Vacuum Technology for 3G Gravitational Wave Antennas

Mike Zucker, LIGO Caltech & MIT

Beampipes for Gravitational Wave Telescopes 2023

27-29 March, 2023

LIGO-G2300708

Topics

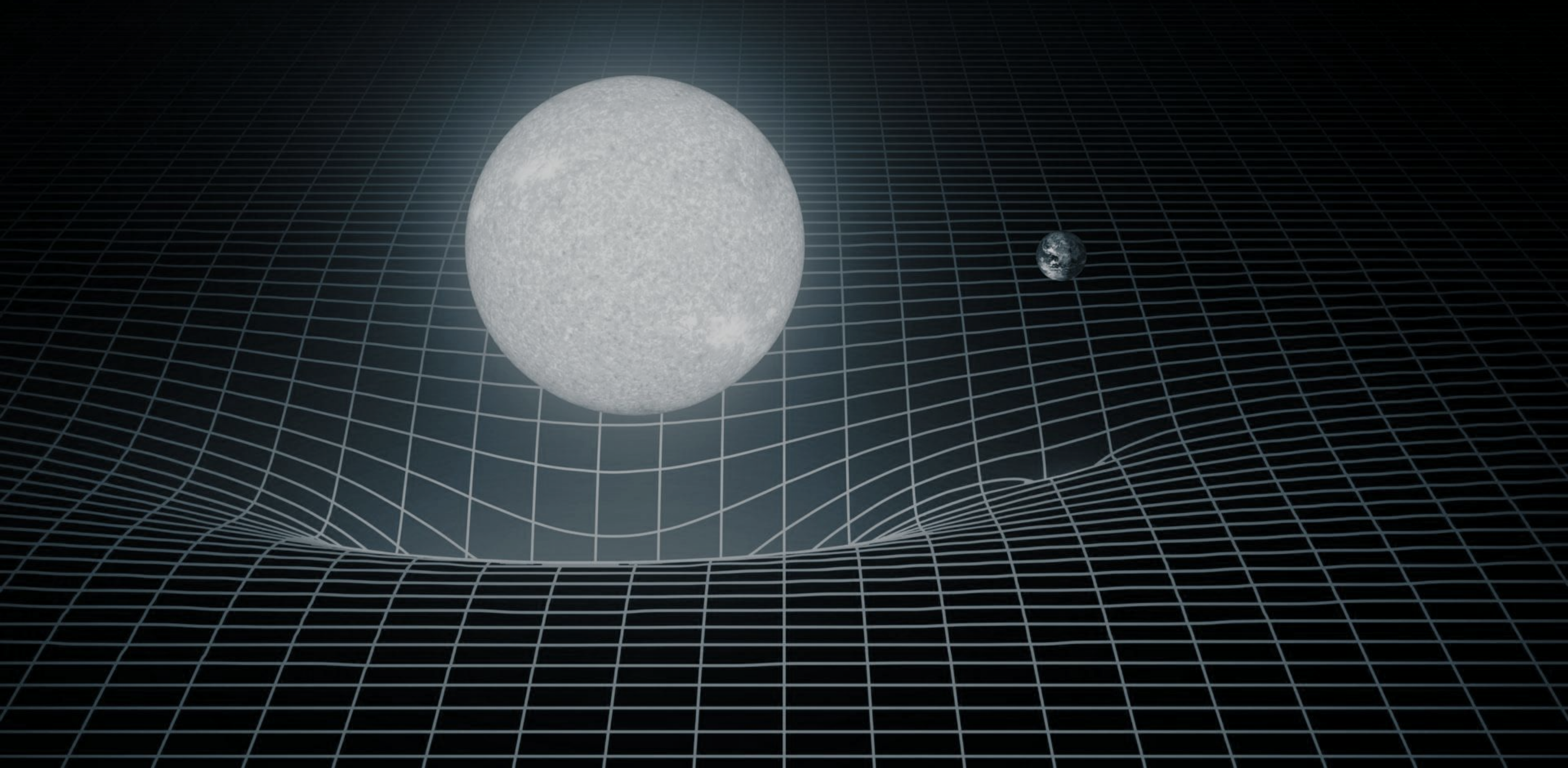
An Introduction

Brief primer: Gravitational Waves

Orientation: Future GW Machines

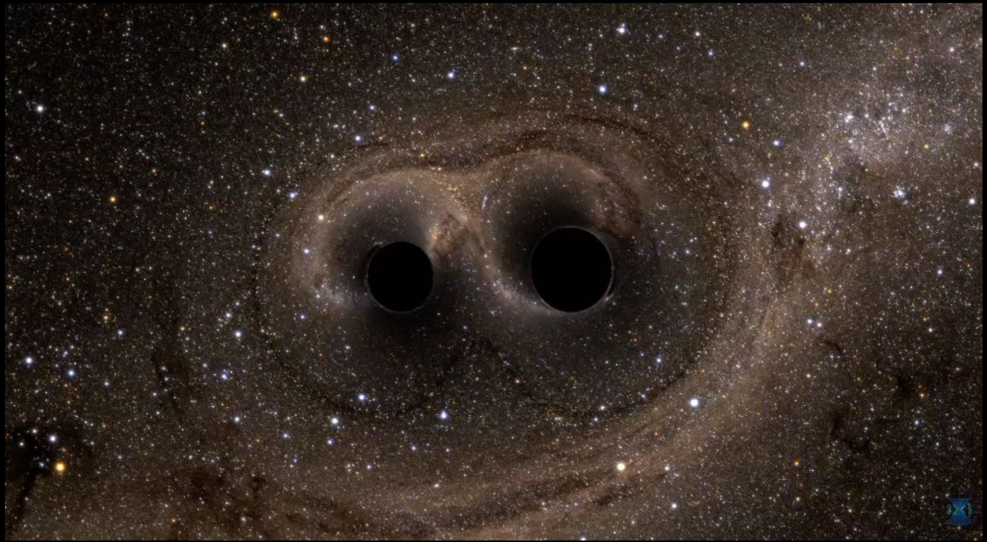
Focus: Vacuum Technology Requirements

Gravity & Curved Space-time



Gravitational Waves

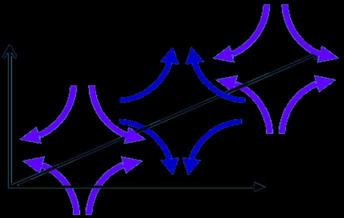
- Propagating dynamic ripples in the curvature of space-time
  - Predicted by Einstein in 1916 (but he didn't believe they could ever be detected)
- Emitted when a collection of mass changes its shape
  - Strength is determined by the time-derivative of the mass quadrupole moment
  - Massive objects moving at relativistic speeds are most likely to produce detectable amplitudes
  - Pass unimpeded through intervening matter
  - Ideal probes of the most extreme conditions in the universe



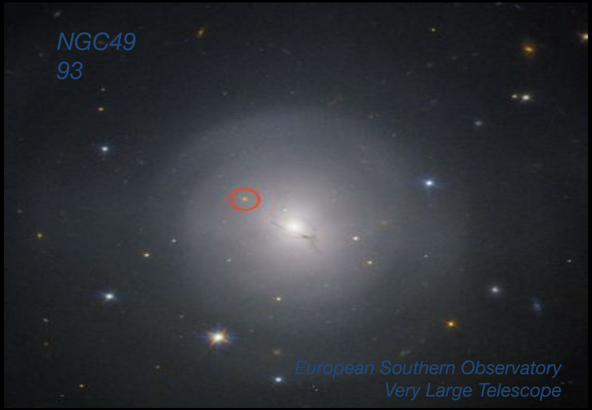
Detecting the effects

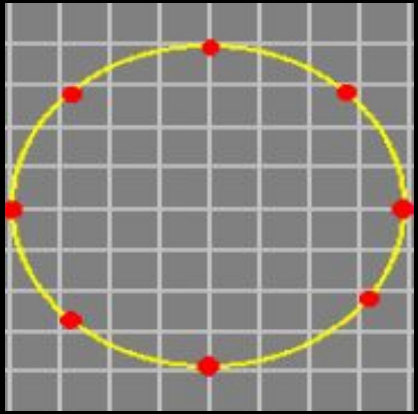
GW's produce time-varying *transverse strain* in space affecting relative separations of *free test particles*

Earth

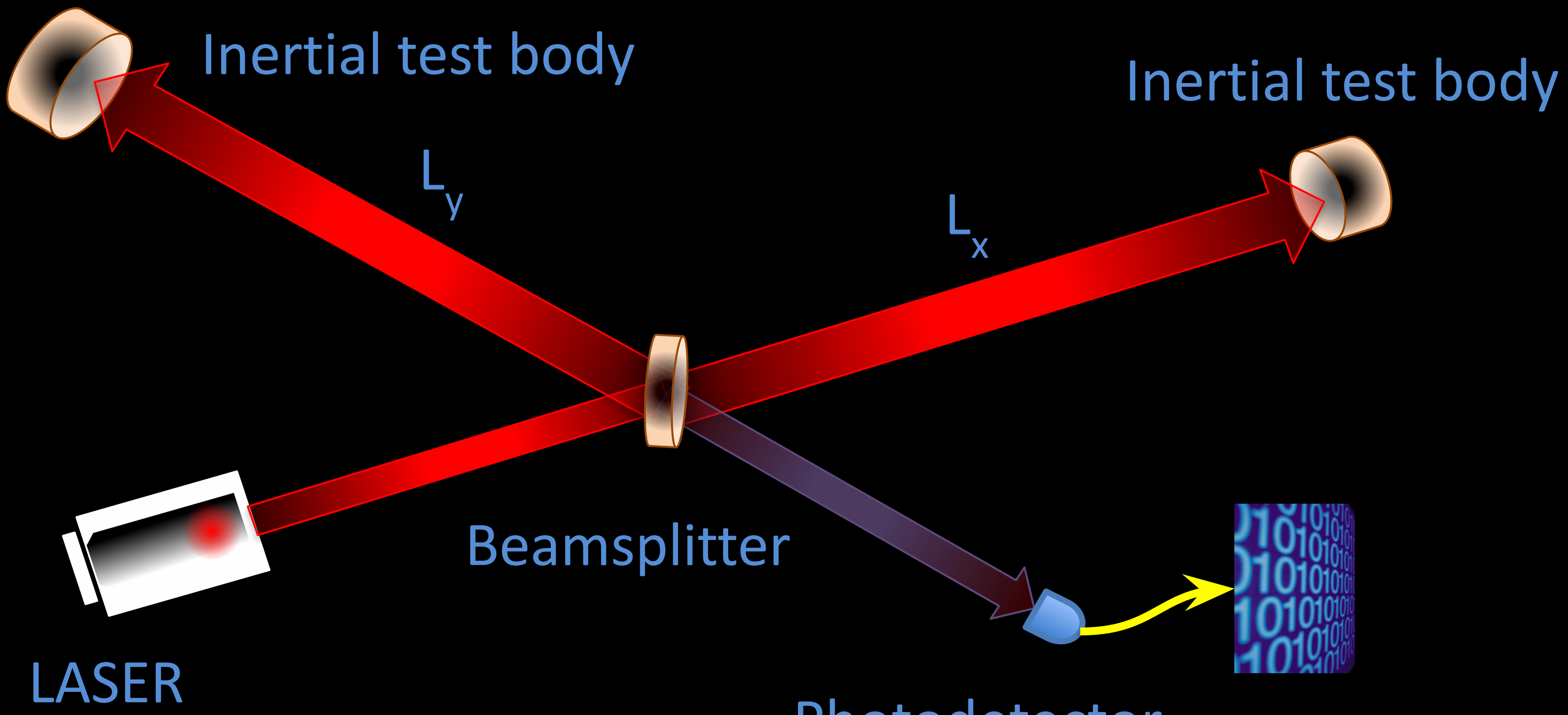


In a galaxy far far away…





Michelson interferometer



The "small" problem…

wave's strength corresponds to *strain* induced in the detector,

$$h = \Delta L / L$$

We can calculate expected strain at Earth;

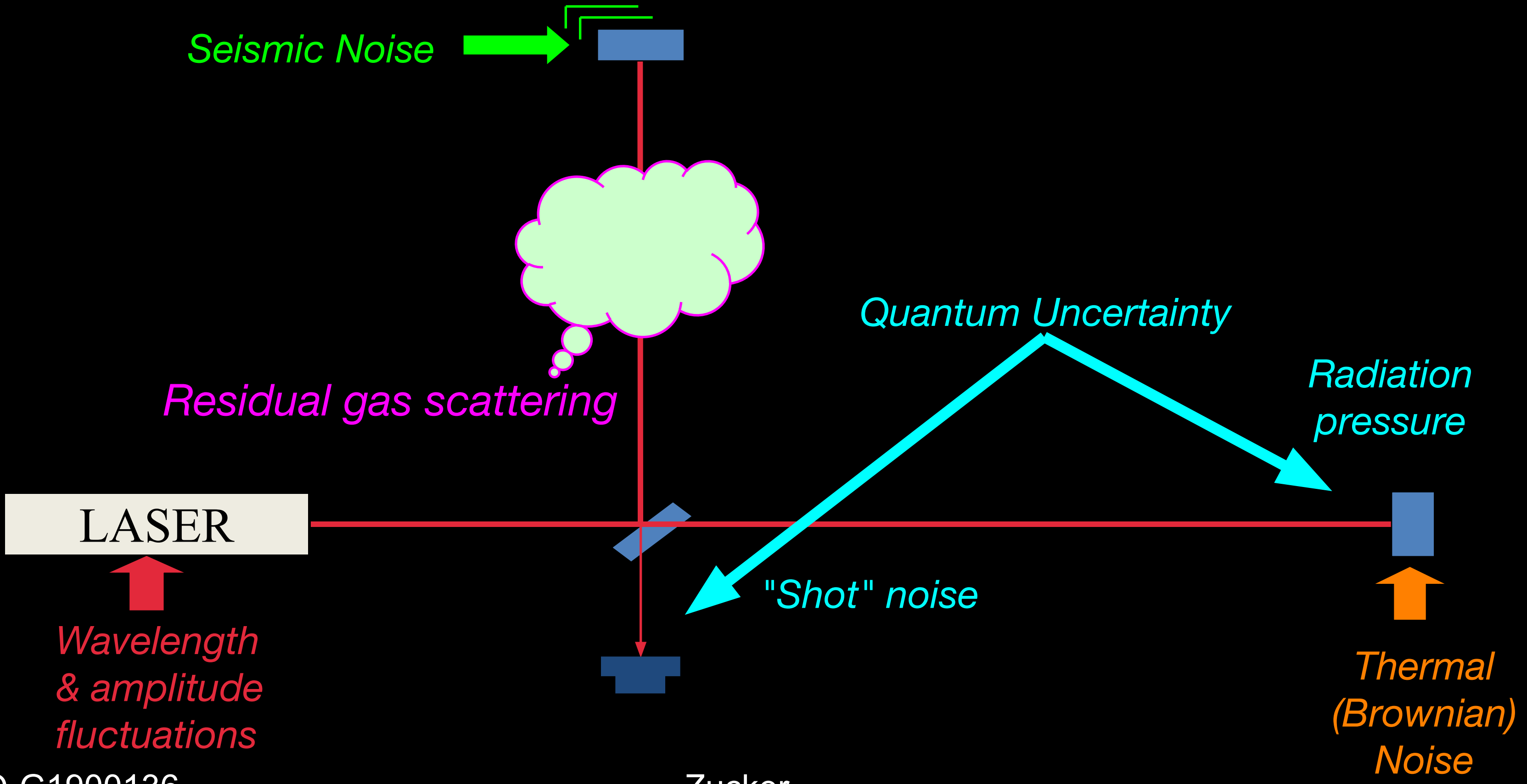
$$|h| \approx 4\pi^2 GMR^2 f_{orbit}^2 / c^4 r \approx 10^{-22} \left(\frac{R}{20\text{km}}\right)^2 \left(\frac{M}{M_\Theta}\right) \left(\frac{f_{orbit}}{400\text{Hz}}\right)^2 \left(\frac{100\text{Mpc}}{r}\right)$$

If we make an interferometer 4,000 meters long,

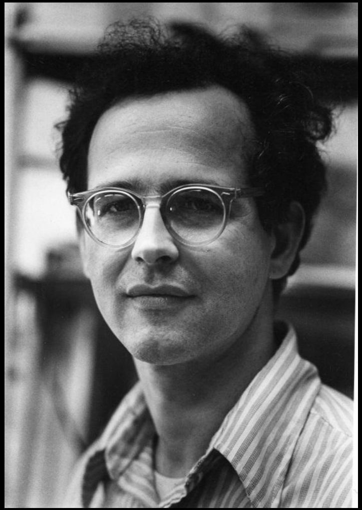
$$\Delta L = h \times L \approx 10^{-22} \times 4,000\, m \approx 4 \cdot 10^{-19}\, m$$

A ten-thousandth the size of an atomic nucleus

The obstacles: NOISE



Interferometric GW Detection



Rai Weiss, MIT

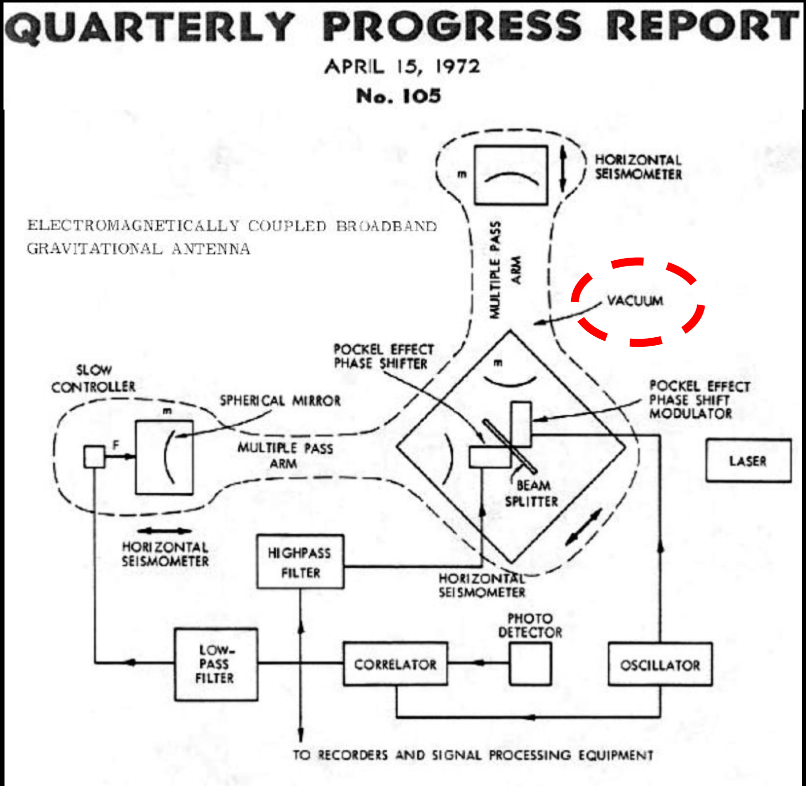
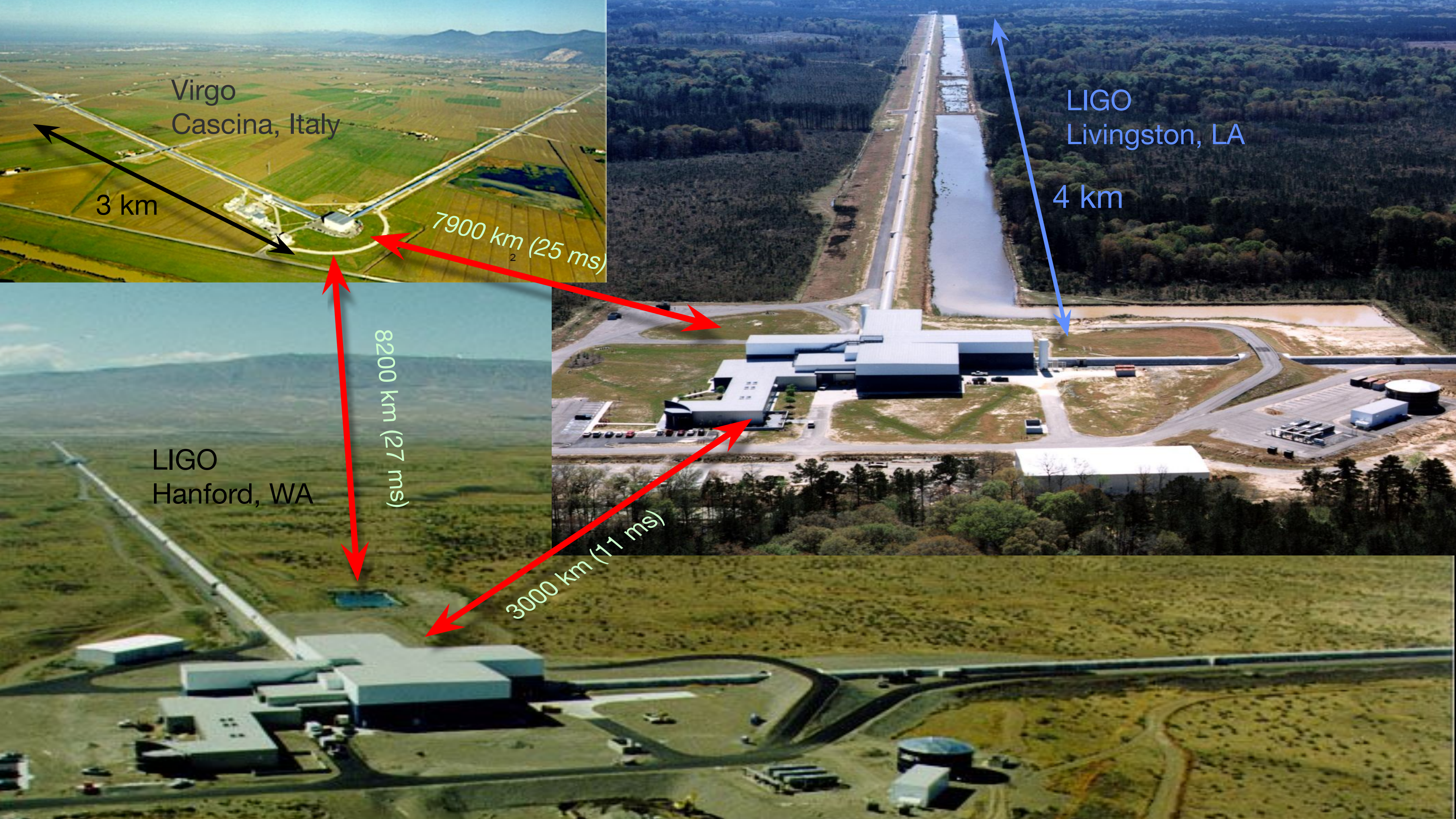


Fig. V-20. Proposed antenna.

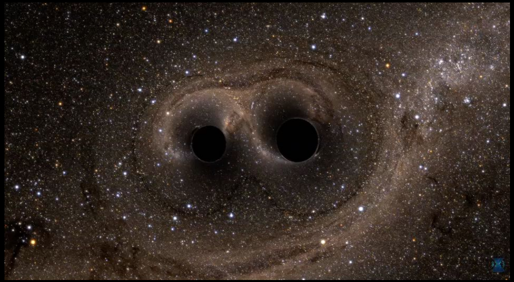

EXIT
Caltech
LSU

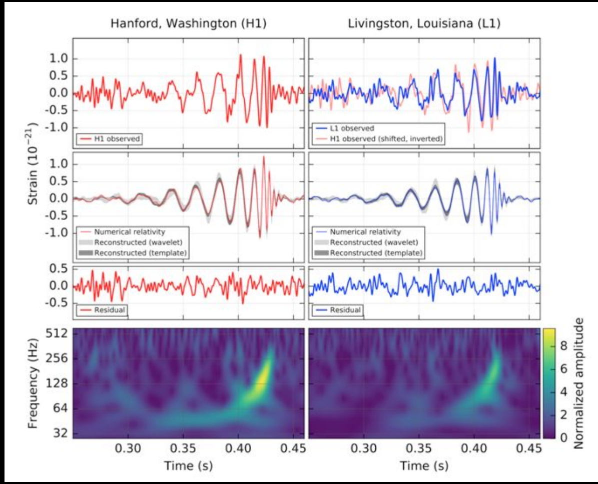


Virgo
Cascina, Italy
3 km
7900 km (25 ms)
LIGO
Livingston, LA
4 km
8200 km (27 ms)
LIGO
Hanford, WA
3000 km (11 ms)

Transformational Discoveries

First Detection of Gravitational Waves:
Binary Black Hole Merger GW150914
Sept 14, 2015

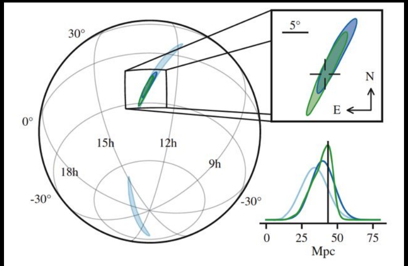




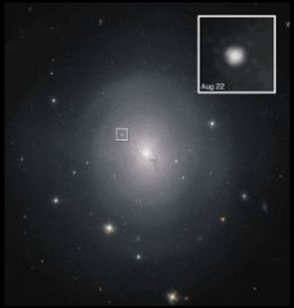
'Kilonova': Binary neutron star merger

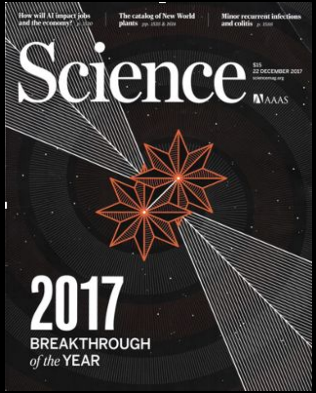
Dawn of Multi-messenger Astronomy with GW:

Binary Neutron Star Merger GW170817
Aug 17, 2017

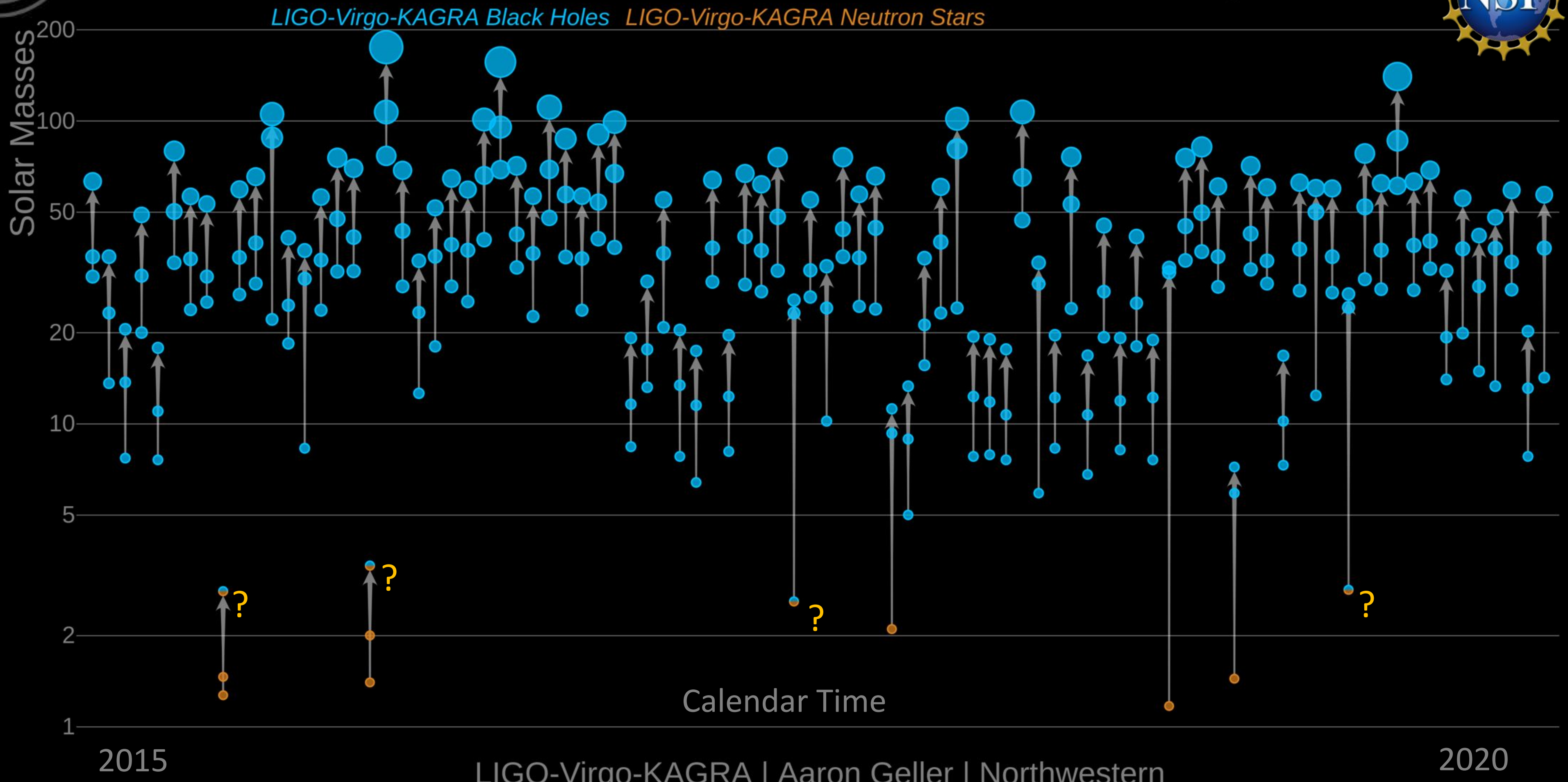


Optical (Hubble Telescope)





Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

An Abridged Astrophysical Gravitational-Wave Source Catalog

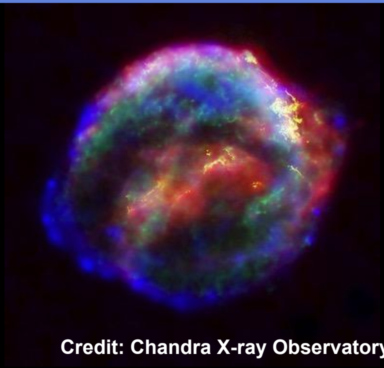
Modeled (Known Waveform) | **Unmodeled (Unknown Waveform)**

Short Duration

Credit: Bohn, Hébert, Throwe, SXS

Compact Binary Coalescences

- Black hole – black hole
- Black hole – neutron star
- Neutron star – neutron star
- Compact Binary Exotica
- (Three-body compact object systems)

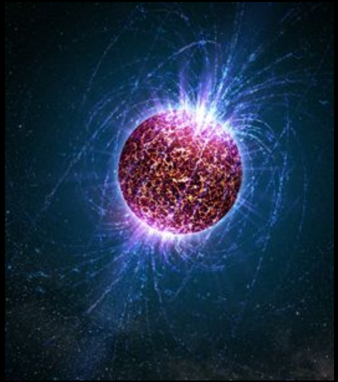


Credit: Chandra X-ray Observatory

'Burst-y'Sources

- Asymmetric core collapse supernovae
- Cosmic strings

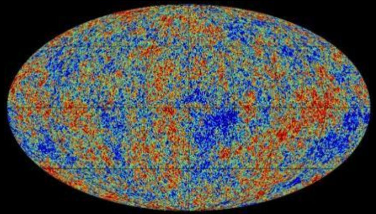
Long Duration



Credit: Casey Reed, Penn State

Continuous Sources

- Spinning neutron stars (including pulsars and radio-invisible NSs)

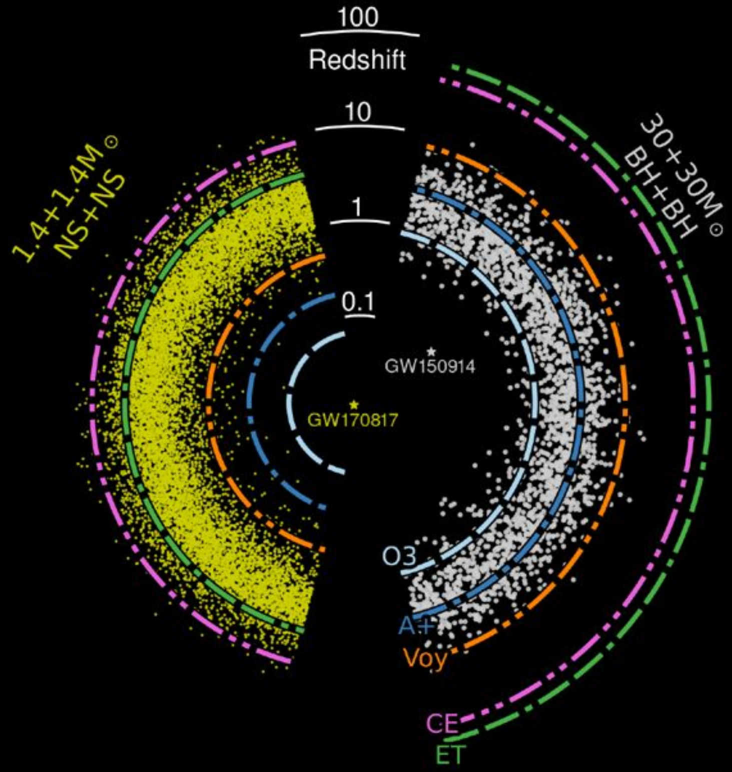


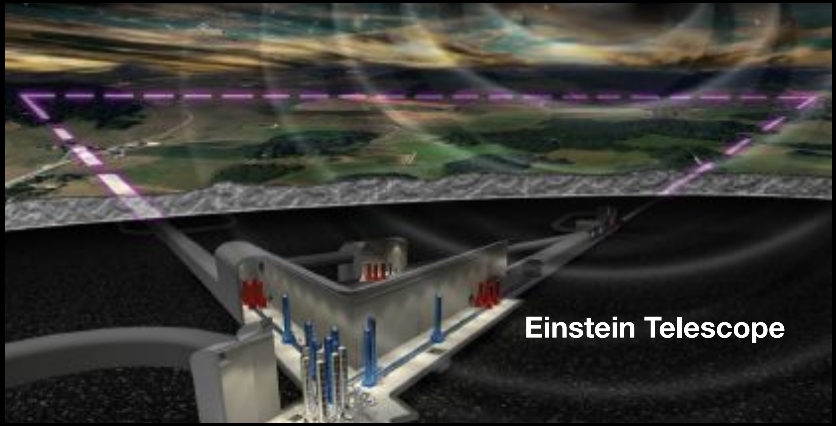
Credit: Planck Collaboration

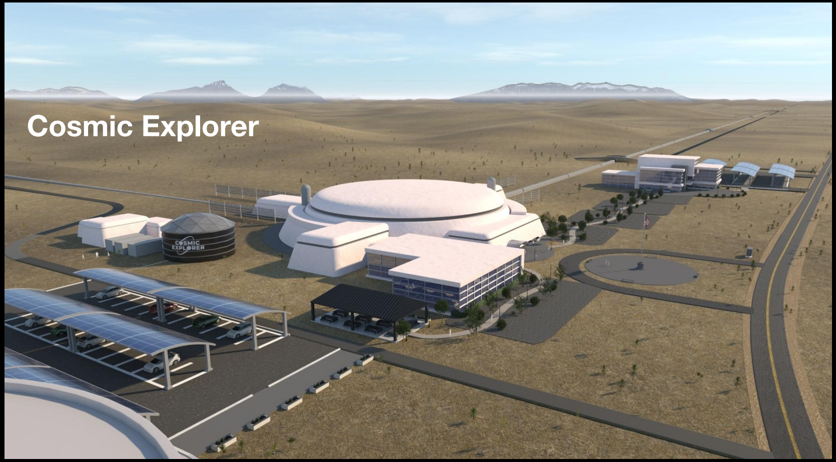
Stochastic Background

- Primordial GWs from the Big Bang
- Incoherent sum of unresolved astrophysical 'point' sources

Next Generation Gravitational Wave Detectors: Einstein Telescope and Cosmic Explorer







ET and CE will see compact binary GW events *to the edge of the star-forming universe*

LIGO-G2300708

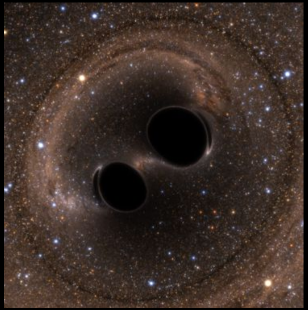
LIGO

An Abridged Astrophysical Gravitational-Wave Source Catalog

Modeled (Known Waveform)

Unmodeled (Unknown Waveform)

Short Duration



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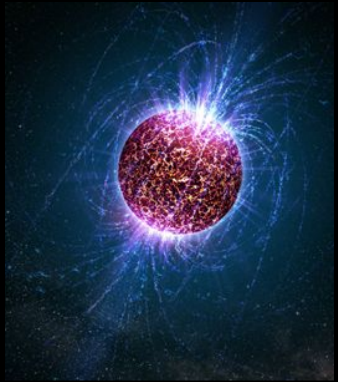

Credit: Casey Reed, Penn State

Cont

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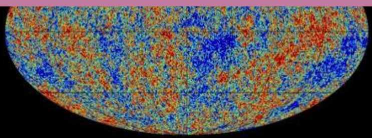

Credit: Planck Collaboration

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The Unexpected ???

ET and CE Vacuum Technology Drivers

Light scattering from residual gas

A function of molecular polarizability and thermal speed

$P(H_2) < 10^{-9}$ Torr

$P(H_2O) < 10^{-10}$ Torr

Brownian recoil of mirrors due to gas molecule impact

$P(H_2) < 10^{-8}$ Torr

Contamination of optics leading to scattering, heating or damage

Mirror absorption: < 0.1 ppm change over operating life

Hydrocarbons: < 1 monolayer/10 years

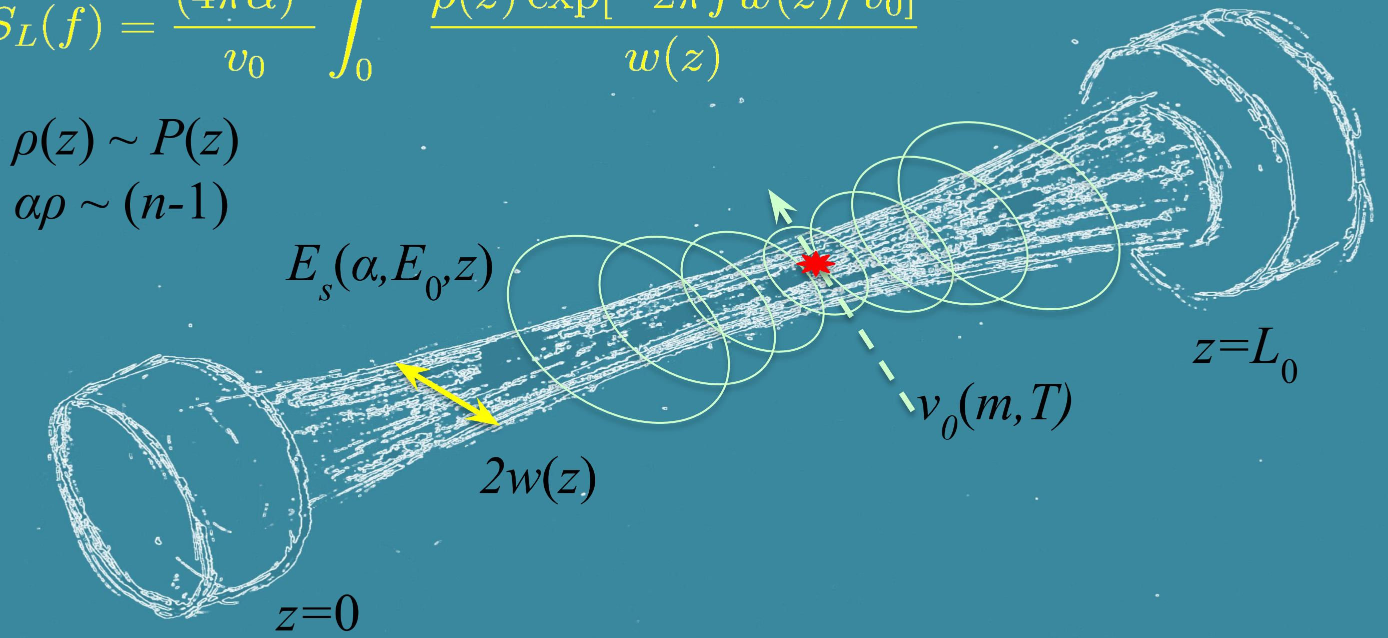
Particles: < one 10 µm particle on any mirror

Light scattering from tube walls

Not "vacuum" per se, but constrains tube diameter, finish, construction

Light Scattering from Residual Gas

$$S_L(f) = \frac{(4\pi\alpha)^2}{v_0} \int_0^{L_0} \frac{\rho(z)\exp[-2\pi f w(z)/v_0]}{w(z)}$$



$S_L(f)$ = mean square deviation in L per unit bandwidth at signal frequency f

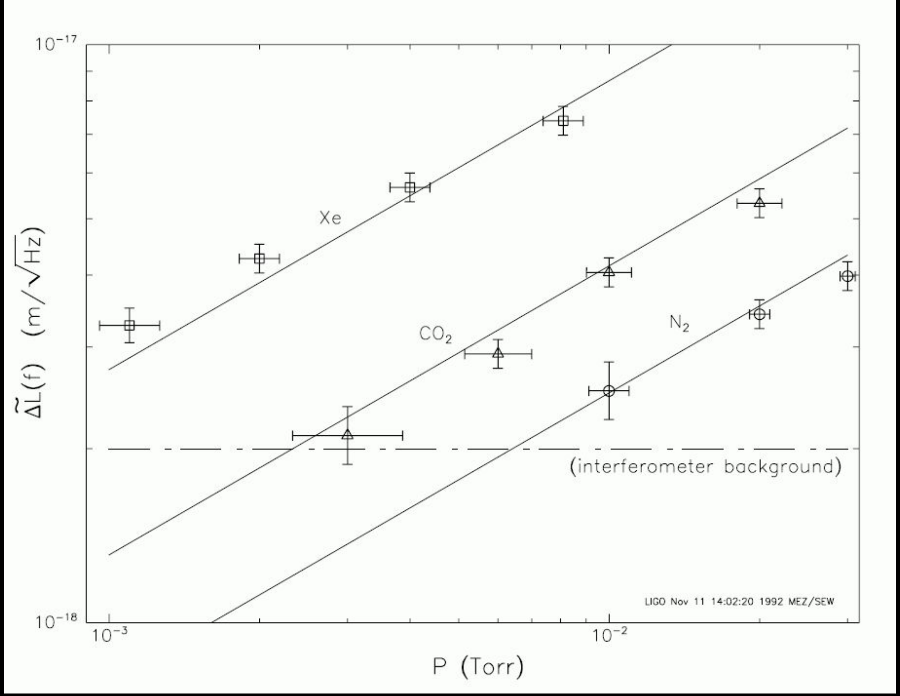
Residual Gas Scattering

Statistical model verified by interferometer experiment

$$S_L(f) = \frac{4\rho(2\pi\alpha)^2}{v_0} \int_0^{L_0} \frac{\exp\left[-2\pi f\, w(z)/v_0\right]}{w(z)}\, dz$$

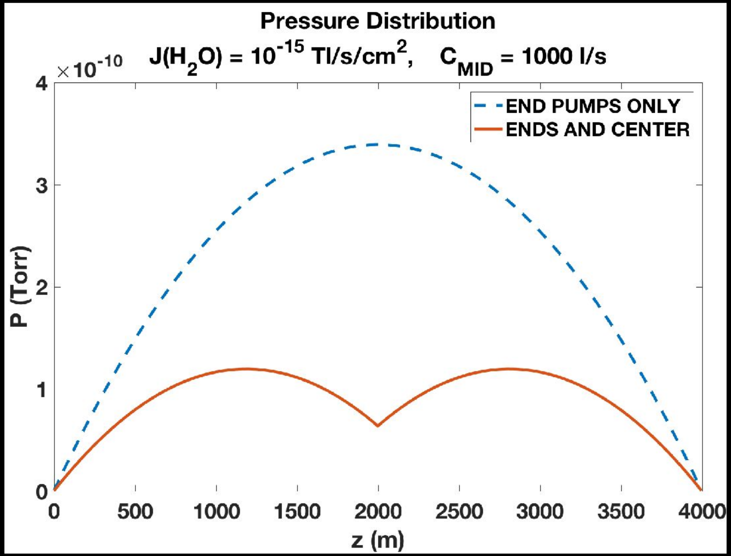
$$\Delta\tilde{L}(f) \equiv \sqrt{S_{\Delta L}(f)} = \sqrt{2 S_L(f)}$$

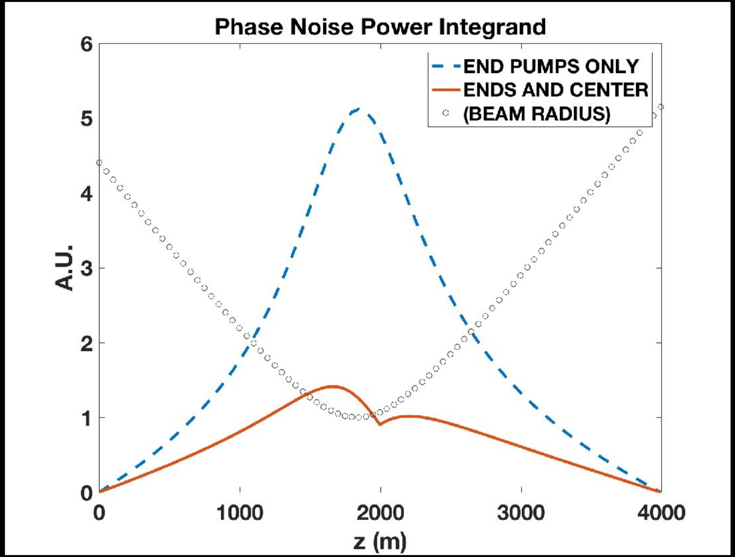
ρ = gas number density ~ pressure
α = optical polarizability ~ (index-1)/pressure
w = beam radius
v_0 = mean thermal speed
L_0 = arm length
ΔL = arm optical path difference



S. Whitcomb and MZ, Proc. 7th Marcel Grossmann Meeting on GR, R. Jantzen and G. Keiser, eds. World Scientific, Singapore (1996).

Gaussian laser beam diameter varies
→ *pressure gradients matter*





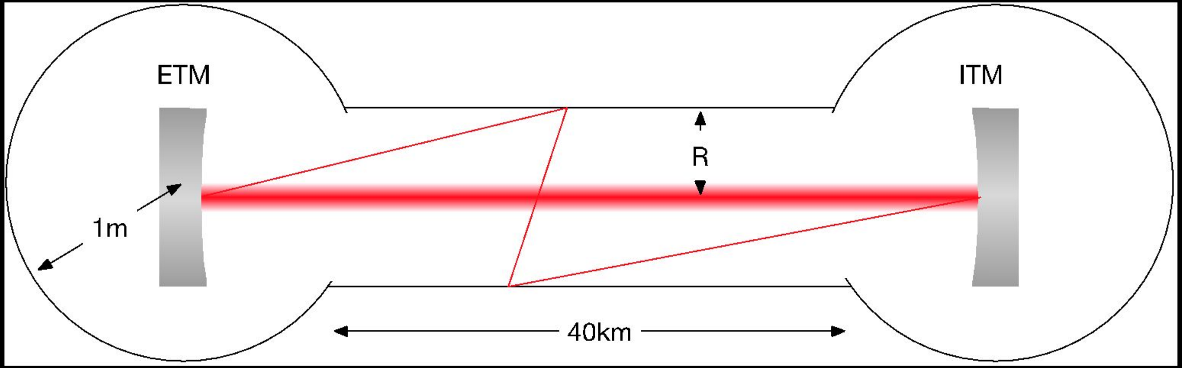
Sample parameters for CE design operating at 1 micron laser wavelength

parameter	aLIGO	CE (1 μm)
L (m)	4,000	40,000
w_0 (mm)	62	83
h_{gas} ($Hz^{-1/2}$)*	$< 2 \times 10^{-25}$	$< 5 \times 10^{-26}$
P[H_2] (Torr)	$< 10^{-9}$	$< 10^{-9}$
P[H_2O] (Torr)	$< 10^{-10}$	$< 10^{-10}$
P[CO_2] (Torr)	$< 2 \times 10^{-11}$	$< 2 \times 10^{-11}$

*3x safety margin

Assuming 40km x 1.2m ϕ tubes with 'LIGO-typical' outgassing, e.g.,
J(H_2O) ~10^{-15} T l s^{-1} cm^{-2} and
J(H_2) ~ 5×10^{-14} T l s^{-1} cm^{-2} ,
this could be achieved with one 1,000 l/s ion pump deployed each kilometer.

Beamtube Optical Scattering



Light scatters out of beam, strikes tube or chamber wall, then re-scatters into beam
Interfering field's phase is imprinted with mechanical noise of the tube wall

- Effect varies as a sensitive function of tube ID
- Scatter amplitudes depend on parameters that are difficult to bound (e.g., mirror topography)

→ Optical baffles must be integrated with design; tube wall finish & reflectance may be constrained
(can complicate processing, assembly, bakeout, and future maintenance)

→ Tube diameter is possibly the first parameter to choose, and definitely the most difficult to change!

Other Practical Constraints

- Rapid, economical degassing (bakeout) to remove adsorbed water
    - Initially <u>and</u> after repair or accident
- Environmental resistance
    - 20-50 year planned lifetime
    - Thermal cycling, humidity, corrosion, steel-eating microbes (!)
    - Earthquakes & tornadoes
    - Lightning strikes
    - Hunter’s bullets (surface construction)
        - Standard deer (or kangaroo) rifle at 200m can pierce 13mm steel!
- Maintainability and Repairability
    - Access and life cycle renewal
    - Recovery from *planned* and *unplanned* vents
- Sustainability and environmental impact
    - Initially, in operation, and after retirement

The BIG ONE

$ COST €

- Direct scaling of LIGO, Virgo, and Kagra techniques can evidently meet all technical requirements, but this would likely exceed budget constraints
- Rapid deployment of a worldwide observing network demands a more cost- and schedule-efficient plan (with low technical risk)
- Our 2019 workshop* illuminated promising routes to this goal
    - *see J. Feicht and F. Dylla's talks later this morning*
- This week will let us share progress and map future priorities

*LIGO-P1900072

Summary

After the pandemic, it's a joy and a relief to resume the important work we started at the January 2019 workshop.

Heartfelt thanks to our European colleagues, especially our CERN hosts, for making this meeting possible!

CE and ET projects have accelerated toward realization since we last met; they, and the future of gravitational wave exploration, are depending on us.

Rai's advice:

"LET'S GET TO WORK."