MaGiC - Matter and Gravitation in relativistic Collisions of Neutron Stars and Heavy Ions -probing the EoS of dense matter by Gravitational Waves

Matthias Hanauske, Luciano Rezzolla, Stefan Schramm, Jan Steinheimer, Horst Stöcker

FIAS Frankfurt Institute for Advanced Studies

Institut für Theoretische Physik Johann Wolfgang Goethe Universität Frankfurt

Förderverein für physikalische Grundlagenforschung Frankfurt

GSI Helmholtzzentrum für Schwerionenforschung Darmstadt

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 published his General Relativity, GR:
Gravity governs the motion of massive bodies mass/energy by curving spacetime.

1915 Karl Schwarzschild, born1873 in Frankfurt am Main, published the static solution of GR - just after Einsteins article - and died soon after.
Consequences of his vision: black and white holes, neutron stars !
Add Einstein's gravitational waves -You see a **whole new Universe**

Einstein equations first solved by Karl Schwarzschild

Einstein tensor — stress-energy tensor

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

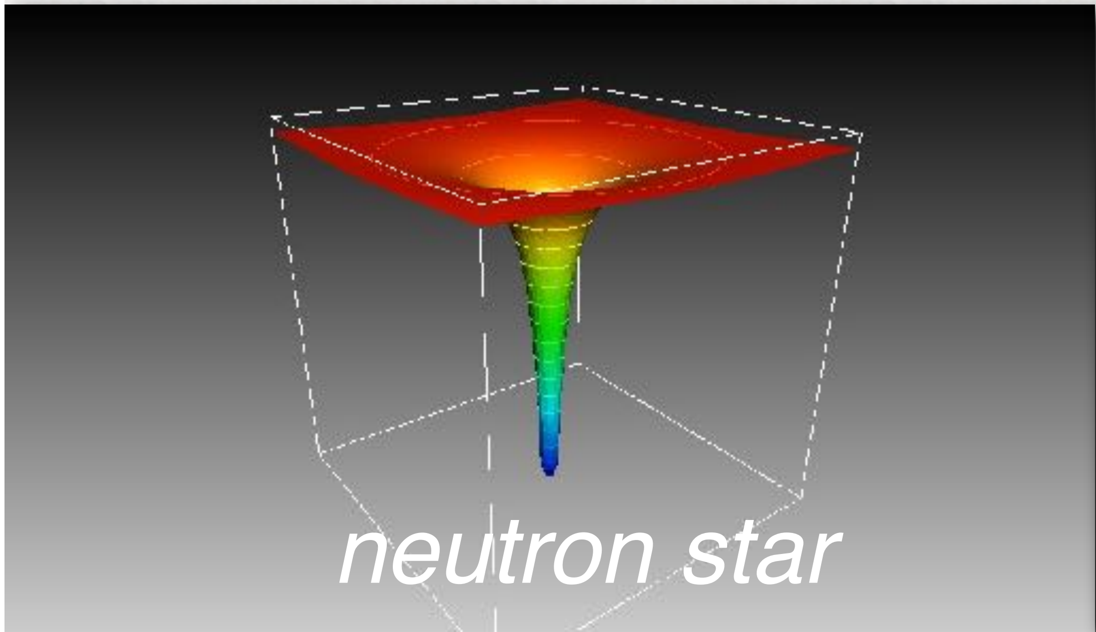
spacetime curvature ⟷ mass and energy in the spacetime

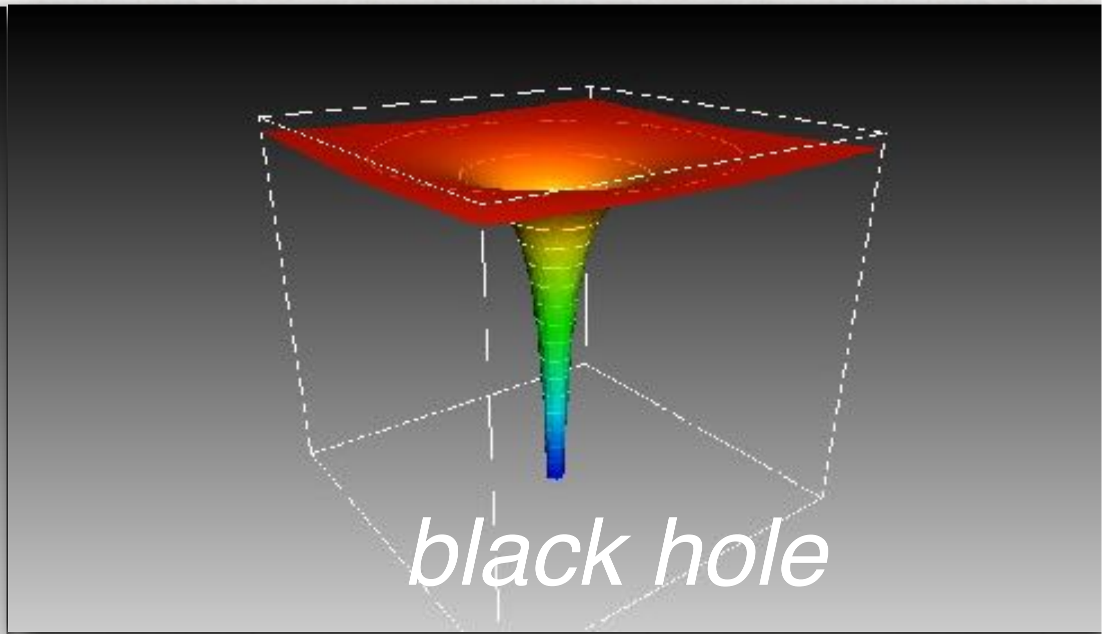
The importance of Einstein equations lies in setting a relation between the **curvature** and the **mass/energy**:

gravity becomes the manifestation of spacetime curvature

Neutron Star or Schwarzschild Black Hole ?

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

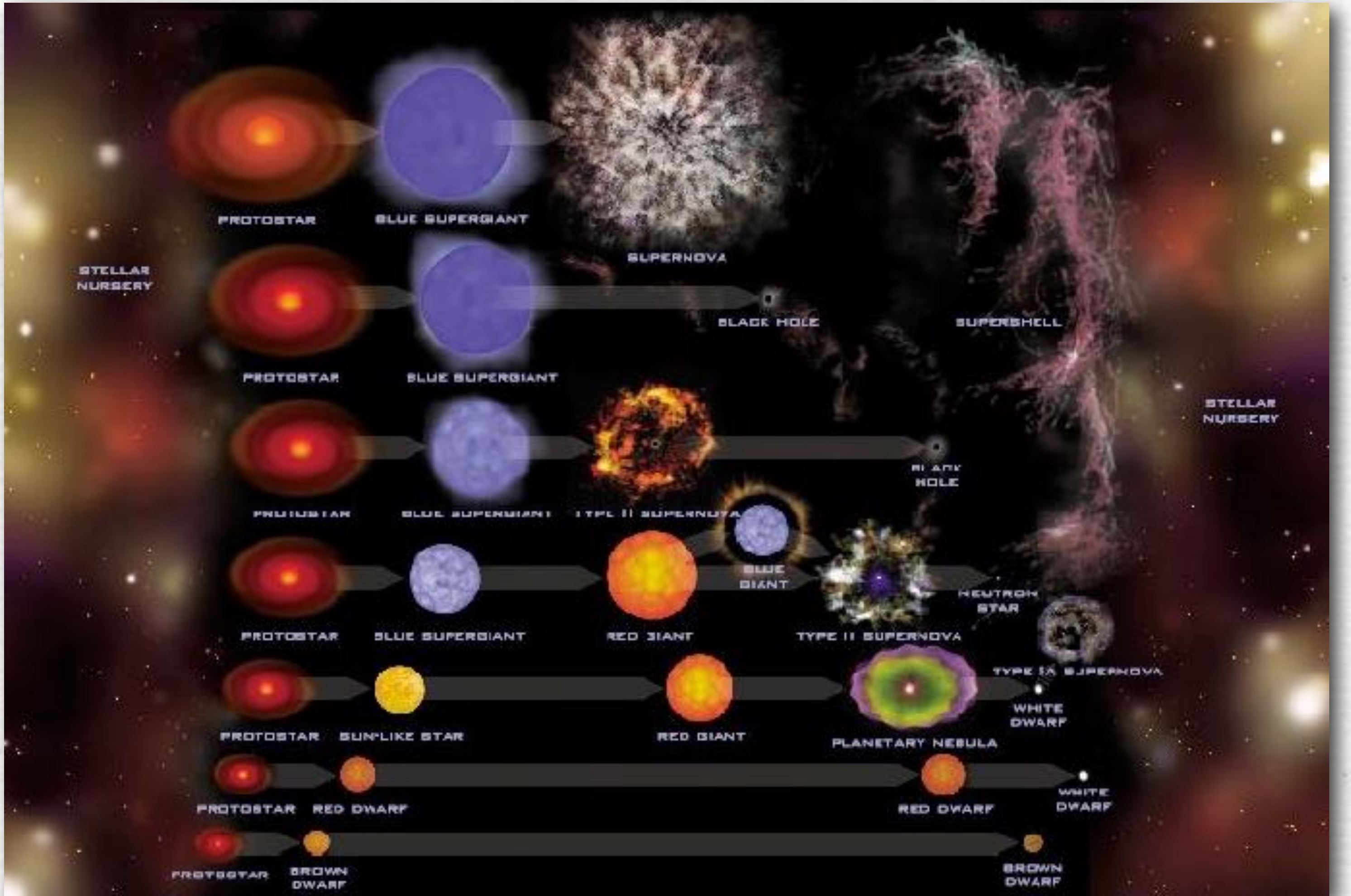


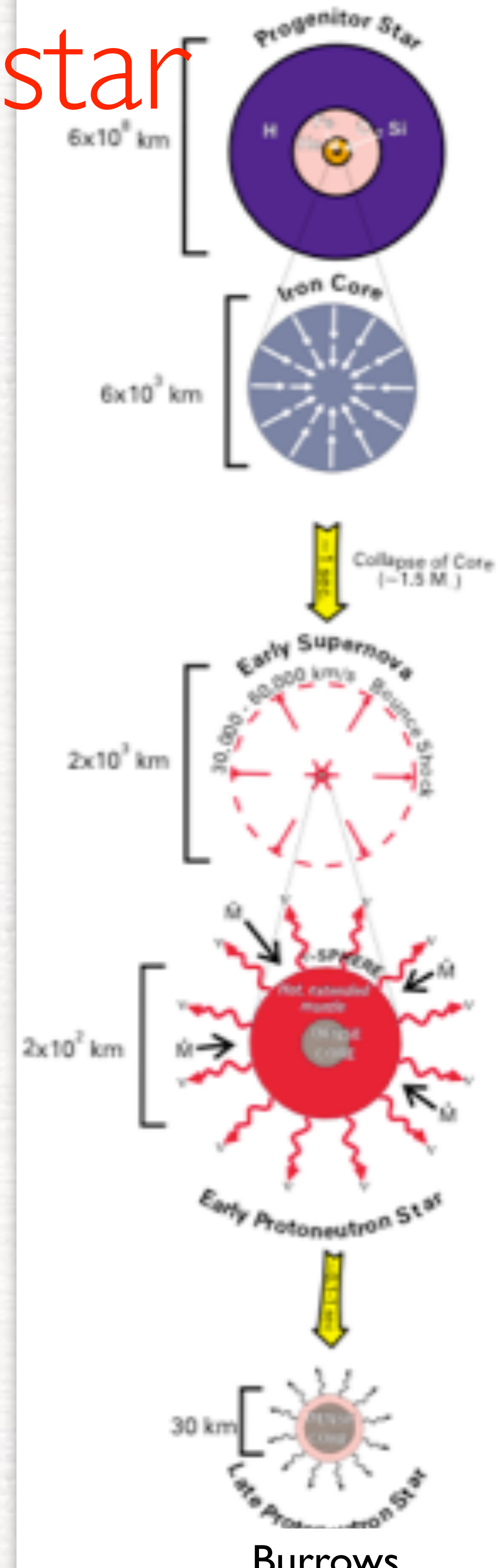


Two aspects differ: Neutron Stars have a ***hard surface***,
the curvature is large - but ***finite*** ;

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

Birth of neutron star - death of star



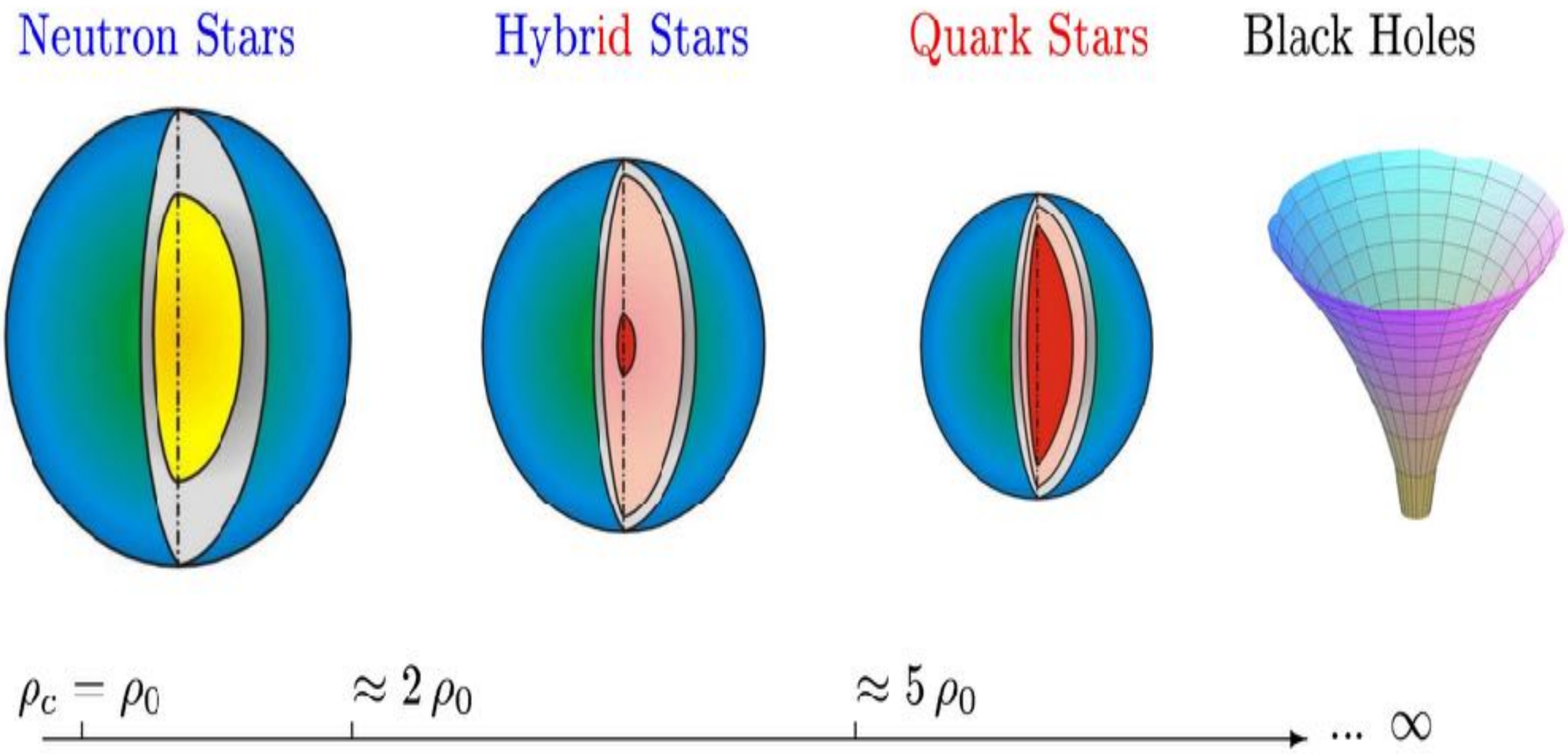


Neutron stars are most commonly born in the violent death of massive stars, i.e. stars with

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

ending their evolution as **supernovae collapse**

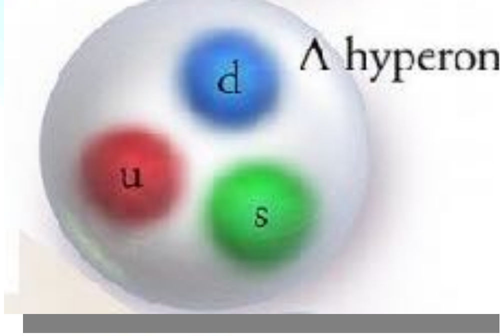
Neutronstars, Quarkstars, Black holes

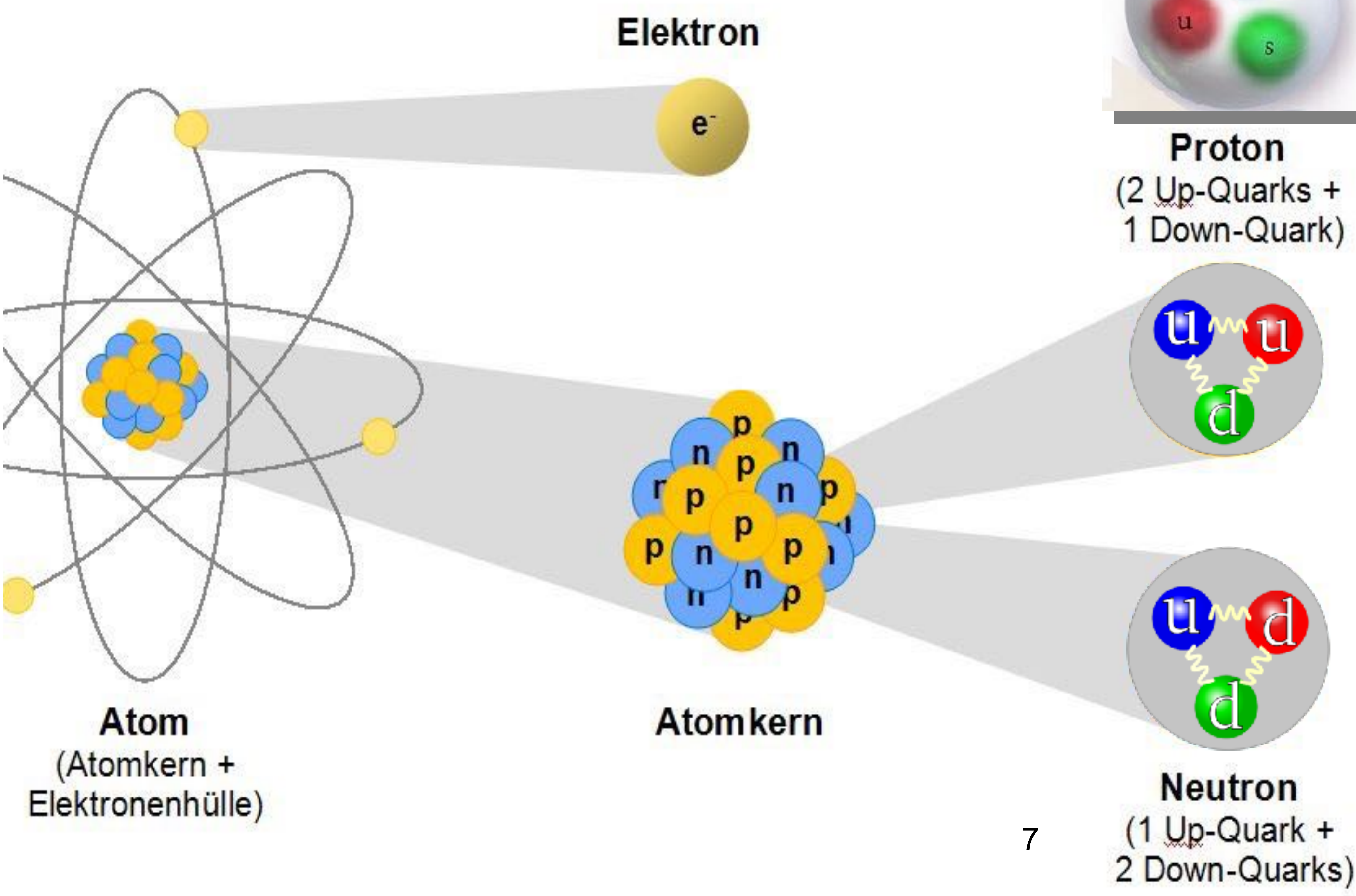


Central density ρ_c in the star

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

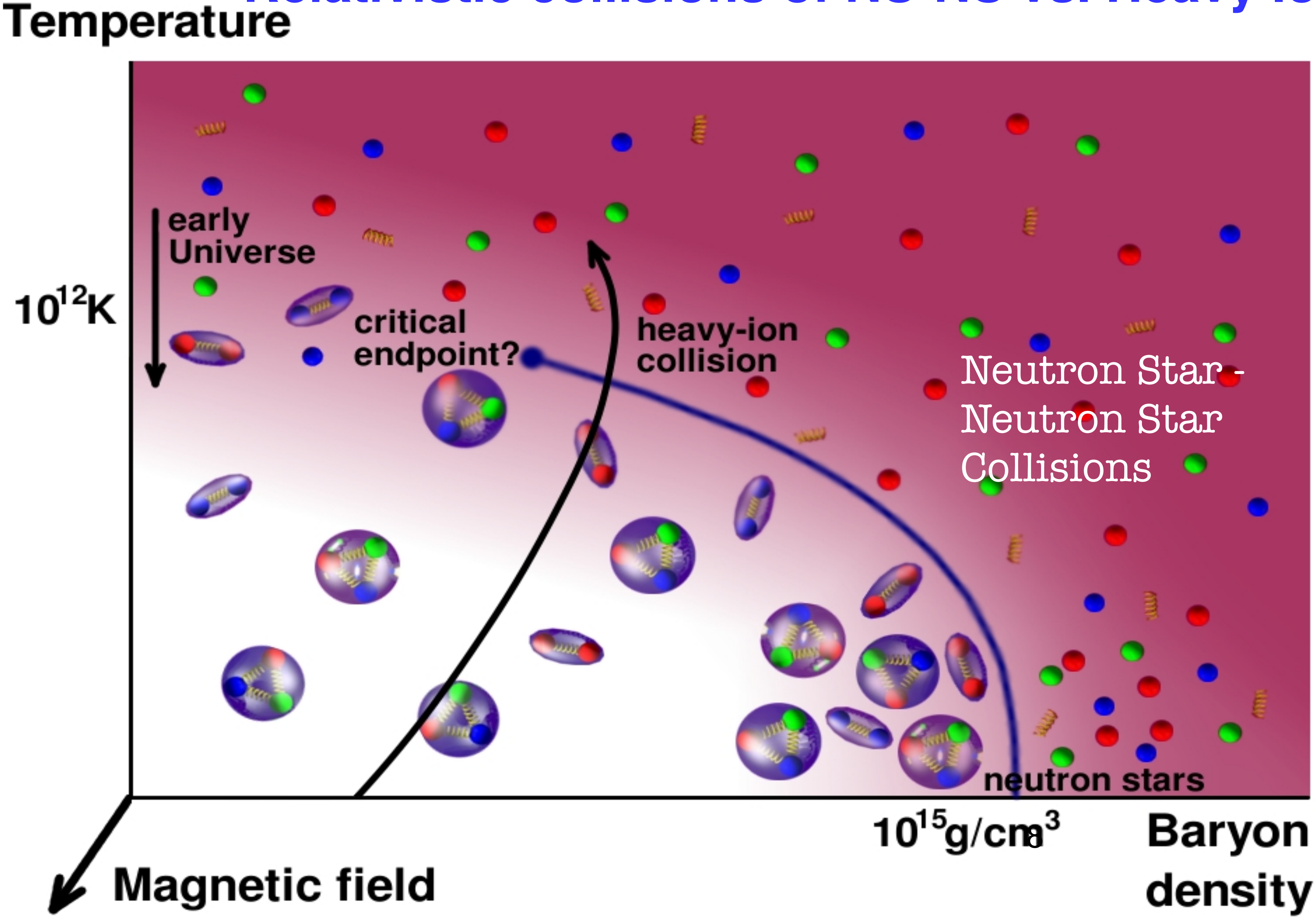
Nuclear Matter, Hypermatter, Quark Matter





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

Relativistic collisions of NS-NS vs. Heavy Ions



FAIR - the death star machine!

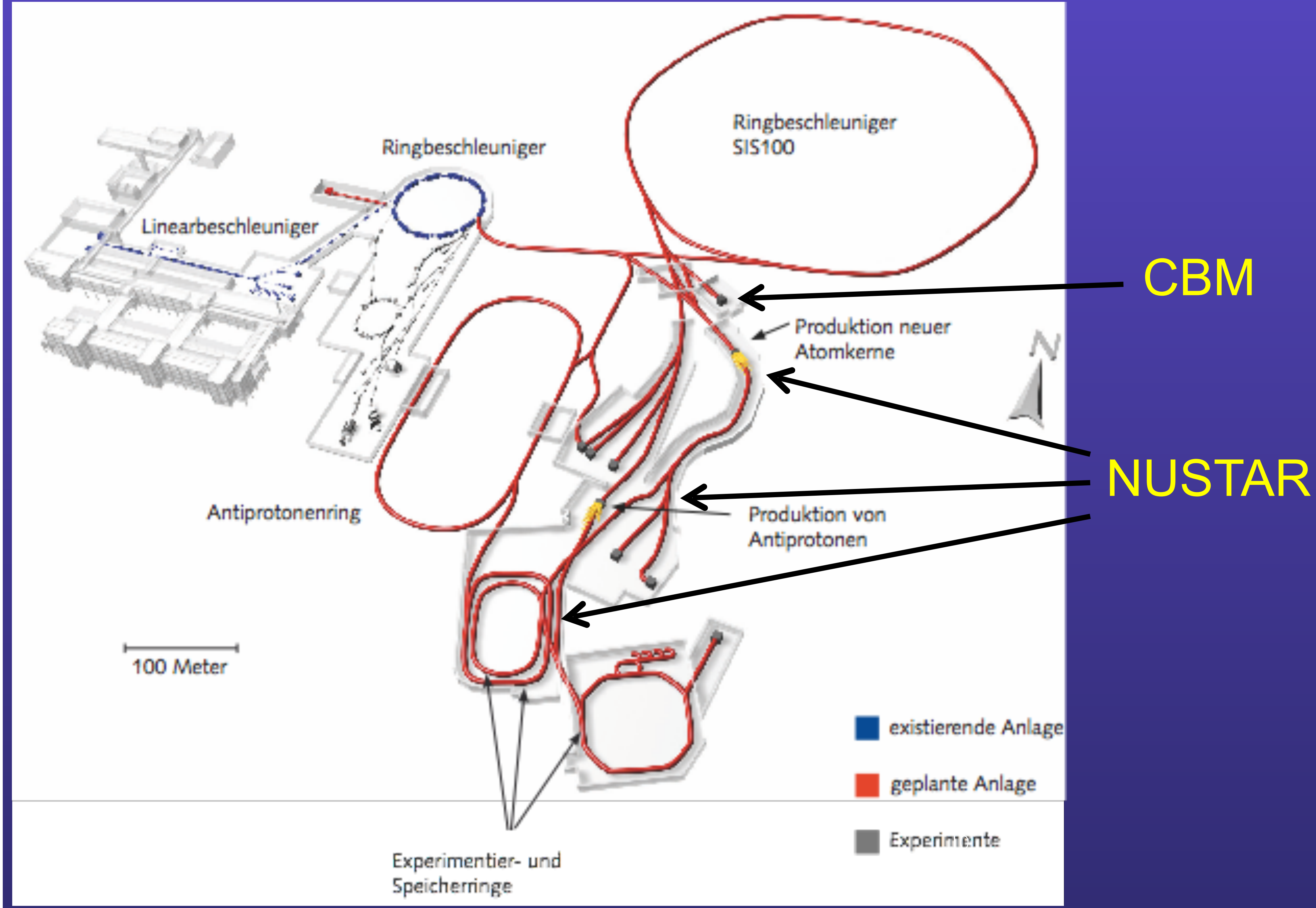
(The Times of India)

**FAIR is ideally equipped for precision studies,
FAIR is ideal to compare relativistic collisions of
neutron stars and heavy ions**

↓

Understanding the high density QCD equation of state

Neutron Star matter in CBM@FAiR/GSI Helmholtzcenter



Neutronstar merger vs. heavy ion collisions
Differences in chemical composition

Quark-Hadron Chiral Parity Doublet Model (QχP):

Only model which is able to consistently describe a chiral crossover and a transition from hadrons to quarks and gluons

A. Mukherjee, J. Steinheimer and S. Schramm, arXiv:1611.10144 [nucl-th].

Calculate:

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

Neutronstar merger vs. heavy ion collisions
Differences in dynamical description.

- ❑ System Size: Kilometers vs. Femtometers
- ❑ Evolution time: Milliseconds vs. fm/c

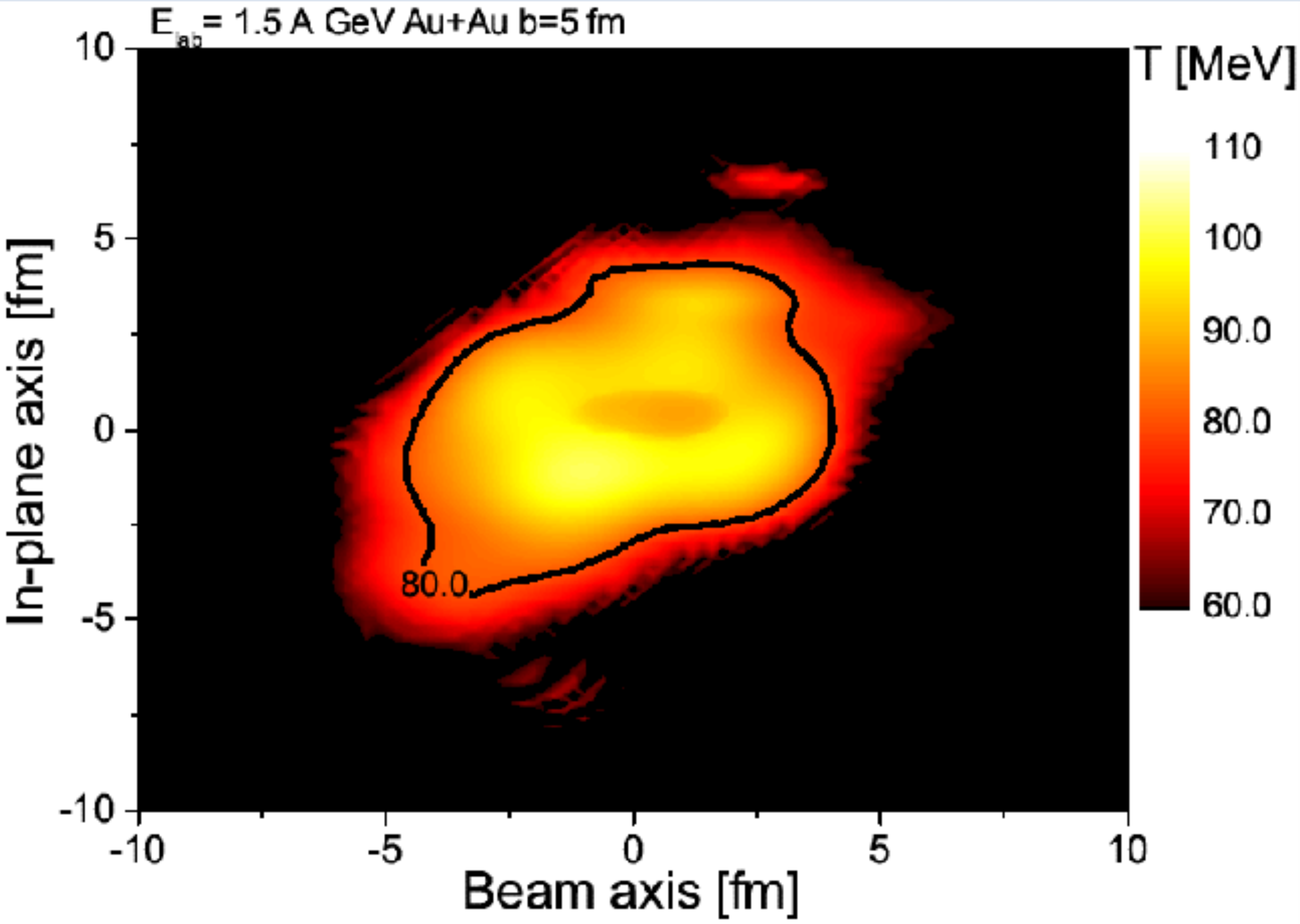
- ❑ Equilibrium: Chemical + Phase-Equilibrium vs. Non-Equilibrium
- ❑ Gravity is relevant - or not ?

- ❑ Yet : hydrodynamics seems to work for both!

➢ **Importance of the equation of state as input for hydrodynamics**

Neutronstar merger vs. heavy ion collisions
What temperatures can we expect?

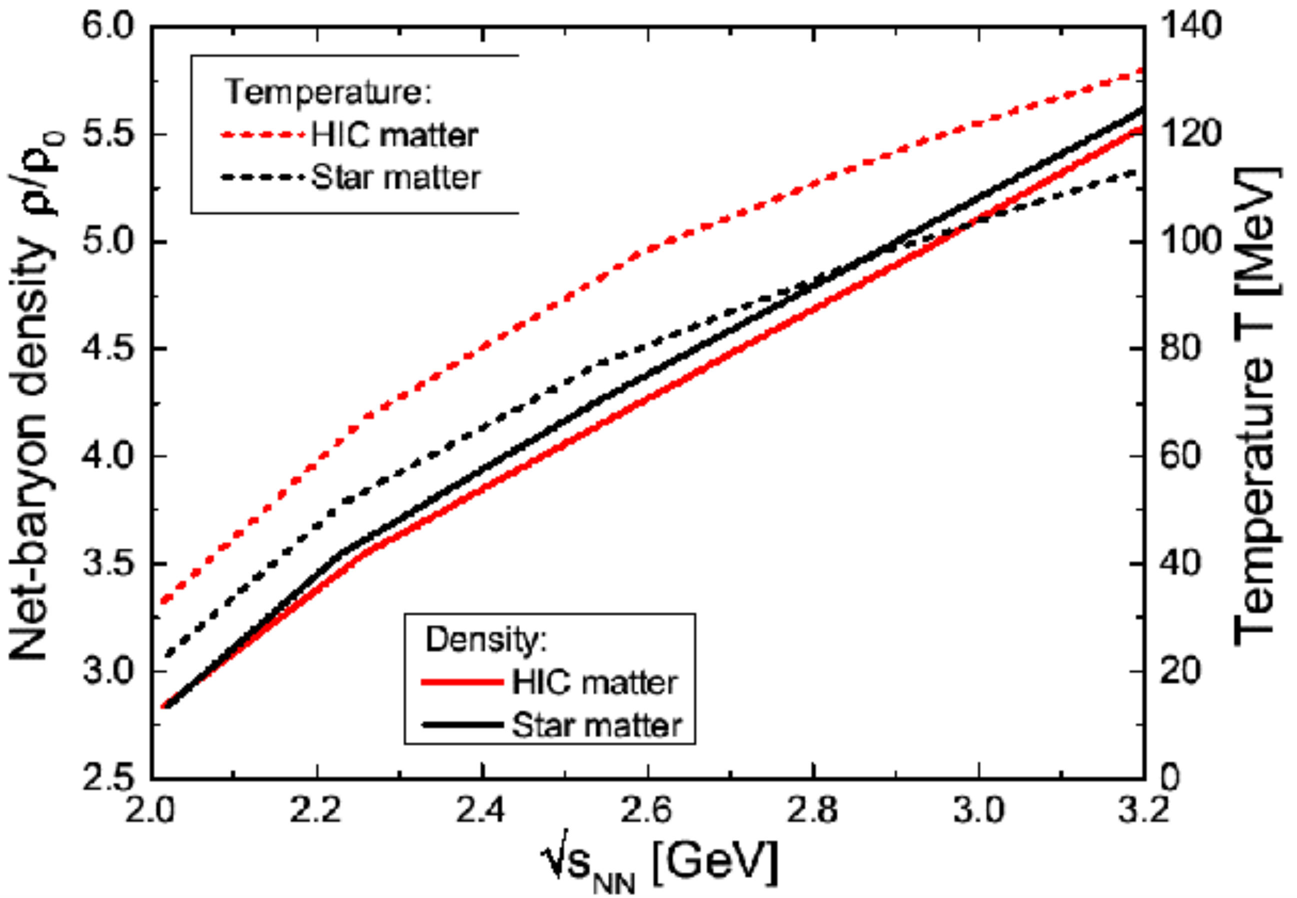
Coarse grained UrQMD simulation input for hydrodynamical evolution



- ❑ Beam energy corresponds to GSI-SIS18.
- ❑ Temperatures up to T=100 MeV reached.
- ❑ Large inhomogeneity.
- ❑ Short lifetime ~ 20 fm/c
- ❑ Small system size ~ 10 fm

Neutronstar merger vs. heavy ion collisions:
Which densities and Temperatures can we expect?

Estimate using the relativistic Rankine Hugoniot Taub Adiabate and the $Q\chi P$ EoS



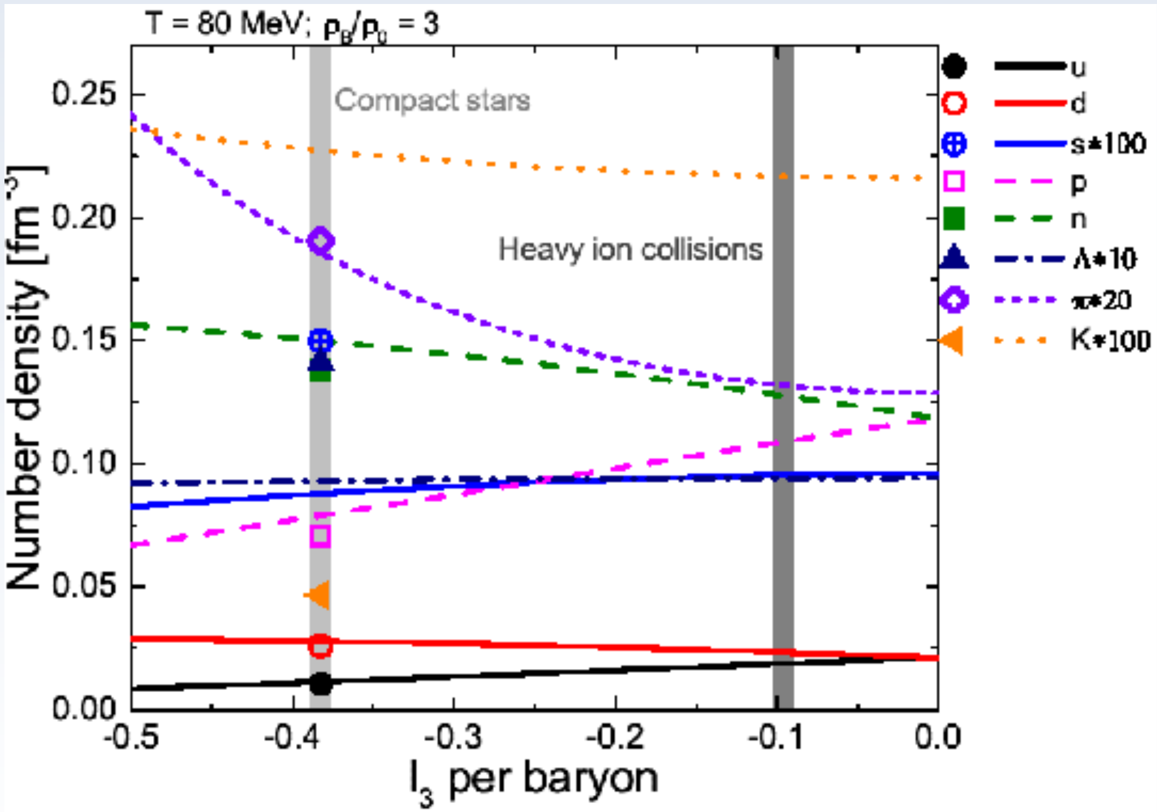
Compare central heavy ion collisions with head-on neutron star collisions

Rankine Hugoniot Taub Adiabate: conserved baryon number and energy momentum current densities across shock front yields 1-Dim, stationary hydrodynamical equation

E^2 -E_0^2 =(p-p_0)(E/n - E_0/n_0)

Neutronstar merger vs. heavy ion collisions
Differences in chemical composition

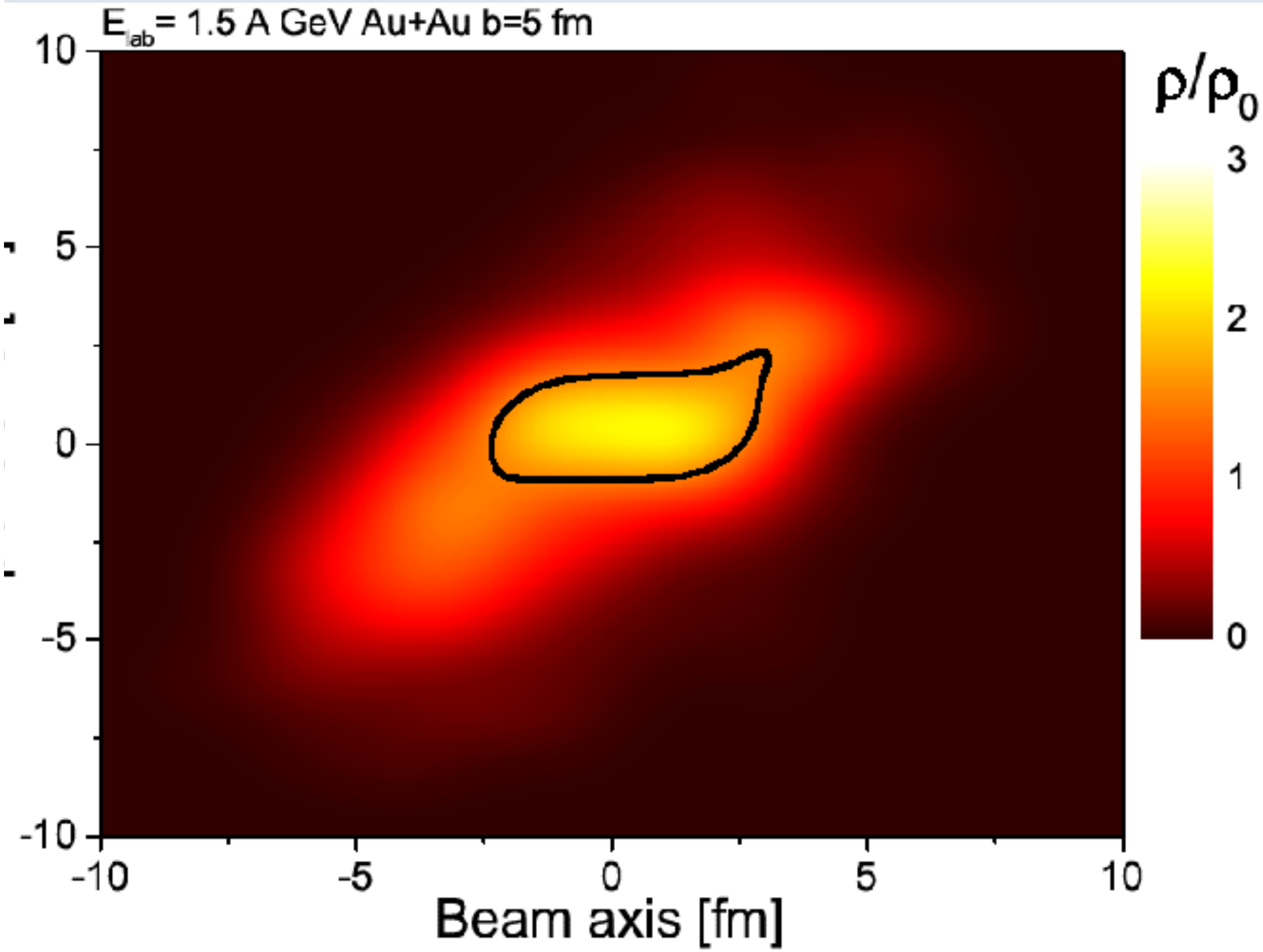
- The EOS for heavy ion collisions: conserved strangeness and no beta-equilibrium
- The EOS for compact stars: in beta-equilibrium



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

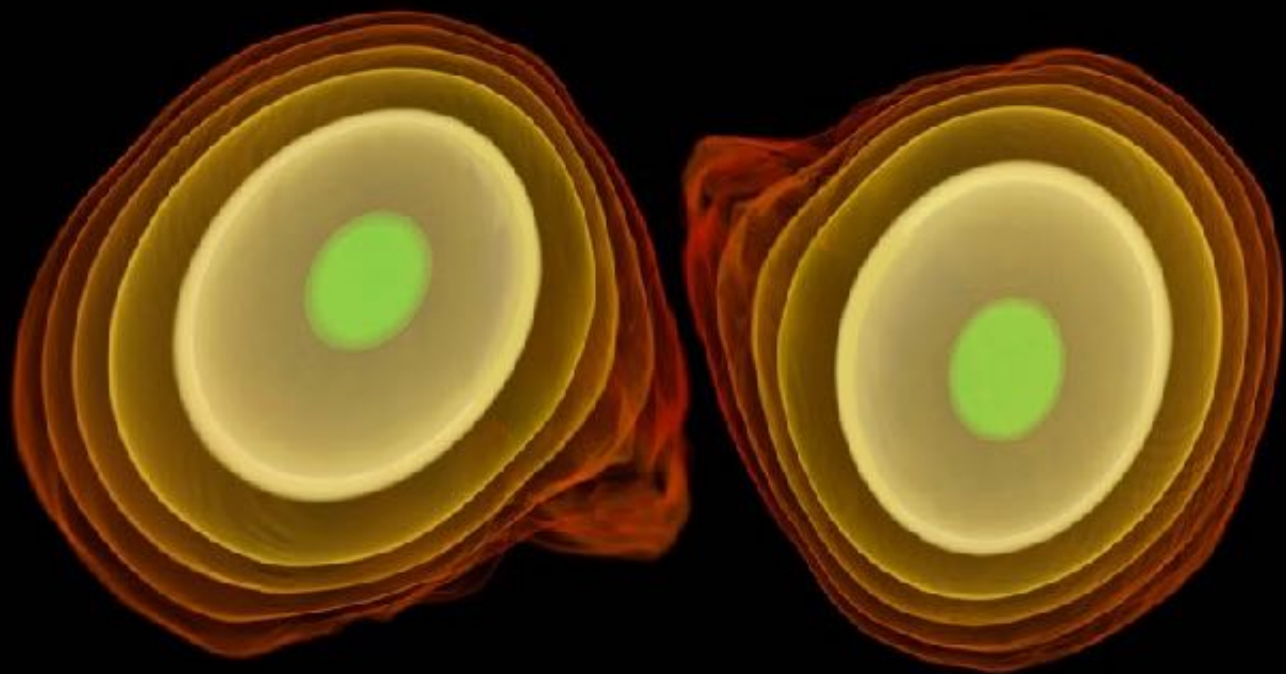
Neutronstar merger vs. heavy ion collisions
What densities can we expect?

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



- 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

Relativistic Collisions of Binary Neutron Stars



The two-body problem in GR

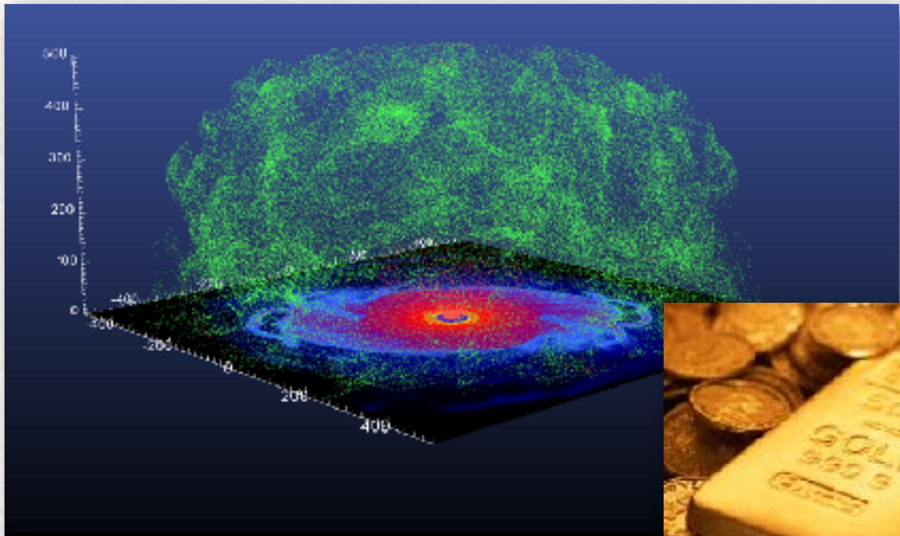
- For BHs we know what to **expect**:

BH + BH ⟶ BH + GWs

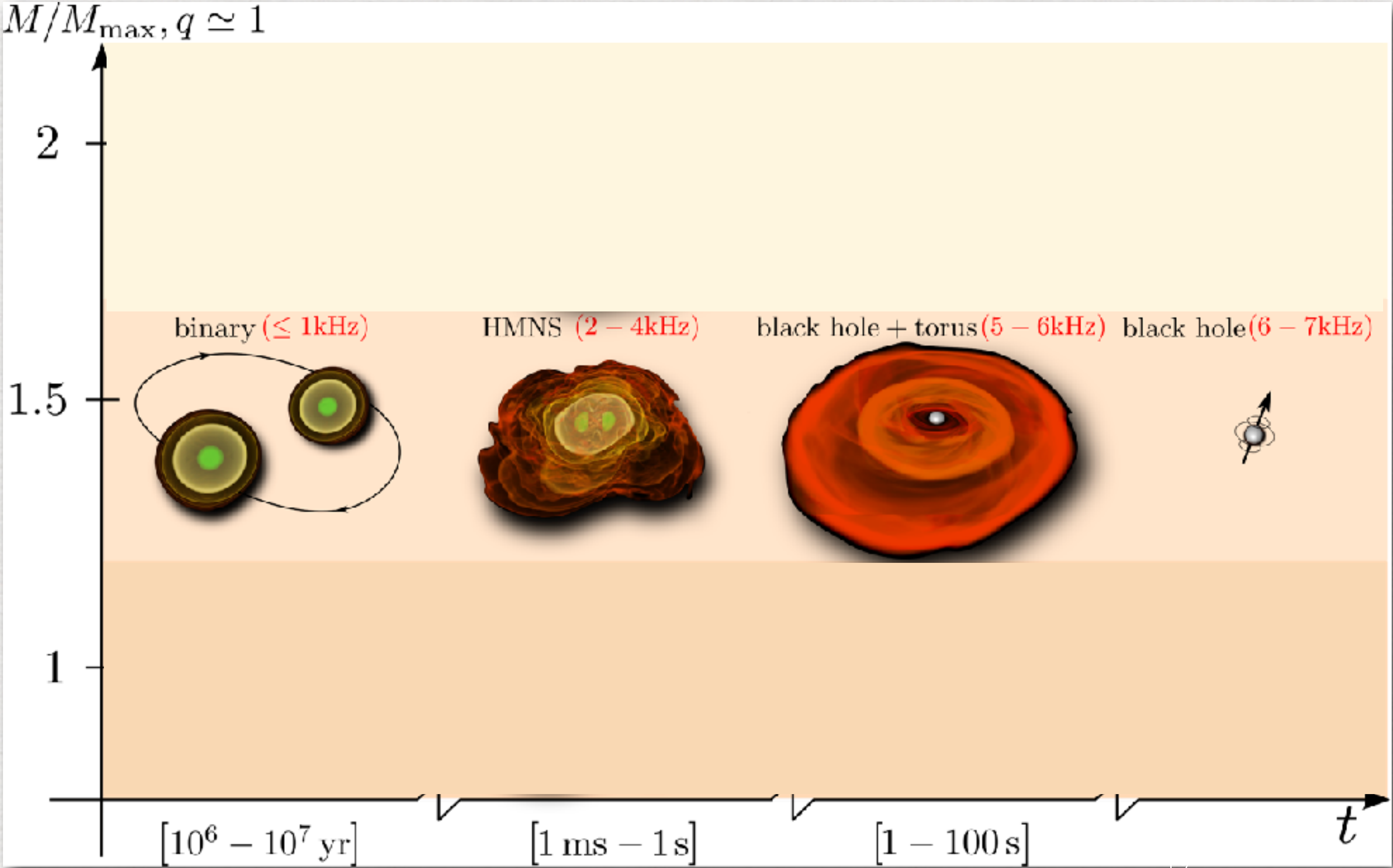
- For NSs the question is more **subtle:** the merger leads to an hyper-massive neutron star (HMNS), ie a metastable equilibrium:

NS + NS ⟶ HMNS + ... ? ⟶ BH + torus + ... ? ⟶ BH

- **ejected matter** undergoes nucleosynthesis of heavy elements

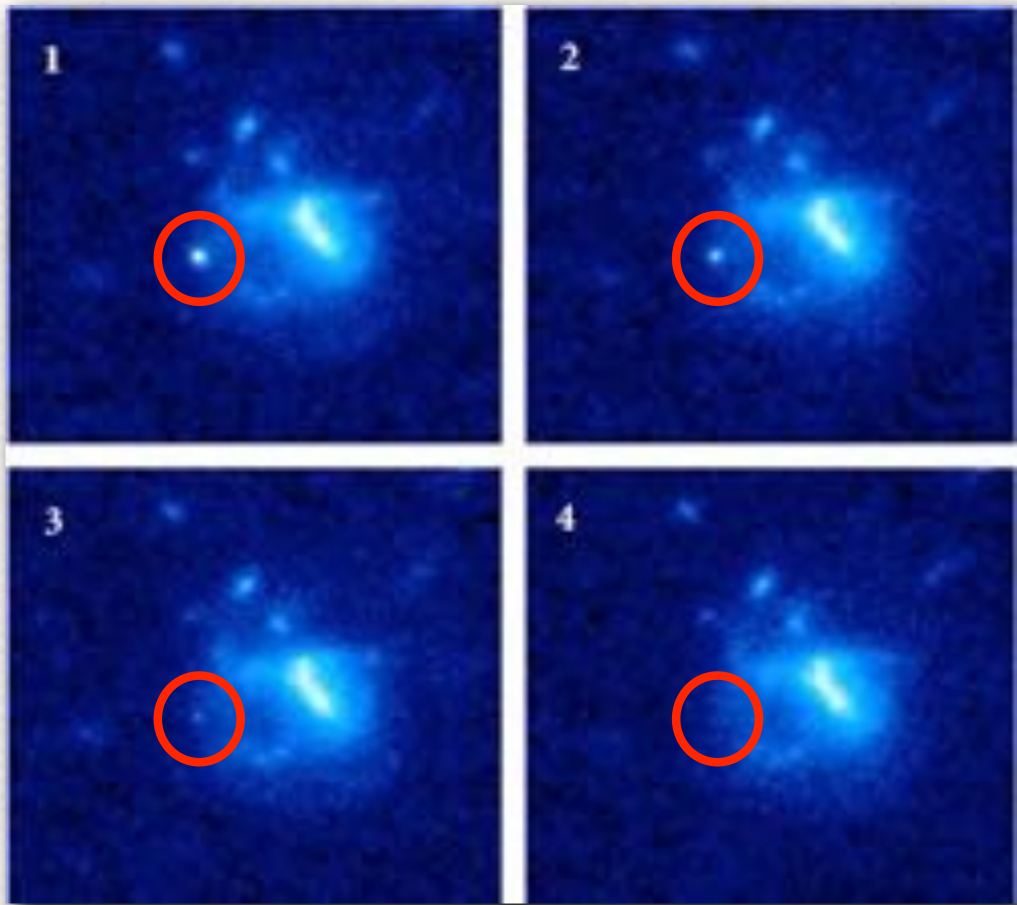


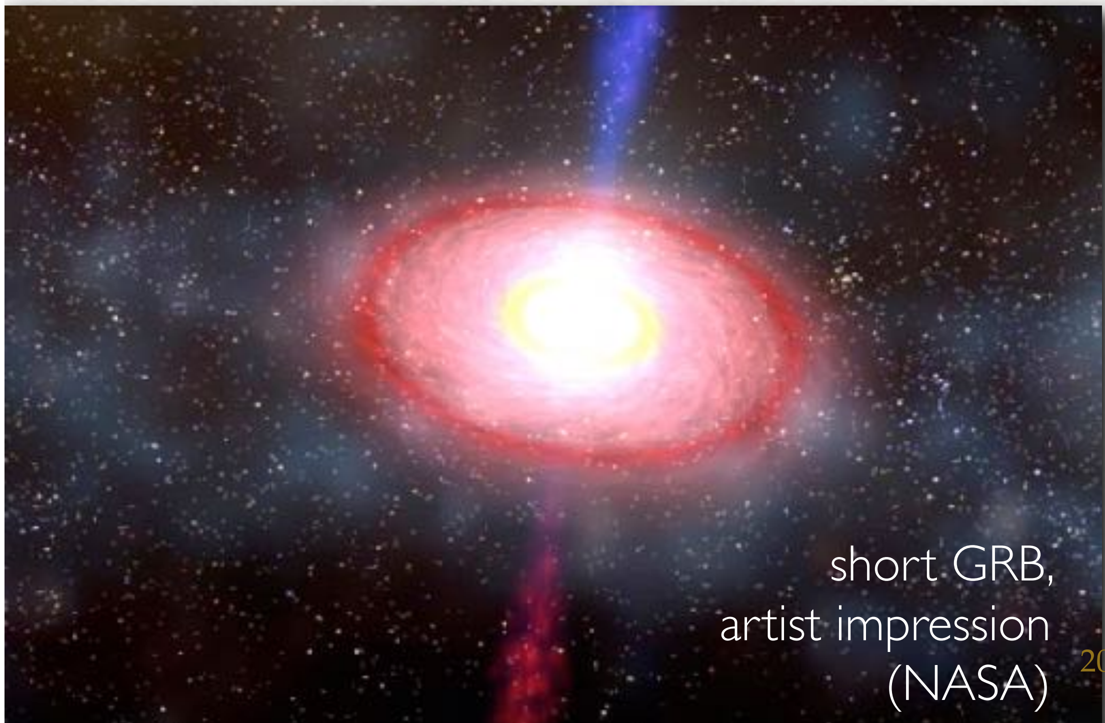
Broadbrush picture



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 !





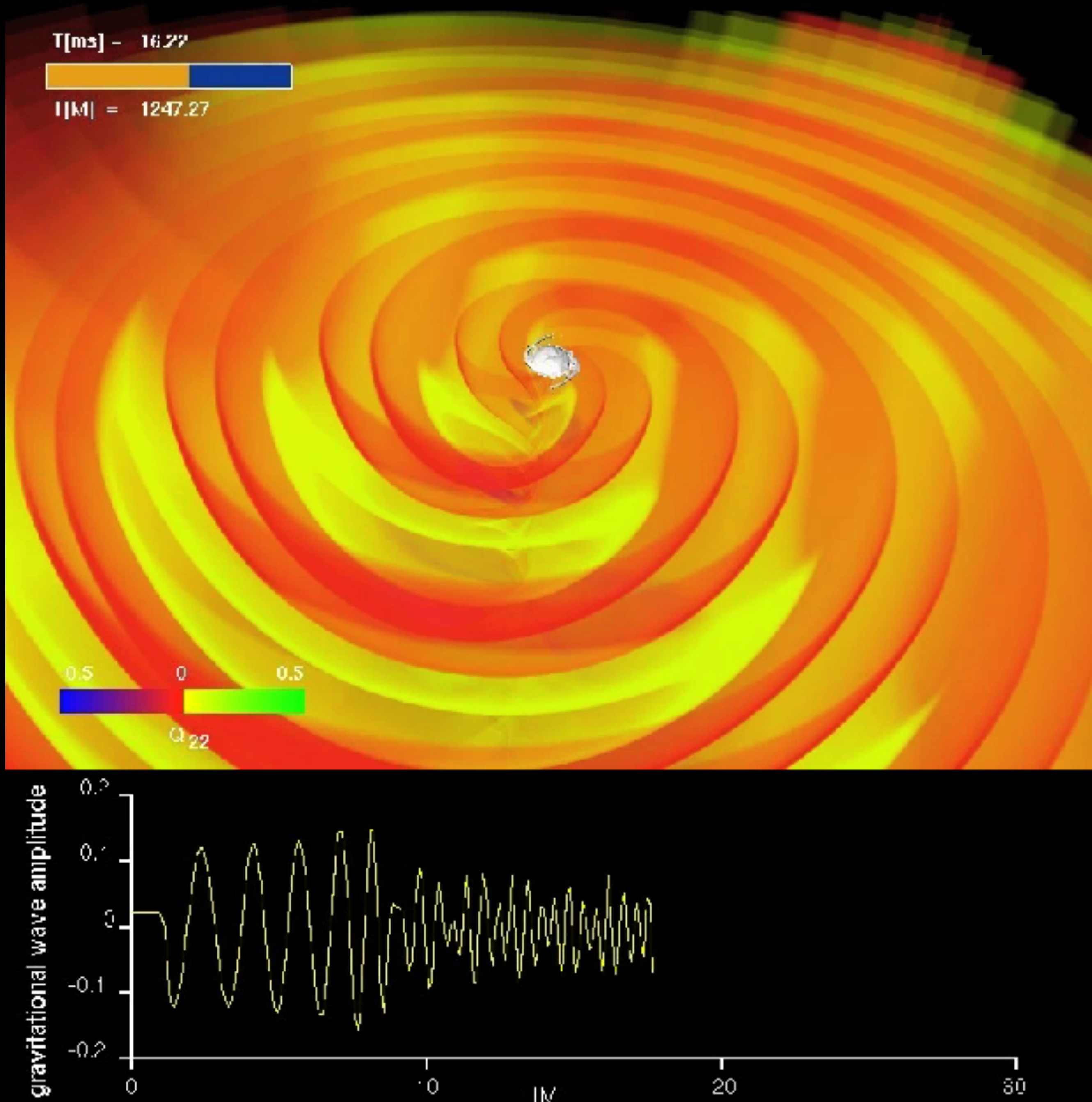
- Despite decades of observations no self-consistent model has yet been produced to explain SGRBs.

"merger → HMNS → BH + torus"

Quantitative differences are produced by:

- **differences induced by the gravitational MASS:**
  a binary with smaller mass will produce a HMNS further away from the stability threshold and will collapse at a later time
- **differences induced by the EOS ("cold" or "hot"):**
  a binary with an EOS with large thermal capacity (ie hotter after merger) will have more pressure support and collapse later
- **differences induced by MASS ASYMMETRIES:**
  tidal disruption before merger; may lead to prompt BH
- **differences induced by MAGNETIC FIELDS:**
  the angular momentum redistribution via magnetic braking or MRI can increase/decrease time to collapse
- **differences induced by RADIATIVE PROCESSES:**
  radiative losses will alter the equilibrium of the HMNS

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**…

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

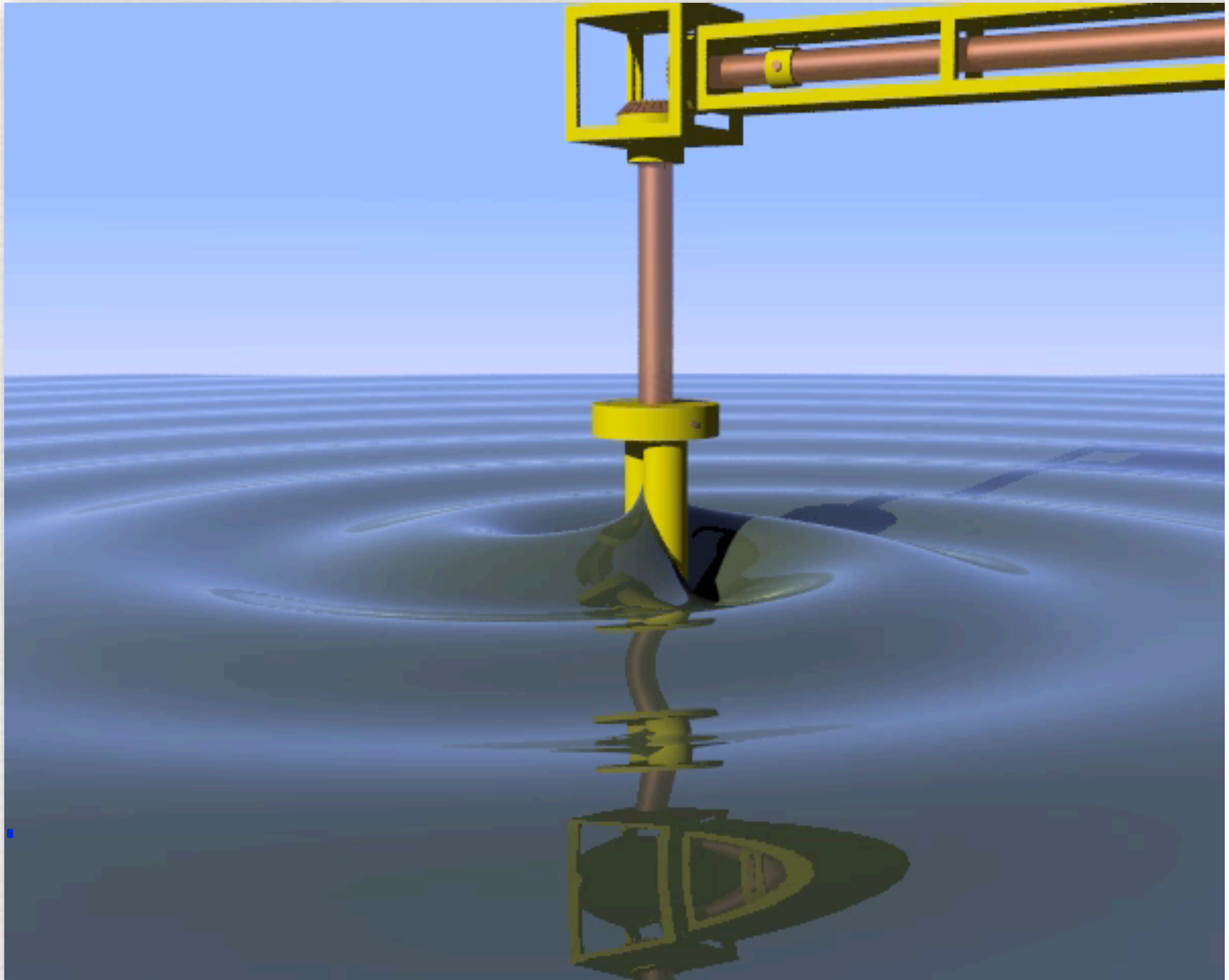
Signalform: melting of two Black Holes

Gravitational waves: ripples in spacetime

We have seen that compact objects like black holes and neutron stars curve the spacetime near them.

- What happens to the curvature when they move?
- What happens if they orbit around the same center of mass?

A mechanical "Gedankenexperiment".

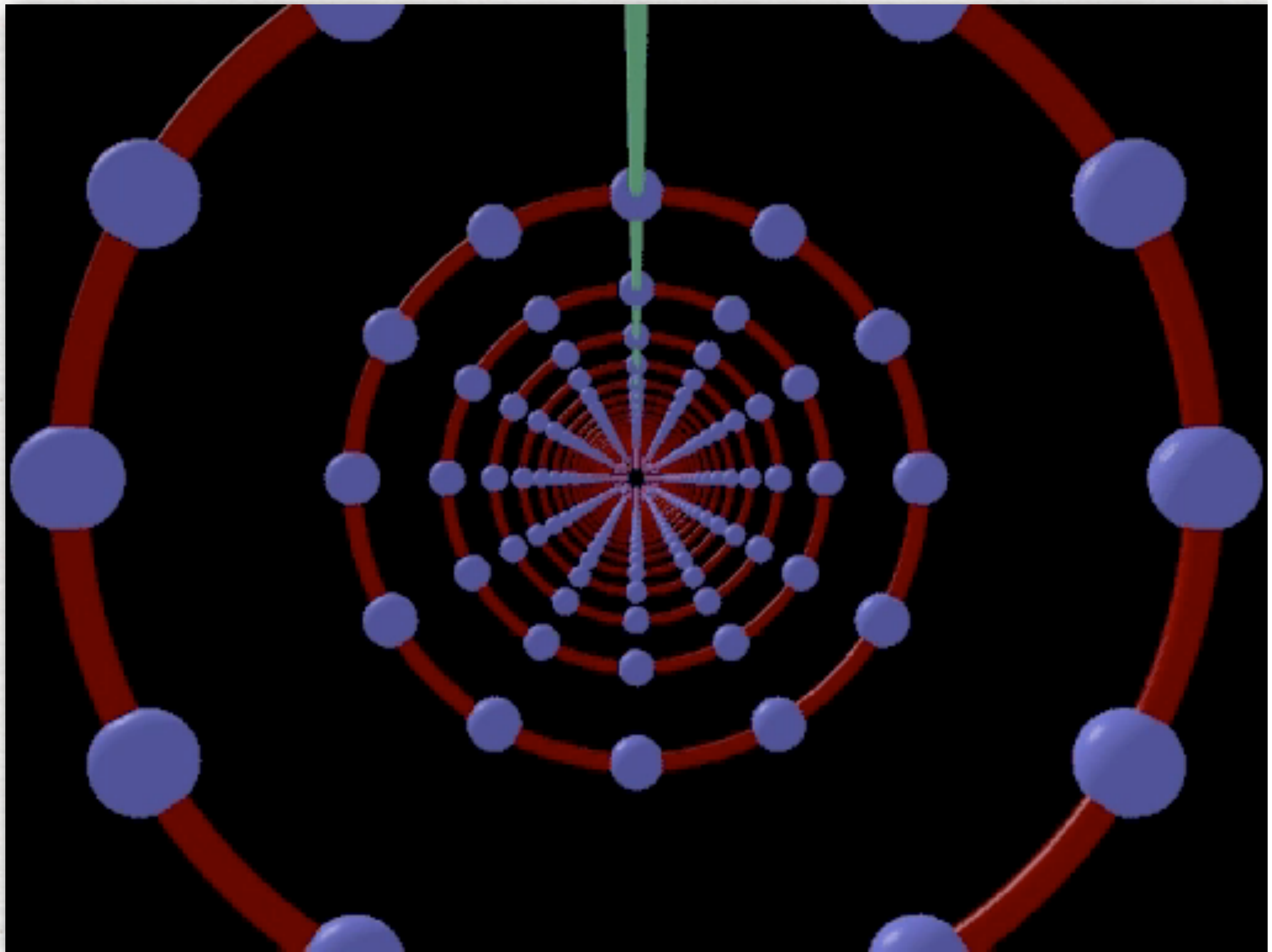


Gravitational waves: ripples in spacetime

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



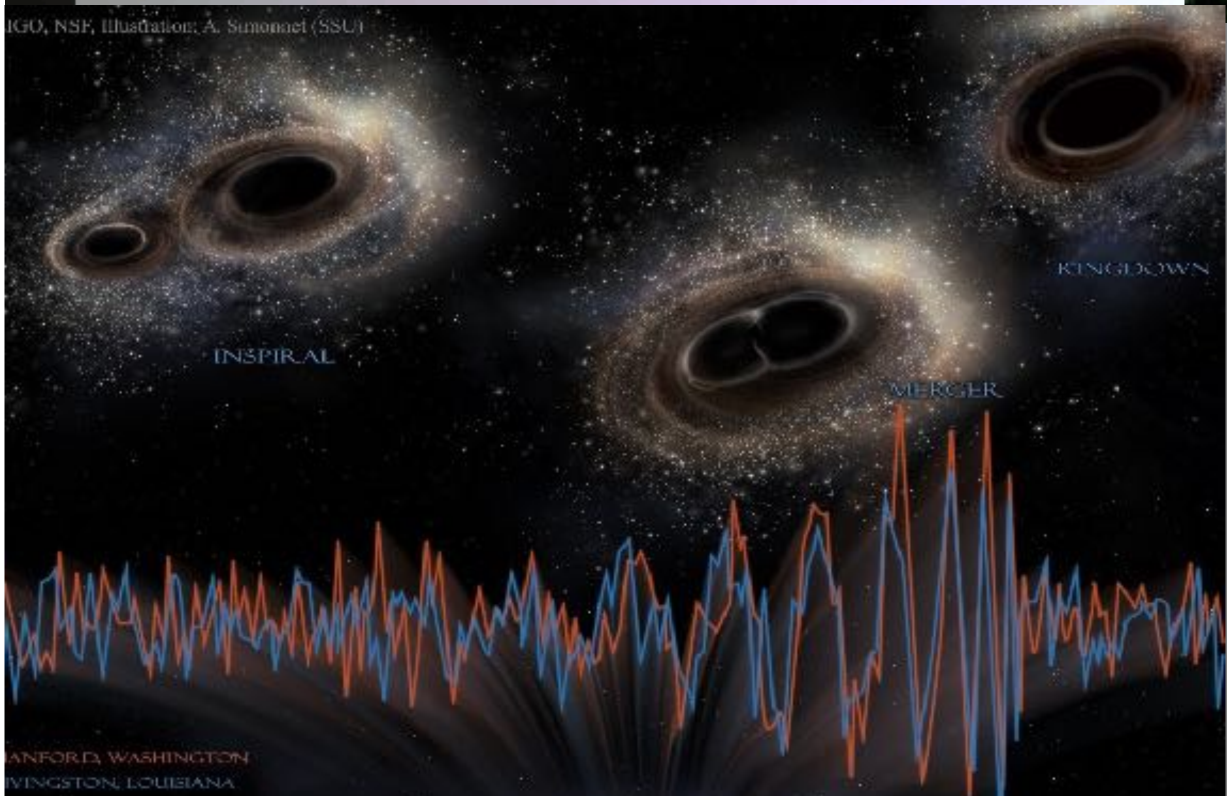
Gravitational Waves discovered ??!!!

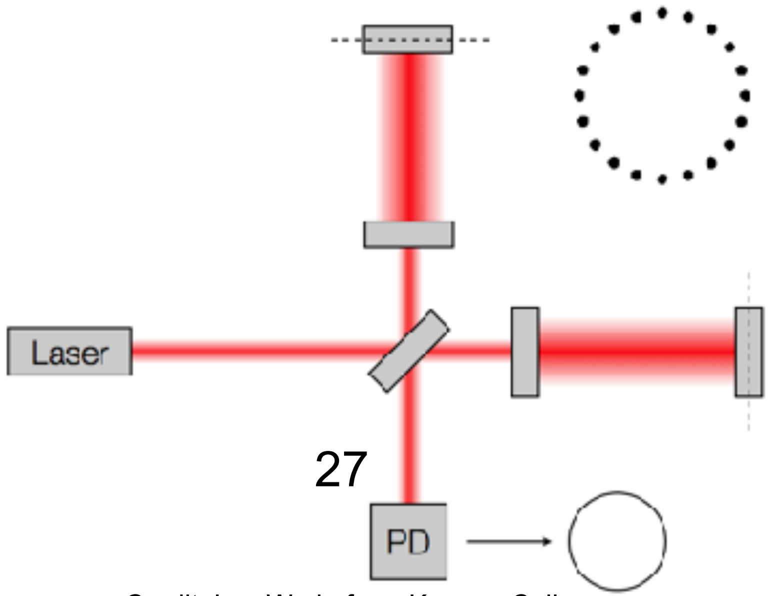
Collision of 2 BHs GW150914

Masses of BHs: 36 & 29 Solar Masses

Distance to Earth 410 Mpc (1340 Million Lightyears)

Length Difference 10^-21 m





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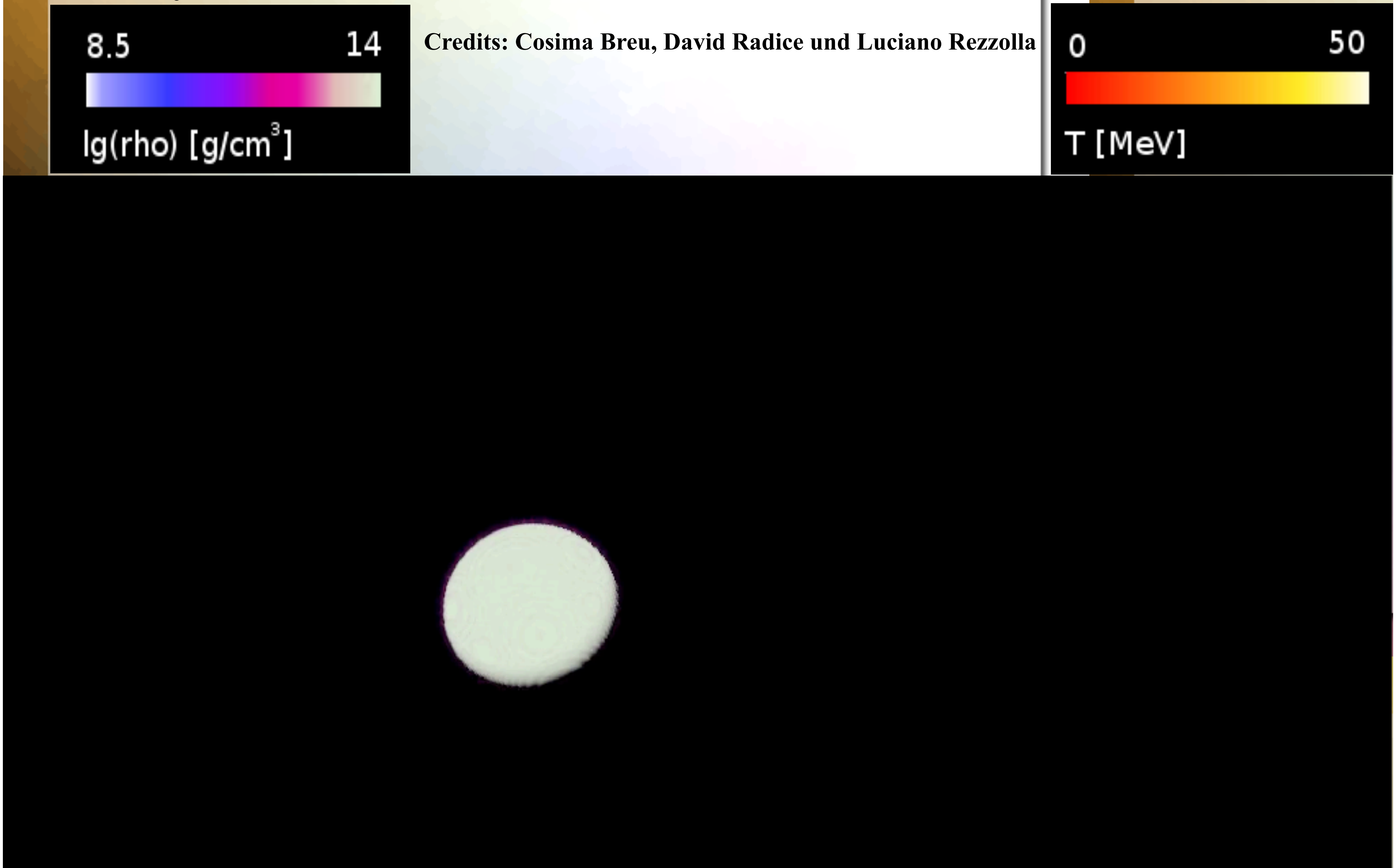
Credit: Les Wade from Kenyon College.

Gen. relativ. Hydro for **Neutronstar-Neutronstar** Collisions

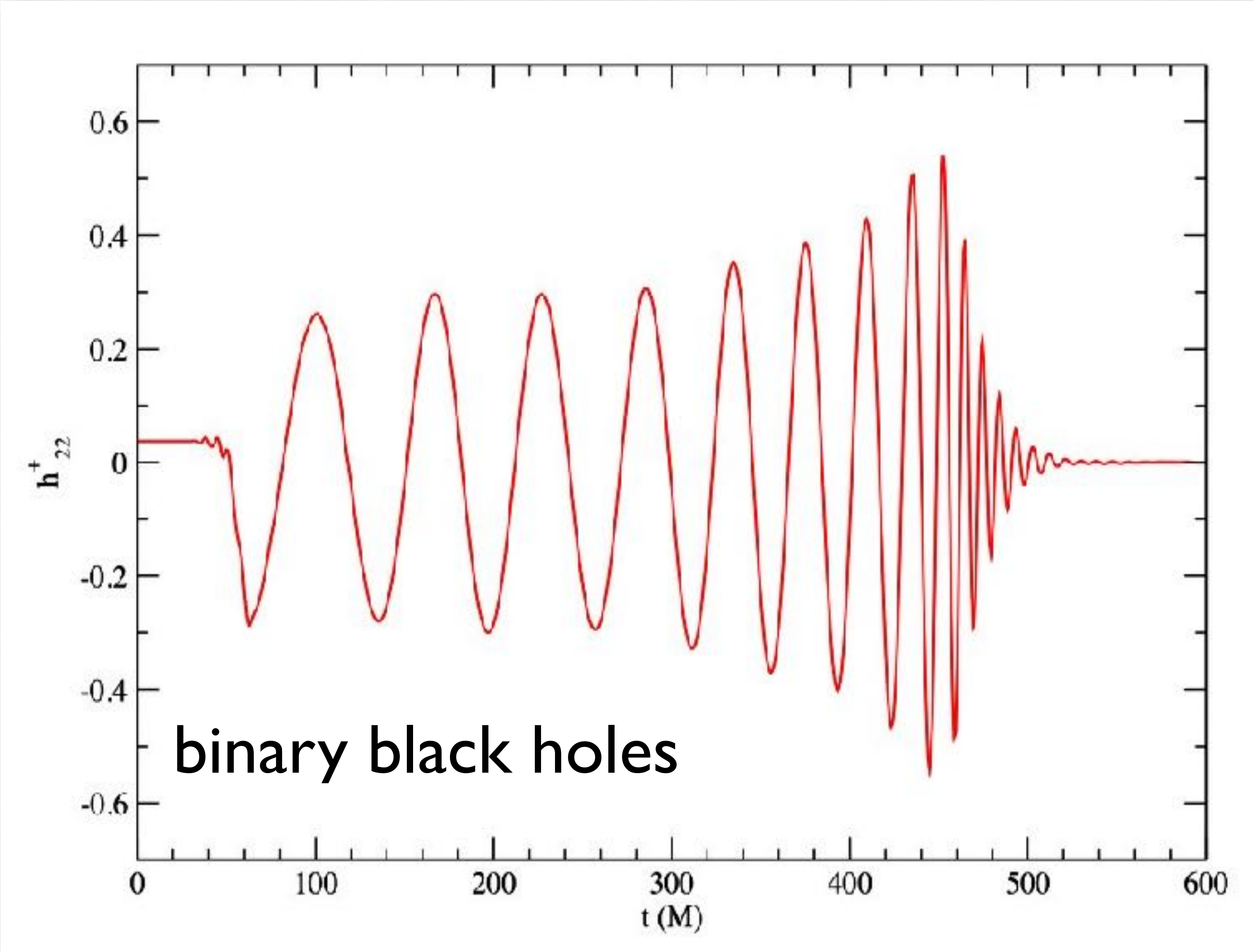
Density of Neutronstar Matter **Temperature of Neutronstar Matter**



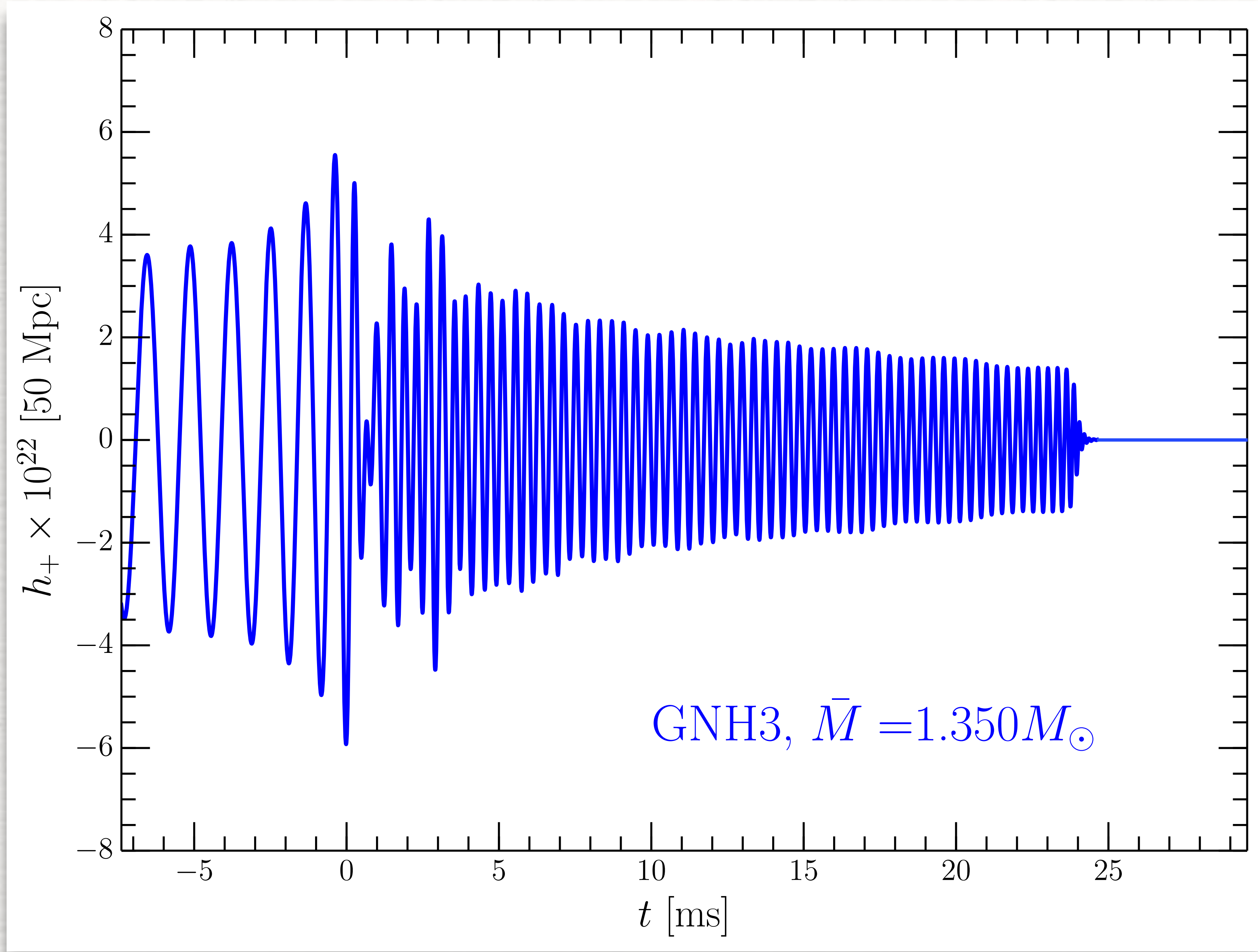
Credits: Cosima Breu, David Radice und Luciano Rezzolla

How to constrain the EOS of superdense neutronstar matter by relativistic binary neutron star- and heavy ion collisions

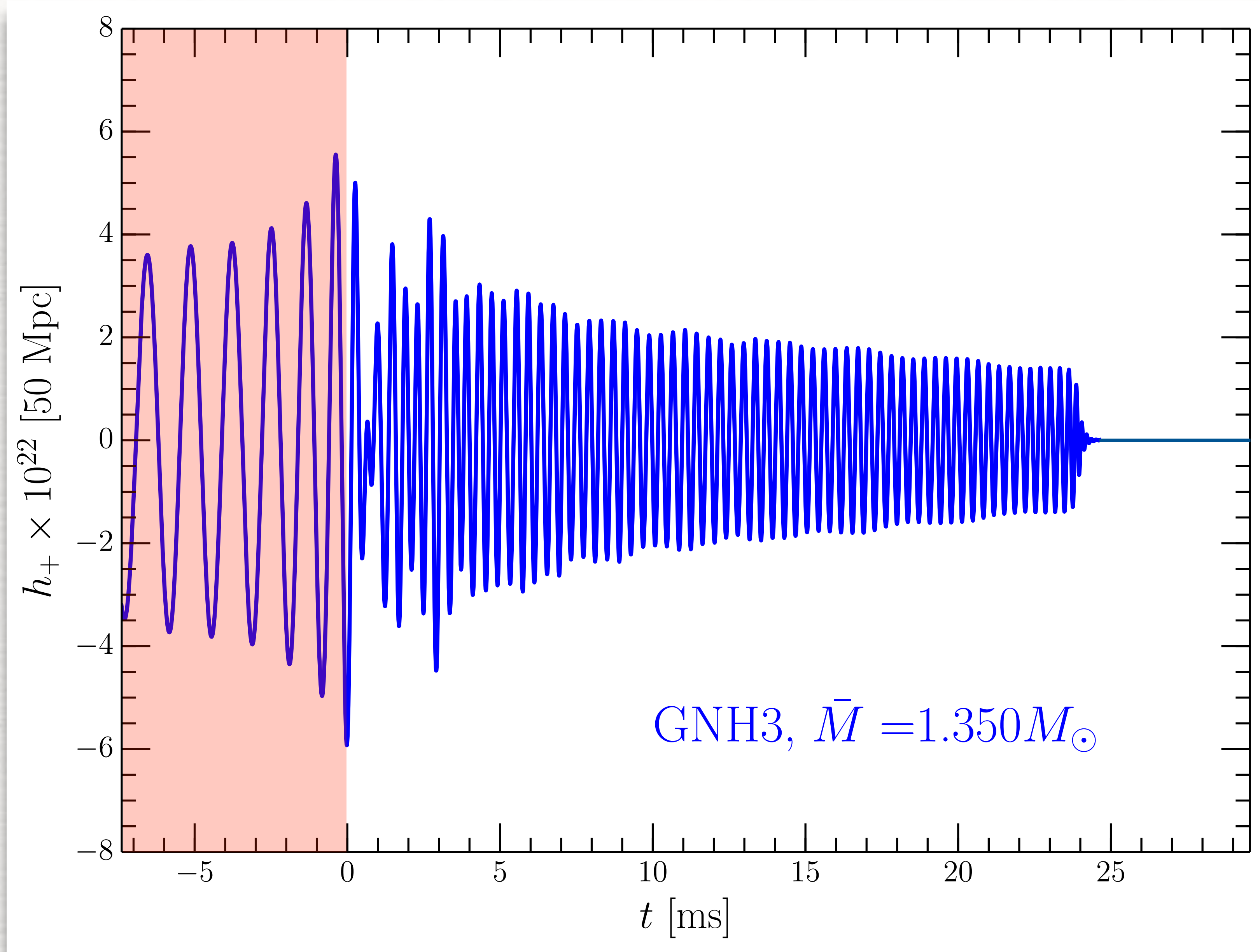
Anatomy of the GW signal



Anatomy of the GW signal

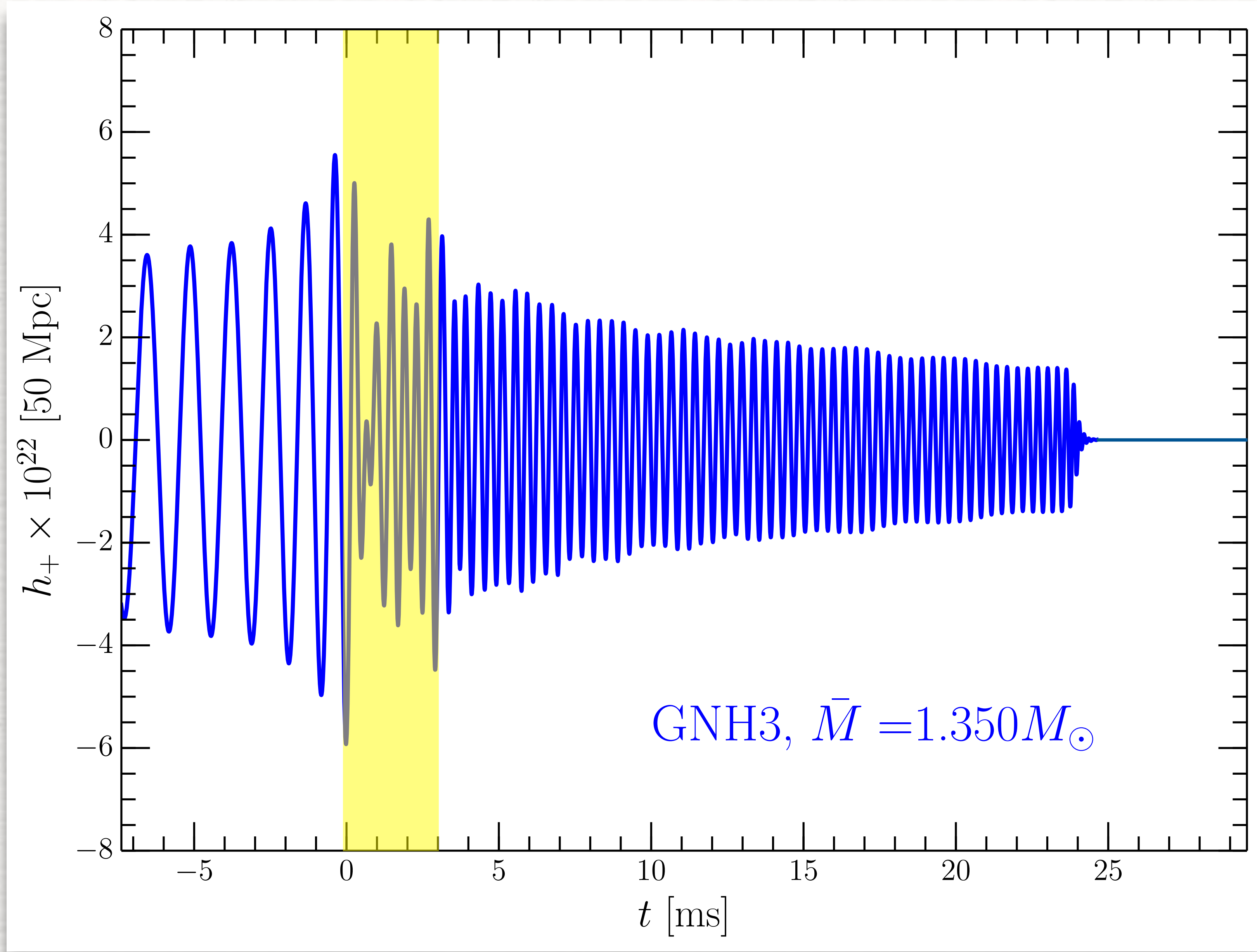


Anatomy of the GW signal



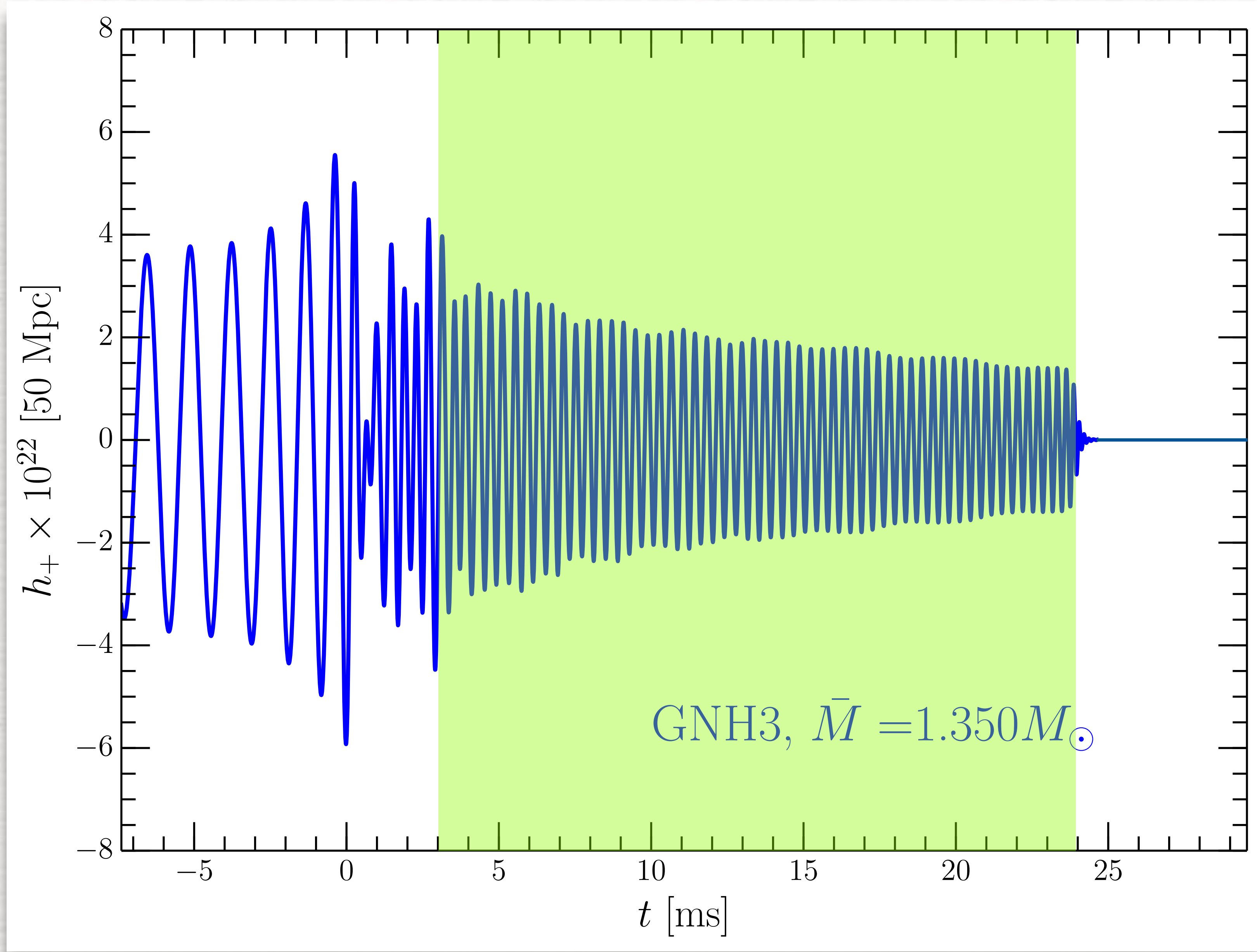
Inspiral: well approximated by PN/EOB; tidal effects important

Anatomy of the GW signal



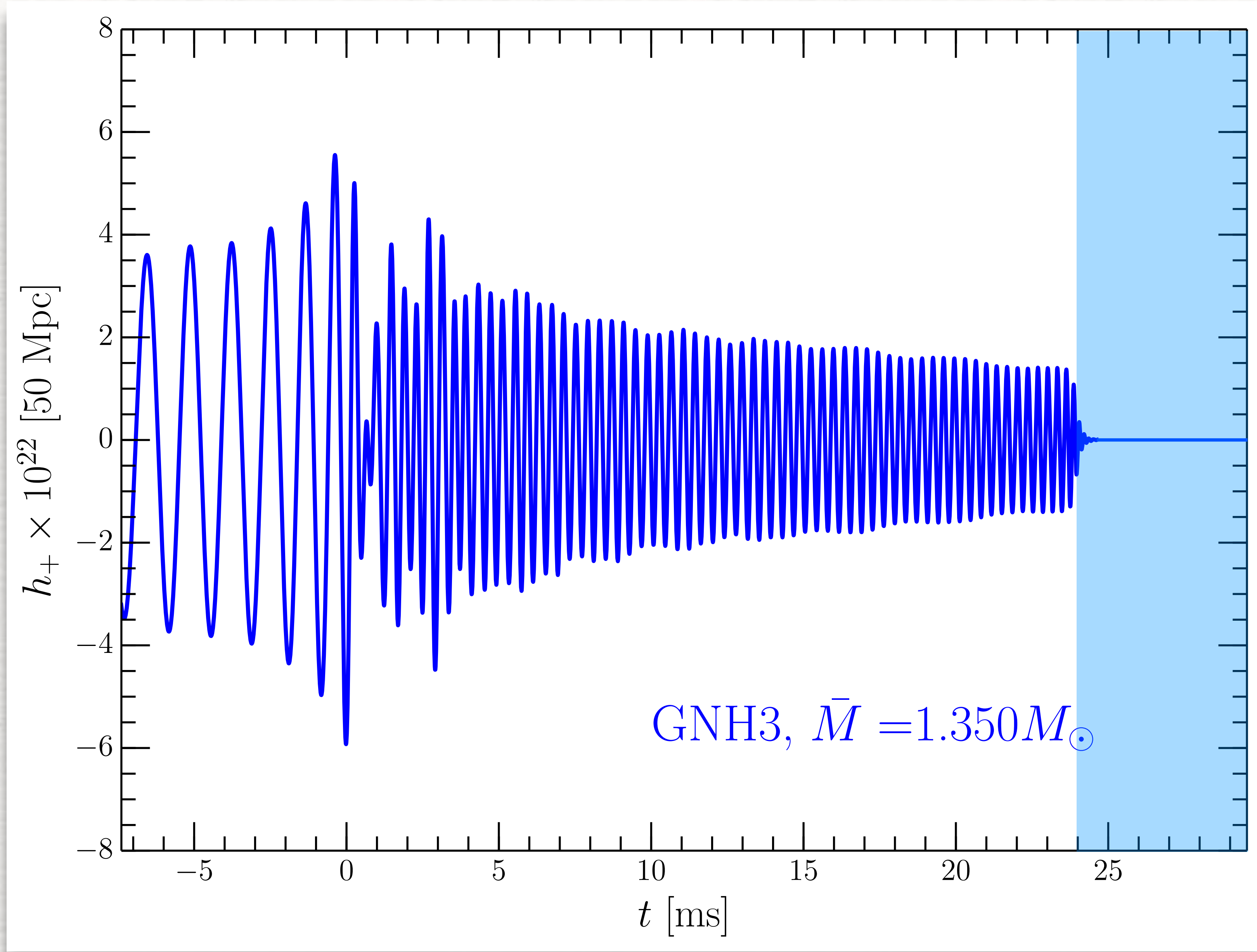
Merger: highly nonlinear but analytic description possible

Anatomy of the GW signal



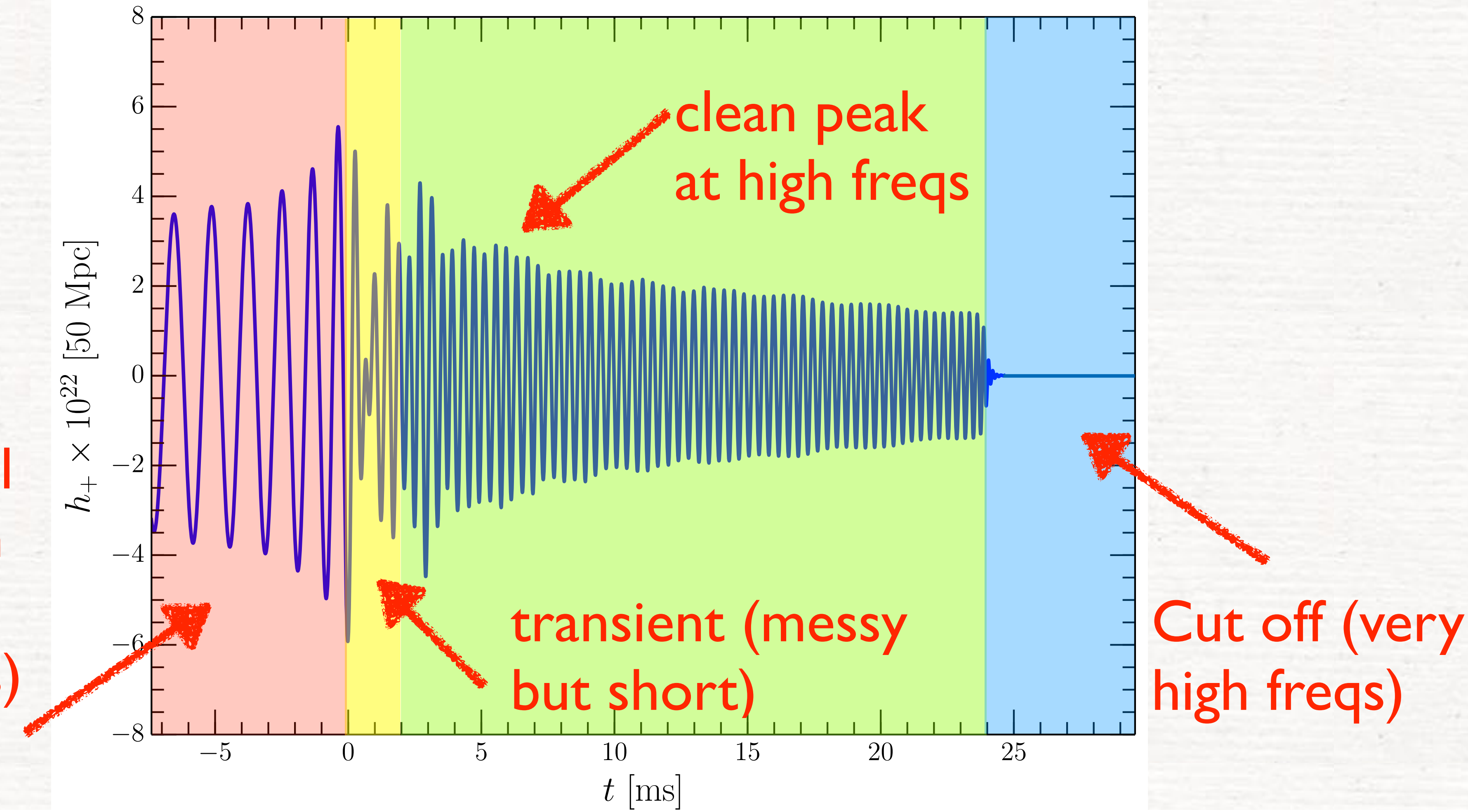
post-merger: quasi-periodic emission of bar-deformed HMNS

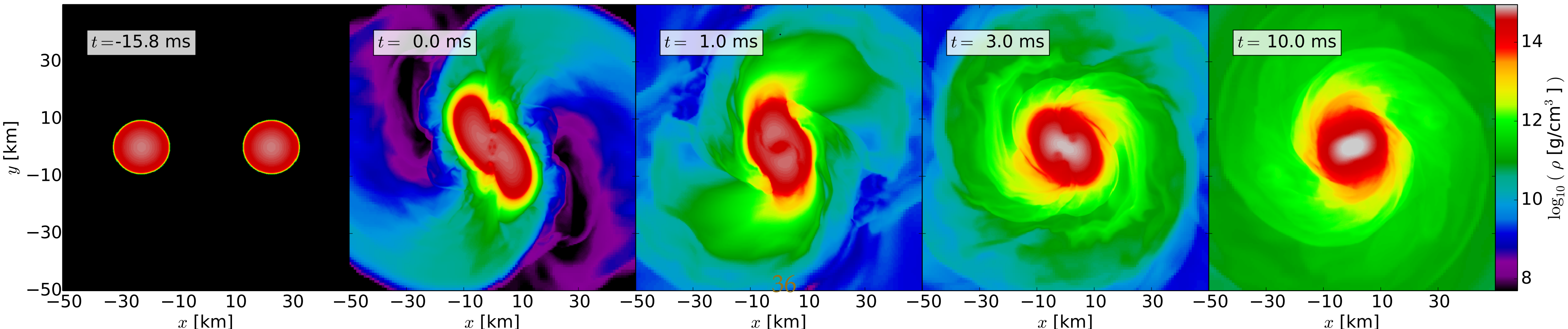
Anatomy of the GW signal



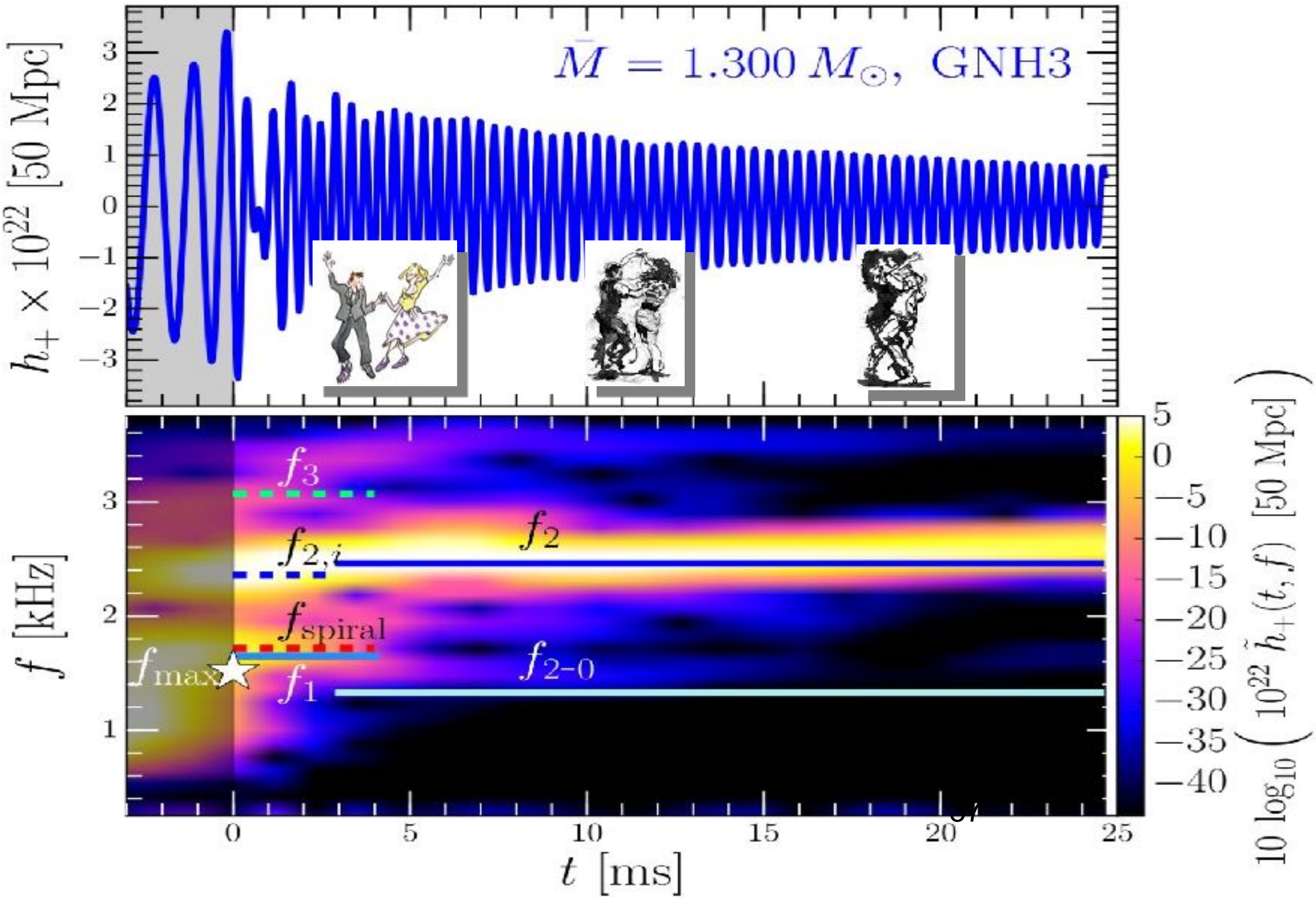
Collapse-ringdown: signal essentially shuts off.

Anatomy of the GW signal

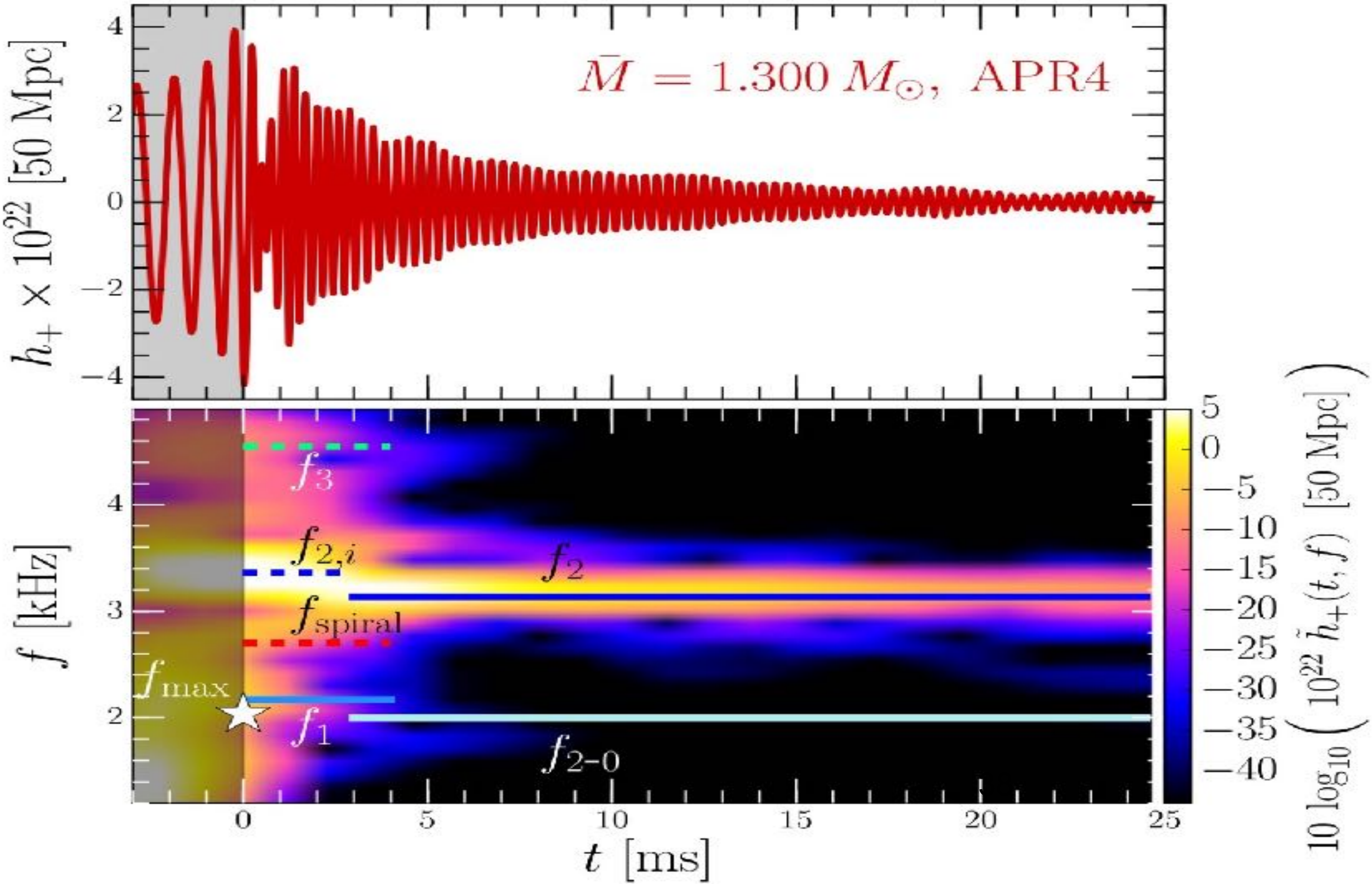




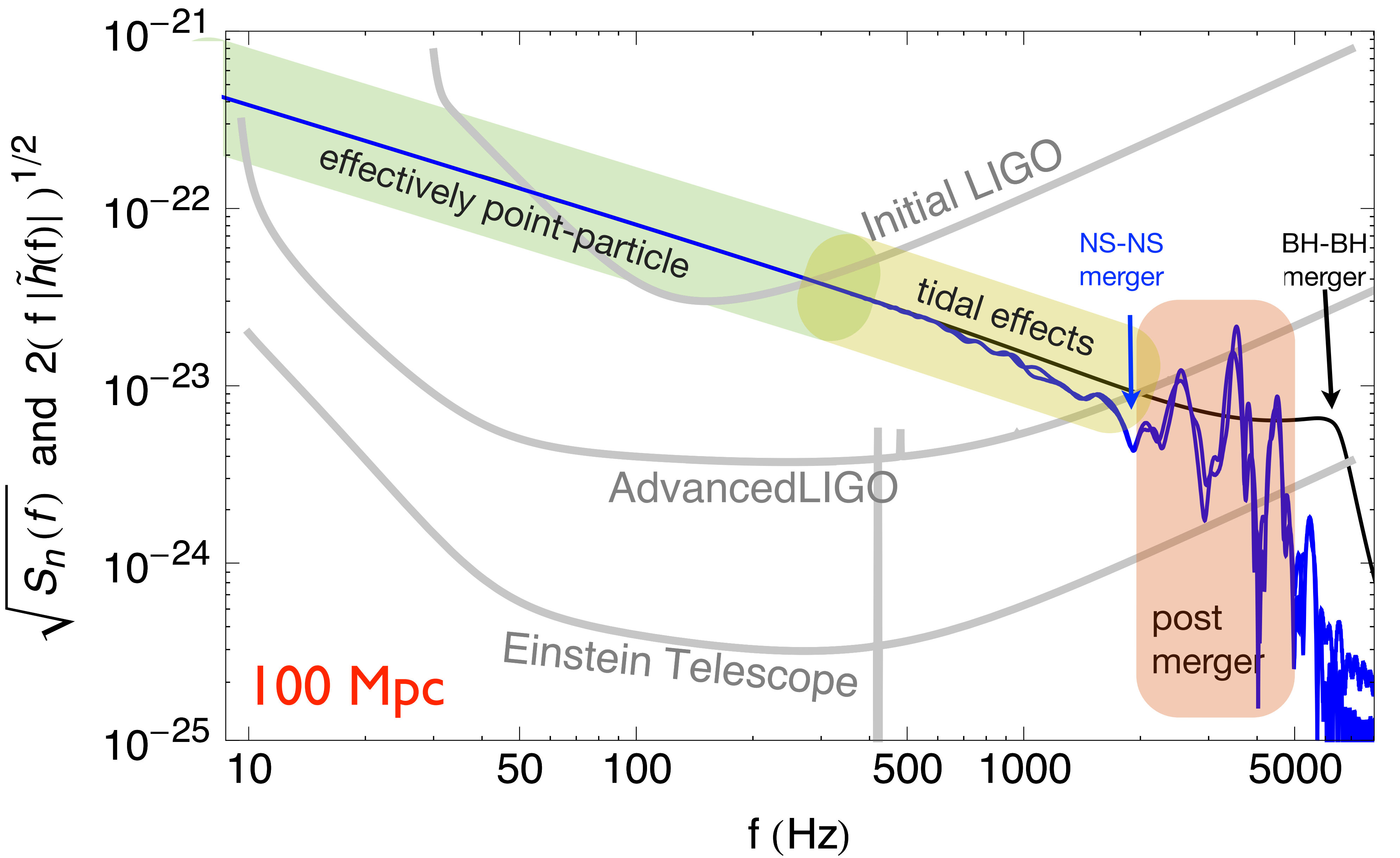
The Gravitational Wave Spectrum for a HARD nuclear EoS



Gravitational Wave Frequency Spectrum: soft nuclear matter EoS



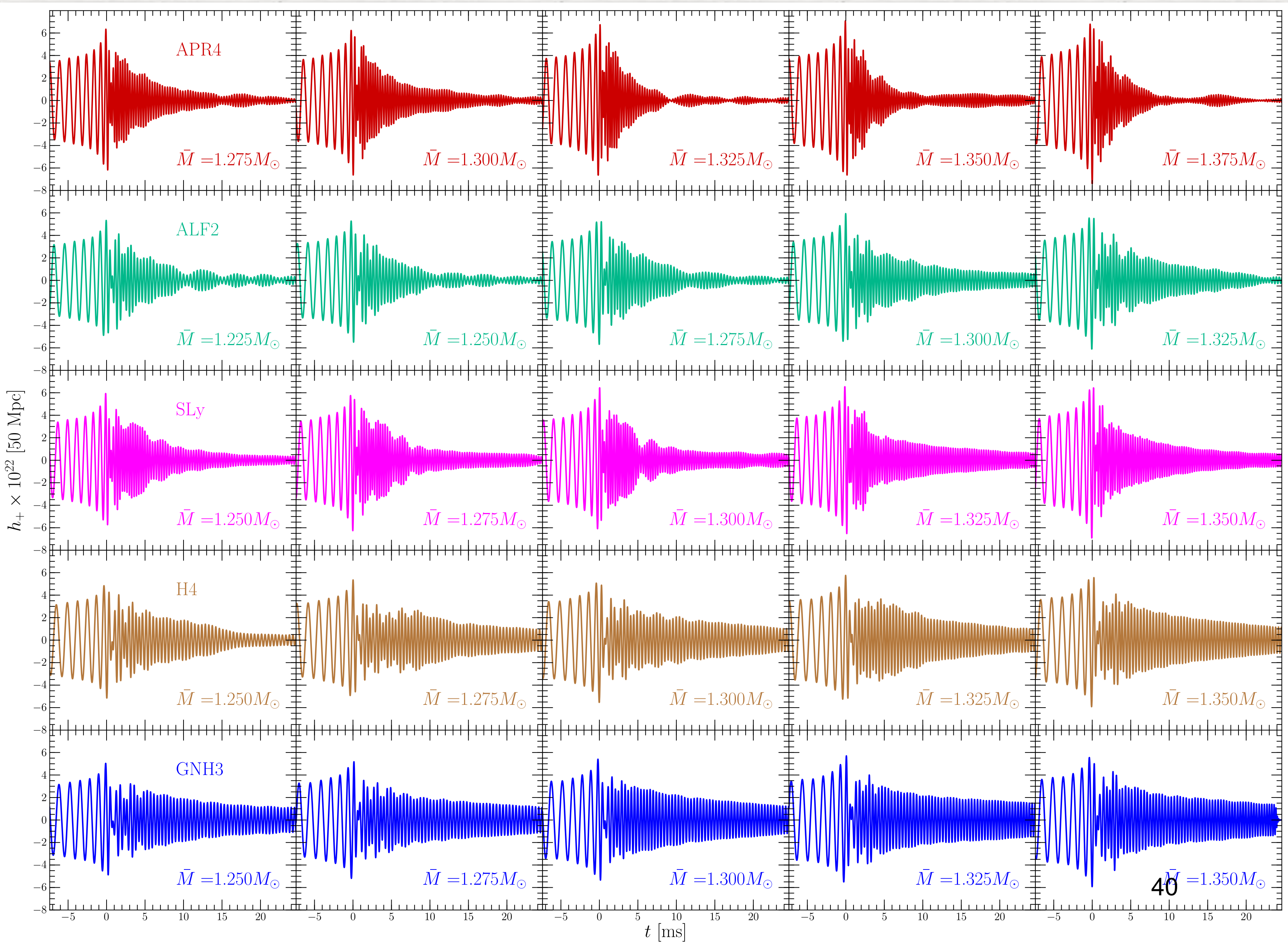
In frequency space



courtesy of Jocelyn Read

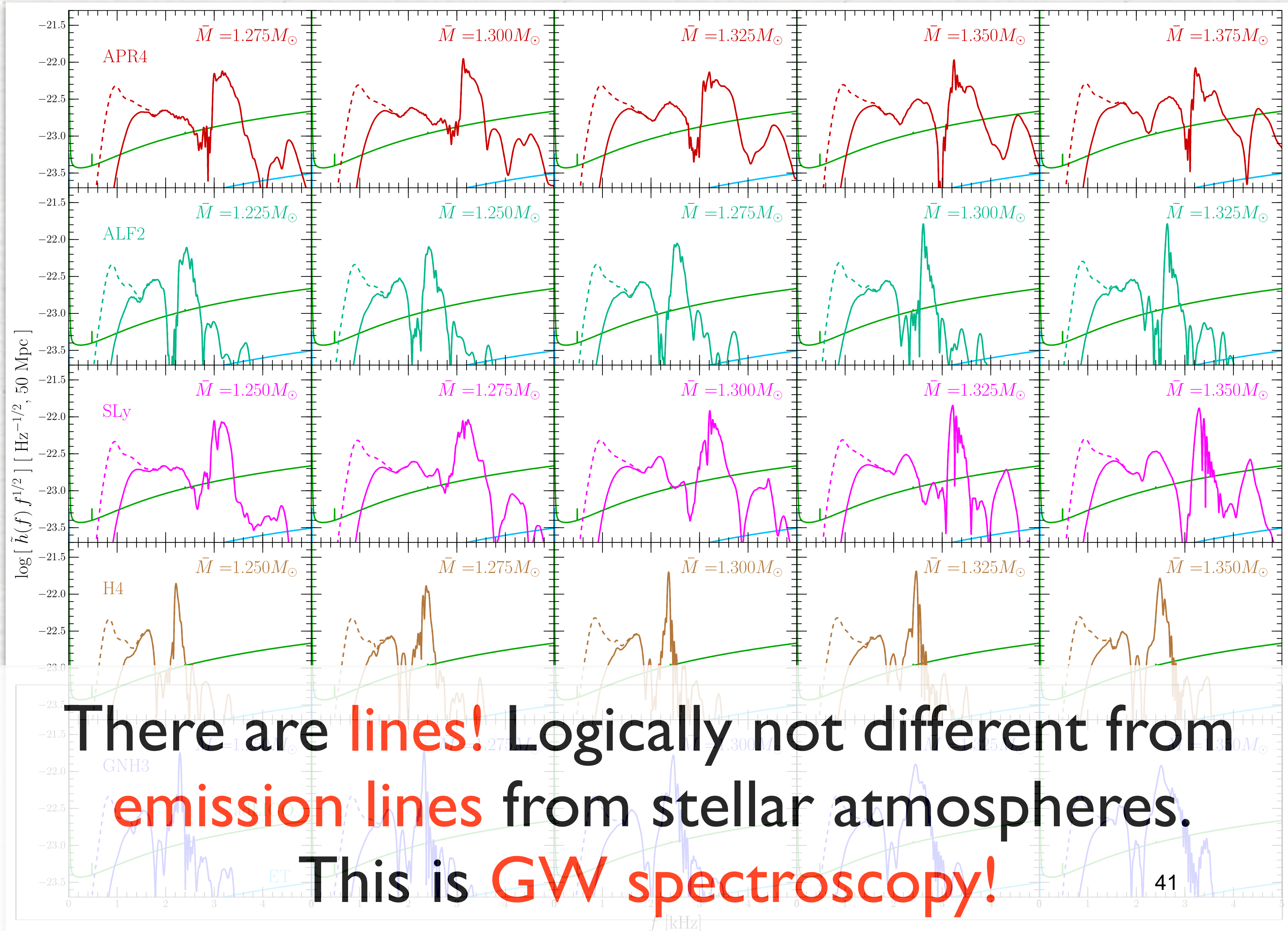
What we can do nowadays

Takami, L.Rezzolla, Baiotti (2014, 2015), LR+ (2016)



Extracting information from the EOS

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



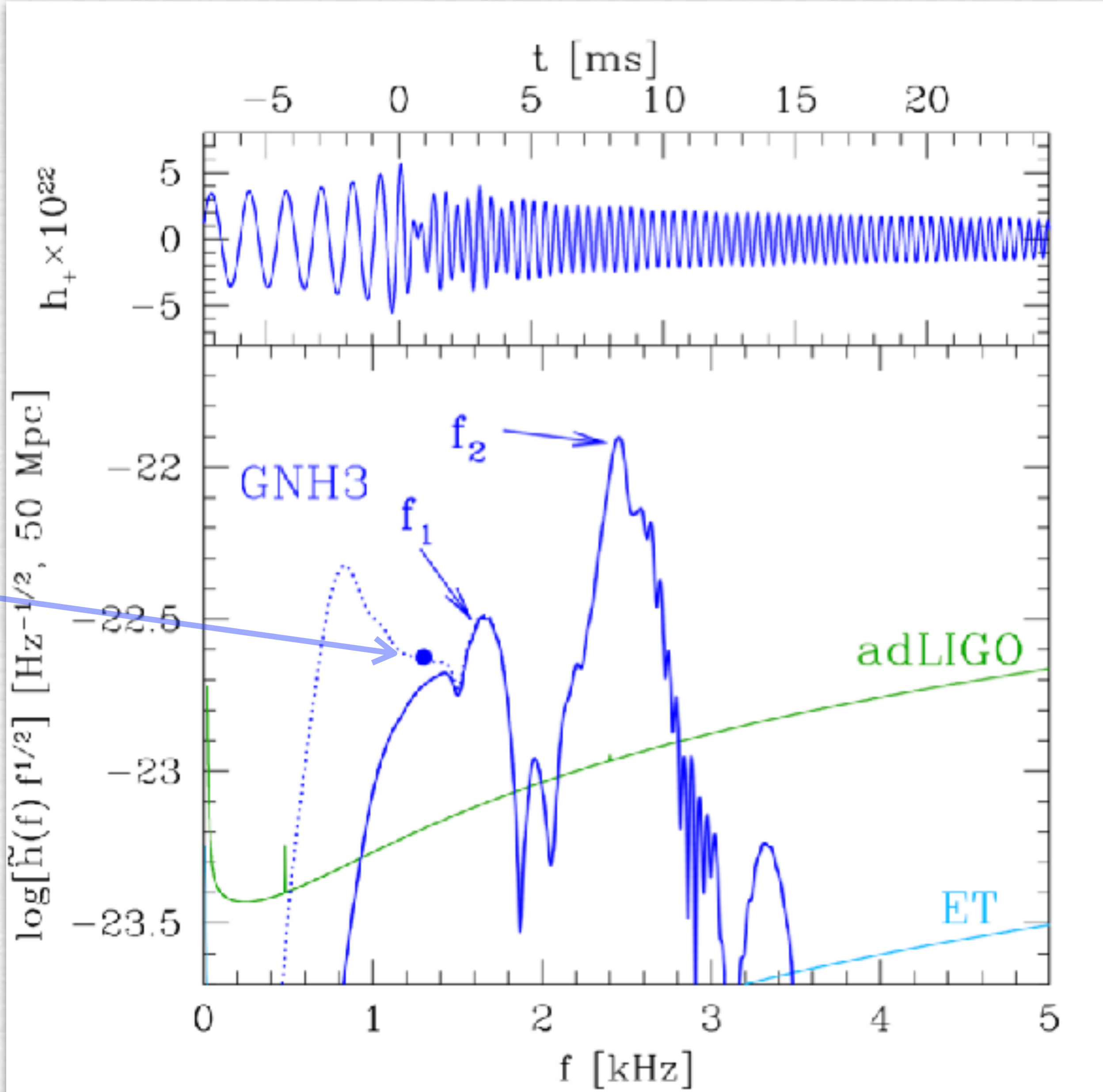
There are lines! Logically not different from emission lines from stellar atmospheres.

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



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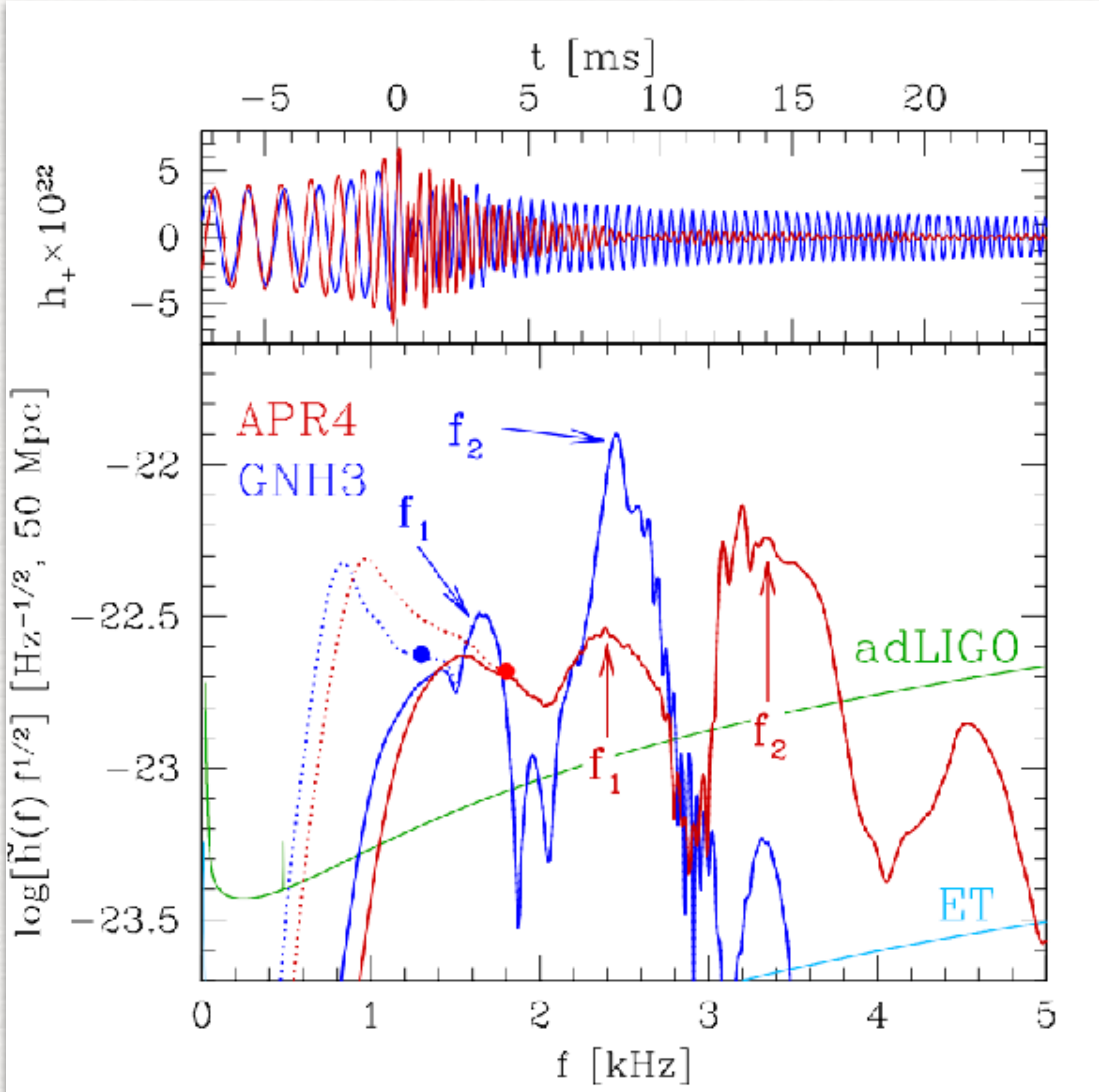
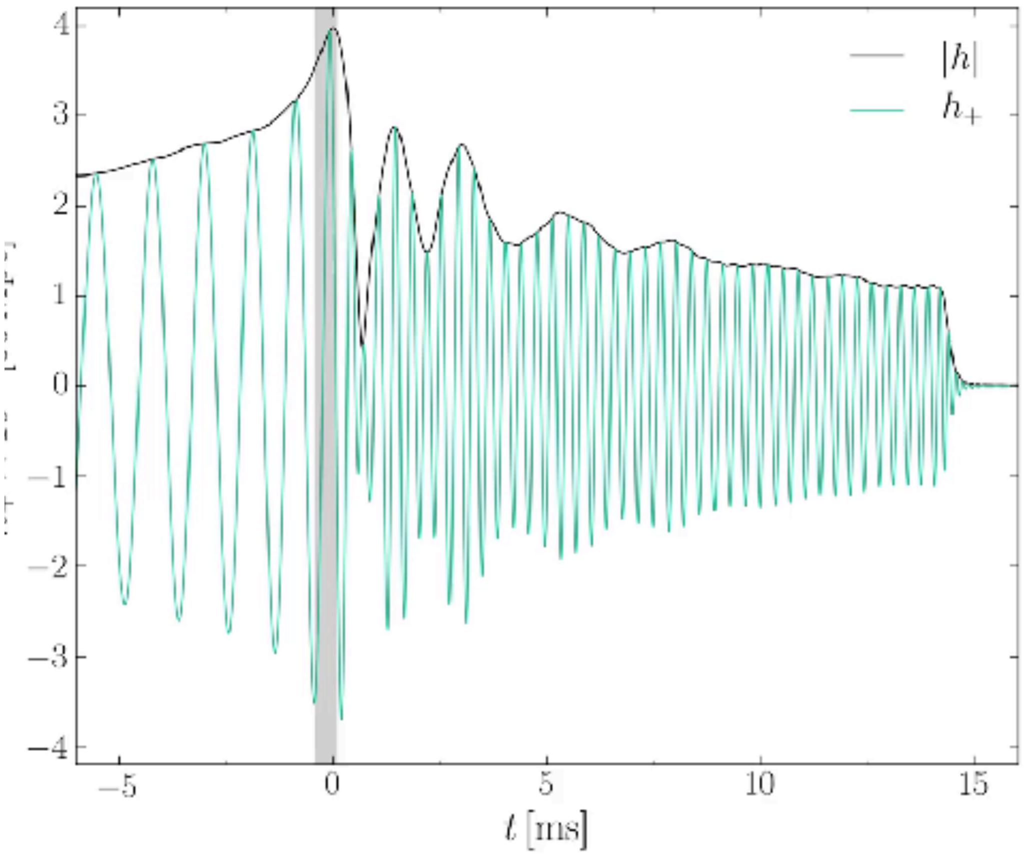


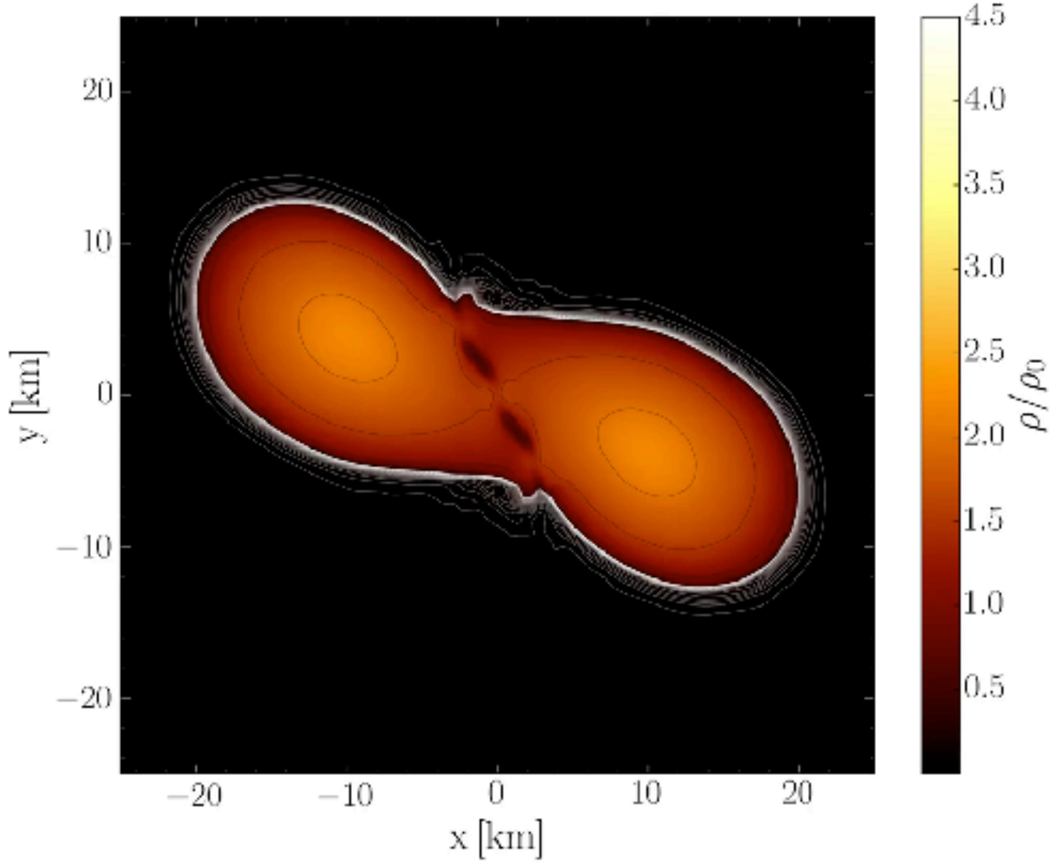
Hypermassive Neutronstar GR Hydro Simulation

EoS Contains Neutrons, Protons, Electrons, Hyperons, Muons

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



Amplitude der emittierten Gravitationswelle im Abstand von 50 Mpc



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

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

Extending the work to MHD

Neutron stars have large magnetic fields: 10^8-10^{12} G and it is the strong magnetic field that makes them observable as radio and pulsars.

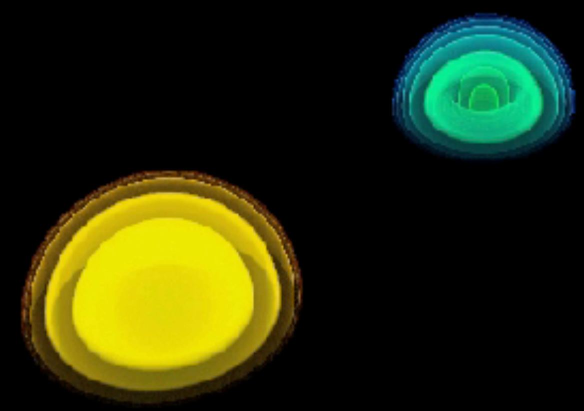
As mentioned above, magnetic fields can play an important role and to study this it is necessary to solve the equations or relativistic magnetohydrodynamics (MHD)

We work within the ideal-MHD limit (i.e. infinite electrical conductivity) and this is an excellent approximation during the inspiral.

For simplicity, the magnetic fields are buried under the surface, to avoid magnetospheric problems

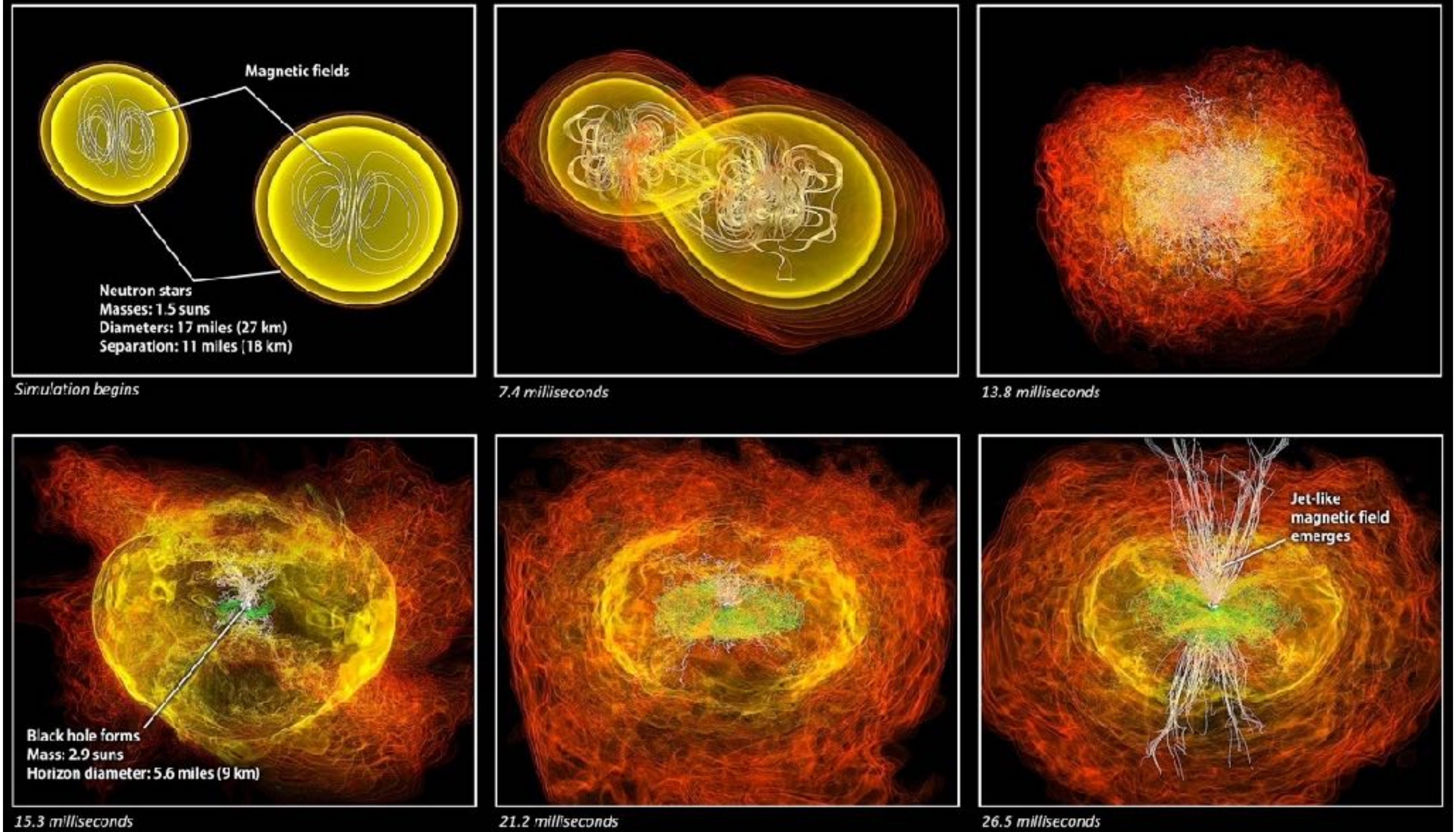
Animations:, L. Rezzolla, Koppitz

Typical evolution for a magnetized binary (hot EOS) $M = 1.5\, M_{\odot}, B_0 = 10^{12}\, \mathrm{G}$



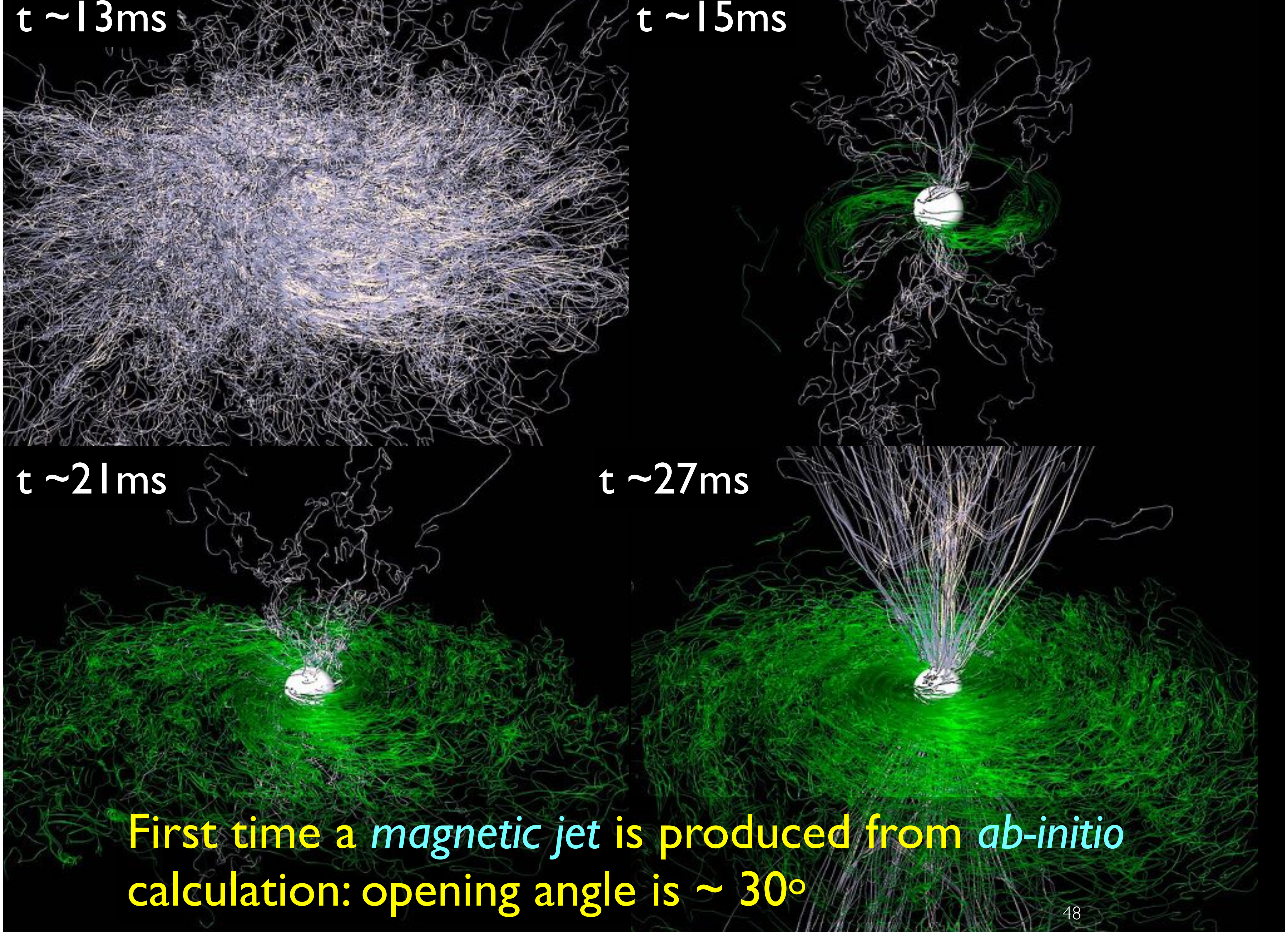
A magnetic jet is produced as a result of MHD instabilities and ultra-strong magnetic fields

Crashing neutron stars can make gamma-ray burst jets



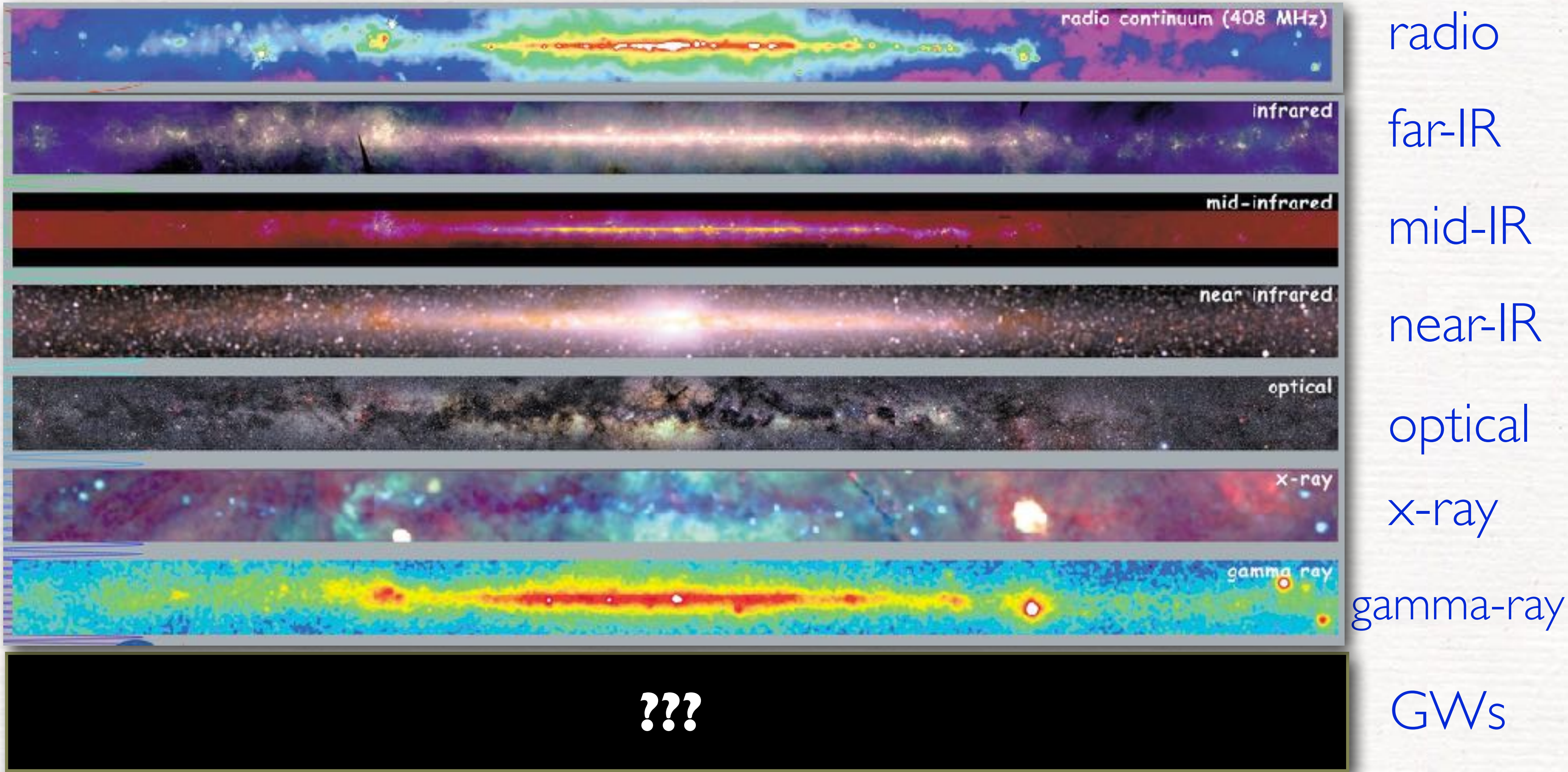
Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

$J/M^2 = 0.83$ $\quad$ $\mathrm{M_{tor}} = 0.063 M_\odot$ $\quad$ $\mathrm{t_{accr}} \simeq M_{\mathrm{tor}}/\dot{M} \simeq 0.3$ s


t ~13ms
t ~15ms
t ~21ms
t ~27ms
First time a *magnetic jet* is produced from *ab-initio* calculation: opening angle is ~ 30°

Conclusions

GSFC/NASA



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