# Dense Matter Science with Cosmic Explorer

**First Cosmic Explorer Conference**

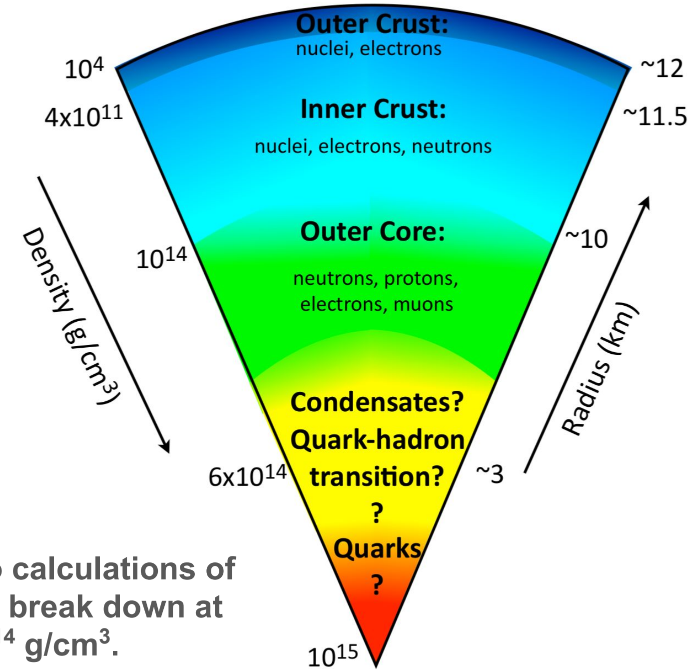
**October 26-30 2020**

Panel: Tanja Hinderer, Phil Landry, Jim Lattimer, Jocelyn Read, Sanjay Reddy, Andrew Steiner

CE-G2000058

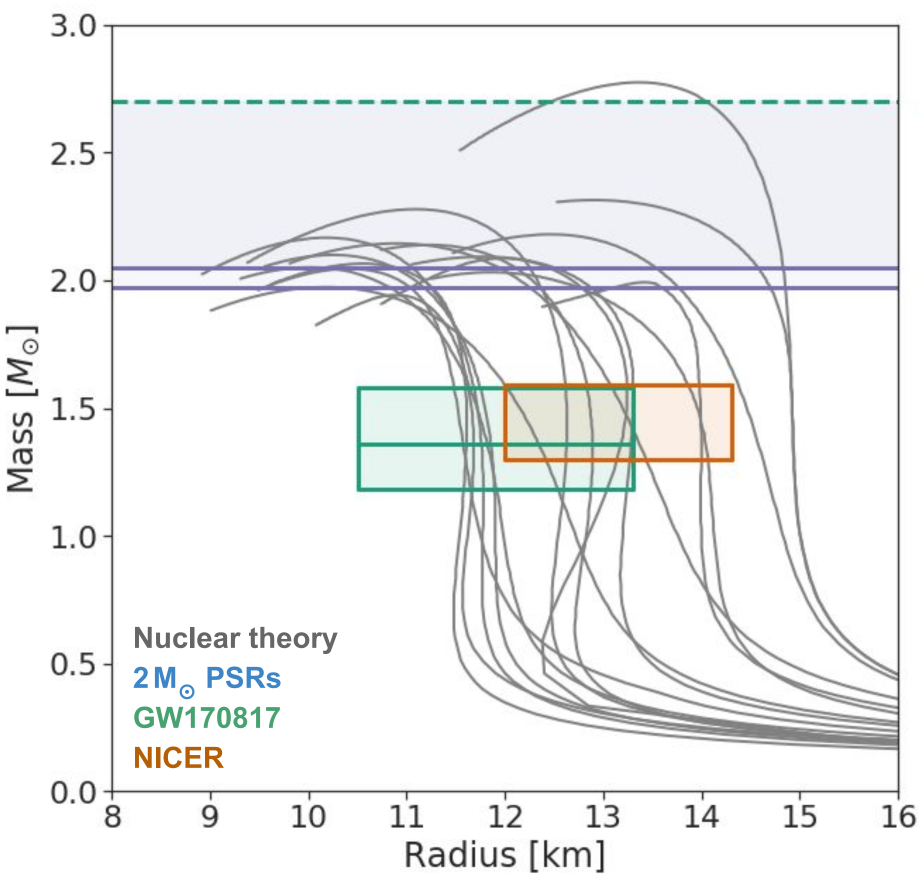
# State of the field

Emerging picture of EOS and phase structure of cold matter above nuclear density from nuclear theory and NS observations.

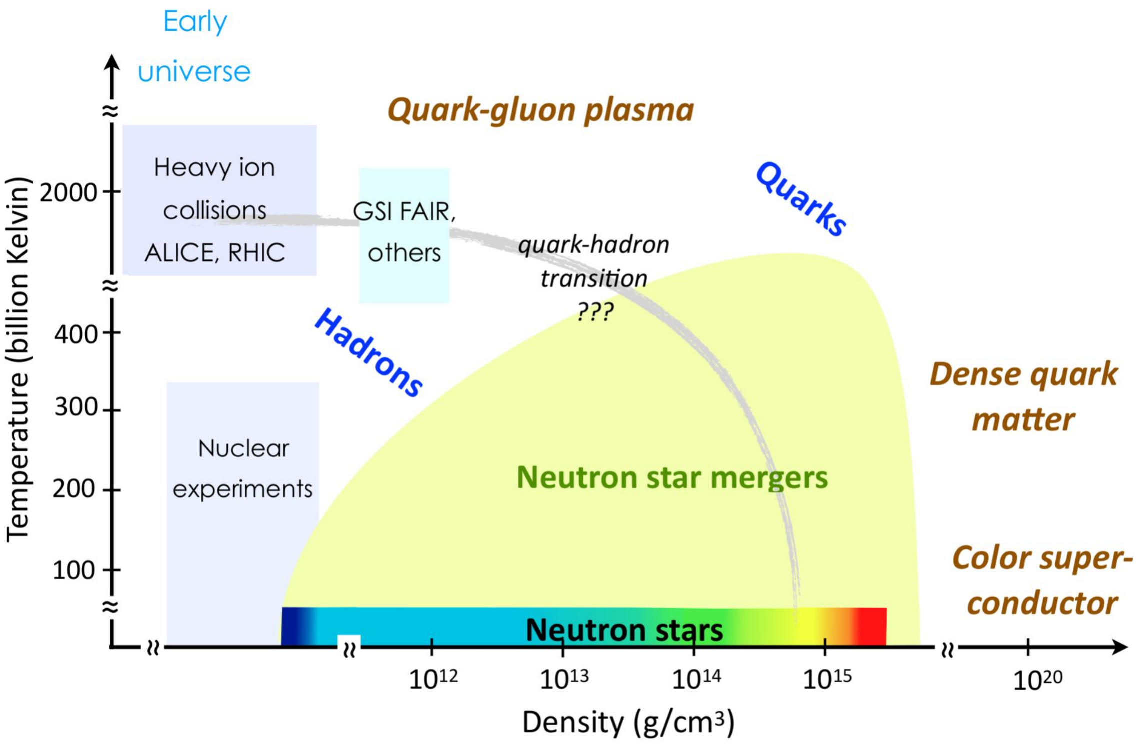



**Ab initio calculations of the EOS break down at ~ 5 x $10^{14}$ g/cm$^3$.**

**Constraints on the NS mass-radius relation.**



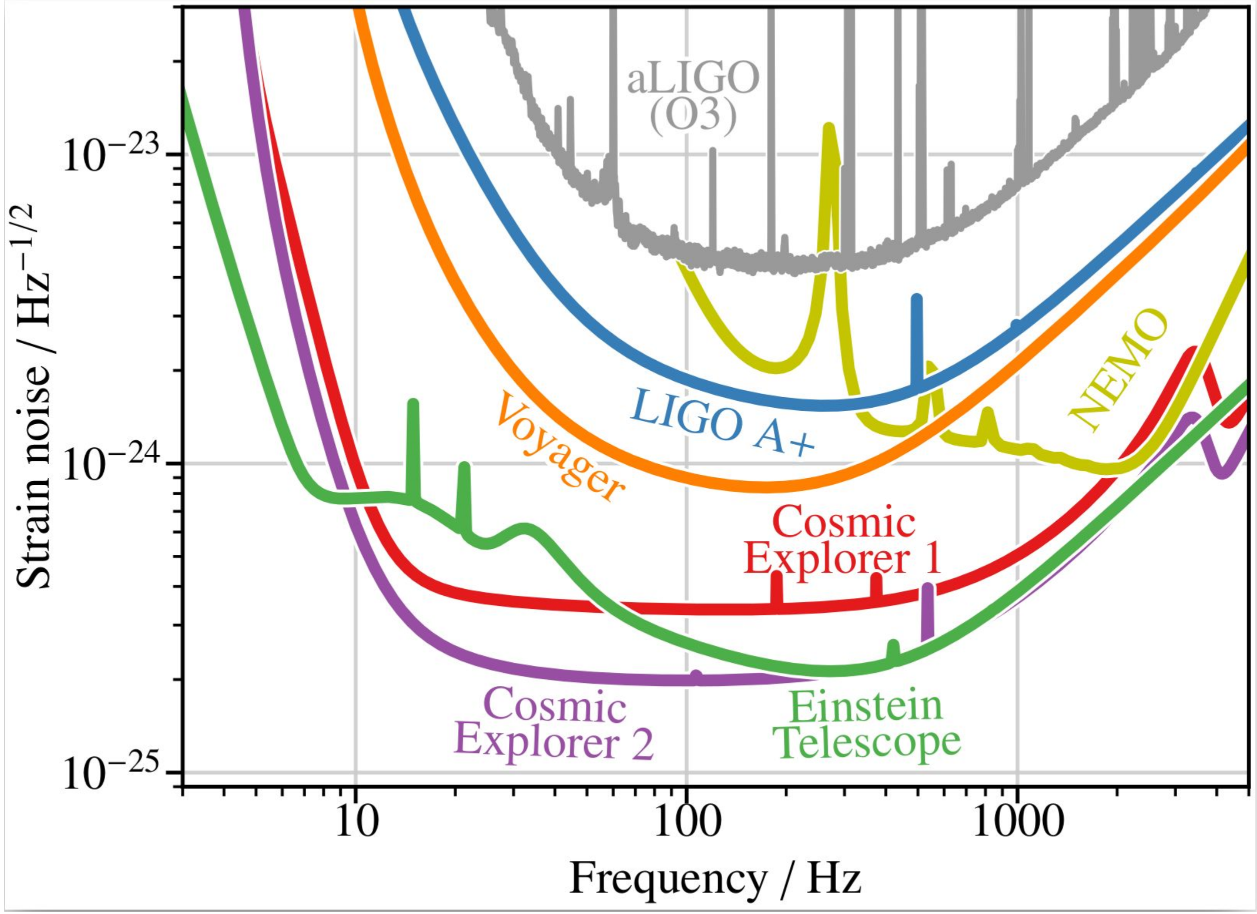
# Open questions




**The phase diagram of quantum chromodynamics.**

- QCD phase structure at high densities, finite temperature?
  *Baym+ Rep Prog Phys (2018)*
- Exotic matter in NS cores?
  *e.g. Annala+ Nat Phys (2020)*
- Dynamical and transport properties of dense matter?
- Dark matter inside NSs?
  *e.g. deLavallaz+Fairbarn PRD (2010)*
- Implications for r-process nucleosynthesis, NS population, ...

# GW observatory landscape




**Planned sensitivity of different future GW observatories.**

| | |
|---|---|
| aLIGO aVirgo KAGRA | 2020 |
| aLIGO → LIGO A+ + LIGO India | 2025 |
| LIGO A+ → Voyager + NEMO | 2030 |
| + Einstein Telescope + Cosmic Explorer | 2035 |

# Cosmic Explorer

Cosmic Explorer will capture NS mergers with incredible depth and precision.

*CE concept talk by E. Hall, CE-G2000048*

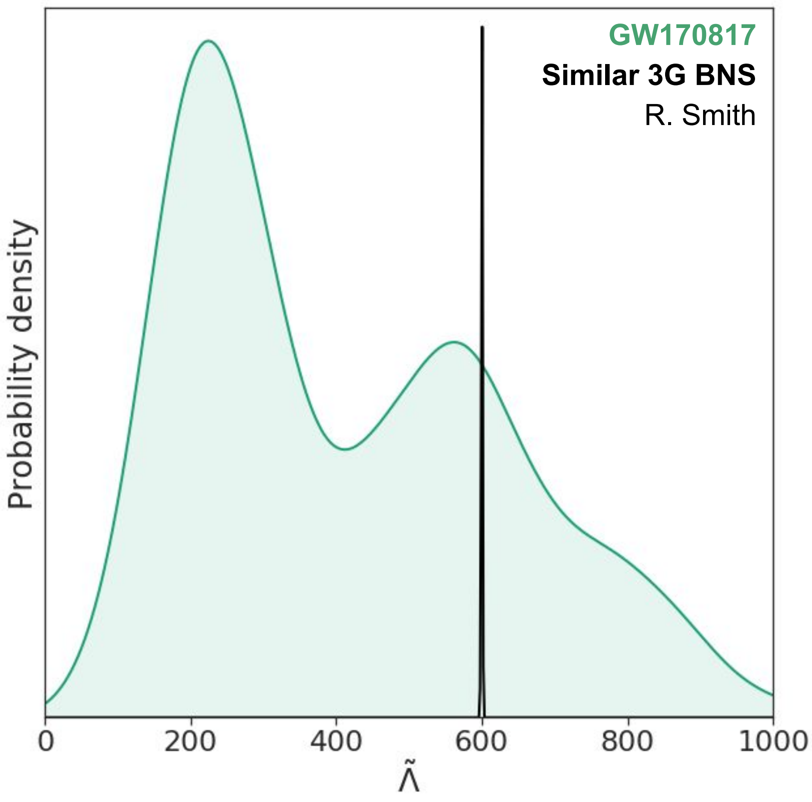
*CE trade study talk by S. Borhanian, CE-G2000054*

**Deeper:** BNS horizon of z ~ 10, complete NS merger catalog to z ~ 1 in 3G network

**Wider:** BNS mergers from 10 Hz to 3 kHz, will see late inspiral, contact + postmerger

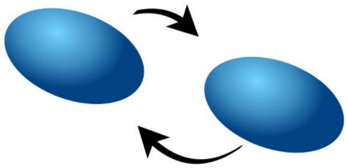
**Sharper:** GW170817-like event in CE will have SNR ~ 1700 instead of ~ 30

**Binary tidal deformability in 2G vs 3G network.**



# Inspiral GWs from the population of NS mergers

Cosmic Explorer will make precision measurements of nearby events and capture the population of merging NSs out to cosmological distances.



Phasing due to adiabatic tides accumulates over the whole inspiral.

**$\tilde{\Lambda}$ - leading-order quadrupole tides @ 5PN**

**$\delta\tilde{\Lambda}$ - next-to-leading-order quadrupole tides @ 6PN** *Wade+ PRD (2014)*

**Gravitomagnetic tides, spin-tide couplings, octupole tides @ 6PN + up** *Banihashemi+Vines PRD (2020)* *Jimenez-Forteza+ PRD (2018)*

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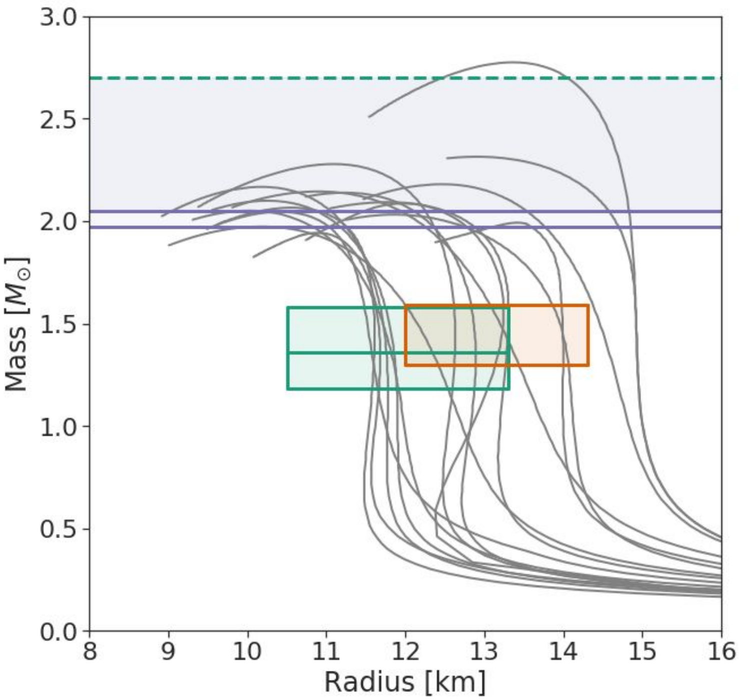
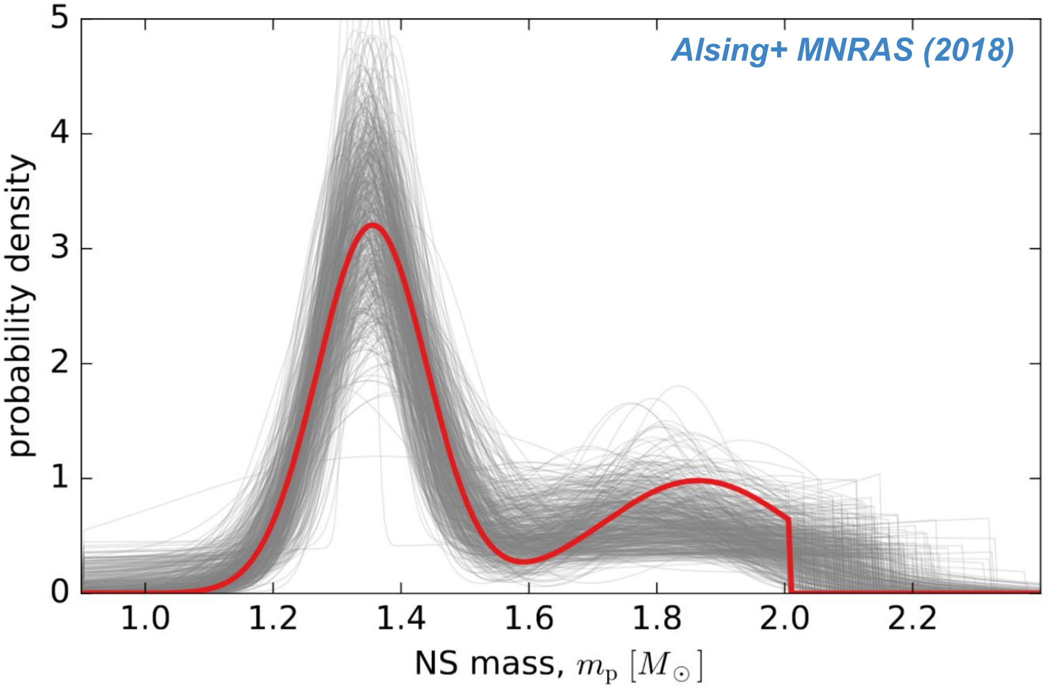
**Constraints on the NS mass-radius relation.**




**Best-fit mass distribution for Galactic pulsars.**



# Inspiral GWs from the population of NS mergers

Cosmic Explorer will make precision measurements of nearby events and capture the population of merging NSs out to cosmological distances.

## Opportunities:

- Measure tidal deformabilities across the full NS mass spectrum
- Precision measurements of masses, spins and tides for the loudest events
- Search for outliers in the population *e.g. Chatziioannou+Han (PRD 2020)*

## Challenges:

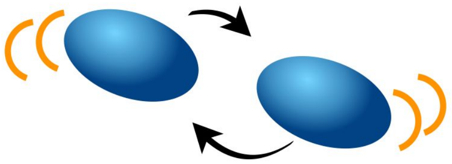
- ⚠️ Simultaneous inference of the EOS and NS population *Wysocki+ arXiv:2001.01747*
- ⚠️ Systematic uncertainties in waveform models *e.g. Huang+ arXiv:2005.11850*

**Will precision measurements of tidal parameters already be done by the 2030s?**

**How much do we learn from the large population of very distant NS mergers?**

# Dynamics of matter in inspiral GWs

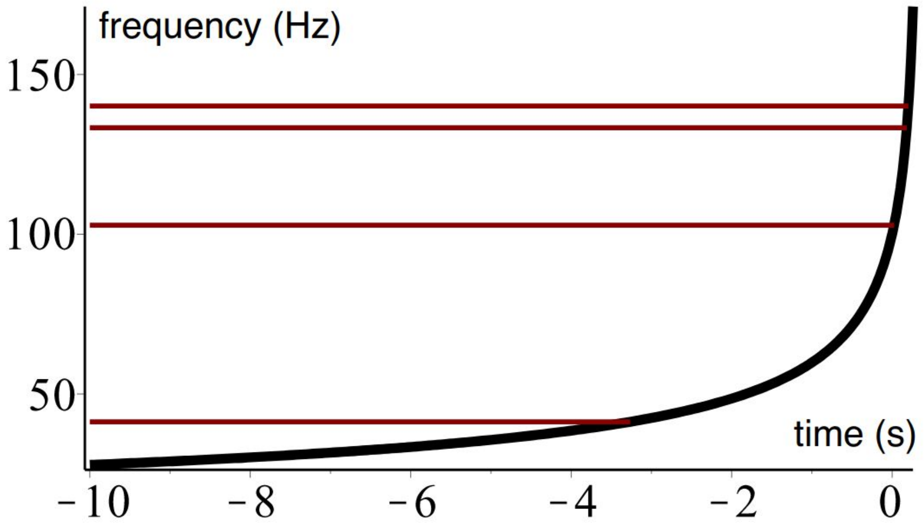
Cosmic Explorer will have ~10x aLIGO sensitivity through the latest stages of the inspiral.



- Tidal field provides driving force for fluid oscillations (f-modes, inertial modes)
  *Kokkotas+Schmidt LRR (1999)*
- Resonances when orbital and mode frequencies match
- Transfer of orbital energy into oscillations accelerates coalescence
- Possible mode-mode couplings and instabilities (e.g. p-g modes)
  *Weinberg+ ApJ (2013)*

**Cartoon of dynamical tidal resonances during BNS inspiral.**

*Poisson PRD (2020)*

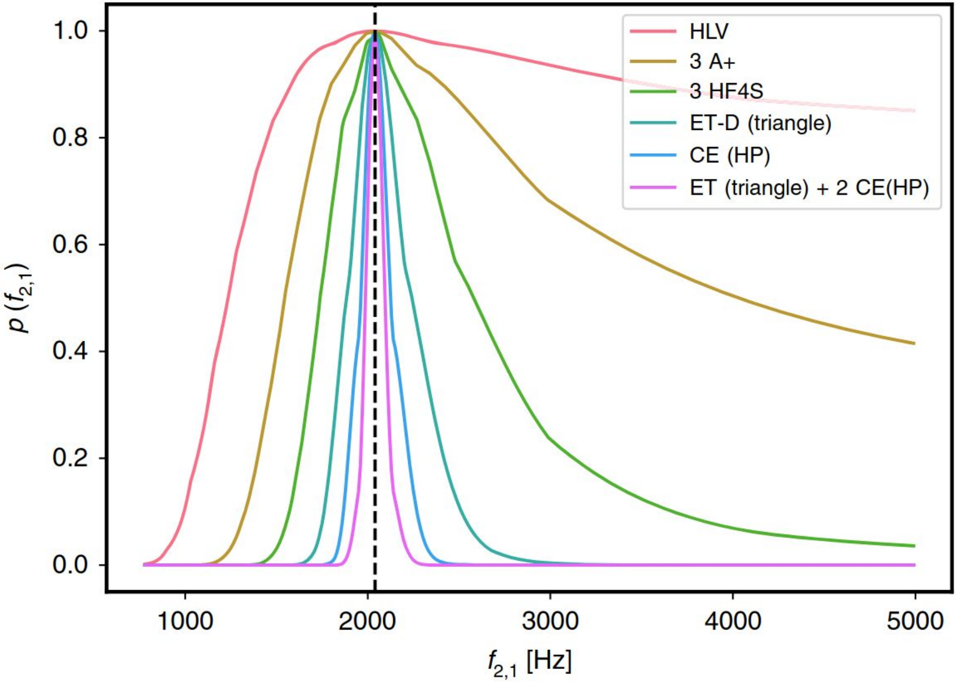


# Dynamics of matter in inspiral GWs

Cosmic Explorer will have ~10x aLIGO sensitivity through the latest stages of the inspiral.

**Constraints on f-mode frequency for a GW170817-like event.**

*Pratten+ Nat Commun (2020)*



# Dynamics of matter in inspiral GWs

Cosmic Explorer will have ~10x aLIGO sensitivity through the latest stages of the inspiral.

**Opportunities:**

- ☐ Measure the resonant frequencies of dense matter’s oscillation modes
- ☐ Search for exotic phases within NSs via GW asteroseismology *e.g. Orsaria+ J Phys (2019)*

**Challenges:**

- ⚠️ Theoretical uncertainty in mode couplings, relativistic corrections
- ⚠️ Develop realistic semi-analytic models for use with phenomenological waveforms

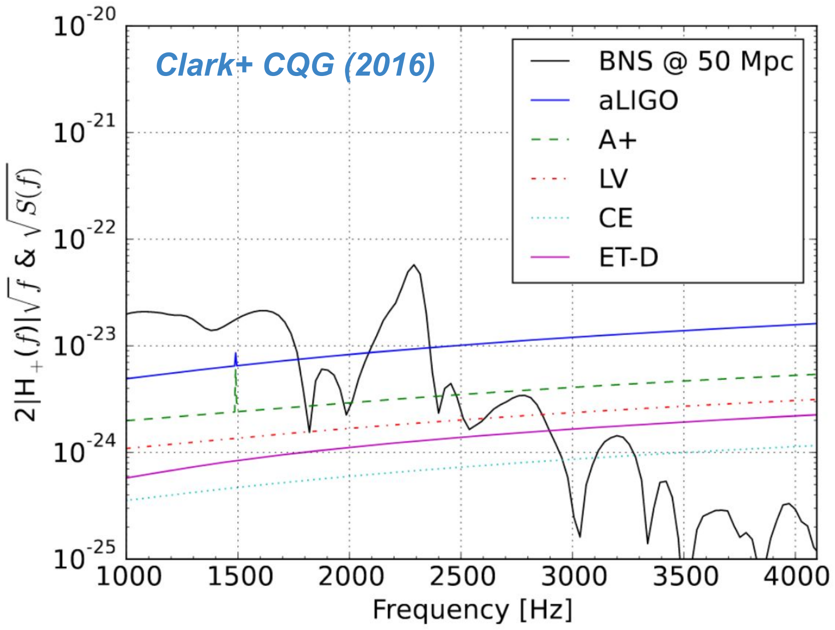
*Schmidt+Hinderer PRD (2019)*

**Will these resonances be individually resolvable in Cosmic Explorer?**

**Is our theoretical understanding of tidal resonances/instabilities complete enough for the 3G era?**

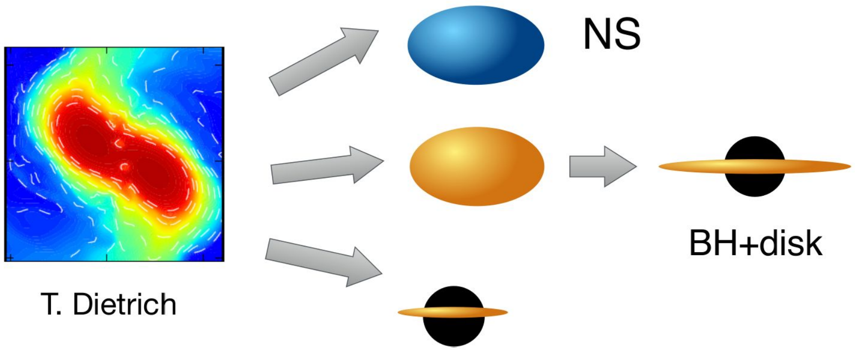
# Postmerger GWs from binary NSs

Cosmic Explorer will detect GWs from the postmerger oscillations of NS merger remnants.




**Characteristic frequency-domain postmerger signal compared to detector sensitivities.**

- The peak frequency is the remnant's fundamental quadrupole oscillation mode (f-mode)
- It is typically 2-3 kHz depending on the EOS
- The morphology of the postmerger signal reveals the fate of the remnant



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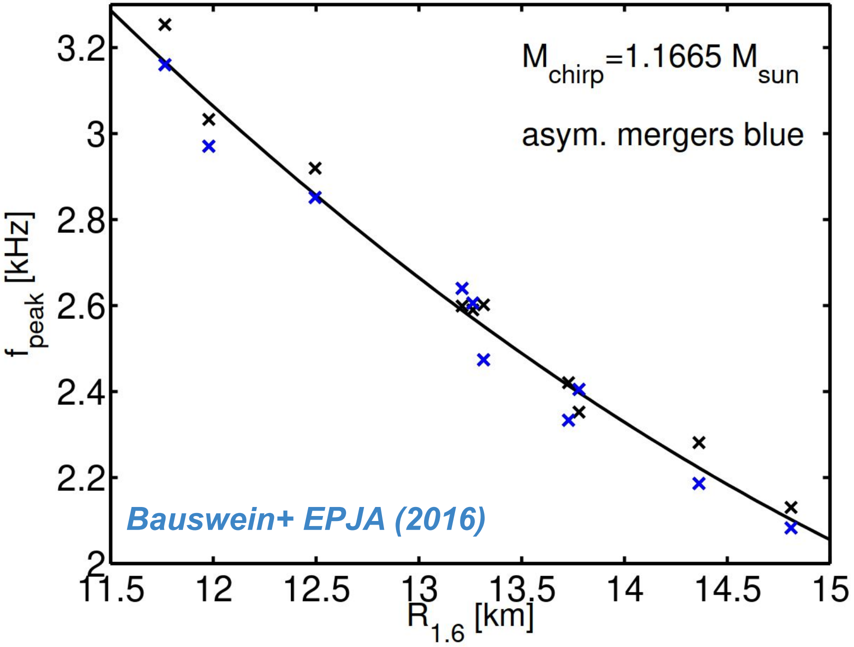


**Correlations between pre- and postmerger observables.**

# Postmerger GWs from binary NSs

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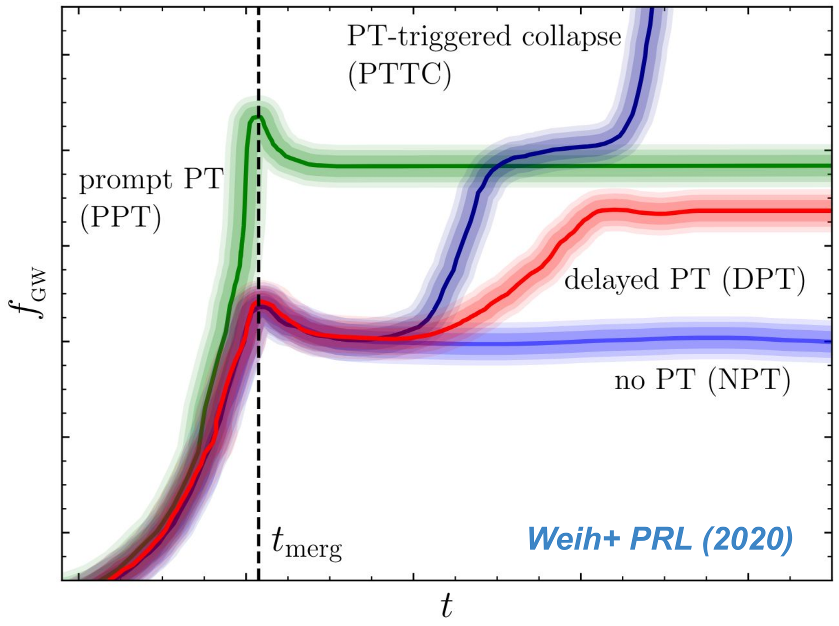



**Time evolution of peak postmerger frequency for different phase transitions.**

# Postmerger GWs from binary NSs

Cosmic Explorer will detect GWs from the postmerger oscillations of NS merger remnants.

## Opportunities:

- ☐ Measure postmerger oscillation frequencies to constrain the high-density, finite-T EOS
- ☐ Observe the signature of a strong phase transition in the postmerger signal morphology
- ☐ Determine the threshold mass for collapse of a rotating NS to a BH

## Challenges:

- ⚠️ Numerical simulations needed to link postmerger observables to matter properties
- ⚠️ Informative postmerger observations rely on precise inspiral measurements

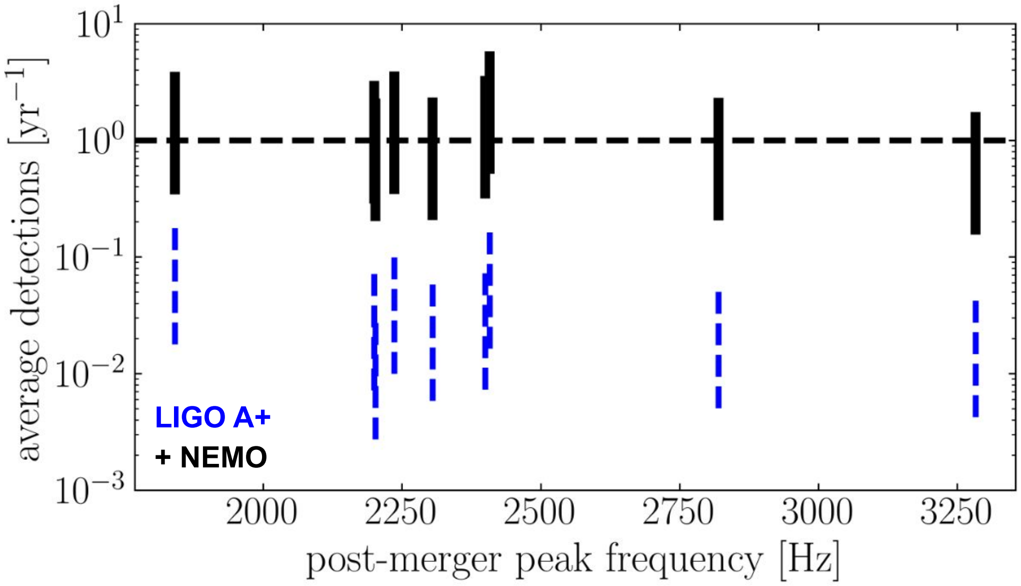
**Should the Cosmic Explorer design be optimized for postmerger signals?**

**What theoretical and computational work is needed to prepare for finite-T EOS inference?**

# NEMO

NEMO is the Australian proposal for a postmerger-optimized GW detector to bridge the gap between LIGO A+ and full-scale 3G detectors.

**Expected number of postmerger signals detected per year in a 2G network with and without NEMO.**




***Ackley+ arXiv:2007.03128***

*NEMO concept talk by D. Ottaway, LIGO-G2001868*

- Interferometer with 4 km arms
- Technology driver for Cosmic Explorer
- Operational by the late 2020s

# Continuous GWs

Cosmic Explorer may detect continuous GWs from pulsar ellipticity or r-modes.

**Monochromatic signal that scales with pulsar rotation, so typical frequencies could range up to ~ 1 kHz.**

***Sieniawska+Bejger Universe (2019)***

## Opportunities:

- ⬜ Probe dense matter in isolated NSs or evolving NS binaries
- ⬜ Explore interplay of dense matter and strong magnetic fields, rotation

## Challenges:

- ⚠️ Theoretical uncertainty in the amplitude of the signal

**Is Cosmic Explorer likely to detect continuous GWs?**

**What’s the most compelling information continuous GWs provide vs compact binaries?**

# Synergy with EM observations of NSs

Cosmic Explorer will help get more dense matter science out of electromagnetic observations of pulsars.

**EM observatory landscape**

Moment of inertia, spin distribution - radio pulsar timing, e.g. Square Kilometer Array *Watts+ arXiv:1501.00042*

Mass, radius - x rays, e.g. NICER, Chandra, eXTP, Athena, Lynx *Watts+ Rev Mod Phys (2016)*

## Opportunities:

- ☐ Joint GW + EM EOS constraints, validate NS radius measurements
- ☐ Compare matter observables across different NS populations

**Will x-ray measurements of pulsar radii be competitive with GWs in the 2030s?**

**What would variability in NS properties between GW and EM populations tell us?**

# Discussion

**What does the next decade hold for dense matter? Will the cold EOS be known by the 2030s?**

**Which kinds of dense-matter observations are unique to Cosmic Explorer?**

**Will we learn more from rare exceptional events or the mundane many in the 3G era?**

**Are current BNS and NSBH waveforms accurate enough for SNR ~ 1000 events?**

**Does Cosmic Explorer have a role to play in dark matter searches?**

**Are postmerger simulations realistic enough to infer the finite-T EOS from observations?**

**Would a single postmerger-optimized 3G detector suffice for dense matter science?**

**What surprise finds would revolutionize dense matter knowledge? Will Cosmic Explorer see them?**