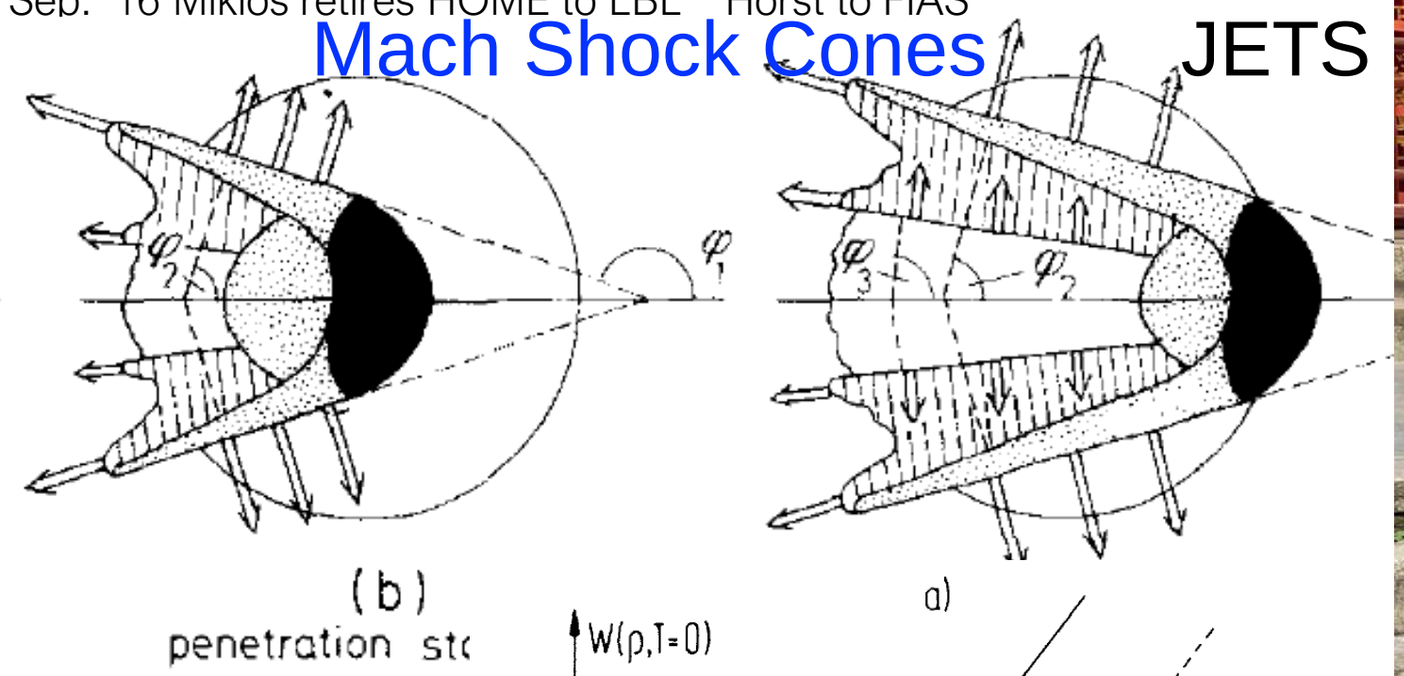

Alles Gute zum 210. Geburtstag, Miklos,
Larry & Jean-Paul

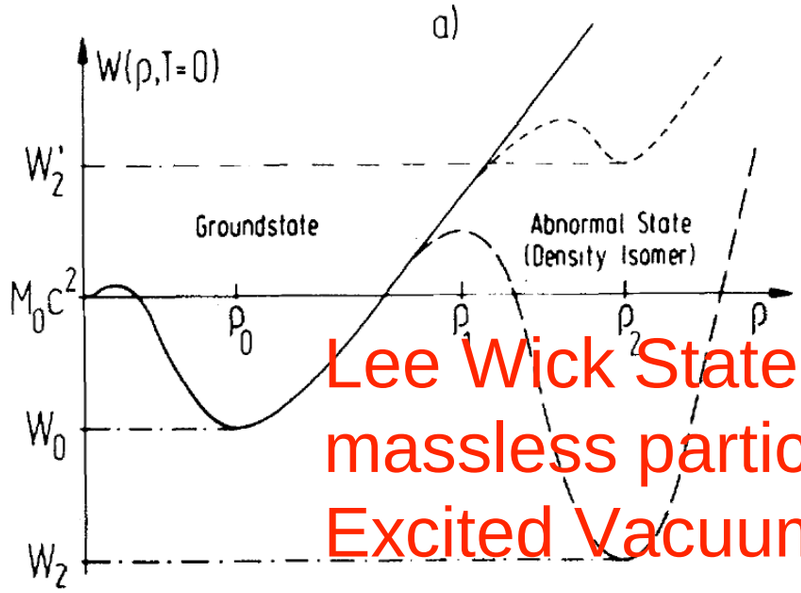
45 Years with Miklos & Gyoergyi … Family & Kids & “La Famiglia”

Summer 1974: QCD - GSI Starts - TD Lee’s Bear Mountain BNL Workshop - LBL-GSI HEHI Summer Study
Sep. ’74 Horst joins Walter Greiner’s Institute as grad.stud. “High Density Nuclear Shock Waves & the EoS”
Oct. ’74-76 Miklos joins as Walter’s Postdoc “Pion Condensation in Dense Hot Matter”
Nov. ’74 First HEHI Kolloq. Marburg
Jan. ’75 Miklos & Horst Bormio Winter Workshop - and many more to come!

Sep. ’80-81 Oda & Horst DAAD-Fellow at LBL Theory Group with Miklos & Gyoergyi, ’82-85 Ass.Prof. MSU + LBL PAC
Sep. ’86-87 Miklos AvH Award at ITP at Uni Frankfurt with Walter, Berndt & Horst, Gyoergyi & Oda
Sep. ’93 Miklos moves to Columbia & RBRC BNL with TD Lee & Larry McLerran. Horst: RHIC PC & AGS PAC
Apr. ’06-07 *MikLaz Visiting Prof. at ITP with Walter & Horst, Gyoergyi & Oda - Horst to GSI
Sep. ’16 Miklos retires HOME to LBL Horst to FIAS

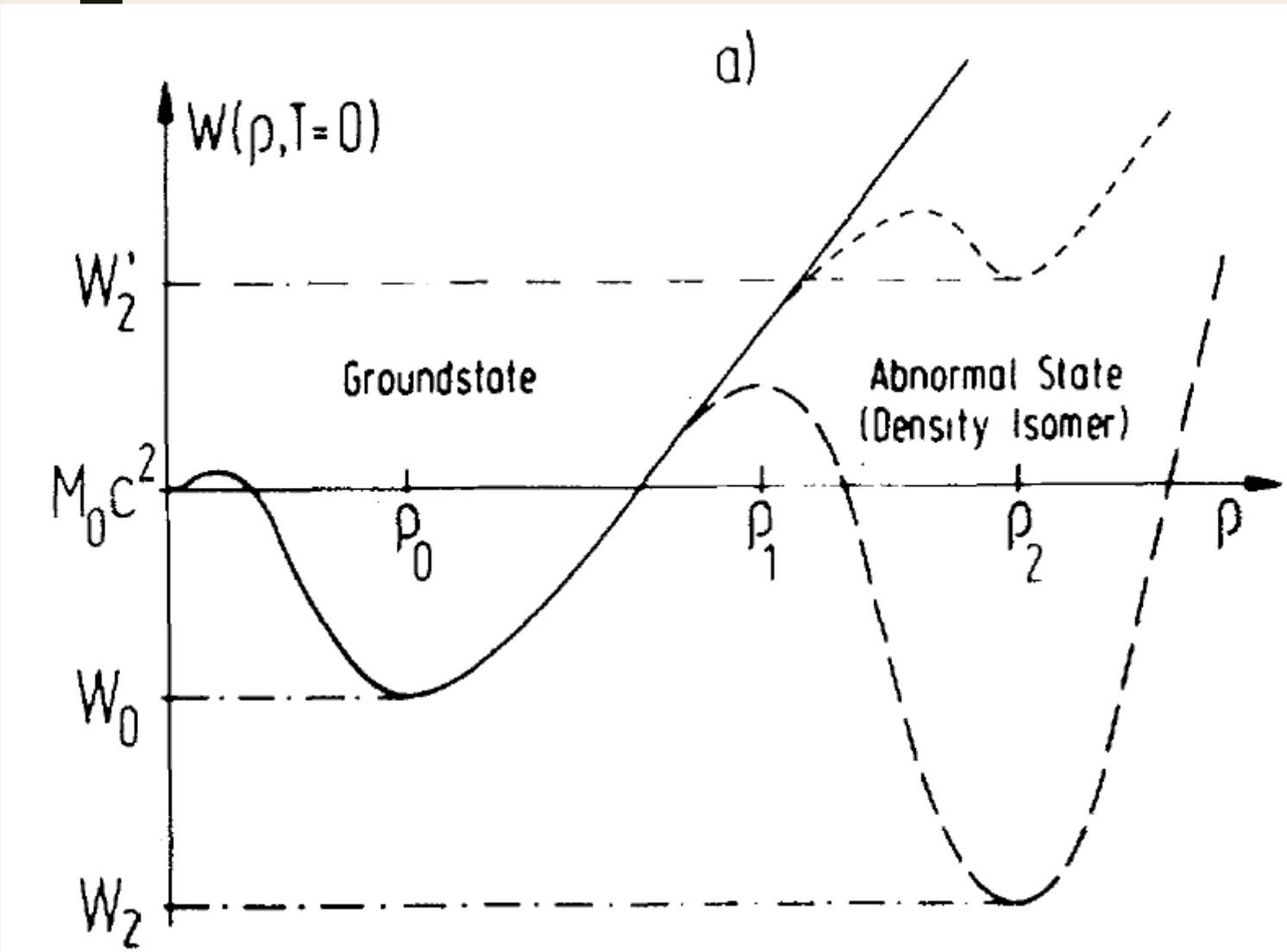
Mach Shock Cones JETS





Lee Wick State of massless particles Excited Vacuum

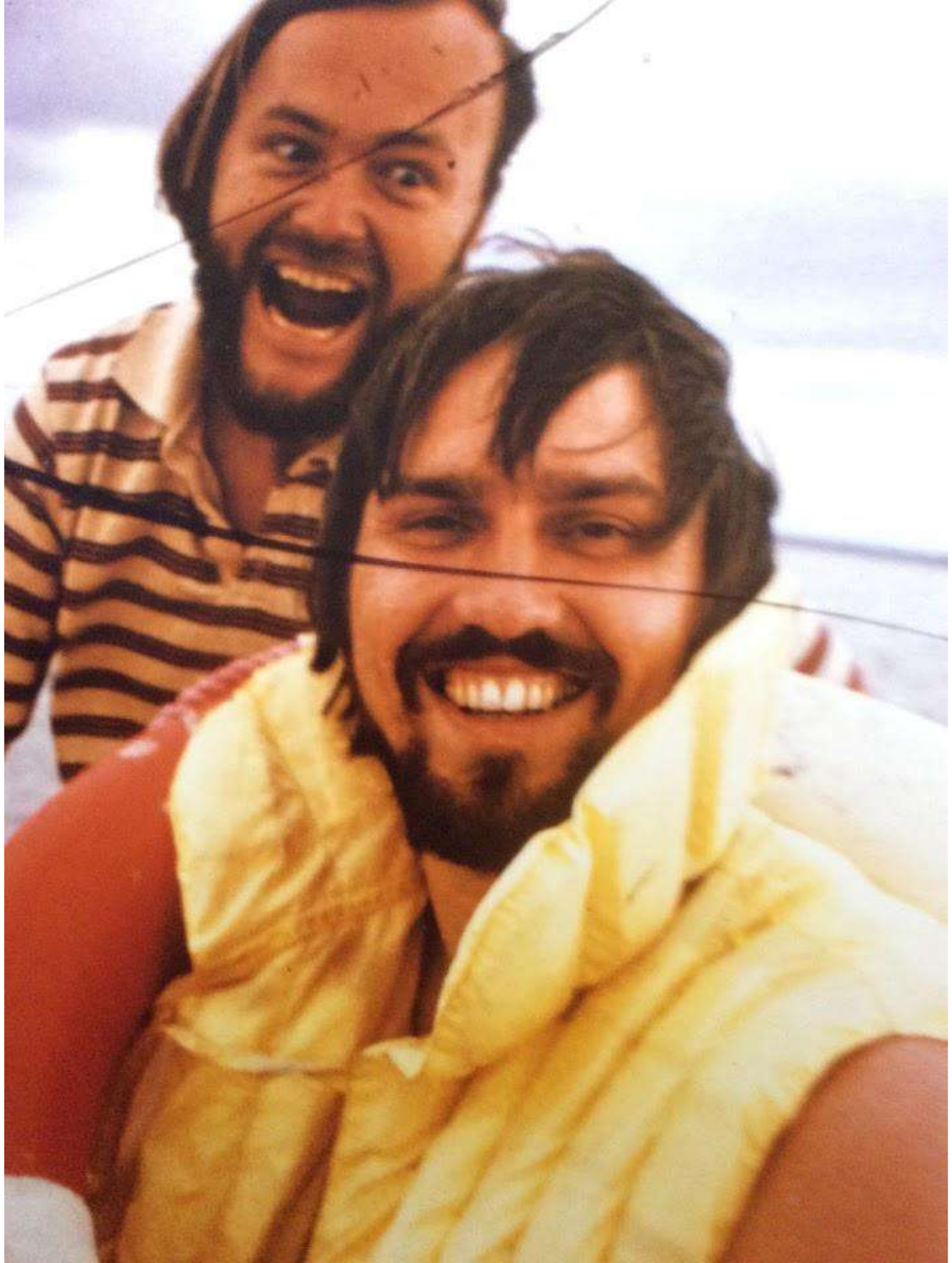
What is the EoS?

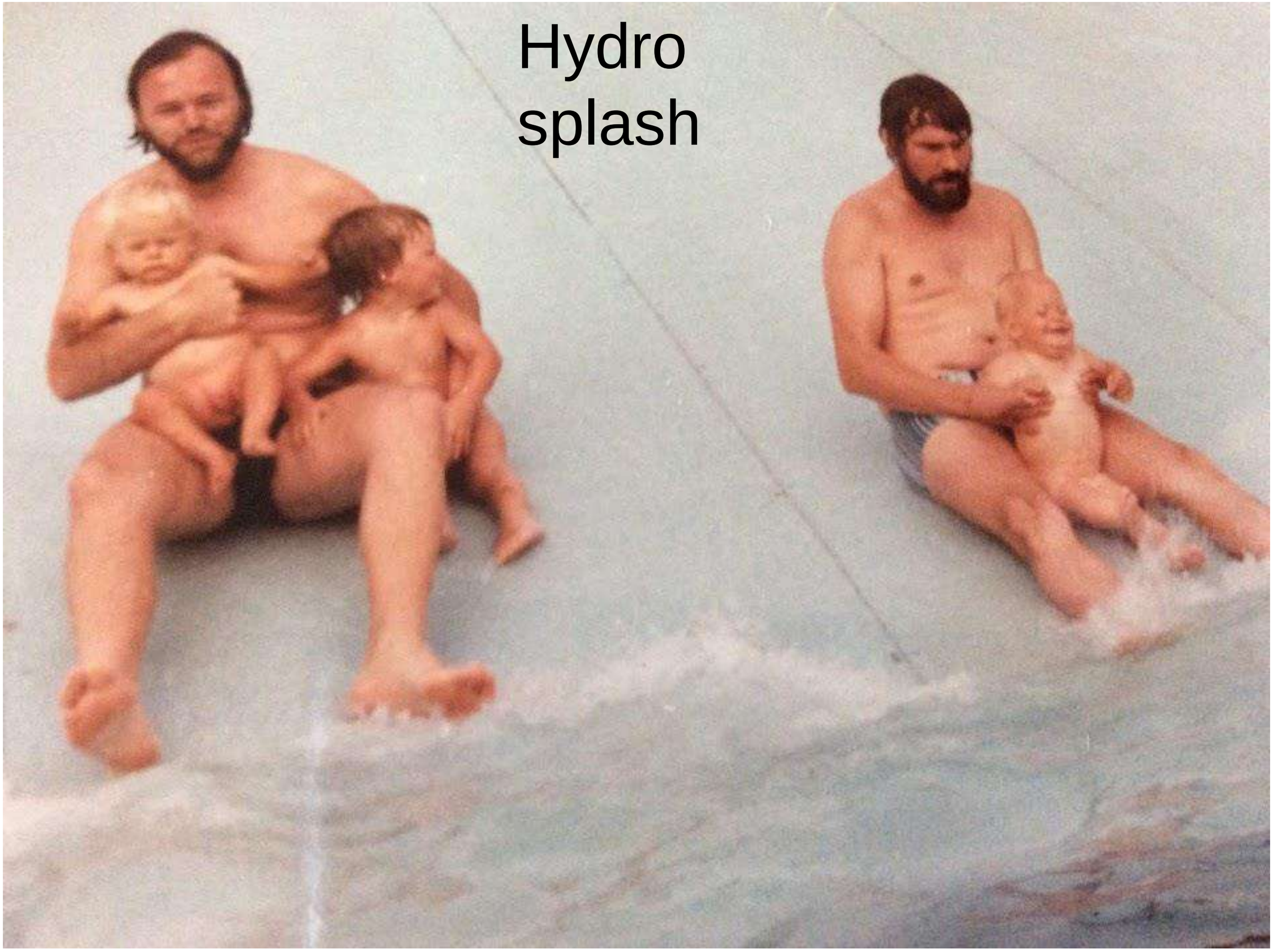


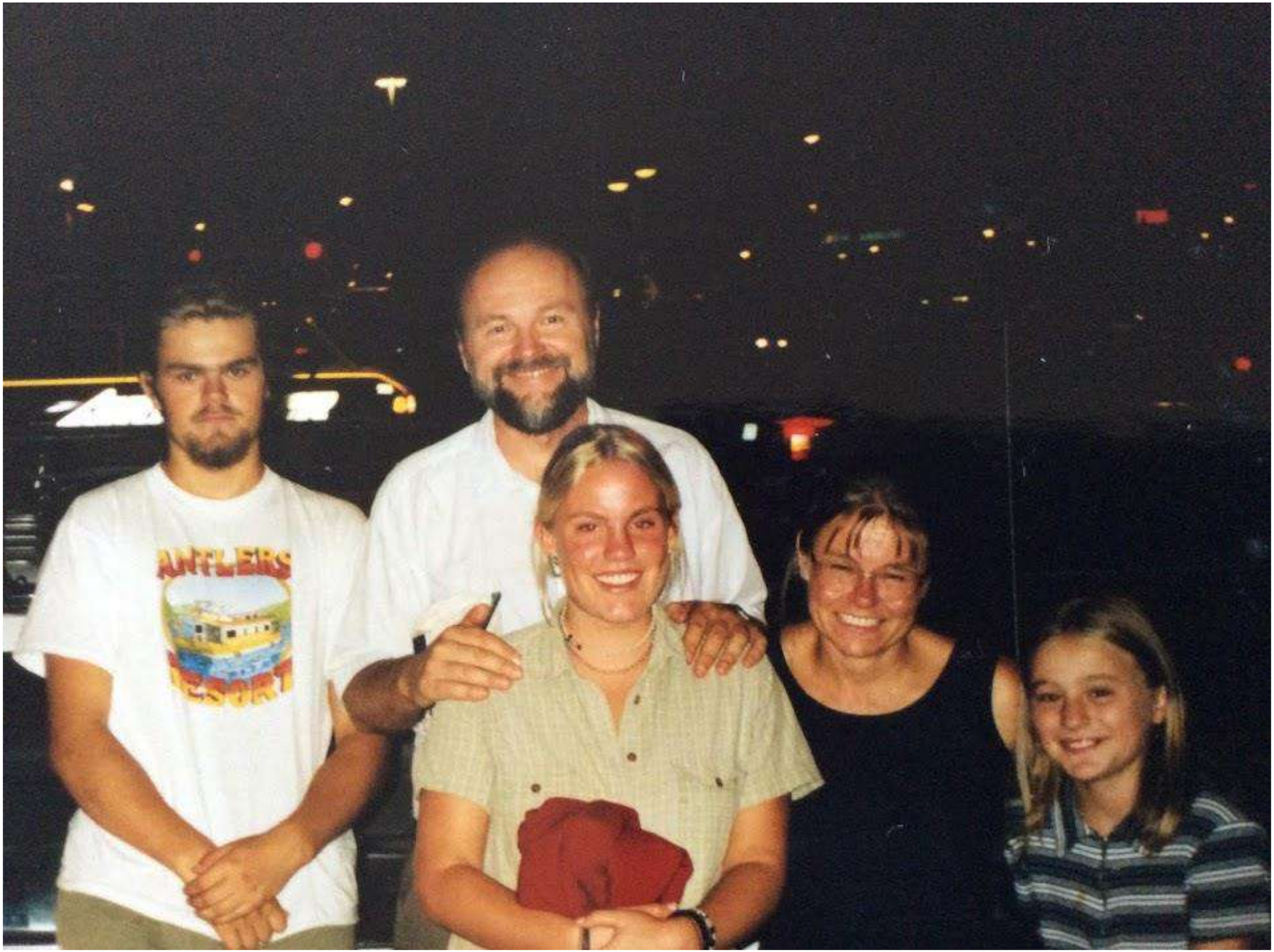
- The nuclear EoS offers endless research opportunities
- Binding energy of nuclear matter as function of the density E/A(n/n_0, T) ; p(n,T)
- n_0 =0.15 particles per fm^3. (Ten to the power of -45 cubic meters)
- How to verify this new state of matter?
- Goal of Heavy Ion Physics!

Larry McLaren: La Famiglia at Walter’s 60th


無
墳
永揚大道
Line
1




Hydro
splash


ANTLERS
RESORT

MAGIC

Matter, **A**strophysics, **G**ravitational waves & **I**on **C**ollisions

E. Most, A. Motornenko, J. Papenfort, M. Hanauske, V. Dexheimer, L. Rezzolla,

Stefan Schramm (deceased), J. Steinheimer, H. Stoecker*

FIAS & Institut Theoretische Physik Goethe Universitaet Frankfurt
*GSI Darmstadt, CCNU, Wuhan; HU, Huzhou; USTC, Hefei

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

FIAS GSI/FAIR

erc

Das Bild kann nicht angezeigt werden.

Matter, Gravity and Neutron Stars

1679 I. Newton published his theory of gravitation. According to Newton, gravity manifests itself as an instantaneous force between masses proportional to their masses and inversely proportional distance squared. With this theory he could explain all of the astronomical observations of this time.

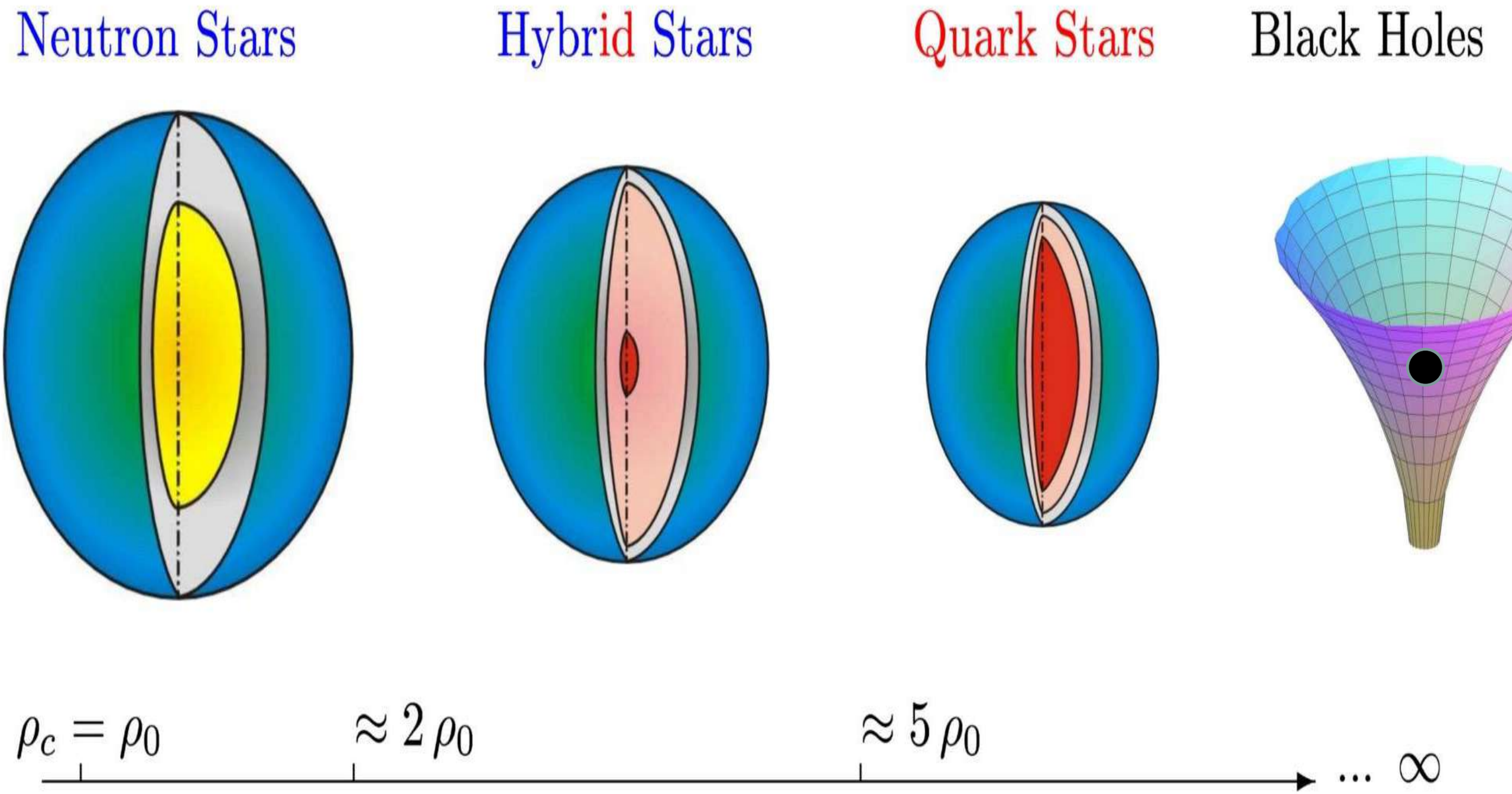
1915 **A. Einstein,** born in Ulm, published GR: Gravity governs the motion of masses and light by curving spacetime.

1915 **Karl Schwarzschild**, born1873 in Frankfurt am Main, found the static solution of GR - died in WW I just after publishing his article.

Consequences of SchwarzSchild's vision: **black holes, neutron stars**

Add Einstein's **Gravitational Waves - see a whole new Universe**

Neutron Star, Quark Star, Black hole ?

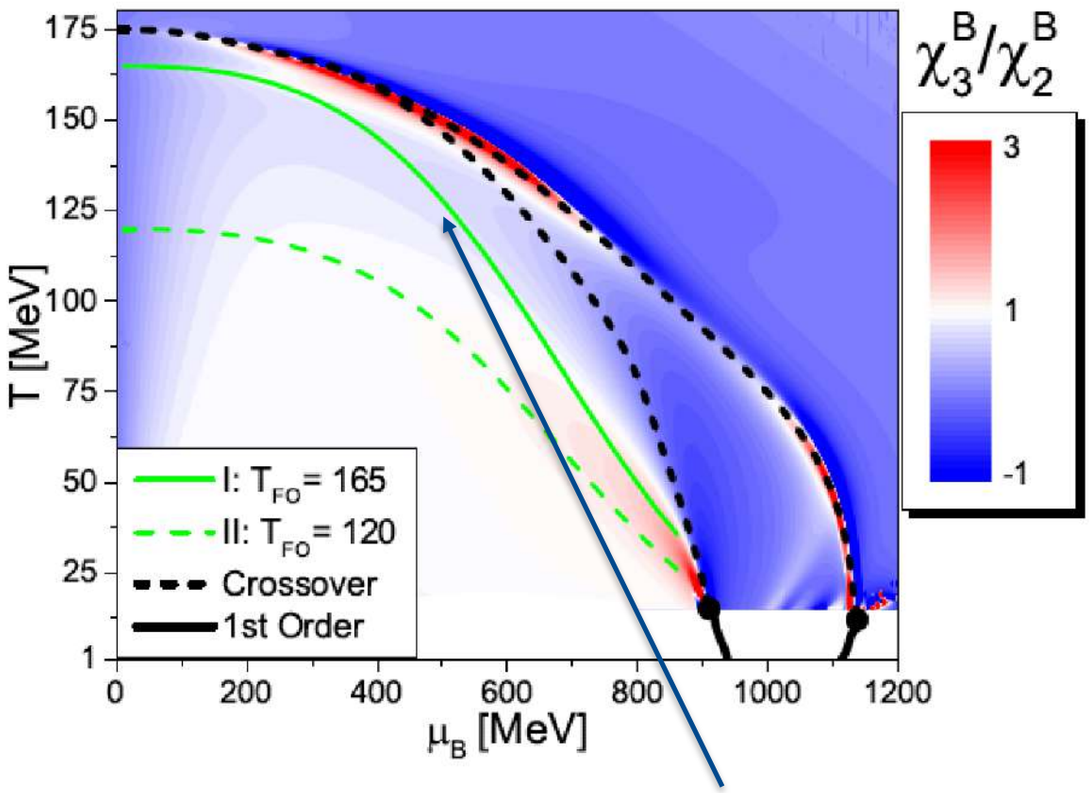


entral density ρ_c in the star

$(\rho_0 := 0.15/\mathrm{fm}^3)$

Chiral Mean Field CMF- Model - Quarks, Gluons and Hadrons in Heavy Ion collisions

PHYSICS



freeze-out curve

relativistic mean field model of quarks and hadrons
Interacting via mesonic fields / condensates

susceptibilities χ_i^B = fluctuations of baryon number

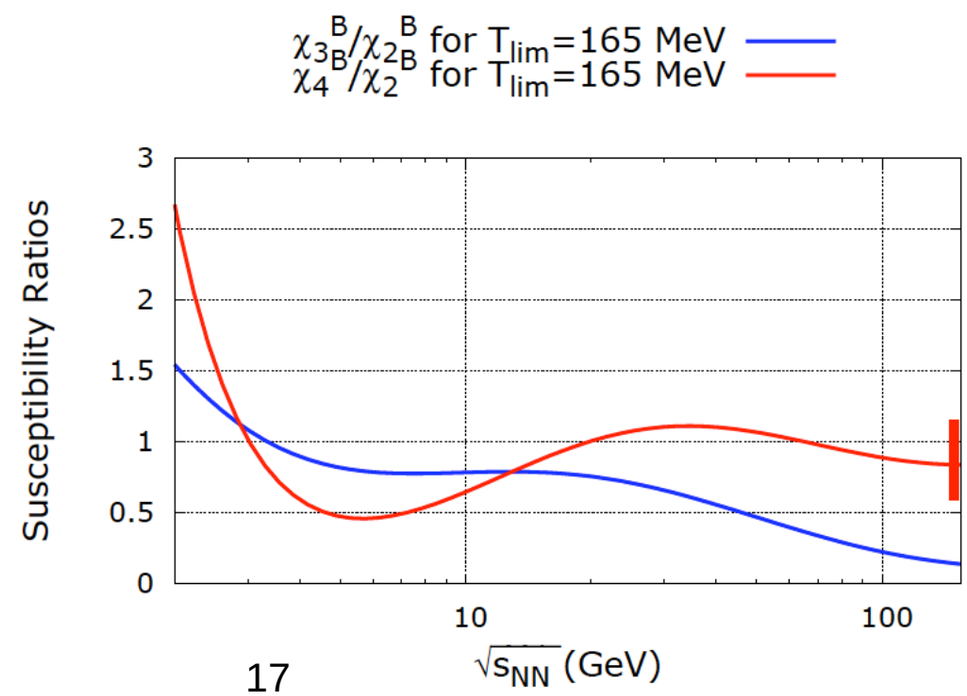
$\propto \langle (N-\bar{N})^i \rangle$

can be related / measured in heavy-ion experiments

structures in particle number fluctuations
Interference of liquid-gas and quark-hadron transitions

analysis requires model with good description of hadronic matter!

BMBF project (with Ivan Kisel)
to be integrated into UrQMD (Marcus Bleicher)

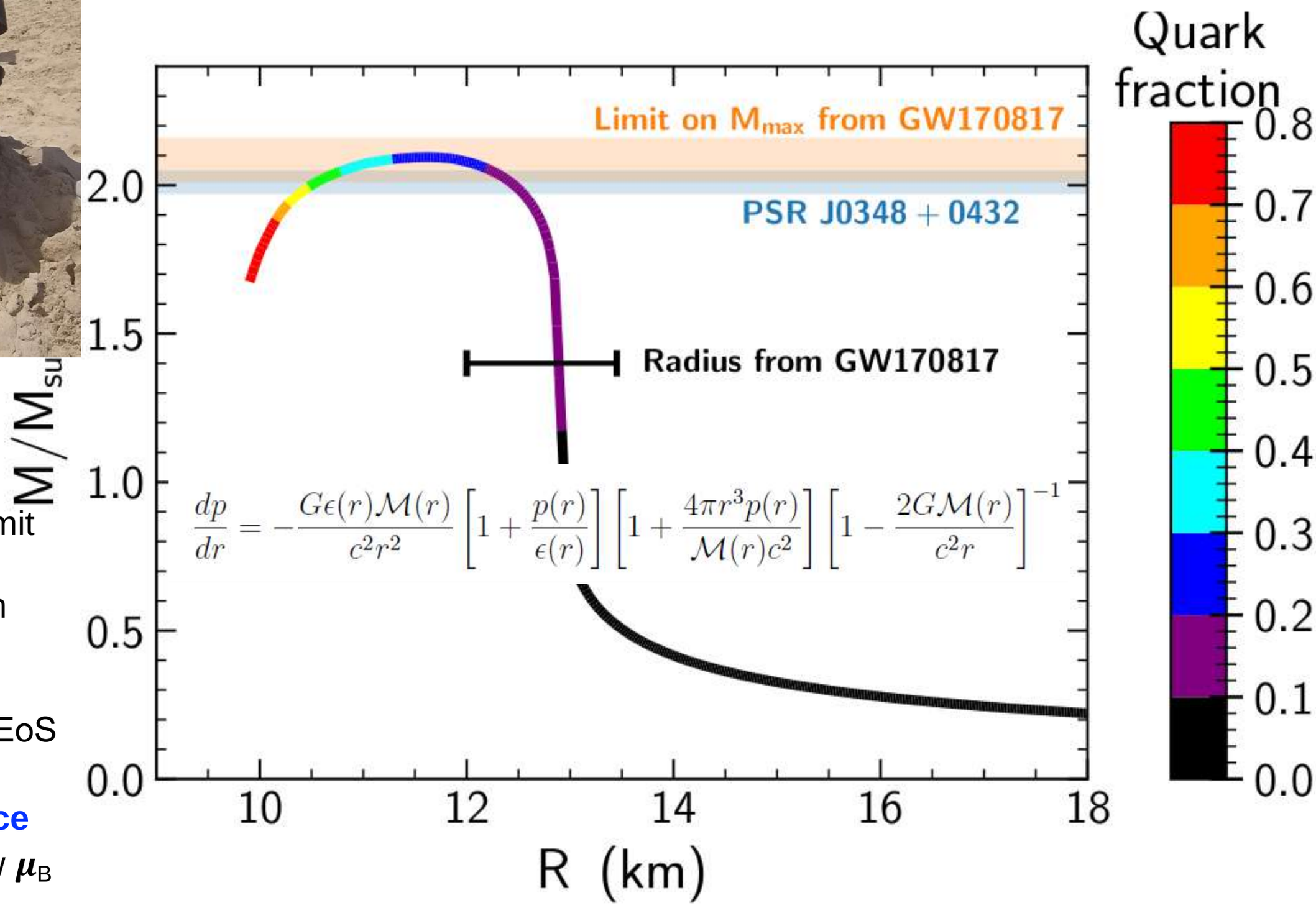


Mukherjee, Steinheimer, Stefan Schramm, arxiv:1611.10144

Neutron Star Masses-Radius Anton Motornenko- Wed

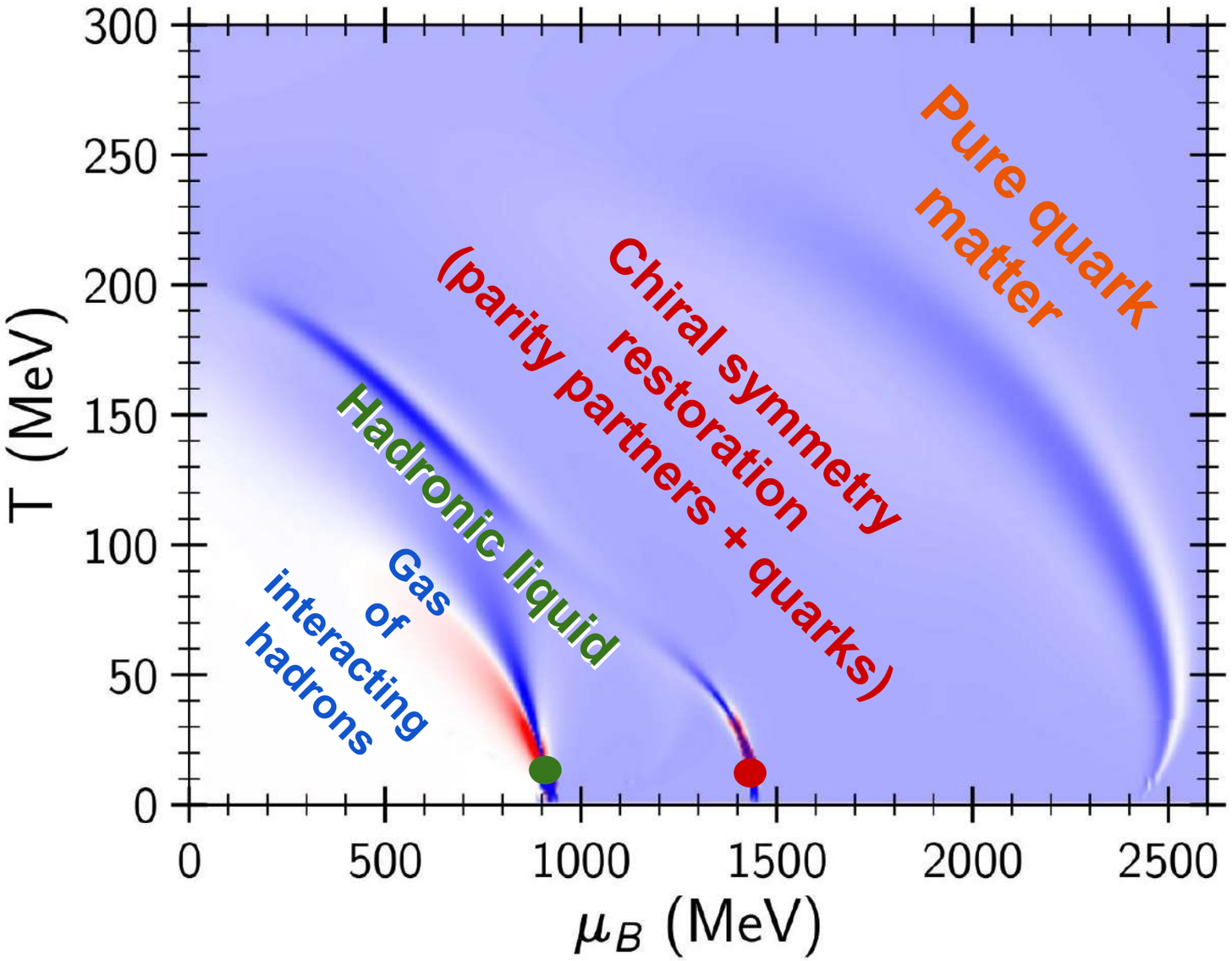
Maximum NS-mass observed =2.0xMsolar & <**2.1xMsolar-** limit of GW170817
Radii ~ 12-13km observed

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

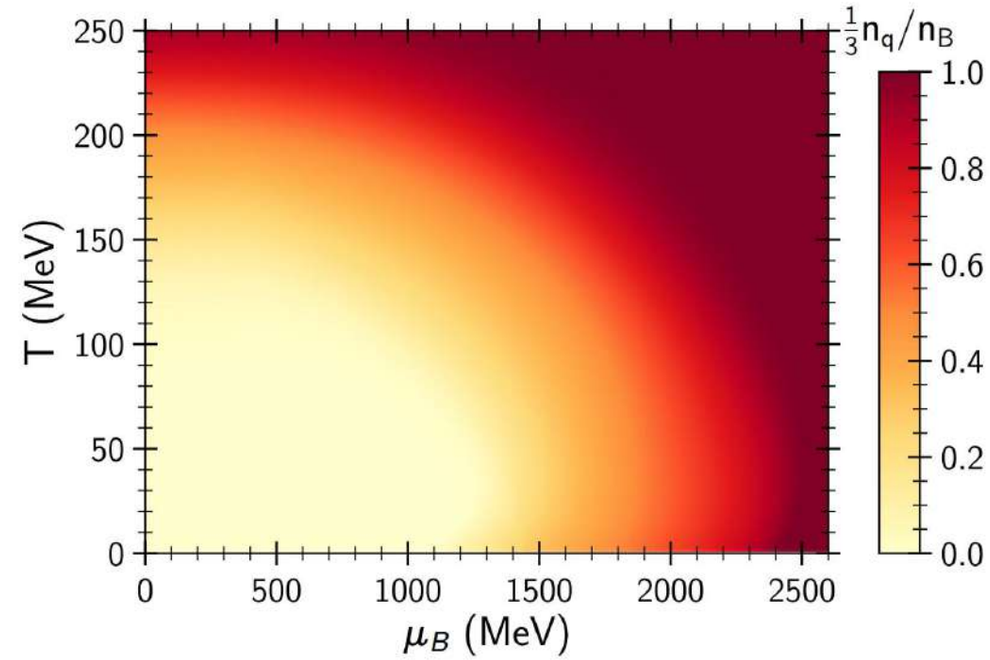


*Anton **Motornenko**, Vovchenko, Steinheimer, Stefan Schramm, Stoecker*
1809.02000, NPA (2019), QM'19 Wuhan

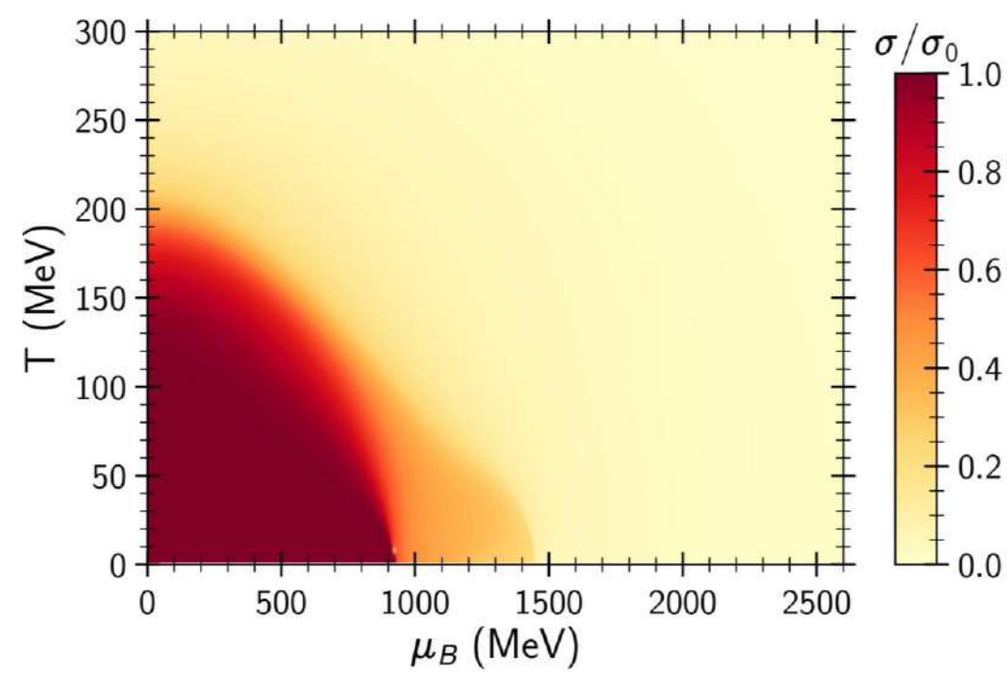
Phase diagram



Quark fraction:



Chiral condensate:



H. Stöcker, 2019

Relating to heavy ion collisions: 1D hydro

We estimate trajectories along the phase diagram with a simple **1D hydro model**:

- baryonic charge in heavy ion collisions is conserved **B = const**
- produced matter is a perfect fluid ⟶ **no dissipations** ⟶ total entropy is constant

This gives: constant entropy per baryon **S/A = const**, the same as entropy density / baryon density **s/n_B = const**

Evolution occurs **along** lines of constant entropy per baryon:

How one can relate collision energy s_{NN} to produced entropy?

Relativistic Rankine-Hugoniot Equations

A. H. Taub
*University of Illinois, Urbana, Illinois and Institute for Advanced Study, Princeton University, Princeton, New Jersey**
(Received April 13, 1948)

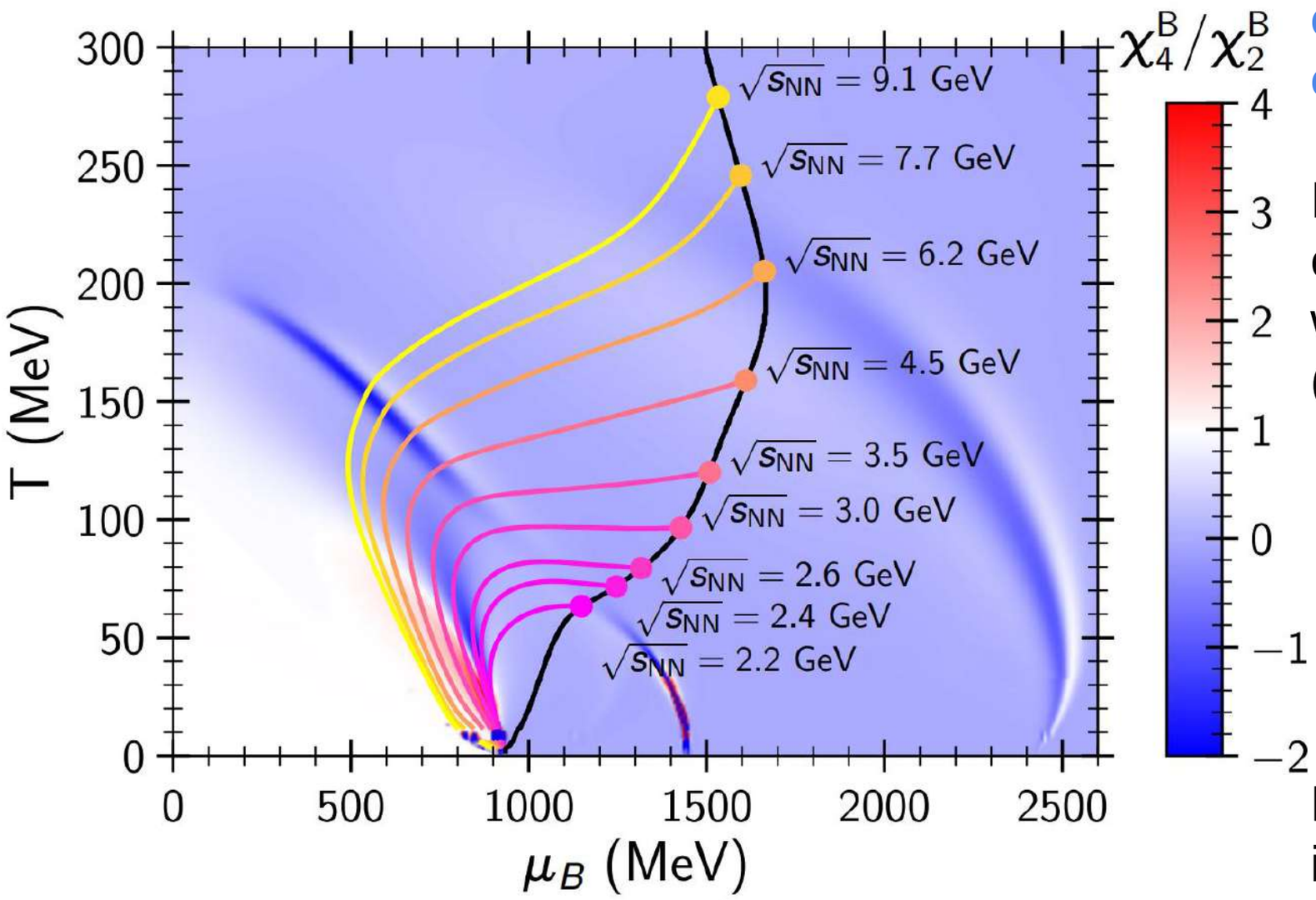
The relativistic Rankine–Hugoniot equations can be derived from the continuity of the

particle flux density	$[j^0] = [\rho u_x] = 0$	
energy flux density	$[T_{0x}] = [\mathrm{i}\, u_0 u_x] = 0$	(II.88)
and momentum flux density	$[T_{xx}] = [\mathrm{i}\, u_x^2 + P] = 0$	

Horst Stoecker and Walter Greiner, Phys.Rept. 137 (1986) 277-392

H. Stöcker, 2019

Probing phase diagram by heavy ions collisions



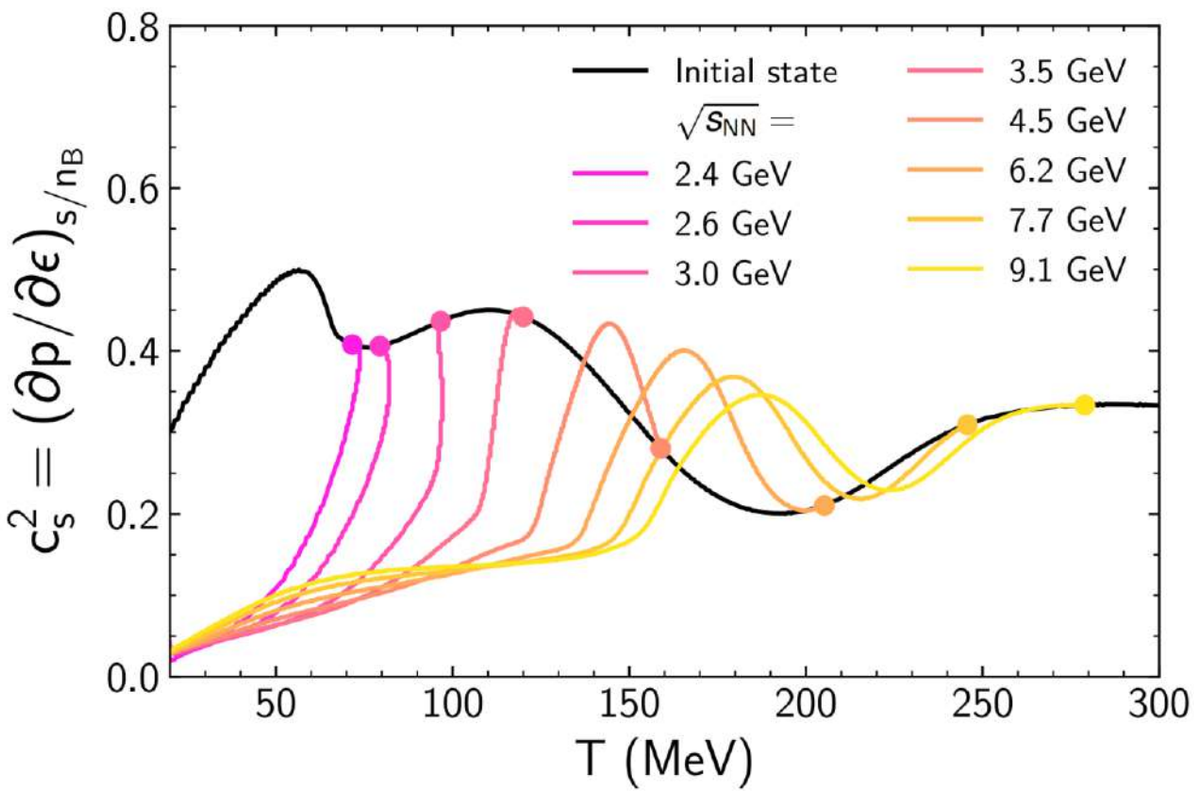
Isentropes (**S/A** = const) illustrate hydrodynamical evolution of the **central region in heavy ion collision**.

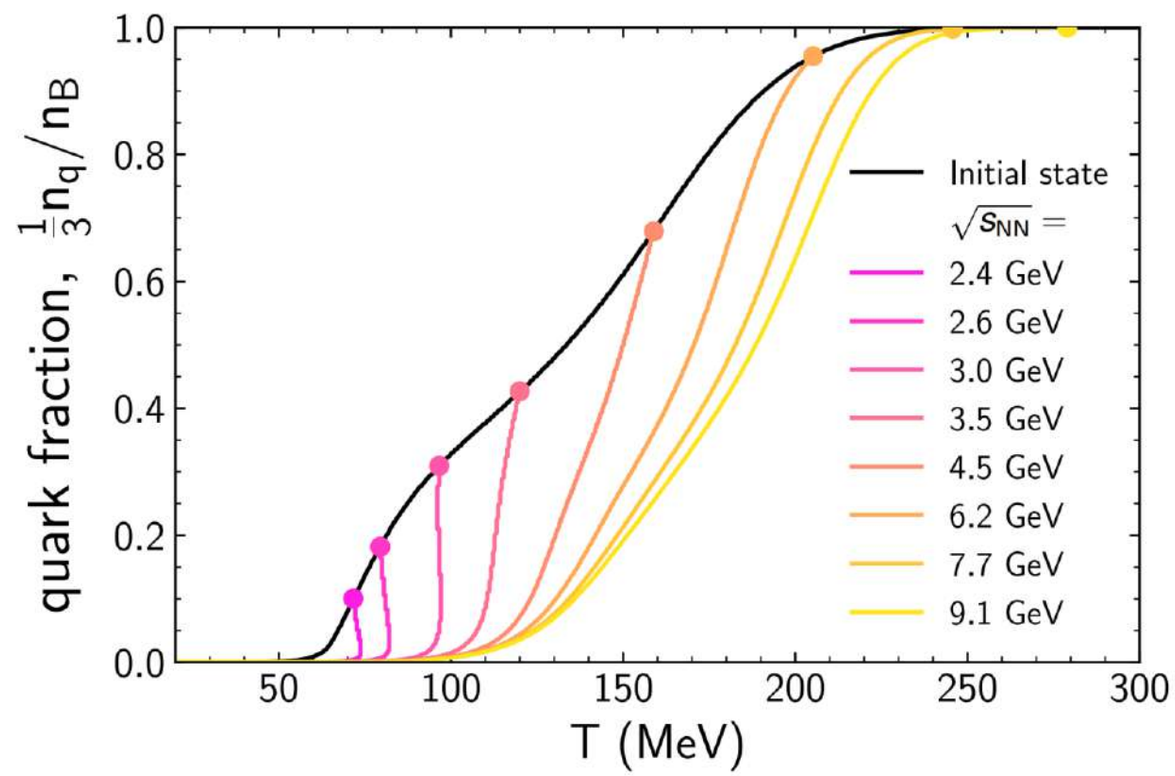
Initial entropy per baryon S/A, was estimated by **Taub adiabat** (shock wave solution):
(*A. H. Taub, Phys. Rev. 74, 328 (1948)*)

$$\begin{cases} \dfrac{(P_0+\varepsilon_0)\,(P+\varepsilon_0)\,n^2}{(P_0+\varepsilon)\,(P+\varepsilon)\,n_0^2} = 1, \\ \gamma = \dfrac{\varepsilon\, n_0}{\varepsilon_0\, n} \\ \gamma = \sqrt{\dfrac{1}{2}\left(1+\dfrac{E_{\rm lab}}{m_N}\right)} \end{cases}$$

P_0, ε_0, and n_0 correspond to the initial pressure, energy density, and baryon density in the local rest frame of each slab

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 $\sqrt{s_{NN}} \gtrsim 7$ GeV:

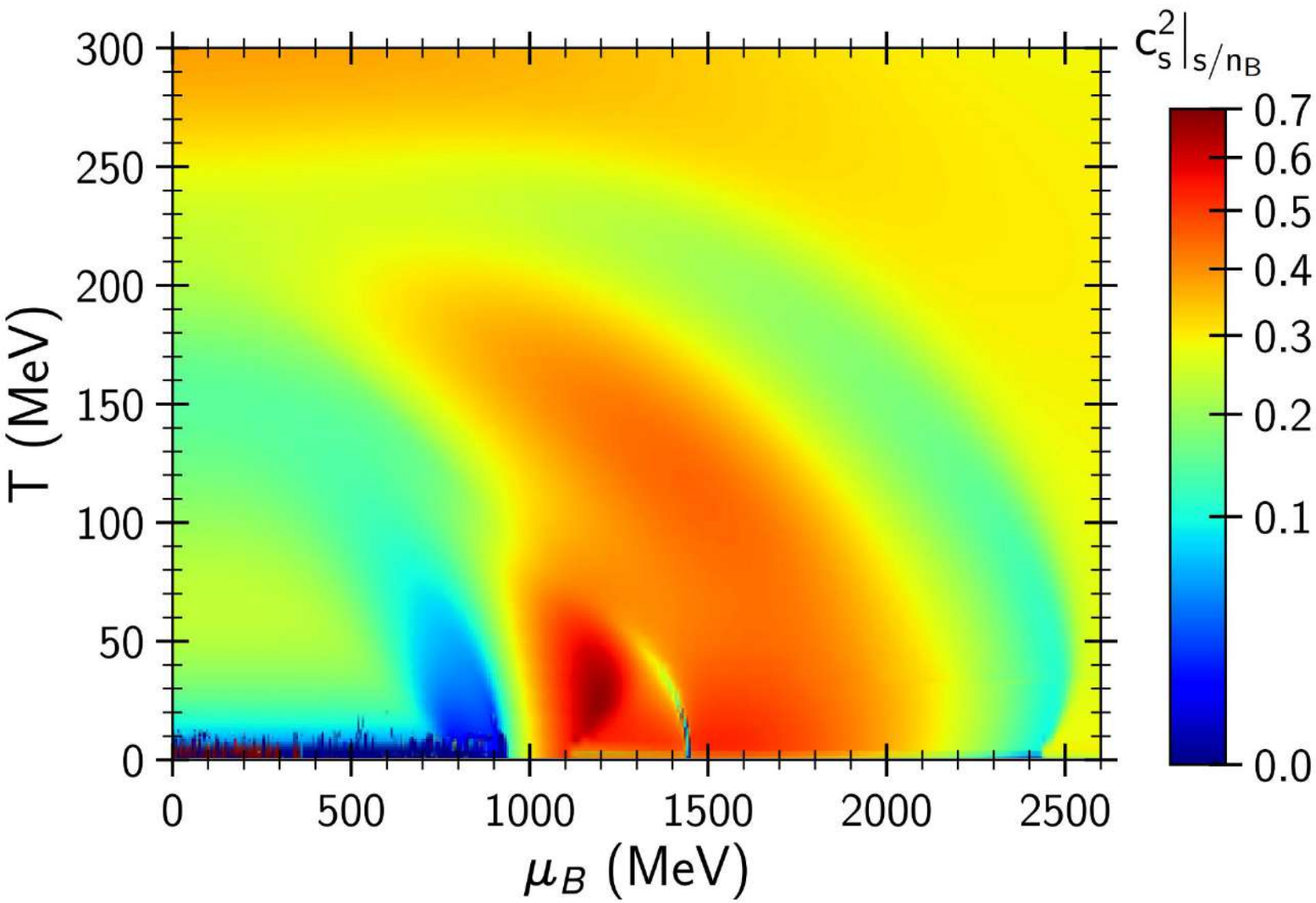
1. start at the quark phase
2. softest point of deconfinement
3. baryons rapidly appear providing repulsion and increase of c_S^2
4. transition to dilute hadronic phase and lowering of c_S^2

H. Stöcker, 2019

Speed of sound

Isentropic speed of sound in T-μ_B plane (S. Floerchinger and M. Martinez, 1507.05569):

$$c_s^2 = \frac{n_B^2\,\partial_T s - 2\,n_B\,s\,\partial_{\mu_B} s + s^2\,\partial_{\mu_B} n_B}{(\epsilon + P)\left(\partial_{\mu_B} n_B\,\partial_T s - (\partial_T n_B)^2\right)}$$



The model provides relativistic consistency **c_s<1**;

Structures in c_s coincide with the structures in the susceptibilities;

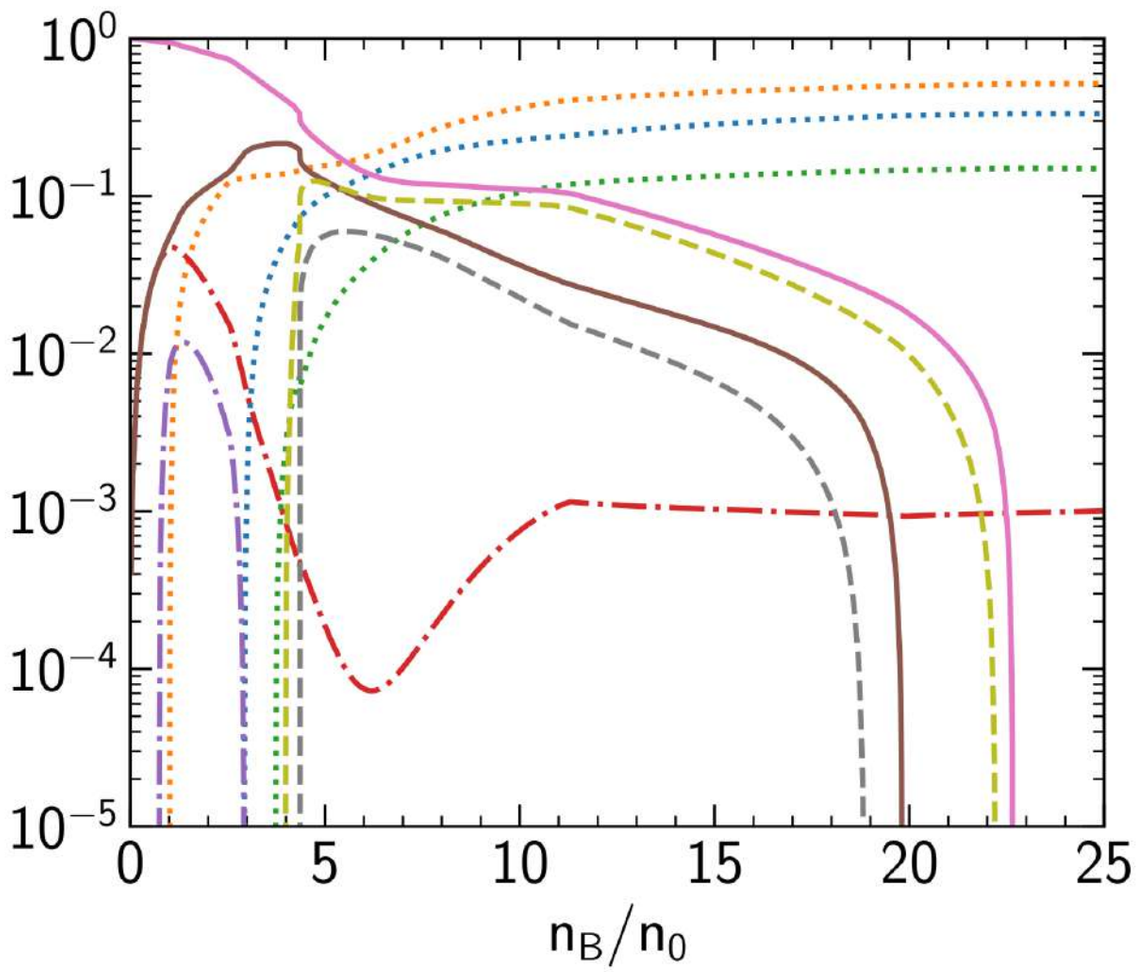
At critical regions local minima of c_s are present;

Nuclear liquid provides **large values c_S≈0.8**, result of the **strong baryon repulsion**;

H. Stöcker, 2019

Equation of state at T=0: neutron stars

Particle yields normalized to baryon density:

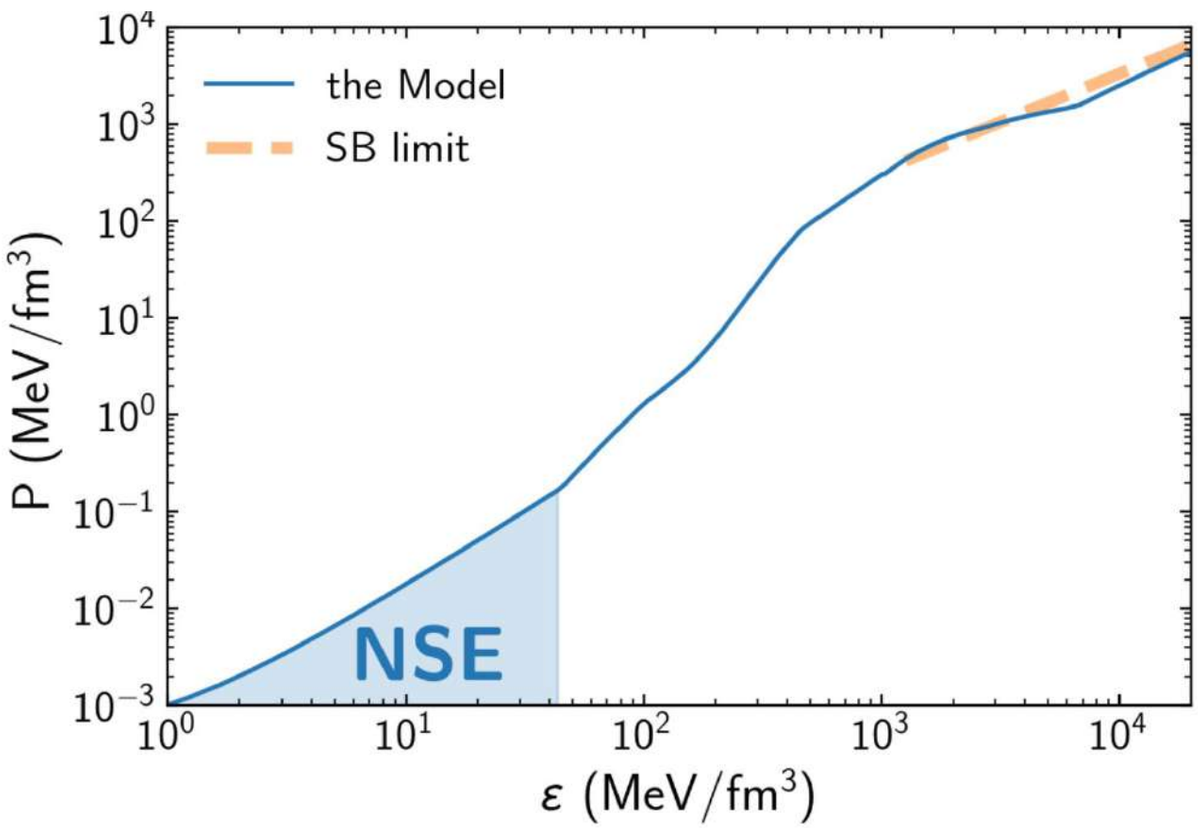


Equation of state for **neutron stars**:

- **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 $T \neq 0$)
- **Strange quarks** are included

H. Stöcker, 2019

Application to neutron stars



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:

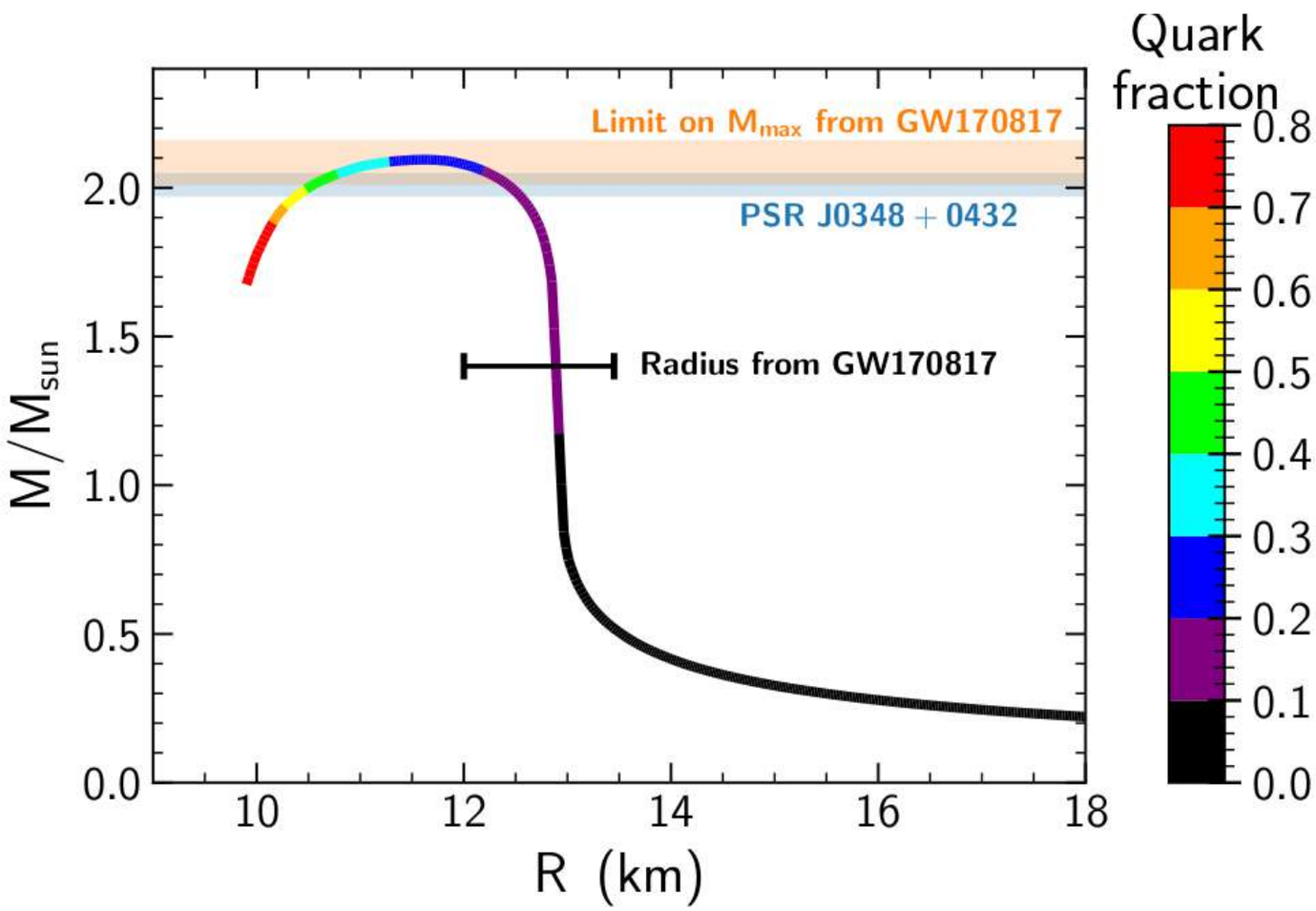
$$\frac{dP}{dr} = -\frac{Gm}{r^2}\rho\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi r^3 P}{mc^2}\right)\left(1-\frac{2Gm}{rc^2}\right)^{-1}$$

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

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

H. Stöcker, 2019

Mass-radius relations

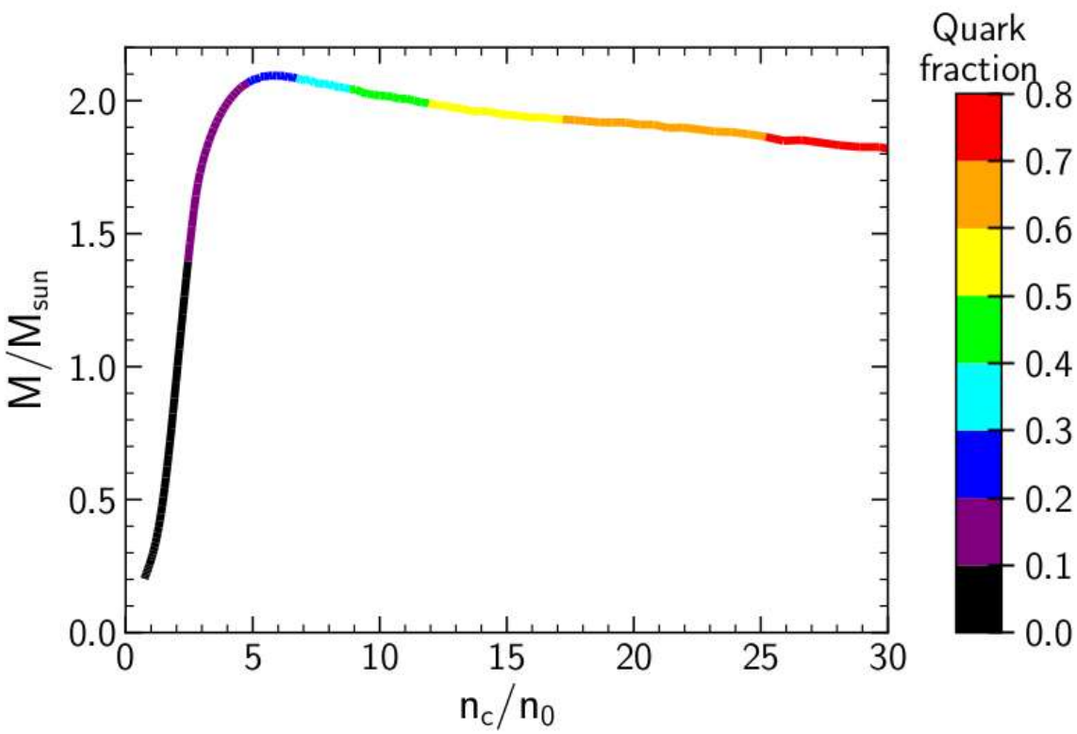


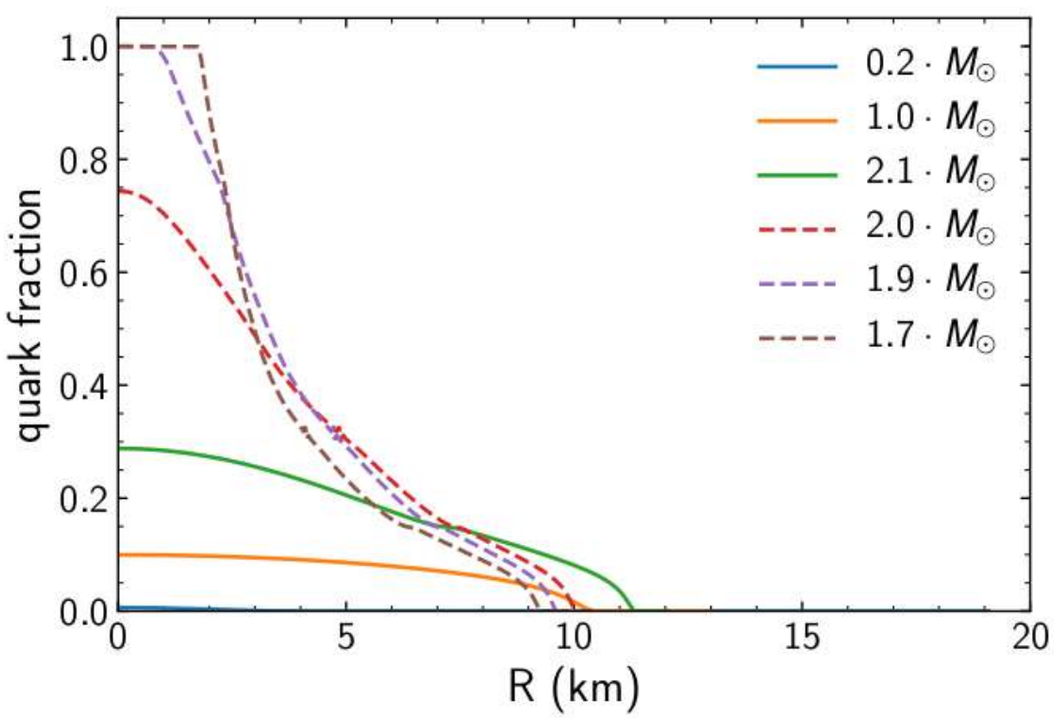
- EoS is stiff enough to provide $2M_{sun}$ neutron stars
- No second family of NS
- quark fraction < 30% for stable stars
- Agreement with observations

Maximal mass is in agreement with recent constraints on maximal mass of neutron star from GW170817:

$$2.01^{+0.04}_{-0.04} \leq M_{\mathrm{TOV}}/M_{\odot} \lesssim 2.16^{+0.17}_{-0.15}$$ *zzolla, Most, Weih, 1711.00314*

Quark content



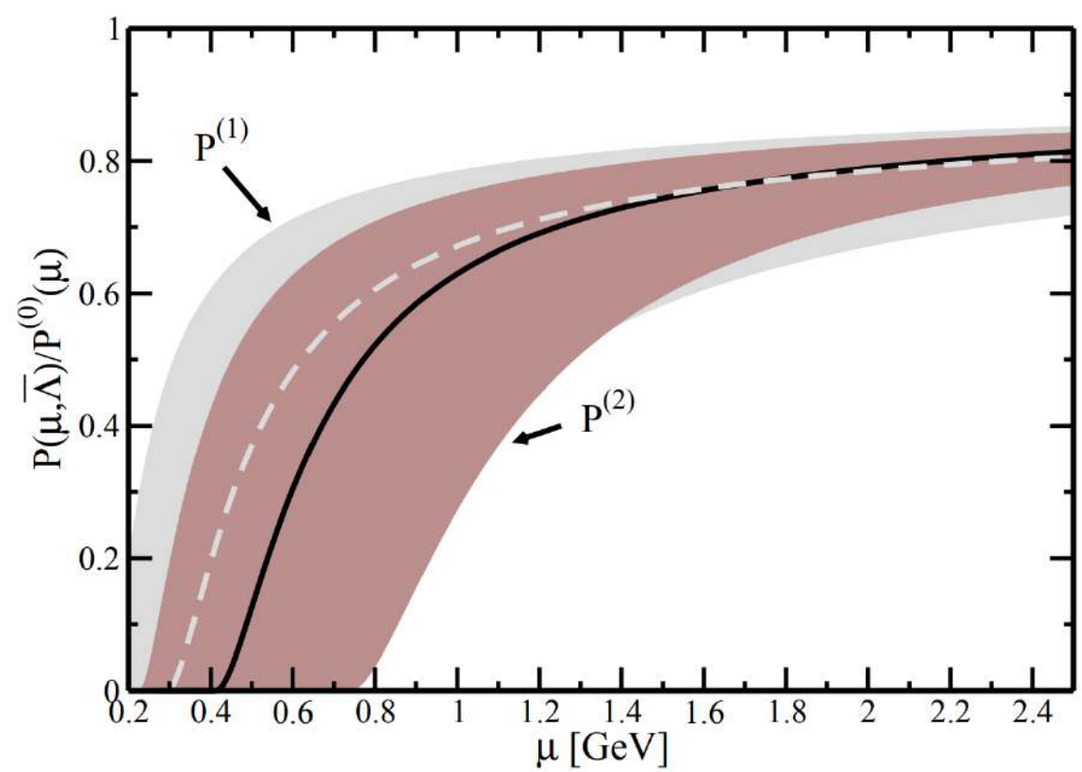


Local quark fraction (dashed — unstable stars):

Quarks appear smoothly — no separation between phases.

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

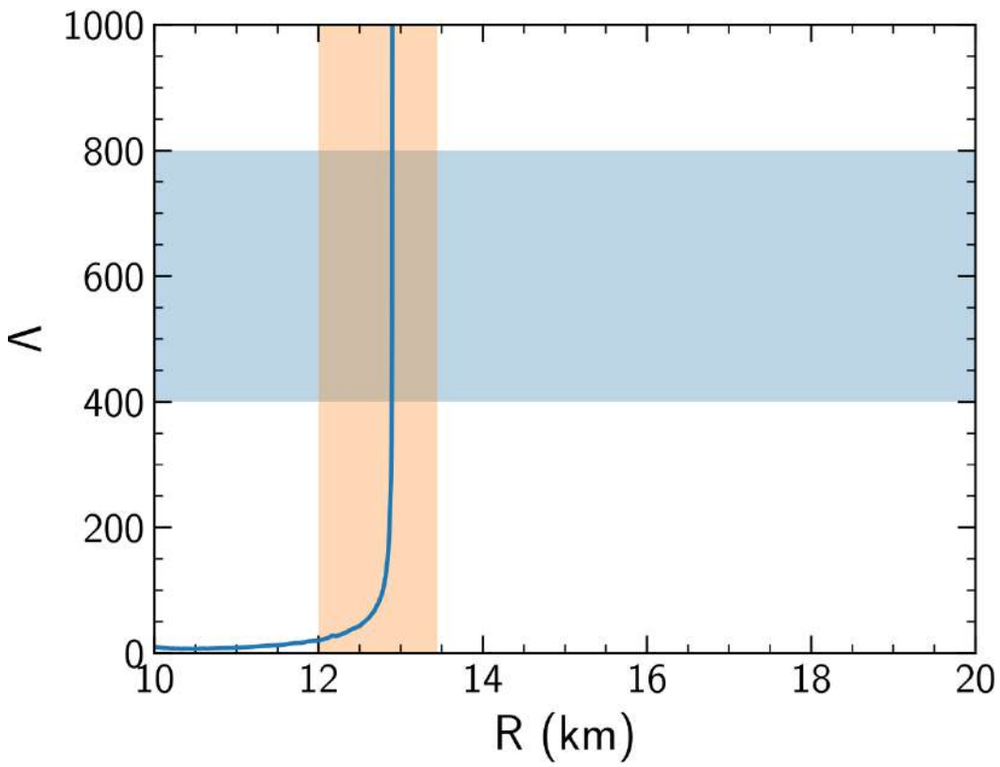
Quarks give significant contribution to stars with central density $n_c > 6n_0$,
where pQCD calculations for EoS are available:

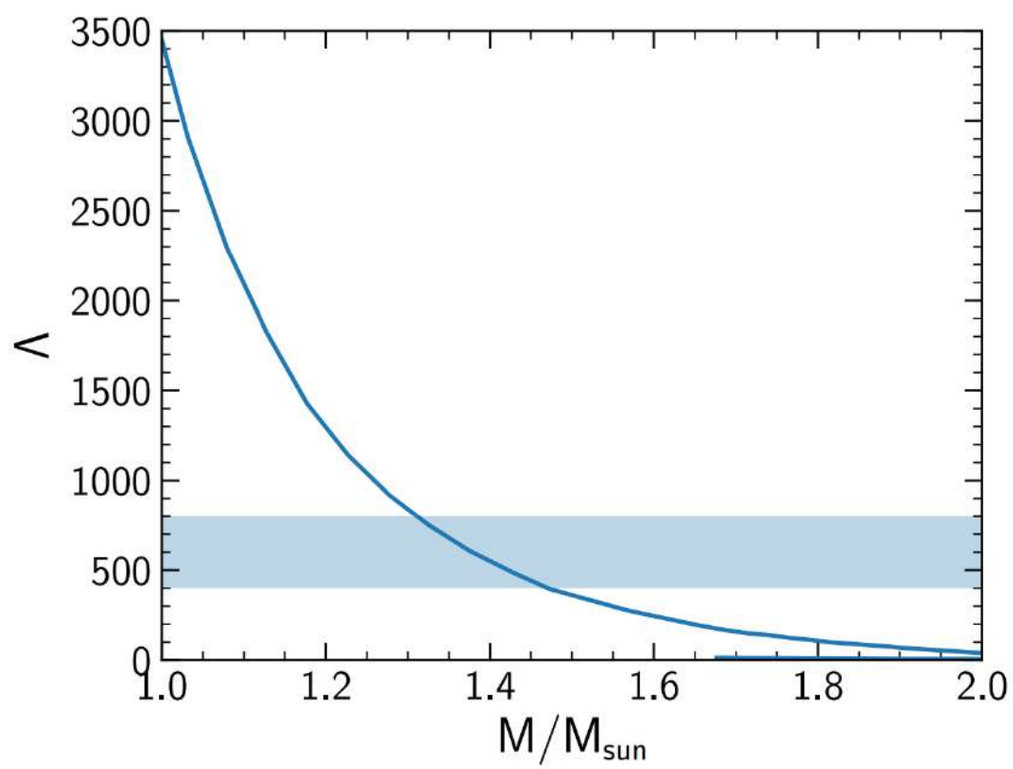


A. Kurkela, P. Romatschke, A. Vuorinen, 0912.1856

H. Stöcker, 2019

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.

H. Stöcker, 2019

Summary

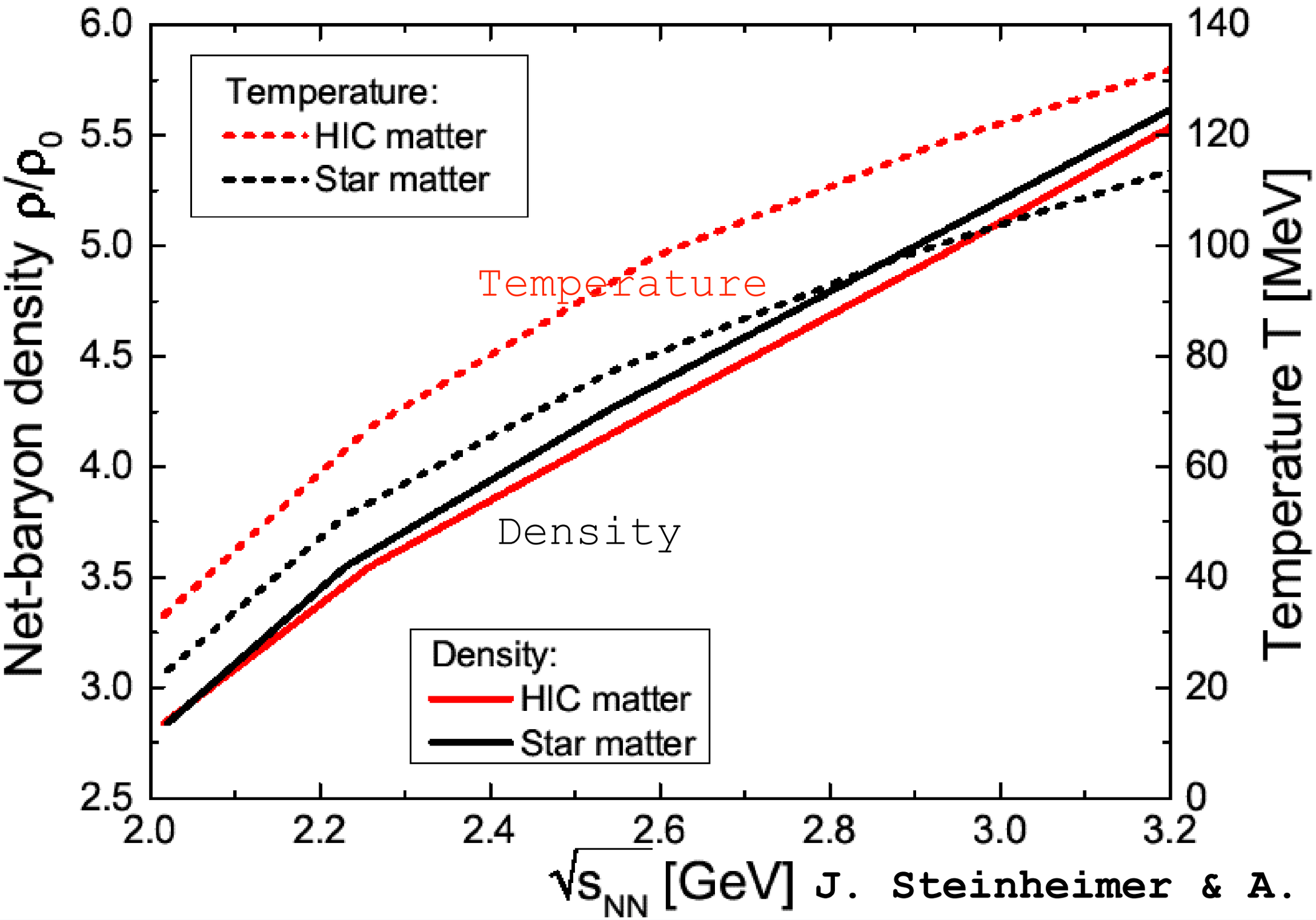
- **Chiral SU(3) parity-doublet quark-hadron mean-field model** — unified phenomenological approach to model QCD thermodynamics at wide range of scales;
- μ_B=0 lattice QCD data is used to constrain parameters of model's quark sector;
- Nuclear liquid-vapor phase transition gives strong signals in fluctuations 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.

Thanks for your attention!

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

FIAS Frankfurt Institute for Advanced Studies

+ 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

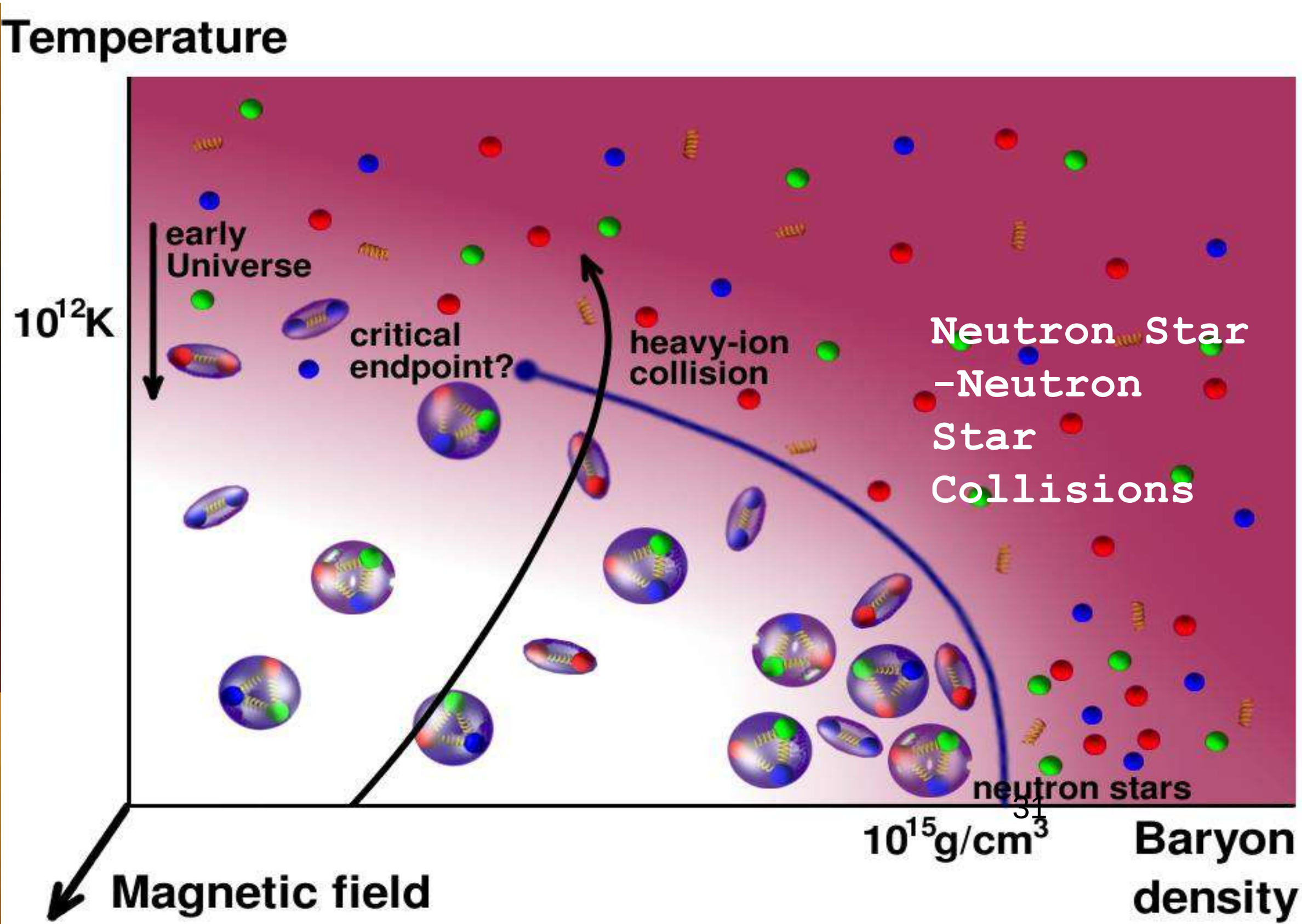
conserve baryon number and energy momentum current densities across shock front yields stationon.1+1D, hydrodynamical equation for n, p vs E:

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

J. Steinheimer & A. Motornenko

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

FAIR: Relativistic collisions of NS-NS vs. Heavy Ions



Death-Star- Machines - FAIR HIAF NICA STAR
NeutronStar matter in the Lab - Heavy Ion Collisions
Charm and Beauty of International Collaboration

Observers

Finland France Germany India Italy Poland Slovenia Spain Sweden Romania Russia

Rosatom

ustria Czech

ungary

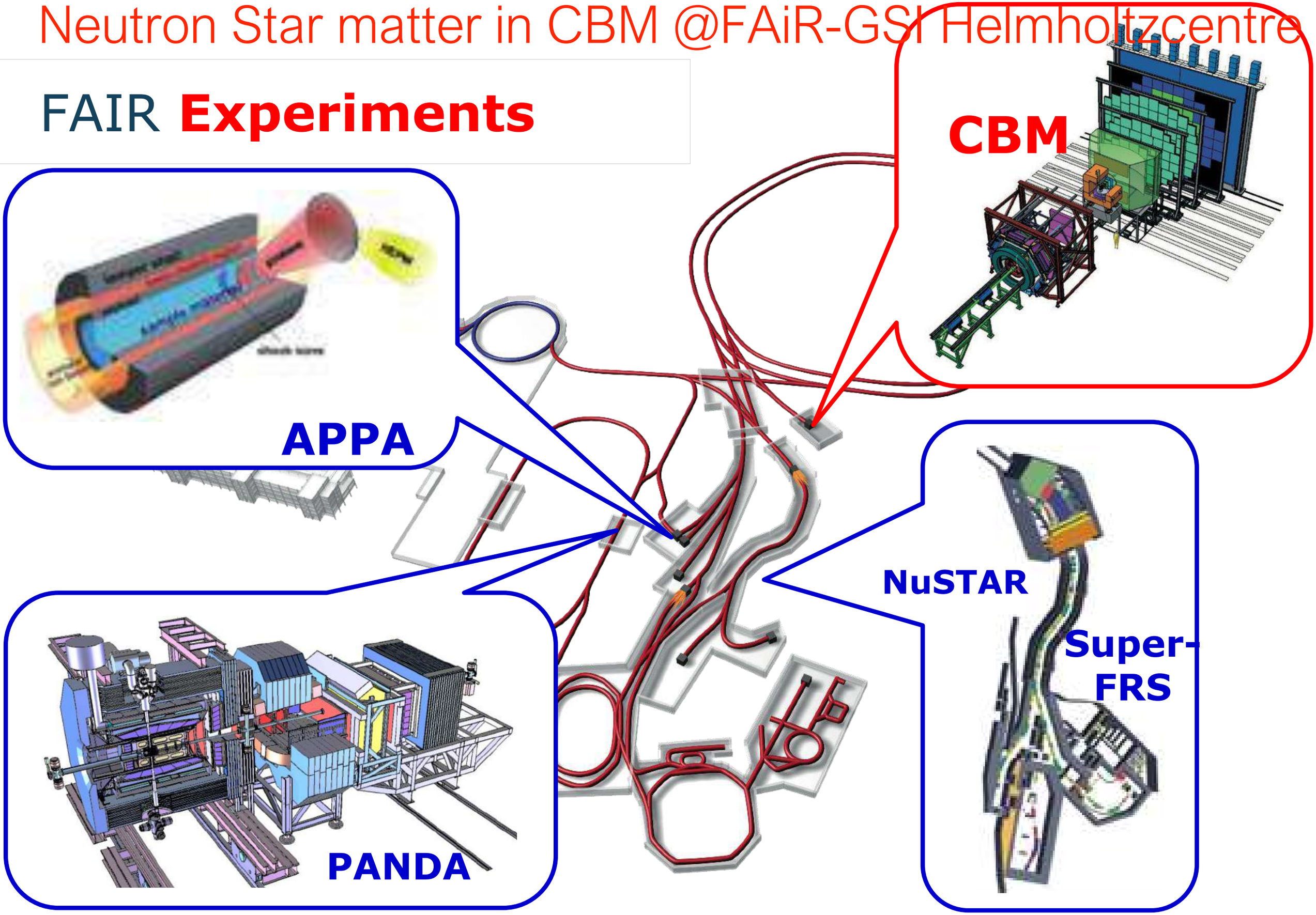
China 11.11. 2019

UK

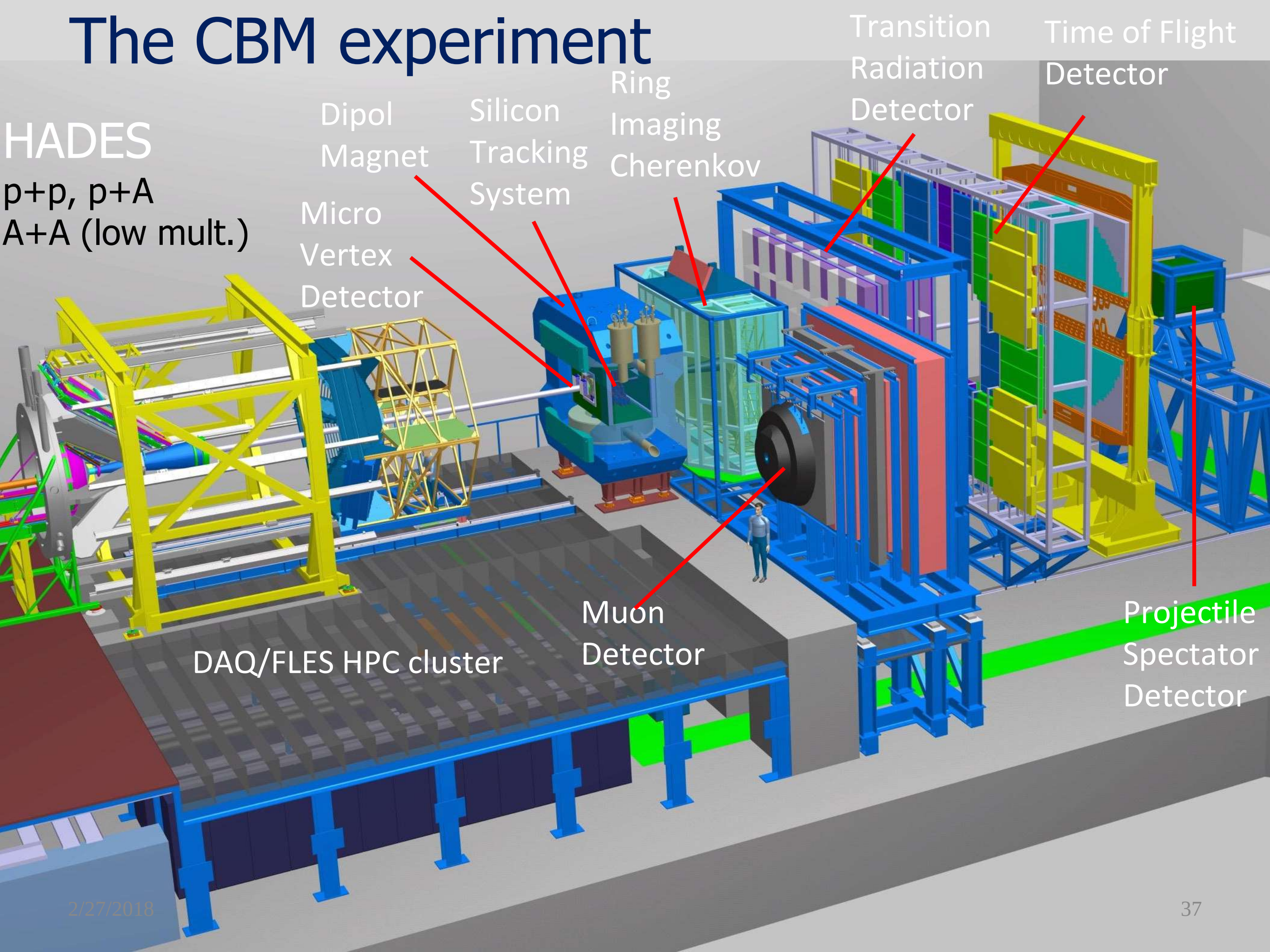

DORR
LIEBHERR

Neutron Star matter in CBM @FAiR-GSI Helmholtzcentre

FAIR **Experiments**



The CBM experiment



CBM: How DL may help when it works

Challenges:

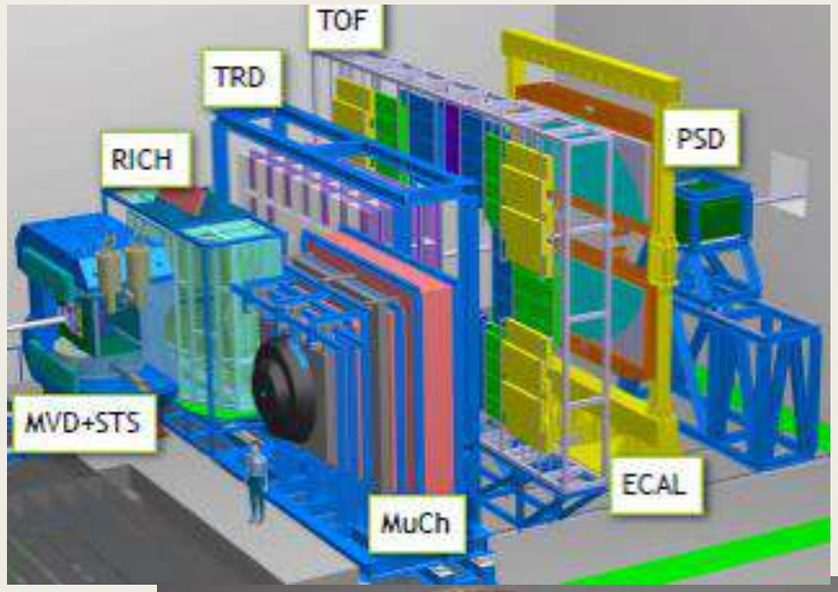
10^5-10^7 collisions per second, high data flux

High radiation load, aging

Many particles/tracks per collision

Solutions:

- AI allows online decoding of underlying physics for the event selection, with controlled accuracy
- AI-algorithms for frequent recalibration and quality control of detector sub-systems
- Great speed-up of tracking and realignment algorithms by AI-optimization



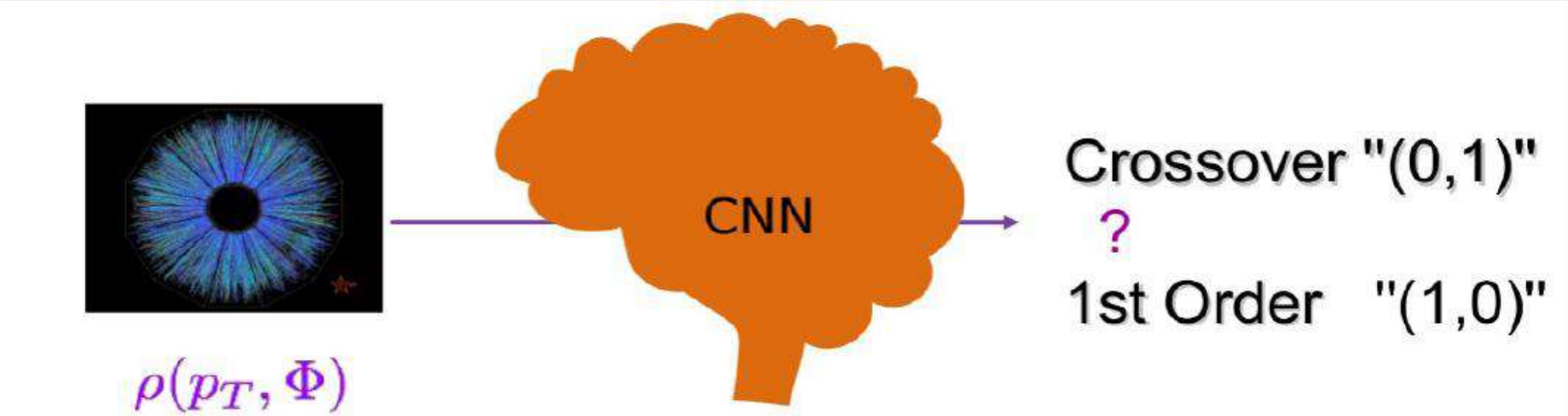
(O. Linnyk)

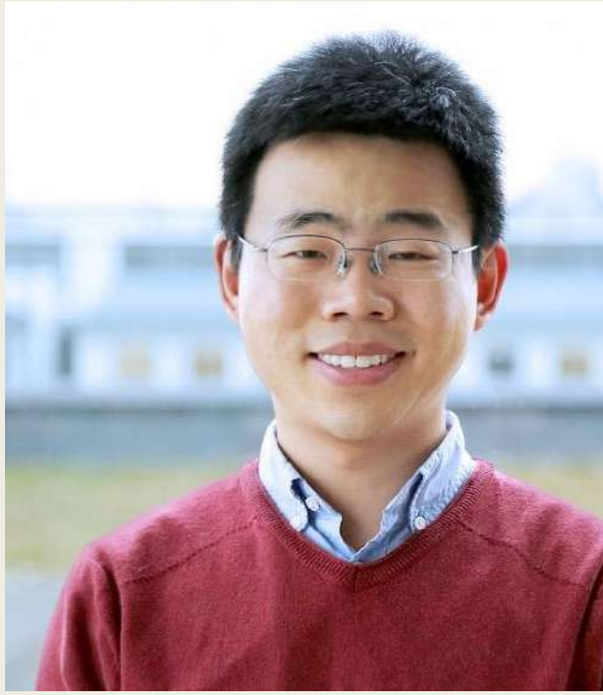
BMBF FSP ErUM-CBM Computing@FIAS
Hiring New Doctoral Students & Postdocs

‚Ice‘ Visiting Student
from SUT Thailand

Analyse data by Deep Machine Learning

Dr. Kai Zhou





- Extracting the softness of the EoS from
- event-by-event data works well 96 % accuracy
- Nature Communications 9, no. 1, 210 (2018),
-
- L.G.Pang, K.Zhou, N.Su,
- H.Petersen, H.Stöcker, X.N.Wang

- Paper selected the #26
- most important paper in physics 2018
- *Nature Communications*

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

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

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

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

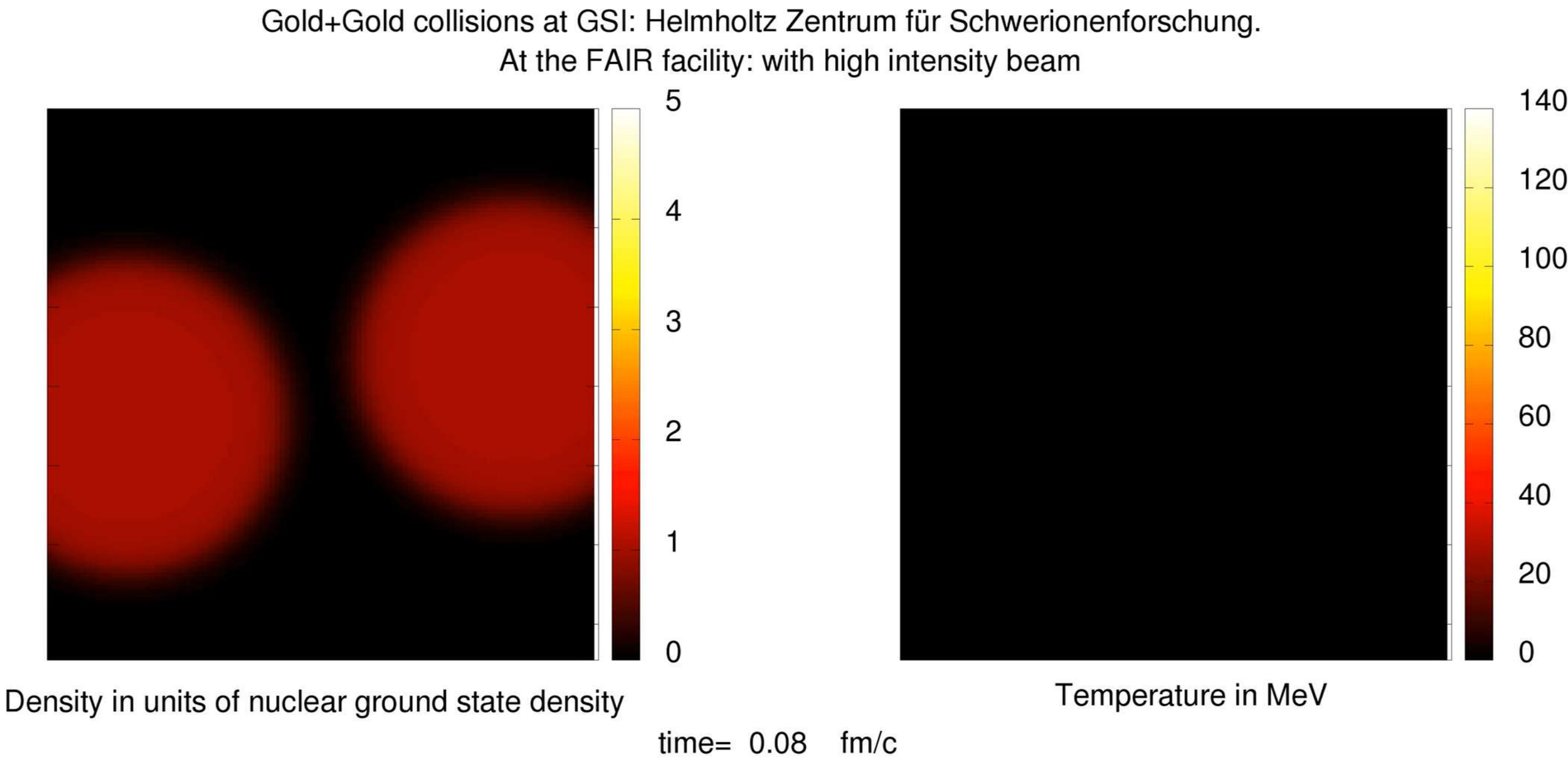
$$\nabla_\nu F^{\mu\nu} = I^\mu \,, \quad \nabla^*_\nu F^{\mu\nu} = 0 \,, \qquad \text{(Maxwell equations)}$$

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

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

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

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

Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Sitzungsberichte der Königlich-Preußischen Akademie der Wissenschaften

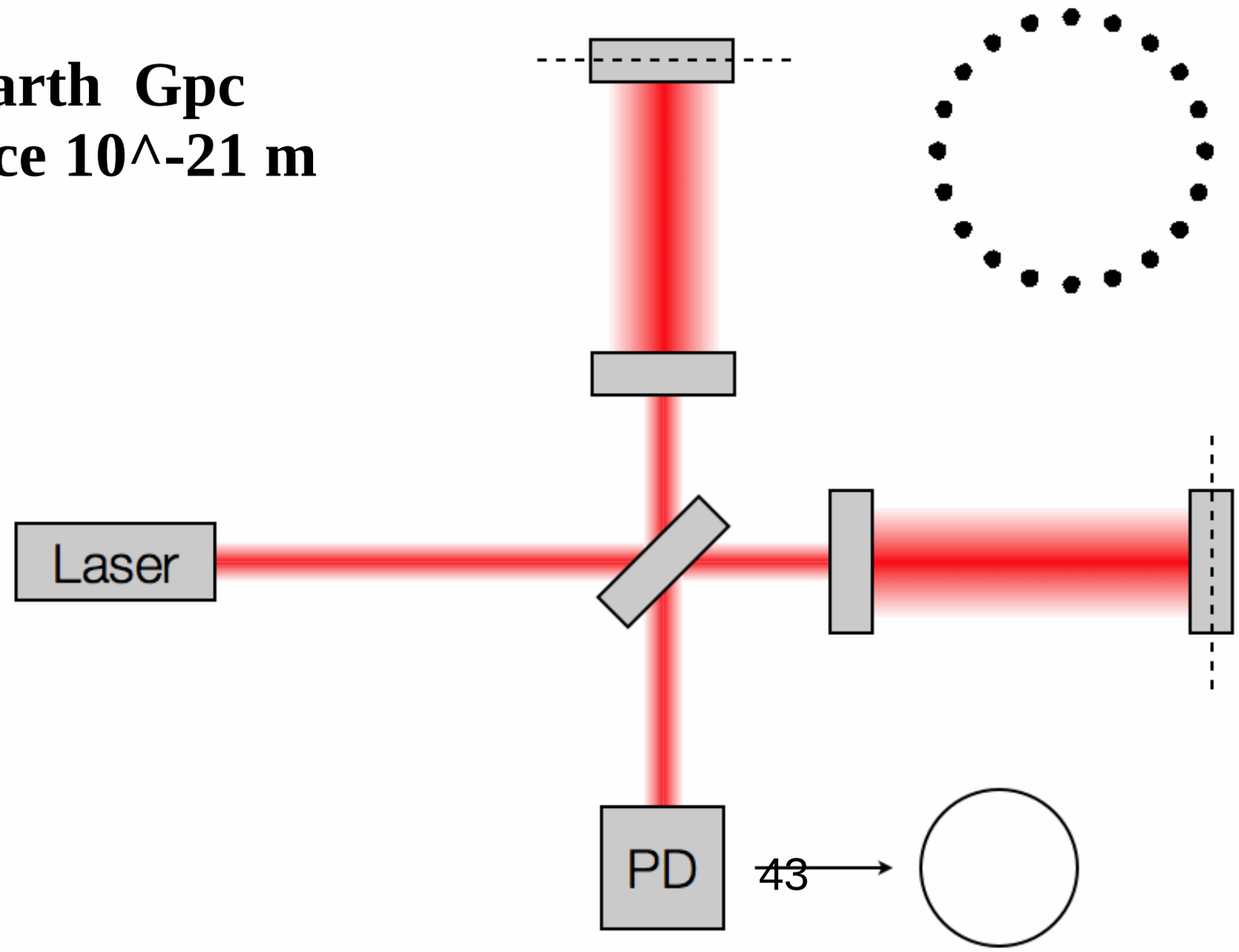
Einstein‘s First work on Gravitational Waves, Juni 1916, was …**wrong**…

Gravitational Waves discovered

Collision of 2 Neutron Stars
GW170817

Masses of BHs: 1.4 &1.4 Solar Masses

Distance to Earth Gpc
Length Difference 10^-21 m

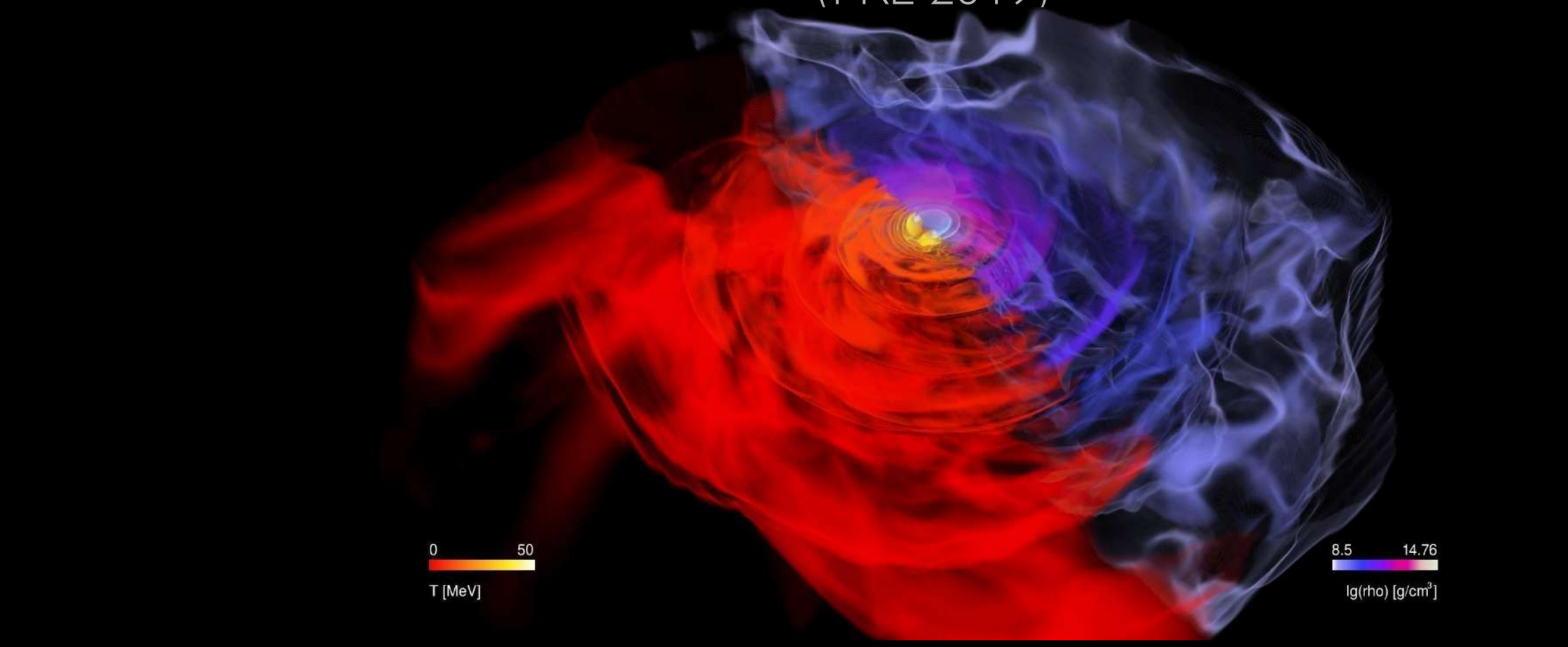


Credit: Les Wade from Kenyon College.

Nuclear Matter EoS in Binary NS Mergers & Quark Matter Phase Transition Signatures in Gravitational Waves

Most, Papenfort, Dexheimer, Hanauske, Schramm, Stoecker, Rezzolla (PRL 2019)

see also Bauswein, Bastian, Blaschke, Chatziioannou, Clark, Fischer, Oertel (PRL 2019)



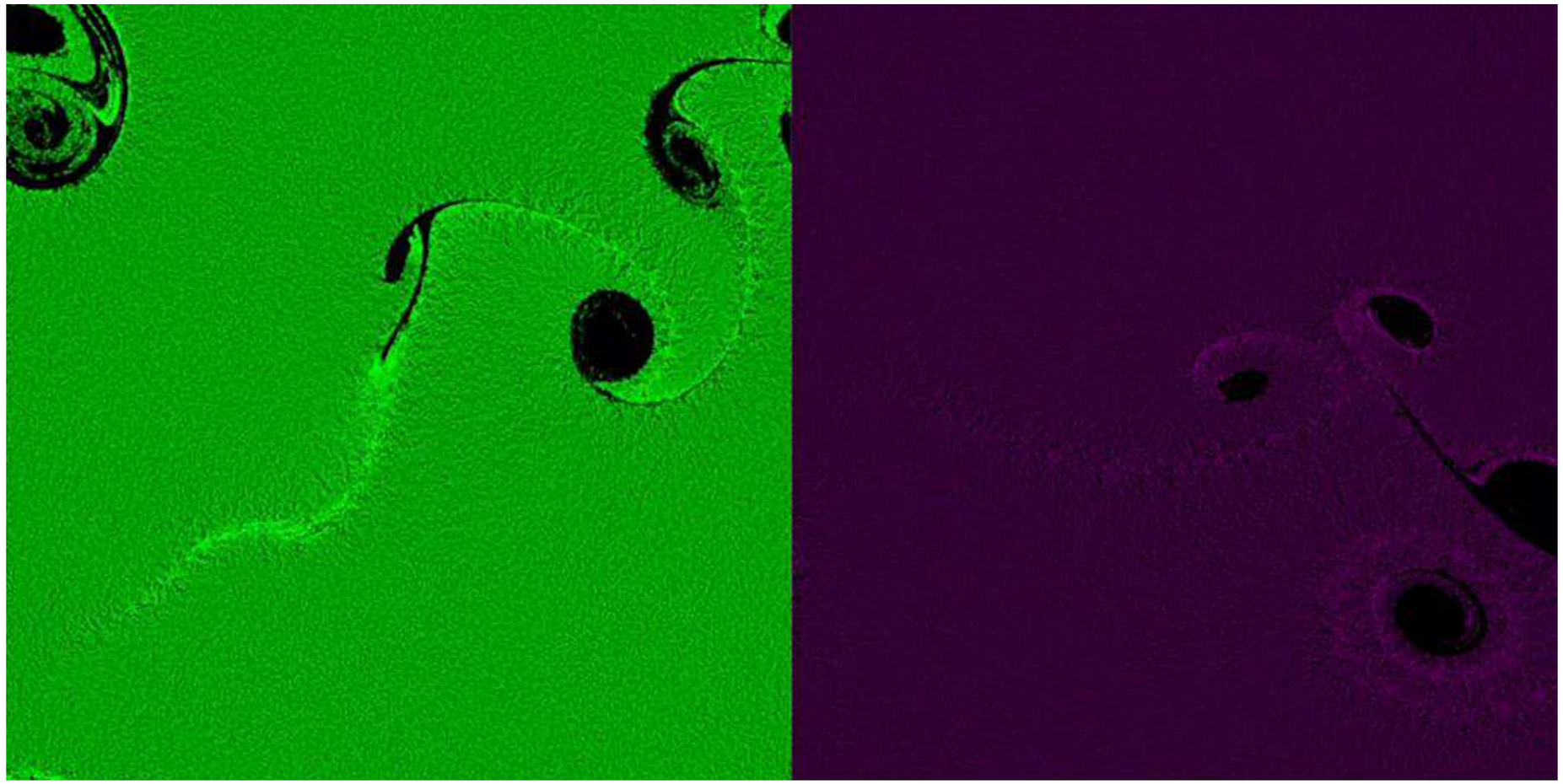
Deep NN hydrodynamic simulations

Kirill Taradiy, Kai Zhou, Jan Steinheimer, Longgang Pang, H.St.*

	NVIDIA GTX 1080 Ti	NVIDIA Titan V	NVIDIA RTX 2080 Ti	AMD Radeon VII
TFLOPs(FMA)	11.3	18.9	16	13.8
Memory Clock	484Gbps GDDR5x	651Gbps HBM2	616Gbps GDDR6	1024Gbps HBM2
Memory Bus Width	352	3072	352	4096
Cores	3584	5120 + 640 tensorcores	4352 + 576 tensorcores	3840
Price	650	2999	1100	800

- 5 Petaflops
- 8 M$ Goethe U.CSC
- 3000 GPUs AMD Rade

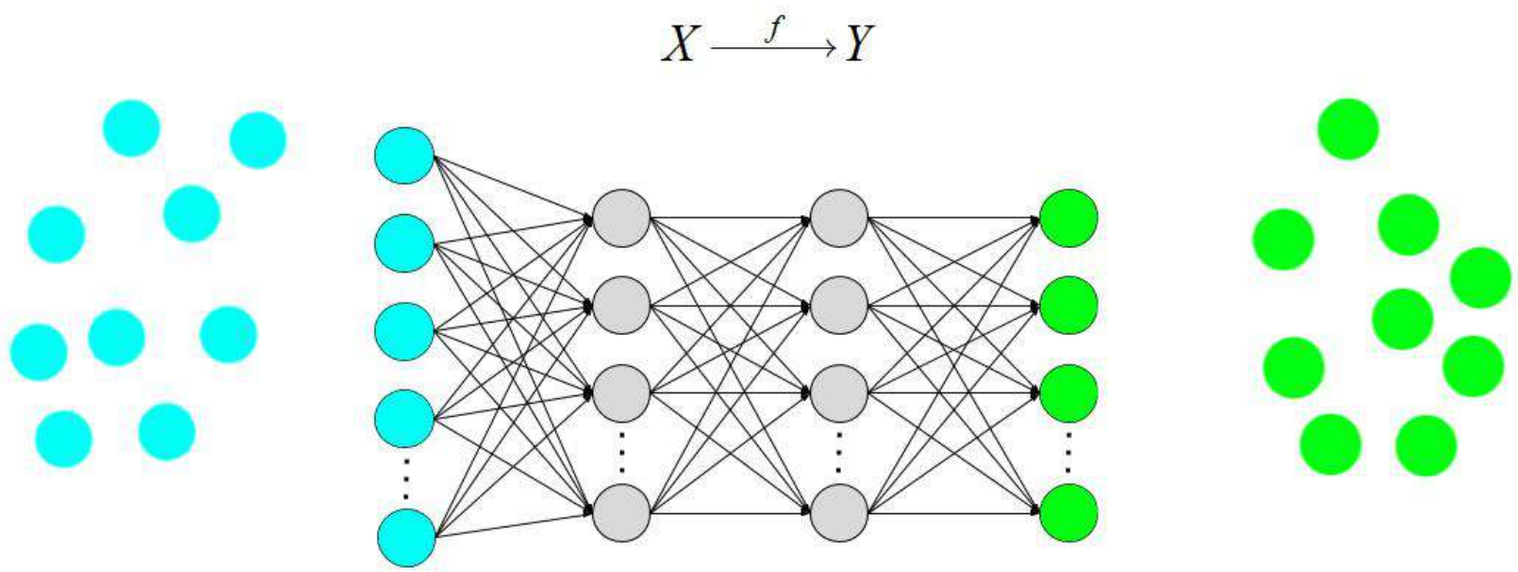
Real time 2D fluid simulation comparison GPU vs CPU



Jesus Martin Berlanga, Real-Time GPU fluid dynamics

Neural Networks for Time evolution tasks

- A feed-forward network with a single hidden layer containing a finite number of neurons can approximate continuous functions on compact subsets



Recently there has appeared a proof for other activation functions

- **Pang, L. G., Zhou, K., Su, N.**, Petersen, H., Stöcker, H., & Wang, X. N. (2018). An equation-of-state-meter of quantum chromodynamics transition from deep learning. *Nature communications*, *9*(1), 210

- Cybenko, G. (1989). Approximation by superpositions of a sigmoidal function. *Mathematics of control, signals and systems*, *2*(4), 303-314.

Riemann Problem

- 1 dimensional task
- Hydro equations are simplified to Euler form
- Piecewise – constant discontinuous initial conditions

Sod Shock Tube

$$1)\quad \begin{cases} \rho_l = 3\rho_r \\ u_l = u_r = 0, \\ p_l = 3p_r \end{cases}$$

$$2)\quad \begin{cases} \rho_l = \rho_r \\ u_l = u_r = 0, \\ p_l = p_r \end{cases}$$

Collision or Expansion

Cauchy momentum equation

$$\frac{\partial}{\partial t}(\rho\,\mathbf{u}) + \nabla\cdot(\rho\,\mathbf{u}\otimes\mathbf{u}) = -\nabla p + \nabla\cdot\boldsymbol{\tau} + \rho\,\mathbf{g}$$

Linear stress constitutive equation

$$\boldsymbol{\sigma} = \zeta(\nabla\cdot\mathbf{u})\mathbf{I} + \mu\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^{\mathrm{T}} - \tfrac{2}{3}(\nabla\cdot\mathbf{u})\mathbf{I}\right)$$

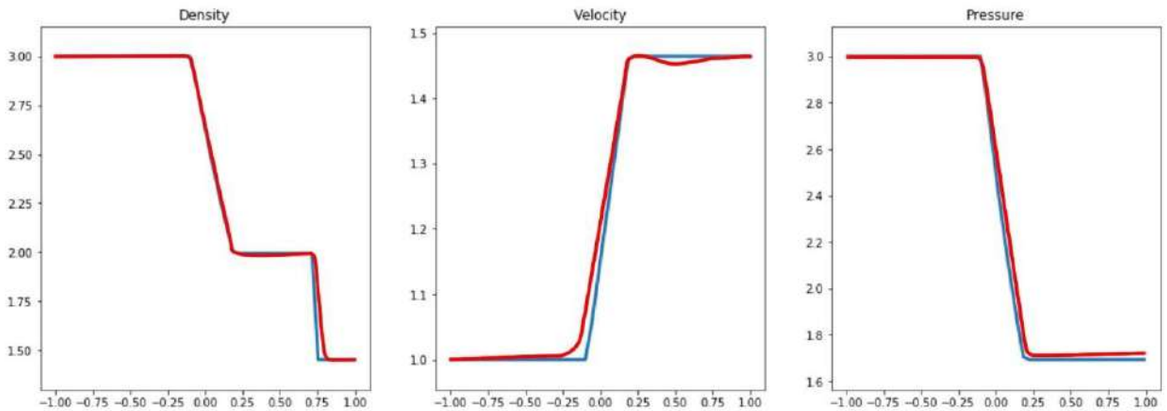
Navier–Stokes momentum equation (*convective form*)

$$\rho\left(\frac{\partial\mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = -\nabla\bar{p} + \mu\,\nabla^2\mathbf{u} + \tfrac{1}{3}\mu\,\nabla(\nabla\cdot\mathbf{u}) + \rho\mathbf{g}.$$

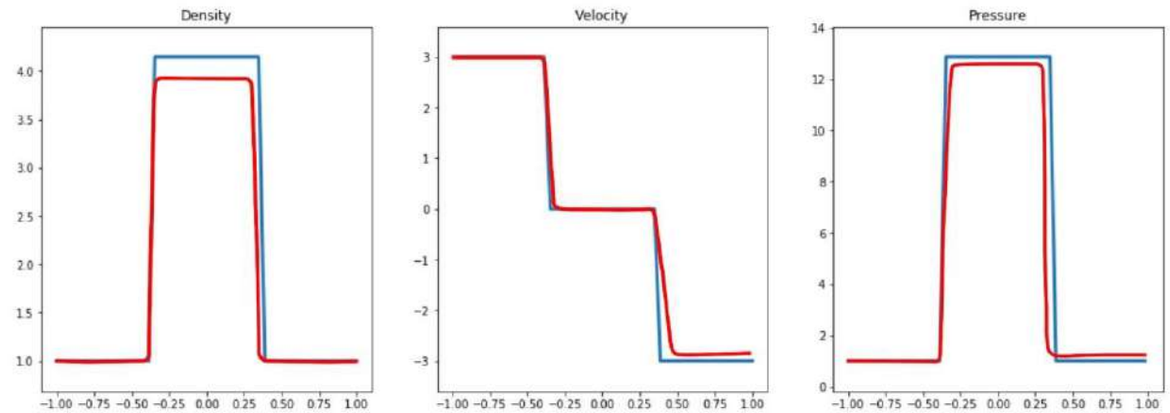
→

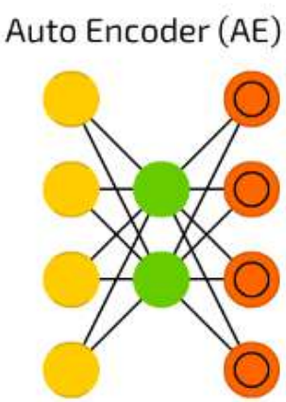
$$\left.\begin{aligned} &\frac{\partial\rho}{\partial t} + \vec{u}\nabla\rho = 0 \\ &\frac{\partial\vec{u}}{\partial t} = -\frac{\nabla p}{\rho} + \vec{g} \\ &\nabla\vec{u} = 0 \end{aligned}\right\}$$

Riemann Problem Special Cases

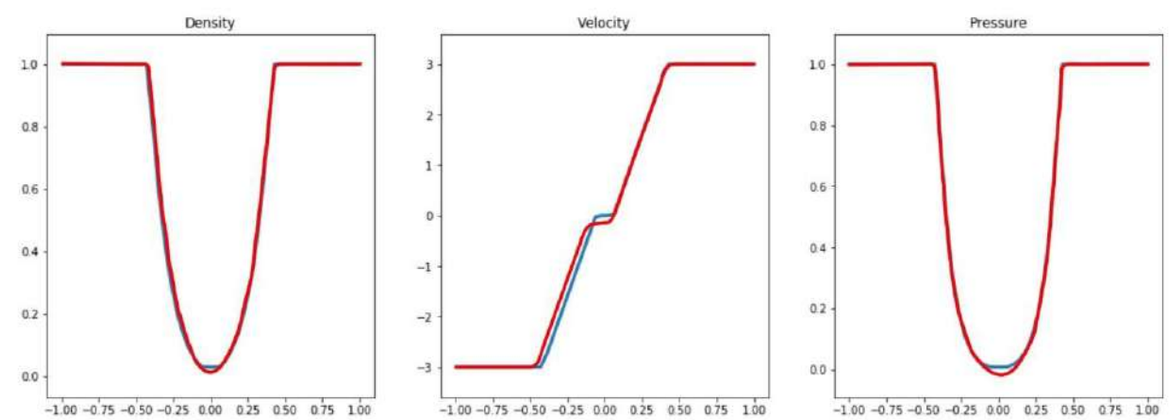


Sod Shock Tube





The purpose is to learn the dependence
rather than the data itself



Expansion and Collision

S. Tokareva, A. Skurikhin, Machine learning approach for the solution of the Riemann problem in fluid dynamics

K. Taradiy, K.Zhou, J. Steinheimer, L.G. Pang, A. Motornenko, H.St.

DNN predicts correctly the time dependence of hydrodynamic evolution !

K. Taradiy, K.Zhou, J. Steinheimer, L.G. Pang, A. Motornenko, H.St.

Adam | Custom sgd (stoch. grad. descent) with momentum:

In range

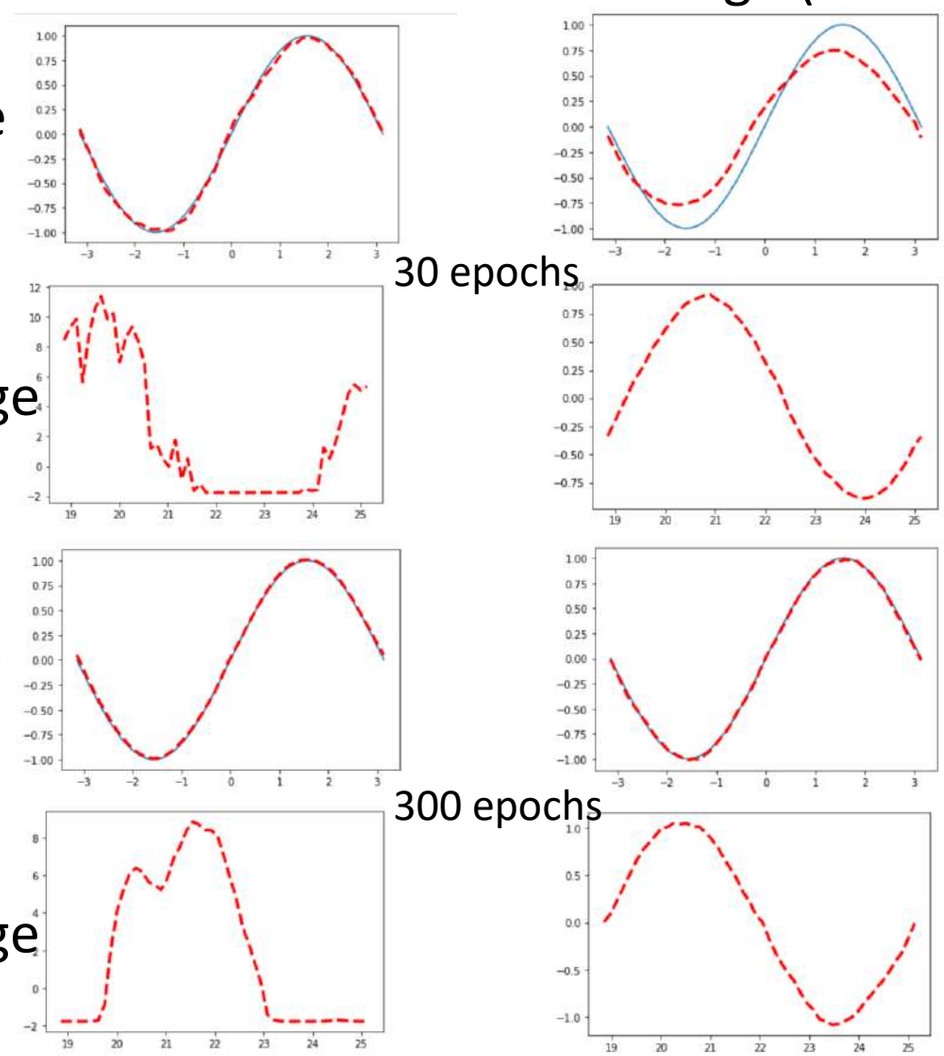
Out of range

30 epochs

In range

Out of range

300 epochs

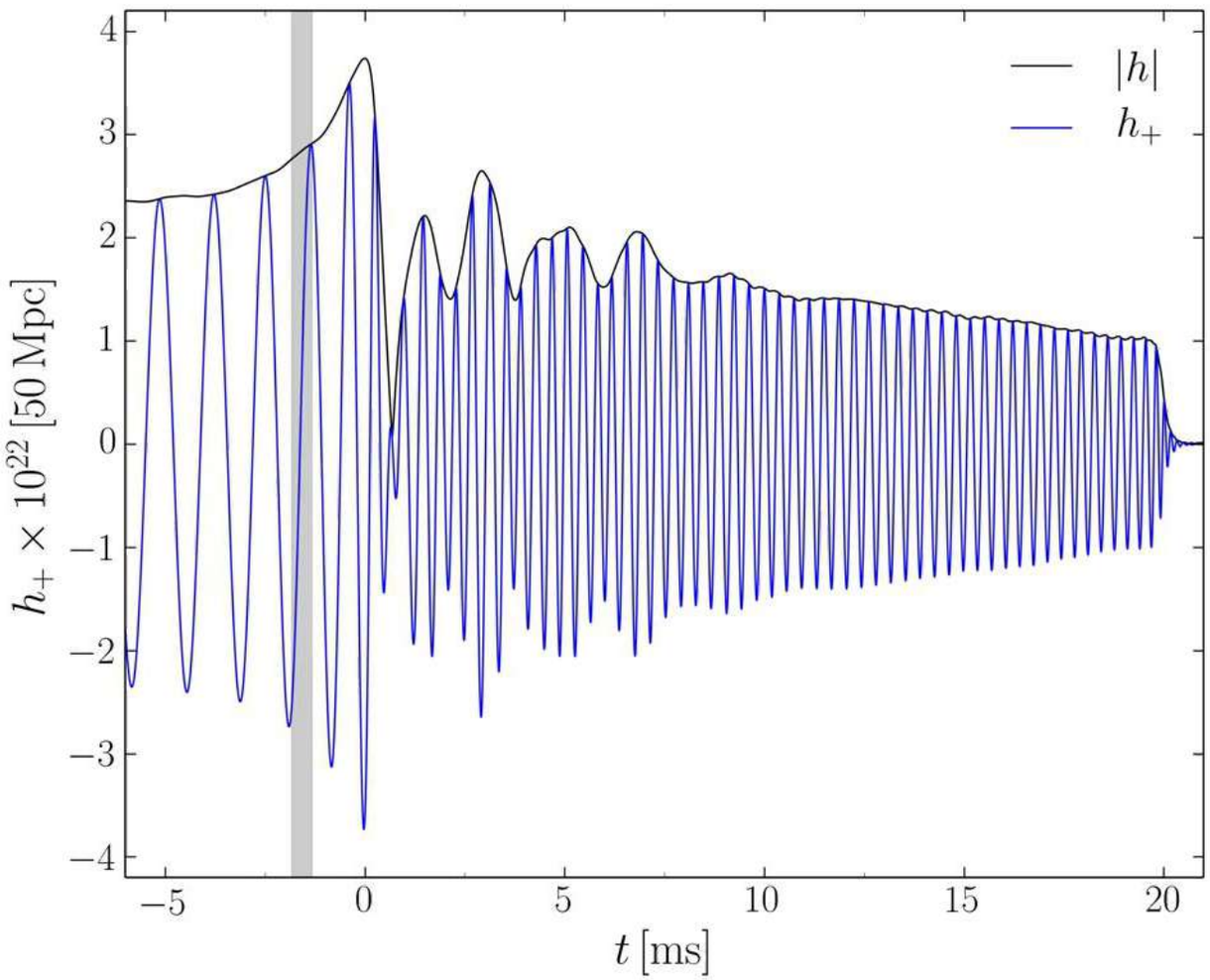


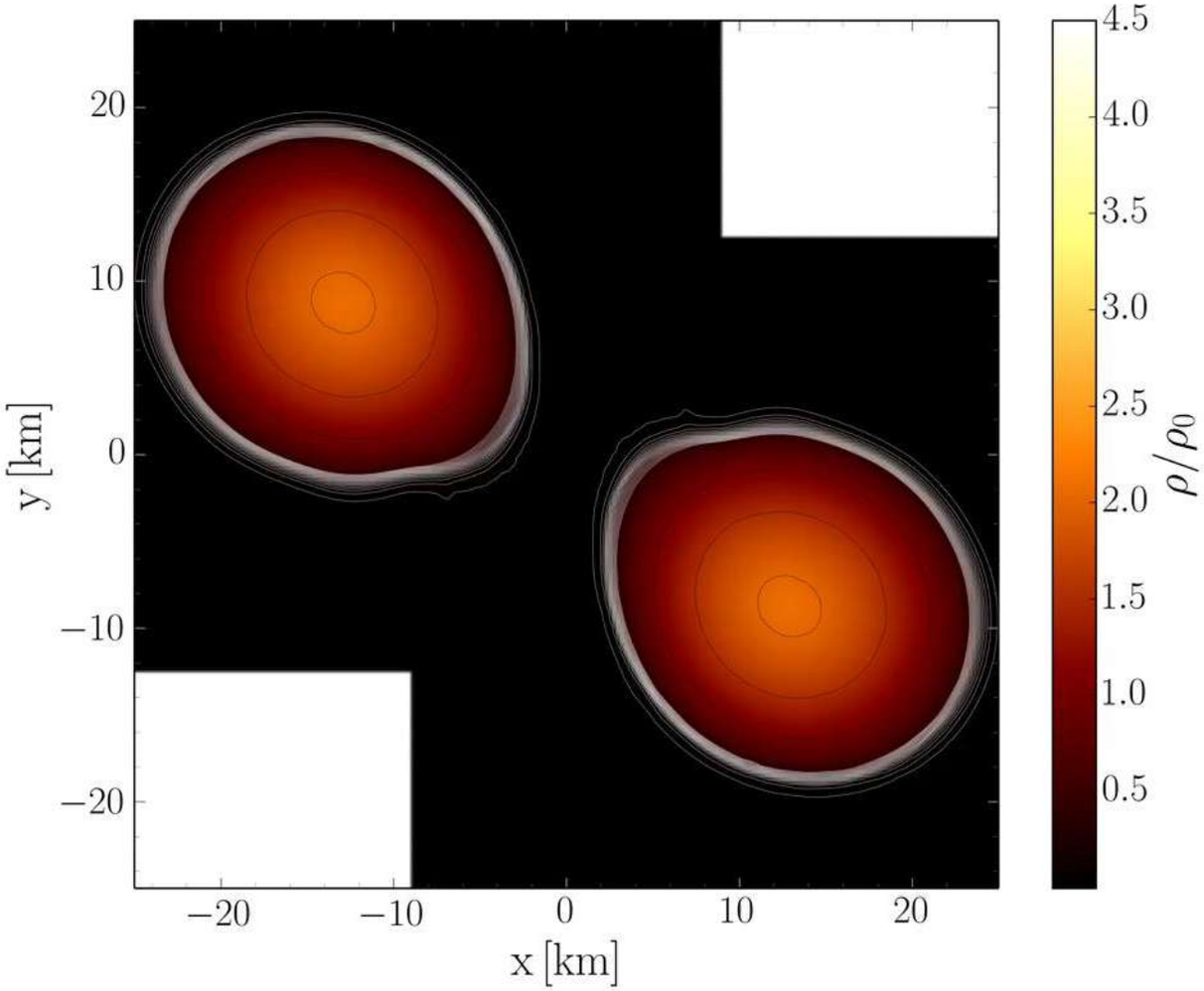
bad network predictability
Outside of the training interval
signal of overfitting

network may perform worse
On the test set, but better
Predictability outside of training
interval - result of particular
local minimum found

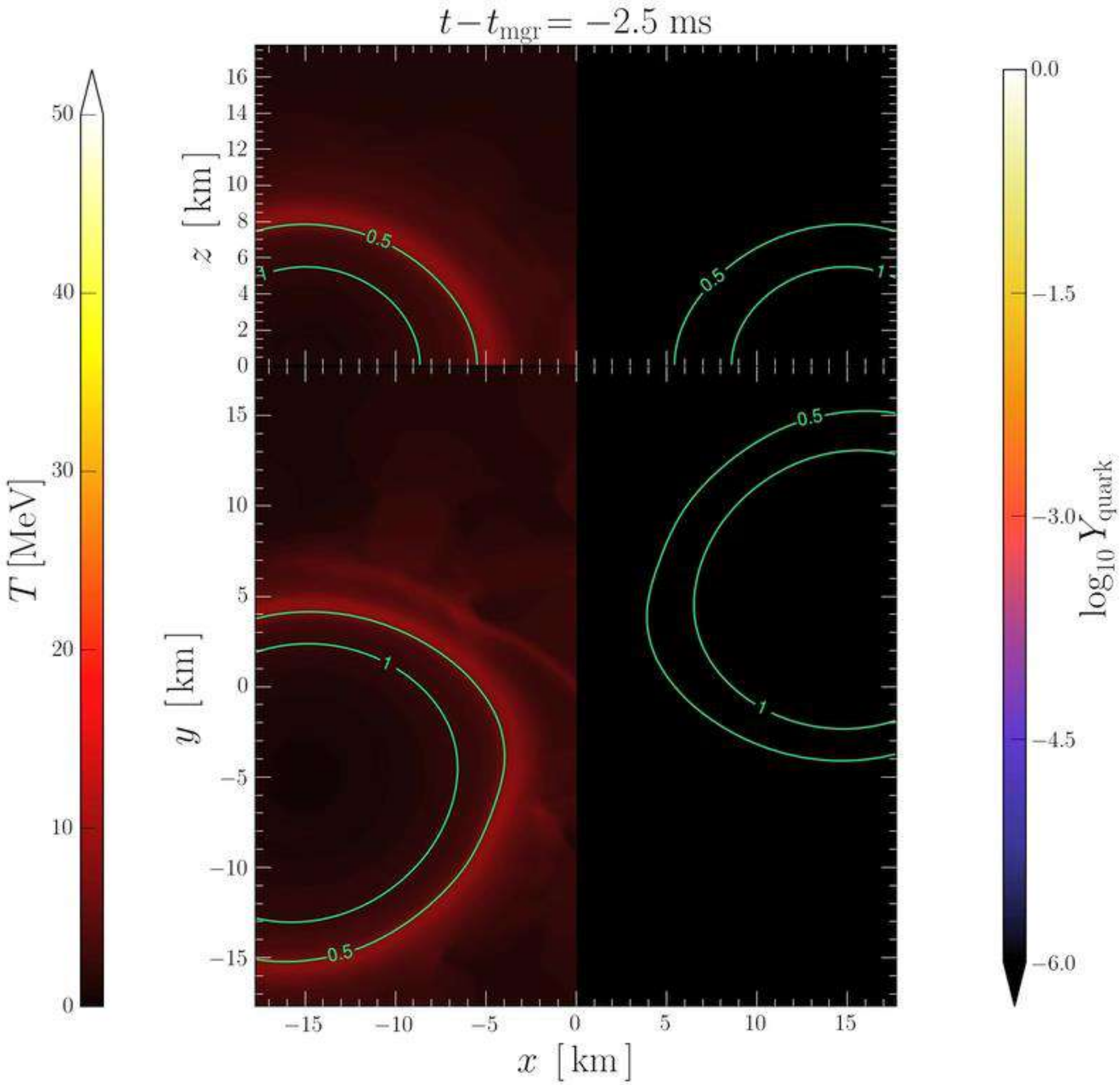
optimizer type + the initial
definition of weights and biases
greatly Influenceds the network's
predictability outside training set.

Disco-Fox, Merengue and Tango- Phase





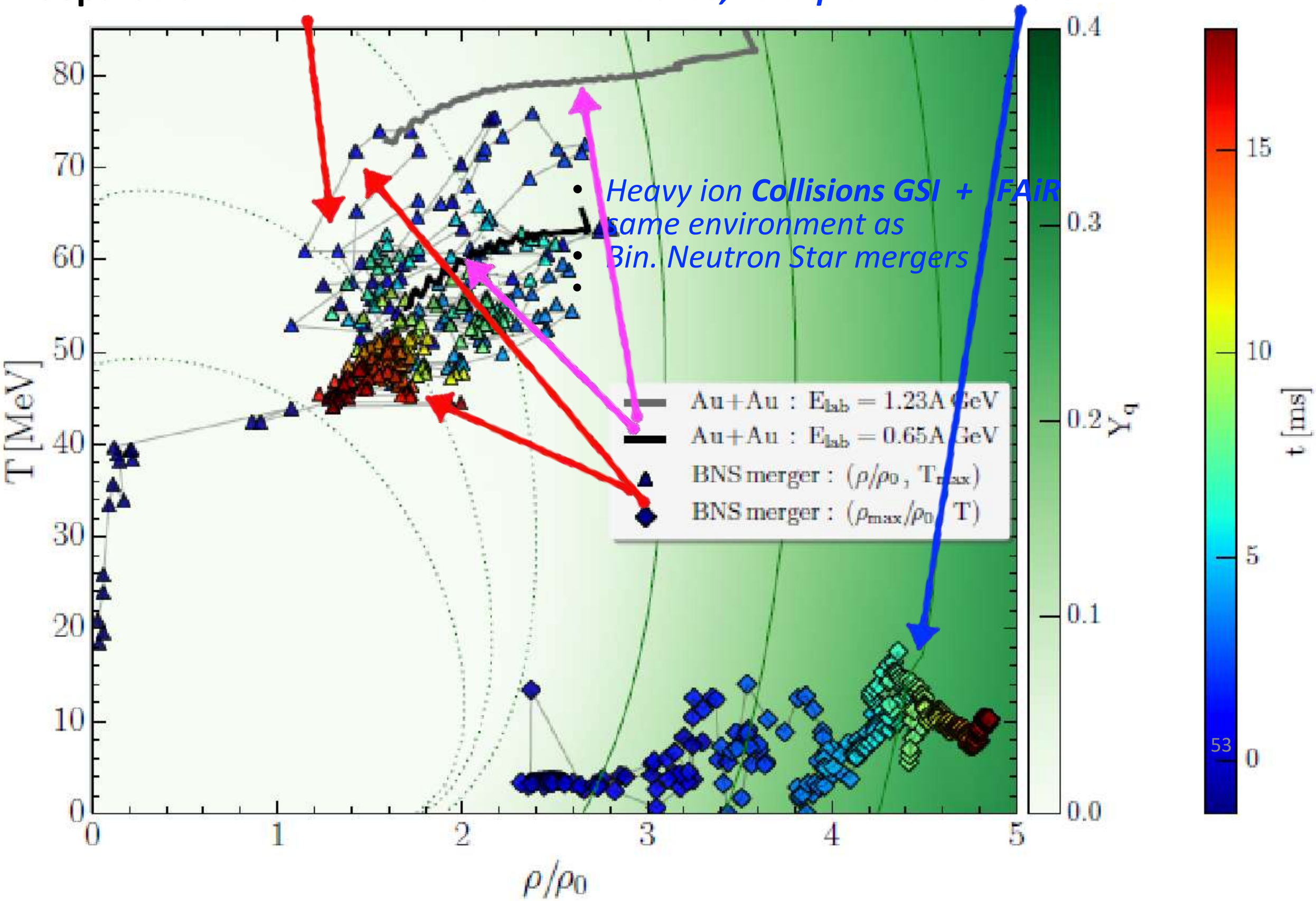
Temperature



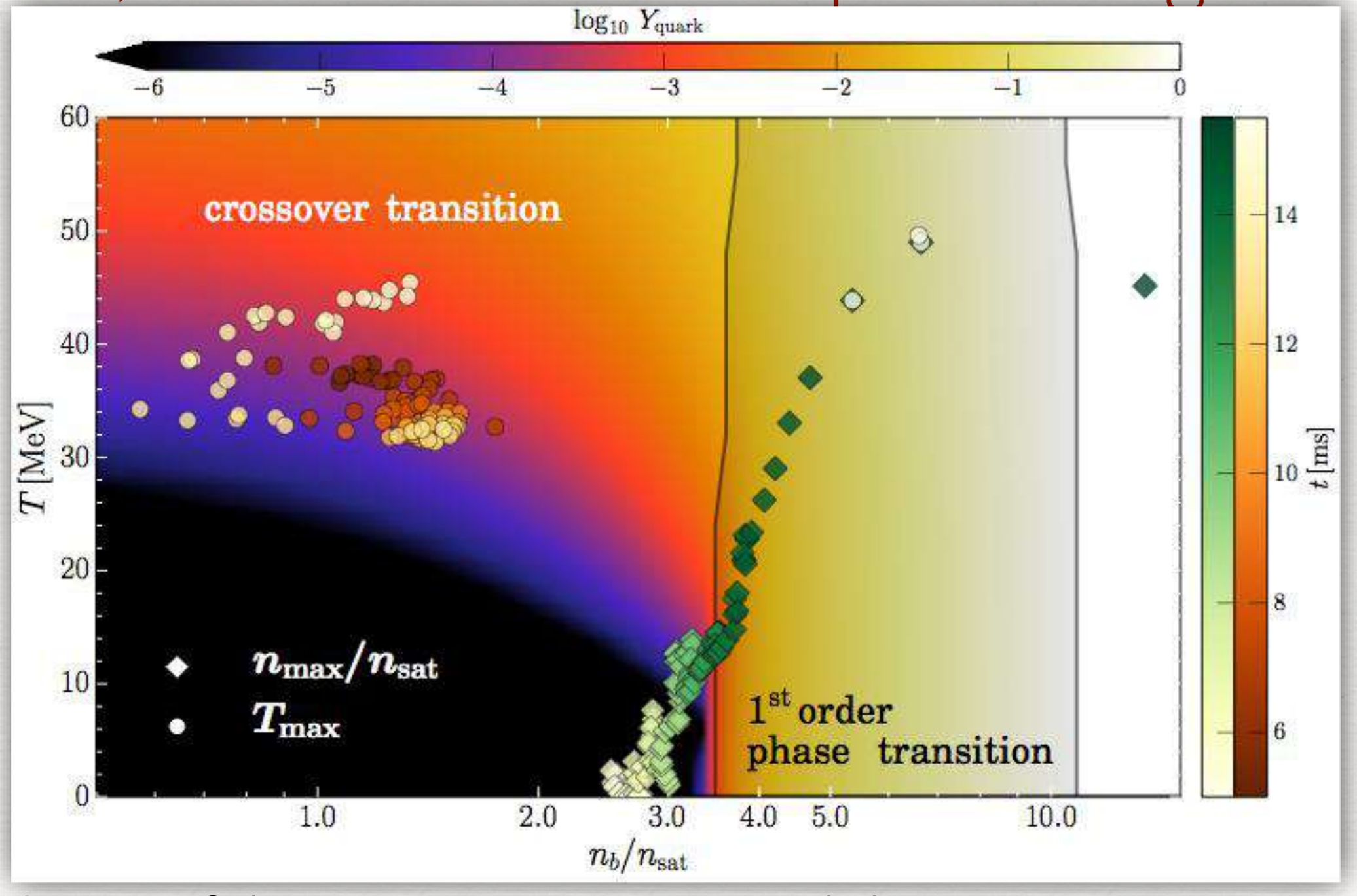
Quark fraction

Where it's hot and dense in neutron star mergers

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



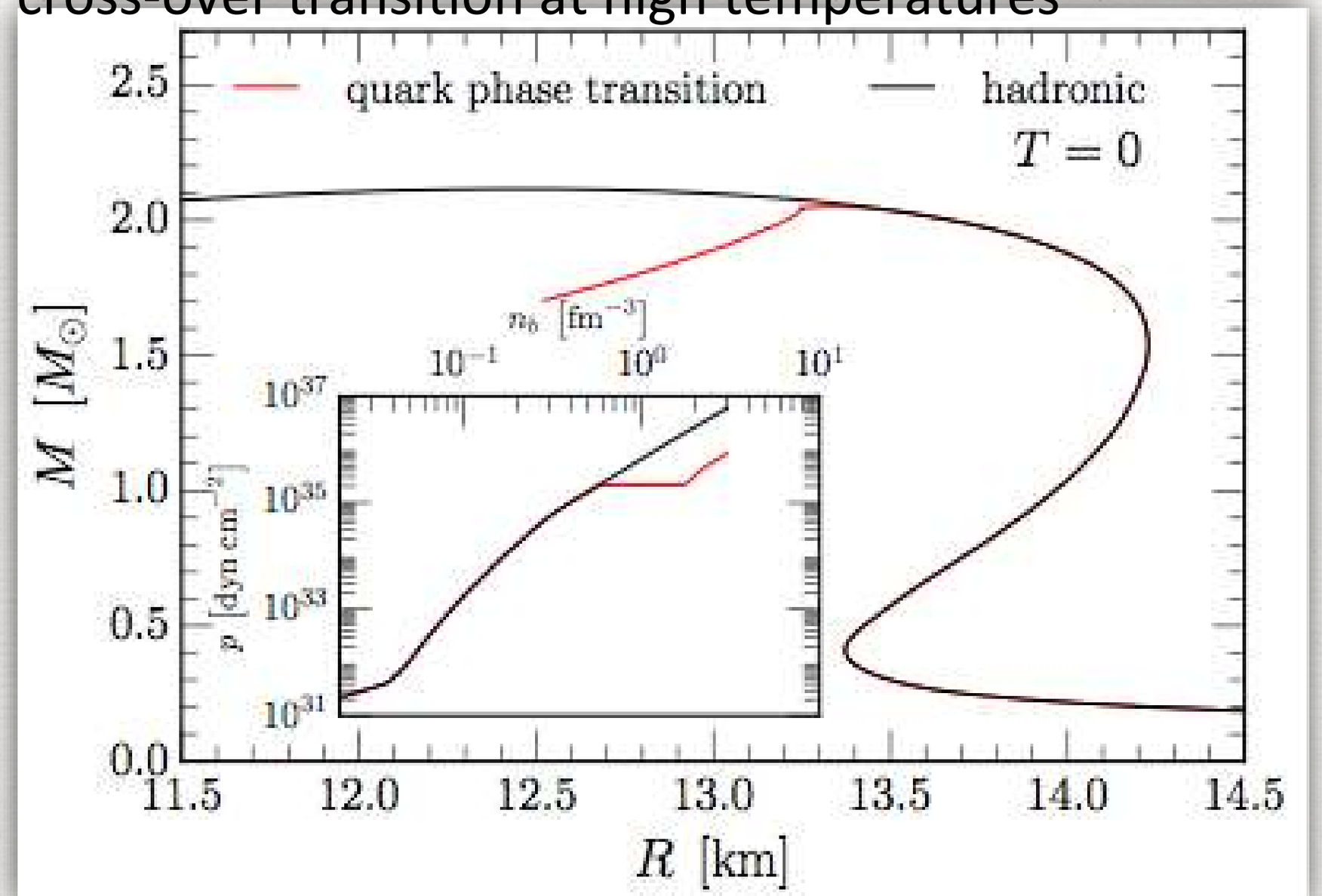
T, n Evolution in the phase diagram



- 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

Modelling a CMF - EOS with Quarks: by Dexheimer & Schramm

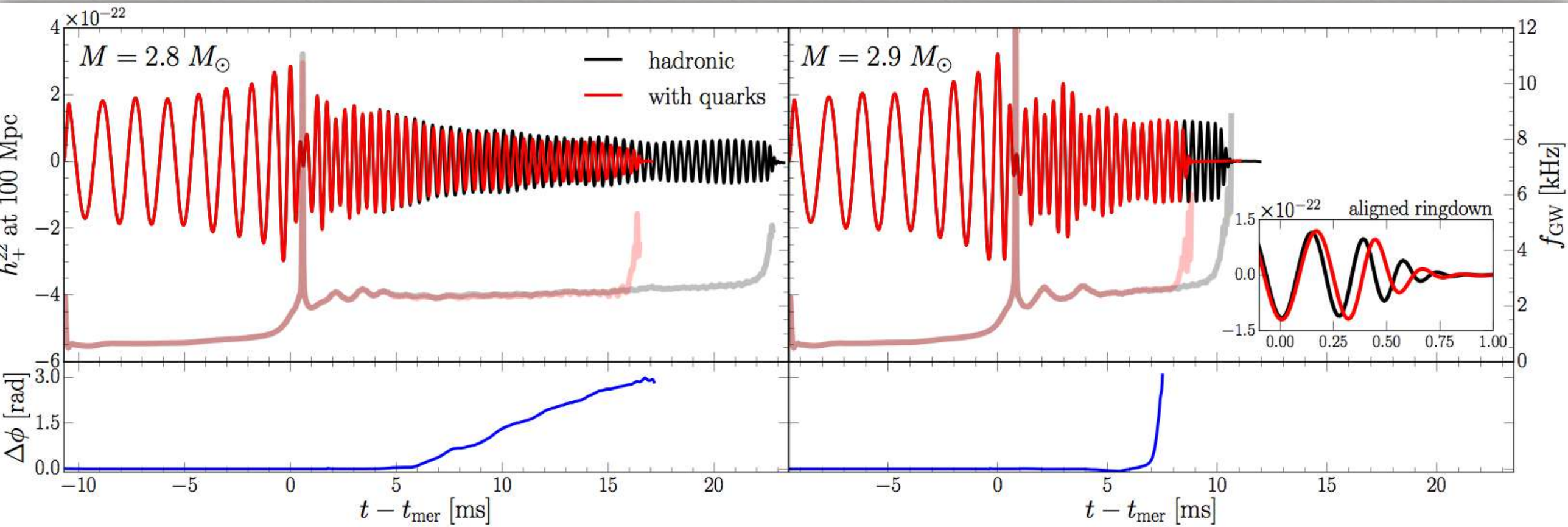
- EOS based on Chiral Mean Field (CMF) and nonlinear SU(3) sigma model
- Includes hyperons and quarks that can be turned on / off
- Uses Polyakov loop to implement a strong first order phase transition
- Includes a cross-over transition at high temperatures



Gravitational Wave Emission from BNSM - ML !

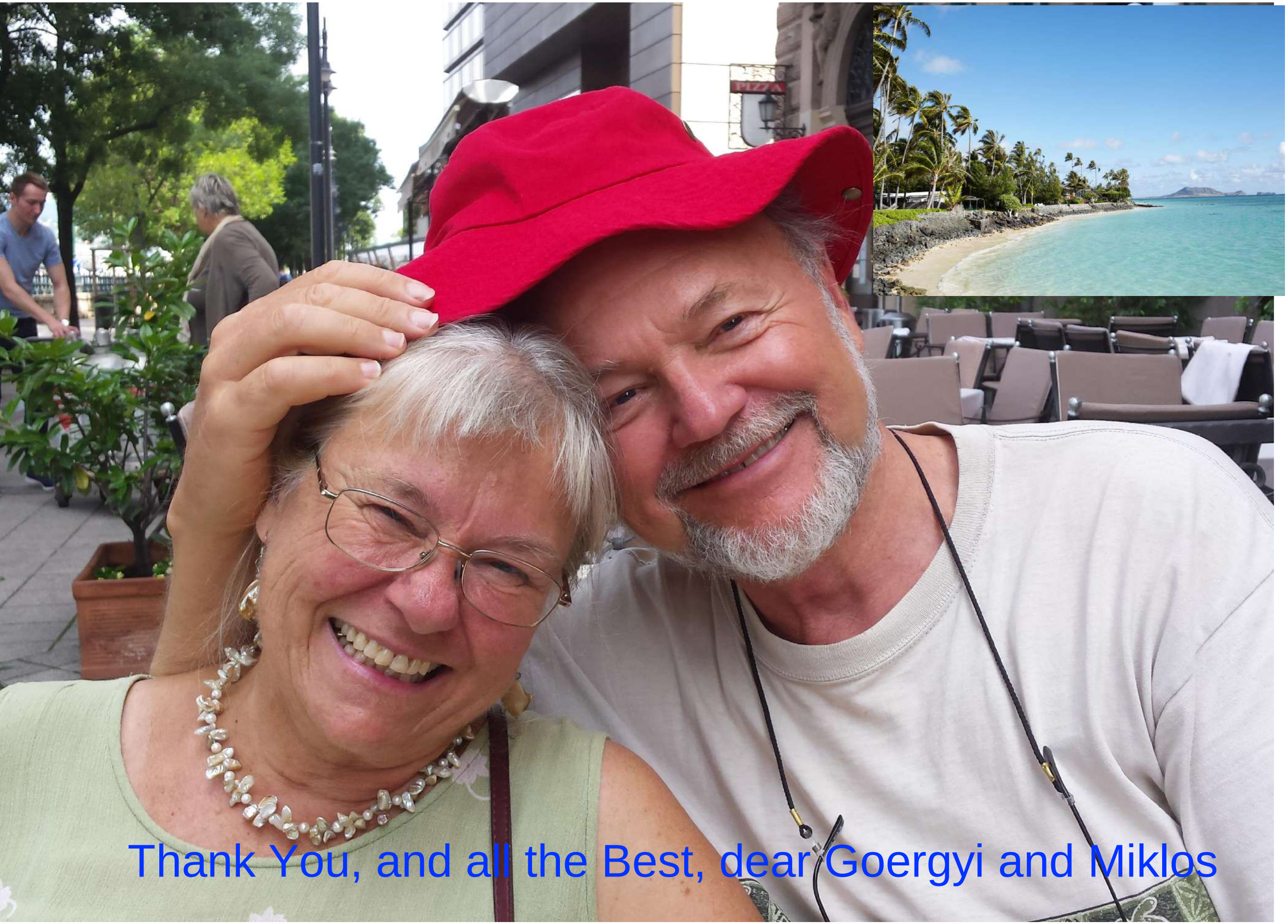
"low-mass" binary

"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. W

Mismatch hadronic **inspiral** and **post-merger** phase: clear **Signature of Quark Matter - crossing or 1.OPT ?**


PIZZA
Thank You, and all the Best, dear Goergyi and Miklos