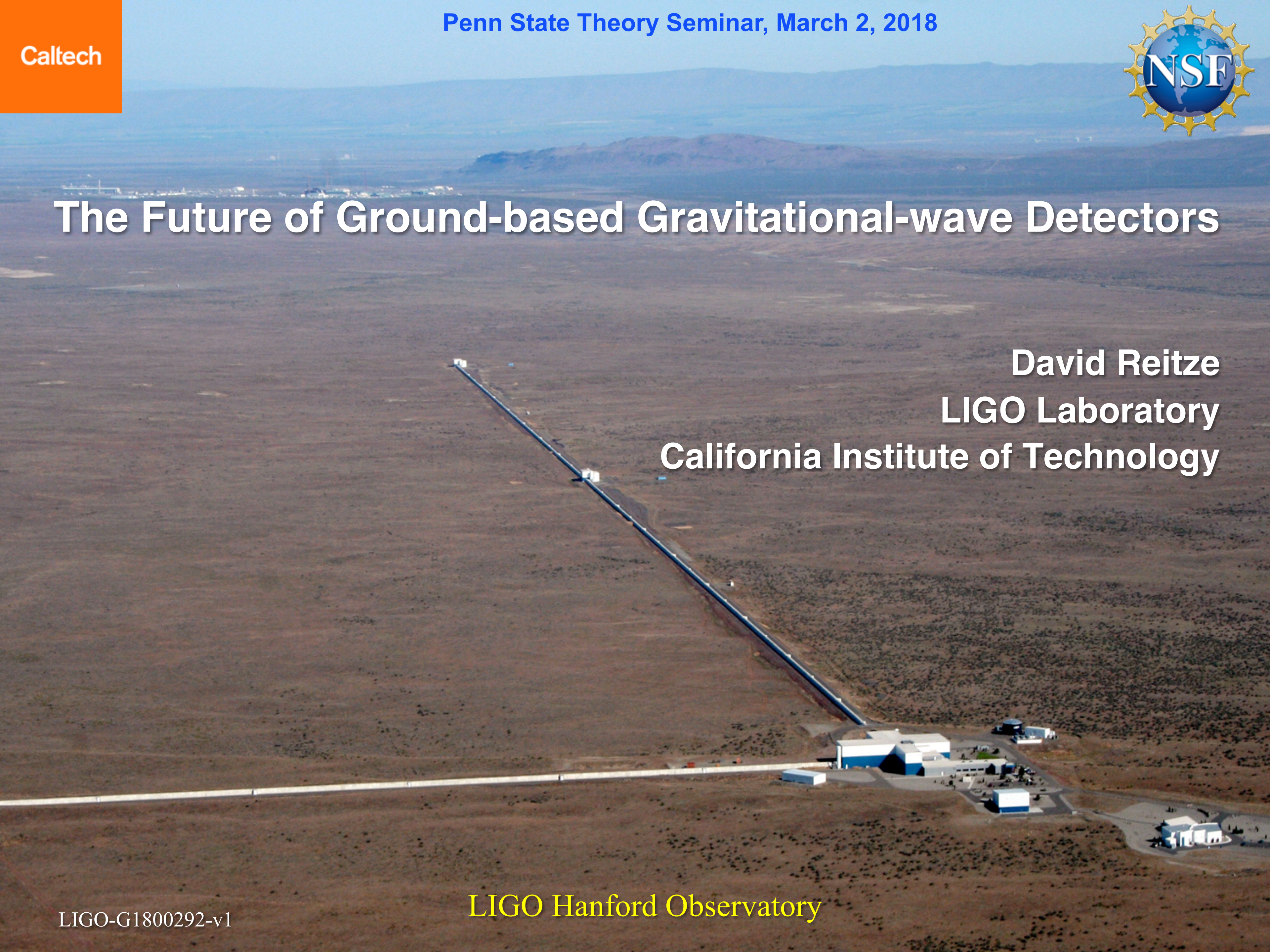
Penn State Theory Seminar, March 2, 2018

# The Future of Ground-based Gravitational-wave Detectors

**David Reitze**
**LIGO Laboratory**
**California Institute of Technology**



LIGO Hanford Observatory

LIGO-G1800292-v1

# *Outline*

- *Why Make Bigger and Better Detectors?*
- *Improving Advanced LIGO: A+*
- *Exploiting the Existing LIGO Facility Limits: Voyager*
- *Future '3G' Facilities: Cosmic Explorer and Einstein Telescope*

# Some of the Questions That Gravitational Waves Can Answer

- **Outstanding Questions in Fundamental Physics**
  - *Is General Relativity the correct theory of gravity?*
  - *How does matter behave under extreme conditions?*
  - *No Hair Theorem: Are black holes truly bald?*

- **Outstanding Questions in Astrophysics, Astronomy, Cosmology**
  - *Do compact binary mergers cause GRBs?*
  - *What is the supernova mechanism in core-collapse of massive stars?*
  - *How many low mass black holes are there in the universe?*
  - *Do intermediate mass black holes exist?*
  - *How bumpy are neutron stars?*
  - *Can we observe populations of weak gravitational wave sources?*
  - *Can binary inspirals be used as "standard sirens" to measure the local Hubble parameter?*
  - *Are LIGO/Virgo's binary black holes a component of Dark Matter?*
  - *Do Cosmic Strings Exist?*

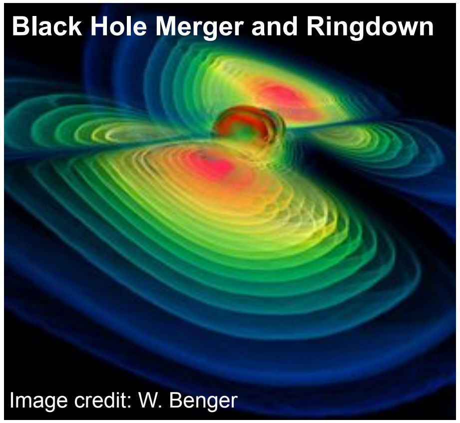
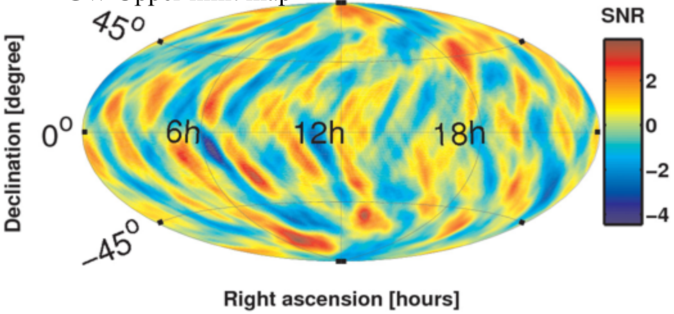

Black Hole Merger and Ringdown

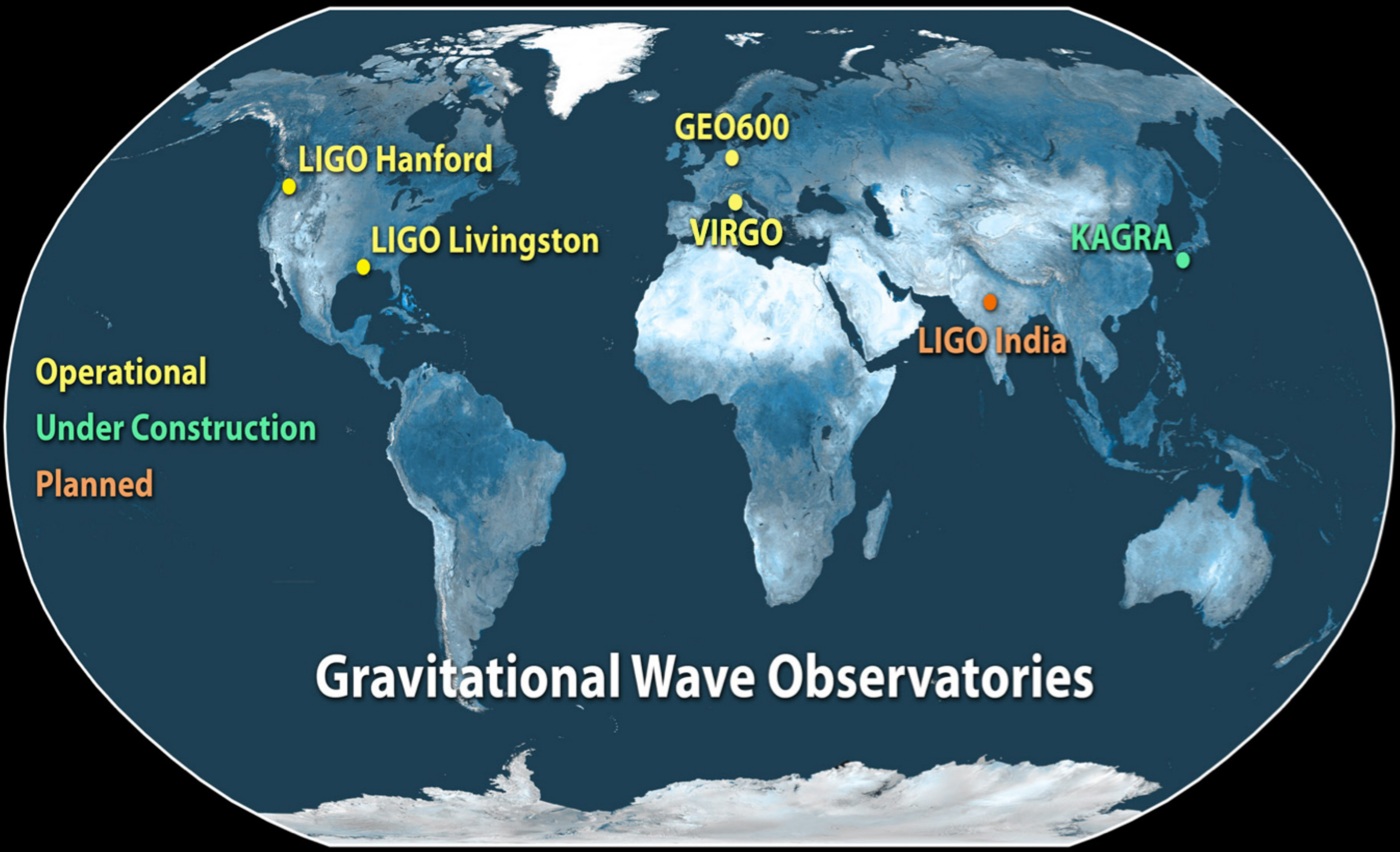
Image credit: W. Benger


Neutron Star Formation

Image credit: NASA

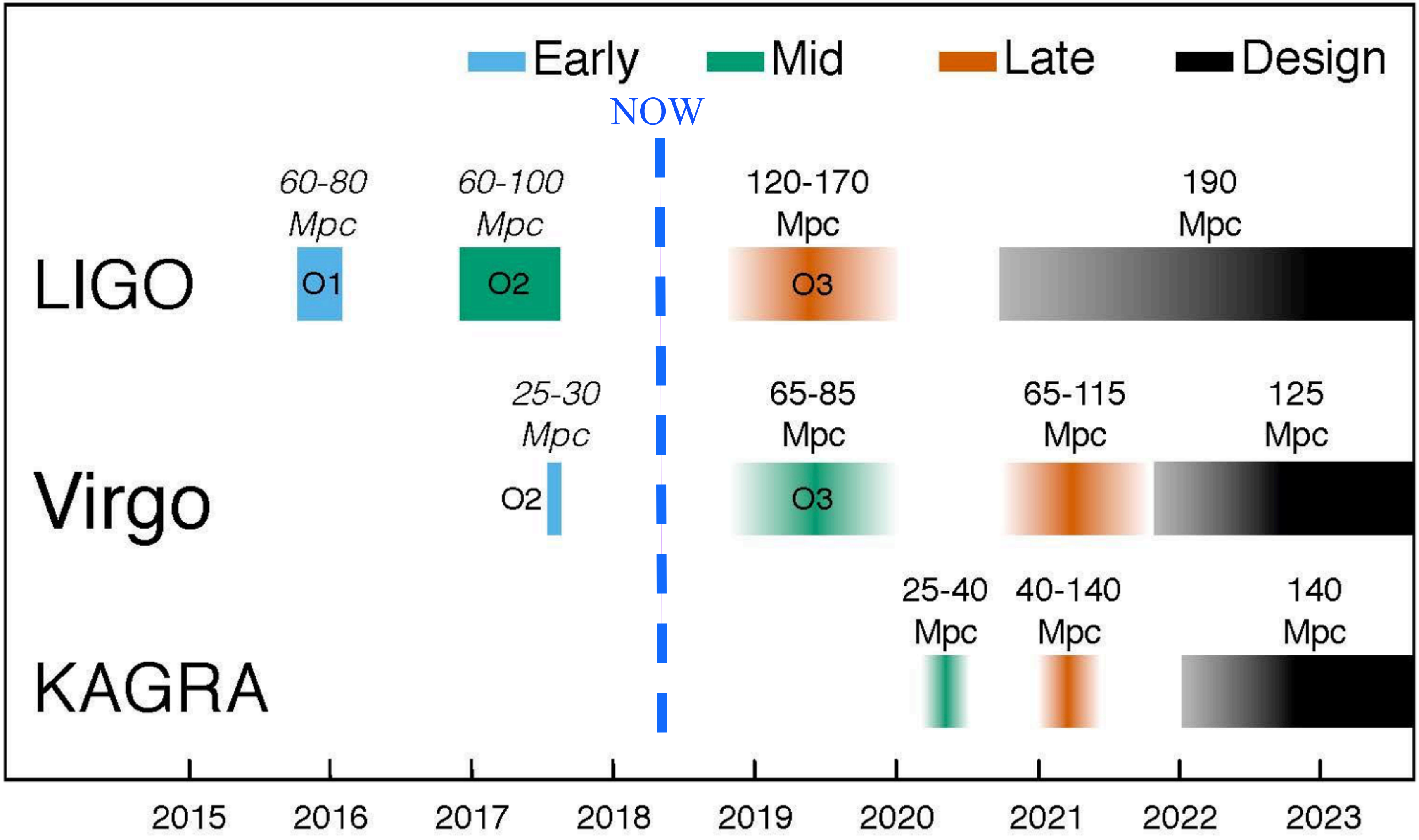
GW Upper limit map





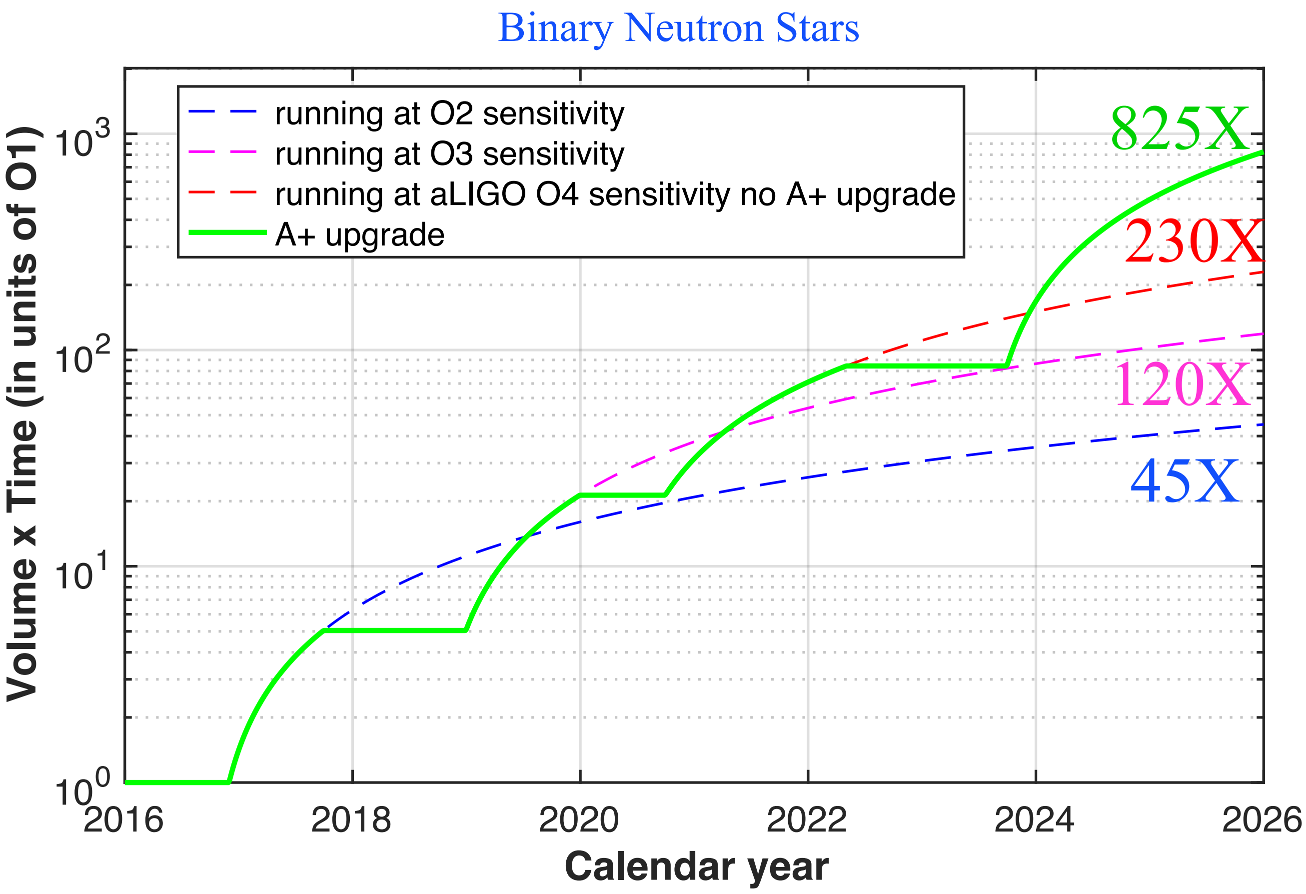
# Gravitational Wave Observatories

# LIGO Observing Plans for the Coming 5 Years



Abbott, et al., "Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA", https://arxiv.org/abs/1304.0670

# *Gravitational-wave Science is Sensitivity Driven*



1) **We want more events**

$$\mathbf{N_{events} = \langle R\rangle VT}$$

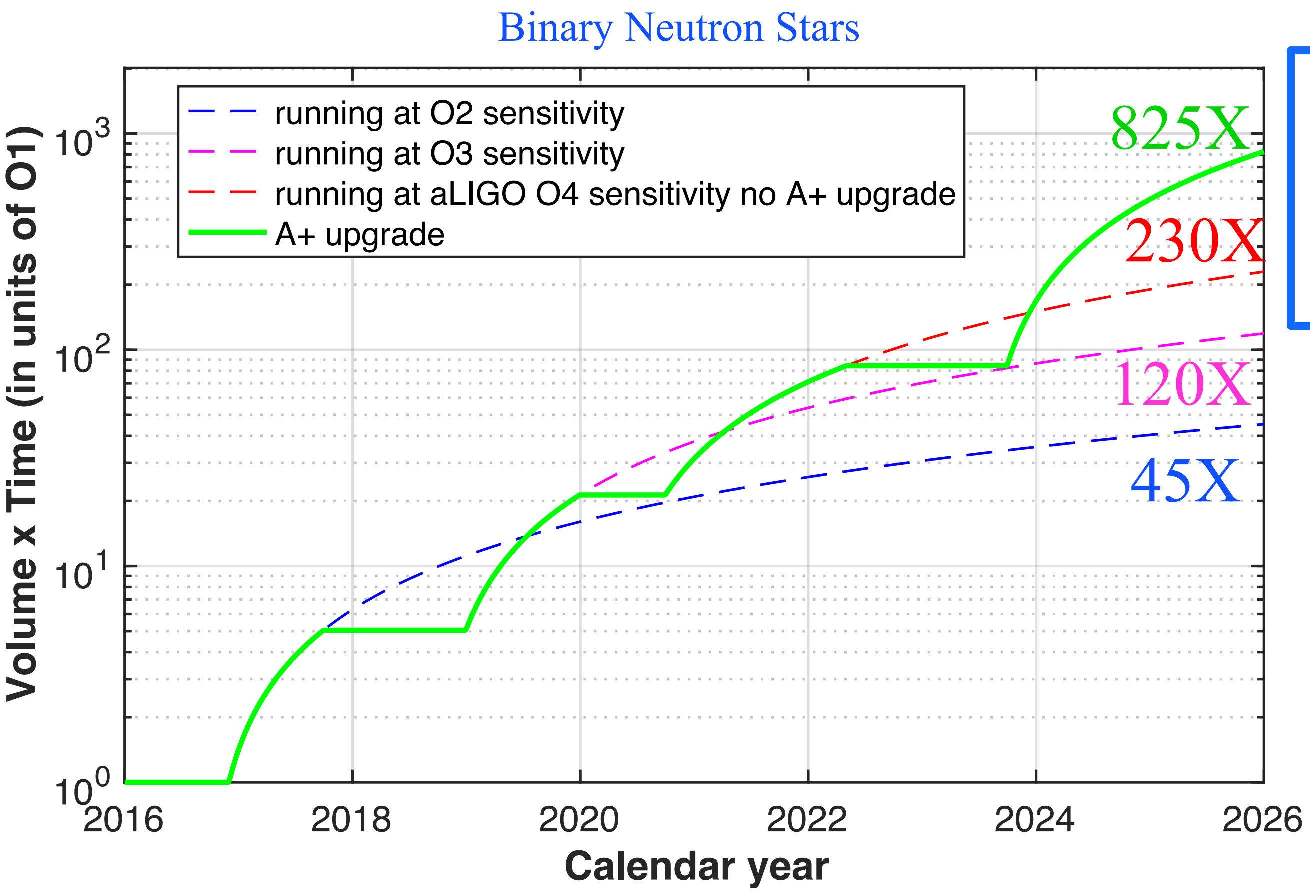
**Where:**

**<R> -- average astrophysical rate**

**V -- volume of the universe probed → $(\text{Range})^3$**

**T -- coincident observing time → t linear**

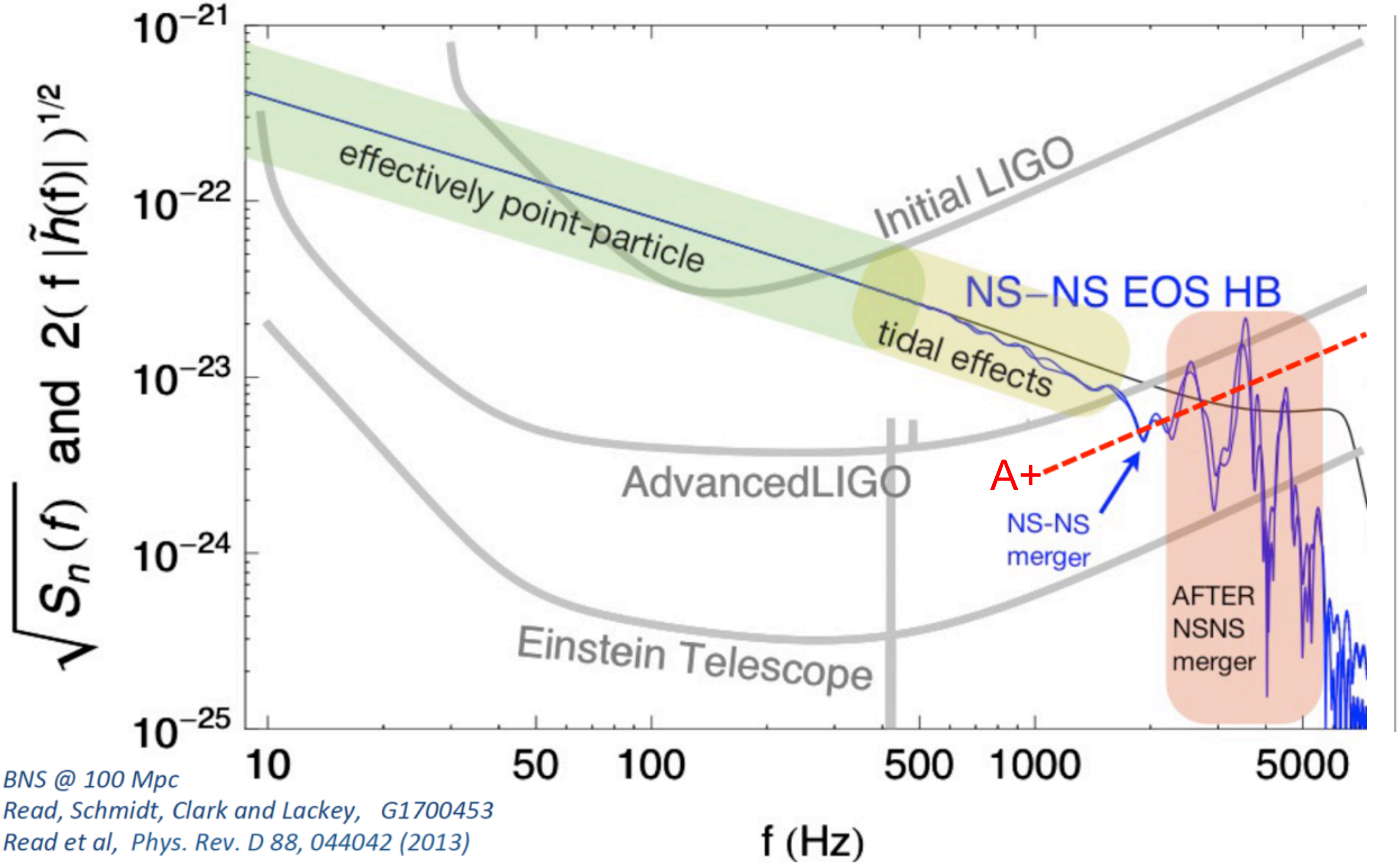
# Gravitational-wave Science is Sensitivity Driven



2) ***Many sources require higher SNR to uncover new astrophysics:***

- tidal disruption in BNS mergers
- tests of alternative theories of gravity
- Black hole ringdowns
- Stochastic background
- Isolated neutron stars
- Galactic supernova
- ....

# Example: Probing the Neutron Star Equation of State

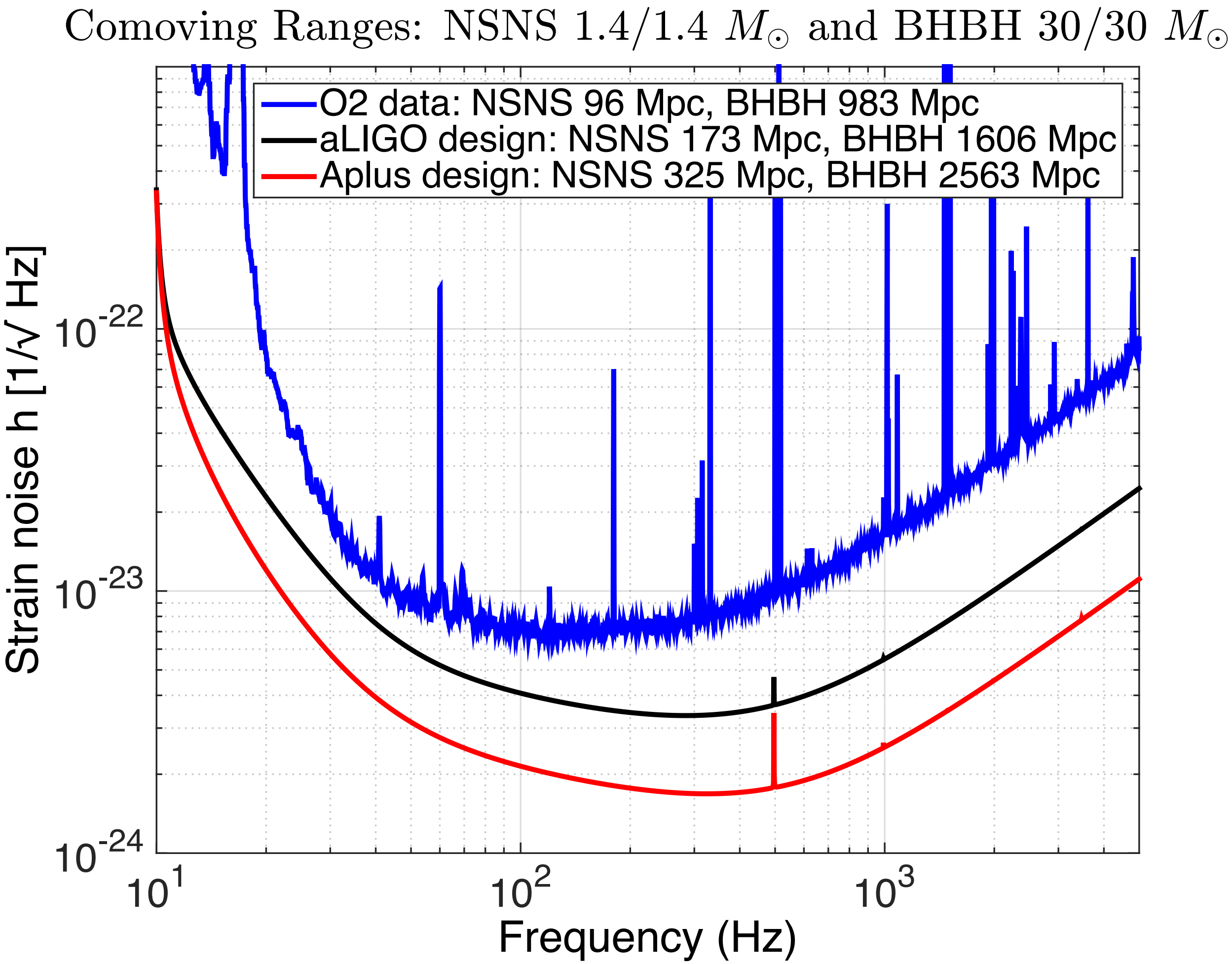


*BNS @ 100 Mpc*
*Read, Schmidt, Clark and Lackey, G1700453*
*Read et al, Phys. Rev. D 88, 044042 (2013)*

# *Improving LIGO: A+*

# *A+: a Mid-Life Enhancement for Advanced LIGO*

- Near term: 'A+', a mid-scale upgrade of Advanced LIGO
  - Improvements across all bands
- Projected time scale for A+ operation: 2023 - 2025



# *The Rationale for A+?*

- A+ is an incremental upgrade to aLIGO *that can happen in the next 5-7 years*
- A+ leverages existing technology and infrastructure, with minimal new investment, and moderate risk
- Target improvement: factor of 1.75* increase in range over aLIGO

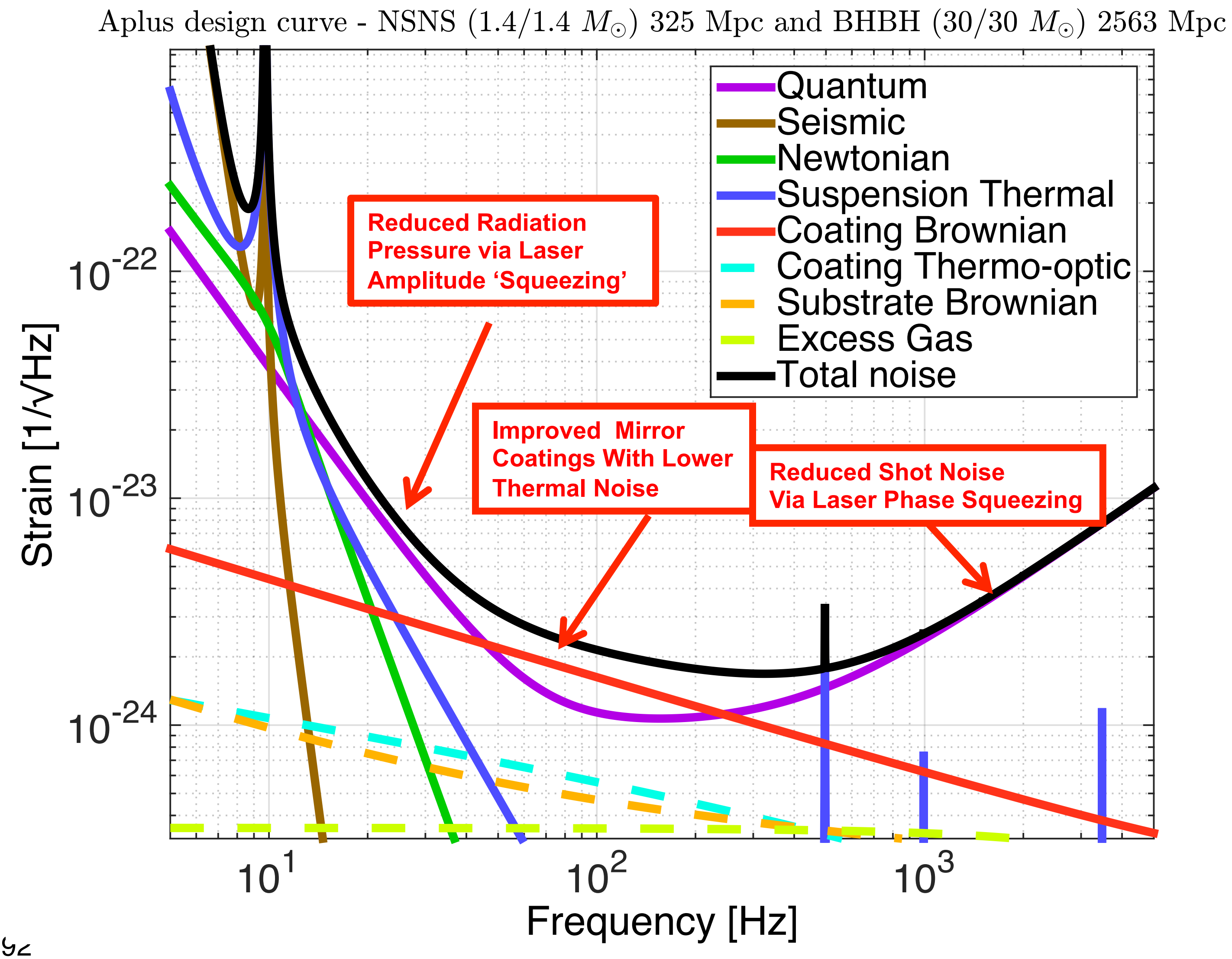
➔ ***A factor of ~ 5 greater CBC event rate***

- A+ is a stepping stone to 3G detector technology
- Can be observing within 5 years (possibly late 2022)
- “Scientific breakeven” within 1/2 year of operation
- Incremental cost: *a small increment of the aLIGO cost*

*BBH 30/30 $M_{\odot}$: 1.87x
*BNS 1.4/1.4 $M_{\odot}$: 1.7x

Slide inspiration: Mike Zucker, LIGO Laboratory

# *Key A+ Upgrades*



Aplus design curve - NSNS (1.4/1.4 $M_\odot$) 325 Mpc and BHBH (30/30 $M_\odot$) 2563 Mpc

**Reduced Radiation Pressure via Laser Amplitude 'Squeezing'**

**Improved Mirror Coatings With Lower Thermal Noise**

**Reduced Shot Noise Via Laser Phase Squeezing**

# Squeezing: Reducing Quantum Noise

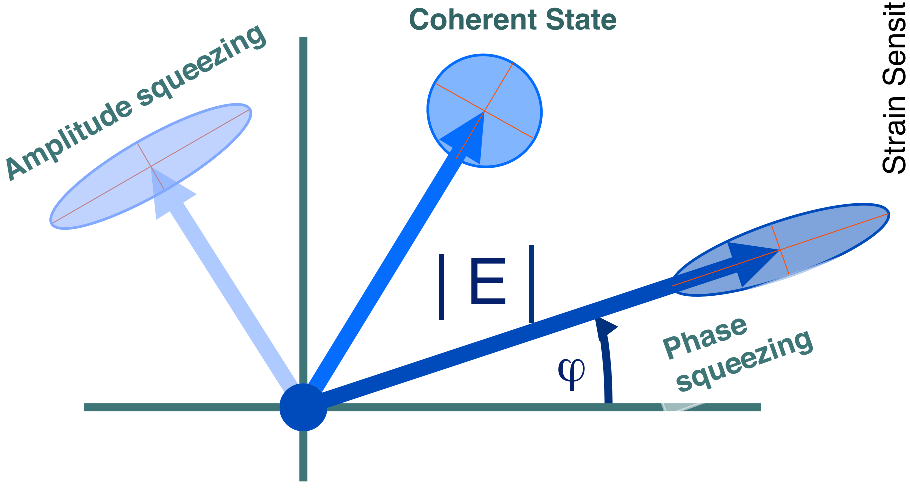
- Electromagnetic fields are quantized:

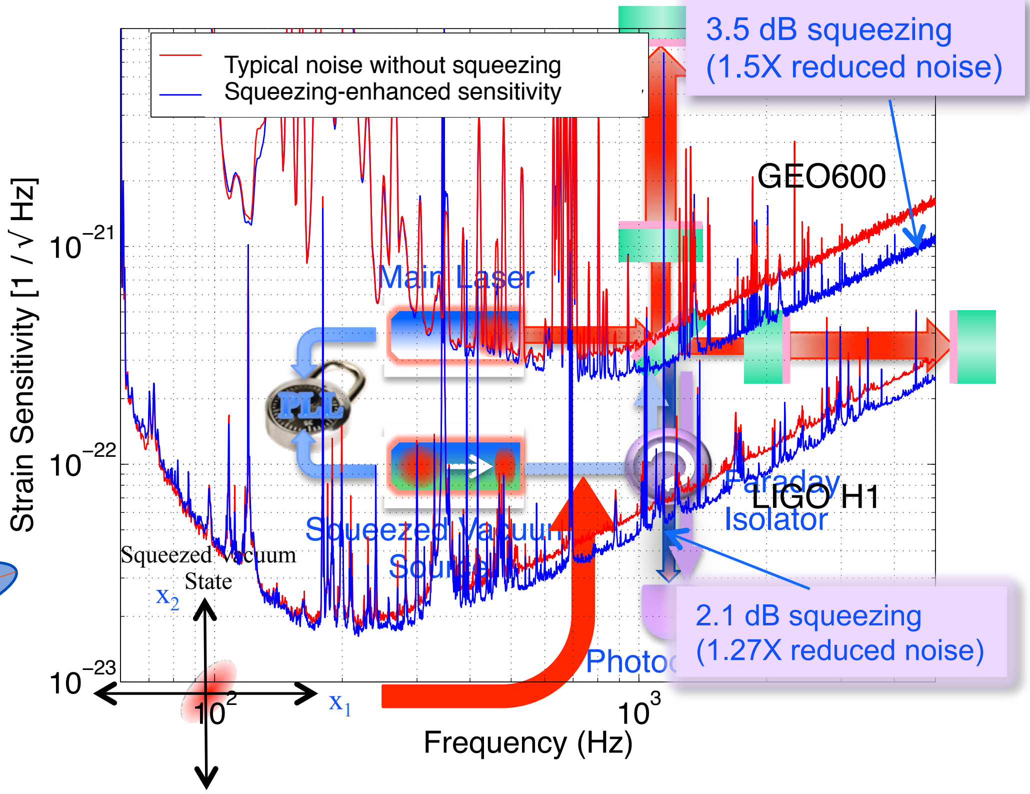
$$\hat{E} = \hat{X}_1 \cos\omega t + i\hat{X}_2 \sin\omega t$$

- Quantum fluctuations exist in the vacuum state:

$$\langle(\Delta\hat{X}_1)^2\rangle\langle(\Delta\hat{X}_2)^2\rangle \geq 1$$

H. P. Yuen, Phys. Rev. A**13**, 2226 (1976)
C. M. Caves, Phys. Rev. D**26**, 1817 (1982)
Wu, Kimble, Hall, Wu, PRL (1986)



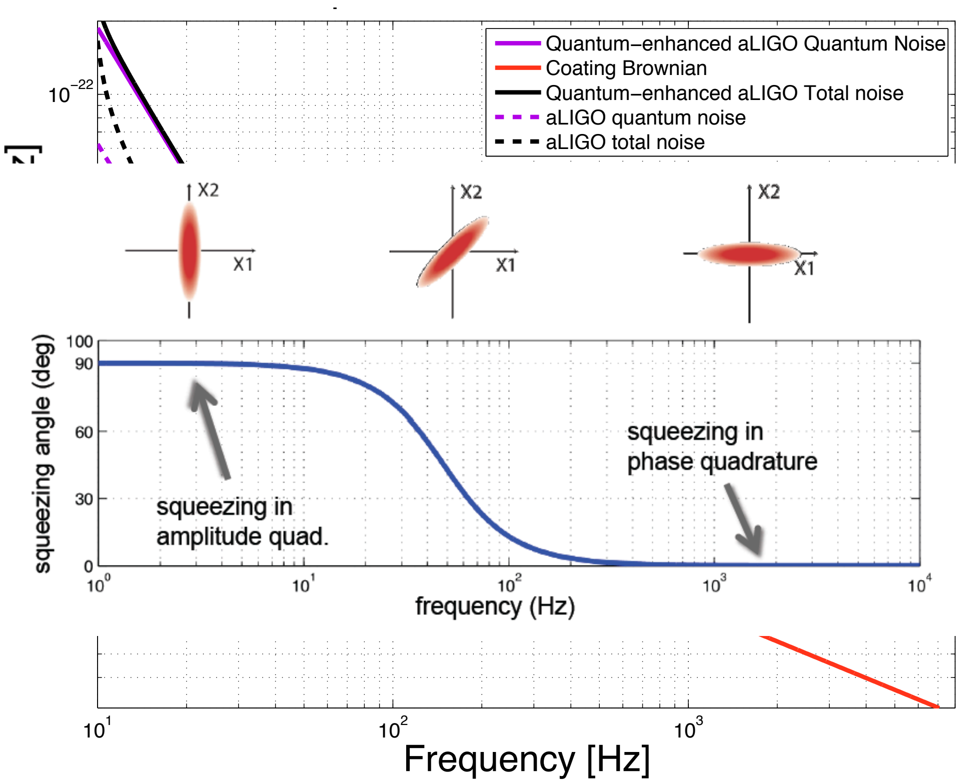


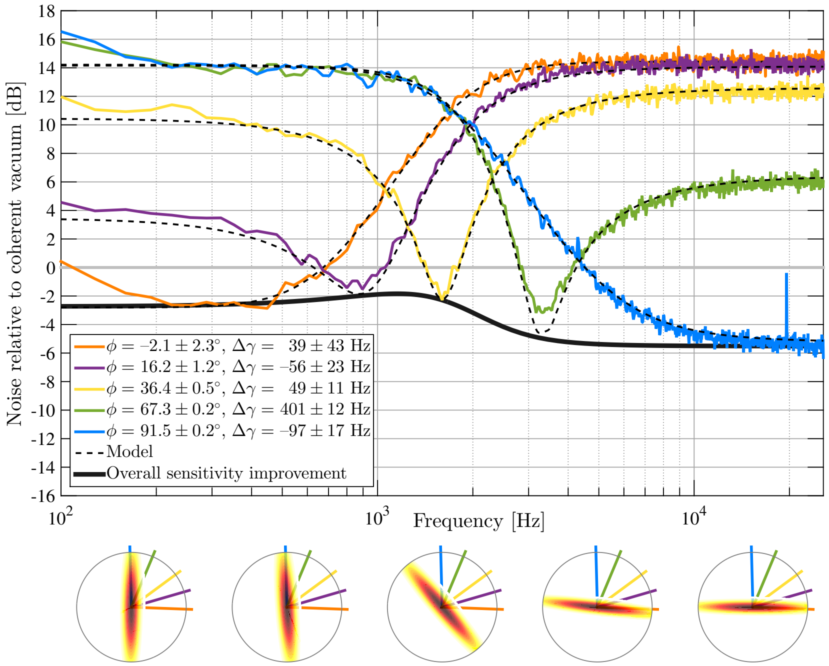
3.5 dB squeezing
(1.5X reduced noise)

2.1 dB squeezing
(1.27X reduced noise)

Aasi, et al., (LIGO Scientific Collaboration), Nature Physics, 7, 962 (2011); Nature Photonics 7 613 (2013).

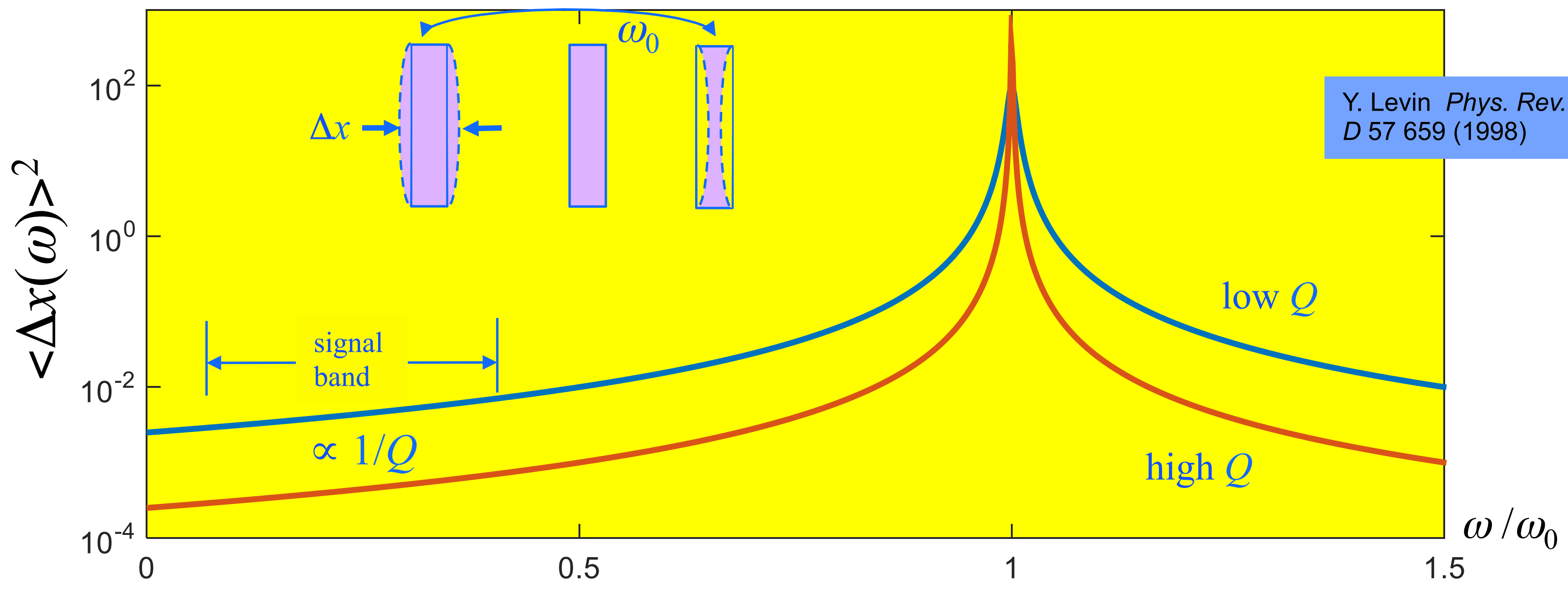
# The Best of Both Worlds: Frequency Dependent Squeezing





Oelker, et al., "Audio-band Frequency-dependent Squeezing", Phys. Rev. Lett. 116, 041102 (2016).

# Thermal Noise in Optical Coatings



Y. Levin *Phys. Rev. D* 57 659 (1998)

- Simple picture: $kT$ of energy per mechanical mode, viscous damping
- For coating dominated noise and structural damping:

coating thickness

coating elastic loss

$$S_x(f,T) \approx \frac{2k_BT}{\pi^2 f}\frac{d}{w^2 Y}\phi\left(\frac{Y'}{Y}+\frac{Y}{Y'}\right)$$

beam radius

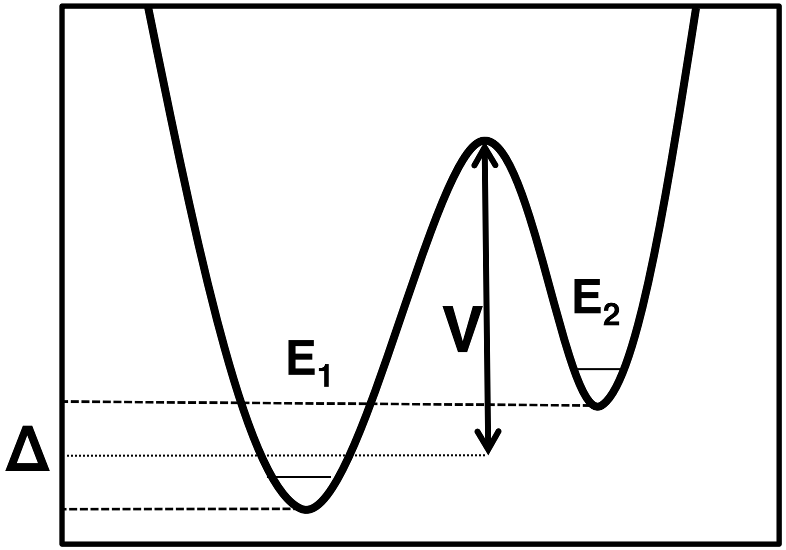
$$\phi_{\mathrm{TiO_2:Ta_2O_5}} = 2\times 10^{-4}$$
$$\phi_{\mathrm{SiO_2}} = 4\times 10^{-5}$$

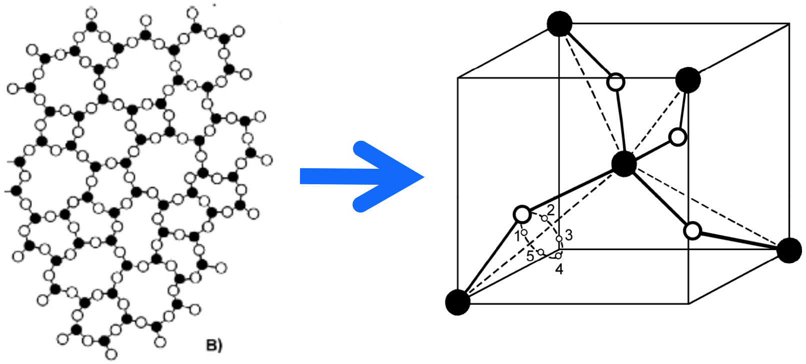
Compare: Bulk Silica $\phi \sim 10^{-6}$-$10^{-8}$

Slide Credit:
Marty Fejer, Stanford

# *Low-frequency losses in amorphous dielectrics*

- Loss mechanism: conventionally associated with low energy excitations (LEEs)
  - conceptualized as two-level systems (TLS); Distribution of TLSs arising from disordered structure
  - Simple physical mechanism: bond flopping in amorphous materials, e.g. $SiO_2$





(● = Si, ○ = O).

Single TLS

$$Q^{-1} = N\frac{\gamma^2}{Y\,kT}\frac{\omega\tau}{1+\omega^2\tau^2}\operatorname{sech}^2\left(\frac{\Delta}{kT}\right) \rightarrow$$

Distribution of TLSs

$$Q^{-1} = \frac{\gamma^2}{Y\,kT}\iint\frac{\omega\tau}{1+\omega^2\tau^2}\operatorname{sech}^2\left(\frac{\Delta}{kT}\right)g(V)\,f(\Delta)\,dV\,d\Delta$$

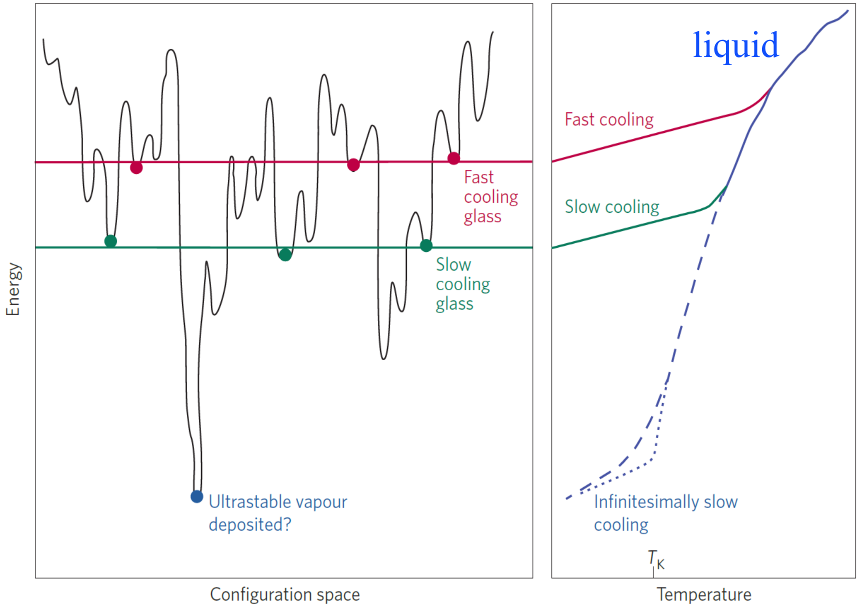
Figures: B.S. Lunin

# Routes to Improved Coatings with Low Thermal Noise

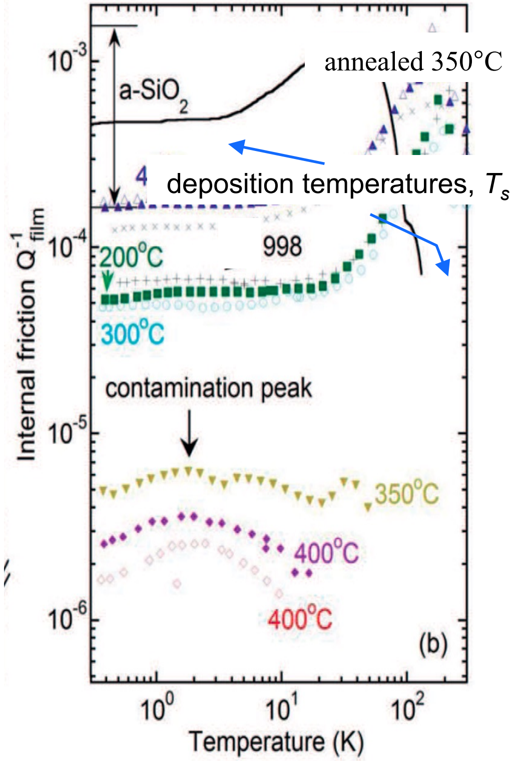
- Goal: ***2X – 4X reduction in coating thermal noise***

- Ultrastable glasses
  - Glasses prepared by physical vapor deposition show extraordinary stability
    - slower cooling liquid reaches lower energy states
  - simulations suggest surface liquid layer has orders of magnitude higher mobility than caged particles in solids

- Internal friction of films deposited at high temperatures $T_s$
  - very different from film annealed at same temperature
  - $\phi \sim 2\text{x}10^{-6}$ vs $\sim 10^{-4}$



S. Singh, et al. *Nature Mater.* 12, 139 (2013); Parisi, *Nature Mater.* 12, 94 (2013)



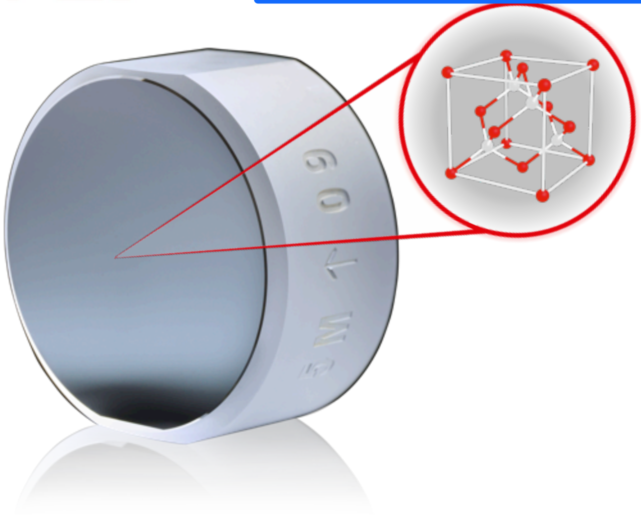
X. Liu, F. Hellman, et al, *Phys. Rev. Lett.* 113, 025503 (2014)

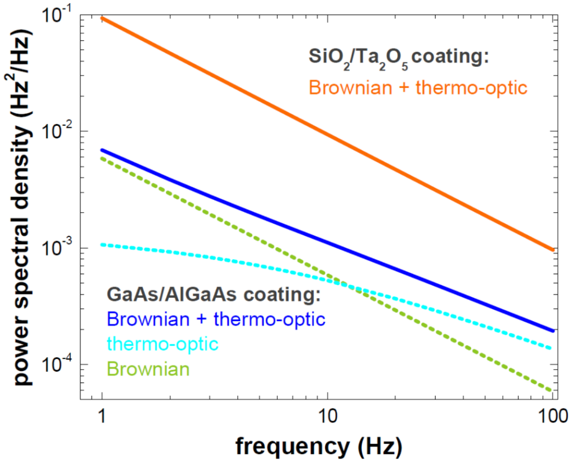
Challenge: extendable to amorphous oxides? Scalable to commercial coating methods?

# Routes to Improved Coatings with Low Thermal Noise

- Goal: ***2X – 4X reduction in coating thermal noise***
  - Crystalline coatings
    - molecular beam epitaxy to generate crystalline GaAs/AlGaAs multilayer
    - mirror disc lithography and etch, substrate removal, and direct bonding on substrate

Challenge: i) Scalability
Current state-of-the-art: 75 mm aperture. LIGO needs: > 300 mm (Cost!)
ii) Coating uniformity: $10^{-4}$ (IBS) vs $10^{-2}$ (crystalline)

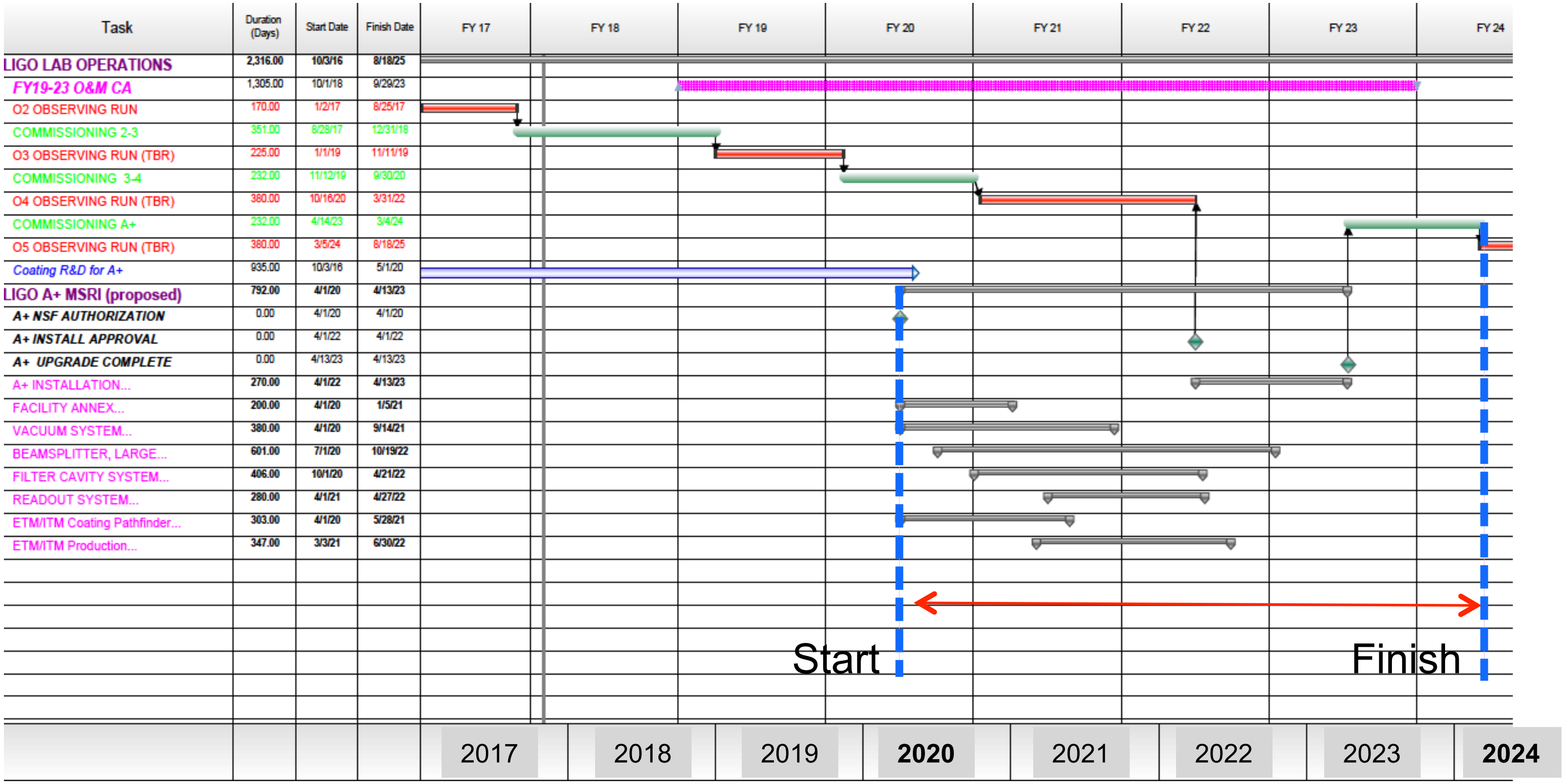




G. D. Cole, W. Zhang, M. J. Martin, J. Ye, and M. Aspelmeyer, *Nature Photonics* (2013)

# *Preliminary A+ Schedule*

- Possible project start date in early 2020 (paced by funding)
- Installation start date early 2022



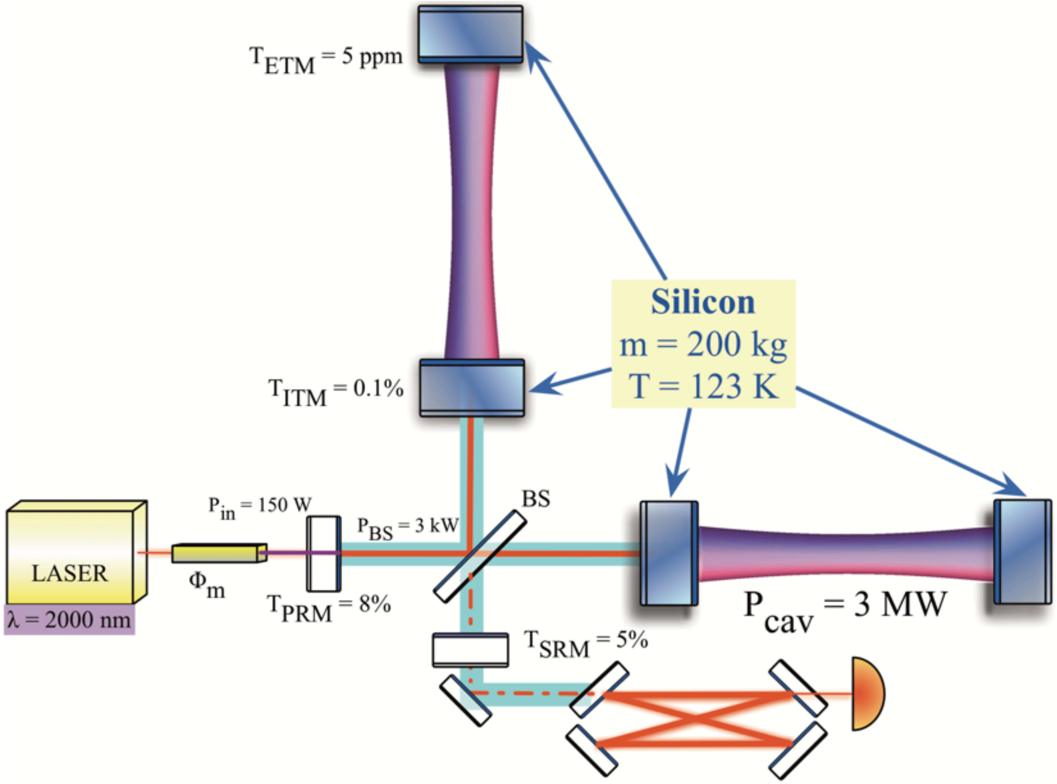
| Task | Duration (Days) | Start Date | Finish Date |
|---|---|---|---|
| **LIGO LAB OPERATIONS** | **2,316.00** | **10/3/16** | **8/18/25** |
| ***FY19-23 O&M CA*** | 1,305.00 | 10/1/18 | 9/29/23 |
| O2 OBSERVING RUN | 170.00 | 1/2/17 | 8/25/17 |
| COMMISSIONING 2-3 | 351.00 | 8/28/17 | 12/31/18 |
| O3 OBSERVING RUN (TBR) | 225.00 | 1/1/19 | 11/11/19 |
| COMMISSIONING 3-4 | 232.00 | 11/12/19 | 9/30/20 |
| O4 OBSERVING RUN (TBR) | 380.00 | 10/16/20 | 3/31/22 |
| COMMISSIONING A+ | 232.00 | 4/14/23 | 3/4/24 |
| O5 OBSERVING RUN (TBR) | 380.00 | 3/5/24 | 8/18/25 |
| *Coating R&D for A+* | 935.00 | 10/3/16 | 5/1/20 |
| **LIGO A+ MSRI (proposed)** | **792.00** | **4/1/20** | **4/13/23** |
| ***A+ NSF AUTHORIZATION*** | 0.00 | 4/1/20 | 4/1/20 |
| ***A+ INSTALL APPROVAL*** | 0.00 | 4/1/22 | 4/1/22 |
| ***A+ UPGRADE COMPLETE*** | 0.00 | 4/13/23 | 4/13/23 |
| A+ INSTALLATION... | **270.00** | **4/1/22** | **4/13/23** |
| FACILITY ANNEX... | **200.00** | **4/1/20** | **1/5/21** |
| VACUUM SYSTEM... | **380.00** | **4/1/20** | **9/14/21** |
| BEAMSPLITTER, LARGE... | **601.00** | **7/1/20** | **10/19/22** |
| FILTER CAVITY SYSTEM... | **406.00** | **10/1/20** | **4/21/22** |
| READOUT SYSTEM... | **280.00** | **4/1/21** | **4/27/22** |
| ETM/ITM Coating Pathfinder... | **303.00** | **4/1/20** | **5/28/21** |
| ETM/ITM Production... | **347.00** | **3/3/21** | **6/30/22** |

# Exploiting the LIGO Observatory Facility Limits:

# LIGO Voyager

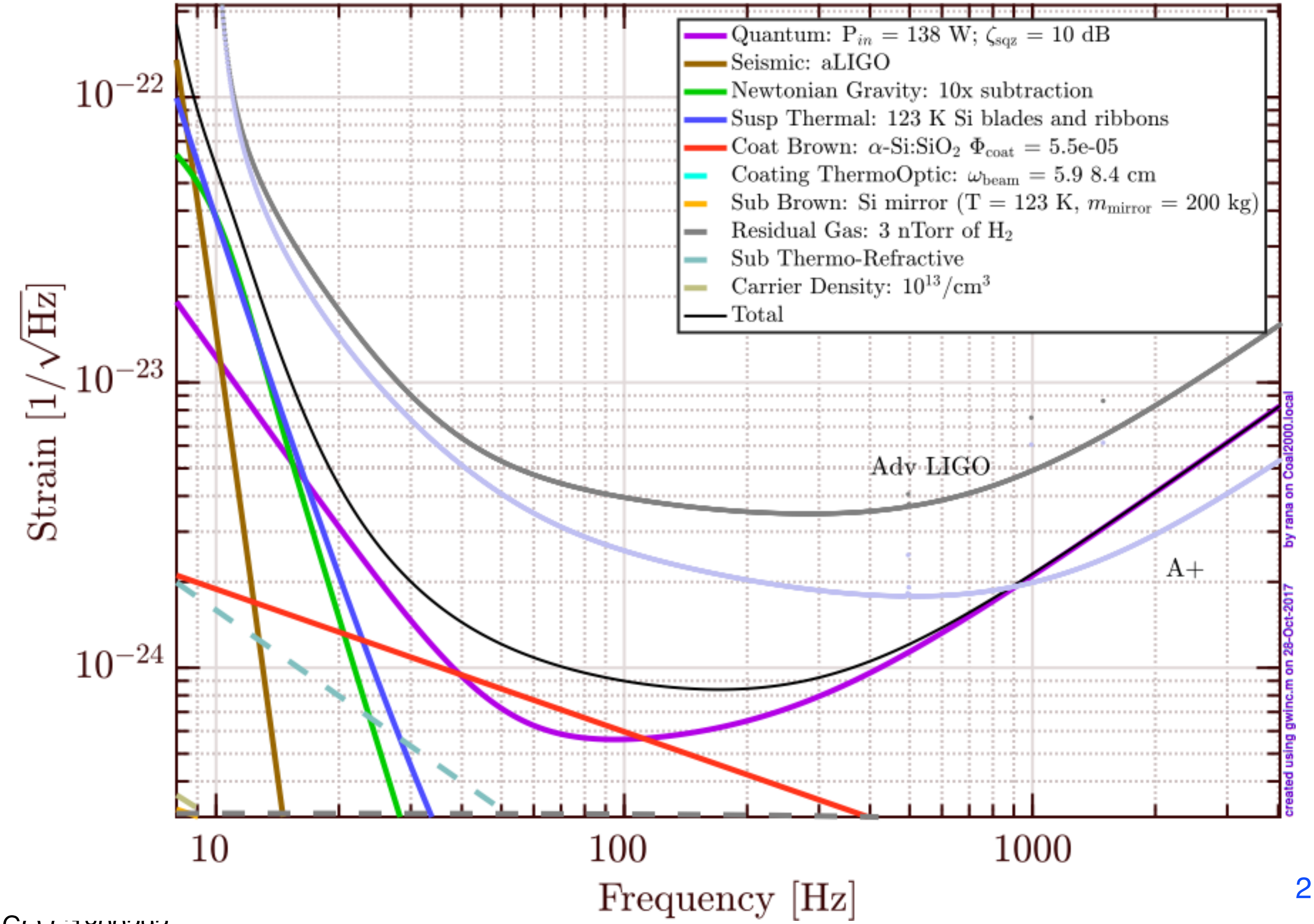
# LIGO Voyager Concept

- *Voyager Key Technologies*
  - **Silicon Mirrors**: 200 kg, 45 cm dia., mCZ process
  - **Mirror Coatings:** α-Si/$SiO_2$ (α-Si: ~lossless thin film)
  - **Cryogenics:** 123 K (zero CTE), radiative (non-contact) cooling
  - **Lasers (2000 nm):** P~ 180 W, $P_{ARM}$ ~ 2800 kW
  - **Wavefront Compensation:** thermally adjustable lenses only (no actuation of test mass)
  - **Photodiode Quantum Efficiency**: 80 -> 99% for 2 micron

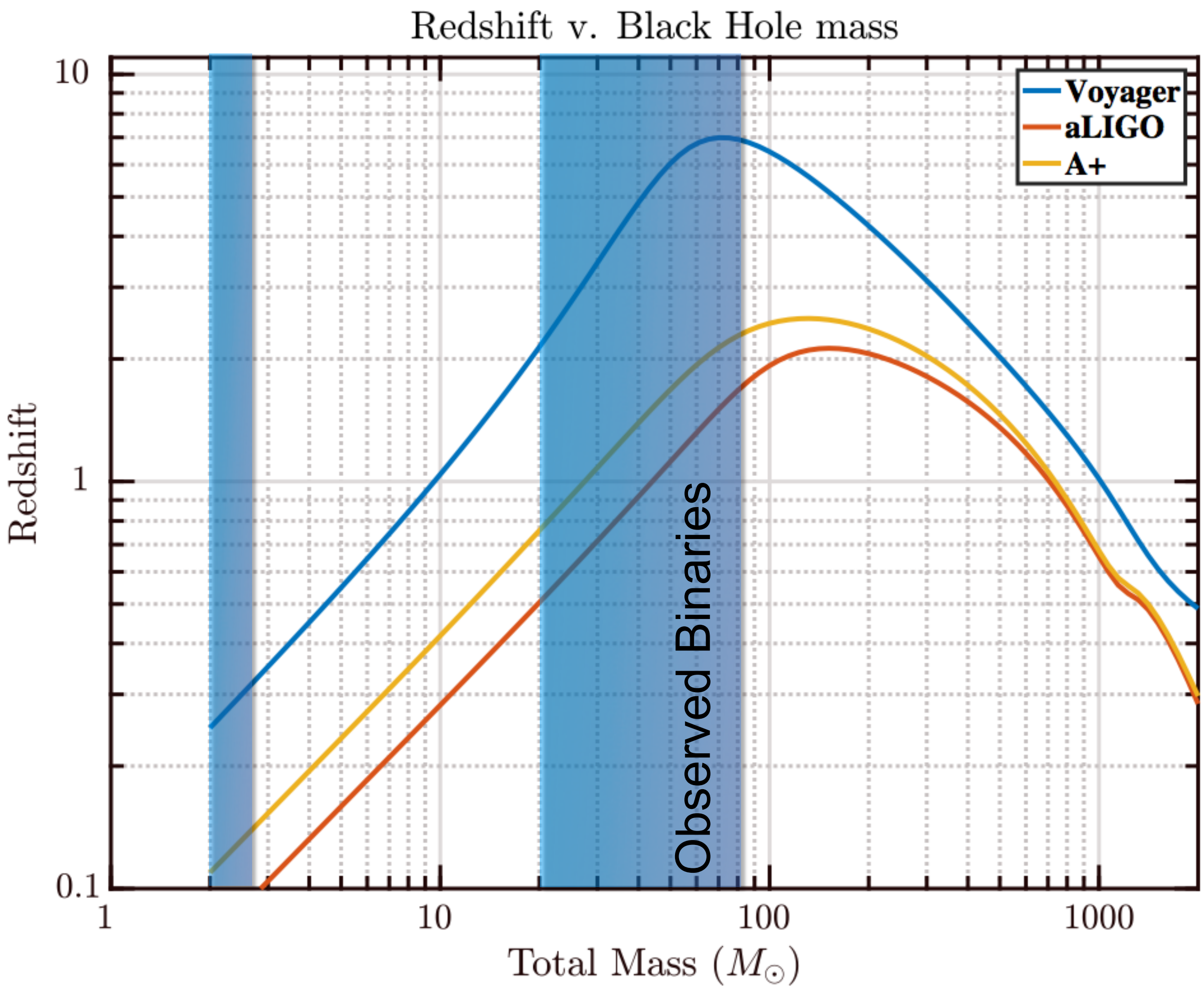


(No change to Advanced LIGO seismic isolation system!)

# *LIGO Voyager Conceptual Design Sensitivity*



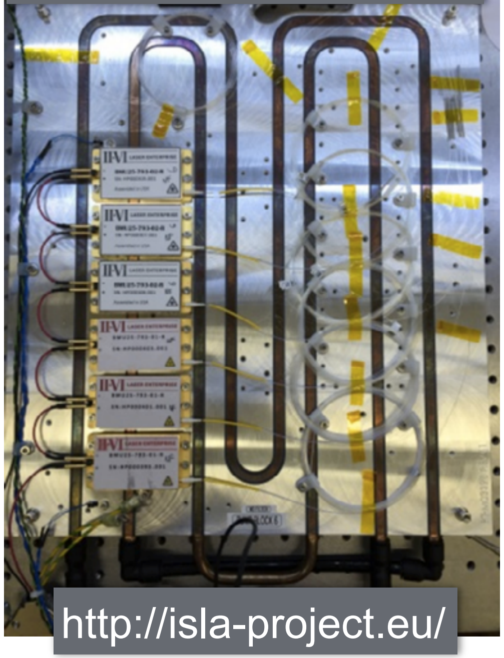
# *Voyager Reach for Compact Binary Mergers*



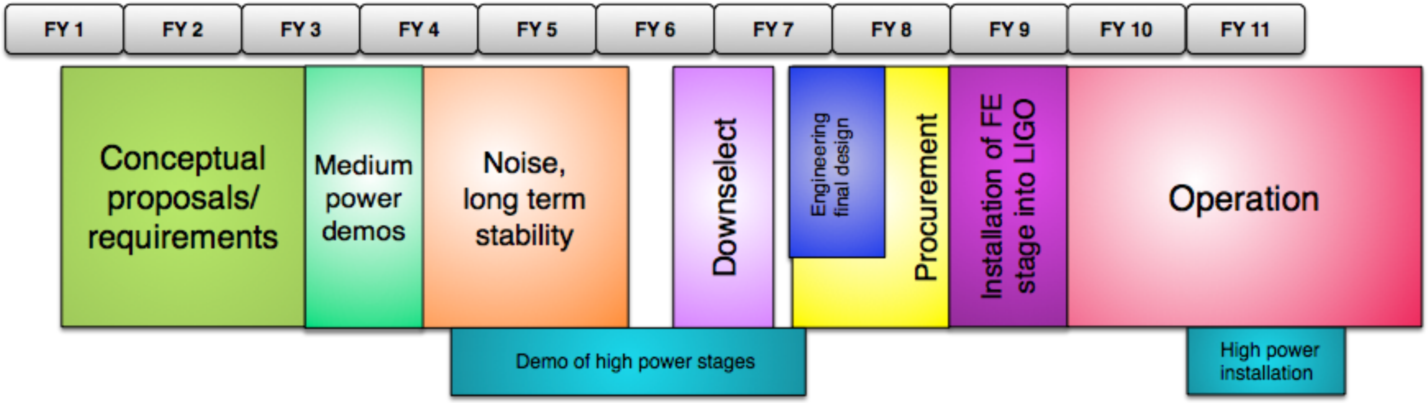
# Technology: 2 Micron Lasers

- 2 $\mu$m Tm:YAG, Ho:YAG commercial lasers exist
  - low power/low noise, or high power/ high noise
- Challenge is to make high power/low noise
- Development programs underway by several gravitational wave groups
  - Decade long program envisioned

EU Funded 2 micron laser study



http://isla-project.eu/



FY 1 | FY 2 | FY 3 | FY 4 | FY 5 | FY 6 | FY 7 | FY 8 | FY 9 | FY 10 | FY 11

Conceptual proposals/ requirements

Medium power demos

Noise, long term stability

Downselect

Engineering final design

Procurement

Installation of FE stage into LIGO

Operation

Demo of high power stages

High power installation

Slide inspiration: Rana Adhikari, LIGO Laboratory

# Technology: 200 kg Silicon Mirror

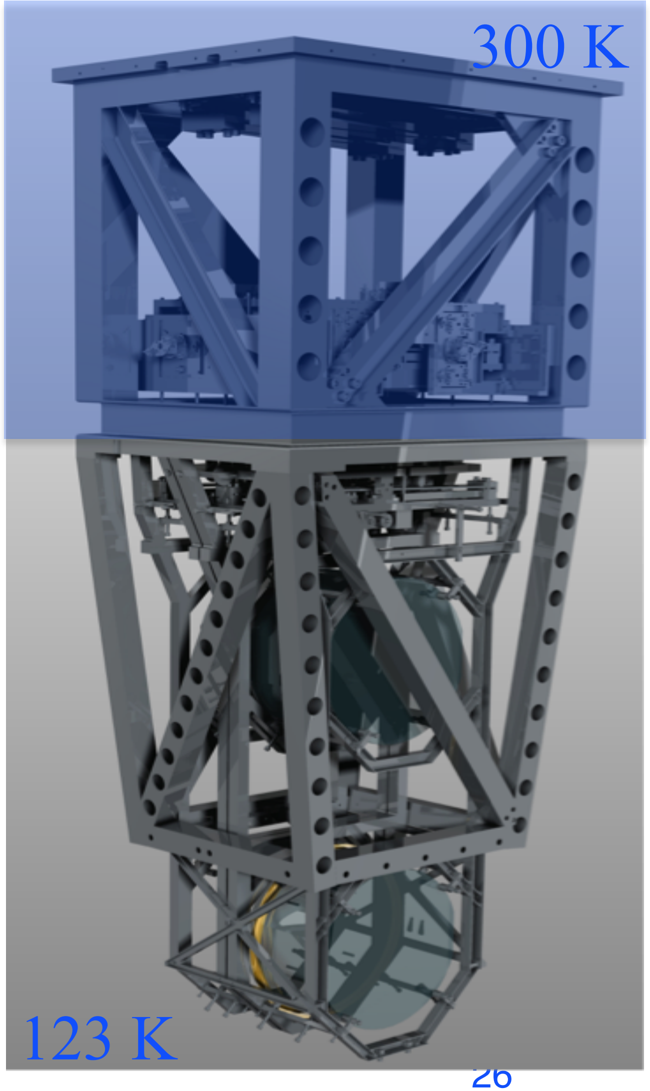
- Main challenges are i) mirror size, ii) absorption
  - **Goal**: absorbed Power < 3 W;
  - 3 ppm/cm (FZ): max diameter ~ 20 cm
  - mCZ from SEH can get
  - samples acquired, absorption measurements done (< 4 ppm)
  - SEH Japan will make 45 cm diameter mCZ
  - how to sequence all of the annealing? Different processes for substrates, coatings.

Slide inspiration: Rana Adhikari, LIGO Laboratory

# *Technology: Cryogenics (Not Really…)*

Cooling needed to (only!)123 K

- Non-contact, radiative cooling
- No cryogens in vacuum
- Only cooling lower 2 stages of mirror suspension
- ~5 W cooling required
- An engineering effort
  - Designs being looked at by several LSC groups

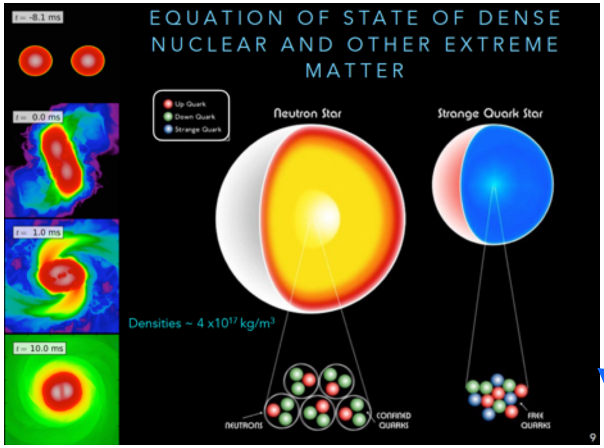


# Future 3G Facilities:

# Einstein Telescope and Cosmic Explorer

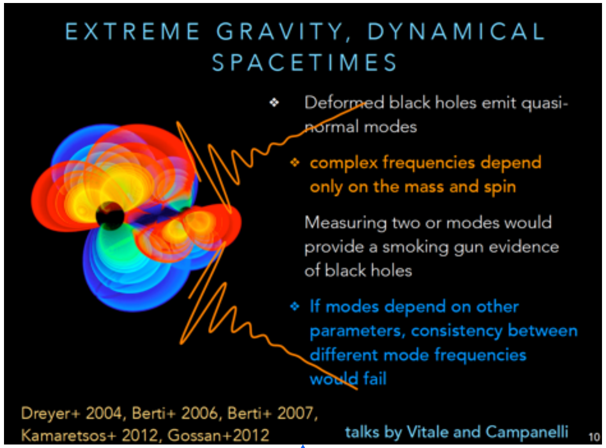
B. Sathyaprakash, Dawn III Workshop,
https://wiki.ligo.org/LSC/LIGOworkshop2017/WebHome

# *Making the 3G Science Case*



## EQUATION OF STATE OF DENSE NUCLEAR AND OTHER EXTREME MATTER

Densities ~ 4 x$10^{17}$ kg/m$^3$

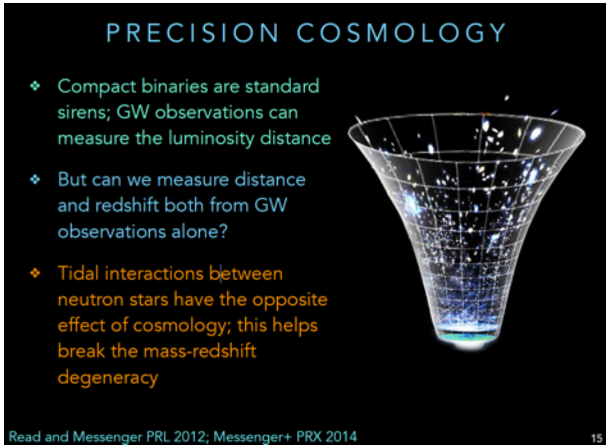


## EXTREME GRAVITY, DYNAMICAL SPACETIMES

- Deformed black holes emit quasi-normal modes
  - complex frequencies depend only on the mass and spin
  - Measuring two or modes would provide a smoking gun evidence of black holes
  - If modes depend on other parameters, consistency between different mode frequencies would fail

Dreyer+ 2004, Berti+ 2006, Berti+ 2007, Kamaretsos+ 2012, Gossan+2012

talks by Vitale and Campanelli

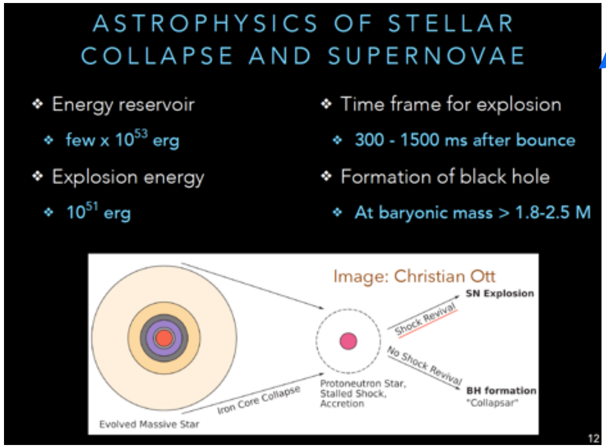


## PRECISION COSMOLOGY

- Compact binaries are standard sirens; GW observations can measure the luminosity distance
- But can we measure distance and redshift both from GW observations alone?
- Tidal interactions between neutron stars have the opposite effect of cosmology; this helps break the mass-redshift degeneracy

Read and Messenger PRL 2012; Messenger+ PRX 2014

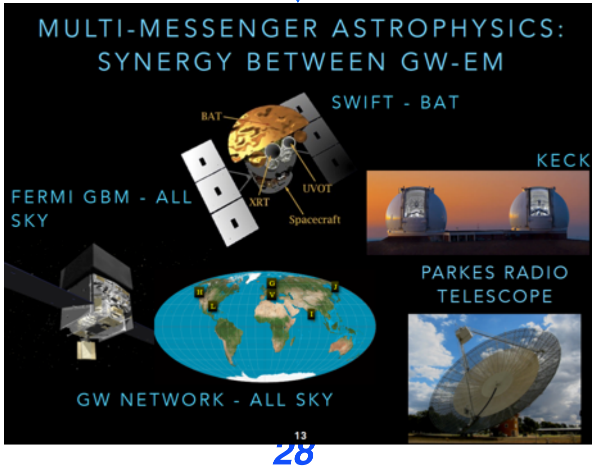
The 3G Gravitational Wave Ground-based Network



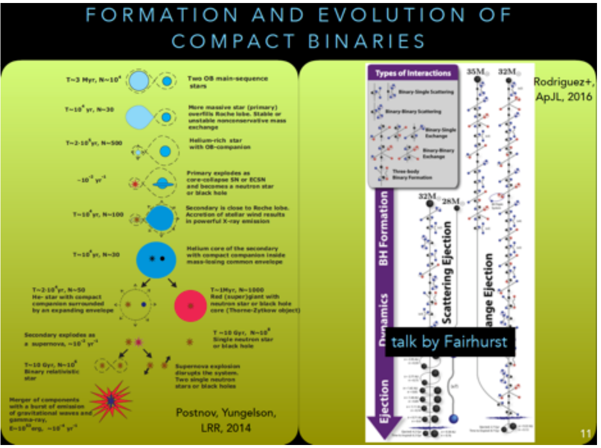
## ASTROPHYSICS OF STELLAR COLLAPSE AND SUPERNOVAE

- Energy reservoir
  - few x $10^{53}$ erg
- Explosion energy
  - $10^{51}$ erg
- Time frame for explosion
  - 300 - 1500 ms after bounce
- Formation of black hole
  - At baryonic mass > 1.8-2.5 M

Image: Christian Ott



## MULTI-MESSENGER ASTROPHYSICS: SYNERGY BETWEEN GW-EM



## FORMATION AND EVOLUTION OF COMPACT BINARIES

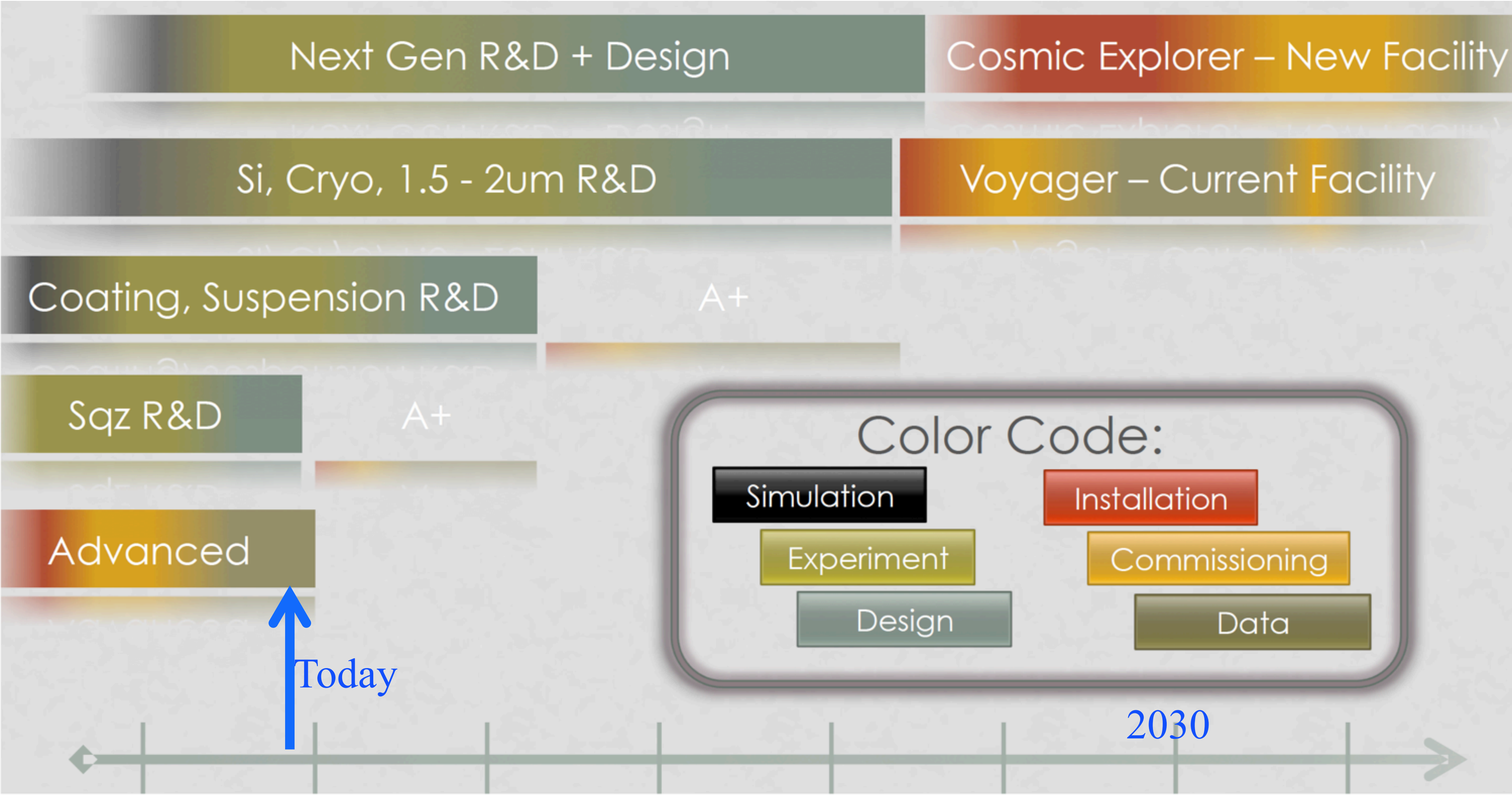
Rodriguez+, ApJL, 2016

Postnov, Yungelson, LRR, 2014

talk by Fairhurst

# *(Very) Conceptual Timeline For New Observatories*

LSC Instrument Science White Paper 2017-2018, LIGO-T1700231–v2



Next Gen R&D + Design

Cosmic Explorer – New Facility

Si, Cryo, 1.5 - 2um R&D

Voyager – Current Facility

Coating, Suspension R&D

A+

Sqz R&D

A+

Advanced

Today

Color Code:

Simulation

Installation

Experiment

Commissioning

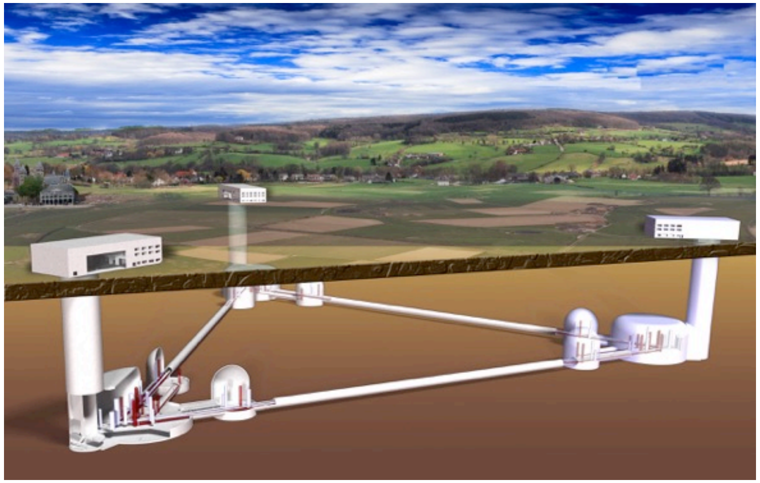
Design

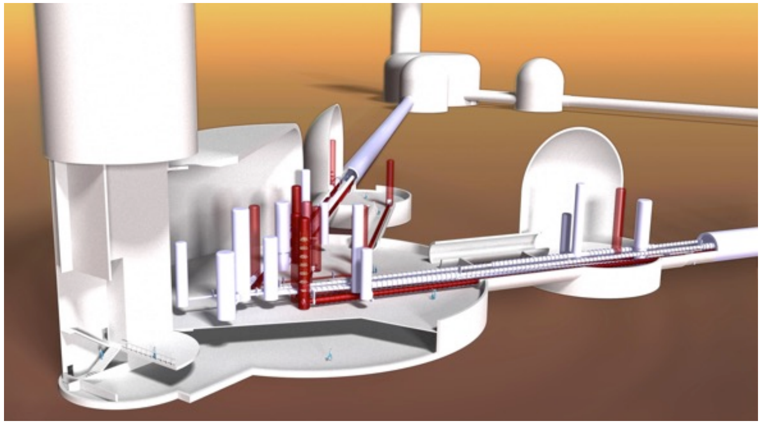
Data

2030

# *Einstein Telescope (Europe)*

- Third-generation GW observatory
- Target sensitivity for Einstein telescope is a factor of ten better in comparison to current advanced detectors
- 10 km long, Underground
- Xylophone configuration, 6 interferometers





Formal Design Study completed in 2011: http://www.et-gw.eu/etdsdocument

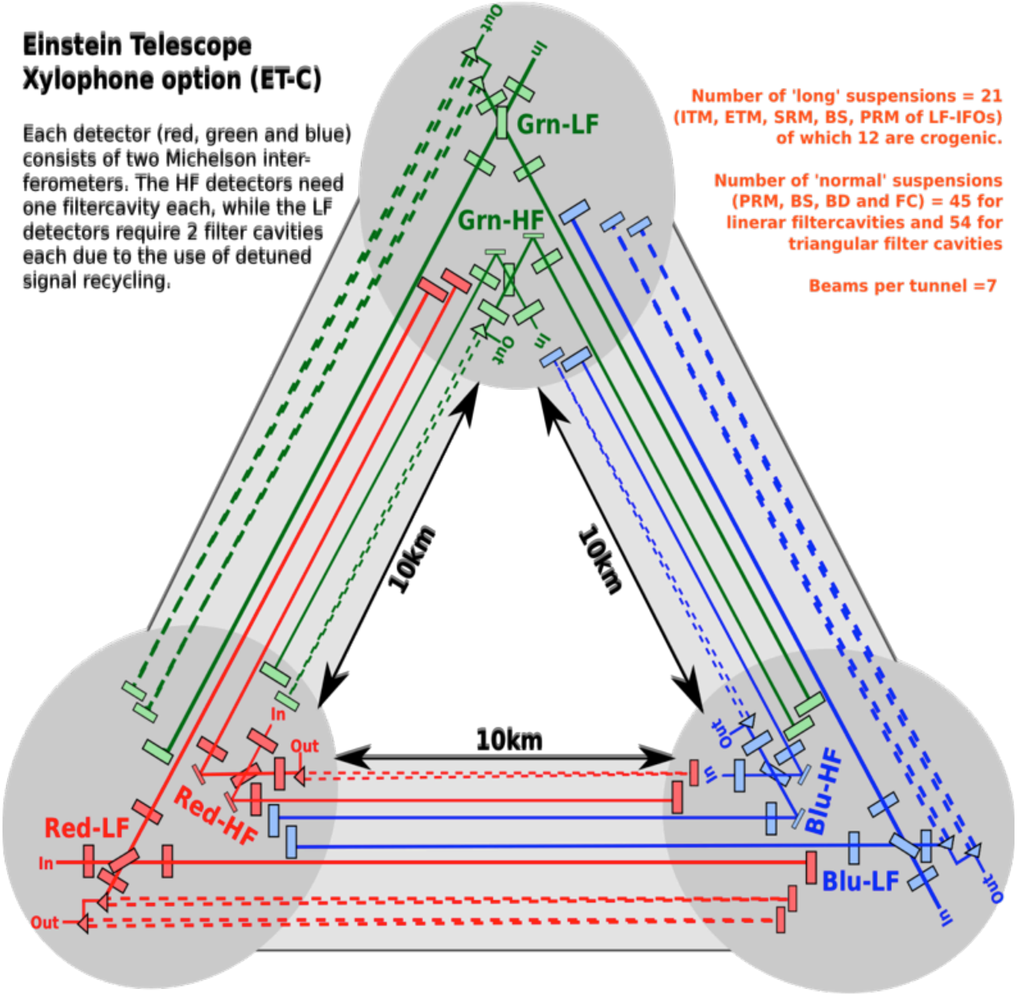
# ET Configuration

Start with a single xylophone detector.

Add second Xylophone detector to fully resolve polarisation.

Add third Xylophone detector for redundancy and null-streams.

Allows upgrading one detector while keeping full functionality of observatory and minimize down time



**Einstein Telescope Xylophone option (ET-C)**

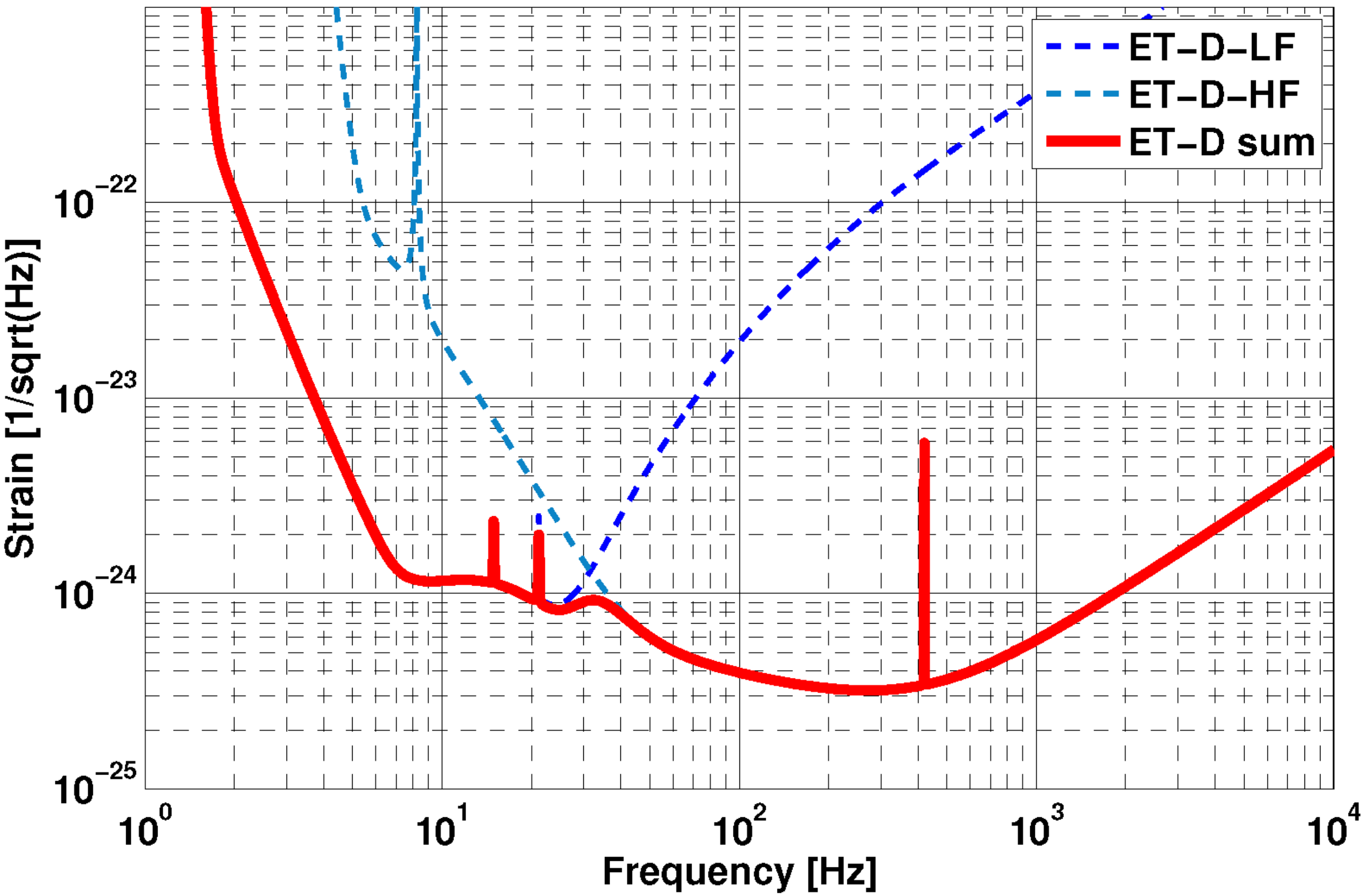
Each detector (red, green and blue) consists of two Michelson interferometers. The HF detectors need one filtercavity each, while the LF detectors require 2 filter cavities each due to the use of detuned signal recycling.

Number of 'long' suspensions = 21 (ITM, ETM, SRM, BS, PRM of LF-IFOs) of which 12 are crogenic.

Number of 'normal' suspensions (PRM, BS, BD and FC) = 45 for linear filtercavities and 54 for triangular filter cavities

Beams per tunnel =7

# *Einstein Telescope Conceptual Design Sensitivity*



http://www.et-gw.eu/index.php/etsensitivities

# Cosmic Explorer (US)

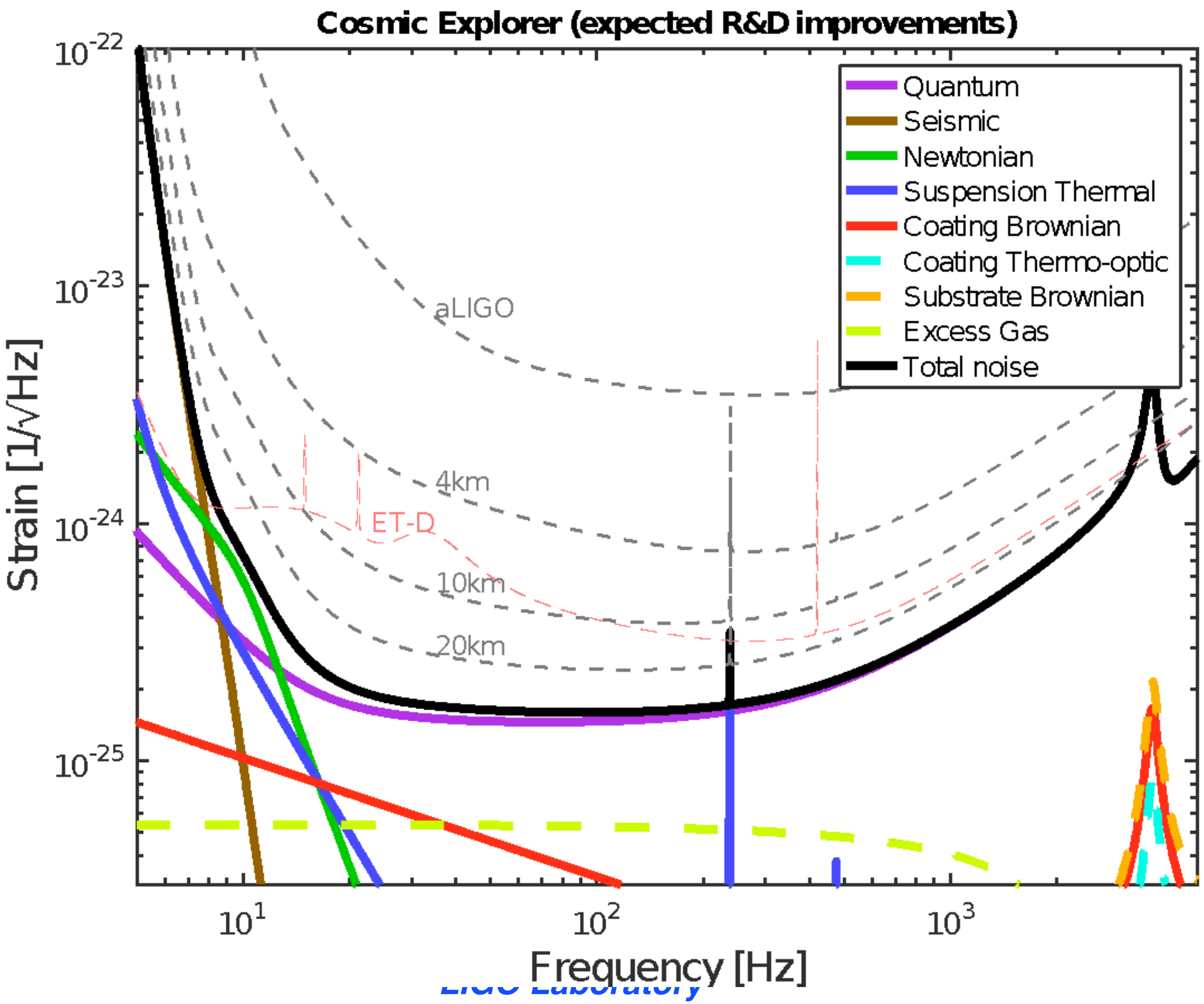
- Third-generation GW observatory
- Target sensitivity a factor of > 10 improvement in comparison to current advanced detectors
- Above ground, 40 km arm length, L configuration

Formal Design Study: not yet, but proposal under development (M. Evans, MIT, PI

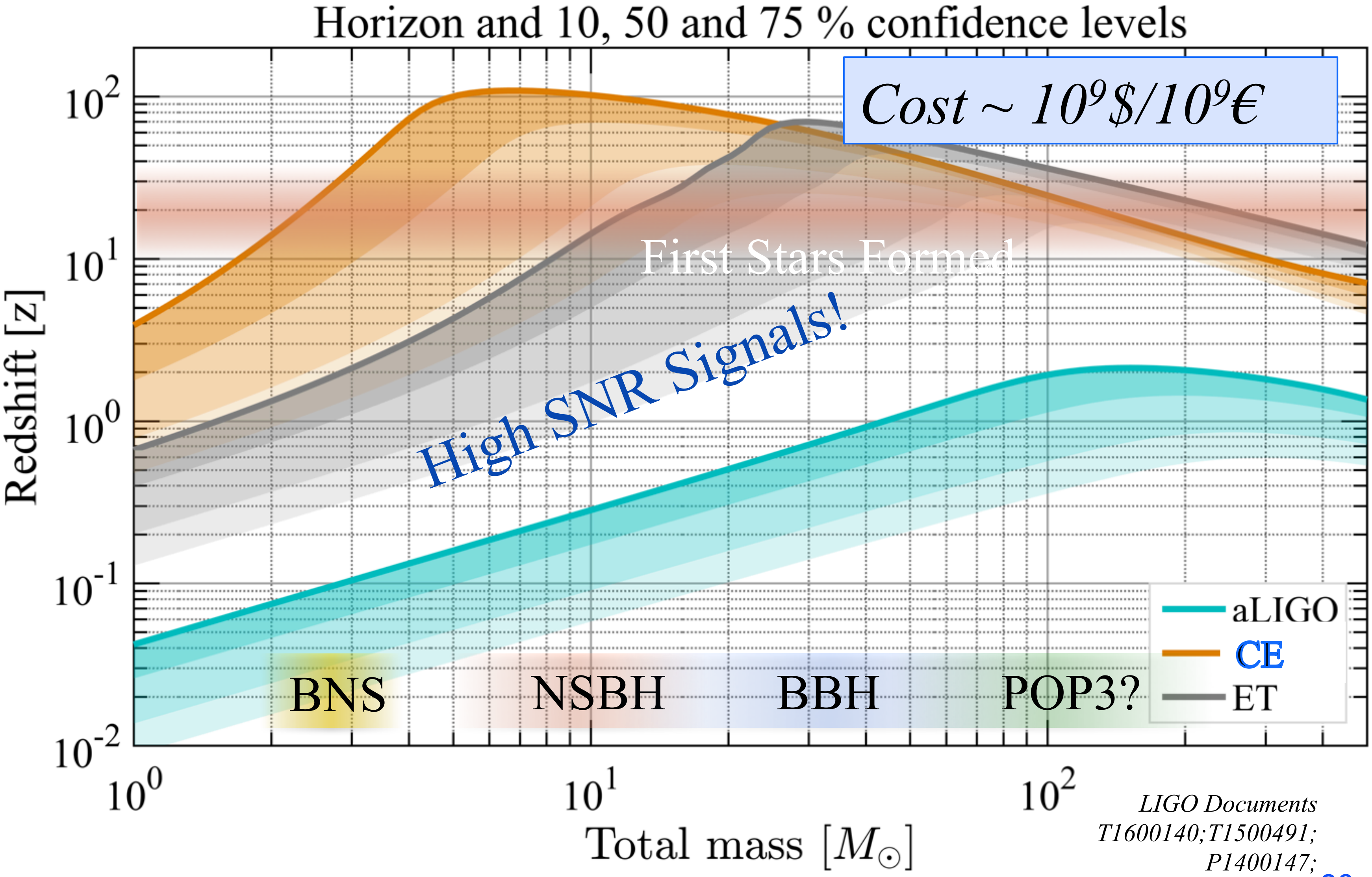
Credit:
R. Ward
S. Ballmer

**Surface, right-angle, 40km on a side, 1 interferometer**

# Cosmic Explorer Conceptual Design Sensitivity



# ET and CE Have Cosmological Reach



*Cost ~ $10^9$\$/$10^9$€*

High SNR Signals!

*LIGO Documents T1600140;T1500491; P1400147; ET Document ET-0106C-10*

# How to Get To A 3rd Generation Observatory?

## GWIC (Gravitational Wave International Committee)

***Body formed in 1997 to facilitate international collaboration and cooperation in the construction, operation and use of the major gravitational wave detection facilities world-wide***

- Affiliated with the International Union of Pure and Applied Physics
  - From 1999 until 2011, GWIC was recognized as a subpanel of PaNAGIC (IUPAP WG.4).
  - In 2011, GWIC was accepted by IUPAP as a separate Working Group (WG.11).

Links to the:
International Astronomical Union (IAU)
International Society for General Relativity and Gravitation (ISGRG)

# GWIC's role in coordinating 3G detector development

## *GWIC Subcommittee on Third Generation Ground-based Detectors*

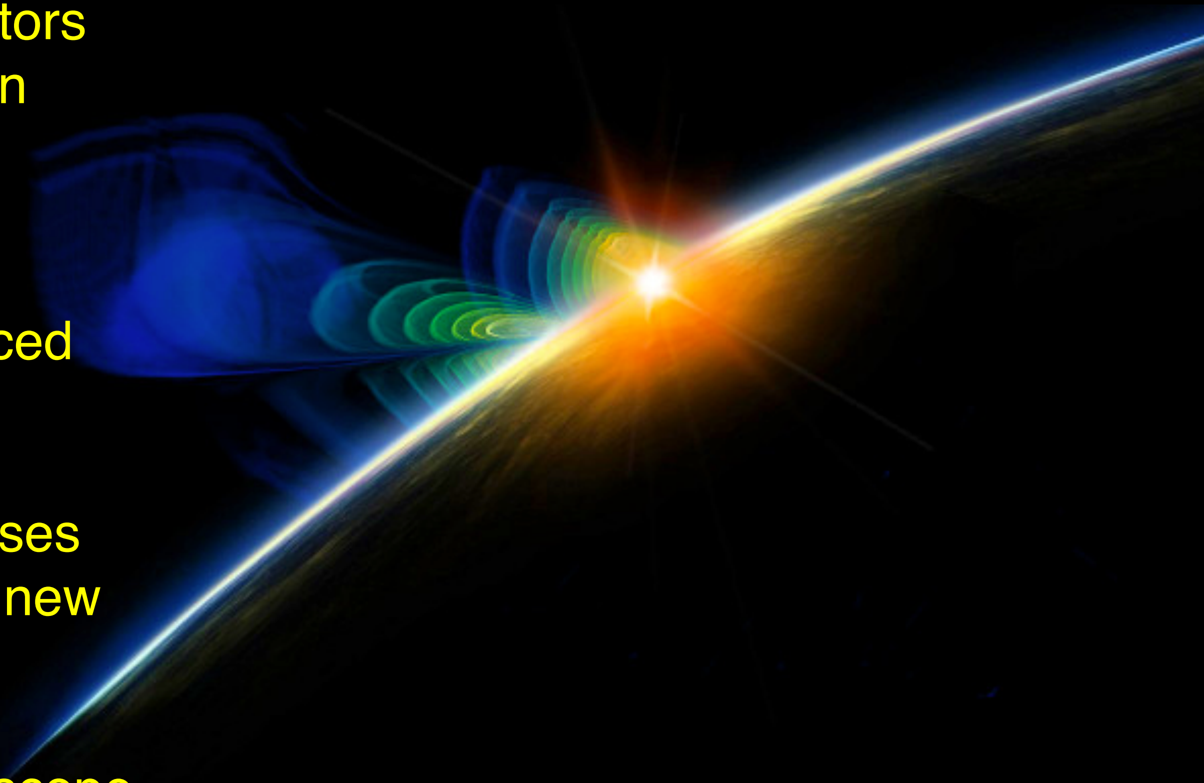
GWIC subcommittee purpose and charge:

With the recent first detections of gravitational waves by LIGO and Virgo, it is both timely and appropriate to begin seriously planning for a network of future gravitational-wave observatories, capable of extending the reach of detections well beyond that currently achievable with second generation instruments.

The GWIC Subcommittee on Third Generation Ground-based Detectors is tasked with examining the path to a future network of observatories/facilities

Web Site https://gwic.ligo.org/3Gsubcomm/

# *Summary: The Future for Gravitational-wave Astronomy is Bright*



- Ground-based GW detectors will continue to advance in sensitivity in the coming decades
- Near term: A+, an Advanced LIGO upgrade
- Medium term: Voyager, uses existing facilities but with new technologies
- Long term: Einstein Telescope and Cosmic Explorer, new facilities

Stay Tuned!

With material from (and thanks to): Rana Adhikari, Matt Evans, Mike Zucker, Harald Lueck, John Miller, B. Sathyaprakash