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

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

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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 and Gravity

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

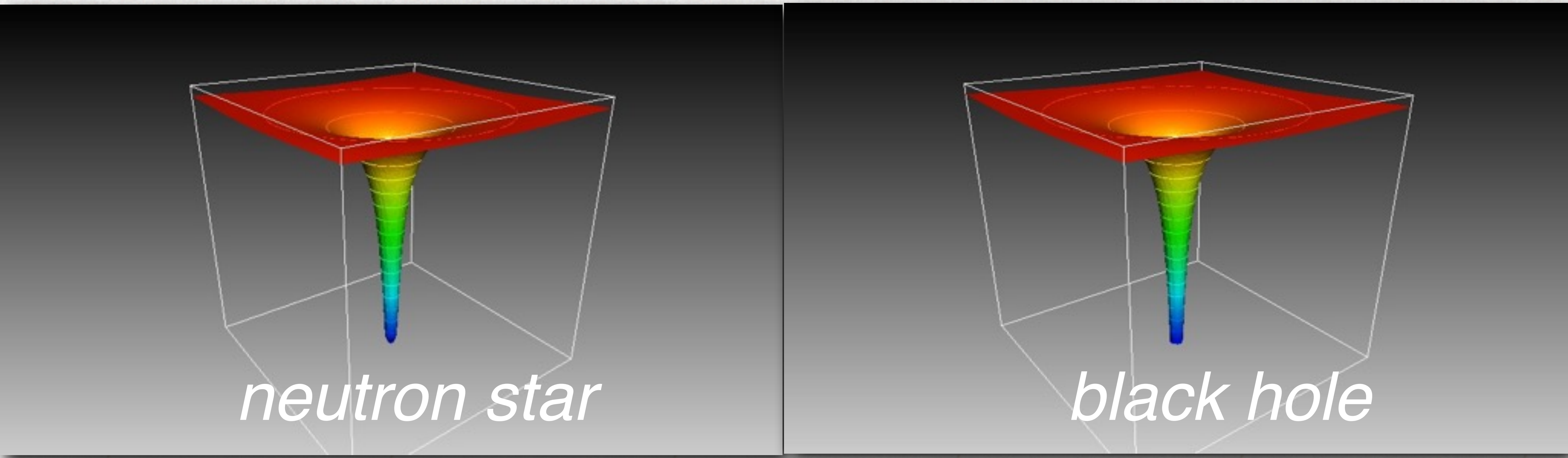
mass and energy in the spacetime

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 ?

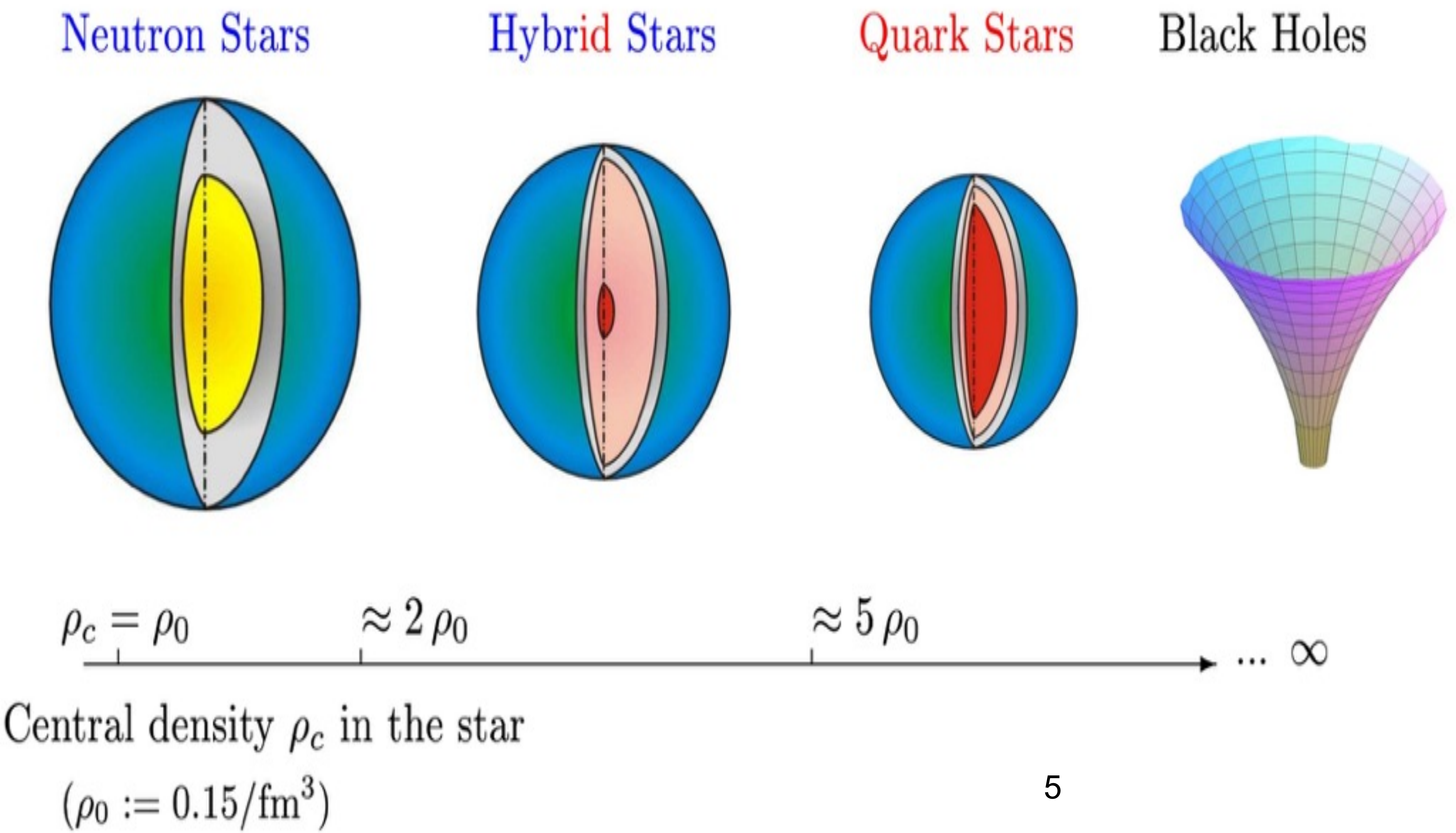
Narrow transition from a very compact star to a black hole - many of the spacetime properties are similar.



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 !

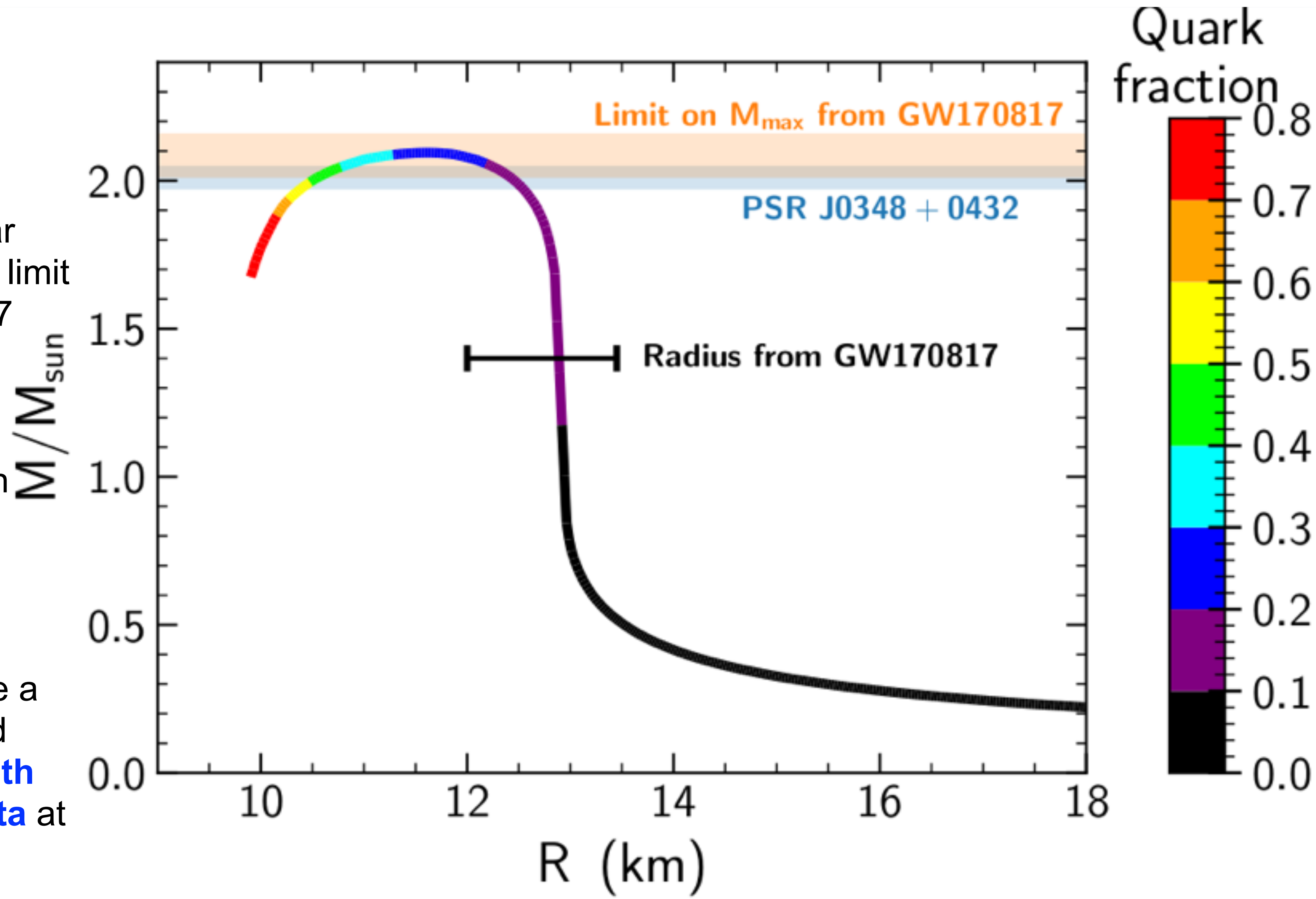
Neutronstars, Quarkstars, Black holes



Neutron Star Masses and Radius - Chiral quark-hadron MF EoS

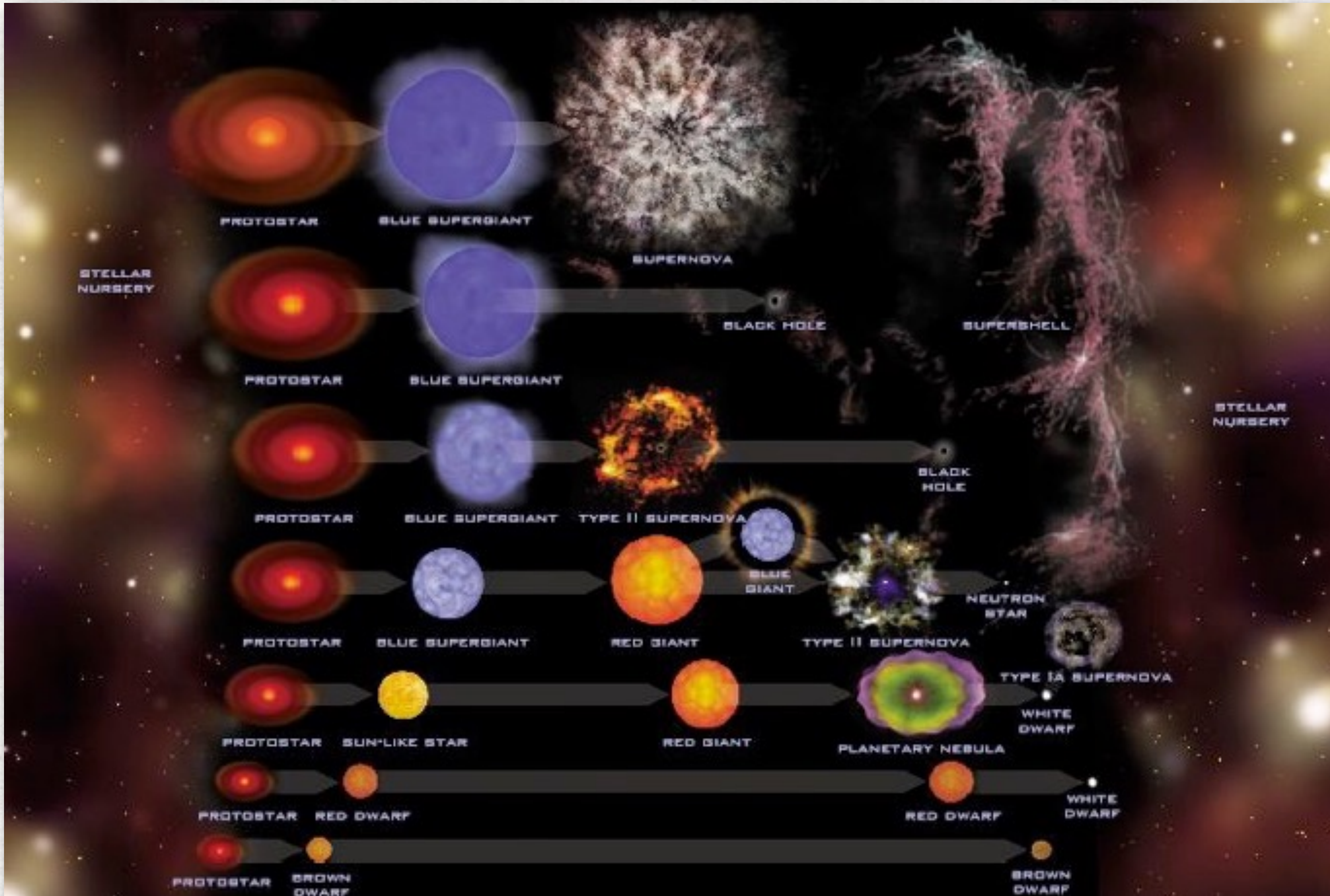
Features:

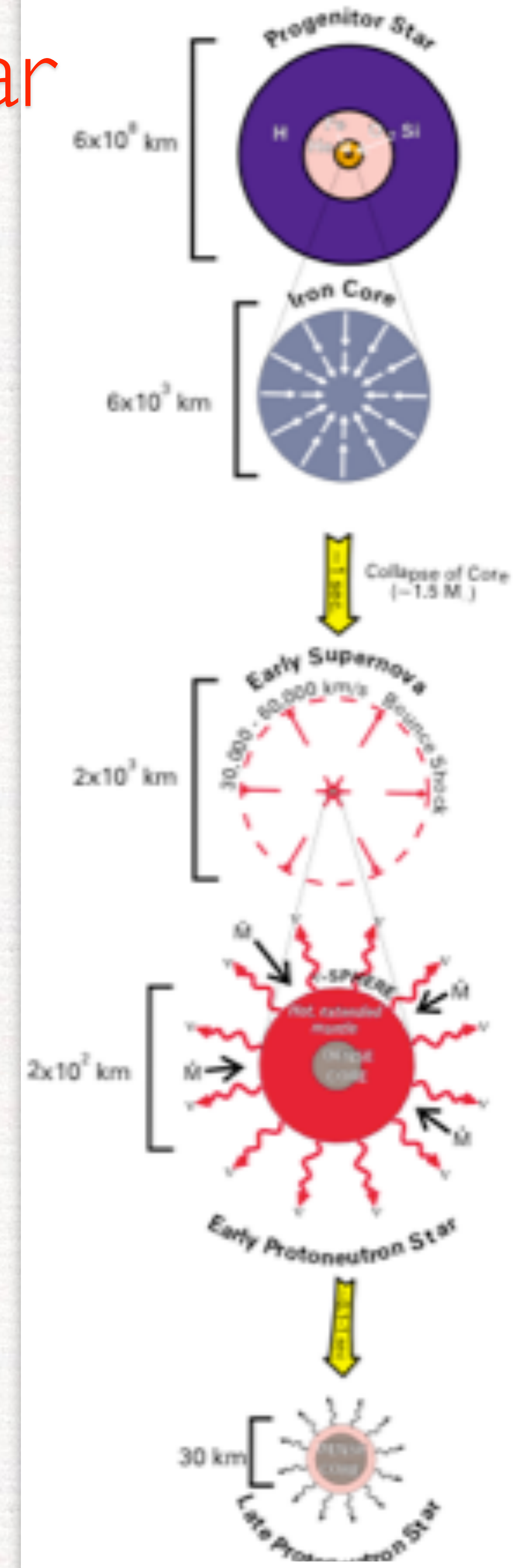
- Maximum mass agrees with observed 2 solar mass stars **and** limit from GW170817
- Radii are small (~13km) in accordance with various experimental findings
- For the first time a model for hybrid stars **agrees with lattice QCD data** at low μ_B



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

Death of a Star - Birth of a Neutron Star





Burrows

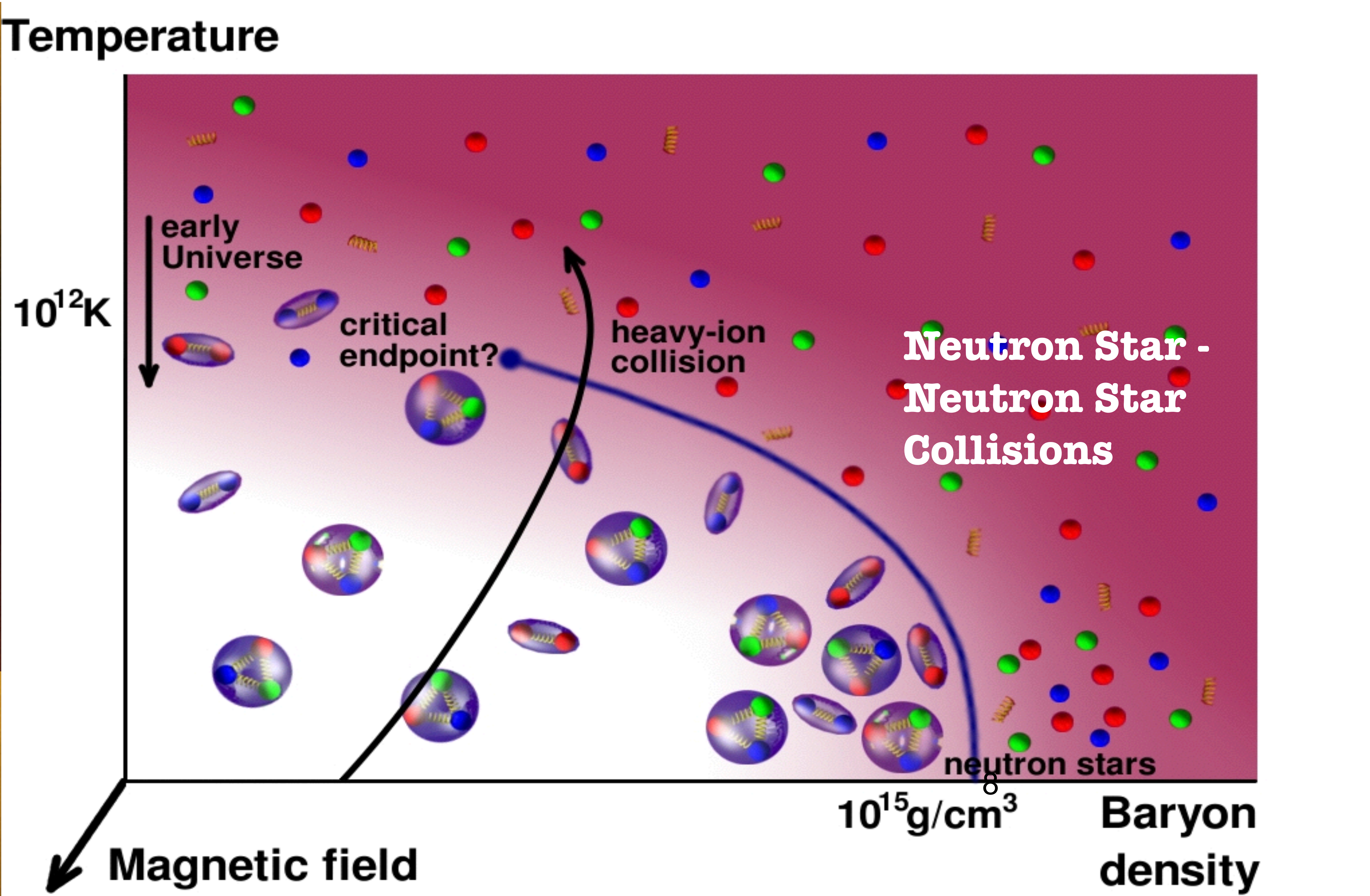
Neutron Stars are most commonly born in the violent death of massive Stars, i.e. Stars with

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

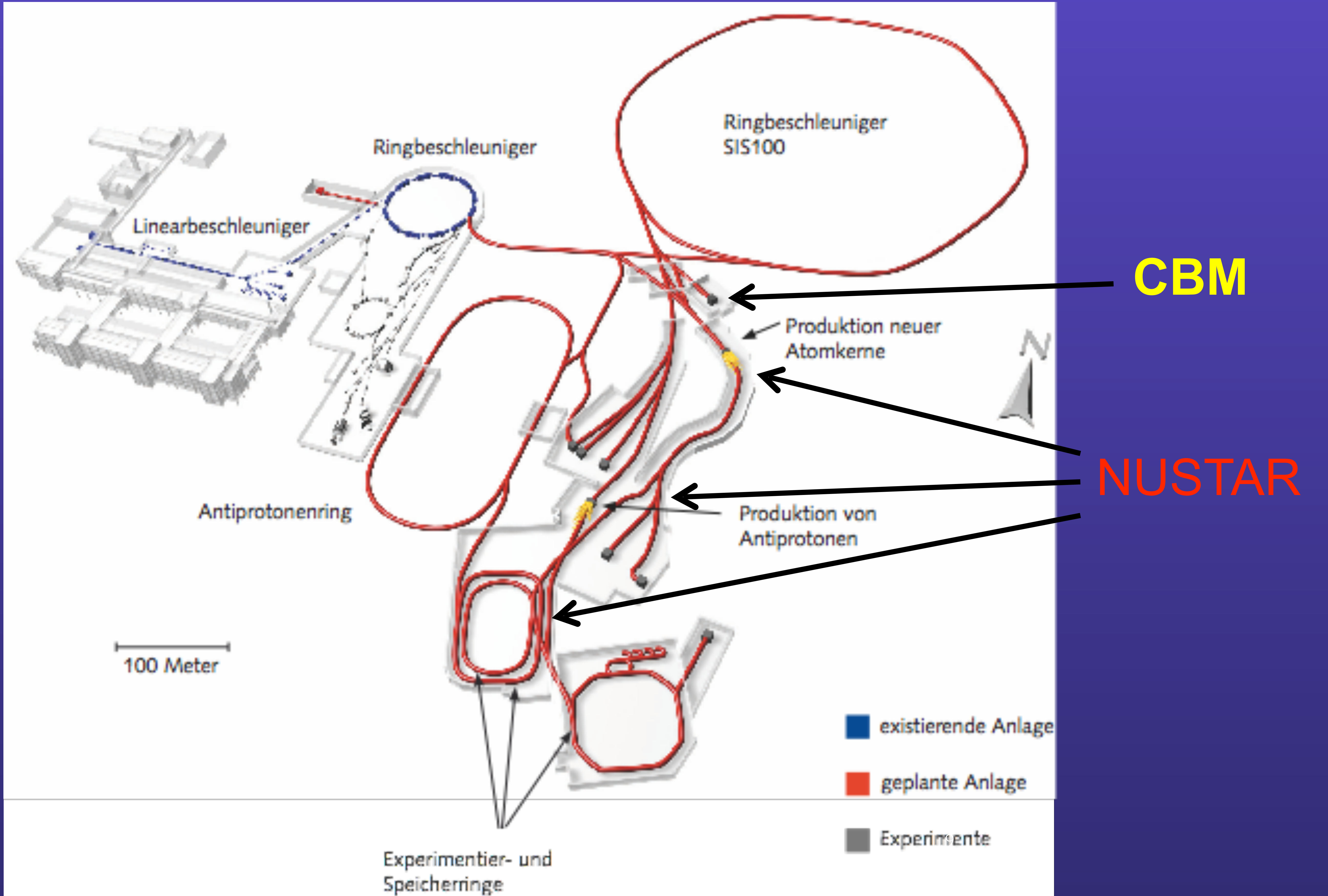
ending their evolution as a **supernova collapse**

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

Relativistic collisions of NS-NS vs. Heavy Ions



Neutron Star matter in CBM @FAiR-GSI Helmholtzcentre



FAIR - the Death Star machine!

(The Times of India)

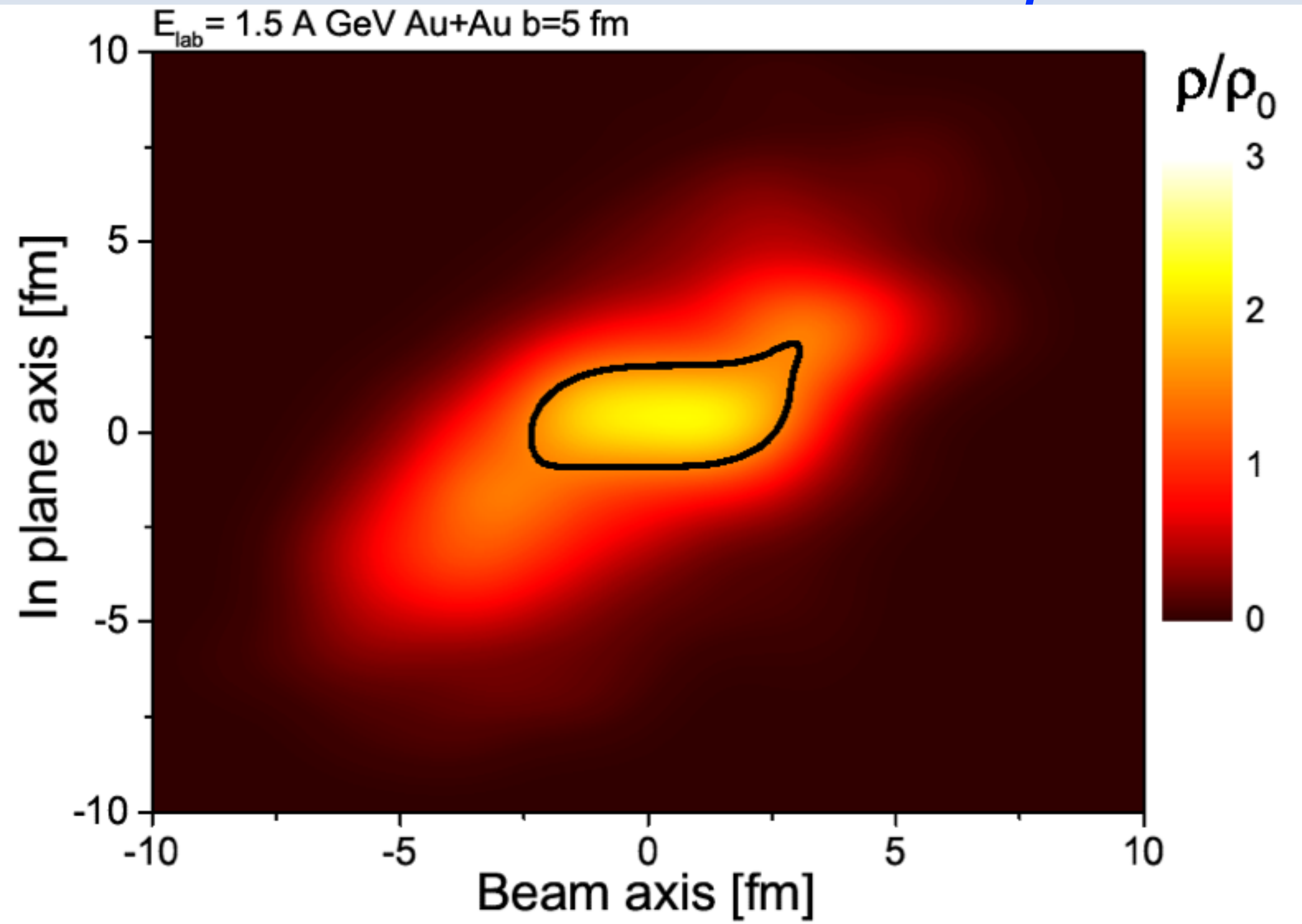
FAIR and NICA ideally equipped for precision studies to compare relativistic collisions between **neutron stars and heavy ions**

- consistent theoretical treatment necessary:

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

- Predict and compare to observational data -

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

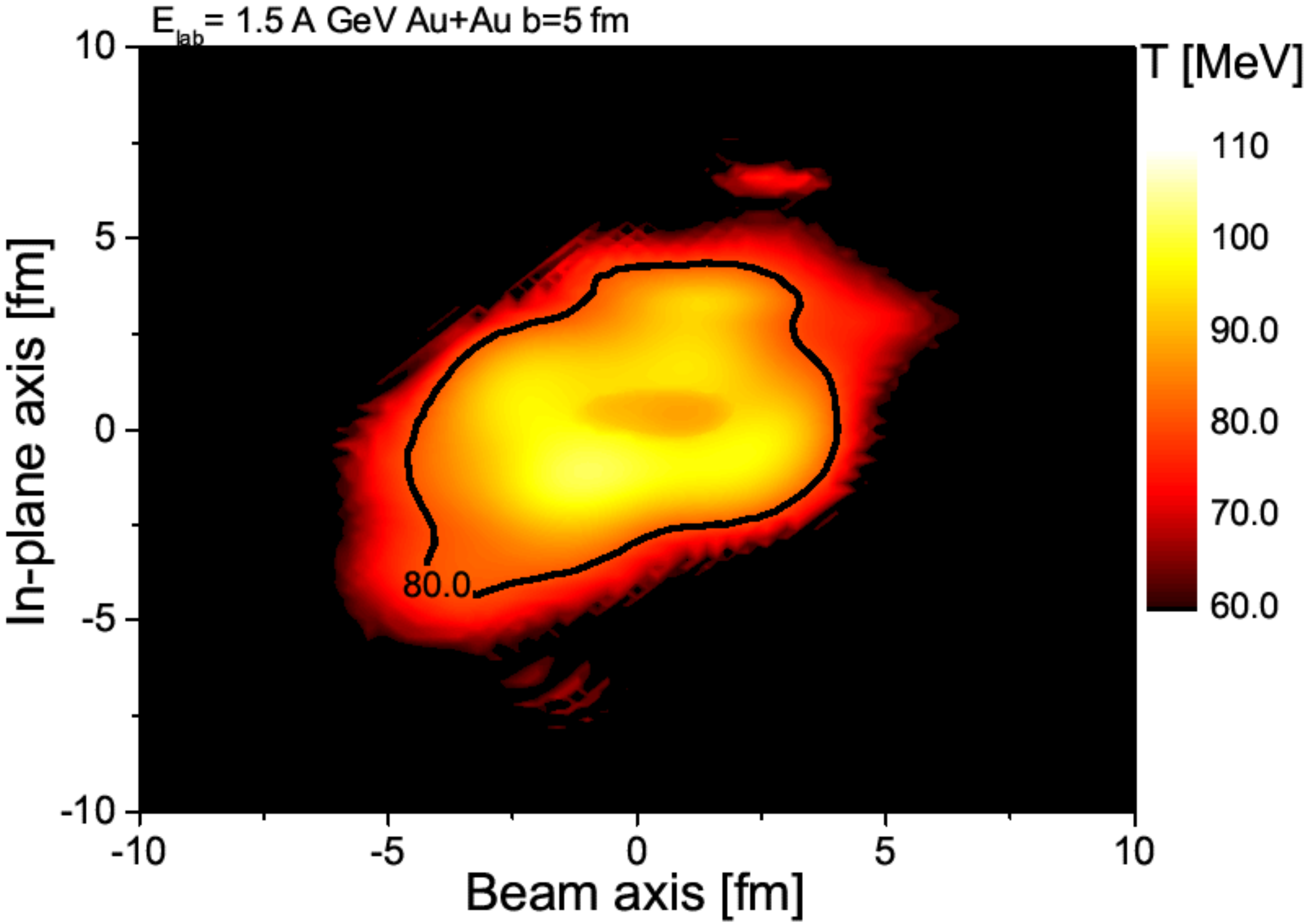


- Beam energy corresponds to GSI-SIS18.
- 3-5 times nuclear ground state density reached.
- Large inhomogeneity.
- Short lifetime ~ 20 fm/c
- Small system size ~ 10 fm

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

Neutronstar merger vs. heavy ion collisions

Which temperatures are expected?



Steinheimer et.al: Coarse - grained UrQMD-simulation input for hydrogen. 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

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

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

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

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

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

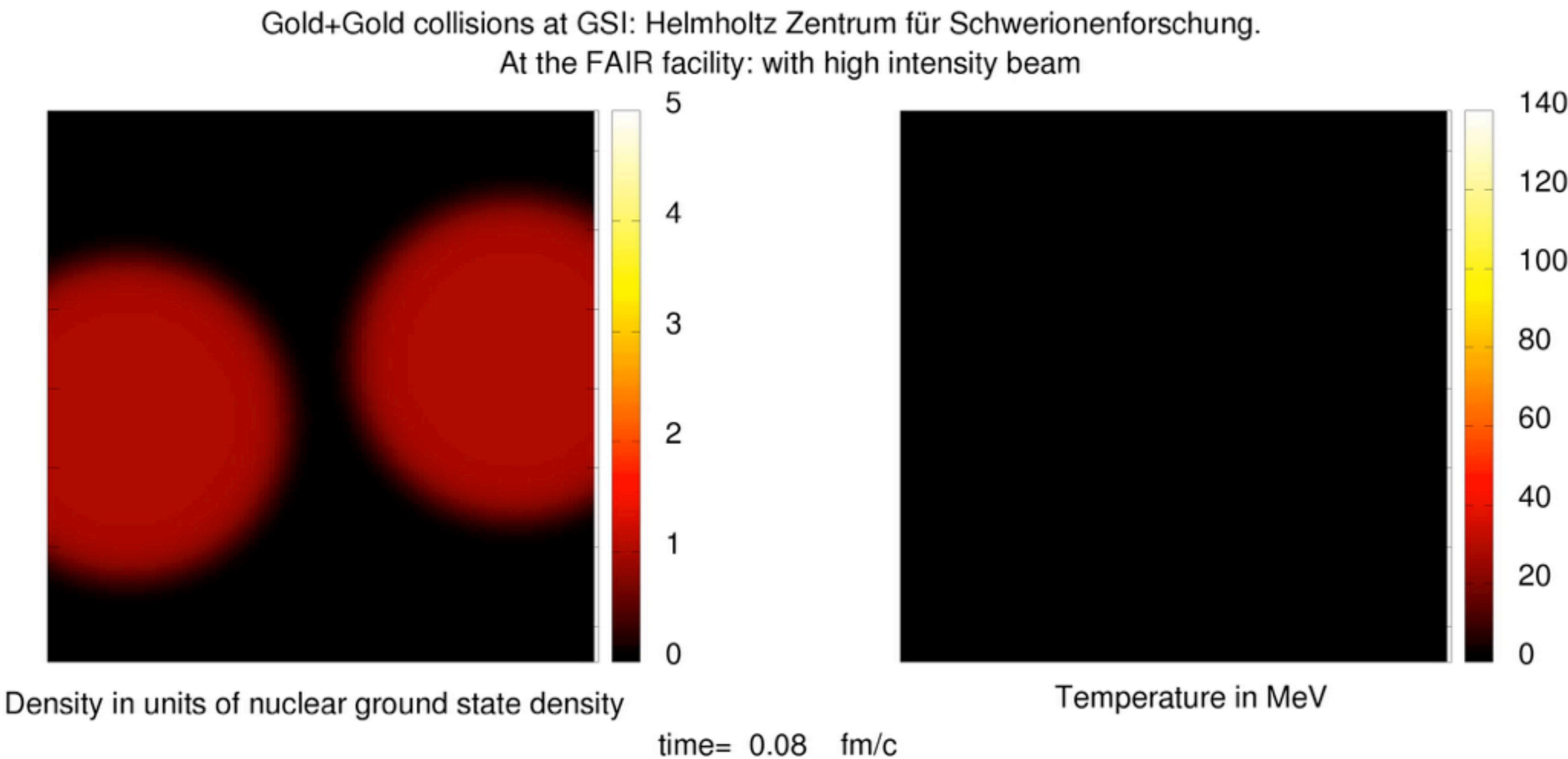
$$\nabla^*_\nu F^{\mu\nu} = 0, \qquad (\text{Maxwell eqs.}: \ \text{induction}, \ \text{zero div.})$$

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

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

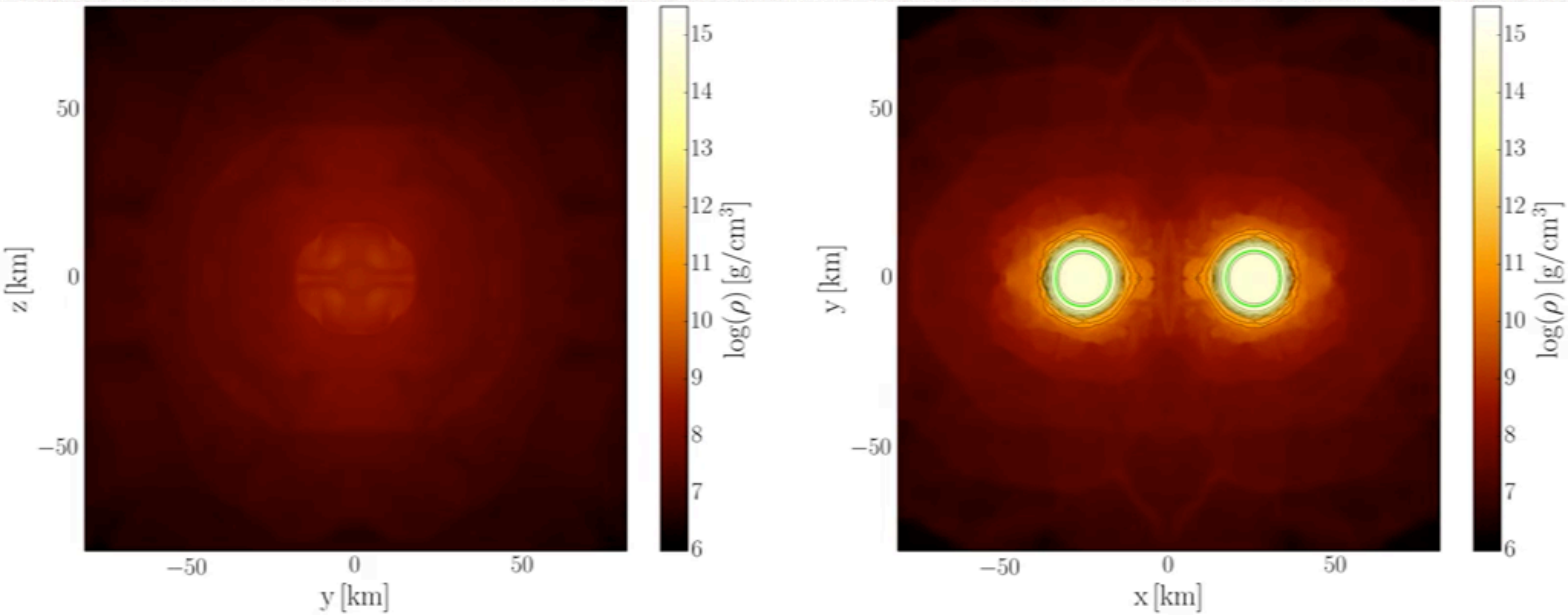
The codes built are "**theoretical laboratories**", representing our approximation to *"reality"*... they must and can be continuously improved: microphysics, magnetic fields, viscosity, radiation transport ,...

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



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

General Relativistic 3+1Dim. Hydro-Dynamical Collision of 2 Neutron Stars



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

- 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 works for both SR & GR!

- Importance of QCD-consistent Relativistic nuclear EoS equation of state
- input for both S-&G- Relativistic Hydrodynamics

SU(3) parity-doublet quark-hadron chiral mean field model

Mesonic fields:

$$
\begin{aligned}
L_{meson} &= -\frac{1}{2}(m_\omega^2\omega^2 + m_\phi^2\phi^2) \\
&- g_4\left(\omega^4 + \frac{\phi^4}{4} + 3\omega^2\phi^2 + \frac{4\omega^3\phi}{\sqrt{2}} + \frac{2\omega\phi^3}{\sqrt{2}}\right) \\
&+ \frac{1}{2}k_0(\sigma^2+\zeta^2) - k_1(\sigma^2+\zeta^2)^2 \\
&- k_2\left(\frac{\sigma^4}{2} + \zeta^4\right) - k_3\sigma^2\zeta + k_6(\sigma^6 + 4\zeta^6) \\
&+ m_\pi^2 f_\pi \sigma \\
&+ \left(\sqrt{2}m_k^2 f_k - \frac{1}{\sqrt{2}}m_\pi^2 f_\pi\right)\zeta ,
\end{aligned}
$$

σ and ζ drive **chiral symmetry** breaking of non-strange and strange sector respectively.

Excluded volume corrections for hadrons:

$$
\rho_i = \frac{\rho_i^{\mathrm{id}}}{1 + \sum_j v_j \rho_j^{\mathrm{id}}}
$$

Baryon octet + partners:

$$
\begin{aligned}
\mathcal{L}_{\mathrm{B}} &= \sum_i (\bar{B}_{\mathrm{i}} i\partial\!\!\!/ B_{\mathrm{i}}) + \sum_i (\bar{B}_{\mathrm{i}} m_{\mathrm{i}}^* B_{\mathrm{i}}) \\
&+ \sum (\bar{B}_{\mathrm{i}}\gamma_\mu(g_{\omega\mathrm{i}}\omega^\mu + g_{\rho\mathrm{i}}\rho^\mu + g_{\phi\mathrm{i}}\phi^\mu)B_{\mathrm{i}}) ,
\end{aligned}
$$

$$
m_{\mathrm{i}\pm}^* = \sqrt{\left[(g_{\sigma\mathrm{i}}^{(1)}\sigma + g_{\zeta\mathrm{i}}^{(1)}\zeta)^2 + (m_0 + n_s m_s)^2\right]} \pm g_{\sigma\mathrm{i}}^{(2)}\sigma \pm g_{\zeta\mathrm{i}}^{(2)}\zeta ,
\quad
B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -2\frac{\Lambda}{\sqrt{6}} \end{pmatrix}
$$

Quarks in PNJL-like approach:

$$
\Omega_{\mathrm{q}} = -T\sum_{\mathrm{i}\in Q}\frac{\gamma_{\mathrm{i}}}{(2\pi)^3}\int d^3k \ln\left(1 + \Phi\exp\frac{E_{\mathrm{i}}^* - \mu_{\mathrm{i}}}{T}\right)
$$

$$
m_{\mathrm{q}}^* = g_{\mathrm{q}\sigma}\sigma + \delta m_{\mathrm{q}} + m_{0\mathrm{q}}
$$

$$
m_{\mathrm{s}}^* = g_{\mathrm{s}\zeta}\zeta + \delta m_{\mathrm{s}} + m_{0\mathrm{q}},
$$

where Polyakov loop Φ controls **deconfinement** with the following potential:

$$
\begin{aligned}
U &= -\frac{1}{2}a(T)\Phi\Phi^* \\
&+ b(T)\log[1 - 6\Phi\Phi^* + 4(\Phi^3 + \Phi^{*3}) - 3(\Phi\Phi^*)^2],
\end{aligned}
$$

$$
a\ (T) = a_0T^4 + a_1T_0T^3 + a_2T_0^2T^2, \quad b(T) = b_3T_0^3T
$$

Ratti, Thaler, Weise, hep-ph/0506234

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

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

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

Unified approach for QCD thermodynamics at wide range of scales.
Includes:

- 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 entergy densities

Main aspects of QCD phenomenology are consistently included

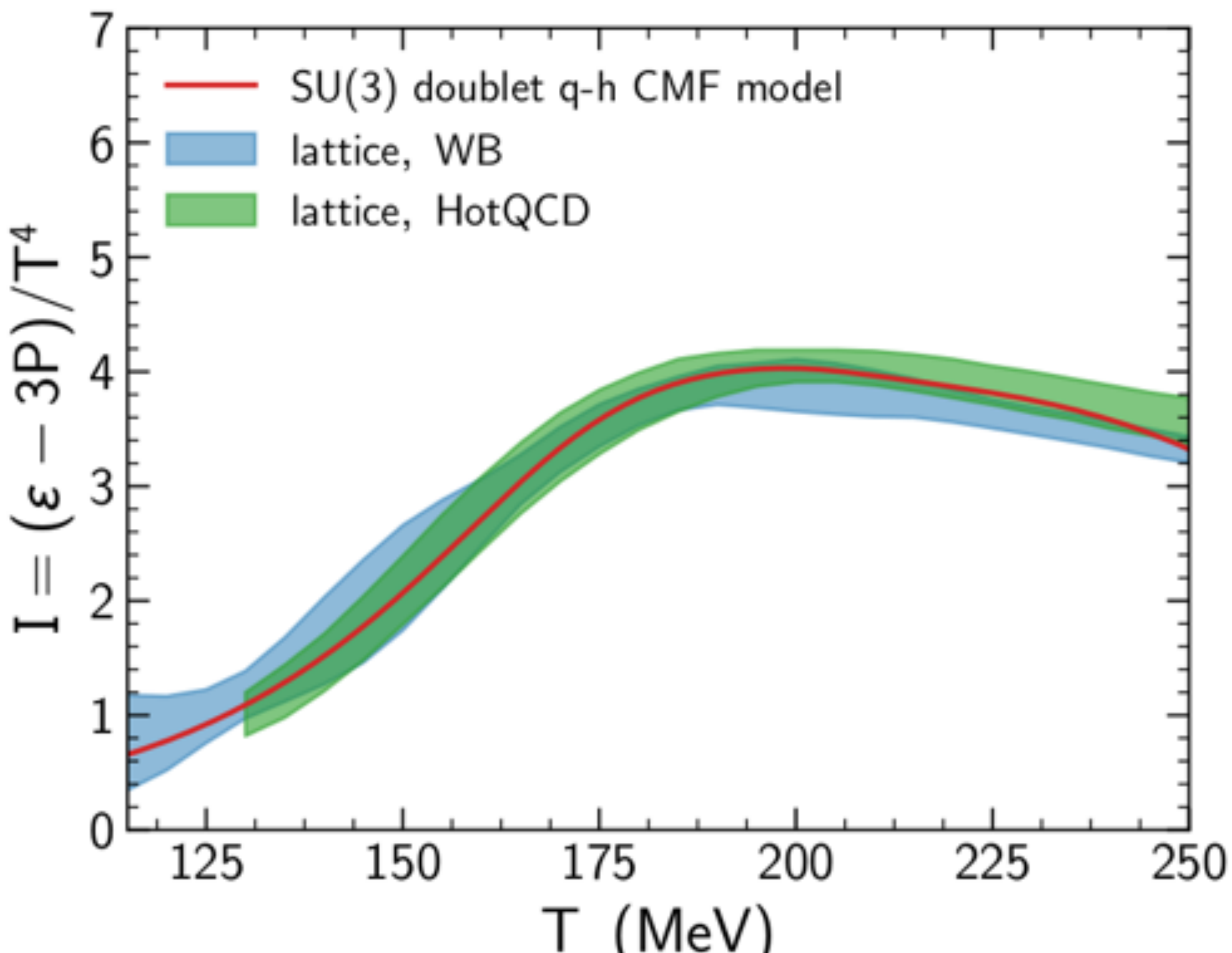
A realistic and relativistic EOS for HI-Coll. at FAIR/NICA and for NS (T=0) and binary NS mergers (T~70 MeV)

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

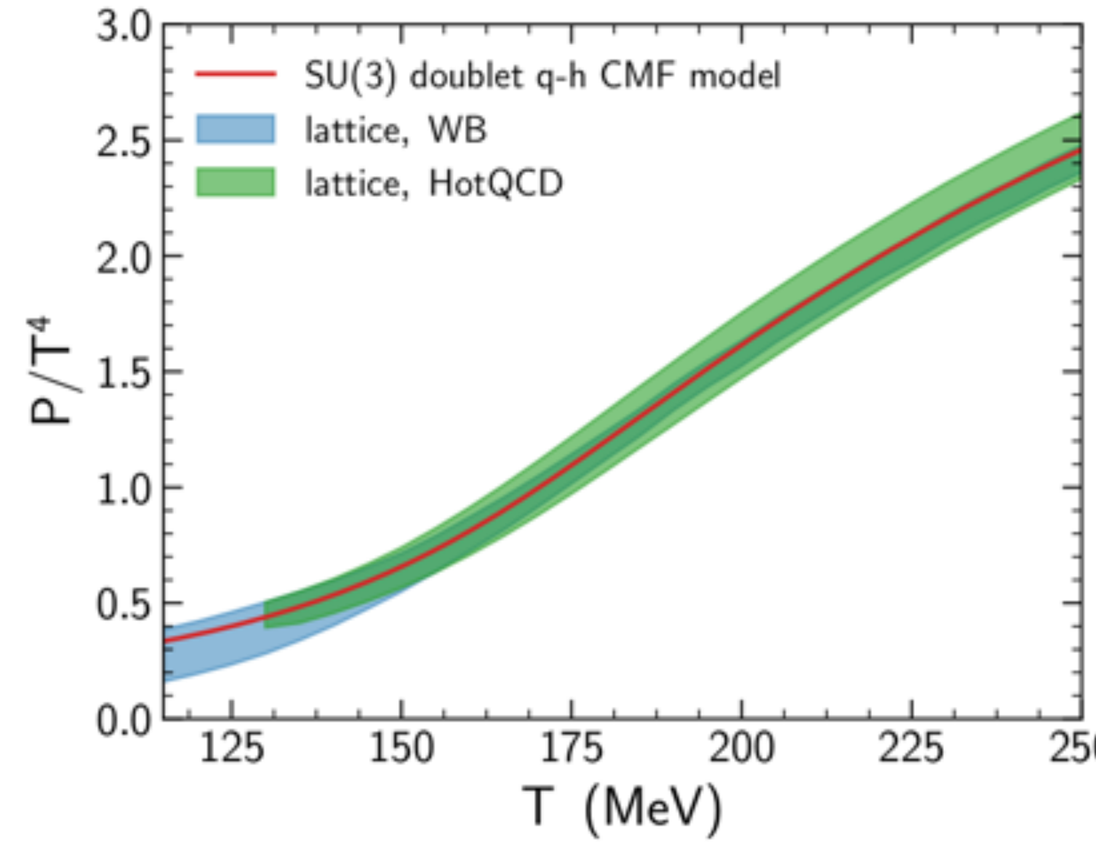
A. Motornenko et al.

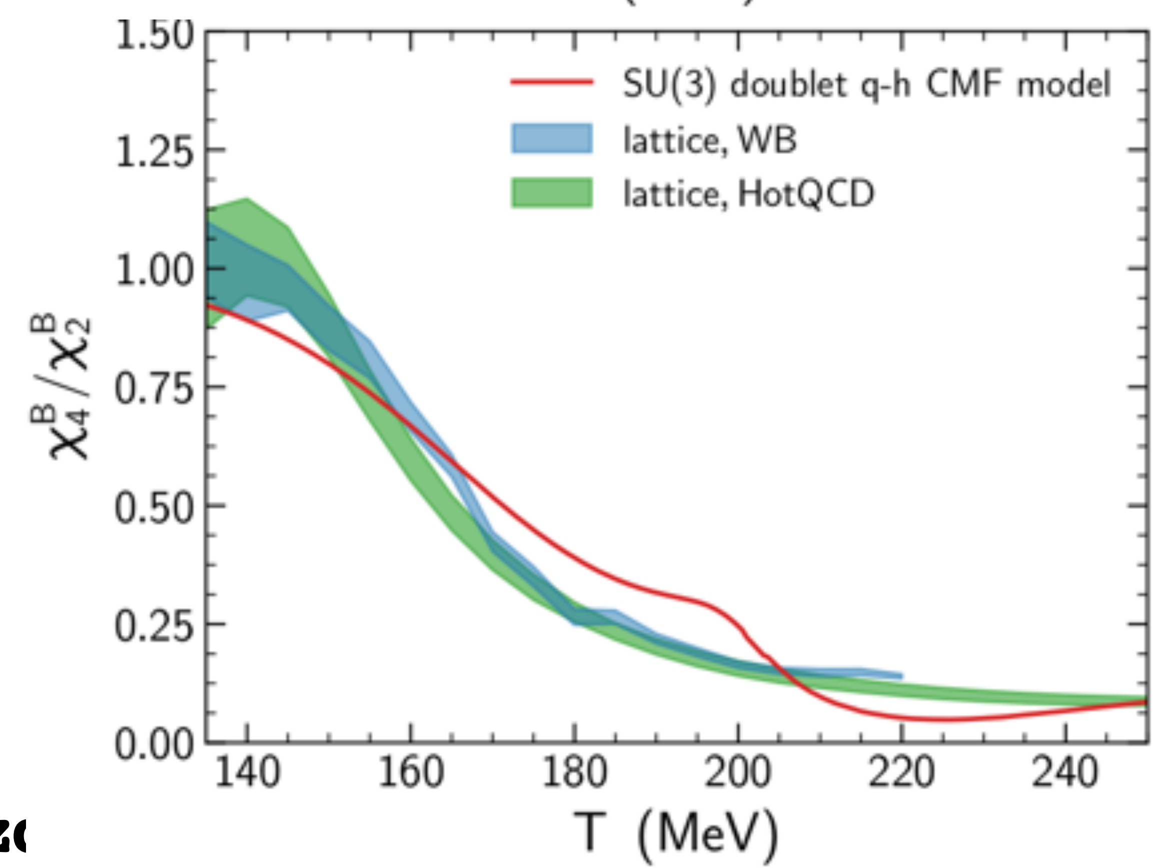
Quark-Hadron-EoS of CMF -fits to Lattice QCD data

A, Motornenko et al.,1809.02000



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



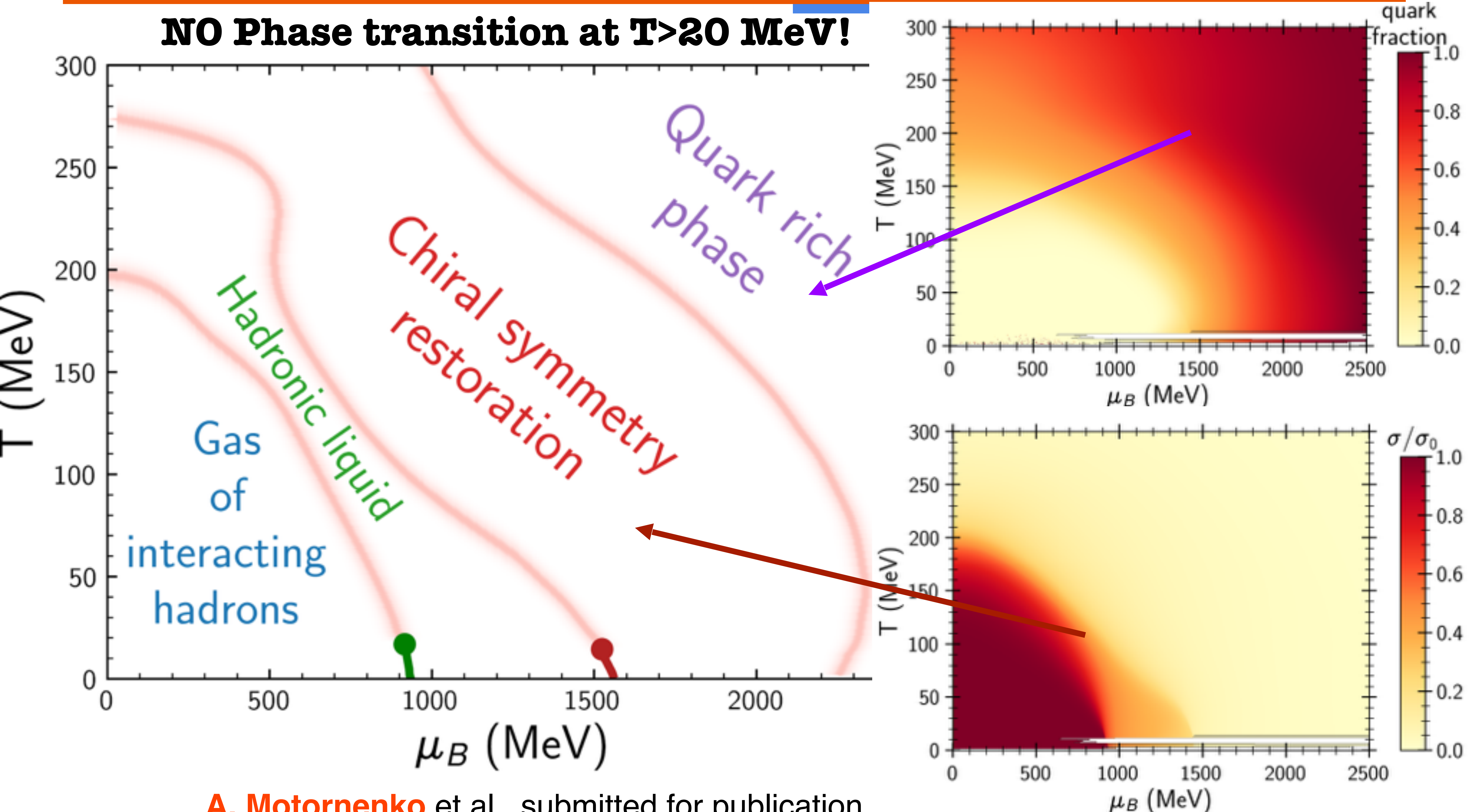


Model successfully reproduces lattice QCD data

A. Motornenko et al.

Phase diagram from relativistic Chiral Mean Field CMF

NO Phase transition at T>20 MeV!

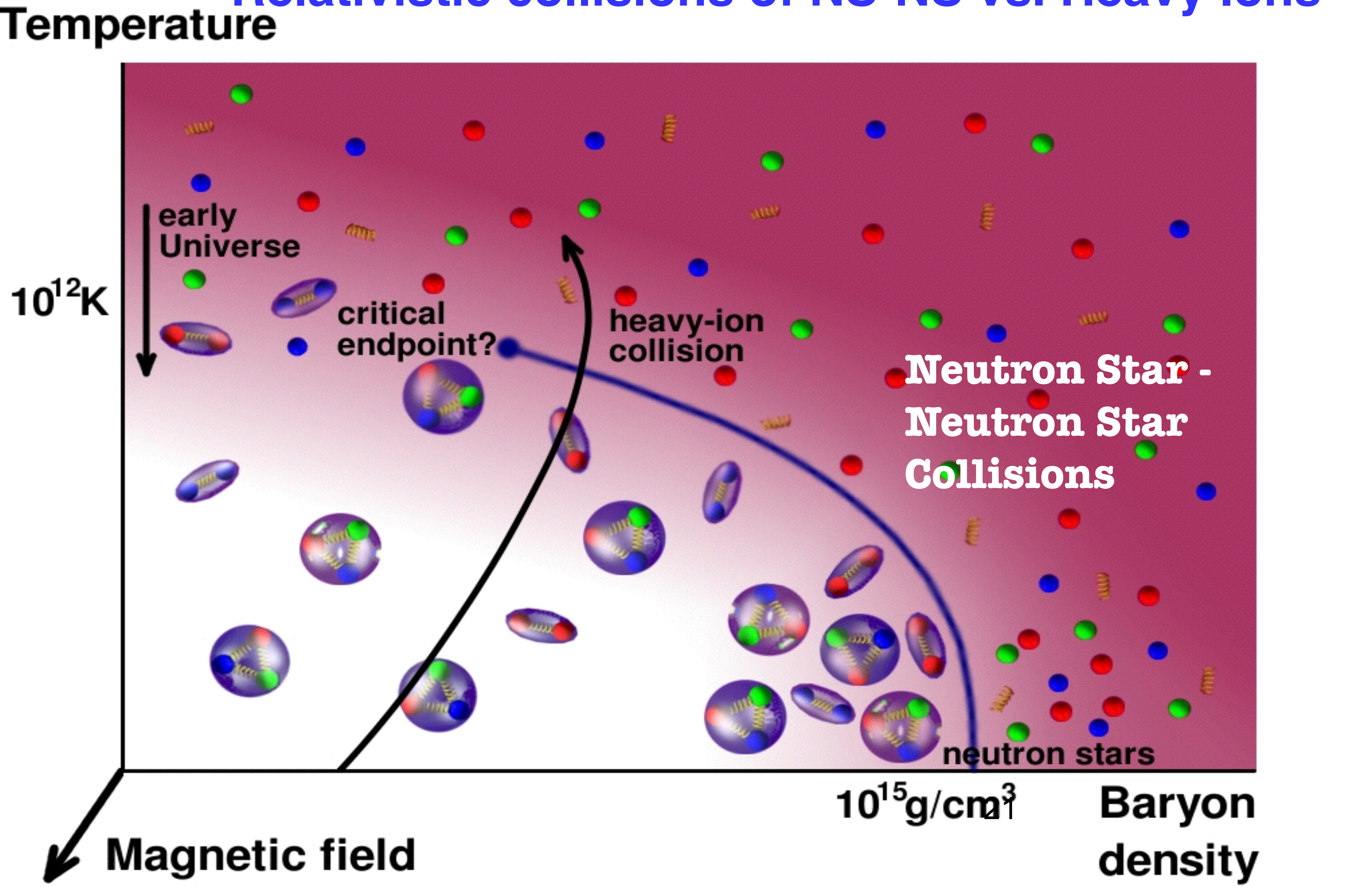


A. Motornenko et al., submitted for publication

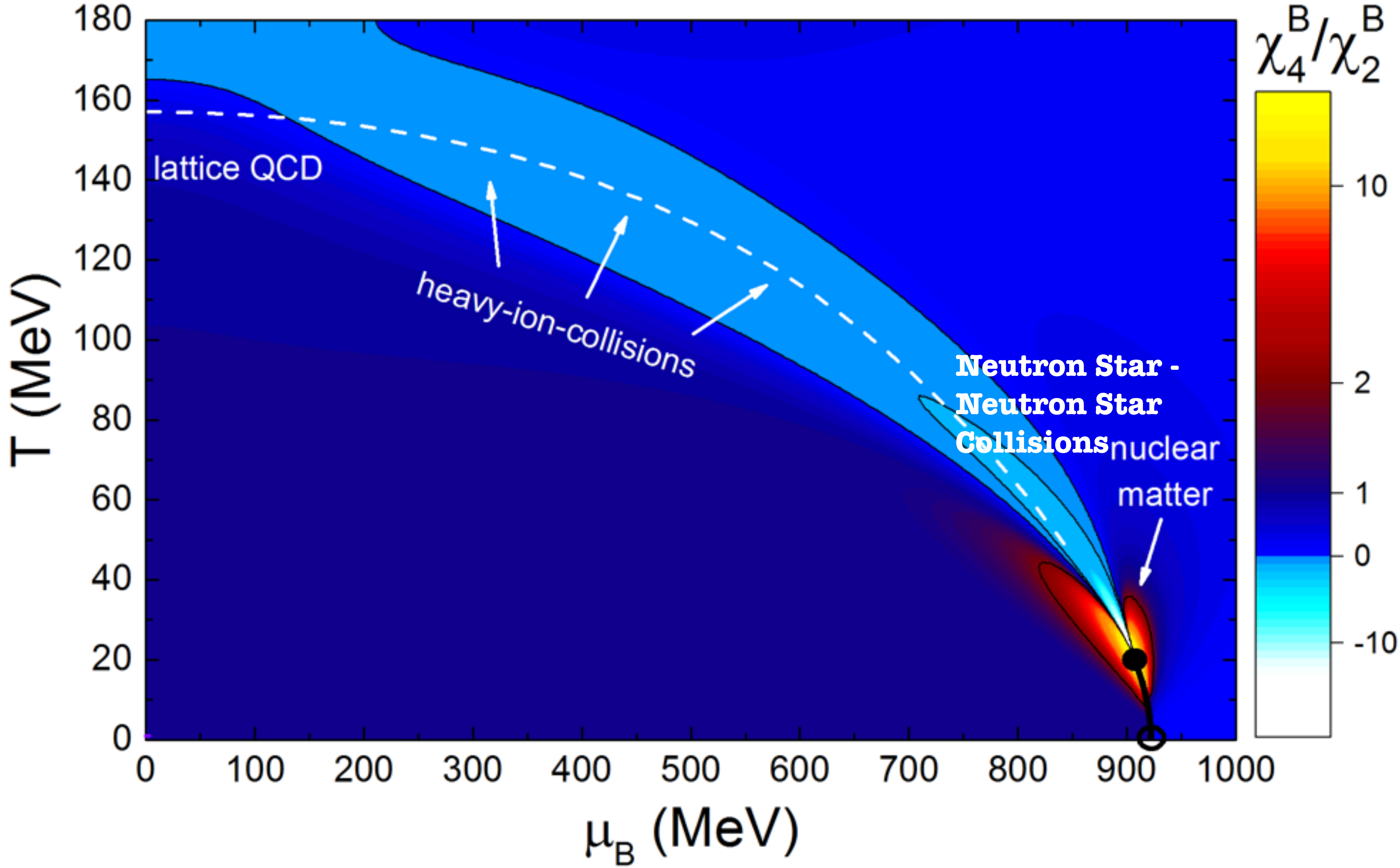
MAGIC Motornenko, Most, Hanauske, Rezzolla, Schramm, Steinheimer, Stoecker

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

Relativistic collisions of NS-NS vs. Heavy Ions



Unlike lattice QCD, QvdW approach is not restricted to zero net-baryon density

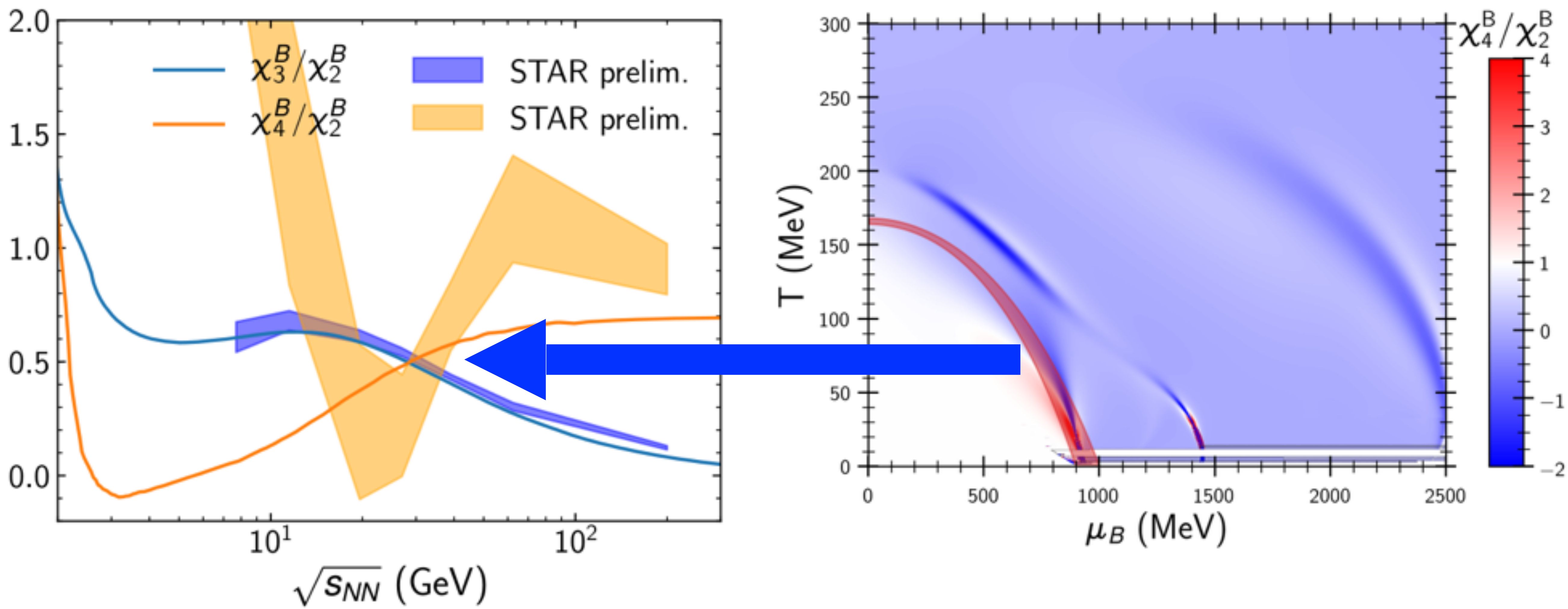


Nuclear matter shines brightly across whole phase diagram probed in HIC & NsNs

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

Probing phase diagram by heavy ions collisions

If one take “freeze-out” curve seriously, higher order susceptibilities may be presented as function of $\sqrt{s_{NN}}$ and compared with preliminary STAR data for proton cumulants.



Freeze-out curve: *Cleymans, Oeschler, Redlich, Wheaton, [hep-ph/0511094]*
STAR data: X. Luo [STAR Collaboration], 1503.02558

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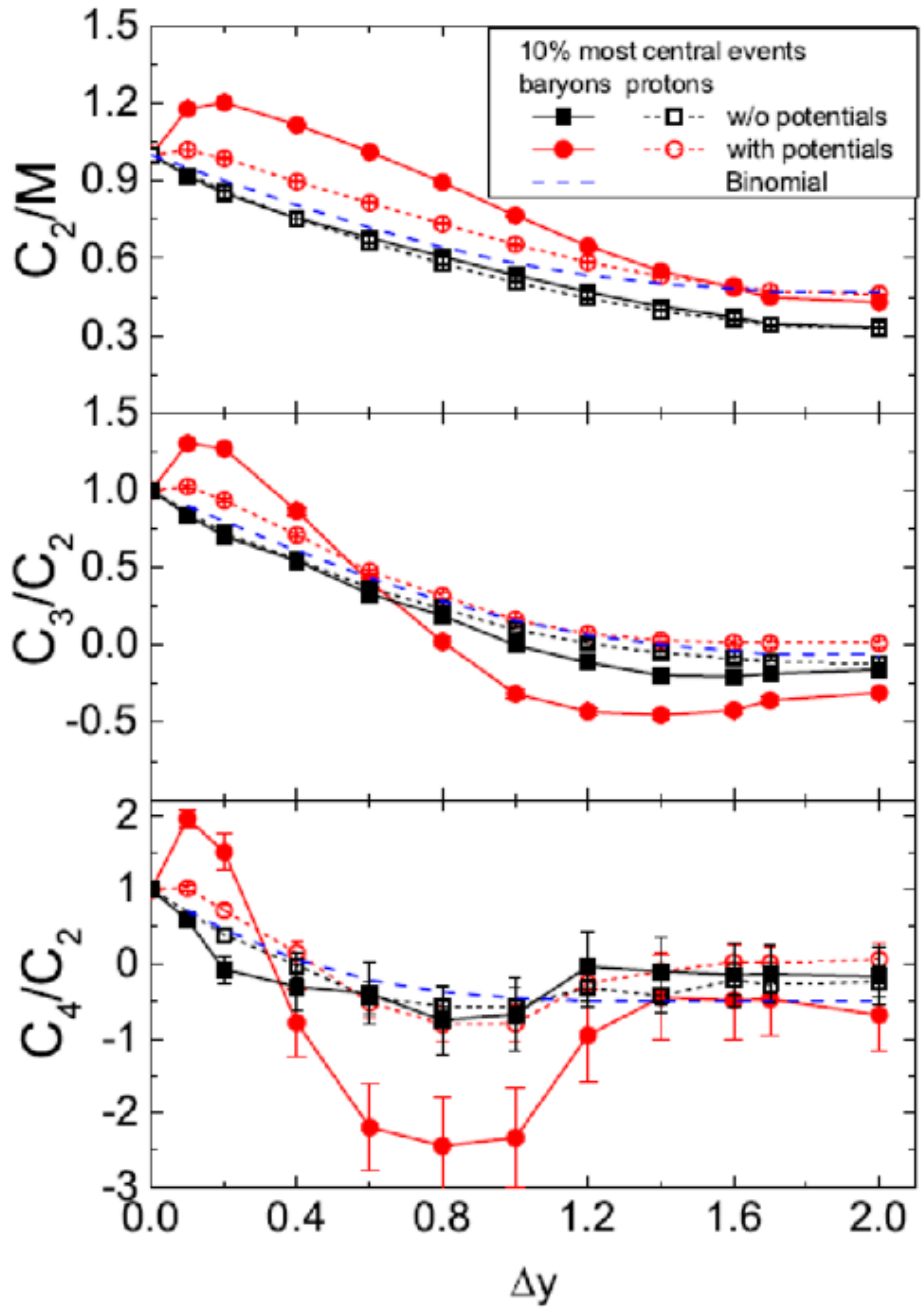
Baryon number fluctuations reveal the attr.-rep. nuclear interactions

- 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.

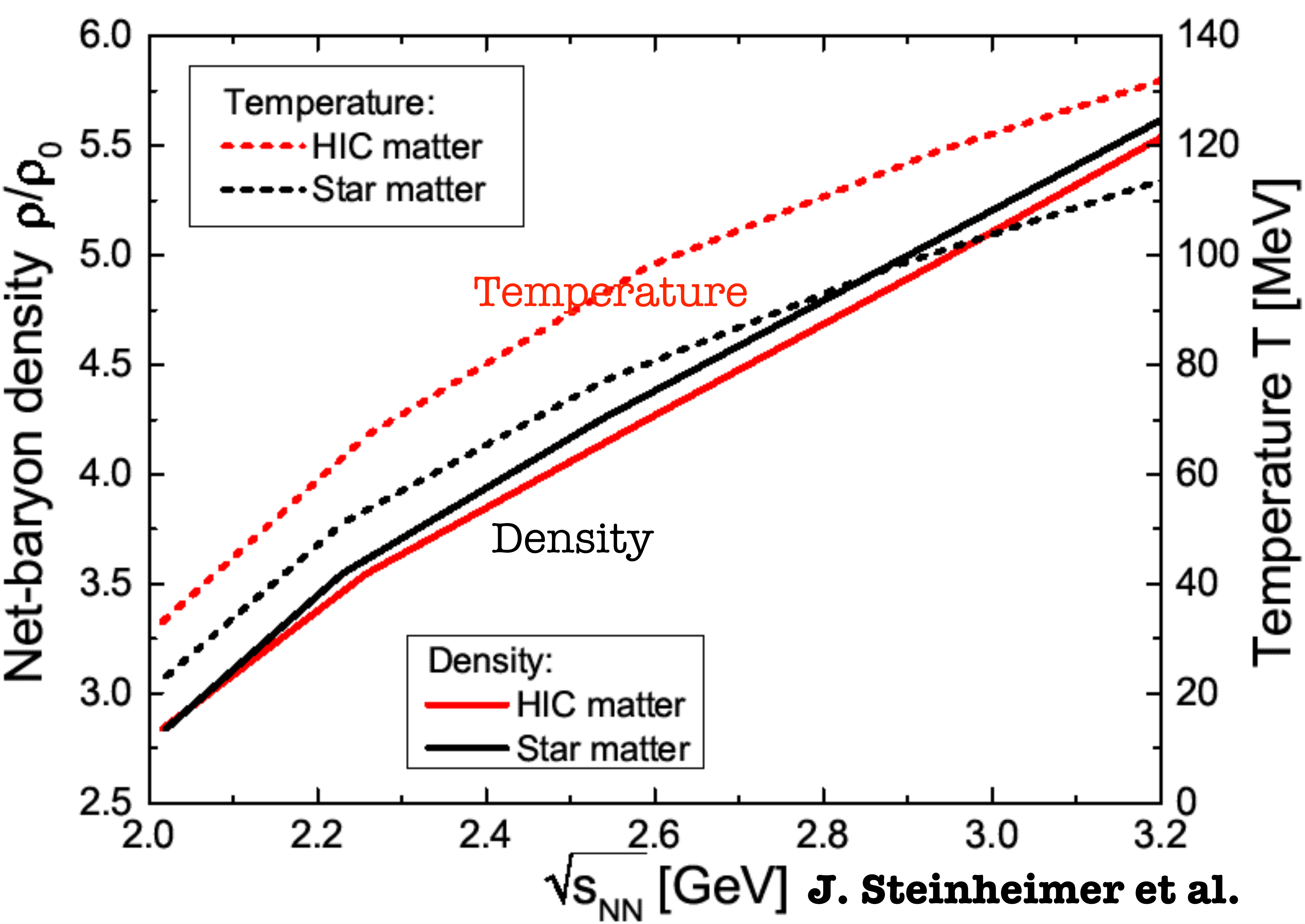
J. Steinheimer, Y. Wang, A. Mukherjee, Y. Ye, C. Guo, Q. Li and H. Stoecker, Phys. Lett. B 785, 40 (2018)

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



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:

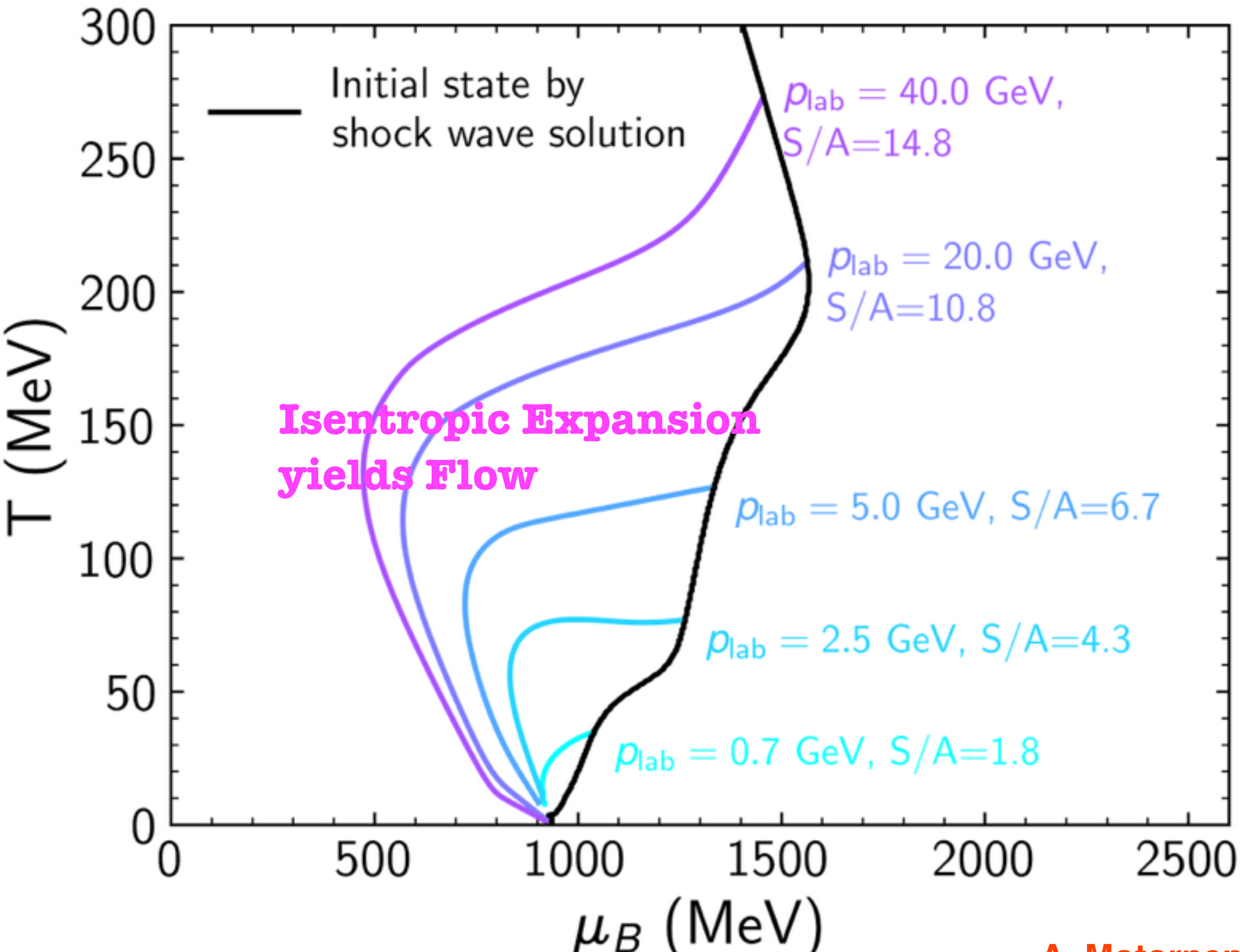
Rankine Hugoniot Taub Adiabate

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)

Probing phase diagram by relativistic heavy ions collisions: Collective Flow from High Pressure initial state by isentropic expansion



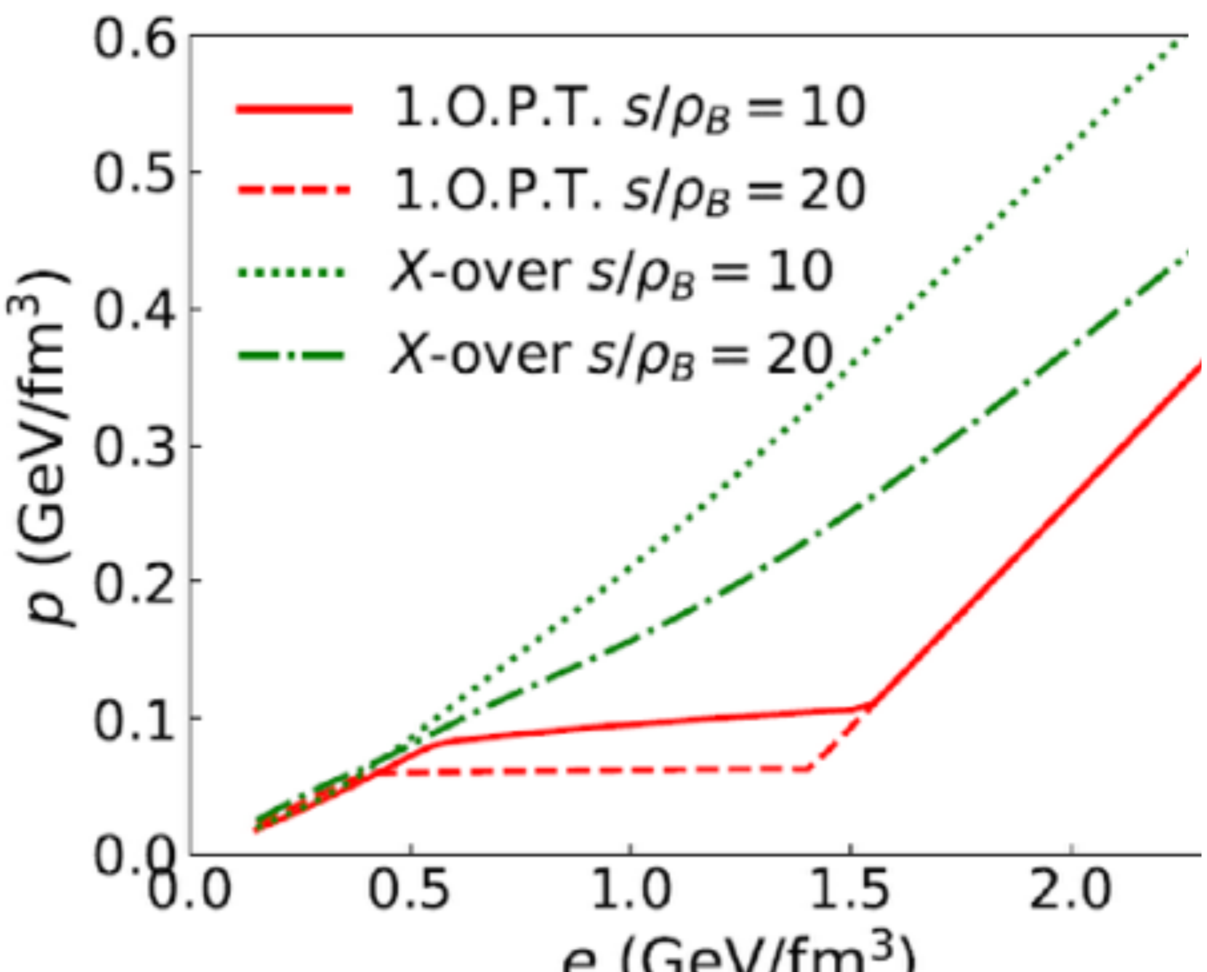
Isentropes = curves of constant entropy illustrate evolution of system created in heavy ion collision. Entropy per baryon S/A computed by relativistic Taub adiabat
- the relativistic stationary hydrodynamic shock wave solution

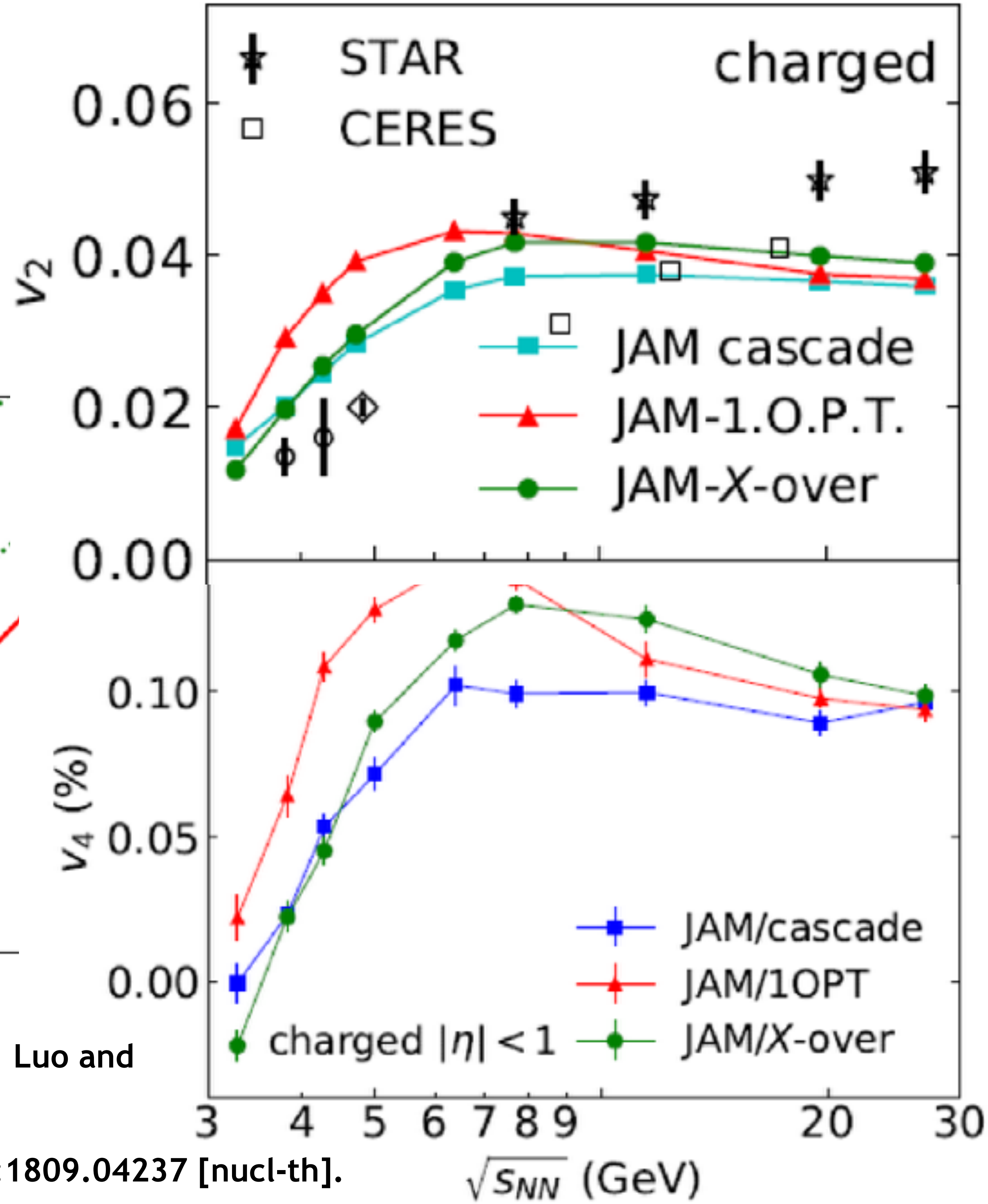
A. Motornenko et al.,1809.02000

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

2.nd and 4.th order coefficient of FLOW will signal a 1. order phase transition

- Calculation relativistic
- JAM transport model
- EoS introduced via azimuthal scattering angle
- Clear peak in v_2 and v_4 for first order phase transition.



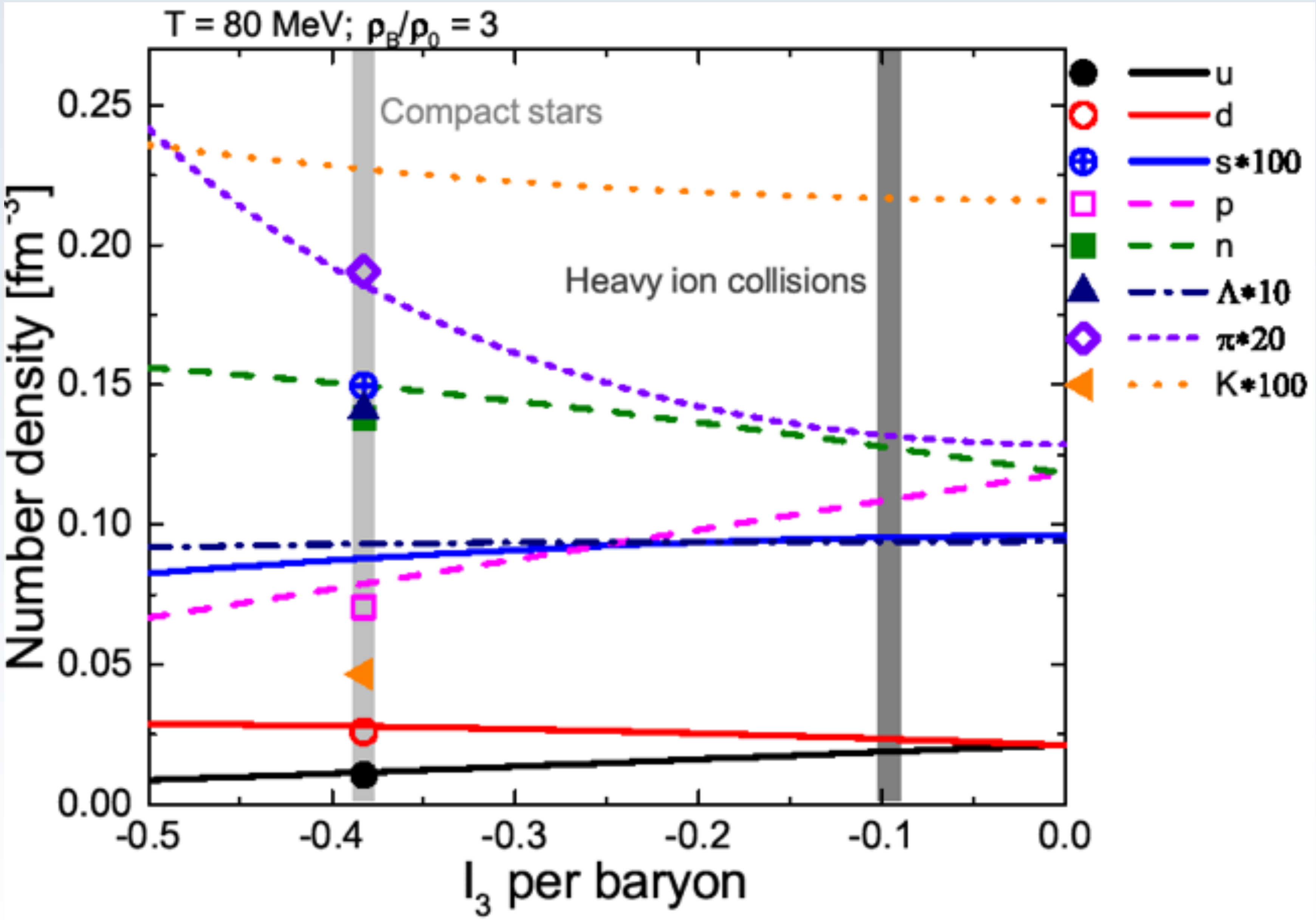


Y. Nara, H. Niemi, A. Ohnishi, J. Steinheimer, X. Luo and H. Stöcker, Eur. Phys. J. A 54, no. 2, 18 (2018)

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

Neutronstar merger vs. heavy ion collisions
Differences in chemical composition

- The EOS for heavy ion collisions: conserved strangeness and NO beta-equilibrium
- The EOS for compact stars: in beta-equilibrium



- T= 80 MeV
- 3 times nuclear ground state density
- Large difference in strangeness content and iso-spin

Neutron stars put constraints on properties of T=0 QCD matter!

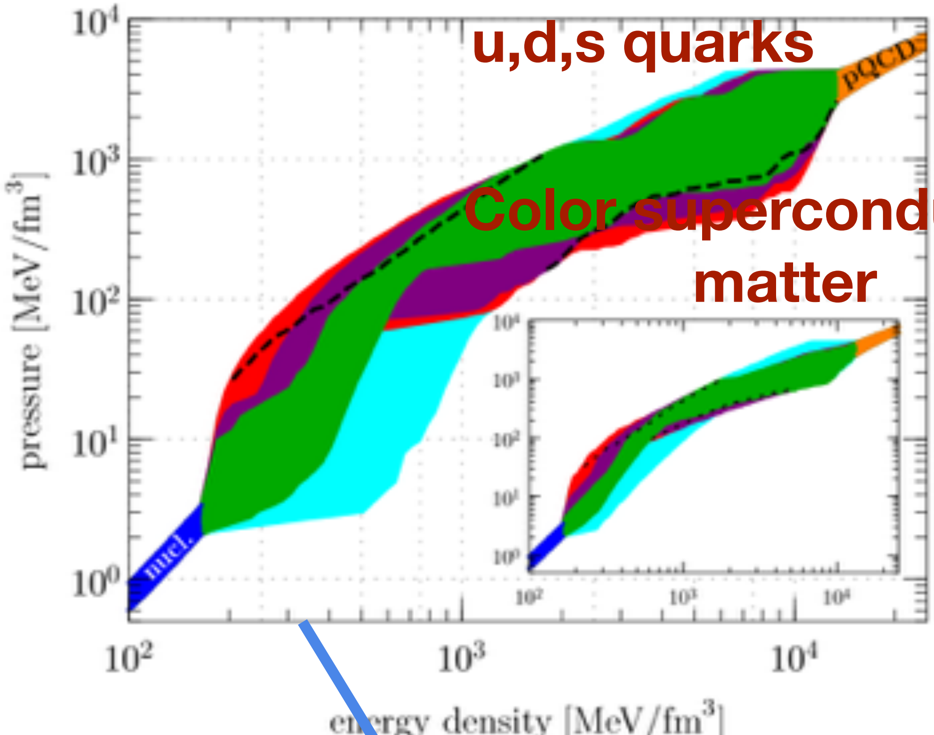
SU(3) parity-doublet quark-hadron chiral mean field model

Hyperons

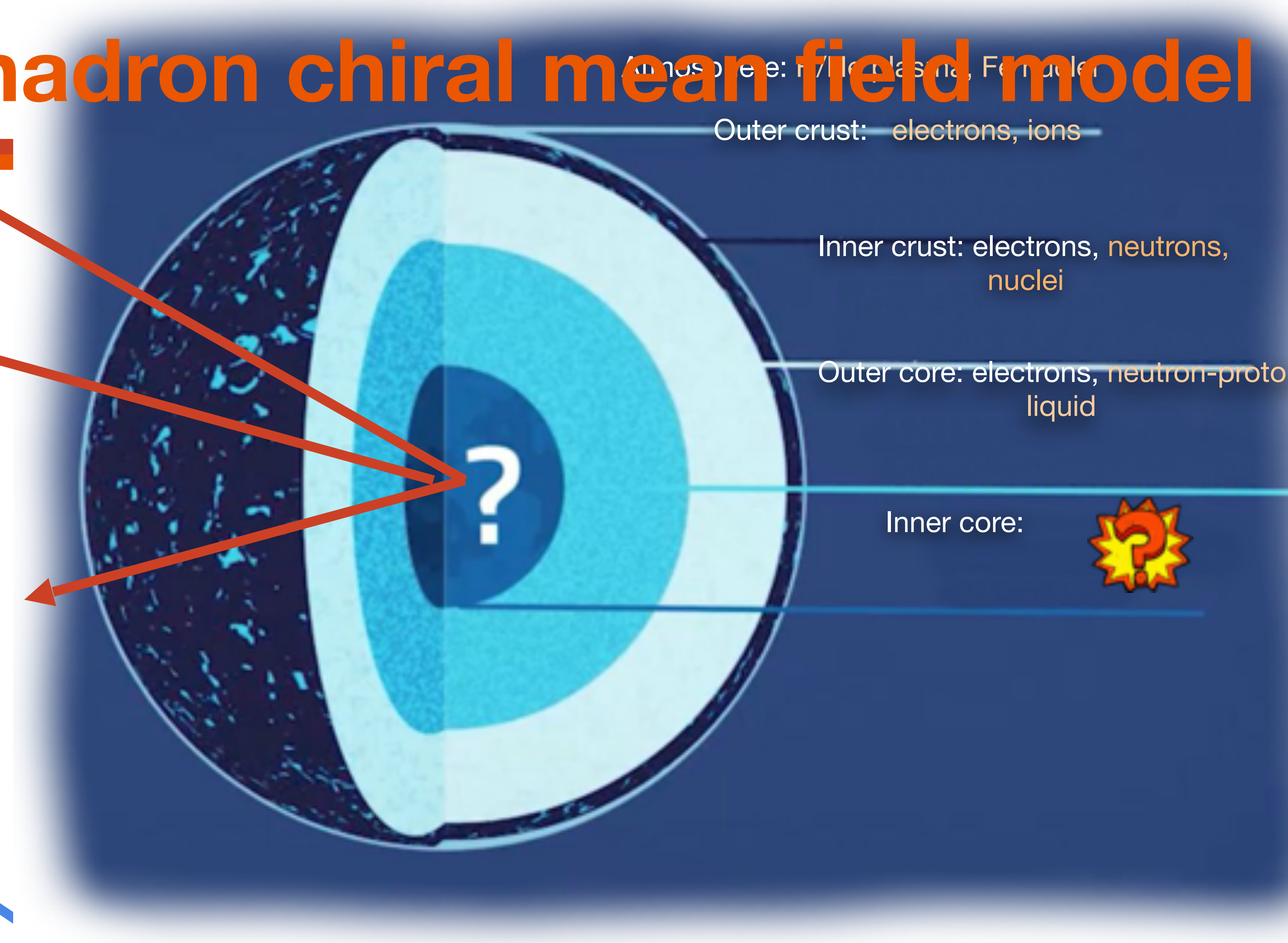
Equation of state at T=0:

u,d,s quarks

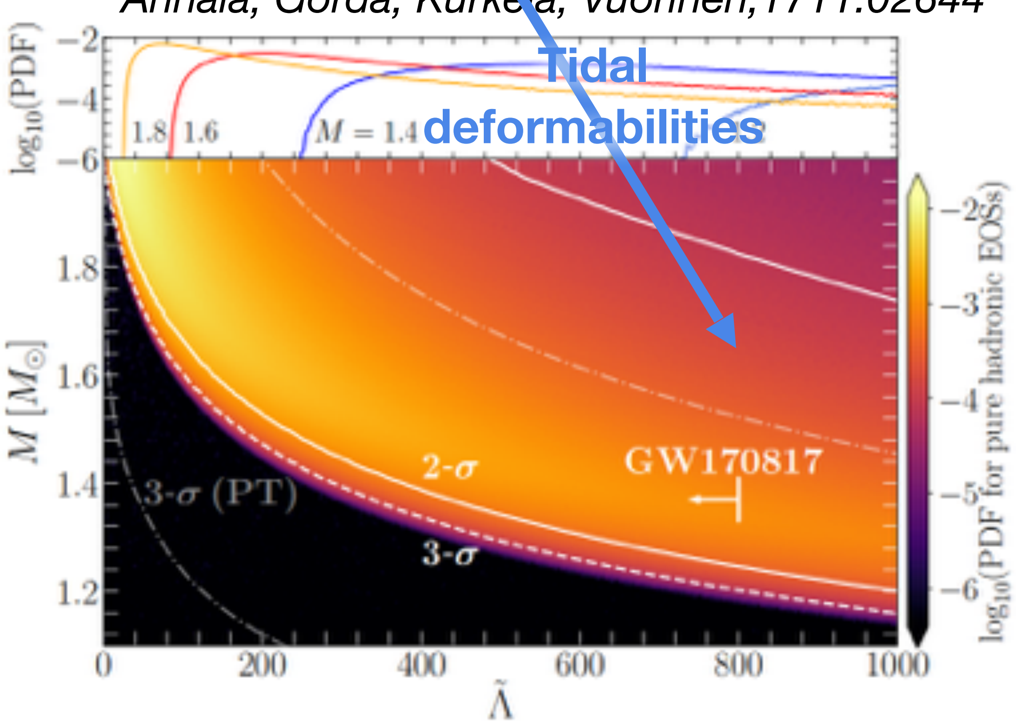
Color superconducting matter



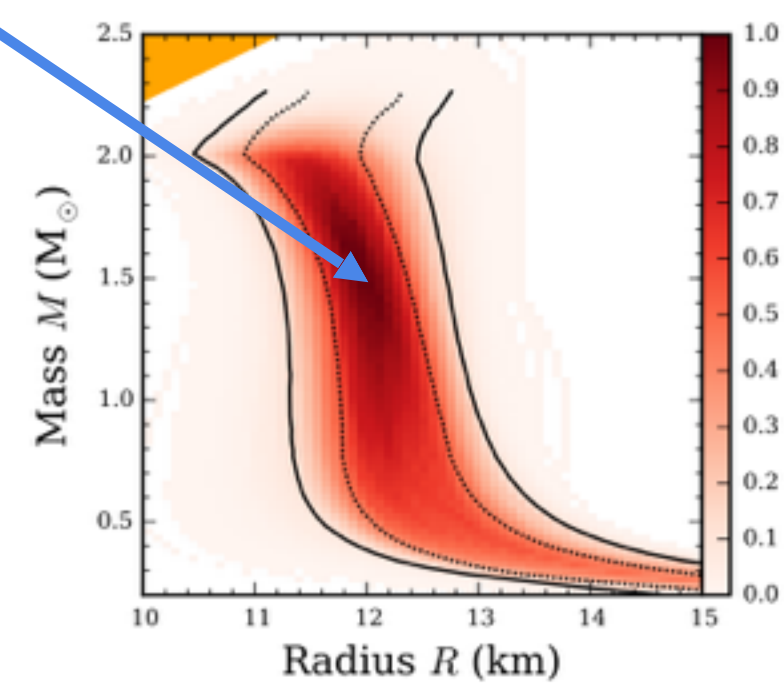
Annala, Gorda, Kurkela, Vuorinen,1711.02644



Tidal deformabilities



Mass-radius relations



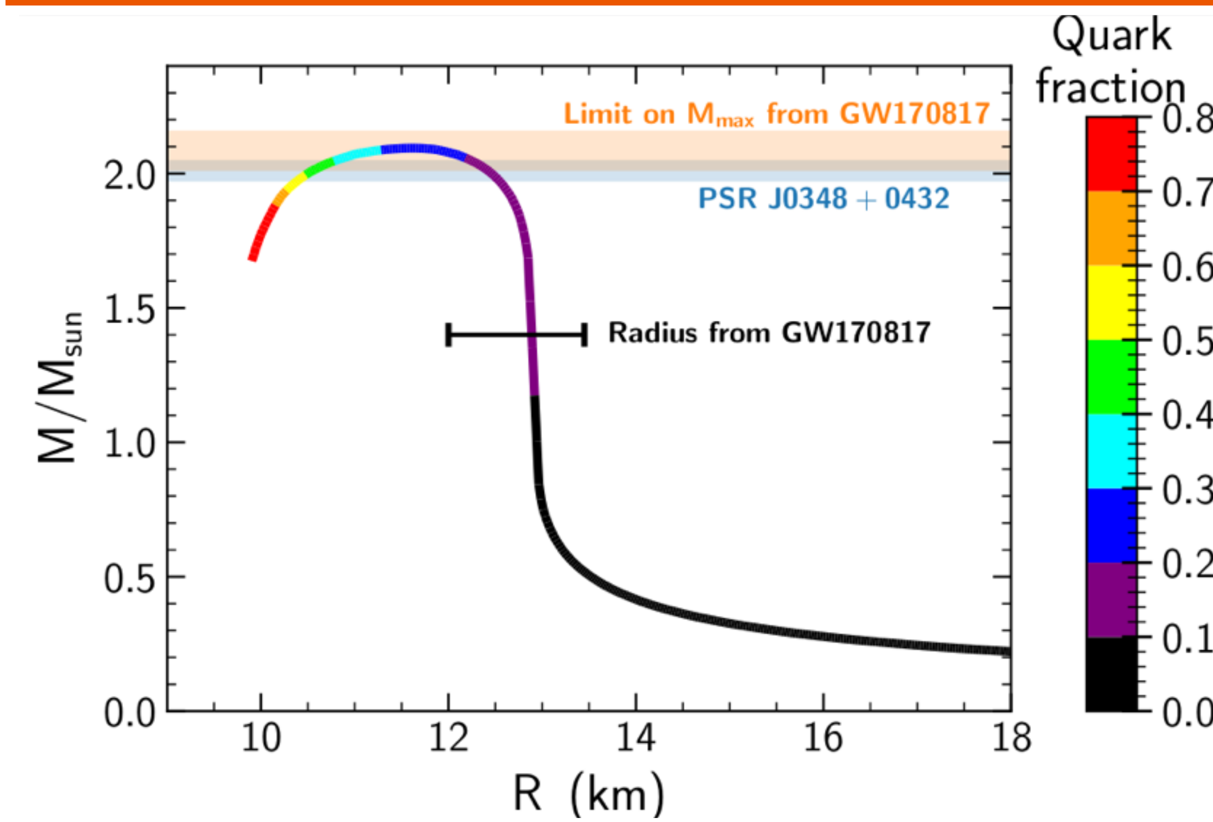
Nättilä et al., 1509.06561

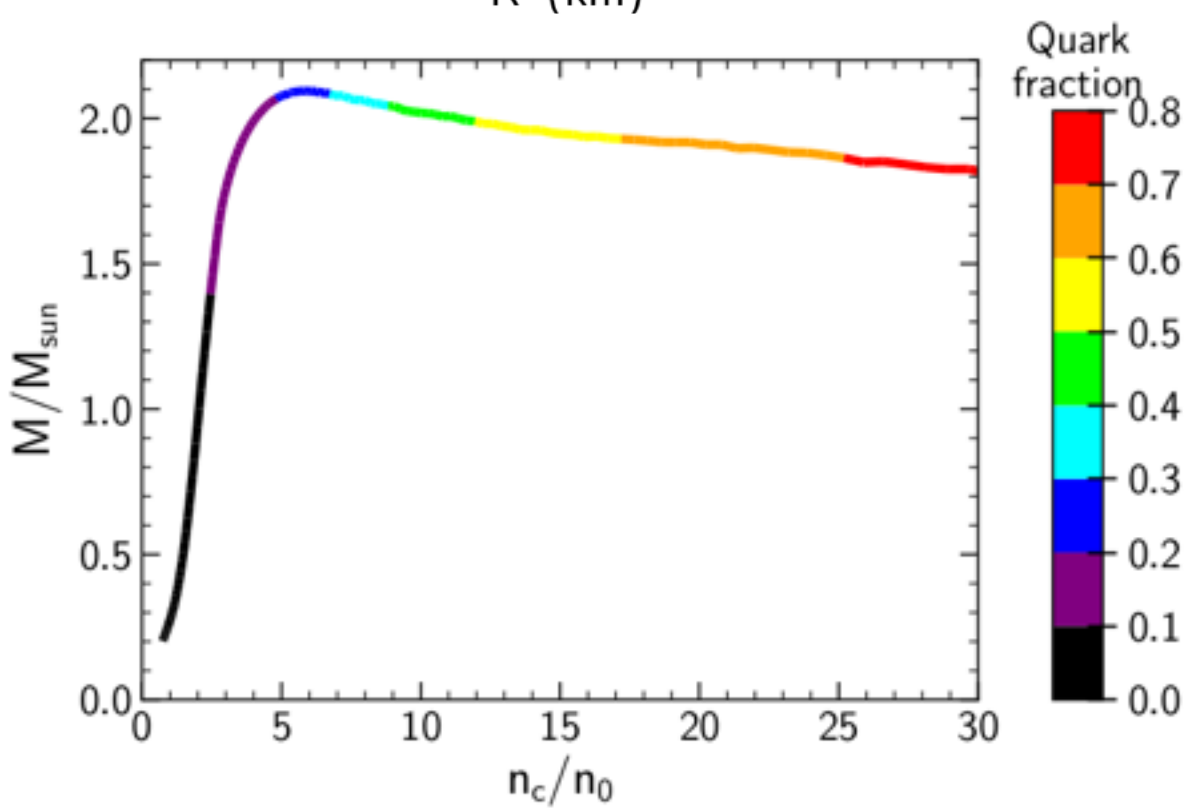
Most, Weih, Rezzolla, Schaffner-Bielich, 1803.00549

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

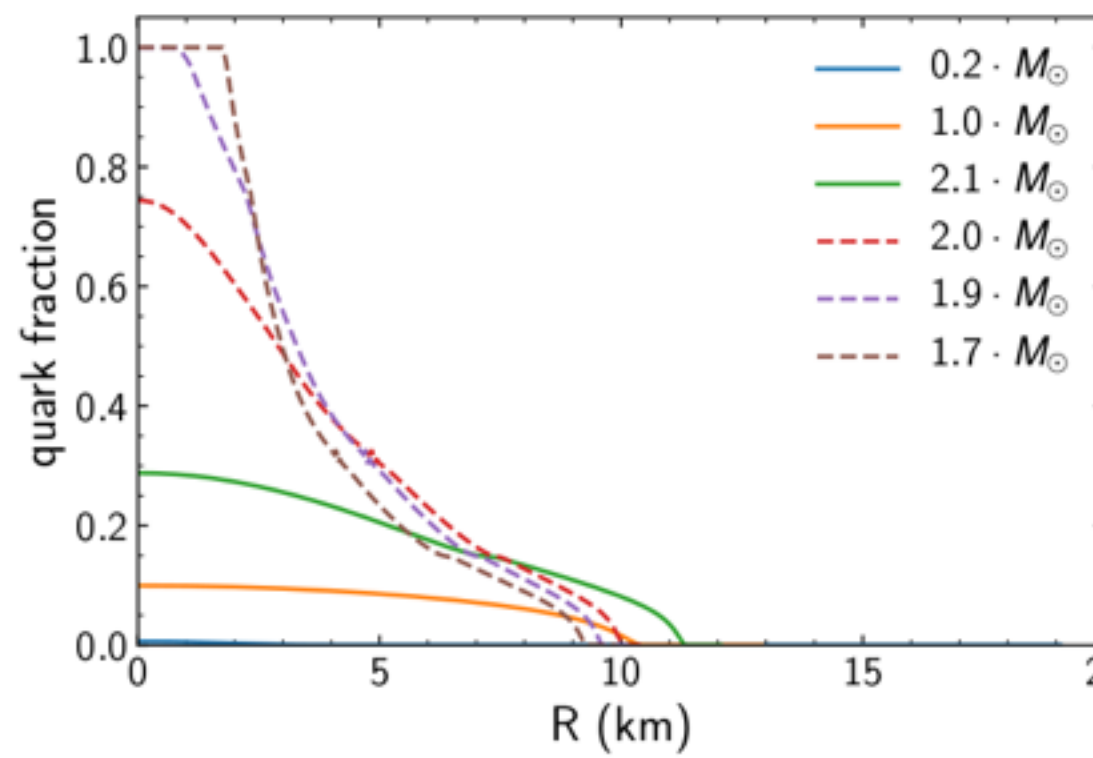
A. Motornenko et al.

Mass-radius relations





Local quark fraction
(dashed — unstable stars):



Maximal mass is in agreement with recent constraints from GW170817:

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

Rezzolla, Most, Weih, Astrophys.J. 852 (2018) no.2, L25

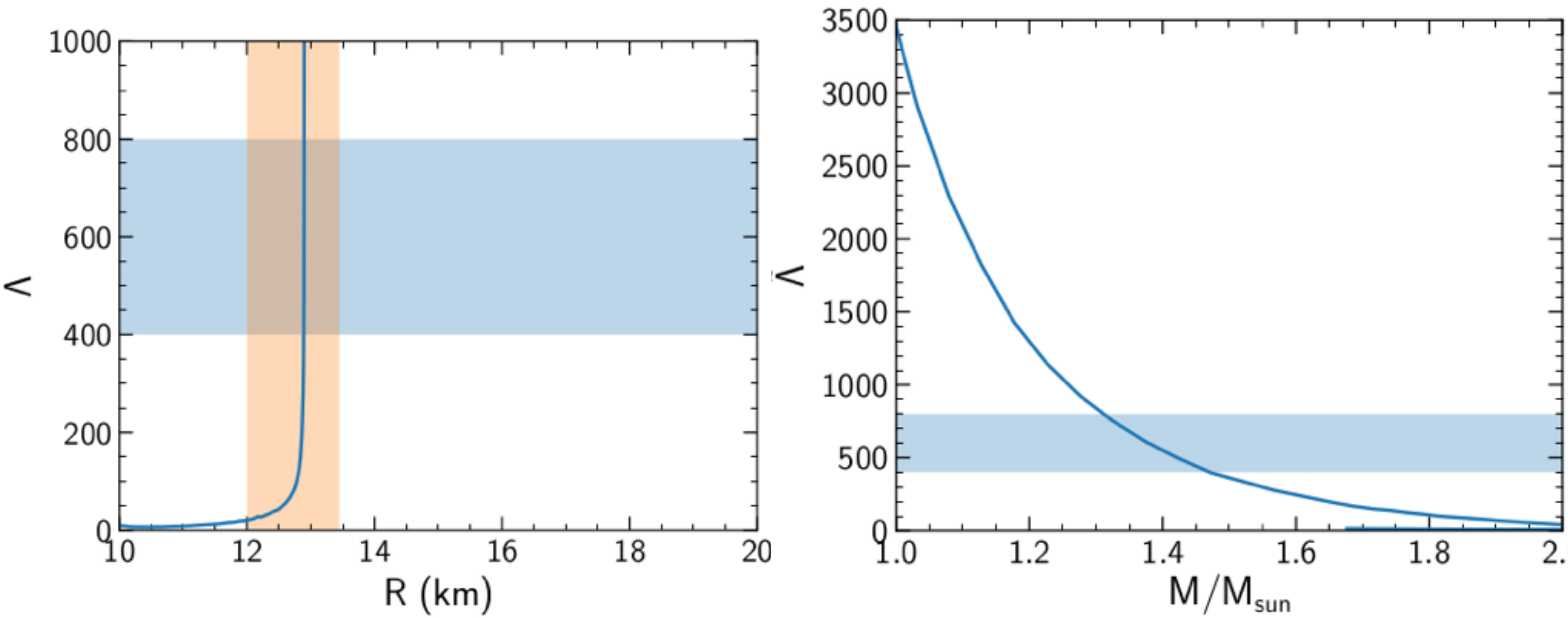
MAGIC Motornenko, Most, Hanauske, Rezzolla, Schramm, Steinheimer, Stoecker

A. Motornenko et al.

Neutron star tidal deformabilities

Tidal deformability $Q_{ij} = - \Lambda \varepsilon_{ij}$ how does star's gravit. field react to external quadrupol field:

- important EoS- dependent quantity for inspiral phase of binary neutron star system.



A. Motornenko, et al., in preparation

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

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

Lines — results on Λ using CMF-EoS

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

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

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**…

100 years later - LIGO:

LIGO: Laser Interferometer Gravitational-Wave Observatory

Selected for a Viewpoint in *Physics*
PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_{\odot}$ and $29^{+4}_{-4} M_{\odot}$, and the final black hole mass is $62^{+4}_{-4} M_{\odot}$, with $3.0^{+0.5}_{-0.5} M_{\odot} c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

First Direct Discovery of Gravitational Waves

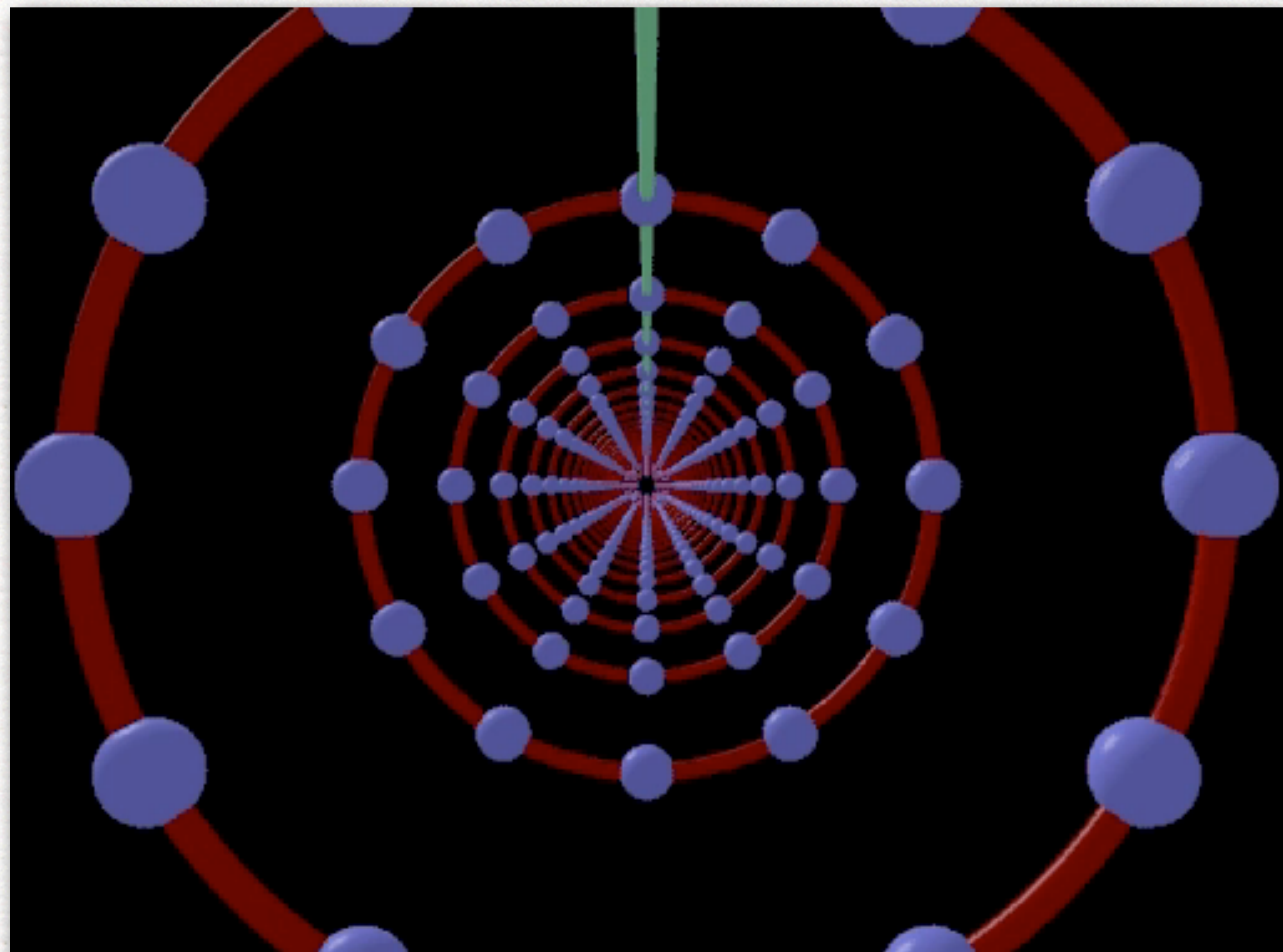
Signalform: melting of two Black Holes

Gravitational waves: ripples in spacetime

The mechanical analogy is very close: general relativity predicts that if masses are accelerated, they produce ***gravitational waves (GWs)***

- GWs are transverse waves moving at the speed of light, i.e. they produce changes in the direction orthogonal to the propagation one

- GWs effect is distorting space and time, producing quadrupole distortions: squeeze in one direction and stretch in the orthogonal one



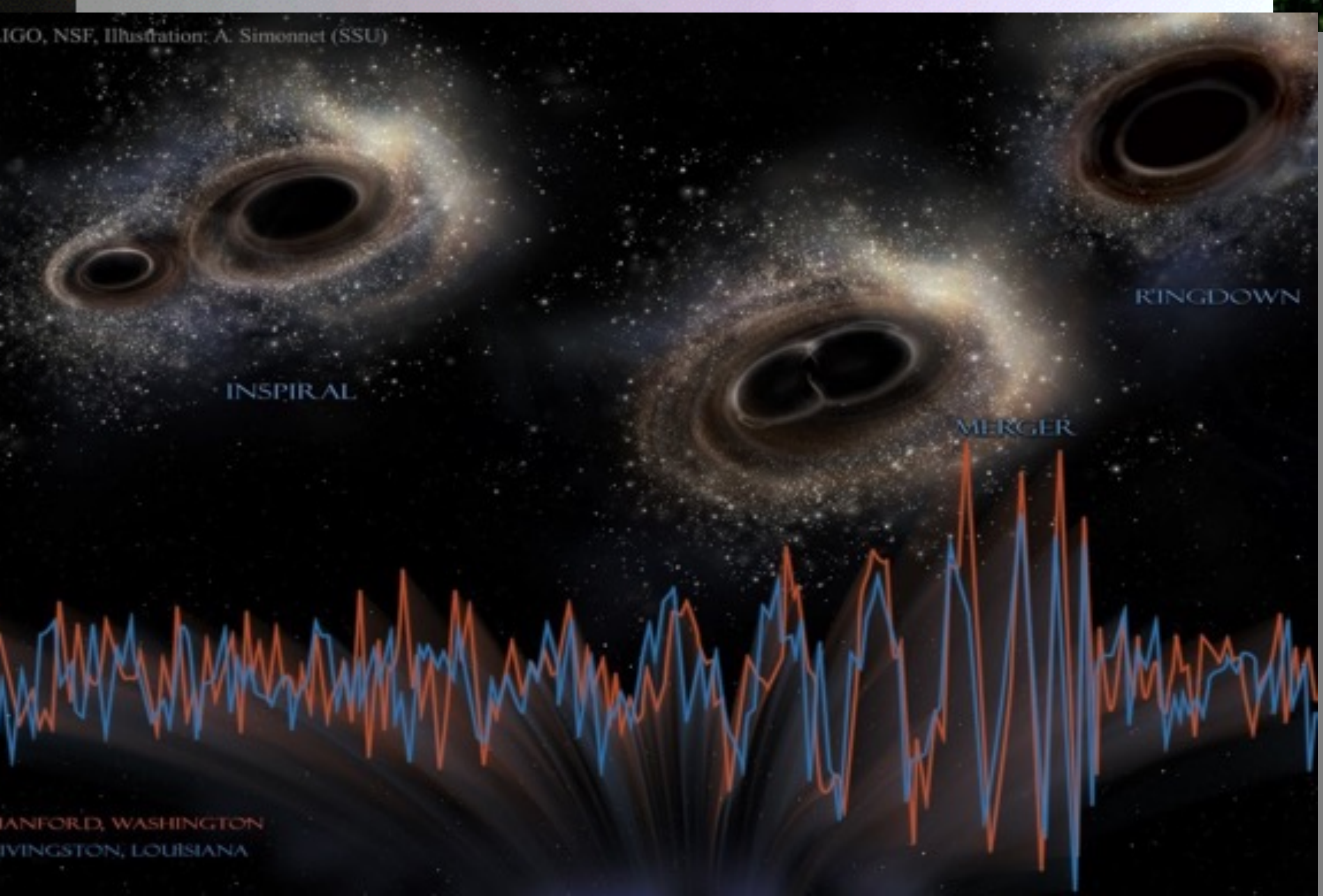
Gravitational Waves discovered ??!!!

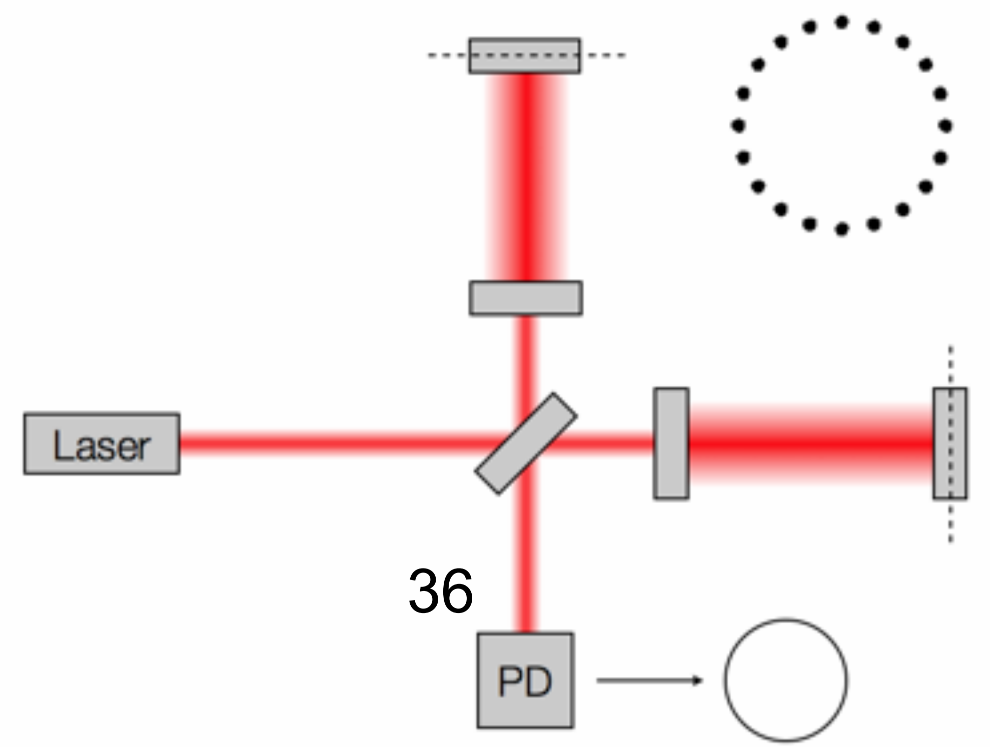
Collision of 2 BHs GW150914

Masses of BHs: 36 & 29 Solar Masses

Distance to Earth 410 Mpc
(1340 Million Lightyears)

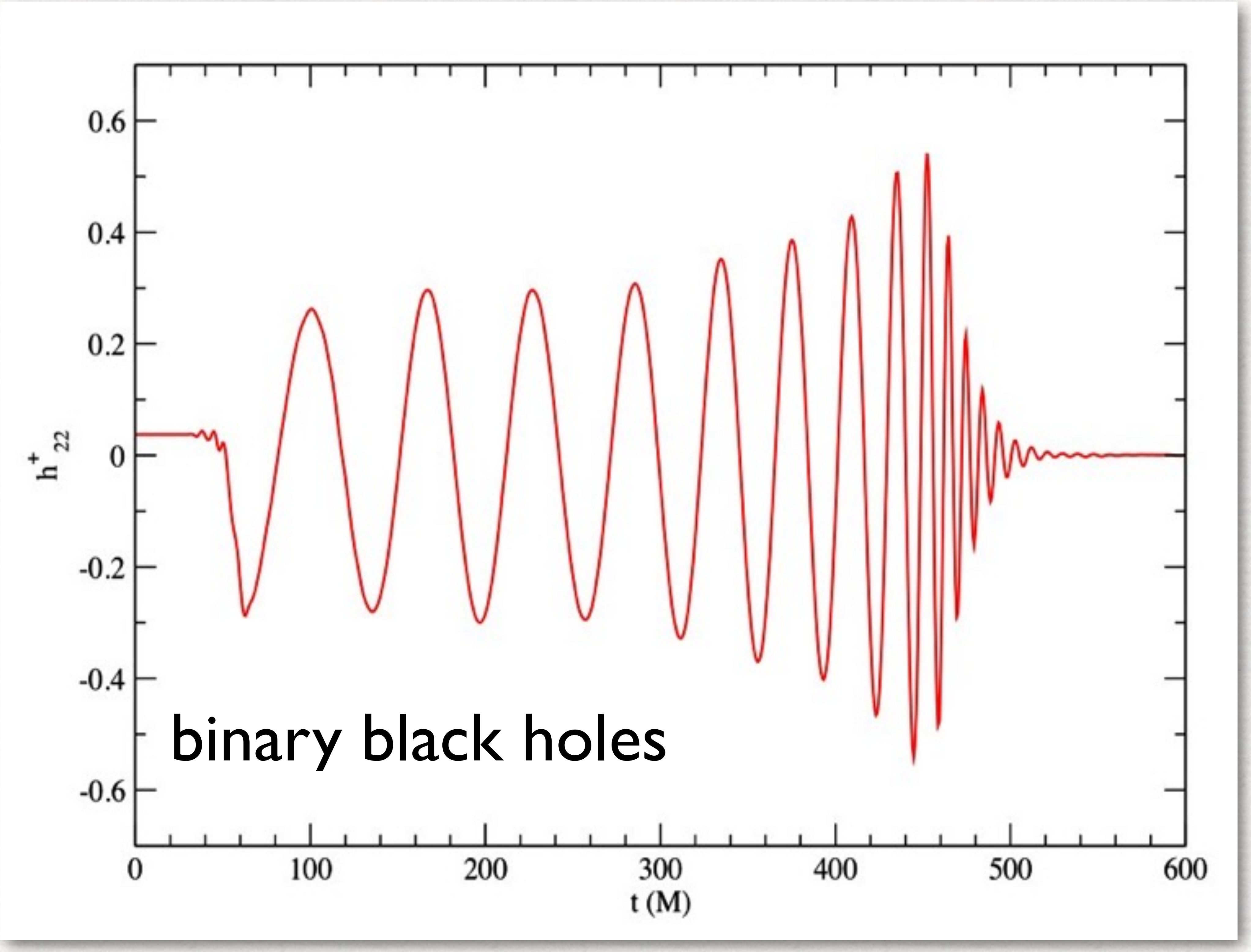
Length Difference 10^-21 m



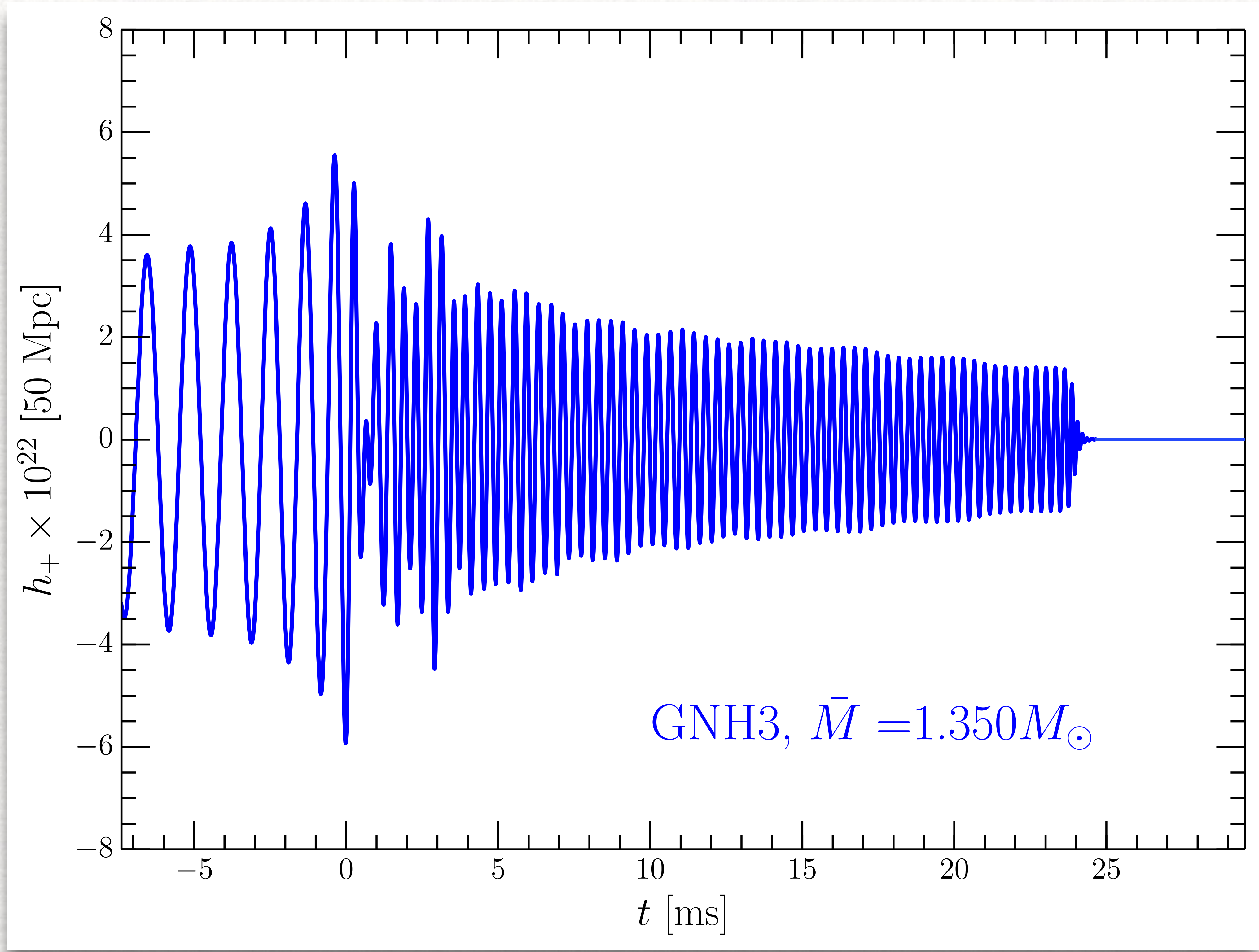


Credit: Les Wade from Kenyon College.

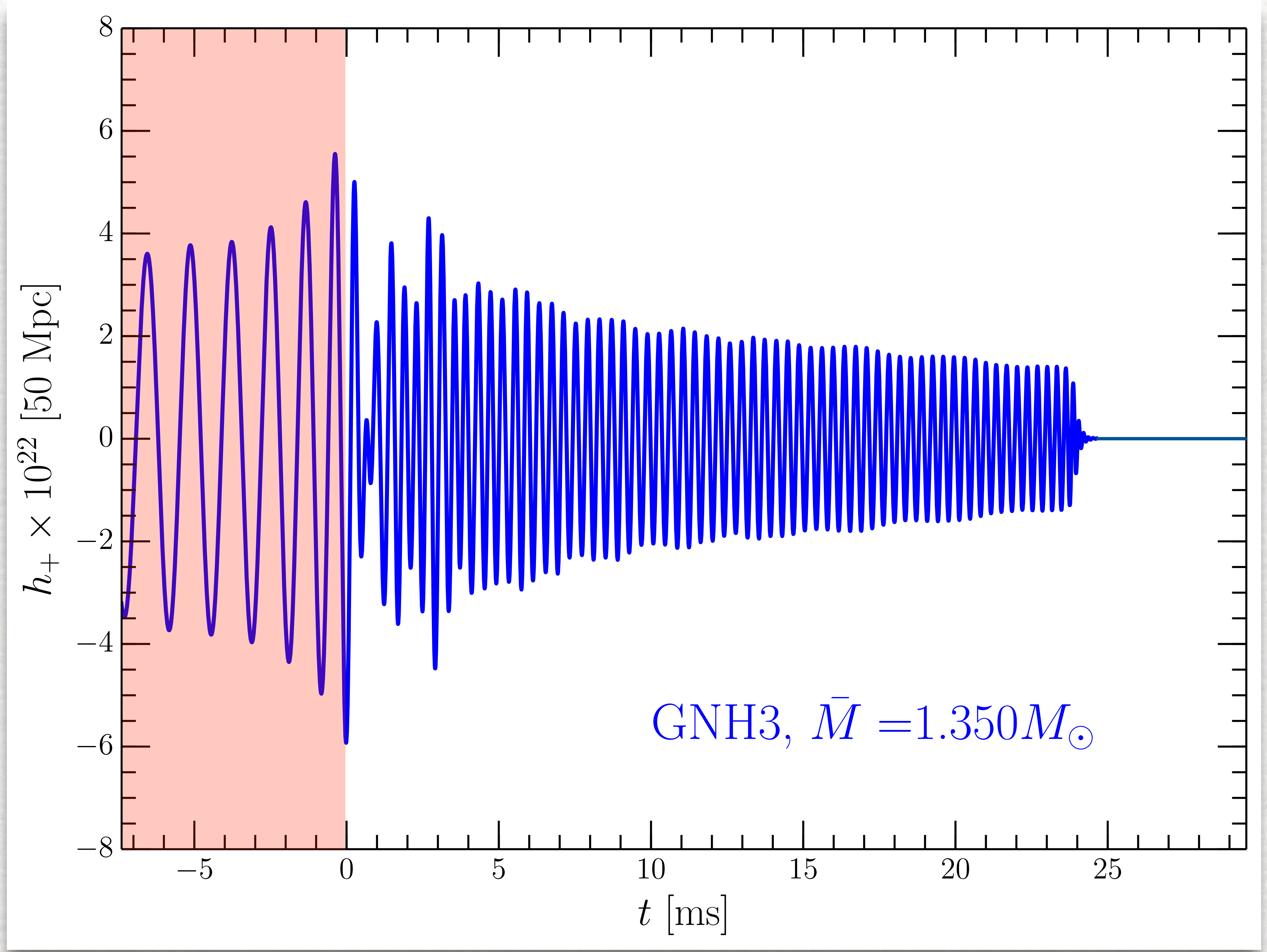
Anatomy of the GW signal for binary **Black Holes**



Anatomy of the GW signal for **binary NS Meger**

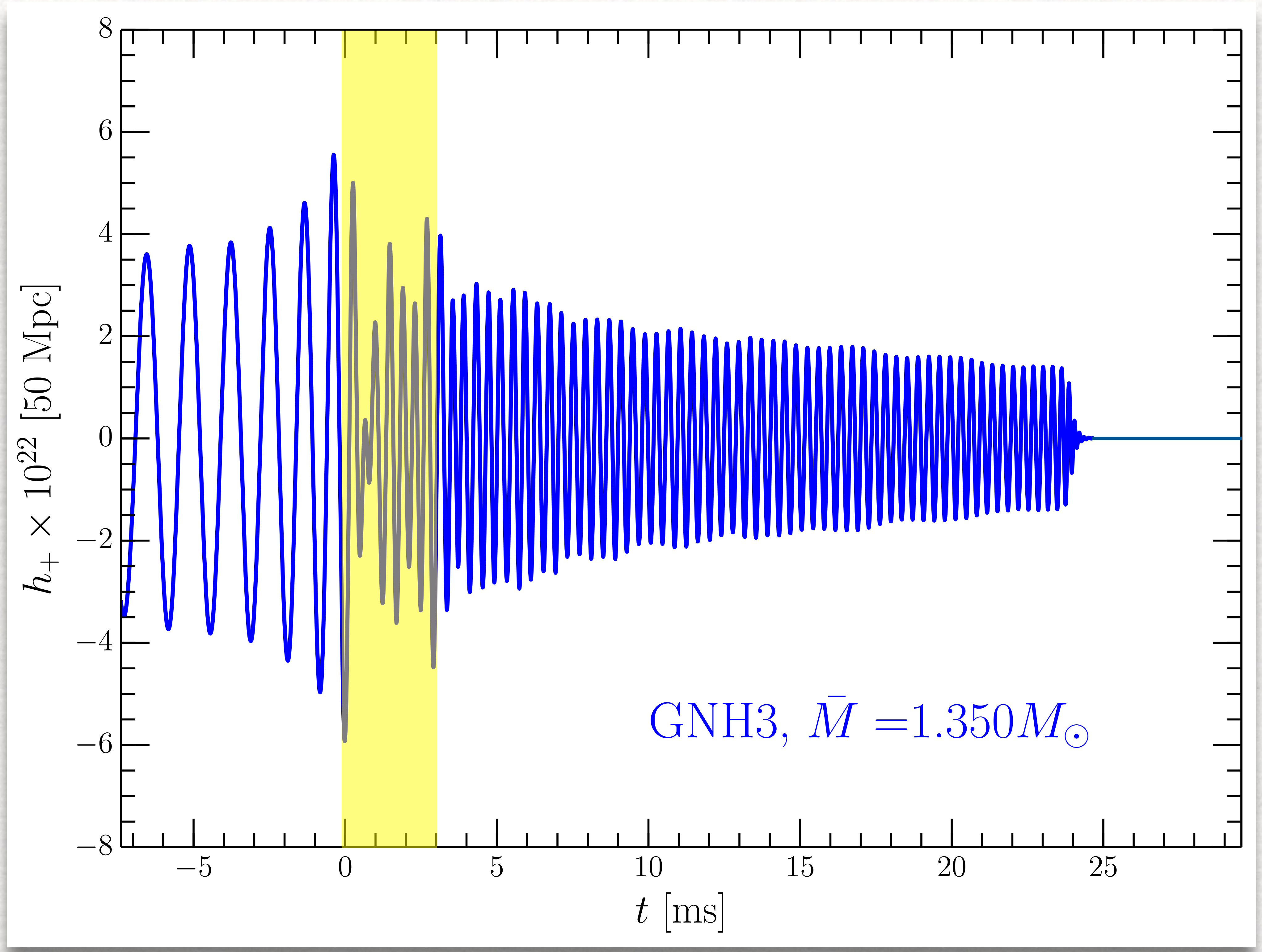


Anatomy of the GW signal **inspiraling** BNSM



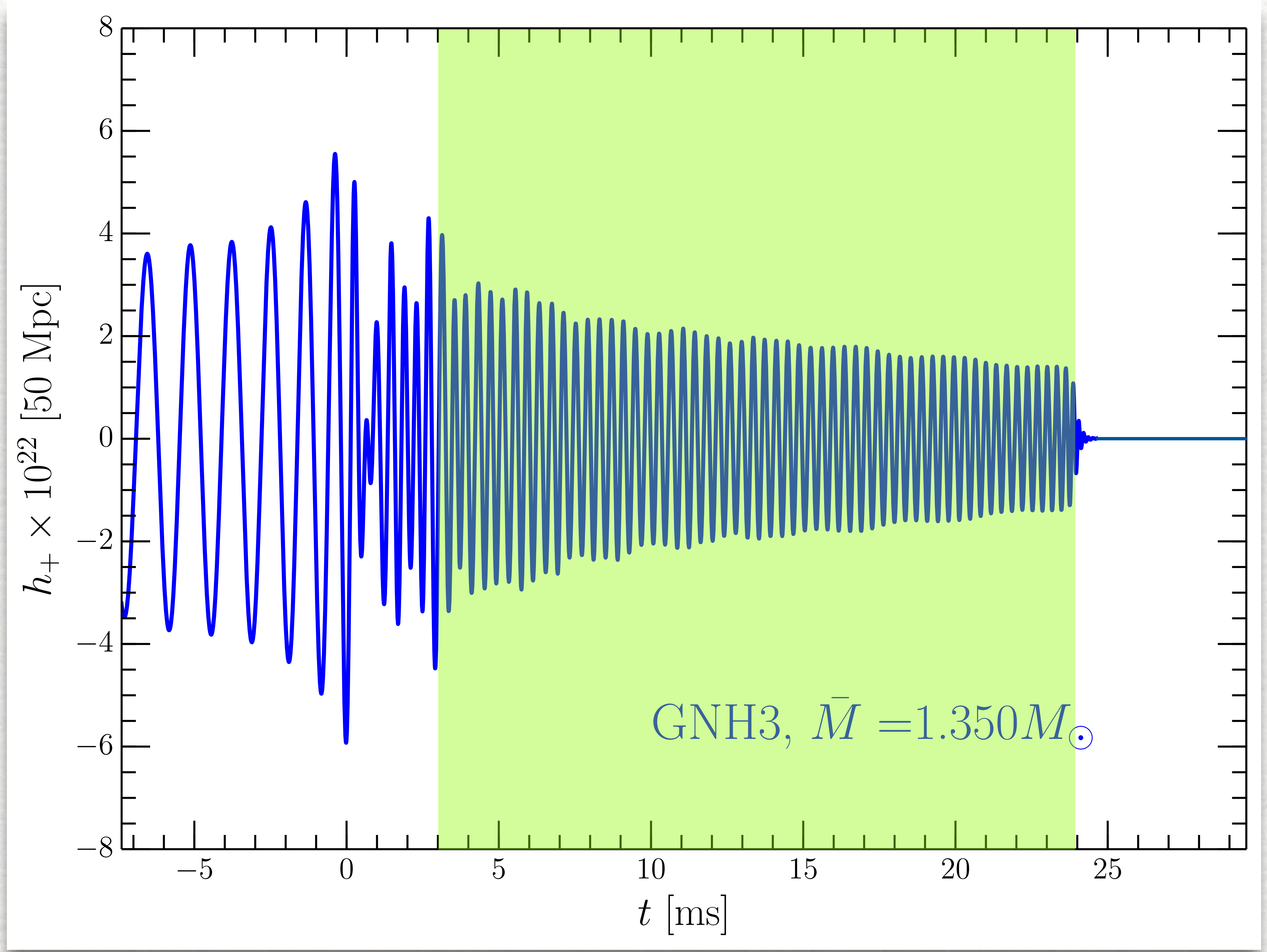
Inspiral: well approximated by PN/EOB; tidal effects important

Anatomy of the GW signal - **Merger**



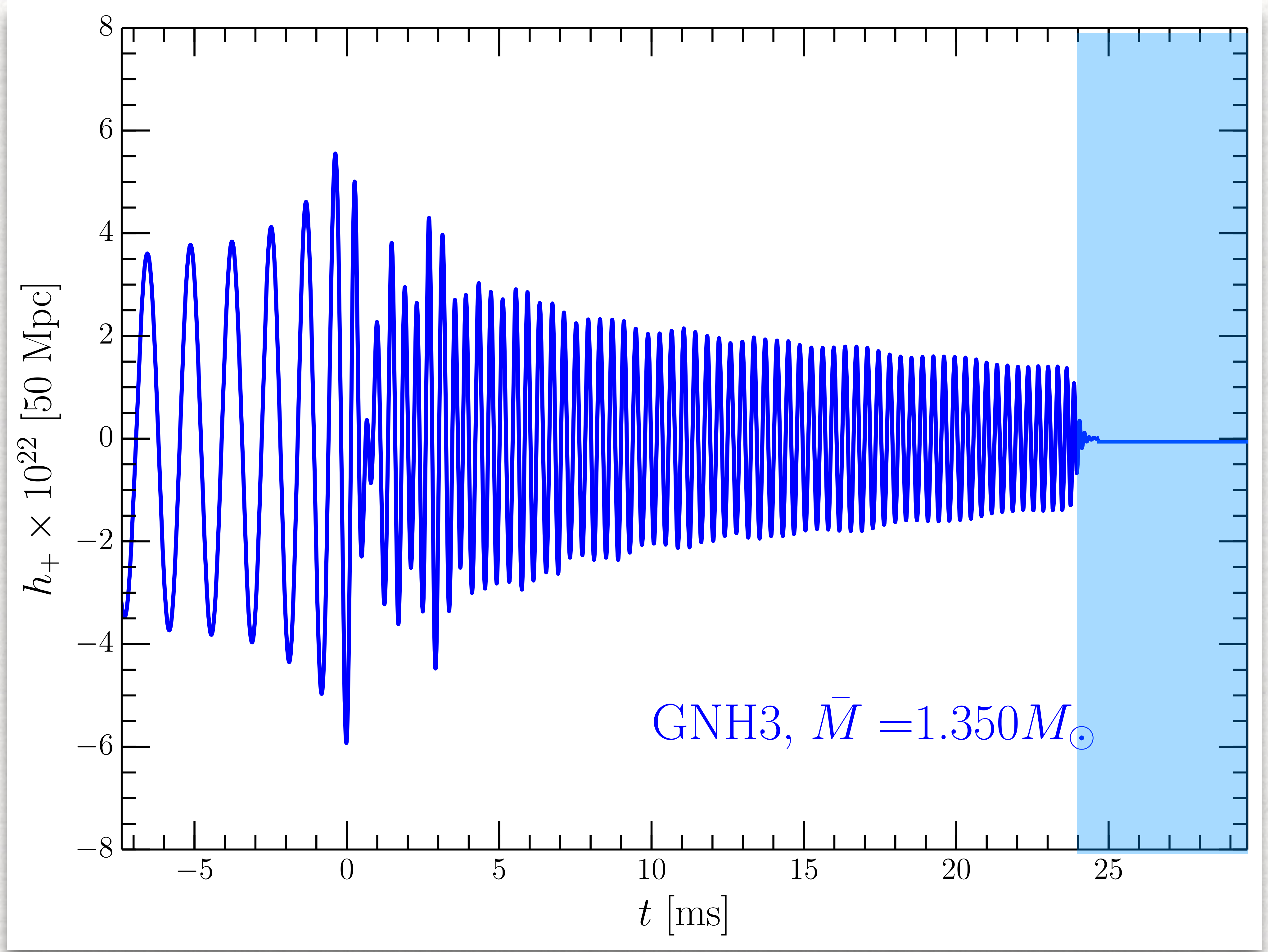
Merger: highly nonlinear but analytic description possible

Anatomy of the GW signal - **post merger**



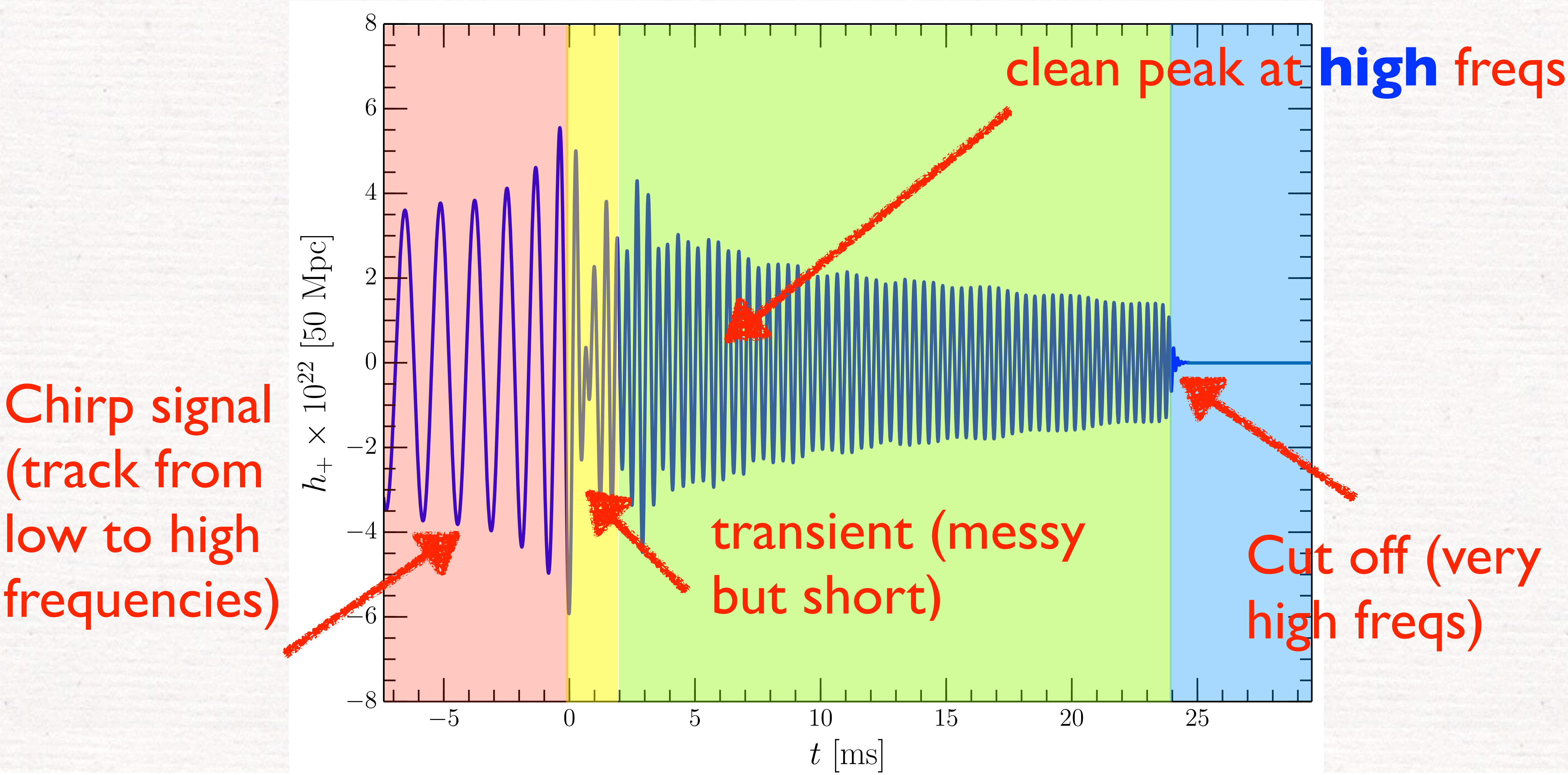
post-merger: quasi-periodic emission of bar-deformed HMNS

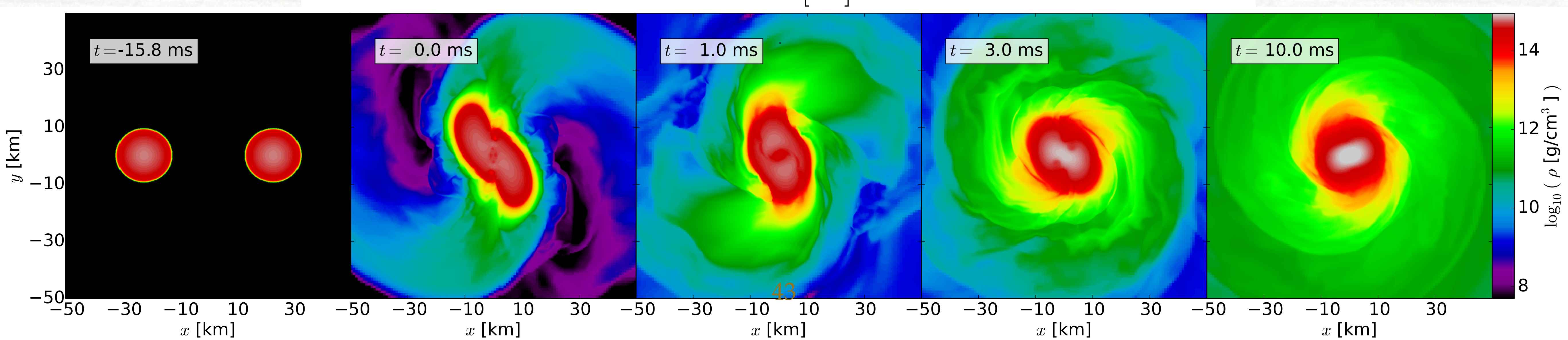
Anatomy of the GW signal > *collapse* > *ringdown* > ***BH***



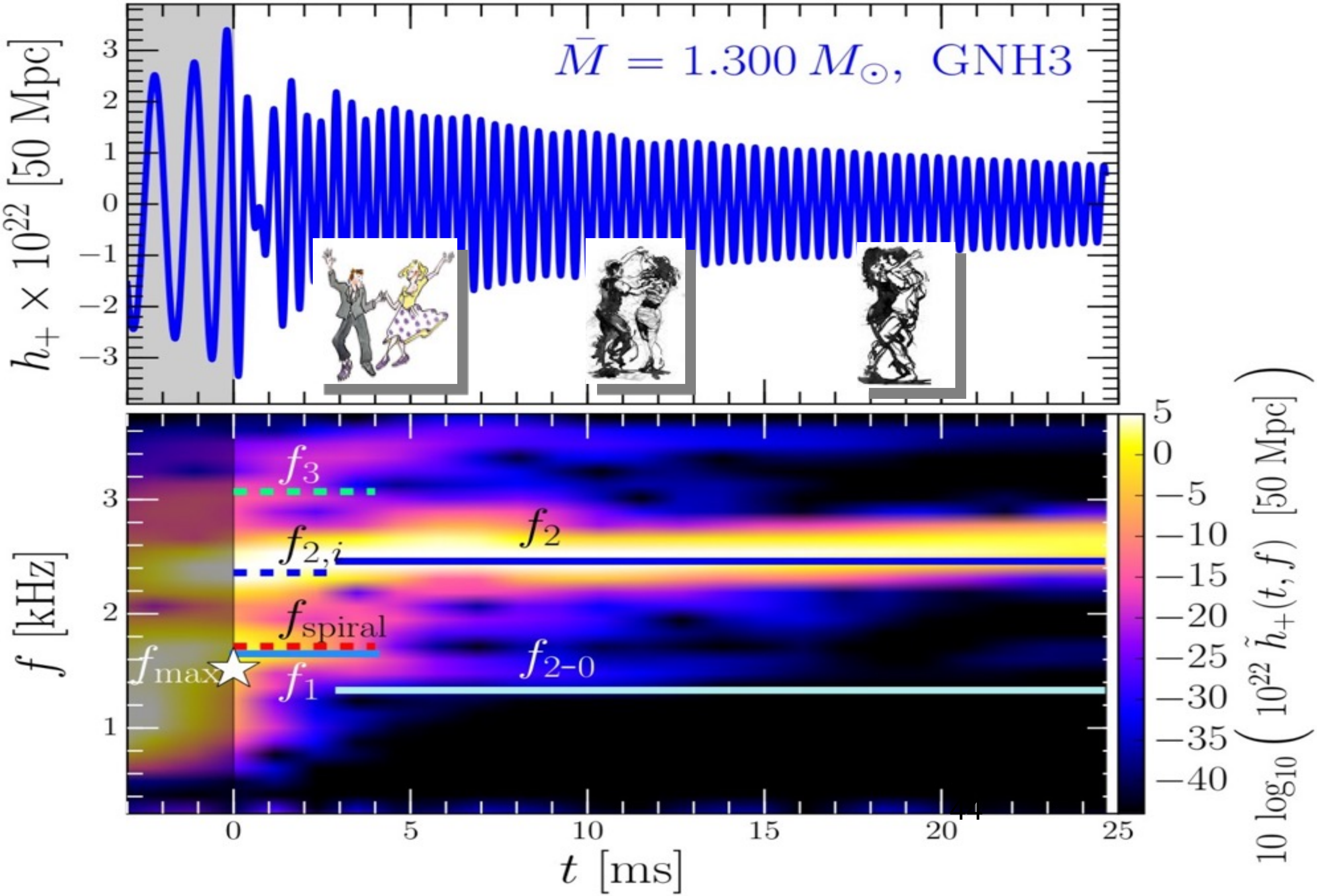
Collapse-ringdown: signal essentially shuts off.

Anatomy of the GW signal

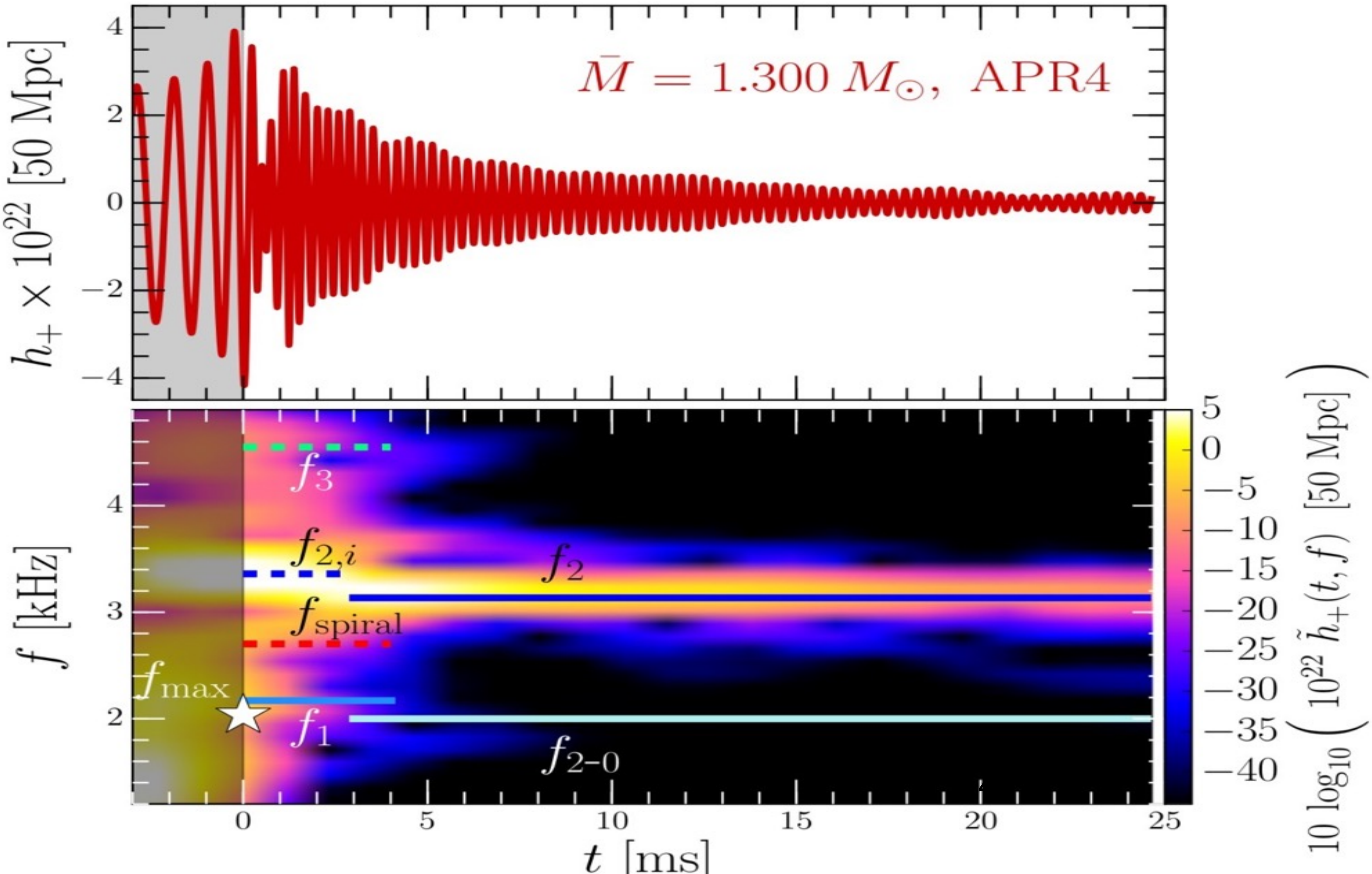




The Gravitational Wave Spectrum for a HARD nuclear EoS



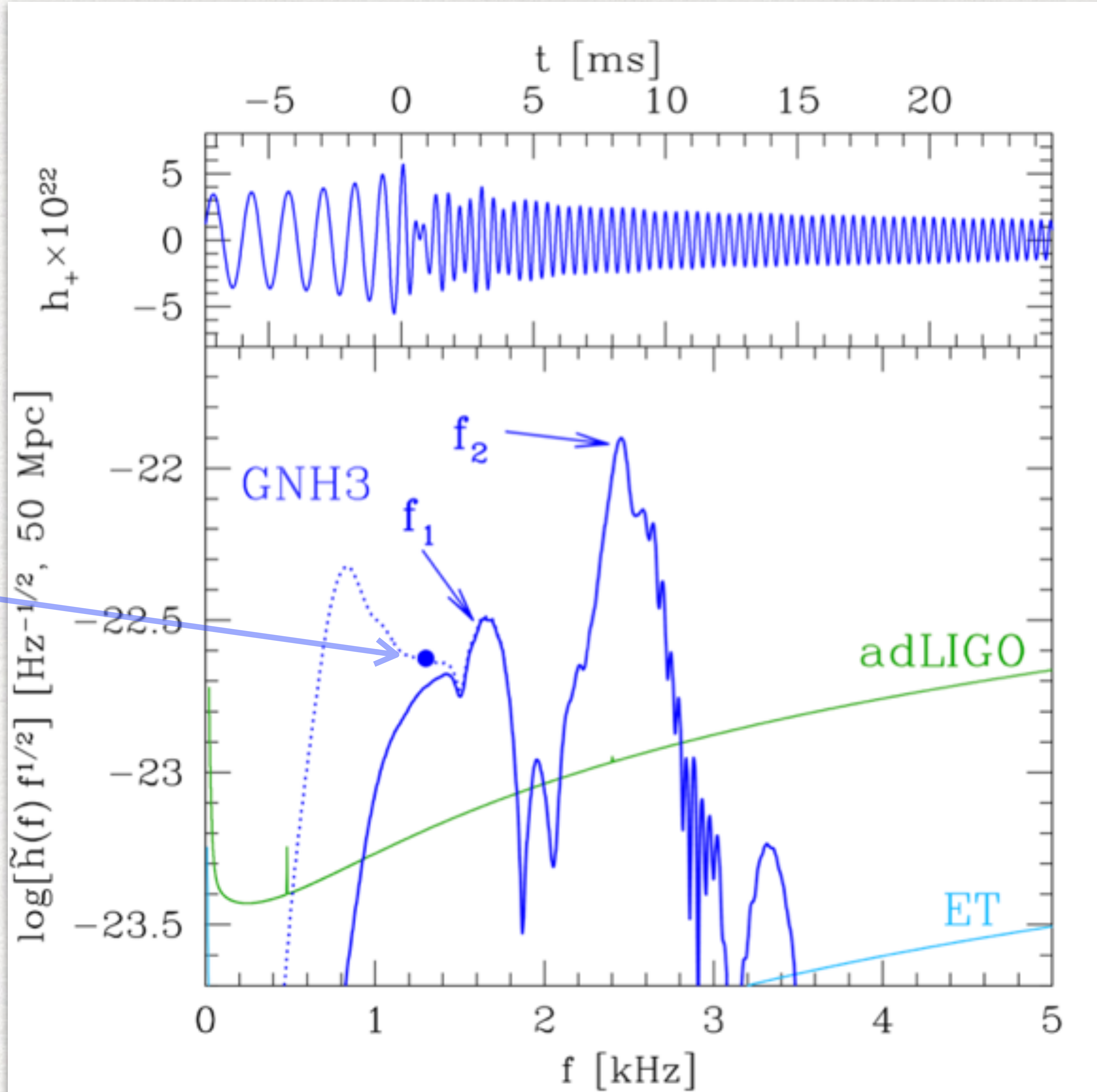
Gravitational Wave Frequency Spectrum: soft nuclear matter EoS



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



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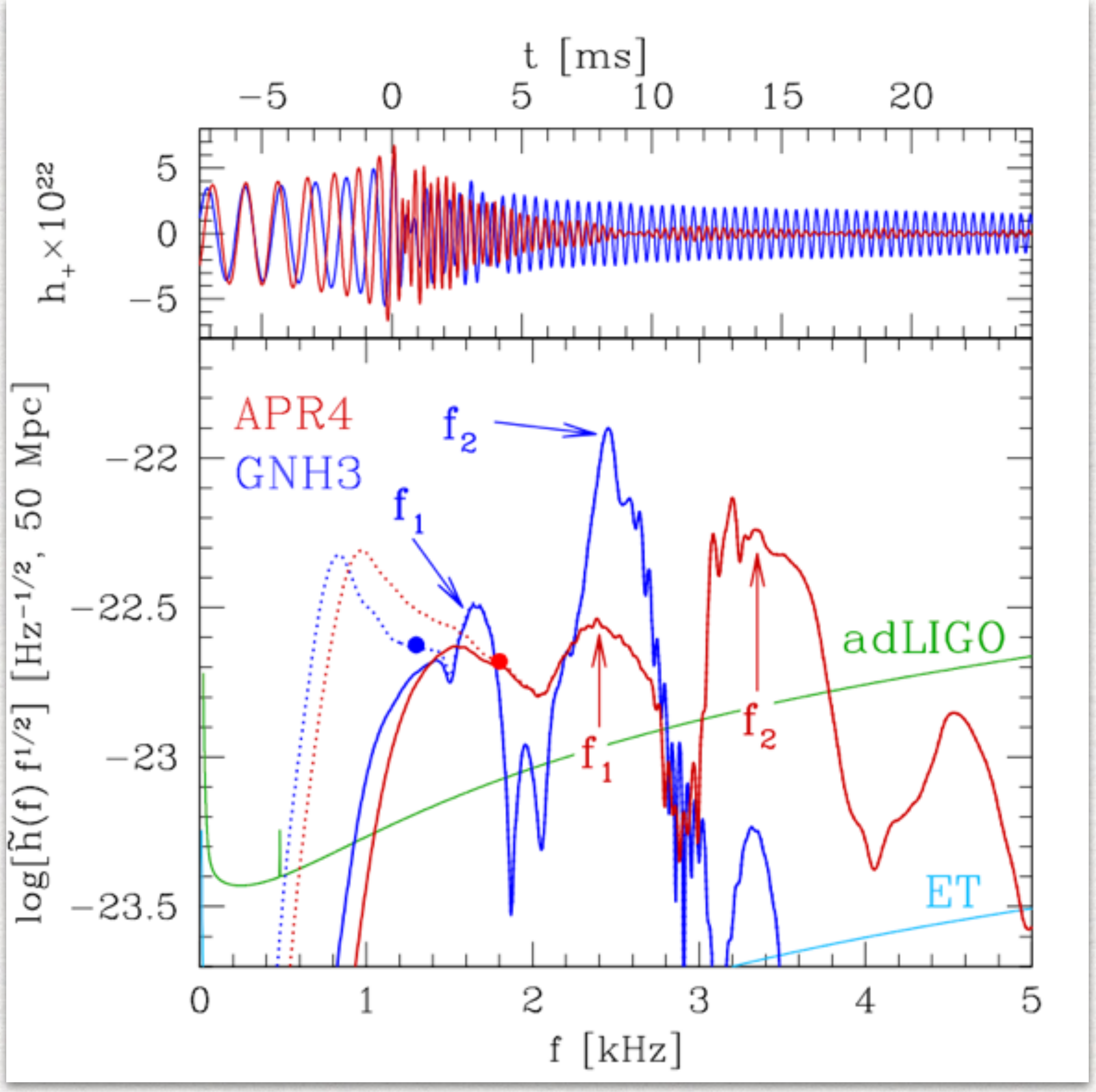
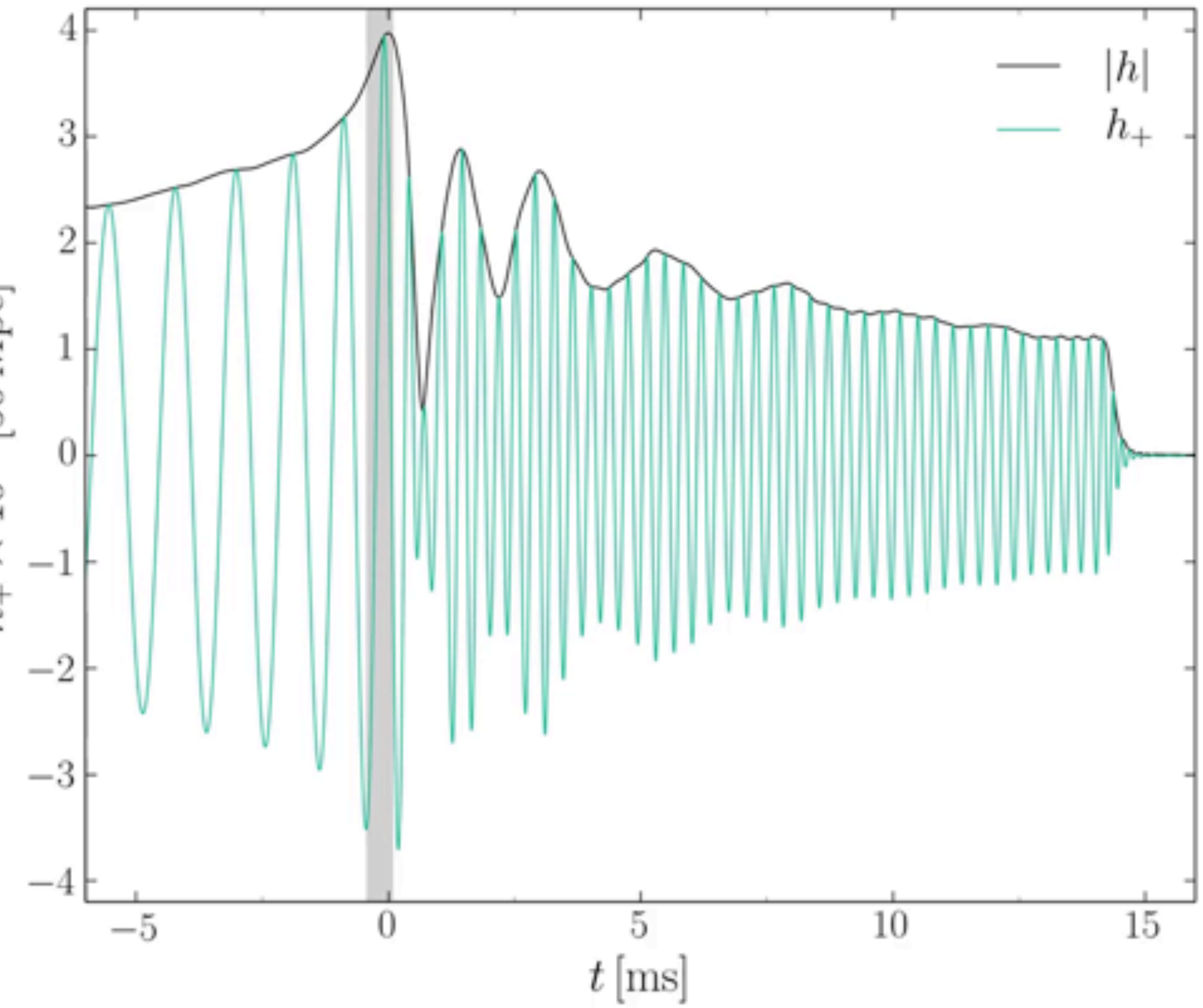
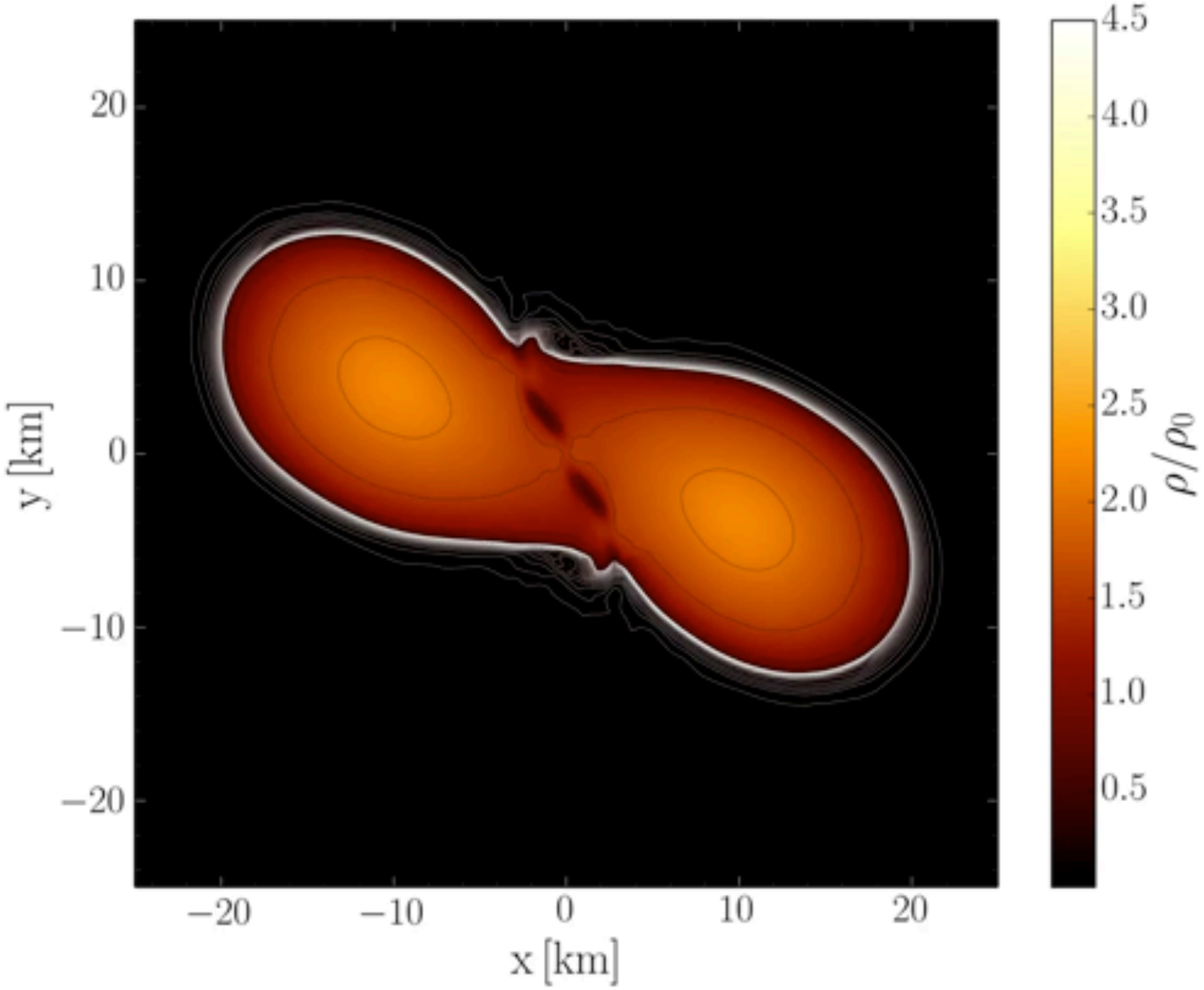


Hypermassive Neutronstar GR Hydro Simulation makes **Quarkmatter**

EoS Contains Neutrons, Protons, Electrons, Hyperons, Muons

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





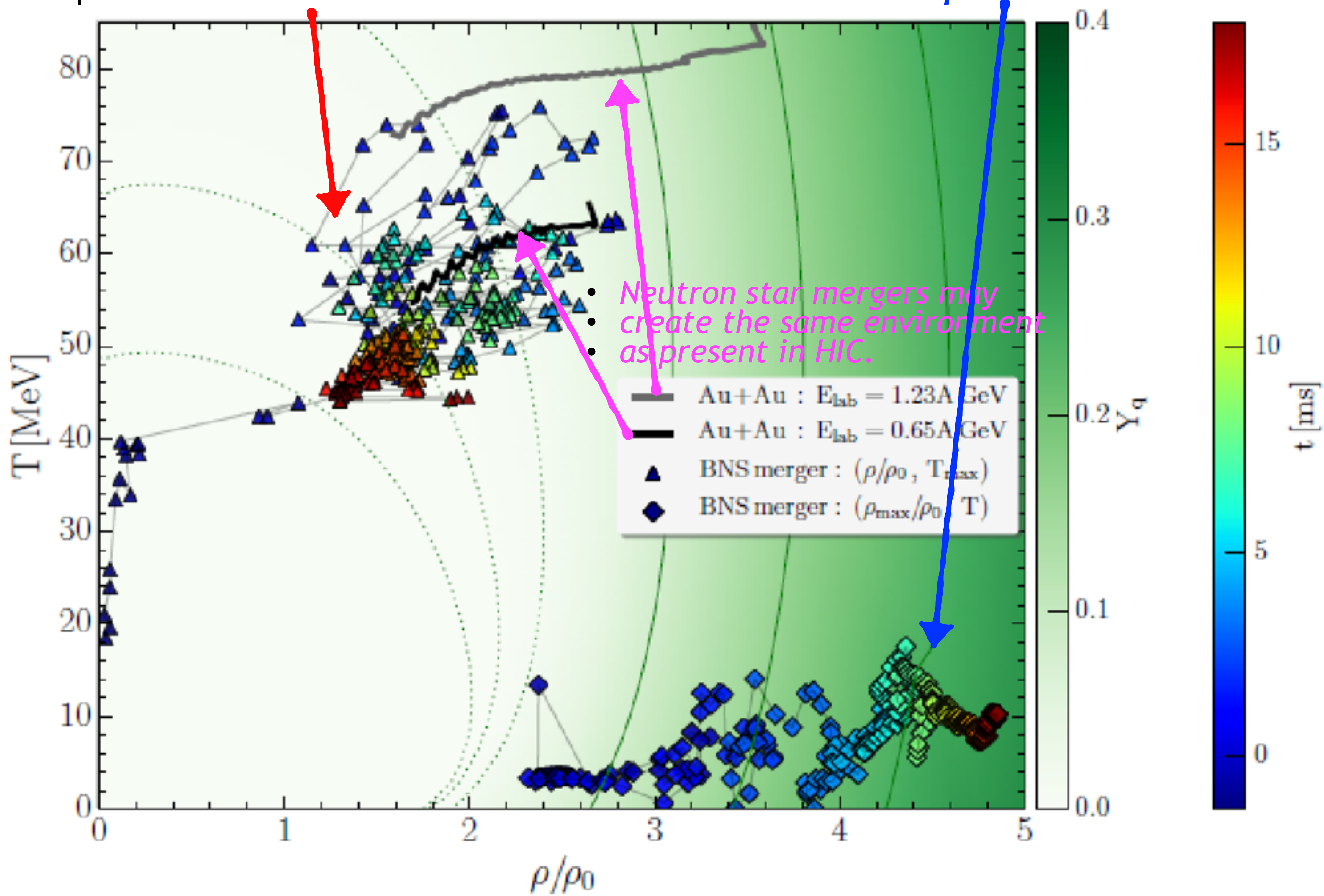
Amplitude der emittierten Gravitationswelle
im Abstand von 50 Mpc

Die Teilchendichte ρ(x,y)
in der äquatorialen Ebene in Einheiten der
normalen nuklearen Dichte ρ_0

M.Hanauske, L. Rezzolla, H.ST. et al. MAGIC Collaboration

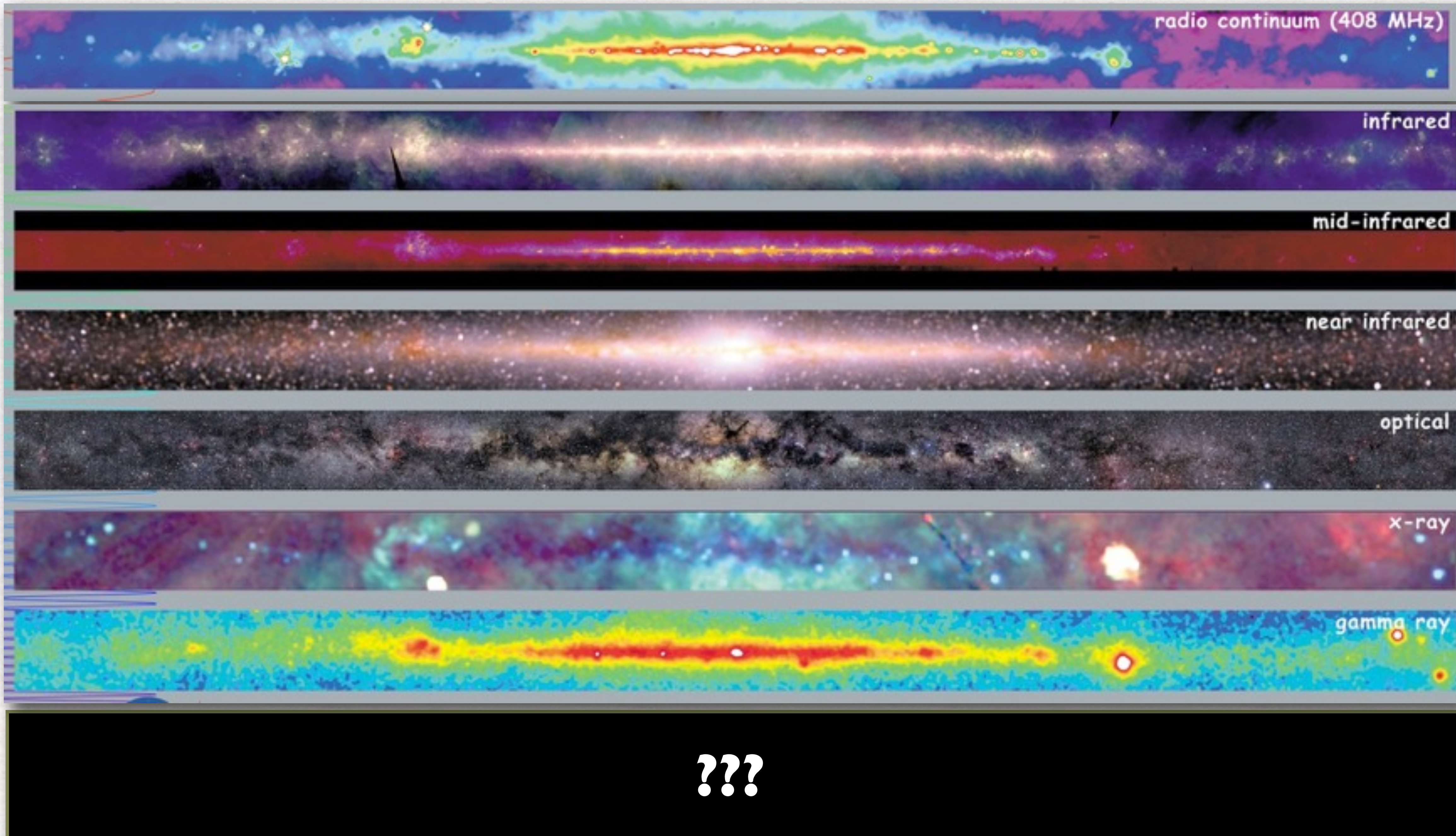
Application of CMF EoS to neutron star mergers

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



Conclusions

GSFC/NASA



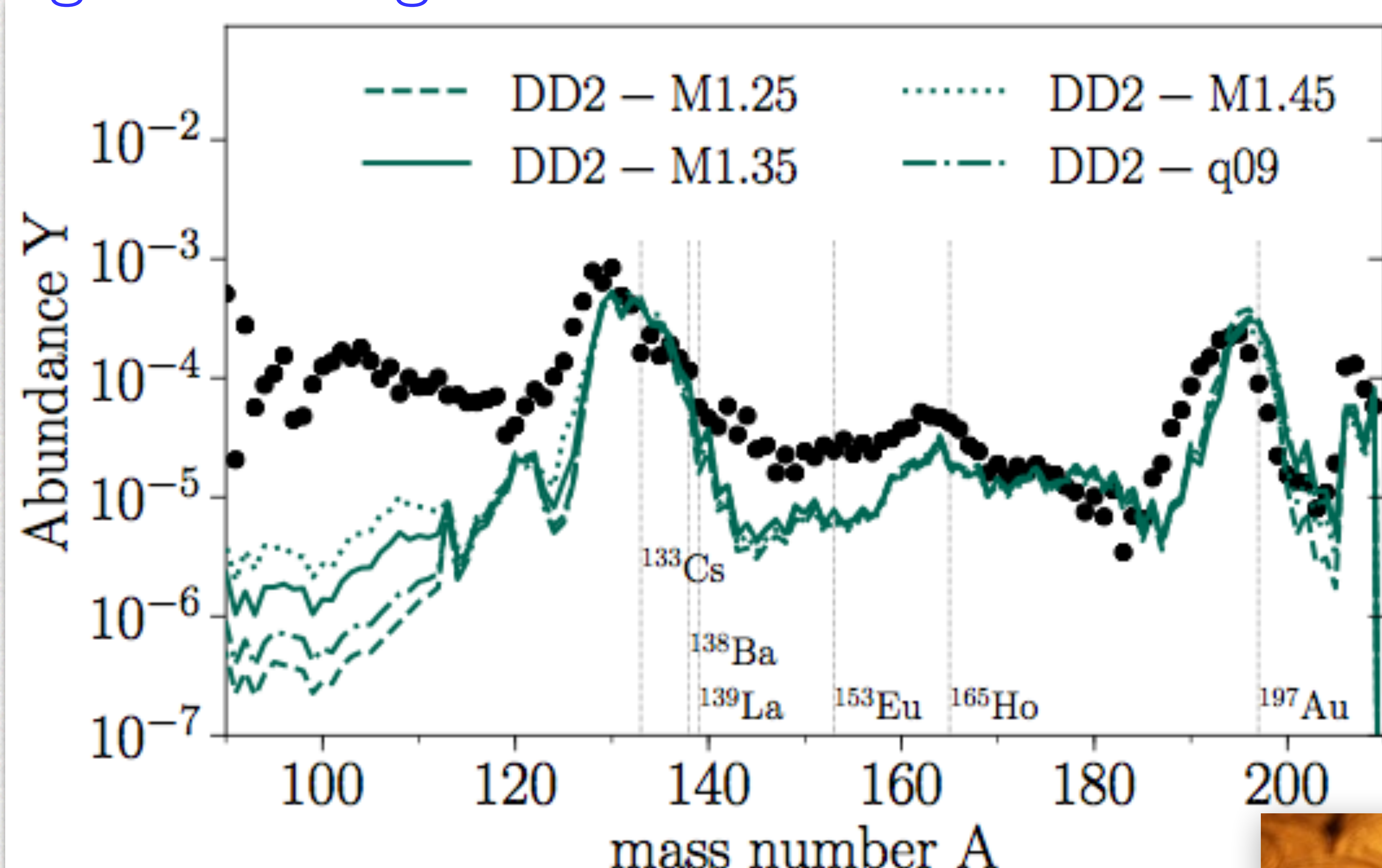
radio
far-IR
mid-IR
near-IR
optical
x-ray
gamma-ray
GWs

It has happened over and over in the history of astronomy: as a new "window" has been opened, a "new", universe has been revealed.

GWs will reveal Einstein's universe of black holes and neutron stars

Light-Flash signals Creation of new Elements

Bovard, et al. 2017



Relative Abundance of cosmic elements - Simulation vs. Observation

GW170817 produced lots of **Gold, Platin:** 10x **M_earth** !

Tell our politicians !

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

Charm and Beauty of International Collaboration