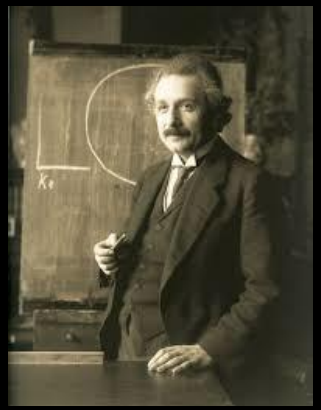
# Status of ground-based gravitational-wave detectors

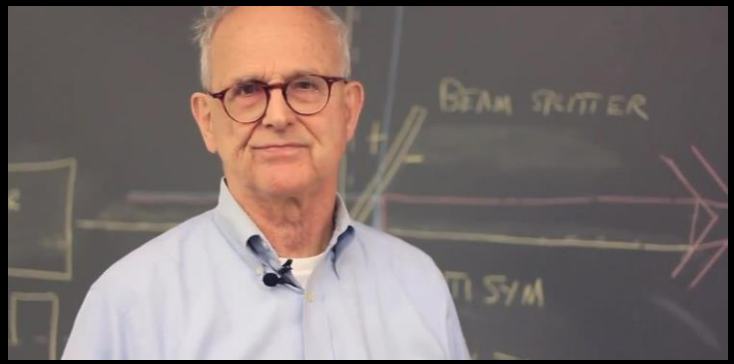
Nergis Mavalvala
MIT

TAUP, Vienna, August 2023

# Gravitational waves are…



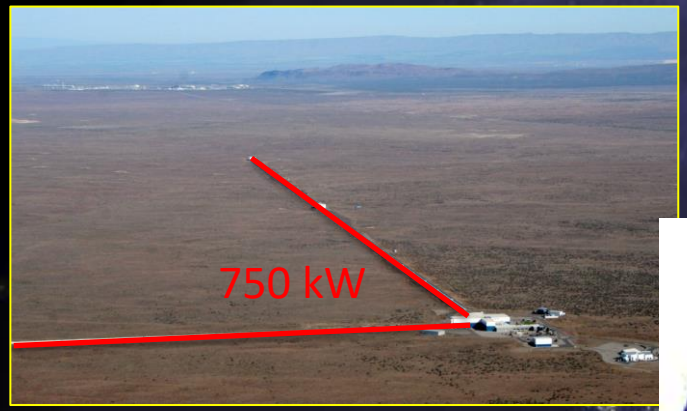
… ripples of spacetime, too faint to ever be useful [detectable] (1916)




… detectable, we just figure out how to measure changes in distance of $10^{-18}$ m (late 1960s and 1970s)

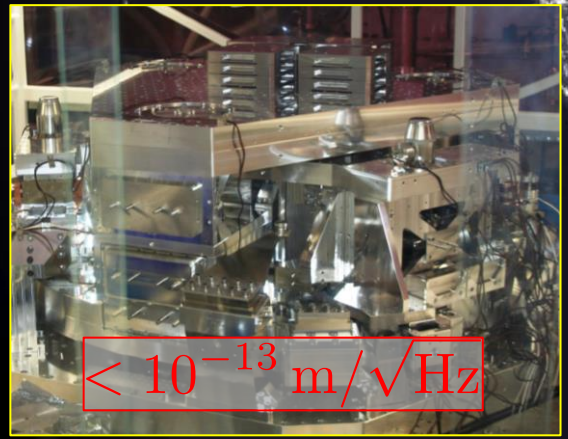
… yep, pretty faint; they have an amplitude of $10^{-21}$ (late 1960s and 1970s)

# LIGO

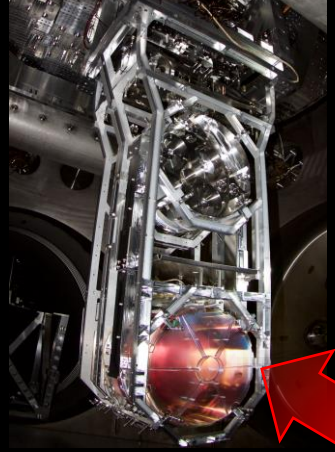


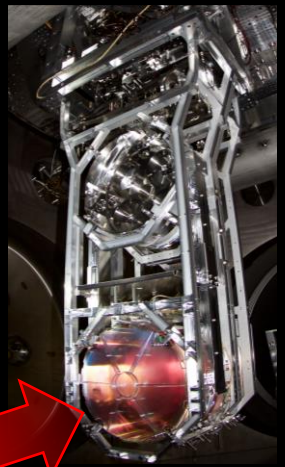


$$\Delta L = 10^{-18}\,\mathrm{m}$$




# The LIGO detectors



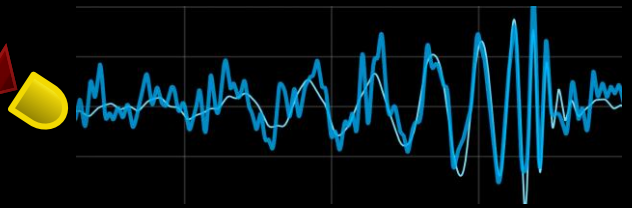


40 kg high quality fused silica mirrors, isolated from the ground

More than 300 control loops needed to keep the interferometer optimally running

Fabry-Perot cavities in the Michelson arms ~400kW laser power

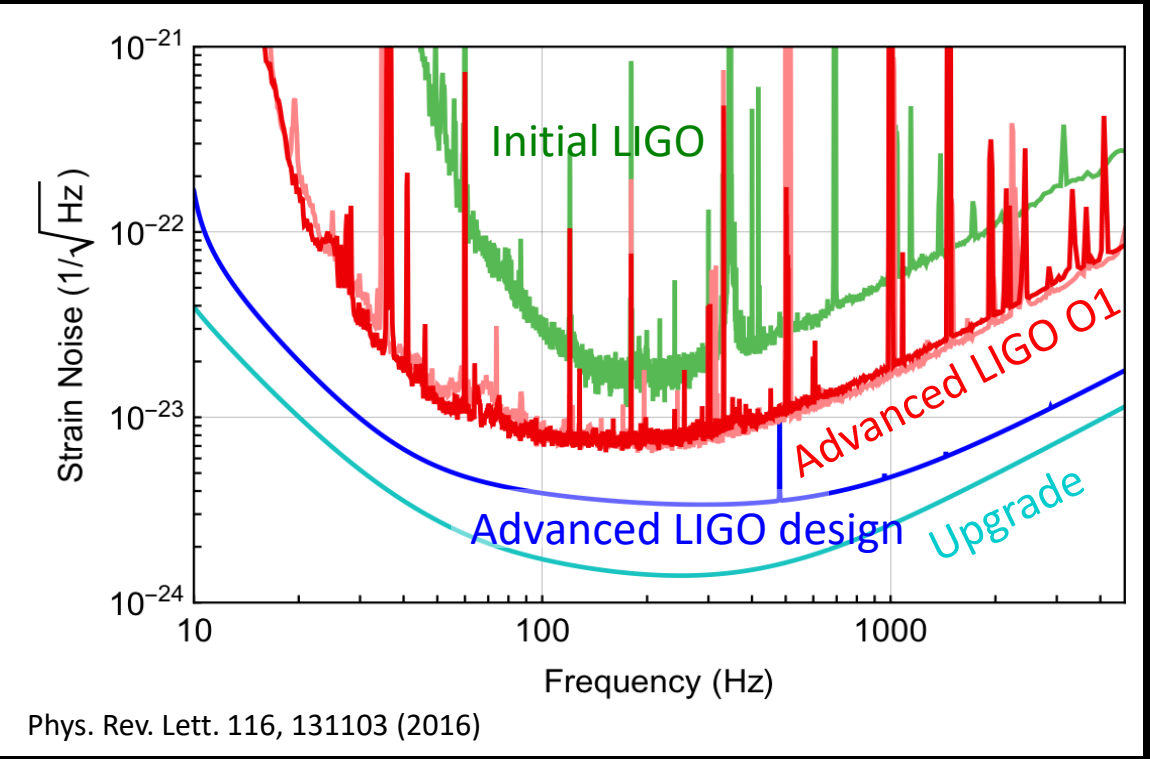
Up to 100W 1064nm laser power delivered



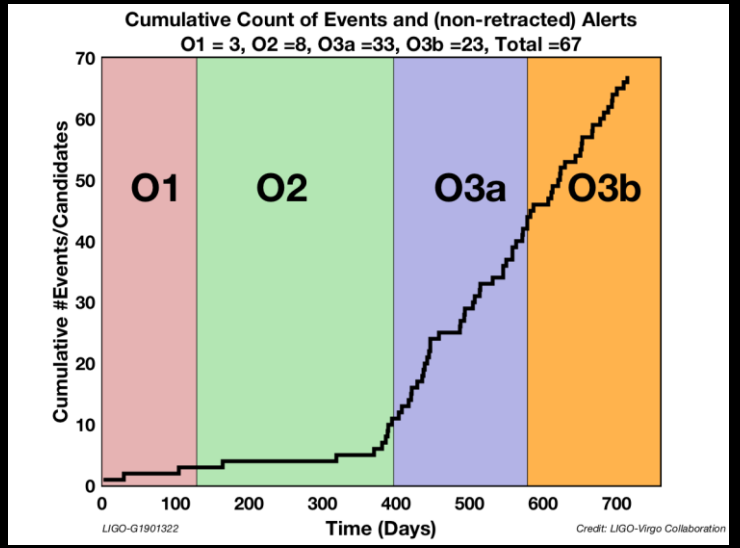
Output photodetector: Interferometer noise + gravitational wave signal

Slide: L. Barsotti

# Opening a new window to the Universe




Phys. Rev. Lett. 116, 131103 (2016)



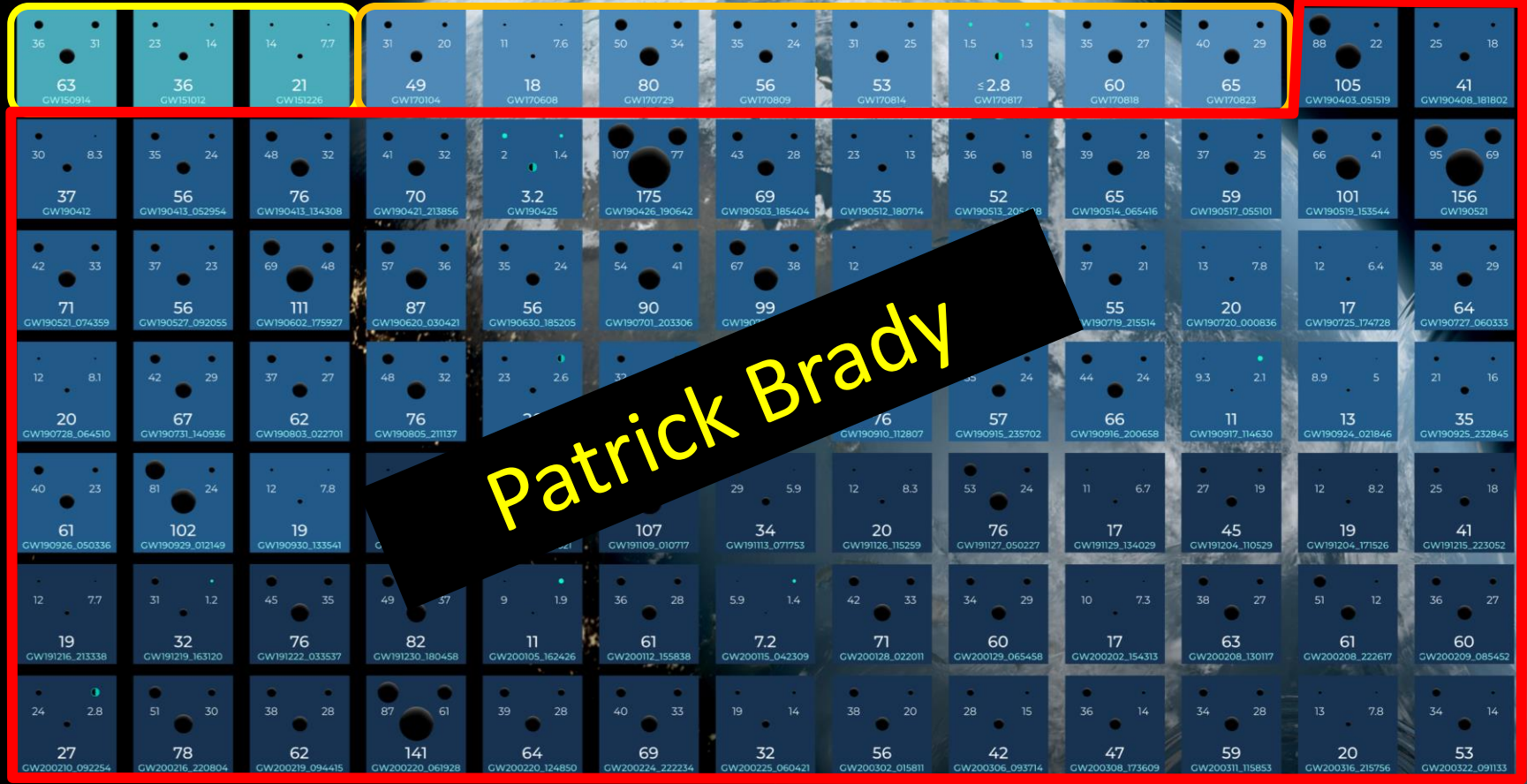

Continually improving the detectors so we can see fainter objects farther away

# Observations

OBSERVING RUN 01
2015 - 2016

02
2016 - 2017

03a+b
2019 - 2020

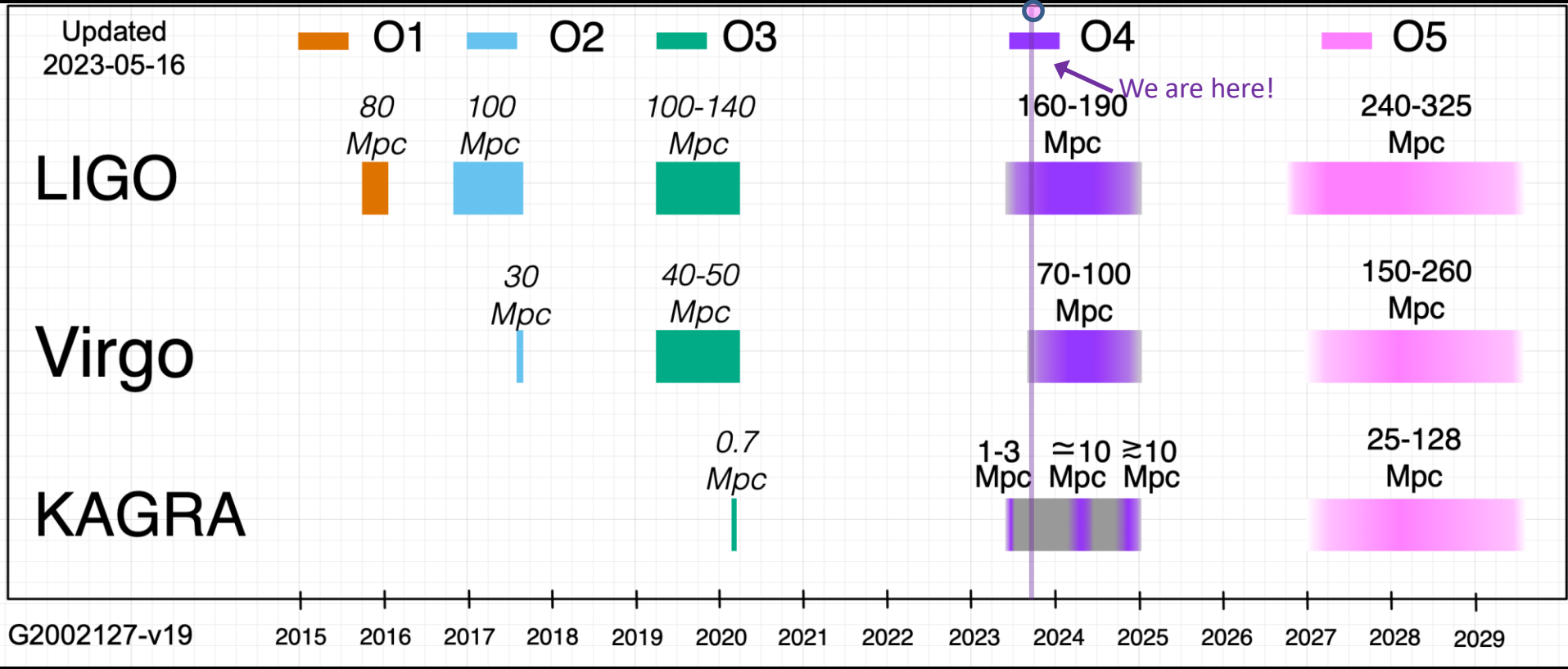



Patrick Brady

Image : Carl Knox (OzGrav, Swinburne University of Technology)

Slide: S. Fairhurst

# Observing timeline




https://observing.docs.ligo.org/plan/#

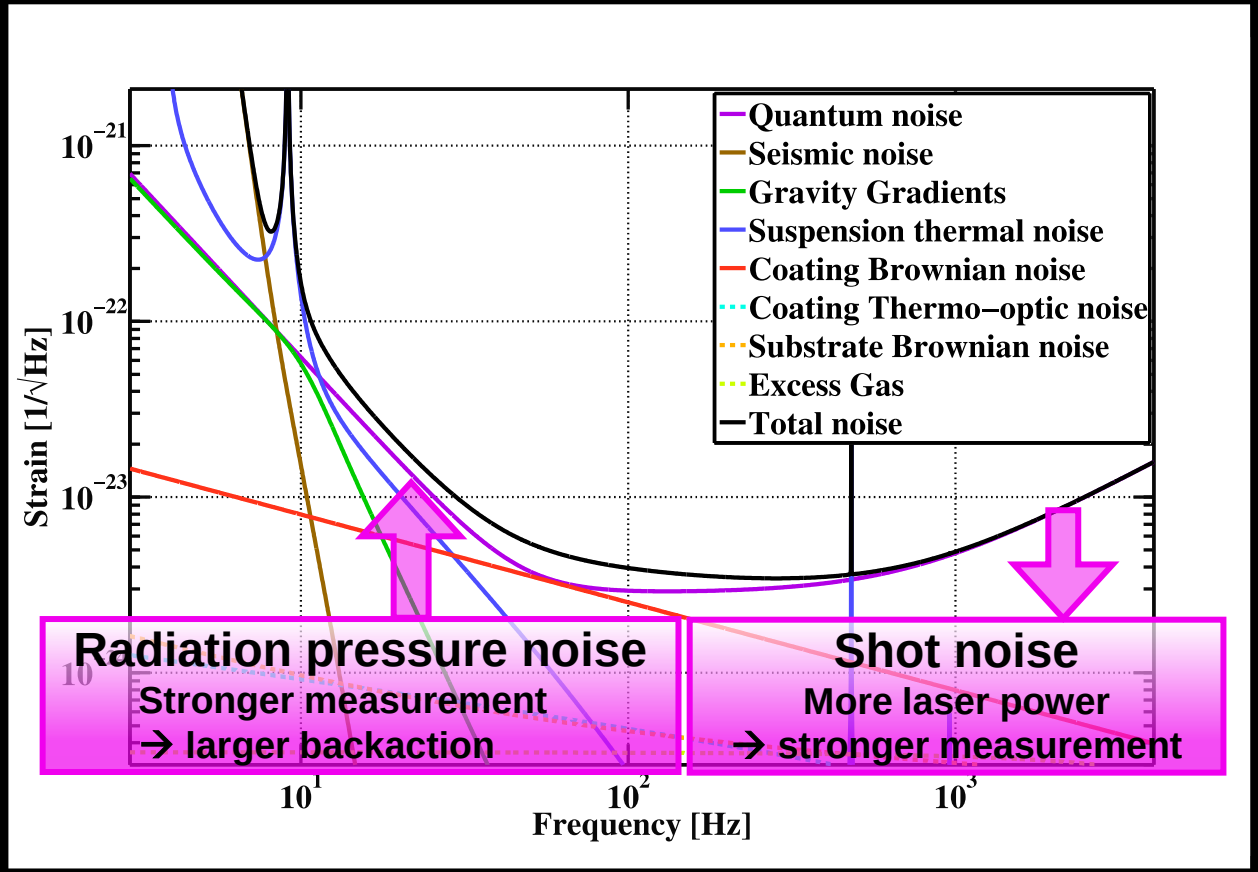
# aLIGO O4 commissioning highlights

- **Increased input laser power** to the interferometer
- Improve auxiliary control loops to minimize **controls noise**
- Replace test masses with egregious **point absorber** in optical coating
- **Scattered light** and **acoustic coupling** mitigated with baffle install and window removal
- **Electromagnetic interference noise** identified at LHO
- Online **noise subtraction** for witnessed noises (lines, auxiliary loops)

# QUANTUM ENGINEERING

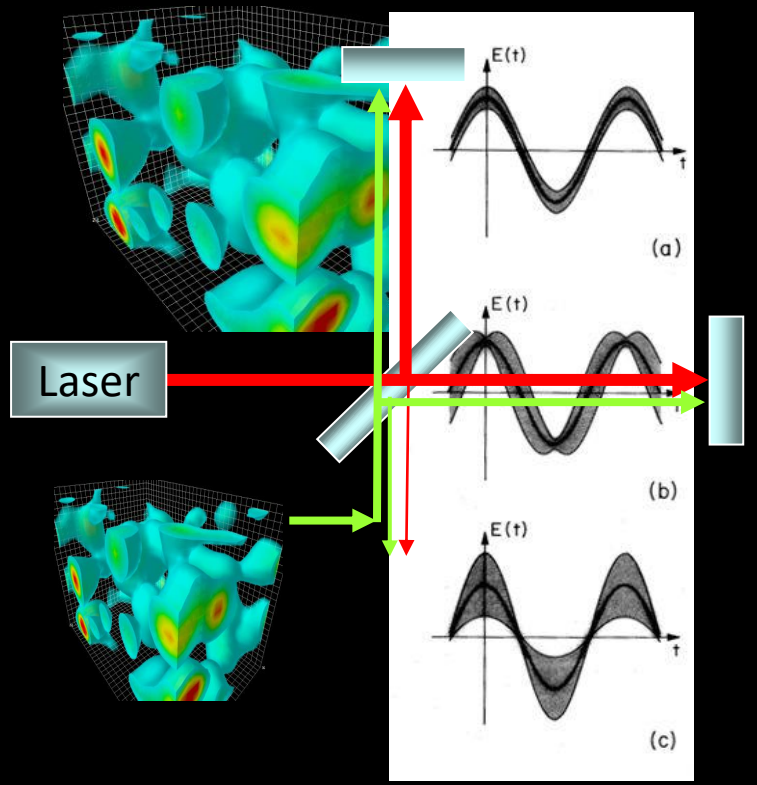
Frequency-dependent squeezed state injection

# aLIGO noise budget

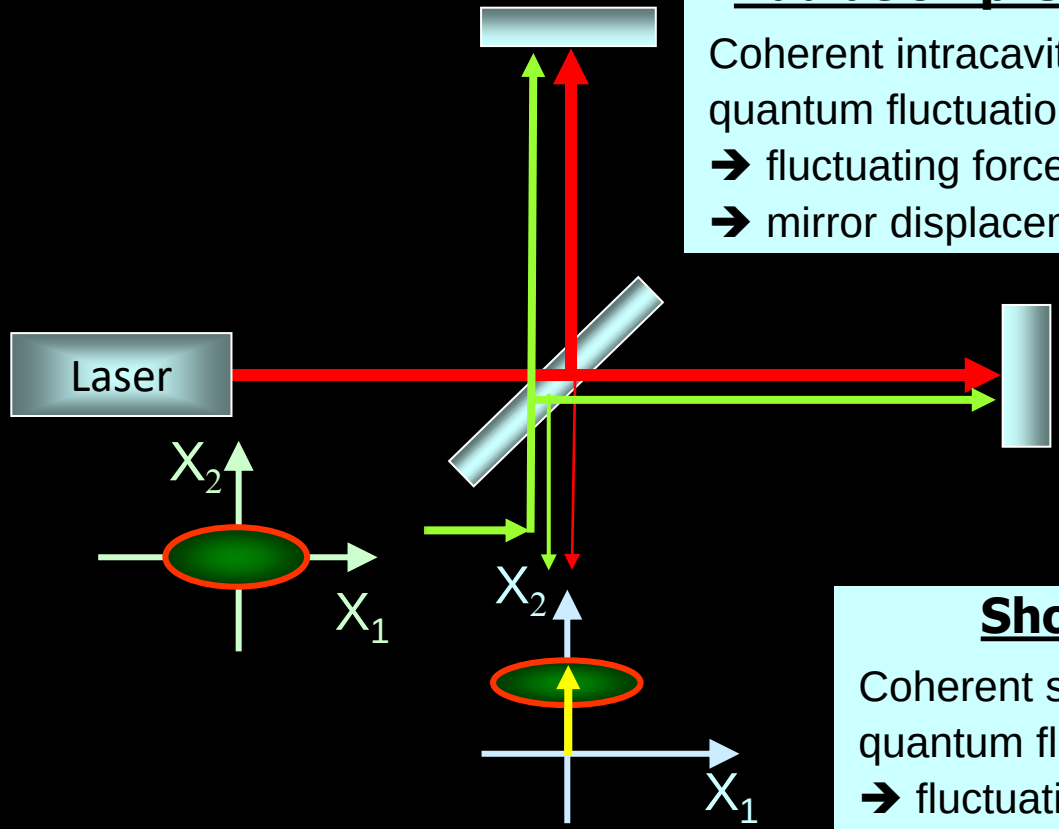


# Quantum imprecision

- Quantum fluctuations
- Quantum optical noise
- Specially engineered quantum states of light



# Quantum Noise in an Interferometer

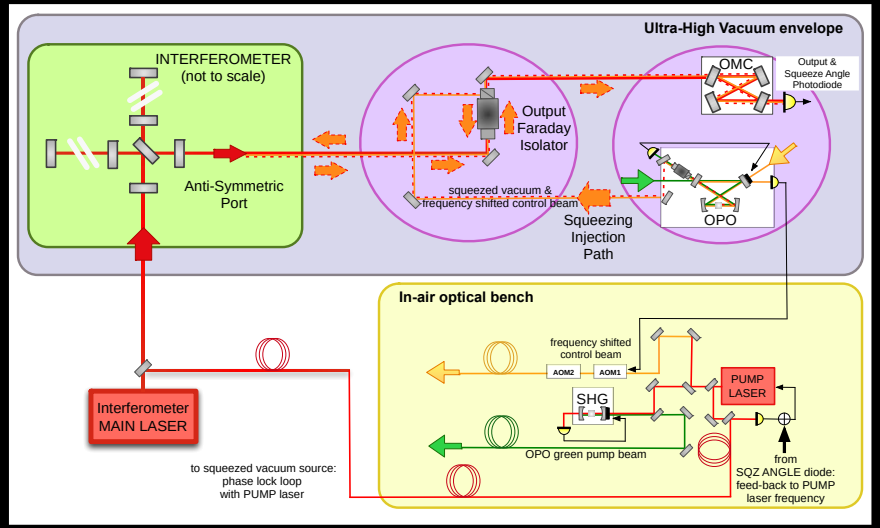

**Radiation pressure noise**

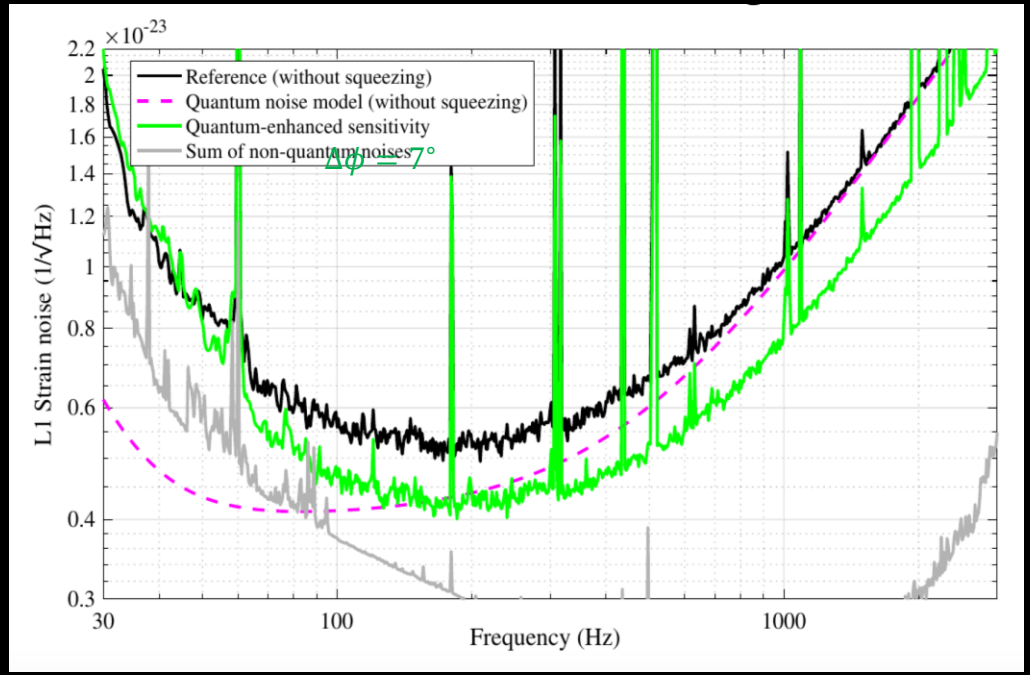
Coherent intracavity field + quantum fluctuations
➔ fluctuating force
➔ mirror displacement

**Shot noise**

Coherent signal field + quantum fluctuations
➔ fluctuating phase

# Squeezing in Advanced LIGO

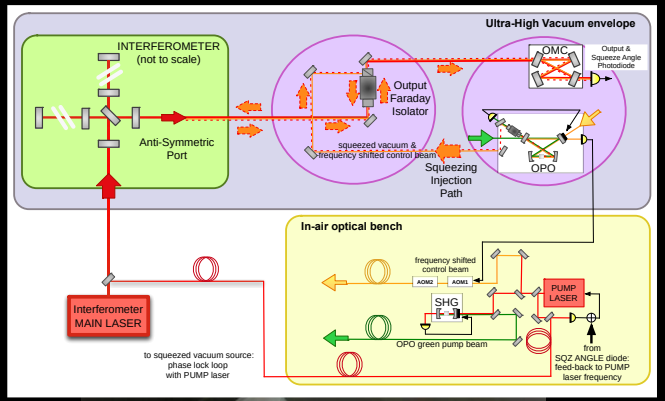


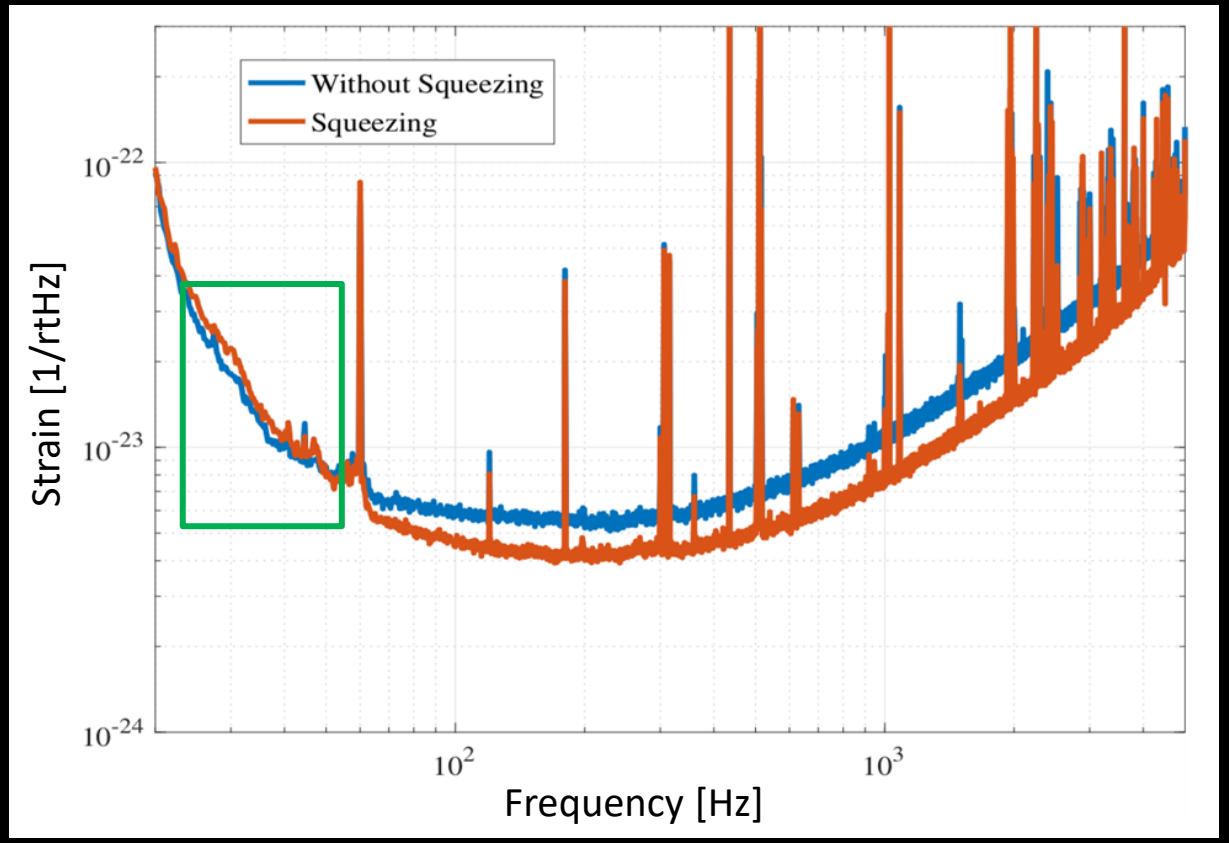




Observing Run 3:
~5 detection events per month
(cf. 1/month in O1 and O2)

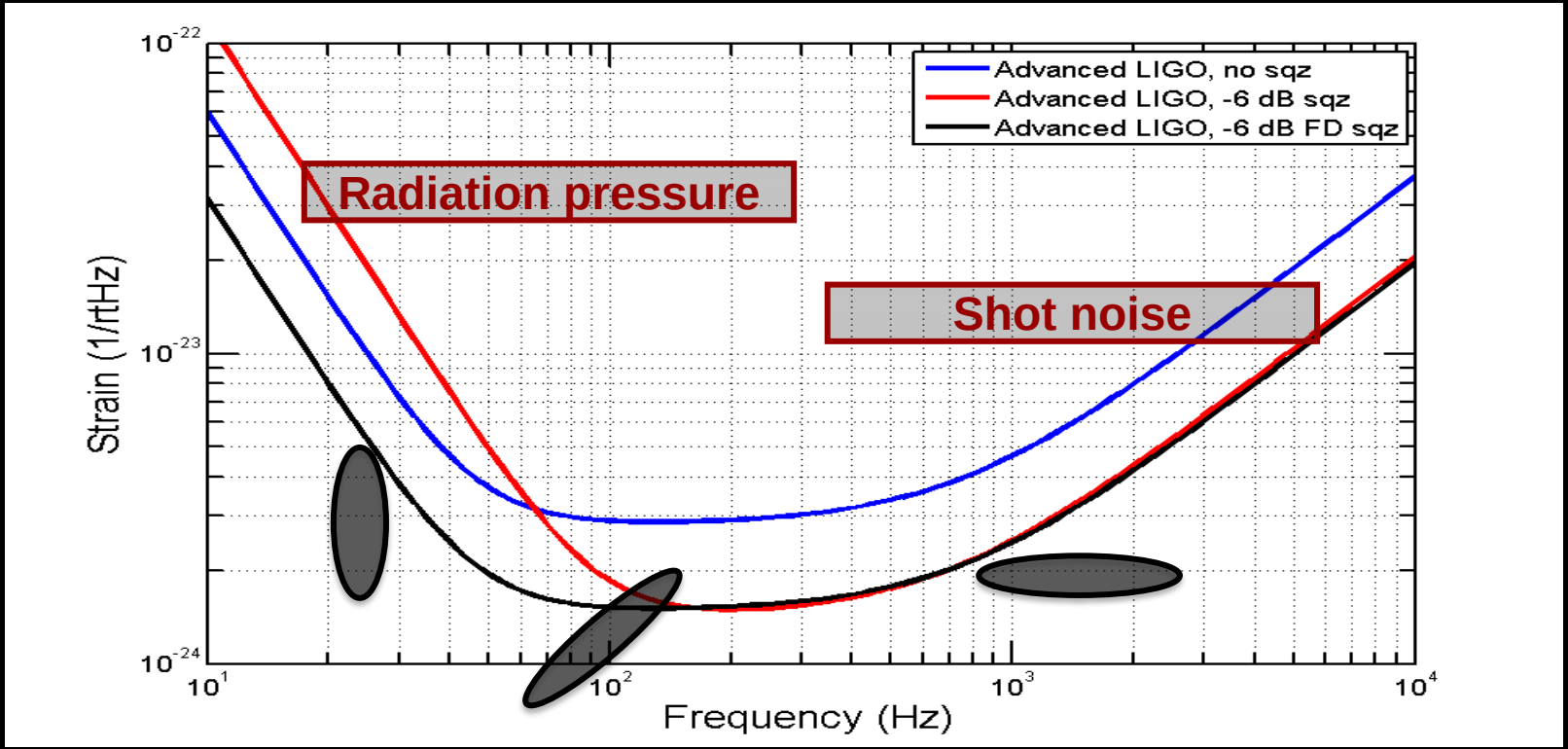
M. Tse, H. Yu, et al, PRL 123, 231107 (2019)

# Squeezing in Advanced LIGO



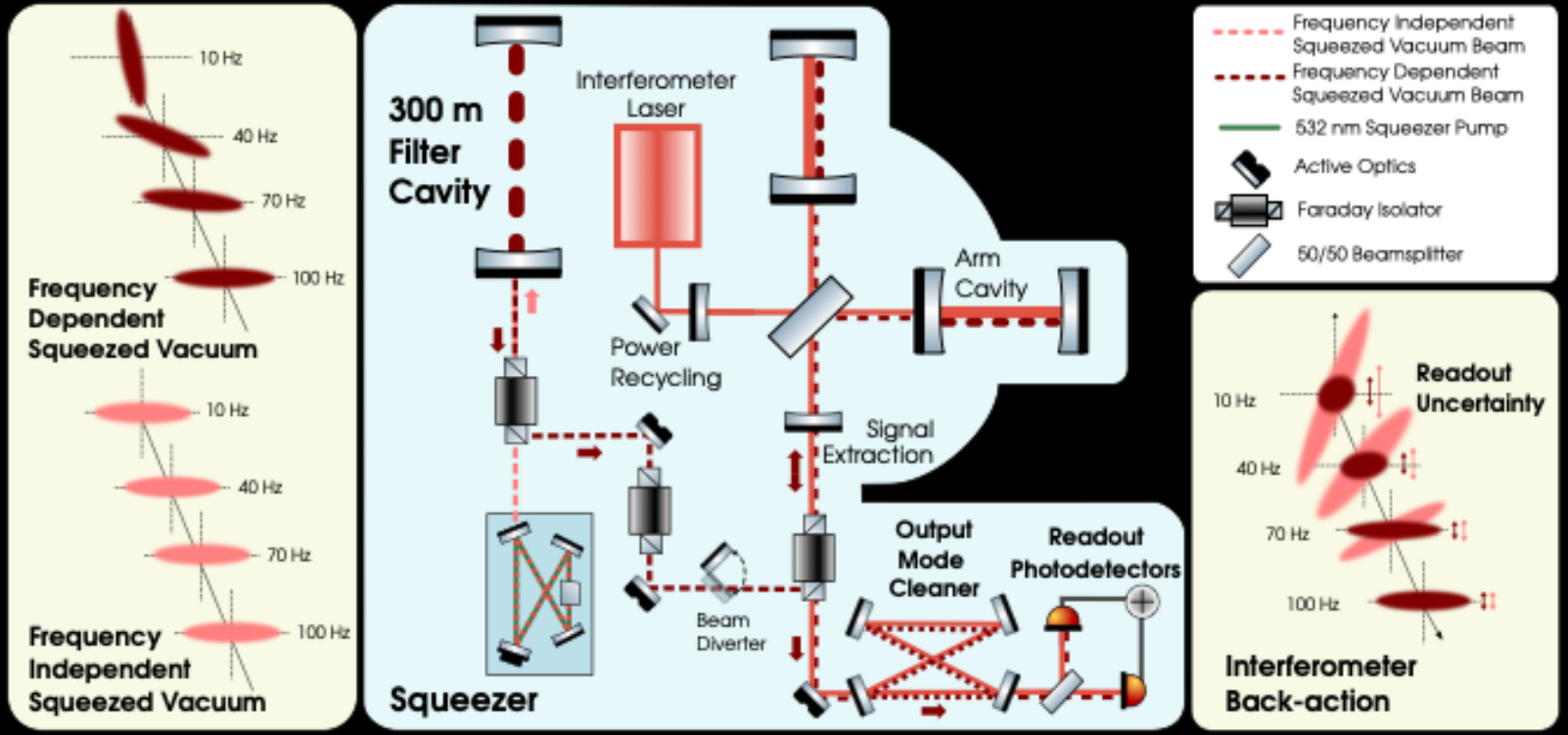



# Broadband quantum enhancement

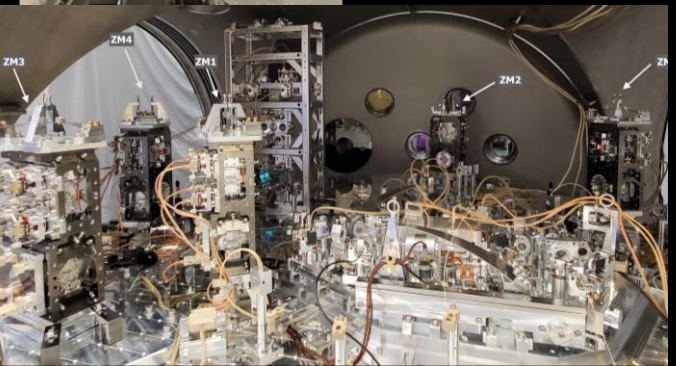


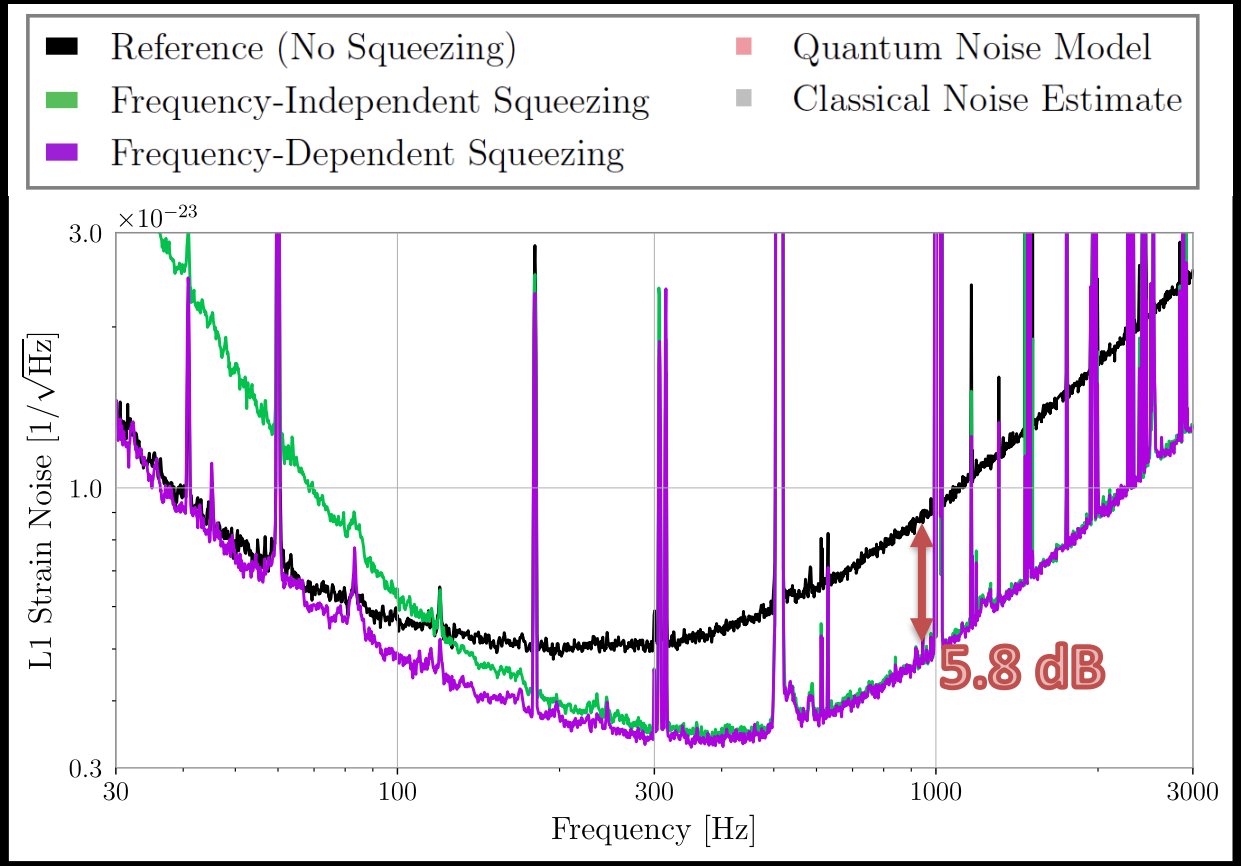

Schnabel, Mavalvala, McClelland, and Lam, Nature Communication (2010)
McClelland, Mavalvala, Schnabel, and Chen, Lasers and Photonics Reviews (2011)

# LIGO Optical Layout (O4)

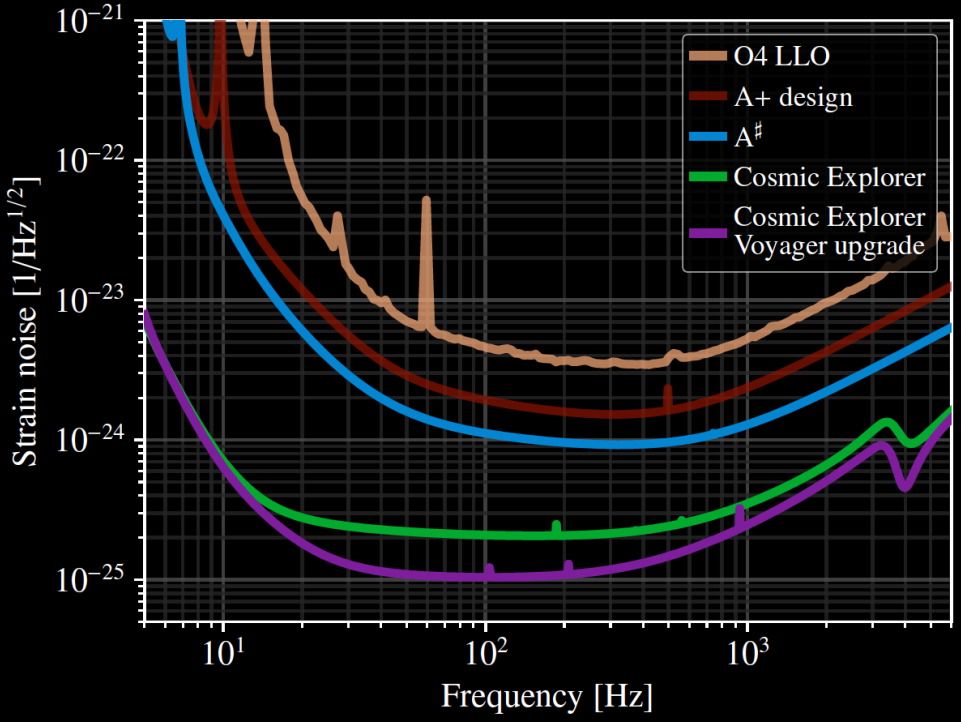


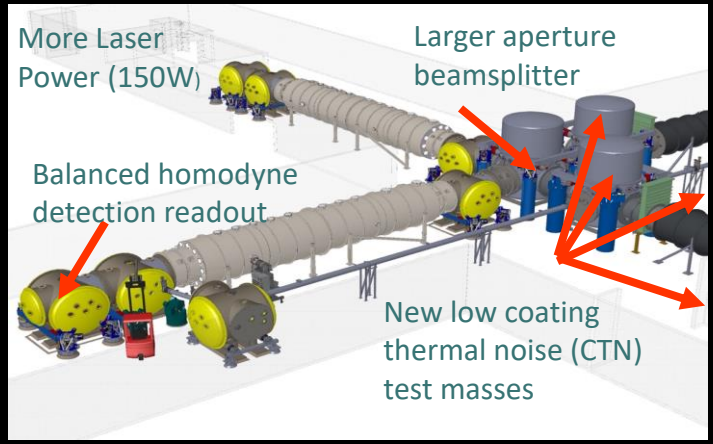
# O4: Broadband quantum enhancement



# O5, A+, A#, CE



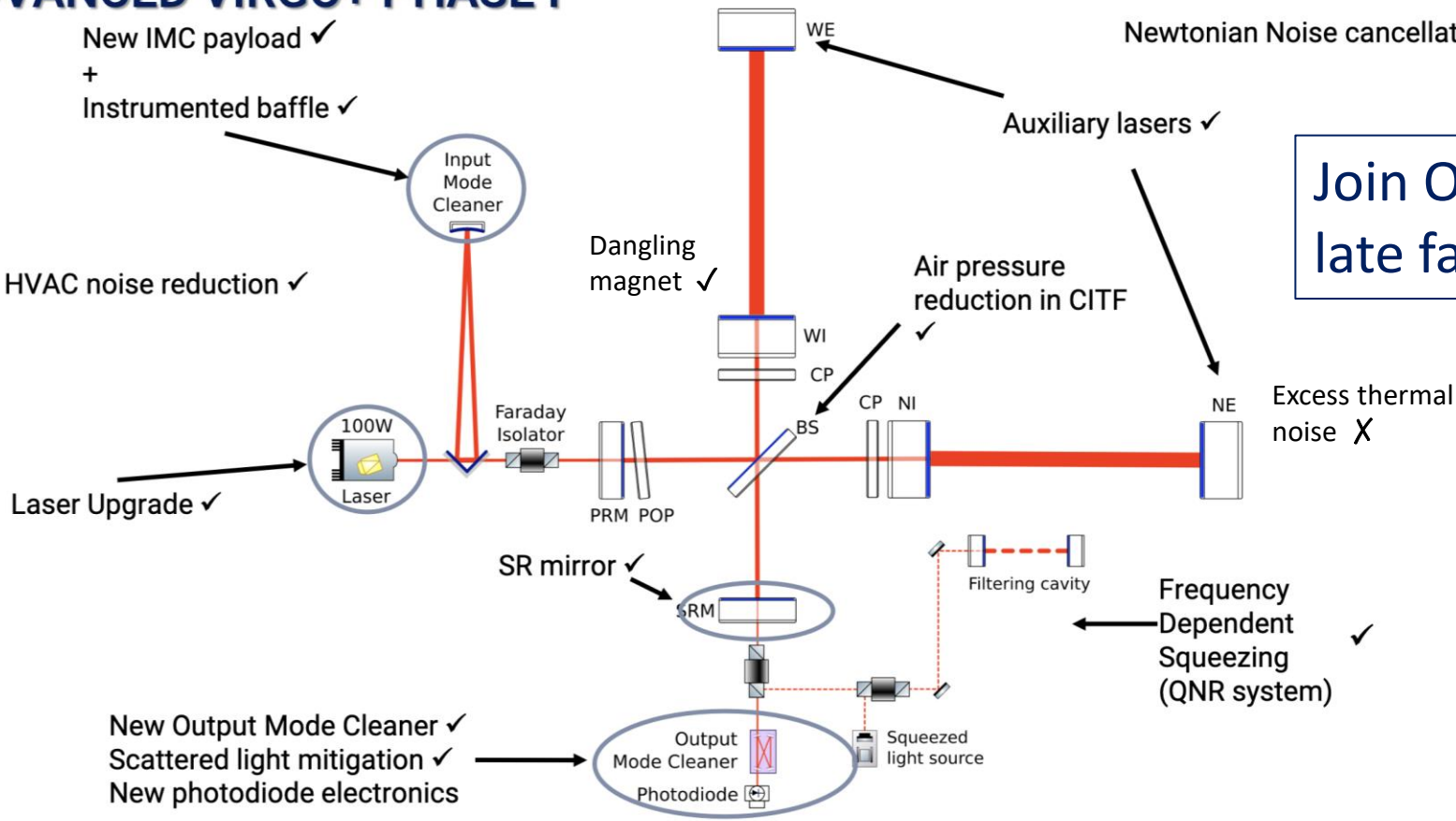

- A+ operations through O5 until 2029
- LIGO's Post-O5 detector: A♯
- US 3G detector Cosmic Explorer: mid-2030s

# AROUND THE WORLD

Virgo, KAGRA, LIGO India


VIRGO
@EGO PHOTO

# ADVANCED VIRGO+ PHASE I



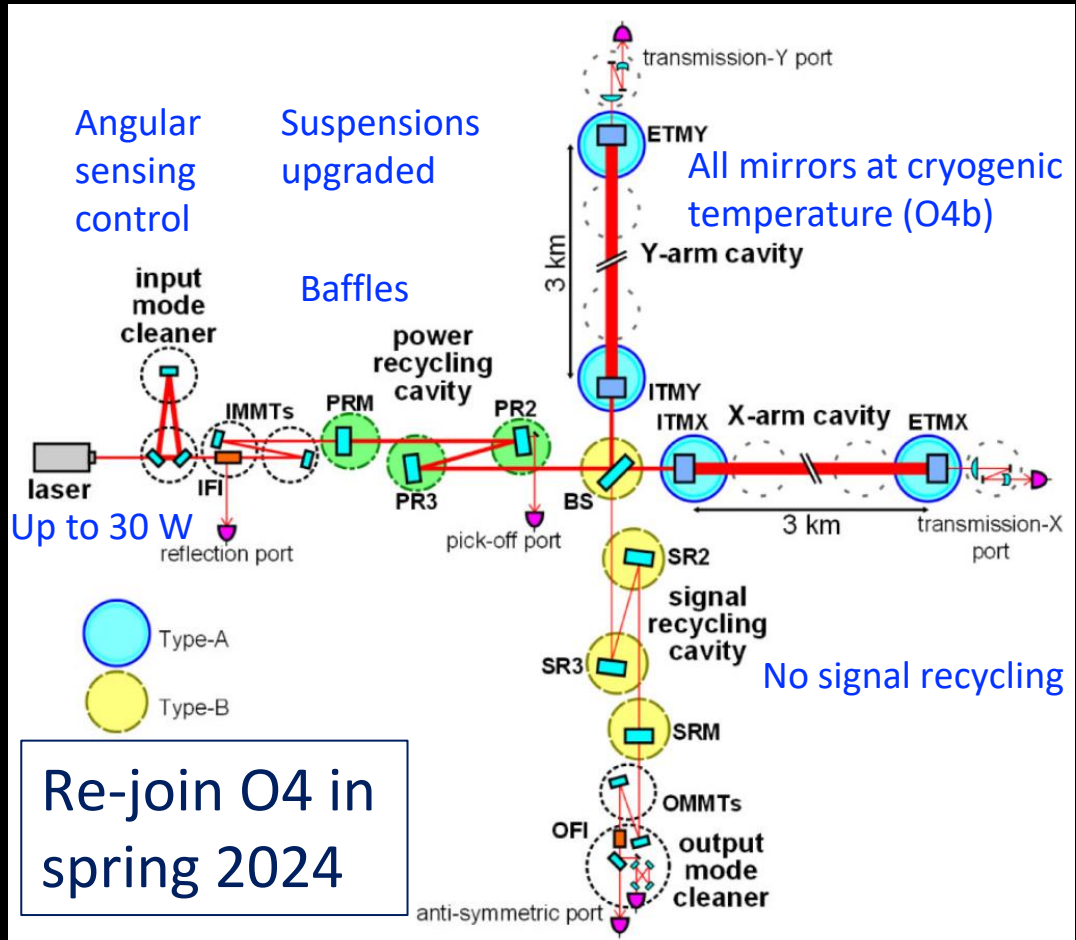

Join O4 in late fall 2023

Slide credit: Gianluca Gemme

# KAGRA

# KAGRA O4 configuration

- Underground (in Kamioka mine)
- Uses cryogenically cooled sapphire test masses
- O3 GK observing run: GEO and KAGRA April 2020, ~1Mpc BNS
- Preparing for O4
  - Upgraded mirror suspension for control noise reduction
  - Installed baffles for stray light reduction
  - Commissioned angular sensing and control




Re-join O4 in spring 2024

https://doi.org/10.1093/ptep/ptac093

Slide courtesy Jun'ichi Yokoyama

# COMING SOON


LIGO
INDIA

# LIGO India

- An India-US partnership to construct a third LIGO observatory in India
  - LIGO detector components already in possession
- Science case: significantly improved localization of GW events
- NSF-DAE-DST MOU signed in 2016
  - "…the LIGO-India project will be a partnership among NSF, DAE, and DST, through their respective awardee institutions and participating laboratories, to provide such a capability, to operate it for a period of at least ten years, and to pursue a program of gravitational-wave science."
- Status:
  - LIGO India Observatory in final design phase
  - Site acquired; construction has begun
  - Vacuum system prototyping program underway
  - LIGO India Testing and Training Facility completed
  - Final approval from Government of India in spring 2023


LIGO-India Design Concept

Vacuum Prototype at VTPL, Bangalore, 2021

LIGO-India Testing and Training Facility
Raju Ramanna Centre for Advanced Technology, 2022

LIGO-India Site Construction, 2022

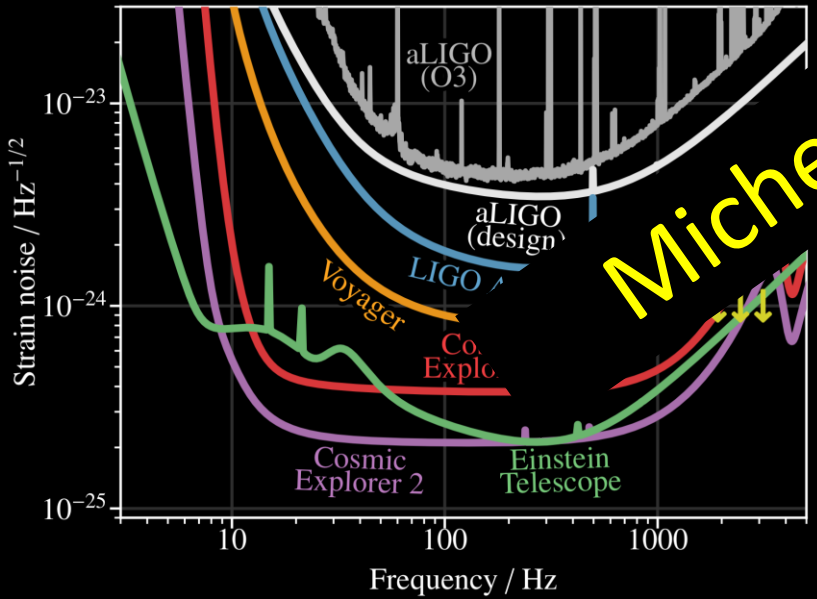
# A BIT LATER

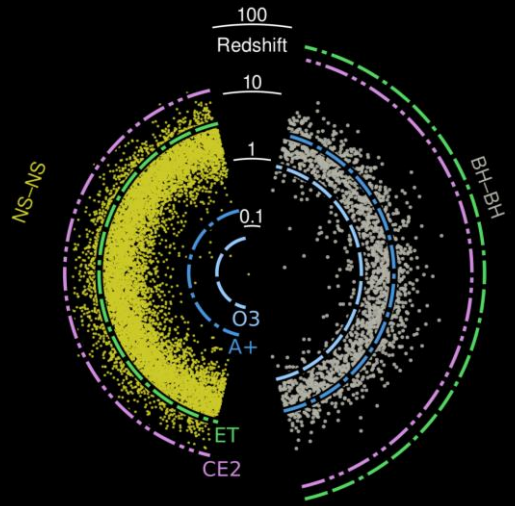
3rd Generation detectors

# 3rd Generation Detectors

- 10 to 40 km long
- Quantum enhanced
- Novel mirrors

- Binary n… …on stars out to z ≈ 6
- Bin… …oles out to z ≈ 10
- … …ae out to 20 Mpc
- … per year



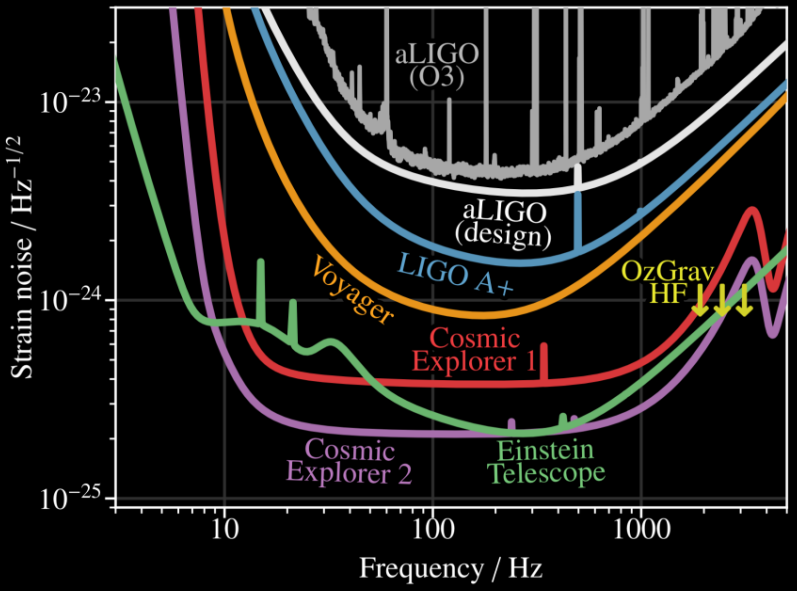




Michele Punturo

# CLOSING REMARKS

# A brilliantly dark and warped future

- Observing run 4 underway
- Worldwide terrestrial network coming online
- Planning and design of future detectors that can map black hole binaries in the observable Universe in full swing



The end