

UltraHigh:
Rai Weiss and LIGO Vacuum

Mike Zucker
Caltech and MIT

Contribution to the Weiss Memorial Symposium
MIT

27 February, 2026

[LIGO-G26abcd](#)

outline

- how Rai (and I) got “sucked in”
- why vacuum, and how much?
- hydrogen
- leaks
- water vapor
- scattered light
- present and future
- conclusion & questions

"All the News
That's Fit to Print"

The New York Times

New England Edition

Today, sunshine mixing with some clouds, cold, high 26. Tonight, cloudy, a flurry or heavier squall late, low 17. Tomorrow, windy, frigid, high 18. Weather map, Page A18.

VOL. CLXV . . . No. 57,140

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FRIDAY, FEBRUARY 12, 2016

\$2.50

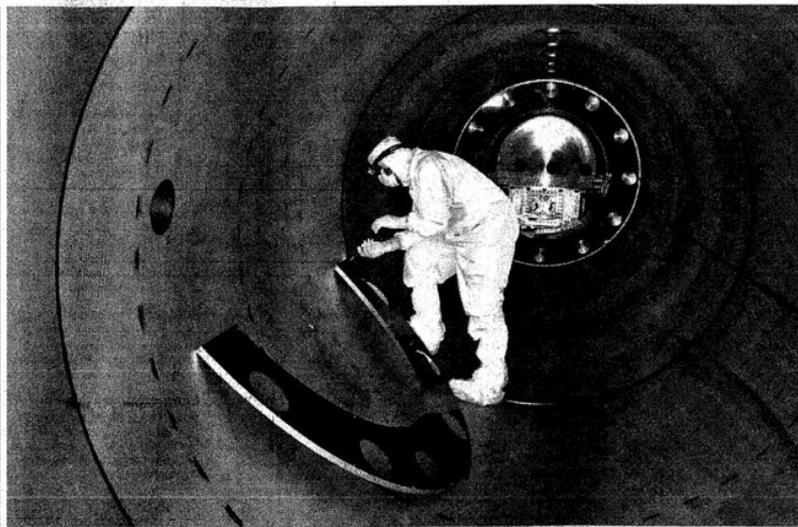
Clinton Paints Sanders Plans As Unrealistic

New Lines of Attack at Milwaukee Debate

By AMY CHOZICK
and PATRICK HEALY

MILWAUKEE — Hillary Clinton, scrambling to recover from her double-digit defeat in the New Hampshire primary, repeatedly challenged the trillion-dollar policy plans of Bernie Sanders at their presidential debate on Thursday night and portrayed him as a big talker who needed to "level" with voters about the difficulty of accomplishing his agenda.

Foreign affairs also took on unusual prominence as Mrs. Clinton sought to underscore her experience and Mr. Sanders excoriated her judgment on Libya and Iraq, as well as her previous praise of former Secretary of State Henry A. Kissinger. But Mrs. Clinton was frequently on the offensive as well, seizing an opportunity to talk about leaders she admired and turning it against Mr. Sanders by bashing his past criticism of President Obama — a remark that Mr. Sanders called a "low



A worker installed a baffle in 2010 to control light in the Laser Interferometer Gravitational-Wave Observatory in Hanford, Wash.

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A RIPPLE IN SPACE-TIME

An Echo of Black Holes Colliding a Billion Light-Years Away

By DENNIS OVERBYE

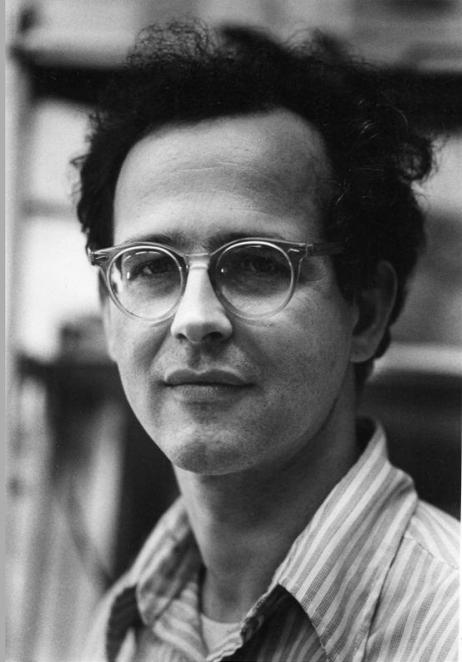
A team of scientists announced on Thursday that they had heard and recorded the sound of two black holes colliding a billion light-years away, a fleeting chirp that fulfilled the last prediction of Einstein's general theory of relativity.

That faint rising tone, physicists say, is the first direct evidence of gravitational waves, the ripples in the fabric of space-time that Einstein predicted a century ago. It completes his vision of a universe in which space and time are interwoven and dynamic, able to stretch, shrink and jiggle. And it is a ringing confirmation of the nature of black holes, the bottomless gravita-

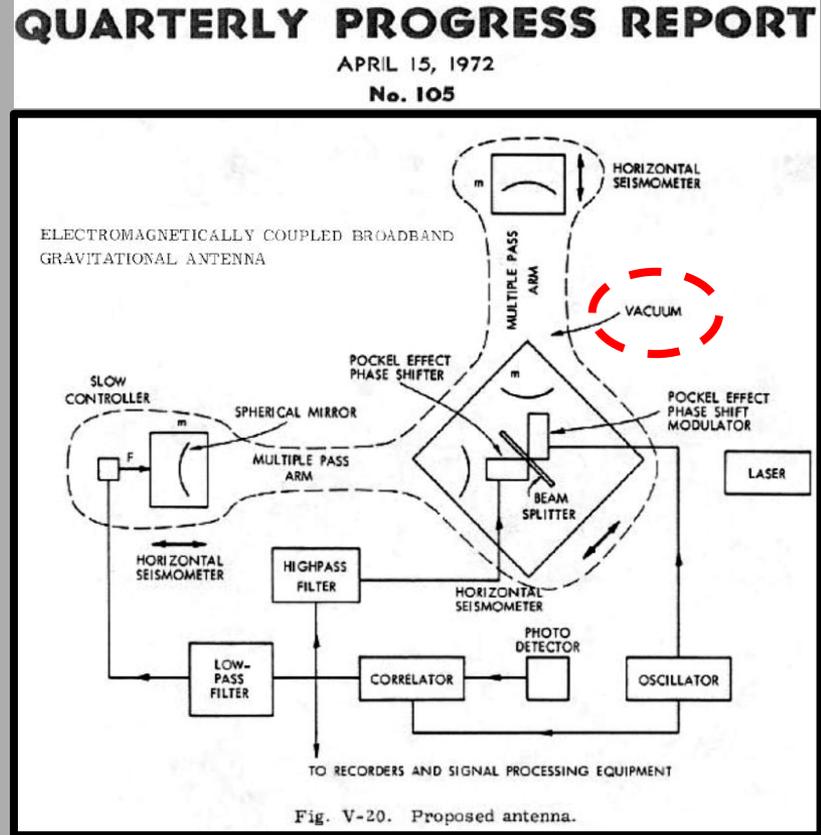
Long in Clinton's Corner. Blacks Notice Sanders Last Occupier

BLACK HOLES SOUND COOL
BUT THE BEAM TUBE GOT THE FRONT PAGE.
ON BEHALF OF THE OTHER 1003 AUTHORS
THANK YOU.

The beginning



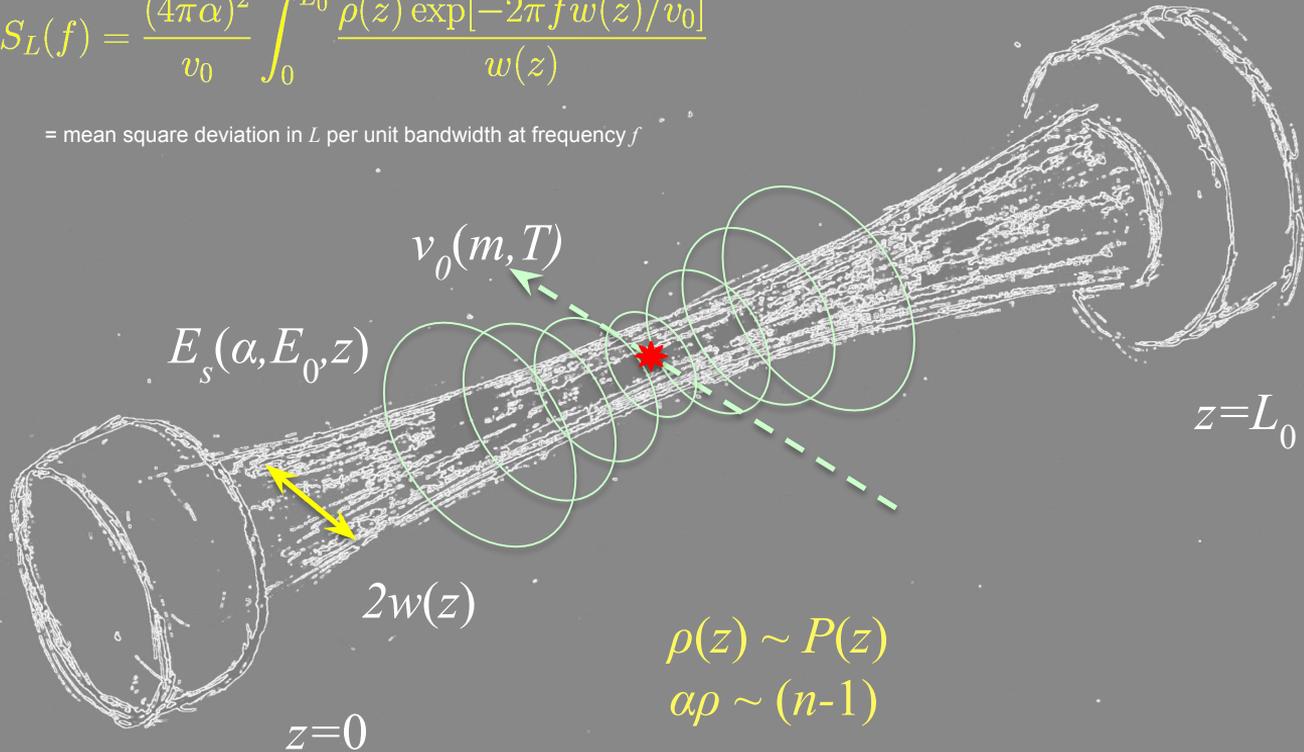
Rai Weiss, MIT



laser scattering from residual gas

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

= mean square deviation in L per unit bandwidth at frequency f



the "Blue Book" (1983)

A STUDY OF A LONG BASELINE
GRAVITATIONAL WAVE ANTENNA SYSTEM

Prepared for the National Science Foundation
under NSF Grant PHY-8109581
to the Massachusetts Institute of Technology

Prepared By:

Paul Linsay	MIT
Peter Saulson	MIT
Rainer Weiss	MIT

With Contributions By:

Stan Whitcomb	CalTech
---------------	---------

Industrial Consultants:

Arthur D. Little Corporation	Cambridge, Massachusetts
Stone & Webster Engineering Corporation	Boston, Massachusetts

OCTOBER 1983

Equations 13 and 15 are the results of this section. Instead of, as in other sections of this report, evaluating the requirements of the system to meet a specified $h(f)$, it is more useful here to look at the break points in vacuum technology. Broadly speaking low vacuum

As indicated in the Arthur D. Little study, we have chosen to price a vacuum system which is able to maintain 10^{-6} mm Hg in the light paths but which can be improved at some additional expense for operation at lower pressures if the need arises in a second generation development of the antenna system.

the LIGO proposal (1989)

Proposal to the National Science Foundation

THE CONSTRUCTION, OPERATION, AND
SUPPORTING RESEARCH AND DEVELOPMENT
OF A

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

Submitted by the
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Principal Investigator and Project Director
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Frederick J. Raab
Co-Investigator
California Institute of Technology

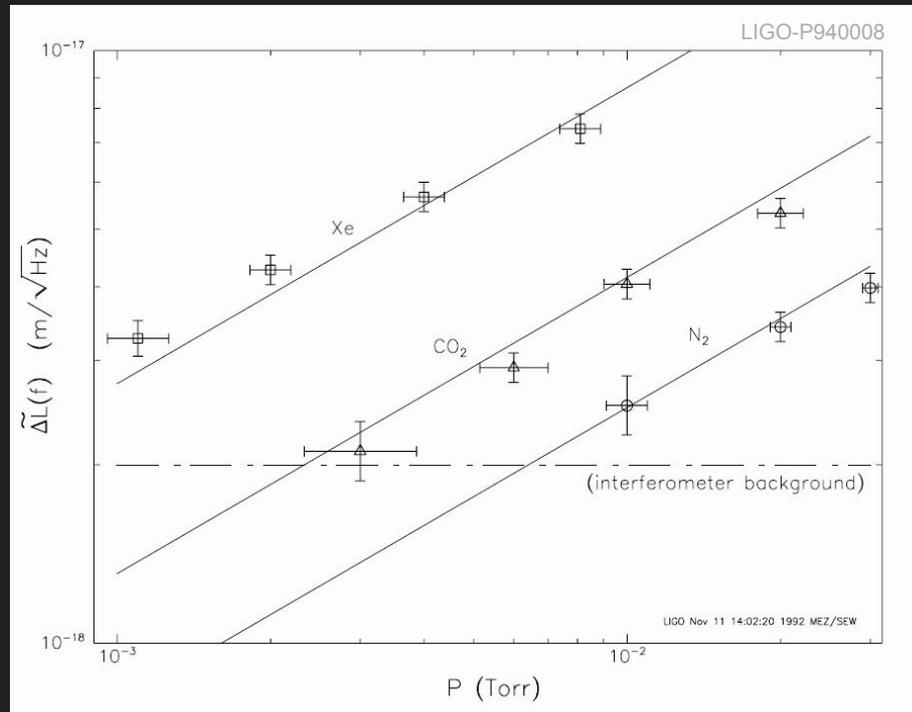
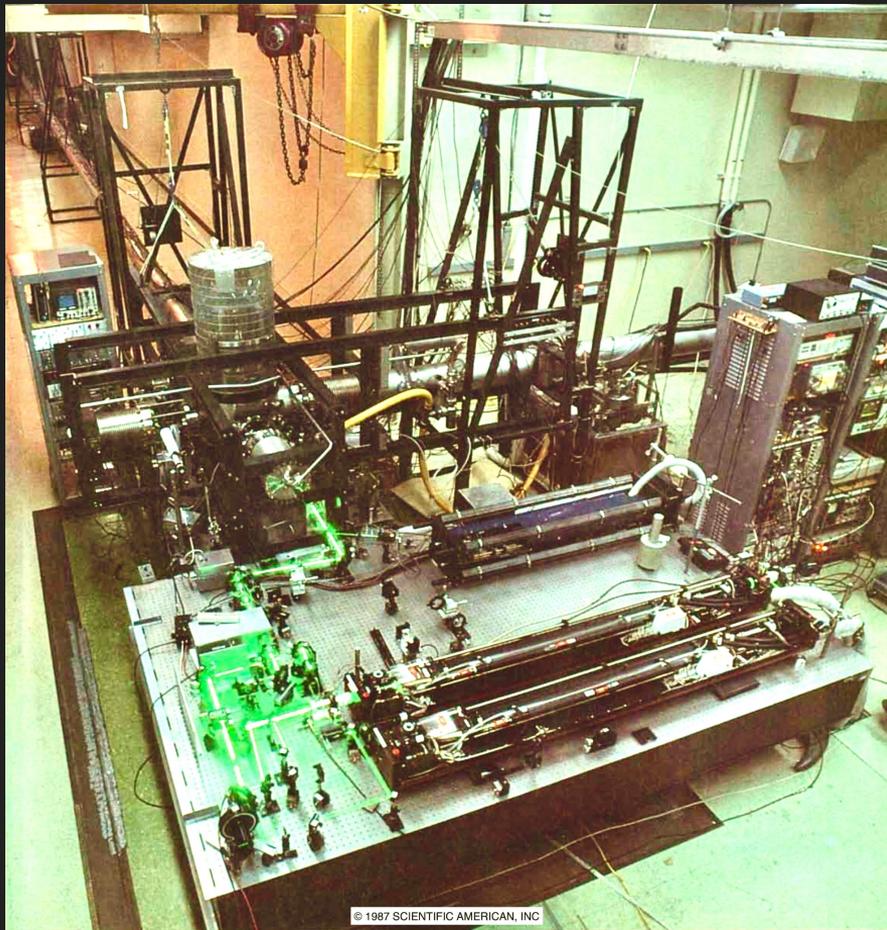
Kip S. Thorne
Co-Investigator
California Institute of Technology

Rainer Weiss
Co-Investigator
Massachusetts Institute of Technology

TABLE II-2
AVERAGE BEAM-TUBE PARTIAL PRESSURES¹
INITIAL REQUIREMENTS AND GOALS

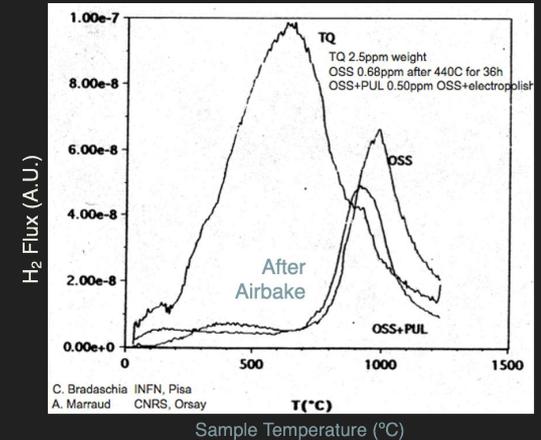
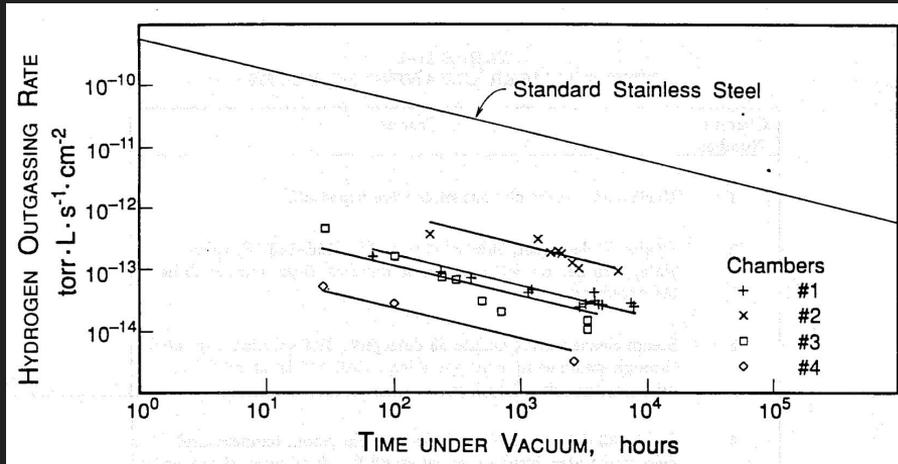
GAS SPECIES	INITIAL REQUIREMENT	GOAL
(torr @ 300 K)		
H ₂	1×10^{-6}	1×10^{-9}
H ₂ O	1×10^{-7}	1×10^{-10}
N ₂	6×10^{-8}	6×10^{-11}
CO	5×10^{-8}	5×10^{-11}
CO ₂	2×10^{-8}	2×10^{-11}

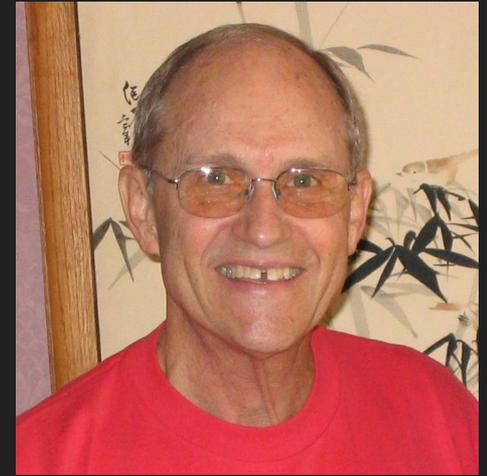
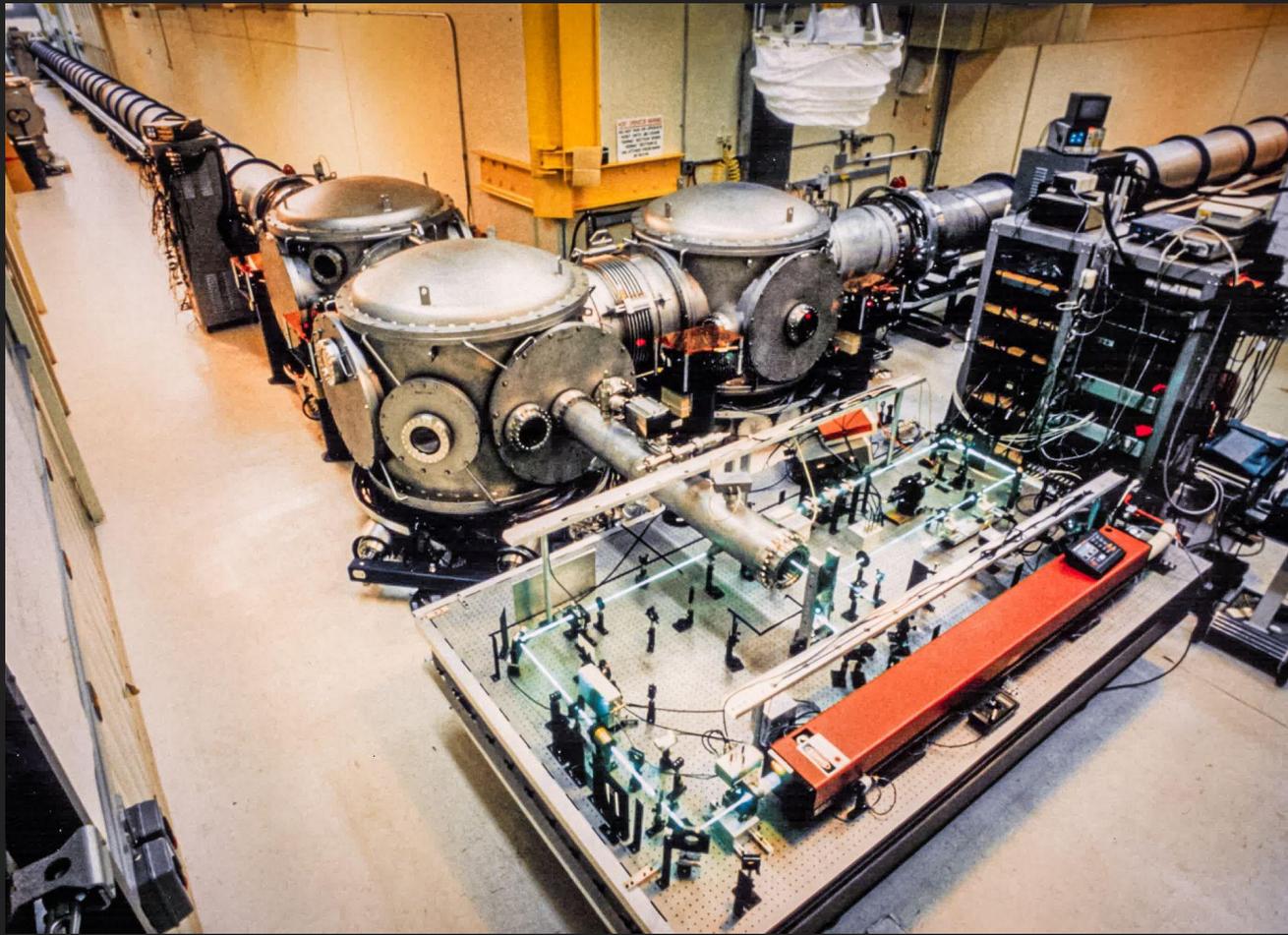
¹Maximum pressure in chambers = 1×10^{-6} torr.



hydrogen

An alternative is to reduce the hydrogen content of the stainless-steel stock prior to fabrication of the vacuum hardware. Vacuum-processing of the molten stainless steel ("vacuum melting") is effective, but would triple the cost of the stock material and could result in major procurement delays because of the limited facilities for such processing. Another approach is to subject coiled stainless-steel sheet to two special annealing steps in which the material is heated in a hydrogen-free purge gas for 24 hr. This annealed product is only nominally more expensive than standard-stainless steel and is readily produced in large quantities.





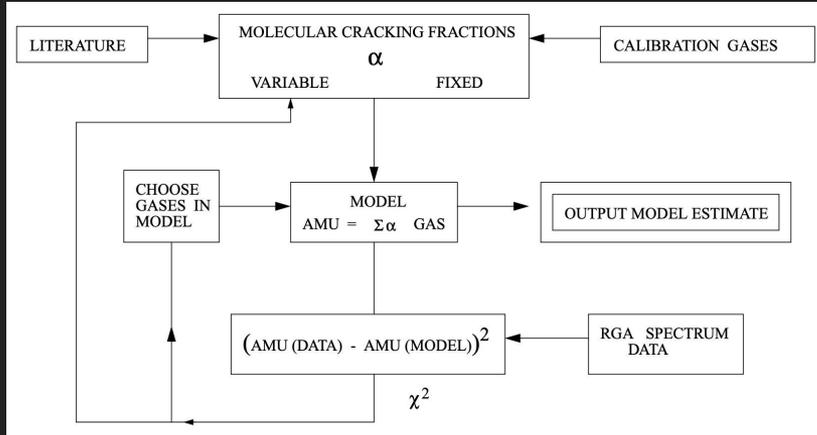
Larry Jones

First industrial production of spiral-welded, air-fired low-hydrogen stainless steel beamtubes
(recycled/reused in the Mk II 40-meter interferometer at Caltech, ca. 1994)

leak detection & localization*



Air Signature Residual Gas Analysis
Weiss, LIGO-T970111



Postbake measurements of module X1 at Hanford
March 11-12, 1999

Table 1: Results from gas model solution of 16.9 hour postbake accumulation ending March 12, 1999 at 10:00AM .

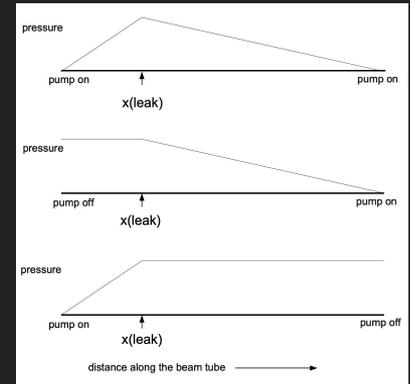
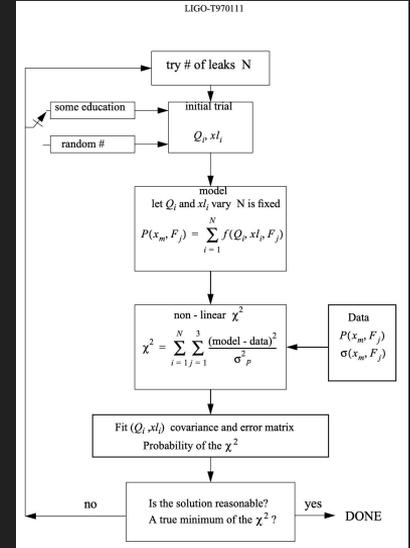
molecule	outgassing rate @ 100C		outgassing rate @ 23C	
	torr liters/sec/cm²	torr	torr liters/sec/cm²	torr
H ₂	1.6 x 10 ⁻¹⁴	1.0 x 10 ⁻⁸	5.2 x 10 ⁻¹⁴	3.4 x 10 ⁻⁹
CH ₄	< 2 x 10 ⁻²⁰	< 3.6 x 10 ⁻¹³	< 8.8 x 10 ⁻²⁰	< 1.5 x 10 ⁻¹²
H ₂ O	< 3 x 10 ⁻¹⁹	< 2.2 x 10 ⁻¹³	< 1.3 x 10 ⁻¹⁸	< 2.3 x 10 ⁻¹²
N ₂	< 9 x 10 ⁻¹⁹ **	< 1.5 x 10 ⁻¹³		
CO	< 1.3 x 10 ⁻¹⁸	< 1.7 x 10 ⁻¹³	< 5.7 x 10 ⁻¹⁸	< 7 x 10 ⁻¹³
O ₂	< 1.2 x 10 ⁻²⁰	< 2.3 x 10 ⁻¹⁴		
A	< 2.5 x 10 ⁻²⁰	< 3.6 x 10 ⁻¹⁴		
OD ₂	< 6.5 x 10 ⁻²⁰	< 1.2 x 10 ⁻¹³	< 2.9 x 10 ⁻¹⁹	< 5.2 x 10 ⁻¹³
NO+C ₂ H ₆	< 1.5 x 10 ⁻¹⁹	< 1.6 x 10 ⁻¹³	< 6.6 x 10 ⁻¹⁹	< 7.2 x 10 ⁻¹³
H ₂ C ₂ O ₄	Σ amu=41, 43, 55, 57 < 1.2 x 10 ⁻¹⁸	< 2.2 x 10 ⁻¹³	Σ amu=41, 43, 55, 57 < 5.3 x 10 ⁻¹⁸	< 9.7 x 10 ⁻¹³

Volume = 2.4 x 10⁶ liters and Area = 7.8 x 10² cm²

** The equivalent air leak into the module Q < 3.5 x 10⁻¹¹ torr liters/sec from amu 28.

Correction from 100C to 23C uses a binding temperature of 8000K for hydrogen and 10000K for all other molecules.

The data shows the outgassing rates of the tube are acceptable. The higher temperature bake at 168C for a shorter time has accomplished a better result than the longer bake at 150C.



water vapor

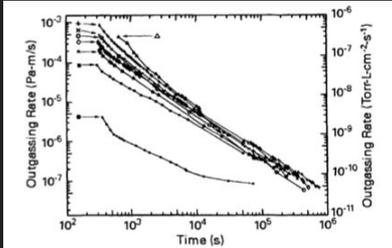
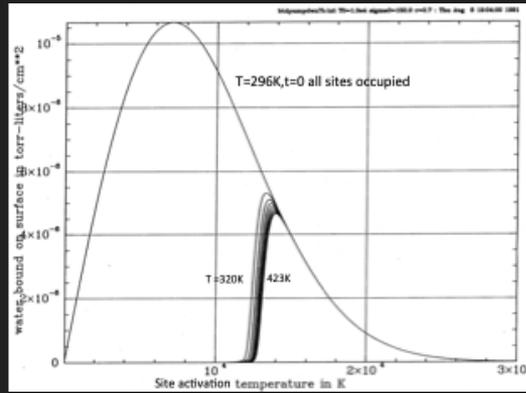
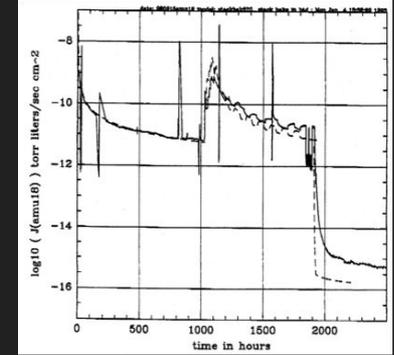


Fig. 4.5 Outgassing measurements for different H₂O exposures during venting of a 304 stainless steel chamber of inner surface area 0.4747 m². ○ Ambient air exposed, 7.8 ml absorbed; △ 600 ml exposed, 16.8 ml absorbed; + 400 ml exposed, 9.2 ml absorbed; × 200 ml exposed, 7.2 ml absorbed; ○ 100 ml exposed, 3.6 ml absorbed; * 10 ml exposed, 2.3 ml absorbed; * N₂ gas with <10 ppm H₂O exposed, 0.7 ml absorbed; * dry N₂ gas exposed, 0.017 ml absorbed; Reprinted with permission from *J. Vac. Sci. Technol. A*, II, p. 1702, M. Li and H. F. Dylla. Copyright 1993, AVS-The Science and Technology Society.

Li and Dylla (1993)
Electropolished 304L
10 ppm water content air re-exposure
 $J(\text{H}_2\text{O}) \sim 4 \times 10^{-12} \text{ T l s}^{-1} \text{ cm}^{-2} \times (1000 \text{ h})/t$

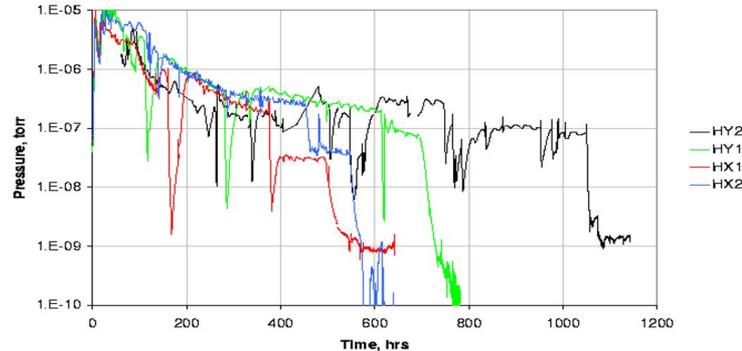


“Dubinin-Radeschewich Isotherm” desorption model (Weiss, T970111)

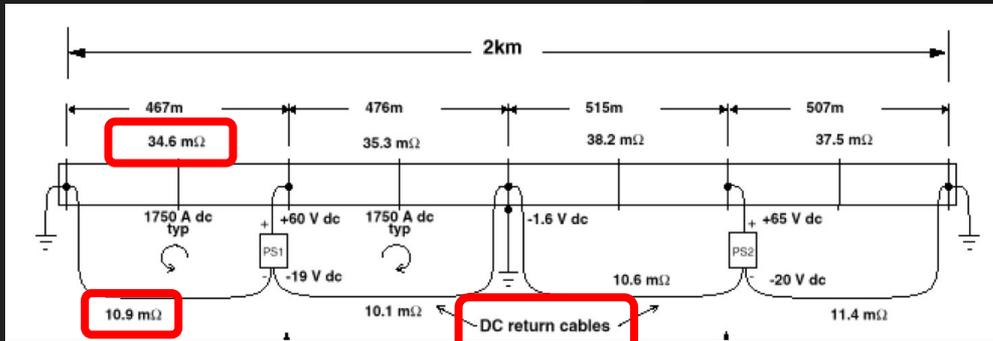
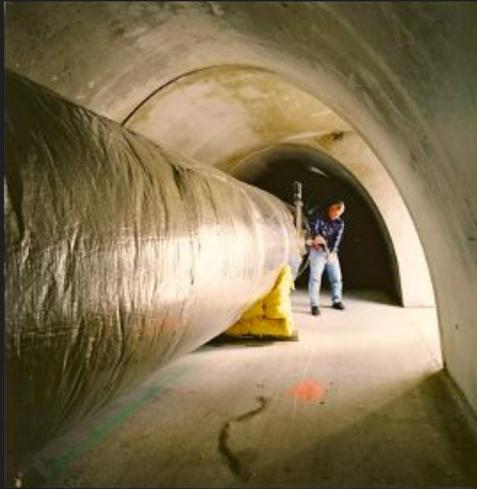


Weiss et al, T940090
BTD at CB&I
 $J(\text{H}_2\text{O}) \sim 3 \times 10^{-12} \text{ T l s}^{-1} \text{ cm}^{-2} \times (1000 \text{ h})/t$
($\sim 10^{-16} \text{ T l s}^{-1} \text{ cm}^{-2}$ post-bake)

H2O PARTIAL PRESSURE DURING BAKEOUT



LIGO beamtube bakeout

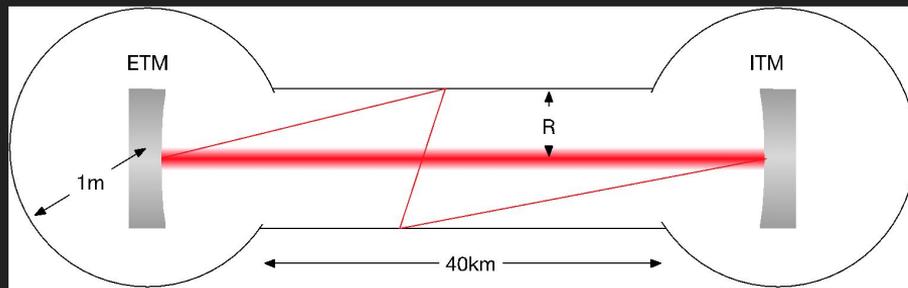
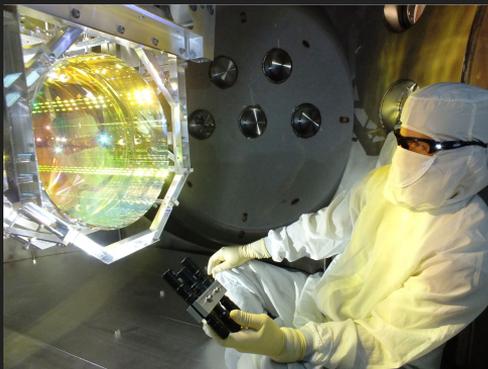


2 layers fiberglass applied by hand

~2,000A DC

160°C for 3 weeks

scattered light



BAFFLE RESEARCH

LIGO-T890018

R.W. 5/25/94

MEASUREMENT OF BEAM TUBE BACK SCATTERING

BACK SCATTER AT $\theta_{GR} < 10^{-2}$
LARGER THAN IN BRO MODEL

LIGO-T890046-cc-R

by R. Weiss
(received 4/25/89)

#81

List of 5/01/89

Processes that may cause noise from scattered light in the instrumentation chambers and associated vacuum pipes.

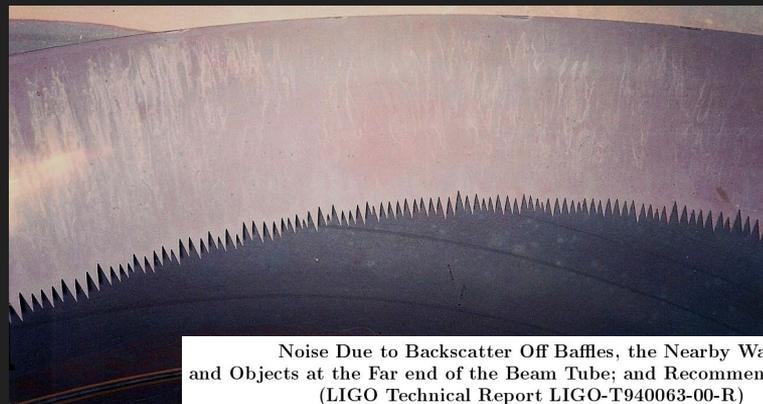
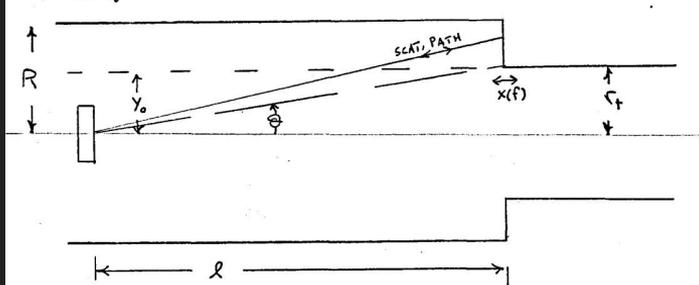
FILE: ROUGHSURF.TEX

MEMO: Optical Properties of the LIGO Beam Tubes

TO: Althouse

FROM: RW (January 17, 1989)

Geometry



Noise Due to Backscatter Off Baffles, the Nearby Wall,
and Objects at the Far end of the Beam Tube; and Recommended Actions
(LIGO Technical Report LIGO-T940063-00-R)

Eanna Flanagan and Kip S. Thorne
Theoretical Astrophysics, California Institute of Technology, Pasadena, CA 91125
(2 August 1994)

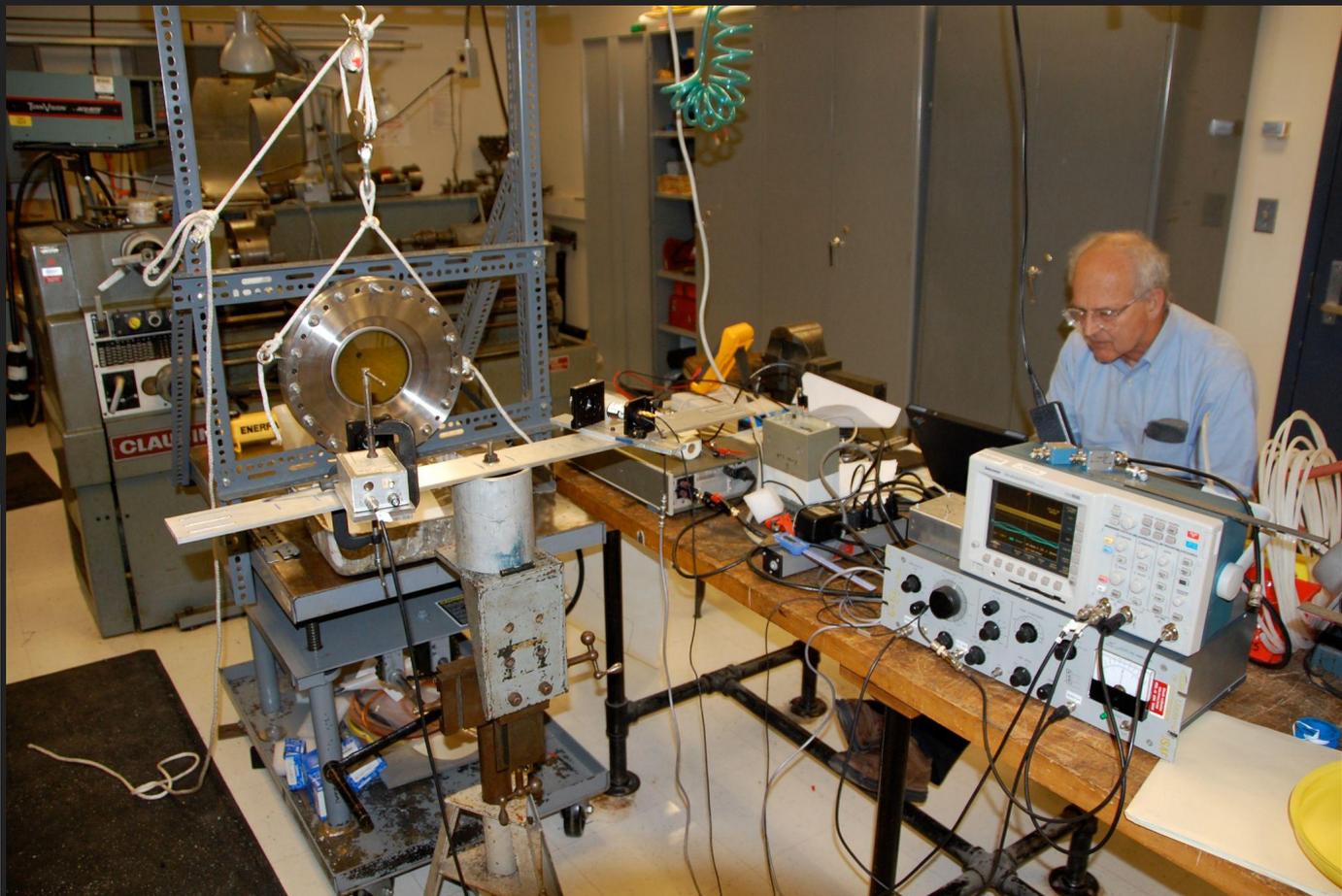
LIGO beamtube fab & field assembly

(by Chicago Bridge and Iron)





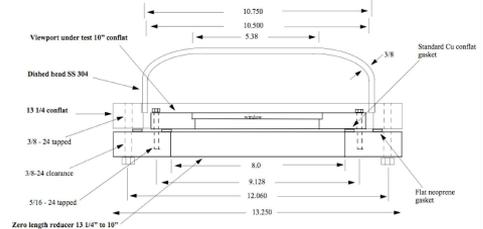
viewport implosion analysis (2008)



LIGO

Burst test chamber
(Weiss)

- Pressure vessel with "inverted" 10" ConFlat sample holder
- Hand pump pressurizes Mobil DTE24 oil to > 20 atm
- Pressure transducer, digitizer & computer data recorder



ionizer for test mass discharge (2010)

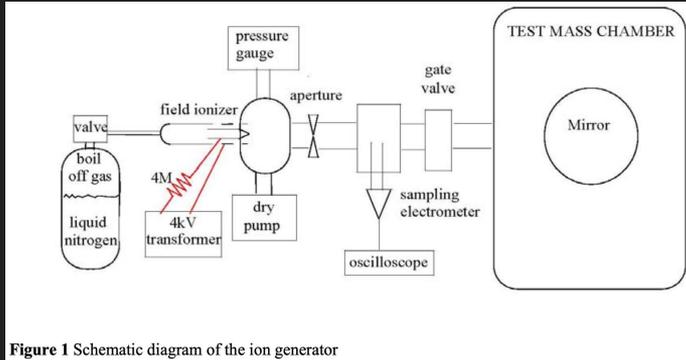
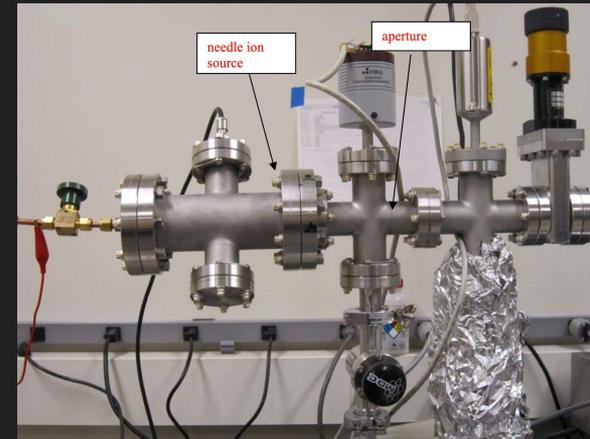
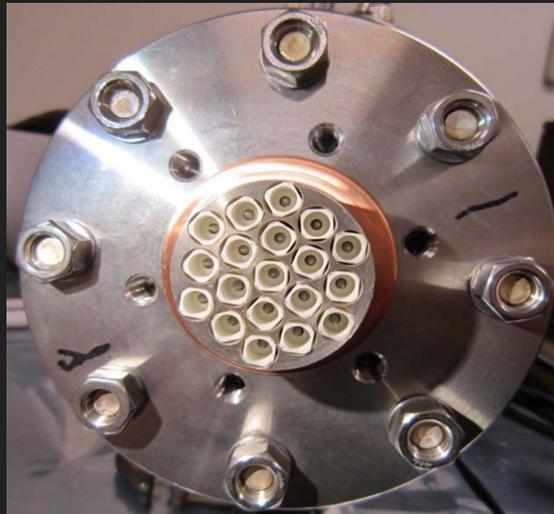
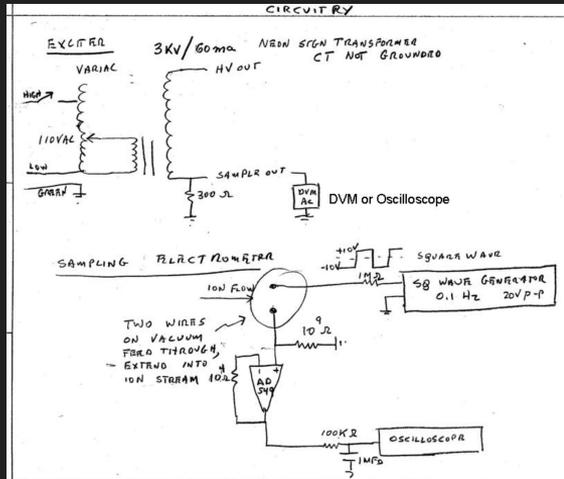


Figure 1 Schematic diagram of the ion generator

Surface charge control of the Advanced LIGO mirrors using externally introduced ions.

R. Weiss November 30, 2010, June 14, 2011

[LIGO-T1100332](#)



the future: Cosmic Explorer and Einstein Telescope

LIGO-P1900072-v1

Workshop Proceedings

1 March 2019

NSF Workshop on Large Ultrahigh-Vacuum Systems for Frontier Scientific Research Instrumentation

LIGO Livingston Observatory

January 29-31, 2019

H.F. Dylla, R. Weiss and M. E. Zucker, eds.

PRELIMINARY STUDY OF A NESTED VACUUM SYSTEM FOR COSMIC EXPLORER

R.Weiss, MIT

NSF Vacuum Workshop

LIGO Livingston Louisiana Site

January 29, 2019

