Interferometer Commissioning Challenges

Rana Adhikari (Caltech / LIGO)
IUCAA, Aug 2016

Outline

- Overview of Commissioning
- Commissioning Timeline
- Challenges
- Path Forward for India

What is Commissioning?

- All of the pieces have been installed
- Sub-system engineers have completed testing
- The some magic happens
- GW signals begin appearing in the data stream

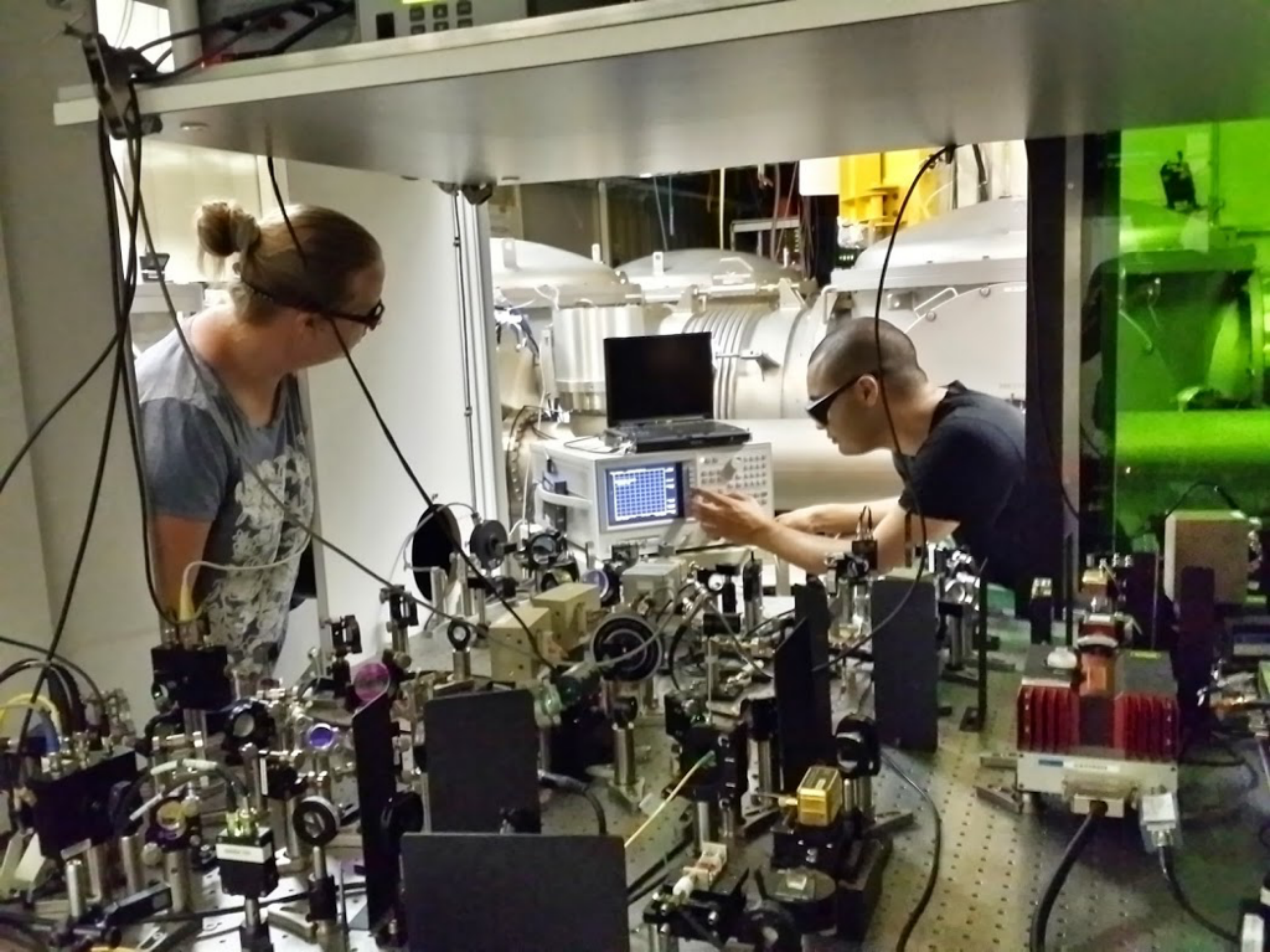
Mainly technicians;
a few engineers

Engineers & Technicians:
+ visiting experts

~2 Experienced Physicists,
+ ~5 postdocs & students
+ +1-2 **superstars**

People

- Daniel Sigg: HEP PhD. PD @ MIT in GW (1997). Head of LHO (1999) Commissioning.
- Keita Kawabe: U Tokyo PhD. PD @ Tokyo, GEO. LHO (2004)
- Valera Frolov: HEP PhD and PD. Head of LLO (2002) Commissioning.
- **Kiwamu Izumi**: PhD @ TAMA & CIT. PD @ LHO (2011)
- **Jenne Driggers**: PhD @ CIT. PD @ LHO (2015)
- **Denis Martynov**: PhD @ CIT / LLO (2013 - 2015)
- **Evan Hall**: PhD @ CIT. LHO (2014 - 2016)
- **Sheila Dwyer**: PhD @ MIT (squeezing 2009-2013). PD@LHO
- **Ryan Derosa**: PhD @ LSU. PD @ LLO (2012)
- **Anamaria Effler**: PhD @ LSU. PD@LLO(2012)
- **Keiko Kokeyama**. PhD @ NAOJ. PD Birmingham. PD LSU/LLO (2010-2014)

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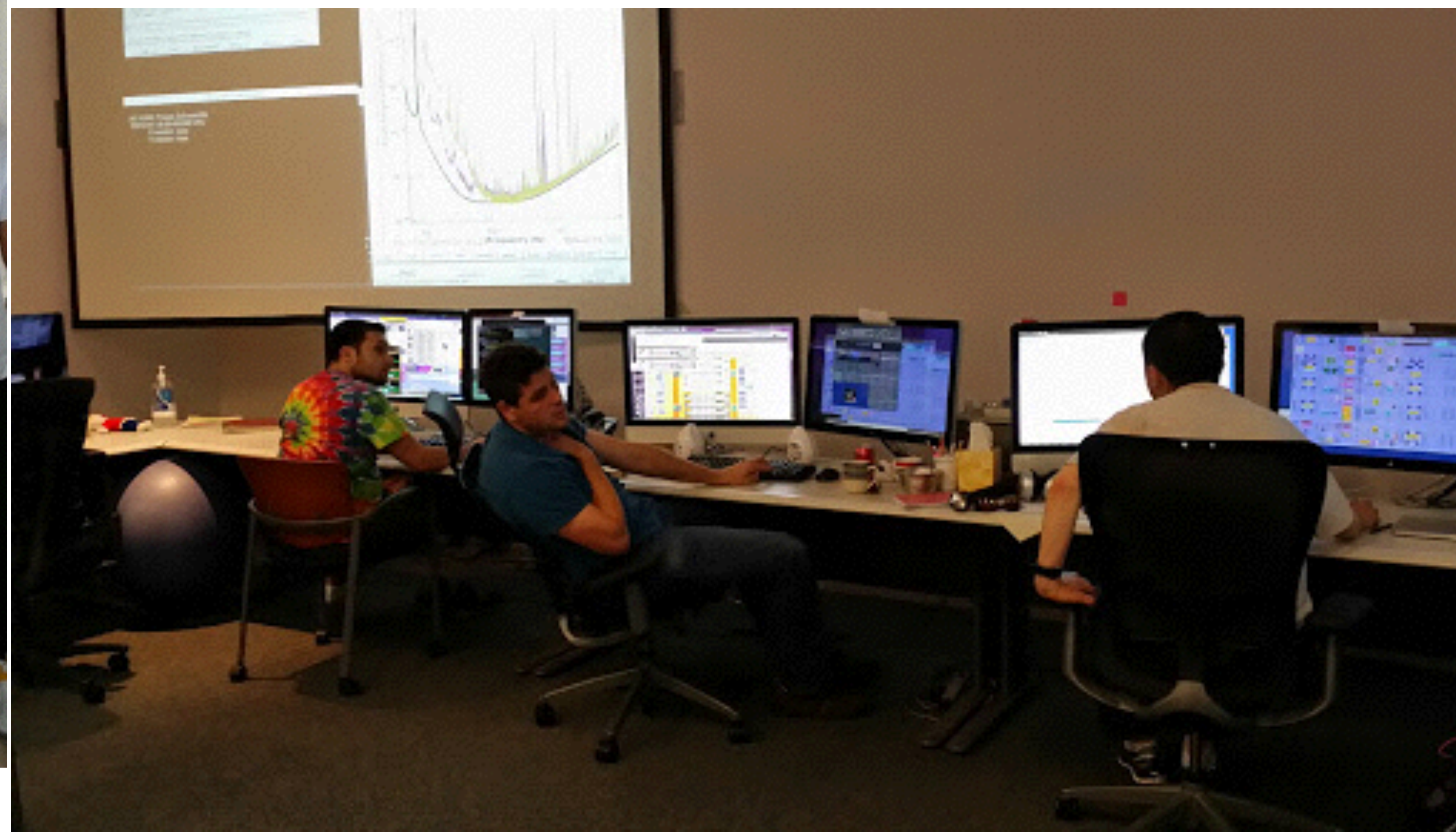
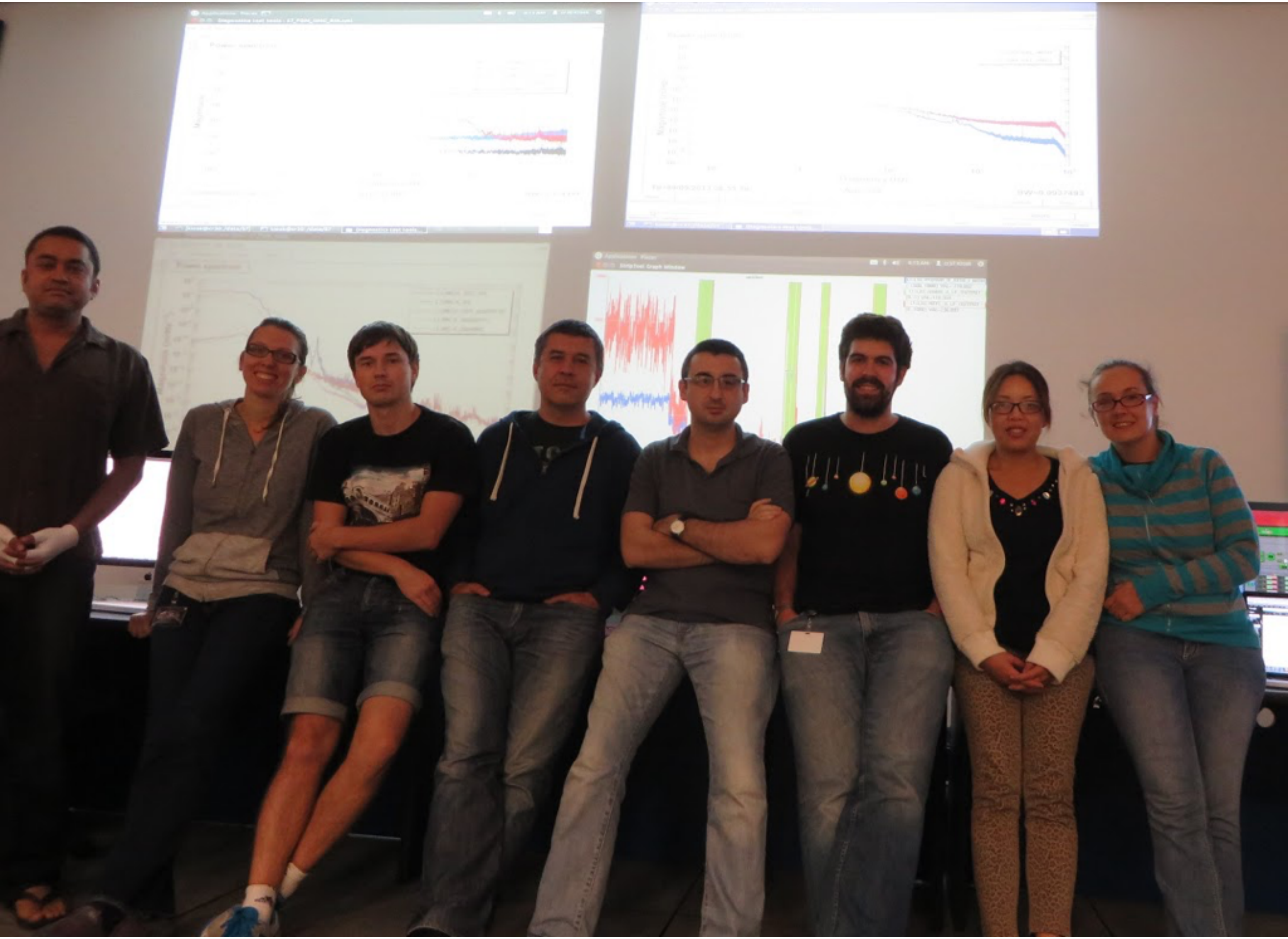
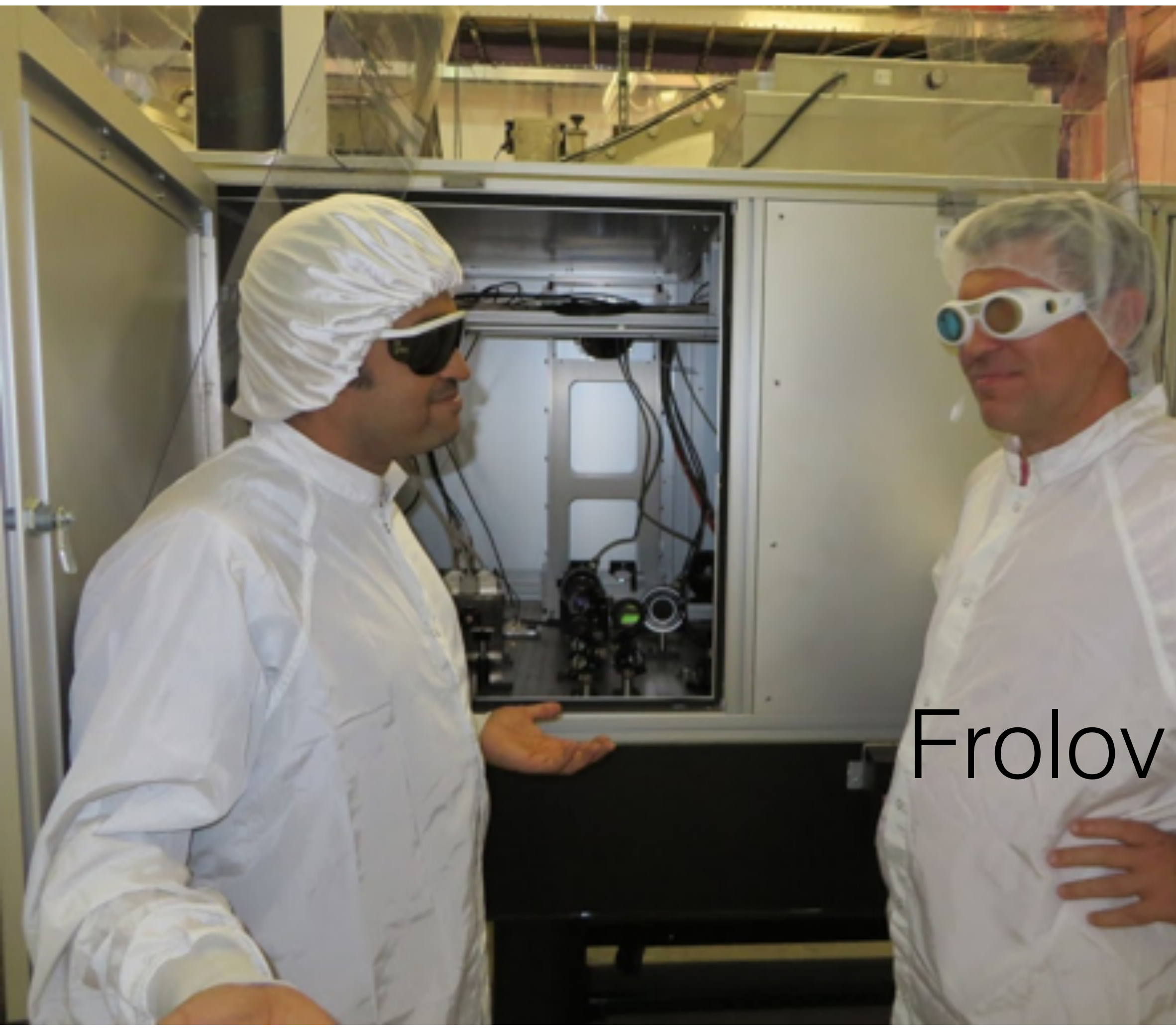
COLLASSO





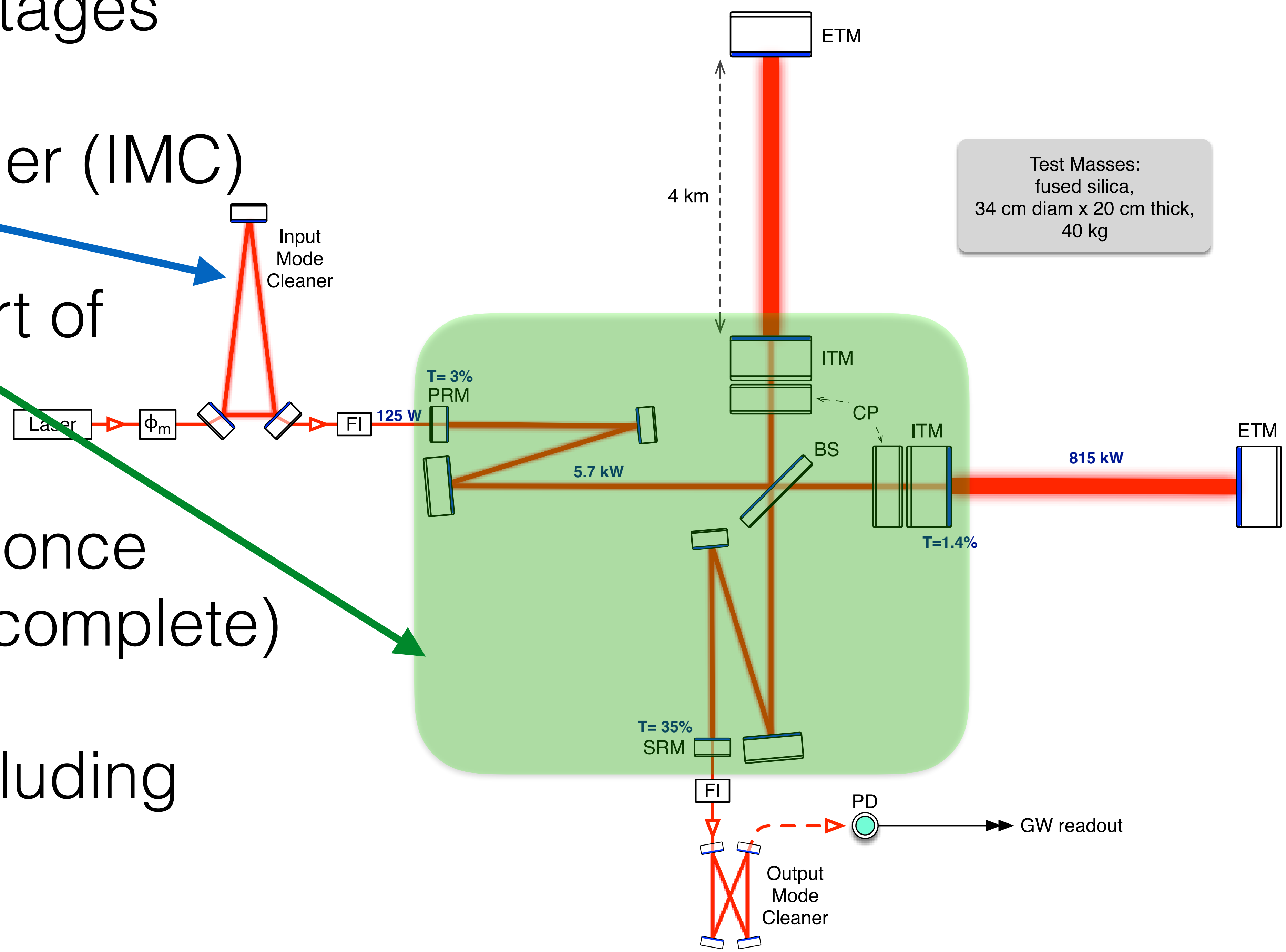

PACIFIC
CENTRAL
GMT
RESOURCES
PEOPLE
THINGS
ILLINOIS

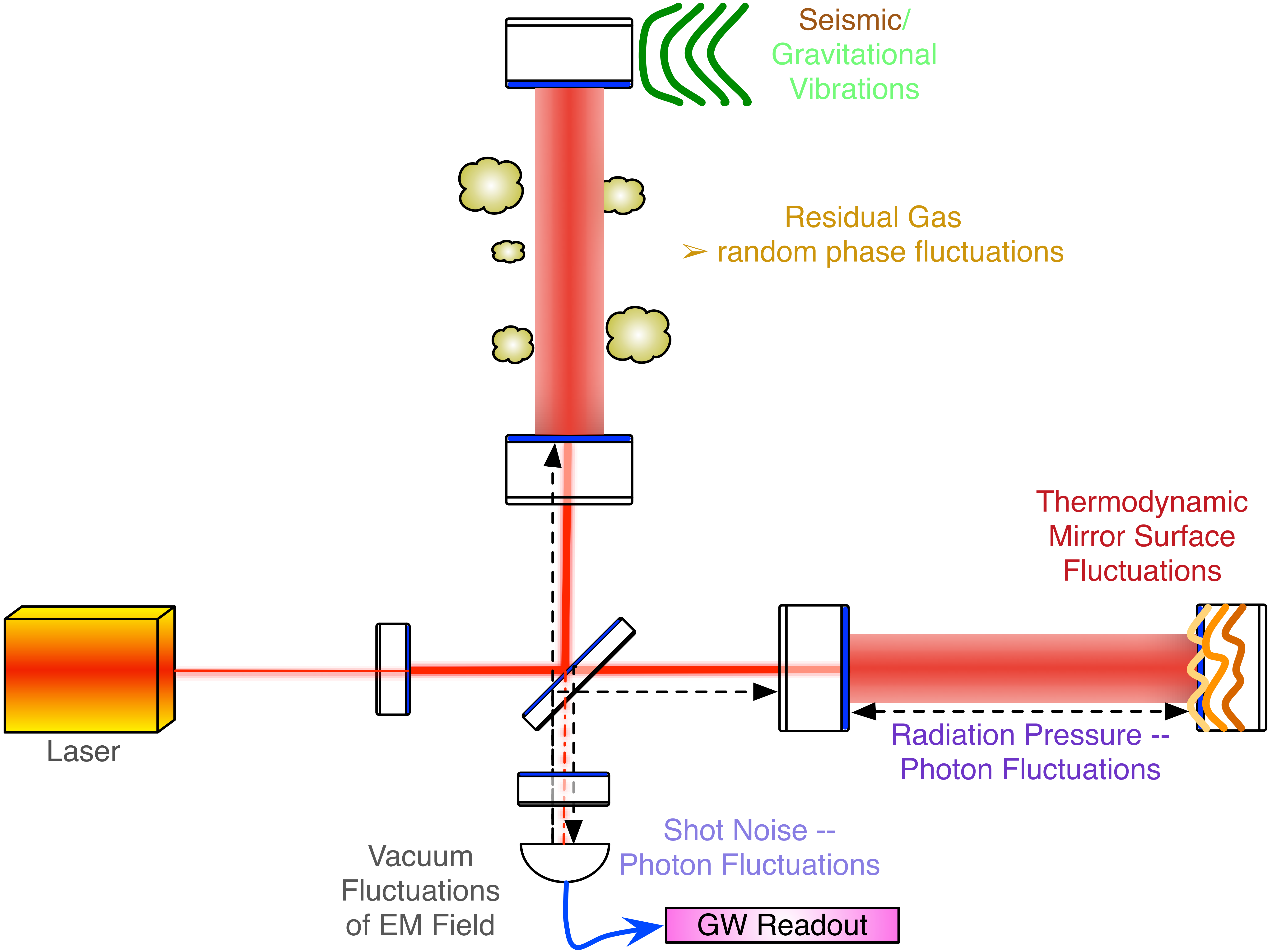

Frolov

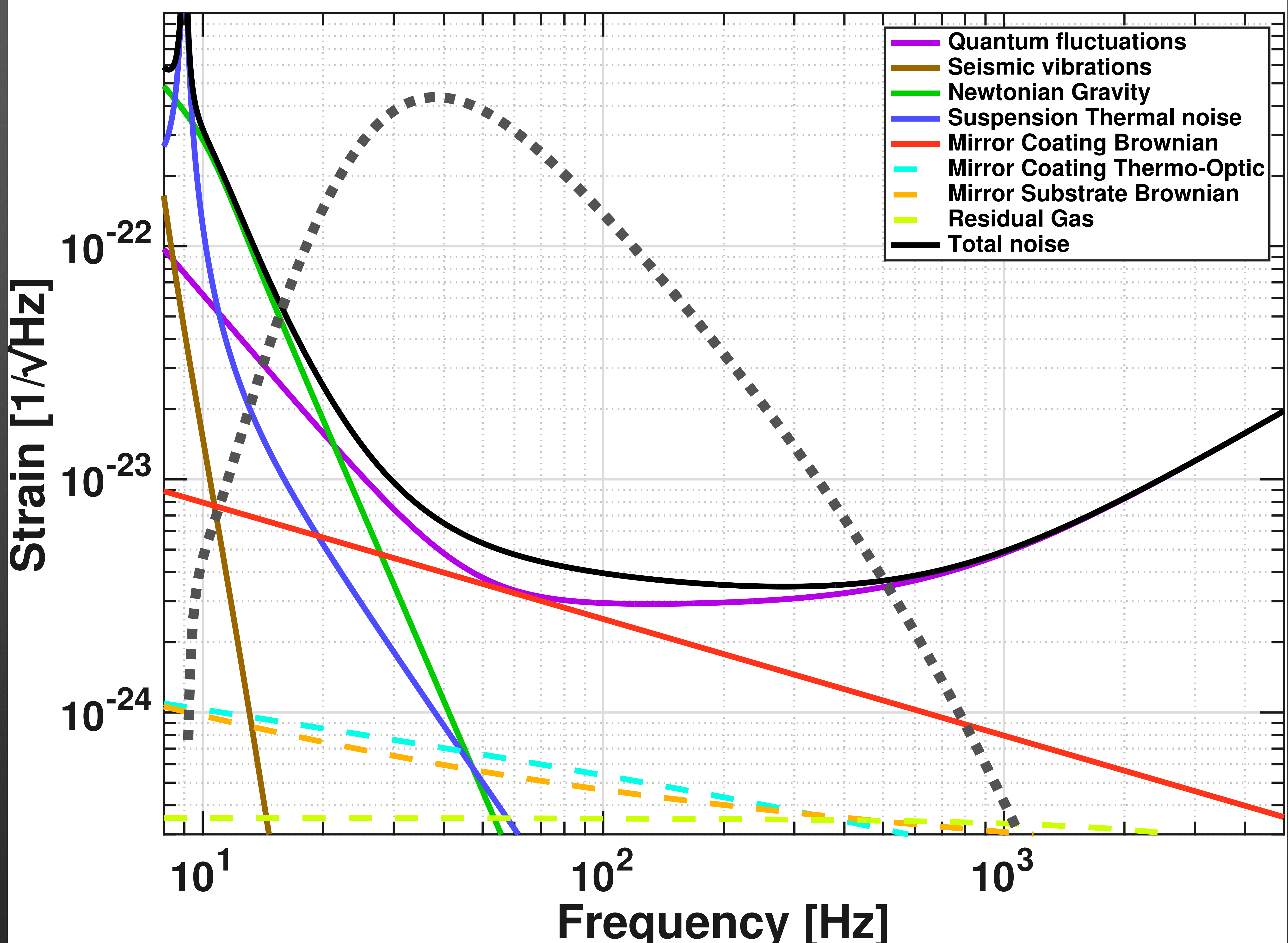

Sigg

What is Commissioning?

- Can proceed in stages
- Input mode cleaner (IMC)
- DRMI (central part of interferometer)
- Each arm cavity (once tube pumping is complete)
- Output chain (including OMC)



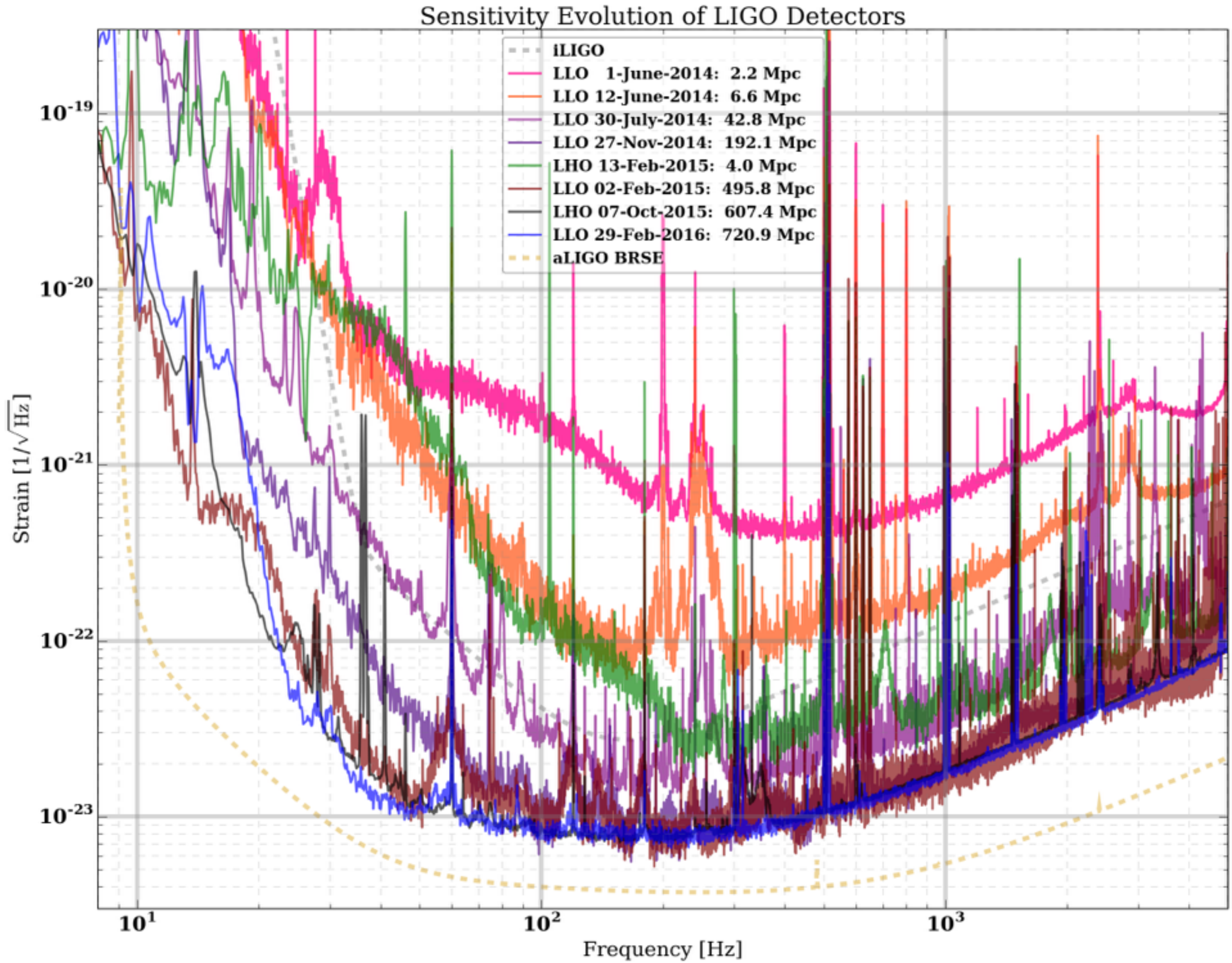

Seismic/
Gravitational
Vibrations
Residual Gas
➢ random phase fluctuations
Thermodynamic
Mirror Surface
Fluctuations
Laser
Radiation Pressure --
Photon Fluctuations
Shot Noise --
Photon Fluctuations
Vacuum
Fluctuations
of EM Field
GW Readout



Quantum fluctuations
Seismic vibrations
Newtonian Gravity
Suspension Thermal noise
Mirror Coating Brownian
Mirror Coating Thermo-Optic
Mirror Substrate Brownian
Residual Gas
Total noise
10^{-22}
10^{-23}
10^{-24}
Strain [1/√Hz]
10^{1}
10^{2}
10^{3}
Frequency [Hz]

Commissioning Schedule

- DRMI: LLO ~ 1 year, LHO ~ 1 month
- **Green** Arms: LHO ~1 year, LLO ~1 month
- 0-60 Mpc: LHO/LLO ~ 7 months

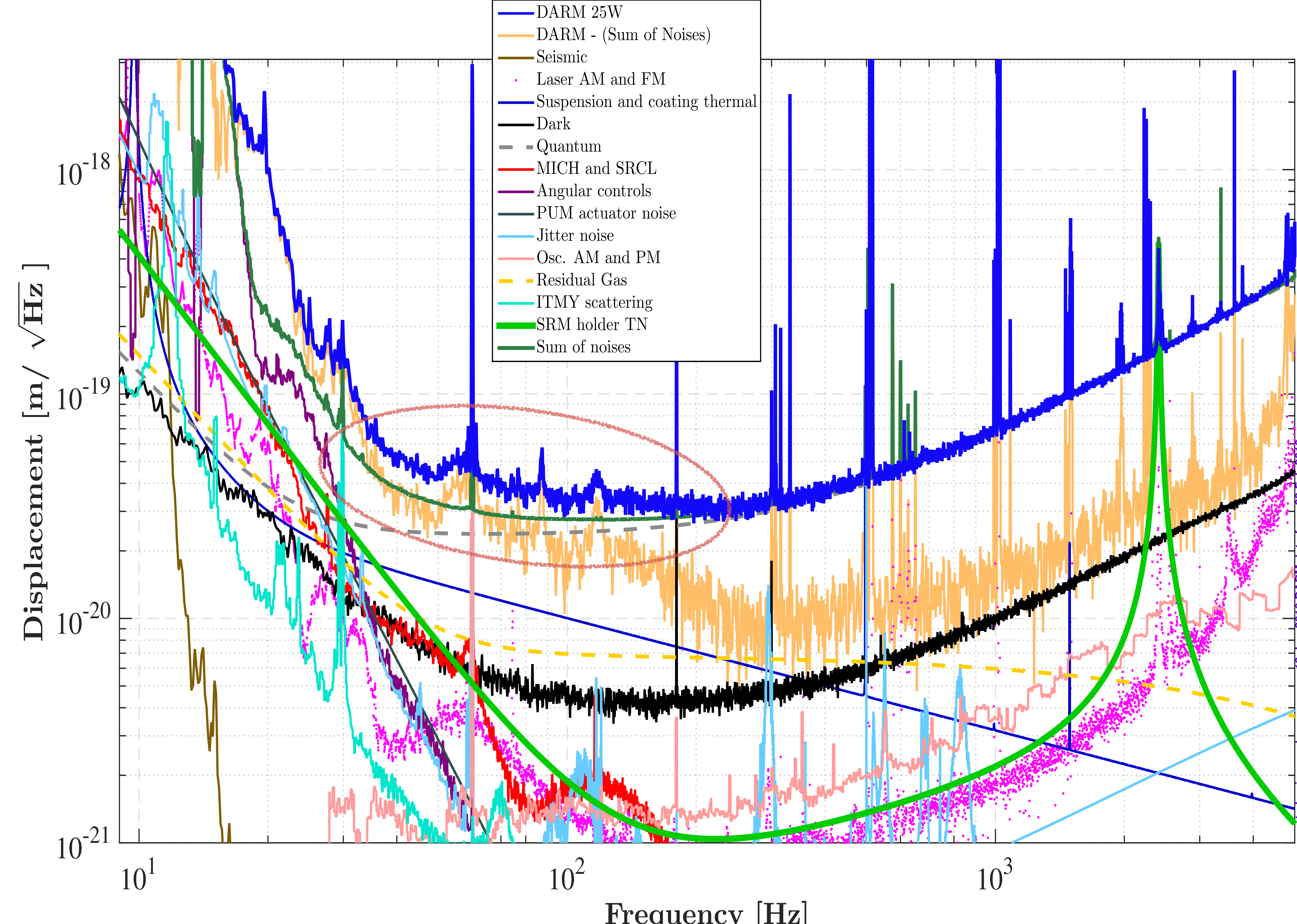


Sensitivity Evolution of LIGO Detectors
iLIGO
LLO 1-June-2014: 2.2 Mpc
LLO 12-June-2014: 6.6 Mpc
LLO 30-July-2014: 42.8 Mpc
LLO 27-Nov-2014: 192.1 Mpc
LHO 13-Feb-2015: 4.0 Mpc
LLO 02-Feb-2015: 495.8 Mpc
LHO 07-Oct-2015: 607.4 Mpc
LLO 29-Feb-2016: 720.9 Mpc
aLIGO BRSE
Strain [1/√Hz]
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{1}
10^{2}
10^{3}
Frequency [Hz]

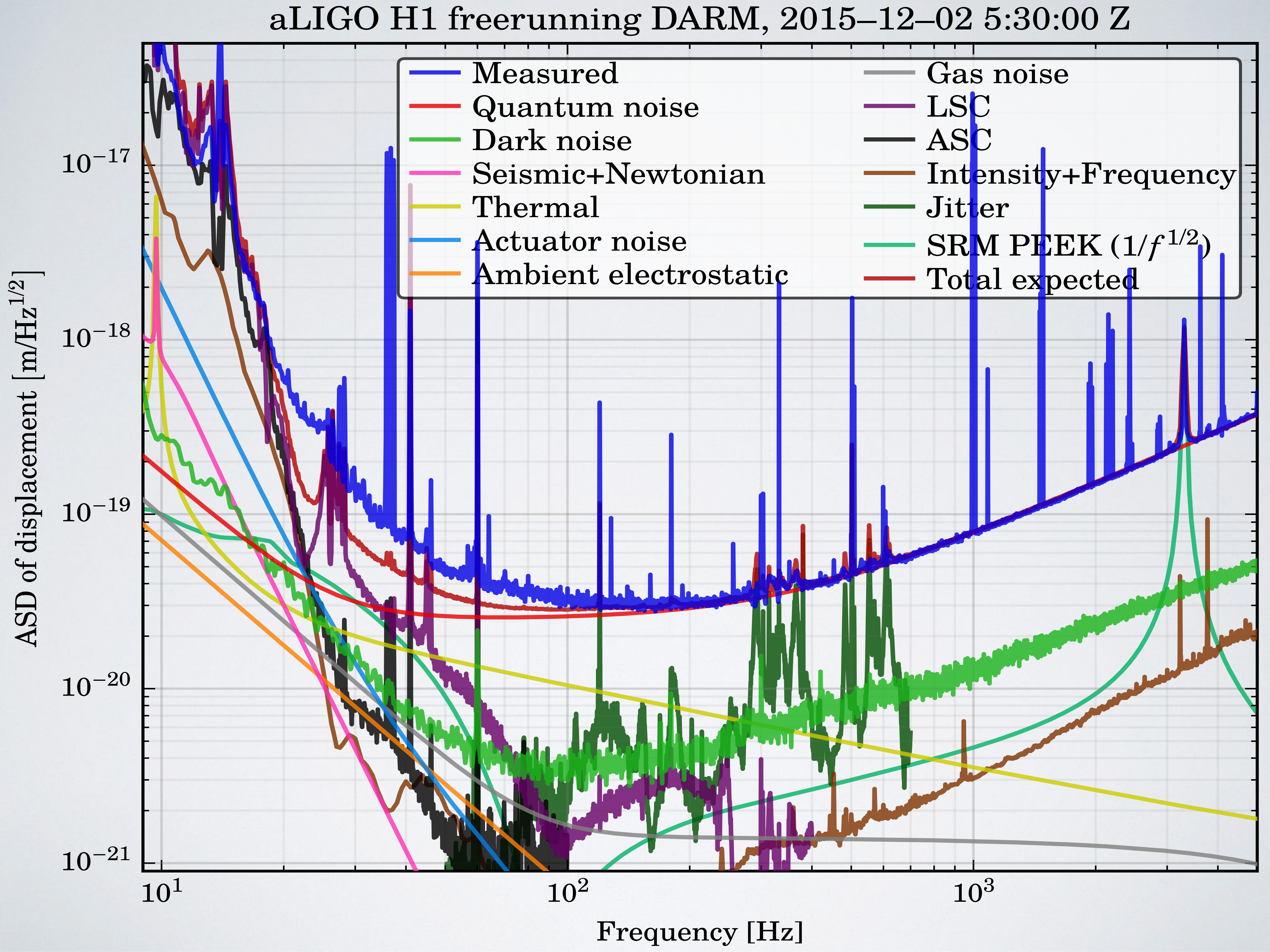

Sources of Environmental Noise
Seismic
Anthropogenic
Radioactive Vitrification Plant
Pine Forest Logging
Trains
Hydro Electric Dams
HVAC Turbulence
Nearby Traffic
Distant Earthquakes 10-100 mHz
Earth Tides
Sun
Moon
Ocean Wave Microseismic
Mt. Saint Helens
Magnetic
Facilities /HVAC Power
Lightning
Solar Flares
Ionospheric Resonances
Lightning
Overhead Power Transmission Lines
Acoustic
Airplanes
Building HVAC
Newtonian Gravity
Atmospheric Pressure
Seismic
Rayleigh Waves
Body Waves
Building Vibrations
HVAC Fans
Walls
Animals
Bumblebee
Cow
Deer

Commissioning Issues

- ETM Coating Transmission: noisy ALS system
- Undamped suspension Vertical modes: many hours each day to damp them
- Decay of PMC
- 3-f RFPD electronics saturations / redesign
- Frequency Dependent balancing of the suspensions: still not complete
- Weather: Rain/Wind make initial lock near impossible
- Backscatter of Light: its everywhere
- Thermal AO / Mode Matching
- Unstable Signal Cavity; Alignment Issues
- Mystery Noise: still mysterious

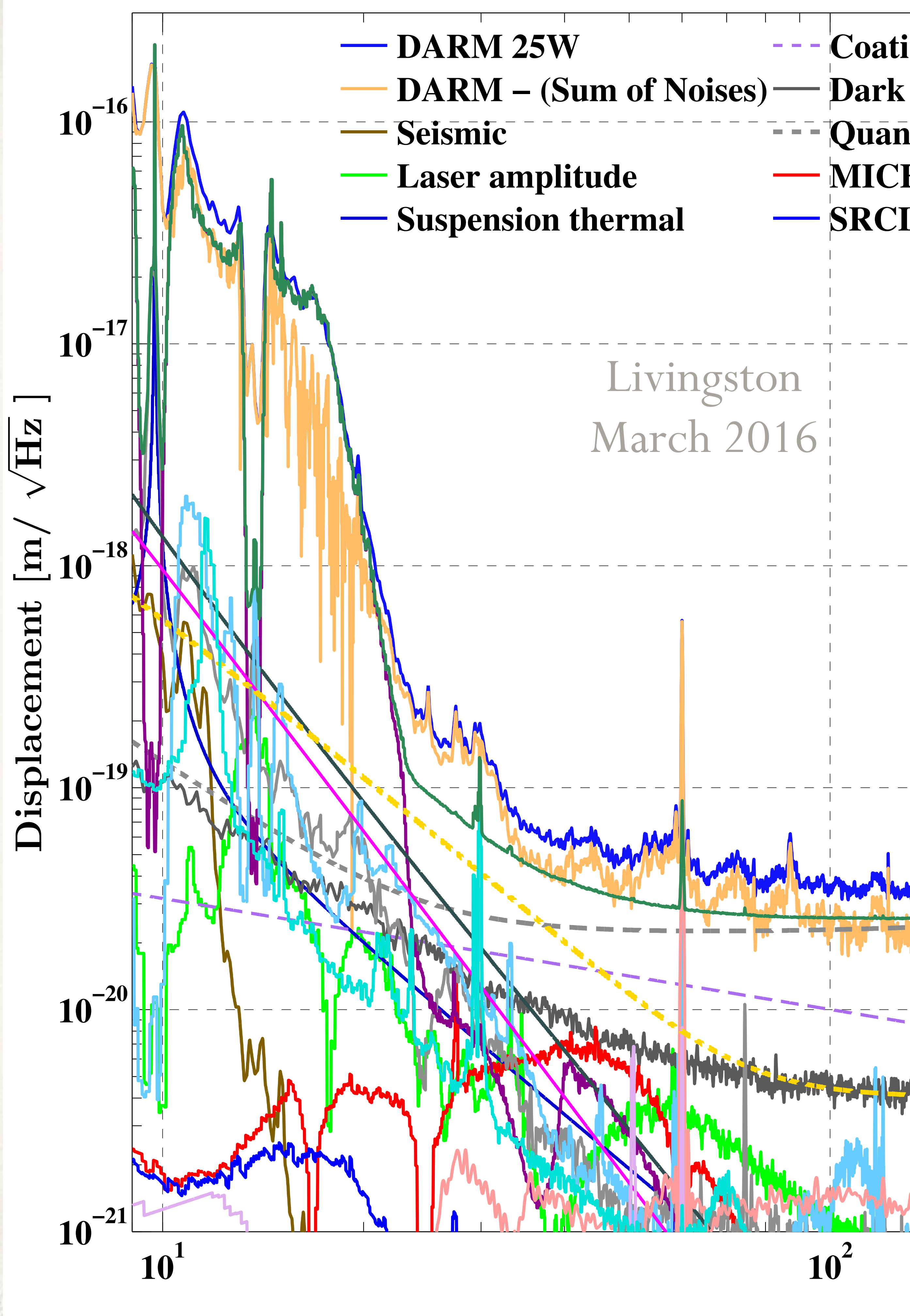


by R. deRosa: LLO budget; Feb 23, 2016 w/ SRM thermal noise estimate added


aLIGO H1 freerunning DARM, 2015–12–02 5:30:00 Z
Measured
Quantum noise
Dark noise
Seismic+Newtonian
Thermal
Actuator noise
Ambient electrostatic
Gas noise
LSC
ASC
Intensity+Frequency
Jitter
SRM PEEK ($1/f^{1/2}$)
Total expected
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
ASD of displacement [m/Hz$^{1/2}$]
10^{1}
10^{2}
10^{3}
Frequency [Hz]

LIGO Angular Controls

- 10-25 Hz dominated by ASC noise injection
- 500x higher than Quantum
- Why?
  - Higher WFS noise (40x & 200x)
  - Bad sensor mixing matrix ?
  - **Higher UGF (yes)**
  - **Higher Length -> Angle coupling**
  - Bad LP filter (yes)
  - Too much beam de-centering ?
- What do we do now?



Abbreviated List of Noise Investigations

1) Bi-/Linear coupling through LSC Aux. Loops
2) Bi-/Linear coupling through ASC noise (> 10 Hz)
3) Radiation Pressure anomaly
4) Laser frequency noise (~bilinear)
5) Laser amplitude noise (~bilinear)
6) Audio RAM from EOM
7) Gas Damping (between ERM and ETM)
8) ESD electronics
9) PUM coil driver electronics
10) Correlated noise in OMC PDs
11) Magnetic fields (~RF and baseband)
12) Electric fields in BSC chambers
13) Direct Seismic motion
14) Vac chamber motion (audio band)

1) Demodulation of f > 100 kHz laser noise to the baseband
2) SRM dummy thermal noise
3) Crackling mechanical noise in the blades of the Quad SUS
4) Excess thermal noise in the Quad monolithic stage (ears/ fibers)
5) TM HR coating Thermal noise
6) Aux / AR coatings (BS, SRC, ITM)
7) Scattering from Aux. chambers
8) Backscatter from the Beamtubes
9) PUM coil driver electronics
10) Magnetic fields (~RF and baseband)
11) Upconversion of LF Seismic
12) Pointing/Intensity noise of TCS lasers
13) TCS Ring heaters

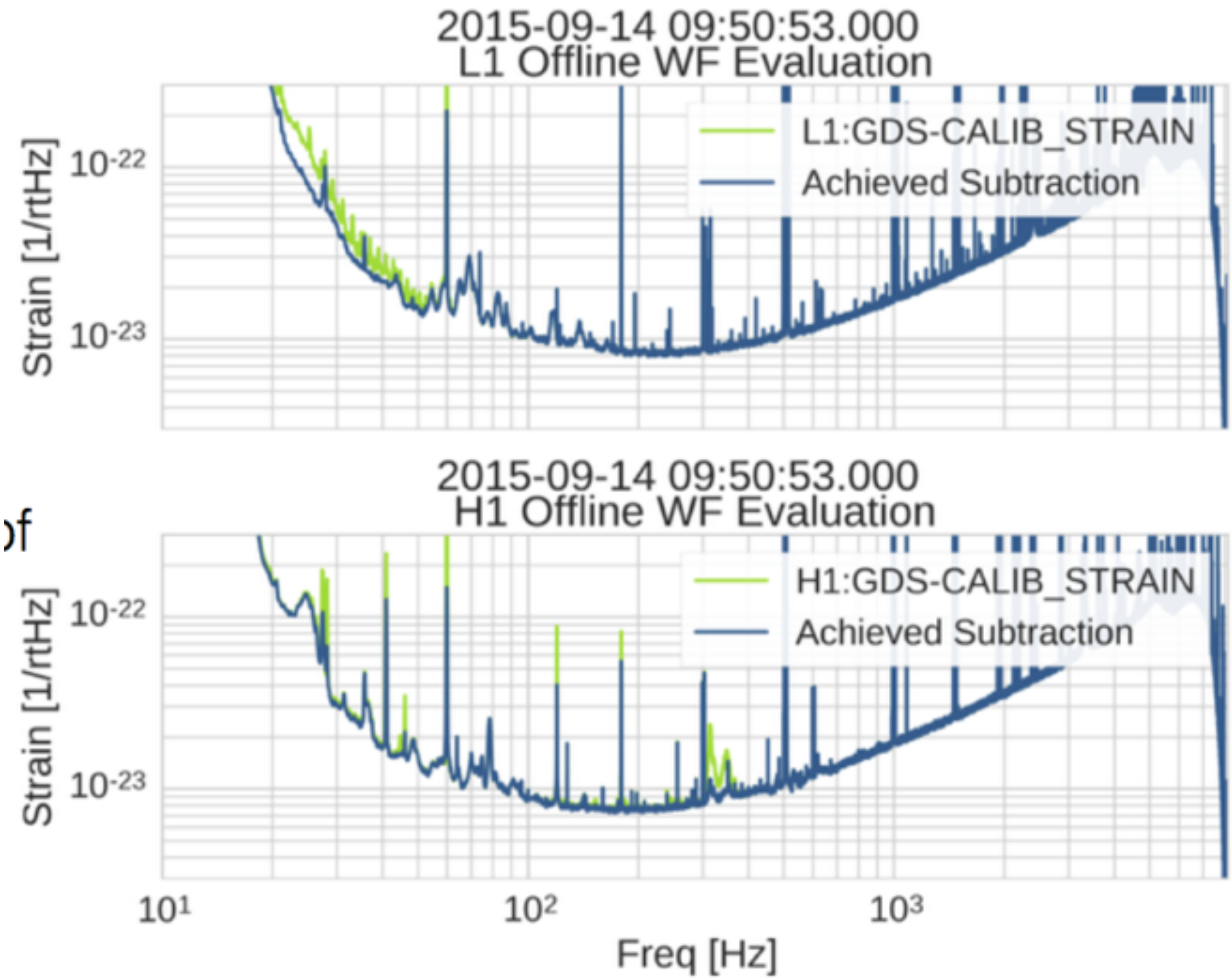
What Next?

Deep Learning

Deep Machine Learning?

- What problems do we want to solve which we cannot do yet?
  - Mystery noise, tilt-horizontal, angular noise,…
- What problems are already solvable but quite difficult?
  - Global feedback design, glitch classification
- Are there techniques out there?

- Linear & Bilinear subtraction
- removal of angular & environmental noise
- Why?
  - 6% higher SNR
  - 7% better BH Mass estimate
  - **Upper limit on BH bringdown**
- What do we do now?



by Eric Quintero (Caltech)

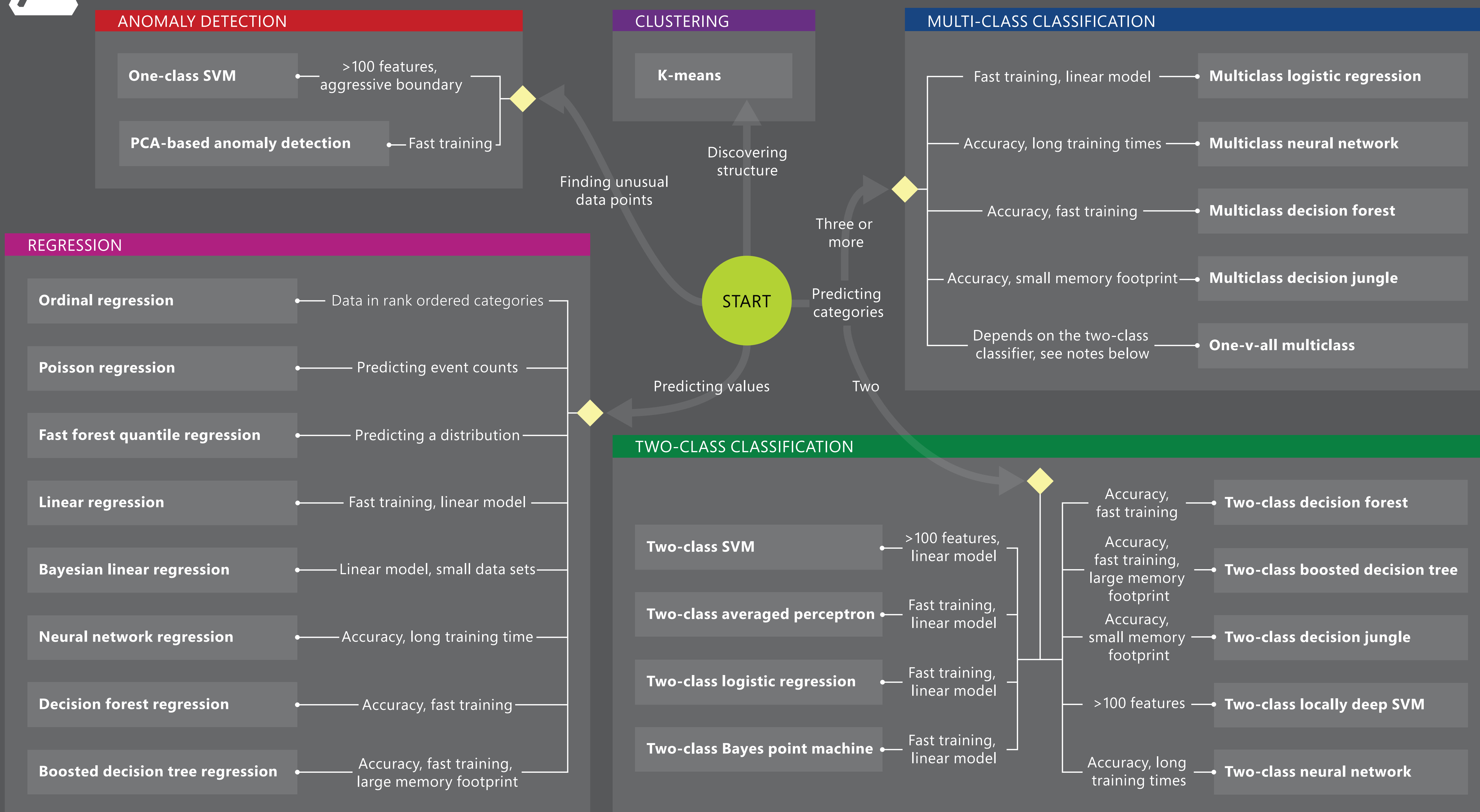

r = sin θ
it Retraces its steps

Some Dreams

- Use the flashing time series to learn how to lock the interferometer. Multiple error signals linearized.
- Use PEM signals to predict glitches
- Array of accelerometers/microphones to synthesize the scattered light noise
- Diagnose noisy states of interferometer before the operators. Send SMS to appropriate scientist.
- Predict imminent failure of facility systems with PEM + HVAC sensors. (power lines, weather, HVAC vibrations)
- Slow trends in backscatter or other couplings indicate device failures. (e.g. photodiodes, DACs, wires, laser alignments)
- poor operating decisions indicate operator is getting tired

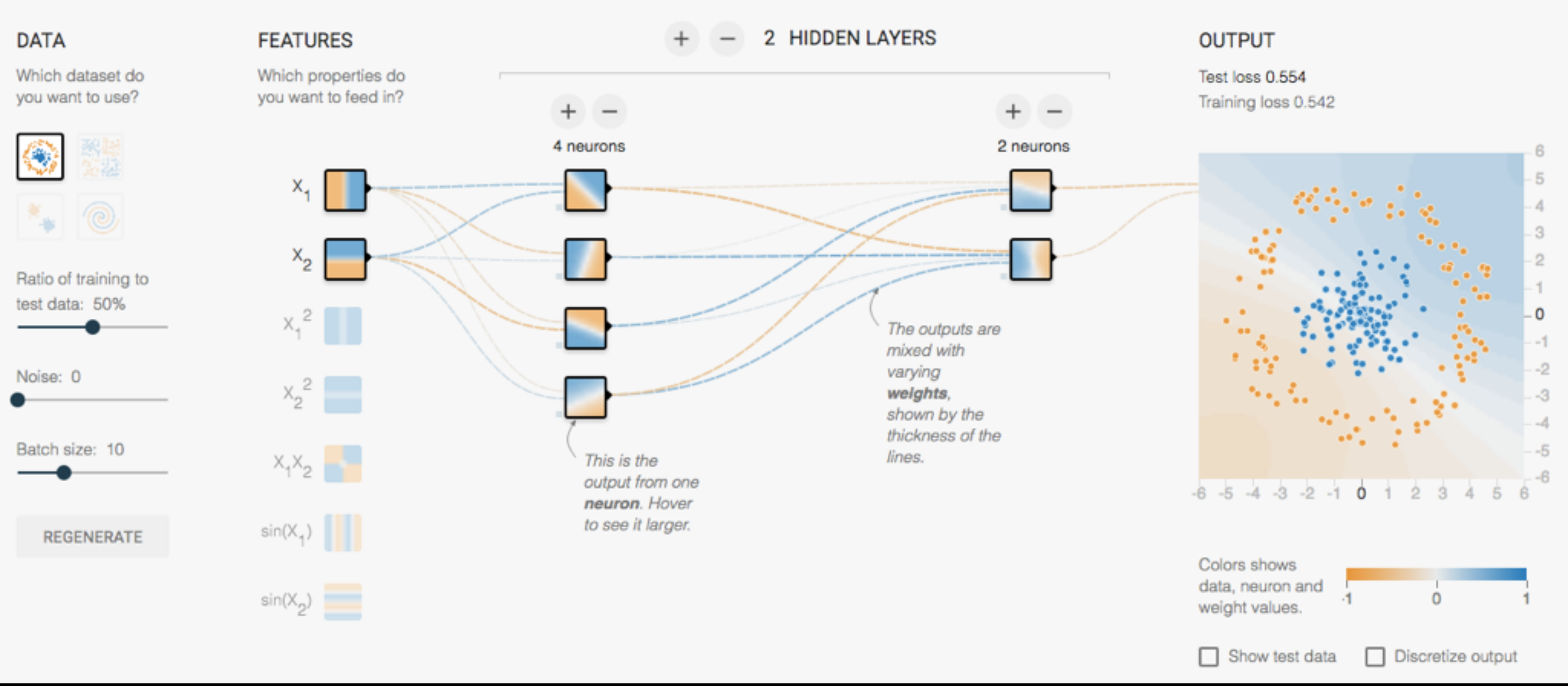
Microsoft Azure Machine Learning: Algorithm Cheat Sheet

This cheat sheet helps you choose the best Azure Machine Learning Studio algorithm for your predictive analytics solution. Your decision is driven by both the nature of your data and the question you're trying to answer.



Created by the Azure Machine Learning Team
Email: AzurePoster@microsoft.com
Download this poster: http://aka.ms/MLCheatSheet
Microsoft

Google TensorFlow

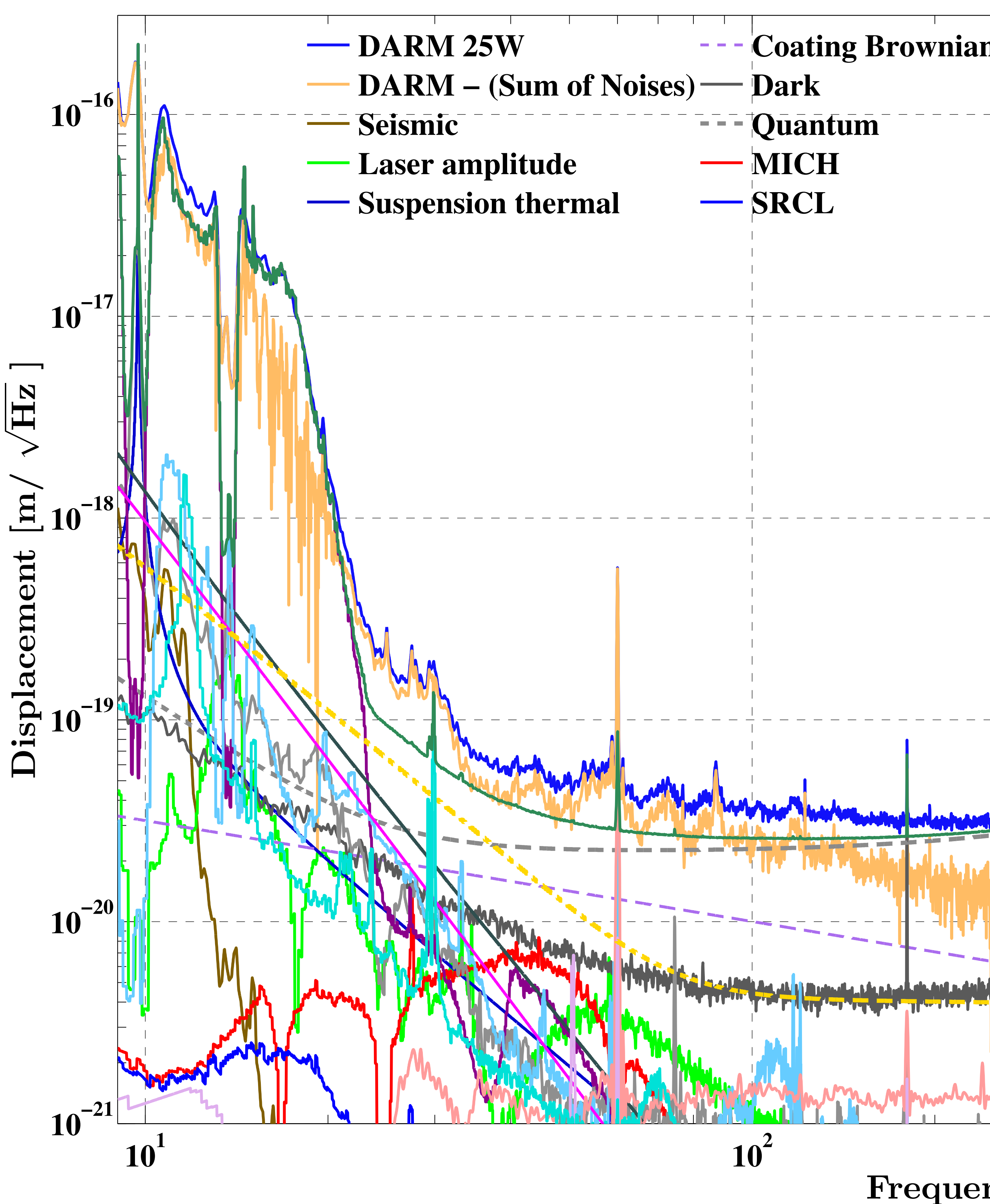


What ML techniques?

- Unsupervised Learning
  - only has input data (no target)
- Supervised Learning (includes all of MS Azure)
  - has both input and output (e.g. PEM & h(t))
- Reinforcement Learning
  - given knowledge of desired output states
  - algorithms learn how to move to desires based on inputs

Removing the Mystery Noise

- Many Noise problems eliminated
- All linear regression combinations checked
- Now testing some bilinear methods by brute force creation of pseudo channels
- Think we need more fully nonlinear estimator



Nonlinear Regression

- Volterra (1890) series representation; expanded by Wiener
- beyond linear regression; includes ‘by-hand’ nonlinear terms (e.g. higher order polynomials)
- kernel based methods, self generate basis
- L1 & L2 norms used to reduce complexity / sparseness