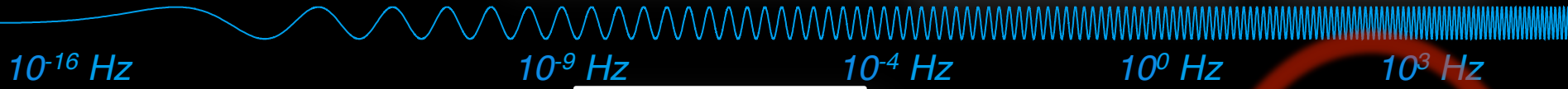
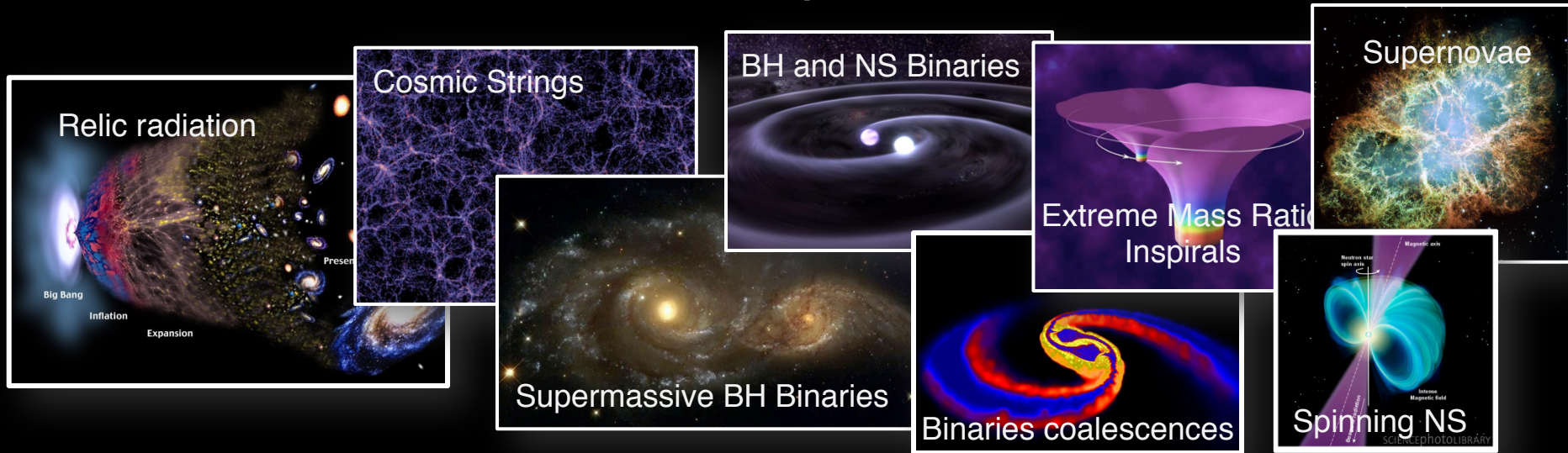


# Future of Ground-Based Gravitational-Wave Detectors

Matthew Evans, MIT

# The Gravitational Wave Spectrum



10<sup>-16</sup> Hz
10<sup>-9</sup> Hz
10<sup>-4</sup> Hz
10<sup>0</sup> Hz
10<sup>3</sup> Hz

Pulsar timing

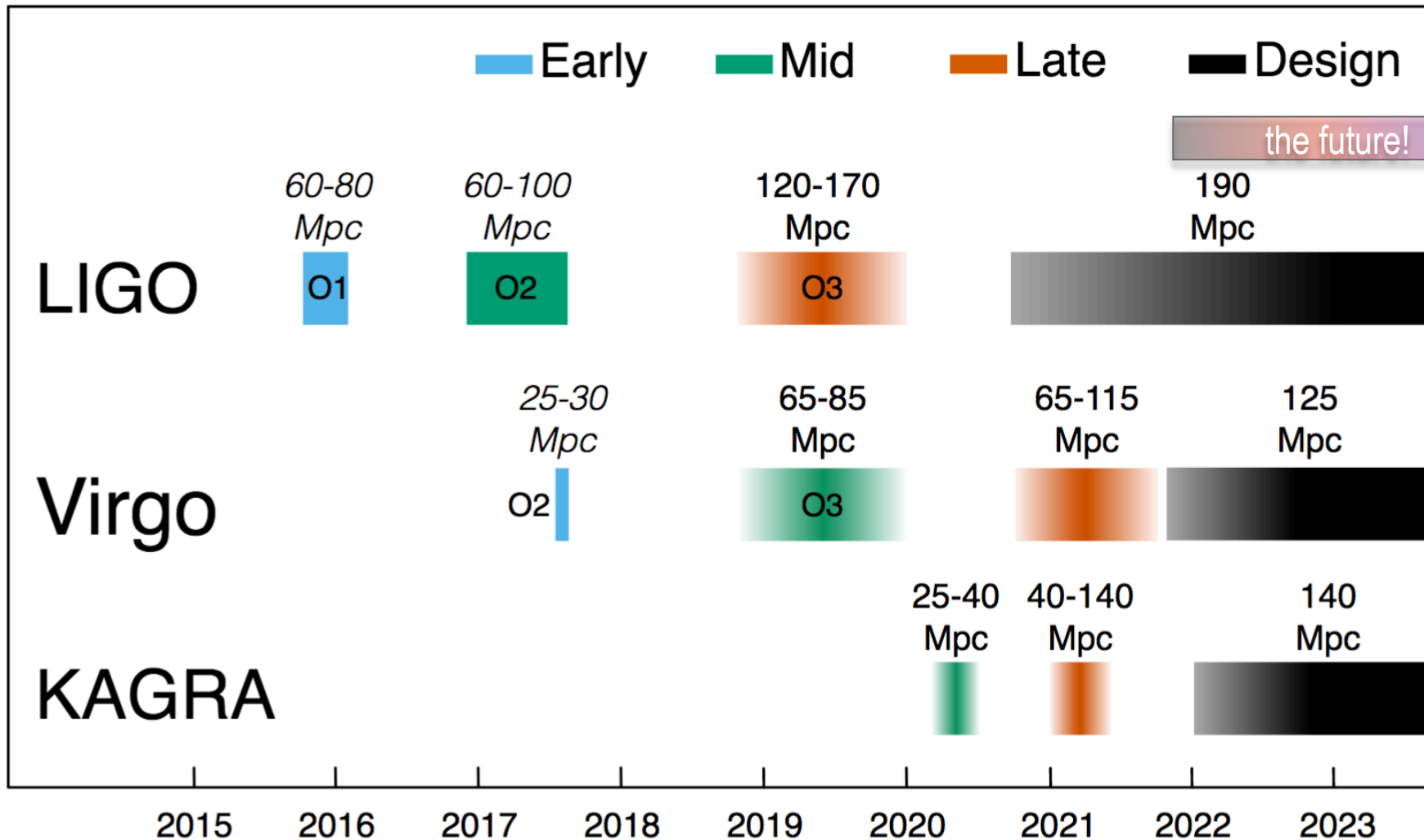
Space detectors

Ground interferometers



Laser  
Gravitational-Wave  
Observatory

# Observing Scenario



# Can we build more sensitive detectors?

YES, we can.

- **More of the same, but even better:** more power, bigger/heavier masses, lower loss mirror coatings, better suspensions, ...
- **New technologies:** squeezed light, alternative wavelengths + cryogenics, alternative optical configurations, ..

- **Make it longer:** take advantage of scaling of noises with arm length
- **Go Underground:** access low frequencies
- **New concepts:** triangular shape, xylophone, ..

ONLY FOR NEW  
FACILITIES

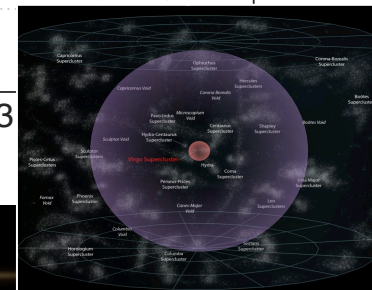
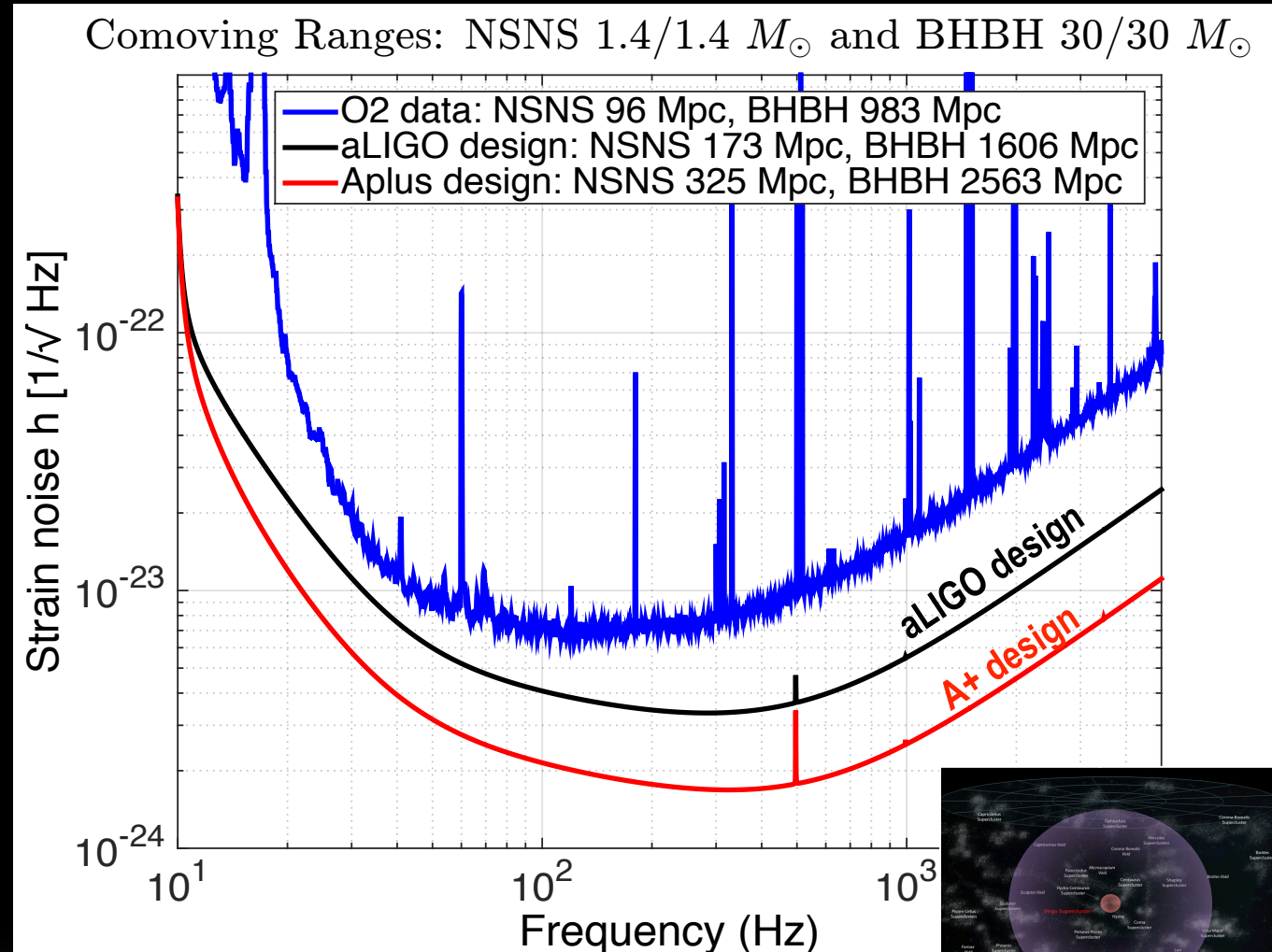
# The Future of LIGO

- **A+**: near term improvement to Advanced LIGO
  - Lower mechanical loss mirror coatings, frequency dependent squeezing
    - ⇒ proposal to the NSF in preparation
    - ⇒ could be operational by mid-22
- **Voyager**: same Advanced LIGO facility, longer laser wavelength, modest cryogenics,
  - ⇒ world-wide R&D in progress

# Beyond Advanced LIGO: A+, a mid-scale upgrade

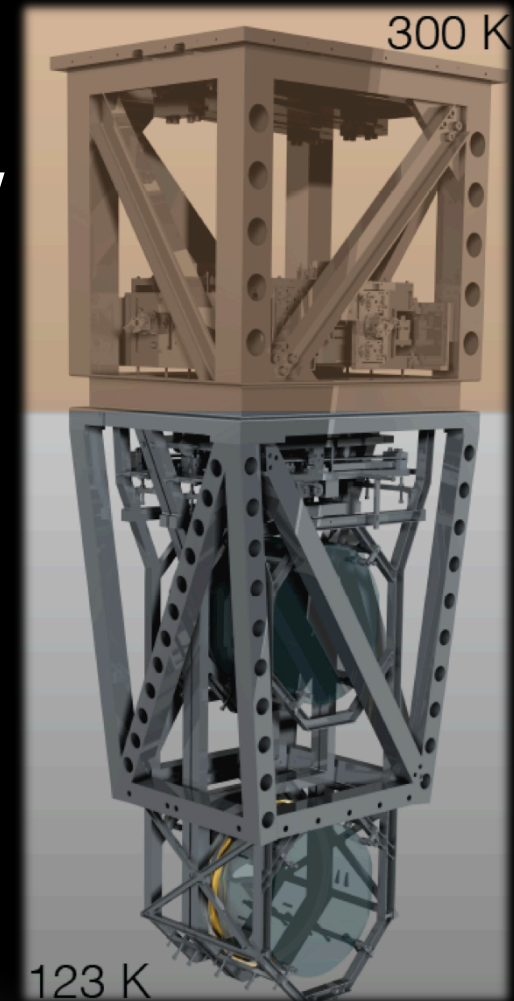
- Improved quantum & thermal noise
- Projected observation: mid-2024
- BNS rate **7x aLIGO**  
**1-13 BNS/month!**
- BBH rate **4x aLIGO**  
**17-300 BBH/month!**

A+ key parameters:  
 thermal noise half of aLIGO  
 12dB injected squeezing  
 15% readout loss  
 FDS, **300 m** filter cavity  
 60 ppm RT FC loss



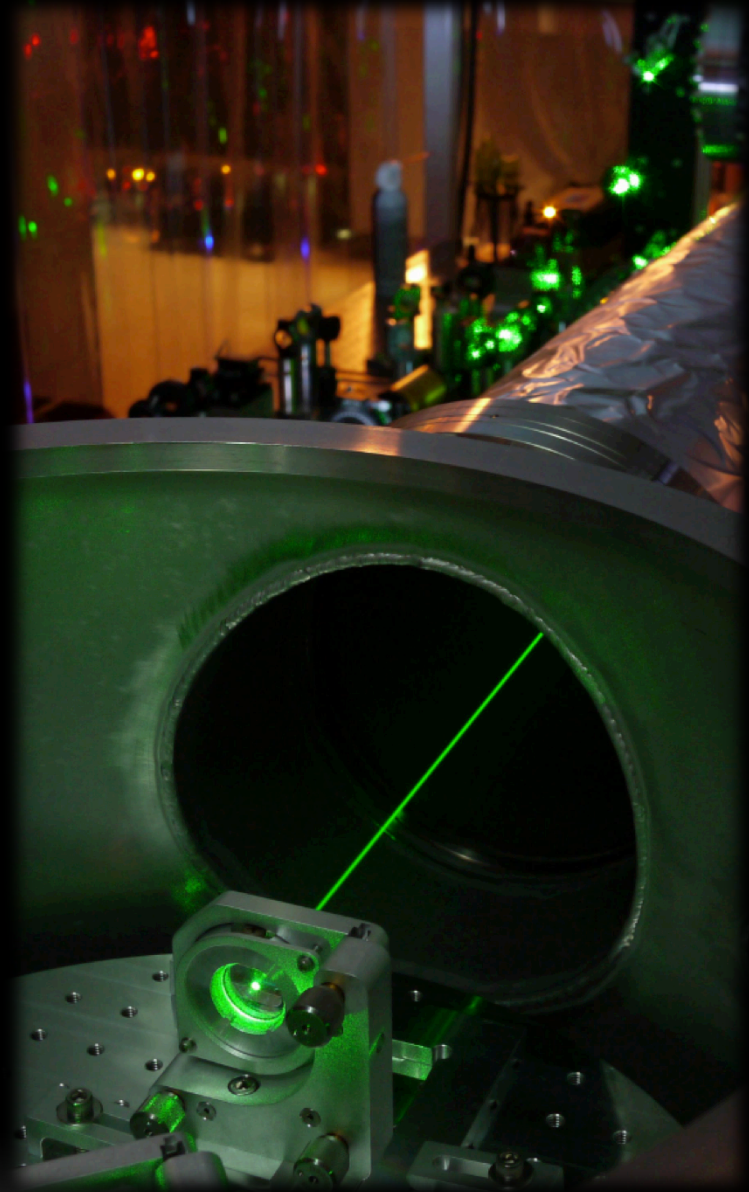
# What is the most we can do with the LIGO 4km facilities? We have a name for that... **Voyager**

- For sometime in the late 2020s
- Major-upgrade to use technology which is currently in R&D phase
- Basic idea
  - better coatings for 1.5 or 2 $\mu$ m laser wavelength
  - use silicon for test-masses at 123K (zero CTE point)
  - range better than A+ by factor of  $\sim 2$
  - allows access to BBH systems out to  $z \sim 5$



# Long-Term Improvements

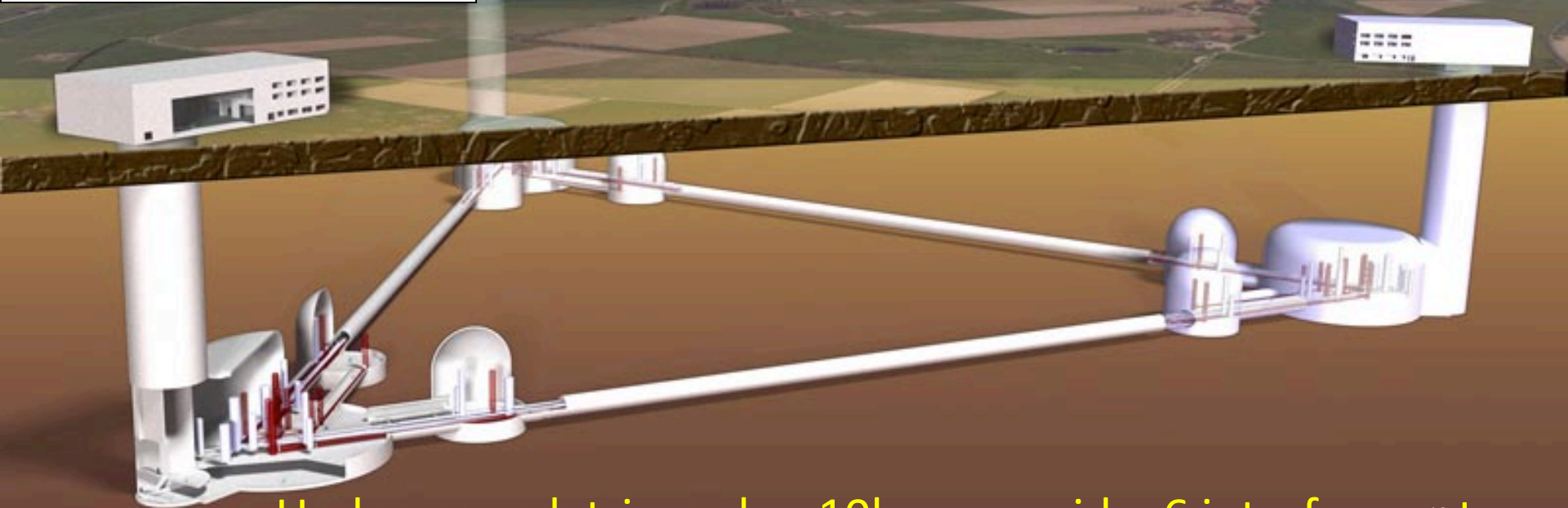
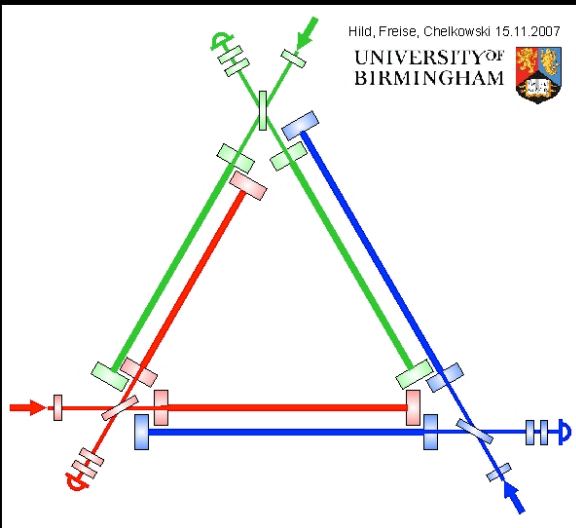
- R&D is driven not only by how to make Advanced LIGO better, but also by the longer term potential of the field
- The next big leap in sensitivity will come from a longer interferometer...



# Going Beyond LIGO and Virgo

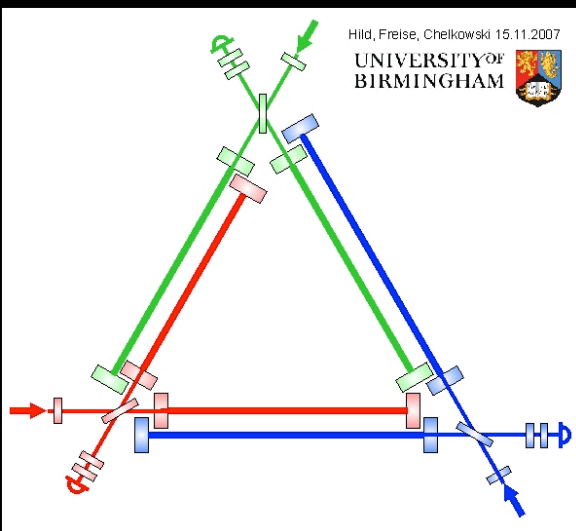


# Einstein Telescope



Underground, triangular, 10km on a side, 6 interferometers

# Einstein Telescope



**Under Development!**



Underground, triangular?, 10km on a side?, 6 interferometers?

An artistic rendering of the Cosmic Explorer gravitational wave observatory. The scene is set on the surface of the moon, which is covered in a reddish-brown dust. In the background, two large, glowing, ring-like structures resembling gravitational wells or wormholes are visible against a dark, starry sky. In the foreground, a large, green, faceted spherical detector is connected to a network of white pipes that form an L-shape on the lunar surface. A white waveform, representing a gravitational wave signal, is overlaid at the bottom of the image.

# Cosmic Explorer

Above-ground, L-shaped, 40km on a side, 1 interferometer

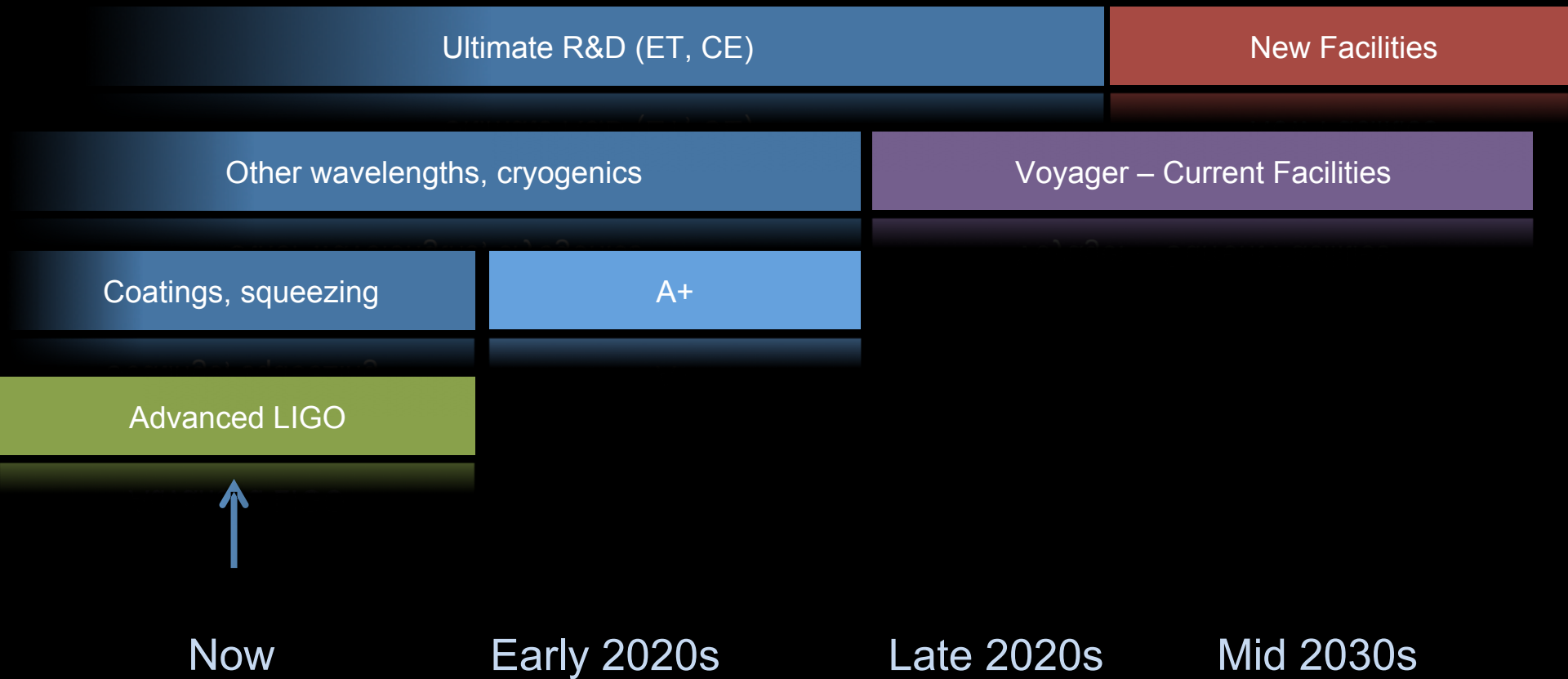
The image depicts a lunar surface with a large L-shaped interferometer structure. The structure consists of three green spherical nodes connected by thin grey lines, forming an L-shape. The background shows a dark sky with two prominent black holes. A white waveform is visible at the bottom of the image.

# Cosmic Explorer

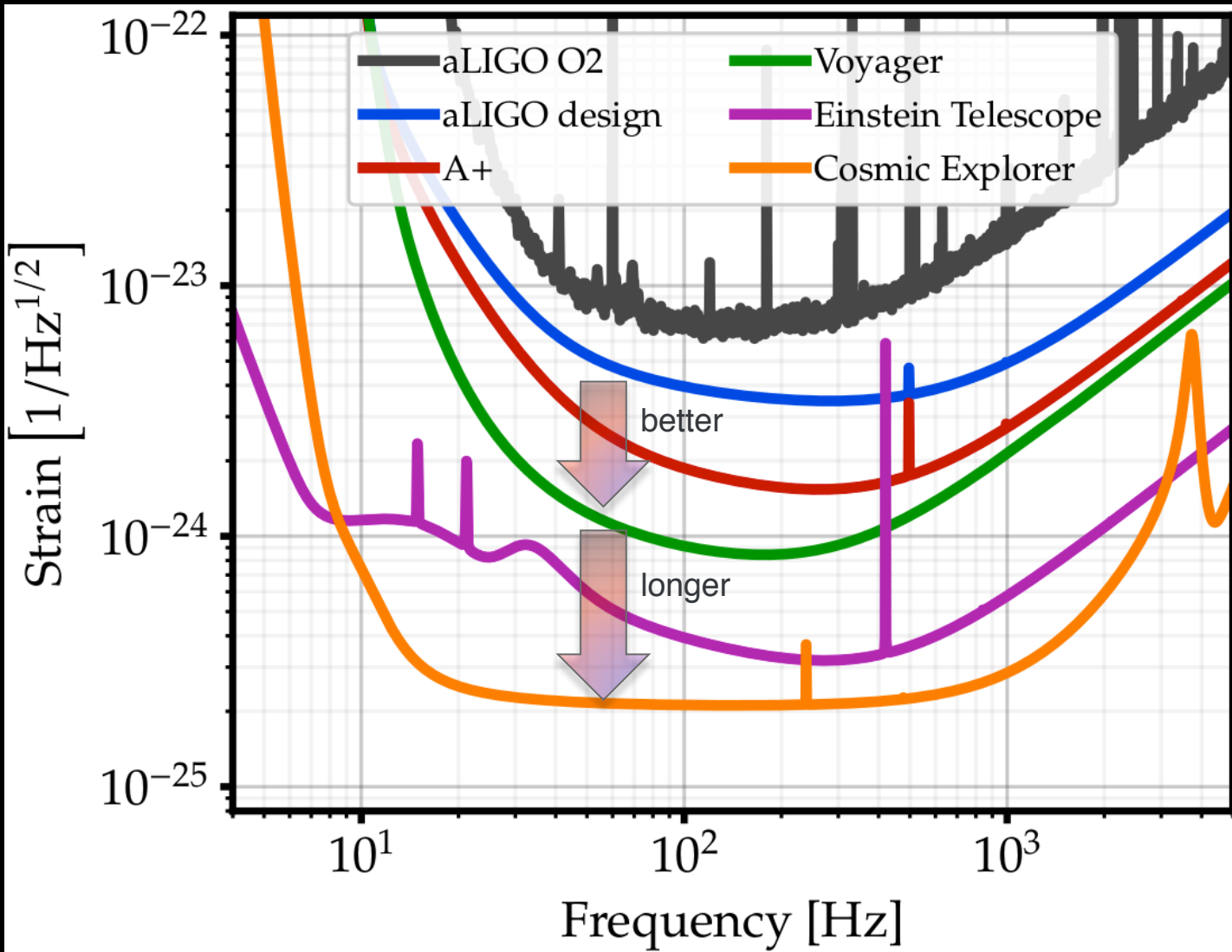
## Under Development!

Above-ground, L-shaped, 40km on a side, 1 interferometer

# Concept Roadmap

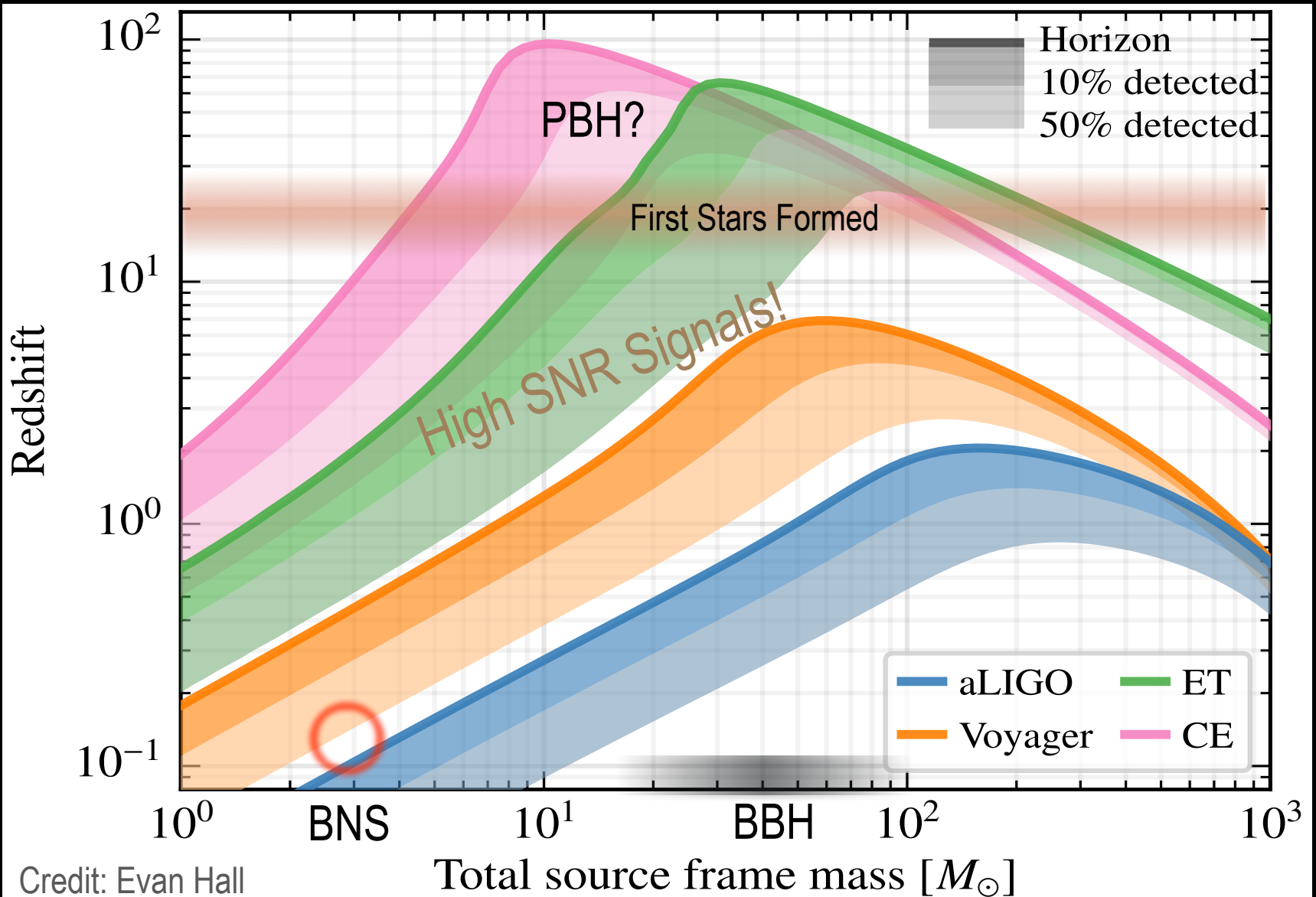


# Example of curve progression



Exploring the sensitivity of next generation gravitational wave detectors  
(2017) CQG 34, 044001

# BBH and BNS from the entire Universe!

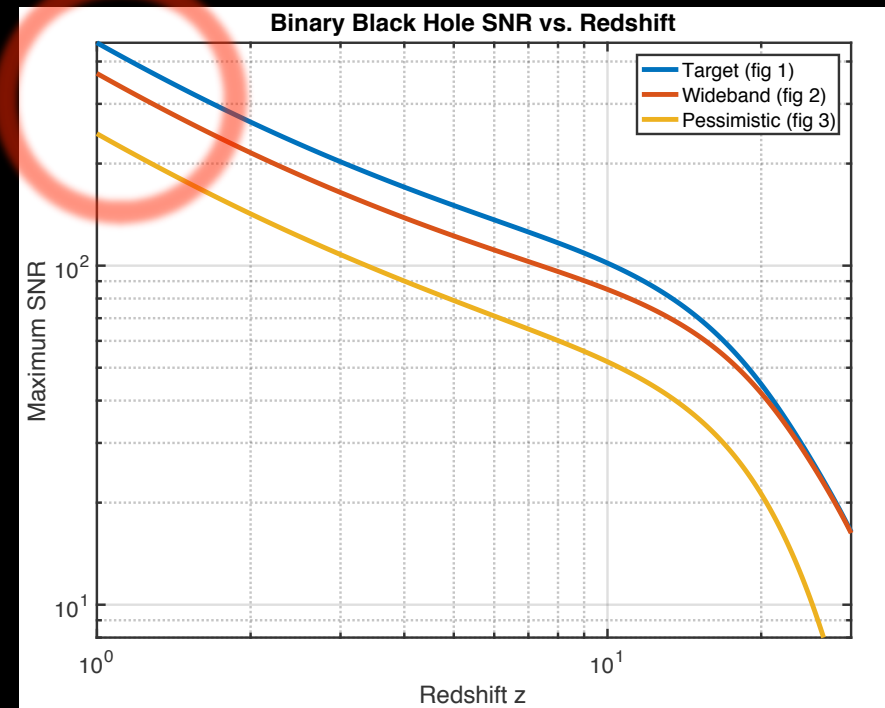


# Gravitational-Wave Science in the 3G Era

- With 3G detectors we will have  $\sim 10^5$  of events each year
  - mostly from  $z \sim 2$  or 3
  - likely astrophysical background of unresolved BNS (BBH separable)
- Population based science won't need good sky localization
  - Mean and median values are meaningful
- Precision test will be done with the nearby high-SNR events
  - Only best  $\sim 10$  events per year will be useful
- Rare or Exotic events may play key role
  - supernovae
  - highly eccentric mergers
  - other exciting things... (cosmic strings?, unknowns?)

# Close BBH Mergers will have high SNR

- SNR > 1000 for BBH like GW150914
- This will allow tests of
  - BH quasi normal modes
  - GW memory effect
  - ...

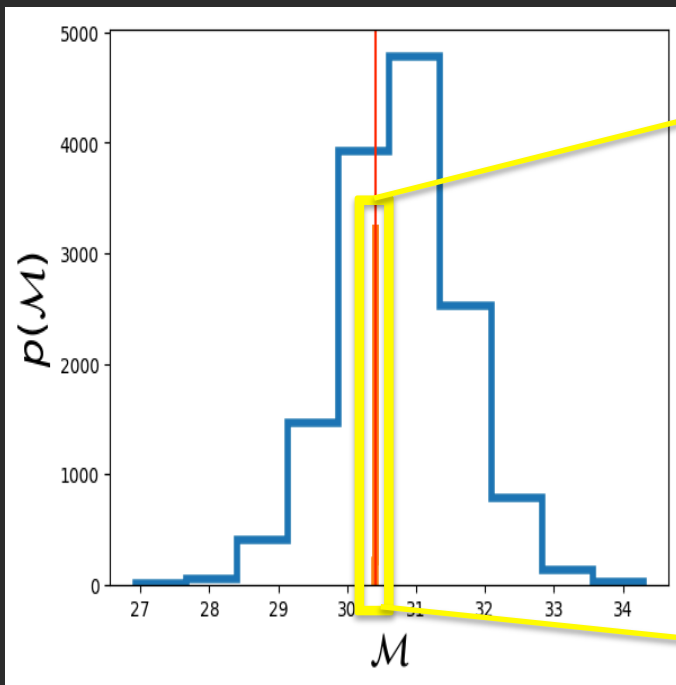


**Exploring the sensitivity of next generation gravitational wave detectors**

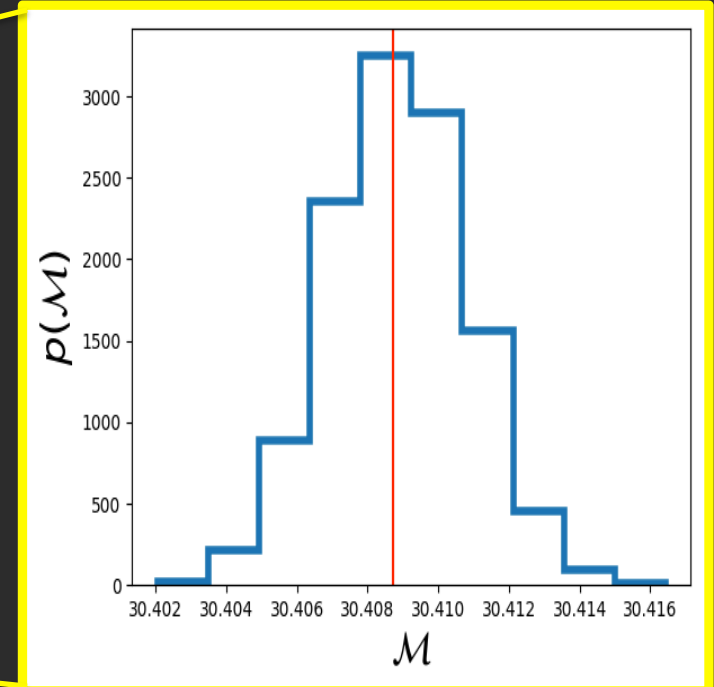
CQG doi:10.1088/1361-6382/aa51f4

# From Salvatore Vitale

- A GW150914-like event will have  $\text{SNR} \sim 2000$  in a Cosmic Explorer facility.
- How well can we do parameter estimation?

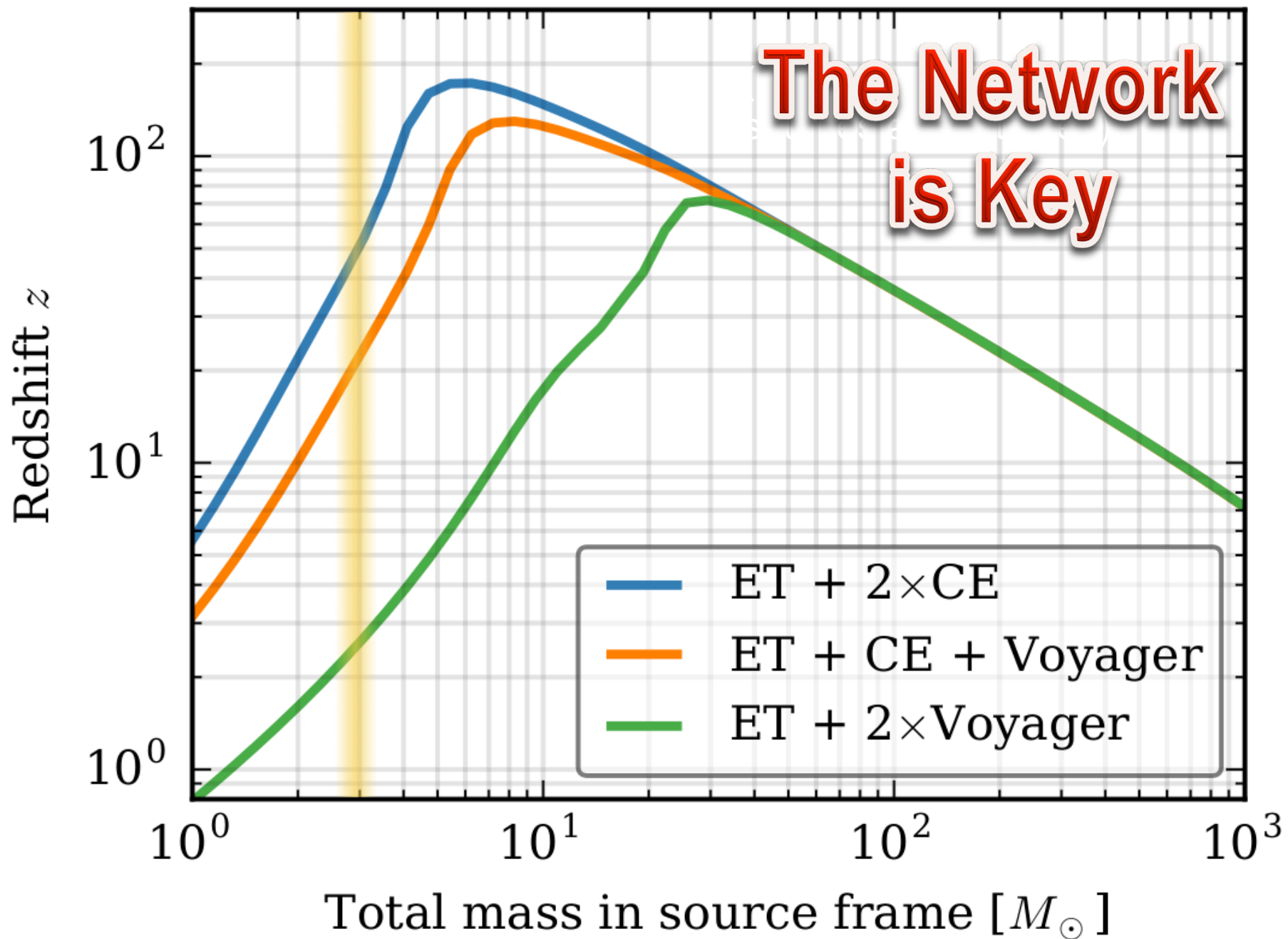


M. Evans at Sackler (Harvard)



Preliminary

# 1% horizon for 3G networks

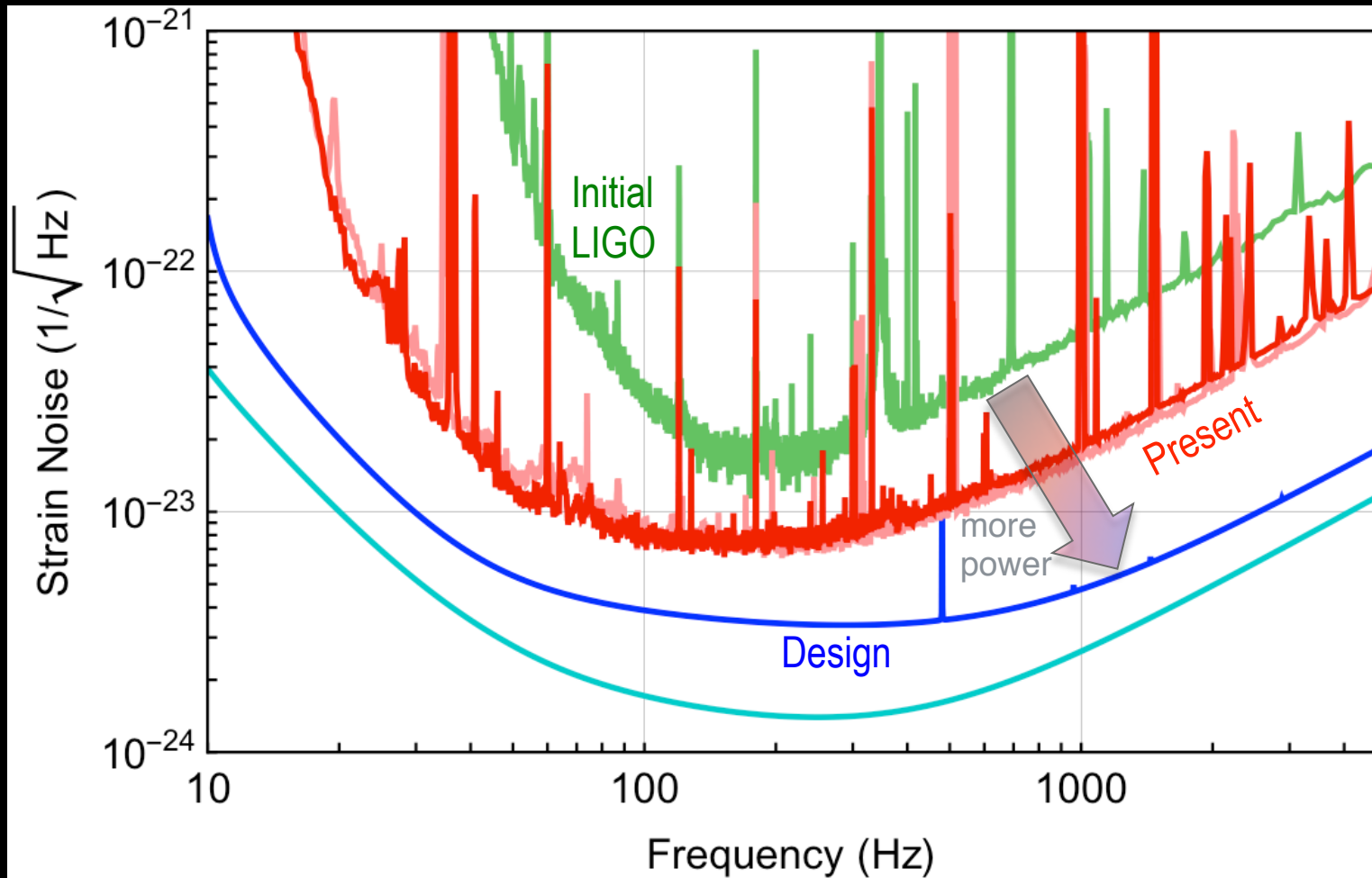


# The Message

- Near-term upgrades will reduce the noise by  $\sim 2$  beyond design
  - event rate may be  $\sim 1$  per day
- The best we can do in the current facility: Voyager
  - roughly another factor of 2, access to high- $z$  BBH
- The next-generation NETWORK will reach the entire Universe
  - BBH and BNS detection rate will be mostly determined by astrophysical population ( $> 10^5$  per year?), not detector sensitivity (peak near  $z \sim 3$ ?)
  - high SNR signals will allow for detailed tests of GR, NS EOS, ...
- **This is just the beginning!**

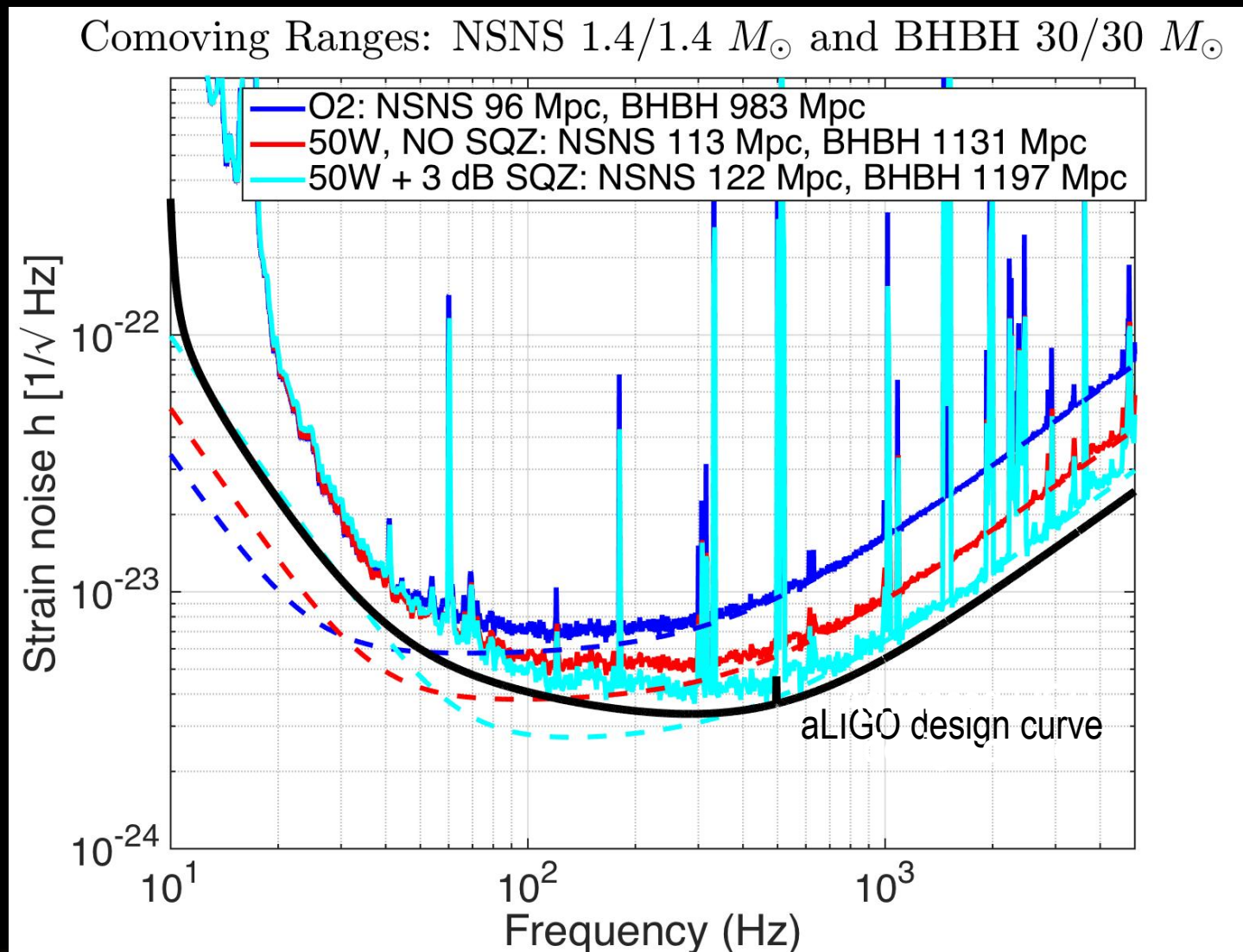
spares...

# Advanced LIGO Noise: Progress

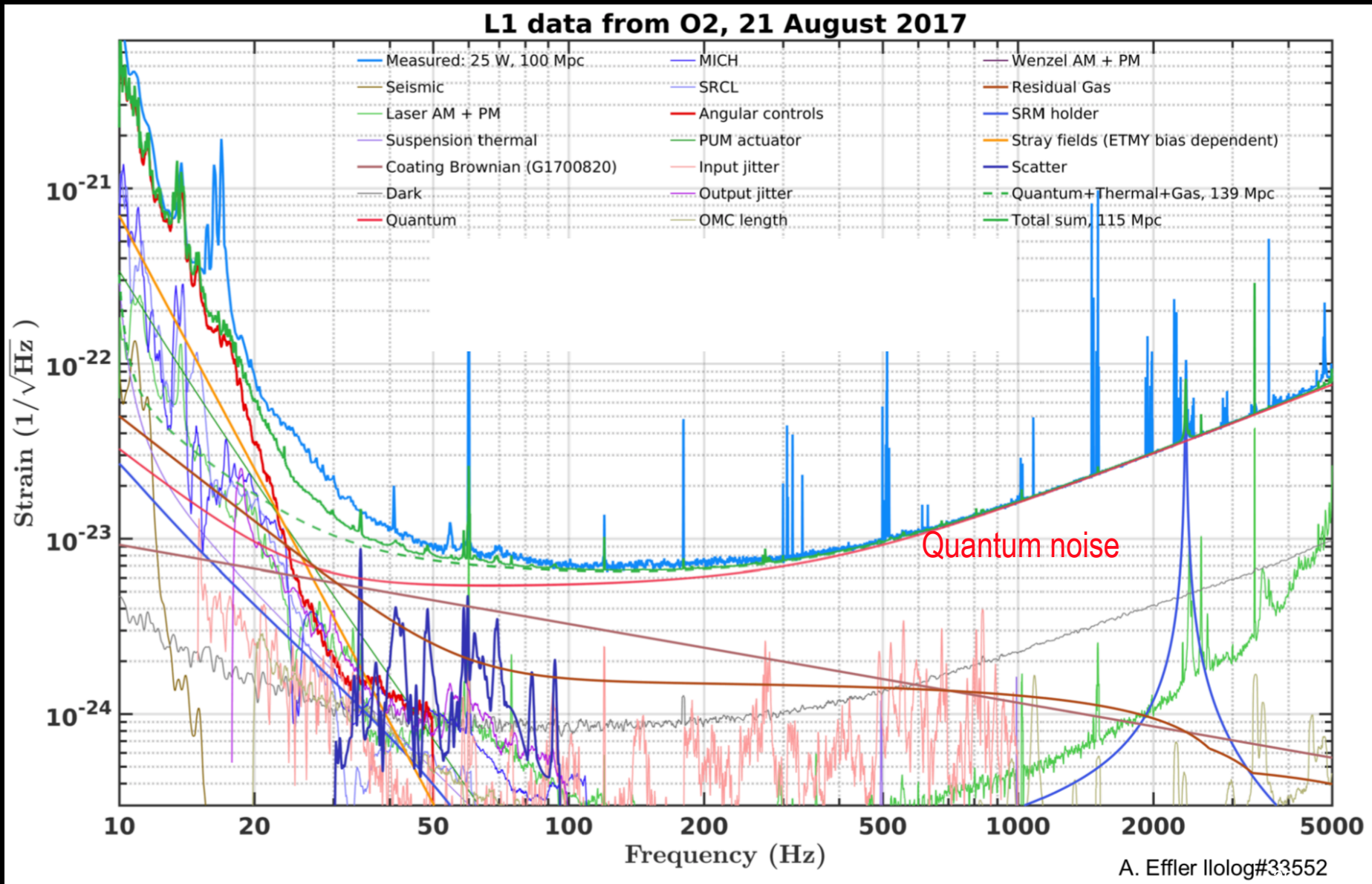


GW150914: The Advanced LIGO Detectors in the Era of First Discoveries. LSC (2016) PRL 116, 131103

# Target for O3: (at least) more power + squeezing



# Low-frequency Improvements: maybe



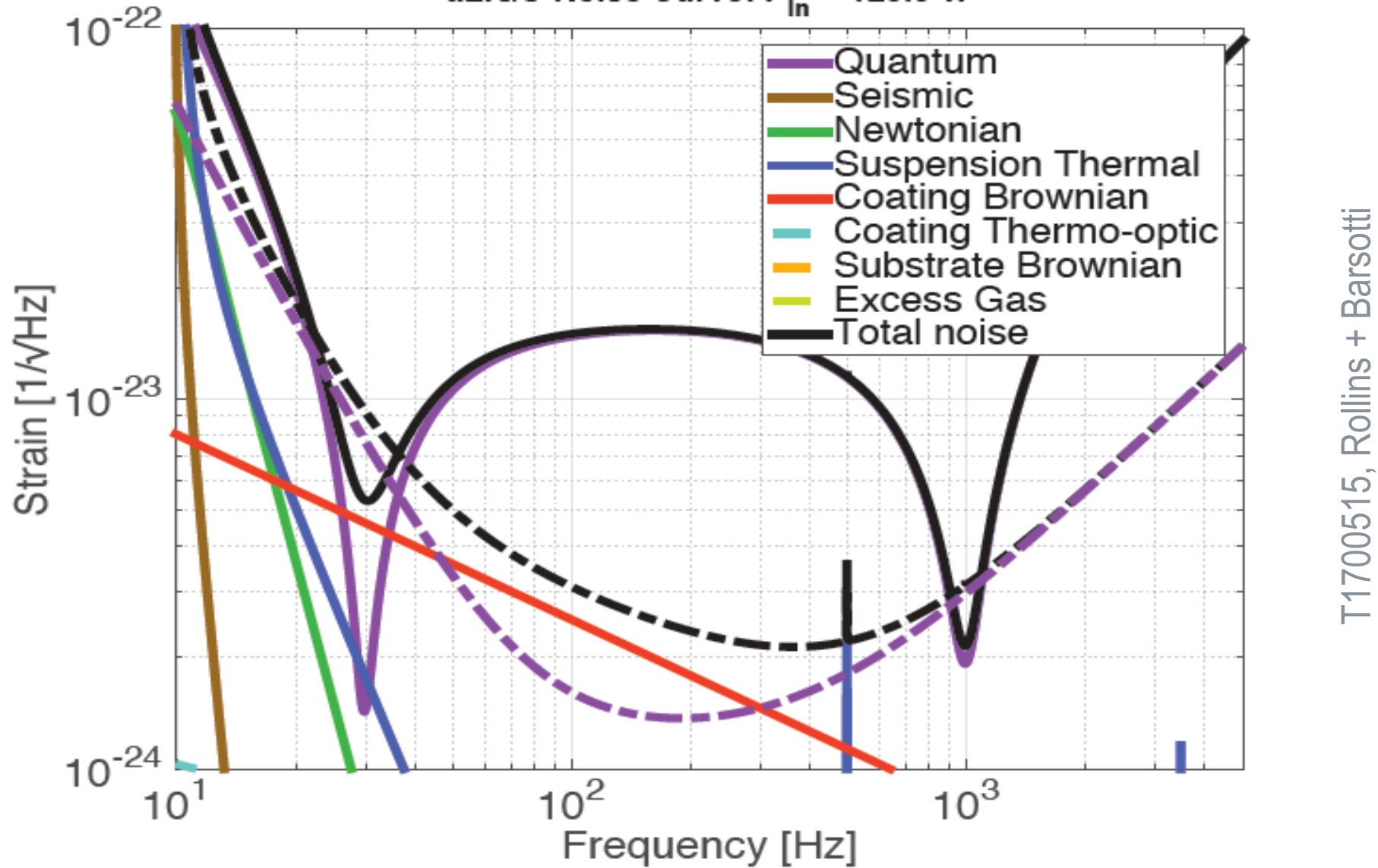
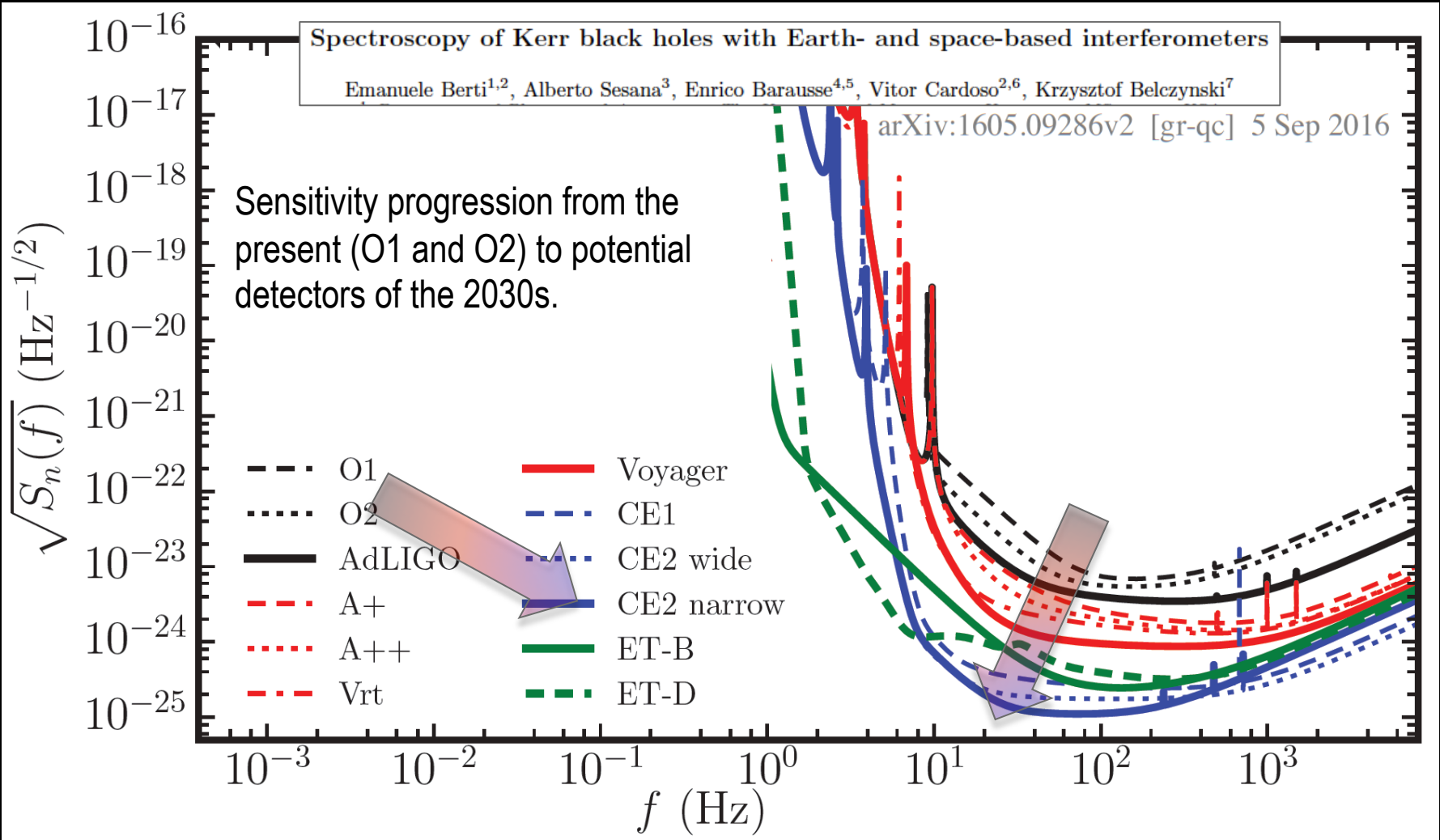


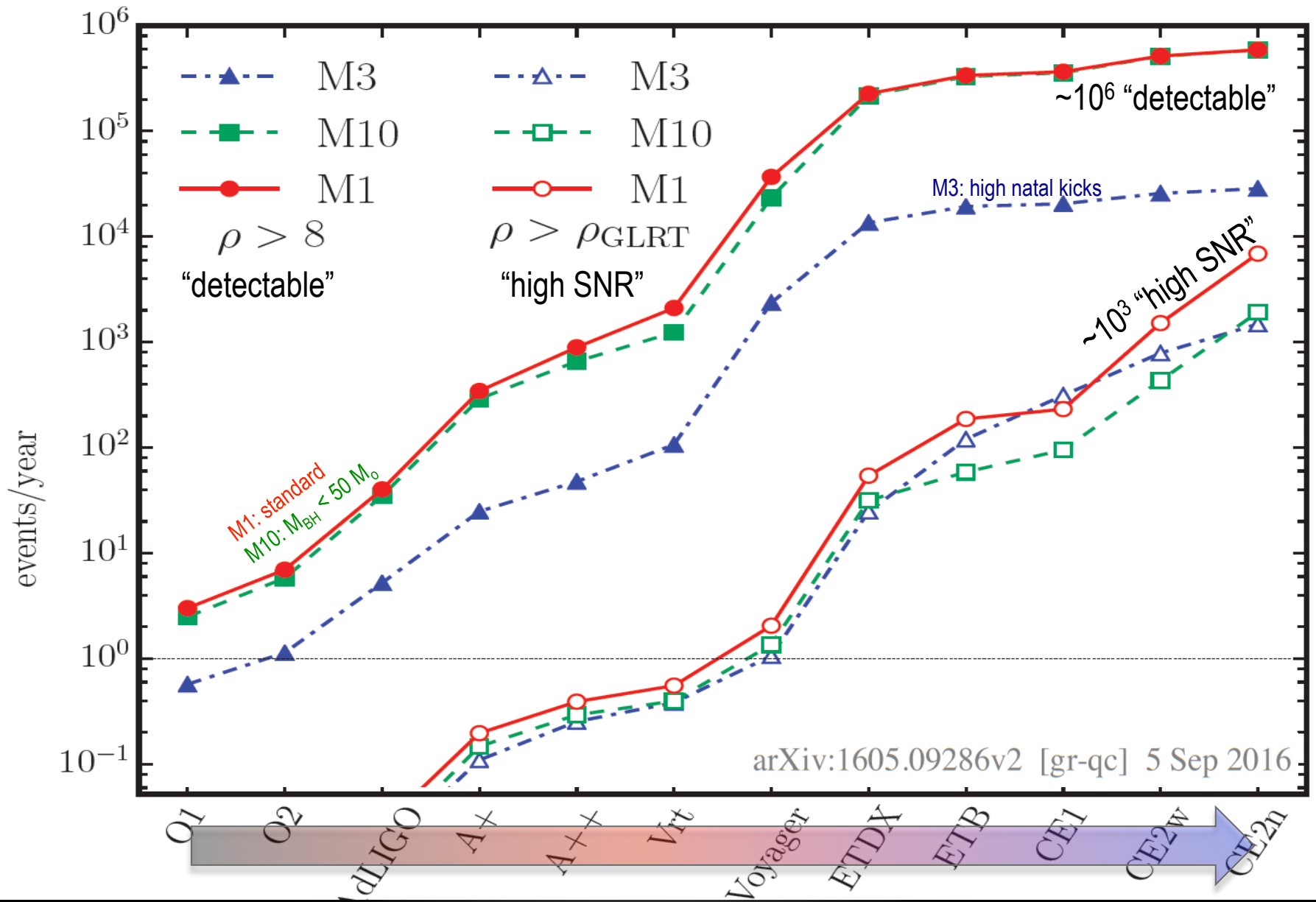
Figure 6: Comparison between a narrow band configuration of the SRC (SRM T=1.1%, SRC phase =  $4.7^\circ$ , quadrature readout phase =  $128^\circ$  - continuous line) with 8 dB of injected frequency dependent squeezing (dashed lines). Per-mirror loss is set to 37.5 ppm both cases. Higher arm loss will further decrease the sensitivity of the narrow band SRC configuration.

# Projected O3 event rates

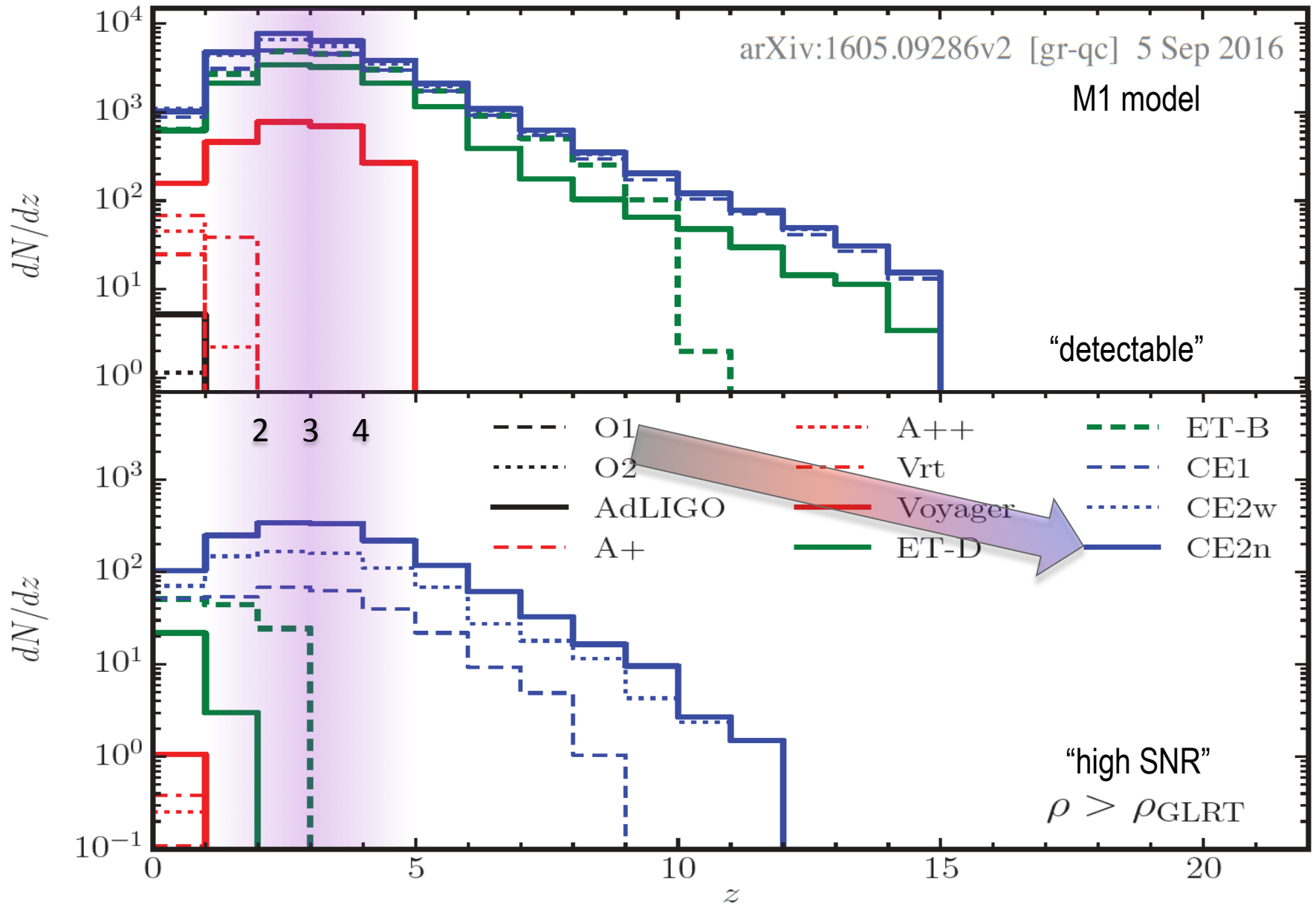
- Binary black holes: up to a few per week, at least few per month
- Binary neutron stars: 1-10 per year, possibly up to 1 per month

# Over the next 20 years...

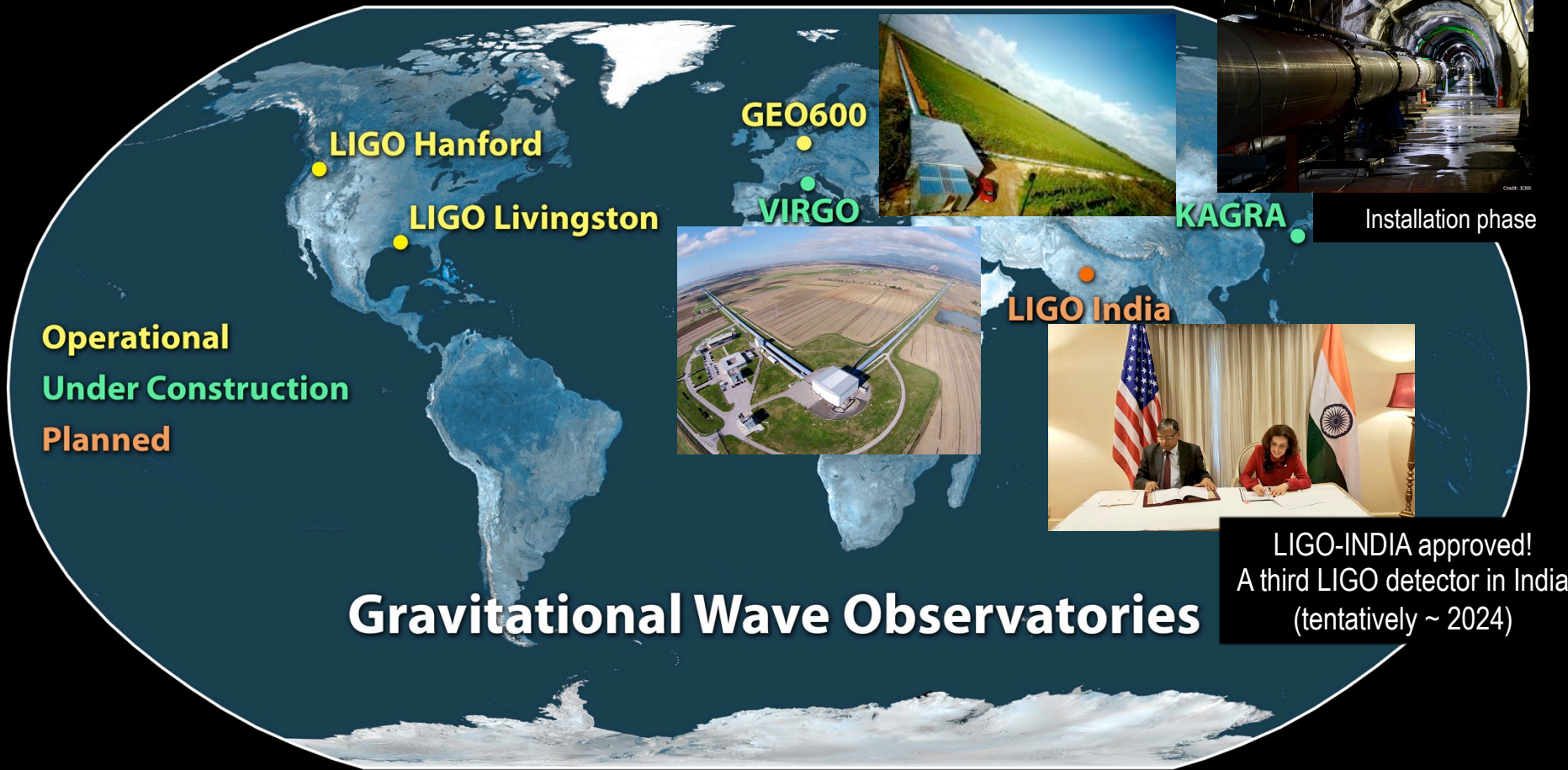


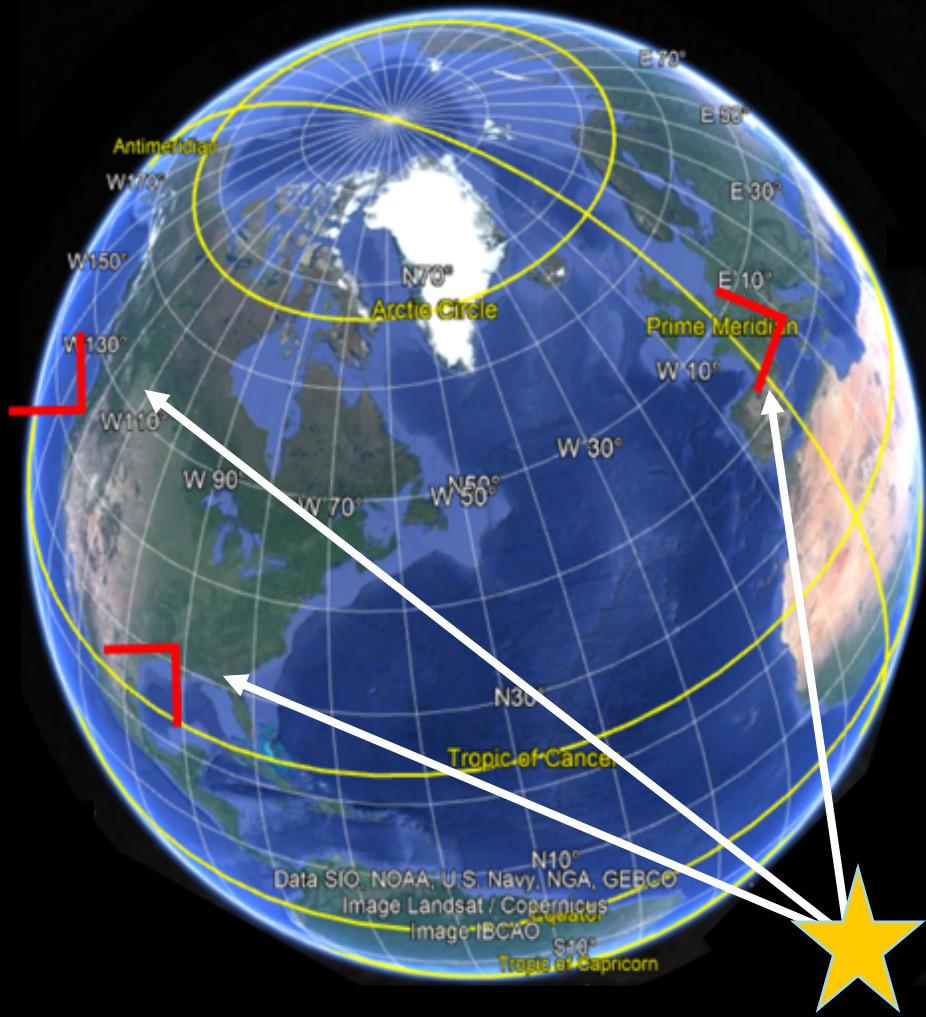


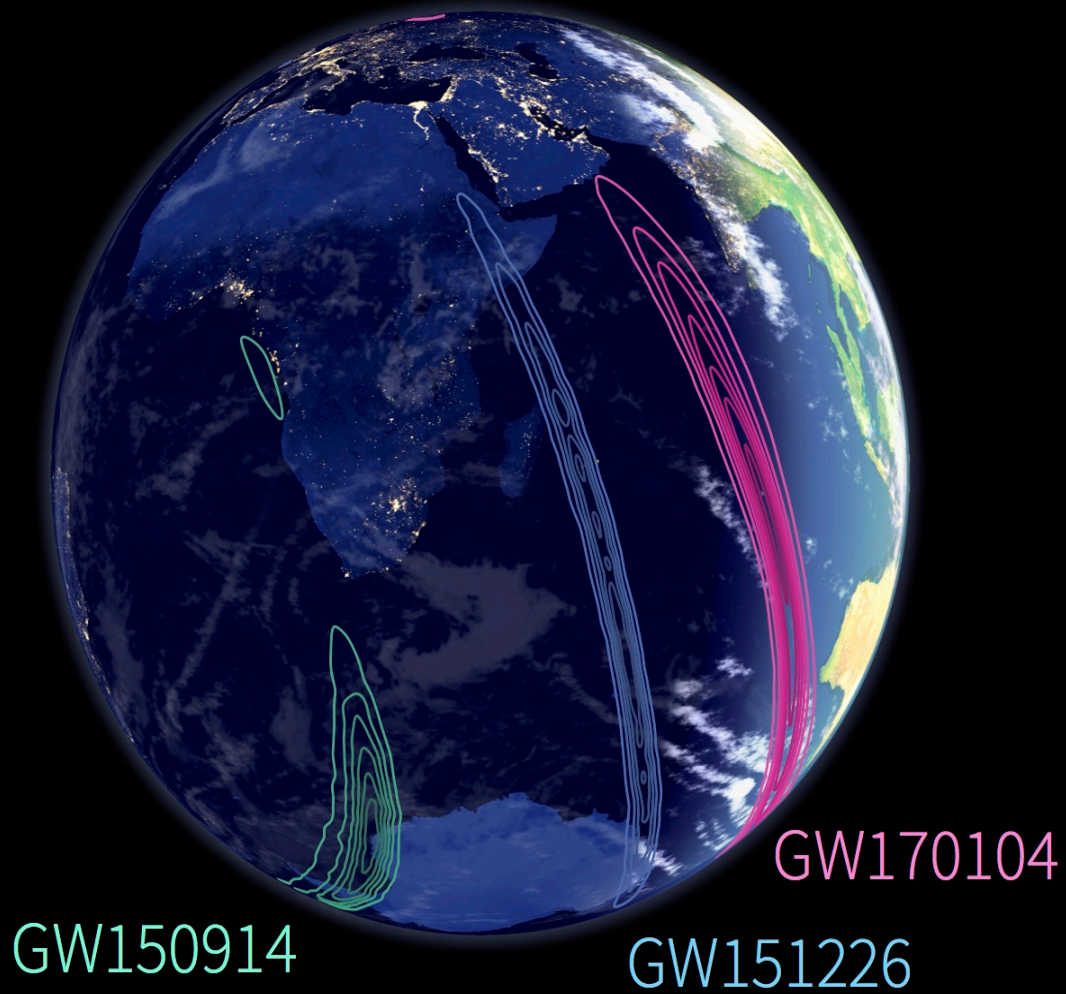
M1 model



# A world-wide network









# How do fundamental noises scale?

Just 1/L, right? Nope...

Shot Noise  
while maintaining bandwidth

$$\frac{h_{\text{shot}}}{h_{0\text{shot}}} = \sqrt{\frac{2 \text{ MW}}{P_{\text{arm}}}} \sqrt{\frac{\lambda}{1.5 \mu\text{m}}} \left(\frac{3}{r_{\text{sqz}}}\right) \sqrt{\frac{40 \text{ km}}{L_{\text{arm}}}}$$

Radiation Pressure Noise  
while maintaining bandwidth

$$\frac{h_{\text{RPN}}}{h_{0\text{RPN}}} = \sqrt{\frac{P_{\text{arm}}}{2 \text{ MW}}} \sqrt{\frac{1.5 \mu\text{m}}{\lambda}} \left(\frac{3}{r_{\text{sqz}}}\right) \left(\frac{320 \text{ kg}}{m_{\text{TM}}}\right) \left(\frac{40 \text{ km}}{L_{\text{arm}}}\right)^{3/2}$$

Coating Thermal Noise  
constant loss angle...

$$\frac{h_{\text{CTN}}}{h_{0\text{CTN}}} = \sqrt{\frac{T}{123 \text{ K}}} \sqrt{\frac{\phi_{\text{eff}}}{5 \times 10^{-5}}} \left(\frac{14 \text{ cm}}{r_{\text{beam}}}\right) \left(\frac{40 \text{ km}}{L_{\text{arm}}}\right)$$

Residual Gas Noise  
facility limit...

$$\frac{h_{\text{gas}}}{h_{0\text{gas}}} = \sqrt{\frac{p_{\text{gas}}}{4 \times 10^{-7} \text{ Pa}}} \sqrt{\frac{14 \text{ cm}}{r_{\text{beam}}}} \sqrt{\frac{40 \text{ km}}{L_{\text{arm}}}}$$

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Shot Noise  
while maintaining bandwidth

$$\frac{h_{\text{shot}}}{h_{0\text{shot}}} = \sqrt{\frac{2 \text{ MW}}{P_{\text{arm}}}} \sqrt{\frac{\lambda}{1.5 \mu\text{m}}} \left(\frac{3}{r_{\text{sqz}}}\right) \sqrt{\frac{40 \text{ km}}{L_{\text{arm}}}}$$

Radiation Pressure Noise  
while maintaining bandwidth

$$\frac{h_{\text{RPN}}}{h_{0\text{RPN}}} = \sqrt{\frac{P_{\text{arm}}}{2 \text{ MW}}} \sqrt{\frac{1.5 \mu\text{m}}{\lambda}} \left(\frac{3}{r_{\text{sqz}}}\right) \left(\frac{320 \text{ kg}}{m_{\text{TM}}}\right) \left(\frac{40 \text{ km}}{L_{\text{arm}}}\right)^{3/2}$$

Coating Thermal Noise  
constant loss angle...

$$\frac{h_{\text{CTN}}}{h_{0\text{CTN}}} = \sqrt{\frac{T}{123 \text{ K}}} \sqrt{\frac{\phi_{\text{eff}}}{5 \times 10^{-5}}} \left(\frac{14 \text{ cm}}{r_{\text{beam}}}\right) \left(\frac{40 \text{ km}}{L_{\text{arm}}}\right)$$

Residual Gas Noise  
facility limit...

$$\frac{h_{\text{gas}}}{h_{0\text{gas}}} = \sqrt{\frac{p_{\text{gas}}}{4 \times 10^{-7} \text{ Pa}}} \sqrt{\frac{14 \text{ cm}}{r_{\text{beam}}}} \sqrt{\frac{40 \text{ km}}{L_{\text{arm}}}}$$

# How do fundamental noises scale?

Just  $1/L$ , right? Nope...

Shot Noise  
while maintaining bandwidth

$$\frac{h_{\text{shot}}}{h_{0\text{shot}}} = \sqrt{\frac{2 \text{ MW}}{P_{\text{arm}}}} \sqrt{\frac{\lambda}{1.5 \mu\text{m}}} \left(\frac{3}{r_{\text{sqz}}}\right) \sqrt{\frac{40 \text{ km}}{L_{\text{arm}}}}$$

Radiation Pressure Noise  
while maintaining bandwidth

$$\frac{h_{\text{RPN}}}{h_{0\text{RPN}}} = \sqrt{\frac{P_{\text{arm}}}{2 \text{ MW}}} \sqrt{\frac{1.5 \mu\text{m}}{\lambda}} \left(\frac{3}{r_{\text{sqz}}}\right) \left(\frac{40 \text{ km}}{L_{\text{arm}}}\right)^3$$

Coating Thermal Noise  
loss angle dependence?

$$\frac{h_{\text{CTN}}}{h_{0\text{CTN}}} = \sqrt{\frac{T}{123 \text{ K}}} \sqrt{\frac{\phi_{\text{eff}}(T)}{5 \times 10^{-5}}} \left(\frac{40 \text{ km}}{L_{\text{arm}}}\right)^{3/2}$$

Residual Gas Noise  
facility limit...

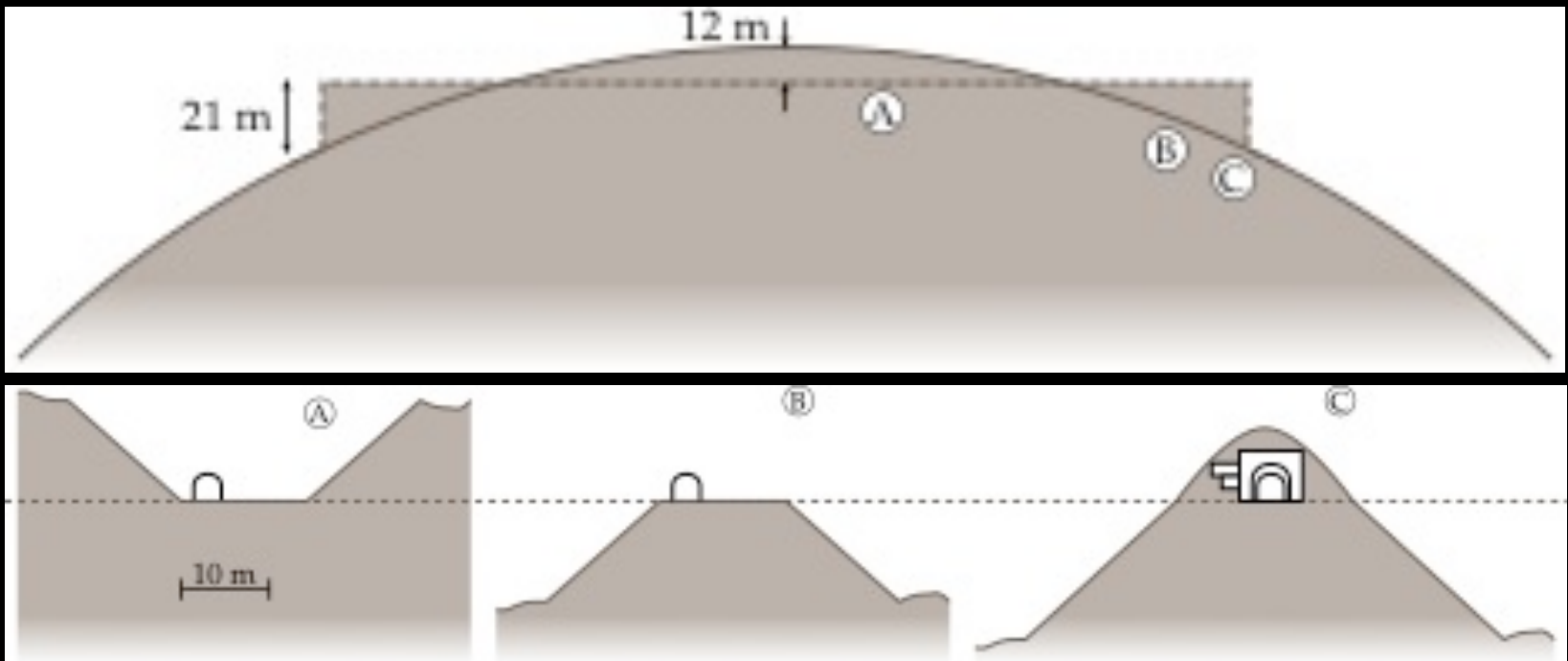
$$\frac{h_{\text{gas}}}{h_{0\text{gas}}} = \sqrt{\frac{p_{\text{gas}}}{4 \times 10^{-7} \text{ Pa}}} \sqrt{\frac{40 \text{ km}}{L_{\text{arm}}^{3/2}}}$$

# Why 40 km?

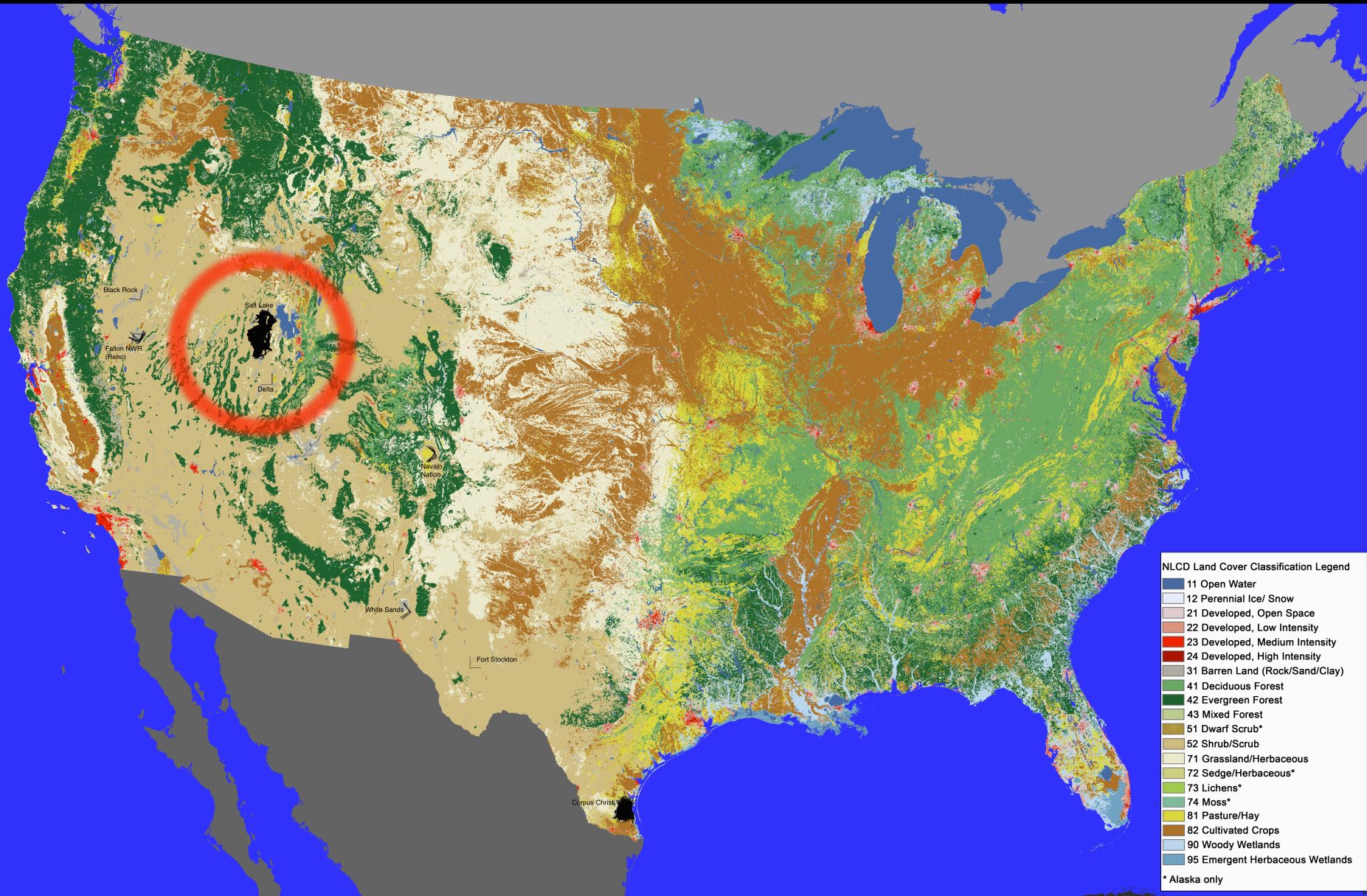
- The bandwidth of an interferometer tends to shrink as it gets longer
  - a 40 km detector is limited to roughly 4 kHz bandwidth, or at least that is where the response of the detector becomes complicated (it leaves the long-wavelength limit)
  - there is a lot of potentially interesting physics at high frequencies (NS EOS, CCSN)
  - the low-frequency end of the band does not move down much as you go longer, so the detection band narrows with increasing length
- Costs grow quickly with length above ~ 40km
  - surface excavation depth is quadratic in length, and that earth must be moved (presumably to the ends to use as fill)
  - flat or bowl-shaped locations become scarce for longer sites

# Why 40 km?

- Costs grow quickly with length above ~ 40km
  - surface excavation depth is quadratic in length, and that earth must be moved (presumably to the ends to use as fill)
  - flat or bowl-shaped locations become scarce for longer sites



# Where could we put a 40km detector?



Salt Lake



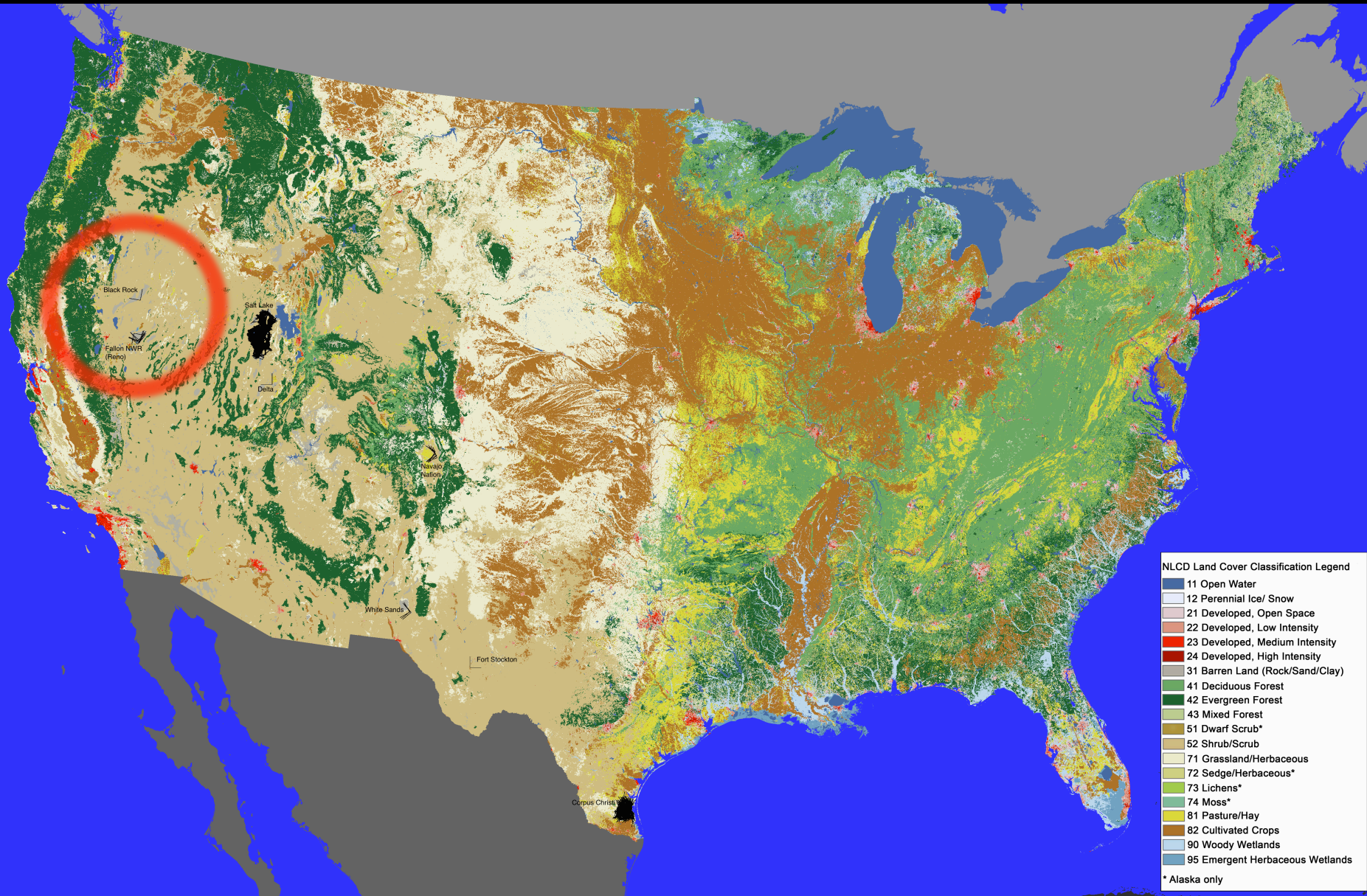
Delta

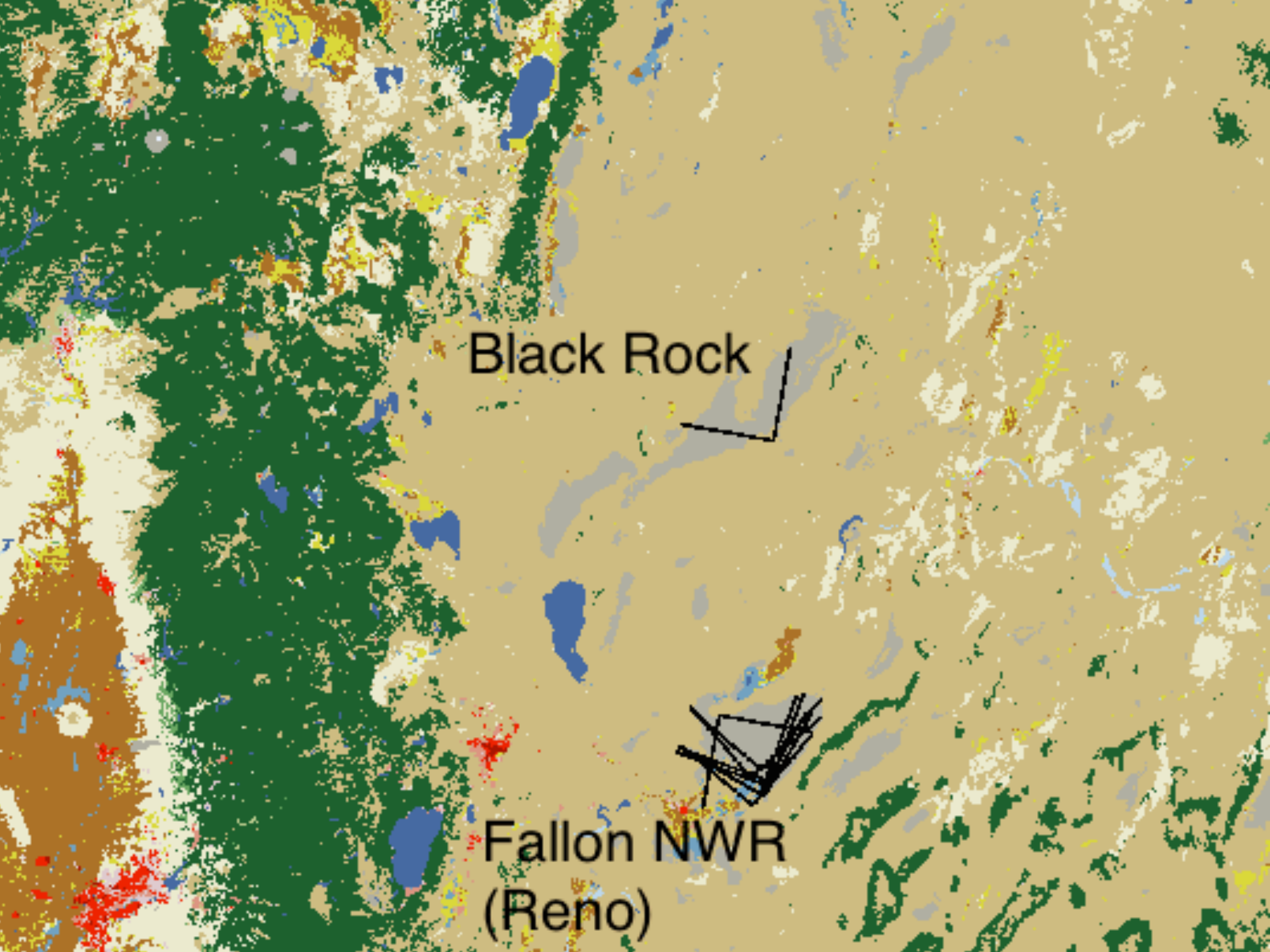


Places like this...

Bonneville Salt Flat, Utah

# Where could we put a 40km detector?





Black Rock

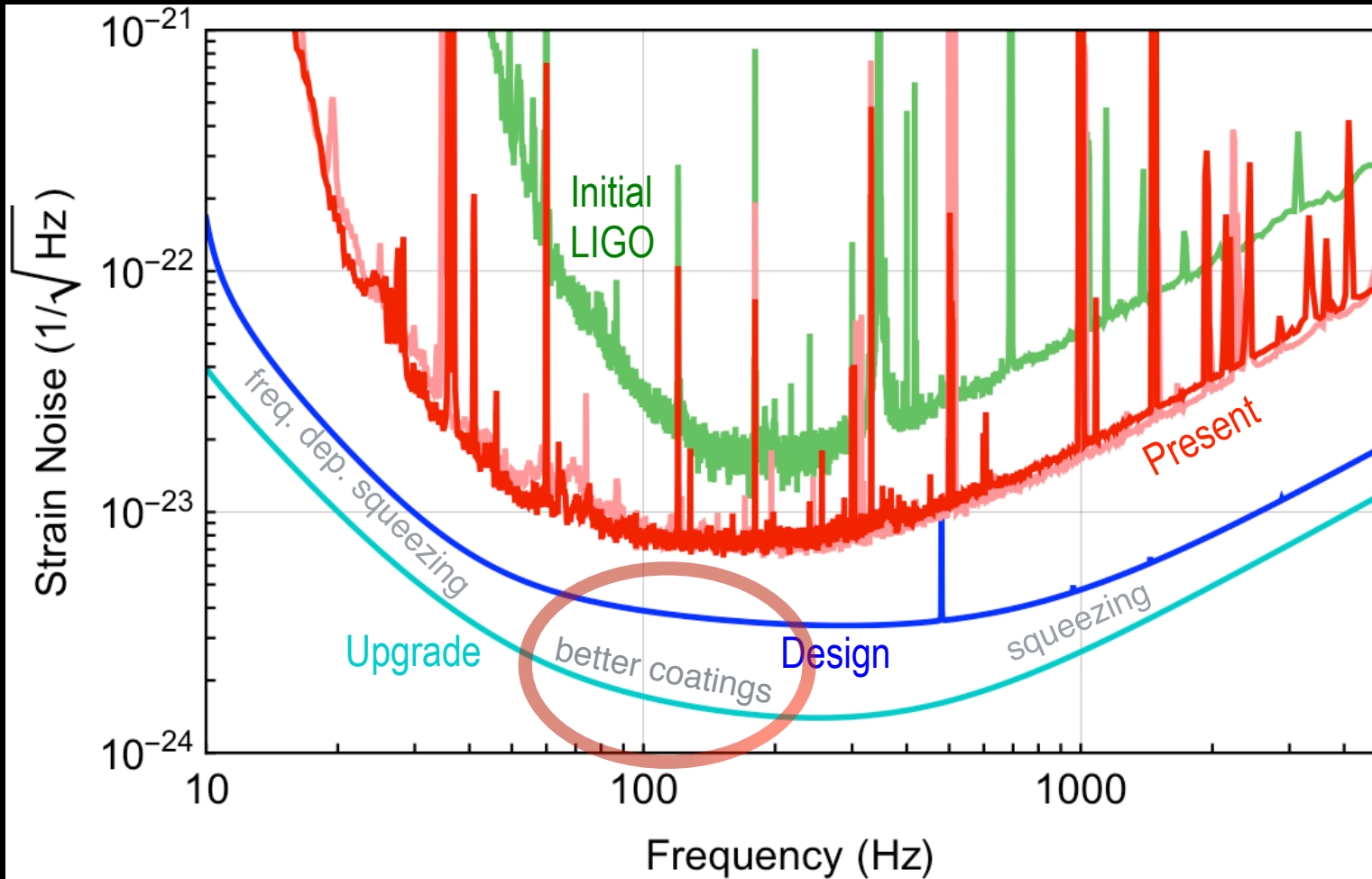
Fallon NWR  
(Reno)



or like this...

Black Rock, Nevada

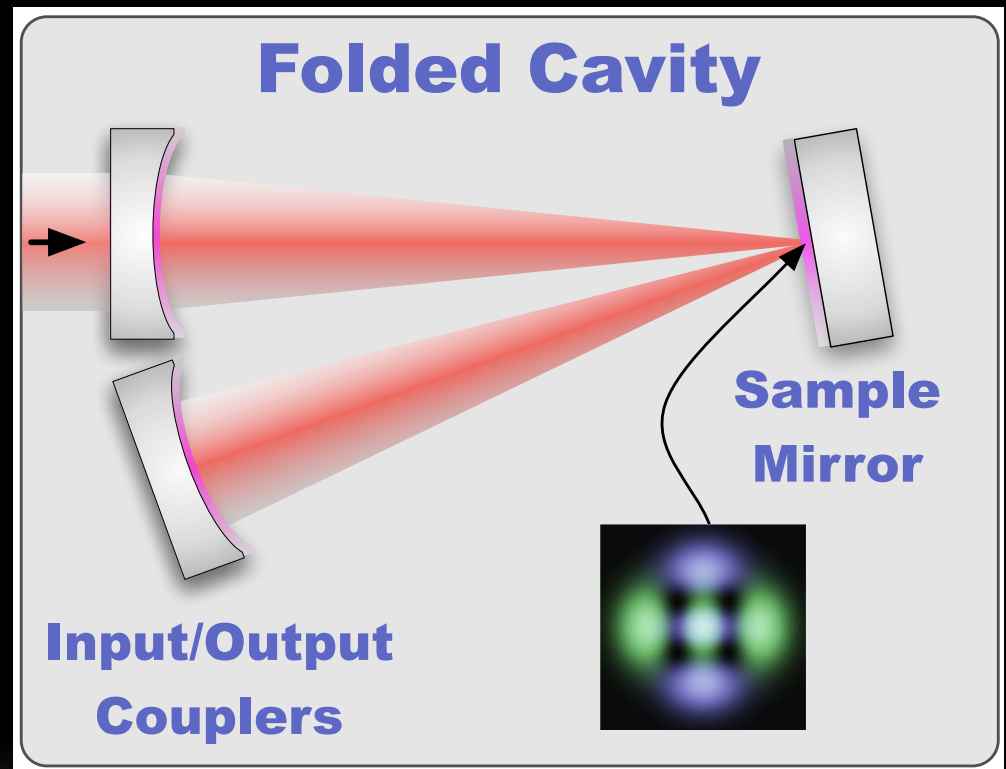
# Getting more out of Advanced LIGO



GW150914: The Advanced LIGO Detectors in the Era of First Discoveries. LSC (2016) PRL 116, 131103

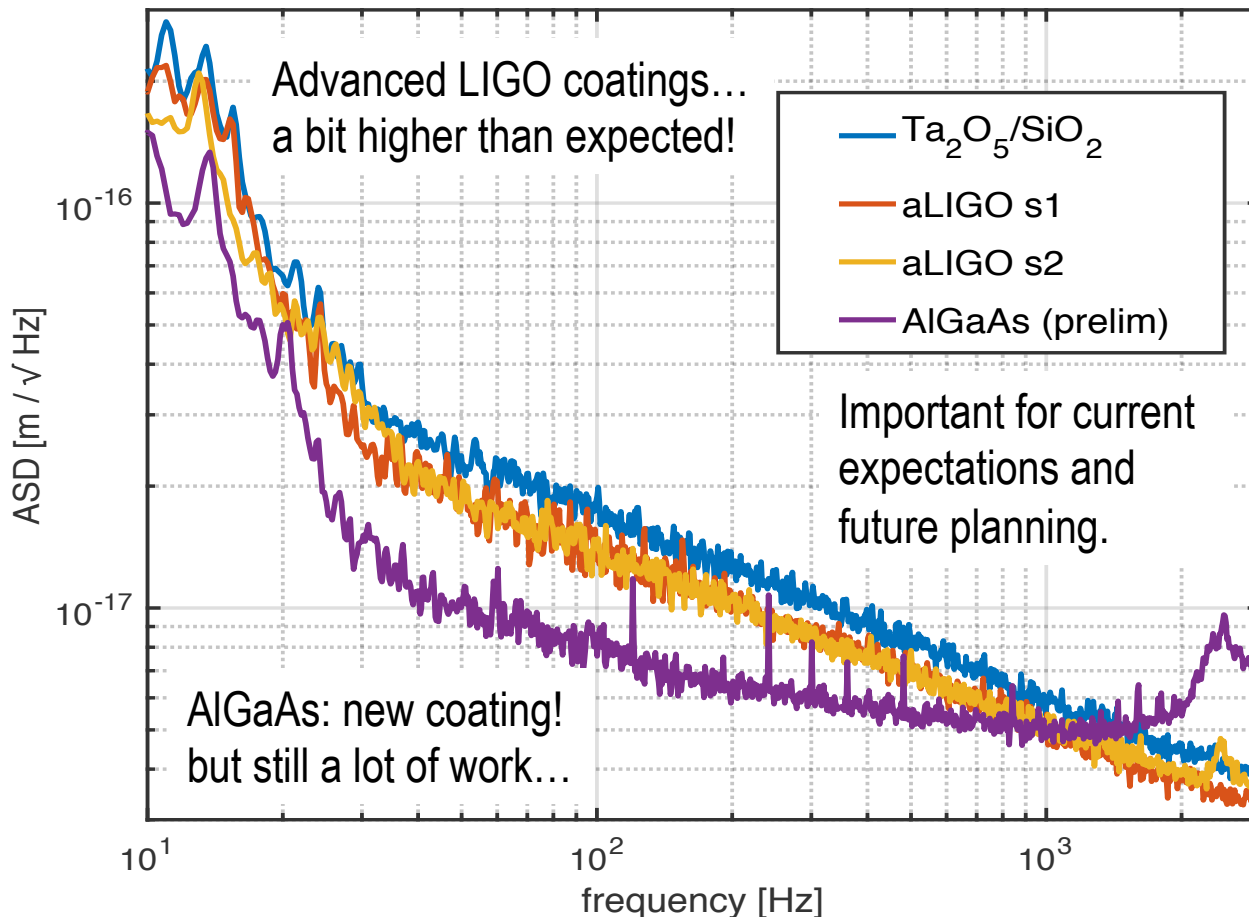
# Coating Research

- We designed a novel experimental technique to remove many of the limitations of previous coating thermal noise measurements
- A small beam on the sample mirror increases the coating noise (our signal) by orders of magnitude over what is seen in LIGO
- We use multiple optical modes in the same cavity to remove cavity length and laser frequency noise from our measurement
- The folded cavity lets us use a standard high-reflector as the sample mirror, and lets us change the sample in a matter of hours

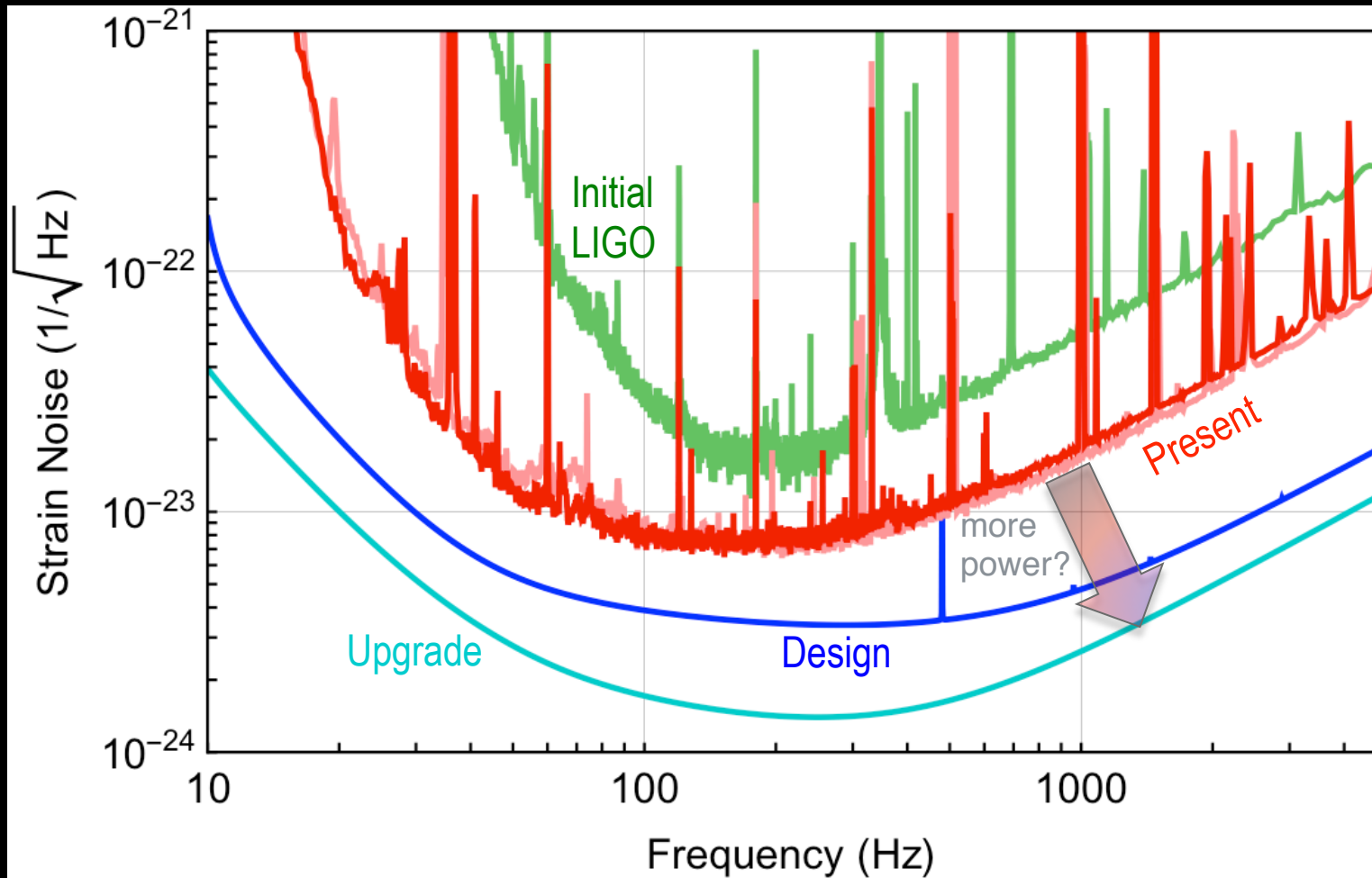


# Coating Research

- We made the first measurement of Advanced LIGO coating thermal noise
- Now we are working with Lincoln Labs and other partners to find better coatings



# Advanced LIGO Noise: Progress



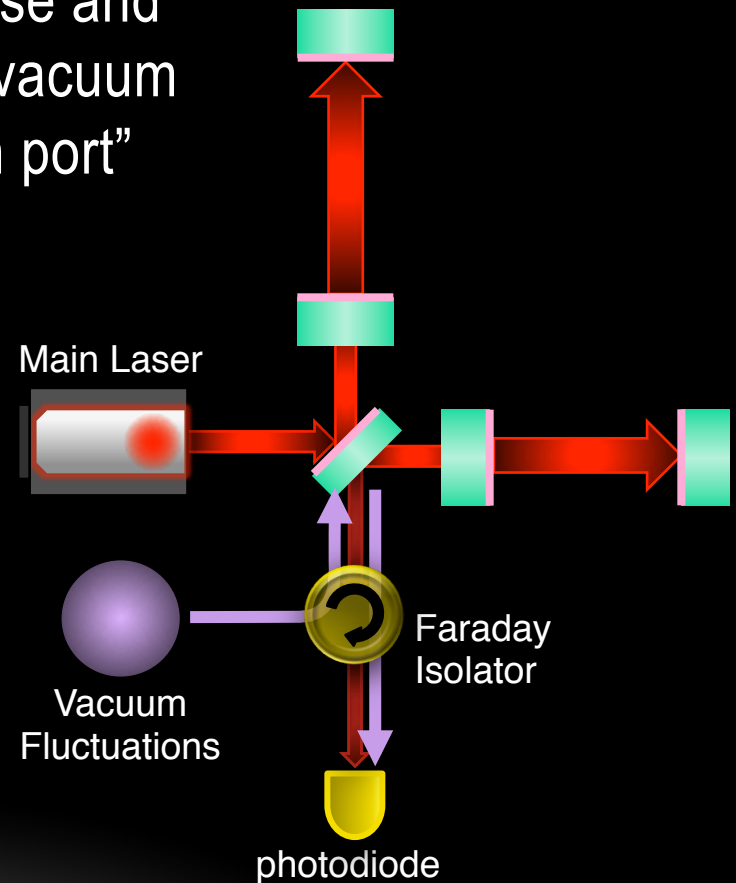
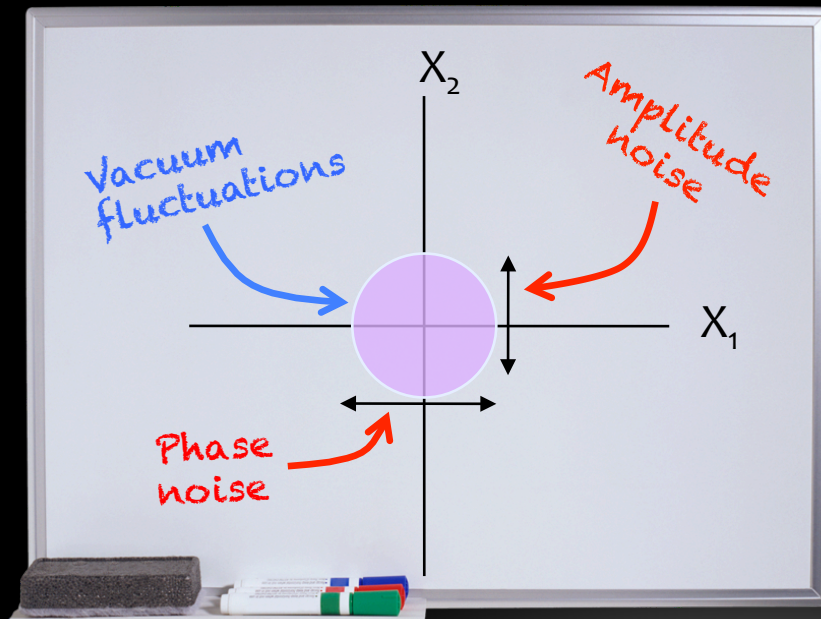
GW150914: The Advanced LIGO Detectors in the Era of First Discoveries. LSC (2016) PRL 116, 131103

# Squeezing Light to Reduced Quantum Noise

- We can't continue to increase the power in the interferometer beyond Advanced LIGO design due to
  - thermal effects
  - radiation pressure driven instabilities
  - quantum radiation pressure noise
- How can we improve?
  - to understand the answer, we have to start from the beginning...

# What is Quantum Noise?

- Quantum optics tells us that shot noise and radiation pressure noise result from vacuum fluctuations that enter at every “open port”



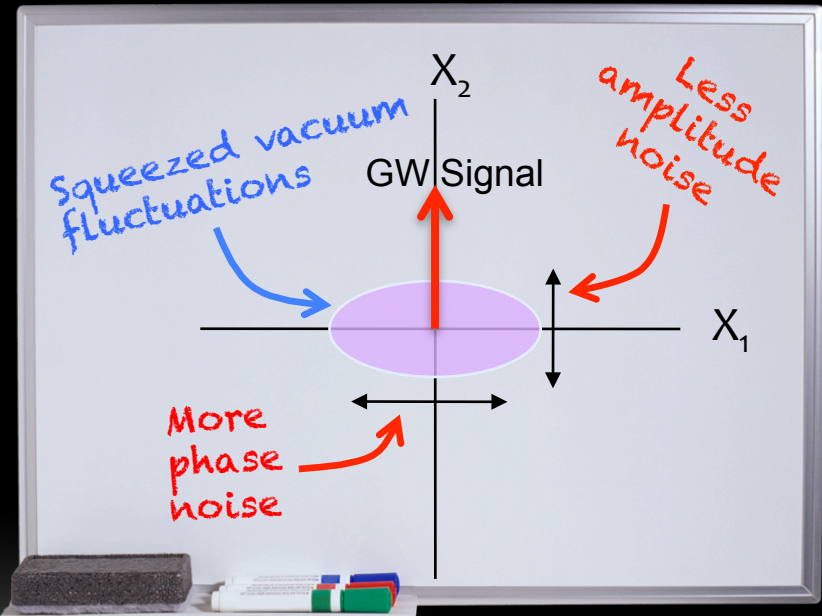
# So, what can we do about it?

- Heisenberg says we can't make the noise smaller, but we can change its shape.
- Can we use a squeezed vacuum state in our detector?

Quantized EM field...

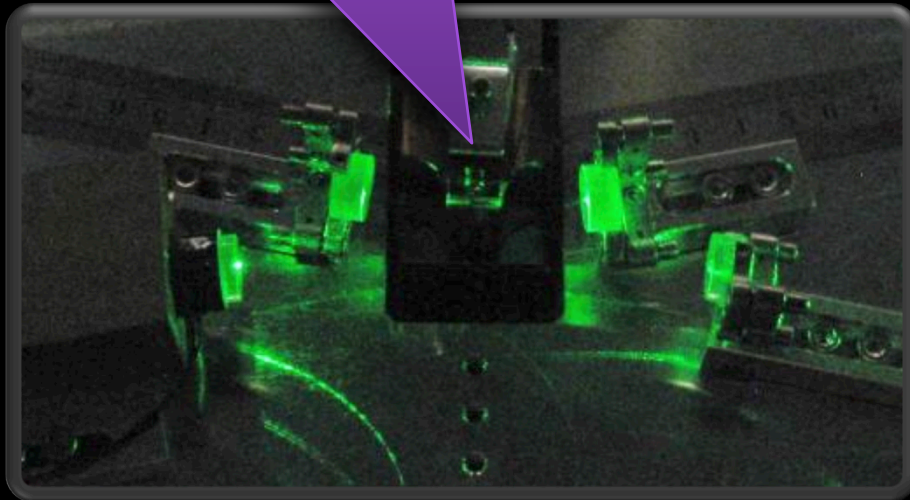
$$\hat{E} = \hat{X}_1 \cos \omega t + i\hat{X}_2 \sin \omega t$$

Heisenberg uncertainty principle:  $\Delta\hat{X}_1 \Delta\hat{X}_2 \geq 1$

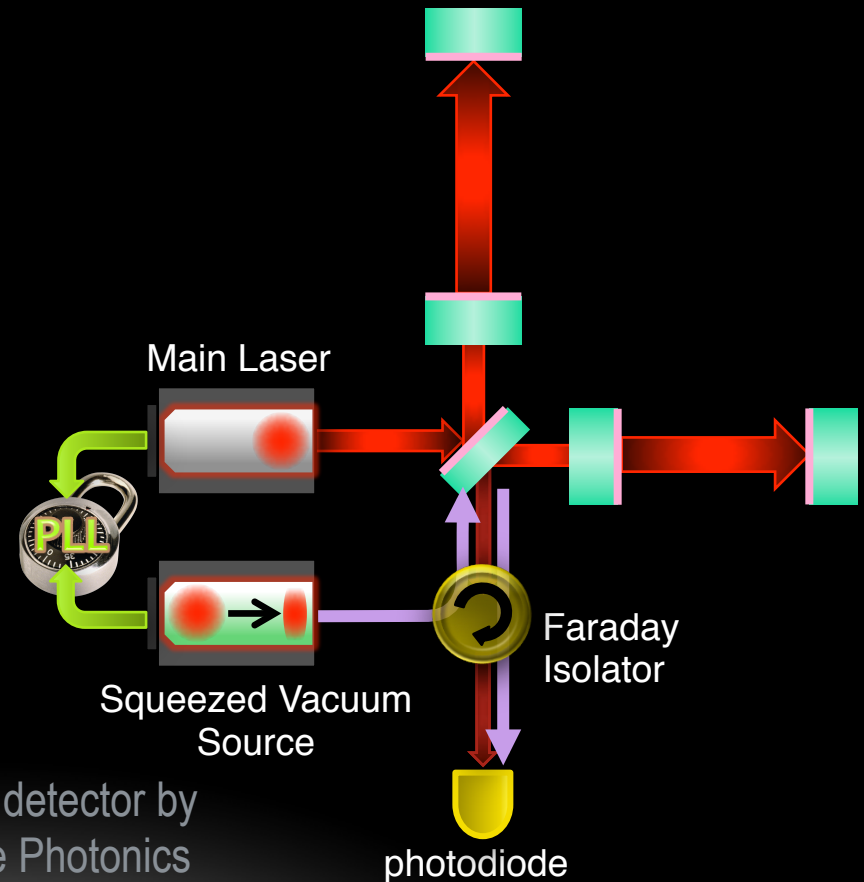


# In theory, sure... but in practice?

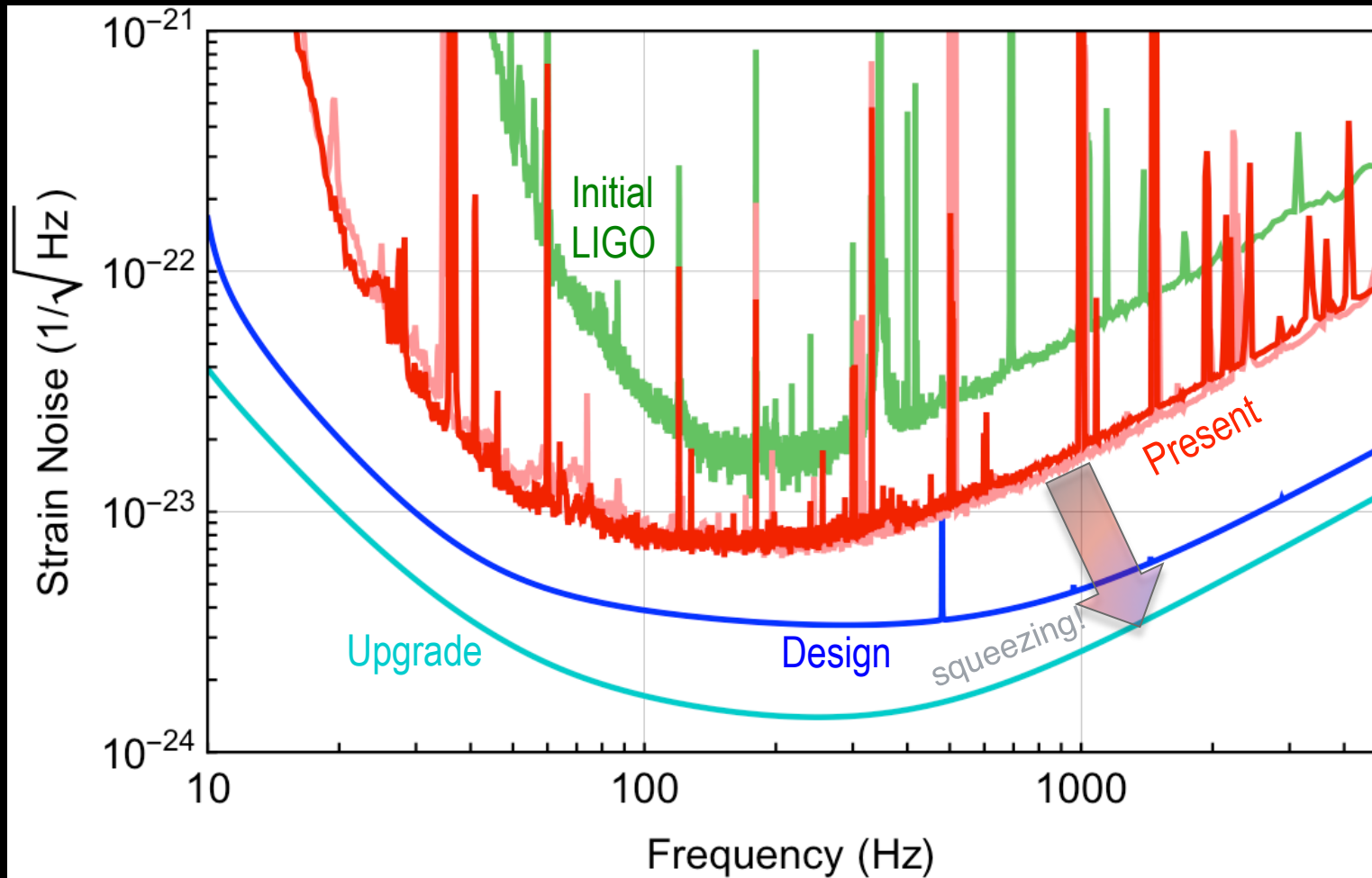
Nonlinear crystal creates entangled photon pairs by parametric down-conversion



Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light. LSC (2015) Nature Photonics



# Advanced LIGO Noise: Progress



GW150914: The Advanced LIGO Detectors in the Era of First Discoveries. LSC (2016) PRL 116, 131103

# The MIT crew at LIGO Louisiana

Lisa  
(MIT scientist)

Me!

Alvaro (MIT grad)

Maggie (MIT grad)



Maggie (MIT grad)

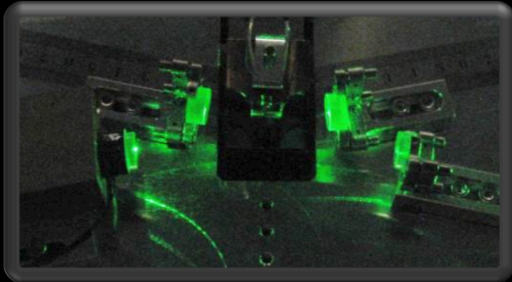


**New Squeezed Light Source!**

So this is easy, right?

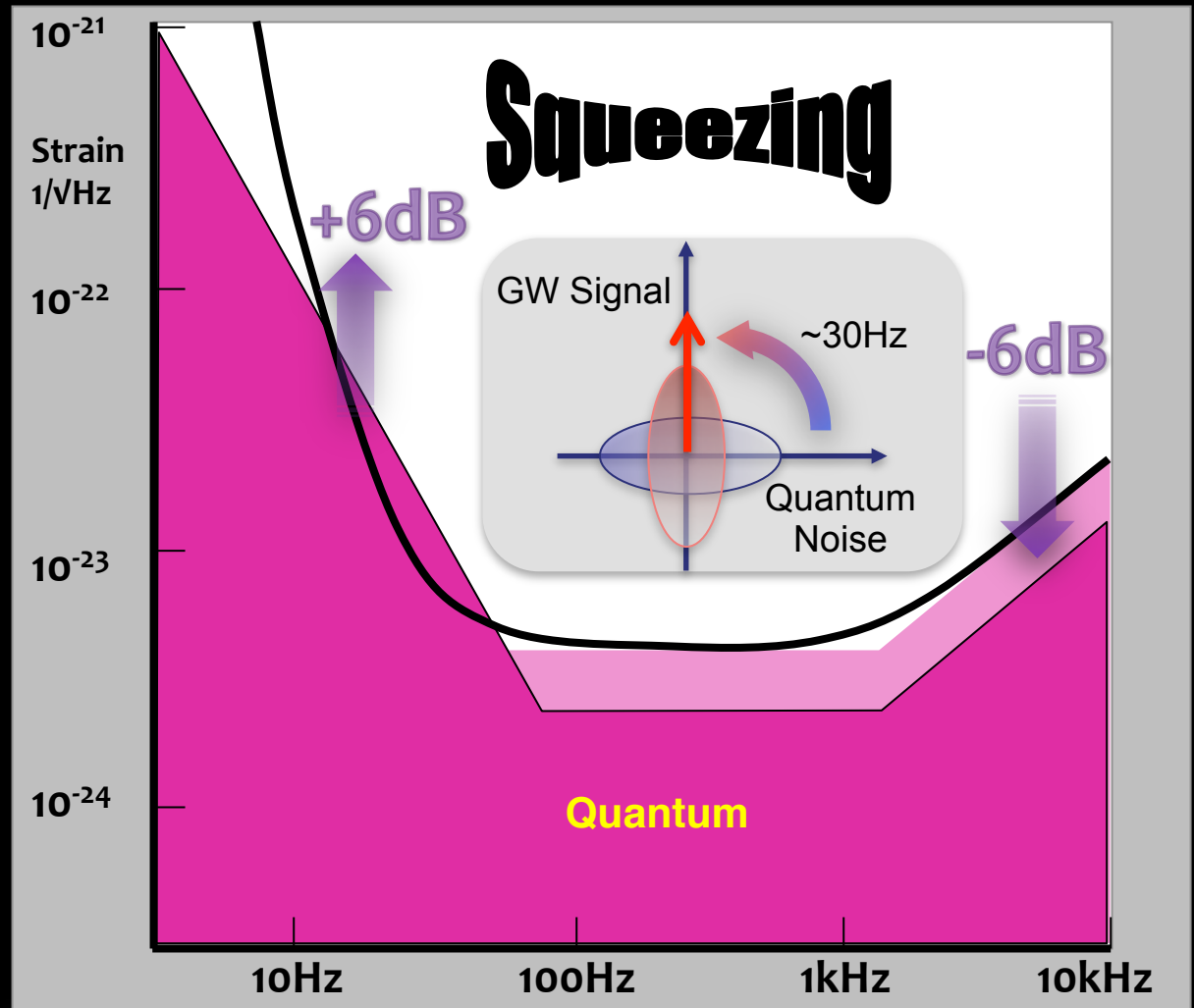
Not really.

Quantum noise can be reduced by squeezing...



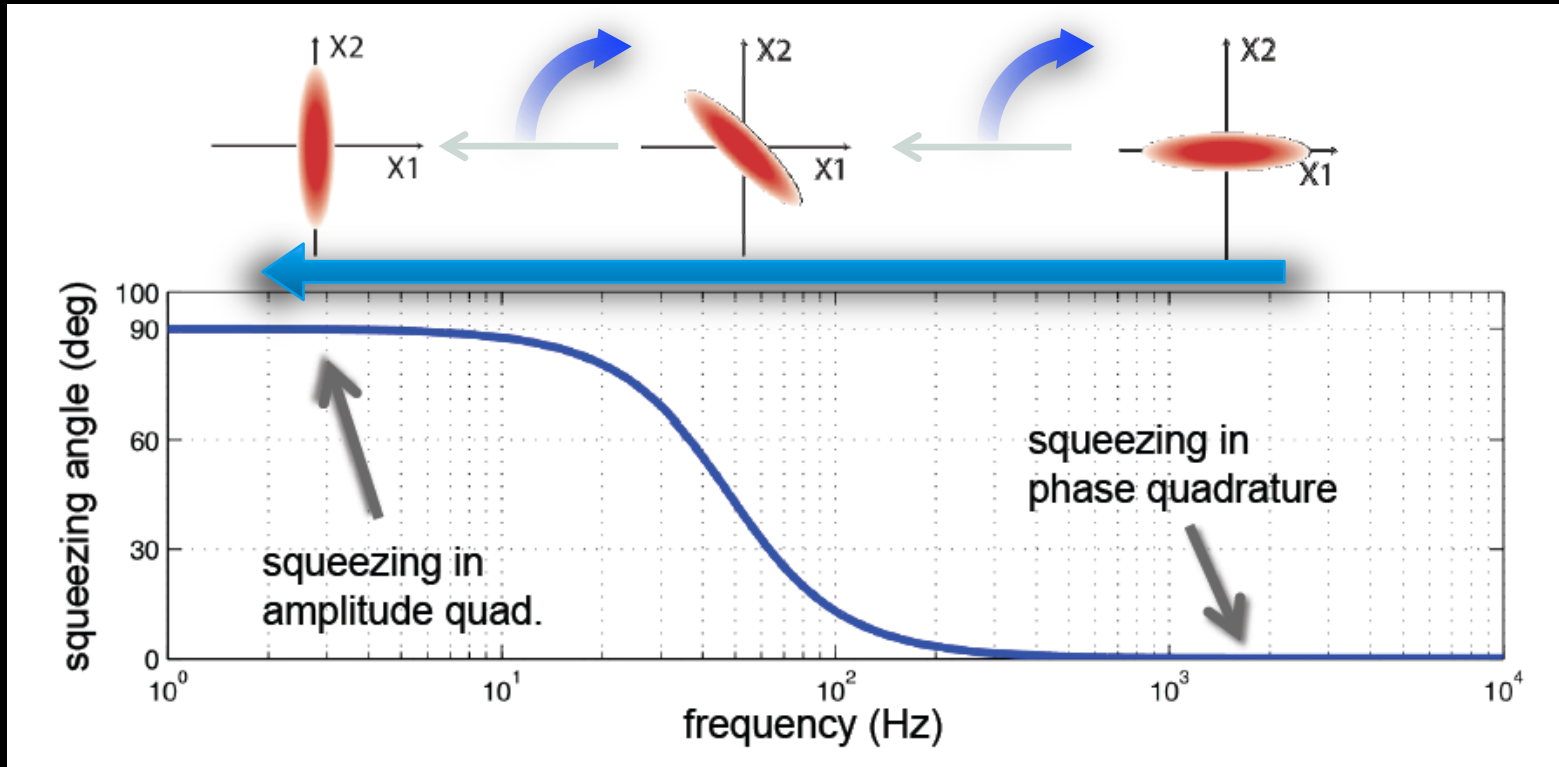
... but nature doesn't make it easy. The vacuum fluctuations rotate at low frequency!

The result is the same as increasing the power!



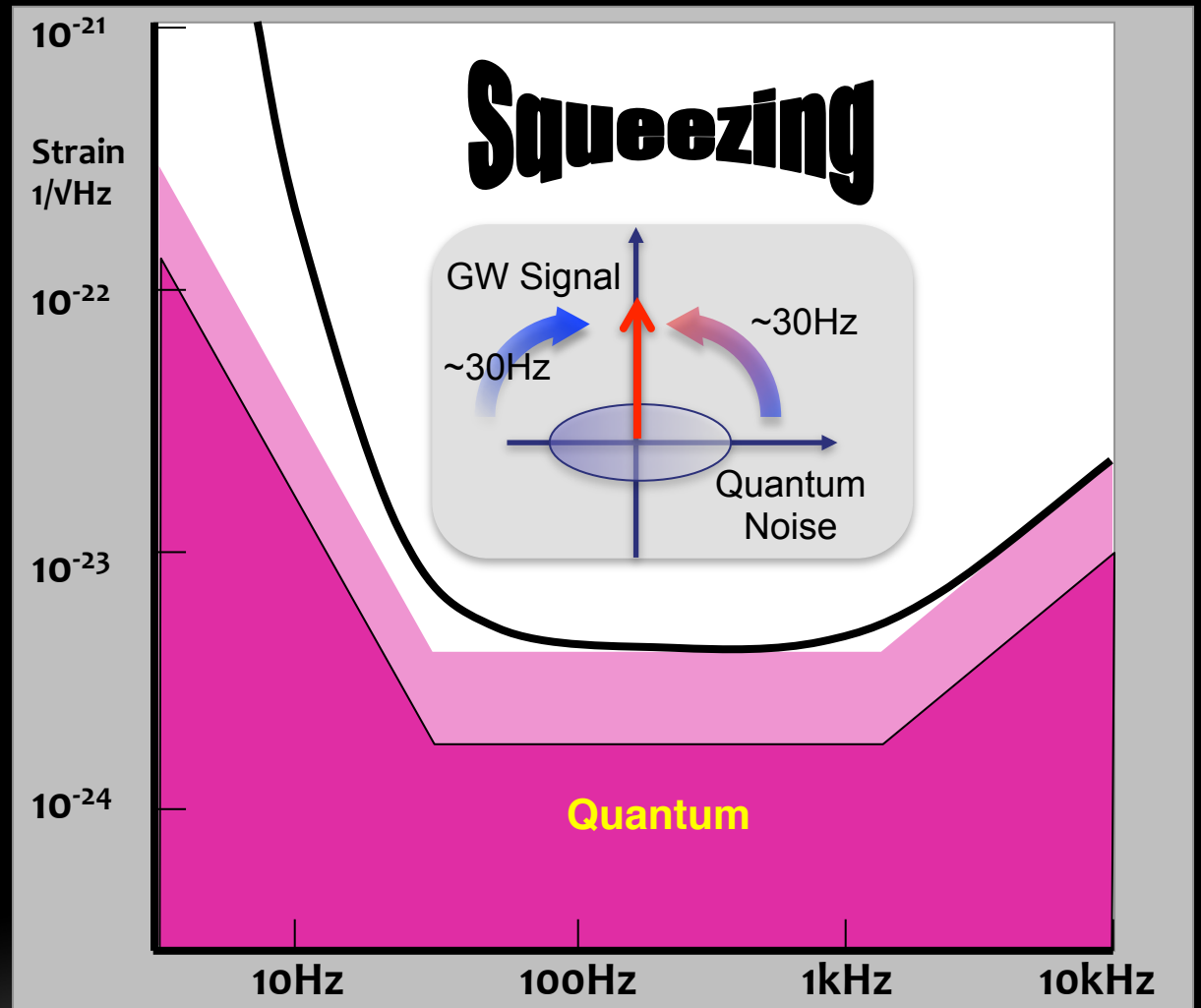
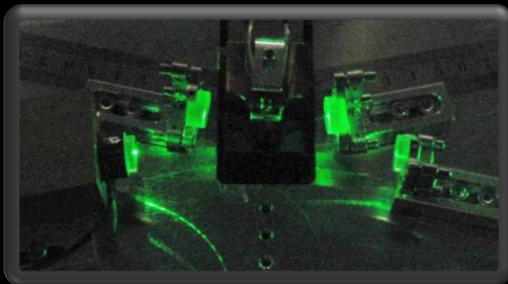
# Frequency Dependent Squeezing: How to win at all frequencies

- To achieve a broadband improvement, we need a frequency dependent rotation of the squeeze angle

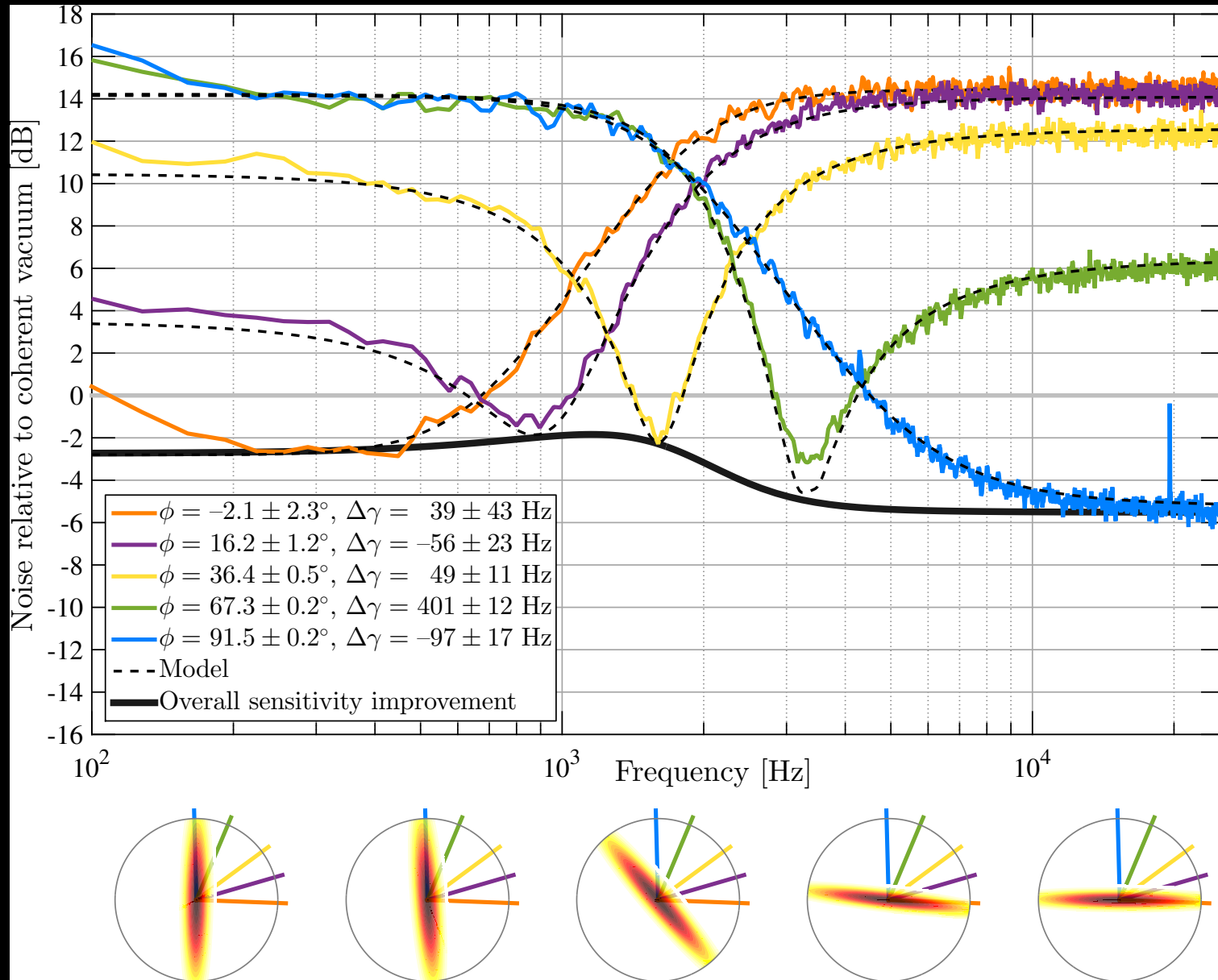


# Frequency Dependent Squeezing: How to win at all frequencies

Quantum noise can be reduced at all frequencies if we can make the squeezed phase change with frequency.



# Frequency Dependent Squeezing at MIT



May, 2018

M. Evans at Sackler (Harvard)

Audio-Band Frequency-Dependent Squeezing for Gravitational-Wave Detectors

(2016) PRL 116, 041102

Decoherence and degradation of squeezed states in quantum filter cavities

(2014) PRD 90, 062006

# Squeezing and Advanced LIGO

- Currently Advanced LIGO is not limited by radiation pressure noise, so we are installing a frequency independent squeezer *for use in the next observing run*

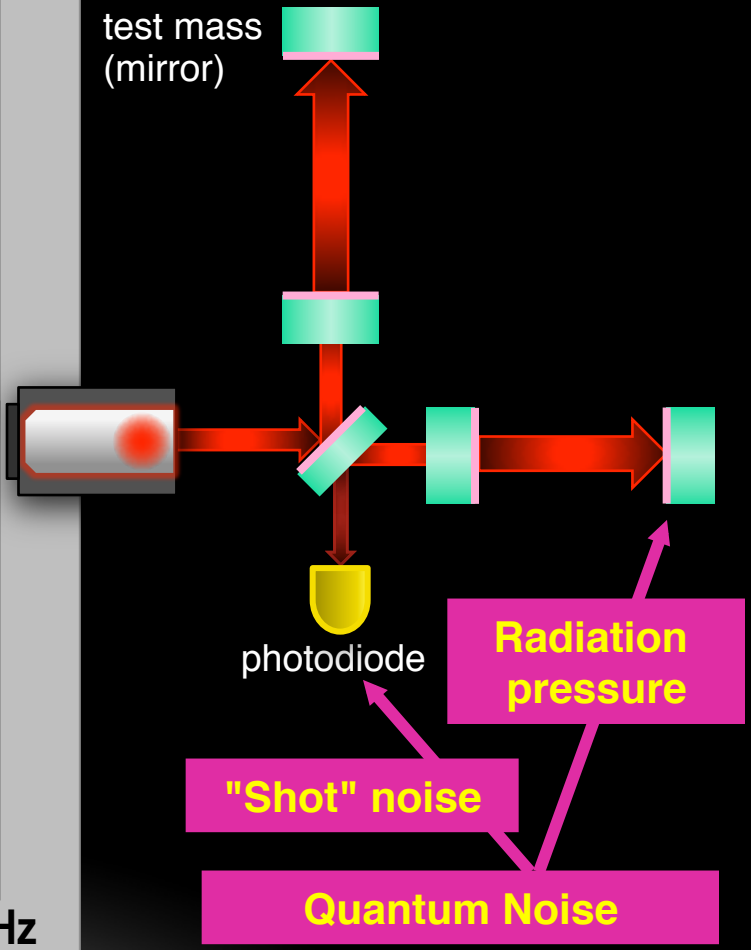
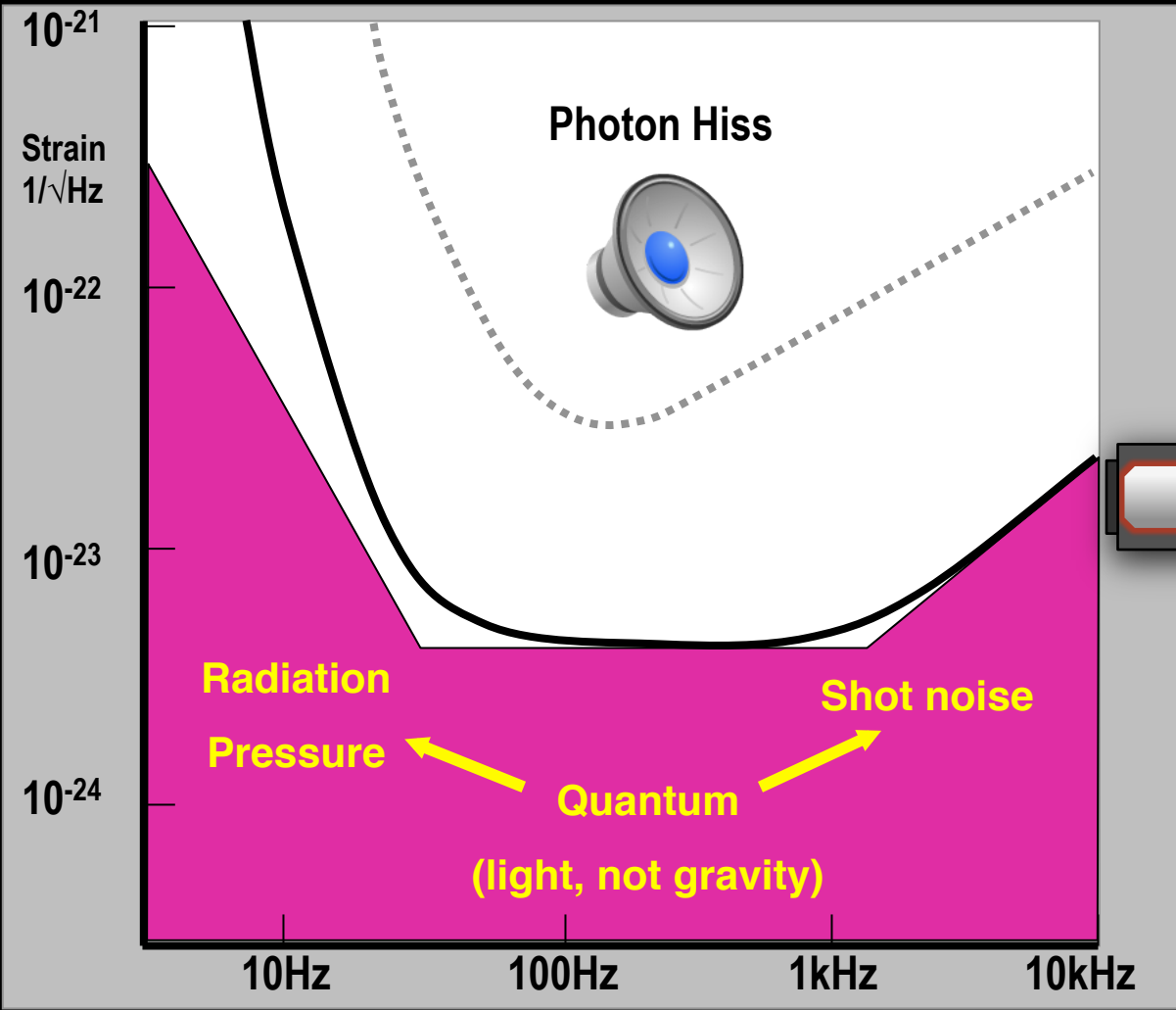
Ultra-low phase noise squeezed vacuum source for gravitational wave detectors.  
..., Evans, Mavalvala (2016) Optica 7, 682

- We are currently building a full-scale frequency dependent squeezed light source for installation in Advanced LIGO *after the next observing run*

Prospects for doubling the range of Advanced LIGO. (2015) PRD 91, 062005  
Realistic filter cavities for advanced gravitational wave detectors. (2013) PRD 88, 022002

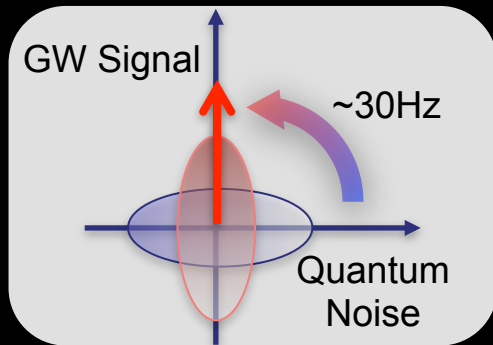


# Advanced LIGO Noise: Quantum Mechanics

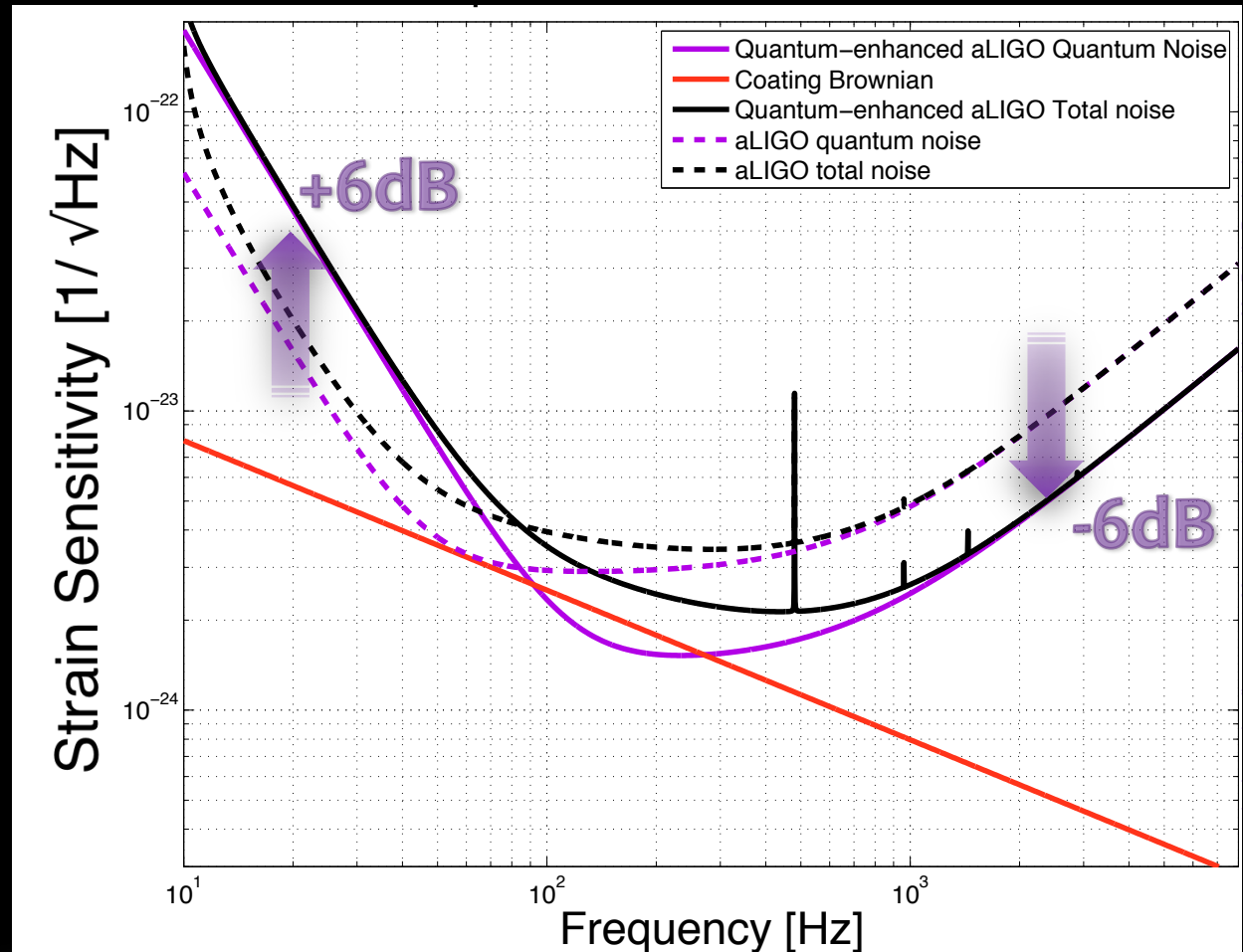


# squeezing is no better than increased power! ??

We're losing at low frequency due to increased radiation pressure noise...



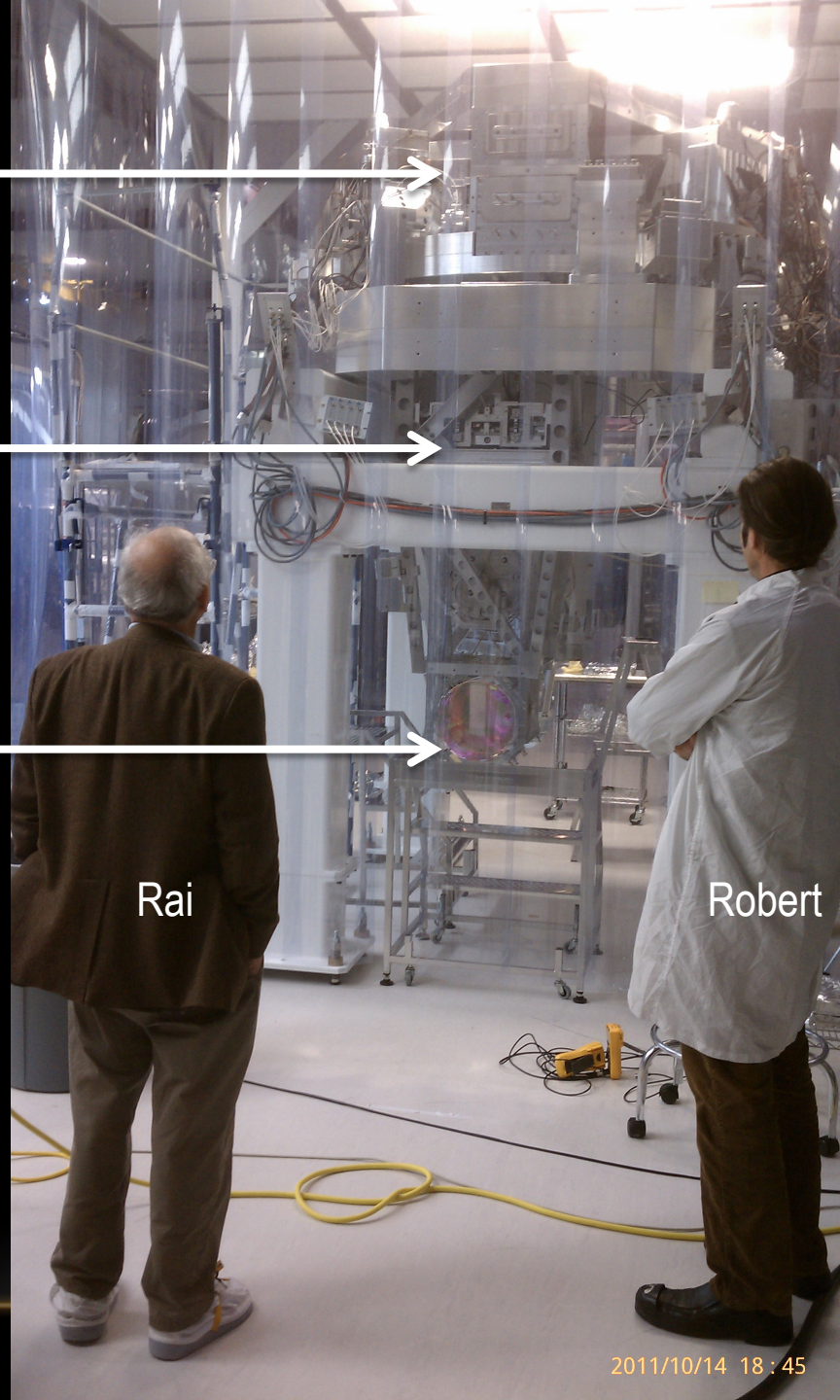
... can we pre-rotate the squeezing ellipse?



Active Seismic Isolation

Passive Isolation

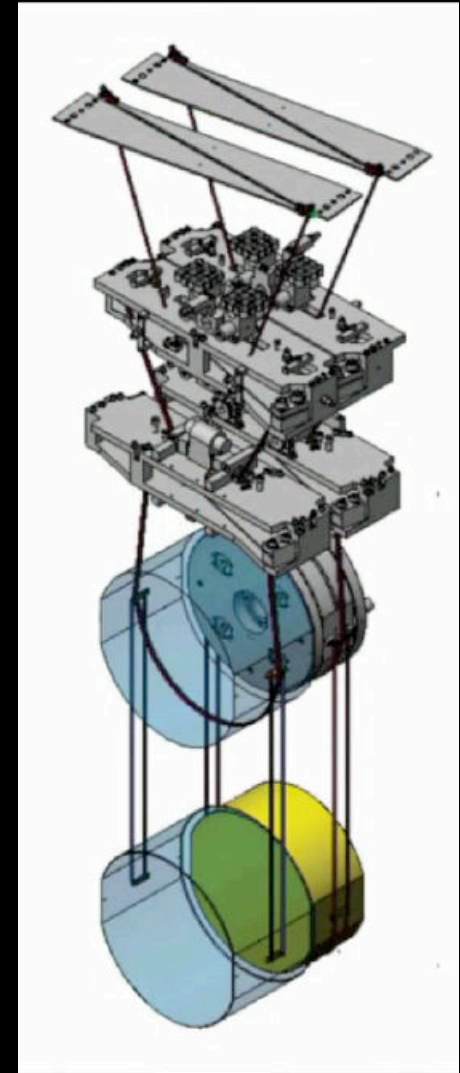
Test mass (mirror)



Rai

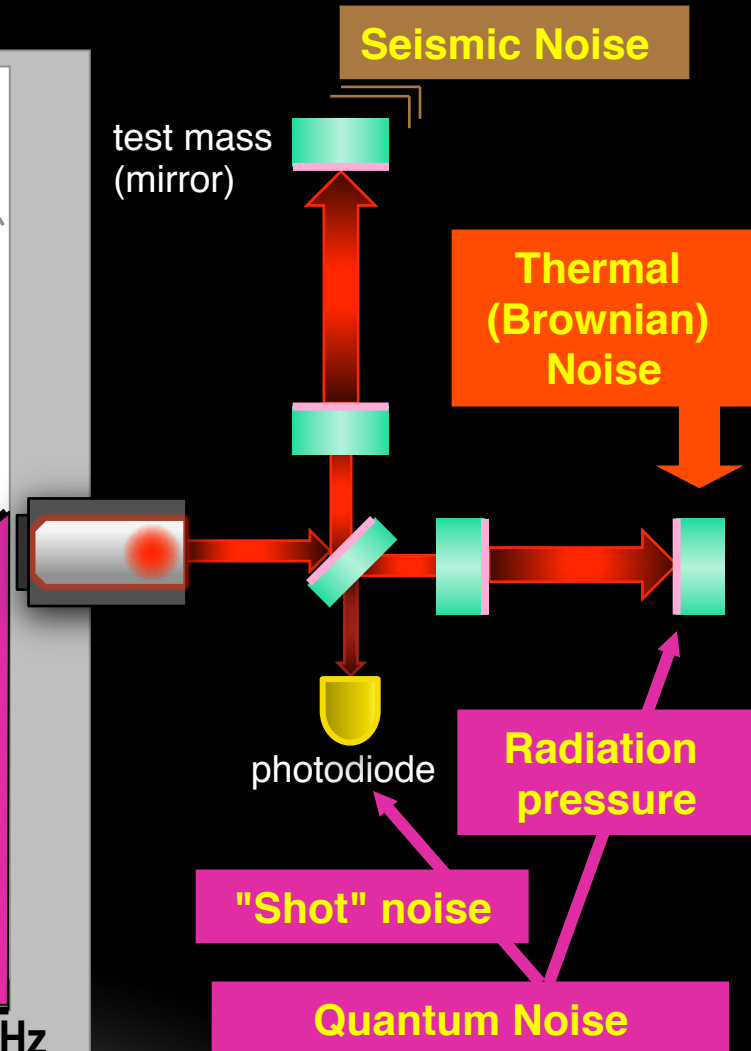
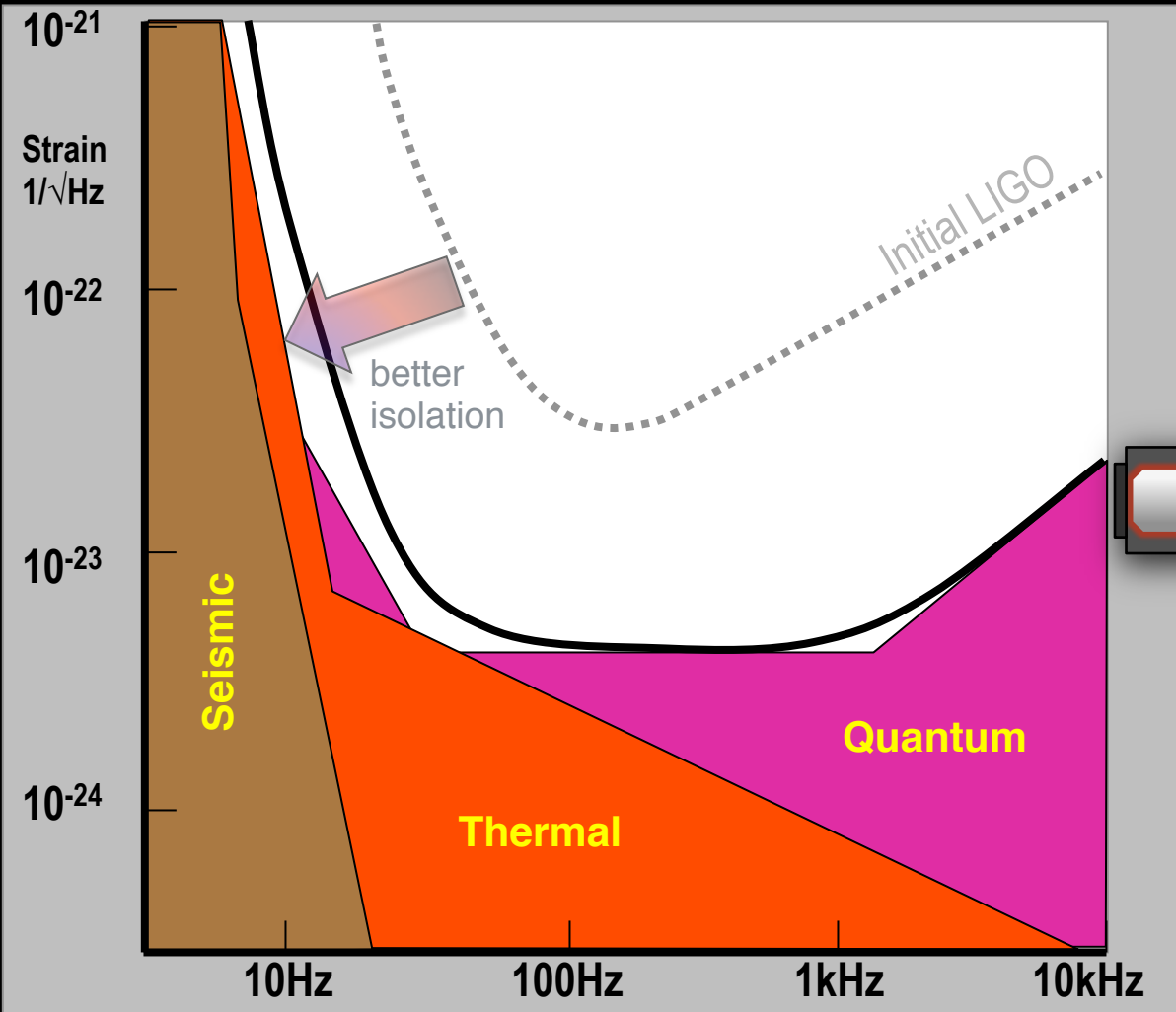
Robert

Passive Isolation



prototype at MIT!

# Seismic Noise



# High Laser Power and Interferometer Stability

- From Initial LIGO to Advanced LIGO – increase the laser power!
  - In the first observing run we had much higher power than Initial LIGO, but we were still about a factor of 8 below the nominal Advanced LIGO power
  - We had learned from Initial LIGO that progress is limited by thermal deformations in the optics, which result in sensitivity and control problems. Advanced LIGO was designed to minimize these problems as much as possible.

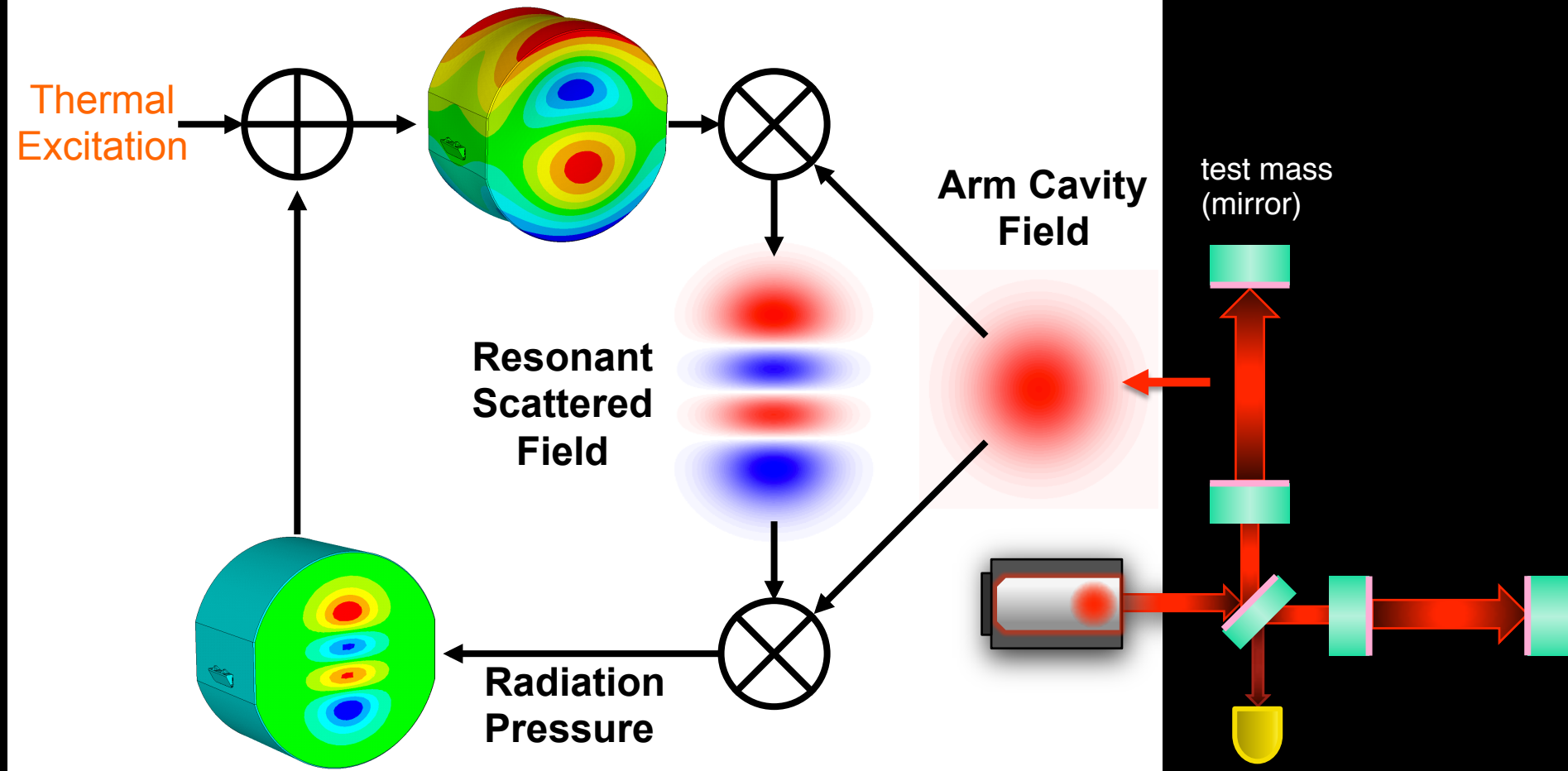
# High Laser Power and Interferometer Stability

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- In 2001 V. Braginsky predicted that radiation pressure effects could lead to a 3-wave parametric instability in interferometers operating at high power
  - while we were unsure if we would see parametric instabilities (PI) in Advanced LIGO, we were prepared
  - as we increased the power after the first observing run, PI became a real problem...

Parametric oscillatory instability in Fabry–Perot interferometer  
Braginsky et. al. (2001) PLA 287, 331–338

# High Power and Parametric Instabilities

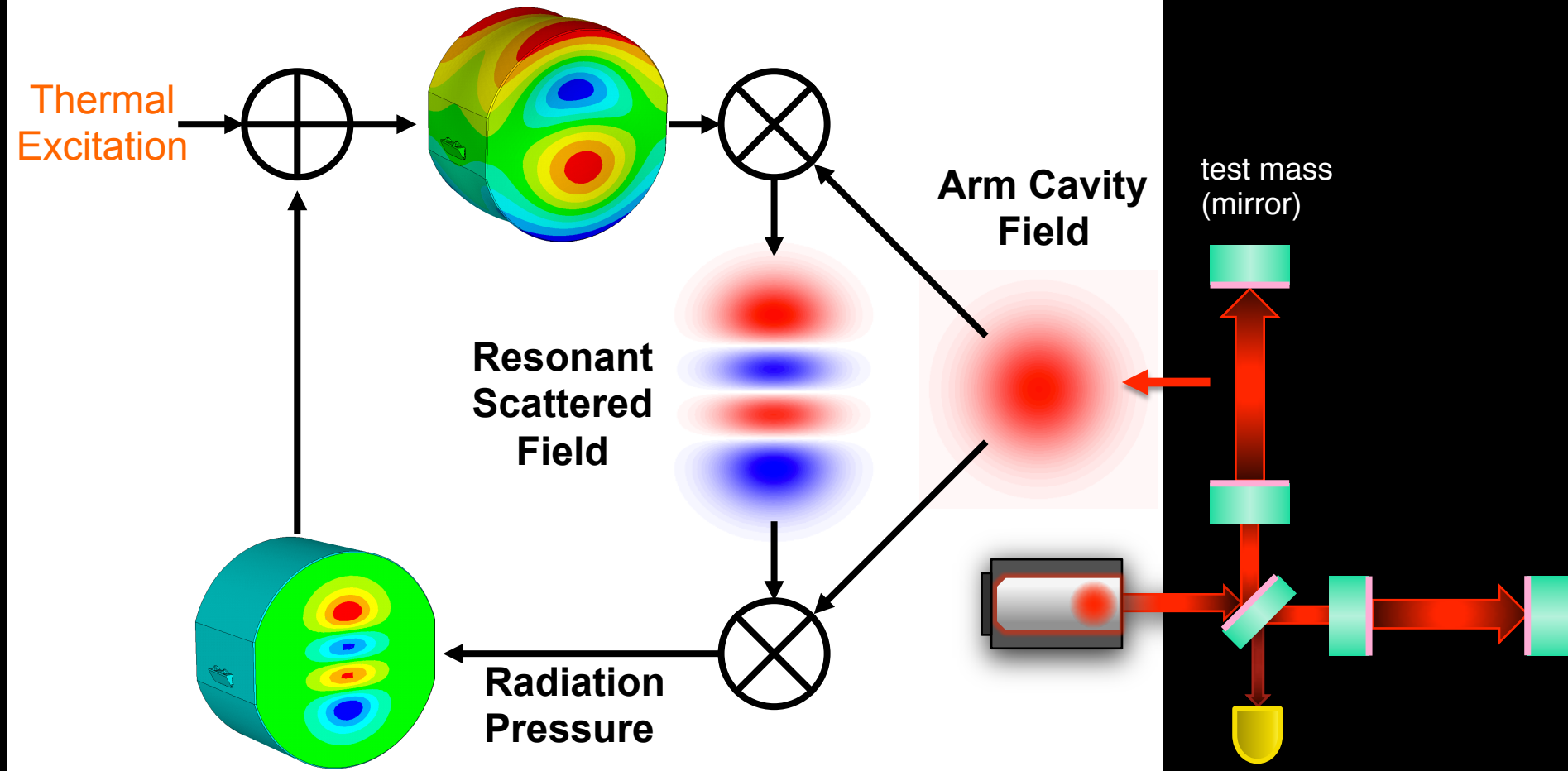
Mechanical Mode with  $Q > 10^7$



Observation of Parametric Instability in Advanced LIGO. Evans, ... (2015) PRL 114, 161102  
A general approach to optomechanical parametric instabilities. Evans, ... (2010) PLA 374, 665–671

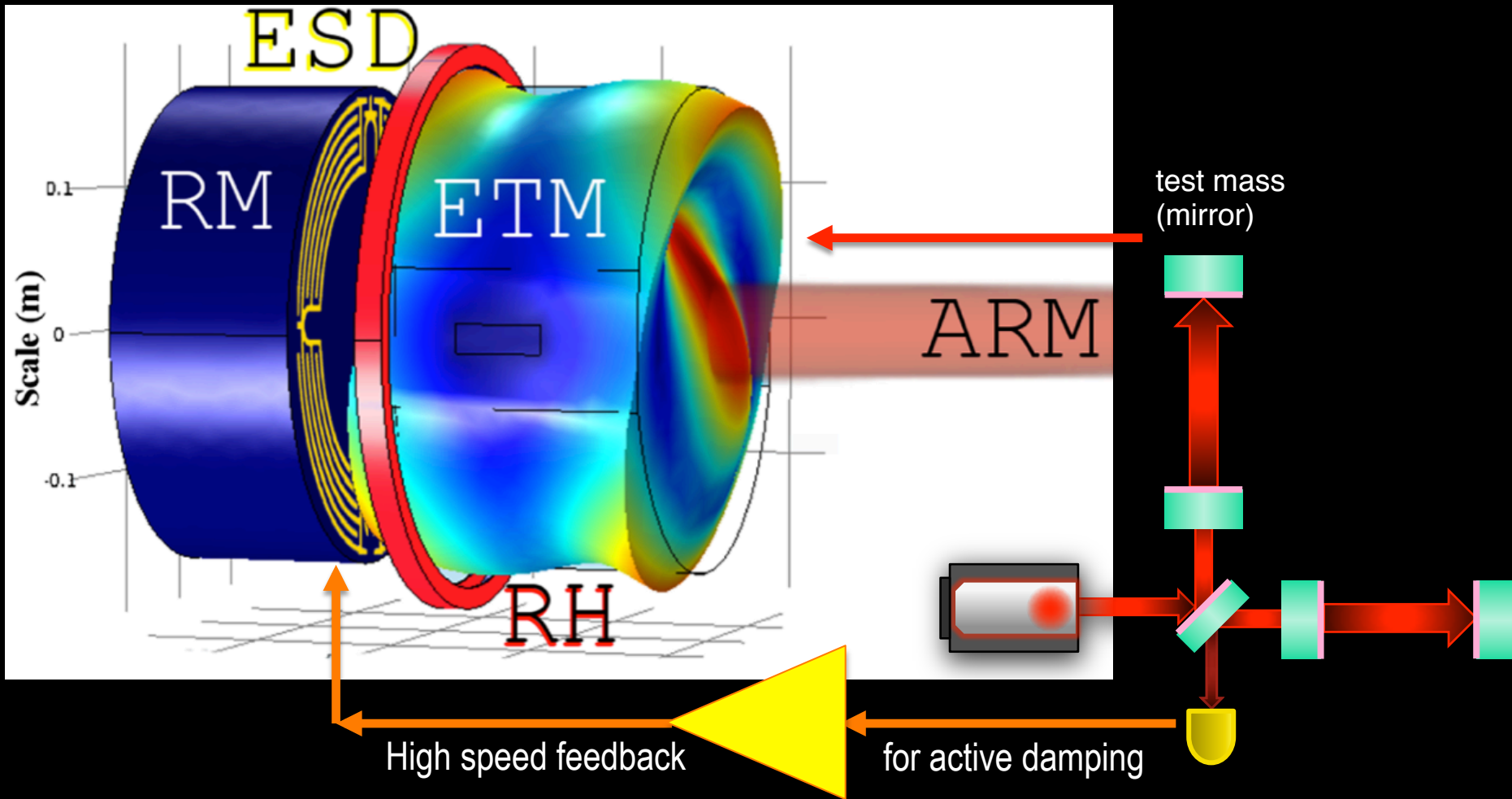
# High Power and Parametric Instabilities

Mechanical Mode with  $Q > 10^7$



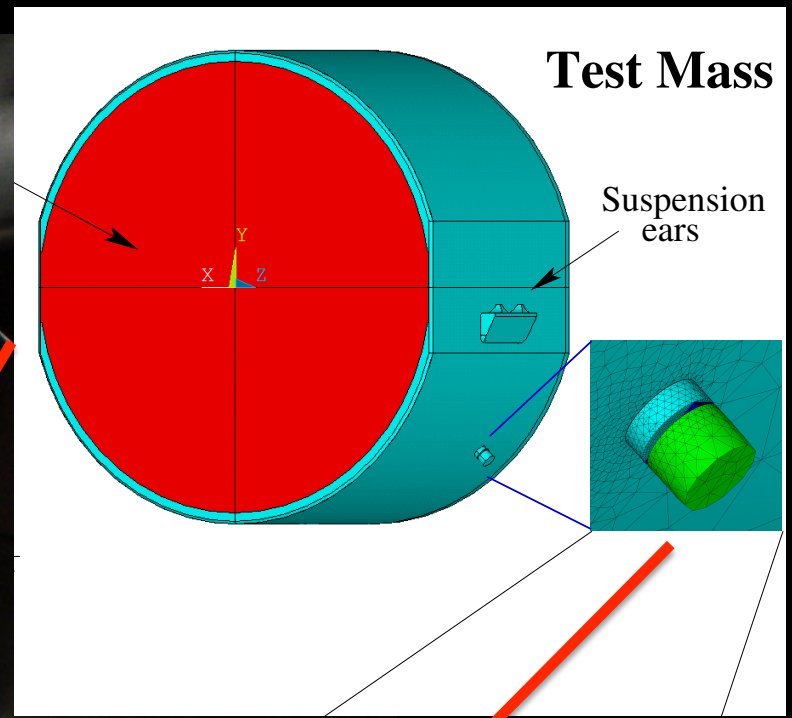
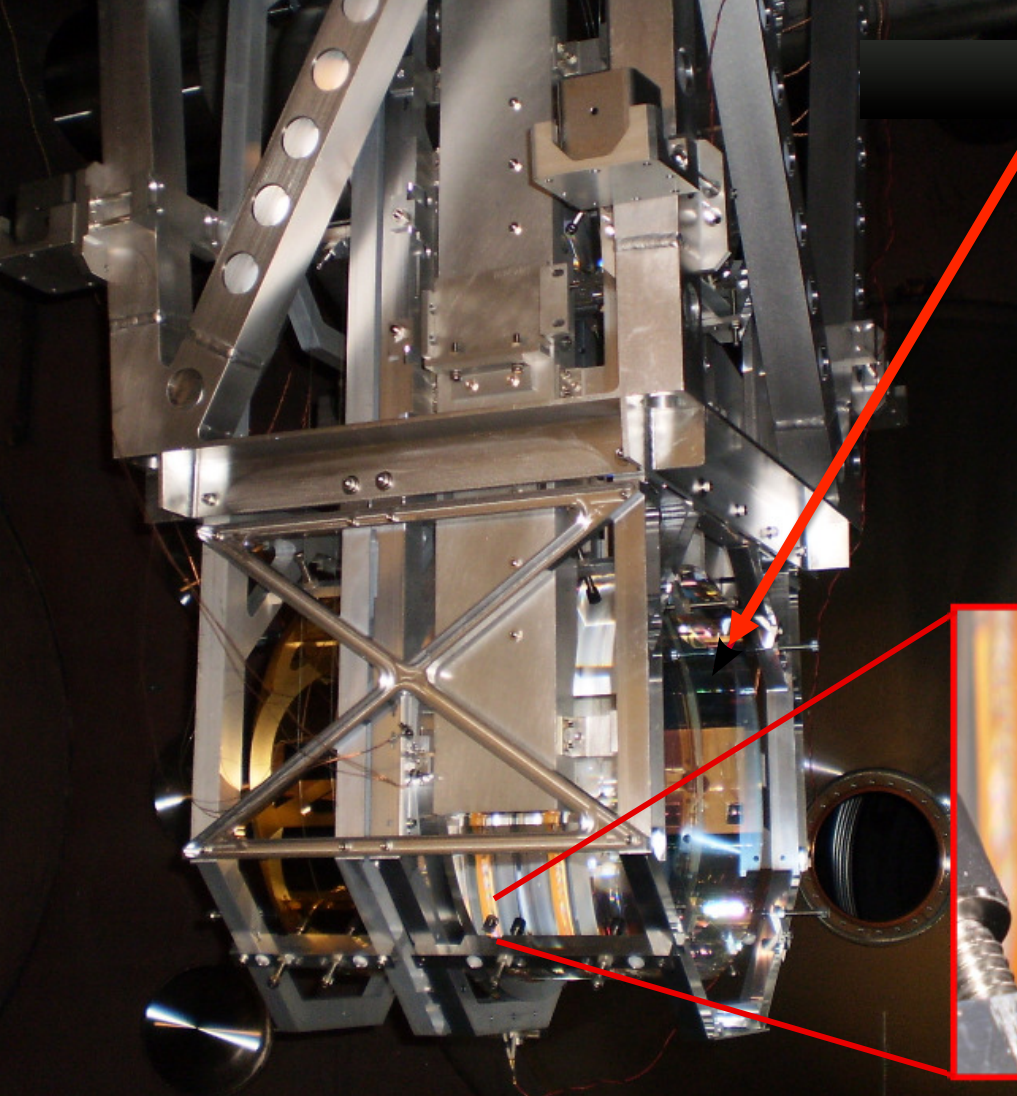
Observation of Parametric Instability in Advanced LIGO. (2015) PRL 114, 161102  
A general approach to optomechanical parametric instabilities. (2010) PLA 374, 665–671

# Damping Parametric Instabilities



First Demonstration of Electrostatic Damping of Parametric Instability at Advanced LIGO. (2017) PRL 118, 151102  
Damping parametric instabilities in future gravitational wave detectors by means of electrostatic actuators. (2011) PLA 375, 788

# Prototype Advanced LIGO suspension at MIT



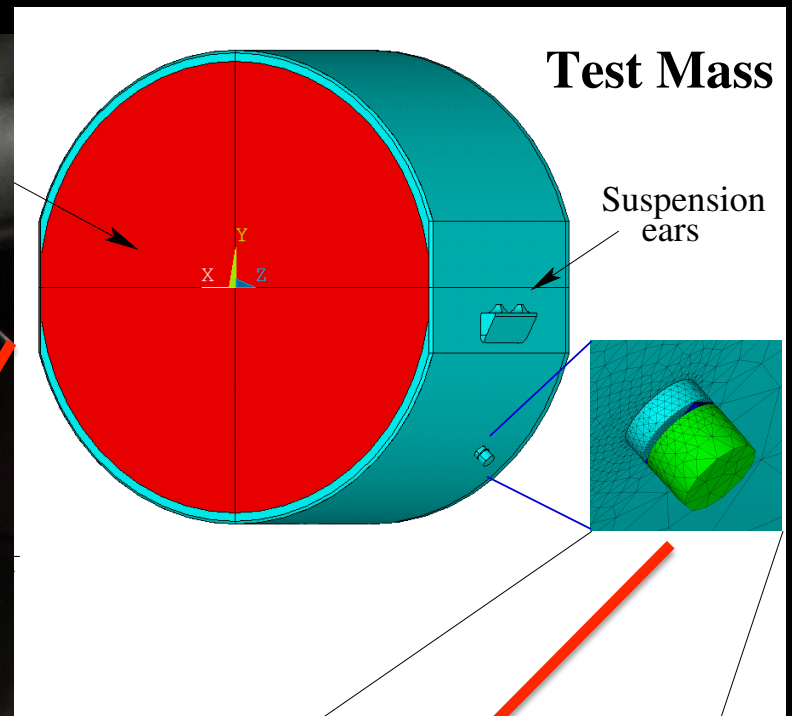
## AMD



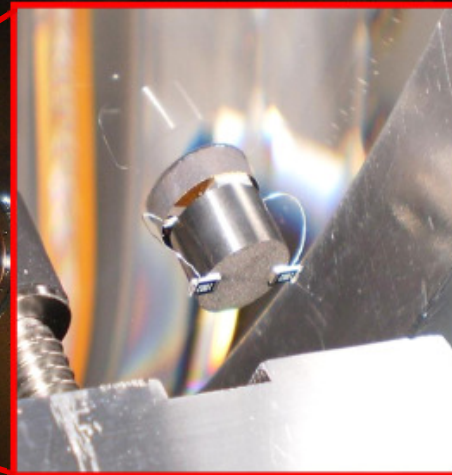
Acoustic Mode Dampers  
reduce the  
mechanical Q  
without adding  
thermal noise

# Prototype Advanced LIGO suspension at MIT

Installation in Advanced LIGO happening TODAY!



## AMD



Acoustic Mode Dampers  
reduce the mechanical Q  
without adding thermal noise

# Laser interferometer design, published 1972 (Weiss at MIT)

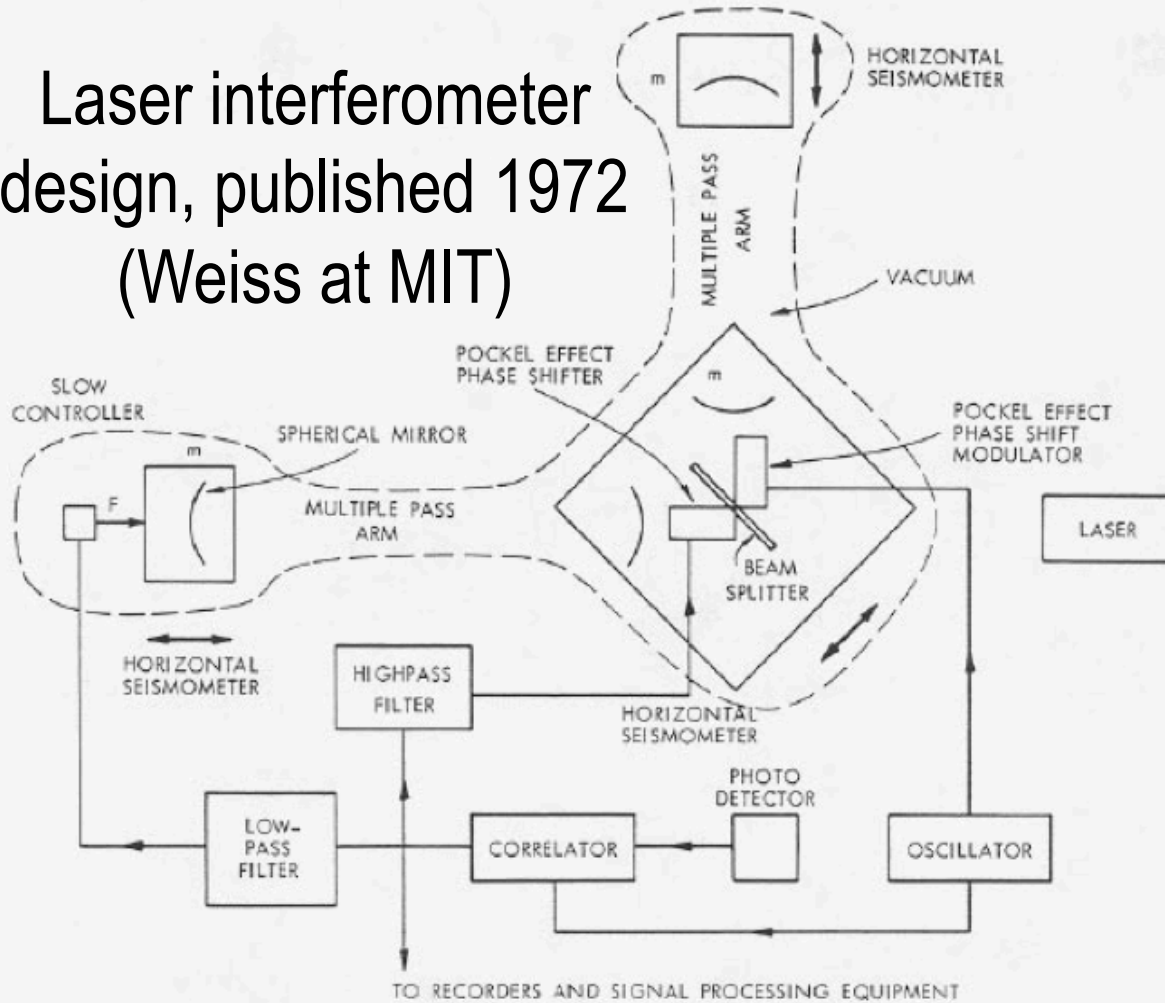
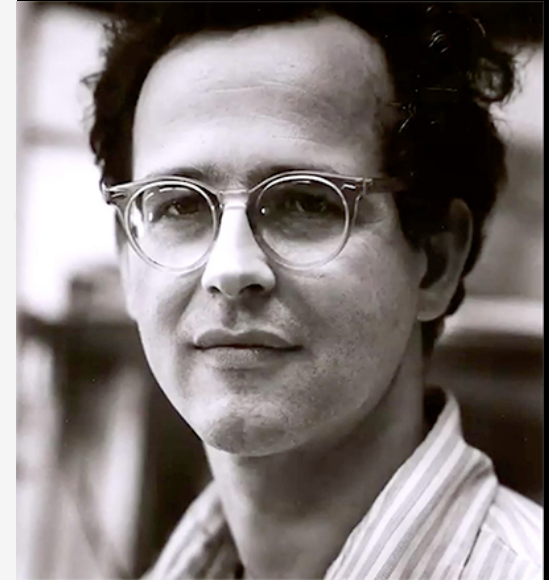
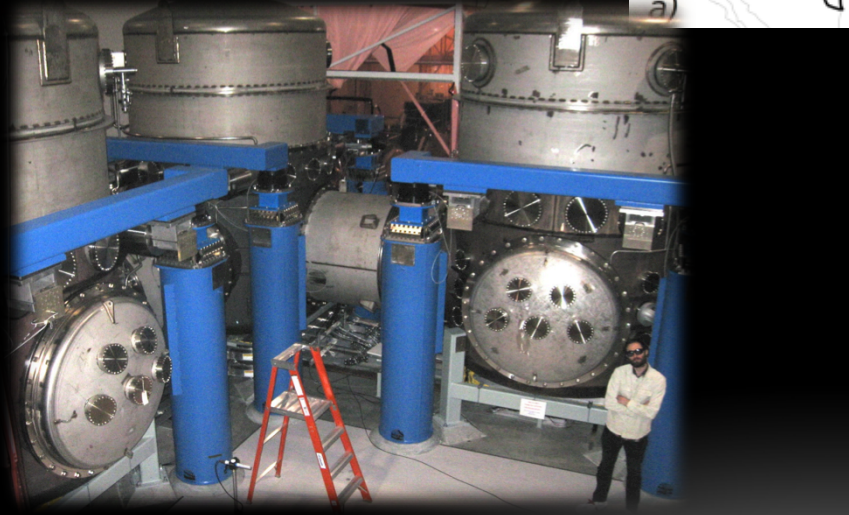
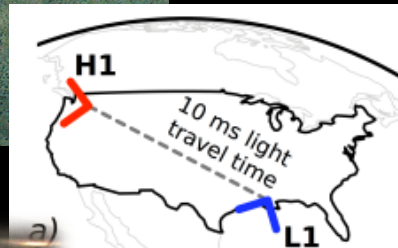
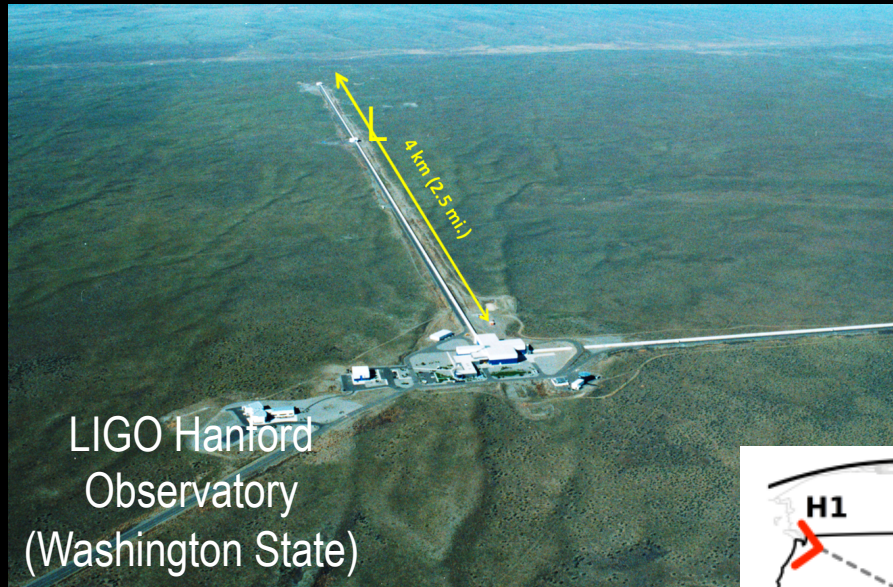


Fig. V-20. Proposed antenna.

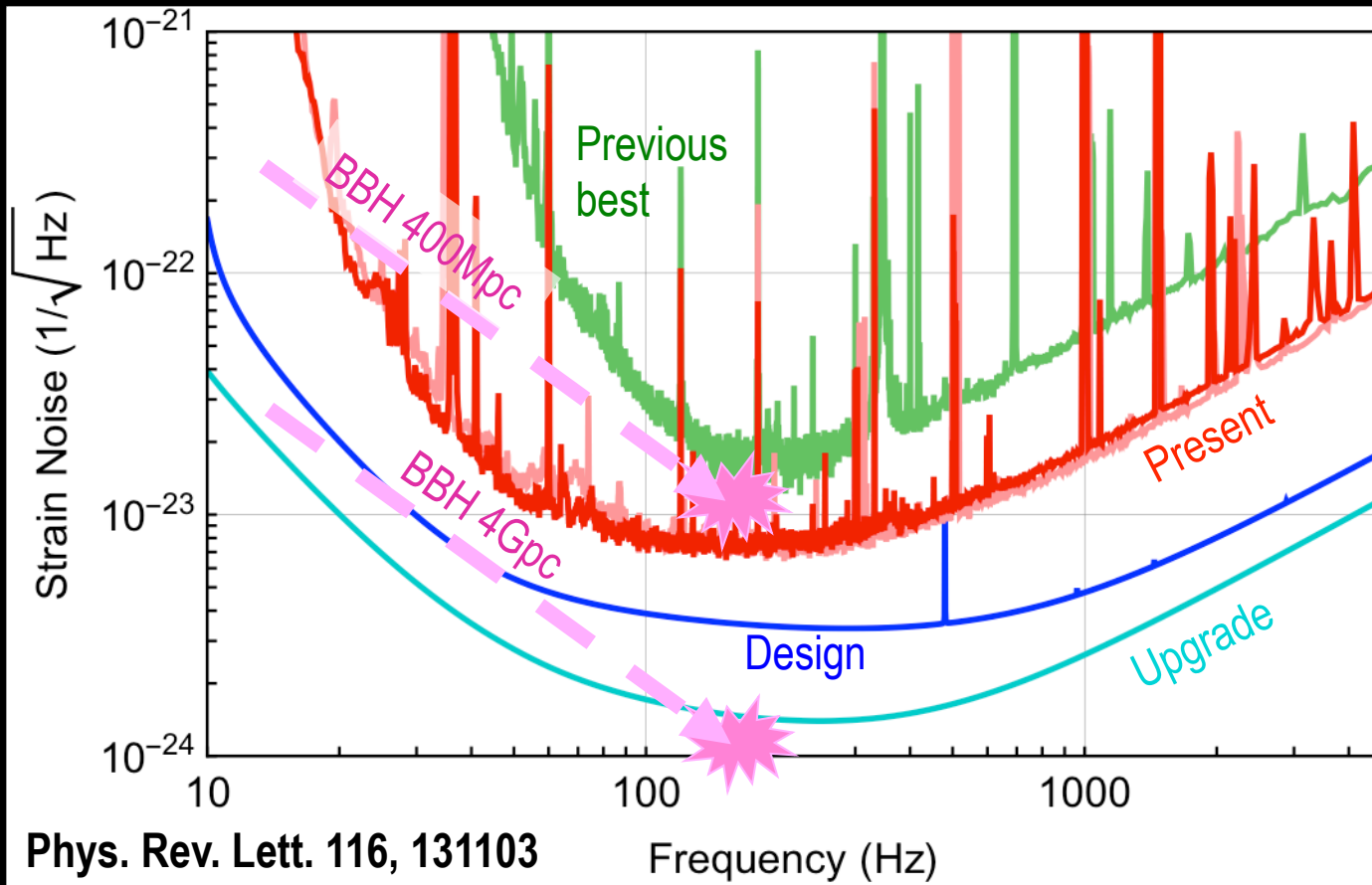


Rai Weiss  
~1970

# 2 LIGO Observatories, each with one laser interferometer with 4 km arms



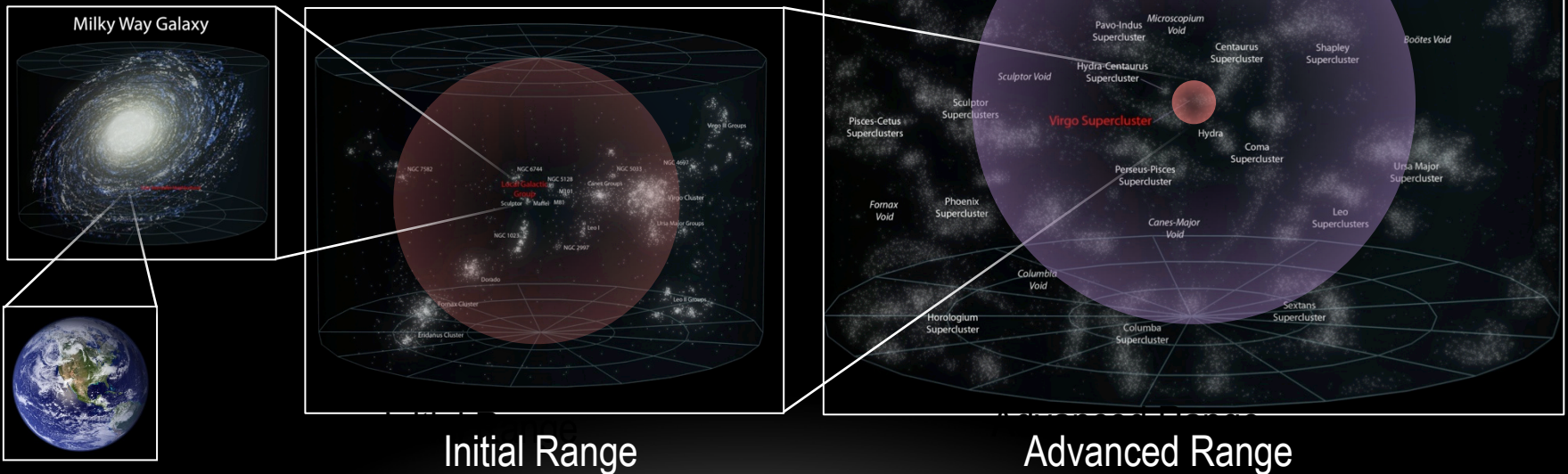
# LIGO Noise: "Range"

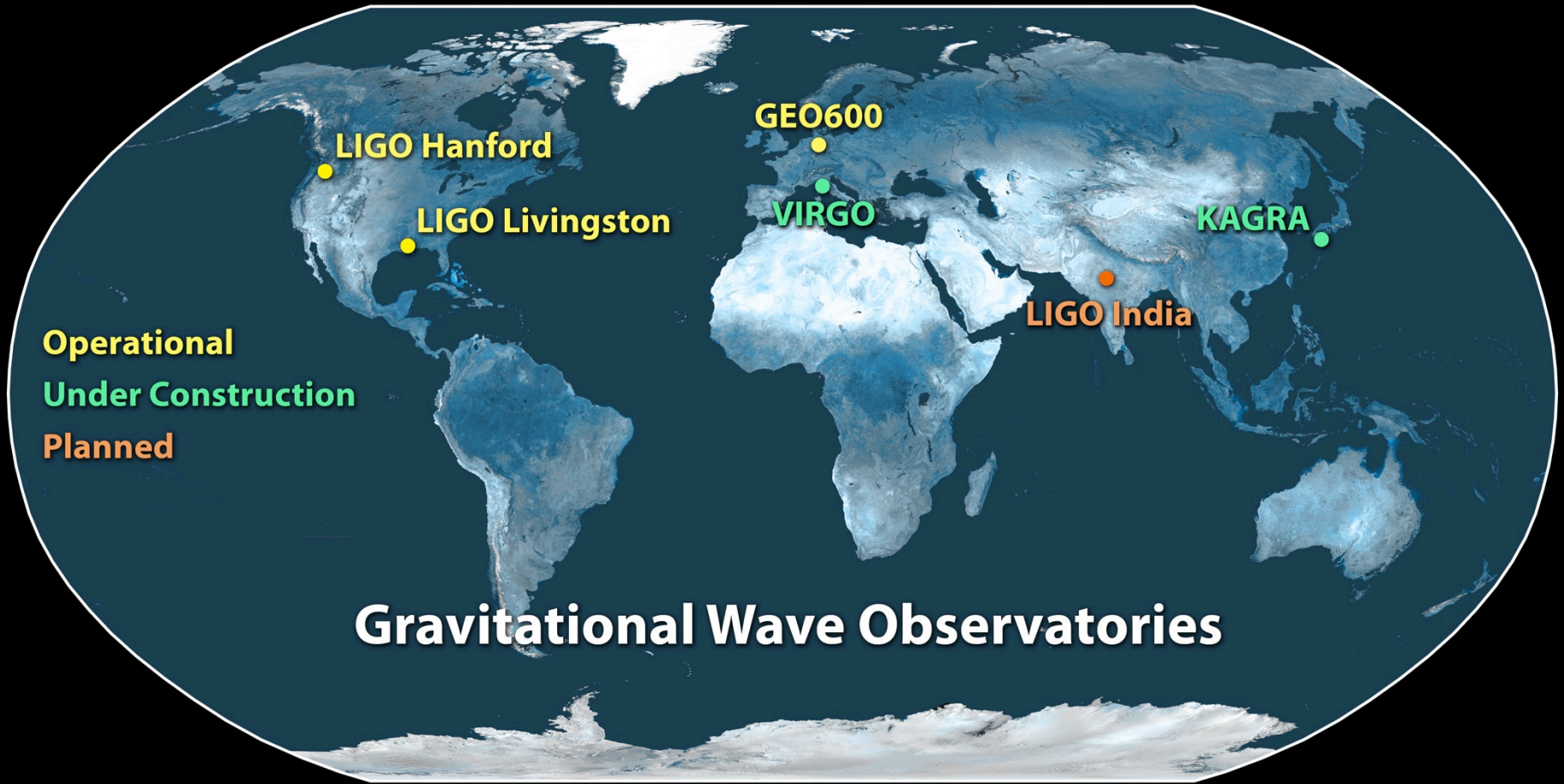


# Advanced LIGO Sensitive Volume

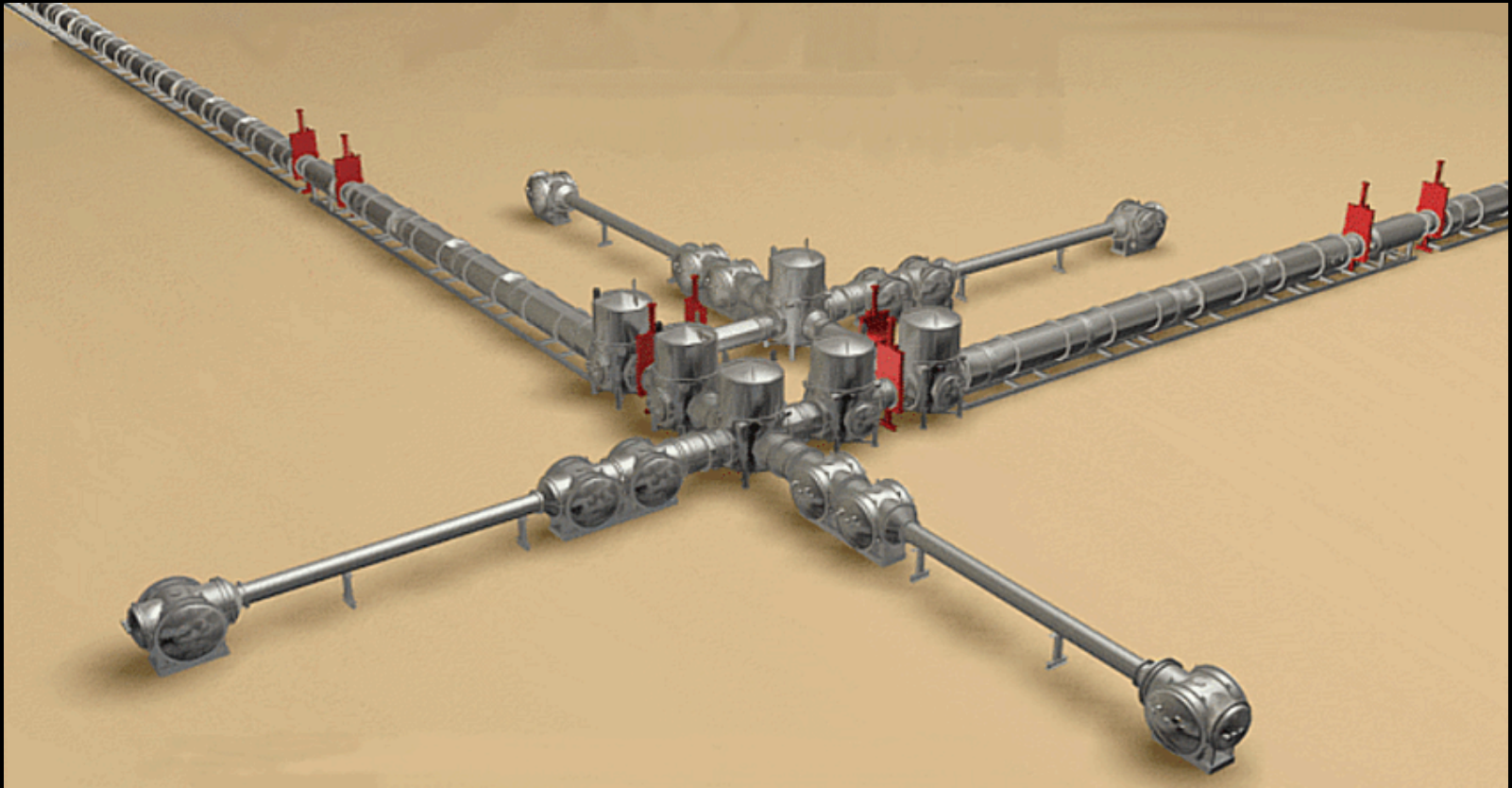
- Rate roughly 50 BBH mergers each year in a volume of 1 Gpc<sup>3</sup>
- About 10 million galaxies per Gpc<sup>3</sup>
- Advanced LIGO range now ~ 0.1 to 1 Gpc, depending on system mass

We expect many more BBH events in the next observing run.

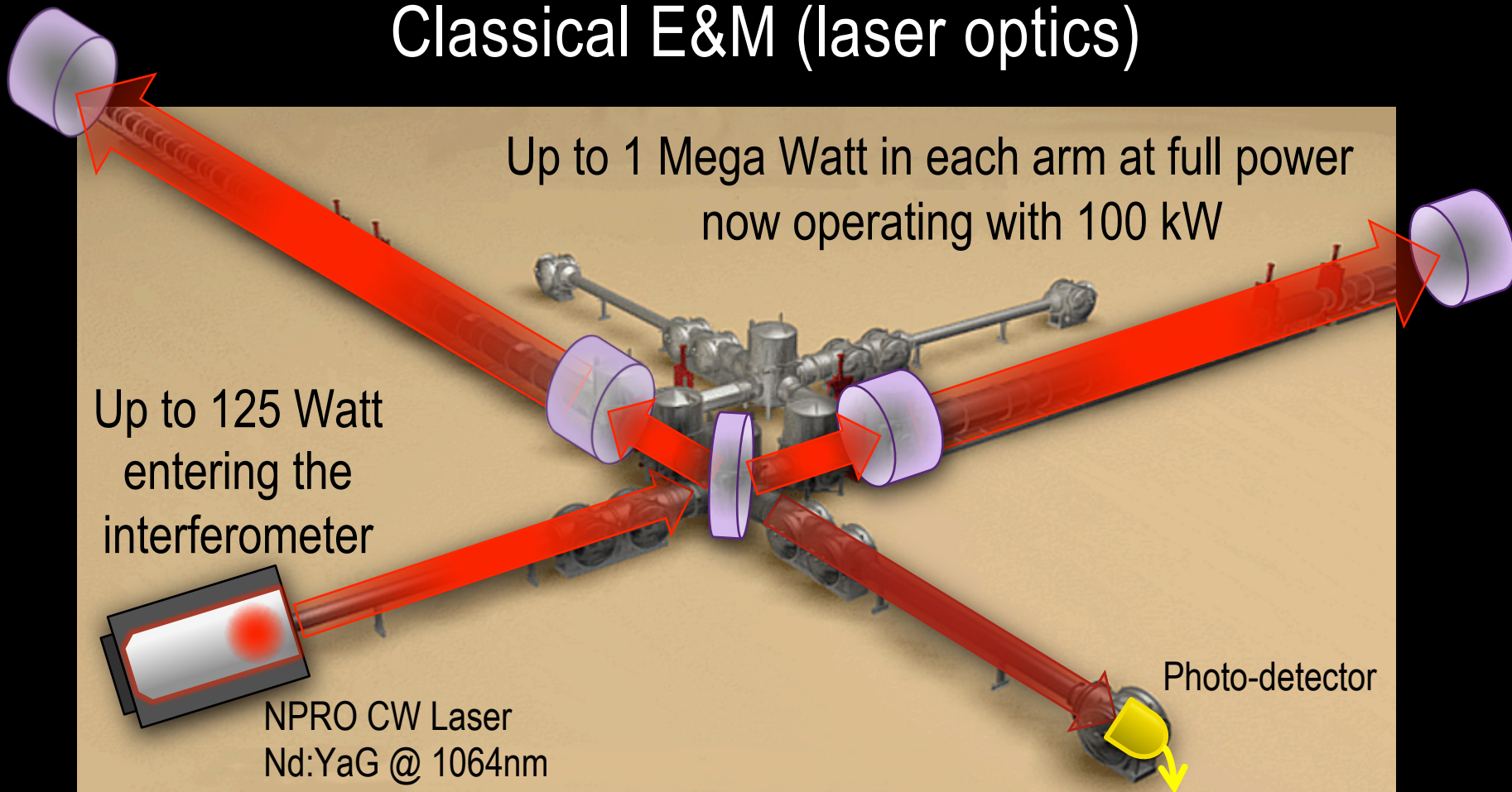




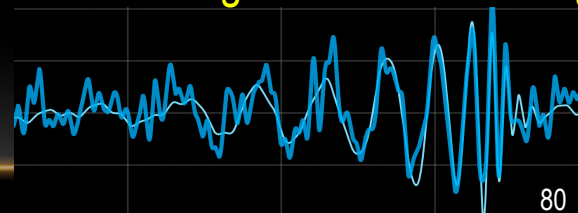
# The Advanced LIGO Interferometer



# The Advanced LIGO Interferometer: Classical E&M (laser optics)



Interferometer noise + gravitational wave signal





# Signal Frequency and Black Hole Mass

## Estimate Period of Last Orbit

For  $30 M_{\odot}$ ,  $R_s \sim 90\text{km}$   
take  $r_1 = r_2 = 2 R_s$  so that  $v = c / 2$

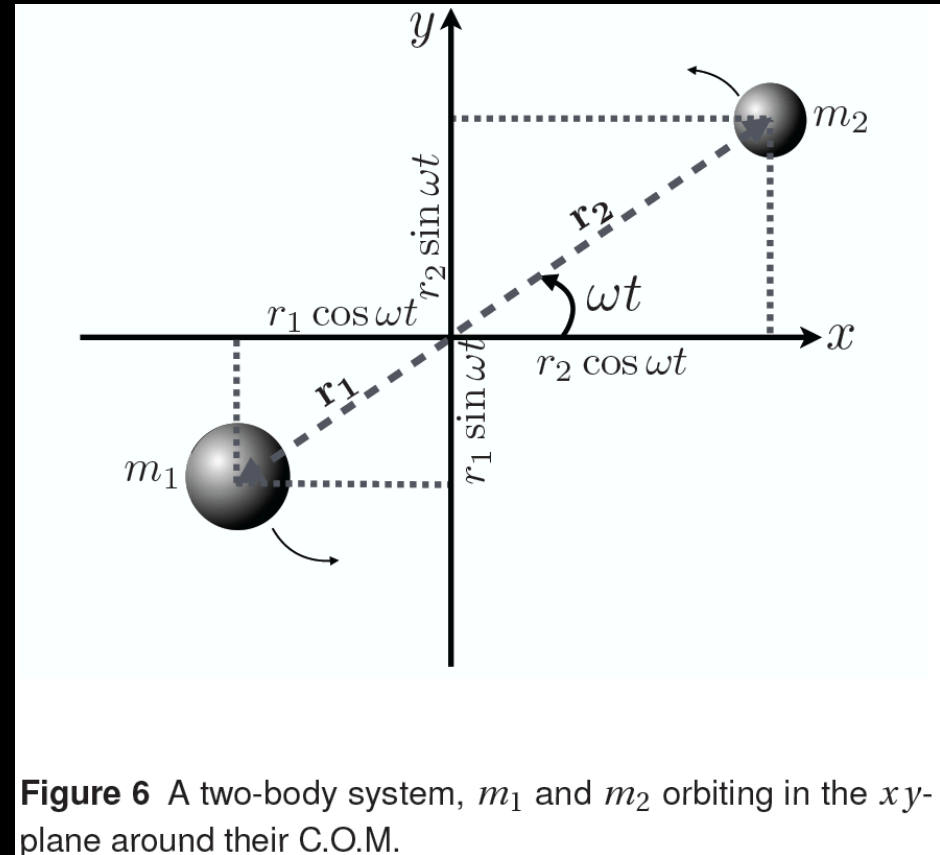
$$T_{\text{orb}} = (4 \pi) 90 \text{ km} / (c / 2) \\ \sim 7.5 \text{ ms}$$

$$f_{\text{orb}} = 1 / T_{\text{orb}} \sim 125 \text{ Hz}$$

$$f_{\text{GW}} = 2 f_{\text{orb}} \sim 250 \text{ Hz}$$

(actual value for GW150914 was  $\sim 200$  Hz)

“The basic physics of the binary black hole merger GW150914” (arXiv:1608.01940)



**Figure 6** A two-body system,  $m_1$  and  $m_2$  orbiting in the  $x$ - $y$ -plane around their C.O.M.

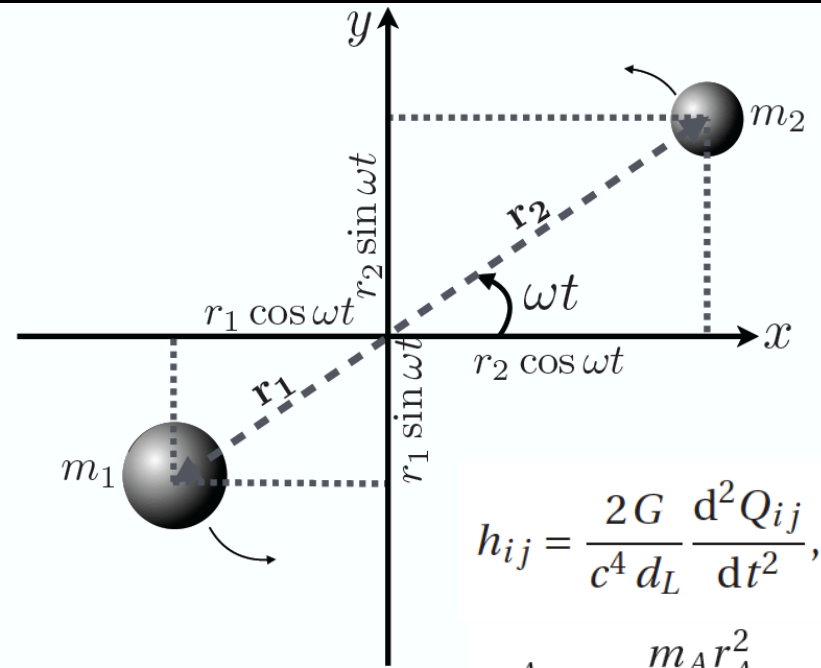
# Signal Amplitude and Distance

## Estimate Distance to Source

For  $30 M_{\odot}$ ,  $R_s \sim 90\text{km}$   
take GW strain at the source  
 $h = 1/4$  (since  $v/c = 1/2$ )

$d_L \sim R_s / (4 h_{\text{obs}}) \sim 2.5 \text{ G light-years}$

(actual value for GW150914 was 1.3 Gly)



**Figure 6** A two-body system,  $m_1$  and  $m_2$  orbiting in the  $xy$ -plane around their C.O.M.

“The basic physics of the binary black hole merger GW150914” (arXiv:1608.01940)