Early quark deconfinement in compact stars & heavy-ion collisions at NICA/FAIR energies

David Blaschke[a,b,c], Tobias Fischer[a], Andreas Bauswein[d] & Mateusz Cierniak[a]

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

DUBNA

Narodowe Centrum Nauki

Grant No. UMO 2019 / 33 / B / ST9 / 03059

Uniwersytet Wrocławski

RSF Russian Science Foundation

Grant No. 17-12-01427

RFBR

Grant No. 18-02-40137

cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

PHAROS THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

THOR

Early quark deconfinement in compact star astrophysics & upcoming experiments at NICA

David Blaschke[a,b,c], Tobias Fischer[a], Andreas Bauswein[d] & Mateusz Cierniak[a]

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

42th Int. School on Nuclear Physics, Erice, 19. September 2021

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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.

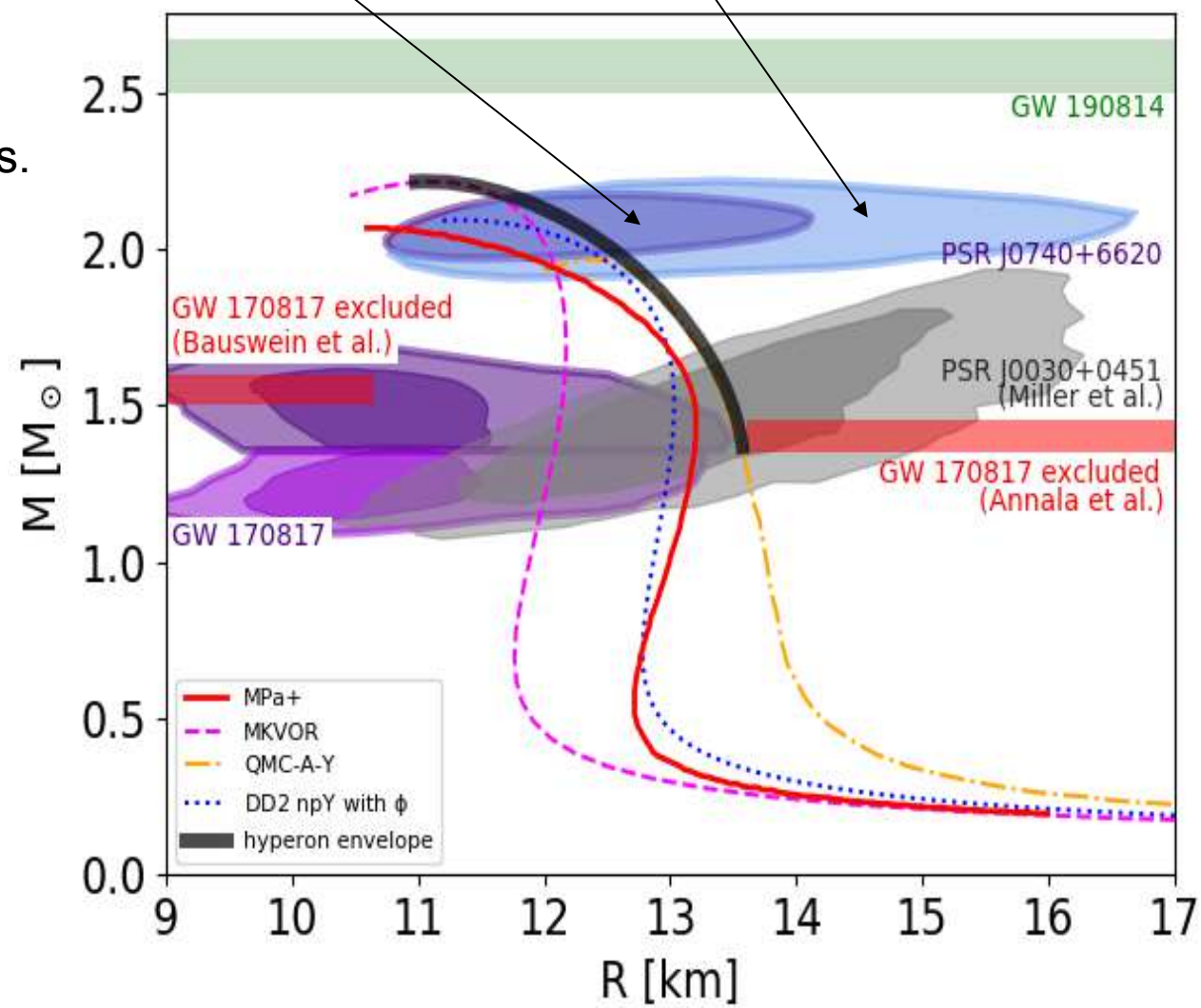
Non-hyperonic nuclear EoS (APR)
Are no longer applicable for
High-mass neutron stars ~2M_sun !

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

Yamamoto et al., PRC 96 (2017)

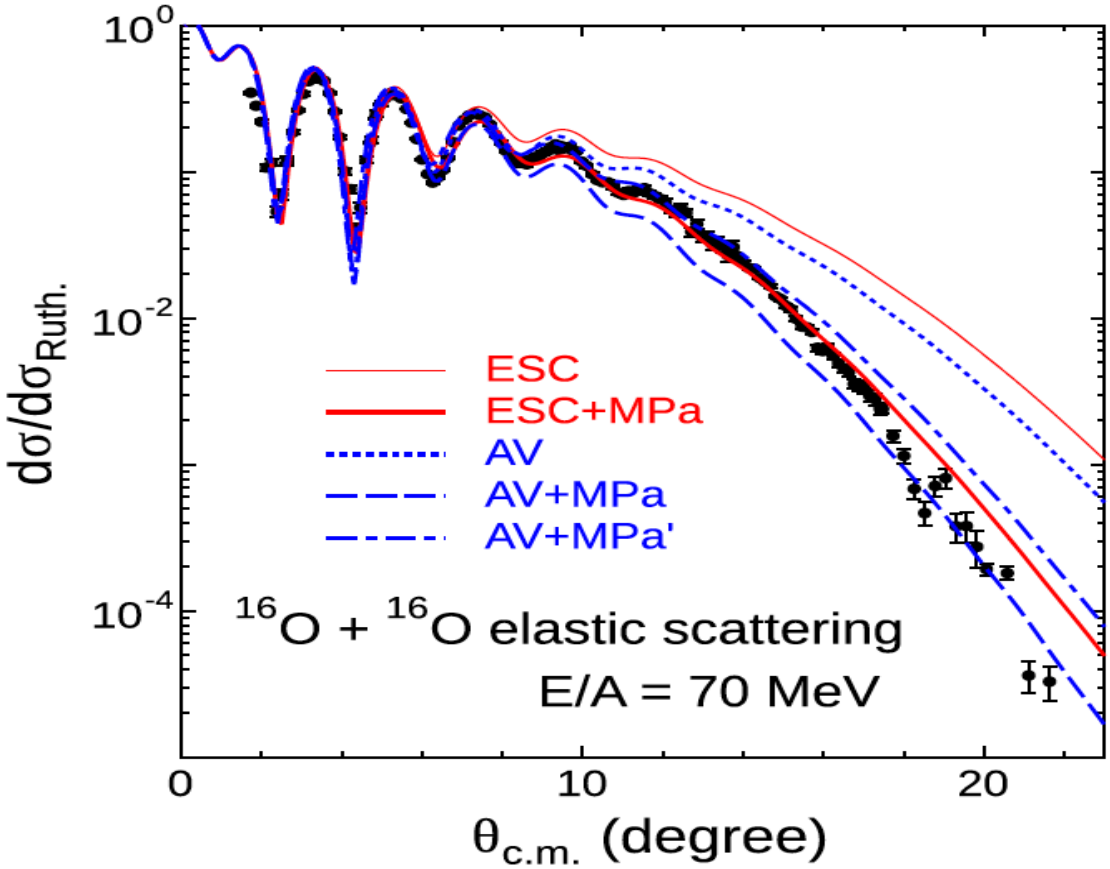
Relativistic mean-field EoS have a
Maximal NS radius R_2.0 ~ 13 km

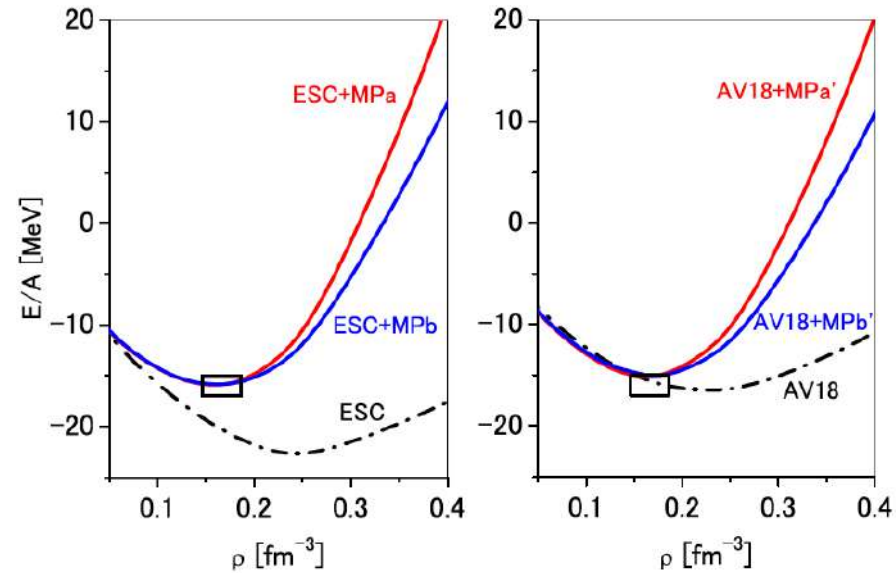
Way out:
early deconfinement to color
superconducting, stiff quark matter !

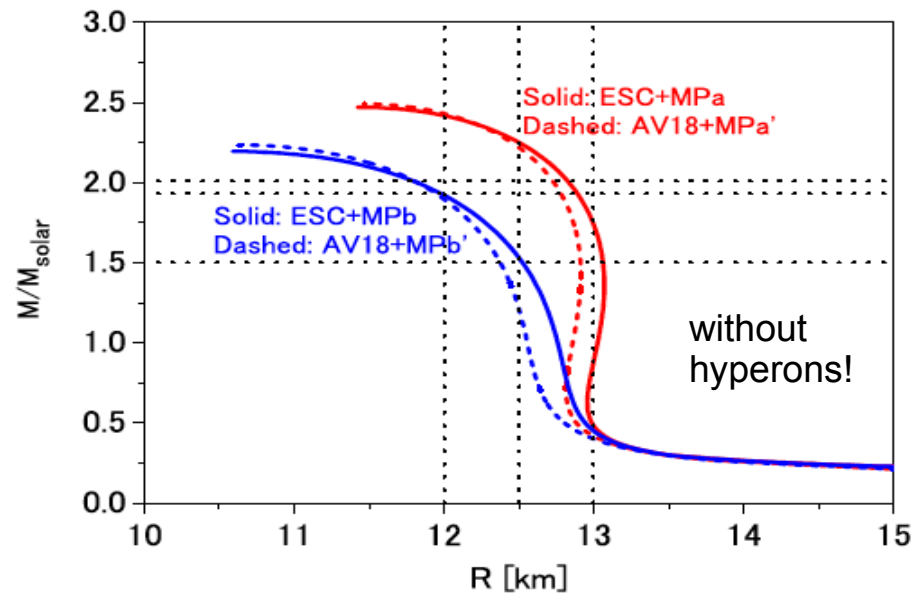


Shall the APR EoS be abandoned?

Y. Yamamoto, H. Togashi, T. Tamagawa, T. Furumoto, N. Yasutake, T. Rijken, PRC 96 (2017)







Short-range multipomeron exchange potential (MPP) added to AV18 potential gives significant improvement of large-angle scattering cross section (s.a.) and the Nuclear saturation properties, when compared to APR.
→ Neutron star radii R(M< 2 M_sun) > 12 km !!

Old paradigm: hybrid stars smaller and lighter

Works on **Special Point** with M. Cierniak: 2012.15785 & 2009.12353; EPJ ST 229, 3663 (2020)

Dense quark plasma in color superconducting phase: nlNJL mode

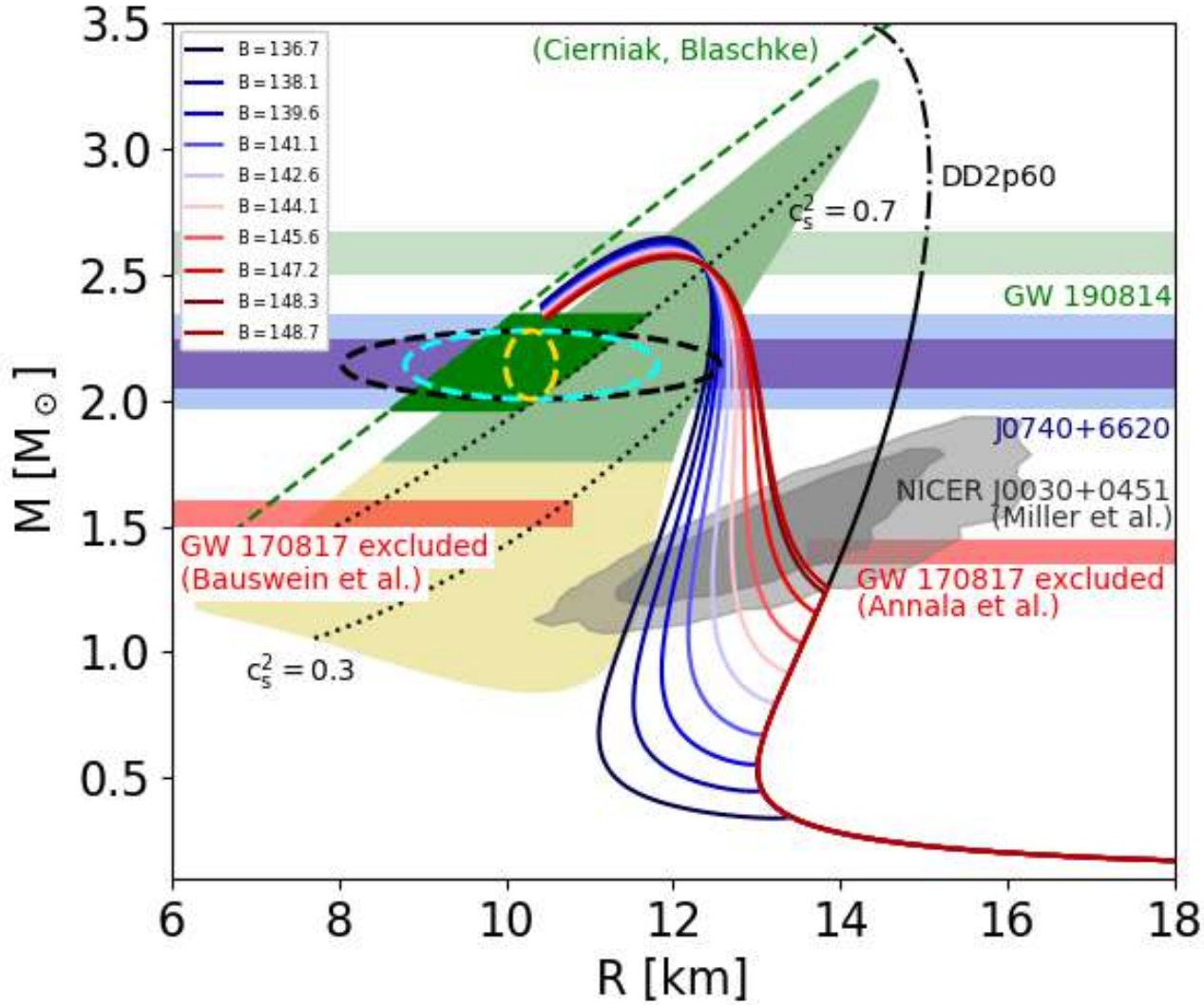
Constant-speed-of-sound (CSS) Equation of state (EoS)

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

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

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

Maxwell construction with (1st order phase transition) Relativistic Density Functional EoS "DD2pxy" by S. Typel With density-dependent coupling And excluded volume v=x.y fm^3



2.6 M_sun object can by a hybrid neutron star! With early onset of deconfinement and twins! NICER radius measurement on PSR J0740+6620 will put constraints on this too!

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)

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

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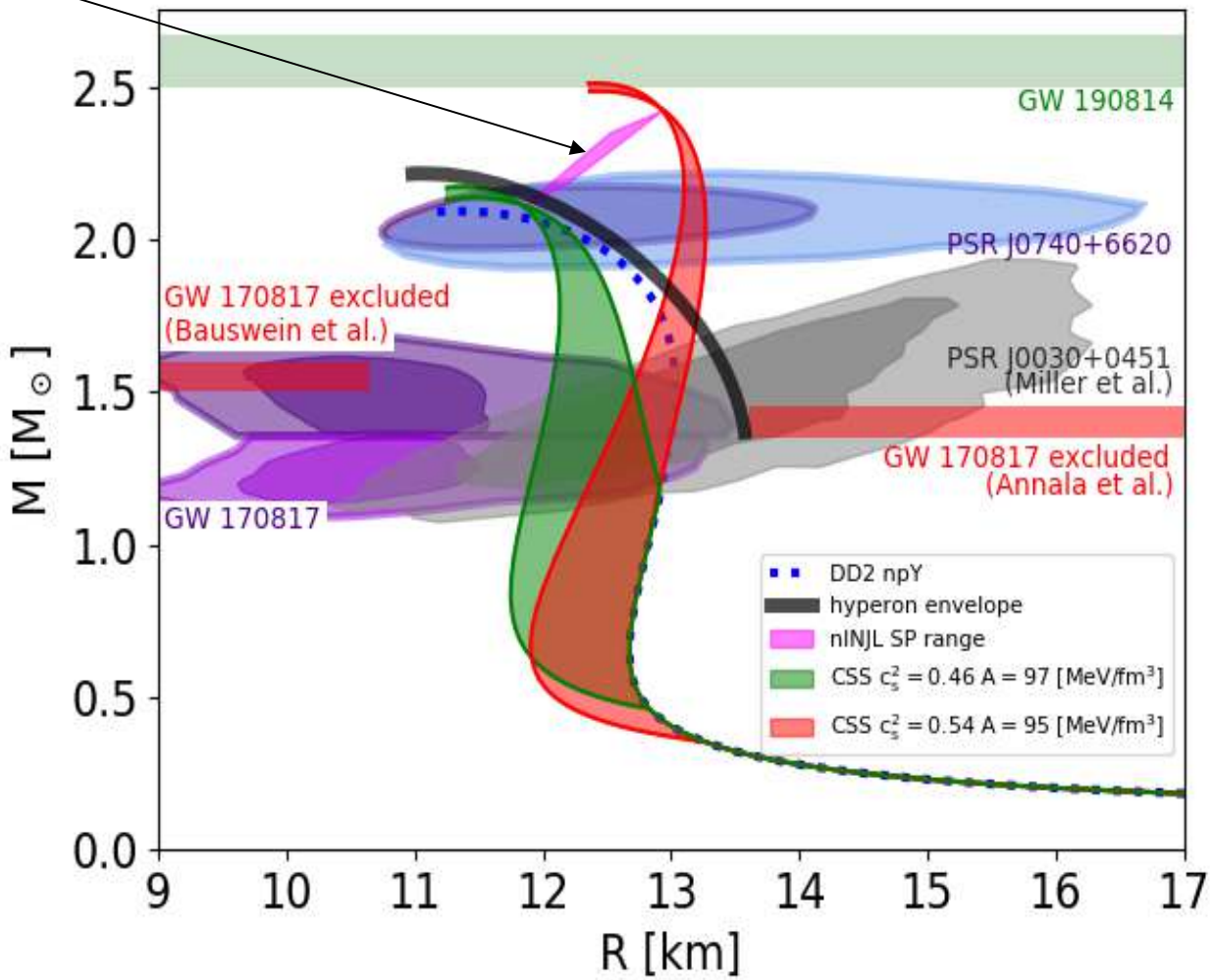
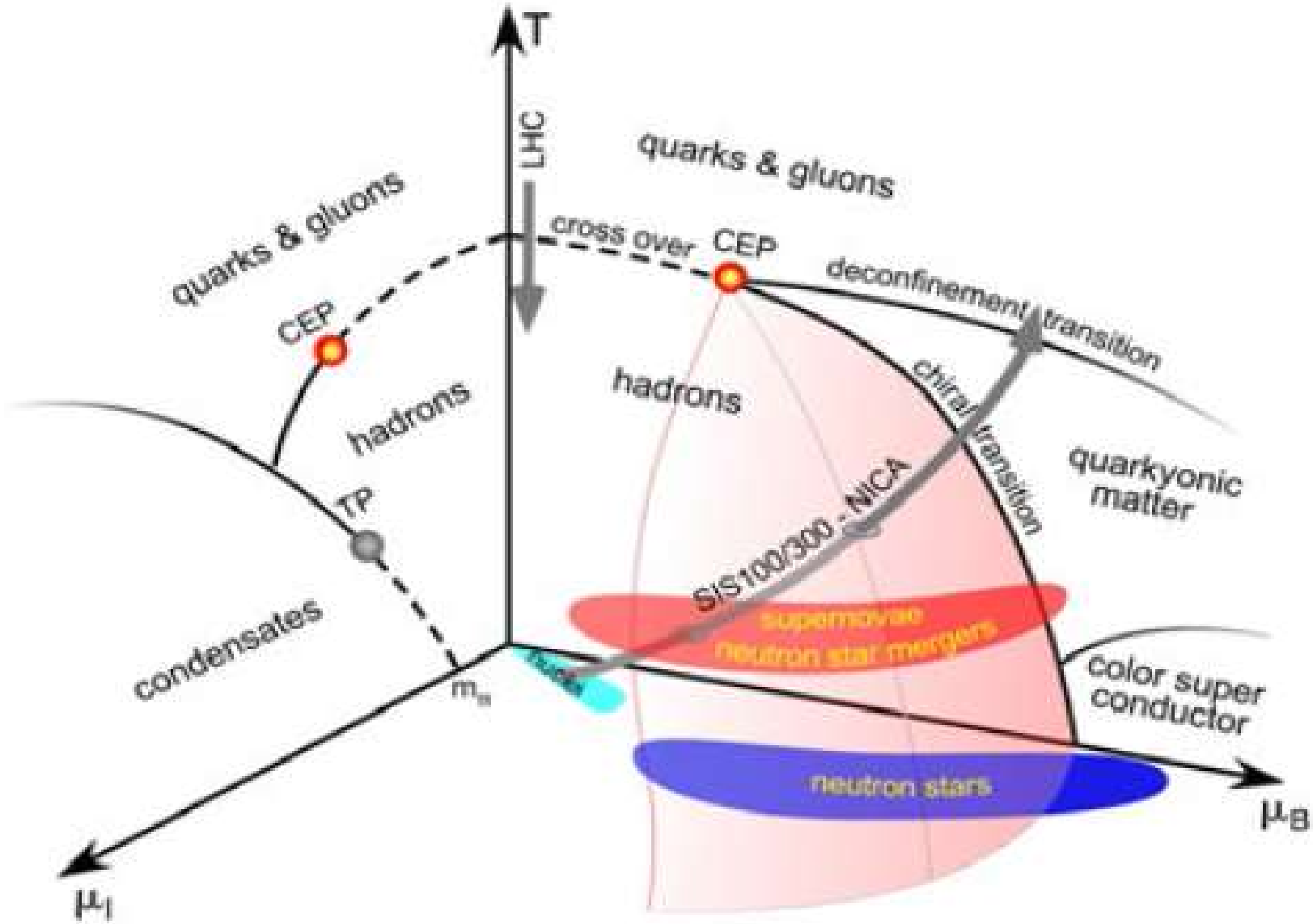
Maxwell construction with (1st order phase transition) Relativistic Density Functional EoS "DD2-Y-T" by S. Typel With density-dependent coupling



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!

CEP in the QCD phase diagram: HIC vs. Astrophysics



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

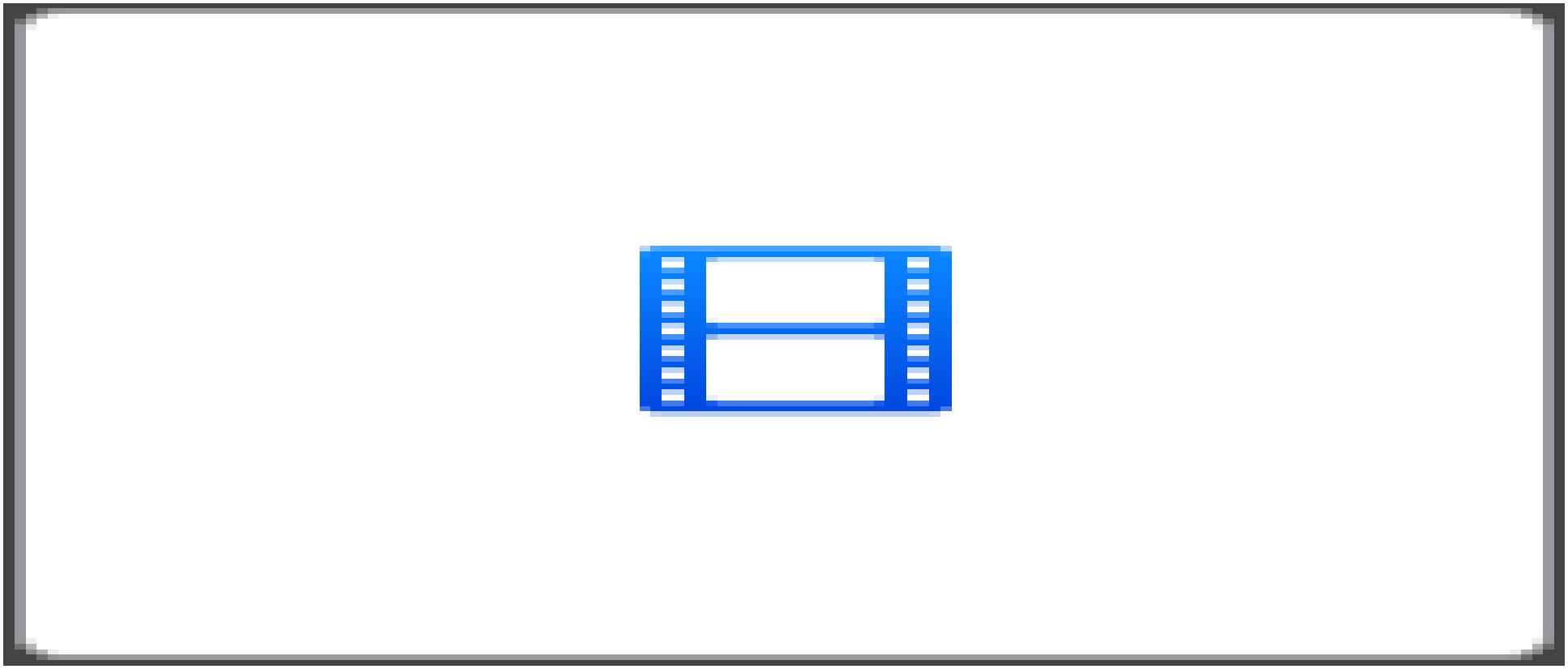
A. Andronic, D. Blaschke, et al., “Hadron production ...”, Nucl. Phys. A 837 (2010) 65 - 86

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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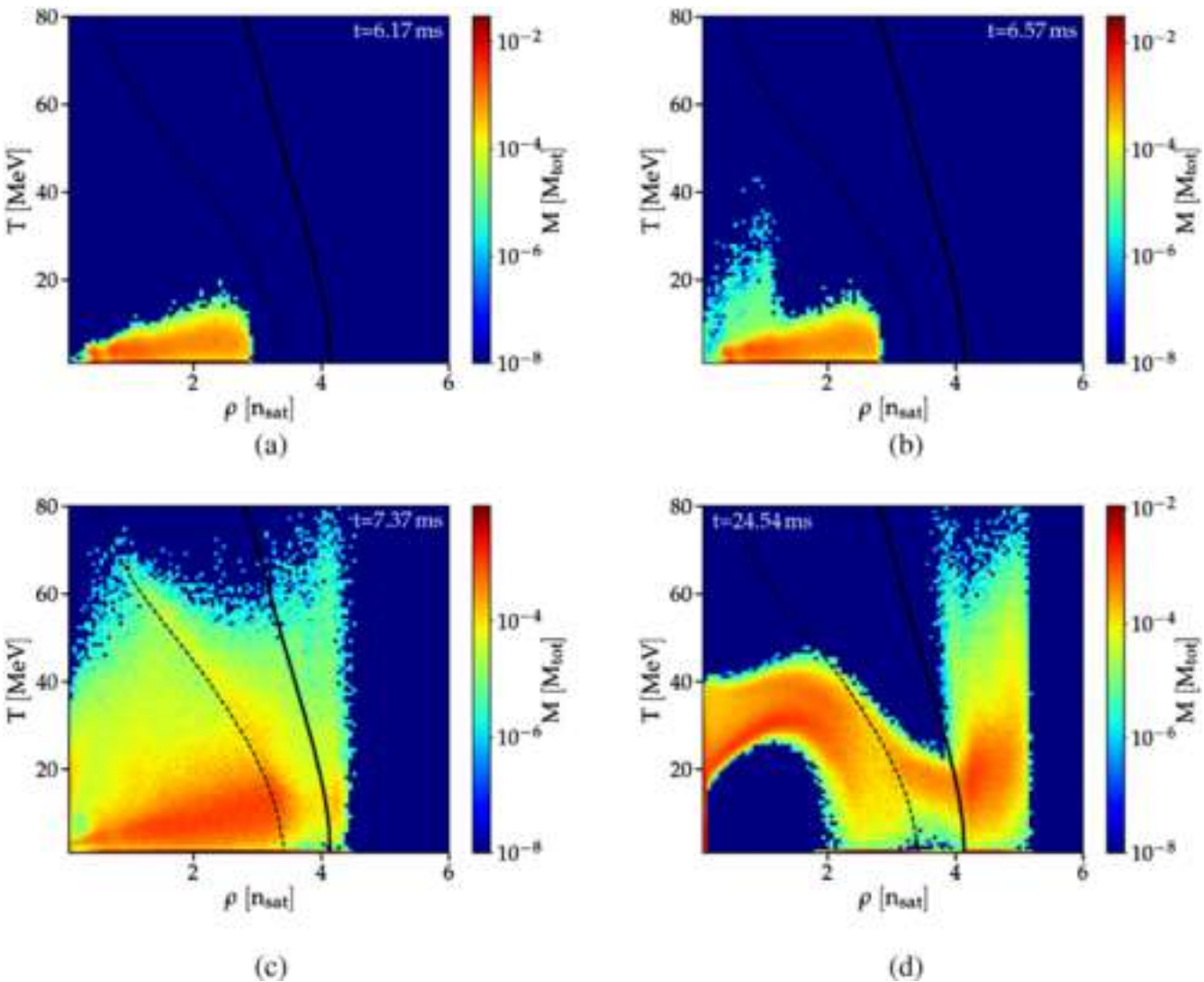


EoS for applications to supernova and merger Simulation:

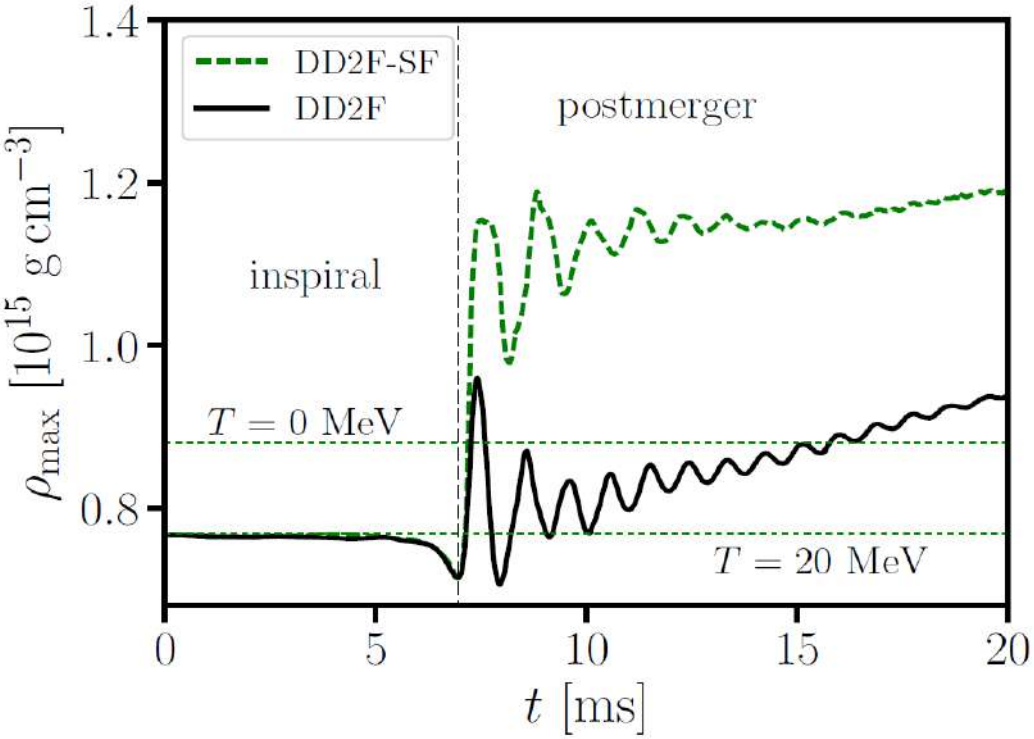
CompOSE

With deconfinement:

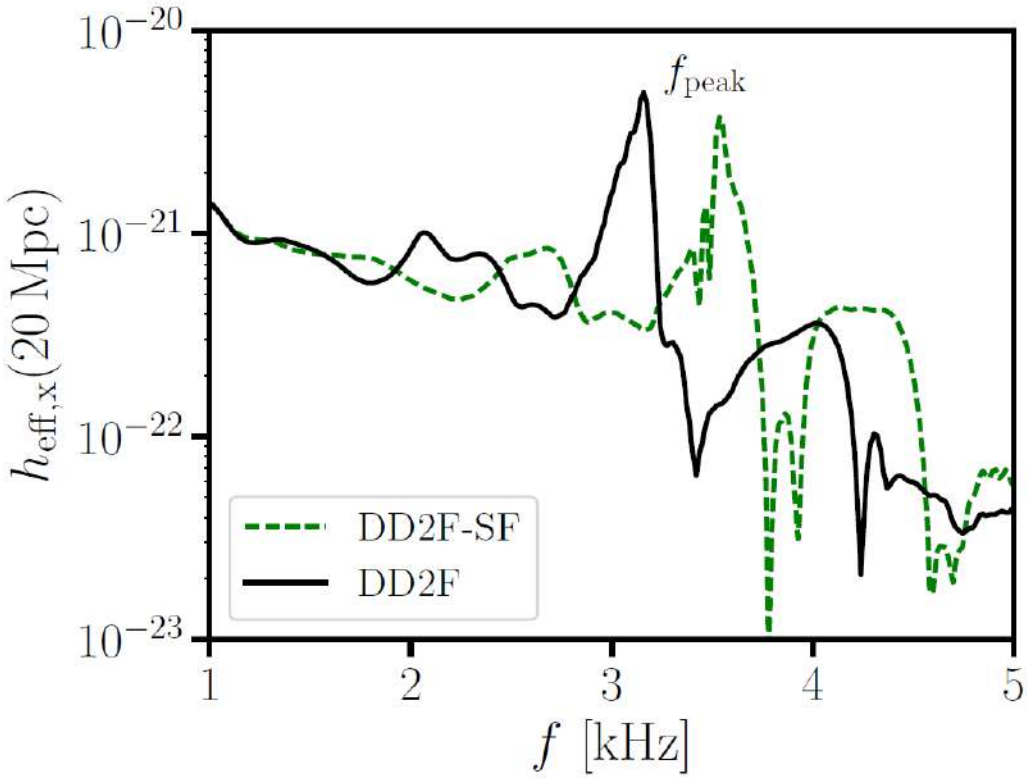
https://compose.obspm.fr/eos/166

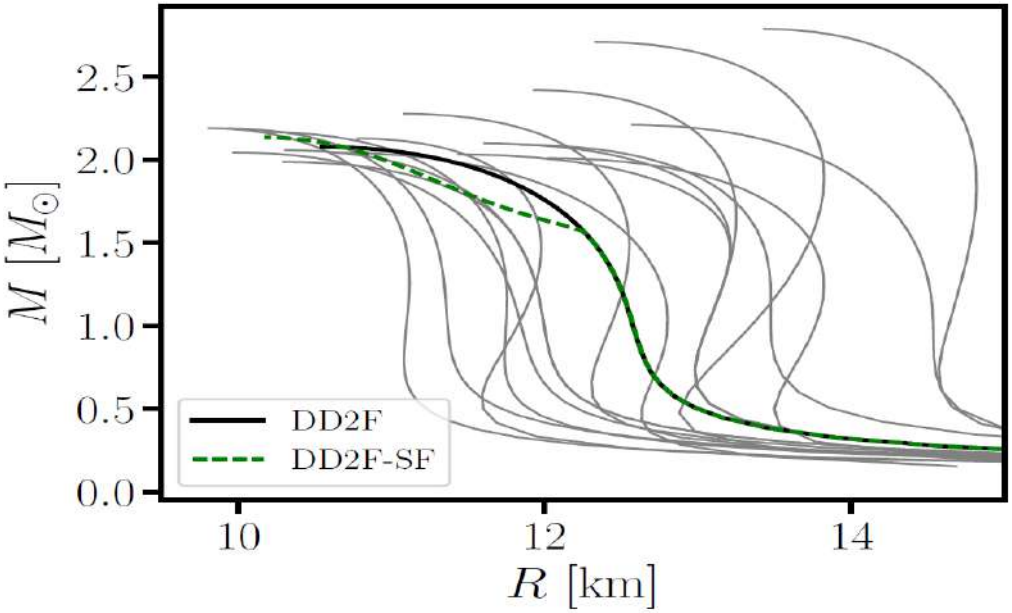
S. Blacker, A. Bauswein, et al., Phys. Rev. D 102 (2020) 123023

Hybrid star formation in postmerger phase



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



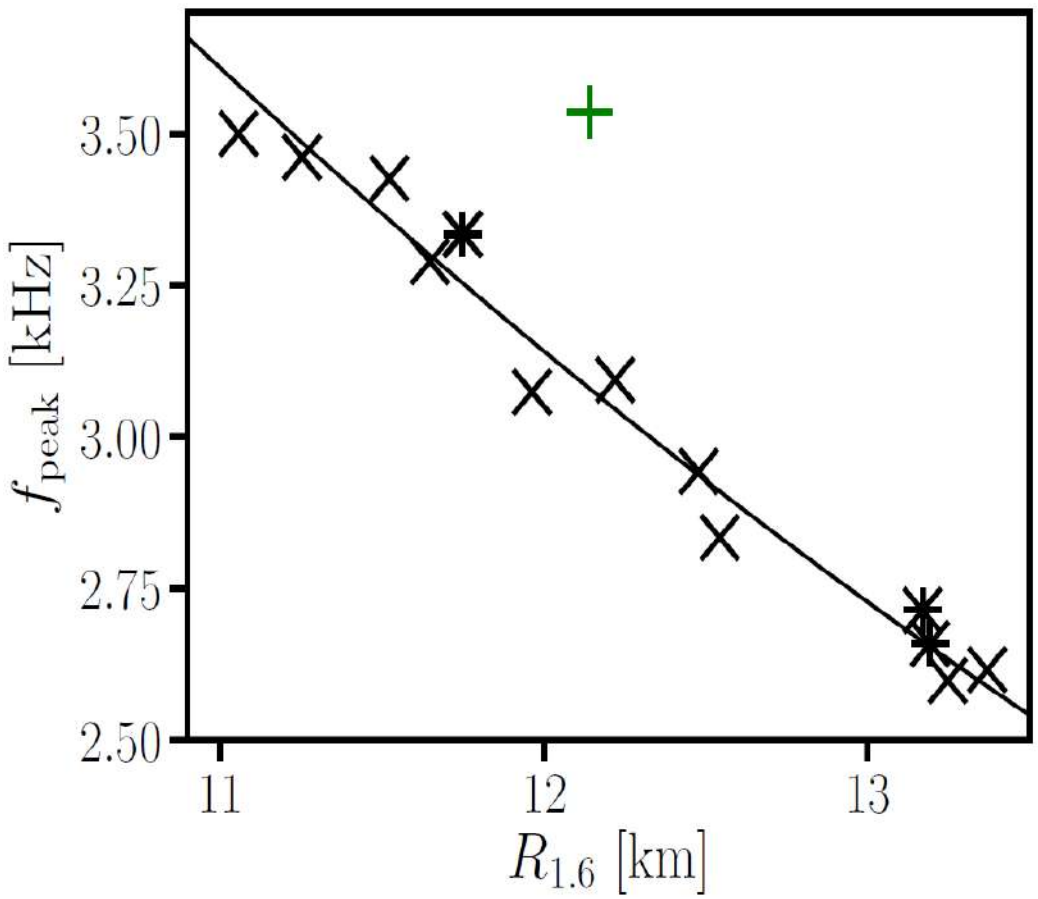


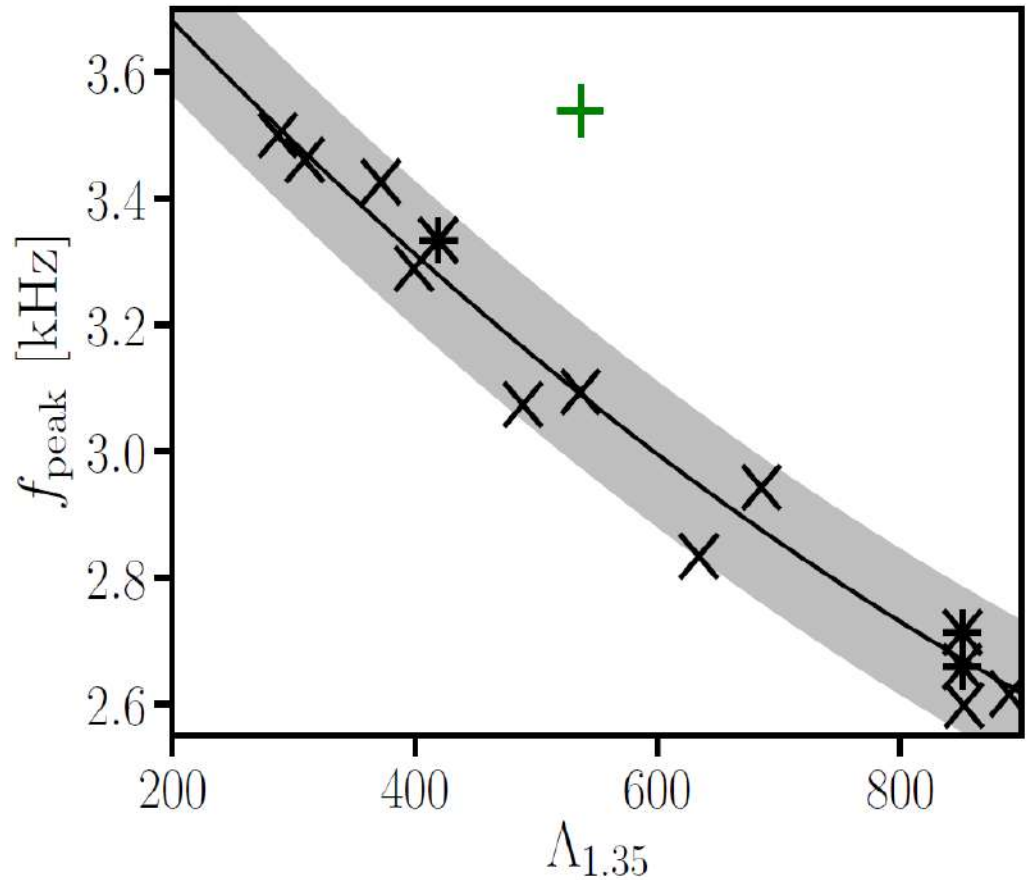
Hybrid star formation during NS merger
→ higher densities and compacter star
→ higher peak frequency of the GW

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]



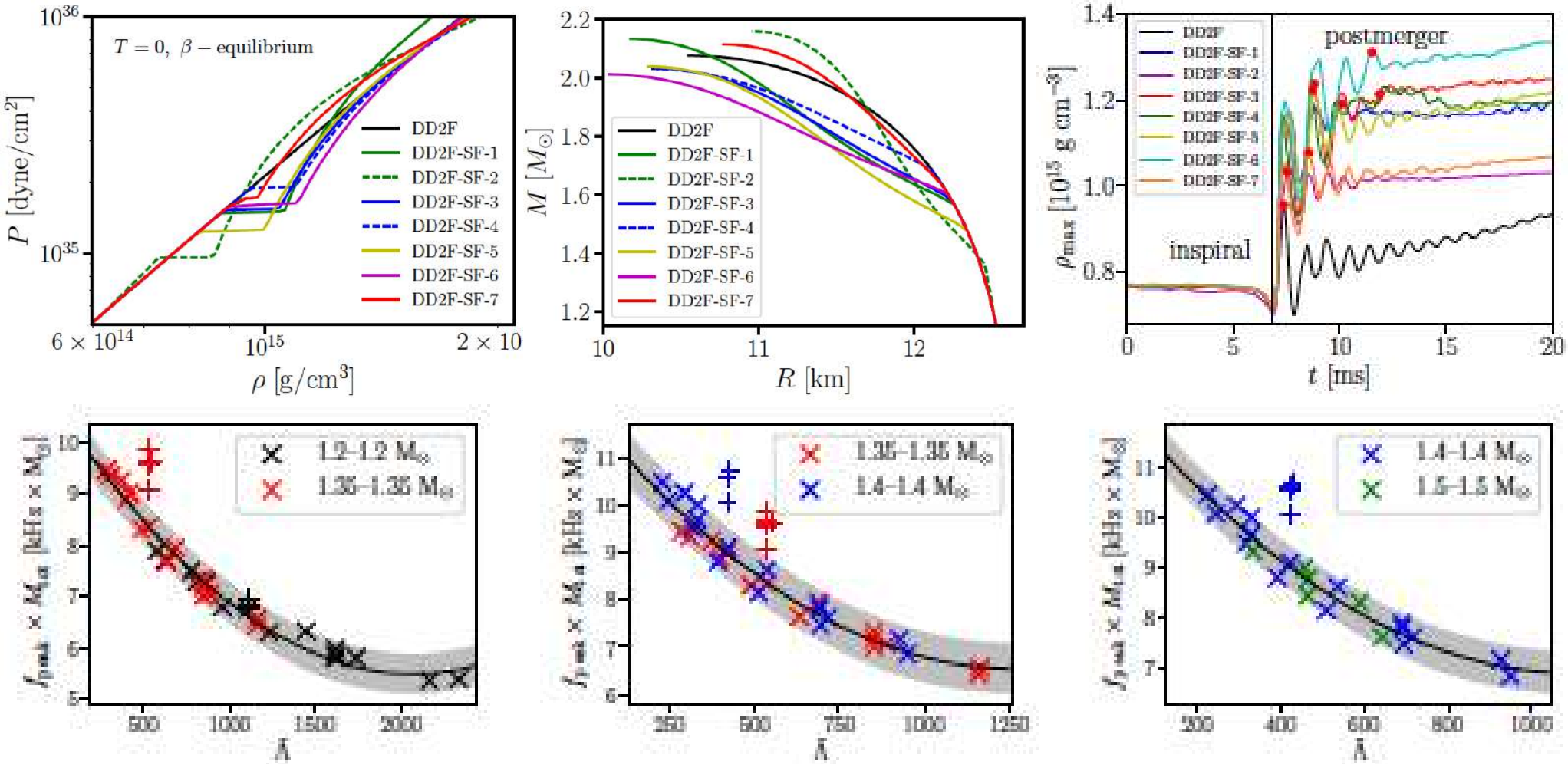


Strong deviation from $\mathbf{f_{peak} - R_{1.6}}$ relation signals **strong phase transition in** NS merger**!**

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

Hybrid star formation in postmerger phase

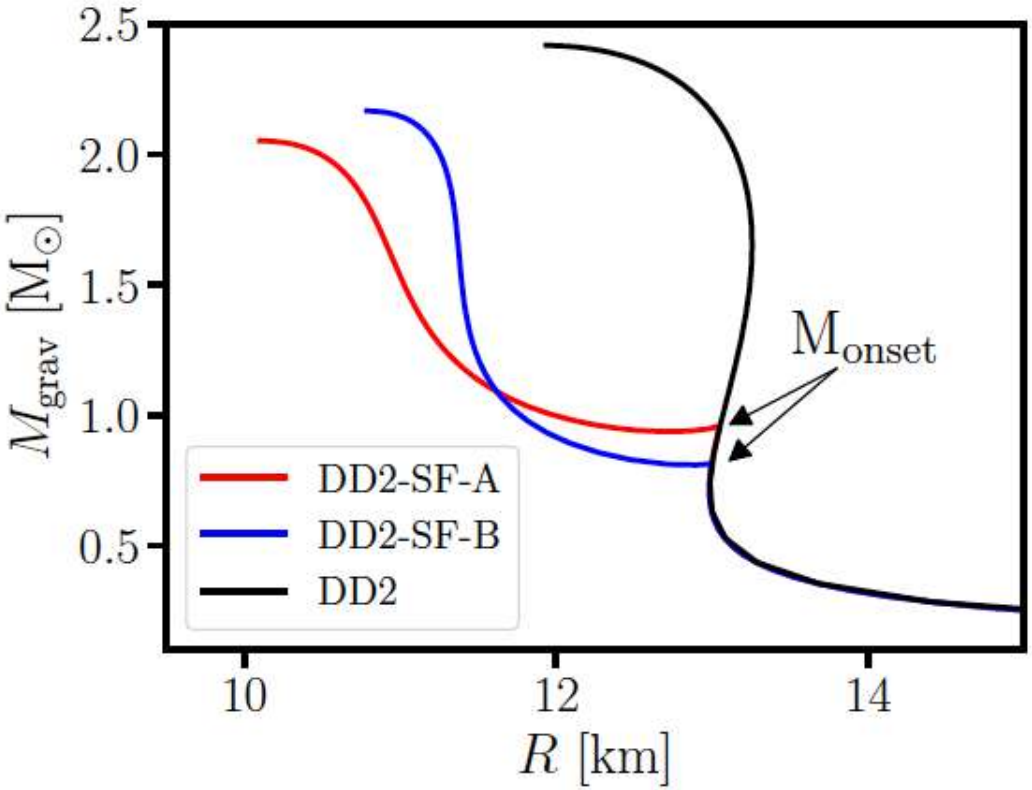
Strong PT in postmerger GW signal, S. Blacker et al., arxiv:2006.03789, PRD102 (2020) 123023

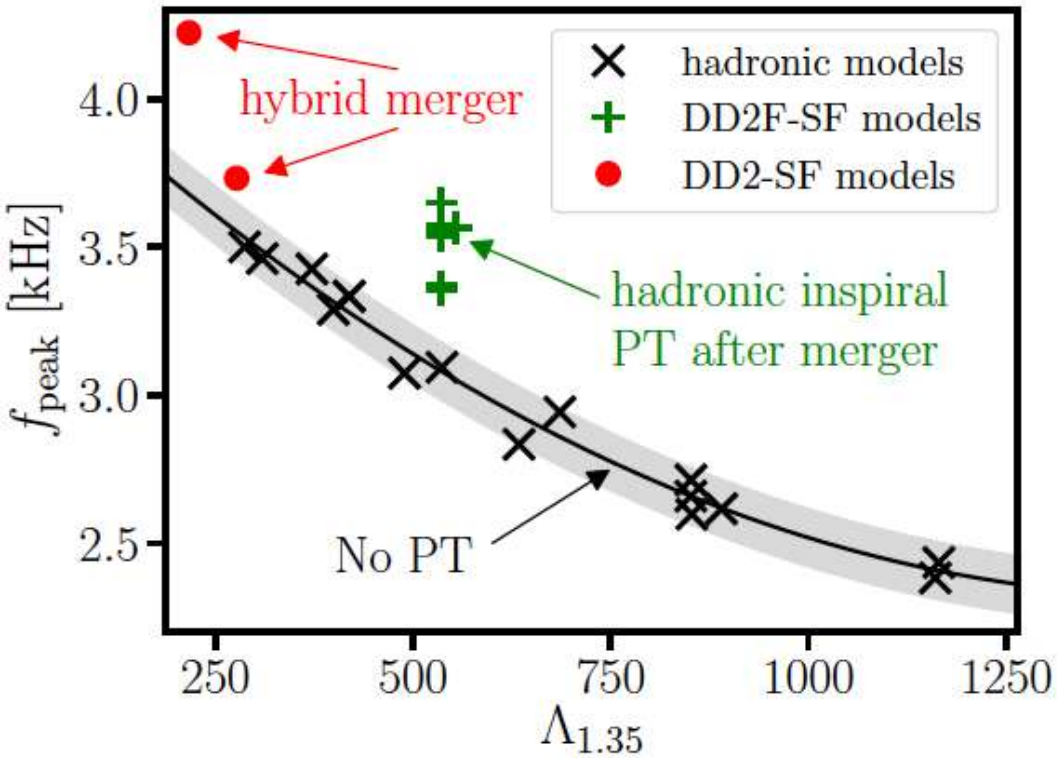


Dominant postmerger frequency f_{peak} vs. tidal deformability $\Lambda_{1.35}$ from inspiral phase:
Results from hybrid models appear as **outliers** of the grey band (maximal deviation of purely hadronic models from a least squares fit) = signalling a **strong phase transition in** NS **!**

GW signal of deconfinement in merger of hybrid stars

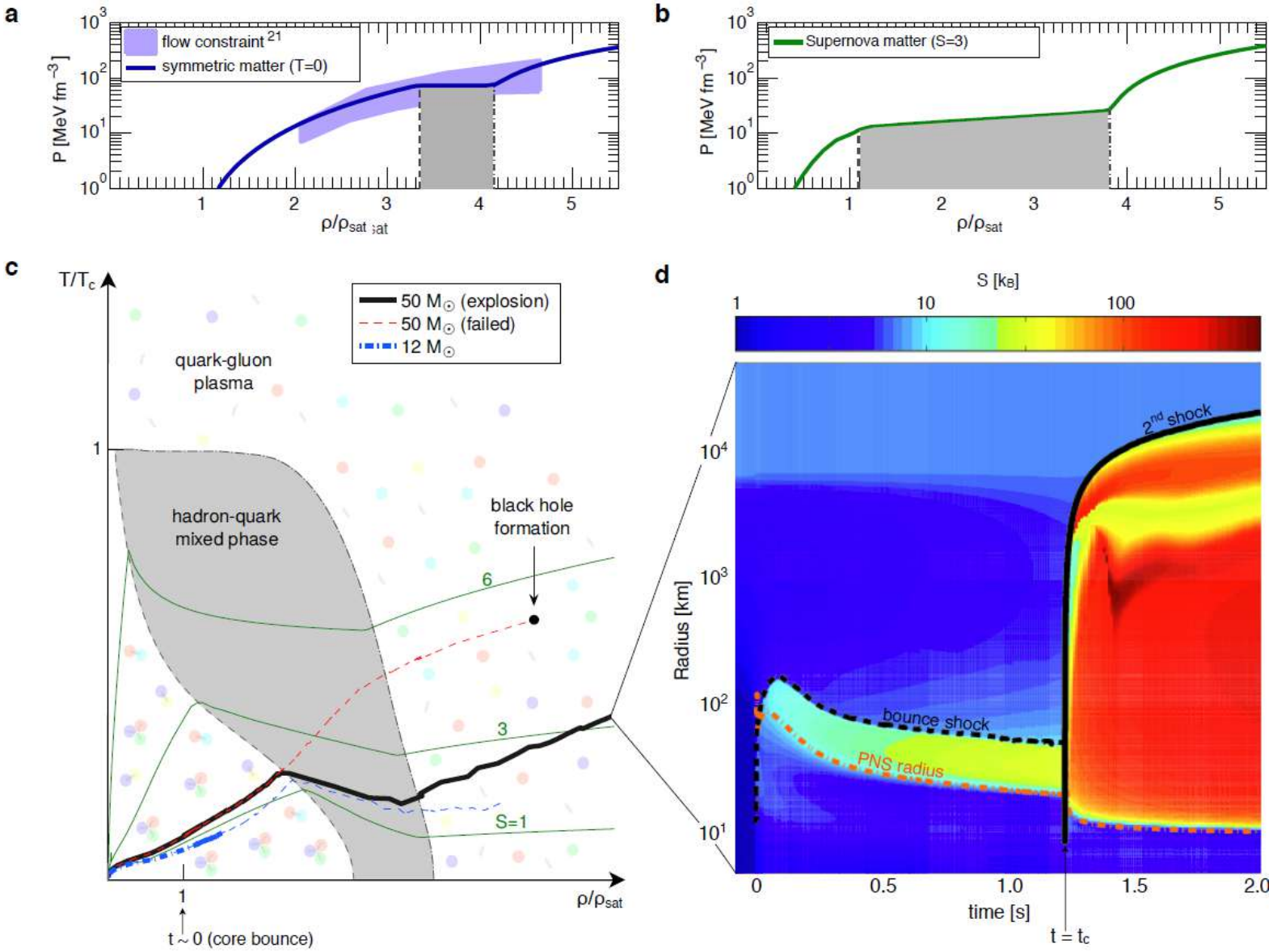
Merger of hybrid stars with early phase transition: Bauswein & Blacker, EPJ ST 229 (2020)





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

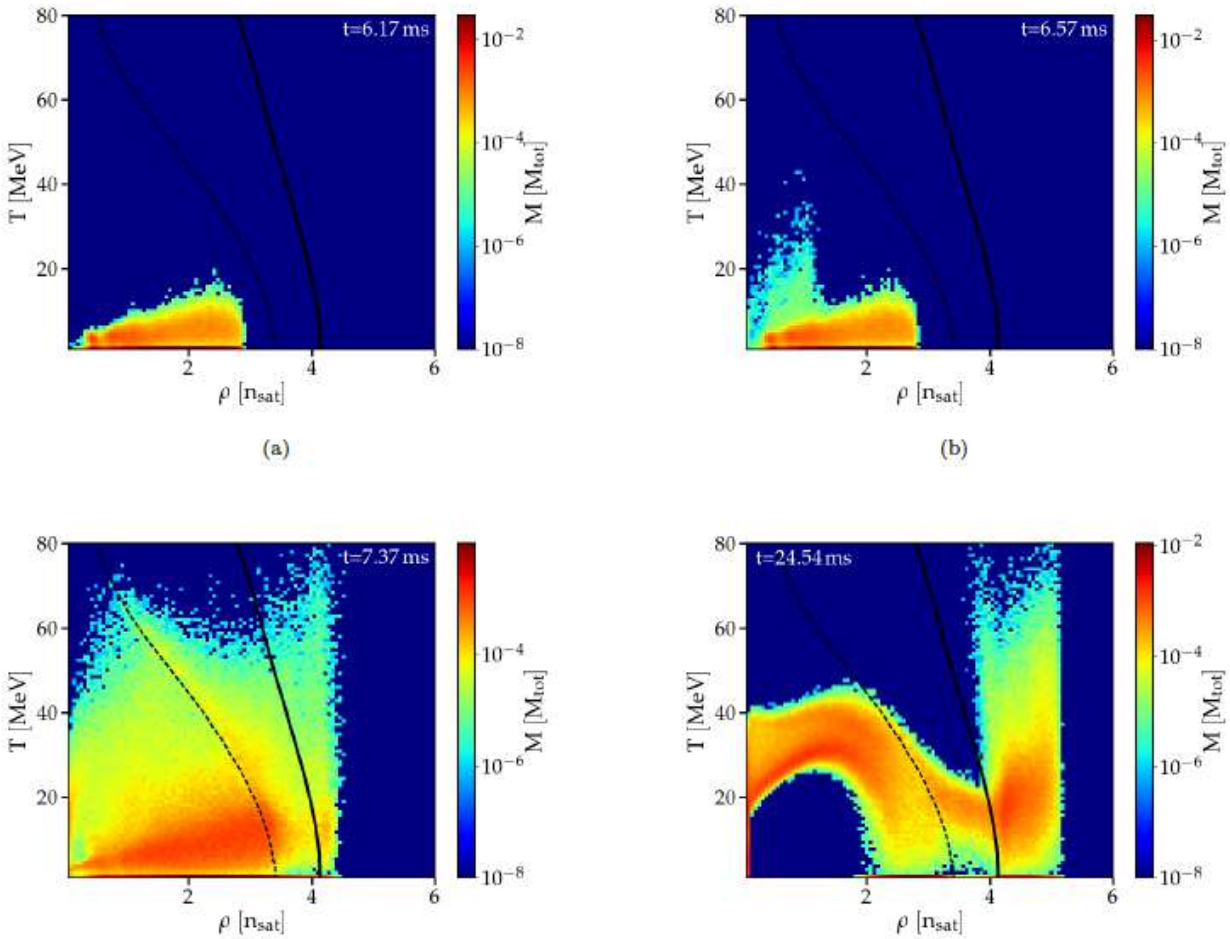


Progenitor:
M = 50 M_O

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

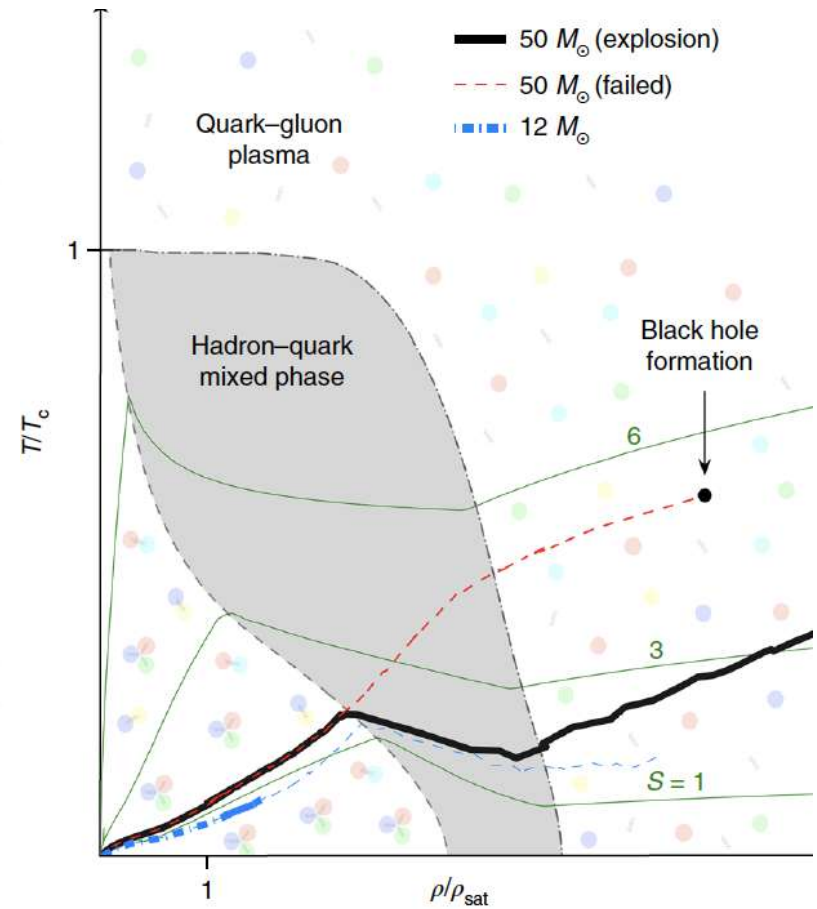
Population of the QCD Phase Diagram in Mergers & SNe

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

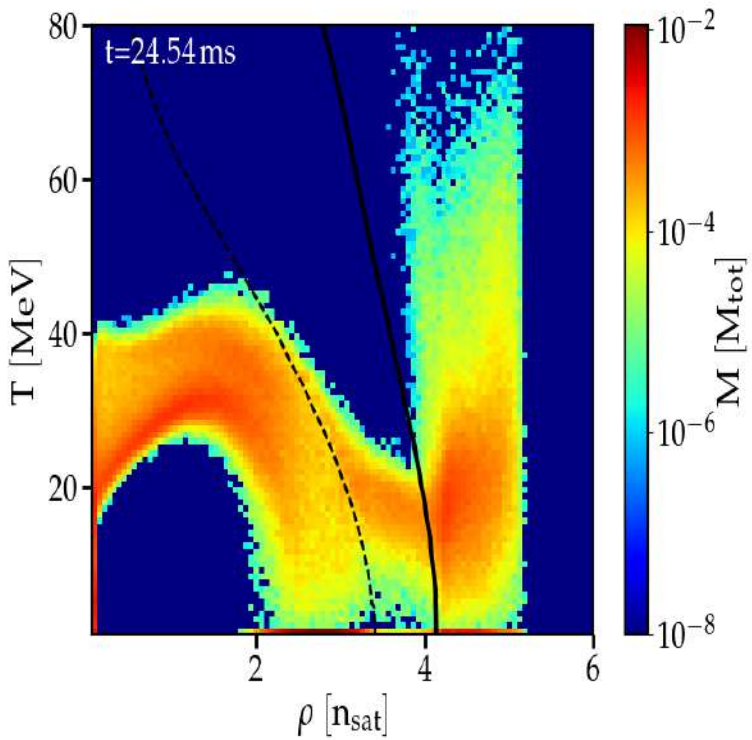
SN explosion, 50 M_sun



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

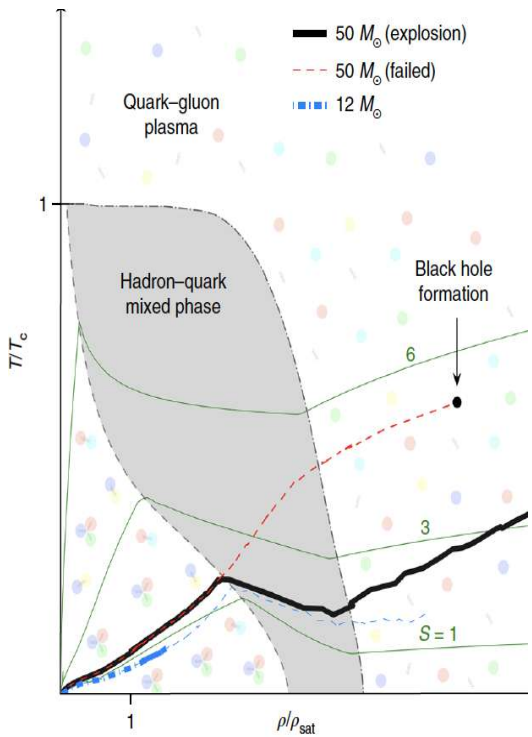
Population of the QCD Phase Diagram

Binary NS merger,
1.35+1.35 M_sun



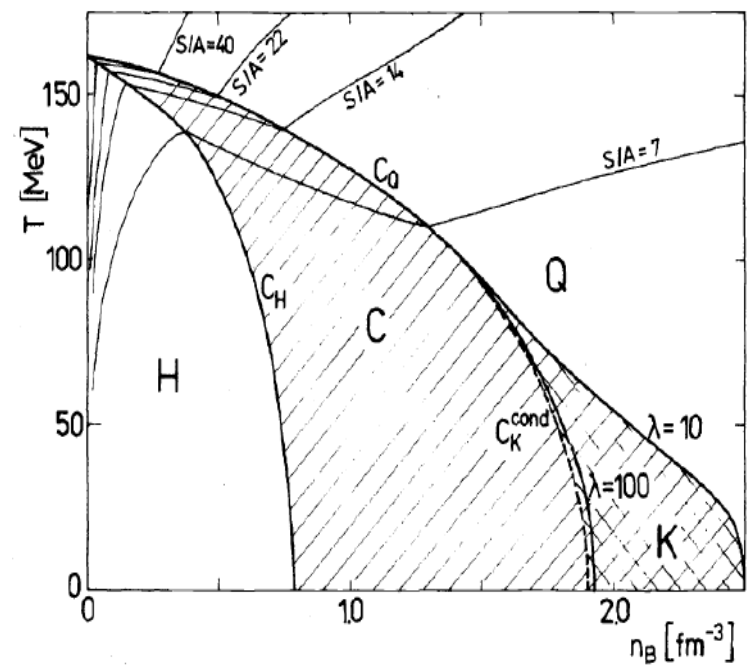
S. Blacker, A. Bauswein et al.,
PRD 102 (2020) 123023
arXiv:2006.03789

SN explosion,
Progenitor 50 M_sun



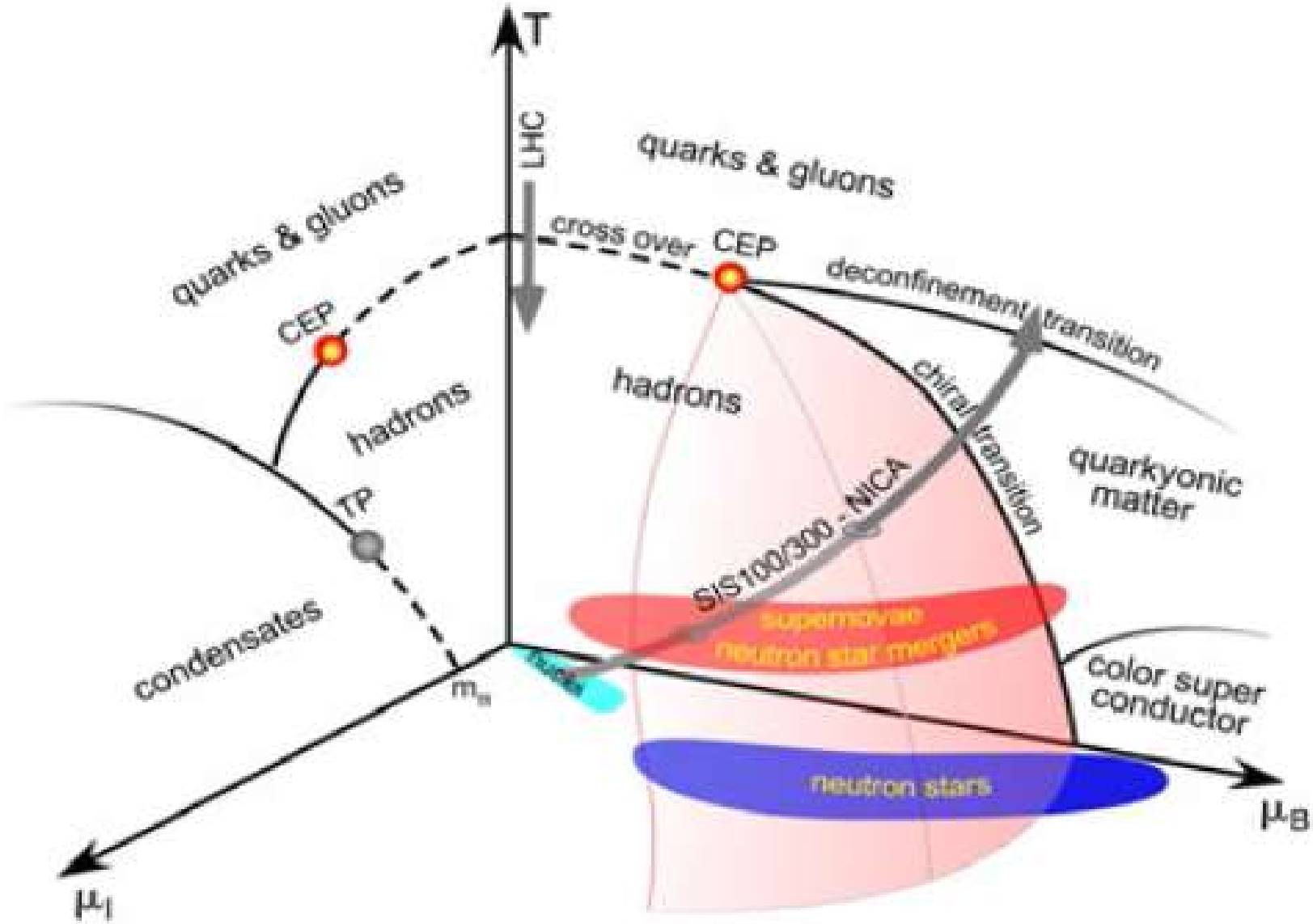
T. Fischer et al.,
Nat. Astron. 2 (2018) 980
arXiv:1712.08788

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

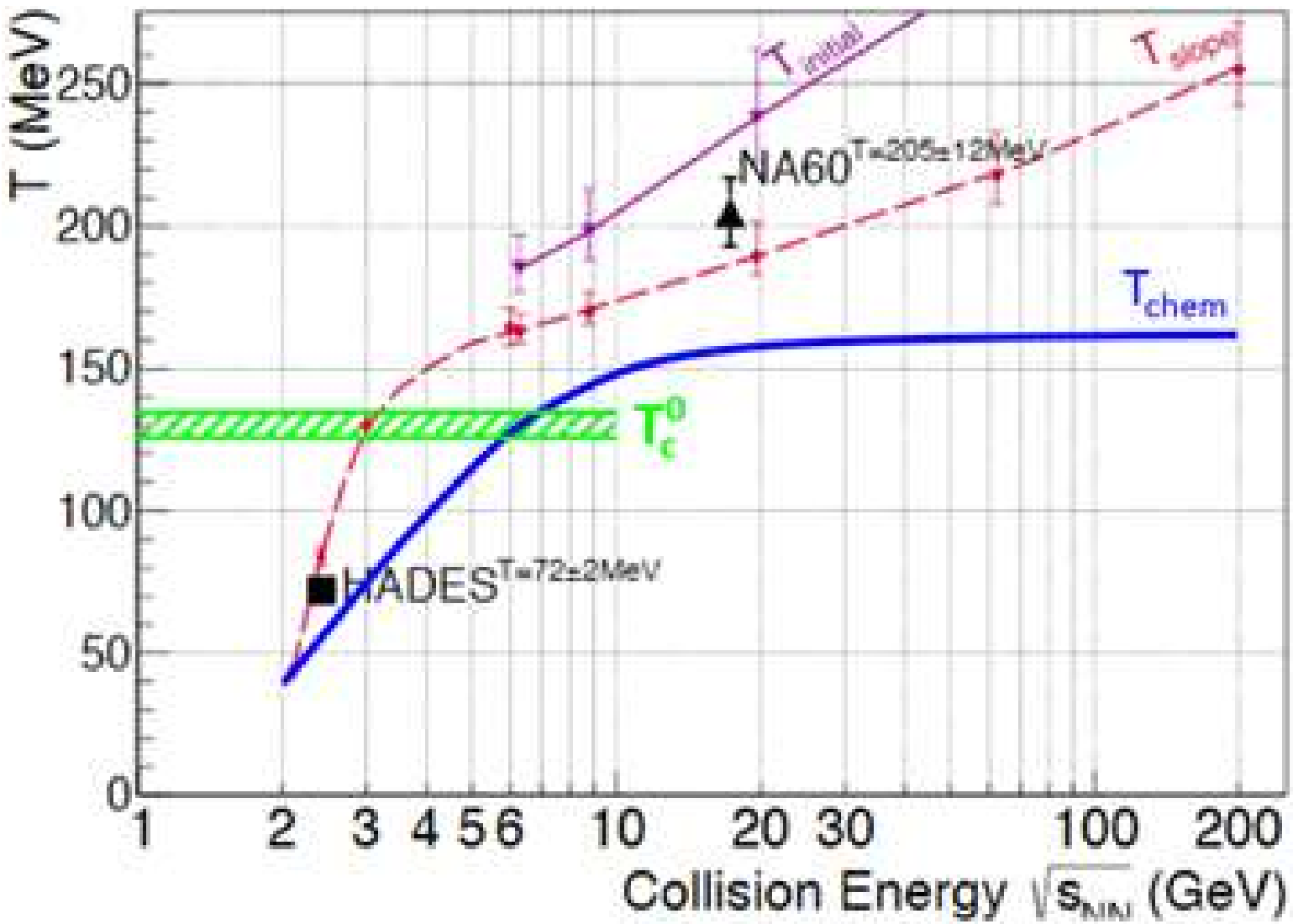


NuPECC Long Range Plan 2017; http://www.nupecc.org

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

CEP in the QCD phase diagram: HIC vs. Astrophysics

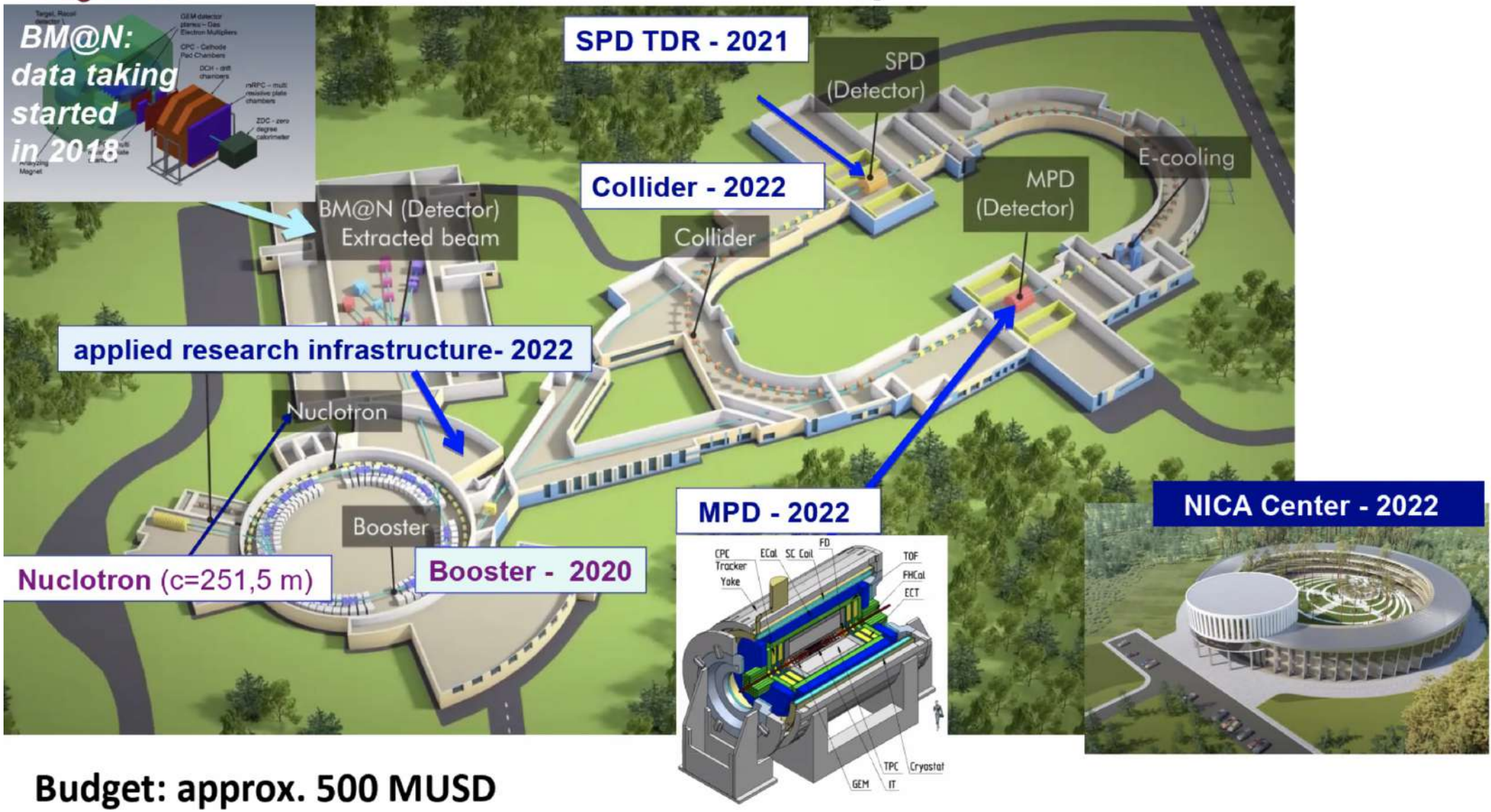
NICA experiments (BM @N, MPD)



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

The NICA Facility at JINR Dubna

NICA Accelerator Complex in Dubna



Budget: approx. 500 MUSD

The NICA Facility at JINR Dubna

NICA construction live

The NICA Facility at JINR

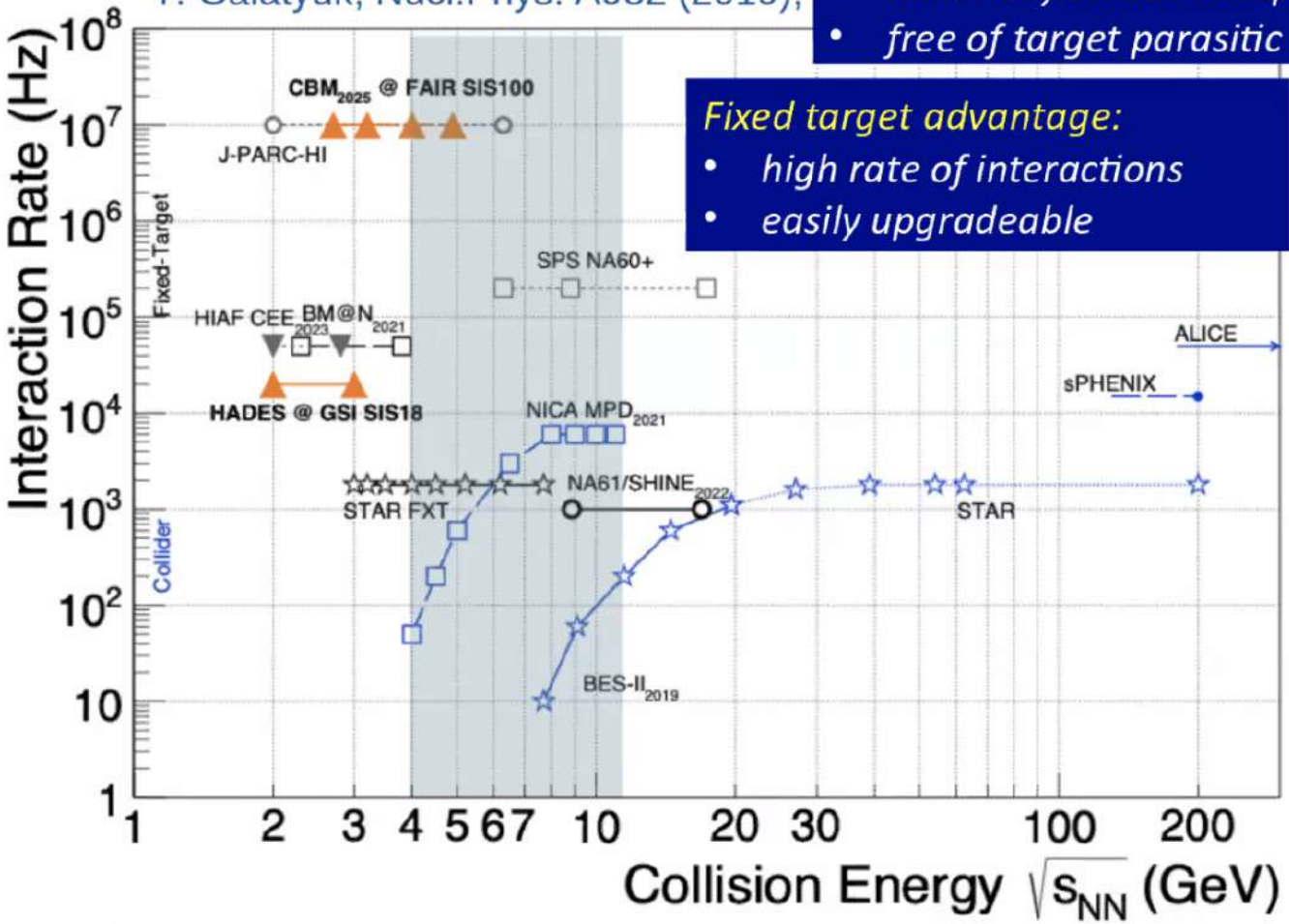
NICA: Unique and complementary

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

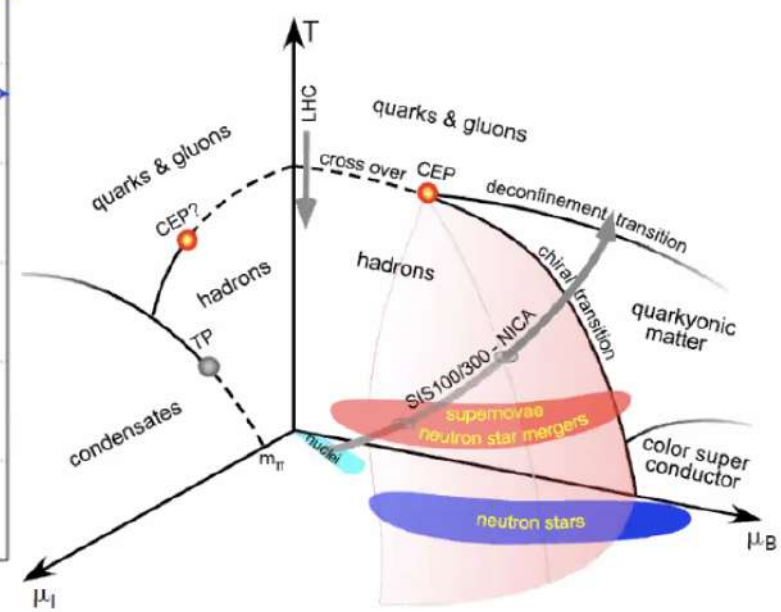
In NICA Collider energy range maximum possible net-baryon density is reached

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

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



NUPECC Long Range Plan 2017



The NICA Facility at JINR Dubna

Main parameters of accelerator complex

Nuclotron

Parameter	SC synchrotron
particles	↑p, ↑d, nuclei (Au, Bi, ...)
max. kinetic energy, GeV/u	10.71 (↑p); 5.35 (↑d) **3.8** (Au)
max. mag. rigidity, Tm	38.5
circumference, m	251.52
vacuum, Torr	10^{-9}
intensity, **Au** /pulse	1 10^{9}

Booster

	value
ion species	A/Z ≤ 3
max. energy, MeV/u	**600**
magnetic rigidity, T m	1.6 – 25.0
circumference, m	210.96
vacuum, Tor	10^{-11}
intensity, **Au** /p	1.5 10^{9}

The Collider

Design parameters, Stage II

45 T*m, 11 GeV/u for Au^{79+}

Ring circumference, m	**503,04**
Number of bunches	**22**
r.m.s. bunch length, m	**0,6**
β, m	**0,35**
Energy in c.m., Gev/u	**4-11**
r.m.s. $\Delta p/p$, 10^{-3}	**1,6**
IBS growth time, s	**1800**
Luminosity, cm^{-2} s^{-1}	**1×10^{27}**

Stage I:

- ***without ECS in Collider, with stochastic cooling***
- ***reduced number of RF***
- ***reduced luminosity***

Collision system limited by source. *Now Available: C(A=12), N(A=14), Ne(A=20), Ar(A=40), Fe(A=56), Kr(A=78-86), Xe(A=124-134), Bi(A=209)*

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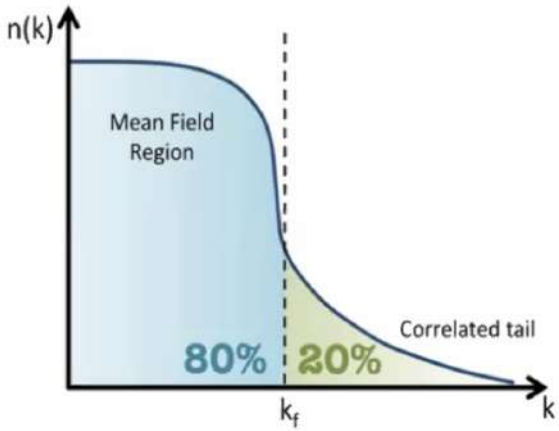
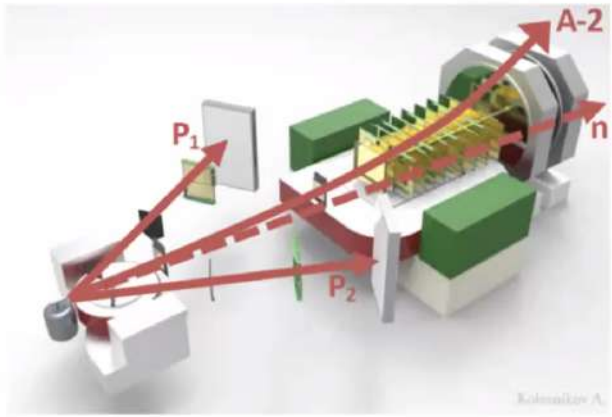
Booster commissioning

- ✓ Booster fully assembled in the tunnel
- ✓ Commissioning and test ongoing for beam diagnostics, beam acceleration, electron cooling, power supply, magnets, cryogenics

The NICA Facility at JINR Dubna

Experiment with BM@N: Short-Range Correlations (SRC)





Experiment at BM@N with a 4A GeV C-beam:

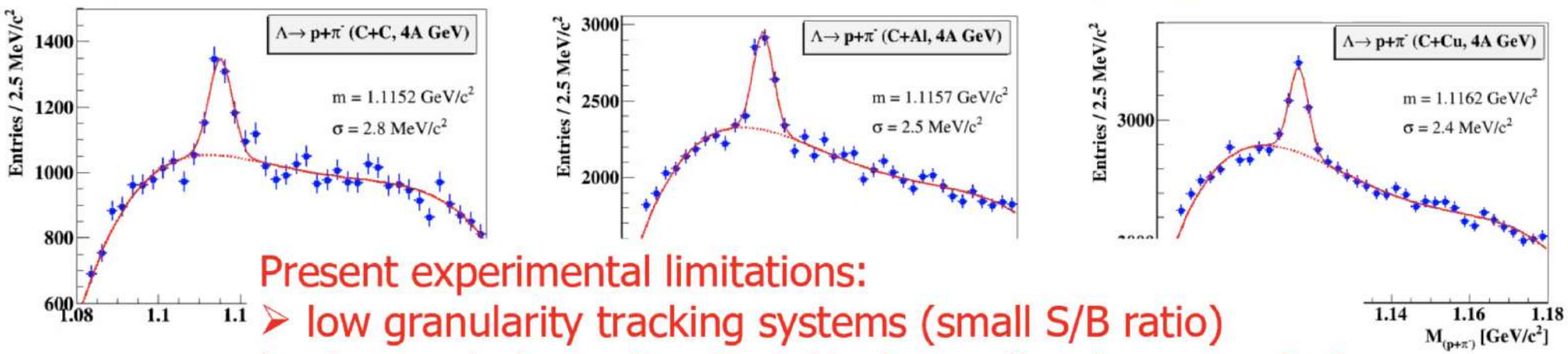
$^{12}C + p \rightarrow 2p + {}^{10}_{4}Be + p$ (pp SRC)

First fully exclusive measurement in inverse kinematics probing the residual A-2 nuclear system!

M. Patsyuk et al., arXiv:2102.02626

Accepted for publication in **nature physics**

Experiment with BM@N: Λ's in C + C, Al, Cu at 4A GeV



Present experimental limitations:

- low granularity tracking systems (small S/B ratio)
- air gaps in beam line from Nuclotron (low beam quality)
- no vacuum beam pipe in BM@N (large background)

The NICA Facility at JINR Dubna

Interior of MPD Hall

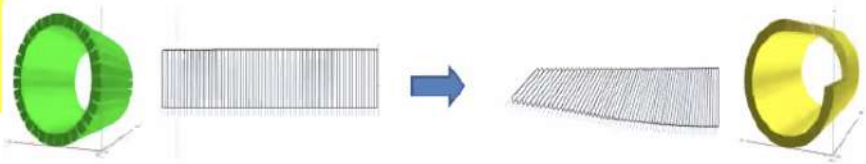
Opening of solenoid sarcophagus: Mar. 23rd

The NICA Facility at JINR Dubna

Electromagnetic Calorimeter (ECAL)

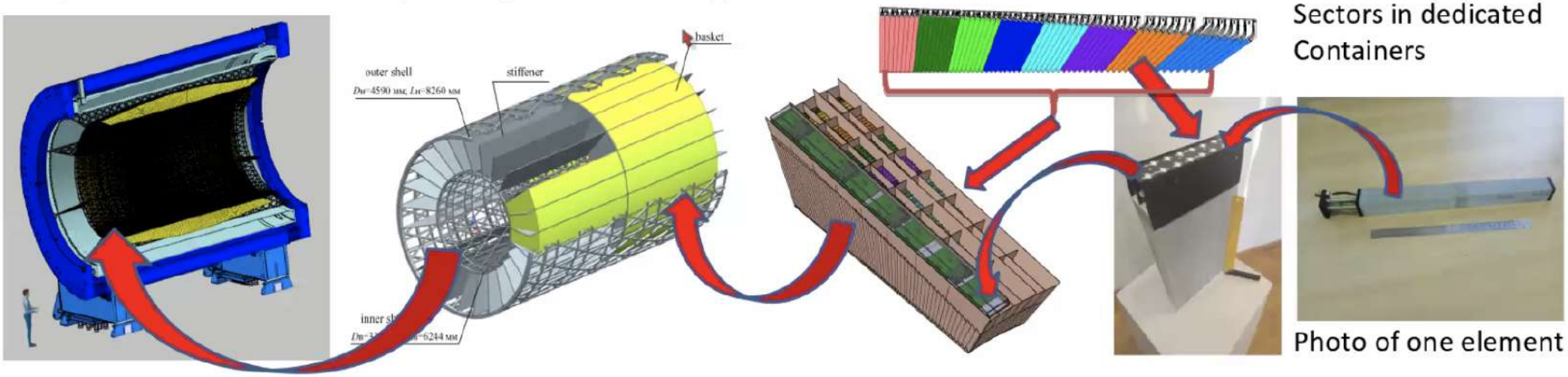
- *Pb+Sc "Shashlyk"* — *read-out: WLS fibers + MAPD* — *L ~35 cm (~ 14 X_0)*
- *Segmentation (4x4 cm²)* — *σ(E) better than 5% @ 1 GeV* — *time resolution ~500 ps*

Barrel ECAL = 38400 ECAL towers (2x25 half-sectors x 6x8 modules/half-sector x 16 towers/module)



Projective geometry

So far ~300 modules (16 towers each) = 3 sectors are produced
Another 3 sectors are planned to be completed by May 2021
Chinese collaborators will produce 8 sectors by the end of 2021
25% of all modules are produced by JINR (production area in Protvino)
75% produced in China, currently funding is secured for approx. 25%



Sectors in dedicated Containers

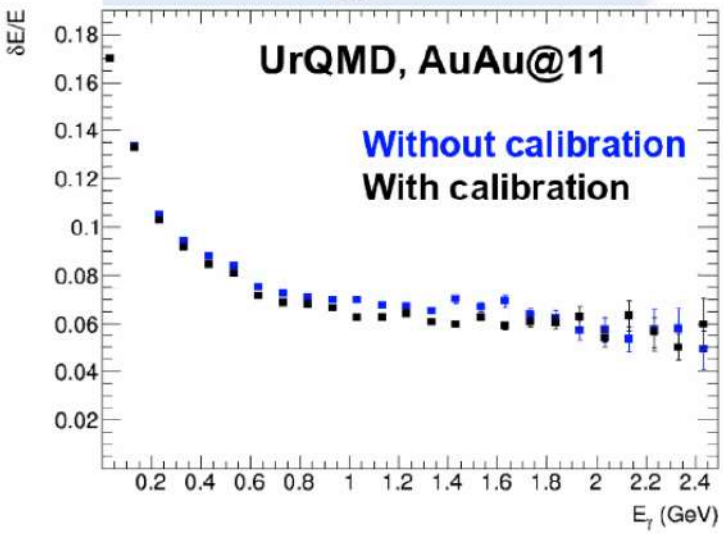
Photo of one element

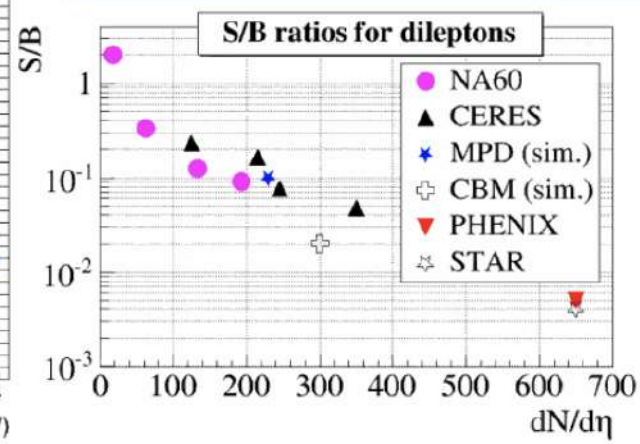
The NICA Facility at JINR Dubna

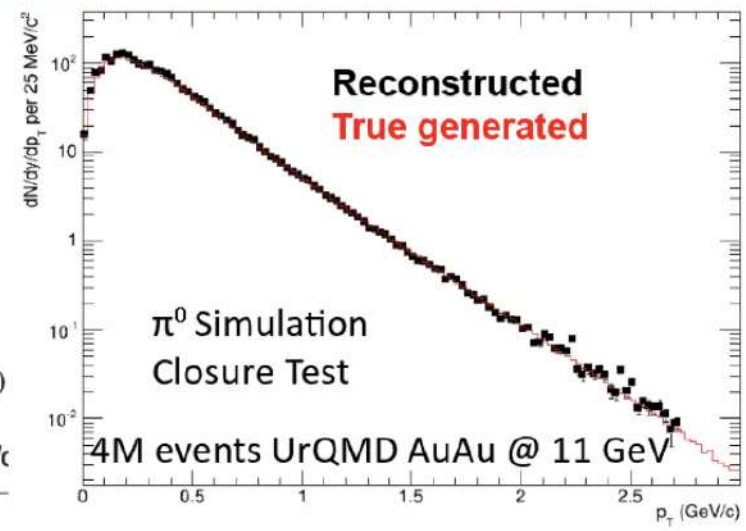
Electromagnetic probes in ECAL

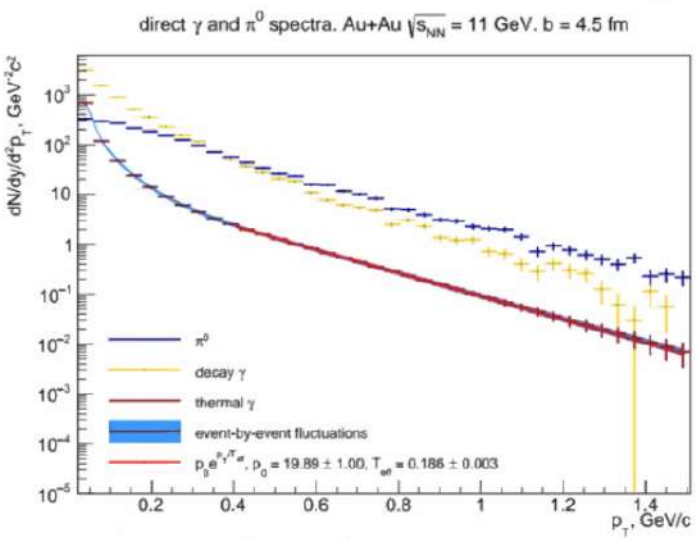
- Realistic ECAL reconstruction & analysis – large acceptance ECAL with good energy resolution: ideal tool for measurement of neutral mesons in a wide momentum range

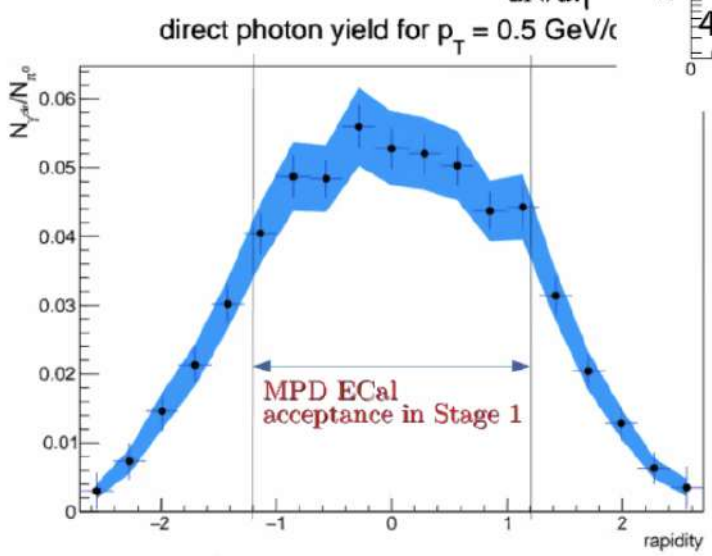
Photon energy resolution











- Promising feasibility studies for prompt photon measurements in MPD

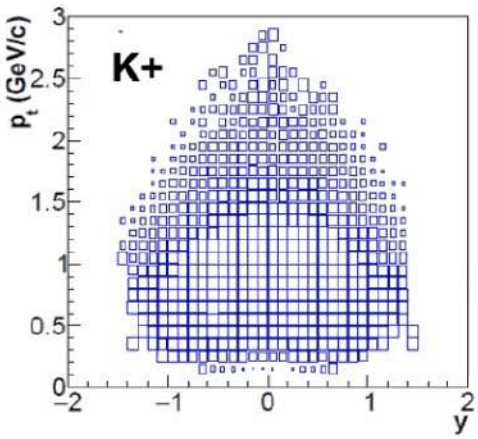
The NICA Facility at JINR Dubna

Hadroproduction with MPD

- **Particle spectra, yields & ratios are sensitive to bulk fireball properties and phase transformations in the medium**
- **Uniform acceptance and large phase coverage are crucial for precise mapping of the QCD phase diagram**

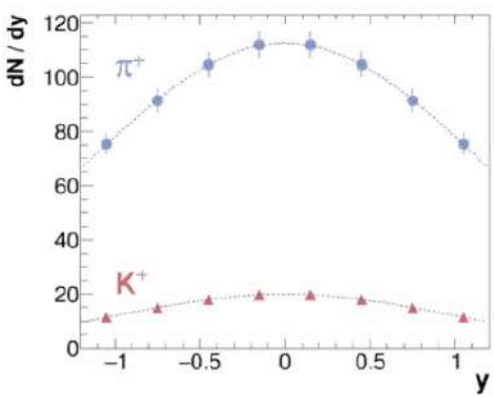
✓ *0-5% central Au+Au at 9 GeV from the PHSD event generator, which implements partonic phase and CSR effects*

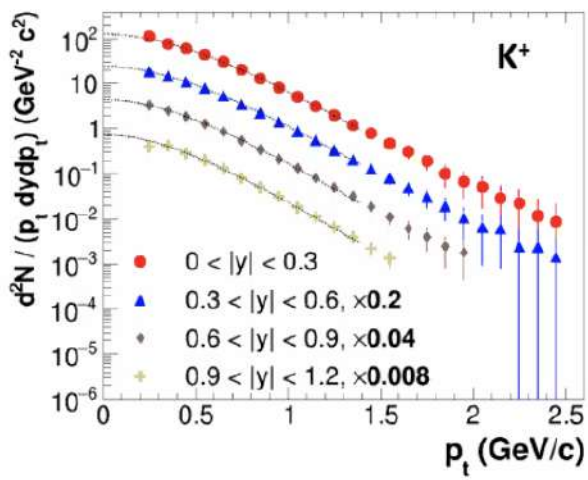
✓ *Recent reconstruction chain, combined dE/dx+TOF particle ID, spectra analysis*

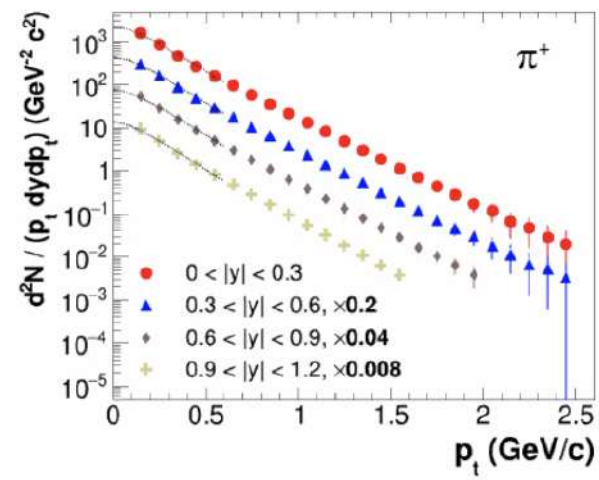


- MPD provides large phase-space coverage for identified pions and kaons (> 70% of the full phasespace at 9 GeV)
- Hadron spectra can be measured from p_T=0.2 to 2.5 GeV/c
- Extrapolation to full p_T-range and to the full phase space can be performed exploiting the spectra shapes (see BW fits for p_T-spectra and Gaussian for rapidity distributions)

Ability to cover full energy range of the „horn" with consistent acceptance







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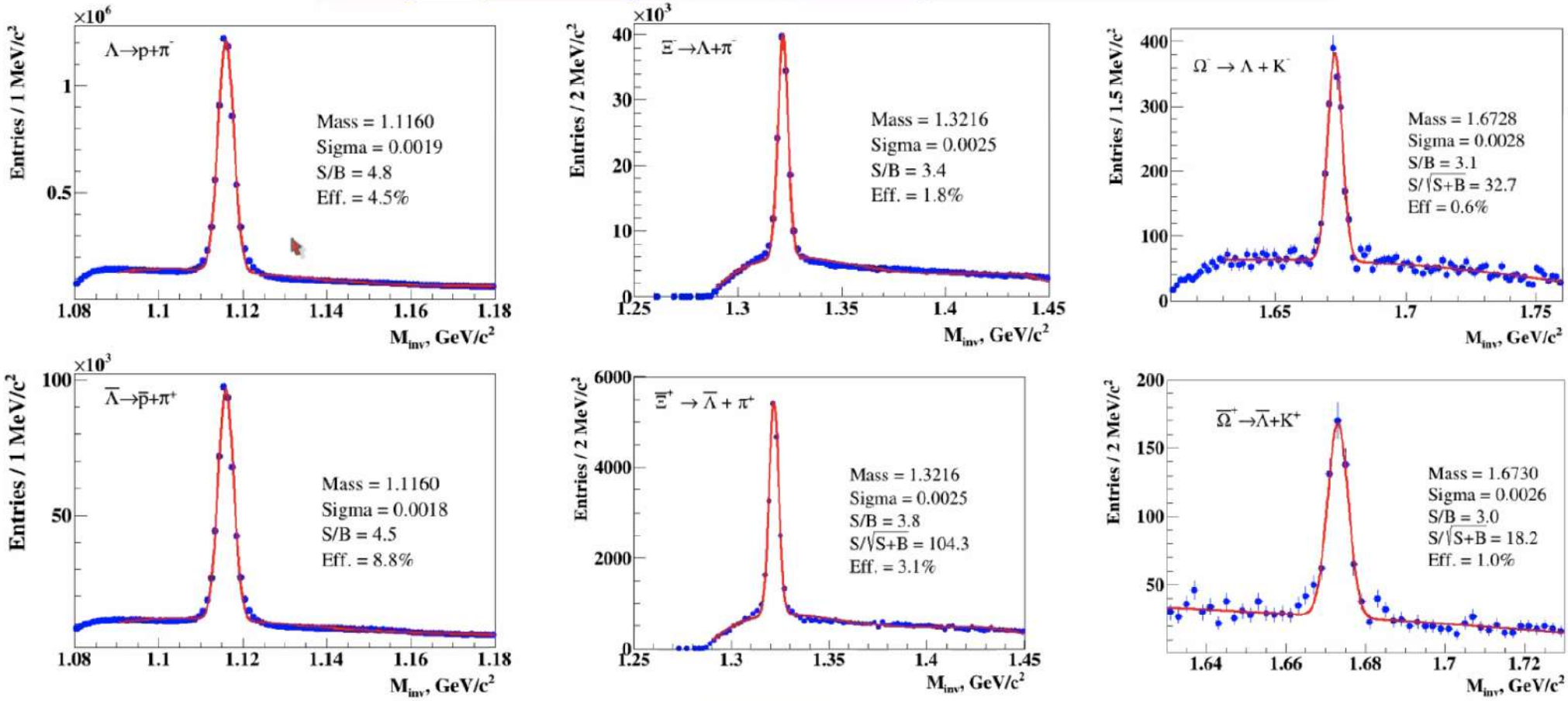
Strange and multi-strange baryons

Stage'1 (TPC+TOF): Au+Au @ 11 GeV, PHSD + MPDRoot reco.



particle	Λ	anti-Λ	Ξ⁻	anti-Ξ⁺	Ω⁻	anti–Ω⁺
yield in 10 weeks	$3 \cdot 10^8$	$3.5 \cdot 10^6$	$1.5 \cdot 10^6$	$8.0 \cdot 10^4$	$7 \cdot 10^4$	$1.5 \cdot 10^4$

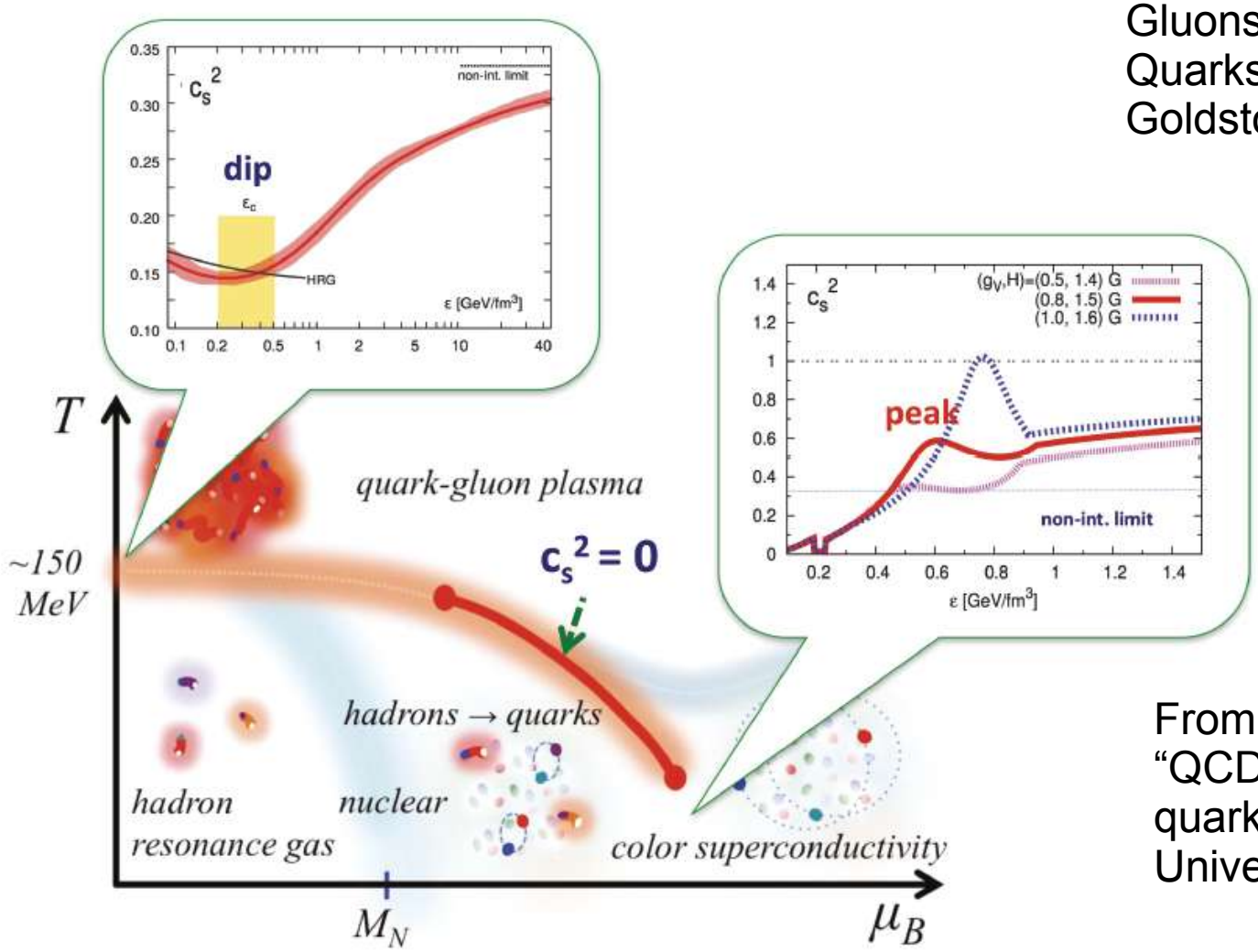
The NICA Facility at JINR Dubna

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

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

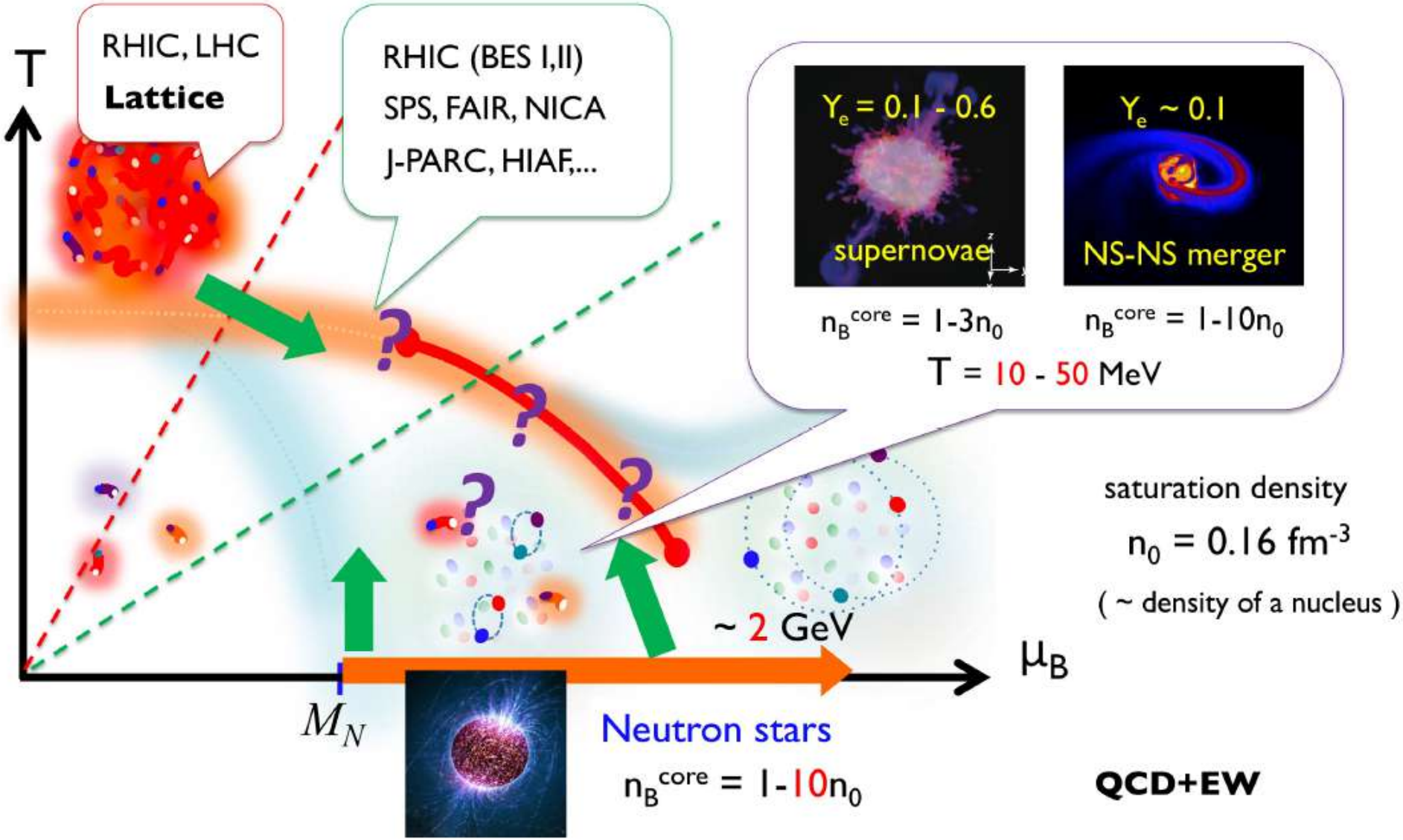
Gluons ↔ Vector mesons
Quarks ↔ Baryons
Goldstones ↔ Pseudoscalar mesons



From: T. Kojo,
"QCD equations of state in quark-hadron continuity",
Universe 4 (2018) 42

T. Schaefer & F. Wilczek, Phys. Rev. Lett. 82 (1999) 3956
C. Wetterich, Phys. Lett. B 462 (1999) 164
T. Hatsuda, M. Tachibana, T. Yamamoto & G. Baym, Phys. Rev. Lett. 97 (2006) 122001

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

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 allow 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 extremely 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)