MAGIC

Matter, Astrophysics, Gravitationalwaves & Ion Collisions

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FIAS Frankfurt Institute for Advanced Studies

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HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

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BLACK HOLE CAM

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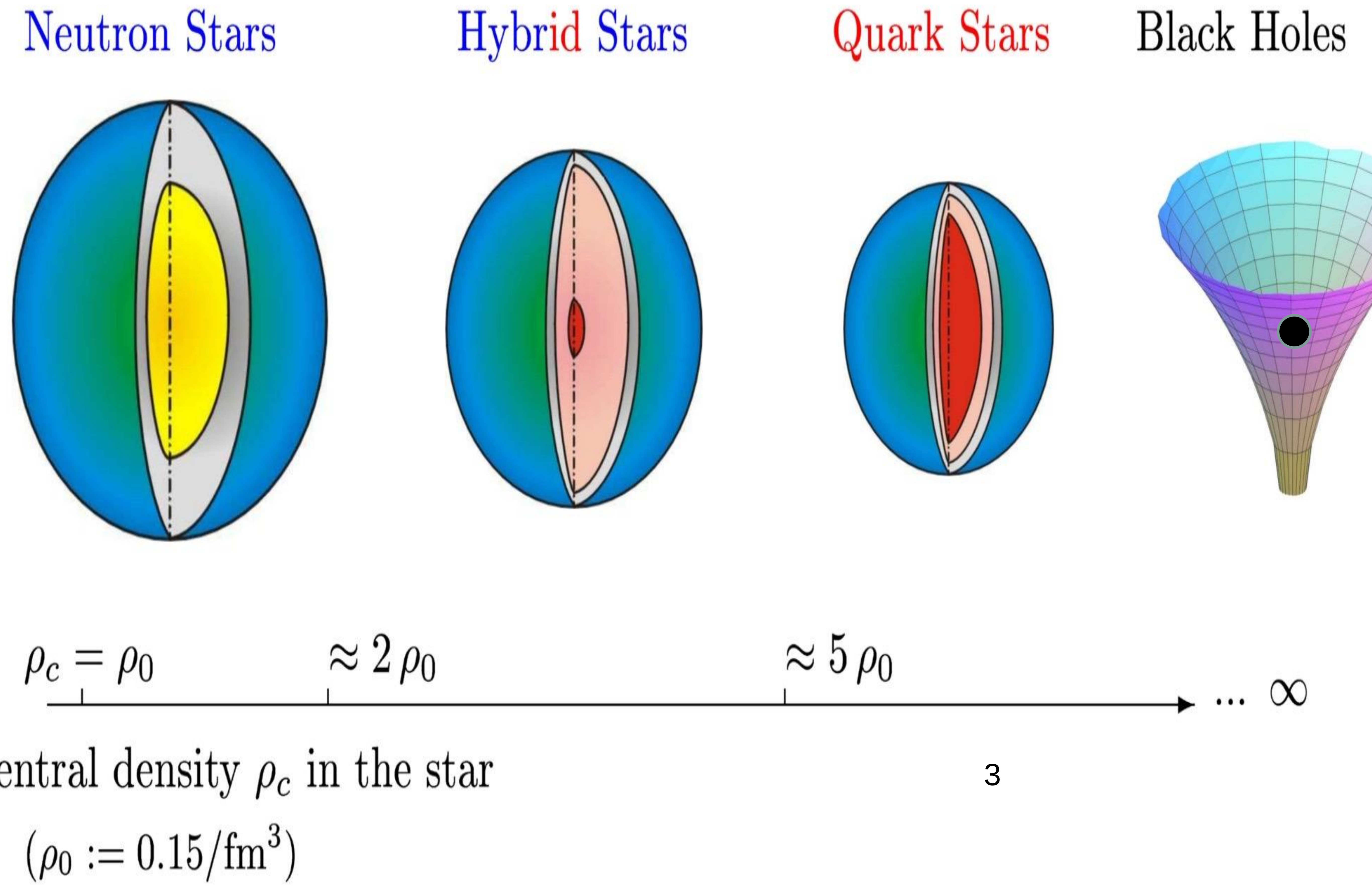
FAIR

Matter, Gravity and Neutron Stars

1915 **A. Einstein,** born in Ulm, published GR:
Gravity governs the motion of masses
and light by curving spacetime.
1915 **Karl Schwarzschild**,
born1873 in Frankfurt am Main,
found the static point source solution of the theory of GR: BHs !
1916 K.S.' last article: "Neutron Star" solution of GR: NS !
SchwarzSchild died in WW I just after publishing these articles..

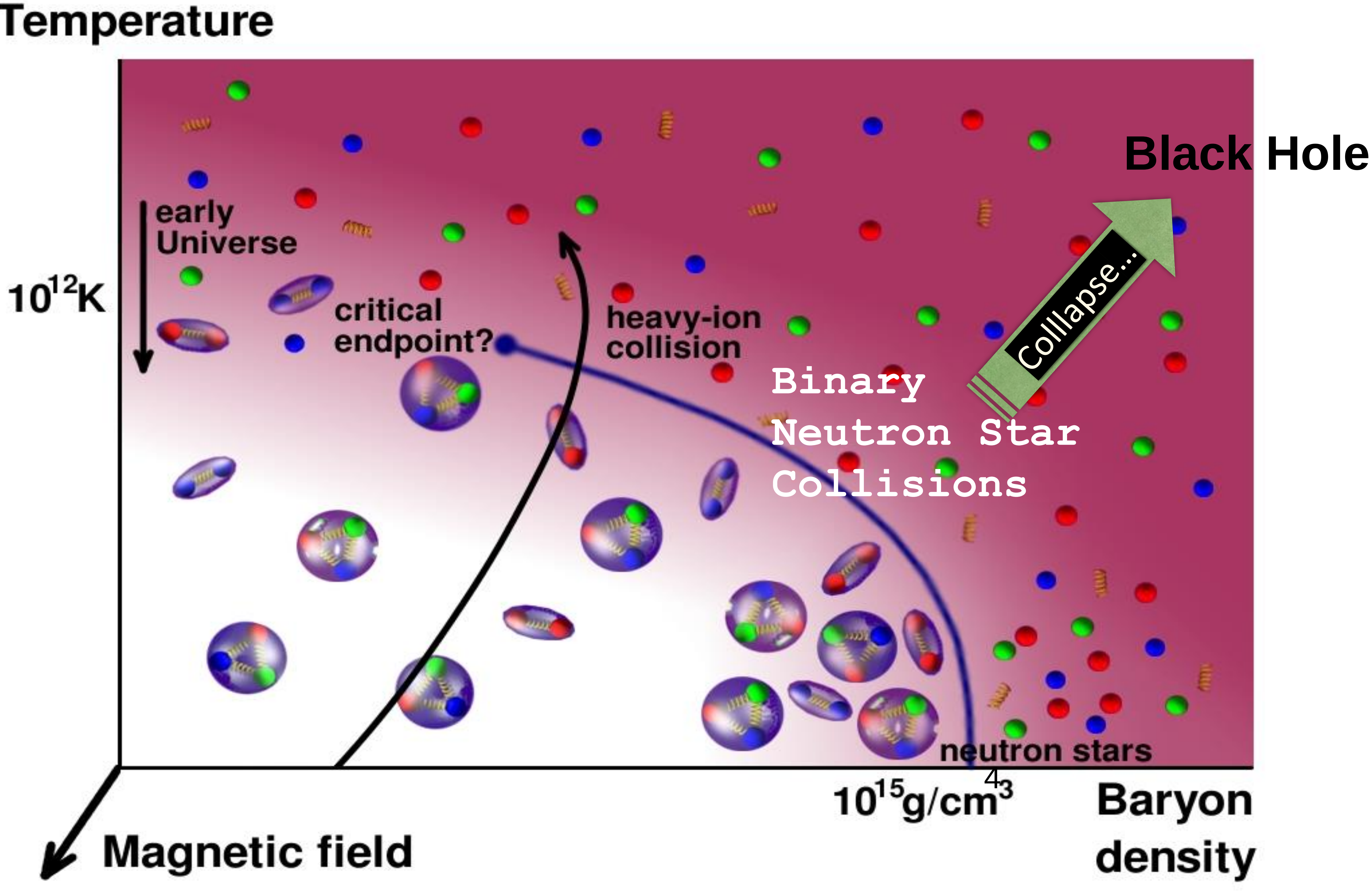
SchwarzSchild's solutions of GR: **black holes & neutron stars**
Add Einstein's **Gravitational Waves - we see a whole new Universe!**

Neutron Star, Quark Star, Black hole ?



Dense Matter, Strange Matter, Quark Matter, Quark Stars?

FAIR: Relativistic collisions of Heavy Ions vs. BNS-NSC



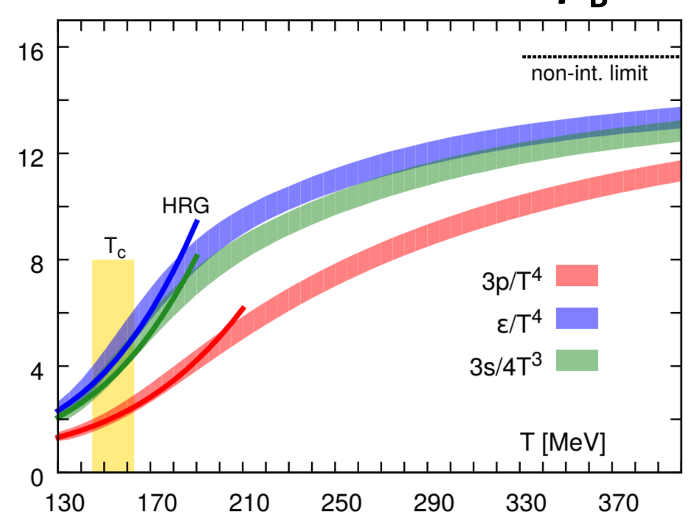
Chiral SU(3)$_f$ parity-doublet Polyakov-loop quark-hadron model

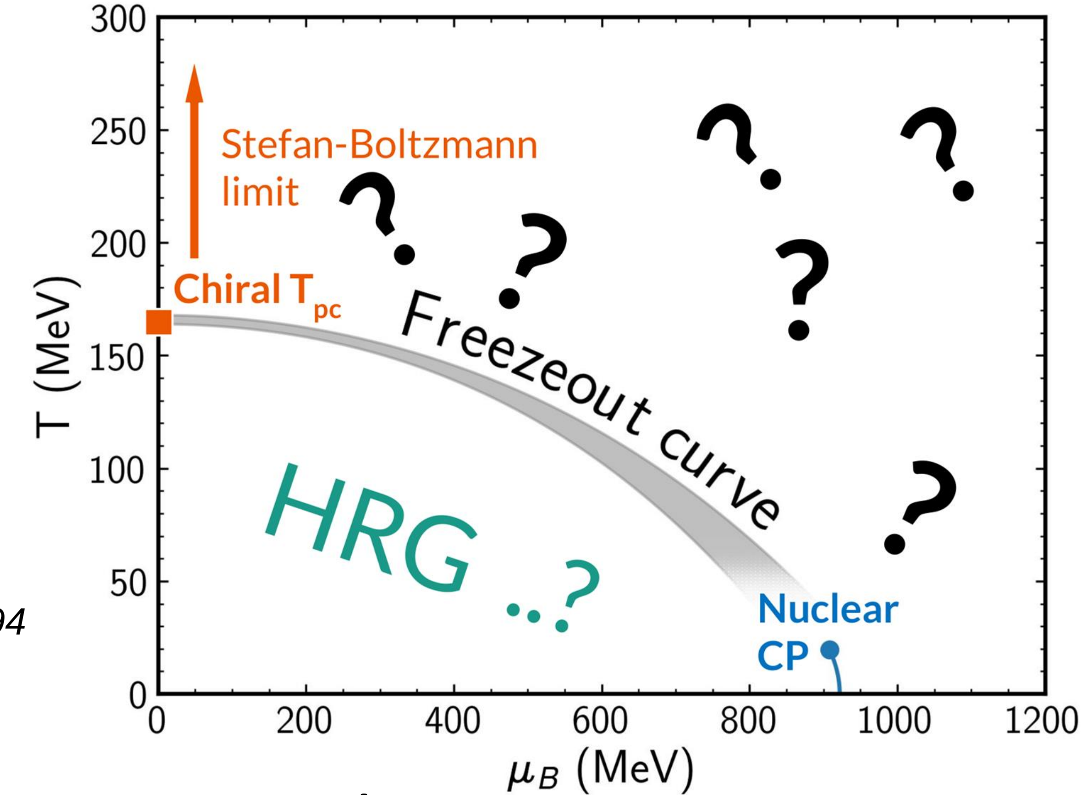
- **Chiral** — chiral symmetry restoration among parity partners and in the quark sector, chiral field is a proxy interaction between quarks and hadrons
- **SU(3)** — 3-flavor (u, d, s) chiral Lagrangian: respective baryon octet interacts through mesonic fields. Realization of σ-ω model.
  P. Papazoglou et al., nucl-th/9706024
- **parity-doublet** — parity doubling among the baryon octet
  C. E. Detar and T. Kunihiro, Phys.Rev. D39 (1989)
  T. Hatsuda and M. Prakash, Phys.Lett. B224 (1989)
  G. Aarts et al., 1703.09246 and 1812.07393
- **quark-hadron** — realization of the deconfinement, PNJL-like
  K. Fukushima, hep-ph/0310121
  C. Ratti, M.A. Thaler, W. Weise, hep-ph/0506234
  J. Steinheimer, S. Schramm, H. Stoecker, 1009.5239

A **single framework** for QCD thermodynamics, **simultaneously** satisfies constraints from **lattice QCD** and known **nuclear matter properties**, as well as **neutron star** observations.

QCD phenomenology for the EoS

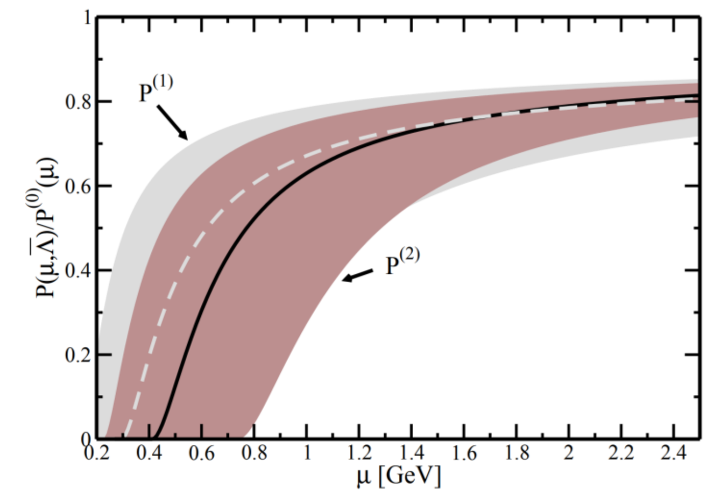
Stefan-Boltzmann limit μ_B=0 *HotQCD, 1407.6387*



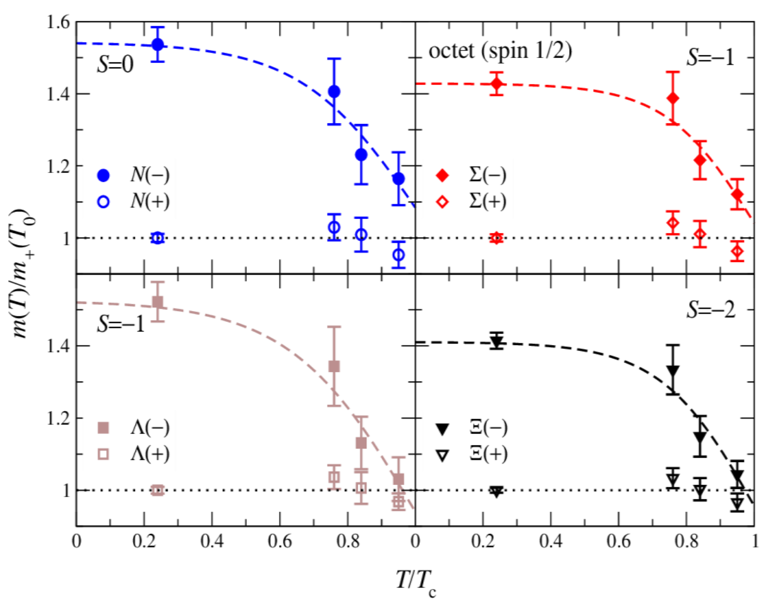


Stefan-Boltzmann limit T=0

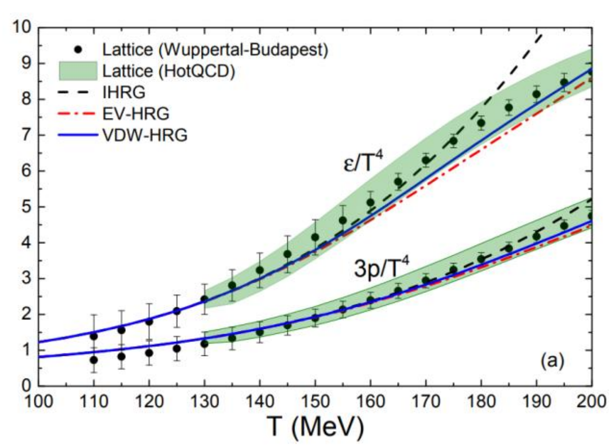
A. Kurkela, P. Romatschke, A. Vuorinen, 0912.1856



Parity doubling *G. Aarts et al., 1710.08294*



Hadron Resonance Gas

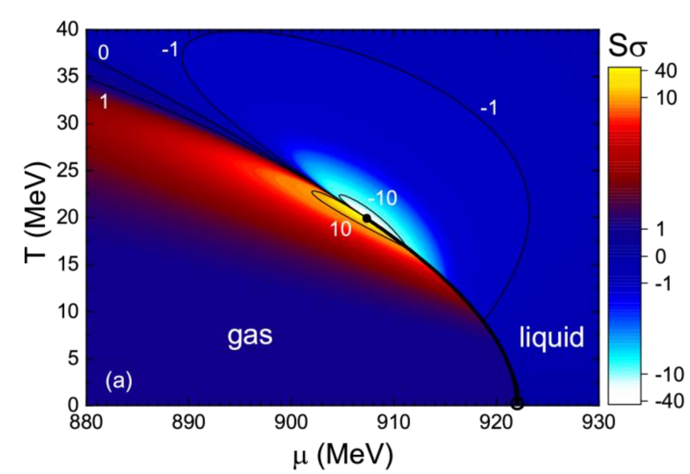


Vovchenko, Gorenstein, Stoecker, 1609.03975

Nuclear matter properties

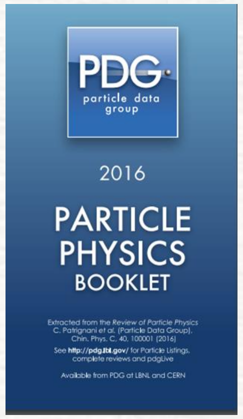
J. Pochodzalla et al., Phys.Rev.Lett. 75 (1995

V. Vovchenko et al., 1506.05763



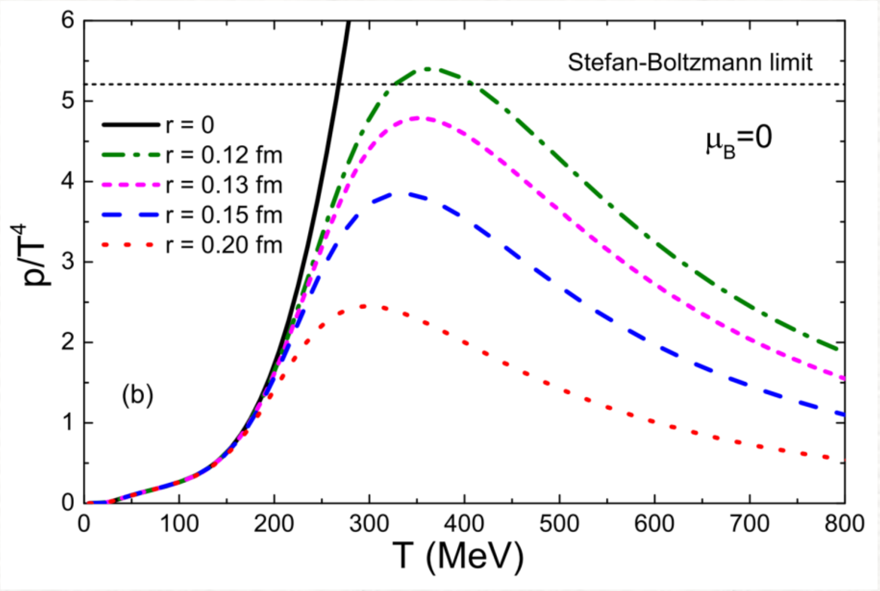
based on 1905.00866, A. Motornenko

Hadronic part: QCD matter at low densities



$$\rho_i = \frac{\rho_i^{\text{id}}(T, \mu_i^* - v_i\, p)}{1 + \sum_j v_j \rho_j^{\text{id}}(T, \mu_j^* - v_j\, p)}$$

$$\varepsilon_i = \frac{\varepsilon_i^{\text{id}}(T, \mu_i^* - v_i\, p)}{1 + \sum_j v_j \rho_j^{\text{id}}(T, \mu_j^* - v_j\, p)}$$



V. Vovchenko, D. Anchishkin, M. Gorenstein, 1412.5478

PDG list of known hadrons is included with Excluded Volume interactions.
EV suppress hadrons at high energy densities.

EV of baryons: 1 fm^3
EV of mesons: 1/8 fm^3

EV triggers the switch between hadron and quark degrees of freedom: **hadron** pressure is **suppressed** as function of T and μ_B — quarks are dominant at high densities.

SU(3)$_f$ octet and parity doubling: nuclear matter and lattice

We include all states of the **SU(3)$_f$** baryon octet:

$$\begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -2\frac{\Lambda}{\sqrt{6}} \end{pmatrix}$$

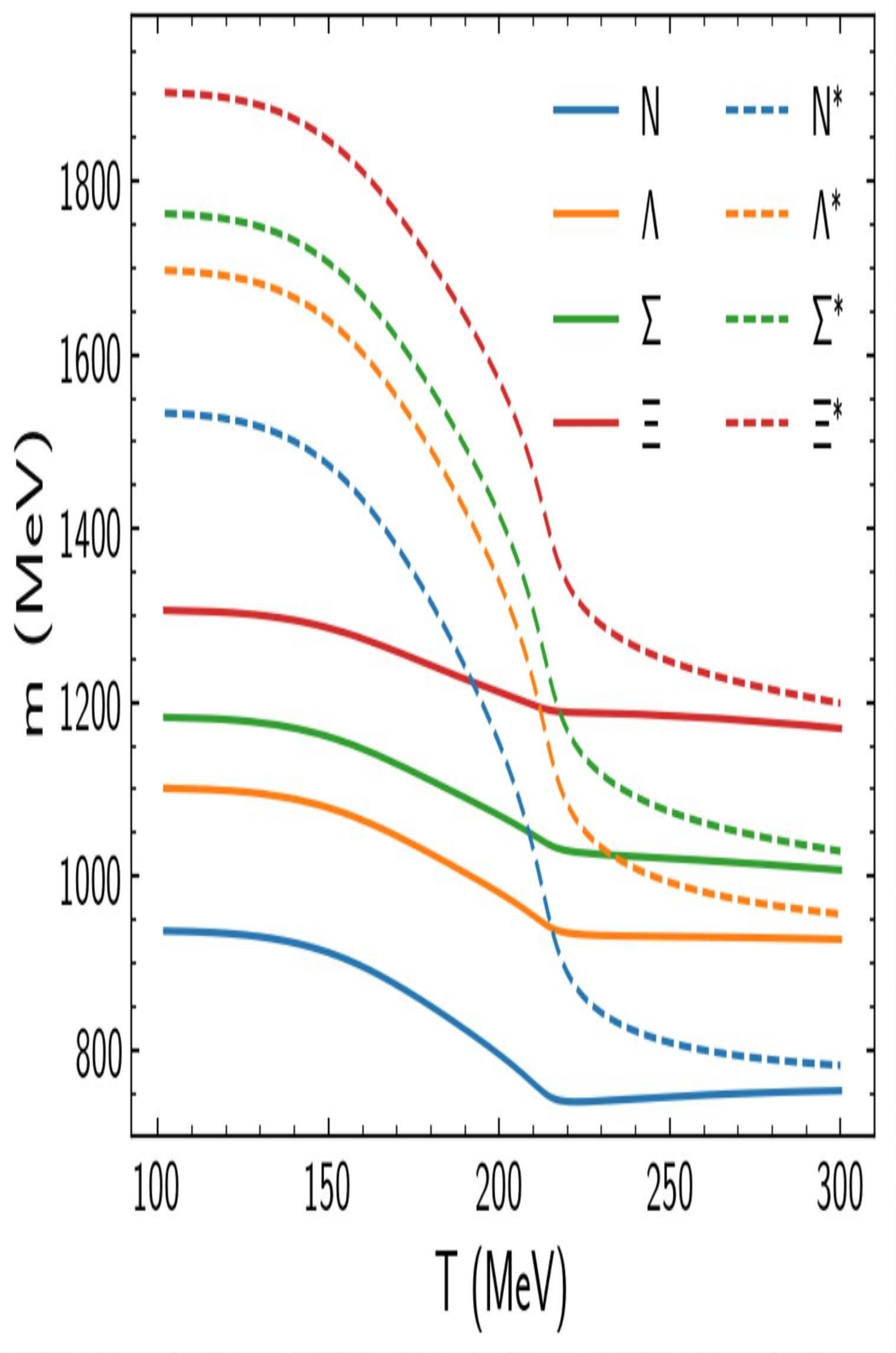
together with their **parity partners** *(G. Aarts et al., 1710.08294)*, i.e. states with the same quantum numbers but **opposite parity**. Those interact within SU(3)$_f$ σ model:

$$\mathcal{L}_B = \sum_i (\bar{B}_i i \partial\!\!\!/ B_i) + \sum_i \left(\bar{B}_i m_i^* B_i\right) + \sum_i \left(\bar{B}_i \gamma_\mu (g_{\omega i}\omega^\mu + g_{\rho i}\rho^\mu + g_{\phi i}\phi^\mu) B_i\right)$$

with effective masses generated by chiral fields **σ** and ***ζ***:

$$m_{i\pm}^* = \sqrt{\left[(g_{\sigma i}^{(1)}\sigma + g_{\zeta i}^{(1)}\zeta)^2 + (m_0 + n_s m_s)^2\right]} \pm g_{\sigma i}^{(2)}\sigma \pm g_{\zeta i}^{(2)}\zeta$$

'+' stands for positive and '−' for negative parity states



A. Motornenko

Including Quarks: PNJL-like approach

Quarks are included within **PNJL** inspired approach (*Fukushima, hep-ph/0310121*):

$$\Omega_q = -VT \sum_{i \in Q} \frac{d_i}{(2\pi)^3} \int d^3k \frac{1}{N_c} \Big[\ln \Big(1 + 3\Phi e^{-\left(E_i^* - \mu_i^*\right)/T} + 3\bar{\Phi} e^{-2\left(E_i^* - \mu_i^*\right)/T} + e^{-3\left(E_i^* - \mu_i^*\right)/T} \Big) + \ln \Big(1 + 3\bar{\Phi} e^{-\left(E_i^* + \mu_i^*\right)/T} + 3\Phi e^{-2\left(E_i^* + \mu_i^*\right)/T} + e^{-3\left(E_i^* + \mu_i^*\right)/T} \Big) \Big]$$

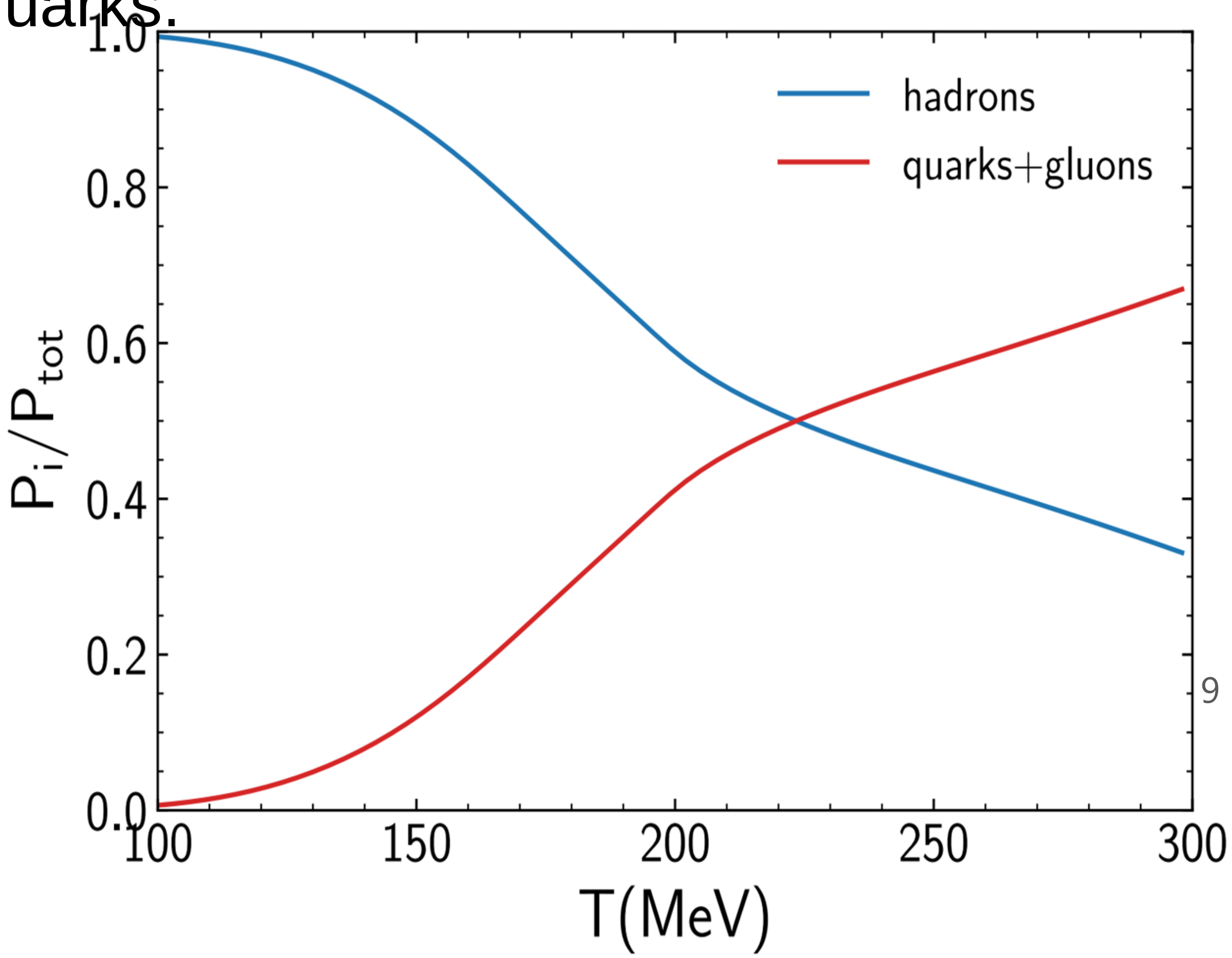
Polyakov loop Φ — is deconfinement order parameter:

Φ=0 — no quarks, **Φ=1** — free quarks.

Φ is controlled by the **potential U(Φ)**:

$$U = -\frac{1}{2}(a_0 T^4 + a_1 T_0 T^3 + a_2 T_0^2 T^2)\Phi\Phi^* + b_3 T_0^4 \log[1 - 6\Phi\Phi^* + 4(\Phi^3 + \Phi^{*3}) - 3(\Phi\Phi^*)^2]$$

Fukushima, hep-ph/0310121
Roessner, Ratti, Weise, hep-ph/0609281



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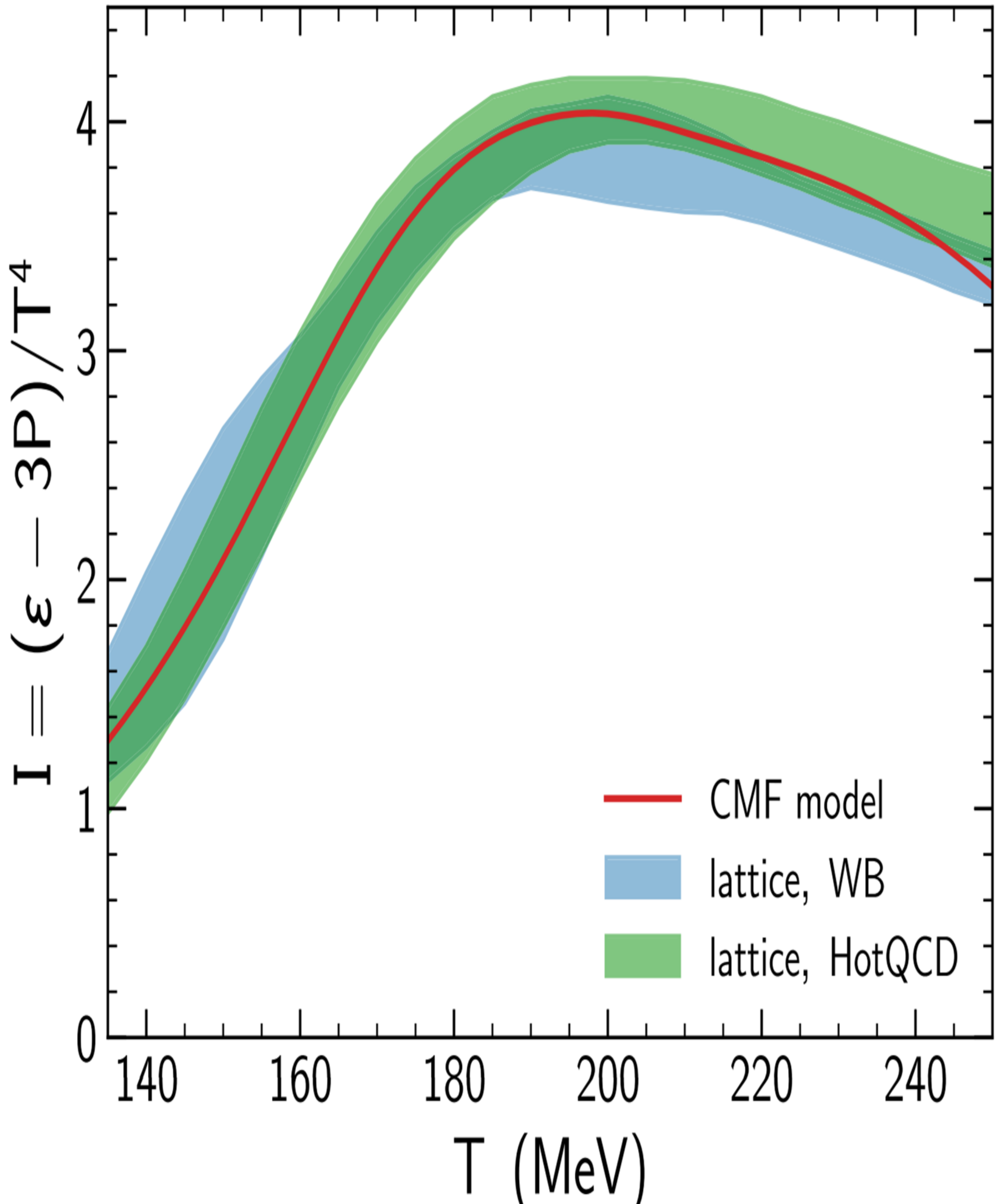
Chiral Mean Field description of QCD matter

- **Chiral SU(3) parity-doublet quark-hadron mean-field model** — unified phenomenological approach to model QCD thermodynamics at wide range of scales;
- μ_B=0 lattice QCD data is used to constrain parameters of model's quark sector;
- Nuclear liquid-vapor phase transition gives strong signals in fluctuations even at μ_B=0;
- Chiral symmetry restoration and transition to quark-dominated phase are at very high μ_B and/or T;
- Model produces neutron stars in agreement with modern constraints;
- Model's EoS can be used as an input for both finite T and T=0 neutron star physics
- … as well as for hydro simulations of heavy ions collisions.

Stefan Schramm: "That is most of what is known about QCD phenomenology"

The CMF model and lattice data



Wuppertal-Budapest collab., 1309.5258
HotQCD collab., 1407.6387

The Interaction measure ***I*** effectively measures rate of increase/decrease of degrees of freedom (N_{dof}~p/T^4) function of temperature (*Fukushima, 0804.3318*):

$$I = \frac{\varepsilon - 3p}{T^4} = T\frac{\partial}{\partial T}\left(\frac{p}{T}\frac{1}{T^3}\right)$$

I is an illustrative quantity for quark appearance.

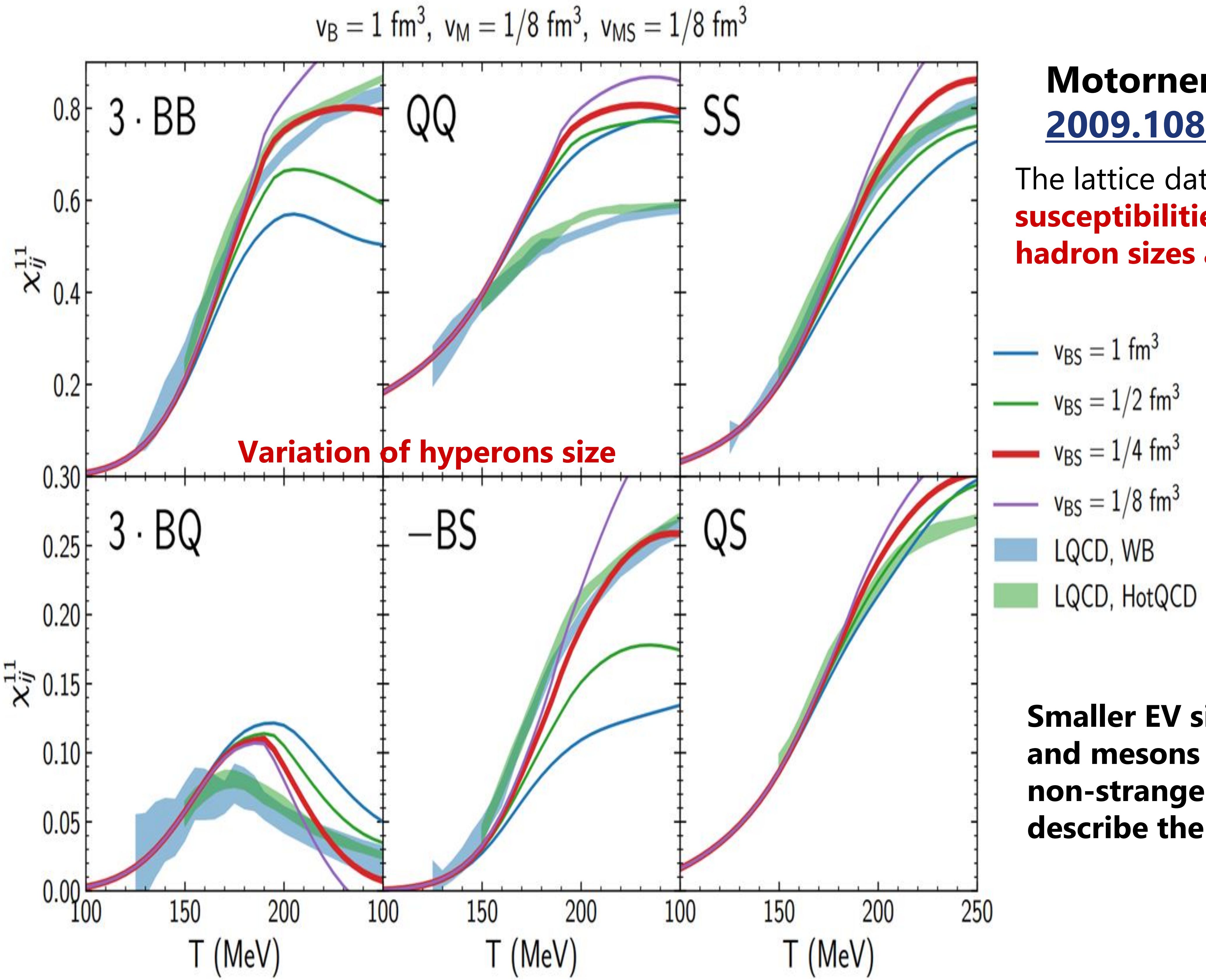
We reproduce ***I*** by fitting coefficients of Polyakov loop potential U(Φ) and quark couplings $g_{q\sigma}$ and $g_{q\zeta}$ to the chiral fields.

$$m_q^* = -g_{q\sigma}\sigma + \delta m_q + m_{0q},$$
$$m_s^* = -g_{s\zeta}\zeta + \delta m_s + m_{0q}$$

$$U = -\frac{1}{2}(a_0 T^4 + a_1 T_0 T^3 + a_2 T_0^2 T^2)\Phi\Phi^* + b_3 T_0^4 \log[1 - 6\Phi\Phi^* + 4(\Phi^3 + \Phi^{*3}) - 3(\Phi\Phi^*)^2]$$

based on 1905.00866, A. Motornenko

The CMF model and lattice data, hadron sizes



Motornenko *et al.*, 2009.10848

The lattice data on second order **susceptibilities are sensitive to hadron sizes at T>T_{pc}**

$$\chi_{ij}^{11} = \frac{\partial P/T^4}{\partial \mu_i \partial \mu_j}$$

We followed ideas of Alba *et al.* 1606.06542 and Vovchenko et al. 1707.09215 of **flavor-dependent EV** interactions, but in quark-hadron model.

Smaller EV sizes of hyperons and mesons as compared to non-strange baryons help to describe the lattice data.

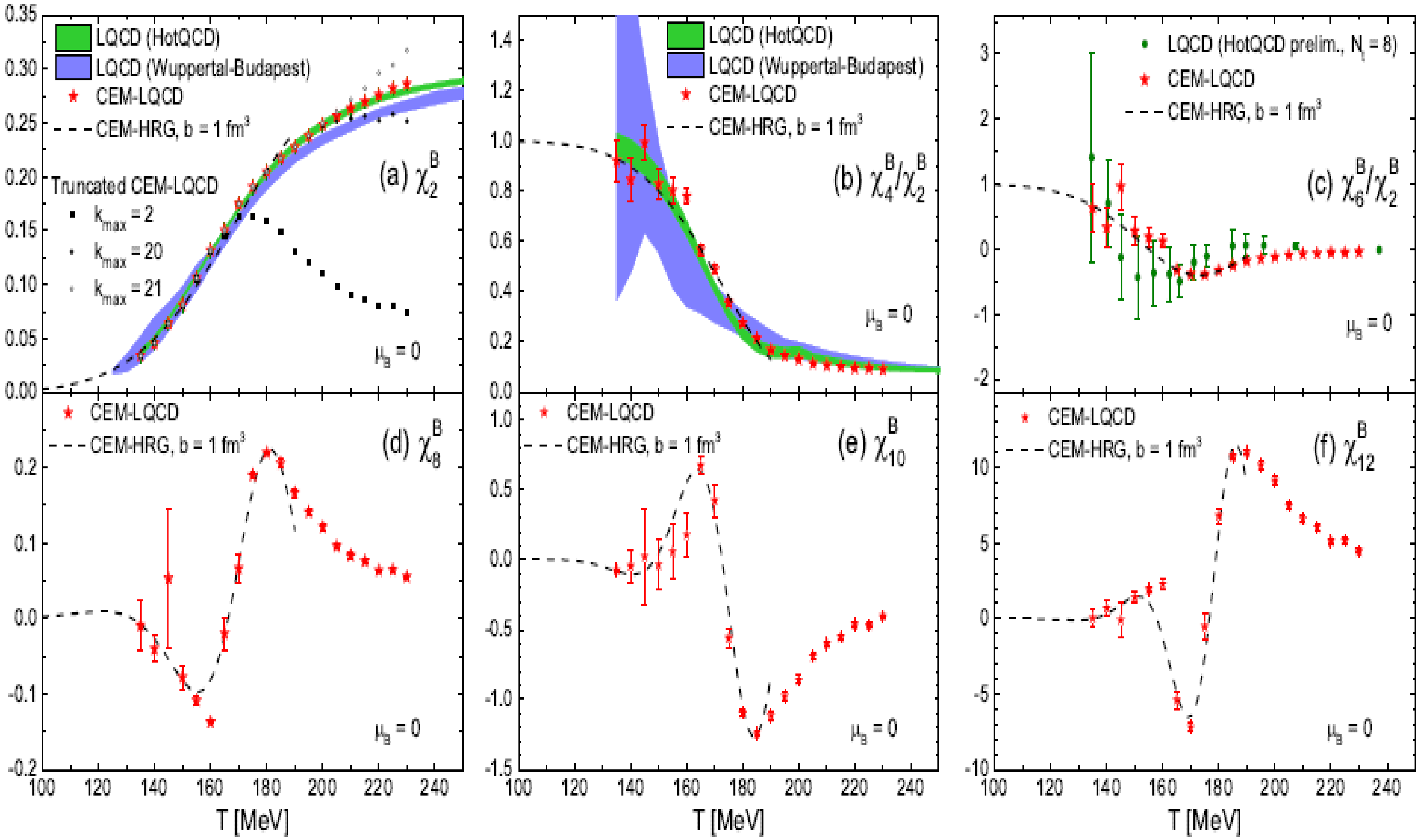
based on 1905.00866, A. Motornenko

Wuppertal-Budapest, 1112.4416
HotQCD, 1203.0784

Expansions in imaginary chemical potential

Using only the Fourier coefficients b_k from imaginary μ_B simulations as input:

- One can write the density of QCD as a cluster expansion:
- $\frac{\rho_B}{T^3} = \frac{\partial(p/T^4)}{\partial(\mu_B/T)} = \sum_{k=1}^{\infty} b_k(T) \sinh\left(\frac{k\,\mu_B}{T}\right)$
- Assuming the proper SB limit and using only the first two coefficients on can exactly predict finite μ_B thermodynamics
- $b_k(T) = \alpha_k \frac{[b_2(T)]^{k-1}}{[b_1(T)]^{k-2}}$. Use these to calculate χ^n.



Results on the applicability

Radius of convergence: $\mu_B/T < \pi$

V. Vovchenko, **JS** , O. Philipsen and H. Stoecker, Phys. Rev. D **97**, no.11, 114030 (2018)

Beyond the lattice data

The lattice QCD calculations allow to go beyond the $\mu_B = 0$ by using Taylor expansion which involves conserved charge susceptibilities χ: (Allton *et al.* hep-lat/0204010)

$$P = P_0 + T^4 \sum_{i,j,k} \frac{1}{i!j!k!} \chi^{i,j,k}_{B,Q,S} \left(\frac{\mu_B}{T}\right)^i \left(\frac{\mu_Q}{T}\right)^j \left(\frac{\mu_S}{T}\right)^k$$

$$\chi^{i,j,k}_{B,Q,S} = \frac{\partial^i \partial^j \partial^k P(T, \mu_B, \mu_Q, \mu_S)/T^4}{\partial\left(\mu_B/T\right)^i \partial\left(\mu_Q/T\right)^j \partial\left(\mu_S/T\right)^k}$$

Radius of convergence — distance to the closest singularity of ***P/T⁴*** in the **complex μ_B/T plane**, could be QCD critical point.

One singularity is known at

$\mu_B/T = i\pi$

Roberge-Weiss transition

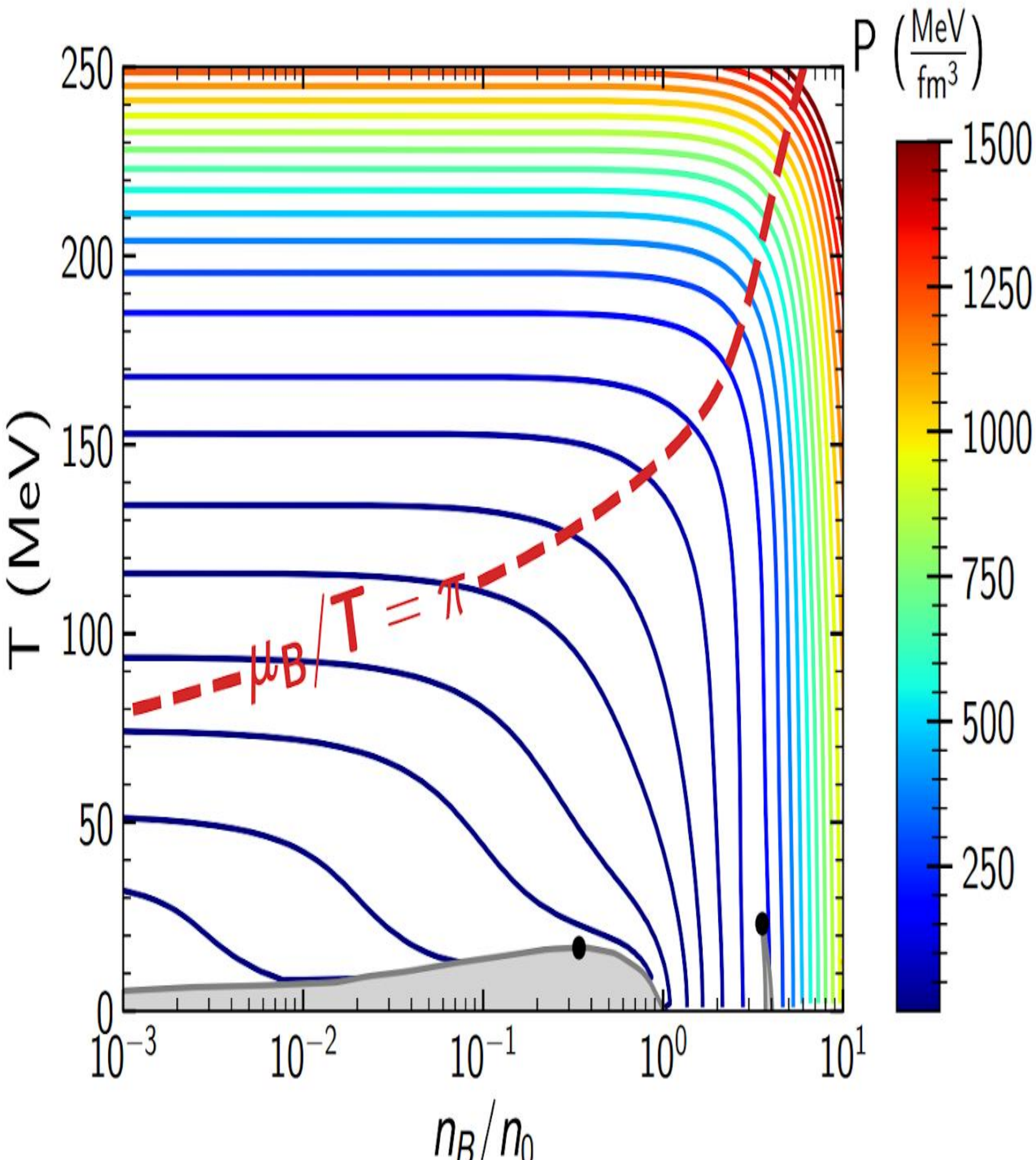
(Roberge, Weiss, *Nucl.Phys.B 275 (1986) 734-745*)

However, estimates suggest $R_{\mu B/T} \approx 2\text{-}3$

(Bazavov *et al.* 1701.04325,

Vovchenko *et al.* 1711.01261,

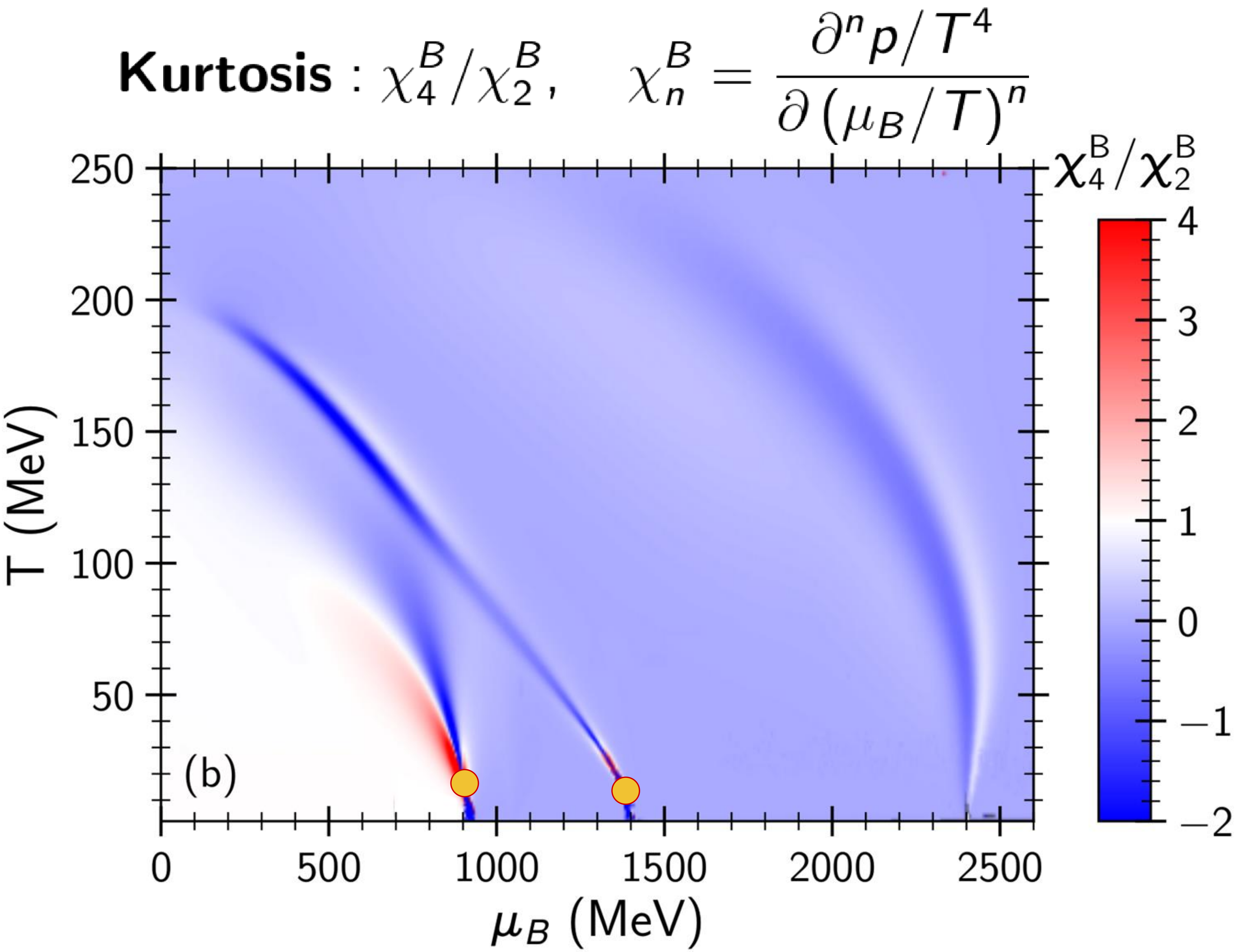
Giordano *et al.* 1911.00043)



Lines of constant pressure. The grey shaded regions: mixed phases by nuclear liquid-vapor and chiral phase transitions. Black dots — critical endpoints.

based on 1905.00866, A. Motornenko

The CMF phase diagram



- Remnants of the well established nuclear liquid-vapor transition visible at μ_B=0
- Chiral transition does not change the baseline in kurtosis
- Third transition is always a crossover, transition from quark-hadron mixture
- to **quark matter**

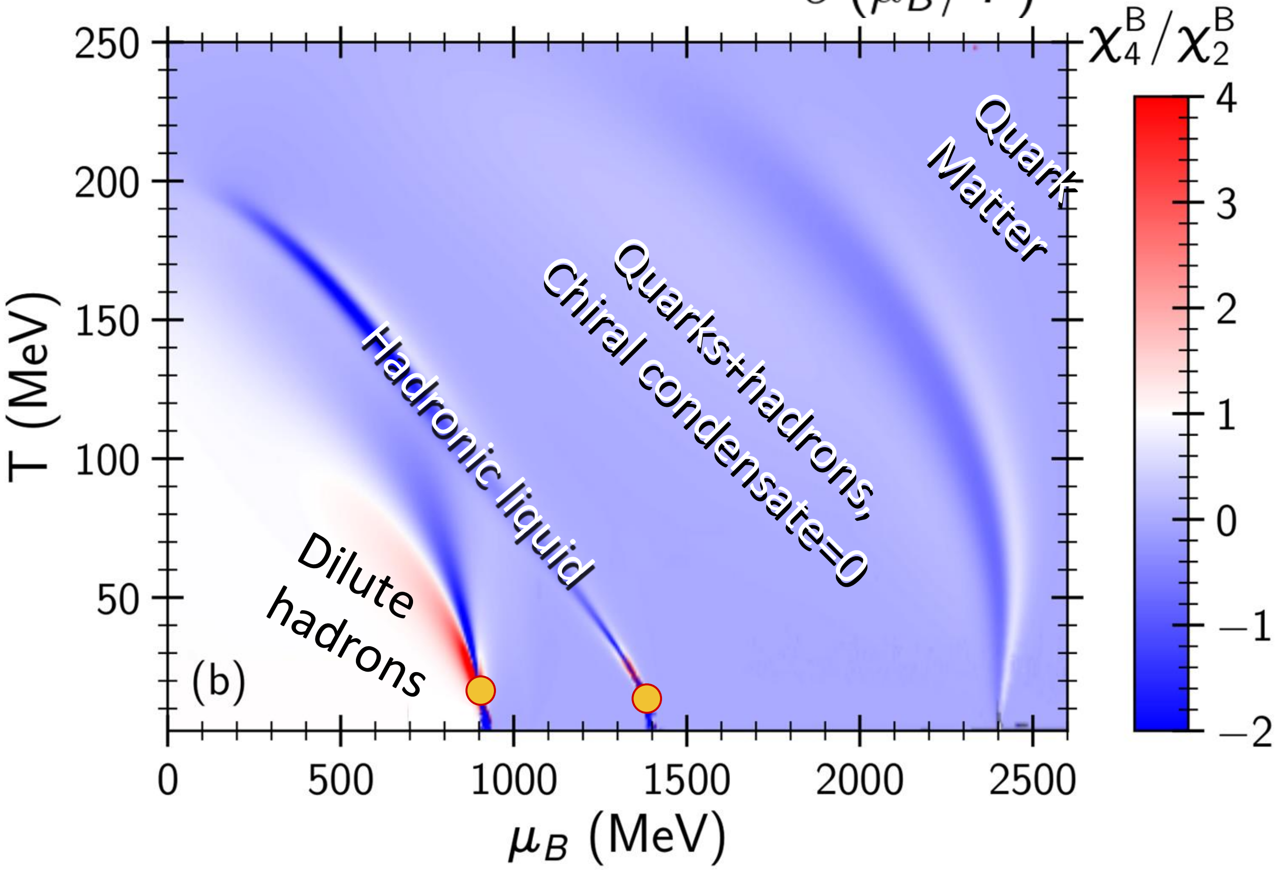
3 transitions: hadron gas ➜ hadronic liquid ➜ chiral symmetry restoration ➜ quark matte

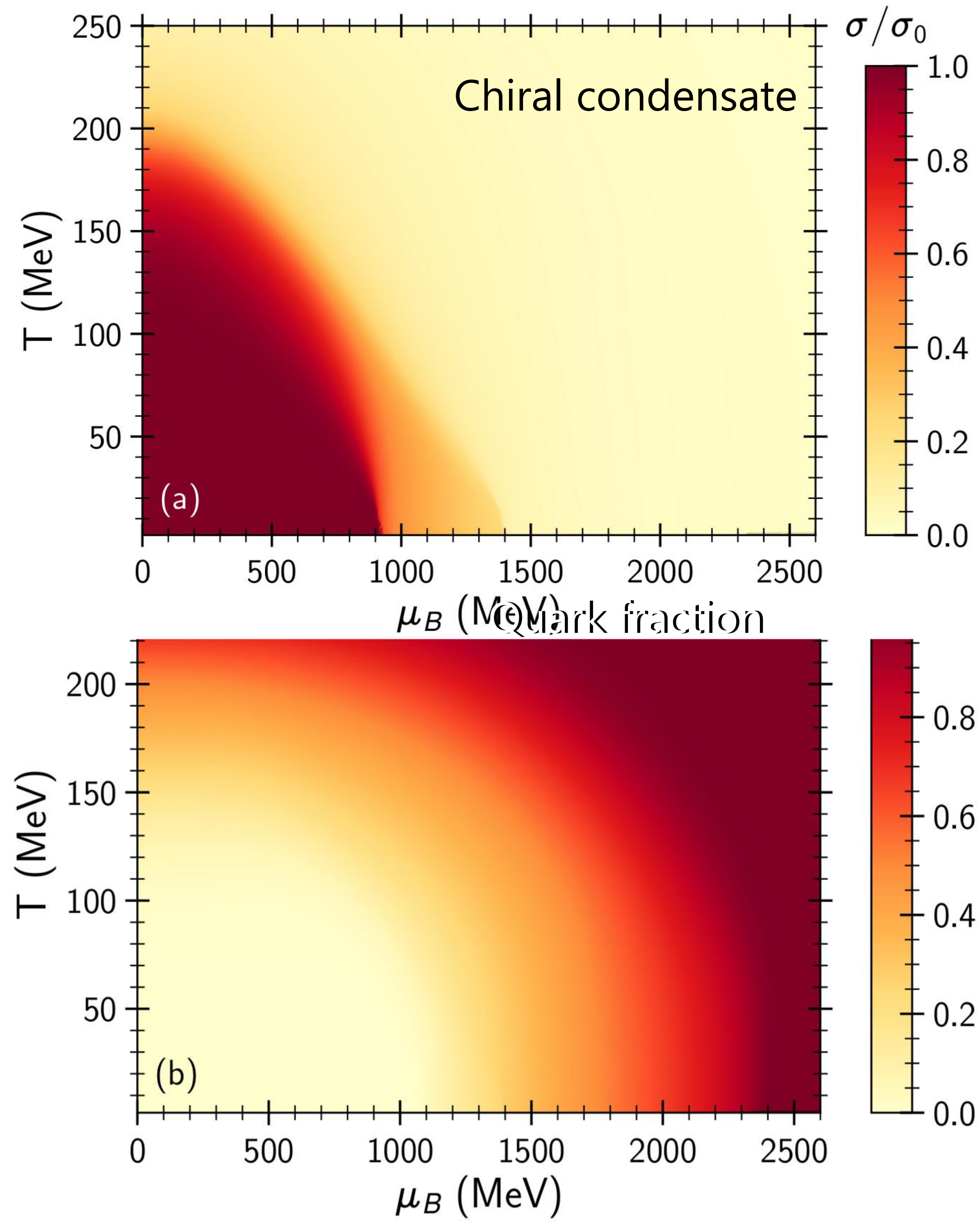
2 critical points: nuclear CP $T_{CP}\approx$ 17 MeV, chiral CP $T_{CP}\approx$ 17 MeV

based on 1905.00866, A. Motornenko

The CMF phase diagram

Kurtosis : χ_4^B/χ_2^B, $\quad \chi_n^B = \frac{\partial^n p/T^4}{\partial(\mu_B/T)^n}$





Three transitions:

hadron gas ➜ hadronic liquid ➜ chiral symmetry restoration ➜ quark matter

Two critical points: nuclear CP T_{CP}≈ 17 MeV, chiral CP T_{CP}≈ 17 MeV

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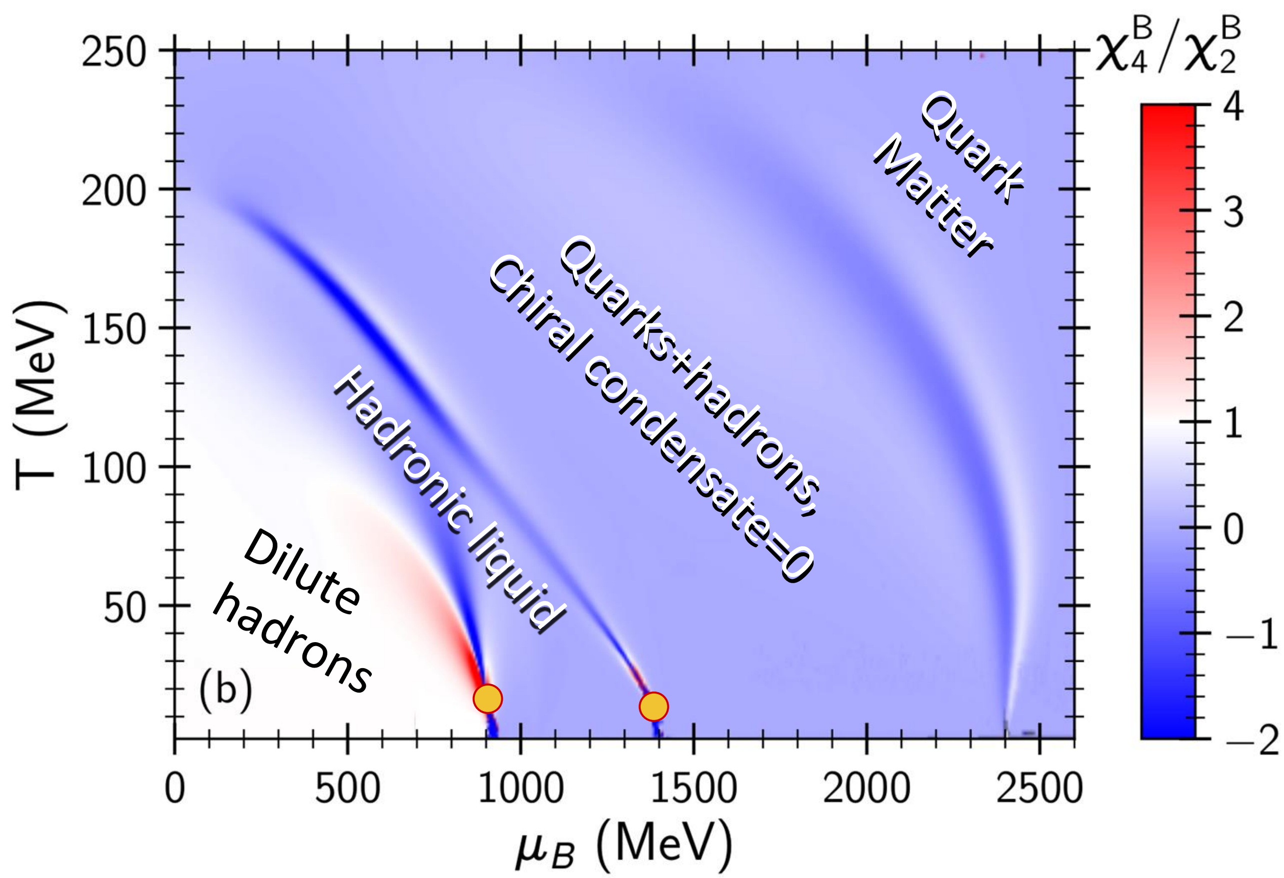
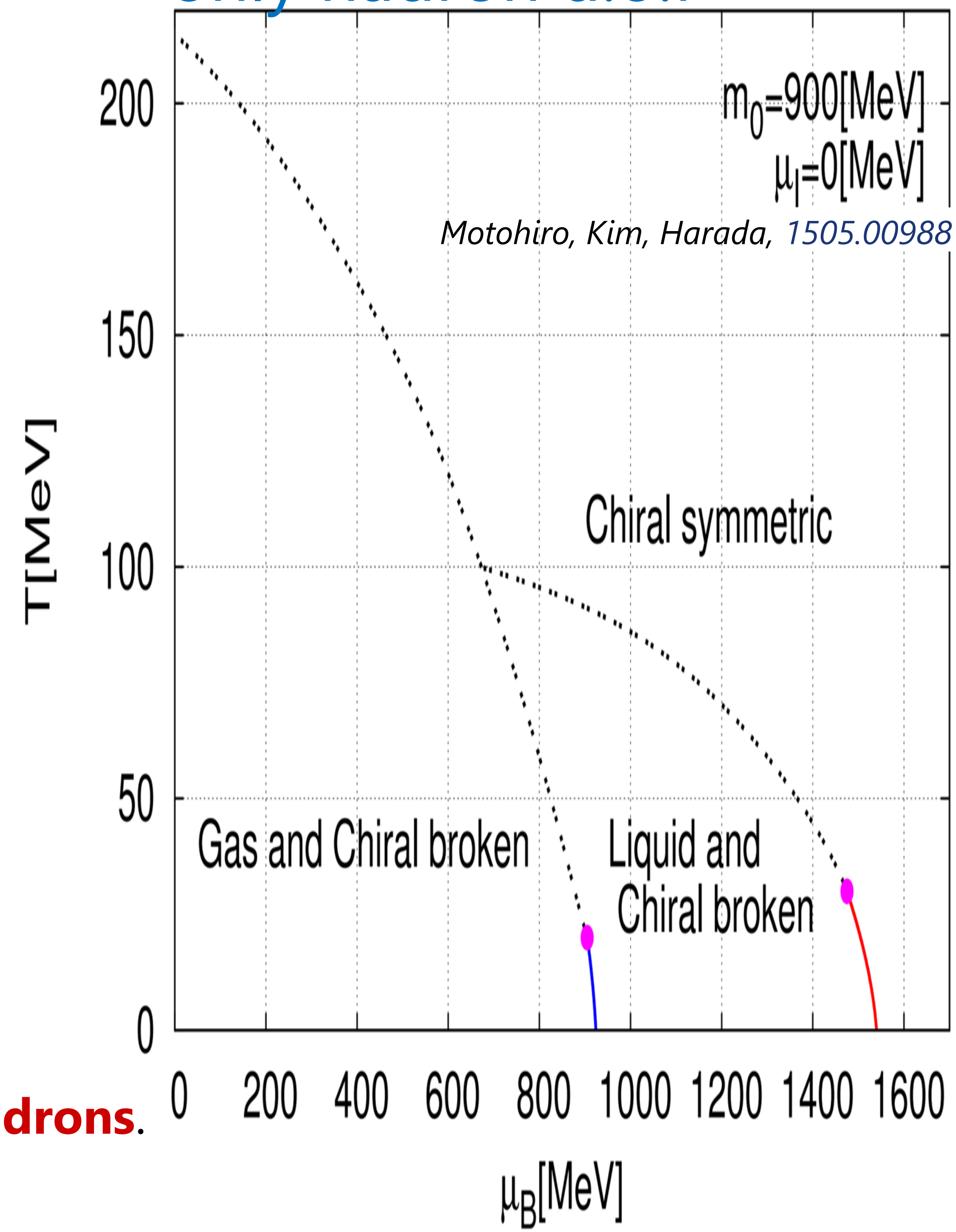
The CMF phase diagram



Parity doublet model with only hadron d.o.f



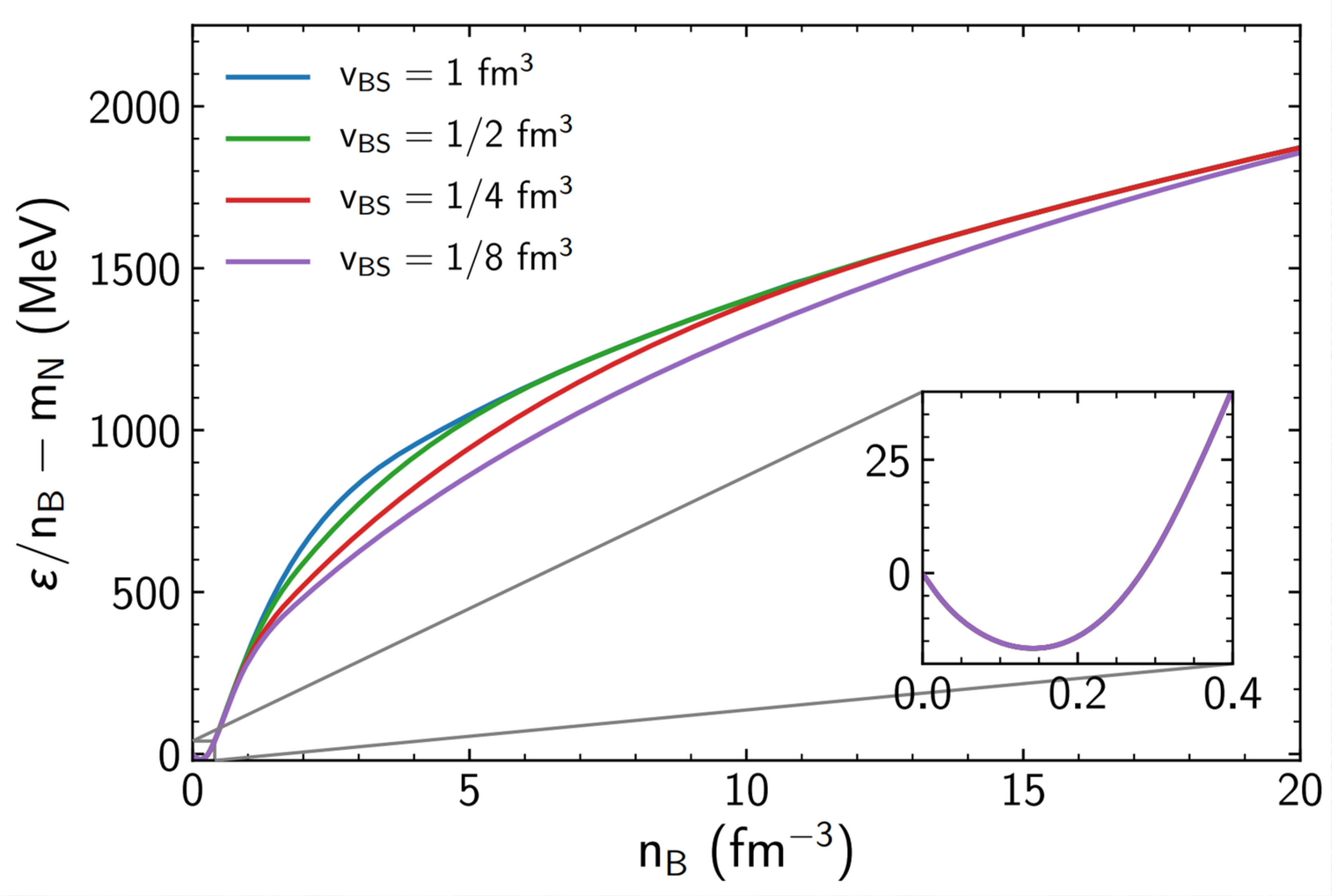
The phase transitions are only driven by **hadrons**.

Deconfinement is always smooth.

based on 1905.00866**, A. Motornenko**

Properties of cold matter

T=0 isospin symmetric mater.



Nuclear ground state is not affected — good.

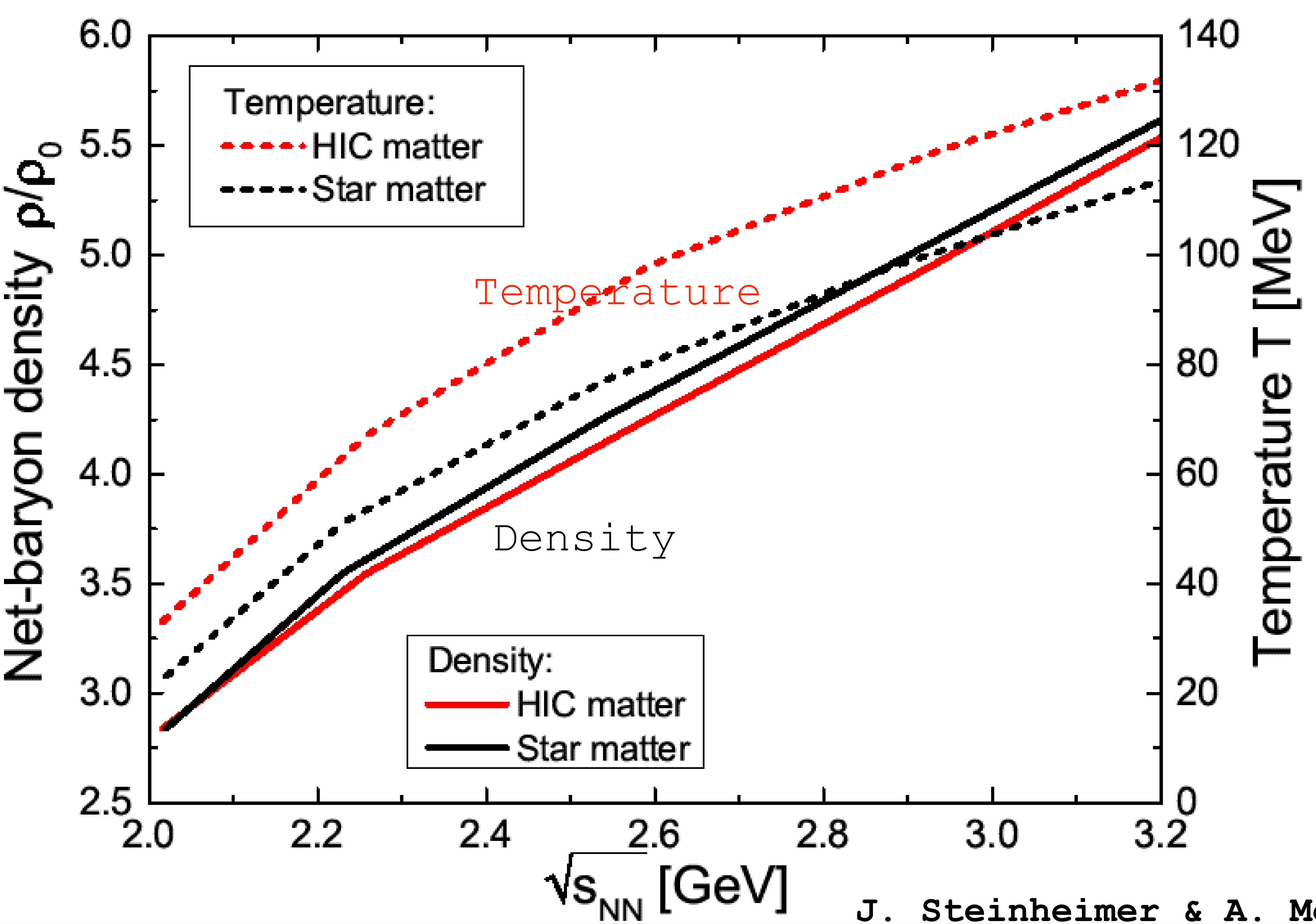
Then at higher densities hyperons start to populate CMF matter — the EOS softens.
Then at extreme densities quarks kick in, hadrons are suppressed.

The appearance of hyperons do produce additional (meta) stable state. Probably additional attraction is needed.

A. Motornenko

Neutron Star merger vs. heavy ion collisions: Baryon *Densities and Temperatures*

+ initialize by Relativistic Rankine Hugoniot Taub Adiabat with Relativistic CMF- EoS



Compare central heavy ion collisions

with head-on neutron star collisions:

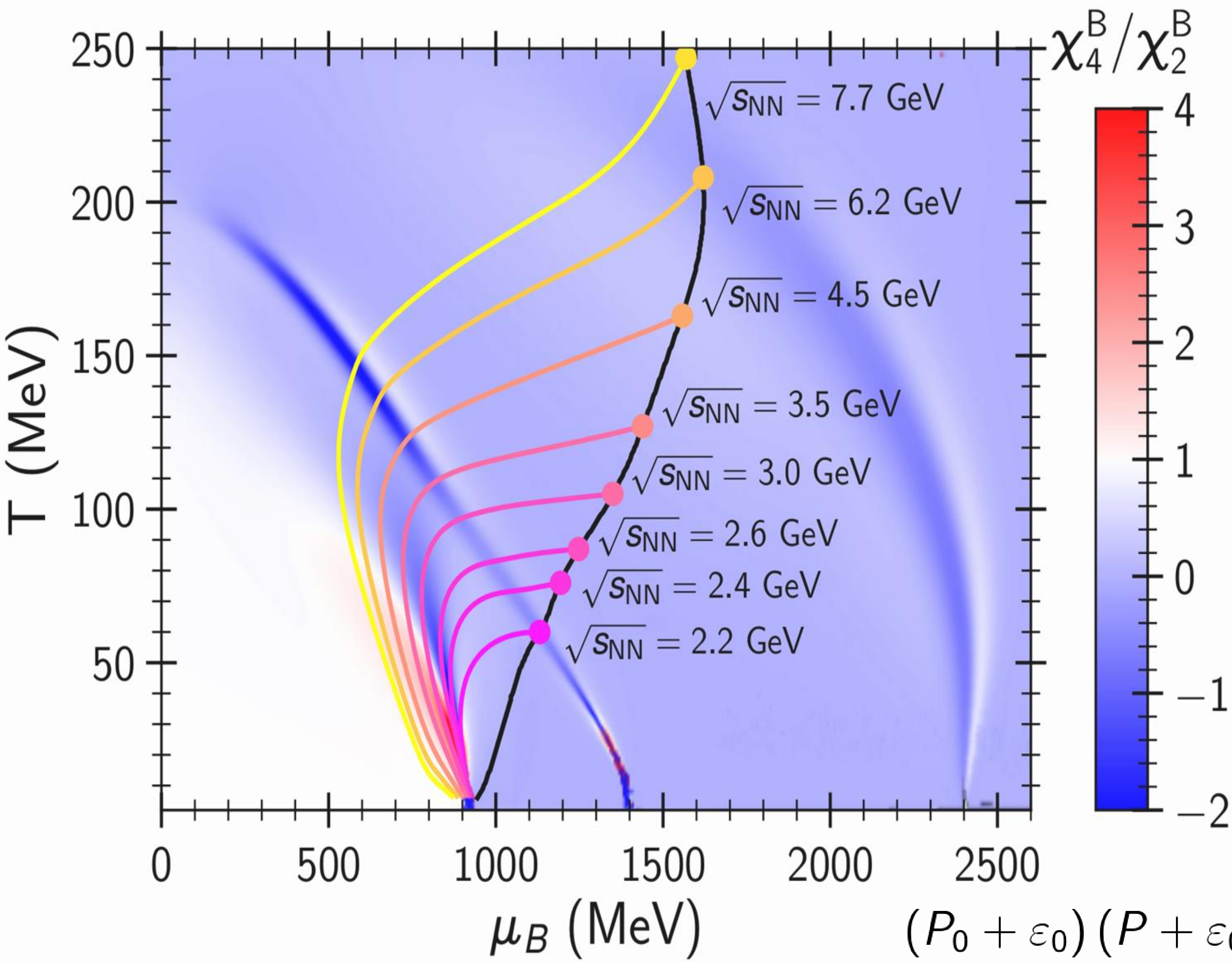
Rankine Hugoniot Taub Adiabate

conserve baryon number and energy momentum current densities across shock front yields stationon.1+1D, hydrodynamical equation for n, p vs E:

E^2 -E_0^2=(p-p0)(E/n- E0/n0)

J. Steinheimer & A. Motornenko

Probing the phase diagram by heavy ions



Hydrodynamical evolution of the **hot central region in heavy ion collision** can be calculated as isentropic expansion (S/A = const, no dissipations).

Initial entropy per baryon S/A is estimated by the relativistic Rankine-Hugoinot-Taub adiaibat (shock wave solution) *A. H. Taub, Phys. Rev. 74, 328 (1948)*

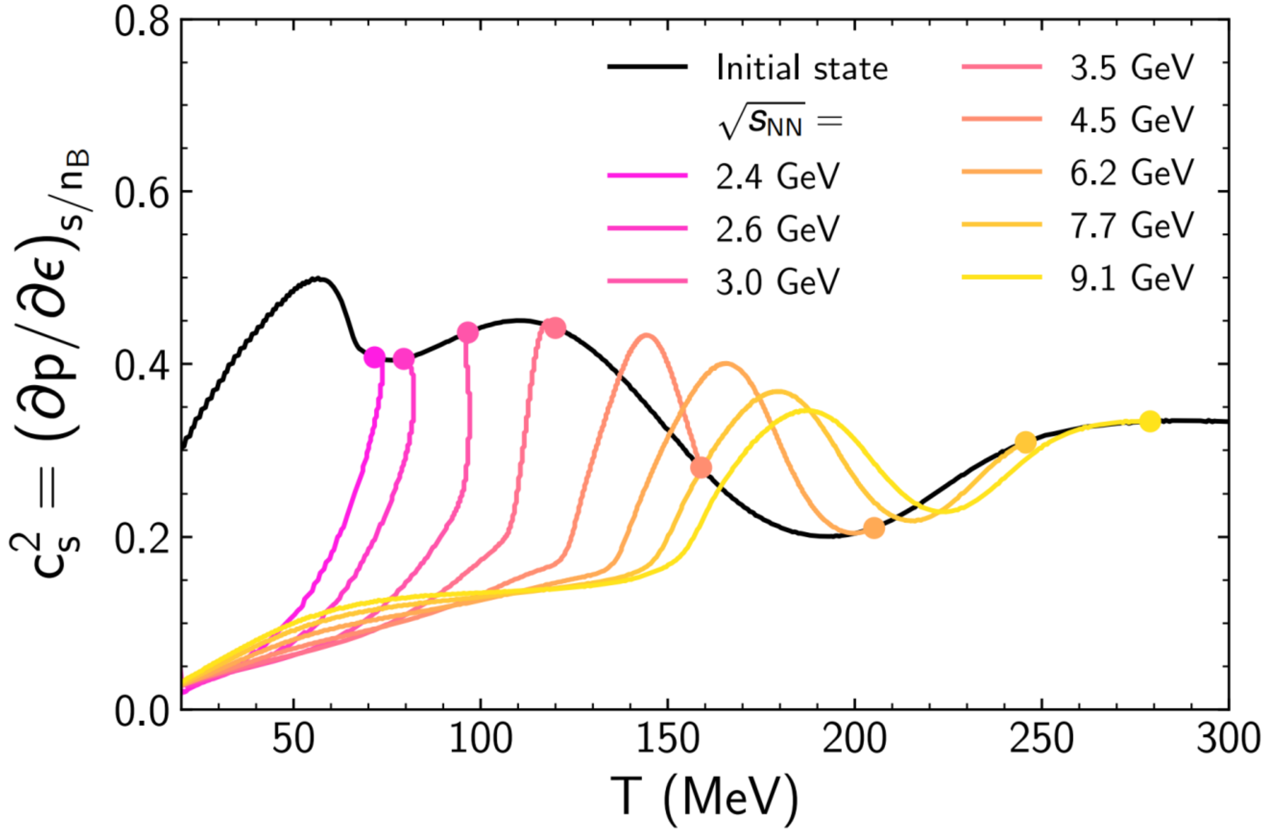
$$(P_0 + \varepsilon_0)\,(P + \varepsilon_0)\, n^2 = (P_0 + \varepsilon)\,(P + \varepsilon)\, n_0^2$$

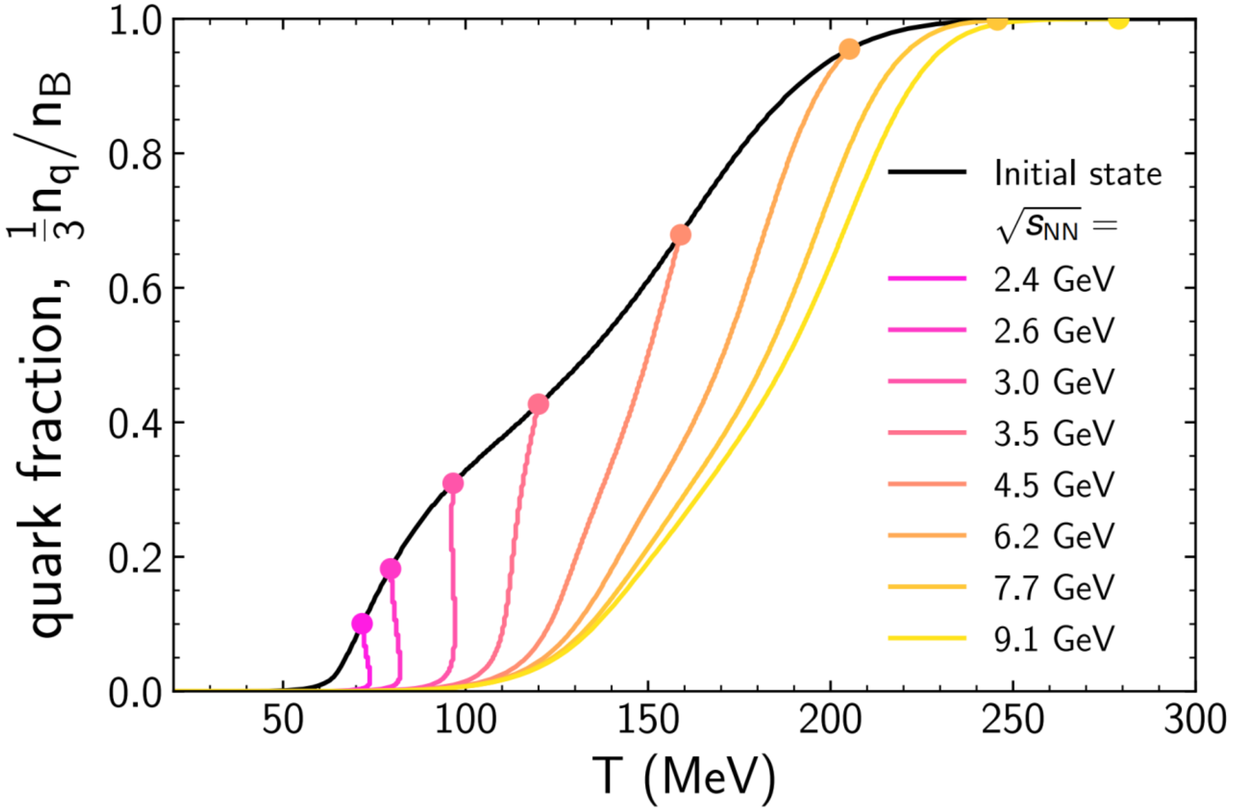
with the initial condition

$$P_0 = 0,\;\; \varepsilon_0/n_0 - m_N = -16\,\text{MeV and } n_0 = 0.16\,\text{fm}^{-3}$$

based on 1905.00866, A. Motornenko

Probing phase diagram by heavy ions collisions





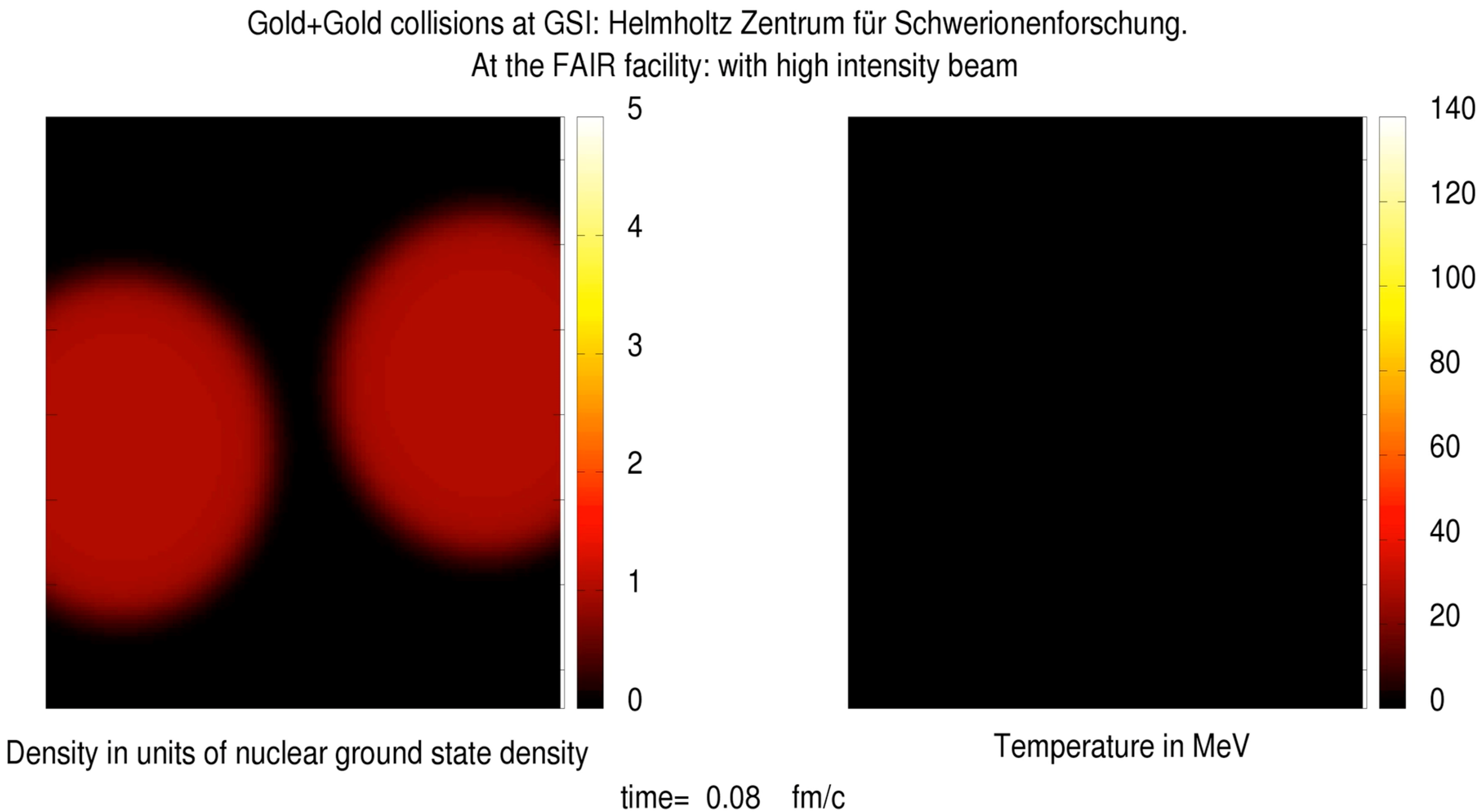
speed of sound c_s^2 (**left**) and **quark fraction** (**right**) along the **isentropes** as functions of temperature T.

Colored lines = different collision energies (initial S/A), black solid line correspond to the initial state speed of sound and quark fraction respectively.

Scenario for higher energy $\sqrt{s_{NN}} > 7$ GeV:

1. start at the quark phase
2. softest point of deconfinement
3. baryons rapidly appear providing repulsion and increase of c_S^2
4. transition to dilute hadronic phase and lowering of c_S^2

Relativistic 4D Hydrodynamics for Heavy Ion Collisions@FAIR

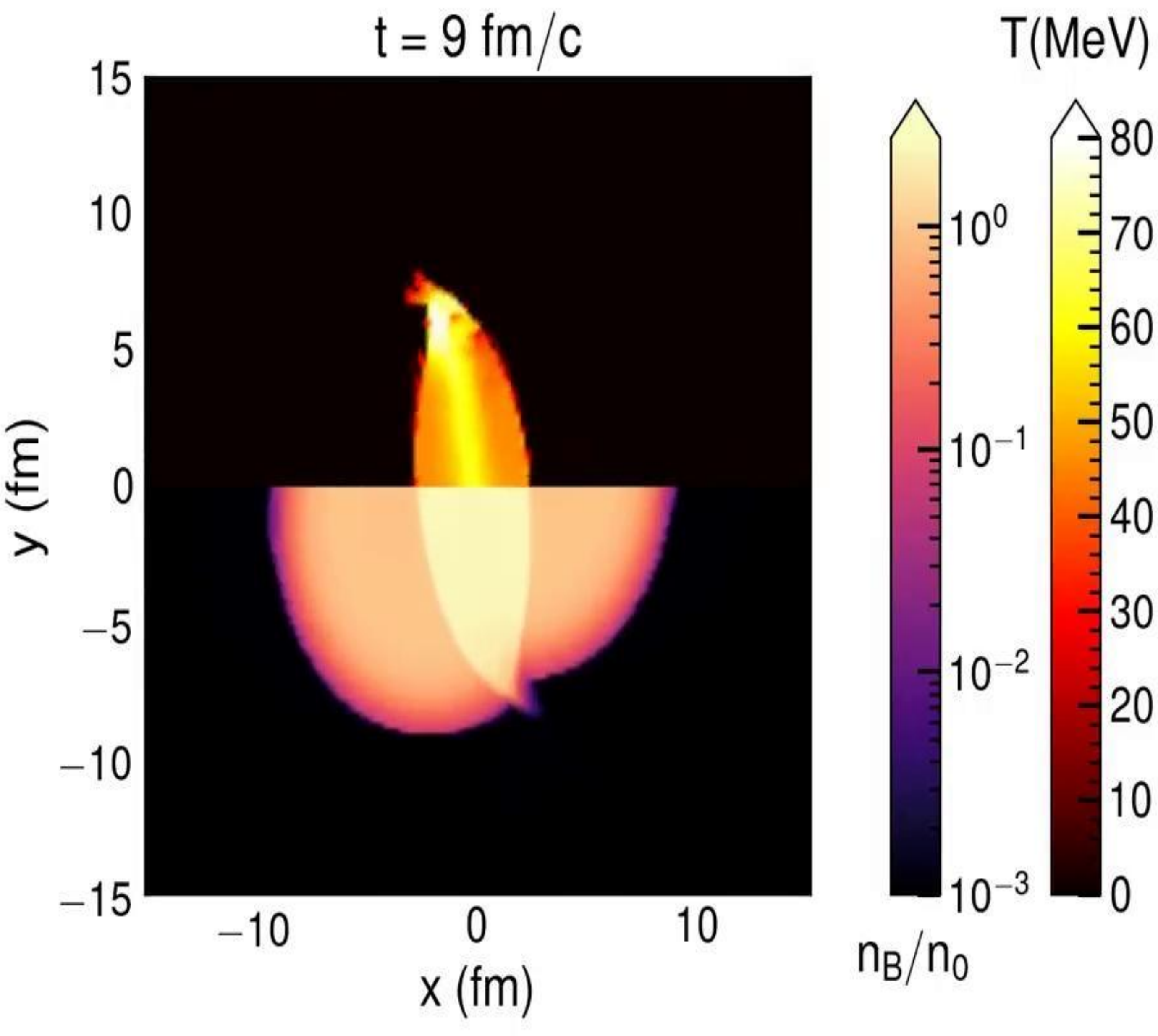


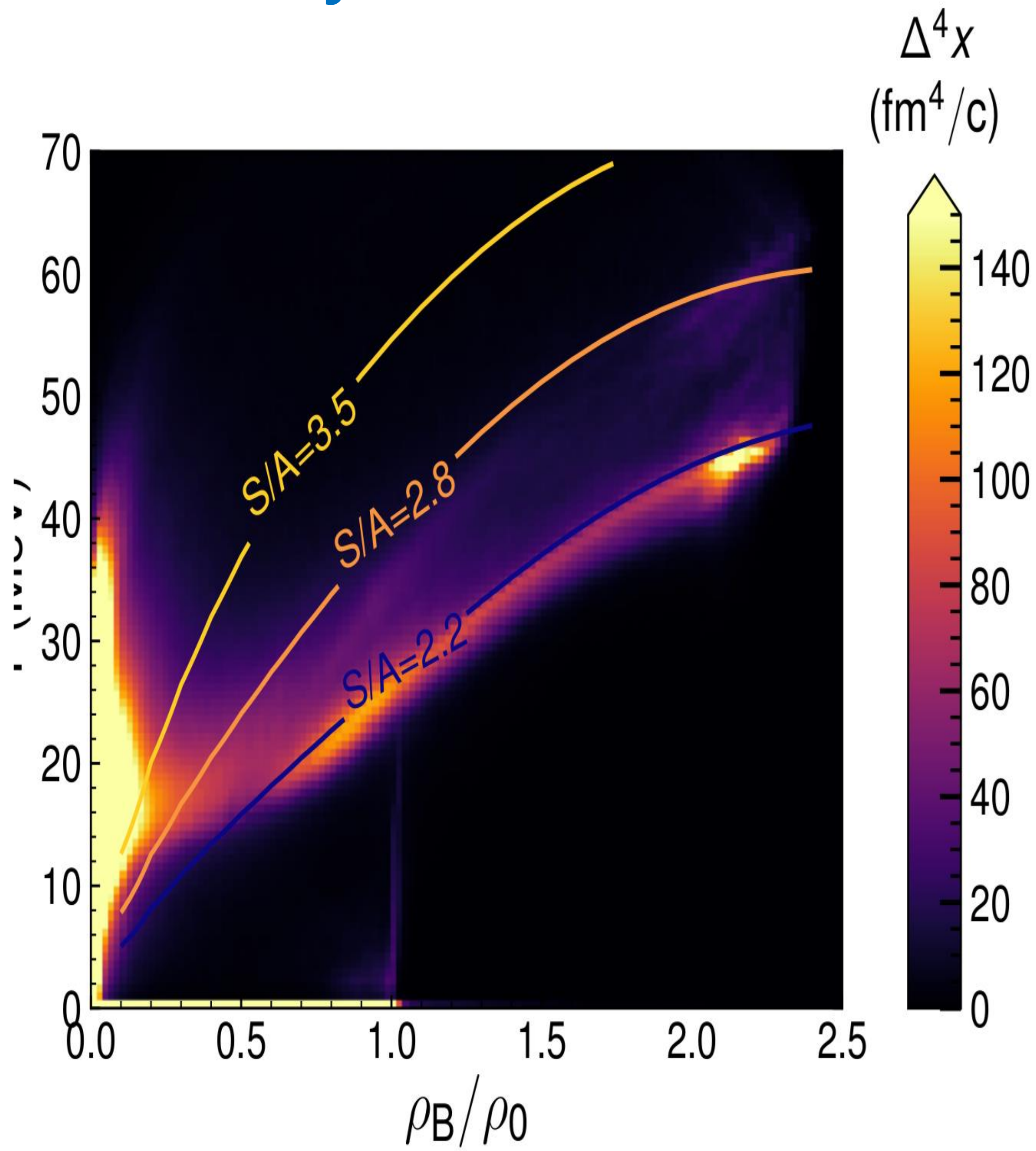
Jan Steinheimer , FIAS Frankfurt
Special Relativistic 3+1Dim Hydrodynamics for HIC ’80-/’90-ies :
G.Graebner, D.Rischke, et al., ITP, Goethe University

Probing the QCD- phase diagram by heavy ions

Full 3+1Dim relativistic hydrodynamic simulation of heavy ion collision at GSI - HADES energies, E_{lab}=600 AMeV

With CMF - a realistic high density EOS for Heavy Ion collisions



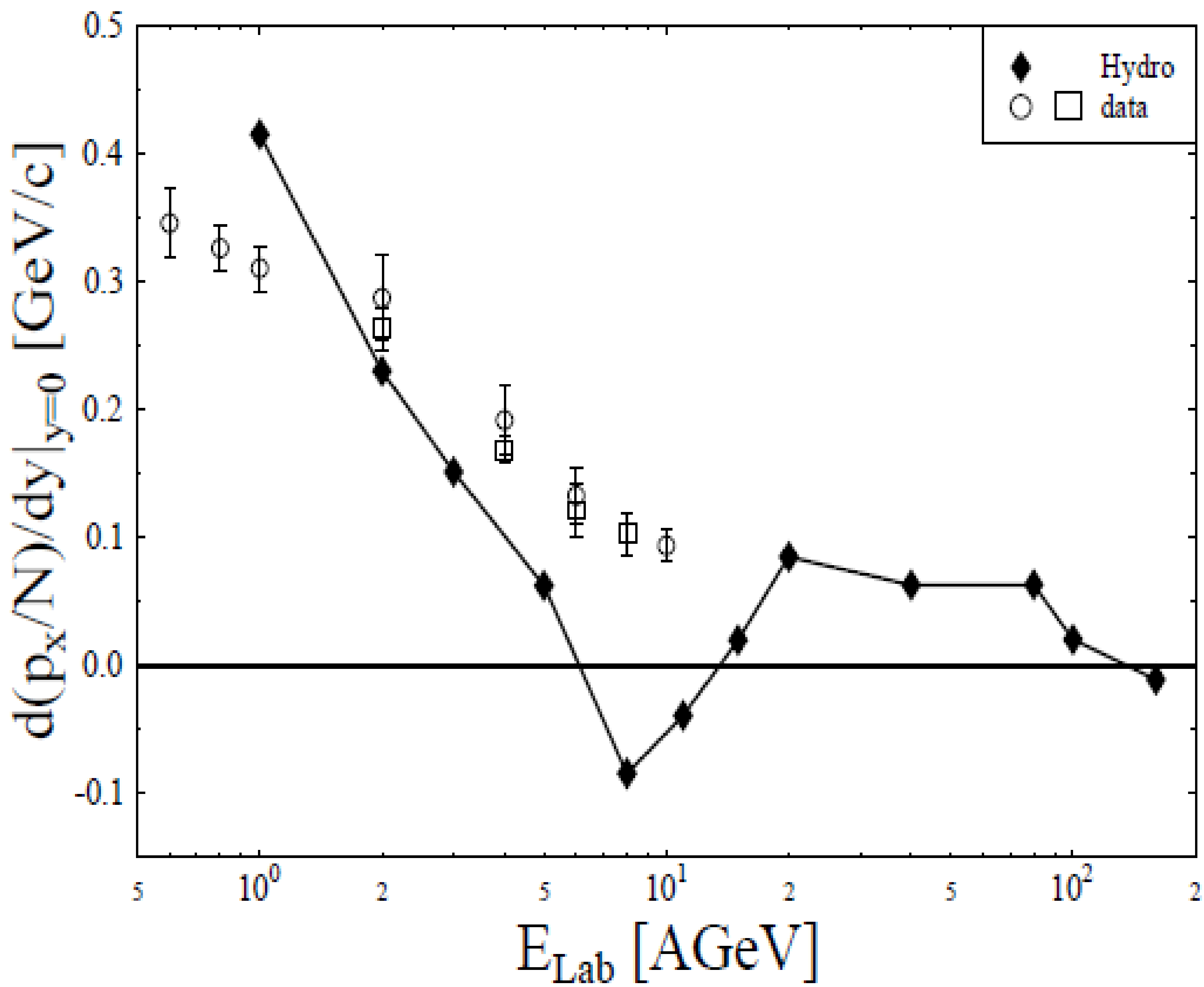


based on 1905.00866, A. Motornenko

Some results

What is directed flow?

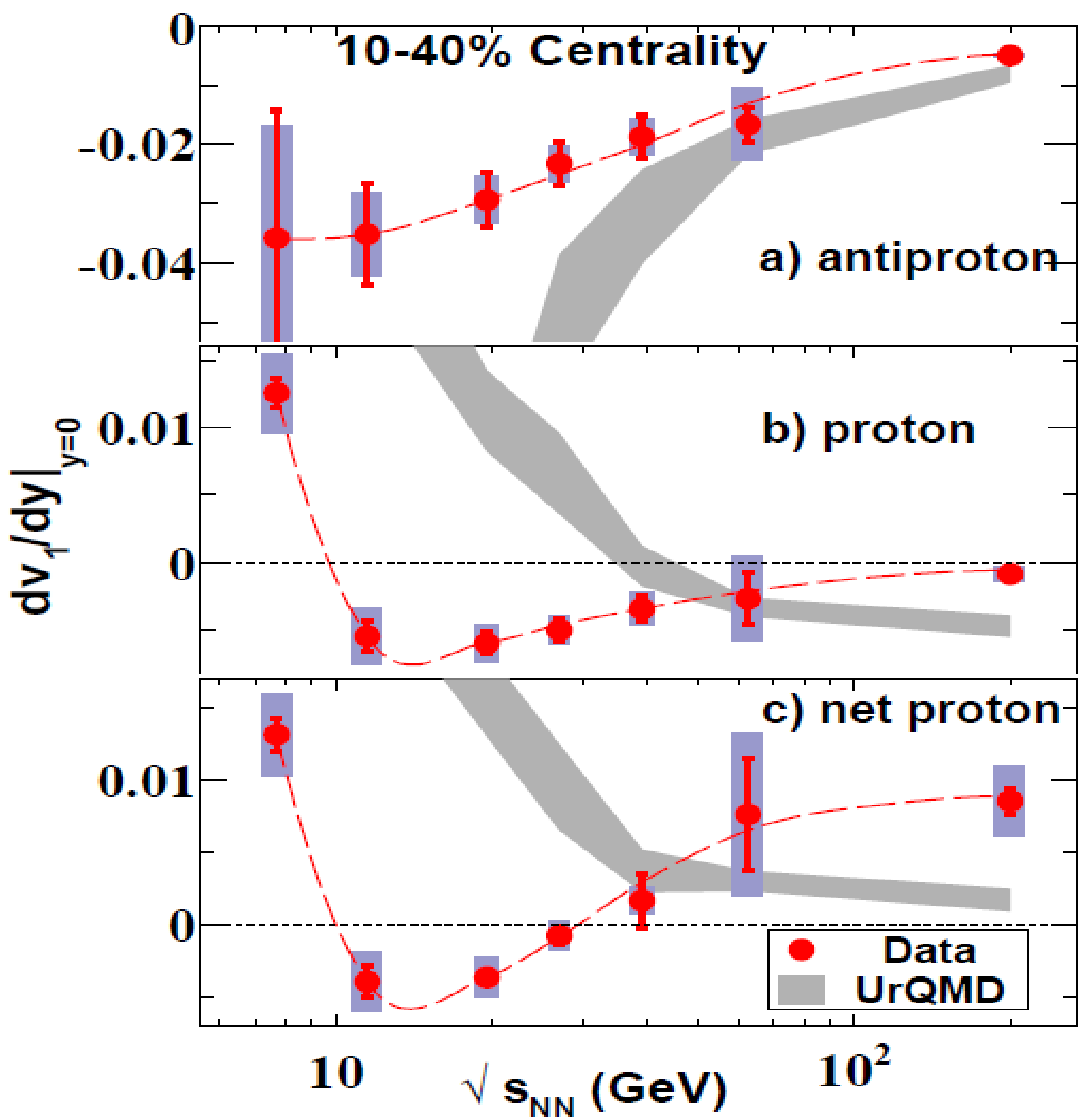
One is interested in the slope of $v_1 = \langle p_x/p_T \rangle (y)$ w.r.t the rapidity.



K. Paech, M. Reiter, A. Dumitru, H. Stoecker and W. Greiner, Nucl. Phy
681, 41 (2001)

a strong effect from the softening of the EoS is observed

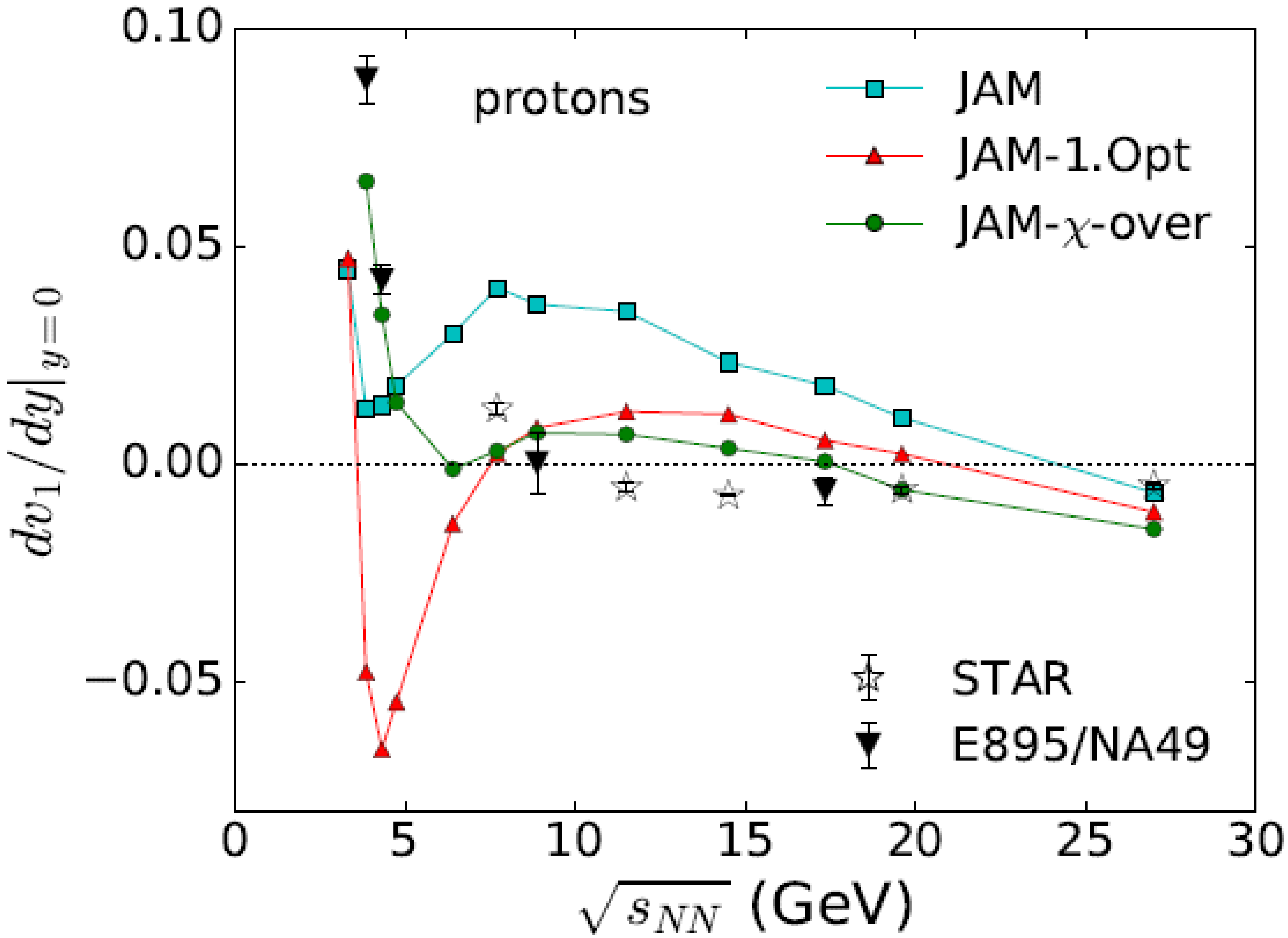
- Resent STAR measurements show a negative slope of net proton v_1.



L. Adamczyk et al. [STAR Collaboration], Phys. Rev. Lett. 112, 162301

Microscopic Transport with EoS

If a fully microscopic transport simulation with EoS (JAM) is used the effect persists.



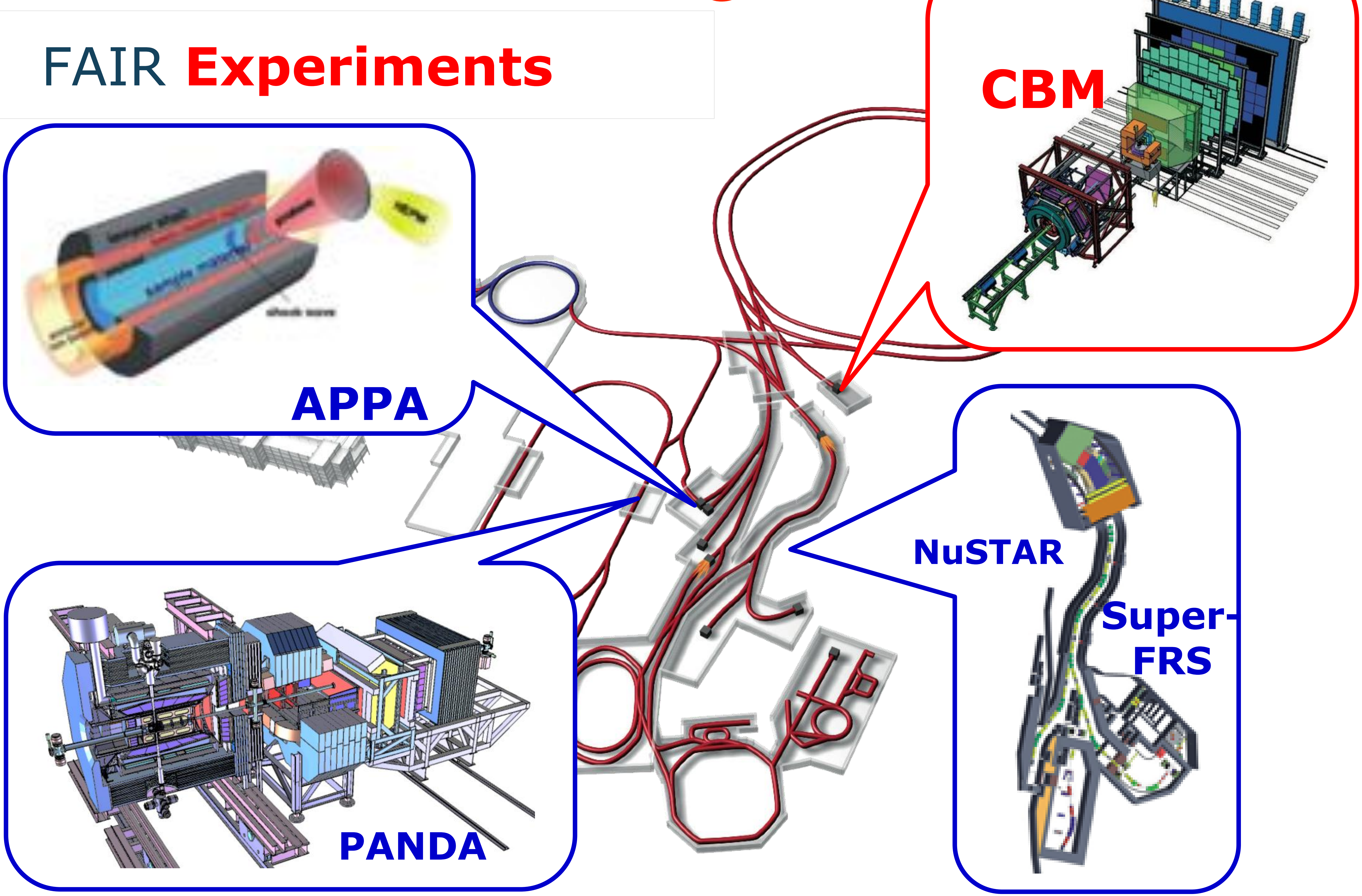
Y. Nara, H. Niemi, **JS** and H. Stöcker, Phys. Lett. B **769**, 543-548 (2017)


Death-Star- Machines - FAIR HIAF NICA STAR
NeutronStar matter in the Lab - Heavy Ion Collisions
Charm and Beauty of International Collaboration
Observers
GSI
FAIR
ustria Czech
ungary
China 11.11. 2019
Finland
France
Germany
India
Italy
Poland
Slovenia
Spain
Sweden
Romania
Russia
Rosatom
UK
38

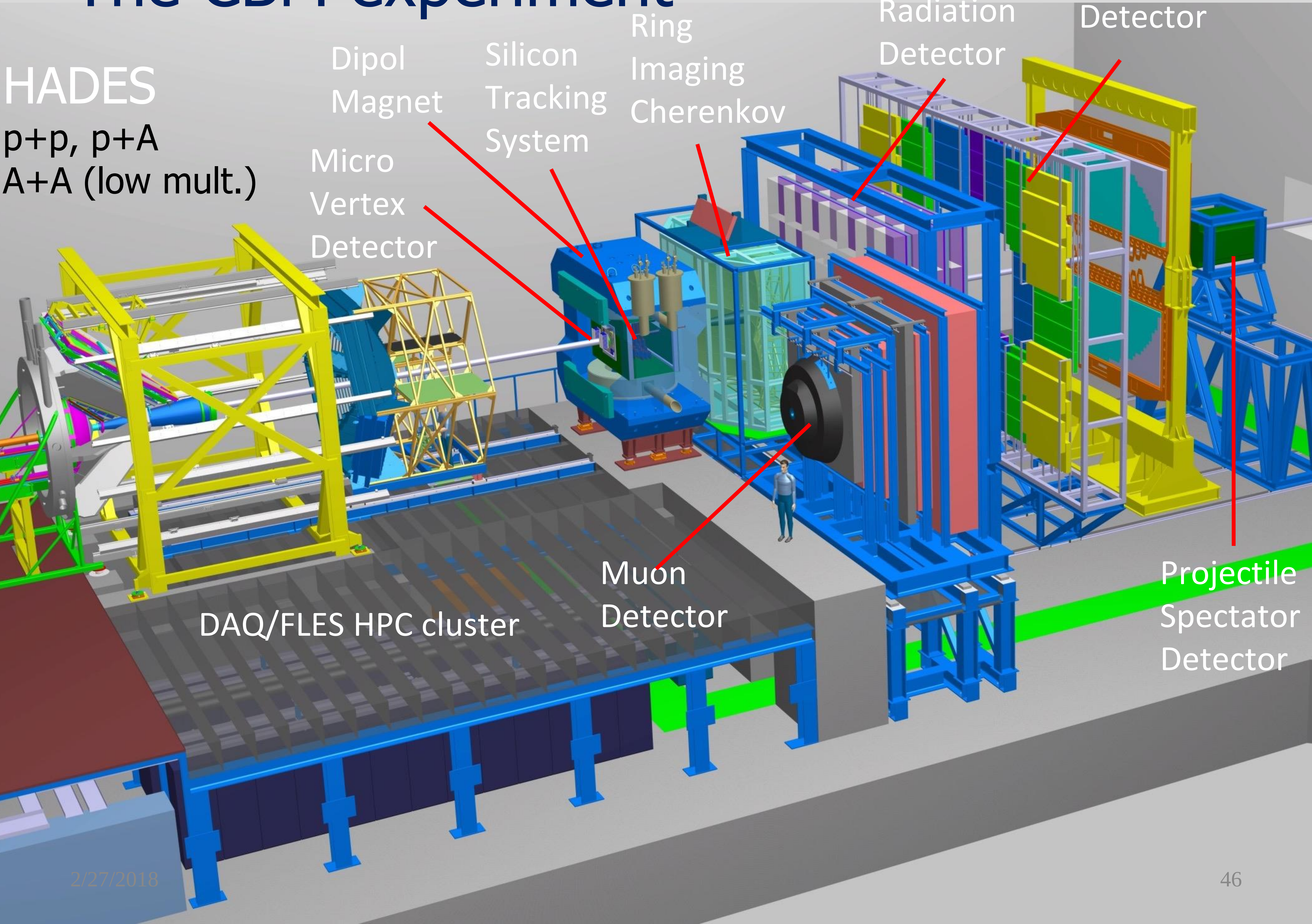

"THE MOST HORRIFYING MOTION PICTURE I HAVE EVER SEEN."
- REX REED
A FILM BY
TOBE HOOPER
THE
FAIR
CHAIN SAW
MASSACRE
Adrian
Amarillo
McLean
Hereford
Palo Duro Canyon State Park
Childress
Lubbock
Dickens
Brownfield
Snyder
Abilene
TEXAS
Midland
Odessa
San Angelo
Sonora
Del Rio
Port Arthur

Neutron Star matter in CBM @FAiR-GSI Helmholtzcentre

FAIR **Experiments**

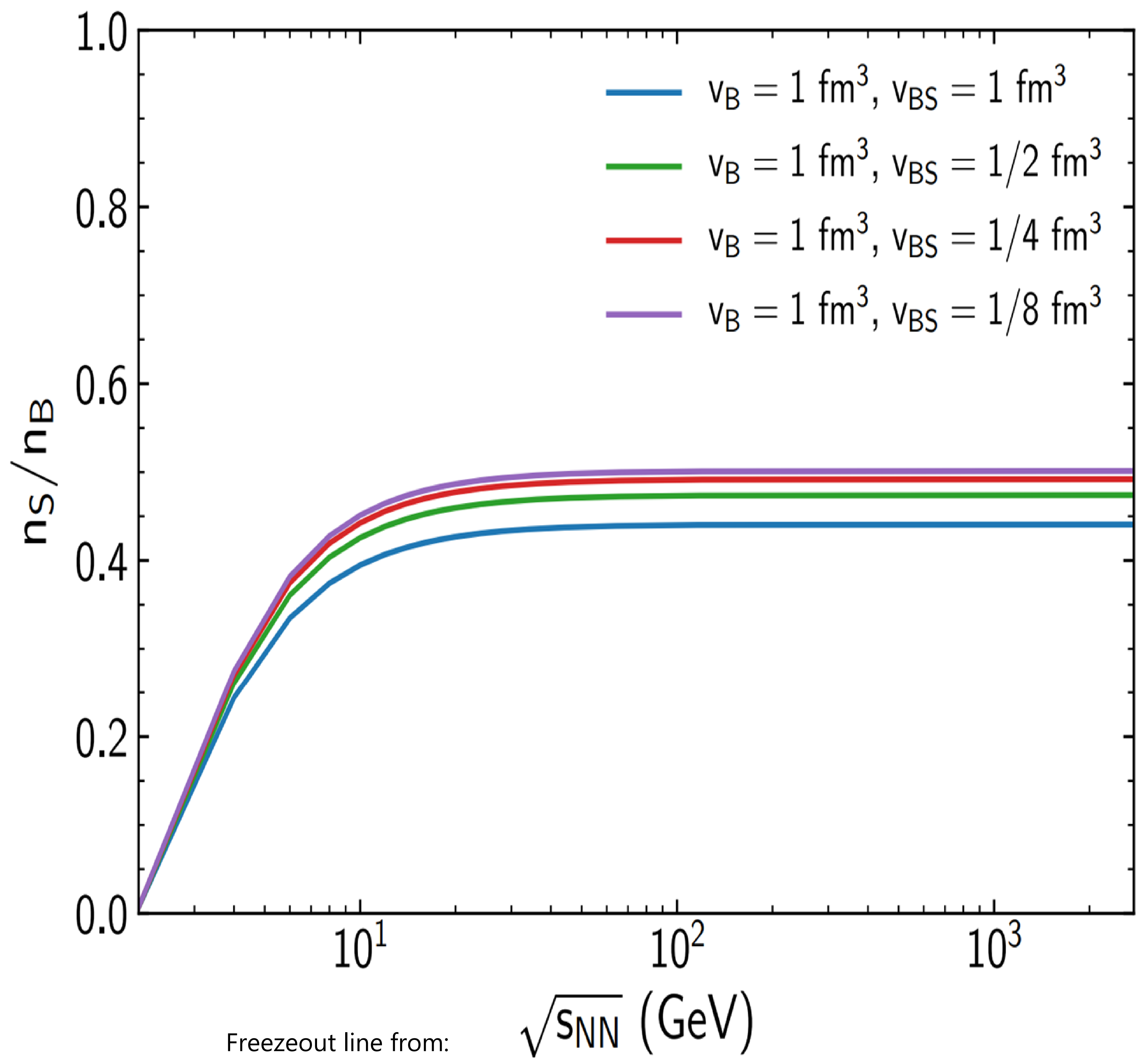


The CBM experiment



CBM Cave under construction

Strangeness at the freezeout



Freezeout line from:
V. Vovchenko, V. Begun, and M. Gorenstein,
Phys. Rev. C 93, 064906 (2016)

At the freezeout curve densities at temperatures are too small to feel EV effects.

Strangeness fraction at the freezeout is only changed slightly.
Other effects to may suppress it even more: strangeness suppression factor, conservation laws…

Hot Nuclear Matter EoS in Binary NS Mergers

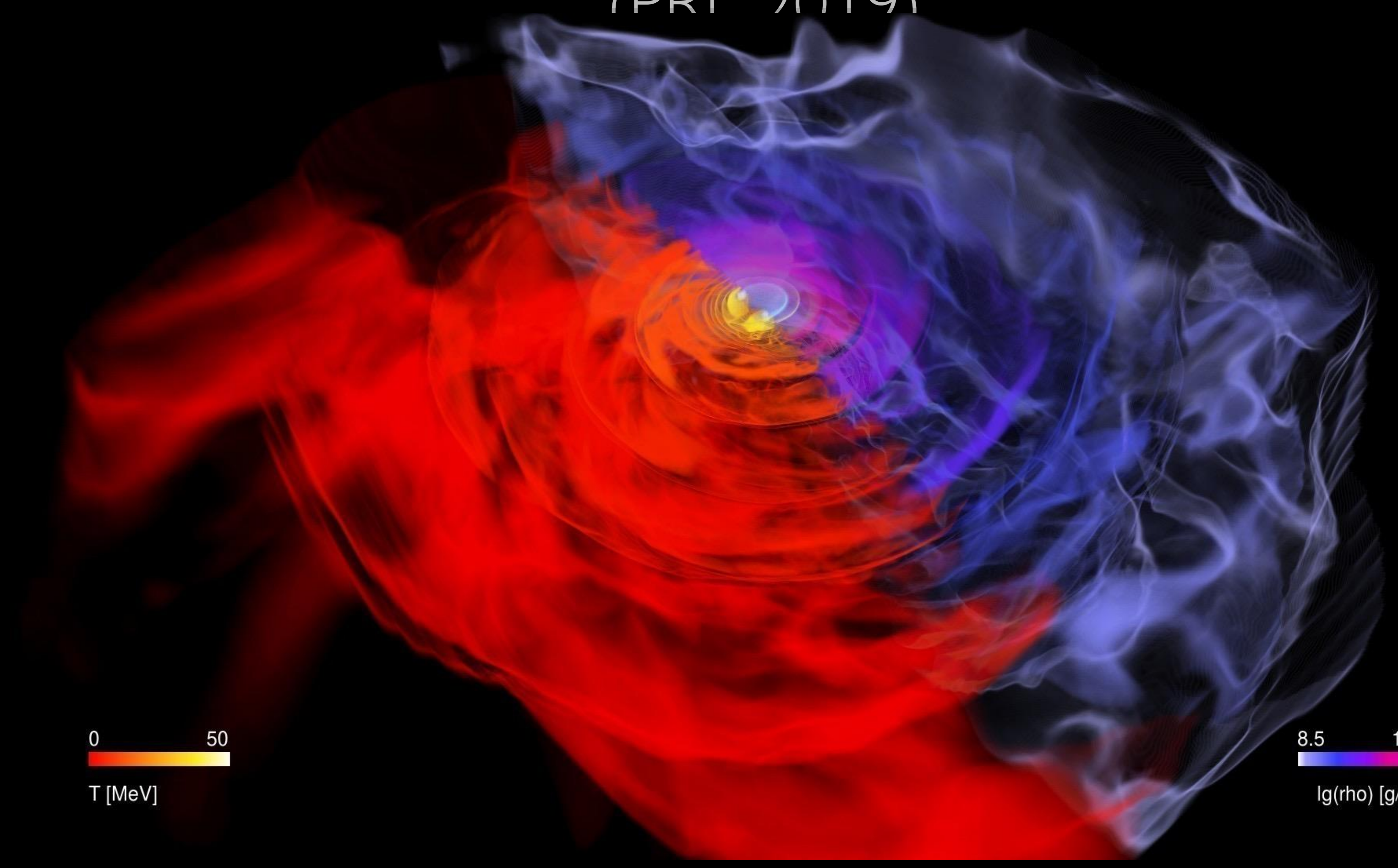
- **Quark Matter Phase Transition**
- Signatures in Gravitational Waves

Most, Weih, Papenfort, Dexheimer, Hanauske,

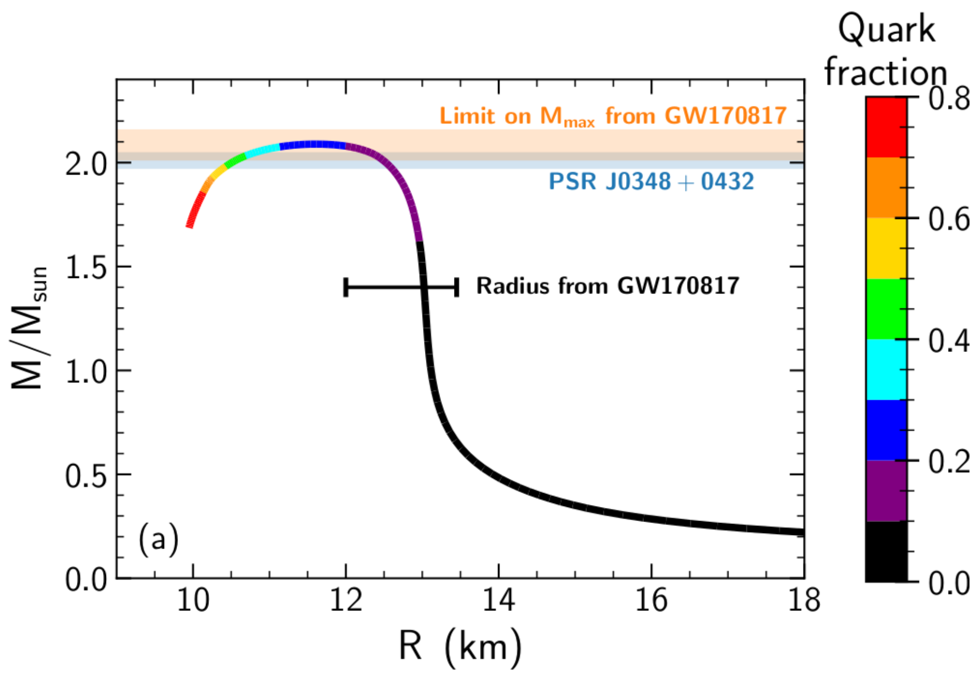
Motornenko, Steinheimer, Schramm, Stoecker, Rezzolla

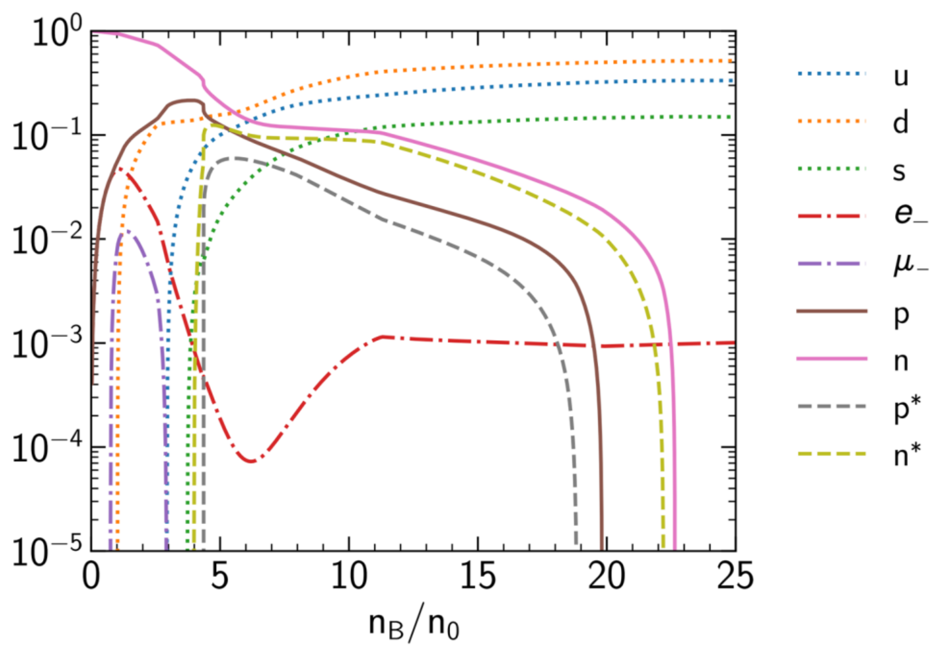
see also Bauswein, Bastian, Blaschke, Chatziioannou, Clark, Fischer, Oertel

(PRL 2019)

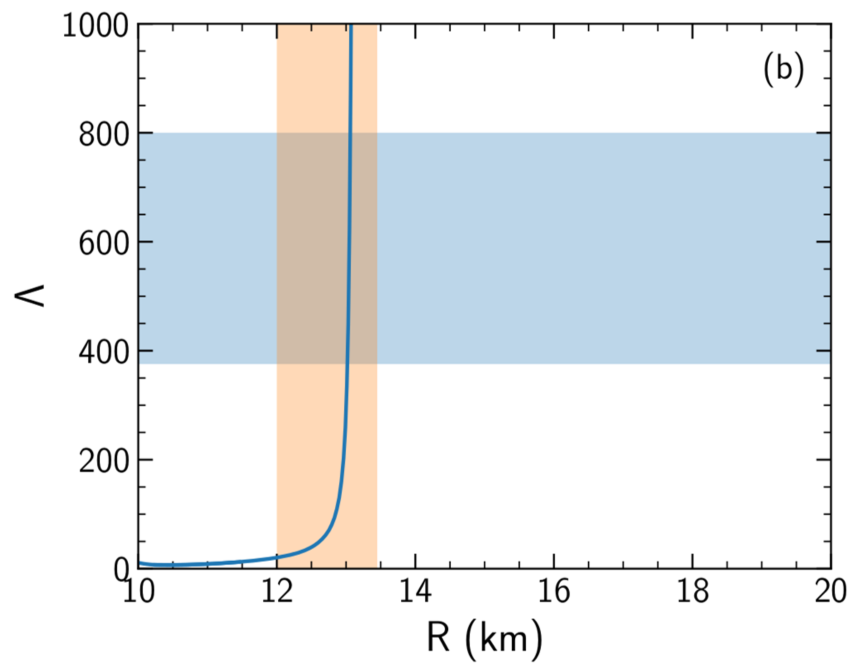


Neutron stars: another benchmark for the QCD EoS





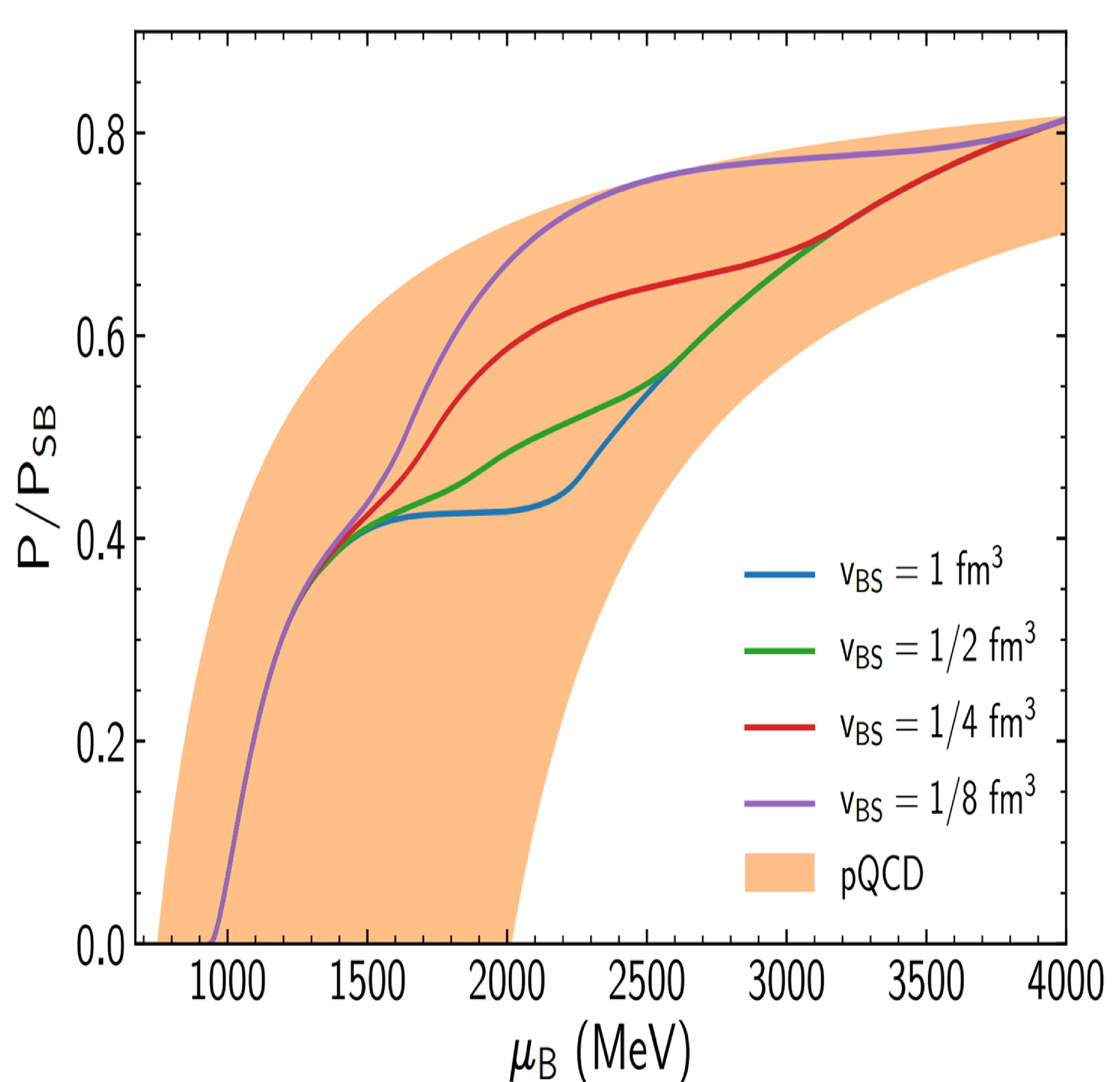
- ➔ The EoS is stiff enough to provide $2M_{sun}$ NS
- ➔ When quarks are dominant — NS are unstable
- ➔ No PT due to the deconfinement
- ➔ quark fraction < 30% for stable stars
- ➔ Agreement with the analysis of GW170817 (Most, Weih, Rezzolla, Schaffner-Bielich, 1803.00549)
- ➔ Maximal mass of NS is in agreement with constraints form universal relations *(Rezzolla, Most, Weih, 1711.00314)*



based on 1905.00866, A. Motornenko

- Lattice QCD data suggests that hyperons are less repulsive than non-strange baryons.
- Non-strange baryon excluded volume: v_B=1 fm^3,
- strange baryon: v_{BS}=1/4 fm^3
- Better description of baryon and strangeness correlators is achieved
- Correlators which involve electric charge are still off the lattice data:
  - Meson EV parameter may be tuned as well
  - However, already by tuning only hyperon EV we prove that we may tune CMF model to any kind of lattice data
- Comparison with PQCD results at T=0 favor $v_{BS} \geq 1/4$ fm^3
- New parameterizations do not produce exotic types of matter

Comparison with pQCD data for cold quark matter



CMF gives reasonable description for v_{BS}=¼ fm^3.

For smaller values — too many degrees of freedom appear, overshooting of PQCD results.

Then at high muB hadrons are suppressed and SB limit is slowly approached.

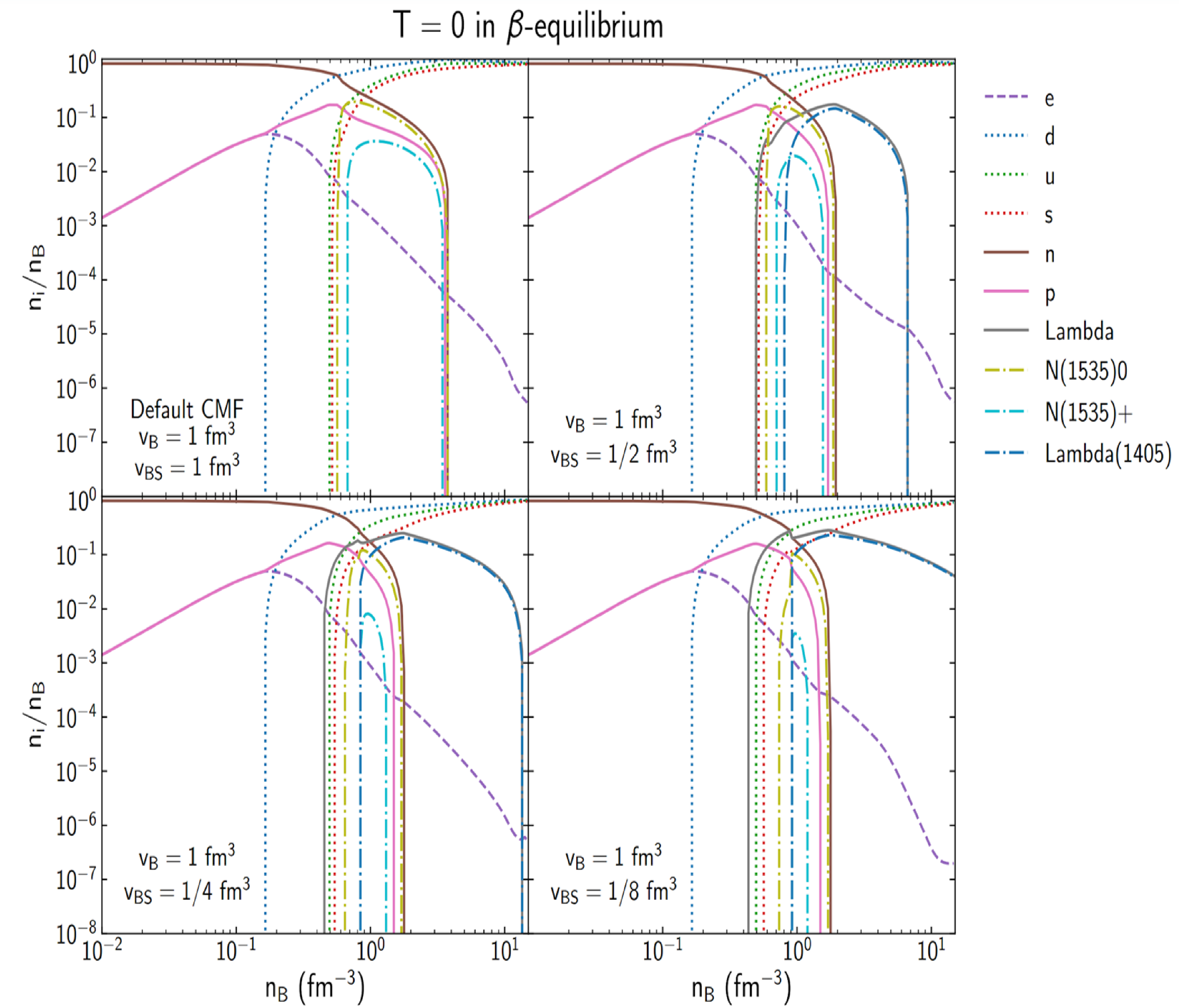
tschke, and A. Vuorinen,
5021 (2010)

Properties of the cold matter: ß-equilibrium

In the default CMF hyperons didn't appear at all for neutron stars.
Now they do !

For small enough EV values hyperons survive up to very high densities.

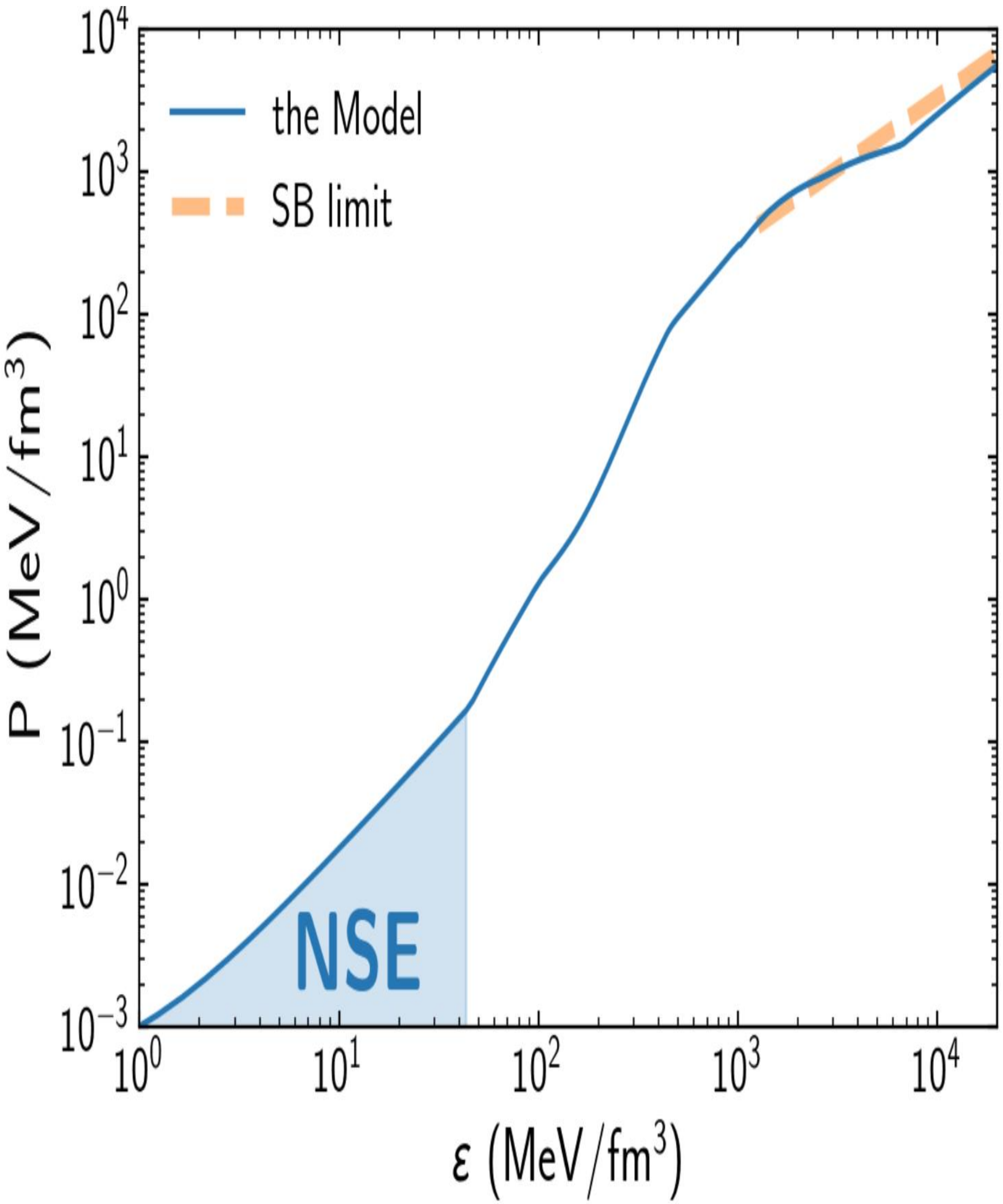
For v_{BS}=¼ fm^3 (value from the LQCD analysis) hyperons are suppressed at n_B=0.7 fm^{-3}



A. Motornenko

Application to neutron stars

- The model approaches **Stefan-Boltzmann**
- limit at high energy densities.



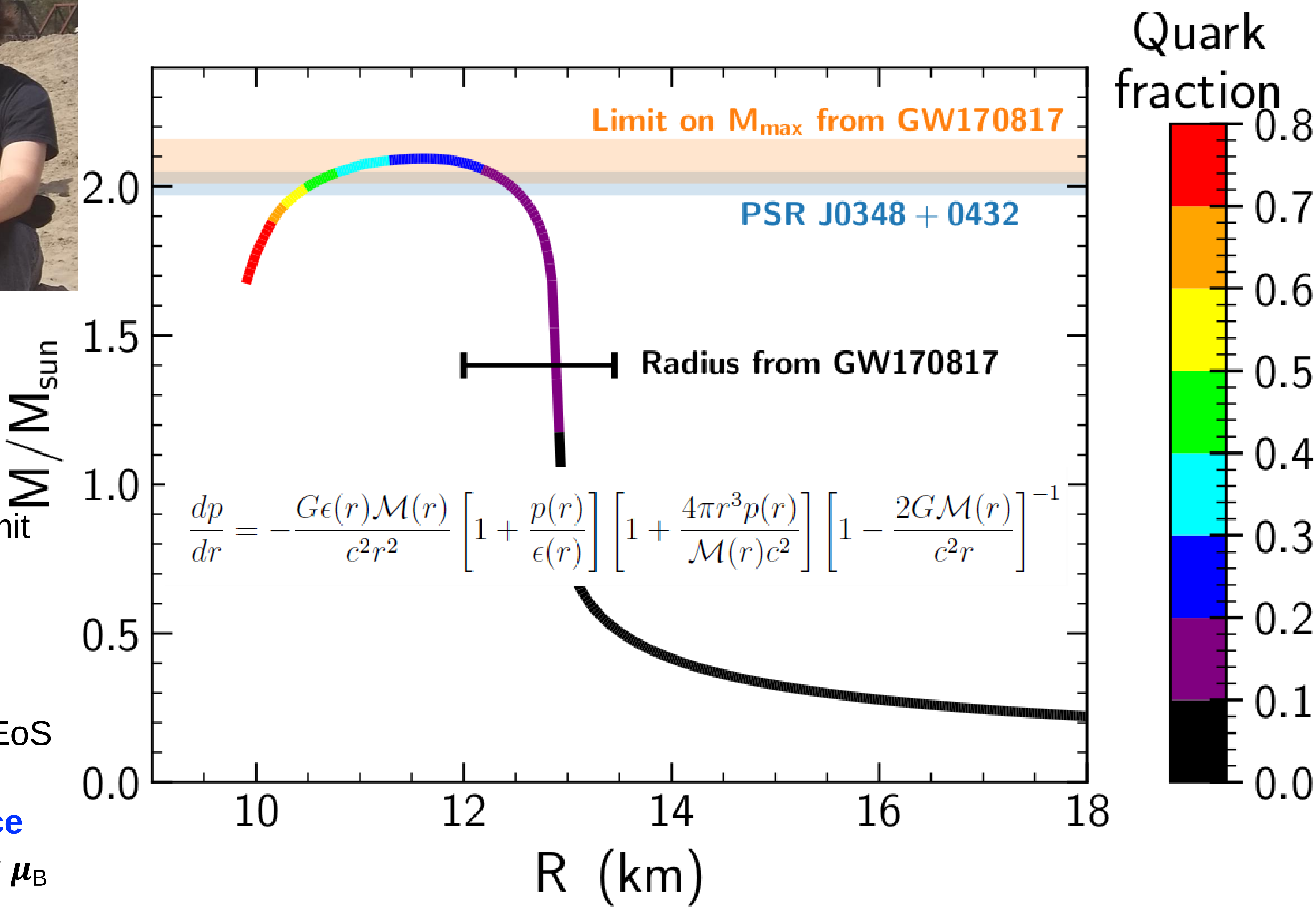
The model can be easily employed for the description of **neutron star matter** at **T=0 in beta-equilibrium** without any changes to the parameters. The EoS then can be used as an input to model neutron stars by solving Tolman–Oppenheimer–Volkoff equation:

$$\frac{dP}{dr} = -\frac{Gm}{r^2}\rho\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi r^3 P}{mc^2}\right)\left(1-\frac{2Gm}{rc^2}\right)^{-1}$$

Additional input is needed to model star's crust — Nuclear Statistical Equilibrium (*Baym, Pethick, Sutherland,1971, Astrophys. J. , 170,299.*)

Neutron Star Masses-Radius

Anton Motornenko



Features:

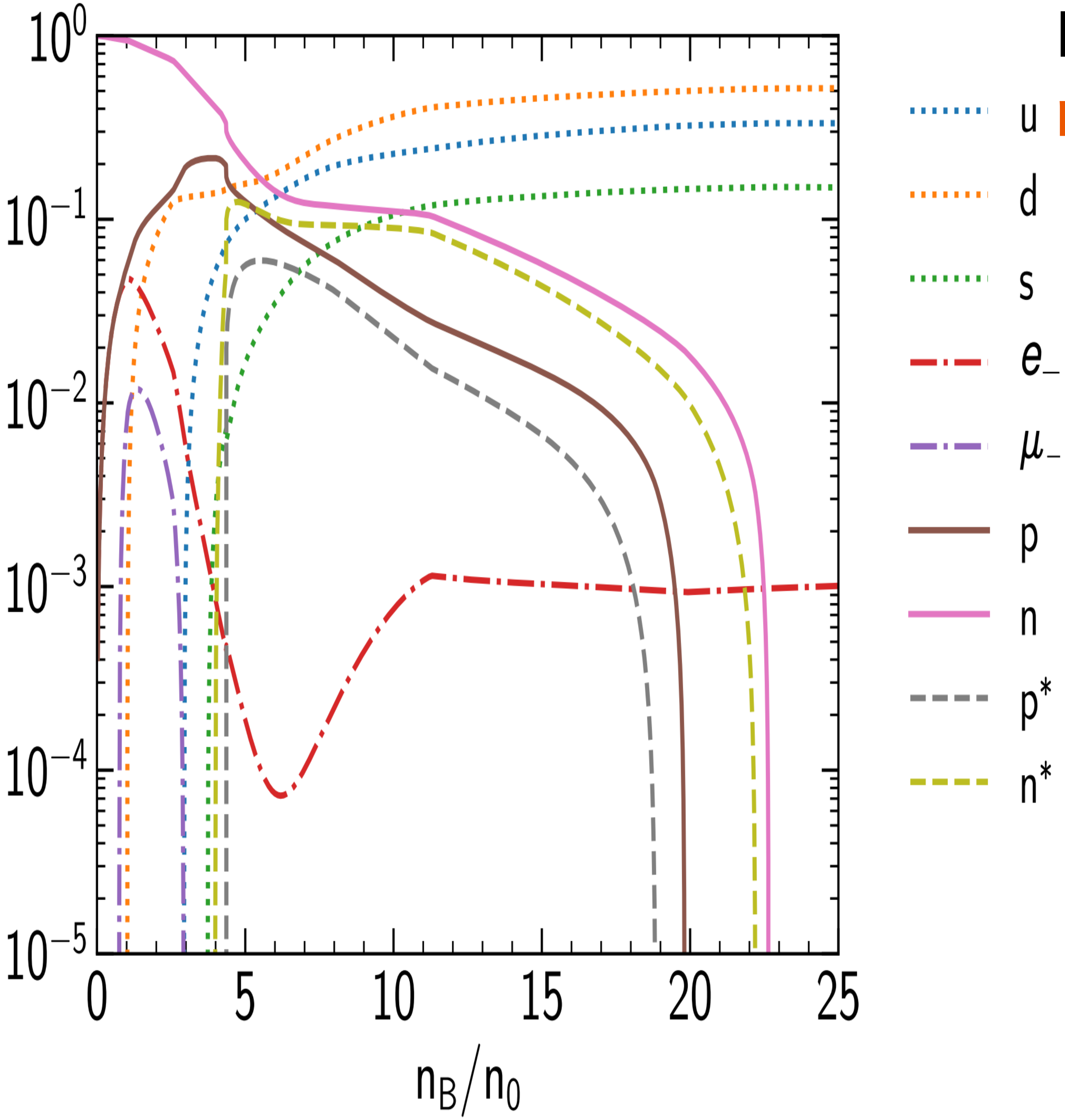
Maximum NS-mass observed =2.0xMsolar & <**2.1xMsolar-** limit of GW170817

Radii ~ 12-13km observed

hybrid star's rel.EoS at high μ_B must **agree with lattice QCD data** at low μ_B

*Anton **Motornenko**, Vovchenko, Steinheimer, Stefan Schramm, Stoecker 1809.02000, NPA (2019), QM'19 Wuhan*

Equation of state at T=0: neutron stars

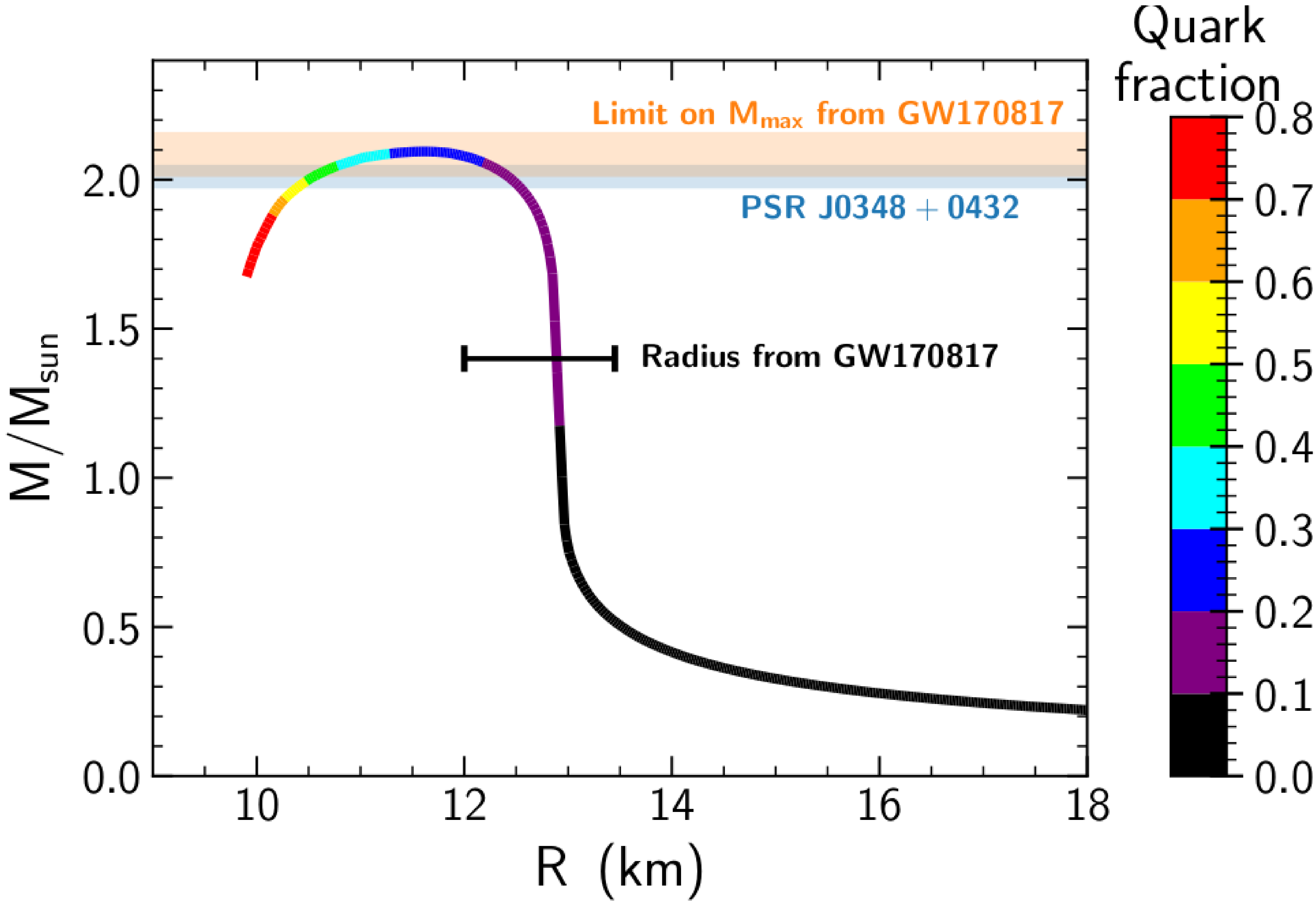


Particle yields normalized to baryon density:

Equation of state for **neutron stars**:

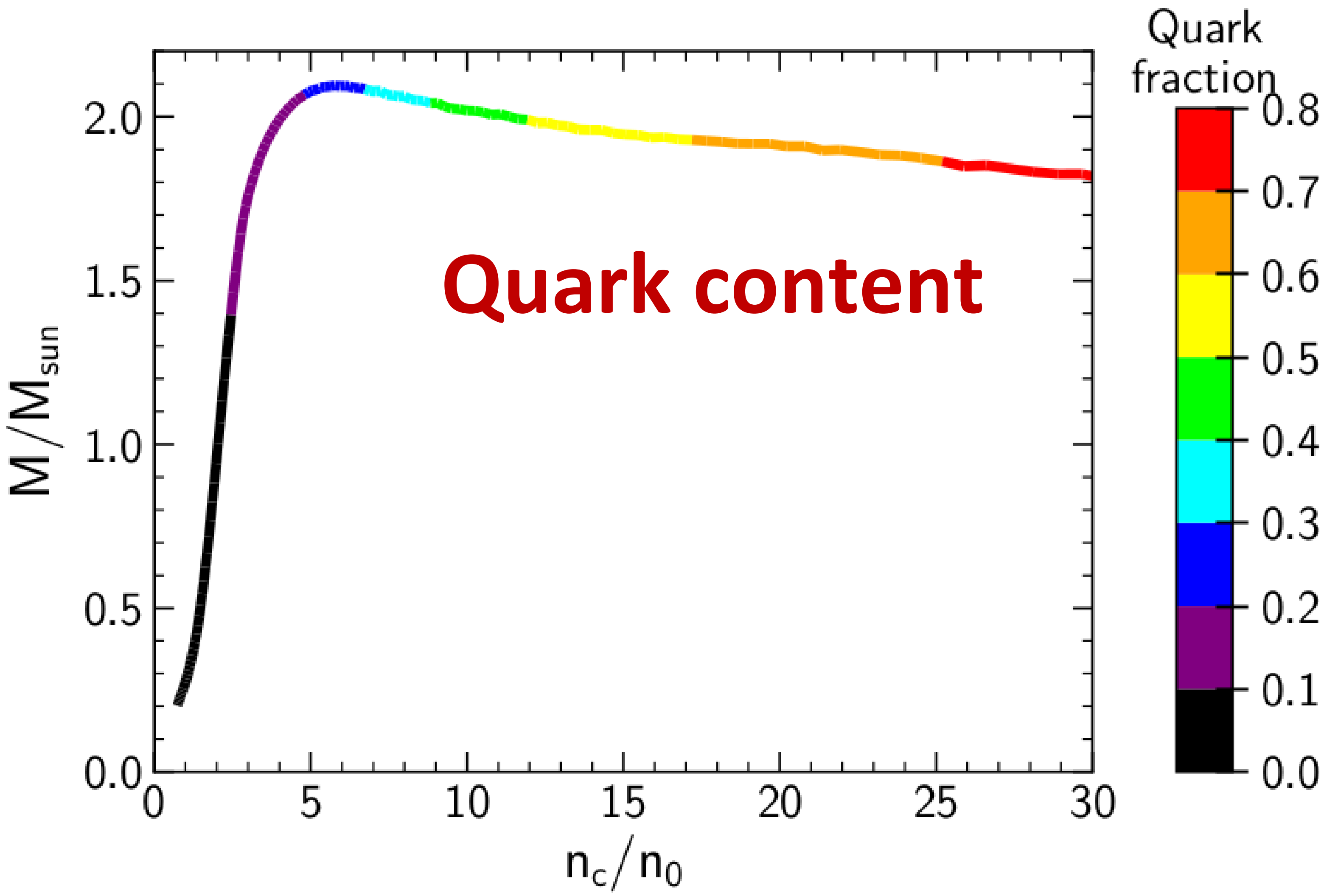
- **T=0**
- Electric charge is **zero**
- **Leptons** are included
- No nuclear ground state
- Chiral transition is at $n \approx 4n_0$
- Quark matter is at $n \approx 23n_0$
- **Hyperons** at T=0 are suppressed by hard-core repulsion (nevertheless are present at T ≠ 0)
- **Strange quarks** are included

Mass-radius relations



- EoS is stiff enough to provide $2M_{sun}$ neutron stars
- No second family of NS
- quark fraction < 30% for stable stars
- Agreement with observations

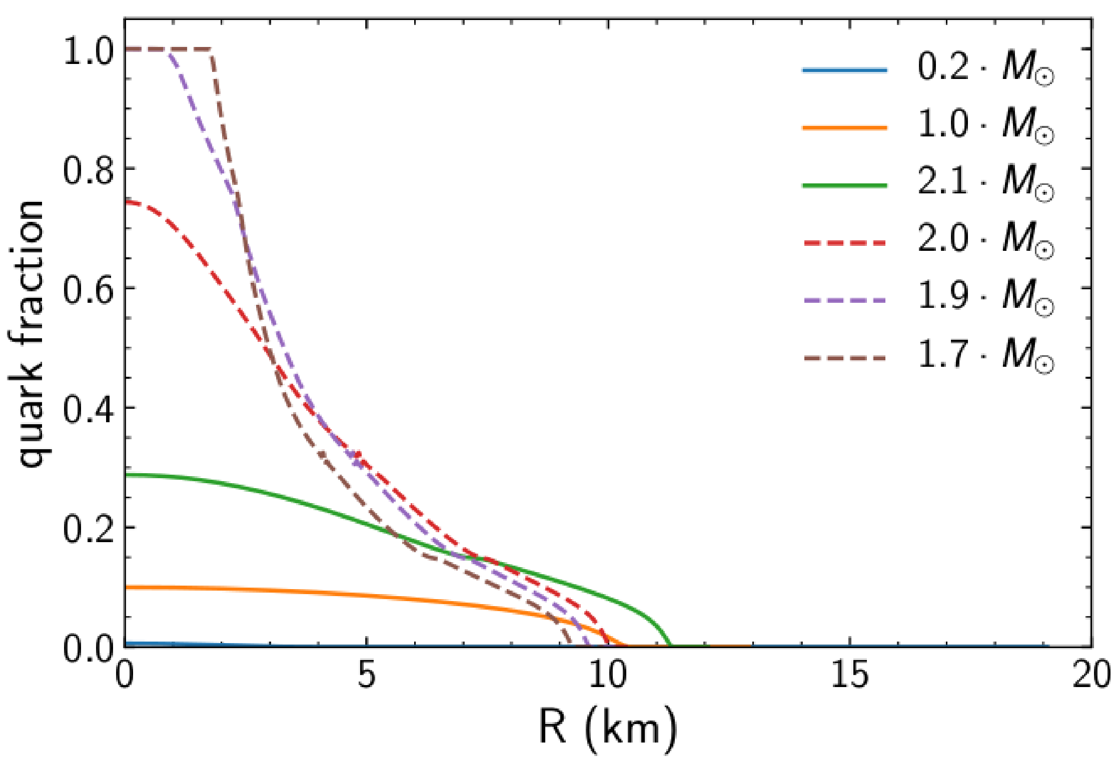
Maximal mass is in agreement with recent constraints on maximal mass of neutron star from GW170817: $2.01^{+0.04}_{-0.04} \leq M_{\rm TOV}/M_{\odot} \lesssim 2.16^{+0.17}_{-0.15}$



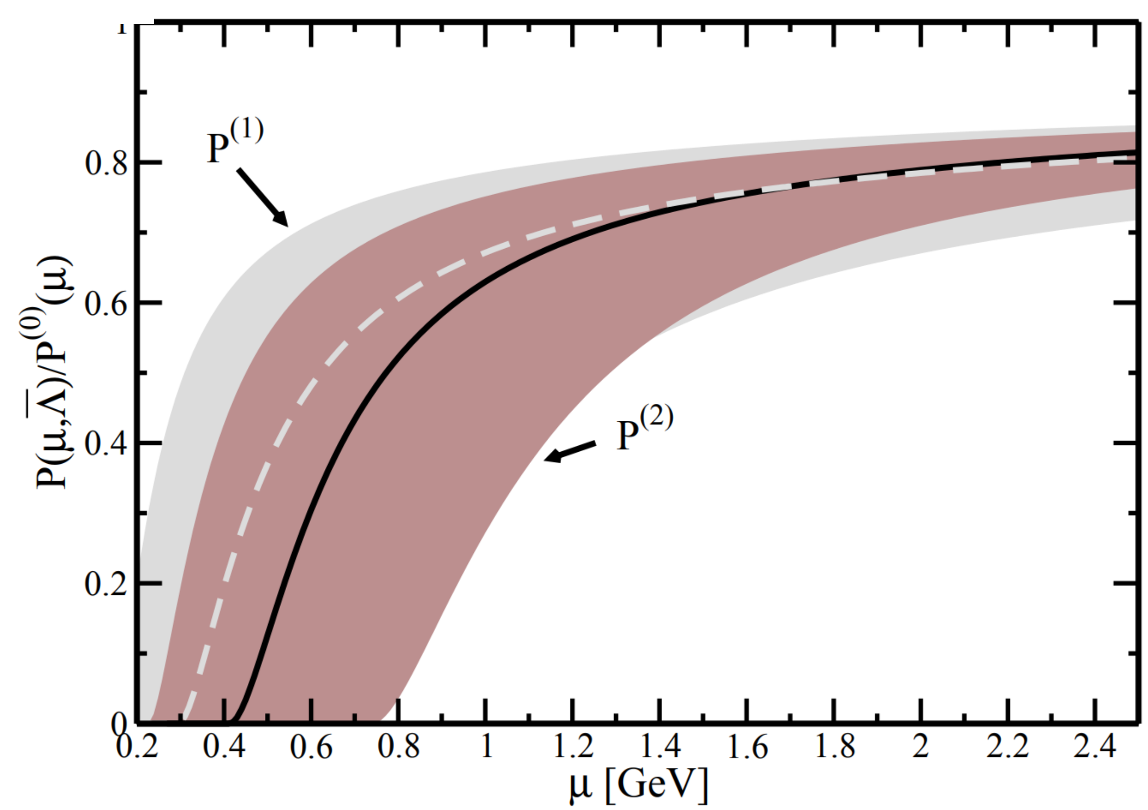
Quarks appear smoothly — no separation between phases.

Strange quark fraction is <13%, produced by weak decays.

Quarks give significant contribution to stars with central density $n_c > 6n_0$, where pQCD calculations for EoS are available:

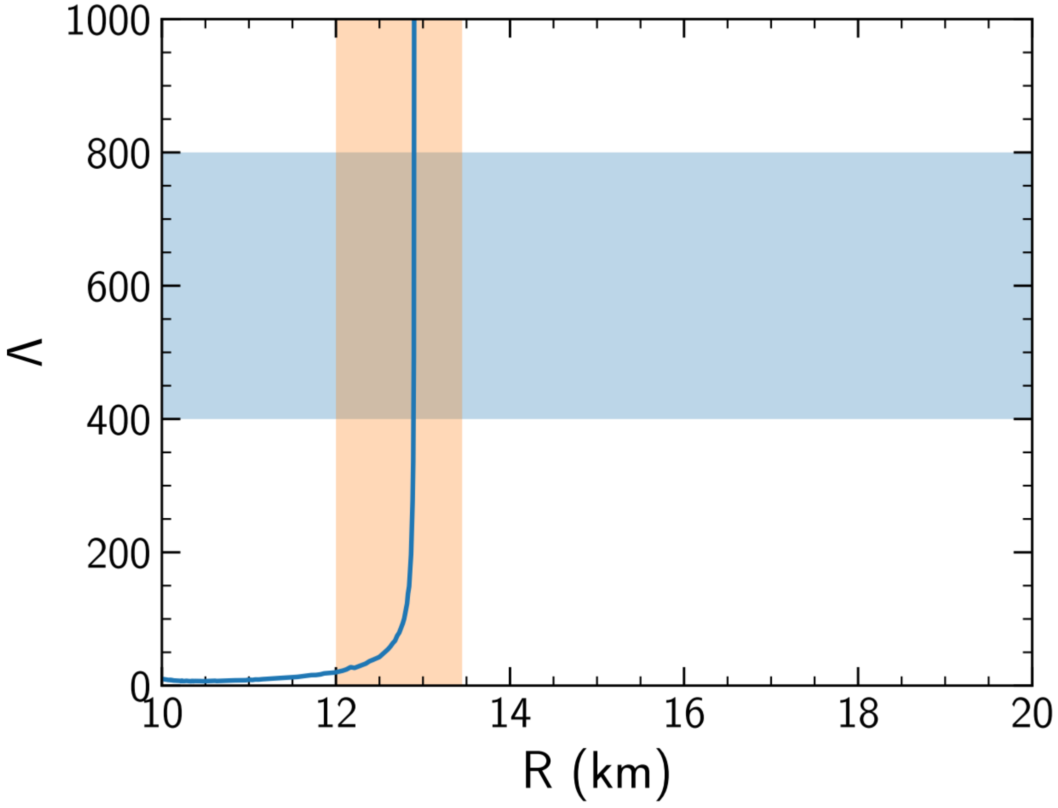


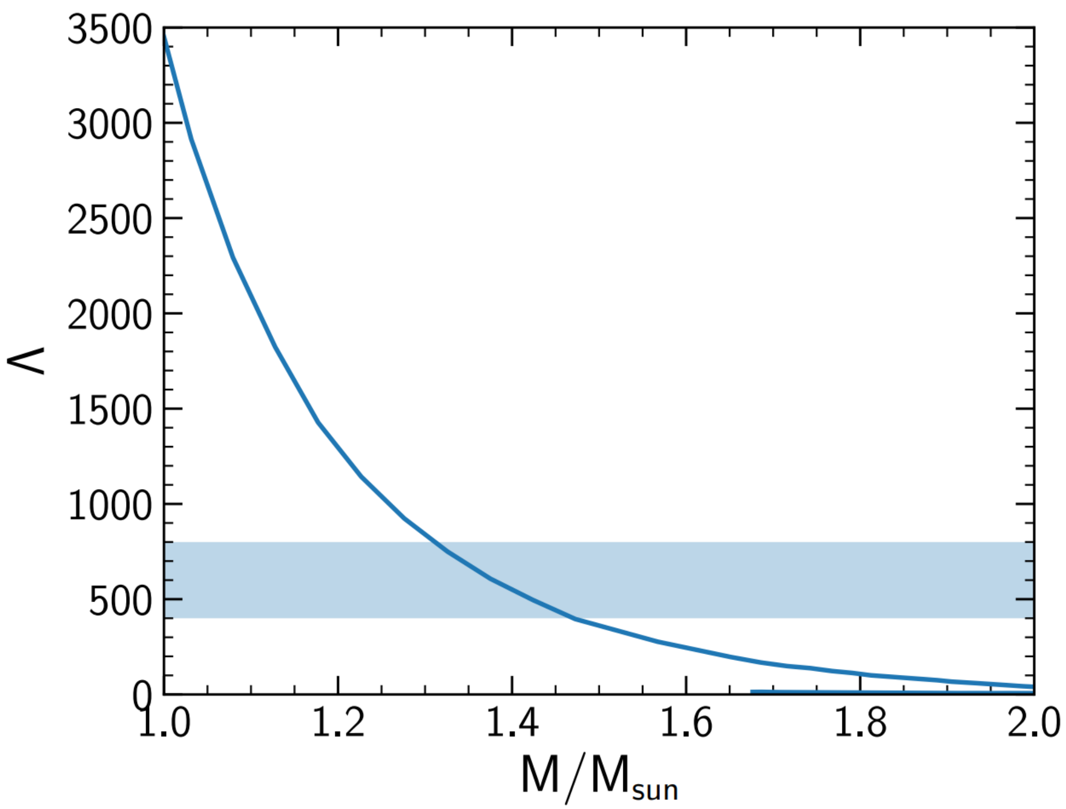
Local quark fraction (dashed — unstable stars):



A. Kurkela, P. Romatschke, A. Vuorinen, 0912.1856

Neutron star tidal deformabilities





Tidal deformability — measures stars' induced quadruple moment Q_{ij} as a response to the external tidal field $\mathcal{E}_{ij}$:

$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

important EoS-dependent quantity for inspiral phase of binary neutron star system. Related to second Love number k_2:

$$\lambda = \frac{2}{3} k_2 R^5$$

One presents the dimensionless tidal deformability Λ (mostly dependent on compactness M/R):

$$\Lambda = \frac{\lambda}{M^5} = \frac{2}{3} k_2 \left(\frac{R}{M}\right)^5$$

Bands — recent constraints for radius and tidal deformability of $1.4M_{sun}$ star.

Most, Weih, Rezzolla, Schaffner-Bielich., 1803.00549

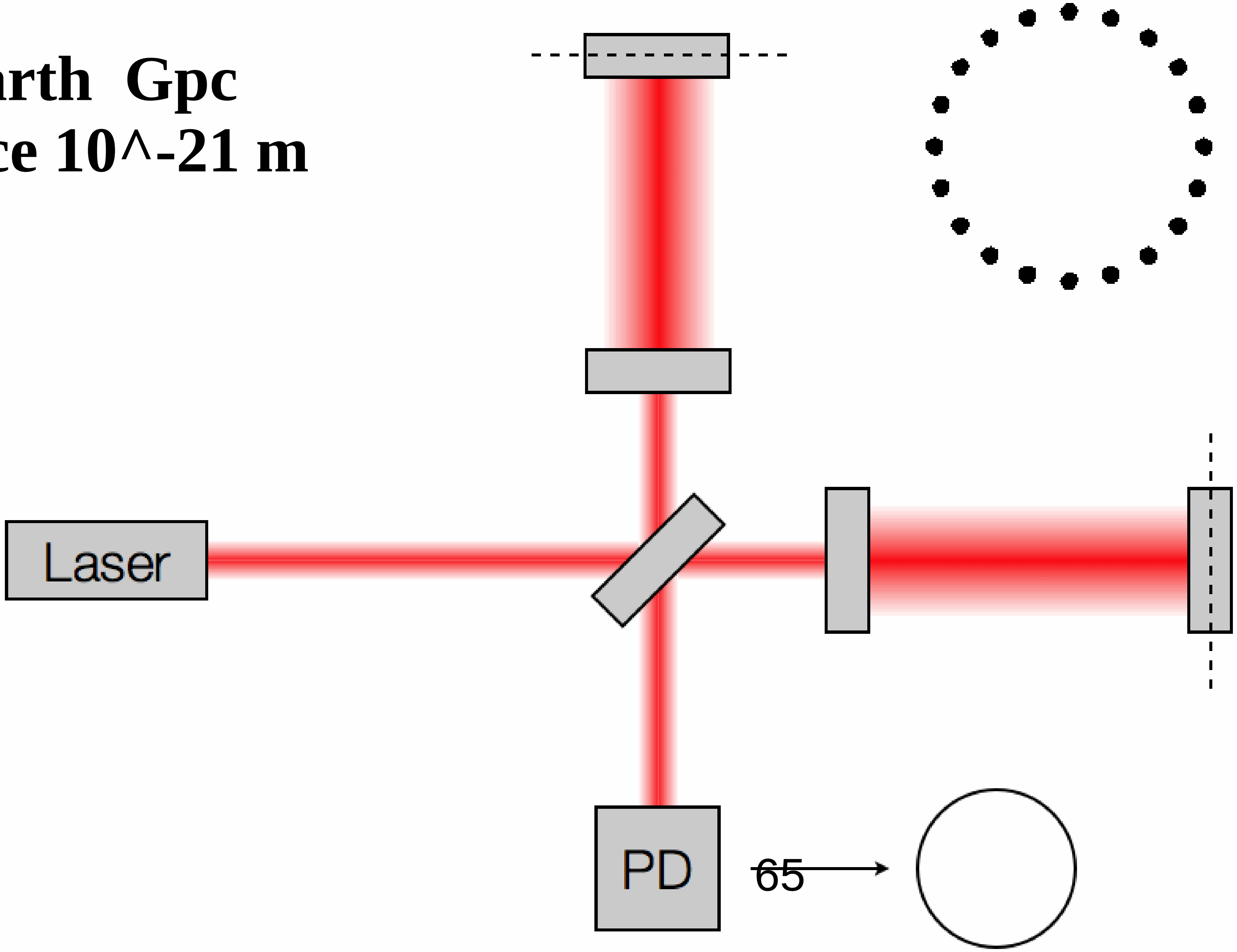
Line — results on Λ using EoS obtained from the model.

Gravitational Waves discovered

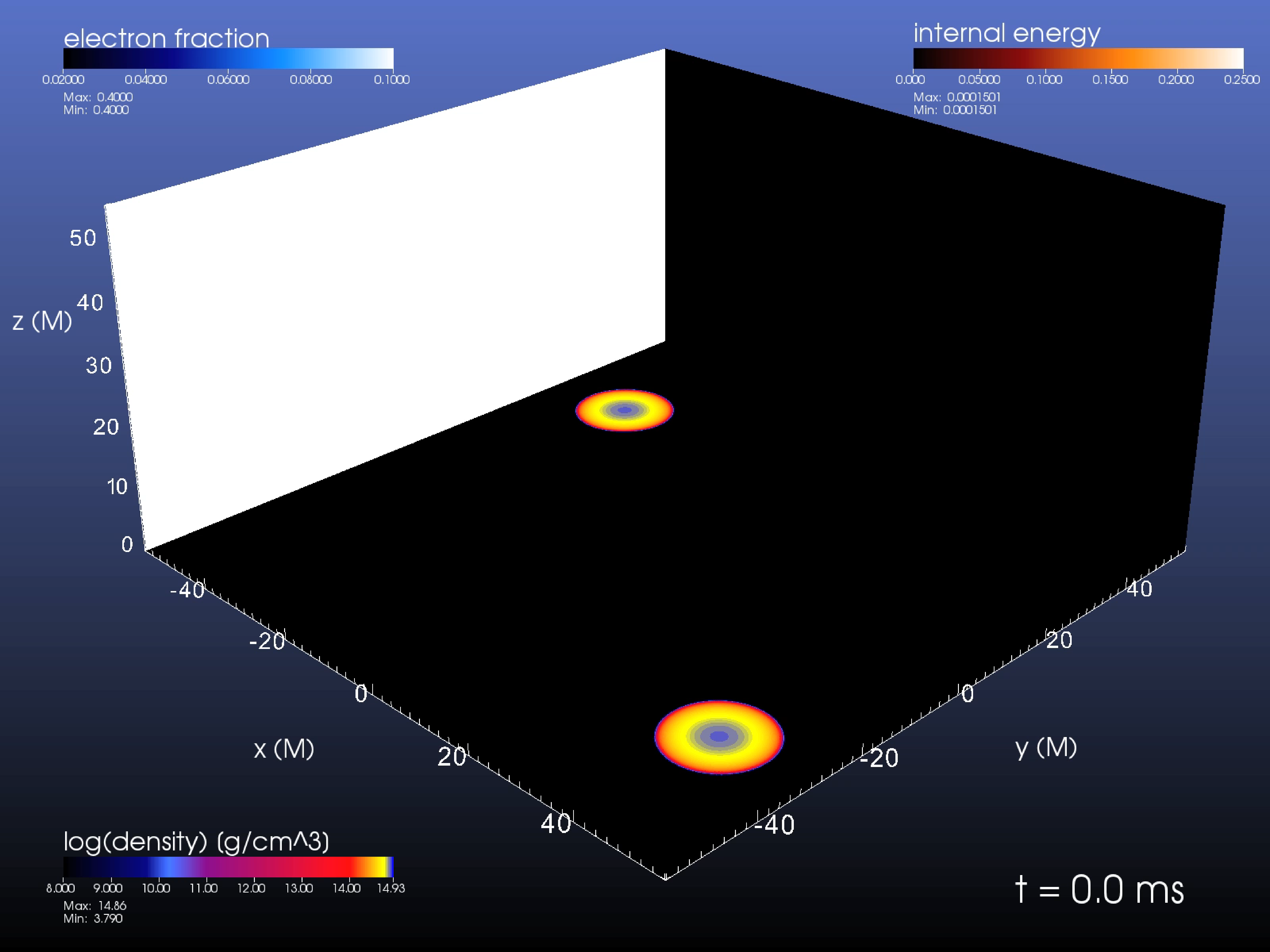
<u>Collision of 2 Neutron Stars</u>
<u>GW170817</u>

Masses of BHs: 1.4 &1.4 Solar Masses

Distance to Earth Gpc
Length Difference 10^-21 m



Credit: Les Wade from Kenyon College.


electron fraction
0.02000
0.04000
0.06000
0.08000
0.1000
Max: 0.4000
Min: 0.4000
internal energy
0.000
0.05000
0.1000
0.1500
0.2000
0.2500
Max: 0.0001501
Min: 0.0001501
z (M)
50
40
30
20
10
0
x (M)
-40
-20
0
20
40
y (M)
40
20
0
-20
-40
log(density) (g/cm^3)
8.000
9.000
10.00
11.00
12.00
13.00
14.00
14.93
Max: 14.86
Min: 3.790
t = 0.0 ms

The ideal fluid equations - but should include bulk- & shear viscosity & thermoconductivity - cf. A. Muronga & J. Noronha

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}\,, \qquad \text{(field equations)}$$

$$\nabla_\mu T^{\mu\nu} = 0\,, \qquad \text{(cons. energy/momentum)}$$

$$\nabla_\mu (\rho u^\mu) = 0\,, \qquad \text{(cons. rest mass)}$$

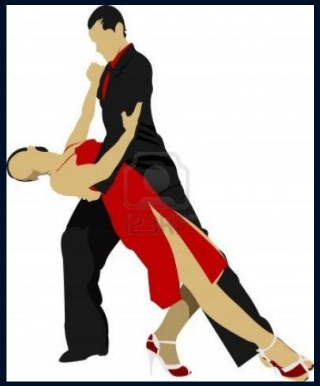
$$\nabla_\nu F^{\mu\nu} = I^\mu\,, \quad \nabla_\nu^* F^{\mu\nu} = 0\,, \qquad \text{(Maxwell equations)}$$

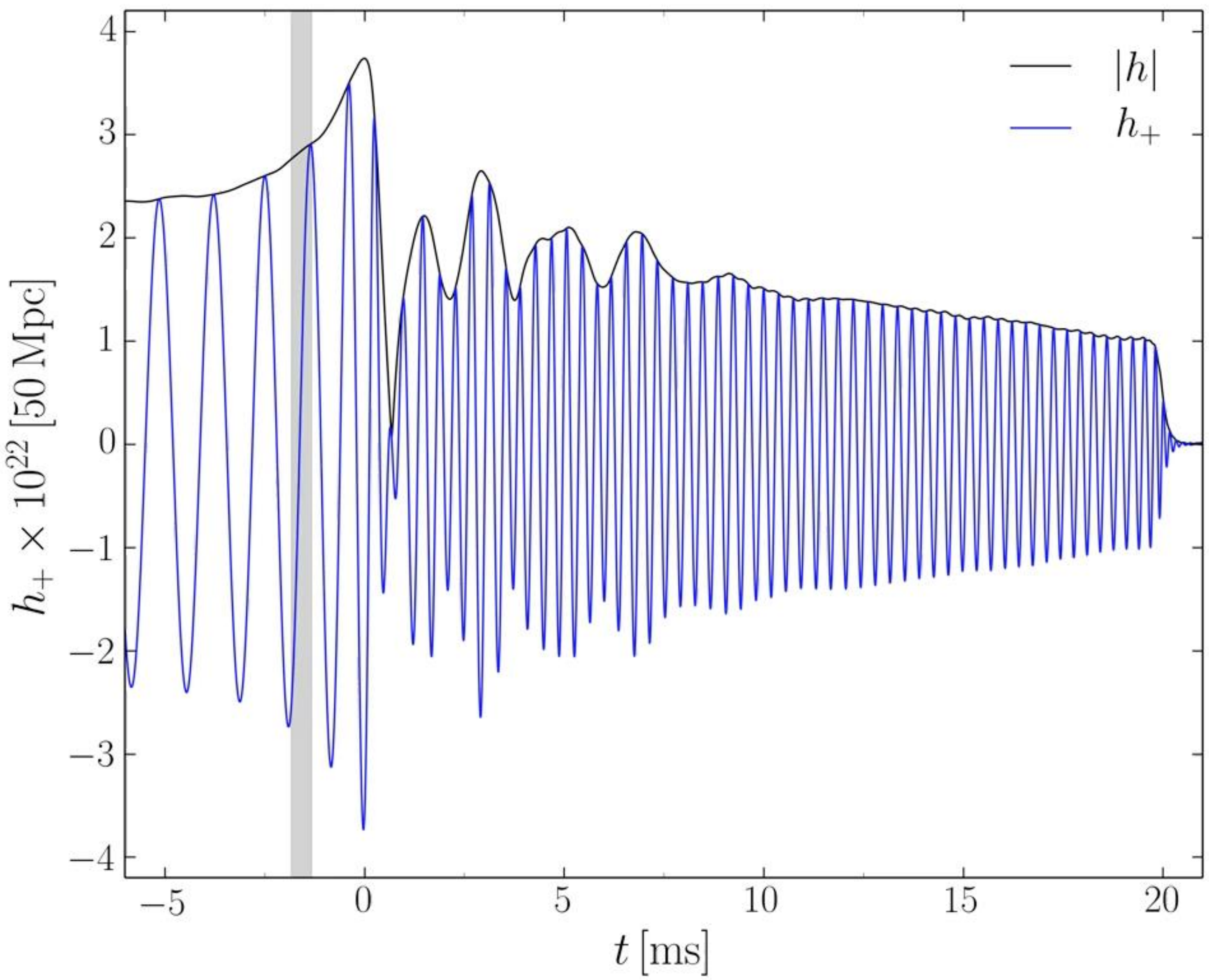
$$T_{\mu\nu} = T_{\mu\nu}^{\text{fluid}} + T_{\mu\nu}^{\text{EM}} + \ldots \qquad \text{(energy} - \text{momentum tensor)}$$

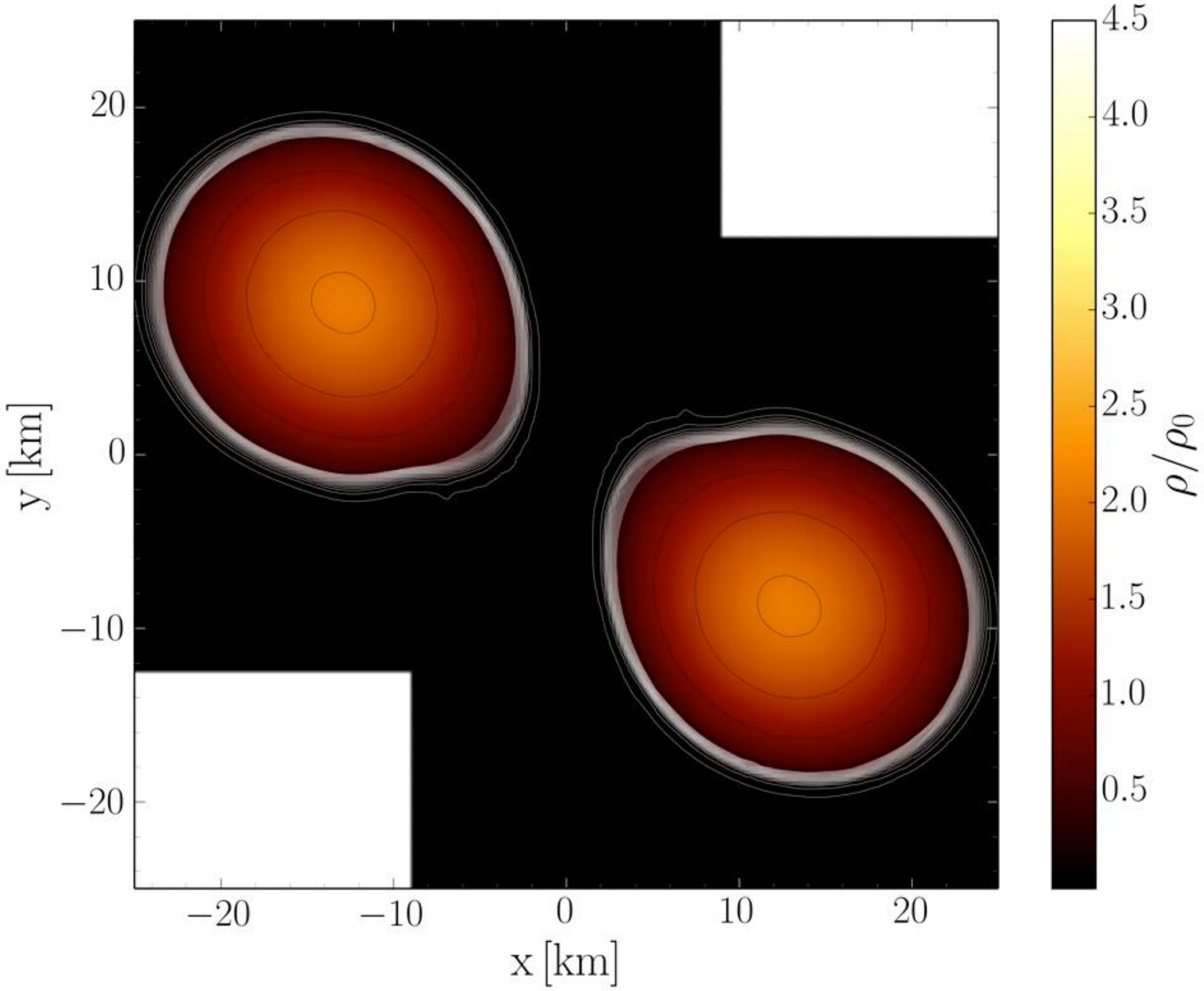
$$p = p(\rho, \epsilon, Y_e, \ldots)\,, \qquad \text{(equation of state)}$$

These equations do not possess analytic solutions in strong-field regimes: numerical approaches inevitable

Disco-Fox, Merengue and Tango- Phase

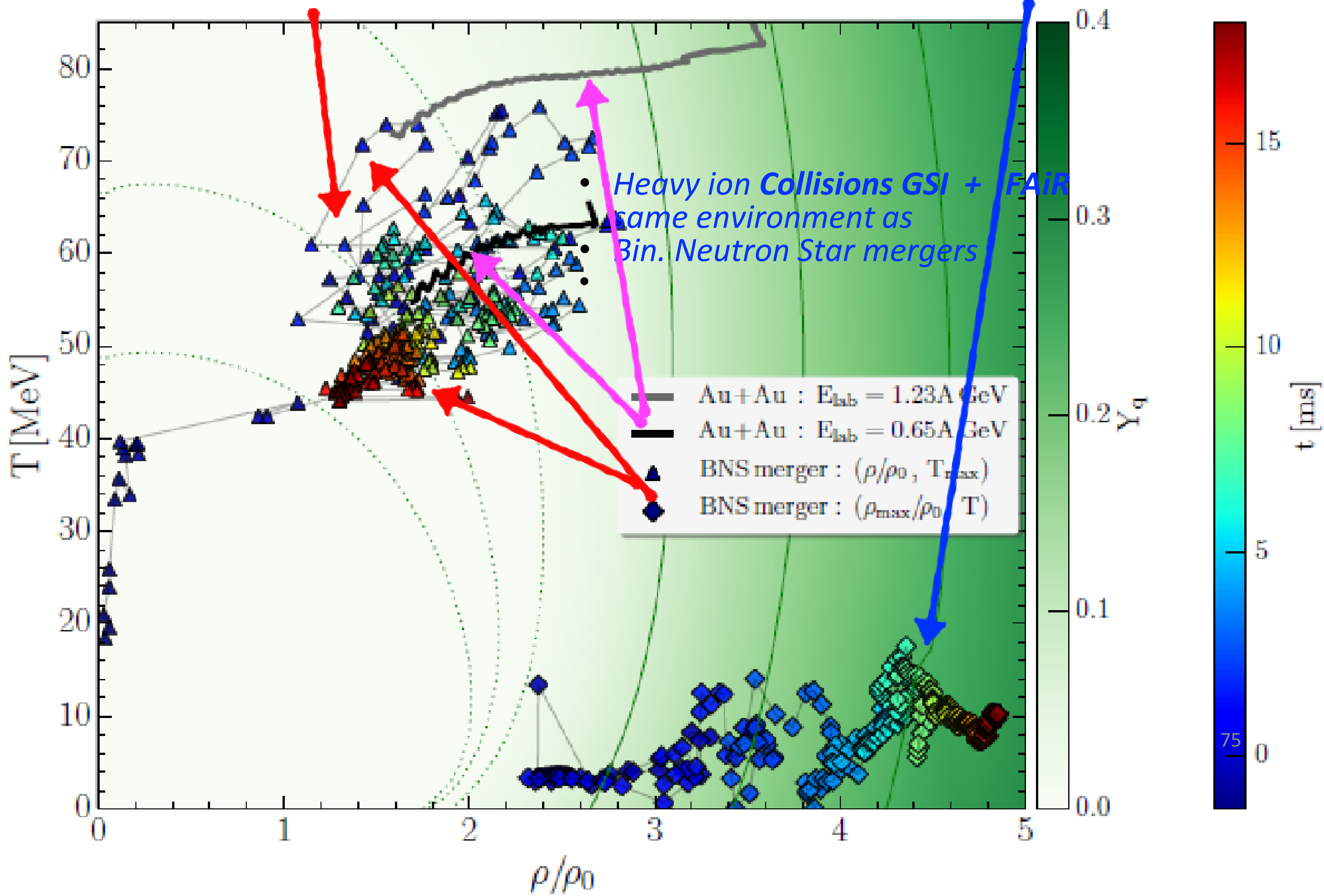




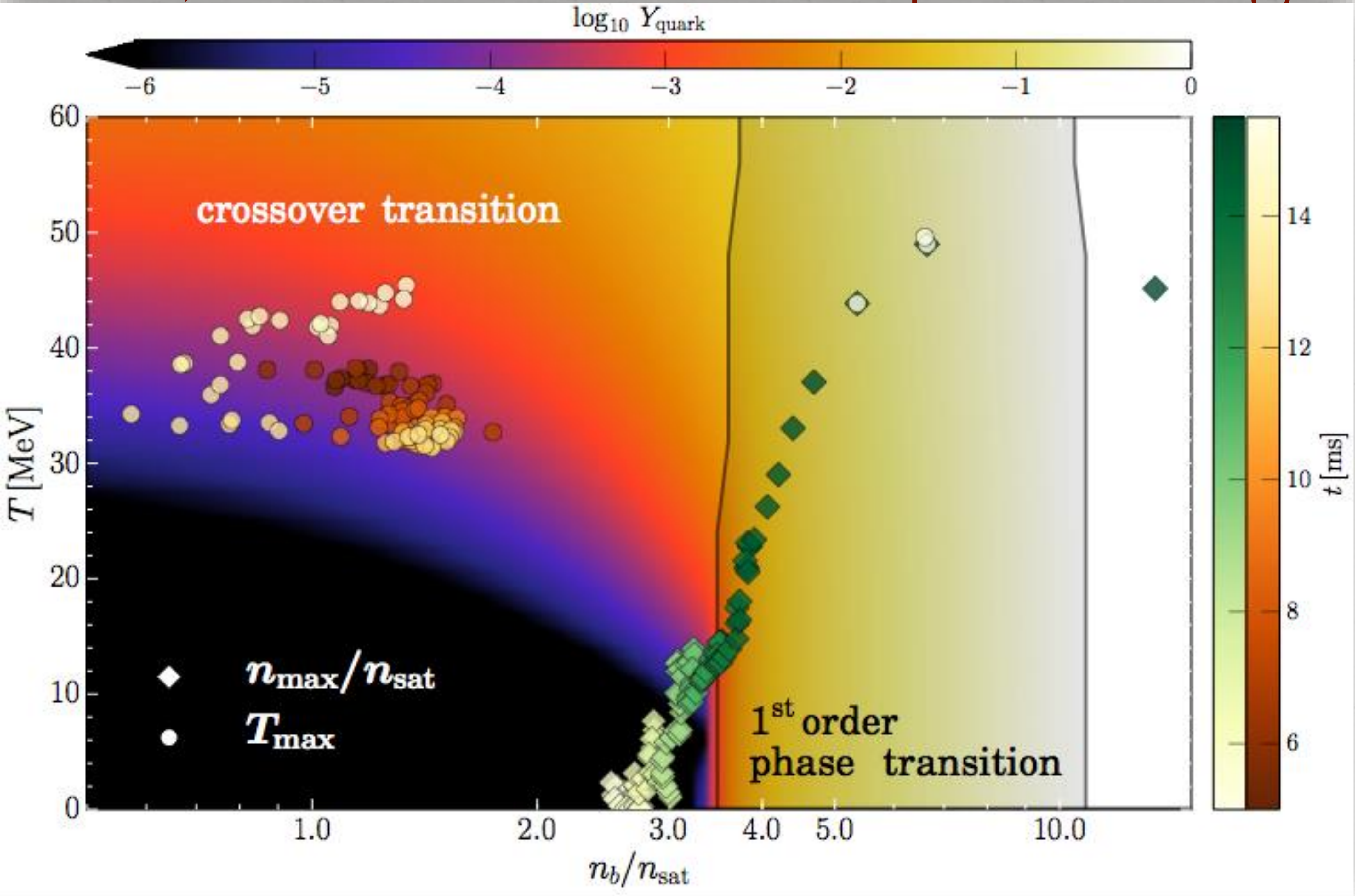


Where it's hot and dense in neutron star mergers

- **Separation** of **hot** hadronic **corona** and ***dense, cold quark matter core***



T, n Evolution in the phase diagram

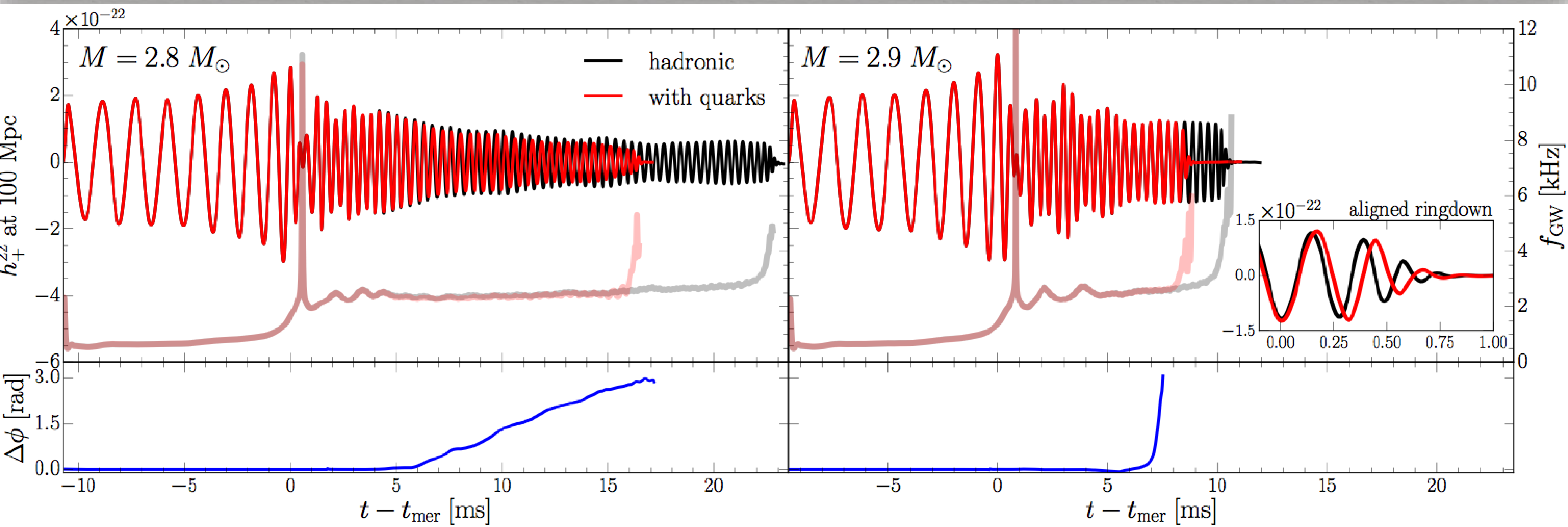


- Evolution of the max. temperature and density.
- Quarks appear early on in Torus: T~50 MeV
- Once core reaches density n/n_0 ~ 3.5, transition into SQM occurs

Gravitational Wave Emission from BNSM- ML!

“low-mass” binary

“high-mass” binary



• In **low-mass binary**, after ~ 5 ms, quark fraction is large enough to change quadrupole moment and yield differences in the waveforms.

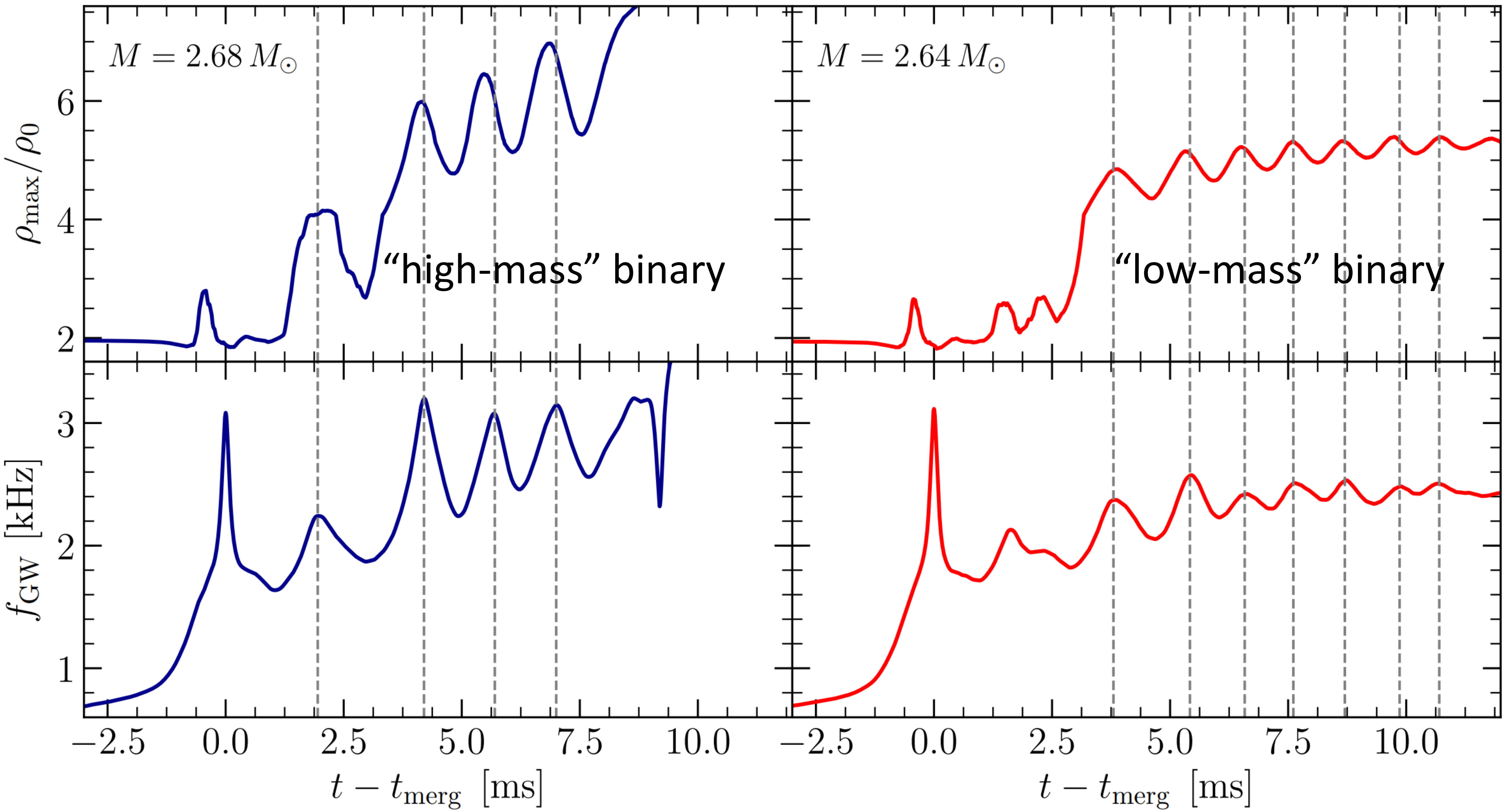
In **high-mass binary**, phase transition takes place rapidly after ~ 5 ms

. Waveforms are similar but **ringdown** is **different** (free fall for PT).

Mismatch hadronic **inspiral** and **post-merger** phase:

clear **Signature of Quark Matter - crossing or 1.OPT ?**

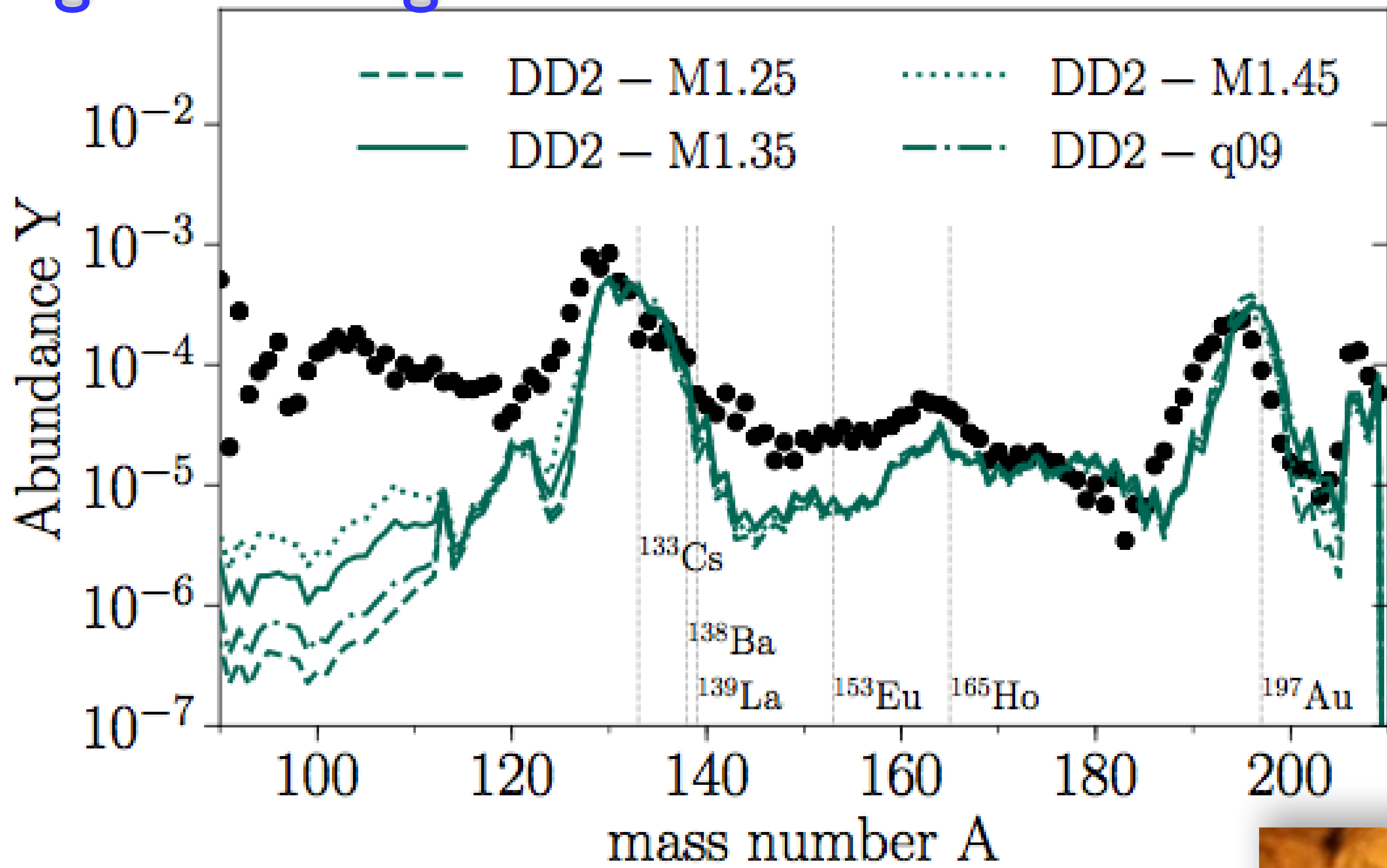
Gravitational Wave Emission from BNSM!



- Time dependence of instantaneous GW frequencies perfectly in phase with maximum density peaks

Light-Flash signals Creation of new Elements

Bovard, et al. 2017



Relative Abundance of cosmic elements
- Simulation vs. Observation
-T. Kodama '77

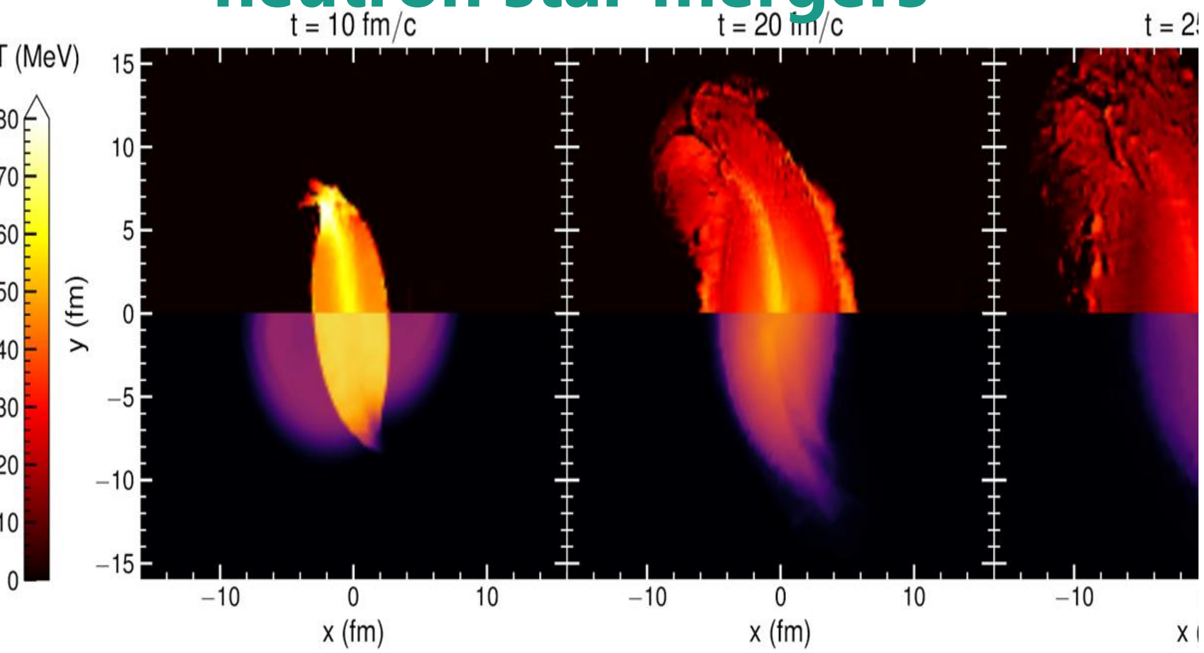
GW170817 produces lots of Gold, Platinum: 10x M_earth !

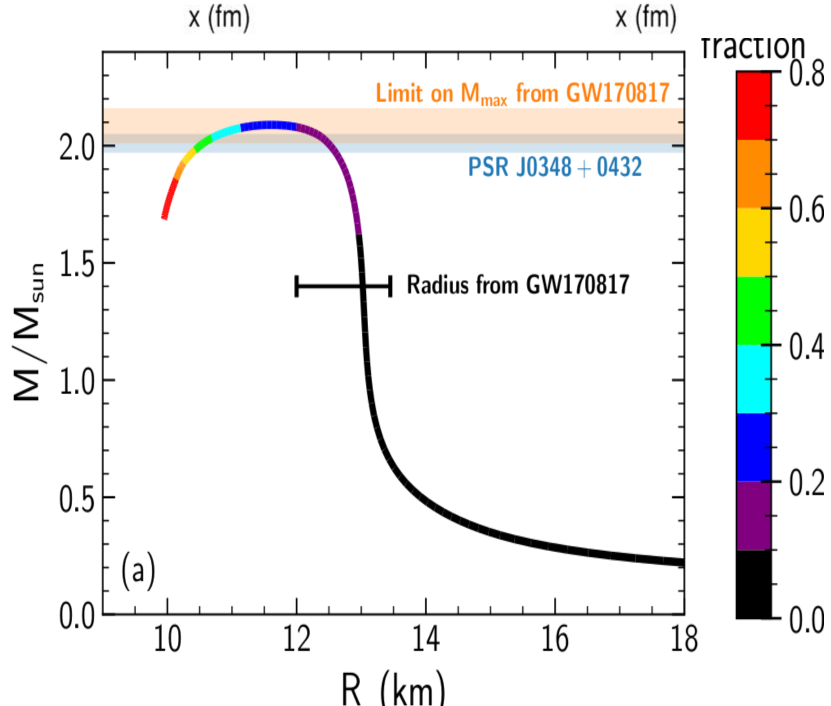
Tell Your politicians !

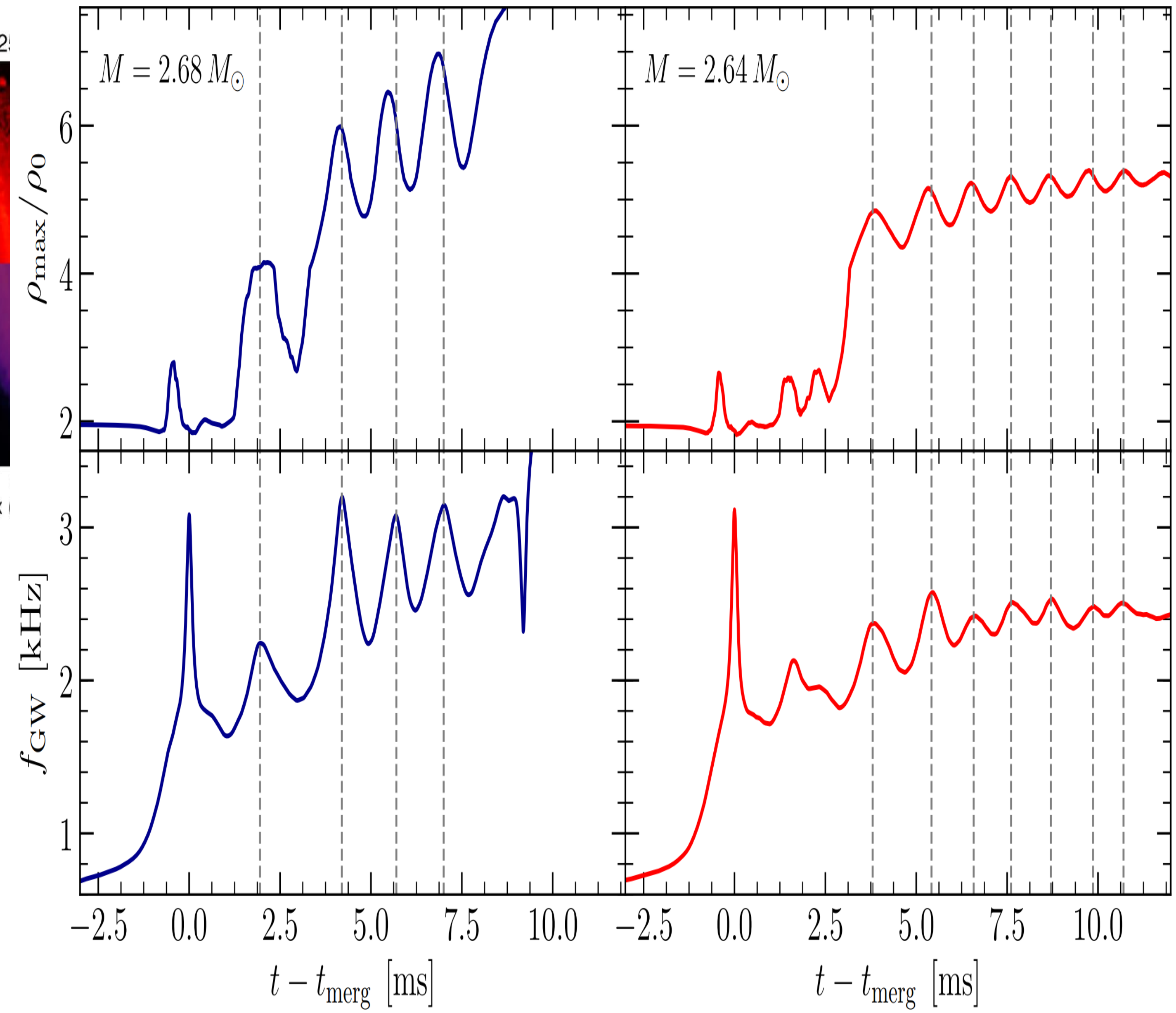
We found TONS of Gold!

The CMF model unified phenomenological approach to QCD thermodynamics, contains nuclear liquid-vapor phase transition, chiral symmetry restoration and crossover to quark matter.

- Perform phenomenological analysis of lattice QCD data
- Access high density regime of QCD thermodynamics
- Can be used as **EOS** for **heavy ion collisions**, **neutron stars**, and **binary neutron star mergers**







based on 1905.00866, A. Motornenko

Thanks for your attention!