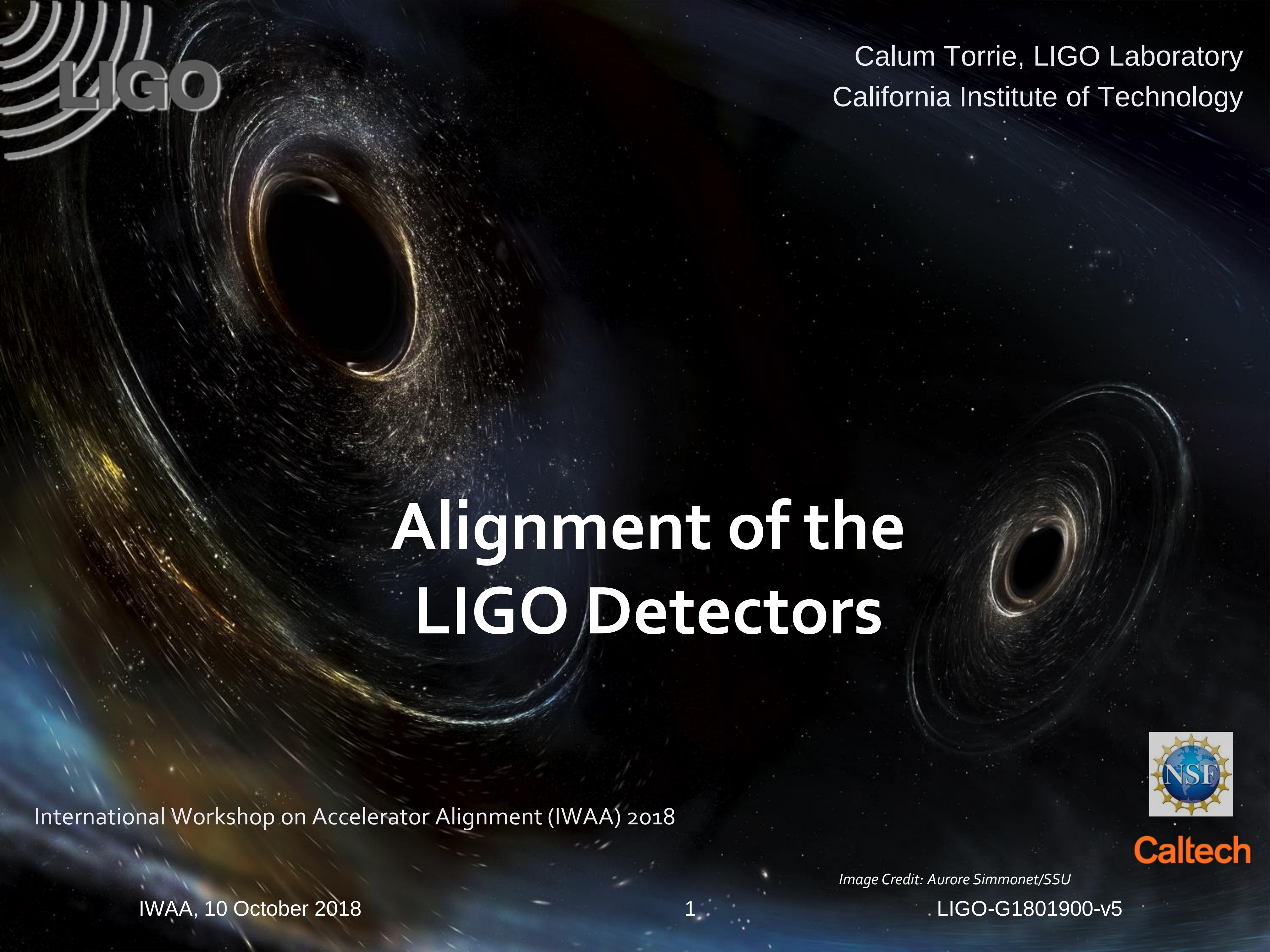
Calum Torrie, LIGO Laboratory
California Institute of Technology



Alignment of the LIGO Detectors

International Workshop on Accelerator Alignment (IWAA) 2018

Image Credit: Aurore Simmonet/SSU

Credit to the LIGO Scientific Collaboration

Abilene Christian University
Albert-Einstein-Institut
American University
Andrews University
Bellevue College
California Institute of Technology
California State Univ., Fullerton
California State Univ., Los Angeles
Canadian Inst. Th. Astrophysics
Carleton College
Chinese University of Hong Kong
College of William and Mary
Colorado State University
Columbia U. in the City of New York
Cornell University
Embry-Riddle Aeronautical Univ.
Eötvös Loránd University
Georgia Institute of Technology
Goddard Space Flight Center
GW-INPE, Sao Jose Brasil
Hillsdale College
Hobart & William Smith Colleges
IAP – Nizhny Novogorod
IIP-UFRN
Kenyon College
Korean Gravitational-Wave Group
Louisiana State University
Marshall Space Flight Center
Montana State University
Montclair State University
Moscow State University
National Tsing Hua University
NCSARG – Univ. of Illinois, Urbana-Champaign

Northwestern University
Penn State University
Rochester Institute of Technology
Sonoma State University
Southern University
Stanford University
Syracuse University
Texas Tech University
Trinity University
Tsinghua University
U. Montreal / Polytechnique
Université Libre de Bruxelles
University of Chicago
University of Florida
University of Maryland
University of Michigan
University of Minnesota
University of Mississippi
University of Oregon
University of Sannio
University of Szeged
University of Texas Rio Grande Valley
University of the Balearic Islands
University of Tokyo
University of Washington
University of Washington Bothell
University of Wisconsin – Milwaukee
USC – Information Sciences Institute
Villanova University
Washington State University – Pullman
West Virginia University
Whitman College

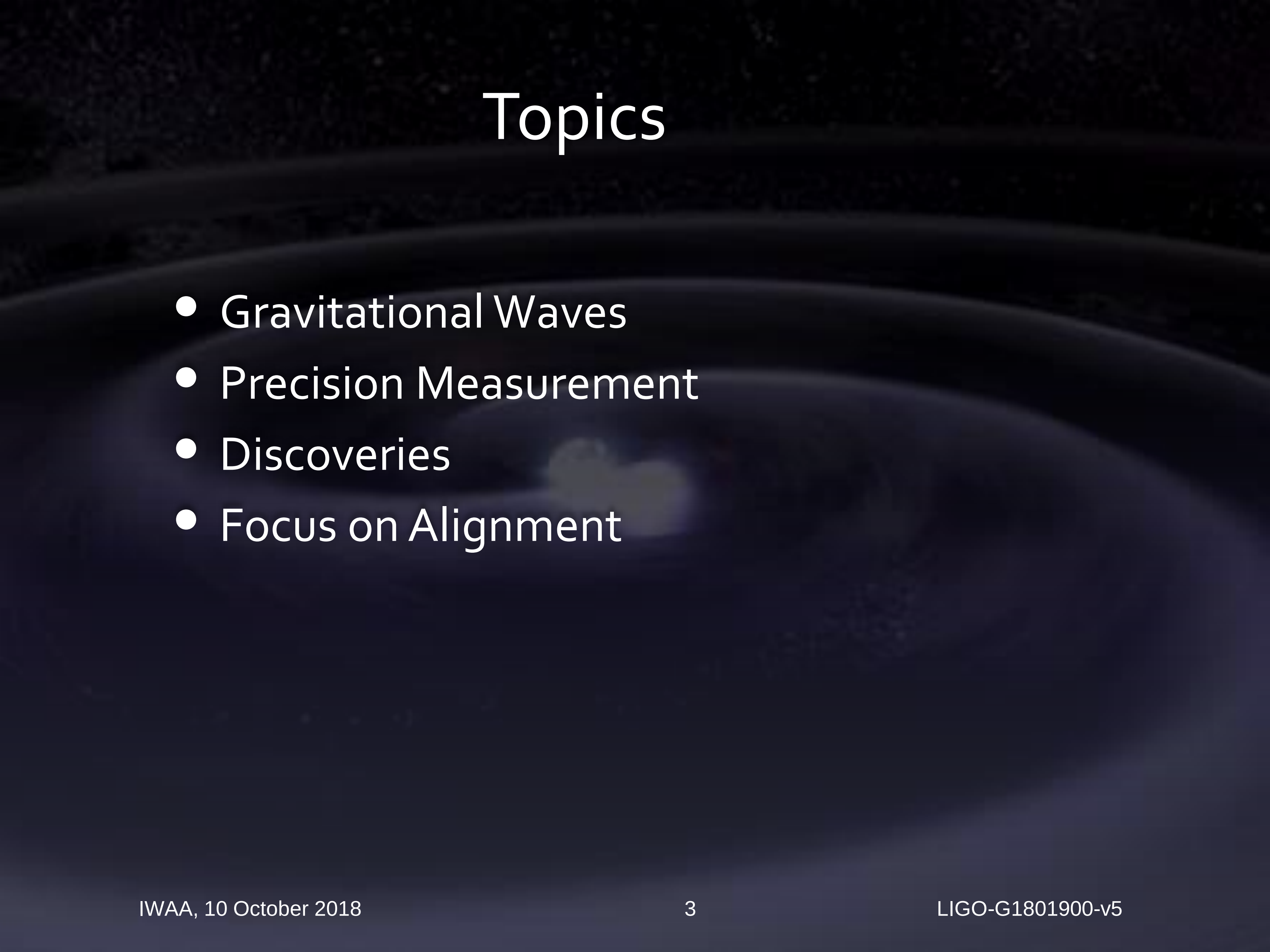
LIGO Laboratory: California Institute of Technology; Massachusetts Institute of Technology; LIGO Hanford Observatory; LIGO Livingston Observatory

Australian Consortium for Interferometric Gravitational Astronomy (ACIGA):
Australian National University; Charles Sturt University; Monash University; Swinburne University; University of Adelaide; University of Melbourne; University of Western Australia

German/British Collaboration for the Detection of Gravitational Waves (GEO600):
Albert-Einstein-Institut, Hannover; Cardiff University; King's College, University of London; Leibniz Universität, Hannover; University of Birmingham; University of Cambridge; University of Glasgow; University of Hamburg; University of Sheffield; University of Southampton; University of Strathclyde; University of the West of Scotland; University of Zurich

Indian Initiative in Gravitational-Wave Observations (IndIGO):
Chennai Mathematical Institute;

Topics



- Gravitational Waves
- Precision Measurement
- Discoveries
- Focus on Alignment

General Relativity and Gravitational Waves

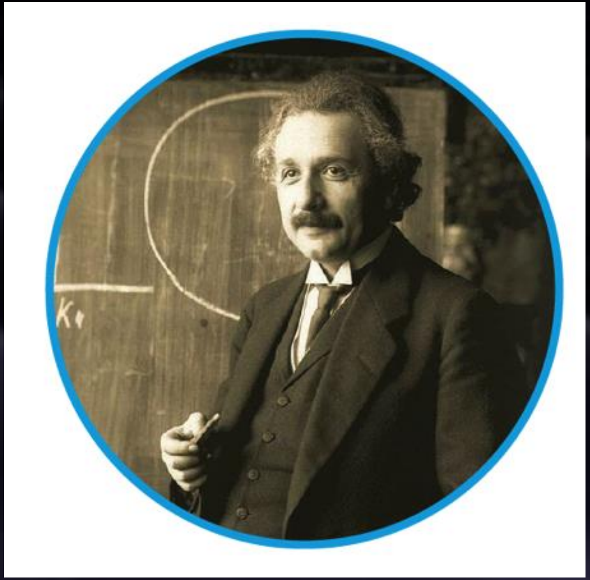
- 2016 was the centenary of Einstein's General Relativity
- A *geometric* theory:

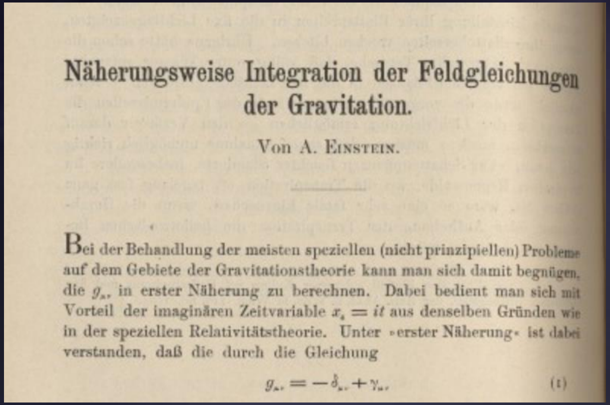
  Gravitation arises from *curvature of space-time*

  Curvature arises from matter, energy
- Bizarre, but so far *completely successful*, predictions:

  Perihelion shift, bending of light, frame dragging, gravitational redshift, gravitational lensing, black holes,…
- **One key prediction remained elusive until September 14th 2015:**

  Gravitational Waves





Näherungsweise Integration der Feldgleichungen der Gravitation.

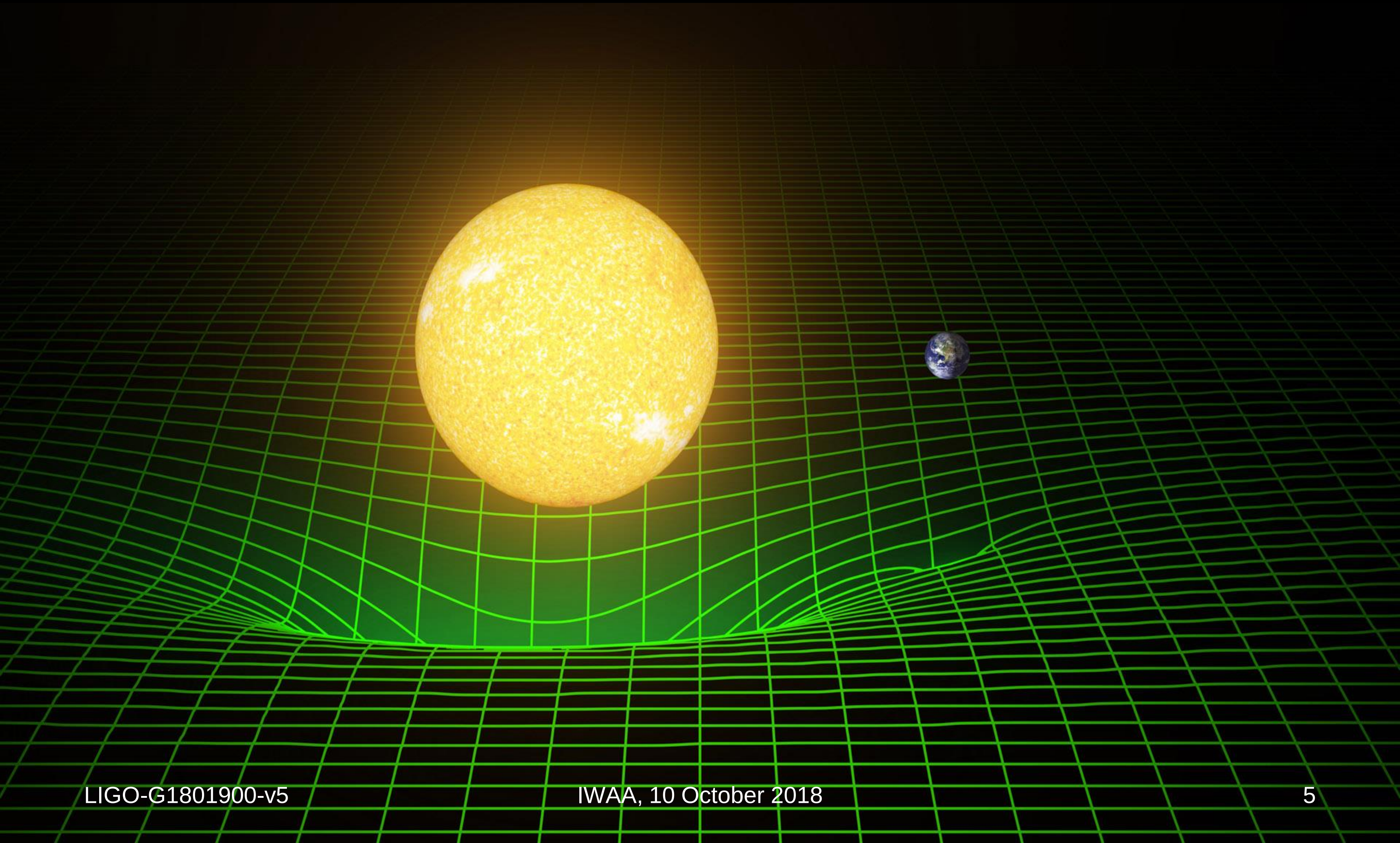
Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

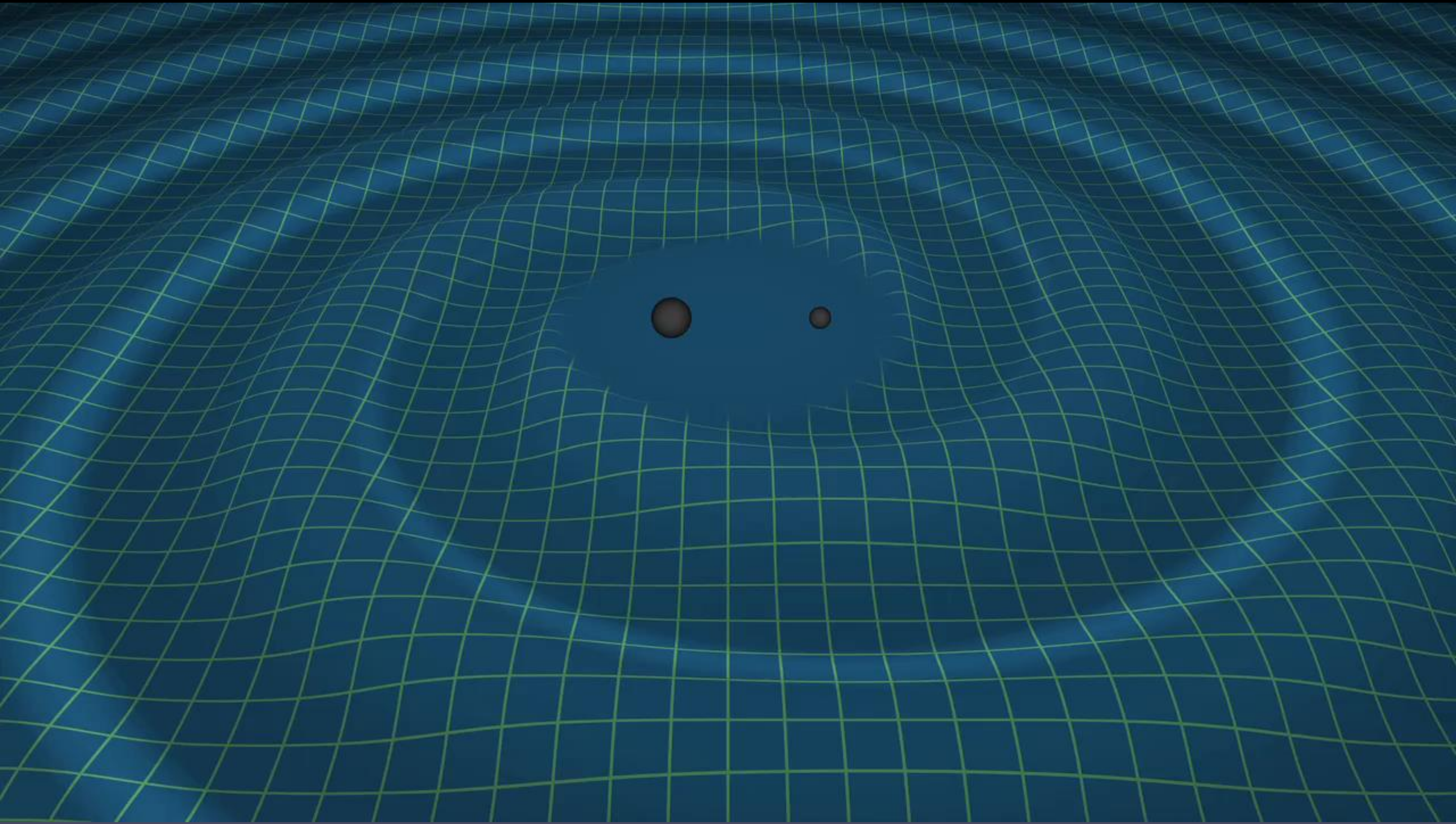
A. Einstein, *Näherungsweise Integration der Feldgleichungen der Gravitation*, 1916

Gravity & Curved Space-time



Gravitational Waves

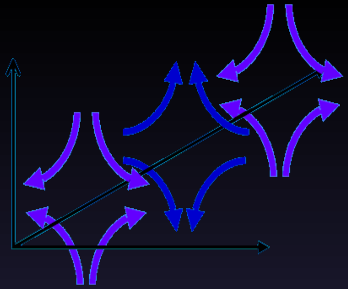
Credit: LIGO/Tim Pyle



Detecting the effects

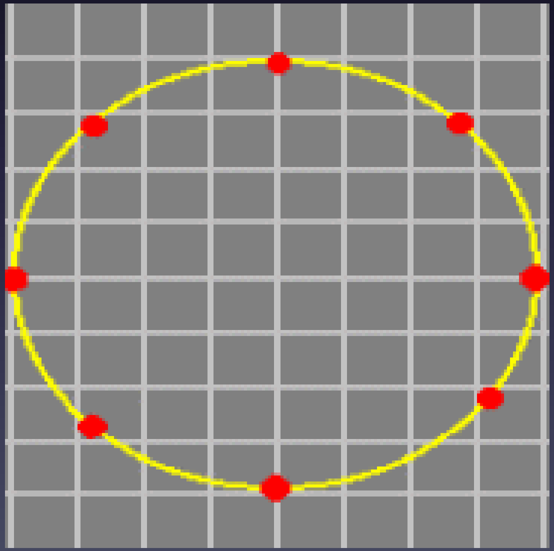
GW's produce time-varying *transverse strain* in space
→ Monitor separations of *free test particles*

(Earth)



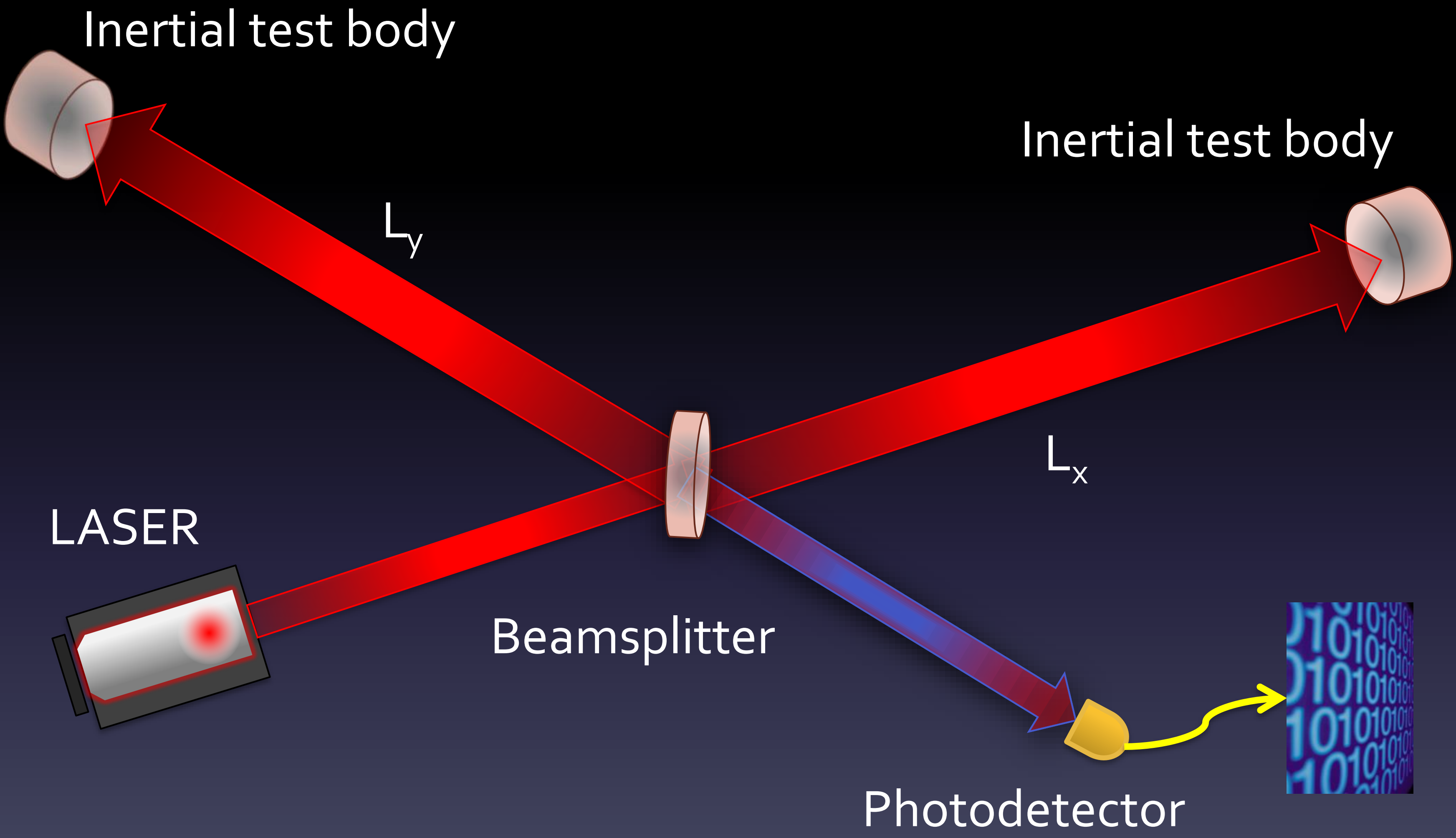
In a galaxy far far away…

European Southern Observatory
Very Large Telescope



Graphic: M. Evans, MIT

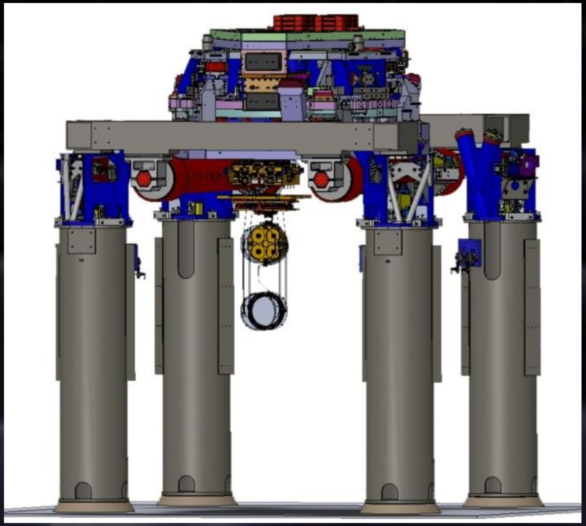
Michelson interferometer



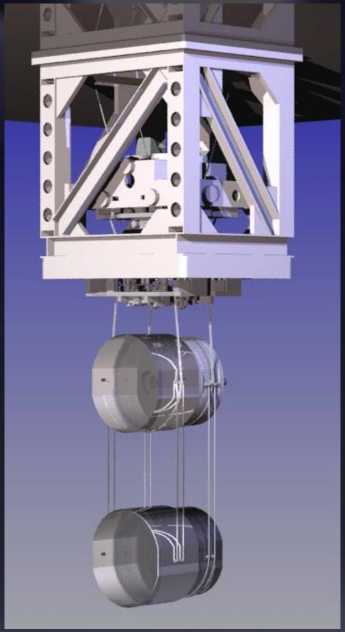
LIGO's Interferometer

Powerful lasers (200W)

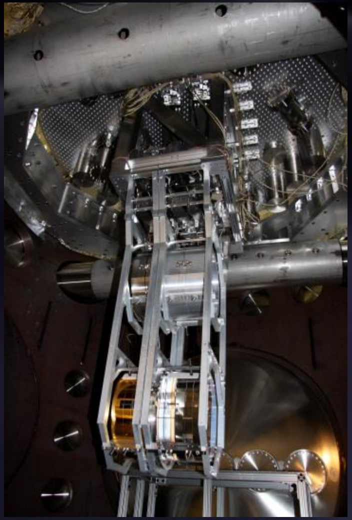
Large 40 kg mirrors with highly reflecting coatings



The interferometer core optics are suspended so that they are vibrationally isolated and free to respond to the passing GW



Each core optic is actively controlled in longitudinal position and tip & tilt

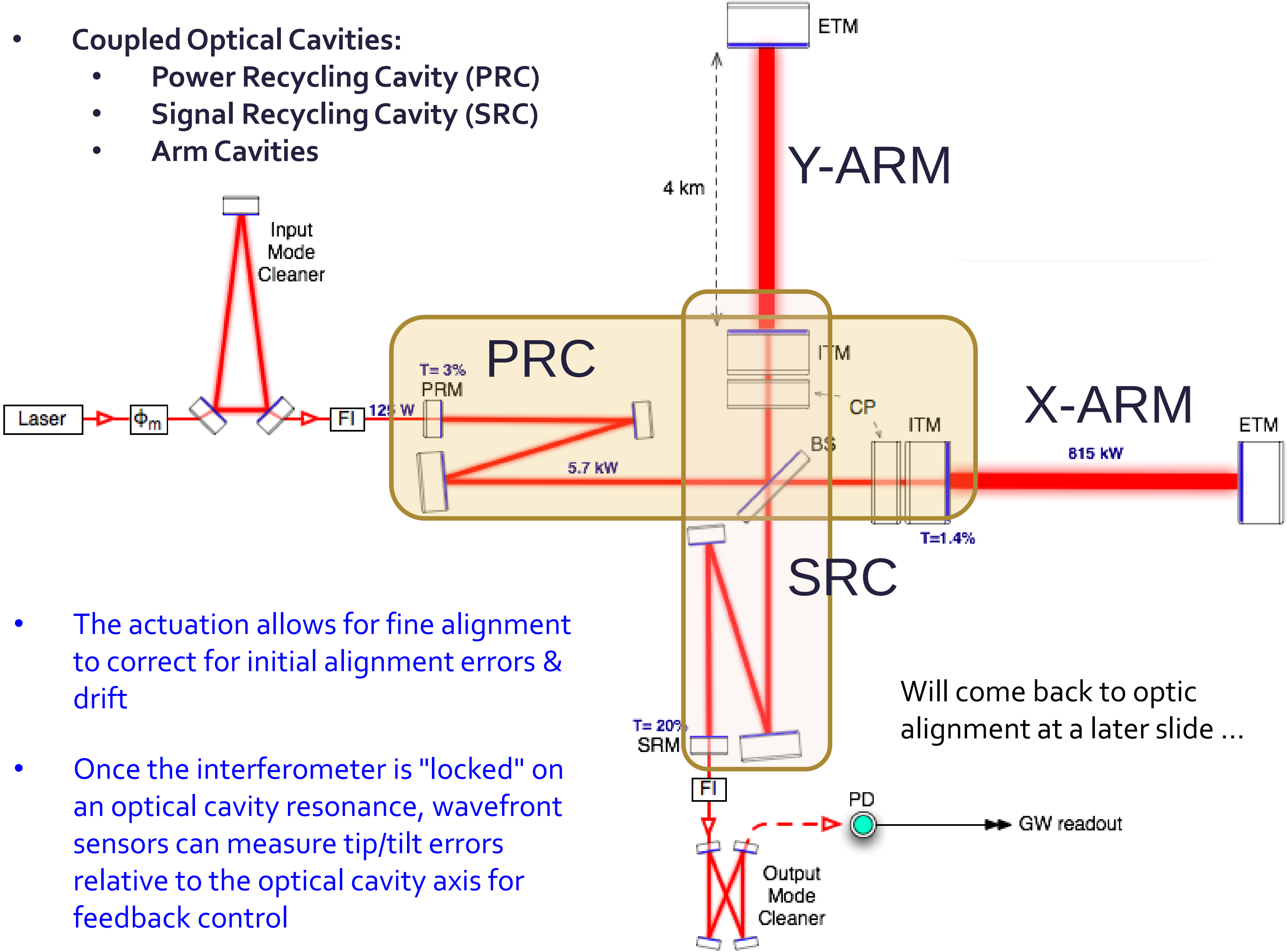


In order to reduce in band injection of noise the core optic actuation is limited in range, so initial alignment must be accurate

Graphic: M. Evans, MIT

LIGO's Optical Configuration

- Coupled Optical Cavities:
  - Power Recycling Cavity (PRC)
  - Signal Recycling Cavity (SRC)
  - Arm Cavities



- The actuation allows for fine alignment to correct for initial alignment errors & drift
- Once the interferometer is "locked" on an optical cavity resonance, wavefront sensors can measure tip/tilt errors relative to the optical cavity axis for feedback control

Will come back to optic alignment at a later slide …

The LIGO Scientific Collaboration: B. Abbott, et al
General Relativity and Quantum Cosmology
https://arxiv.org/abs/0711.3041

A “small” problem…

A wave’s strength is measured by the *strain* induced in the detector,

$$\boxed{h \; = \Delta L / L}$$

We can calculate expected strain at Earth;

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

If we make our interferometer arms 4,000 meters long,

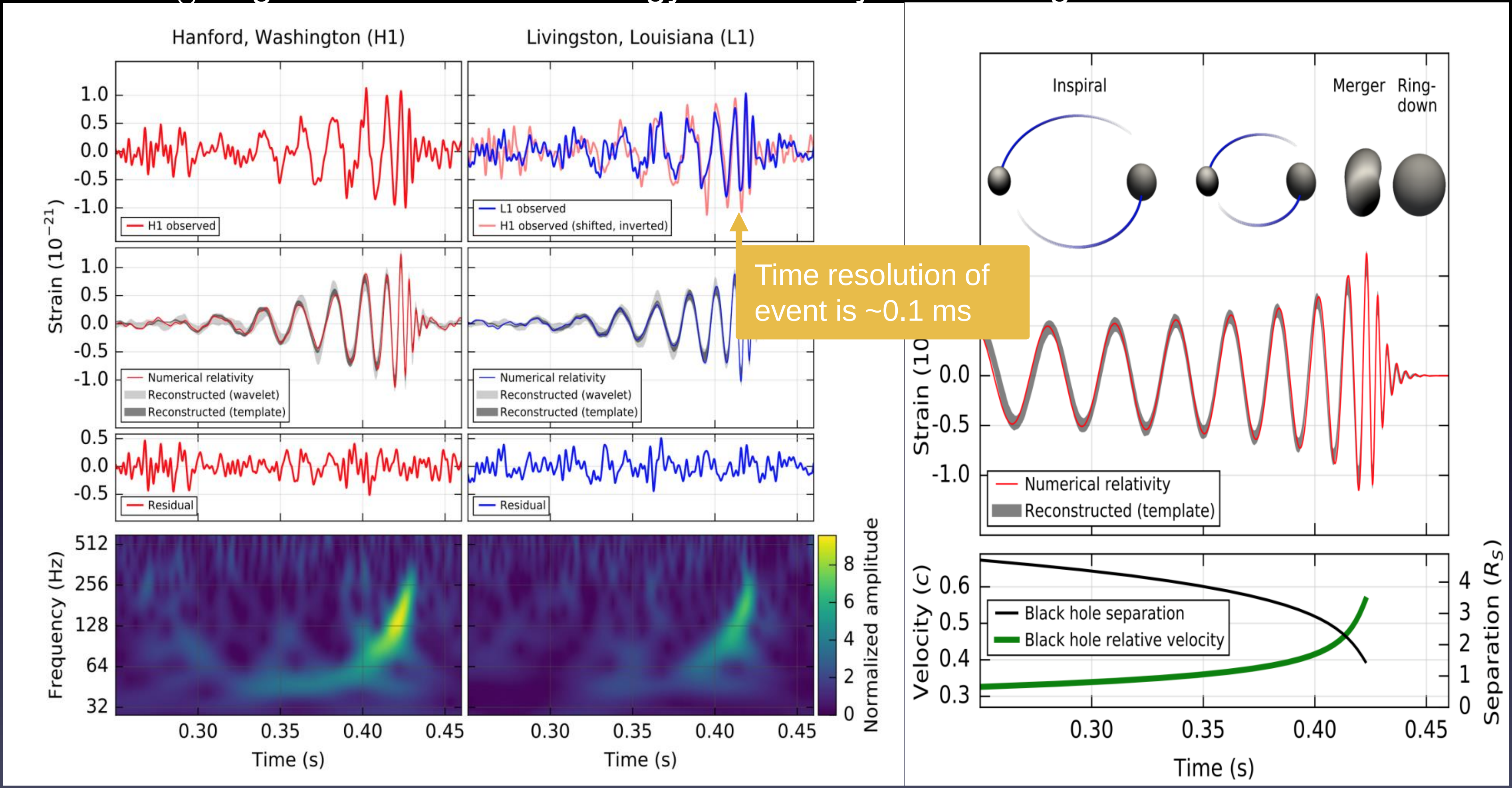
$$\mathrm{D}L = h \times L \approx 10^{-22} \times 4,000\, m \approx 4 \cdot 10^{-19}\, m$$

!!

A ten-thousandth the size of an atomic nucleus

First direct detection of the inspiral and coalescence of a Black Hole Pair (14 Sep 2015) GW150914

29$M_\odot$ and 36$M_\odot$ black holes 1.3 billion light years away inspiral and merge, emitting 3$M_\odot$ of gravitational wave energy and briefly “outshining” the entire universe



Time resolution of event is ~0.1 ms

Abbott et al Phys. Rev. Lett. 116 (2016) 061102

the LASER Interferometer Gravitational-wave Observatory

"For the greatest benefit to mankind"
Alfred Nobel

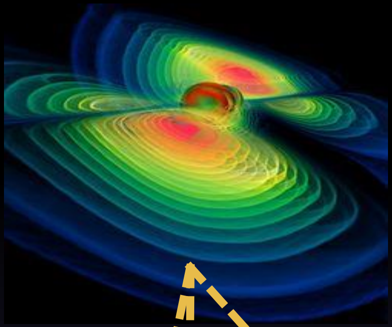
2017 NOBEL PRIZE IN PHYSICS

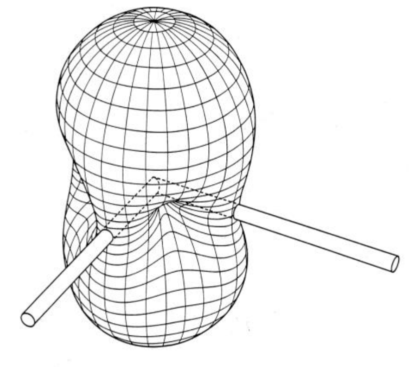
Rainer Weiss
Barry C. Barish
Kip S. Thorne

LIGO Proposal to the NSF 1989, https://dcc.ligo.org/LIGO-M890001/public

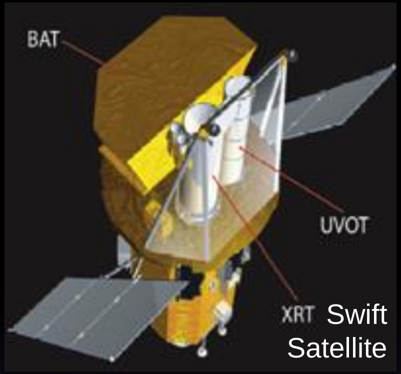
Network Aperture Synthesis and EM Source Follow-up

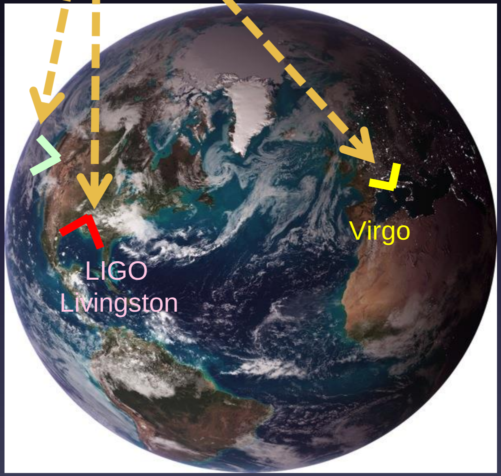
Image: W. Benger





Each detector is ~omnidirectional

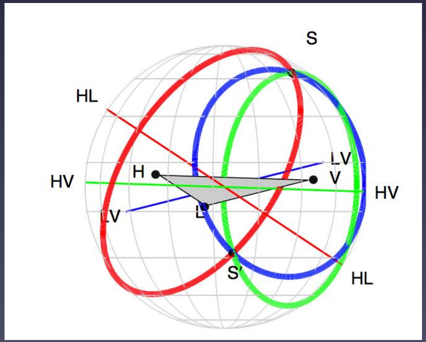




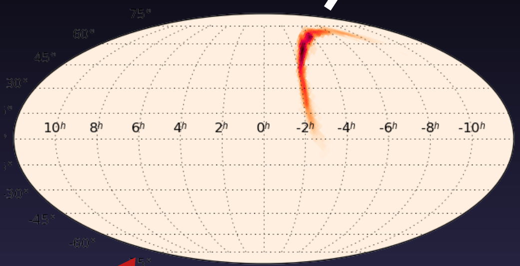
http://earthobservatory.nasa.gov/

$$(t_L, t_H, t_V)$$

Arrival time triangulation



Sky map

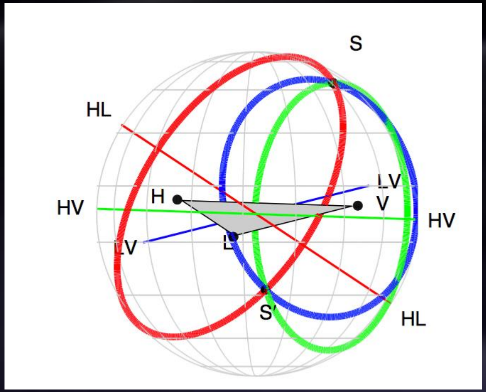


X-ray, γ-ray follow-up

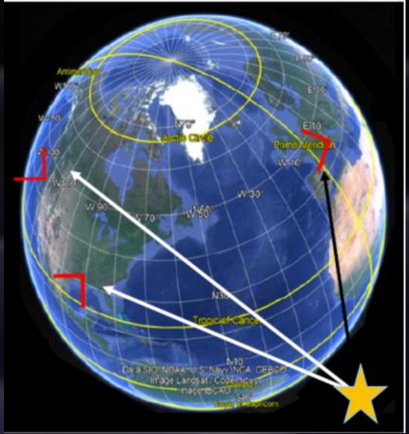
Optical follow-up

Source “Triangulation”

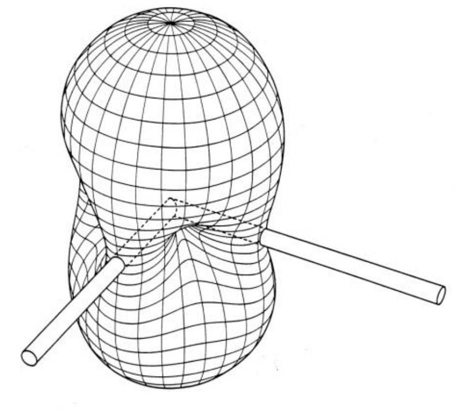
Arrival time triangulation



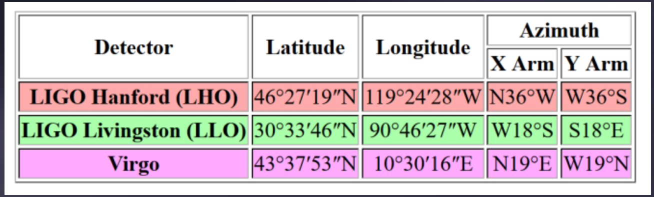
Indicates the direction of the arms relative to local north.



Each detector is ~omnidirectional

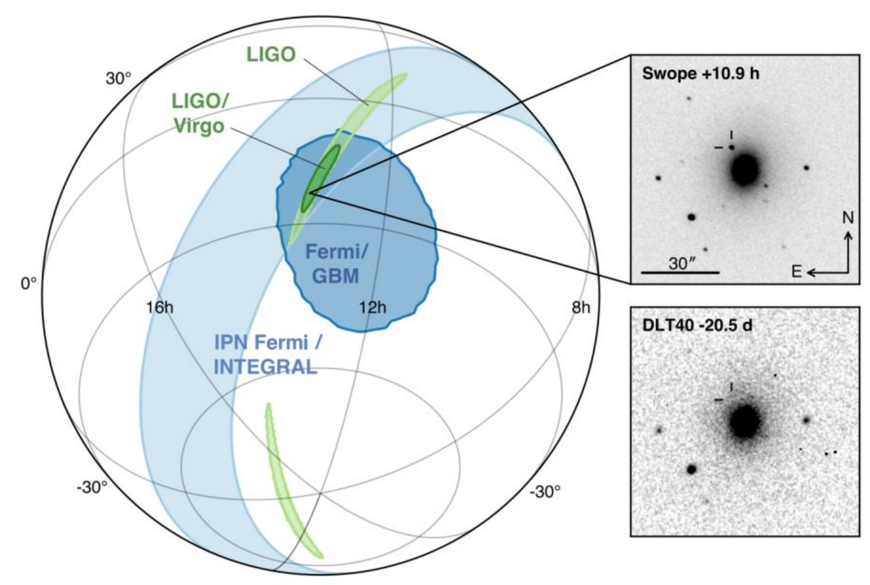


- Interferometer Angular Orientation
  - Sensitivity changes only in 2nd order to arm deviation from orthogonality
  - Coincident sensitivity changes only in 2nd order relative to angular misalignments
  - 0.5 deg error in either arm orthogonality or relative orientation between the observatories results in only a ~10 ppm sensitivity decrease
  - Not just “triangulation” – also use two waveform polarizations and astrophysical constraints



Detector	Latitude	Longitude	Azimuth	
			X Arm	Y Arm
LIGO Hanford (LHO)	46°27′19″N	119°24′28″W	N36°W	W36°S
LIGO Livingston (LLO)	30°33′46″N	90°46′27″W	W18°S	S18°E
Virgo	43°37′53″N	10°30′16″E	N19°E	W19°N

Source “Triangulation”



Abbott et al. Ap. J. Lett., 848:2 (2017)

- Observatory-to-Observatory baseline distance accuracy
  - Data timing accuracy (1 usec, derived from GPS, checked by atomic clock) x Light Speed = ~300 m
  - Actual waveform (signal) timing accuracy is ~0.1 ms (SNR = 10)
  - GPS provides baseline accuracy (~5 m) << required

Beam Tube Alignment

- Requirement to maintain a 1m clear aperture through the 4 km long arms
- A straight line in space varies in ellipsoidal height by 1.25 m over a 4km baseline
- A maximum deviation from straightness in inertial space of 5 mm rms
- An orthogonality between arm pairs of better than 5 mrad
- This quality of alignment comfortably meets LIGO requirements

Field assembly of the beam tubes

- The alignment of the LIGO system was done using dual-frequency differential GPS
- The BT's are fabricated from 3 mm thick, spirally welded 304L stainless steel in 20 m sections.
- 4x controlled interface points were defined along each arm.
- These points were identified by monuments having measured geodetic coordinates.

Beam tubes were aligned using dual-frequency differential GPS, 5 mm/4 km straightness*

See Rev. Sci. Instr. V 72, No. 7 p 3086, July 2001.

Transport

Position

Field fitup

Butt **weld**

Leak check

Add next section

Beam Tube Alignment

Final Alignment (images from)

- GPS Antenna Mounted on the Beam Tube Support Ring
- GPS Antenna Cart (equipped with linear bearings & a plumb alignment with a fixed height antenna rod) checking Position of Beam Tube "Surveyor's Nail

LIGO-G970294-18-B

Hanford Beam Tube “Surveyor’s Nail” at Slab Edge (1997)

GPS Antenna Mounted on Beam Tube Support Ring (1997)

GPS Antenna Cart (equipped with linear bearings & a plumb alignment with a fixed height antenna rod) checking Position of Beam Tube "Surveyor's Nail“.

Beam Tube Alignment

Beam Tube Support

Beam Tube Support

Final Alignment

- Supports were aligned for the final time after installation had proceeded for three to four sections, i.e., 80 m from the installation activity.
- This was just before the beam tube became covered by cement enclosures.

Chamber Alignment

- Chambers house complex primary as well as input/output optic suspension systems / fixed mirrors
- X and Y – Azimuth "Offset" monuments were established from the existing monuments used to position the beam tubes.
- These axial and transverse positional coordinates are referenced to the global coordinates set, by conventional optical survey techniques


BSC Chambers at the Vertex


HAM Chambers

IFO Alignment: Modes of Operation

Initial Alignment Mode

- Adjust input beam direction to go down the beamtubes and be centered on the optics
- Pre-align (“dead reckon”) main optics without optic actuation based on optical survey (100 μ rad)
- Static initial alignment of main optics using actuation (acquisition tolerance 0.5 μ rad)

Acquisition Alignment Mode (allows IFO locking)

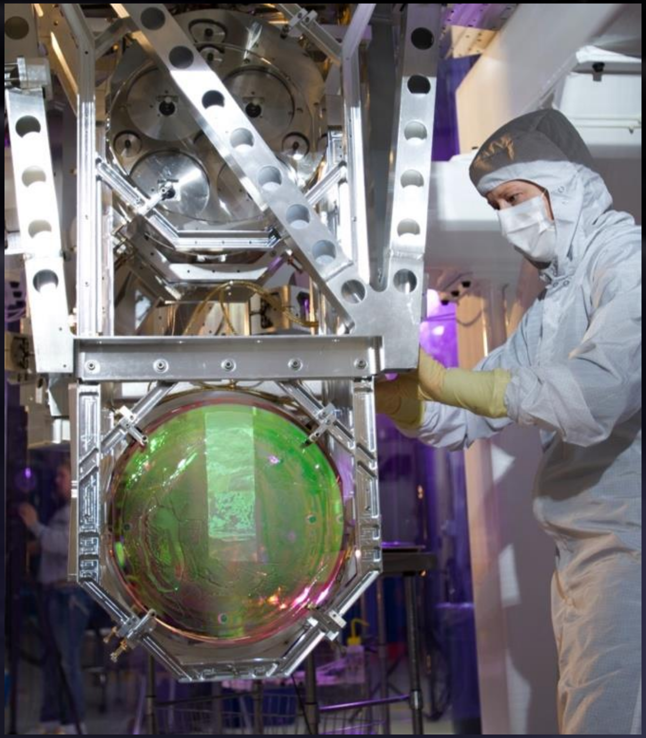
- Holding mode: main optics are held within the acquisition alignment tolerance continuously during the lock acquisition procedure

Detection Mode

- sense and control alignment of the IFO (3 nrad rms)
- sense and control centering of the beams of the main optics

Diagnostic / Calibration Mode

- provide diagnostic capability of performance
- provide calibration procedures



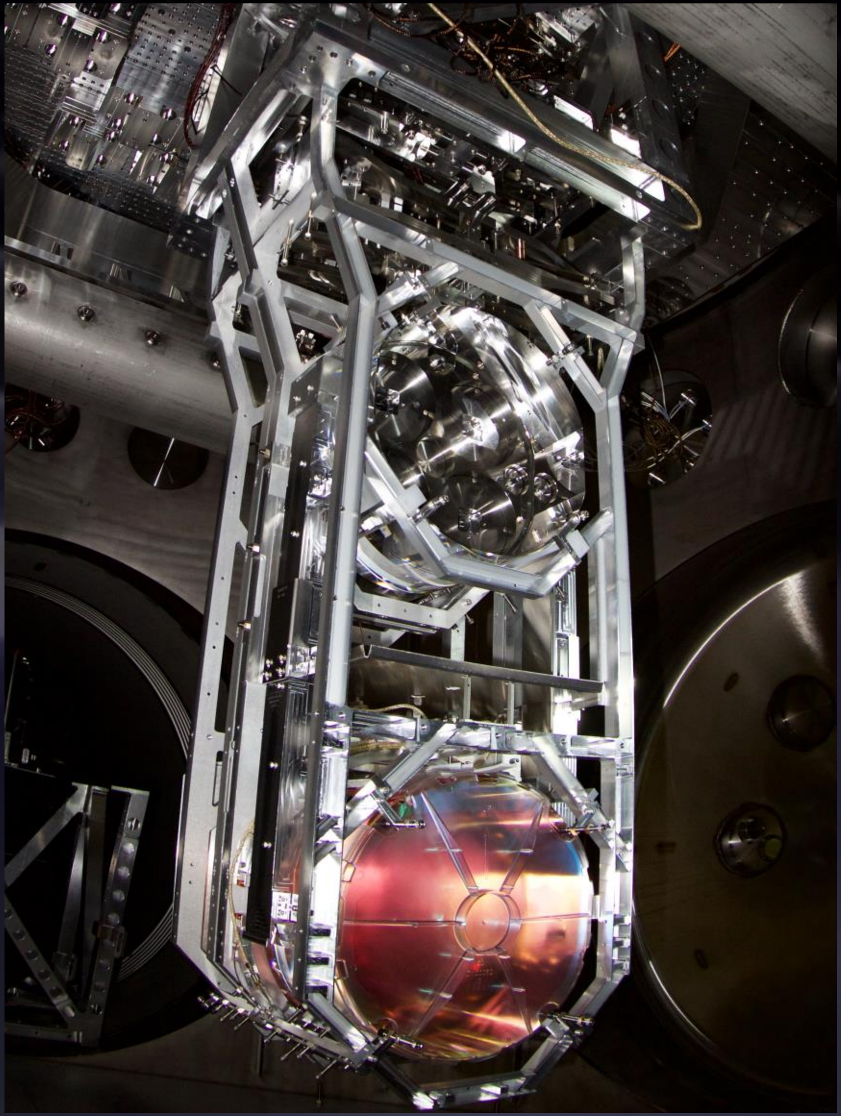
The optics are freely suspended, must position to a small fraction of a wavelength of main laser light (1064nm) in order to enable active, linear, servo-control.

Initial Alignment Plan Dwyer et al. https://dcc.ligo.org/LIGO-G1400193

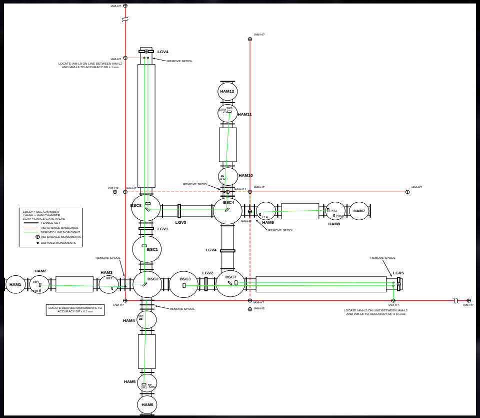
Footnote explaining the dual use of the term "initial alignment": LIGO commissioners co-opted the term "initial alignment". They mean it in a different sense than is used for the "Initial Alignment System (IAS)". In G1400193, IAS is referred to as "coarse alignment".

Interferometer Components/Optics Initial Alignment

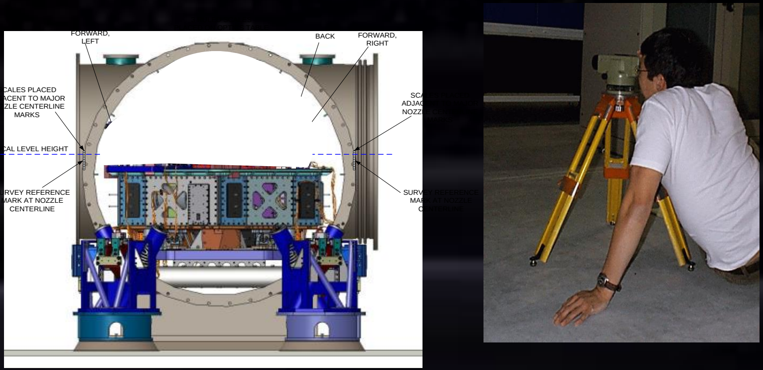
- Primary Optic placement and alignment tolerances
  - Axial positioning within ± 3 mm
  - Transverse position within ± 1 mm vertically and ± 2 mm (depending on optic)
  - Angular pointing to within 10% of the actuator dynamic range, which corresponds to ± ~100µrad generally



Chamber and Interferometer Components Alignment

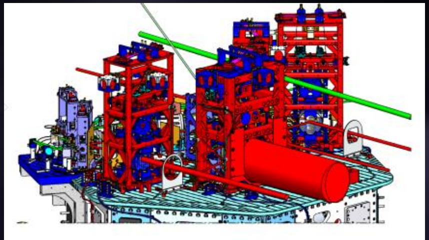


1. Additional monuments placed with view of optics

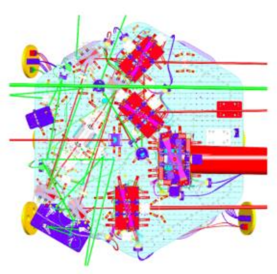


2. Tables positioned and aligned using “Total” Station” Theodolite & Optical Level

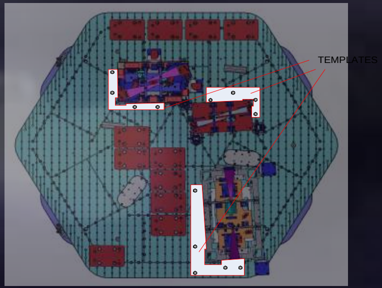
3. Zemax OpticStudio used for Ray Trace



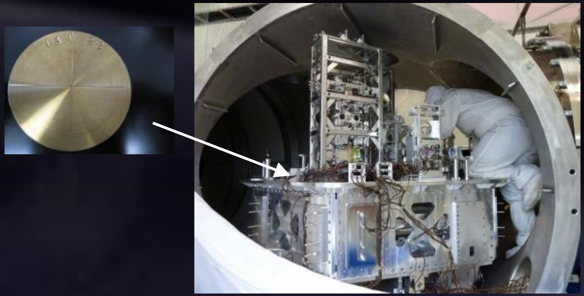
4. Co-ordinates transferred in 3D CAD (SolidWorks)



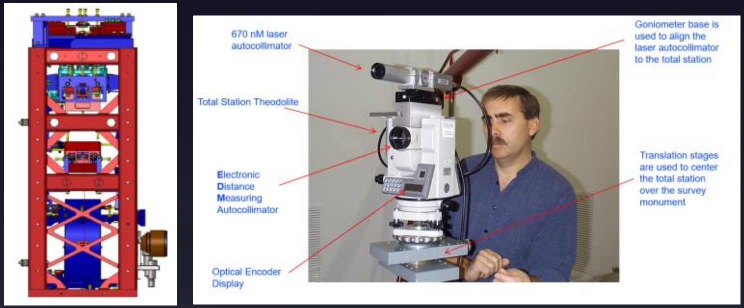
5. Then once layout complete checked with rays



6. Approximate Alignment using Templates



7. On table monuments also used for Approximate Alignment



670 nM laser autocollimator

Goniometer base is used to align the laser autocollimator to the total station

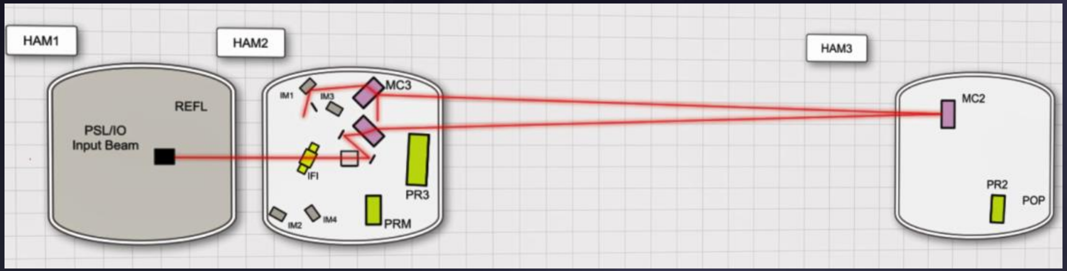
Total Station Theodolite

Translation stages are used to center the total station over the survey monument

Electronic Distance Measuring Autocollimator

Optical Encoder Display

8. Precise alignment: in situ using retro-reflectors with attached target and a laser autocollimator mounted on the Total Station



9. Integrated Alignment check: Using PSL beam in low power mode projecting through particular group of optics

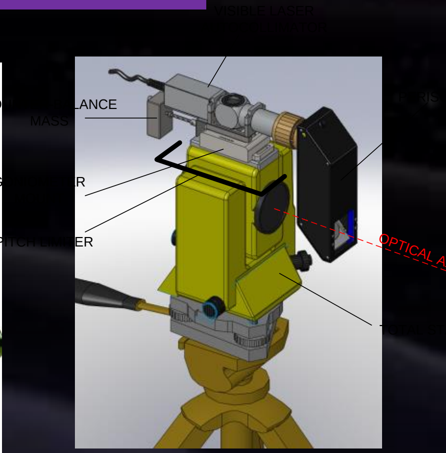
Key Equipment Used by LIGO

Full details at https://dcc.ligo.org/LIGO-T1000230/public

Optical level (Sokkia B2o AutoLevel)

Optical Transit Square (Brunson model 75-H)

Total Station (Sokkia Set2BII and SetX1)



Visible Laser Autocollimator (Newport LDS vector) with custom periscope.

Infrared Laser Autocollimator (4W fiber coupled laser and Davidson D-271-106)

Coordinate Measuring Machine (Romer)

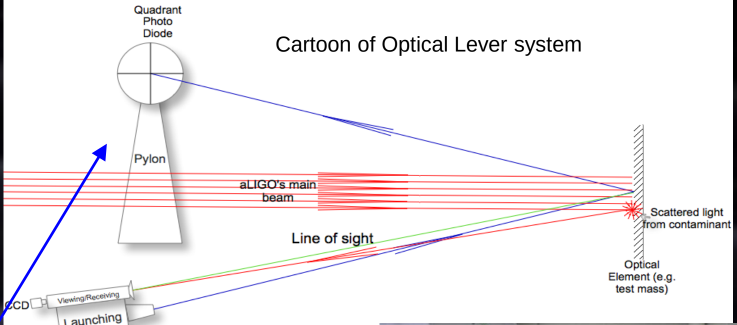
Lateral Transfer Retroeflectors (PLX)

LIGO: Optical Levers

https://dcc.ligo.org/LIGO-T1000517/public

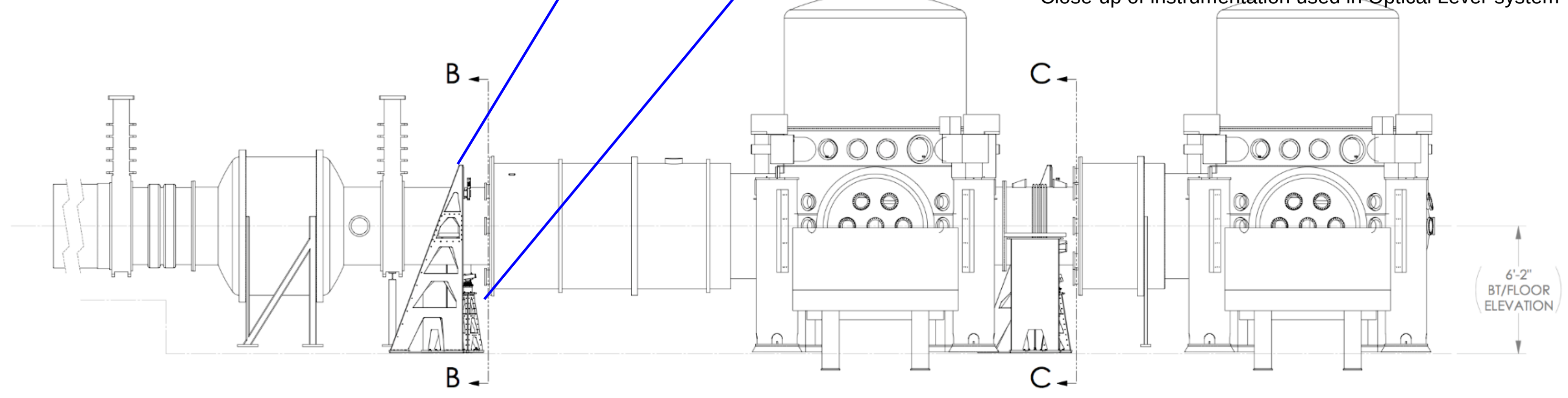
Optical Levers in aLIGO

- Serve as optical alignment references to 1 micro radian over a time span of one hour
- To keep the interferometer aligned until lock is acquired and the interferometer's angular feedback system can take over.
- Also very useful in case where lock is lost, can go back and look at last position of optical levers as starting point.


Cartoon of Optical Lever system


Close-up of instrumentation used in Optical Lever system

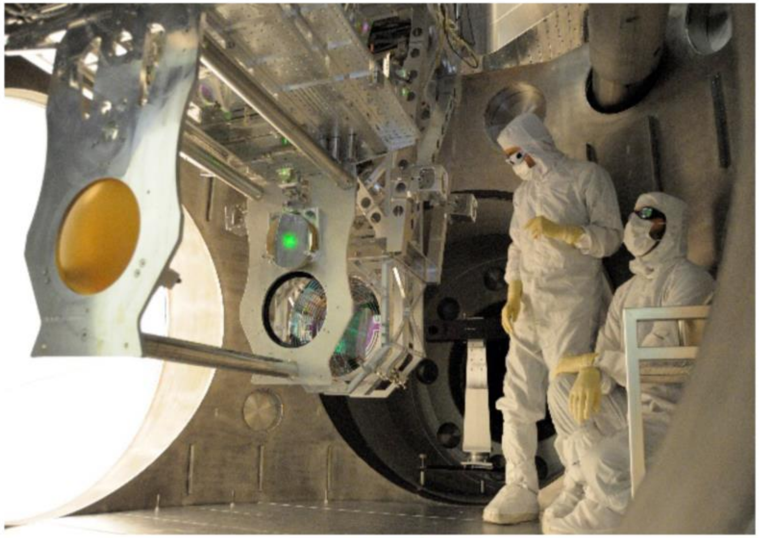
Side view of end station at LHO with Optical Levers shown



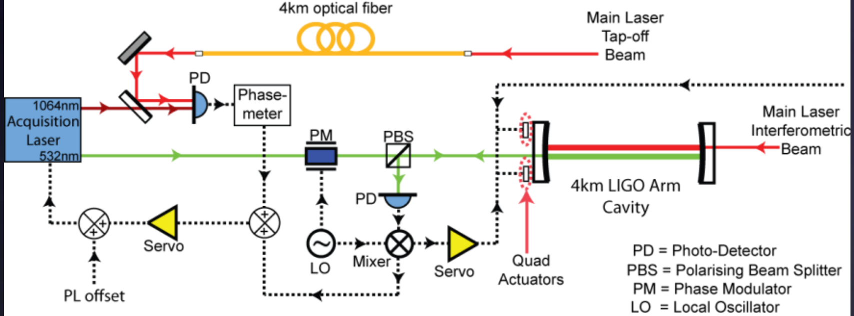
Arm Length Stablisiation

Arm Length Stabilization (ALS)

- Alignment is facilitated by locking the Fabry-Perot arm cavities independent of the rest of the interferometer with auxiliary low finesse 532 nm (doubled frequency) lasers.
- First the light of each auxiliary laser is made to resonate within each respective arm.
- Next the feedback is handed off to the cavity length actuators, so that the cavity length follows the laser frequency.
- The auxiliary lasers are then phase locked to the main science laser, so that the cavities can be tuned on and off resonance with the main laser beam.
- The cavities are only tuned onto resonance with the main beam once the rest of the interferometer is locked.
- Finally the feedback is switched from the auxiliary laser to the main laser.



Installation of the green (532nm) Arm Length Stabilization(ALS) subsystem for AdvLIGO. *Credit: Caltech/MIT LIGO Laboratory.*

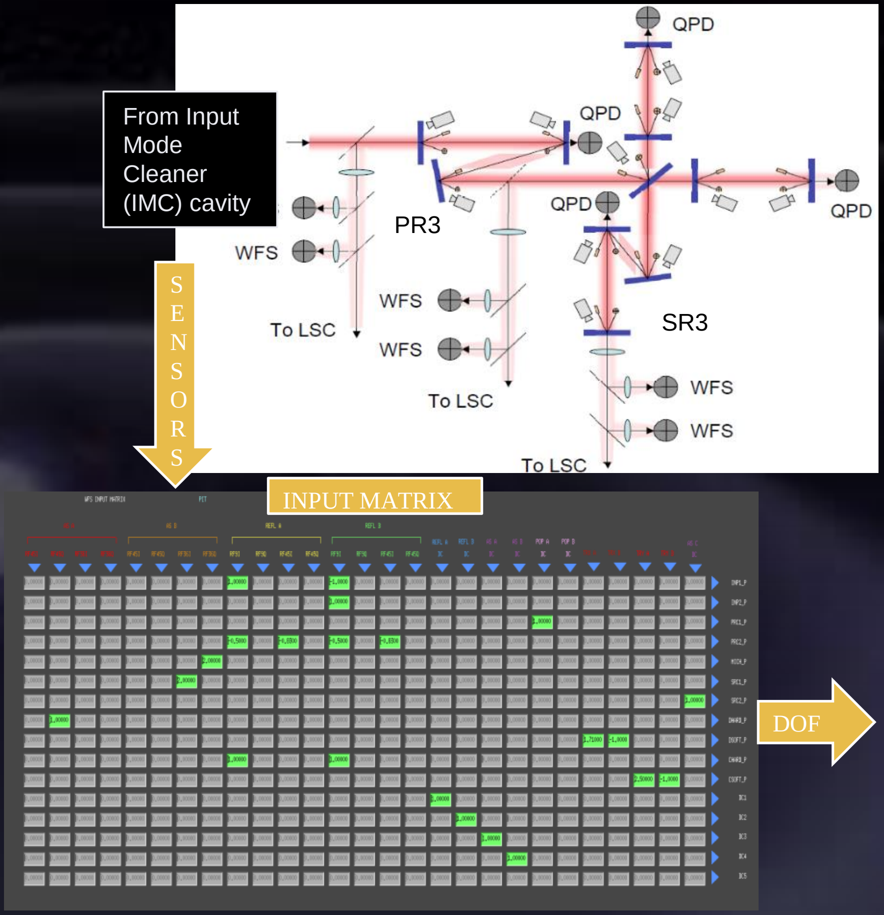


Simplified schematic of the ALS system for LIGO

A Staley et al **Achieving resonance in the Advanced LIGO gravitational-wave interferometer**
Classical and Quantum Gravity, Volume 31, Number 24

Alignment Sensing & Control (ASC)

- Requirement is to suppress the angular motion of the mirrors without reintroducing noise in the gravitational-wave signal
- The angular motion has two fundamental contributors:
    - seismic noise transmitted to the mirrors via their suspension systems and
    - shot noise of the sensors transmitted to the mirrors via the control system itself
- Sensing in LIGO
    - Quadrant Photo-Diodes (QPD)
        - Relative position → pitch & yaw
    - Wavefront Sensors (WFS)
        - RF QPD yields In-Phase and Quadrature Phase pitch & yaw
        - References the optical axis of the cavity
- 26 degrees-of-freedom
    - Input beam (pos + angle)
    - 11 optics form the PRC, SRC, FP arm cavities (yaw, pitch)



Input & Output Matrices are used to project the sensing to the controlled degrees-of-freedom (dofs)

Alignment Sensing and Control in Adv. LIGO, LIGO-P0900258, Class. Quantum Grav. 27 (2010) 084026
Advanced LIGO Angular Control System (ASC), LIGO-G1500923

What next?

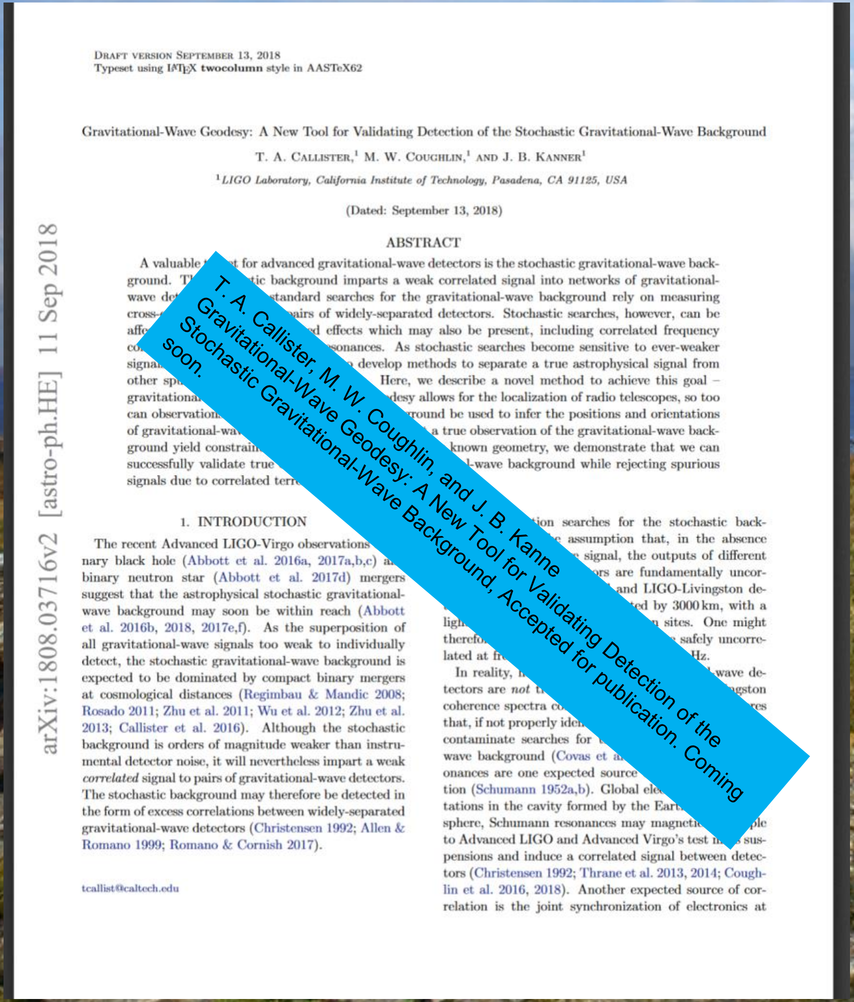
Alignment technology played a key role in opening a revolutionary new window on the Universe

This is a new field- we've just scratched the surface. We have plans for increasing sensitivity to sample 100x greater volume of space.

Beyond that, we are developing concepts for bigger instruments, up to 40km in size, that can map the *entire universe* in gravitational waves

Leading to New alignment challenges

Thank you



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arXiv:1808.03716v2 [astro-ph.HE] 11 Sep 2018

Gravitational-Wave Geodesy: A New Tool for Validating Detection of the Stochastic Gravitational-Wave Background

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(Dated: September 13, 2018)

ABSTRACT

A valuable t t for advanced gravitational-wave detectors is the stochastic gravitational-wave back-
ground. Th tic background imparts a weak correlated signal into networks of gravitational-
wave de standard searches for the gravitational-wave background rely on measuring
cross-c airs of widely-separated detectors. Stochastic searches, however, can be
affe d effects which may also be present, including correlated frequency
co sonances. As stochastic searches become sensitive to ever-weaker
signa o develop methods to separate a true astrophysical signal from
other sp Here, we describe a novel method to achieve this goal –
gravitational desy allows for the localization of radio telescopes, so too
can observation round be used to infer the positions and orientations
of gravitational-wa a true observation of the gravitational-wave back-
ground yield constrain known geometry, we demonstrate that we can
successfully validate true l-wave background while rejecting spurious
signals due to correlated terr

1. INTRODUCTION

The recent Advanced LIGO-Virgo observations
nary black hole (Abbott et al. 2016a, 2017a,b,c) a
binary neutron star (Abbott et al. 2017d) mergers suggest that the astrophysical stochastic gravitational-wave background may soon be within reach (Abbott et al. 2016b, 2018, 2017e,f). As the superposition of all gravitational-wave signals too weak to individually detect, the stochastic gravitational-wave background is expected to be dominated by compact binary mergers at cosmological distances (Regimbau & Mandic 2008; Rosado 2011; Zhu et al. 2011; Wu et al. 2012; Zhu et al. 2013; Callister et al. 2016). Although the stochastic background is orders of magnitude weaker than instrumental detector noise, it will nevertheless impart a weak *correlated* signal to pairs of gravitational-wave detectors. The stochastic background may therefore be detected in the form of excess correlations between widely-separated gravitational-wave detectors (Christensen 1992; Allen & Romano 1999; Romano & Cornish 2017).

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tion searches for the stochastic back-
e assumption that, in the absence
e signal, the outputs of different
ors are fundamentally uncor-
and LIGO-Livingston de-
ted by 3000 km, with a
ligh n sites. One might
therefo safely uncorre-
lated at fr Hz.

In reality, wave de-
tectors are *not* t ngston
coherence spectra co res
that, if not properly iden
contaminate searches for
wave background (Covas et a
onances are one expected source
tion (Schumann 1952a,b). Global ele
tations in the cavity formed by the Eart
sphere, Schumann resonances may magneti ple
to Advanced LIGO and Advanced Virgo's test m s sus-
pensions and induce a correlated signal between detectors (Christensen 1992; Thrane et al. 2013, 2014; Coughlin et al. 2016, 2018). Another expected source of correlation is the joint synchronization of electronics at

T. A. Callister, M. W. Coughlin, and J. B. Kanne Gravitational-Wave Geodesy: A New Tool for Validating Detection of the Stochastic Gravitational-Wave Background, Accepted for publication. Coming soon.

Trig Pillar from near my home Island of Islay, Scotland