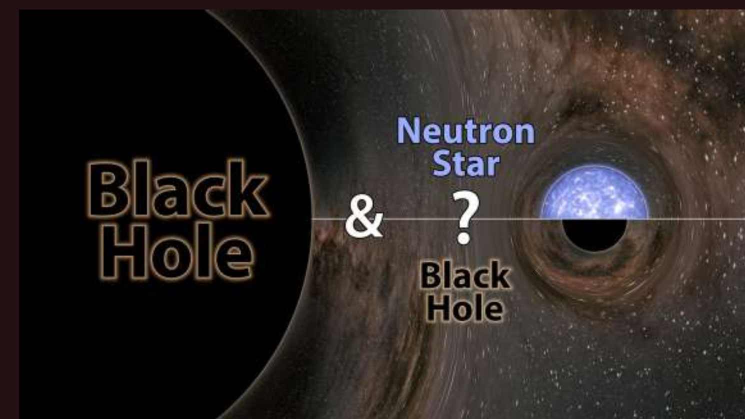
GW190814 - Enigma

Heaviest NS or Lightest BH ??

$M_1 = 22.2 - 24.3\ M_O$

$M_2 = 2.50 - 2.67\ M_O$

(Abbott et al., ApJL 896:L44 (2020))



LVC radius constraint
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PSR J0740+6620
(Miller et al., arxiv:2105.06979)

NICER radius measurement on PSR J0740+6620

New, large NICER radius for J0740: Riley et al., 2105.06980; Miller et al., 2105.06979

1-σ regions, 60% confidence

Attention:

Above ~1.5 M_sun hyperons
Appear in the center of neutron stars.

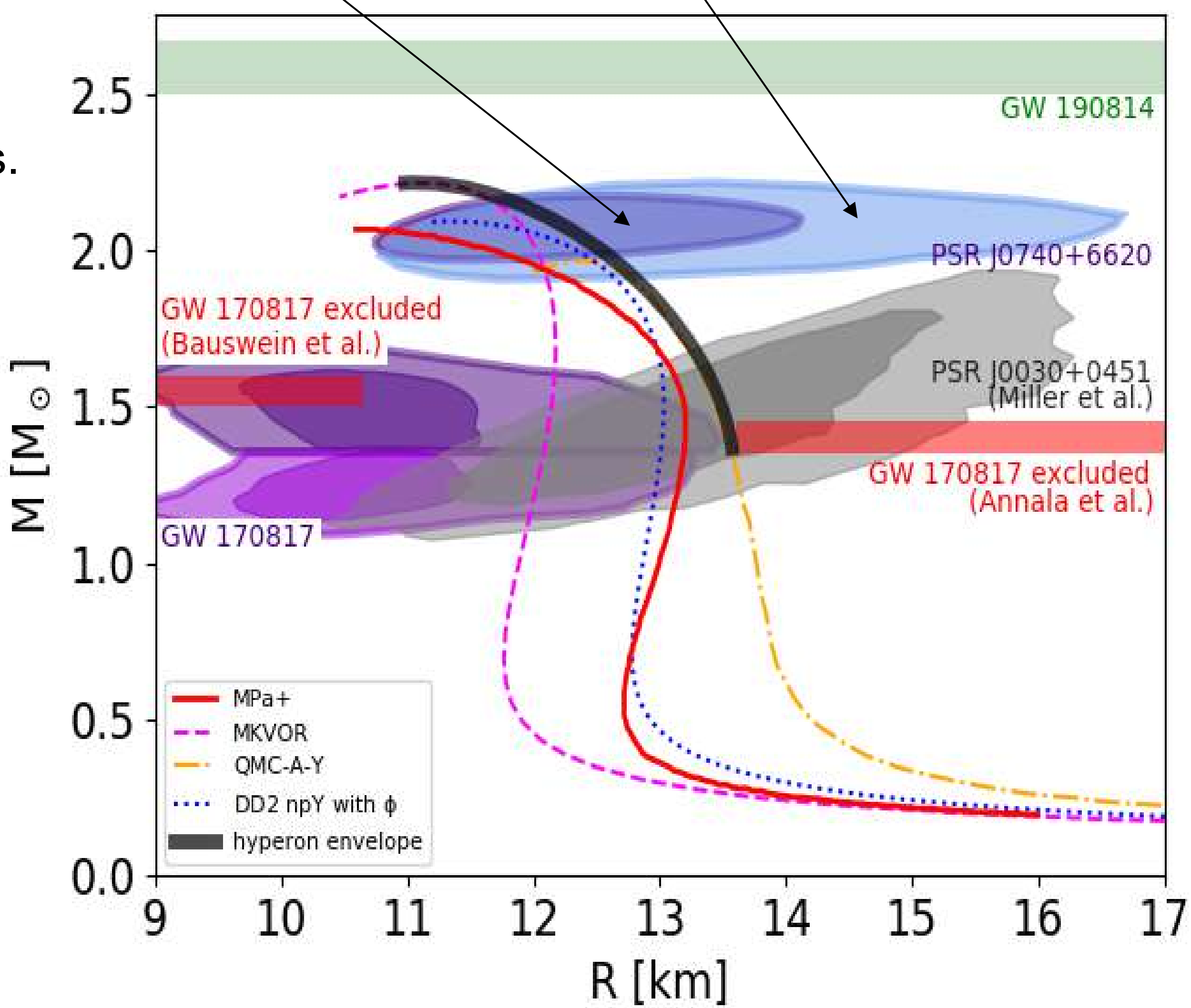
Non-hyperonic nuclear EoS (APR)
Are no longer applicable for
High-mass neutron stars ~2M_sun !

Microscopic EoS need high-density
Stiffening of the hypernuclear EoS,
e.g., by multi-pomeron interactions.

Yamamoto et al., PRC 96 (2017)

Relativistic mean-field EoS have a
Maximal NS radius R_2.0 ~ 13 km

Way out:
early deconfinement to color
superconducting, stiff quark matter !



What is the special point? What are its properties?

The TOV equation

$$\frac{\partial P(r)}{\partial r} = -\frac{\epsilon(r)M(r)\left(1+\frac{P(r)}{\epsilon(r)}\right)\left(1+\frac{4\pi r^3 P(r)}{M(r)}\right)}{r^2\left(1-\frac{2M(r)}{r}\right)}, \qquad \frac{\partial M(r)}{\partial r} = 4\pi r^2 \epsilon(r).$$

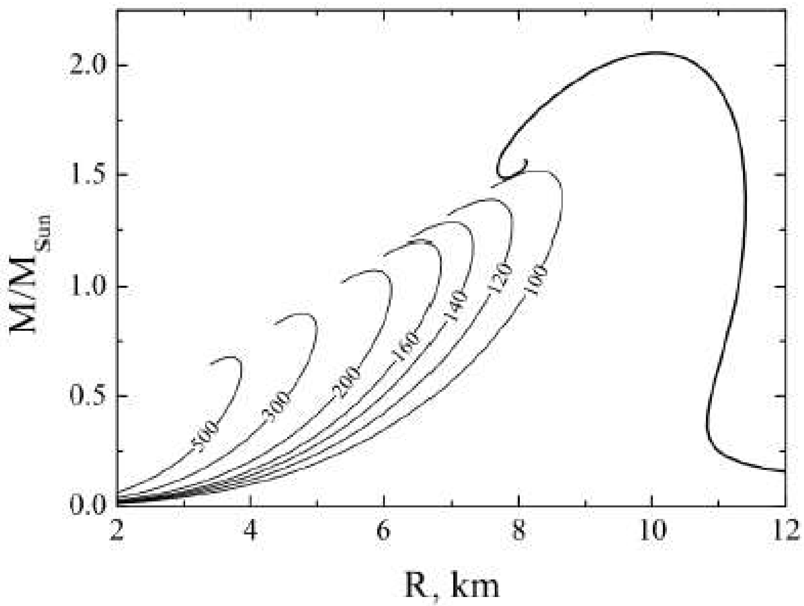


Fig. 1. Mass–radius diagram for a star made of ordinary matter (thick line) and purely quark stars (thin lines). The numbers at the lines indicate the parameter B.

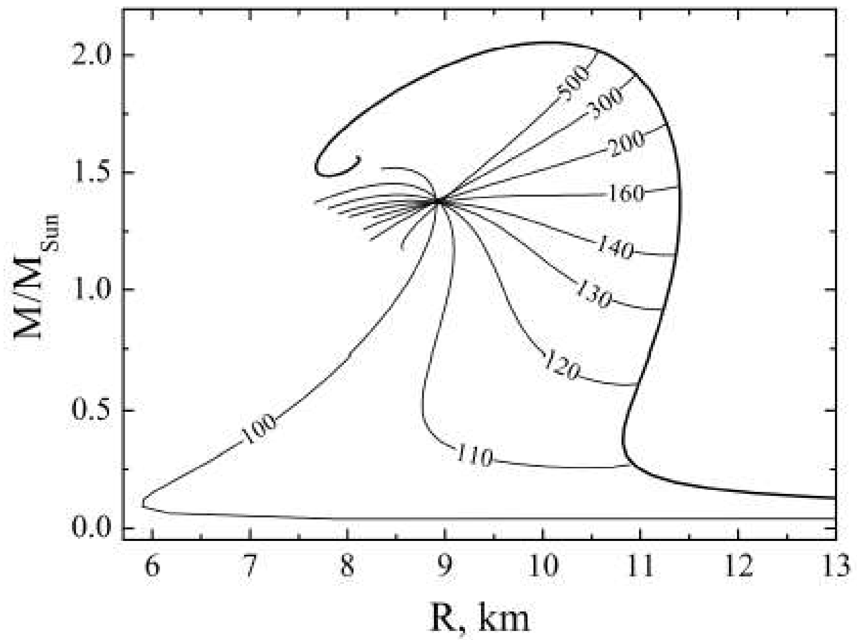
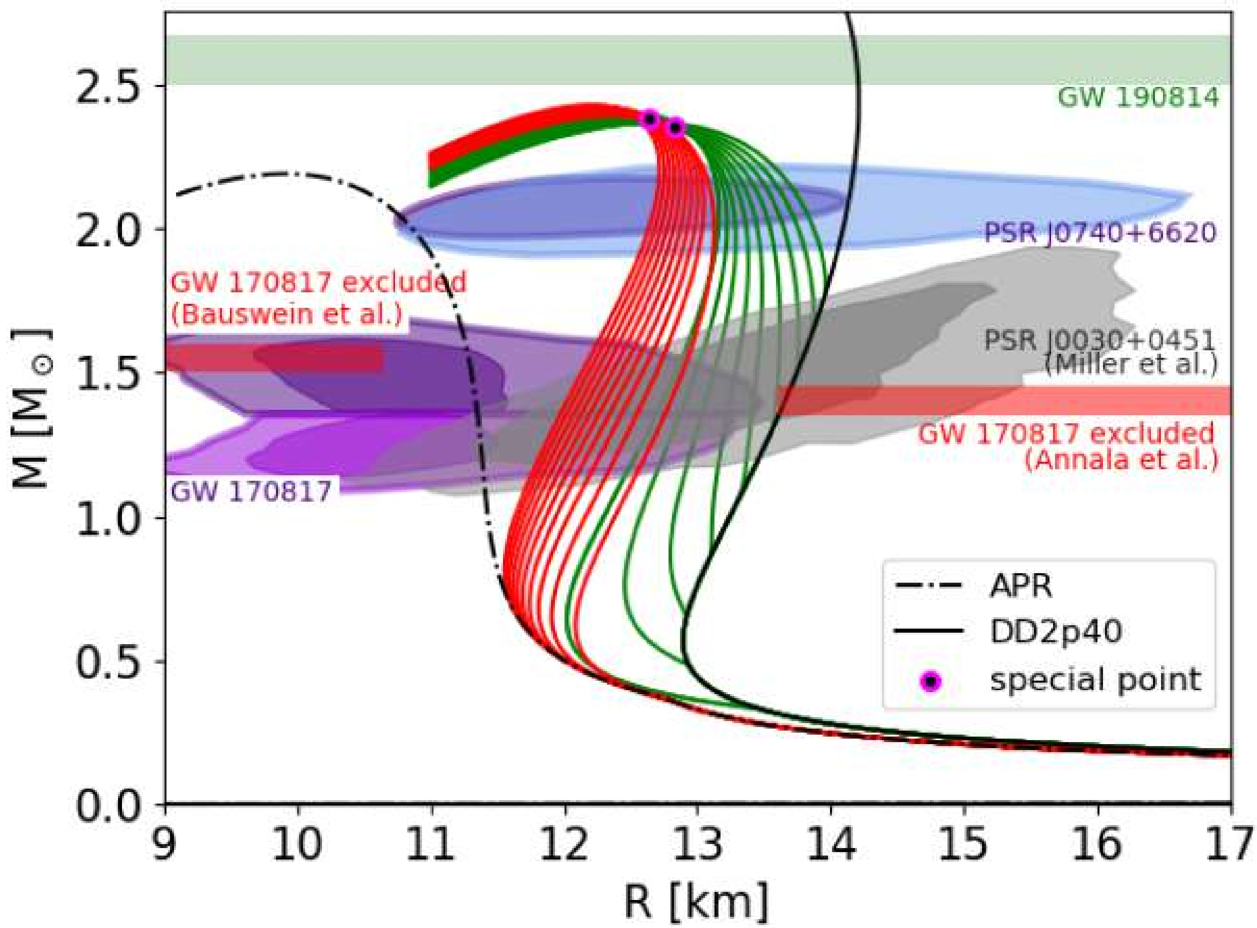


Fig. 2. Mass–radius diagram of hybrid stars for various values of the parameter B

[1]Yudin et al., Astron. Lett. **40** (2014), 201

Dependence on the phase transition construction?

Invariance w.r.t. Maxwell $->$ interpolation construction (soft - stiff transition)



[5] Cierniak, Blaschke, Astron. Nachr. (2021), arXiV: 2106.06986

Constant sound speed (CSS) vs. nonlocal NJL model

$$\mathcal{L} = \bar{\psi}\left(-i\not{\partial} + m_c\right)\psi - \frac{G_S}{2} j_S^f j_S^f - \frac{G_D}{2}[j_D^a]^\dagger j_D^a + \frac{G_V}{2} j_V^\mu j_V^\mu \,, \quad \eta_D = G_D/G_S \text{ and } \eta_V = G_V/G_S$$

Nonlocal currents, formfactor g(z)

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

$$j_D^a(x) = \int d^4z\, g(z) \bar{\psi}_C(x + \frac{z}{2}) i\gamma_5 \tau_2 \lambda^a \psi(x - \frac{z}{2}) \,,$$

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

CSS equation of state

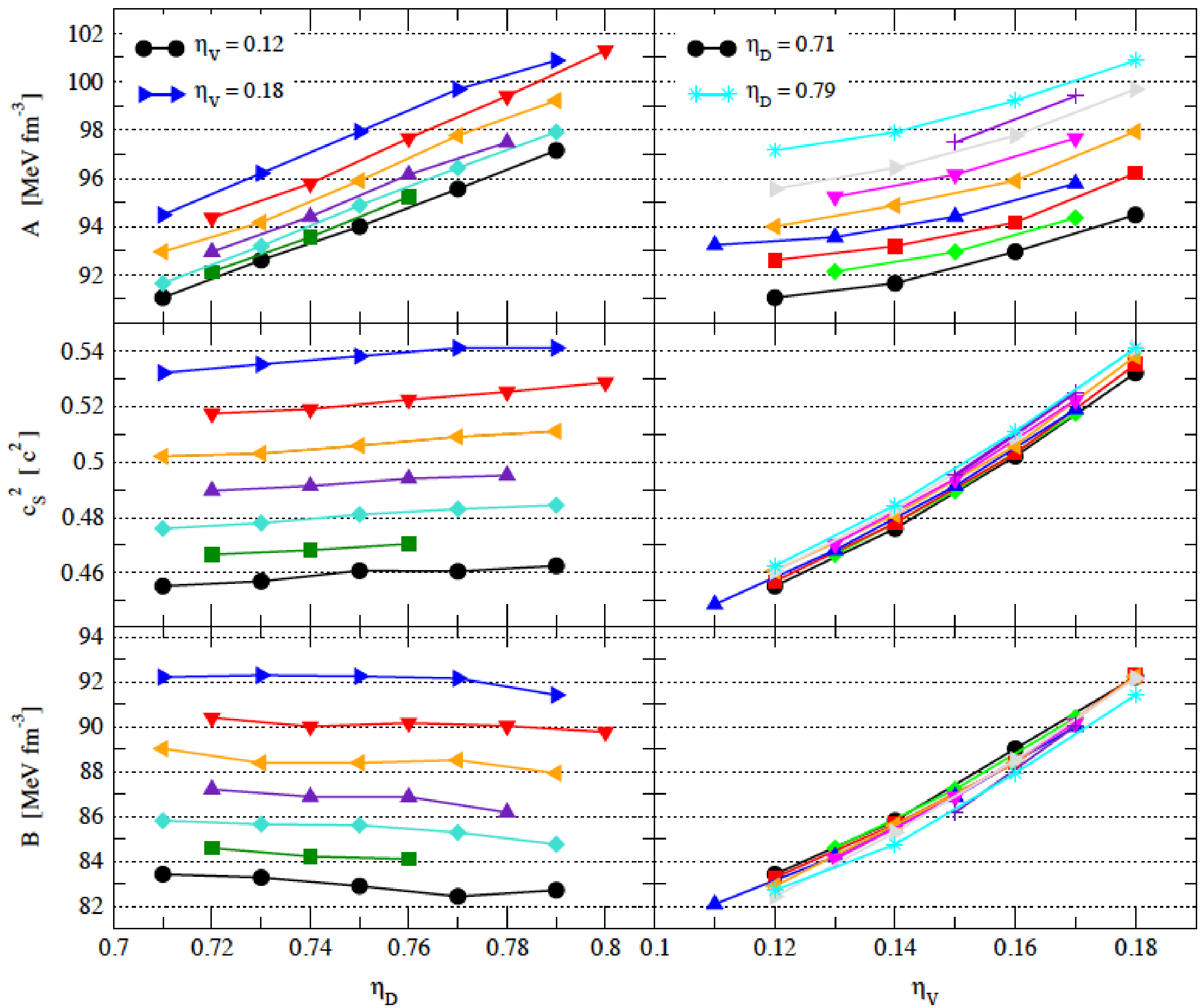
$$P(\mu) = A\left(\frac{\mu}{\mu_x}\right)^{1+\beta} - B,$$

Fitted relationship, see figure →

$$A = a_1\eta_D + b_1\eta_V^2 + c_1$$

$$c_s^2 = a_2\eta_D + b_2\eta_V^2 + c_2$$

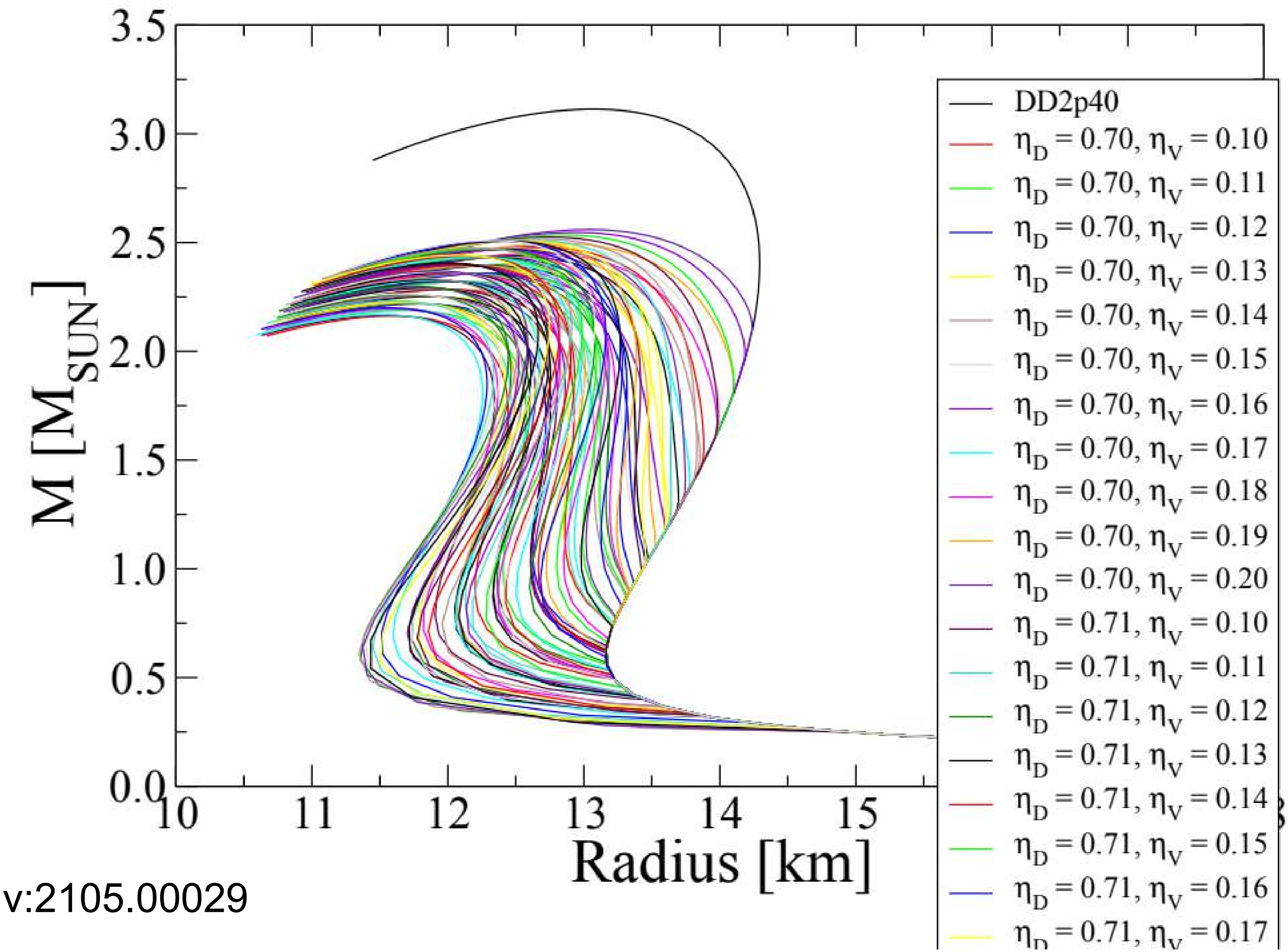
$$B = a_3\eta_D + b_3\eta_V^2 + c_3,$$



Perfect mapping nlNJL → CSS, Antic et al., arxiv:2105.00029

Constant sound speed (CSS) vs. nonlocal NJL model

“Trains” of special points, when η_D and η_V are varied systematically (grid)



Antic et al., arxiv:2105.00029

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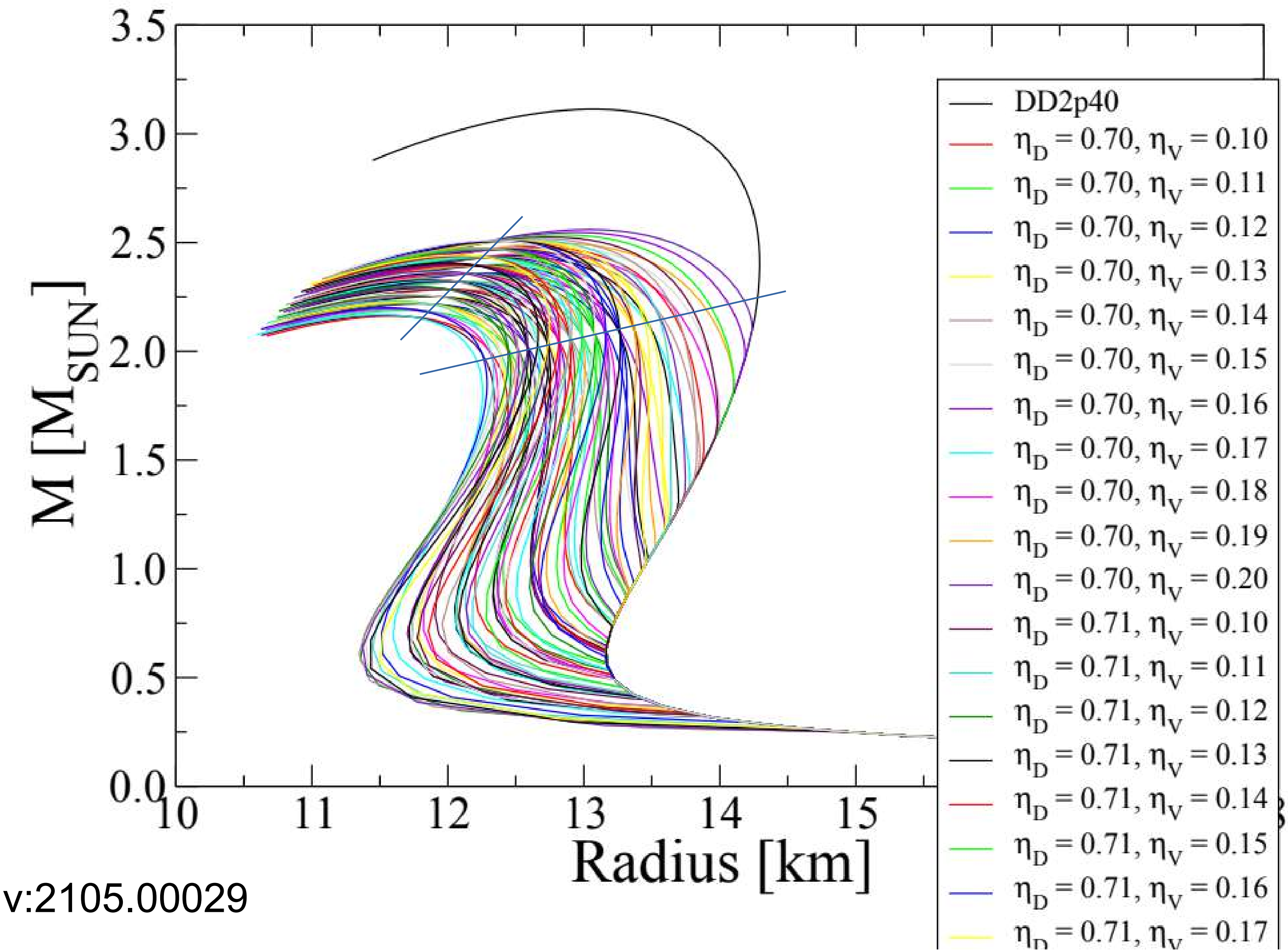


Antic et al., arxiv:2105.00029

New paradigm: hybrid stars larger and heavier

Work based on **Special Point location** with M. Cierniak, in preparation

Dense quark plasma in color superconducting phase: nlNJL model

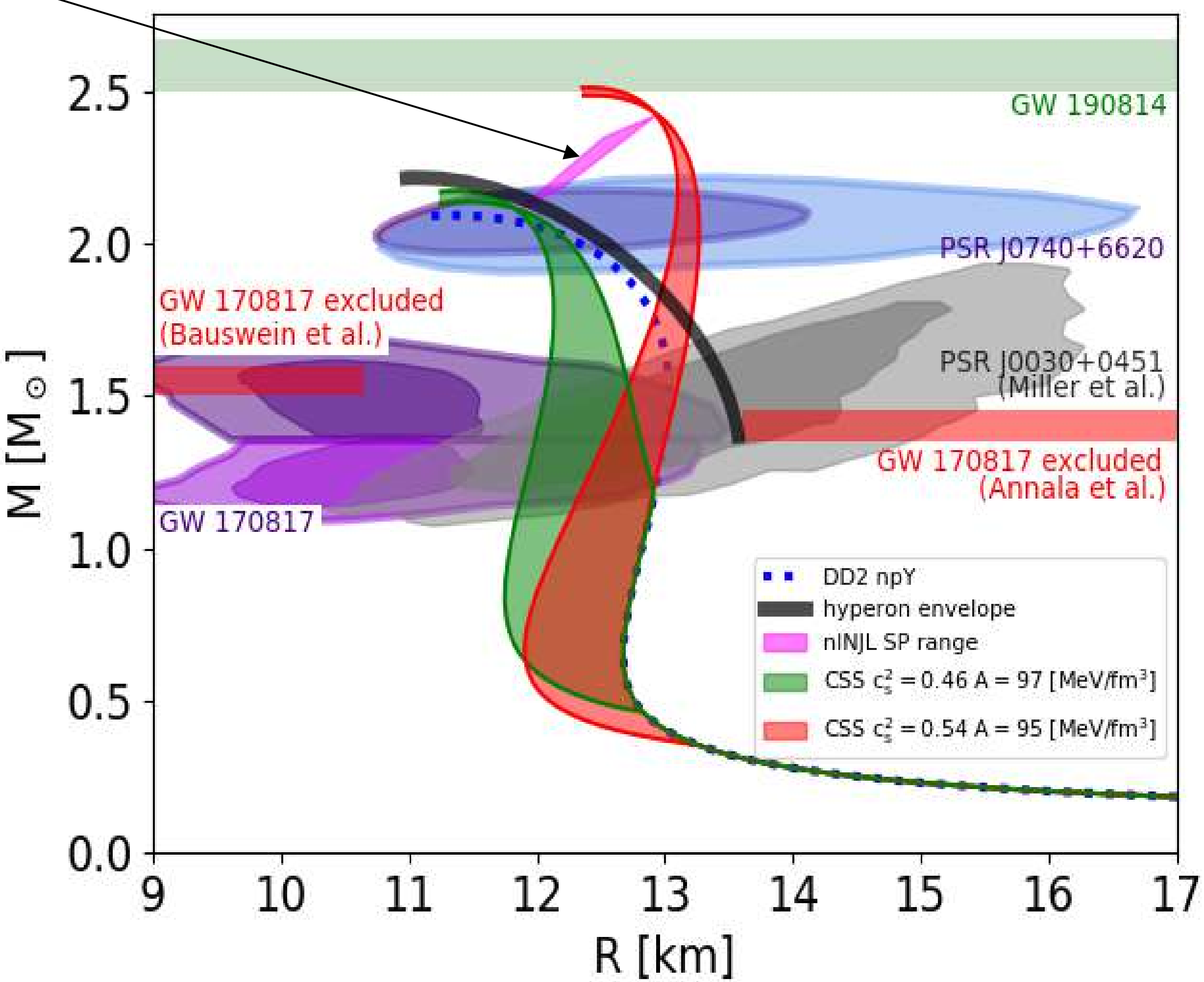
Constant-speed-of-sound (CSS) Equation of state (EoS)

$$p(\mu) = A(\mu/\mu_0)^{1+c_s^{-2}} - B$$

$$p = c_s^2 \varepsilon - (1 + c_s^2) B$$

Perfect mapping nlNJL → CSS , Antic et al., arxiv:2105.00029

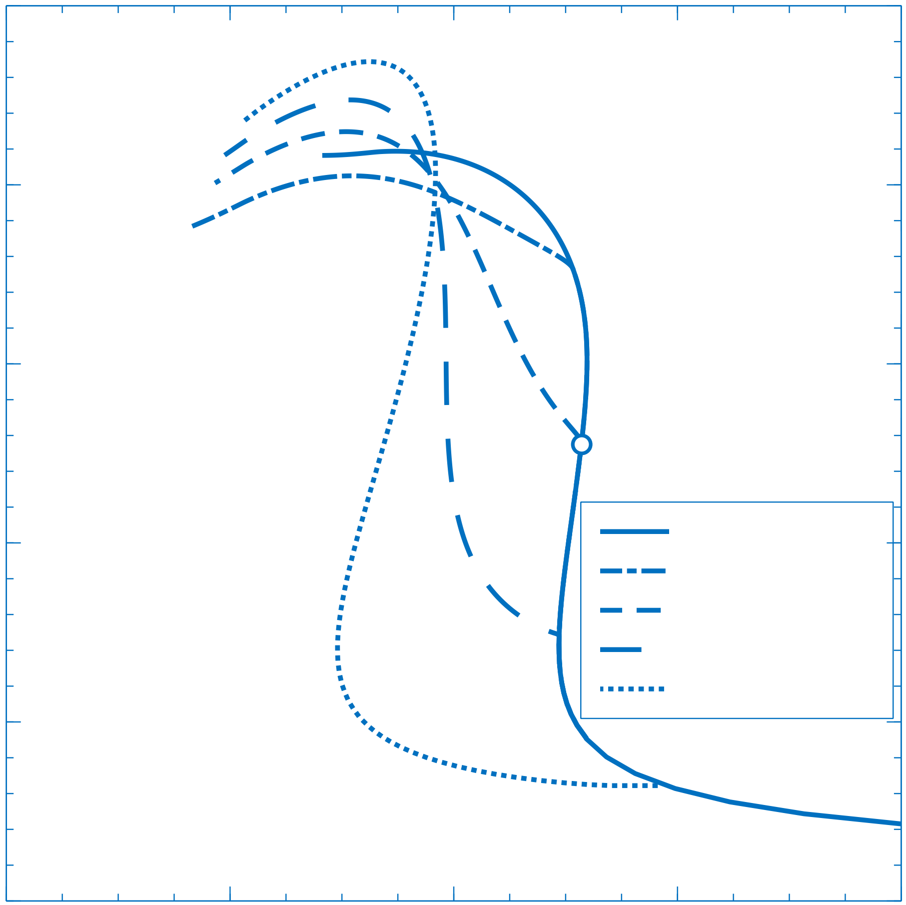
Maxwell construction with (1st order phase transition)
Relativistic Density Functional EoS “DD2-Y-T” by S. Typel
With density-dependent coupling

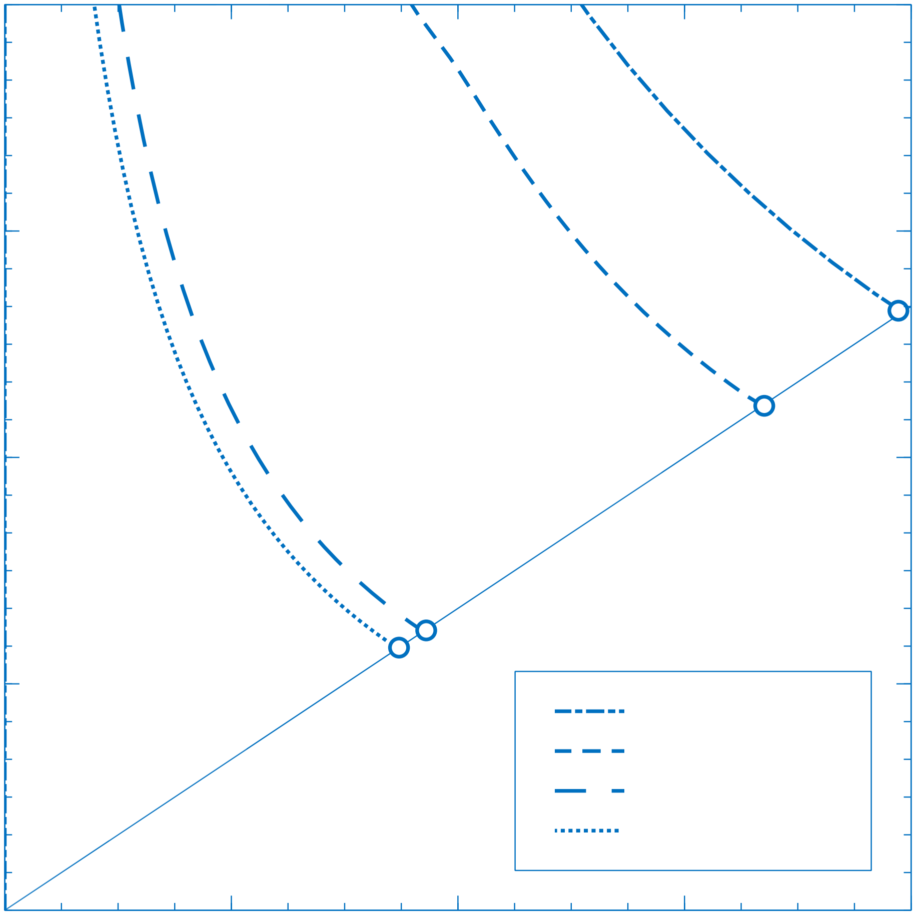


2.5 M_sun object can by a hybrid neutron star! With early onset of deconfinement!
NICER radius measurement on PSR J0740+6620 best described by hybrid stars!

New DFT for quark matter with confinement & CSC

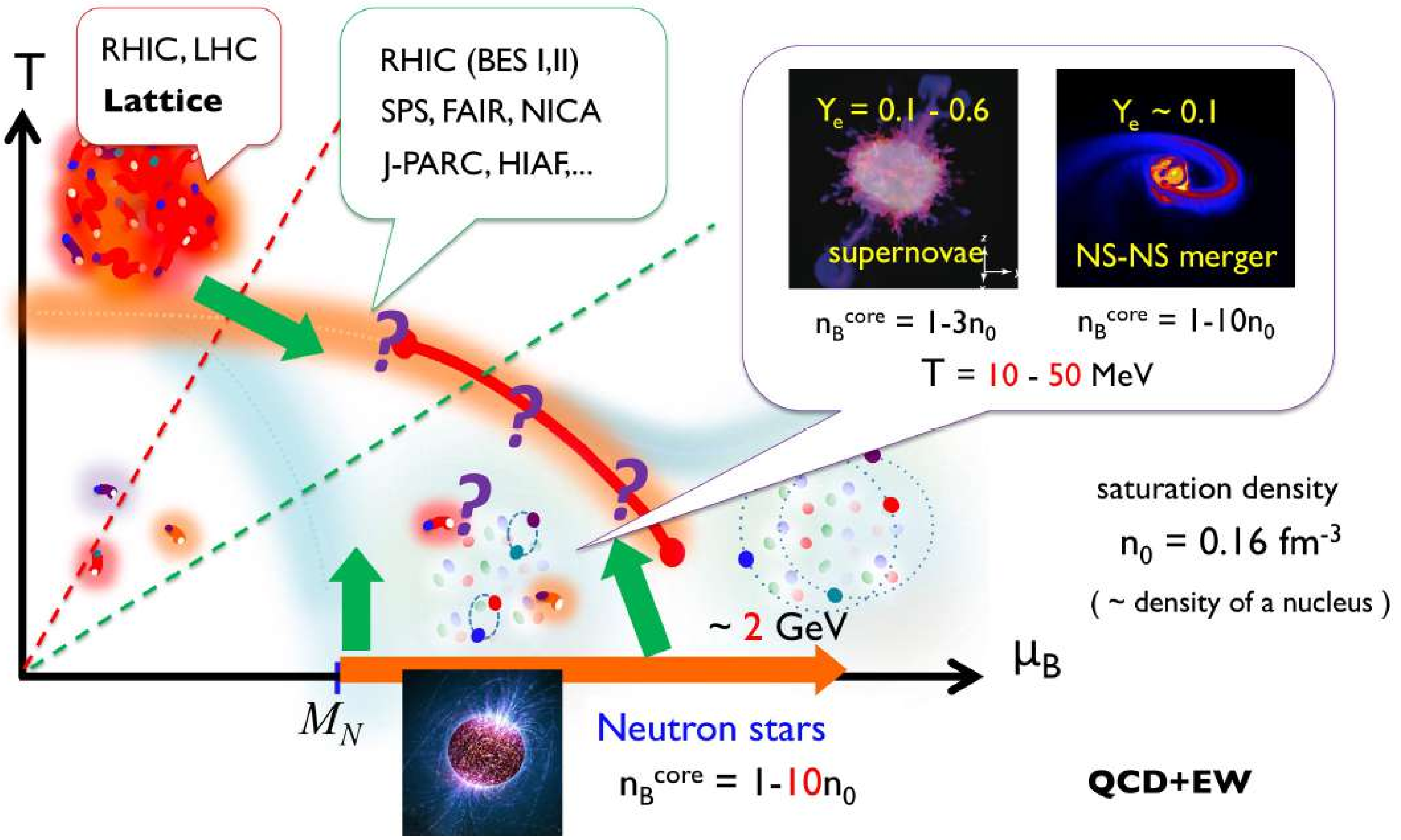
Work based on **Relativistic Density Functional** with O. Ivanytskyi, in preparation





High mass at large radius and low tidal deformability at 1.4 M_sun simultaneously obtained !

2nd or no CEP in QCD phase diagram: Crossover all over ?



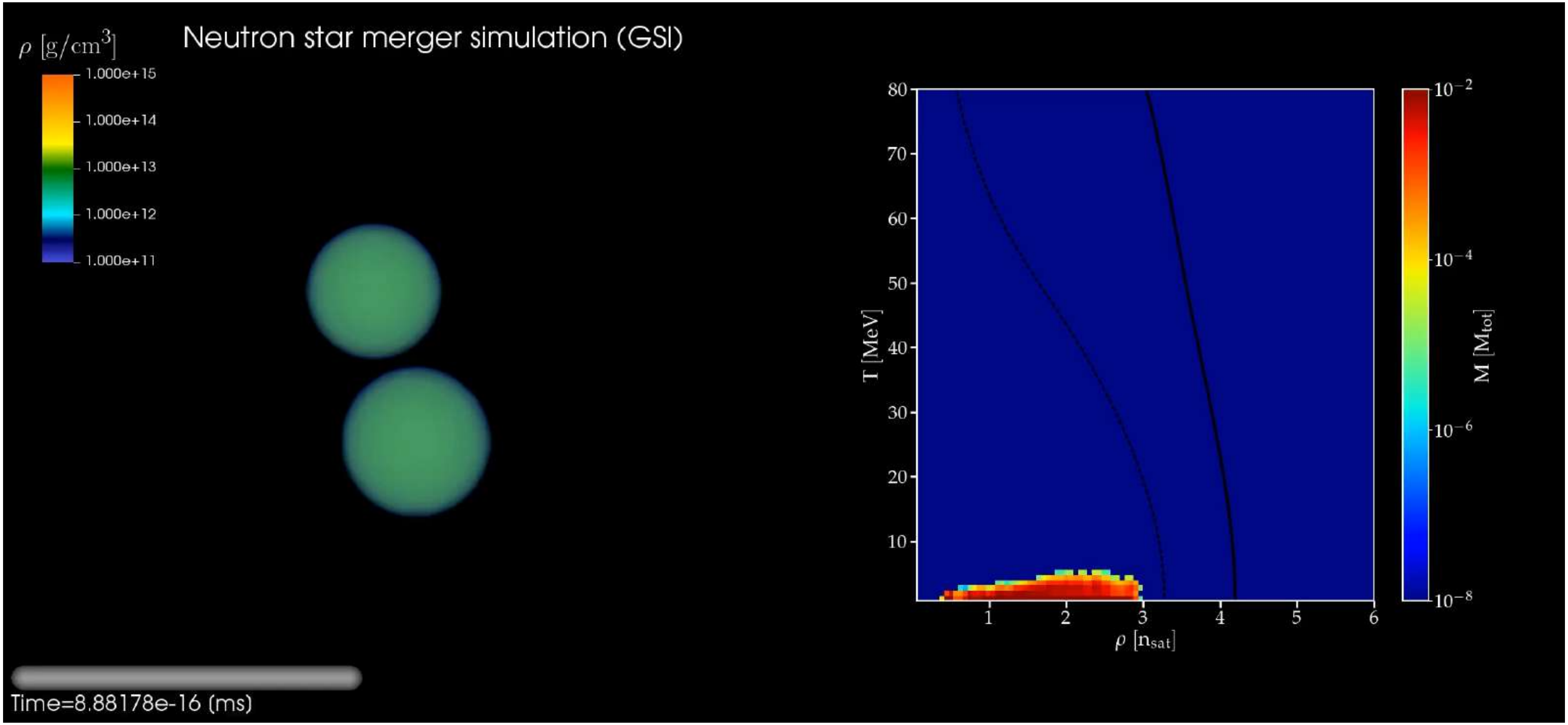
From: T. Kojo, "Delineating the properties of neutron star matter in cold, dense QCD", PoS Lattice2019, 244

Binary neutron star merger simulation

S. Blacker & A. Bauswein (GSI Darmstadt), 1.35 M_sun + 1.35 M_sun

https://www.gsi.de/fileadmin/theorie/simulation-neutron-star-merger.mp4

Population of the QCD phase diagram with mixed phase, 6… 25 ms



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

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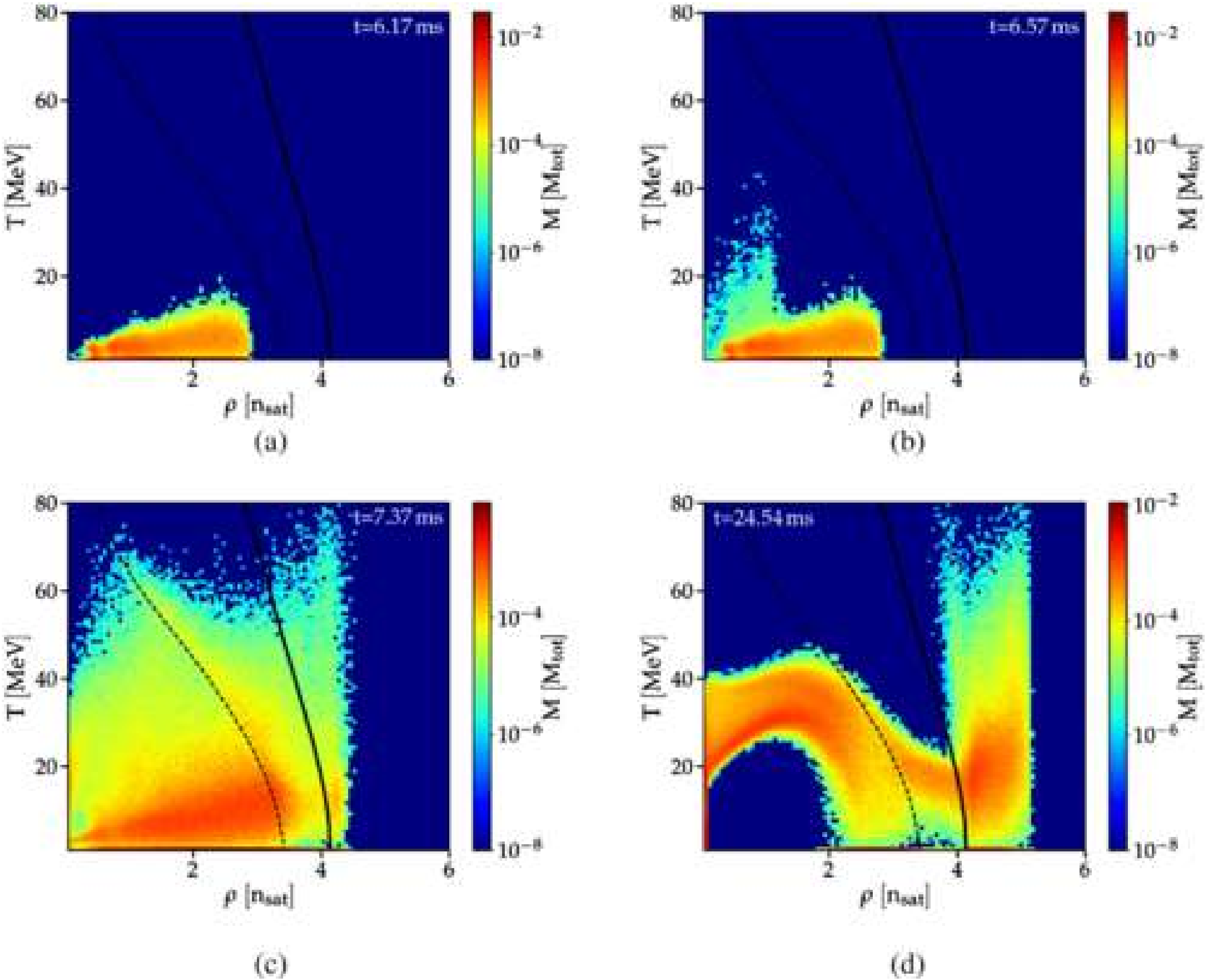


EoS for applications to supernova and merger Simulation:

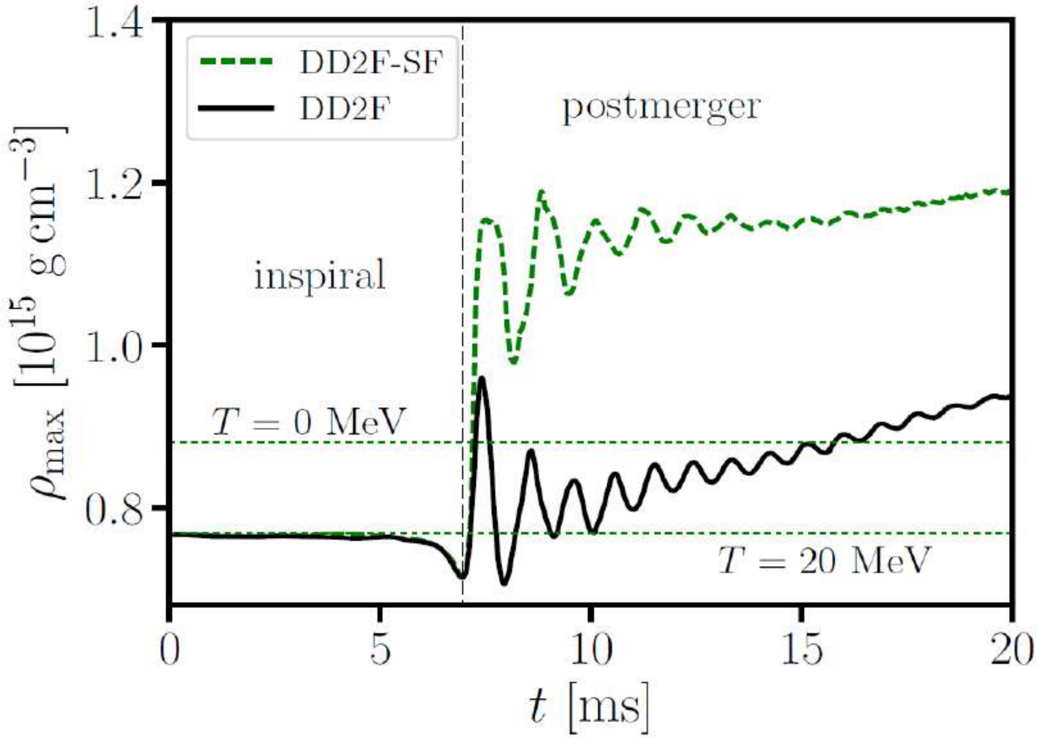
CompOSE

With deconfinement:

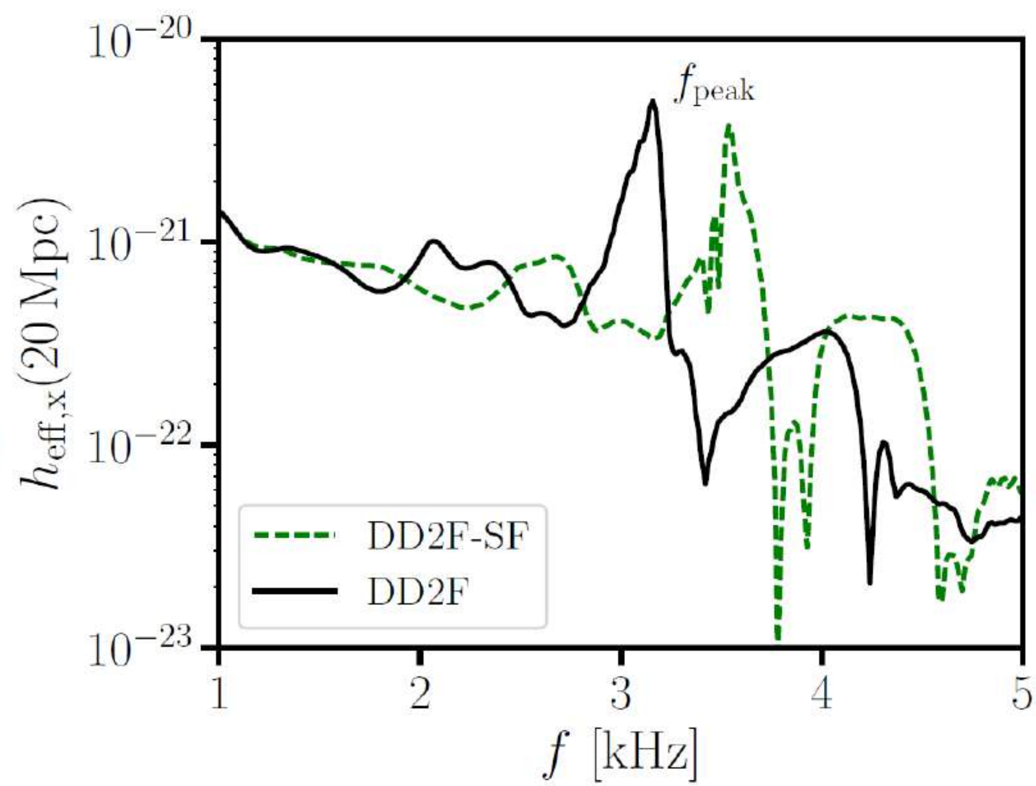
https://compose.obspm.fr/eos/166

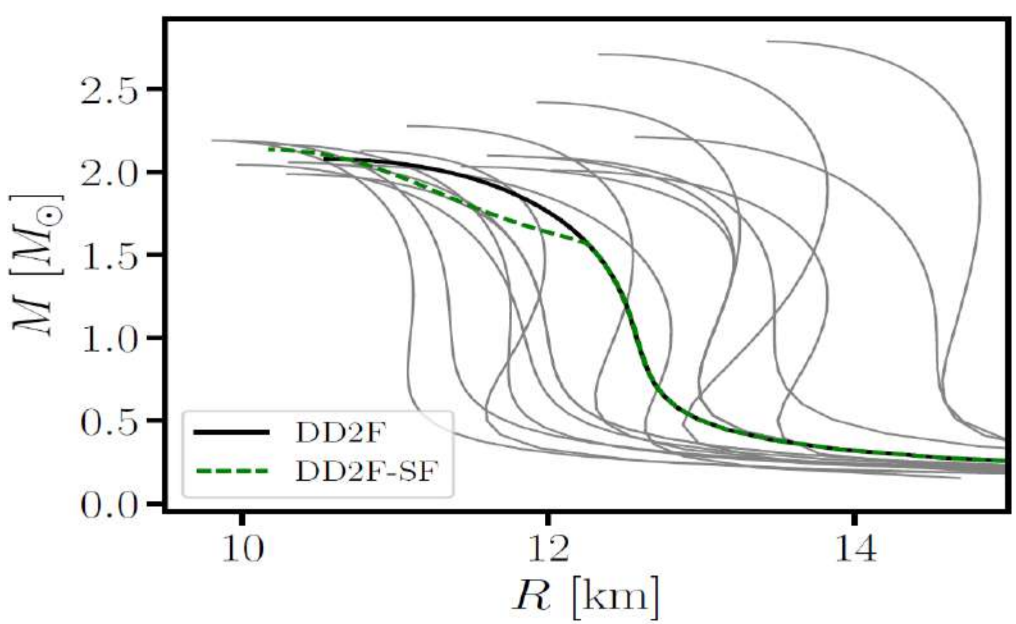
S. Blacker, A. Bauswein, et al., Phys. Rev. D 102 (2020) 123023

Hybrid star formation in postmerger phase



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



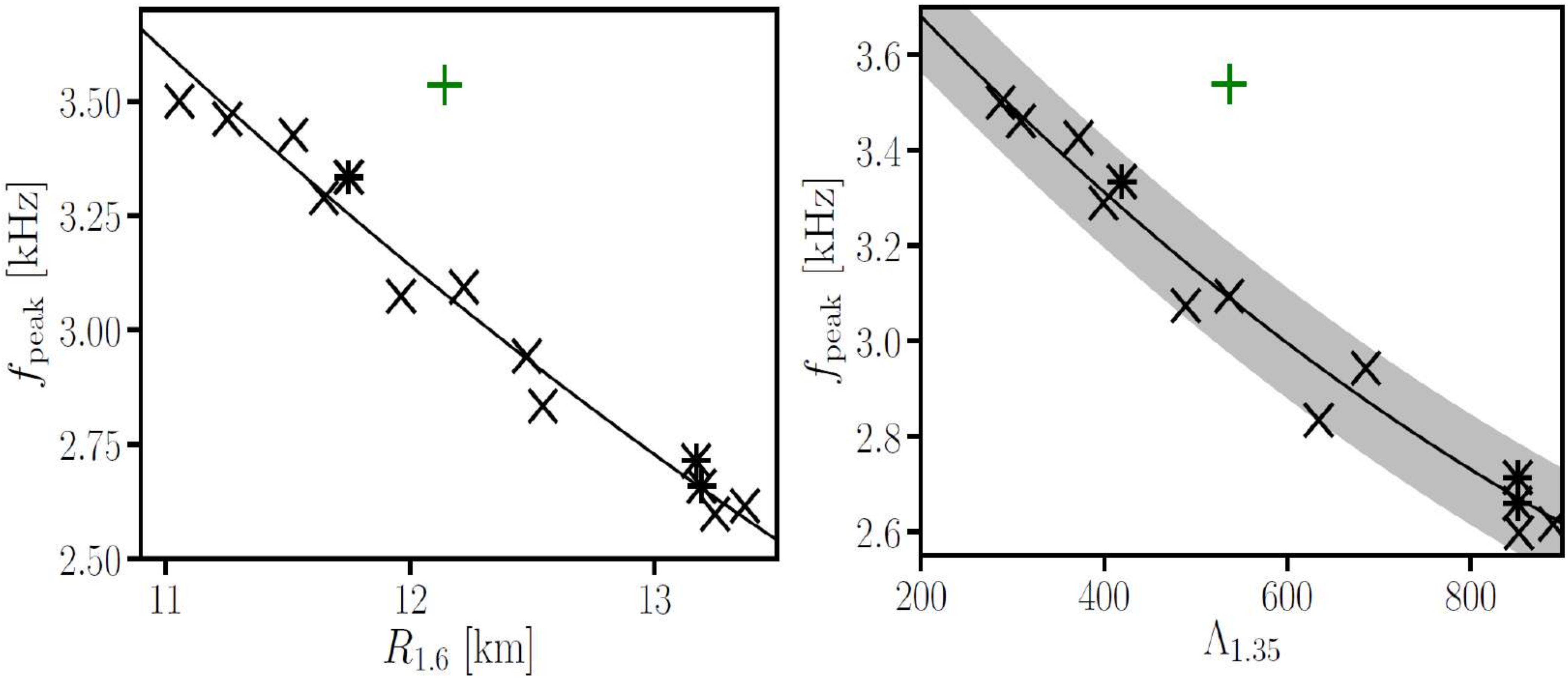


Hybrid star formation during NS merger
→ higher densities and compacter star
→ higher peak frequency of the GW

A. Bauswein et al., PRL 122 (2019) 061102

Hybrid star formation in postmerger phase

Strong phase transition in postmerger GW signal,
A. Bauswein et al., PRL 122 (2019) 061102; [arxiv:1809.01116]

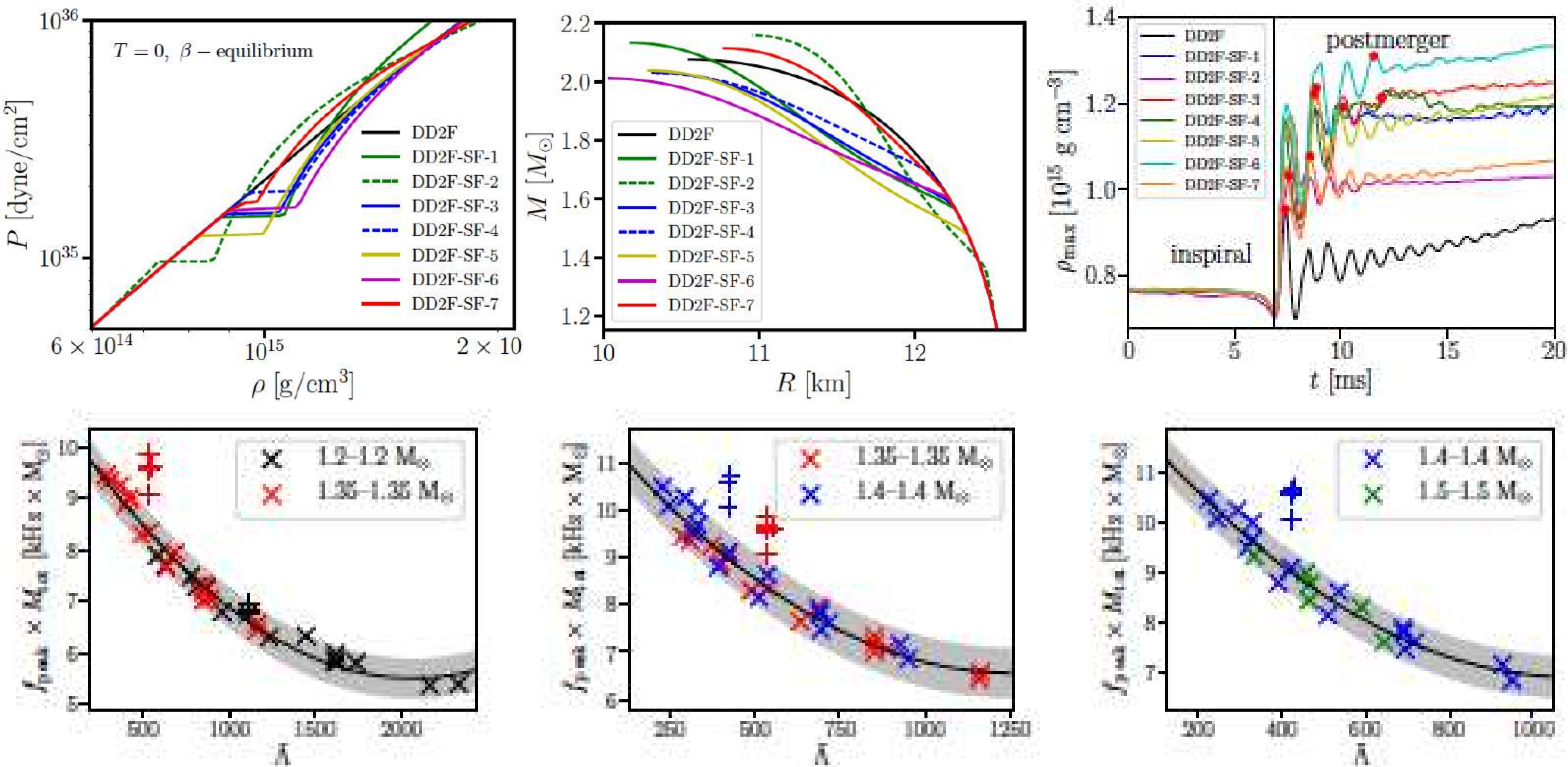


Strong deviation from **f_{peak} – $R_{1.6}$** relation signals **strong phase transition in** NS merger**!**

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

Hybrid star formation in postmerger phase

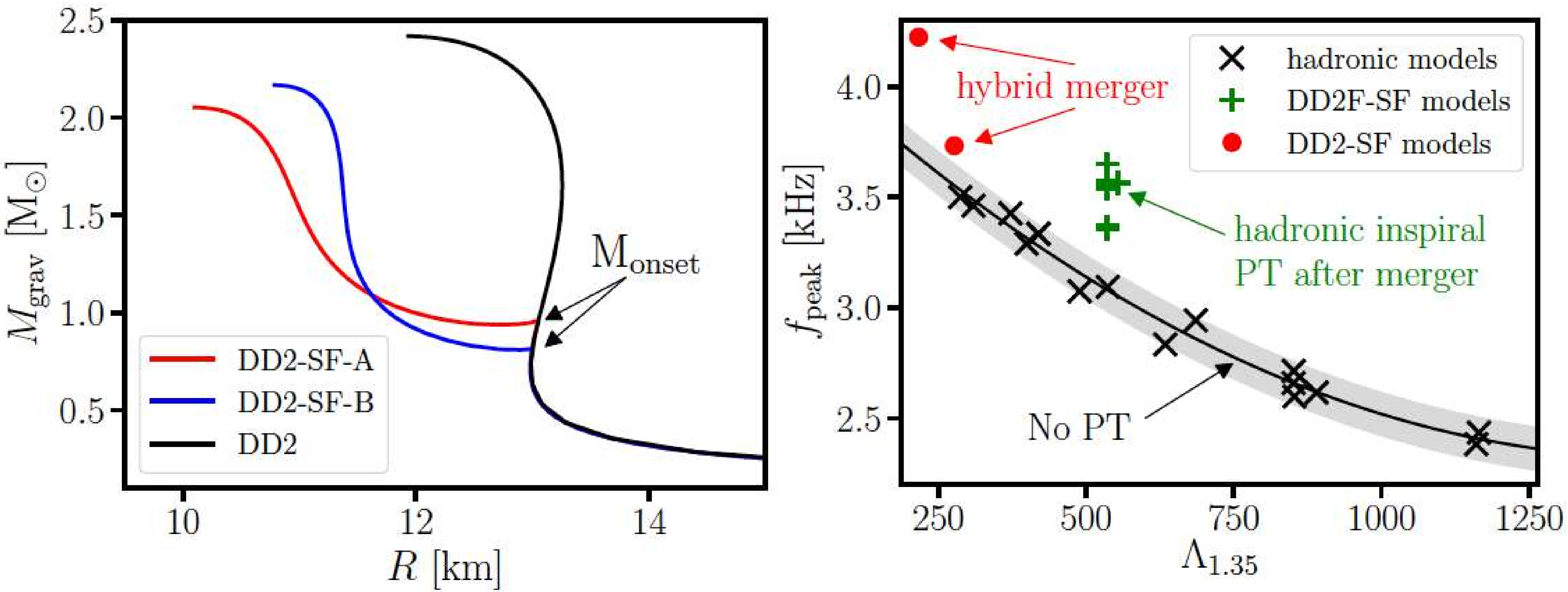
Strong PT in postmerger GW signal, S. Blacker et al., arxiv:2006.03789, PRD102 (2020) 123023



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

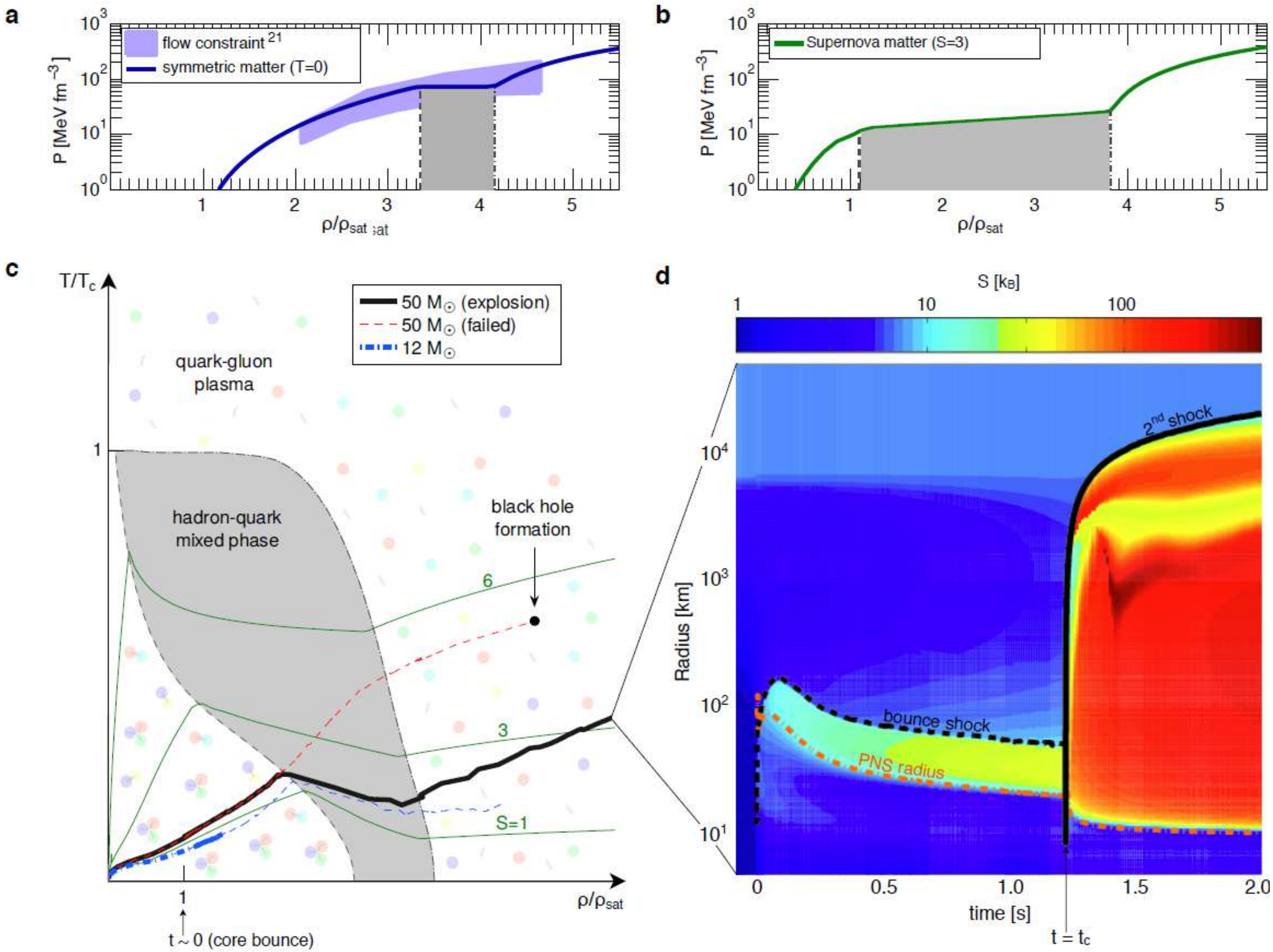
GW signal of deconfinement in merger of hybrid stars

Merger of hybrid stars with early phase transition: Bauswein & Blacker, EPJ ST 229 (2020)



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

Deconfinement transition as SN explosion mechanism

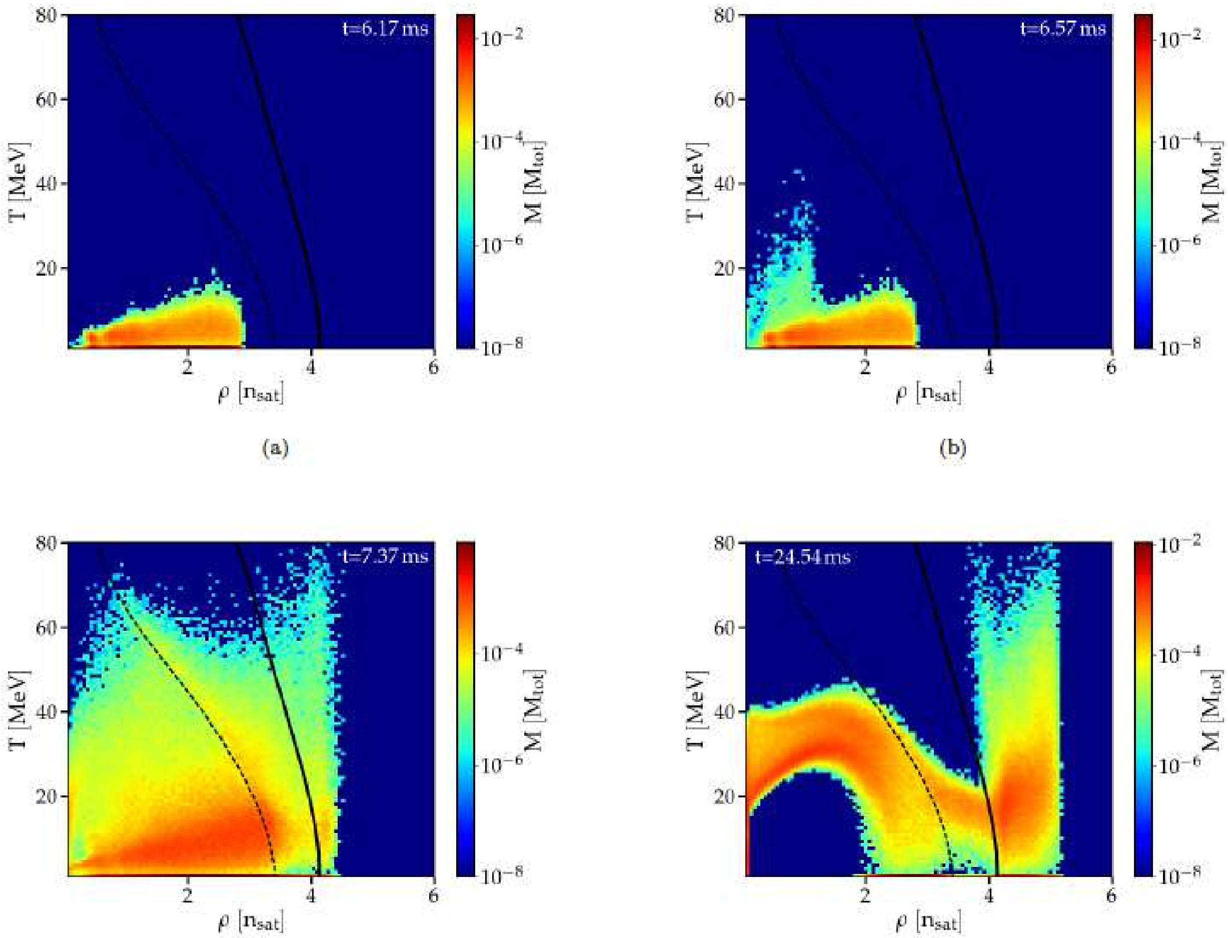


Progenitor:
M = 50 M_O

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

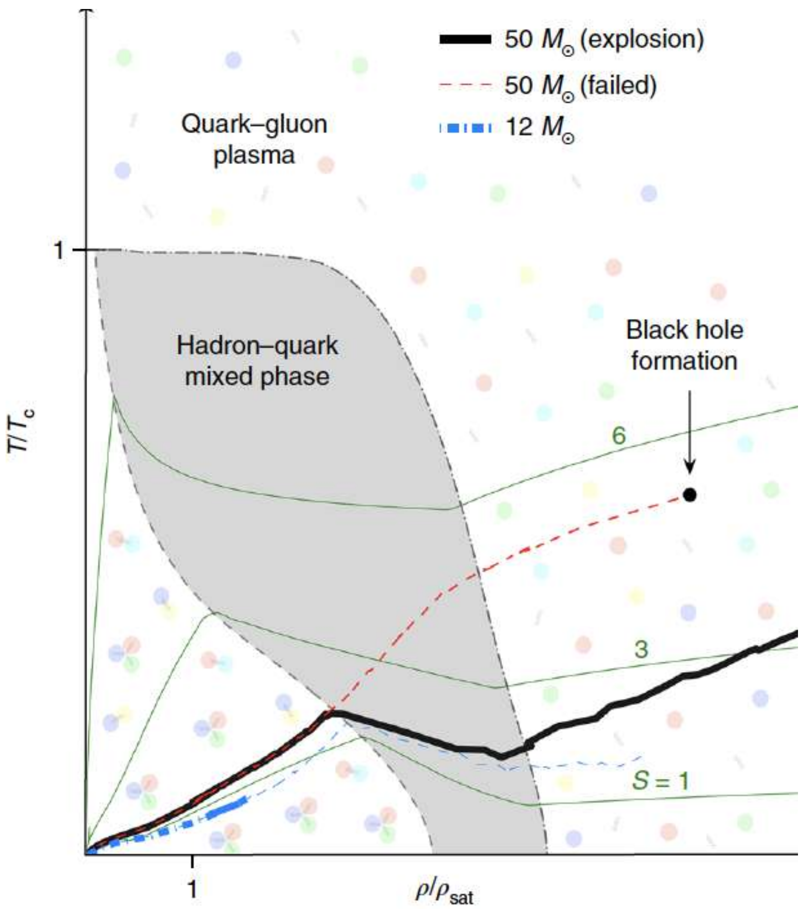
Population of the QCD Phase Diagram in Mergers & SNe

Binary NS merger, 1.35 M_sun + 1.35 M_sun



S. Blacker, A. Bauswein et al.,
Phys. Rev. D102 (2020) 123023; arxiv:2006.03789

SN explosion, 50 M_sun



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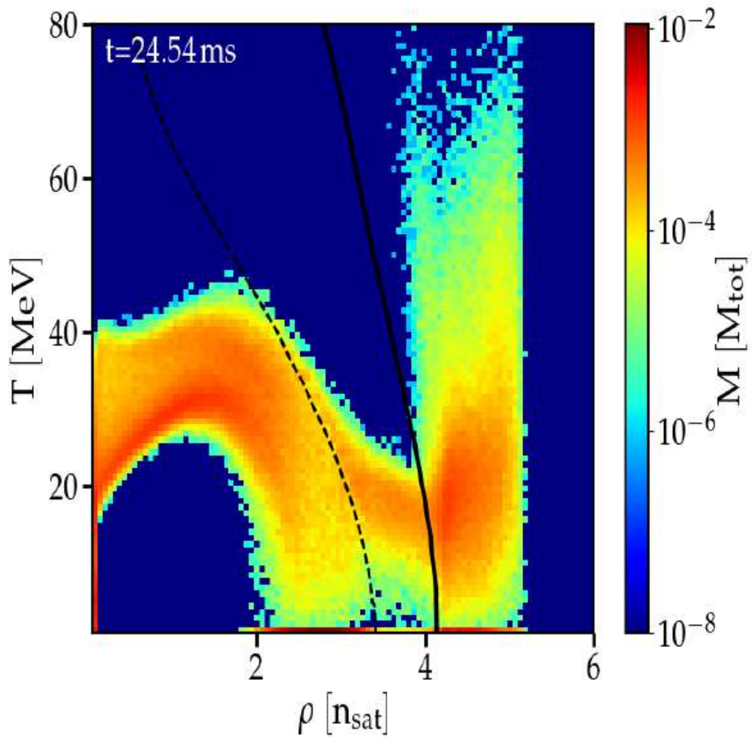
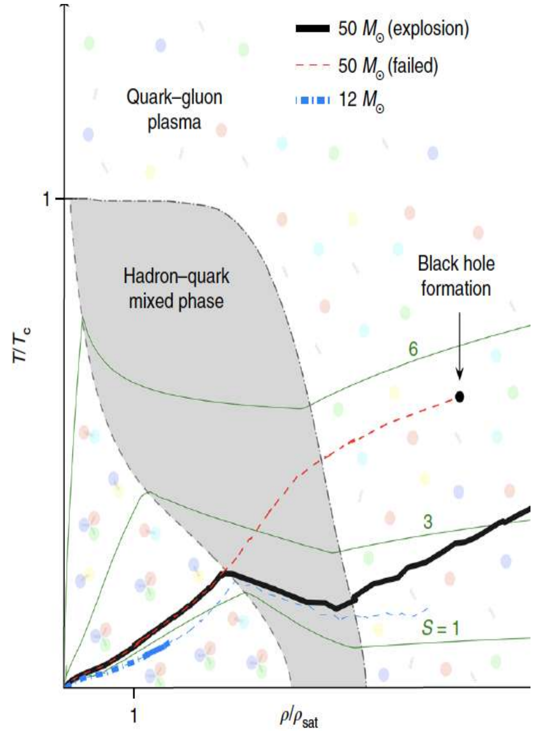
Population of the QCD Phase Diagram

Binary NS merger,
1.35+1.35 M_sun



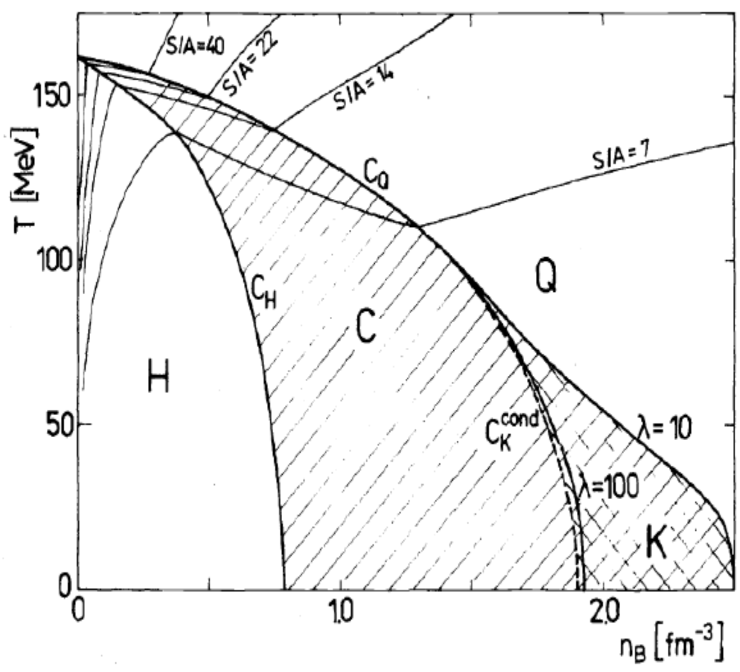
S. Blacker, A. Bauswein et al.,
PRD 102 (2020) 123023
arXiv:2006.03789

SN explosion,
Progenitor 50 M_sun



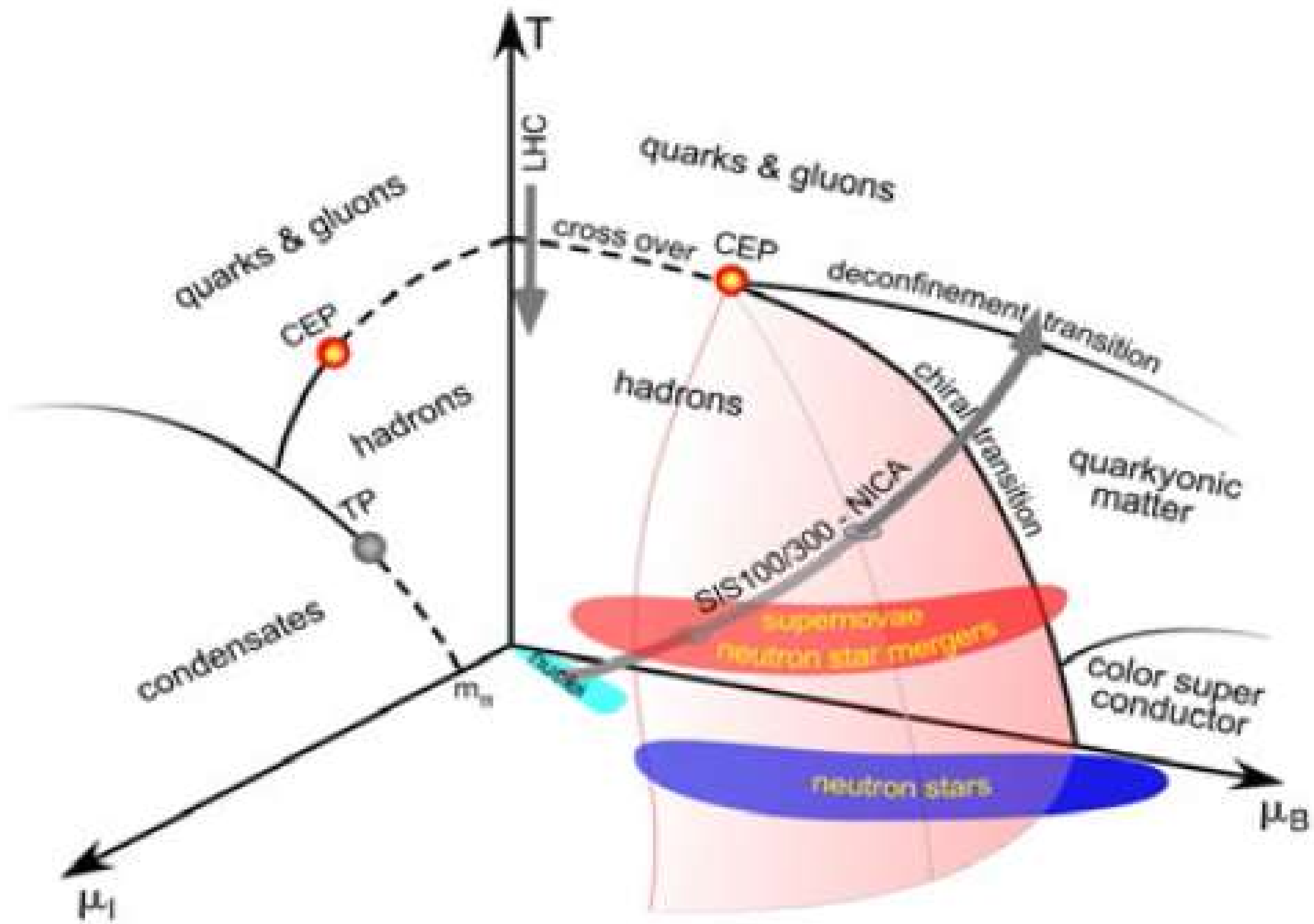
T. Fischer et al.,
Nat. Astron. 2 (2018) 980
arXiv:1712.08788

Ultrarelativistic HIC,
√s [GeV]=16, 10, 7, 4



H.W. Barz, B. Friman et al.,
PRD 40 (1989) 157
GSI Preprint, GSI-89-13

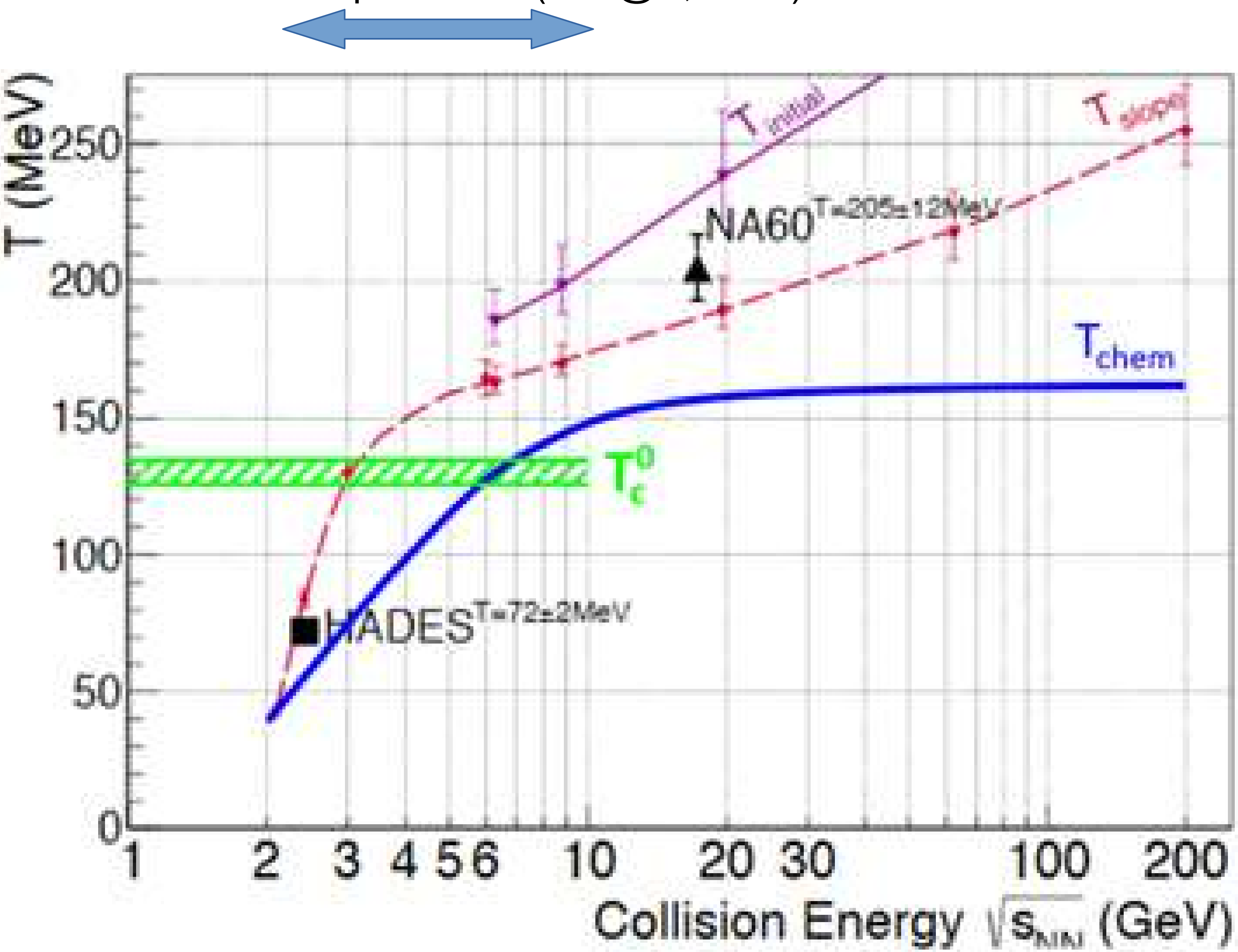
CEP in the QCD phase diagram: HIC vs. Astrophysics



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

CEP in the QCD phase diagram: HIC vs. Astrophysics

NICA experiments (BM @N, MPD)



For “seeing” a first-order transition in heavy-ion collisions, one needs energies below √s ~ 6 GeV !

This is the domain of NICA experiments !

P. Senger, Phys. Scripta 96 (2021) 054002; and references therein !

Conclusions

- First observations of binary mergers open new possibilities to constrain properties of the Quark-gluon plasma at low temperatures and high baryon densities. Hybrid EoS are developed that allows to estimate quark plasma parameters in hypermassive (proto-) neutron stars

- GW170817: narrow window of small radii at 1.4 M_sun (Capano et al.: 10.4< R_1.4[km] <11.9) strongly suggests an early onset of deconfinement with a critical density n_c < 2 n_0 and an onset mass M_onset < 1.0 M_sun [Blaschke & Cierniak: 2012.15785]

- GW190814: the lighter object in the extemely asymmetric merger with its 2.6 M_sun can be either the heaviest neutron star or the lightest black hole. The central baryon density in such high-mass hybrid stars reaches 5.3 n_0. Our EoS allows it to be a hybrid star ...

- NICER radius measurement on PSR J0740+6620 triggers a new paradigm:
  NS with M> 2M_sun should have a deconfined quark matter core when R_2.0 > 13 km !

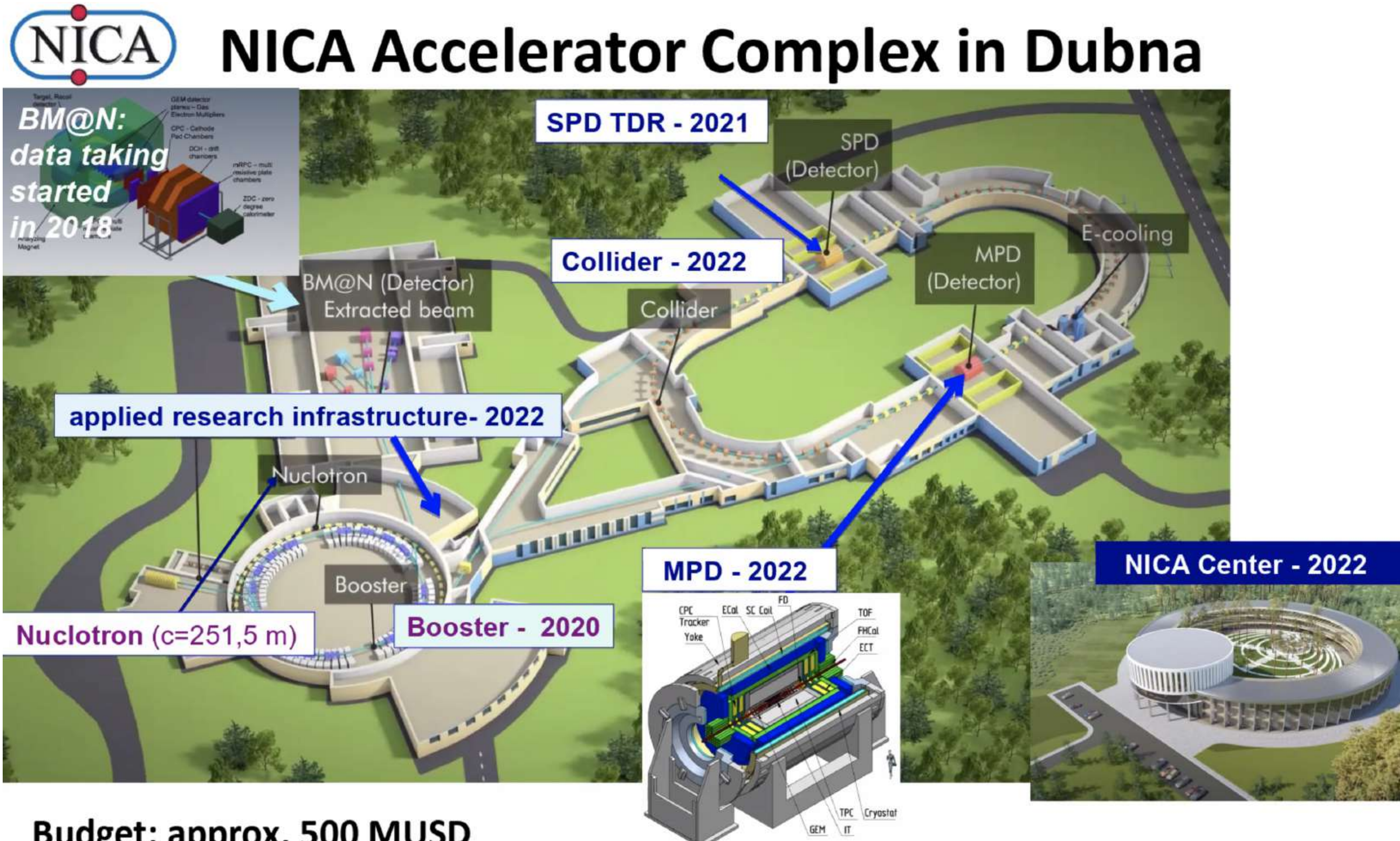
  Such a result is similar to the “two families” scenario of Drago & Pagliara, PRD 102 (2020)
  For the baryon density at the center of a star with 2.1 M_sun we find n < 5 n_0, n_0=0.15 fm^-3.

- Consequences for supernova simulations: A new lower limit for onset of deconfinement?

- Consequences for merger simulations: Check the GW signal for deconfinement !

- Good news for entering a color superconducting quark matter phase at NICA (BMaN, MPD)

The NICA Facility at JINR Dubna



Budget: approx. 500 MUSD

The NICA Facility at JINR Dubna

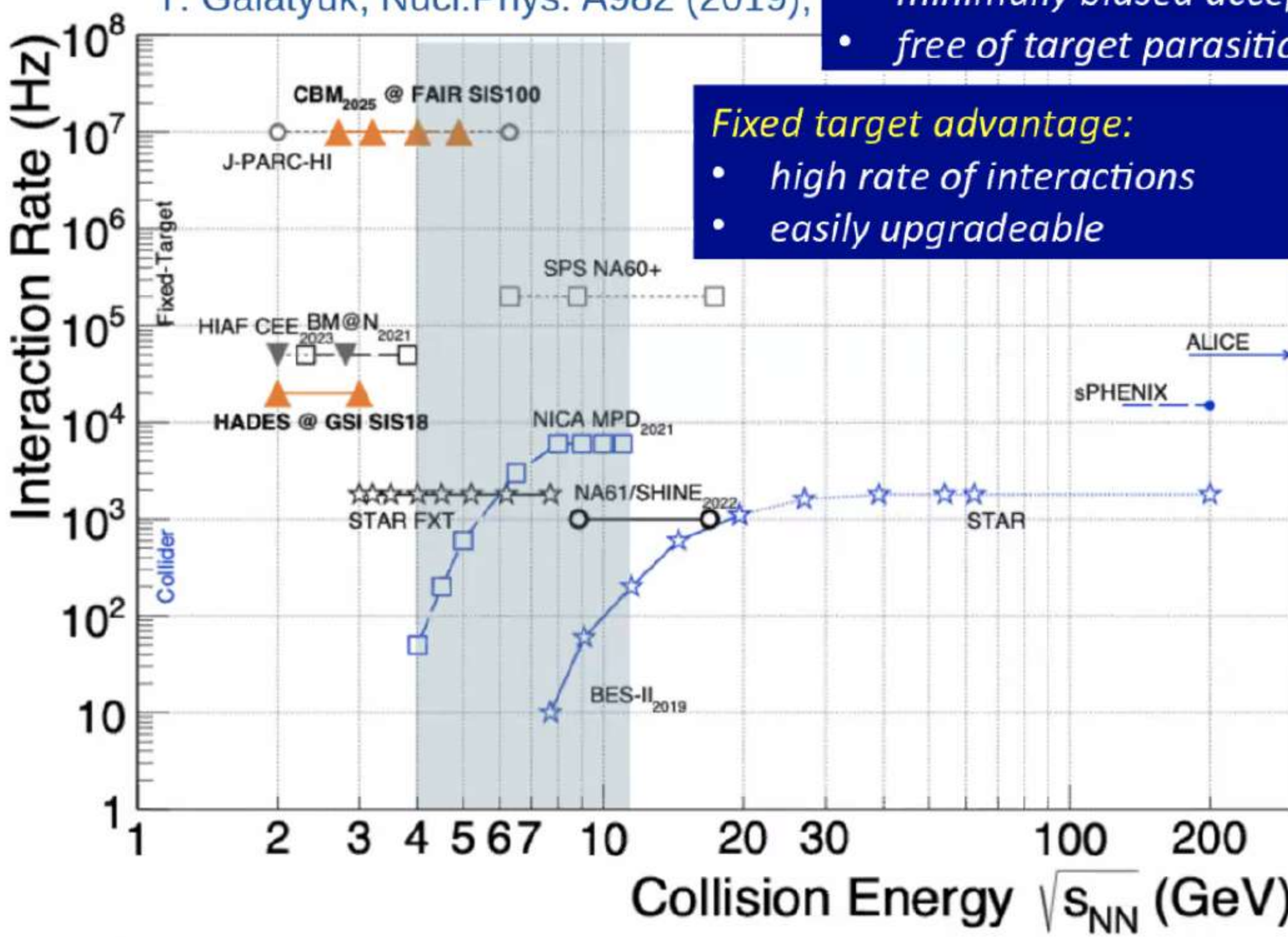
NICA: Unique and complementary

Collider advantage:
- *coverage of max. phase space*
- *minimally biased acceptance*
- *free of target parasitic effects*

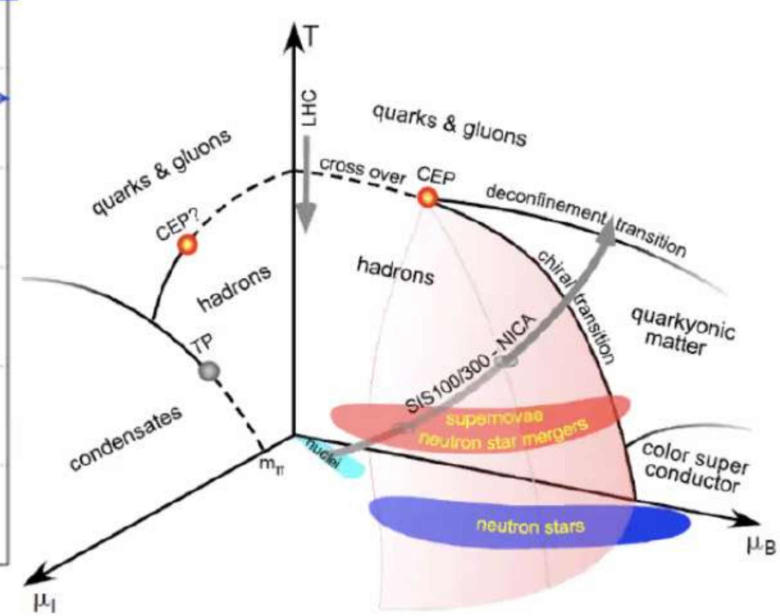
In NICA Collider energy range maximum possible net-baryon density is reached

Fixed target advantage:
- *high rate of interactions*
- *easily upgradeable*

T. Galatyuk, Nucl.Phys. A982 (2019);



NUPECC Long Range Plan 2017



The NICA Facility at JINR Dubna

NICA

NICA Facility running plan

- **Year 2021:**
  - Extensive commissioning of Booster accelerator
  - Heavy-ion (Fe/Kr/Xe) run of full Booster+Nuclotron setup
- **Year 2022:**
  - Completion of NICA Collider and transfer lines
- **Year 2023:**
  - Initial run of NICA with Bi+Bi @ 9.2 AGeV (other energies a second priority)
  - Goal to reach luminosity of 10^{25} $cm^{-2}s^{-1}$
- **Year 2024:**
  - Goal to have Au+Au collisions and acceleration in NICA (up to 11 AGeV)
- **Beyond 2024:**
  - Maximizing luminosity, possibility of collision energy and system size scan

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Advertisement: International School Events in 2022

1) 58th Karpacz Winter School in Theoretical Physics on

"Heavy Ion Collision: From First to Last Scattering",

Karpacz (Poland) in June 2022

Website shall appear here:

http://ift.uni.wroc.pl/conferences

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2) International Summer School on

"Dense Matter in Heavy-Ion Collisions and Astrophysics"

JINR Dubna, July-August 2022

Website shall appear here:

http://theor.jinr.ru/meetings/2022/