Probing dense matter physics with gravitational waves from neutron star binary inspirals

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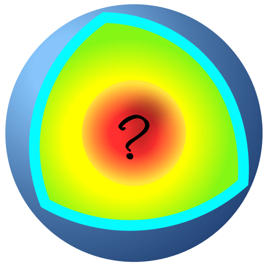
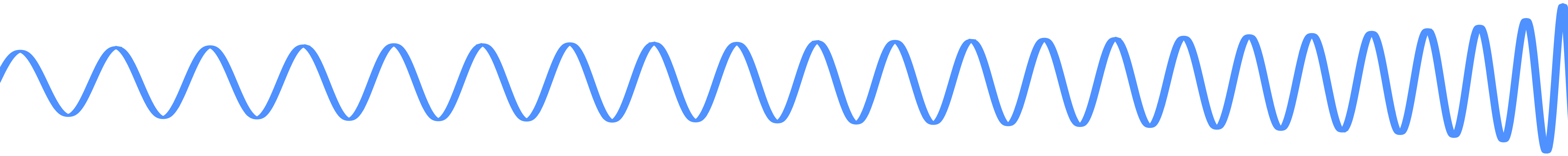
Overview

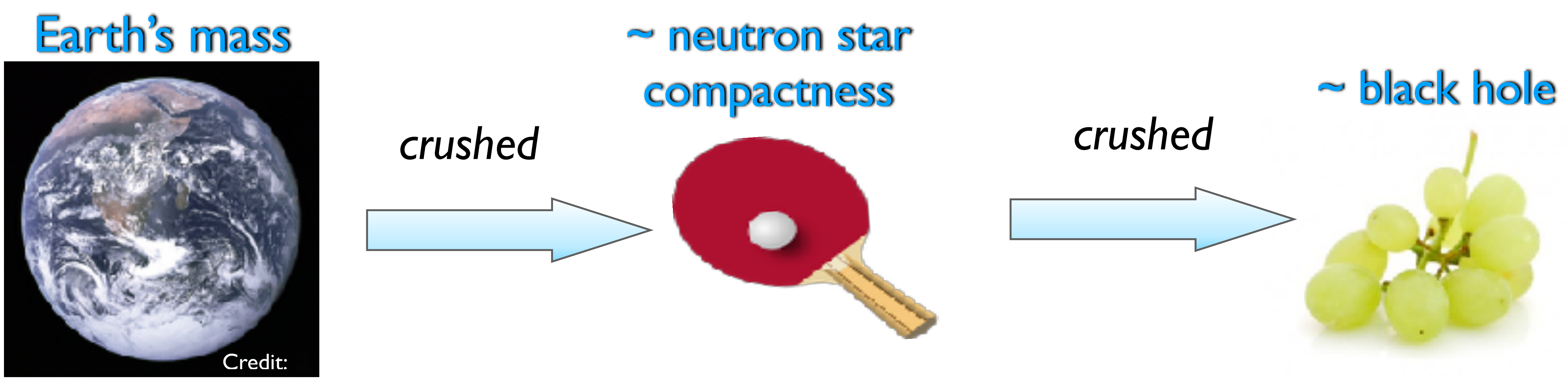
- Neutron stars: unique laboratories for extreme gravity and matter
- How can gravitational waves probe matter physics?
  - Extracting information from the data requires theoretical understanding & modeling
- What have we learned from recent discoveries?
- Outlook to exciting future prospects and remaining challenges





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 ~ $0.7\,M_\odot$

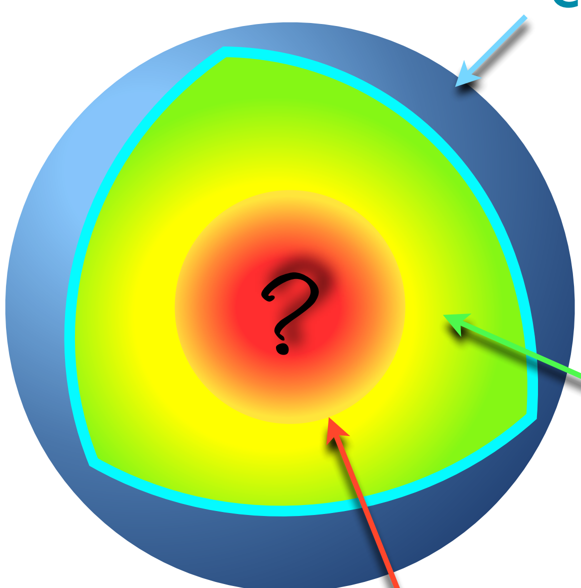
[Oppenheimer & Volkoff 1939]

- 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/cm³]



crust ~ *km*

Lattice of neutron rich nuclei

10^{10} times stronger than steel

free neutrons

~ 10^{6} g/cm³ inverse β-decay

~ 10^{11} g/cm³ neutron drip

outer core

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

deep core

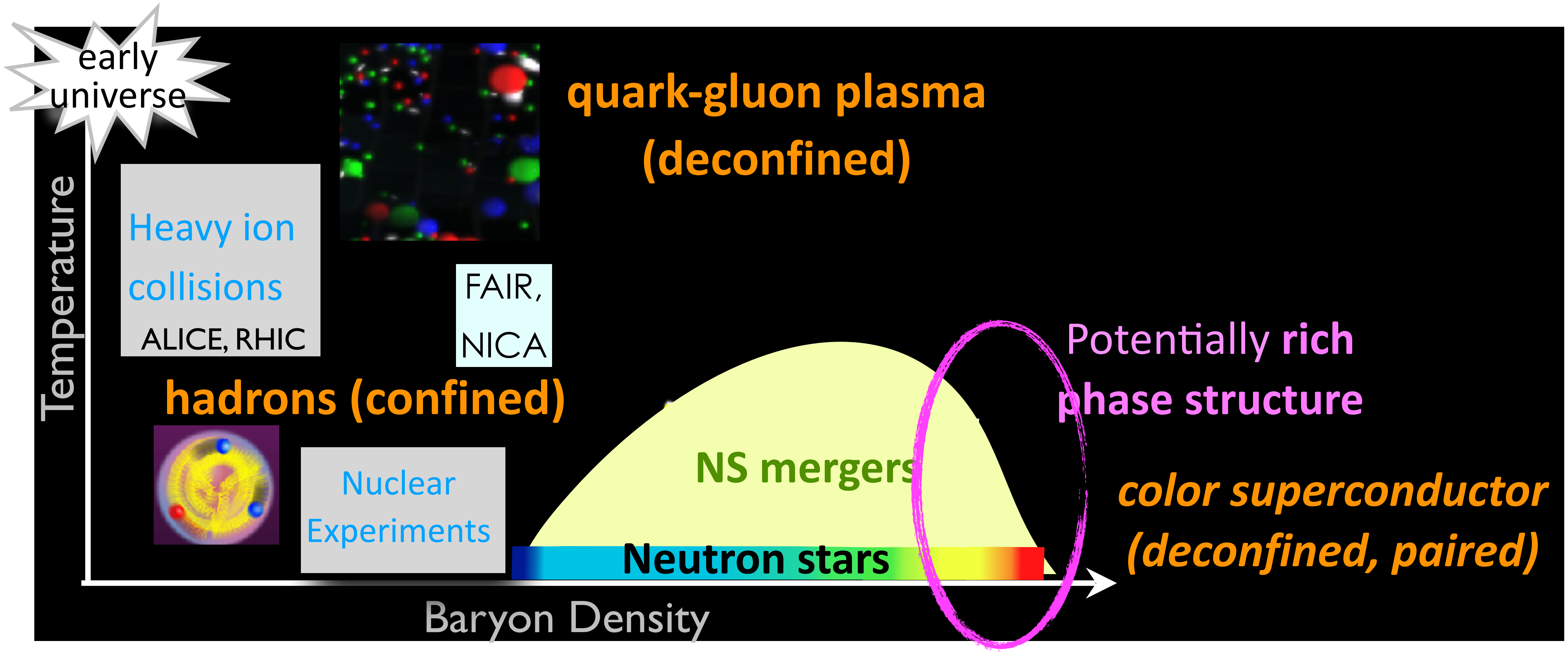
~ few x 10^{14} g/cm³

$\gtrsim$2x nuclear density, nucleons overlap - new degrees of freedom relevant

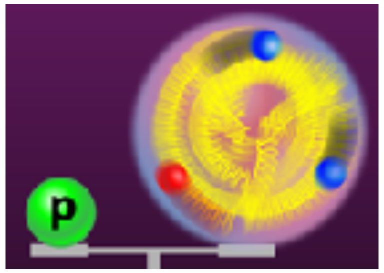
deconfined quarks?

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

Neutron stars as QCD labs



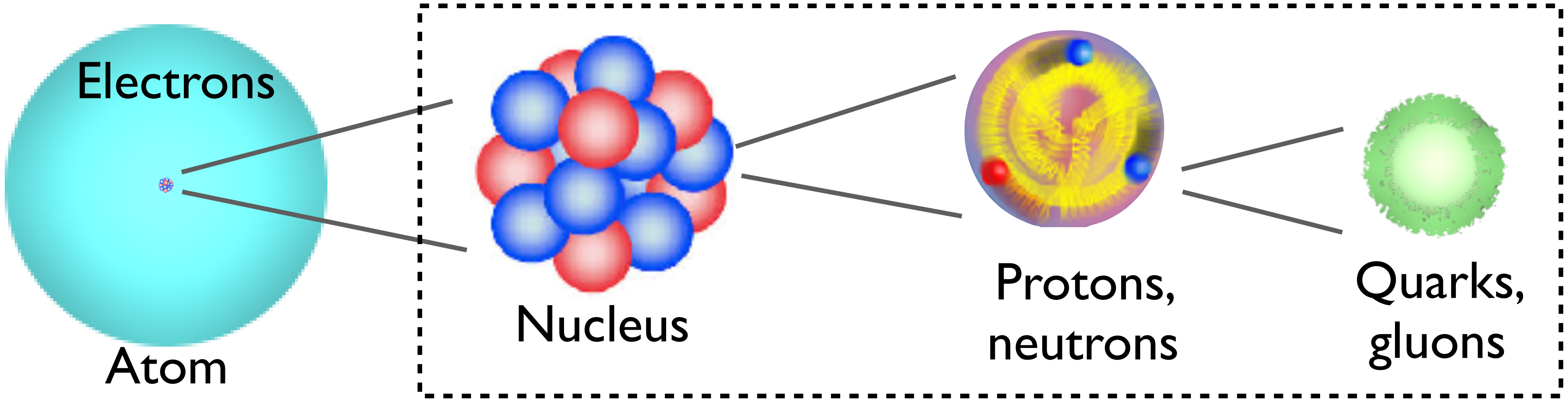
- Characterize phases of QCD, probe deconfinement
- Deeper understanding of strong interactions, their unusual properties, e.g.
  - asymptotic freedom (weak coupling at shorter distances)
  - Vacuum (condensate) has important effects, e.g. mass



proton mass: ~ 938 MeV
only ~ 1% due to Higgs

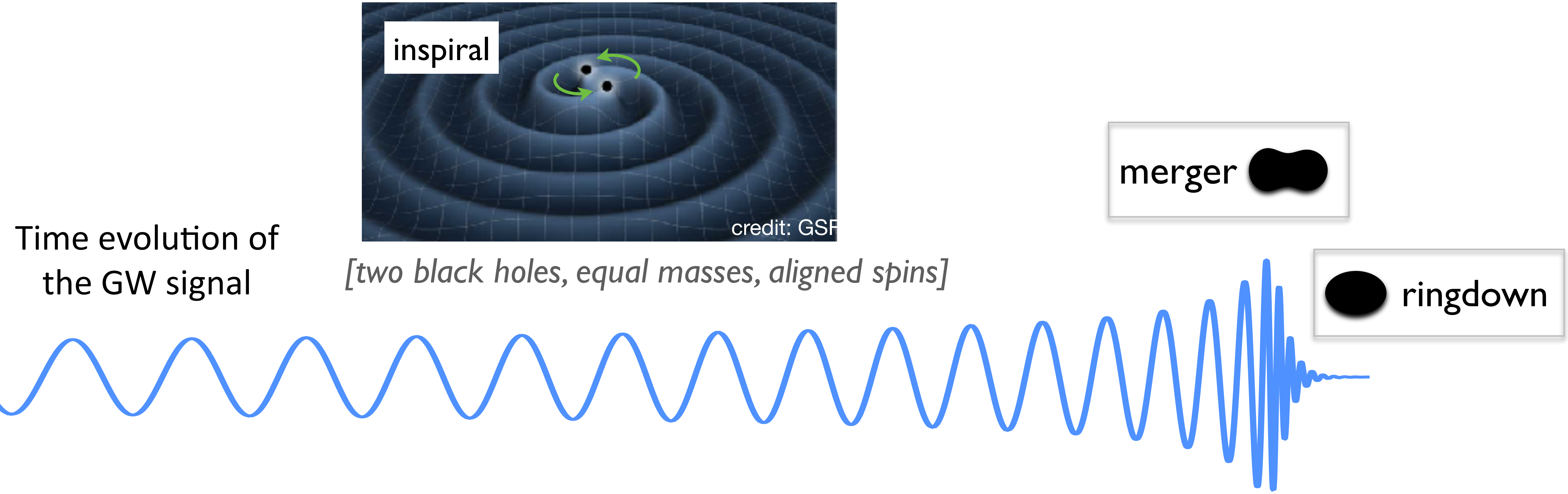
NSs as labs for emergent structural complexity

Building blocks of matter

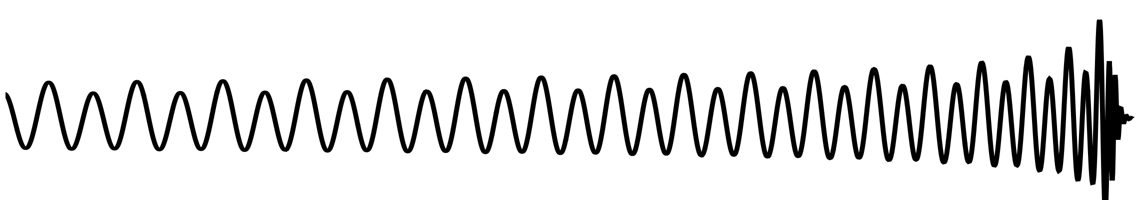


- Collective phenomena, multi-body interactions
- Effects of the excess of neutrons over protons (isospin asymmetry)?
- How do nucleons and their quarks and gluons assemble and interact to create the structure of matter?

Gravitational waves (GWs) from binary systems



- Details of the waveform encode fundamental source properties

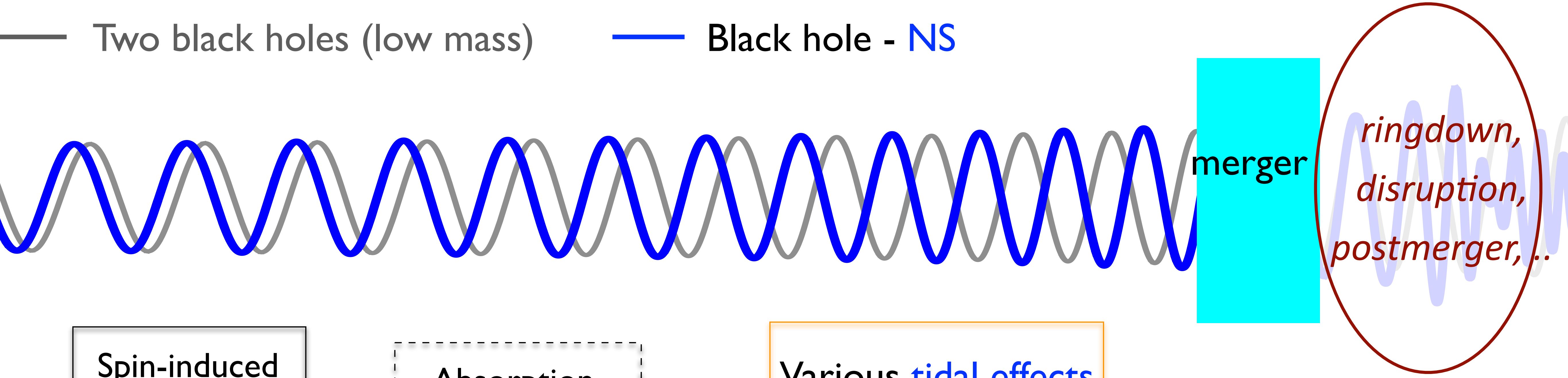


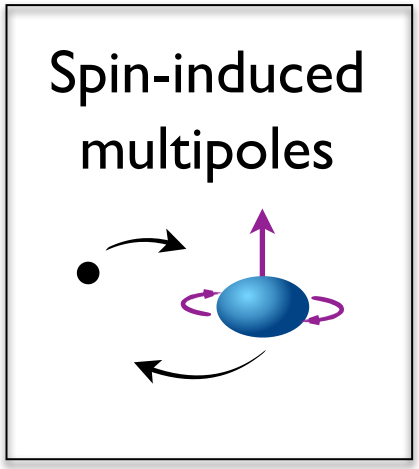
mass ratio 1:10

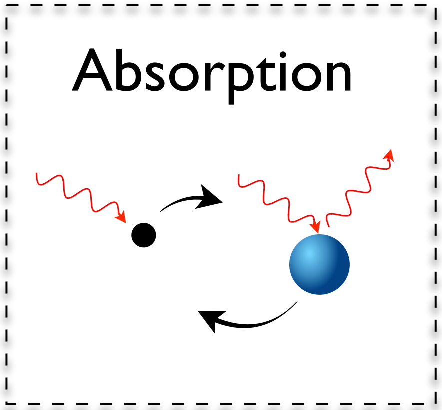
misaligned spins

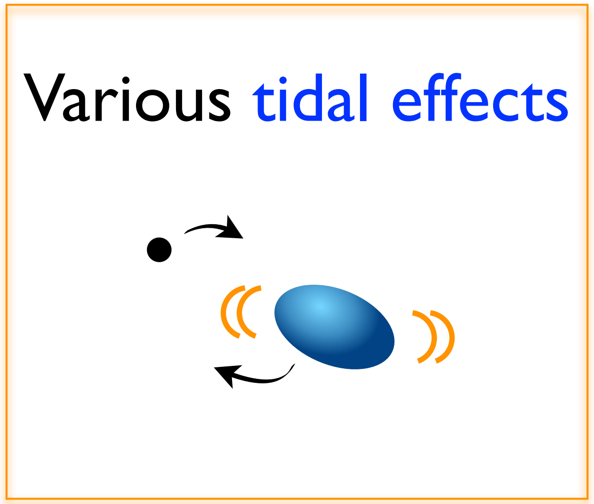
- Measurements: data cross-correlated with theoretical waveform models

GW signatures of matter









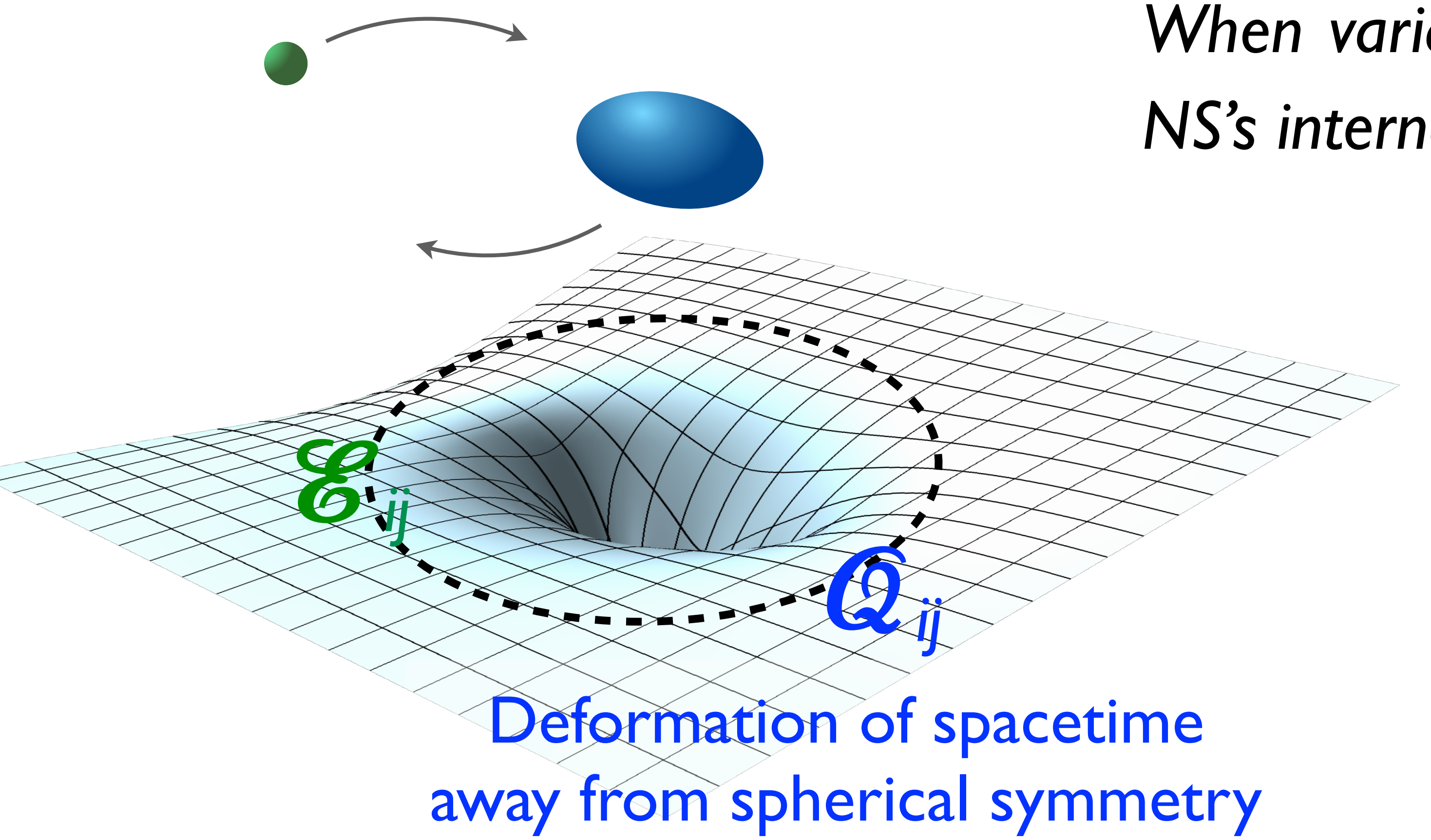
Generic phenomena (any objects that are not classical GR black holes in 4d),

associated characteristic parameters set the size of the GW signatures, encode object's internal structure

- Inspiral: matter effects small but cumulative, accessible with current detectors

Example of a characteristic matter parameter

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



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

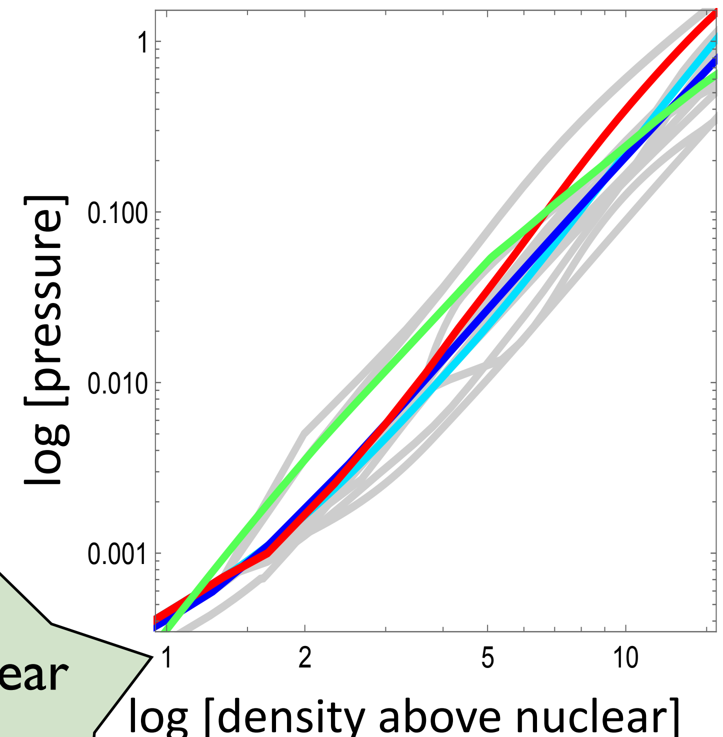
=0 for a black hole

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

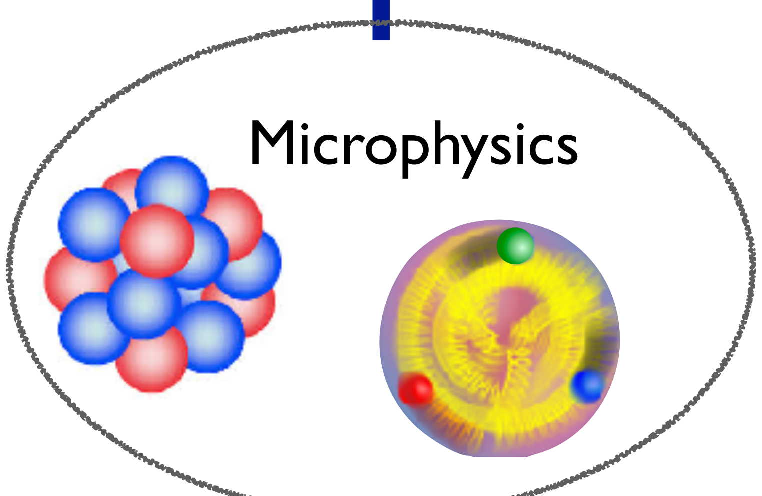
Properties of NS matter reflected in global observables

NS matter models (equations of state EoS)

Perturbative QCD



Nuclear EFT, …



Einstein field equations &

stress-energy conservation

Stationary perturbations to equilibrium

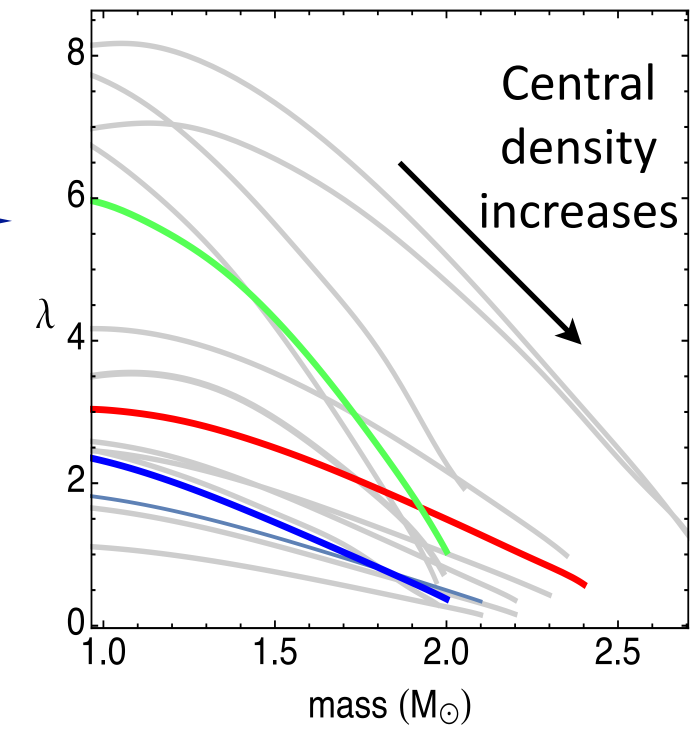
[TH 2008]

advantageous to instead consider wave scattering

Gastón Creci, TH, Jan Steinhoff

arXiv:2108.03385

Tidal deformability λ vs. mass

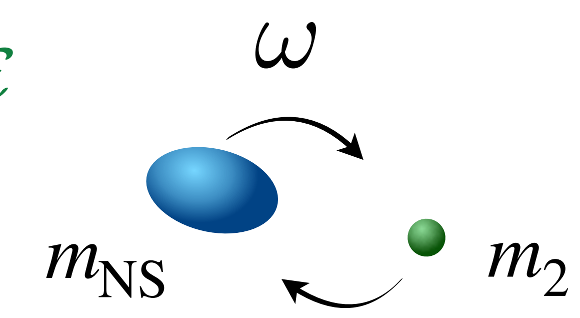


Main influence on GWs

- Energy goes into deforming the NS:

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

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



- moving multipoles contribute to gravitational radiation

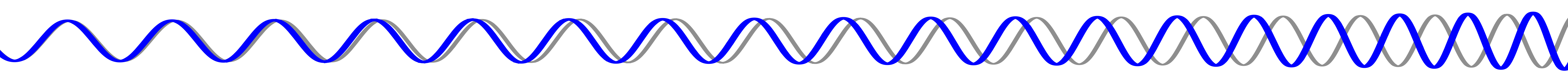
$$\dot{E}_{\rm GW} \sim \left[\frac{d^3}{dt^3}\left(Q_{\rm orbit} + \mathcal{Q}\right)\right]^2$$

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

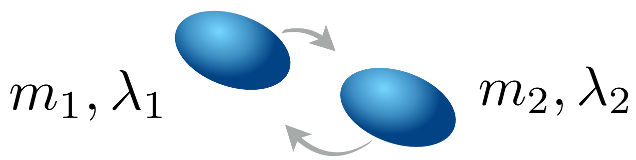
- approx. GW phase evolution from energy balance:

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

[Flanagan, TH 2008]



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



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

- Effects included in state-of-the-art waveform models (full black hole baseline) for data analysis

[Damour, Nagar, TH+2016, Steinhoff+, Dietrich+, Henry+, Schmidt, Pratten +]

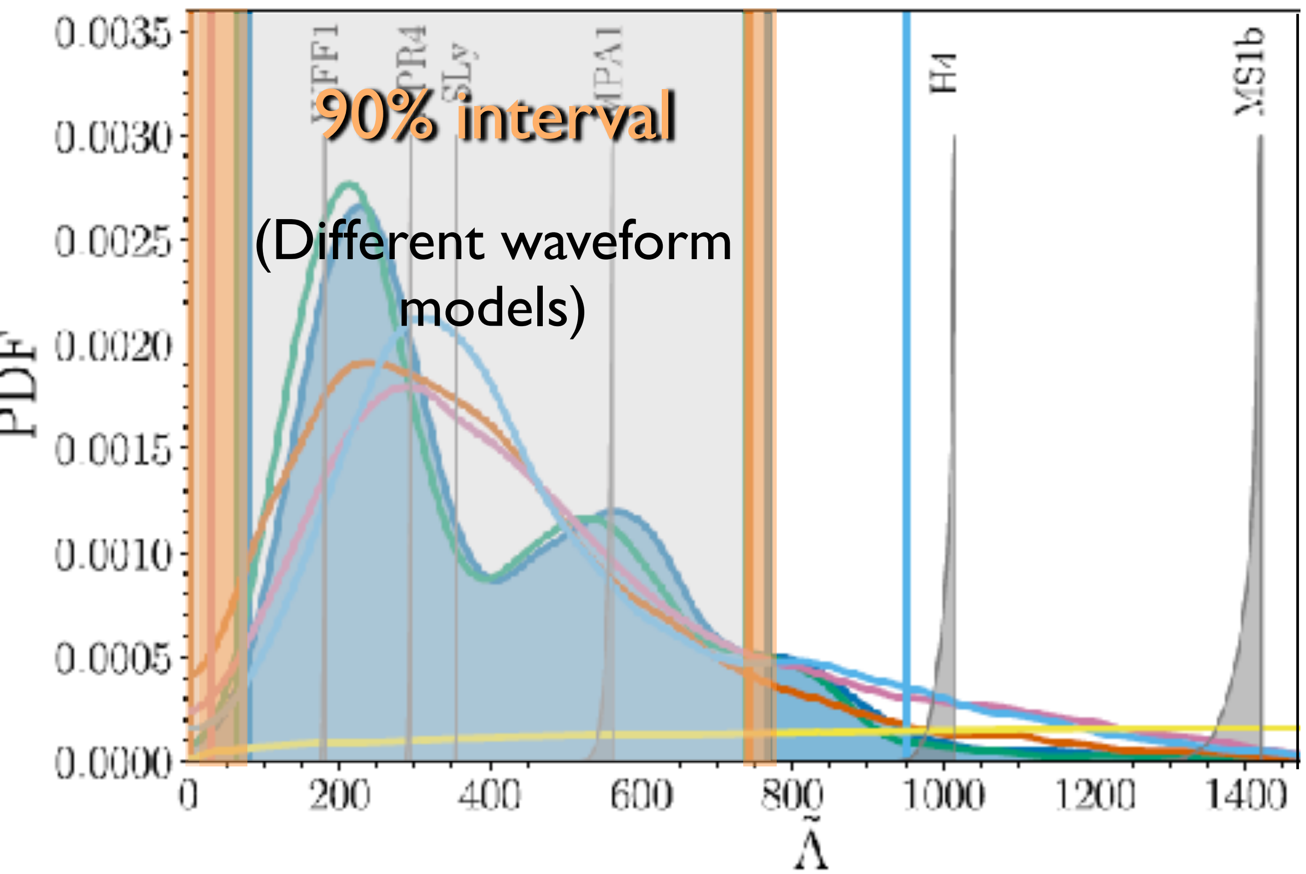
Measurements/constraints on tidal deformability

Results with low spin priors (Dimensionless spin < 0.05)

GW170817

Total mass ~ 2.8 Msun

Distance ~ 40Mpc



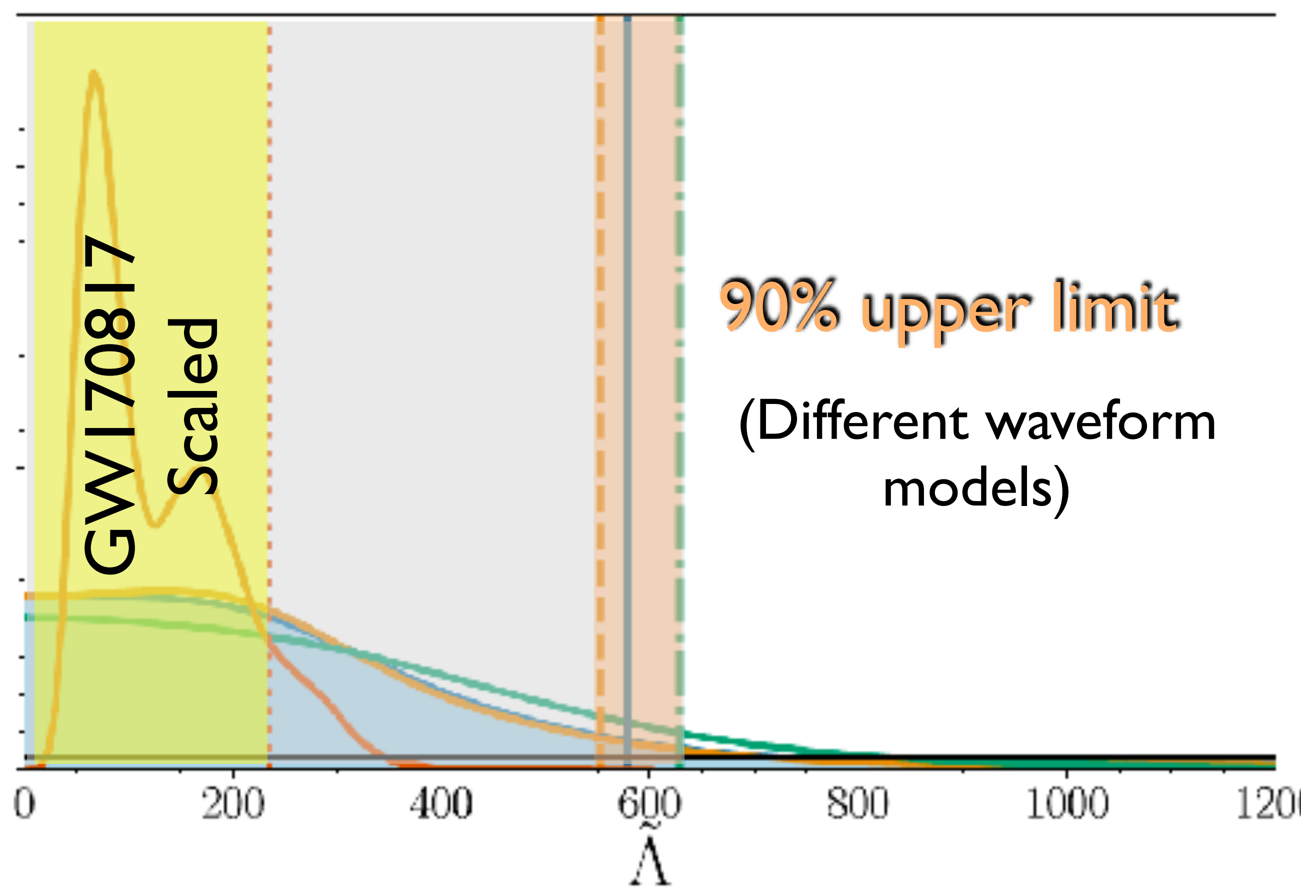
LVC GWTC-1

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

GW190425

Total mass ~ 3.4 Msun

Distance ~160Mpc



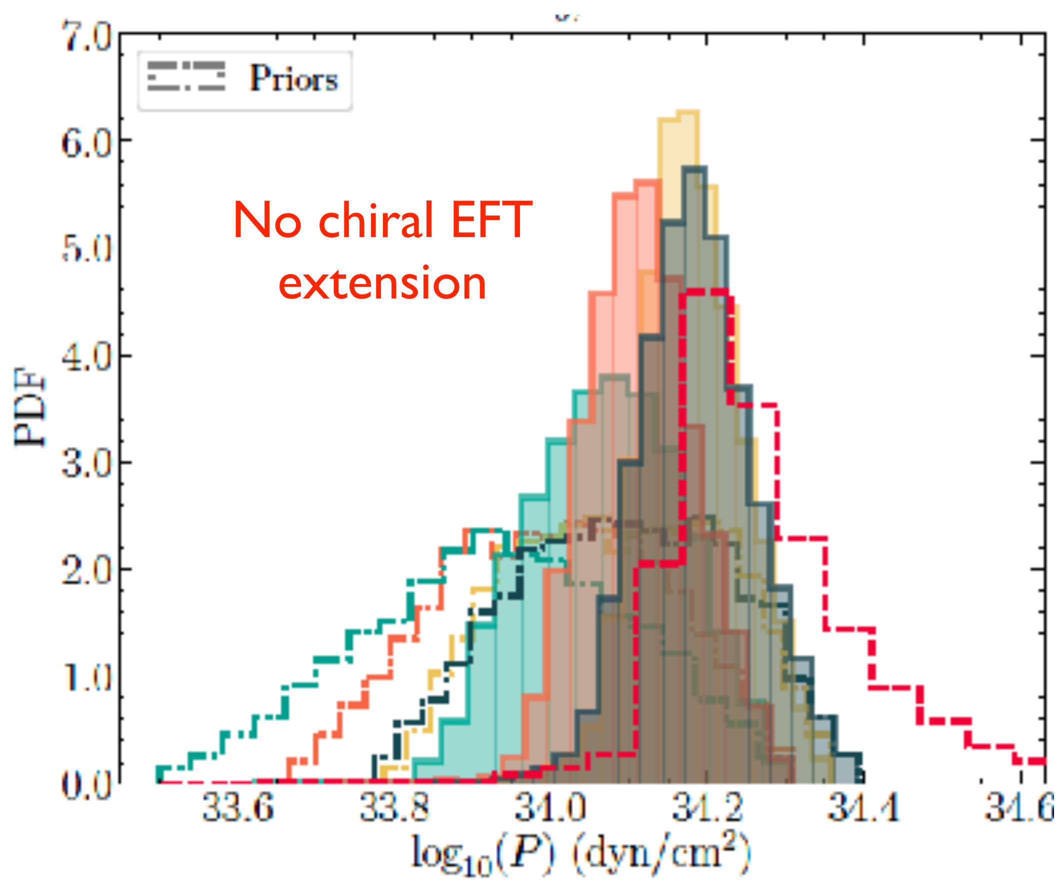
LVC ApJ Lett. 892 L3 (2020)

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

Example implications for subatomic physics

- Joint constraints: GWs, kilonova, NICER/xMMNewton, radio pulsars, nuclear/QCD physics

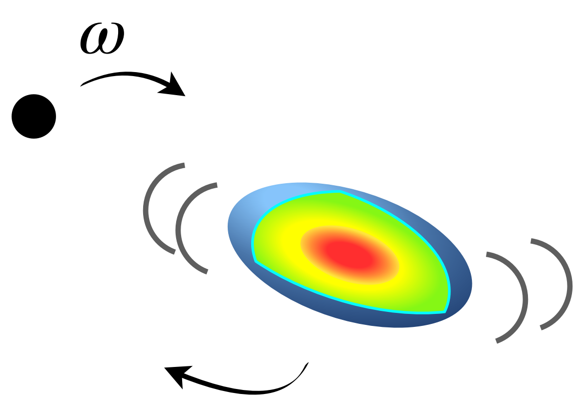
pressure at 1.5 nuclear saturation density
(different extensions)



Priors for different chiral effective field theory extensions (nuclear multi-body interactions, symmetry energy …)

Geert Raaijmakers+ 2021 arXiv:2105.06981

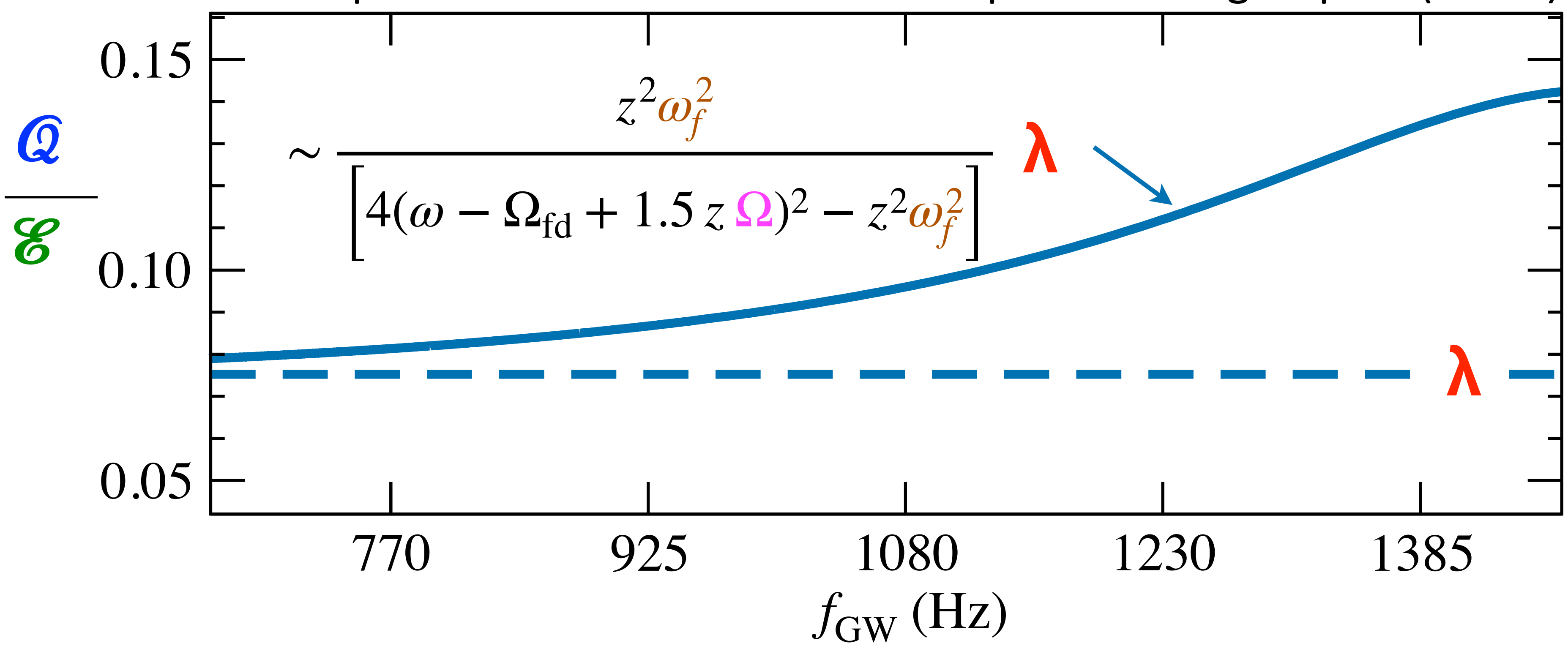
More realistic descriptions of tidal effects



- NSs have a rich spectrum of quasi-normal oscillation modes
- Several have frequencies < kHz: tidal excitations in inspirals
- Spectroscopy of NS interiors, possible EM flares

- Even non-resonant excitations can lead to significant effects, e.g. fundamental modes with ω_f

Example fundamental-mode tidal response during inspiral (NSBH)



Response also impacted by:

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

[Steinhoff, TH+2021]

A rotating NS also has gravitomagnetic modes

- *inertial modes* associated with the Coriolis effect [includes 'r-modes']
- Mode frequencies ∝ spin frequency Ω
  - Will pass through full resonance at some point during inspiral
- Dominant coupling to the gravitomagnetic tidal tensor $\mathscr{B}_{ij} = {}^*R_{0i0j}$

  ~ frame-dragging field, no Newtonian analog

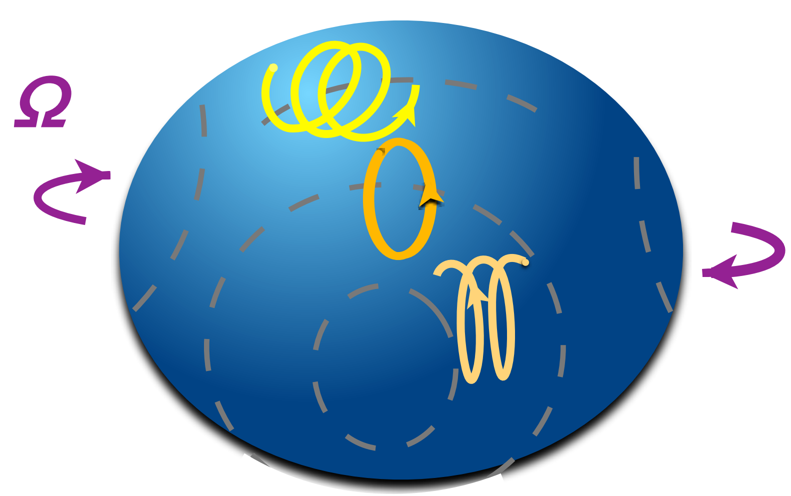
Coriolis effect: air motion in the atmosphere

Credit: A. Persson, wikipedia.org

- Several interesting features

[Kumar, Steinhoff, TH 2020]

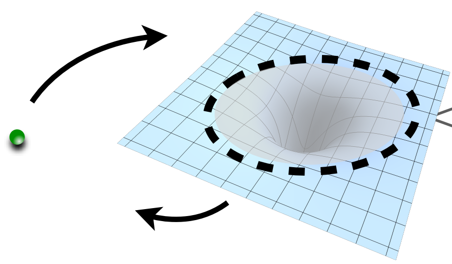
NS: fluid motion



[post-Newtonian analyses for GWs:
Racine & Flanagan 2006, Poisson 2020, Ma & Chen 2021, Ho & Lai 2001 (Newtonian), many other works on r-modes, Love numbers]

Modeling tidal effects in a binary system (slow rotation approximation)

spacetime near the NS viewed on the orbital scale:



worldline + multipoles

$m, S^i, Q^{ij}, Q^{ij}_{\mathcal{B}}, \ldots$

tidally induced mass & (matter contributions to) current multipoles

Gravitomagnetic modes

Effective action describing the binary dynamics:

$$S \approx S_{pp} + \int d\tau \left[\quad \right]$$

point-particle part

[Steinhoff, TH +2016, 2020, 2021]

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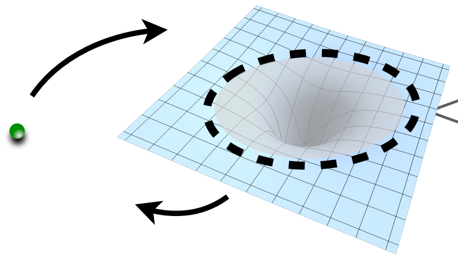

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Gravitomagnetic modes

Effective action describing the binary dynamics:

redshift

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

point-particle part

multipoles interact with companion's spacetime curvature

[Steinhoff, TH +2016, 2020, 2021]

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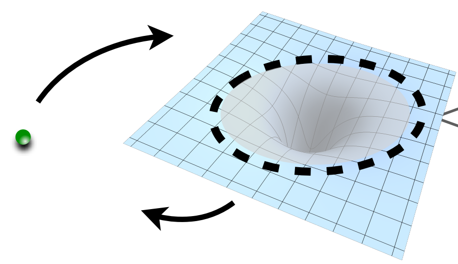

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Gravitomagnetic modes

Effective action describing the binary dynamics:

Internal dynamics of the multipoles (modes)

redshift

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

point-particle part

multipoles interact with companion's spacetime curvature

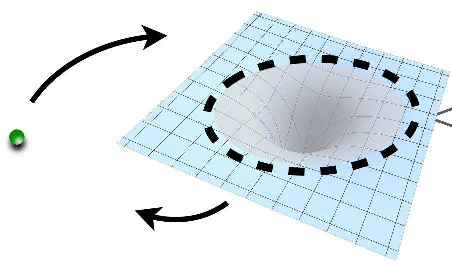
Effects of NS's spin on tidal response & restoring force for gravitomagnetic modes

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

[Steinhoff, TH +2016, 2020, 2021]

Modeling tidal effects in a binary system (slow rotation approximation)

spacetime near the NS viewed on the orbital scale:



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[Steinhoff, TH +2016, 2020, 2021]

Modeling tidal effects in a binary system (slow rotation approximation)

Multipoles behave as harmonic oscillators:

$$L^{\rm osc} \approx \frac{z}{4\lambda z^2 \omega_f^2} \frac{dQ_{ij}}{d\tau} \frac{dQ_{ij}}{d\tau} - \frac{z}{4\lambda} Q_{ij} Q_{ij} + \ldots$$

dominated by *f*-modes

g-modes (phase transitions), higher multipoles, … also contribute [not shown]

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

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dominated by *f*-modes

g-modes (phase transitions), higher multipoles, … also contribute [not shown]

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

subdominant but important for future GW detections

two different magnetic tidal deformabilities

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

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

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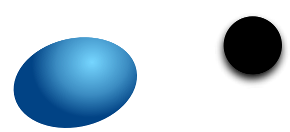
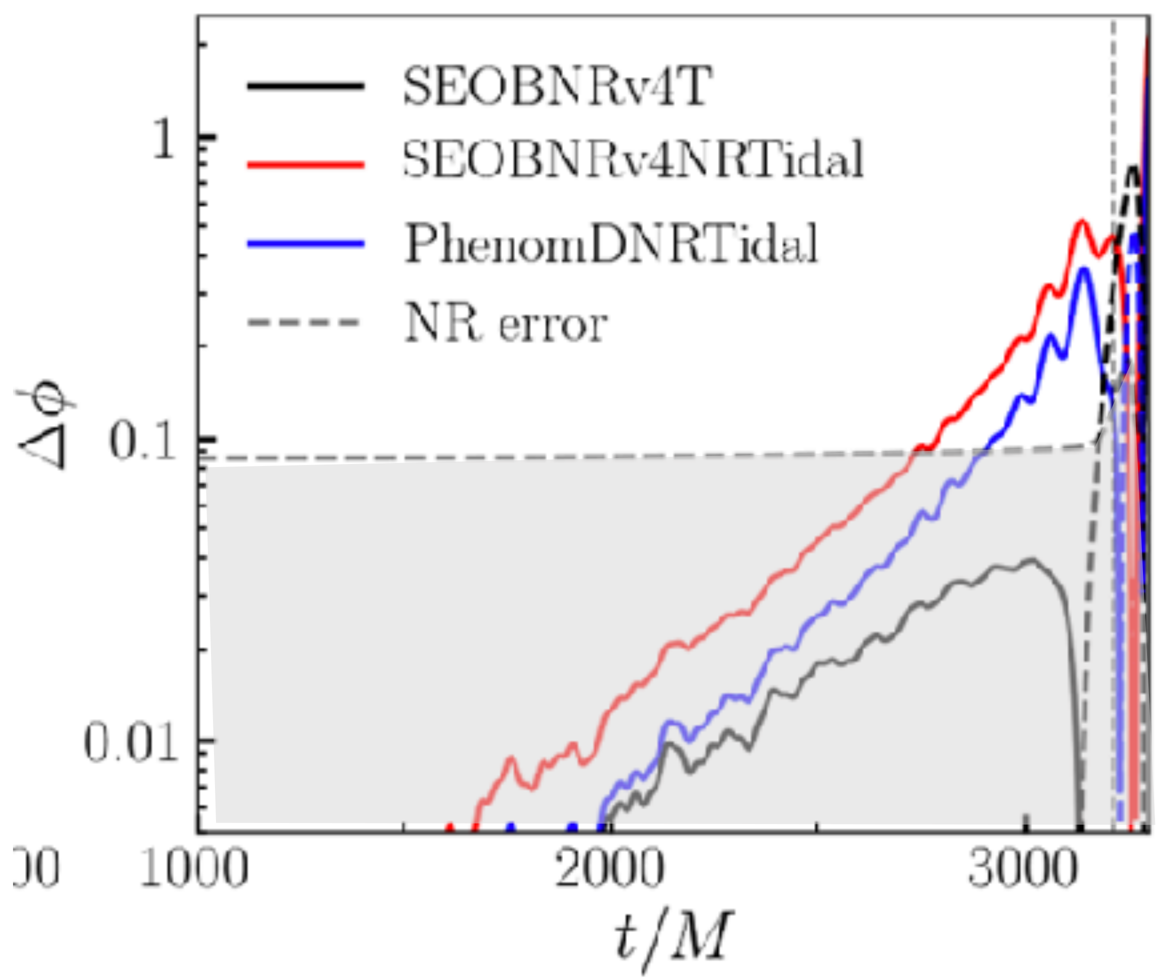
[Steinhoff, TH +2016, 2020, 2021]

Testing models against numerical relativity results

- Approximate f-mode effects included in the model SEOBNRv4T [TH+2016]
  - Other models available based on different tidal enhancement (amplified tidal field) and different BH baseline (Phenom)
  - Approximate quasi-universal relation between ω_f and λ [Chan + 2014]



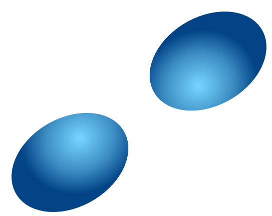
Example comparisons: NSBH phase differences

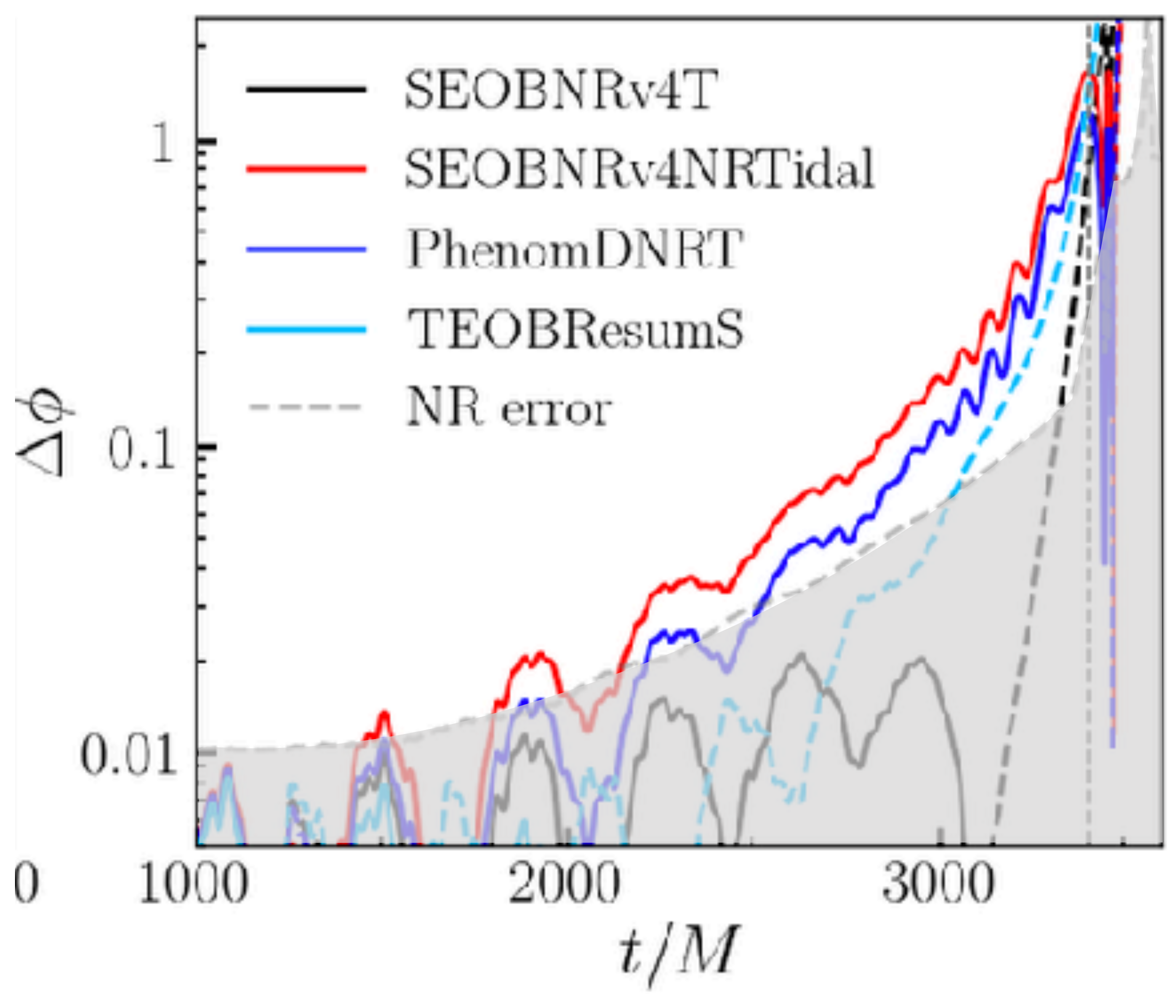


Foucart+2018

Testing models against numerical relativity results

- Same system but with the BH replaced by another NS



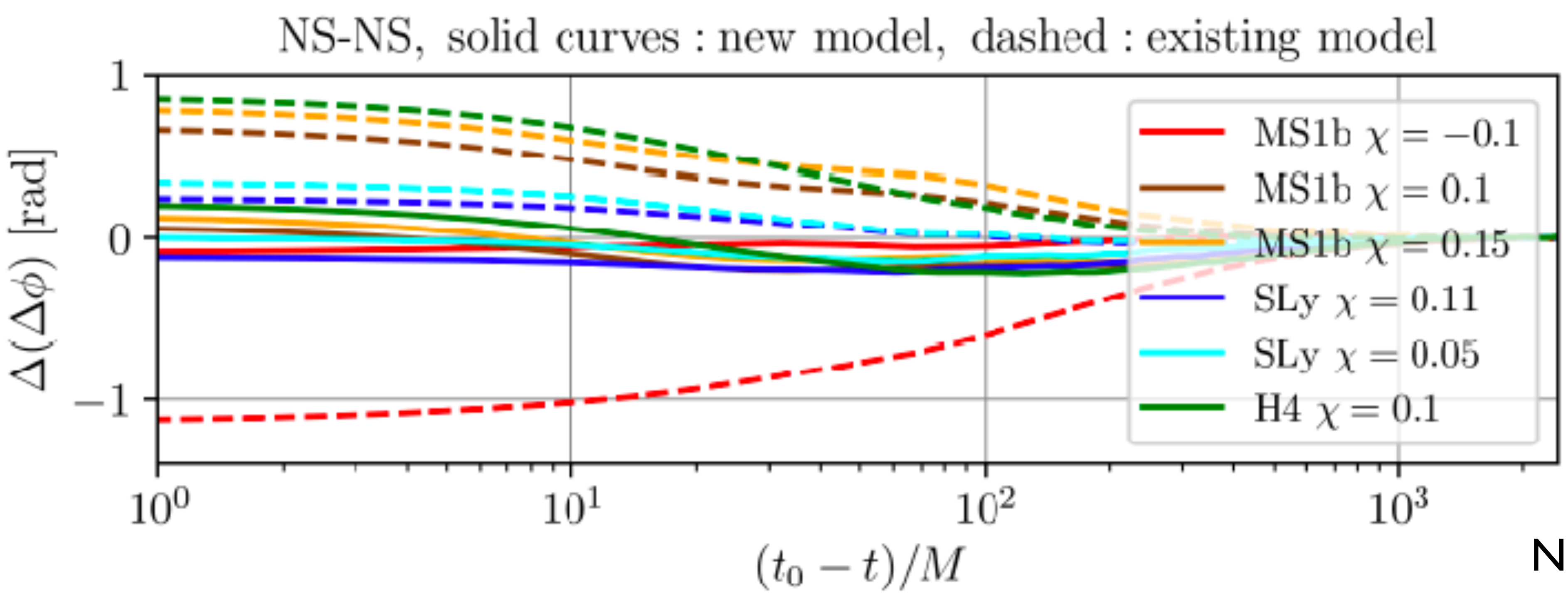


Foucart+2018

- Several other examples tested, also with waveforms from different codes.

Testing models against numerical relativity

- recently added: NS spin effect on resonance in SEOBNRv4T model
- Diagnostic quantity: phase difference to nonspinning phase difference



NR data from T. Dietrich

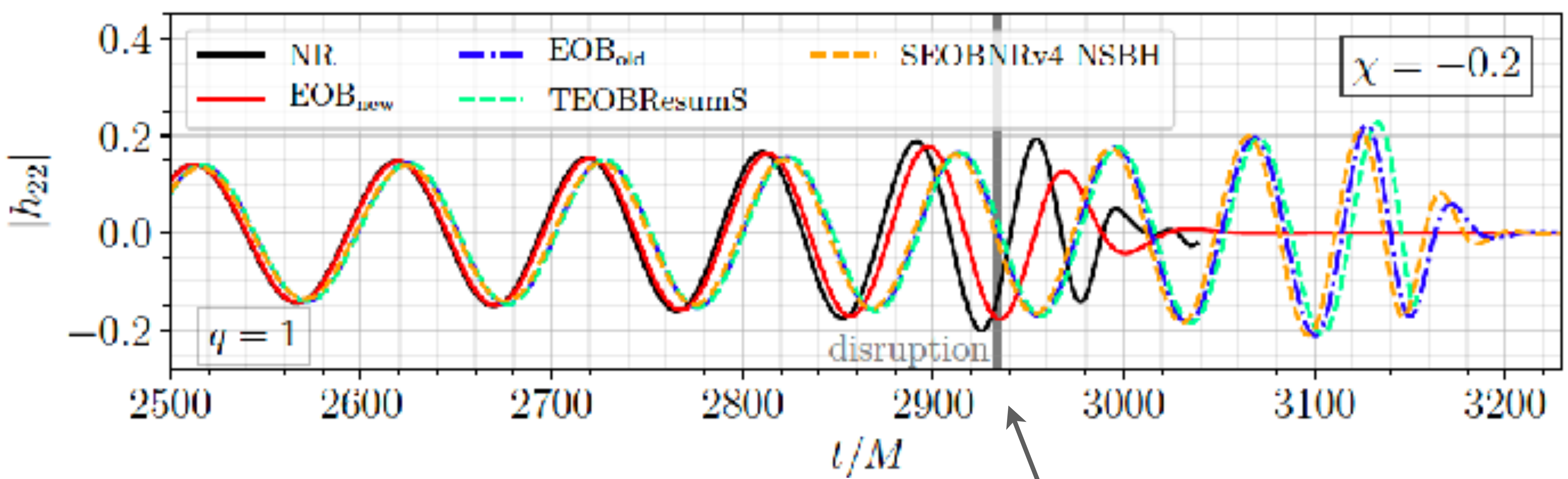
Similar results when compared with

- other existing waveform models
- NS-BH numerical relativity waveforms from the SpEC code *[Francois Foucart]*

[Steinhoff, TH,Dietrich, Foucart 2021]

Comparison to numerical relativity: NS-BH

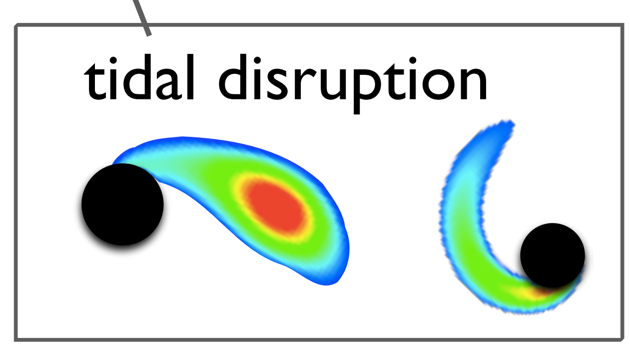
- NR data: SpEC code *[F. Foucart, SXS]*
- Link between f-mode and tidal disruption GW signature:
  - SEOBNRv4T waveform tapered to zero at the resonance



Red: new model

Black: NR

Orange: NSBH model



[Steinhoff, TH,Dietrich, Foucart 2021]

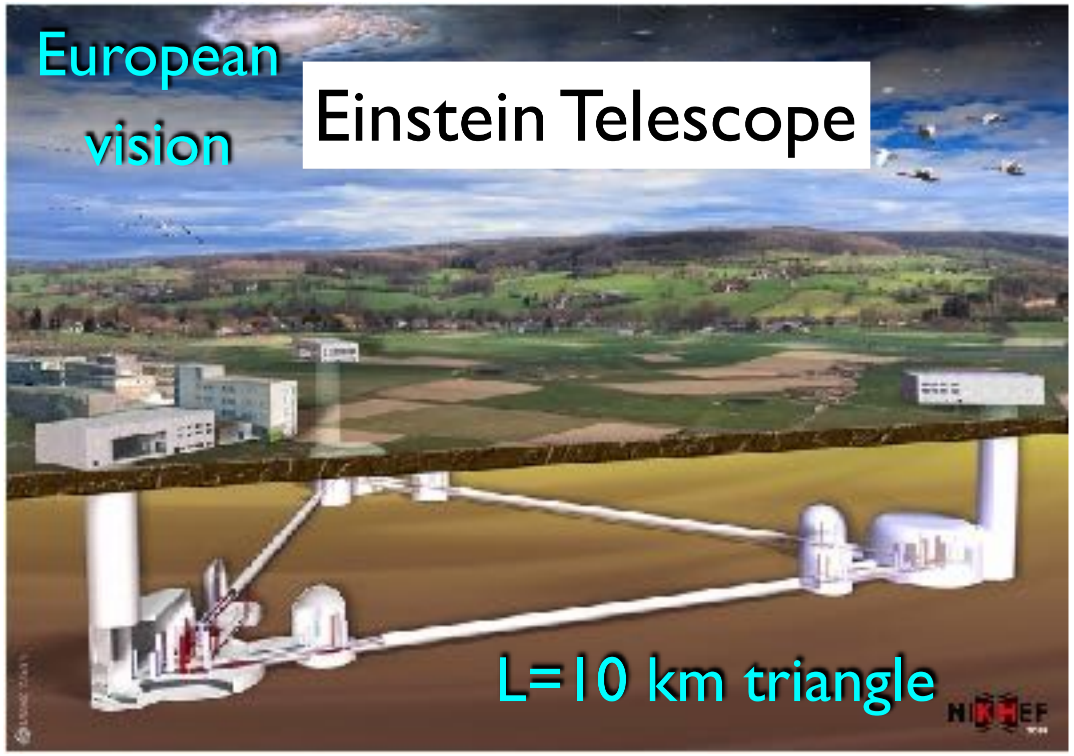
Near-term future prospects

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

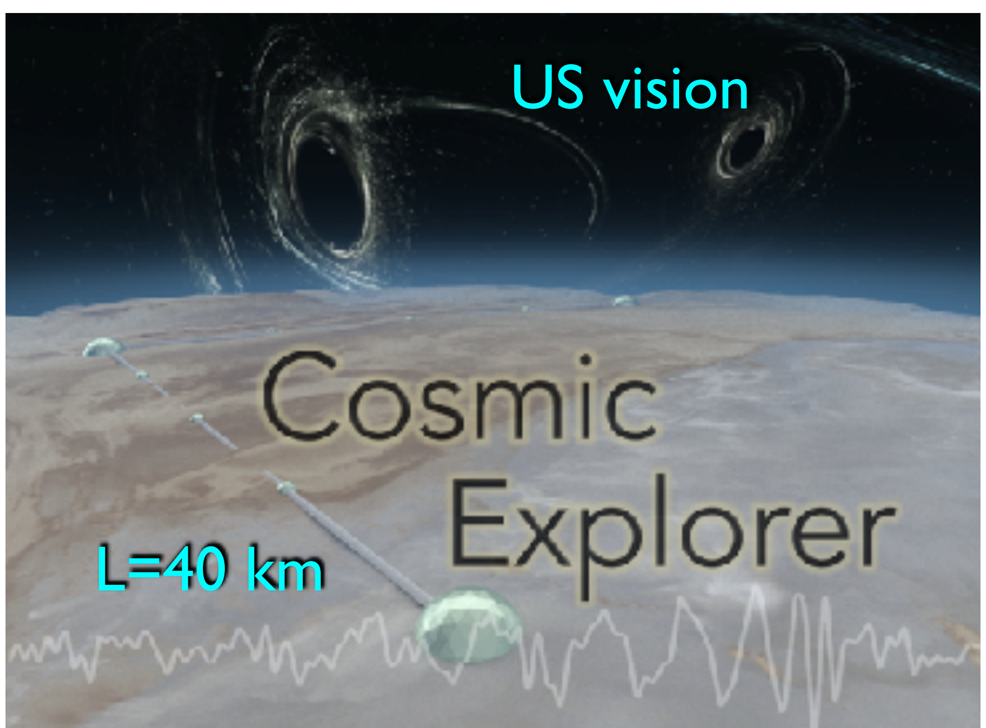
Further upgrades scheduled

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

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



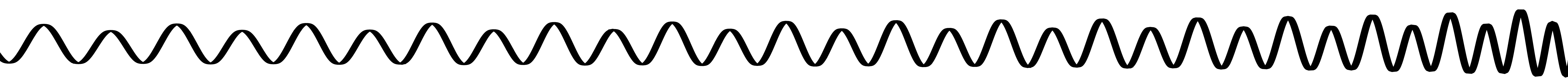
- Prototype being built in Maastricht



- 10 times better sensitivity than LIGO/Virgo
  - O(100 000) binary merger detections per year!
  - High precision studies of nearby sources
- Wider frequency range:
  - measure post-merger & tidal disruptions
  - early alerts for EM
  - tidal resonances in early inspiral

Many remaining theoretical challenges

- high accuracy and efficient waveforms over wide parameter space
- subdominant matter effects, higher modes of GW signals, arbitrary spins, more relativistic corrections, …
- Understand complex NS-NS merger regimes, include more realistic microphysics
- degeneracies (e.g. alternative gravity, dark matter)
- Eccentricity
- connection of GW parameters to fundamental matter physics
- effects of using universal relations?
- …..

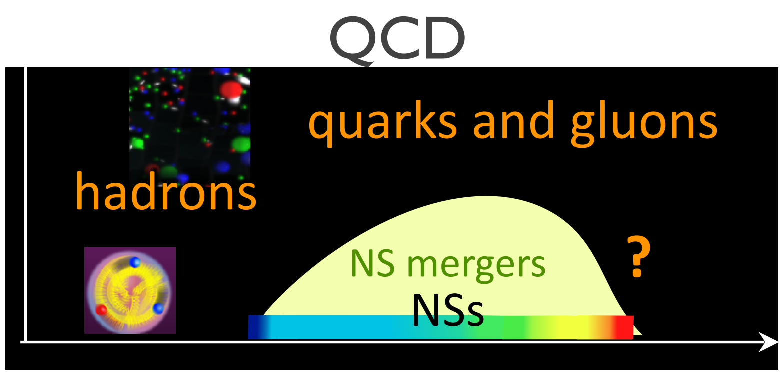


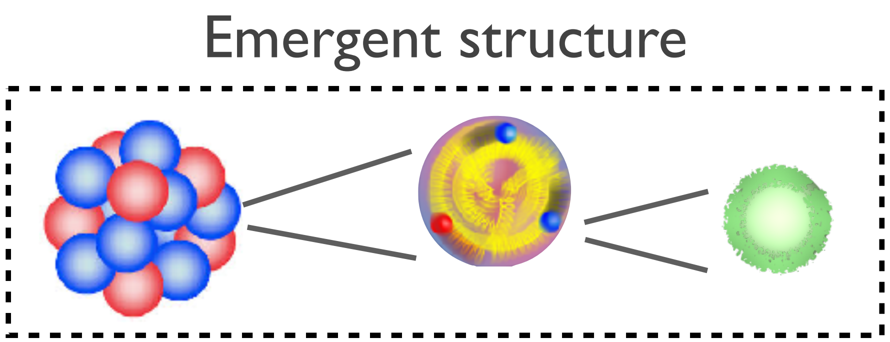
Strengthen the numerous interdisciplinary connections to maximize science benefits:

EM counterparts, x-ray & radio pulsars, nuclear & QCD theory and experiments, …

Summary and outlook

Neutron stars are unique laboratories for frontiers in fundamental physics





- GWs are new probes of NS physics
- Optimizing the science gains requires connections with various interdisciplinary information (theory, experiments, observations)
- Exciting near- & longer-term future with larger & more precise datasets
  - Much work remains on modeling, interpretation, synthesis to fully realize the science potential