Title: Unlocking the Universe with quantum materials

Speakers: Jess McIver

Collection: Quantum Matter Workshop

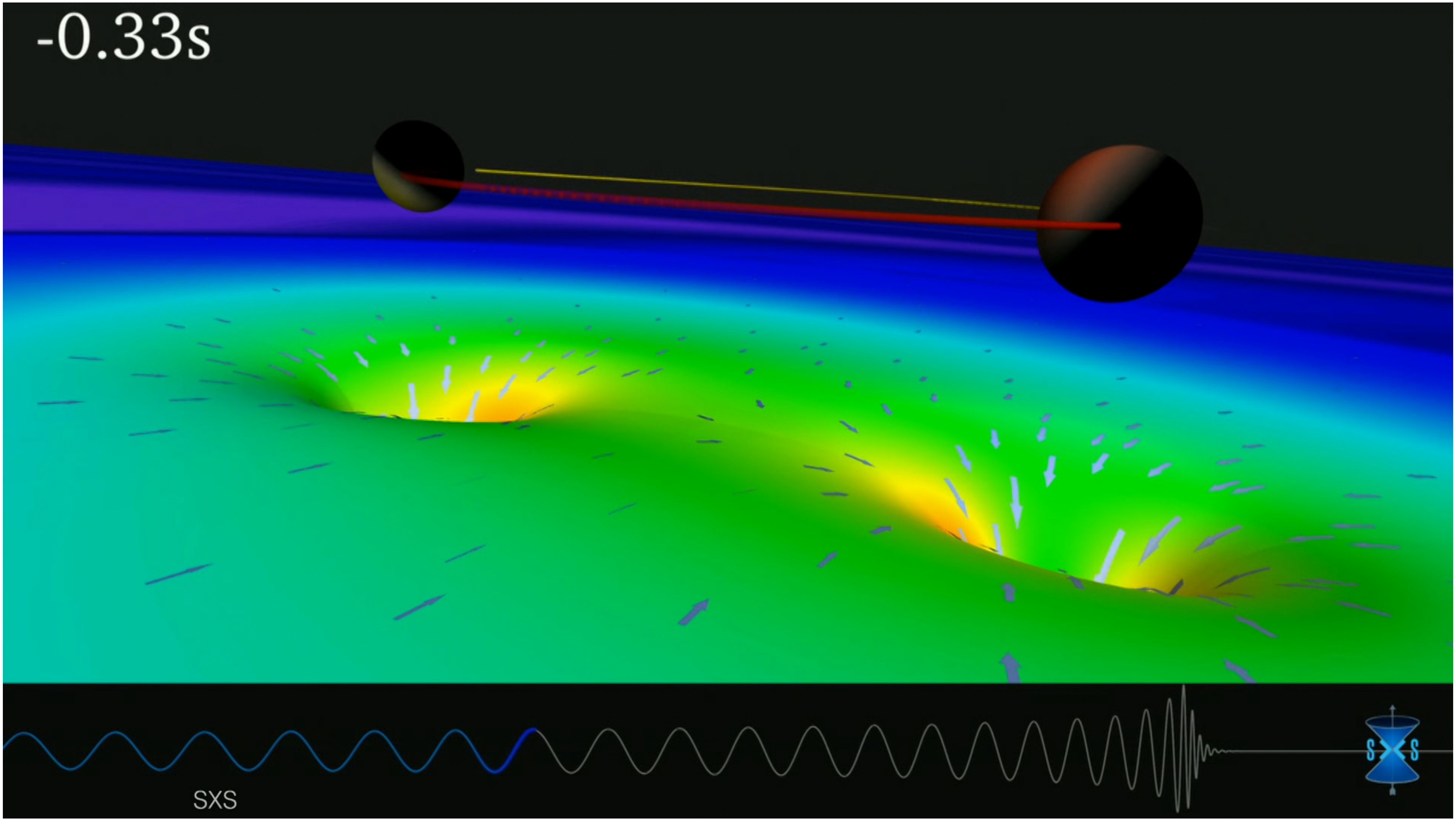
Date: November 16, 2022 - 2:00 PM

URL: https://pirsa.org/22110077

Abstract: Just seven years after their first detection, gravitational waves (GWs) have revealed the first glimpses of a previously hidden dark Universe. Using the GW signature of distant compact-object collisions, we have discovered a new population of stellar remnants and unlocked new tests of general relativity, cosmology, and ultra-dense matter. Materials with low mechanical loss (and strong constraints on other properties, e.g. reflectivity) are integral to the design and success of the GW detectors making these groundbreaking measurements. I'll summarize recent results from LIGO-Virgo and their wide-reaching implications, and discuss quantum materials advances required to enable future ground-based gravitational wave detectors, including Cosmic Explorer, to sense black hole collisions all the way back to the dawn of cosmic time.

The GW detector coatings team at the Stewart Blusson Quantum Matter Institute

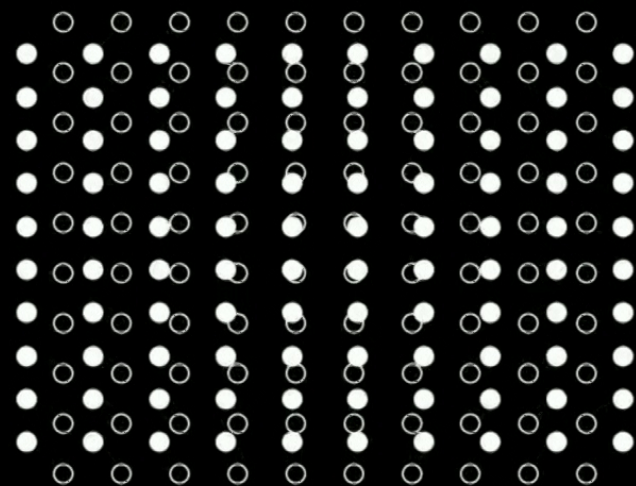

NASA
gravitational waves
a new view of the universe
3

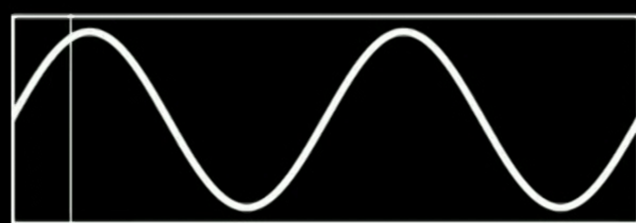

-0.33s
SXS

Gravitational wave strain

Induced spacetime strain h(t)

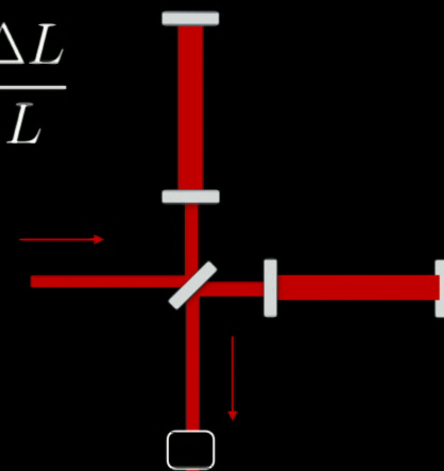
$$h_{ij}(t) \propto \frac{G}{c^4 r} \frac{d^2 I_{ij}}{dt^2}$$





Measured spacetime strain h(t)

$$\frac{\Delta L}{L}$$



Movie: Carl Rodriguez

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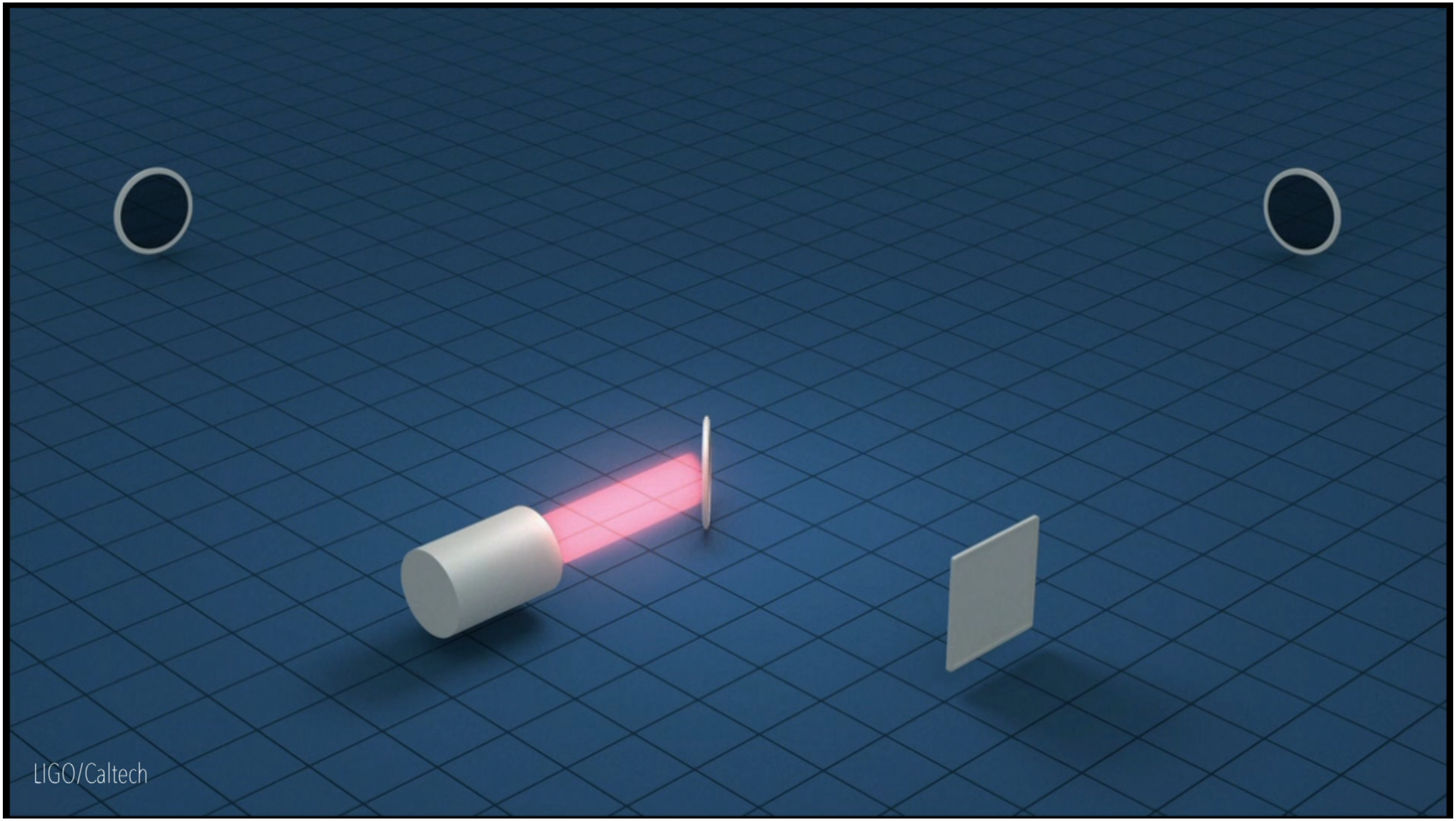
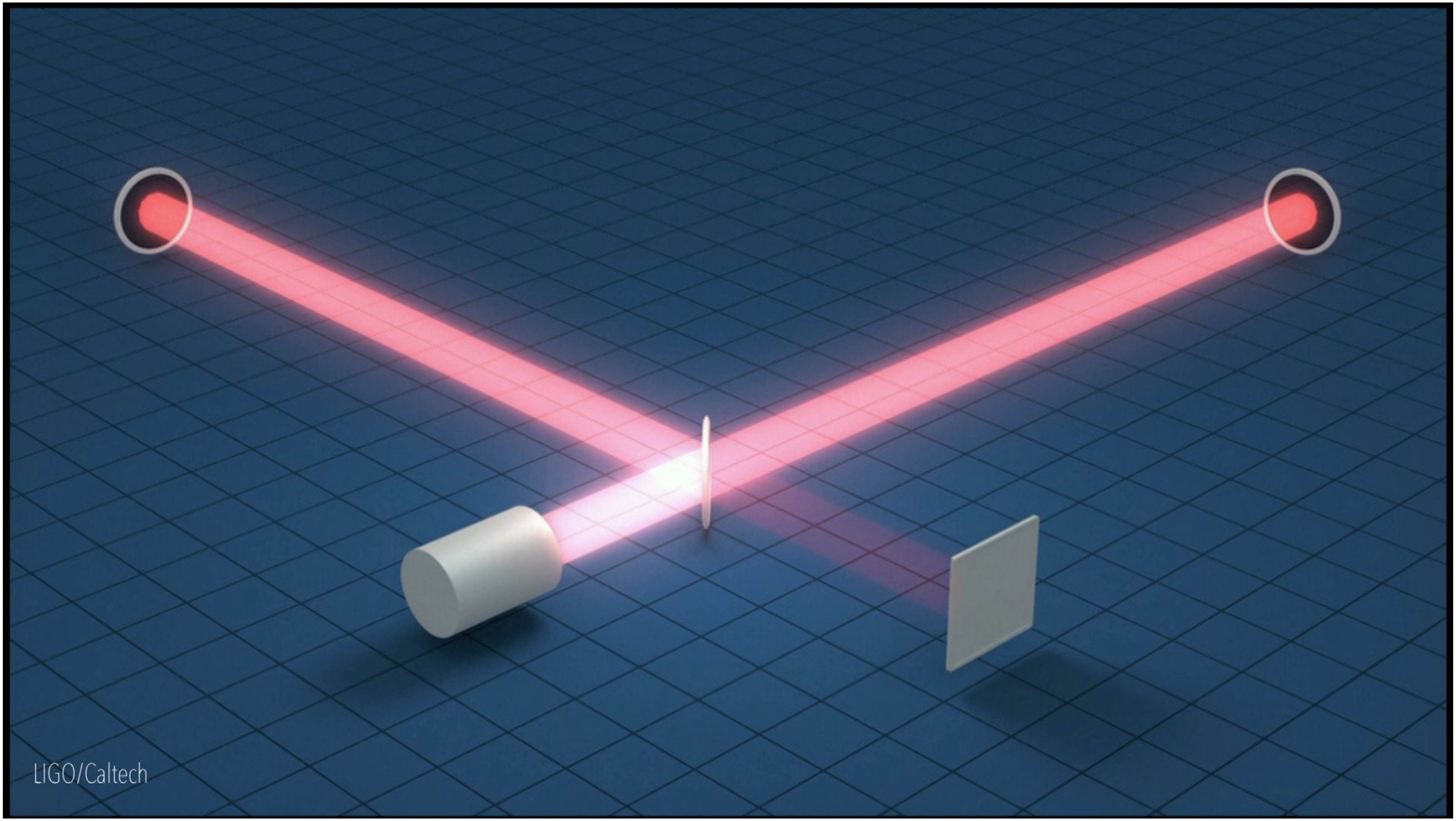
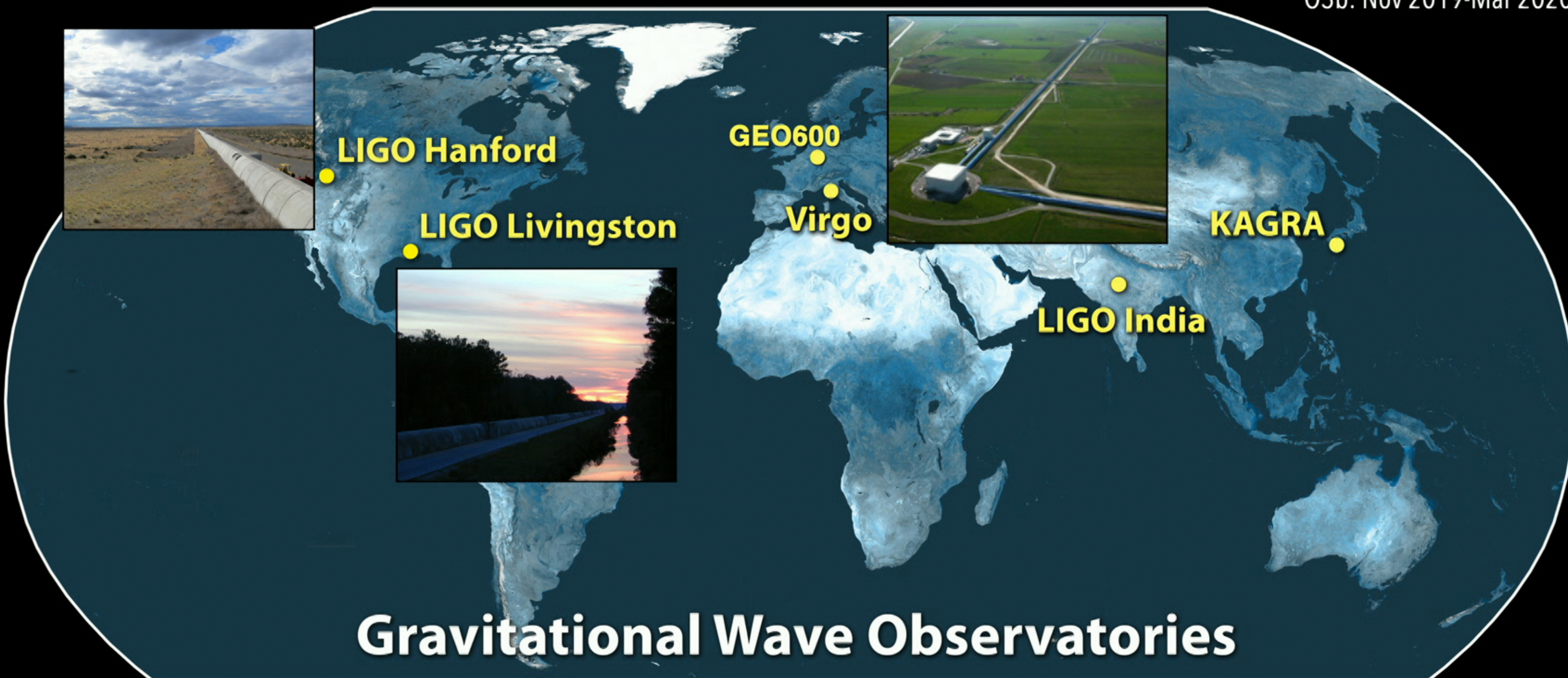

LIGO/Caltech


LIGO/Caltech

Detector network in LIGO-Virgo's third observing run: O3

O3a: April 2019-Oct 2019
O3b: Nov 2019-Mar 2020



LIGO/Caltech

A brief history of LIGO

2002-2007: Initial LIGO operation

Upper limits

First upper limits from LIGO on gravitational wave bursts

B. Abbott *et al.* (LIGO Scientific Collaboration)
Phys. Rev. D **69**, 102001 – Published 7 May 2004

Search for gravitational waves from primordial black hole binary coalescences in the galactic halo

B. Abbott *et al.* (LIGO Scientific Collaboration)
Phys. Rev. D **72**, 082002 – Published 25 October 2005

S1-S5:
0 detections

12

A brief history of LIGO

2008-2010: Enhanced LIGO operation

Better upper limits!

Search for gravitational waves from binary black hole inspiral, merger, and ringdown in LIGO-Virgo data from 2009–2010

J. Aasi *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. D **87**, 022002 – Published 23 January 2013

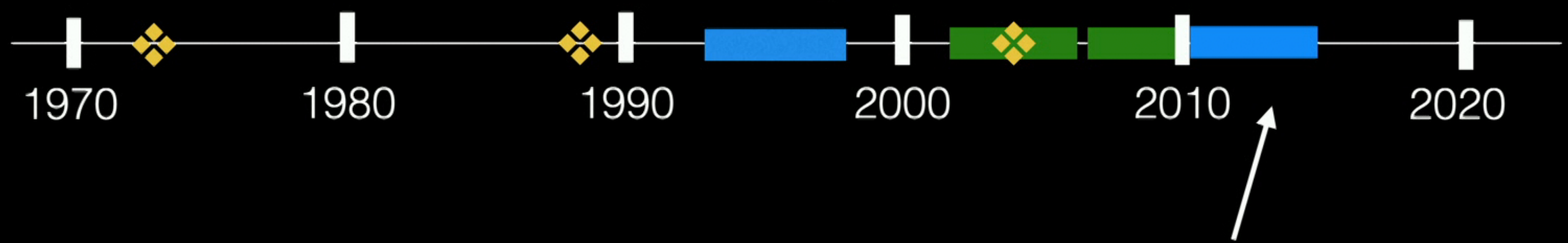
Search for gravitational wave ringdowns from perturbed intermediate mass black holes in LIGO-Virgo data from 2005–2010

J. Aasi *et al.* (The LIGO Scientific Collaboration and the Virgo Collaboration)
Phys. Rev. D **89**, 102006 – Published 27 May 2014

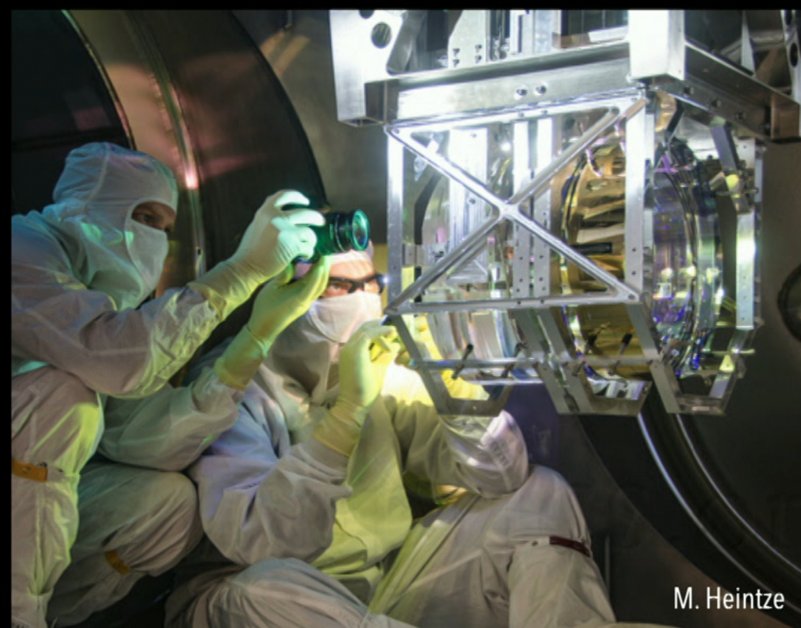
S6:
0 detections

13

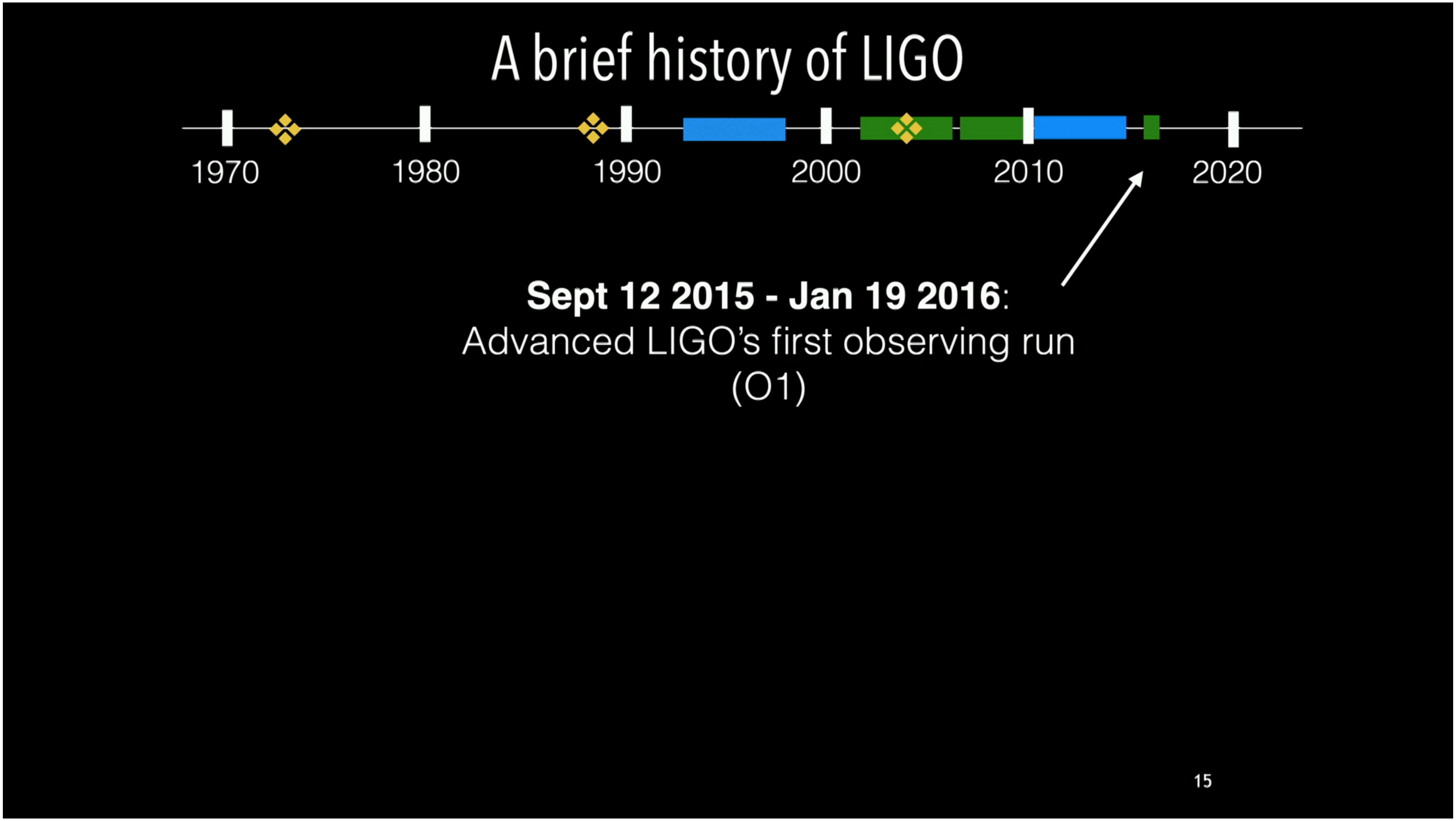
A brief history of LIGO



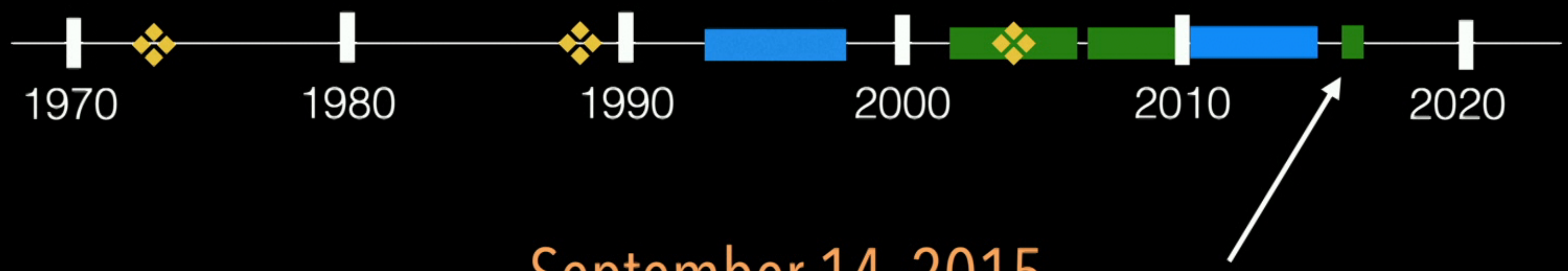
2010-2015: Advanced LIGO installation



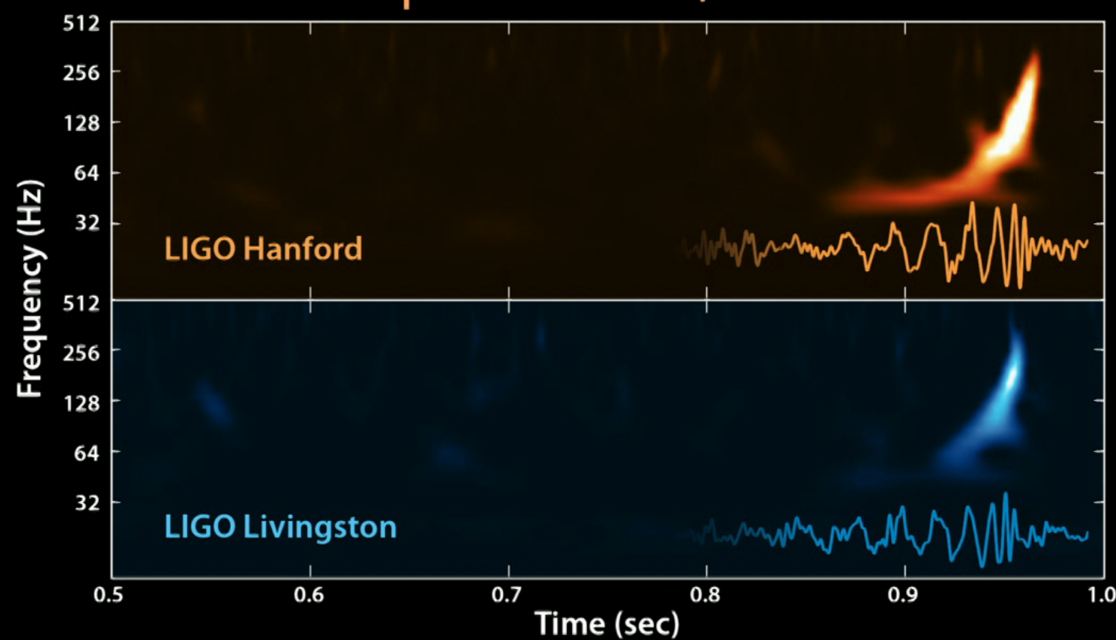
14


A brief history of LIGO
1970
1980
1990
2000
2010
2020
Sept 12 2015 - Jan 19 2016:
Advanced LIGO's first observing run
(O1)
15

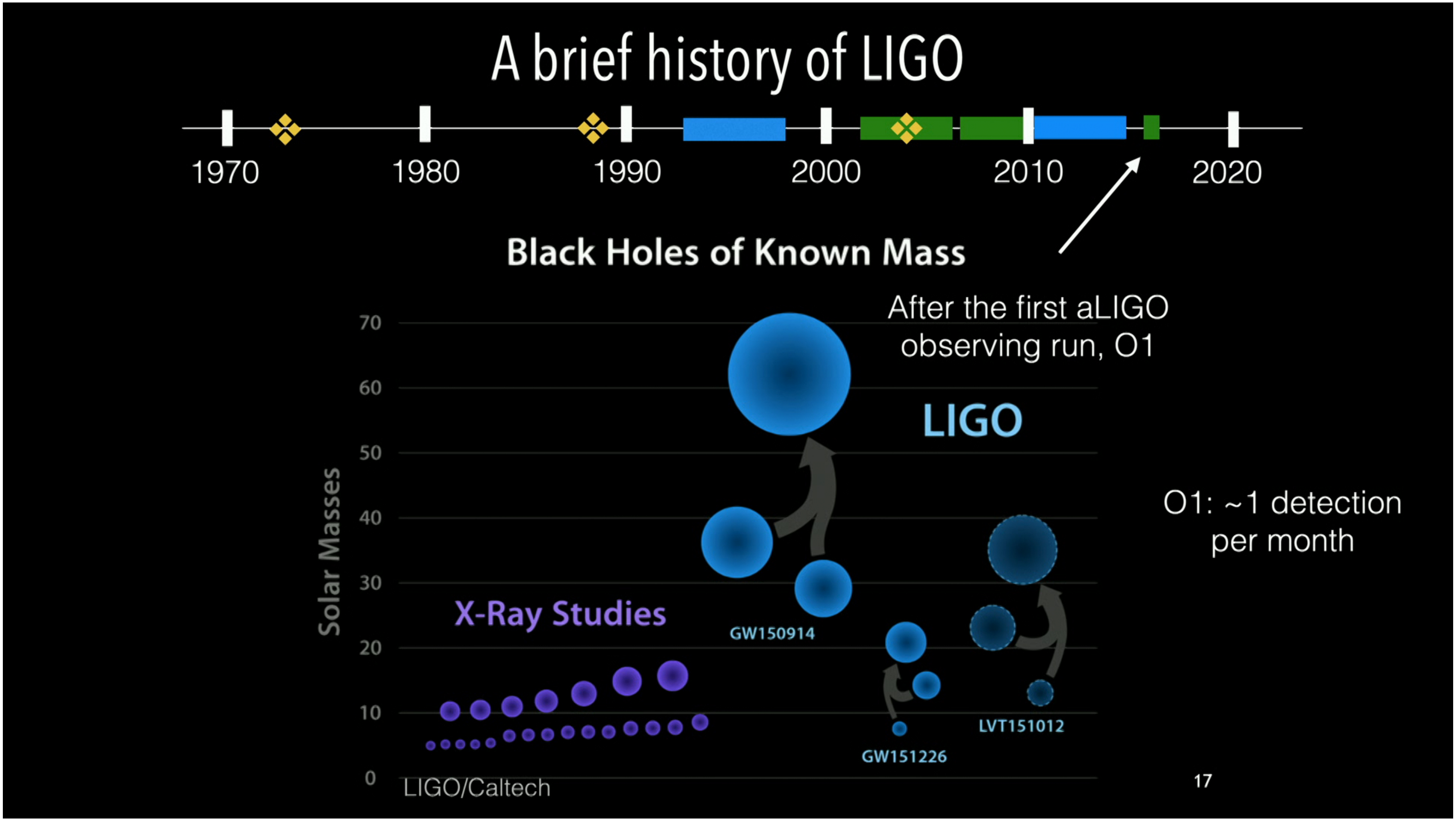
A brief history of LIGO



September 14, 2015

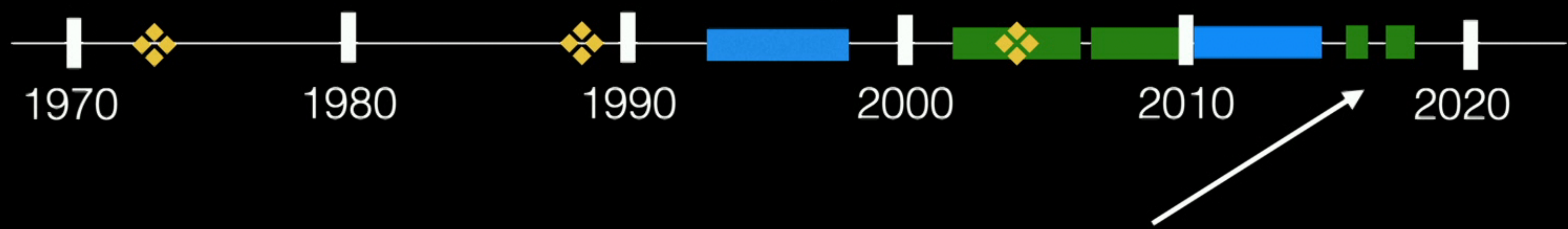


16



A brief history of LIGO
1970
1980
1990
2000
2010
2020
Black Holes of Known Mass
After the first aLIGO observing run, O1
70
60
50
40
30
20
10
0
Solar Masses
LIGO
X-Ray Studies
GW150914
GW151226
LVT151012
O1: ~1 detection per month
LIGO/Caltech
17

A brief history of LIGO

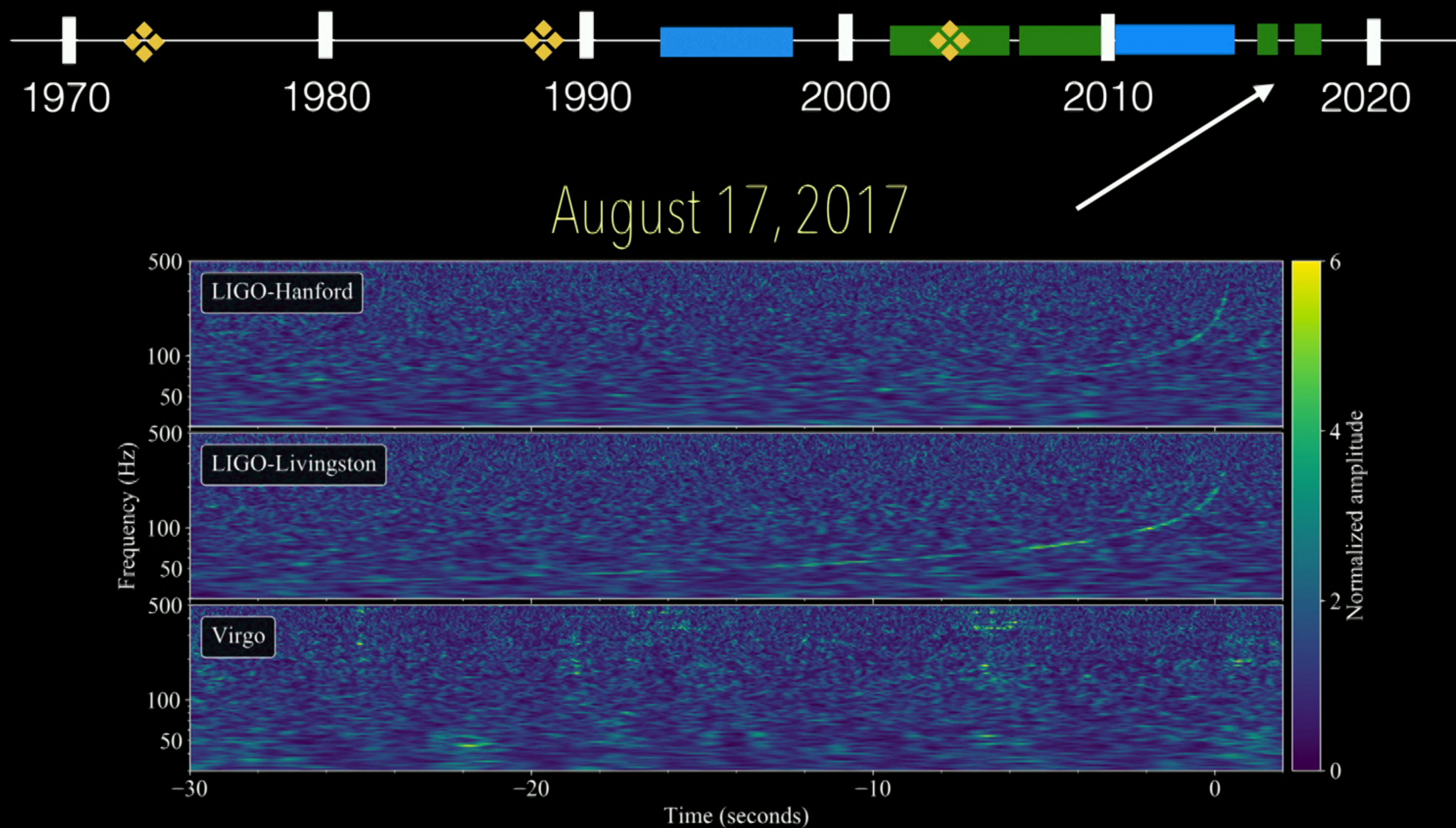


Nov 30 2016 - Aug 26 2017:

Advanced LIGO's second observing run (O2)

18

A brief history of LIGO



LIGO/Virgo/Lovelace, Brown, Macleod, McIver, Nitz

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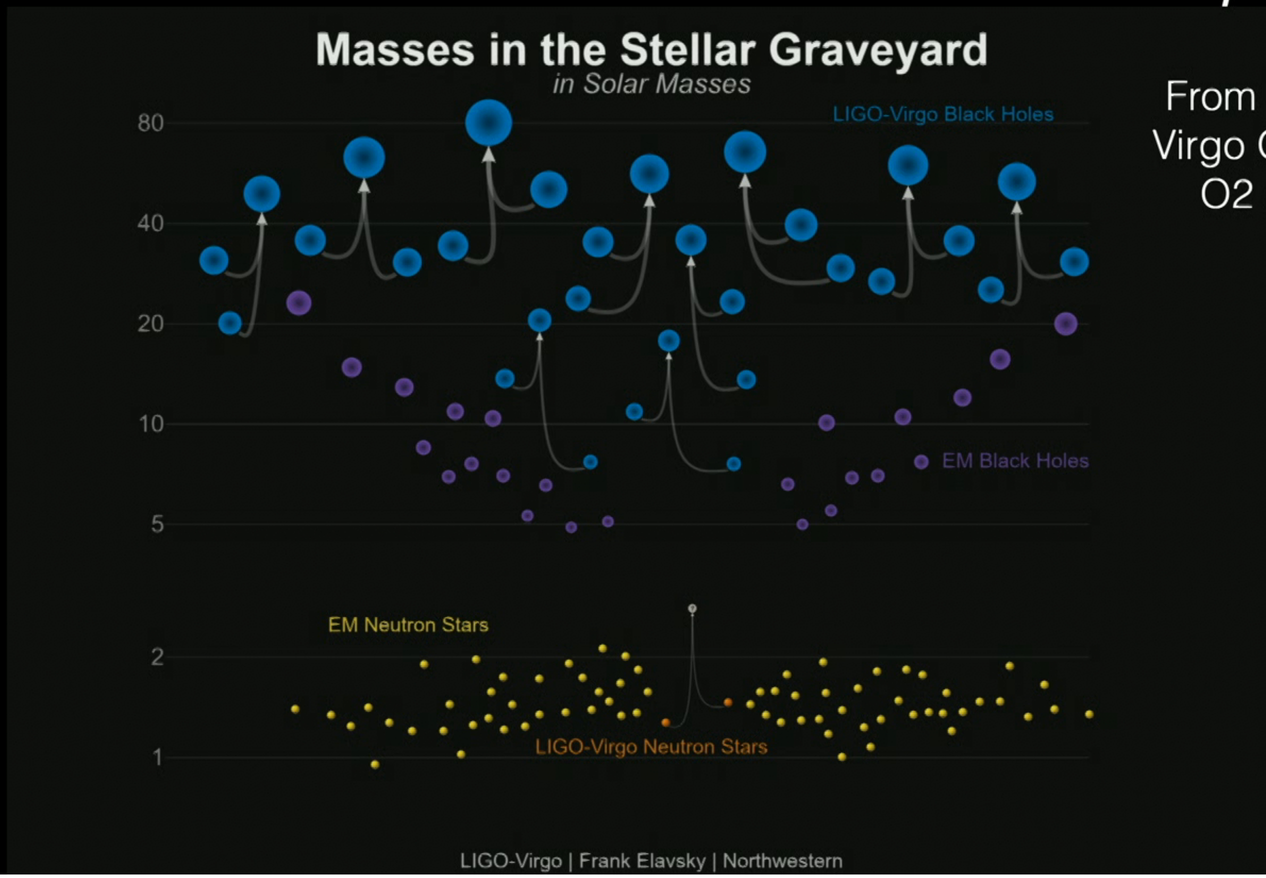
NASA/Goddard Space Flight Center/CI Lab
20

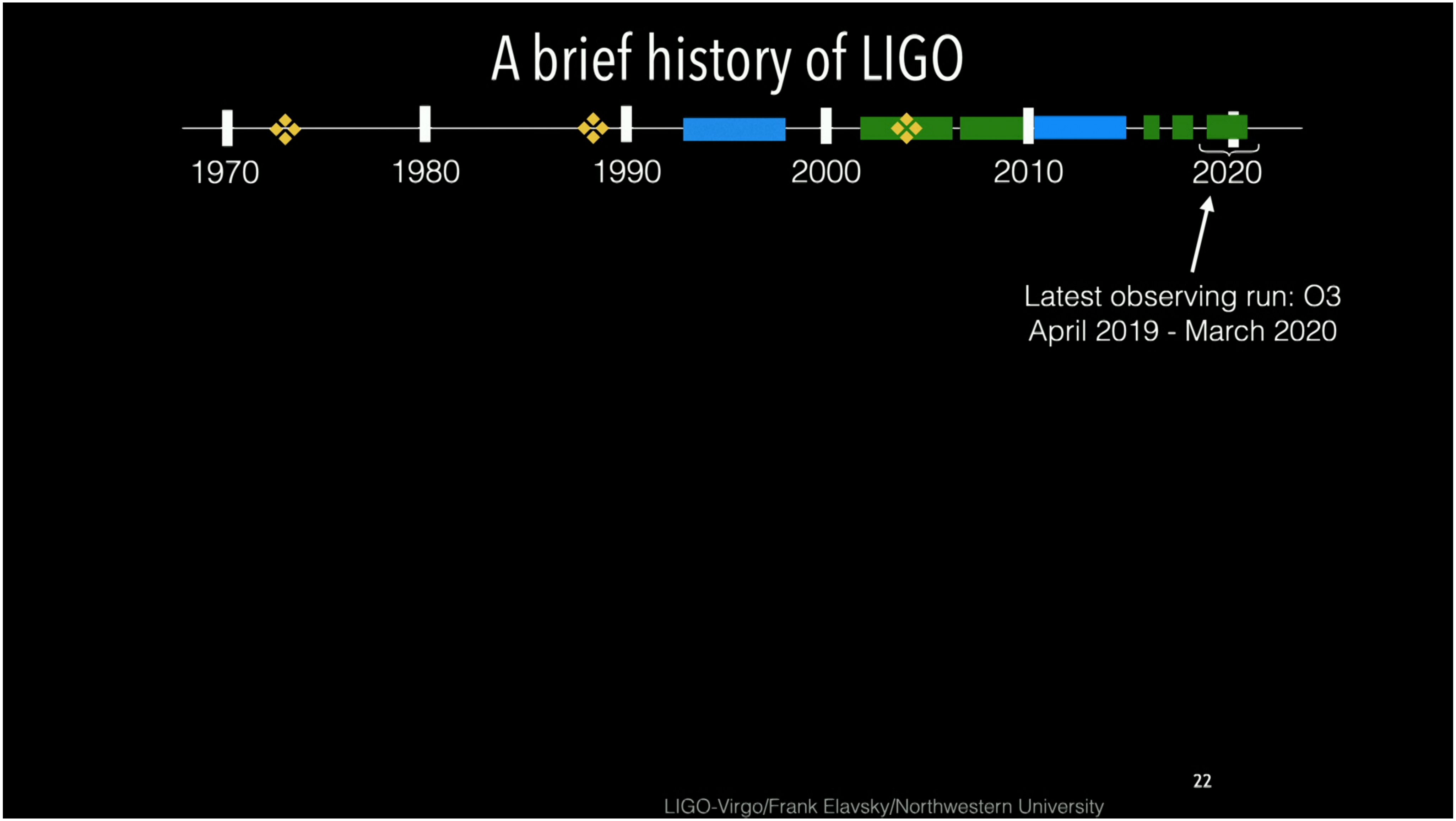
A brief history of LIGO: results from O2



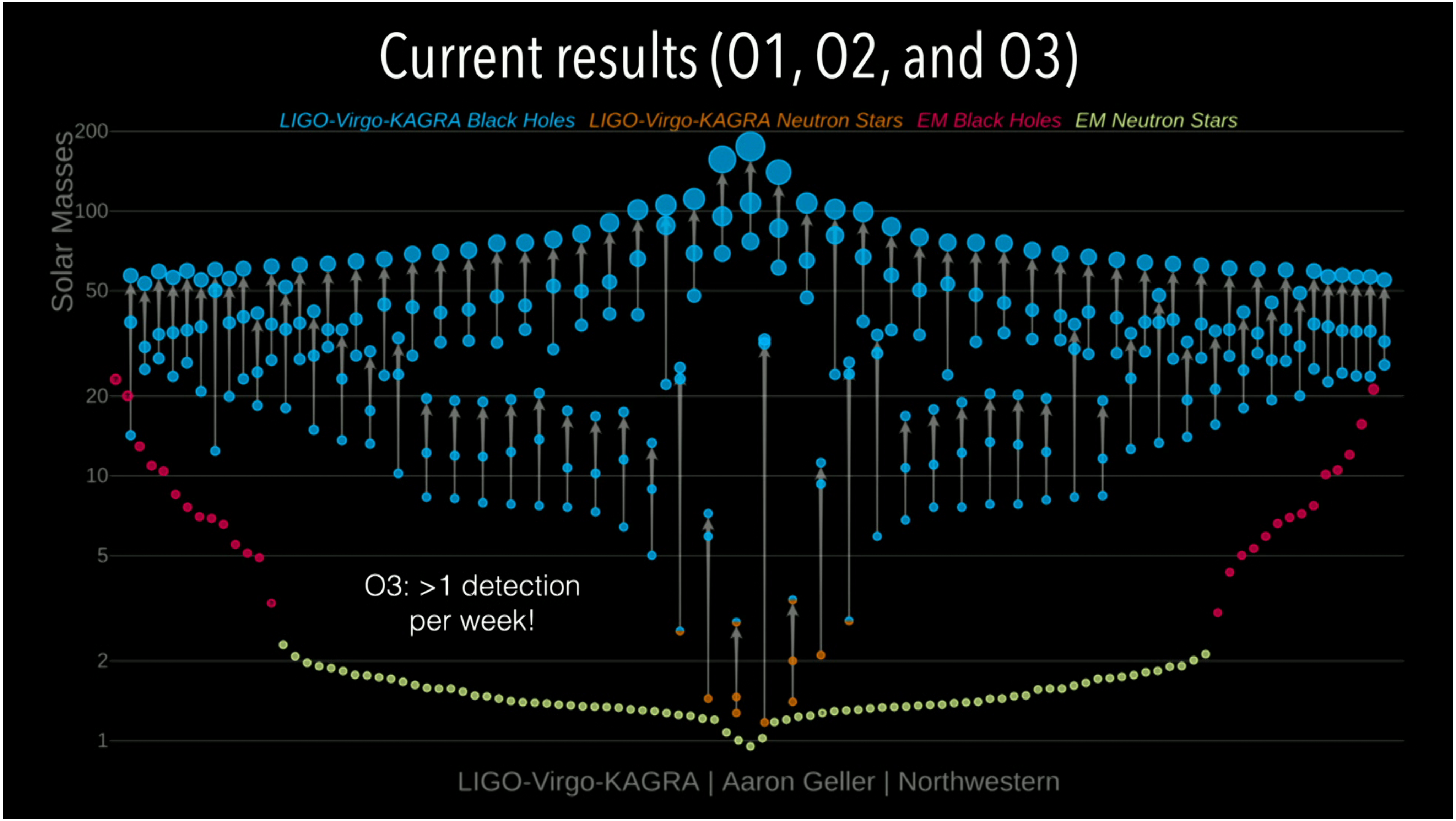
From LIGO-Virgo O1 and O2 runs

O2: ~1 detection every 2.5 weeks

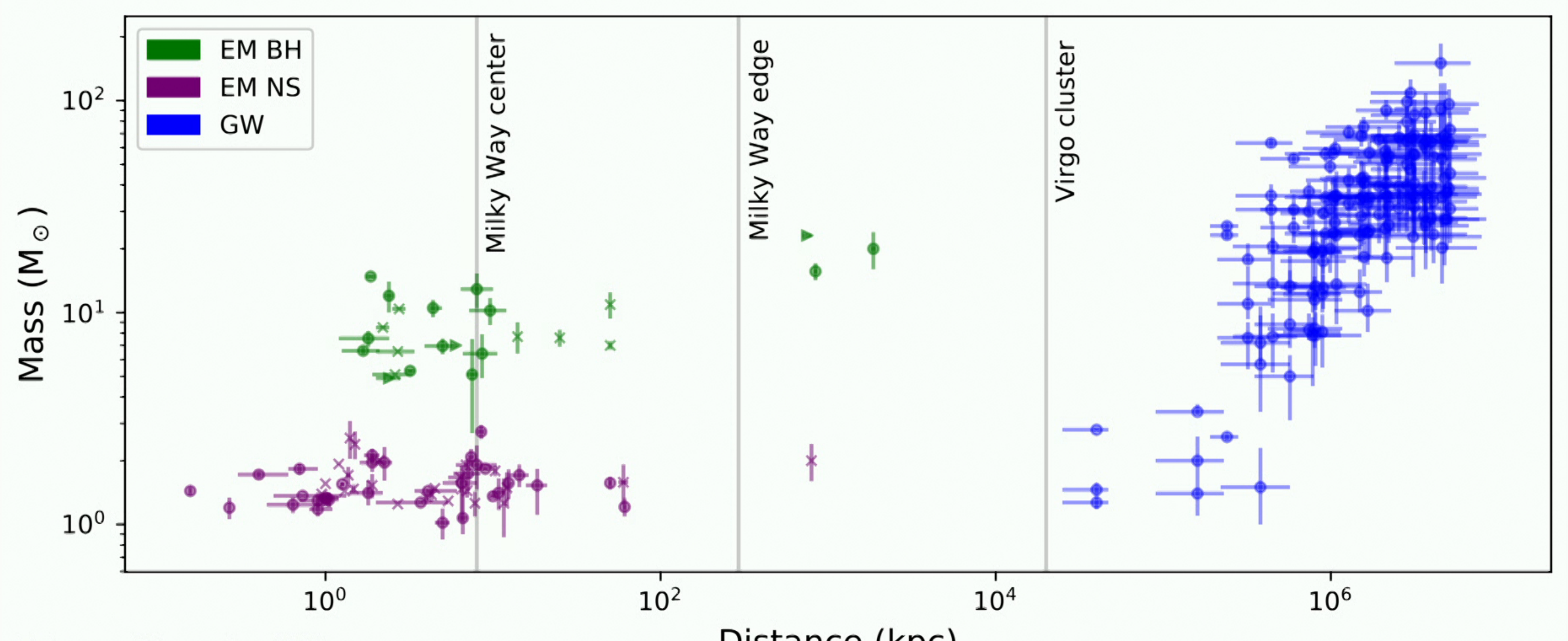
21



A brief history of LIGO
1970
1980
1990
2000
2010
2020
Latest observing run: O3
April 2019 - March 2020
22
LIGO-Virgo/Frank Elavsky/Northwestern University

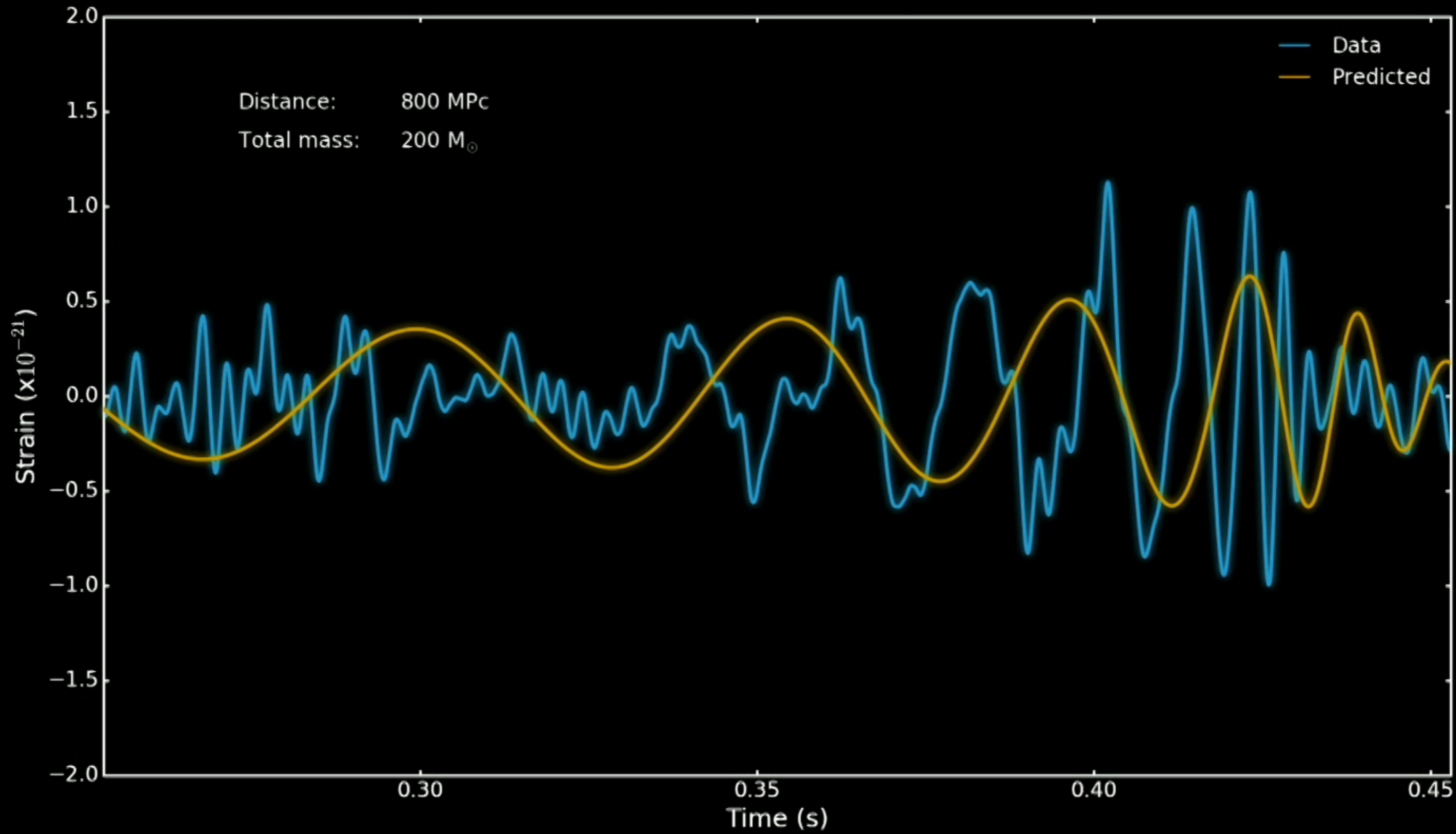

Current results (O1, O2, and O3)
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
O3: >1 detection
per week!
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Known compact object masses vs. estimated distance



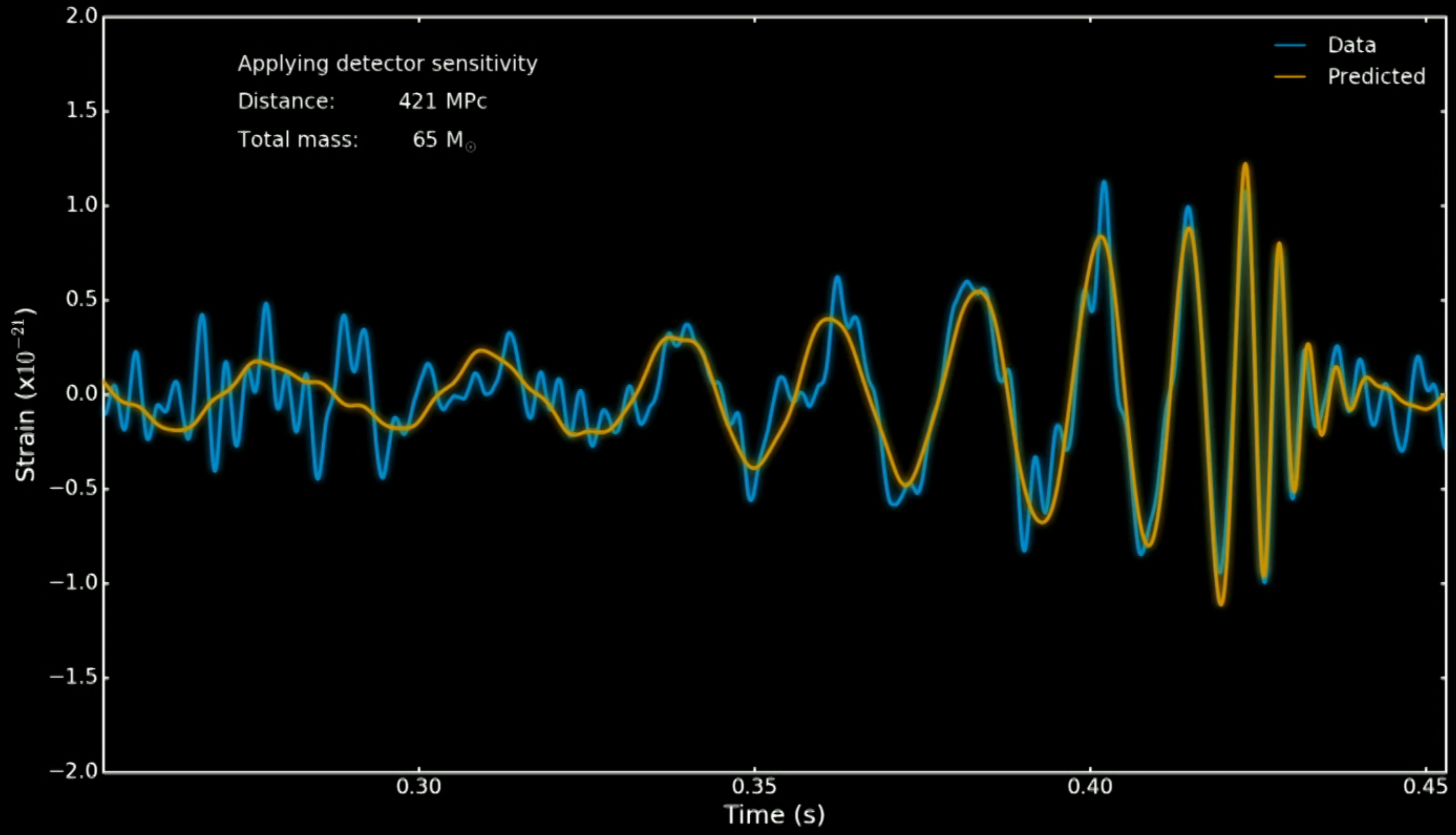
McIver and Shoemaker, 2021

Inferring mass and distance



Credit: LIGO/Cardiff University/C.North/M.Hannam

Inferring mass and distance

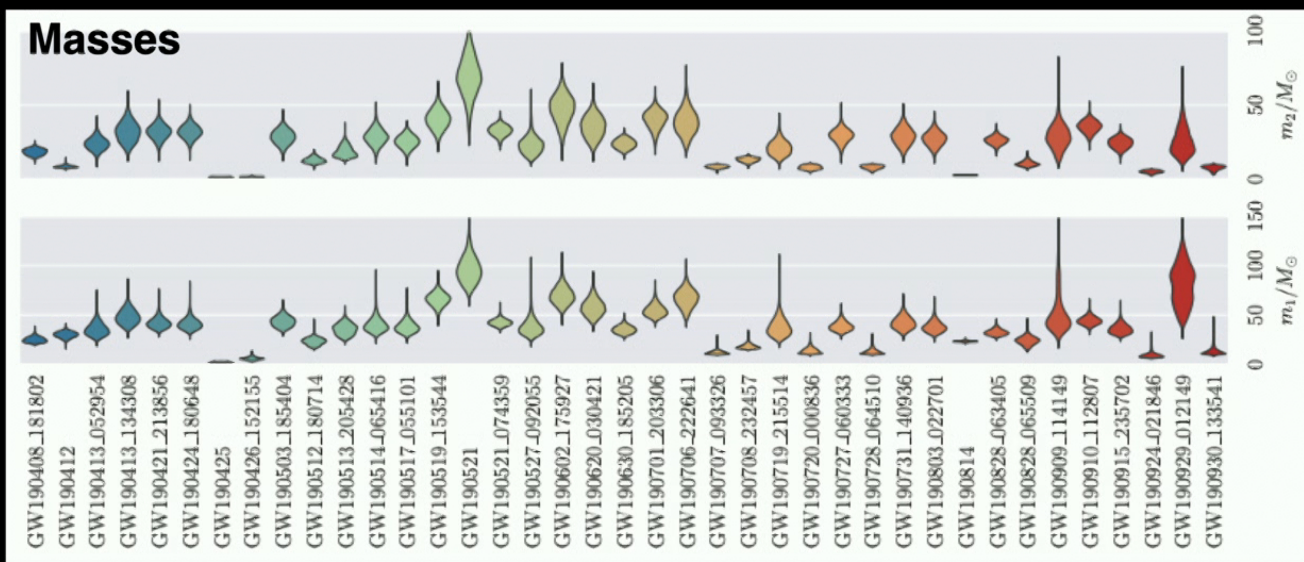


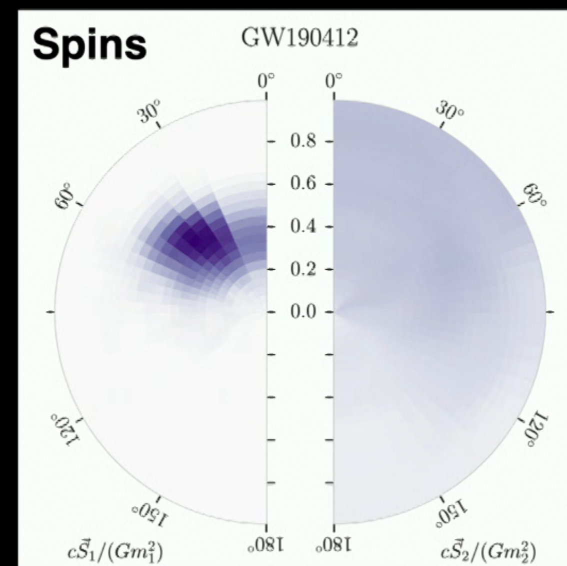
Credit: LIGO/Cardiff University/C.North/M.Hannam

Bayesian inference of source properties

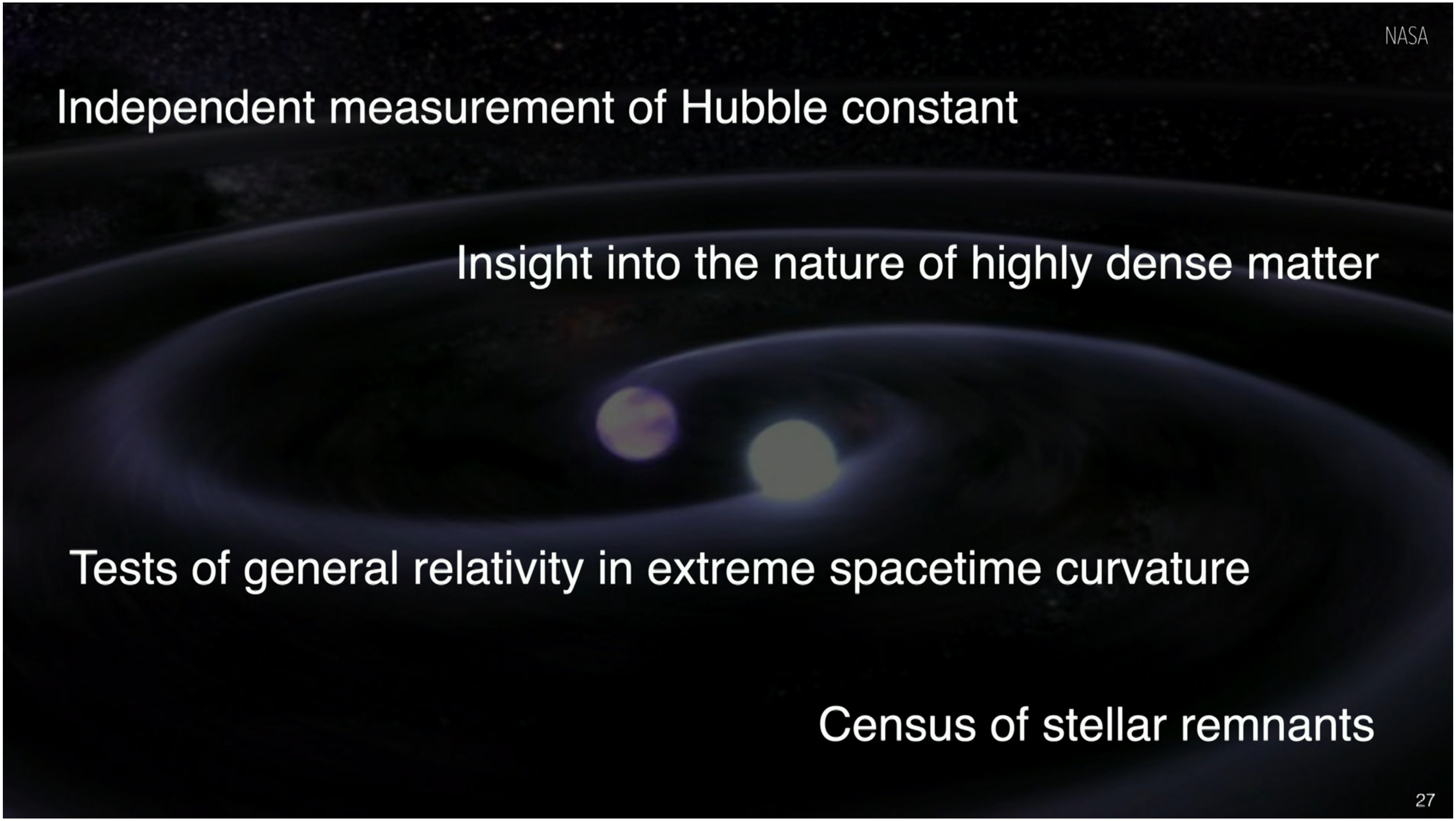
$$d = h + n.$$ ⟵ Data model d = signal (through lens of detector network) h + detector noise n

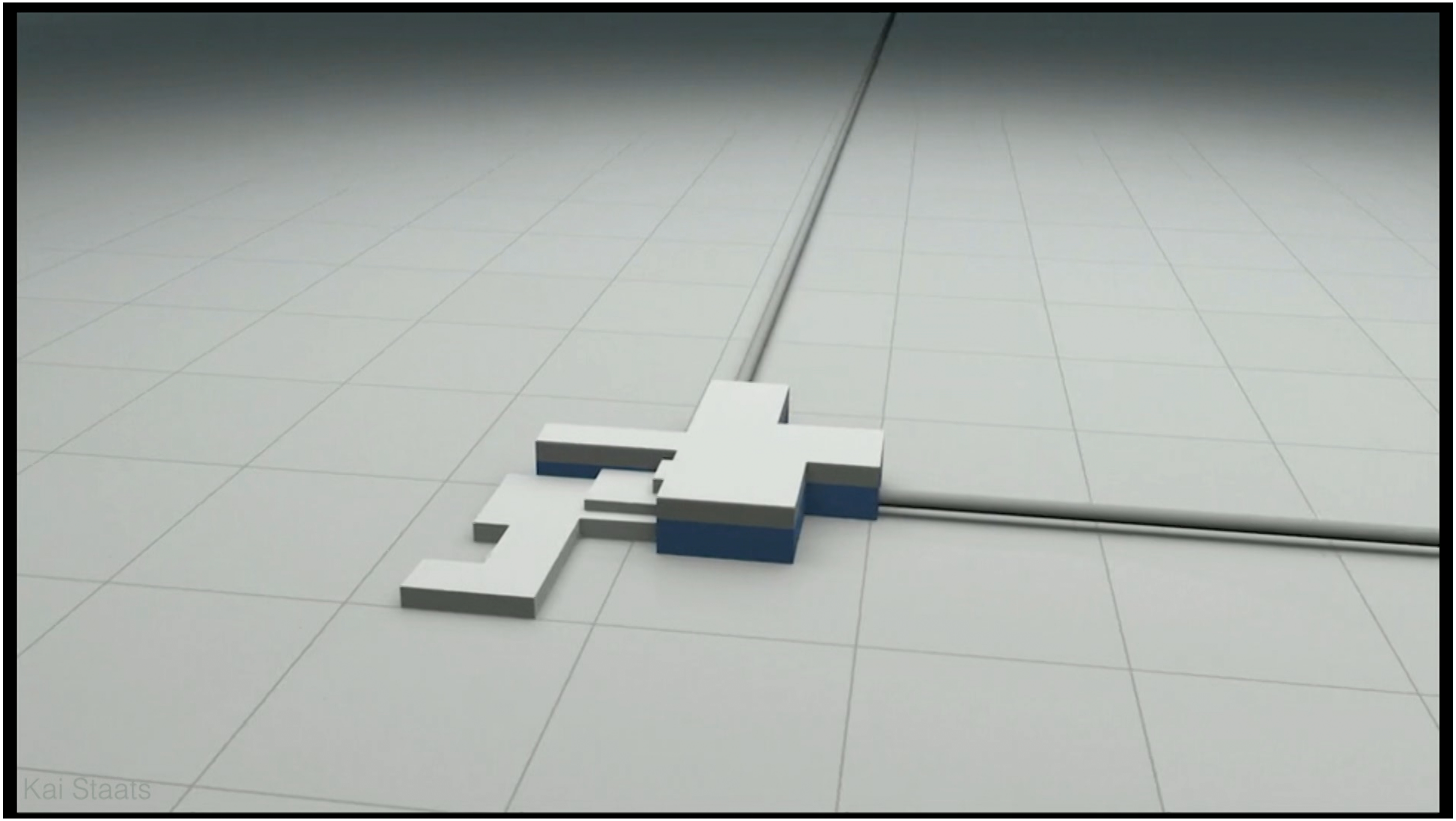
$$p(\boldsymbol{d}|H_N, S_n(f)) = \exp \sum_i \left[-\frac{2|\tilde{d}_i|^2}{T S_n(f_i)} - \frac{1}{2} \log(\pi T S_n(f_i)/2) \right]$$ ⟵ Likelihood: we expect the residual of d-h to be consistent with Gaussian noise

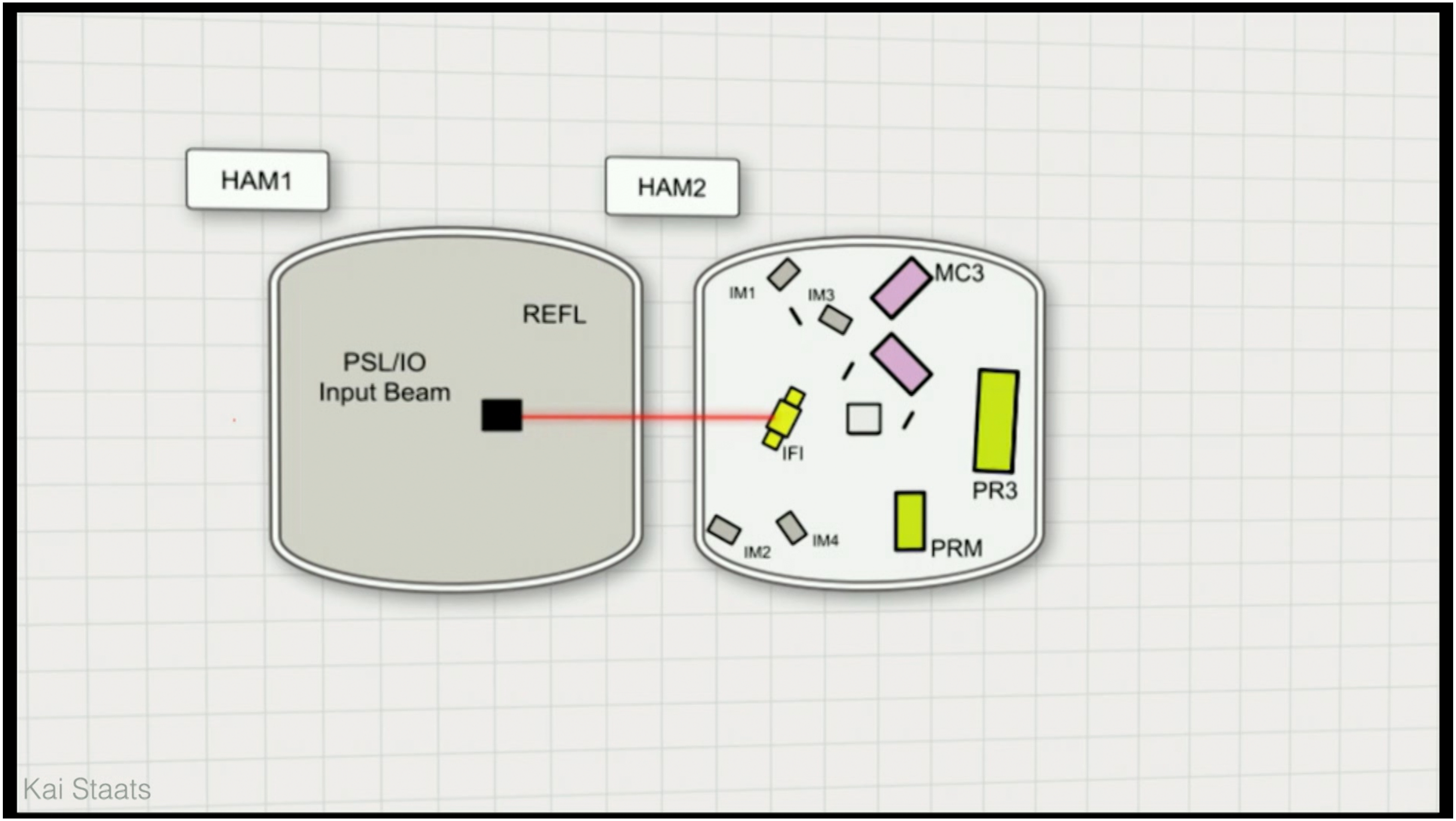


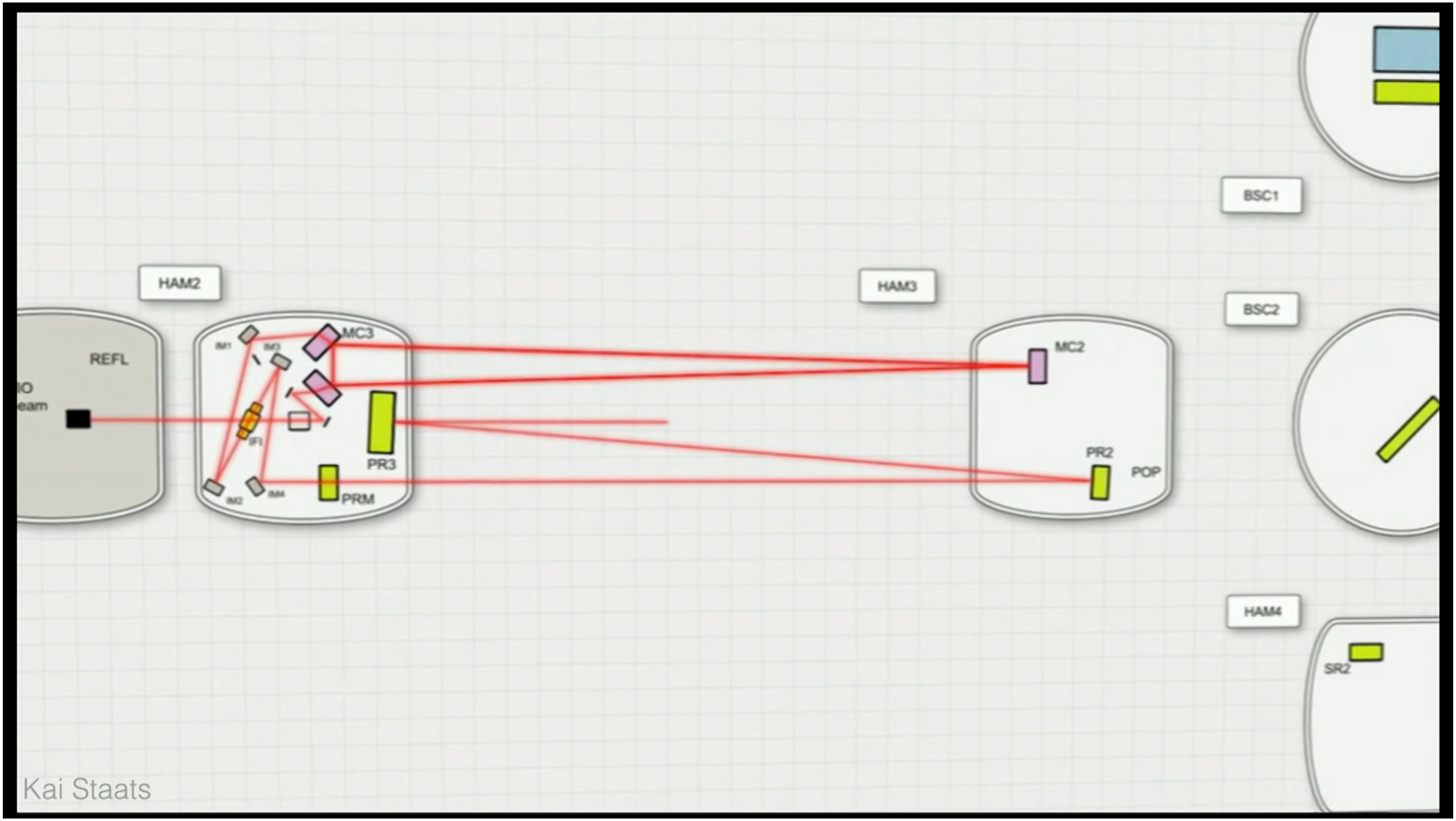


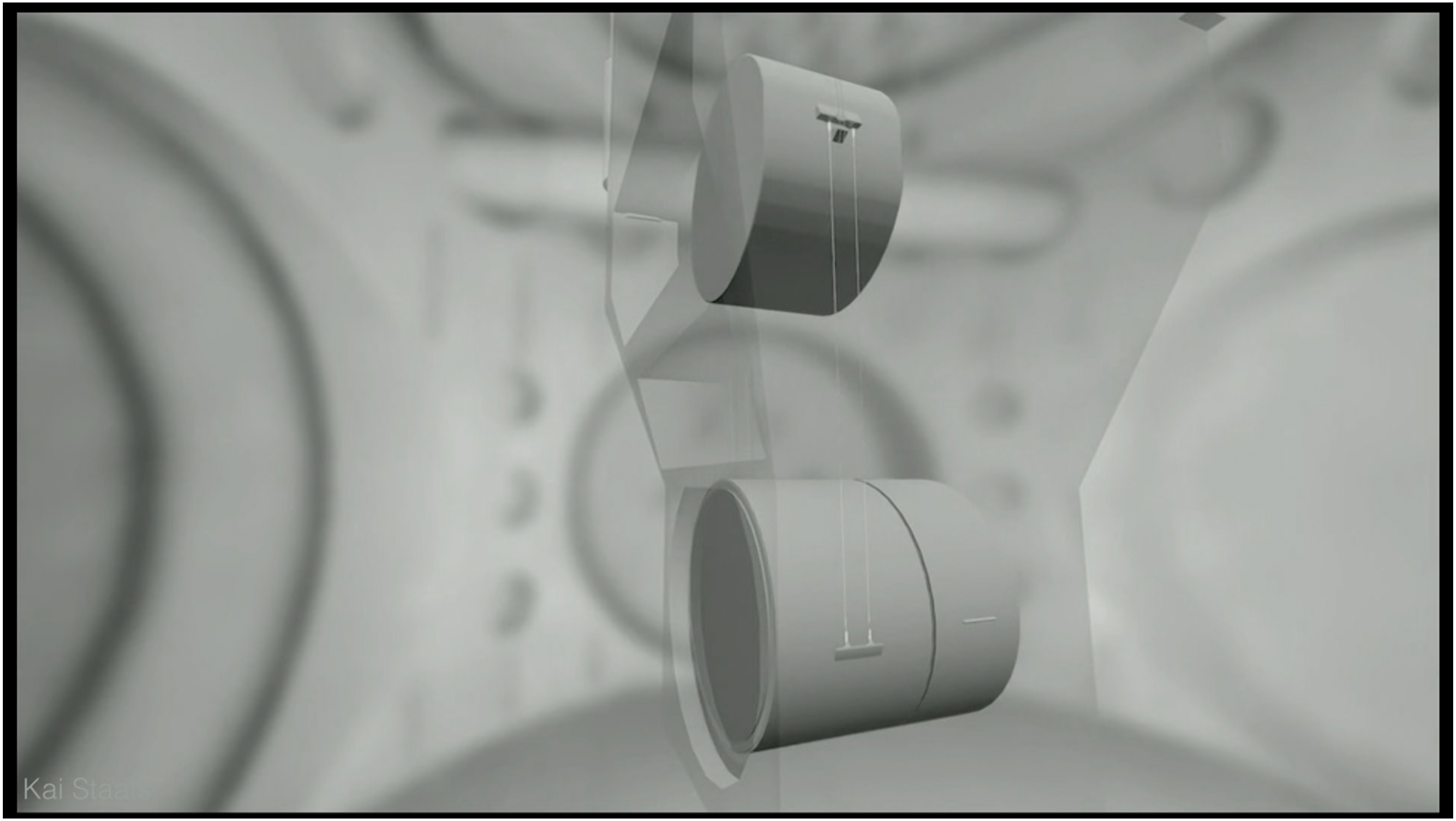
LIGO/Virgo GWTC-2 (2020)

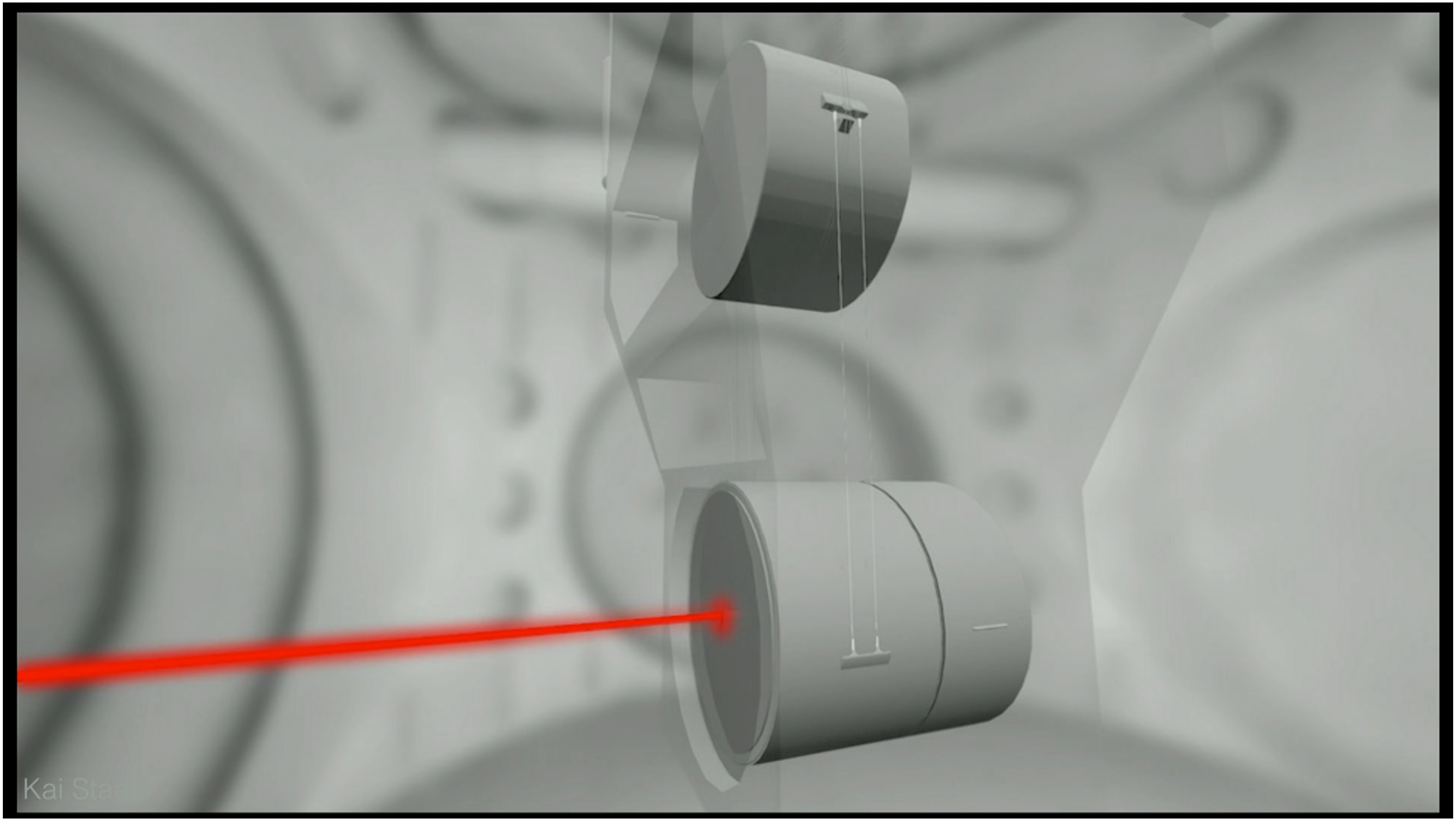

NASA
Independent measurement of Hubble constant
Insight into the nature of highly dense matter
Tests of general relativity in extreme spacetime curvature
Census of stellar remnants
27

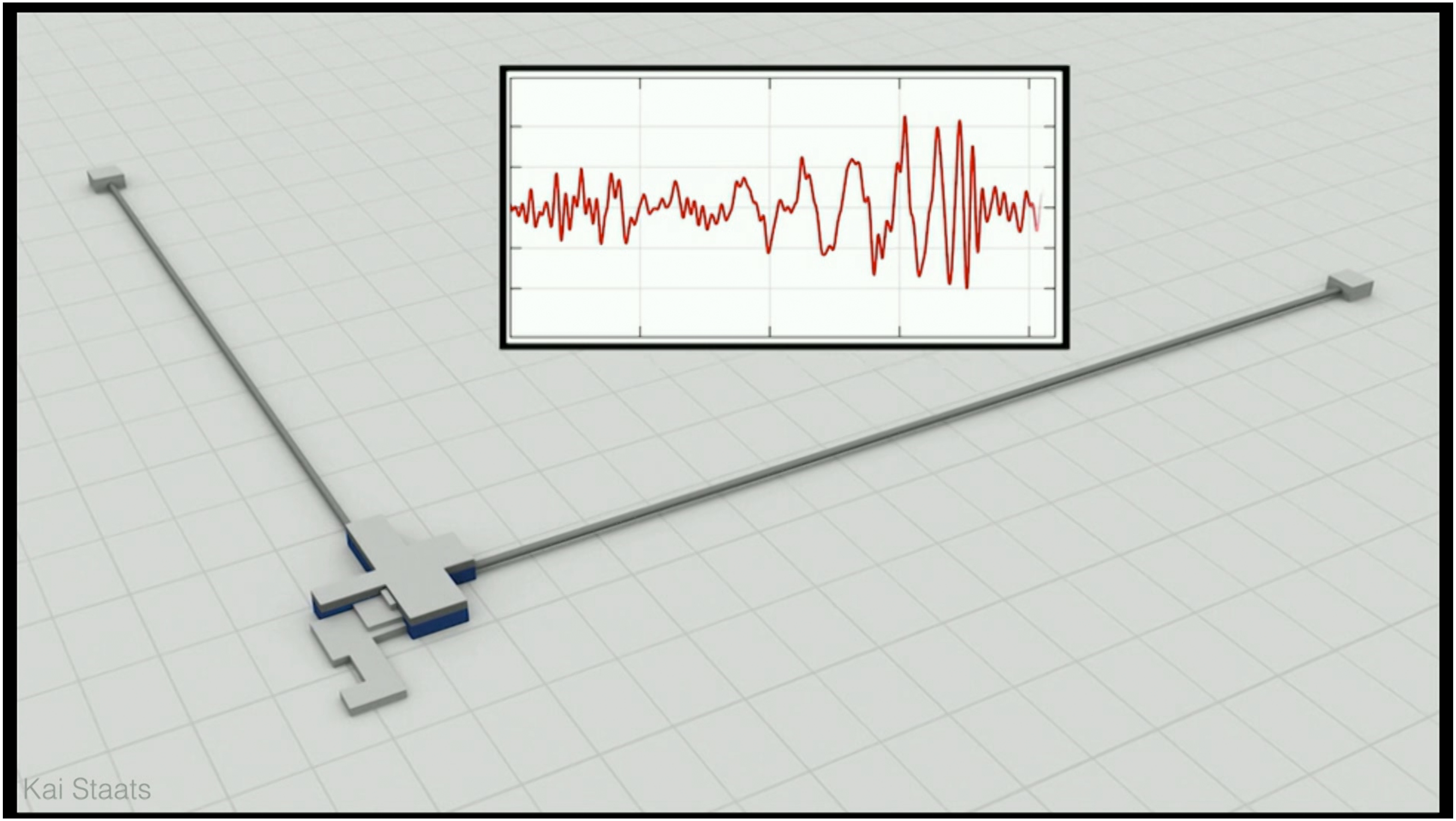

Kai Staats


HAM1
HAM2
REFL
PSL/IO
Input Beam
MC3
IM1
IM3
IFI
PR3
PRM
IM2
IM4
Kai Staats

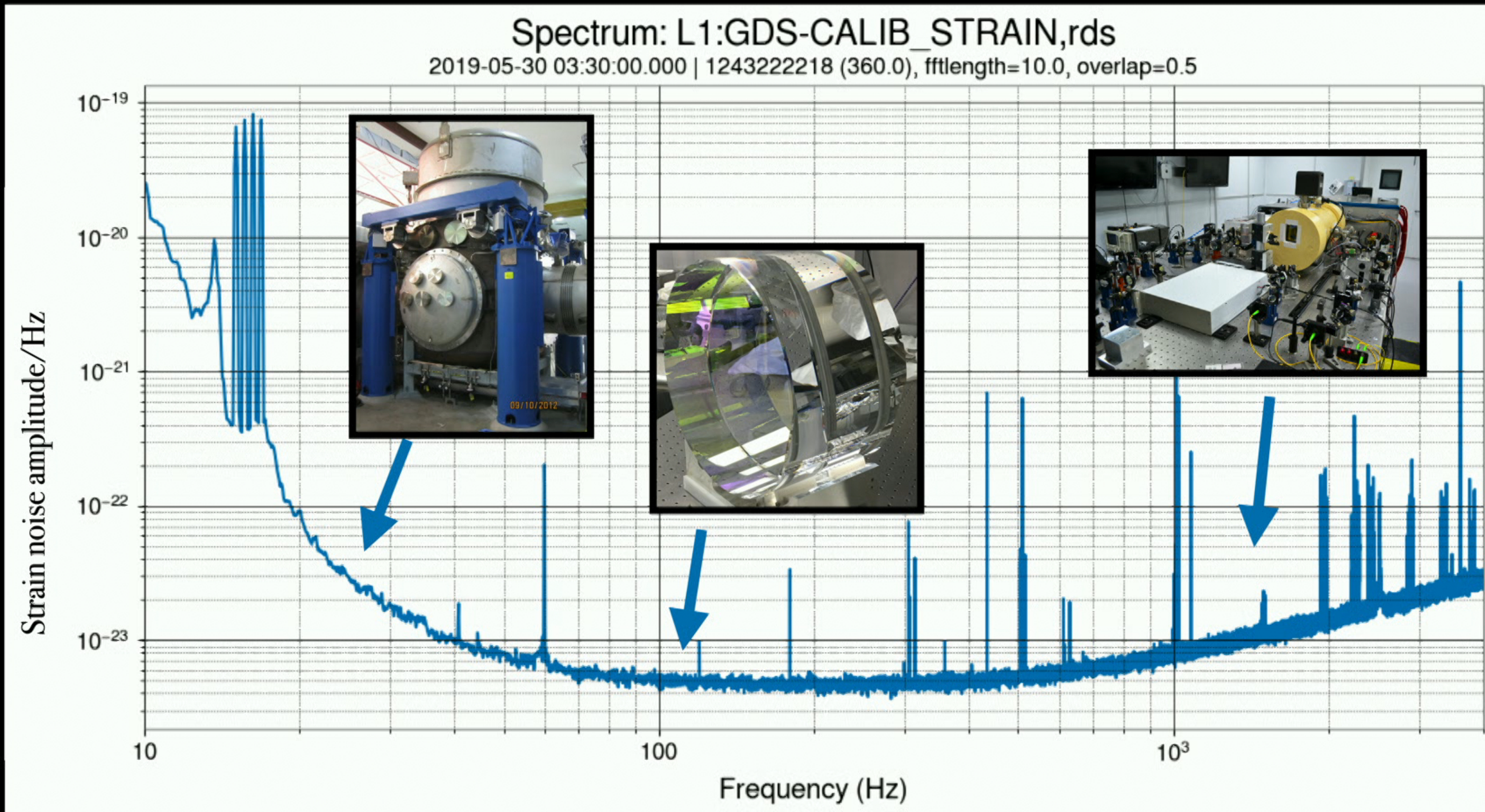

HAM2
HAM3
BSC1
BSC2
HAM4
REFL
IO
eam
MC3
PR3
PRM
IFI
MC2
PR2
POP
SR2
Kai Staats


Kai Staats


Kai Staats


Kai Staats

Advanced LIGO noise



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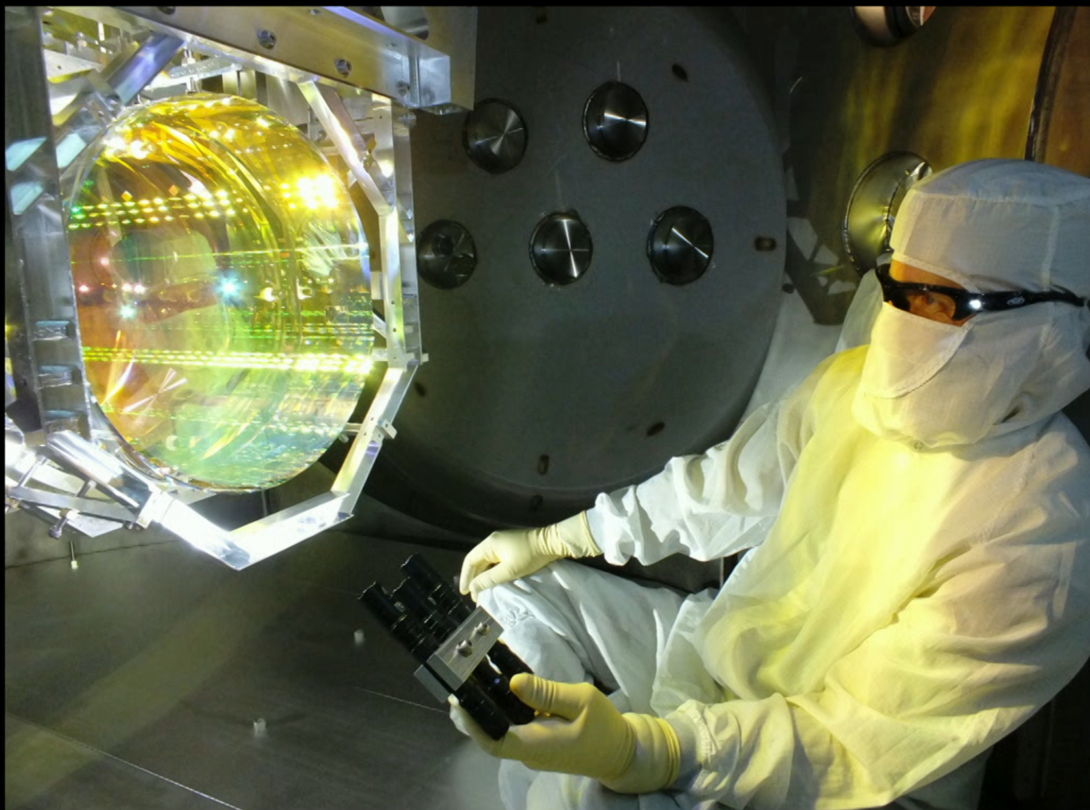
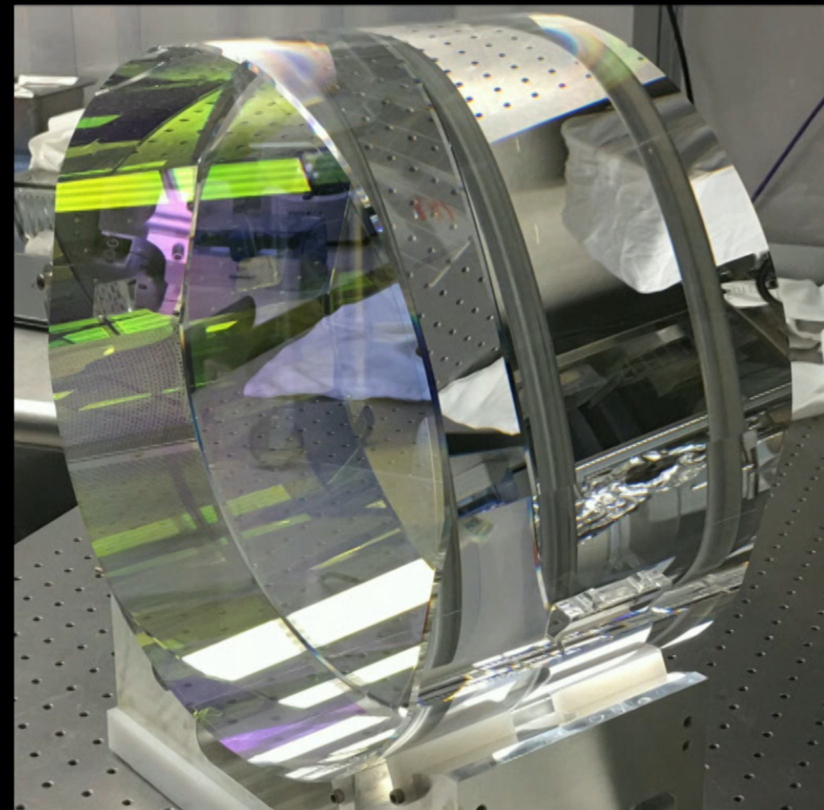
Advanced LIGO optics and coatings

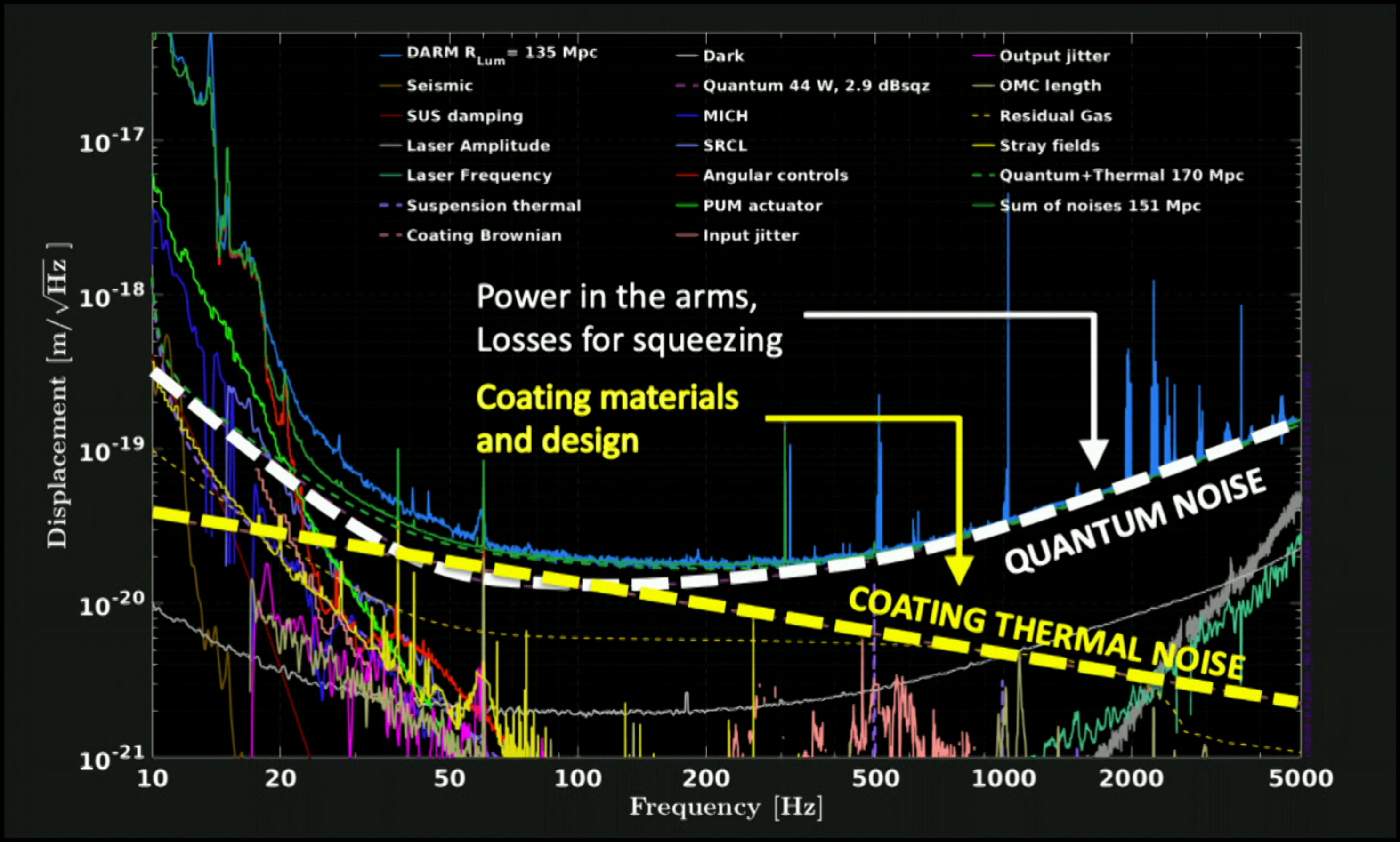




M. Heintze

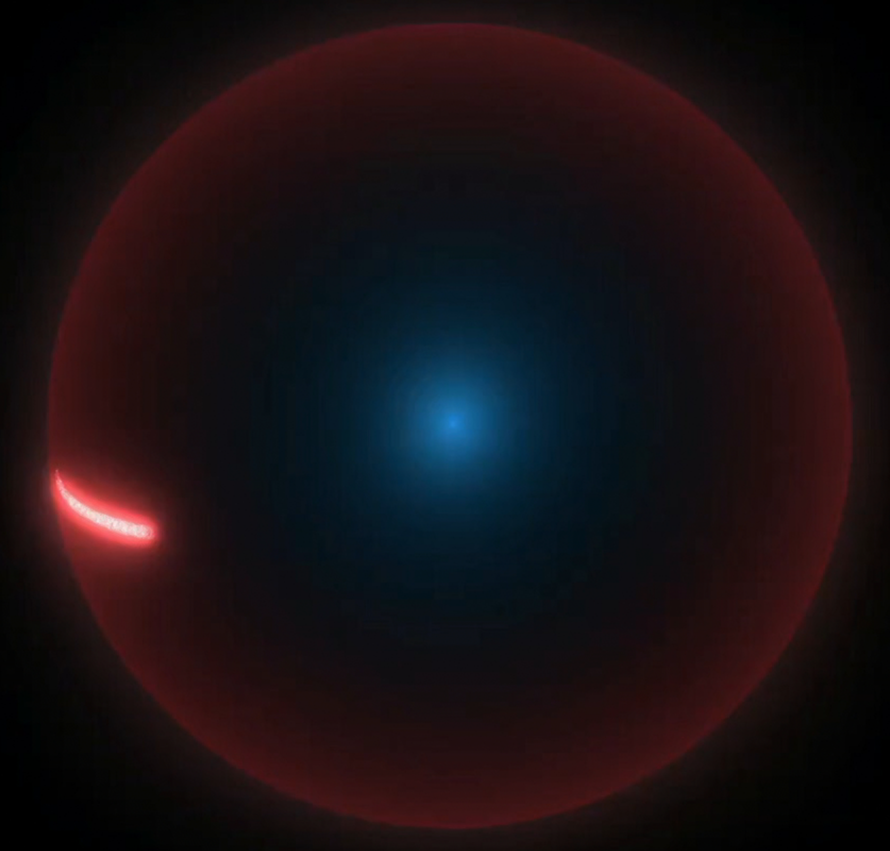
K. Toland

Advanced LIGO noise budget

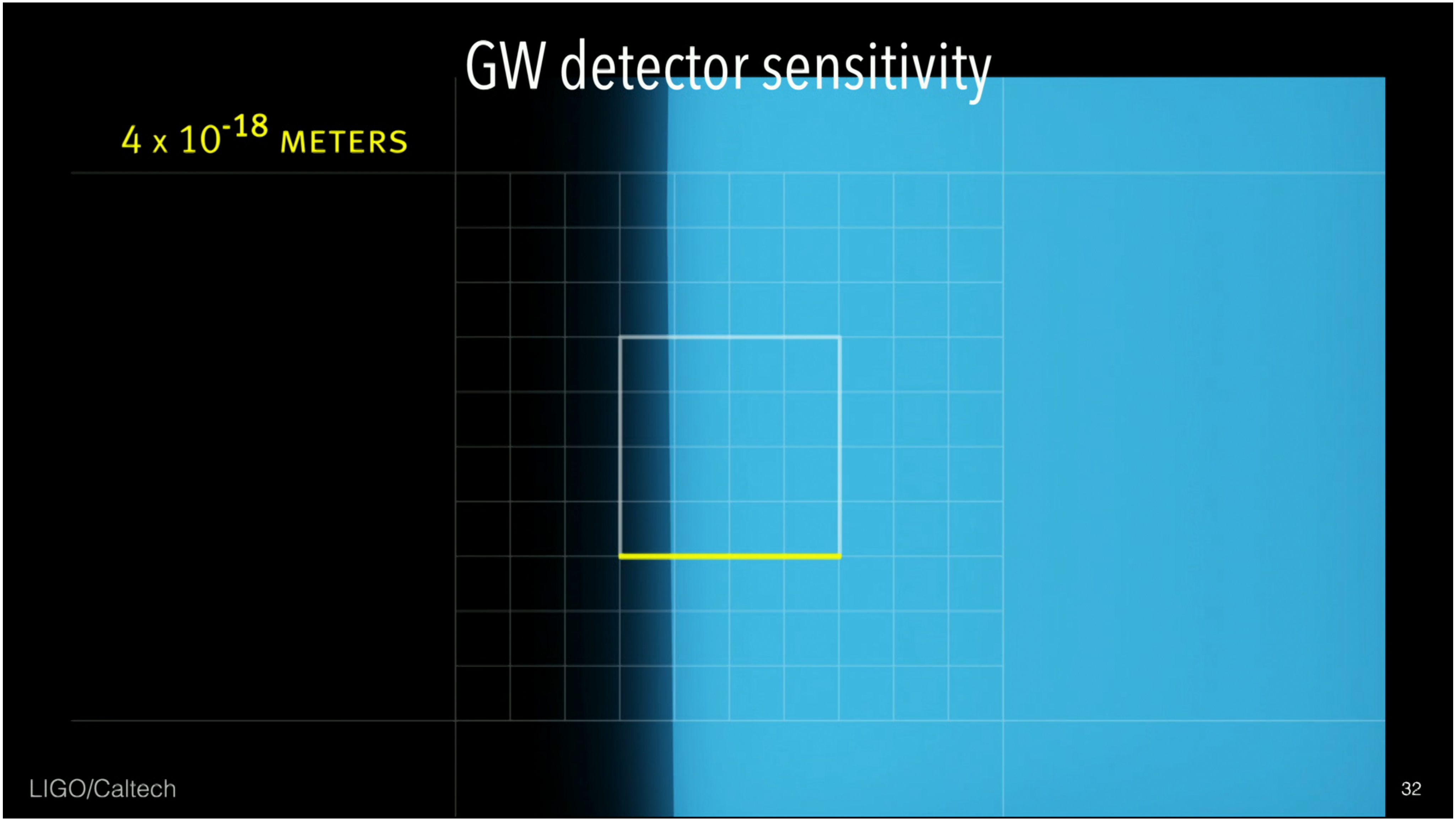


https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=48889. Slide by G. Vajente

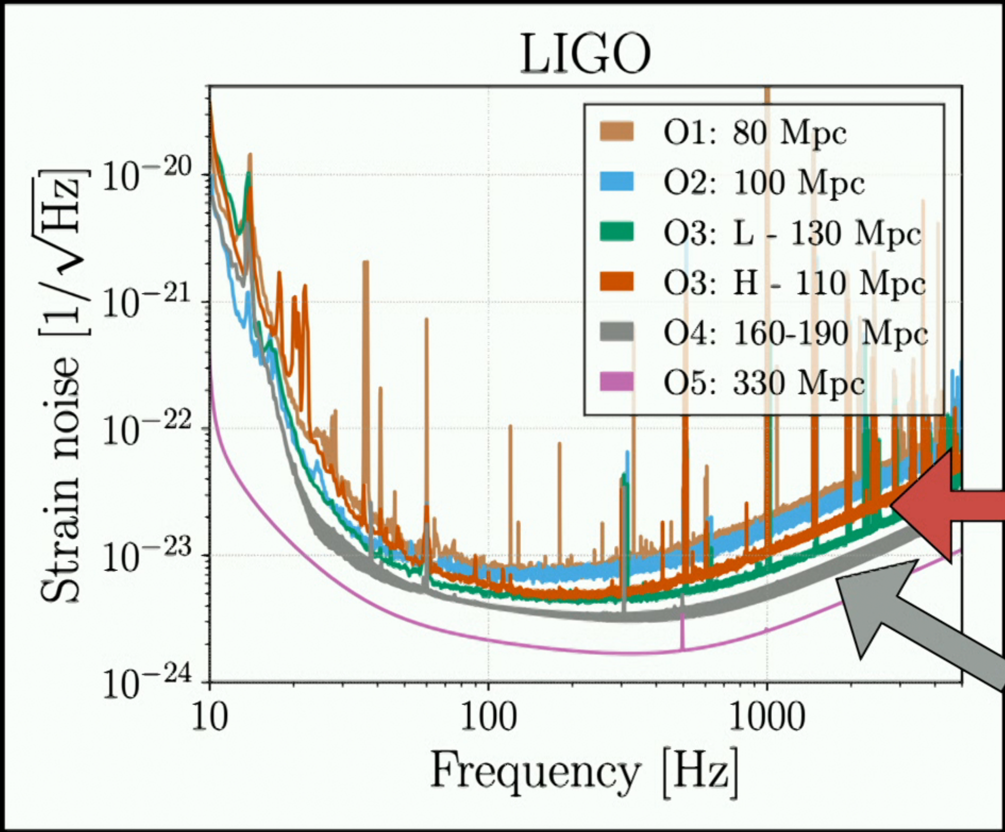
GW detector sensitivity



LIGO/Caltech


GW detector sensitivity
4 x 10-18 METERS
LIGO/Caltech
32

Roadmap to LIGO design sensitivity



Currently preparing for O4, expected to start in March 2023

Expectation for the third LIGO observing run (O3)
1 signal/week!

Up to **1 signal/ day** at design sensitivity!

LIGO-Virgo arXiv 1304.0670 v11

The next generation of GW detectors

A+/AdV+
- 3-4 km detectors
- **300 K**
- 1064 nm laser
- 40 kg mirrors

2025

Voyager
- 4 km detectors
- **123 K**
- 1.5-2 microns
- 160 kg mirrors

2030

Einstein Telescope
- 10 km detectors
- **300 K** and **< 23 K**
- 2 microns
- 200 kg mirrors

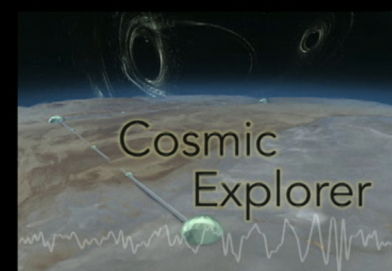
2035

Cosmic Explorer 1
- 20-40 km detectors

  300 K
- 1-2 microns (?)
- 320 kg mirrors

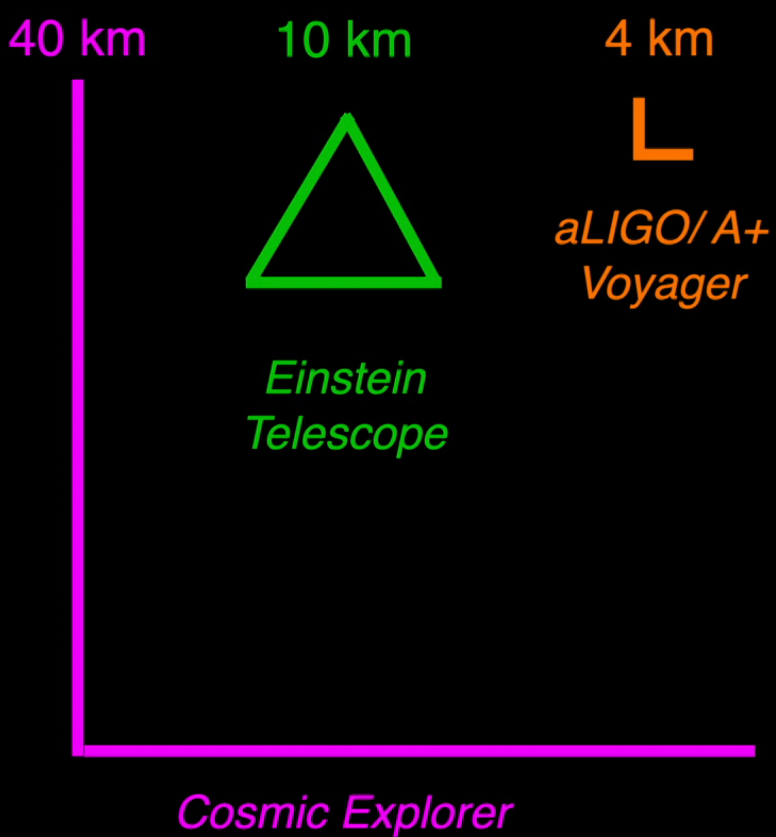
Cosmic Explorer 2
- 20-40 km detectors
- **123 K**
- 1-2 microns (?)
- 320 kg mirrors

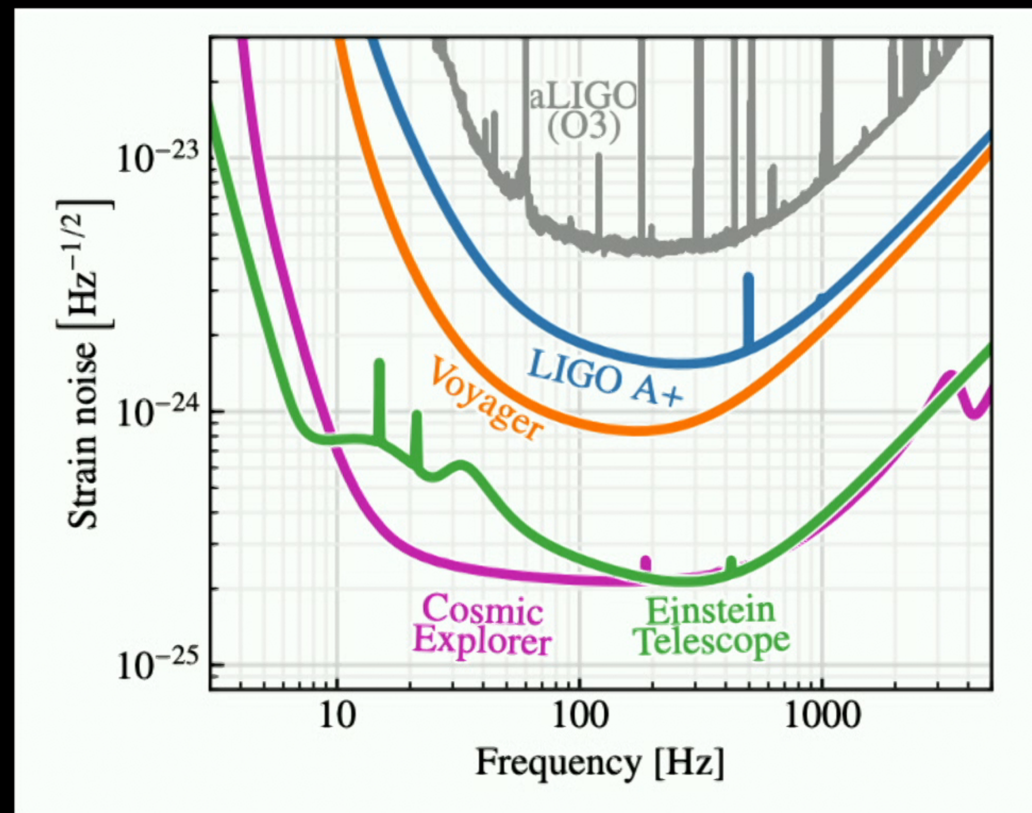
2040



Dawn IV workshop report (McIver et al, 2019); Cosmic Explorer Astro 2020 decadal submission (Reitze et al 2020); Einstein Telescope Conceptual Design Study (Punturo et al 2020)

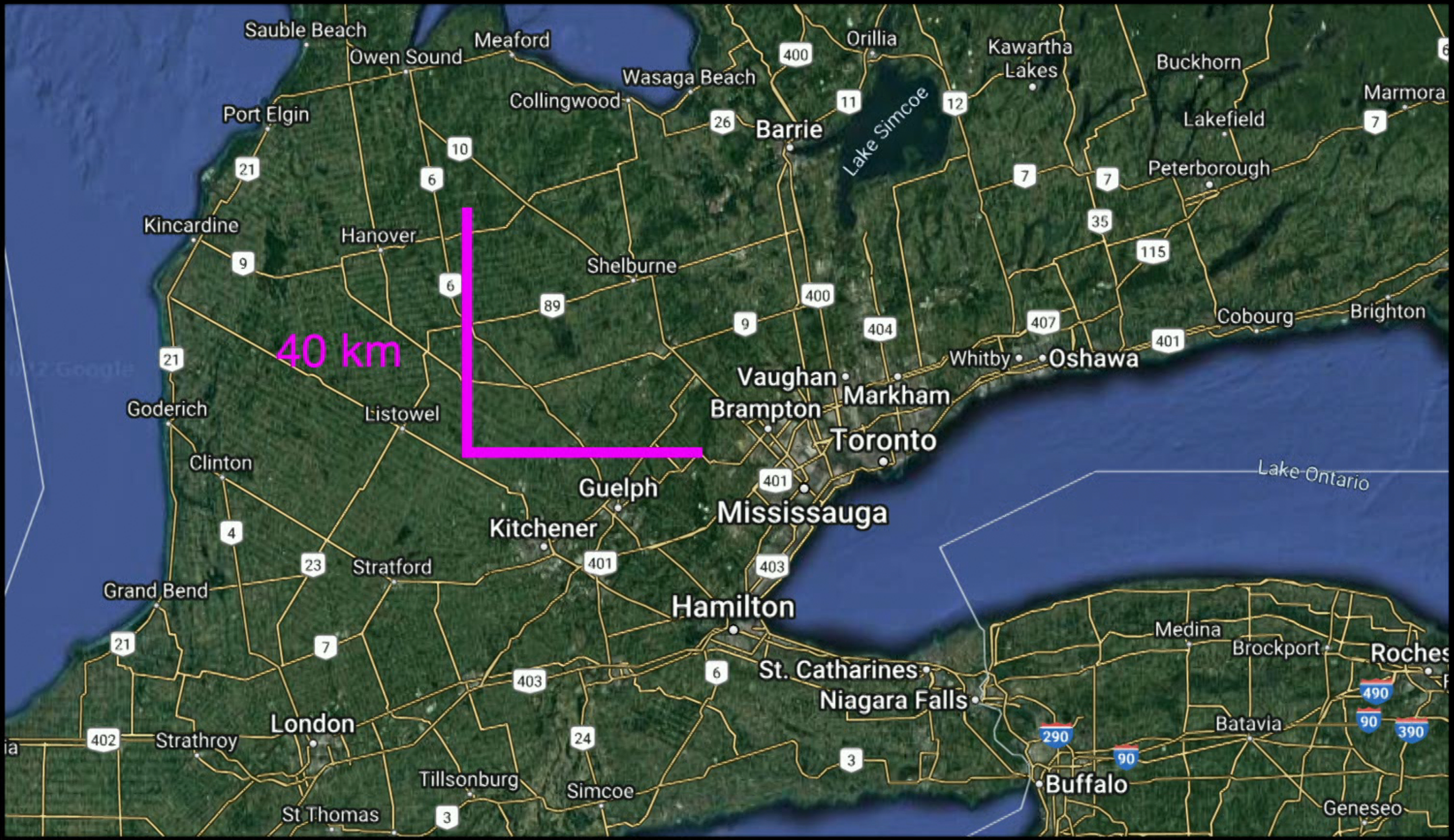
The next generation GW detectors



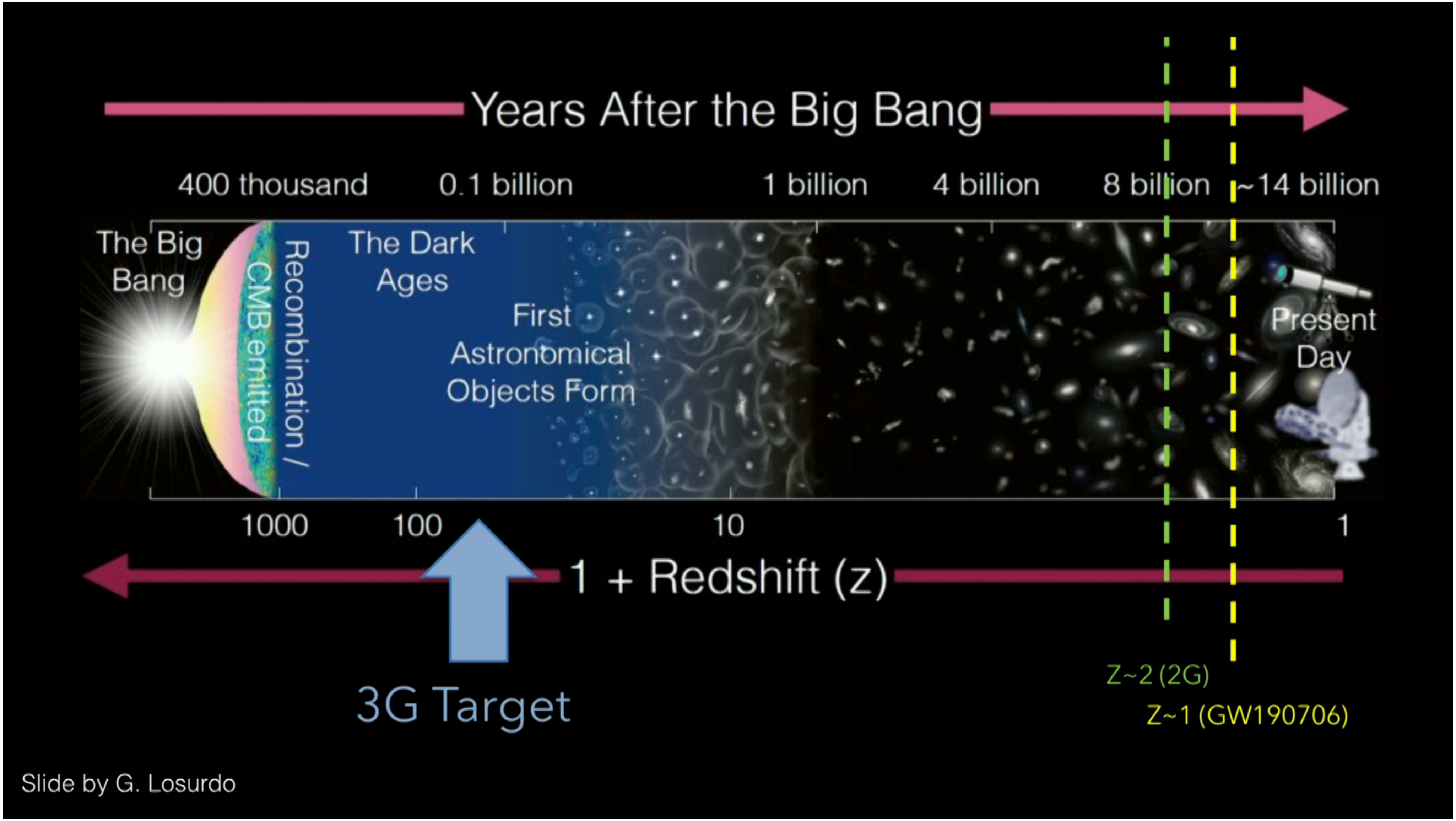


S. Gossan et al. ApJ 926 231 (2022)

The next generation GW detectors

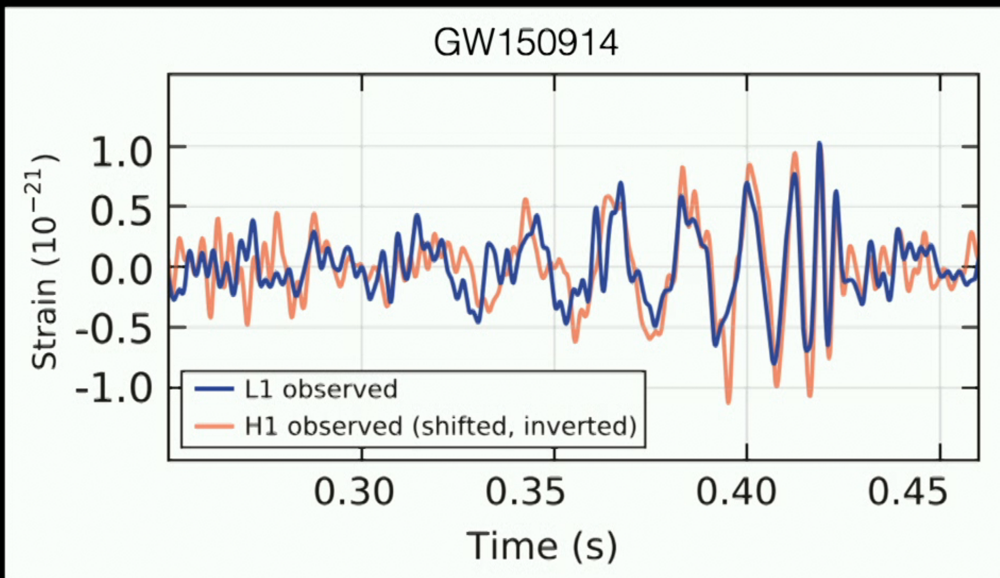


Google maps

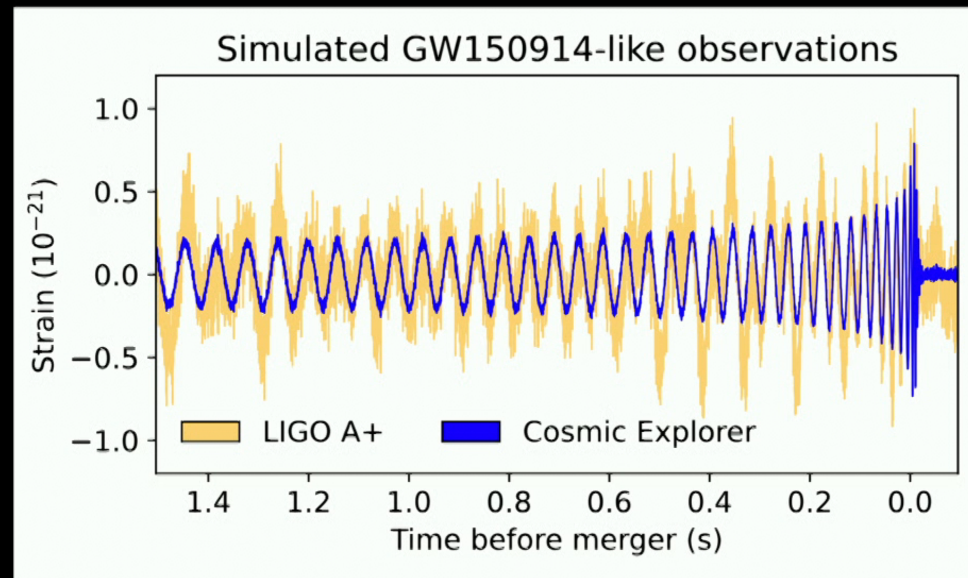


Years After the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
~14 billion
The Big Bang
CMB emitted
Recombination /
The Dark Ages
First Astronomical Objects Form
Present Day
1000
100
10
1
1 + Redshift (z)
3G Target
Z~2 (2G)
Z~1 (GW190706)
Slide by G. Losurdo

Along with cosmological reach: large SNRs



LIGO-Virgo, PRL 116.061102 (2016)



CE Horizon Study, CE–P2100003–v7 (2021)

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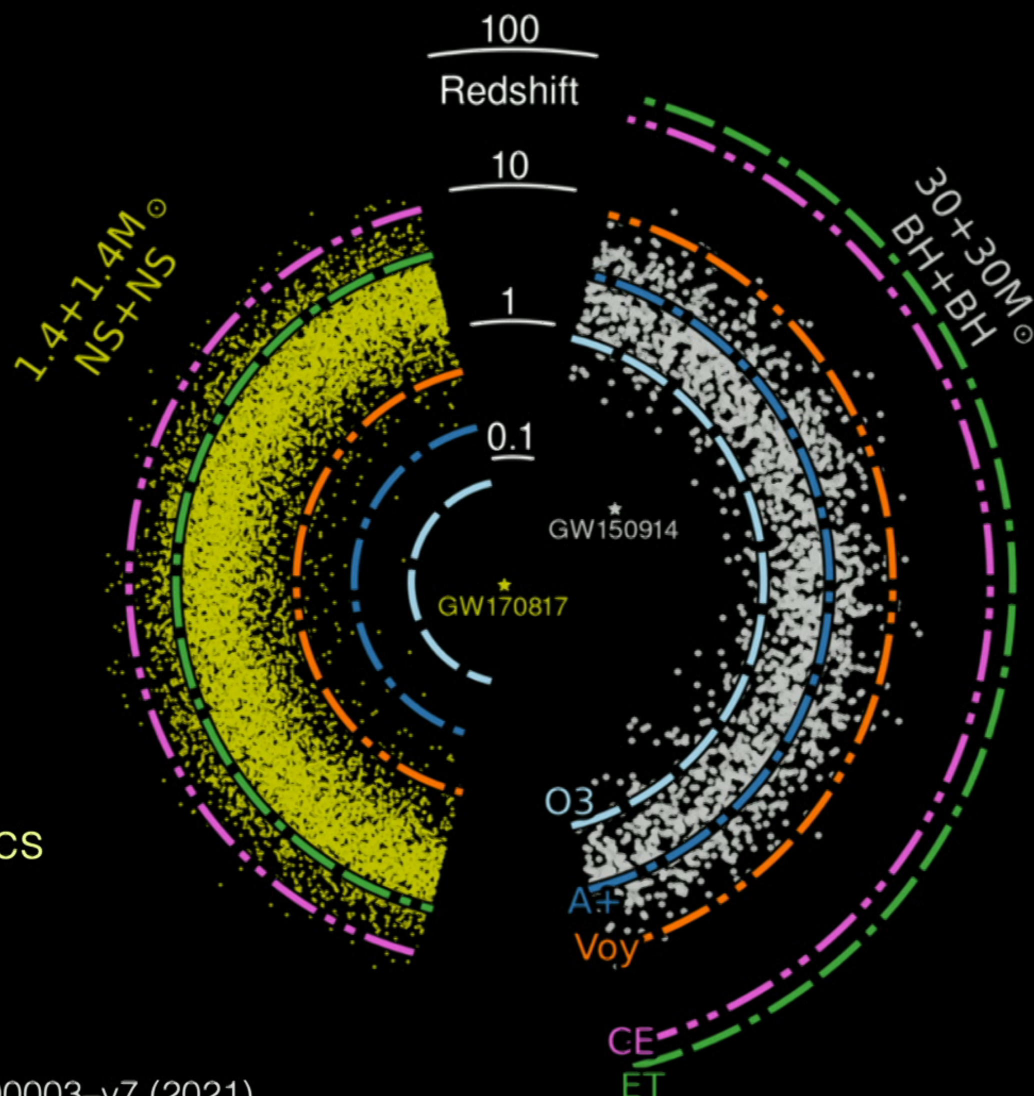
300,000 BNS mergers!

1 merger every 100 seconds!

~5 will have SNR >300, unlocking post merger physics (NS EoS)



100,000 BBH mergers!

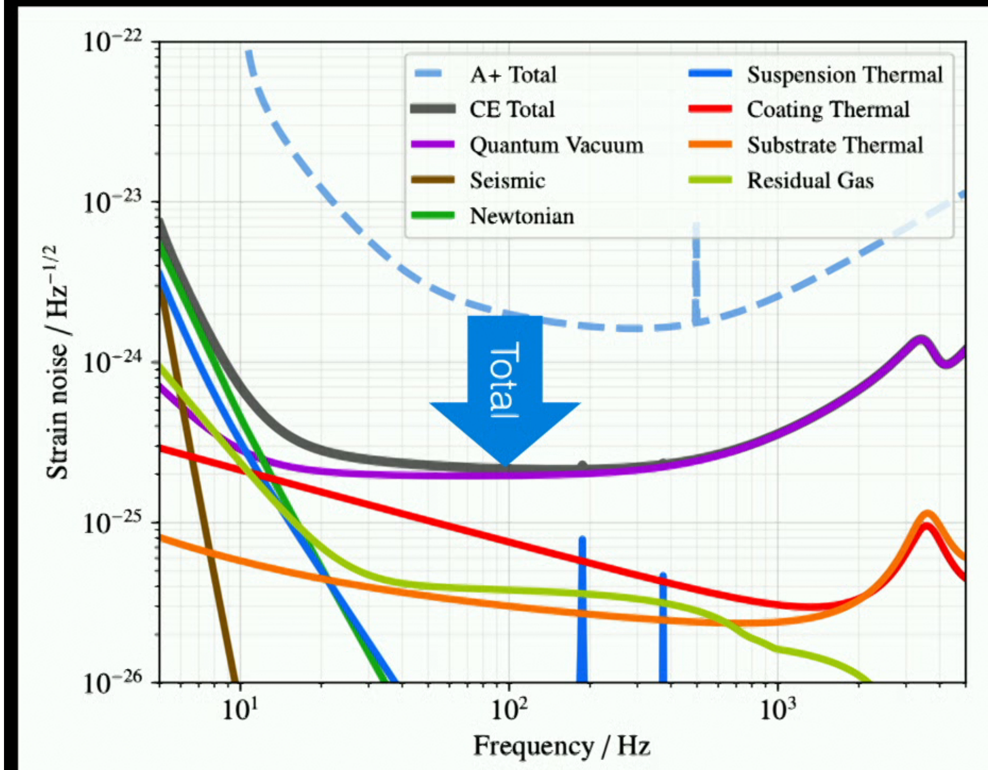
1 merger every 5 minutes!

~8 will be nearby (z<0.1) with median SNR of 600, up to SNR of ~2500!

Hall and Evans, 2019

CE Horizon Study, CE–P2100003–v7 (2021)

Cosmic Explorer noise budget

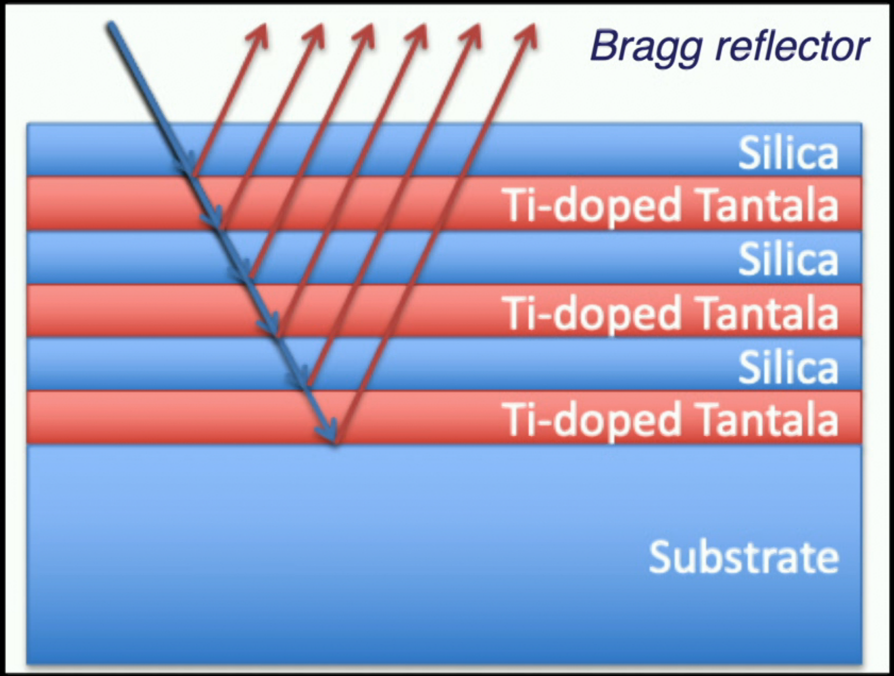


	Quantity	Units	LIGO A+	CE	CE (2 μm)
	Arm length	km	4	40	40
	Laser wavelength	μm	1	1	2
	Arm power	MW	0.8	1.5	3
	Squeezed light	dB	6	10	10
	Susp. point at 1 Hz	pm/$\sqrt{\text{Hz}}$	10	0.1	0.1
Test masses	Material		Silica	Silica	Silicon
	Mass	kg	40	320	320
	Temperature	K	293	293	123
Suspensions	Total length	m	1.6	4	4
	Total mass	kg	120	1500	1500
	Final stage blade		No	Yes	Yes
Newtonian noise	Rayleigh wave suppr.	dB	0	20	20
	Body wave suppr.	dB	0	10	10
Optical loss	Arm cavity (round trip)	ppm	75	40	40
	SEC (round trip)	ppm	5000	500	500
	BNS horizon redshift		0.19	8.3	11.7
	BBH horizon redshift		2.7	41	41
	BNS SNR, $z = 0.01$		75	1260	1460
	BNS warning, $z = 0.01$	min	4	103	103

CE Horizon Study, CE–P2100003–v7 (2021)

Coatings thermal noise: where are we starting from?

Current aLIGO coatings at *room temperature:*



- high reflectivity > 99.9995 %
- low absorption < 0.5 ppm
- scattering < 13 ppm

Material	Refractive index	Loss angle
Silica SiO_2	1.45	0.4×10^{-4}
Titania-doped tantala Ta_2O_5-TiO_2	2.07	**~3.6×10^{-4}**

G. Vajente, R. Bassiri

Coating thermal noise: a materials breakthrough is needed

$$S_x(f) = \frac{4k_BT}{\pi^2 f}\frac{d}{Y_s\omega^2}\phi$$

Temperature

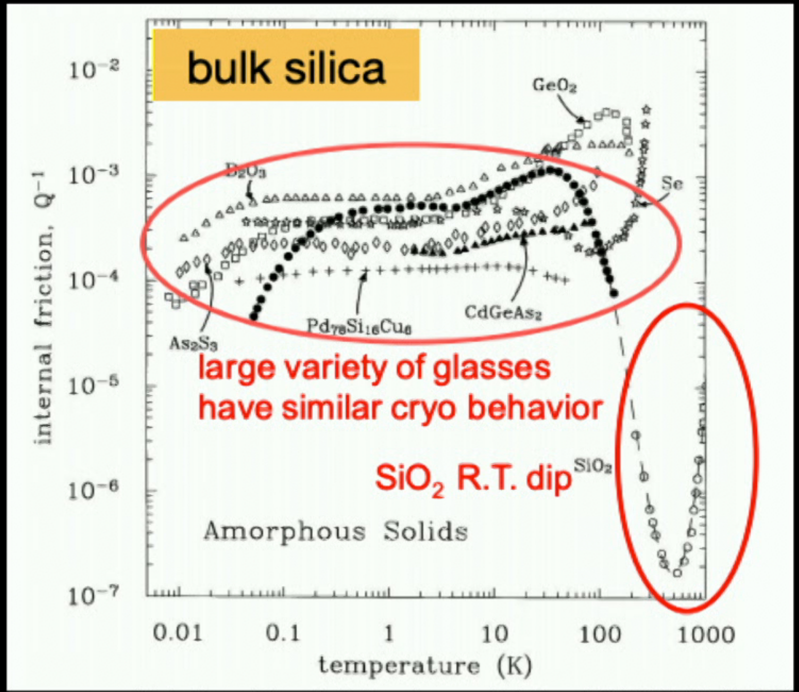
Coating thickness

Mechanical loss (much higher for current materials at lower temp)

Substrate Young's modulus

Beam radius

Harry et al. 2002



K.A. Topp Physik B Condensed Matter 101 235-45 (1996)

Still need (for target laser wavelength):

- High reflectivity
- Low absorption
- Low scattering

Up to 60 cm diameter mirrors.

Doped Germanium? *Crystalline GaAs/AlGaAs ?*

Amorphous SiO_2/Si?

CE Horizon Study, CE–P2100003–v7 (2021)

What is this mechanical loss "angle" ϕ?

- A number that quantifies the dissipation of mechanical vibrations.
- A higher loss angle implies more dissipation, i.e., a 'noisier' coating.

Complex stress-strain relation:

$$\tilde{\sigma} = \tilde{E}\tilde{\varepsilon}$$

stress ($\tilde{\sigma}$), Young's modulus ($\tilde{E}$), strain ($\tilde{\varepsilon}$)

$$\tilde{\sigma} = (E' + iE'')\tilde{\varepsilon}$$

storage modulus (E'), loss modulus (E'')

$$\tilde{\sigma} = E'(1 + i\eta)\tilde{\varepsilon}$$

loss factor (η)

$$\eta = \frac{E''}{E'} = \tan(\phi)$$

loss factor (η), loss angle (ϕ)

Slide by Dr. Kirsty Gardner

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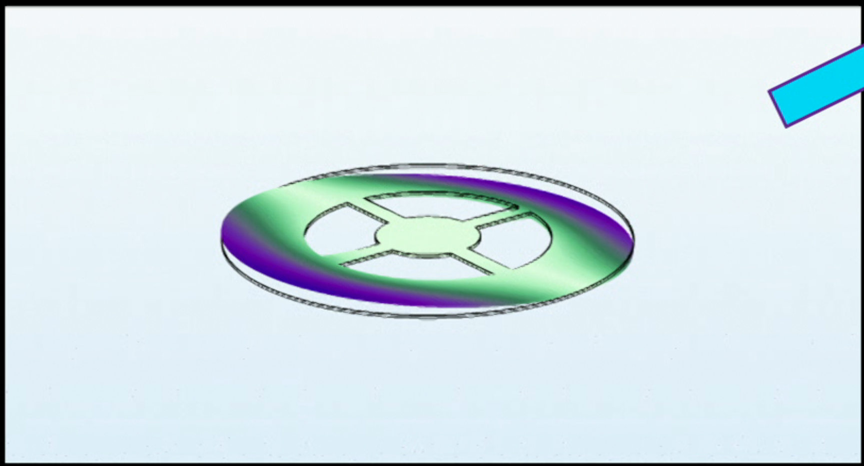
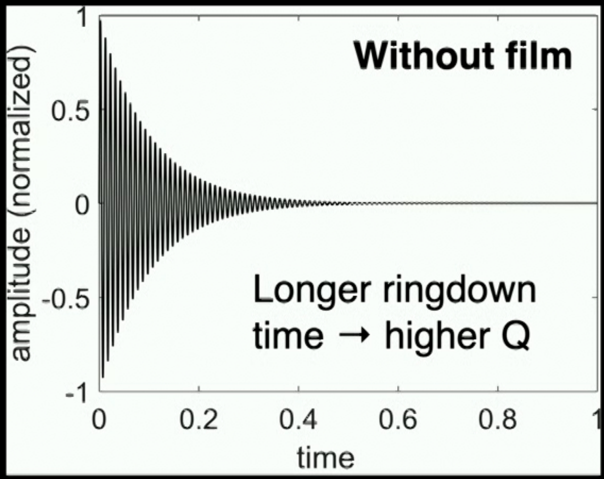
Measuring ϕ

$$\phi = \frac{1}{Q}$$





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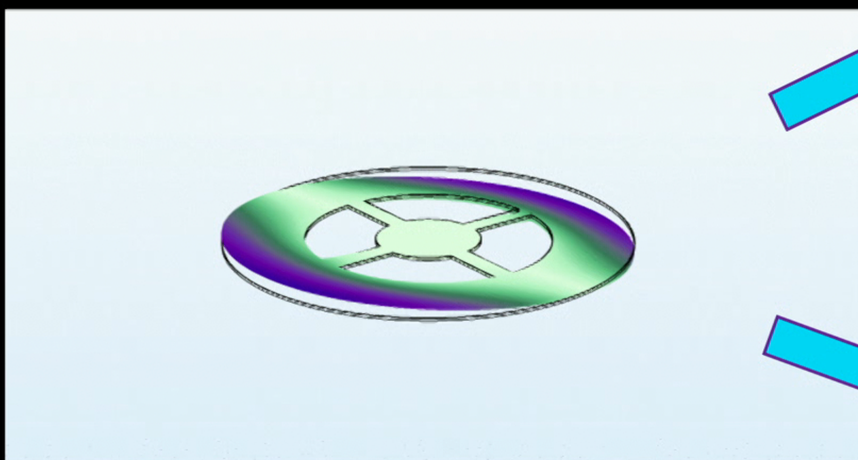
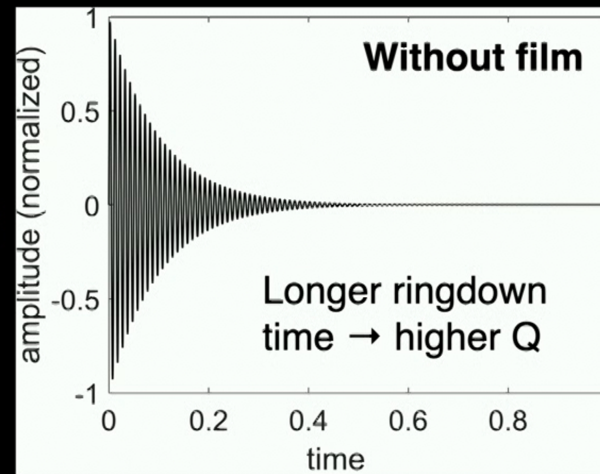
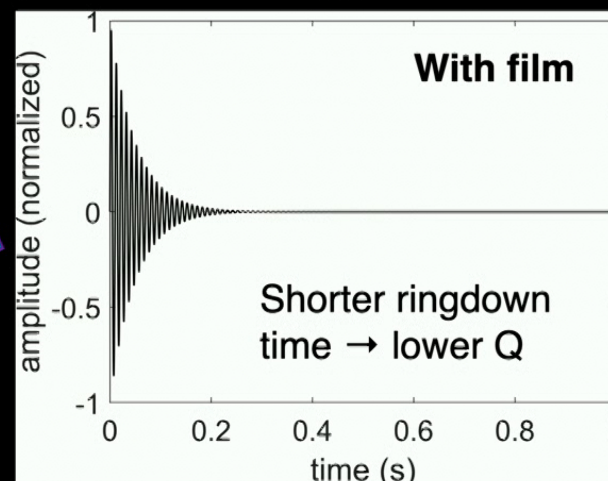
Measuring ϕ

$$\phi = \frac{1}{Q}$$







Any difference must be due to the film!

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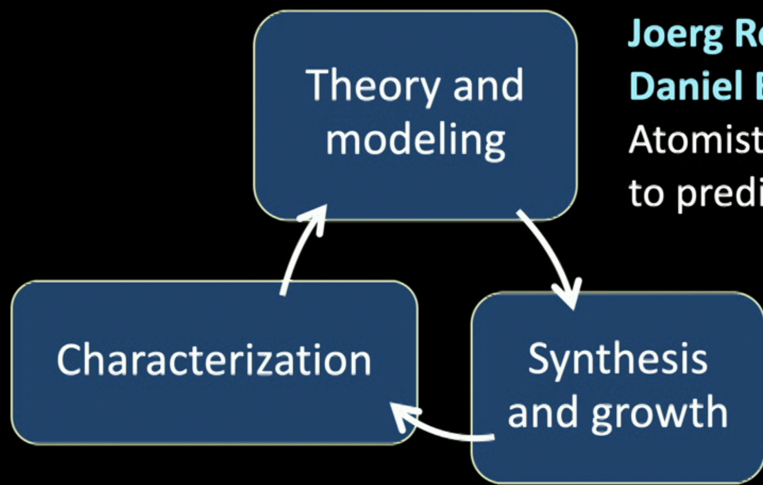
‘Entropy by design’

Developing GW detector coatings at SBQMI

Jess McIver
Liaise with the LIGO collaboration and GW community



Joerg Rottler, Daniel Wong, Daniel Bruns
Atomistic simulations of materials to predict mechanical loss

Jeff Young, Kirsty Gardner, Matthew Mitchell
Measure mechanical loss of synthesized materials

Ke Zou, Fengmiao Li
Thin film growth of candidate materials by molecular beam epitaxy

New Frontiers in Research Fund
Fonds **Nouvelles frontières** en recherche
EXPLORATION

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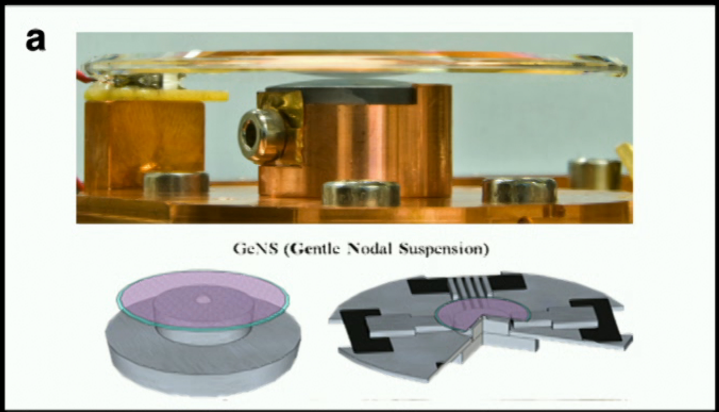
Current methods of measuring loss angle

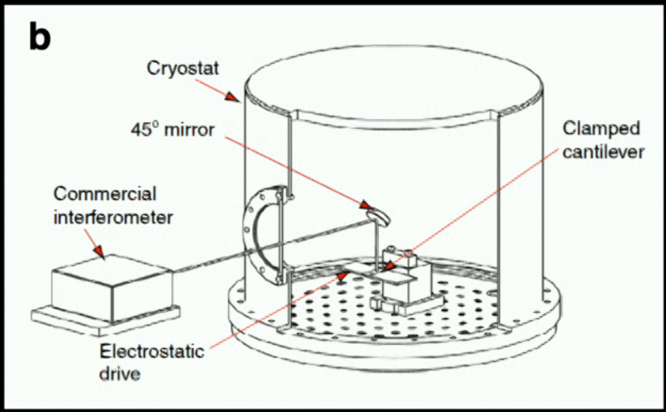
- Very high quality!
- Low throughput
- Tend to require a larger amount of material to be tested

Gentle Nodal Suspensions (GeNS)



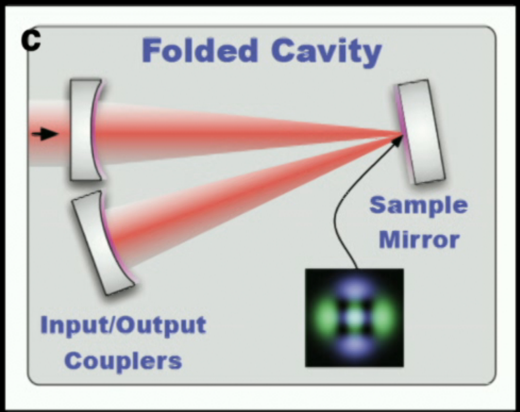
Cesarini, E. *et al. Proceedings of Gravitational-waves Science&Technology Symposium — PoS(GRASS2018)* 006 (2018)

Large cantilever



Martin, I. *et al. Class. Quantum Grav.* **25**, 055005 (2008).

Folded cavity



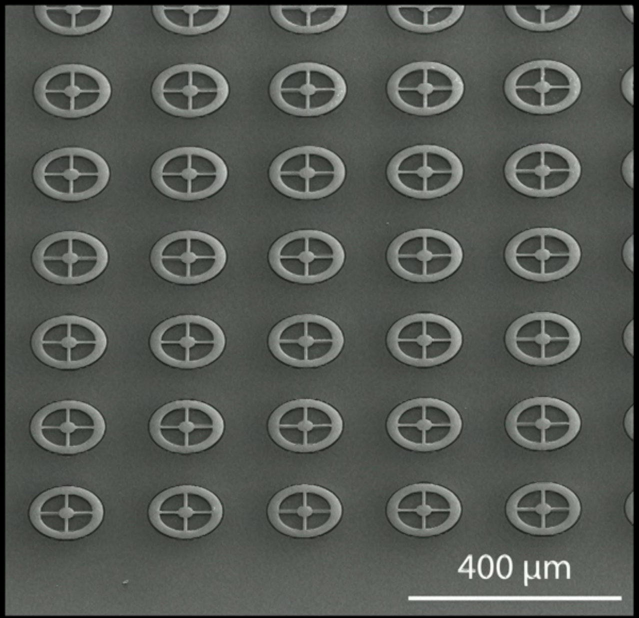
Gras, S. & Evans, M. *Phys. Rev. D* **98**, 122001 (2018)

UBC's method of measuring loss angle

The UBC team uses microdisks fabricated from silicon-on-insulator (SOI) wafer

Kirsty Gardner

- ~100 microdisks per chip enables high throughput testing
- Microdisks use minimal material for testing

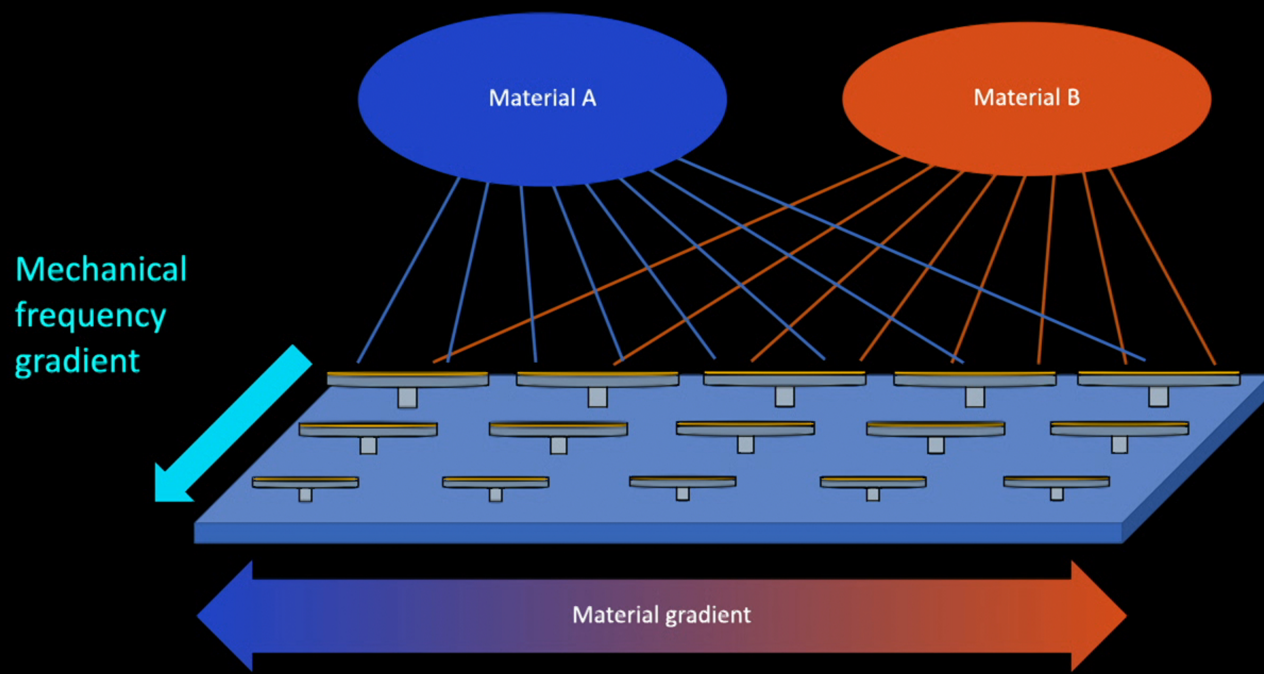


Matthew Mitchell

Mechanical microresonators

Developing GW detector coatings at SBQMI

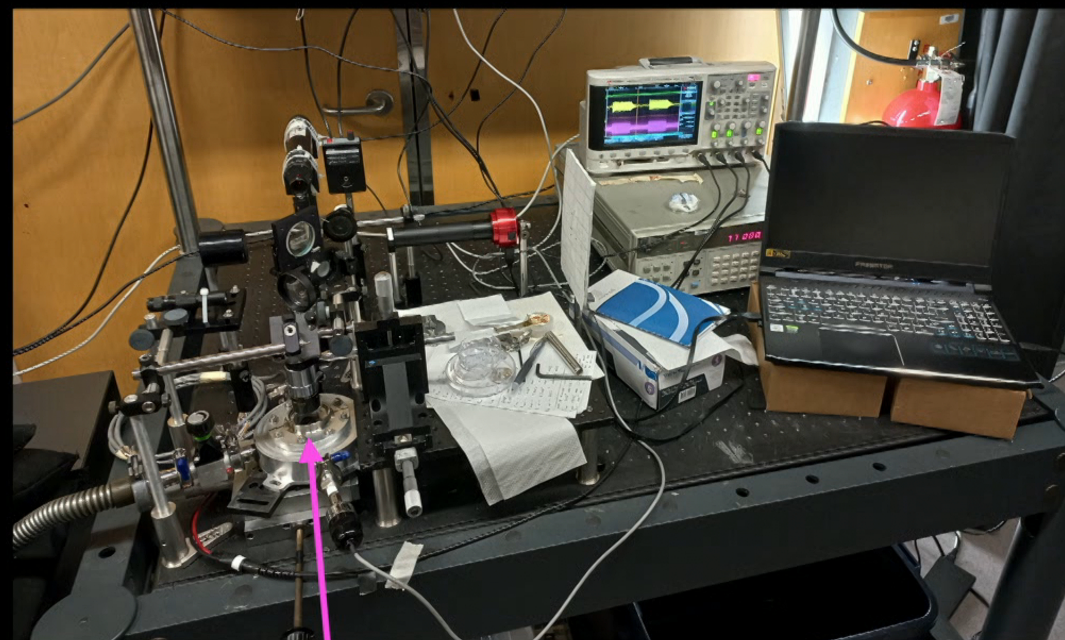
- Gradient coatings: test different materials on the same chip
- Easy integration into ‘standard’ cryostat setups for low-temperature testing



Slide by Dr. Kirsty Gardner

Mechanical microresonators

Developing GW detector coatings at SBQMI



Microresonators

Latest from Kirsty et al: We recently performed our very first ringdown measurement!

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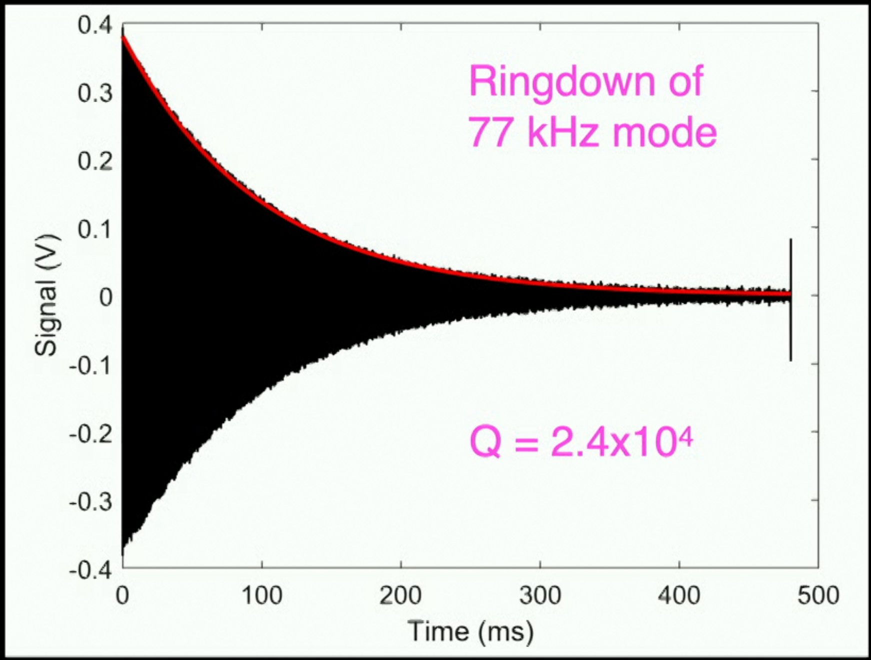
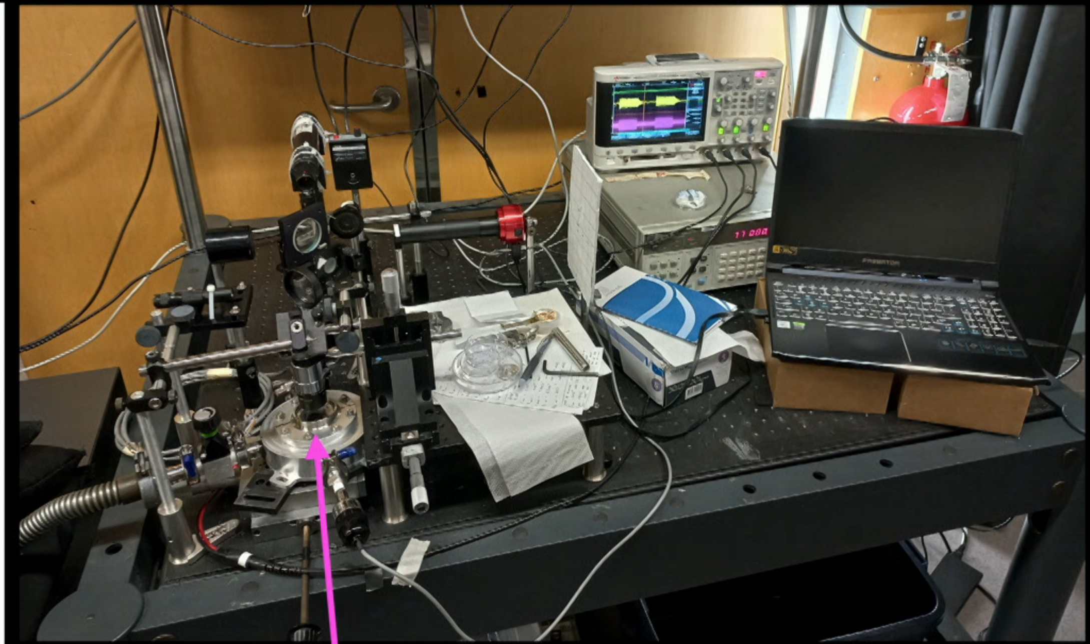
Mechanical microresonators

Developing GW detector coatings at SBQMI



Dr. Kirsty Gardner



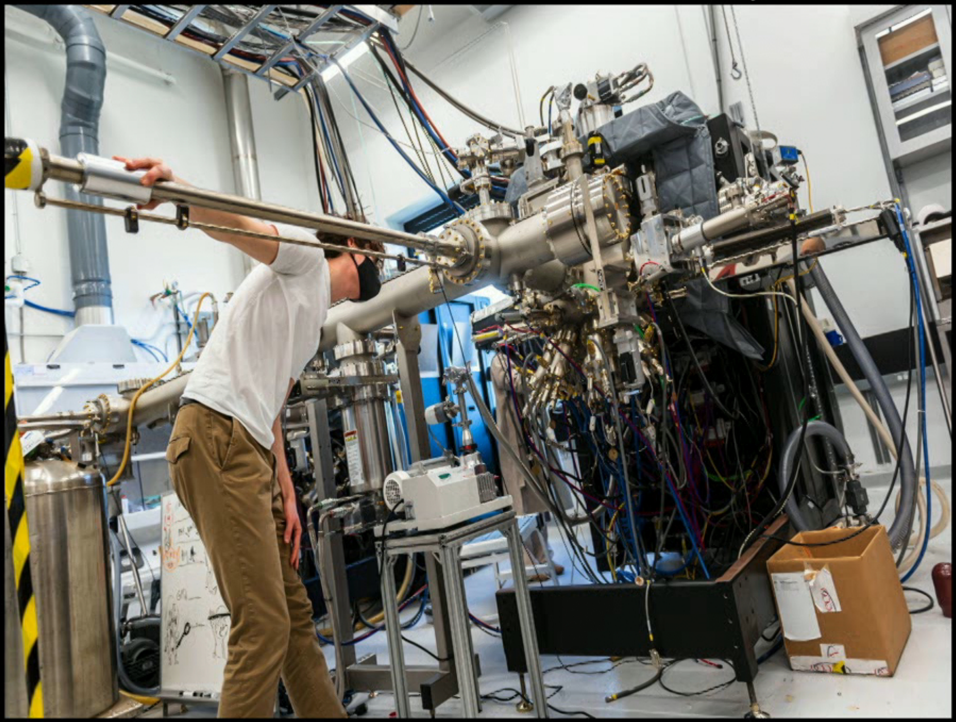
Microresonators

Latest from Kirsty et al: We recently performed our very first ringdown measurement!

Molecular Beam Epitaxy deposition

Developing GW detector coatings at SBQMI

MBE system at UBC.



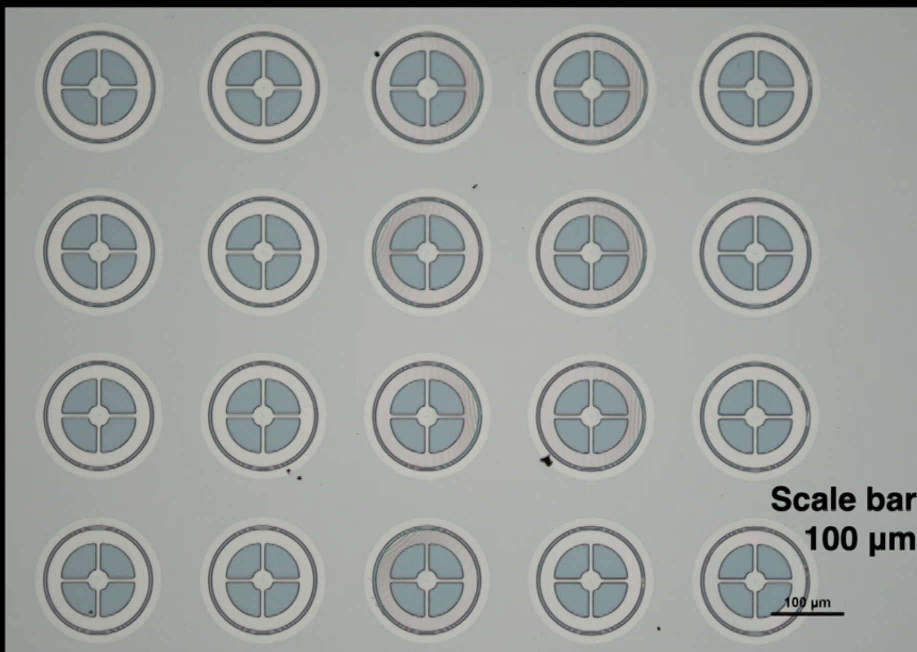
- High quality thin films
- Large variety of materials (Ti, Ni, La, Nd, Sr, Mg, Ag, Fe, Ge, Te, Bi, and Se)
- Ultra-high vacuum chamber (10^{-11} Torr) to minimize chamber impurities
- Amorphous growth at low temperature and crystal growth at high temperature

Slide by Dr. Kirsty Gardner

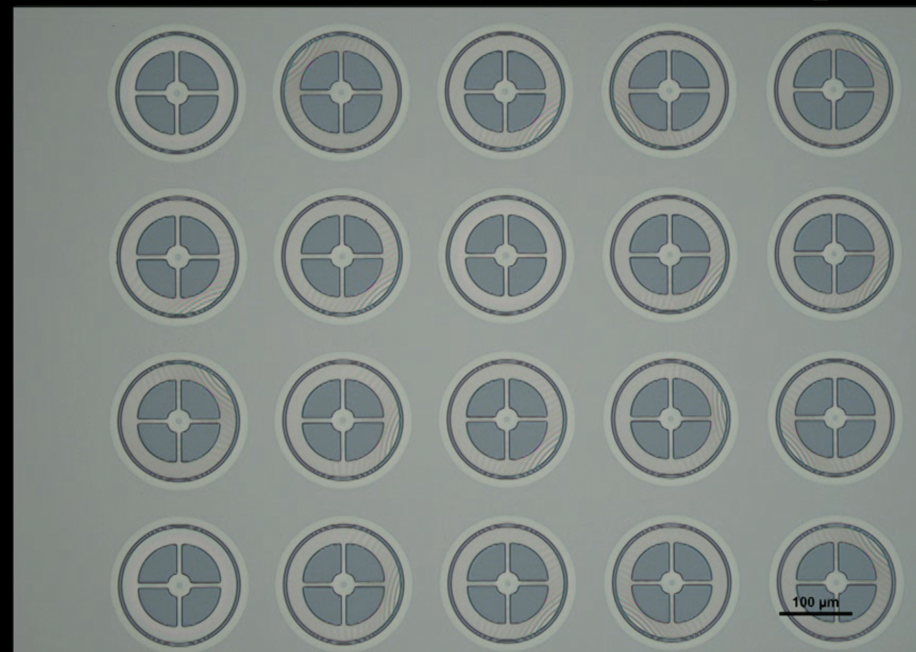
Molecular Beam Epitaxy deposition

Developing GW detector coatings at SBQMI

Uncoated microdisks



Microdisks coated with 25 nm TiO_2



Latest from Fengmiao et al: We have successfully deposited 25 nm of TiO_2 onto our microresonators with minimal deformation.

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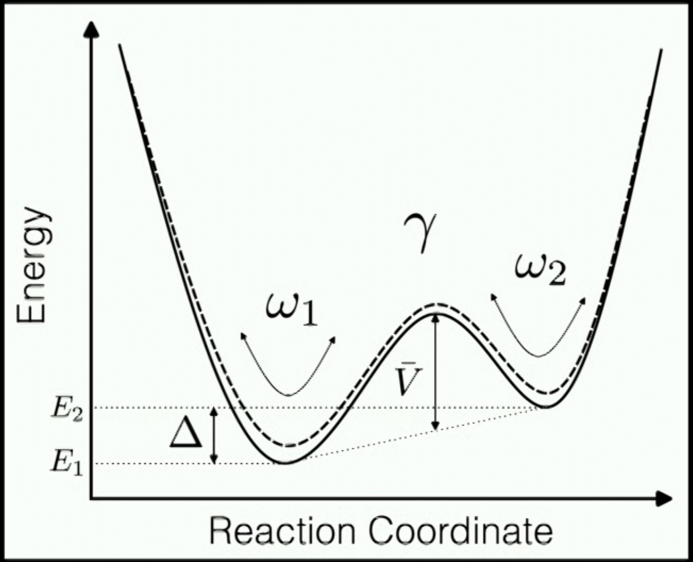
Atomistic modeling: two level systems in a-Si

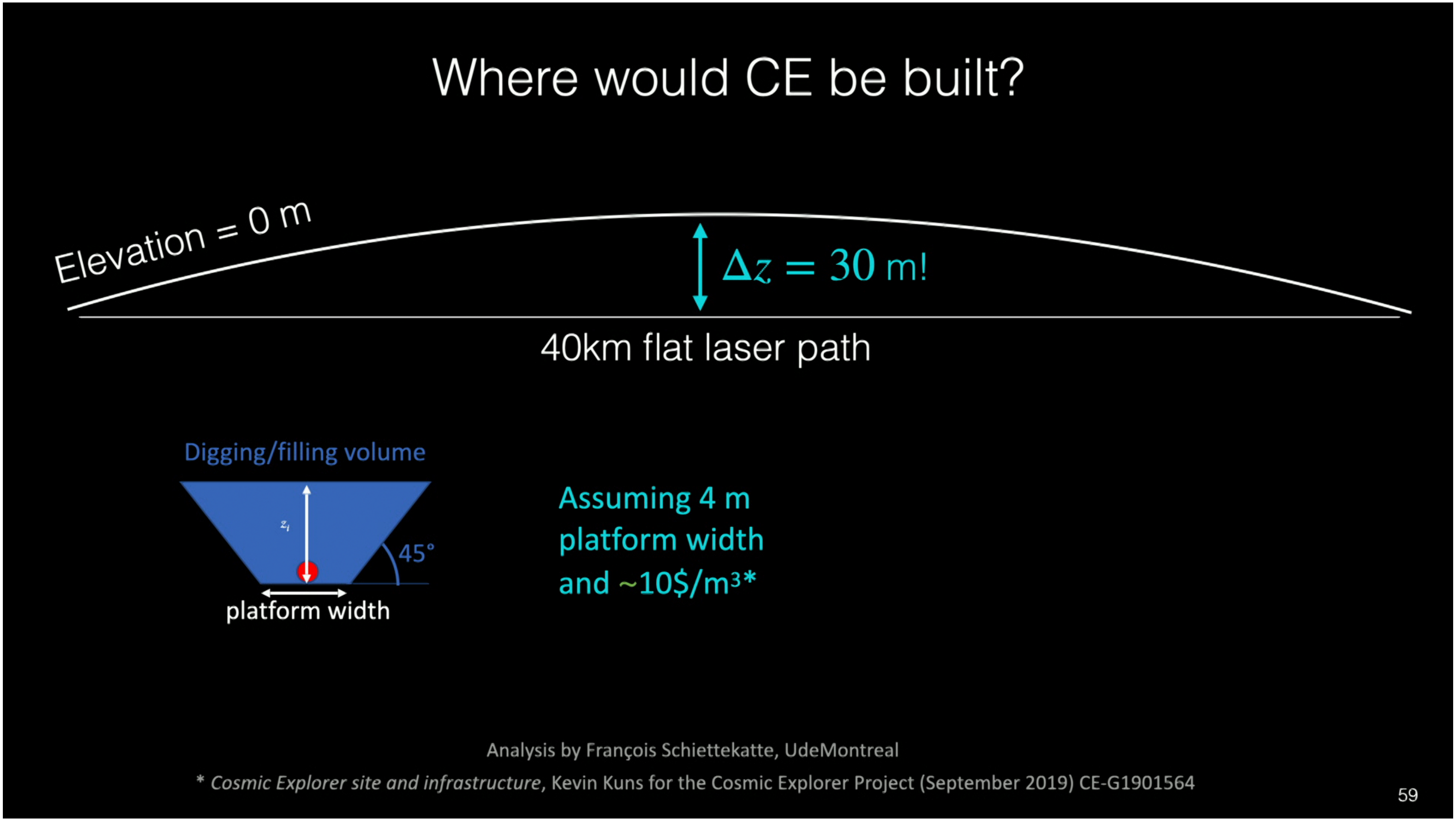
Developing GW detector coatings at SBQMI

- Mechanism of internal friction: Two-Level-Systems (TLS) where thermally activated transitions between these energy states produce dissipation
- The theory team characterizes TLS parameters using atomistic simulations

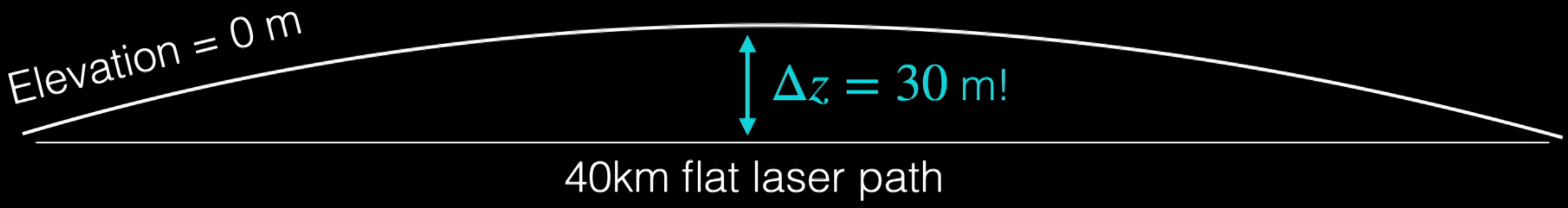


Latest from Daniel Wong et al: Results indicate that a small number of TLS are responsible for most of the dissipation. *Daniel Bruns currently onboarding…*

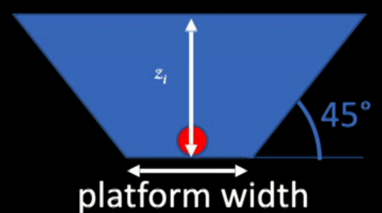
Slide by Dr. Kirsty Gardner, plot by Daniel Wong


Where would CE be built?
Elevation = 0 m
$\Delta z = 30$ m!
40km flat laser path
Digging/filling volume
z_i
45°
platform width
Assuming 4 m platform width and ~10$/m3*
Analysis by François Schiettekatte, UdeMontreal
* Cosmic Explorer site and infrastructure, Kevin Kuns for the Cosmic Explorer Project (September 2019) CE-G1901564
59

Where would CE be built?



Digging/filling volume



Assuming 4 m platform width and ~10$/m³*

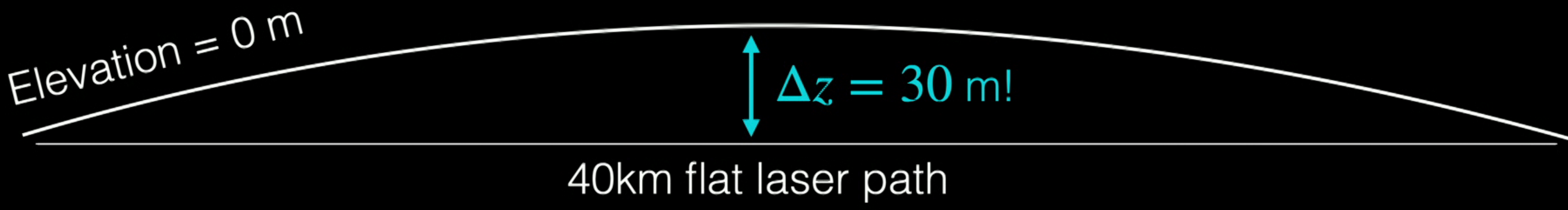
For each 40 km *arm*:

V = 43 000 x 10^3 m^3 (~430 M$)

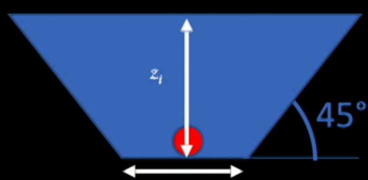
Analysis by François Schiettekatte, UdeMontreal

* *Cosmic Explorer site and infrastructure*, Kevin Kuns for the Cosmic Explorer Project (September 2019) CE-G1901564

Where would CE be built?



Digging/filling volume



Assuming 4 m platform width and ~10$/m³*

For each 40 km *arm*:
V = 43 000 x 10^3 m^3 (~430 M$)

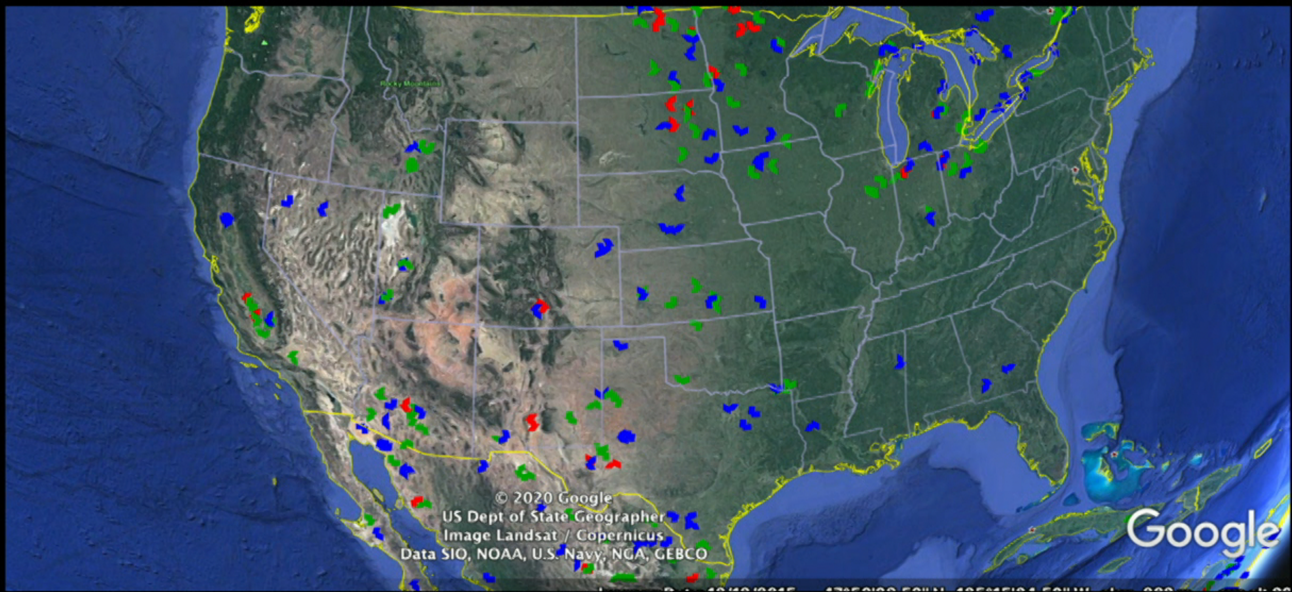
Choose a site with concave elevation such that $\Delta z \approx 0$

V = 375 x 10^3 m^3 (3-4 M$!!)

Analysis by François Schiettekatte, UdeMontreal

* *Cosmic Explorer site and infrastructure*, Kevin Kuns for the Cosmic Explorer Project (September 2019) CE-G1901564

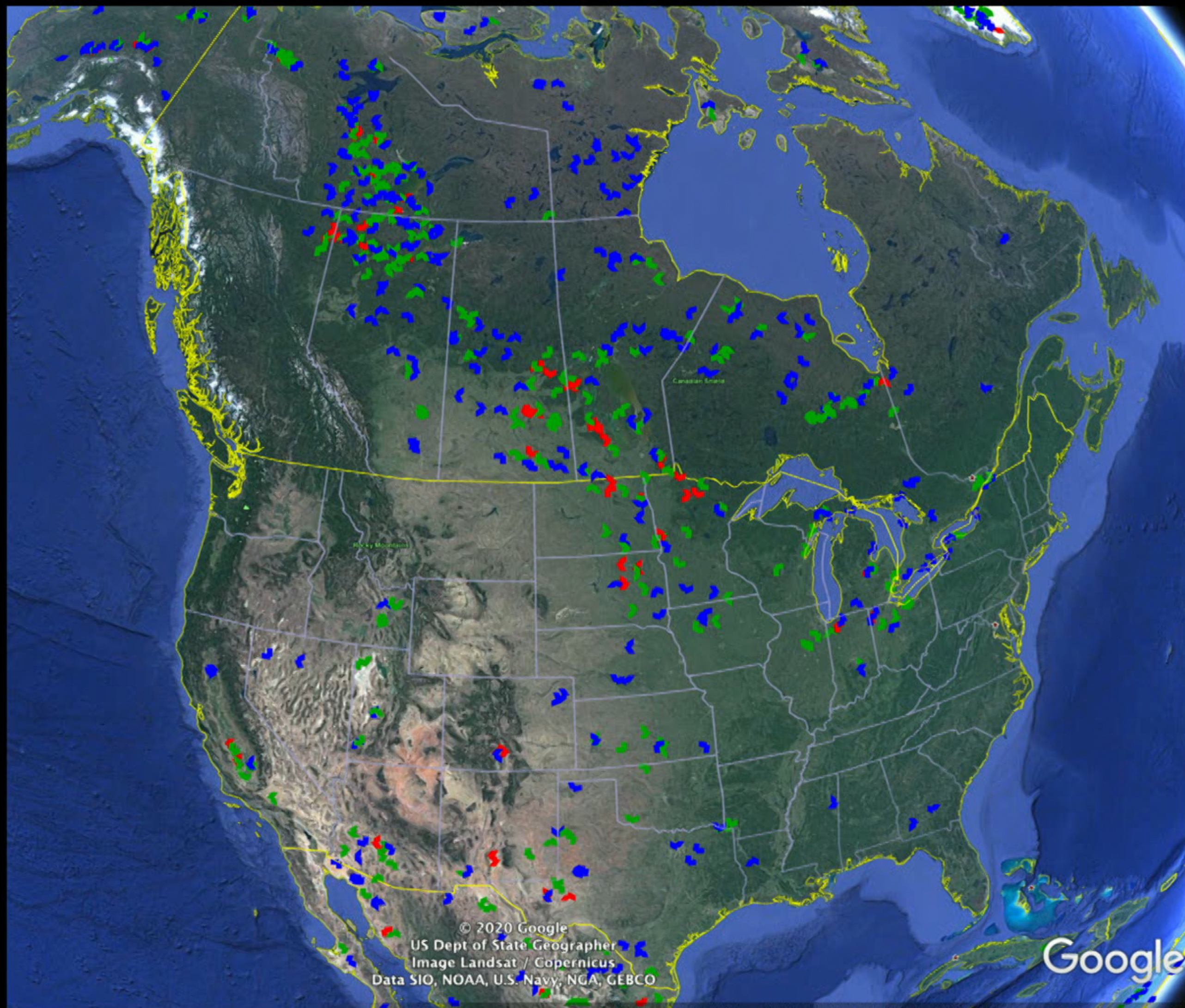
red
300-900
green
900-1400
blue
1400-2000
x 10^3 m^3



Analysis by François Schiettekatte, UdeMontreal

Based on analysis by Kevin Kuns, MIT

red
300-900
green
900-1400
blue
1400-2000
x 10^3 m^3



All sites overlap with unceded indigenous territories and/or nations.

Many locations in Canada!

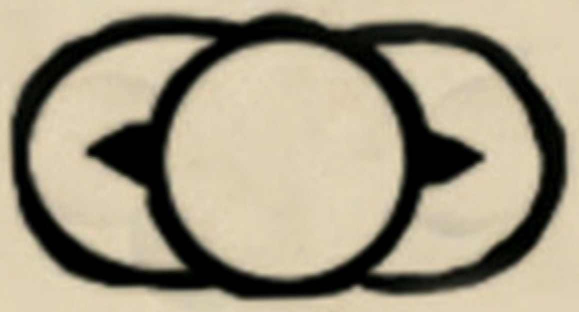
Analysis by François Schiettekatte, UdeMontreal

Based on analysis by Kevin Kuns, MIT

WE HAVE THE RIGHT INSTRUMENT.

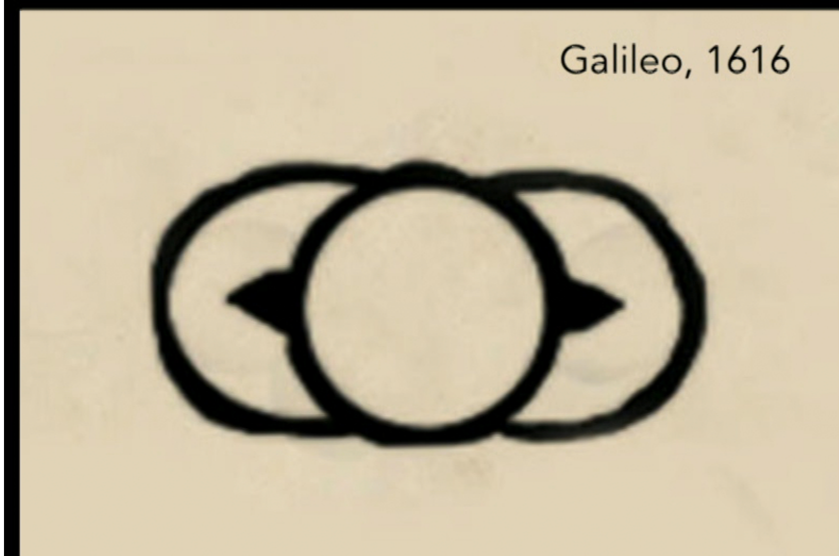
Galileo, 1610

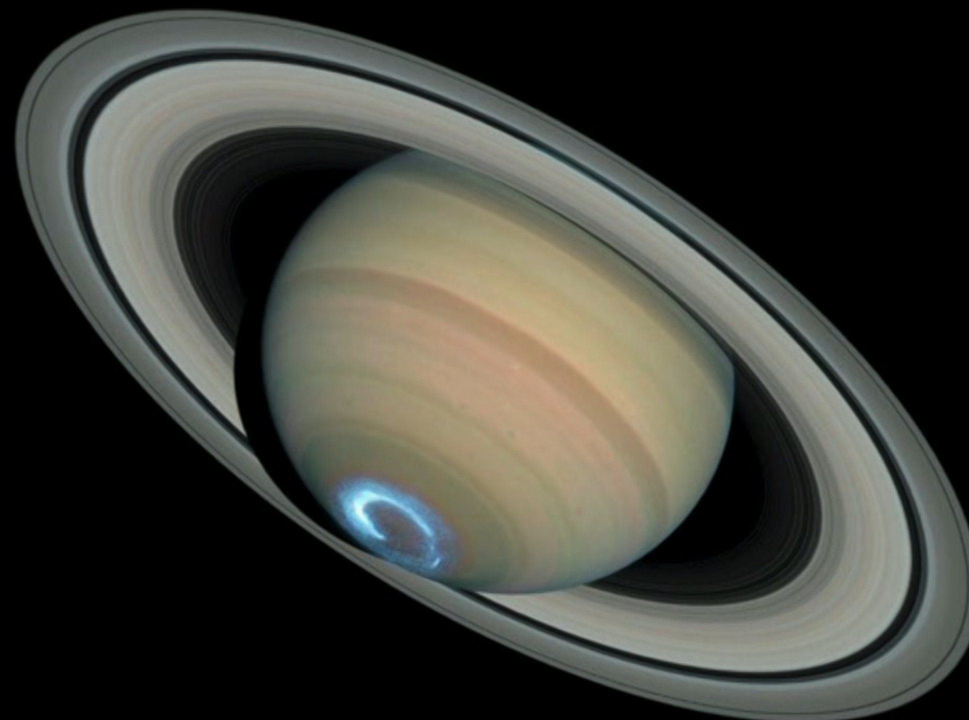
Galileo, 1616



WE HAVE THE RIGHT INSTRUMENT.
NOW WE NEED TO MAKE IT BETTER AND BETTER AND BETTER…


Galileo, 1610


Galileo, 1616


HST, 400 yrs later

Slide by Giovanni Losurdo