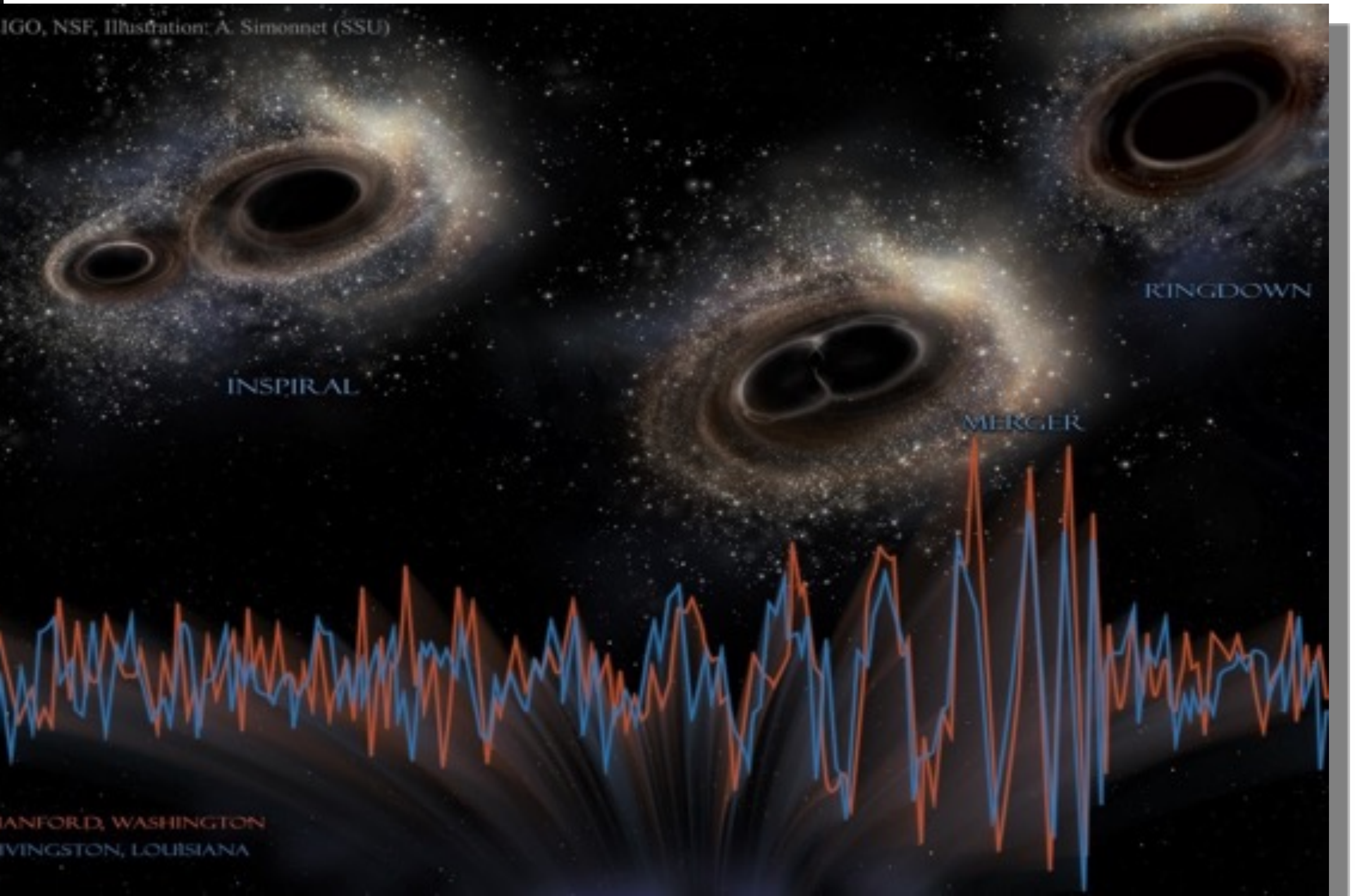
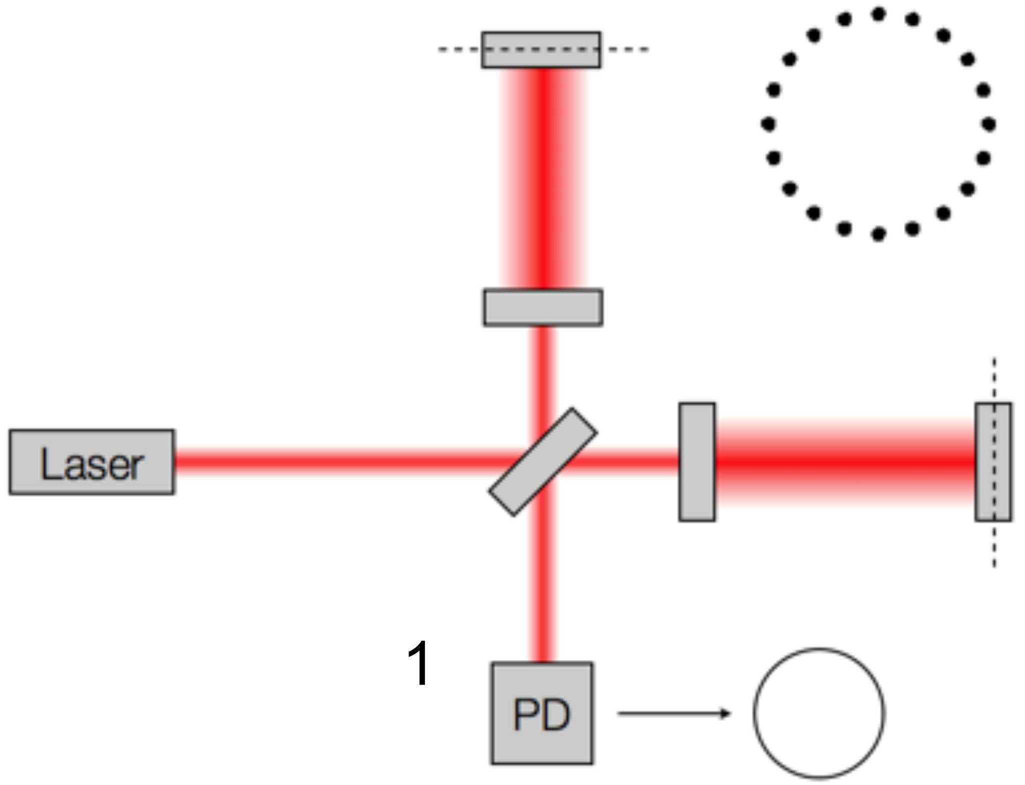
Gravitational Waves discovered !!!

Collision of 2 BHs GW150914
Masses of BHs: 36 & 29 Solar Masses
Distance to Earth 410 Mpc/1.340 GLy
Length Difference 10^-21 m in Ligo

Binary NeutronStar Merger GW170817
Masses of the two NS ~ 1.4 M_s each
GW sensitive to EoS and Phase transition !





Credit: Les Wade from Kenyon College.

MaGiC: Matter And Gravitation In Collisions of Relativistic Heavy Ions and GR Neutron Star Mergers

Probe the EoS of hot, dense matter by Flow + Gravitational Waves

Anton Motornenko, Stefan Schramm, Jan Steinheimer, Volodymyr Vovchenko,

Matthias Hanauske, Elias Most, Jens Papenfort, Luciano Rezzolla, Horst Stöcker *

FIAS Frankfurt Institute for Advanced Studies, Giersch Science Campus and

Institut für Theoretische Physik, Johann Wolfgang Goethe Universität Frankfurt

GSI Helmholtzzentrum für Schwerionenforschung GmbH Darmstadt

***Walter Greiner Gesellschaft zur Förderung der physikalischen Grundlagenforschung e.V., Frankfurt**

Matter, Gravity and Neutron Stars

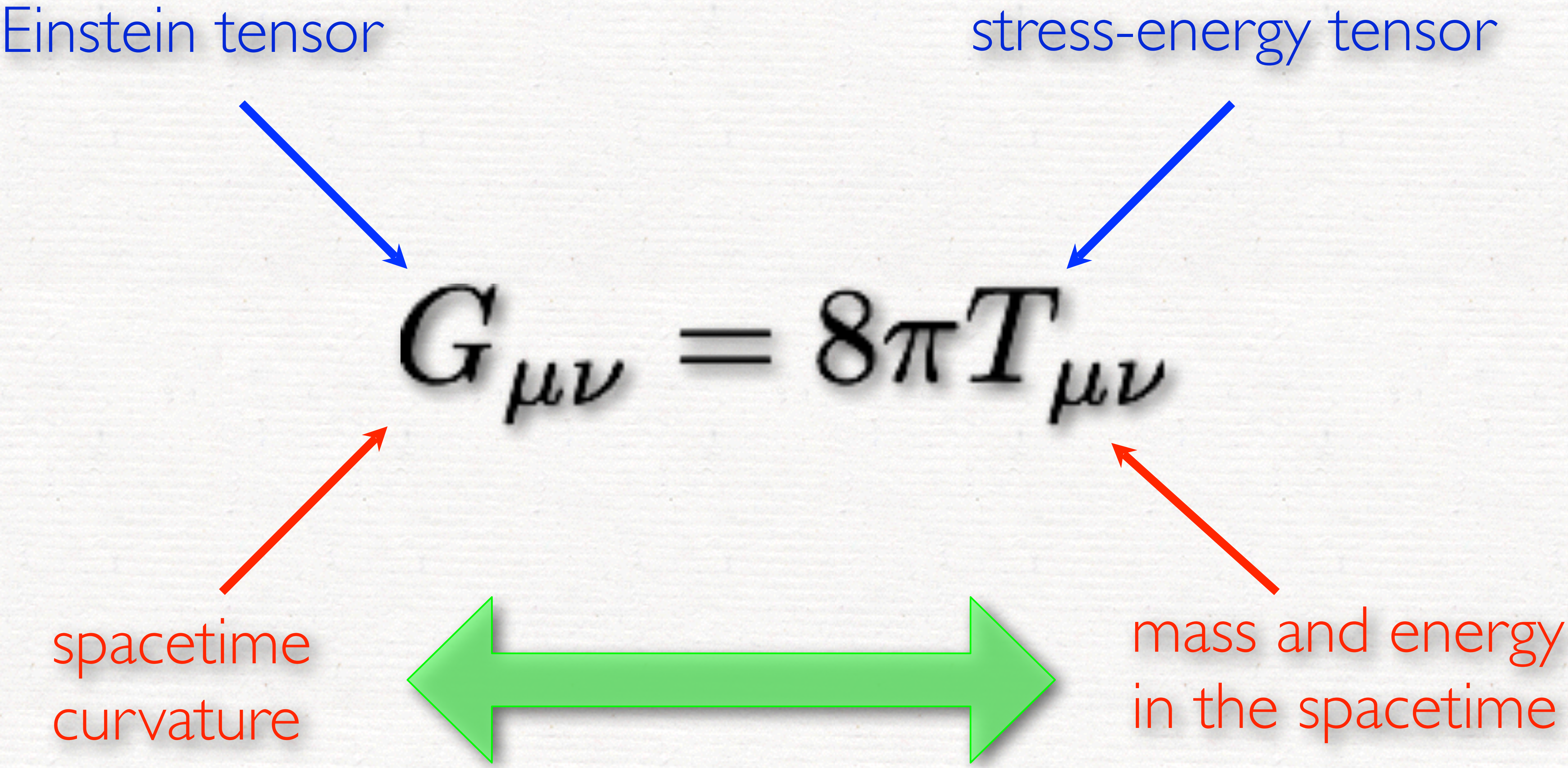
1679 I. Newton published his theory of gravitation. According to Newton, gravity manifests itself as an instantaneous force between masses proportional to their masses and inversely proportional distance squared. With this theory he could explain all of the astronomical observations of this time.

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 + we see a **whole new Universe**

Einstein equations - first solved by Karl Schwarzschild



Einstein tensor

stress-energy tensor

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

spacetime curvature

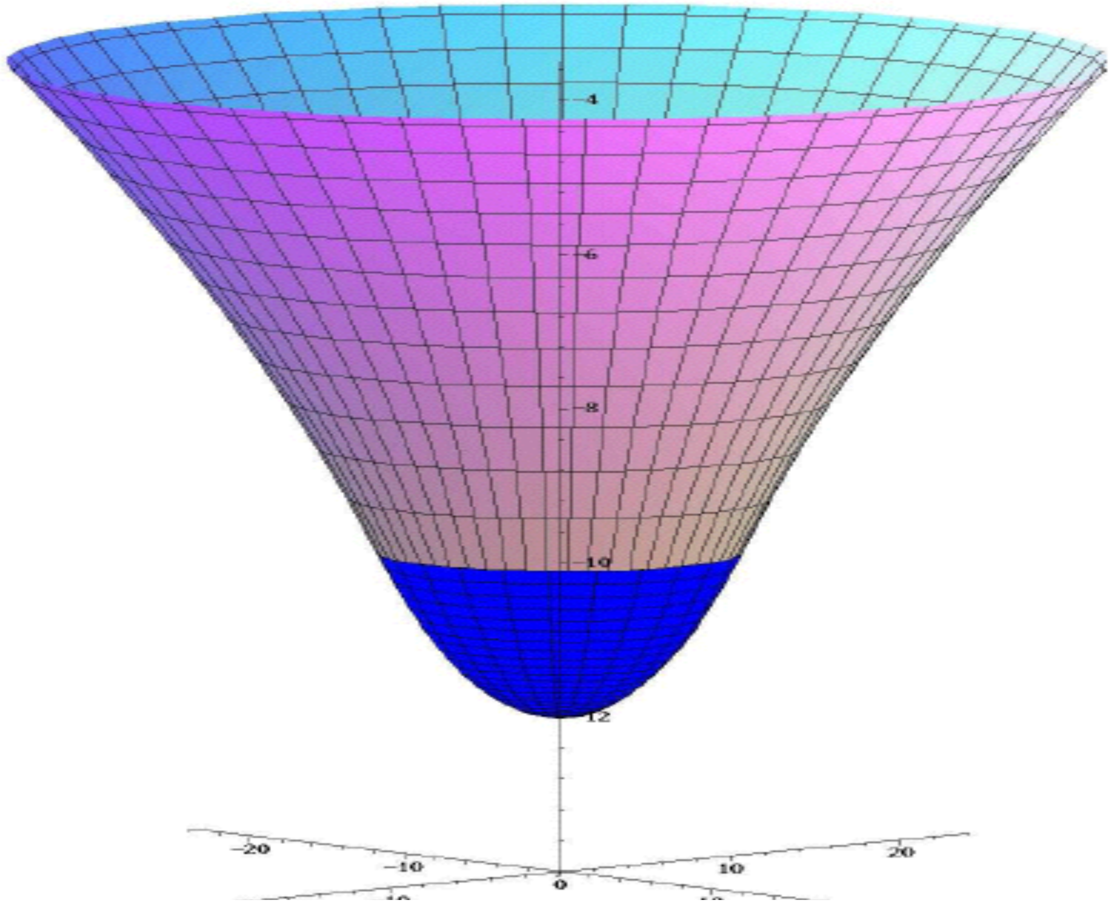
mass and energy in the spacetime

The importance of Einstein equations lies in setting a relation between the **curvature** and the **mass/energy**:

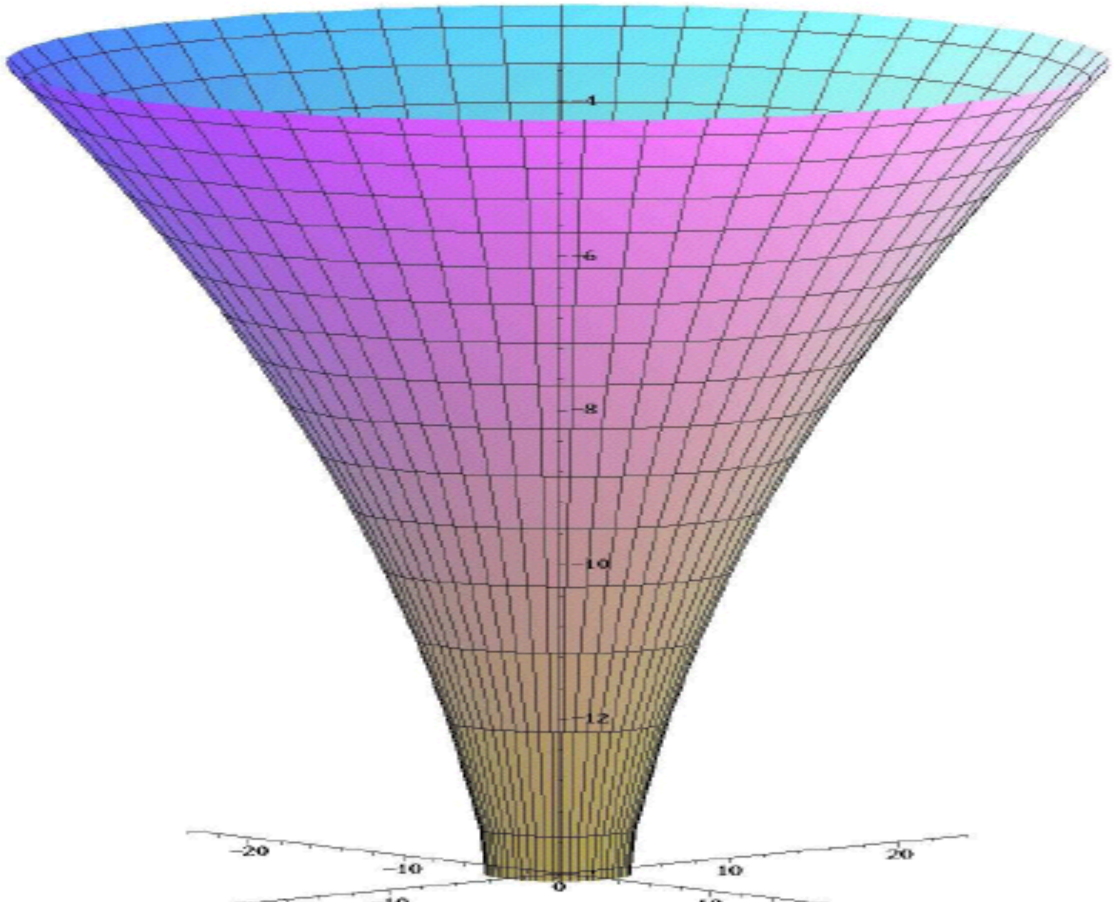
gravity becomes the manifestation of spacetime curvature

Neutron Star - or Schwarzschild's Black Hole ?

Narrow transition from a very compact neutron star to a black hole - many of the spacetime properties are similar.



Neutron Star

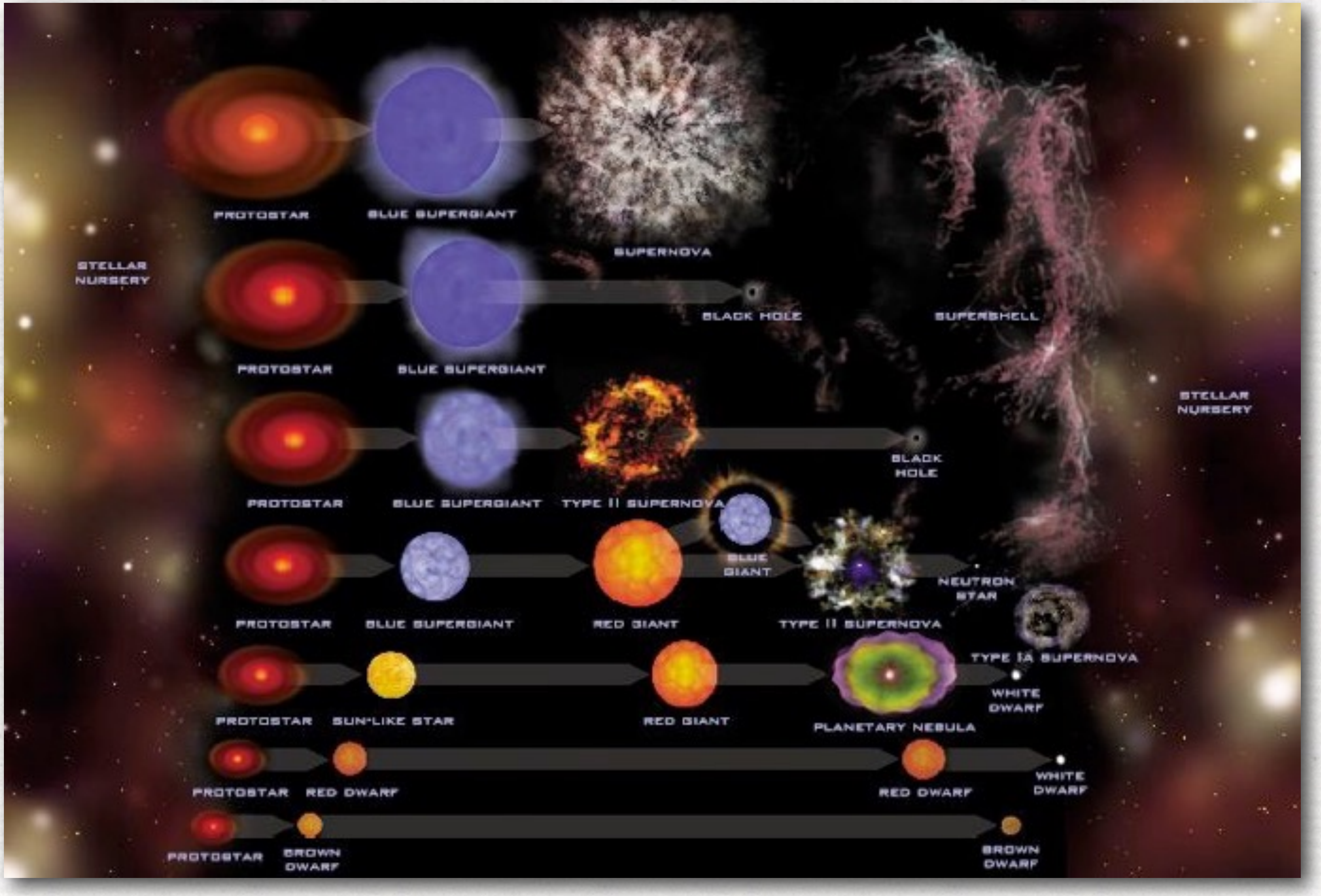


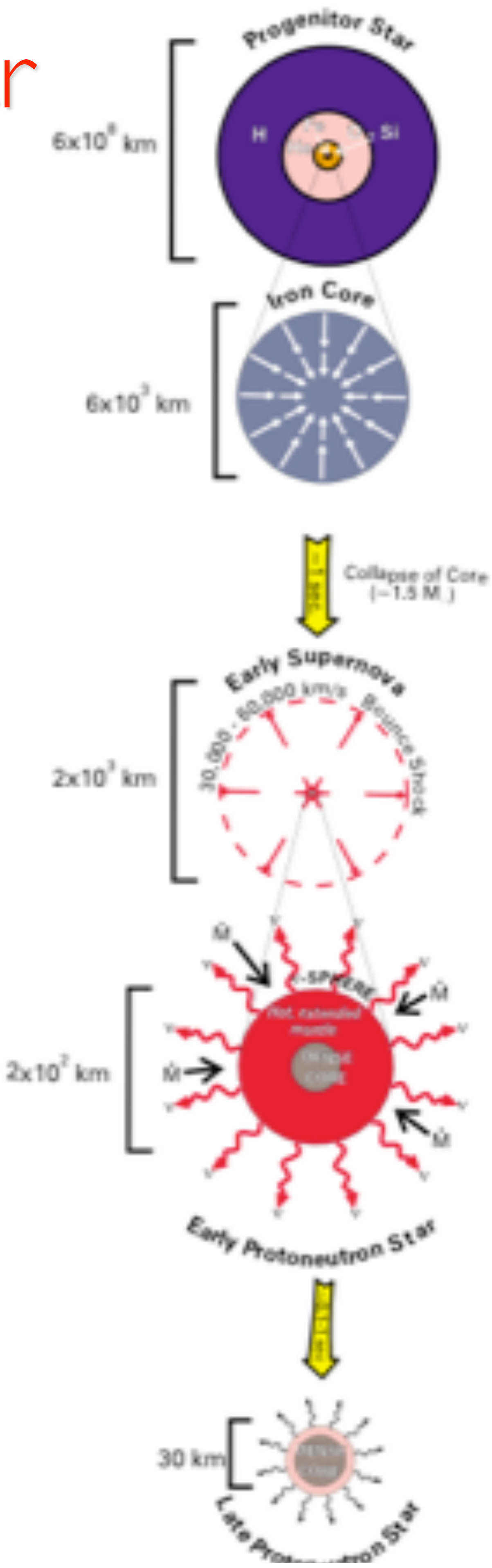
Black Hole

Two aspects differ: Neutron Stars have a ***hard surface***, the curvature is large - but ***finite*** ;

Black Hole: ***No Surface*** - curvature is ***infinite*** at the centre - but there is a SINGULARITY : NEVER divide by zero !

Death of a Star - Birth of a Neutron Star





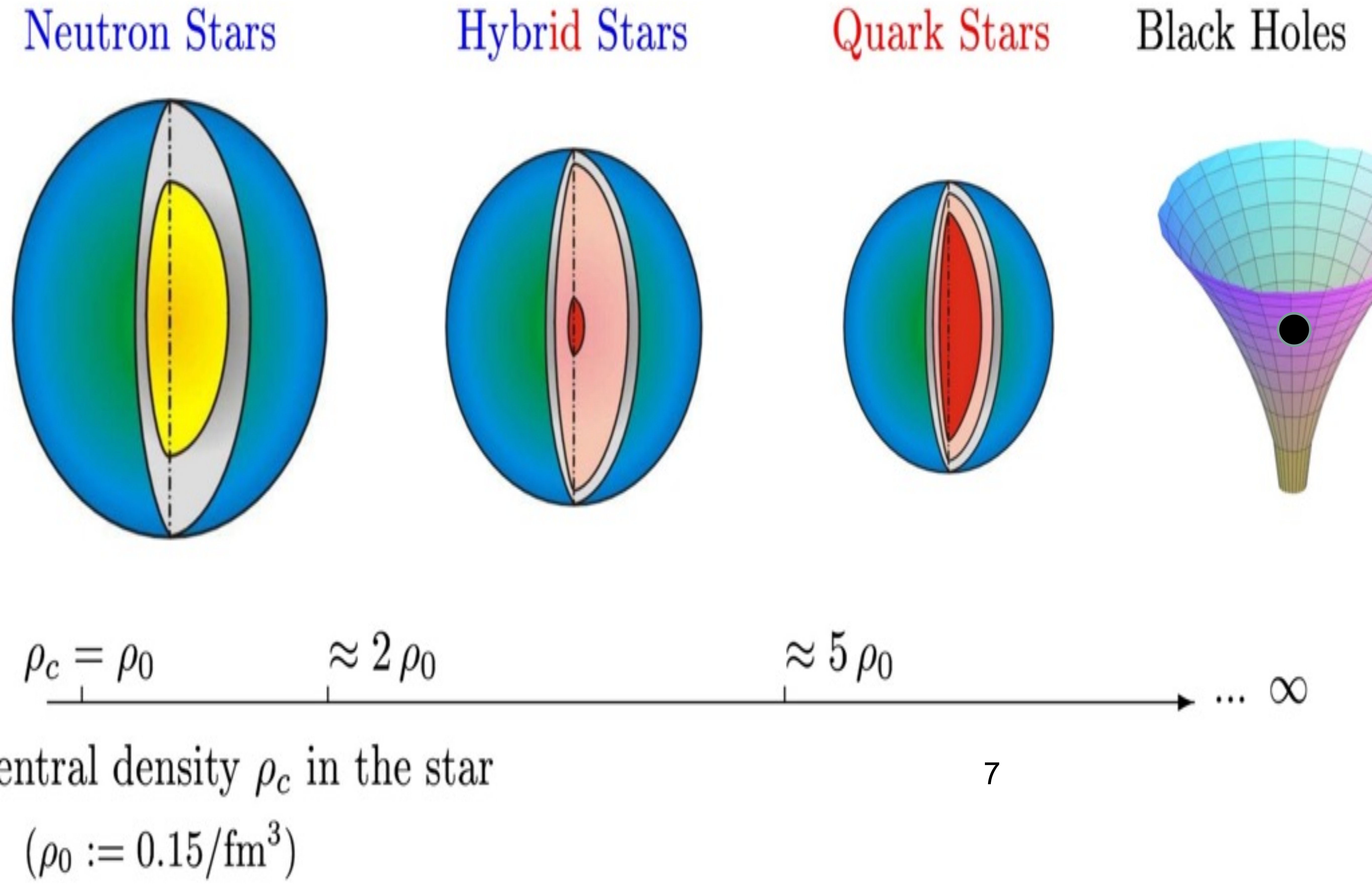
Burrows

Neutron Stars are most commonly born in the violent death of massive Stars, i.e. Stars with

$$10M_\odot \lesssim M \lesssim 100M_\odot$$

ending their evolution as a **supernova collapse**

Neutron Star, Quark Star, Black hole ?



Neutron Star Masses-Radius:

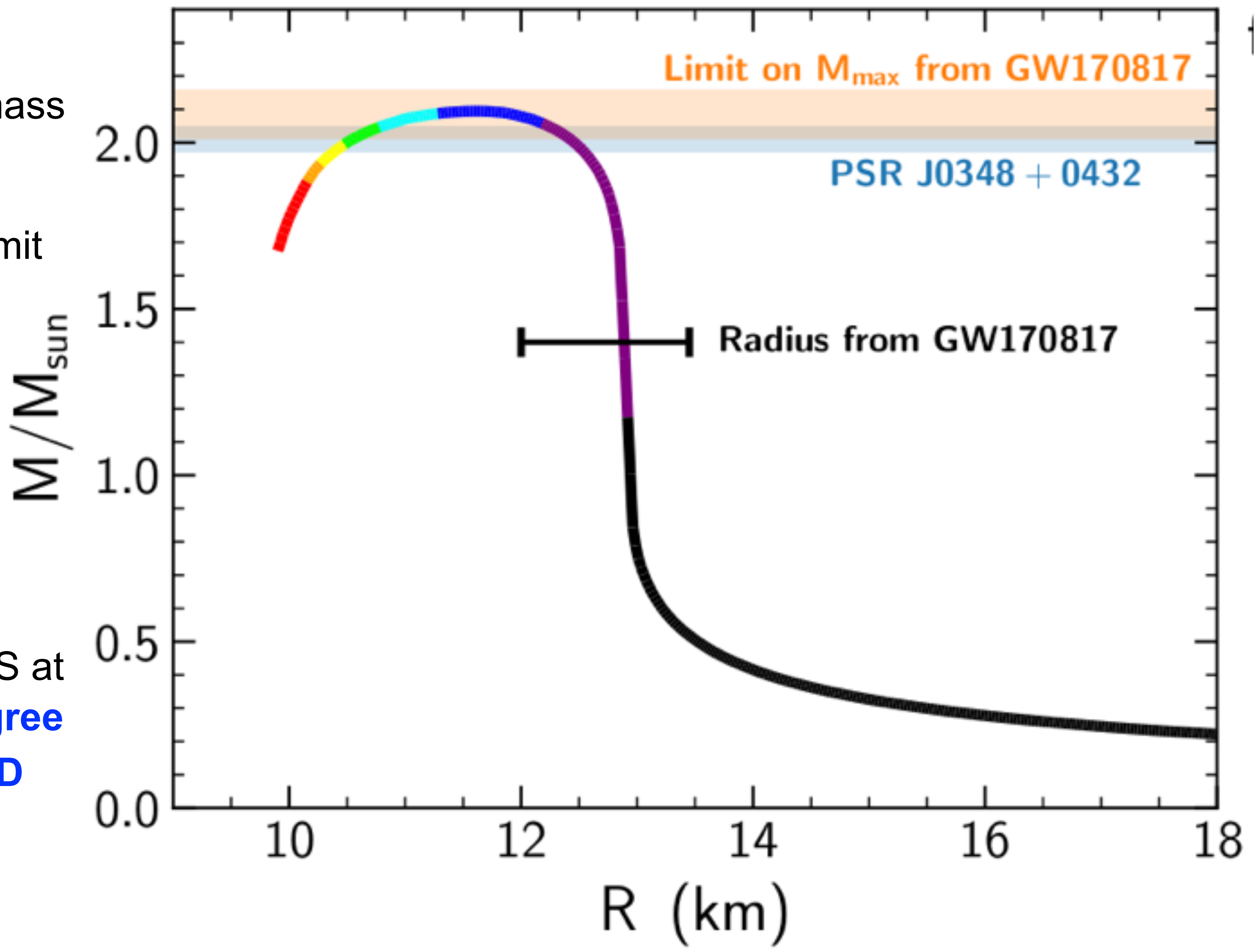
Anton Motornenko- Wednesday

Features:

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

- Radii ~13km according to
- various observational findings

- hybrid star’s EoS at high μ_B must **agree with lattice QCD data** at low μ_B



*A. **Motornenko,** Vovchenko, Steinheimer, Schramm, Stoecker 1809.02000*

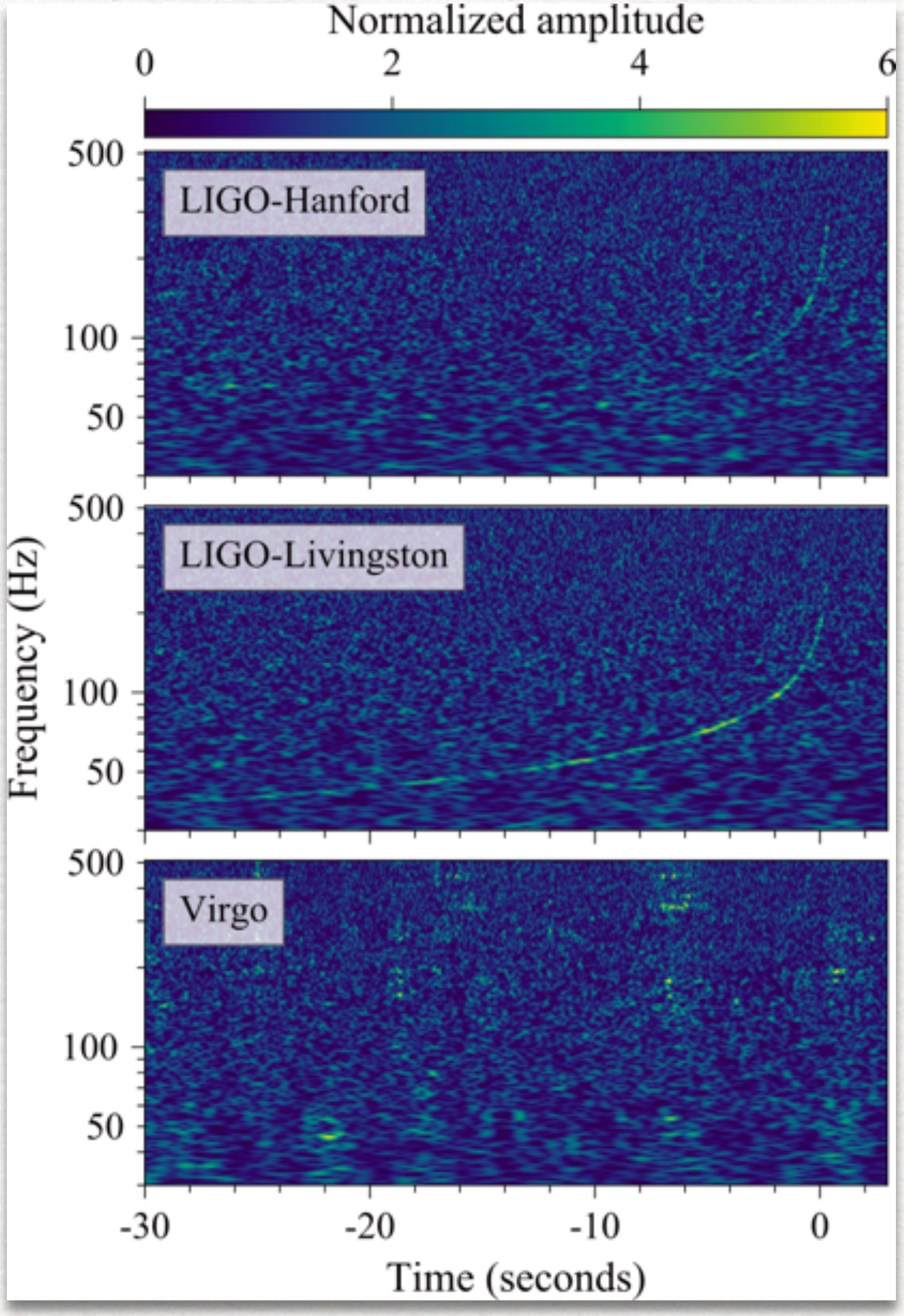
The riddle of the maximum mass

- As mentioned already, the EOS of nuclear matter is **unknown**.
- Hence, unknown is the **maximum mass**, i.e., mass above which it will collapse to a BH.
- The observation of GW170817 can help solve this riddle

$$M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot$$

$$M_1 = 1.36 - 1.60 M_\odot$$

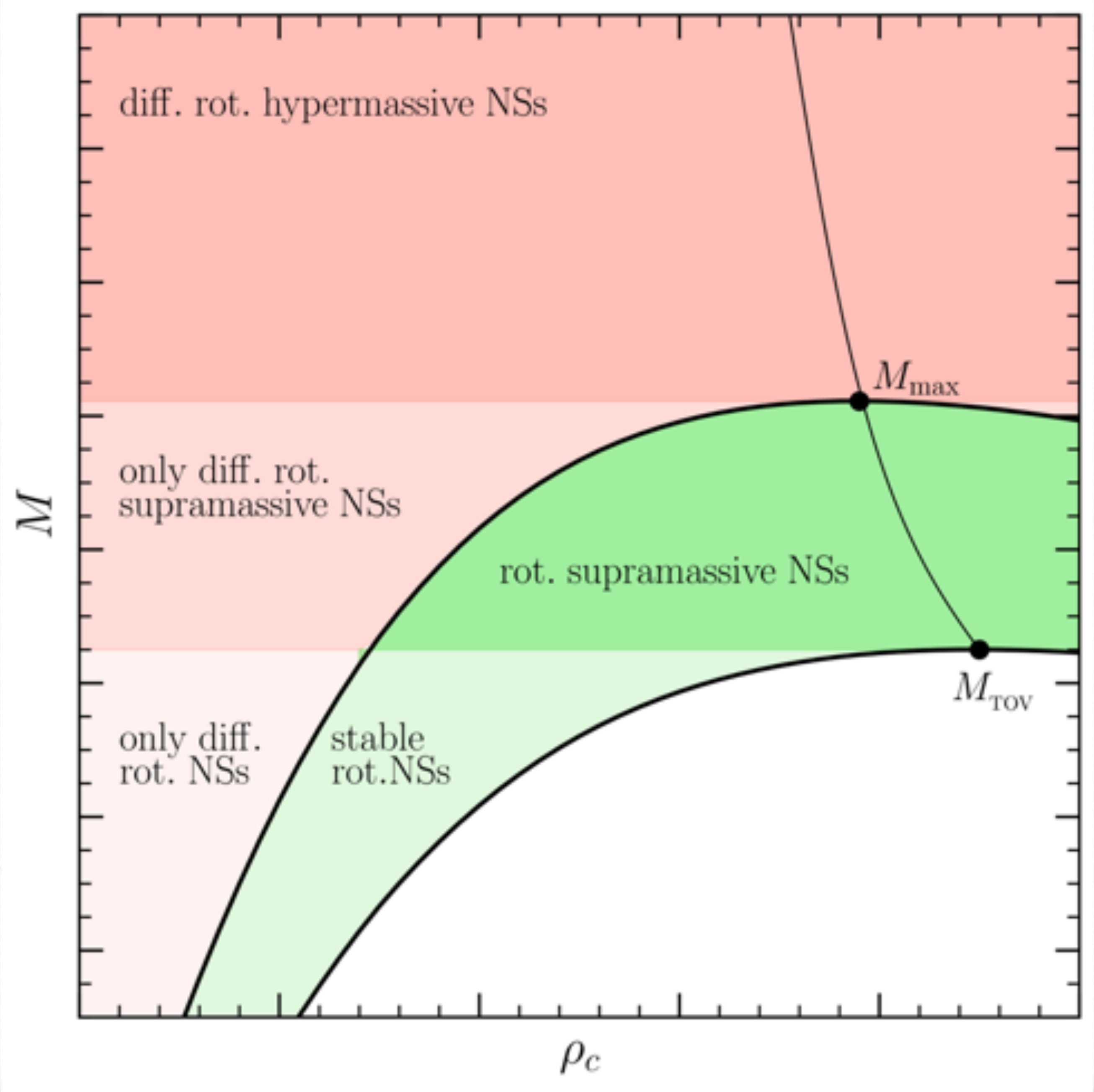
$$M_2 = 1.17 - 1.36 M_\odot$$



The outcome of GW170817

- The product of GW170817 was likely a hypermassive star, i.e. a differentially rotating object with initial **gravitational** mass

$$M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot$$



- Green region is for **uniformly** rotating equilibrium models.
- Salmon region is for **differentially** rotating equilibrium models.
- **Supramassive** stars have

$$M > M_{\rm TOV}$$

- **Hypermassive** stars have

$$M > M_{\rm max}$$

The Death Star will be revived only once she is attracted to her Partner !

Credits: Cosima Breu, David Radice und Luciano Rezzolla

Density of NeutronenStar Matter

Temperature of NeutronStar Matter

Numerical Relativity: probing the extreme with relativistic EoS and relativistic Hydro

$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu} \qquad (\text{field eqs}: \; 6+6+3+1)$$

$$\nabla_\mu T^{\mu\nu} = 0 \,, \qquad (\text{cons. en./mom.}: \; 3+1)$$

$$\nabla_\mu (\rho u^\mu) = 0 \,, \qquad (\text{cons. of baryon no}: \; 1)$$

$$p = p(\rho, \epsilon, \ldots) \,. \qquad (\text{EoS}: \; 1+\ldots)$$

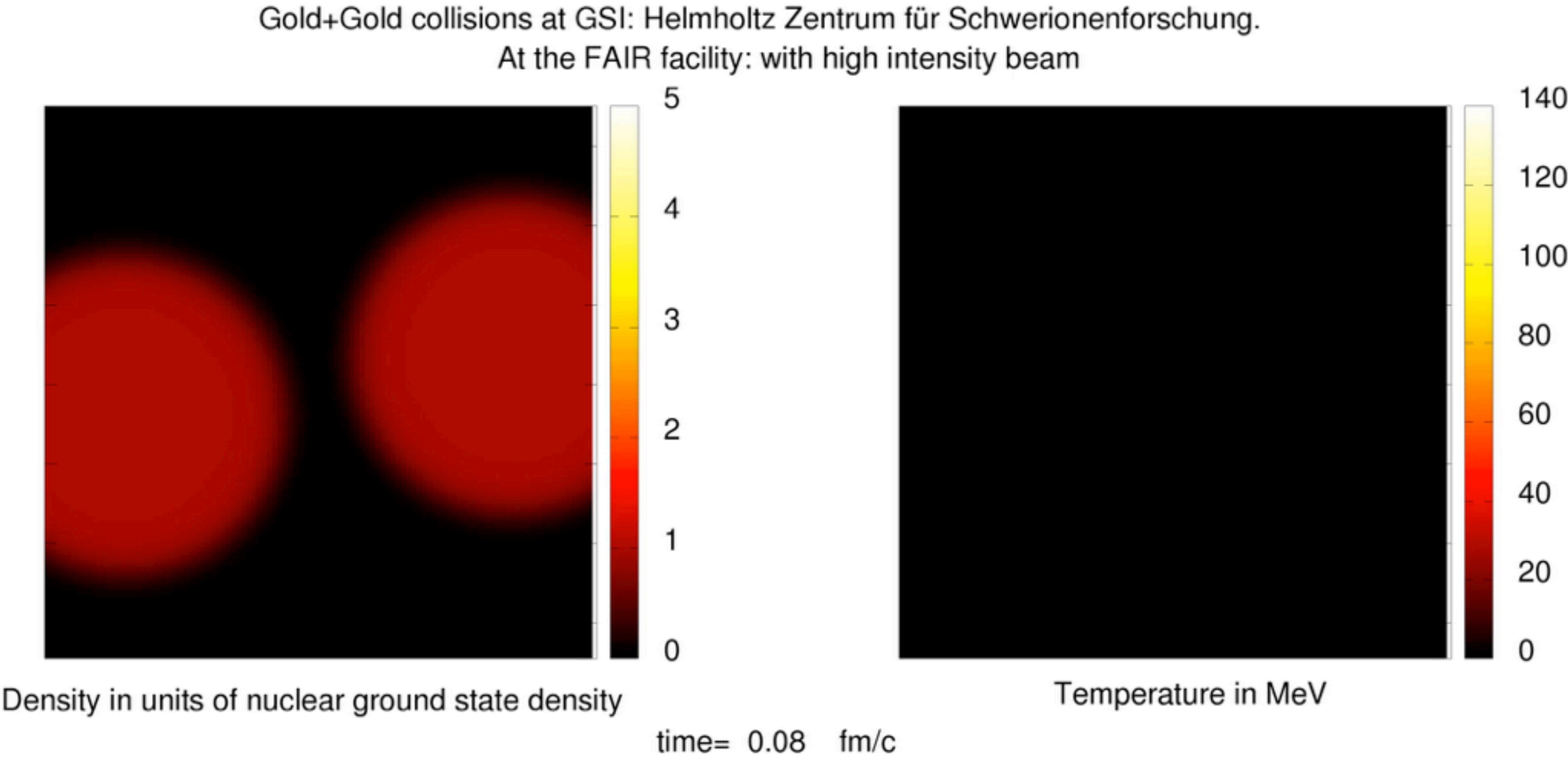
$$\nabla^*_\nu F^{\mu\nu} = 0, \qquad (\text{Maxwell eqs.}: \; \text{induction}, \; \text{zero div.})$$

$$T_{\mu\nu} = T^{\text{fluid}}_{\mu\nu} + T^{\text{em}}_{\mu\nu} + \ldots$$

These are the equations we normally solve: Einstein equations and those of relativistic hydrodynamics and MHD

The codes built are "**theoretical laboratories**", representing our approximation to *"reality"*... they must and can be continuously improved: microphysics, magnetic fields, viscosity, radiation transport ,...

Relativistic 3+1Dim Hydrodynamics for Heavy Ion Collisions@FAIR


Gold+Gold collisions at GSI: Helmholtz Zentrum für Schwerionenforschung.
At the FAIR facility: with high intensity beam

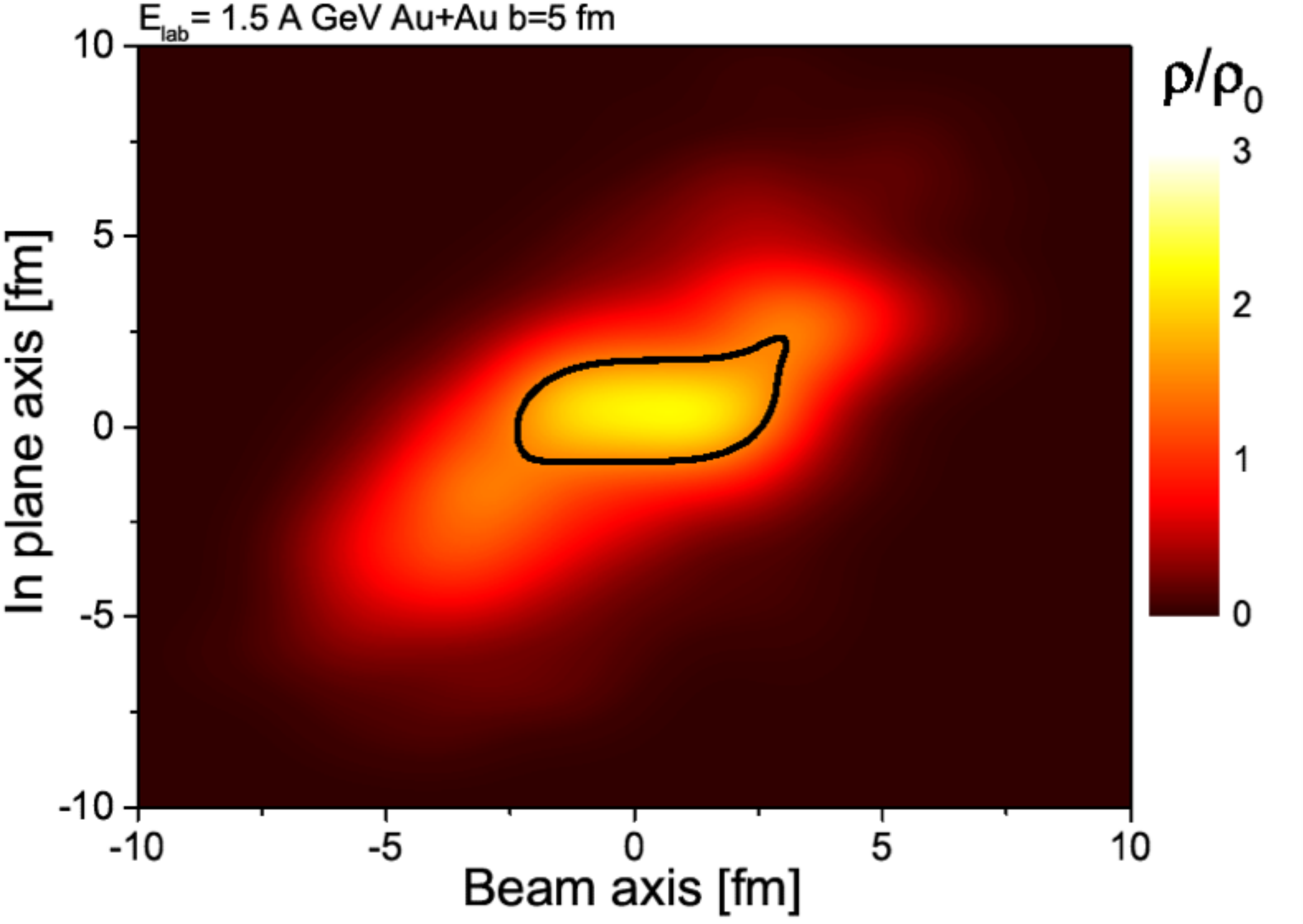
Density in units of nuclear ground state density

Temperature in MeV

time= 0.08 fm/c

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

Neutronstar merger vs. heavy ion collisions *Which densities are expected ?*

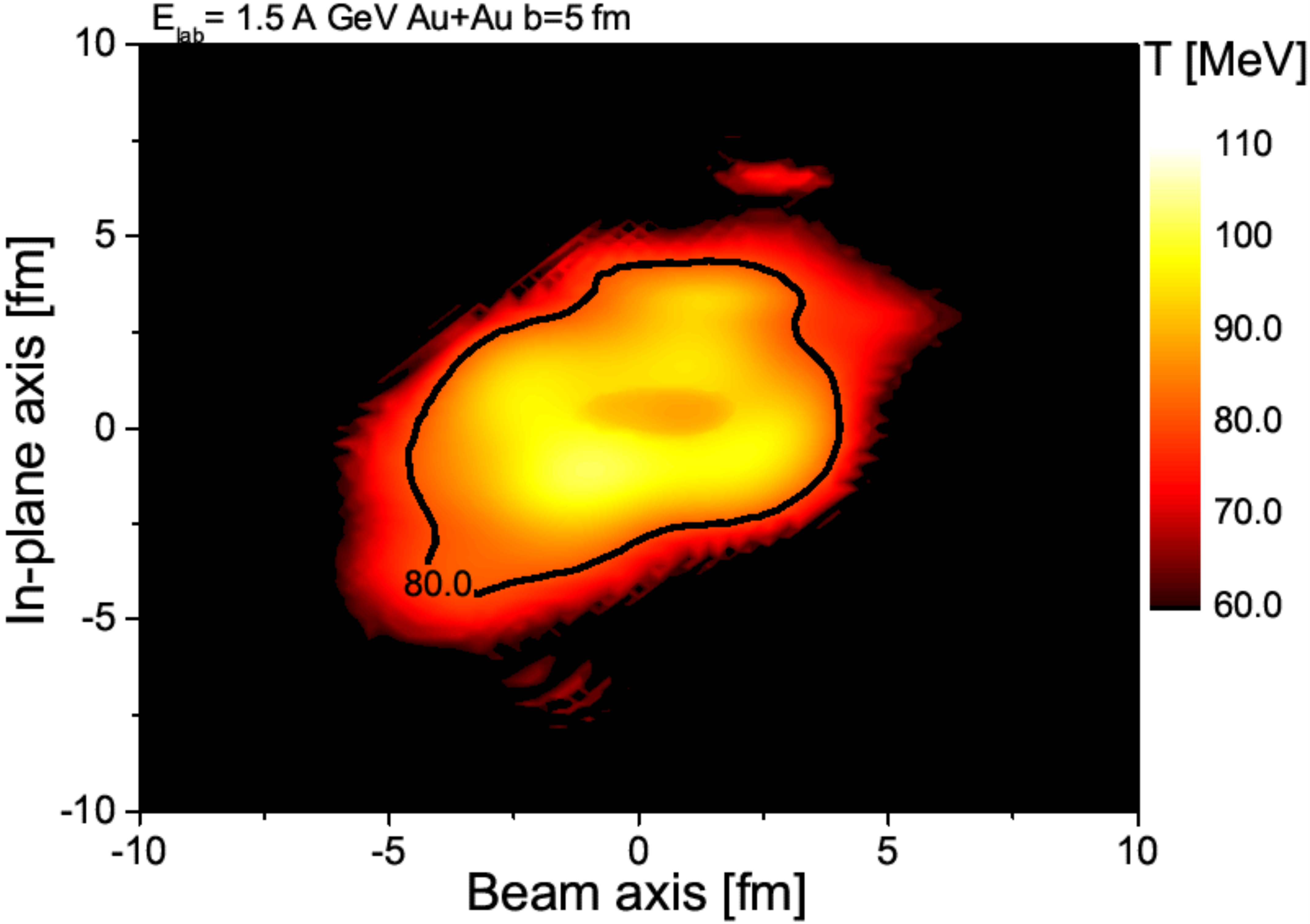


- Beam energy corresponds to GSI-SIS18.
- 3-5 times nuclear ground state density reached.
- Large inhomogeneity.
- Short lifetime ~ 20 fm/c
- Small system size ~ 10 fm

Coarse grained UrQMD simulation input for hydrodynamical evolution; **Jan Steinheimer et al**

Neutronstar merger vs. heavy ion collisions

Which temperatures are expected?

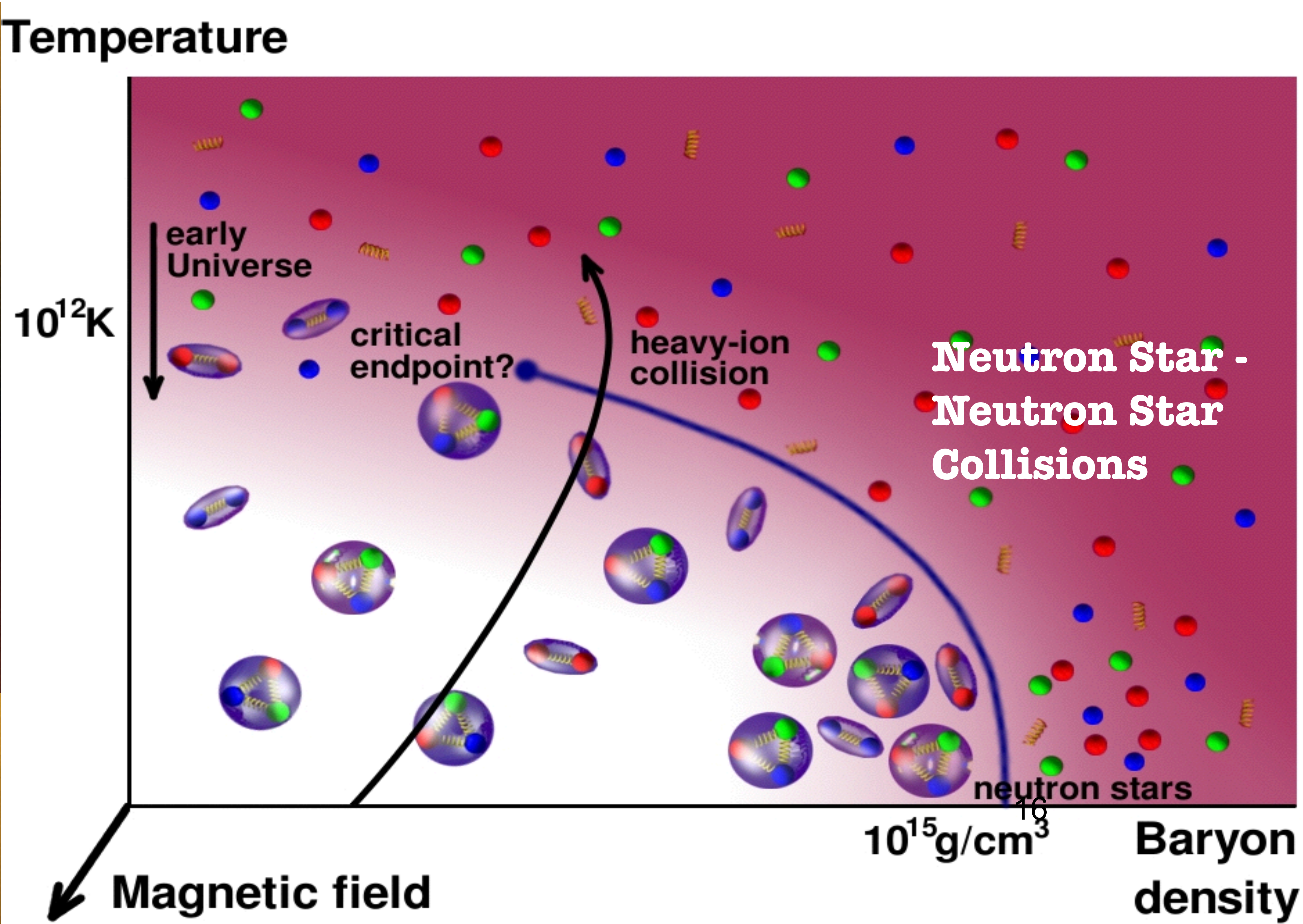


JanSteinheimer et.al: Coarse - grained UrQMD-simulation input for hydrodyn. evolution

- ❑ Beam energy corresponds to GSI-SIS18.
- ❑ Temperatures up to T=90 MeV reached.
- ❑ Large inhomogeneity.
- ❑ Short lifetime ~ 20 fm/c
- ❑ Small system size ~ 10 fm

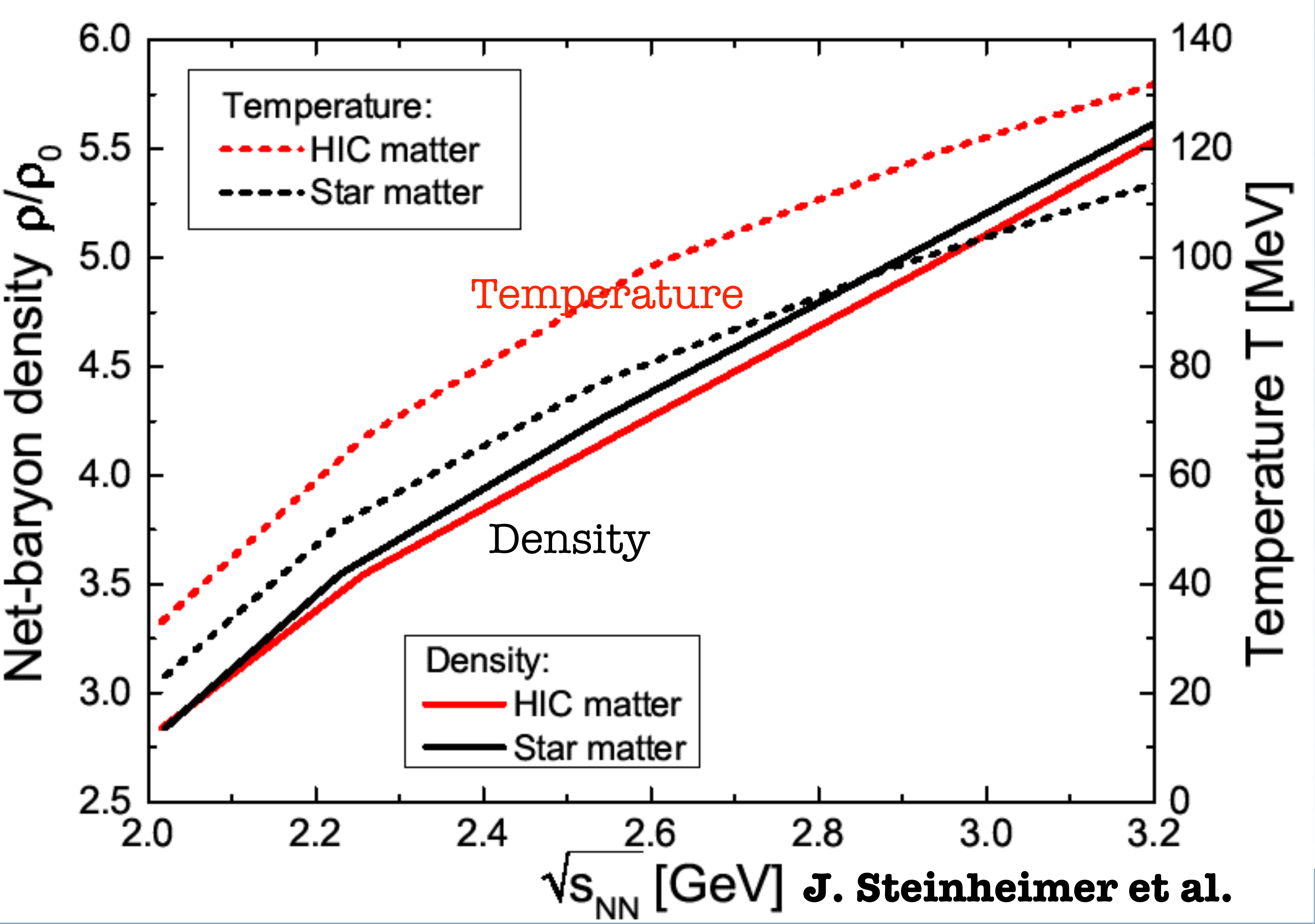
FAIR: Dense Matter, Strange Matter, Quark Matter, Quark Stars?

Relativistic collisions of NS-NS vs. Heavy Ions



Neutron Star merger vs. heavy ion collisions: *Which initial Densities and Temperatures are reached?*

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



J. Steinheimer et al.

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 1-Dim, stationary hydrodynamical equation for n, p vs E_cm=E:

E^2 -E_0^2 =

(p-p_0) (E/n - E_0/n_0)

Neutron Star mergers vs. Heavy Ion collisions: No Difference in Hydro-Dynamics? Really? Why?

- Hydro-Dynamics is scale invariant !

- System Size: Kilometers vs. Femtometers - does not matter !
- Evolution time: Milliseconds vs. fm/c - does not matter !

- Chemical Equilibrium & Phase-Equilibrium vs. Non-Equilibrium ?
- **Gravity is relevant ! Attraction** is enormous- Special Relativity vs. GR: BHs

- Relativistic Hydro-Dynamics the theory for both SR & GR!

- Relativistic nuclear **Equation of State** must be conform to QCD- Thermodyn.
- EoS most important input for Relativistic Hydrodynamics, SR and GR

”The Death Star machine!” (The Times of India)

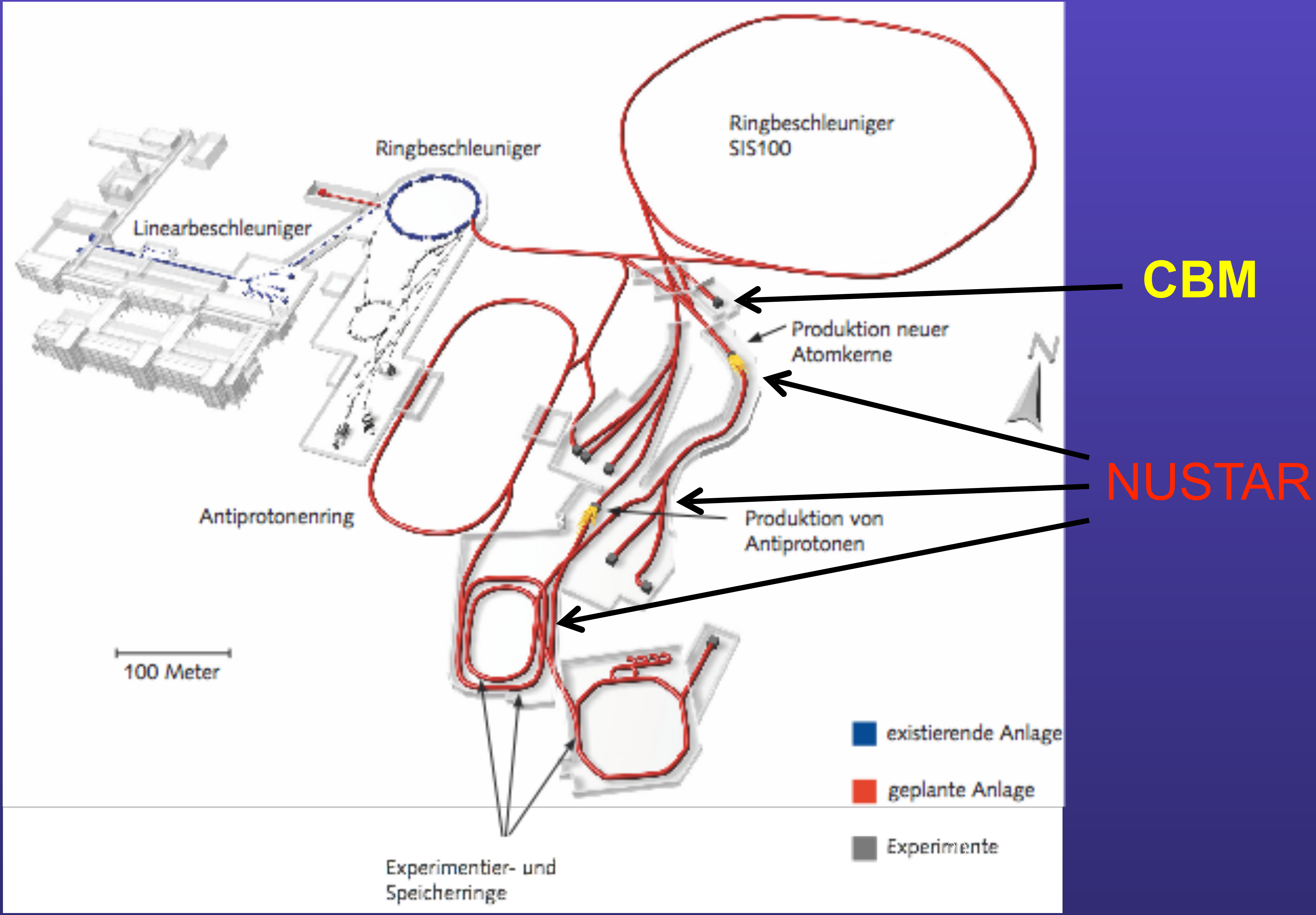
FAIR and NICA ideally equipped for precision studies
to compare relativistic collisions between
heavy ions and neutron stars

- Consistent theoretical treatment:

Relativistic EoS Equation of State of dense QCD Matter
input into
General Relativistic 3+1 Dim Hydrodynamical Transport

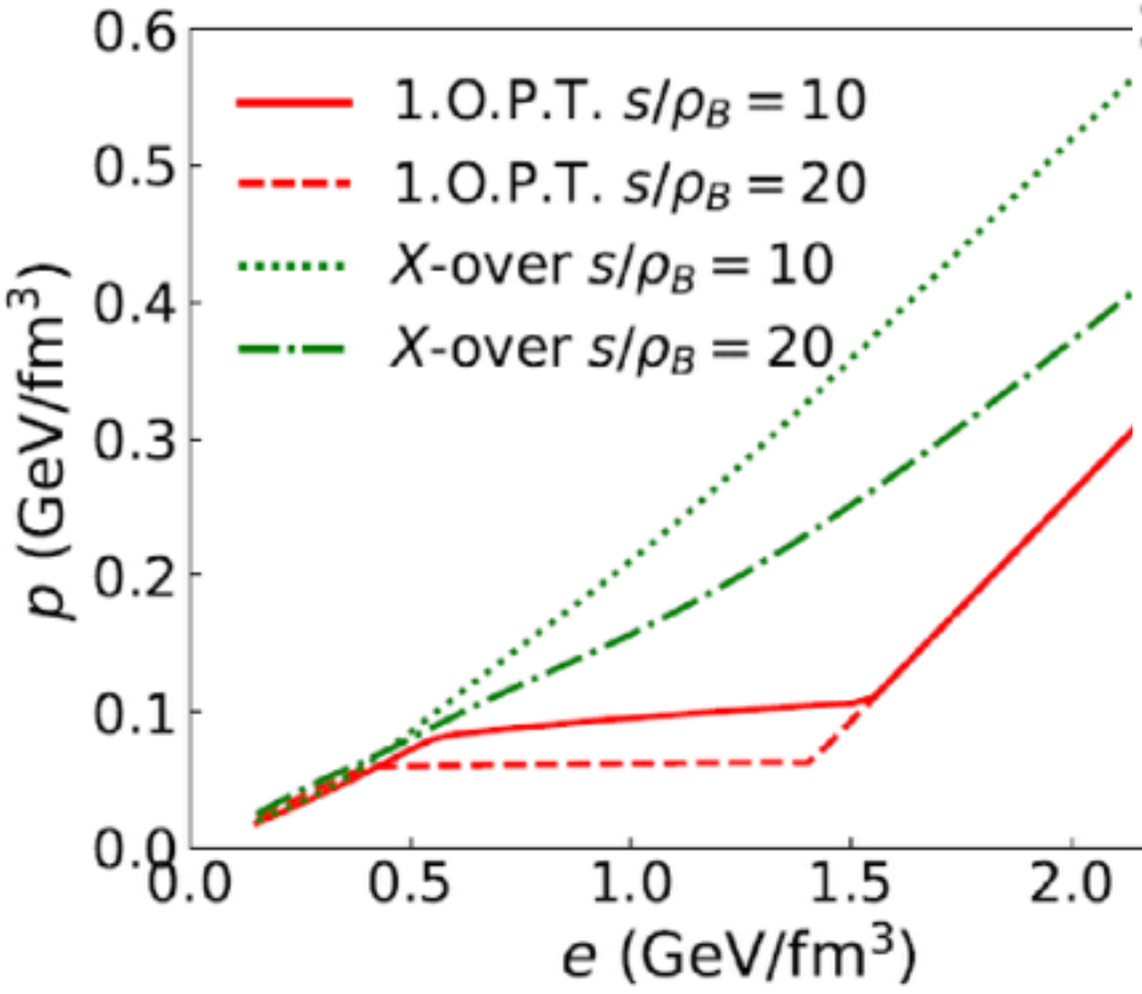
- Predict and compare to observational data -

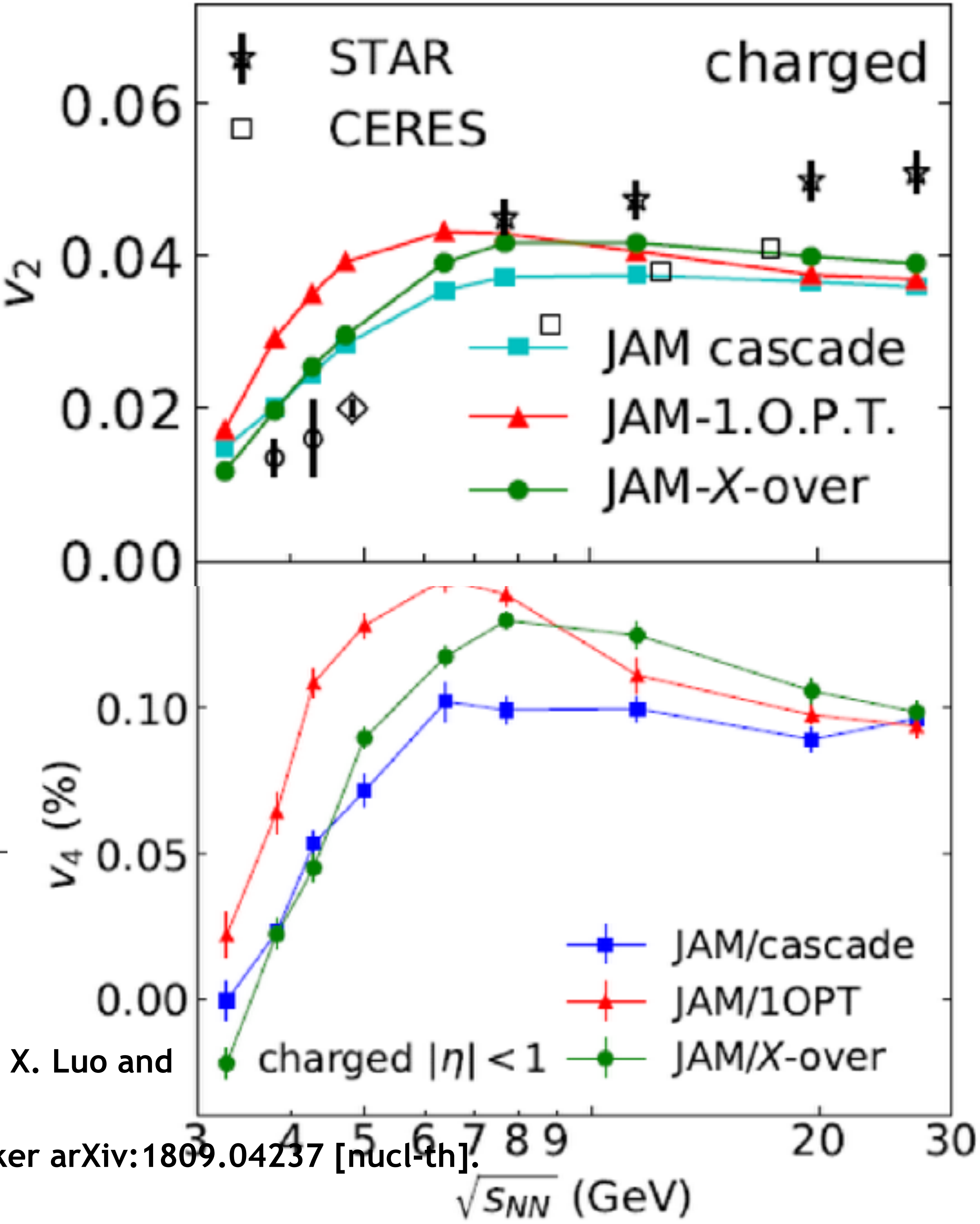
Neutron Star matter in CBM @FAiR-GSI Helmholtzcentre



1.st, 2.nd and 4.th order coefficient of FLOW can signal a 1.Order phase transition

- JAM relativistic transport model
- EoS introduced via azimuthal scat angle
- **IF** there is a 1. order phase transition?
- **Then=> v_1 Drop** & v_2 and v_4 **PEAK**





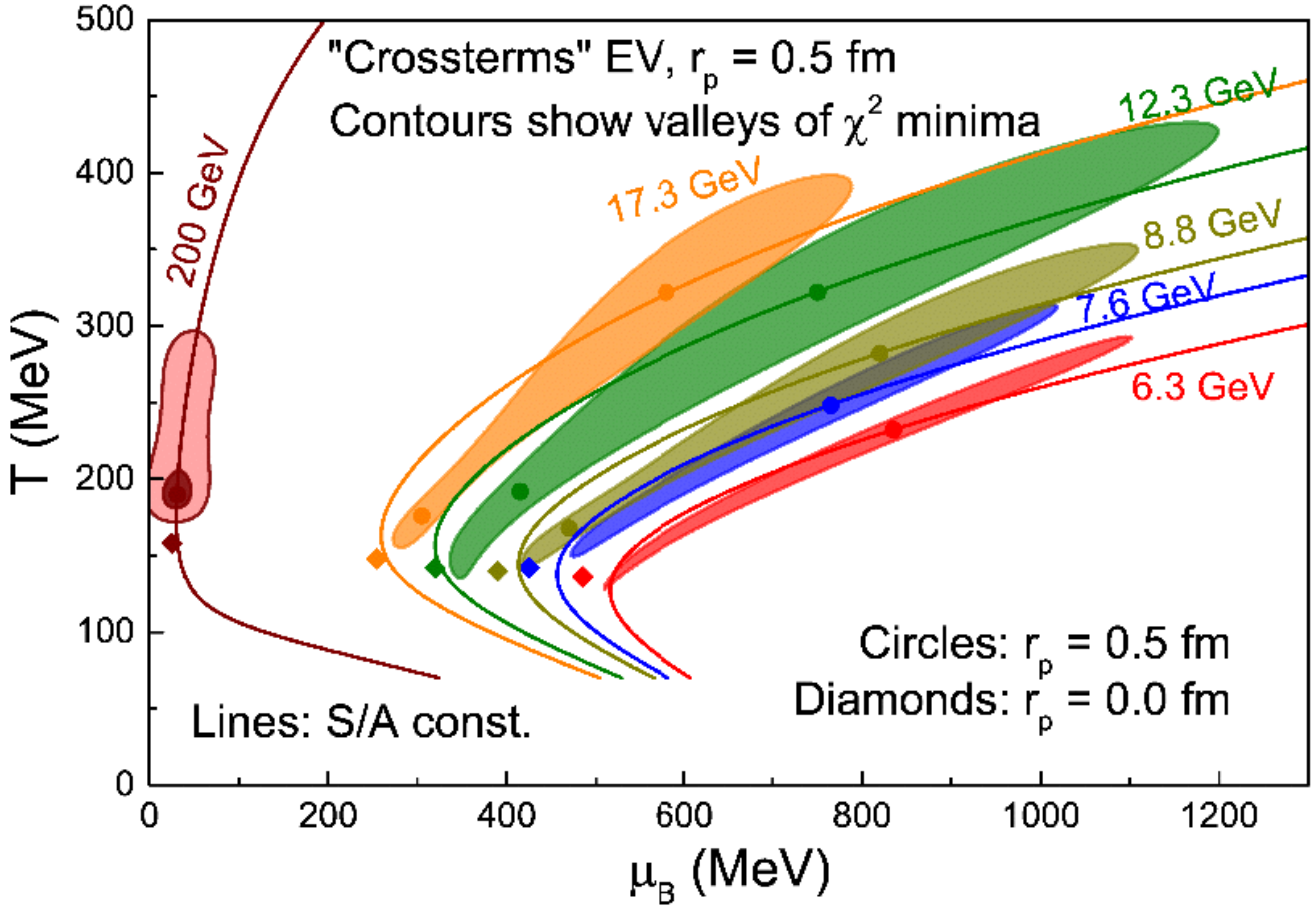
Y. Nara, H. Niemi, A. Ohnishi, J. Steinheimer, X. Luo and H. Stöcker, Eur. Phys. J. A 54, no. 2, 18 (2018)

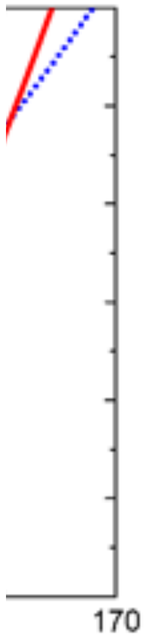
Yasushi Nara, J. Steinheimer and H. Stoecker arXiv:1809.04237 [nucl-th].

V. Vovchenko, H. Stoecker, Phys. Rev. C (2017)

Excluded-volume interactions and thermal fits

QvdW-Excluded-volume interactions have a surprisingly large effect on thermal fits





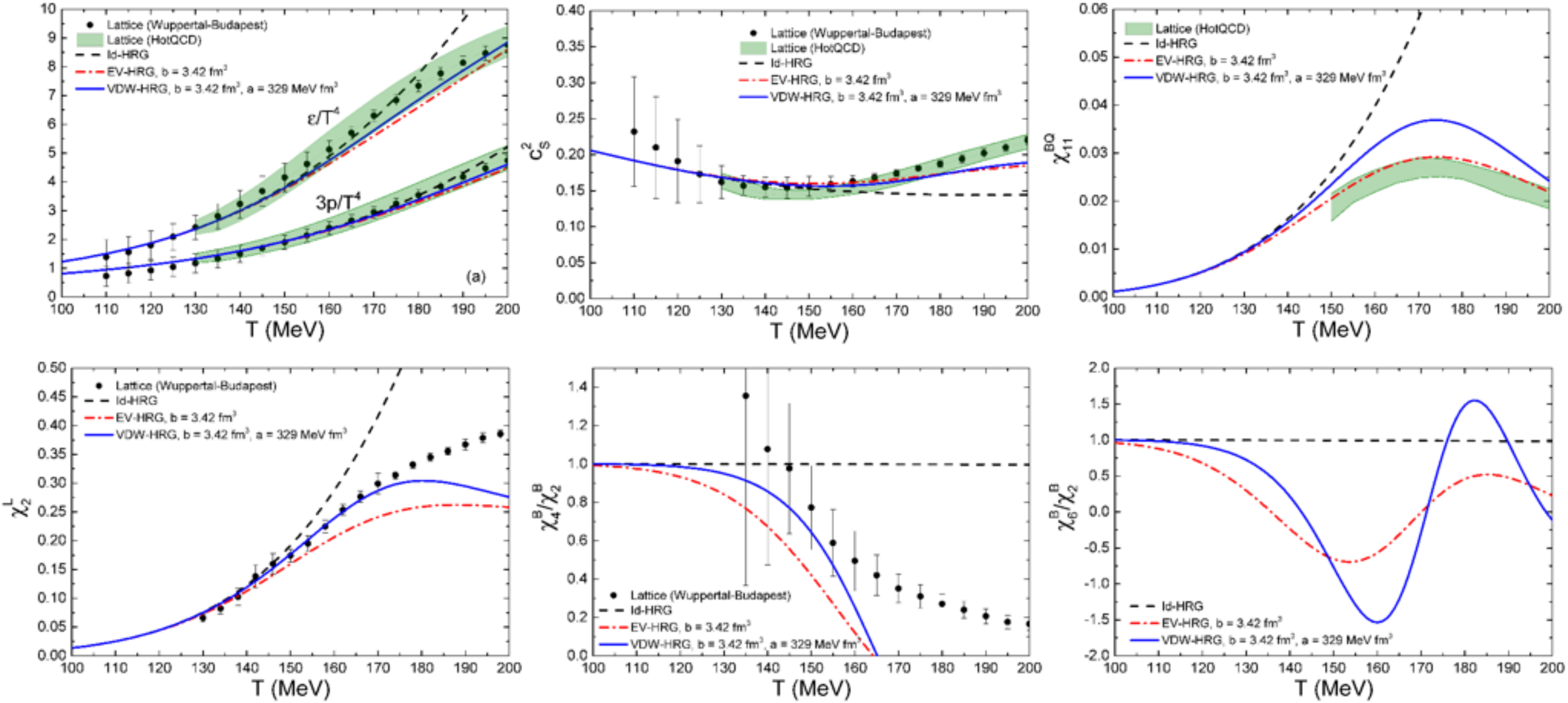
V. Vovchenko, H. Stoecker, 1610.02346

P. Alba et al., 1606.06542

V. Vovchenko, M.I. Gorenstein, H. Stoecker, Phys. Rev. Lett. (2017), 1609.03975

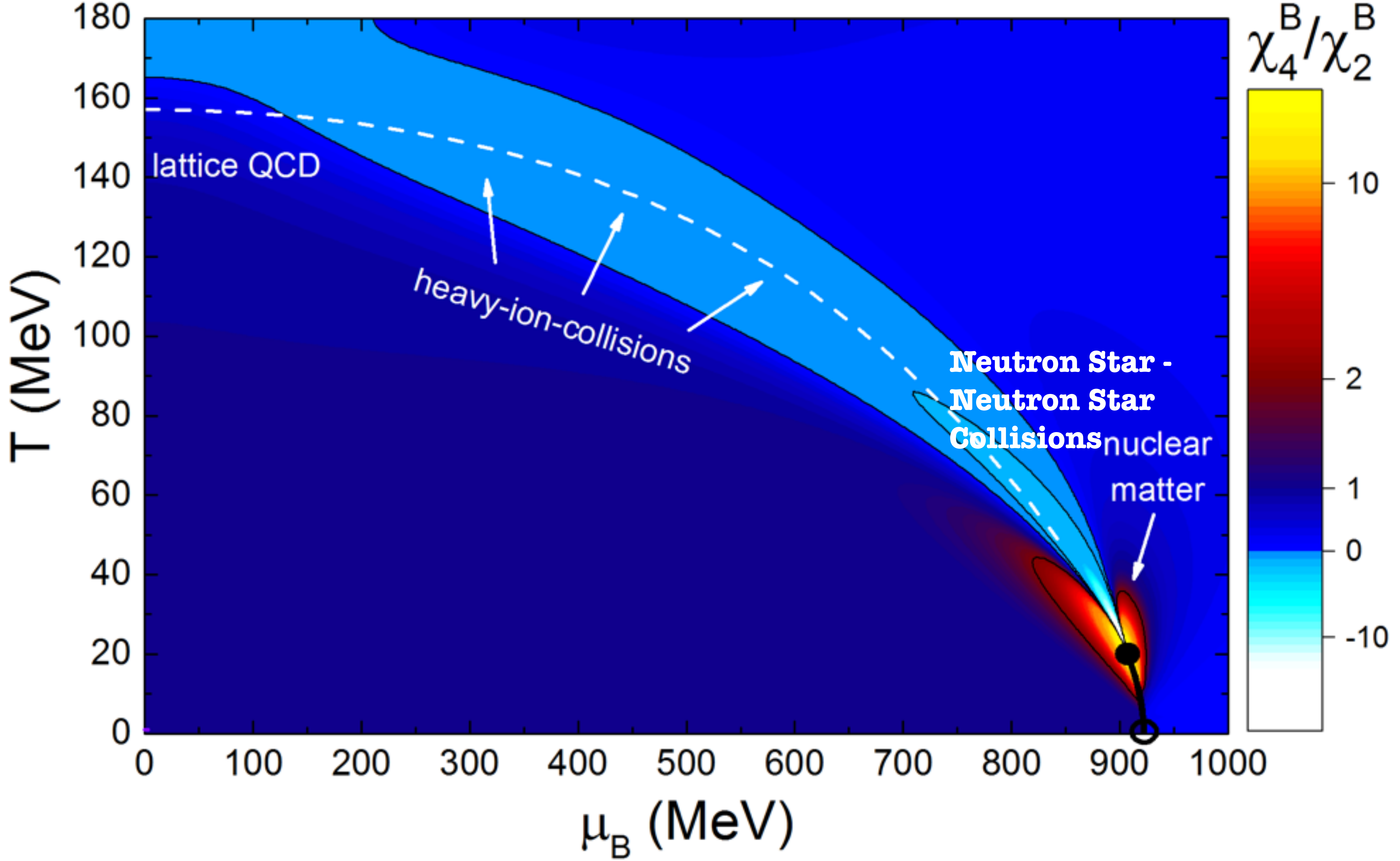
van der Waals interactions and lattice QCD

Quantum van der Waals terms for baryons: parameter-free LQCD data description



QvdW can- beyond LQCD- explore high baryochemical potential and neutron star matter at high density, needs little computing power

Quantum van der Waals describes HR-Fluid at non- zero net-baryon density



Neutron Star - Neutron Star Collisions

Nuclear matter shines brightly across whole phase diagram probed in HIC & NsNs

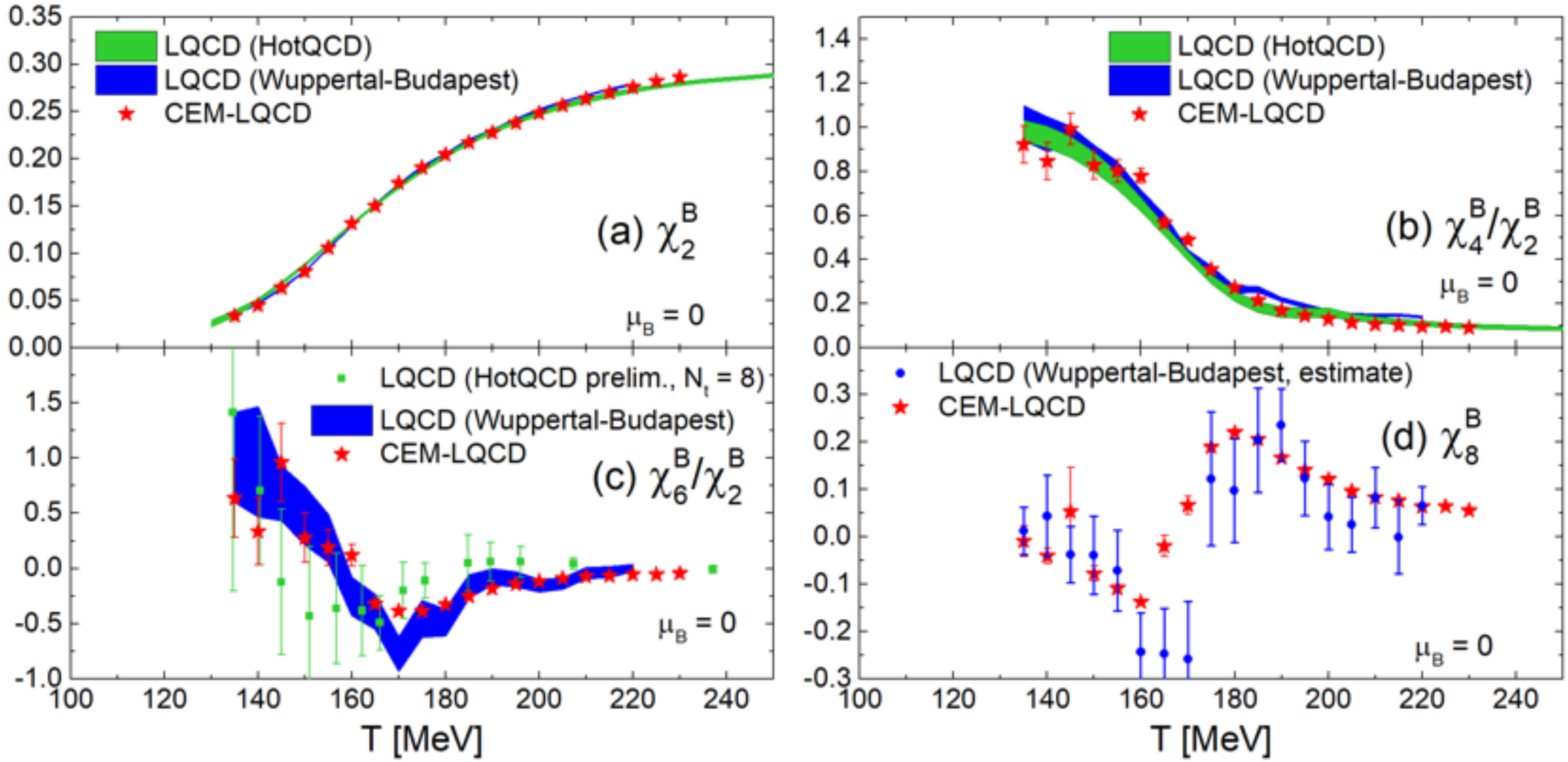
V. Vovchenko, M.I. Gorenstein, H. Stoecker, Phys. Rev. Lett. (2017), 1609.03975

V. Vovchenko - talk Friday

Cluster Expansion Model

A state-of-the art lattice based model for QCD EoS at finite density

$$\frac{p(T,\mu_B)}{T^4} = p_0(T) - \frac{2}{27\pi^2}\frac{\hat{b}_1^2}{\hat{b}_2}\left\{4\pi^2\left[\mathrm{Li}_2(x_+)+\mathrm{Li}_2(x_-)\right] + 3\left[\mathrm{Li}_4(x_+)+\mathrm{Li}_4(x_-)\right]\right\}$$



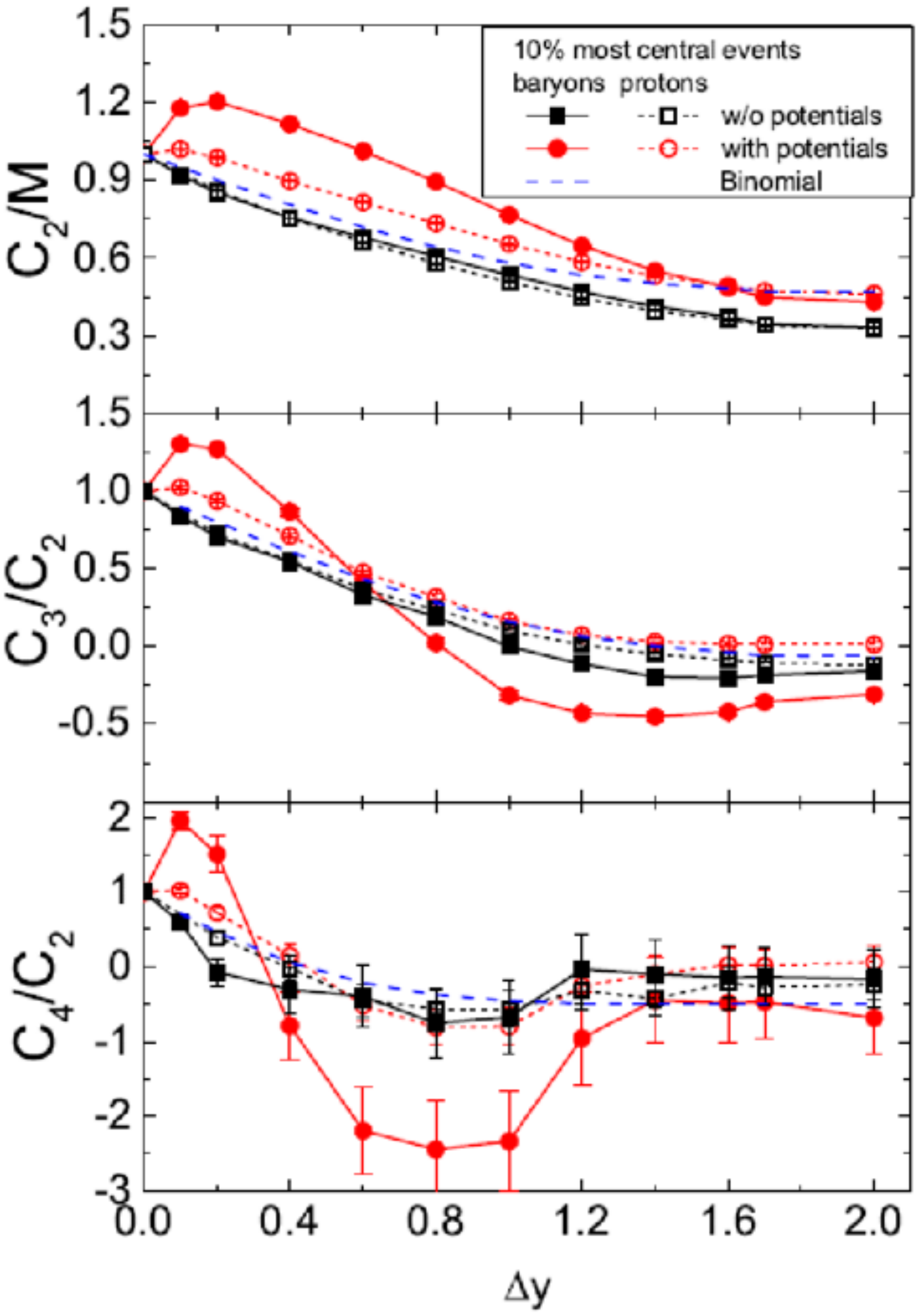
V. Vovchenko, J. Steinheimer, O. Philipsen, HSt, Phys. Rev. D 97, 114030 (2018)

Baryon number fluctuations reveal the attr.-rep. nuclear interactions

- Simulations of central Au+Au collisions with UrQMD at HADES/GSI SIS18 beam energy.
- Either use cascade mode or include Skyrme potentials.
- Calculations with potentials see an significant increase of all cumulant ratios, at small rapidity windows
- Can we find effects of the
- nuclear L-G critical point?
- Work in progress.

J. Steinheimer, Y. Wang, A. Mukherjee, Y. Ye, C. Guo, Q. Li and H. Stoecker Phys. Lett.B785,40(2018)

Y. Ye et al.arXiv:1808.06342[nucl-th].



EoS by SU(3) Parity-doublet Quark-Hadron Chiral Mean Field CMF

A. Motornenko, P. Rau, J.Steinheimer, S.Schramm, H.ST.

…. includes consistently main aspects of QCD phenomenology

Unified effective QCD approach and thermodynamics in a wide range of scales.

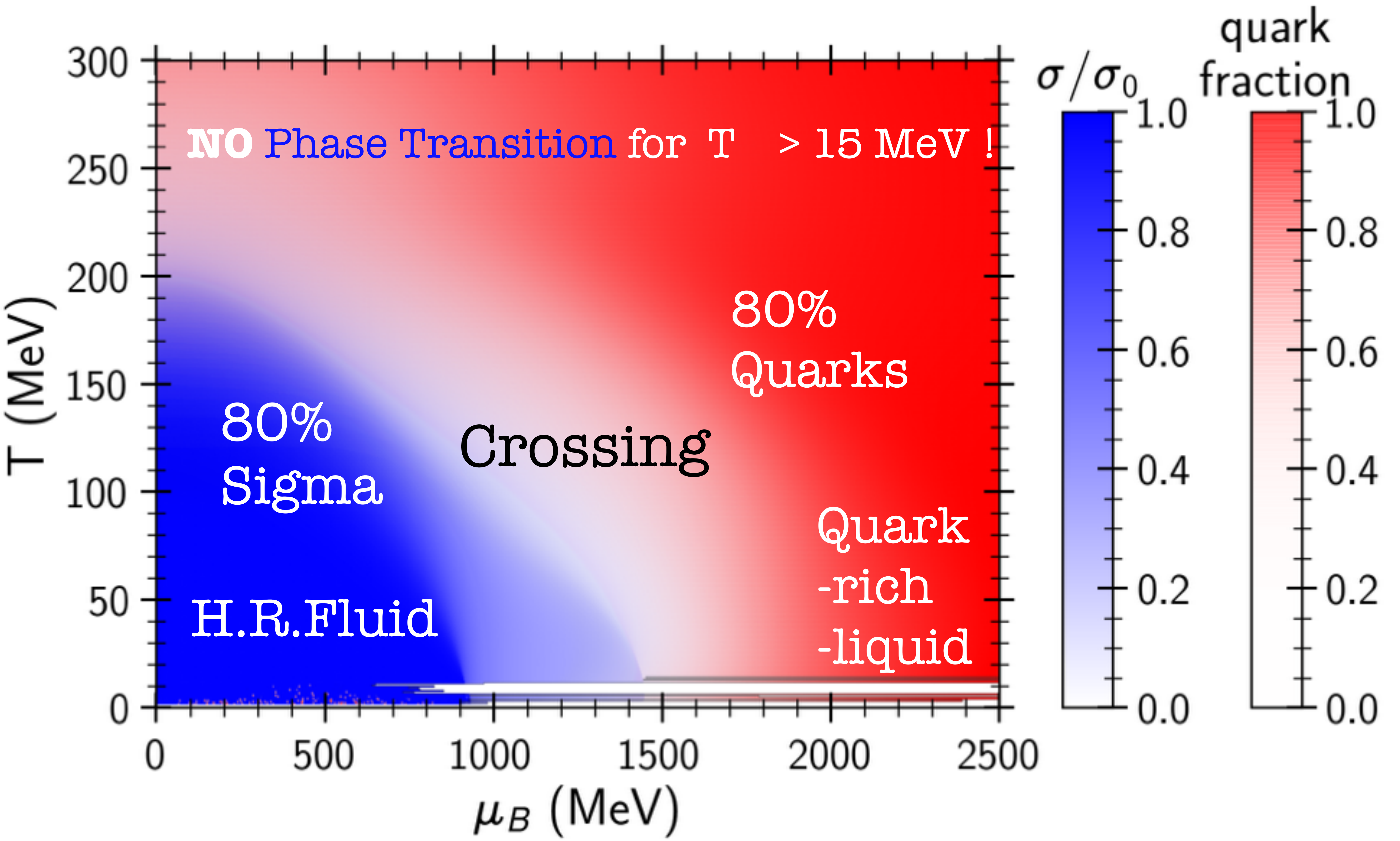
- PDG vacuum hadrons - plus quarks and gluons
- Proper description of nuclei, hypernuclei, single particle states, SHE
- nuclear and neutron star matter, cold and hot
- Chiral crossover: Parity partners' masses become equal
- Deconfinement: comes separate at higher energy densities

A realistic and relativistic EOS
for Heavy Ion Collisions at FAIR/NICA and
for NS (T=0) and binary NS mergers (T~70 MeV)

P. Papazoglou, S. Schramm et al., Phys. Rev. C 57, 2576 (1998).
P. Papazoglou, D. Zschiesche S. Schramm et al., Phys. Rev. C 59, 411 (1999).
J. Steinheimer, S. Schramm, H. Stoecker, Phys.Rev. C84 045208 (2011)
P. Rau, J. Steinheimer, S. Schramm, H. Stoecker, Phys.Lett. B733 (2014) 176-182
A. Mukherjee, J. Steinheimer, S. Schramm, Phys.Rev. C96 (2017) no.2, 025205
A. Motornenko, V. Vovchenko, J. Steinheimer, S. Schramm, H. Stoecker, 1809.02000

Phase diagram from relativistic Chiral Mean Field CMF

A. Motornenko - talk Wednesday



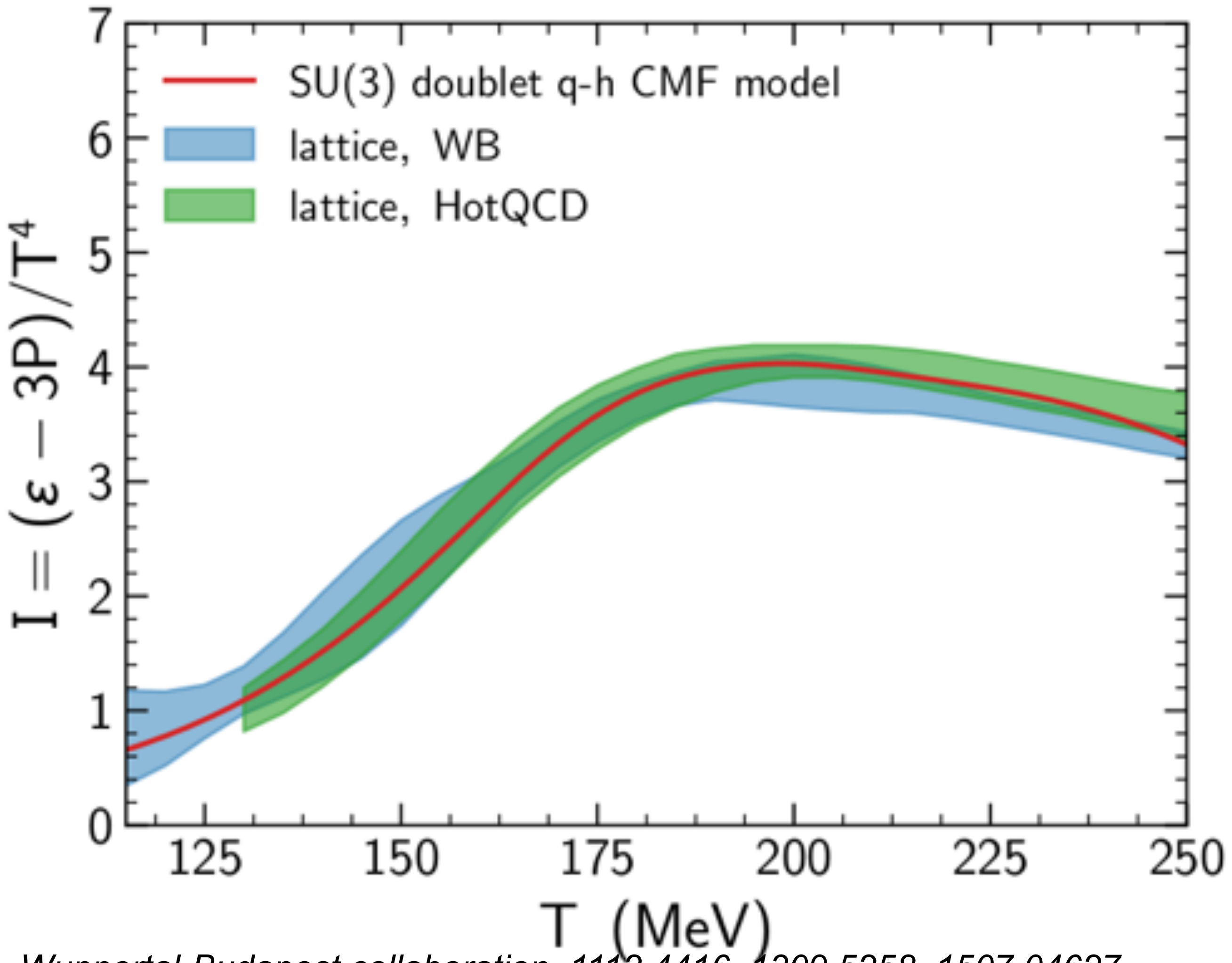
NO Phase Transition for T > 15 MeV !

MAGIC Motornenko, Most, Hanauske, Rezzolla, Schramm, Steinheimer, Stoecker

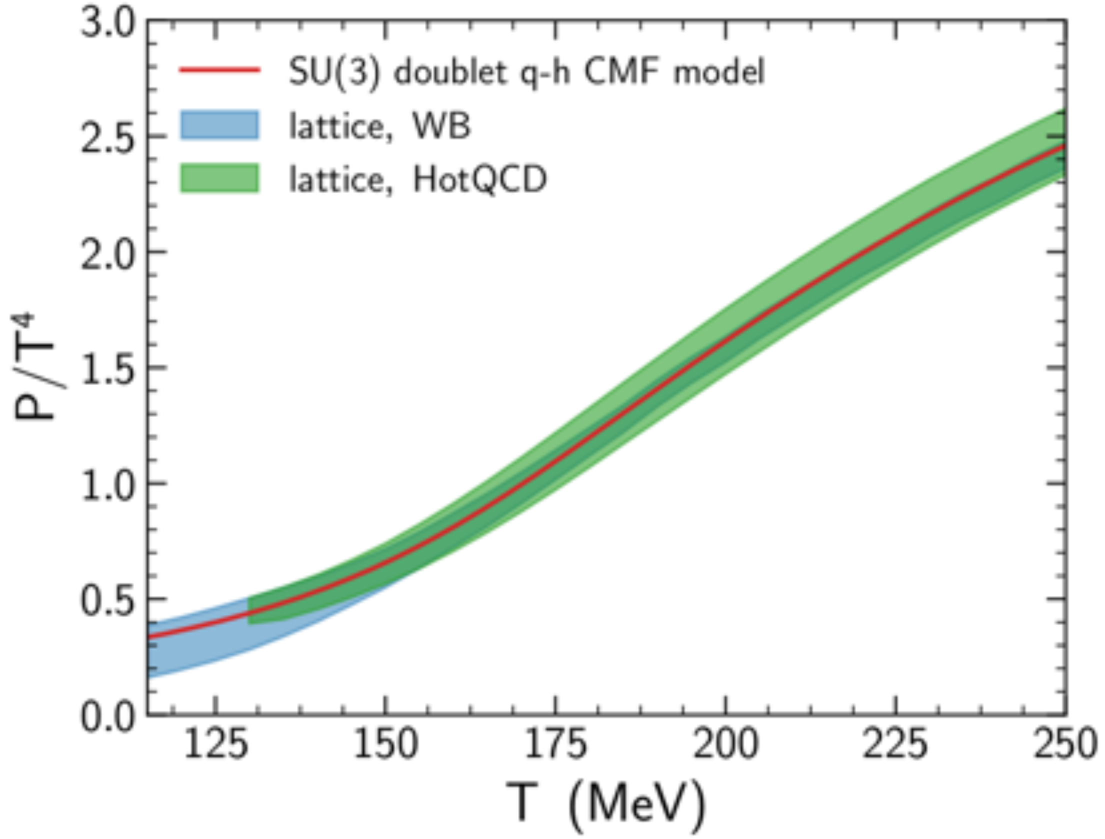
A. Motornenko - talk wednesday

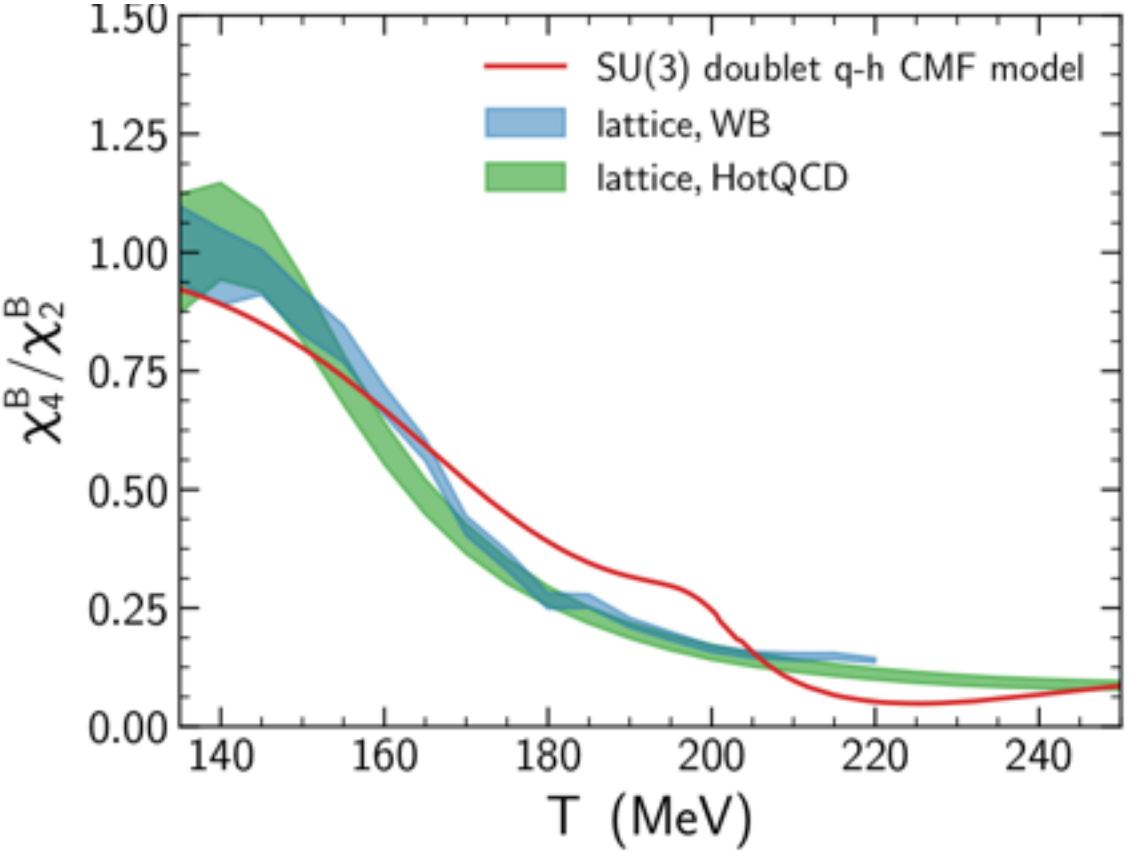
Quark-Hadron-EoS of CMF -fits to Lattice QCD data

A, Motornenko et al.,1809.02000



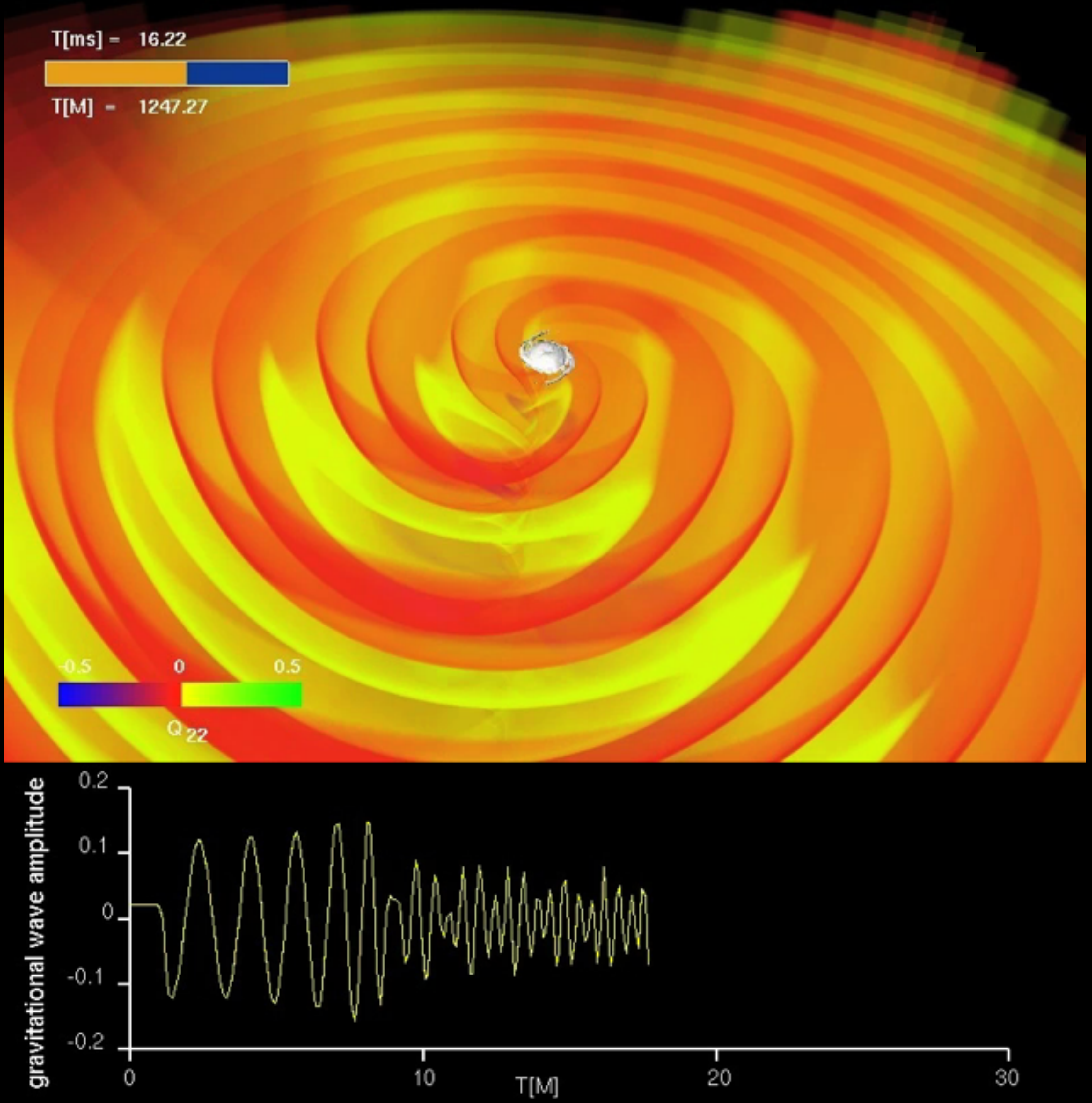
Wuppertal-Budapest collaboration, 1112.4416, 1309.5258, 1507.04627
HotQCD collaboration, 1203.0784, 1407.6387, 1701.04325

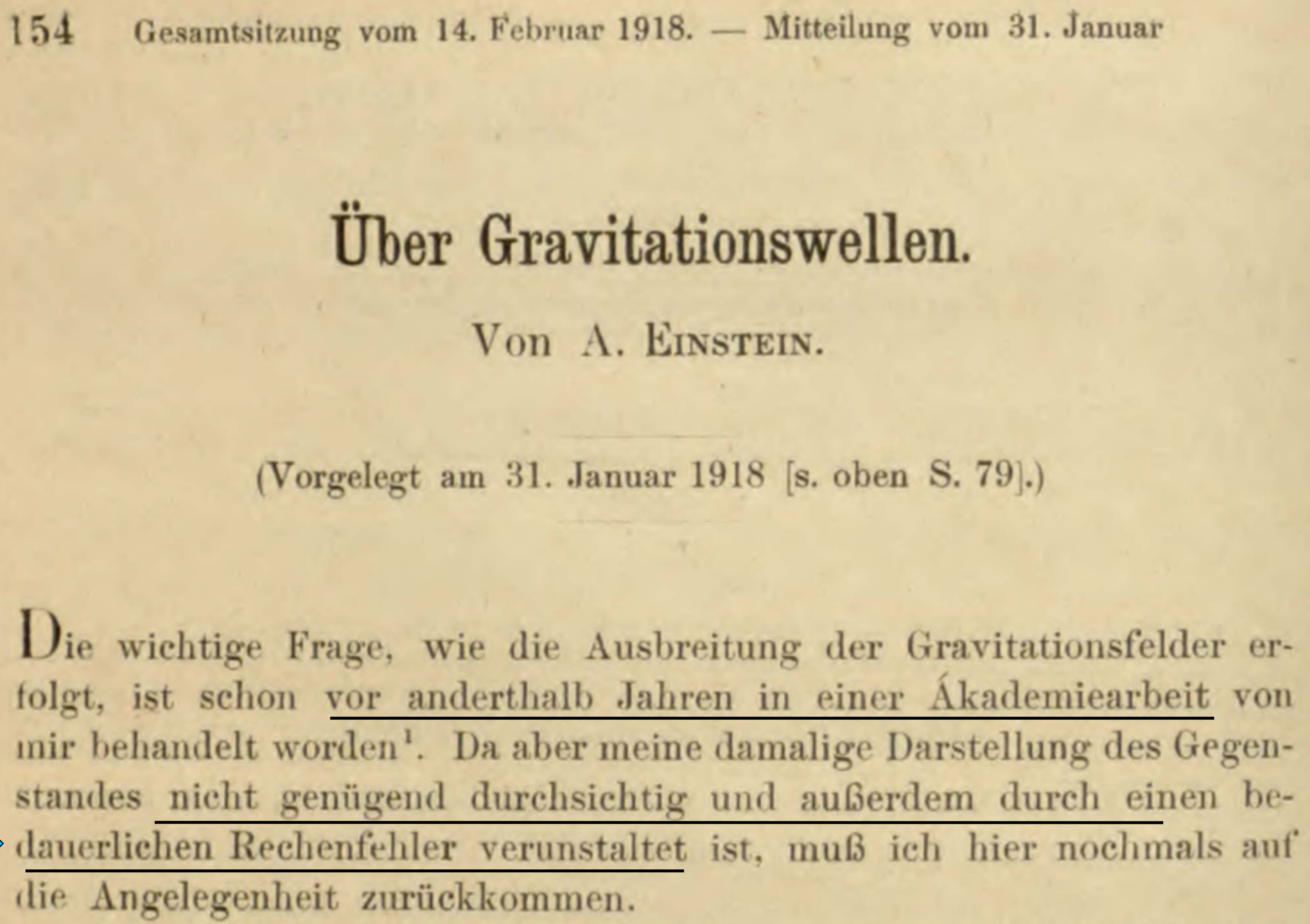




Model successfully reproduces lattice QCD data

Gravitational waves: Einstein’s last prediction





Über Gravitationswellen.

Von A. Einstein.

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

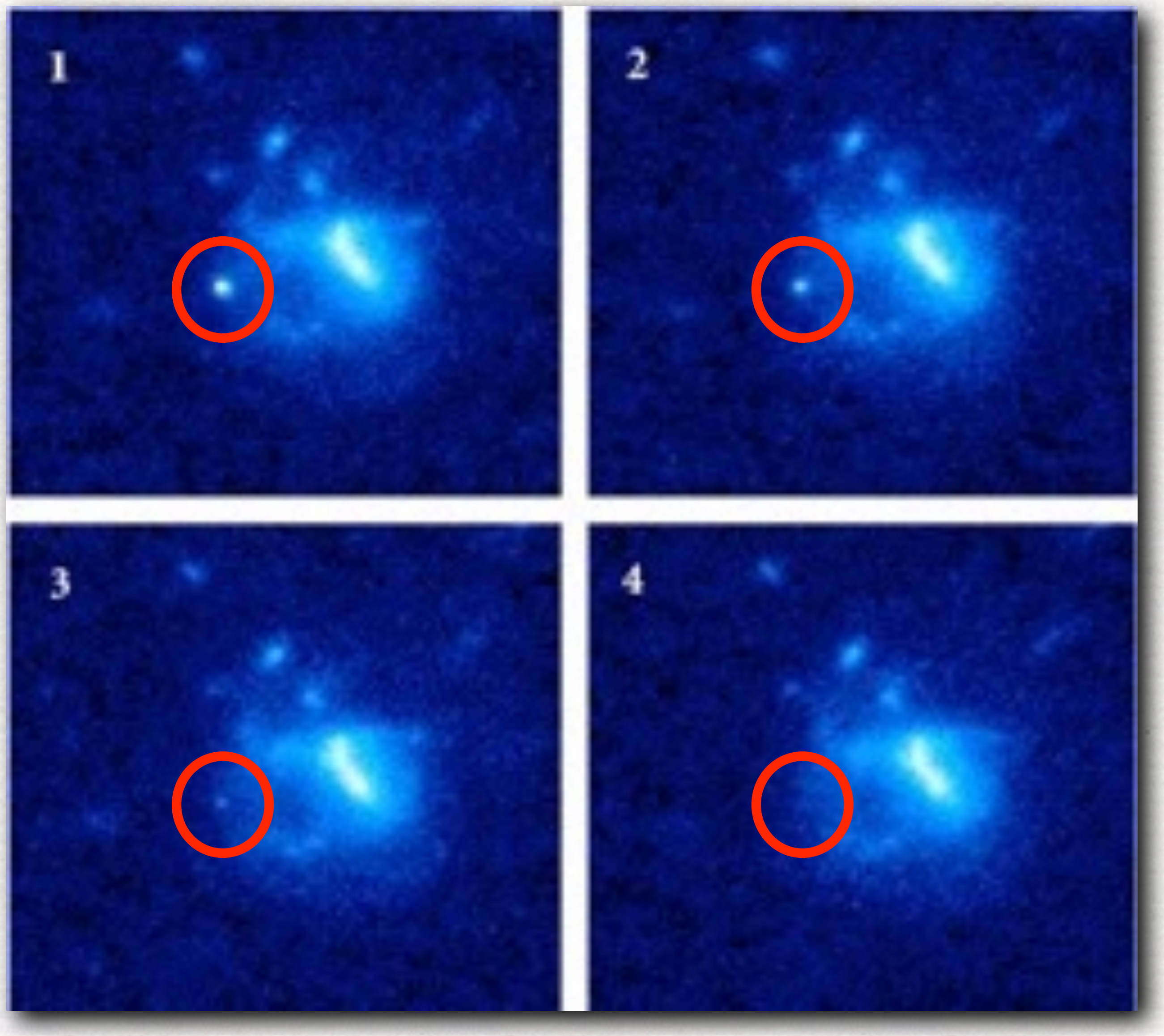
Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet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

Probe the EoS in collisions of binary neutron stars

- We know they exist - among the strongest sources of GWs
- We expect them related to SGRBs:
- energies released are huge: 10^{48-50} erg.
- Equivalent to what is released by the whole Galaxy over ~ 1year !



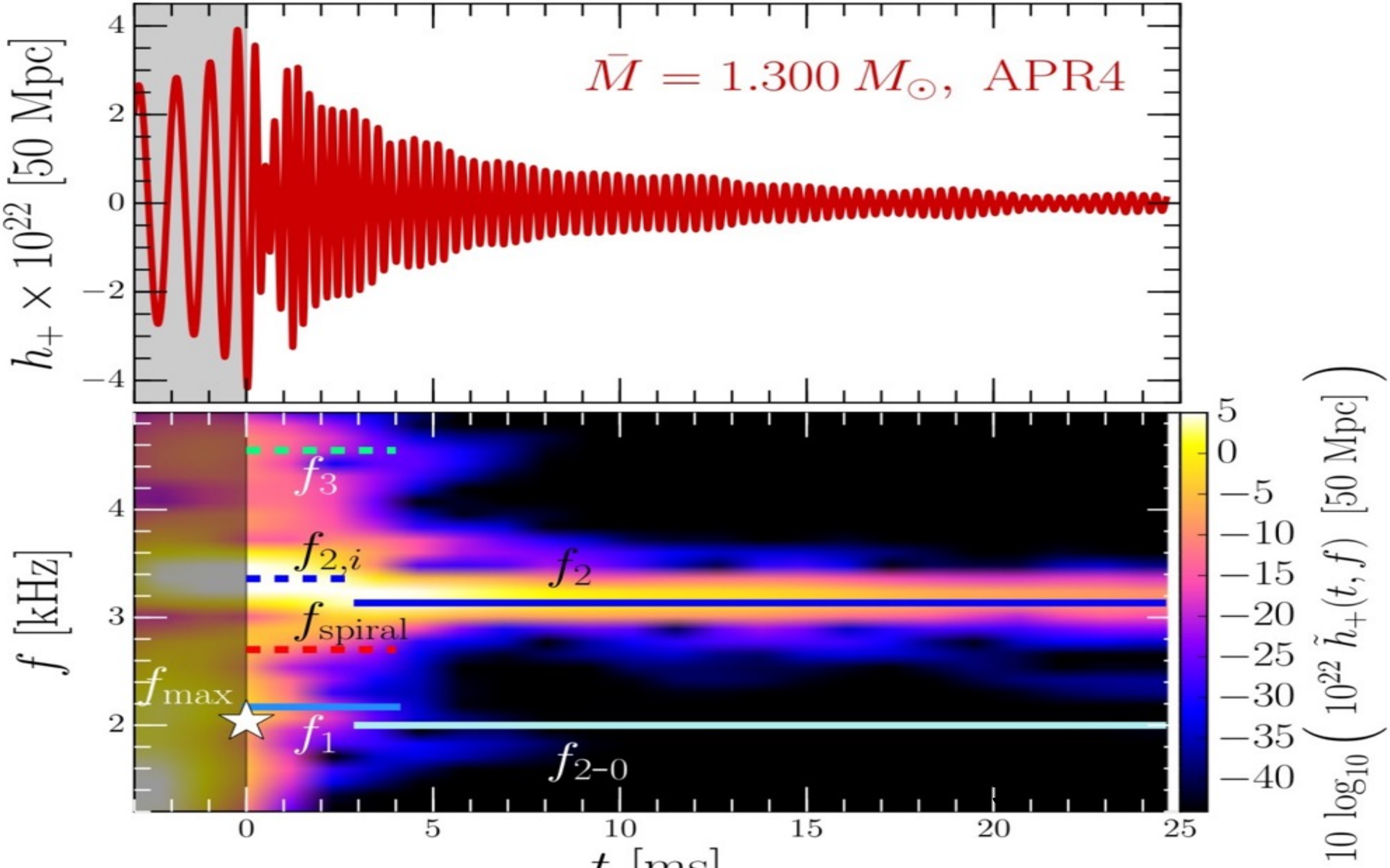

short GRB,
artist impression
(NASA)

- Despite decades of observations no self-consistent model has yet been produced to explain SGRBs.

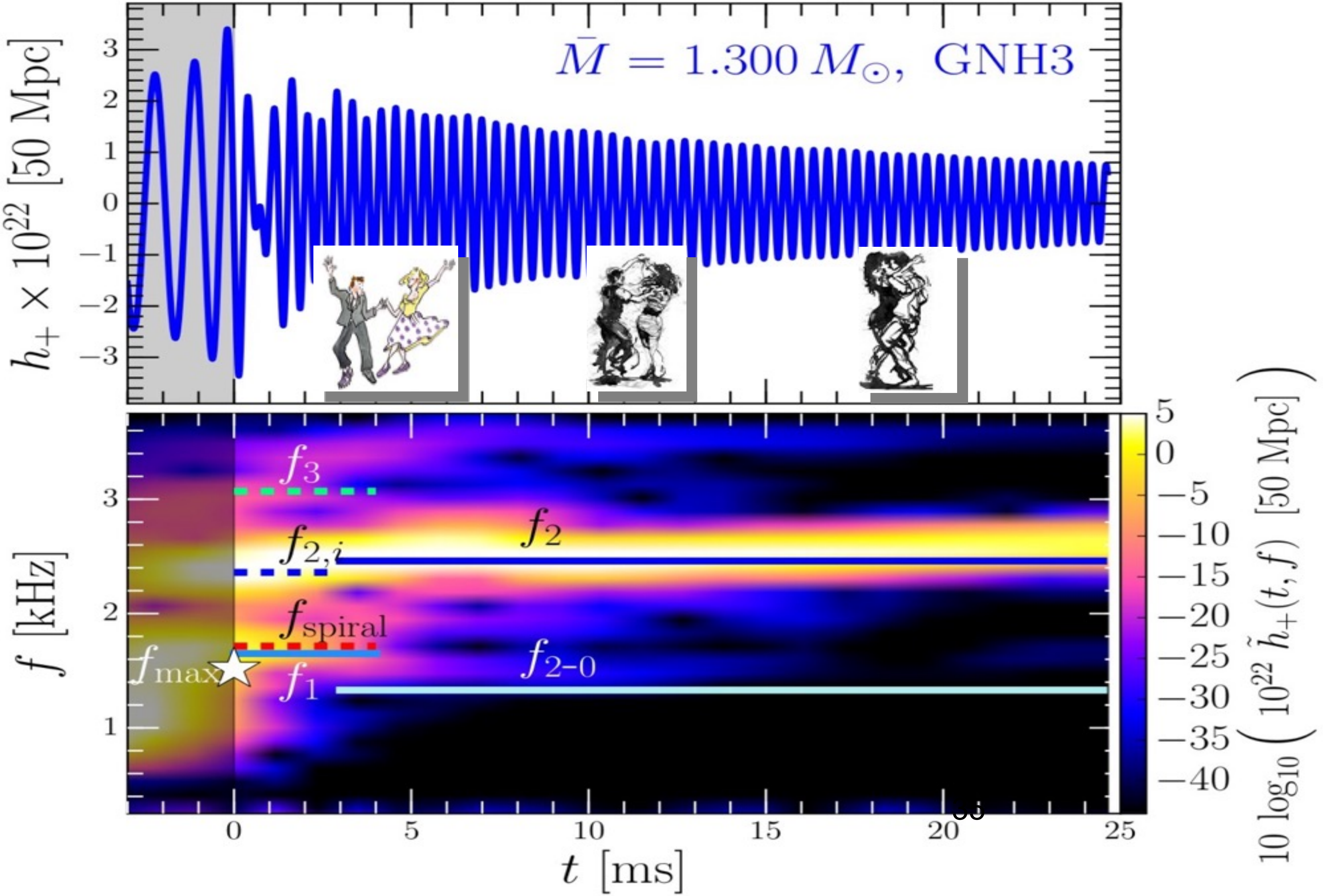
How to constrain the EOS of superdense neutron star matter by relativistic binary neutron star - collisions

- and the EoS of superdense hot nuclear matter by relativistic heavy ion - collisions

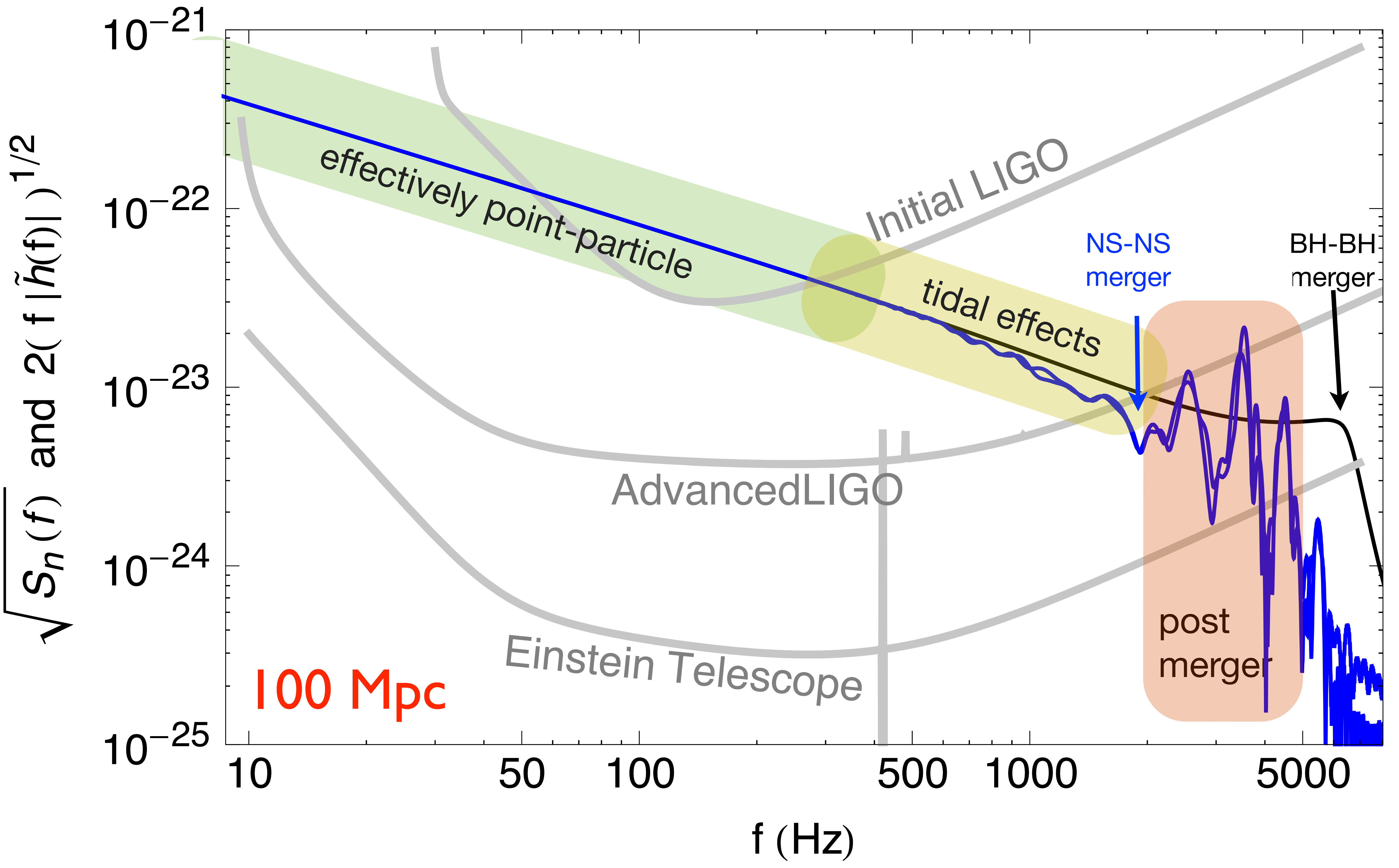
G-Wave Frequency Spectrum depends on EoS: soft nuclear matter EoS



The G-Wave Spectrum for a **HARD** nuclear EoS



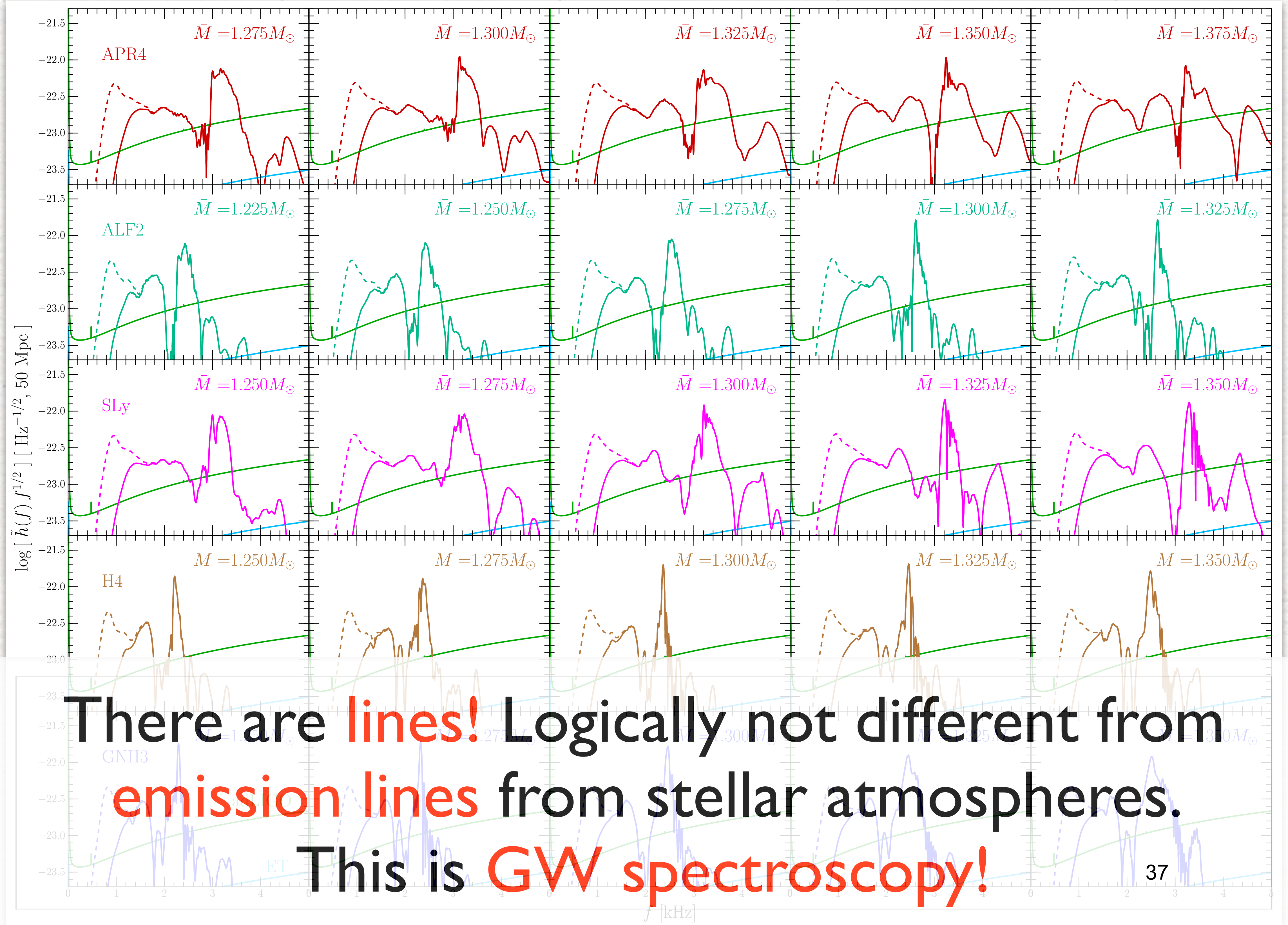
In frequency space



courtesy of Jocelyn Read

Extracting information from the EOS

Takami, LR, Baiotti (2014, 2015), LR+ (2016)

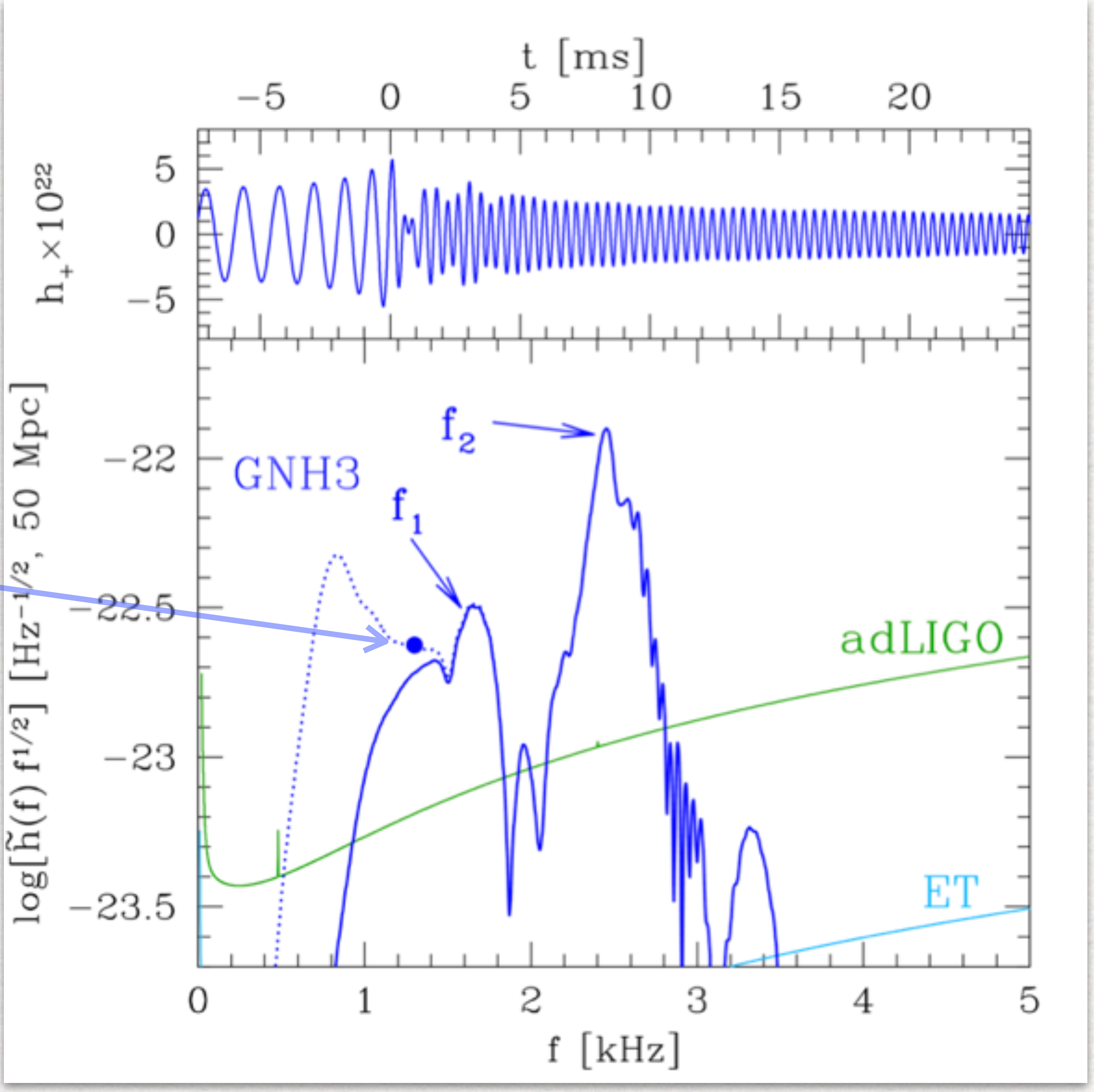


There are lines! Logically not different from emission lines from stellar atmospheres. This is GW spectroscopy!

A new approach to constrain the EOS

Oechslin+2007, Baiotti+2008, Bauswein+ 2011, 2012, Stergioulas+ 2011, Hotokezaka+ 2013, Takami 2014, 2015, Bernuzzi 2014, 2015, Bauswein+ 2015, LR+2016…

merger frequency



How to constrain the EOS by GW high freq.s

Oechslin+2007,

Baiotti+2008,

Bauswein+ 2011, 2012,

Stergioulas+ 2011,
Hotokezaka+ 2013,

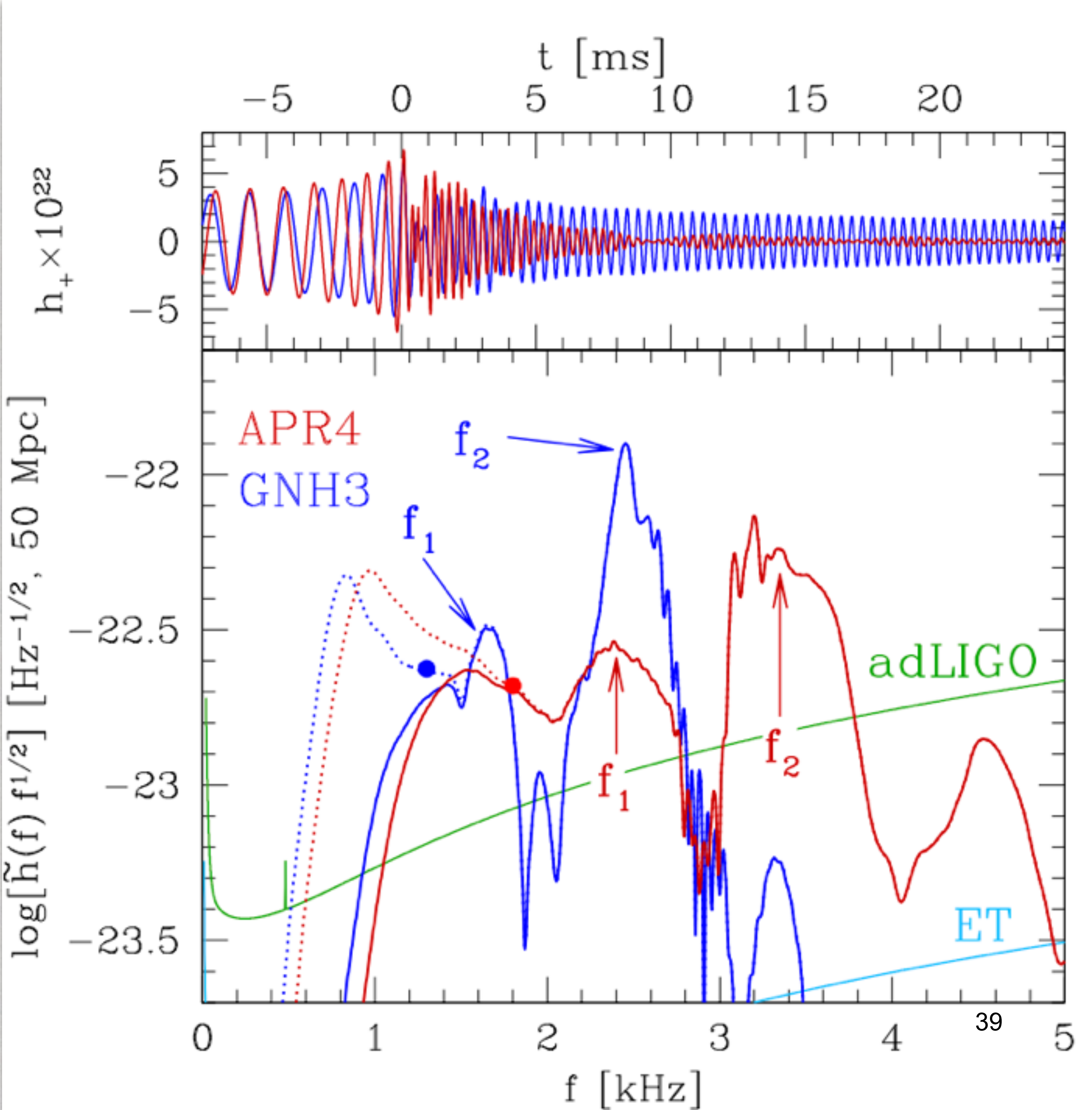
Takami 2014, 2015,

Bernuzzi 2014, 2015,

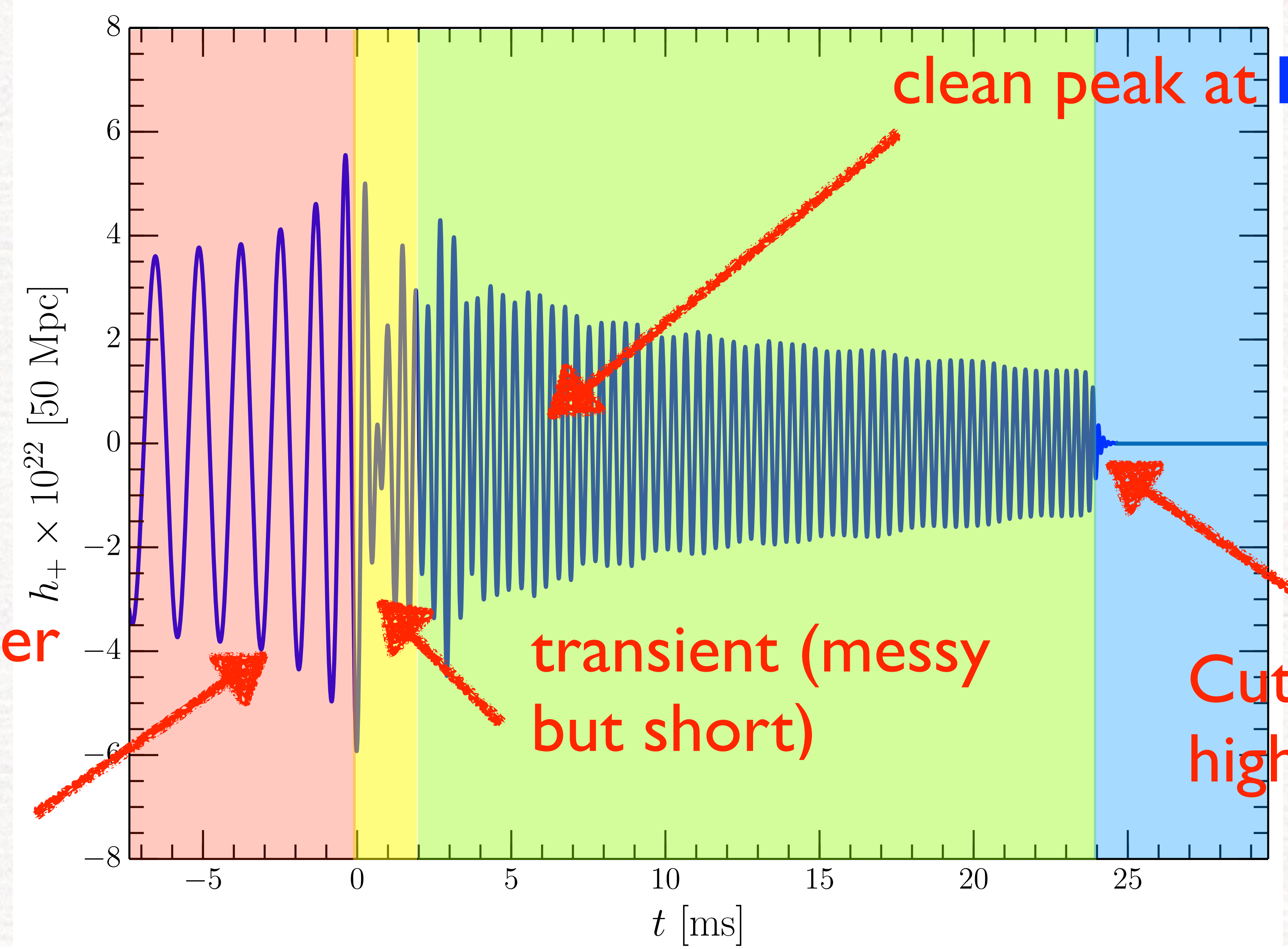
Bauswein+ 2015,

LRezzolla+2016

…



Anatomy of the GW signal

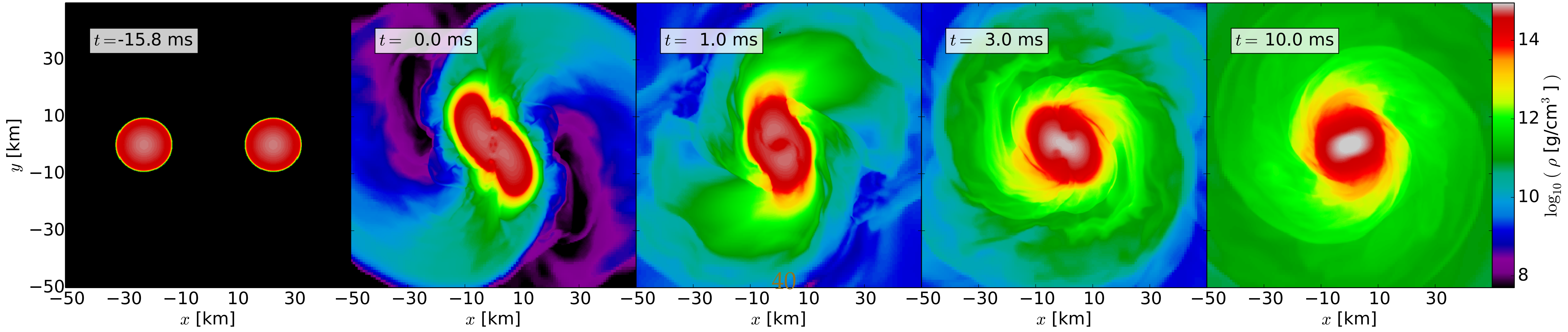


clean peak at **high** freqs

Chirp signal (track from **low** to higher frequencies)

transient (messy but short)

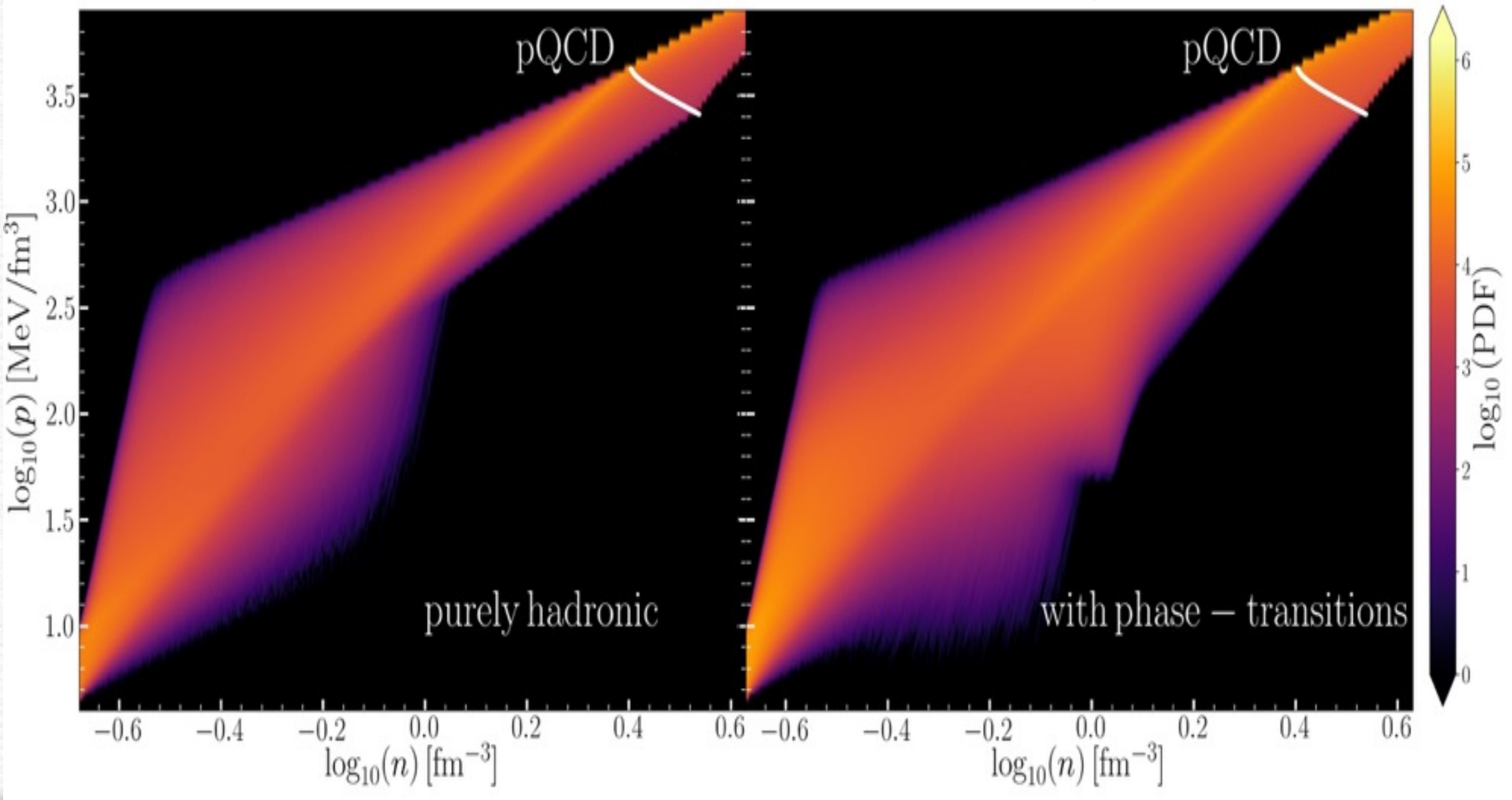
Cut off (very high freqs)



What about Quark Matter phase transition?

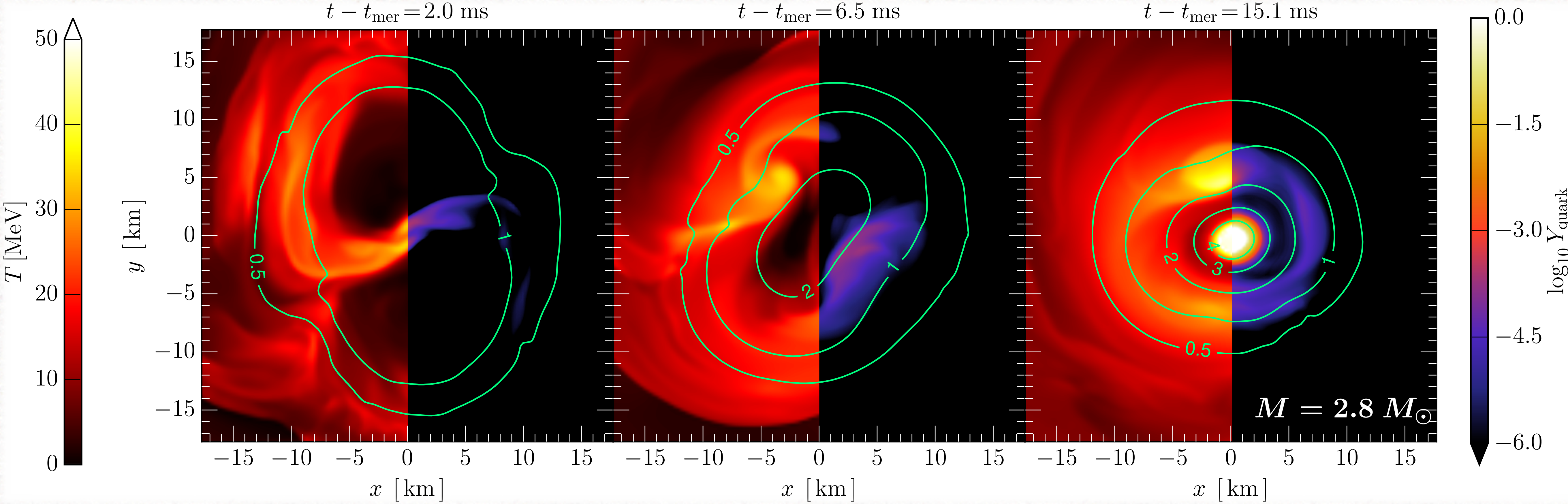
- All EOSs so far purely hadronic - a conservative, but at high density un-**reasonable** assumption.

- What about the possibility of **H-QM-phase transition**? These are not trivial, and difficult to model consistently relativistic.



Formation of a quark core in BNS mergers

- Small quark fraction present in regions of high temperature (cross-over phase transition)

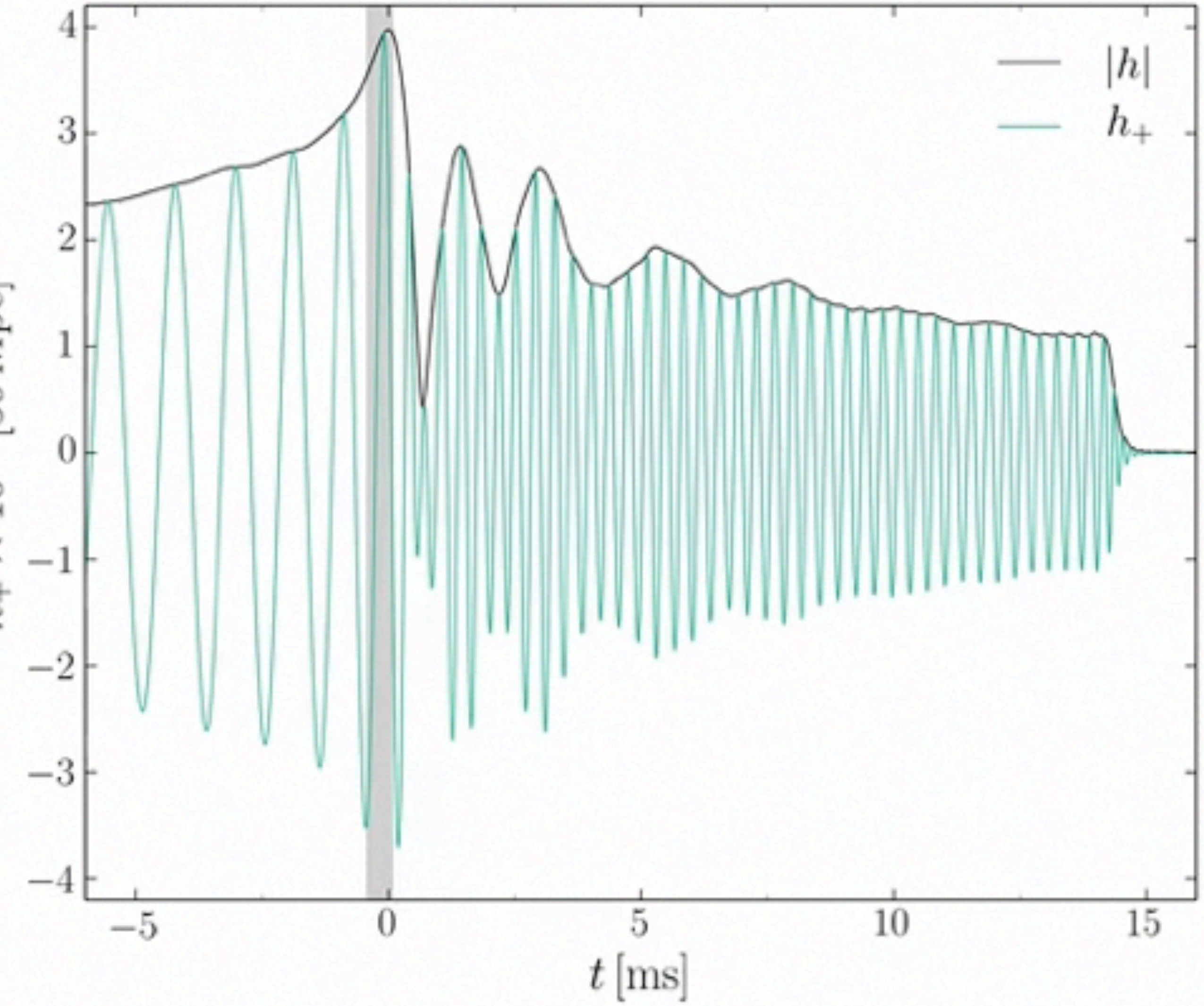


First order phase transition produces hot (unstable) quark core in the centre of the remnant

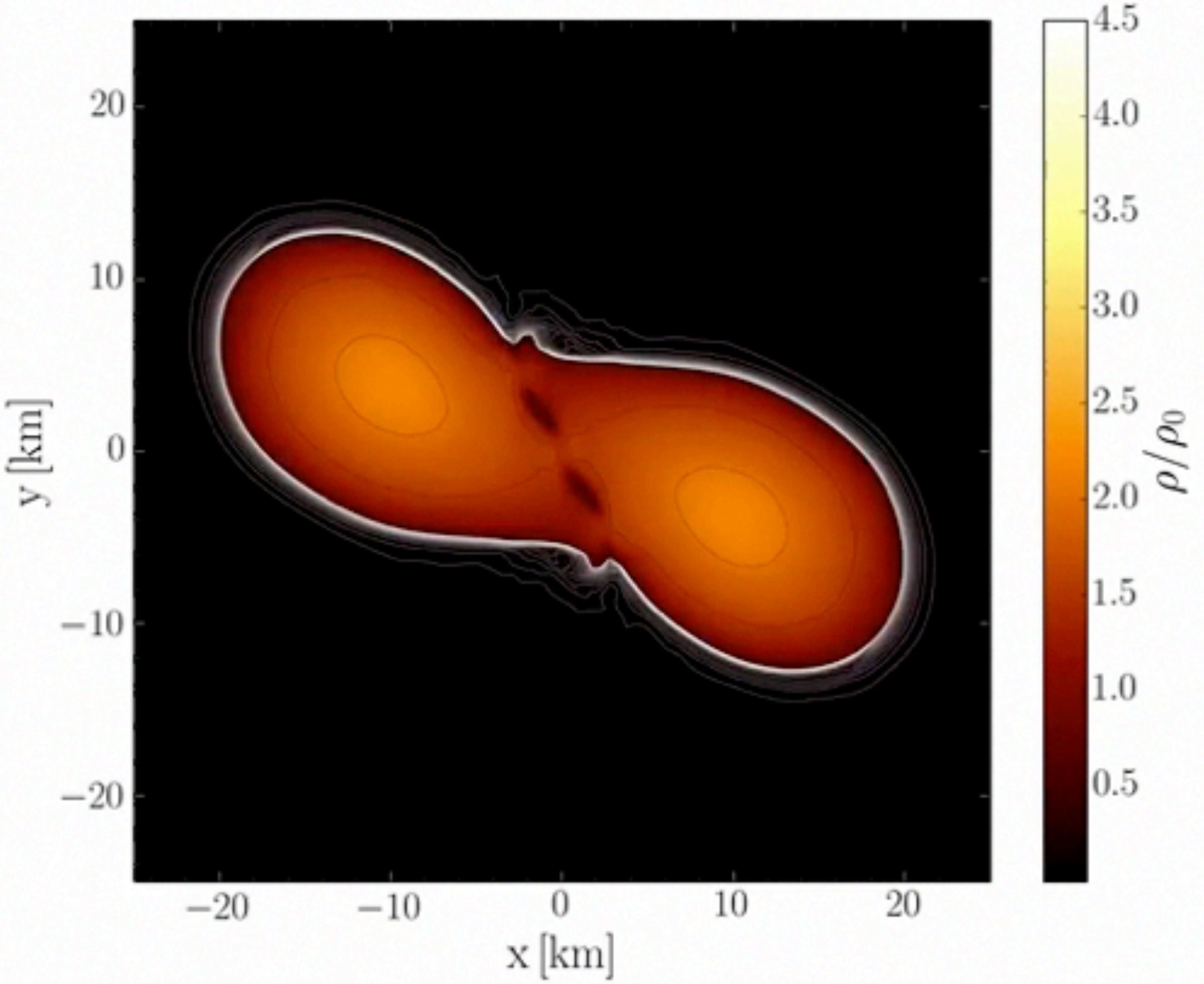
Hypermassive Neutronstar GR-Hydro: Making **Quarkmatter BHs**

EoS Contains Neutrons, Protons, Electrons, Hyperons, Muons

Quarkmatter at high net baryon density ($3\rho_0$) !   Each NS: M = 1.35 Solar Mass



Amplitude of the emitted Gravitational Wave at a distance of 50 Mpc

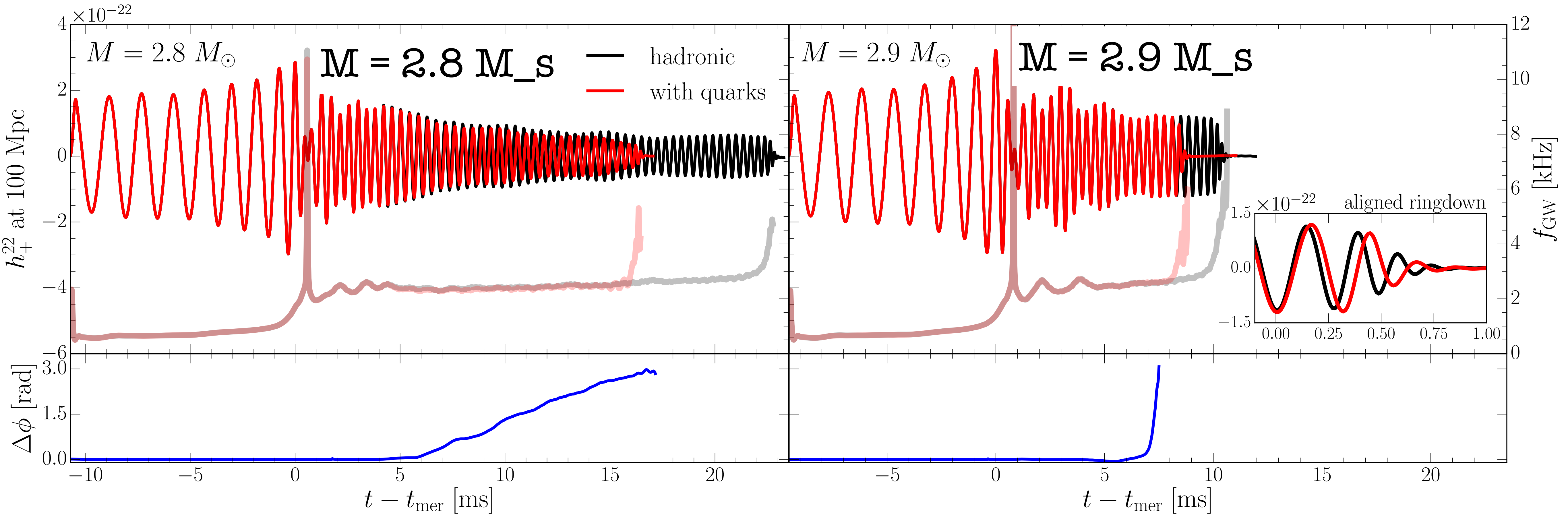


particle density ρ(x,y) in the equatorial slice in Units of normal nuclear groundstate density ρ_0

M.Hanauske, L. Rezzolla, H.ST. et al., MAGIC Collaboration, Phys.Rev.D 2017

Quark Matter seen in gravitational waves?

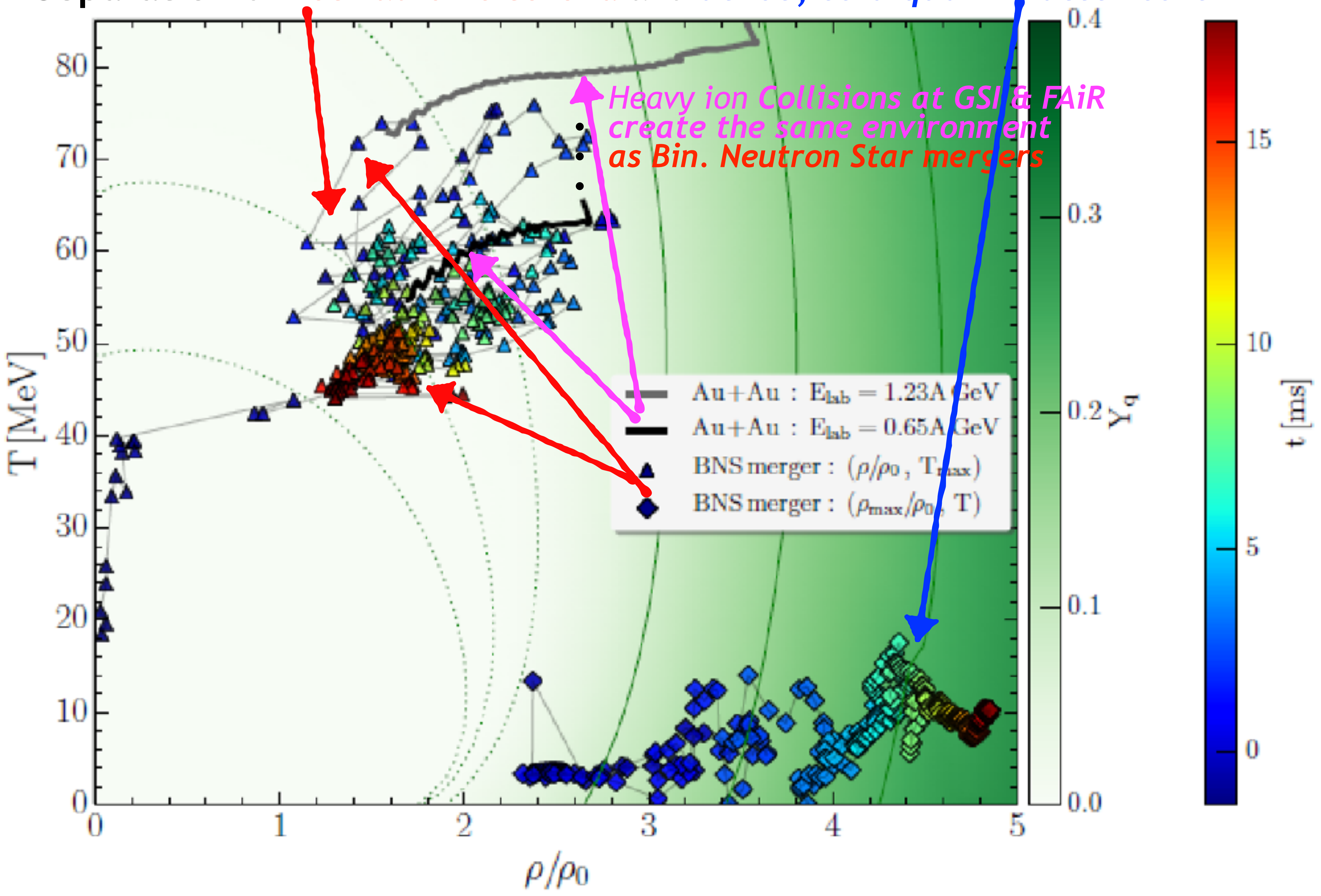
- No quarks are present in the inspiral phase !



Continued presence of small quark fraction leads to a de-phasing of the waveform in the post merger

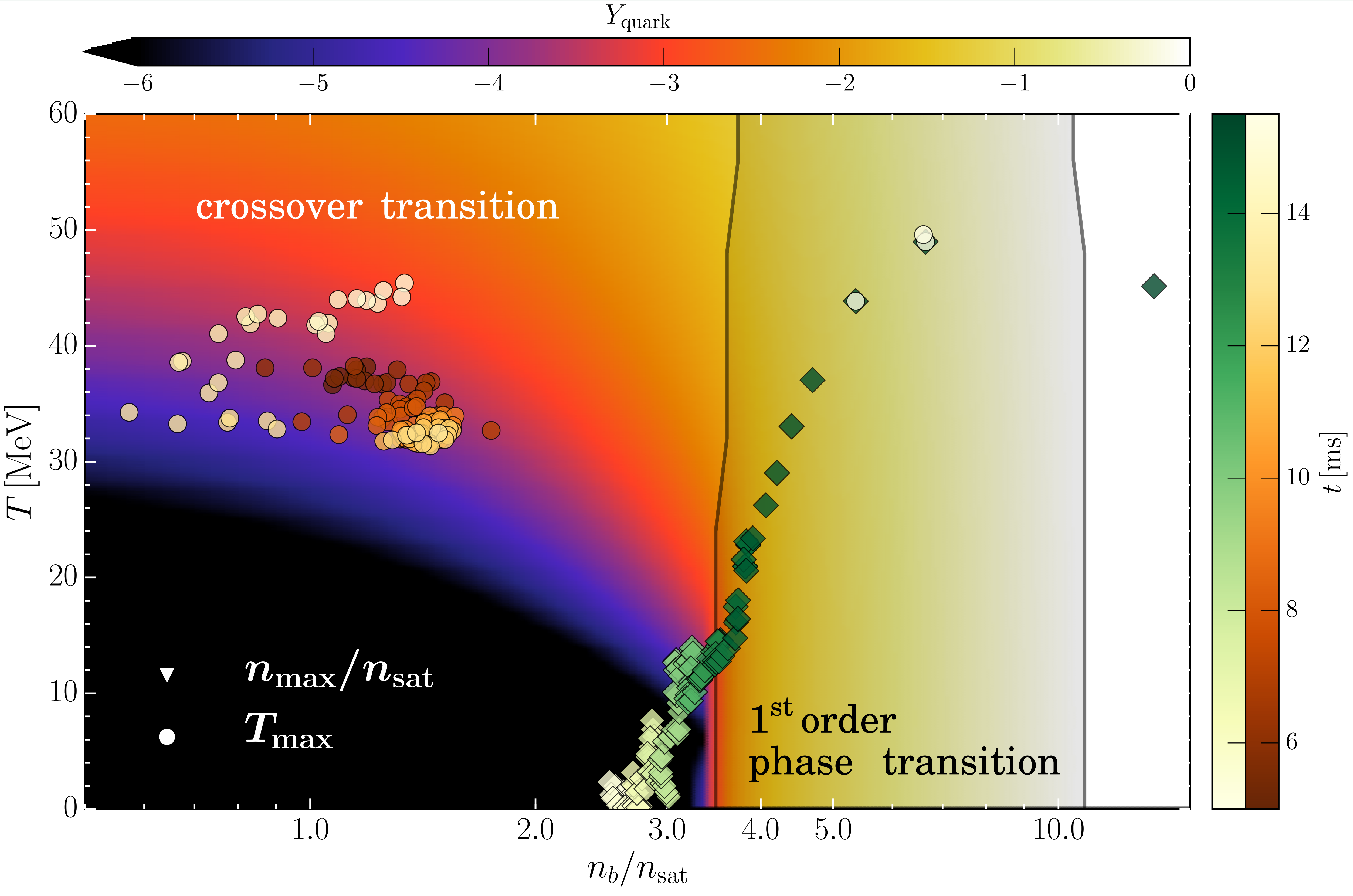
Where it's hot and dense in neutron star mergers

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



Heavy ion Collisions at GSI & FAiR
create the same environment
as Bin. Neutron Star mergers

Observing a 1. Order phase transition ?



Most Dexheimer Schramm Rezzolla H.ST. et al 2018

✳more to come

✳Spectra of post-merger shows peaks, some **”quasi-universal”**.

✳When used together with tens of observations, they will set tight constraints on EOS: radius known with ~1 km precision.

✳ Magnetic fields unlikely to be detected during the inspiral but **important** after the merger: instabilities and EM counterparts.

✳**Mergers** lead to tiny but important ejected matter and kilo-/macro-nova emission - **“high-*A*” nucleosynthesis very robust.**

✳**GW170817** provided new limits on **maximum mass** and **radii:**

$$2.01^{+0.04}_{-0.04} \leq M_{\rm TOV}/M_{\odot} \lesssim 2.16^{+0.17}_{-0.15}$$

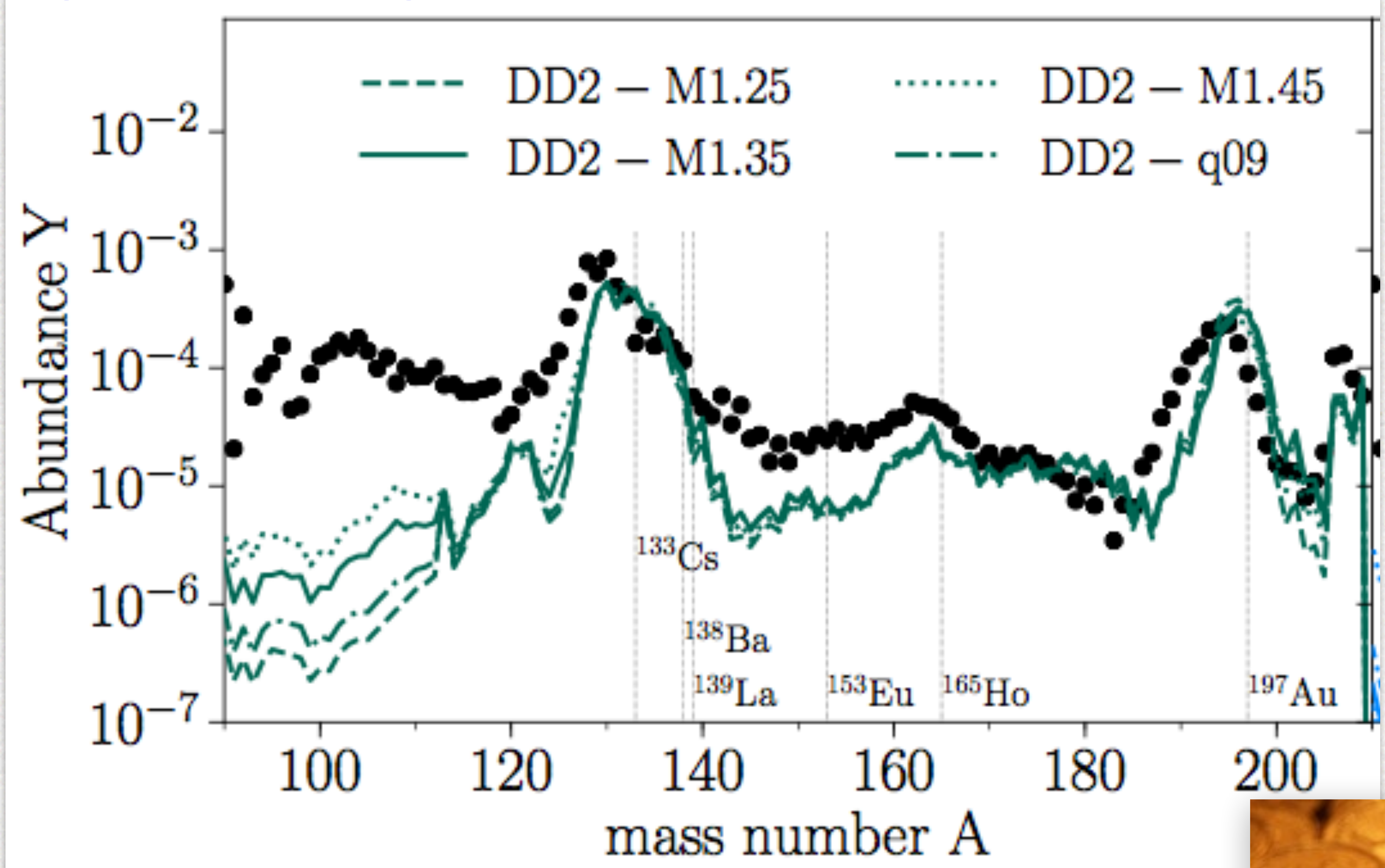
$12.00 < R_{1.4}/{\rm km} < 13.45$ $\bar{R}_{1.4} = 12.45\,{\rm km}$ **hadronic EOSs**

$8.53 < R_{1.4}/{\rm km} < 13.74$ $\bar{R}_{1.4} = 13.06\,{\rm km}$ **phase transitions**

Merging binaries of NSs are Einstein’s richest laboratory: GWs, nuclear physics, astrophysic: more to come!…

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 !

The “Death-Star- Machines” FAIR and NICA: Neutron-Star matter by Nuclear Collisions in the Lab !

Charm and Beauty of International Collaboration

Observers

Austria-Czech

Hungary

China

Finland

France

Germany

India

Italy

Poland

Slovenia

Spain

Sweden

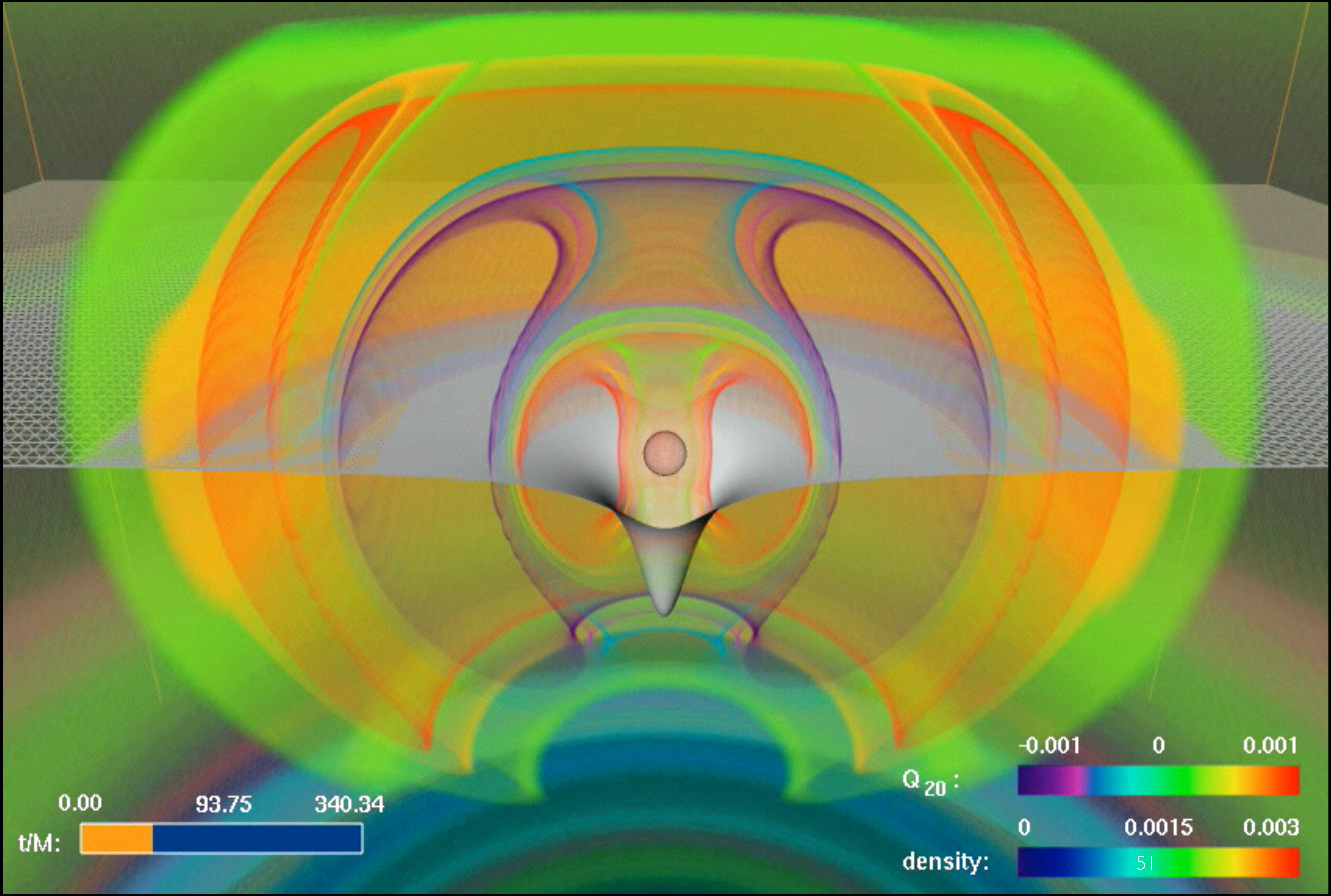
Romania

Russia

Rosatom

UK

Numerical Relativity



Supercomputers as “astrophysical laboratories”

The complexity of the Einstein equations and the absence of symmetries force the use of parallel supercomputers.

In essence the problem at any time is broken in many smaller pieces, one for each of the many processors. If necessary, data can be exchanged between neighbouring processors

Damiana @ AEI, LCSC, Green Cube at GSI

We also employ AMR (adaptive mesh refinement) to increase the resolution where needed

Typical simulation:

- 500 processors
- 1 TB memory
- 4-6 weeks of running time
- 3-4 TB of data produced

Numerical Relativity: probing the extreme

- Einstein equations are highly nonlinear and so are the equations of relativistic hydrodynamics and MHD in conditions where shocks are expected to develop =>CBM.
- Furthermore, the need to compute gravitational waves requires that we consider highly non-symmetrical configurations, eg binaries. This implies that we need to solve the equations in 3 spatial dimensions plus time (3+1)
- Numerical relativity is focussed on solving Einstein equations and those of relativistic hydrodynamics and MHD in those regimes in which no approximation holds: eg in the most nonlinear regimes of the theory.

Programs for Young Researchers

Special Programs for Junior Researchers at FAIR and FIAS :

Support of international Ph.D.- Students and Postdocs
through GSI, Helmholtz, BMBF and HIC for FAIR @ FIAS

Helmholtz Graduate School HIRe for FAIR@FIAS
Large inter-university Graduate School with excellent connections to GSI

Education and training of young researchers: one of key pillars at FIAS !!

- Large number of international doctoral students
- Numerous power weeks and workshop-type events - every year
- Handling of scholarships of various funding sources by FIAS

Support international young investigators: key advantage for FAIR@ FIAS
Large highly visible activities, including public outreach, every year at FIAS