Gravitational Wave detectors: Accomplishments and Plans for the Future

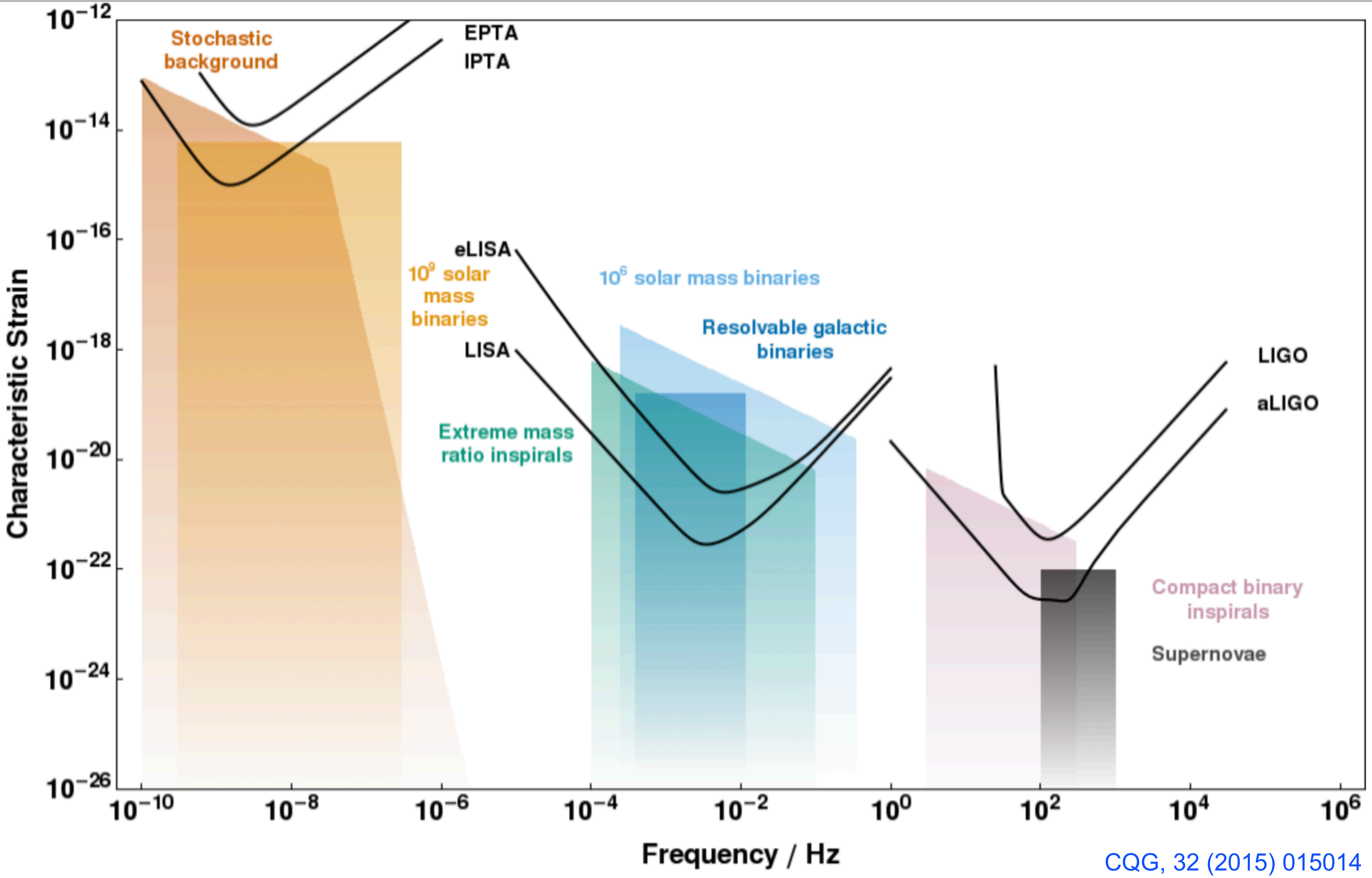
Nordita
21 June 2017

David Shoemaker, ed.
For the LSC and Virgo, and
The LISA Consortium

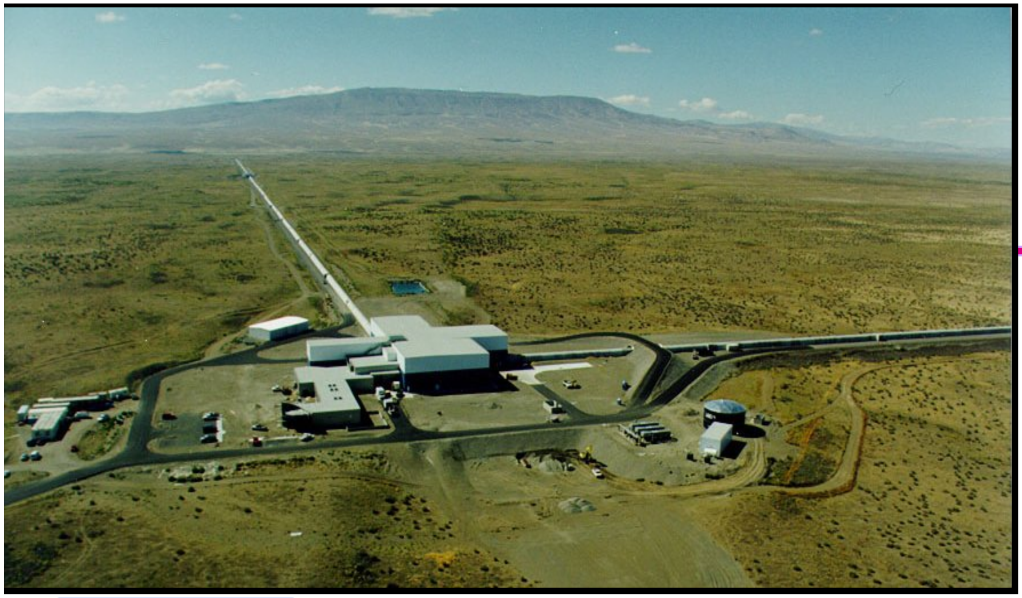
LIGO-G1701145-v1

- What are the ground-based Gravitational-wave detectors?
- What limits their sensitivity?
- What have we accomplished with them to date?
- What improvements can we expect in the next year, several years, decades?
- …and space?

A spectrum of GW Sources and Sensors



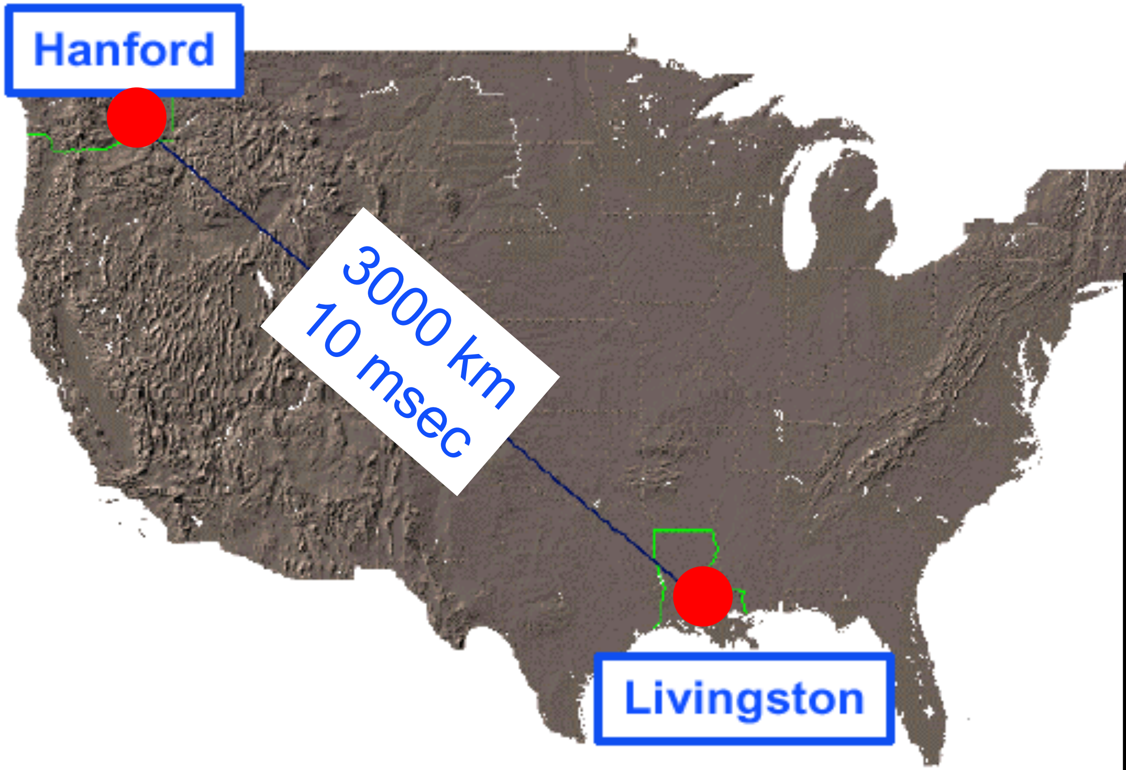
CQG, 32 (2015) 015014



LIGO Laboratory
– Caltech, MIT –

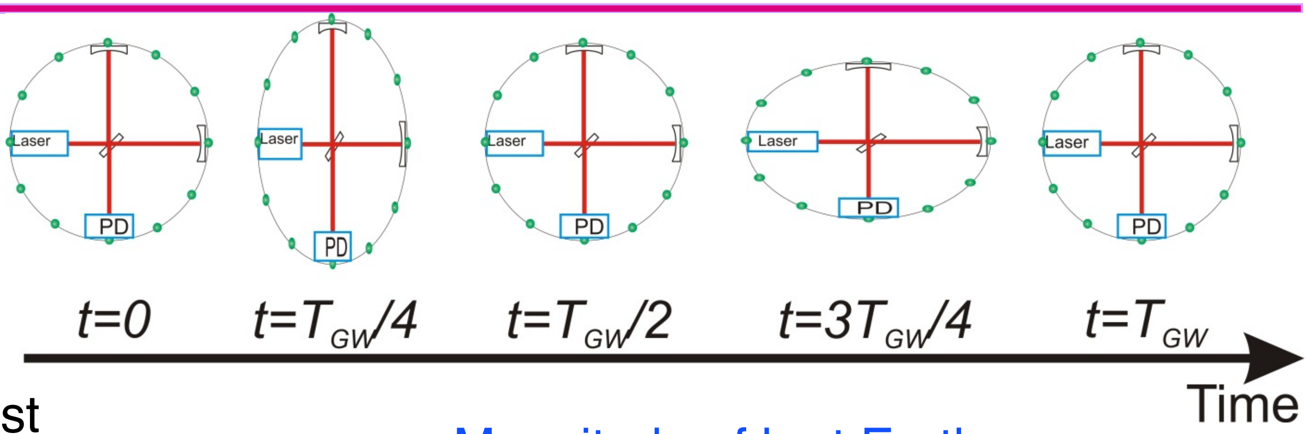
built observatories
in ‘90s

Built, then observed
with initial detectors
2005-2011;
Advanced LIGO
Project 2008-2015



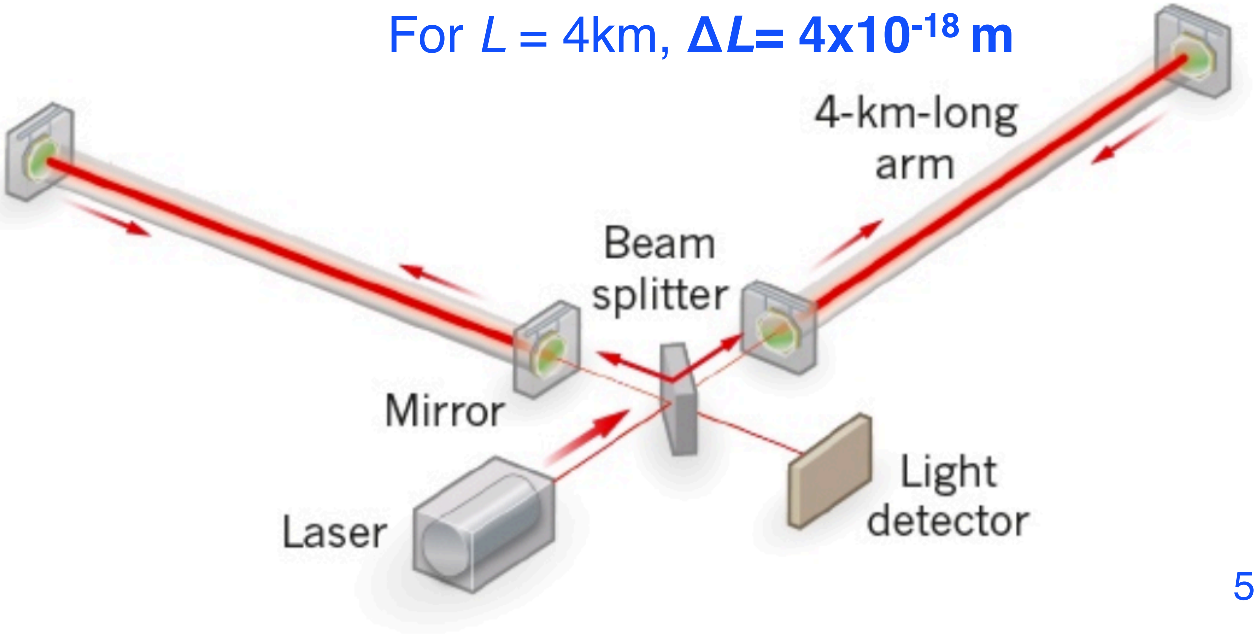
What is LIGO’s measurement technique?

- Enhanced **Michelson interferometers**
  - LIGO, Virgo, and GEO600 use variations
- Passing GWs modulate the distance between the end test mass and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent proportional to the strain amplitude
- **Arms are short compared to our GW wavelengths, so longer arms make bigger signals**
  → multi-km installations
- Arm length limited by taxpayer noise….

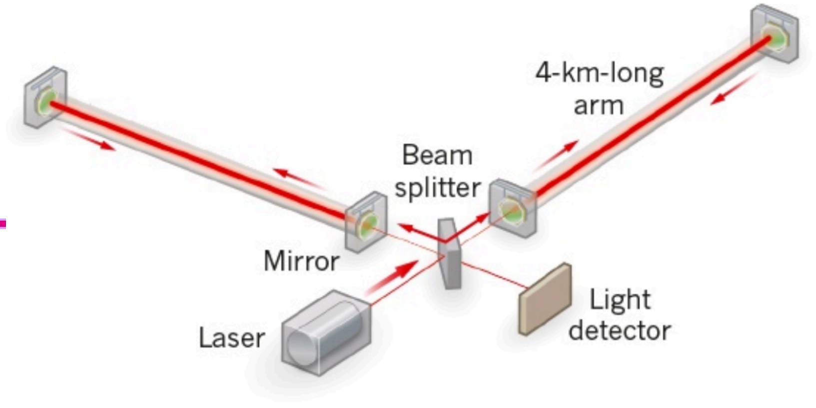


$$\boxed{h \approx \frac{\Delta L}{L}}$$

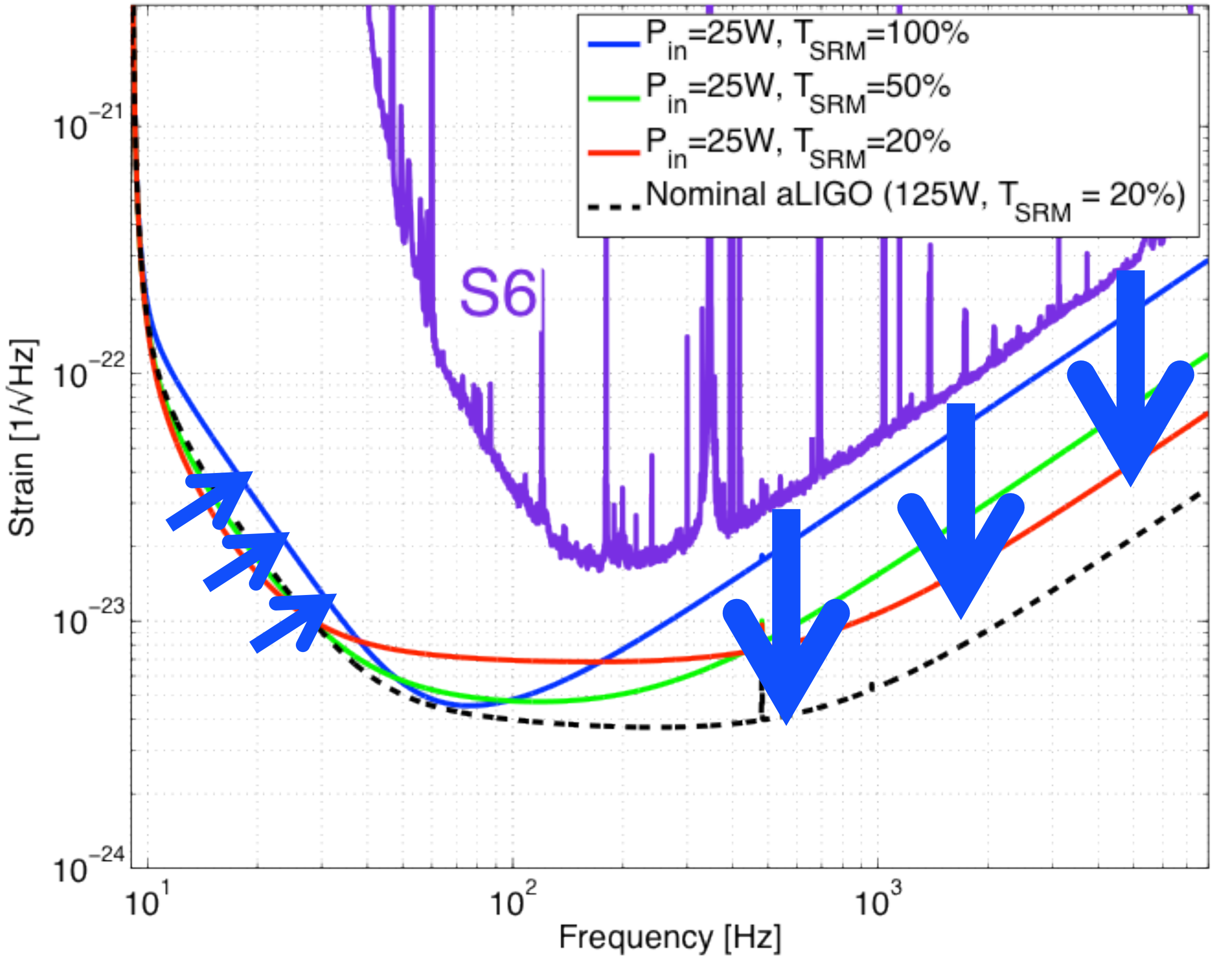
Magnitude of h at Earth:
Largest signals h ~ 10^{-21}
(1 hair / Alpha Centauri)
For L = 1 m, ΔL= 10^{-21} m
For L = 4km, **ΔL= 4x10^{-18} m**



Measuring Δ*L*= 4x10^{-18} m
Readout

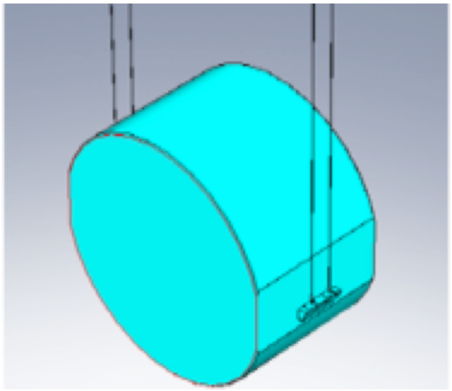


- **Shot noise** – ability to resolve a fringe shift due to a GW (counting statistics)
- *Zum gegenwärtigen Stand des Strahlungsproblems*, A. Einstein, 1909
- Fringe Resolution at high frequencies improves as as (laser power)$^{1/2}$
- Point of diminishing returns when buffeting of test mass by photons increases low-frequency noise – use heavy test masses!
- **‘Standard Quantum Limit’**
- Advanced LIGO will reach this limit with its **200W laser, 40 kg test masses**

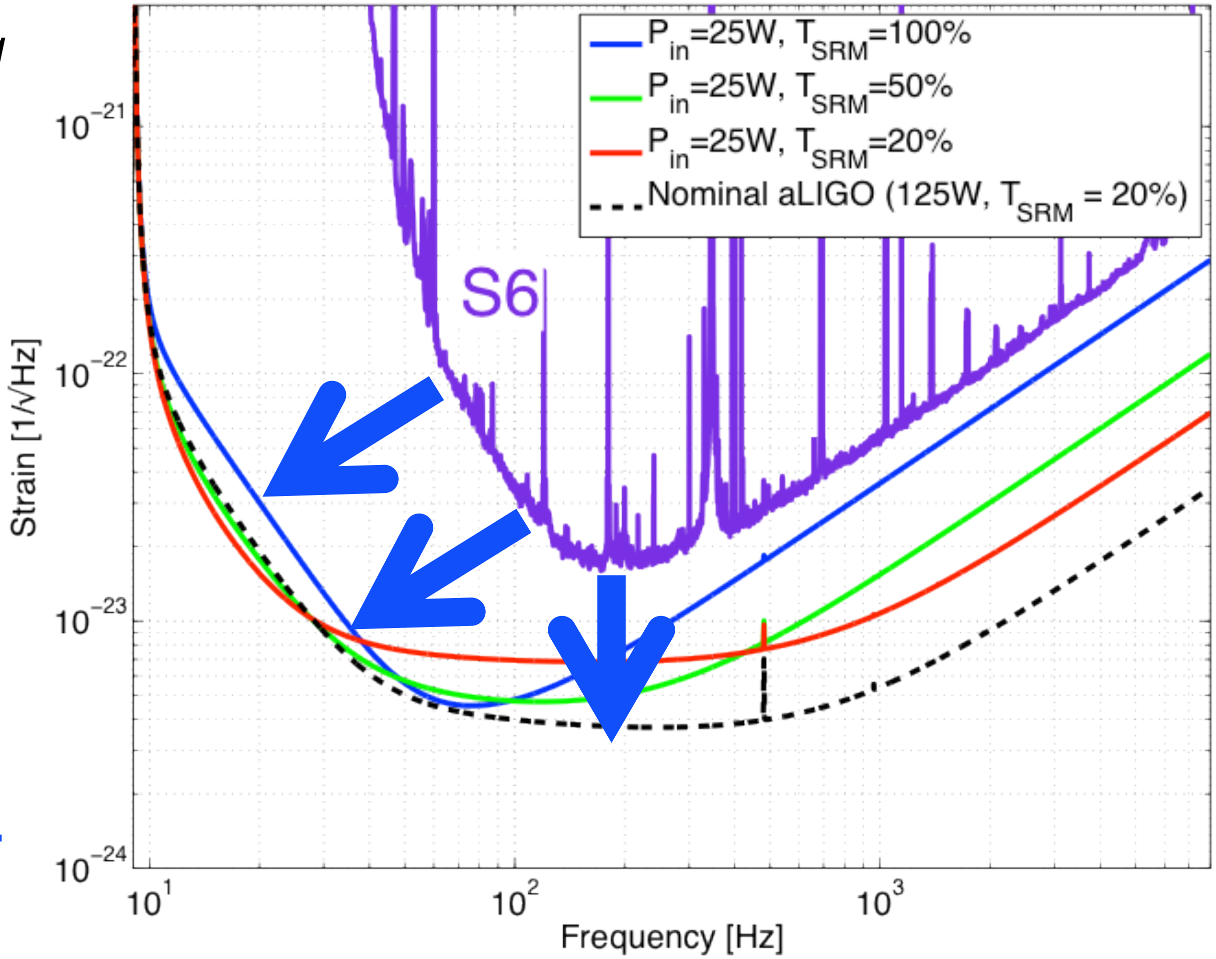


Measuring $\Delta L = 4\mathrm{x}10^{-18}$ m

Internal motion

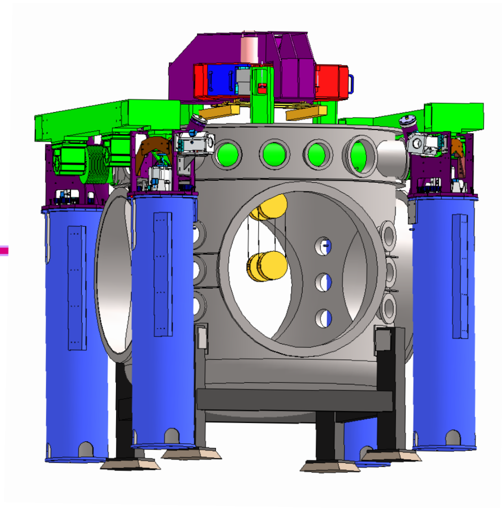


- **Thermal noise** – kT of energy per mechanical mode
- *Über die von der molekularkinetischen Theorie der Wärmegeforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen,*
  A. Einstein, 1905
- Motion of components due to thermal energy masks GW
- Low mechanical loss materials gather this motion into a narrow peak at resonant frequencies
- Realized in aLIGO with an all **fused-silica test mass suspension** – *Q* of order 10^9
- **Test mass internal modes, Mirror coatings engineered for low mechanical loss**

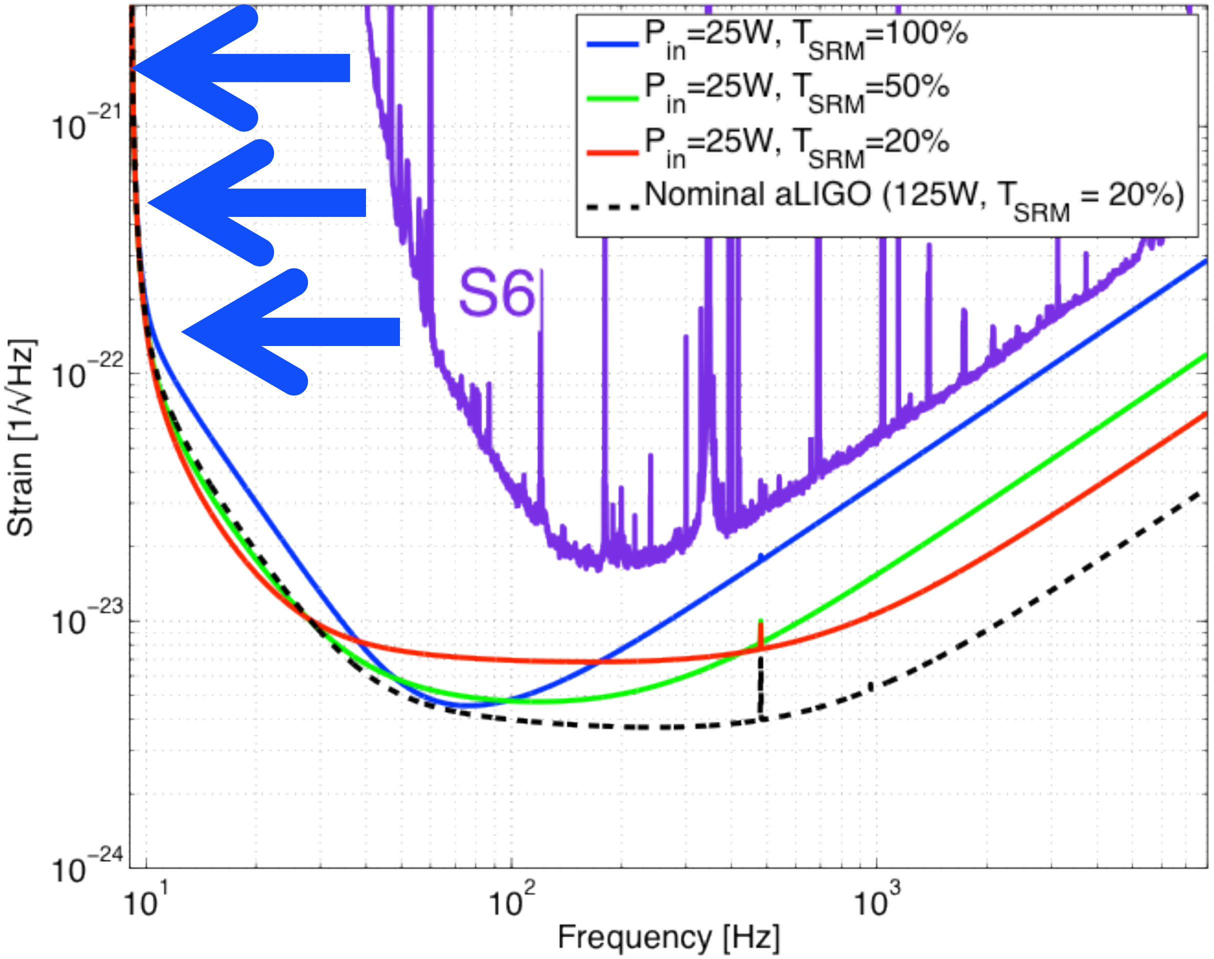


Measuring Δ*L*= 4x10^{-18} m

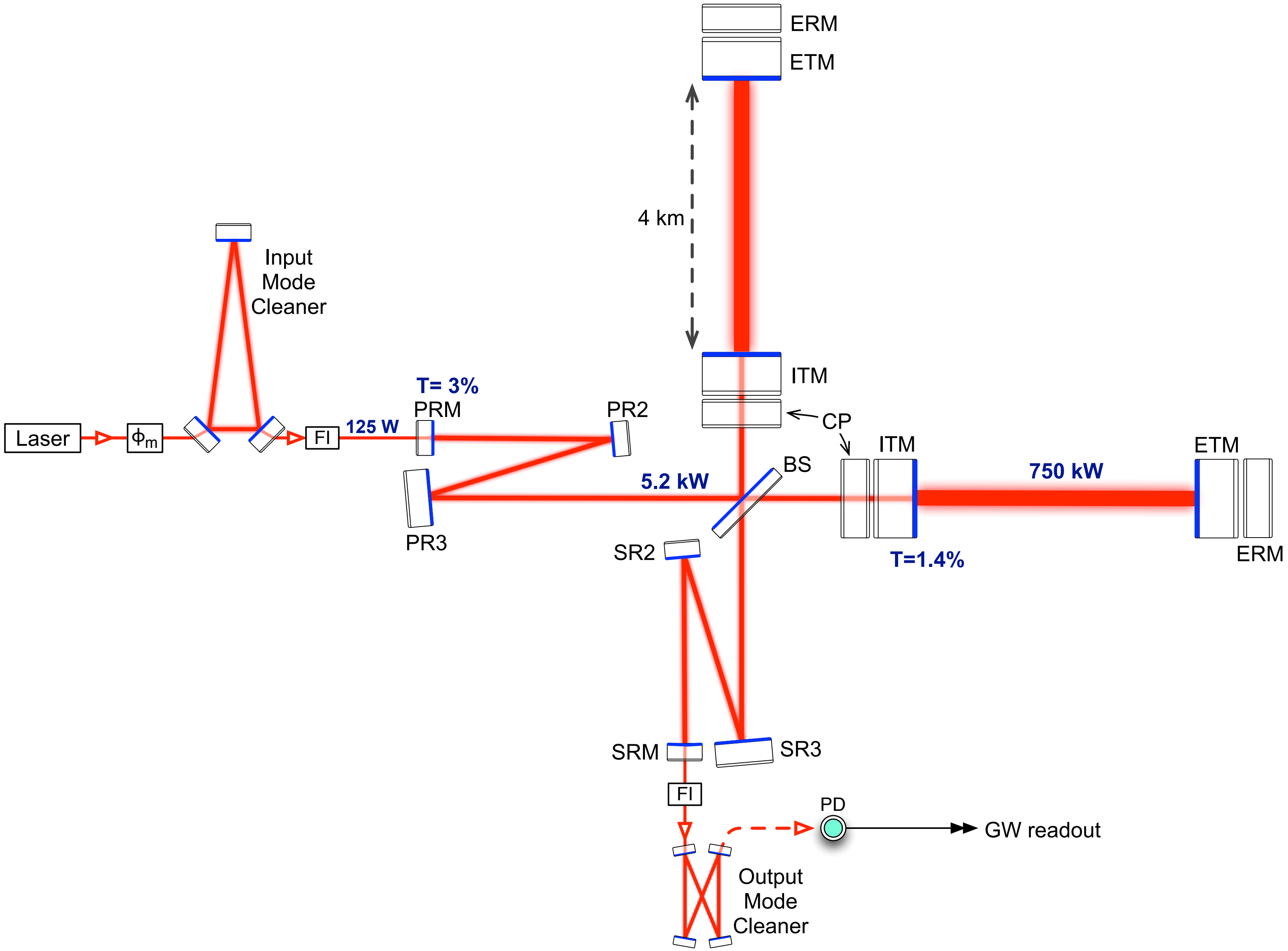
Forces on test mass



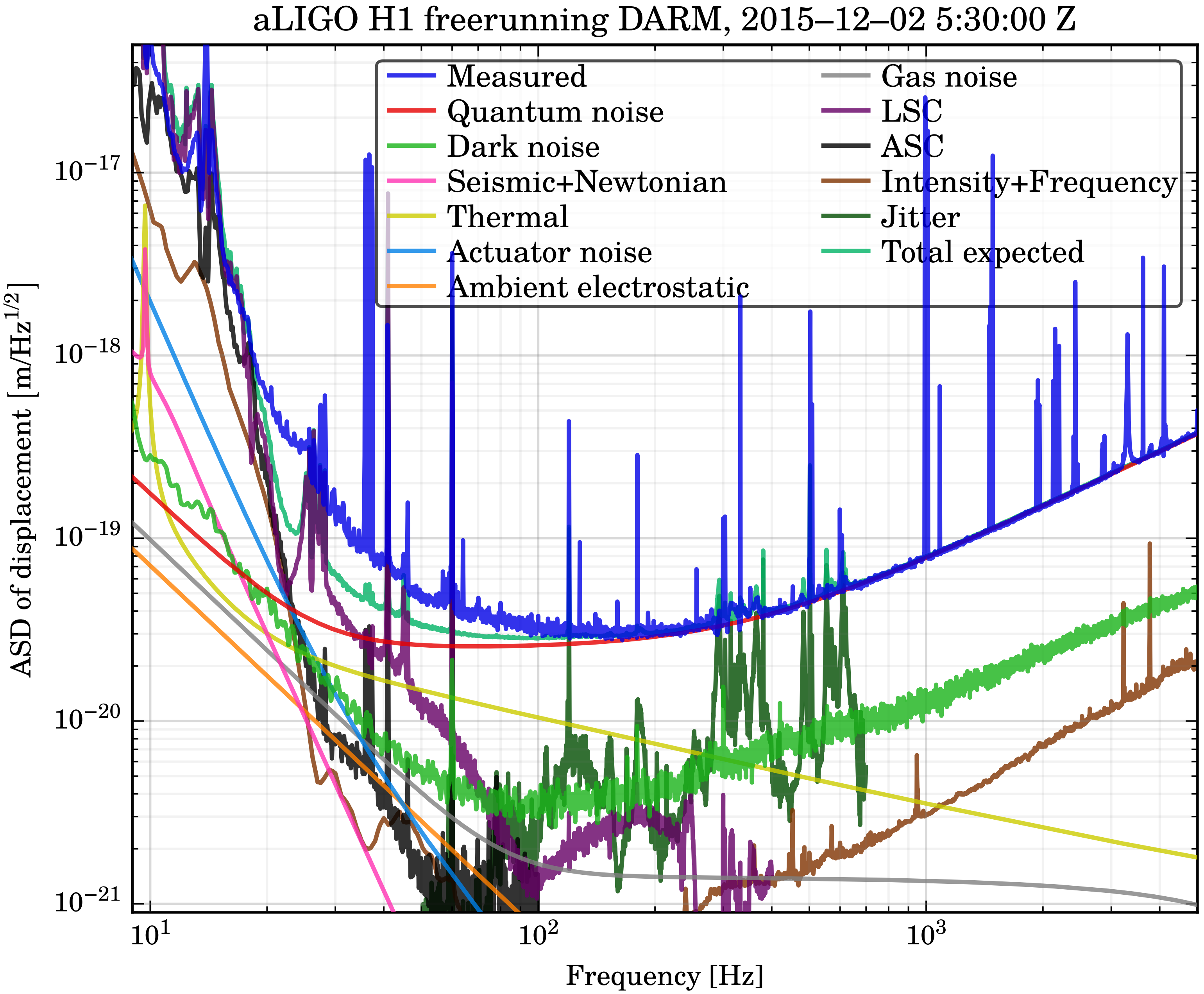
- **Seismic noise** – must prevent masking of GWs, enable practical control systems
- *(did Einstein work on seismic motion…?)*
- Motion from waves on coasts…and people and their machines
- GW band: 10 Hz and above – direct effect of masking
- Control Band: below 10 Hz – forces needed to hold optics on resonance and aligned
- aLIGO uses **active servo-controlled platforms, multiple pendulums**
- Ultimate limit on the ground: Newtownian background – wandering net gravity vector; a limit in the 10-20 Hz band



The complexity of a real instrument…

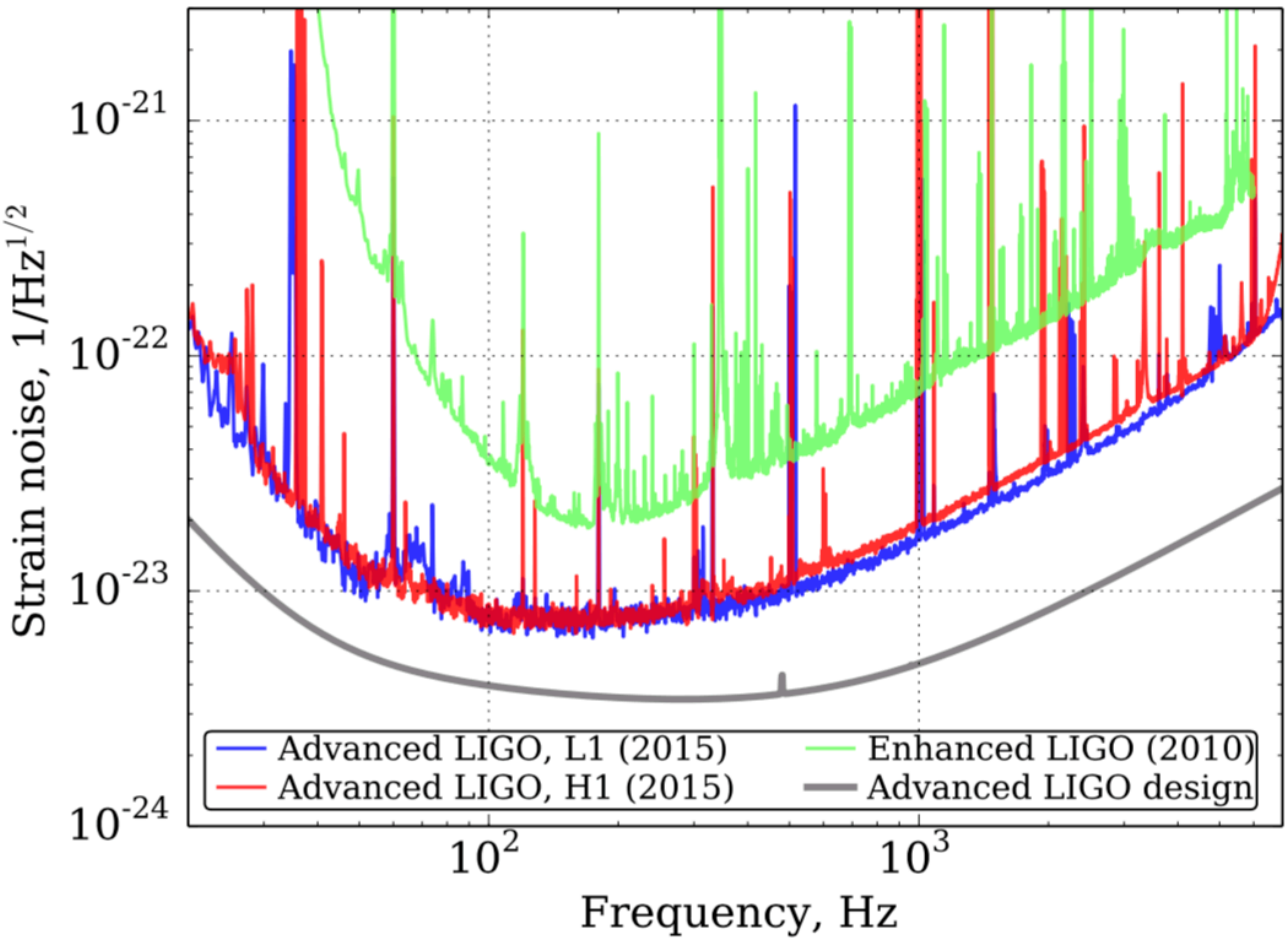


And technical noise sources….



Current Sensitivity, Observing Schedule

- O1 started 12 September 2015, ended 19 January 2016
- O2 started 30 November 2016, will end ~ 31 August 2017



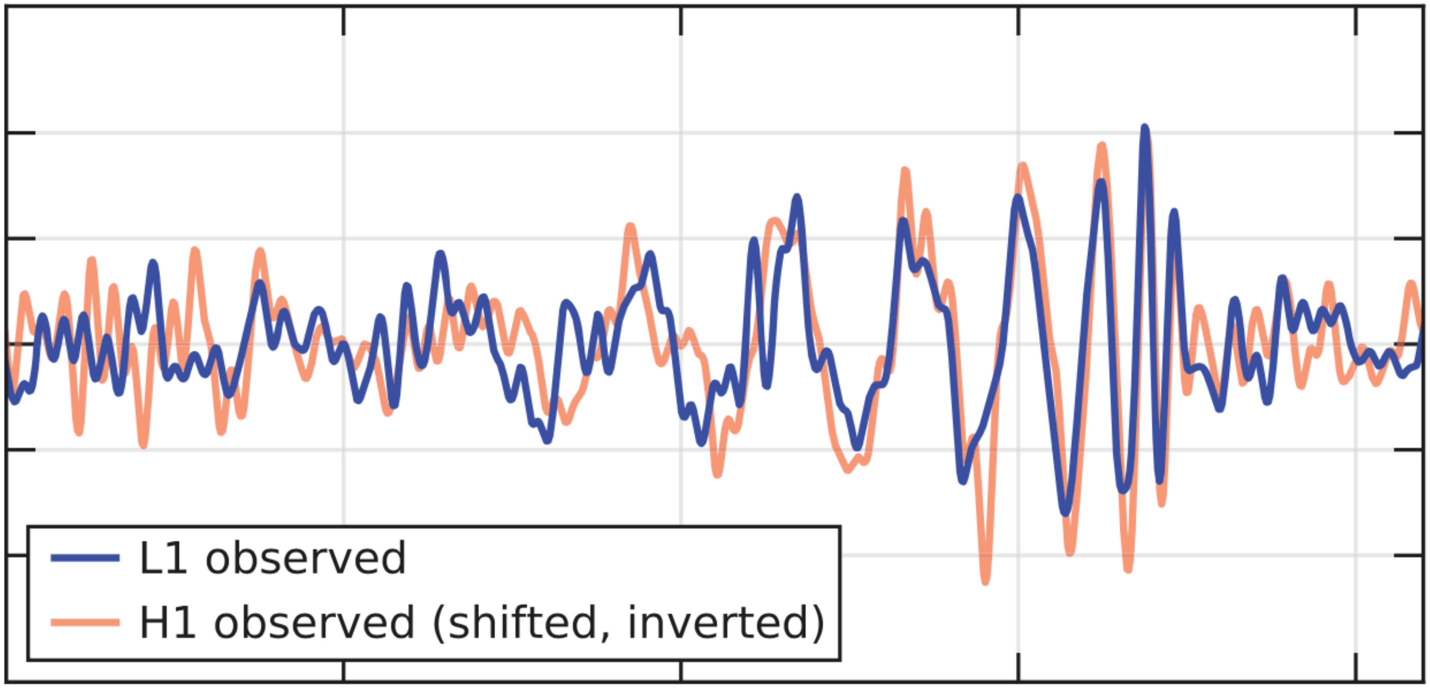
Initial LIGO

O1 aLIGO

Design aLIGO

Two days after the start of observing in O1: Our first detection

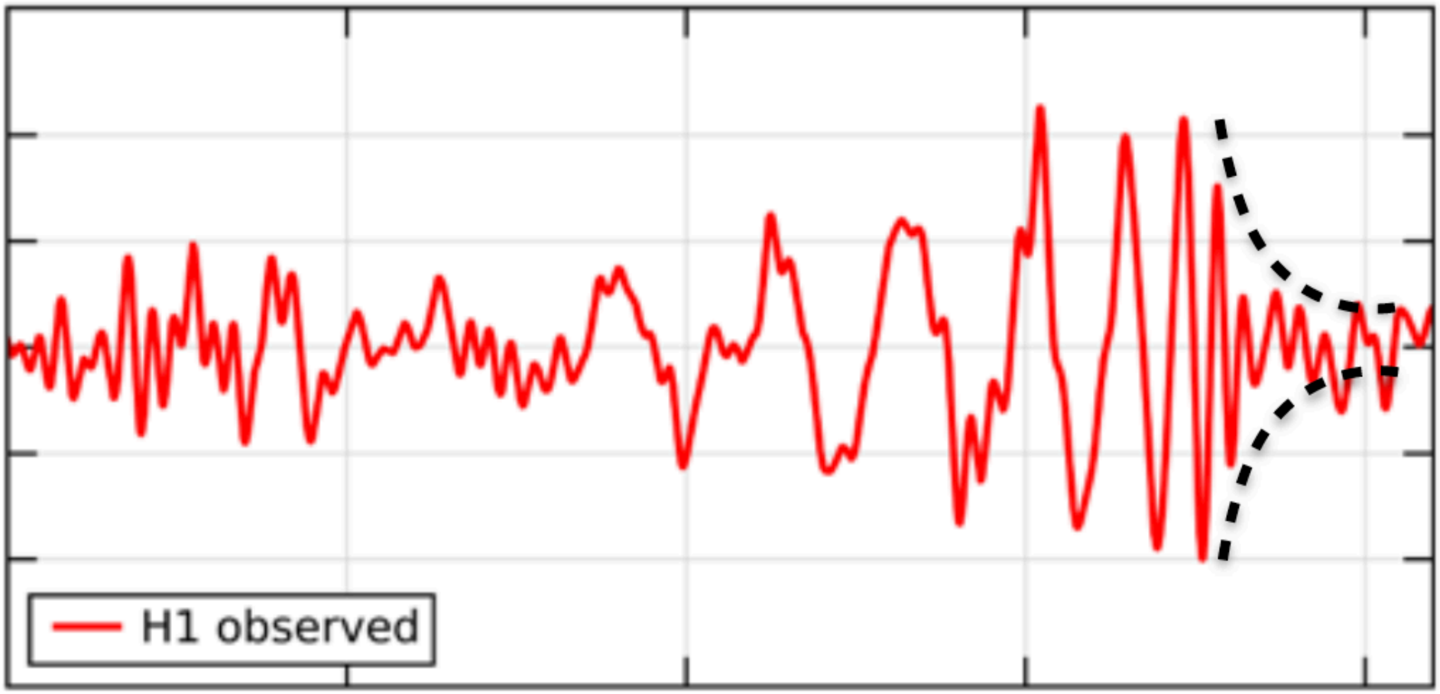
- GW150914: the merger of two BHs
- Masses $m_1 = 36^{+5}_{-4} M_\odot \quad m_2 = 29^{+4}_{-4} M_\odot$
- Final black hole $M_f = 62^{+4}_{-4} M_\odot \quad \chi_f = 0.67^{+0.05}_{-0.07}$
- Luminosity distance $D_L = 410^{+160}_{-180}\mathrm{Mpc}$

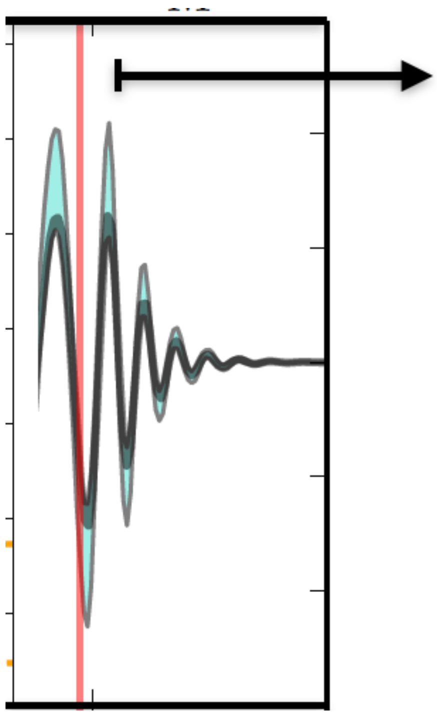


LVC arXiv:1602.03837

Ringdown of final black hole

- We *almost* see a ringdown of the remnant – SNR ~ 8
- Waveform post-merger is consistent with pre-merger
- But cannot isolate it and measure the frequency and Q with precision
- (we'll come back to this)

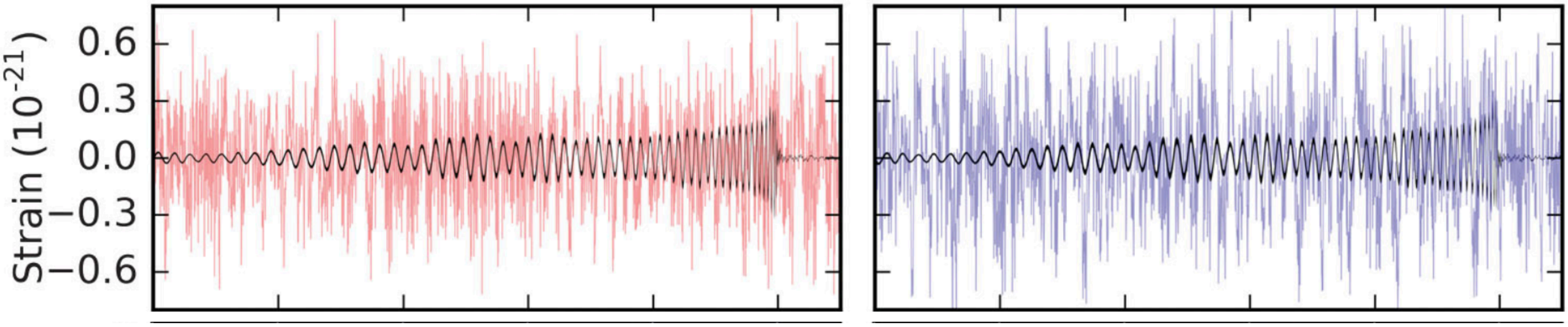




LSC, arXiv:1602.03841

The second detection:
"Boxing Day" GW151226

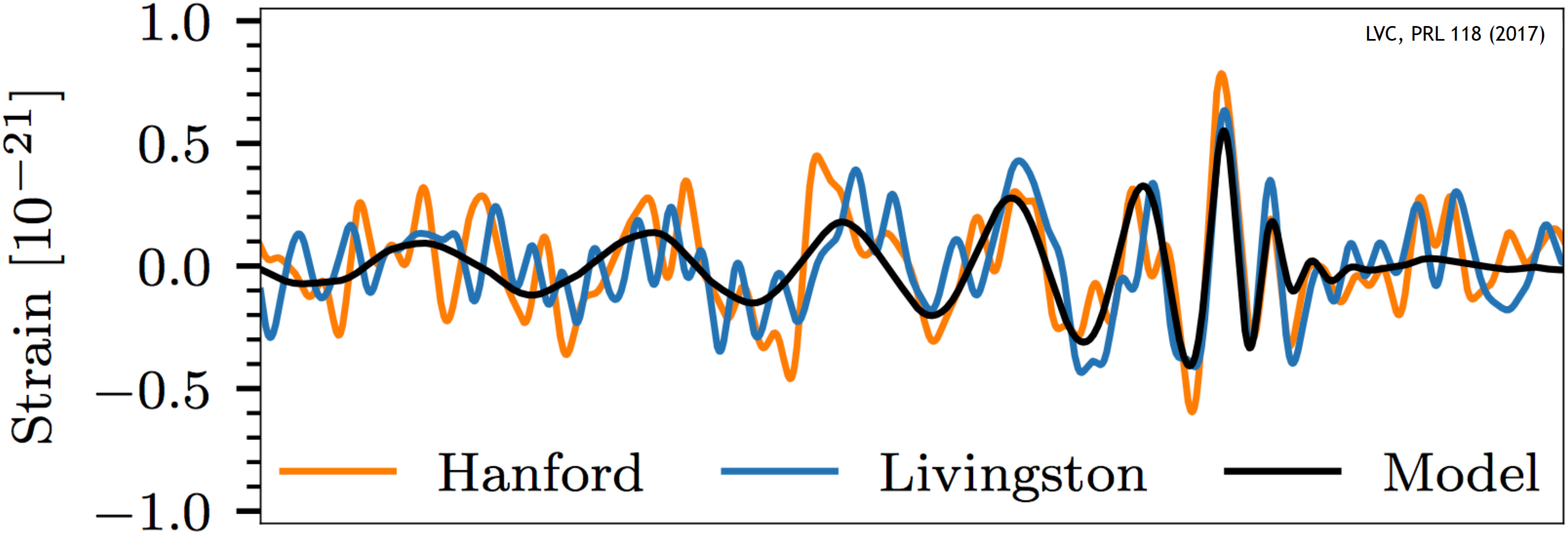
Primary black hole mass	$14.2^{+8.3}_{-3.7} M_\odot$
Secondary black hole mass	$7.5^{+2.3}_{-2.3} M_\odot$
Chirp mass	$8.9^{+0.3}_{-0.3} M_\odot$
Total black hole mass	$21.8^{+5.9}_{-1.7} M_\odot$
Final black hole mass	$20.8^{+6.1}_{-1.7} M_\odot$
Radiated gravitational-wave energy	$1.0^{+0.1}_{-0.2} M_\odot c^2$
Peak luminosity	$3.3^{+0.8}_{-1.6} \times 10^{56}$ erg/s
Final black hole spin	$0.74^{+0.06}_{-0.06}$
Luminosity distance	440^{+180}_{-190} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$



PRL **116,** 241103 (2016)

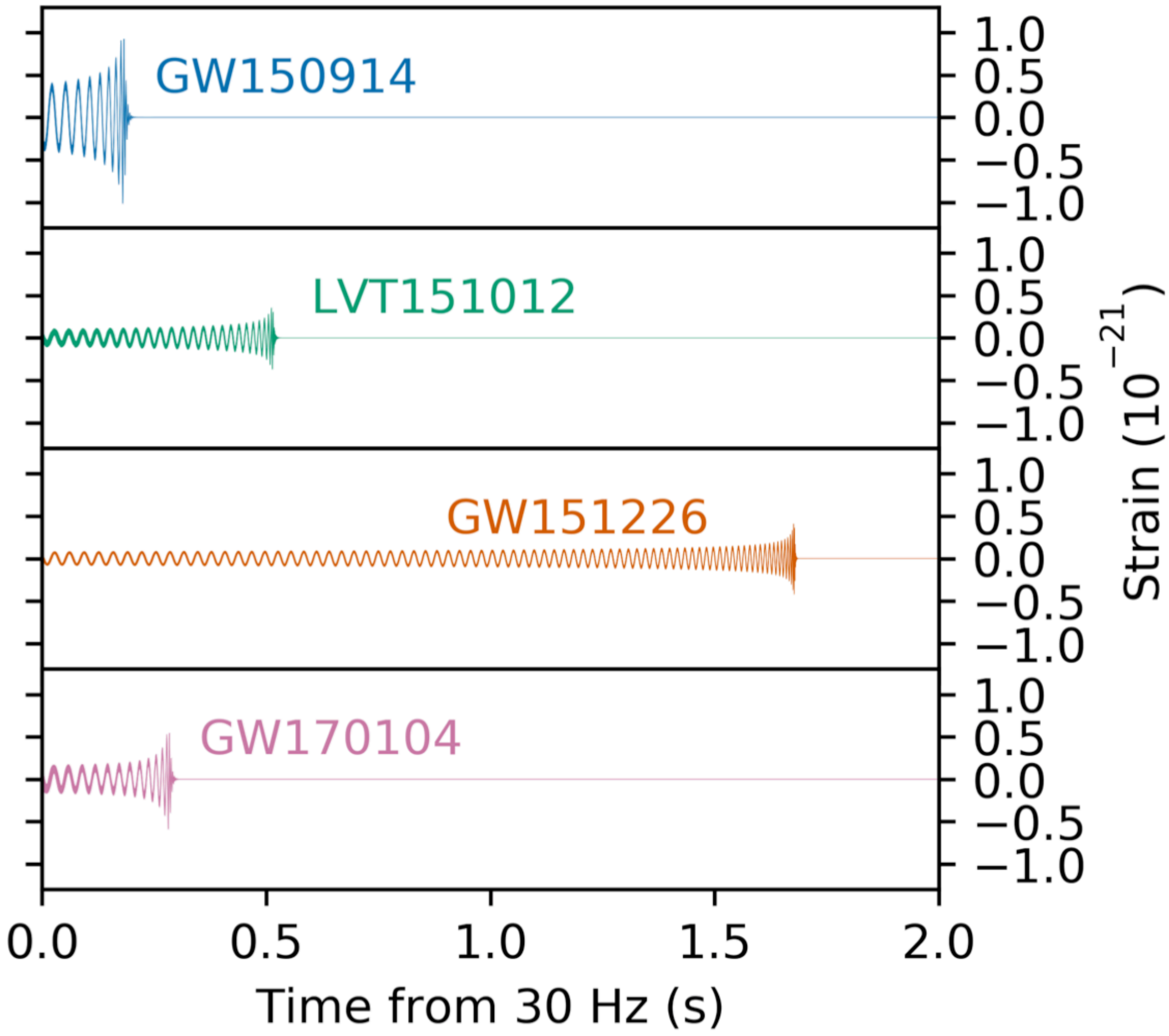
Our third discovery:
GW170104

Primary black hole mass m_1	$31.2^{+8.4}_{-6.0}\ M_\odot$
Secondary black hole mass m_2	$19.4^{+5.3}_{-5.9}\ M_\odot$
Total mass M	$50.7^{+5.9}_{-5.0}\ M_\odot$
Final black hole mass M_f	$48.7^{+5.7}_{-4.6}\ M_\odot$
Luminosity distance D_L	880^{+450}_{-390} Mpc
Source redshift z	$0.18^{+0.08}_{-0.07}$

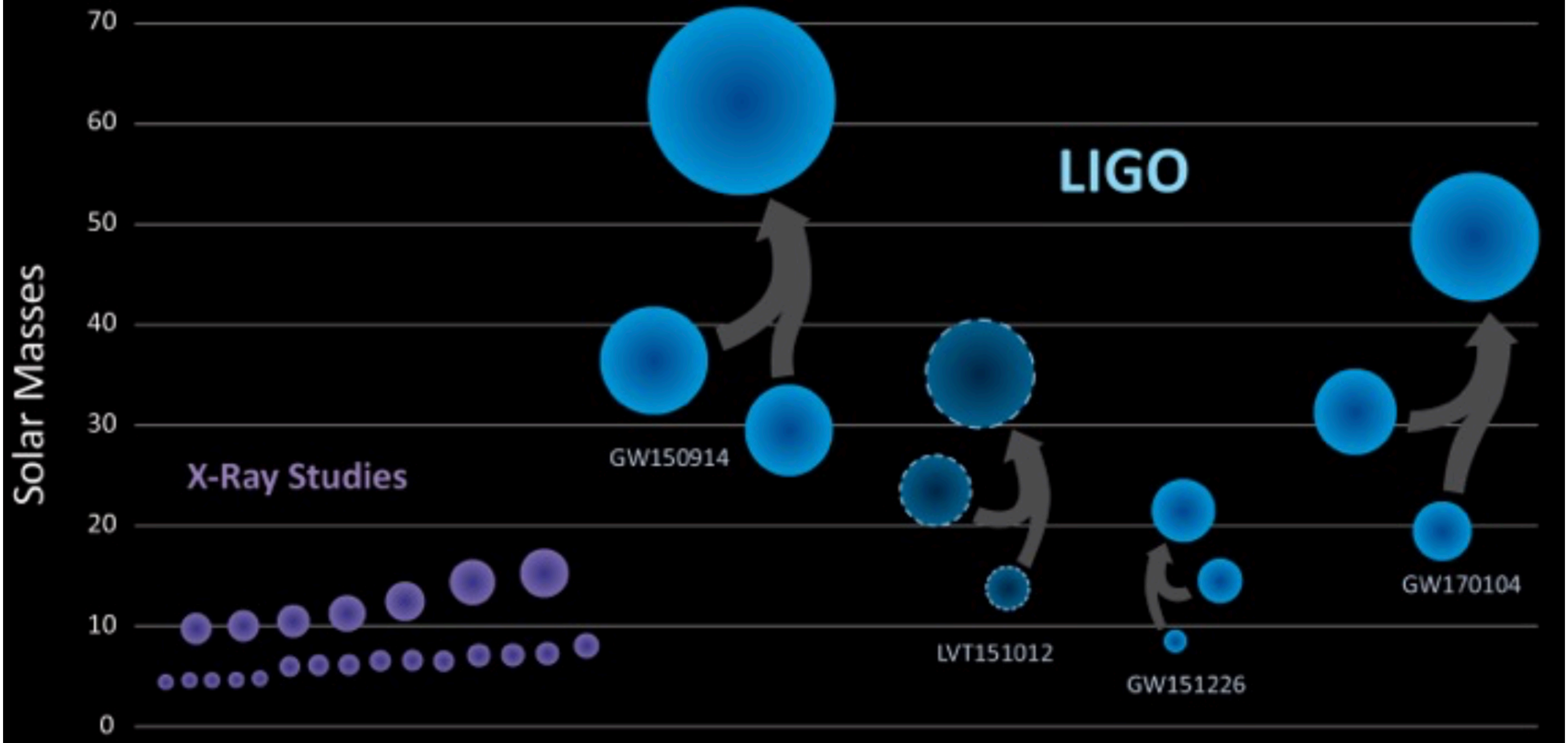


LVC, PRL 118 (2017)

The 3.5 signals all together



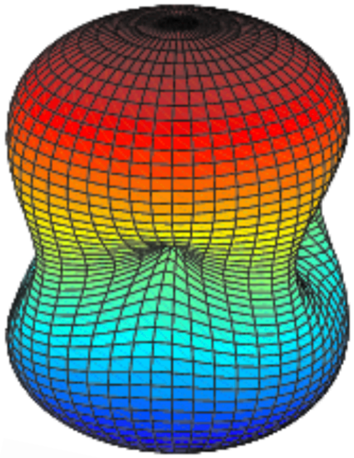
Black Holes of Known Mass

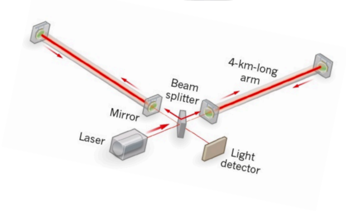


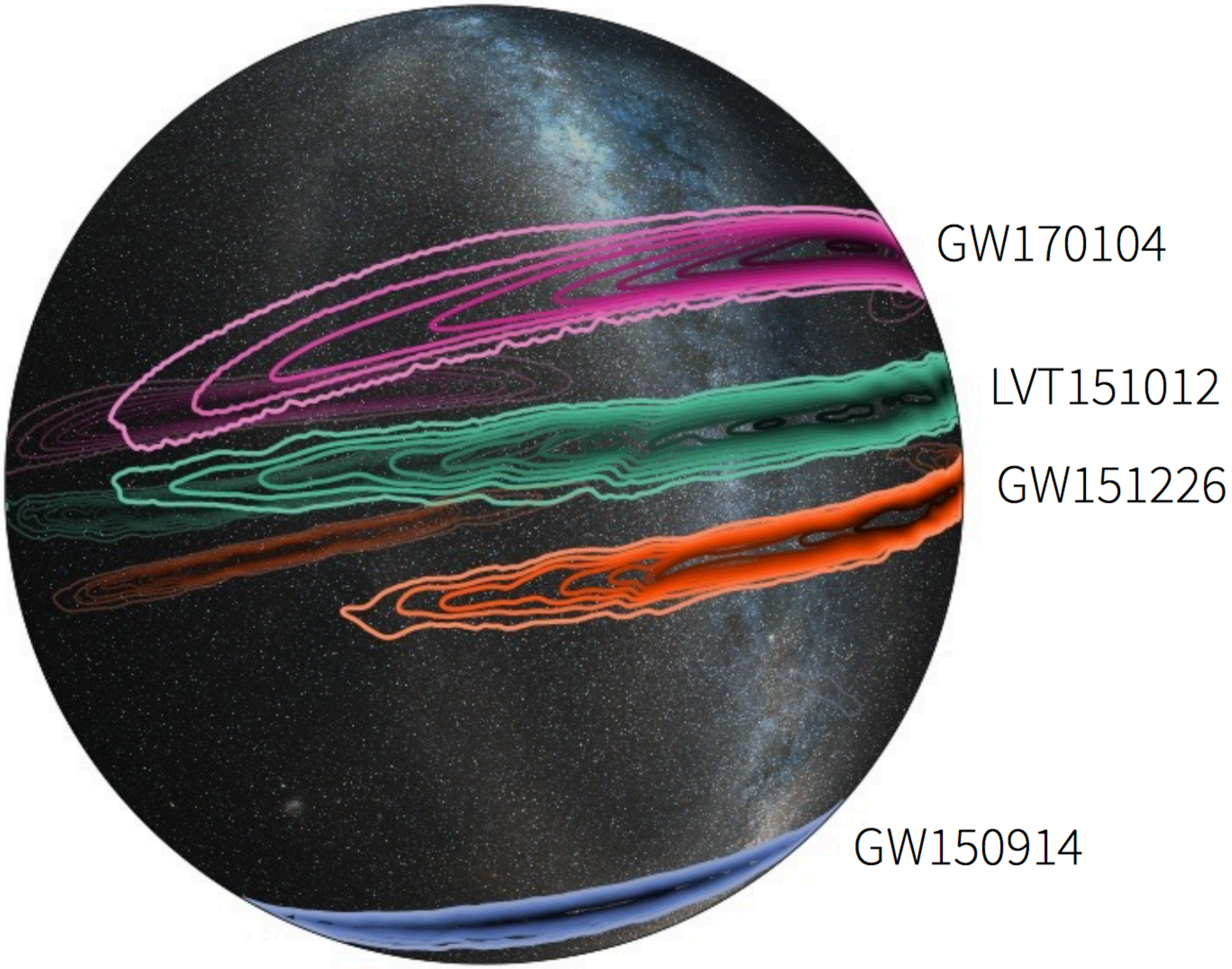
LSC/Sonoma State University/Aurore Simonnet

Localization with two detectors

- An Annulus, with some further refinement from the antenna pattern:



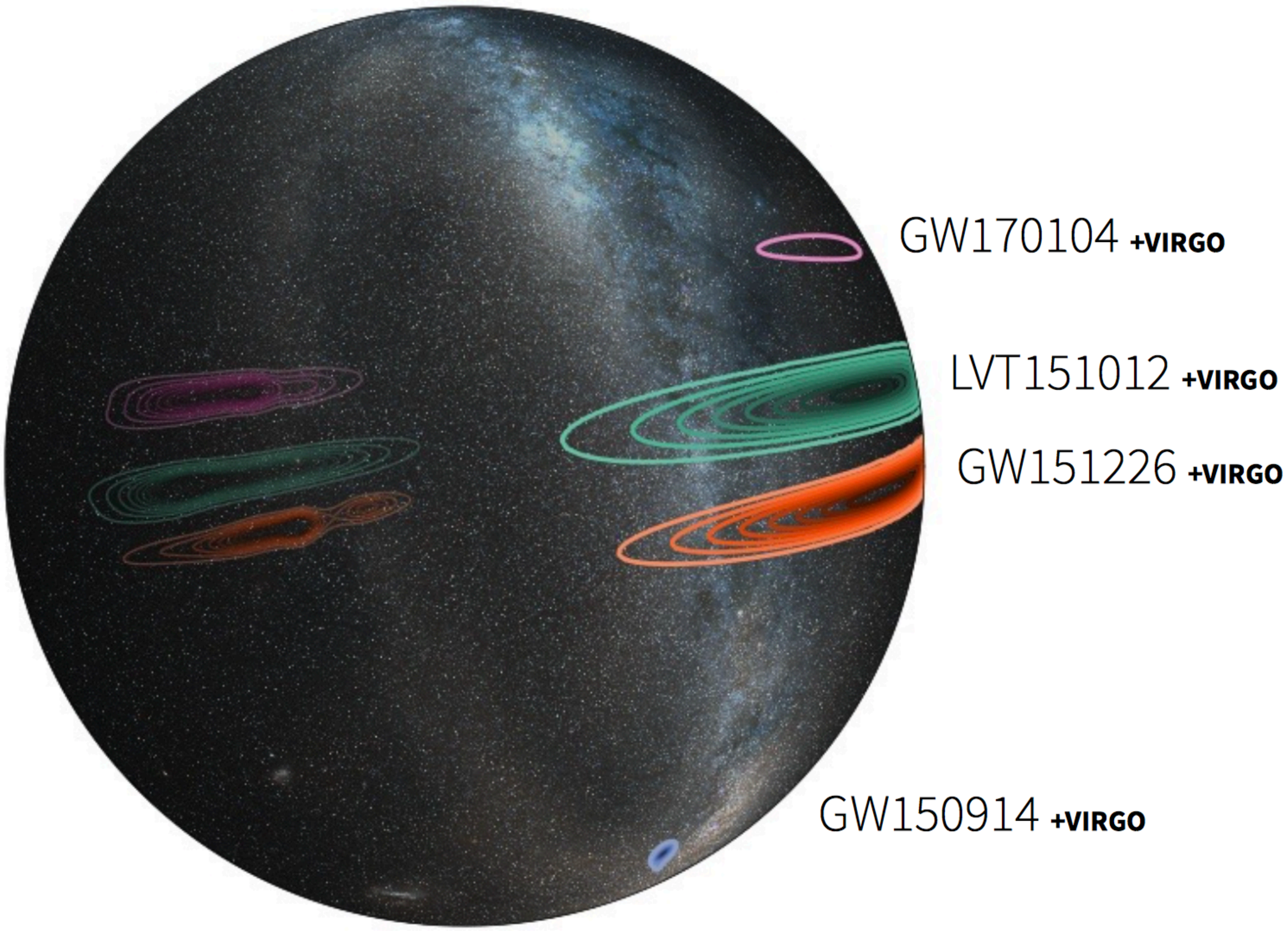




LSC/Leo Singer (Milky Way image: Axel Mellinger)

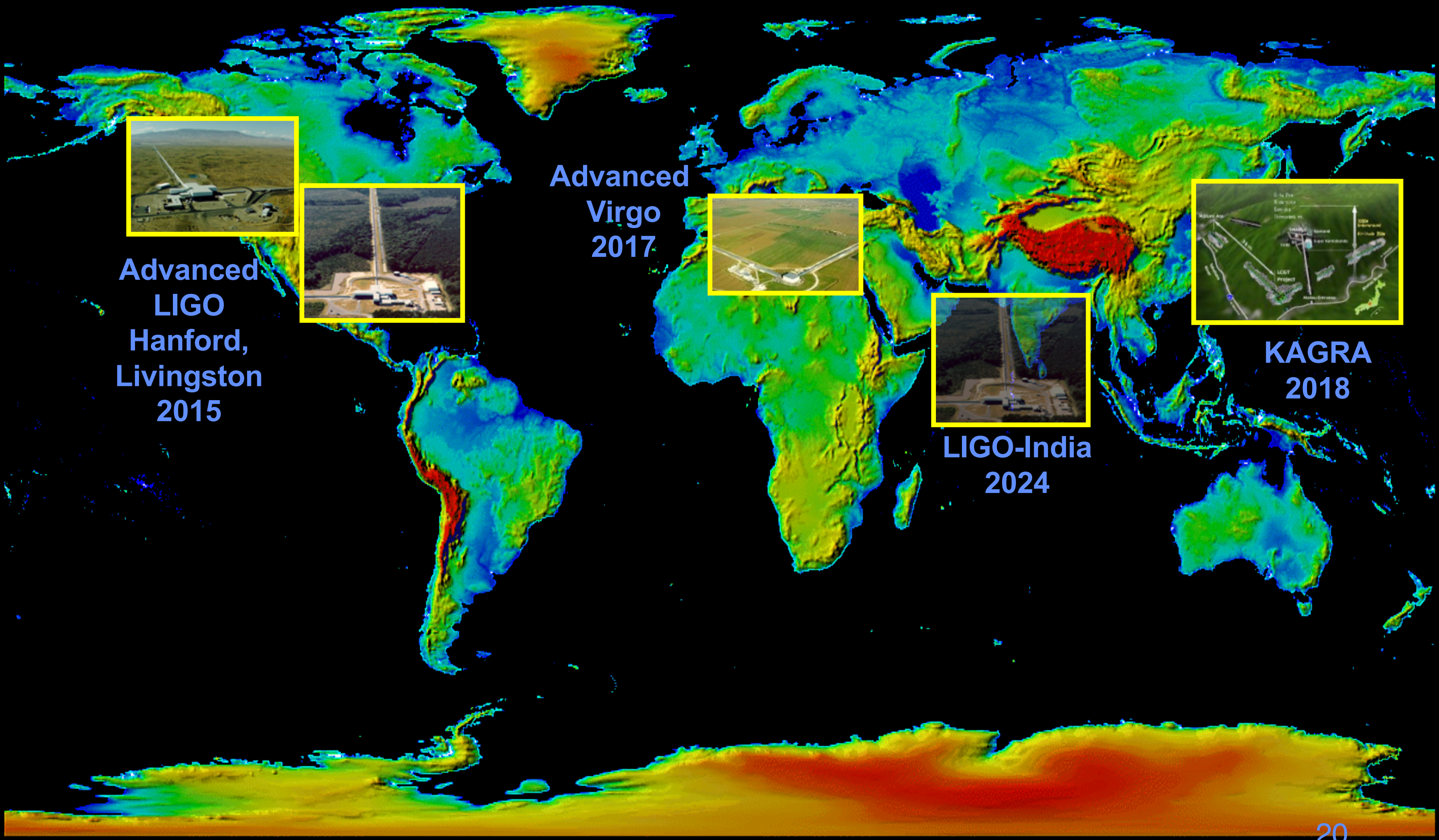
Adding a 3rd detector helps

Virgo arriving soon!



LSC/Leo Singer (Milky Way image: Axel Mellinger)

The advanced GW detector network



Advanced LIGO Hanford, Livingston 2015

Advanced Virgo 2017

LIGO-India 2024

KAGRA 2018

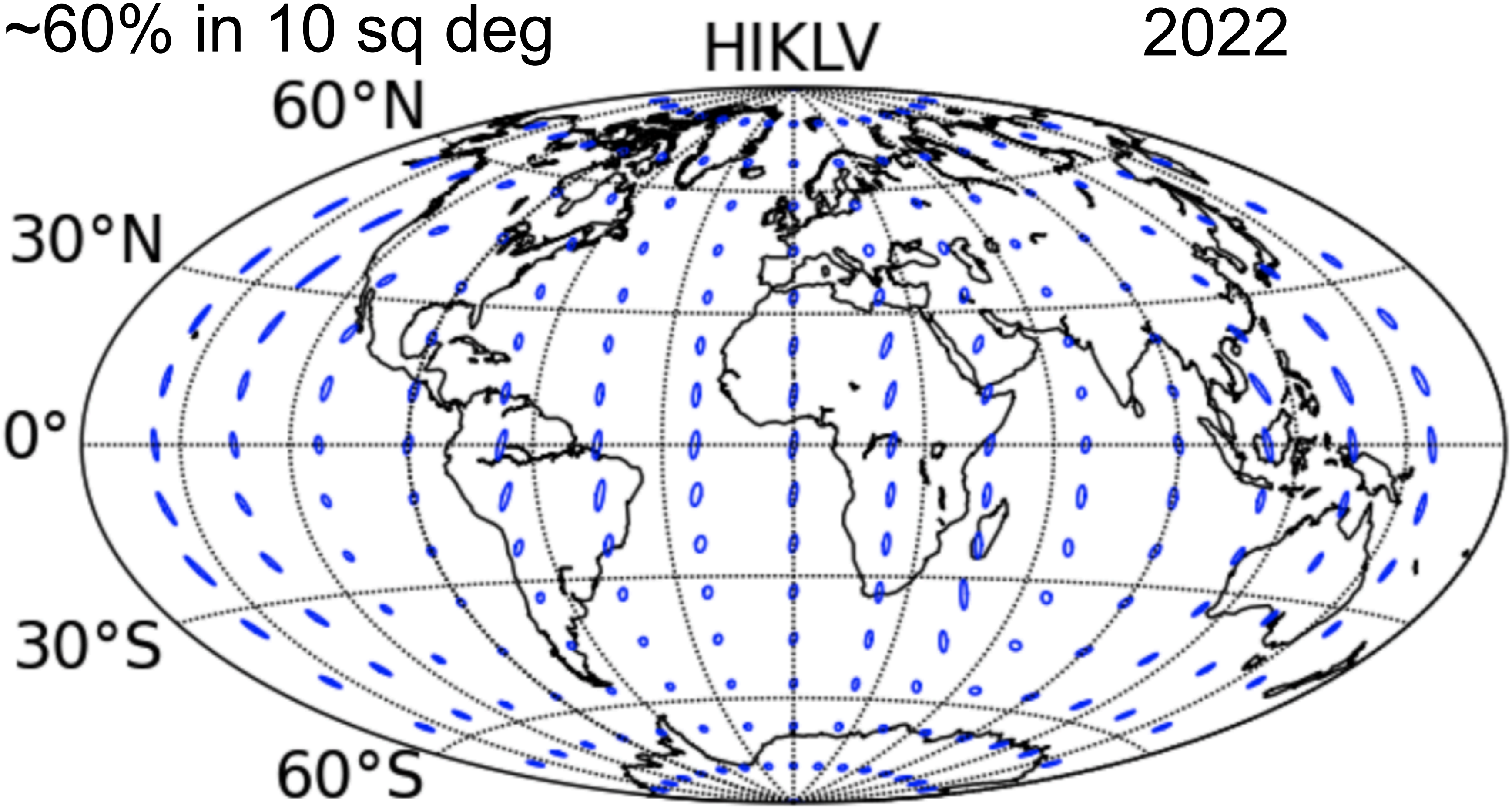
2024 Sensitivity/configuration:

5 detectors

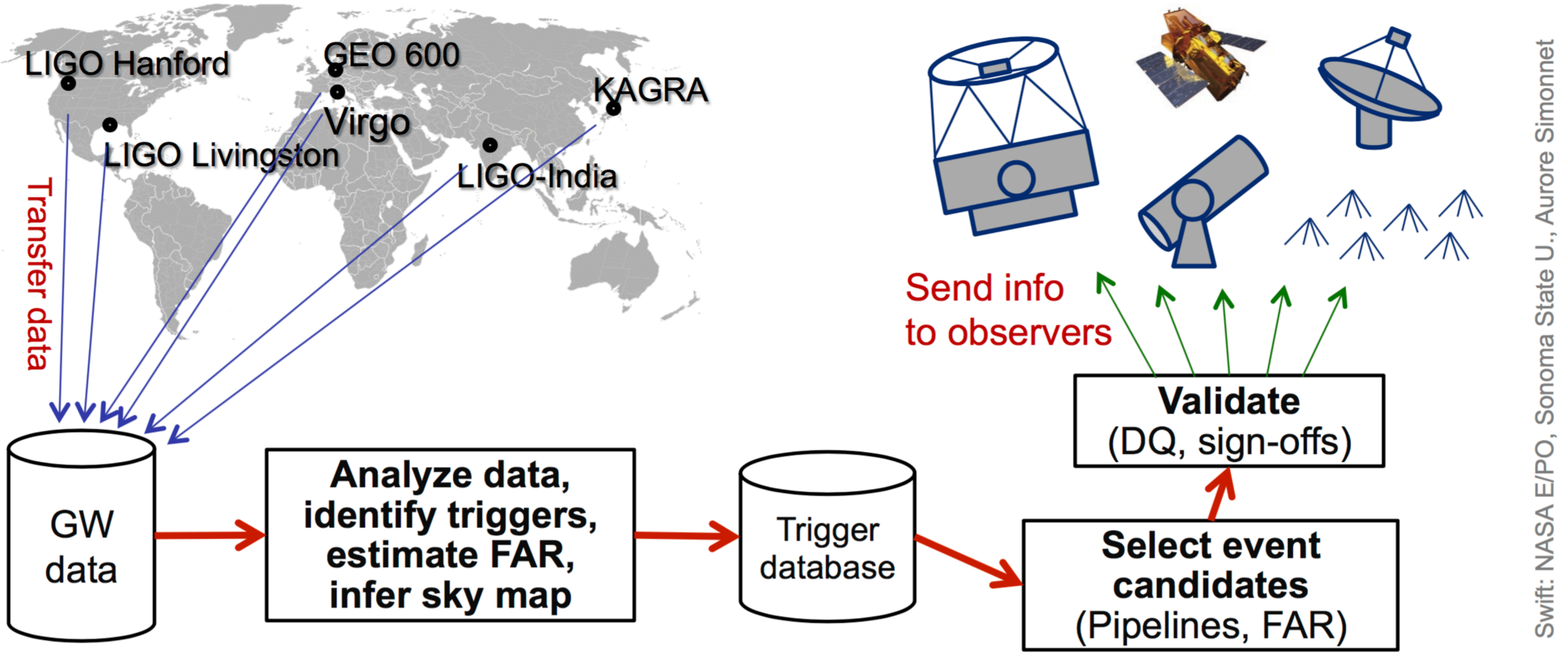
far improved source localization

~60% in 10 sq deg

2022



EM followup



GW data

Analyze data, identify triggers, estimate FAR, infer sky map

Trigger database

Select event candidates
(Pipelines, FAR)

Validate
(DQ, sign-offs)

Swift: NASA E/PO, Sonoma State U., Aurore Simonnet

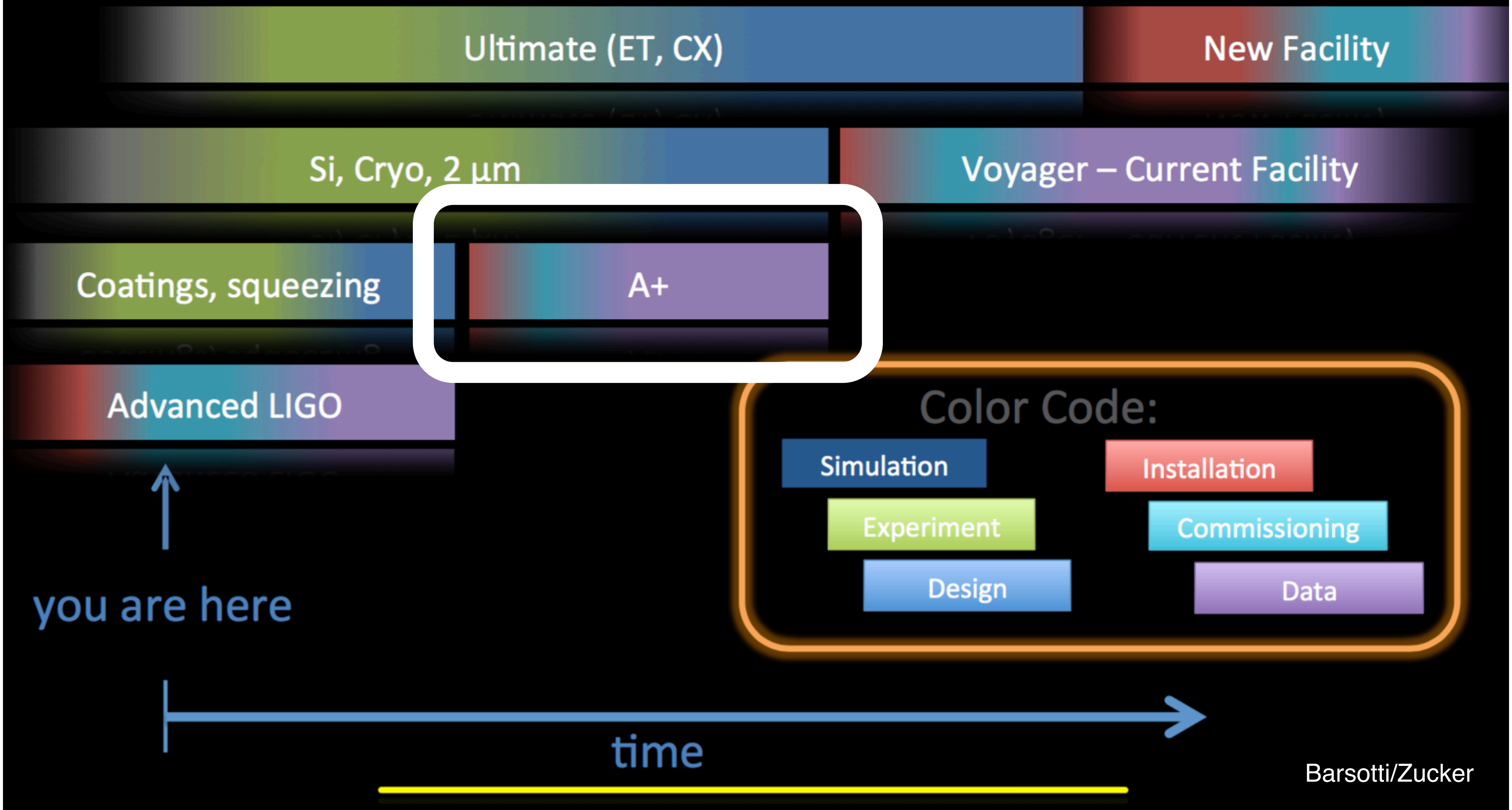
Try to capture and identify an EM counterpart to a GW event

So far 80+ groups have signed MOUs with LIGO+Virgo

- No EM counterparts have been identified yet...black holes are quiet.
  - Hope to have a detection soon with a Neutron Star

LIGO Concept Roadmap

(Mike's talk, adapted from G1401081)



Ultimate (ET, CX)

New Facility

Si, Cryo, 2 μm

Voyager – Current Facility

Coatings, squeezing

A+

Advanced LIGO

you are here

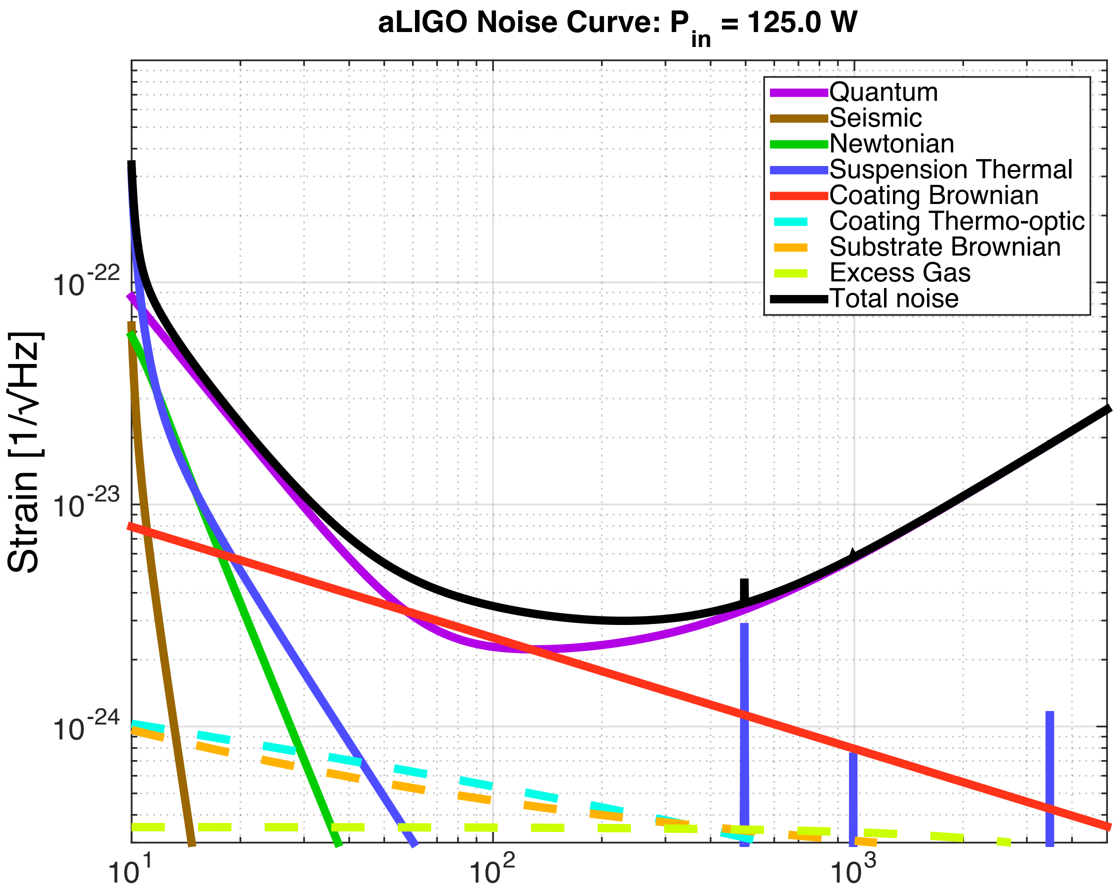
Color Code:

- Simulation
- Experiment
- Design
- Installation
- Commissioning
- Data

time

Barsotti/Zucker

aLIGO operating at full power and fully commissioned (~3x better than now)

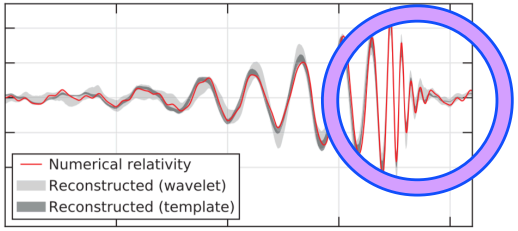


aLIGO

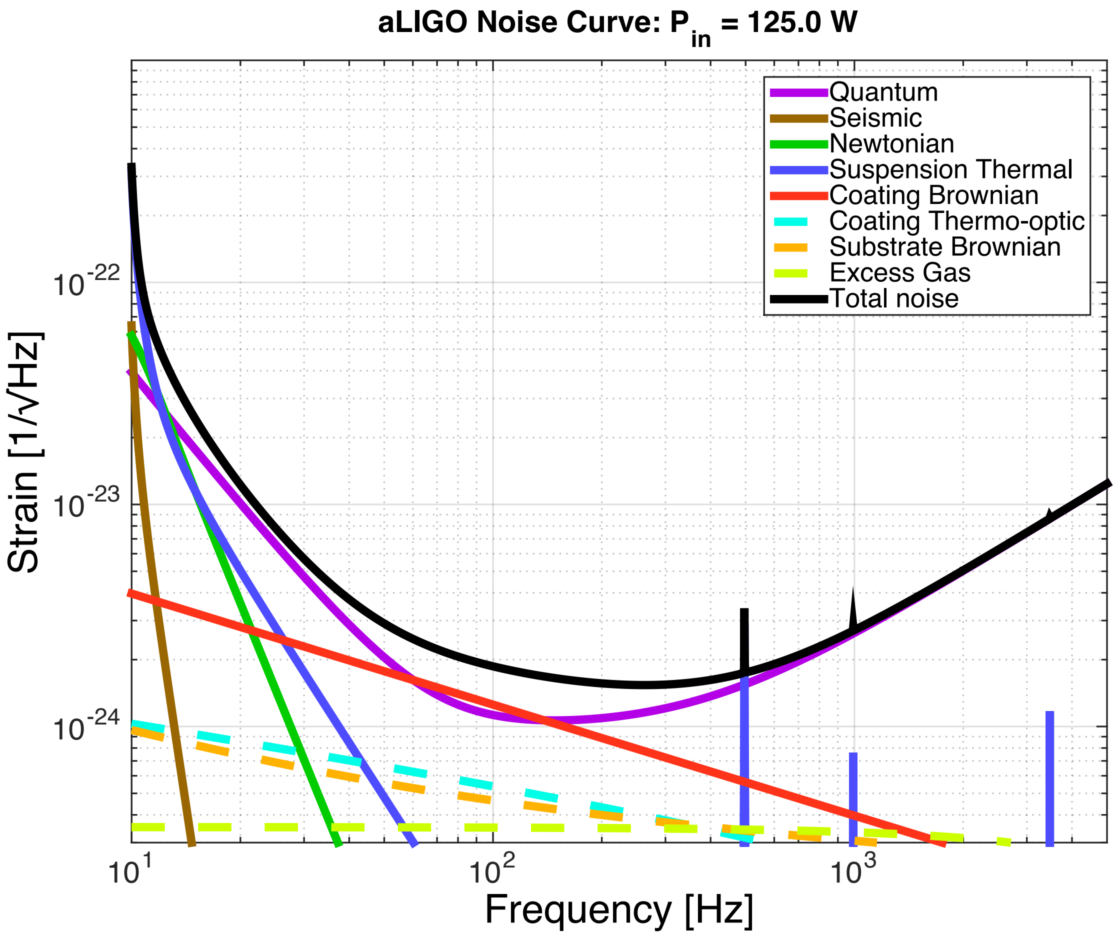
BNS reach: 180 Mpc

BBH reach: 2200 Mpc
(z = 0.2)

QNM SNR ~25
(for an event like
GW150914)



aLIGO with the addition of frequency-dependent squeezing and lowered optical coating thermal noise



A+

BNS reach: 510 Mpc

BBH reach: 3700 Mpc
(z = 1.1)

QNM SNR ~40
(for an event like
GW150914)

A+

- An incremental upgrade to aLIGO
- leverages existing technology and infrastructure, with
  - minimal new investment,
  - moderate risk, and
  - modest interruption in observing
- Target: factor of 1.7* increase in range over aLIGO

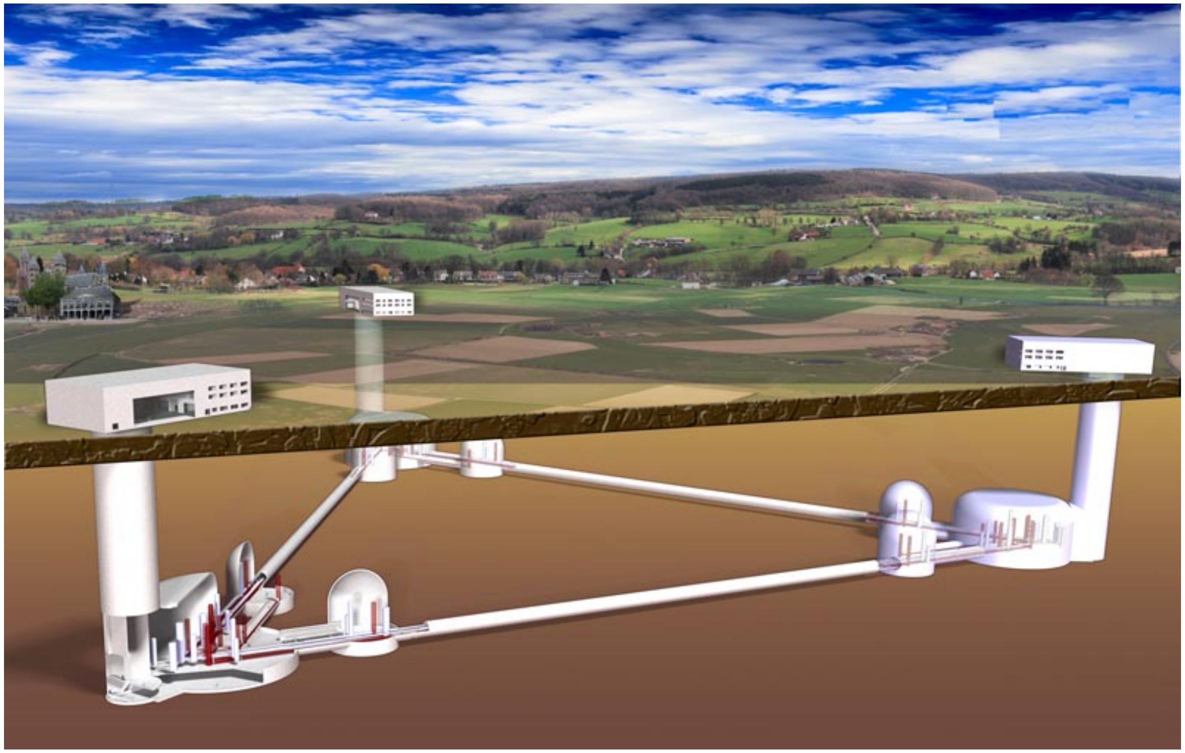
  ➔ **About a factor of 5 greater event rate**
- Stepping stone to future 3G detector technologies
- Link to future GW astrophysics and cosmology
- **Could be observing within < 6.5 years (mid-2022)**
  - (with FY'19 or earlier funding)
- "Scientific breakeven" within 1/2 year of operation
- Incremental cost: *a small fraction of aLIGO*
  - **Formulating proposal now**

*BBH 20/20 $M_\odot$: 1.64x

*BNS 1.4/1.4 $M_\odot$: 1.85x

Further Future Improvements: The 3rd generation

- European Concept: Einstein Telescope
- Significant design study undertaken for both Facility and Instruments
- Underground construction proposed to reduce Newtonian Background
  - (and be compatible with densely-populated Europe)
- Triangle – LISA-like – with 10km arms
- Multiple instruments in a ‘Xylophone’ configuration
  - Allows technical challenges for low- and high-frequency to be separated
- Designed to accommodate a range of detector topologies and mechanical realizations
  - Including squeezing and cryogenics

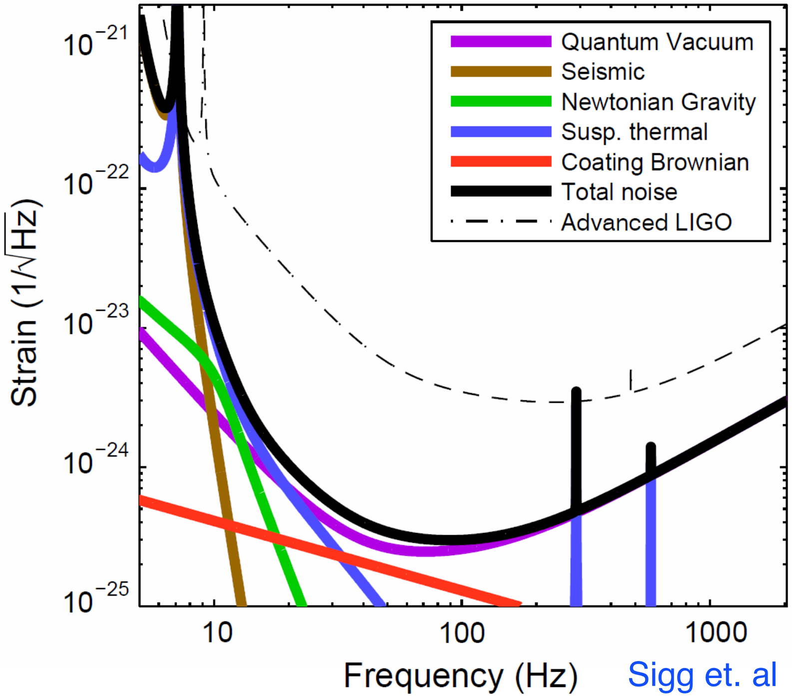


US Concept:
Make Advanced LIGO 10x longer, 10x more sensitive

Signal grows with length – ***not*** most noise sources

- Thermal noise, radiation pressure, seismic, Newtonian unchanged
- Coating thermal noise improves faster than linearly with length
- 40km surface Observatory ‘toy’ baseline
  - can still find sites, earthmoving feasible; costs another limit…
- Concept offers sensitivity without new measurement challenges; could start at room temperature, modest laser power, etc.

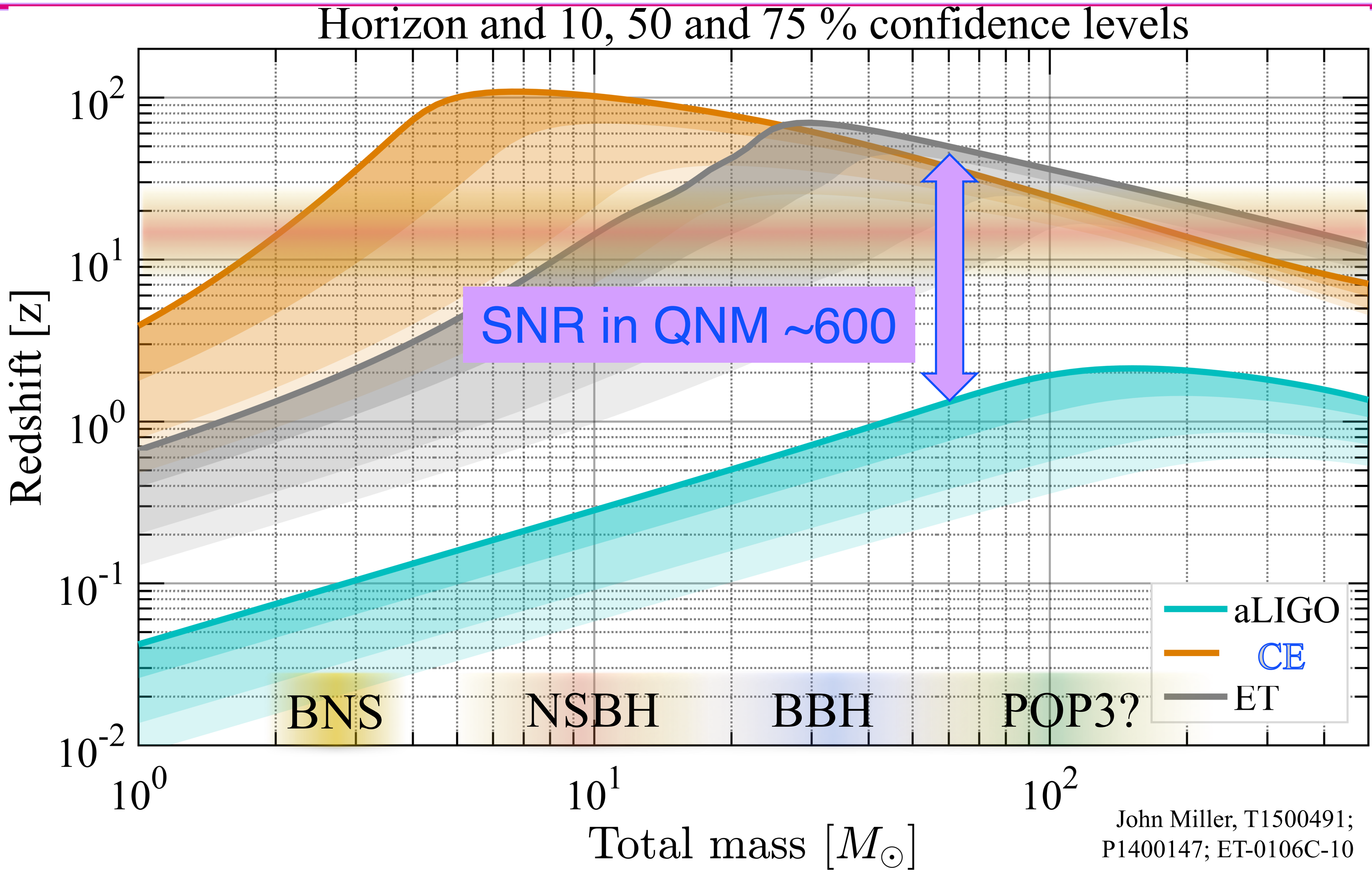
	Adv. LIGO	**40 km LIGO**
Arm length	4 km	40 km
Beam radius	6.2 cm	11.6 cm
Measured squeezing	none	5 dB
Filter cavity length	none	1 km
Suspension length	0.6 m	1 m
Signal recycling mirror trans.	20%	10%
Arm cavity circulating power	775 kW	
Arm cavity finesse	446	
Total light storage time	200 ms	2 s



Sigg et. al

Einstein Telescope, Cosmic Explorer

'Green field' multi-generation Observatories ~G$/G€



John Miller, T1500491; P1400147; ET-0106C-10

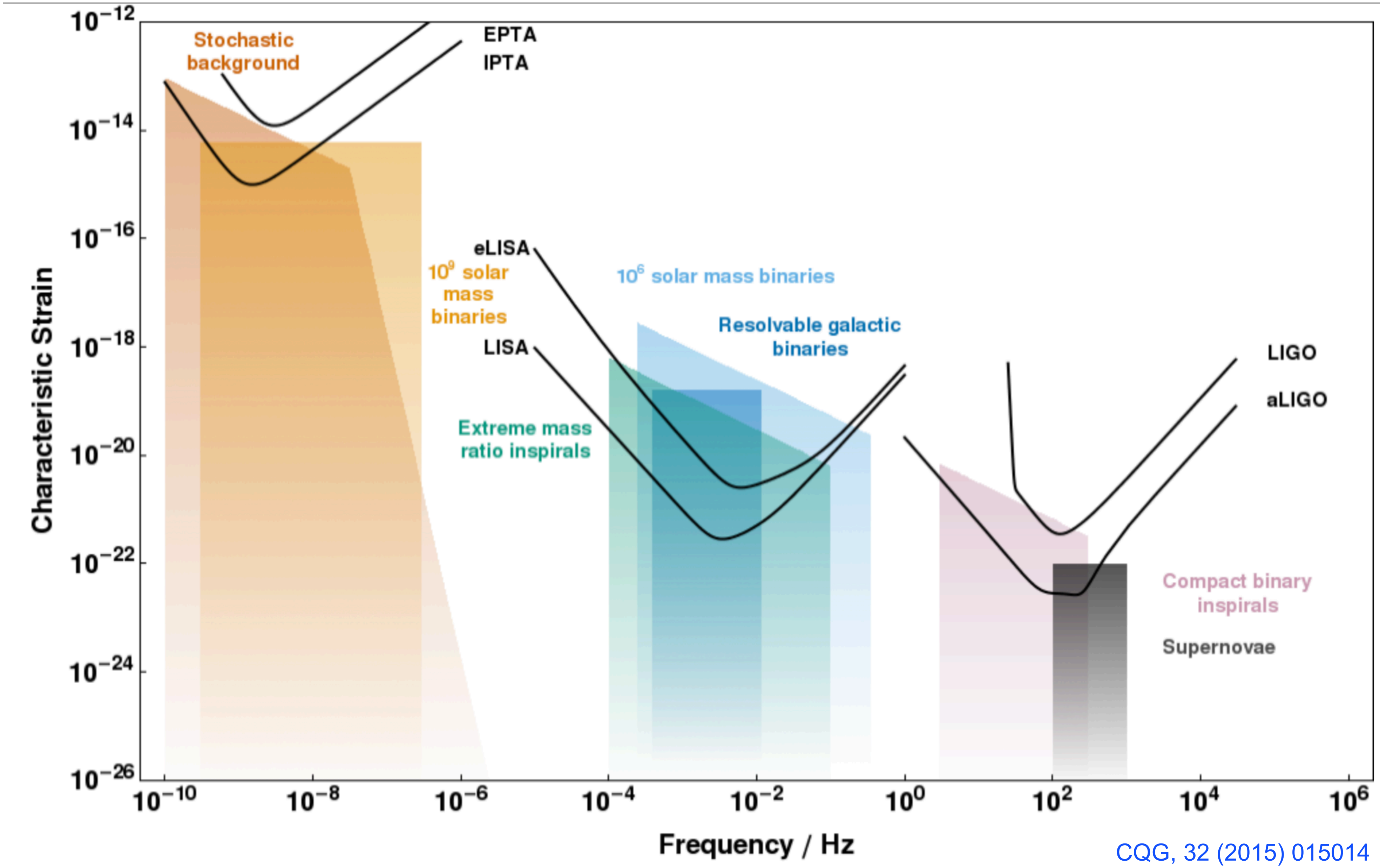
ZUCKER Sigg et. al

3^{rd} Generation

- When could this new wave of ground instruments come into play?
- Appears 15 years from *t*=0 is a feasible baseline
  - Initial LIGO: 1989 proposal, and at design sensitivity 2005
  - Advanced LIGO: 1999 White Paper, GW150914 in 2015
- Modulo funding, could envision…
  - Einstein Telescope in the early 2030’s
  - Cosmic Explorer in the mid-2030s
- Should hope – and strive and plan – to have great instruments ready to ‘catch’ the end phase of binaries seen in LISA (ref. Sesana)

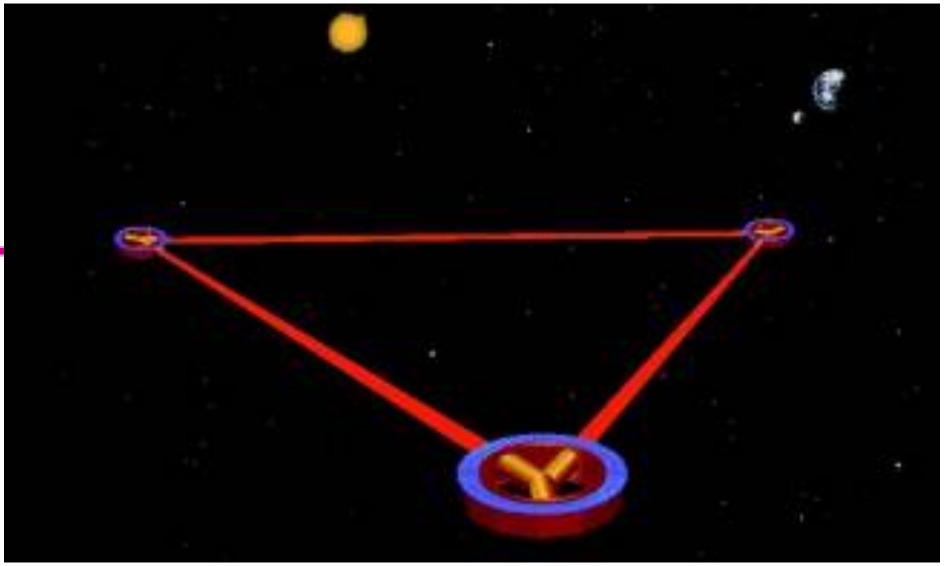
- Crucial for all these endeavors: to grow the scientific community planning on exploiting these instruments far beyond the GR/GW enclave
  - Costs are like TMT – needs a comparable audience

A spectrum of GW Sources and Sensors

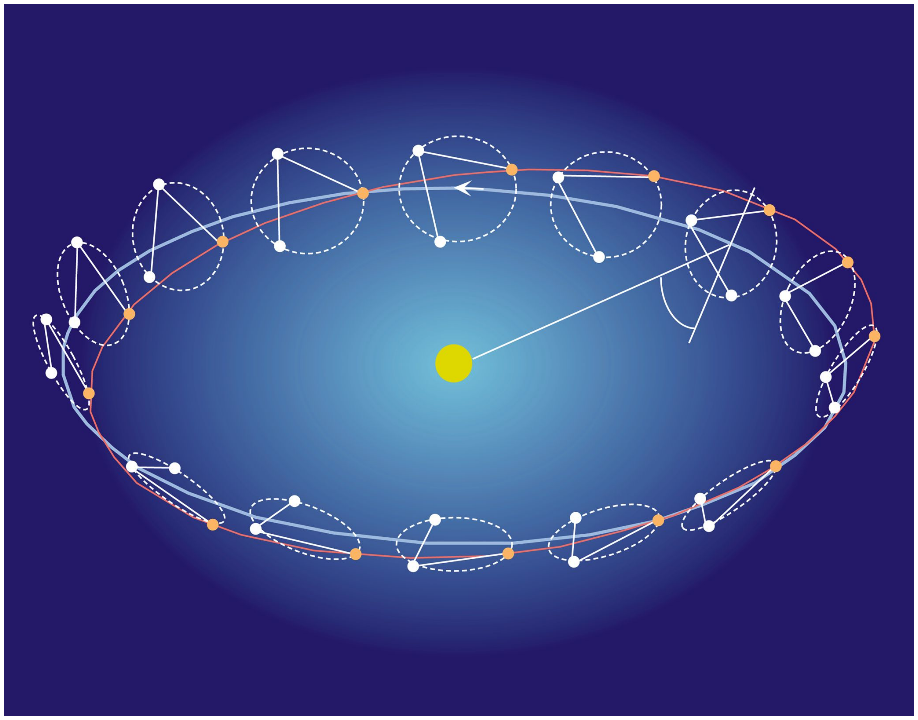


CQG, 32 (2015) 015014

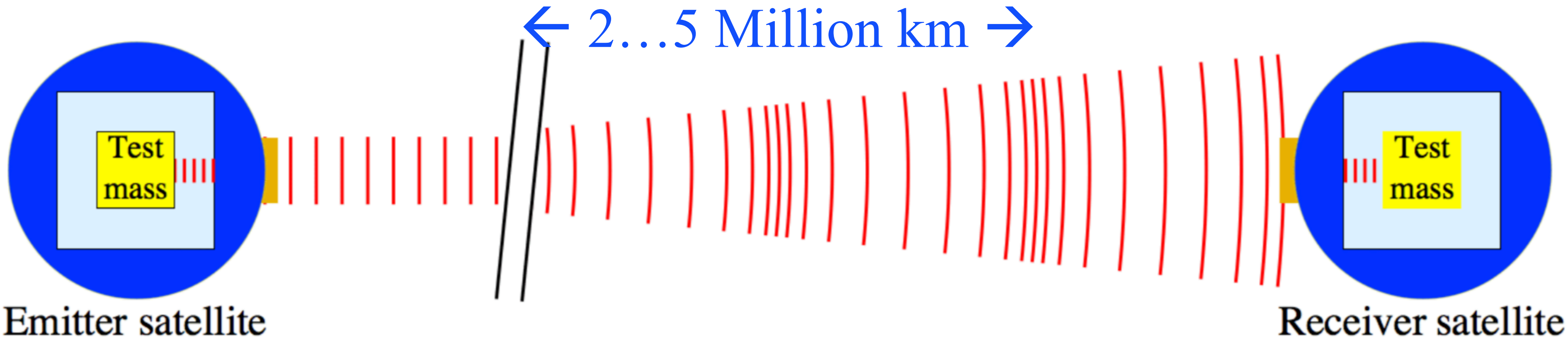
LISA



- Notion of a space-based interferometric detector dates from 1974
  - Rai Weiss and Peter Bender
- Basically a timing measurement between test masses in space
- Take advantage of vacuum in space: make very long arms
  - $h = \Delta L/L$; L can be ~10^9 m, making ΔL ~10^{-12} m (not LIGO's 10^{-19})
  - Also moves best sensitivity to milliHz region – explores much more massive objects
- Triangular configuration
- Sums and differences around the triangle
  - Allows both polarizations of the gravitational waves to be measured
  - Provides signals to remove laser frequency noise
- Earth-trailing orbit provides scan of the sky, provides sky localization



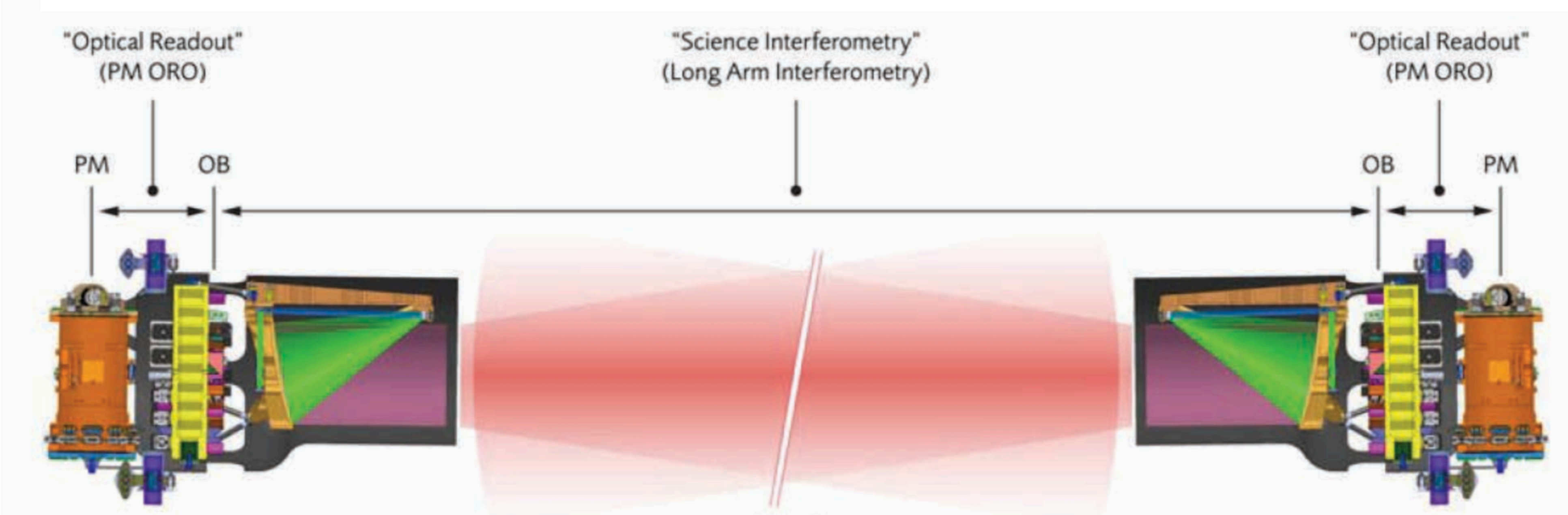
The LISA link



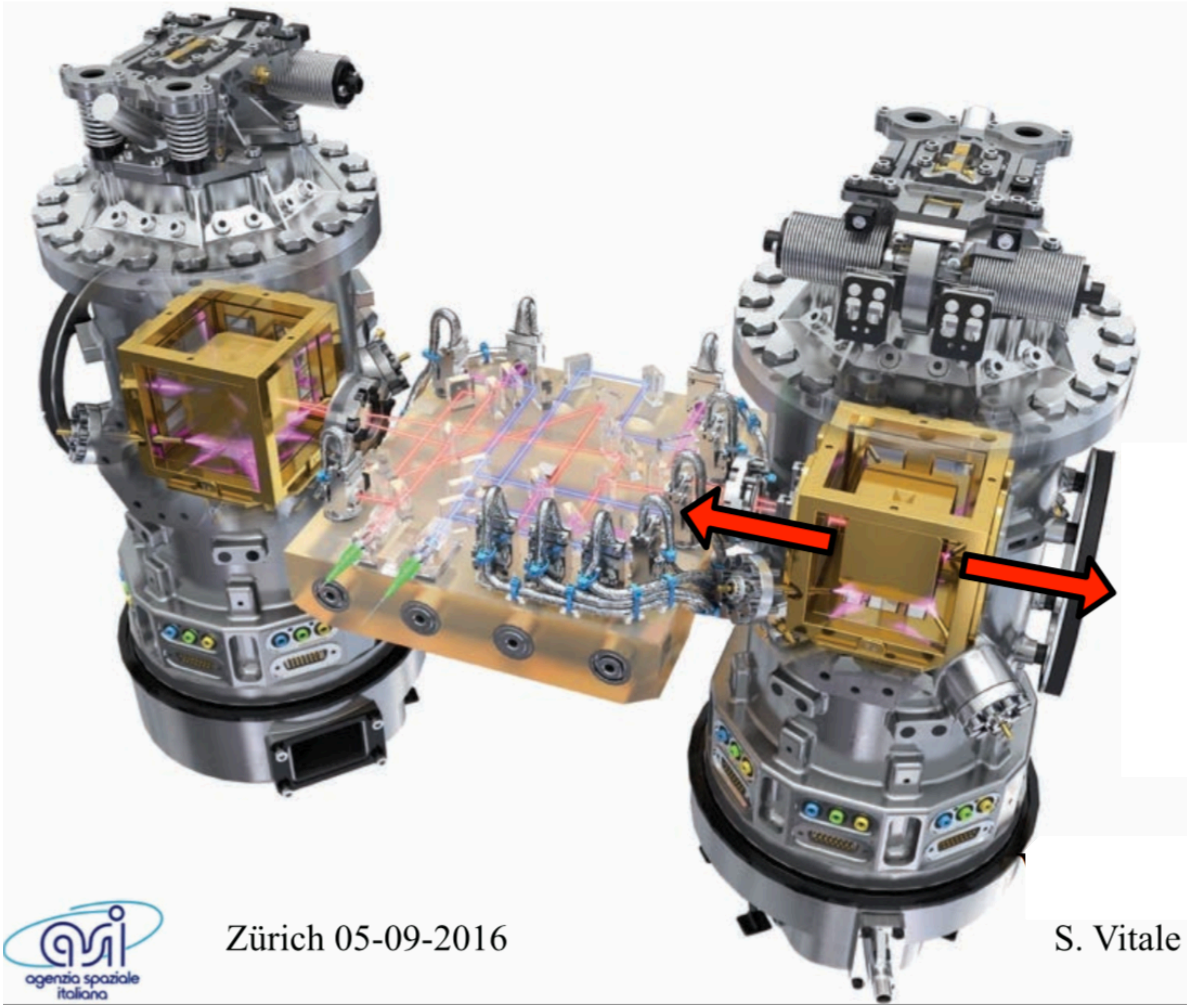
Protect test masses with slaved shield satellites

Send out watts, receive picowatts

Weigh the zip-tie tails…



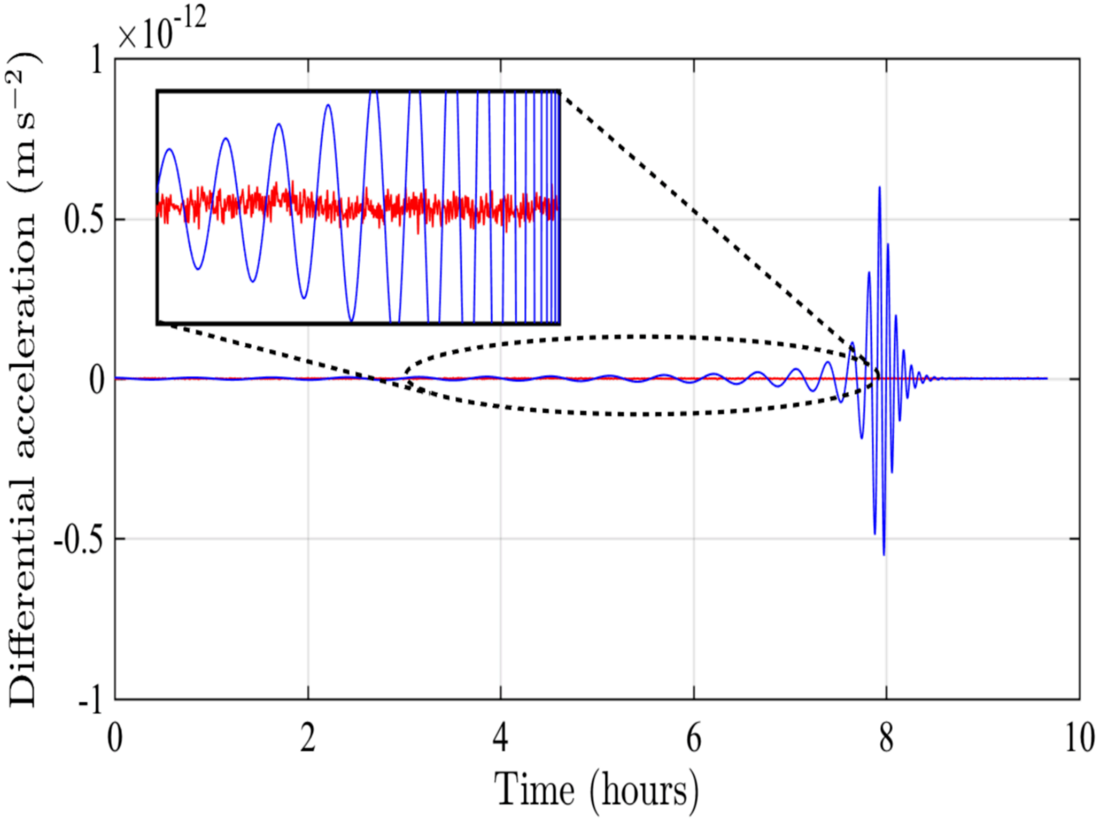
LISA Pathfinder test mission, now underway: interferometry between two LISA test masses



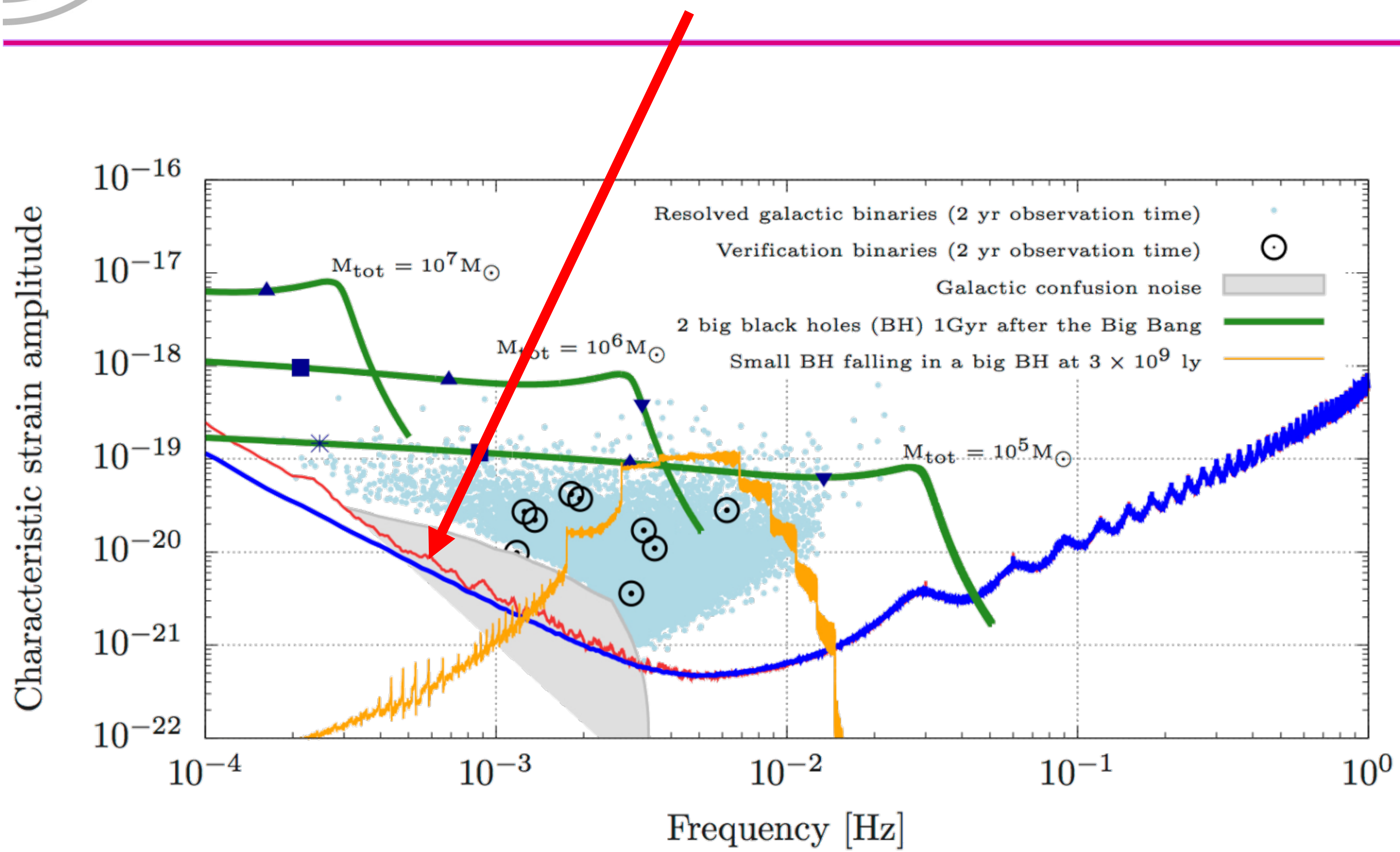
LISA Pathfinder

- LISA Pathfinder worked *very* well – far better than its requirements, basically meeting the ful LISA requirements
- Demonstrated all technologies needed for LISA that can only be tested in space
- Development for Telescope, etc. remain but are low risk

- Blue: Simulated signal for inspiral of two 5x10^5 Black Holes inspiraling at z=5
- Red: LISA Pathfinder interferometer performance



LISA Sensitivity, with current Pathfinder Performance



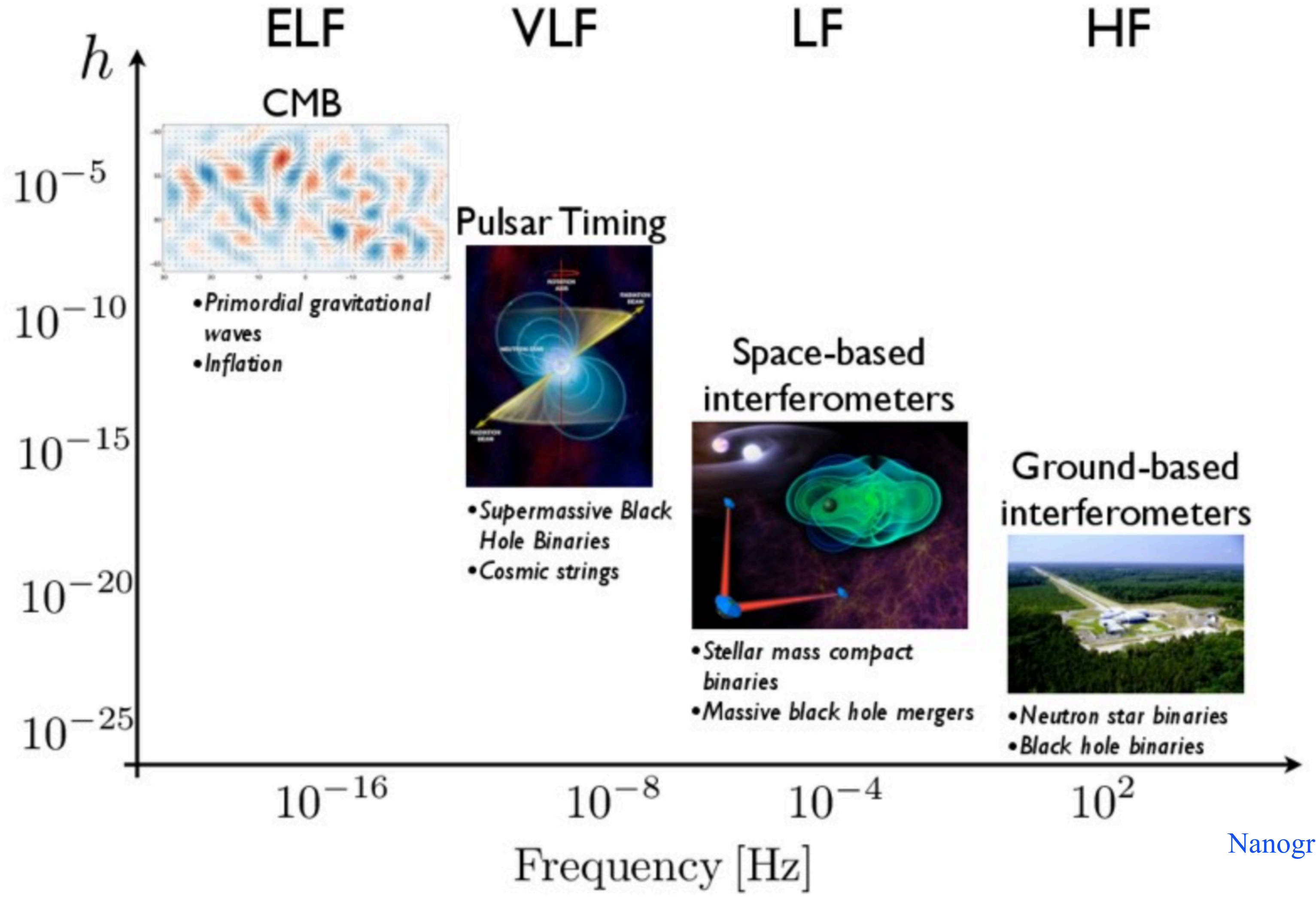
A. Petiteau 2016

LISA Status

- ESA-led mission; NASA minority partner
  - Both Agencies enthusiastic
- ESA-NASA discussions underway on specific contributions
- EU-US community joint collaboration
  - Both Communities enthusiastic, too!
  - In US, the ‘L3 Study Team’ the Community ‘motor’
- EU-US team proposed to ESA 16 January
- **Approved as an ESA mission yesterday!**
- Phase A imminent; mission adoption planned for 2024 (maybe 2022?)
- Launch date nominally 2034; may bring in to ~2030
- Next major challenge for the US NASA participation in LISA: 2020 Decadal

The End – and
The Beginning

Wonderful GW science opportunities within the reach of technology



Nanograv