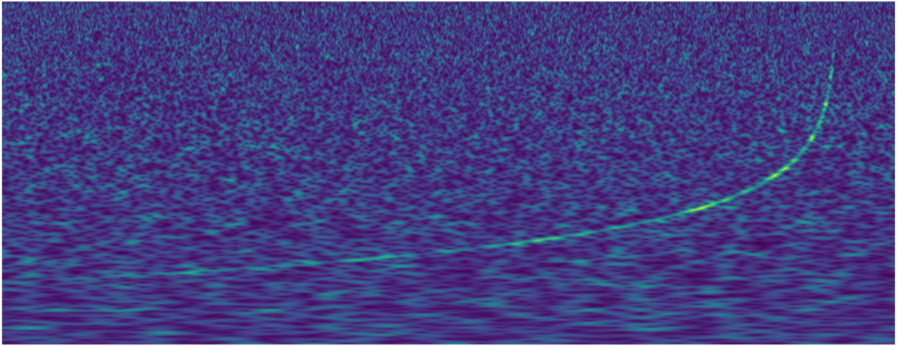
GW170817 detection and characterization



Michał Wąs
for the LIGO and Virgo collaborations

LIGO-G1702344 / VIR-0927A-17

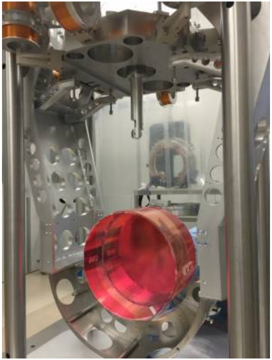
Basics of interferometric gravitational wave detections

Need two ingredients: two test masses and a ruler

Basics of interferometric gravitational wave detections

Need two ingredients: two test masses and a ruler

Test mass

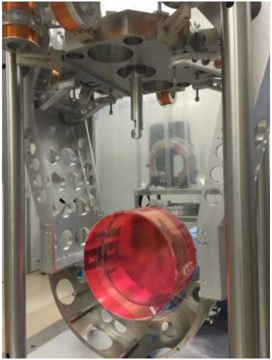


"Free falling" objects that sense the gravitational wave

Basics of interferometric gravitational wave detections

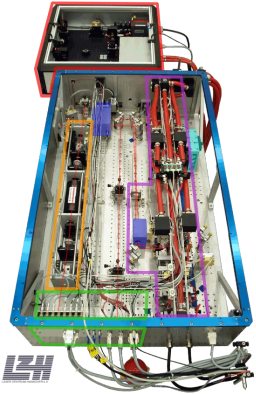
Need two ingredients: two test masses and a ruler

Test mass



"Free falling" objects that sense the gravitational wave

Ruler

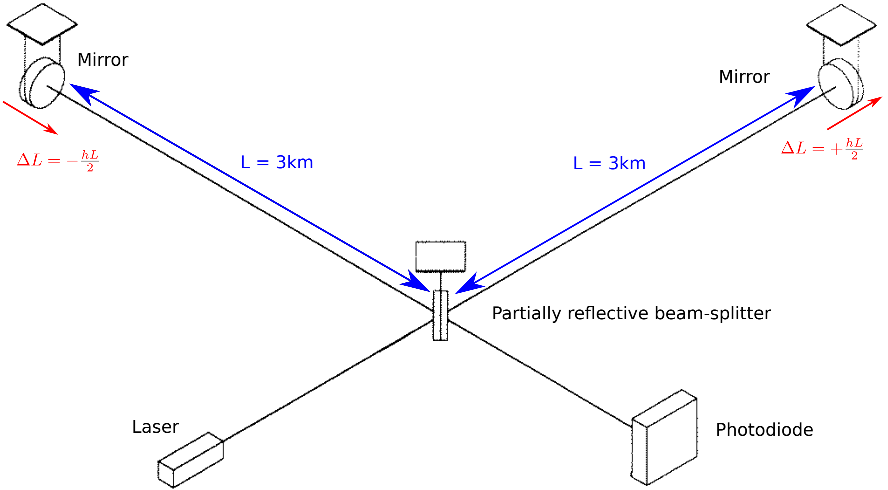


$\Rightarrow$ laser light

$\rightarrow$ the wavelength is the ruler tick mark

Basics of interferometric gravitational wave detections

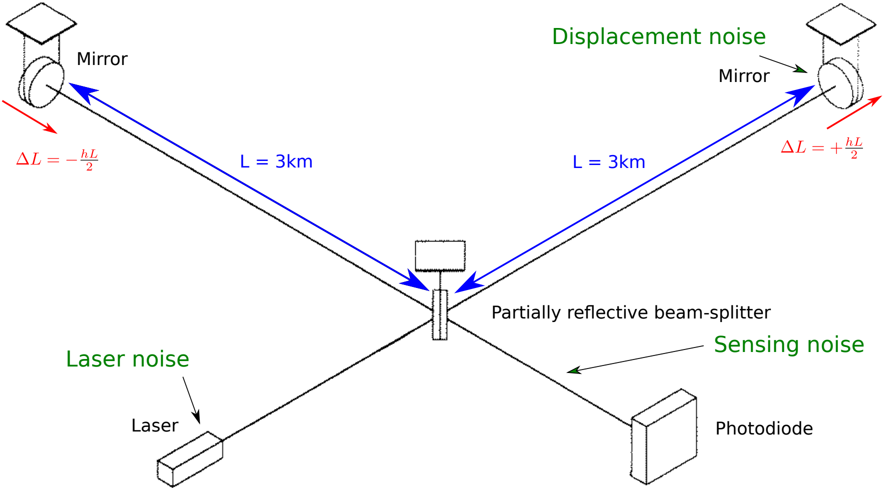
Need two ingredients: two test masses and a ruler



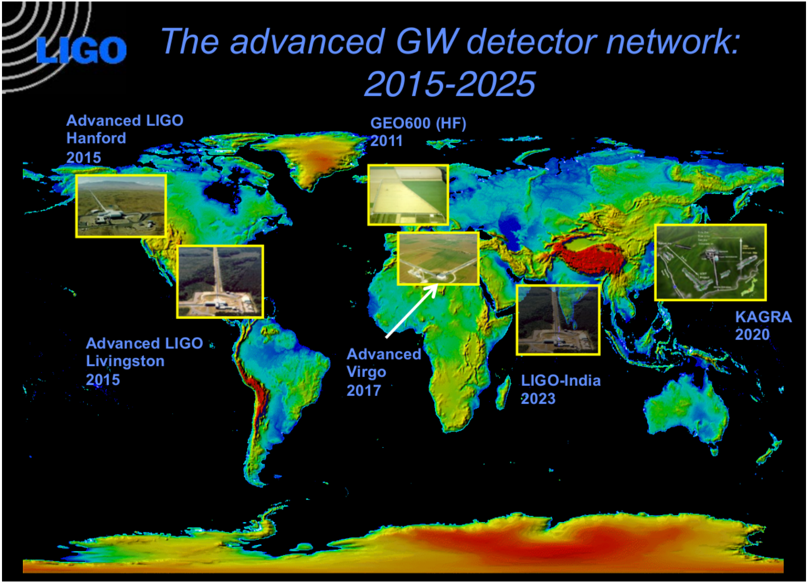
- Longer arms $\longrightarrow$ larger effect
- Sees only one gravitational wave polarization

Basics of interferometric gravitational wave detections

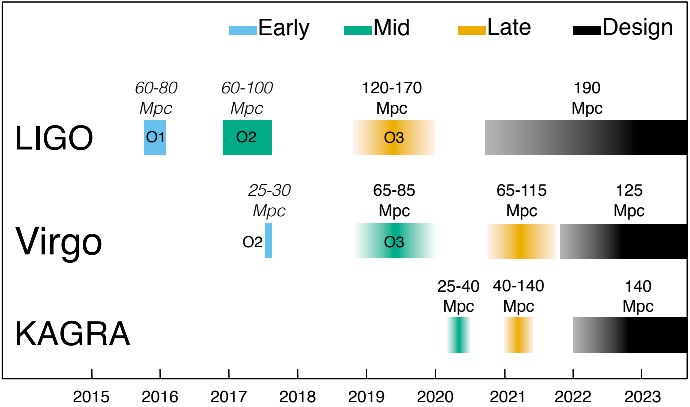
Noise can spoil measurements in many different ways



- Most noises don't increase with arm length


LIGO
The advanced GW detector network: 2015-2025
Advanced LIGO
Hanford
2015
GEO600 (HF)
2011
KAGRA
2020
Advanced LIGO
Livingston
2015
Advanced
Virgo
2017
LIGO-India
2023

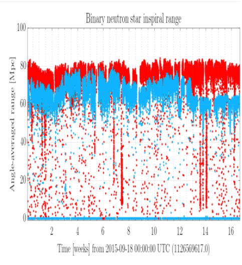
Advanced detectors time-line

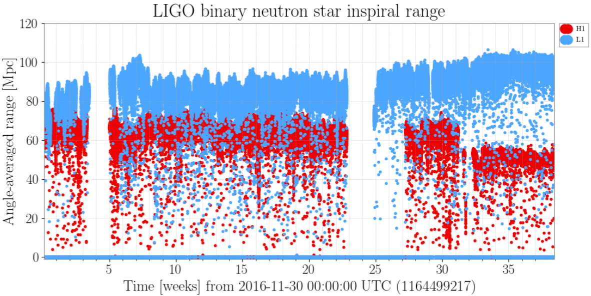


- Stephen Fairhurst will talk on Thursday about future observations

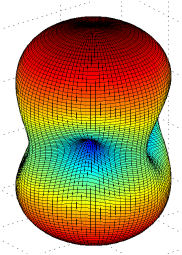
KAGRA/LIGO/Virgo arXiv:1304.0670

O2 vs O1 in LIGO

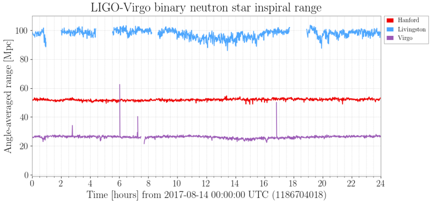


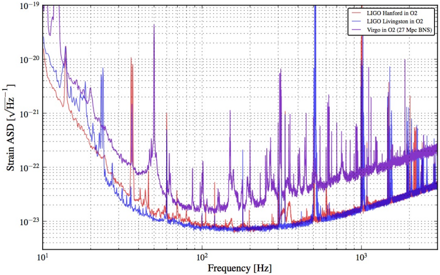


- Binary neutron star range:
  - Average horizon distance
  - Horizon $\simeq 2.26 \times$ range
- Similar sensitivity
- Longer duration
  - O1: 16 weeks, $\sim$50 days of coincident operations
  - O2: 37 weeks, $\sim$120 days of coincident operations



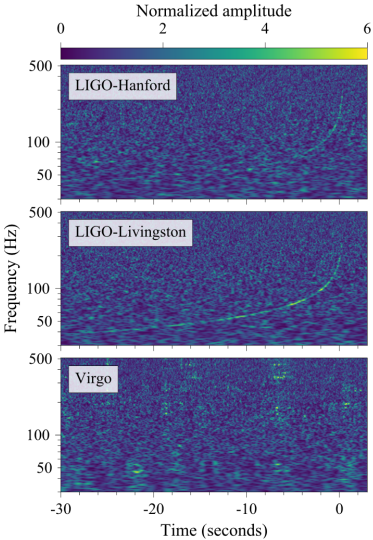
advanced Virgo joined O2 for last month

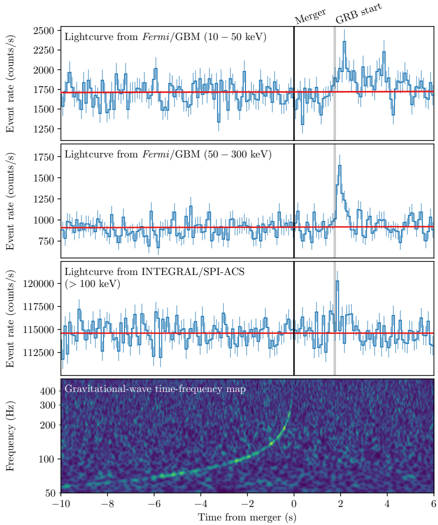




- Only 3.5 weeks
- Sensitivity 2-3 times lower than LIGO
- Improves sky localization by factor 10

GW170817 / GRB 170817A





- combined signal to noise ratio = 32, loudest GW event so far
- More on GRB 170817A, next talk by Peter Veres

LIGO/Virgo/Fermi/Integral arXiv:1710.05834

GW170817 sky localization

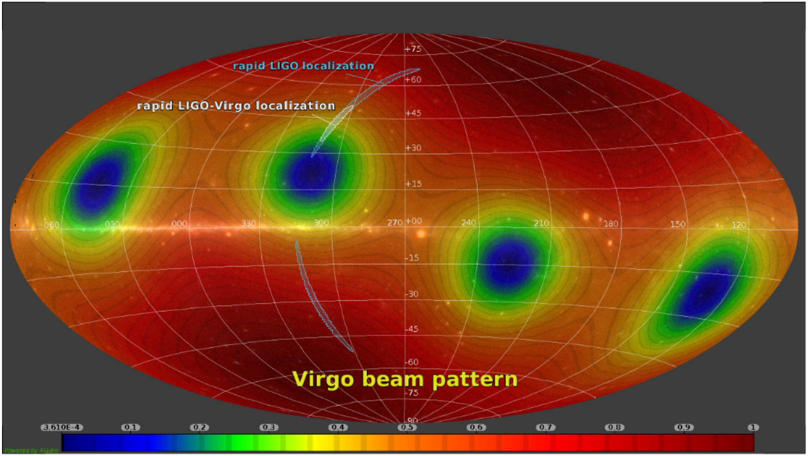
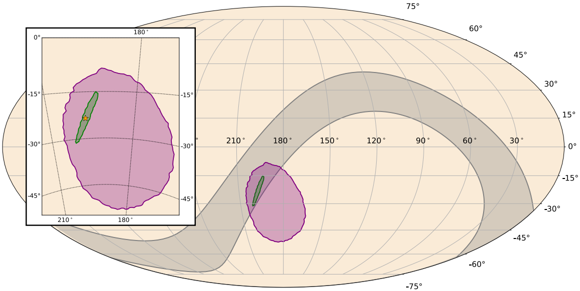


Image credit : Arnaud, Greco, Branchesi, Vicere

- No clear signal in Virgo
- exclude regions of good sensitivity and very close to blind spot

GW170817 / GRB 170817A have a common origin

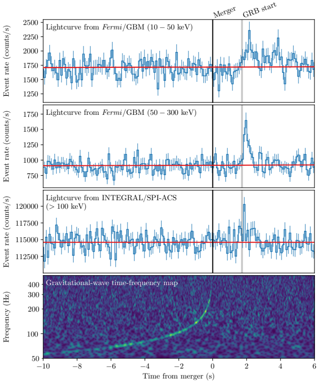


- 1.74 s time delay vs 0.12 SGRB per day $\Rightarrow$ p-value 5×10^{-6}
- sky location overlap $\Rightarrow$ p-value 0.01

$\Rightarrow$ p-value 5×10^{-8} or 5.3σ

LIGO/Virgo/Fermi/Integral arXiv:1710.05834

GW170817 / GRB 170817A - fundamental physics test



- 1.74 s delay over 130 million years of propagation
- Assuming gamma emission delayed by [0,10] s

$$-3 \times 10^{-15} \leq \frac{v_{GW} - v_{EM}}{v_{EM}} \leq 7 \times 10^{-16}$$

- Shapiro effect: gravitational potential slows clocks down

⇒ Equivalence principle test, GW and EM clocks are affected the same, $\gamma_{GW} = \gamma_{EM} = 1$

- Only using Milky Way potential at large distances (100 kpc)

$$-2.6 \times 10^{-7} \leq \gamma_{GW} - \gamma_{EM} \leq 1.2 \times 10^{-6}$$

- Many dark matter emulating GR modification are excluded

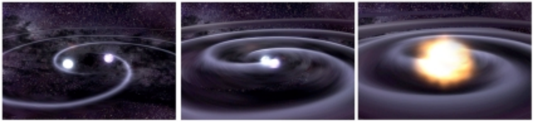
LIGO/Virgo/Fermi/Integral arXiv:1710.05834, Boran et al. arXiv:1710.06168

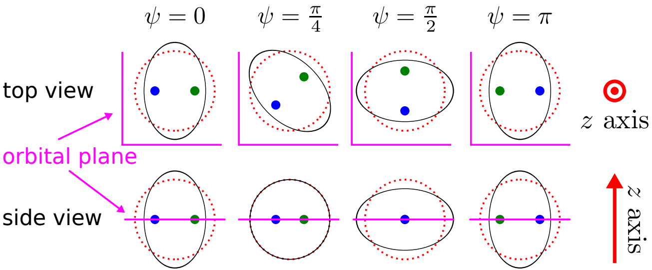
Distance vs inclination degeneracy – quadrupolar approximation

Approximation: far field + slow moving source

- Dominant source: mass distribution quadrupolar moment

$$h_{jk}^{TT} = \underbrace{\frac{2G}{rc^4}}_{\text{1/distance}} \underbrace{P_{jkmn}}_{\text{projection}} \underbrace{\ddot{I}^{mn}\left(t - \frac{r}{c}\right)}_{\text{quadrupolar moment}}$$

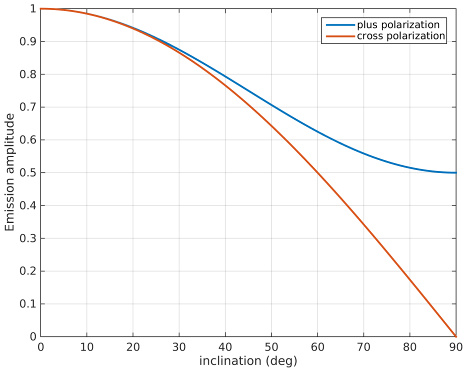




circular polarization
$h_+ = \pm i h_\times$

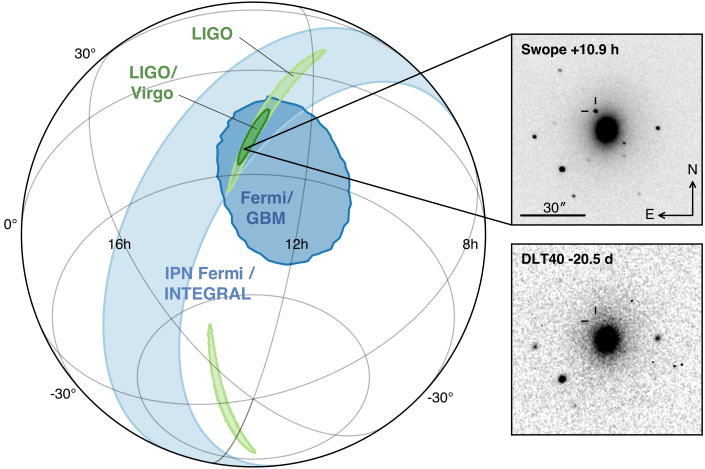
linear polarization
$h_+ \neq 0, \quad h_\times = 0$

Distance vs inclination degeneracy – direct measurement



- LIGO Hanford and Livingston aligned
  $\Rightarrow$ sensitive to only one polarization
- A strong signal in 3 detectors
  $\Rightarrow$ measure polarization: circular vs linear
  $\Rightarrow$ direct measurement of system inclination only for inclination $> 50\,\mathrm{deg}$

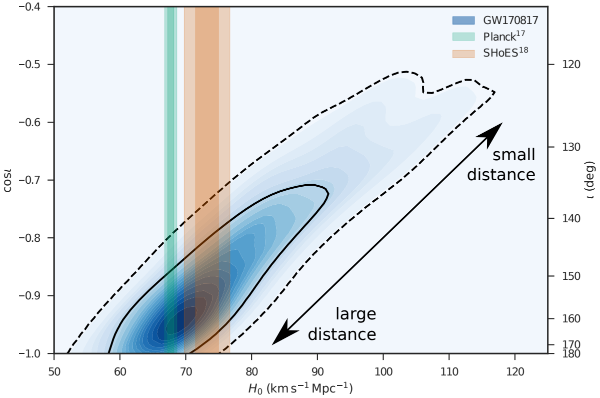
There is an optical counter part



⇒ Redshift of host galaxy

LIGO/Virgo/EM partners arXiv:1710.05833

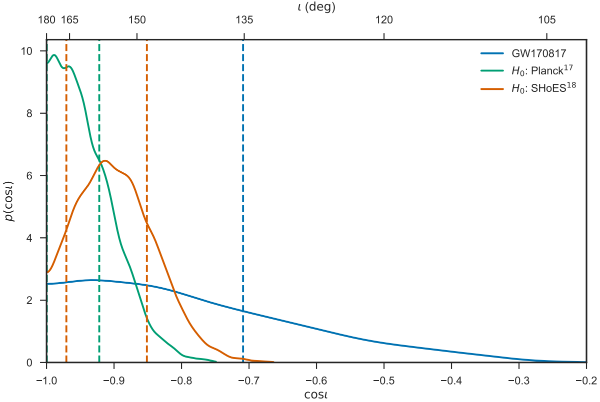
Distance vs inclination degeneracy – optical counter part



- Clear degeneracy $\Rightarrow \cos\iota \propto 1/D$
- Counterpart host galaxy redshift 0.01 $\Rightarrow D \propto 1/H_0 \sim 40\,\mathrm{Mpc}$
- Known values of H_0 break the distance vs inclination degeneracy

LIGO/Virgo arXiv:1710.05835

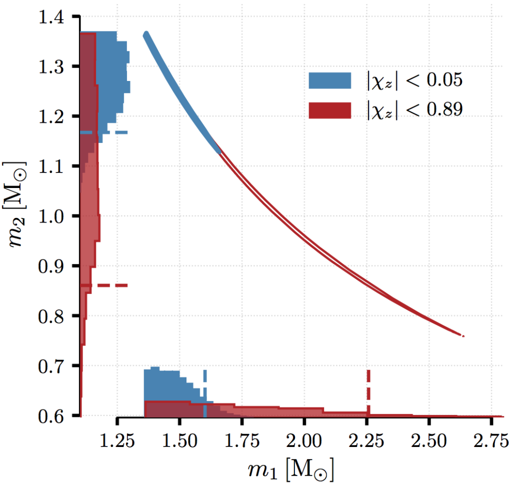
Inclination remains not well constrained



- GW data and host galaxy distance consistent with an aligned system
- Inclination < 28 (or 36) degrees depending on assumed H0 value

LIGO/Virgo arXiv:1710.05835

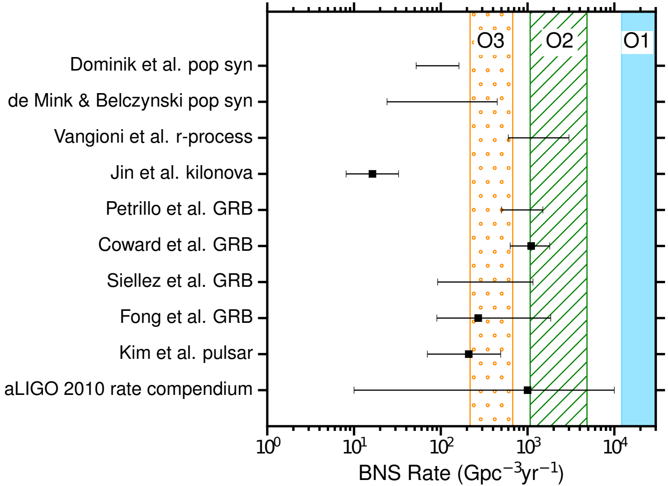
Binary system masses - one mass combination very well measured



- Both objects have mass sufficiently low to be a neutron star
- Assuming spins not larger than most extreme known system PSR J0737-3039A
  - $\Rightarrow$ Masses are close to equal, in 1.17-1.60 $M_\odot$ range

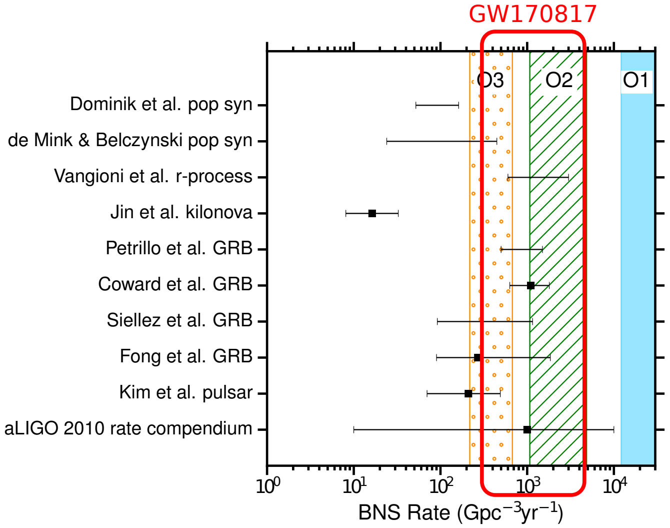
LIGO/Virgo arXiv:1710.05832

Single event ⇒ a measure of the BNS merger rate



LIGO/Virgo arXiv:1607.07456, LIGO/Virgo arXiv:1710.05832

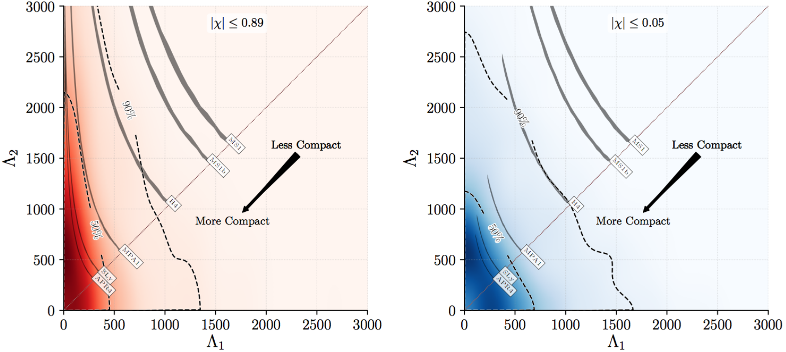
Single event ⇒ a measure of the BNS merger rate



- Measured merger rate: $300 - 5000\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- compatible with O1 upper limit, and theoretical expectations

LIGO/Virgo arXiv:1607.07456, LIGO/Virgo arXiv:1710.05832

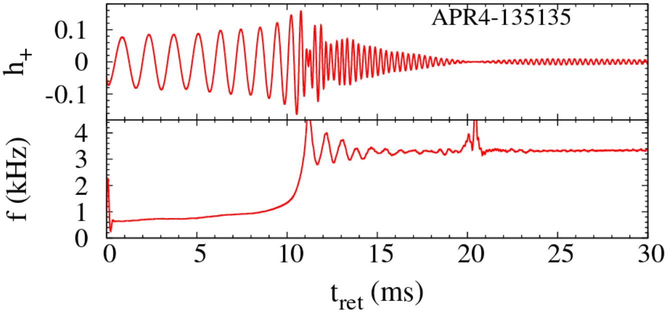
Tidal deformability



- NS tidal deformation speeds up binary coalescence
- Disfavors stiff equations of states that result in large neutron stars
- More on EOS on Wednesday in talk by Jocelyn Read

LIGO/Virgo arXiV:1710.05832

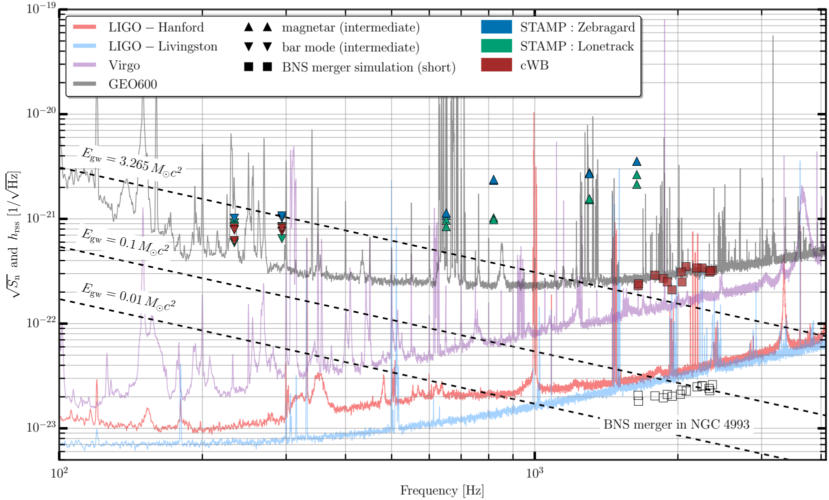
Post-merger scenarios



- prompt collapse to a BH
  - Small amplitude and high frequency signal $\longrightarrow$ not detectable
- hypermassive NS collapsing to a BH $\lesssim 1\,s$
  - Numerical relativity simulations, short signal
- supramassive or stable NS with $\gtrsim 10\,\mathrm{s}$ lifetime
  - Semi-analytical computation of unstable modes

LIGO/Virgo arXiv:1710.09320, Hotokezaka et al. arXiv:1307.5888

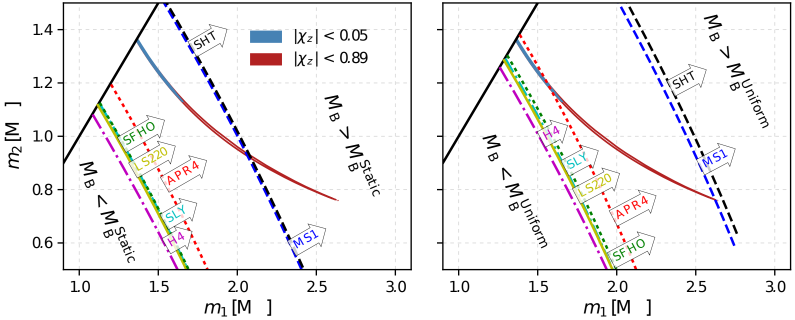
No direct information on post-merger signal



- A detectable signal ∼ most of remnant evaporating in gravitational waves

LIGO/Virgo arXiv:1710.09320

Remnant stability



- Tidal effects disfavors MS1, SHT equations of state that support large masses
- Total mass above uniformly rotating maximum mass for most equations of state
- A supramassive or stable NS remnant is unlikely

LIGO/Virgo/Fermi/Integral arXiv:1710.05834

Conclusion

- BNS mergers happen in the local universe at $\sim$ expected rate
- Inclusion of third GW detector allows useful sky localization
- LIGO/Virgo can measure inclination only when it is large
- Tidal effects constrain possible NS equation of states
- No direct information on post-merger remnant
- GRB association offers a precision fundamental physics test
  - Gravitational wave speed
  - Equivalence principle
  - Strong constraint on modified gravity theories