G1801672

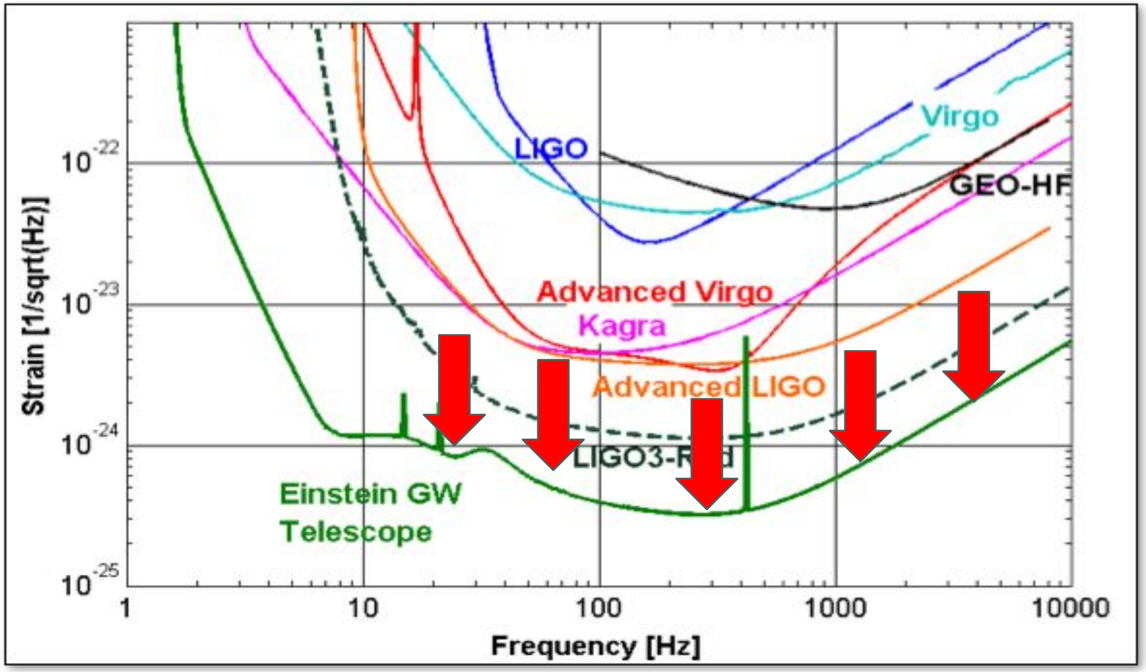
Trade off science gained at low frequencies vs. observatory requirements

Stefan Hild (Glasgow) and Stefan Ballmer (Syracuse)
With lots of input from many others ...

Disclaimer

- Obviously, very hard to trade-off science vs effort/money. Actually, one might even argue that right now IT IS IMPOSSIBLE. :(
- So far we had too few signals to really confidently extrapolate to 2030. Our current thinking might be biased/coloured by what we have discovered so far.
- In the following, as an exemplary exercise, we will try to look (more qualitative than qunatitative) at the benefits and challenges of extending the sensitivity into the sub-10Hz region.
- As you will see we there are more questions than answers.
- Hopefully, there will still some fruit for thought to take away.

Motivation



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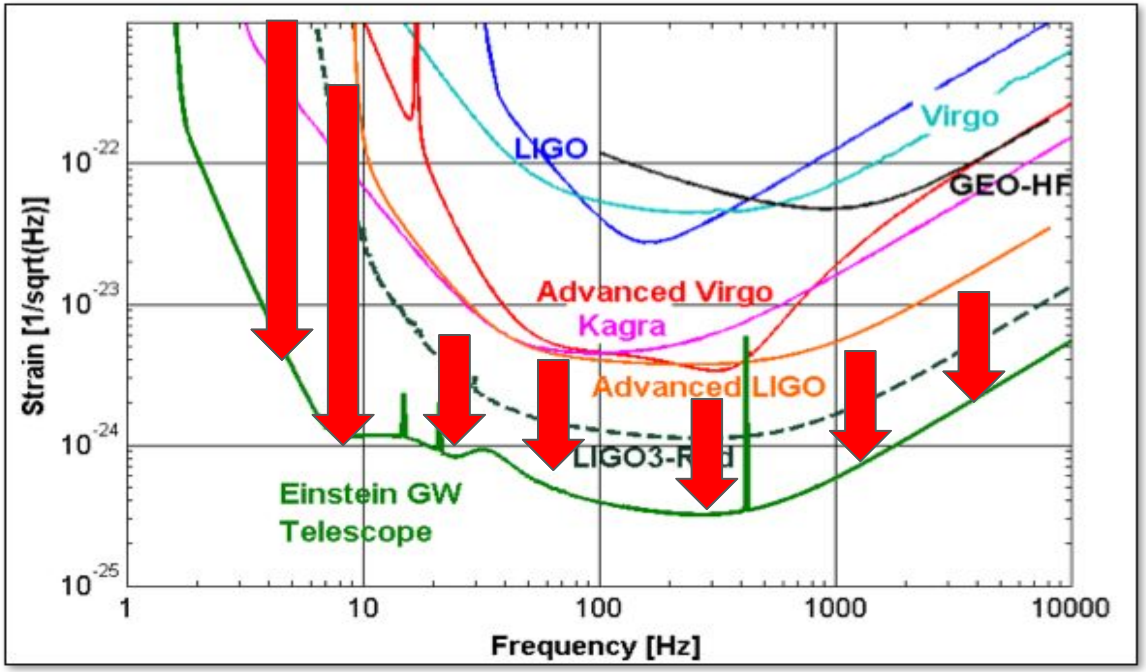

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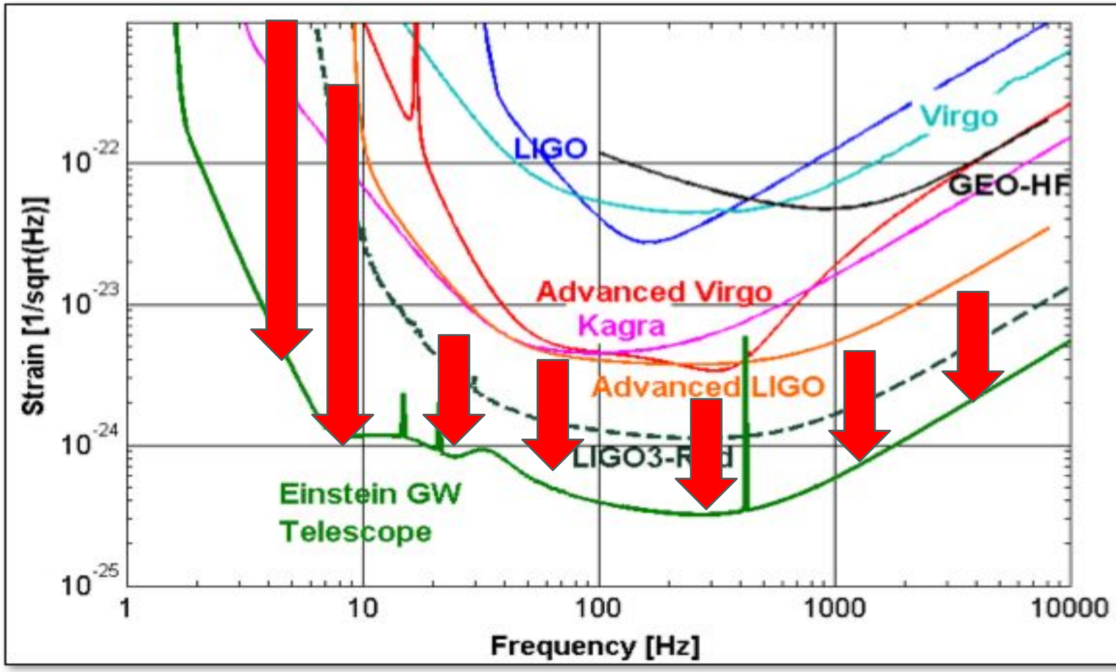
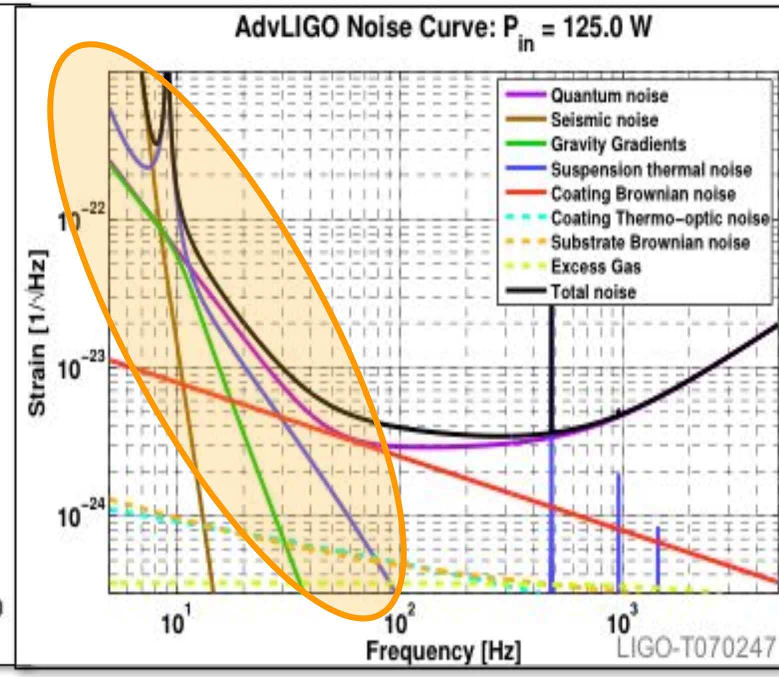




- When going from 2G to 3G we need to improve by about a factor 10 above 10Hz, but by a factor 100-10000 for frequencies below 10Hz.
- 3G low frequency sensitivity requires disruptive technology/concepts.
- Need to reduce several noise sources very significantly.
- **Key-question: What do you gain from that in terms of Science and how to find the optimum effort to science ratio.**

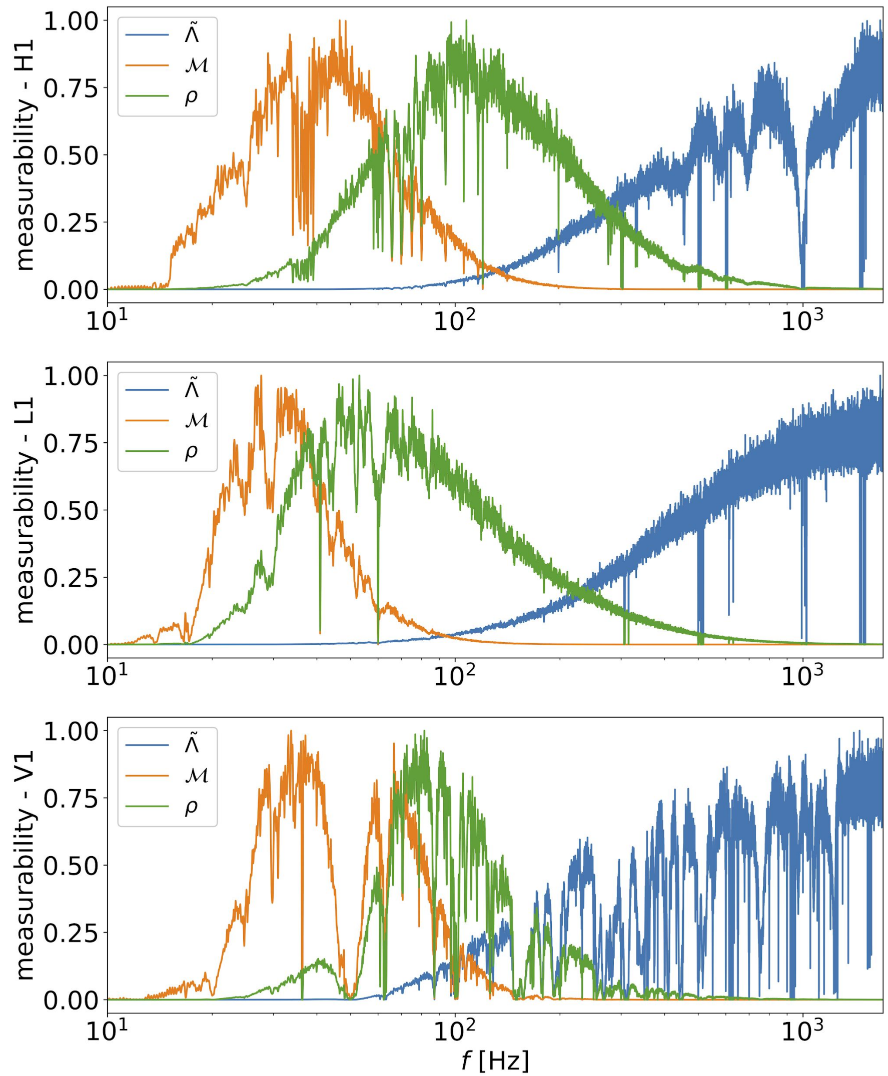
Lets have a look at the science ….

Parameter Estimation of GW170817 (aLIGO)

Useful exercise: In which frequency band is information about certain source parameter accumulated?

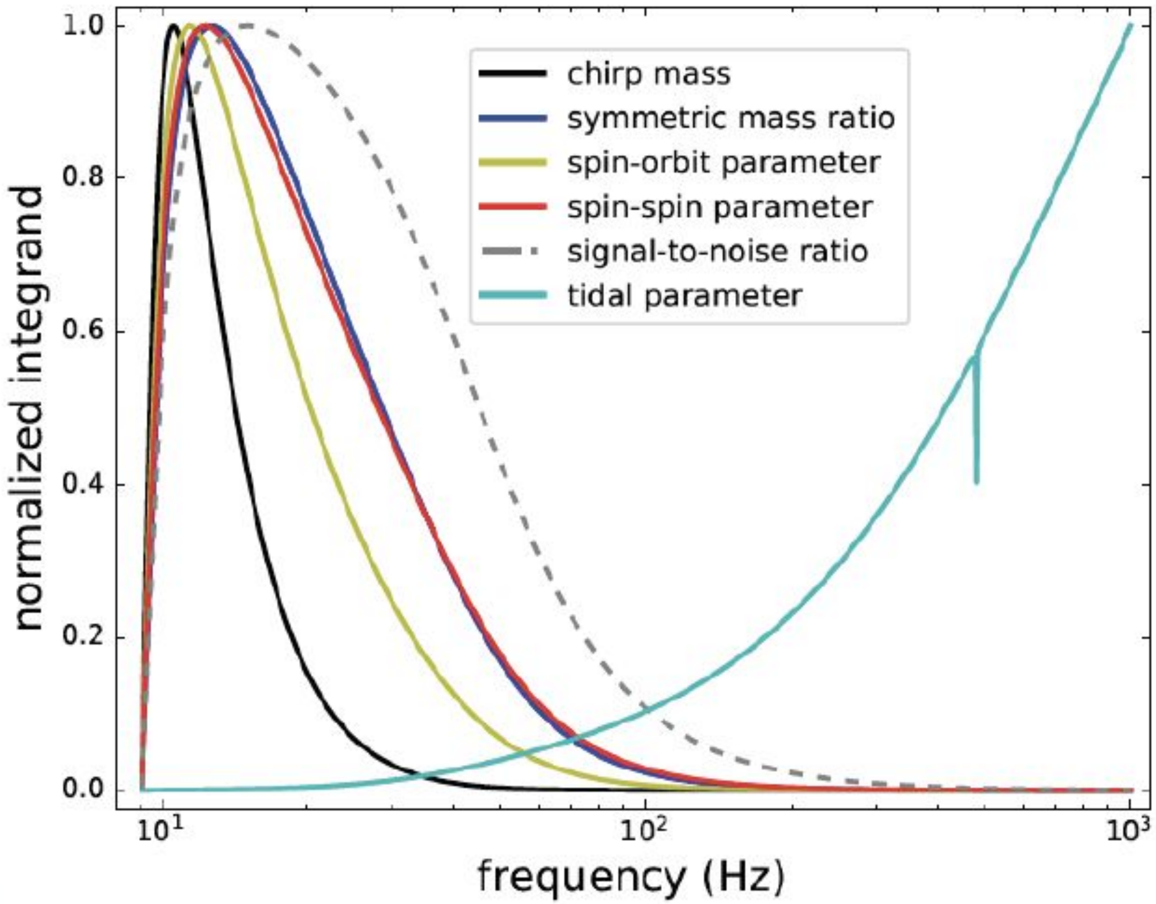
Example: GW170817

- Mid frequencies = SNR
- Low frequencies = Chirp Mass
- High frequencies = deformability



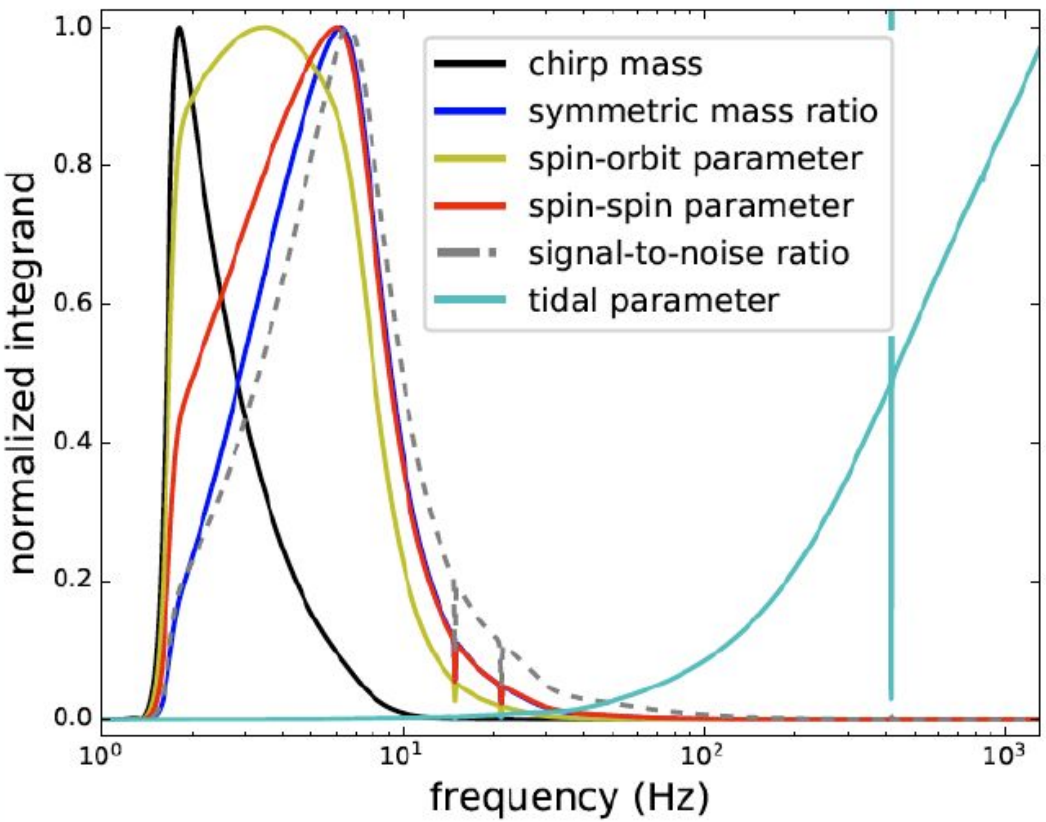
Credit: arXiv:1804.08583

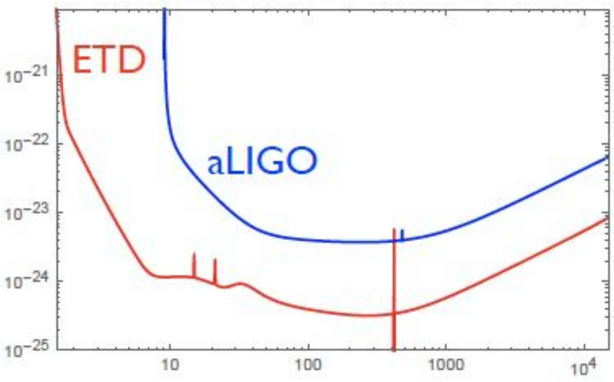
Parameter Estimation of BNS (aLIGO design)



I. Harry & T. Hinderer arXiv:1801.09972

Parameter Estimation of BNS (ET design)

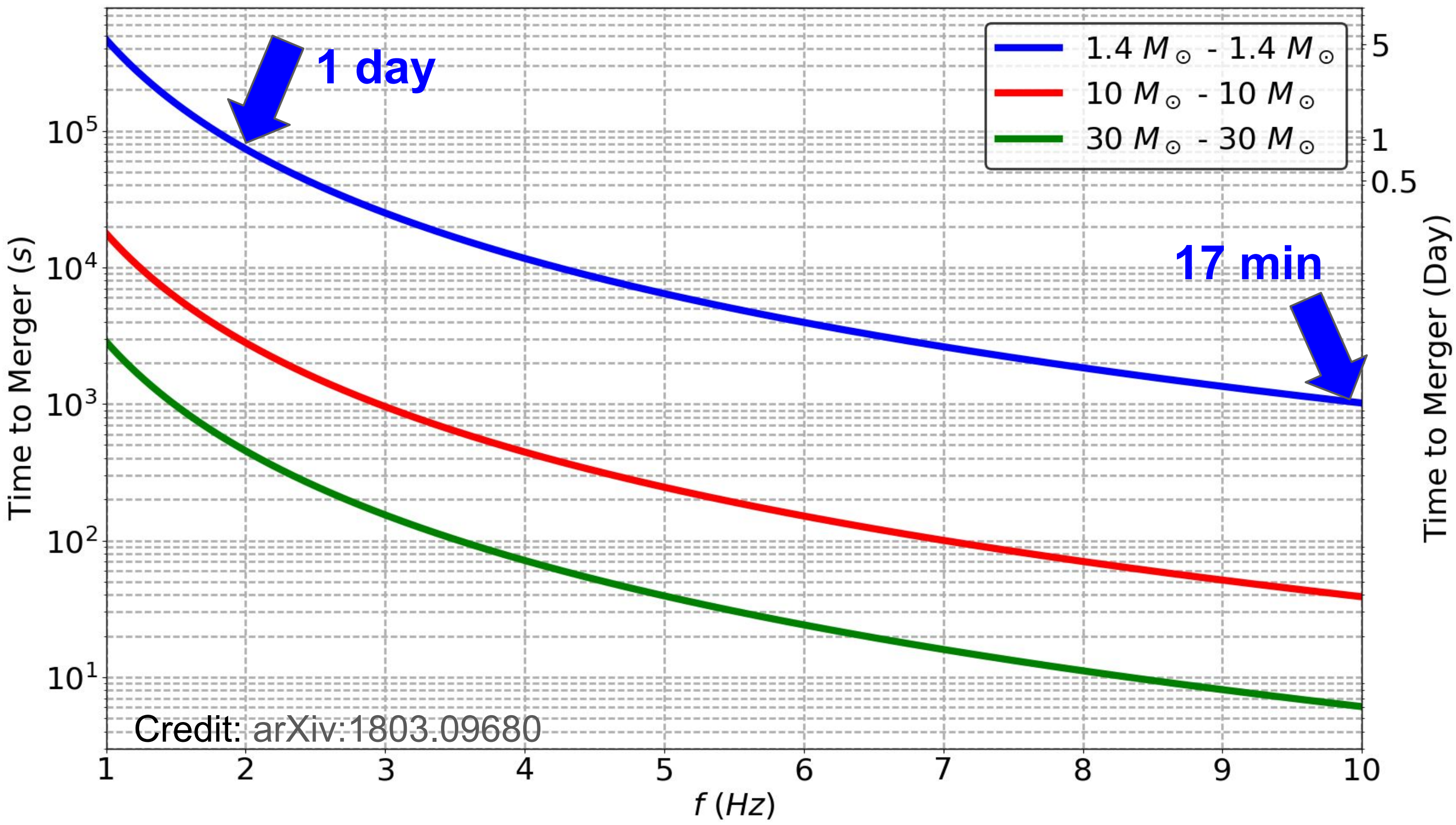




Credit: I. Harry, T. Hinderer, private communication

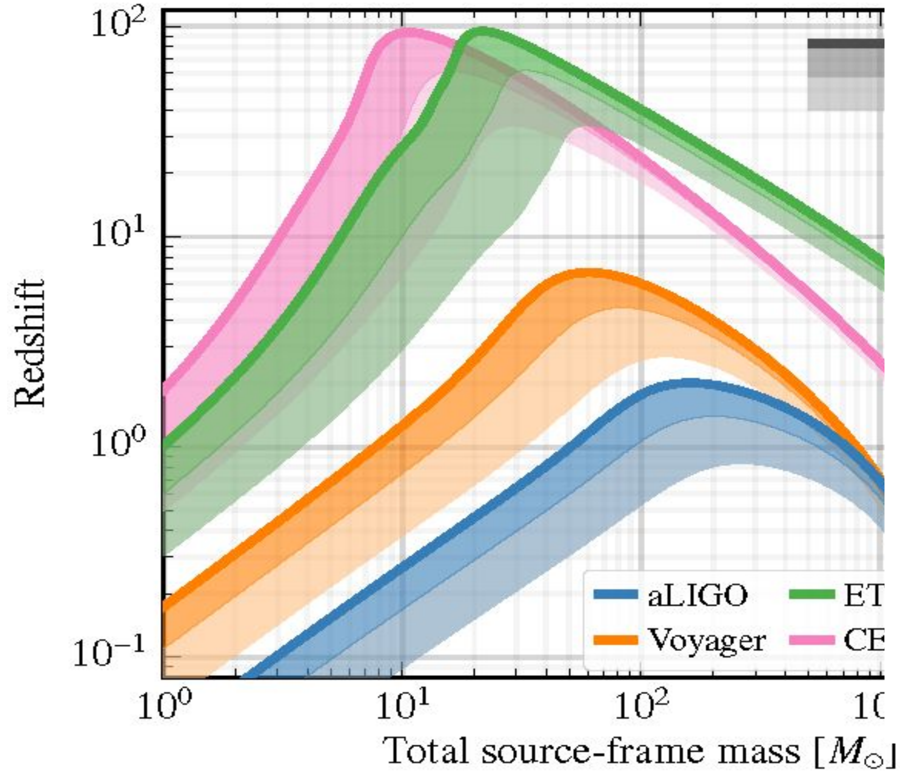
For the ET example we find that the different parameters split up in the low frequency range.

In-band time for CBC sources => Early warning time



- The lower the frequency cut-off, the more pre-merger warning time we obtain.
- Note: Approach above over-simplified, i.e. need to subtract time it takes to make detection (i.e. accumulate SNR =8). Also ideally would need sky-localisation.
- Also note that computing requirements increase with length of waveforms.

Gaining sensitivity for heavy binaries, i.e. IMBH



Credit: Evan Hall, John Miller

- The lower the frequency cut-off the more massive binaries can be observed.
- Also the lower the frequency cut-off the further out one can see systems because distant systems are significantly red-shifted.

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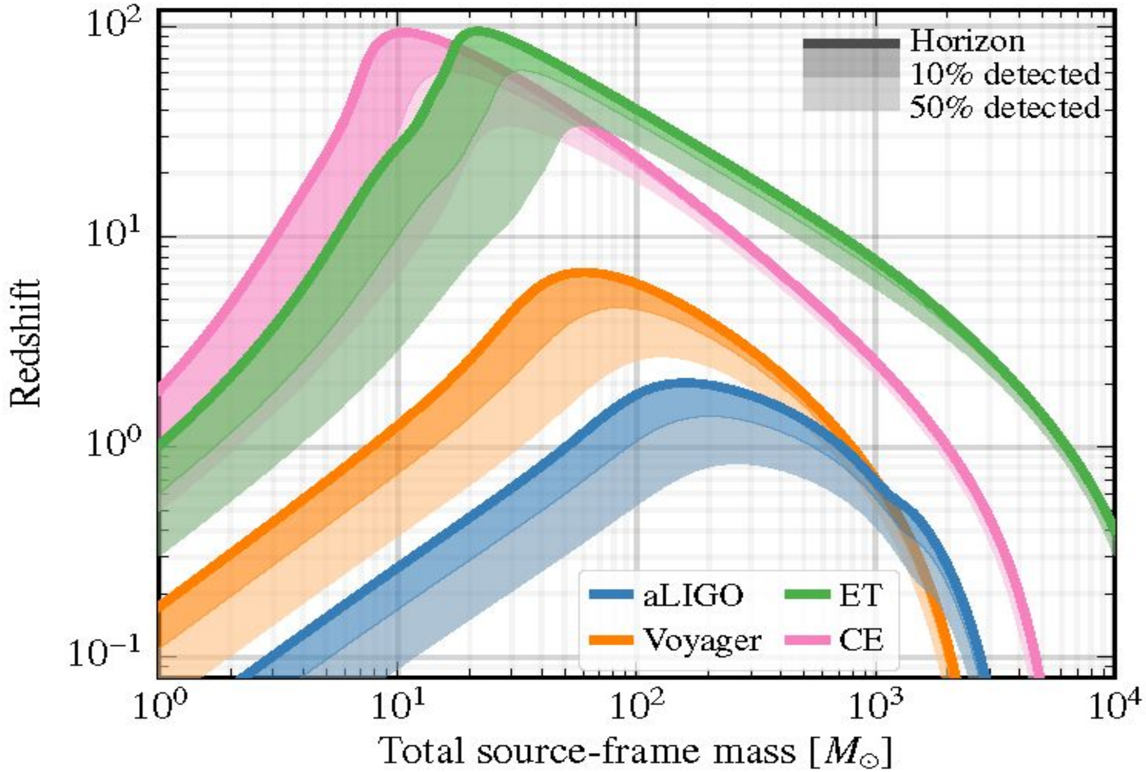

Credit: Evan Hall, John Miller

- The lower the frequency cut-off the more massive binaries can be observed.
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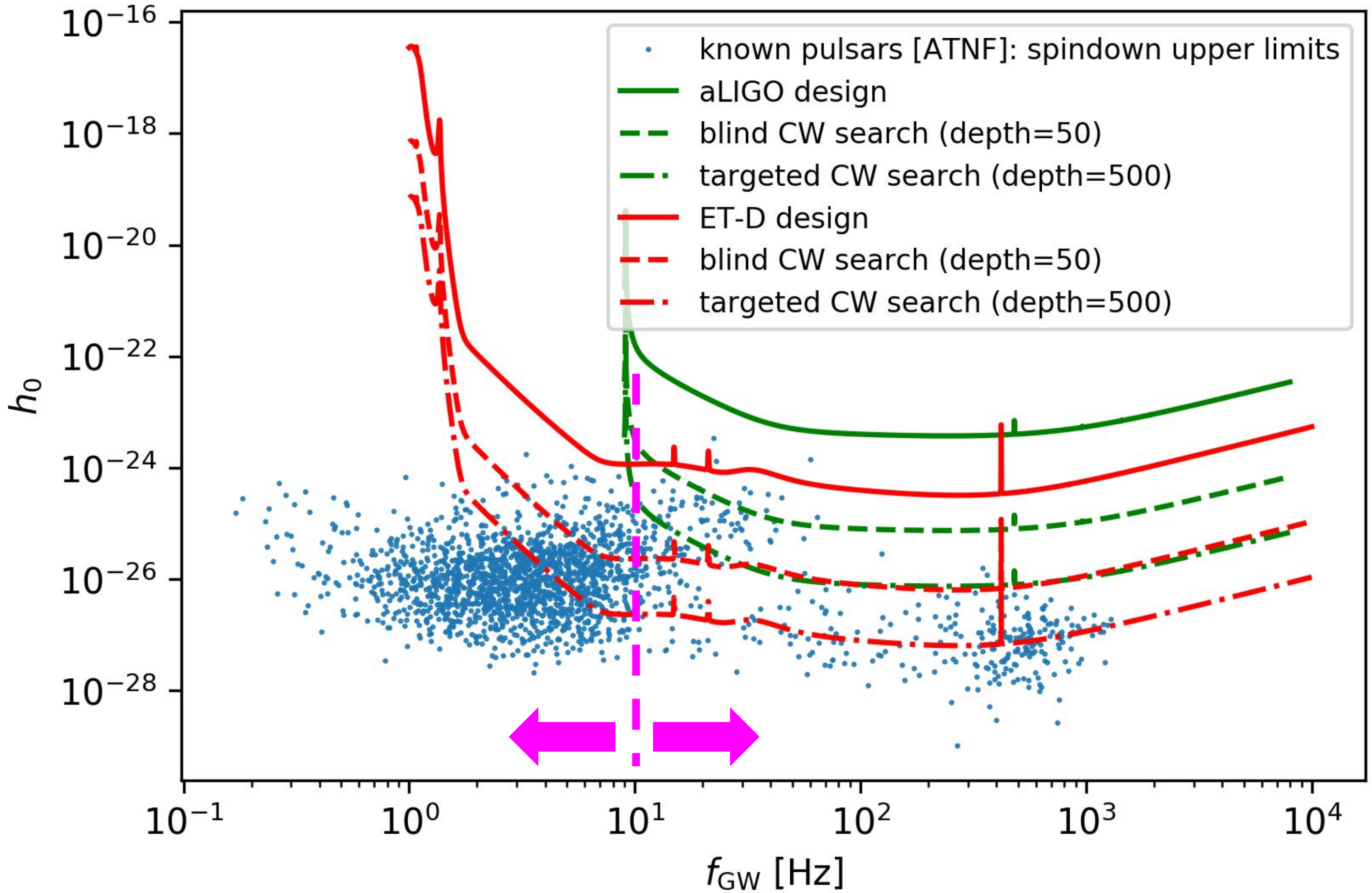
- Can we probe seeds for SMBH?
- (Sidenote: currently our searches are not limited by low frequency cut-off.)

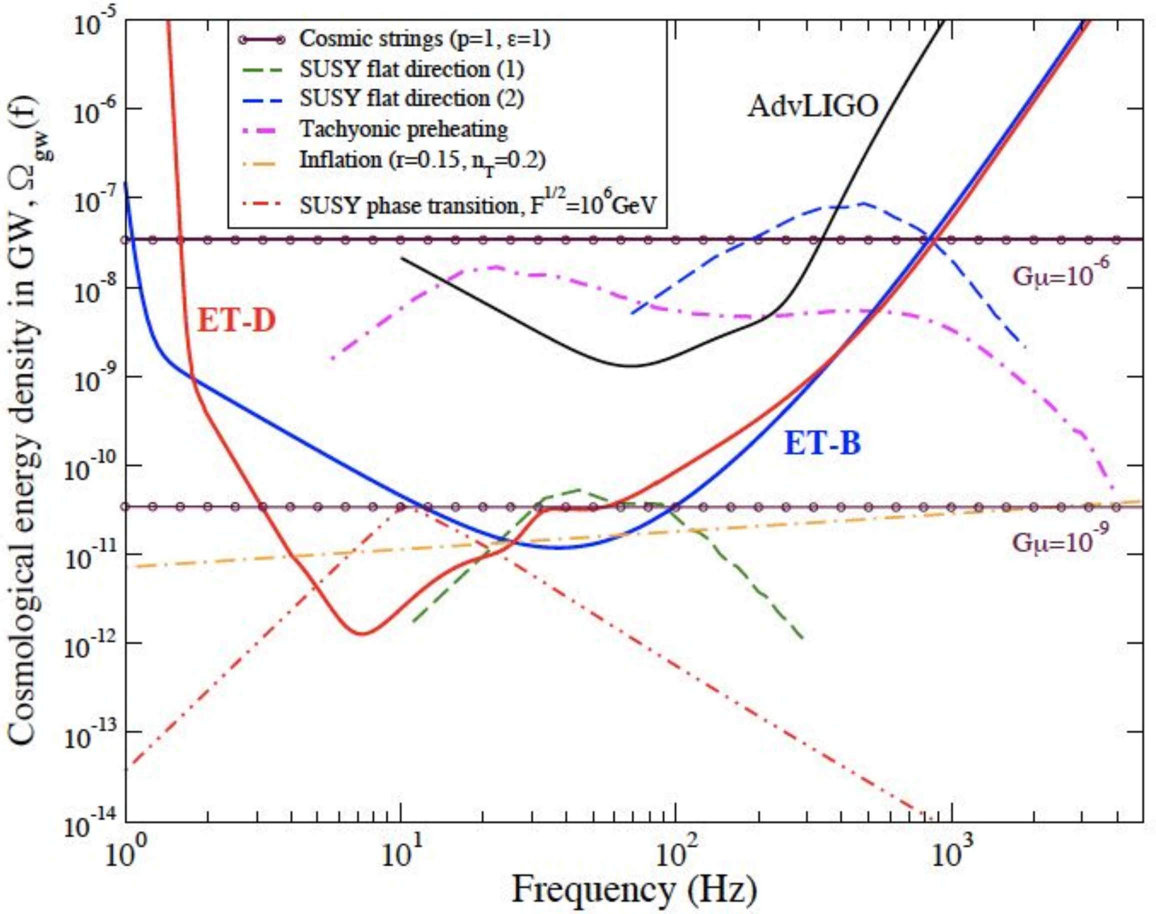
Low frequency pulsars



Credit: D. Keitel

- Lower frequency cut-off simply means more sources.
- Question: How interesting are the sub 10Hz pulsars?

Stochastic Backgrounds



Credit: ET design study

Low frequency essential for stochastic backgrounds.

Scale-invariant spectrum falls faster with frequency than coating thermal noise.


Lets have a look at the technical challenges ….
15

Seismic Newtonian Noise

- Seismic causes density changes in the ground and shaking of the mirror environment (walls, buildings, vacuum system).
- These fluctuations cause a change in the gravitational force acting on the mirror.
- Cannot shield the mirror from gravity. ☹

$$N_{\mathrm{GG}}(f)^2 = \frac{4 \cdot \beta^2 \cdot G^2 \cdot \rho_r^2}{L^2 \cdot f^4} \cdot X_{\mathrm{seis}}^2,$$

Coupling constant (depends on type of seismic waves, soil properties, etc) → β

Gravitational constant → G

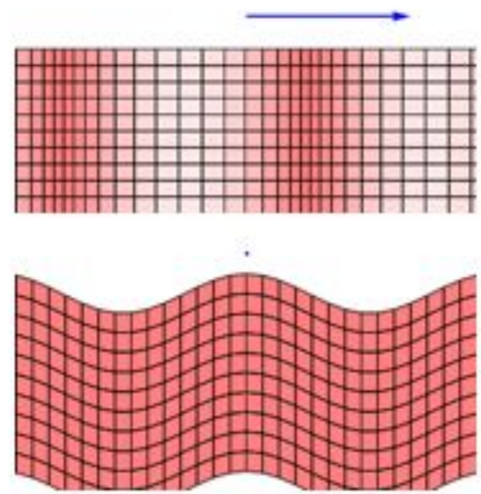
Density of ground → ρ_r

PSD of strain → $N_{\mathrm{GG}}(f)^2$

Arm length → L

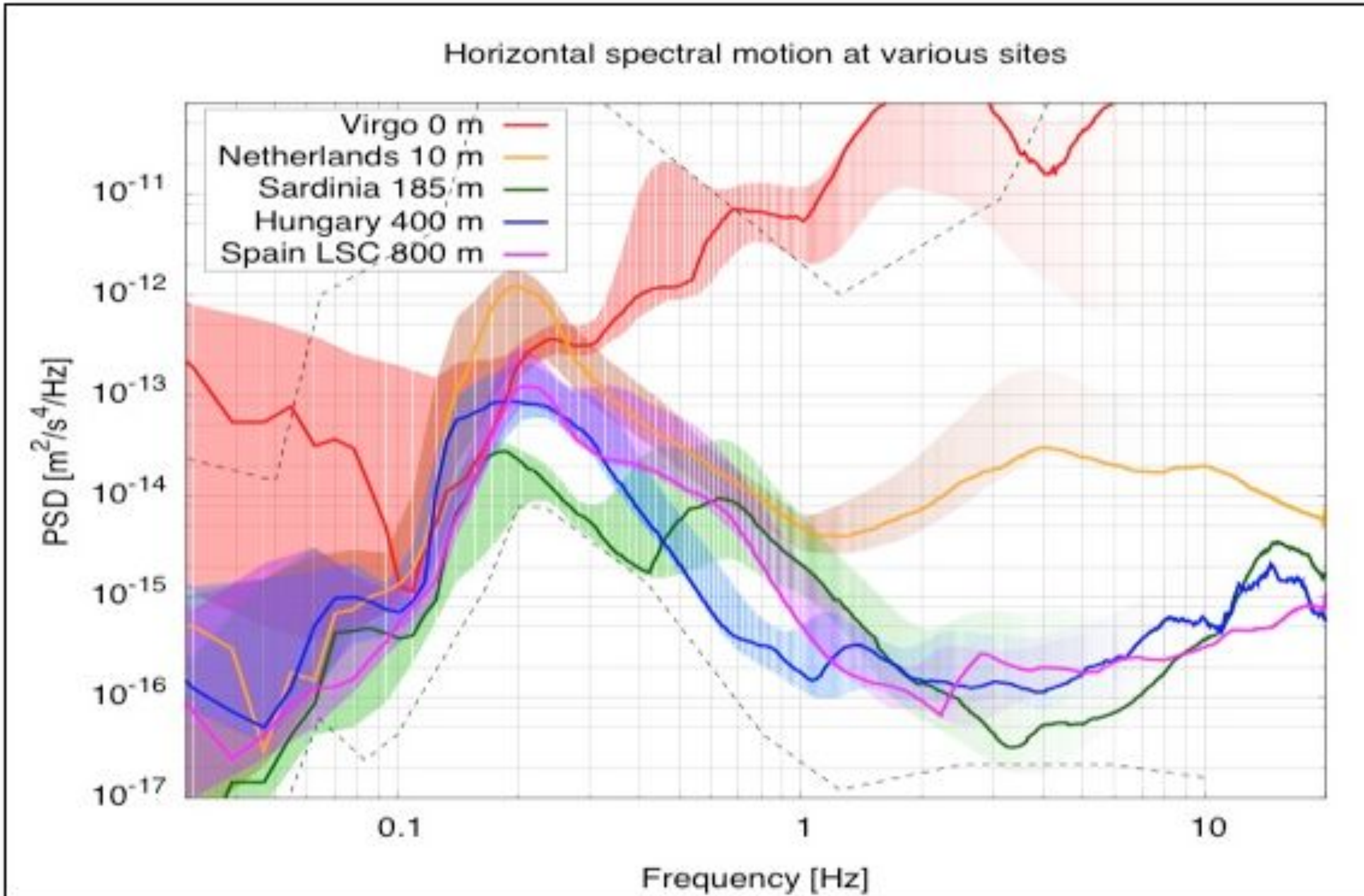
frequency → f

PSD of seismic → X_{seis}^2



Images: courtesy G.Cella

Going Underground

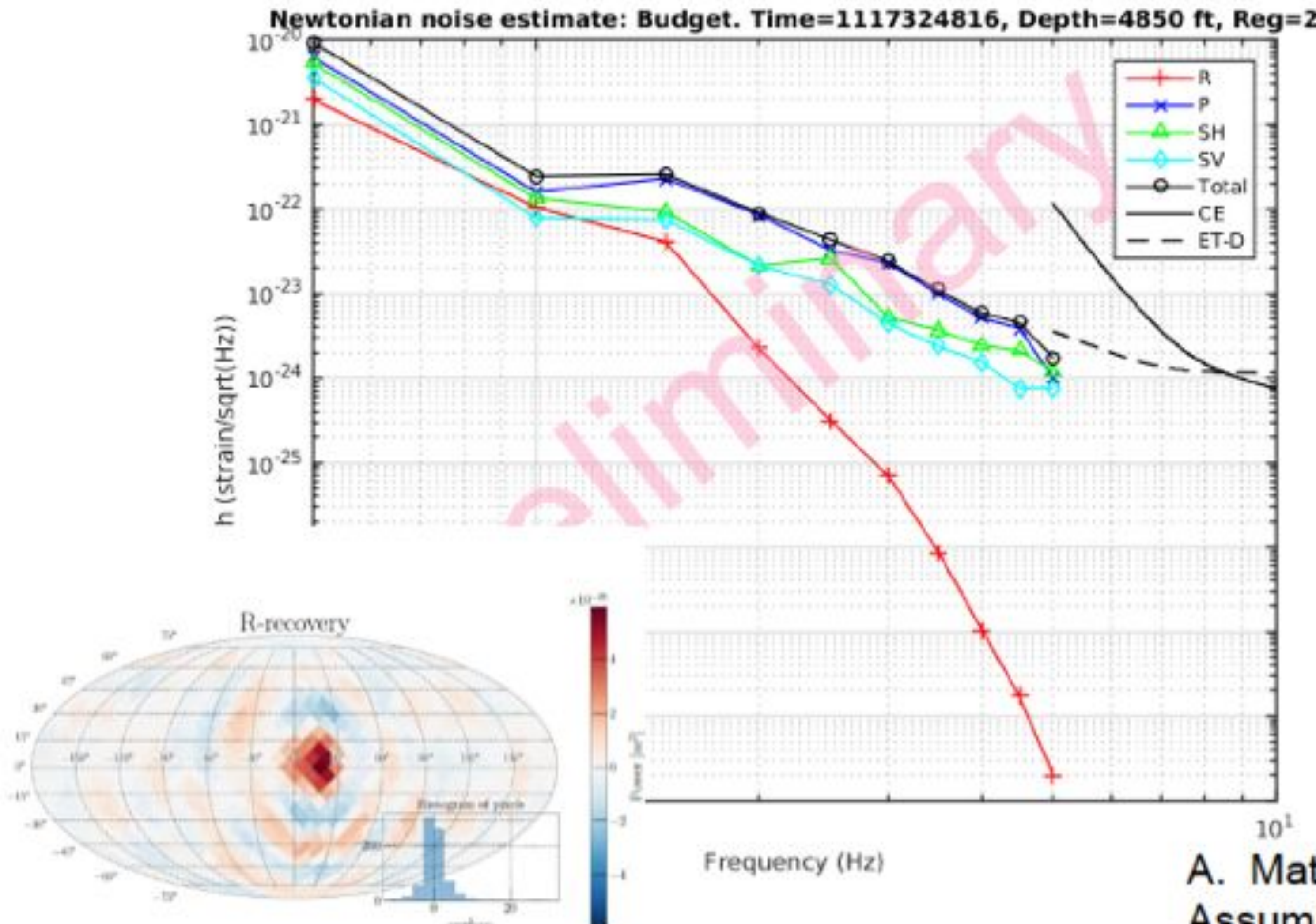


Credit: ET design study

Homestake Results

Vuk Mandic

4850 ft (1600 m)



Seismic array:

Seismic spectrum decomposed into mode types (with different depth dependence)

A. Matas

Assuming CE design

Atmospheric NN

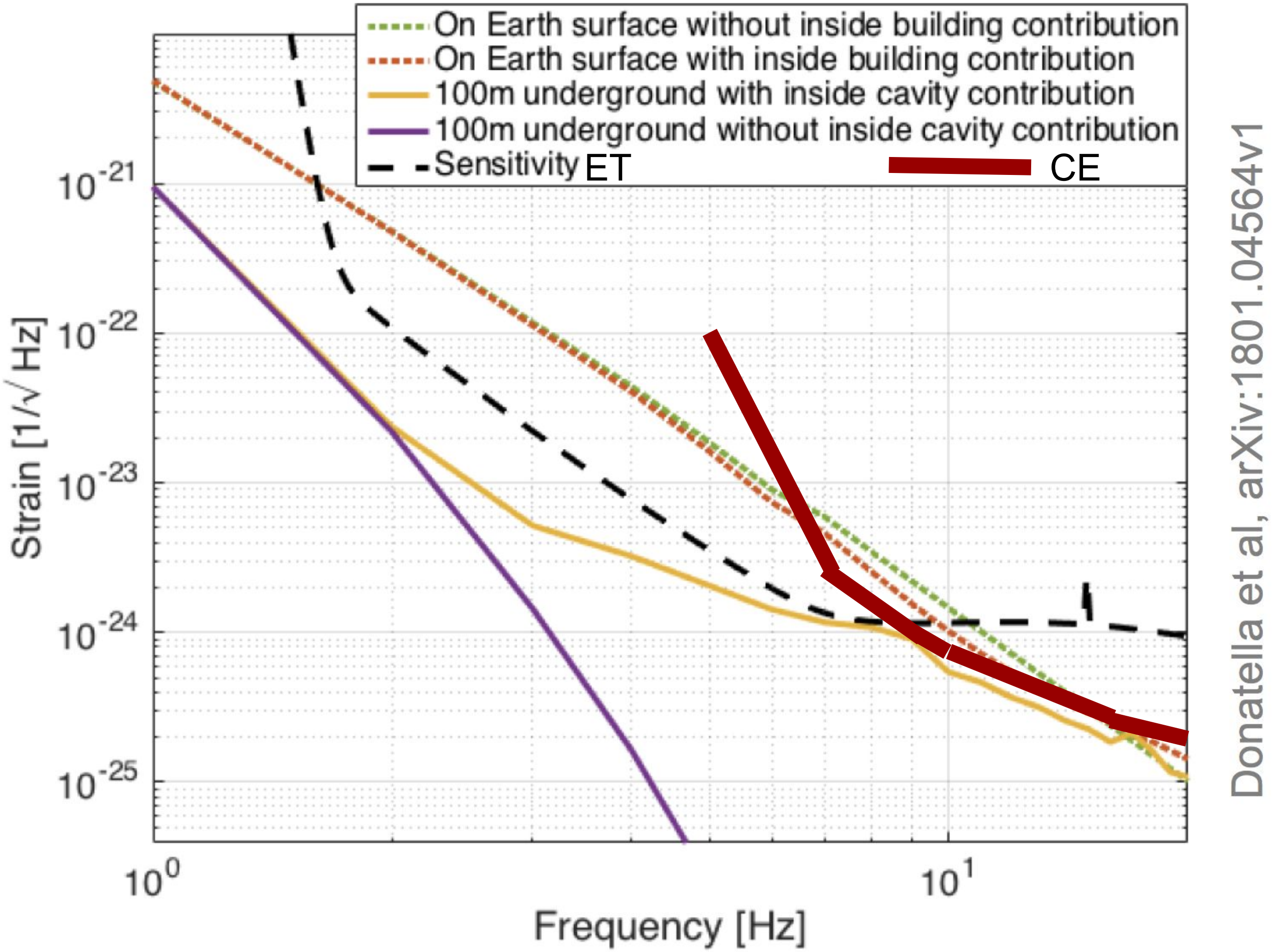


FIG. 11. Infrasound NN for an ET like laser interferometer.

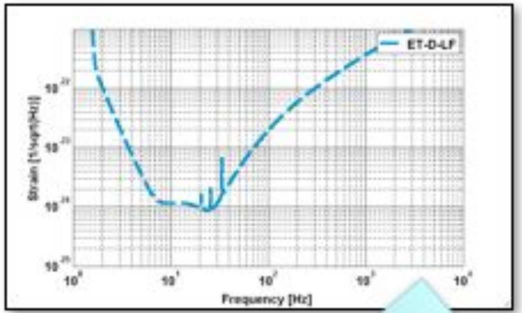
Double the hardware: Xylophone for ET

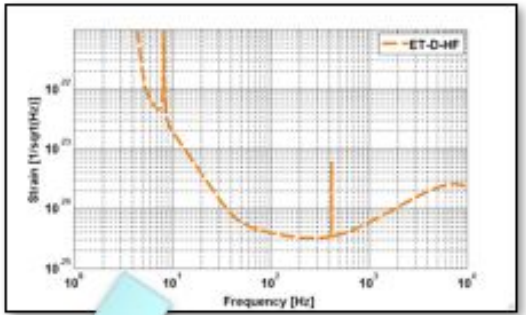
- As our detectors become more and more complex and at the same time aim increase even further the observation bandwidth the xylophone concept becomes more and more attractive.
- The xylophone concept was originally suggested for advanced LIGO:

  R.DeSalvo, CQG 21 (2004) S1145-S1154
  G.Conforto and R.DeSalvo, Nuc. Instruments 518 (2004) 228 - 232
  D.Shoemaker, presentation at Aspen meeting (2001), http://www.ligo.caltech.edu/docs/G/G010026-00.pdf

- Allows to overcome 'contradicting' requirements in the technical detector design:
  - To reduce shot noise you have to increase the light power, which in turn will reduce the sensitivity at low frequencies due to higher radiation pressure noise.
  - Need cryogenic mirrors for low frequency sensitivity. However, due to residual absorption it is hard to combine cryogenic mirrors with high power interferometers.
- For ET we choose the conservative approach (designing an infrastructure) and went for a 2-band xylophone: low-power, cryogenic low-frequency detector and a high-power, room-temperature high-frequency detector.

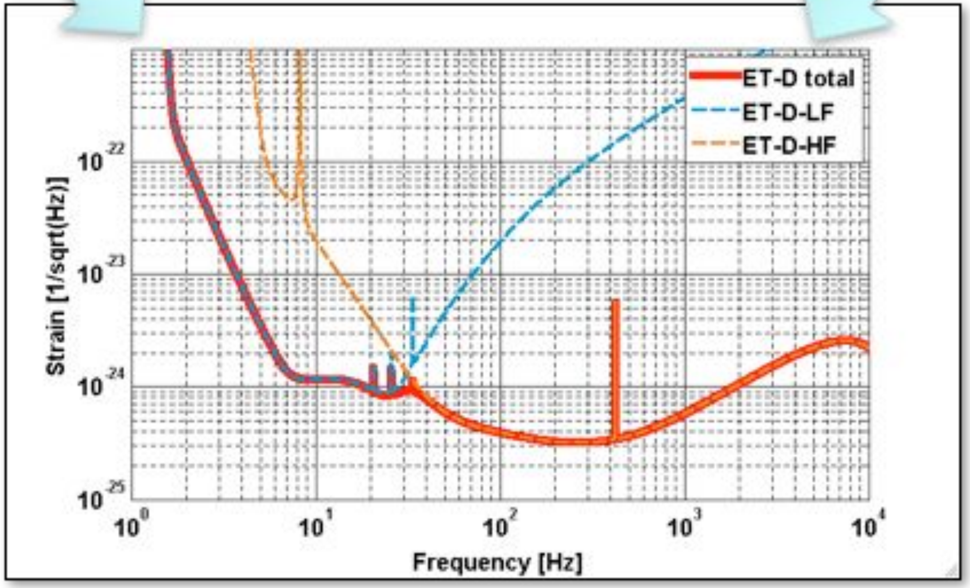
Double the hardware: Xylophone for ET





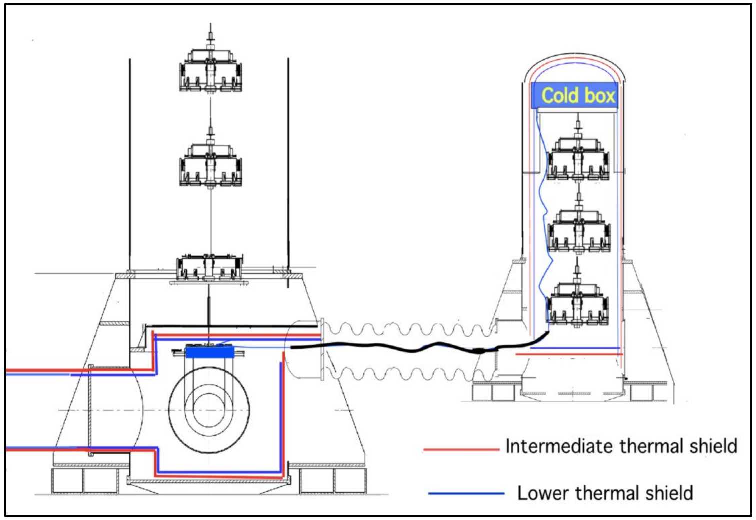
ET-D-LF

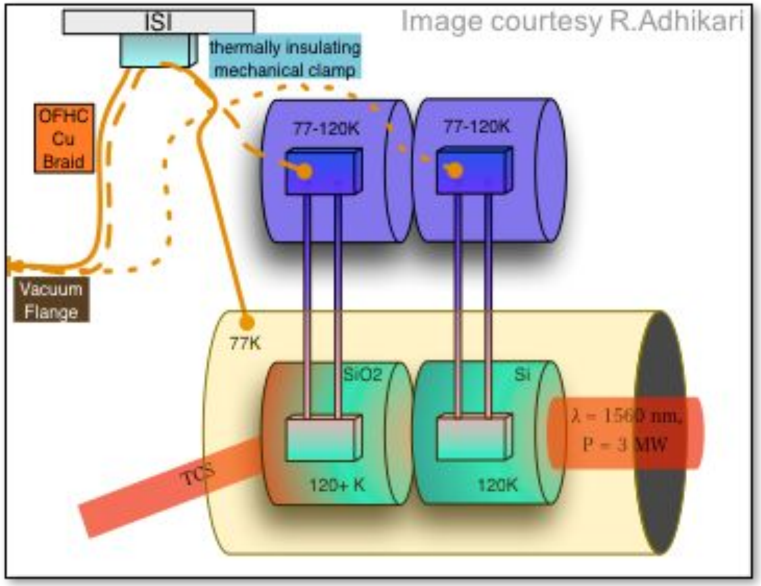
ET-D-HF



Cryogenics

- Motivation: Reduction of thermal noise (improve low frequency) and for 120K also enable high power operation (improve high frequency).
- Obviously, going cryogenic is a large effort, especially when going to the 10-20K range (new materials, new wavelength, new designs, additional machinery).
- Seismic noise / newtonian noise due to cryogenic machinery?
- Additional noises like scattering due to heat shields etc ...

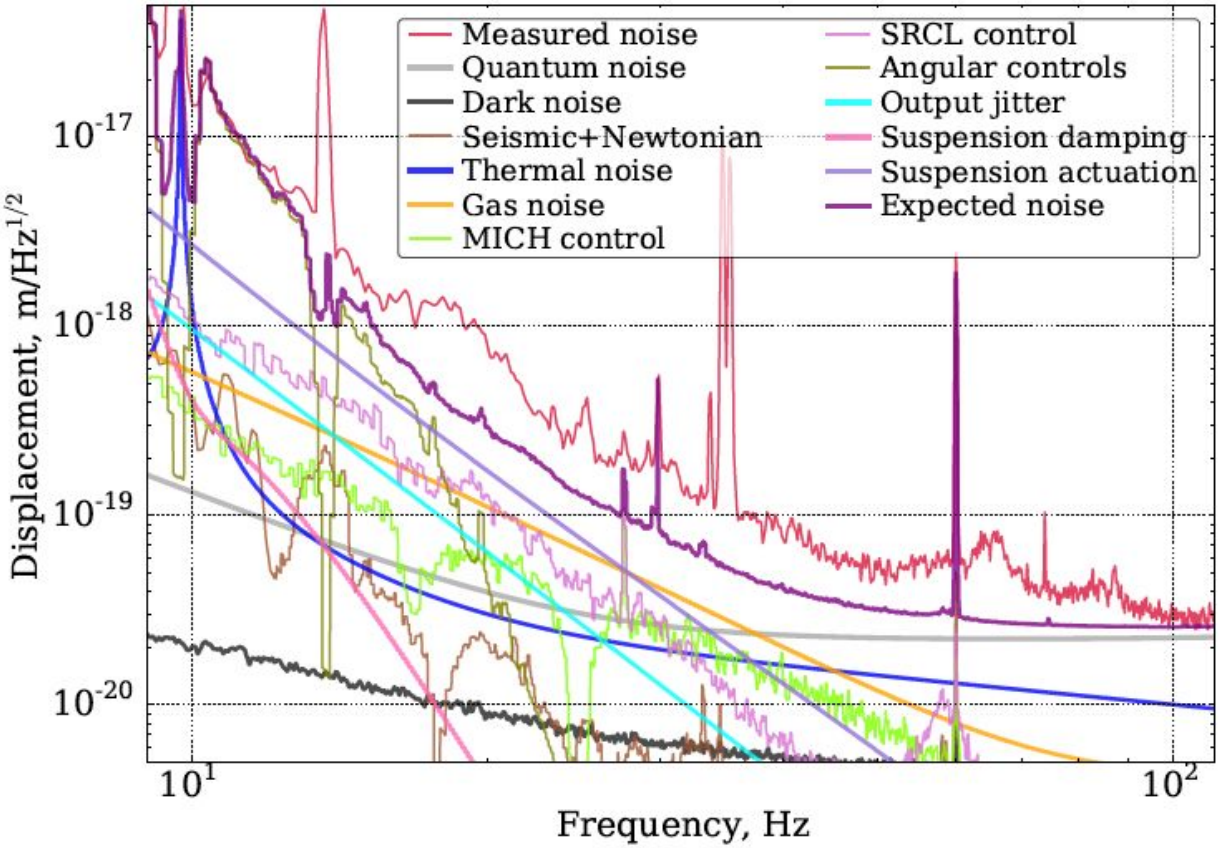




Control noises

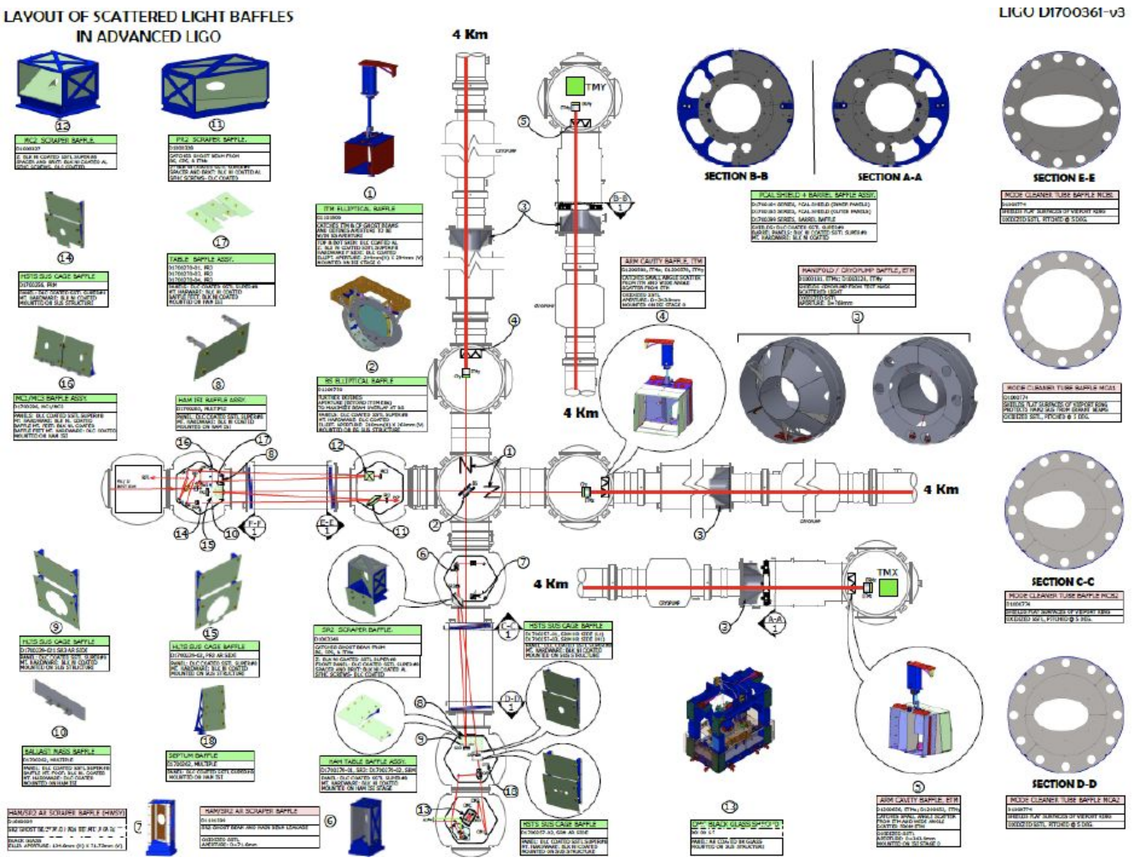
- Seismic+Newtonian is far from limiting noise source in current detectors
- Realistic control design is essential for predicting actual performance
- Still unknown noise left…

- O2 noise budget Livingston:



(a) LIGO Livingston Observatory

Scattered light



- Light ‘taking the wrong path’. Creates loss, but more importantly for low frequency sensitivity: creates noise.
- Large engineering effort to mitigate.
- So far only observed as phase noise. In future also causing radiation pressure noise?

How can one approach a trade-off?

- For a single source or figure of merit it should not be too difficult to come up with a number in units [science/$$$]
- How to combine such numbers for various sources or science targets?

EXTRA SLIDES

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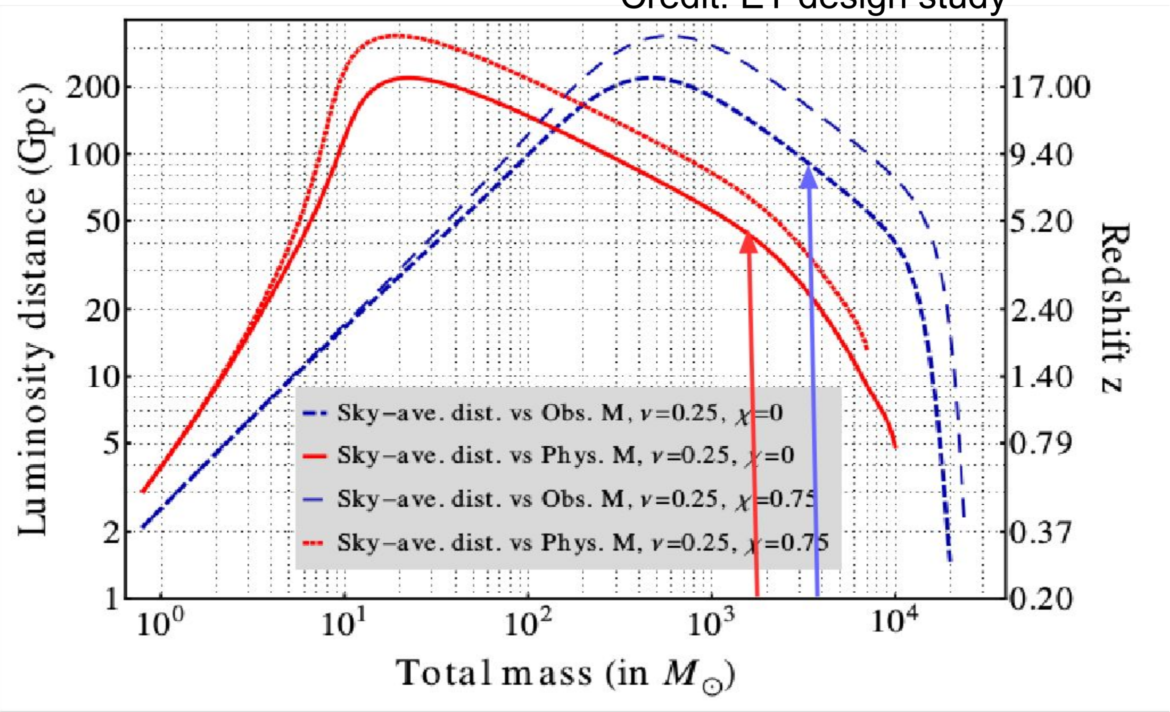
Credit: ET design study



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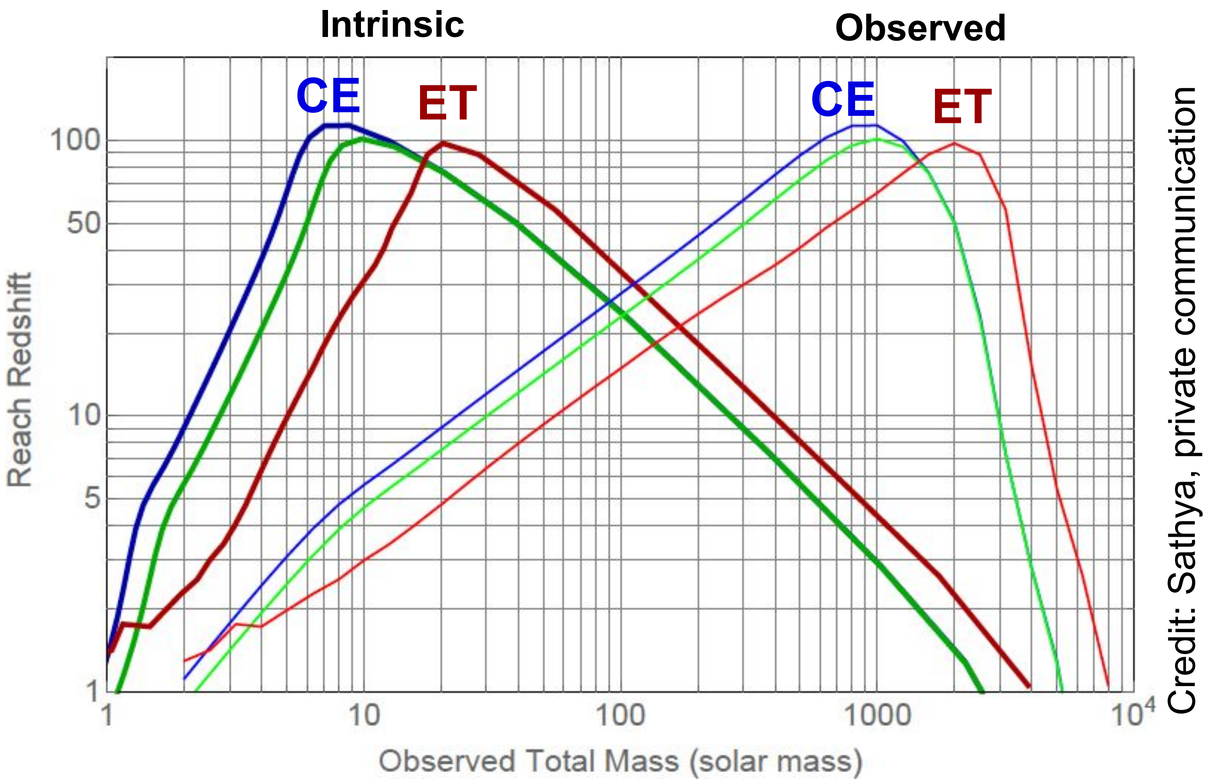

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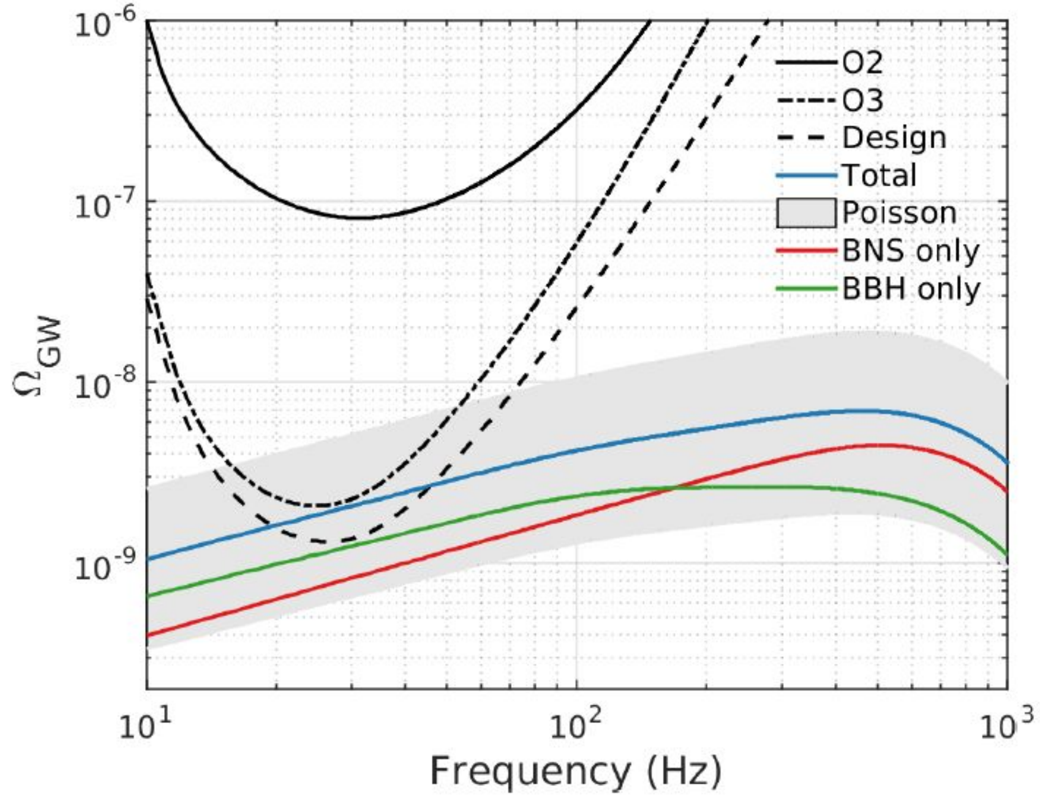

Gaining sensitivity for heavy binaries, a caveat...

Lessons for 2G:

For heavy/short signals the glitch foreground is more severe

True reason for our current cut-off at higher masses