Getting ready: exploit LISA to improve LIGO's tests of General Relativity

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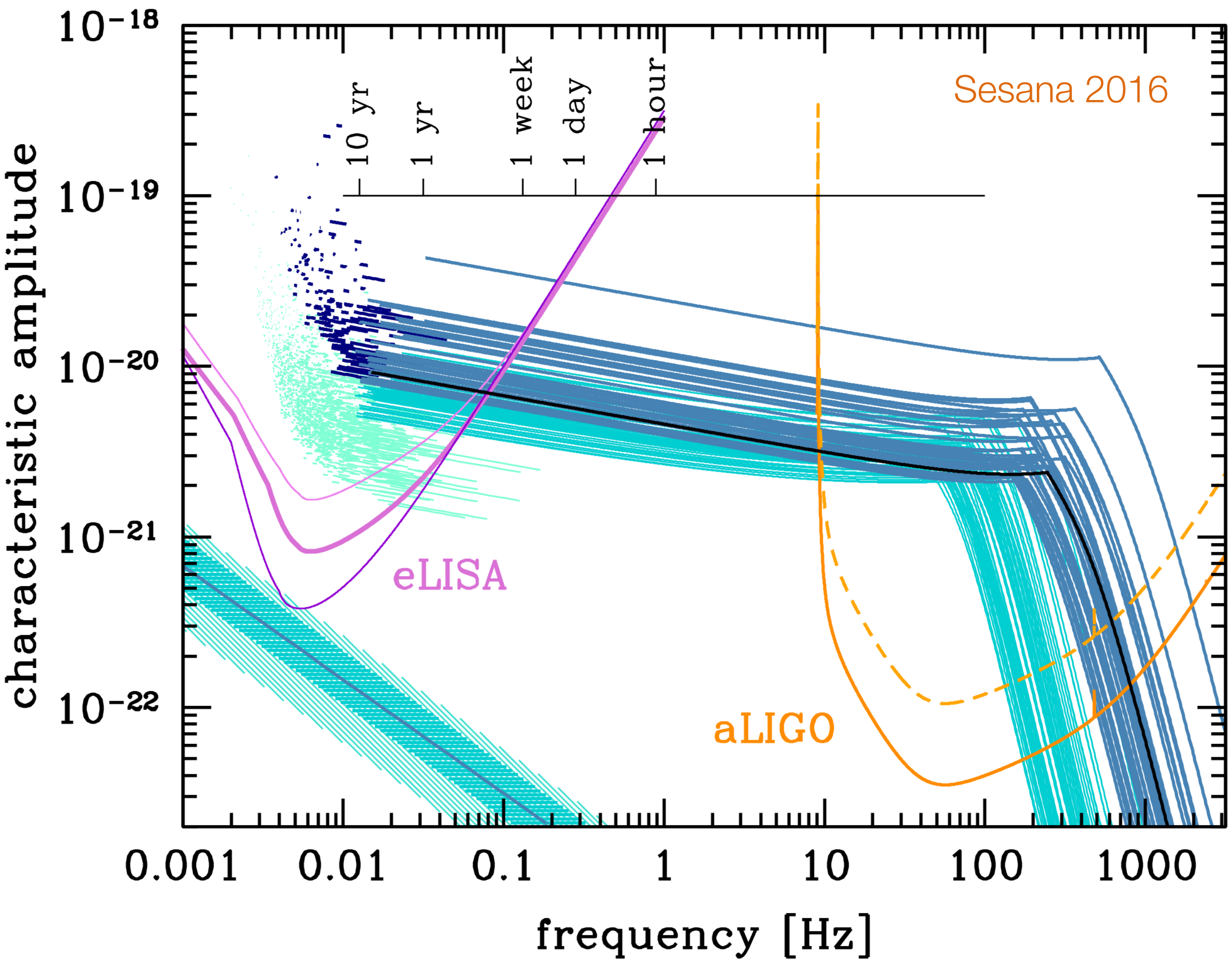
Outline

1. LISA forewarnings
2. Black-hole spectroscopy
3. Optimizing LIGO
4. Results
5. Next?

LISA forewarnings

Multi-band GW observations with $30 M_\odot$ binaries



Multi-band GW science

- Catch counterparts, if any
  Sesana 2016
- Constrain low-PN modifications of GR like dipole emission
  Barausse+ 2016
- Eccentricity measurements to constrain formation channels
  Nishizawa+ 2016, Brievik+ 2016
  Samsing D'Orazio 2018
- Improve LIGO parameter estimation
  Vitale+ 2016
- New class of standard sirens
  Del Pozzo+ 2016
- Stay tuned for a white paper…

LISA will predict when (time) and where (frequency) the merger will happen in LIGO with years of forewarning!

Can we get ready for that?

We know a source is coming and have some knowledge of it

Masses ok but probably no spins info…

Can we maximize the scientific return of the ground-based observations?

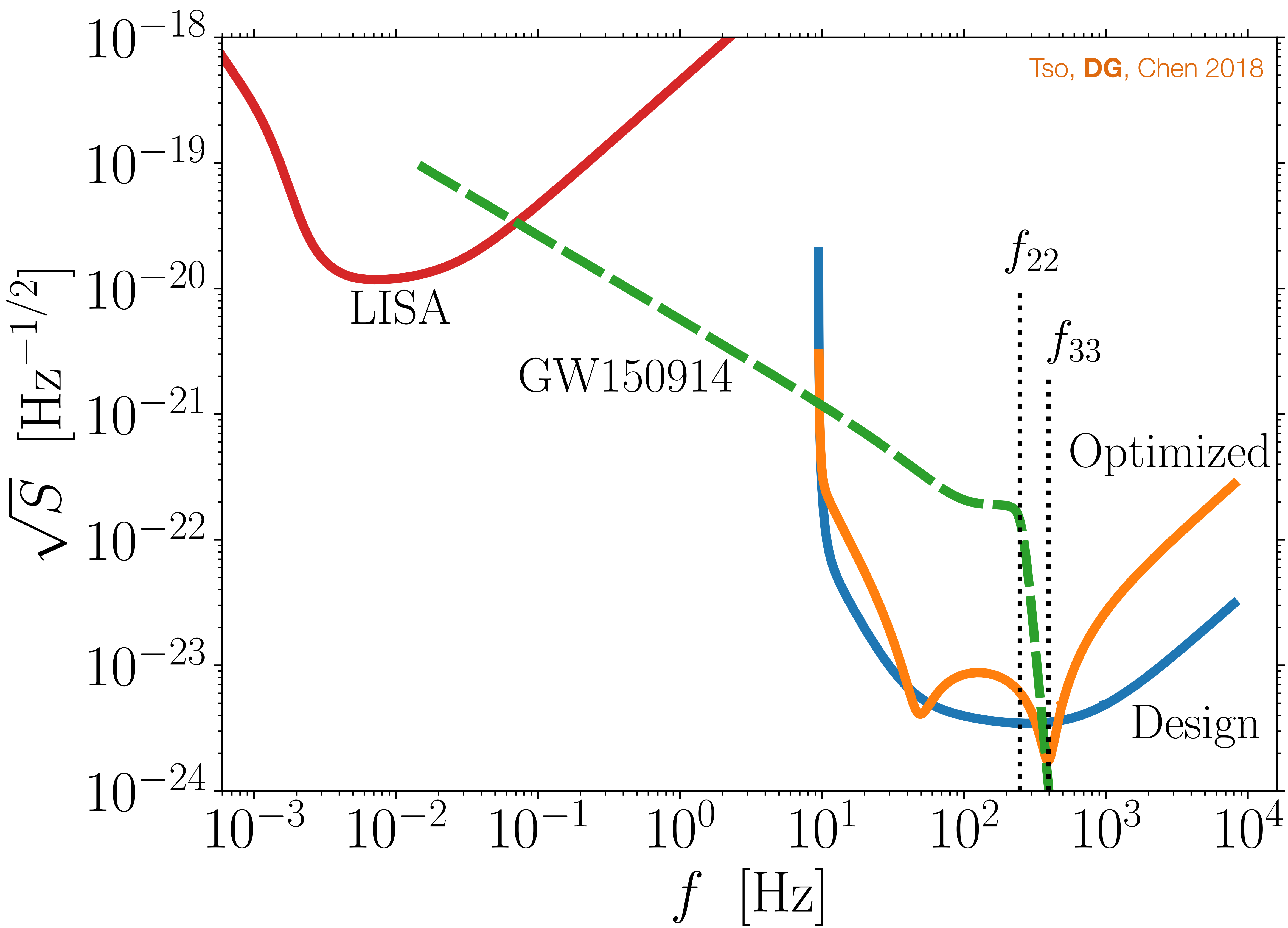
Easy: make sure ground-based detectors are operating. Plan detector upgrades and duty cycle accordingly.

Hard: change the optical configuration of the ground-based interferometer targeting that specific GW source.

This talk:
proof of principle to explore the potentials of the hard way…

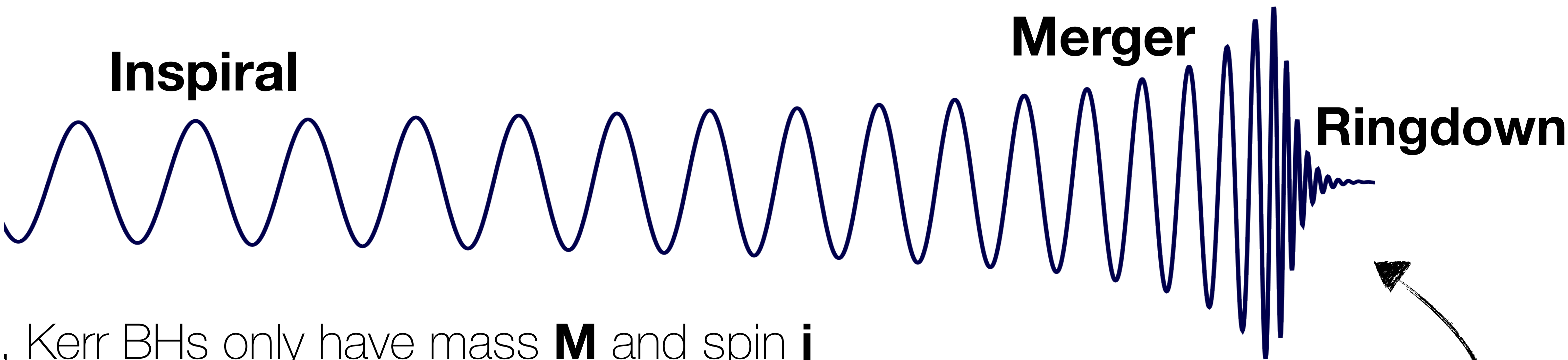
Optimized narrow-banding

Better catch a feature of the signal somewhere in frequency

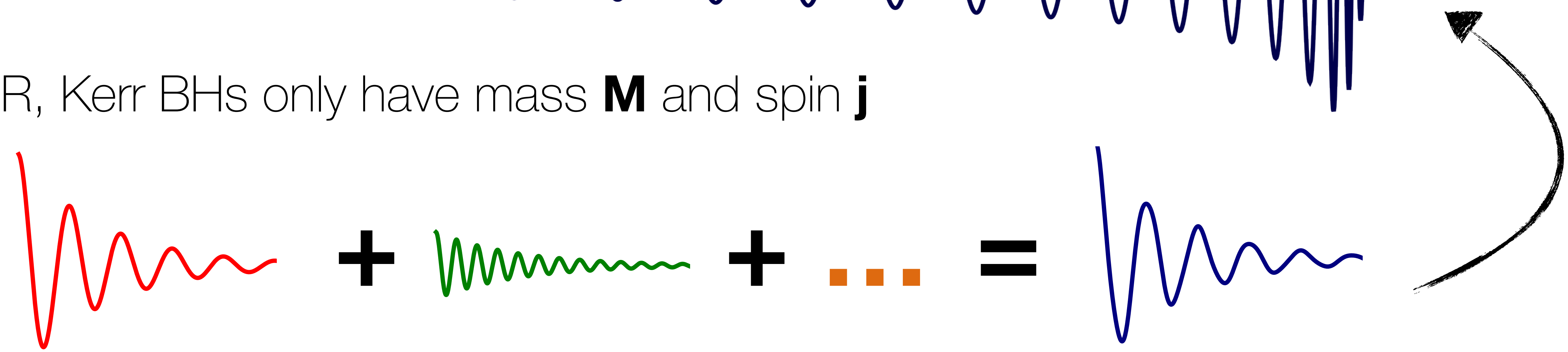


Black-hole spectroscopy

Testing the Kerr nature of astrophysical BHs with their ringdown emission



In GR, Kerr BHs only have mass **M** and spin **j**



Dominant mode	First subdominant	Infinitely many	Ringdown signal
$(f, \tau) \to (M, j)$	$(f, \tau) \to (M, j)$		

Measurement of one mode is an estimate of **(M,j)**
Measurement of any additional mode is a test of the theory

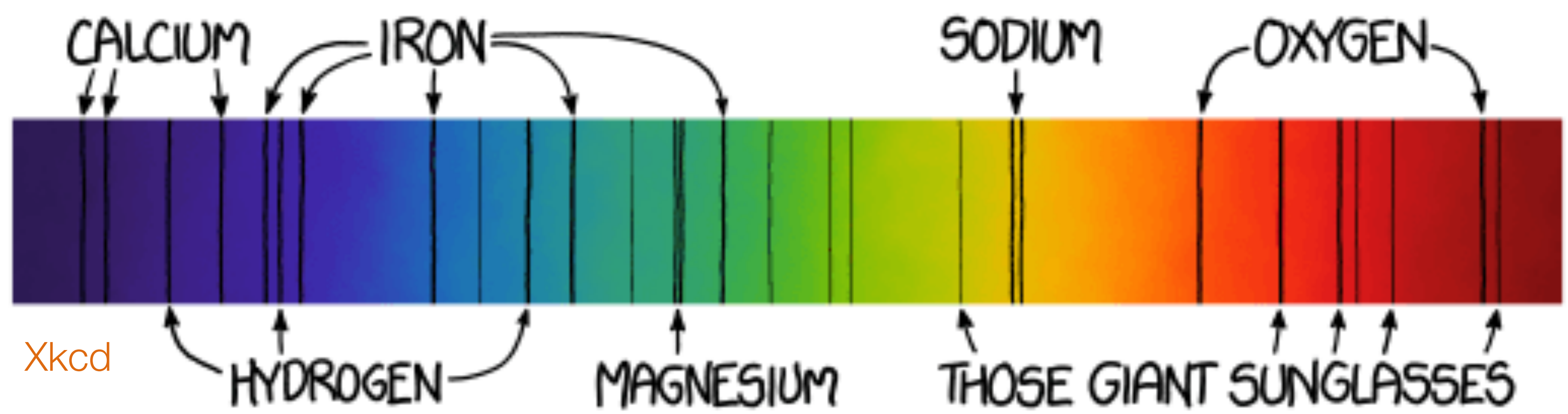
That's challenging! Subdominant modes are weak. Many ideas…

Berti+ 2016, Maselli+2017, Baibhav+2018, Yang+ 2017

Black-hole spectroscopy

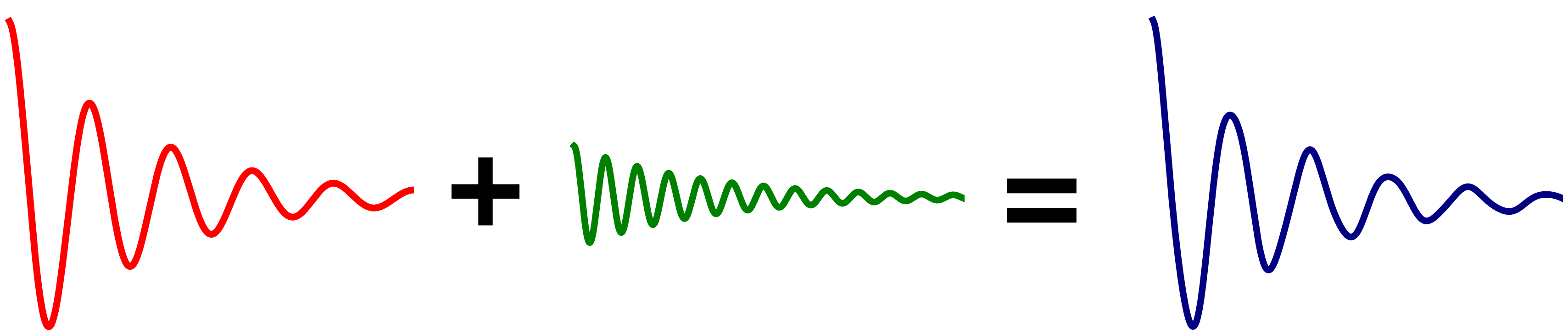
Detwiler+ 1980

Atom's spectral lines: identify elements and test quantum mechanics



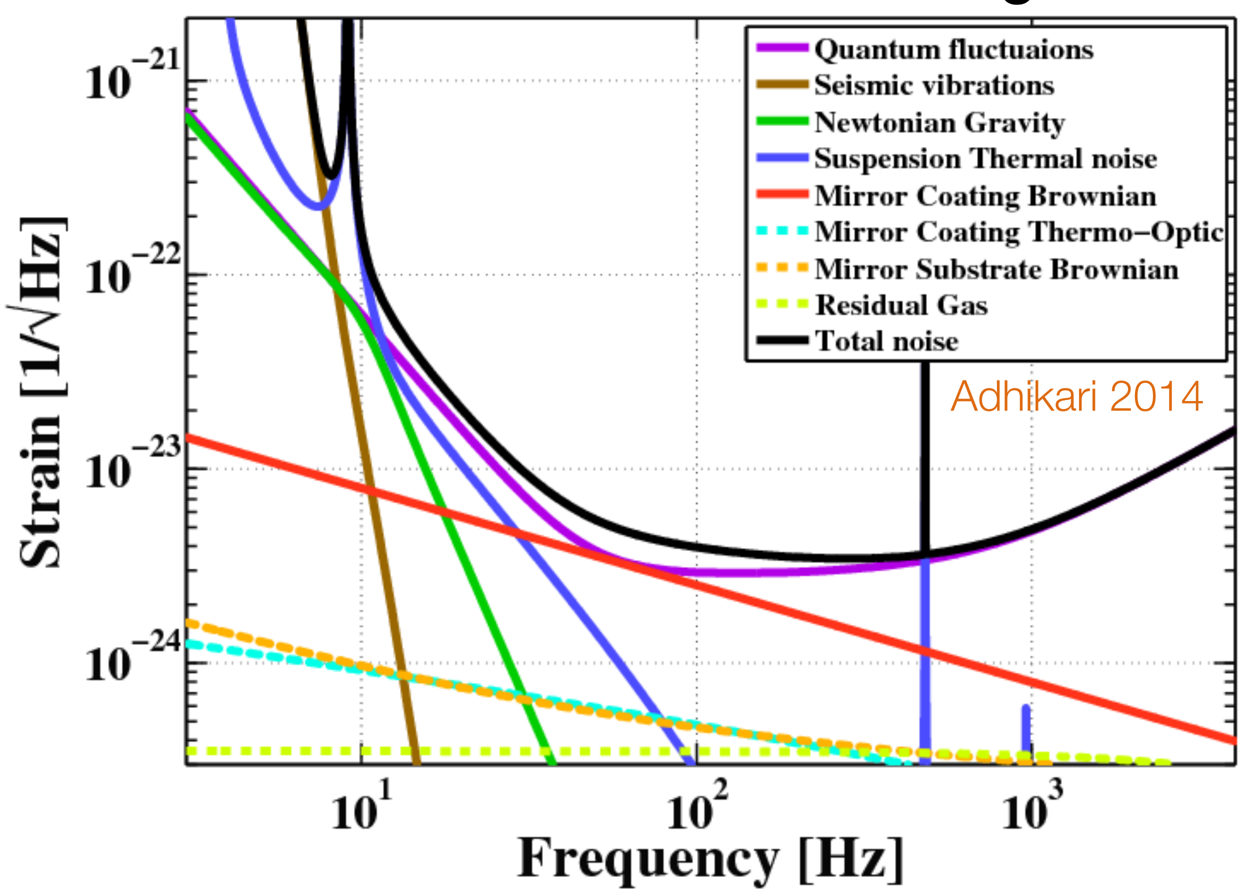
Xkcd

Quasi-normal modes: probe the nature of BHs and test gravity



Optimizing LIGO for BH science

Advanced LIGO noise budget



Optimizing the quantum noise contribution

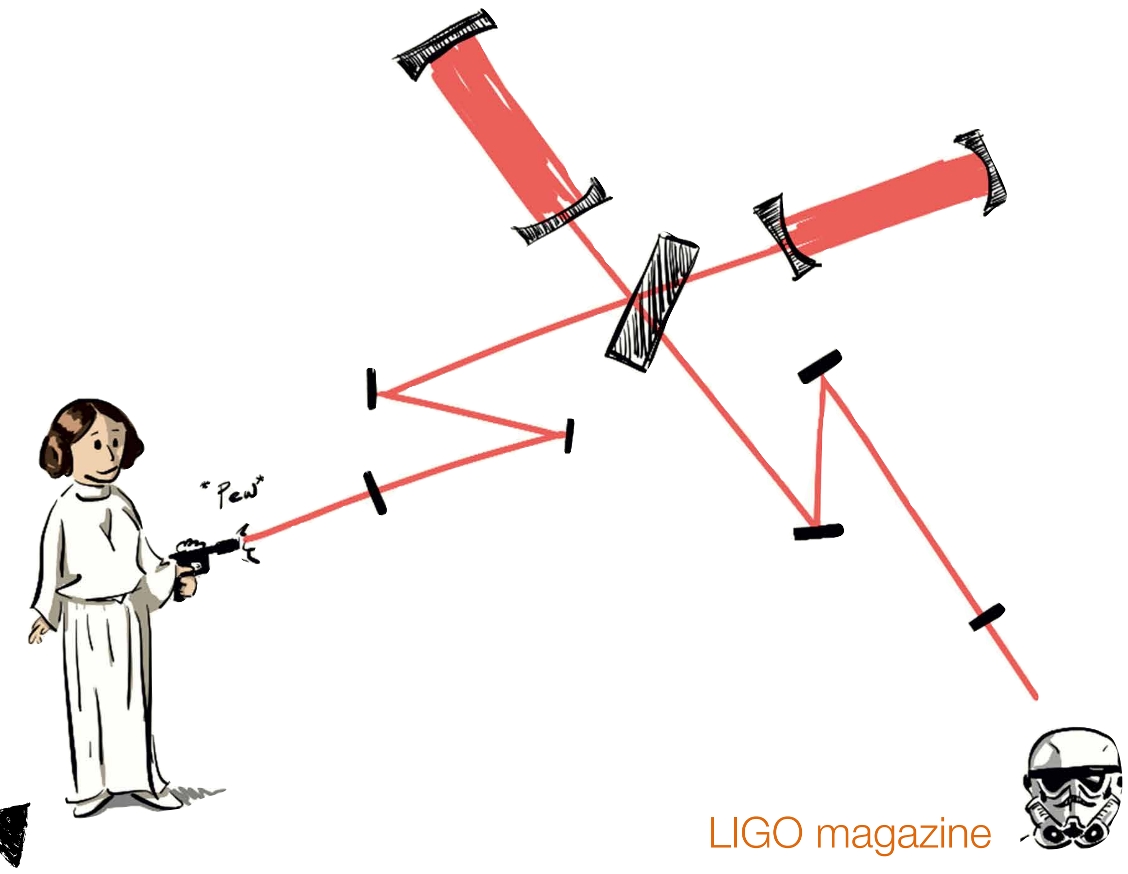
- Input optical power
- Signal recycling mirror transmissivity
- Cavity tuning phases
- Squeeze factors
- etc…

Previous explorations:

- NS post-merger signals Hughes 2002, Miao+ 2017, Martynov+ (in prep)
- Stochastic background Tao Christernsen 2018

As an example of narrow-banding, here we explore cavity detuning

This is probably very hard in practice
(tested on the 40m prototype) Ward 2010

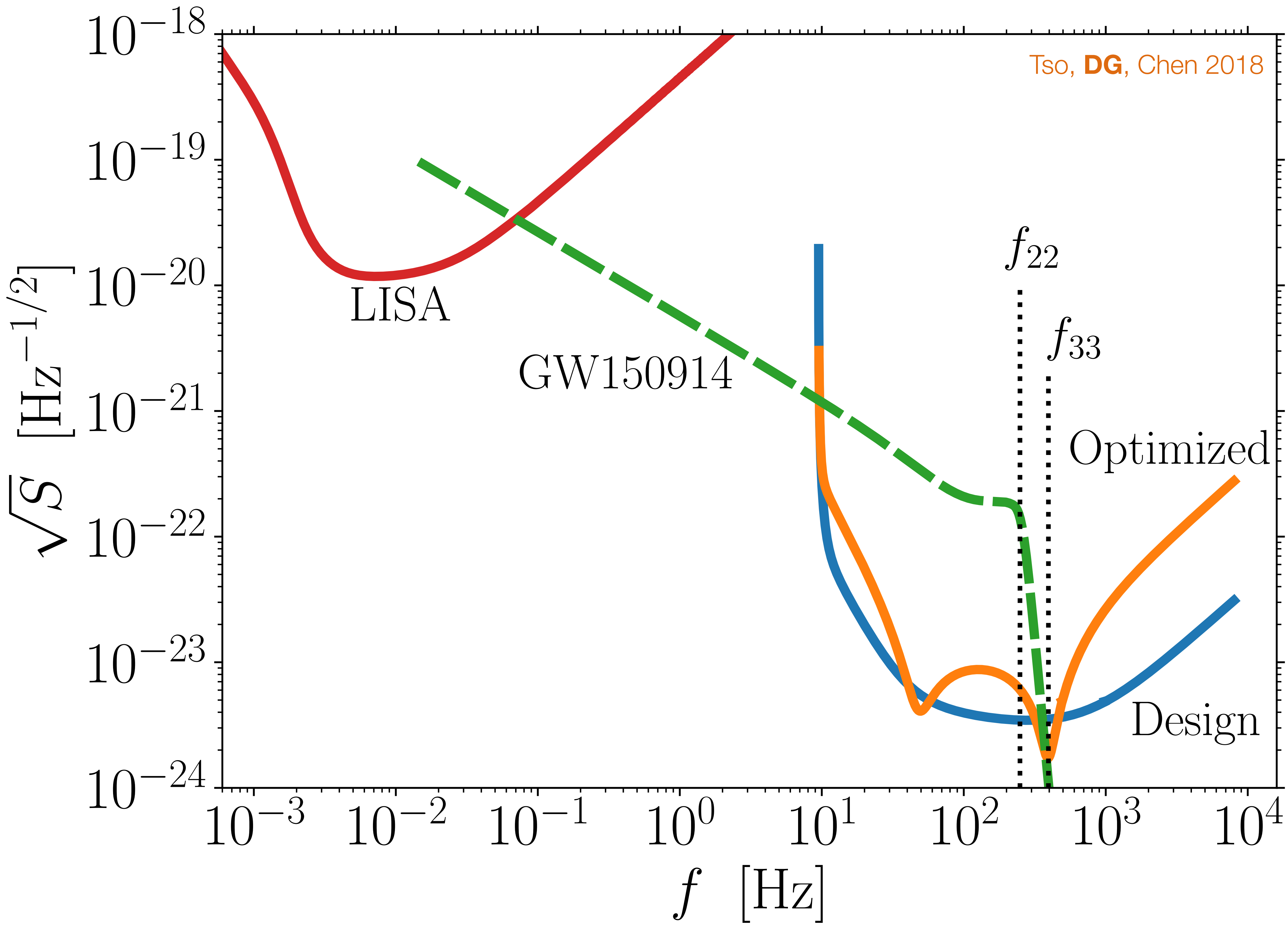


LIGO magazine

… this is LIGO for theorists

Optimized narrow-banding

Better catch a feature of the signal somewhere in frequency



What should we optimize for?

In the spirit of BH spectroscopy: $h = h_{22}(M_{22}, j_{22}) + h_{33}(M_{33}, j_{33})$

Construct Fisher matrix: $\boldsymbol{\Gamma}^{-1} = \begin{bmatrix} \boldsymbol{\Gamma}^{-1}_{2222} & \boldsymbol{\Gamma}^{-1}_{2233} \\ \boldsymbol{\Gamma}^{-1}_{3322} & \boldsymbol{\Gamma}^{-1}_{3333} \end{bmatrix}$

Confidence ellipses

Consider 2x2 diagonal blocks

$$\boldsymbol{\Gamma}^{-1}_{2222} \qquad \boldsymbol{\Gamma}^{-1}_{3333}$$

and draw confidence ellipses for (M,j)

Spectroscopy estimator

Consider random variables

$$\delta M = \delta M_{22} - \delta M_{33}$$
$$\delta j = \delta j_{22} - \delta j_{33}$$

and construct a Fisher-like quantity

$$\delta \mathrm{GR} = \begin{vmatrix} \langle \delta M^2 \rangle & \langle \delta M \delta j \rangle \\ \langle \delta j \delta M \rangle & \langle \delta j^2 \rangle \end{vmatrix}^{1/4}$$

Catch (3,3) and lose a bit of (2,2)

GW150914-like source…

$m_1 + m_2 = 65 M_\odot \quad q = 0.8$

$\iota = 150^\circ \quad \beta = 0$ optimally oriented

… but 10 times closer

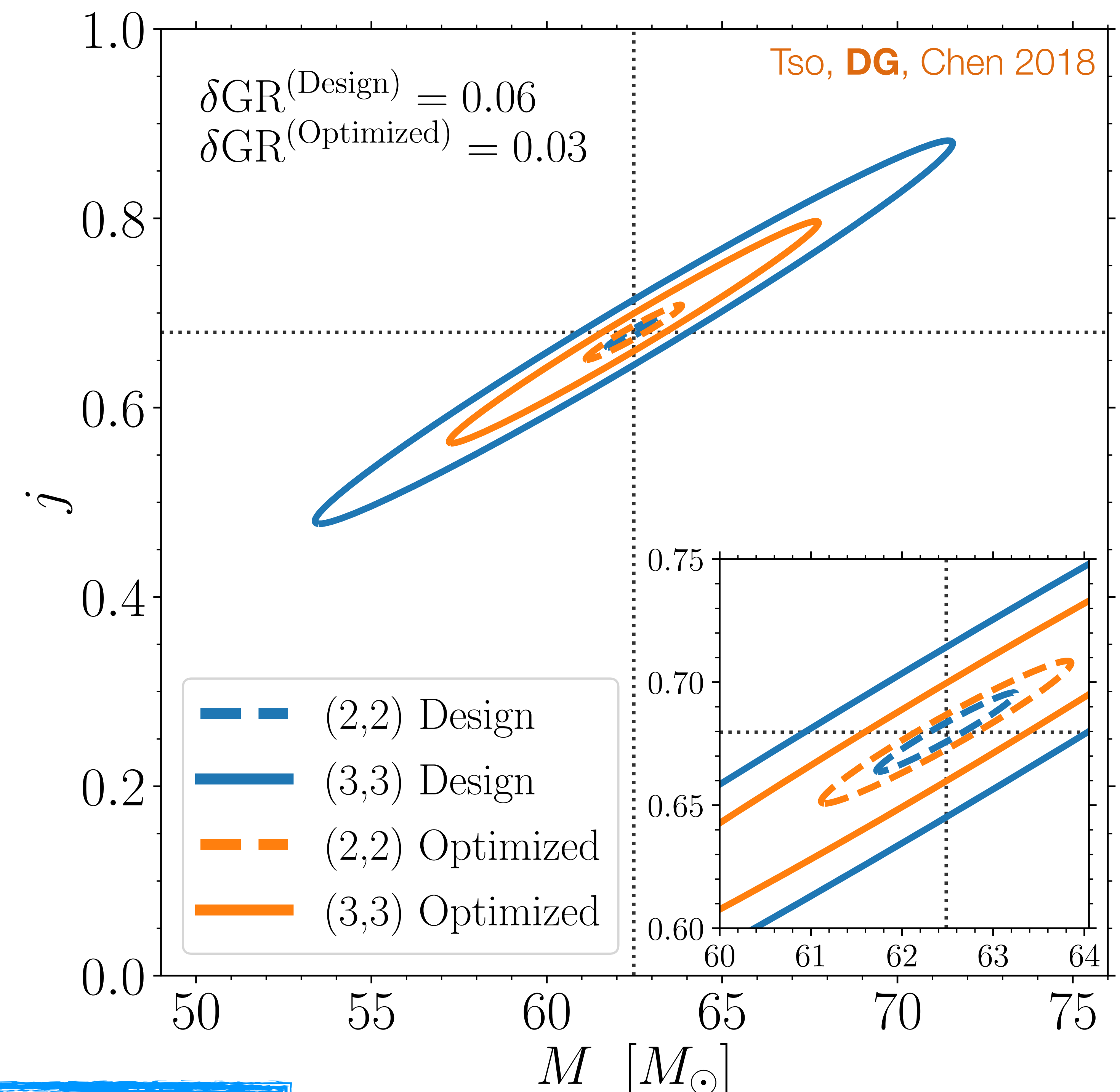
$D = 40\,\mathrm{Mpc}$

Perturbed BH:

$M = 62.5 M_\odot \quad j = 0.68$

Broadband: only the dominant mode

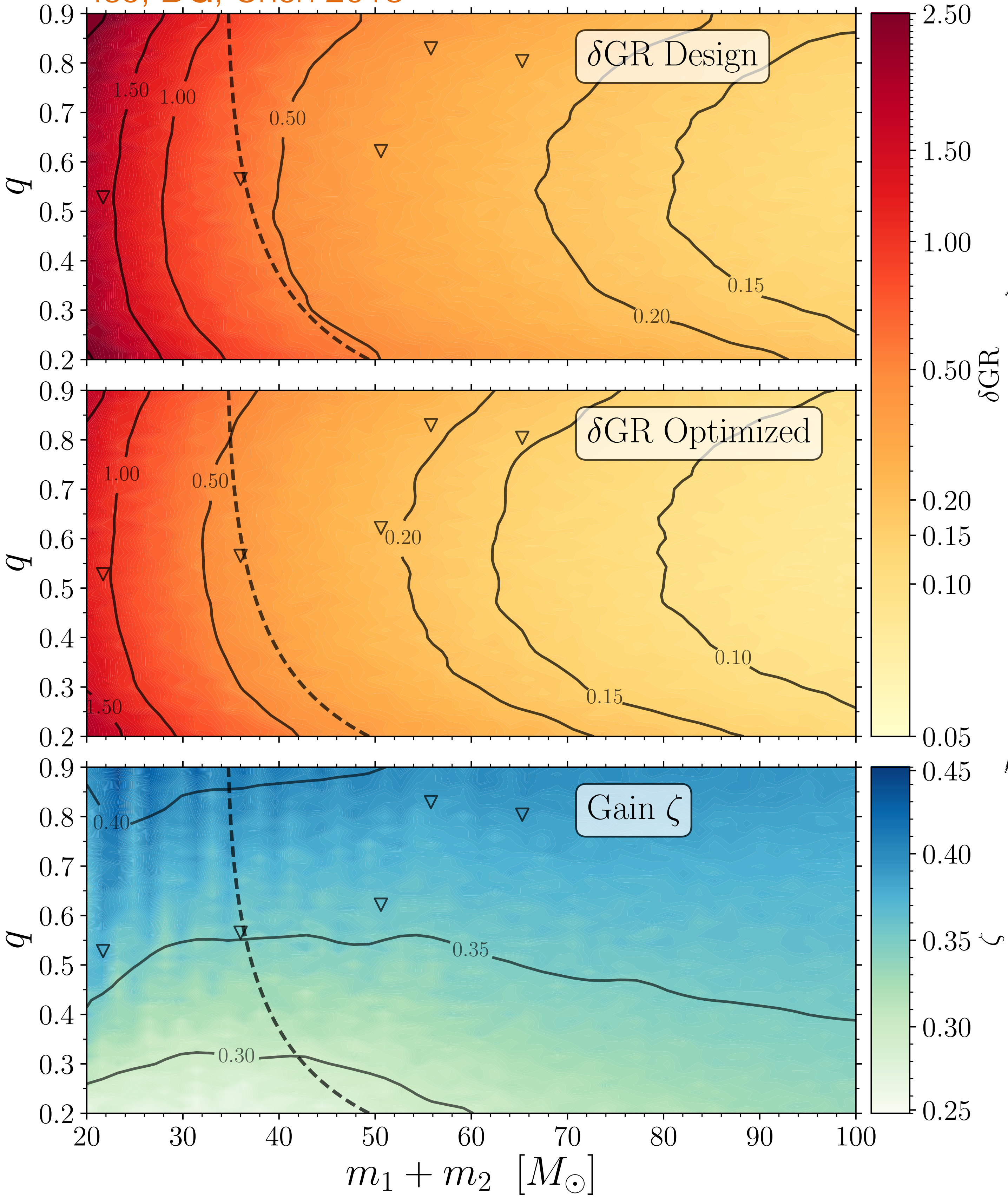
Optimized: greatly improve the subdominant mode, while losing a bit of the other one



Test of GR is a factor of 2 stronger!

Potential narrowband gain

Tso, **DG**, Chen 2018



Isotropic population of BH binaries at $D = 100\,\mathrm{Mpc}$

Median $\delta\mathrm{GR}$

- Stronger tests for high masses (ringdown in band). Higher LISA SNR
- Weak test for q~1 and q~0 (excitations suppressed)

Median gain

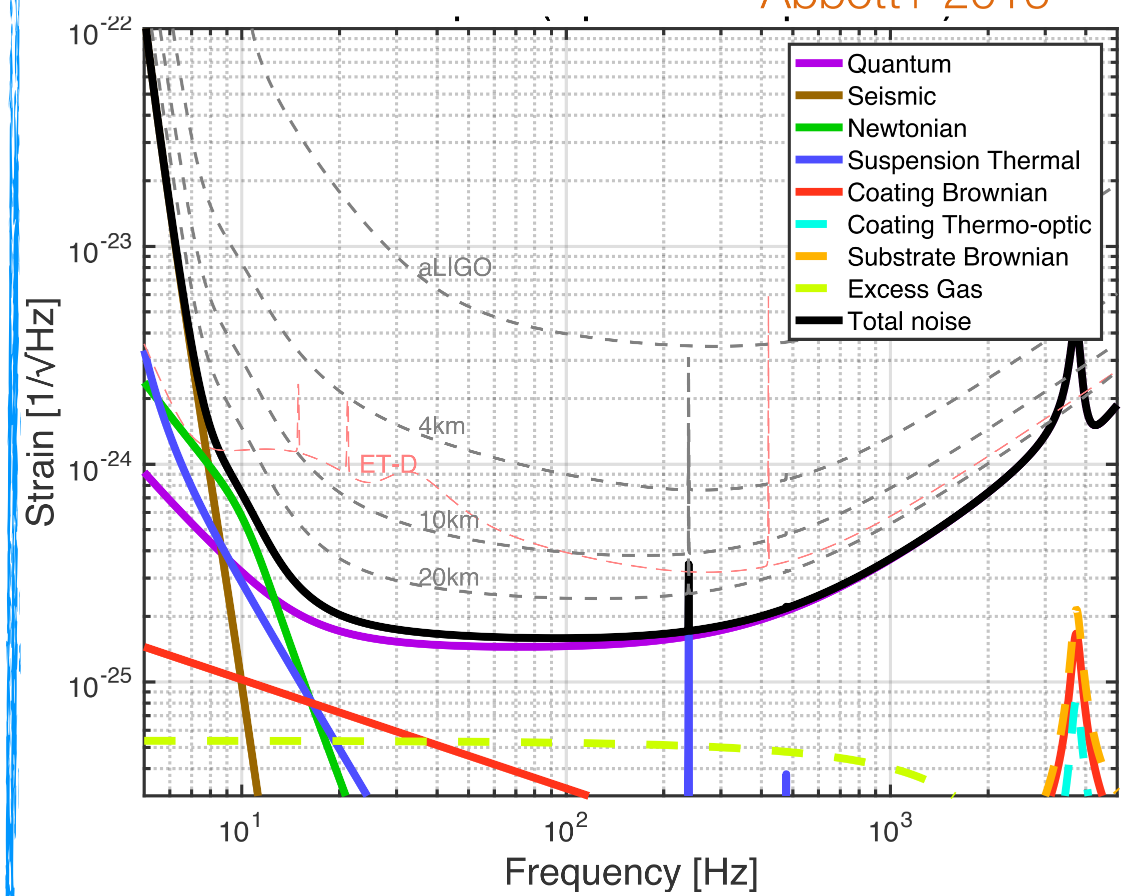
$$\zeta = \frac{\delta\mathrm{GR}^{(\mathrm{Design})} - \delta\mathrm{GR}^{(\mathrm{Optimized})}}{\delta\mathrm{GR}^{(\mathrm{Design})}}$$

Gain between 25% and 50% everywhere in parameters space

How about 3G?

Cosmic explorer

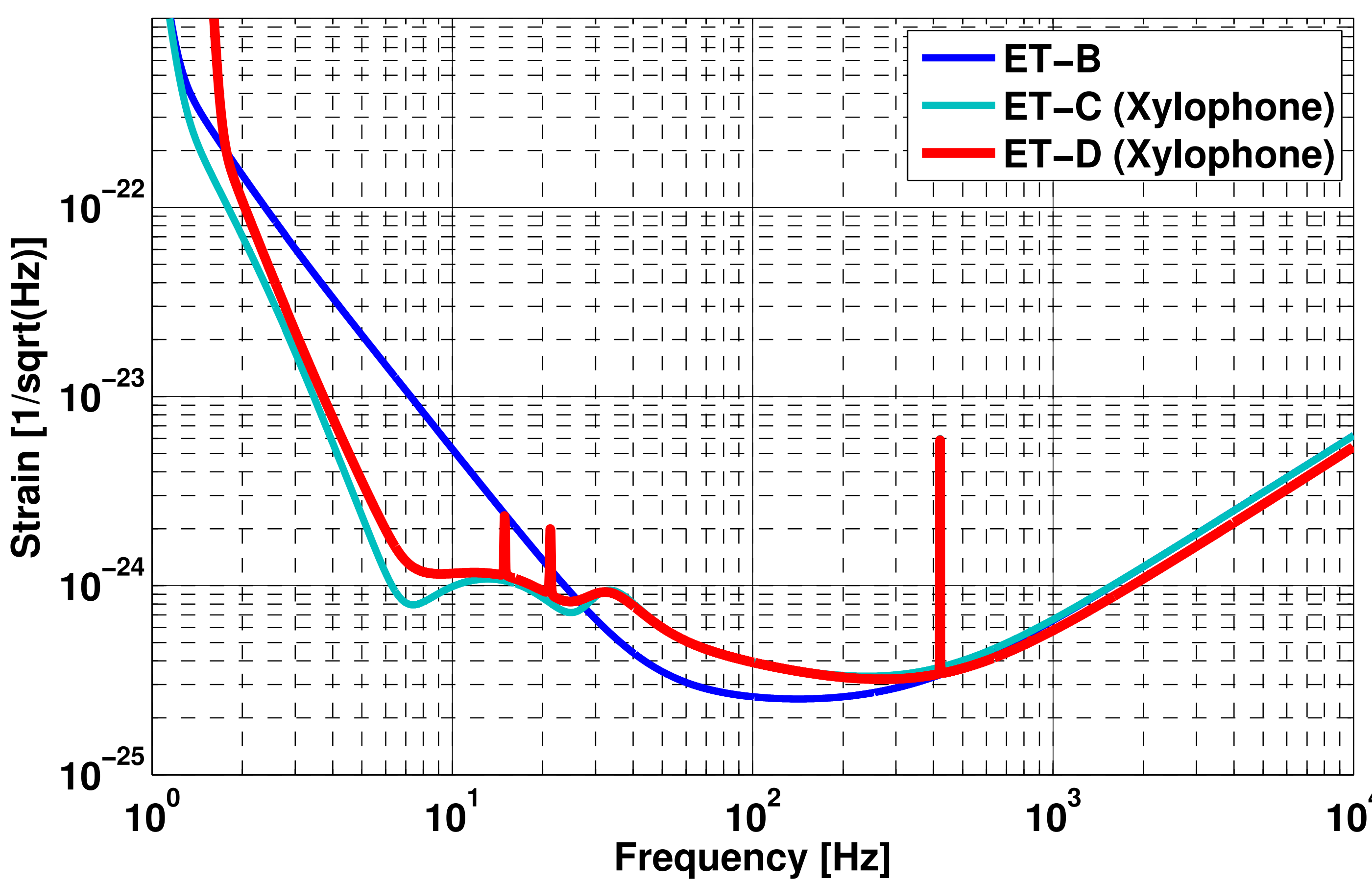
Abbott+ 2016



Quantum-noise dominated over a wide frequency range

Einstein Telescope

Hild+ 2010



Optimistic design is a sum of two interferometers, one of them is detuned

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