Title: Gravitational Waves Experiments

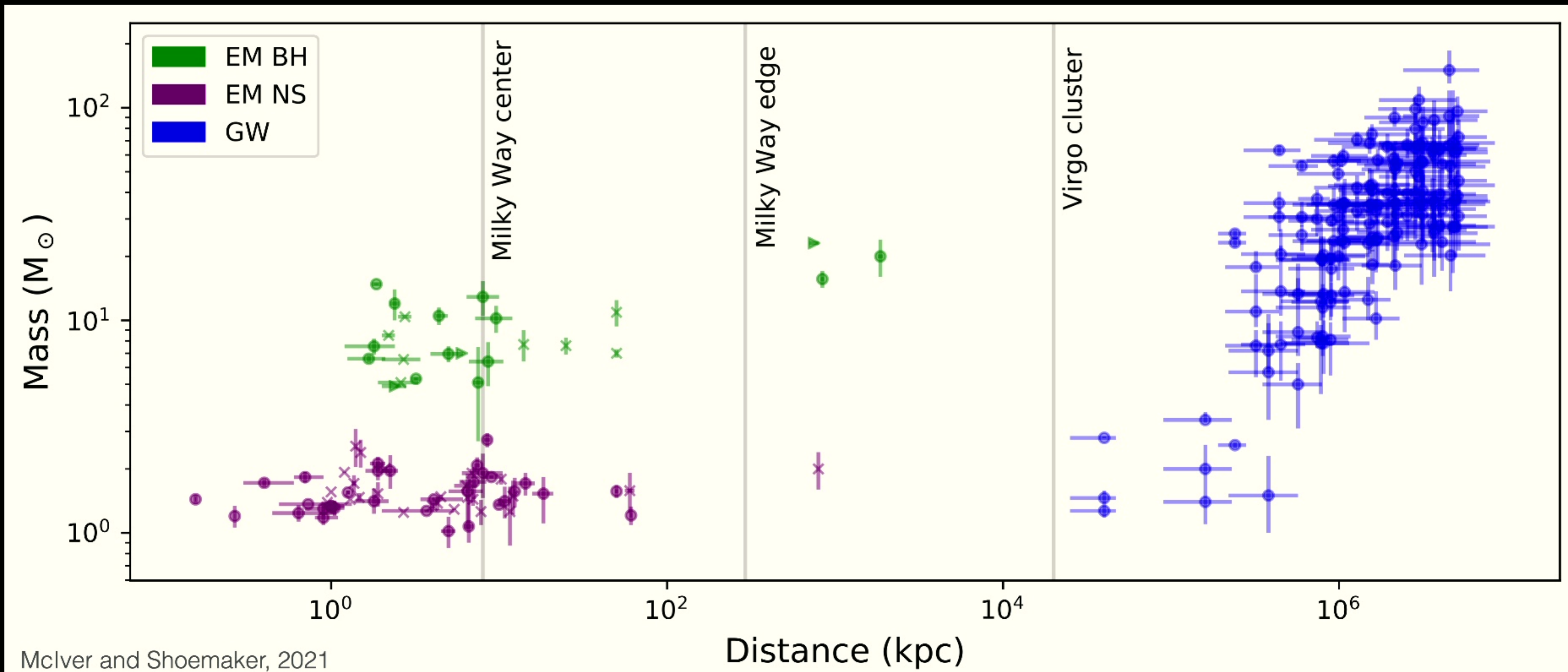
Speakers: Jess McIver

Collection: TRISEP 2023

Date: June 23, 2023 - 4:30 PM

URL: https://pirsa.org/23060063

Known compact object masses vs. estimated distance



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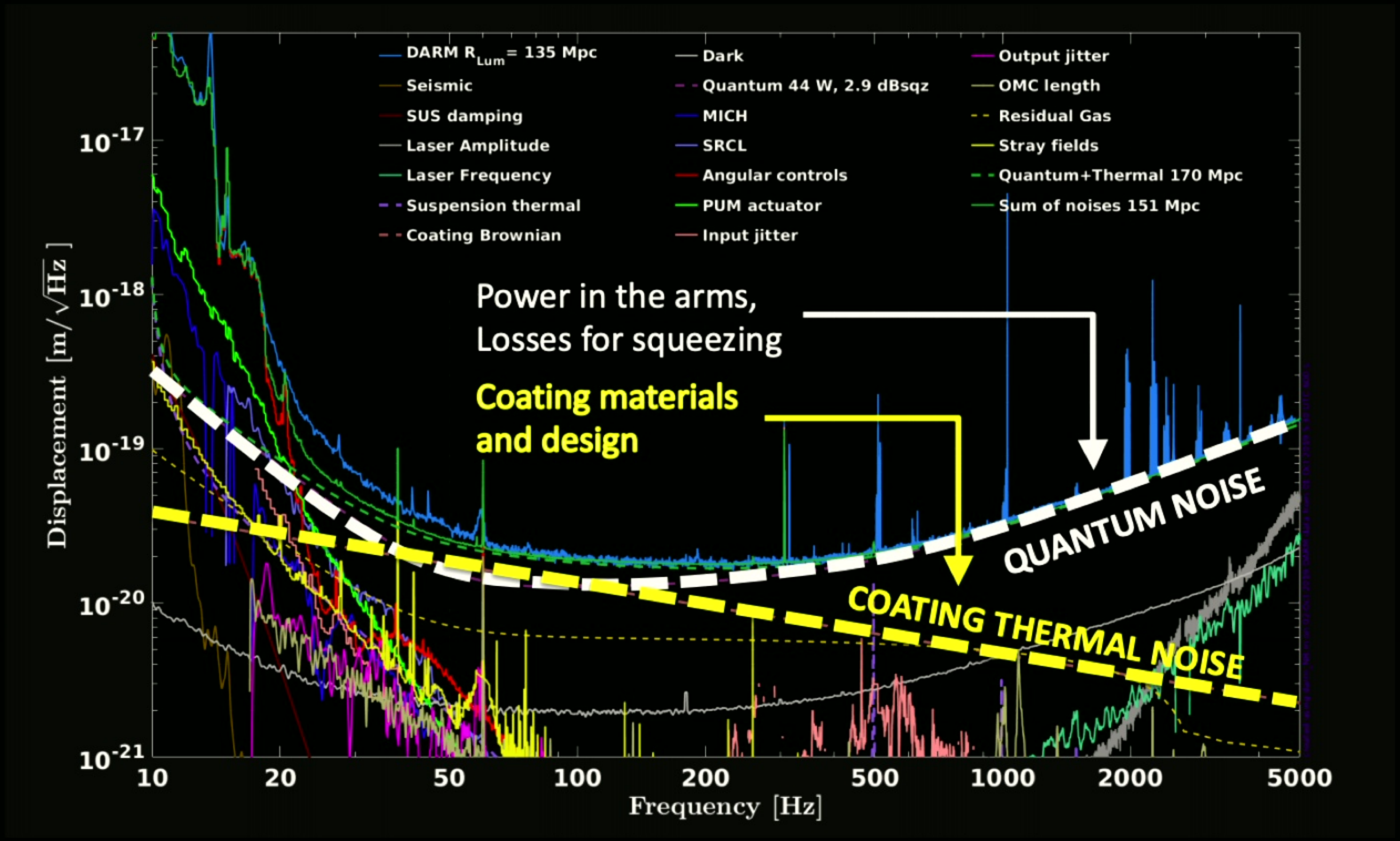
Advanced LIGO noise budget



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

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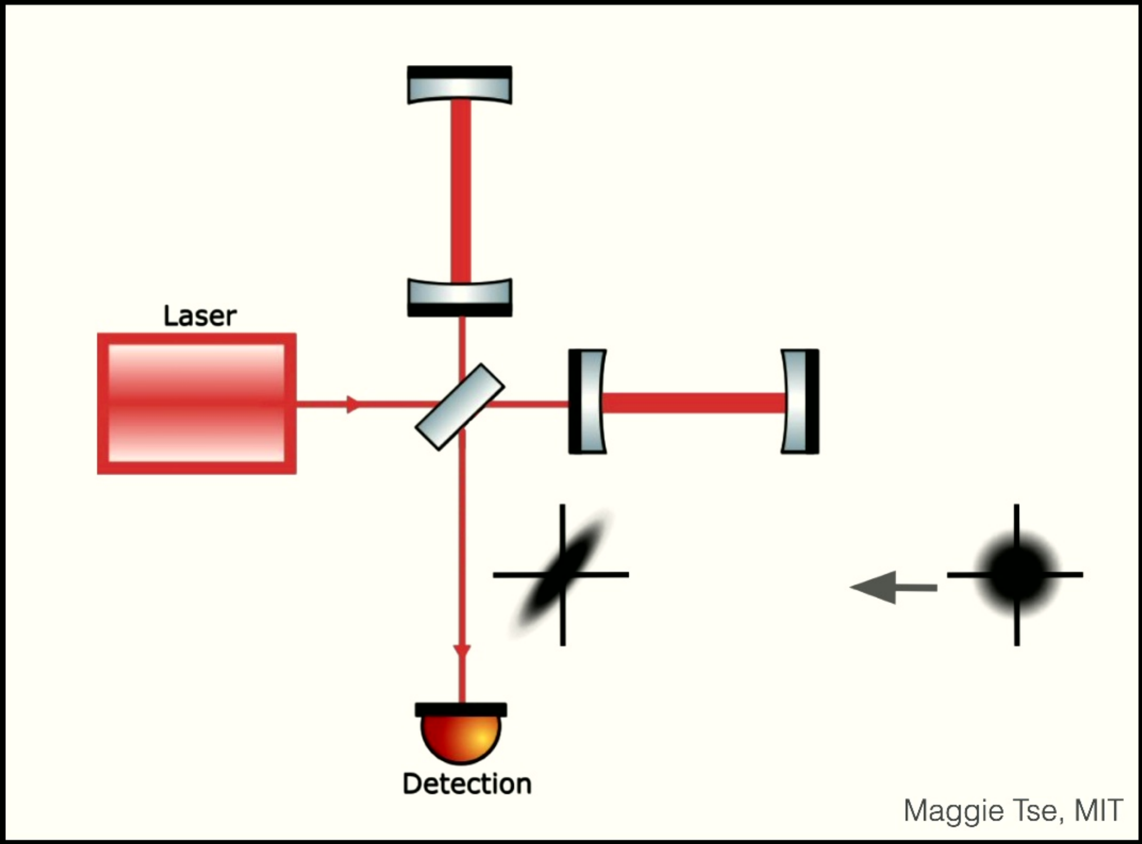
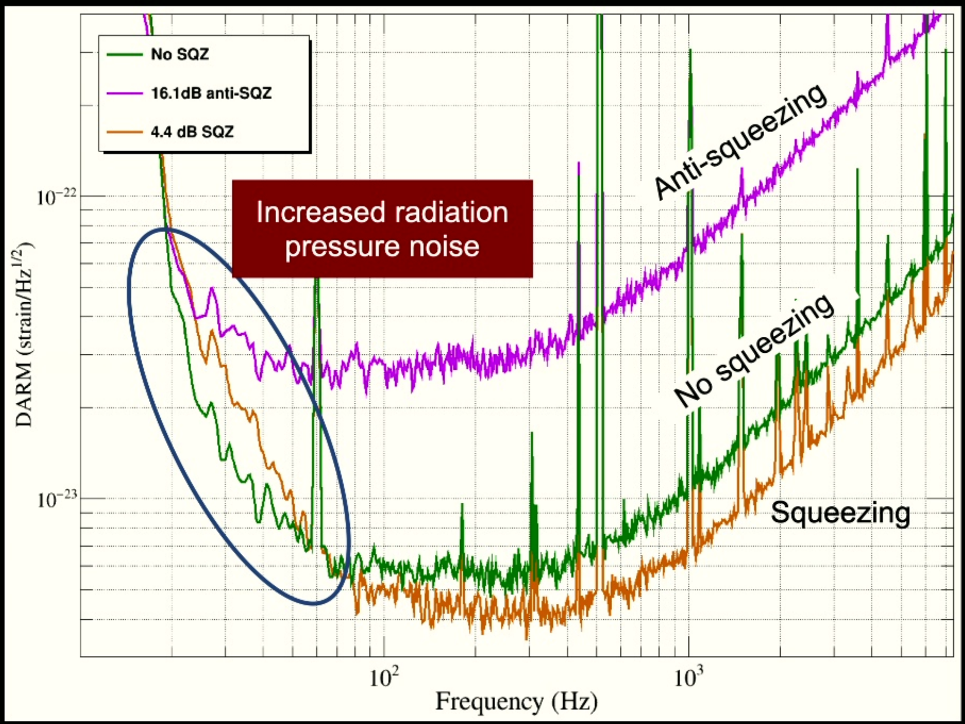
Squeezing for Advanced LIGO



Frequency-Independent Squeezing in LIGO detectors

Slide by Wenxuan Jia

LLO 60854



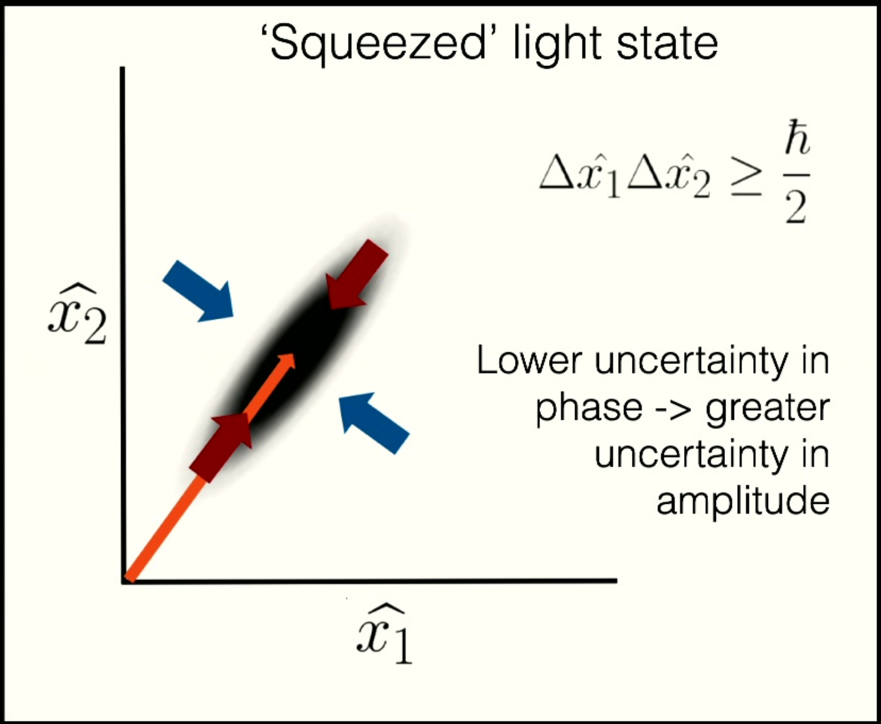
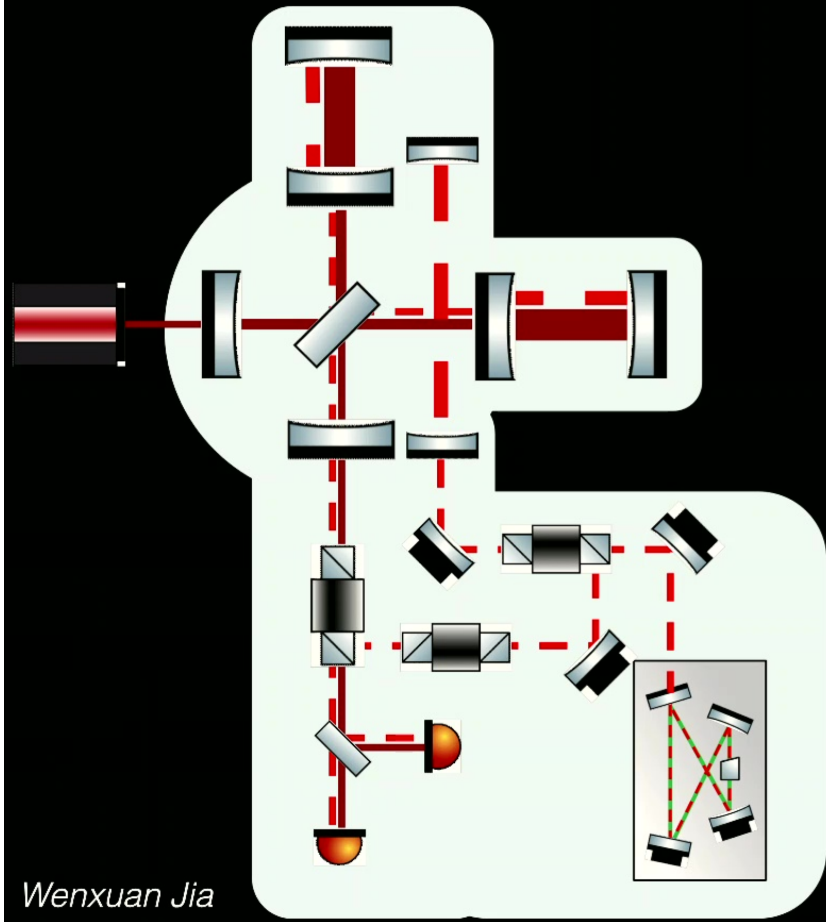


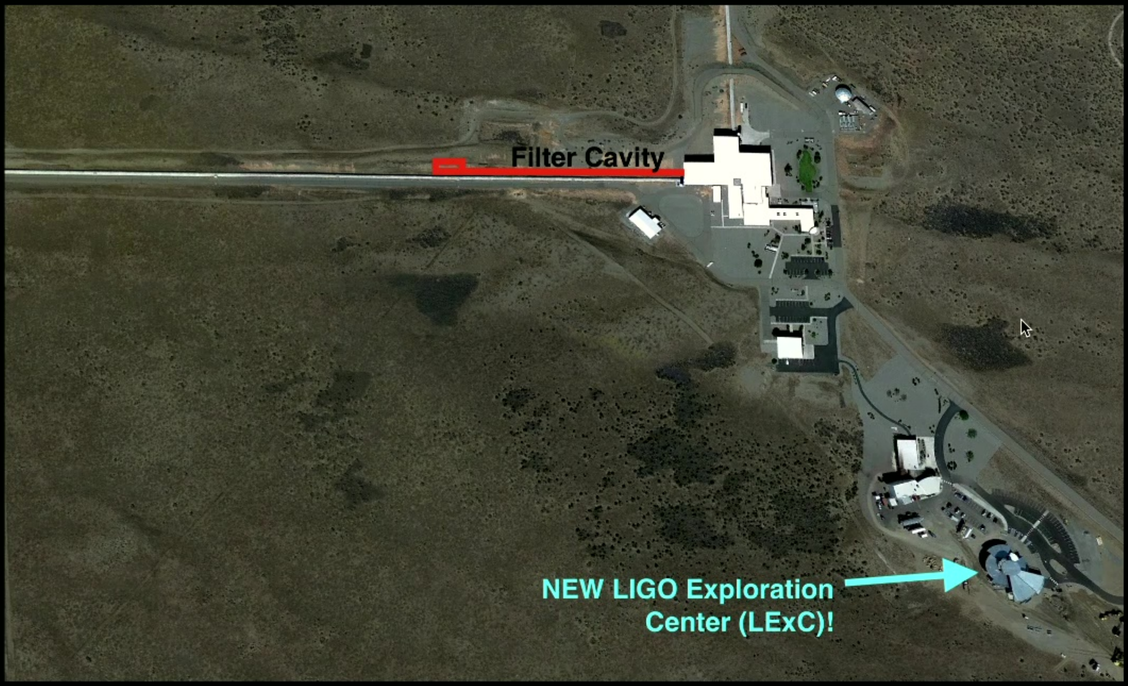
Figure by Maggie Tse

Both sites achieved 4.4 dB squeezing on shot noise:

- More squeezing than O3 (~3 dB)
- But sacrificed radiation pressure noise → **need for filter cavity**

New for O4: a 300 m filter cavity



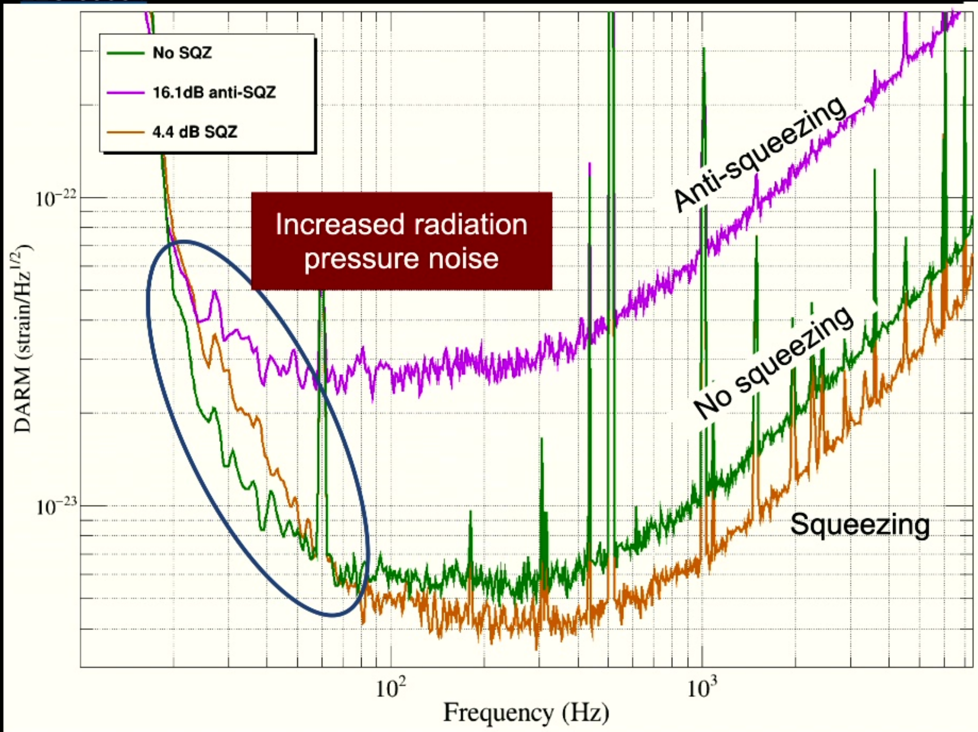


Wenxuan Jia

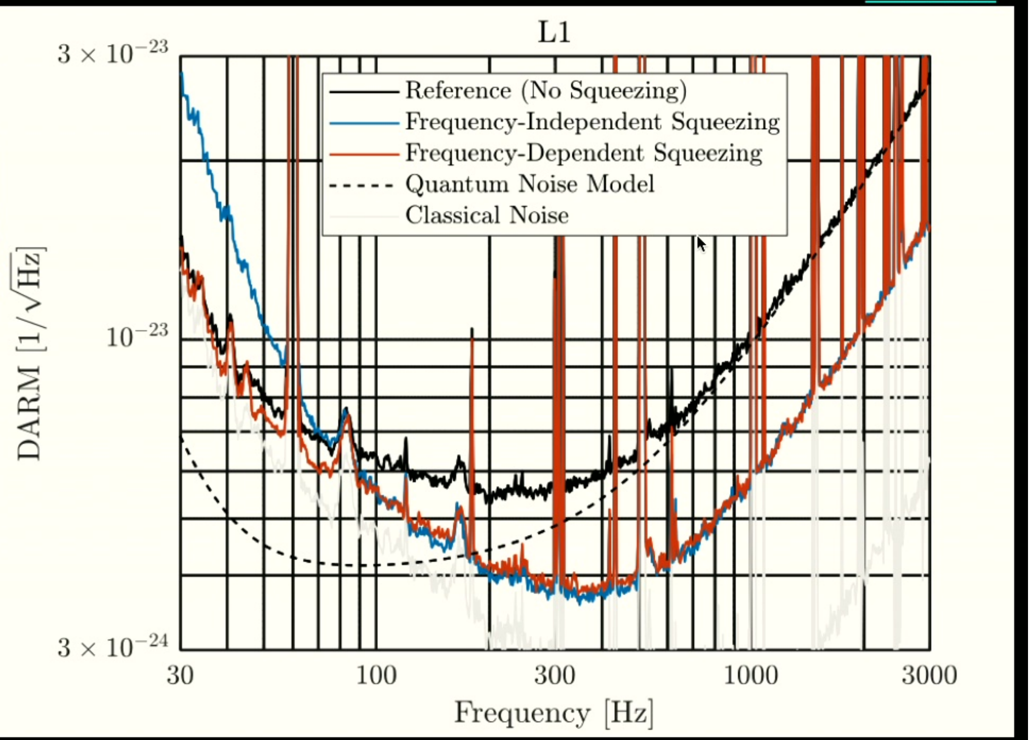
LIGO Lab

Frequency-Independent Squeezing in LIGO detectors

LLO 60854



LLO 63508

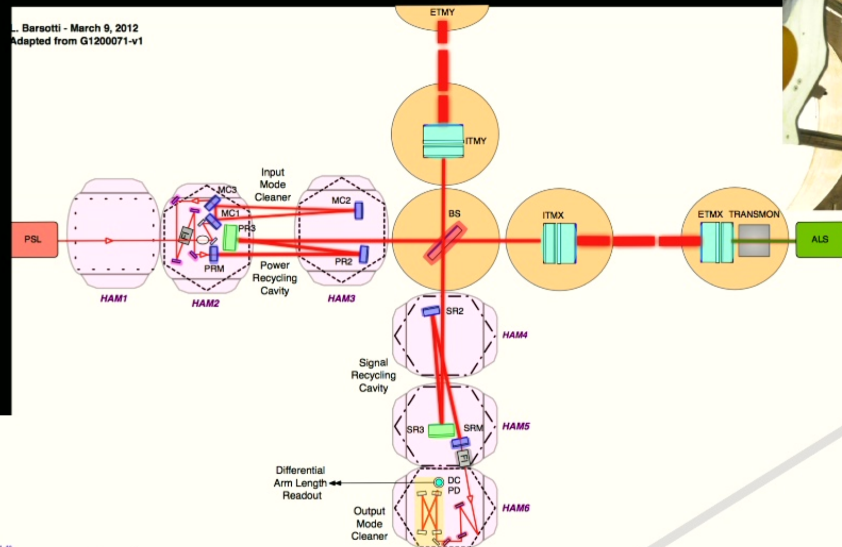


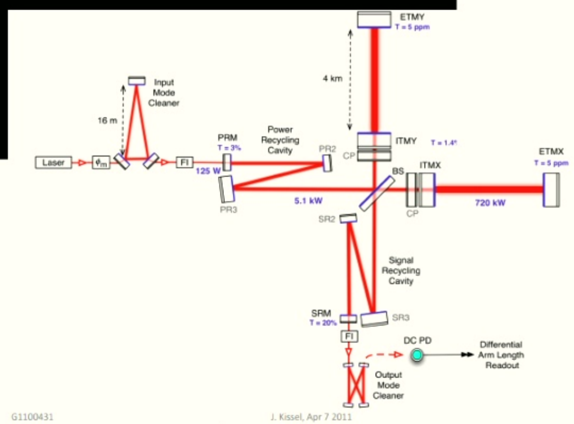
- More squeezing than O3 (~3 dB)
- But sacrificed radiation pressure noise
- → **need for filter cavity**

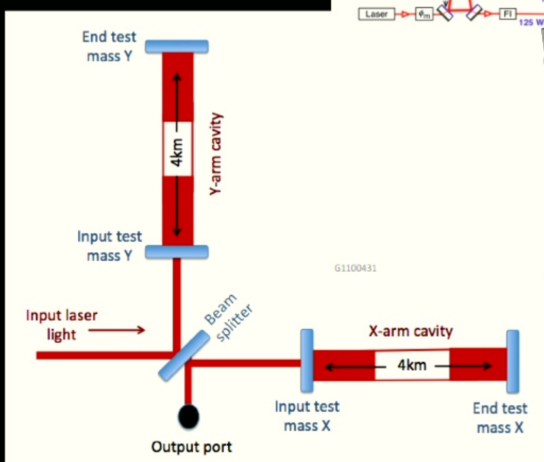
- 250 kW arm power
- 5.1 dB noise reduction visible on DARM at ~2 kHz
- 1 dB at ~80 Hz

Slide by Wenxuan Jia

Interferometric GW detectors are extremely complex.







Reality

Adapted from D. Shoemaker

Challenge: known causes of GW detector glitches

Lightning	Birds	Refrigerators	Radio contamination
Ocean waves	Earthquakes	Air conditioners	Telephones
Low humidity	Trains	Snow plows	Thunder
Forklifts	Helicopters	Airplanes	Logging

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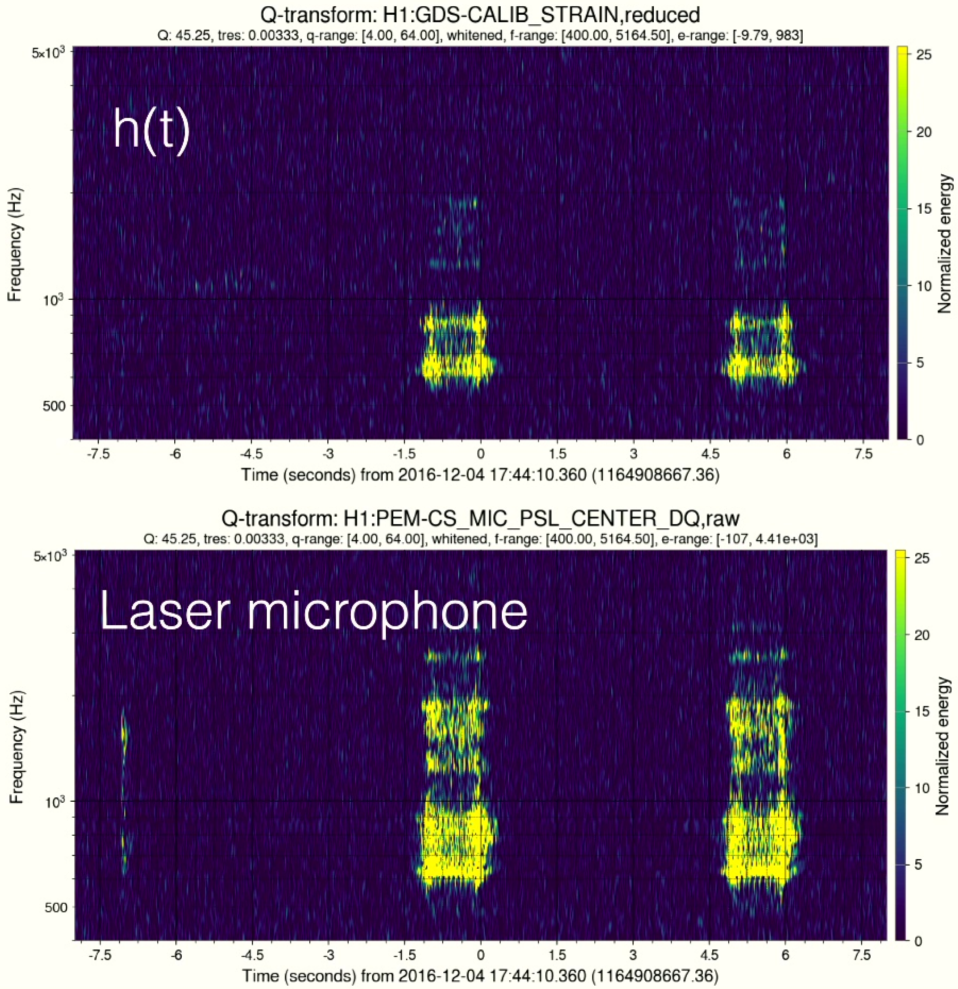
Laser glitches - h(t) vs. microphones

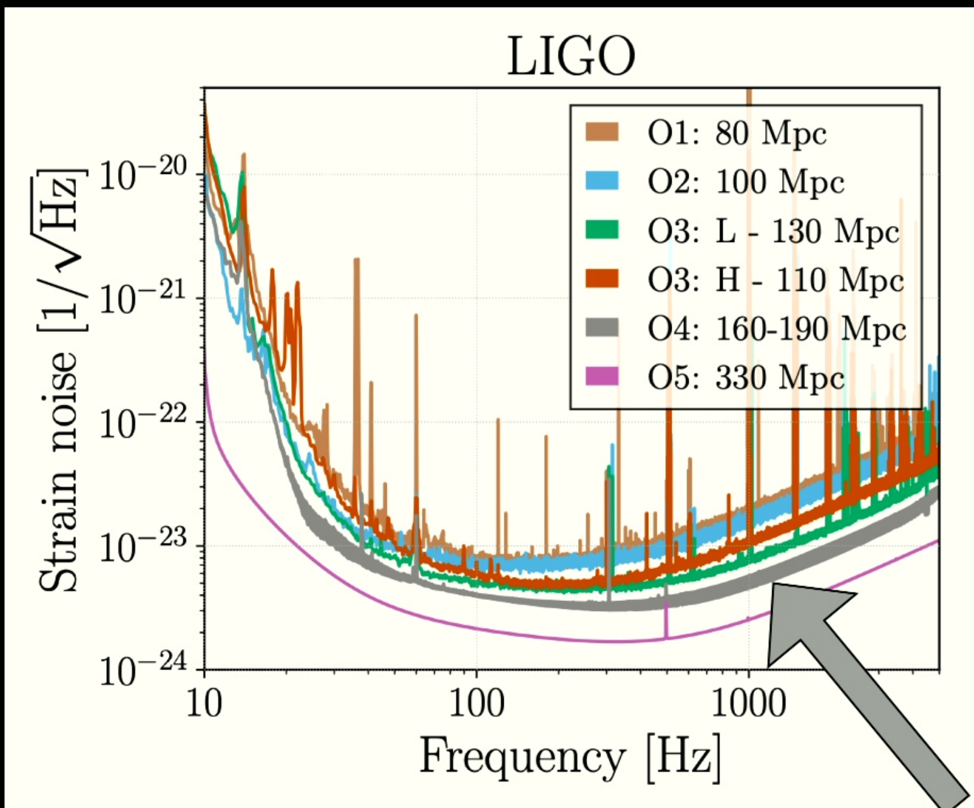


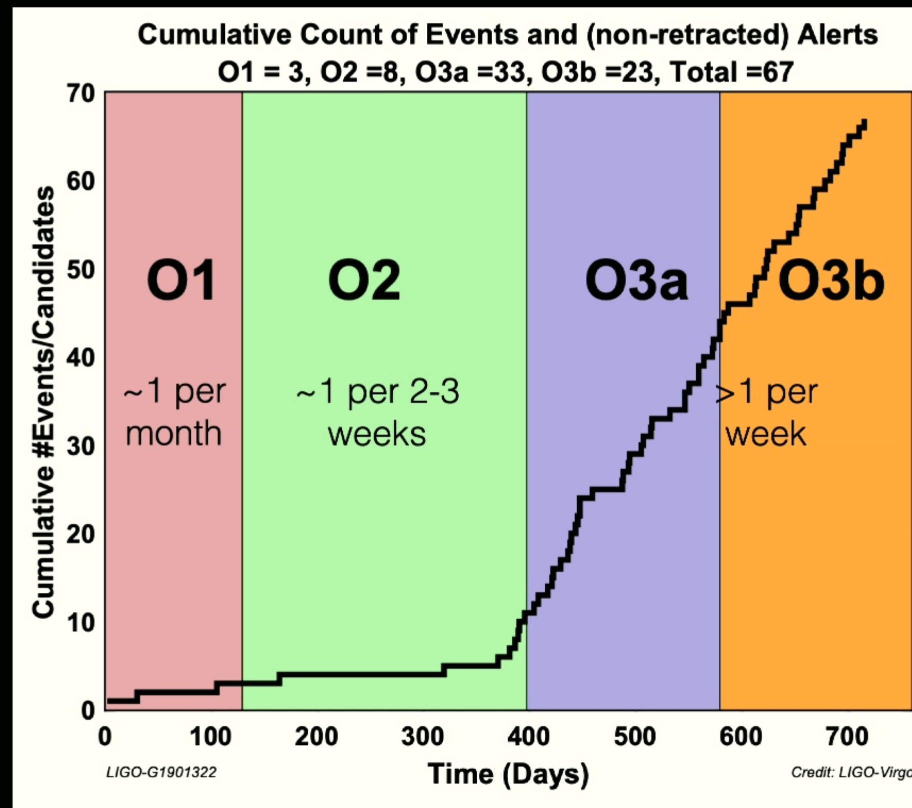
LHO alog #32503: https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=32503

Sensitivity and detection rate

O4 started on May 24!

As the GW detection rate increases, automation will become more important.

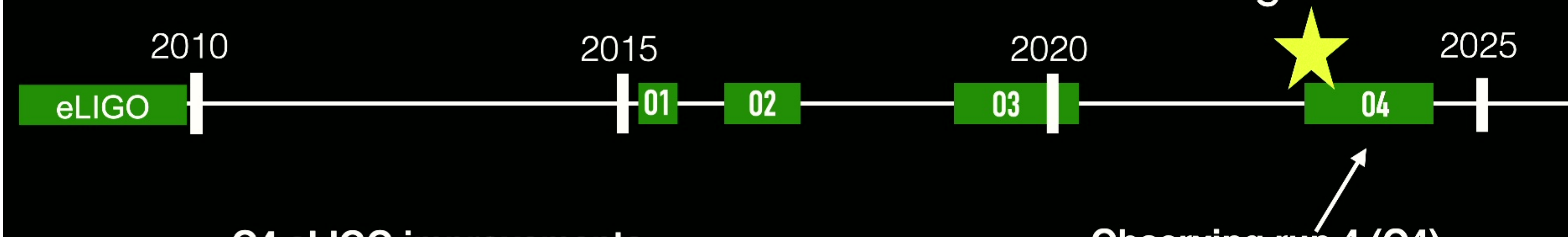




LIGO-Virgo arXiv 1304.0670 v11

O4 expectation: up to a few signals per week

Timeline of Advanced LIGO and Advanced Virgo



O4 aLIGO improvements

- Upgrade pre-stablized lasers to input100W into the interferometer (for 400 kW in the arm cavities)
- New baffles to combat stray light noise
- Replace some test mass mirrors to improve coatings
- New 300 meter cavity for frequency-dependent squeezed light

Observing run 4 (O4)

- Began May 24 (2 LIGO detectors) with improved detector sensitivity
- Target: move toward Advanced LIGO and Advanced Virgo design sensitivity
- KAGRA also plans to join at a reduced sensitivity

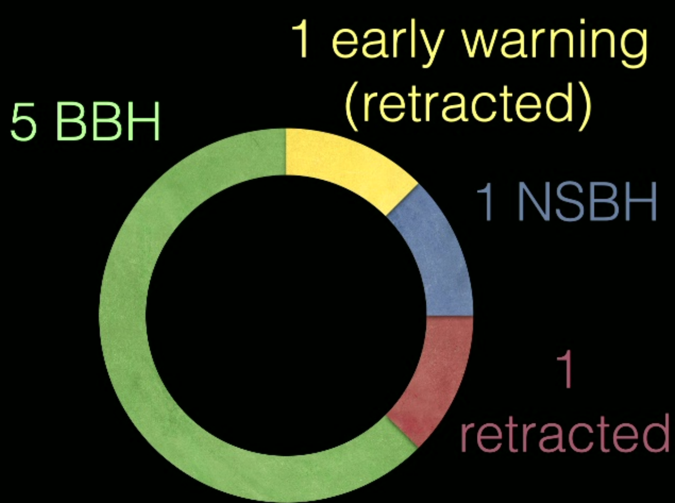
O4 snapshot so far

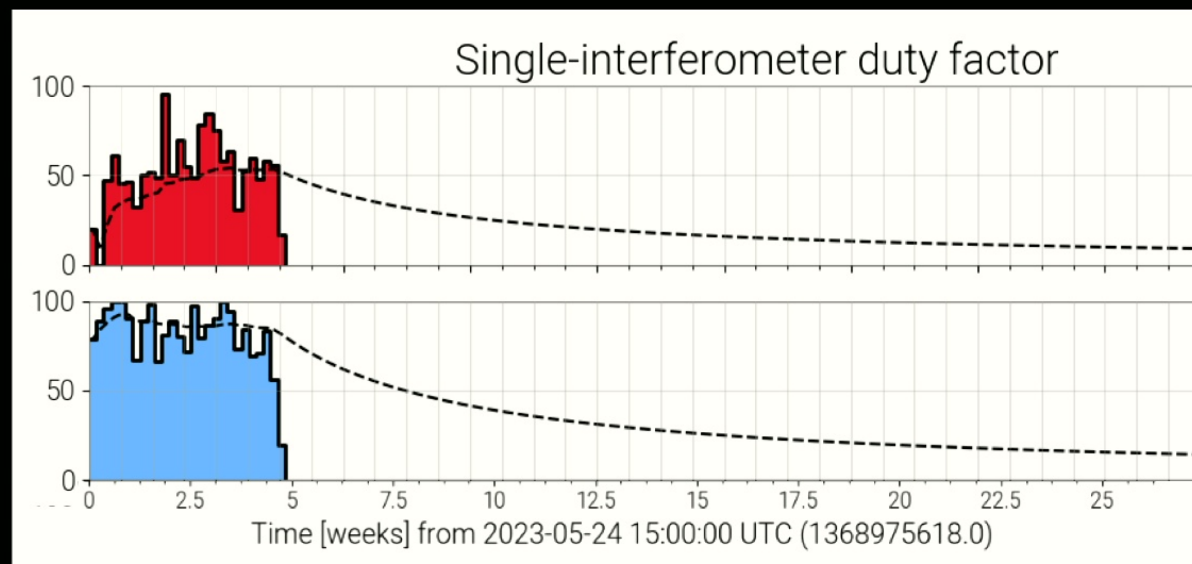
https://gracedb.ligo.org/superevents/public/O4/

Started May 24, 2023
with the 2 LIGO detectors

O4 Significant Detection Candidates: **6** (7 Total - 1 Retracted)

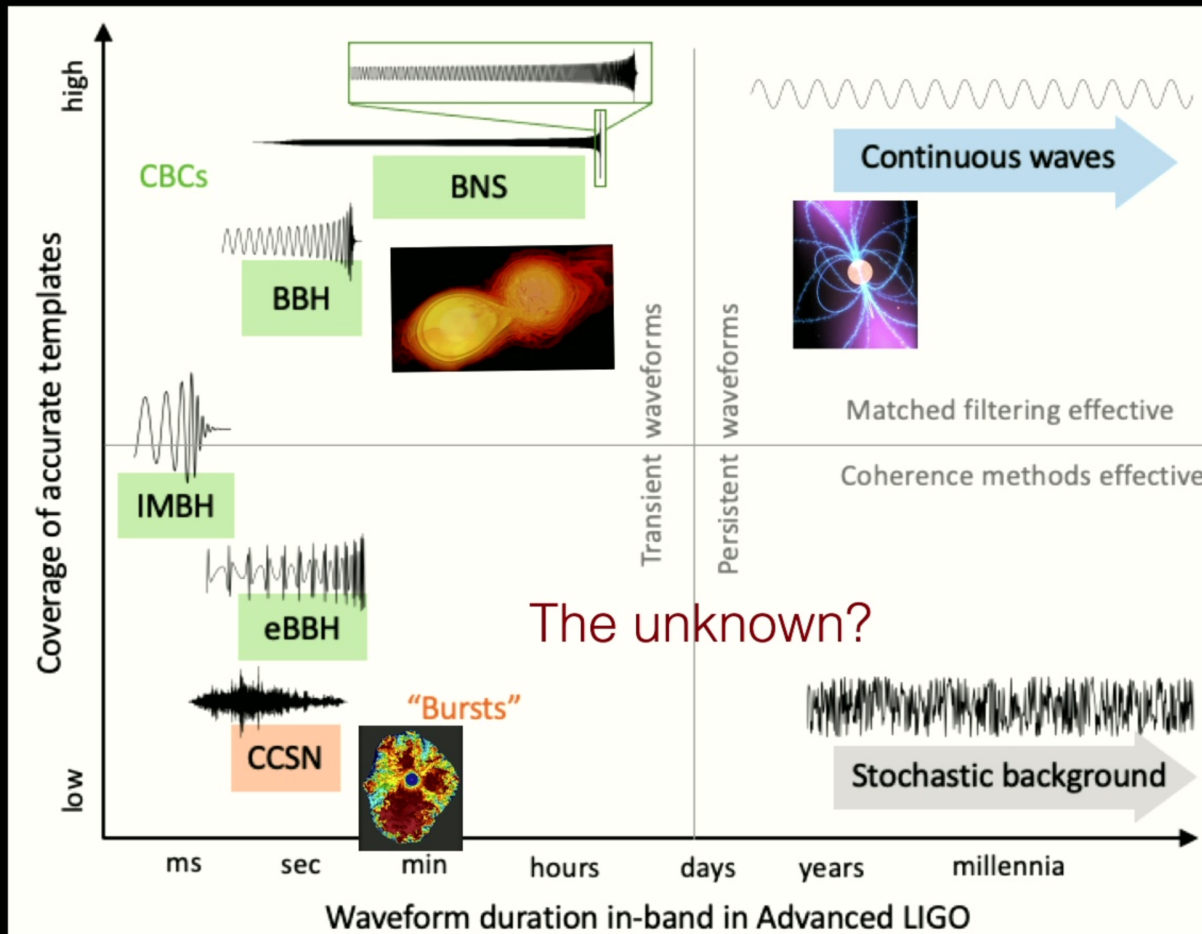
O4 Low Significance Detection Candidates: **63** (Total)





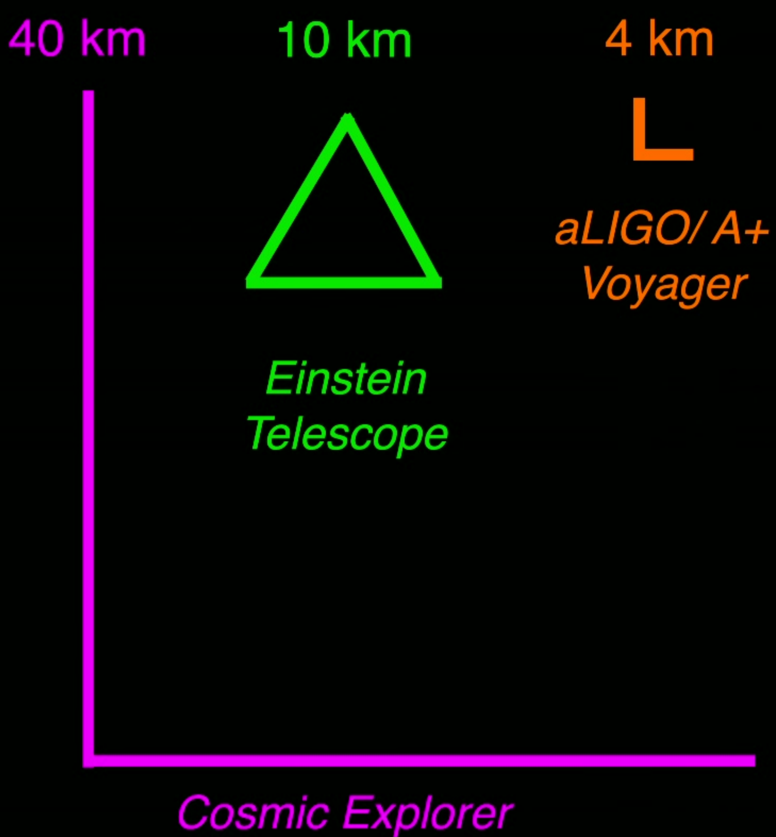
https://ldas-jobs.ligo.caltech.edu/~detchar/summary/

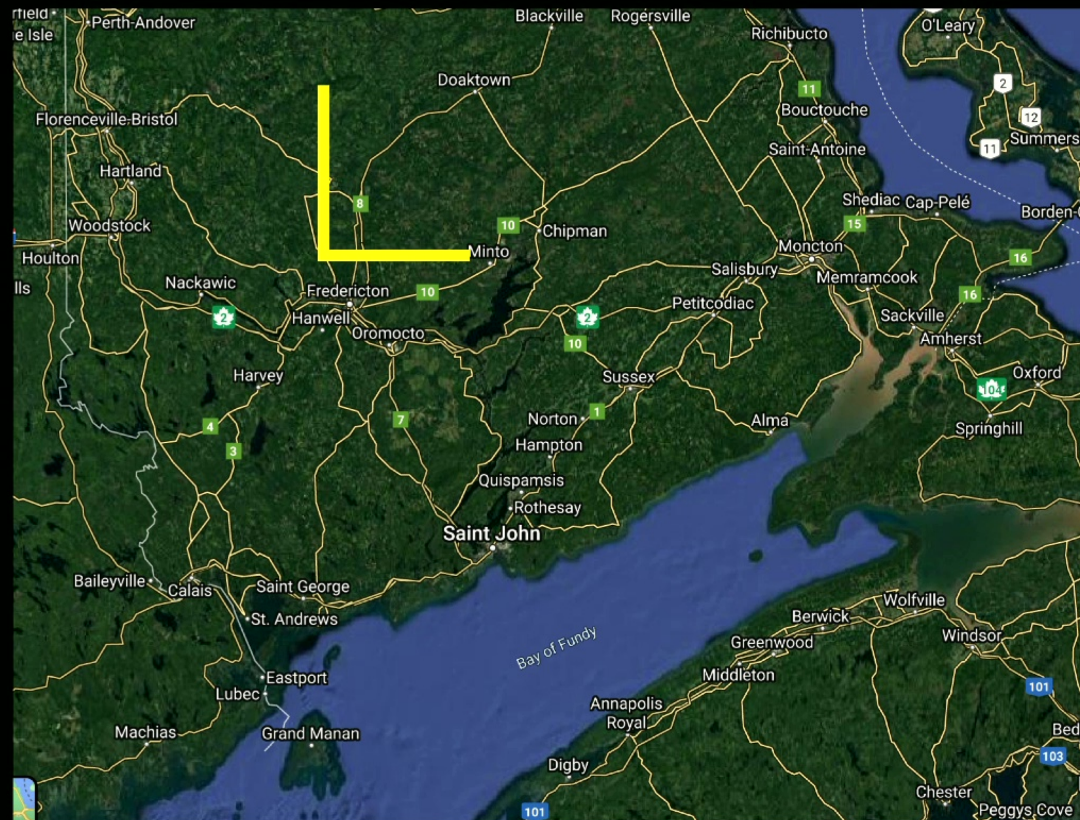
What else might we detect with current detectors?

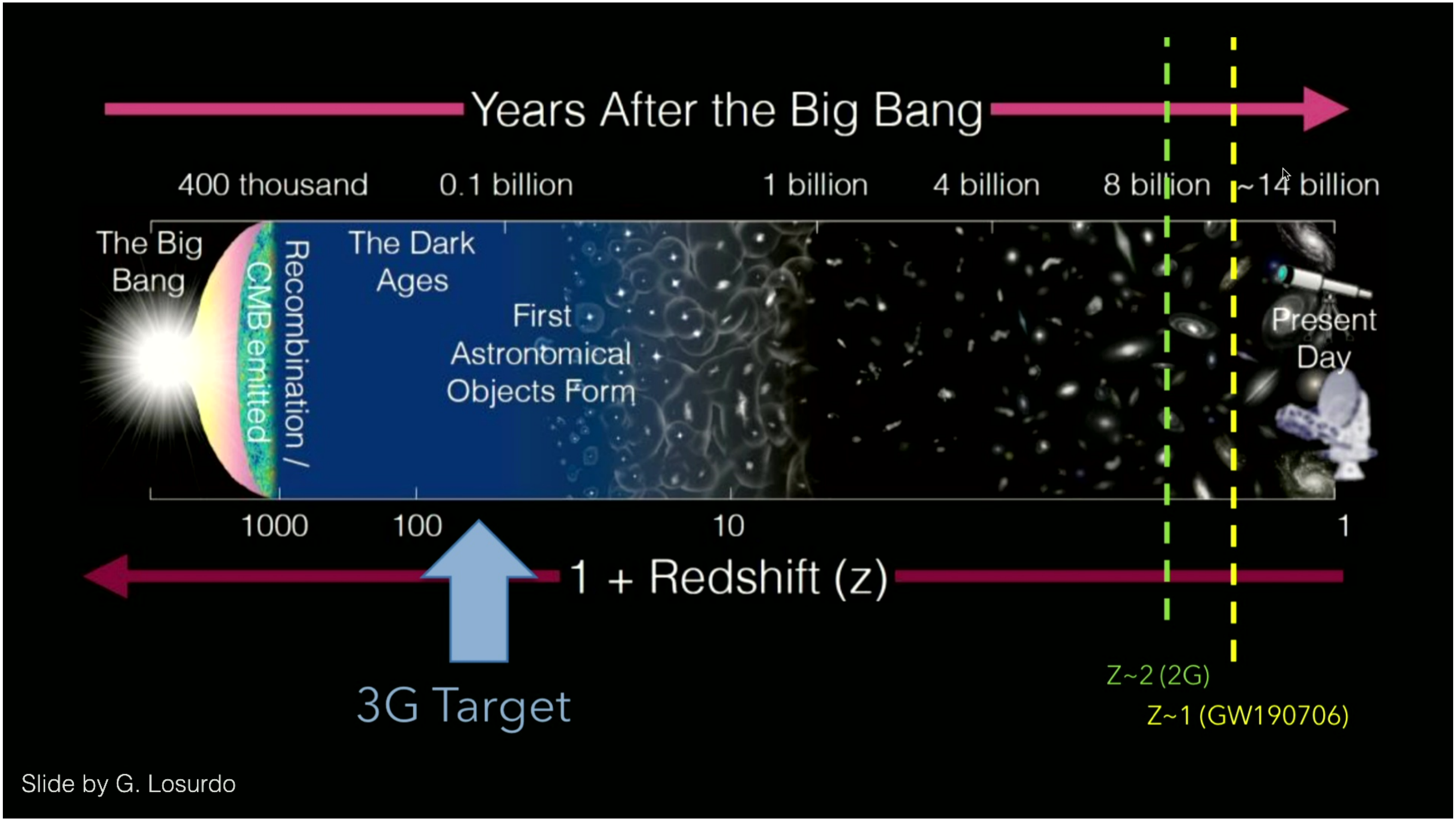


McIver and Shoemaker, 2021

The next generation GW detectors



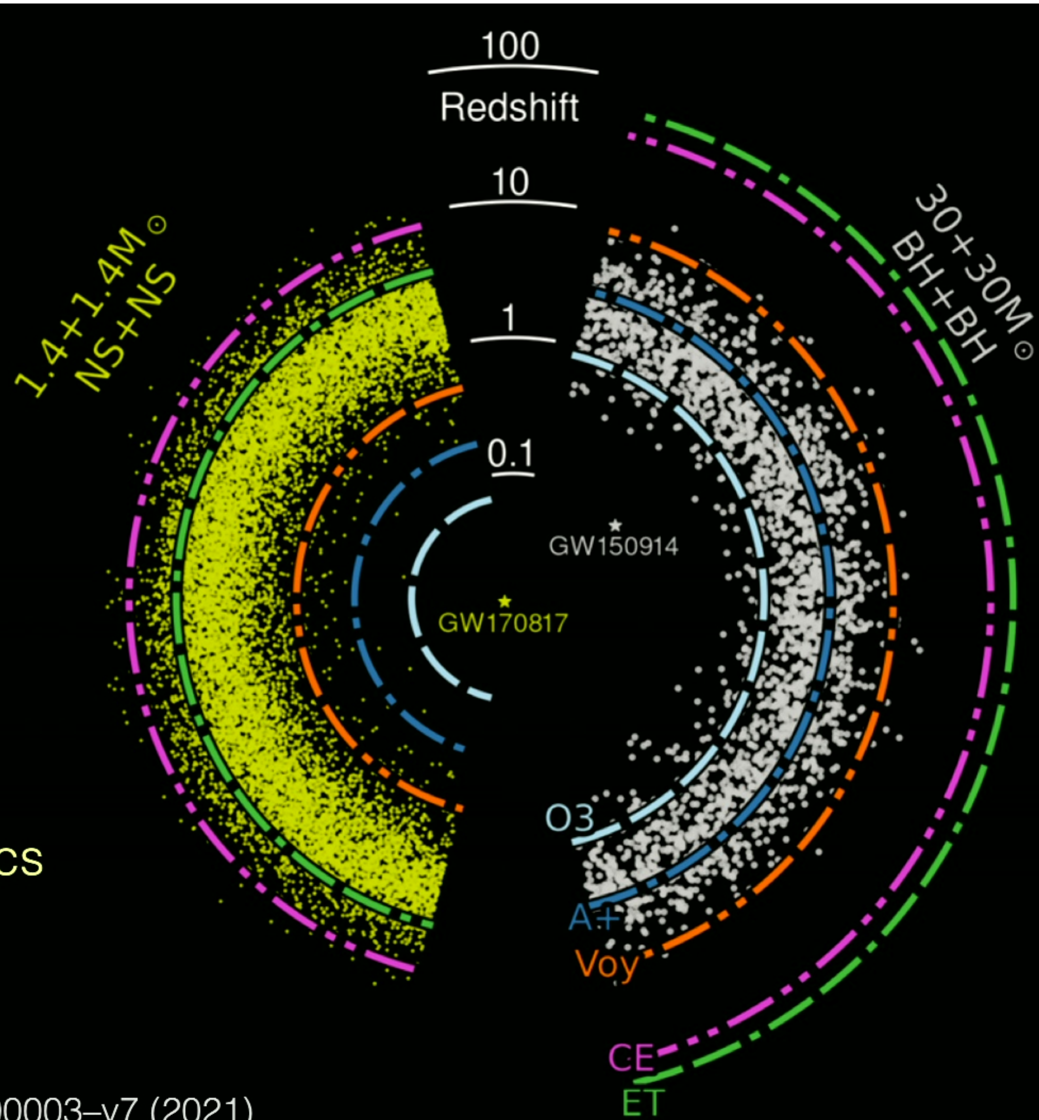



Years After the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
~14 billion
The Big Bang
Recombination / CMB emitted
The Dark Ages
First Astronomical Objects Form
Present Day
1000
100
10
1
1 + Redshift (z)
3G Target
Z~2 (2G)
Z~1 (GW190706)
Slide by G. Losurdo

300,000 BNS mergers!

1 merger every 100 seconds!

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



100,000 BBH mergers!

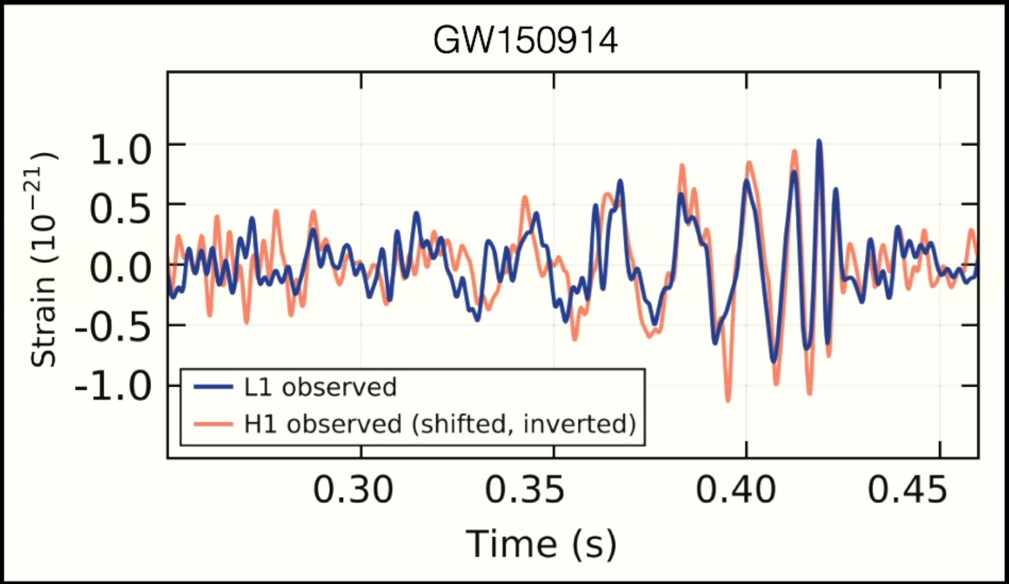
1 merger every 5 minutes!

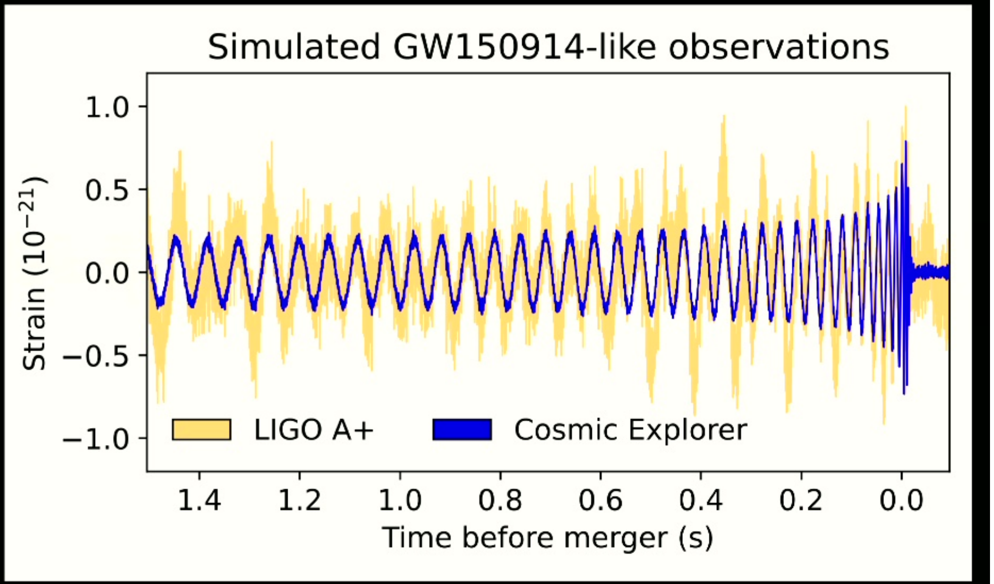
~8 will be nearby (z<0.1) with median SNR of 600, up to SNR of ~2500!

Hall and Evans, 2019

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

Along with cosmological reach: large SNRs

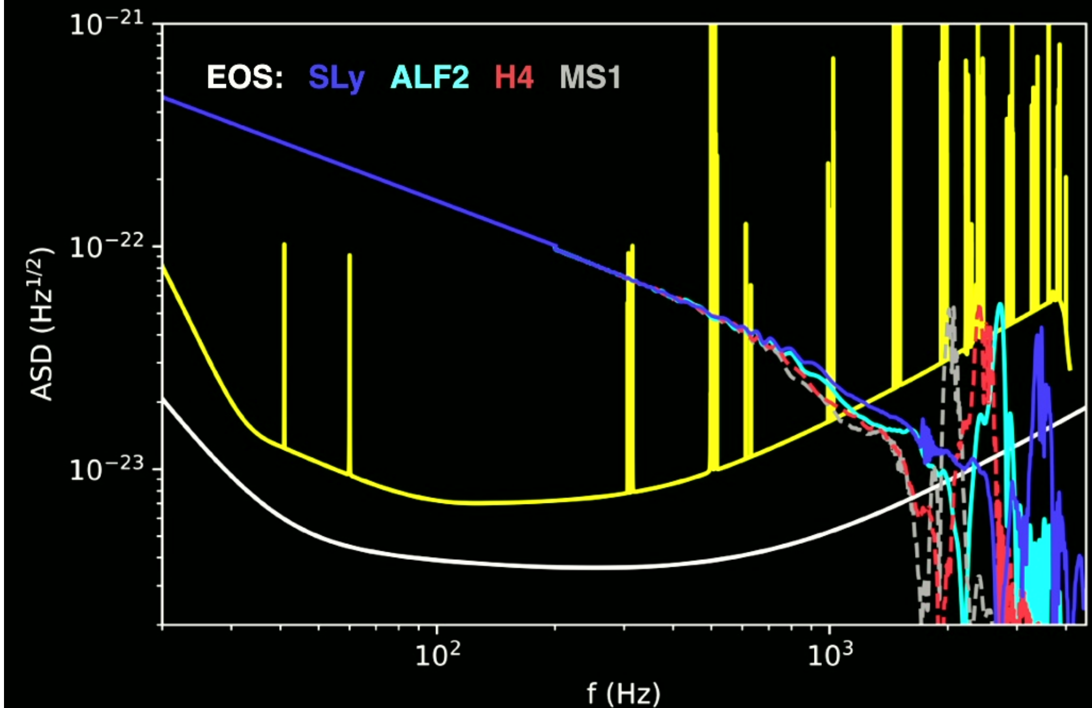


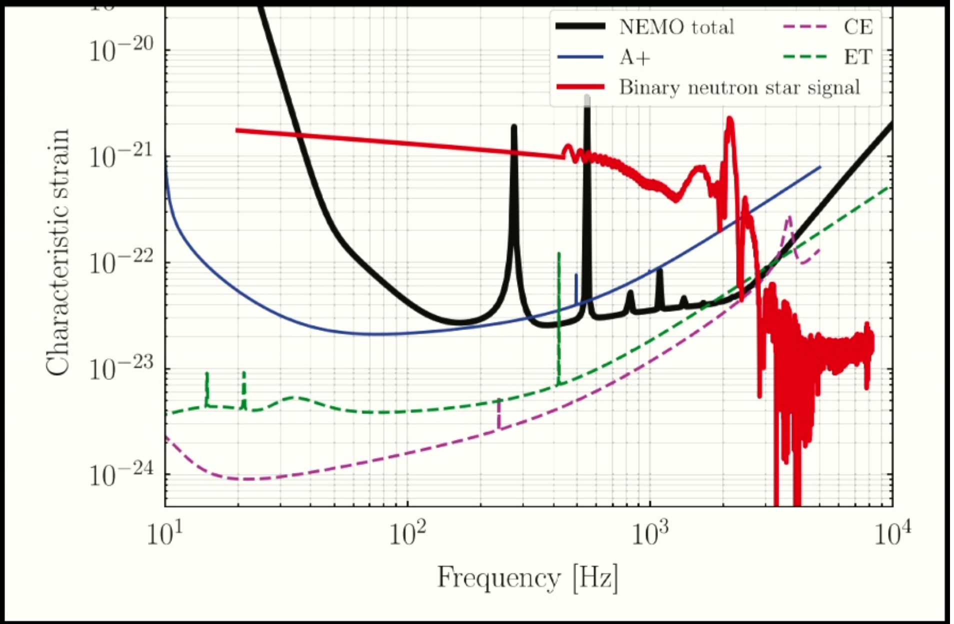


LIGO-Virgo, PRL 116.061102 (2016)

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

Broadband observations with next generation detectors

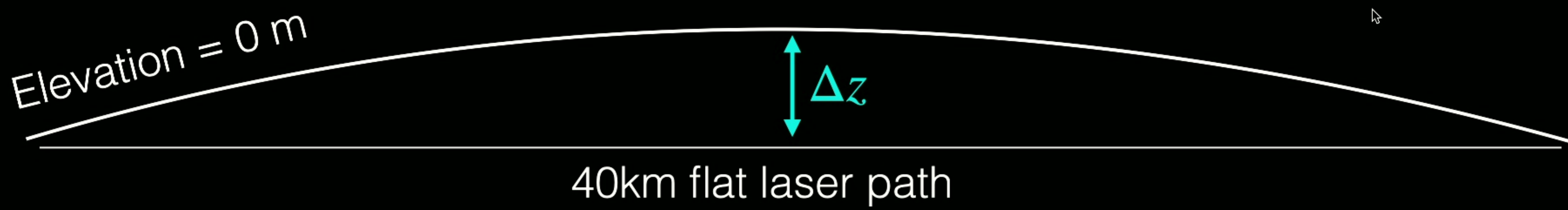




Jocelyn Read

NEMO design paper, AAAP, Ackley et al, 2020

Where would CE be built?



Question: what is the height of Δz ?

1 m
5 m
10 m
20 m
30 m

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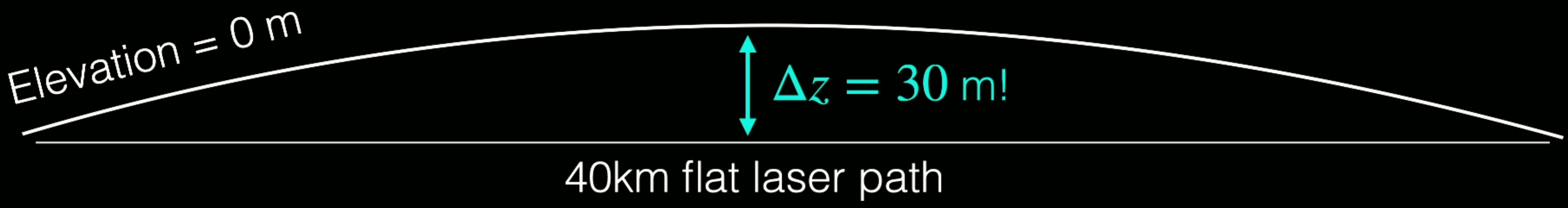
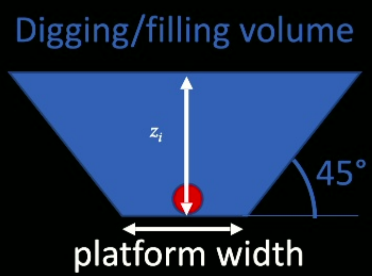
Where would CE be built?



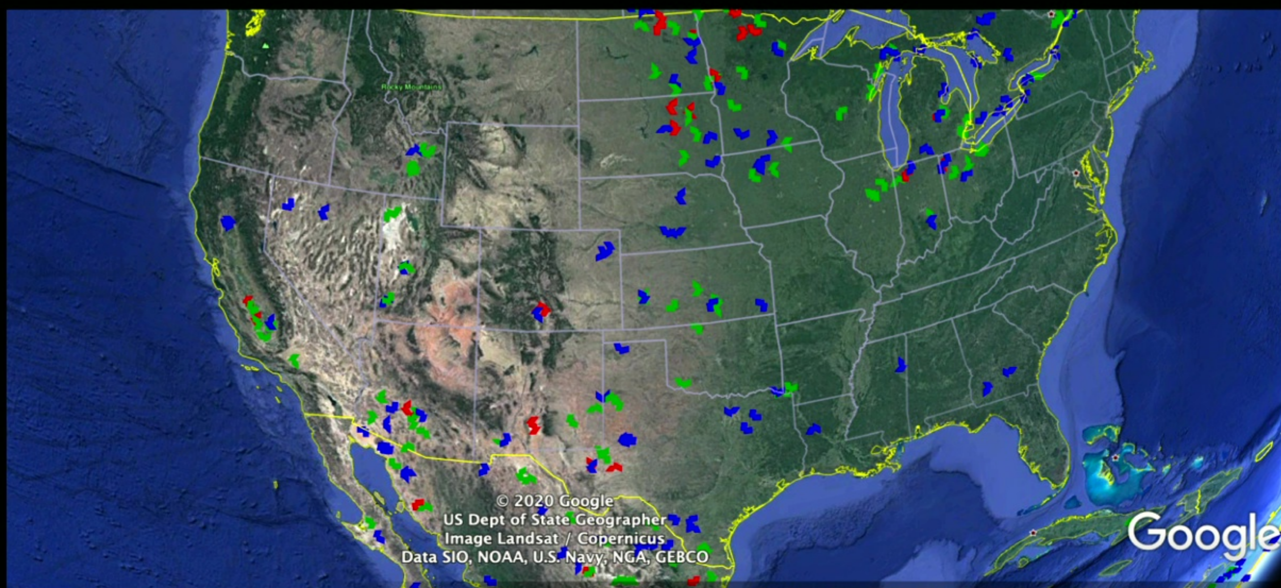


Assuming 4 m platform width and ~10$/m³*

Analysis and slide 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 approach by
Kevin Kuns, MIT.
This is not a CE
Consortium analysis

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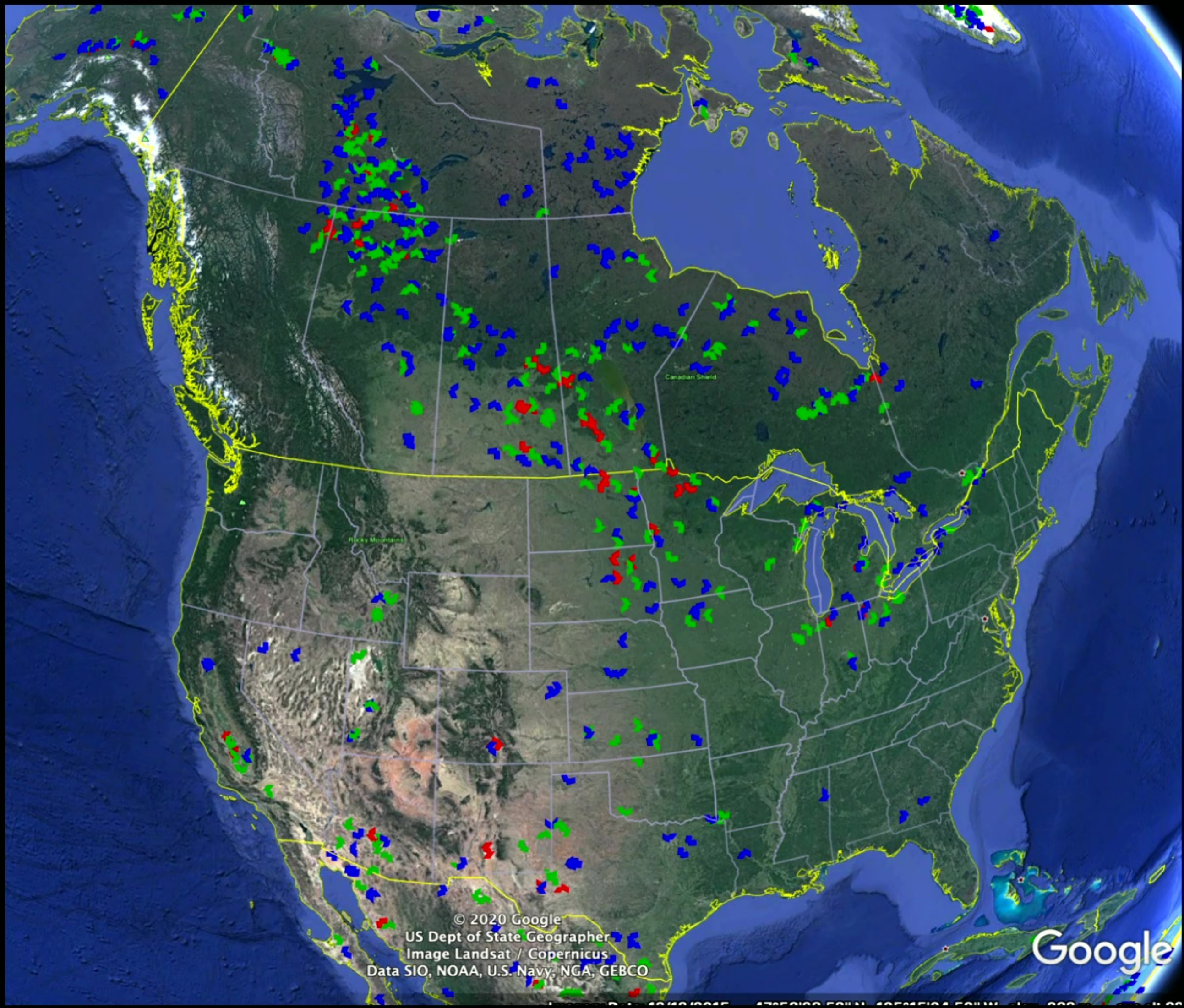
red
300-900
green
900-1400
blue
1400-2000
x 10^3 m^3

Many locations in Canada!

Analysis by
François
Schiettekatte,
UdeMontreal



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

Based on approach by
Kevin Kuns, MIT.
This is not a CE Consortium analysis

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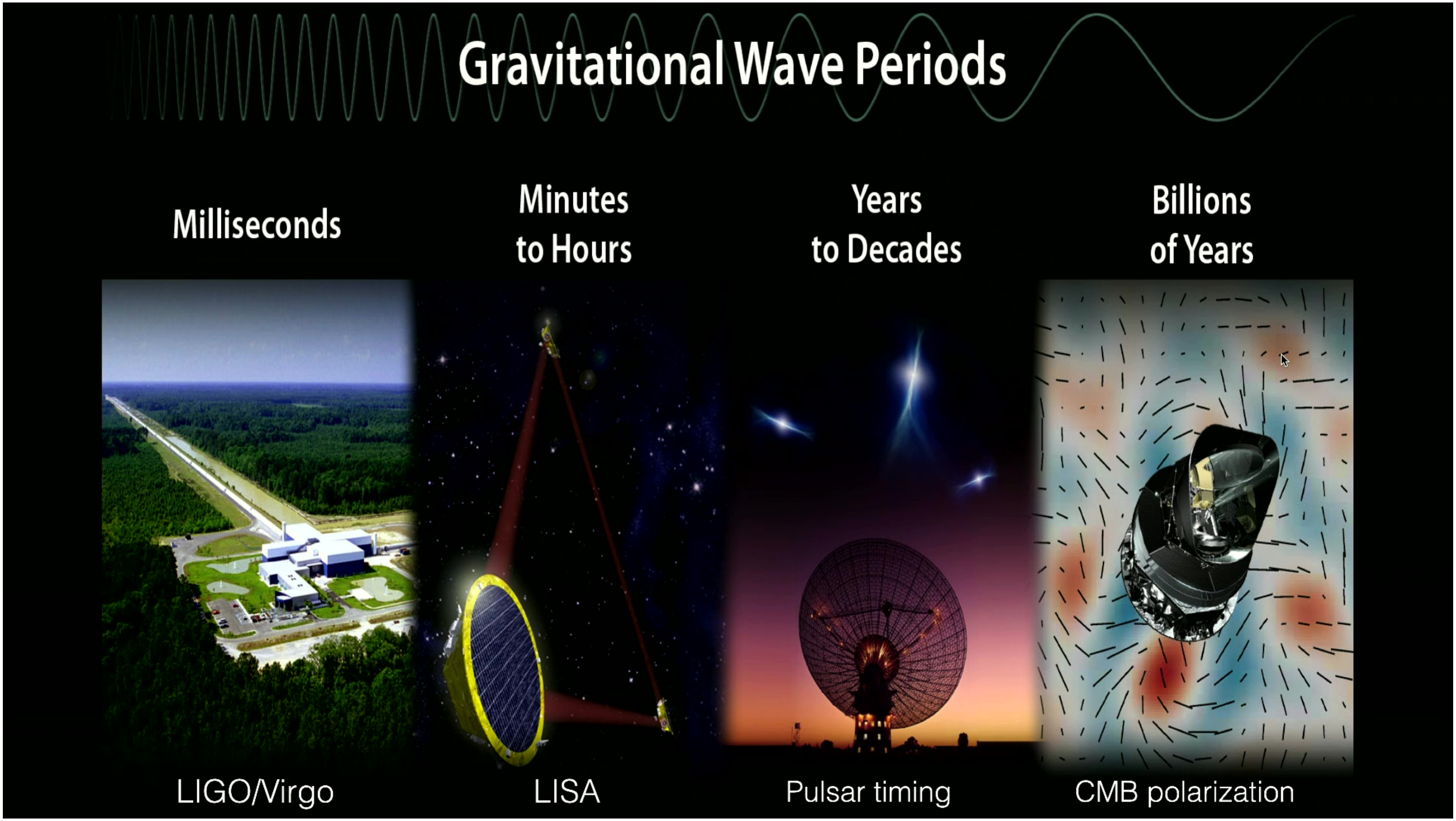
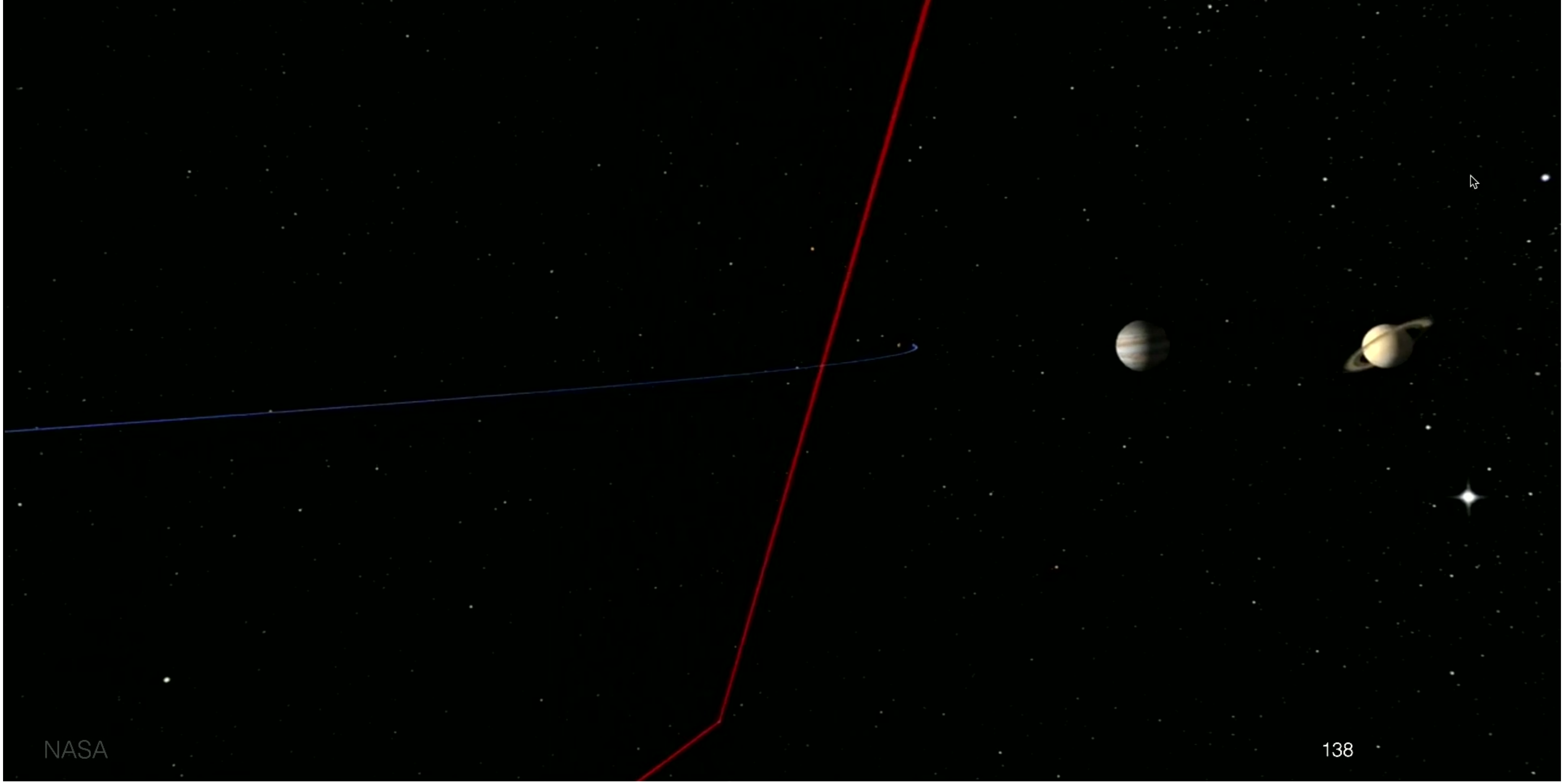

Gravitational Wave Periods
Milliseconds
Minutes to Hours
Years to Decades
Billions of Years
LIGO/Virgo
LISA
Pulsar timing
CMB polarization

The LISA mission



Question - Recall the relationship between gravitational wave strain amplitude and quadrupole moment:

$$h_{ij}(t) \propto \frac{G}{c^4}\frac{d^2 I_{ij}}{dt^2}\frac{1}{r} \quad \text{and recall} \quad I_{ij} = \int \rho(\vec{r}) x_i' x_j' d^3 r'$$

Consider two black hole binary systems at an equal distance from Earth, with the same orbital separation between the black holes, a, and roughly circular orbits.

If system A is two 500 $M_\odot$ black holes and system B is two 50 $M_\odot$ black holes, *which system will emit higher amplitude GWs?*

Question - Recall the relationship between gravitational wave strain amplitude and quadrupole moment:

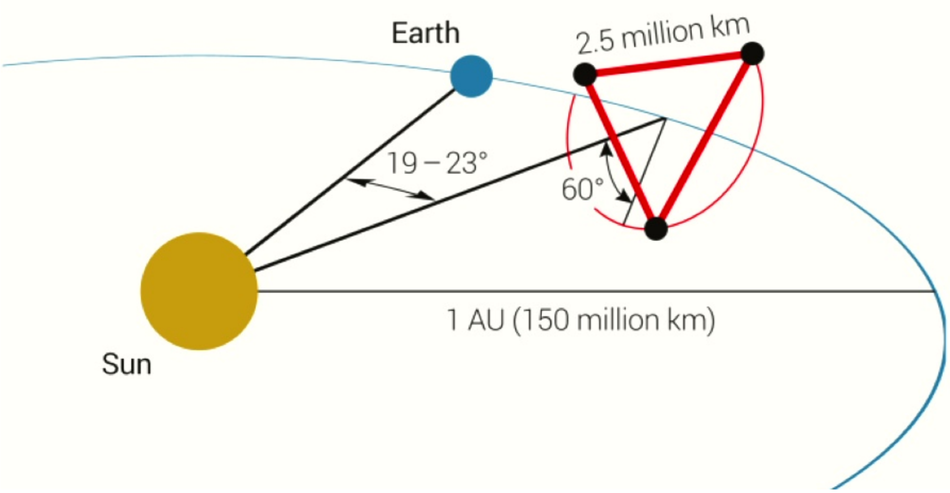
$$h_{ij}(t) \propto \frac{G}{c^4}\frac{d^2 I_{ij}}{dt^2}\frac{1}{r} \quad \text{and recall} \quad I_{ij} = \int \rho(\vec{r}) x_i' x_j' d^3 r'$$

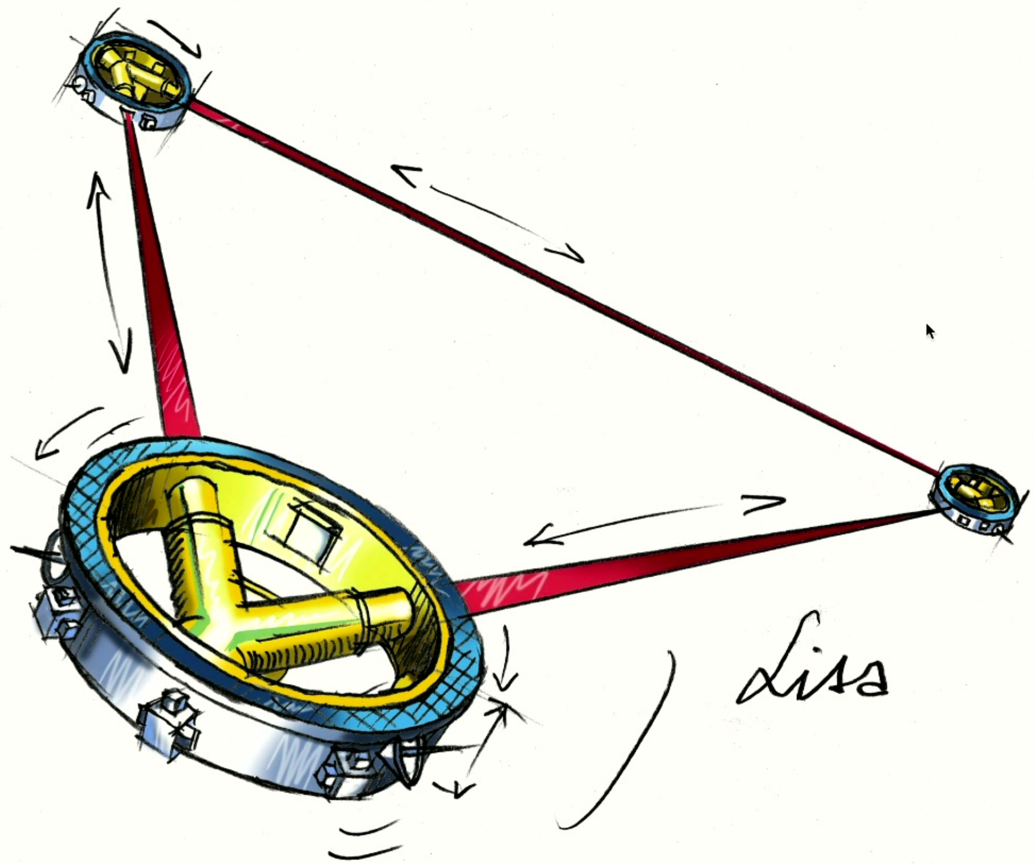
Hint: you may also find this useful: $f_{LSO} \sim 220 \, \frac{20 \text{ M}_\odot}{M} \text{ Hz}$

Question - Why doesn't LIGO observe black hole mergers with total mass > ~250 $M_\odot$?

The LISA mission:

- 2.5 million km arms
- GW observation: 100 mHz – 1 Hz
  - Signals in-band for months-years; allows precise sky localization
- 4 year nominal mission (10 year extended mission)





ESA, C. Vijoux

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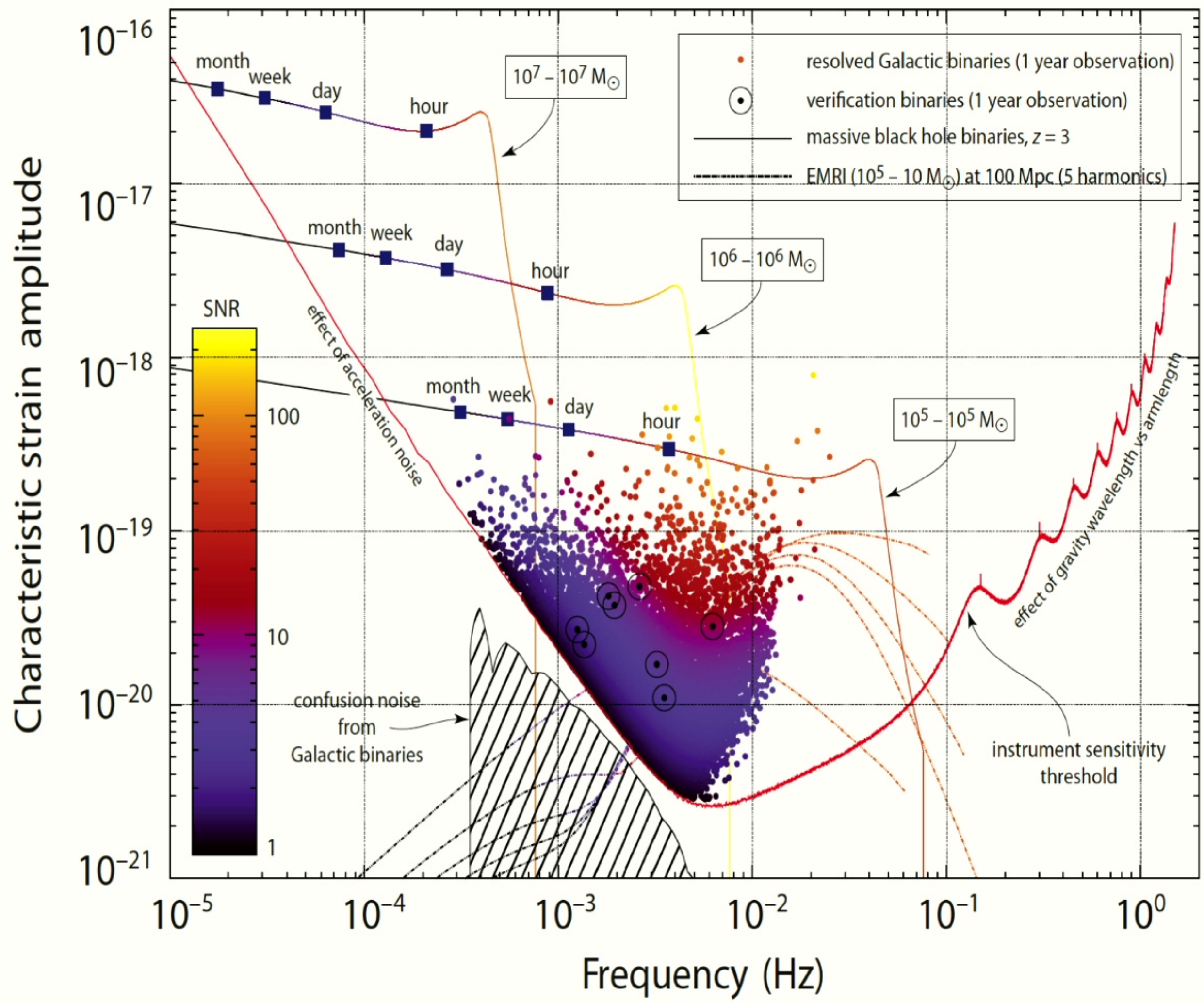
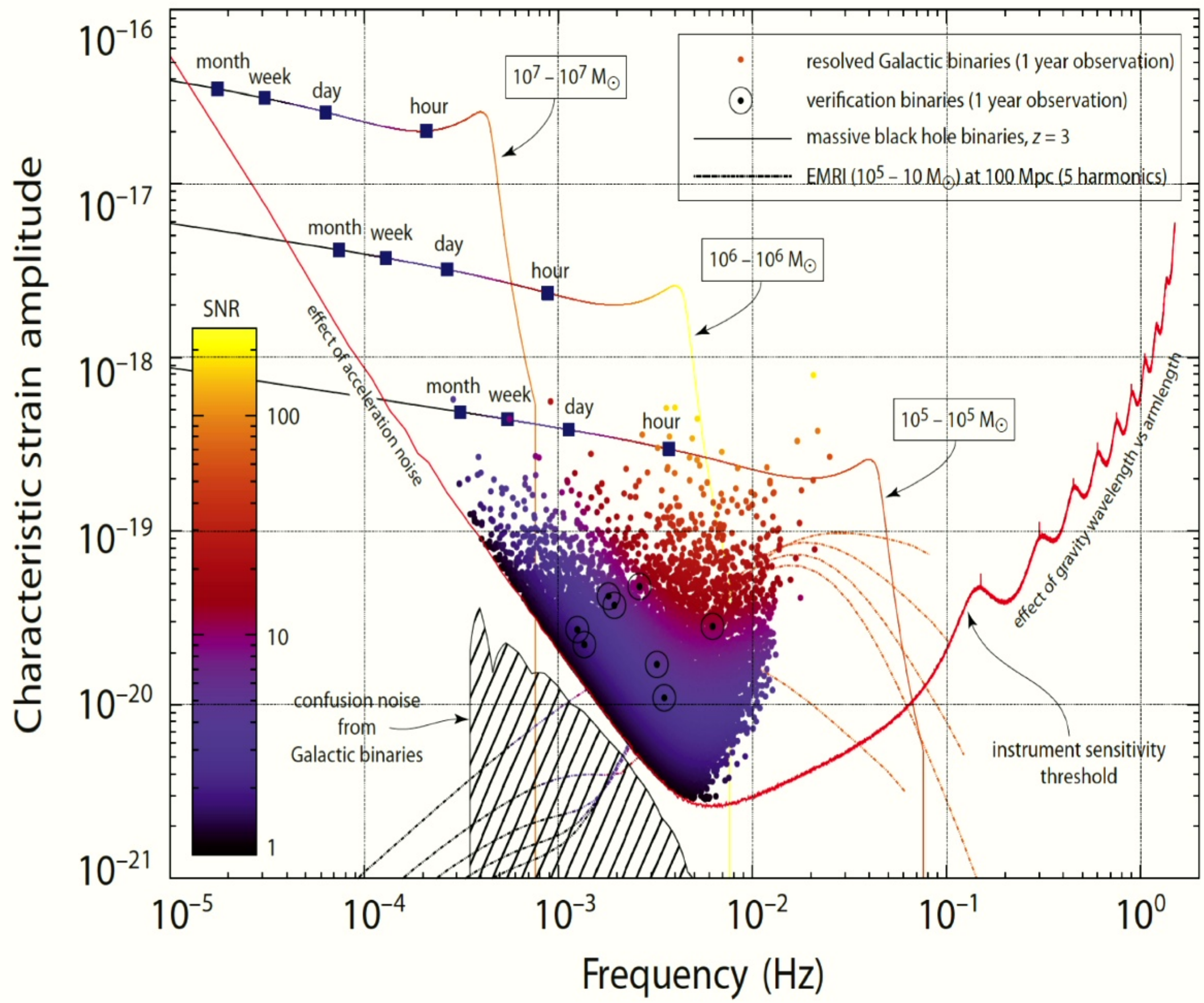
LISA Discovery Space



lisa

ESA, K. Holley-Bockelmann

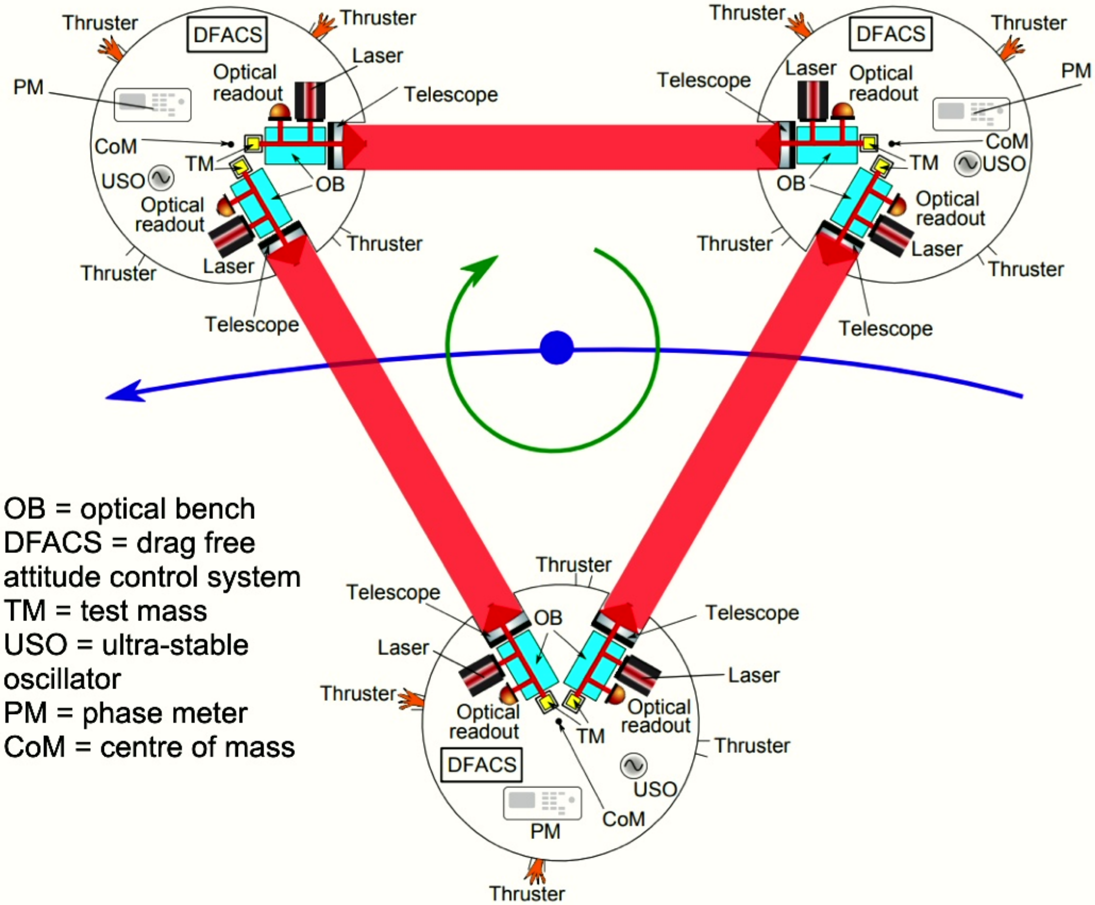
Question: Why are the identified verification binaries not the highest expected SNR binaries?



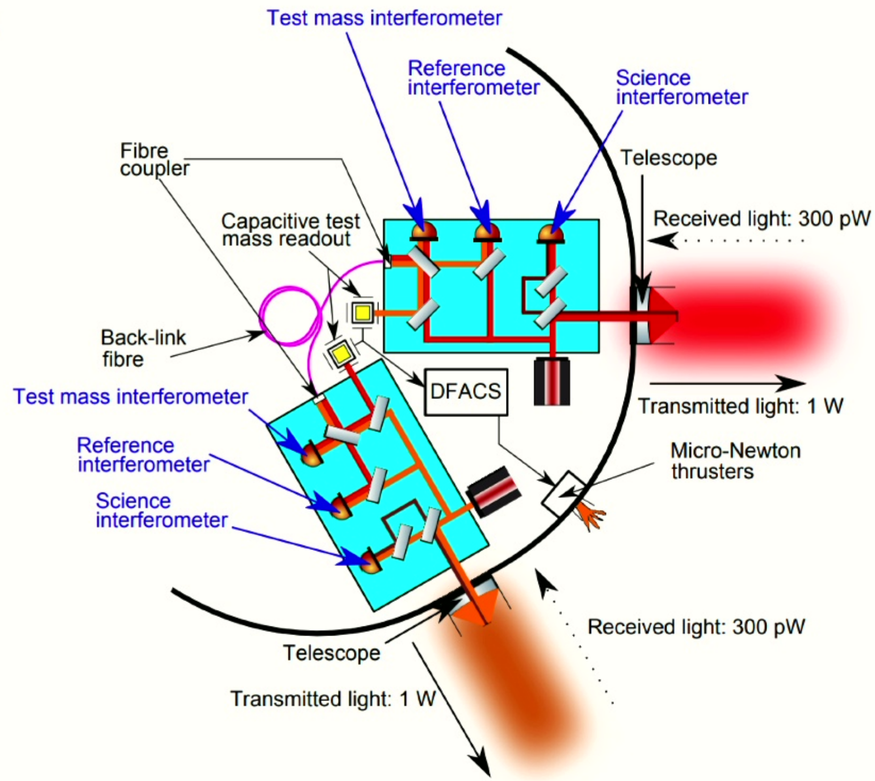
lisa

ESA, K. Holley-Bockelmann

How does LISA work, exactly?



OB = optical bench
DFACS = drag free attitude control system
TM = test mass
USO = ultra-stable oscillator
PM = phase meter
CoM = centre of mass



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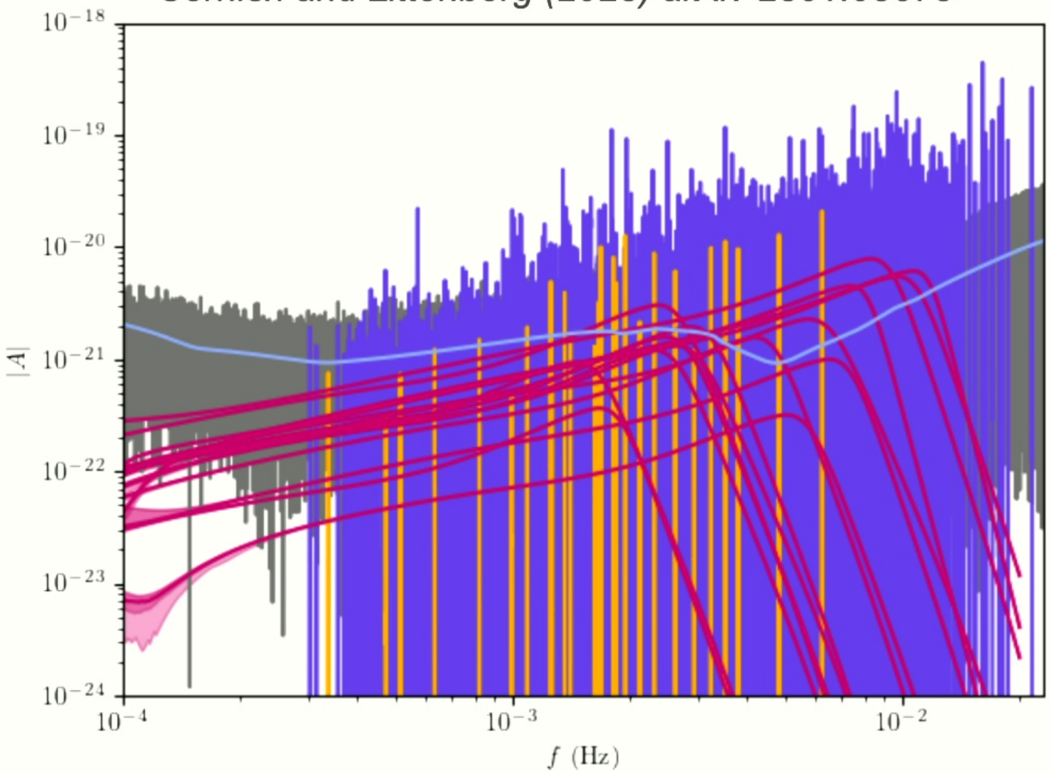
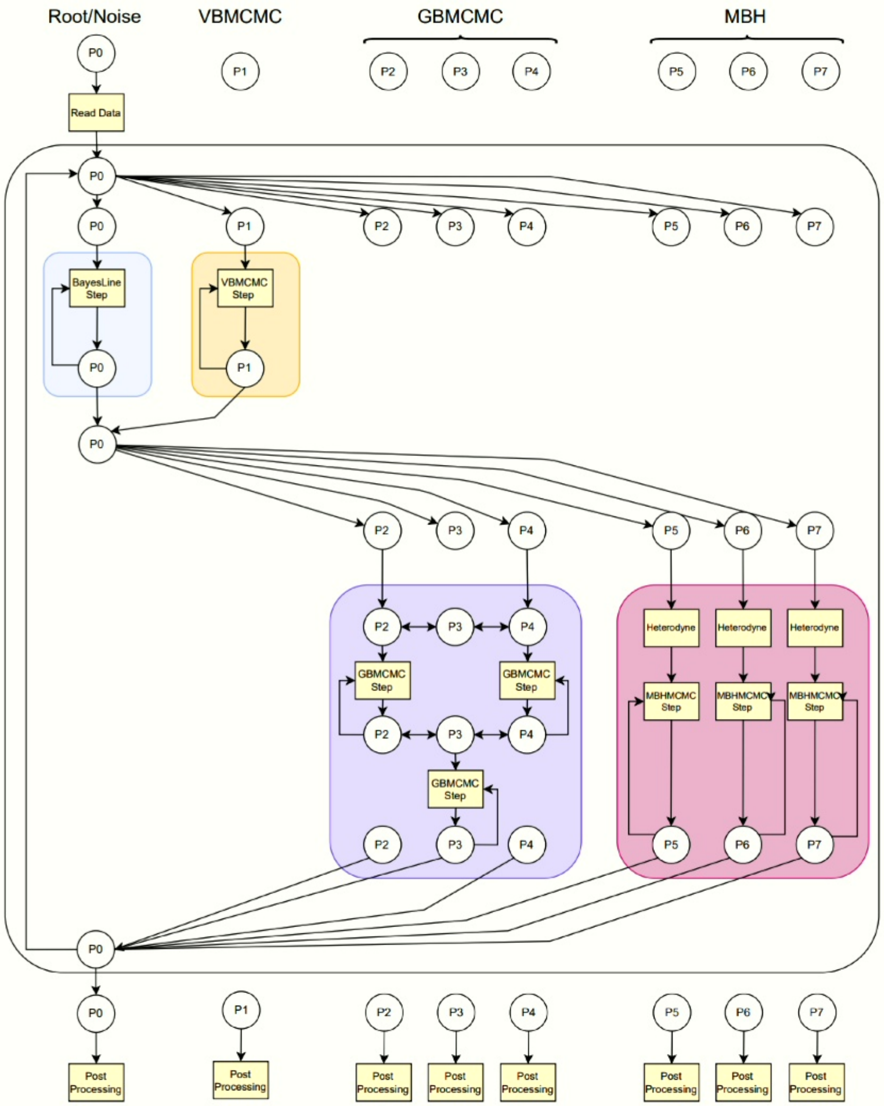
Markus Otto PhD thesis

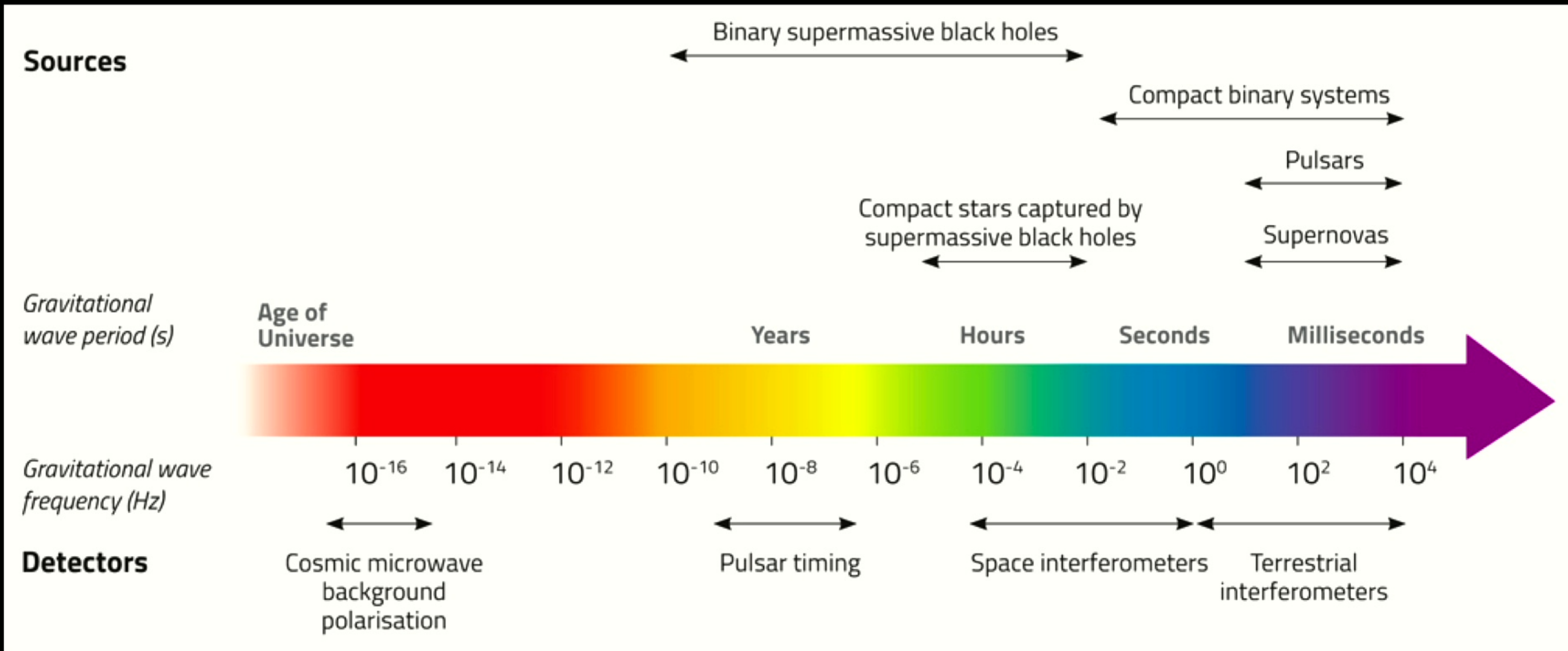
Dealing with overlapping signals: the "global fit" approach

Cornish and Littenberg (2023) arXiv 2301.03673



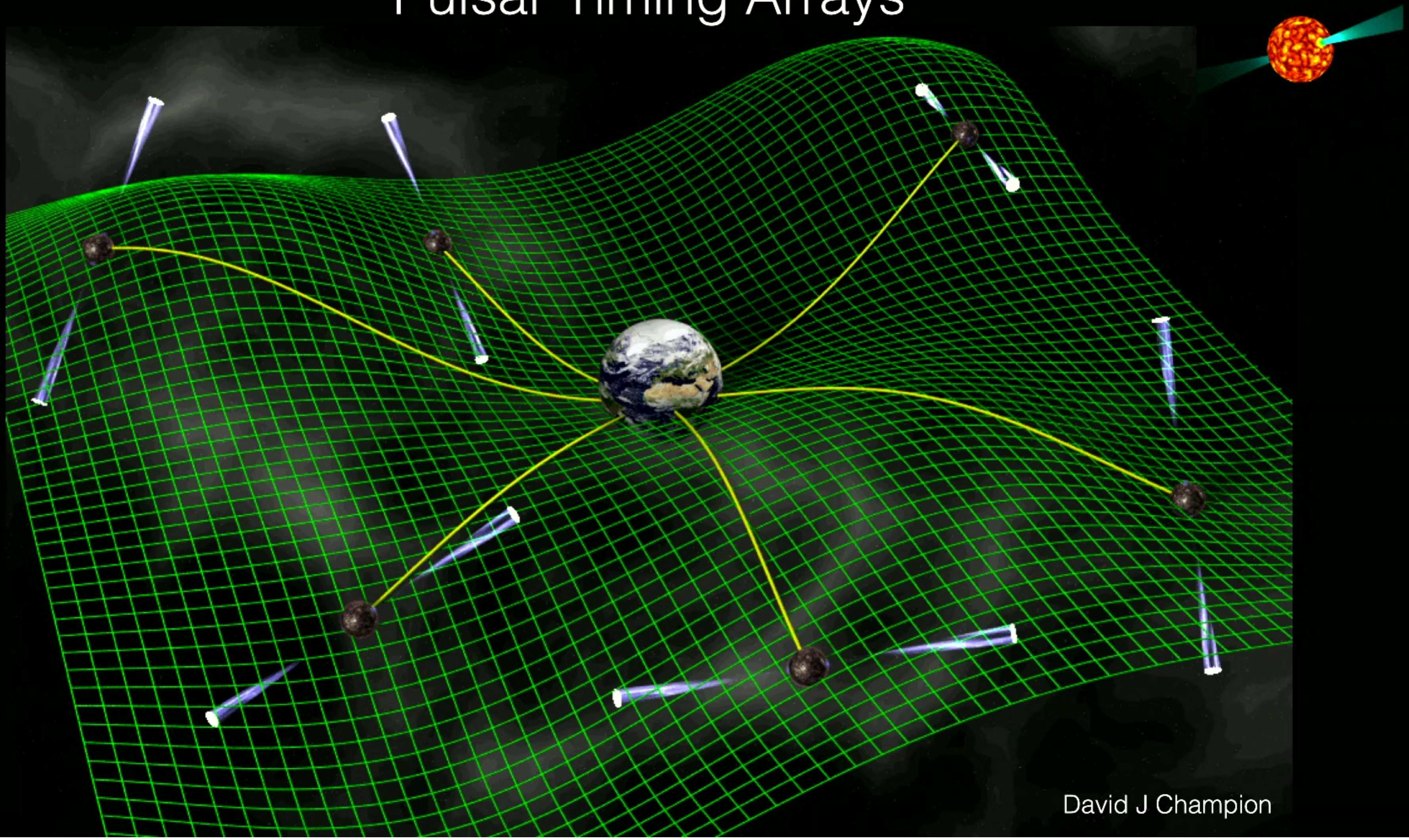


The GW spectrum

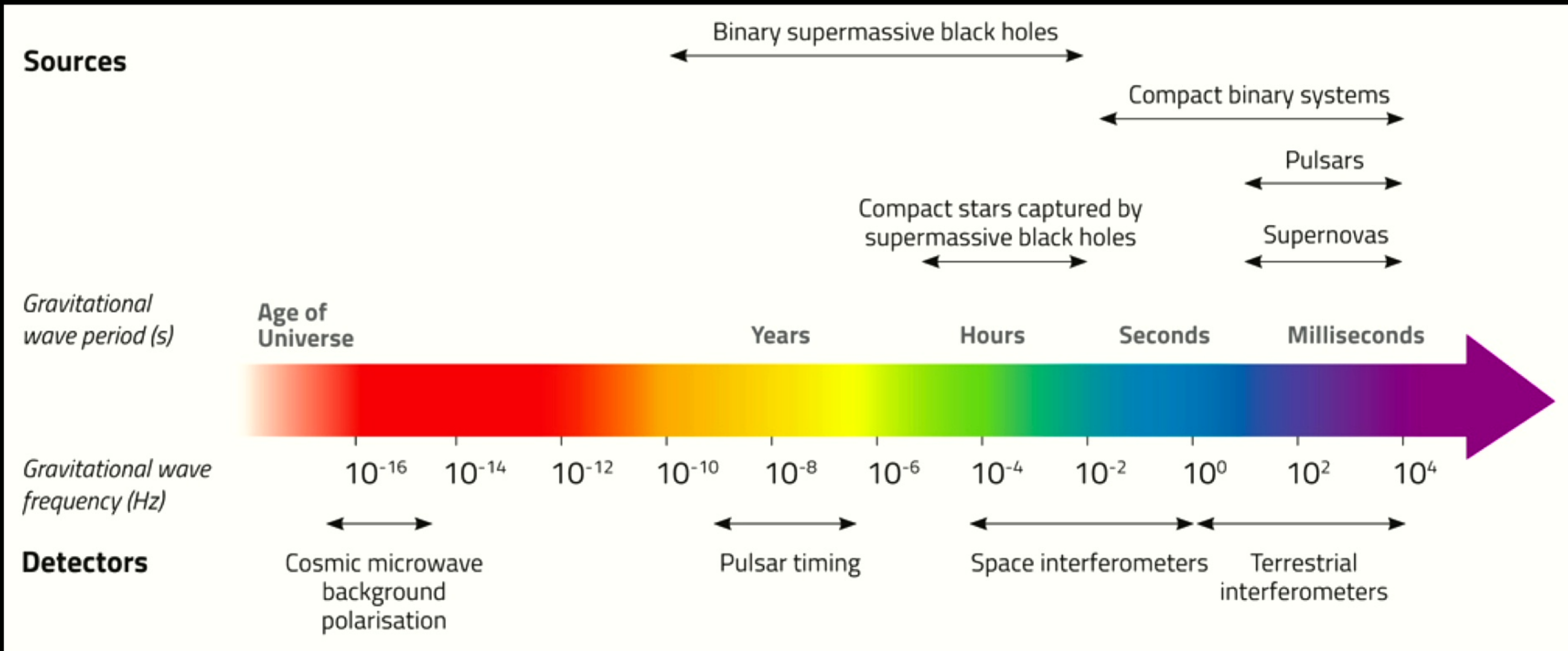


Science in School

Pulsar Timing Arrays

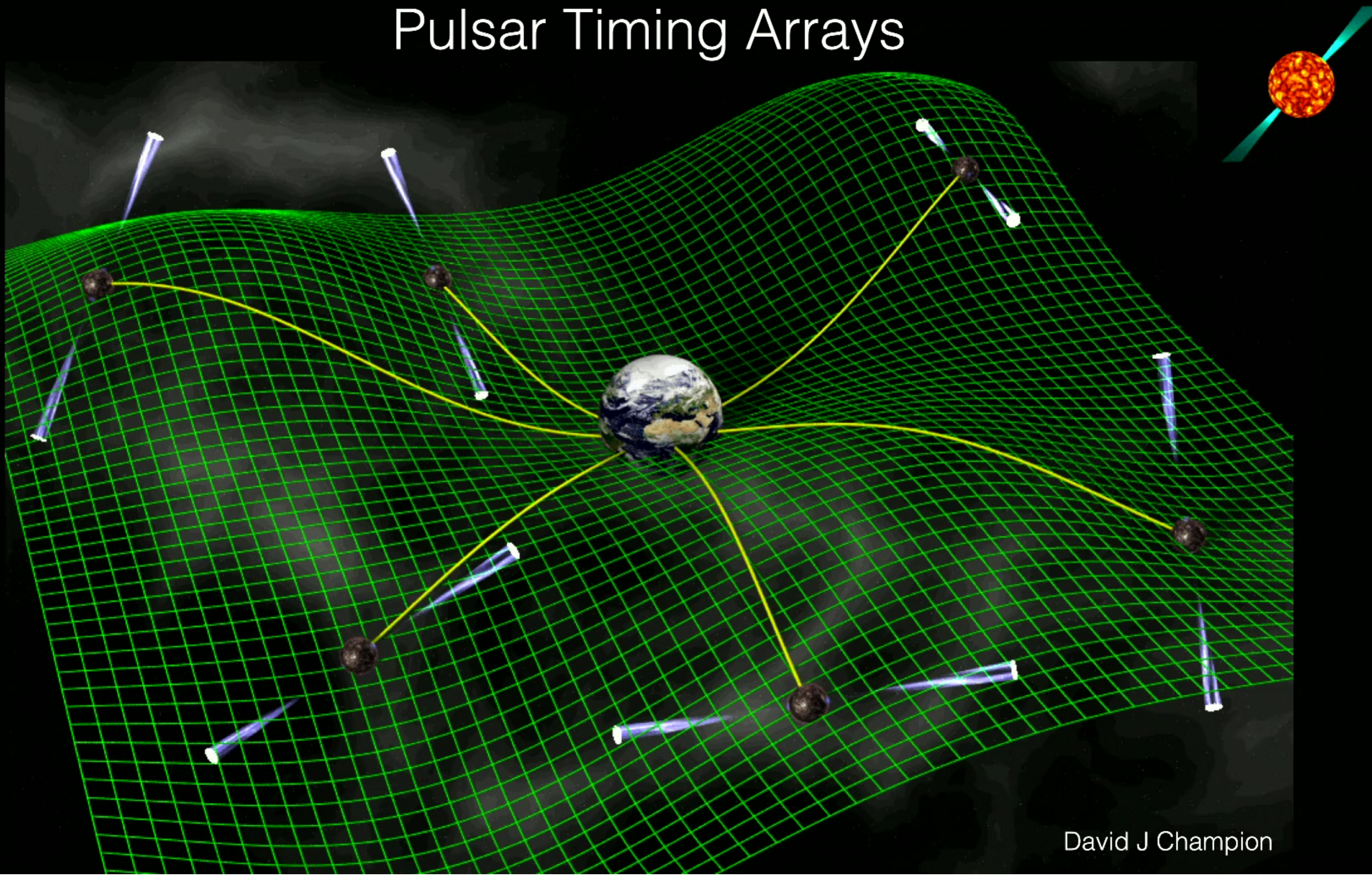


The GW spectrum



Science in School

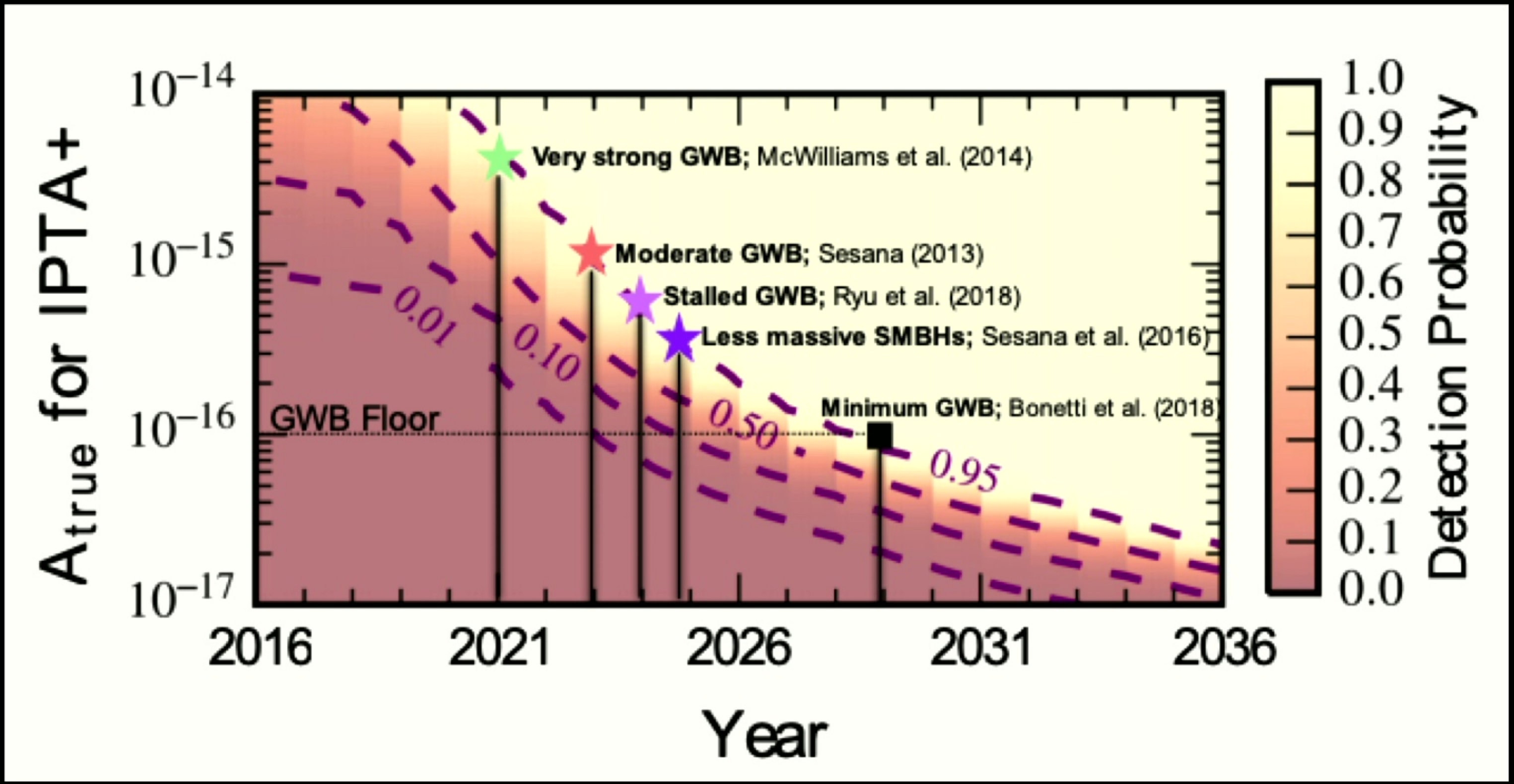
Pulsar Timing Arrays



An International Radio Telescope Effort

IPTA

IPTA detection prospects



C. Mingarelli and S. Taylor

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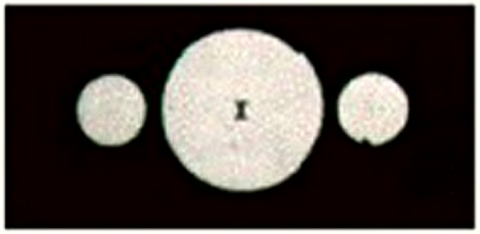
This is just the beginning of gravitational wave astrophysics!



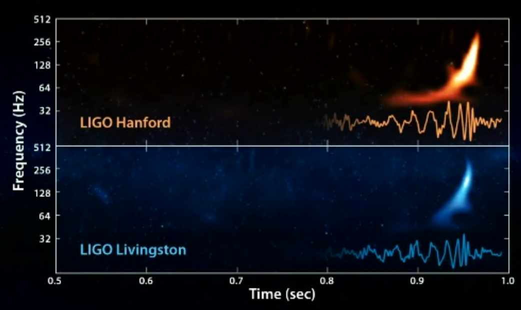
Galileo first sketch
1610

Better telescope
1616

Rice

400 years later…

HST



?

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Get involved with GW physics/astrophysics

Open invitation to join the **CITA GW astrophysics focus group** (meets weekly on Tuesdays at 3pm Eastern) led by Phil Landry (CITA) - reach out to Phil at plandry@cita.utoronto.ca

Join the **Cosmic Explorer Consortium** - open membership: https://cosmicexplorer.org/

Explore the **Gravitational Wave Open Science Centre** (host of LIGO/Virgo data and analysis tutorials/web courses) - gwosc.org

Join the **LISA Consortium** - Chat with the PI of your local LISA group

Explore previous **LISA Canada workshops** - LISA Canada 2021 white paper, Talks on YouTube

Apply to join the **LIGO Scientific Collaboration** - chat with your institutional LIGO PI