Multiband gravitational-wave (astro)physics

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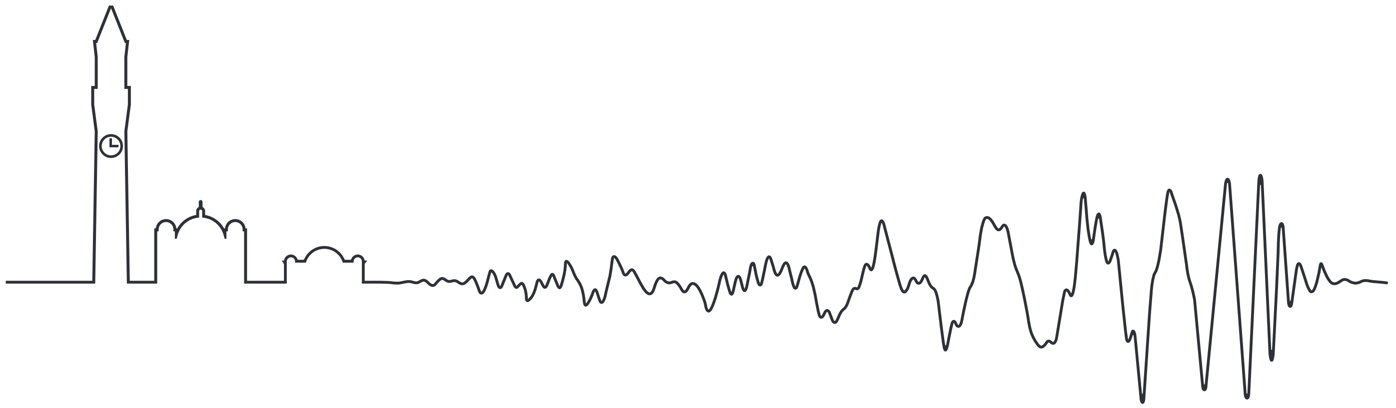
GrEAT winter school
Birmingham, UK

UNIVERSITY OF BIRMINGHAM



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Outline

1. Multiband prospects
2. How many?
3. Detectability (signal-to-noise ratio threshold)
4. Optimizing LIGO with LISA

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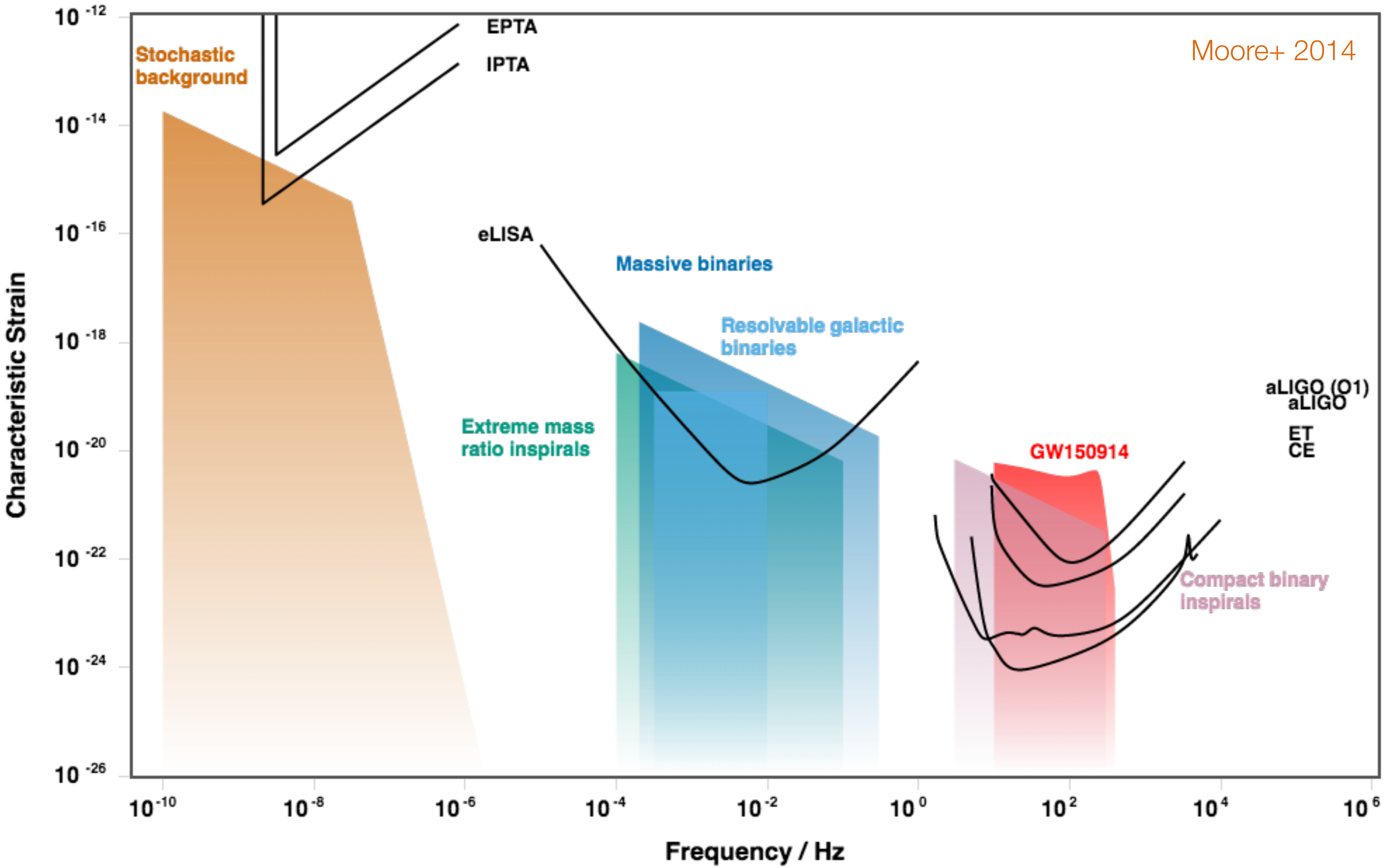
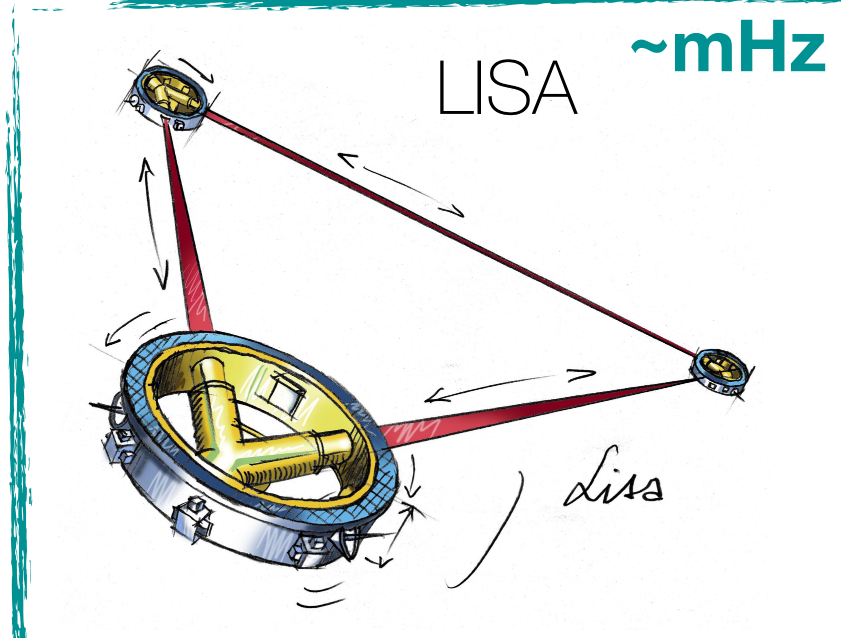
The gravity spectrum



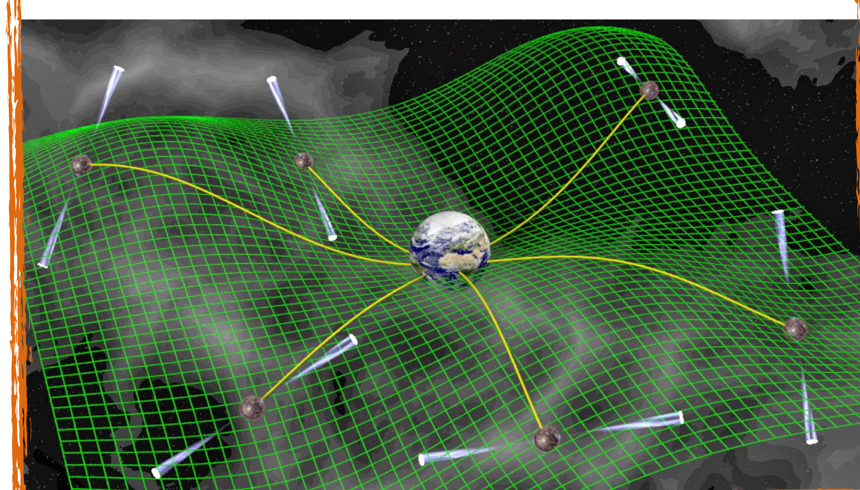
New bands, new detectors, new sources

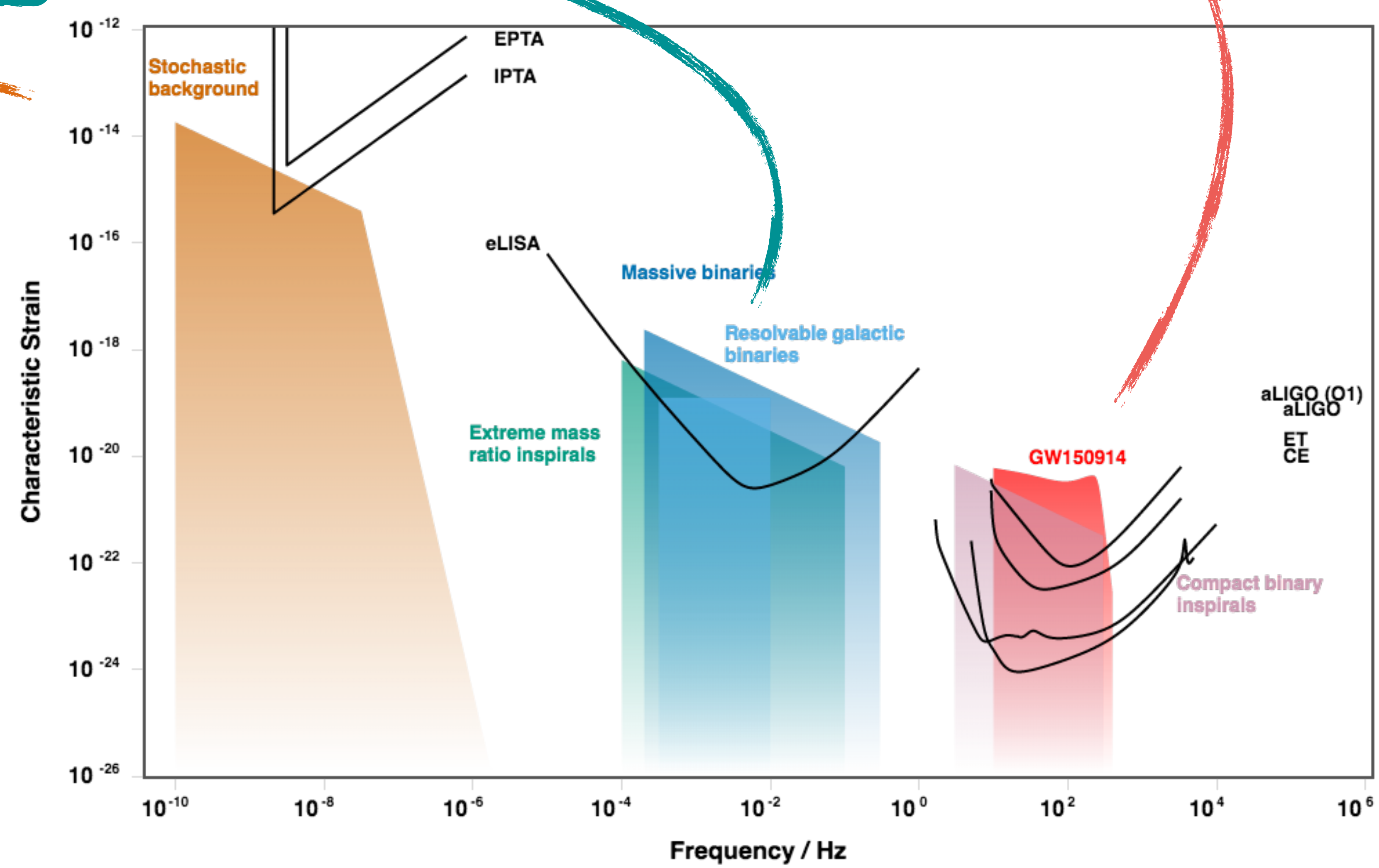
LISA ~mHz



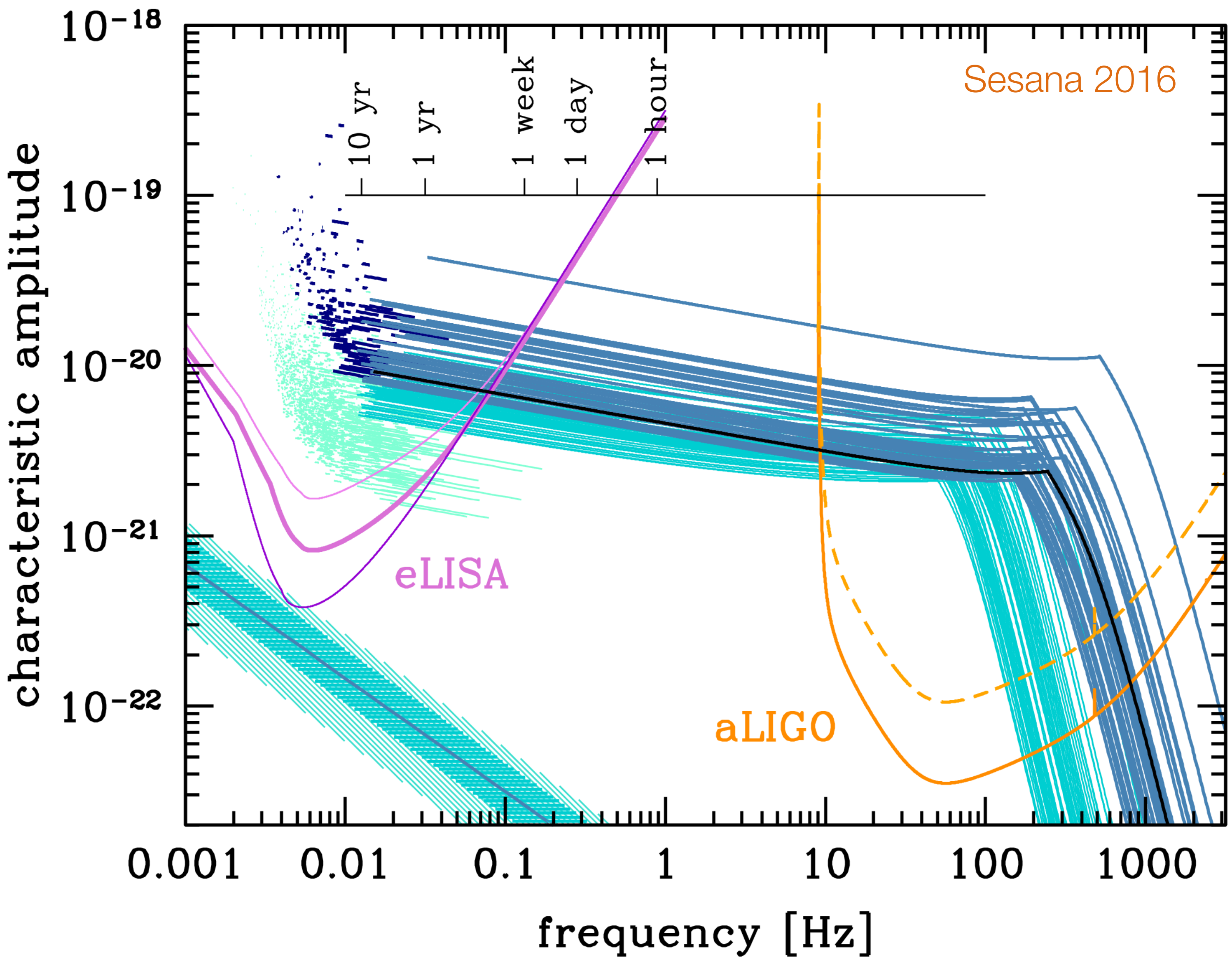
LIGO, Virgo, and more ~100Hz

Pulsar timing arrays ~nHz





LISA forewarnings



Multi-band GW science

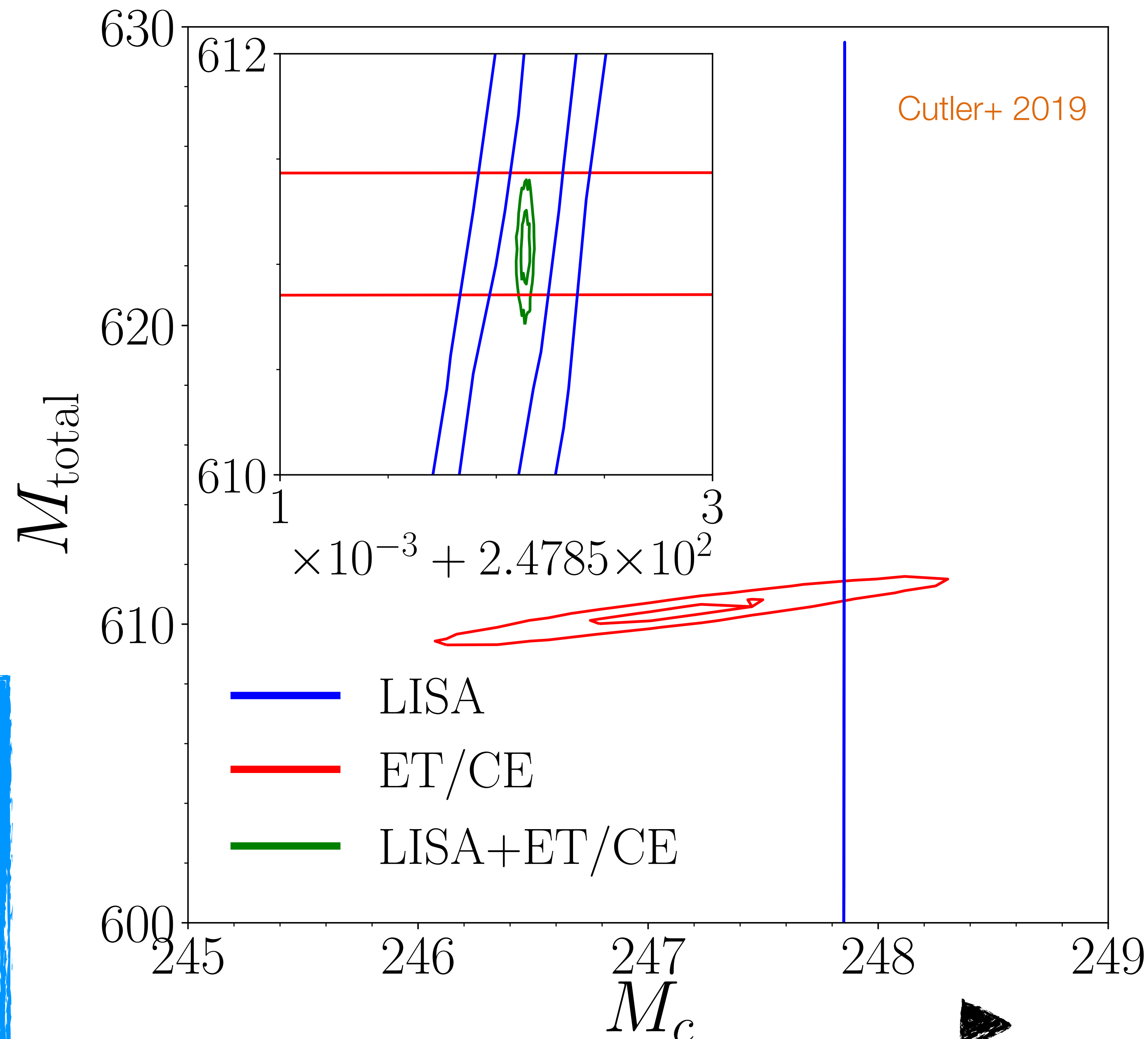
- Catch counterparts, if any
  Sesana 2016
- Constrain low-PN modifications of GR like dipole emission
  Barausse+ 2016, Gnocchi + 2019, Carson+2019
- Eccentricity measurements to constrain formation channels
  Nishizawa+ 2016, Brievik+ 2016
  Samsing D'Orazio 2018, 2019, Kremer+ 2019
- Improve LIGO parameter estimation
  Vitale+ 2016
- New class of standard sirens
  Kyutoku+ 2017, Del Pozzo+ 2018
- Prepare ground-based operations
  Tso, **DG**+ 2019
- Expand LISA horizon Wong+ 2018

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

Together is better than alone

- **Space**: early inspiral, chirp mass
- **Ground**: merger, total mass
- **Multiband**: breaks degeneracies

Complementary information in each band



For optimistic mass values

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DG, Ma, Wong+ arXiv:1902.00021

Event rates from the ground

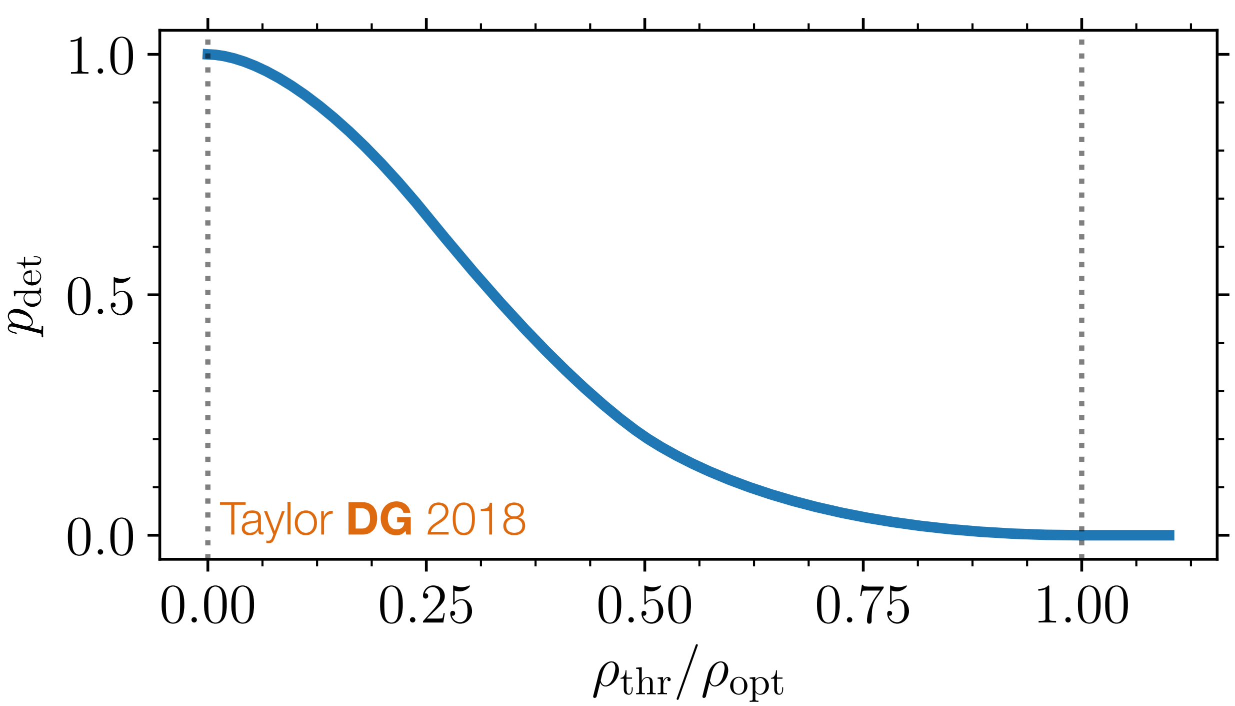
$$r_{\rm ground} = \iint dz d\lambda\, \mathcal{R}(z)\, p(\lambda) \frac{dV_c(z)}{dz} \frac{1}{1+z}\, p_{\rm det}(\lambda, z)$$

$N_{\rm ground} = r_{\rm ground} \times T_{\rm obs}$ (The usual LIGO expression)

Ground

Selection effects:

- Injection campaigns LVC 2018a
- VT calibration factors LVC 2018b
- Semi-analytical approximation Finn, Chernoff 1993



$$\omega = \sqrt{\frac{(1+\cos^2\iota)^2}{4} F_+^2(\theta,\phi,\psi) + \cos^2\iota F_\times^2(\theta,\phi,\psi)}$$

$$\rho = \omega \times \rho_{\rm opt}$$

$$p_{\rm det}(\lambda, z) = \int_{\rho_{\rm thr}/\rho_{\rm opt}(\lambda,z)}^{1} p(\omega) d\omega$$

Comparisons show $\rho_{\rm thr} \sim 8$

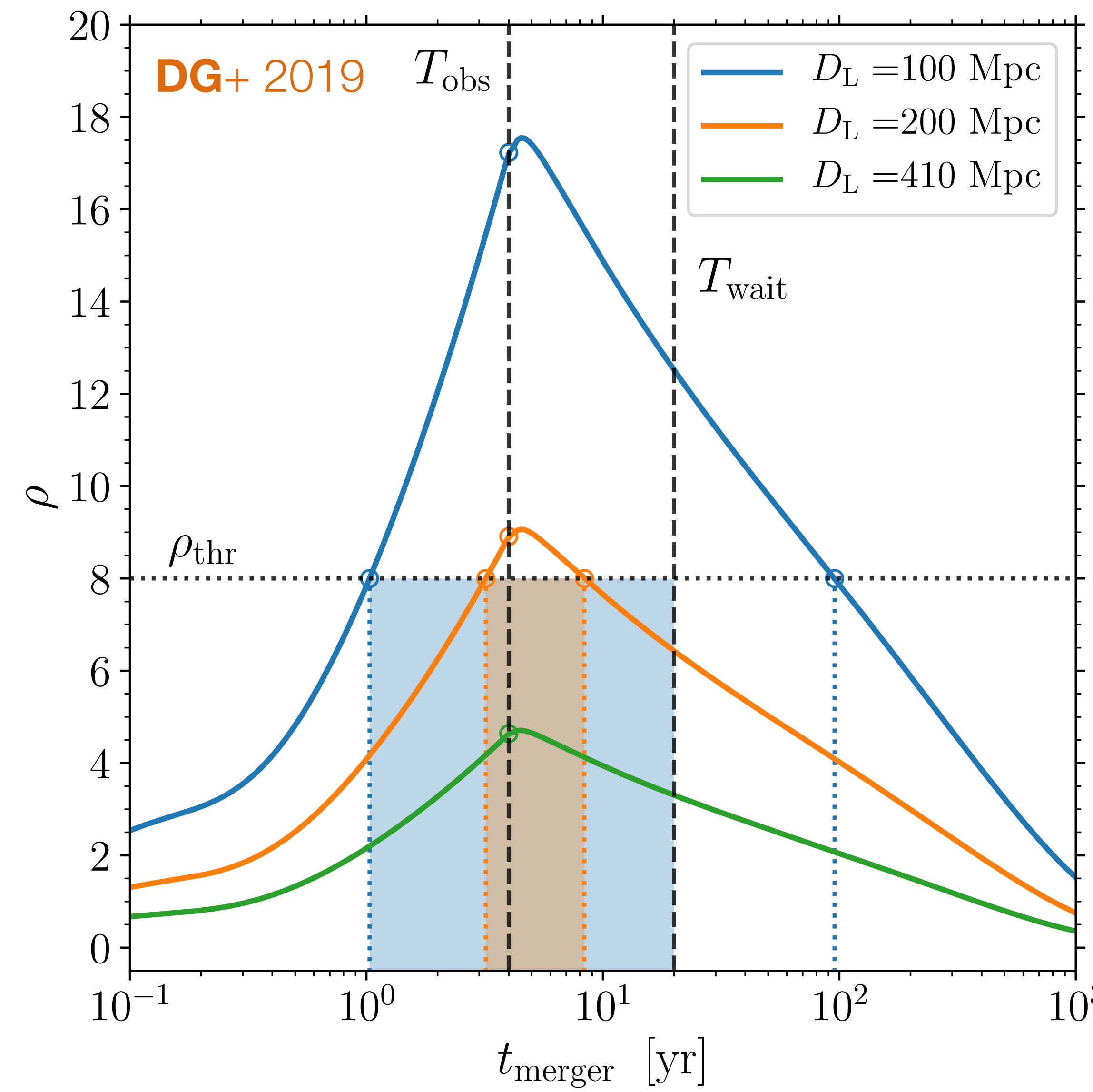
Event rates from space

Label binaries with time to merger and compute effective time window

$$N_{\rm space} = \iint dz d\lambda\, \mathcal{R}(z)\, p(\lambda) \frac{dV_c(z)}{dz} \frac{1}{1+z} \times \left| t_{\rm thr1}(\lambda, z) - t_{\rm thr2}(\lambda, z) \right|$$

$$r_{\rm space} = \frac{N_{\rm space}}{T_{\rm obs}}$$

Space



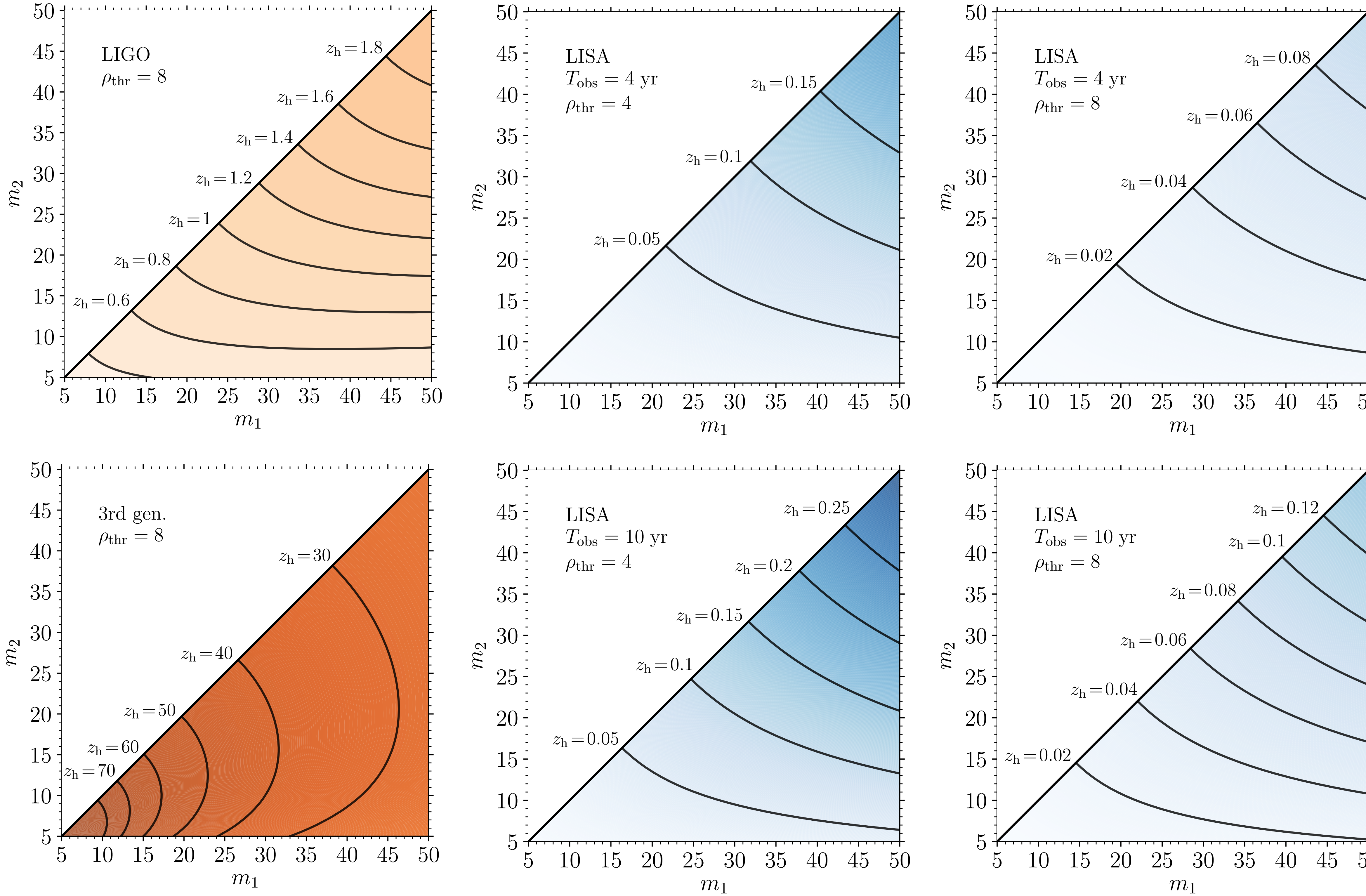
$$N_{\rm multib} = \mathcal{F} \iint dz d\lambda\, \mathcal{R}(z)\, p(\lambda) \frac{dV_c(z)}{dz} \frac{1}{1+z}\, p_{\rm det}(\lambda, z) \times \Big| \min\left[t_{\rm thr1}(\lambda, z), T_{\rm wait}\right] - \min\left[t_{\rm thr2}(\lambda, z), T_{\rm wait}\right] \Big| ,$$

$$r_{\rm multib} = \frac{N_{\rm multib}}{\mathcal{F}\; T_{\rm obs}}$$

Multiband

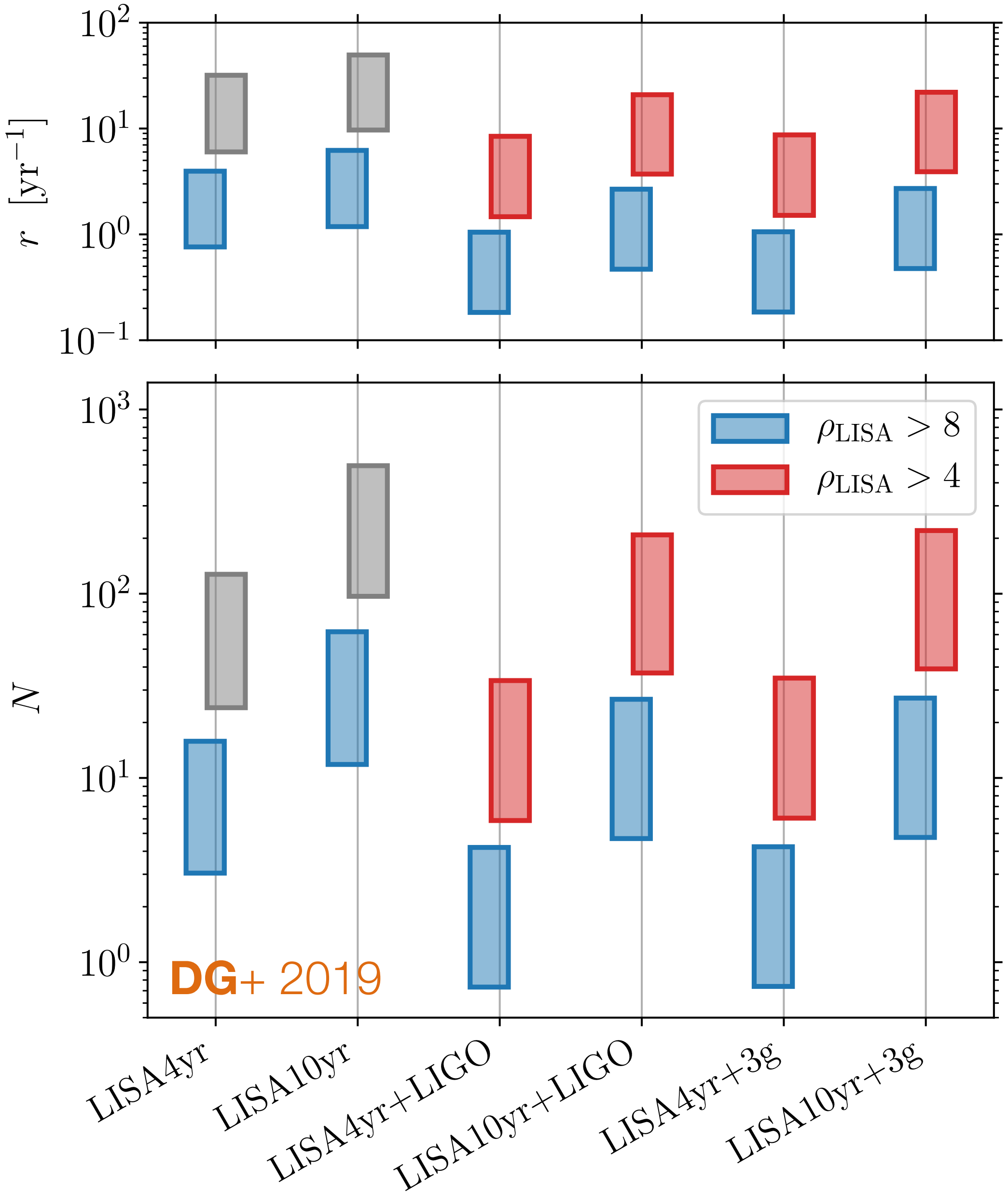
First, a look at the horizon redshifts

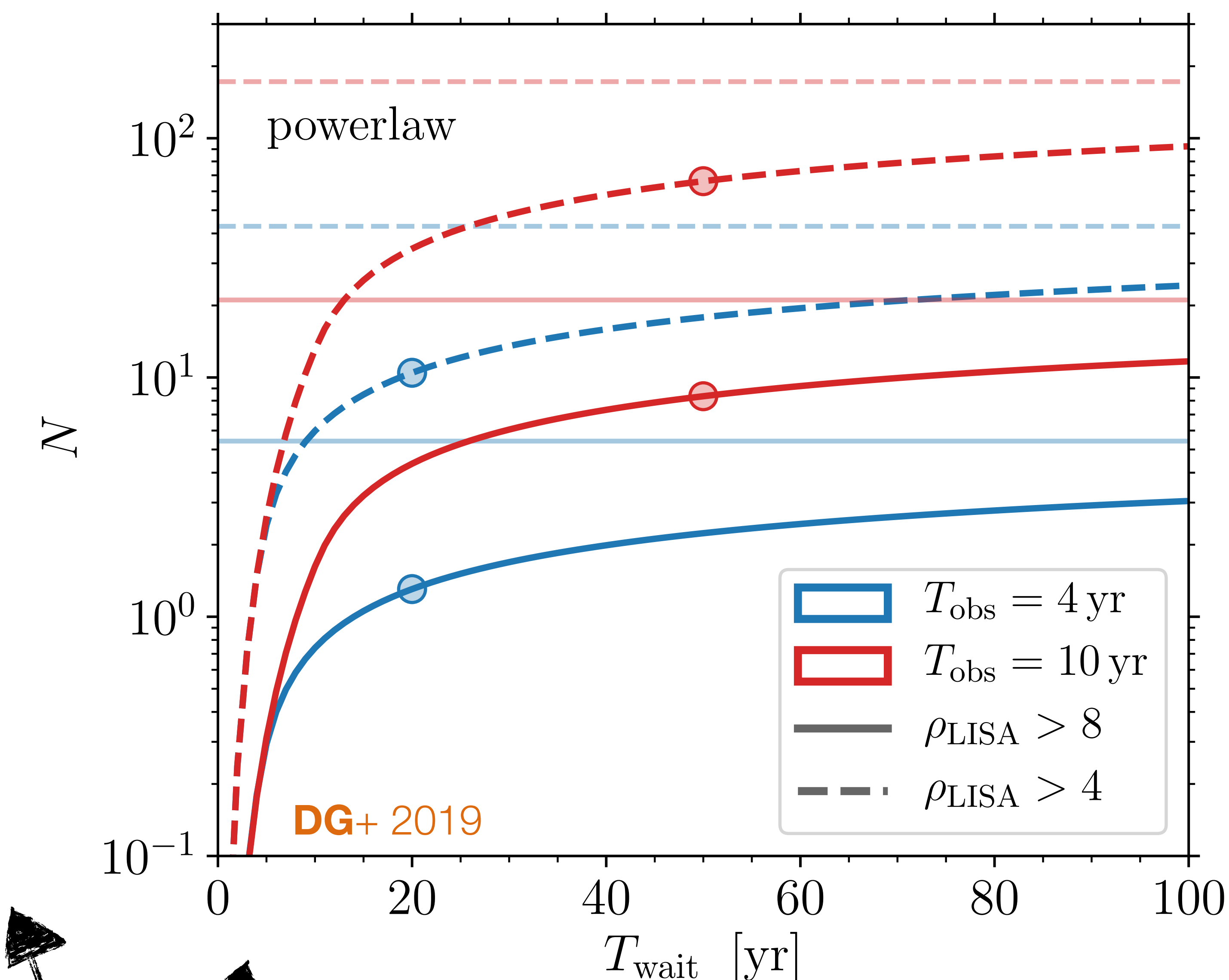
DG+ 2019



LIGO-calibrated predictions

Merger rates from the LIGO O1+O2 catalog





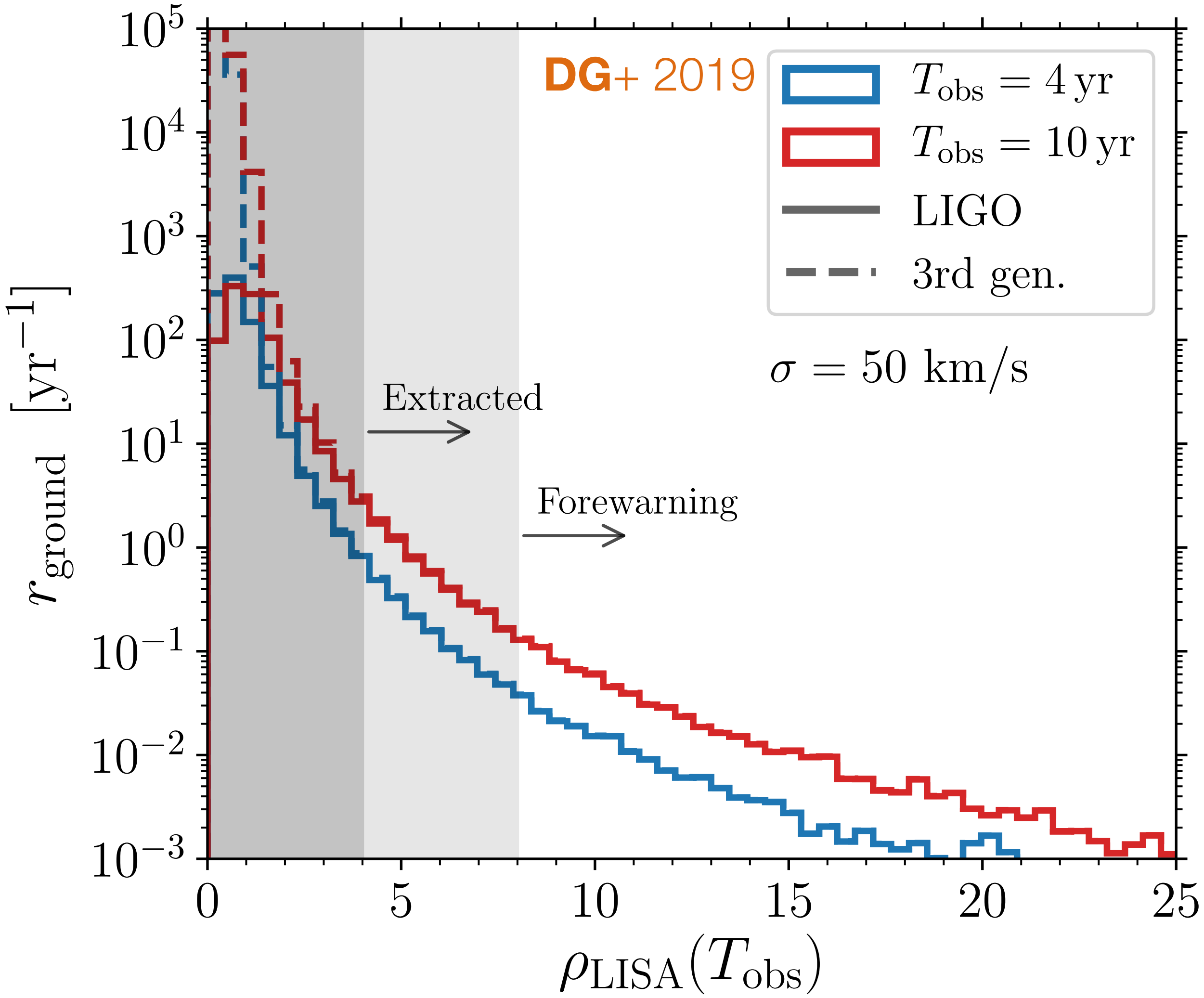
Number of multiband-sources

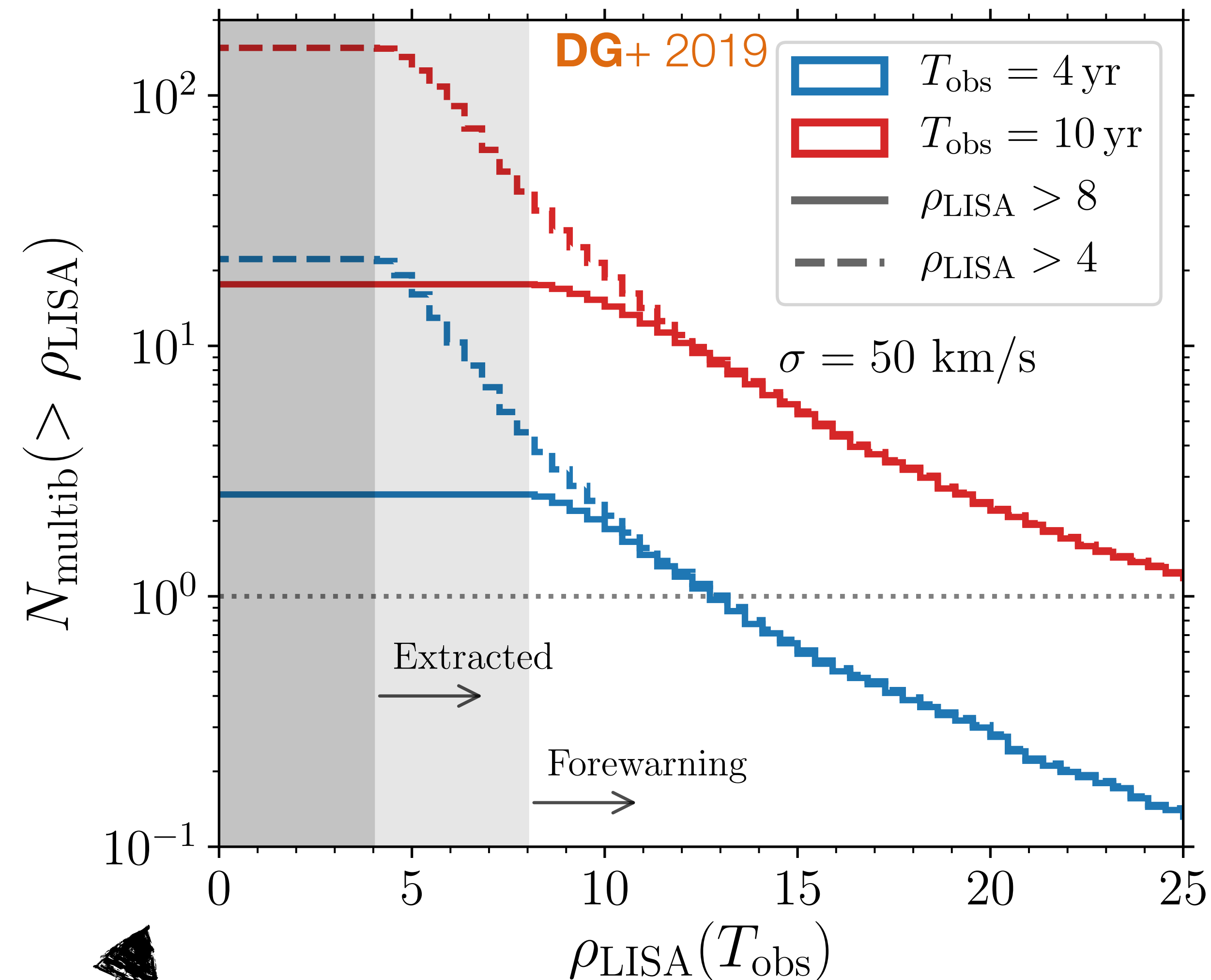
If you're willing to wait a bit longer

With astro models...

Using population synthesis simulations of field binaries from **DG**+ 2018

(cf Belczynski+ 2016, Wysocki+ 2018)





Ground-based detection rate accessible by LISA

Number of multiband sources "above threshold"

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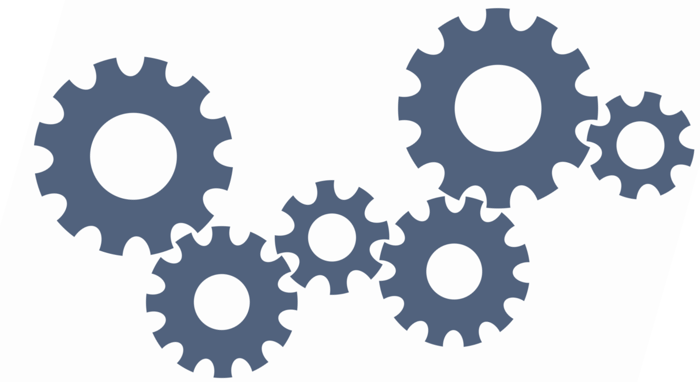
Moore, **DG**, Klein arXiv:1905.11998

The SNR threshold…

…. depends on the number of templates

Buonanno+2003, Chua+ 2017



GW signals $h_\alpha(t) = \rho\,\hat{h}_\alpha(t)\exp(i\phi_s)$

Statistics $\sigma_\alpha = \max_{\phi_s} \langle s|\hat{h}_\alpha\rangle$

If noise only $f_0(\sigma_\alpha) = \sigma_\alpha \exp\left(-\frac{\sigma_\alpha^2}{2}\right)$

If signal $f_1(\sigma_\alpha,\rho) = \sigma_\alpha \exp\left(-\frac{\sigma_\alpha^2+\rho^2}{2}\right) I_0(\rho\sigma_\alpha)$

Detection claimed if threshold is exceeded

$$P_F(\sigma_{\rm thr}) = \int_{\sigma_{\rm thr}}^{\infty} \mathrm{d}\sigma_\alpha\ f_0(\sigma_\alpha)\ \Rightarrow\ \sigma_{\rm thr}(P_F) = \sqrt{-2\ln P_F}$$

Set false-alarm rate 10^{-3} and assume $\{\sigma_\alpha\,|\,\alpha = 1,2,\ldots,N_{\rm bank}\}$ independent

Detection probability

$$P_F = \frac{10^{-3}}{N_{\rm bank}}$$

$$P_D(\rho) = \int_{\sigma_{\rm thr}}^{\infty} \mathrm{d}\sigma_\alpha\, f_1(\sigma_\alpha,\rho) \approx \Theta(\rho-\rho_{\rm thr})$$

The SNR threshold…

…. depends on the number of templates

Buonanno+2003, Chua+ 2017

… which depends on the complexity of the signal

Sathyaprakash & Dhurandhar 1991, Gair+ 2004, Cornish Porter 2005

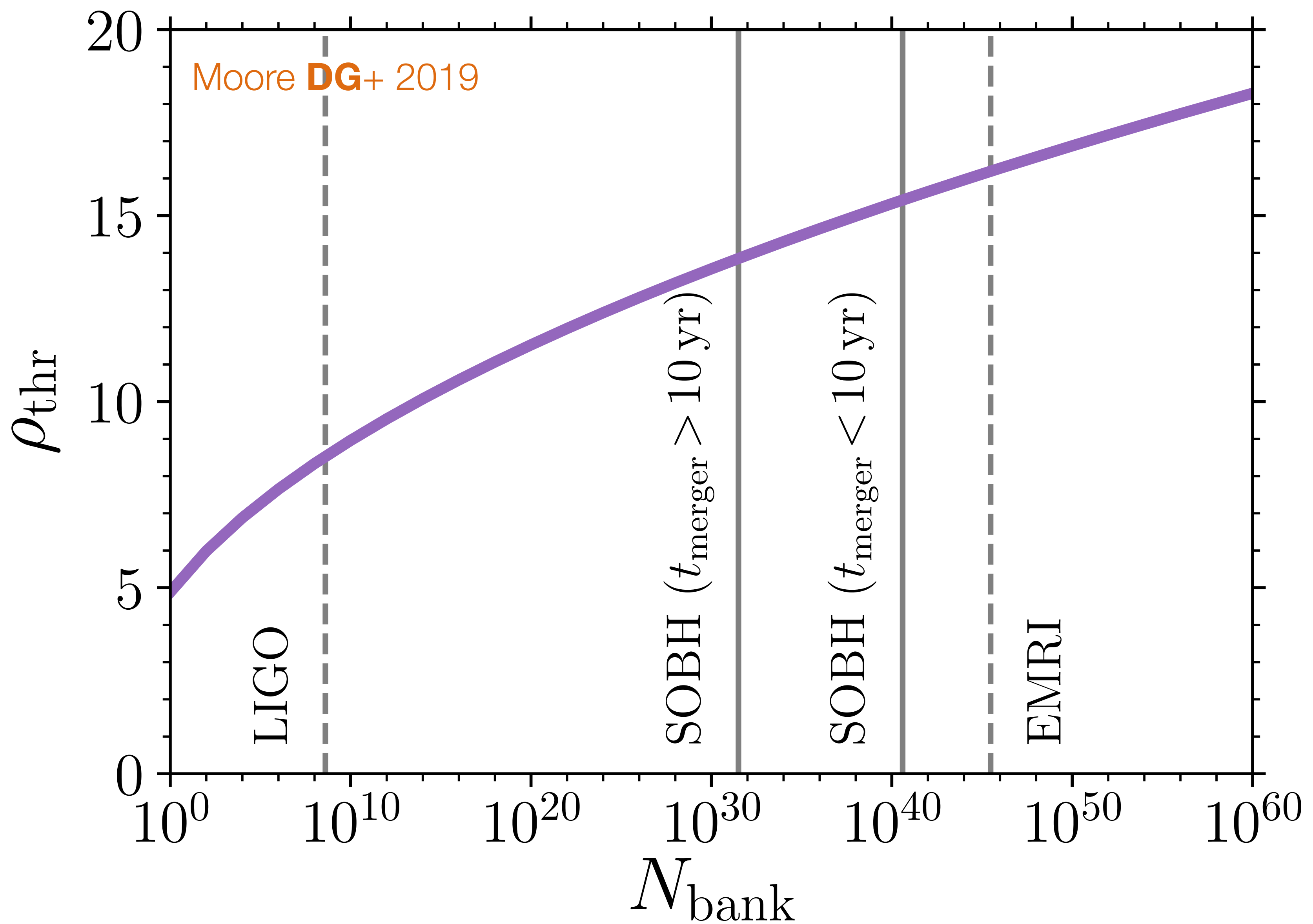
$$\mathrm{FAR} \sim 10^{-3}$$

$$N_{\mathrm{bank}} \approx \int \mathrm{d}\lambda \, \sqrt{\det \tilde{\Gamma}}$$

$\rho \gtrsim 8$ for LIGO BHs

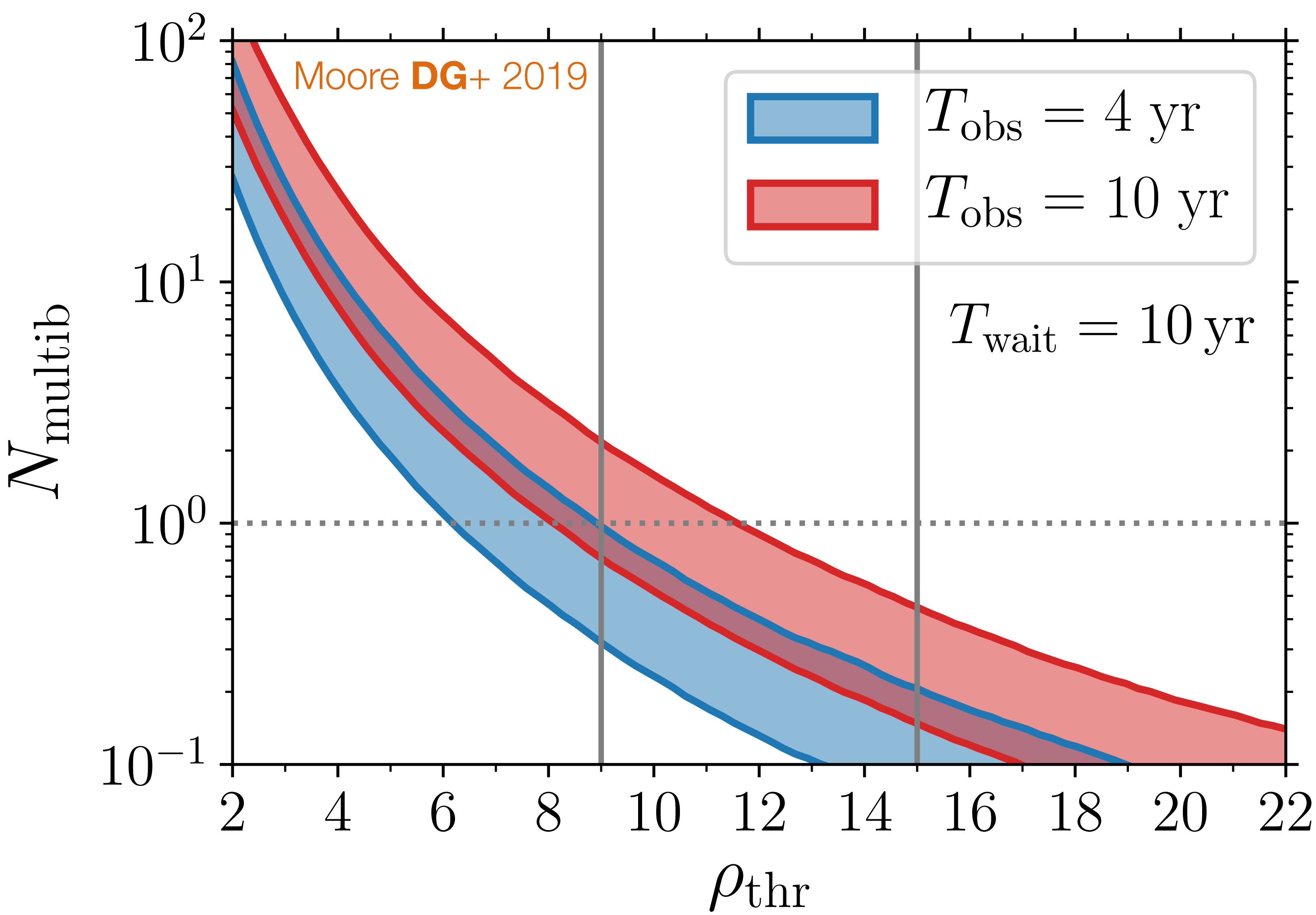
$\rho \gtrsim 17$ for EMRIs

$\rho \gtrsim 15$ for multiband!



Are stellar-mass BHs too quiet for LISA?

$$N(\rho_{\rm thr}) \propto \int_{\rho>\rho_{\rm thr}} \frac{1}{\rho^4} \propto \frac{1}{\rho_{\rm thr}^3}$$



Possible ways out

- Revisit past LISA data
- BHs of 100 solar masses
- Better performance at high frequency (here conservative)
- A population of events merging in a very long time

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Tso, **DG**, Chen arXiv:1807.00075

Can we get ready for multiband GWs?

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

Masses ok but probably no spins info…

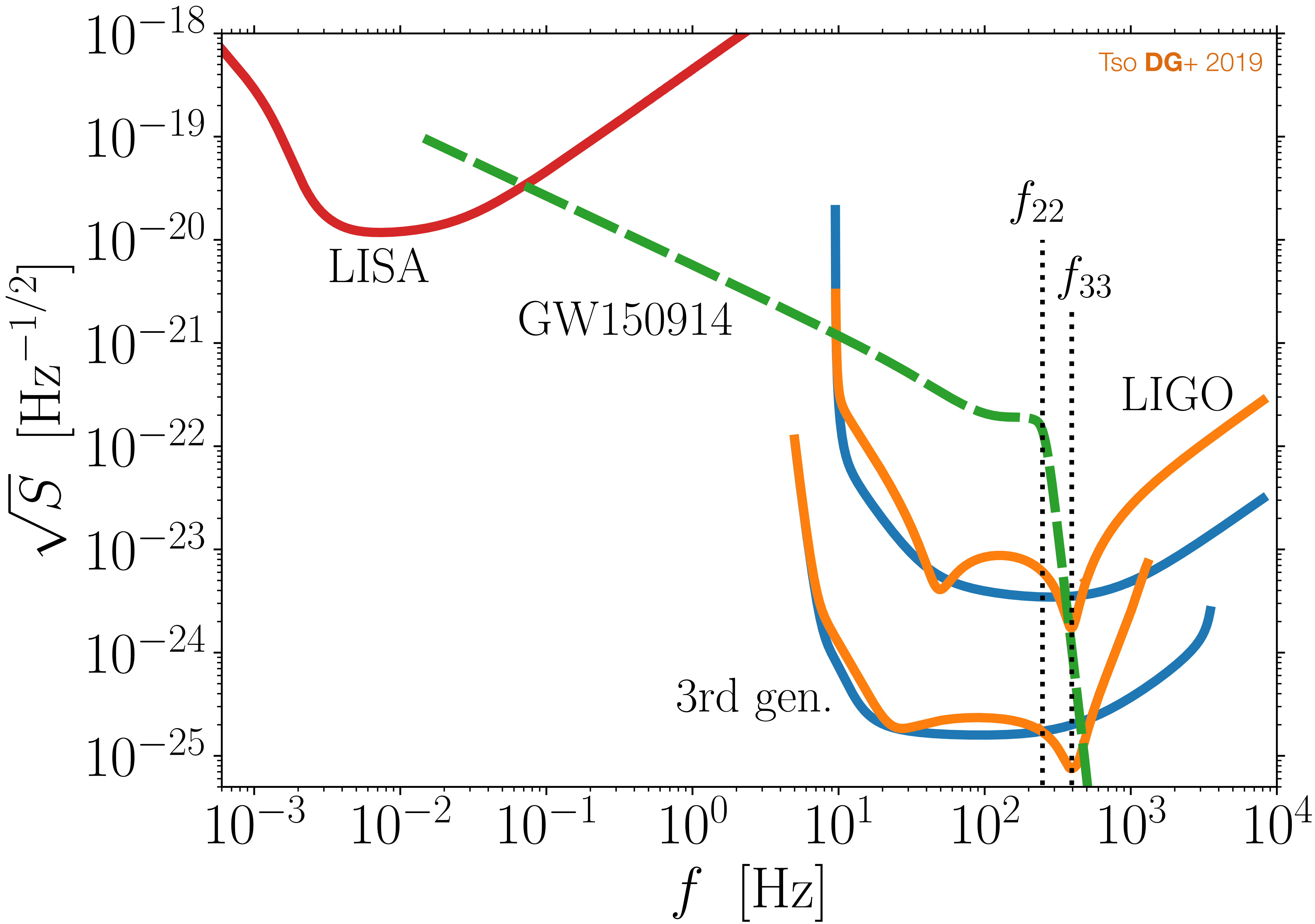
Can we maximize the scientific return of the ground-based observations?

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.

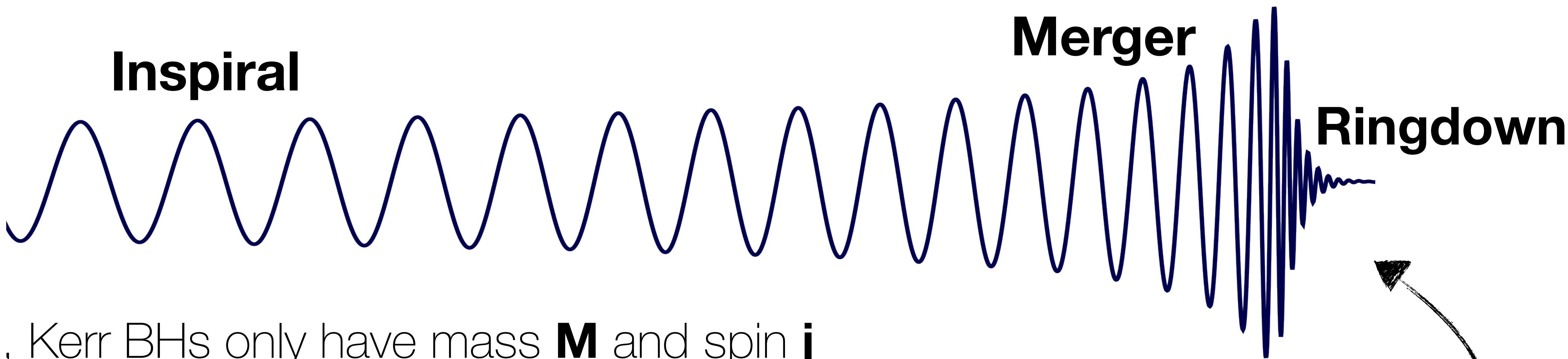
Here:
proof of principle to explore the potentials of the hard way…

Optimized narrow-banding

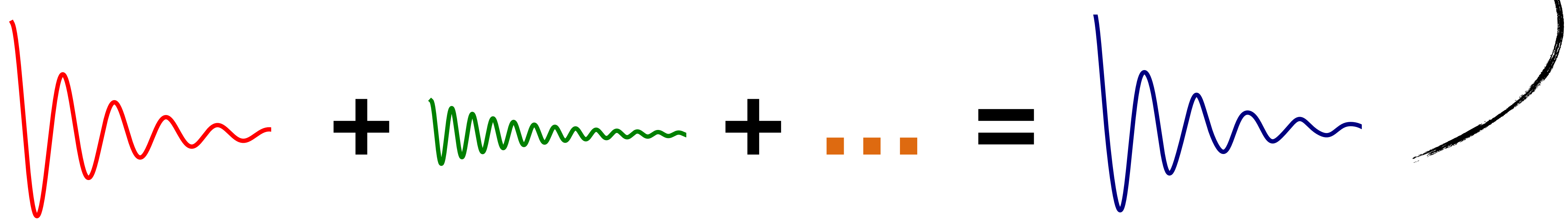


Black-hole spectroscopy

Testing the Kerr nature of astrophysical BHs with their ringdown emission



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



Dominant mode $(f, \tau) \to (M, j)$

First subdominant $(f, \tau) \to (M, j)$

Infinitely many

Ringdown signal

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

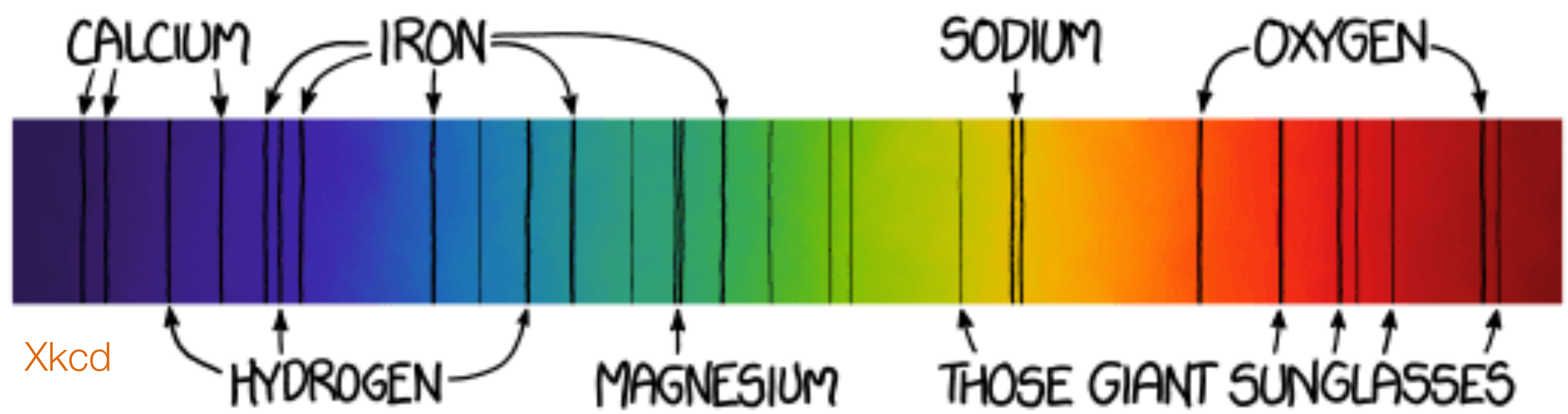
That's challenging! Subdominant modes are weak. Many ideas…

Berti+ 2016, Maselli+2017, Baibhav+2018, Yang+ 2017, Geisler+ 2019

Black-hole spectroscopy

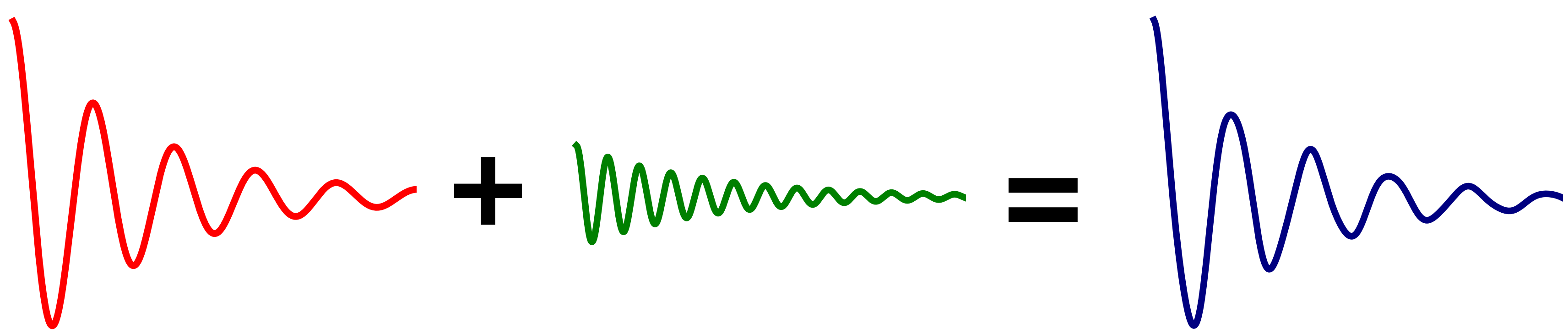
Detwiler+ 1980

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



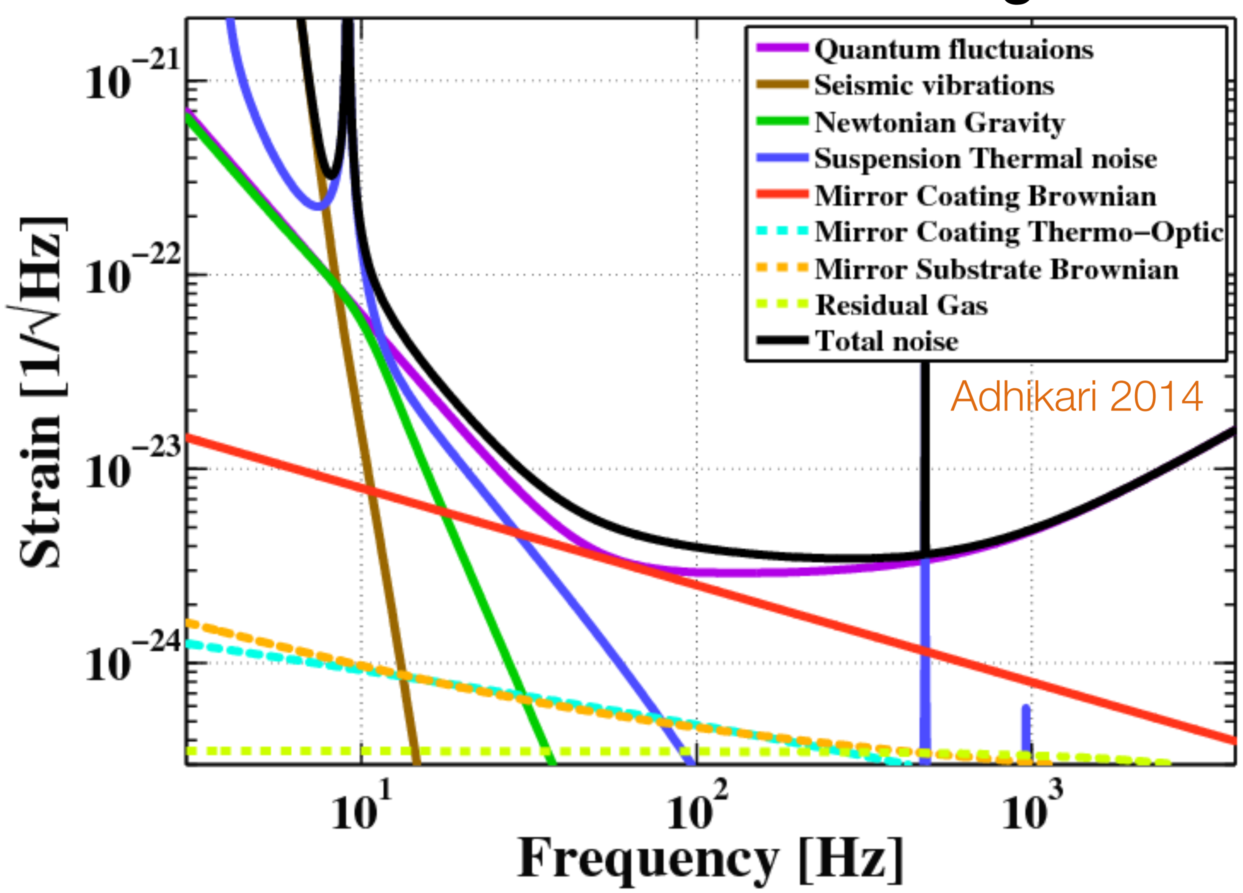
Xkcd

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…

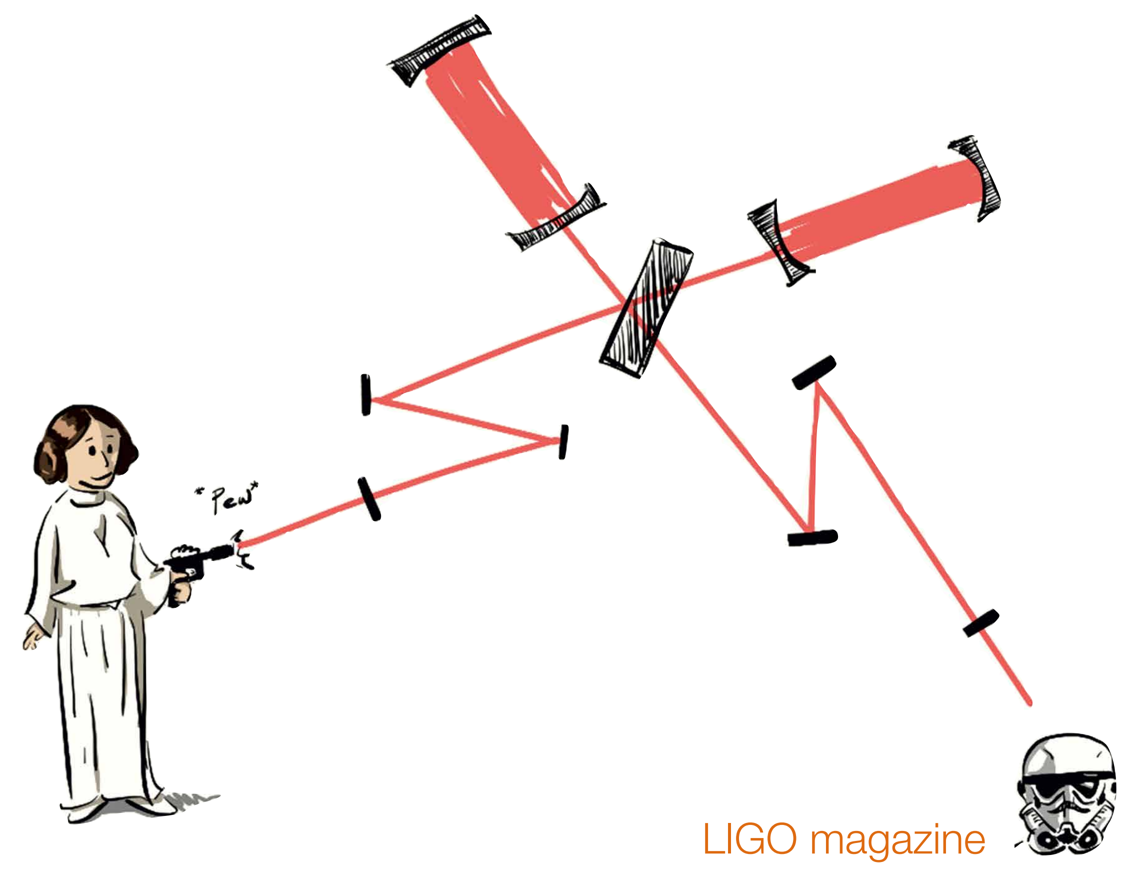
Previous explorations:

- NS post-merger signals Hughes 2002, Miao+ 2017, Martynov+ 2019
- 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

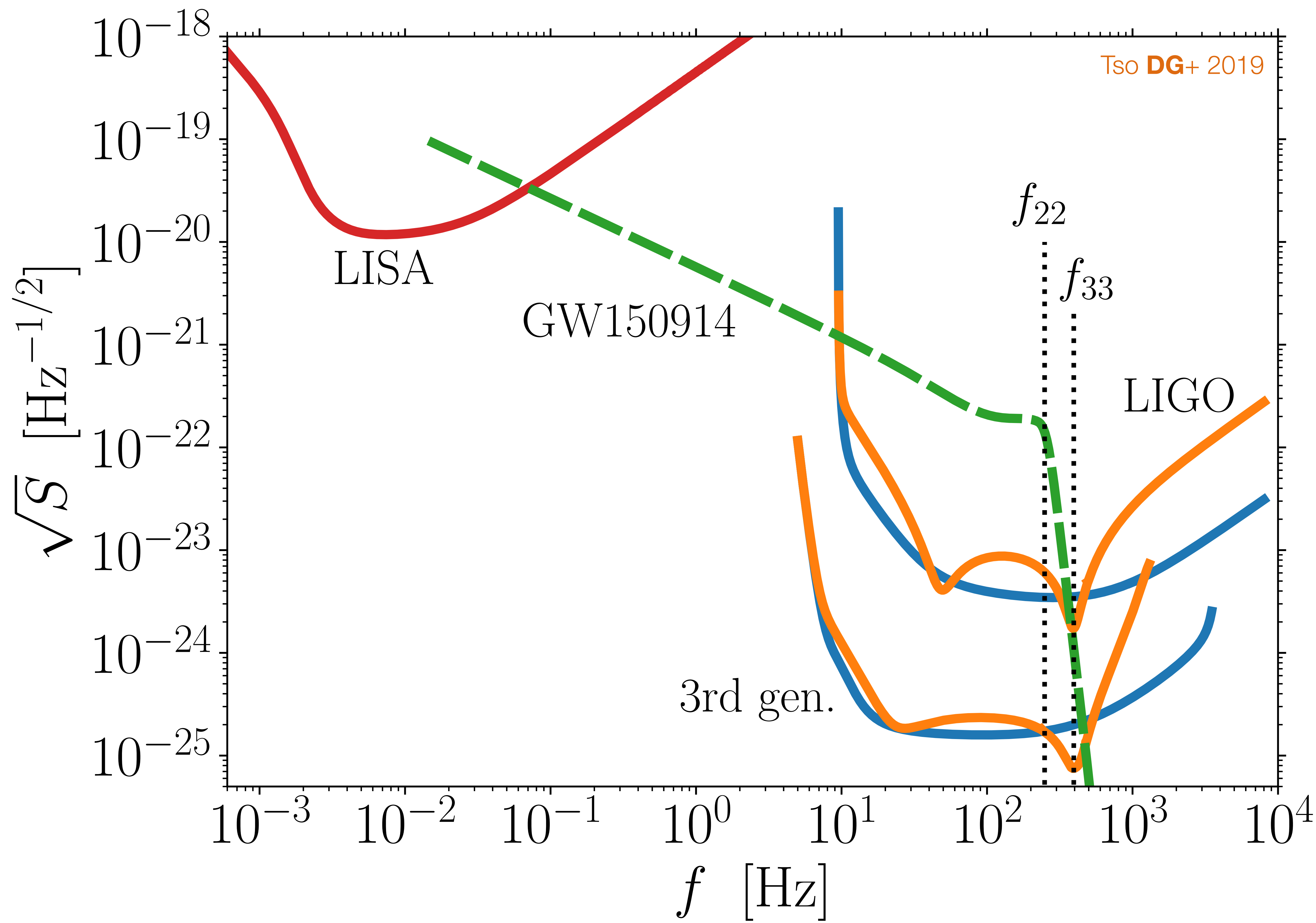
… this is LIGO for a theorist like me



LIGO magazine

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: $\mathbf{\Gamma}^{-1} = \begin{bmatrix} \mathbf{\Gamma}^{-1}_{2222} & \mathbf{\Gamma}^{-1}_{2233} \\ \mathbf{\Gamma}^{-1}_{3322} & \mathbf{\Gamma}^{-1}_{3333} \end{bmatrix}$

Confidence ellipses

Consider 2x2 diagonal blocks

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

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

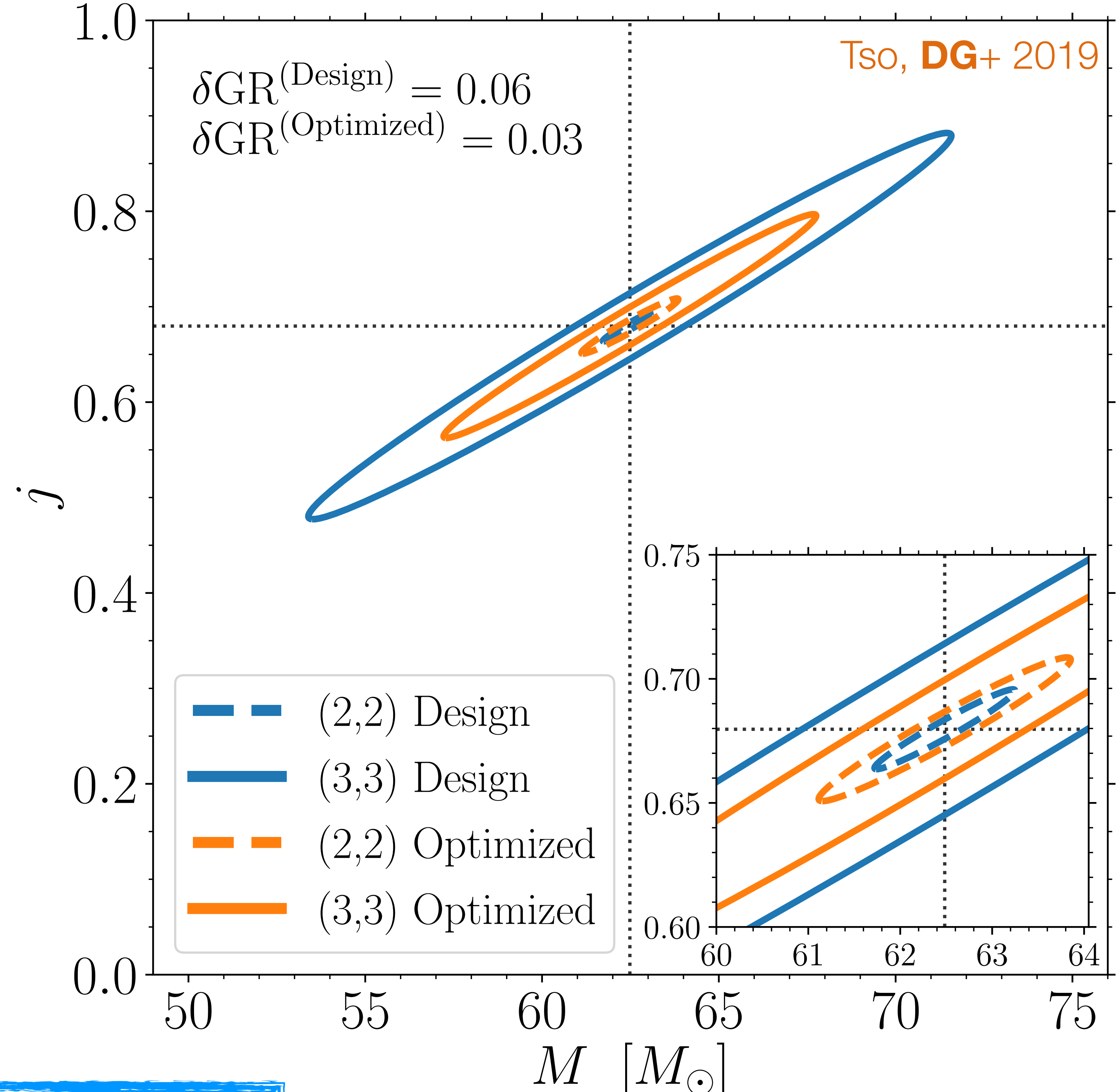
$D = 40\,\mathrm{Mpc}$

Perturbed BH:

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

Broadband: only the dominant mode

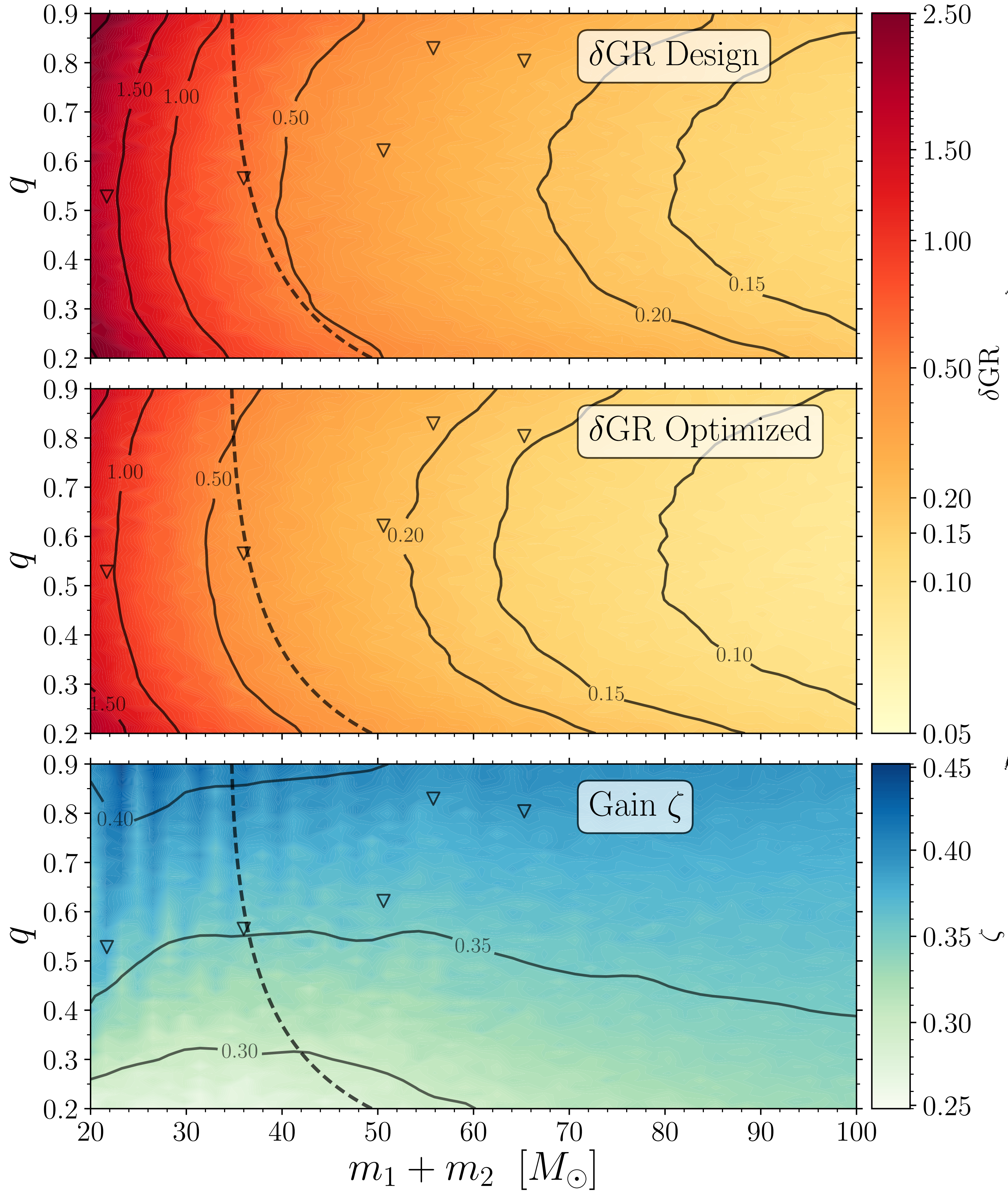
Optimized: greatly improve the subdominant mode, while losing a bit of the other one



Test of GR is a factor of 2 stronger!

Potential narrowband gain

Tso, **DG**+ 2019



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

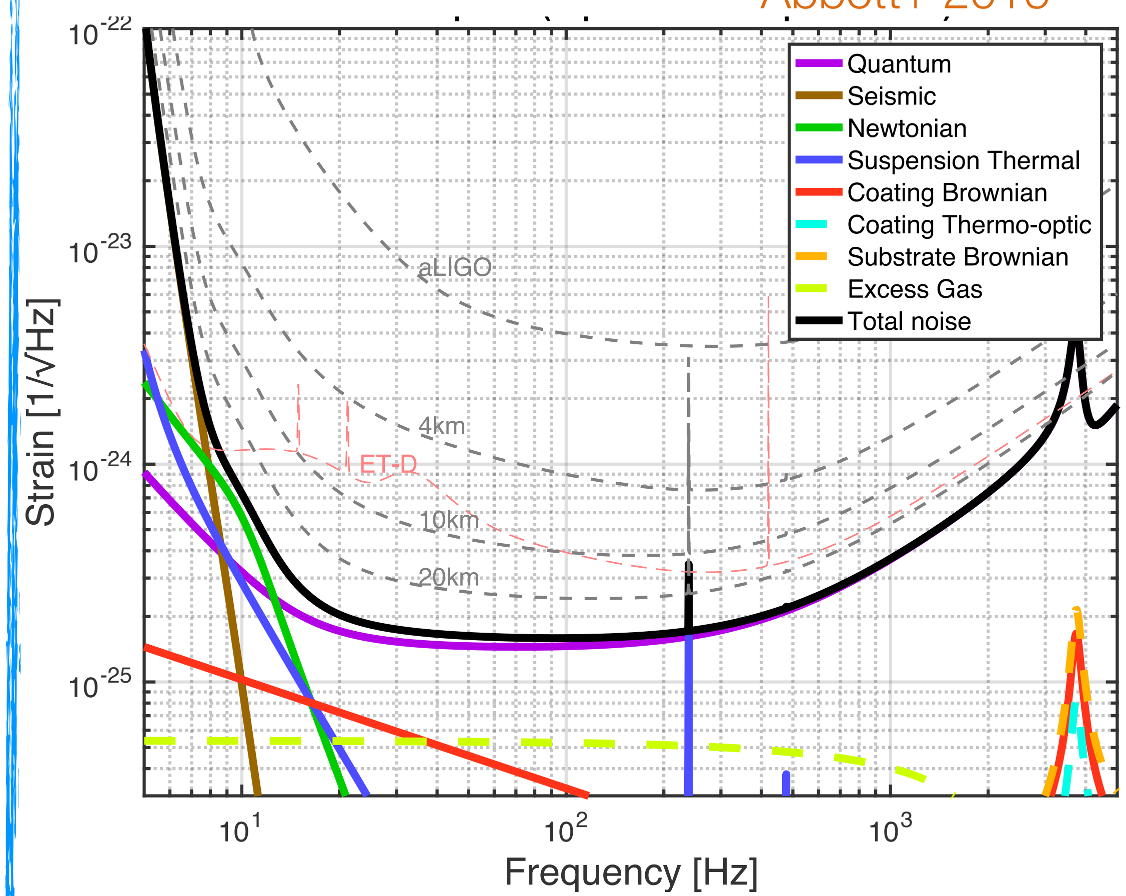
$$\zeta = \frac{\delta\mathrm{GR}^{(\mathrm{Design})} - \delta\mathrm{GR}^{(\mathrm{Optimized})}}{\delta\mathrm{GR}^{(\mathrm{Design})}}$$

Gain between 25% and 50% everywhere in parameters space

How about 3G?

Cosmic explorer

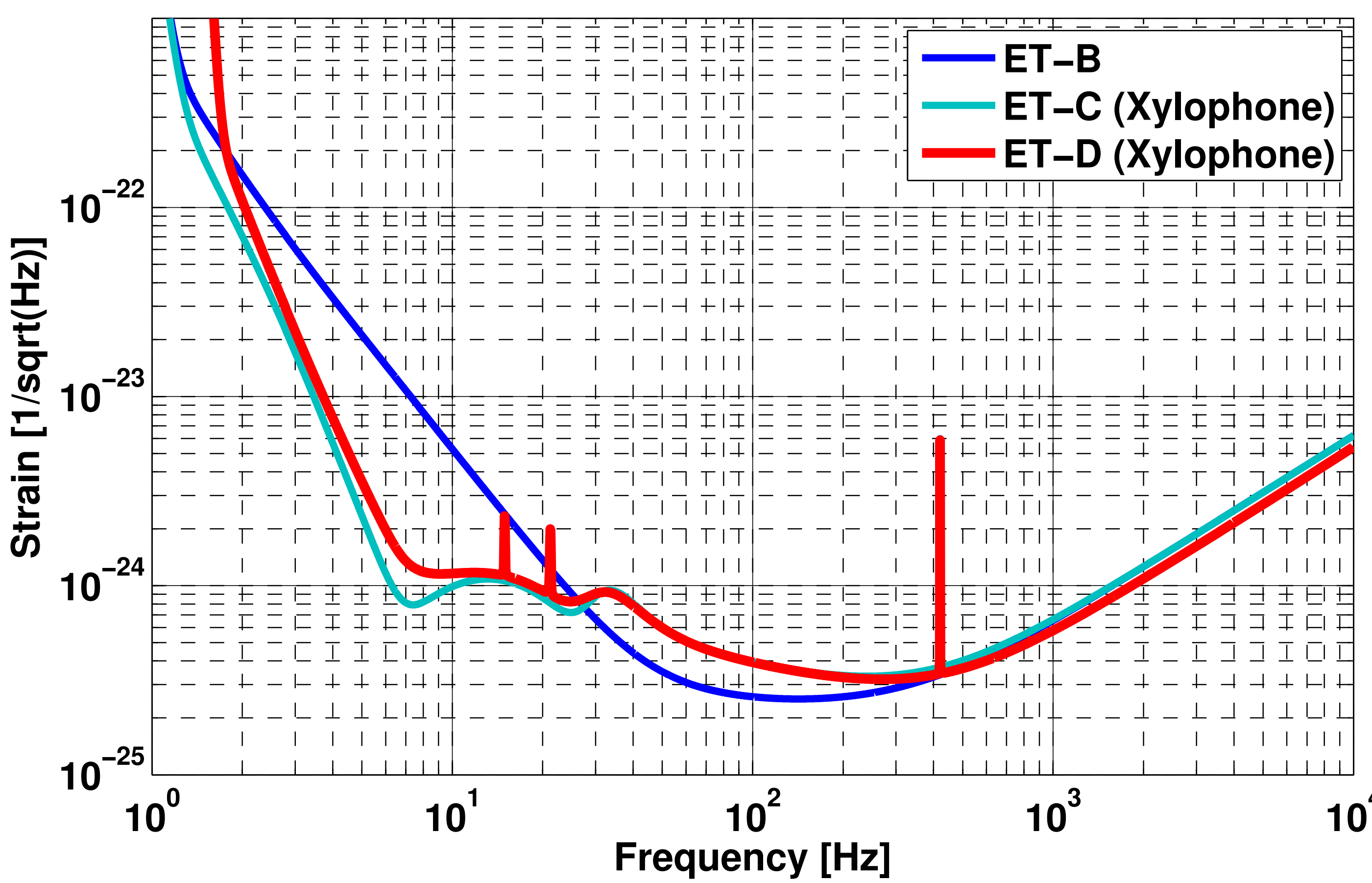
Abbott+ 2016



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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November 1st, 2019

GrEAT winter school

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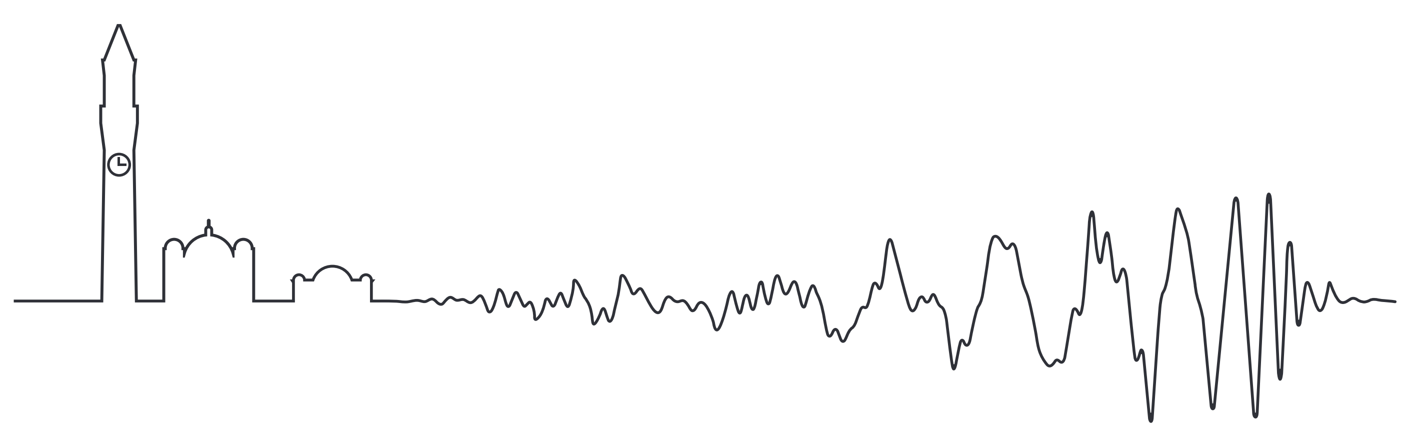

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