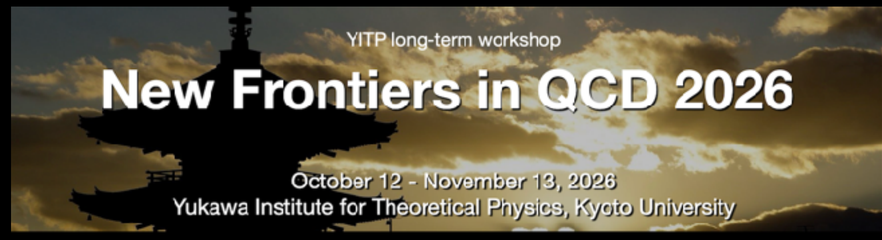
Binary Neutron Stars: from macroscopic collisions to microphysics

Luciano Rezzolla

Institute for Theoretical Physics, Frankfurt

Kyoto, October 29, 2026



Q. What is a gravitational physicist actually doing at a QCD conference?

GR in vacuum

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 0 \qquad \text{(Einstein equations)}$$

GR in vacuum

$$
\begin{aligned}
\partial_t \tilde{\gamma}_{ij} &= -2\alpha \tilde{A}_{ij}^{\mathrm{TF}} + 2\tilde{\gamma}_{k(i}\partial_{j)}\,\beta^k - \frac{2}{3}\tilde{\gamma}_{ij}\partial_k\,\beta^k + \beta^k\partial_k\tilde{\gamma}_{ij}\,, \\
\partial_t \tilde{A}_{ij} &= \phi^2\left[-\nabla_i\nabla_j\alpha + \alpha\left(R_{ij} + \nabla_i Z_j + \nabla_j Z_i - 8\pi S_{ij}\right)\right]^{\mathrm{TF}} + \alpha\tilde{A}_{ij}\left(K - 2\Theta\right) \\
&\quad -2\alpha\tilde{A}_{il}\tilde{A}^l_j + 2\tilde{A}_{k(i}\partial_{j)}\,\beta^k - \frac{2}{3}\tilde{A}_{ij}\partial_k\,\beta^k + \beta^k\partial_k\tilde{A}_{ij}\,, \\
\partial_t \phi &= \frac{1}{3}\alpha\phi K - \frac{1}{3}\phi\partial_k\beta^k + \beta^k\partial_k\phi\,, \\
\partial_t K &= -\nabla^i\nabla_i\alpha + \alpha\left(R + 2\nabla_i Z^i + K^2 - 2\Theta K\right) + \beta^j\partial_j K - 3\alpha\kappa_1\left(1+\kappa_2\right)\Theta + 4\pi\alpha\left(S - 3\tau\right)\,, \\
\partial_t \hat{\Gamma}^i &= 2\alpha\left(\tilde{\Gamma}^i_{jk}\tilde{A}^{jk} - 3\tilde{A}^{ij}\frac{\partial_j\phi}{\phi} - \frac{2}{3}\tilde{\gamma}^{ij}\partial_j K\right) + 2\tilde{\gamma}^{ki}\left(\alpha\partial_k\Theta - \Theta\partial_k\alpha - \frac{2}{3}\alpha K Z_k\right) - 2\tilde{A}^{ij}\partial_j\alpha \\
&\quad +\tilde{\gamma}^{kl}\partial_k\partial_l\beta^i + \frac{1}{3}\tilde{\gamma}^{ik}\partial_k\partial_l\beta^l + \frac{2}{3}\tilde{\Gamma}^i\partial_k\beta^k - \tilde{\Gamma}^k\partial_k\beta^i + 2\kappa_3\left(\frac{2}{3}\tilde{\gamma}^{ij}Z_j\partial_k\beta^k - \tilde{\gamma}^{jk}Z_j\partial_k\beta^i\right) \\
&\quad +\beta^k\partial_k\hat{\Gamma}^i - 2\alpha\kappa_1\tilde{\gamma}^{ij}Z_j - 16\pi\alpha\tilde{\gamma}^{ij}S_j\,, \\
\partial_t \Theta &= \frac{1}{2}\alpha\left(R + 2\nabla_i Z^i - \tilde{A}_{ij}\tilde{A}^{ij} + \frac{2}{3}K^2 - 2\Theta K\right) - Z^i\partial_i\alpha + \beta^k\partial_k\Theta - \alpha\kappa_1\left(2+\kappa_2\right)\Theta - 8\pi\alpha\,\tau\,, \\
\partial_t \alpha &= -2\alpha\left(K - 2\Theta\right) + \beta^k\partial_k\alpha\,, \\
\partial_t \beta^i &= f B^i + \beta^k\partial_k\beta^i\,, \\
\partial_t B^i &= \partial_t\hat{\Gamma}^i - \beta^k\partial_k\hat{\Gamma}^i + \beta^k\partial_k B^i - \eta B^i\,,
\end{aligned}
$$

CCZ4 formulation

GR in non-vacuum

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

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

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

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

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

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

$$\nabla_\mu T^{\mu\nu}_{\text{rad}} = S^\nu \,, \quad \text{(radiative losses)}$$

Animations: Breu, Radice, LR

A prototypical simulation with possibly the best code looks like this…



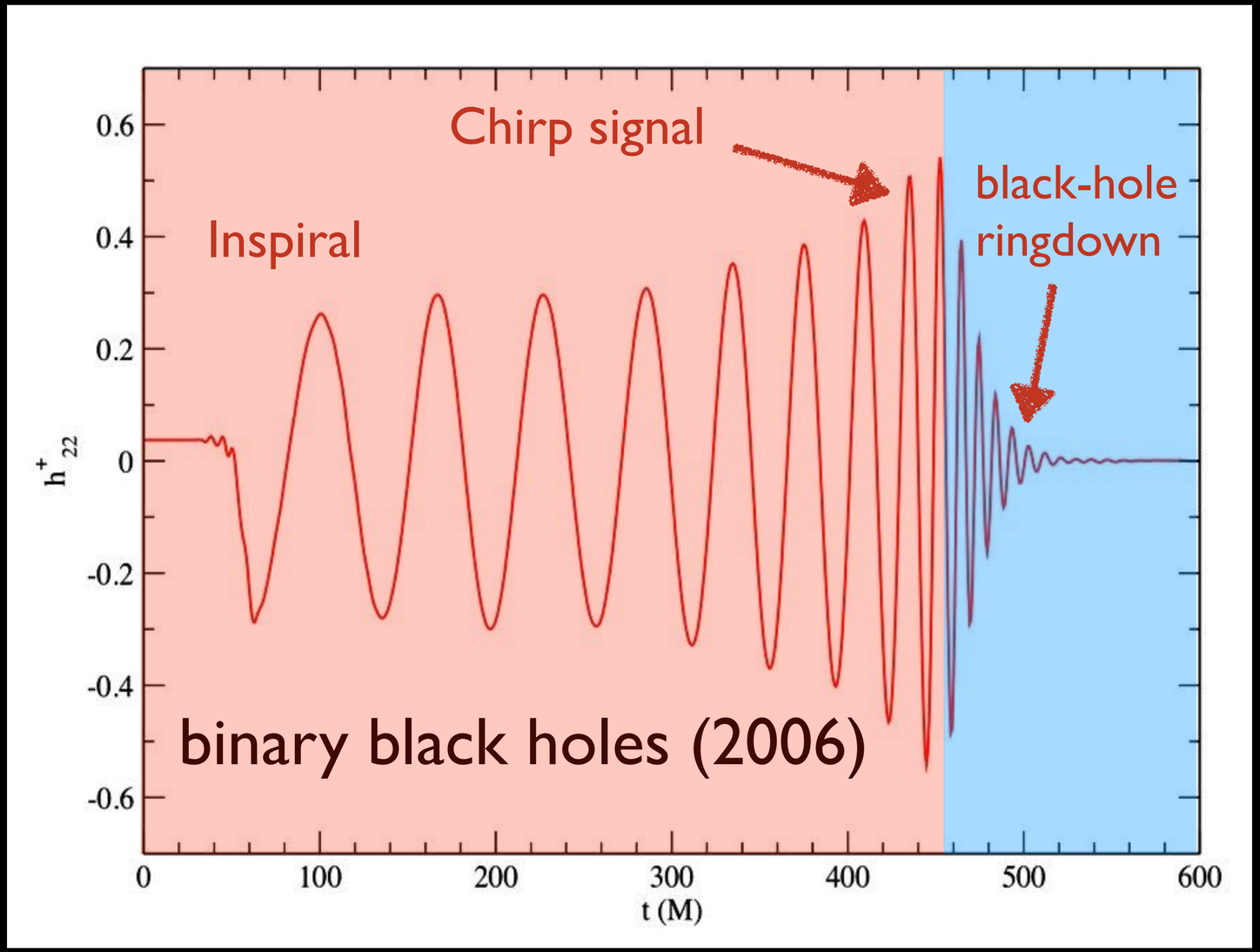
merger → HMNS → BH + torus

$M = 2 \times 1.35\, M_\odot$

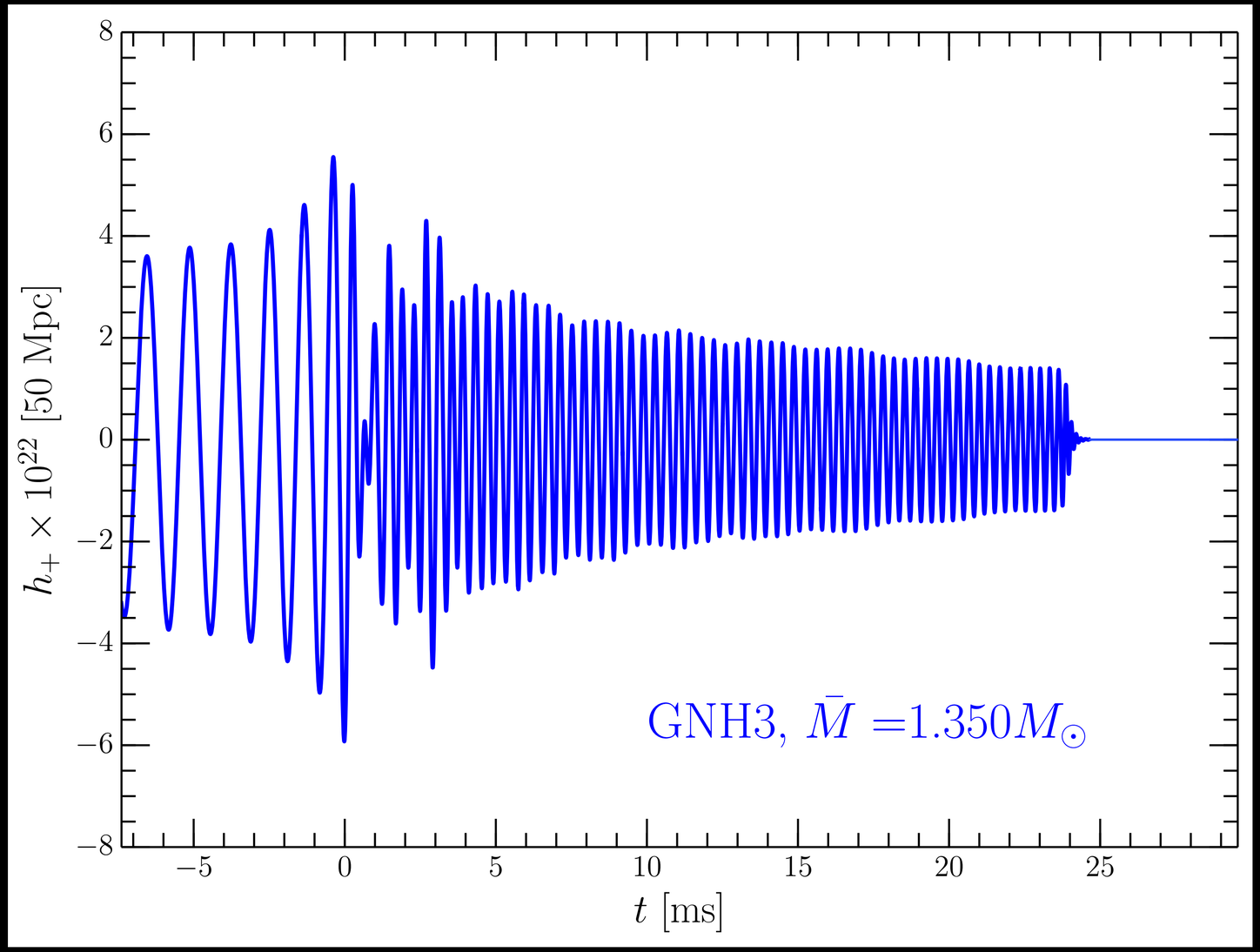
timescale for all this is 0.01-1 sec

LS220 EOS

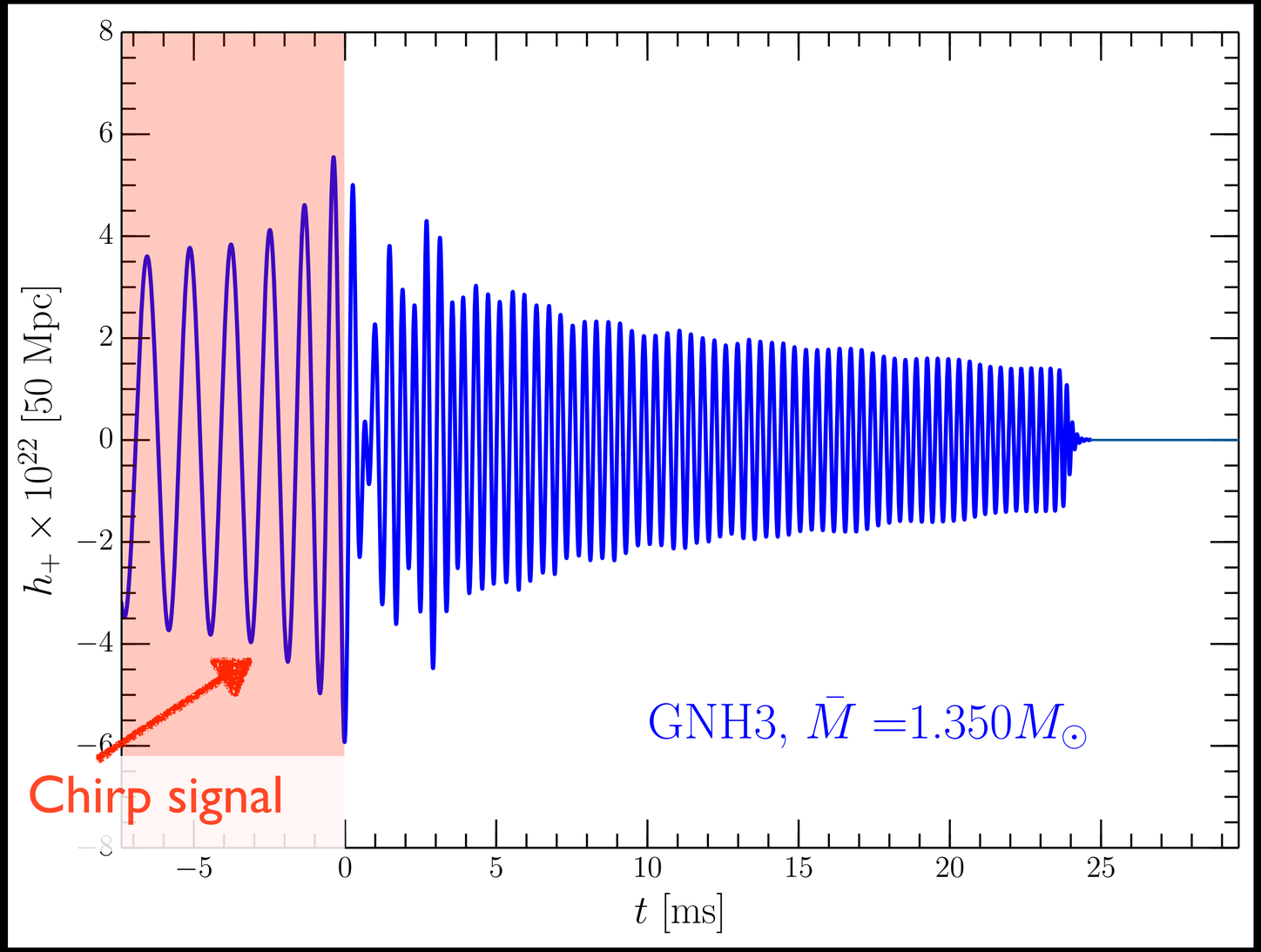
Anatomy of the GW signal



Anatomy of the GW signal

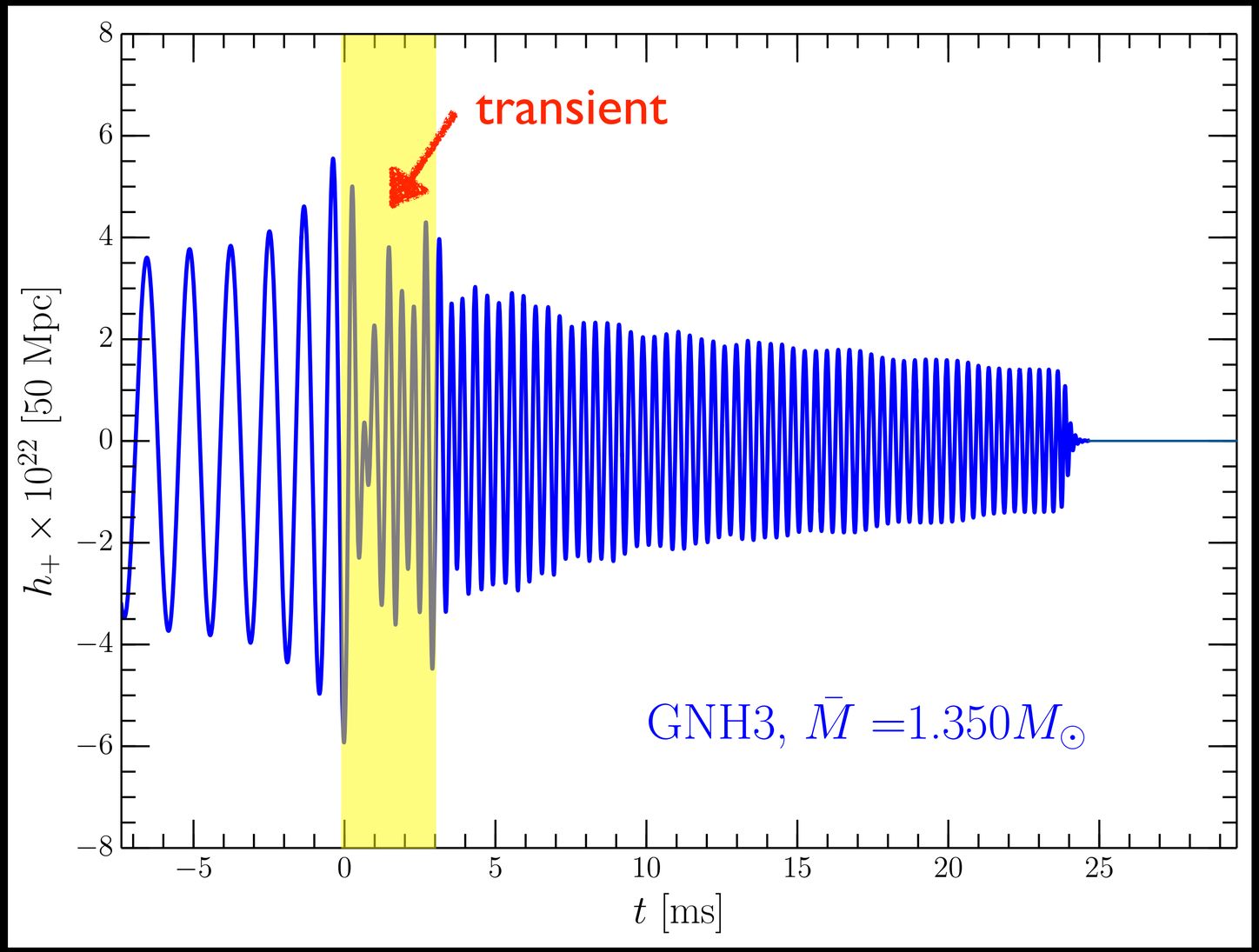


Anatomy of the GW signal



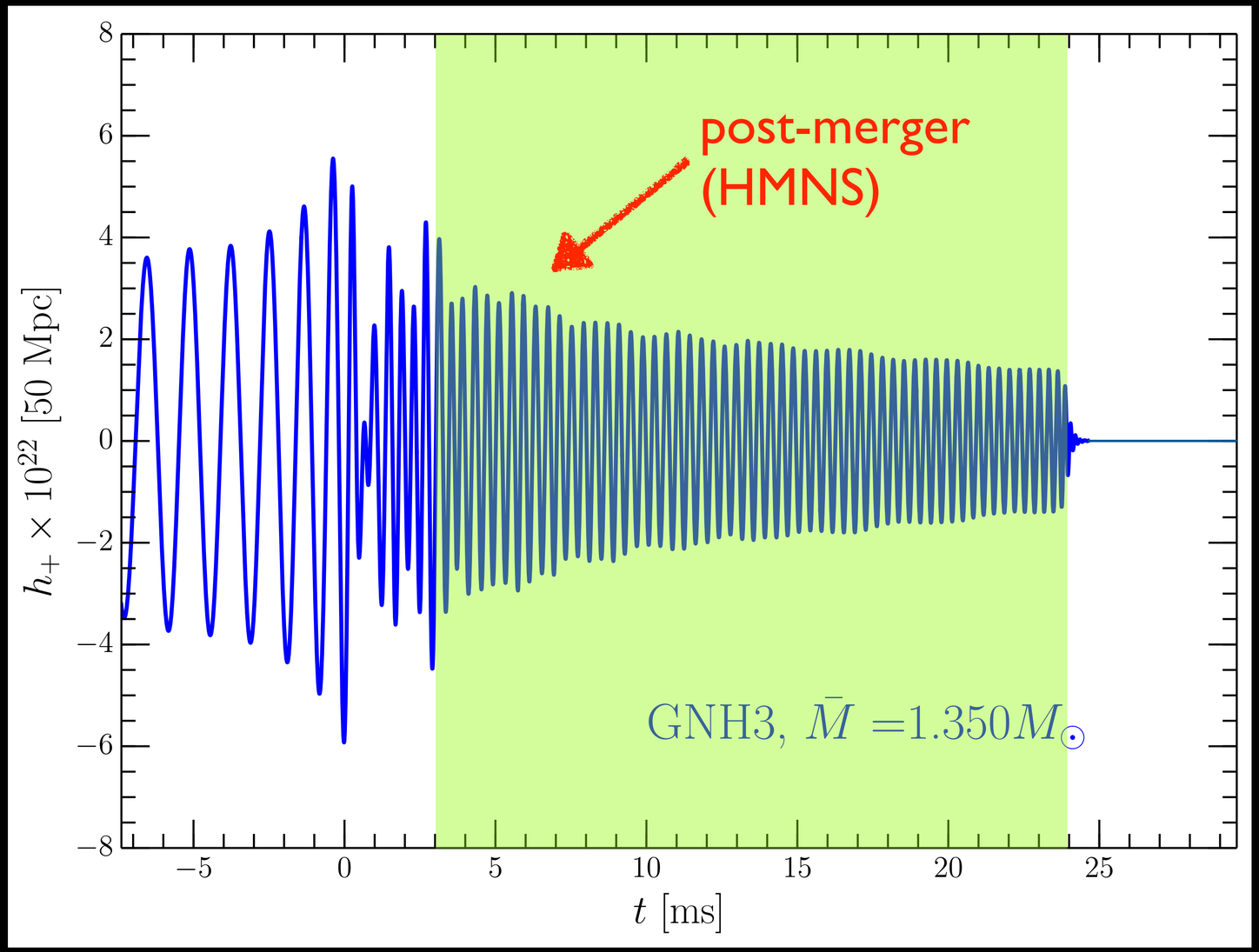
Inspiral: well approximated by PN/EOB; tidal effects important

Anatomy of the GW signal



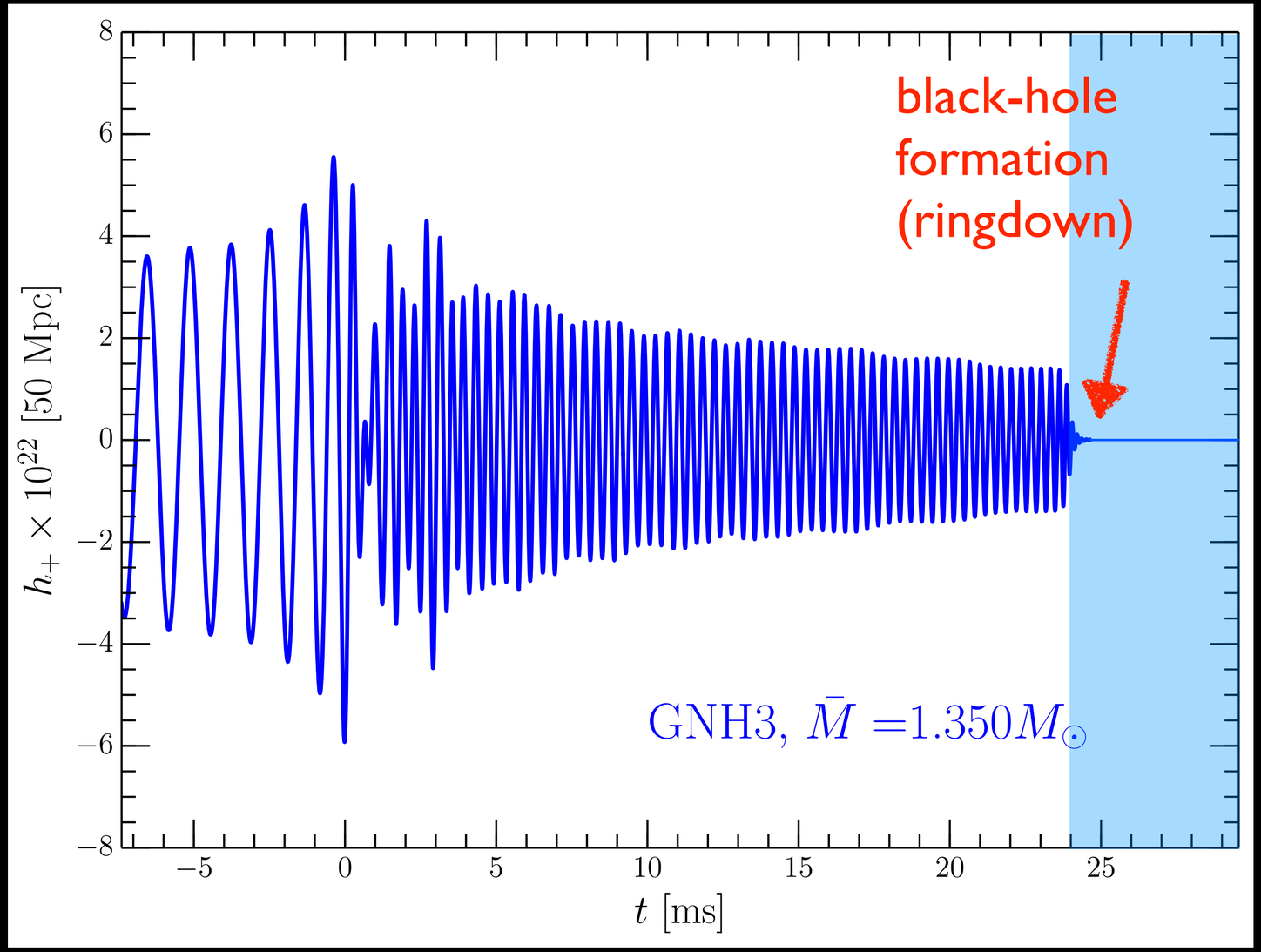
Merger: highly nonlinear but analytic description possible

Anatomy of the GW signal



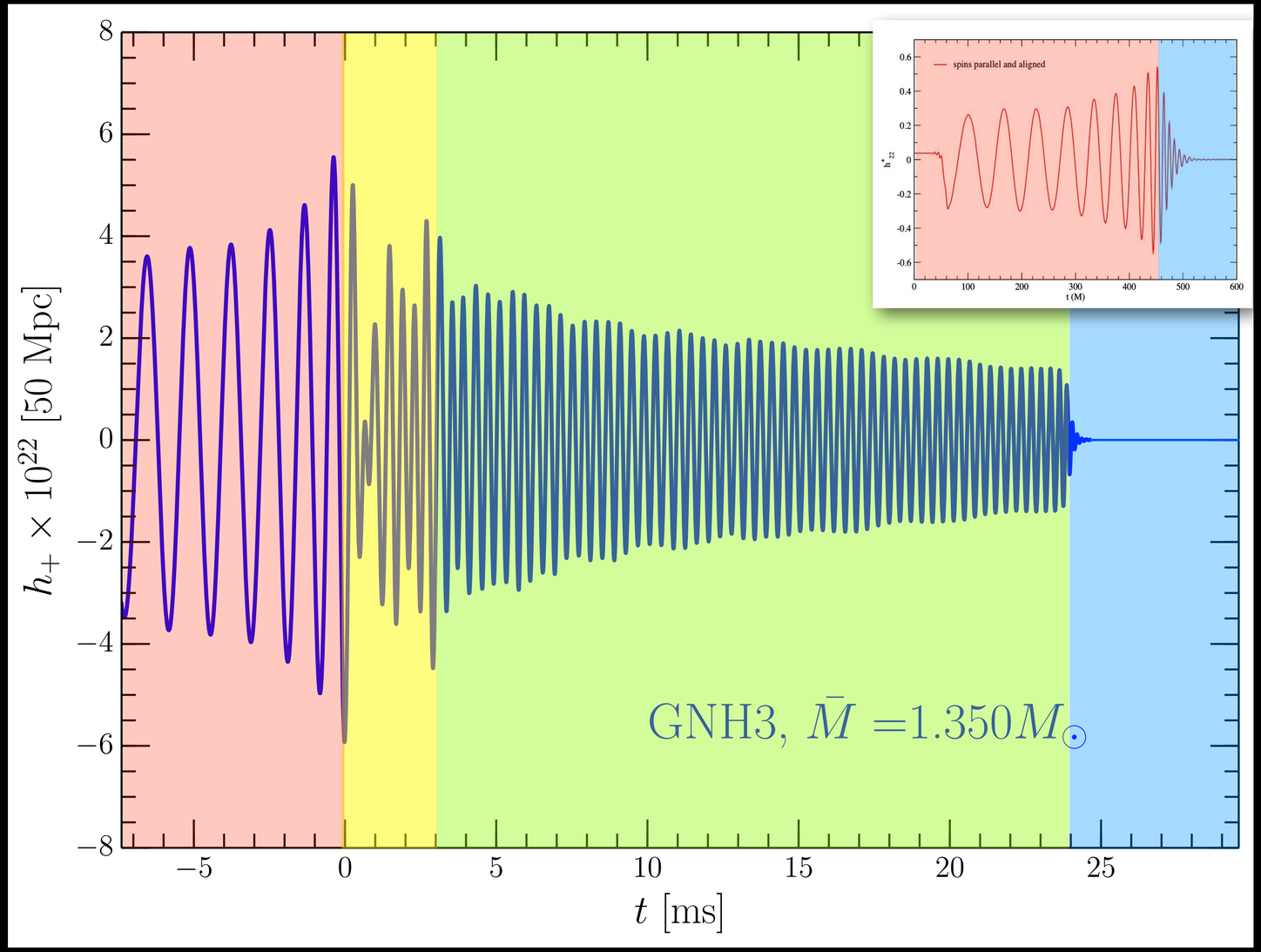
post-merger: quasi-periodic emission of bar-deformed HMNS

Anatomy of the GW signal



Collapse-ringdown: signal essentially shuts off

Anatomy of the GW signal

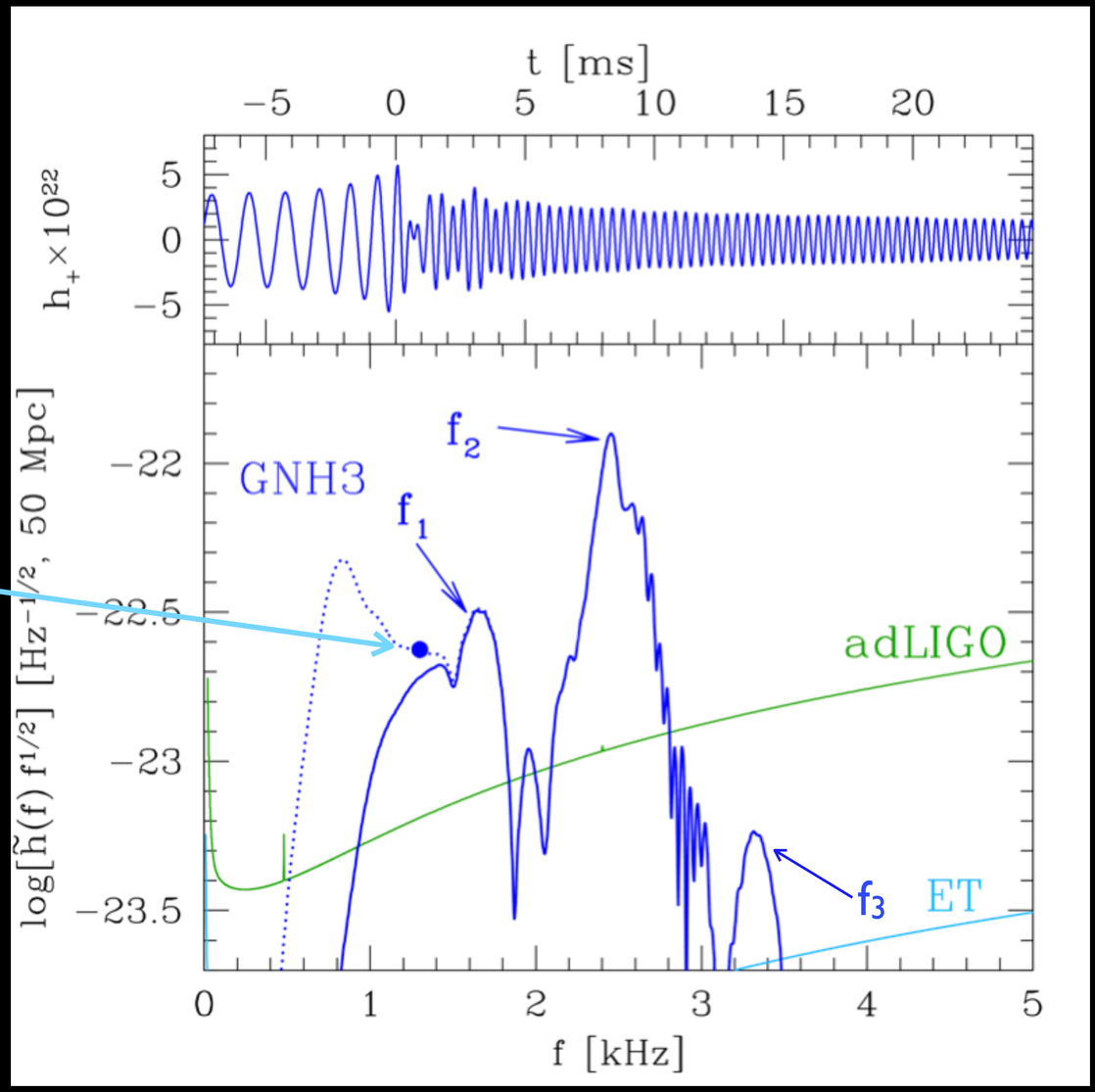


Postmerger signal: peculiar of binary NSs

A spectroscopic approach to the EOS

Oechslin+2007, Baiotti+2008, Bauswein+ 2011, 2012, Stergioulas+ 2011, Hotokezaka+ 2013, Takami 2014, 2015, Bernuzzi 2014, 2015, Bauswein+ 2015, Clark+ 2016, LR+2016, de Pietri+ 2016, Feo+ 2017, Bose+ 2017 …

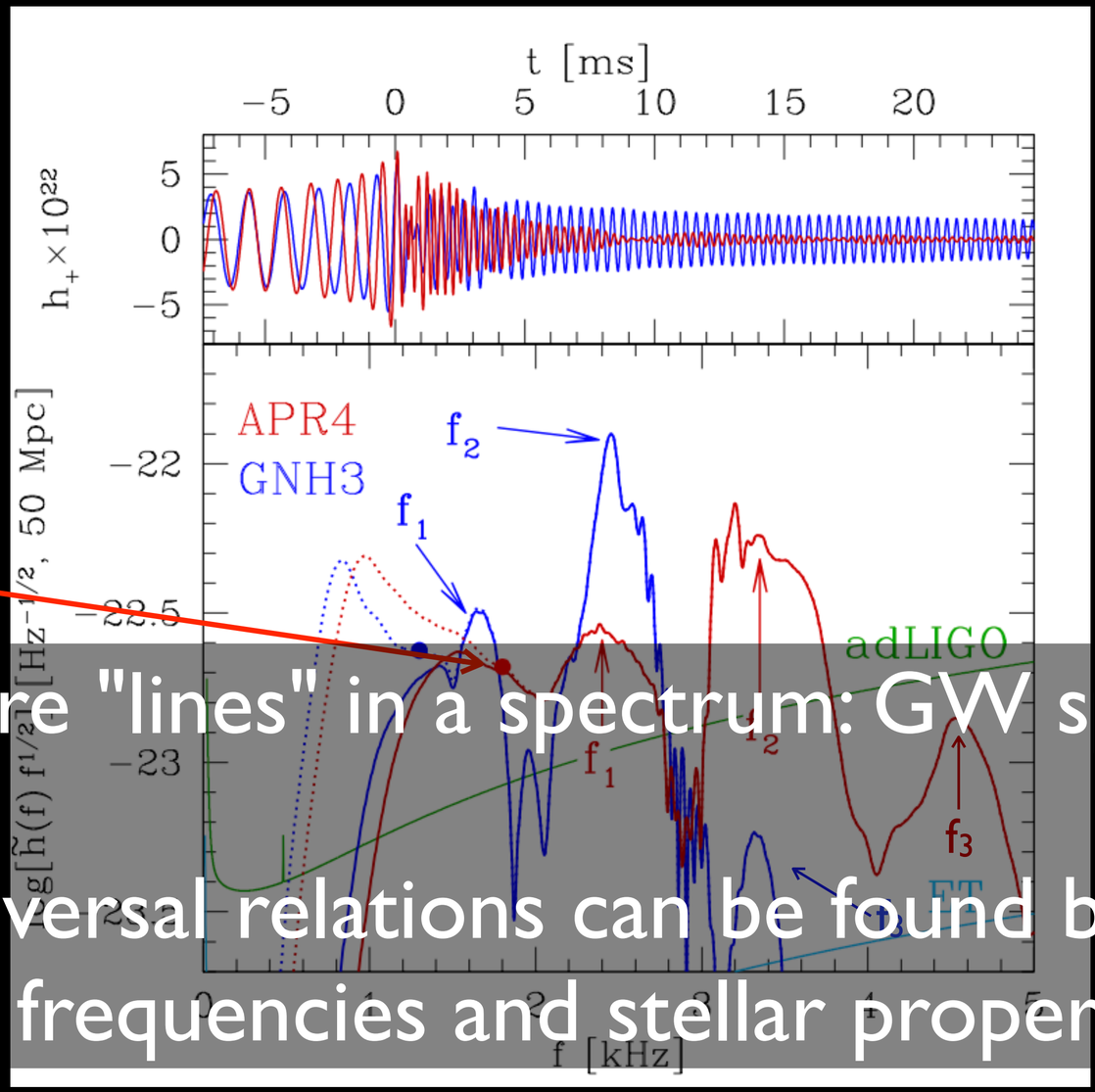
merger frequency



A spectroscopic approach to the EOS

Oechslin+2007, Baiotti+2008, Bauswein+ 2011, 2012, Stergioulas+ 2011, Hotokezaka+ 2013, Takami 2014, 2015, Bernuzzi 2014, 2015, Bauswein+ 2015, Clark+ 2016, LR+2016, de Pietri+ 2016, Feo+ 2017, Bose+ 2017 …

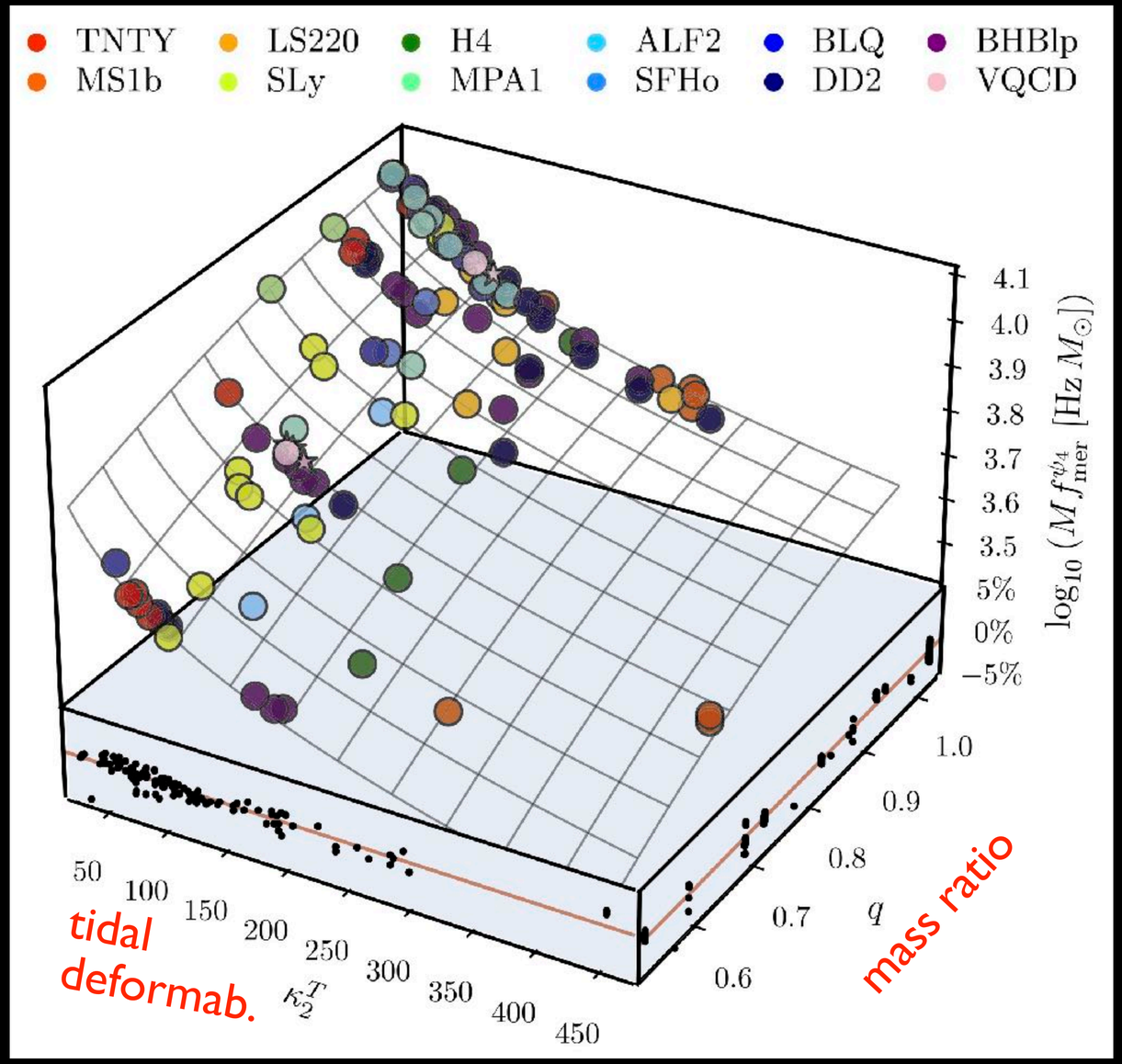
merger frequency



These are "lines" in a spectrum: GW spectroscopy

Universal relations can be found between frequencies and stellar properties

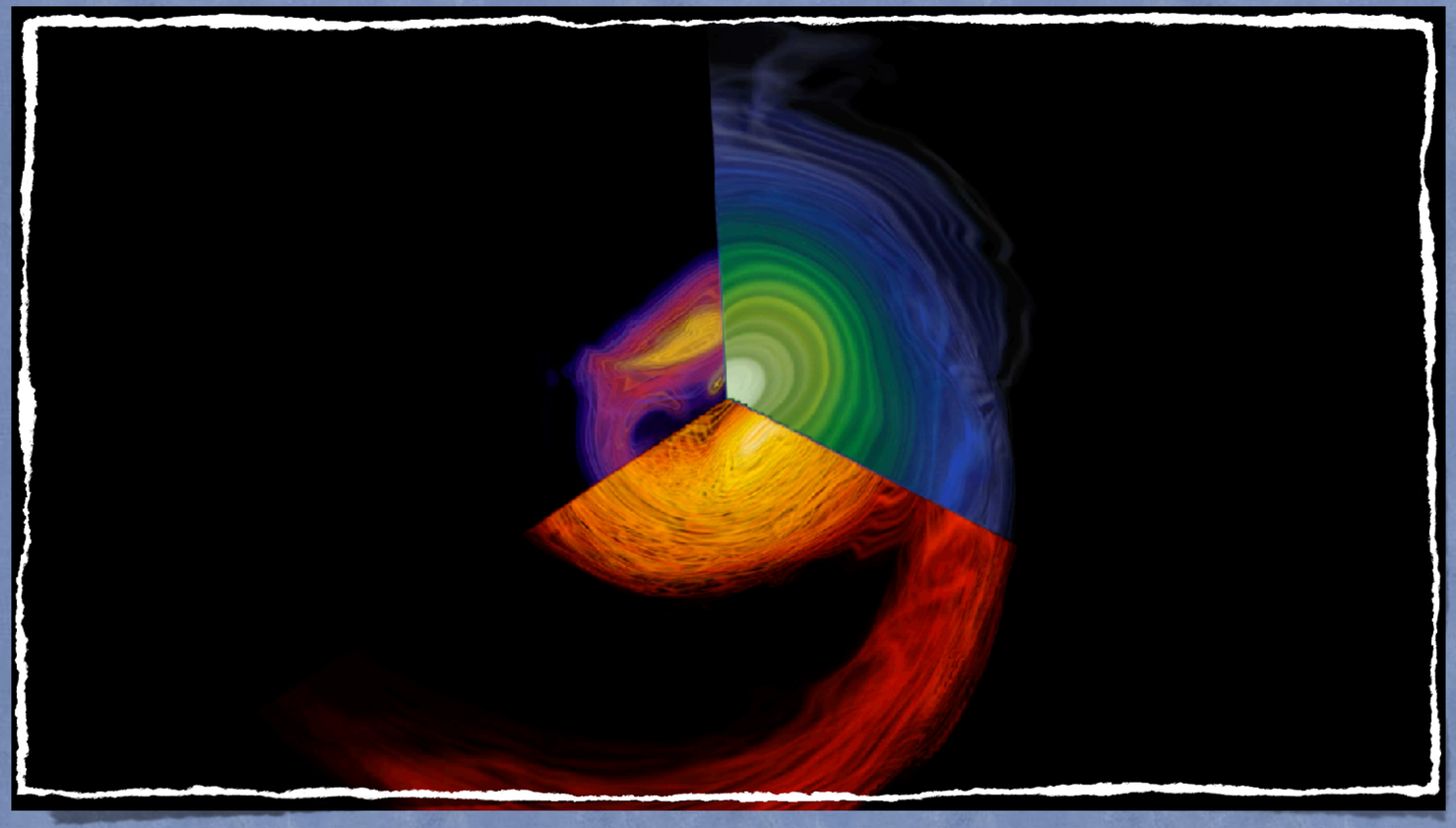
Example of quasi-universal behaviour: f_{max}



Quasi-universal behaviour of GW frequency at amplitude peak (Baiotti, LR 2016, Radice+2022 for reviews)

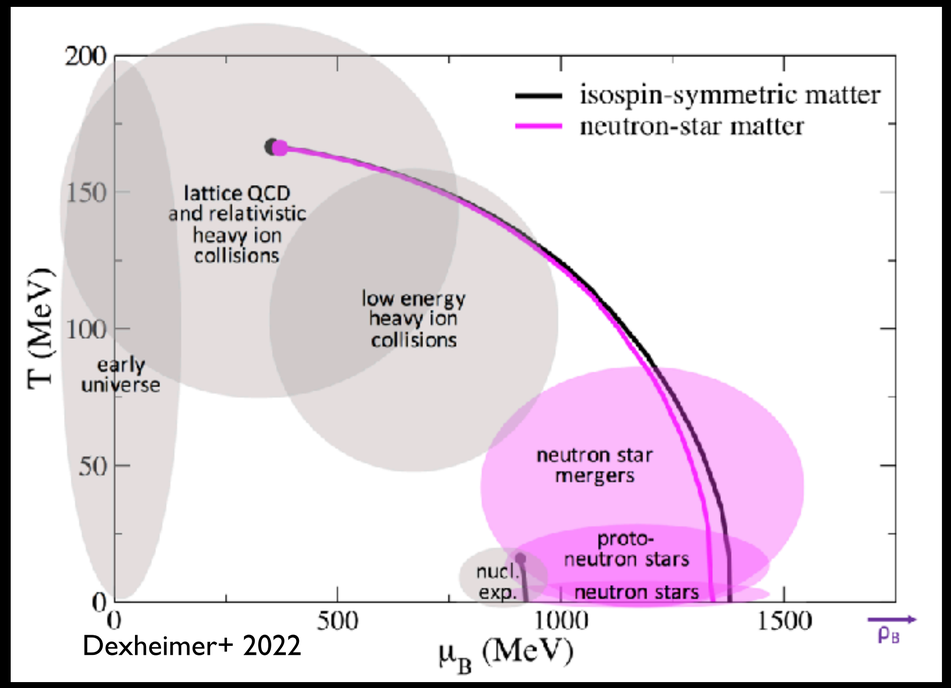
In other words, once $f_{\rm mer}$ is measured, so is the tidal deformability but also $I, Q, M/R\ldots$

Beyond pure hadronic NSs

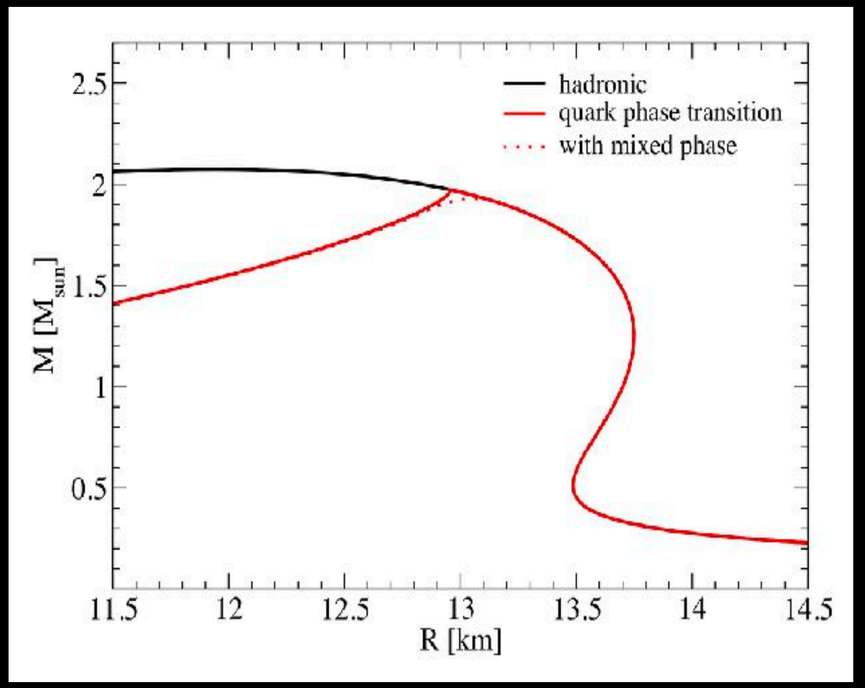


Most, Papenfort, Dexheimer, Hanauske, Schramm, Stoecker, LR (2019)
Weih, Hanauske, LR (2020)
Tootle, Ecker, Topolski, Demircik, Järvinen, LR (2022)

- Neutron-star **binary** mergers reach temperatures up to **80 MeV** and probe regions complementary to accelerator experiments

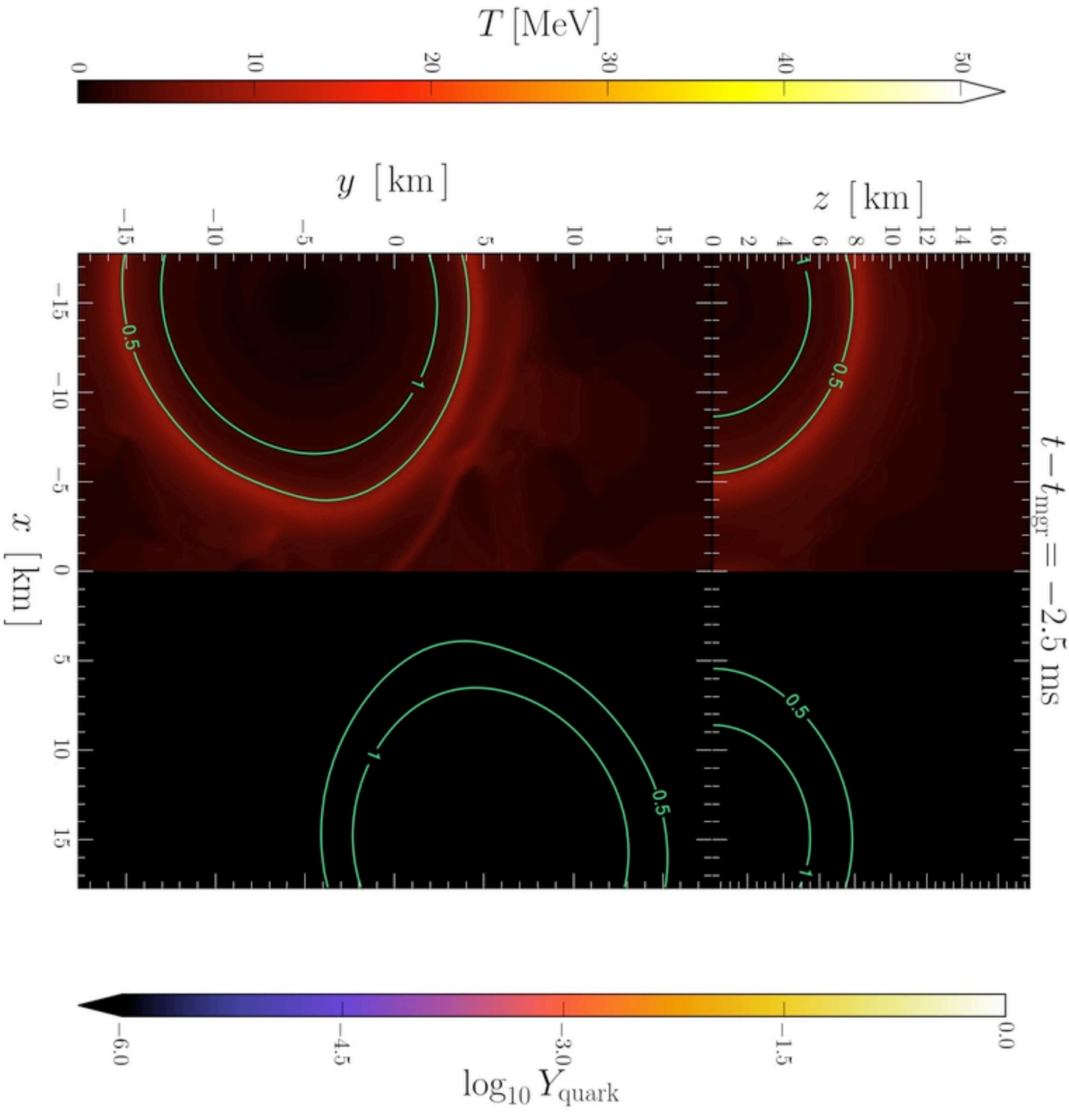


Dexheimer+ 2022

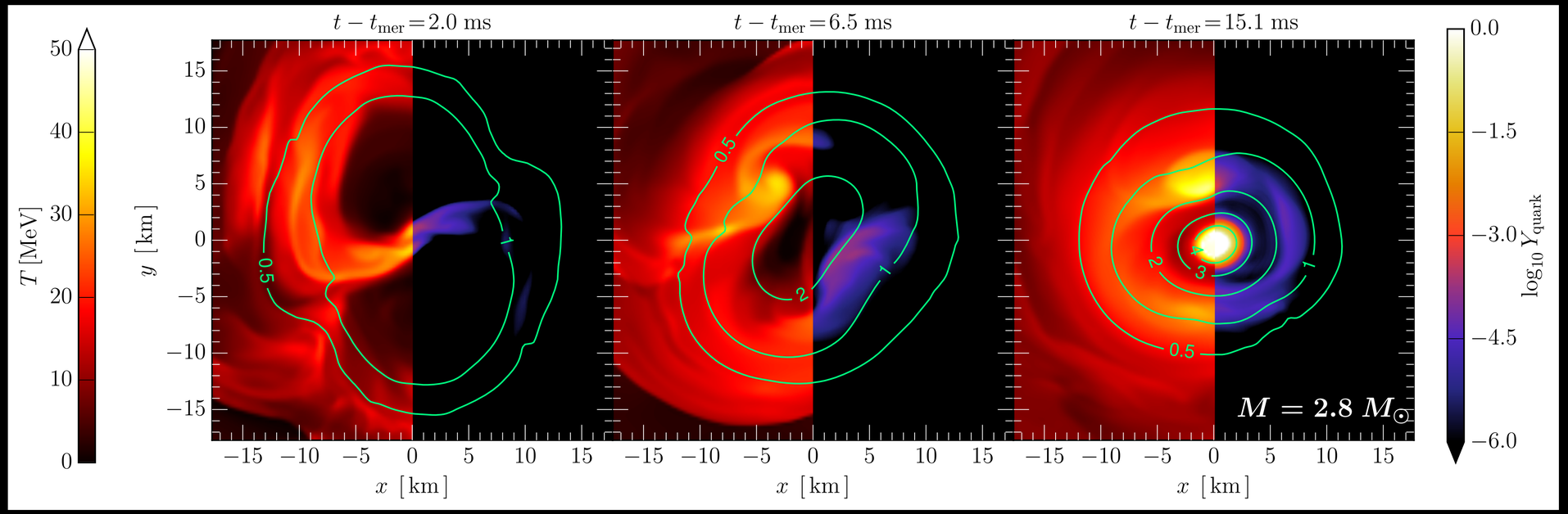


- Considered EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model.

Temperature



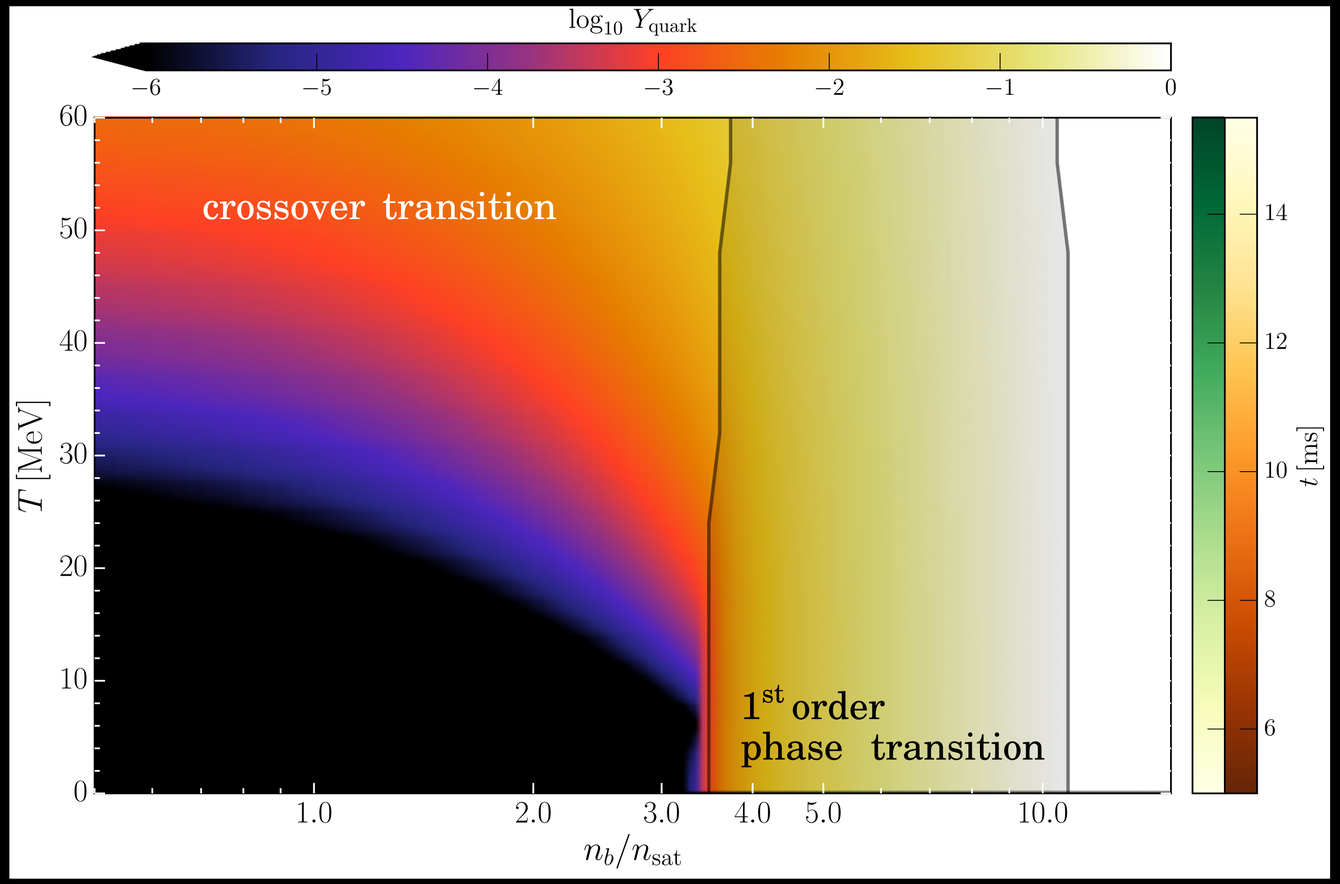
Quark fraction



Quarks appear at sufficiently large temperatures and densities.

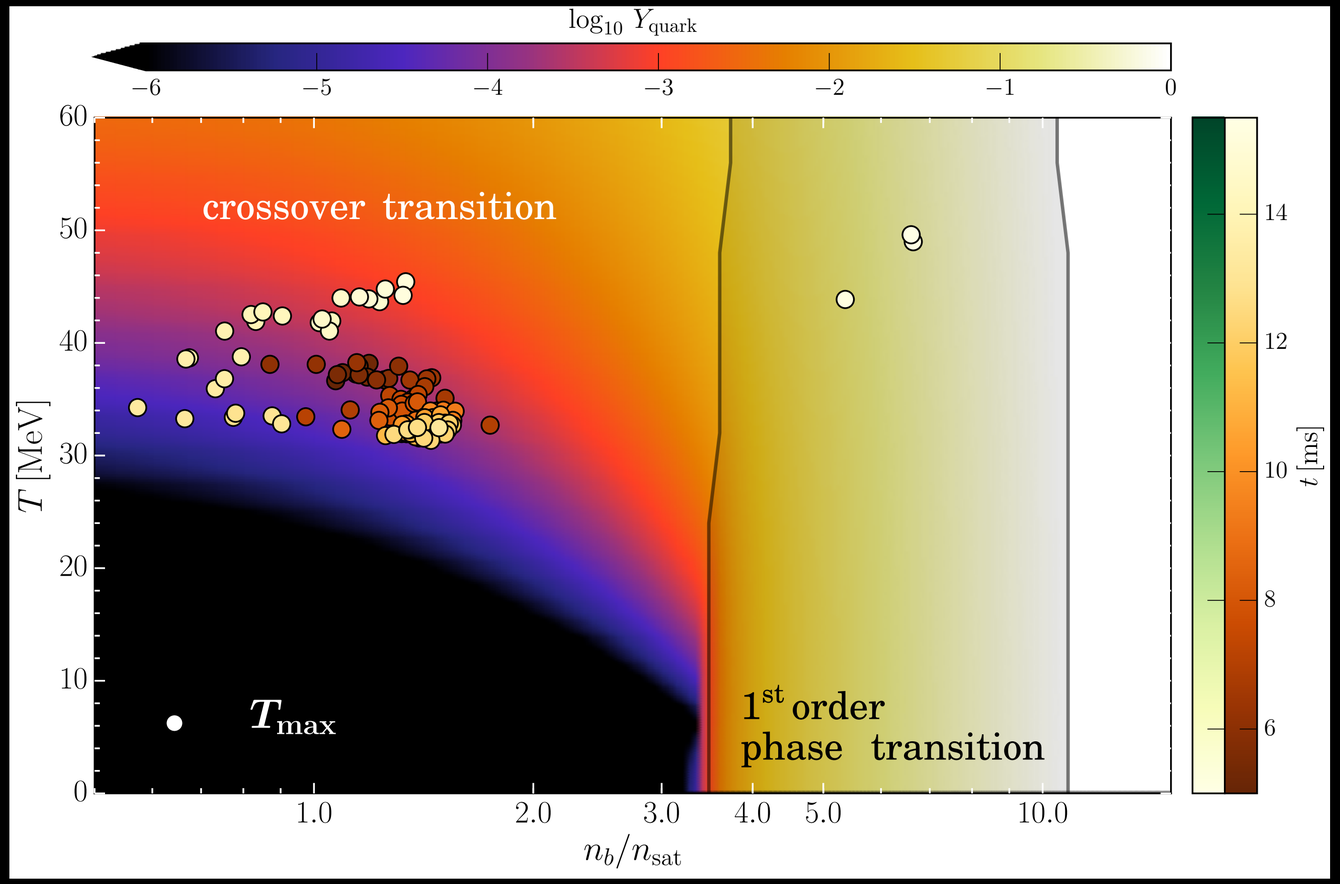
When this happens the EOS is considerably softened and a BH produced.

Comparing with the phase diagram



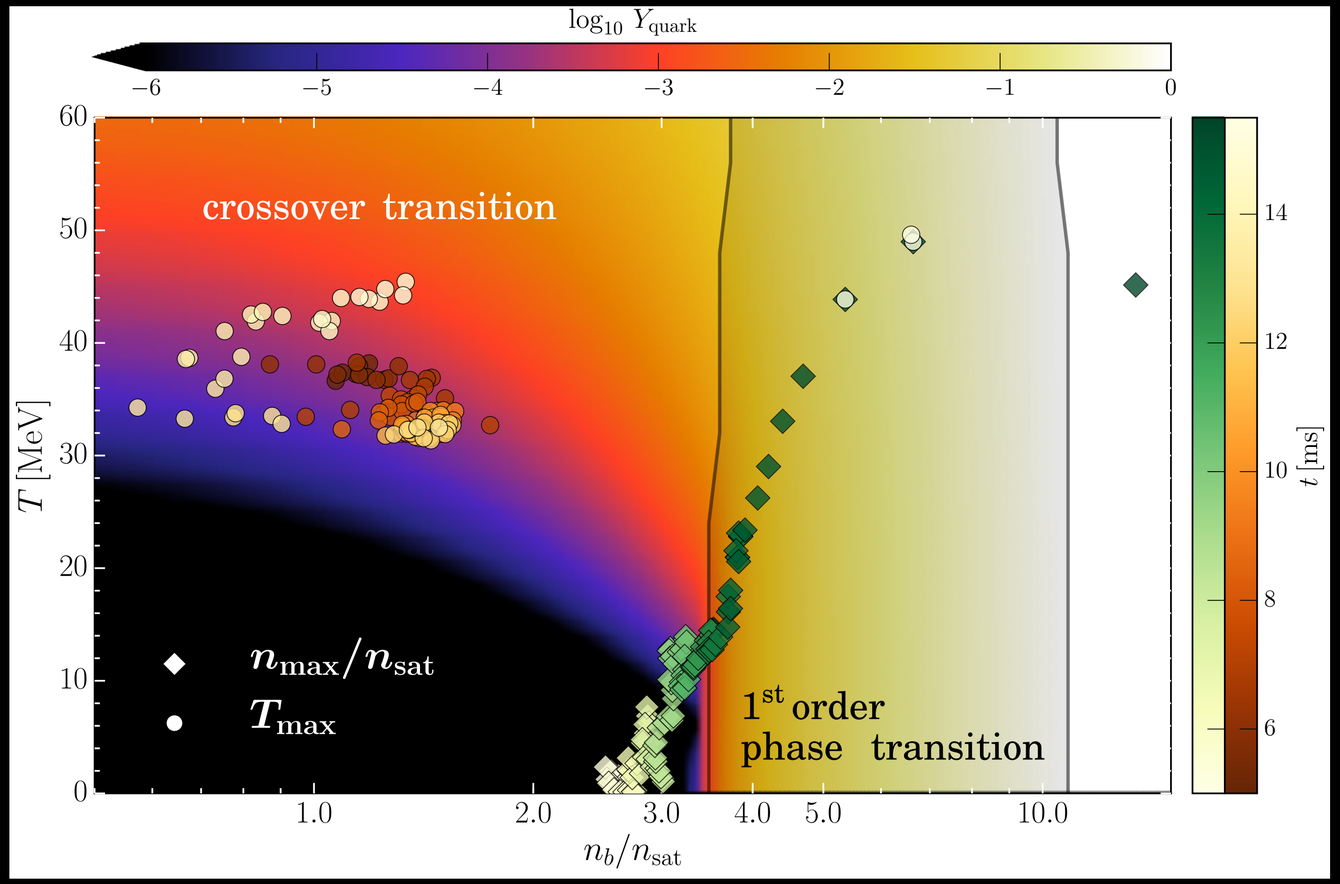
- Phase diagram with quark fraction

Comparing with the phase diagram



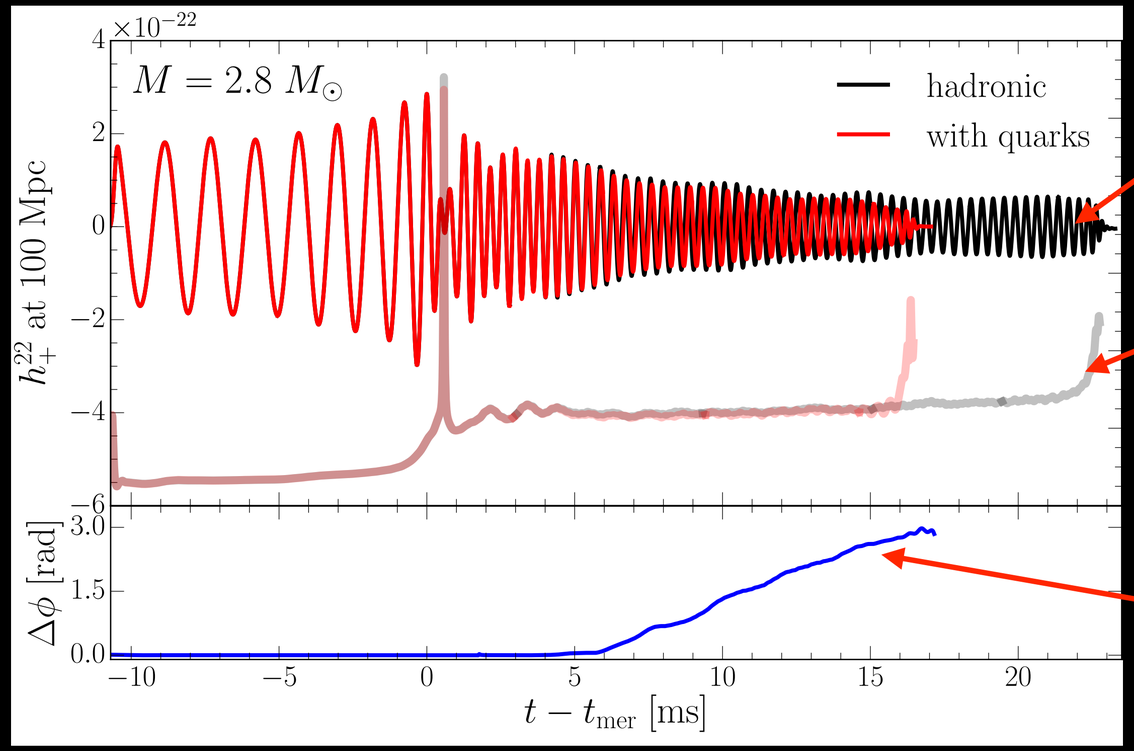
- Phase diagram with quark fraction
- Circles show the position in the diagram of the maximum temperature as a function of time

Comparing with the phase diagram



- Reported are the evolution of the max. temperature and density.
- Quarks appear already early on, but only in small fractions.
- Once sufficient density is reached, a full phase transition takes place.

Gravitational-wave emission



waveforms

GW frequencies

phase difference

- After ~5 ms, quark fraction large enough to yield differences in GWs
- Softening of PT leads to collapse and **different** phase evolution.

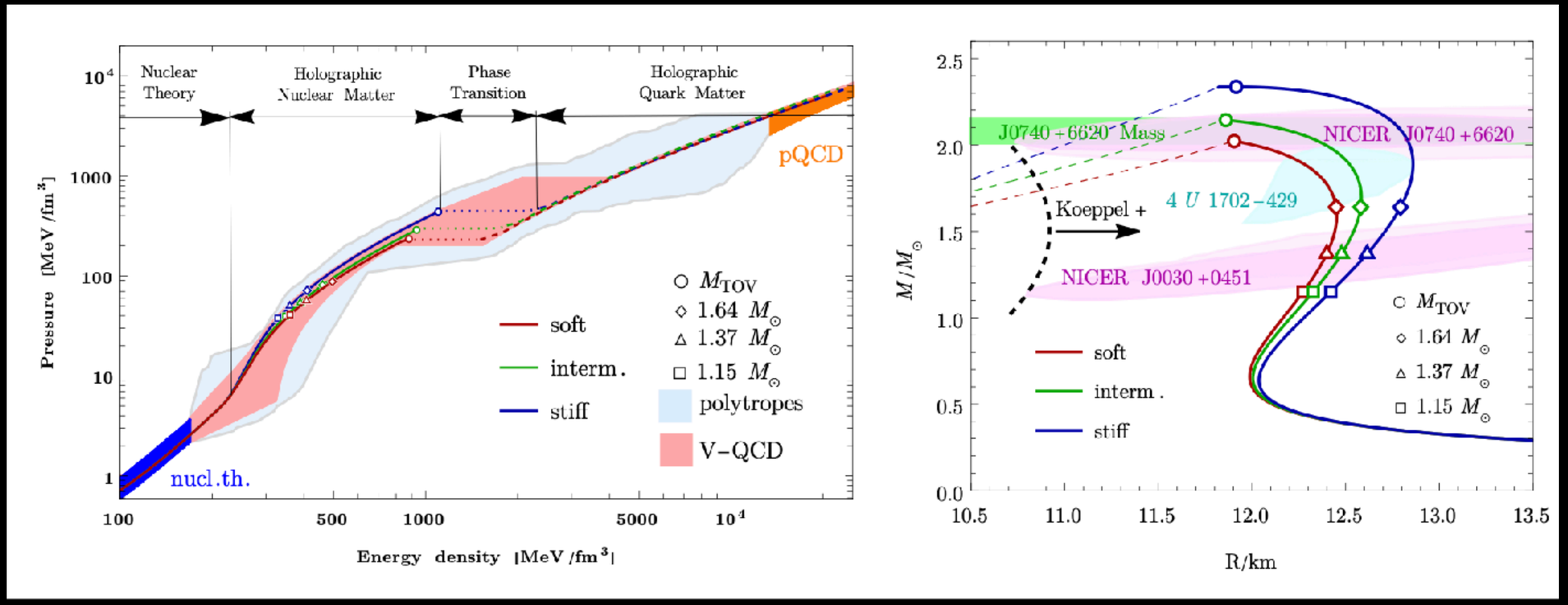
Observing mismatch between **inspiral** (fully hadronic) and **post-merger** (phase transition): clear **signature** of a **PT**

Using a more consistent EOS: V-QCD

Tootle, Ecker, Topolski, Demircik, Järvinen, LR (2022)

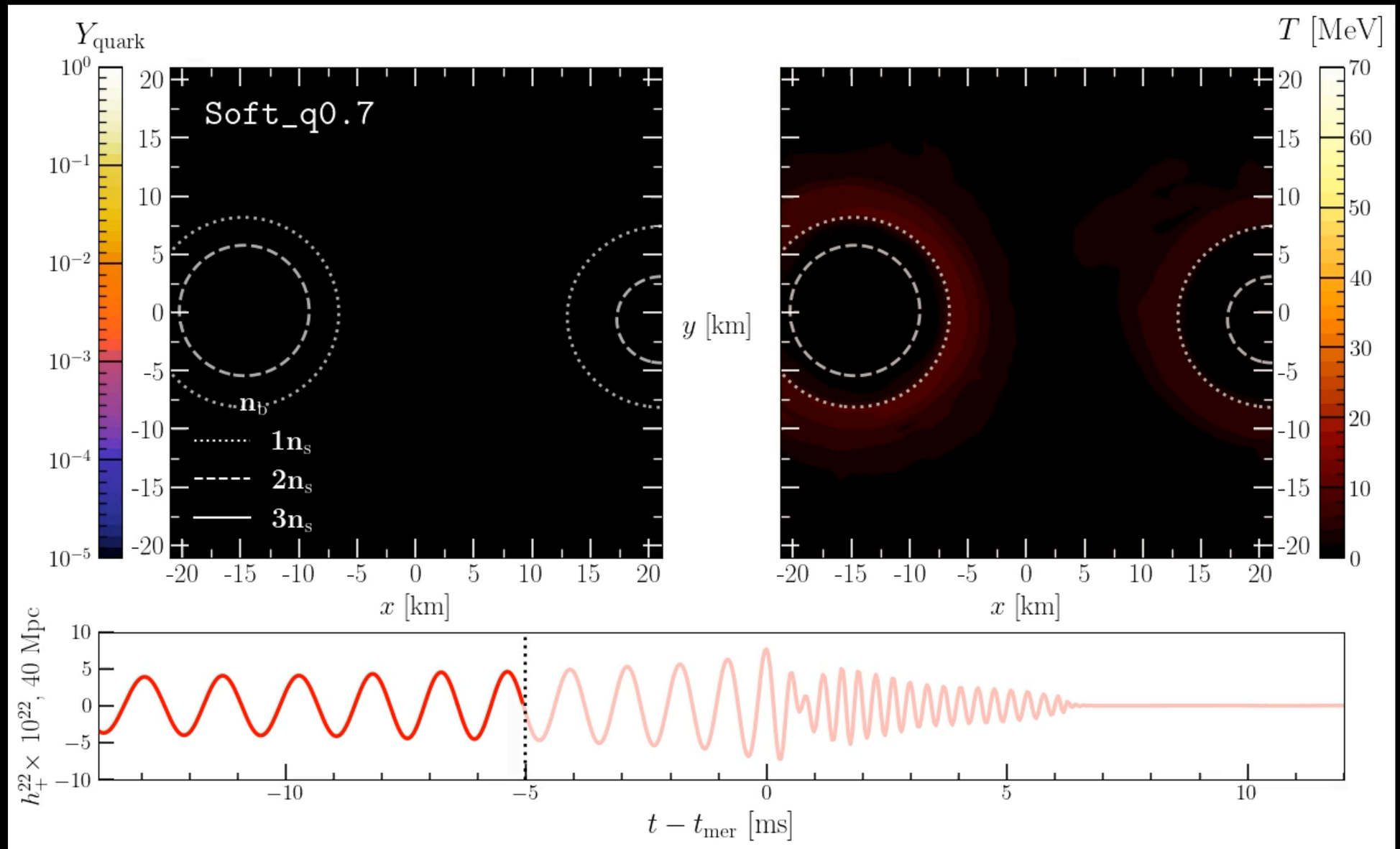
Thermal effects need consistent treatment. Used V-QCD model (Demircik+ 2021) and three variants in terms of stiffness.

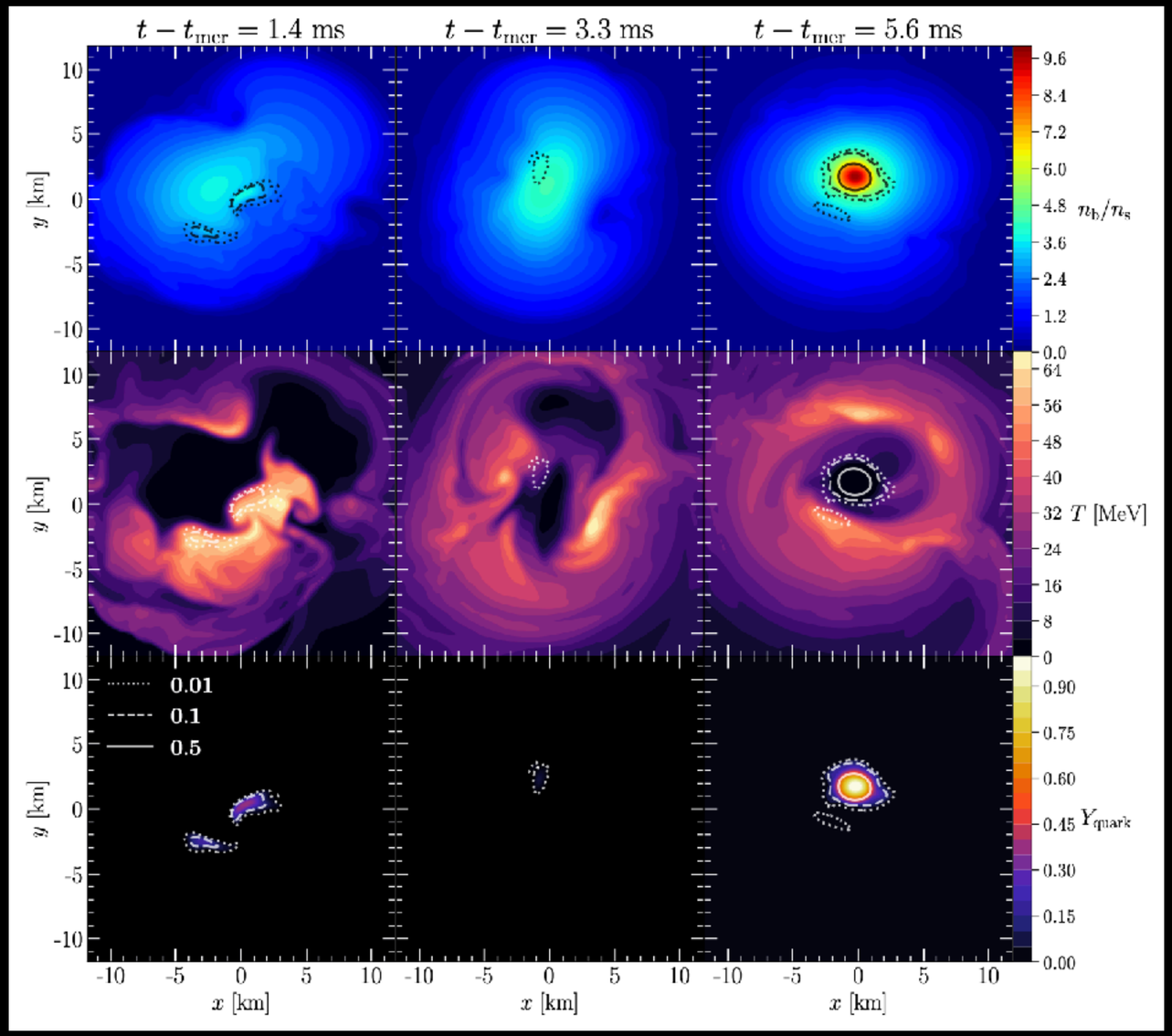
Q: could GW170817 have collapsed as a result of PT?



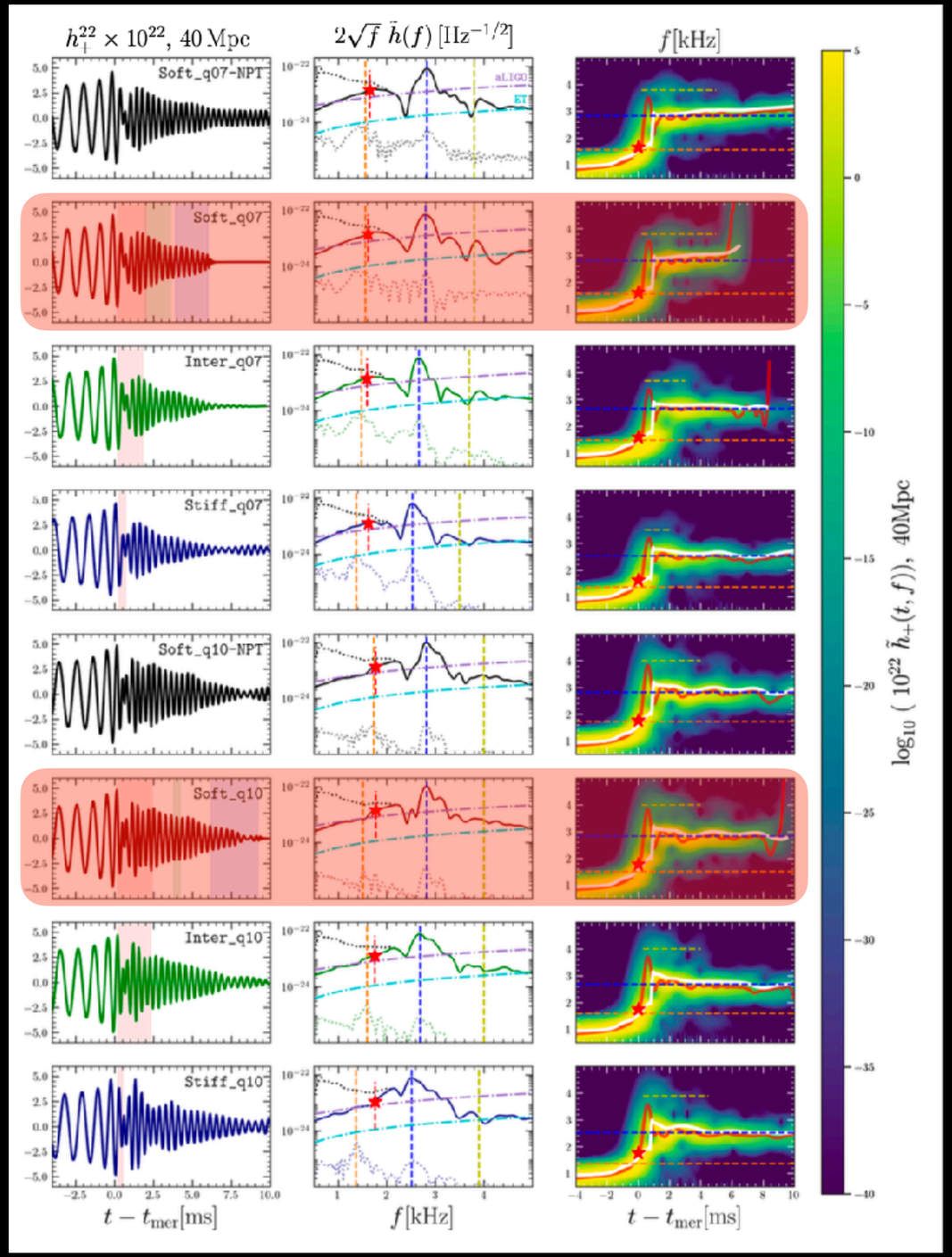
More consistent microphysics: V-QCD

Tootle, Ecker, Topolski, Demircik, Järvinen, LR (2022)





The dynamics is very similar to previous simplified thermal treatment: as soon as the PT takes place, softening induces a rapid collapse.



From GWs to the phase diagram

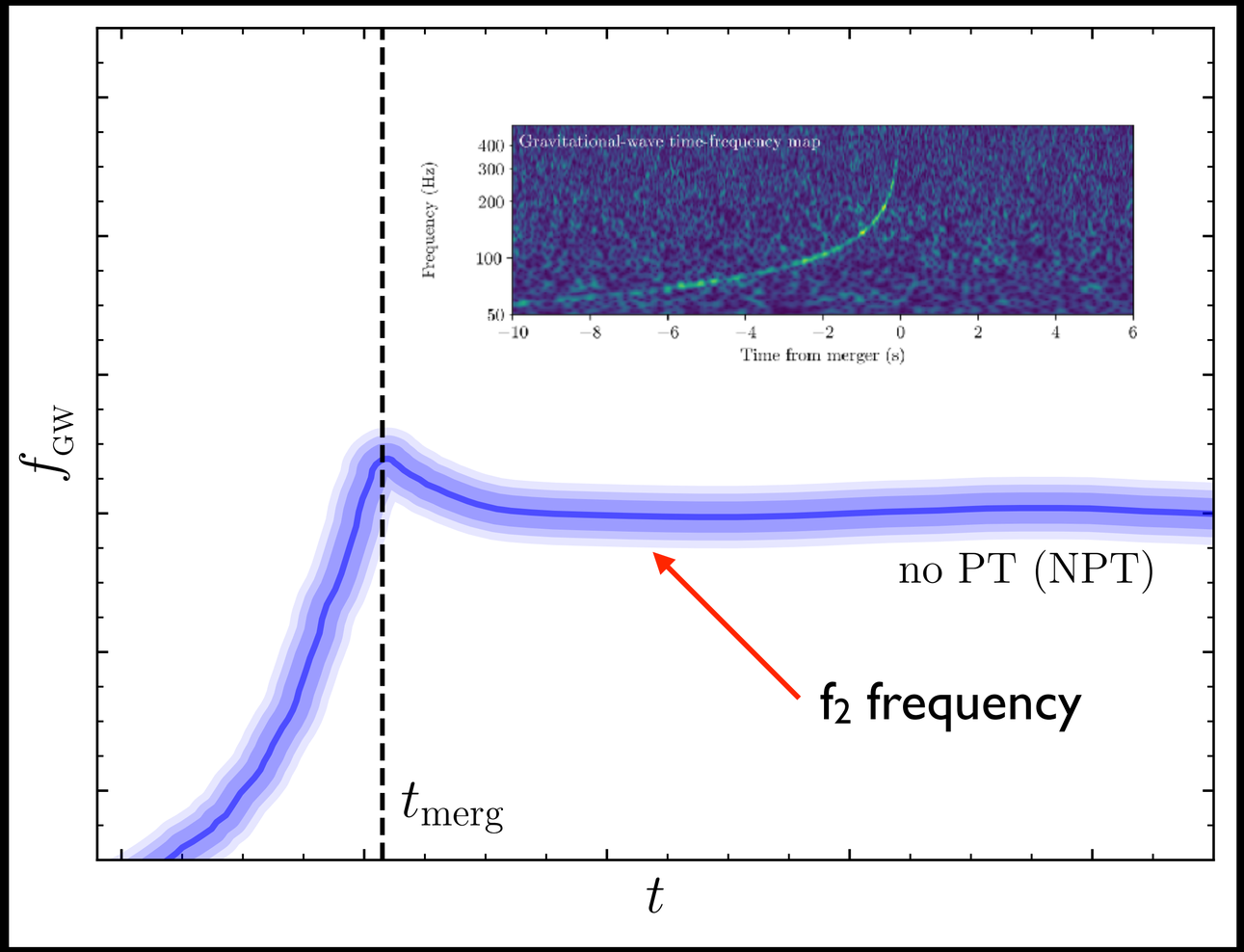
Soft version of V-QCD ruled out by **GW170817:** collapse too early.

Expectation is the collapse has been after 0.9 s.

Example that GW events can constrain appearance of QCD PT.

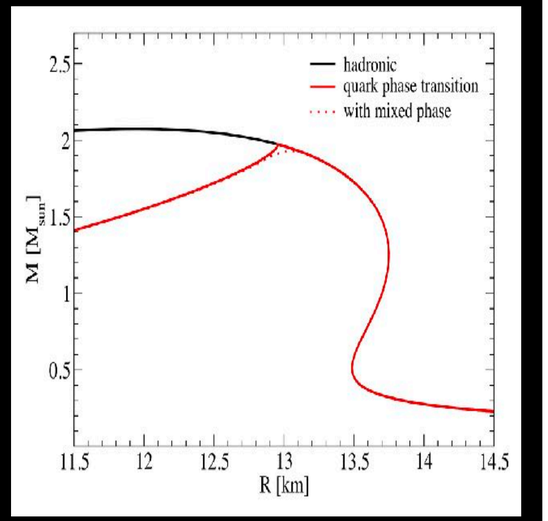
A zoology of possible behaviours

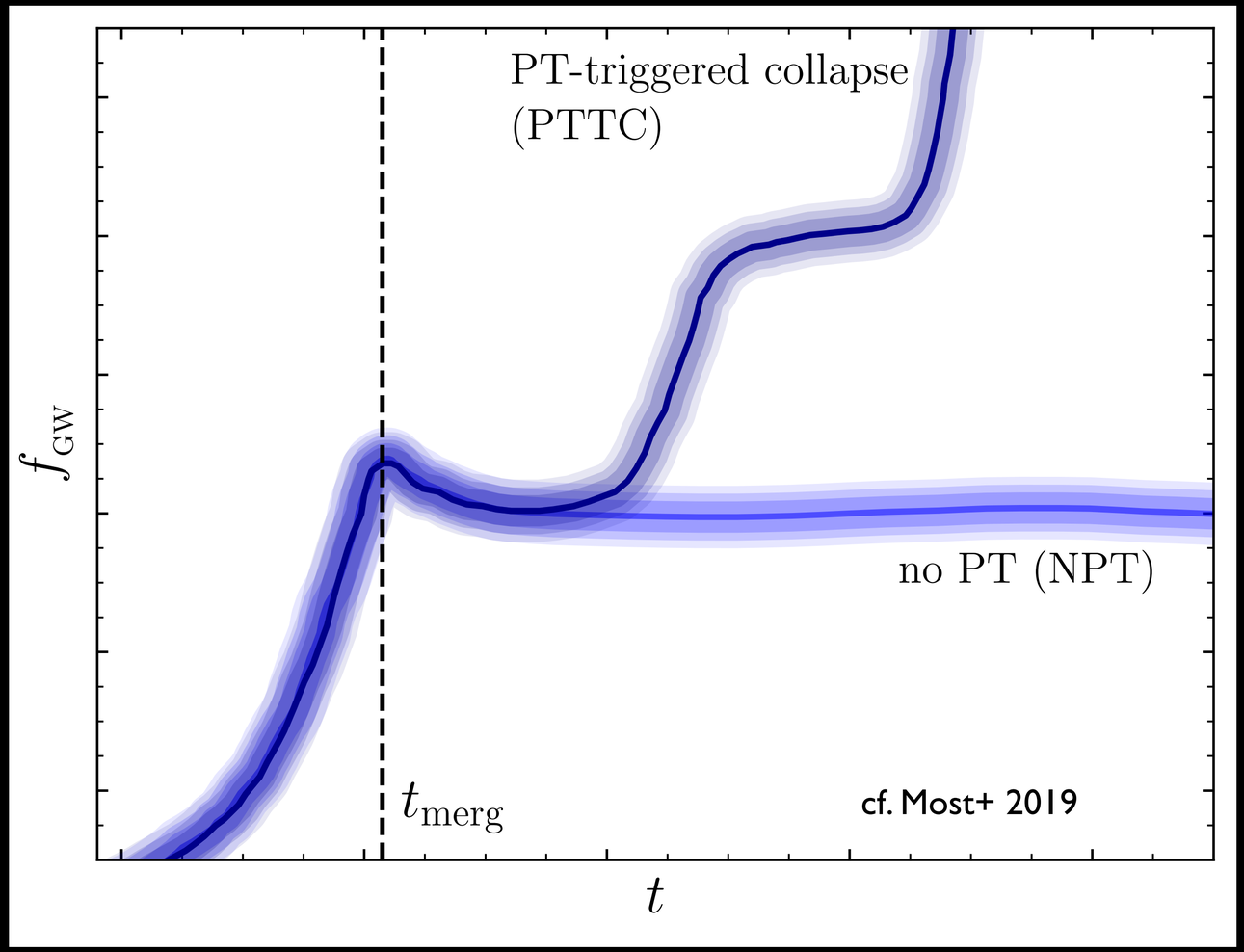
The occurrence of a PT can take place in a number of different ways.
What shown is only one. Here are the other possibilities:



A zoology of possible behaviours

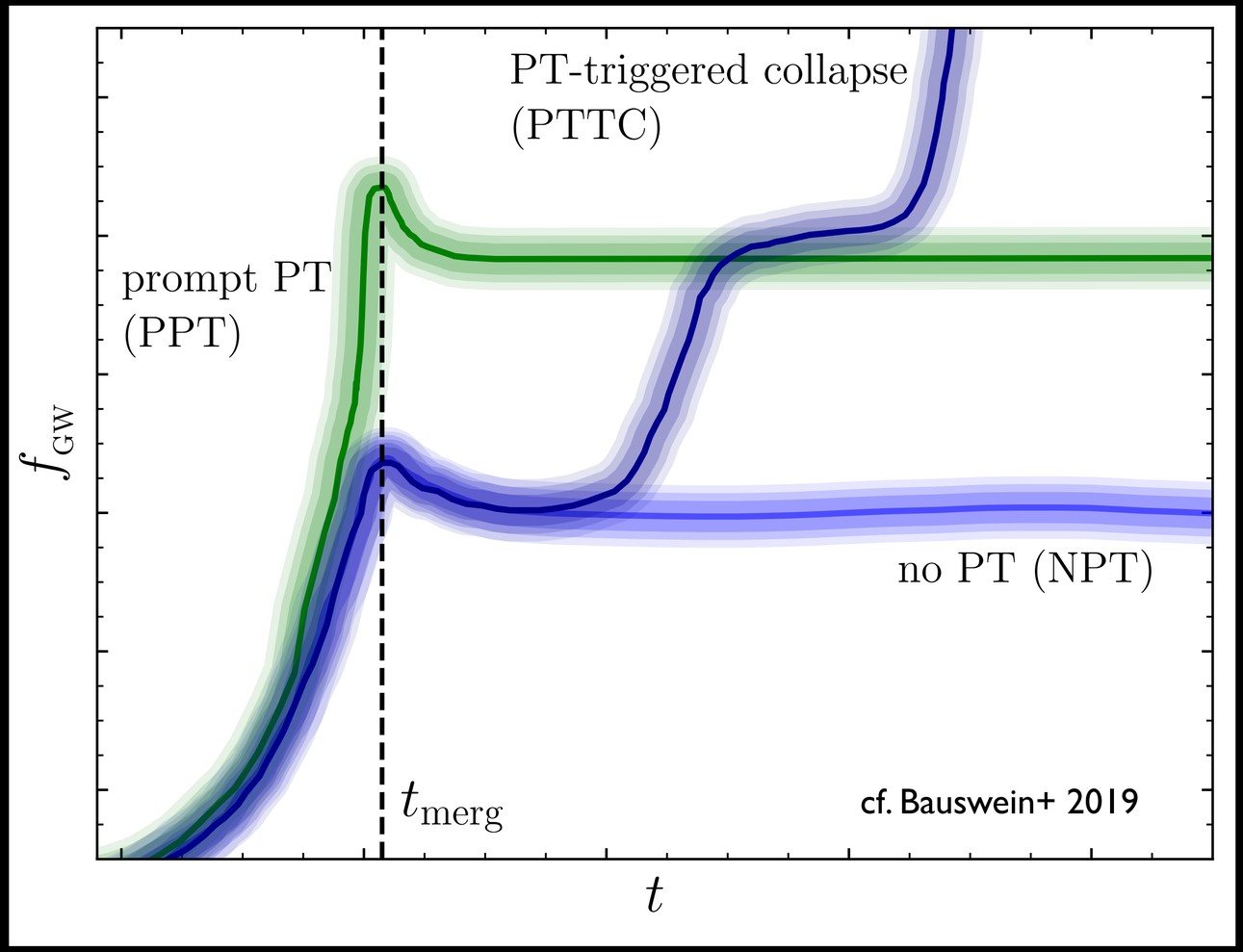
The occurrence of a PT can take place in a number of different ways.
What shown is only one. Here are the other possibilities:





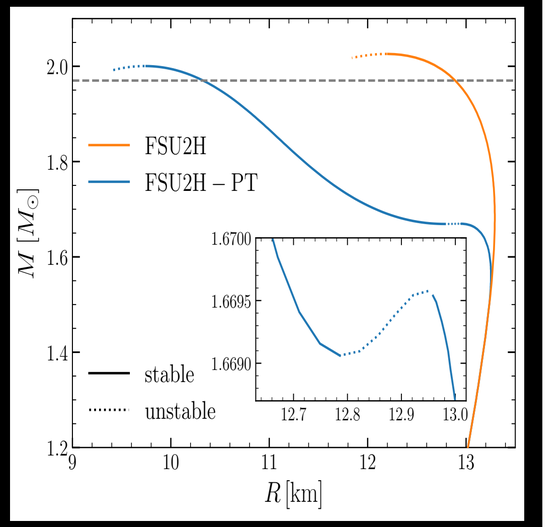
A zoology of possible behaviours

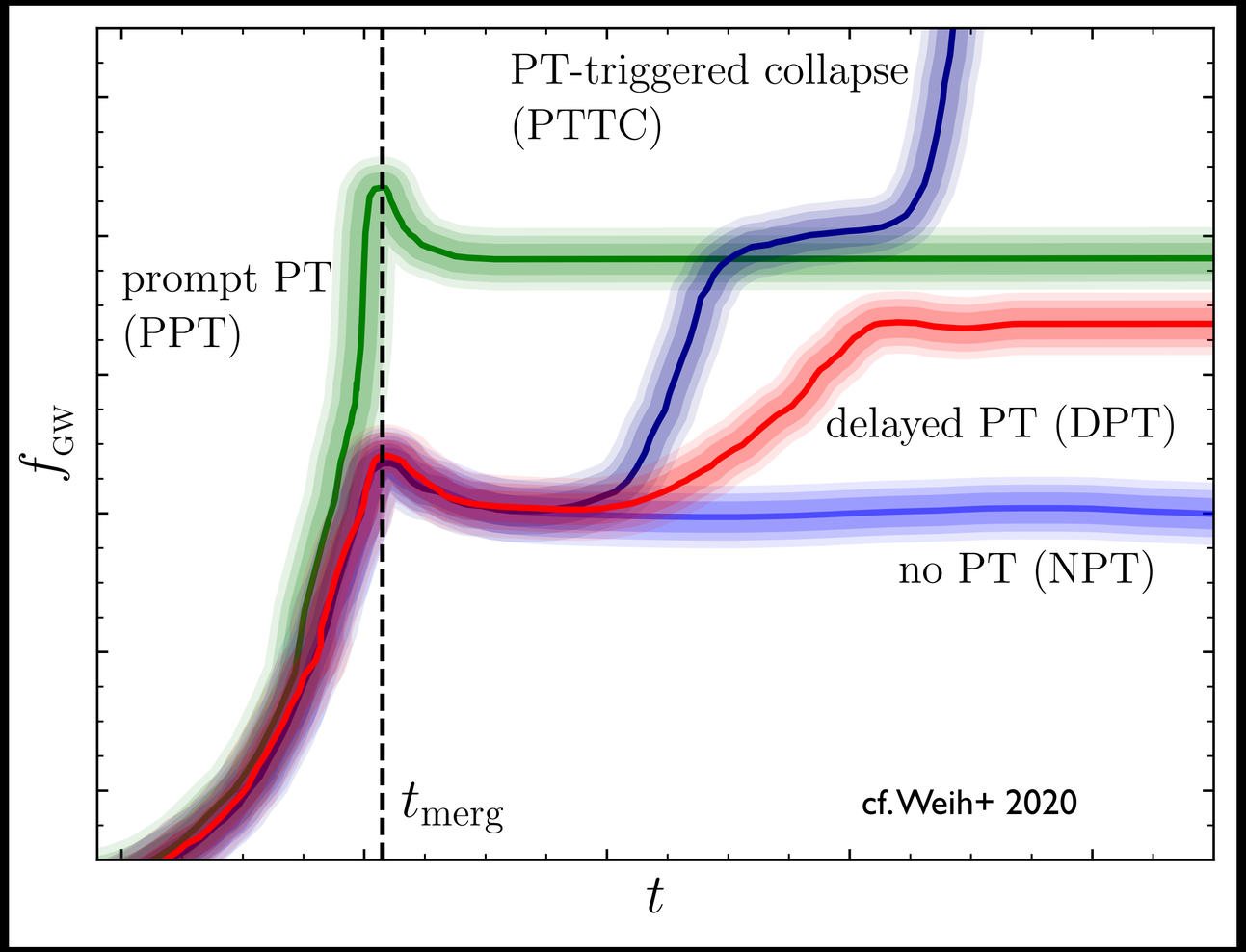
The occurrence of a PT can take place in a number of different ways.
What shown is only one. Here are the other possibilities:



A zoology of possible behaviours

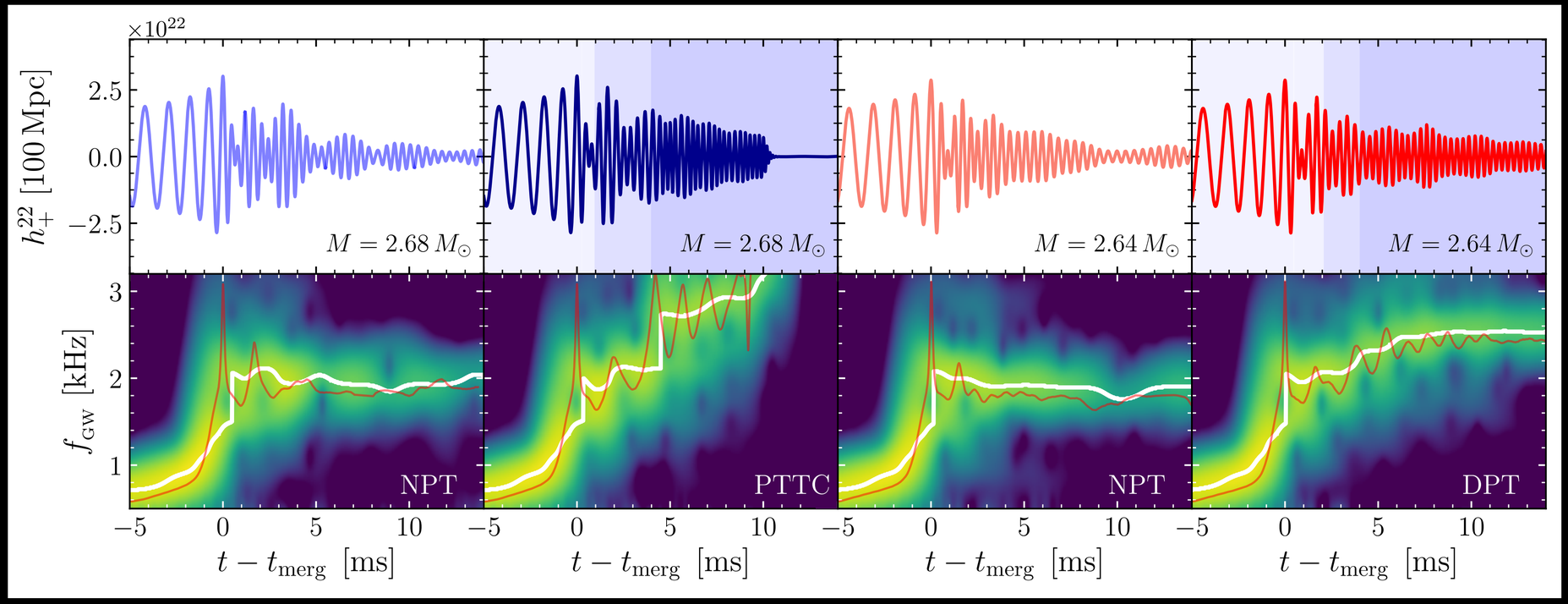
The occurrence of a PT can take place in a number of different ways.
What shown is only one. Here are the other possibilities:





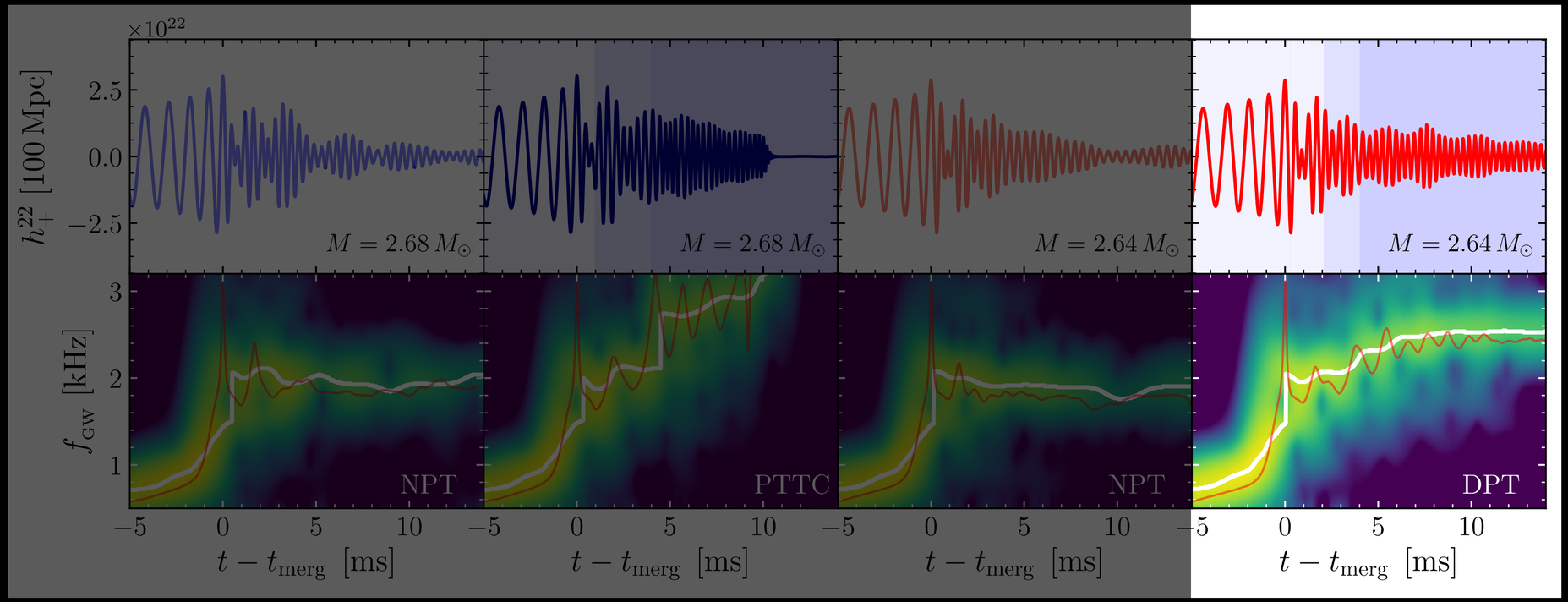
A more comprehensive picture

Zoology discussed above can be recognised when shown in terms of the gravitational waves and their spectrograms.



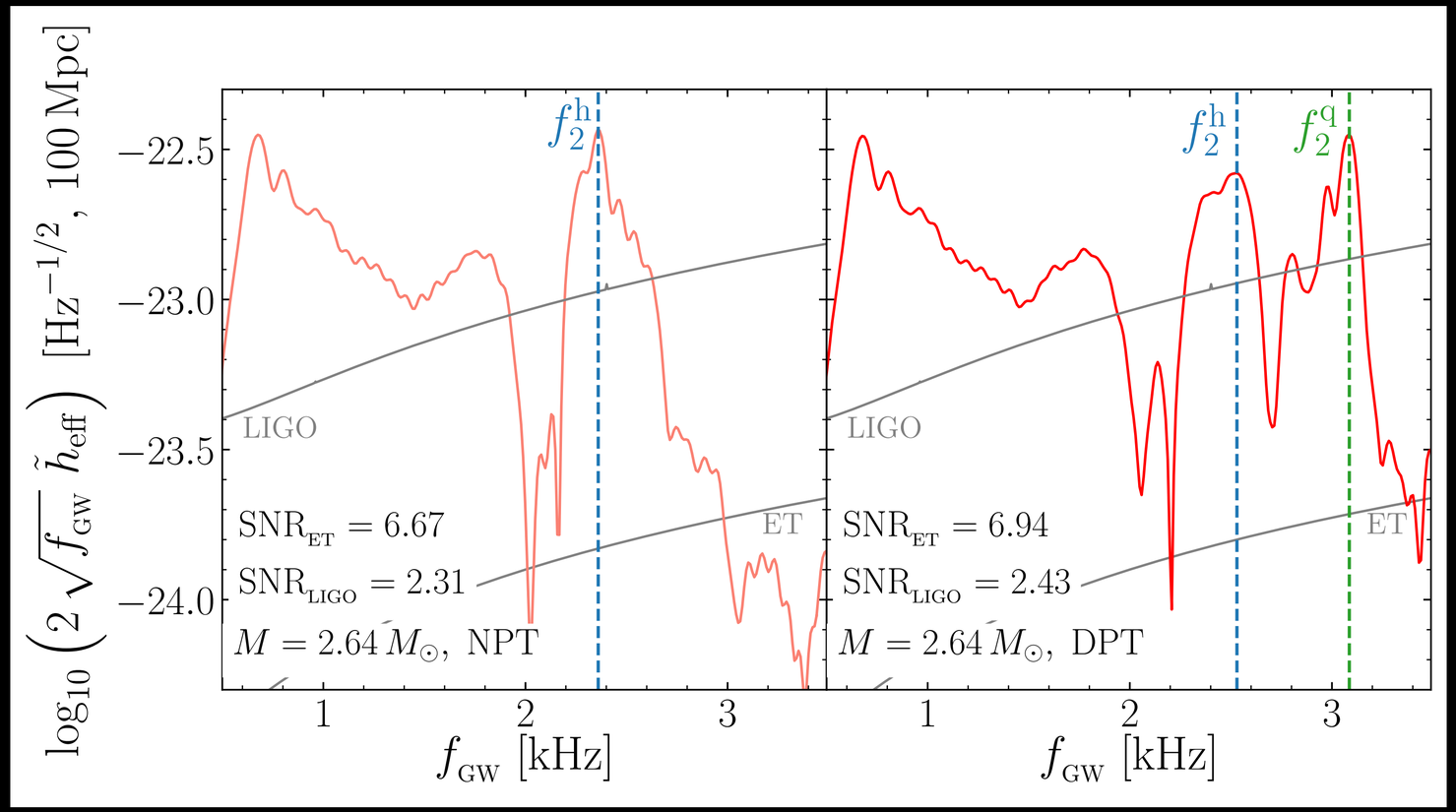
A more comprehensive picture

Zoology discussed above can be recognised when shown in terms of the gravitational waves and their spectrograms.



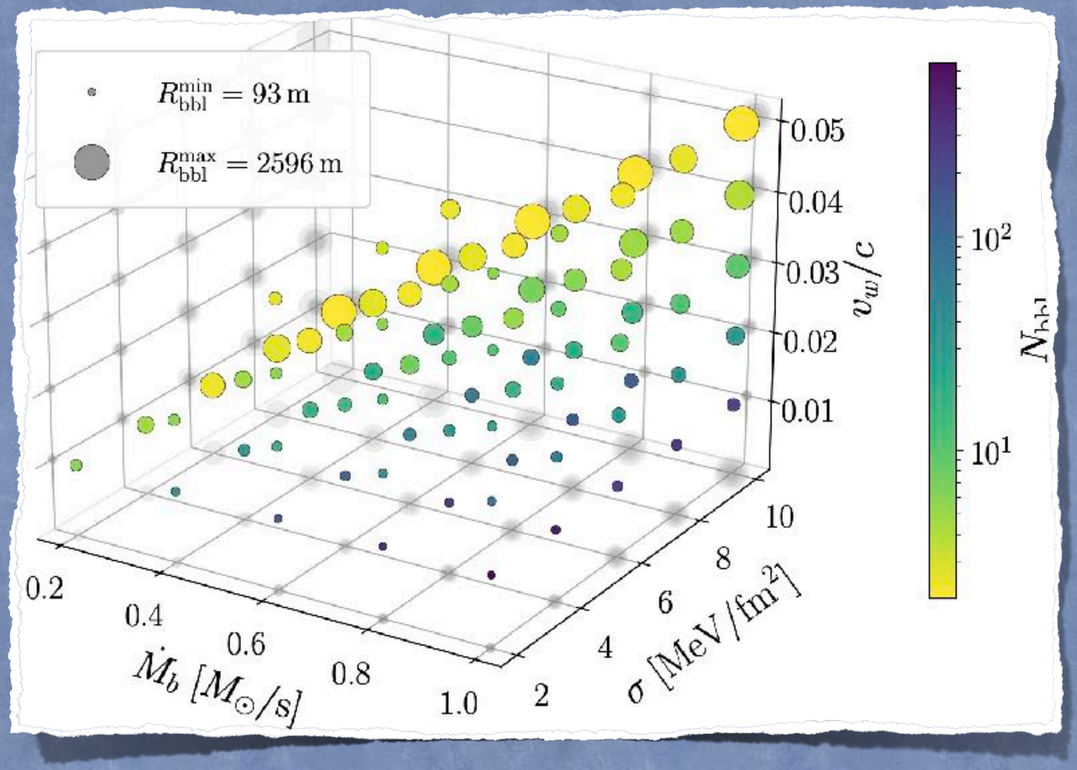
Importance of **DPT** is that it leads to **two** different "stable" f_2 **frequencies** that are easily distinguishable in the PSD

Why DPT is the most interesting case



Importance of **DPT** is that it leads to **two** different "stable" f_2 **frequencies** that are easily distinguishable in the PSD

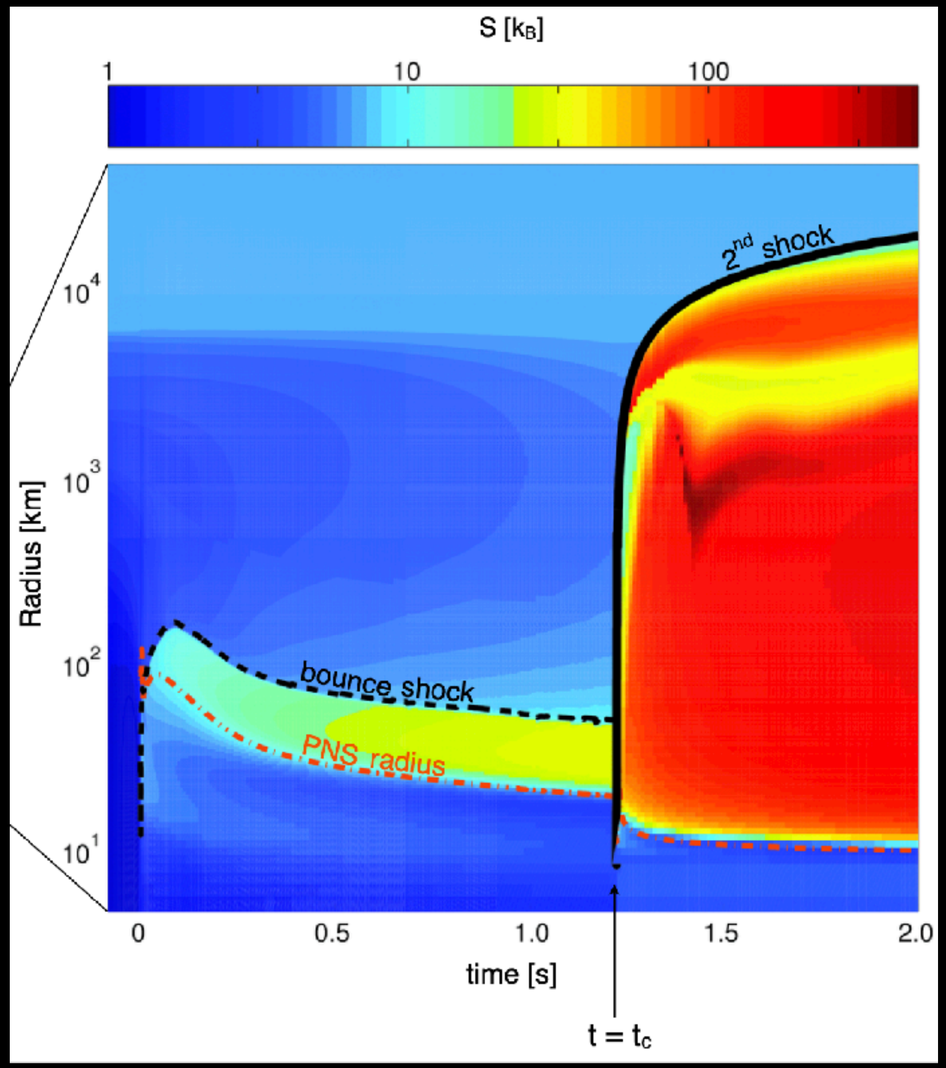
Zooming in on the PT



Ecker, Giliberti, LR, 2609.29761

More than kHz and more than BNSs

Fischer+ 2017



BNSs not only scenario leading to a first-order PT

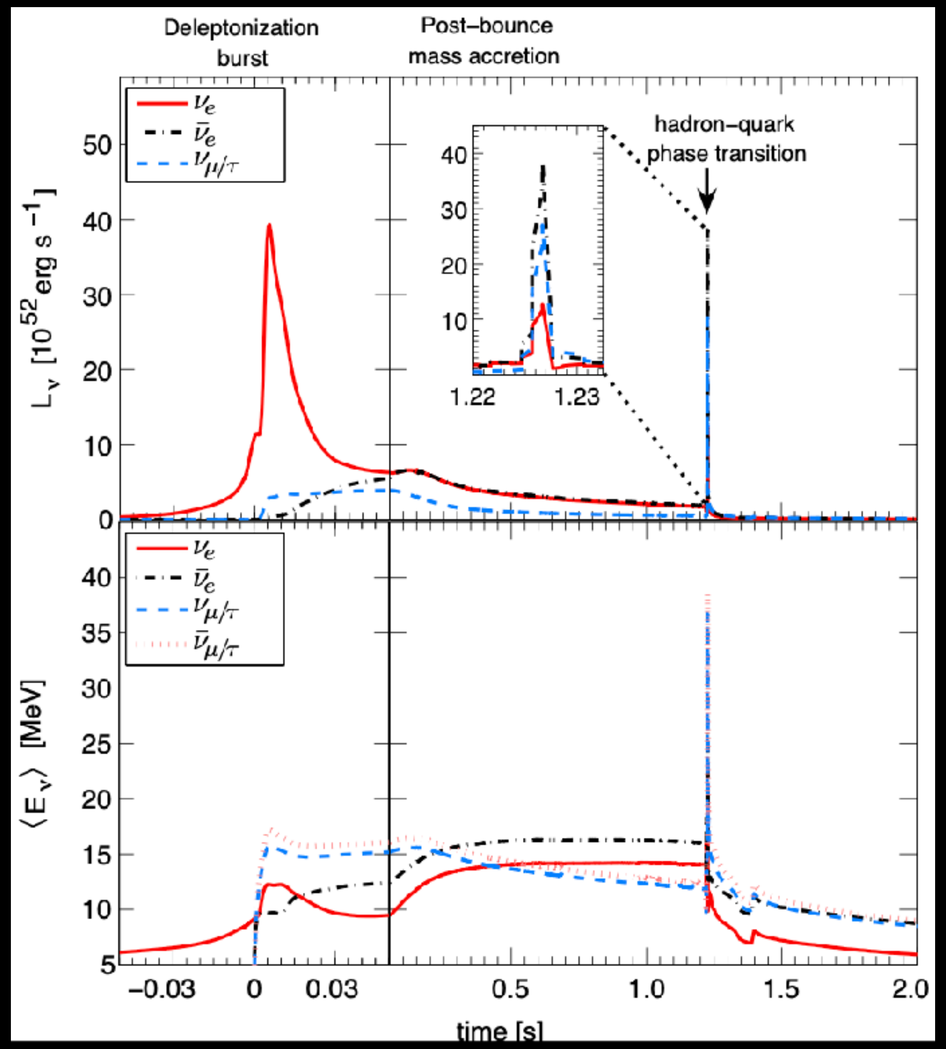
A hadronic proto-neutron star (PNS) produced in a supernova will accrete matter after bounce

As the central density increases, a PT can take place and produce a second collapse

The new PNS will be more compact and with a quark core producing second-shock

More than kHz and more than BNSs

Fischer+ 2017



The core-bounce at PNS formation leads to a GW burst with frequencies around 1-2 kHz

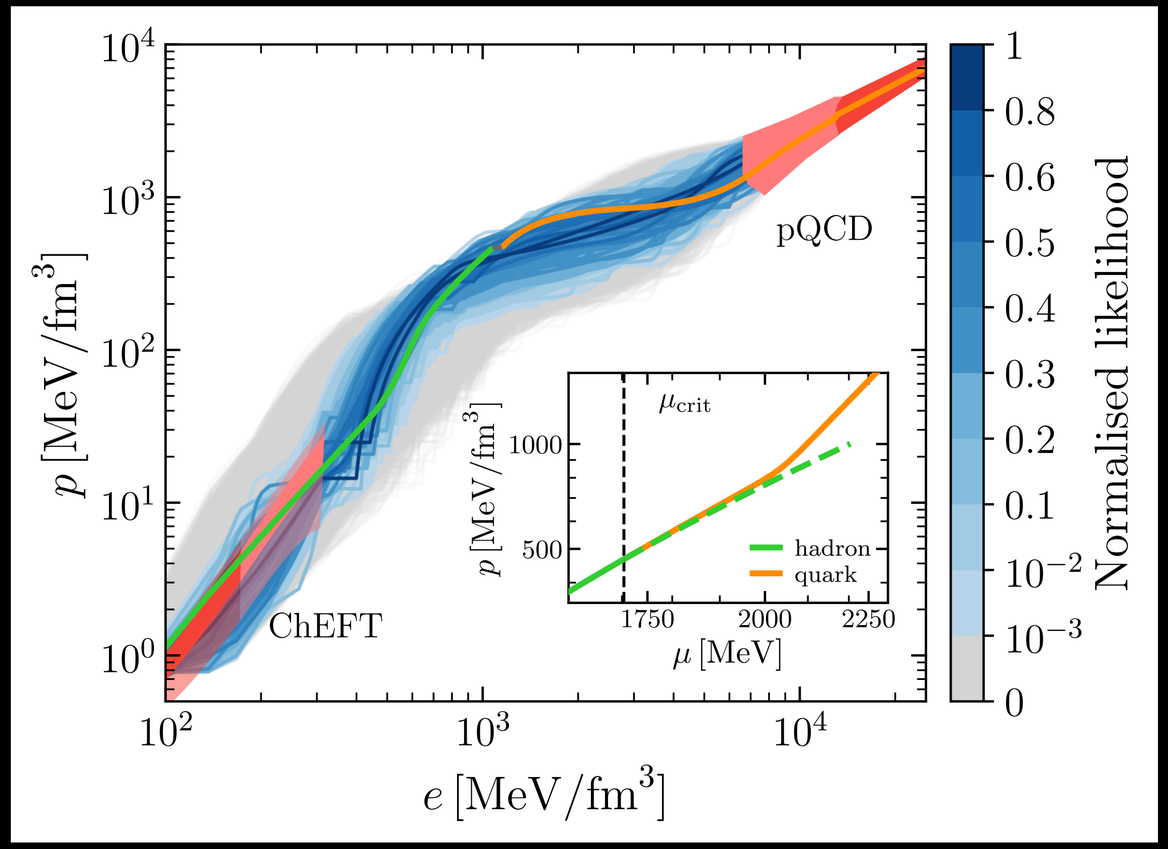
The occurrence of the PT and core contraction will also lead to a second burst of neutrinos

The luminosity will be comparable to the first burst at core-bounce but much shorter

All of this has been investigated for more than 15 years (Sagert+2009)

Is there more to this picture?

More than kHz and more than BNSs



Obviously, there is much more both in terms of GWs and neutrinos!

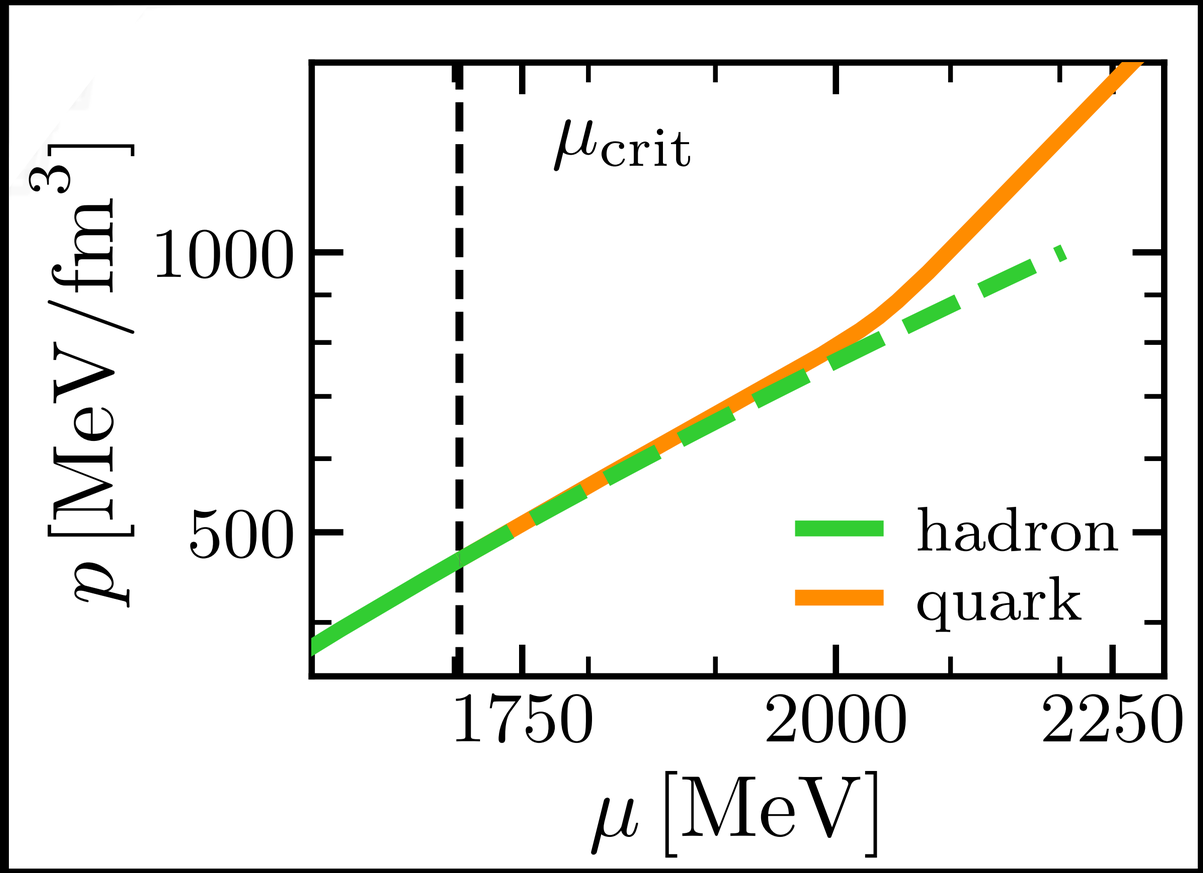
To remove the specific dependence on a specific EOS we have built a set of $\sim 5 \times 10^4$ agnostic EOSs containing a PT

More than kHz and more than BNSs

A prototypical EOS of this type will have a hadron branch and a quark branch

The PT occurs at a critical baryon chemical potential where the pressures are the same: $p_q(\mu_{\rm crit}) = p_h(\mu_{\rm crit})$

The two branches can lead to "twin-stars" we avoid by enforcing the Seidov criterion for the energy densities: $e_q < 3(e_h + p_{\rm crit})/2$



A 1st order PT needs nucleation of quark bubbles expanding in the hadron plasma

Bubble nucleation is exponentially suppressed at the critical pressure but increases as the hadron phase goes into a metastable state

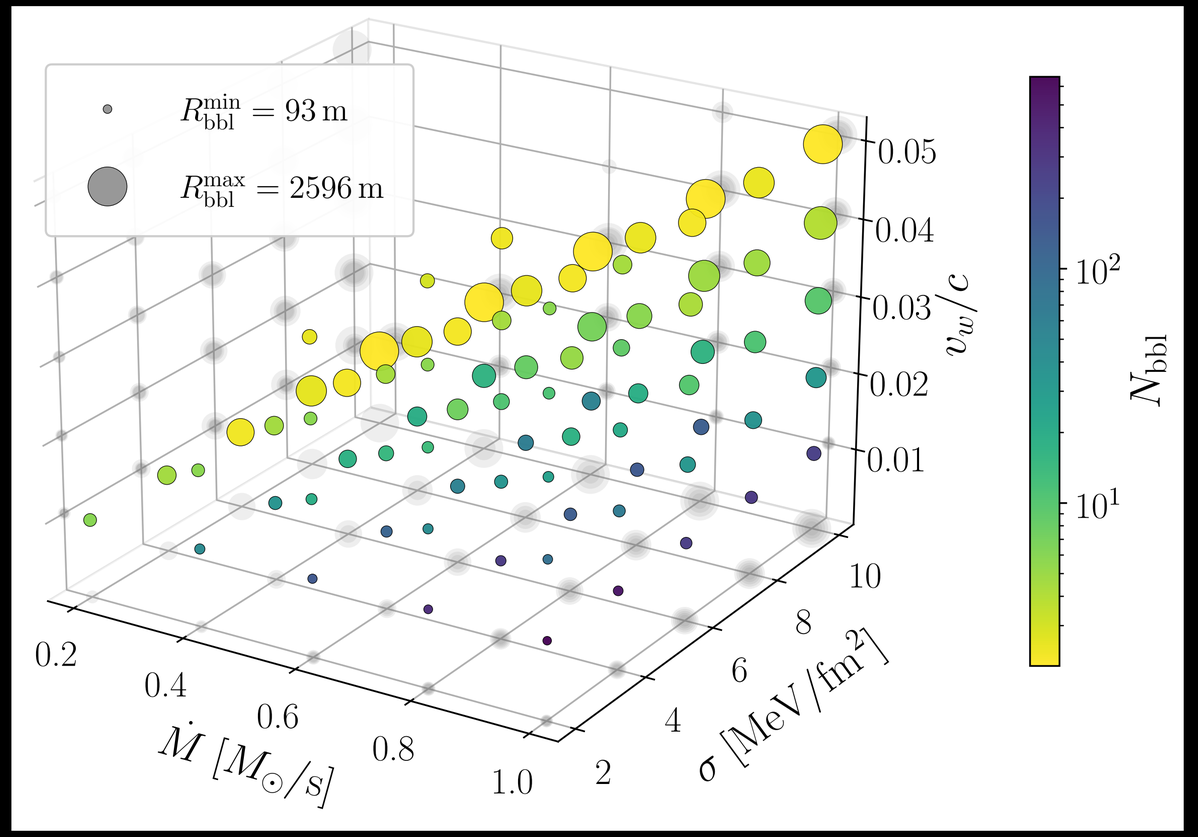
A simple bubble-nucleation rate is given by

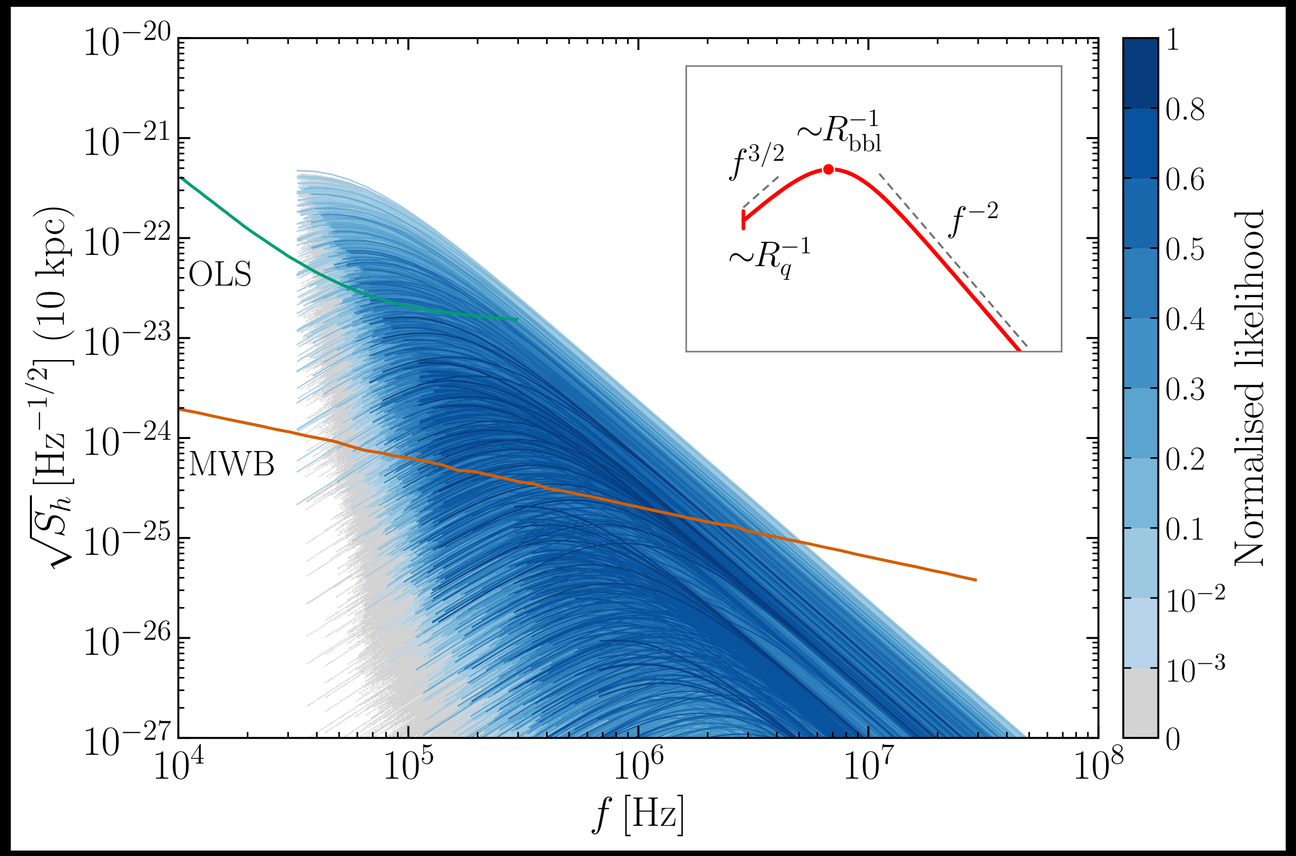
$$\Gamma(t) = \mathcal{S}_{\rm nuc}^4 \exp\left[-\frac{27\pi^2\sigma^4}{2(\Delta p(t))^3}\right]$$

and depends on surface tension σ and pressure jump in the two phases Δp

Bubble dynamics is regulated by the wall velocity v_w and the mass-accretion rate $\dot{M}_b$

Overall: 5-dimensional space parameters

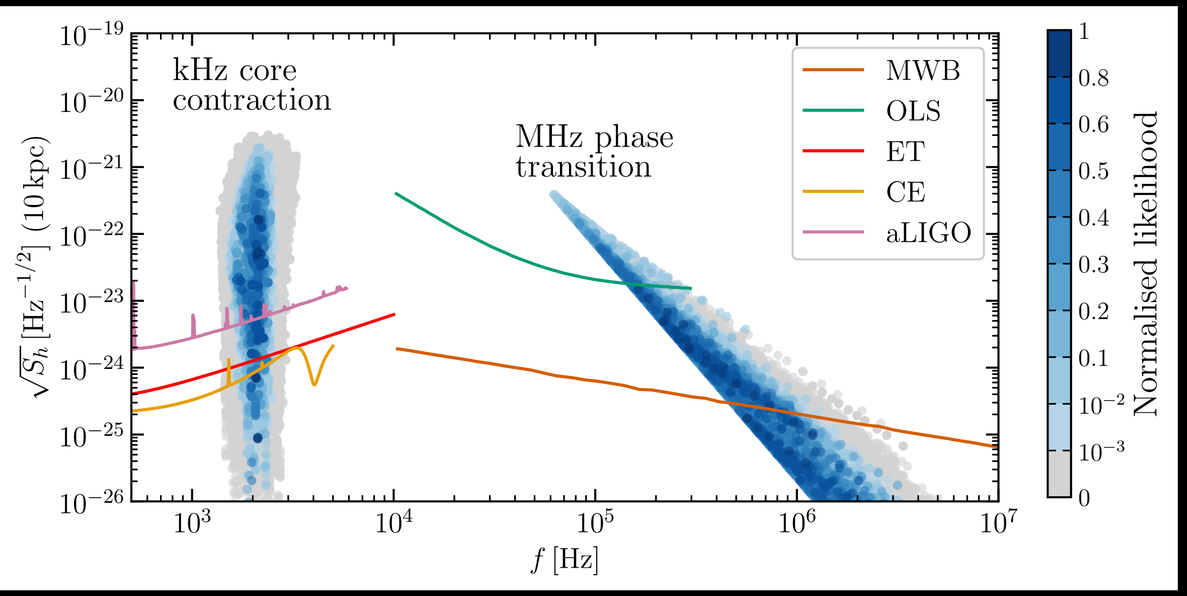




As the quark bubbles expand and collide in the dense matter, high-frequency GWs are produced.

Given the bubble size and speed, the emission is mostly in the MHz range (Blas+ 2026).

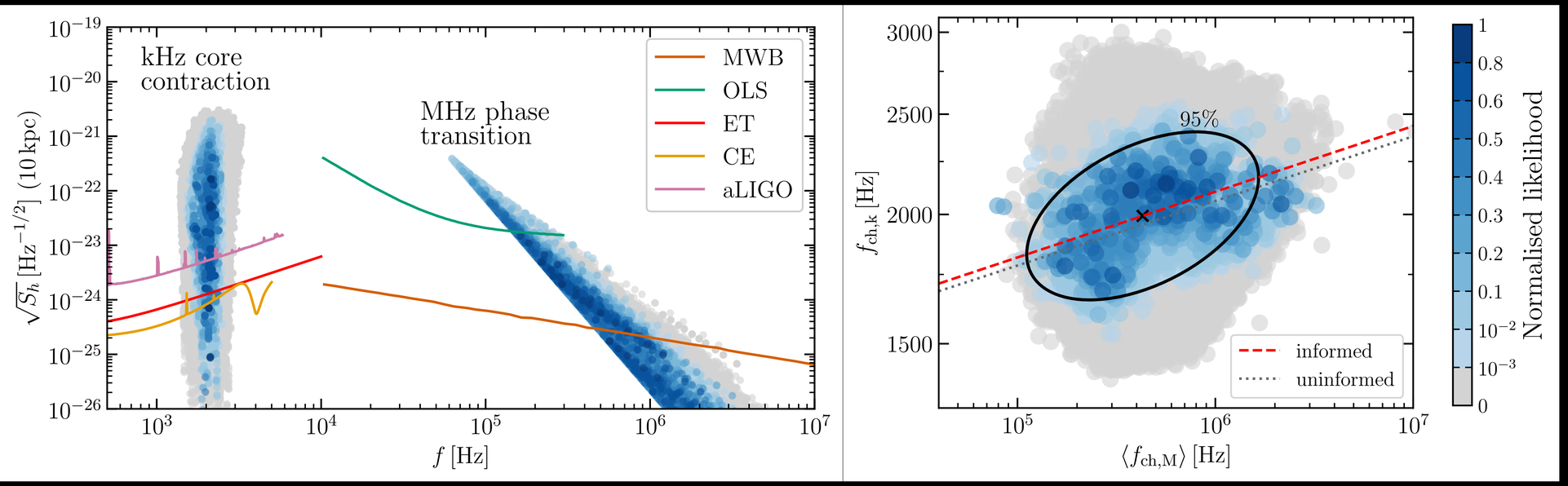
For any EOS, the GW spectrum is broken power-law; min. frequency set by quark-core size R_q^{-1} and a max. amplitude set by the bubble size at nucleation $R_{\rm bubble}^{-1}$



The GW emission is multi-band: a kHz emission due to core collapse (M, R, Λ, Q) and a MHz emission due to the bubble expansion and collision $(\sigma, v_w, \dot{M}_b)$

Shown are characteristic strain and frequency in the two bands for all the EOSs

The kHz signal has much smaller variance and the MHz one is in principle detectable by future GW detectors

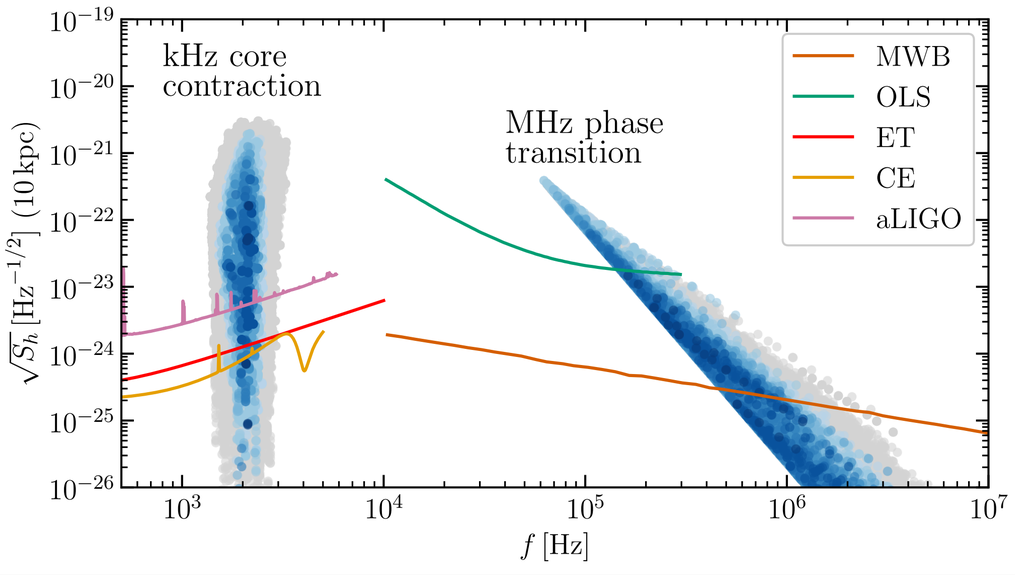


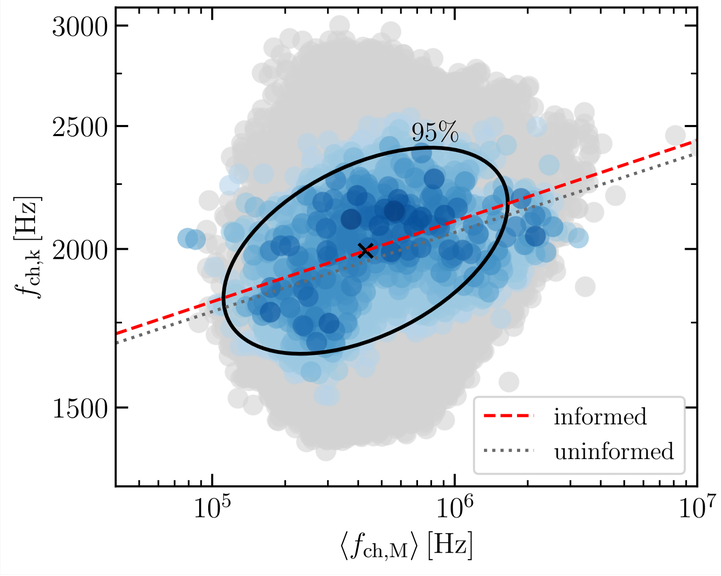
The GW emission in the two bands is correlated via a simple power law

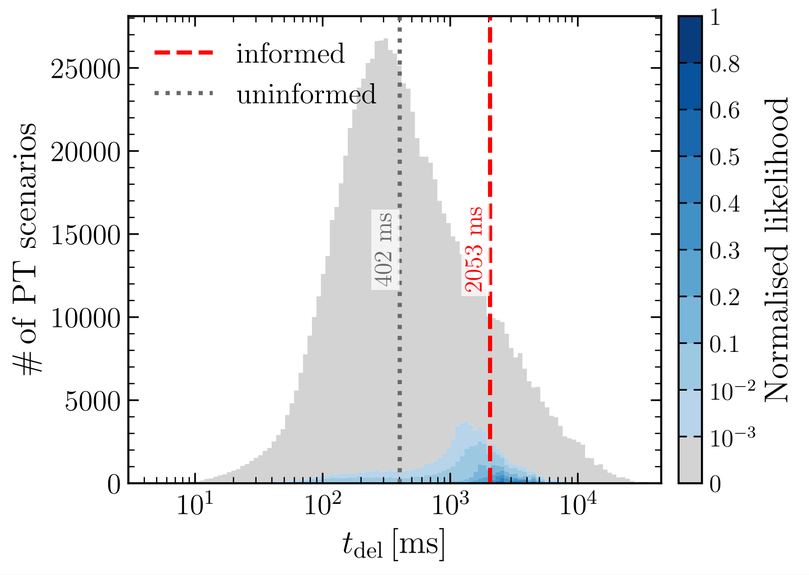
$$\log_{10}\left(\frac{f_{\mathrm{ch,k}}}{\mathrm{Hz}}\right) \simeq k_1 + k_2 \log_{10}\left(\frac{\langle f_{\mathrm{ch,M}} \rangle}{\mathrm{Hz}}\right),$$

Hence, information in kHz signal restricts the range of MHz frequencies.

Combined detection provides additional constraints on the EOS and on the PT







The multi-band GW emission will be accompanied by a delayed neutrino burst

The delay can be computed in terms of the time interval between core-collapse ($t_{\rm crit}$) and bubble nucleation ($t_{\rm nuc}$): $t_{\rm del} \simeq t_{\rm nuc} - t_{\rm crit}$

$t_{\rm del}$ depends on all free parameters but posterior has a clear peak at $t_{\rm del} \simeq 2.1$ s.

The multi-messenger (MM) information will provide new details on the EOS and PT

Conclusions

- Spectra of post-merger shows peaks, many of which follow "quasi-universal" laws.

- A **PT** after a BNS merger leaves GW **signatures** and opens a gate to access quark matter beyond accelerators.

- A first-order **PT** in a star generates bubbles of new phase and a MHz signal. For a PNS, this will lead to a multi-band and MM signals.

A. Convince you that neutron stars (NSs) are alternative probes of the QCD phase diagram