# THE EVOLUTION OF COLLABORATIONS AND DETECTORS FOR GRAVITATIONAL WAVES IN THE US AND EUROPE

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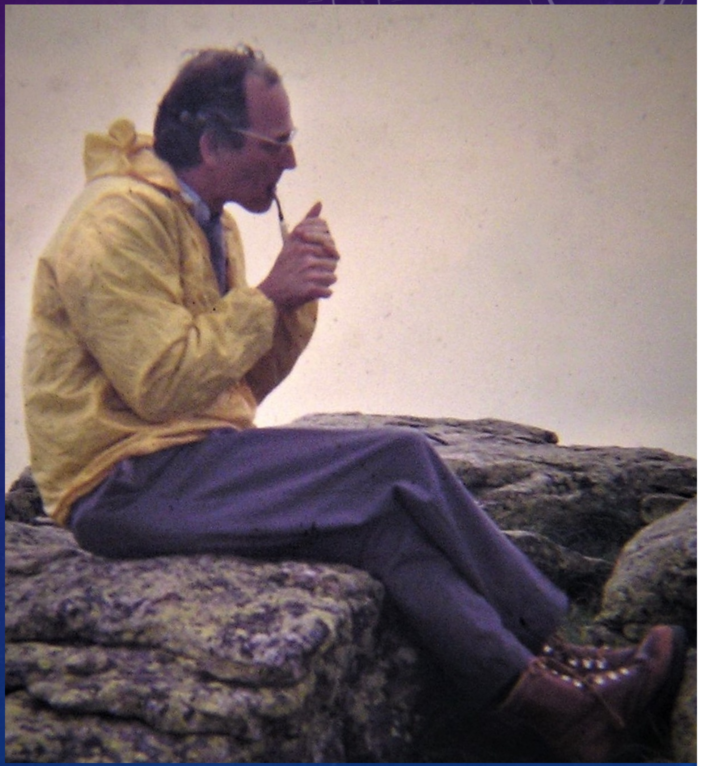
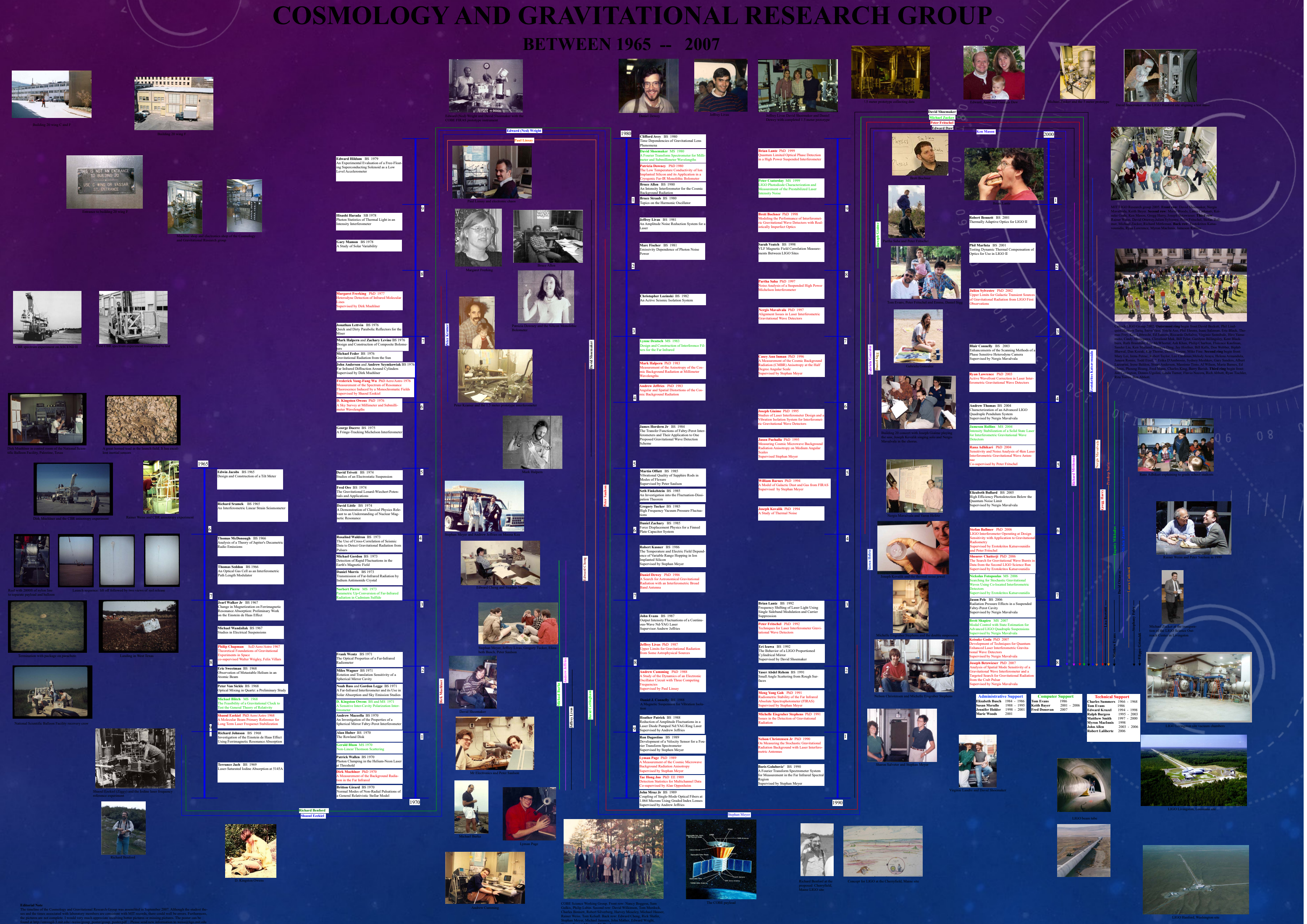
# RAI WEISS

SEPTEMBER 29, 1932, BERLIN, GERMANY
AUGUST 25, 2025, CAMBRIDGE, MASSACHUSETTS, U.S.

- 1972 Internal Report –
  roadmap for making instruments that work
- 1975 discussion with Kip –
  triggering the activity at Caltech leading to LIGO
- 1983 Blue book with MIT-Caltech authors –
  put LIGO on a firm quantified basis
- 1986 NSF Blue Ribbon Panel – Convinced Garwin
- 1990 10,001 analyses to manage Drever's imagination
- 1994 Designing and watching over the beam tube realization
- 1997 Launching the LSC; current Analysis domains
- 2000 Constant presence at the LIGO Sites, LIGO BT leaks
- Mentoring many of the leaders of the field, 1972-2025



# WEISS GROUP TIMELINE CMB+GW



# OBJECTIVES

- Give a reminder of the growth of the observational field
  - Limited to terrestrial interferometric detectors
  - LIGO and Virgo (lack knowledge to speak to KAGRA)
- Tease out some differences and repercussions;
  a personal view
- Organized around Epochs:
  - Prototypes on a range of scales
  - Coalescence of Experimental groups
  - Observatory proposals
  - Observatory design and construction
    - Start of the Collaboration Epoch
  - Observatory Operations and Upgrades
  - Next-generation Observatories

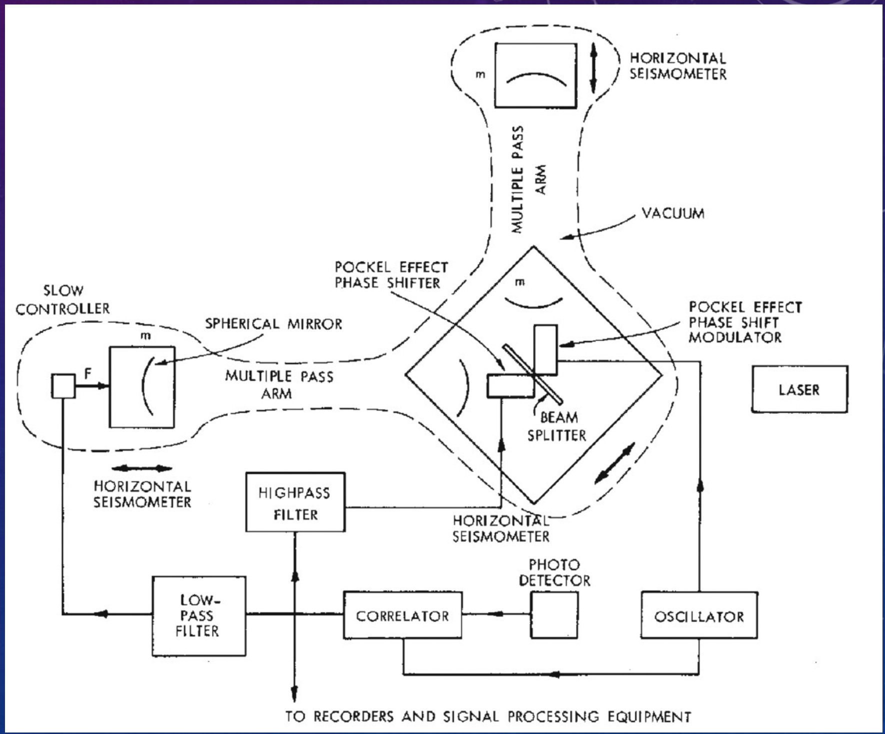
# TRAJECTORY

- 1975-83 MIT Weiss group; COBE, GW
- 1983-86 Garching Max Planck group
- 1986-89 Orsay Brillet group
- 1989- MIT LIGO, LISA, CE
  Many years of European advisory bodies

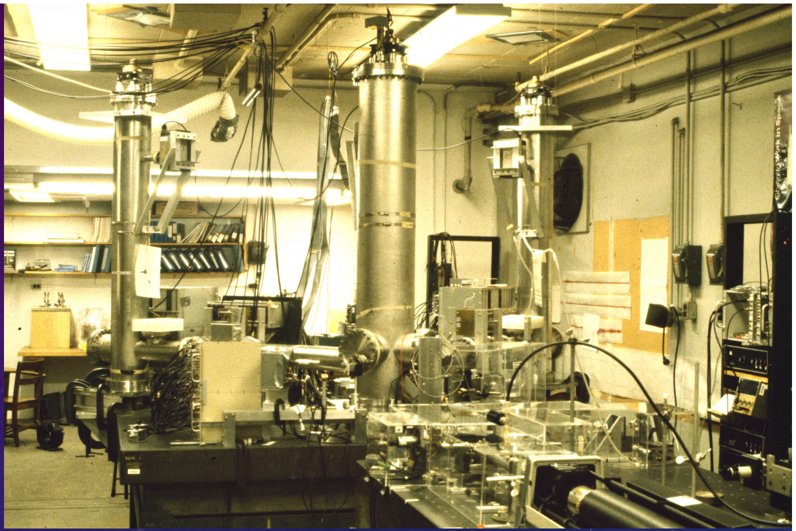
# RAI WEISS

https://link.springer.com/article/10.1007/s10714-022-03021-3
https://link.springer.com/article/10.1007/s10714-022-03022-2

- **Electromagnetically coupled broadband gravitational antenna**
- 1972 Internal Report – roadmap for making instruments that work
- Both analysis and instrument concept show Dicke's influence
- Basic concept sketched →
- 'Basis Set' of stochastic forces and optical sensing limitations, with conceptual designs and derivation of requirements

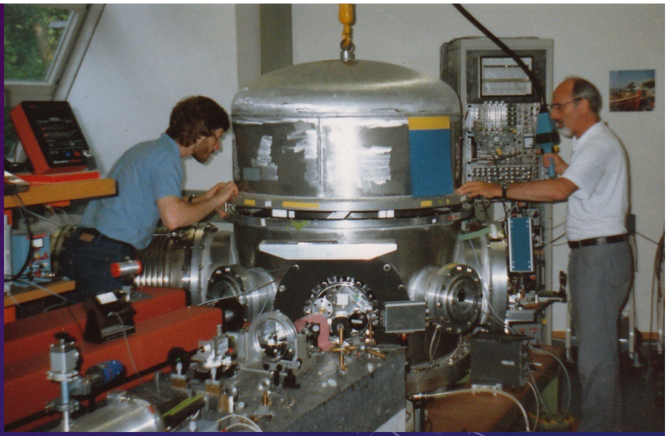


# 1970-80 R&D

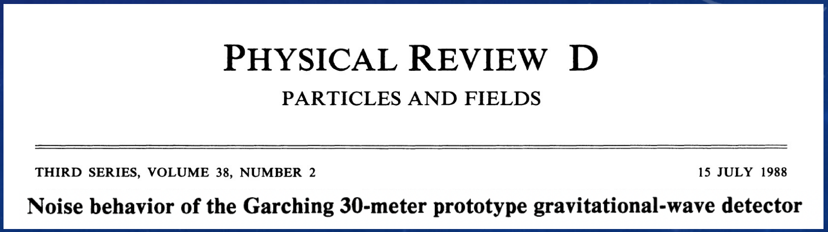


- Glasgow/Caltech
  - Developing ideas for interferometry; **Fabry-Perot cavities, power and signal recycling** (Drever, Hough, Strain, Meers…)
- Orsay
  - Bringing forward interferometry topologies, frequency stabilization, and **Nd:YAG lasers** (Brillet)
- Pisa
  - Trying first active isolation controls, then multiple **6 degree-of-freedom pendulums** (Giazotto)
- Early MIT experimental effort started from the 1972 report
  - 1.2m Michelson interferometer using Delay Lines in the arms, data acquisition and instrument monitoring, a search for signals – **a complete system**, of marginal sensitivity (Weiss, Dewey, Livas, Shoemaker…)

# 1970-80 R&D: GARCHING GROUP



- (Schilling, Rüdiger, Maischberger, Winkler, Schnupp)
- Seasoned instrument builders, in MPI Astrophysics
- Backed up by electronics and mechanics specialists and shops
- Built the best room-temperature Weber bars, saw nothing
- Received Weiss' proposal to NSF by back door; adopted interferometry
- Built several prototypes, final one of 30m armlength
- Perfectly suited to work through Weiss' 1972 paper, providing experimental basis to complement Weiss' 'theory' paper
- Gave LIGO instrument design credibility, and a model for how to do lab work
- As for NR, the Max Planck approach key



PHYSICAL REVIEW D
PARTICLES AND FIELDS

THIRD SERIES, VOLUME 38, NUMBER 2 — 15 JULY 1988

**Noise behavior of the Garching 30-meter prototype gravitational-wave detector**

# BY THE MID-1980S…

- Viable notions of the instrumentation for full-scale detectors
- Initial concepts for managing quantum noise
- Independent studies of  full-scale detectors from US, France/Italy, Germany, UK
- Initial efforts at analyzing data
- Growing interest by funding agencies of this new field

- Most work was undertaken in isolated groups, in ‘friendly competition’

# EXPERIMENTAL GROUP COALESCENCE

- Driven by Weiss and the NSF, Caltech and MIT joined forces
  - After some early efforts, Robbie Vogt named director, at Caltech (1987)
  - Brought authority, project experience, and engineering resources
  - Dictated changes in MIT and Caltech experimental groups, instilled ‘Project’ mentality, and led to some loss of staff
- Orsay and Pisa joined forces
  - Real complementarity in instrument skills (lasers, seismic isolation)
  - Brillet had optics and interferometry experience; was a leader in laser stabilization
  - Giazotto had project experience from HEP (and good connections)
- Garching→Hannover (Danzmann) and Glasgow joined forces
  - Similar working vision, similar interests

# EUROPEAN GROUP BIFURCATION

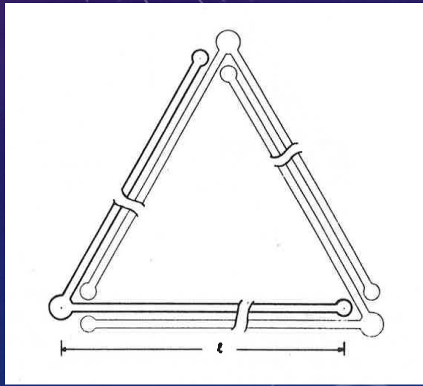
- Glasgow/Hannover and Pisa/Orsay shifted from Pan-European work to really independent effort
- What caused this split?
- Giazotto took advantage of an opening to get funding for Virgo (1992/3)
  - In some measure a violation of agreements for pan-European planning
- Germany and Glasgow believed firmly in the need for prototypes
  - Not Pisa and Orsay – Desire not to incur the delay of realizing prototypes
  - This may have had long-term effects in depriving Virgo of new generations of commissioners
  - With hindsight, some Virgo design decisions might have been avoided
  - Glasgow/Germany may have believed that Orsay/Pisa lacked necessary experience/judgement

# KEY LIGO PROTOTYPE DEVELOPMENTS

- Weiss 1972: need both displacement AND phase sensitivity
  - Demonstrate that the test masses can isolated from seismic etc. noise such that the apparent displacement from GW will dominate, in some freq. range
  - Demonstrate required ability to measure a phase shift due to a GW
- Caltech 40m prototype
  - Did not have an optical sensing system that would work for LIGO
  - …but did show good enough isolation of the masses >500 Hz; 1995
- MIT 5m prototype
  - Did have an optical system that resembled a very simplified LIGO
  - Was shot-noise limited (circulating power) to required level; 1999
- LIGO Lab – and NSF – convinced of need for these demonstrations
  - Virgo could use these as proof of principle as well

# EUROPEAN OBSERVATORY PROPOSALS

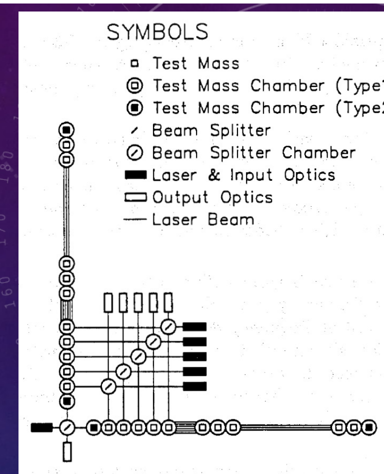
- Germany and UK had plans for one or two km-scale observatories
  - A triangular configuration to be in Germany (1985) made good progress in the funding arena, until…
    The Berlin Wall came down (1989)
  - GEO-600 was a fallback, with significant local funding



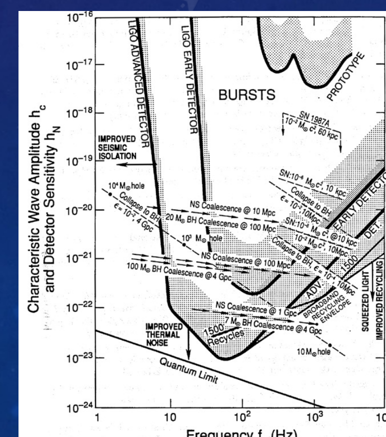
MPQ 101

- France and Italy conceived of Virgo (1989)
  - Opportunistic jump forward by Giazotto in Italy cast a die in European relations
  - Particle physics funding sources
  - Kernel of the Virgo 'experiment' Collaboration formed

# LIGO PROPOSAL (1989, 1994)




- Decision to jump from 40m to 4km (no intermediate step); Weiss' insight
- Two detectors, large separation, considered necessary
- National Science Foundation funding (under the Physics Division)
- Significant rescoping from Drever's initial vision to a realistic approach
    - 6 interferometers per site, rapid test-mass swap, etc.
    - …replaced by 1 detector Livingston, and 1 full-length and one half-length at Hanford
- Joint MIT-Caltech work to prepare the proposal and defend it key to transformation to a single team, facilitated by Vogt and a 'circle the wagons' mentality
- Carried the message that detection was plausible, but that 'advanced detectors' would be inevitable and probably required
    - Infrastructure prepared for better sensitivity
- Significant activity *in* the NSF (Isaacson, Bardon) to support LIGO



# OBSERVATORY PROPOSAL EPOCH ASTROPHYSICS

- Early efforts in data analysis
  - 1992 Sam Finn “Detection, measurement and gravitational radiation”
  - 1996 Bruce Allen’s GRASP
  - 1995 LIGO Research Community; open to all, informal, led to…
- Most of those proposing and working on instruments mostly laser, optics, precision measurement, or ’project’ people
  - Many really interested in the measurement science – not GWs
- Astrophysics arguments to motivate the building of detectors from the ‘external’ astro community
  - Typically with one or several ‘liaisons’ to the Projects (e.g., Kip)
- Analysis, data quality, confidence, MMA developed in student theses and ‘demonstration’ observing runs using the prototypes
  - At MIT, ‘science’ was a necessary ingredient for a PhD

# PROPOSAL EPOCH MEASUREMENT THEORY

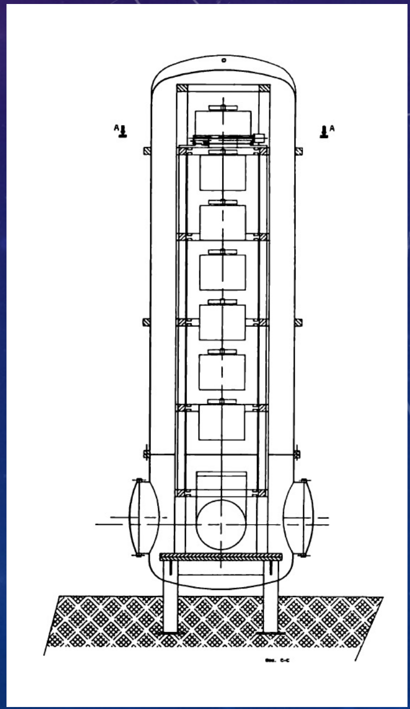
- Thorne and Braginsky groups important for LIGO’s success
  - For Virgo, one example is Jean-Yves Vinet
- Broader measurement theory community lively contributor
- Interferometer configurations
  - Glasgow an important contributor – Strain, Meers; novel ideas tested at Orsay (Brillet, Man)
- Quantum measurement concerns and opportunities
  - Initially pretty simple stuff – shot noise, modulation schemes
  - Caves’ insights triggered a slow tsunami of a more sophisticated view of quantum noise
  - Coupling of shot noise to radiation pressure via signal recycling
  - Now to frequency-dependent squeezing and speedmeters, etc.
- Thermal noise (Levin)
- ‘Ordinary’ work undertaken by theorists
  - Light scattering (LIGO Baffles)
  - Huygen’s principle applied to optical modeling

# OBSERVATORY DESIGN AND CONSTRUCTION: LIGO

- Drever, and then Vogt, separated from LIGO
  - Did not conform to obligatory constraints of successful Project discipline
- Barish (Director) and Sanders (Project Manager), 1994 – 2006
  - Brought HEP Big Science Project insights and practice.
  - **Key step forward.**
- Robust support from the NSF; collaborative interaction with NSF
- Significant participation (intellectually, funding) from UK, Germany
  - N.B.: Continued fallout from the 'Bifurcation'
- Caltech was Project Lead; MIT key to design and realization, but minor engineering and management role
  - MIT (the Institution) uninterested in Project responsibilities;
  - Caltech did not want equal partnership
  - Continues to today (…and tomorrow)

# OBSERVATORY DESIGN AND CONSTRUCTION: VIRGO

- Initially one group each in France and Italy; 1991 Collaboration formally established
  - Leadership alternating between Giazotto and Brillet
- 3km baseline (LIGO is 4km)
  - Provides a standing barrier to LIGO-Virgo equality in sensitivity
- Low  frequency instrument design focus
  - Giazotto targeted GW signals from Pulsars ~10 Hz
  - (Note that Virgo and LIGO have now similar *realized* low-frequency sensitivity)
- Facility buildings tightly designed around isolators
  - Creates challenges for modifications
- Instrument, like LIGO, needed a series of fixes and upgrades
  - Was there a negative consequence of the lack of prototypes?



https://www.ego-gw.it/wp-content/uploads/sites/12/2020/04/VIRGO_Proposal_1989_VIR-0517B-15.pdf?utm_source=chatgpt.com

# THE VIRGO ORGANIZATION

- Early Collaboration a handful of University/Institute groups in Italy and France focused on building the initial detector (1993)
  - Experimenters did not initially welcome others, e.g., astro/GR folks
  - Now many nations and groups involved, with Observational Science included (2004)
  - Basic Collaboration structure and 'charter' has remained the same
- Individual groups obtain funds for subsystems;
  design, build, deliver, commission, maintain (and maintain control of) hardware
- Top level Virgo design determined by *consensus* of groups in Virgo
- Establishment 2000 of European Gravitational Observatory (EGO) at site
  - Intended to be a source of technical maintenance, not a scientific partner
- Spokesperson has the role of establishing *consensus* for the instrument plan and key design issues (as well as now the Observational Science)
  - Only 'moral' authority; decision discussions are on their own time line

# THE LIGO ORGANIZATION:
# LIGO LABORATORY + LIGO SCIENTIFIC COLABORATION

# THE LIGO ORGANIZATION: LIGO LAB

- 1997: Creation of LIGO Laboratory
  - In parallel with the creation of LIGO Scientific Collaboration
- Caltech and MIT only. Not a “Collaboration”
  - Employees carrying out job responsibilities; hierarchical organization
- Observatory activities are Lab responsibility (and staff)
  - Visitors possible under Lab direction
- Caltech and MIT Campuses focused on R&D, engineering, and management
- NSF supports via ‘cooperative agreement’ with Caltech
  - MIT on subaward
  - 5-year funding cycle gives stability
  - Separate proposals for upgrades (e.g., Advanced LIGO)
- …and Lab members are LSC members – mutually supportive

# (ASPEN CENTER FOR PHYSICS MEETINGS)

LES HOUCHES FOR LIGO

- Collection of meetings organized by Caltech/MIT (Syd Meshkov)
- Yearly from 1995 to 2001, molted into GWADW (Elba etc.)
- Focus was always on ‘future detectors’ – aLIGO, then beyond
- First meeting simple reporting of R&D
- Second meeting discussion of need to focus on relevance (1996)
  - Choices of ‘competing’ ideas for design elements
  - Complemented by NSF asking LIGO Lab to review proposals
- This process led to the initial concept for Advanced LIGO
  - Key insight: Glasgow monolithic suspensions to manage thermal noise
  - → Setting requirements on seismic isolation for aLIGO
- **A key event – the focusing of R&D**

# THE LIGO ORGANIZATION: LSC

- 1997: Creation of LIGO Scientific Collaboration
- Not a significant source of deliverable instrumentation to the Observatories; Caltech and MIT produce installed equipment
- …but LSC a very important contributor of R&D for new instrumentation
- Contributing to the science from LIGO the main criteria for membership
- Principal foci: Data Quality, Data Analysis, Astrophysical Interpretation
  - And a lot of bureaucracy to measure and monitor contributions
  - ‘Payment’ in authorship of LSC papers;
    24→18→ 13 month proprietary period
- UK, Germany, Australia strong elements in the LSC (…not in Virgo…)

# LSC VS VIRGO APPROACHES TO INSTRUMENTATION

- Both recognize importance of engaging the hardware R&D community
- Virgo gives responsibility to the distributed community for deliverables to the detector
  - Serves to maintain a wide group of instrument scientists and funding
  - Profits (and suffers) from pan-European collaboration and social environment
  - Presents challenges for systems design, project management
- LIGOLab/LSC has a two-step approach
  - LSC Working Groups develop ideas (Initially at Aspen, 1996)
  - Presented to LIGO Lab when demonstrated to be useful for detector
  - LIGO Lab takes over engineering, fabrication, installation, ownership

# CURRENT LSC, VIRGO, KAGRA → IGWN

- All strain data are analyzed by all members of all 3 Collaborations
  - Papers are signed jointly
  - Instrument specific tasks – calibration, data quality – separate
- Successes: development of analysis pipelines, scientific interpretation, published papers
- Problems: different rules, separate decision-making processes, imbalances in computing contributions → inefficiencies and a sense of inequity in members
- Solution chosen: combine the 3 Collabs under one set of rules.
- ~2500 persons, checks on contributions, bureaucracy
- Hope is to reduce the highly variable levels and values of contribution
- Data remain proprietary for a period of a year+
- (For some future talk: not a long-term sustainable path!)

# OBSERVATORY OPERATIONS AND UPGRADES

- LIGO and Virgo detectors have undergone a series of upgrades
  - Detection rate grows as cube of sensitivity!
  - Now, e.g., the most spectacular application of quantum sensing
- To date, all instruments stop and start observing together
  - May be an error from the greater astrophysics perspective
- Virgo and LIGO use many similar technologies
  - Seismic isolation approach very different (multiple pendulums vs. servos)
  - Virgo did not adopt a key optical upgrade ('mode-stable input/output cavities')
  - May entail a significant 'downtime' in coming years for Virgo
- Strategy for observation, interface with Astro world needs evolution

# ADVANCED LIGO

Key advances that enabled 1st detection:

- Reduction of stochastic forces
  - Seismic noise
  - Thermal noise
- Reduction of sensing noise
  - Lower-loss optics
  - Change in light coupling cavities
  - Increase in circulating power

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- Reduction of stochastic forces
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- Reduction of sensing noise
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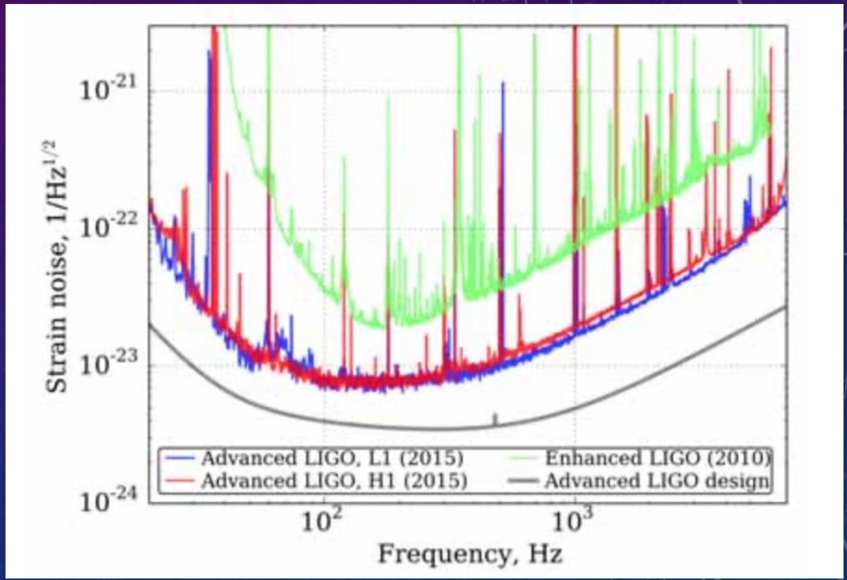
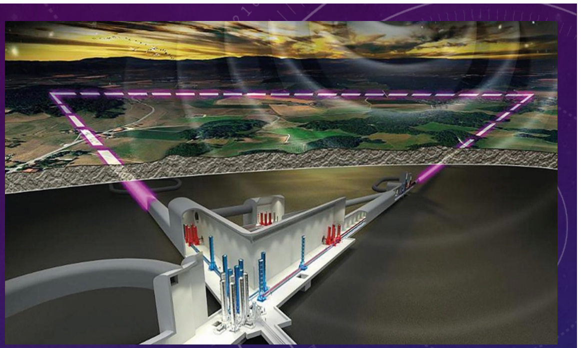
  - …after the comment yesterday about ‘noise curves’ I had no choice but to include one!



# NEXT-GENERATION OBSERVATORIES: ET



- Einstein Telescope very well advanced in the funding/political/organizational senses
- Interestingly focus is again on low frequencies (~3 or 5 Hz)
  - Goals: pre-merger MMA guidance; IMBH
  - Drives the instrument underground to reduce gravity gradients – arm length of 10 (or 15) km
  - Drives the plan for low- and high-frequency detectors, cryogenics
  - Brings expense and challenges – and potential great science
- Instrument goals require significant technical advances -- very motivating for the ET instrument community!
- See differences north-south Europe once again
  - Sites, configurations, organization…cultural, or chance?
  - But this time UK and Germany may put focus on Europe, not US, for next-generation
- See tensions between 'the Collaboration' and 'The ET Organization'
  - Funding agencies need control; the Scientists want ownership
- See tensions ET vs Virgo –
  - Limited number of skilled experimentalists;
  - Much more generous funding for ET than Virgo

# NEXT-GENERATION OBSERVATORIES: CE

- Cosmic Explorer the planned next US Terrestrial GW Observatory
- Started much later than ET, less developed, smaller community
- A giant LIGO (40km instead of 4km); surface, room temperature
  - Low-risk approach for the observatory, and the initial detector
  - Generates less excitement for the instrument scientists
  - Plan on evolution of the detector over ~50-year lifetime of Observatory
- Ever closer connection CE-LIGO Lab
  - Anticipate a single entity in future
- Greatest risk and challenge: making constructive relationships with the indigenous peoples whose land will host CE
  - TMT as a cautionary tale

# CE AND ET NETWORK

- Evident that the Observatories will need each other to leverage the data
  - ET initially conceived before first detections, and planned to be the 'one' next generation detector
  - Now likely that US-based CE will be built, as a single detector
    - 40km and 20km is the 'baseline' but unlikely to be funded
  - LIGO-India, using components from US LIGO in an Indian Observatory, will likely form the 3rd leg of the tripod; progress there has been slow
    - Could (should) be adopted by CE/ET as a central element of the next-generation program

# CLOSING THOUGHTS – PERSONAL OPINIONS!

- We have learned how to design, build, and operate successful detectors
  - Net uptime with upgrades is suboptimal
  - Virgo's performance limited by its organization
- Have developed Collaborations which deliver excellent science
  - Early-career scientists can get lost in thousand-person organizations
  - Proprietary data and payment in authorship unattractive elements
- Have visions of technology to make 10x improvement
  - ET excessively complicated
  - CE may not have timely funding and site options

We have been / will be well rewarded for solving our past and future challenges!