Probing neutron star interiors with gravitational waves from binary inspirals

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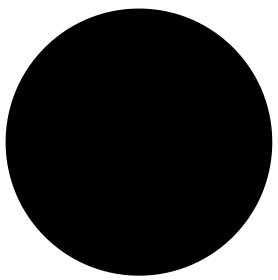
Overview

- Gravitational waves (GWs) now available as unique probes of fundamental physics
  - Here: interior structure of neutron stars with binary inspirals
- Interpretation of the data contingent on accurate theoretical models
- Examples of signatures in GWs that encode matter properties: tidal effects
- Selected recent progress on richer phenomena when including more realistic physics
- Outlook to upcoming future prospects and remaining challenges

Examples of compact objects in GR

Black holes



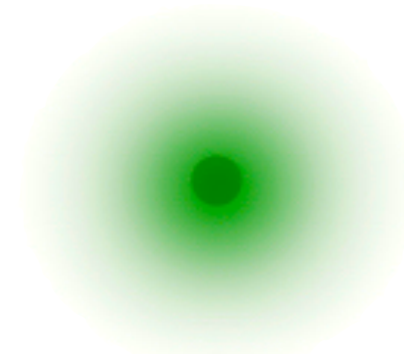
Horizon,
no hair conjectures

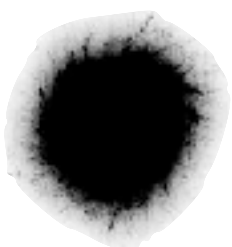
Neutron stars

Subatomic physics

Strong gravity-matter couplings

Exotic objects





Condensates of dark matter / dark energy, bumpy black holes / fuzzballs / micro state geometries, …

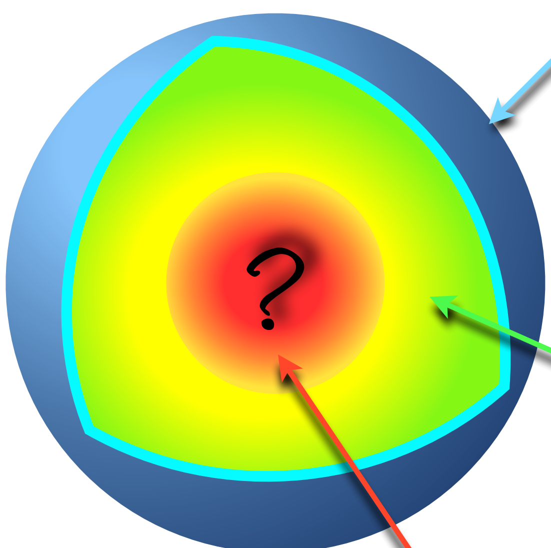
Theoretical methods in this talk apply to any object, many applications will focus on neutron stars

Neutron stars (NSs)

- Gravity compresses ~ $1 - 2M_\odot$ of material to ~ 10km radius
- Quantum pressure (neutron degeneracy) can support $\lesssim$ 0.7 $M_\odot$ against collapse

$\Rightarrow$ structure dominated by subatomic physics

[density of iron ~ 10 g/cm³]



crust ~ *km*

Lattice of neutron rich nuclei,
free neutrons

~ 10^6 g/cm³ inverse ***β***-decay

~ 10^{11} g/cm³ neutron drip

outer core

uniform liquid (mainly neutrons)

deep core

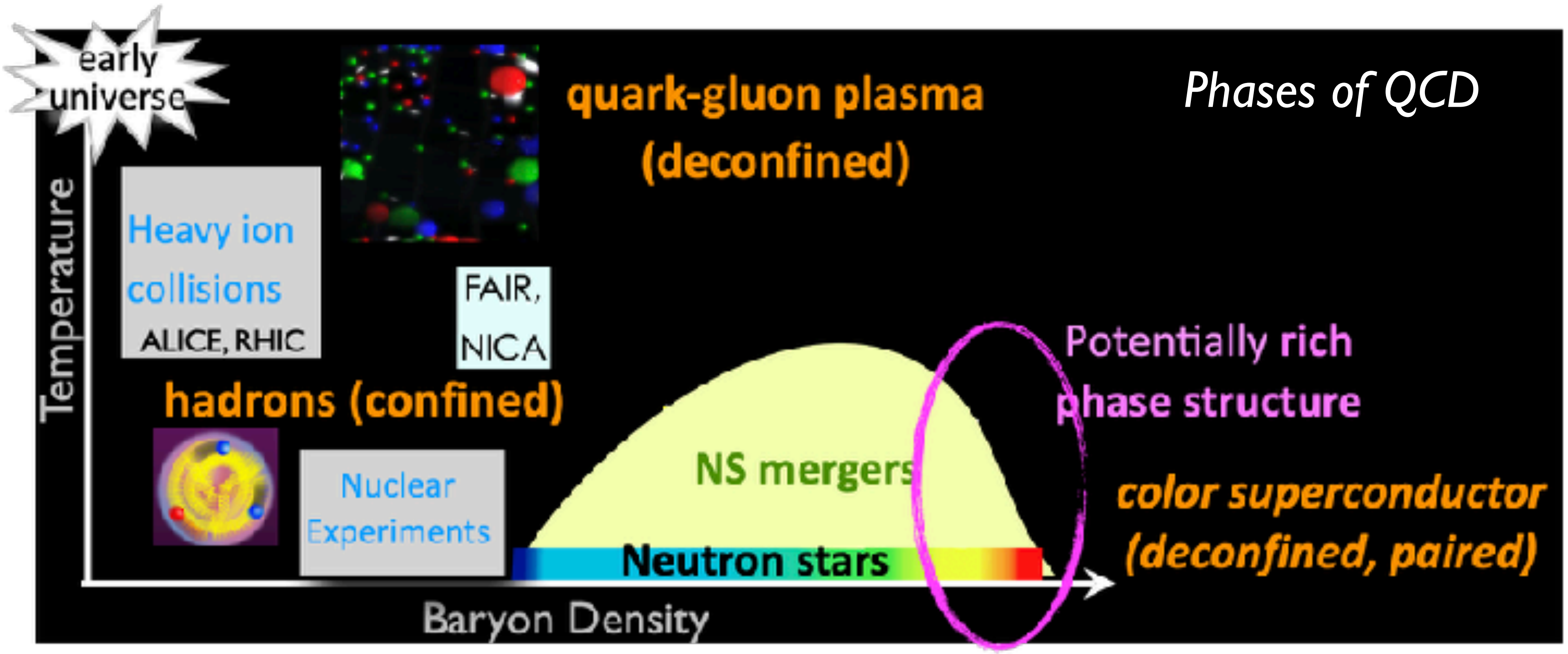
$\gtrsim$2x nuclear density, nucleons overlap

- new degrees of freedom relevant

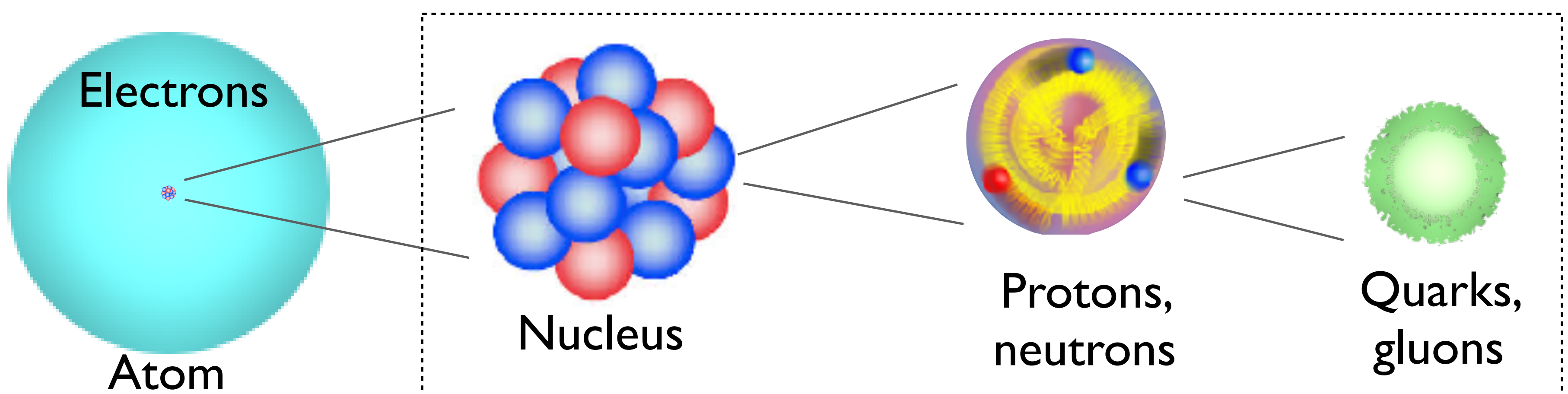
~ few $\times 10^{14}$ g/cm³

Deconfined quarks? Intermediate condensate states of heavy hadrons?

Unique laboratories for QCD and emergent structure



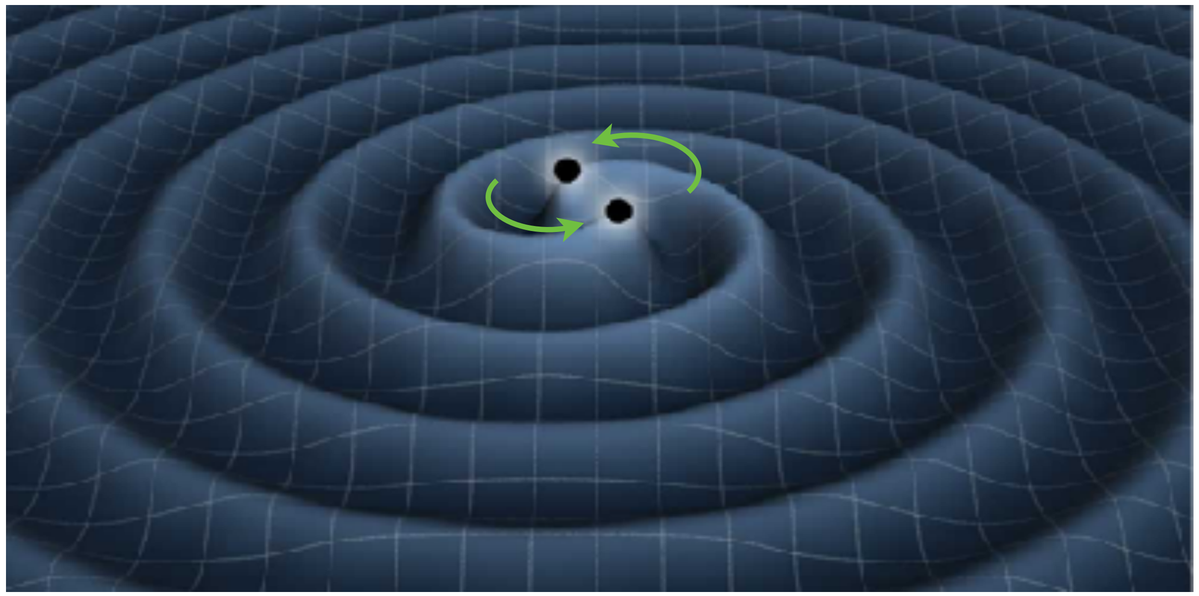
Emergent structure of matter from fundamental building blocks



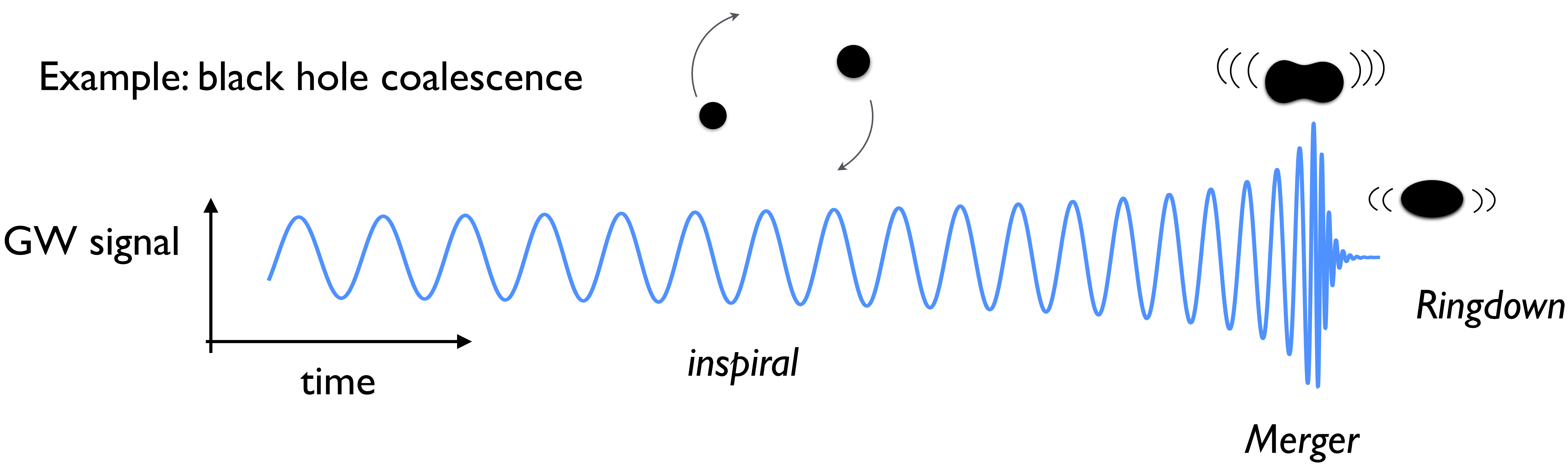
- Collective phenomena
- multi-body interactions

Compact objects in binary systems

dynamical spacetime ⇒ gravitational waves (GWs)

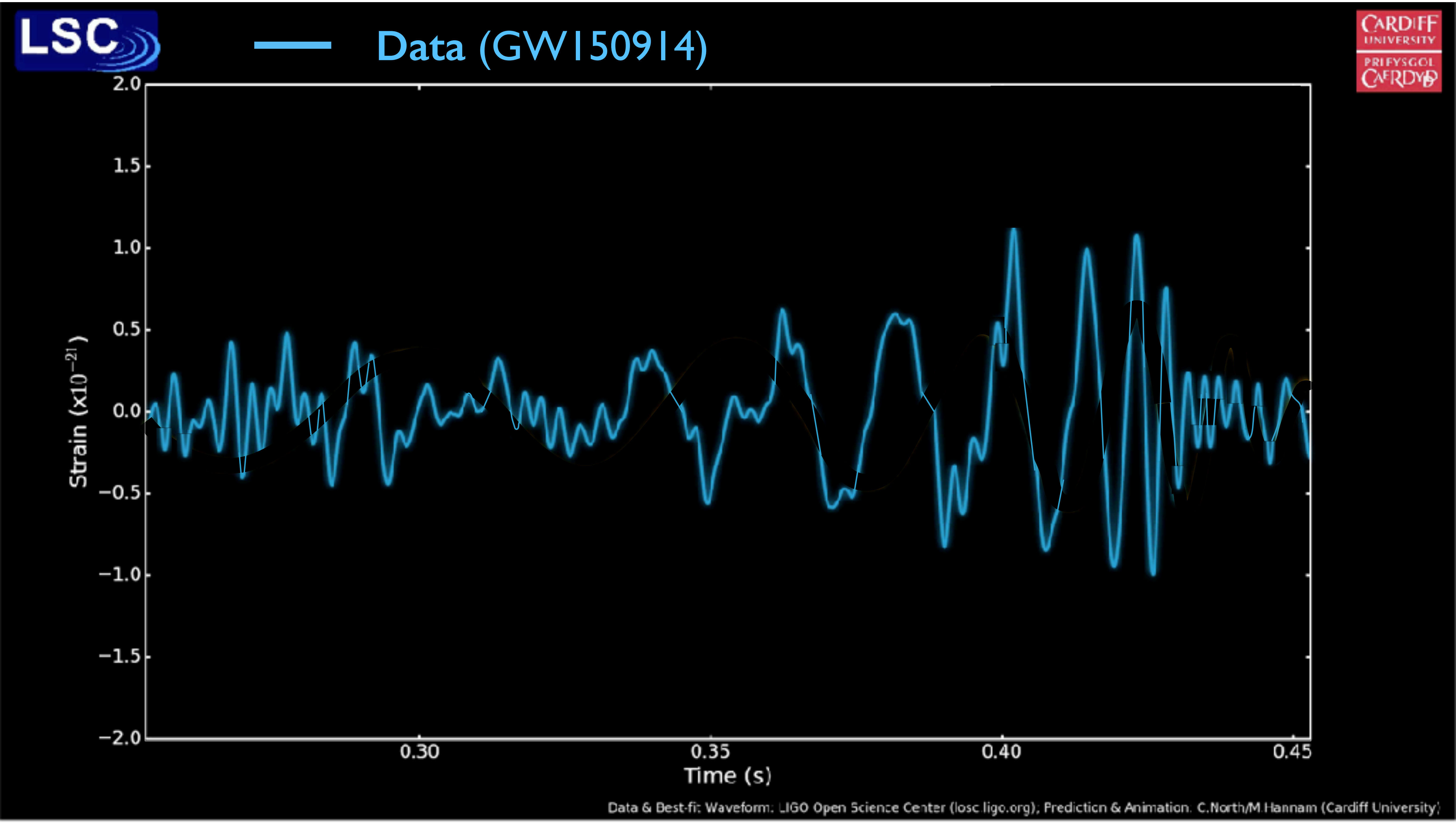


Example: black hole coalescence



- GW signals are fingerprints of the fundamental source properties

Interpreting such GW signals relies on theoretical models



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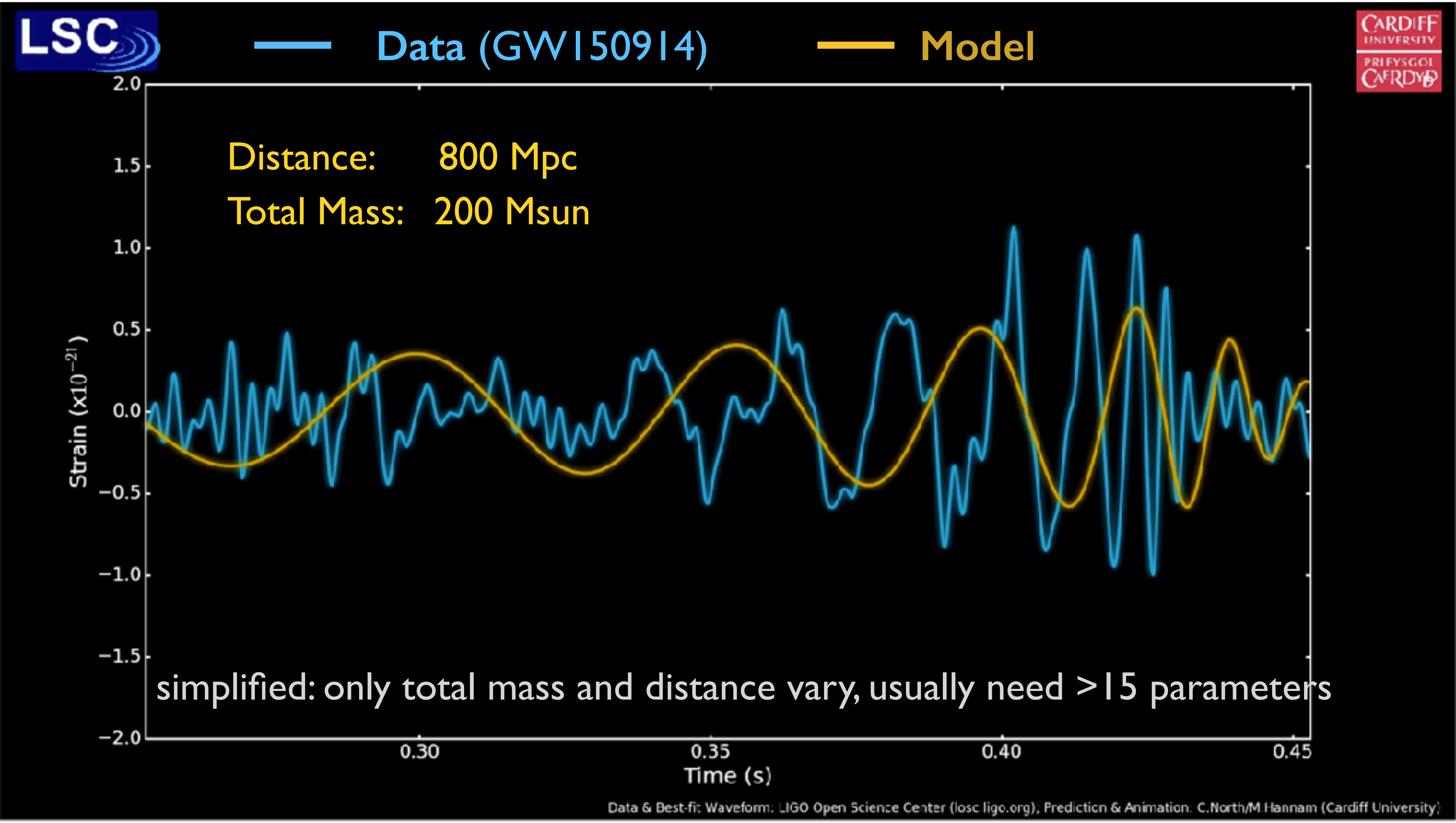
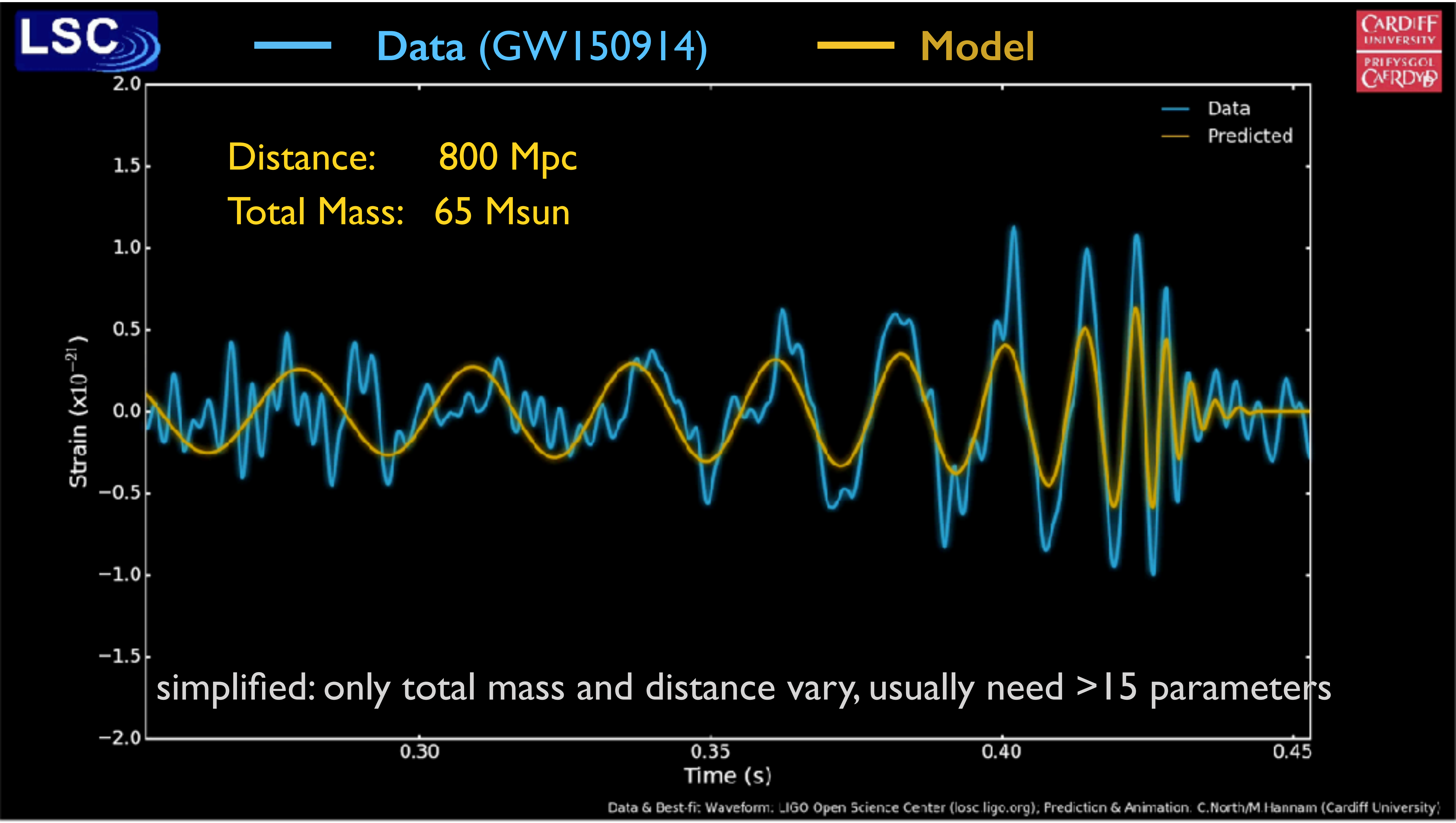


Waveforms are characteristic fingerprints of their sources

Interpreting such GW signals relies on theoretical models



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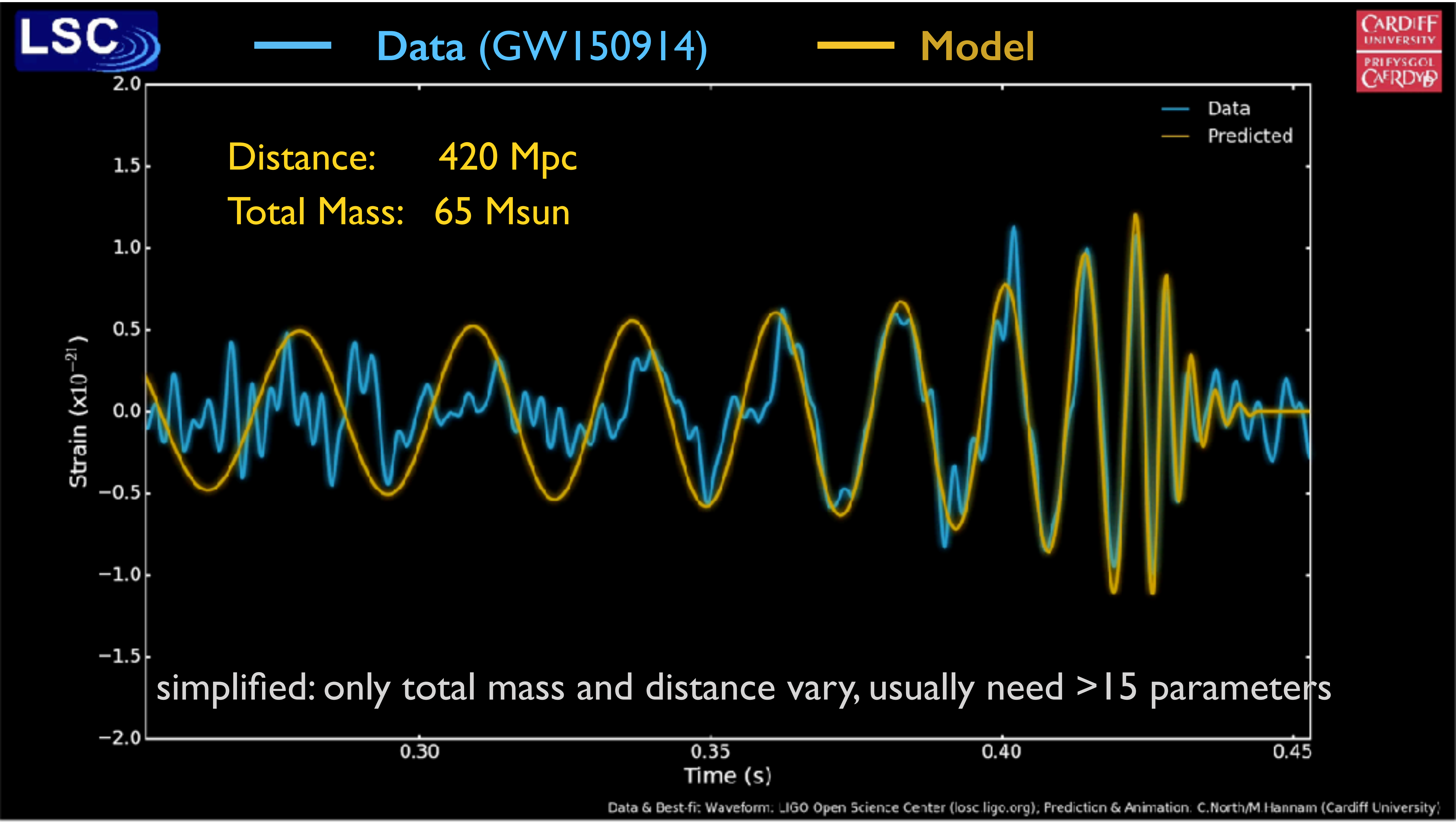

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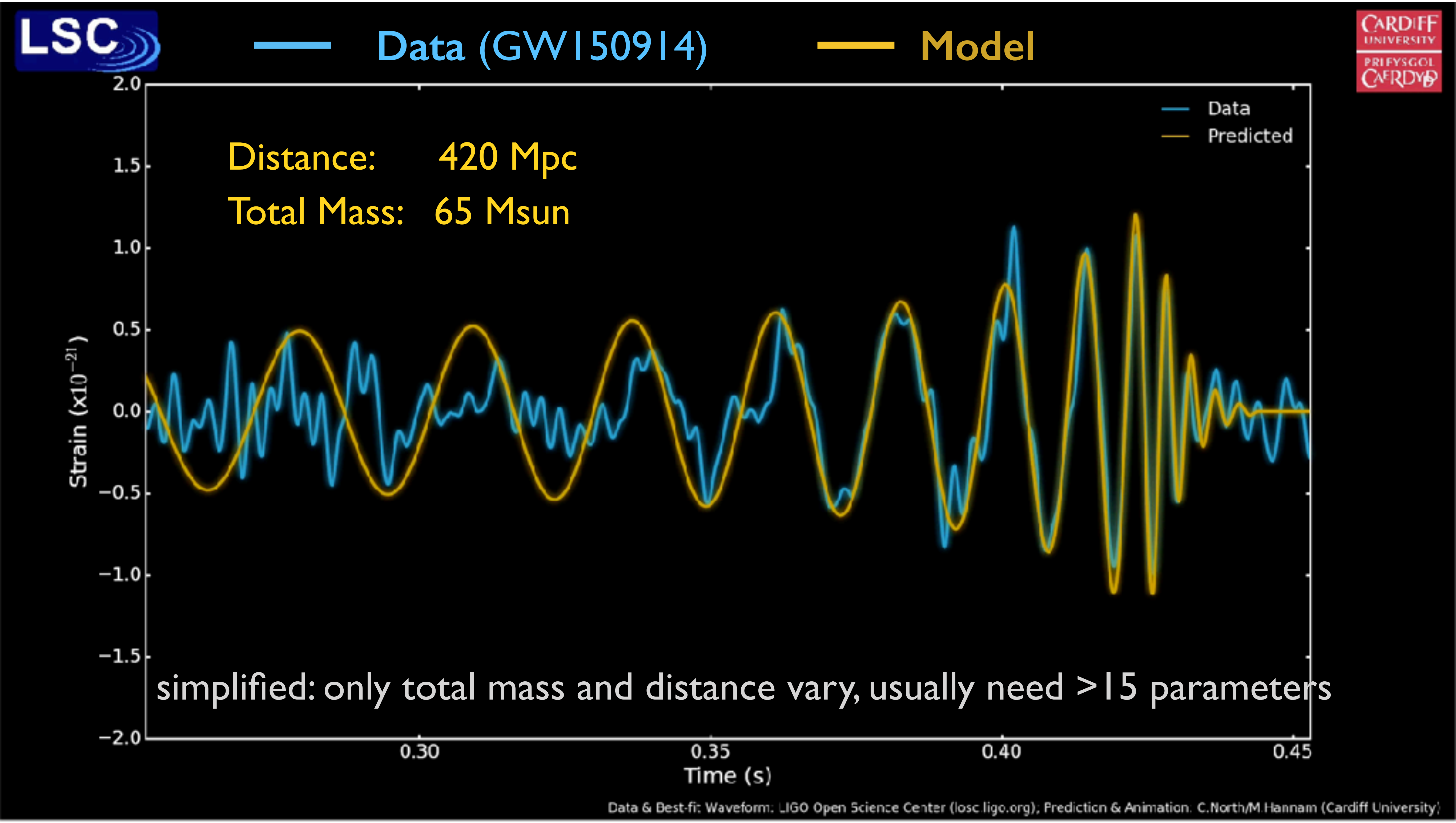

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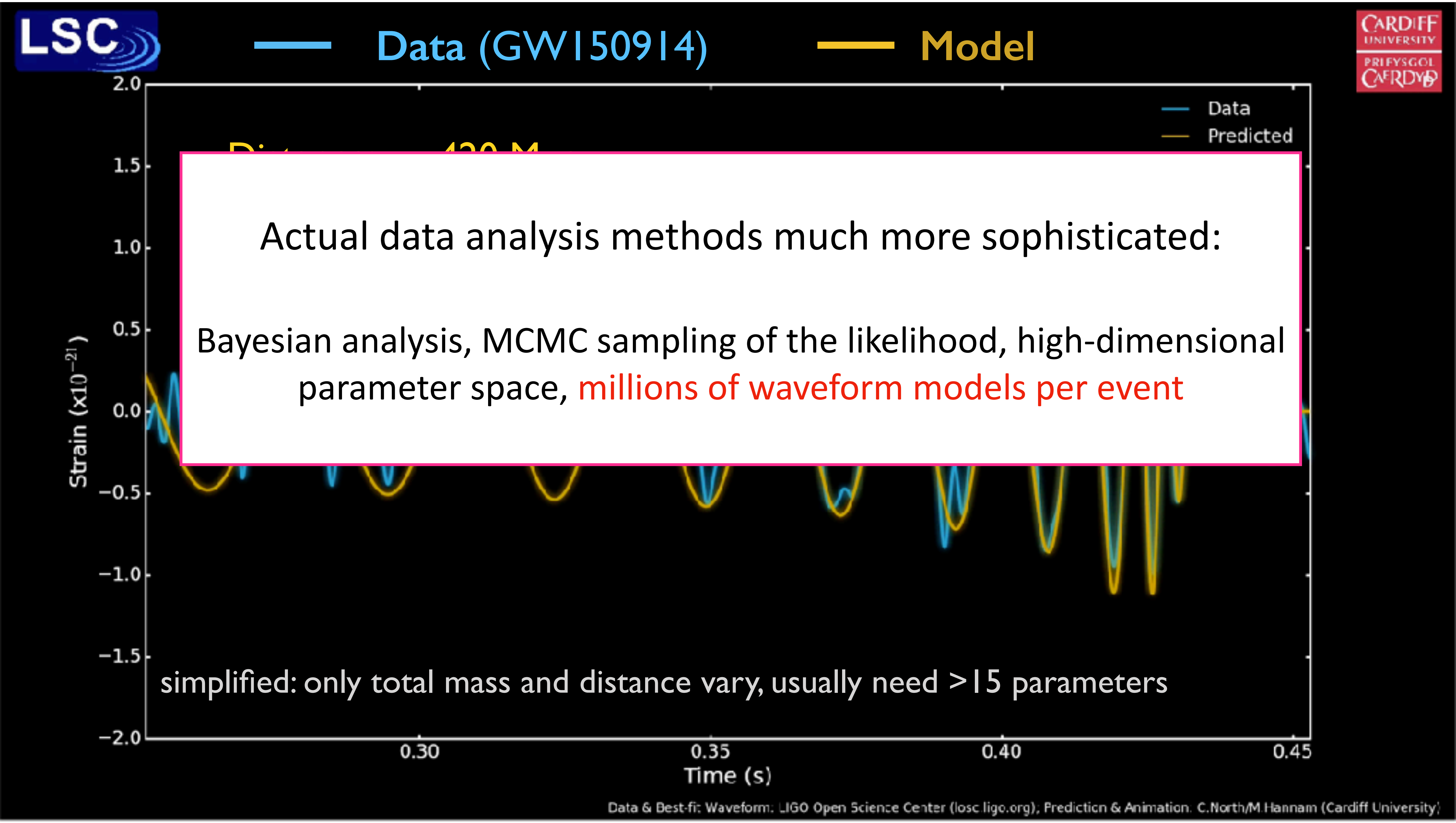


Actual data analysis methods much more sophisticated:

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

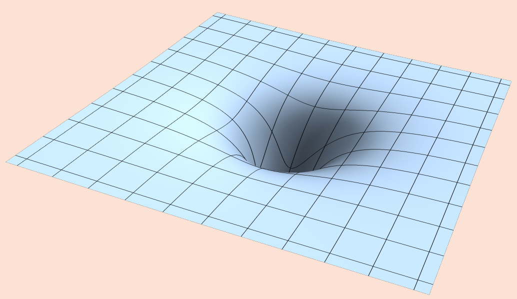
Waveforms are characteristic fingerprints of their sources

Theoretical challenge: compute the dynamical spacetime

- Analytical approximations when different physics dominates at different scales:
    - Example hierarchy of scales during binary Inspiral

Nonlinear flow of information

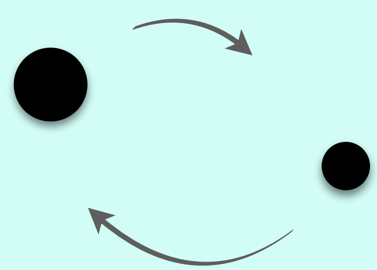
Strong-gravity object + *perturbations from distant companion*



R

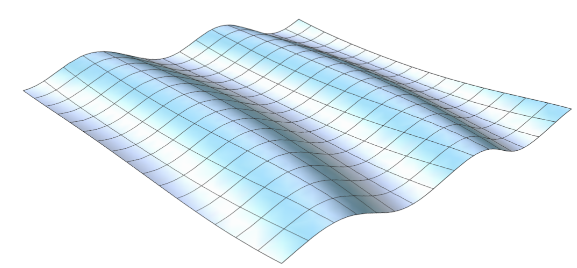
Nonlinear flow of information

Orbital scale: Newtonian point-masses + *relativistic* & *finite-size corrections*



L

Distant wave zone: flat space + *asymptotic multipolar waves*



λ_{GW}

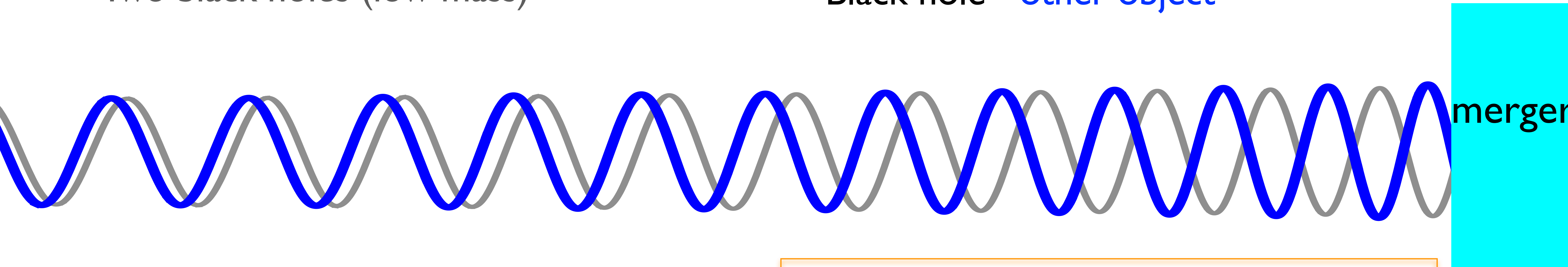
$R \ll L \ll \lambda_{GW}$

Connected by matching. Information can also be re-summed into Effective One Body models

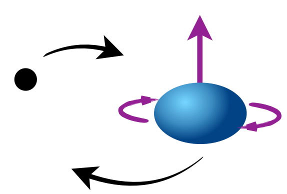
GW signatures of interior structure during inspiral

Two black holes (low mass)

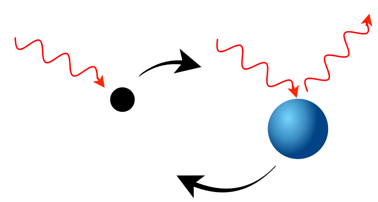
Black hole - other object



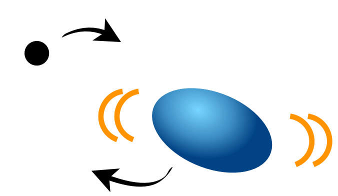
Spin-induced multipoles



Absorption



Various tidal effects



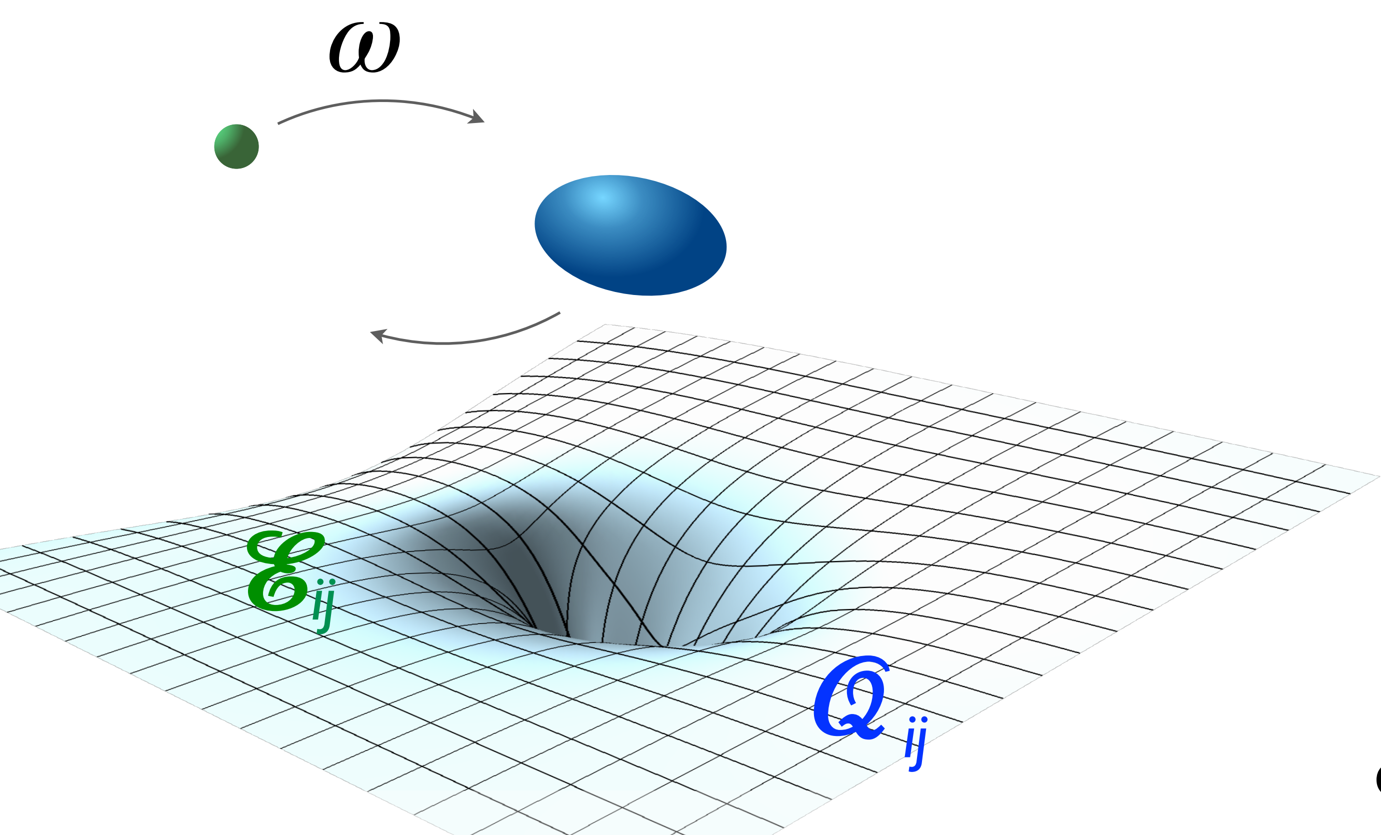
Resonant & non-resonant excitation of isolated characteristic modes

GW spectroscopy of objects' interiors

- Generic phenomena
- effects are small but clean and cumulative over many GW cycles

Dominant tidal effects (non-spinning objects)

- In a binary: tidal field $\mathcal{E}_{ij} = C_{0i0j}$ 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

e.g. Newtonian uniform stars, no viscosity:

$$\approx \frac{\lambda}{1-(2\,\omega\,/\,\omega_0\,)^2}$$

fundamental mode frequency

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

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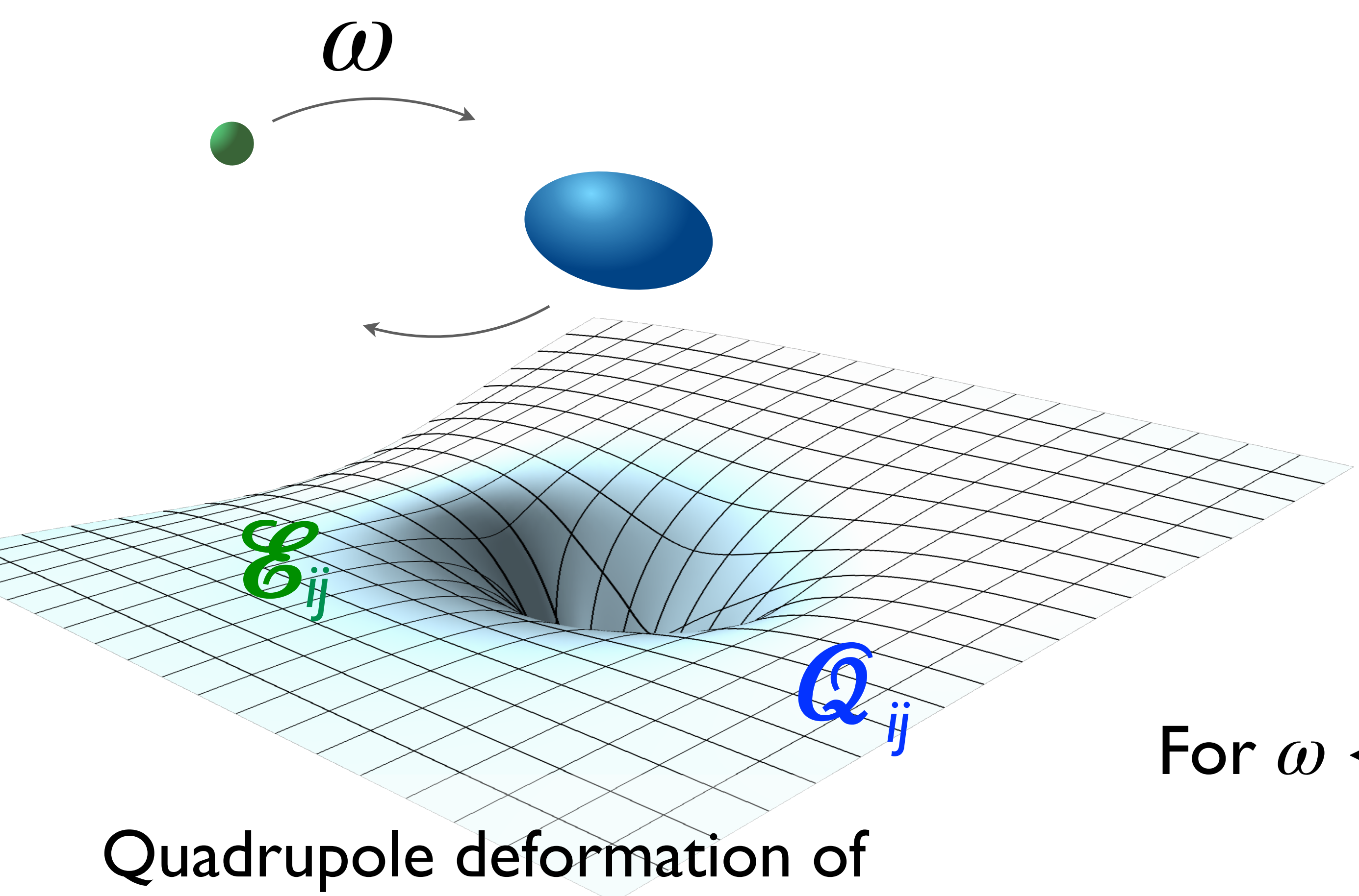

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induced deformation

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

frequency-dependent response

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

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

tidal Love number / deformability / polarizability

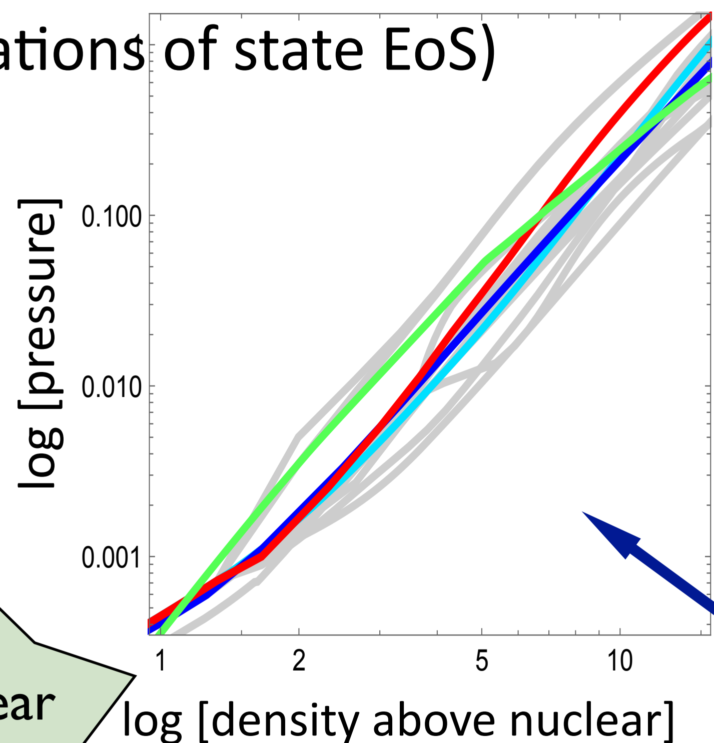
[TH 2008, Damour & Nagar 2009, Binnington & Poisson 2009, …]

Tidal Love numbers reflect object's interior

- classical black holes in GR in 4 spacetime dimensions: $\lambda = 0$

Perturbative QCD

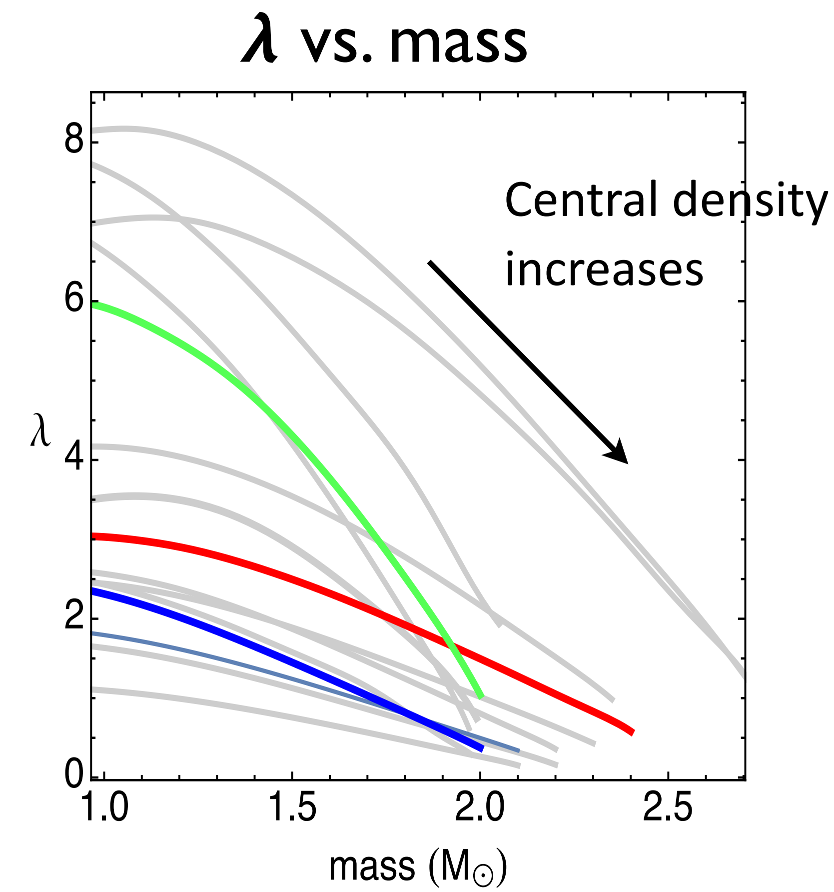
Neutron star matter models (equations of state EoS)



Nuclear EFT, …

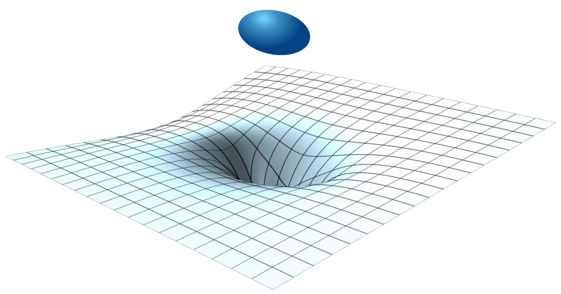
linearized perturbations to

Einstein field equations + stress-energy conservation



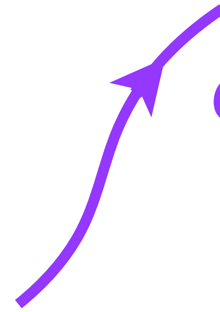
Different models for subatomic physics (3-nucleon forces, symmetry energy, composition, …)

GWs require the link with a skeletonized description



Effective description

(Large distance)



Center of mass worldline + multipole moments

['Skeleton']

Relativistic effective action (neglect viscosity, absorption):

Point mass description

'Redshift'

Multipoles couple with external fields

oscillator dynamics correspond to response function & are more general, e.g. no divergence

$$S \approx -m \int z\, d\tau + \int z\, d\tau \left[-\frac{1}{2} \boldsymbol{Q_{ij}} \mathcal{E}^{ij} + c_1 \frac{D\boldsymbol{Q_{ij}}}{d\tau} \frac{D\boldsymbol{Q^{ij}}}{d\tau} - c_2 \boldsymbol{Q_{ij}} \boldsymbol{Q^{ij}} \right]$$

Coupling coefficients determined by matching to the full description of the perturbed object & spacetime

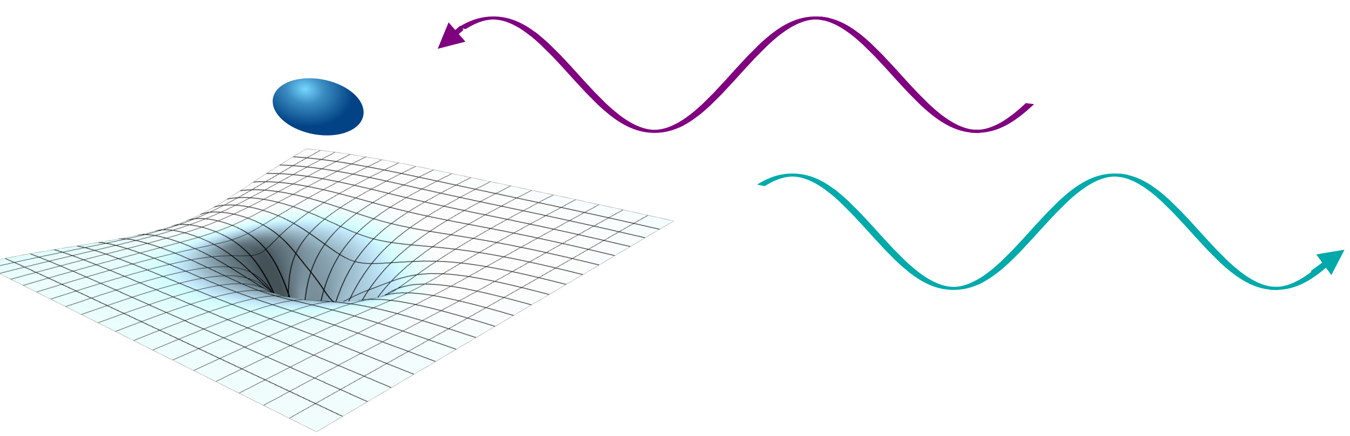
$$c_1 = \frac{1}{4\,\lambda\, z^2\, \omega_0^2} \qquad c_2 = z^2\, \omega_0^2\, c_1$$

More rigorous setting for matching: scattering

- Previous concerns about potential ambiguities due to nonlinearities of GR

  S. Gralla: On the Ambiguity in Relativistic Tidal Deformability, arXiv:1710.11096

- Scattering calculations to identify coupling coefficients avoid these issues:



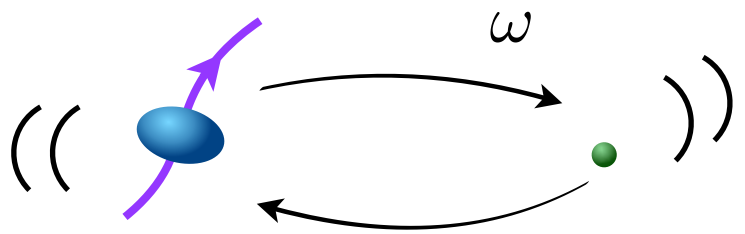
linear wave-like perturbations via relativistic perturbation theory

Identifications with skeletonized effective action at null infinity:

- Spacetime $\approx$ flat
- Ratio of invariant in- and outgoing amplitudes
- Double-null coordinates with clear geometric meaning

Creci, TH, Steinhoff arXiv:2108.03385 [scalar], Ivanov & Zhou 2022 [gravity] for BHs

Dominant adiabatic influence on dynamics and GWs



Dynamics & GWs: double perturbative expansion in finite-size & post-Newtonian effects

- Energy goes into the deformation:

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

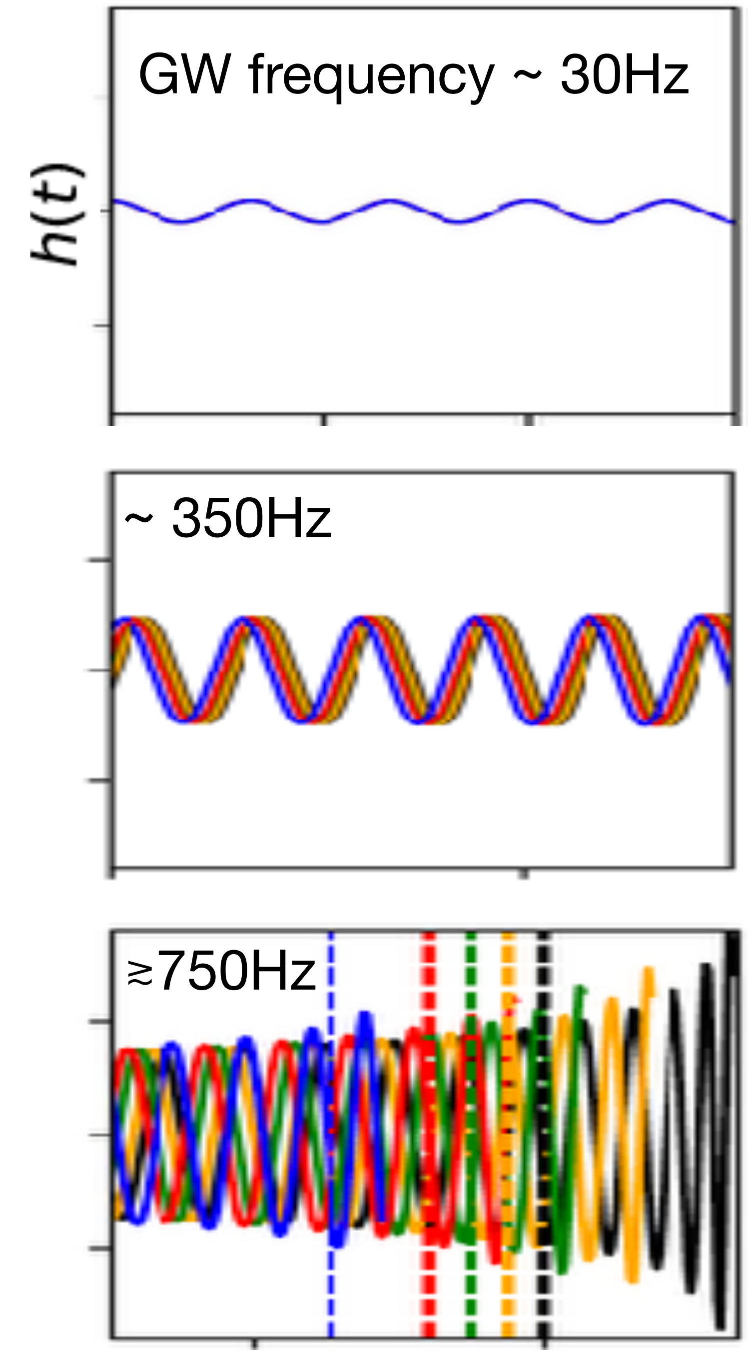
- moving multipoles contribute to gravitational radiation

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

- approx. GW phase evolution from energy balance:

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

Examples for neutron stars with different EoSs aligned at 30 Hz

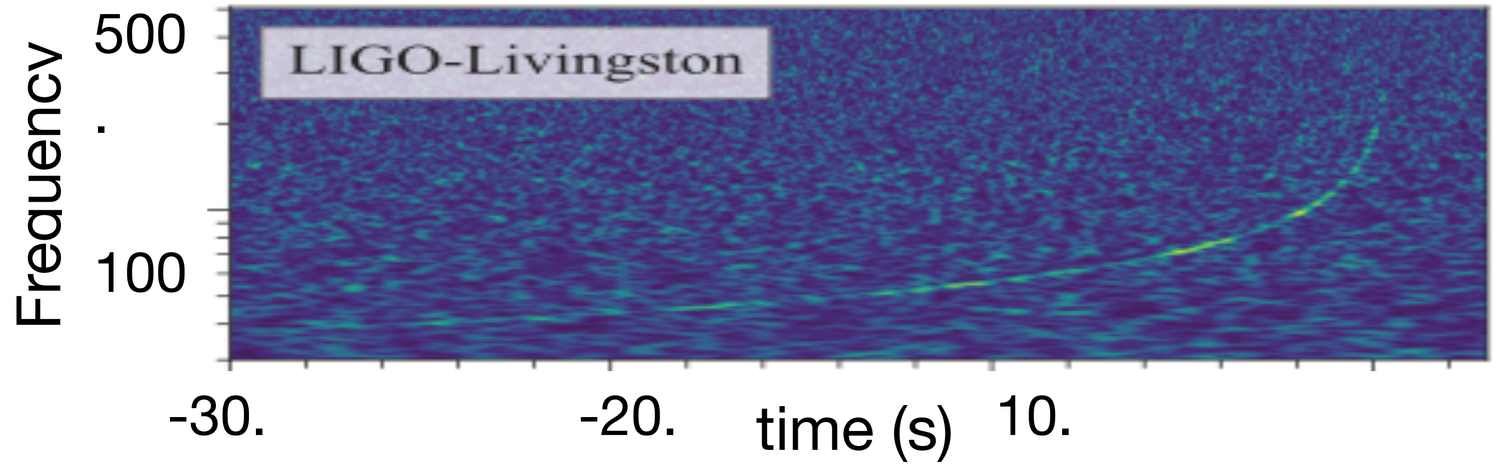


Dashed lines: 1kHz

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

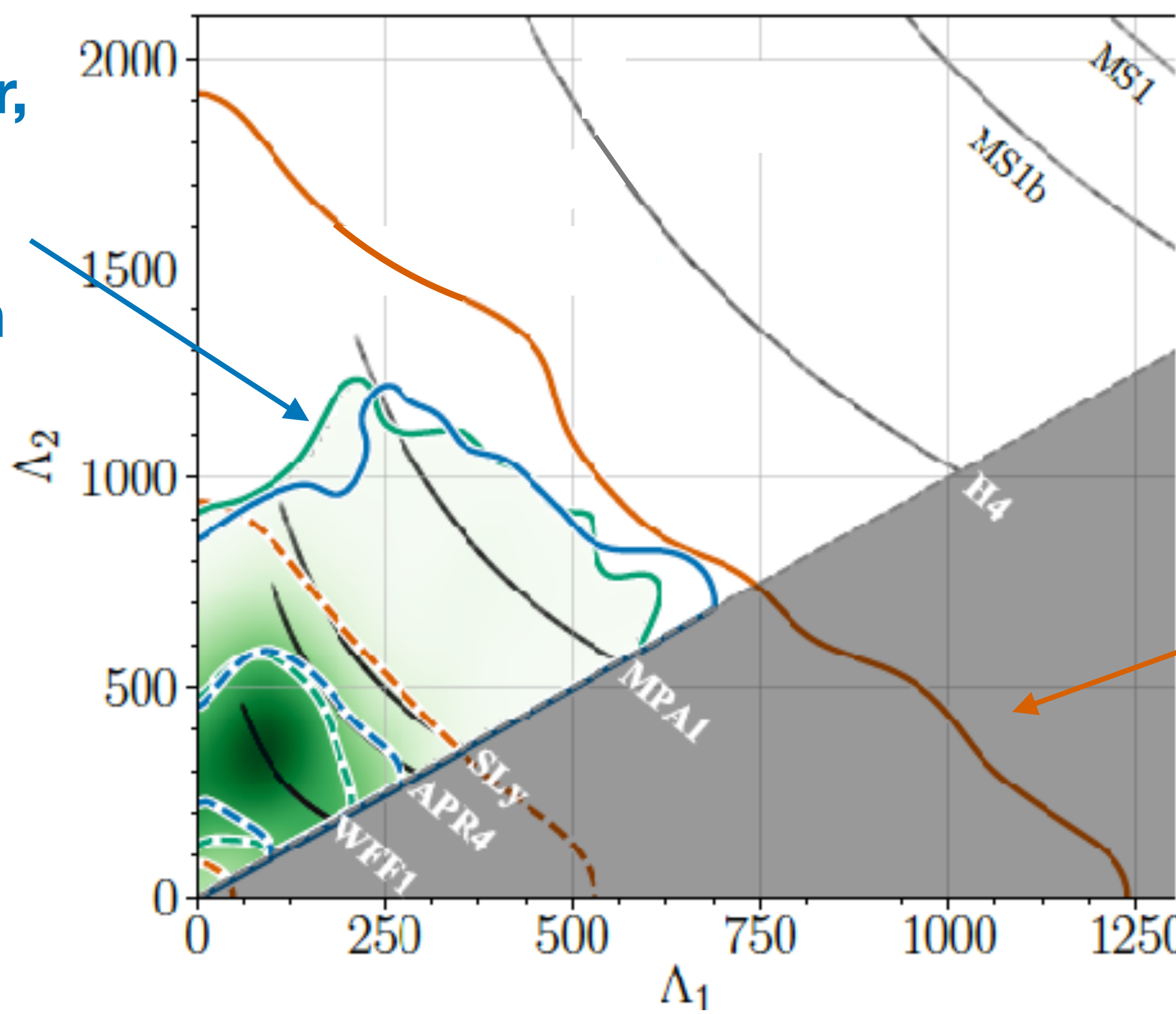
GW170817: NS binary inspiral measured in GWs

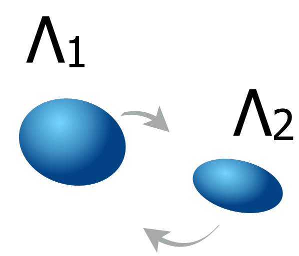
August 17, 2017:



First empirical results for tidal deformability

90% contour, low-spin + same EoS assumption





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

90% confidence contour, low-spin assumption

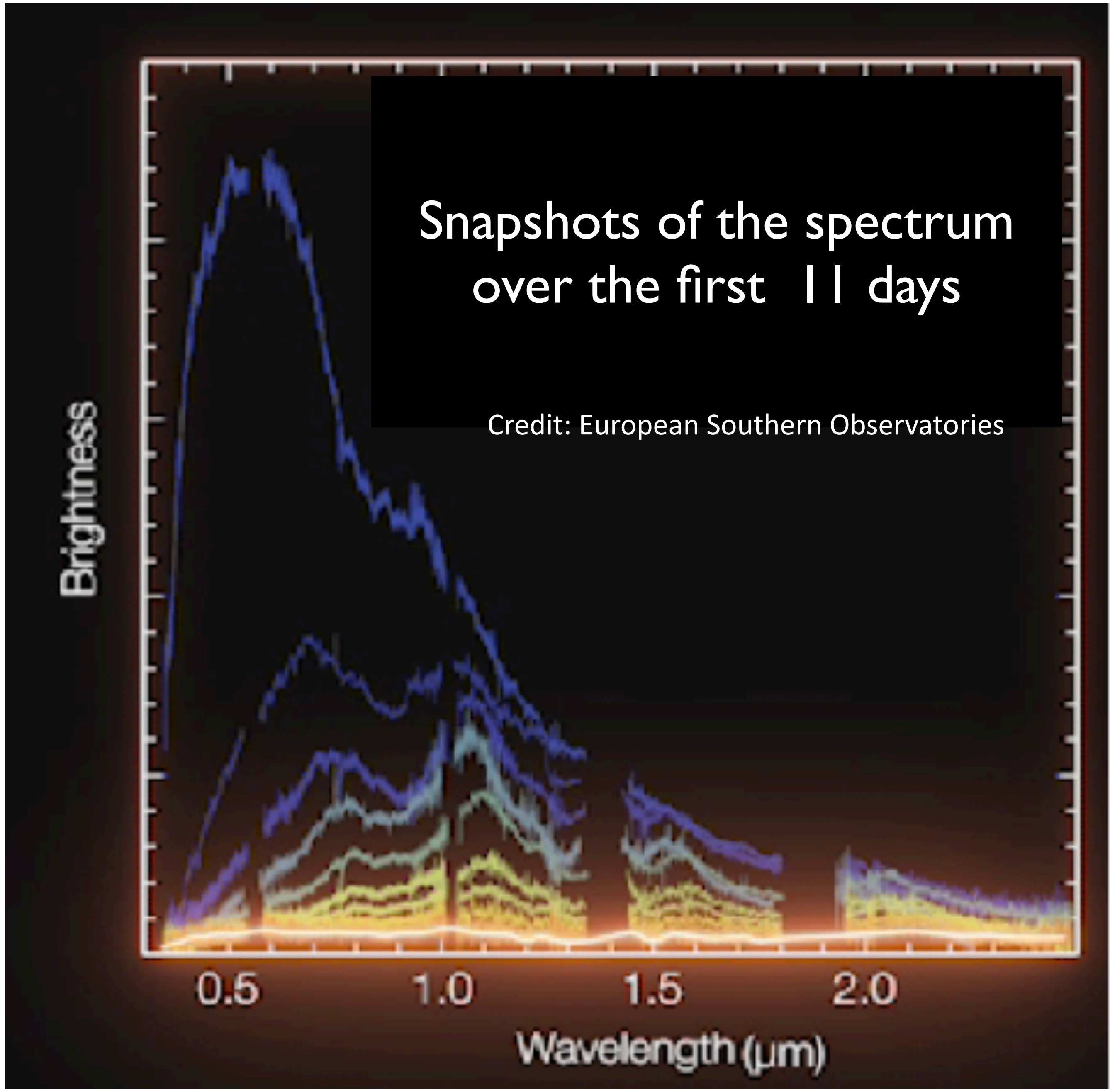
LVC arXiv:1805.11581

Merger not measured in GWs but EM counterparts:

Incl. **kilonova:**

characteristic of r-process nucleosynthesis

- Radioactivity heats thousands of unstable nuclides
- Millons transition levels in UV-visible-IR



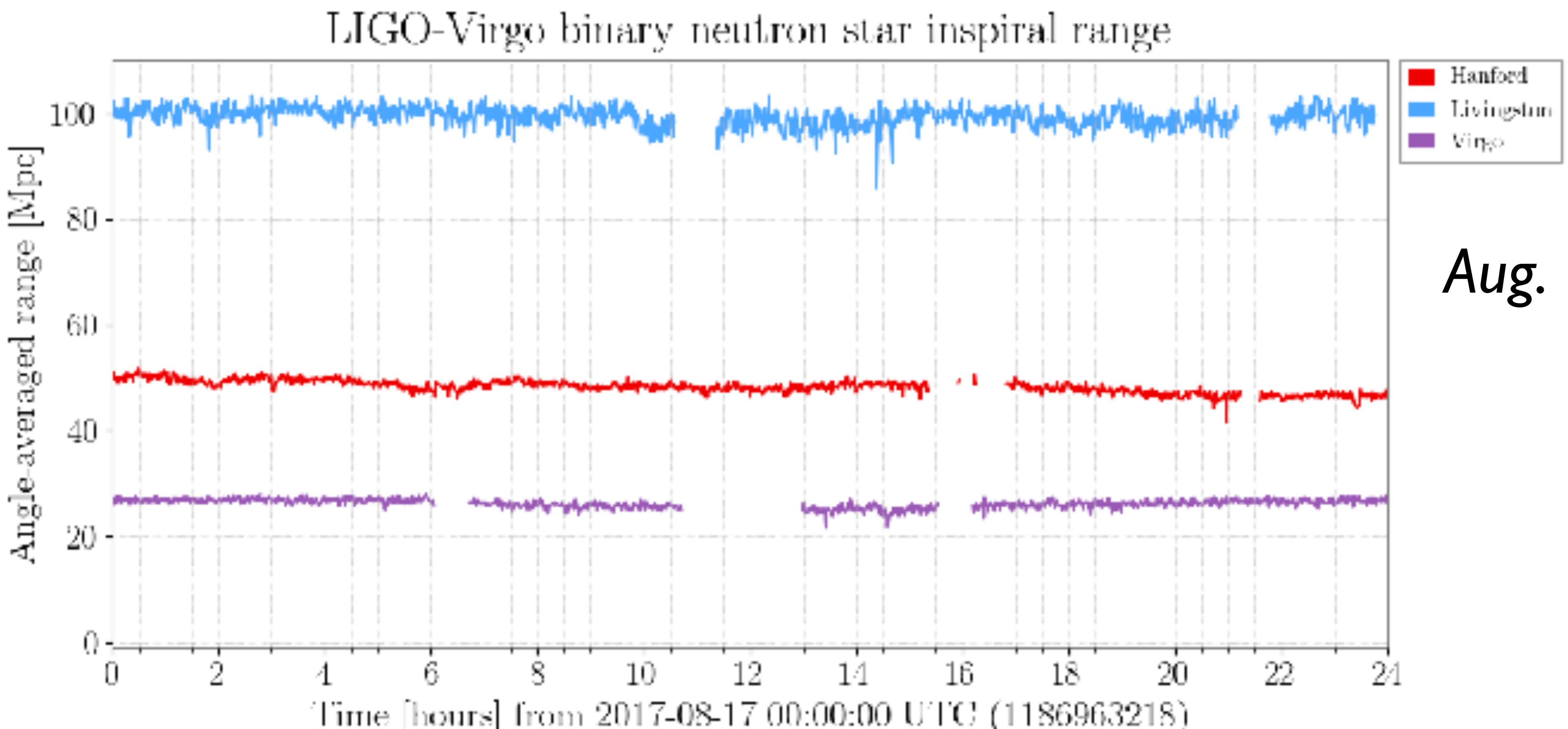
Brightness: ejecta mass, velocity, opacity (Ye), nuclear heating rate

Timescale & energetics: set by the photon diffusion time to escape ejecta

Also yields constraints on NS EoS *e.g. Raaijmakers + 2102.11569*

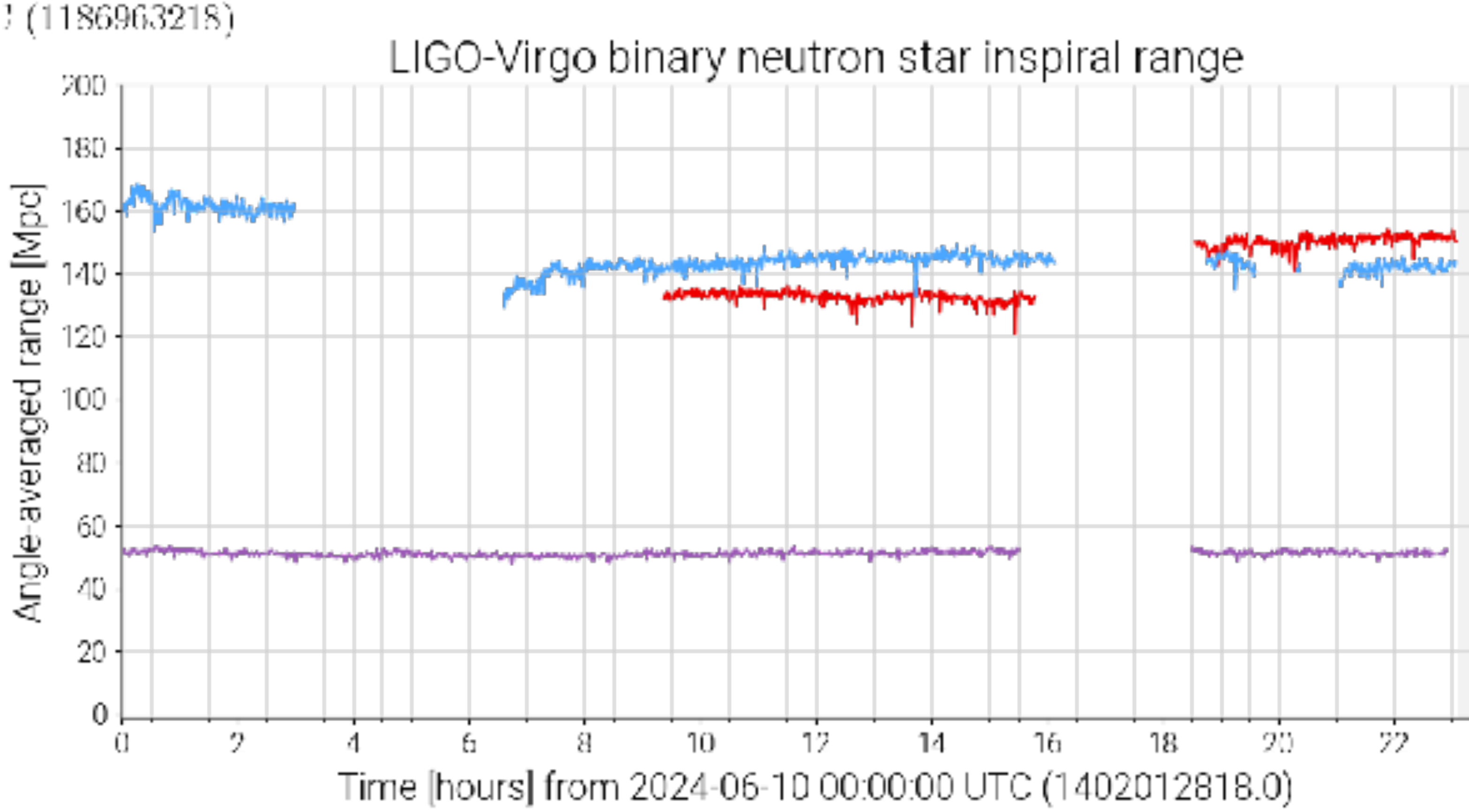
Observing run O4 ongoing

From GWOSC
https://gwosc.org/detector_status/



Aug. 17, 2017

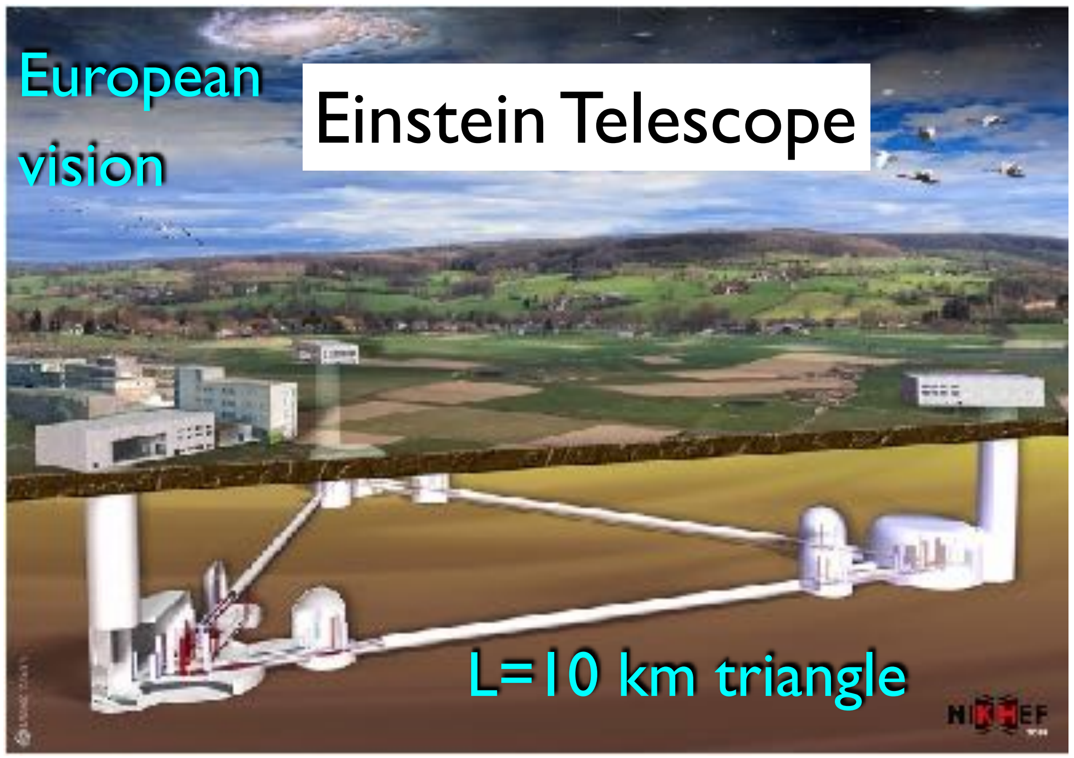
Yesterday



- Higher precision measurements of nearby sources
- greater number & diversity of events

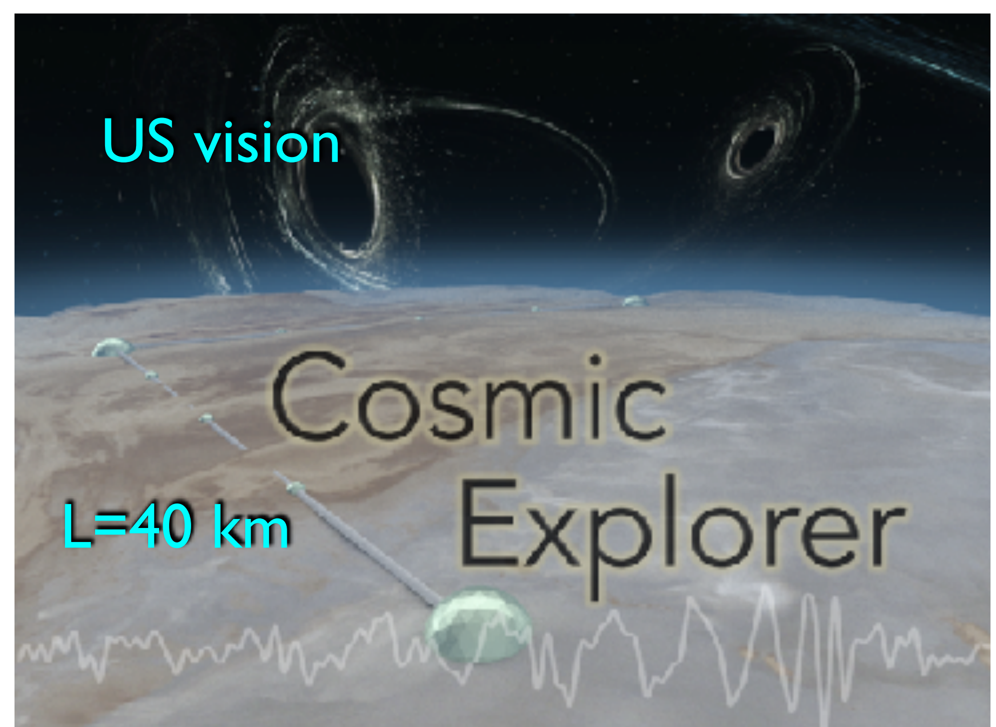
Next step for precision GW studies of neutron stars

Planned 3rd generation ground-based detectors (~2035)

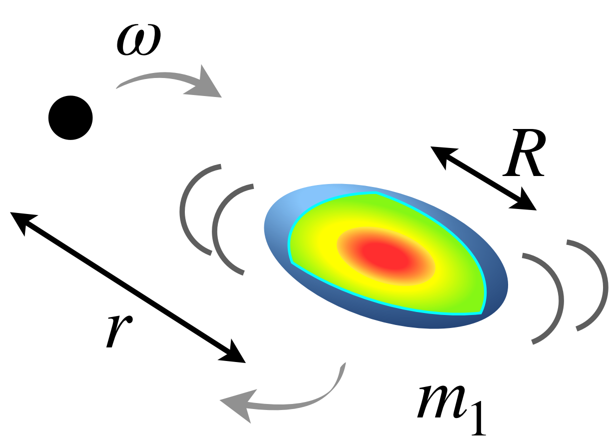


- 10 times better sensitivity than LIGO/Virgo
- wider frequency range
- O(100 000) binary merger detections per year

- Prototype in Maastricht



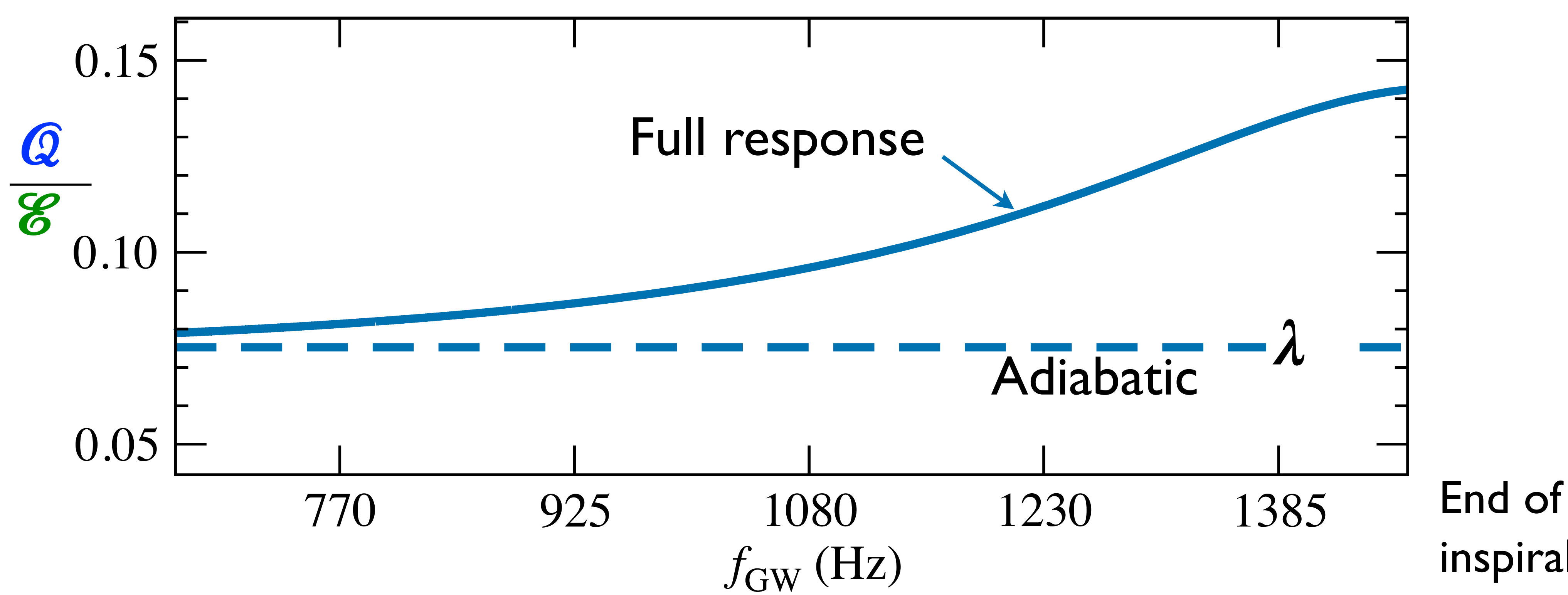
Dynamical tides



- *f*undamental oscillation modes have by far the strongest tidal couplings
- ***f***-mode frequency: $\omega_0 \sim \sqrt{G\,m_1/R^3}$ (internal-structure-dependent)
- **tidal forcing** frequency: $\sim 2\omega \sim 2\sqrt{G\,M/r^3}$ [circular orbits]

Enhanced tidal effects even if the resonance is not fully excited

f-mode tidal response during inspiral (NS-BH example)



[TH +2016]

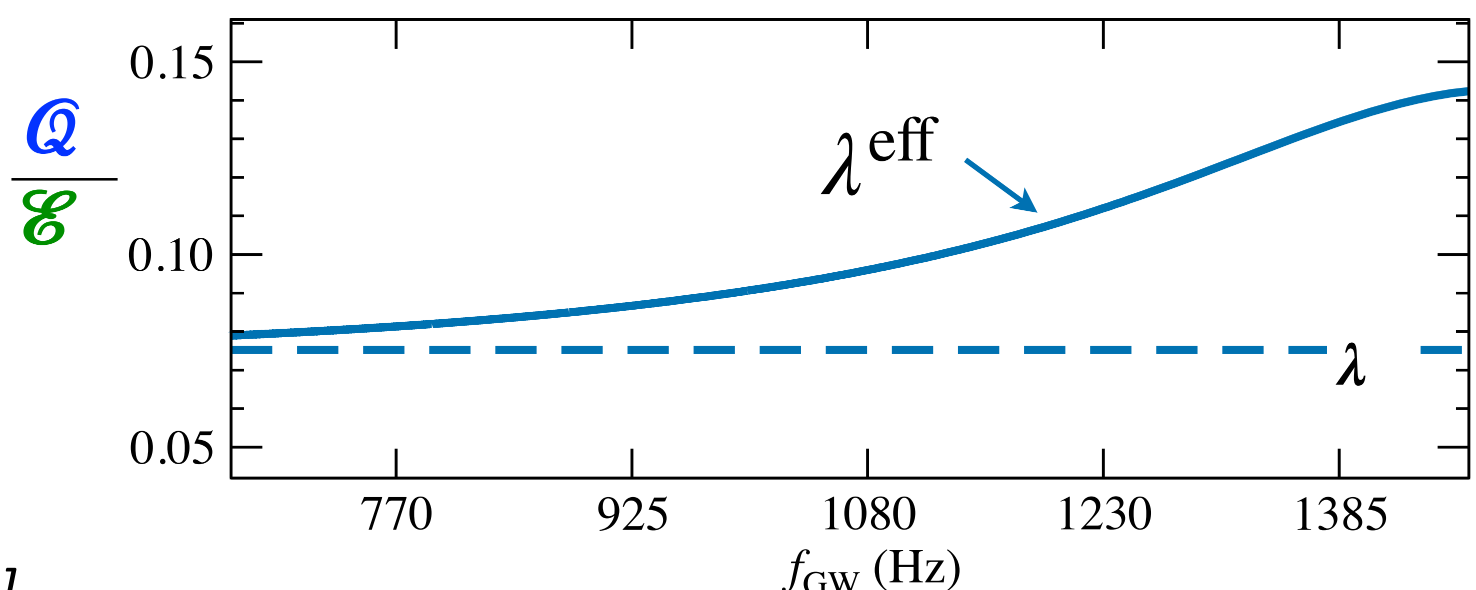
Approximate effects of dynamical tides in inspirals

- inspirals: need evolution of the system near/through resonances
- multi-scale approx. + matched asymptotic expansions determine approx. *effective* response:

$$\frac{\lambda^{\rm eff}(\omega)}{\lambda} \sim \frac{\omega_0^2}{\omega_0^2 - (2\,\omega)^2} \;\&\; \frac{\omega_0^2}{\phi - \phi_0} \;\&\; \cos[(\phi - \phi_0)^2]\,{\rm FresnelS}(\phi - \phi_0)$$ + after res.

before resonance

near resonance where $\phi \sim \phi_0$

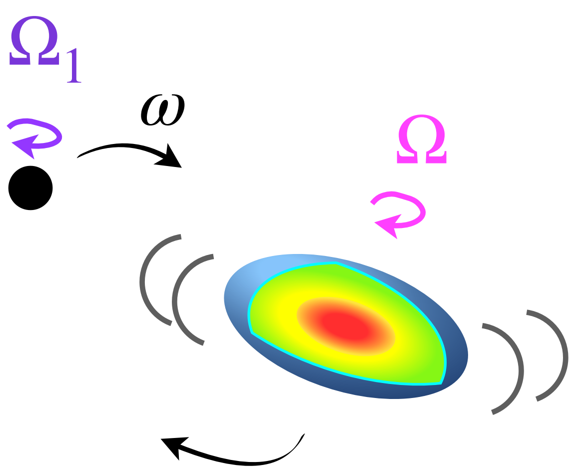


Implemented in SEOBNRv4T

[TH +2016]

Richer physics from spins & relativistic effects

- angular momentum of dynamical multipoles couples with orbital & companion's spin: frame-dragging effects
- Tidal forcing frequency felt by the object is redshifted due to its strong gravity
- Effective frequency also impacted by object's spin



- more realistic description of response (linear in Ω) :

[Steinhoff, TH + 2021]

$$\frac{\lambda^{\text{eff}}}{\lambda} \sim \frac{z^2\omega_0^2}{\left[4(\omega - \Omega_{\text{fd}} + 1.5\, z\, \Omega)^2 - z^2\, \omega_0^2\right]} + \ldots$$

frame dragging

(Angular momentum couplings)

Approx. coefficient inferred from quasi-normal mode calculations

object's spin

Model tested against numerical relativity simulations

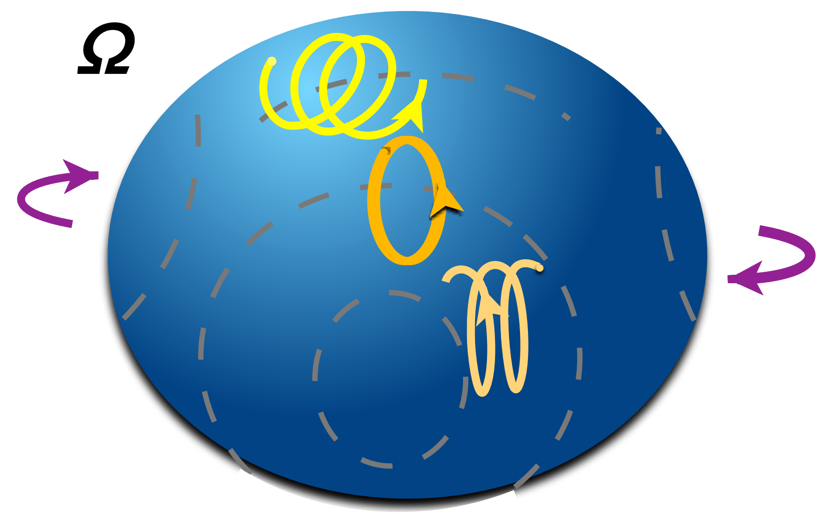
Example of other modes: gravitomagnetic sector

- gravitomagnetic tidal tensor $\mathcal{B}_{ij} = {}^*C_{0i0j}$

  ~ relativistic frame-dragging fields, no Newtonian analog

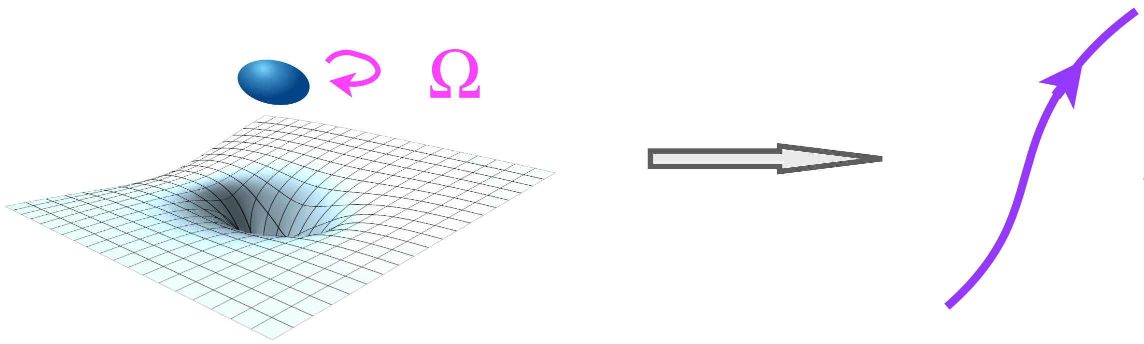
- Tidally induced current multipole moments
- 'r-modes', restoring force: Coriolis effect
- *Perturbation theory calculations:*
  - mode frequencies $\propto$ spin frequency Ω
  - two different Love numbers $\sigma_{\rm stat}$ & $\sigma_{\rm irrot}$

Fluid motion



[Landry, Poisson, Pani+, Damour, Nagar, …]

Skeletonization determines relevant Love numbers for GWs



Skeletonized effective description

Gravitomagnetic effects add to the total tidal action:

Matter contribution to current quadrupole

$$S_{\text{magn. tid.}} \approx \int z\, d\tau \left[-\frac{1}{2} \dot{\boldsymbol{q}}_{ij} \mathscr{B}_{ij} + L^{\text{Coriol.}} + b_1 \frac{d\dot{\boldsymbol{q}}_{ij}}{d\tau} \frac{d\dot{\boldsymbol{q}}_{ij}}{d\tau} + b_2 \mathscr{B}_{ij} \mathscr{B}_{ij} \right]$$

$$L^{\text{Coriol.}} = -2\, \hat{\omega}_B\, \Omega\, \epsilon_{ijk}\, \dot{\boldsymbol{q}}^{ij}\, \boldsymbol{q}^{ki} \qquad b_1 = \frac{3}{32(\sigma_{\text{stat}} - \sigma_{\text{irrot}})} \qquad b_2 = \frac{2\sigma_{\text{stat}}}{3}$$

Normalized mode frequency

- different adiabatic behavior (Love number combinations) before & after resonances
- Different spin orientations ⇒ different $m-$mode excitations

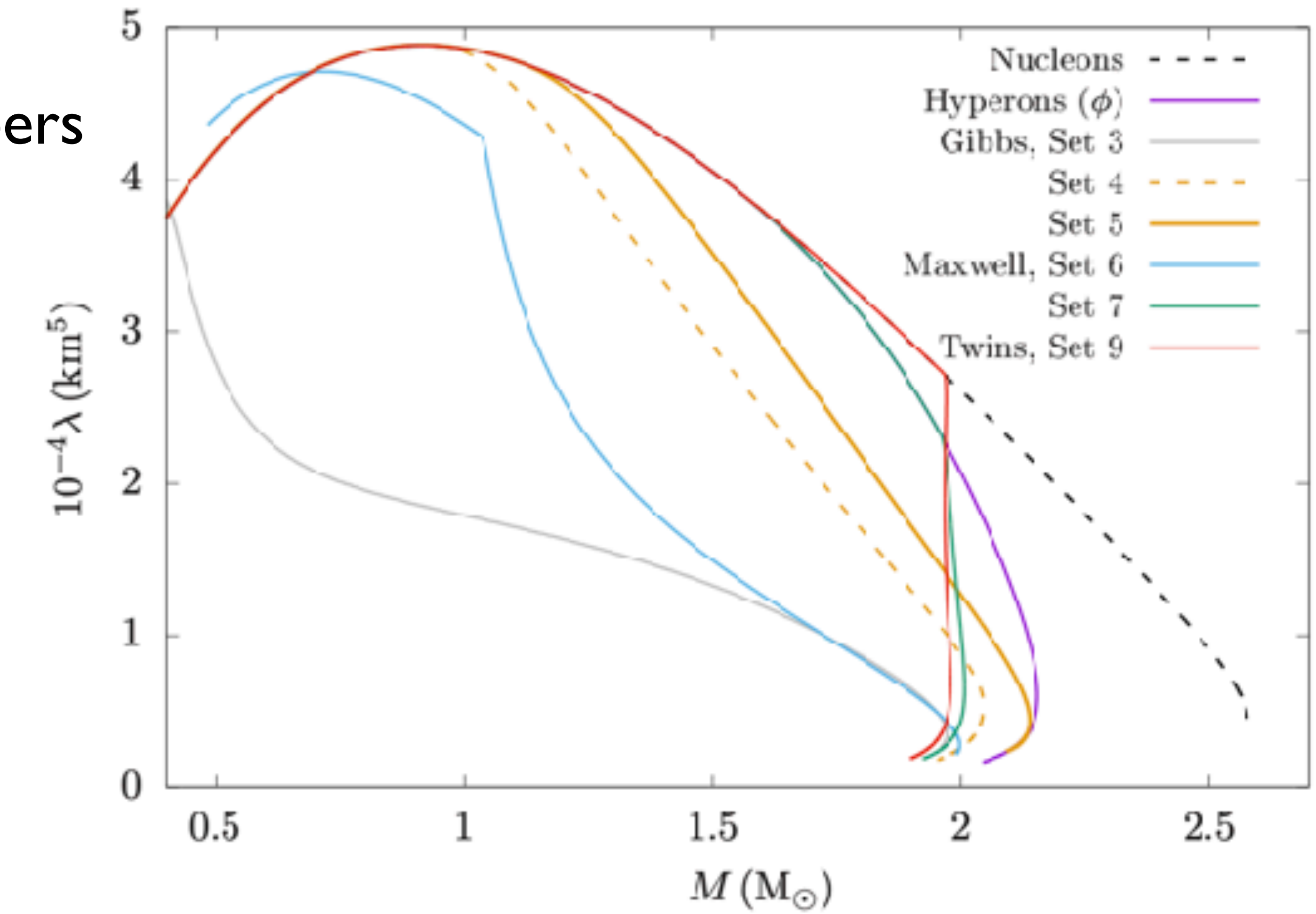
[Gupta, Steinhoff, TH 2021, 2023]

Signatures of phase transitions, composition gradients?

- Several works studied features in Love numbers

  Example from Gomes+ 1806.04763

- Spectrum of f- and r-modes also affected



- Direct signatures from 'g-modes':
  - Restoring force: buoyancy
  - mode frequency strongly depends on transition density + size of discontinuity
  - extremely long damping times

e.g. recent calculations of quasi-normal mode frequencies: *Tonnetto+ 2003.01259*

Newtonian study of GWs from g-modes due to hyperons: *Yu & Weinberg 1705.04700*

Effects of viscosities in inspirals ?

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

  Ripley & Yunes 2306.15633

  Linearized tidal lag due to viscosity

… and expect richer behavior with dynamical tides:

- mode excitations - tidal heating - microscopic viscosities generally dependent on temperature and frequency

  Estimates of coupled feedback loop: *Arras & Weinberg 1806.04163*

  Viscosity effects for modes in isolated NSs e.g. *Alford+2010, Alford+ 2014*

- More realistic description of modes with effects of (neutron) superfluidity: doubling of mode spectrum

  E.g. Kantor, Gusakov

Examples of effects in inspirals that remain to be fully explored

- Further relativistic + spin effects for dynamical tides

  adiabatic spin-tidal Love numbers in GWs: *Castro, Gualtieri, Maselli, Pani 2204.12510*

- Nonlinear mode interactions

  Newtonian case study: *Yu, Weinberg, Arras, Kwon, Venumadhav 2211.07002*

- Modes that affect the NS crust ⇒ electromagnetic counterparts

  e.g. symmetry energy constraints from interface modes: *Neill, Newton, Tsang 2403.03798*

- *Degeneracies* e.g. with presence of dark matter, modified gravity, ….

- *eccentricity:* richer behavior due to greater variety of tidal driving frequencies, …

- *Late inspiral:* tidal disruption, overlapping matter distributions, magnetic fields…. , connection with merger & beyond, …

- ….

Conclusion

- GWs are unprecedented probes of compact objects: clean gravitational channel of information, spectroscopic studies even during inspiral
- 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 with numerical relativity
- significant further efforts required to realize the full GW science potential