Cosmology with gravitational waves

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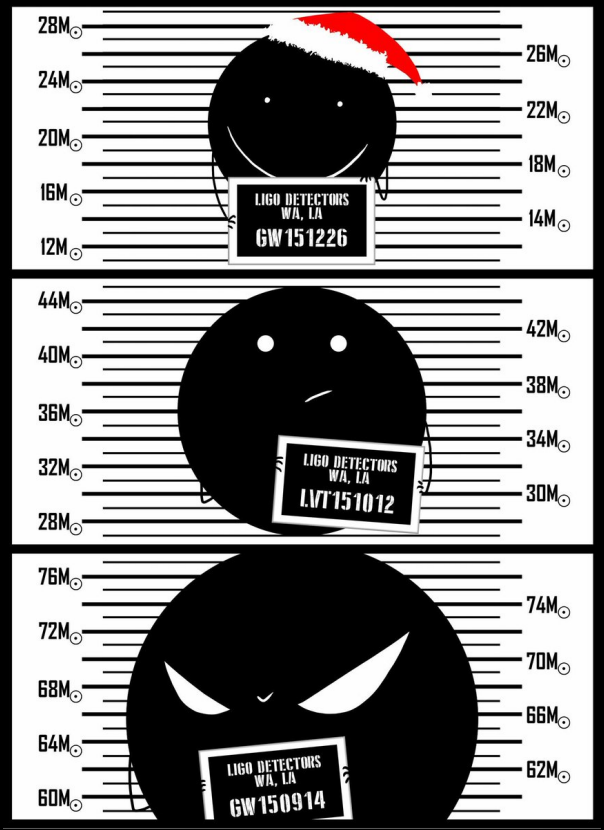
Compact binary coalescences

- The first two gravitational waves (GWs) detected by LIGO were emitted by compact binary coalescences (CBCs)
  - GW150914 – 36-29 $M_\odot$ binary black hole (BBH)
  - GW151226 – 14-7 $M_\odot$ binary black hole
- Both objects at redshift of ~0.1 (LVC 1606.04856)
- Well... We don't actually measure redshifts!



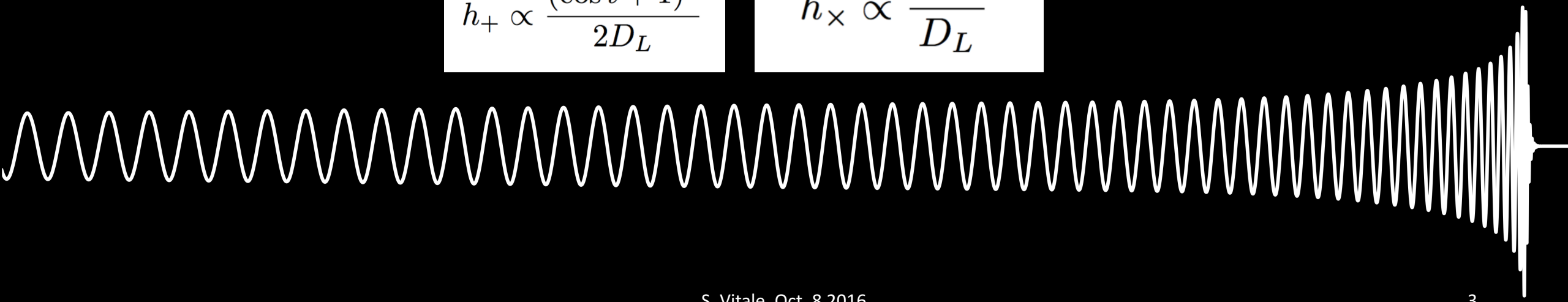
N. Kijbunchoo

GW anatomy –Amplitude

- The amplitude of GWs emitted by compact binaries depends on the *luminosity distance*
- The luminosity distance enters both polarizations in combination with the orbital inclination angle

$$h_+ \propto \frac{(\cos\iota + 1)^2}{2D_L}$$

$$h_\times \propto \frac{\cos\iota}{D_L}$$



GW anatomy - phase

- The redshift does not *typically* enter the waveforms in any measurable way
- All mass parameters enter in combination with $(1 + z)$
- What one measures is $(1 + z)M$

From distance to redshift

- The redshift quoted in LVC 1606.04856 were calculated *from* the measured luminosity distance *assuming* Planck cosmology (A&A 594, A13)

- In the future we will want to estimate the cosmological parameteres using GW

Cosmology

- To measure the cosmology one needs luminosity distance *and* redshift of the source

$$D_L(z) = \begin{cases} \frac{(1+z)}{\sqrt{\Omega_k}} \sinh[\sqrt{\Omega_k} \int_0^z \frac{dz'}{H(z')}] & \text{for} \quad \Omega_k > 0 \\ (1+z) \int_0^z \frac{dz'}{H(z')} & \text{for} \quad \Omega_k = 0 \\ \frac{(1+z)}{\sqrt{|\Omega_k|}} \sin[\sqrt{|\Omega_k|} \int_0^z \frac{dz'}{H(z')}] & \text{for} \quad \Omega_k < 0 \end{cases}$$

$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda E(z, w(z))}$$

$$E(z, w(z)) = (1+z)^{3(1+w_0+w_1)} e^{-3w_1 z/(1+z)}$$

- The GW data analysis will provide the distance
- How do we get the redshift?

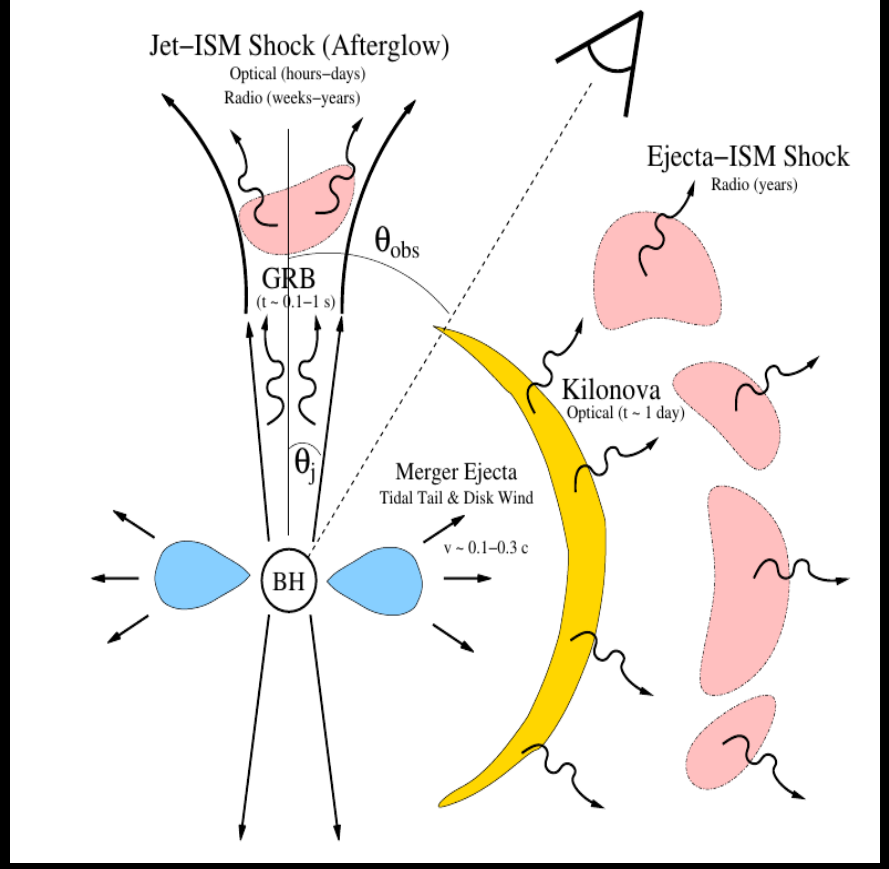
How to measure the redshift?

- If the CBC produces an EM counterpart (e.g. GRB) (Sathyaprakash+ CQG 27 215006, Nissanke+ 1307.2638)
- If one knows the neutron star (NS) equation of state (Read & Messenger PRL 108 091101; Del Pozzo+ 1506.06590)
- If the post-merger signal is observed (Messenger+ PRX 4, 041004)
- If the shape of NS mass distribution is known (Taylor+ PRD 85 023535; Taylor & Gair PRD 86, 023502)
- Even if no EM is found, but there is a reliable galaxy catalog (Schutz, Nature 1986, Del Pozzo PRD 86 043011)

Short GRBs

- Compact binaries with one or two neutron stars are thought to be progenitors of short GRBs
  - Joint GW – EM detections
- If the GRB is detected, that would provide the redshift
- Challenges
  - GRB is beamed, not many will point to Earth
  - GW skymaps are typically large, might be hard to follow up

Metzger, Berger



Neutron stars equation of state

- GW phase encodes the equation of state of neutron stars
  - Depends on the source-frame masses
- If the EOS is known through other means (EM) one can measure both source-frame and redshifted masses, hence get the redshift.
- Challenges
  - EOS terms in the waveforms are high order and hard to measure
  - Need to know the EOS

Neutron stars post merger peak

- Numerical simulations suggest merging neutron stars will release a short burst of GWs after merger, with a characteristic frequency
- Comparing measured redshifted frequency with expected frequency gives redshift.
- Challenges
  - Feature contains little signal-to-noise ratio
  - Requires more numerical simulations
  - Some dependence on the equation of state

Mass distribution

- Neutron star masses are expected to lie in a narrow range
- If one knew the shape of mass distribution could compare measured (redshifted) masses with expected ones, and infer the redshift
- Challenges
  - Relies on knowledge of mass distribution

Statistical approach

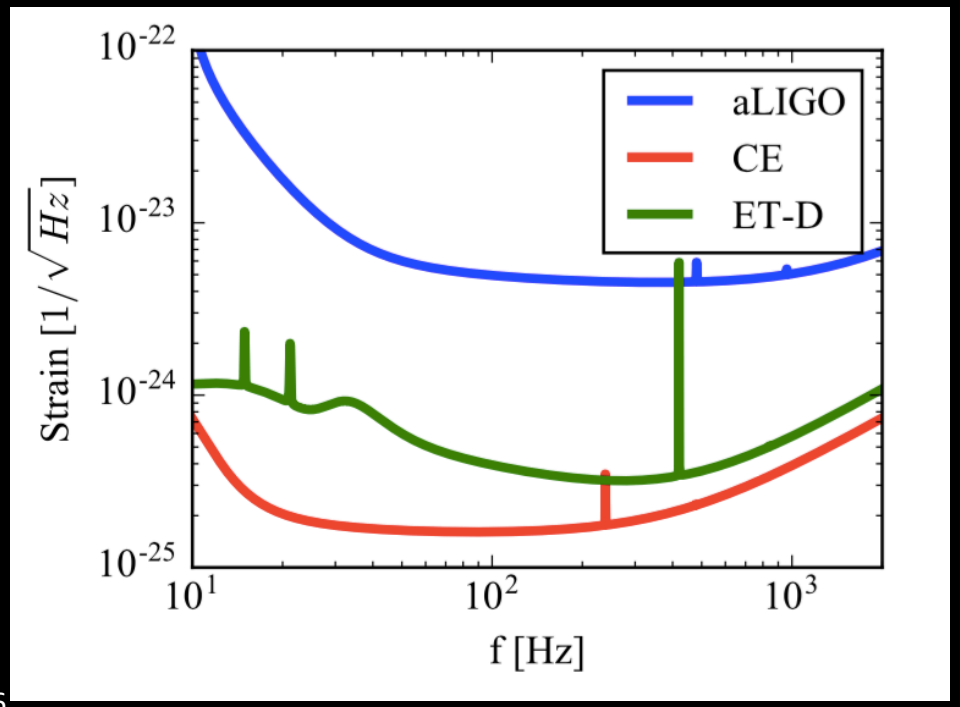
- For each event, one could simply consider all the galaxies in the error box and calculate the cosmology assuming each is the host of GW
  - True host will give true cosmology, all others will act as noise
  - If enough detections are made the true value will eventually prevail.
- Challenges
  - Might need lot of sources
  - Must handle galaxy catalog incompleteness

What do we need, then?

- All these methods require either
  - Many events (better statistics, increases number of GRB)
  - Very loud events (decreases number of potential galaxy hosts)

Third generation of GW detectors

- Given the current estimate for the rate of binary NS, might be challenging with current detectors
- Next generation would add another factor of ~10 in sensitivity
  - Einstein Telescope
  - Cosmic explorer



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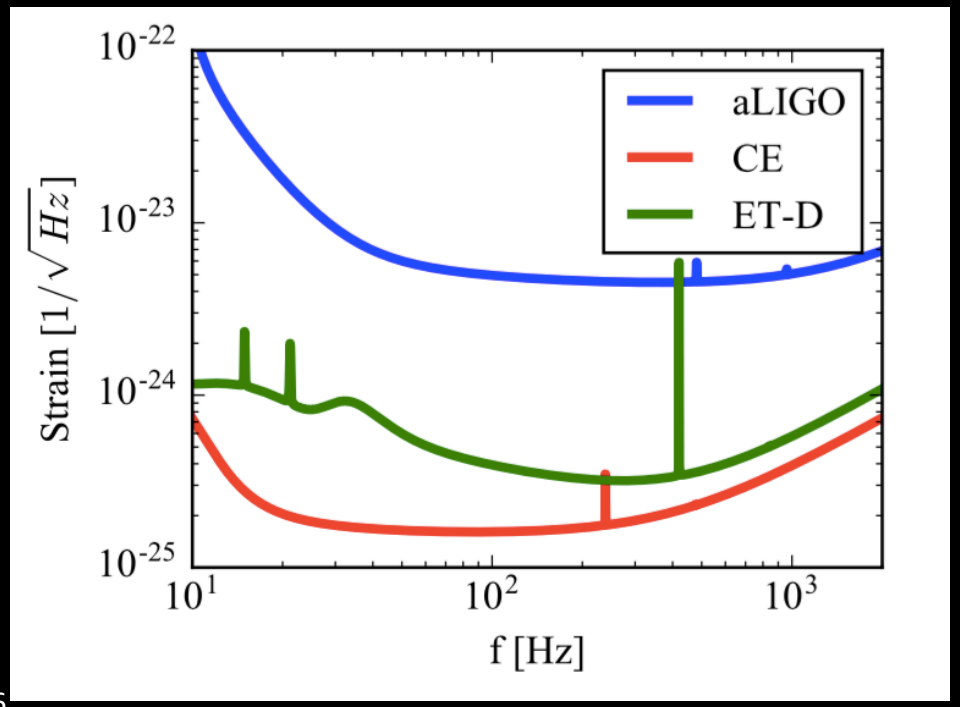
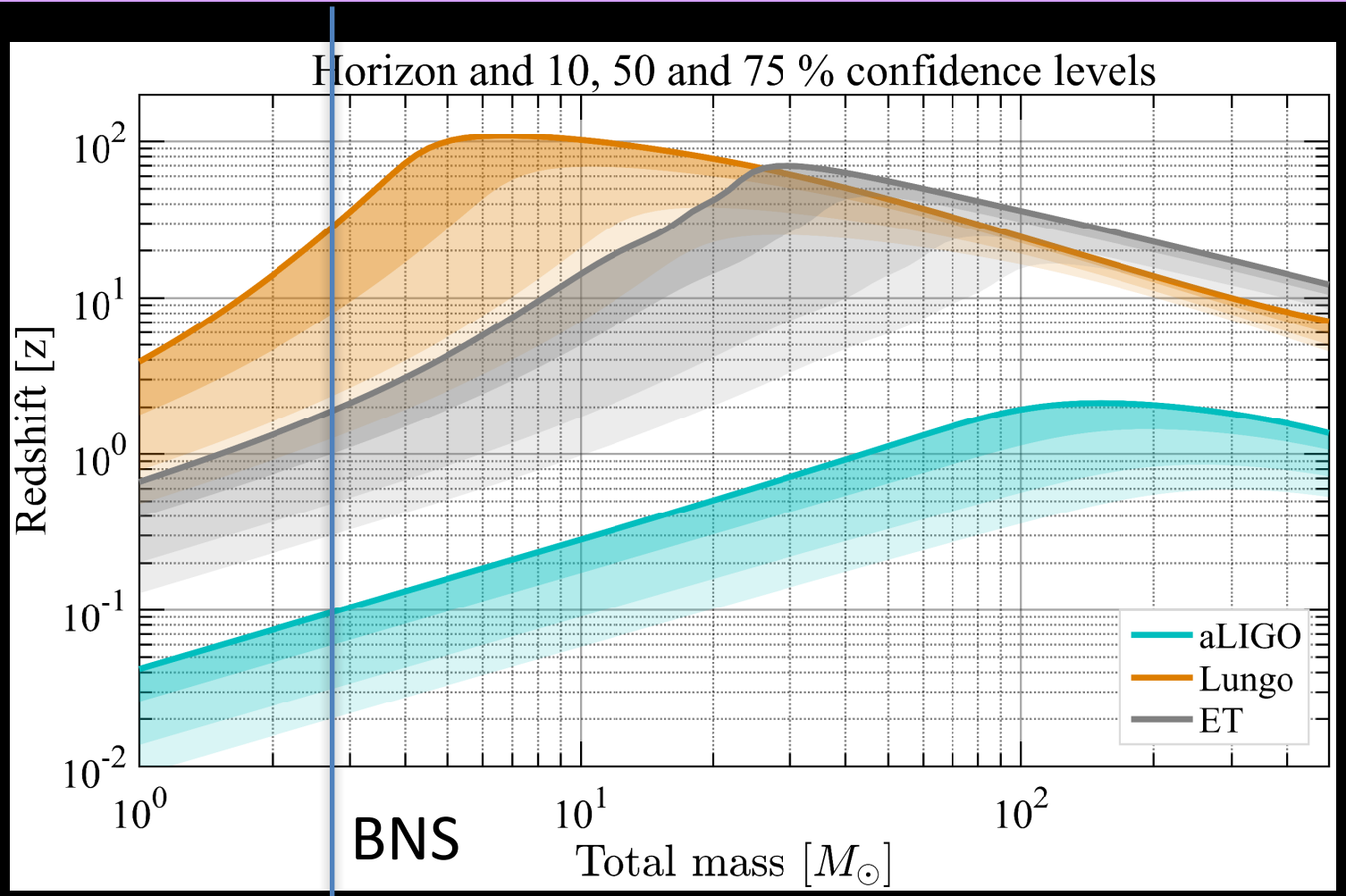
Large price tag: don't forget to leave an offer!



BNS range

- Next generation of detectors could see BNS up to redshifts of ~2
- Current generation only up to ~0.1



Plot: J. Miller

Short GRBs

- Nissanke+ 1307.2638 looks at the prospects for 2G detectors
  - Assumes N joint GW+EM detections and look at measurement of H_0
    - Statistical of few % with O(10) joint detections
    - Uncertainty in the rate and beaming angle -> could take months of decades
- Sathyaprakash+, CQG 27 215006, considers 3G (Einstein telescope)
  - Assumes 10^{-3} of BNS will be detected with EM counterparts→ 1000 joint detections over 3 years
  - H_0 assumed known
  - 1-sigma Ω_M at 18%, Ω_Λ at 4%, w 18%
  - Errors are smaller if weak lensing systematics can be corrected

NS equation of state

- Proof of principle in Read and Messenger (PRL 108 091101)
- Full Bayesian analysis in Del Pozzo+ (1506.06590)
  - Einstein Telescope, 1000 BNS sources, no EM required
  - Considers different equation of state and estimate *all* cosmological parameters
    - H_0 with 90% confidence interval of ~10%
    - Ω_M: ~65%
    - Ω_Λ: ~40%
    - w_0 and w_1: 0.8 and 0.9 (factor of 3 better if the rest is known)

Mass distribution

- Taylor+ (PRD 85 023535 and 86 023502) assume mass distribution for NS in BNS it is Gaussian with unknown mean and sigma

- Measure mass distribution parameters together with cosmology
  - 2G : H_0 at 10% with ~100 BNS if true mass distribution sigma <0.04$M_\odot$
  - 3G: All known except DE. Precision comparable with EM with 10^5 BNS

Statistical approach

- For each GW detection, just use all galaxies in sky error
- Del Pozzo (1108.1317) finds for 2G:
  - H_0 at 15% (95% CI) with 10 sources. Better if more than 3 interferometers online or more detections.
  - Omega's unmeasurable with 50 sources
  - Did not consider DE
- 3G: Ongoing…

Known systematics from GWs

- Calibration of the instrument
  - Currently ~7% in amplitude. Can improve
- Waveforms
  - 2 independent waveform families used for the 2 detections, similar results
  - Uncertainties in distance ~10% larger for one of the two
  - Can improve
- Weak lensing
  - Negligible for 2G detectors, will affect 3G
  - Should not give a net bias since it is a zero-mean process

… and the black holes?

- Most of these methods have been shown to work when at least one neutron star is involved
- However, most of the sources will be binary black holes!
- The statistical method can be extended to BBH
  - Challenge: high redshifts, many galaxies
- But an event like GW150914 would have signal-to-noise ratio of >>100 with 3G detectors -> small uncertainties and very few galaxies (Vitale+, in prep)

How to measure the redshift?

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REQUIRE NEUTRON STARS

- If the post-merger signal is observed (Messenger+ PRX 4, 041004)
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OK FOR BOTH NS AND BH

Conclusions

- Measurement of cosmological parameters will be challenging with 2G detectors
  - H_0 measurable with a few tens of **binary neutron stars** detections
  - Other parameters hardly measurable
- Third-generation detectors will open new possibilities
  - Can measure all parameters with **binary neutron stars,** precision depends on method and number of sources.
  - More work needed for binary black holes
- Uncertainties not better than EM, but totally different systematics