Constraints on neutron star equation of state from future gravitational wave observations

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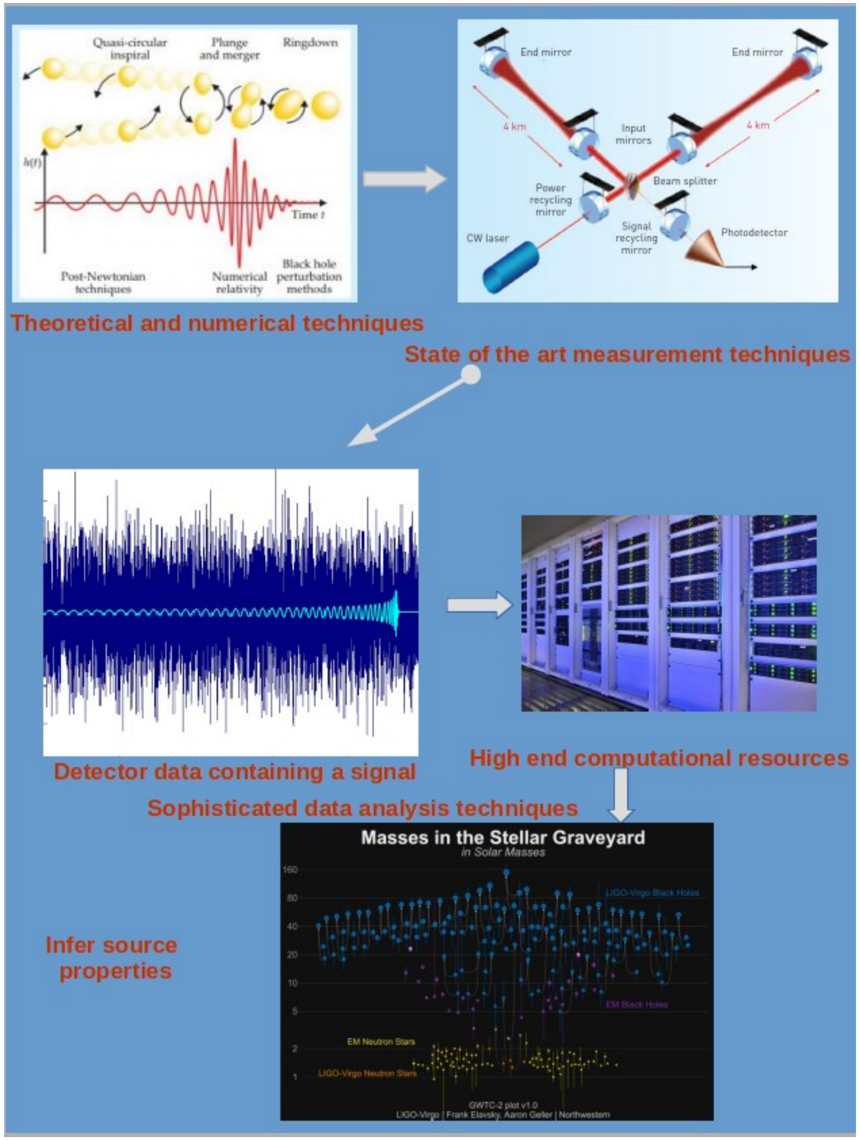
Plan of talk

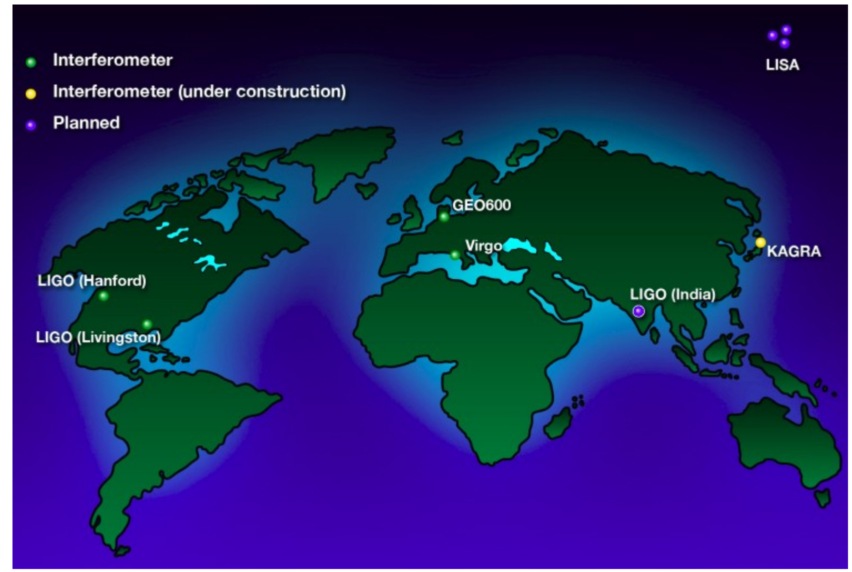
- Challenges and Science with future detectors:
  - Overlapping signals in data.
  - Systematics from incomplete modelling.
  - Extracting quasi-universal relations from future detector era.

Gravitational wave astronomy and data analysis

- Gravitational wave signals characterised by parameters describing their source; estimated using *statistical analysis* of data.
- *Sophisticated models needed in presence of a neutron star*.
- *Incomplete understanding of physics may lead to a modified signal*.



Future detectors

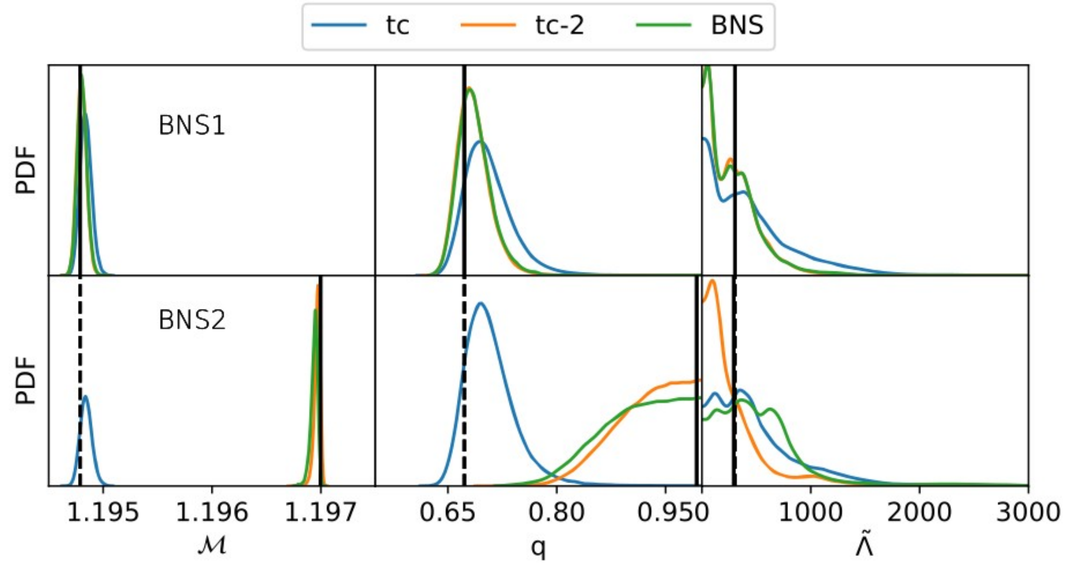


https://writescience.wordpress.com/

More sensitive detectors; more accurate measurements while data analysis challenges from systematics

Data analysis challenge: overlapping signals

- In the third generation era, GW data will contain overlapped signals.
- Such signals will still be detected; may pose a problem for robust parameter estimation.



BNS parameter estimates when two BNSs overlap

Rate	BBH mergers > 1	BNS mergers > 1	Any mergers > 1
Low rate	48	155	374
Median rate	127	2412	3663
High rate	303	15581	20149

Samajdar, Janquart, Van Den Broeck, Dietrich, Phys. Rev. D 104, 044003 (2021)

Overlapping signals

- Extracting parameters of individual signals may become problematic with current parameter estimation infrastructure.

- Other challenges remain: parameter estimates in case of multiple overlaps, presence of spins ...

Imprint of tidal deformabilty

- Neutron stars (NSs) characterised by equation-of-state $\Lambda(m)$; how deformable a NS is.

- Tidal deformability imprinted in the GW phasing as a neutron star binary inspirals.

$$Q_{ij} = -\lambda(m)\,\mathcal{E}_{ij}$$

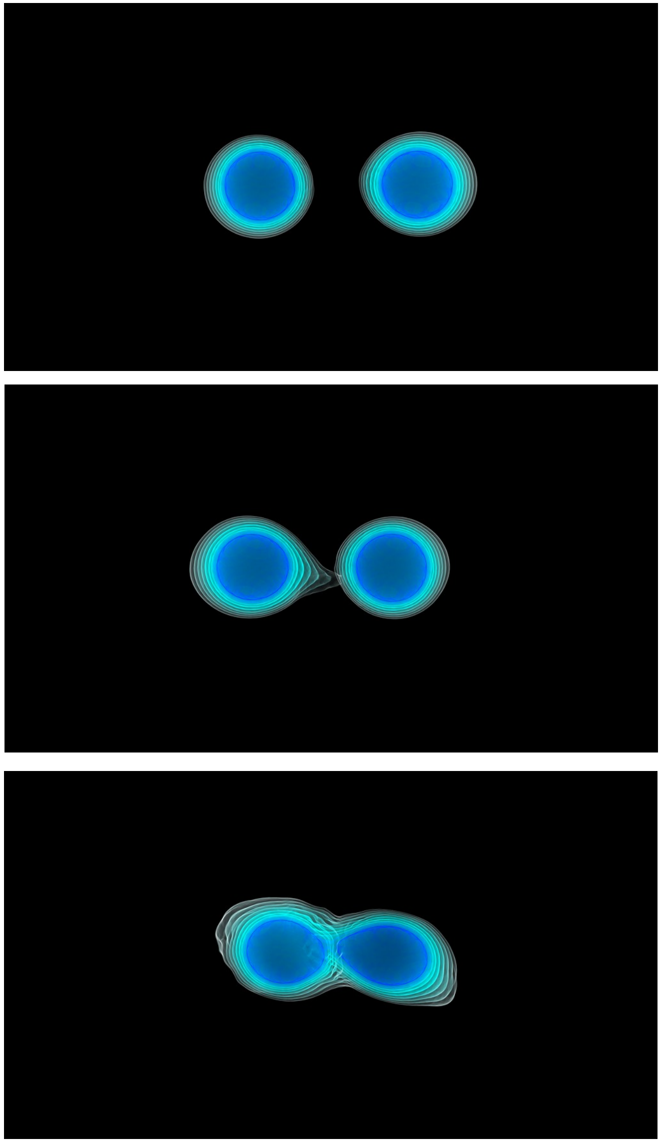


Figure courtesy: Tim Dietrich

Extracting tidal deformability

$$h = \mathcal{A}(f)\exp^{i\Psi(f)}$$

For a binary neutron star waveform:

$$\Psi(f) = \Psi_{\rm PP}(f) + \Psi_{\rm SO}(f) + \Psi_{\rm SS}(f) + \Psi_{\rm Tides}(f)$$

Point-particle phasing

Tidal phasing

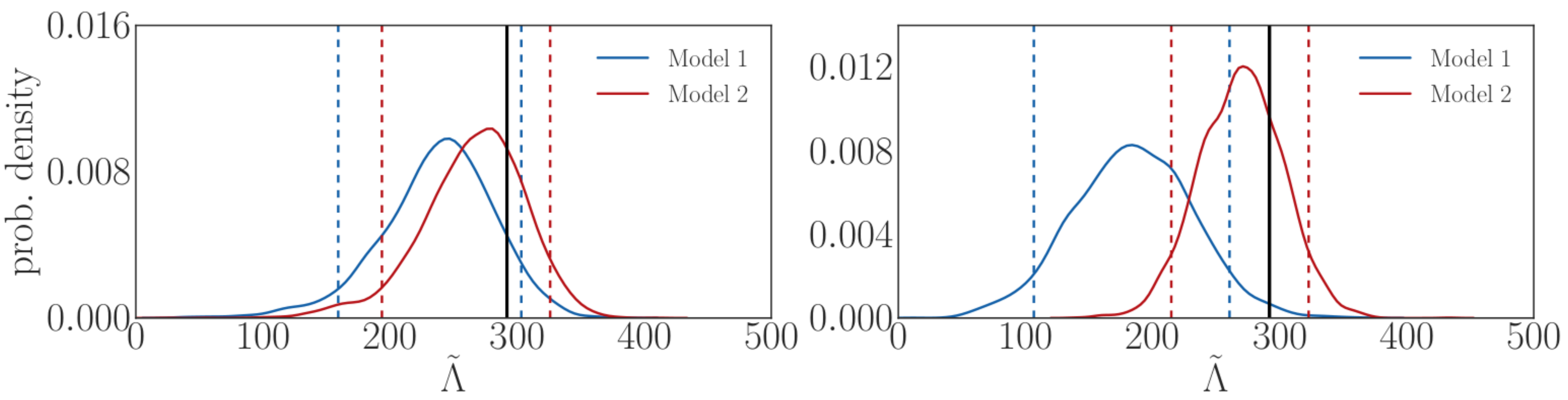
Do tidal estimates change as the tidal description is kept fixed, but the assumptions to model the inspiral dynamics are changed?

Estimate tidal parameter: $\tilde{\Lambda} = \frac{16}{13}\sum_{i=1}^{2}\Lambda_i\left(\frac{m_i}{M}\right)^4\left(12 - 11\frac{m_i}{M}\right)$

$$\Lambda_i = \frac{2}{3}k_2^i\left(\frac{R_i}{m_i}\right)^5$$

Extracting tidal deformability in design sensitivity of Advanced LIGO and Virgo

- Simulated sources in noise in design sensitivity.
- Tidal estimates consistent among waveform models for GW170817 – no longer true in future era.
- Varying the inspiral model for a GW170817-like source in design sensitivity:



Samajdar and Dietrich, Phys. Rev. D 98, 124030 (2018)

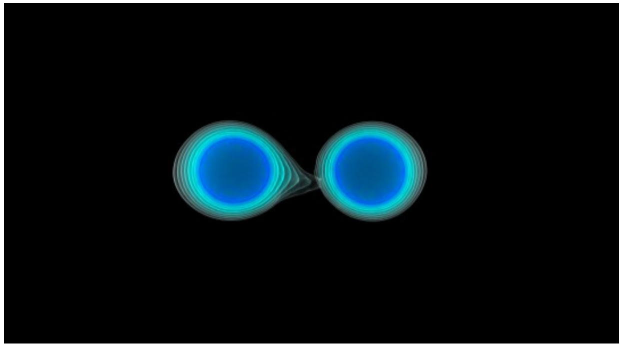
Quasi-universal relations

- Spinning NSs become oblate and acquire an additional spin-induced quadrupole moment *q*

$$q = -\frac{5}{2}\lim_{r\to\infty}\left(\frac{r}{M}\right)^3\int_{-1}^{1}\nu(r,\theta)P_2(\cos\theta)d\cos\theta$$

where $P_2(x) = (3x^2 - 1)/2.$

$$q \sim -Q\chi^2$$



- Relations found to hold across equations-of-state – quasi universal (QU) relations (Yagi and Yunes, Science 341, 365 (2013)):

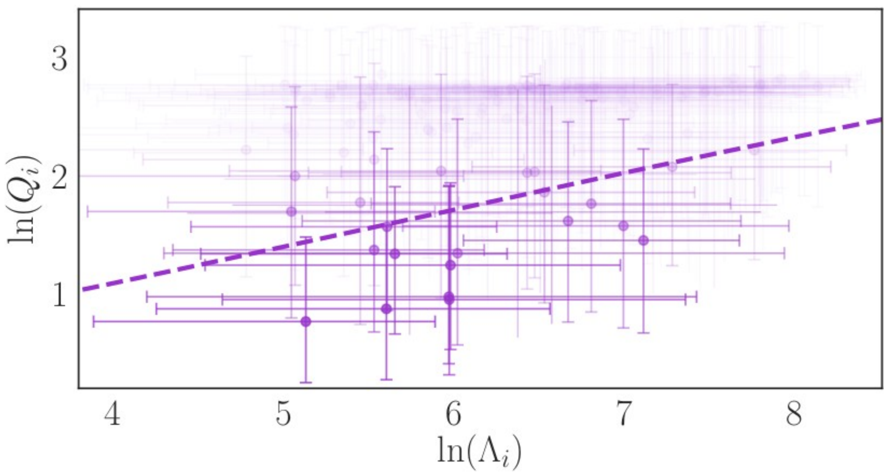
$$\ln Q_i = a + b\ln\Lambda_i + c\ln{\Lambda_i}^2 + d\ln{\Lambda_i}^3 + e\ln{\Lambda_i}^4$$

$a = 0.194, b = 0.0936, c = 0.0474, d = -4.21\times10^{-3}, e = 1.23\times10^{-4}$

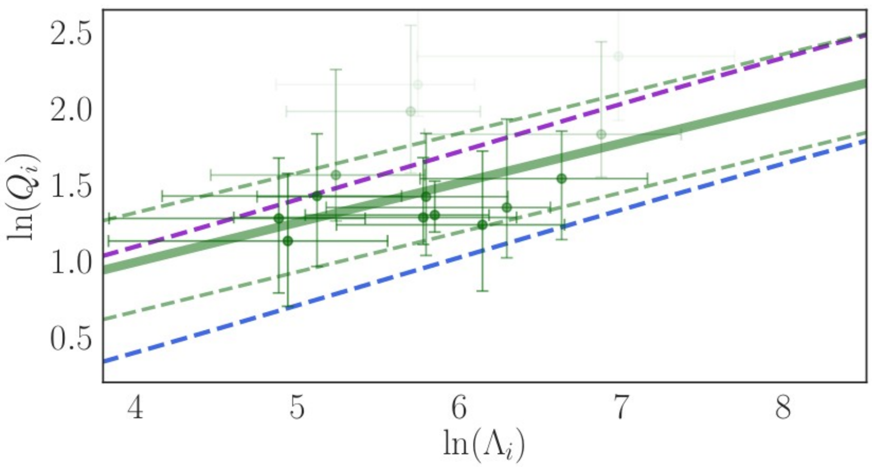
Verifying QU relations from data

- Extracting QU relations from GW data:
  - Verify Yagi-Yunes (YY) relation
  - *Ad-hoc QU relation*; $Q \rightarrow Q_{YY}/2$
- Simulate several binary neutron star sources in design sensitivity and third generation era.
- Find the best fit relation from recovered Q versus Λs.

Verifying Yagi-Yunes relation



Simulations in design sensitivity



Simulations in 3G network

Best fit relation:

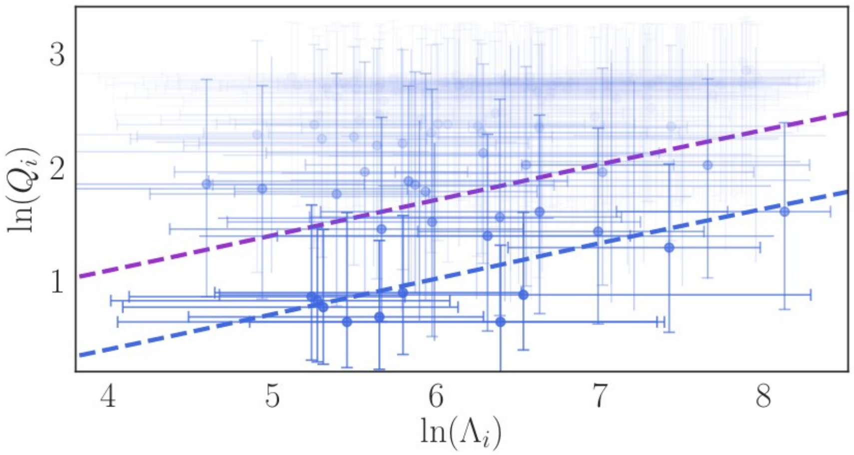
$$\ln Q = \hat{a}_i + \hat{b}_i \ln \Lambda$$

where

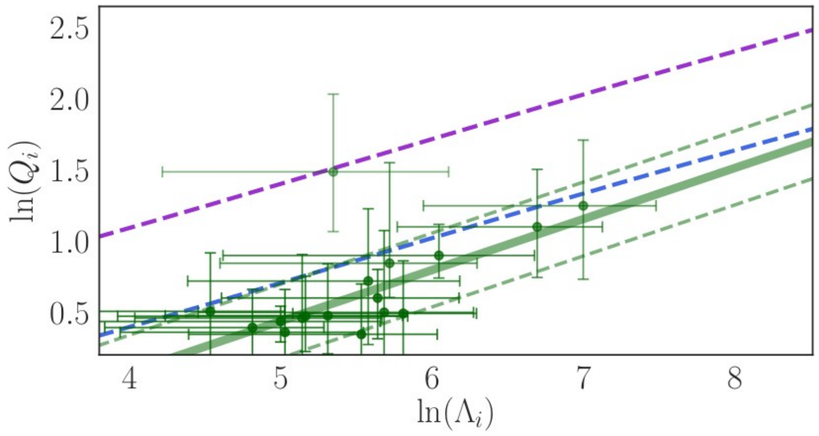
$\hat{a} = -0.05014, \ \hat{b} = 0.2595$

Samajdar and Dietrich, Phys. Rev. D 101, 124014 (2020)

Verifying other QU relation



Simulations in design sensitivity



Simulations in 3G network

Best fit relation:

$$\ln Q = \hat{a}_i + \hat{b}_i \ln \Lambda$$

$$\text{where } \hat{a} = -1.348, \ \hat{b} = 0.357$$

Samajdar and Dietrich, Phys. Rev. D 101, 124014 (2020)

Summary

- GW sources seen so far have already provided stringent constraints on fundamental Physics.
- While future detectors will be more sensitive, challenges remain to overcome systematics.
- Further constraints on fundamental Physics possible with future detectors.