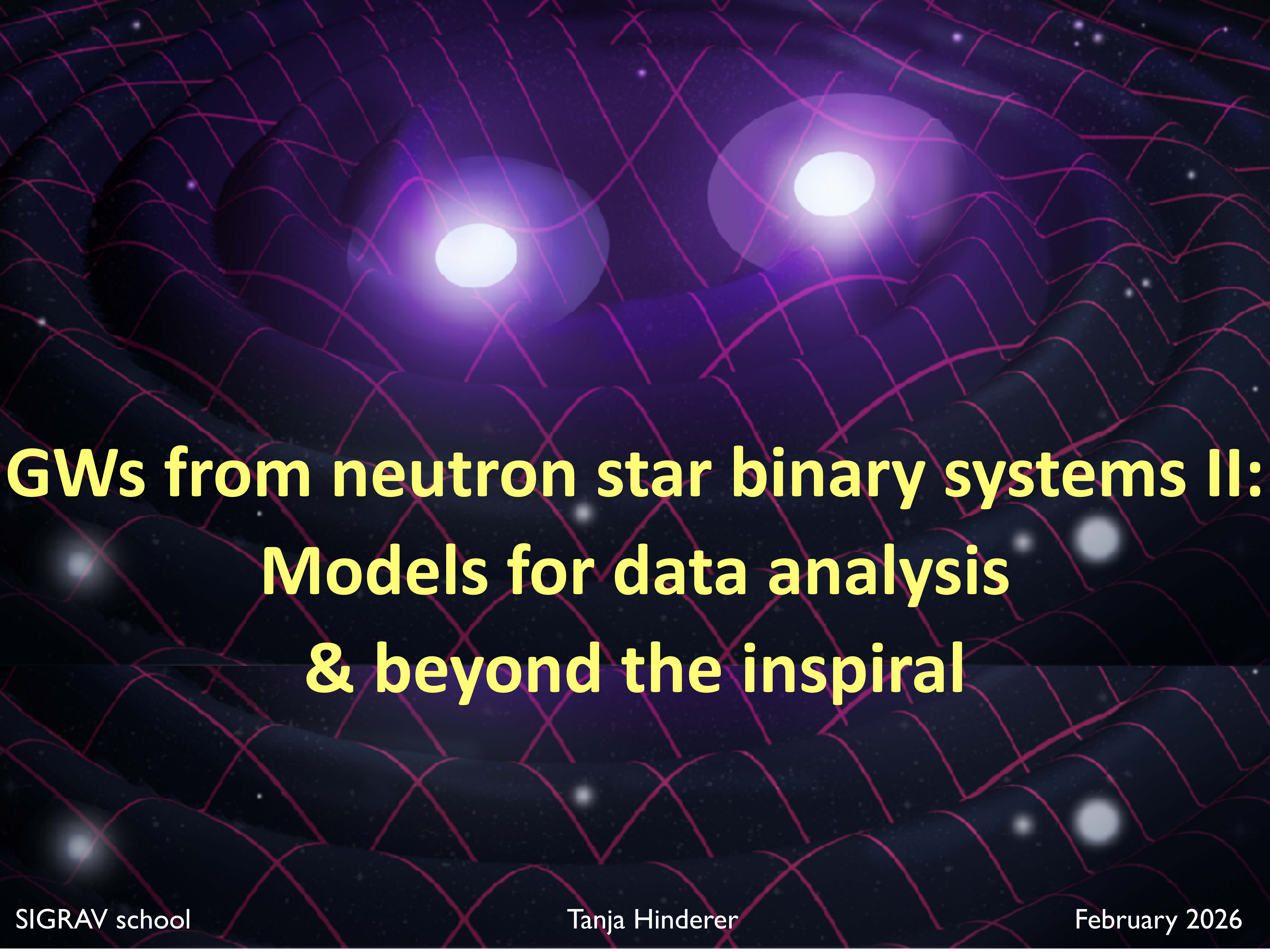


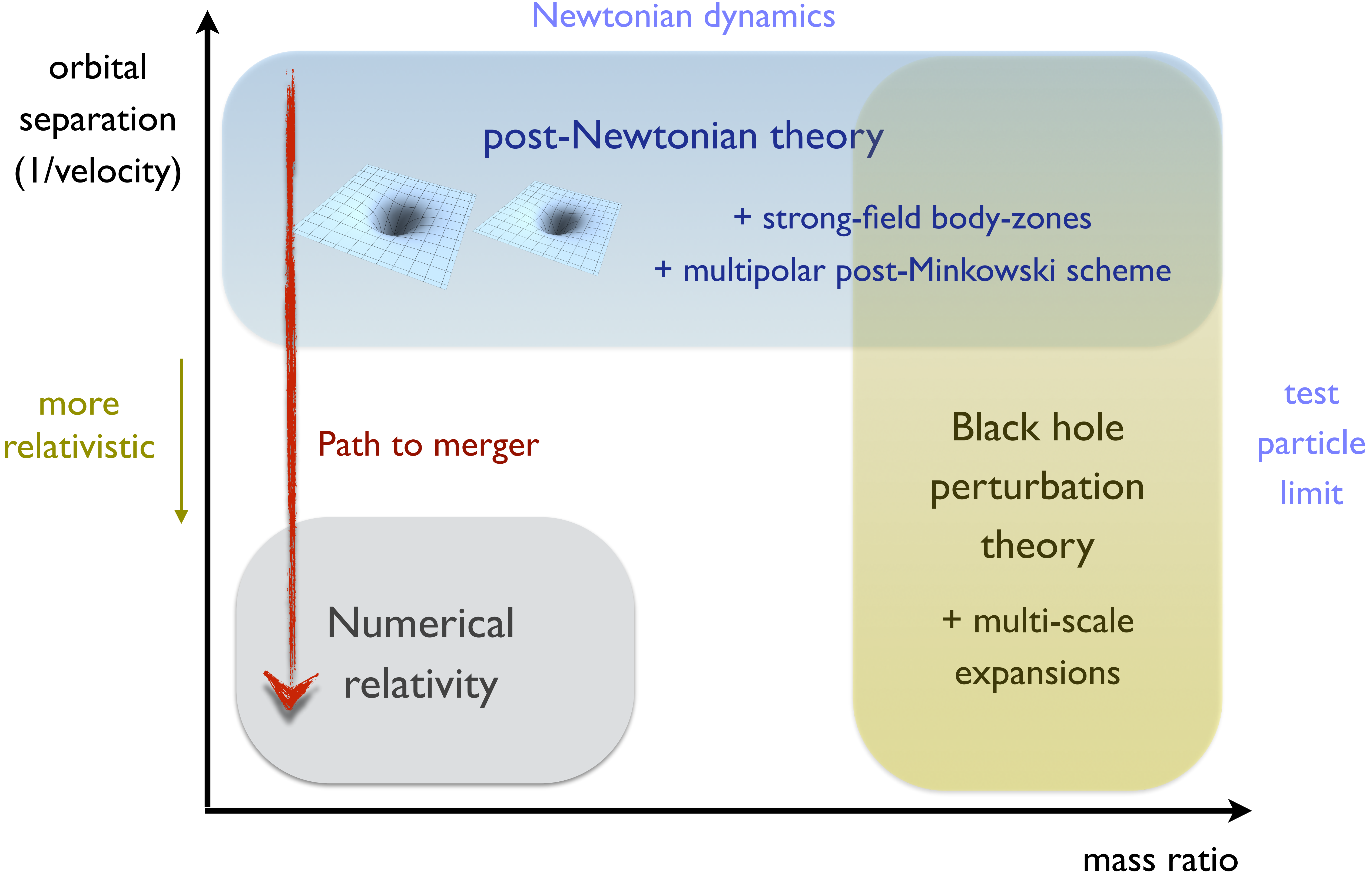
GWs from neutron star binary systems II: Models for data analysis & beyond the inspiral

SIGRAV school

Tanja Hinderer

February 2026

Approaches to computing waveforms



Newtonian dynamics

orbital
separation
(1/velocity)

post-Newtonian theory

+ strong-field body-zones

+ multipolar post-Minkowski scheme

more
relativistic

Path to merger

Black hole
perturbation
theory

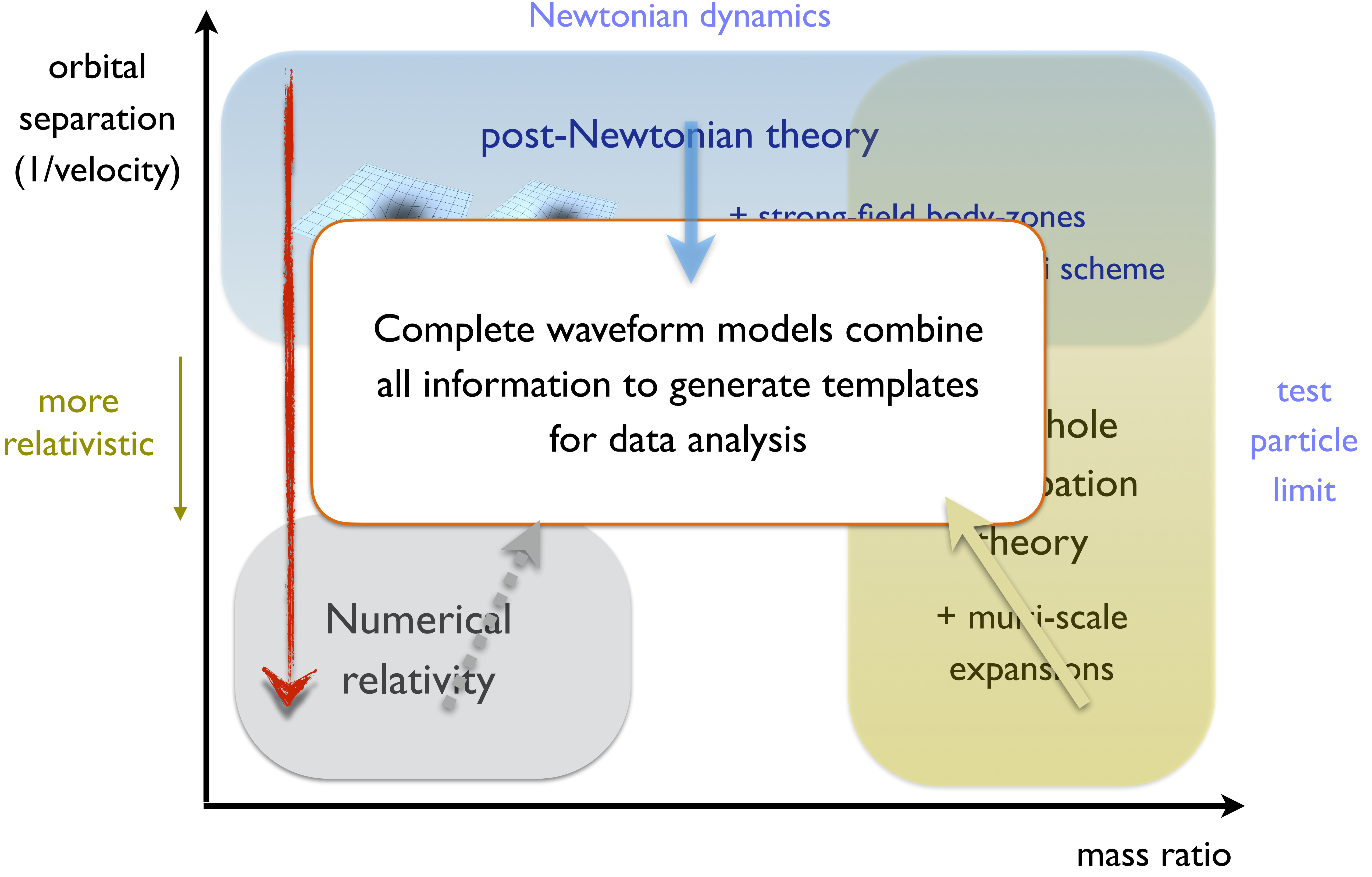
+ multi-scale
expansions

test
particle
limit

Numerical
relativity

mass ratio

Approaches to computing waveforms



Newtonian dynamics

orbital
separation
(1/velocity)

more
relativistic

post-Newtonian theory

+ strong-field body-zones

i scheme

Complete waveform models combine
all information to generate templates
for data analysis

hole
ation
theory

+ mu i-scale
expans ons

test
particle
limit

Numerical
relativity

mass ratio

References

Disclaimer: will only give a basic idea here, *not* an overview of state-of-the-art work & references.
You can find the omitted information in the following recent reviews:

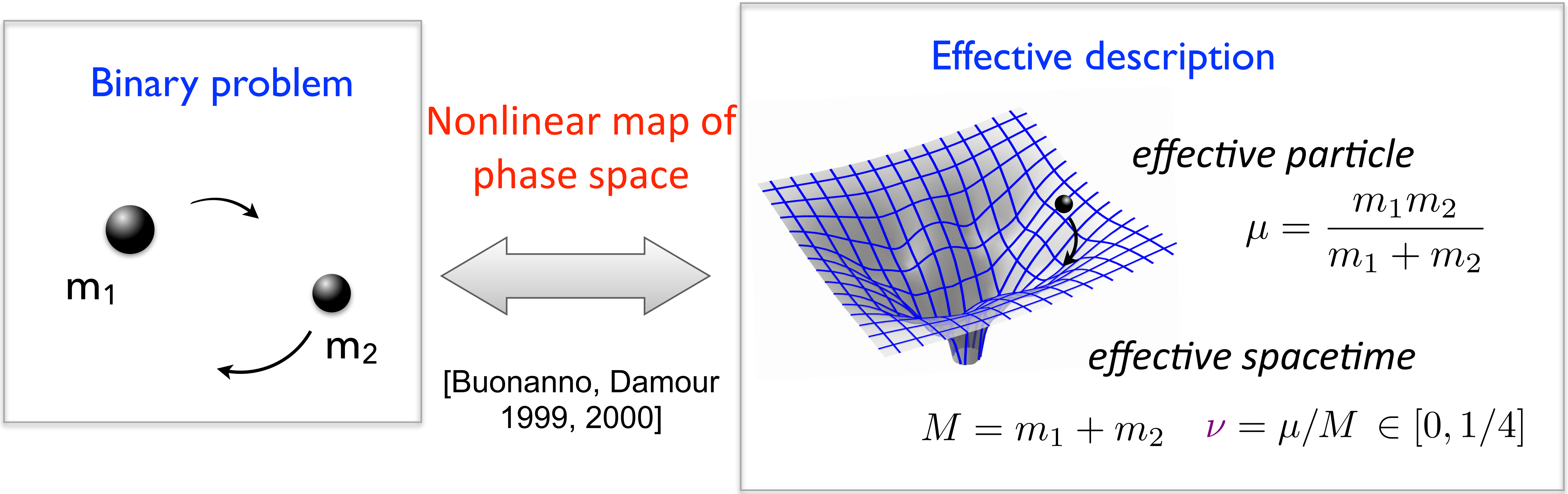
Einstein Telescope bluebook arXiv:2503.12263

(Ch. 8 on waveforms, Ch. 6 on subatomic physics)

LISA waveform modeling white paper arXiv:2311.01300

Effective One-Body (EOB) model

- Basic idea for non-spinning black holes:



Binary problem

Nonlinear map of phase space

[Buonanno, Damour 1999, 2000]

Effective description

effective particle

$$\mu = \frac{m_1 m_2}{m_1 + m_2}$$

effective spacetime

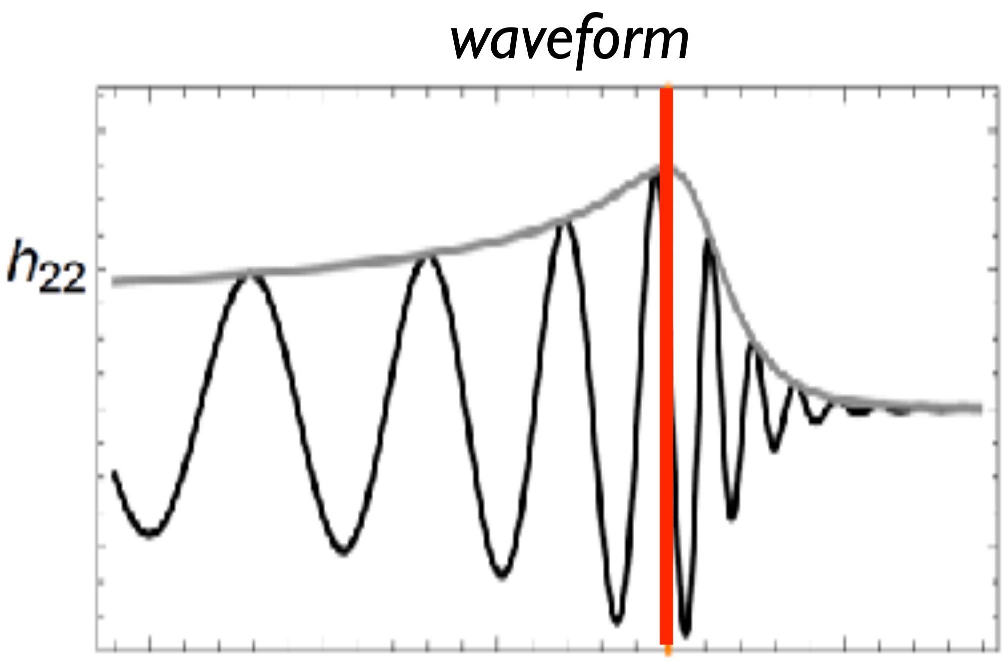
$$M = m_1 + m_2 \qquad \nu = \mu/M \in [0, 1/4]$$

EOB Hamiltonian + GW dissipation + wave generation + merger-ringdown

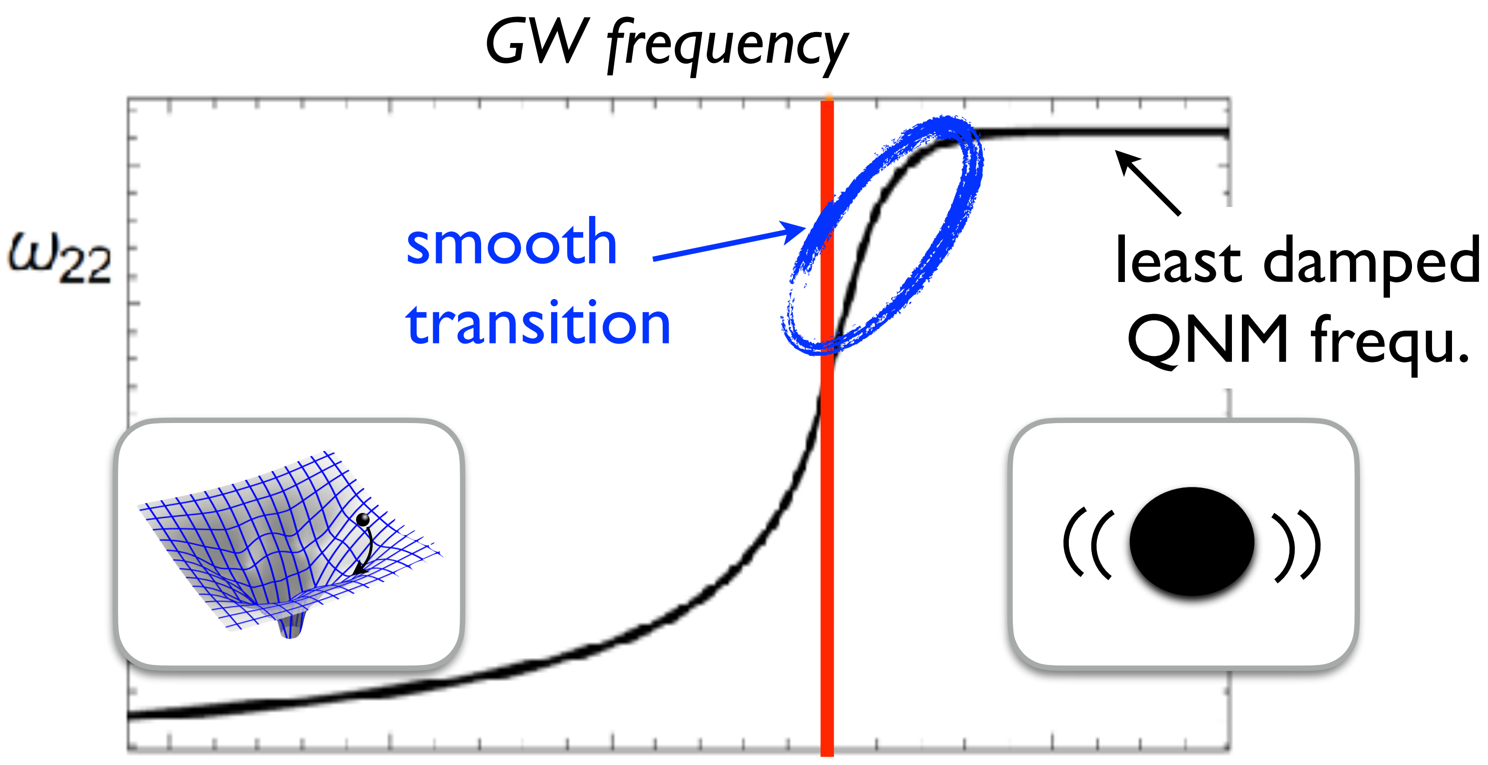
Original paper https://arxiv.org/abs/gr-qc/9811091 inspired by similar approach for QED

`Relativistic Balmer Formula Including Recoil Effects', Brezin, Itzykson, Zinn-Justin (1970)

Black hole baseline



EOB light ring (LR)

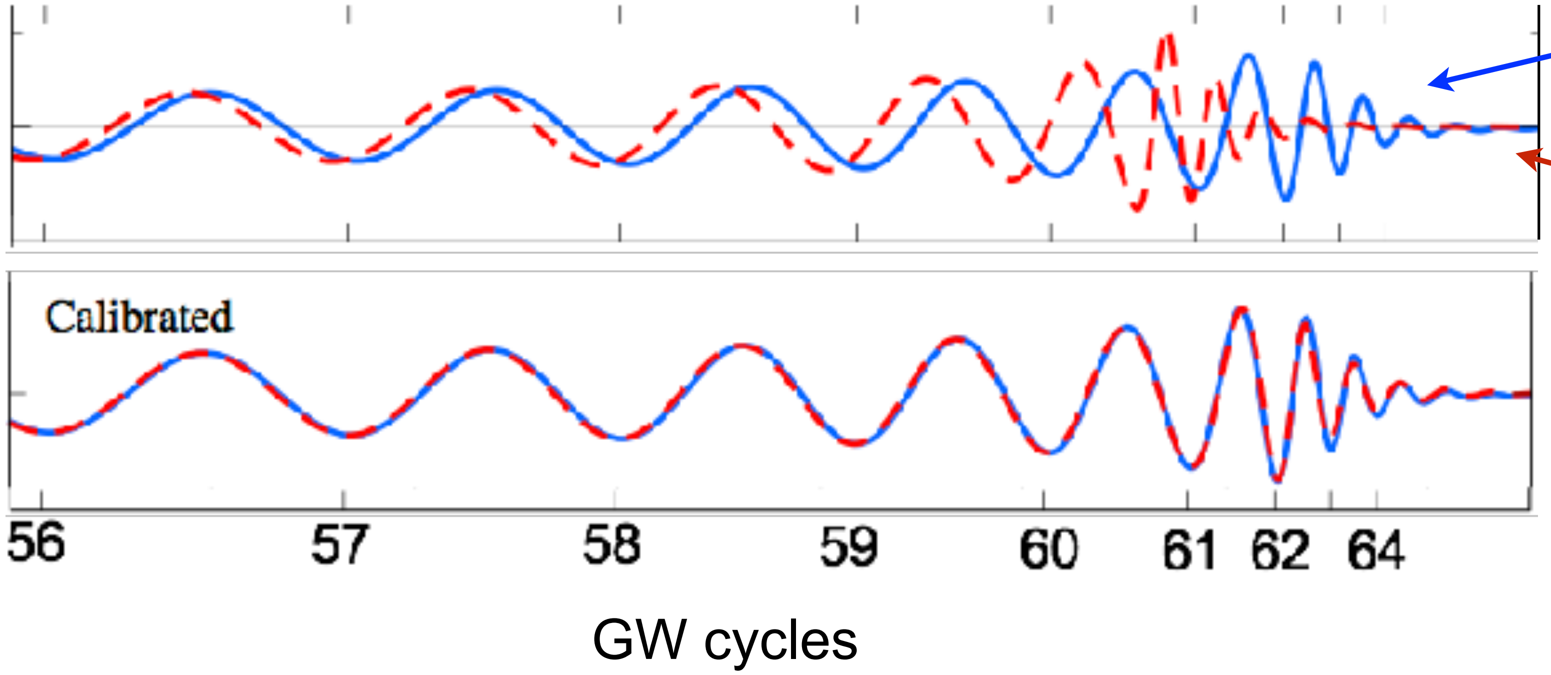


smooth transition

least damped QNM frequ.

LR

- performance of EOB waveforms:



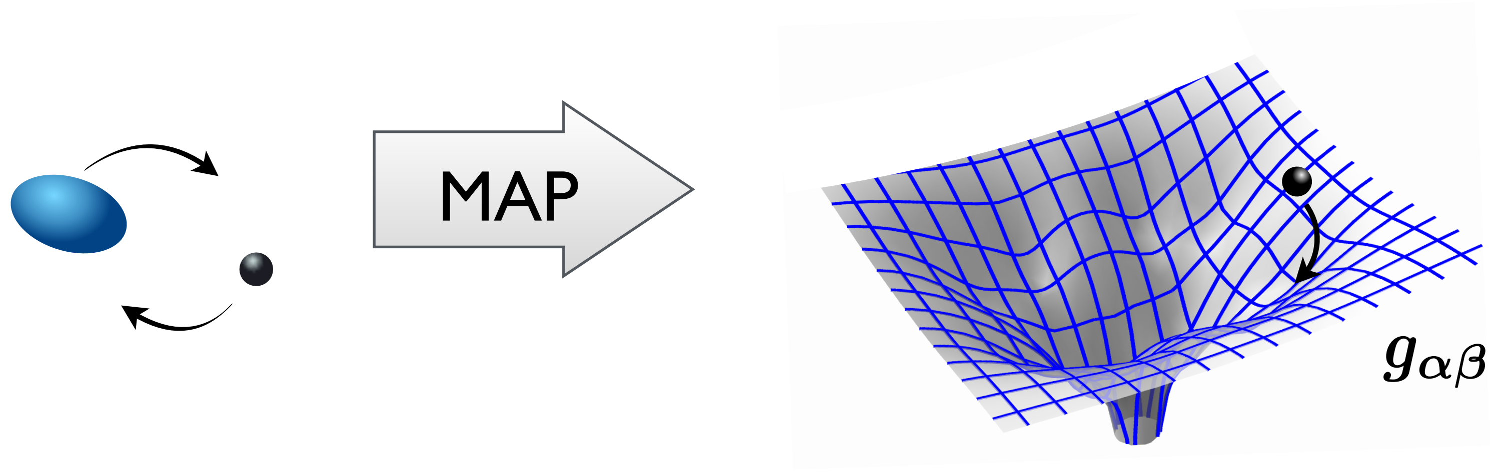
Numerical relativity

EOB, analytical knowledge only

EOB, *calibrated*

[courtesy A. Taracchini]

Adiabatic tidal effects in the EOB model



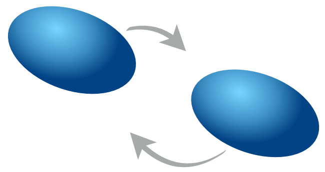
effective spacetime

$$g_{\alpha\beta} \sim g_{\alpha\beta}^{\mathrm{Kerr}} + \nu\, \delta g_{\alpha\beta} + \lambda\, \delta g_{\alpha\beta}^{\mathrm{Tidal}}$$

[Damour, Nagar, Bini, Faye, Bernuzzi+2009-2014]

- for NS-NS: dominant tidal contribution to the energy (and EOB Hamiltonian) characterized by

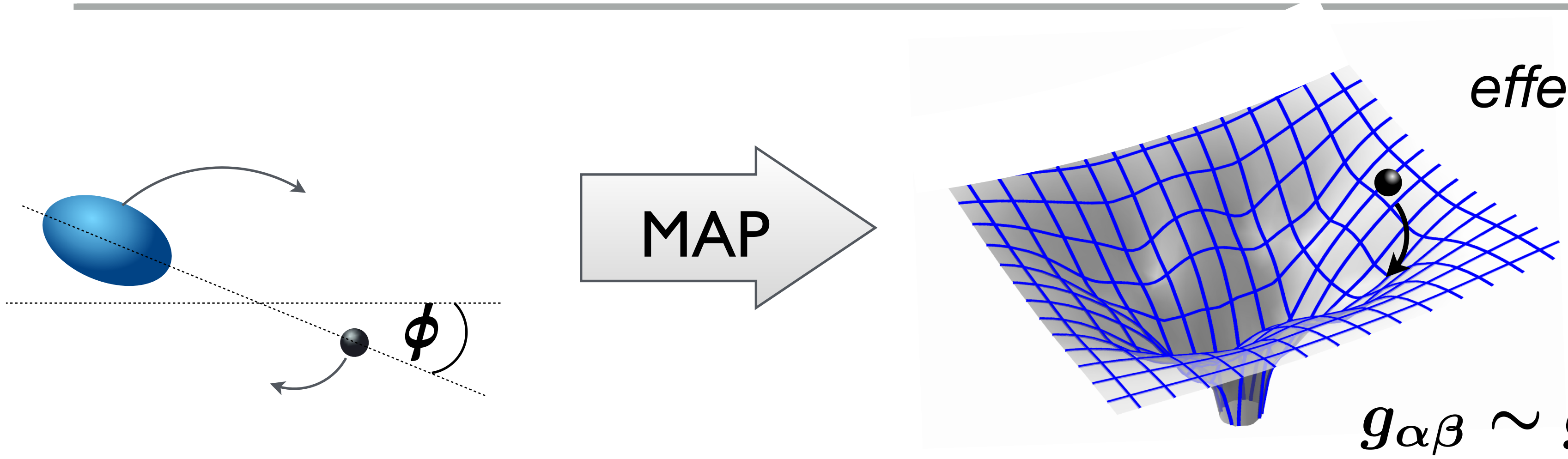
$$\kappa_2^{\mathrm{T}} = 3\left(\frac{m_2}{m_1}\lambda_1 + \frac{m_1}{m_2}\lambda_2\right)$$



+ tidal correction to GW amplitudes/ factorized EOB waveforms

- TEOBResumS: PN results for tidal effects mapped to EOB & resummed + augmented by self-force-inspired terms

SEOBNR with *approximate* dynamic tides



effective spacetime

from $\mathcal{E}_{ij}\mathcal{E}^{ij}$

$$g_{\alpha\beta} \sim g^{\rm Kerr}_{\alpha\beta} + \nu\, \delta g_{\alpha\beta} + \lambda^{\rm eff}\, \delta g^{\rm Tidal}_{\alpha\beta}$$

- effective tidal deformability approximates dynamical tides:

$$\frac{\lambda^{\rm eff}_\ell}{\lambda_\ell} \sim \frac{\omega_f^2}{\omega_f^2 - (m\Omega)^2} \ \& \ \frac{\omega_f^2}{(\phi - \phi_f)} \ \& \ \cos\left[(\phi-\phi_f)^2\right] \mathrm{FresnelS}(\phi - \phi_f)$$

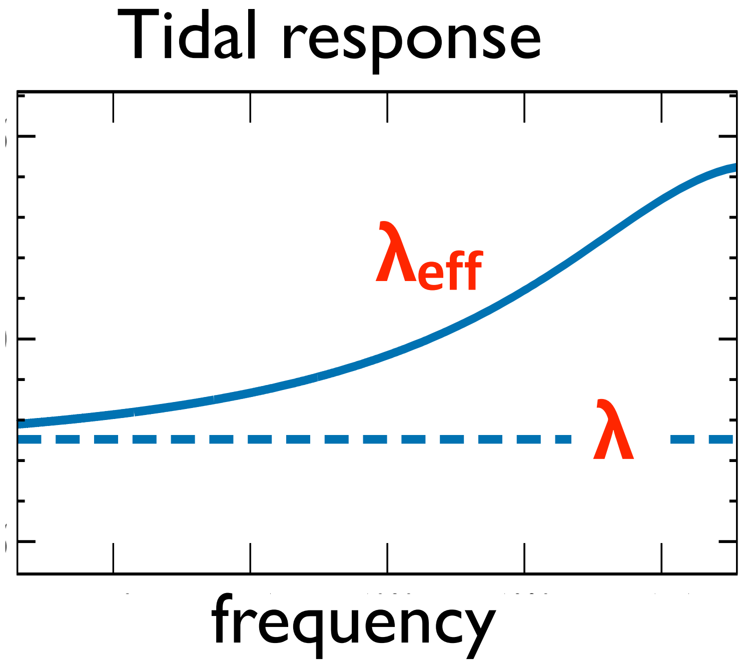
before resonance

— common term

near resonance where $\phi \sim \phi_f$

all fns. of $\{M, \nu, \omega_f, r\}$

Similarly for tidal contributions to EOB factorized $h_{\ell m}$ modes

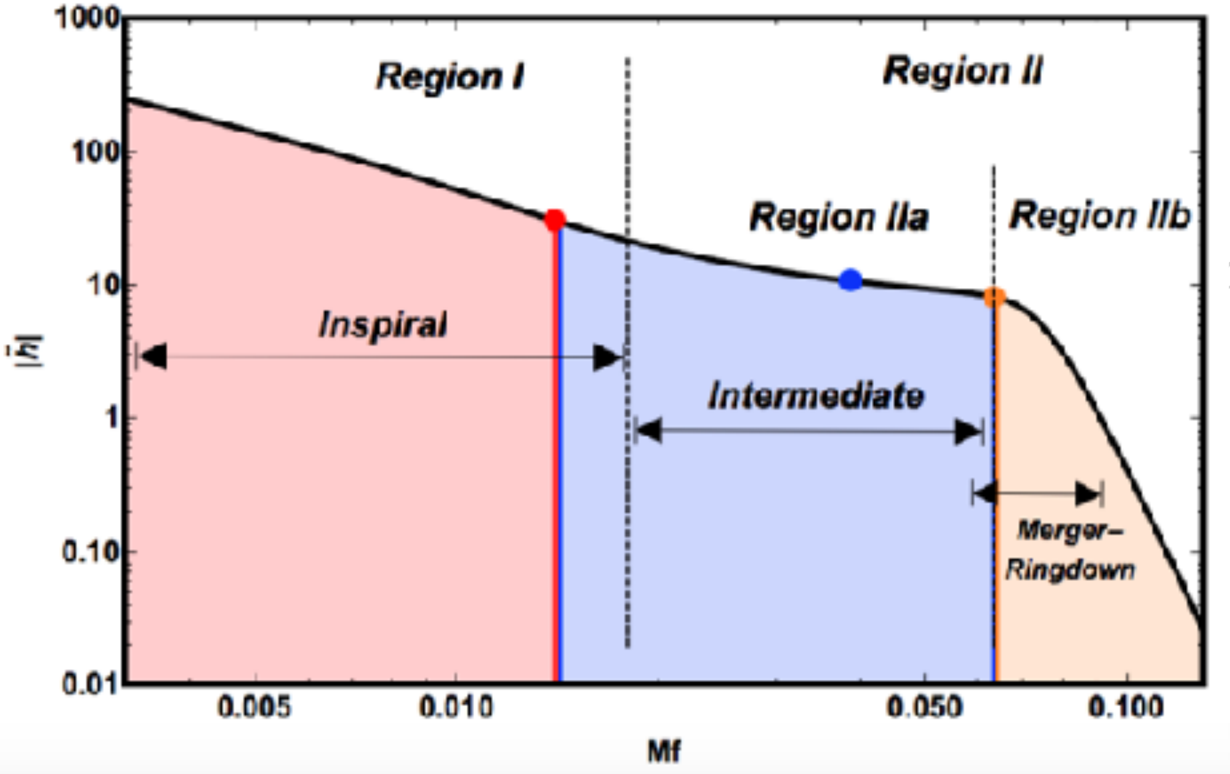


Phenomenological models: basic idea for black hole baseline

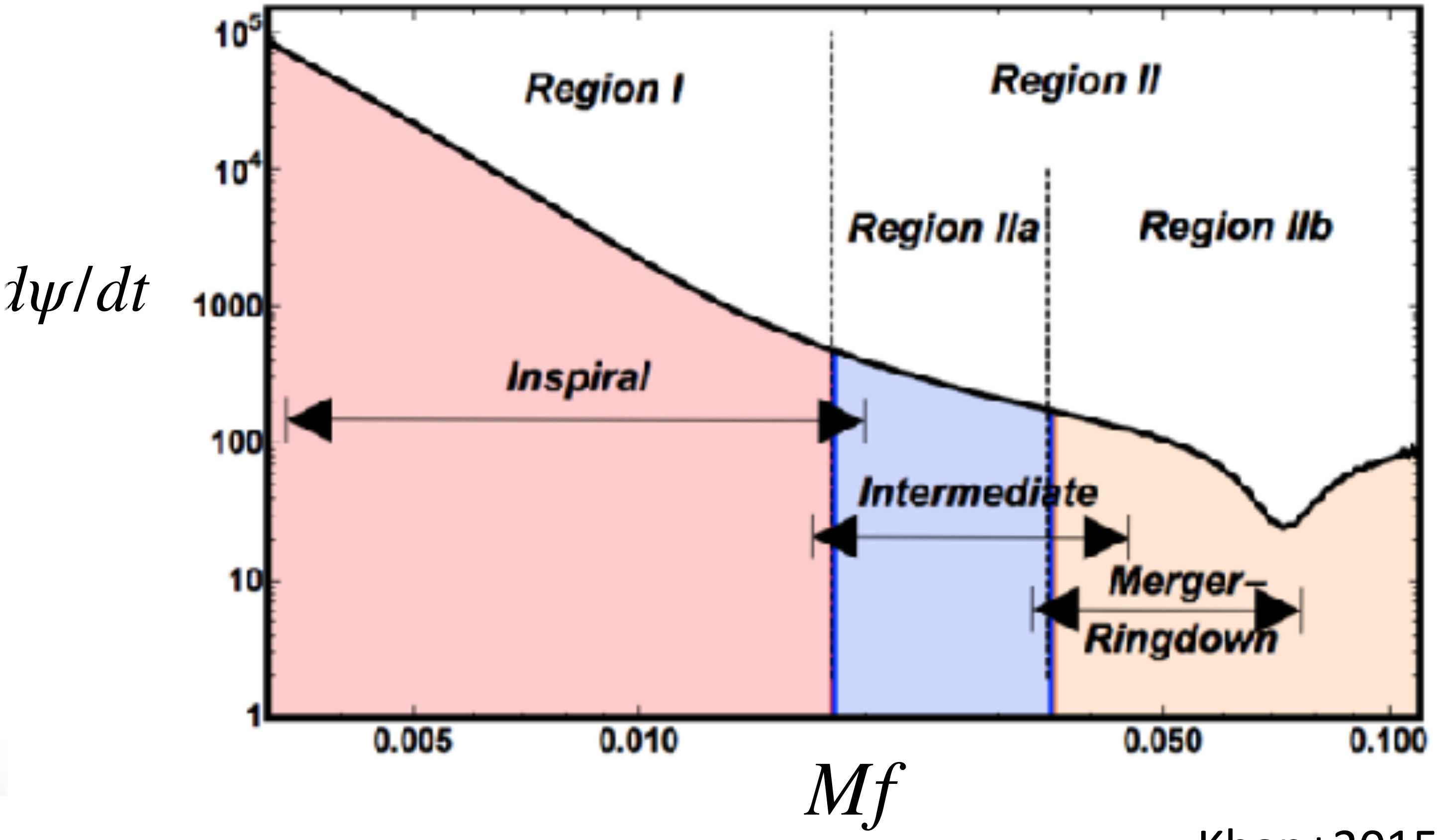
Fits of the frequency-domain GWs using PN (EOB-resummed) + numerical relativity

Closed-form fits divided into 3 regimes, smoothly connected

rms Fourier GW amplitude



Derivative of the GW Fourier phase



Khan+2015

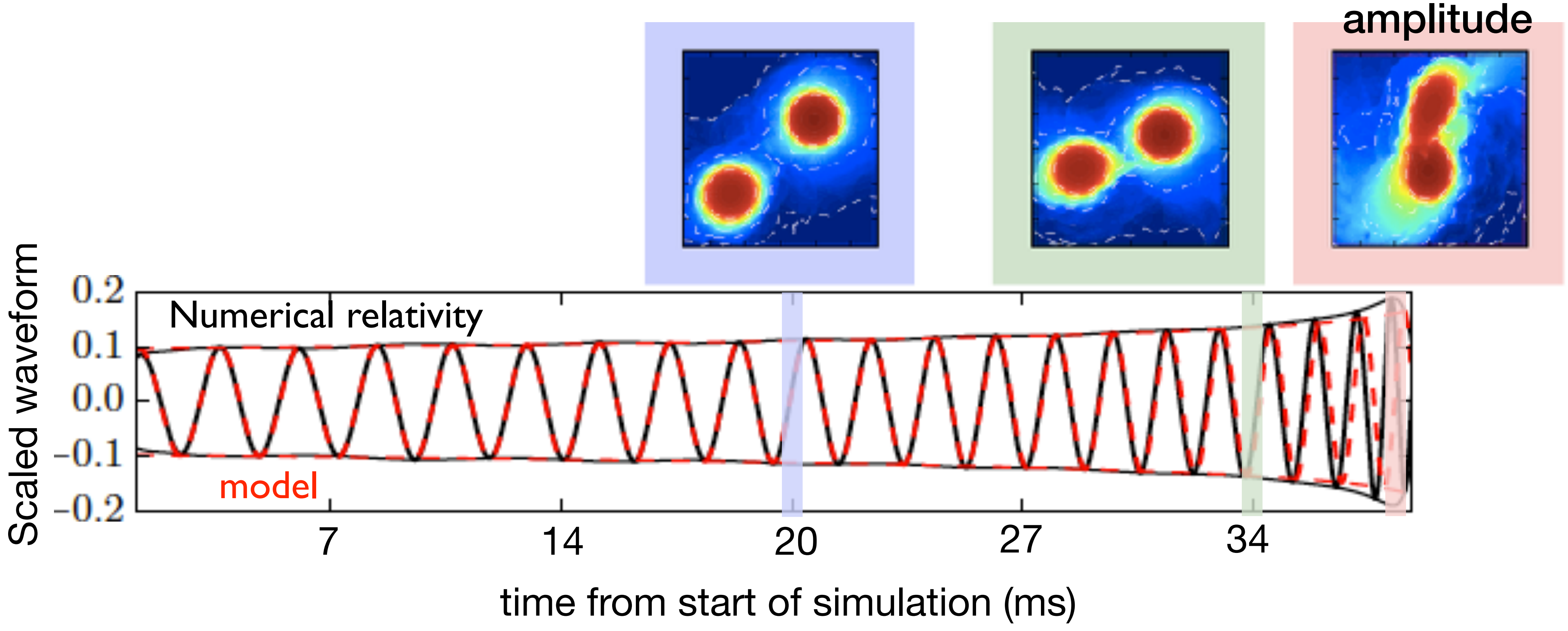
'NRTidalvX' models built on Pade-resummend PN tidal results+fits to numerical relativity

Recent NRTidalv3 model also includes f-mode dynamic tides

Models are tested against numerical relativity simulations

- Many groups perform different tests
- Crucial to understand errors in numerical simulations

Example case:



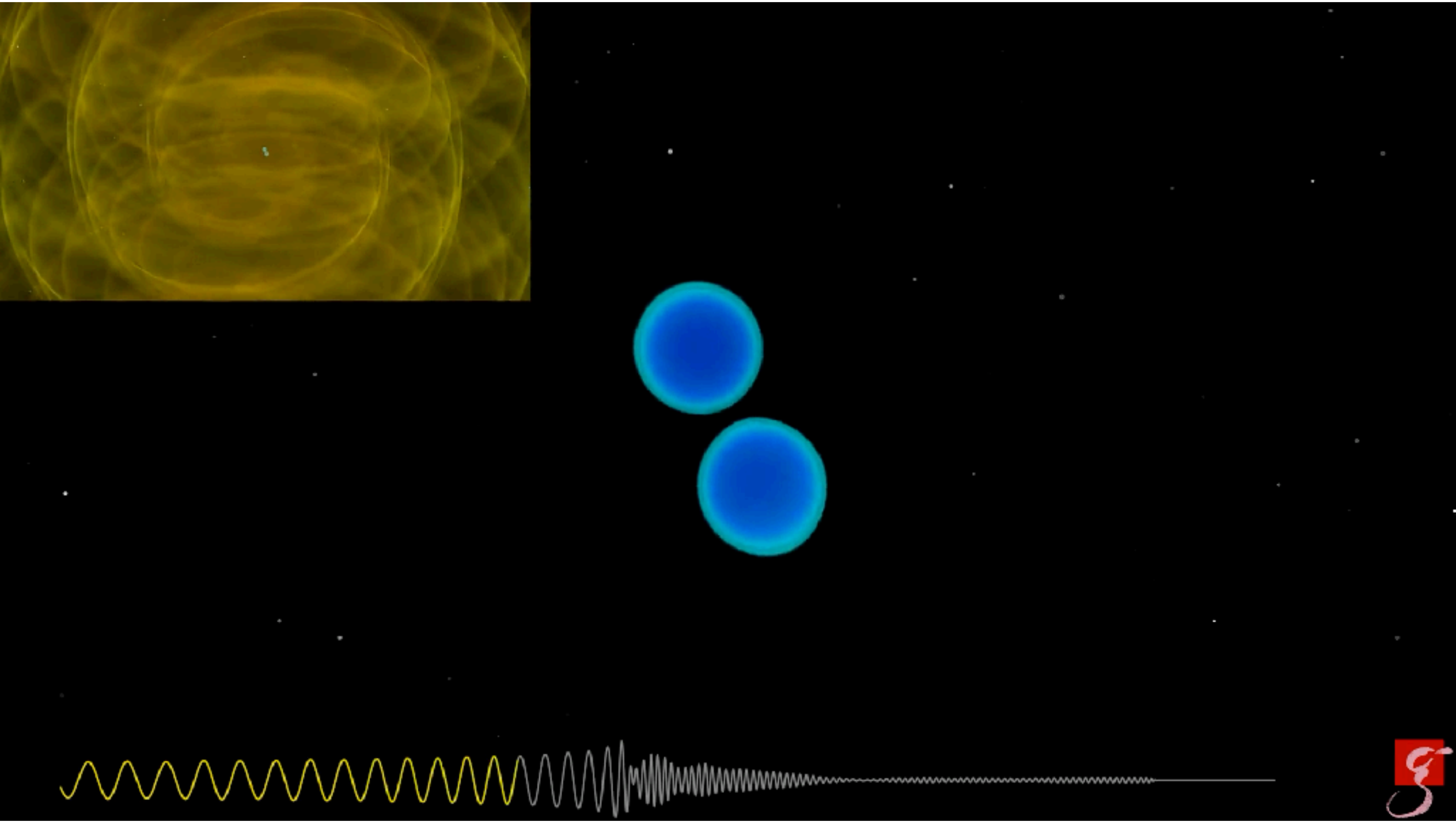
merger=
peak in GW
amplitude

- Phasing especially closely analyzed (not shown)

NS-NS merger part I

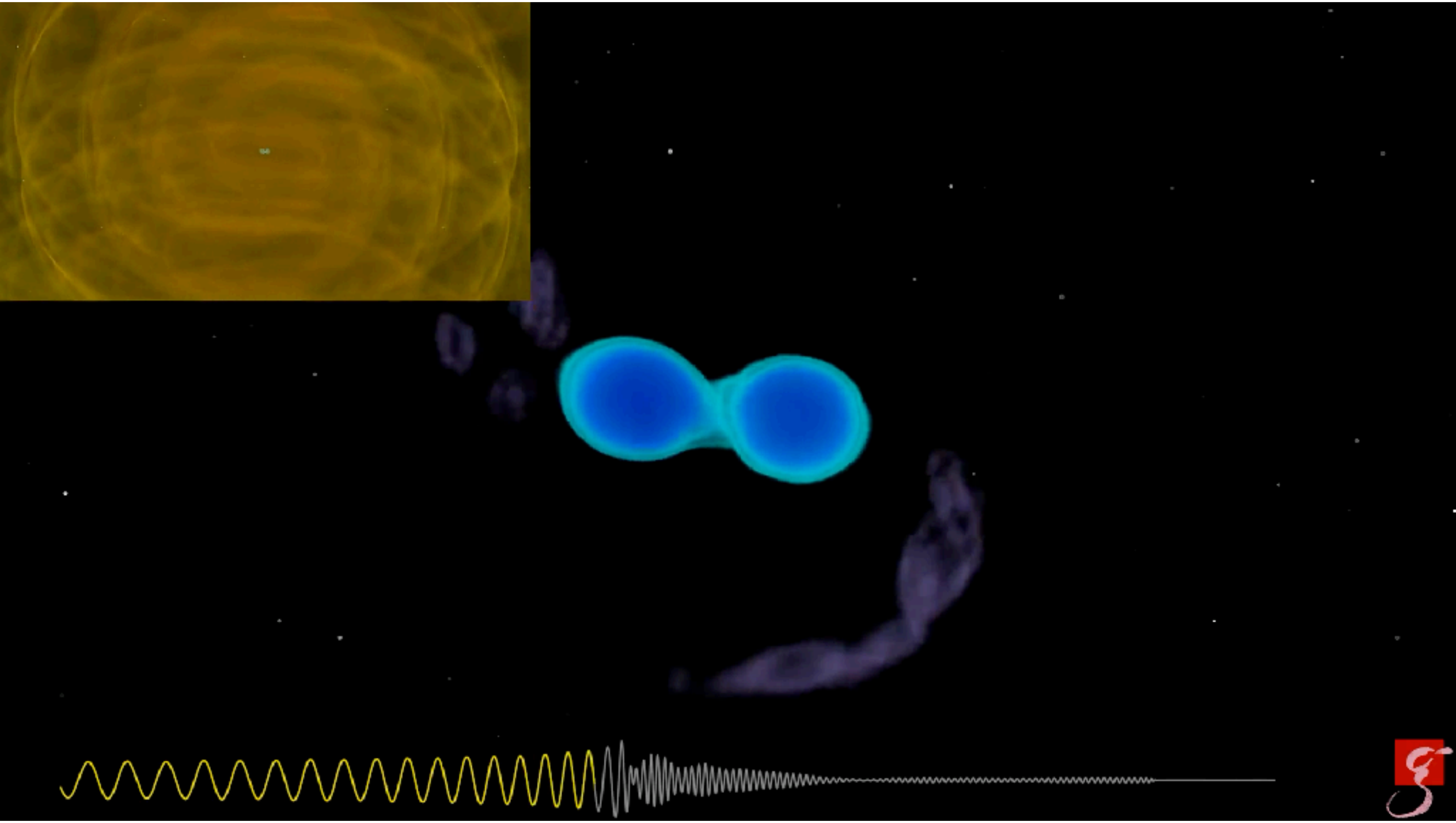
Credit: T. Dietrich

NS-NS merger part II



Credit: T. Dietrich

NS-NS merger part III

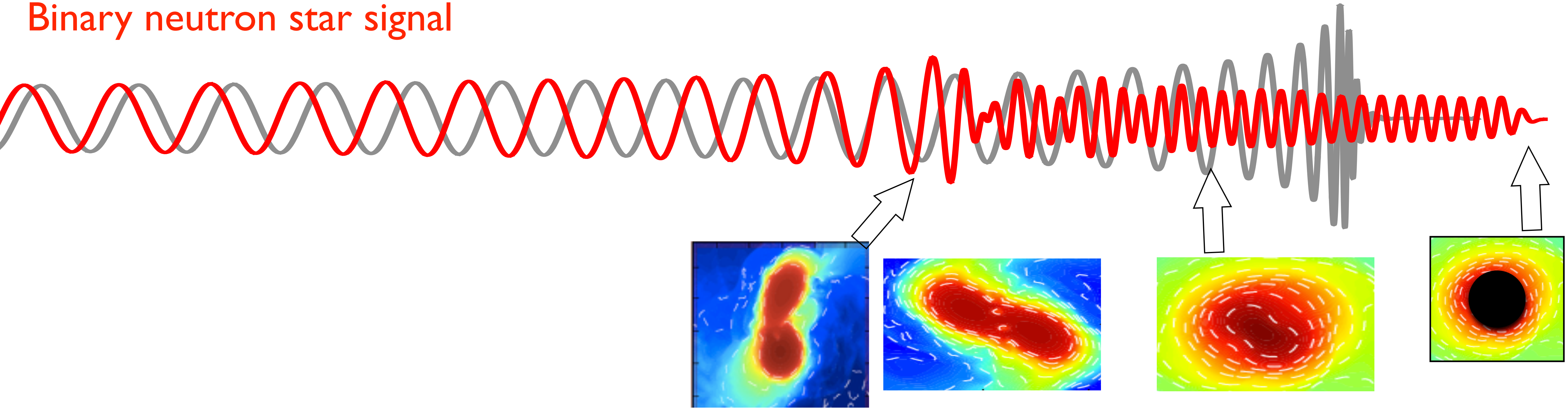


Credit: T. Dietrich

What happens post-inspiral? Example

NR data: T. Dietrich

Binary neutron star signal

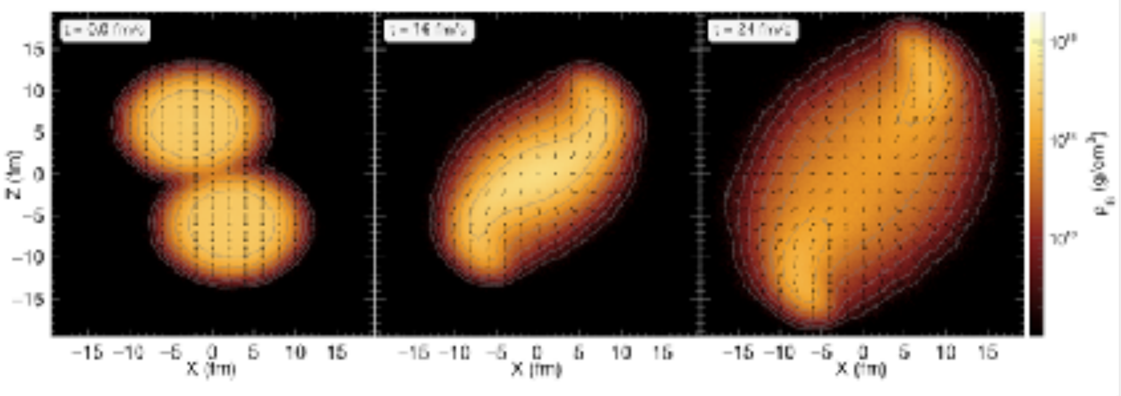


merger

Postmerger

Collapse
To BH

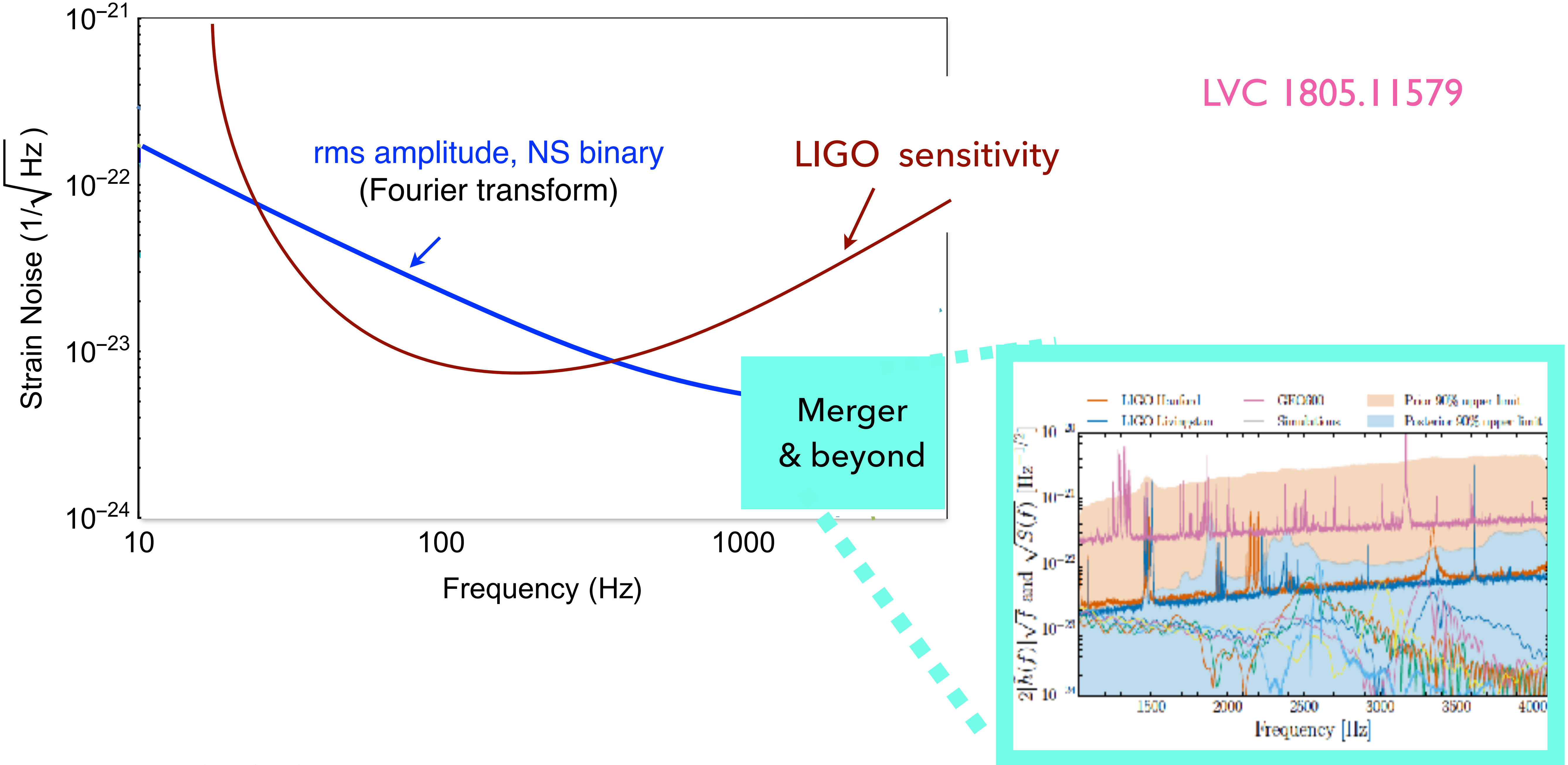
c.f. Au+Au heavy ion collision:



From Hanauske+

Signal of GW170817

- No direct info on post-in spiral from GWs



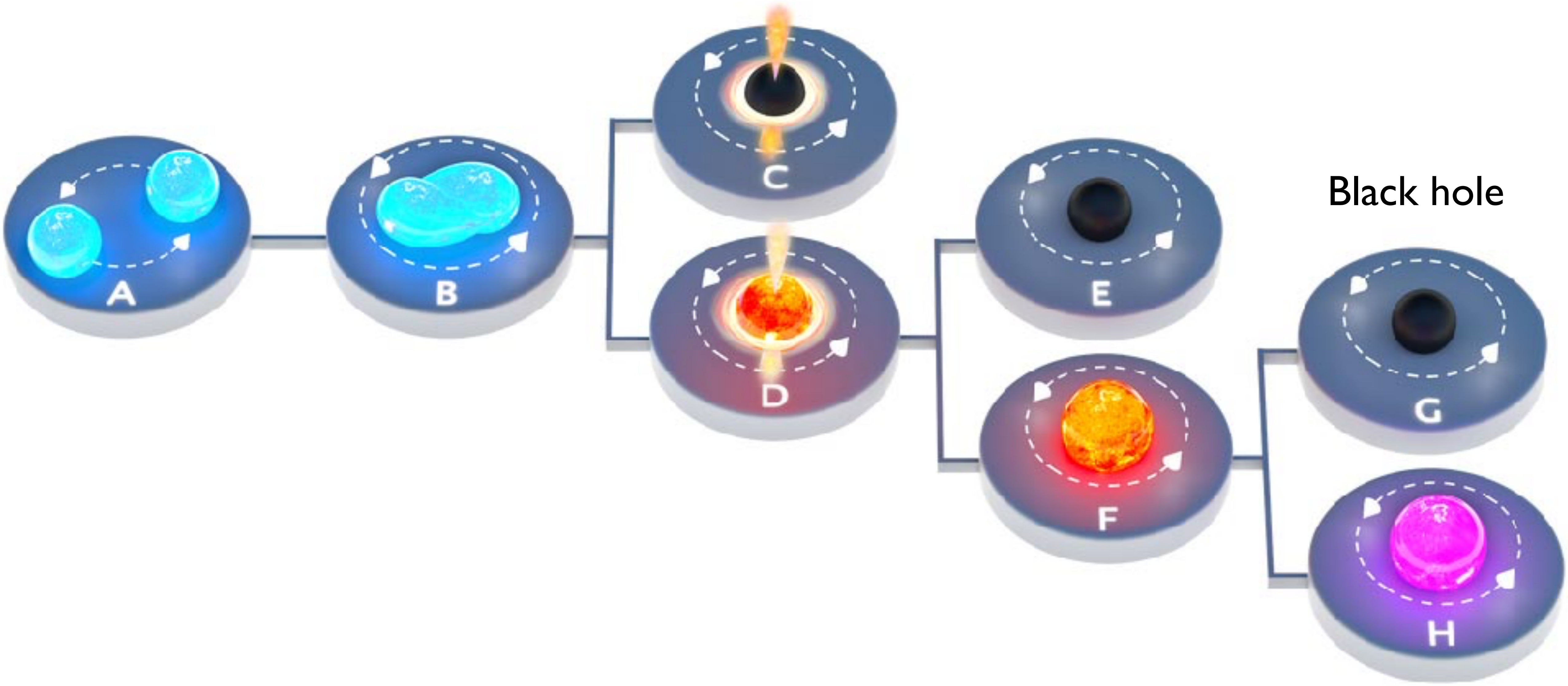
Schematic illustration

LVC 1805.11579

But lots of info from EM counterparts

Variety of merger outcomes in binary neutron stars

Depends on properties of the progenitor system



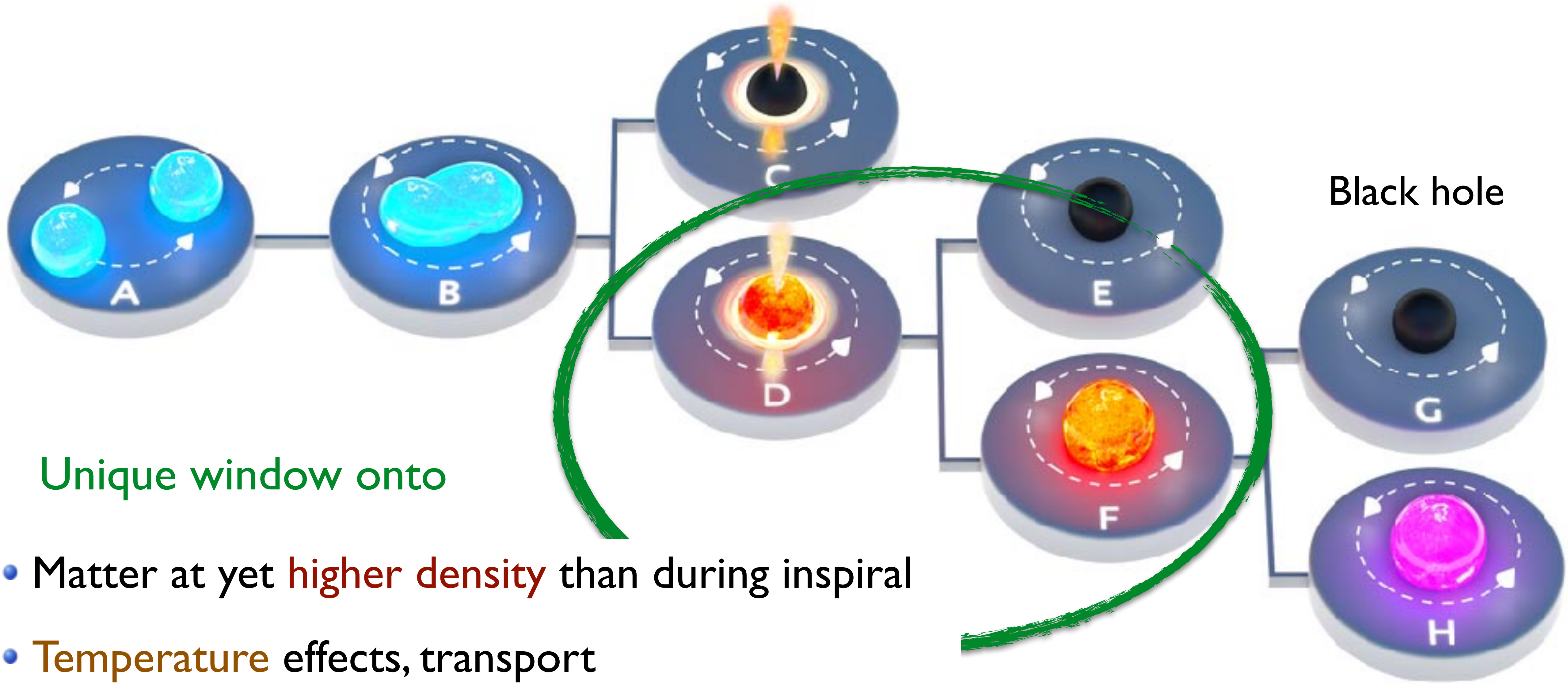
Black hole

Neutron star

Credit: C. Knox

Variety of merger outcomes in binary neutron stars

Depends on properties of the progenitor system



Black hole

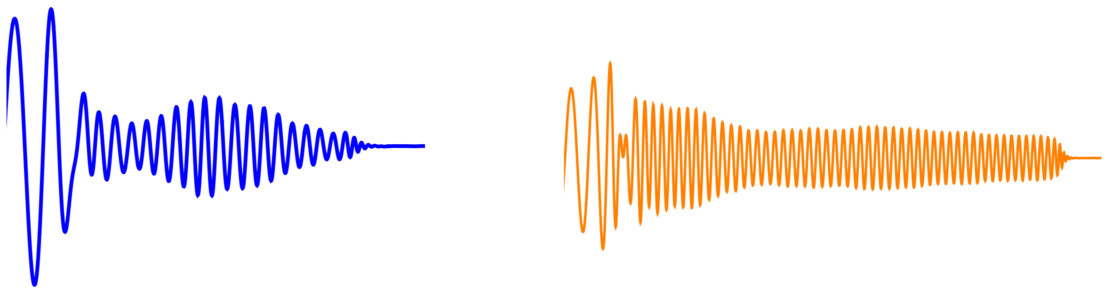
Neutron star

Unique window onto

- Matter at yet higher density than during inspiral
- Temperature effects, transport
- Role of small-scale phenomena, neutrino physics
- BH formation

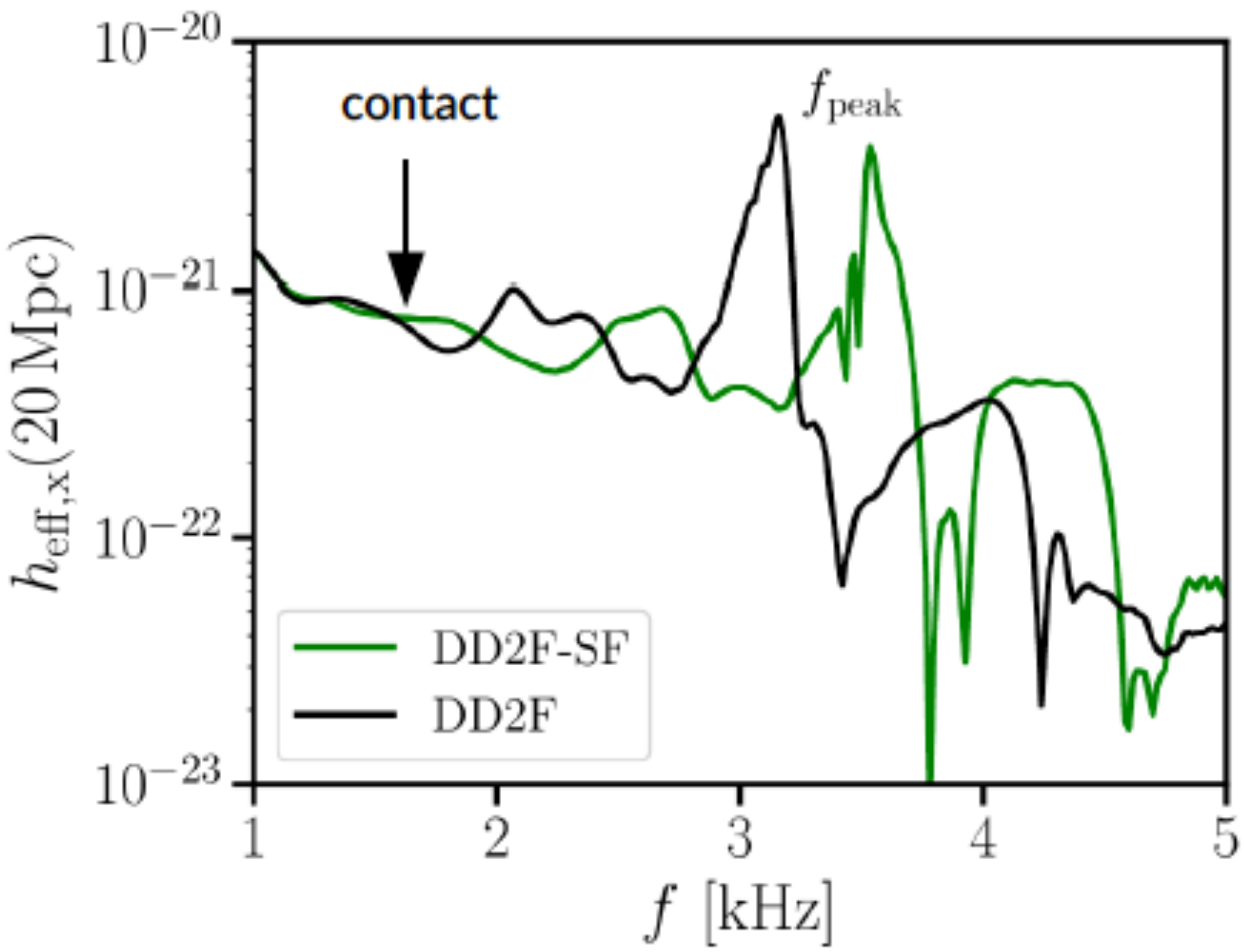
Post-merger GW signals

Example GW signals



credit: T. Dietrich

Example Fourier spectrum



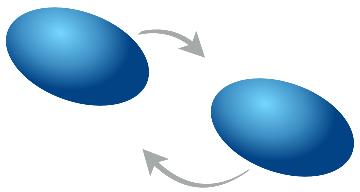
Bauswein+ 2018

- Rich frequency spectrum
- Sensitive to *lots* of physics
- Key challenge: numerical resolution & inclusion of 'realistic' physics
- See Ch. 6 of the Einstein Telescope bluebook for more details

To maximize the science payoffs, need to combine with inspiral

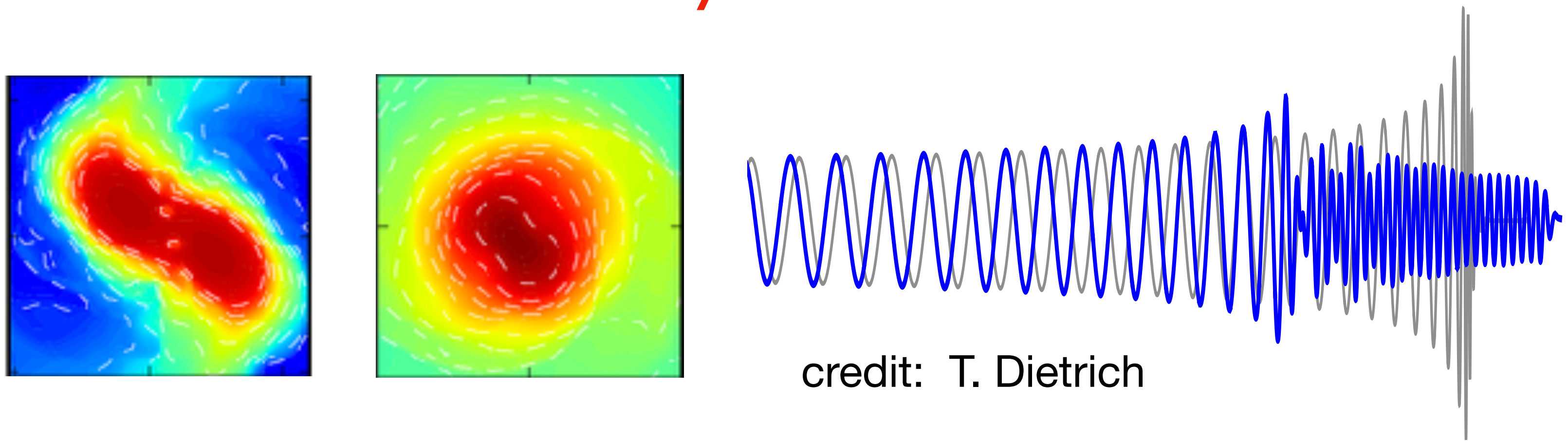
Similar to heavy ion collisions, need to

- Accurately characterize initial state:



masses, spins, EoS at zero temperature, orbital eccentricity, …

- Track the collision and beyond

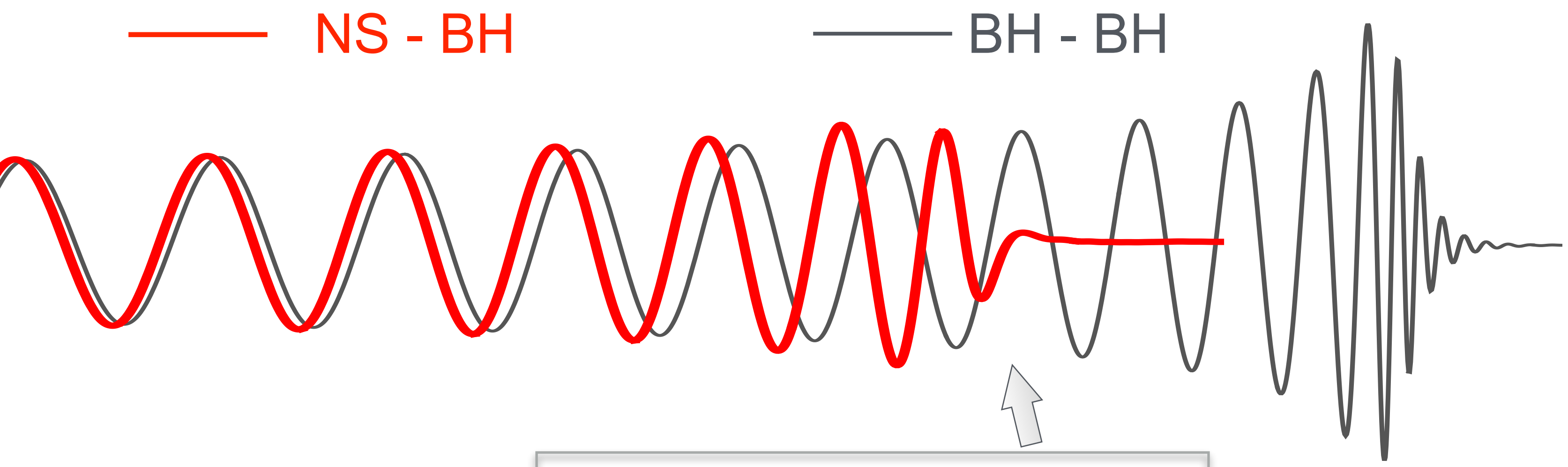


credit: T. Dietrich

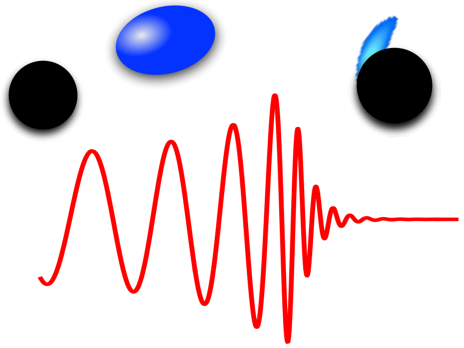
+ EM, neutrino probes

- identify & explore new physics and parameter-dependence

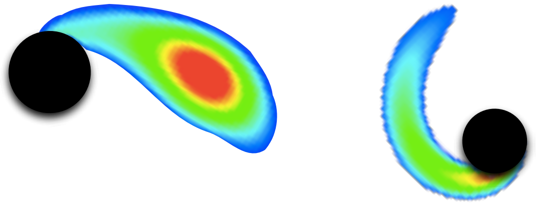
GW signal from NS-black hole (BH) binaries



- alternative outcome: plunge



tidal disruption

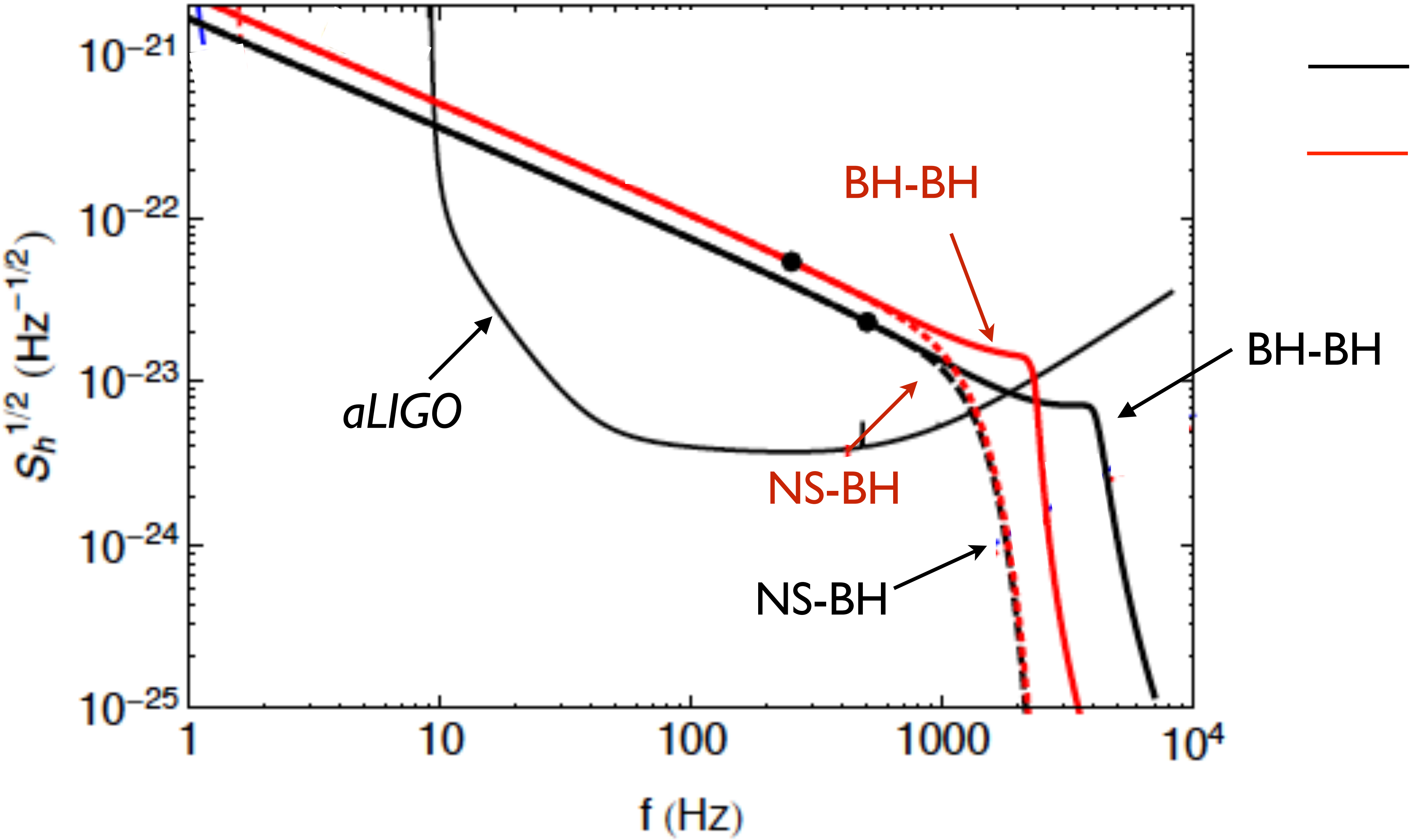


Key signature:
'shutoff' in GW amplitude

Shutoff frequency depends on parameters
(mass ratio, spins, EoS, …)

Very clean probes of cold EoS !

Frequency domain NS-BH signal



Dimensionless spin

$$\chi = \frac{cJ}{Gm^2} \leq 1$$

For a black hole

[B. D. Lackey+ Phys.Rev. D89 (2014), 043009]

Plans for future ground-based detectors underway

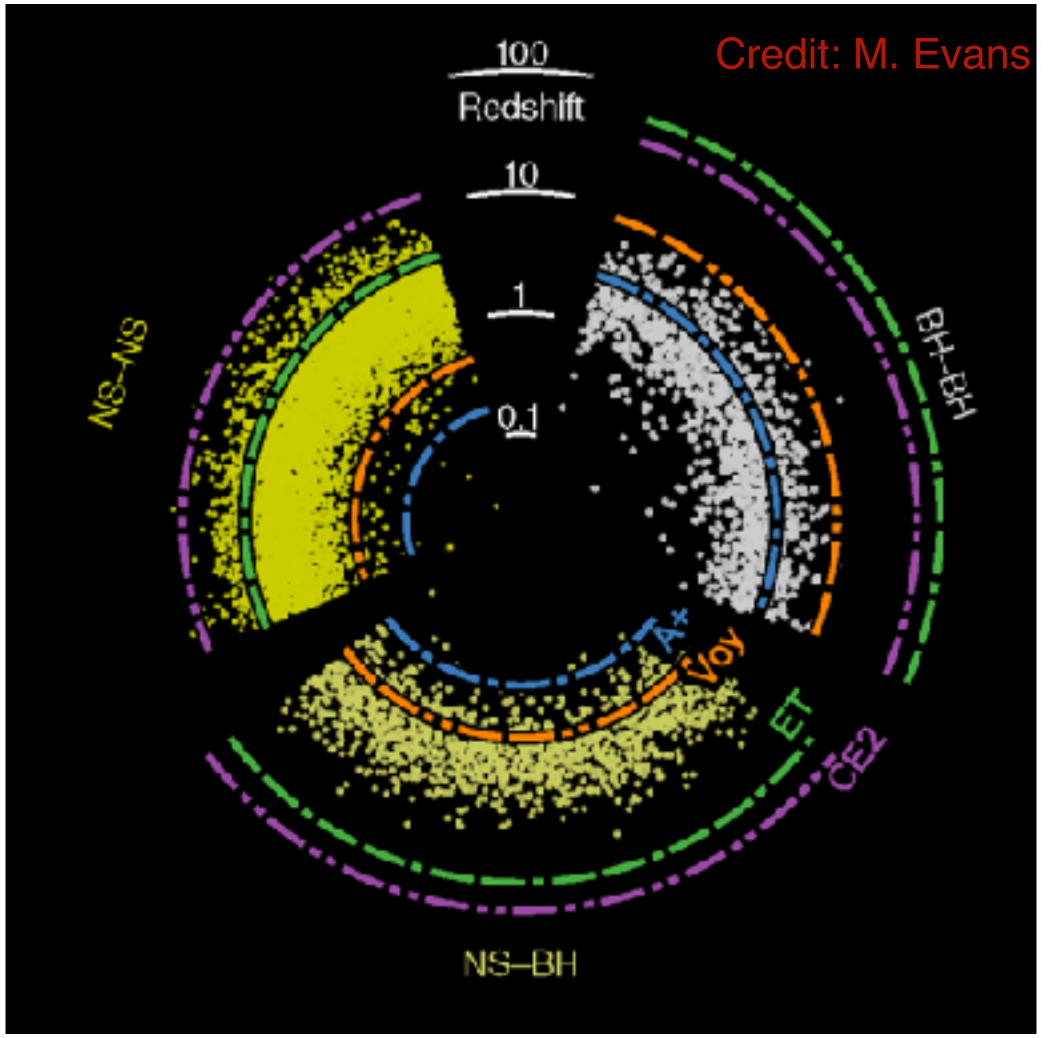
Next 6-months observing run to start fall 2026

Next-generation detectors being planned:

Einstein Telescope: on ESFRI roadmap, funding efforts underway, pathfinder in Maastricht

~mid 2030s [Europe]

US effort: Cosmic Explorer(s) [US]



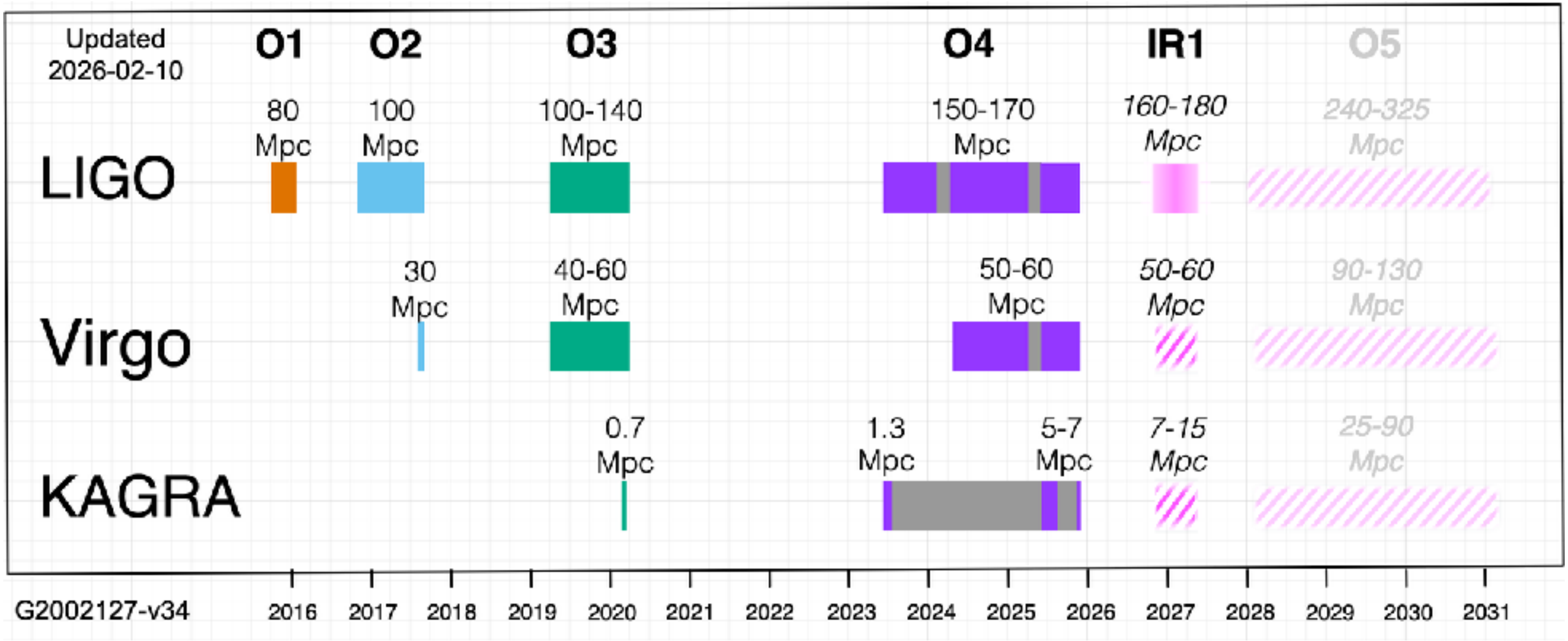
Credit: M. Evans

$O(10^5)$ binary detections / year

Greater number and diversity of GW events,

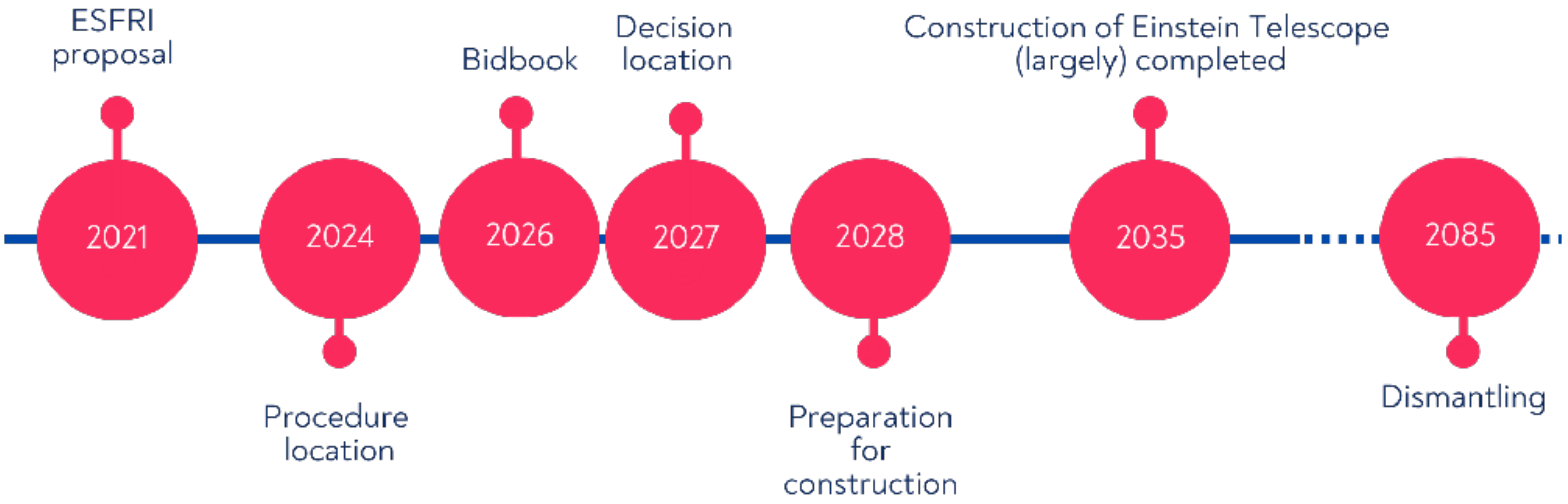
Higher measurement accuracy for nearby sources

Observing plans for current detectors



https://observing.docs.ligo.org/plan/

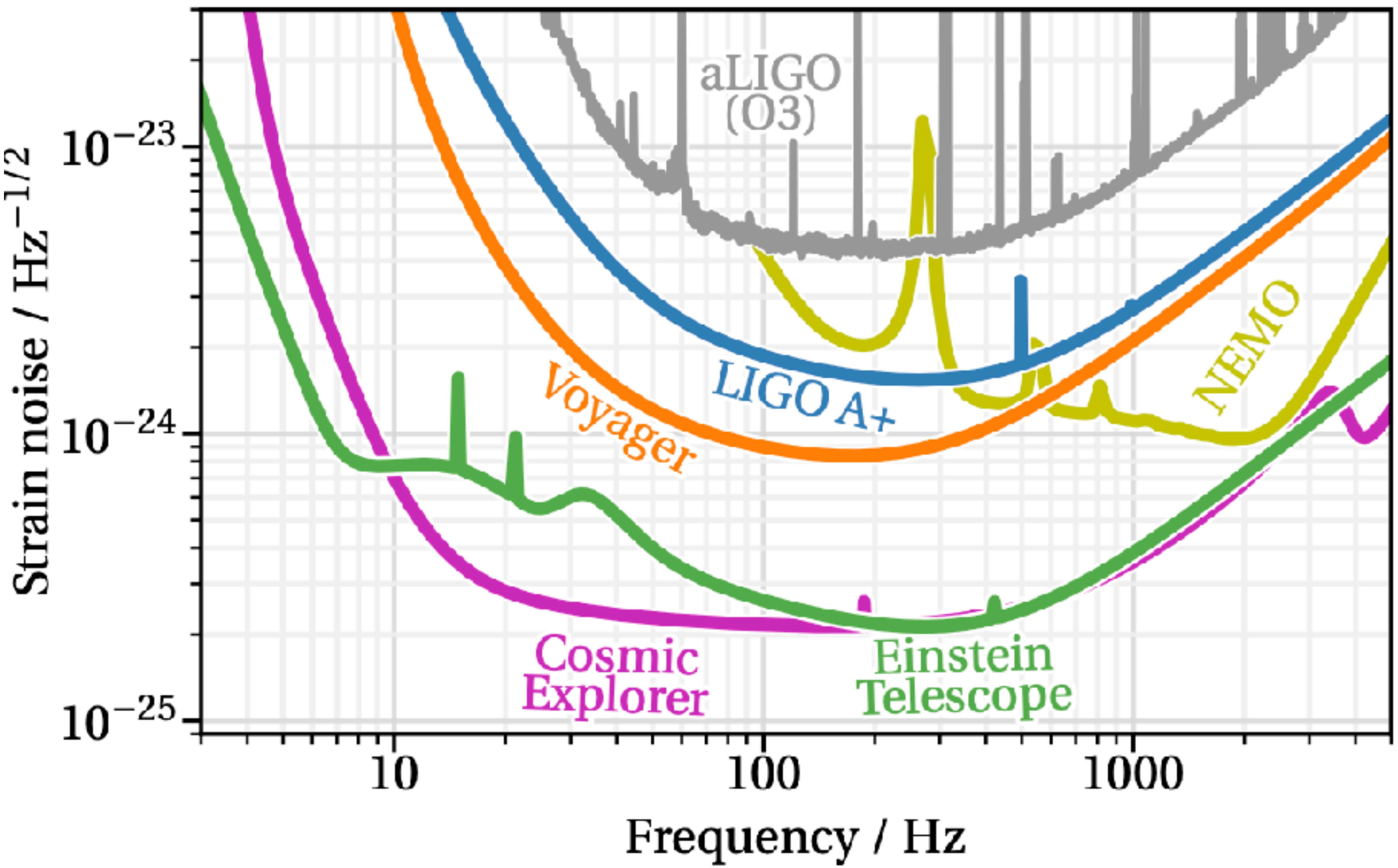
Einstein Telescope tentative timeline



https://www.einsteintelescope-emr.eu/en/organisation-and-timeline/

Cosmic Explorer: horizon study completed 2021, ongoing work on Science Traceability, possible sites, …

Anticipated sensitivity curves



Conclusions

Recent GW discoveries provided first constraints on neutron star interiors — clean, purely gravitational channel

main science payoffs with GWs for neutron stars yet to come, expect a wealth of new insights in the future

Main limitation for future science will be shortcomings in modeling, missing physics

Much recent progress, many tools developed but need further advances in understanding & modeling matter effects in GWs with more realistic physics, synergies between analytical & numerical relativity