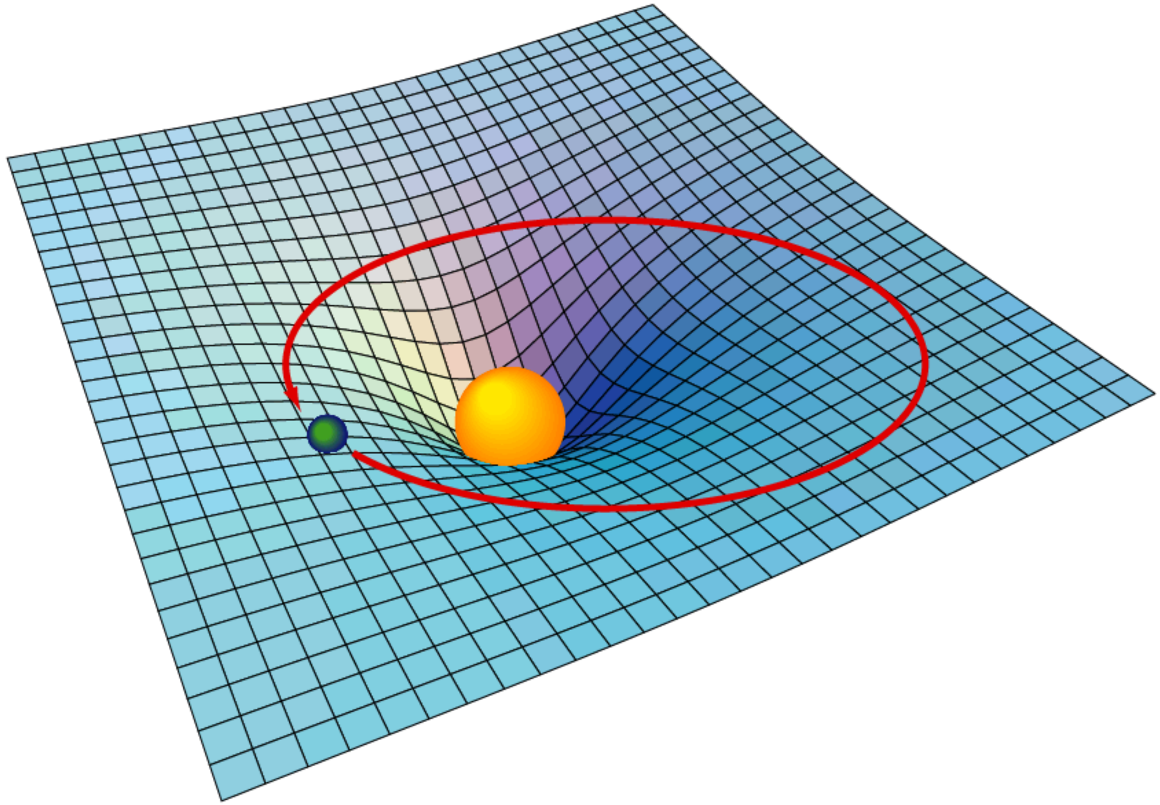
Gravitational Wave Experiments

TOC

- About GW (I will skip most of it)
- Interferometers and LIGO
  - Time line
  - Evolution from prototypes to 1st gen to 2nd gen and how
  - Advanced LIGO's first observation run, O1
  - Future

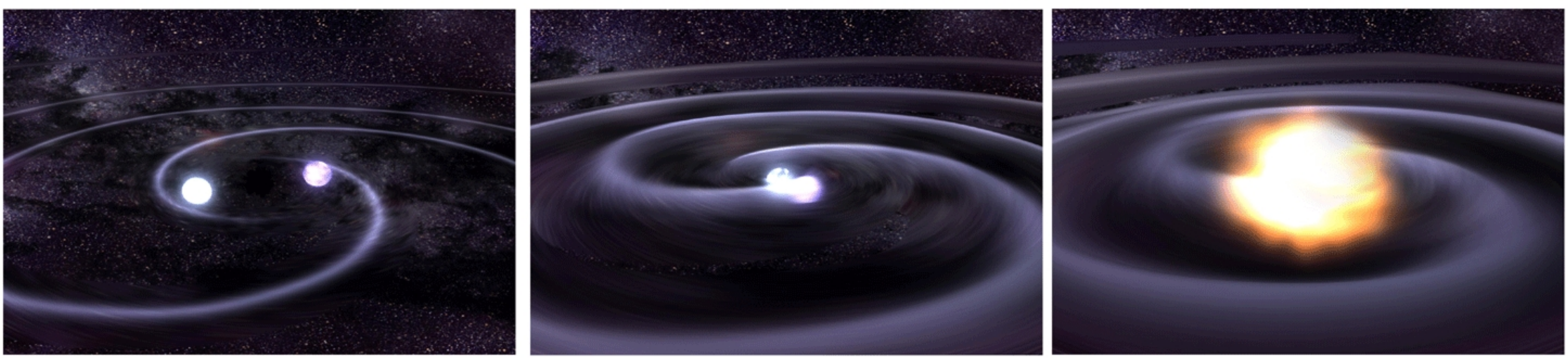
Spacetime is not entirely unlike stretchy fabric



- It dynamically interacts with matters, stretching and shrinking as matters move while telling them where to move next.

1917: Einstein's prediction of Gravitational Waves

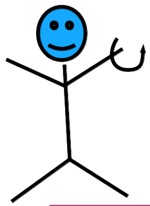
- GW = Wave solution of the linearized Einstein field equations in vacuum.
- Ripple in spacetime when it is stirred up by rapid motions of large concentrations of matter or energy.



Credit: NASA

But GW is very, very small

- There are stars accelerating/decelerating violently, which are the primary sources of GW.
  - But the wave amplitude falls as 1/distance.
- We're talking about the "stretching" of spacetime by $O(10^{-21})$ at most on the earth, for example.
- Therefore it wasn't until much later (1960's) when the technology reached the point where people started to think seriously about the detection of GW.
- GW generation in lab? No.
  - Despite a popular myth, waving your hands around will NOT generate gravitational wave unless you live 10^6 years or so. See appendix.



OK, so why do we want to detect GW?

- After all, existence of GW was already experimentally confirmed by PSR B1913+16.
  - And these people already got Nobel!

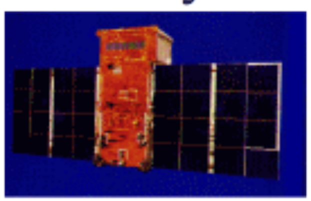
OK, so why do we want to detect GW?

- Opening a new window for the Universe!
  - Astronomy and Astrophysics
- B. Sathyaprakash on GW astronomy and GR test on Wed.
- P. Ajith on GW astronomy on Thu.

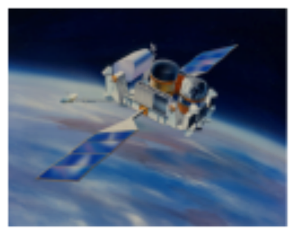
We want to open a new window…

Visible light

X-ray



Gamma



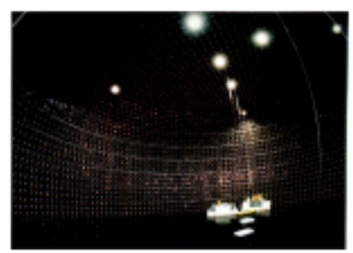
Gravitational Wave!

Visible light

radio

IR, UV etc.

Neutrino



LLTA 1600's Starting 1930' – 60's Starting 1980's Starting 2010's

All images wikimedia commons except Gallilei's telescope which is from IMSS Firenze

But who are trying other than tracking orbital decay of PSR B1913+16?

Turns out that there are many techniques for different frequency windows,

1. Direct measurement by looking at the “distance” between two or more free falling masses modulated by GW.
   - Terrestrial Interferometers: This talk, O(1~1000) Hz source frequency
   - Space Interferometers: O(weeks~seconds) source period
     - LISA path finder just launched (Dec 2015)! Awesomeness!!
   - Pulsar Timing Arrays: Dick Manchester’s talk, O(1~100 years) source period
   - Doppler tracking of satellites (not actively pursued for now)
2. Direct measurement by looking at the the deformation of elastic body caused by GW tidal force.
   - Cylinders, spheres, torsion resonators etc.: Narrow band AF
3. Measure the GW signature imprinted in the B-mode polarization of CMB
   - Silvia Galli’s talk about Keplar and CMB polarization on Thu.: Source period O(universe’s age).

Many potentially interesting sources.

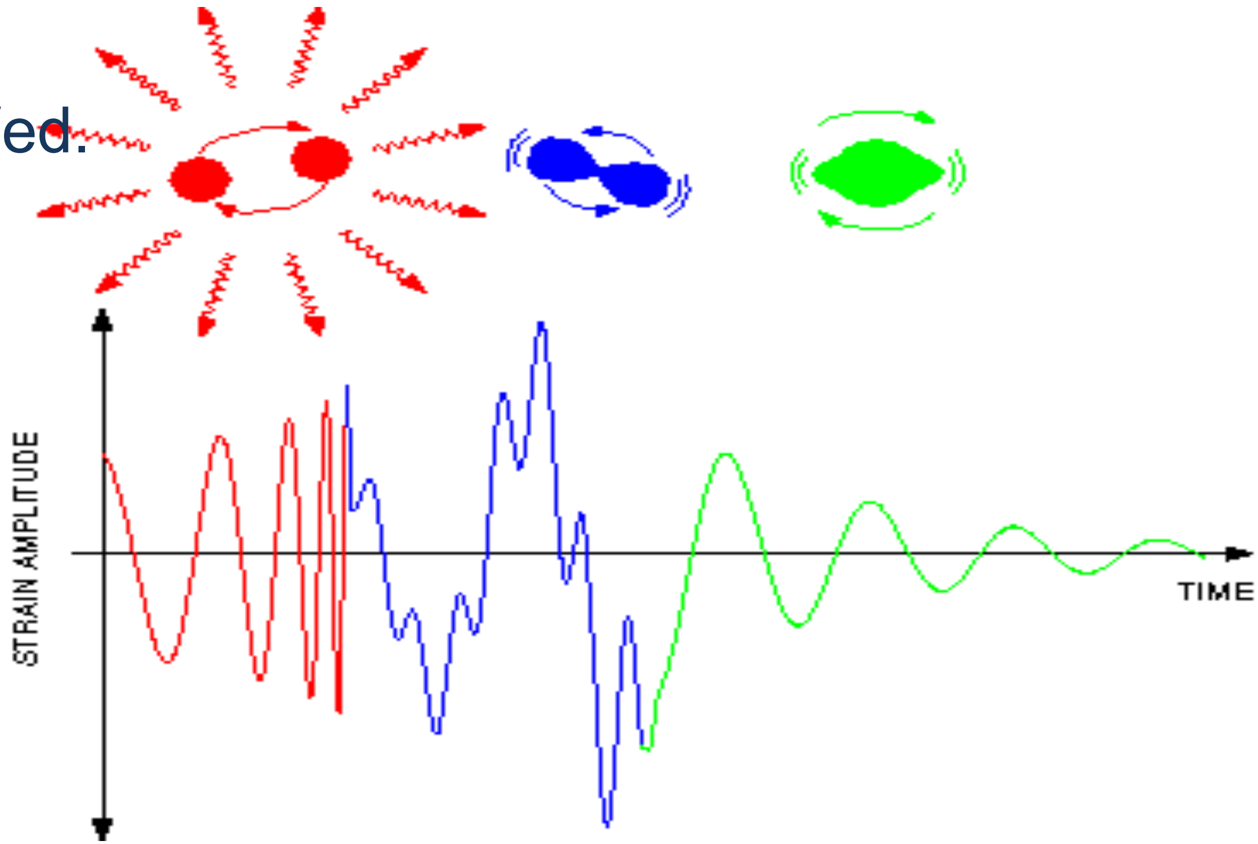
Coalescing binary system

- NSNS, BHBH, NSBH
  - Terrestrial interferometers for compact system
  - Space IFOs for the massive BBH.
  - PTAs for super massive BBH.

Artistic animation: NASA/Goddard Space Flight Center

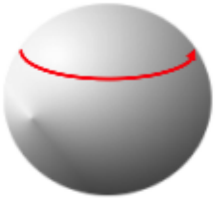
Coalescing binary system: Numerical relativity is the key

- Numerical relativity is the primary tool to know the waveform, and is essential for the detection and source parameter extraction.
- Luc Branchet today.
- Harald Pfeiffer on Wed.

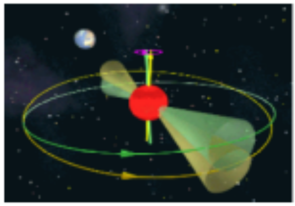


Periodic sources and Bursts

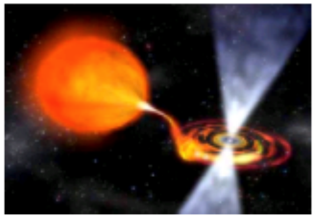
- Periodic: Binary pulsars, spinning NS, X-ray binaries



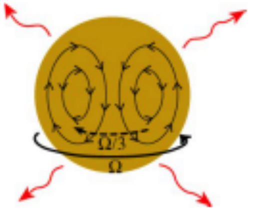
"Mountain" on neutron star



Wobbling neutron star



Accreting neutron star

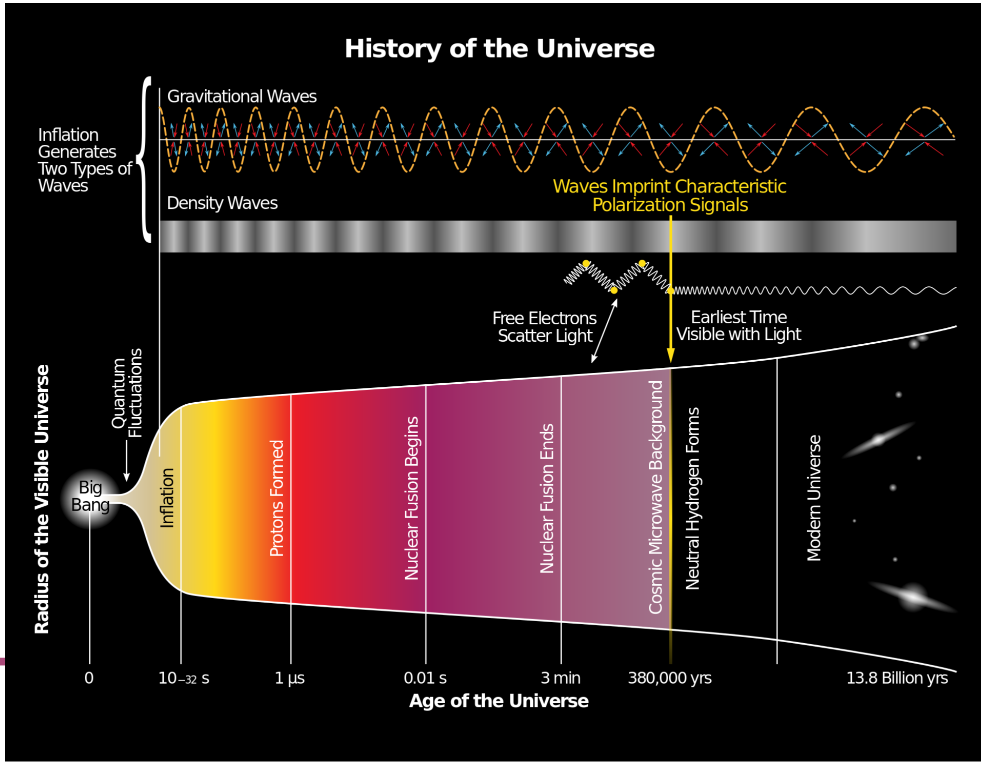


R-modes

- Burst: e.g. supernovea with asymmetric collapse.
  - Unknown waveform
  - Mostly for terrestrial detectors

Stochastic GW

- Superposition of many binary mergers, rotating NS, magnetars, supernovae
  - Terrestrial IFO, Space IFO, PTA, depending on the frequency
- Primordial GW
  - Terrestrial and space IFO, PTA, and B-mode polarization searches, depending on the frequency

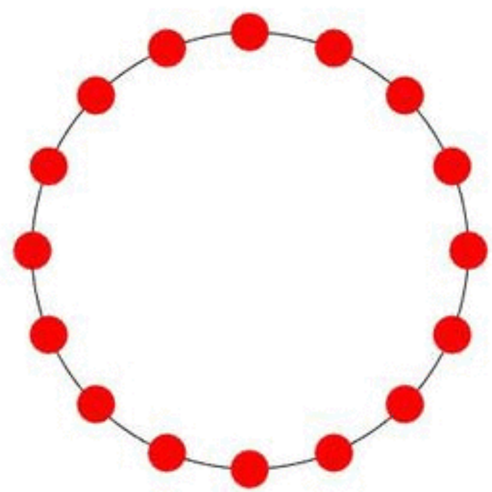


Interferometers and LIGO

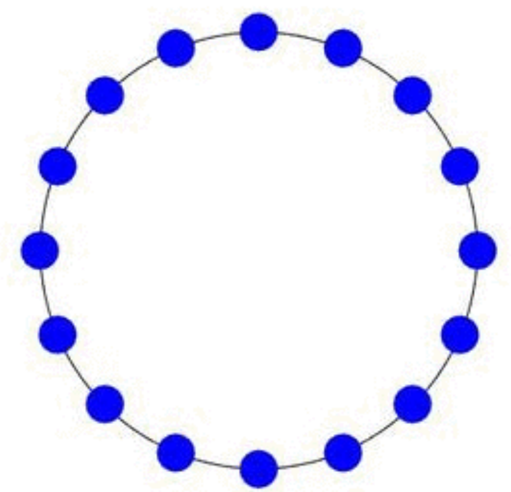
Effect of GW on free-falling masses

- Distance between free-falling masses is stretched in one direction, compressed in the other.
- Two polarizations.

Propagation axis
(perpendicular to screen)



“Plus”-polarized

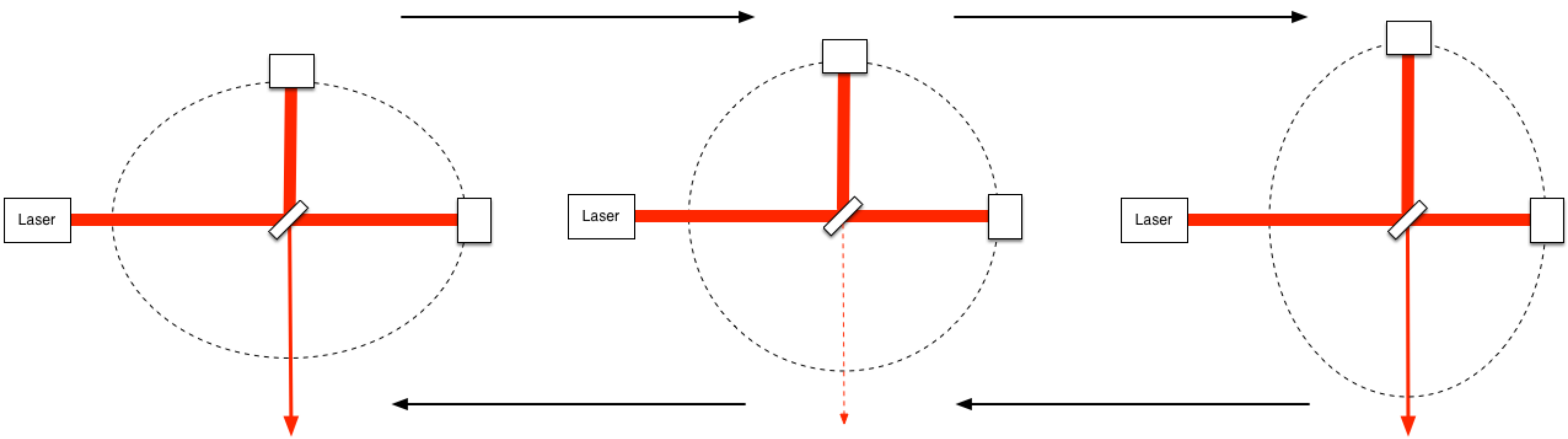


X-polarized wave

“X”-polarized

How interferometers detect GW

- Example: Simple Michelson interferometer and "plus"-polarized GW travelling vertical to the screen.

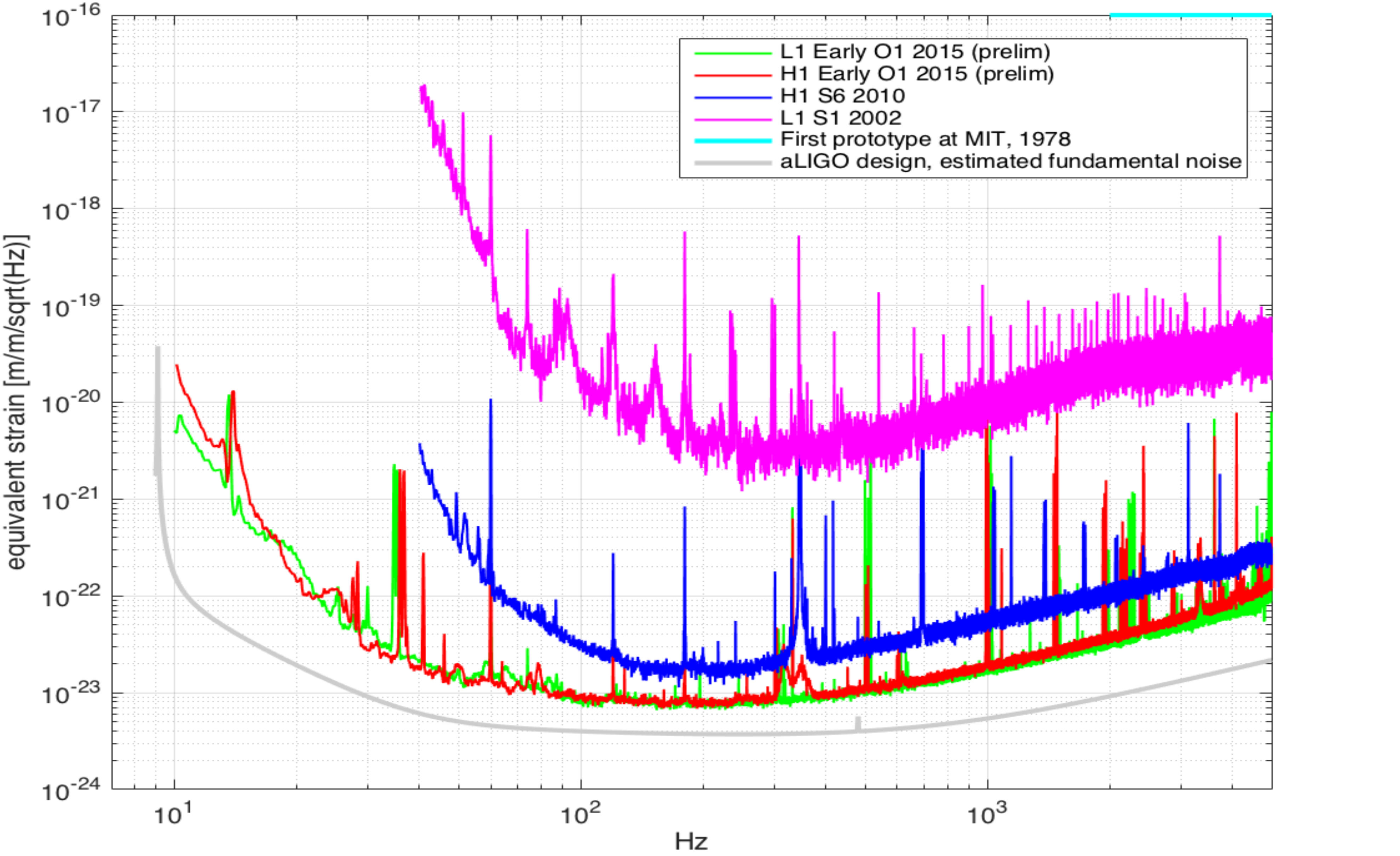


- GW information is encoded in the power of light coming out of IFO. We decode this light power.
- An output of one IFO is one-dimensional time series not unlike a single microphone.

IFO is like a microphone that measures noise except when there's an event

- Noise is the single most important characteristic of an instrument.
- We often use amplitude spectral density of the noise in terms of "equivalent strain" that would be imprinted in the instrument by GW.
- The smaller the noise, the smaller signal we can detect, thus the farther we can listen to the events.

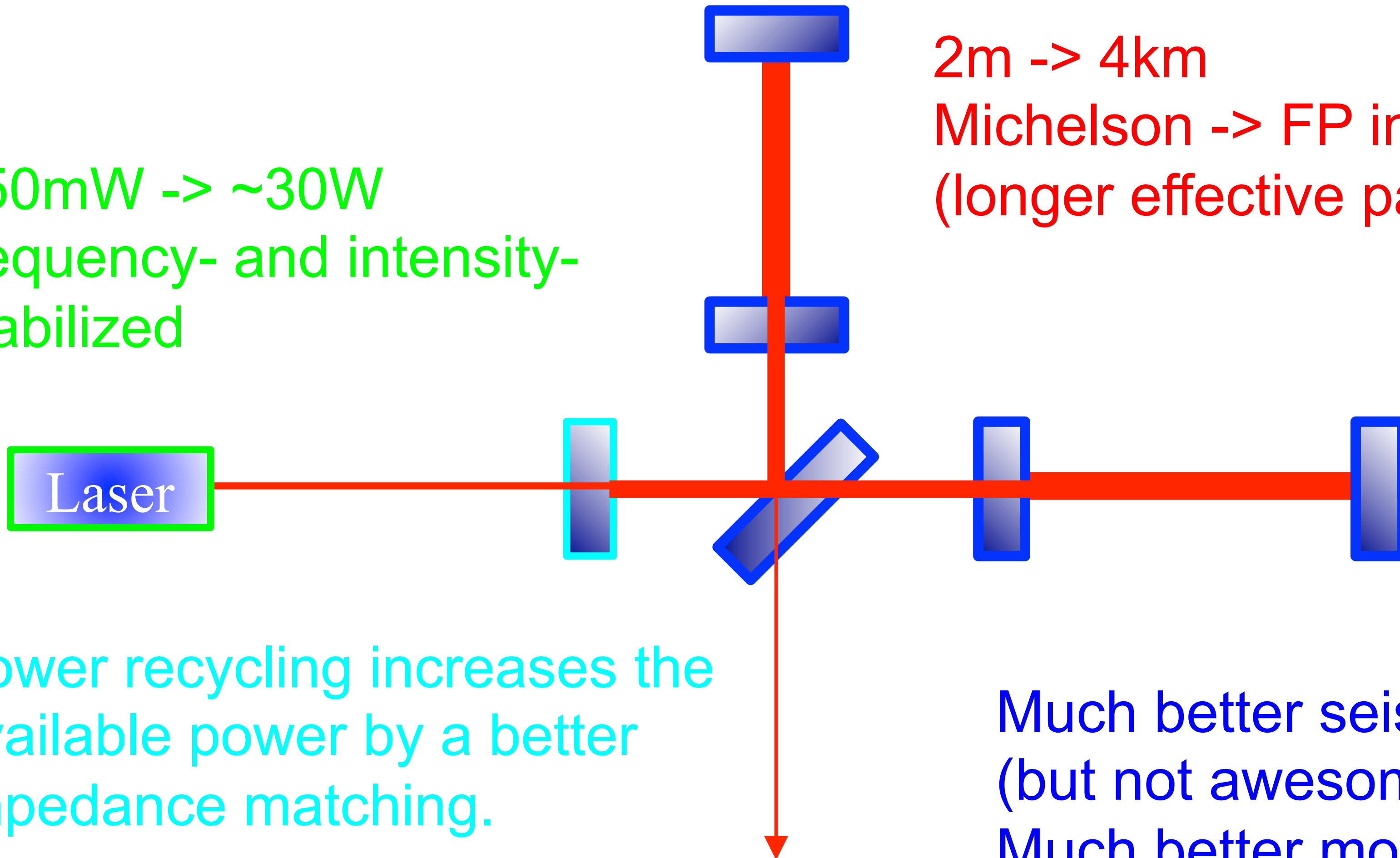
Evolution from Michelson prototype to iLIGO to aLIGO



From the very 1st prototype to iLIGO over-simplified

~50mW -> ~30W
frequency- and intensity-stabilized

2m -> 4km
Michelson -> FP in the arms
(longer effective path length)



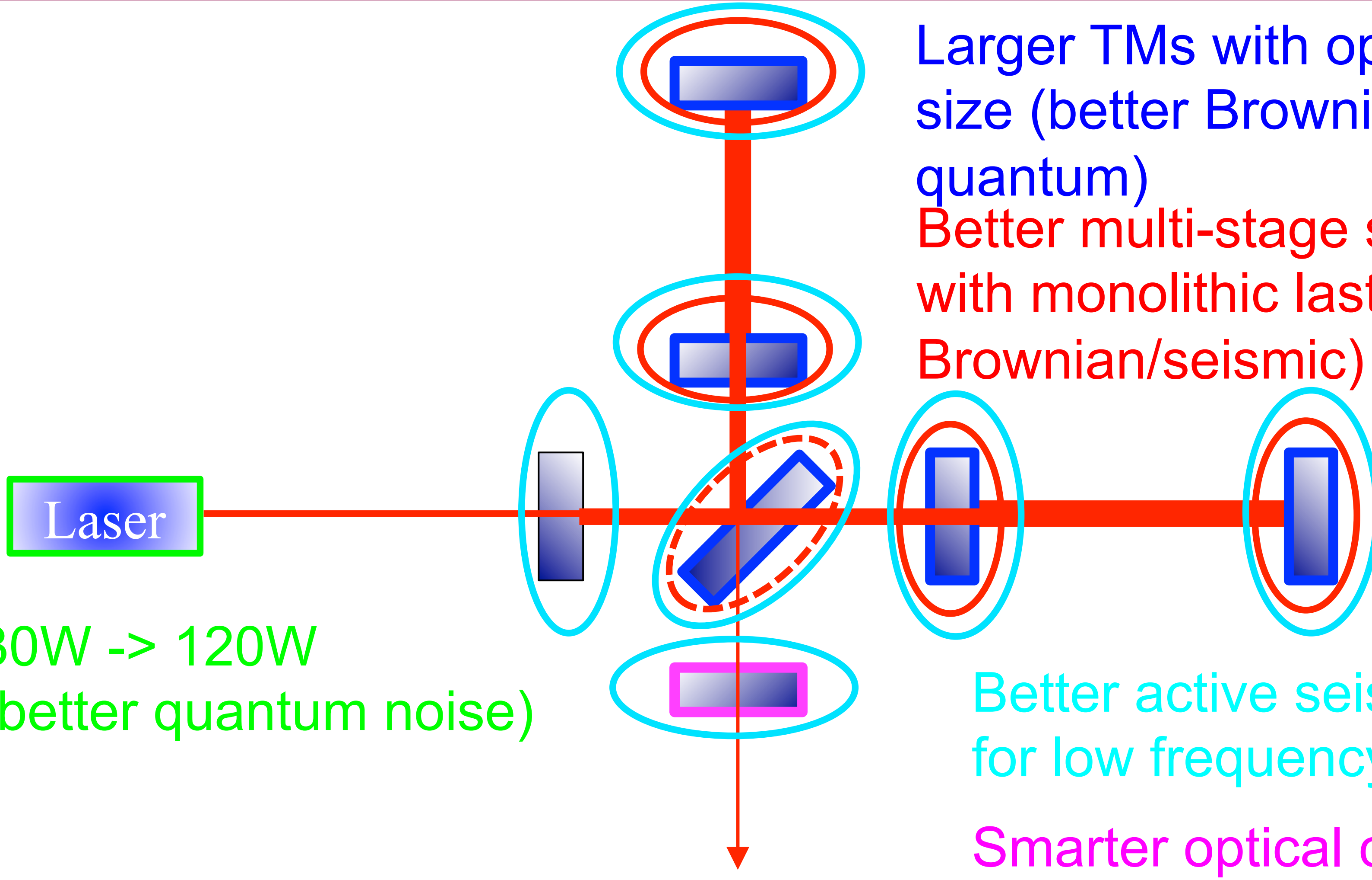
Power recycling increases the available power by a better impedance matching.

Much better seismic isolation, (but not awesome).
Much better monolithic mirrors.

iLIGO on one page

- 6 science runs, with other projects
- Exceeded the design sensitivity in S6, ~1yr data.
- NSNS range ~20Mpc (Virgo cluster!)

1st gen (iLIGO) to 2nd gen (aLIGO) again over-simplified



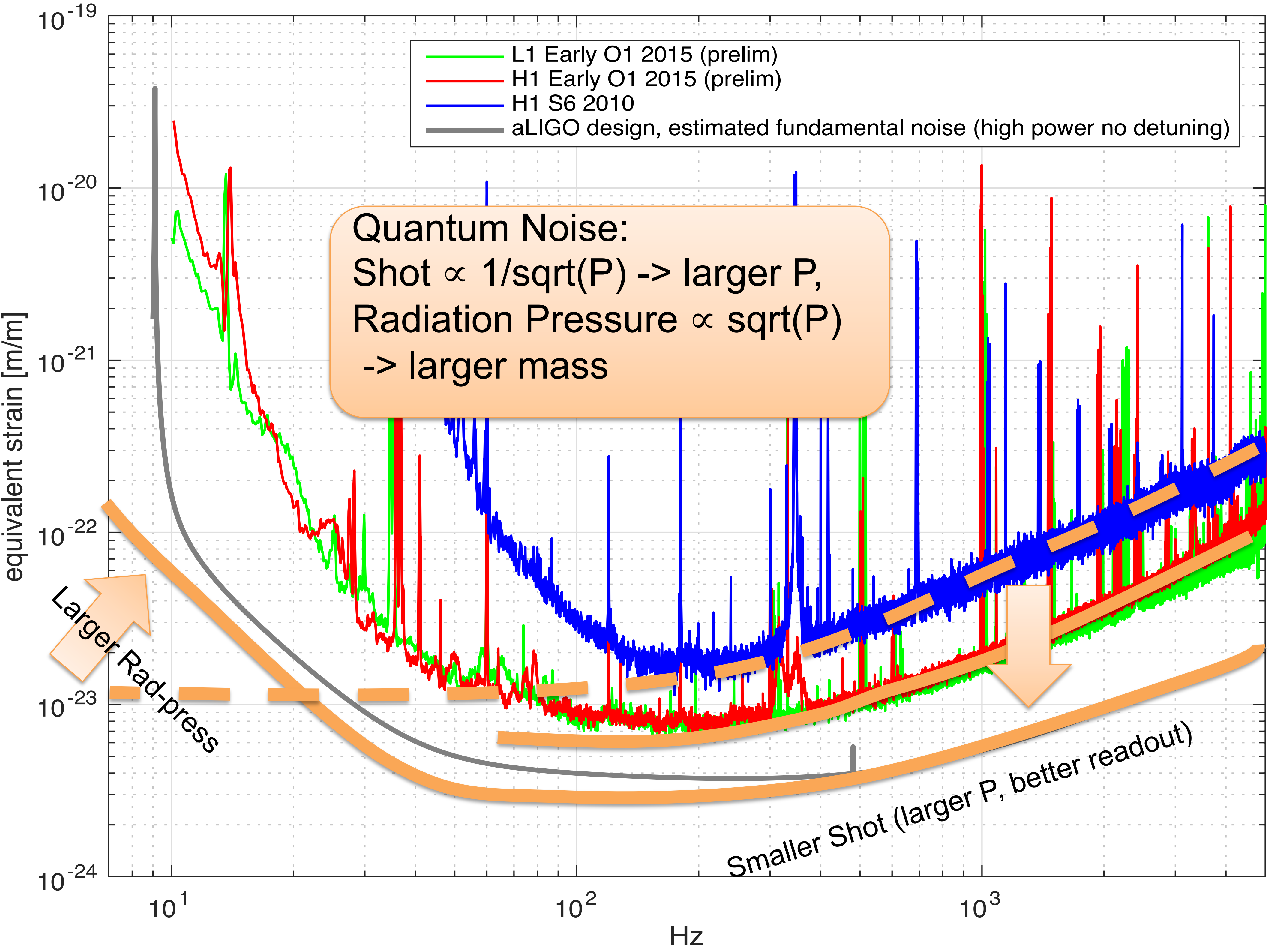
Larger TMs with optimized beam size (better Brownian and quantum)

Better multi-stage suspension with monolithic last stage (better Brownian/seismic)

30W -> 120W (better quantum noise)

Better active seismic isolation for low frequency performance

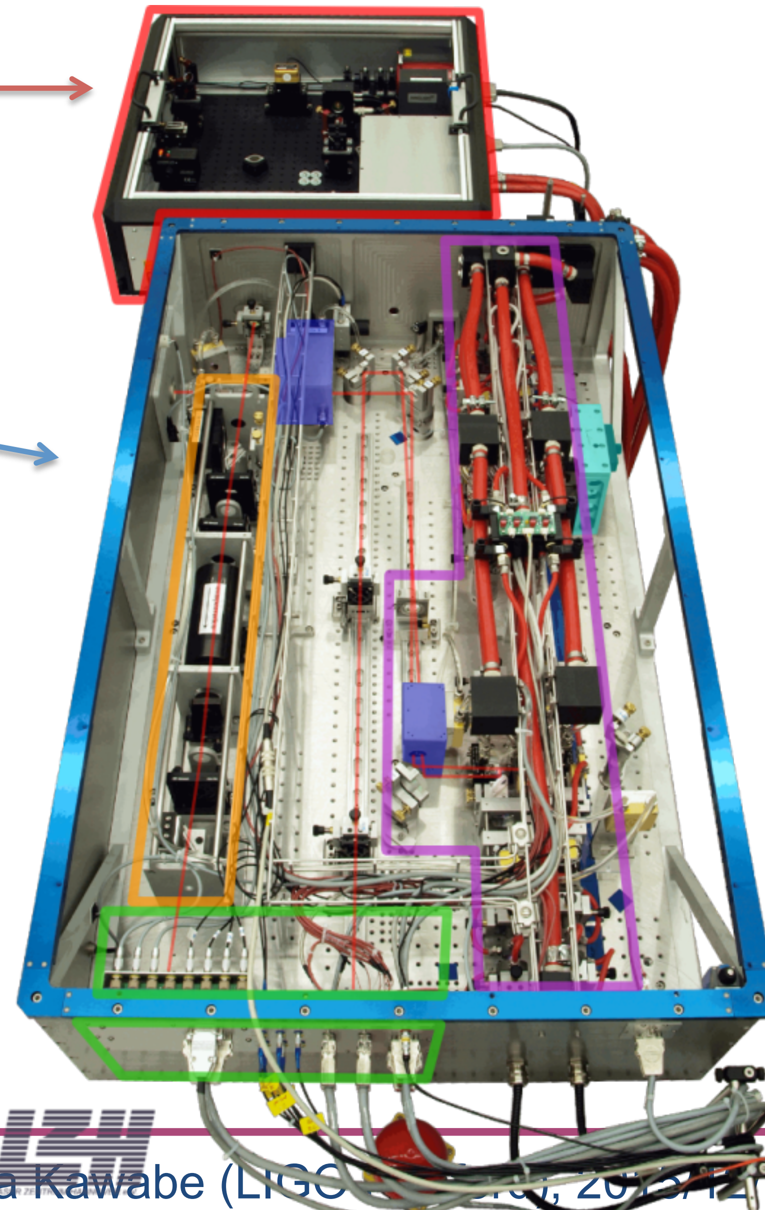
Smarter optical configuration (better use of power, optimized quantum noise)



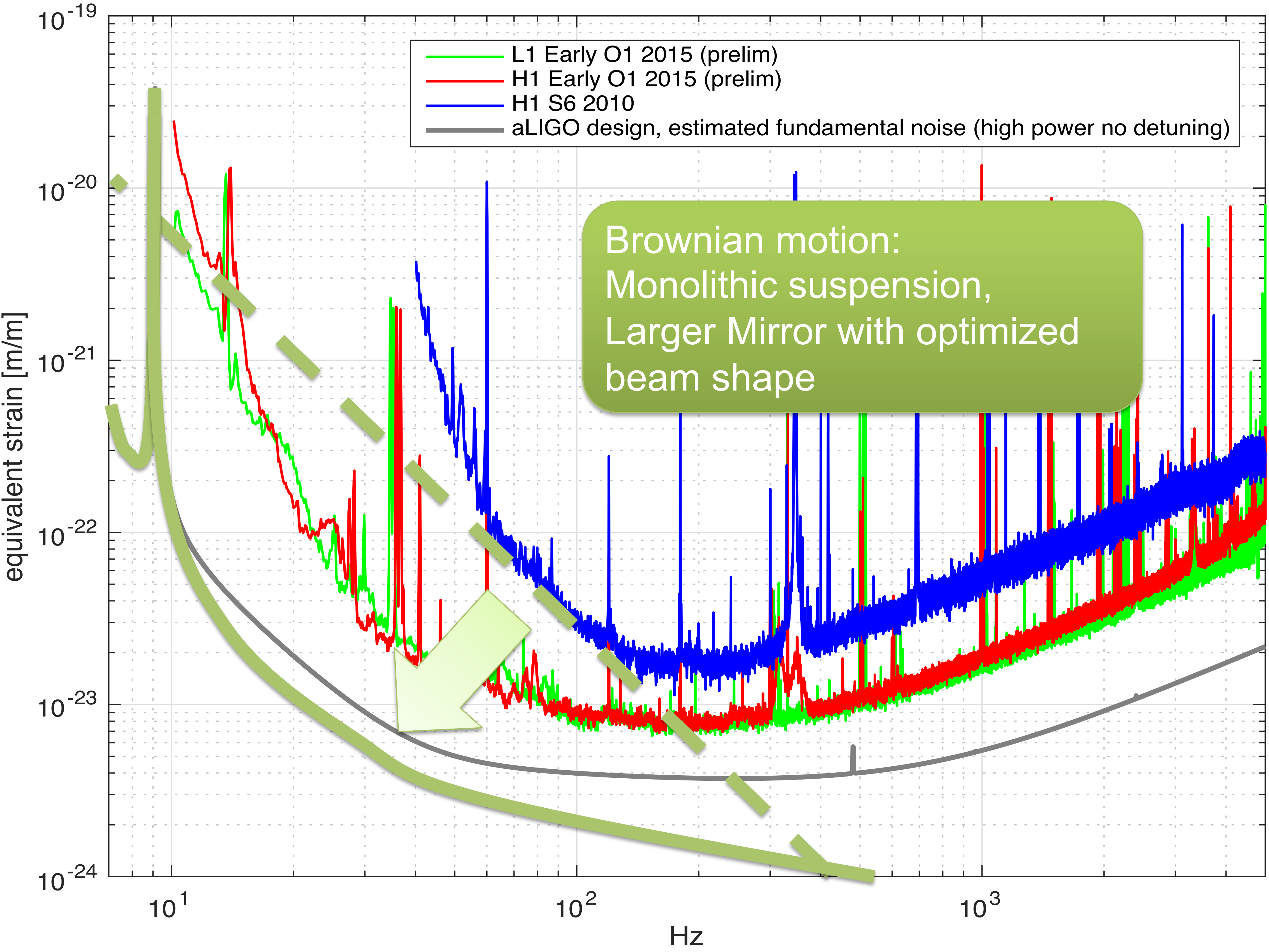
L1 Early O1 2015 (prelim)
H1 Early O1 2015 (prelim)
H1 S6 2010
aLIGO design, estimated fundamental noise (high power no detuning)
Quantum Noise:
Shot ∝ 1/sqrt(P) -> larger P,
Radiation Pressure ∝ sqrt(P)
-> larger mass
Larger Rad-press
Smaller Shot (larger P, better readout)
equivalent strain [m/m]
Hz
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}

High power laser, bigger mirror

- NPRO + 35W medium power amplifier used in iLIGO
- 180W high power stage for aLIGO

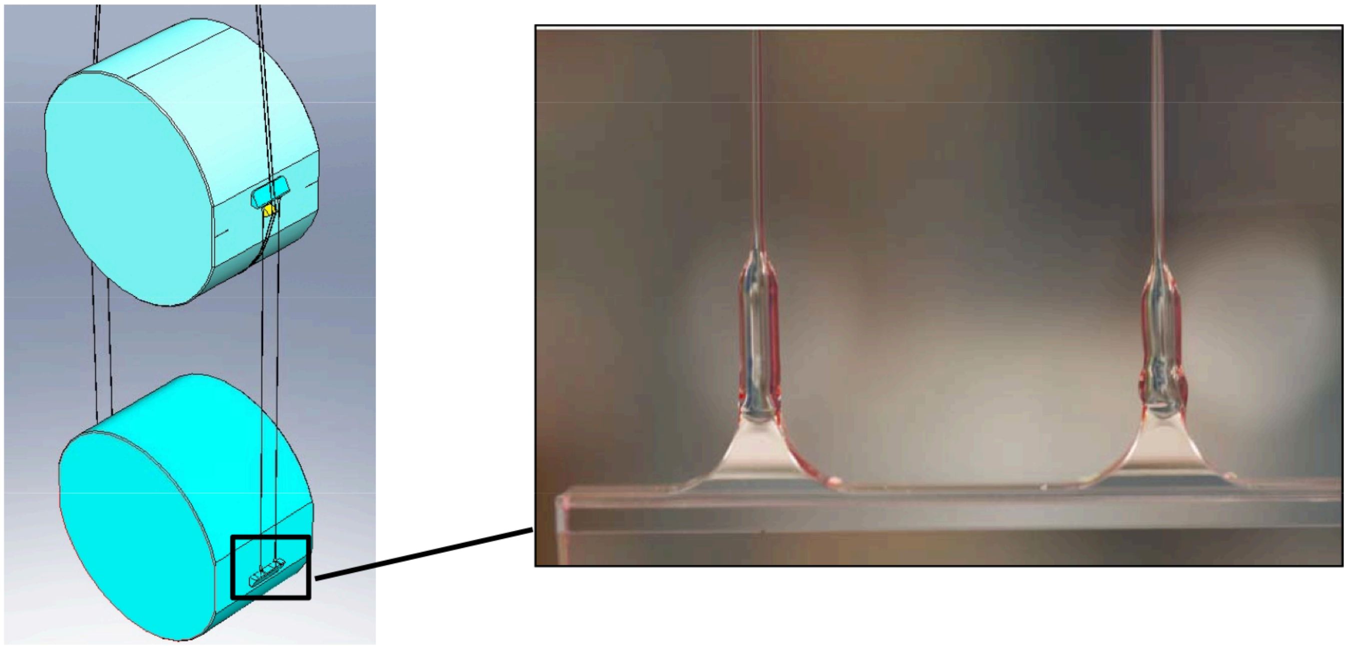


Harry, G. M., *et al.* *CQG* 27.8 (2010): 084006.

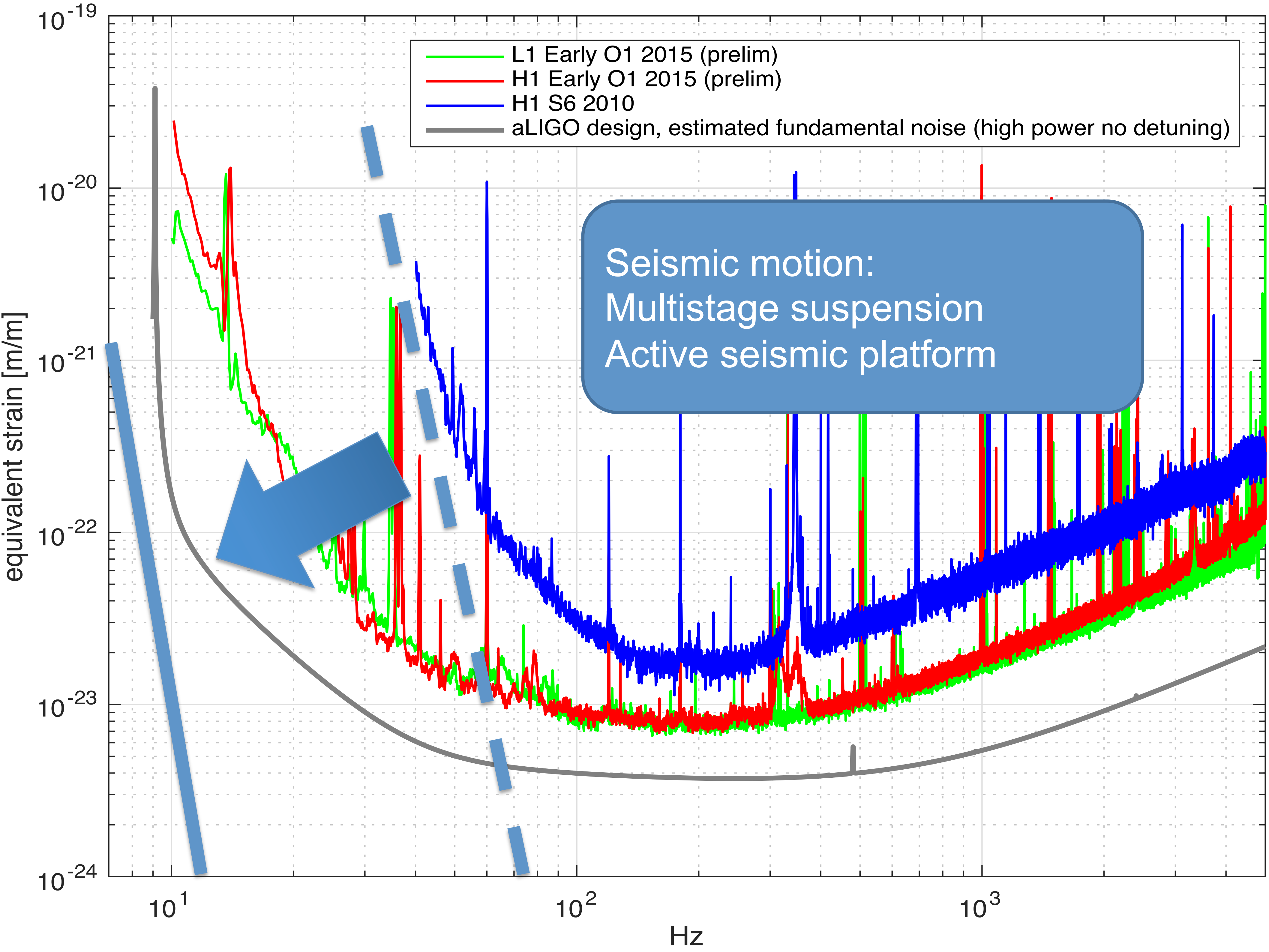


L1 Early O1 2015 (prelim)
H1 Early O1 2015 (prelim)
H1 S6 2010
aLIGO design, estimated fundamental noise (high power no detuning)
Brownian motion:
Monolithic suspension,
Larger Mirror with optimized
beam shape
equivalent strain [m/m]
Hz
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}

Smaller Brownian motion



- Monolithic suspension for lower mechanical dissipation (think dissipation-fluctuation theorem) for pendular thermal motion
- Larger mirror with optimized beam size reduce the sensitivity for thermal excitation of mirror deformation



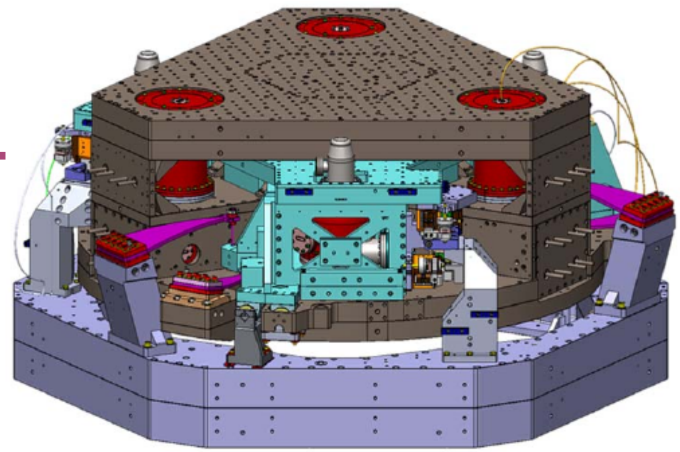
L1 Early O1 2015 (prelim)
H1 Early O1 2015 (prelim)
H1 S6 2010
aLIGO design, estimated fundamental noise (high power no detuning)
Seismic motion:
Multistage suspension
Active seismic platform
equivalent strain [m/m]
Hz
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10^1
10^2
10^3

Seismic isolation

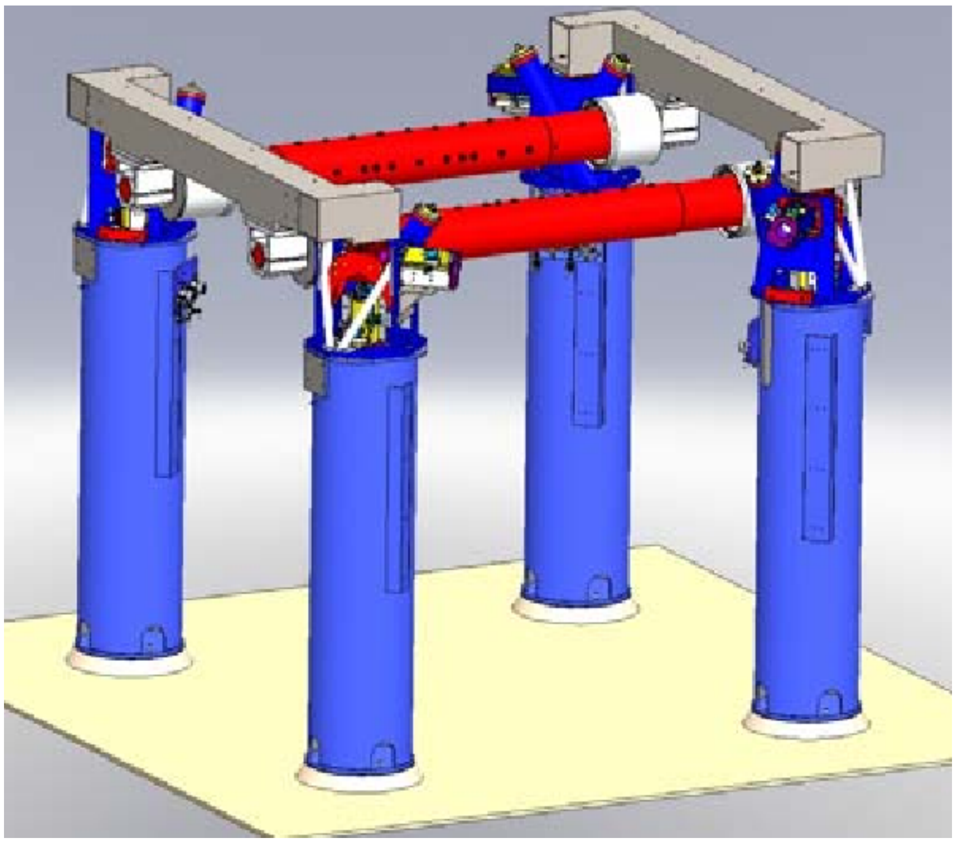
- Multi-stage (quad) suspension, which is isolated by
  - ISI (Internal Seismic Isolation) system, which is isolated by
    - HEPI (Hydraulic External Pre-Isolator)

Seismic isolation

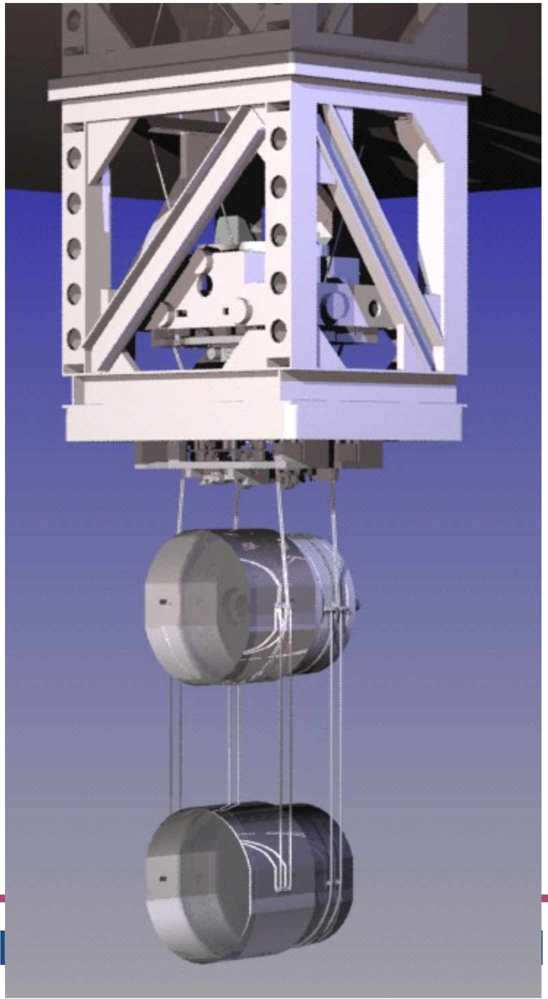
ISI



HEPI



Quad



(But fundamental noise sources are not the only ones we fight)

- Technical noise: See appendix

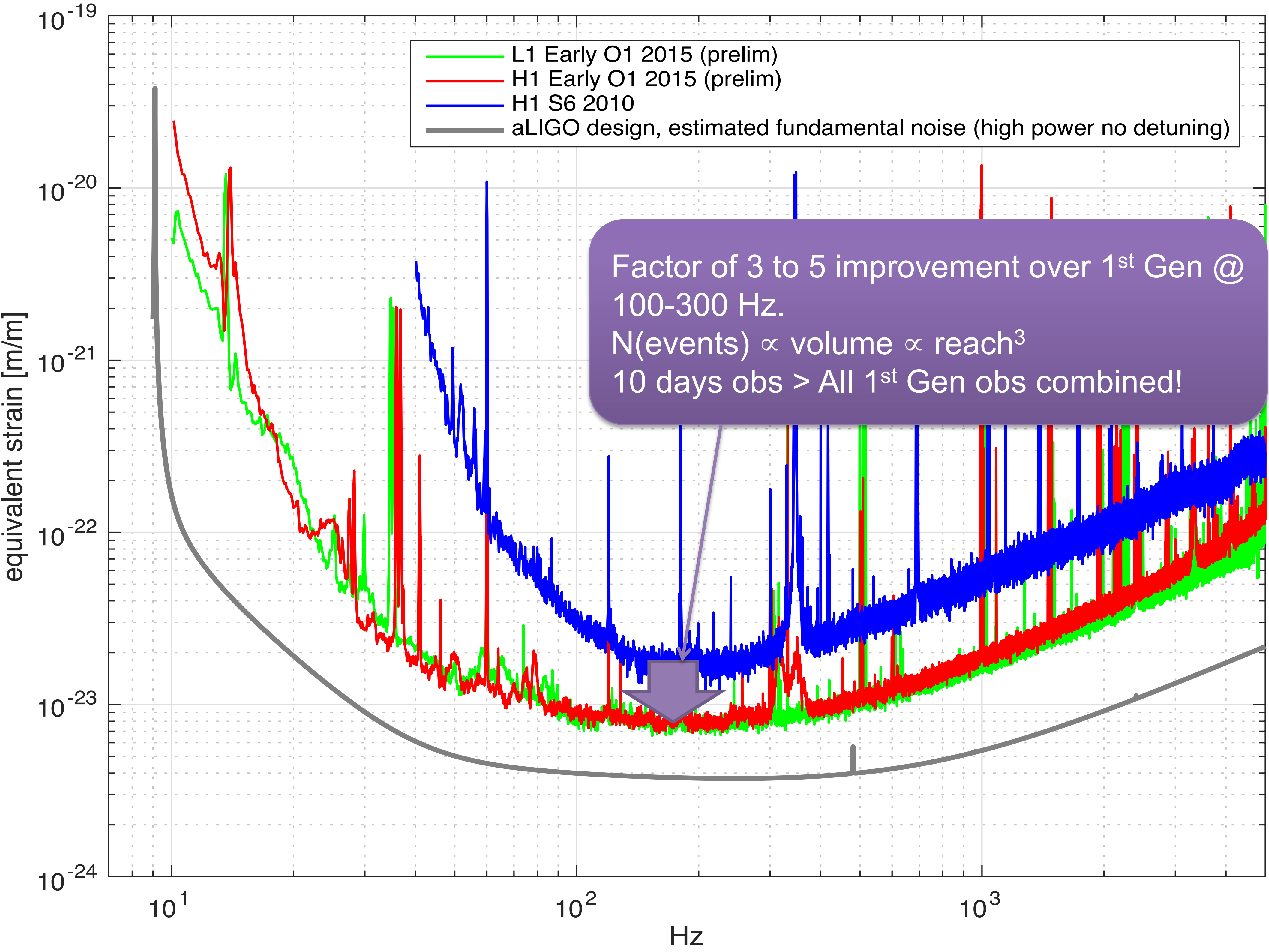
Over-Simplified IFO Time Line

- 1970-80's: Prototypes with O(1) to O(10) meters arms.
  - MIT, Caltech, Garching, Glasgow among others.
- 1990's: Mid-scale (TAMA, GEO), and then first gen large IFOs (LIGO, VIRGO) emerge. O(100) to O(1000) meters.
- 2000's: Science runs by 1st gen detectors. LIGO finally exceeds its design sensitivity in 2010, reaching ~20Mpc NSNS range (*Virgo cluster*!).
- LIGO (2010) and VIRGO (2011) go on hiatus for fundamental upgrade ("advanced" 2nd gen detectors).
- 2015: aLIGO's first observation run, O1, started on Sep/18 with non-final configuration, ~40Mpc NSNS initially (but 60-80 now).
- 2016: O1 will likely end on Jan/14. Another O run (O2) after an upgrade. VIRGO will come back online.
- 2019(?): LIGO reaches its design sensitivity, ~180Mpc.

aLIGO’s first observational run, O1

aLIGO's first observational run, O1

- First run using LIGO's two "advanced" instruments separated by 3000km or 10ms.
- Started on Sep/18/2015, run period ~ 4 months.
- Non-final configuration
  - 20W instead of 120~150W
  - End mirrors not final
  - SRM not final
- Both instruments running with unprecedented sensitivity, NSNS inspiral 60~80 Mpc (preliminary).
- EM followup partnership in place.

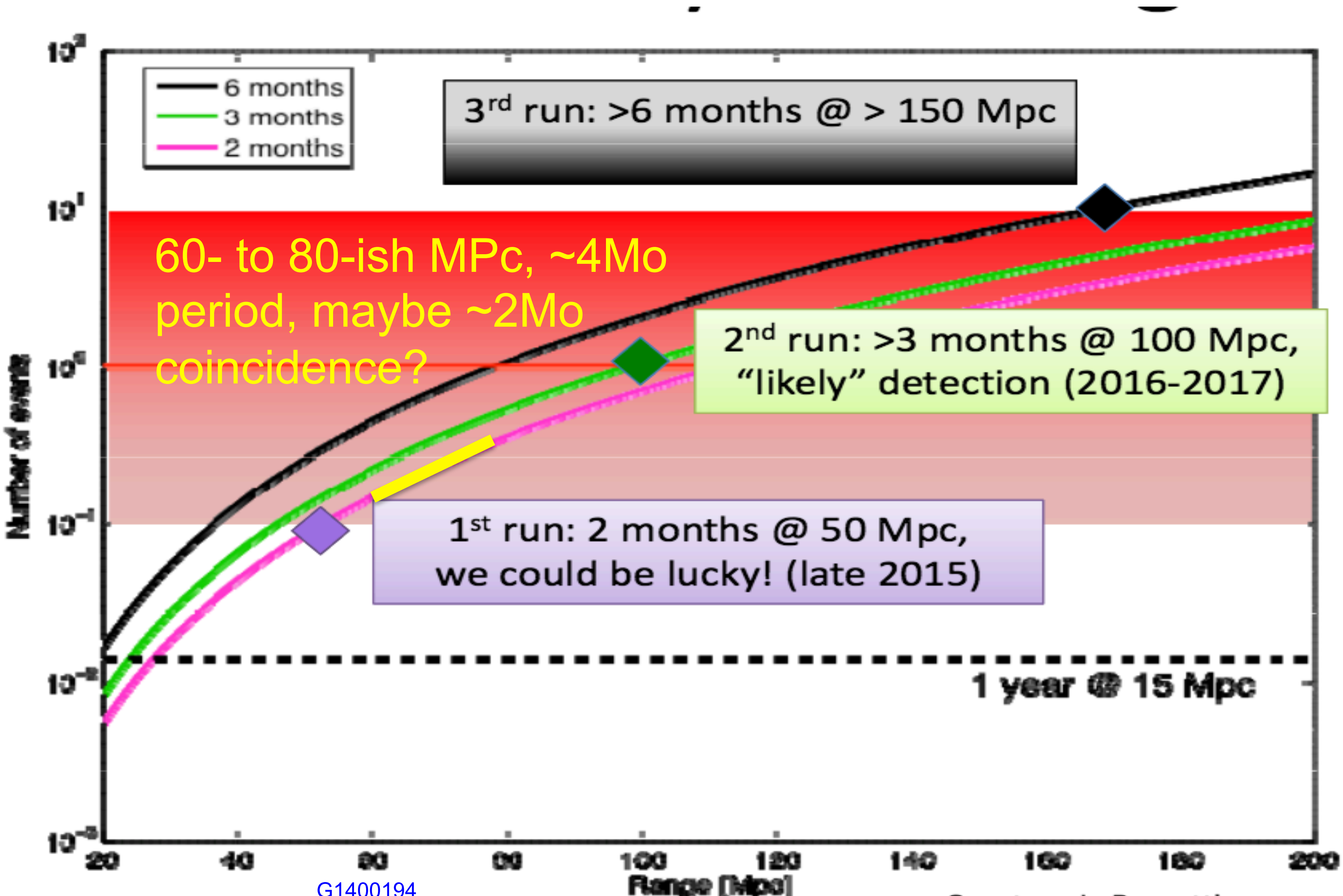


L1 Early O1 2015 (prelim)
H1 Early O1 2015 (prelim)
H1 S6 2010
aLIGO design, estimated fundamental noise (high power no detuning)
Factor of 3 to 5 improvement over 1st Gen @ 100-300 Hz.
N(events) ∝ volume ∝ reach^3
10 days obs > All 1st Gen obs combined!
equivalent strain [m/m]
Hz
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^1
10^2
10^3

O1, cont'd

- Non-negligible detection likelihood
  - Let's say NSNS merger happens 1/Mpc^3/Myear
    - "Realistic" (but uncertain) rate, LIGO-P0900125, arxiv 1003.2480
  - Observing with 60Mpc reach will give us roughly 1/year event. If our double IFO duty factor is ~50%, 4 month run will give us O(0.1) event.

O1, optimistic guess



G1400194

Courtsey L. Barsotti

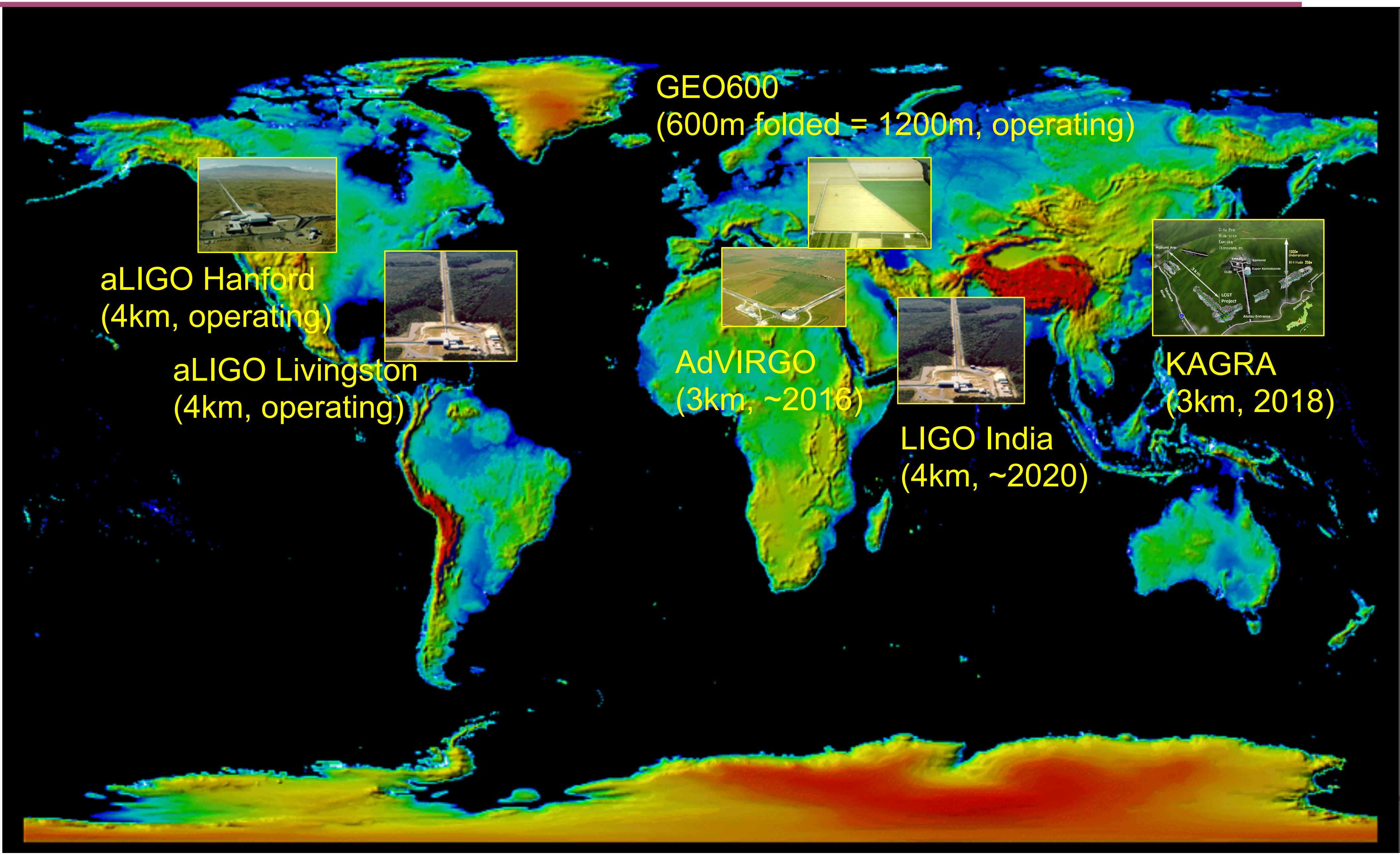
What happens in the future?

- LIGO repeats several upgrade-run cycles
  - Because, in reality, there are many many technical noise that need to be eliminated before we can enjoy the benefits of any upgrade.
  - Next upgrade before O2 will be the laser power (both), fixing Faraday (L1), and lots of technical noise hunting!
- O2: ~100 Mpc, >3 Months in 2016, O(1) expected event.
- O3: >150 Mpc, 6 Months, O(10) expected events.

And others will join soon!

- Advanced VIRGO
  - Installation/integration going on right now
  - First “lock” expected in spring 2016, hopefully join O2 later
- KAGRA
  - Underground@Kamioka
  - Cryogenic
  - Installing initial version. Final version 2018
- LIGO-India (will talk later)

Network of km-scale instruments

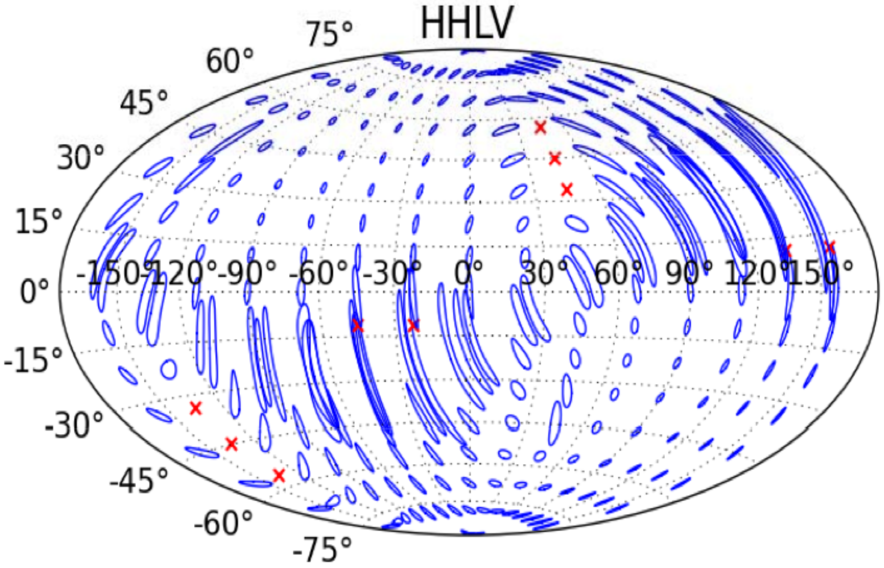


Do we need more than one instrument?

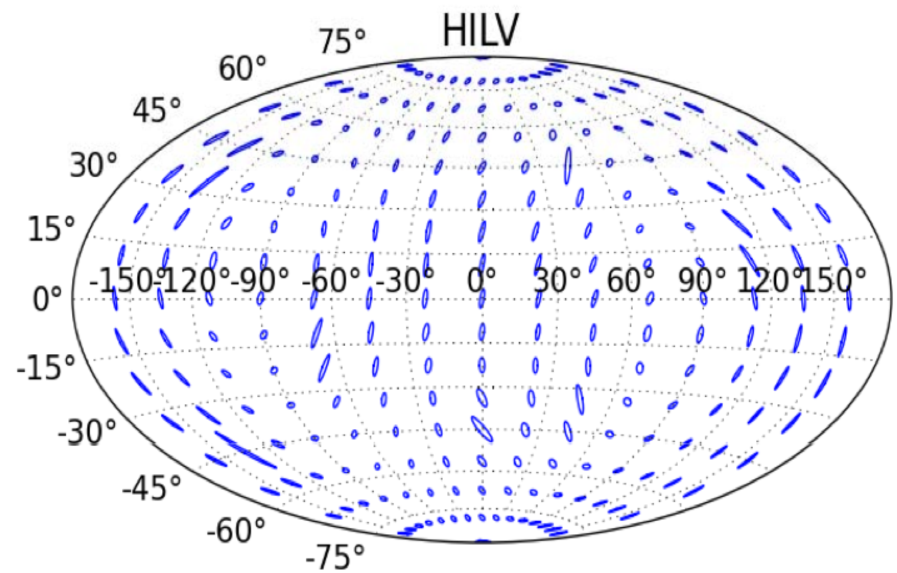
- It’s all about sky localization.
- Being an immobile “microphone”, each instrument cannot pinpoint the sky location of an event, even though it has an antenna pattern.
- Need three instruments for triangulation.
  - Each IFO has its antenna pattern as well as polarization sensitivity, so it’s more than triangulation.
- The more instruments out of a plane we have, the tighter the sky localization.

That's where LIGO India comes in

- Localization with Hanford, Livingston and Virgo



- Localization with Hanford, Livingston, India and Virgo



LIGO India

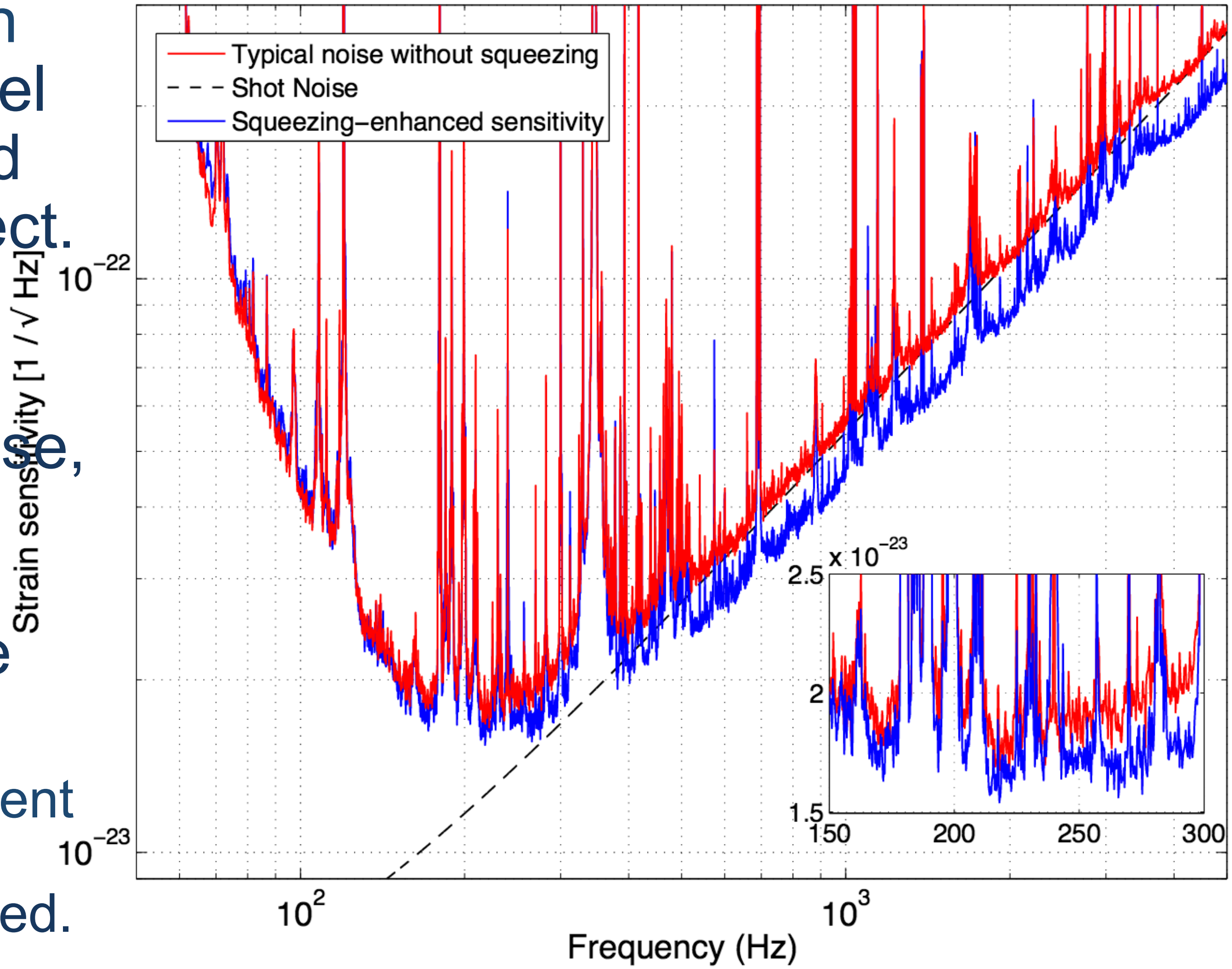
- LIGO US will provide components for one aLIGO instrument
  - Components were put on storage at LHO.
- LIGO India will provide facility, staffs and operating funds through 2026
- Expected to come online ~2020
- Awaiting for final approval by Indian government
- http://gw-indigo.org

And then? We'll go 3rd Gen.

- Manipulate quantum noise by using non-classical field: Squeezing
  - Simple squeezing demonstrated on GEO and then iLIGO.

Squeezing demonstration in initial LIGO: Technology is there.

- 2+ dB decrease in the shot noise level was demonstrated without any ill effect.
- But simple squeezing means smaller phase noise, larger amplitude noise i.e. larger radiation pressure noise.
  - Frequency-dependent squeezing will eventually be needed.



And then? We'll go 3rd Gen.

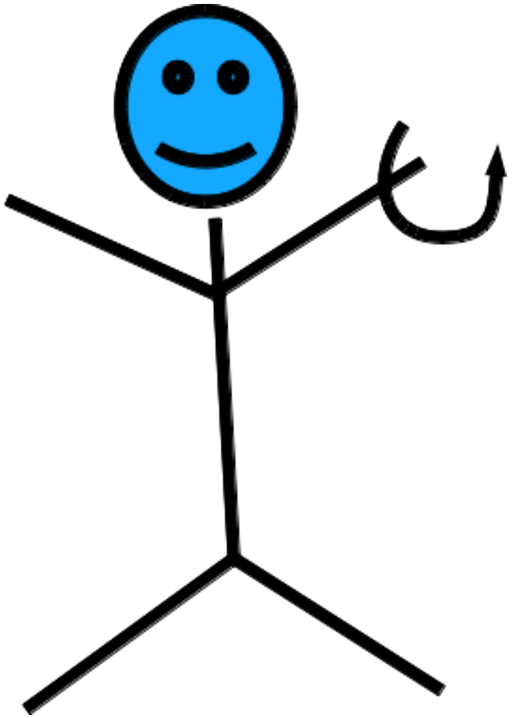
- Manipulate quantum noise by using non-classical field: Squeezing
  - Simple squeezing demonstrated on GEO and then iLIGO.
  - Potential near-term upgrade for aLIGO.
  - Non-simple squeezing a must-have for 3rd-gen.
  - N. Mavalvala talk on Wed.
- Design studies going on
  - Einstein Telescope in Europe, http://www.et-gw.eu/
  - LSC AIC working group on near, mid and long term LIGO path, e.g. LIGO-T1500290.
  - The reach of z>O(10) for BNS doesn't seem to be impossible (!!).

Summary

- Interferometer technology is maturing, allowing us to operate km-scale instruments reliably with unprecedented sensitivity.
  - Current aLIGO: NSNS 40 to 60-80Mpc (preliminary), will reach 150-180Mpc by 2019, some O runs in between.
- First detection imminent.
- A new window for astronomy/astrophysics will be opened by world network of 2nd Gen instruments.
  - aLIGO, AdVIRGO (2016), KAGRA (2018), LIGO India (2020)
- 3rd Gen instruments being envisioned and studied.

Appendix

Live long to emit GW!



$L_{int} = M\, l^{2} w^{3}/24$ → Misner, Thorne and Wheeler "Gravtitation" p979, for rotating beams

M=10 kg (!!!)
l = 1 m
w = 2*pi*3 Hz (!!)

$L_0=c^5/G=3.53\ 10^{59}$ erg/sec
$L_{out} \sim (L_{int}/L_0)^2 L_0 \sim 2\ 10^{-39}$ erg/sec
$E_{graviton}=hf=6.62\ 10^{-27}$ erg sec x 3 Hz ~ 2 x 10^{-26} erg

emission rate = $L_{out}/E_{graviton} \sim 10^{-13}$ /sec

~ 3 x 10^{-6} / year

First Prototype GW IFO

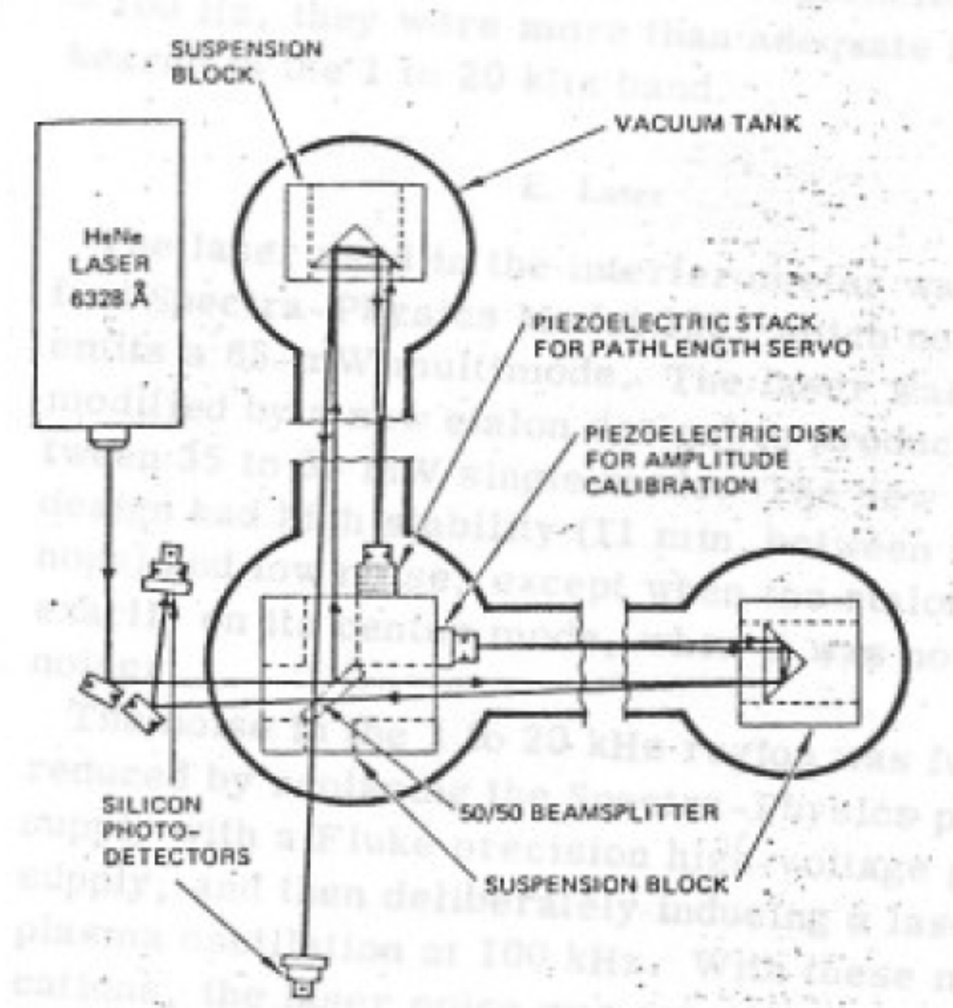
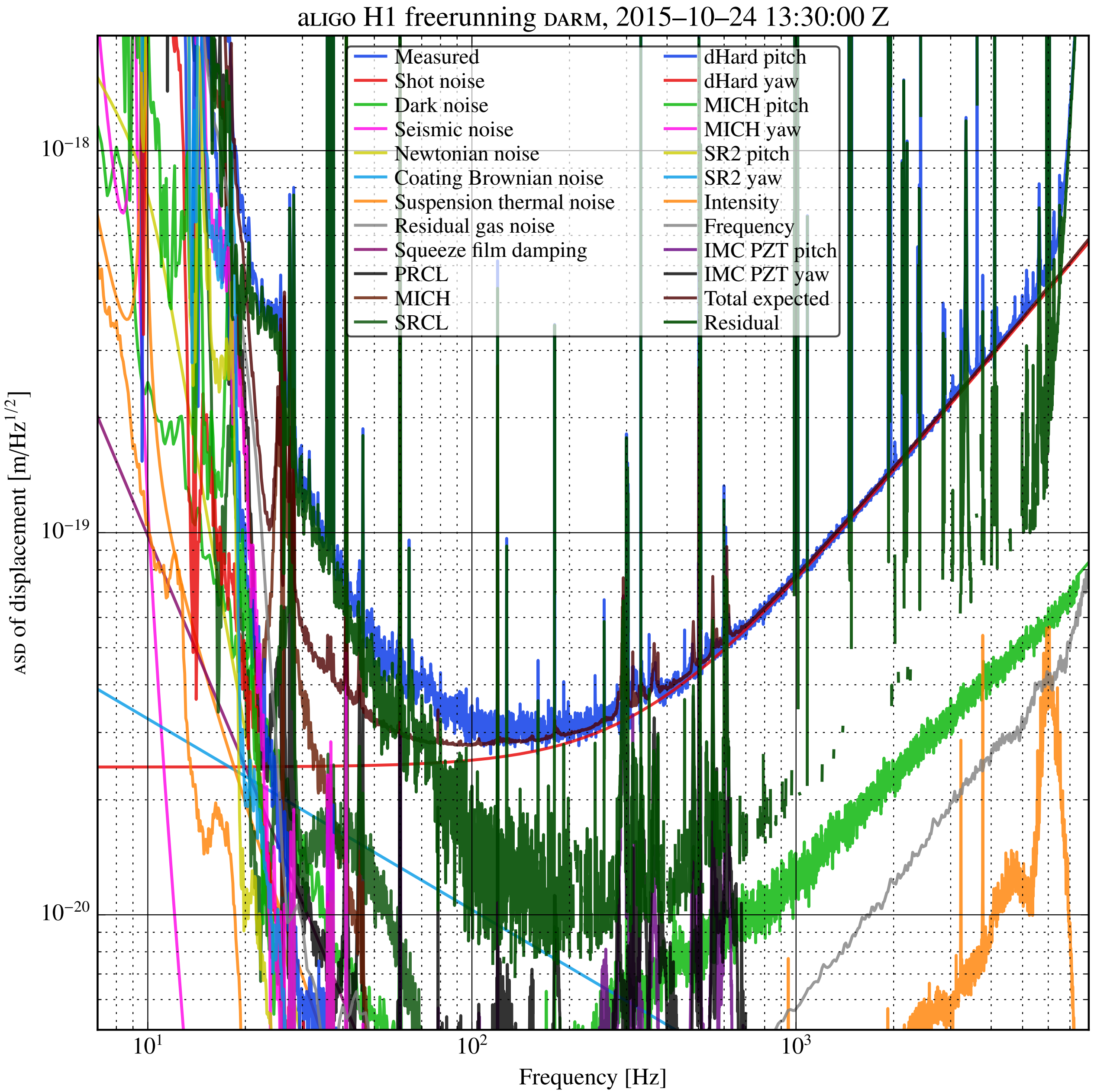


FIG. 7. Schematic of folded optical path.

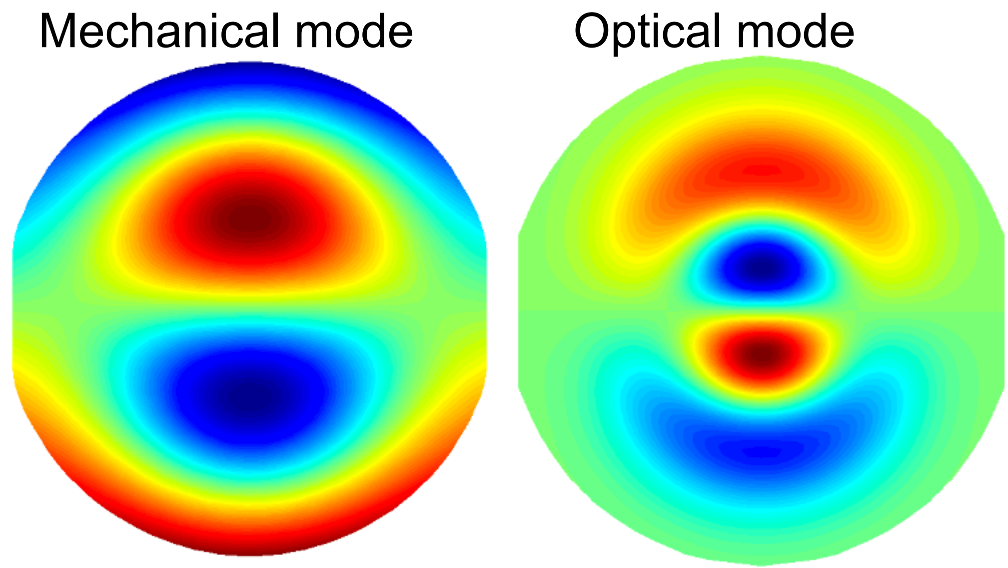
- 1972, proposal by R. Weiss
- 1978, implementation (R. L. Forward)
- Simple Michelson, 2m arm (folded, 4.25m path)
- 35-55mW laser
- Strain~O(10^{-16}) /sqrt(Hz) @ ~kHz

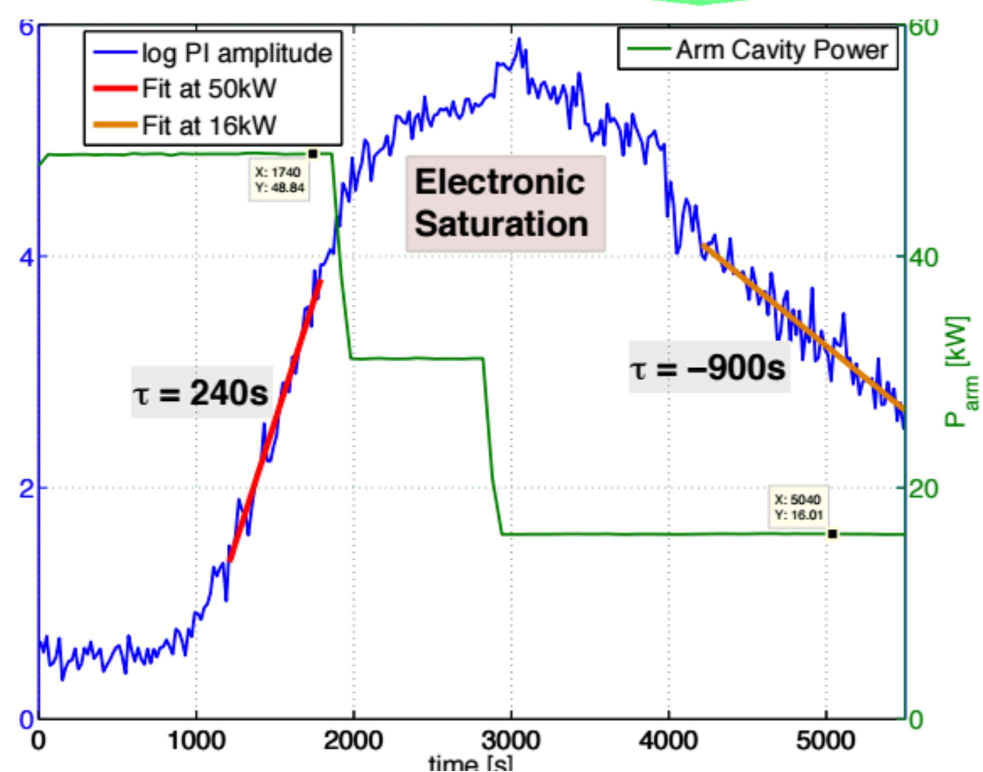
IFO noise in reality: Technical Noise



Parametric Instability

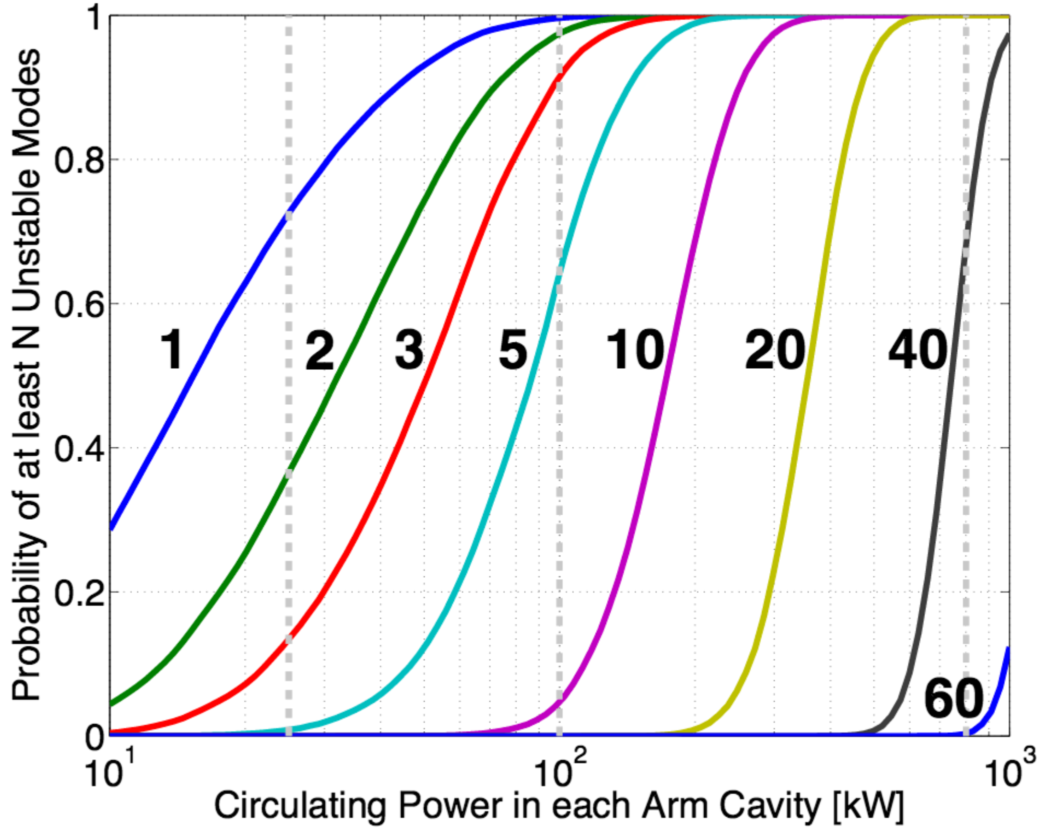
- First observed at L1, then H1 at about 15kHz
  - 100kW in each arm
- https://dcc.ligo.org/P1400254
- Mitigation strategies:
  - Thermal tuning for now.
  - Fast DAQ for single mode damping via ESD.



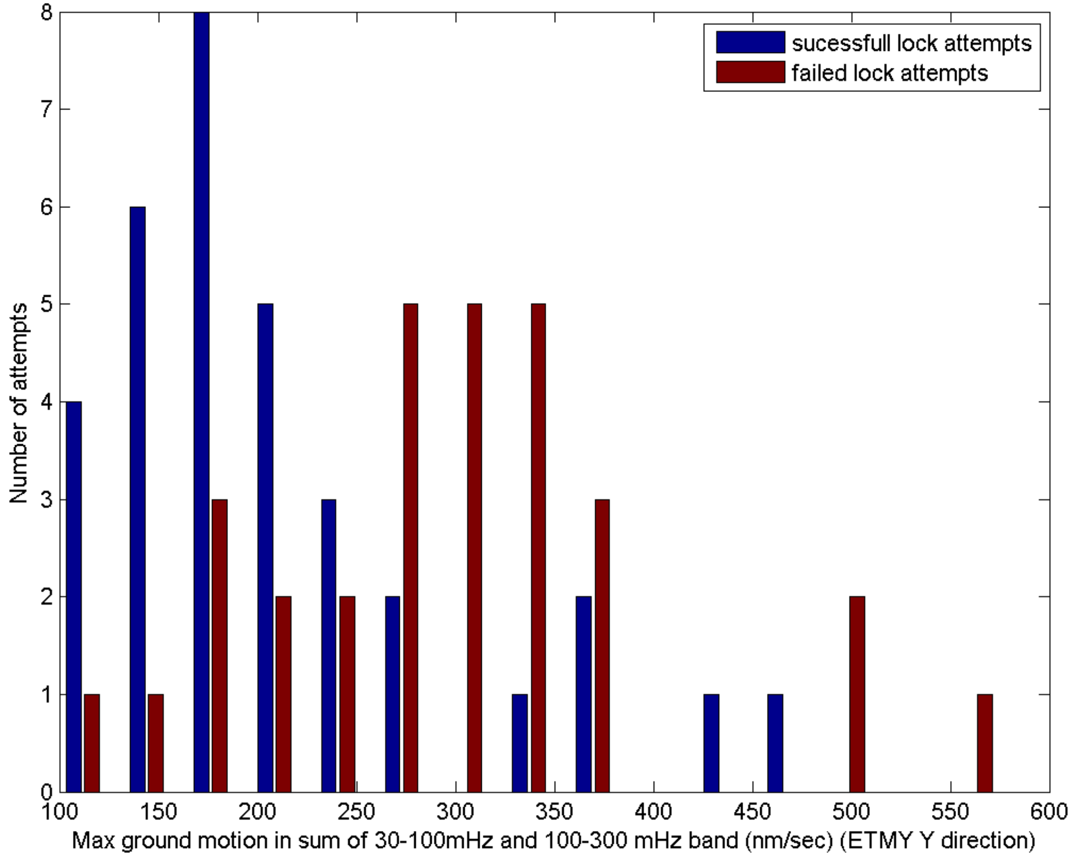


PI, cont'd

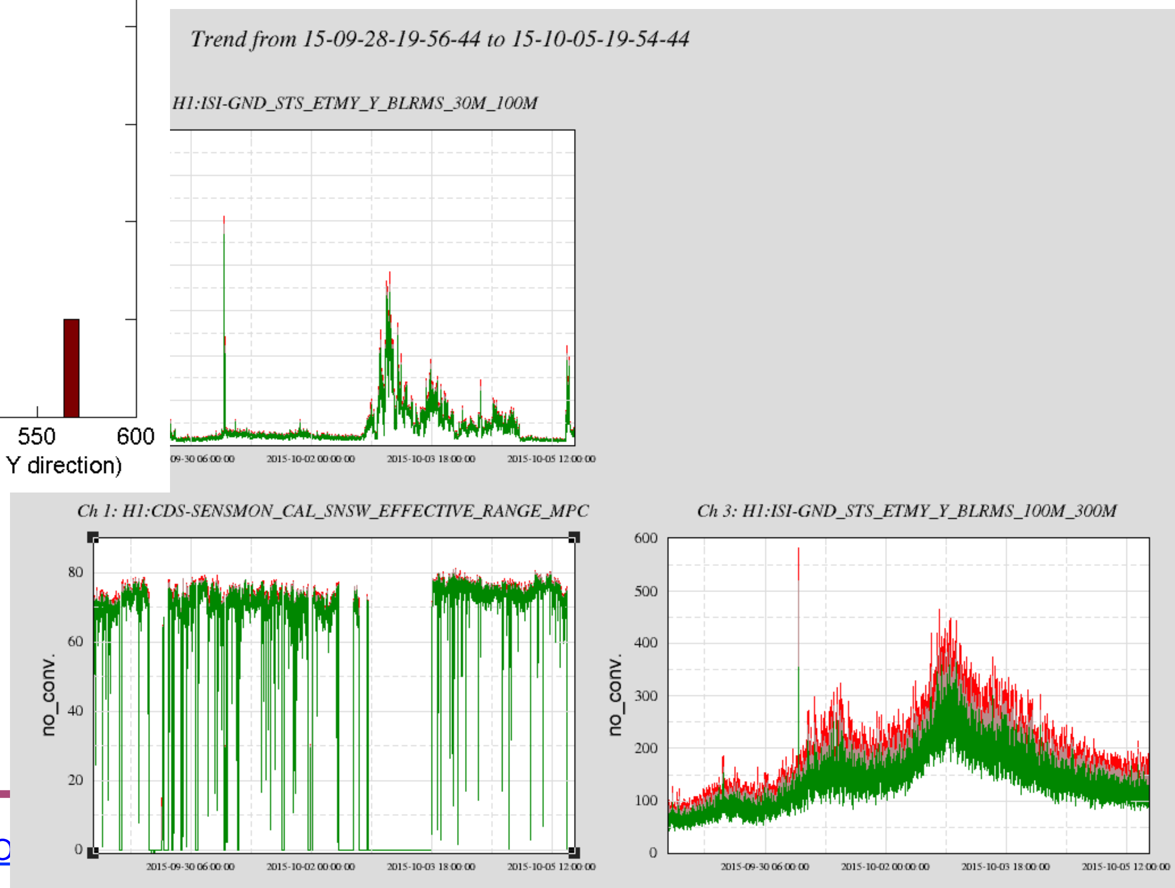
- We cannot operate IFO with full designed power without doing something.
- In the future, resonant damper on the TM to absorb the mechanical energy of offending modes.



Lock acquisition success rate is a function of seismic level



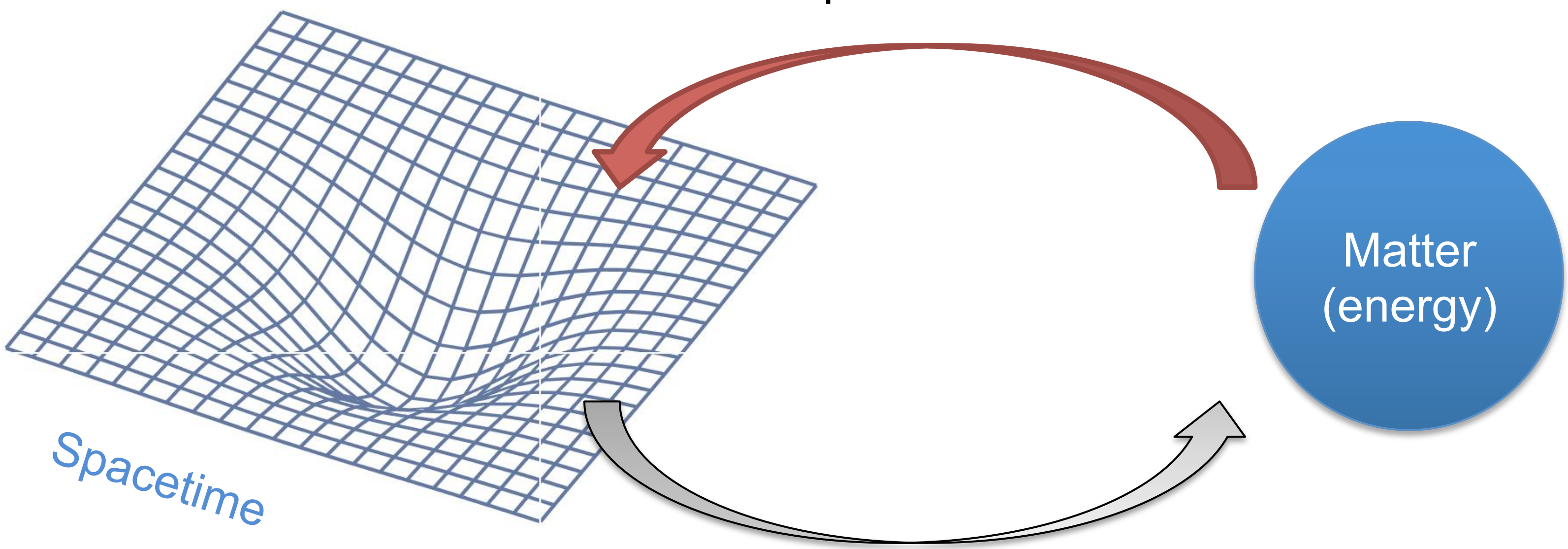
- This is from early O1, but no fundamental change up to now



General Relativity, Spacetime and Matter

$$G_{\mu\nu} = 8 \pi T_{\mu\nu}$$

Matter “tells” spacetime how to curve



Spacetime “tells” matter how to move