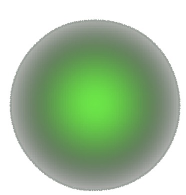
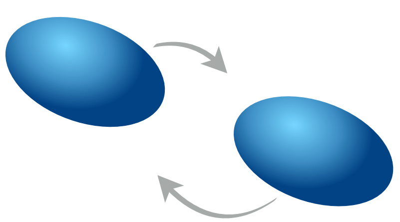
Probing the fundamental physics of supra-dense matter with gravitational waves from neutron star binaries



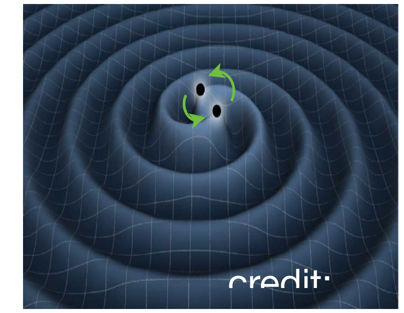
Tanja Hinderer

Radboud University Nijmegen, NL

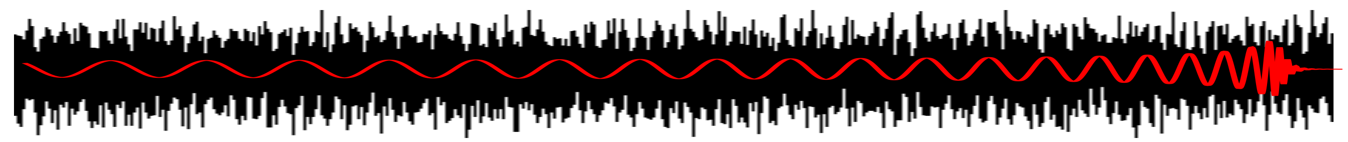


Outline of this talk

- Gravitational waves (GWs): a new tool for probing fundamental physics in extreme conditions

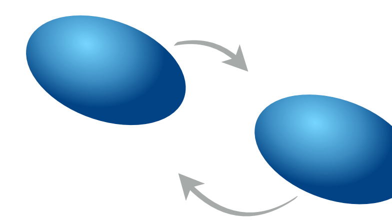


- Theoretical models needed to extract the information encoded in GWs from binary systems



- Main focus of this talk: GW signatures of neutron star matter during an inspiral

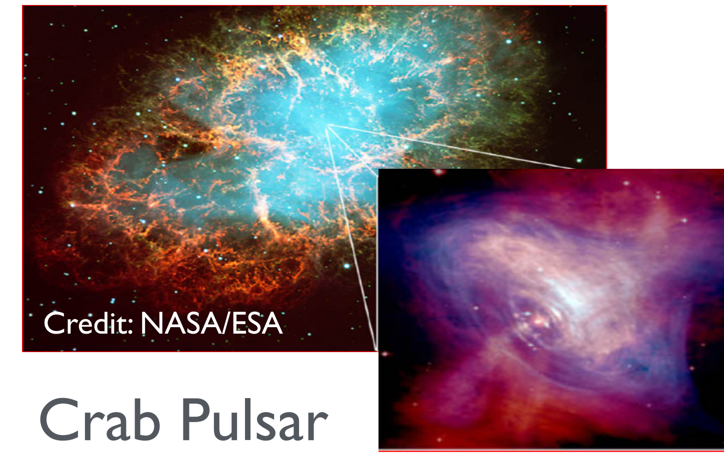
- Outlook



Neutron stars (NSs)

- densest stable material objects known in the universe
- 1939: theoretical description *[Oppenheimer & Volkoff]*
- thousands observed to date
- masses $\gtrsim$ 1-2 solar masses (?), radii ~ 8-16 km (?)

debris from a supernova explosion in 1054



Crab Pulsar
(neutron star rotating at 30 rev/sec)

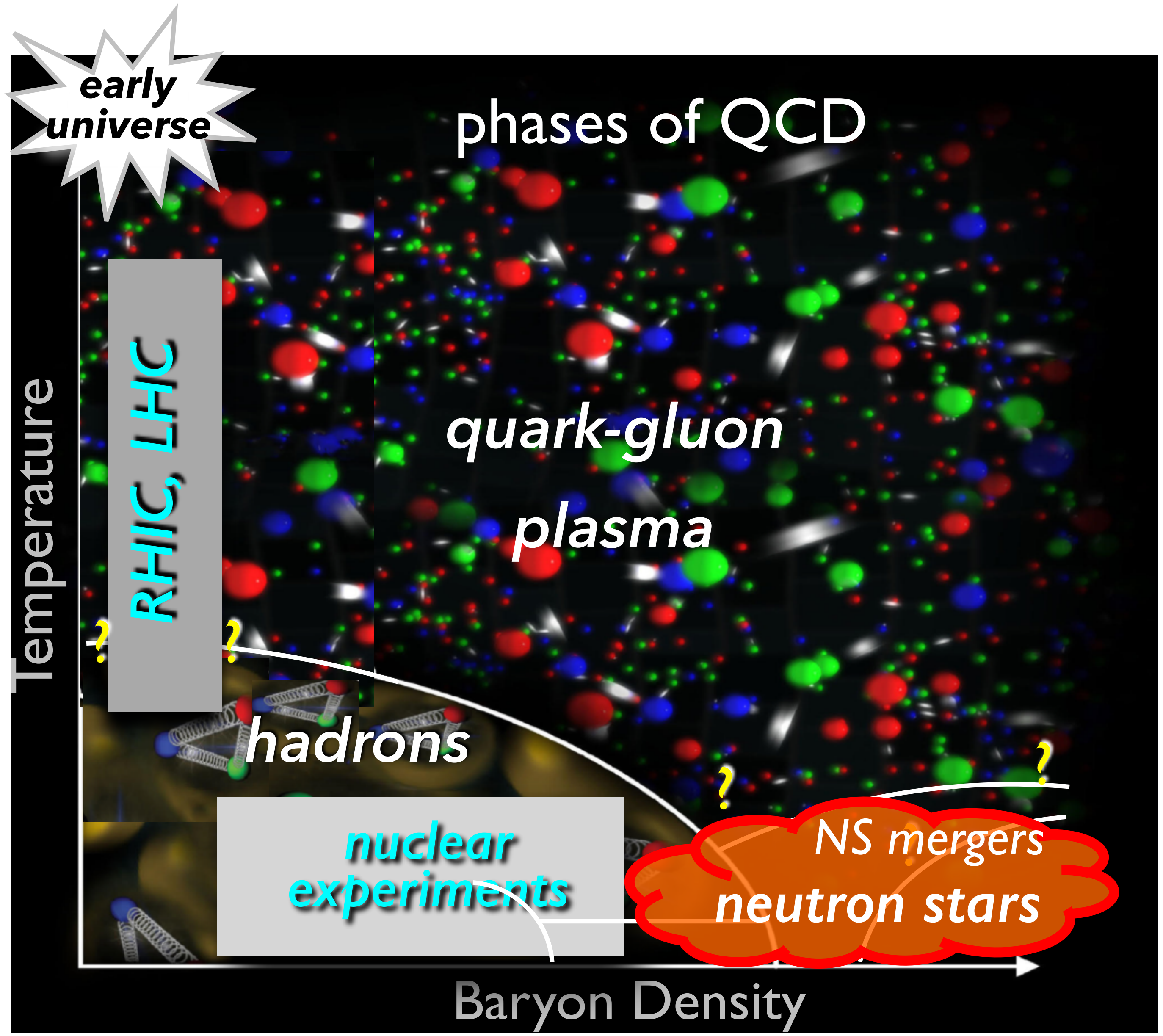
crushed to neutron-star compactness

crushed

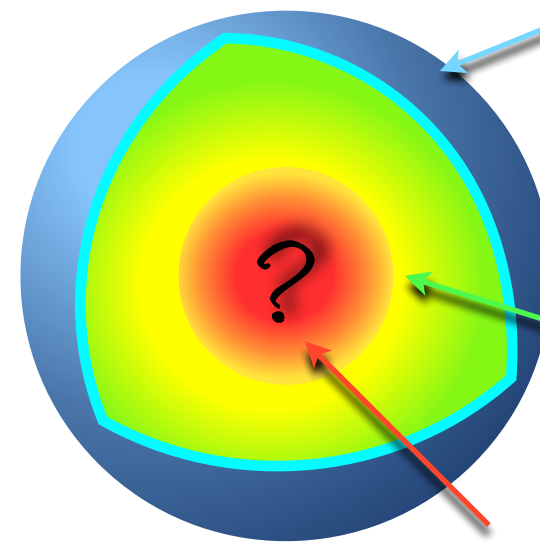
Black hole

What is the nature of matter in such extreme conditions?

Conjectured NS structure



Credit: F. Linde



crust ~ *km*

neutron rich ions,

free neutrons

outer core ~ *few km*

uniform liquid

deep core

~2-10x nuclear density

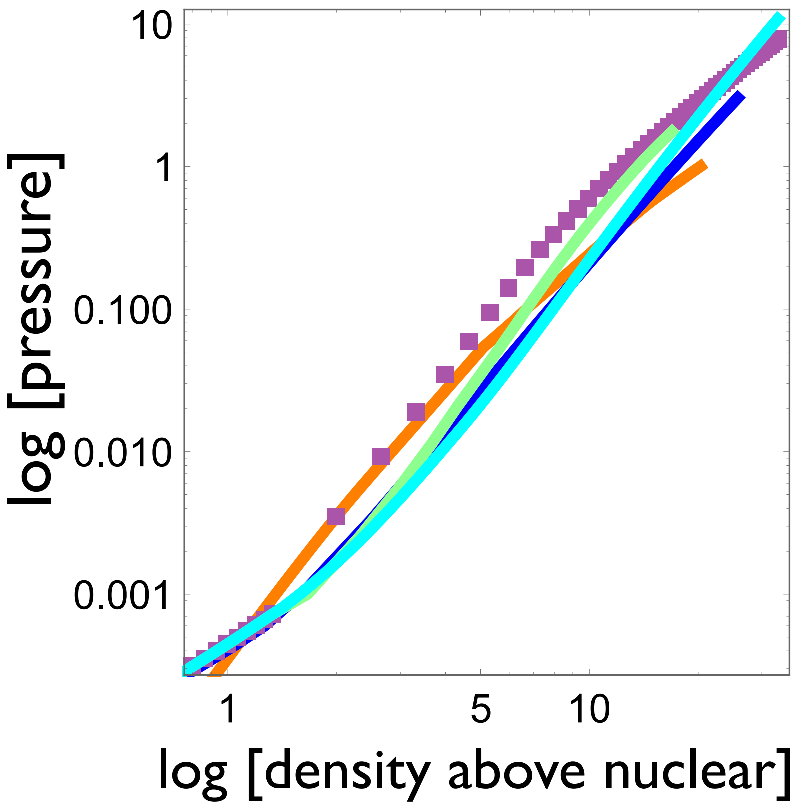
exotic states of matter?

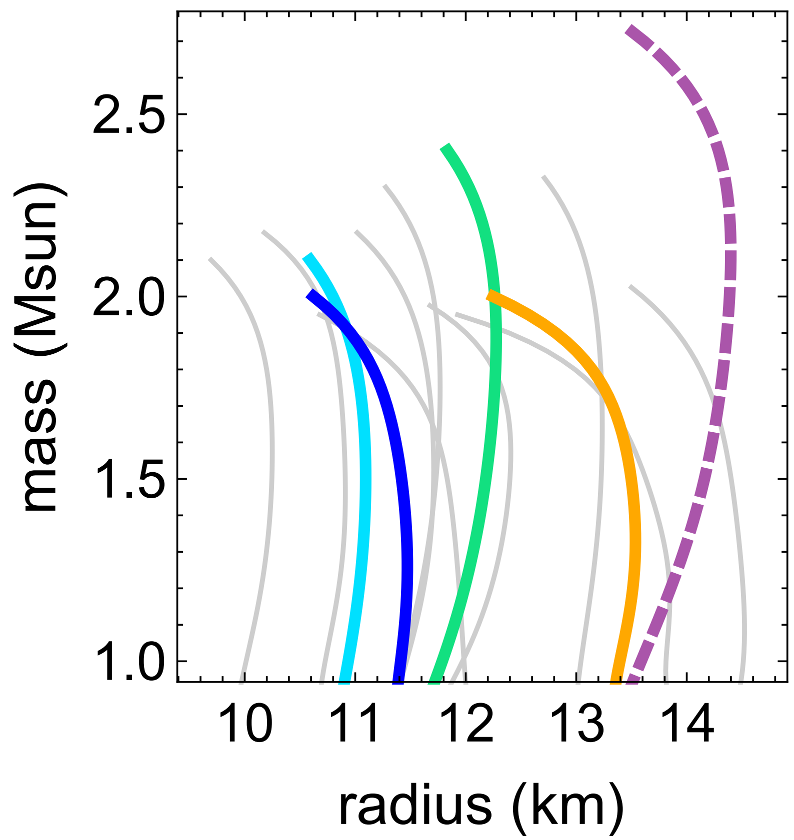
deconfined quarks?

- many theoretical difficulties
- far extrapolations from known physics

Astrophysics: matter impacts global NS properties

NS matter models (equations of state) ⟷ NS mass vs. radius



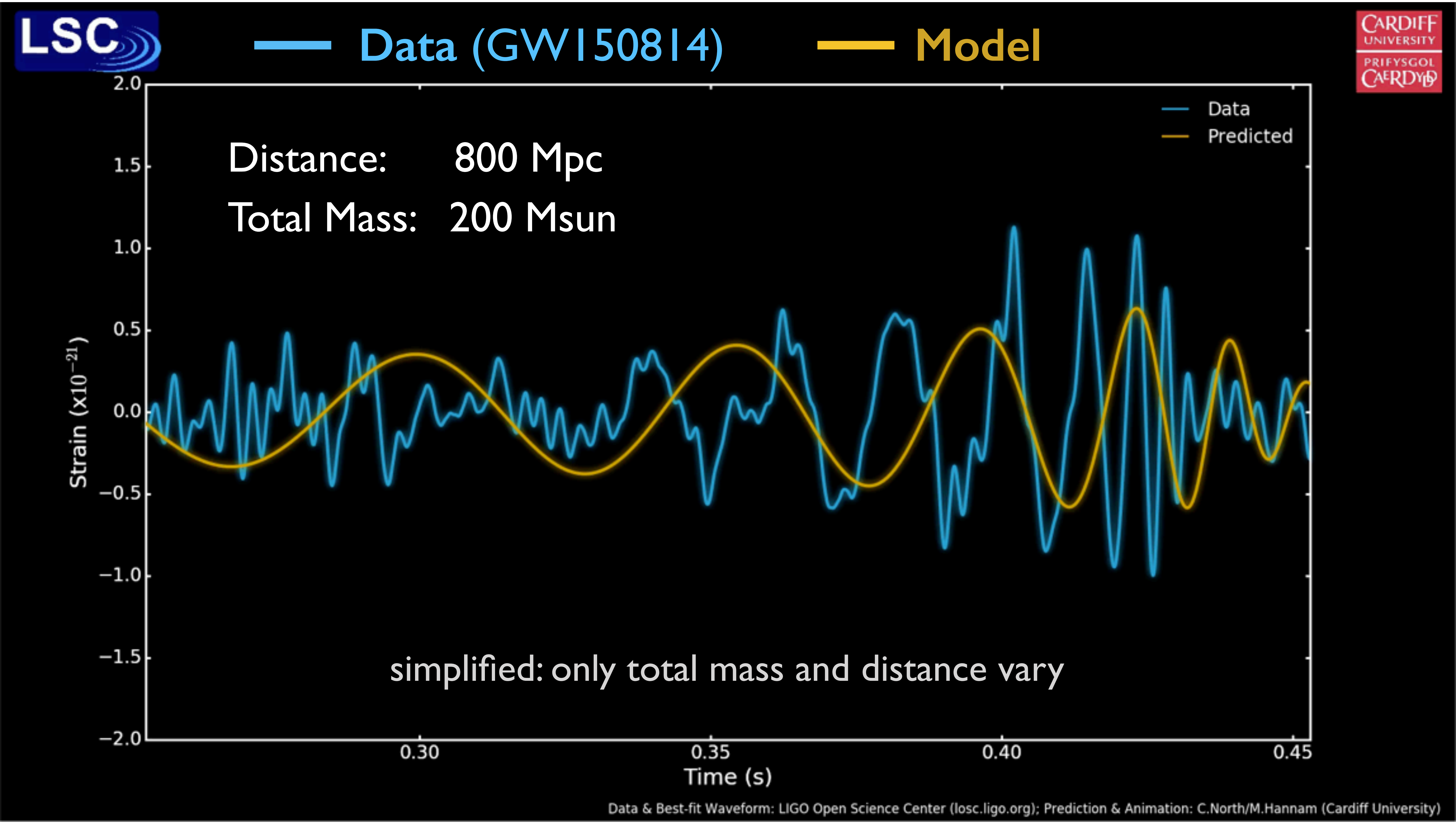


- Masses measured to ~0.0001% from pulsar timing
- ~2 Msun NSs observed
- Radii: very difficult to determine, *requires many assumptions*
- Upcoming results from NICER: new kind of measurement

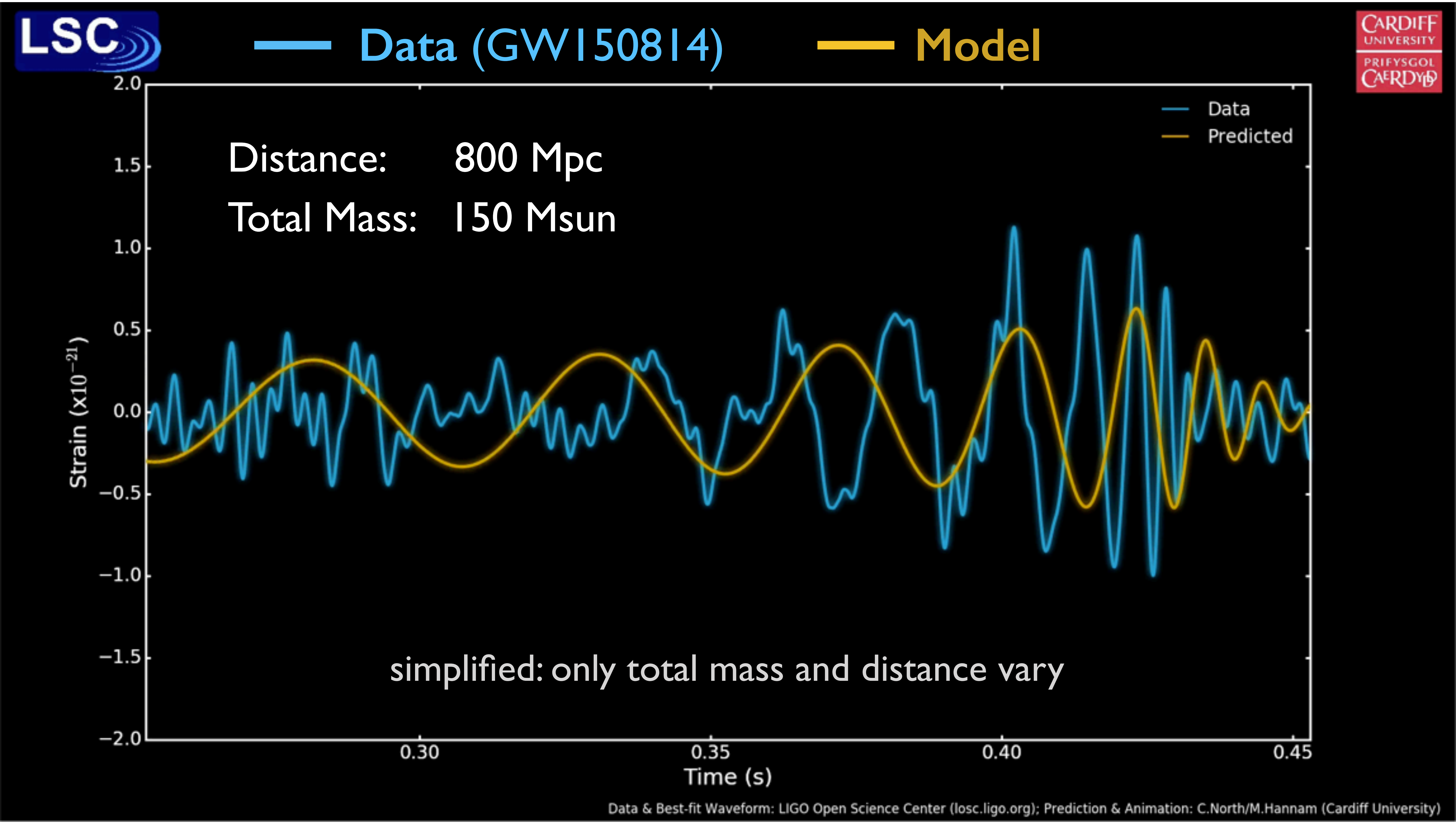
New probe of NS matter: gravitational waves (GWs)

D. A. Hardy

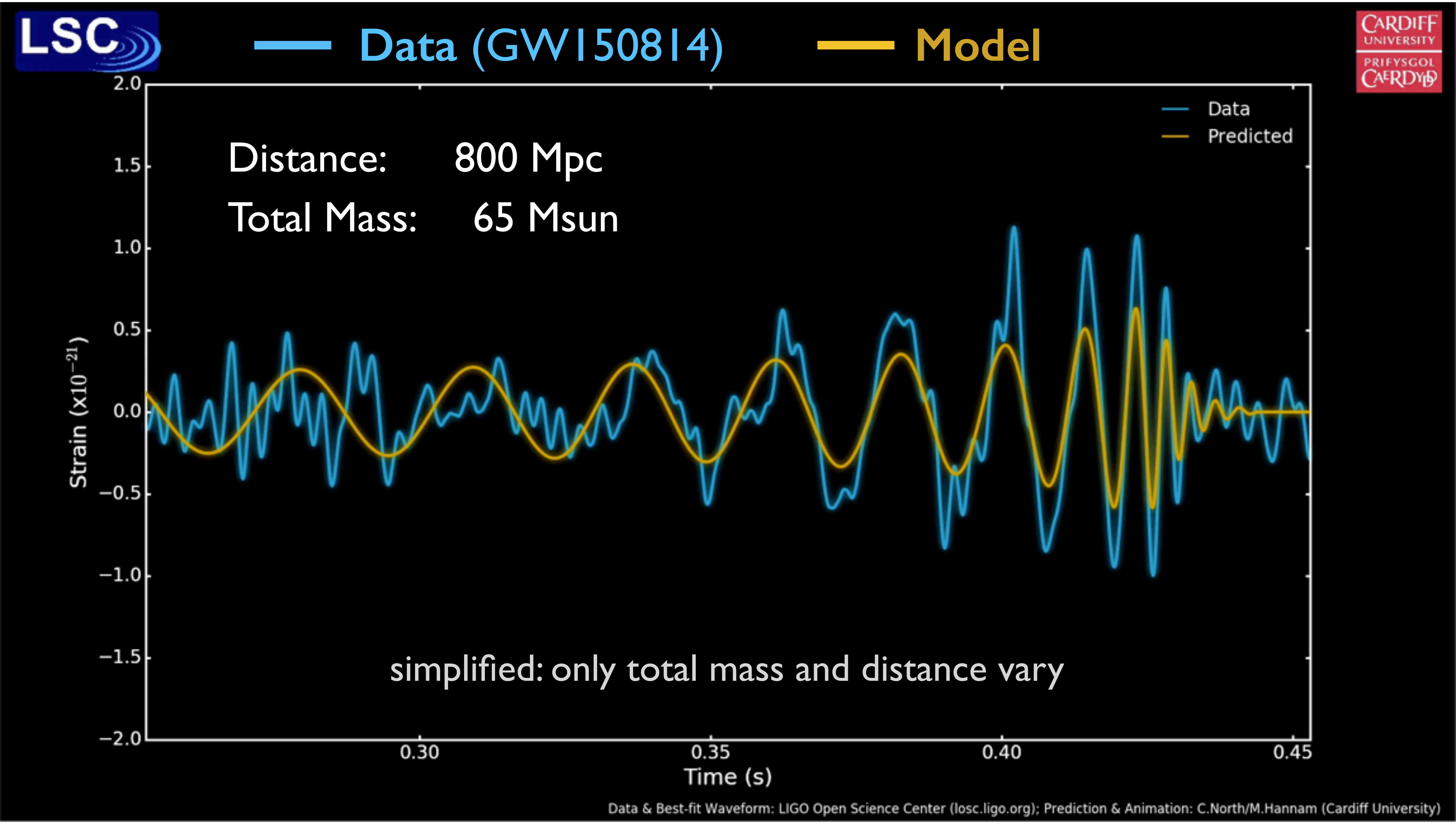
Interpreting GW signals via matched filtering



Interpreting GW signals via matched filtering

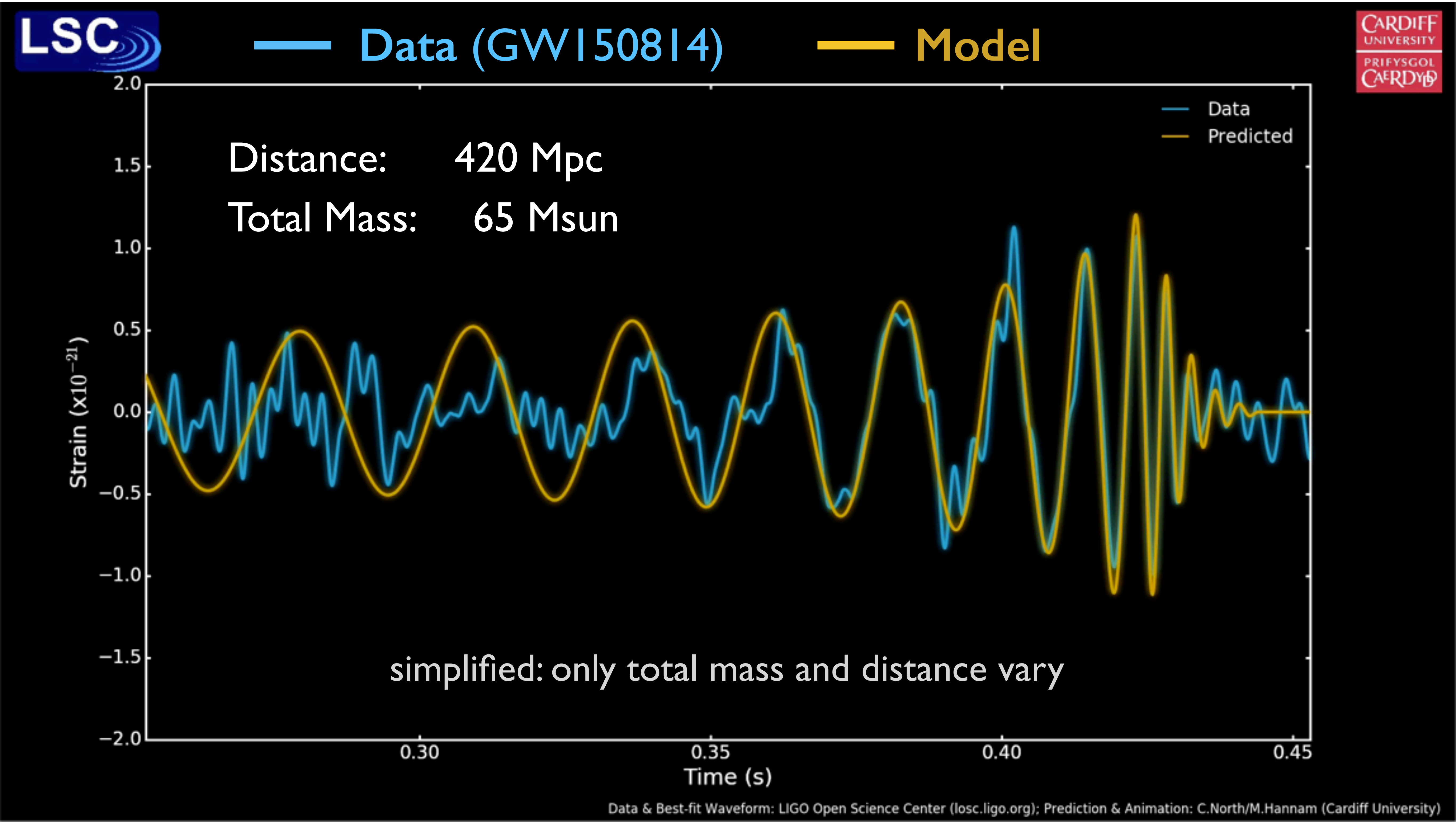


Interpreting GW signals via matched filtering



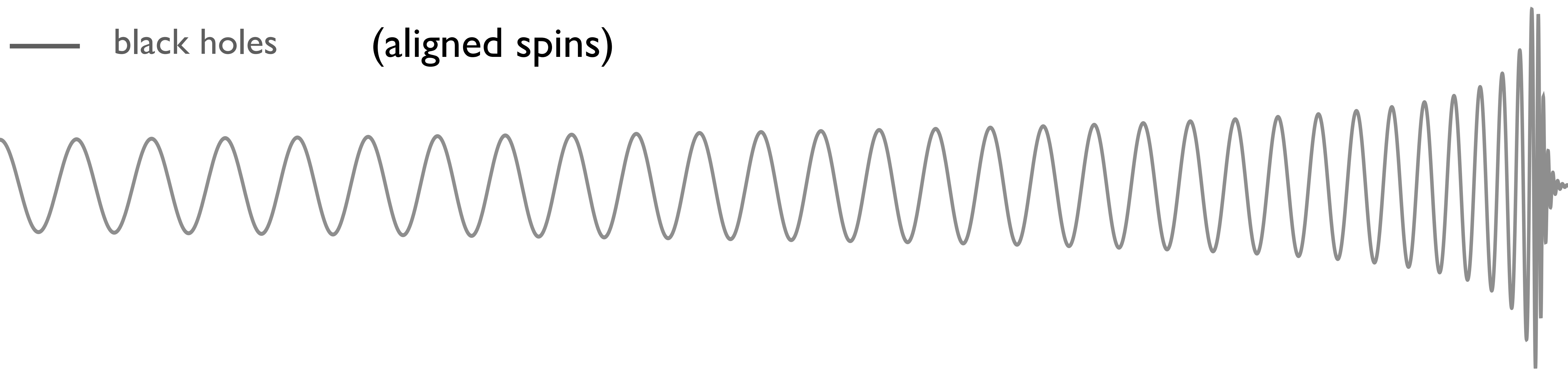
very sensitive to the phase

Interpreting GW signals via matched filtering



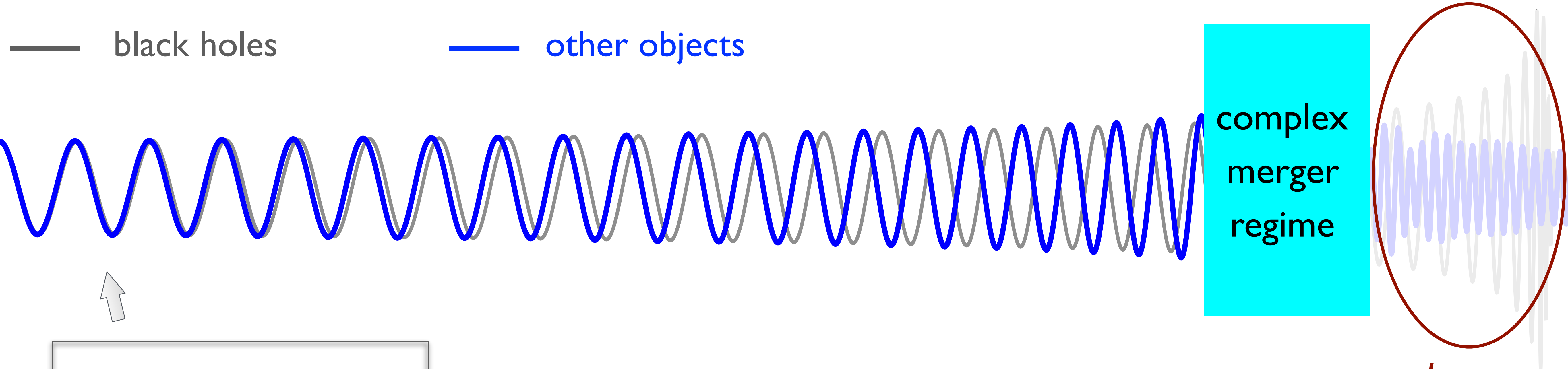
very sensitive to the phase

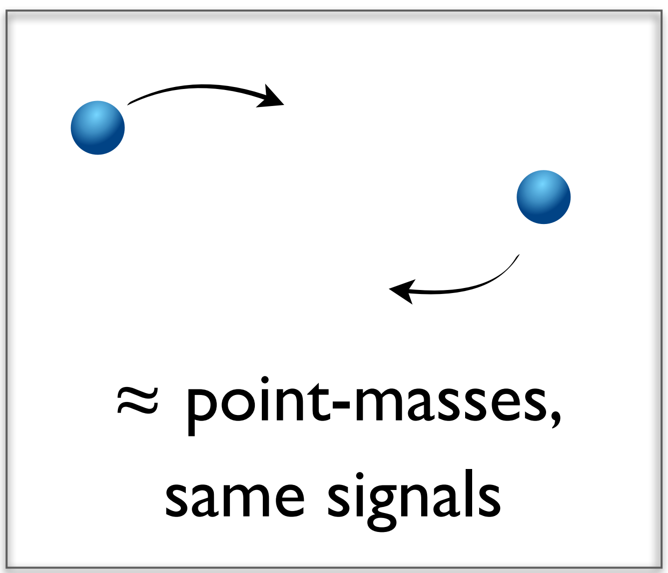
Imprints of objects' internal structure on GWs



What changes for non-black hole objects?

Imprints of objects' internal structure on GWs



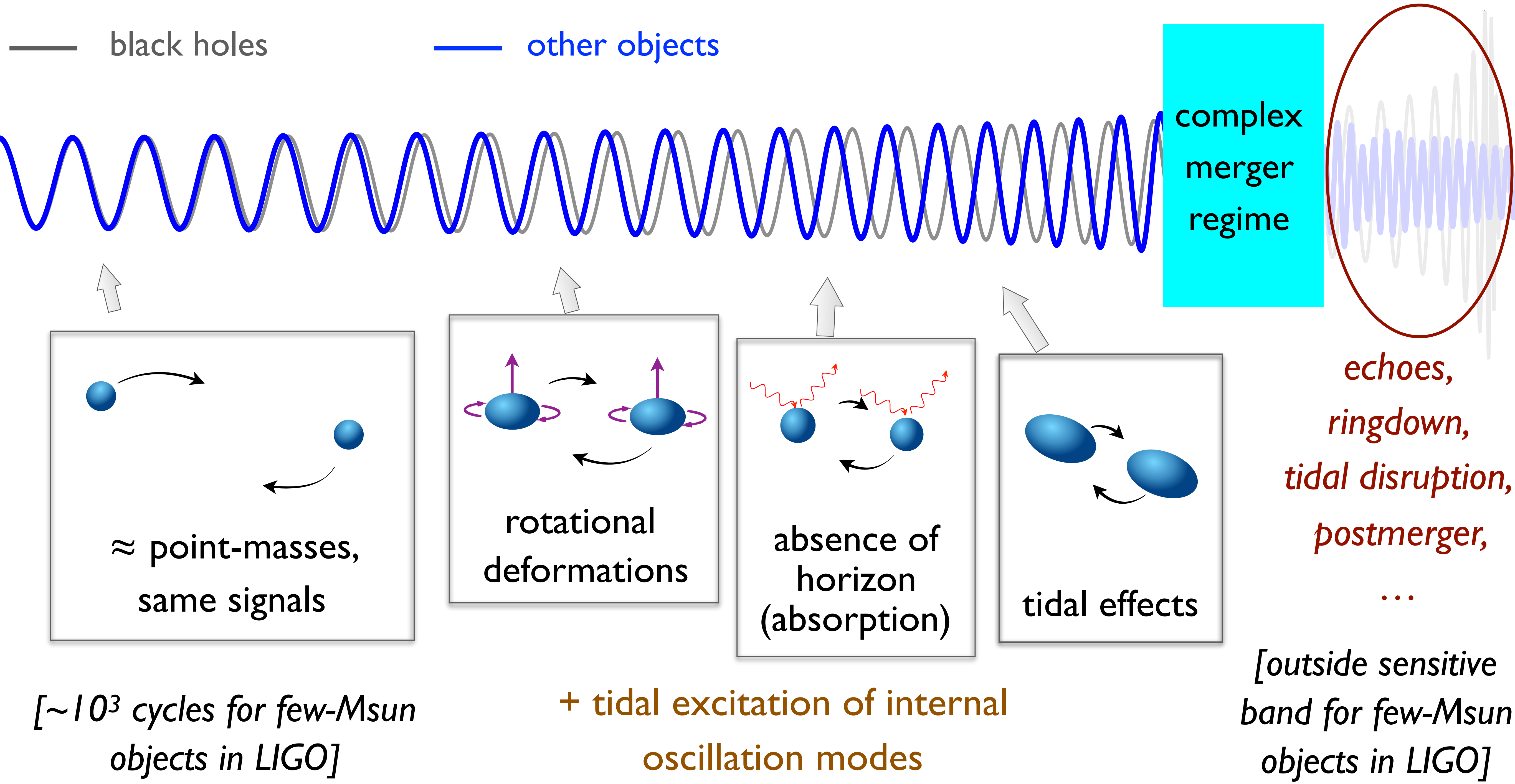


[~10^3 cycles for few-Msun objects in LIGO]

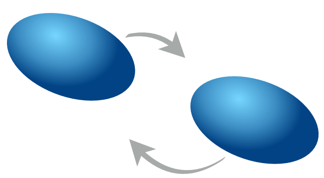
echoes,
ringdown,
tidal disruption,
postmerger,
…

[outside sensitive band for few-Msun objects in LIGO]

Imprints of objects' internal structure on GWs



Dominant tidal effects



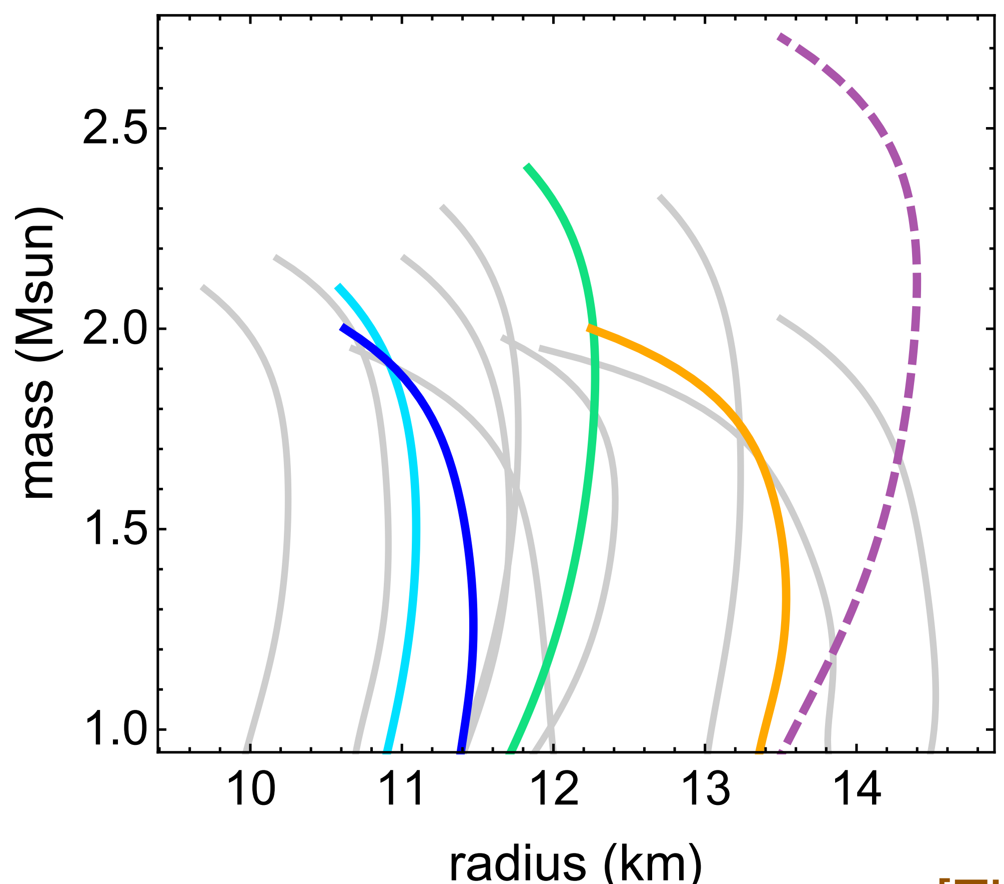
induced deformation $Q_{\rm NS} = \lambda\, \mathcal{E}_{\rm tidal}$ ← tidal field (companion)

↑ tidal deformability — computed from Einstein's eqs.

=0 for a black hole

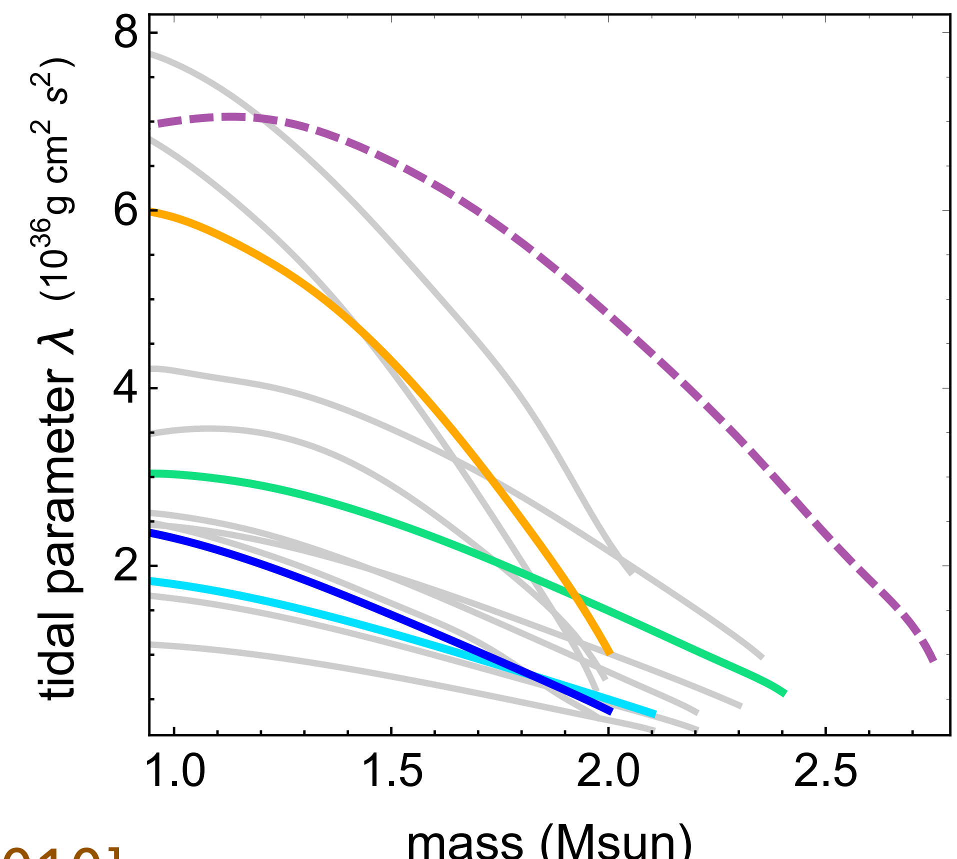
[Flanagan & TH 2008, TH 2008]

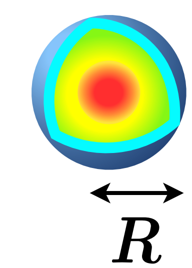
Mass vs. radius



[TH+ 2010]

tidal deformability vs. mass





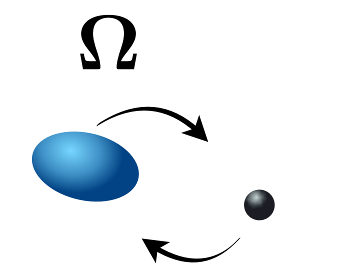
$$\lambda = \frac{2}{3} k_2 R^5$$

↑ dimensionless Love number

- Straightforward extension to higher multipoles [Damour- Nagar, Binnington-Poisson 2009]

Influence on the GWs

- Energy goes into deforming the NS



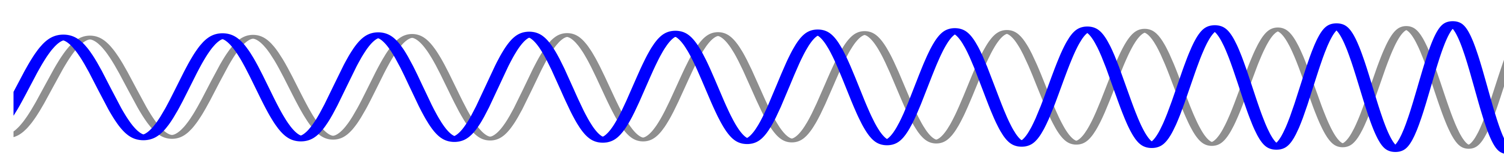
- moving tidal bulges contribute to gravitational radiation

$$Q_{\mathrm{NS}} = \lambda\, \mathcal{E}_{\mathrm{tidal}}$$

- Imprint in GW phasing:

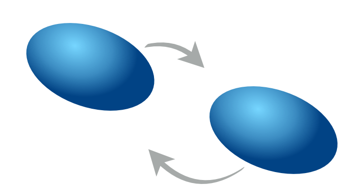
$$\Delta\phi_{\mathrm{GW}}^{\mathrm{tidal}} \sim \lambda \frac{(M\Omega)^{10/3}}{M^5}$$

$$M = m_1 + m_2$$



- for NS-NS: most sensitive to the weighted average:

$$\tilde{\Lambda} = \frac{1}{26}\left[\left(1 + 12\frac{m_2}{m_1}\right)\lambda_1 + \left(1 + 12\frac{m_1}{m_2}\right)\lambda_2\right]$$



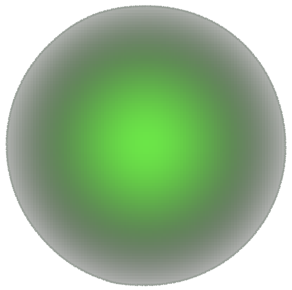
[Flanagan & TH, 2008, Vines+ 2011]

- More sophisticated models incl. more details of NS's tidal response available

[Damour, Nagar, Bini, Faye, Bernuzzi, + , Steinhoff+/Hinderer+, Maselli+, Dietrich+, Kawaguchi+]

Examples of broader uses of tidal deformability

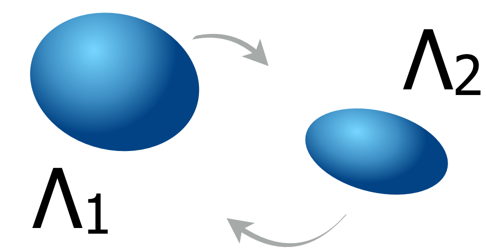
- nuclear equation of state, quark matter
- QCD vacuum energy [Csaki+ arXiv:1802.04813]
- Other observables:
  - astrophysics: NS radius
  - Nuclear experiments: neutron skin thickness of lead 208 [Fattoyev+ 1711.06615]

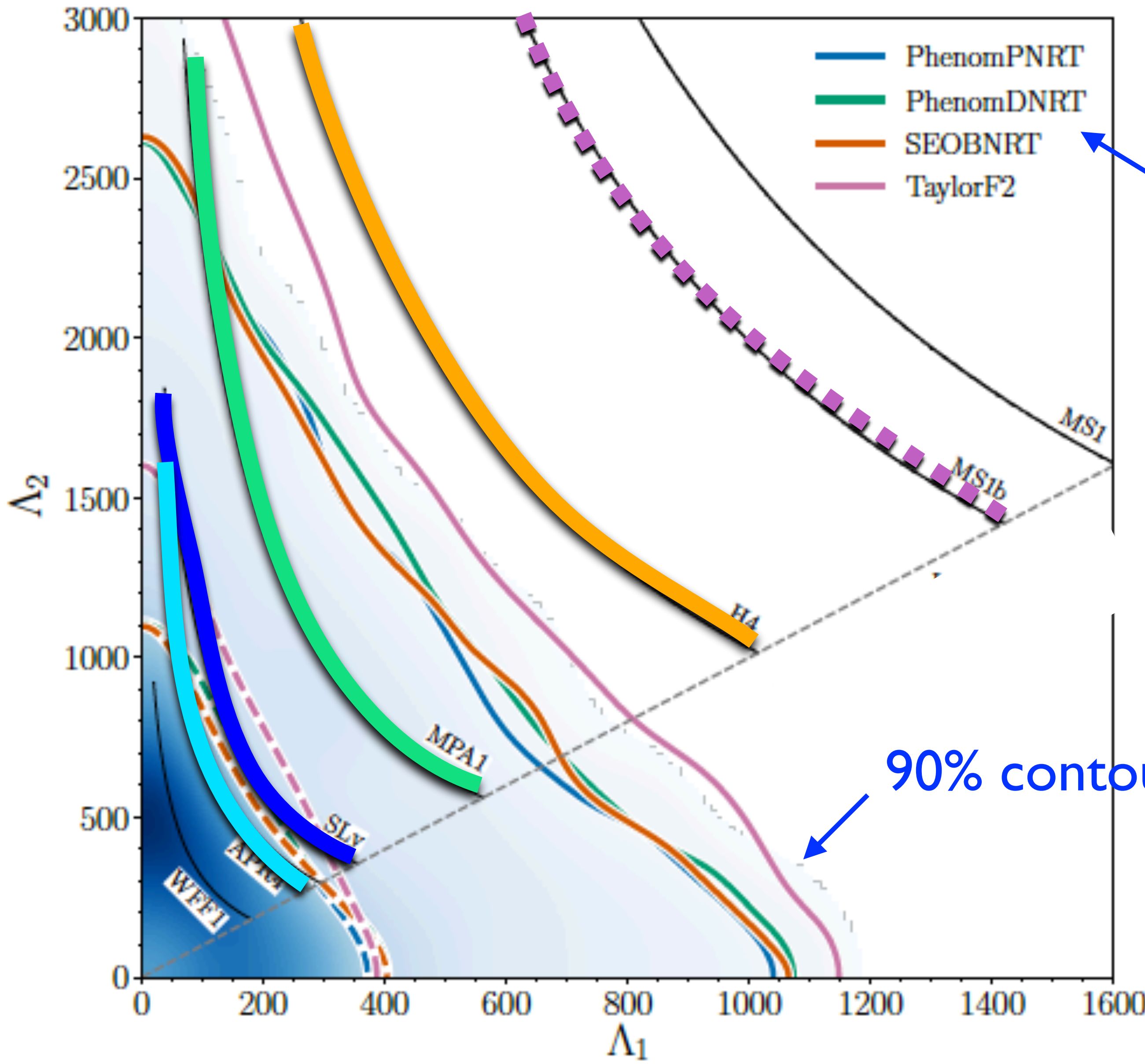


- exotic objects [e.g. Cardoso, Pani,+, Sennett+, Johnson-McDaniel+]
- axion-like particles [e.g. Baumann+1804.03208]
- dark matter halos [e.g. Nelson + arXiv:1803.03266v1]

Measurements of tidal deformability for GW170817

- Distance: ~40 Mpc, total mass: ~ 2.74 Msun
- Results for dimensionless tidal deformability $\Lambda = \dfrac{\lambda}{m_{\rm NS}^5}$





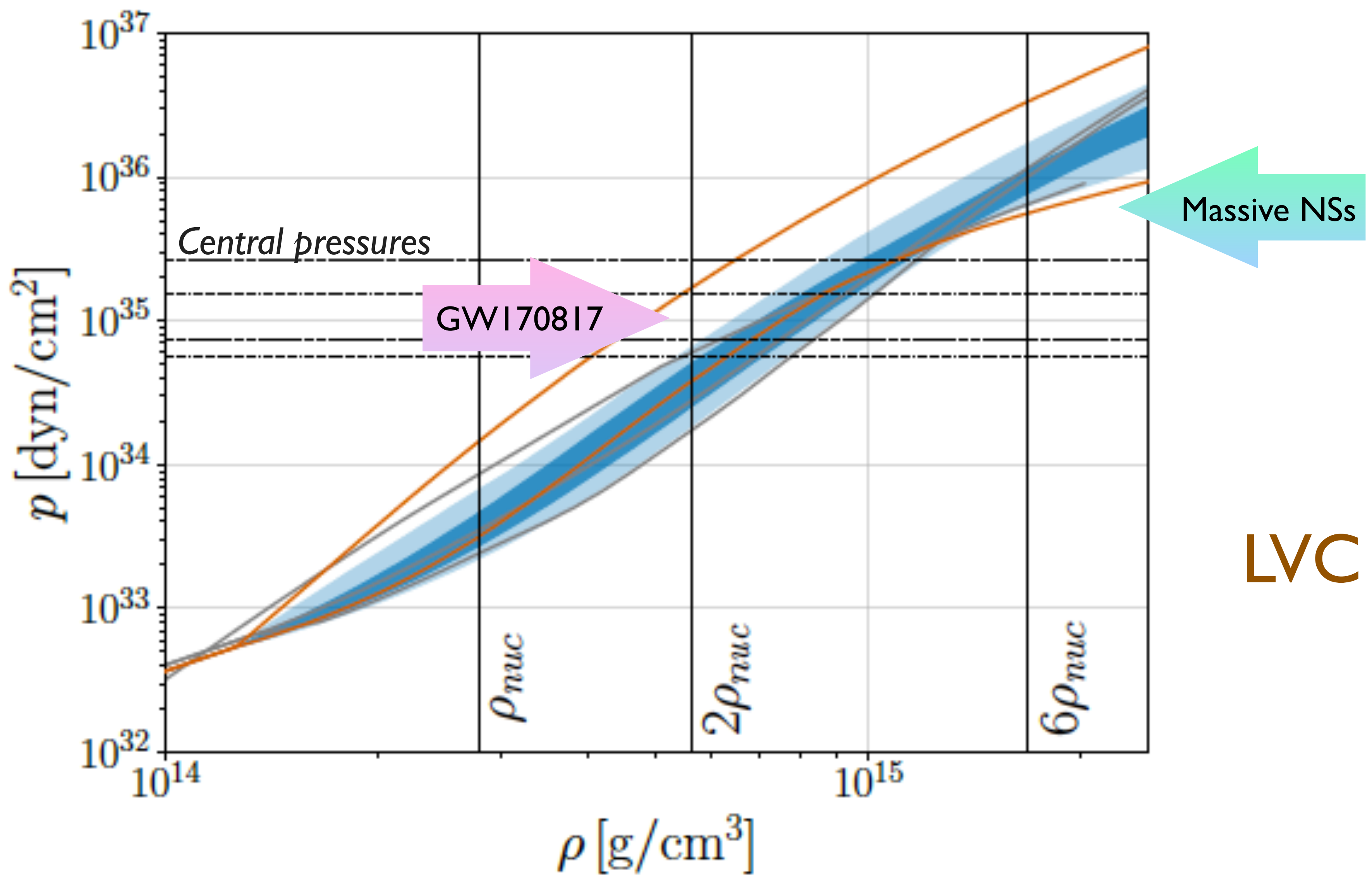
Different GW models

LVC arXiv:1805.11579

EoS results using restrictive assumptions

- low-spin priors $\chi<0.05$
- both objects have the same equation of state (EoS)

- Results with spectral EoS parameterization [Lindblom] incl. ~1.97Msun constraint



LVC arXiv:1805.11581

Was GW170817 a NS + black hole?

- Tidal effects in GW phase: difficult to distinguish NS-BH from NS-NS with softer EoS
- Electromagnetic counterparts: can exclude extreme corners of parameter space

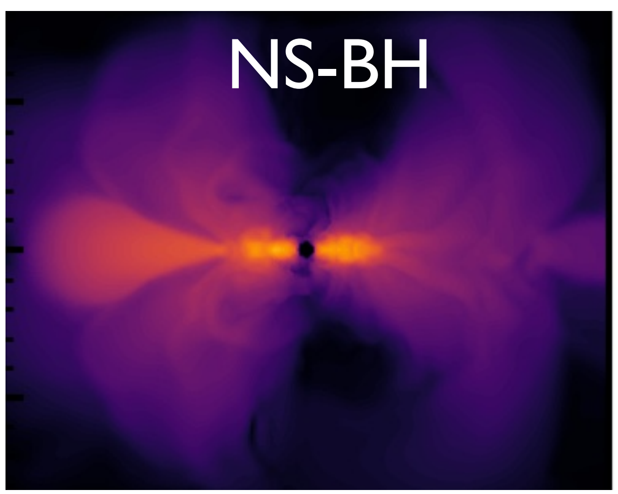
New NR simulations

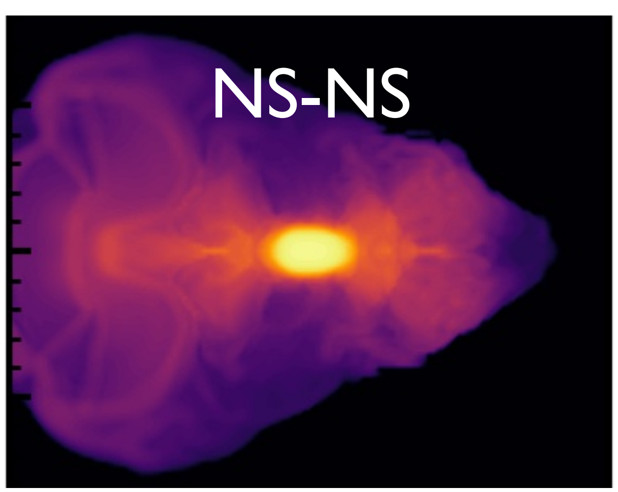
[F. Foucart, T. Vincent, +]:

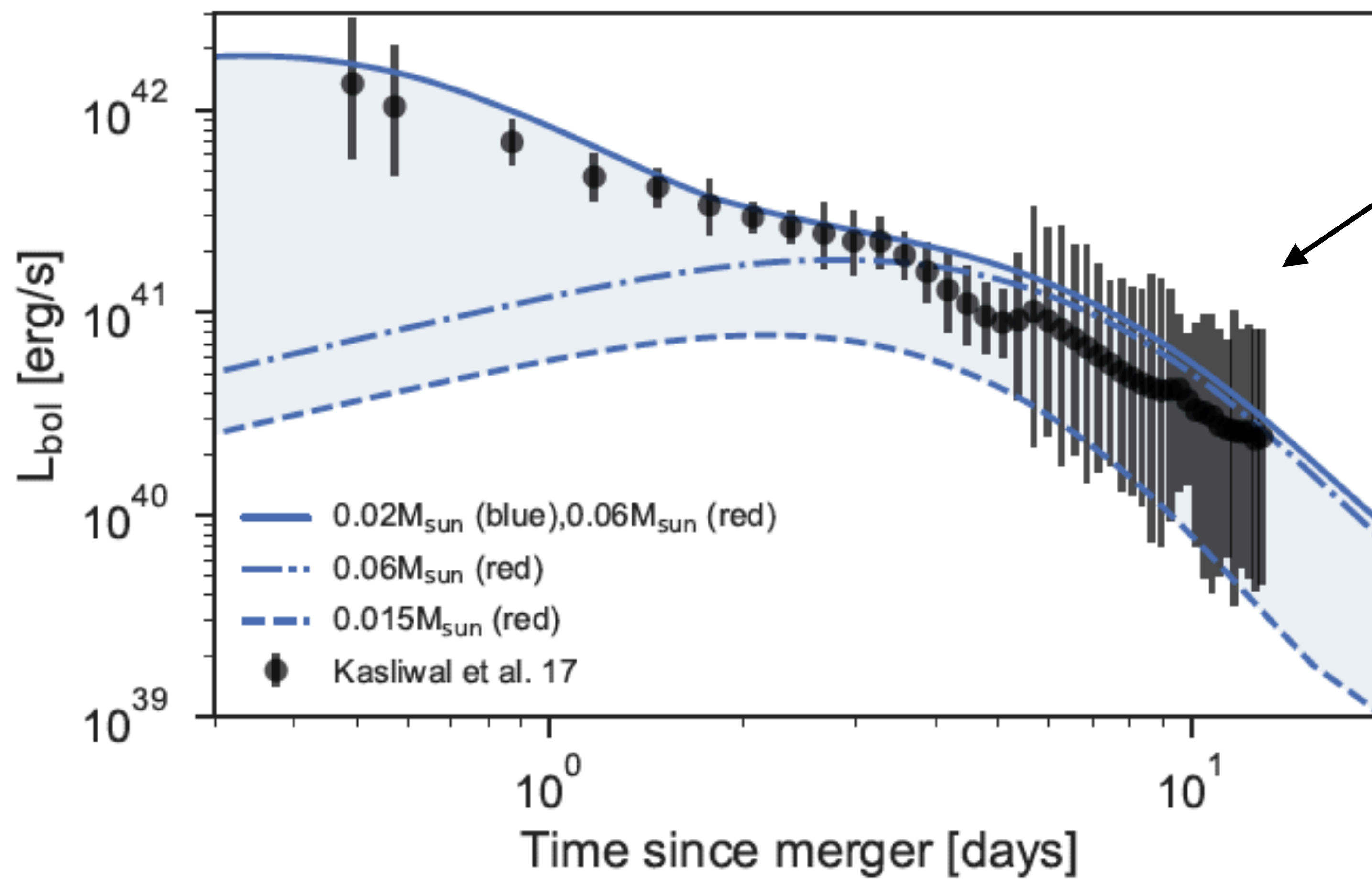
One-to-one comparison

Samaya Nissanke's talk (next)

Requirements on ejecta (incl. large uncertainties)







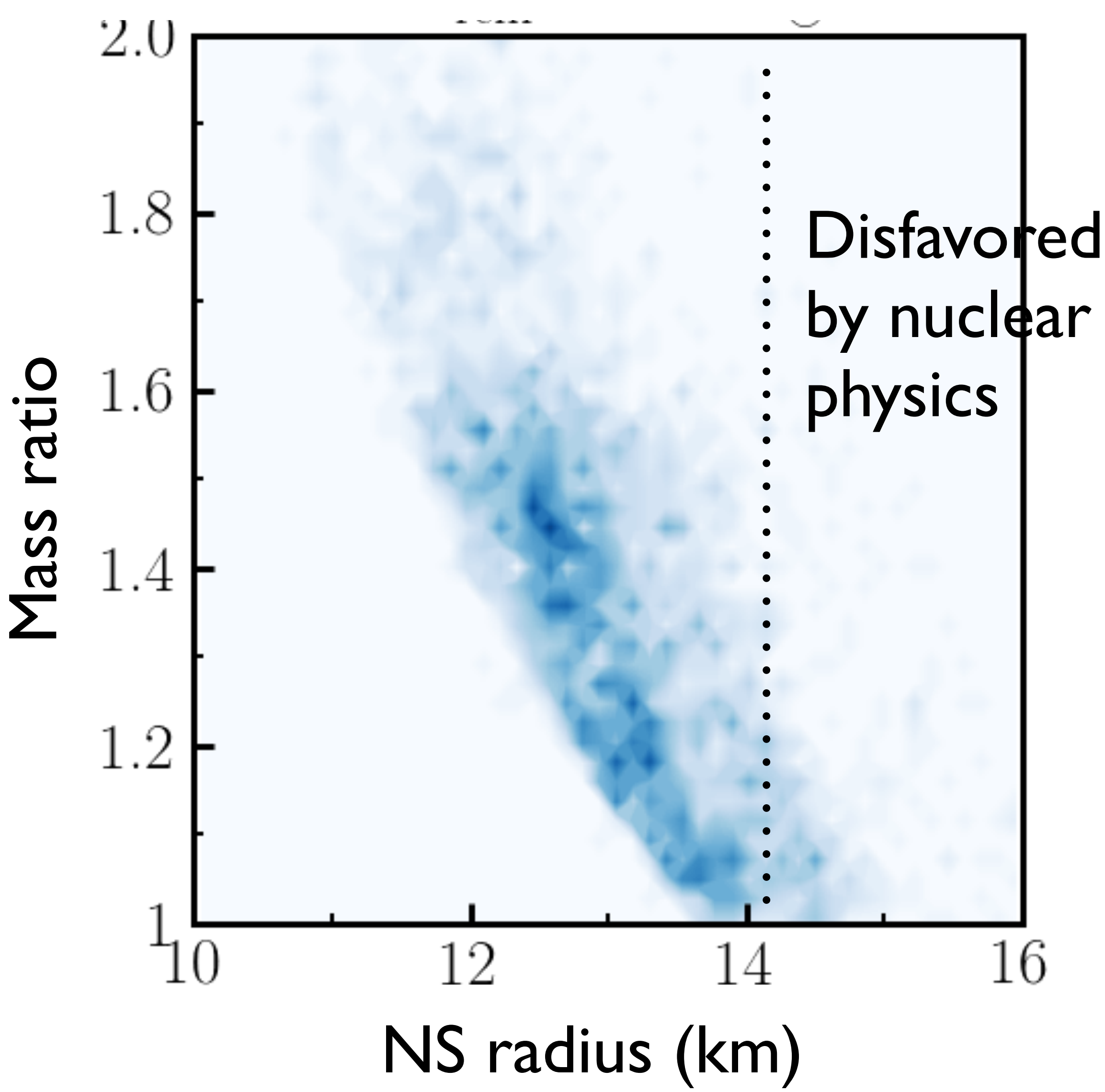
Observed

TH, Nissanke, Foucart,

Hotokezaka+ arXiv:1808.03836

Was GW170817 a NS + black hole?

- More interesting: joint analysis with electromagnetic counterpart information
  - Posterior probability distribution of inferred source parameters when *assuming* GW170817 was a NS-BH + EM constraints



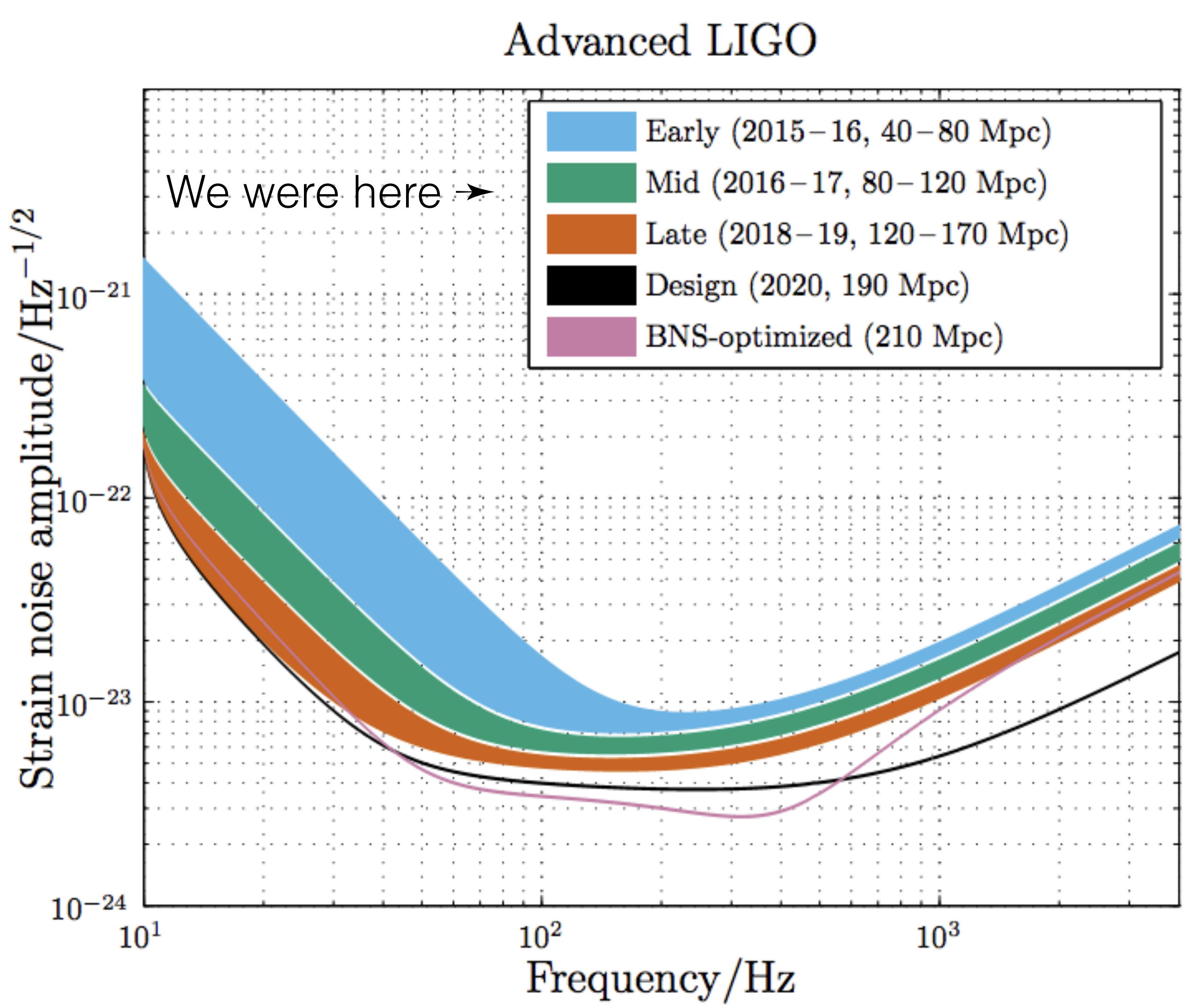
Key input: model for remnant mass given progenitor NS-BH parameters

Foucart, TH, Nissanke 1807.00011

TH, Nissanke, Foucart, Hotokezaka + 1808.03836

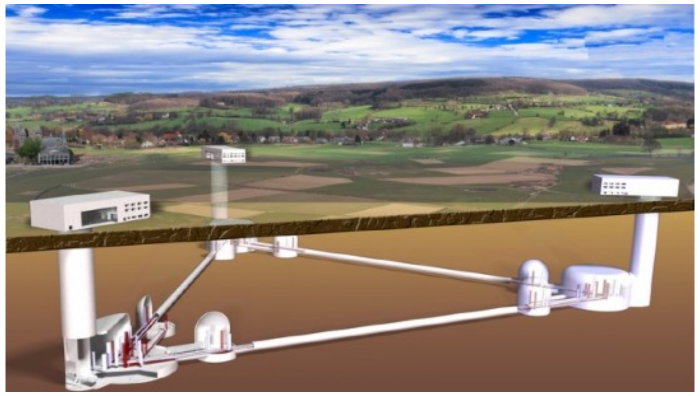
Outlook

- Anticipated detector improvements:
  - observe binary NSs ~ 2x further away (or at same distance with better accuracy)
  - Improve high-frequency sensitivity by ~ factor of 5



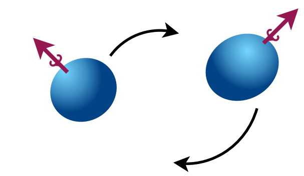
Living Reviews in Relativity; 21:3; 2018

- Third-generation detectors
  - e.g. Einstein Telescope: ~ 10x better sensitivity



Outlook

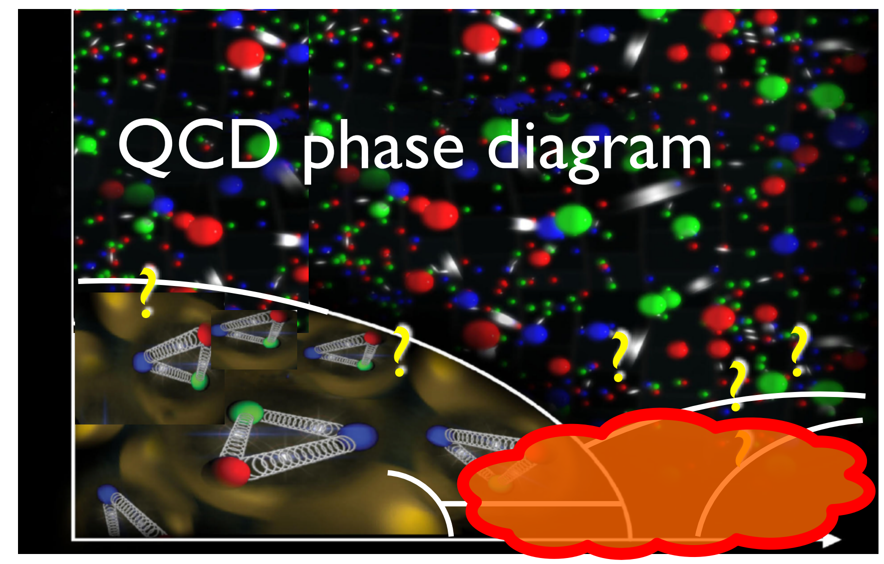
- Combine information from multiple binary NS detections?



Current rate estimate: 320–4740 $Gpc^{-3}\ yr^{-1}$ [LVC PRL 119, 161101 (2017)]

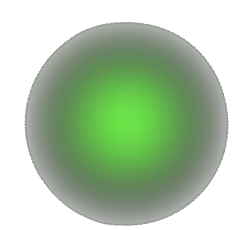
For 1000 $Gpc^{-3}\ yr^{-1}$: ~ 40 per yr (aLIGO design) [LVC Class. Q. Grav. 27, 173001 (2010)]

- Measure subdominant effects?
- Oscillation modes - asteroseismology?
- Observe merger/postmerger, tidal disruption?

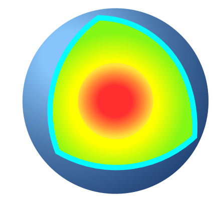


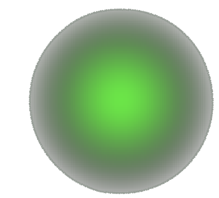
*Much **interesting science potential — requires advances in modeling***

- higher accuracy, larger parameter space coverage
- include more realistic physics
- flexibility to look for new phenomena/effects/physics
- ….

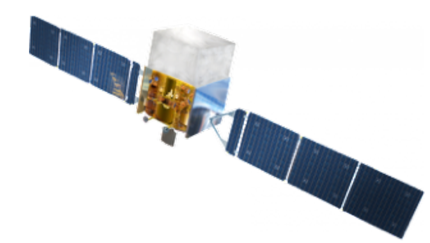


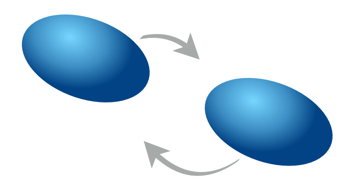
Conclusion



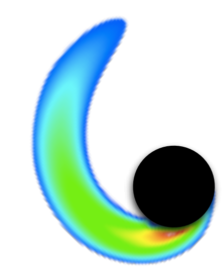


- Abundant scientific opportunities with GWs
  - much of the potential remains to be explored
- Accurate models essential to extract source physics & gain deeper understanding
- Much recent progress but further advances needed

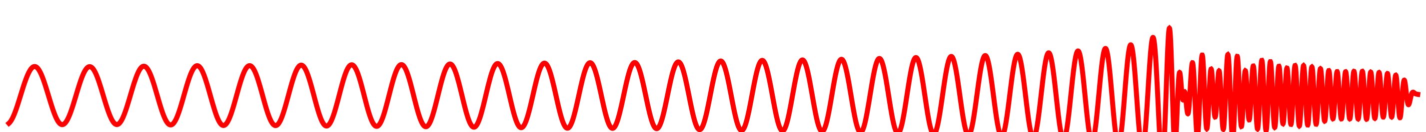




  - GW source modeling
  - Link to EM counterparts
  - data analysis strategies & tools
  - Connection with developments in nuclear physics / pulsars / theory



- Expect a wealth of new insights in the coming years



Credit: T.Dietrich