Probing subatomic physics with gravitational waves from neutron star binary inspirals

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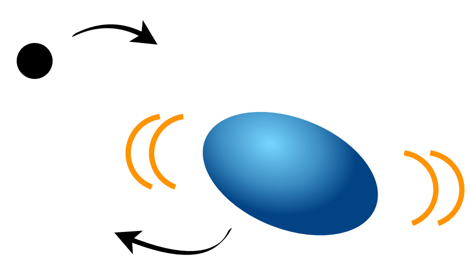
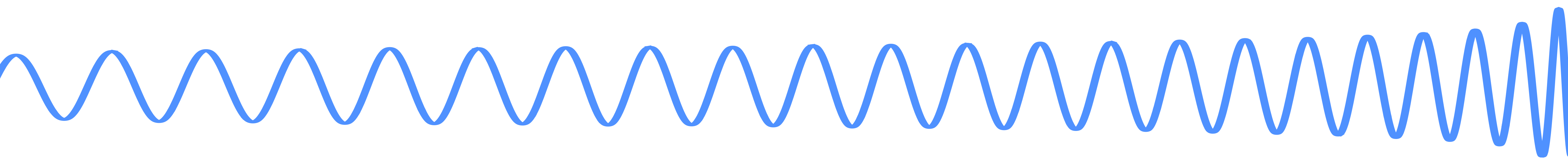
Overview

- Gravitational waves (GWs) now available as unique probes for fundamental physics
    - e.g. dense matter in neutron stars
- Extracting this information from the data requires theoretical understanding & accurate modeling
- Focus in this talk: tidal effects during a binary inspiral
    - Main characteristic parameters
    - Effects on the dynamics and GWs

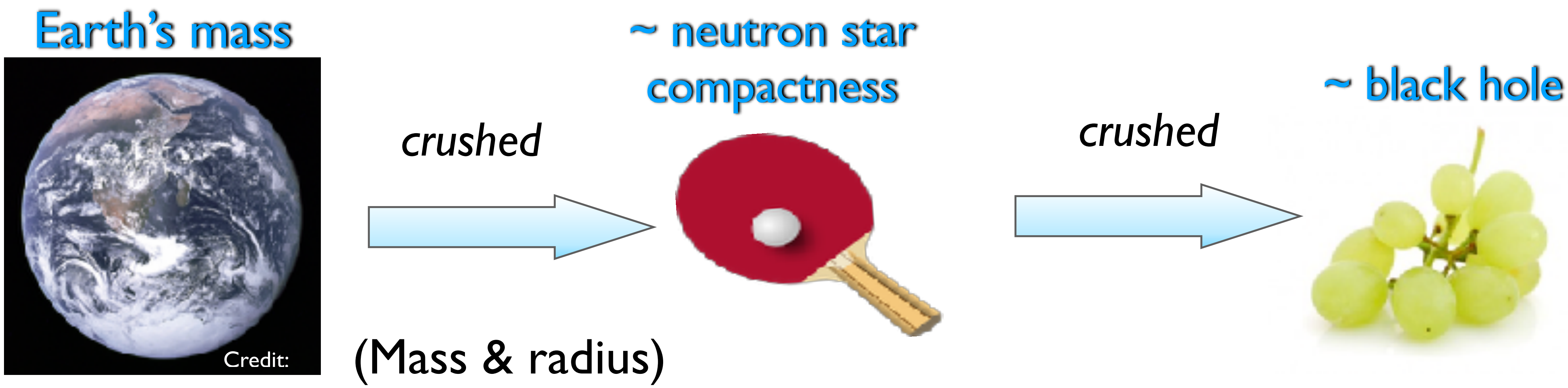


- Outlook to remaining challenges and future prospects



Neutron stars (NSs)

- Gravity compresses matter to up to several times nuclear density
- Large extrapolation from known physics



- Thousands observed to date, some masses > $2\,M_\odot$
- Quantum pressure (neutron degeneracy) can only support up to ~ $0.7\,M_\odot$

[Oppenheimer & Volkoff 1939]

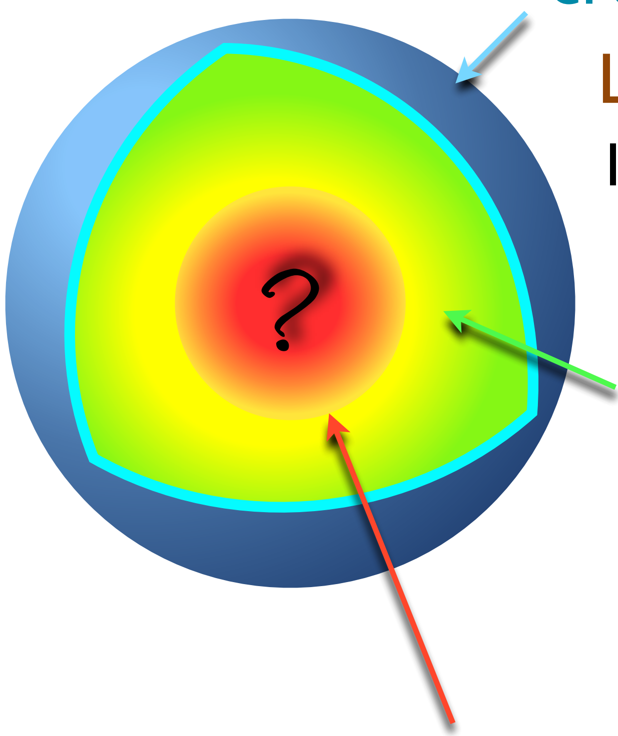
- Unique window onto strongly-interacting subatomic matter

Conjectured NS structure

NS matter ranges over nearly 10 orders of magnitude in density: rich variety of physics

[density of iron ~ 10 g/cm^3]

crust ~ *km*



Lattice of neutron rich nuclei ~ 10^{6} g/cm^3 inverse β-decay

10^{10} times stronger than steel

free neutrons ~ 10^{11} g/cm^3 neutron drip

outer core

uniform liquid (neutron superfluid, superconducting protons, electrons, muons)

deep core ~ few x 10^{14} g/cm^3

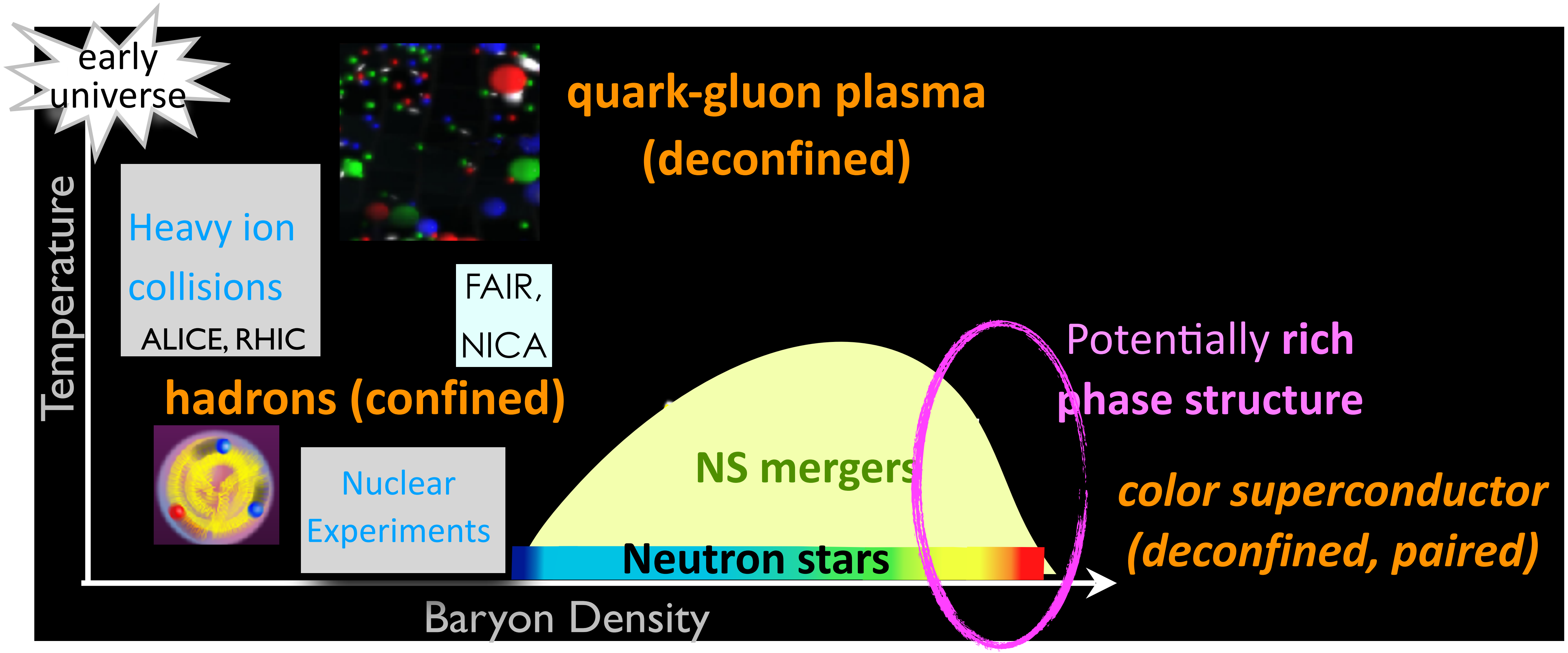
$\gtrsim$2x nuclear density, nucleons overlap -

new degrees of freedom relevant

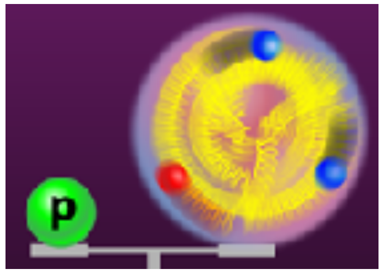
deconfined quarks?

intermediate exotic condensates (hyperons, kaons, pions, …)?

Neutron stars as QCD labs



- Characterize phases of QCD, probe quark deconfinement
- Deeper understanding of strong interactions, their unusual properties
  - asymptotic freedom
  - Vacuum (condensate) effects

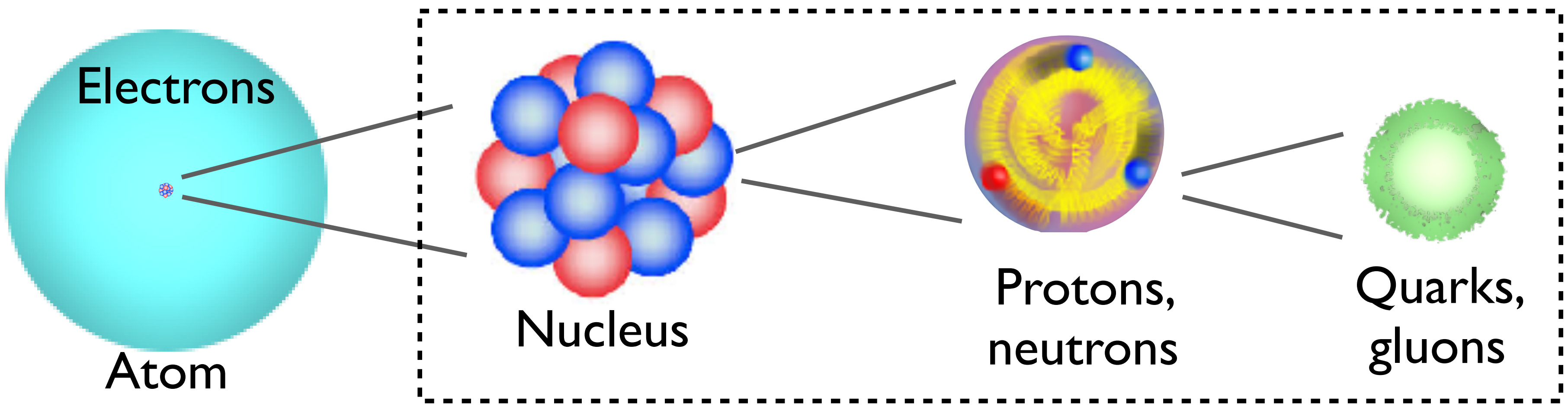


proton mass: ~ 938 MeV

only ~ 1% due to Higgs

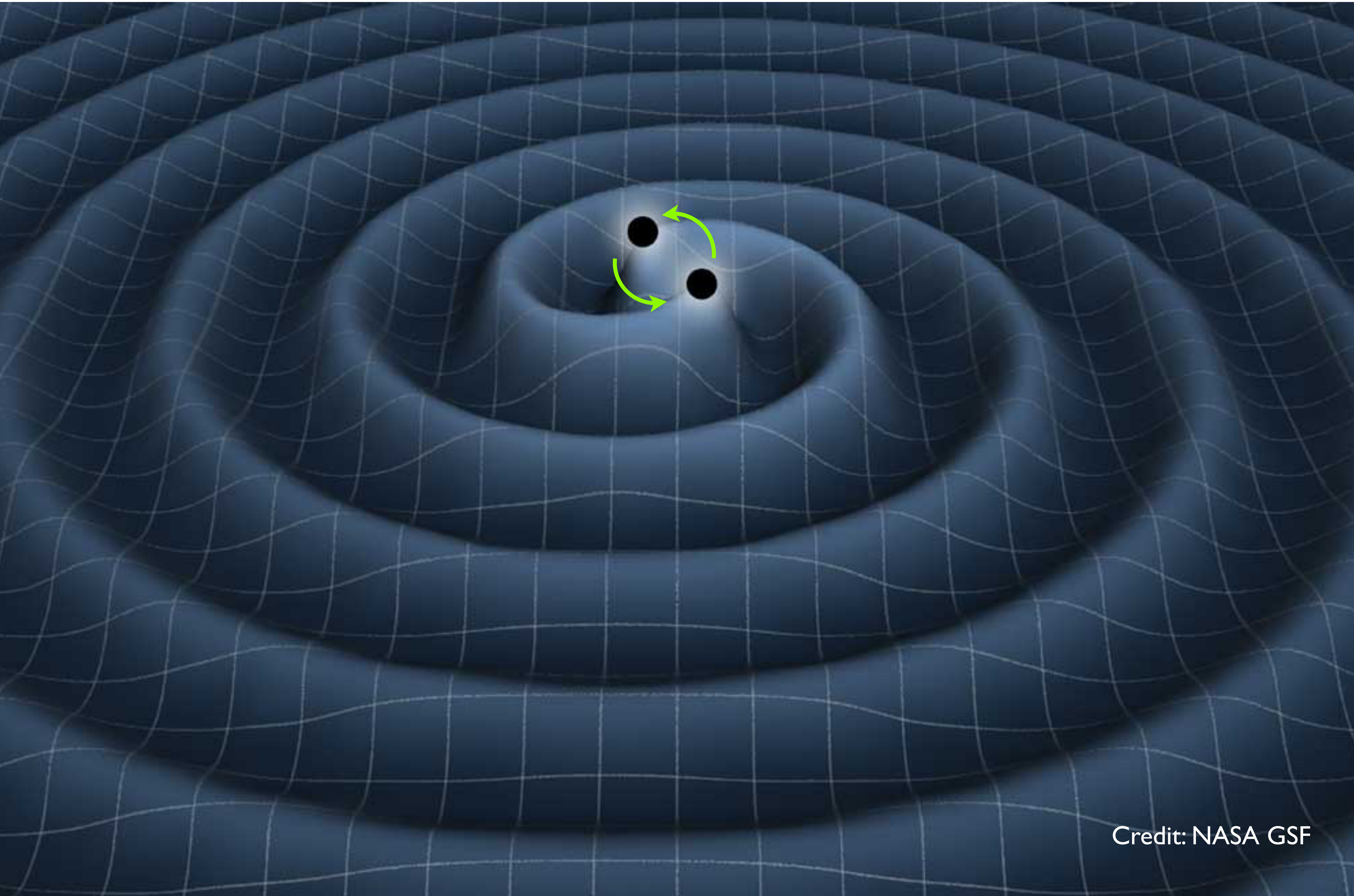
NSs as labs for emergent structural complexity

Building blocks of matter



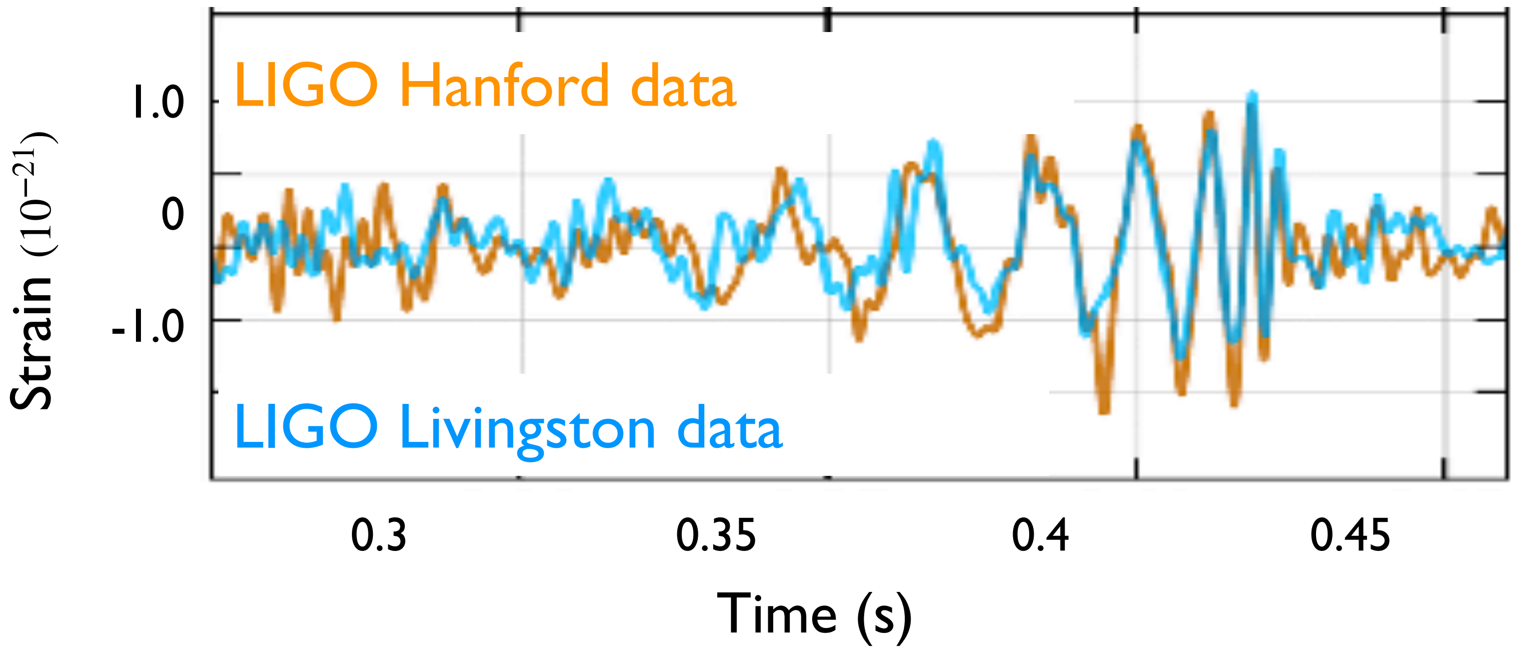
- Collective phenomena, multi-body interactions
- Effects of the excess of neutrons over protons (isospin asymmetry)?
- How do nucleons and their quarks and gluons assemble and interact to create the structure of matter?

Gravitational waves from compact-object binary systems



Credit: NASA GSF

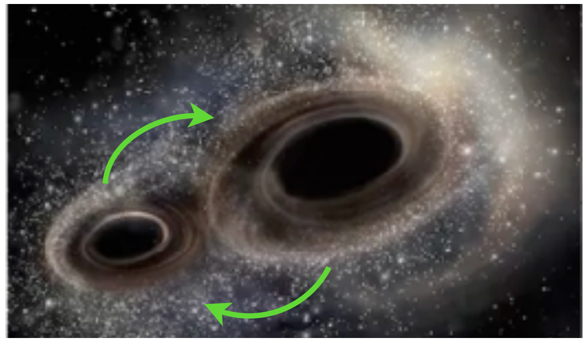
Models are essential to detect and interpret GW signals



The first detection:
GW150914 data

Cross-correlating the data with theoretical models revealed:

it was the signal from a black hole merger

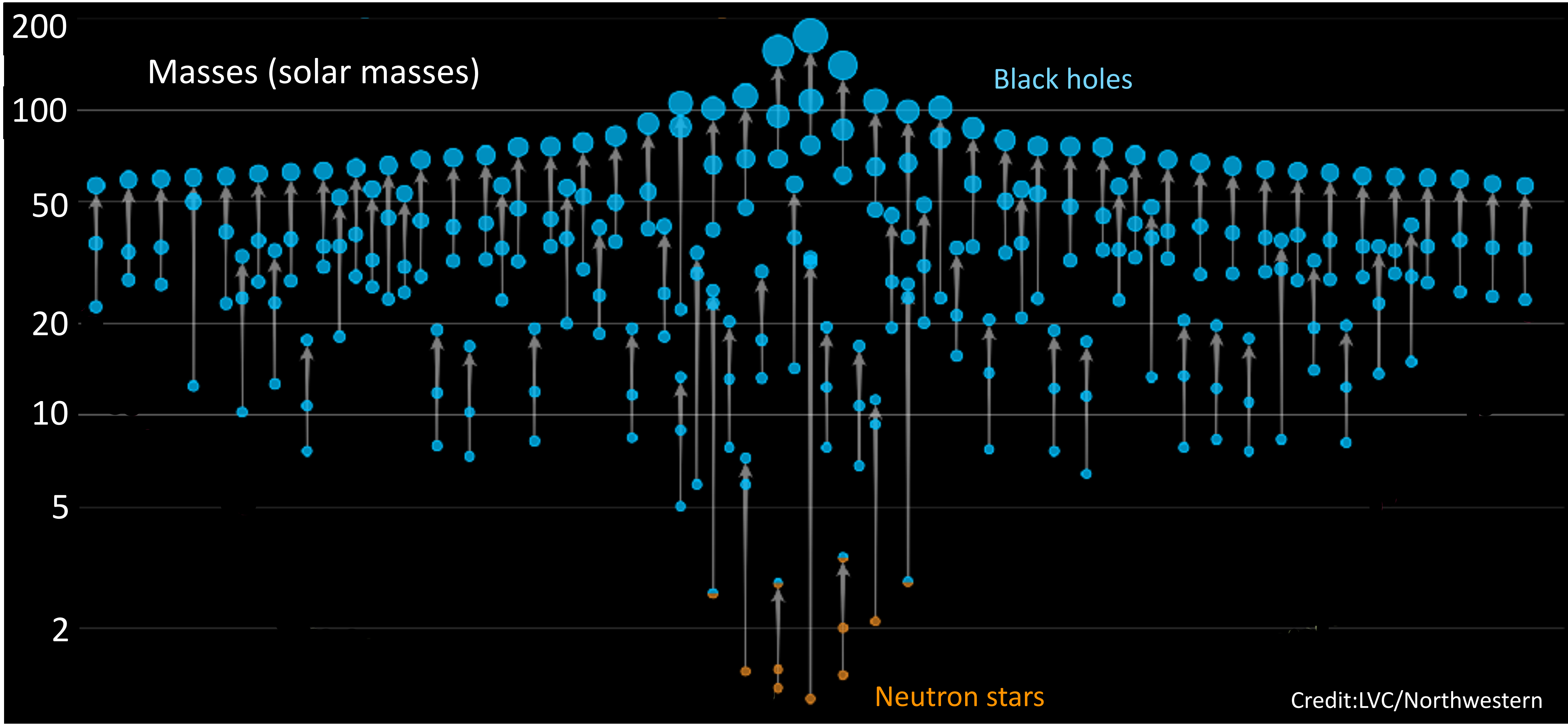


Two black holes of ~ 30 sun masses
Orbiting at 50,000km/sec …

Spiral together until
they collide …

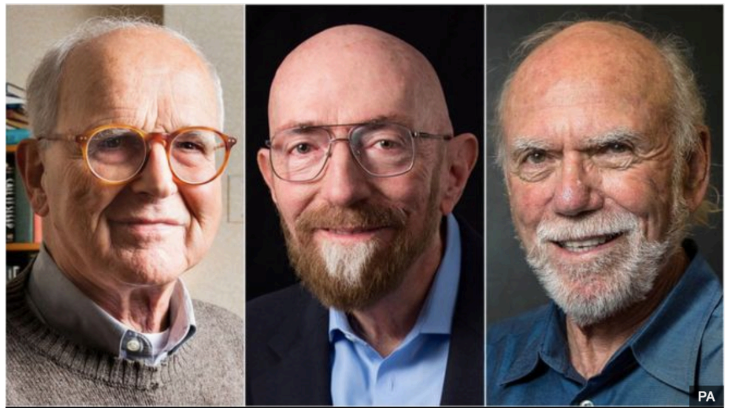
… and form a single
black hole remnant

Census of binary mergers measured to date



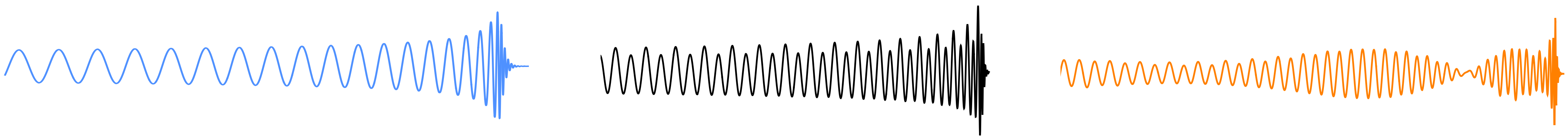
2017 Nobel prize

R. Weiss, K. Thorne, B. Barish



GW measurements (binary systems)

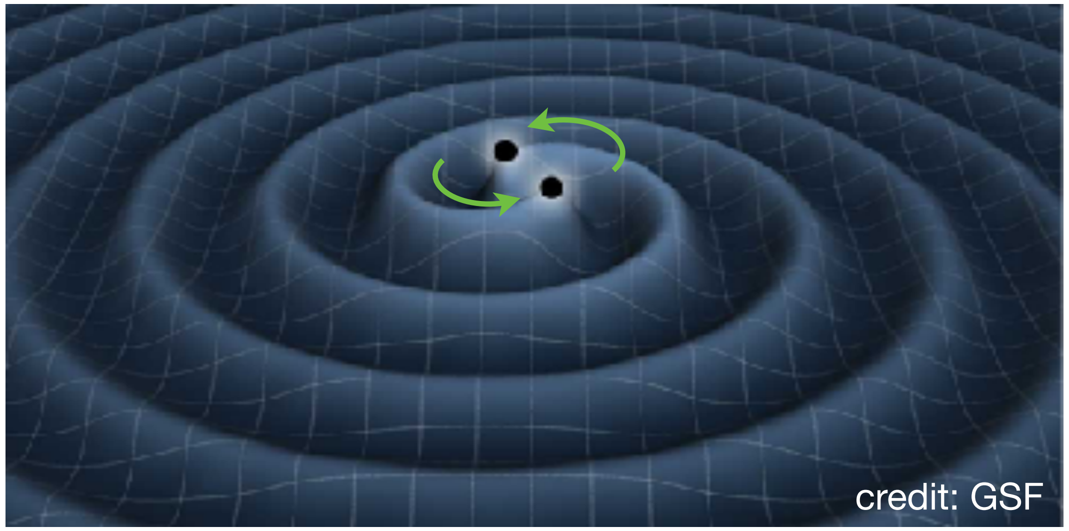
- Details of the waveforms encode fundamental source properties (masses, spins, …)



- Measurements cross-correlate millions of template models with the data to determine the source parameters

- Computation of template waveforms is very challenging:

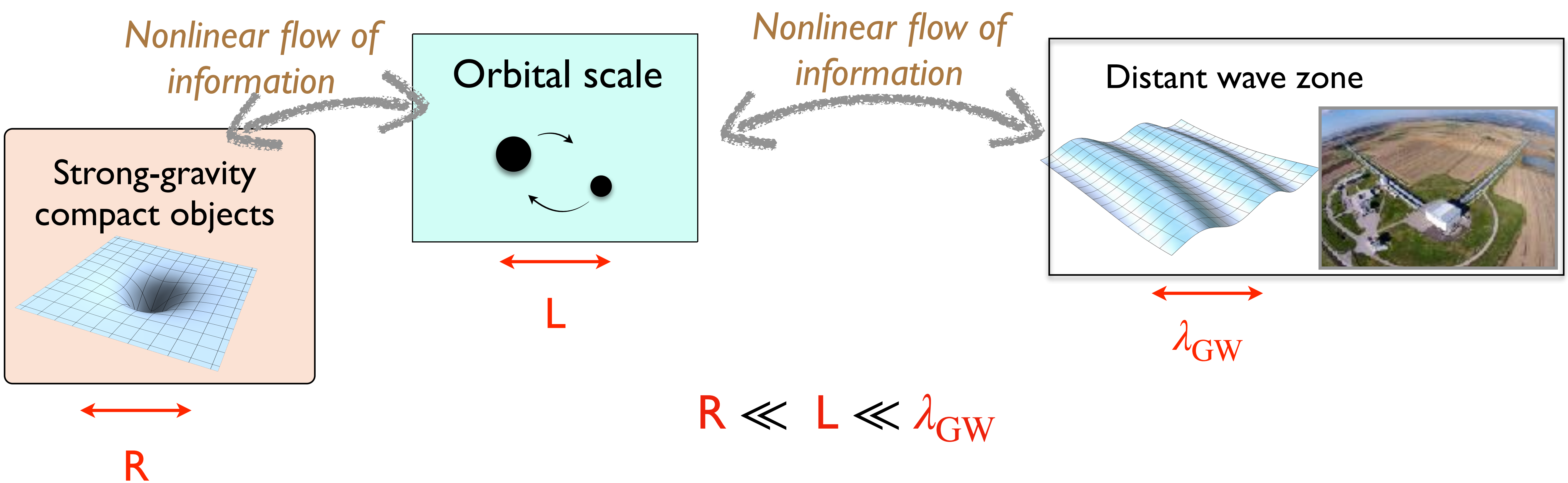
Must solve the nonlinear Einstein Field equations coupled with the matter equations of motion for the dynamical spacetime



Approaches to computing waveforms

- Numerical relativity simulations: access to complex merger regimes … limited in parameter space . sometimes difficult to identify fundamental physics parameters based solely on numerical outputs
- When different physics dominate at different scales:
    - tapestry of approximation schemes in different patches of spacetime
    - Can be further re-summed, e.g. into the effective one body framework

Example for comparable-mass inspirals:

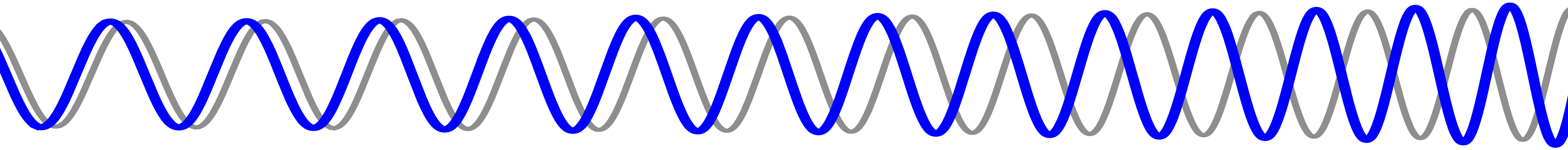


$$R \ll L \ll \lambda_{GW}$$

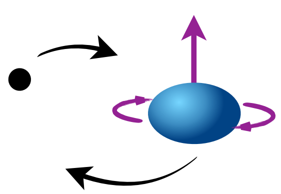
~10km ~400km ~4000 km

GW signatures of interior structure during inspiral

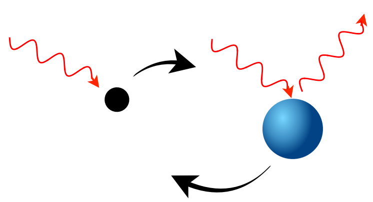
Two black holes (low mass) — Black hole - other object



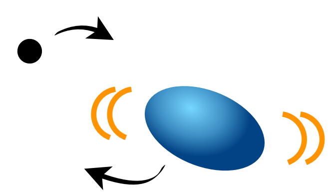
Spin-induced multipoles



Absorption



Various tidal effects



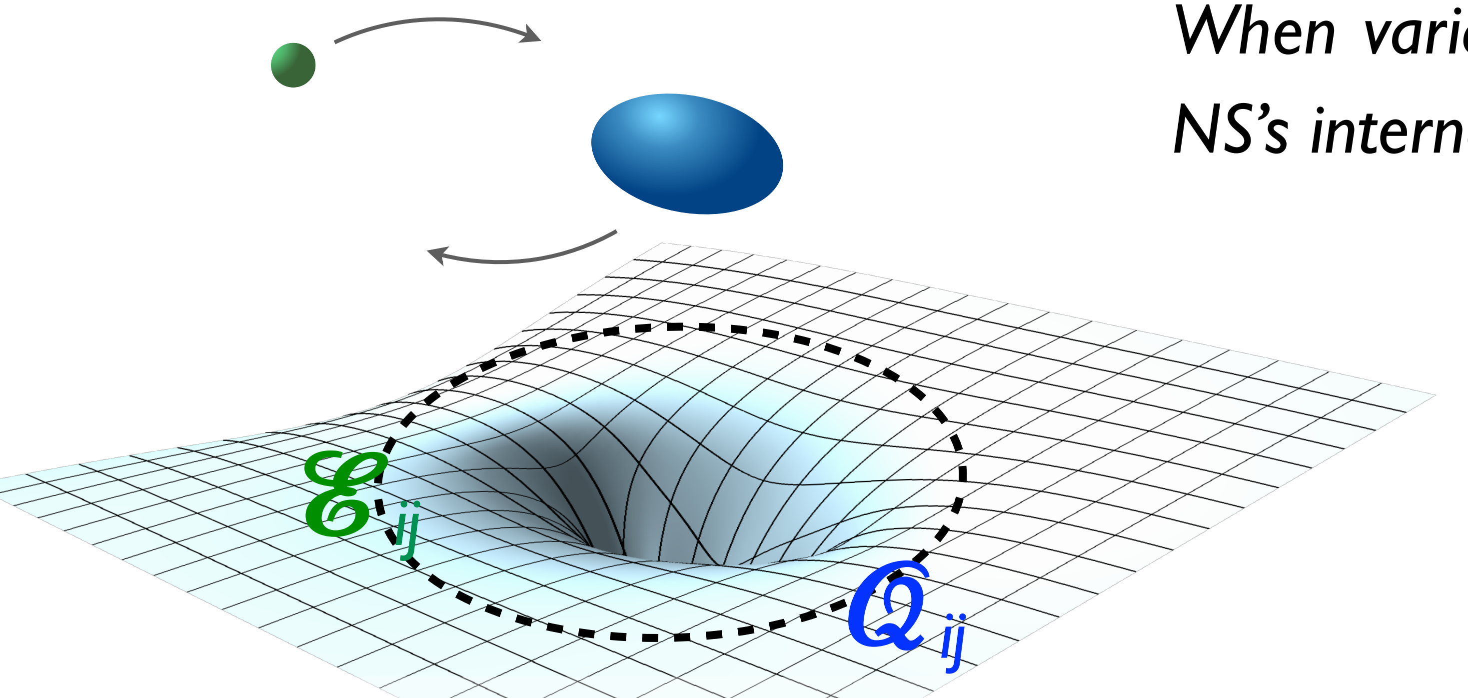
Resonant & non-resonant excitation of isolated characteristic modes

GW spectroscopy of NS interiors

- Generic phenomena, effects are small but clean and cumulative, accessible with current detectors
- associated characteristic parameters (e.g. Love numbers, quasi-normal mode frequencies) set the size of the GW signatures, encode object's internal structure

Dominant tidal effects

- In a binary: tidal field $\mathcal{E}_{ij} = R_{0i0j}$ due to spacetime curvature from companion



Quadrupole deformation of spacetime away from spherical symmetry

When variations in tidal field are much faster than NS's internal timescales (adiabatic limit):

Induced deformation:

$$\mathcal{Q}_{ij} = -\lambda \mathcal{E}_{ij}$$

tidal deformability parameter

[TH 2008, Flanagan, TH 2008]

=0 for a black hole

[Kol,Smolkin '11,Pani+ , Chia '20, Casals, LeTiec '20,...]

Similarly for higher multipoles

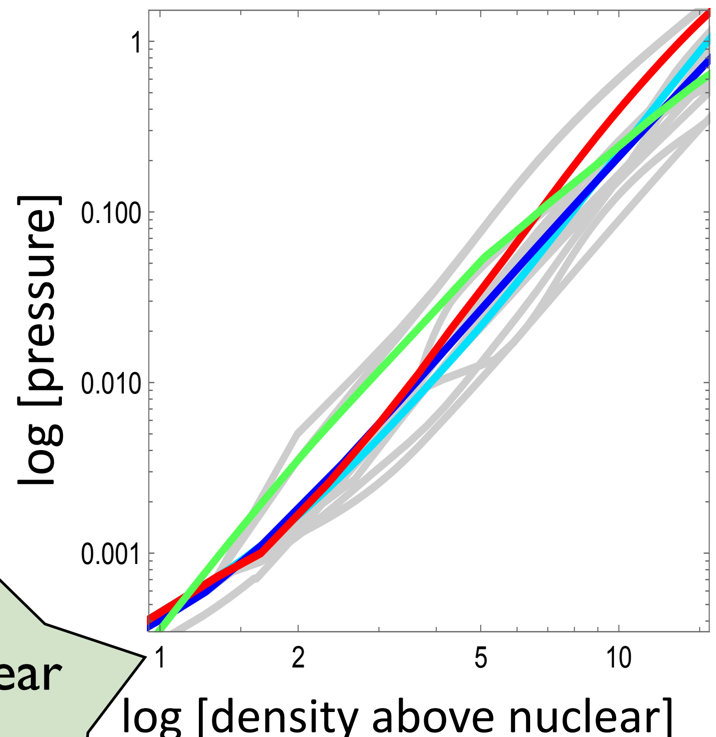
[Damour& Nagar, Binnington &Poisson 2009]

+ much recent work on intriguing connections with symmetries etc

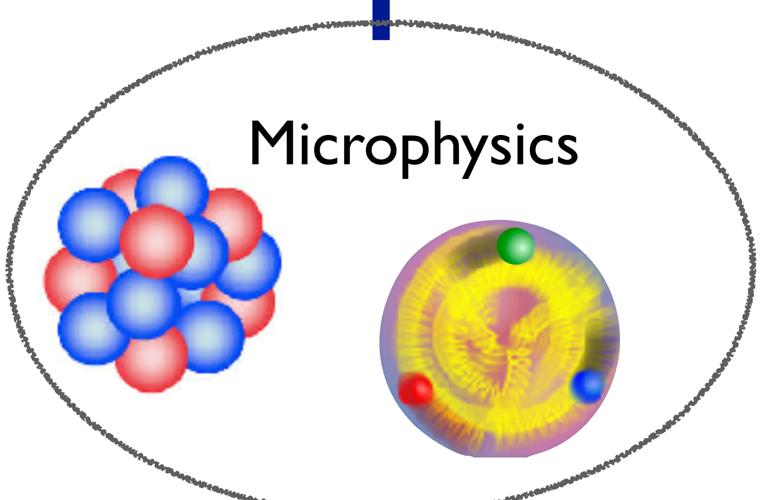
Properties of NS matter reflected in tidal deformability

NS matter models
(equations of state EoS)

Perturbative QCD



Nuclear EFT, …



Einstein field equations &

stress-energy conservation

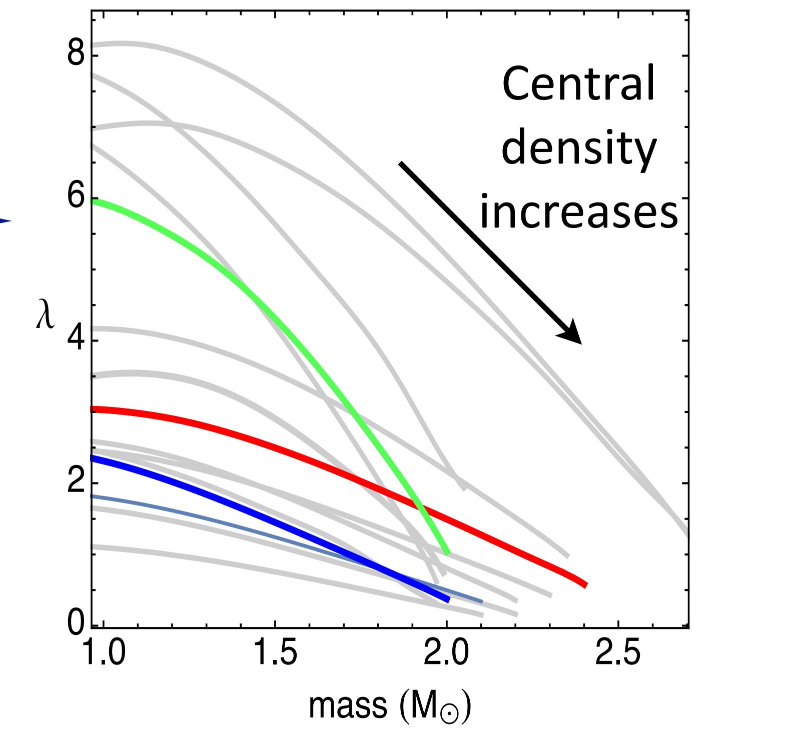
Stationary perturbations to equilibrium

[TH 2008, many others]

or wave scattering

[Creci, TH,Steinhoff 2021]

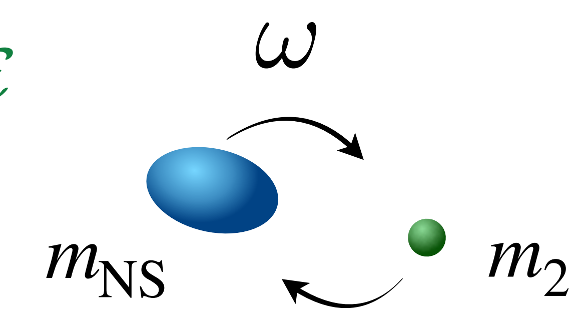
Tidal deformability λ vs. mass



Main influence on GWs

- Energy goes into deforming the NS:

$$\mathcal{Q} = -\lambda\,\mathcal{E}$$



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

- moving multipoles contribute to gravitational radiation

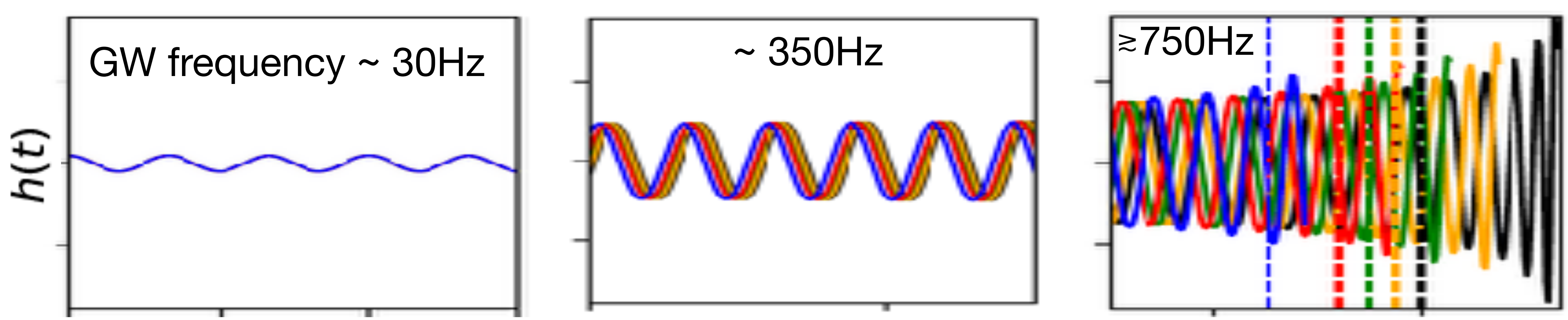
$$M = m_{NS} + m_2$$

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

- approx. GW phase evolution from energy balance:

$$\Delta\phi_{\rm GW}^{\rm tidal} \sim \lambda\,\frac{(M\omega)^{10/3}}{M^5}$$

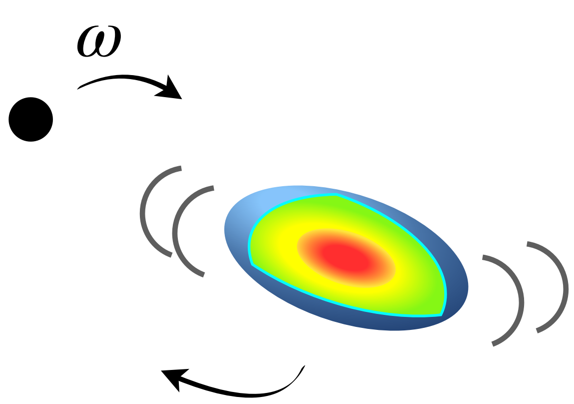
Examples for different EoSs aligned at 30 Hz



Dashed lines: 1kHz

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

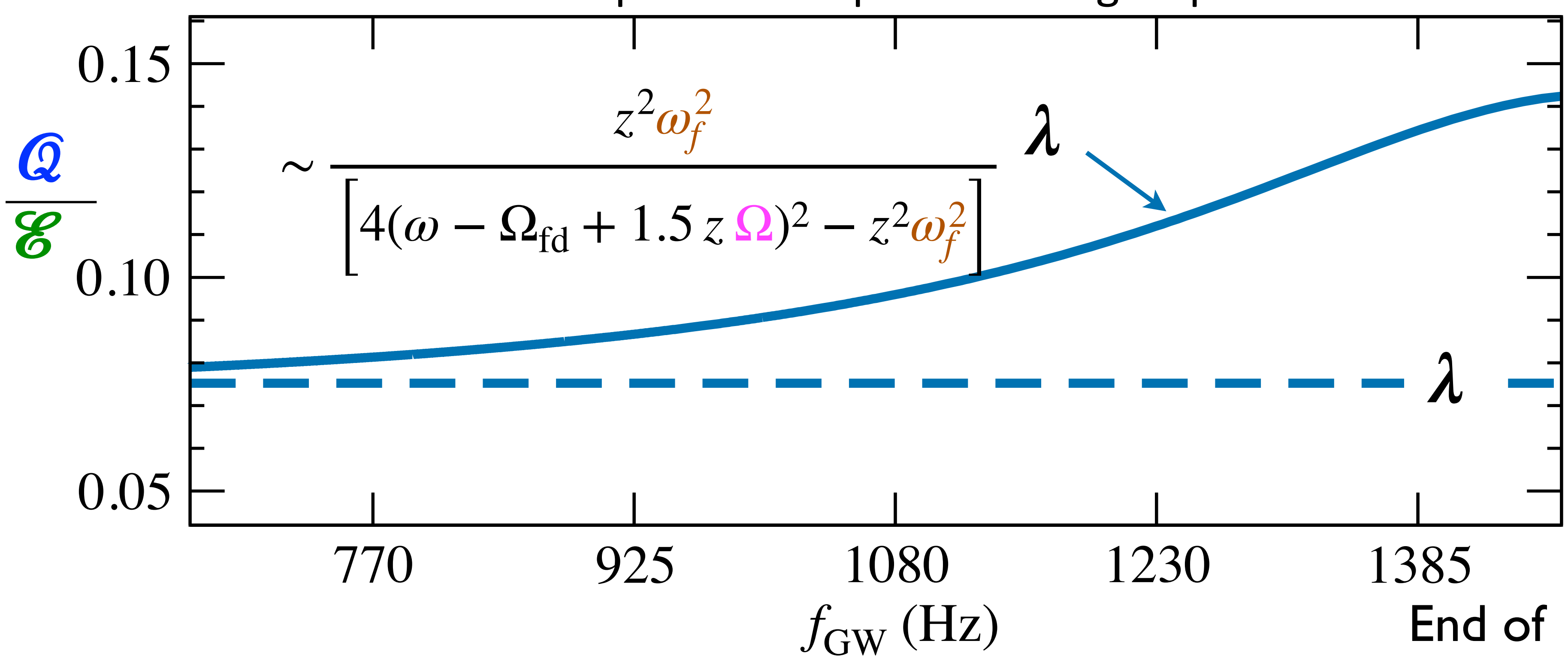
Taking into account more realistic physics



- Q corresponds (mainly) to the $f$undamental oscillation modes
- f-mode frequency: $\omega_f \sim \sqrt{G m / R^3}$ (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

Example tidal response during inspiral



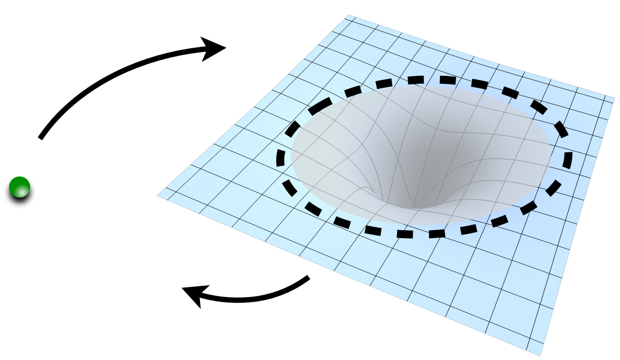
During an inspiral:

Response also impacted by:

- relativistic redshift z
- frame dragging $\Omega_{\rm fd}$ (from GR & companion's spin)
- NS's spin Ω

[Steinhoff, TH +2016, 2021]

More realistic couplings of matter to orbital dynamics



Extended object viewed on the orbital scale:

- Central worldline + multipole moments
- Effective action for the binary dynamics:

gravitomagnetic tidal tensor

$$\mathcal{B}_{ij} = {}^{*}R_{0i0j}$$

Matter contribution to induced current quadrupole

redshift

Internal dynamics of the multipoles (modes)

$$S \approx S_{pp} + \int d\tau \left[-\frac{z}{2} Q_{ij}\mathcal{E}_{ij} - \frac{z}{2}\dot{Q}^{\mathcal{B}}_{ij}\mathcal{B}_{ij} + L^{\mathrm{Coriolis}} + L^{\mathrm{FD}} + L^{\mathrm{osc}} + \ldots \right]$$

point-particle part

multipoles interact with companion's spacetime curvature

Effects of NS's spin on tidal response & restoring force for gravitomagnetic modes

Q's angular momentum interacts with orbital angular momentum & companion's spin

[Steinhoff, TH +2016, 2020, 2021]

More realistic couplings of matter to orbital dynamics

Multipoles behave as harmonic oscillators:

$$L^{\rm osc} \approx \sum_n \frac{z}{4\lambda_{(n)} z^2 \omega_{(n)}^2} \frac{dQ_{ij}^{(n)}}{d\tau} \frac{dQ_{ij}^{(n)}}{d\tau} - \frac{z}{4\lambda_{(n)}} Q_{ij}^{(n)} Q_{ij}^{(n)} + \dots$$

Different quadrupolar modes contribute, dominated by fundamental modes

+ similarly for higher multipoles

$$+ \frac{3z}{32(\sigma_{\rm stat} - \sigma_{\rm irrot})} \frac{d\dot{Q}_{ij}^{\mathcal{B}}}{d\tau} \frac{d\dot{Q}_{ij}^{\mathcal{B}}}{d\tau} + \frac{2z\sigma_{\rm stat}}{3} \mathcal{B}_{ij}\mathcal{B}_{ij} + \dots$$

subdominant but important for future GW detections

two different magnetic tidal deformabilities

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

$$S \approx S_{pp} + \int d\tau \left[-\frac{z}{2} Q_{ij}\mathcal{E}_{ij} - \frac{z}{2} \dot{Q}_{ij}^{\mathcal{B}} \mathcal{B}_{ij} + L^{\rm Coriolis} + L^{\rm FD} + L^{\rm osc} + \dots \right]$$

point-particle part

multipoles interact with companion's spacetime curvature

Effects of NS's spin on tidal response & restoring force for gravitomagnetic modes

Q's angular momentum interacts with orbital angular momentum & companion's spin

[Steinhoff, TH +2016, 2020, 2021]

Many subtleties in the GR interplay of matter with gravity

- Nontrivial to define a 'worldline skeleton' [Dixon 1970]

- 1990s: does GR give rise to new couplings between internal degrees of freedom and orbital dynamics? E.g. seemingly numerical evidence for a ``relativistic crushing force” in NS binaries

VOLUME 75, NUMBER 23 PHYSICAL REVIEW LETTERS 4 DECEMBER 1995

Instabilities in Close Neutron Star Binaries

J. R. Wilson[1] and G. J. Mathews[2]

+ follow-up papers

… surprising evidence that GR effects may cause otherwise stable stars to individually collapse prior to merging

Sociological account: Kennefick 2000 ``Star crushing: theoretical practice & the theoretician's regress''

- rigorous analysis using matched asymptotic expansions of spacetimes showed that there are no such new forces under the assumptions for this case (c.f. also other numerical studies)

  [Flanagan 1998: ``GR coupling between orbital motion & internal degrees of freedom ..'' paper]

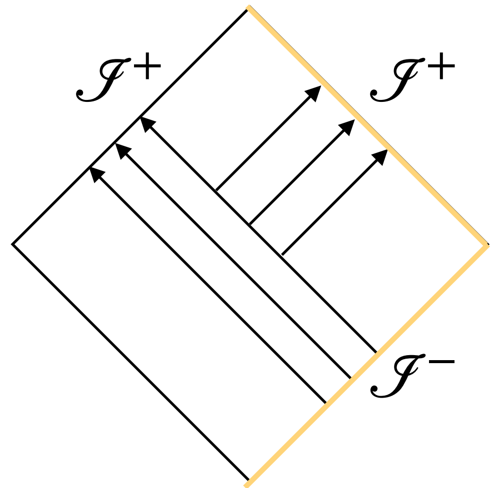
- More recently: seemingly numerical findings of large tidal fields at higher post-Newtonian order, subtleties with gravitomagnetic tidal response, ambiguities in tidal deformability?, …

Computing the tidal response from scattering

- Some concerns in the literature about potential ambiguities in tidal deformability

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

- Advantages of scattering calculations:
  - Identifications at null infinity, using double-null coordinates (geometric meaning)
  - invariant scattering amplitudes



Parameters in effective action in flat space matched to asymptotics of relativistic perturbations

- work with in- and outgoing waves instead of stationary perturbations

Gastón Creci, TH, Jan Steinhoff arXiv:2108.03385

Computing the tidal response from scattering

- Response determined by the in- and outgoing wave amplitudes through:

$$\lambda_\ell(\omega) = i\,\Xi_\ell \left[1 - 2\left(1 + \frac{C_\ell^{\rm in}}{C_\ell^{\rm out}} e^{i\frac{\pi}{2}(D-1)} \right)^{-1} \right]$$

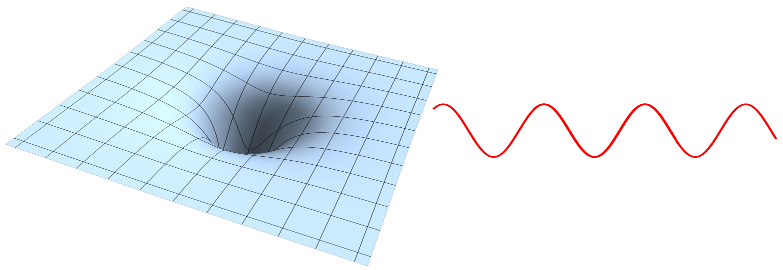
D=spatial dimensions

Matching reveals:

$$\frac{C_\ell^{\rm in}}{C_\ell^{\rm out}}\Big|_{\rm Minkowski} = \frac{A_{\rm in}^{\infty}}{A_{\rm out}^{\infty}}\Big|_{\rm Schwarzschild}$$

$$\Xi_\ell = -\frac{4\pi^{(D-2)/2}}{2^\ell}\left(\frac{2}{\omega}\right)^{(D-2)+2\ell}\Gamma\left(\frac{D-2}{2}+\ell+1\right)$$

Calculated from relativistic perturbation analysis in the full theory



Final result for the scalar case

- Substituting details: information contained in the response function is as expected:

  - e.g. in $D = 3$ spatial dimensions, in the limit $M\omega \ll 1$

$$\lambda_{\ell=0}(\omega) = -\underbrace{4r_{\text{horizon}}^2\pi}_{\text{Black hole absorption cross section (scalar waves)}}\, i\omega$$

Black hole absorption cross section (scalar waves)

    - Real part of the response is zero: tidal Love number vanishes

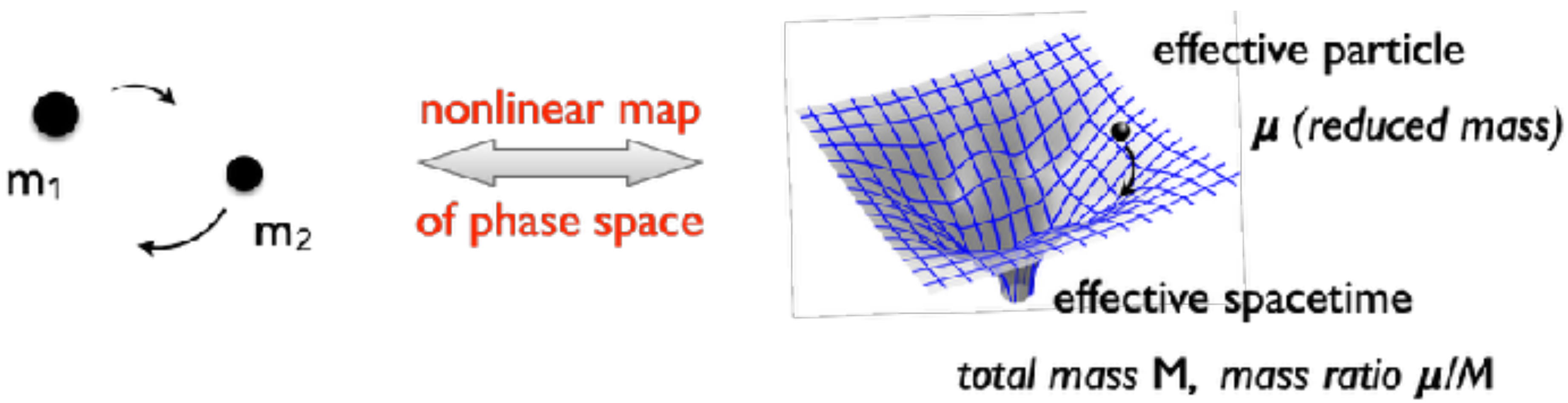
- Similar to frequency-dependent response in optics ↔ material's refractive index
  - Imaginary part: absorption
  - Real part: refraction, phase shift compared to incident beam

Finite size effects included in models for data analysis

Matter effects on top of full black hole baseline models

Effective one body (EOB) models:

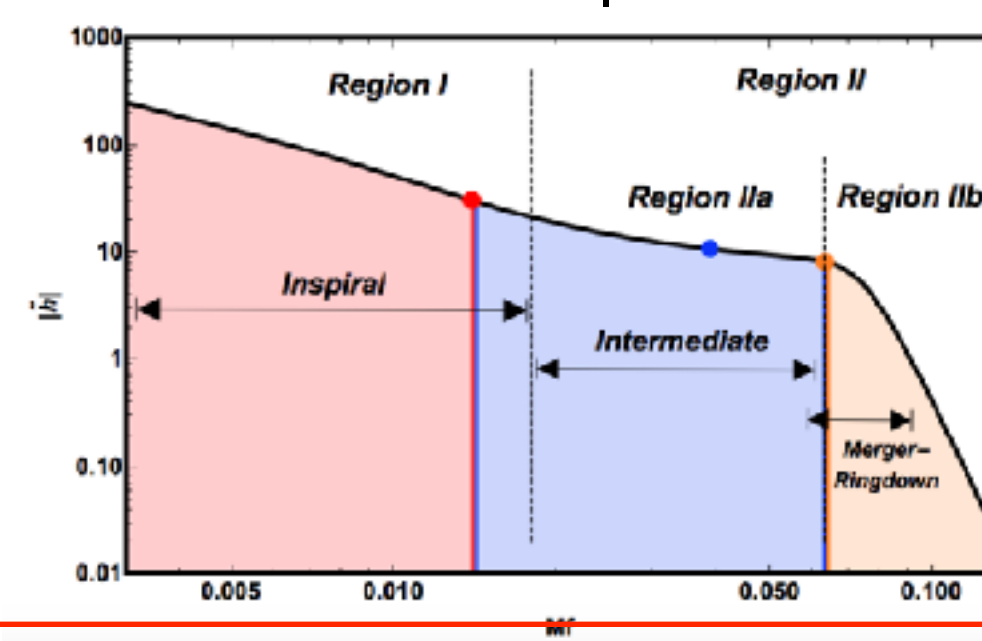
resummation of information



Phenomenological (Phenom) models:

closed-form expressions for frequency-domain GWs

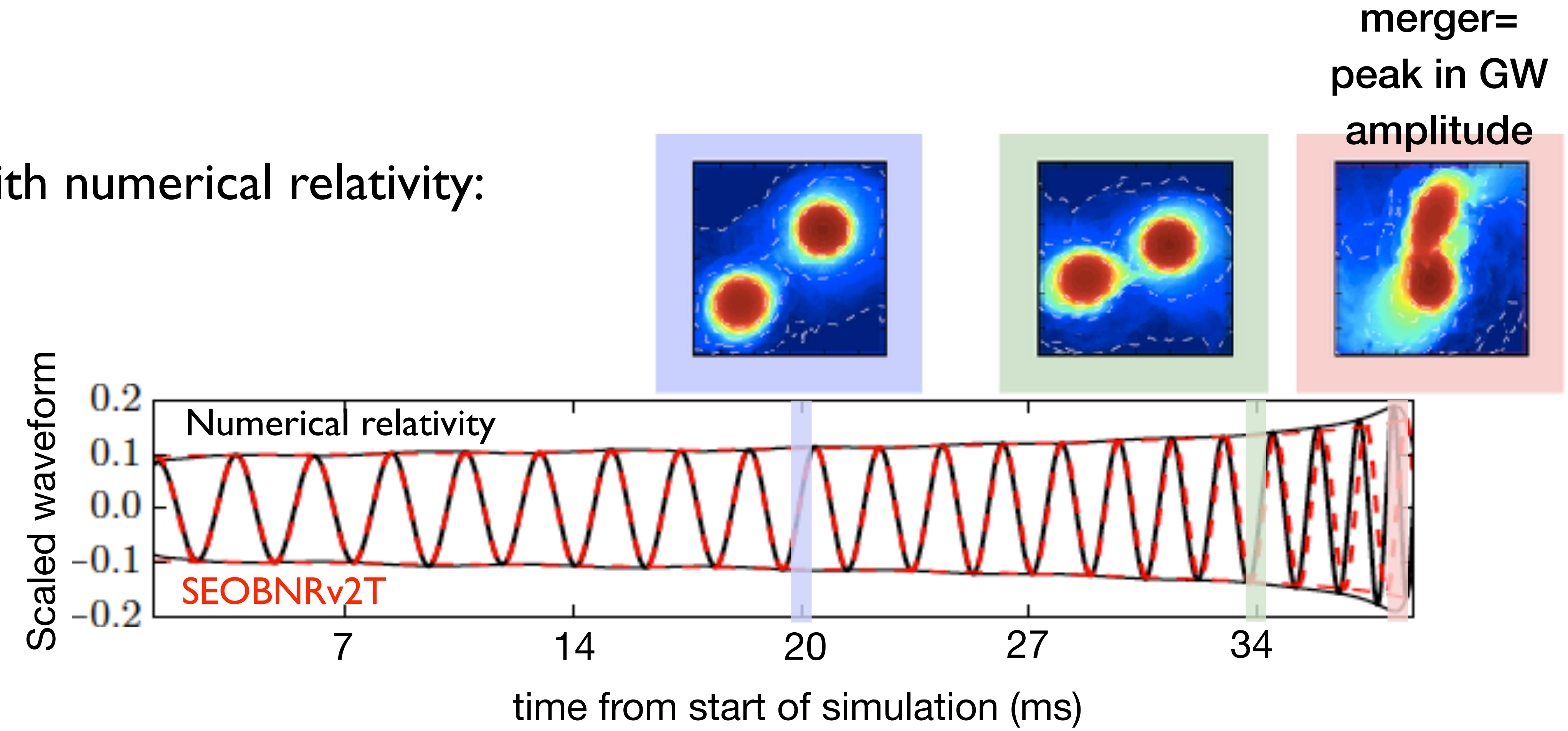
GW amplitude



Matter effects in models for data analysis

- For inspirals: variety of physics & assumptions, e.g. some but not all of the models
  - Rely on quasi-universal relations used to reduce matter parameters to λ_1, λ_2
  - Are calibrated to numerical relativity
  - Include some dynamical tidal effects
  - …

Comparison with numerical relativity:



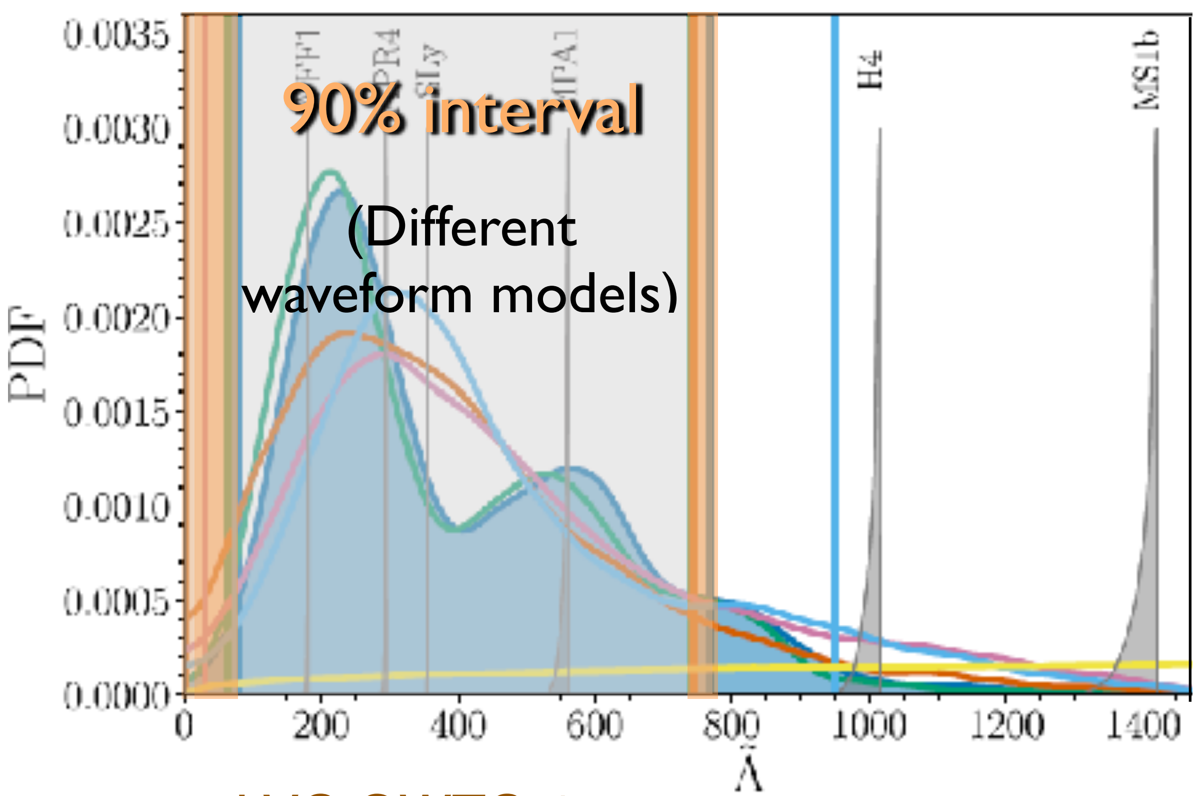
Measurements/constraints on tidal deformability

Results with low spin priors (Dimensionless spins < 0.05)

GW170817

Total mass ~ 2.8 Msun

Distance ~ 40Mpc



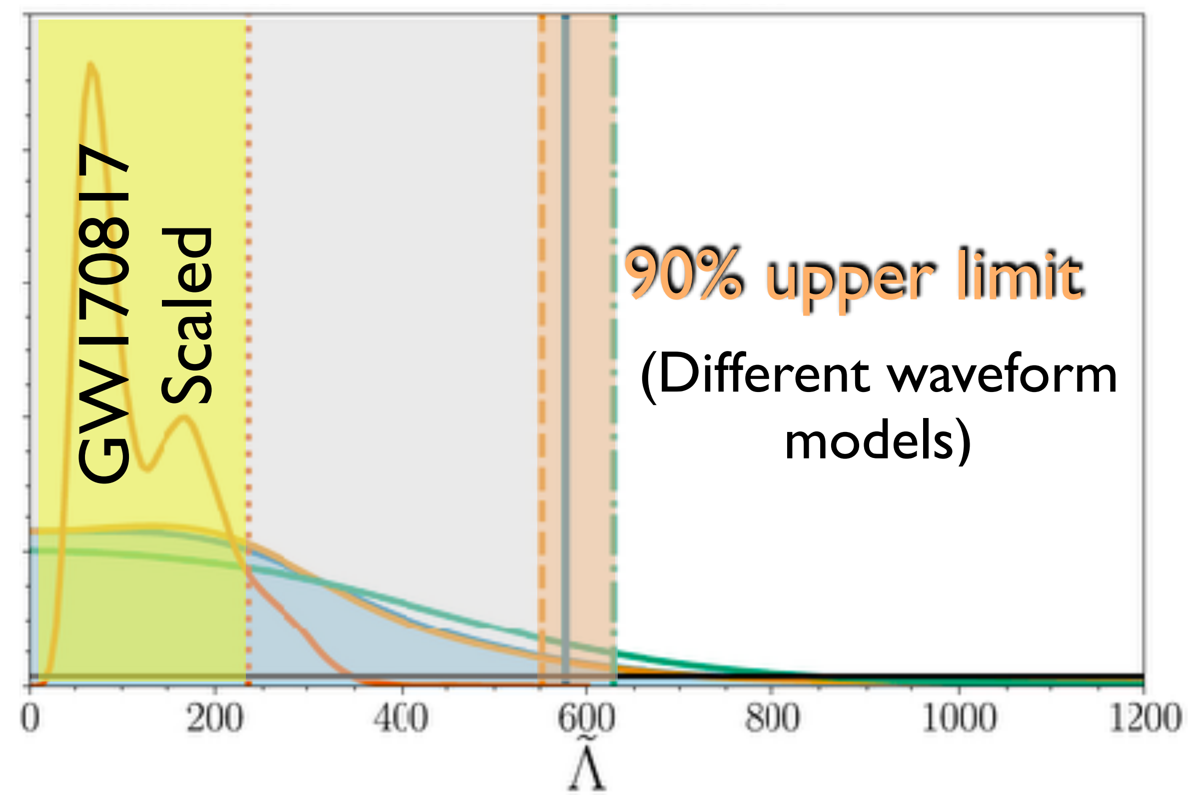
LVC GWTC-1

[updated results compared to initial papers, e.g. detector calibration, …]

GW190425

Total mass ~ 3.4 Msun

Distance ~160Mpc



LVC ApJ Lett. 892 L3 (2020)

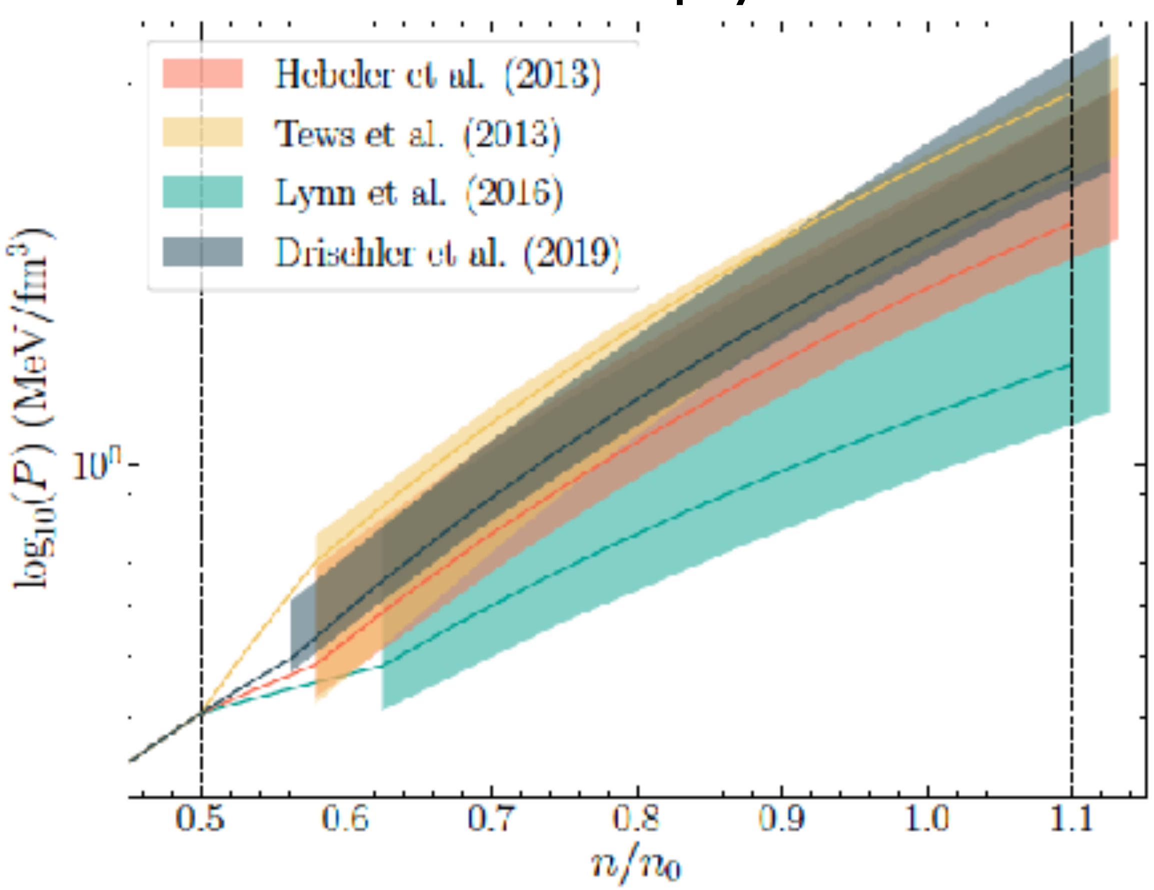
- for two NSs: GWs most sensitive to the combination (similar to chirp mass):

$$\tilde{\Lambda} = \frac{13c^{10}}{16\,G^5 M^5}\left[\left(1+12\frac{m_2}{m_1}\right)\lambda_1 + \left(1+12\frac{m_1}{m_2}\right)\lambda_2\right]$$

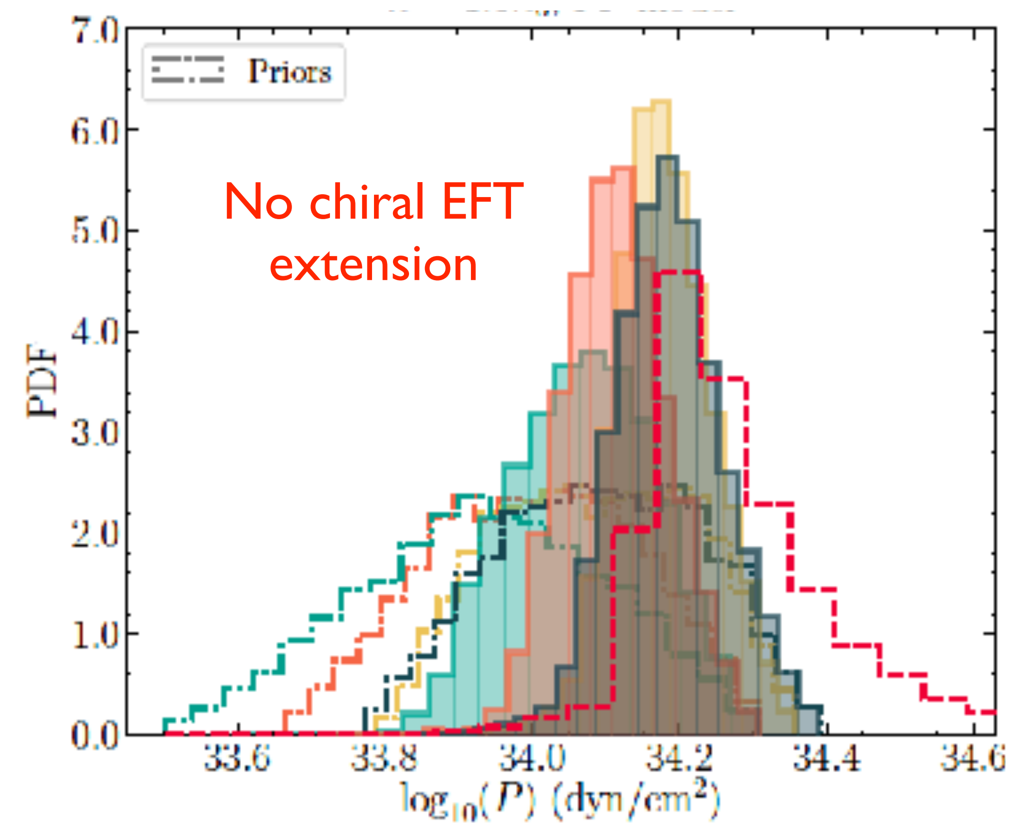
Example implications for subatomic physics

- Joint constraints with other observations (kilonova, x-ray, radio) + subatomic physics
- E.g. can start to inform chiral effective field theory extensions (nuclear multi-body interactions, symmetry energy …):

Different nuclear physics models

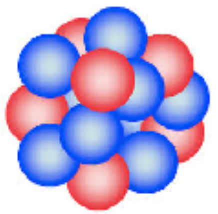


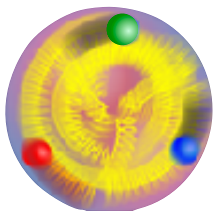
pressure at 1.5 nuclear saturation density (different extensions)



Geert Raaijmakers+ 2021 arXiv:2105.06981

many different groups have studied all kinds of different aspects

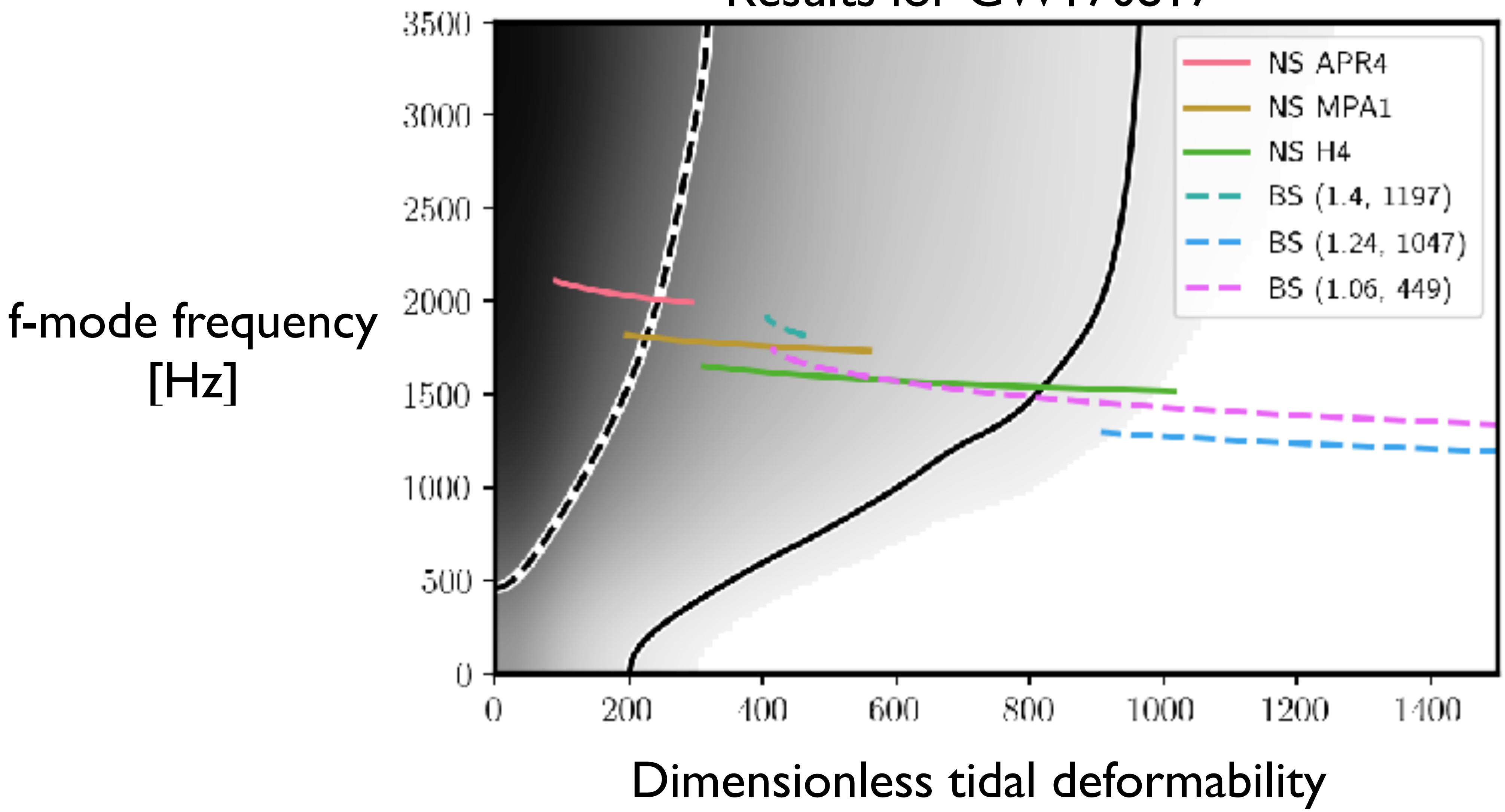




Proof of principle: GW constraints on *f*-mode frequency

- Measuring both λ and ω_f
- quadrupole & octupole for each star: 8 matter parameters, expect deterioration in measurements
- more efficient approximate frequency-domain model [Schmidt, TH 2019]

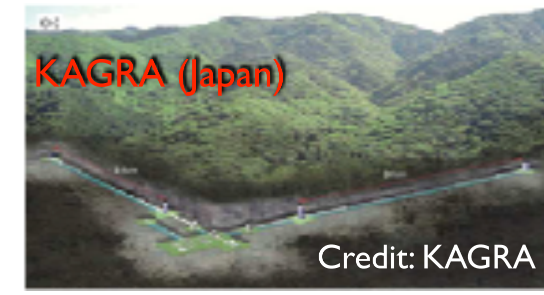
Results for GW170817



Pratten, Schmidt, TH 2020

Near-term future prospects

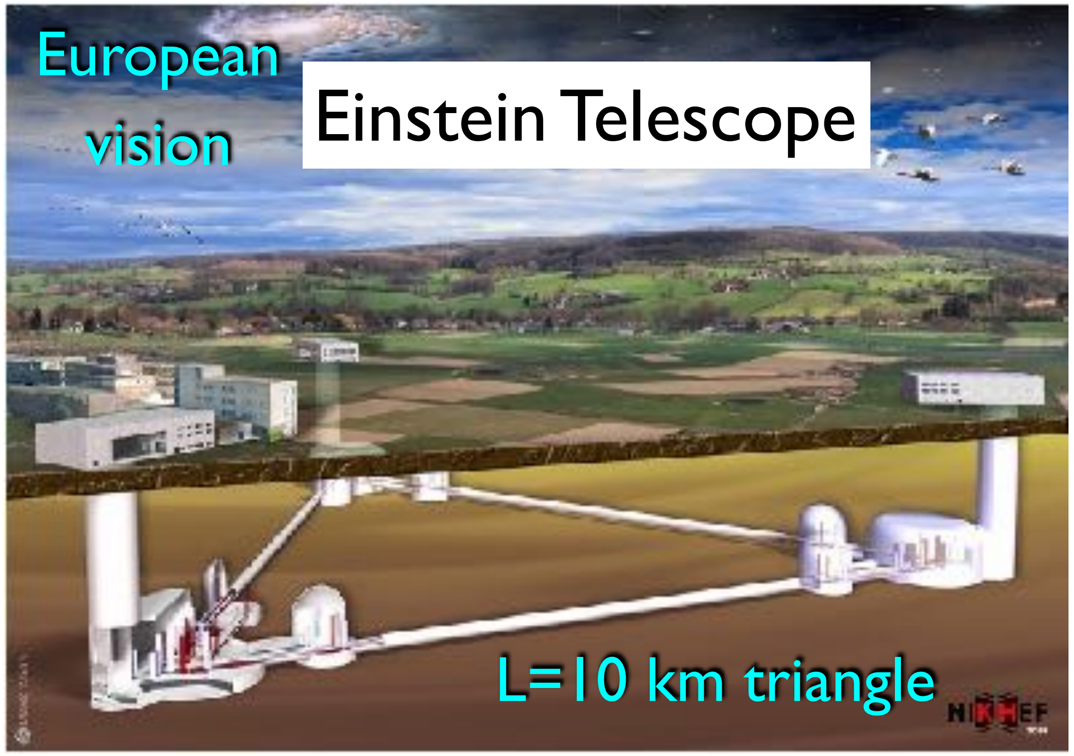
next observing run O4: LIGO/Virgo near/reaching design sensitivity



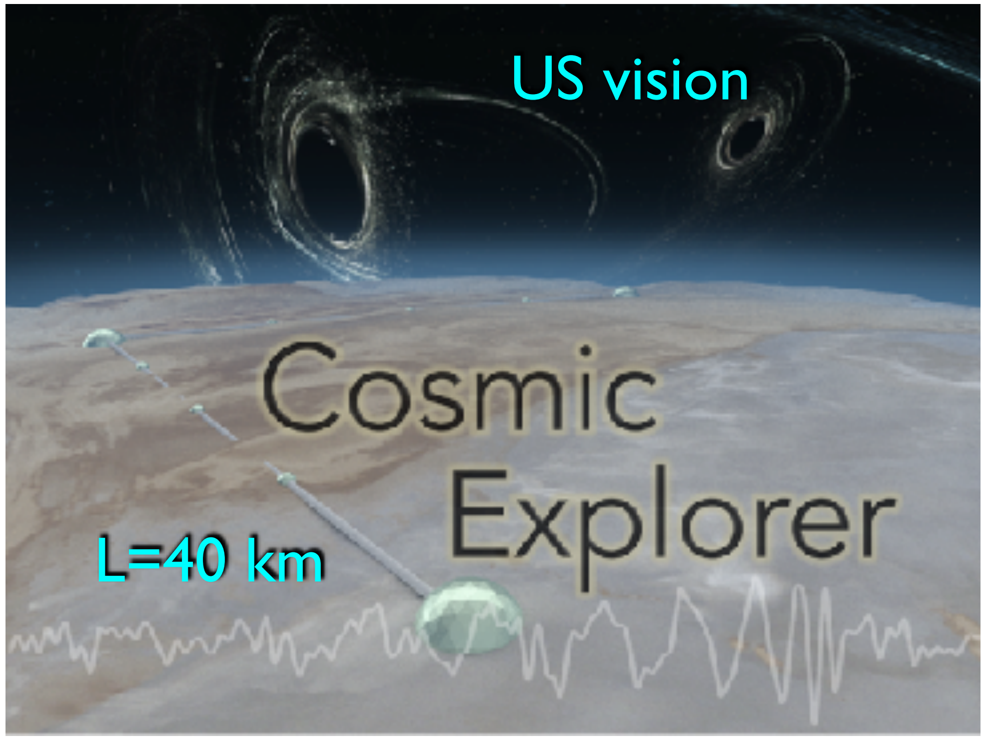
Further upgrades scheduled

- More accurate measurements of nearby sources
- greater number & diversity of events

Plans for next-generation detectors moving ahead (~2035)



- Prototype being built in Maastricht

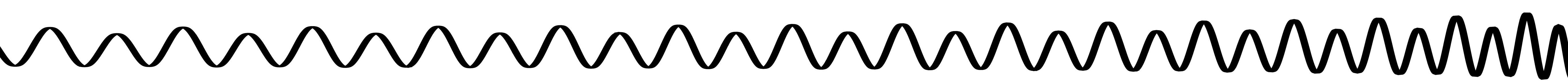


- 10 times better sensitivity than LIGO/Virgo, wider frequency range
  - O(100 000) binary merger detections per year
  - High precision studies of nearby sources

A few examples of remaining theoretical challenges

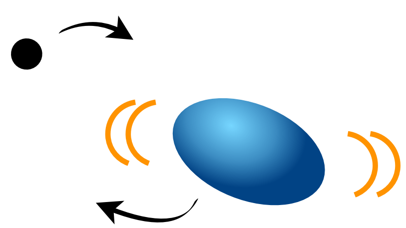
Need high-accuracy and efficient waveforms over wide parameter space

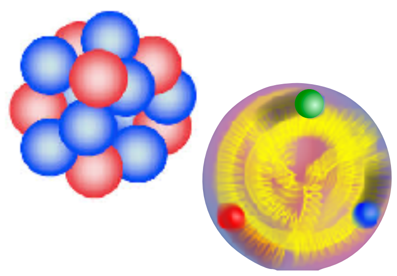
- more matter effects & relativistic corrections
- arbitrary spins
- eccentricity, …
- role of beyond zero-temperature, equilibrium matter?
- …..
- degeneracies (e.g. modified gravity, dark matter/BSM physics), …
- …..

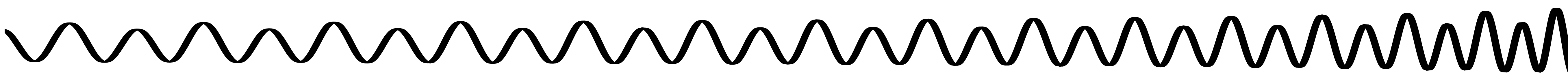


Conclusions

- GWs are new probes of NS physics: clean gravitational channel of information
- Exciting near- & longer-term prospects with larger & more precise datasets
- Simultaneous advances in modeling are essential to fully realize the science potential, reduce bias in measurements and interpretation







- Significant progress on understanding, modeling relevant phenomena but much work remains
- Synergy of theoretical approaches important (diverse analytical + numerical)
- Interdisciplinary cooperation needed on connections and fundamental inputs