Probing nuclear physics with gravitational waves from neutron star binary inspirals

Tanja Hinderer

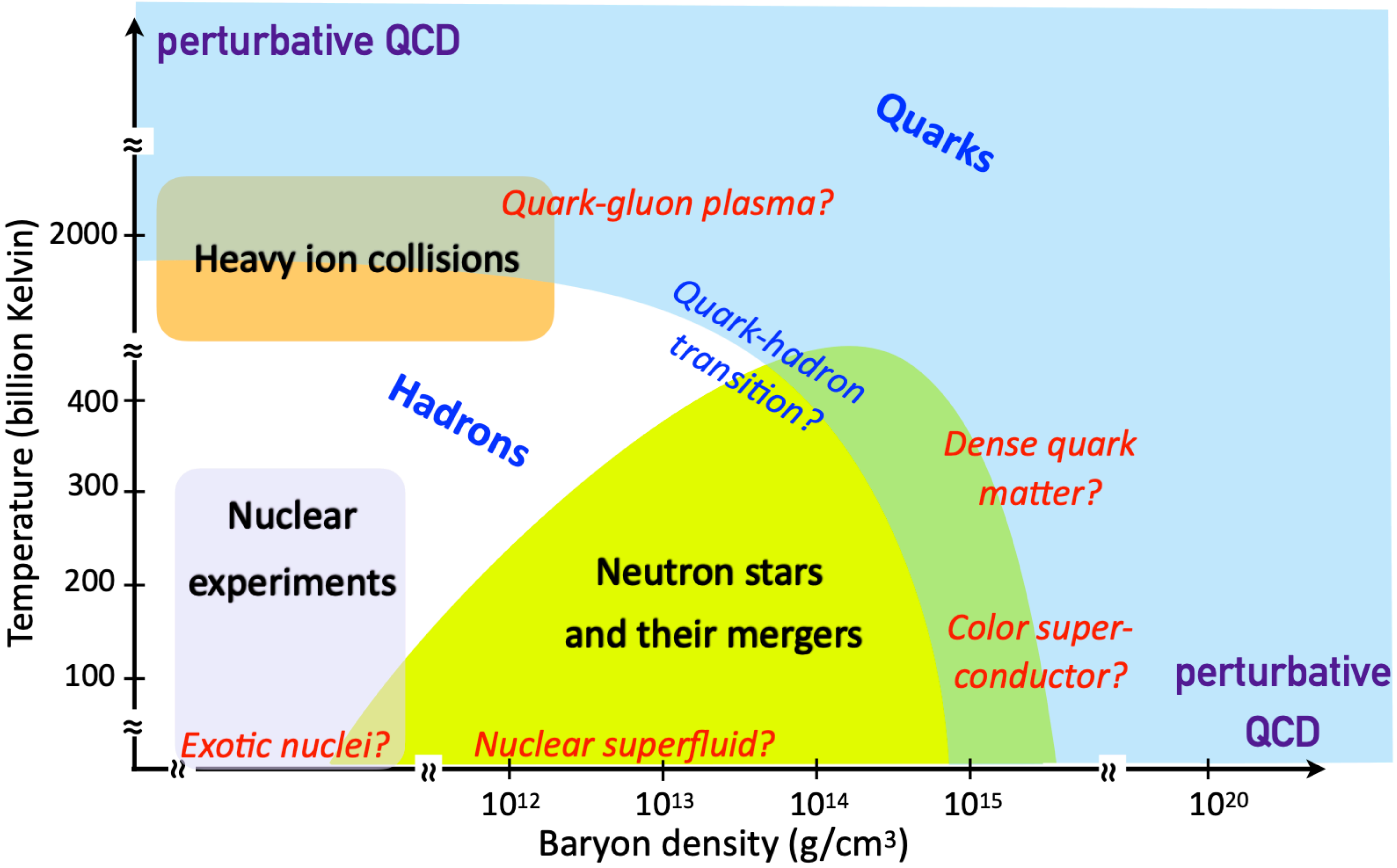
Institute for Theoretical Physics,
Utrecht University

Overview

- Gravitational waves (GWs) from neutron star binary systems now available as clean, purely gravitational probes of subatomic matter
- Interpreting the data requires detailed theoretical understanding & modeling
- Example signatures in GWs that encode matter properties: tidal effects
- What have we learned from recent measurements?
- Outlook to upcoming future prospects and remaining challenges

Neutron stars (NSs)

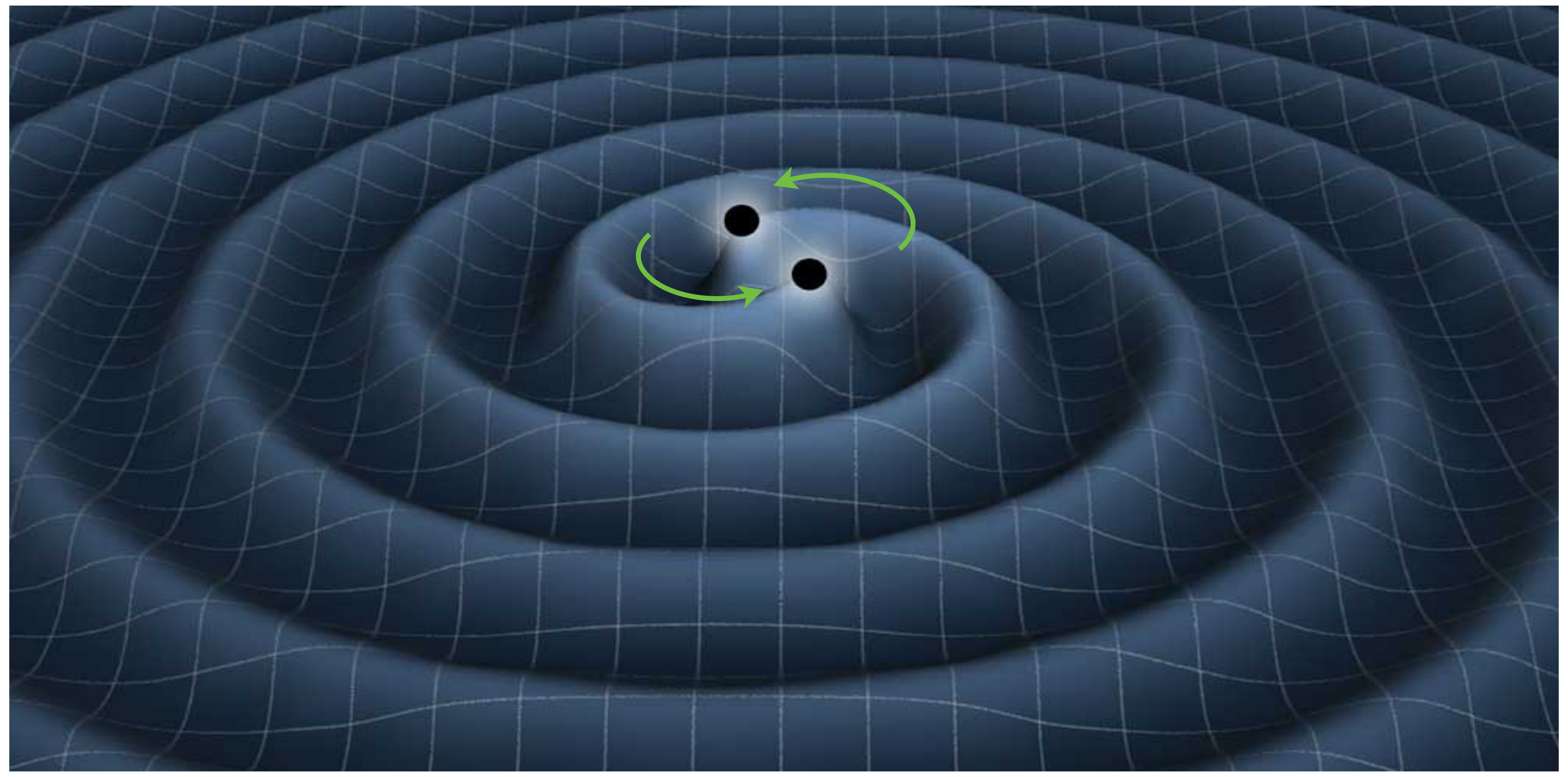
- Gravity compresses ~ $1.5\,M_{\odot}$ of material to ~ 10km radius
- Dense matter near ground state, multi-body interactions, emergent collective phenomena



From NL consortium on Probing the Phase Diagram of QCD

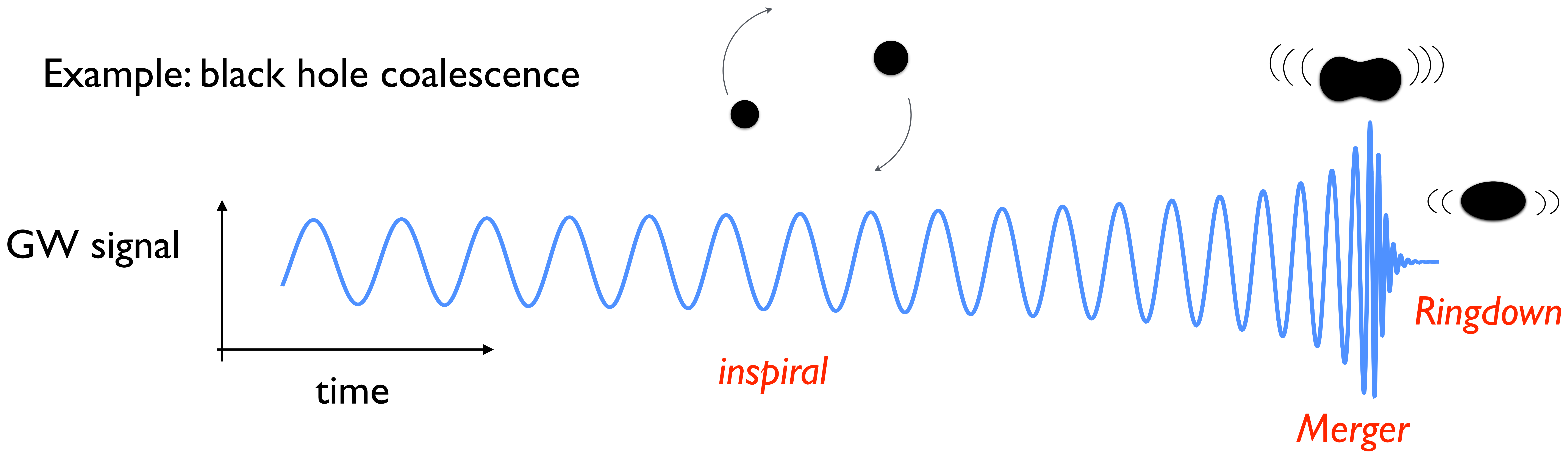
Compact objects in binary systems

dynamical spacetime ⇒ gravitational waves (GWs)



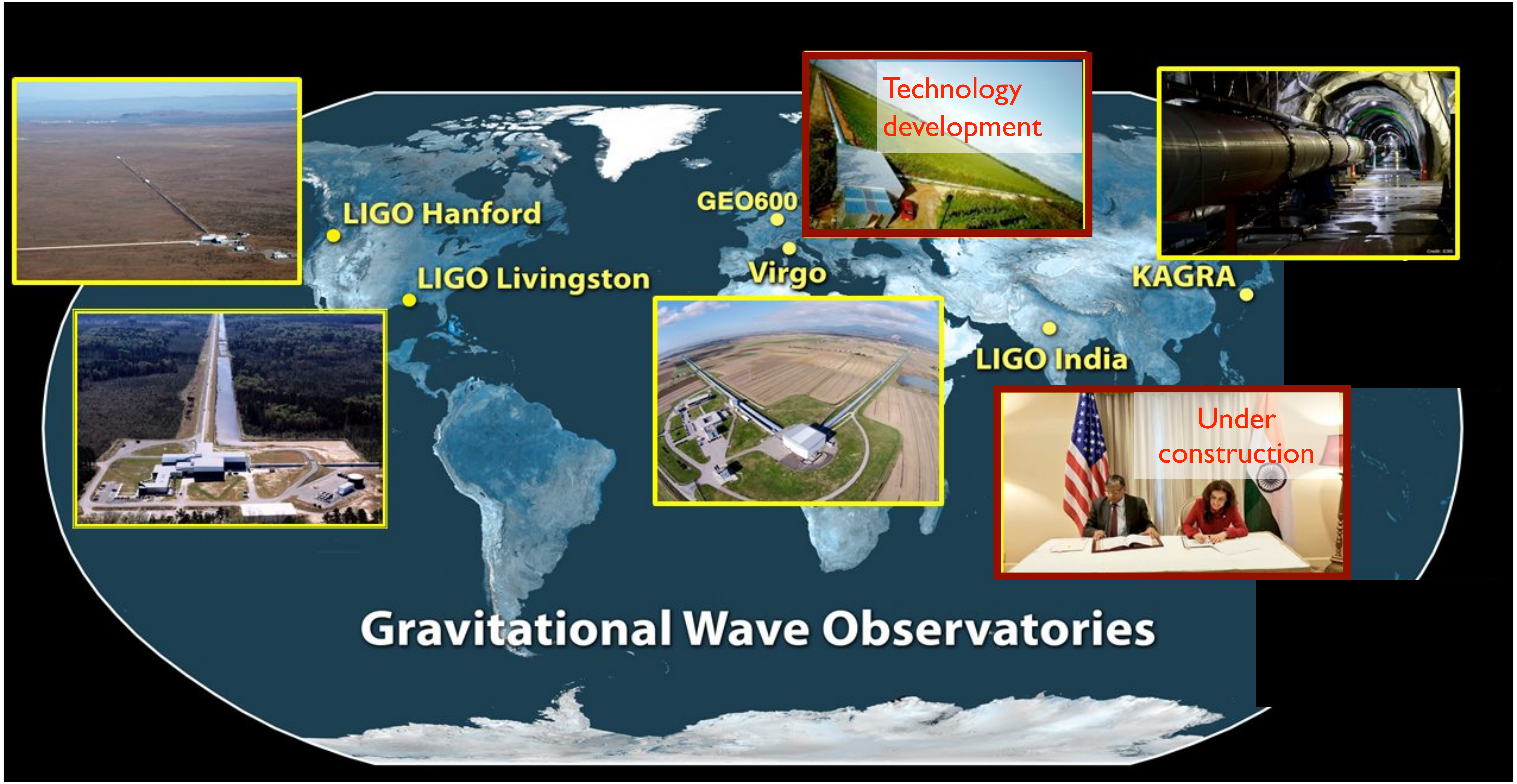
- enormous energy → only tiny amplitudes
- Interact very weakly with matter: unimpeded by absorption, attenuation, ….

Example: black hole coalescence

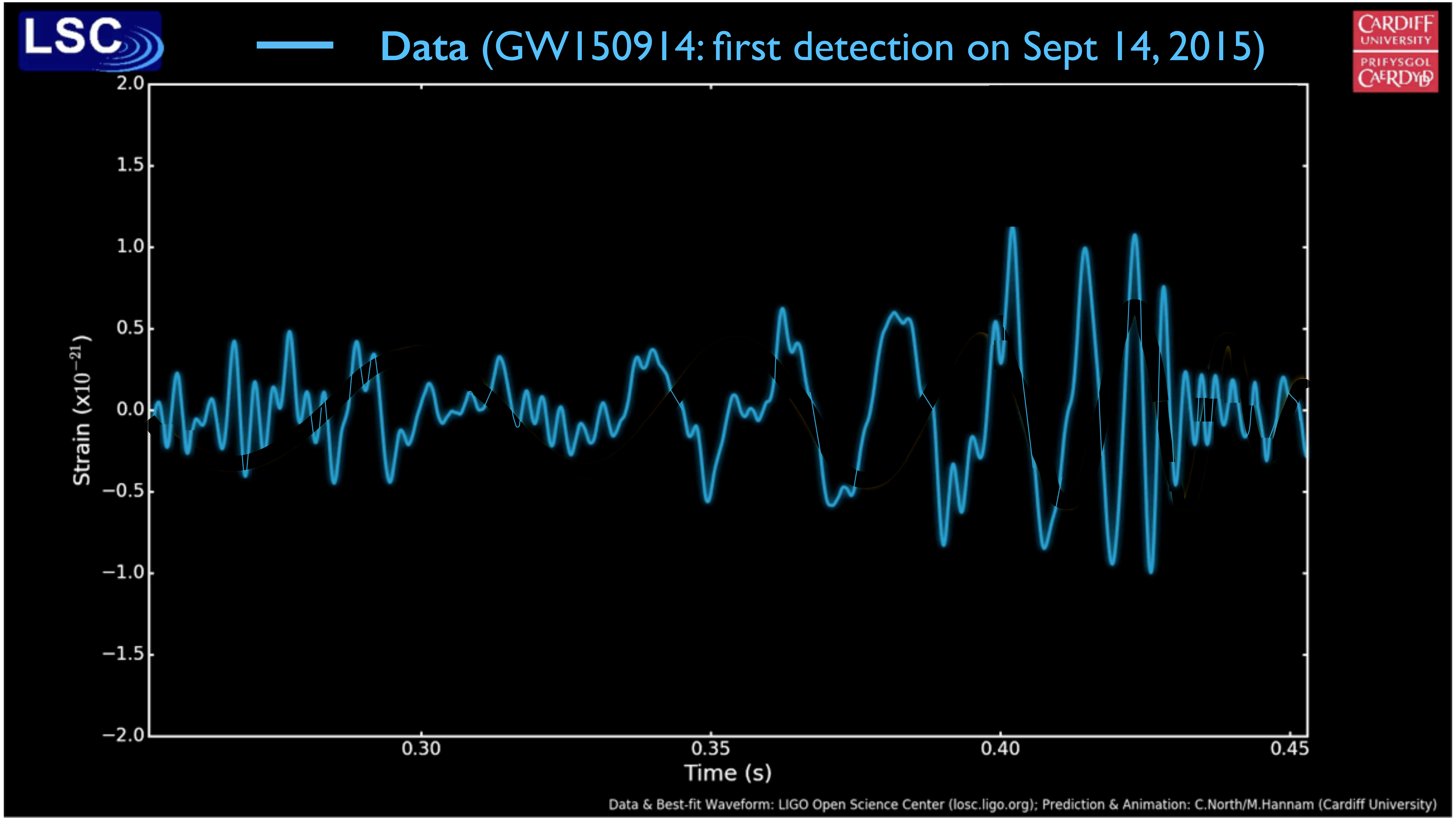


‣ GW signals are fingerprints of the fundamental source properties

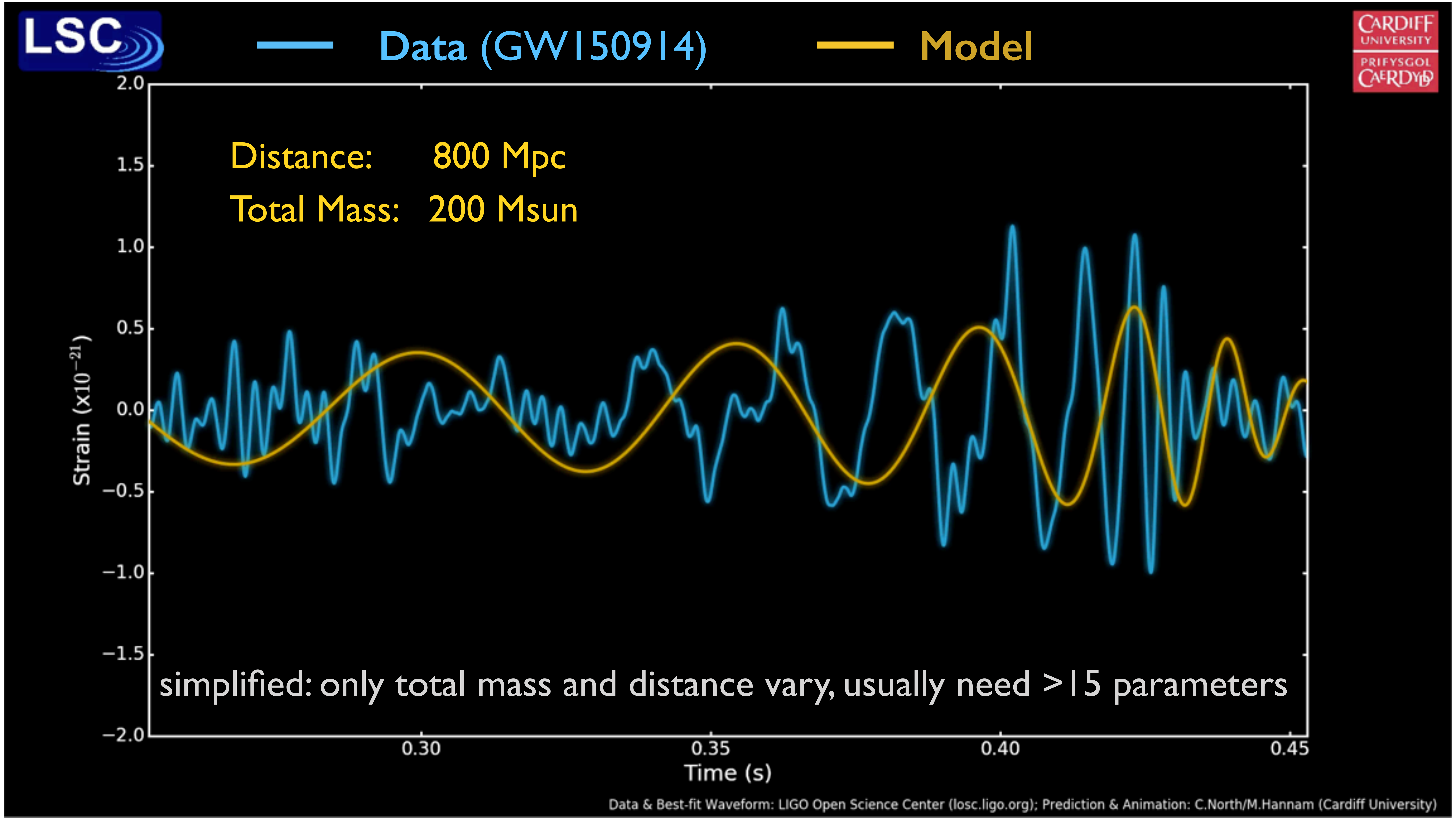
Worldwide network of GW detectors



Interpreting GW signals relies on theoretical models

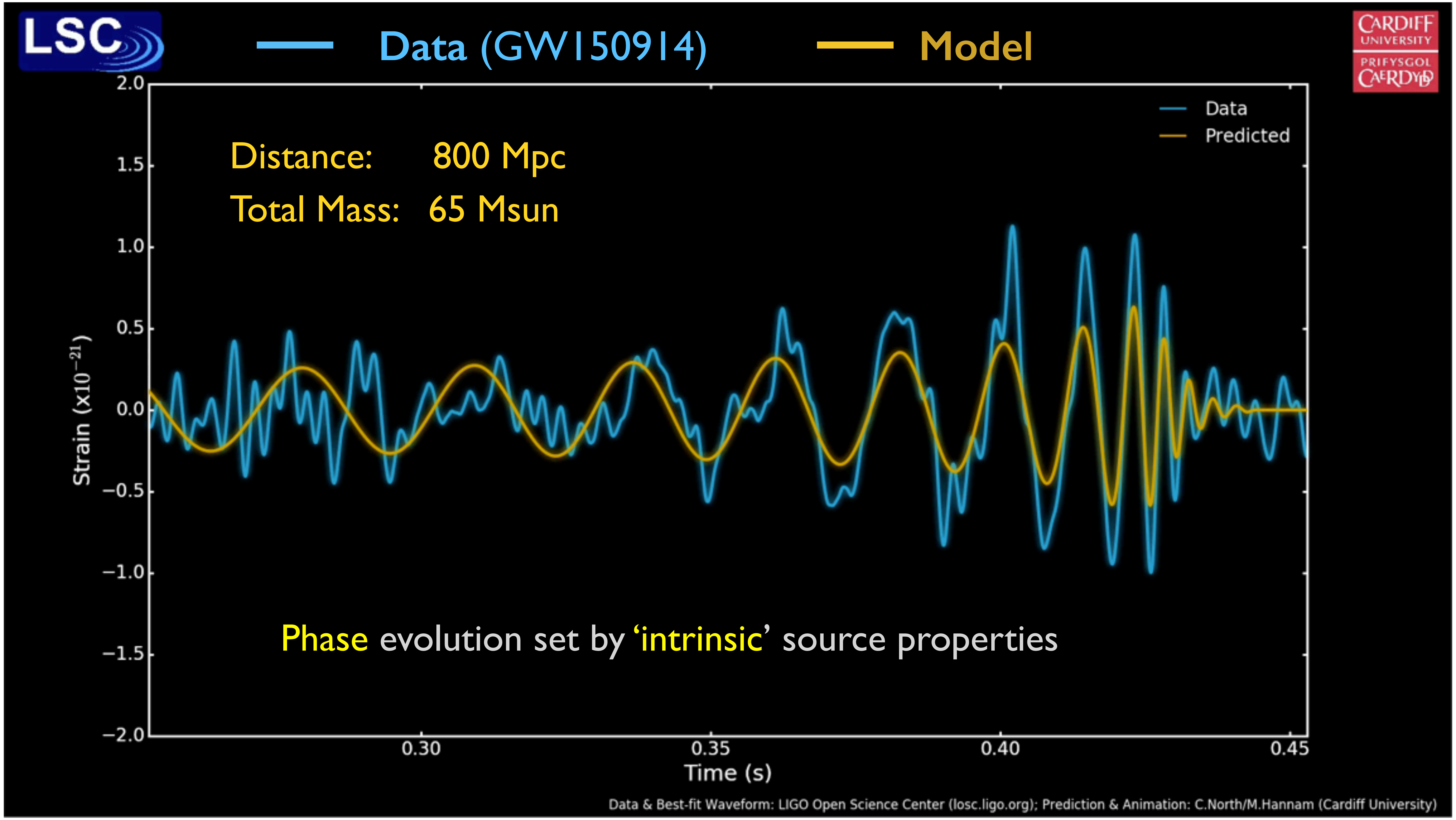


Interpreting GW signals relies on theoretical models



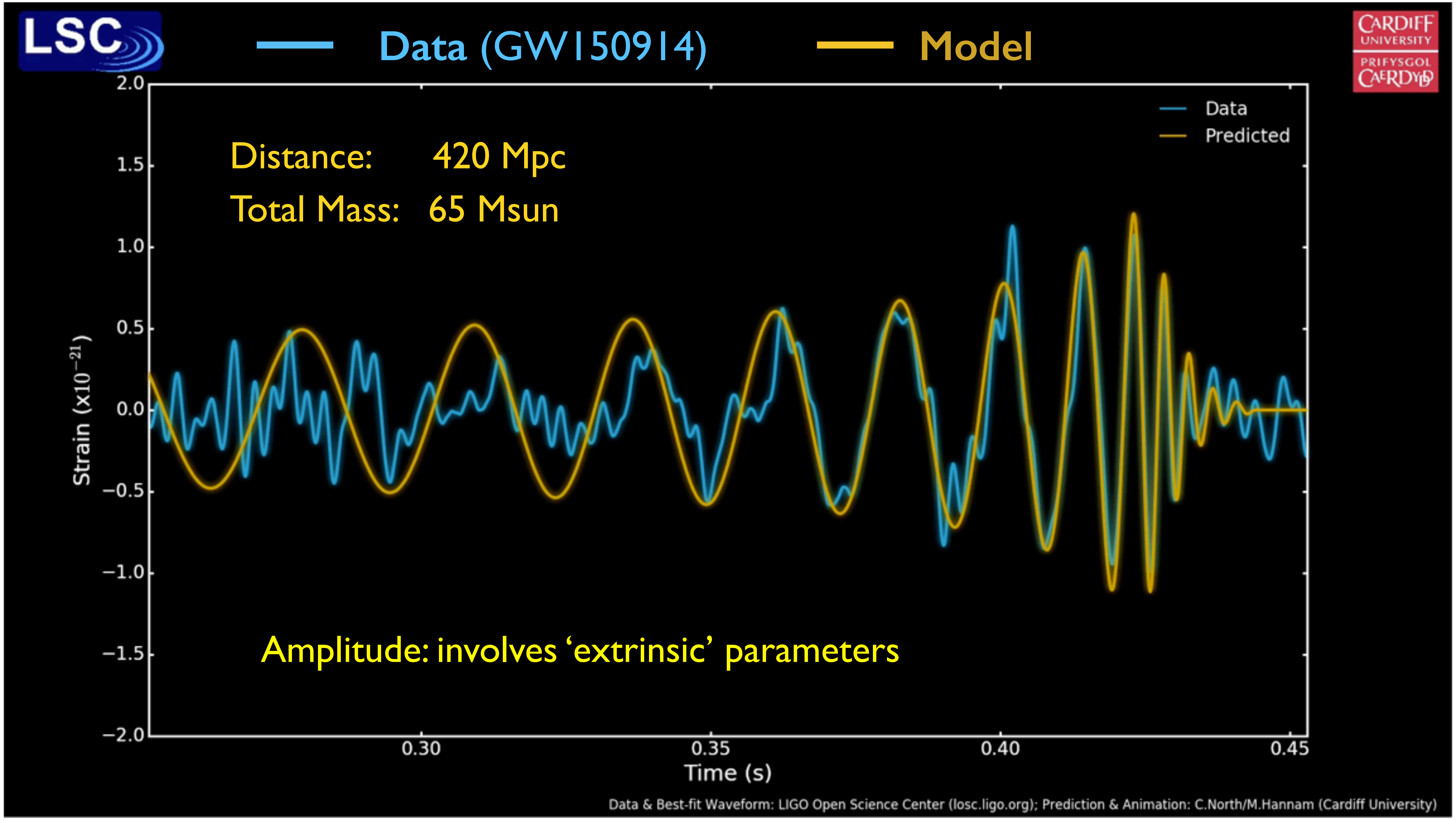
Waveforms are characteristic fingerprints of their sources

Interpreting GW signals relies on theoretical models



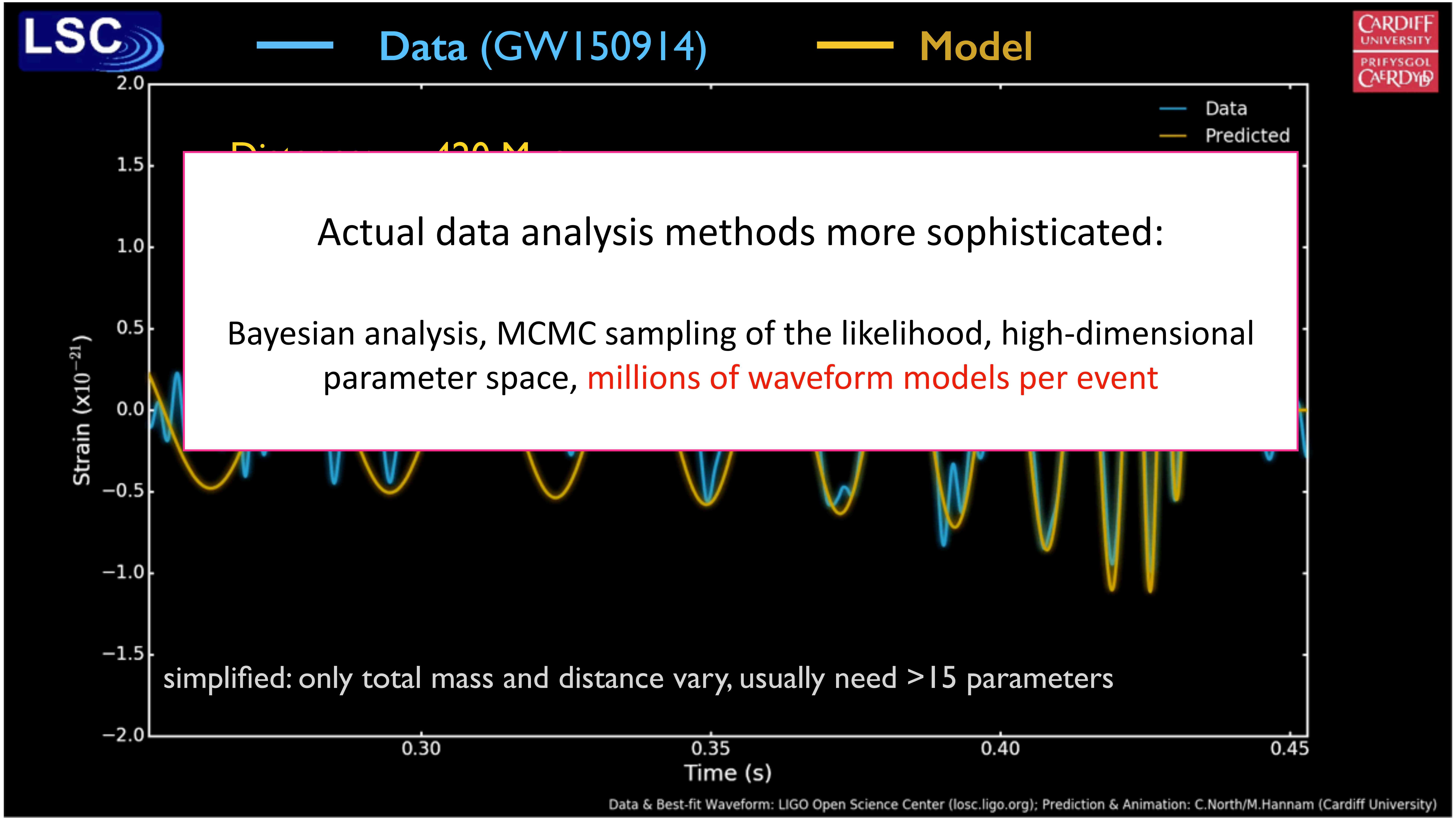
Measurements are extremely sensitive to the phase evolution

Interpreting GW signals relies on theoretical models



Measurements are extremely sensitive to the phase evolution

Interpreting GW signals relies on theoretical models

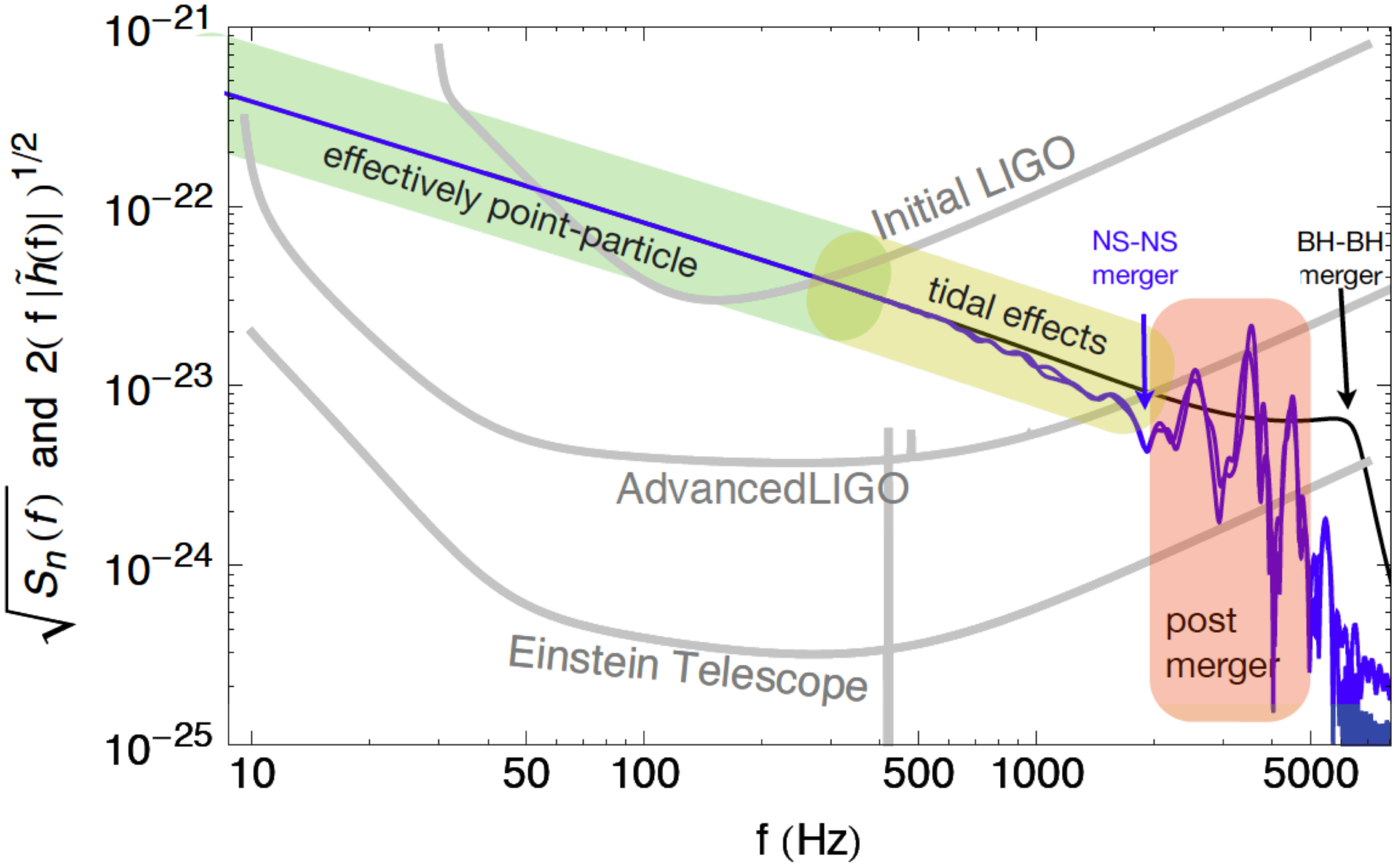


Actual data analysis methods more sophisticated:

Bayesian analysis, MCMC sampling of the likelihood, high-dimensional parameter space, millions of waveform models per event

Waveforms are characteristic fingerprints of their sources

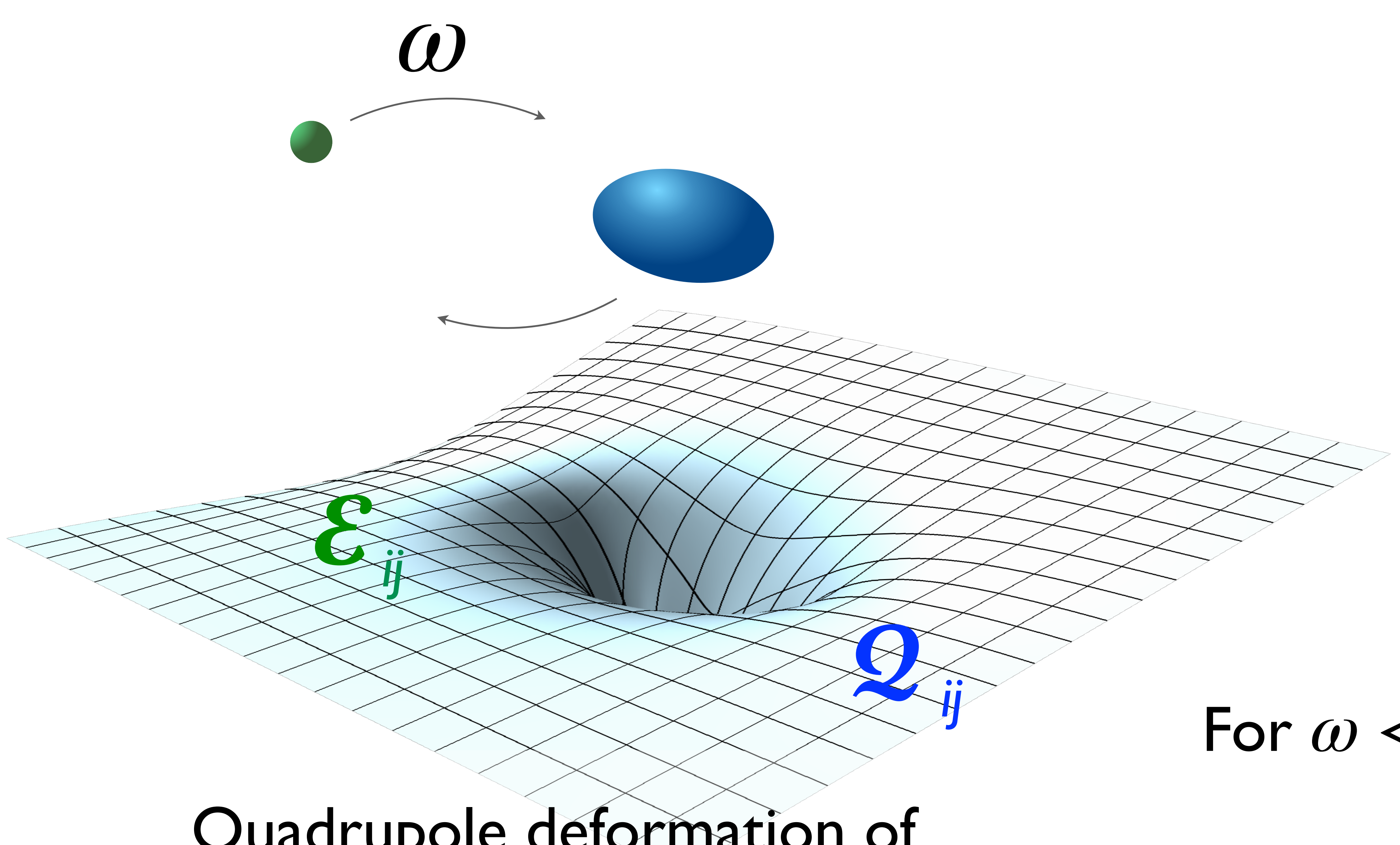
NS-NS: root-mean-square GW amplitude in detector sensitivity



Credit: J. Read

Dominant tidal effects (non-spinning objects)

- In a binary: tidal field $\mathcal{E}_{ij}$ due to spacetime curvature from companion



Quadrupole deformation of exterior spacetime away from spherical symmetry

induced deformation

$$Q_{ij} = -\lambda_{ijkl}(\omega)\mathcal{E}^{kl}$$

frequency-dependent response

For $\omega \ll$ internal mode frequencies (adiabatic limit):

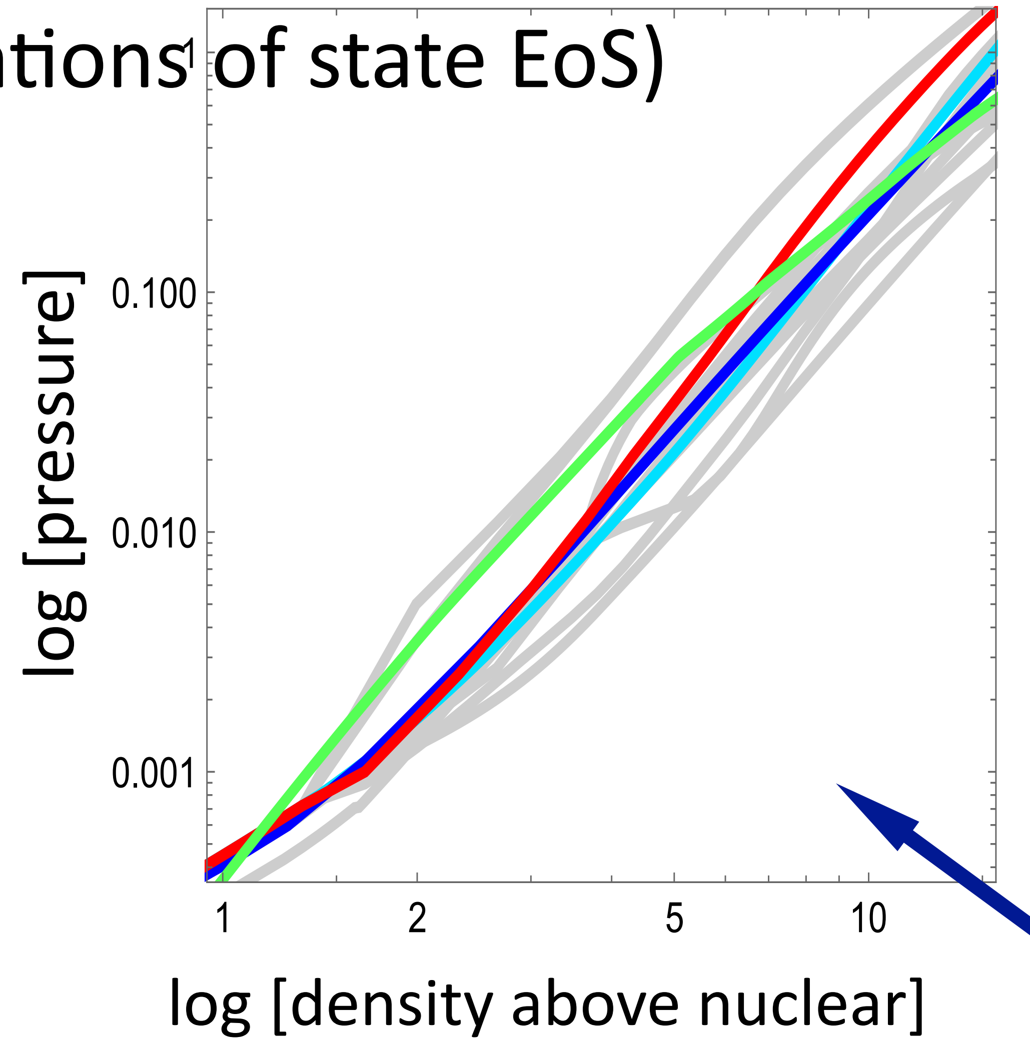
$$\approx \lambda + O(\omega)$$

tidal Love number / deformability / polarizability

[TH 2008, Damour & Nagar 2009, Binnington & Poisson 2009, …]

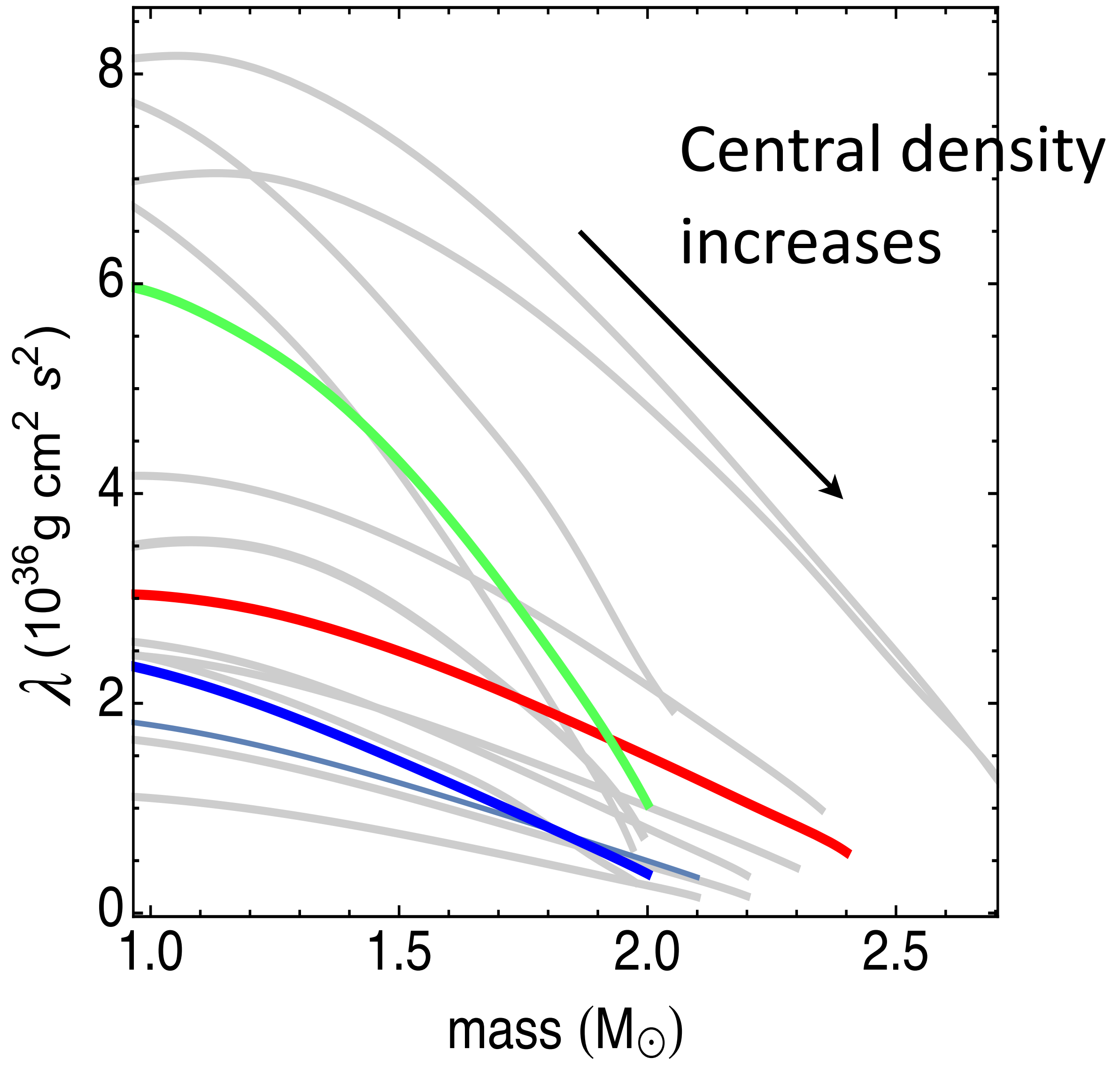
Tidal Love numbers reflect interior matter properties

Neutron star matter models
(equations of state EoS)



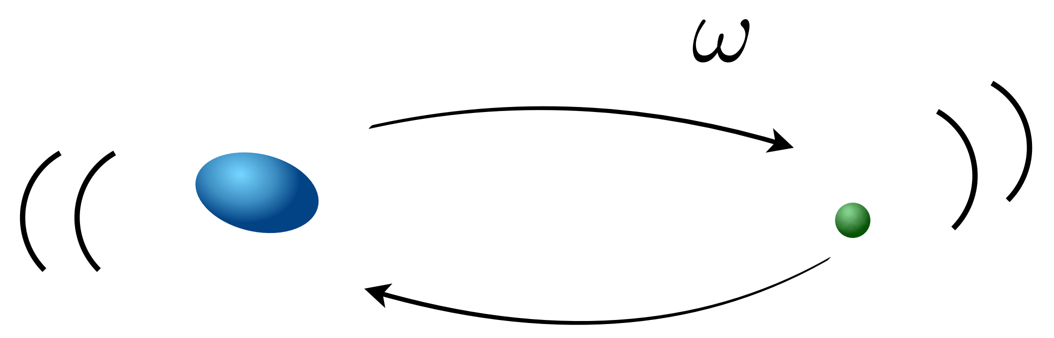
In practice: solve for NS configuration
(TOV equations)
+ one more ODE to get λ

λ vs. mass



symmetry energy, composition, 3-nucleon forces, … different calculational methods, approximations

Main influence on dynamics & GWs



- Energy goes into the deformation:

$$E \sim E_{\text{orbit}} + \frac{1}{4}\mathcal{Q}\,\mathcal{E}$$

- moving tidal bulges contribute to gravitational radiation

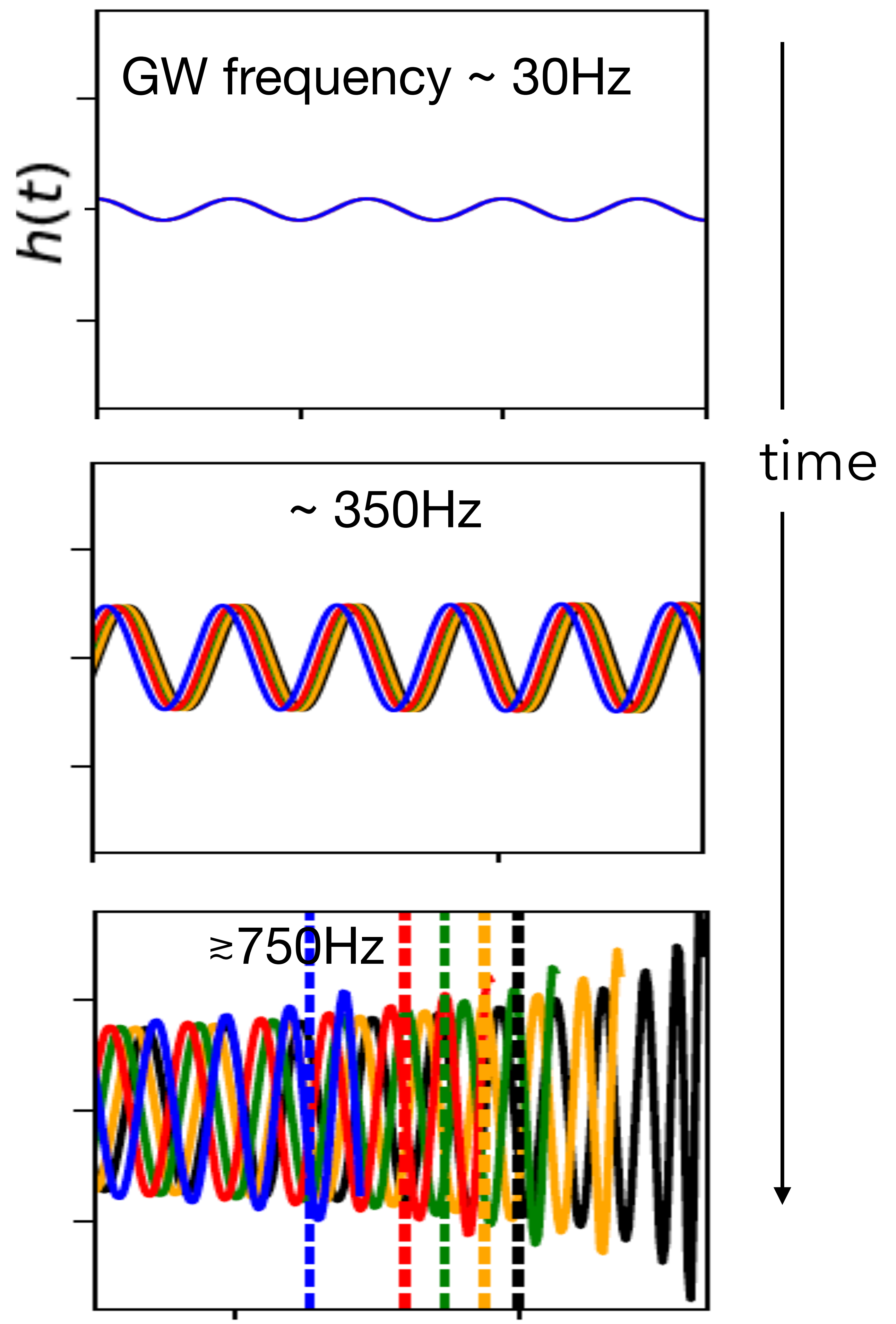
$$\dot{E}_{\text{GW}} \sim \left[\frac{d^3}{dt^3}\left(Q_{\text{orbit}} + \mathcal{Q}\right)\right]^2$$

G=c=1 units

- approx. GW phase evolution from energy balance:

$$\Delta\phi_{\text{GW}}^{\text{tidal}} \sim \lambda\frac{(M\omega)^{10/3}}{M^5} \qquad M = m_1 + m_2$$

Examples for different EoSs aligned at 30 Hz

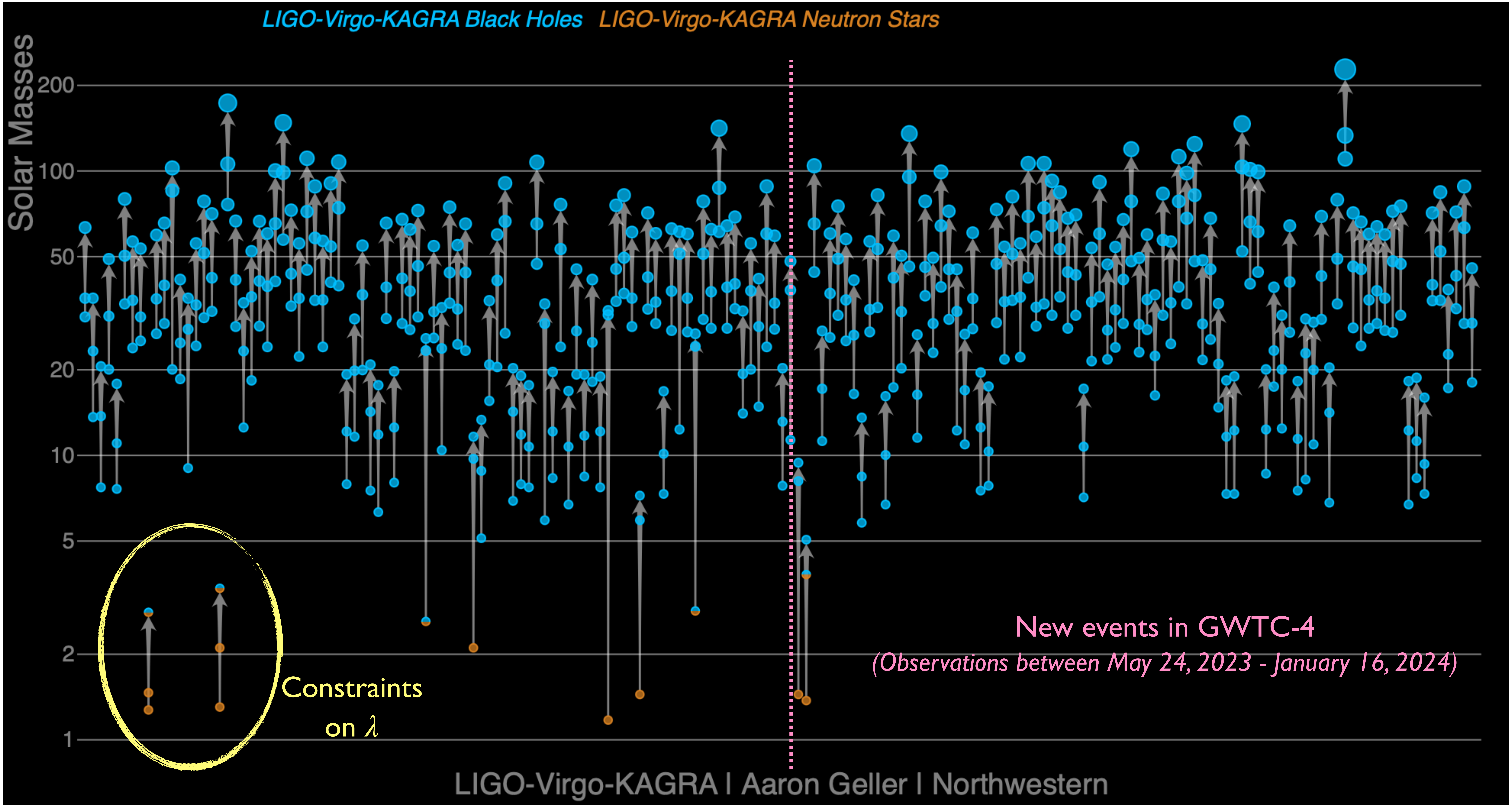


Dashed lines: 1kHz

[Flanagan, TH 2008, Vines+ 2011, Damour, Nagar+ 2012, Henry+2021]

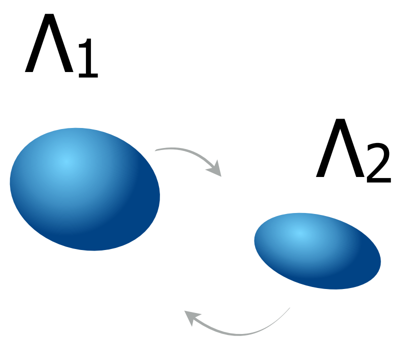
GW detections analyzed so far

GWTC-4.0: arXiv 2508.18082



Aug. 17, 2017: binary NS inspiral GW170817

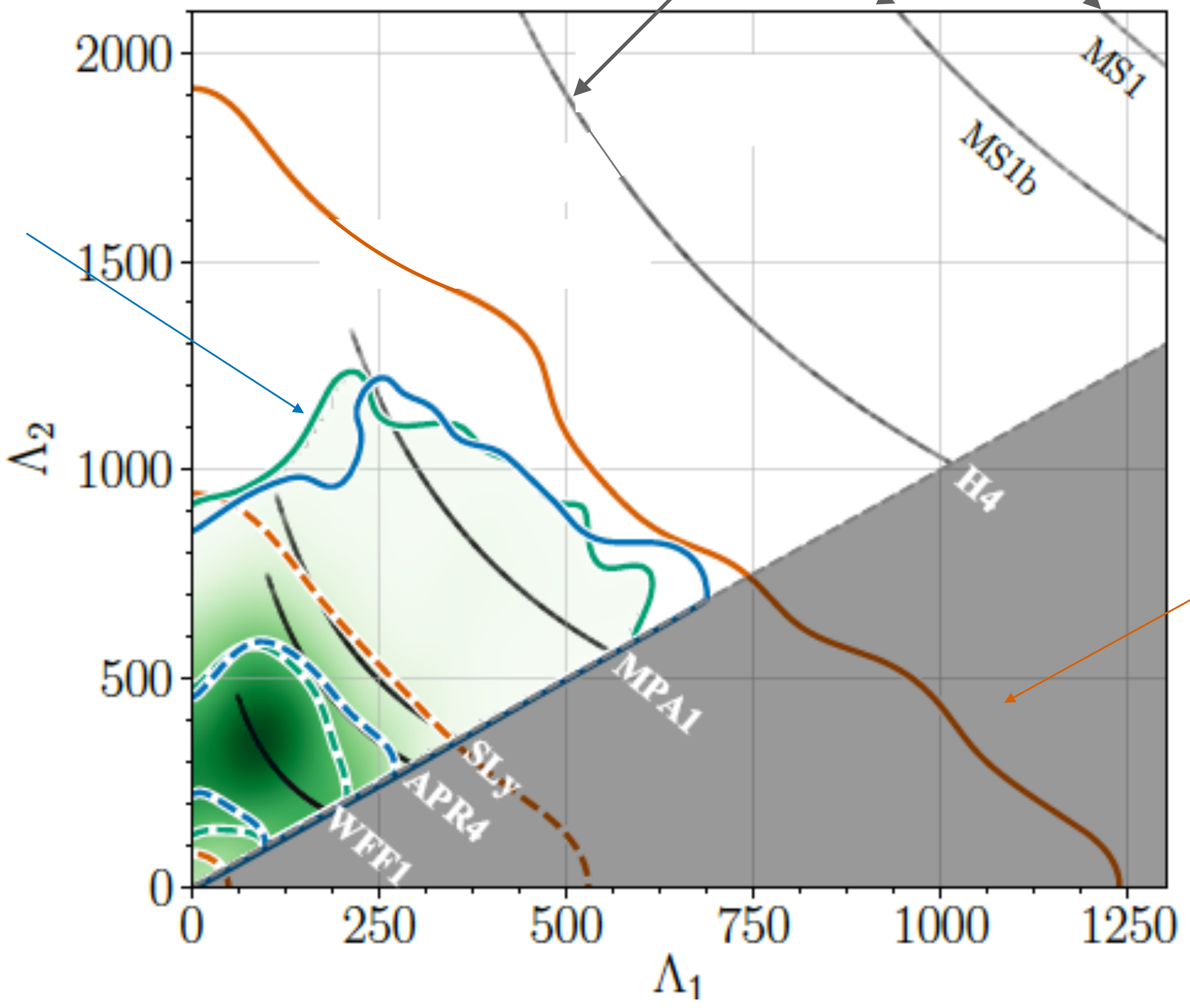
First empirical constraints on tidal deformability



$$\boldsymbol{\Lambda} = G\,\boldsymbol{\lambda}\left(\frac{c^2}{G m_{\mathrm{NS}}}\right)^{5}$$

Example EoS models

90% contour, low-spin + same EoS assumption



90% confidence contour, low-spin assumption

LVC arXiv:1805.11581

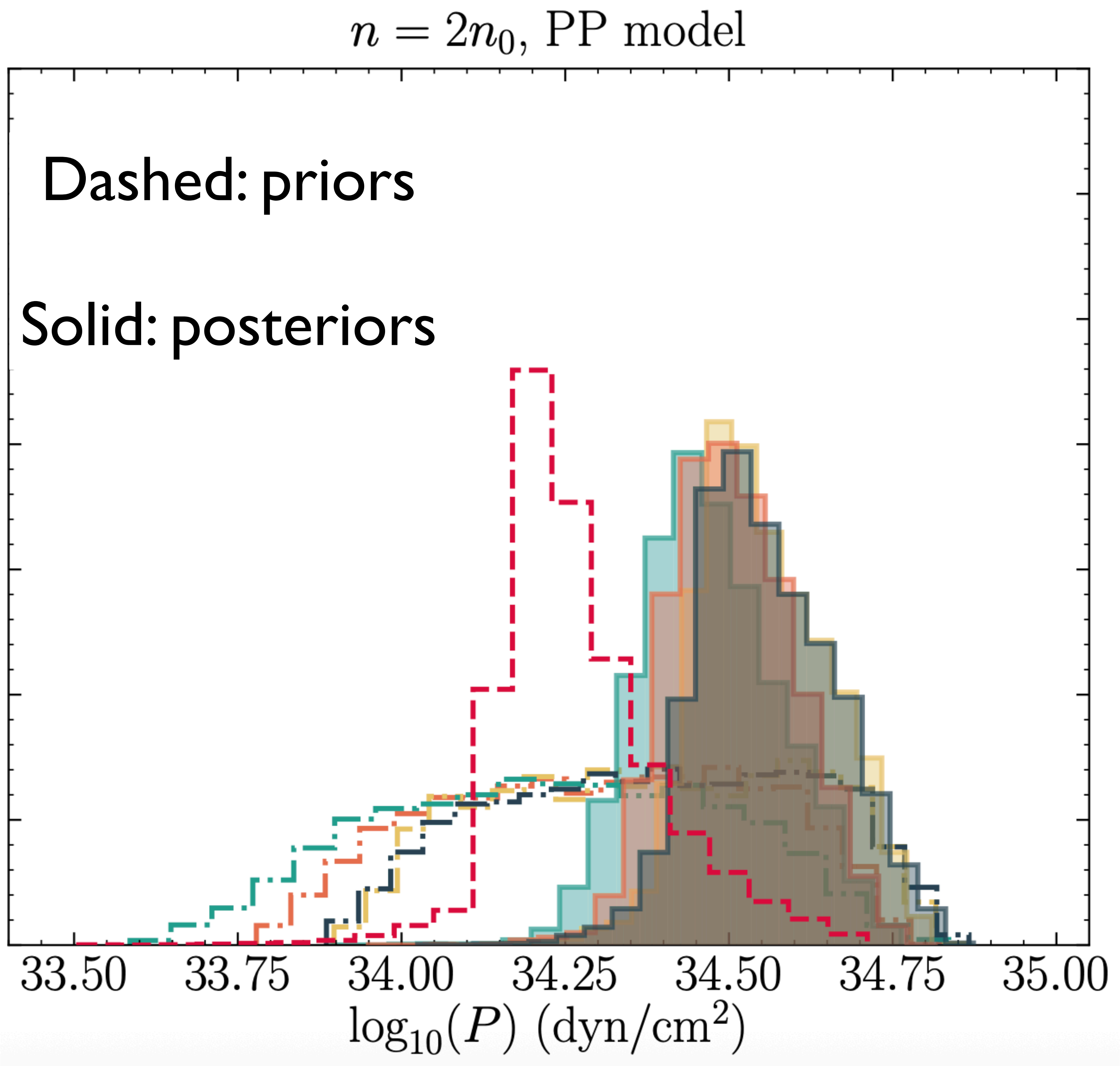
Gray shaded area: no new information from interchanging body labels

Best GW event for EoS constraints still to date

Example implications for subatomic physics

- Joint constraints: GWs, EM counterpart to GW170817, astrophysical (radio, x-ray)measurements

pressure at 2 × nuclear saturation density



More in Anthea Fantina's talk @ 14:00 today (Inspire 2)

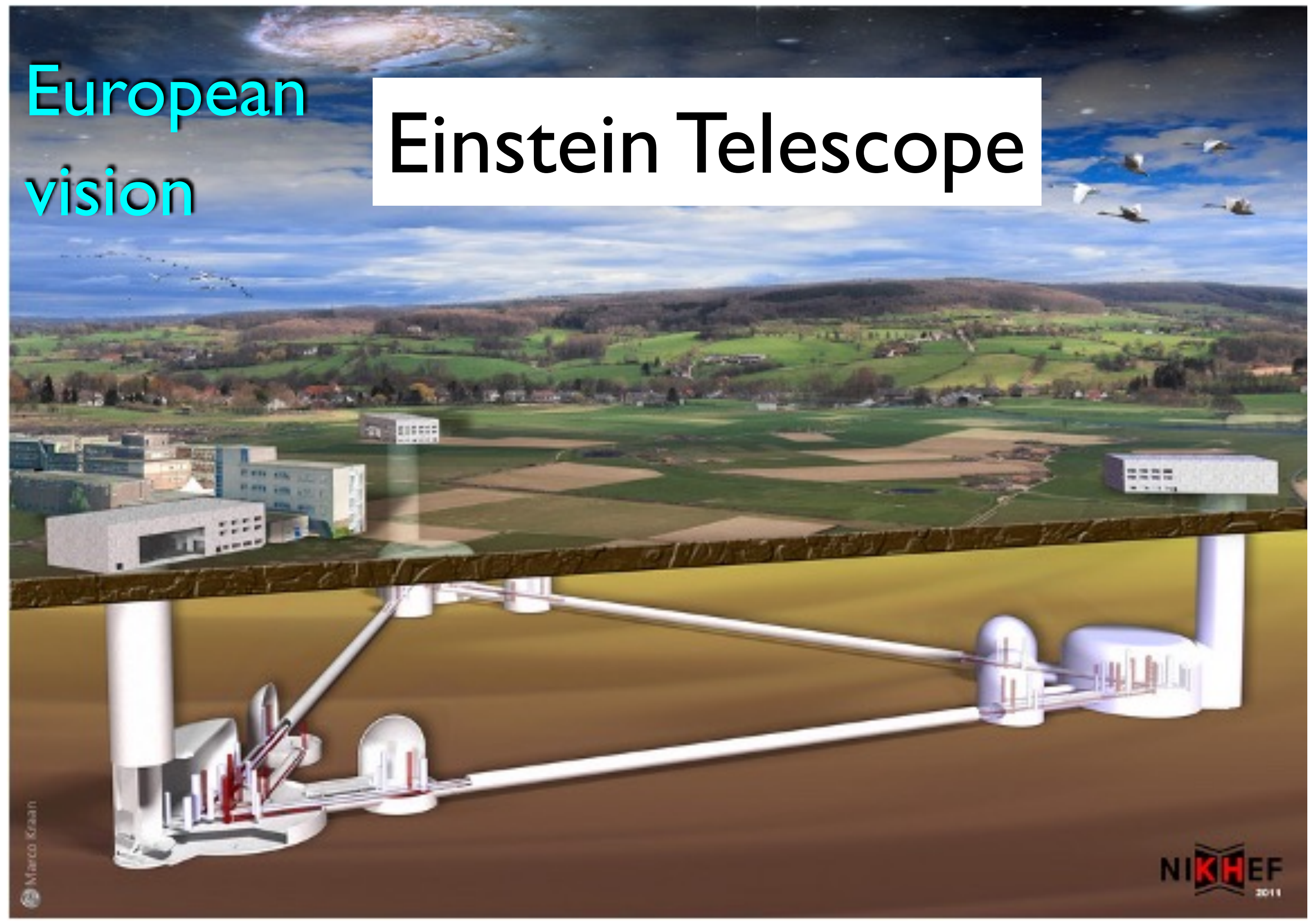
Raaijmakers+ arXiv:2105.06981

Upcoming capabilities

- Observing run O4c ongoing until November: $\gtrsim$ 1.5 better sensitivity than in 2017

- Further upgrades and observing runs possible

- Next major step: 3rd generation detectors (~2035)

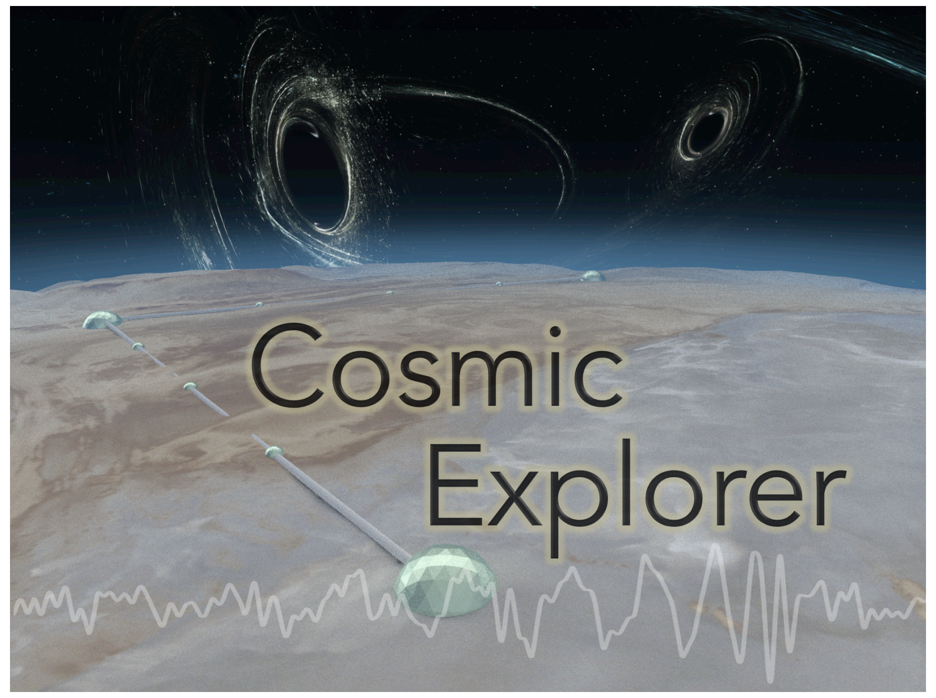


Prototype in Maastricht

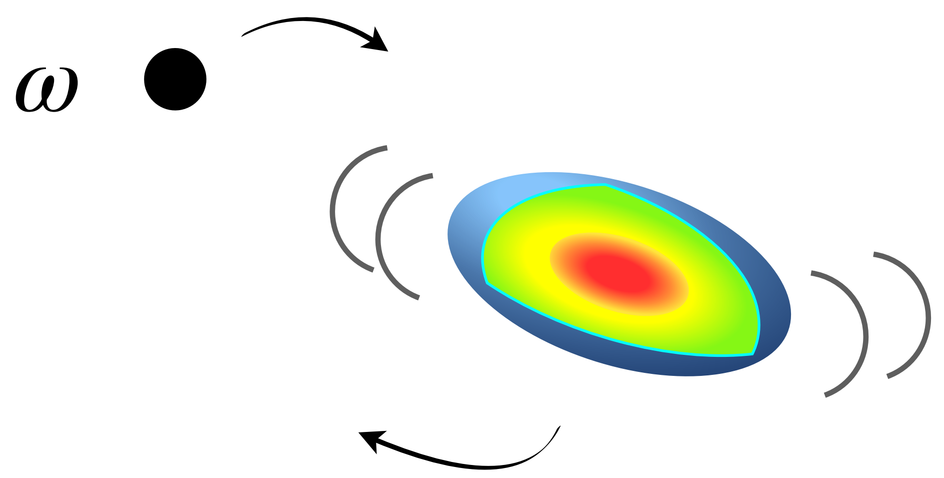
- better sensitivity: GW170817 ~ 50 times higher signal-to-noise ratio
- wider frequency range
- Signal-dominated: ~10 000 binary NS merger detections per year

$\approx$ all merging NSs in the universe

US vision

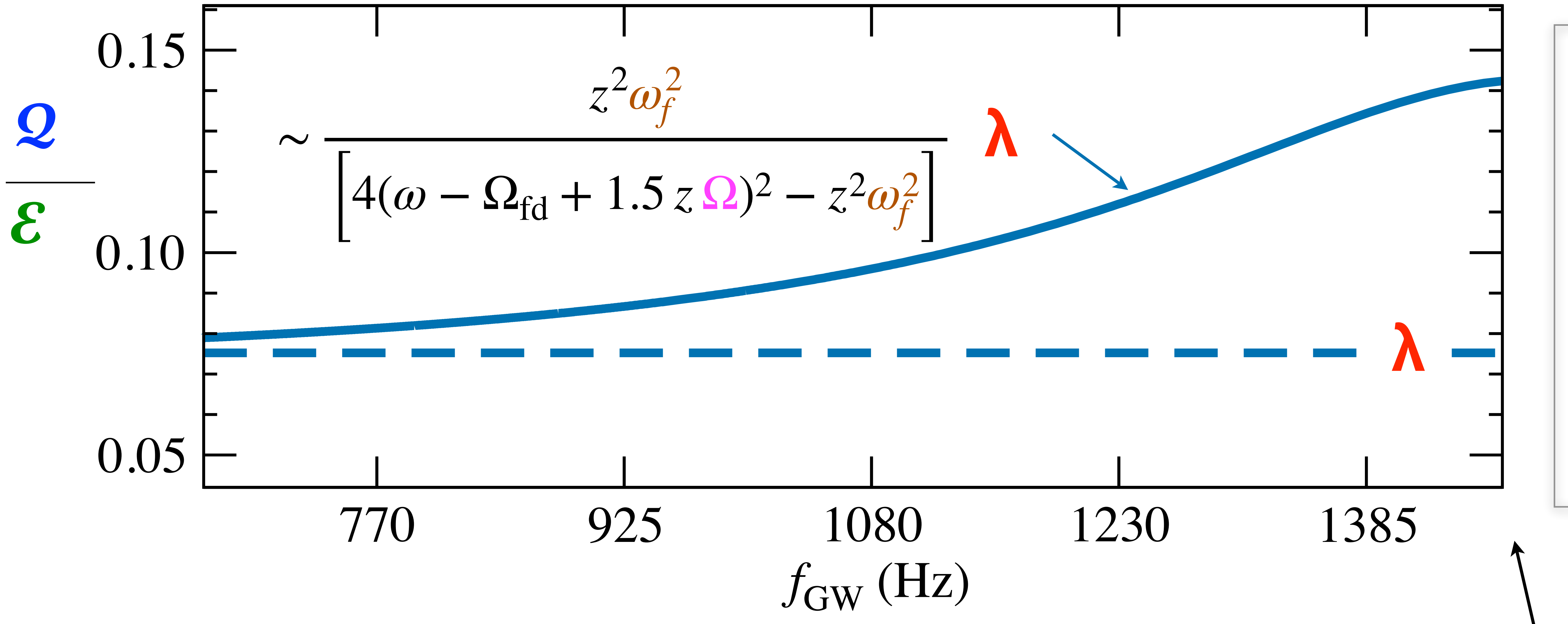


More realistic descriptions of tidal effects



- NSs have a rich spectrum of oscillation modes
- Fundamental modes have strongest tidal coupling, resonance frequencies ω_f ~ O(kHz)
- Even non-resonant modes can lead to enhanced matter effects vs. strictly static case

Example fundamental-mode tidal response during inspiral (NSBH)



End of inspiral

Response also impacted by:

- redshift z
- frame dragging Ω_{fd} (GR, companion spin)
- NS's spin Ω

New relativistic effect: Gravitomagnetic tides

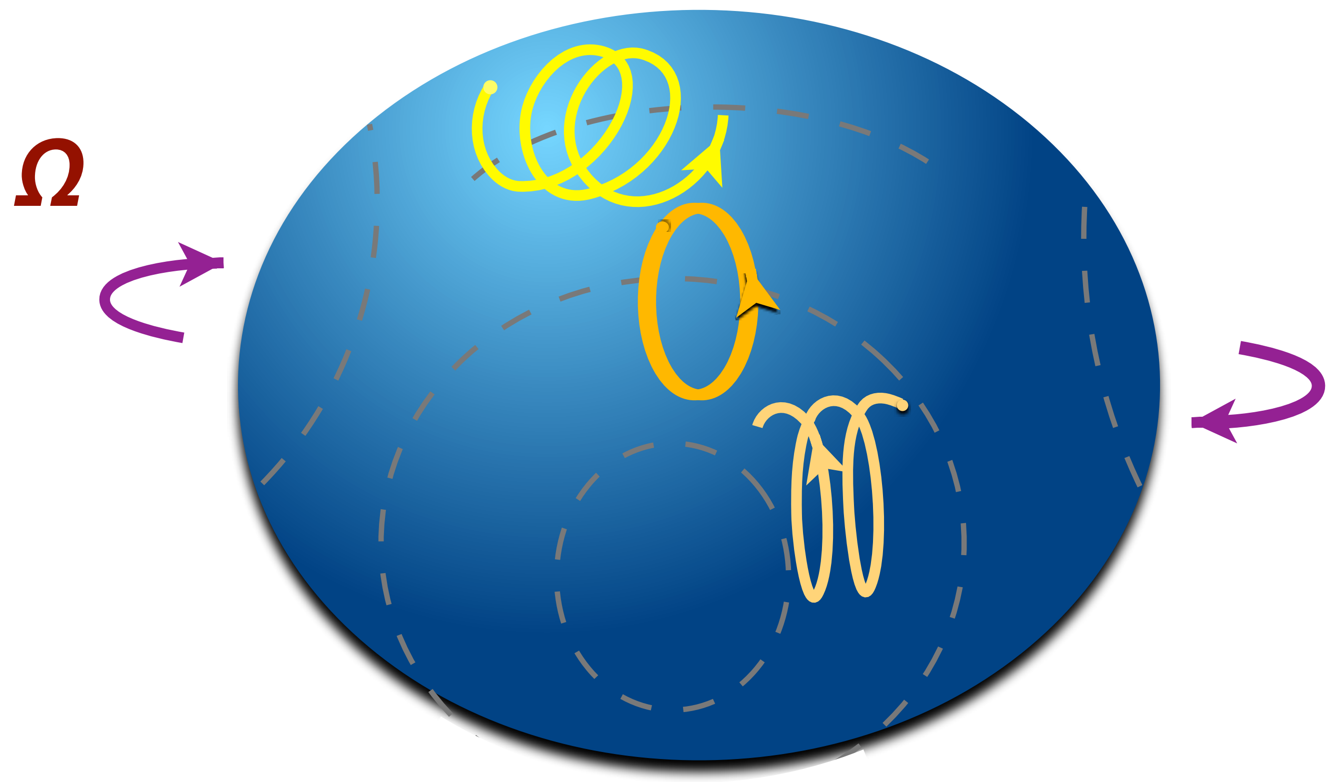
- Relativistic gravito-magnetic tidal fields $\mathscr{B}_{ij}$

  Frame-dragging, no Newtonian analog

- Tidally induced velocity perturbations

  - 'r-modes', restoring force: Coriolis effect
  - mode frequencies $\propto$ spin frequency Ω ⇒ full resonance during inspiral
  - two different Love numbers σ_{stat} & σ_{irrot} *[Landry, Poisson, Pani+, Damour, Nagar, ...]*

Induced fluid motion



Interesting features, relevant for future GW measurements

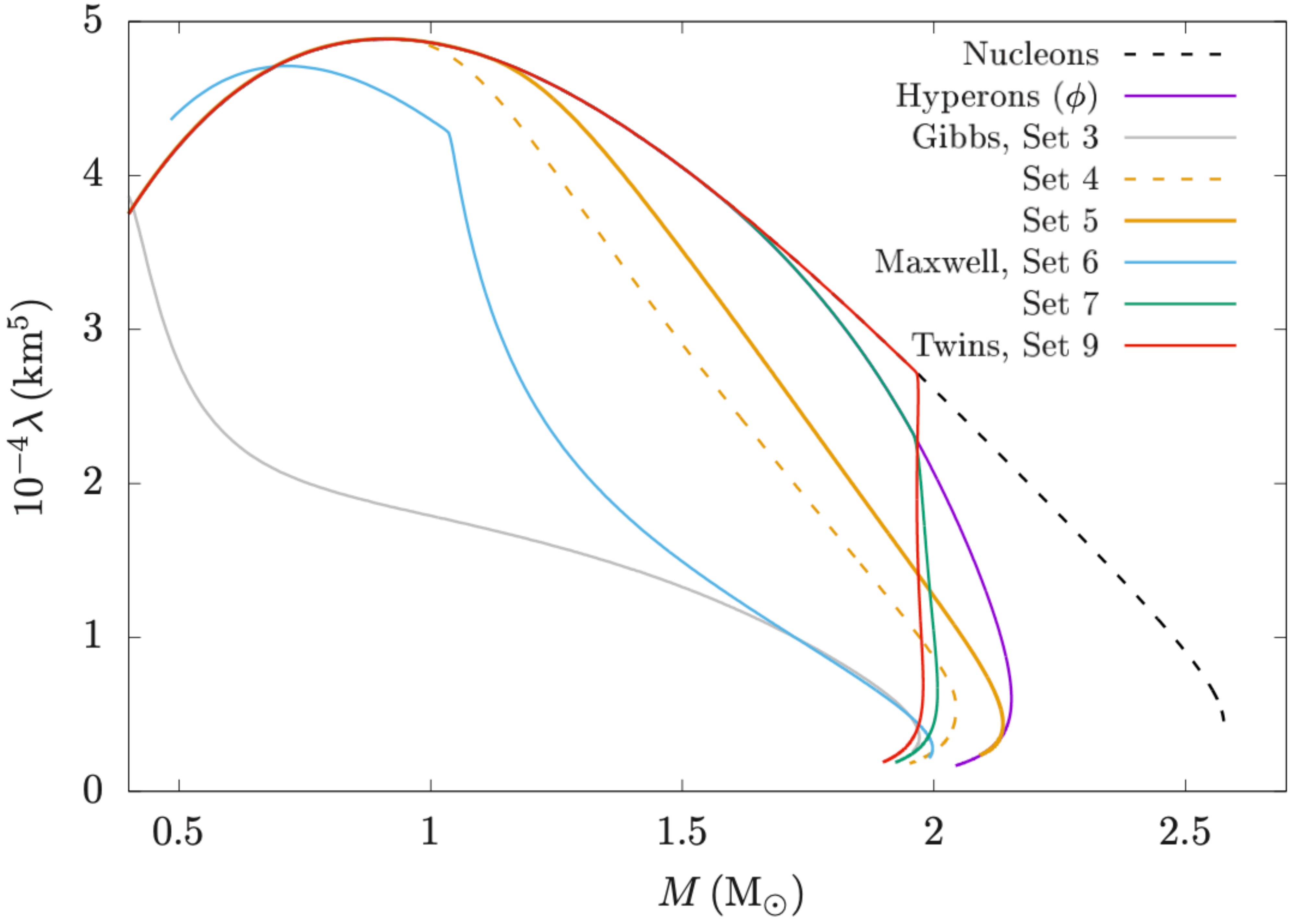
[Kumar, TH, Steinhoff 2022, 23, Racine & Flanagan 2007, Poisson 2021, Ma & Chen 2021, Forteza+ 2018, ...]

Signatures of phase transitions, composition gradients?

For sharp transitions:

- Distinctive features in λ vs mass ⇒ probed with population of NSs

Many studies, example plot from
Gomes+ 1806.04763



- new modes directly associated composition gradients & interfaces ⇒ tidal resonances

e.g. hyperons: *Yu & Weinberg1705.04700*, quarks: Counsell+ 2504.06181, *Pereira*+ 2504.16911

Effects of viscosities, superfluidity in inspirals ?

- Parameterized study based on $Q_{ij} = -\lambda \left[1 + i\,\tau\,\omega + O(\omega^2)\right] \mathscr{E}_{ij}$

  Ripley & Yunes 2306.15633

  Linearized tidal lag due to viscosity

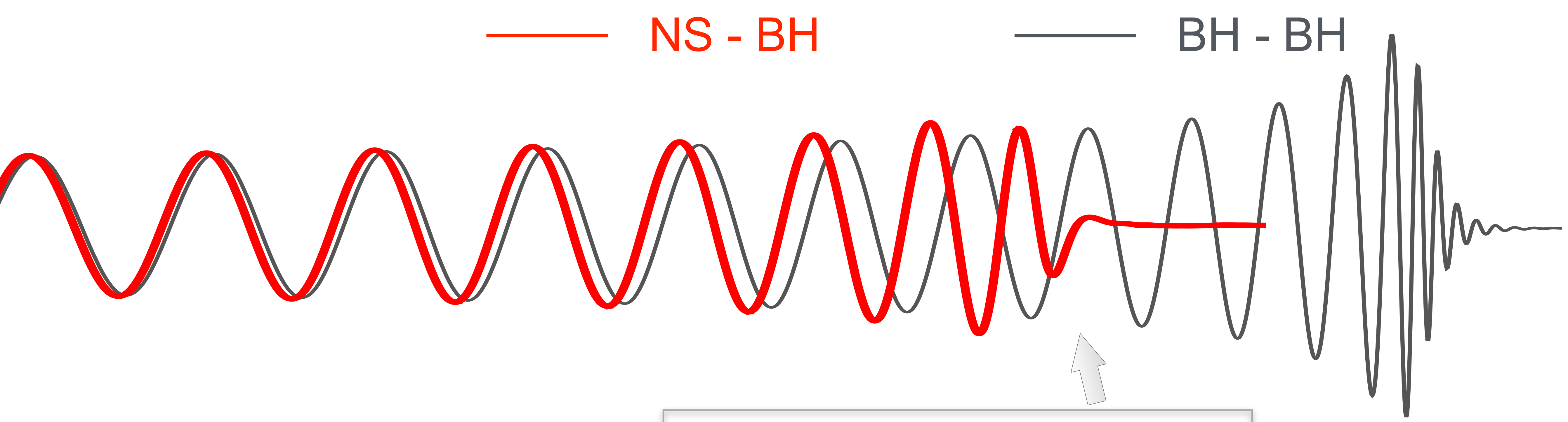
- dynamical modes - tidal heating - viscosities dependent on temperature & frequency

  Arras & Weinberg 1806.04163

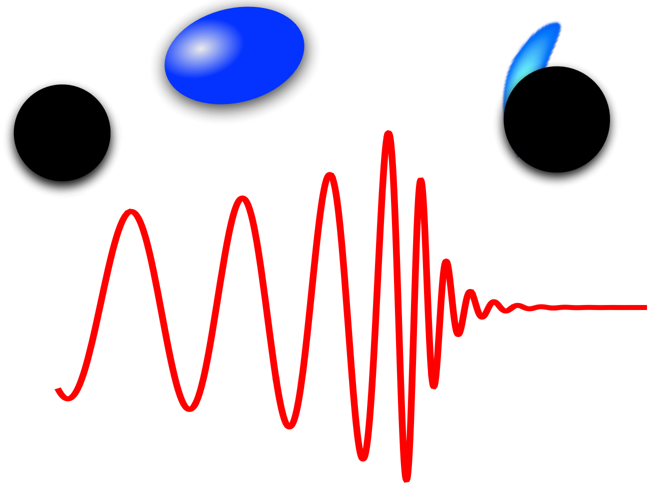
- Effects of (neutron) superfluidity: doubling of mode spectrum

Many of these + <u>many other</u> effects remain to be fully explored

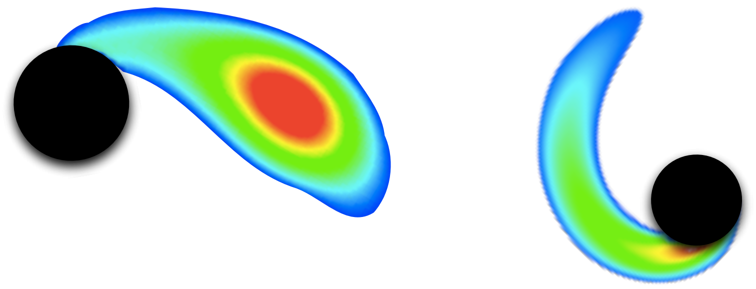
GW signal from NS-black hole (BH) mergers



- alternative outcome: plunge



tidal disruption



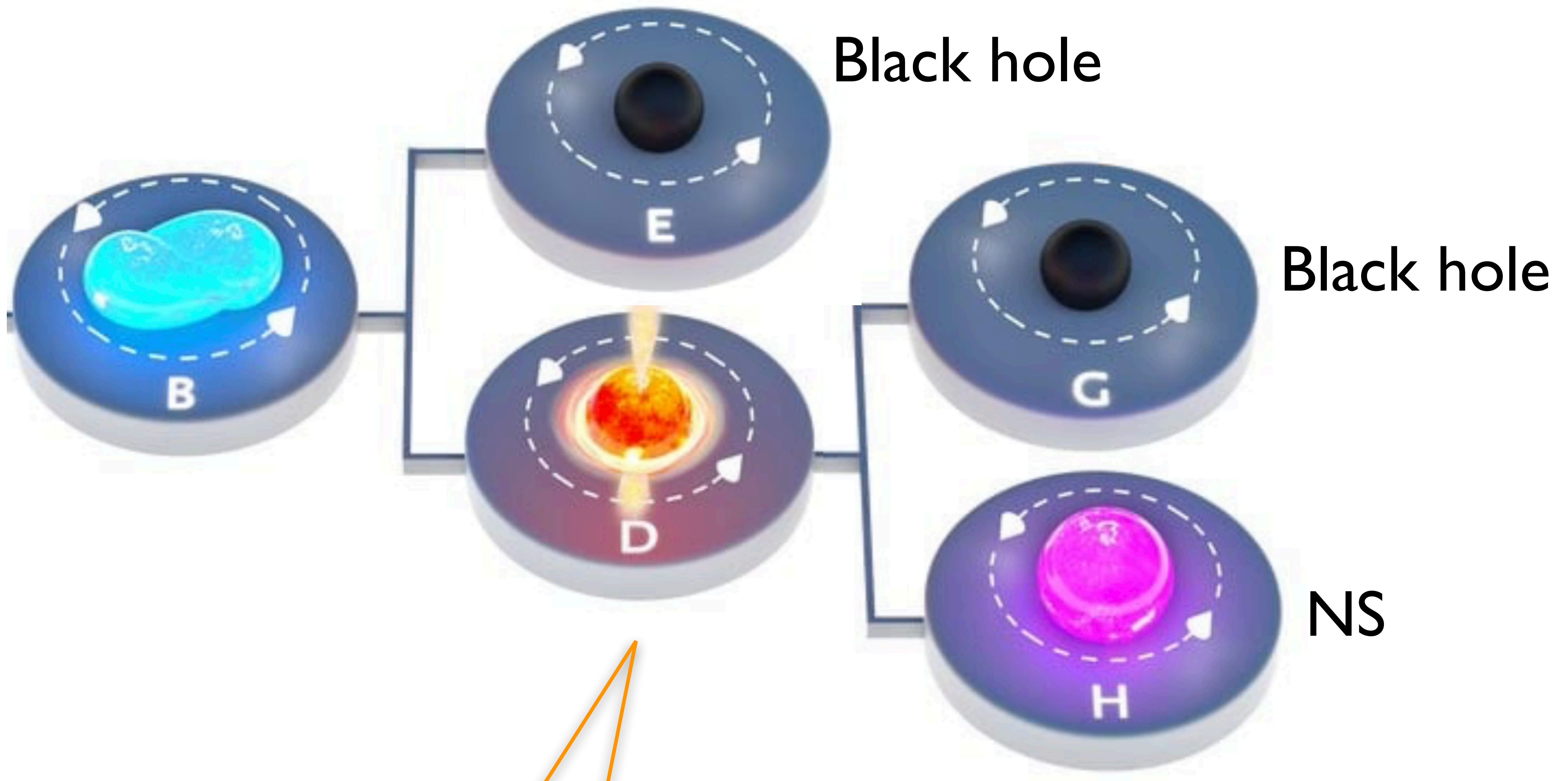
Key signature:
'shutoff' in GW
amplitude

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

Clean probes of cold EoS

(Some) NS-NS mergers: completely unexplored matter physics

NS-NS merger outcomes depend on the properties of the binary system. Broad categories:



Credit: C. Knox

- higher density, temperature
- neutrino physics, small-scale turbulence, transport
- Rich GW frequency spectrum

Conclusion

- GWs are unprecedented probes of compact objects: clean gravitational channel of information
- Exciting future ahead: larger, more precise GW datasets to come
- *In the future:* many discoveries & science payoffs expected to be limited by accuracy/physics included in theoretical models
- much recent progress, efforts to advance models, develop new theoretical tools + synergies analytical/ numerical relativity
- Interdisciplinary connections essential for interpretation, microphysics inputs
- significant further efforts required to realize the full GW science potential