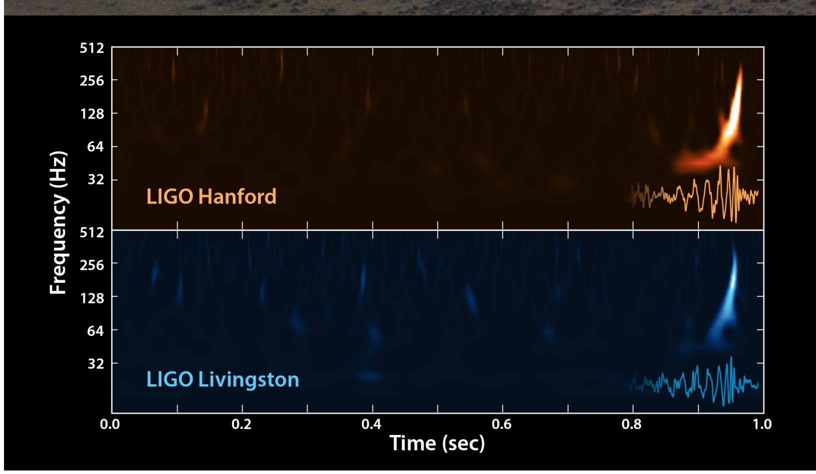
Supernovae & the next generation of GW observatories



LIGO-G1700567

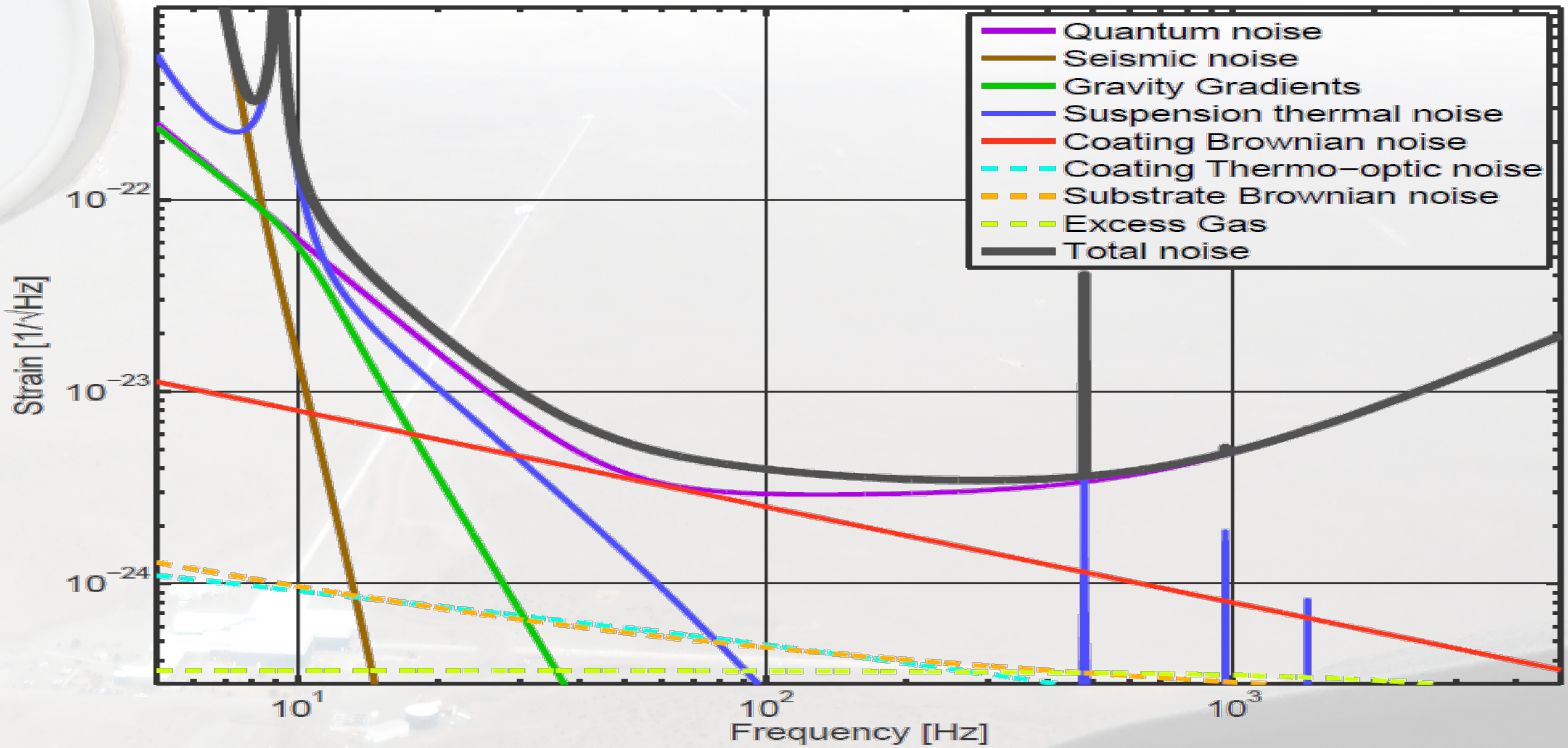
Supernovae Workshop
Pasadena
March 18, 2017
Stefan Ballmer

Photo: Robert Ward / Stefan Ballmer (2016/03/12)

Upgrade Path

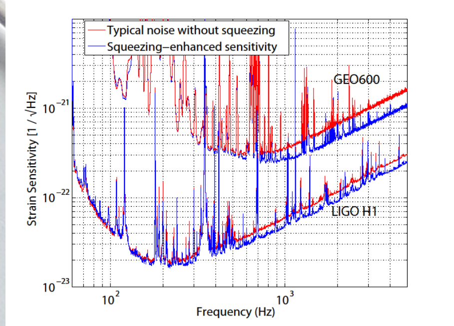
At higher frequencies relevant for SN:

- Current observatories limited by quantum noise, coating thermal noise

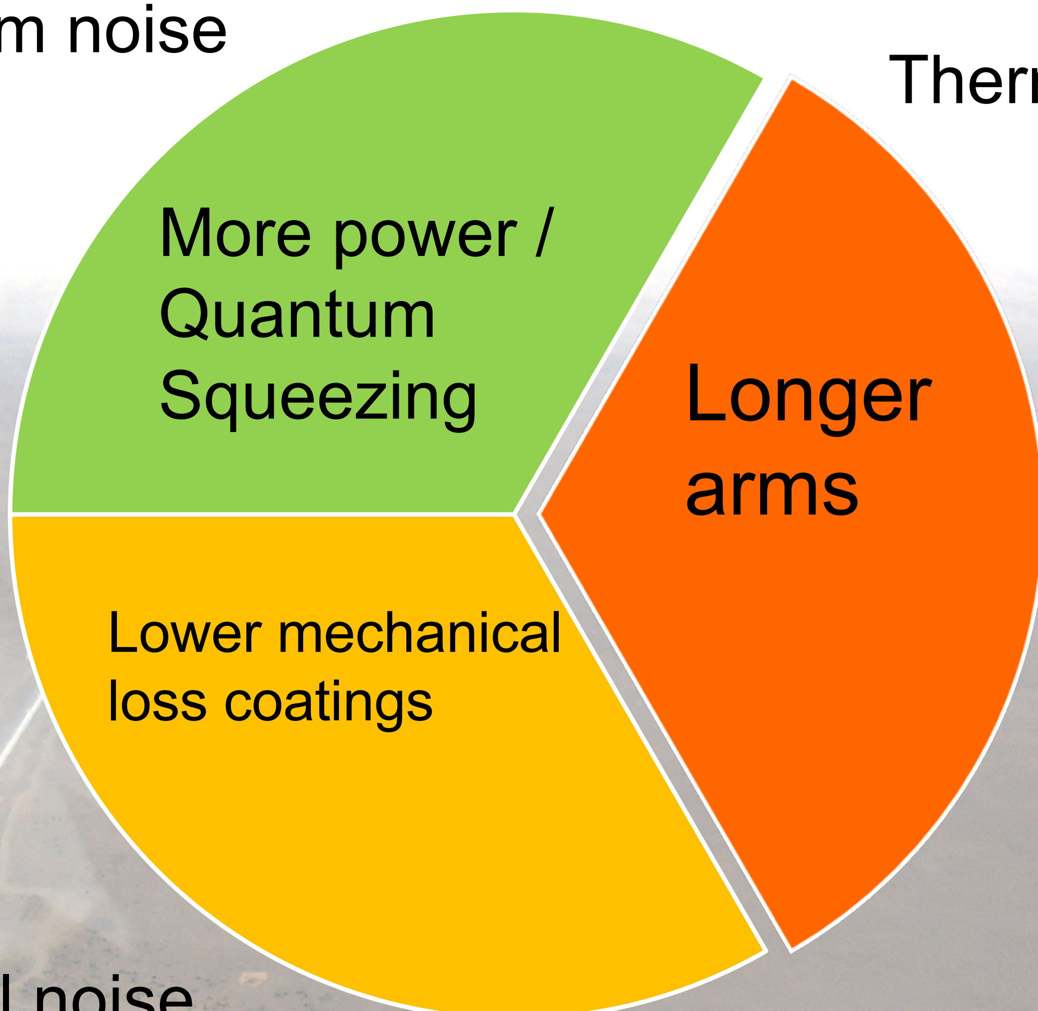


The ways forward

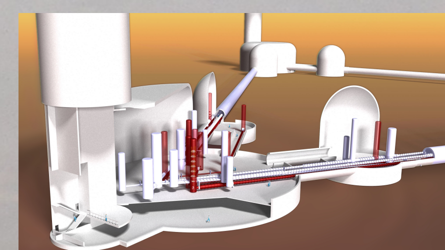
Reduce quantum noise

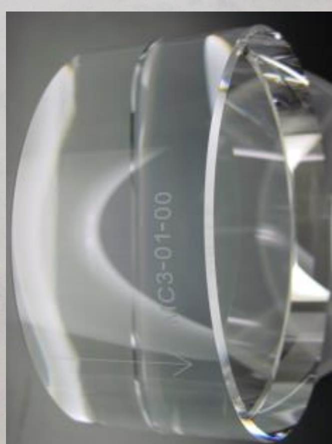


Thermal noise ~$L^{-3/2}$



Any Displacement noise ~L^{-1}





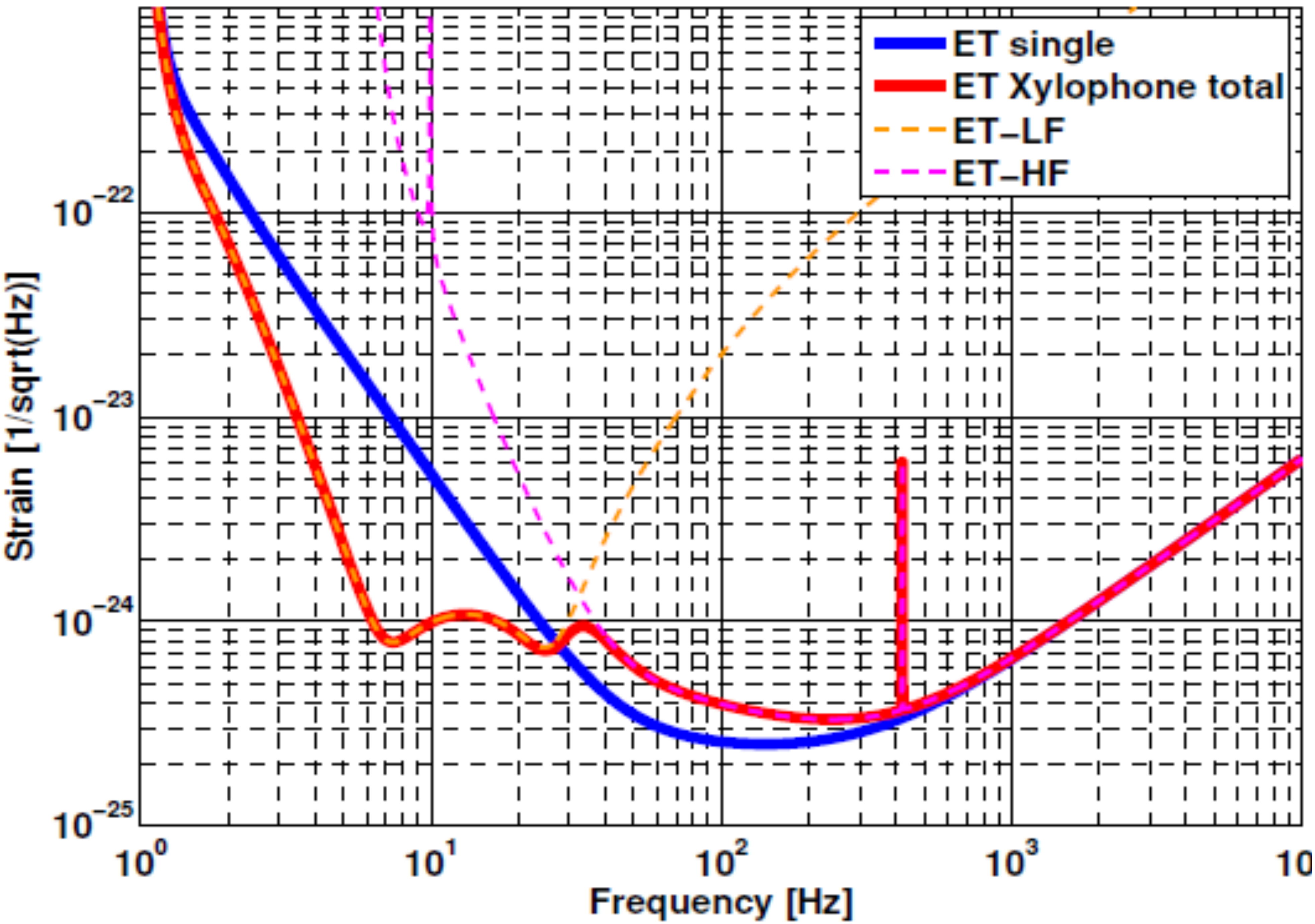
Reduce thermal noise

Cosmic Explorer/Einstein Telescope

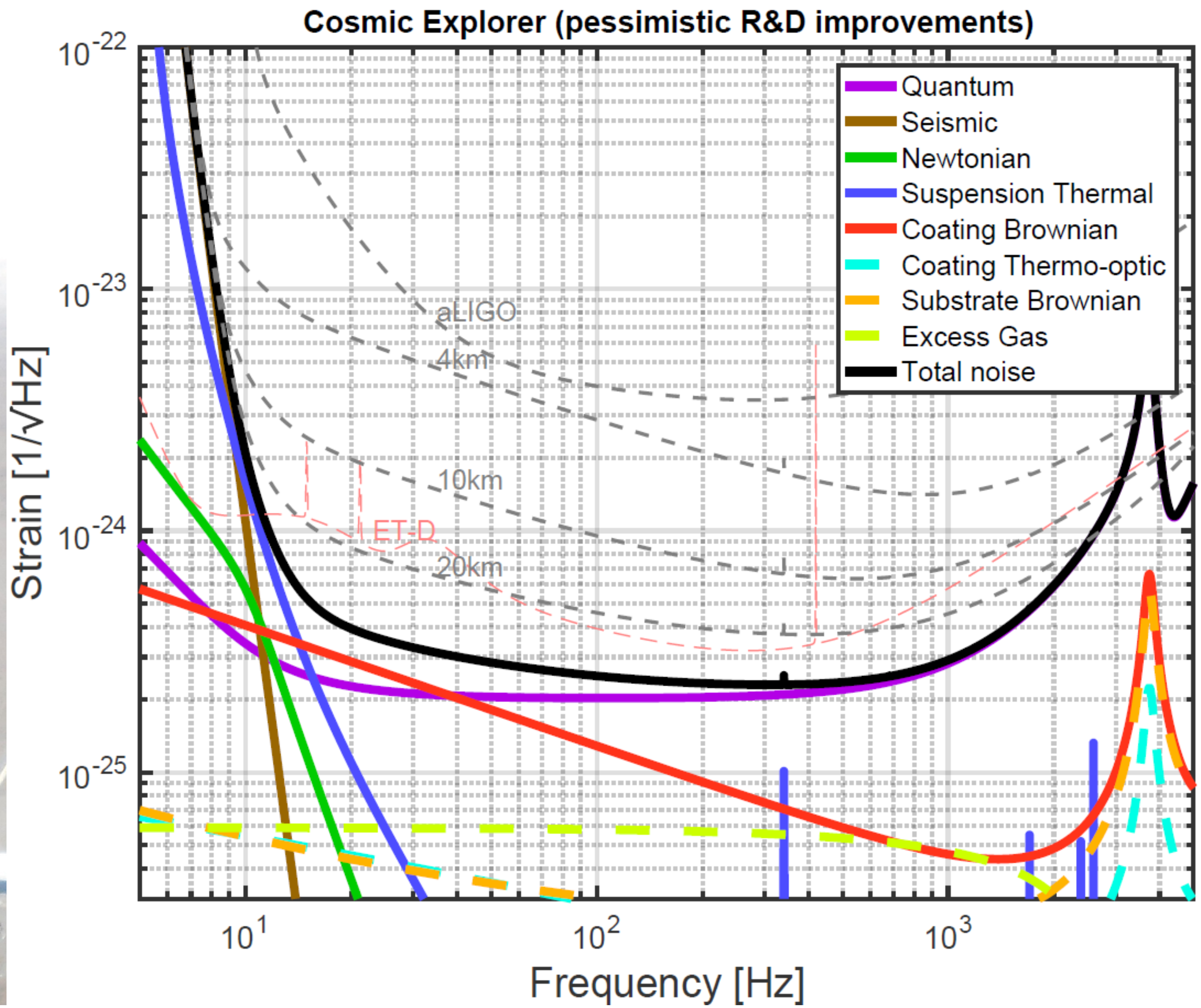
- 40km
- On surface

- 10km
- Underground
- Xylophone

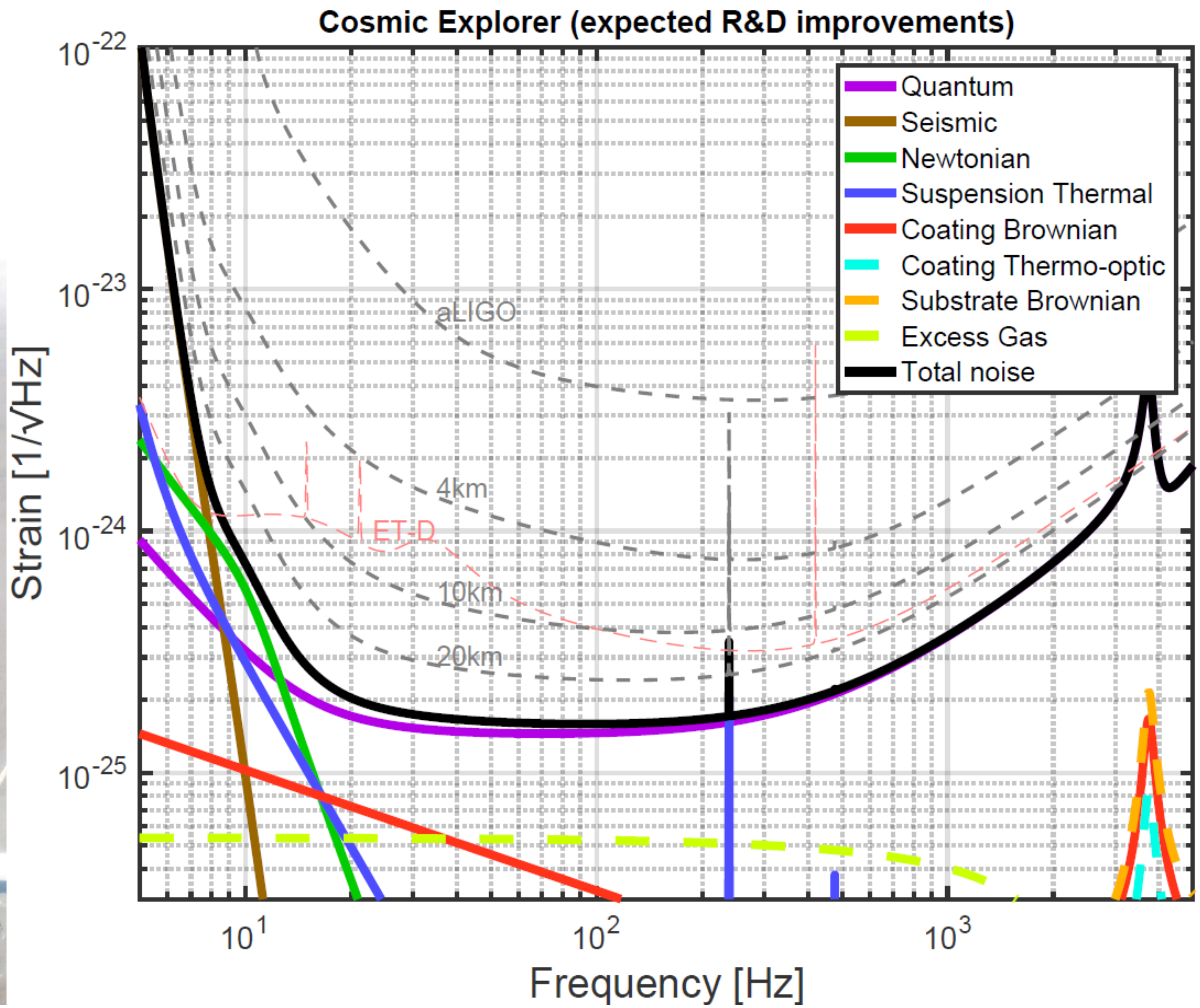
	CE	CE pess	ET-D (HF)	ET-D (LF)
L_{arm}	40 km	40 km	10 km	10 km
P_{arm}	2 MW	1.4 MW	3 MW	18 kW
λ	1550 nm	1064 nm	1064 nm	1550 nm
r_{sqz}	3	3	3	3
m_{TM}	320 kg	320 kg	200 kg	200 kg
r_{beam}	14 cm	12 cm	9 cm	7 cm (LG_{33})
T	123 K	290 K	290 K	10 K
ϕ_{eff}	5×10^{-5}	1.2×10^{-4}	1.2×10^{-4}	1.3×10^{-4}


ET single
ET Xylophone total
ET–LF
ET–HF
Strain [1/sqrt(Hz)]
Frequency [Hz]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{0}
10^{1}
10^{2}
10^{3}
10

CE pessimistic
scale matched to previous slide

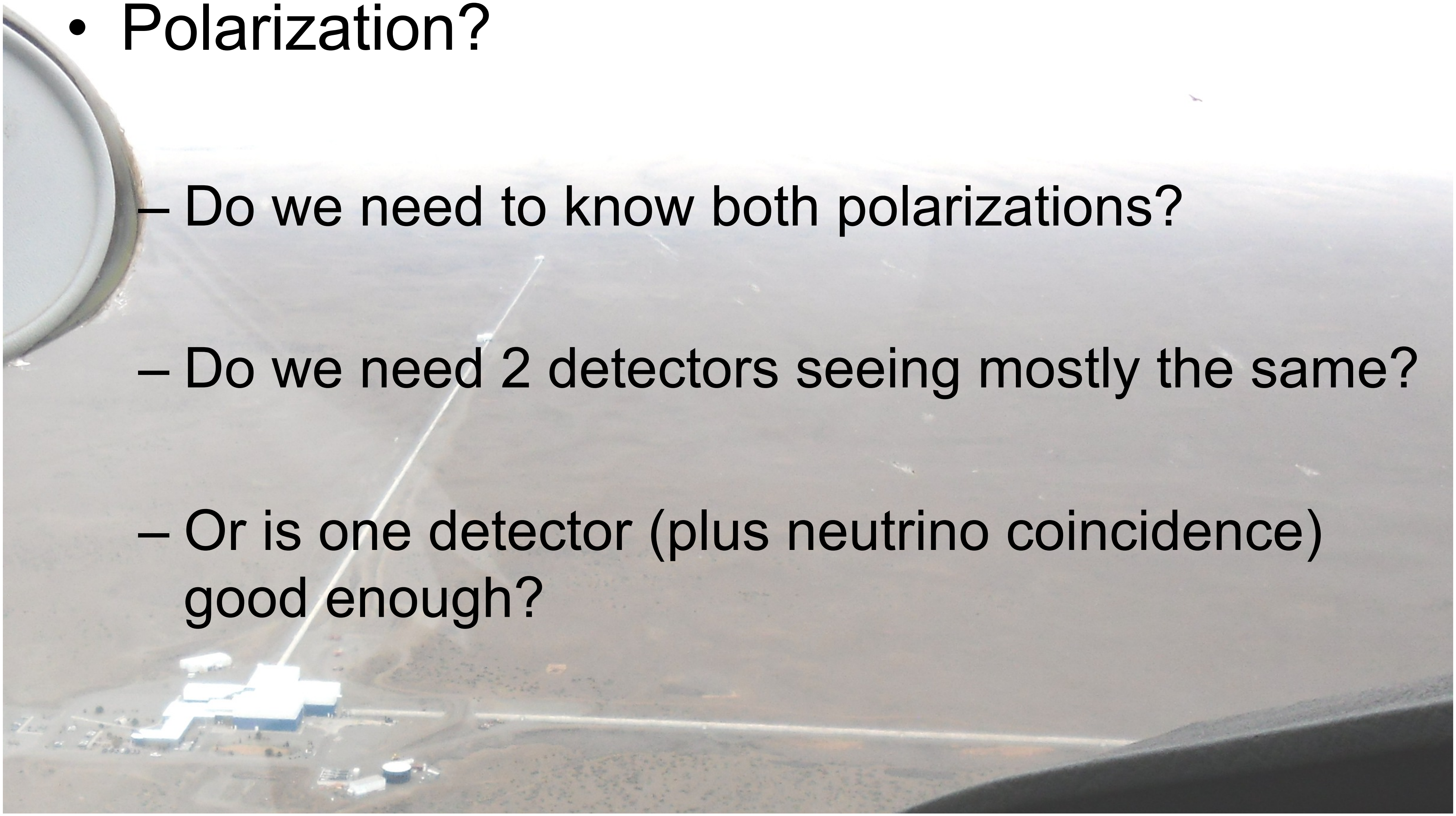


CE expected
scale matched to previous slide



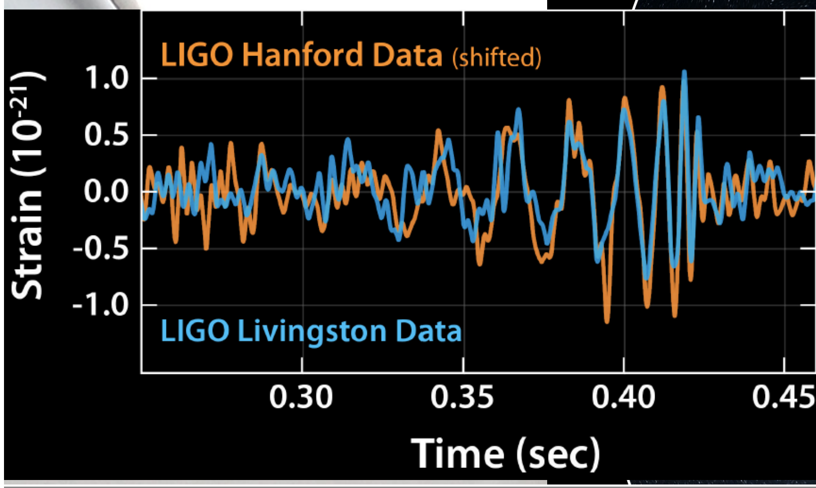
12/01/2016

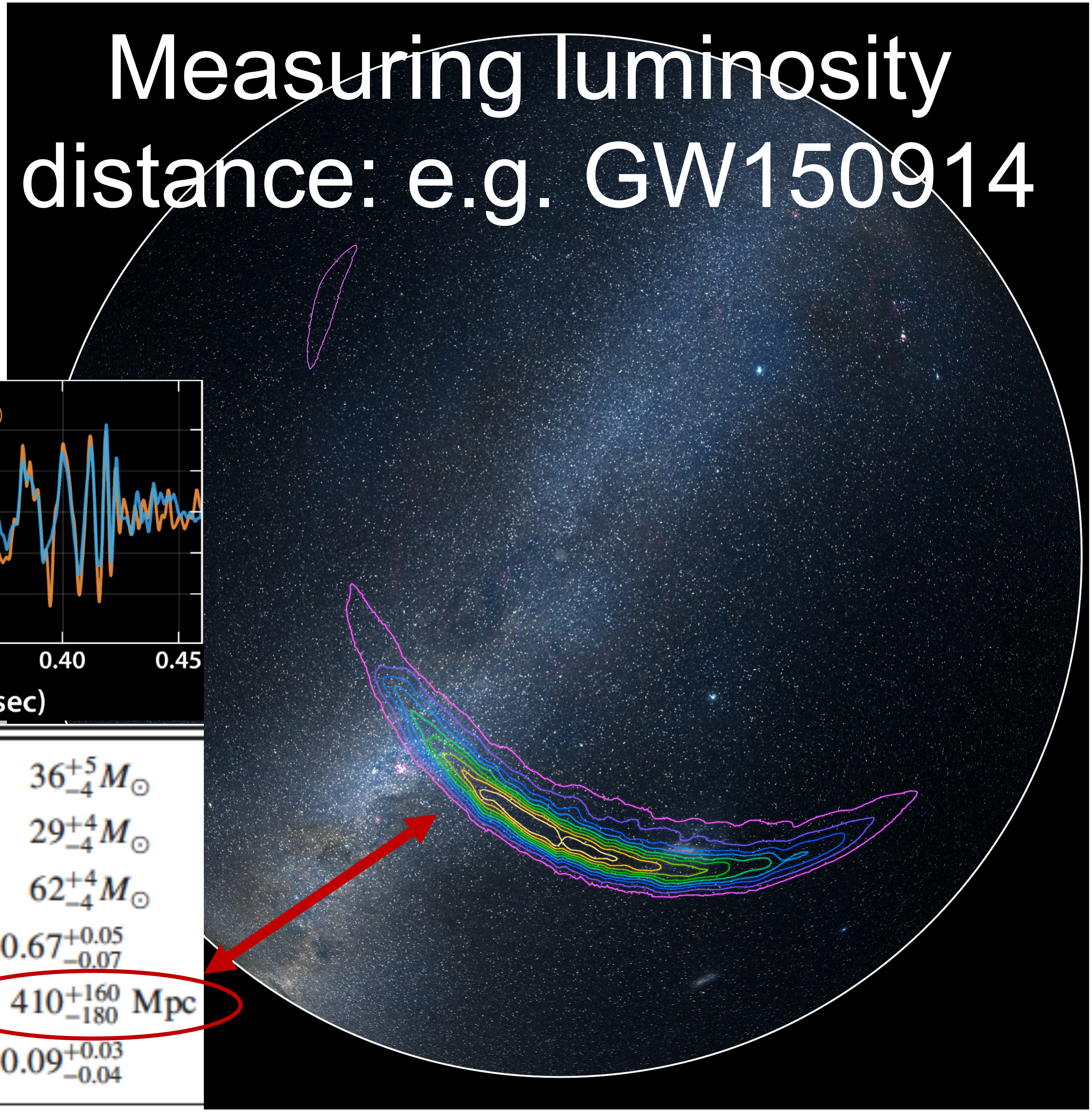
LIGO Additional thoughts, 1



- Polarization?
  - Do we need to know both polarizations?
  - Do we need 2 detectors seeing mostly the same?
  - Or is one detector (plus neutrino coincidence) good enough?

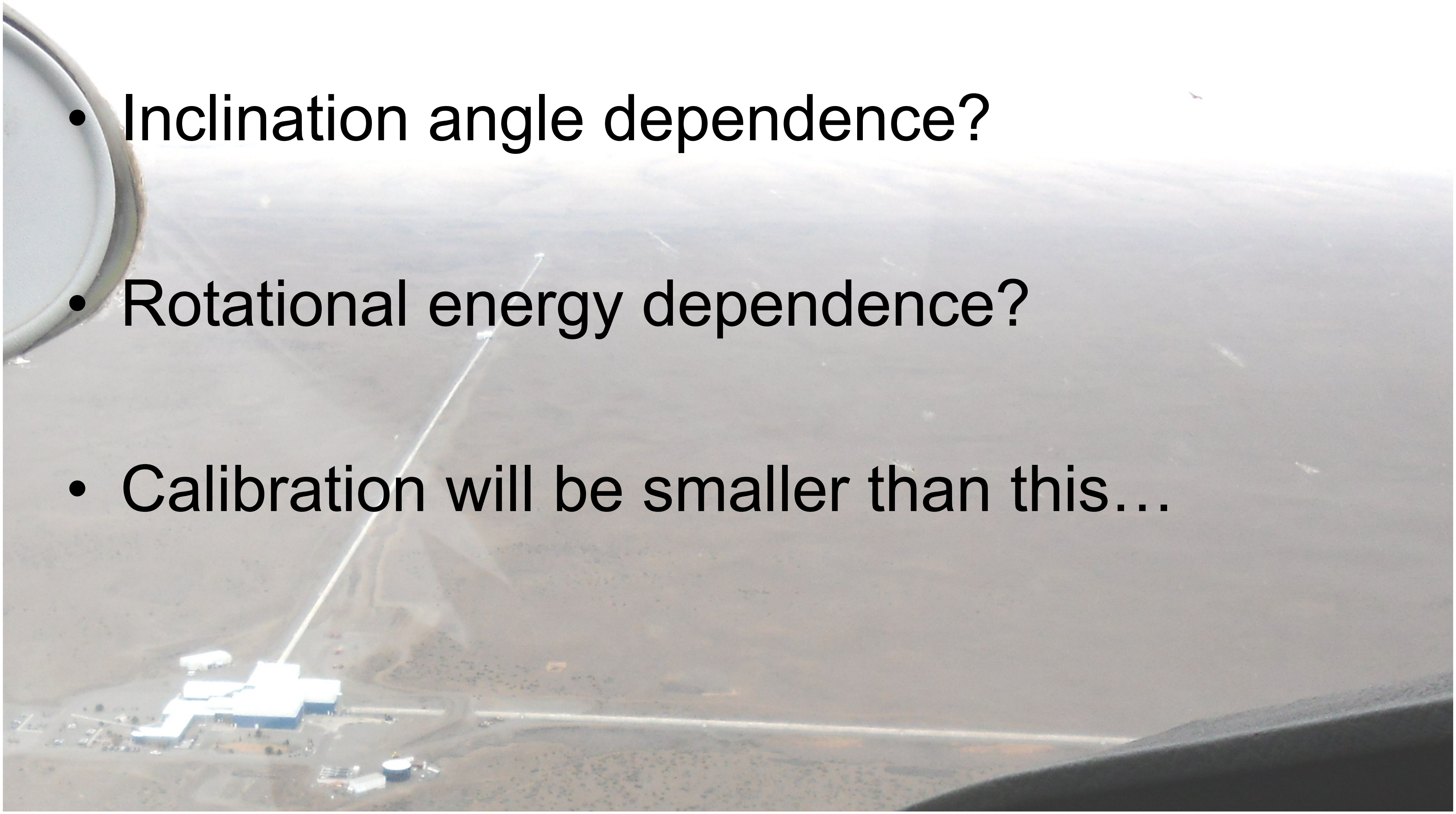
Measuring luminosity distance: e.g. GW150914





Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

LIGO Additional thoughts, 2



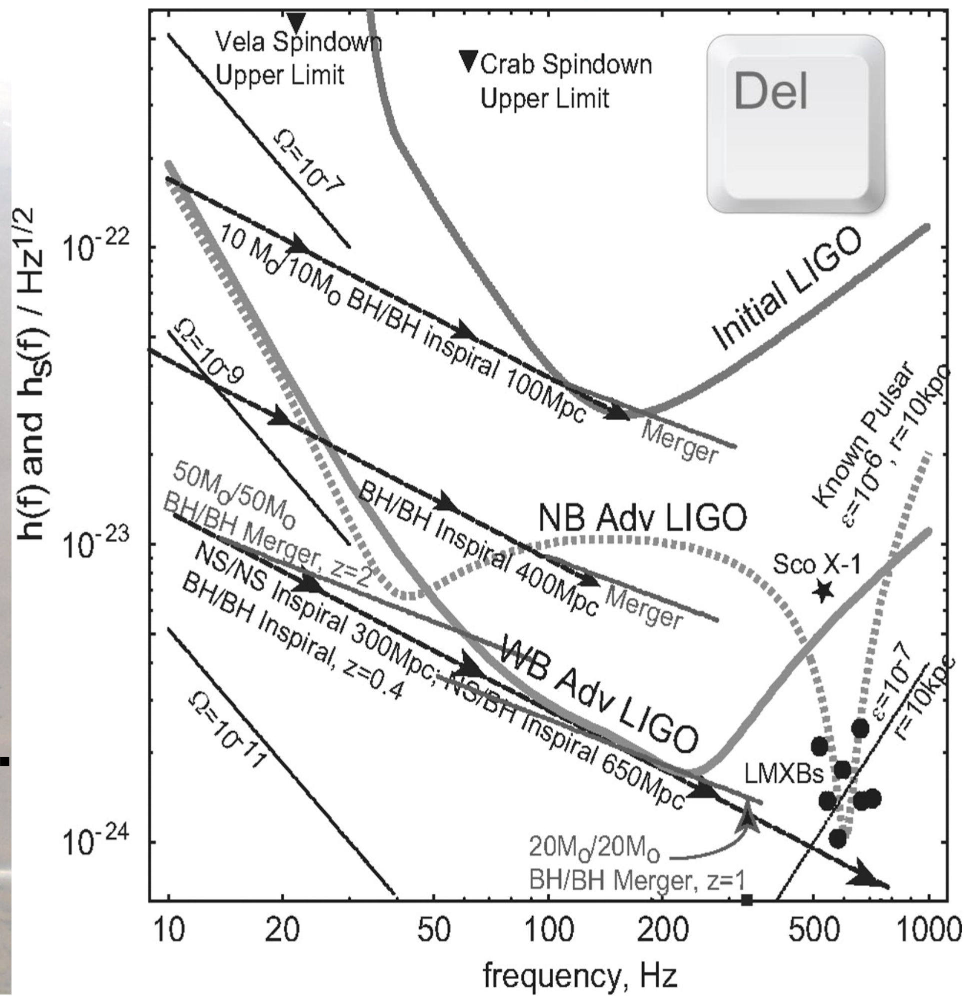
- Inclination angle dependence?
- Rotational energy dependence?
- Calibration will be smaller than this…

Message:

- Don't worry about calibration…

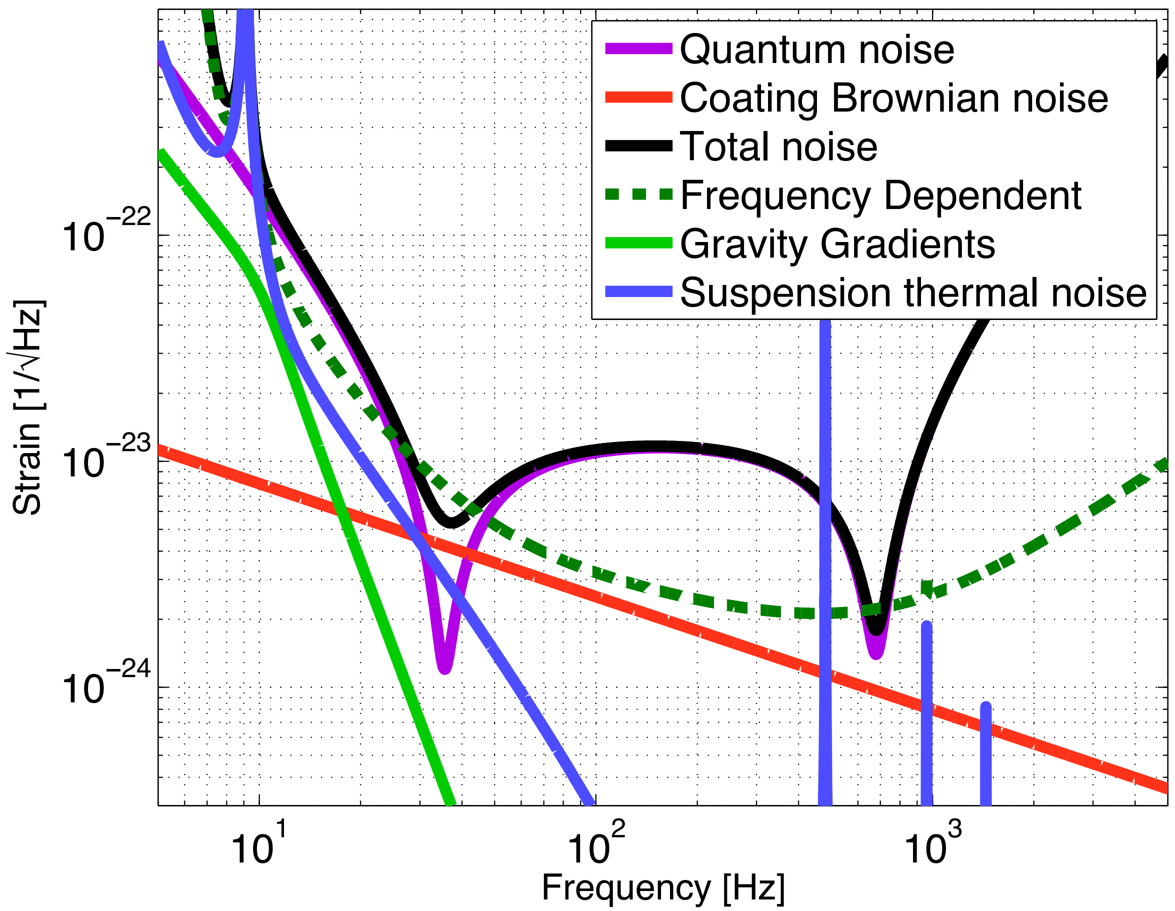
What about detuning?

- You can still find old detuned Advanced LIGO design curves with Google (Internet has no delete button)
- The idea was:
  - With an off-resonance signal recycling mirror an optical resonance can enhance the sensitivity
- Has serious problems…



Signal Recycling Detuning

- In principle, ability to target high frequency sources without squeezing
- Less hardware investment with respect to squeezing, but challenge from the controllability of the interferometer
- Given the same loss in the interferometer, **benefit at high frequency is comparable to frequency dependent squeezing in a narrow band, worse elsewhere**

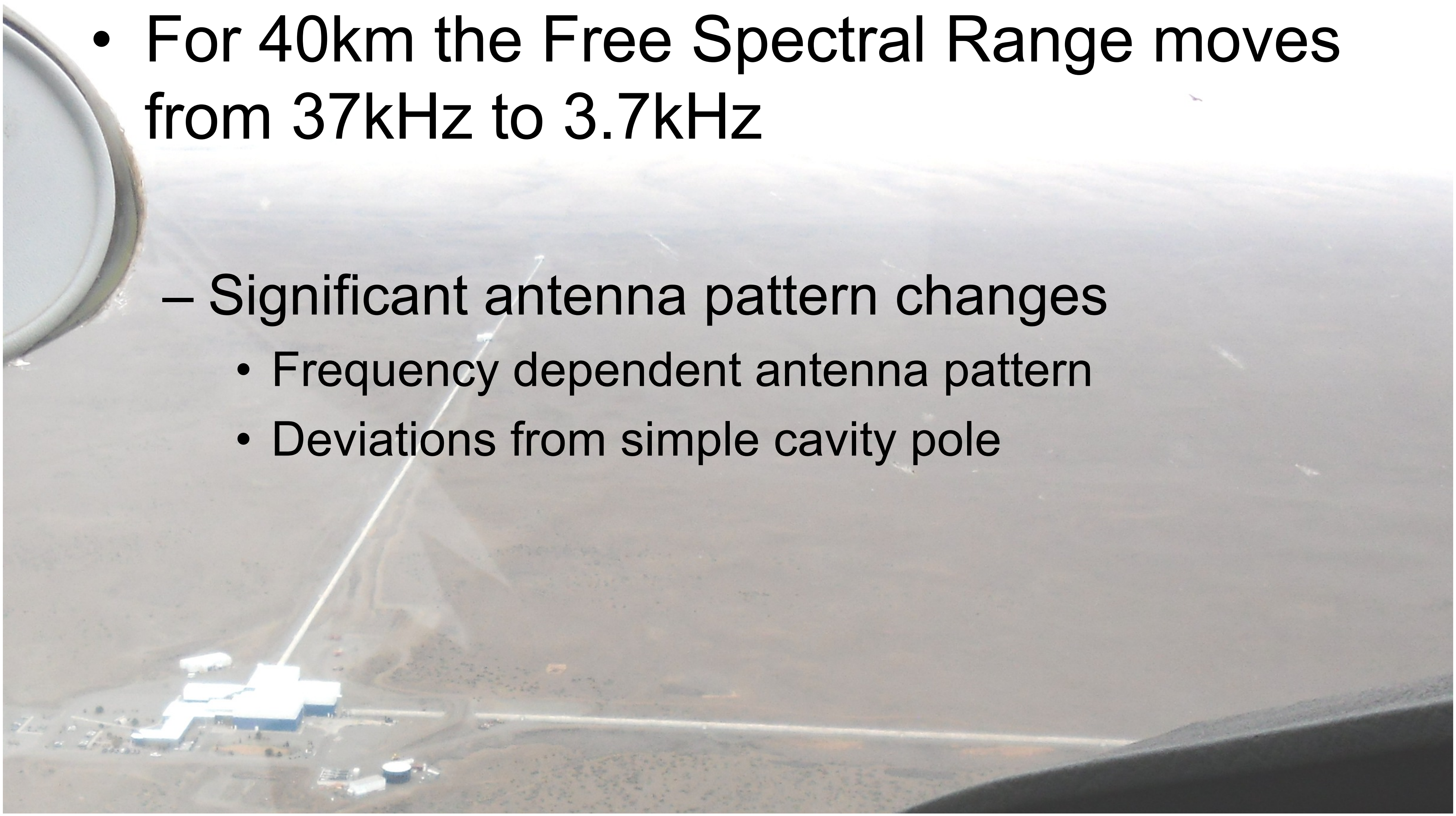


→ Signal recycling detuning not particular beneficial for high frequency sources
→ Interesting cases for low-mid frequencies regions
→ Interferometer control more challenging

See G1500599

High frequency response of long IFO

- For 40km the Free Spectral Range moves from 37kHz to 3.7kHz
  - Significant antenna pattern changes
    - Frequency dependent antenna pattern
    - Deviations from simple cavity pole



Still relevant – for 40km divide all frequencies by 10…

Frequency corrections to antenna-patterns: forward detector transfer function

LSC Burst Group Telecon. Sept. 26, 2006

Malik Rakhmanov

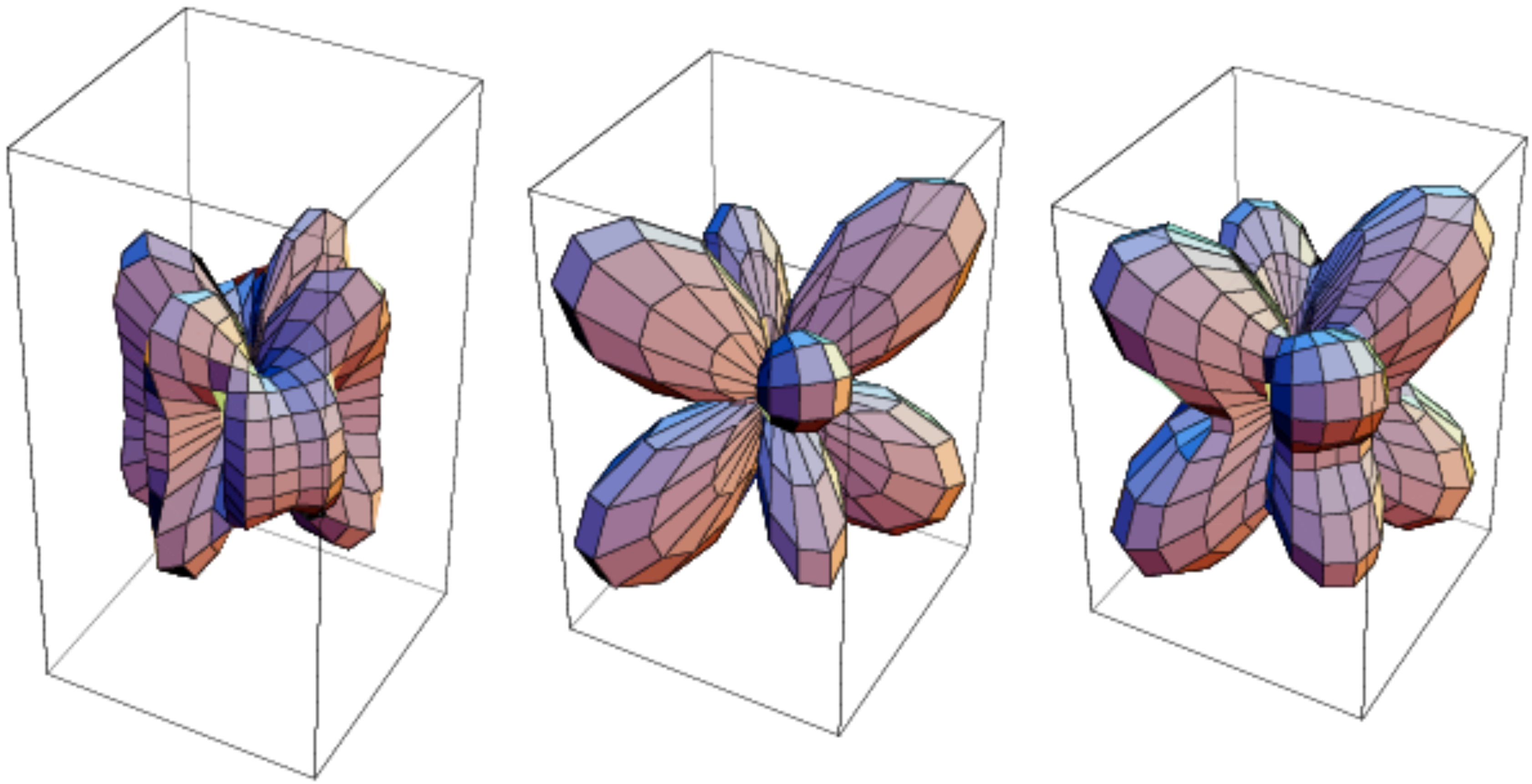
LSC documents regarding the frequency dependence of the antenna patterns and its implication for calibration:

- T970101-B, D. Sigg, *Strain calibration in LIGO*,
- T030296, D. Sigg and R. Savage, *Analysis proposal to search for gravitational waves at multiples of the LIGO arm cavity free-spectral-range frequency*,
- T030186, J. Markowicz, R.L. Savage, and P. Schwinberg, *Development of a readout scheme for high-frequency gravitational waves*,
- G050205, M. Rakhmanov and R. Savage, *LIGO detector response at high frequencies and its implications for calibration above 1kHz*,
- T050136, Hunter Elliott, *Analysis of the frequency dependence of the LIGO directional sensitivity (Antenna Pattern) and implications for detector calibration*,
- T060xxx, Jeffrey Parker, *Development of a high-frequency burst pipeline.*

See LIGO-G060665

High-frequency antenna patterns

Antenna patterns at FSR: response to +polarization ($\psi = 0°$), response ×polarization ($\psi = 90°$), averaged response.



from T970101-B, D.Sigg, *Strain calibration in LIGO*.

Brief derivation of the detector response to GW

Polarization tensor in the wave frame E_{gw} and the vector pointing to the source $\vec{n}$:

$$E_{gw} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \qquad \begin{aligned} n_x &= \sin\theta\cos\phi \\ n_y &= \sin\theta\sin\phi \\ n_z &= \cos\theta. \end{aligned}$$

Transformation from the wave frame to the detector frame, $R = R_z(\psi)R_y(\theta)R_z(\phi)$, induces the transformation of the polarization tensor: $E_{det} = R^T\, E_{gw}\, R$.

$$A_i = \frac{1 - e^{-(1-n_i)sT}}{1 - n_i}, \qquad B_i = \frac{1 - e^{-(1+n_i)sT}}{1 + n_i}.$$

Introduce the equivalent phase response and the cavity field response:

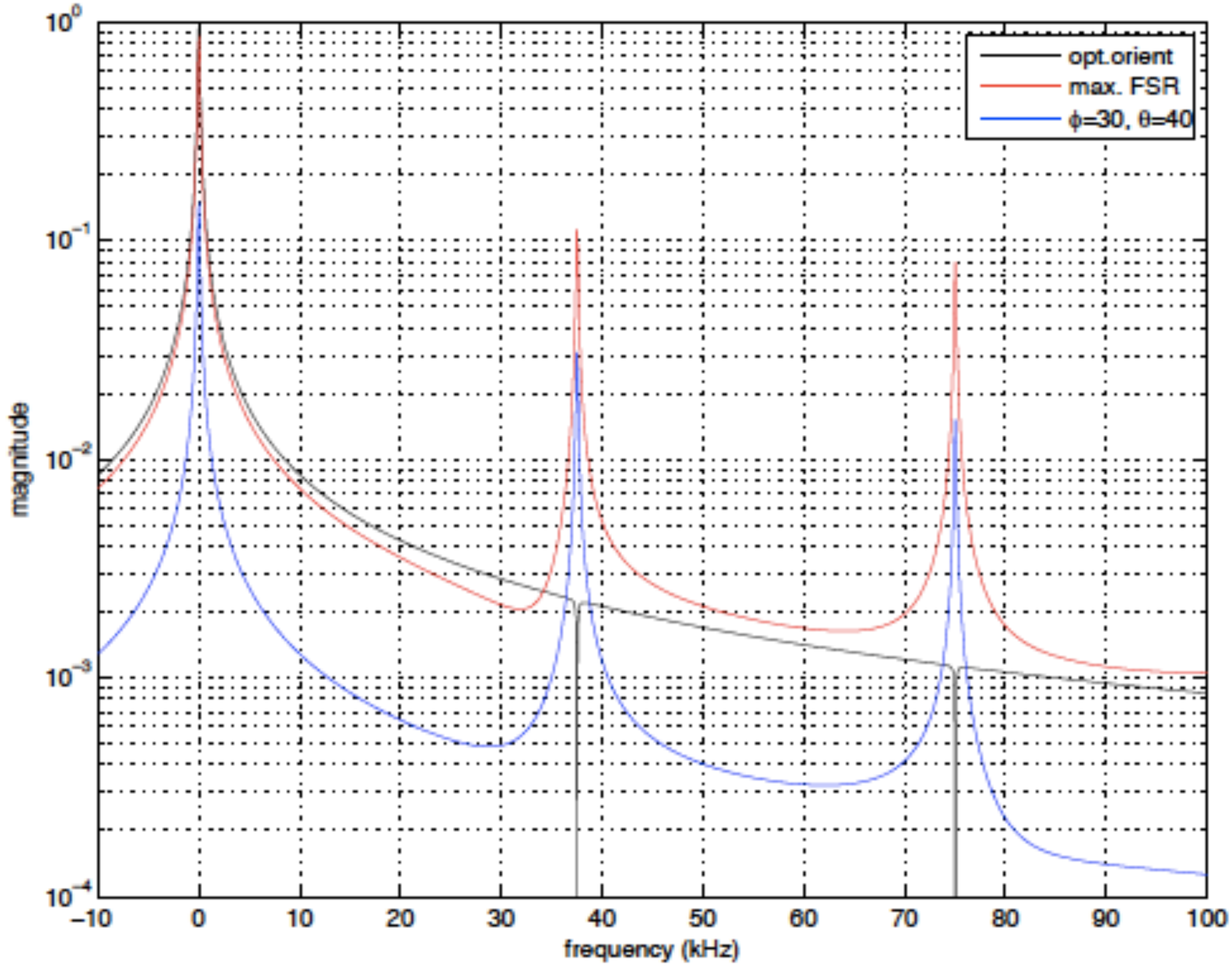
$$\phi_i = \frac{A_i - B_i e^{-2sT}}{2sT}, \qquad H_{cav}(s) = \frac{1 - r_a r_b}{1 - r_a r_b e^{-2sT}},$$

and two polarization components in detector frame: $E_{xx} = E_{det}(1,1), E_{yy} = E_{det}(2,2)$.

Then response to gravitational waves is

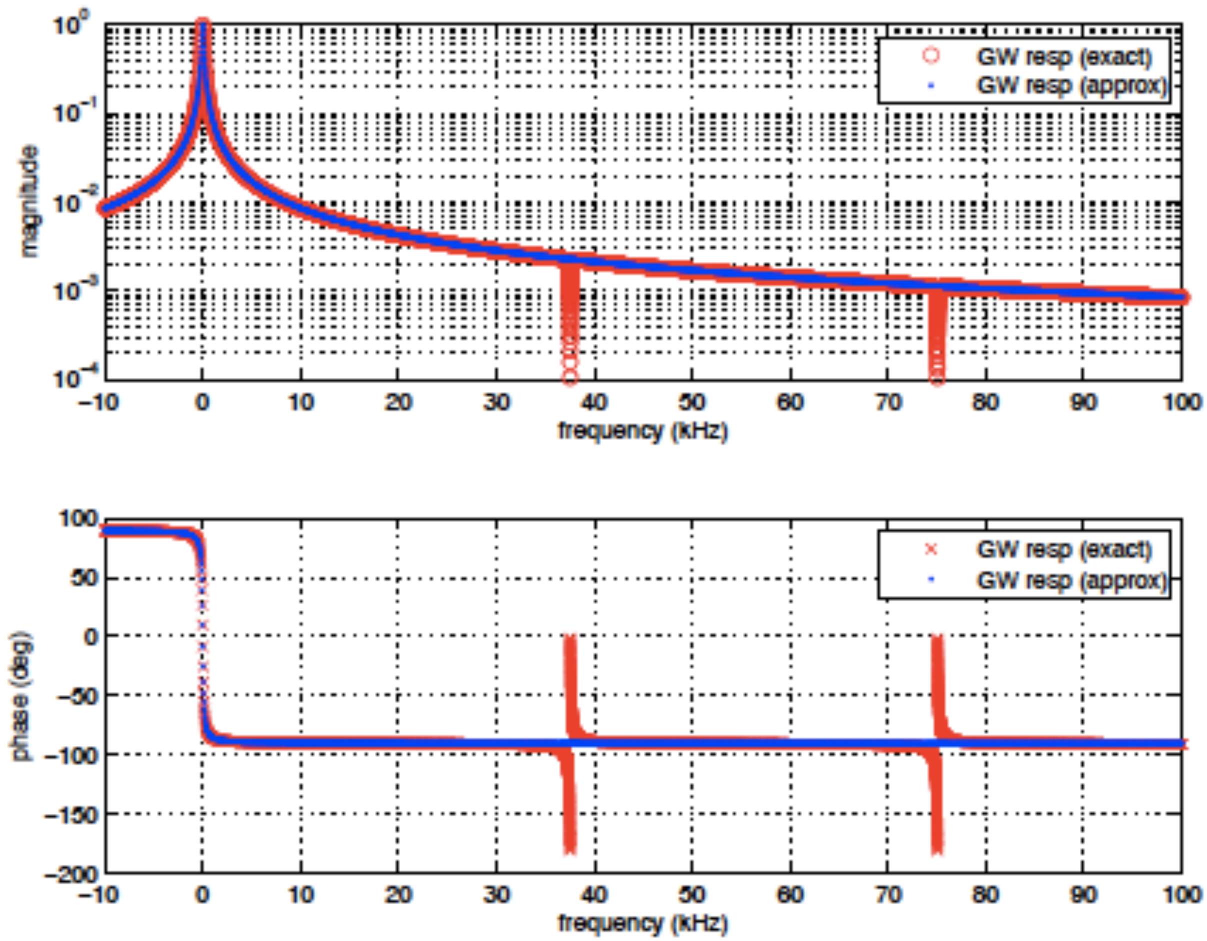
$$H_{gw}(s) = \frac{1}{2}\, H_{cav}(s)\, (E_{xx}\phi_x - E_{yy}\phi_y).$$

Magnitude of $H_{gw}(s)$



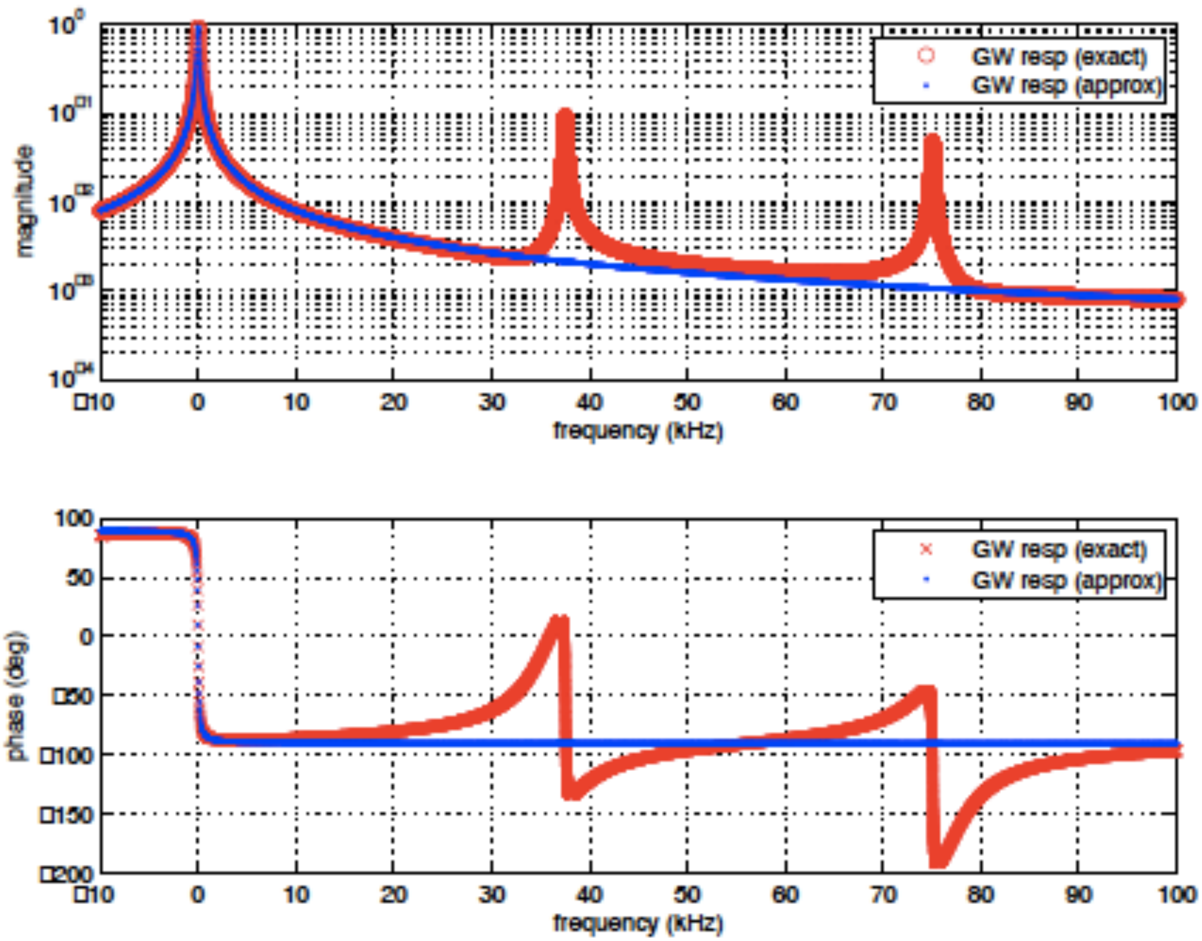
$H_{gw}(s)$: exact and approximate forms (1)

Source coordinates: $\phi = 0$, $\theta = 0$, $\psi = 0$.



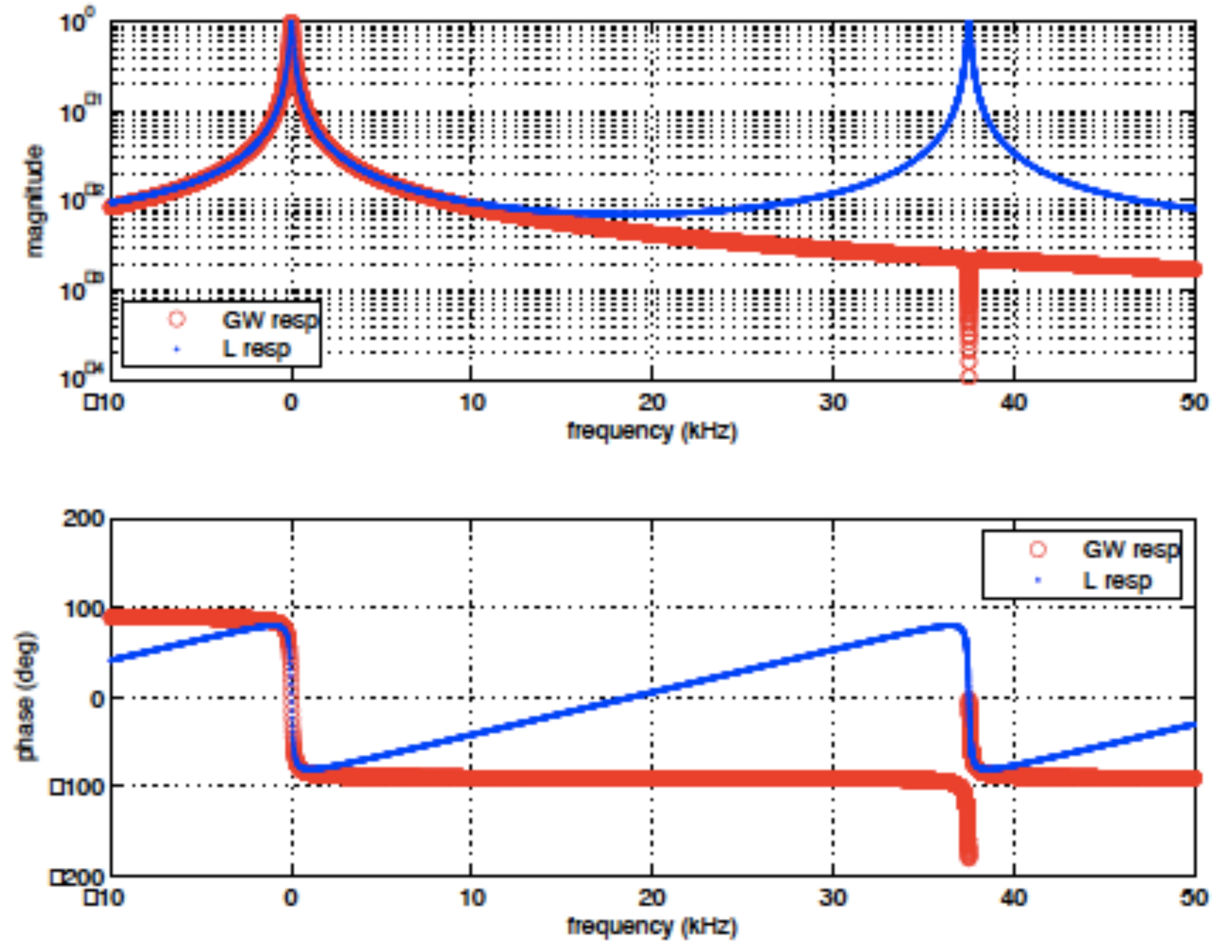
$H_{gw}(s)$: exact and approximate forms (2)

Source coordinates: $\phi = 0$, $\theta = 20°$, $\psi = 0$.



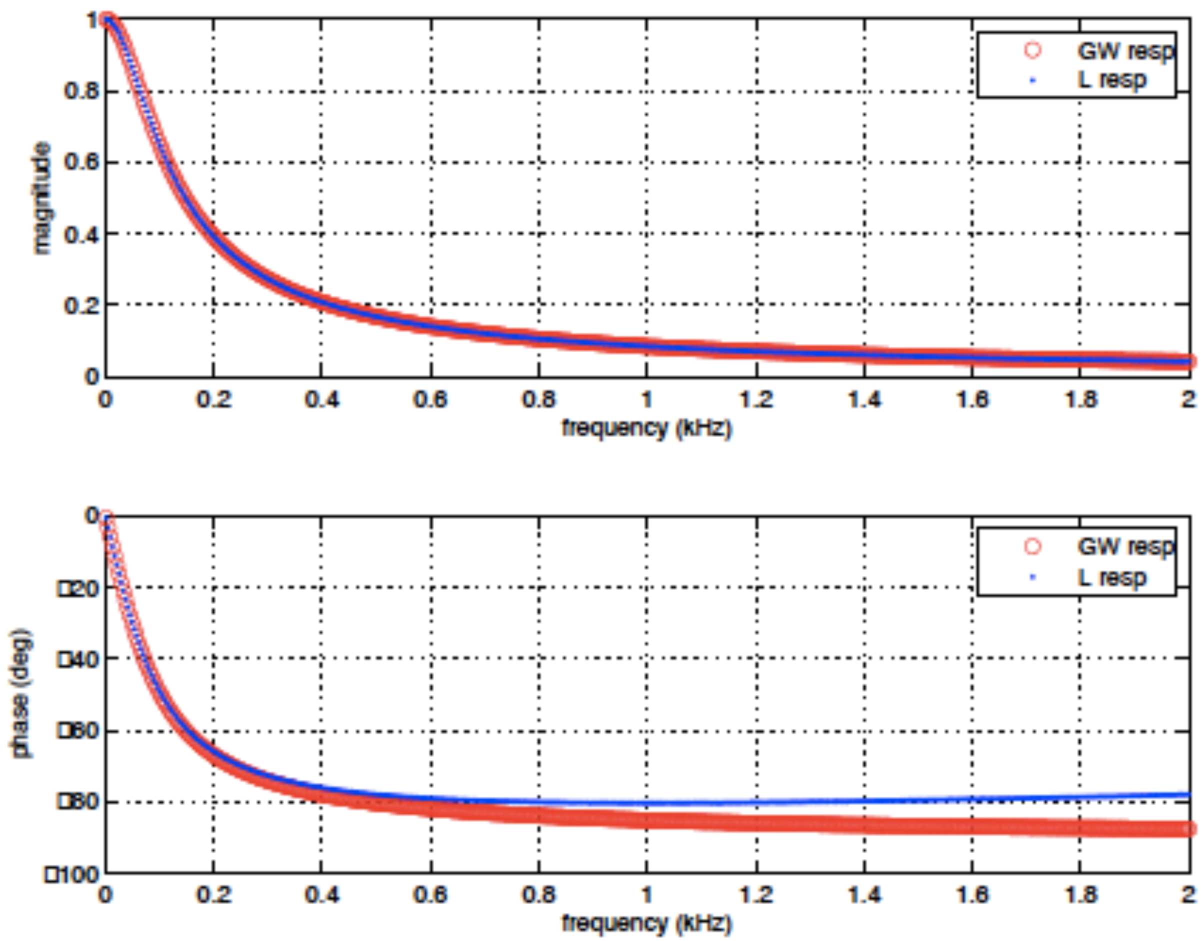
Comparison of $H_{gw}(s)$ and $H_L(s)$ (1)

Calibration: provides $H_L(f)$ not $H_{gw}(f)$. The sensing function in the inverse calibration, $C(f)$, is the response to length. This is transferred to the $h(t)$-channel.



Comparison of $H_{gw}(s)$ and $H_L(s)$ (2)

At low frequencies the magnitude of the length response and that of the gravitational-wave response are almost the same. The phase is slightly different though.



Extra Slides

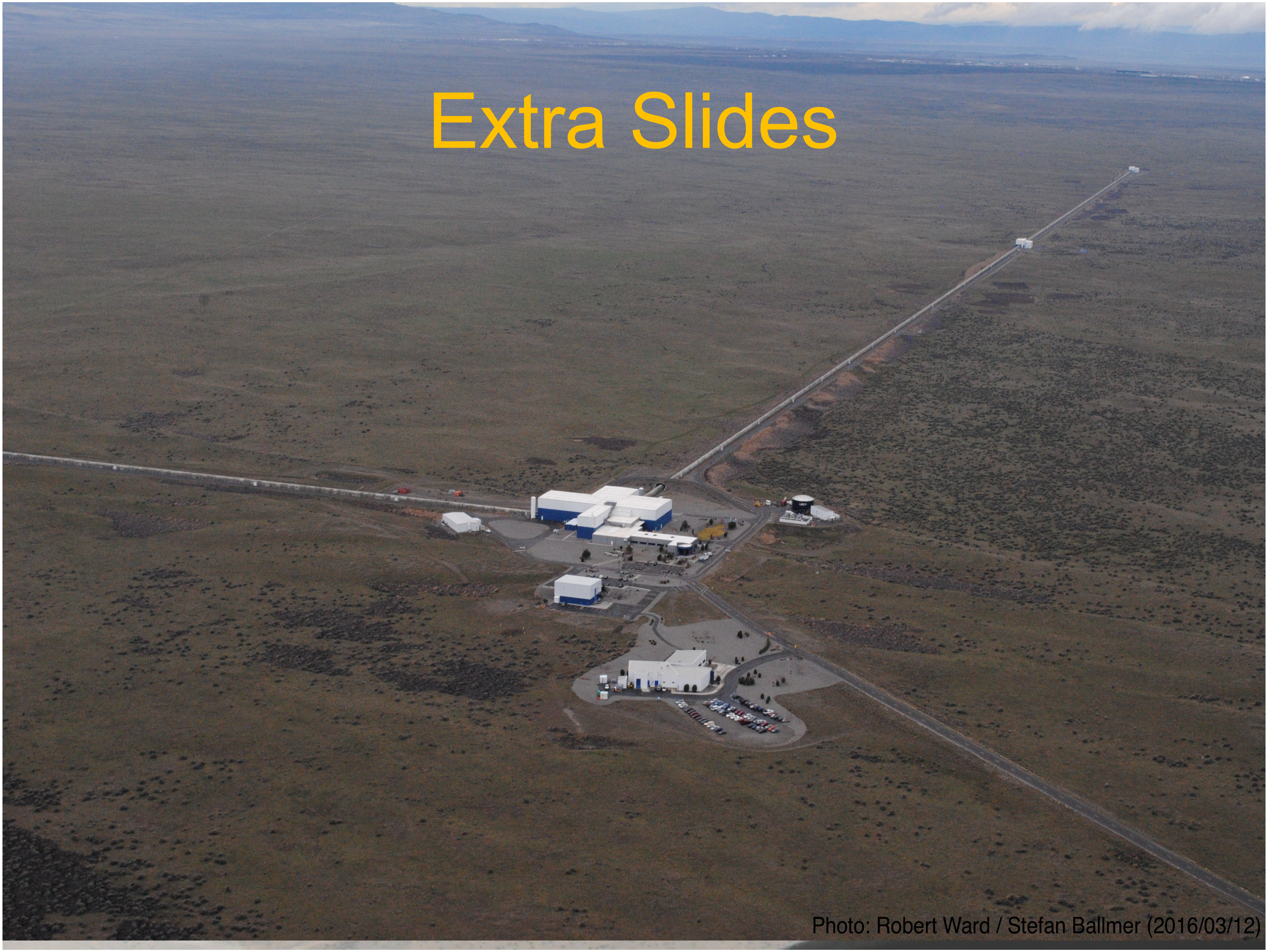


Photo: Robert Ward / Stefan Ballmer (2016/03/12)