2012 Texas Section APS/AAPT/SPS
Joint Meeting

Advanced LIGO: The Next Generation of Gravitational Wave Observatories

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for The LIGO Scientific Collaboration

LIGO-G1200139

Overview

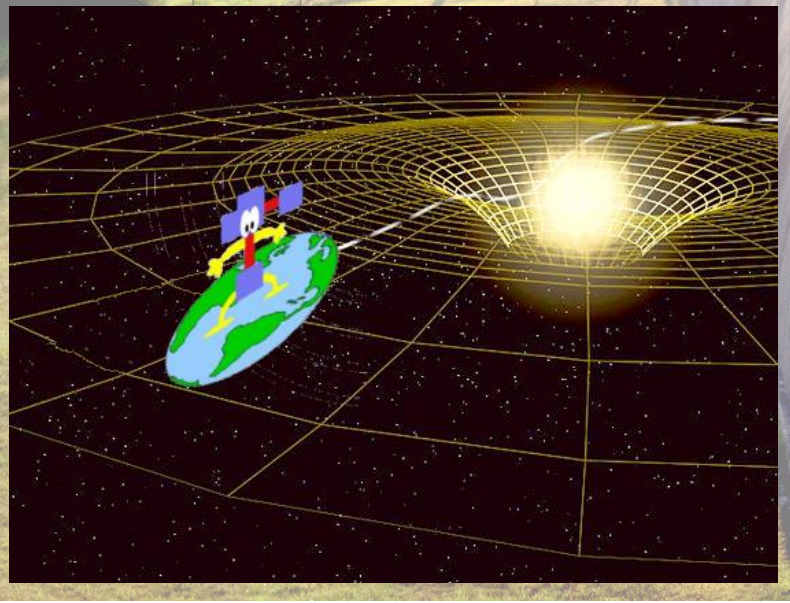
- Gravitational Waves (GWs)
  - What are they?
  - Indirect evidence of their existence?
  - What are their sources?
- GW Detection
  - Detectors
  - Signal Bands
- Interferometric Detectors
  - Explained
  - Decoding GW signals
  - Sensitivity evolution
- Summary of Results and Techniques
- Arguments for advanced detectors
- Advanced LIGO Detectors
  - New technologies
  - Timeline
  - New opportunities
  - Rapid analysis
  - Instrument characterization
- Advanced Detector Era Tweaking
  - Squeezed Light
  - Subtracting Newton's Gravity
- GW Astronomy
  - A global network
- Conclusions

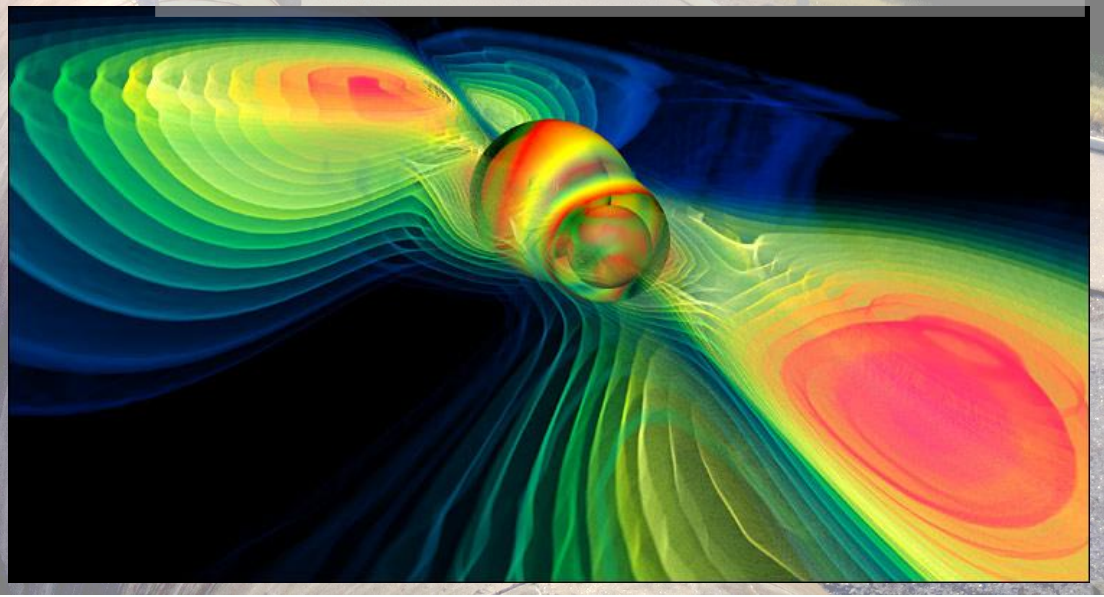
Gravitational Radiation

Gravitational Waves

- Newton's Gravity vs Einstein's Gravity
  - Information propagation finite!
  - Space is geometrical

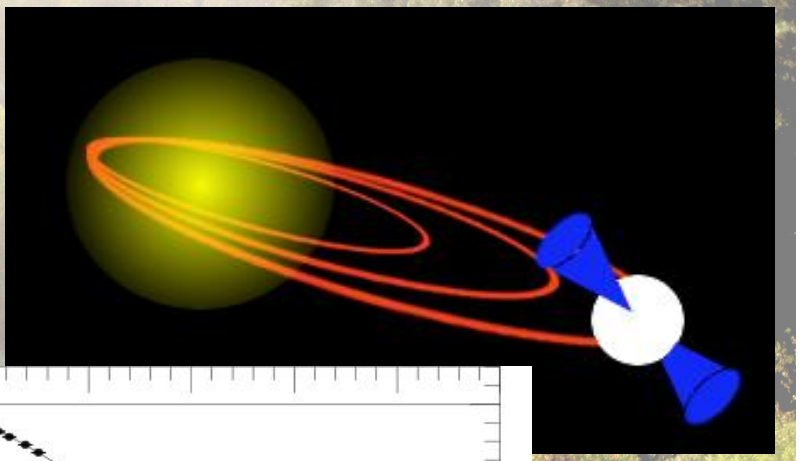
- polarizations
  - Cross
  - Plus
- asymmetrical mass distributions

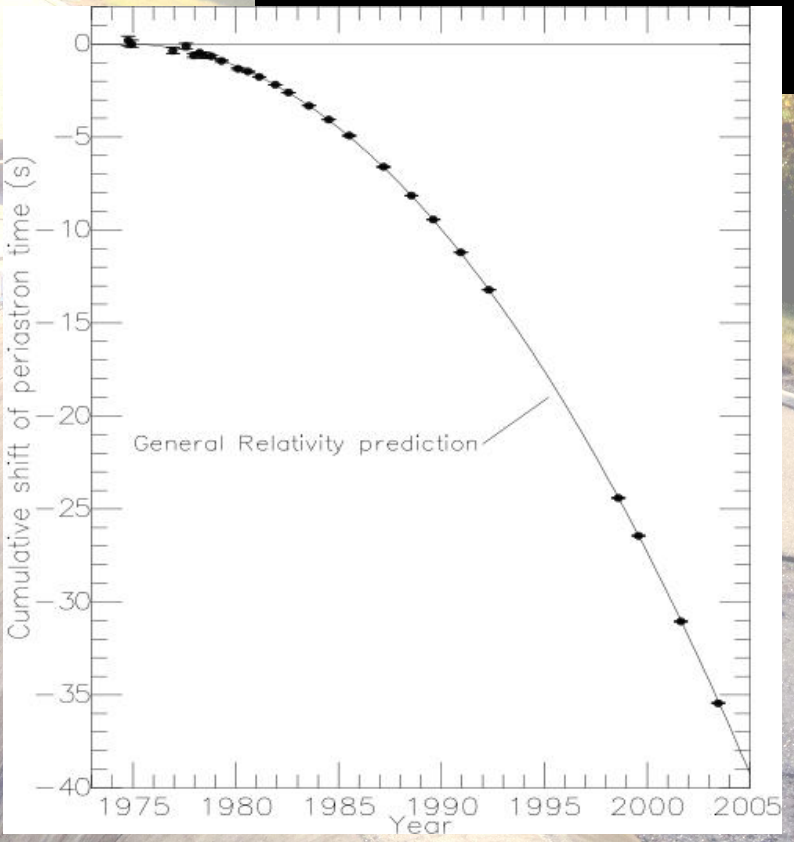




Indirect Evidence of GWs

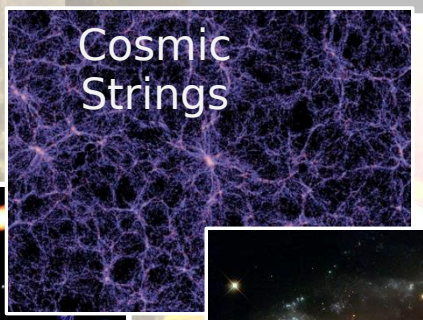
- Hulse Taylor Pulsar *PSR 1913+16*
- Binary system composed of one steady pulsar
- Period of system decreasing with time
- GR predicts rate of decrease consistent with GW emission of system energy

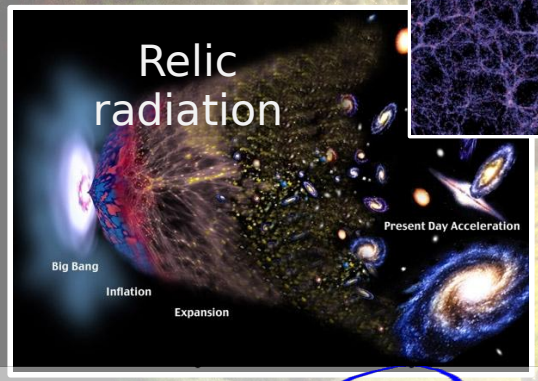


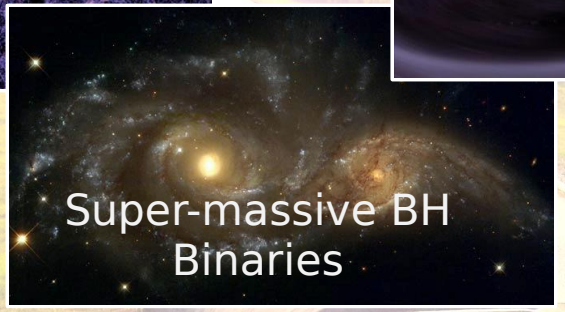


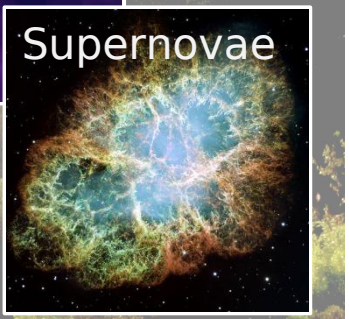
Weisburg and Taylor 2004

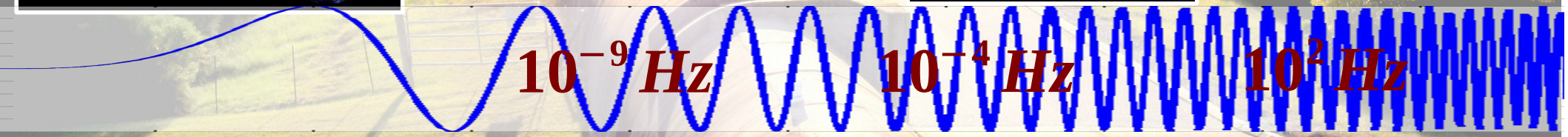
Gravitational Wave Sources

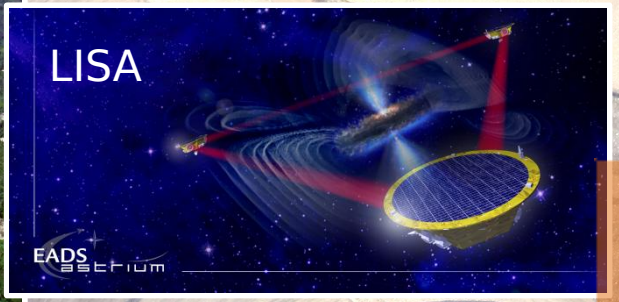












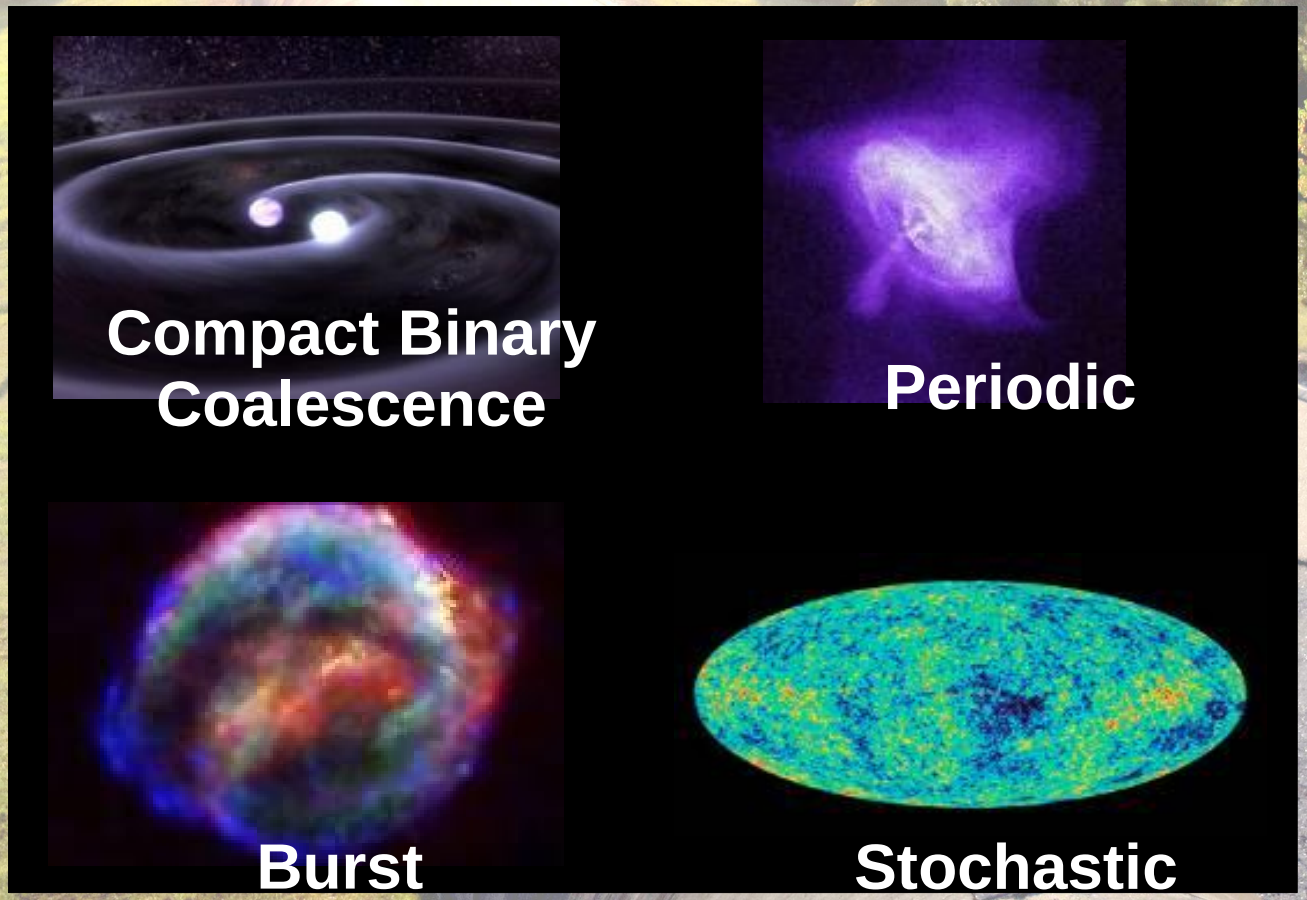
Ground
interferometers

Sources for Ground Based Detectors

- Band: 10s to 100s of Hz
- Timescale: seconds, to weeks

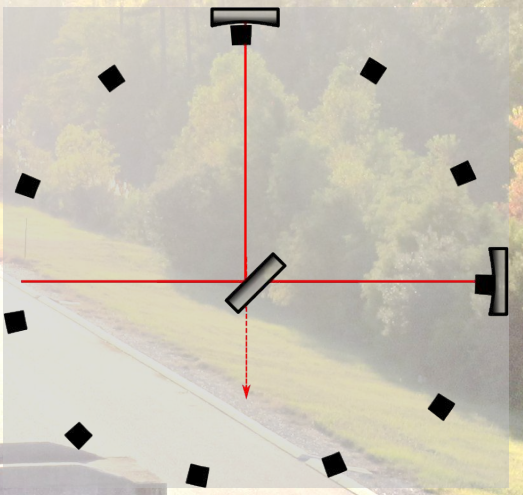
Short Duration to Long Duration Signals

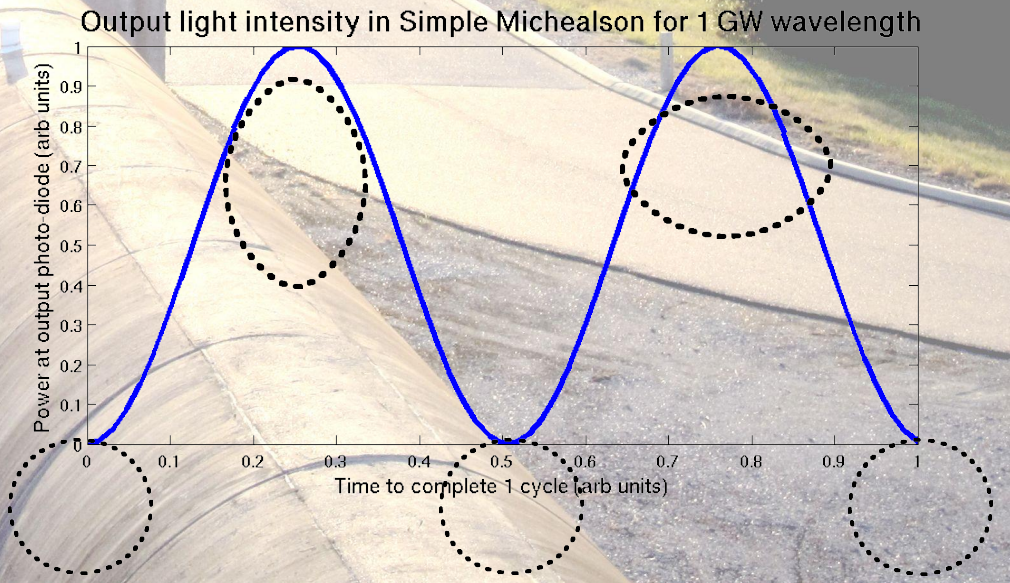
Unknown Waveform to Known Waveform



Designing a GW Detector

- GW Signals cause *differential* space-time distortion
- Polarizations
  - Cross “x”
  - Plus “+”
- Wave Properties
  - Transverse
  - Speed of light

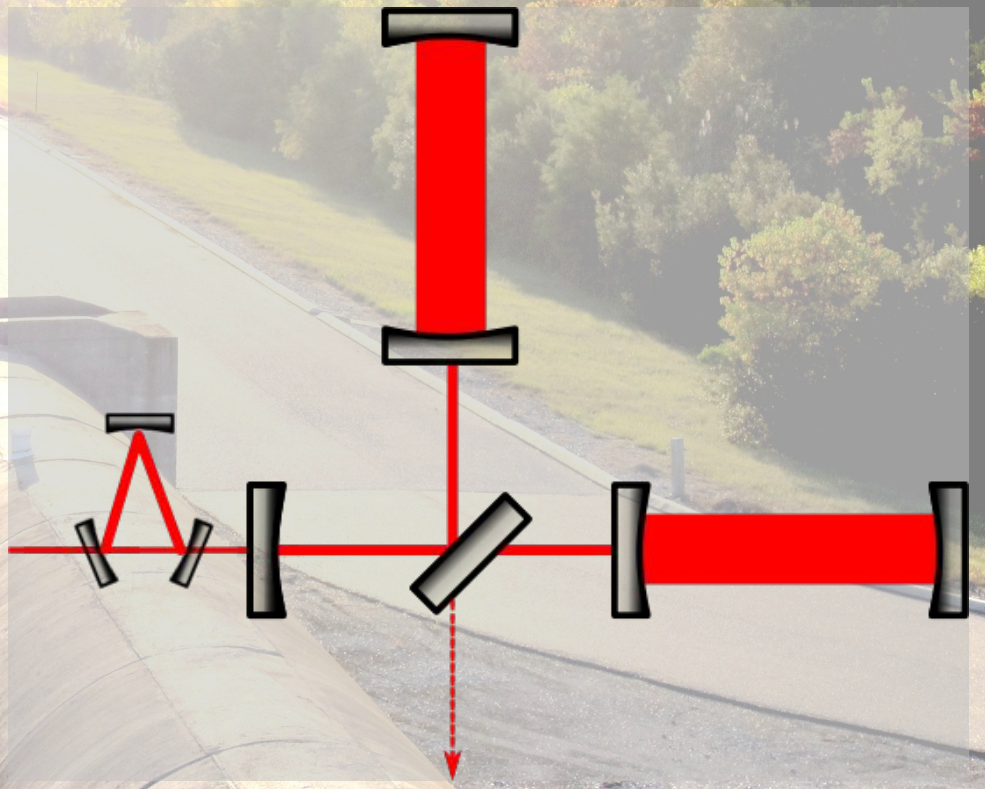




More realistic detector

Fabry-Perot Michelson

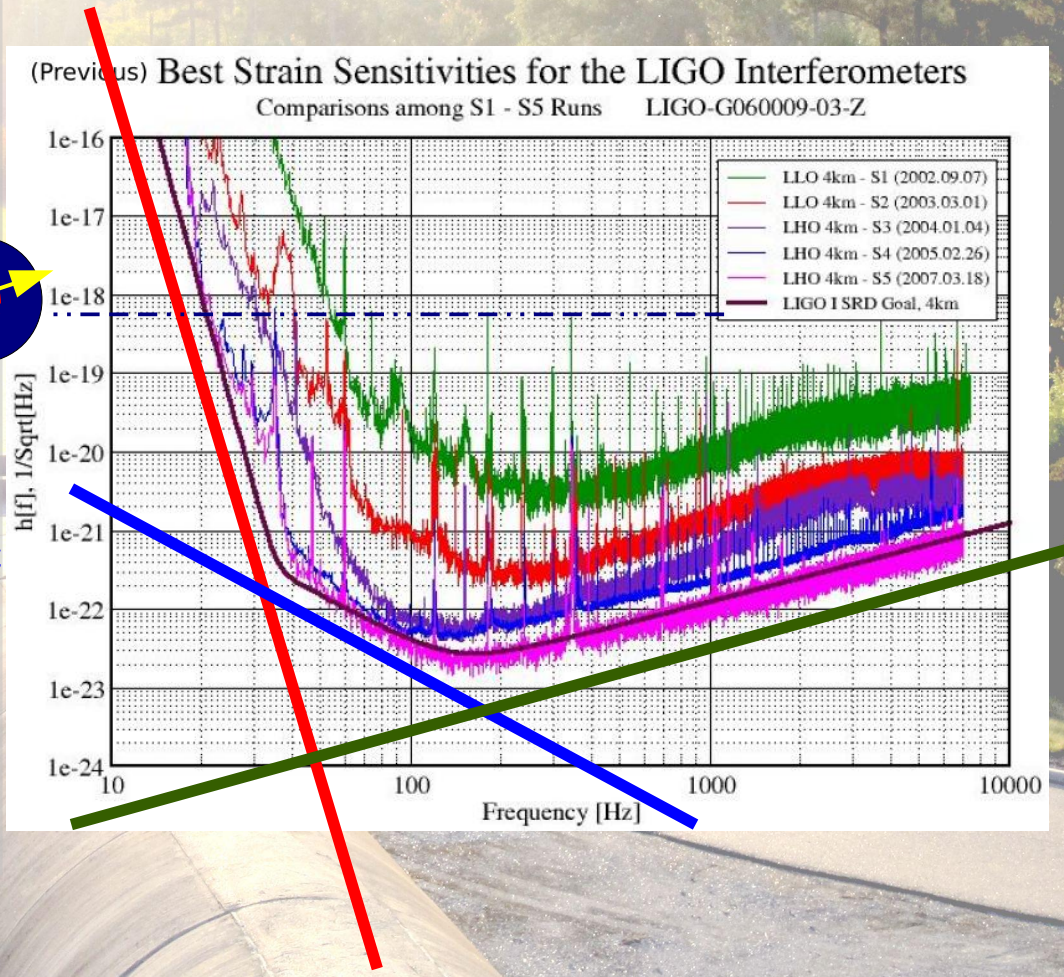
- Instrument arms
  - Fabry-Perot cavities
  - Store light, increasing sensitivity
- Signal Recycling Optic
  - Increase power of resonant light
- Input mode cleaner
- Sensing differential motion has evolved



$$\frac{\Delta L}{L} \propto 10^{-23}, f \approx 100\text{Hz}$$

Detector Sensitivity Evolution

- **Seismic Noise** mechanical transmission of local ground motion to optics motion
- **Suspension/Thermal Noise** thermally induced vibration agitation affecting optic motion
- **Shot Noise** randomized photo arrival times



Milestones: 1999 Inauguration, S1 2003, Design Sensitivity 2005, iLIGO 2007, aLIGIO Expected Components Install Completed 2014, .., ?

Arguments for future detectors

Increasing Sensitivity

- Upper limits becoming interesting
- Observing volume growing

- Evolving instrumental technology yielding this progress

Expected Detection Rates for LIGO type detectors

Source	Initial GW Era (Events/Yr)	Advanced GW Era (Events/Yr)
BHBH	1/140	20
NSBH	1/250	10
NSNS	1/50	40

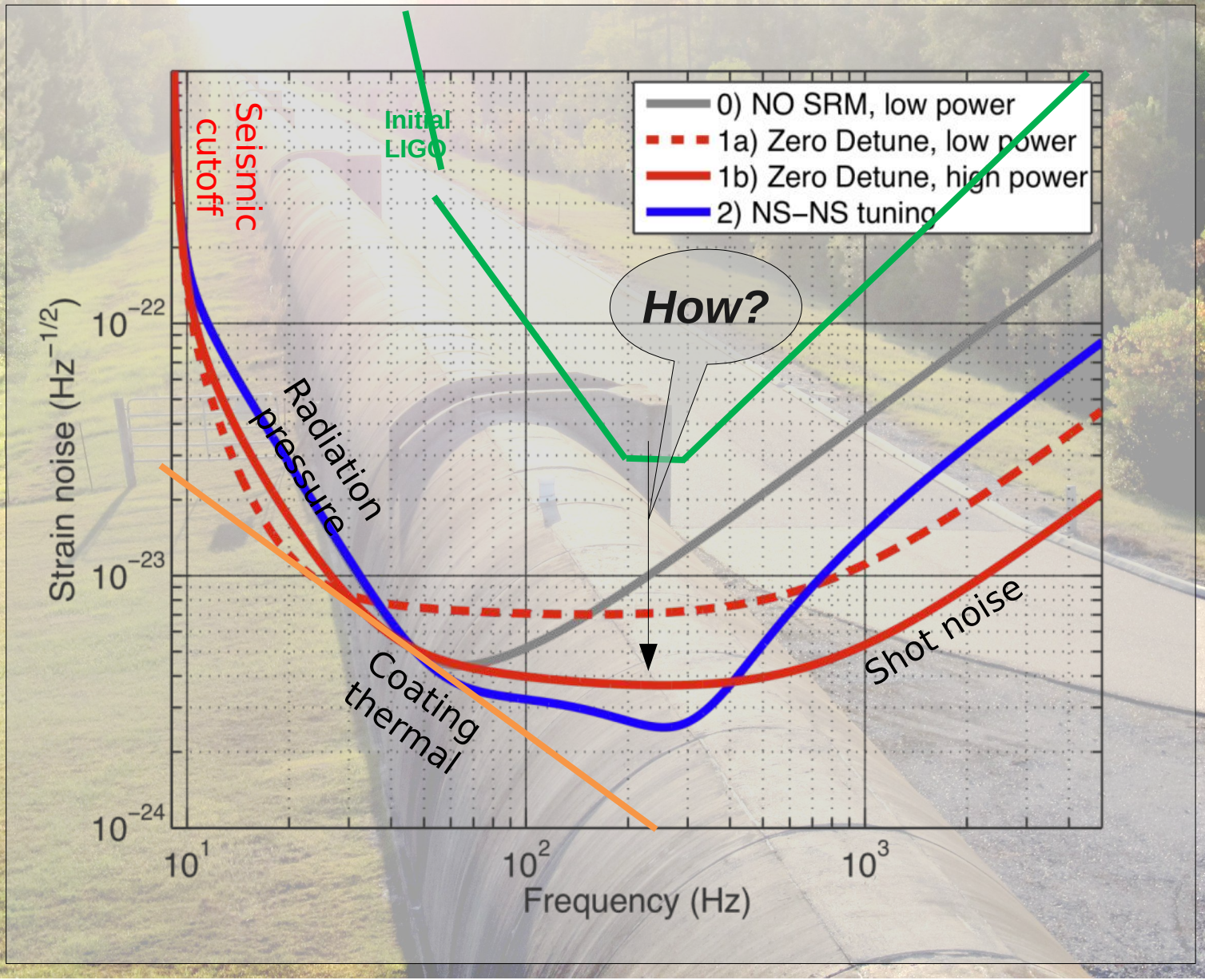
CQG 27 (2010) 173001

Run	Year	Binary Inspiral NSNS; ***BHNS***	Distance	Journal
S1	2002	170 yr^{-1} $MWEG^{-1}$	0.15Mpc	PhysRevD.69.122001
S2	2003	47 yr^{-1} $MWEG^{-1}$	0.90Mpc	PhysRevD.72.082001
S3	2004	***15 yr^{-1} $L10^{-1}$***	30Mpc	Phys.Rev.D78:042002
S4	2005	***0.5 yr^{-1} $L10^{-1}$***	80Mpc	PhysRevD.77.062002
S5	2006	***4.4*10^{-4} yr^{-1} $L10^{-1}$***	200Mpc	PhysRevD.82.102001

How to build an Advance Era Detector

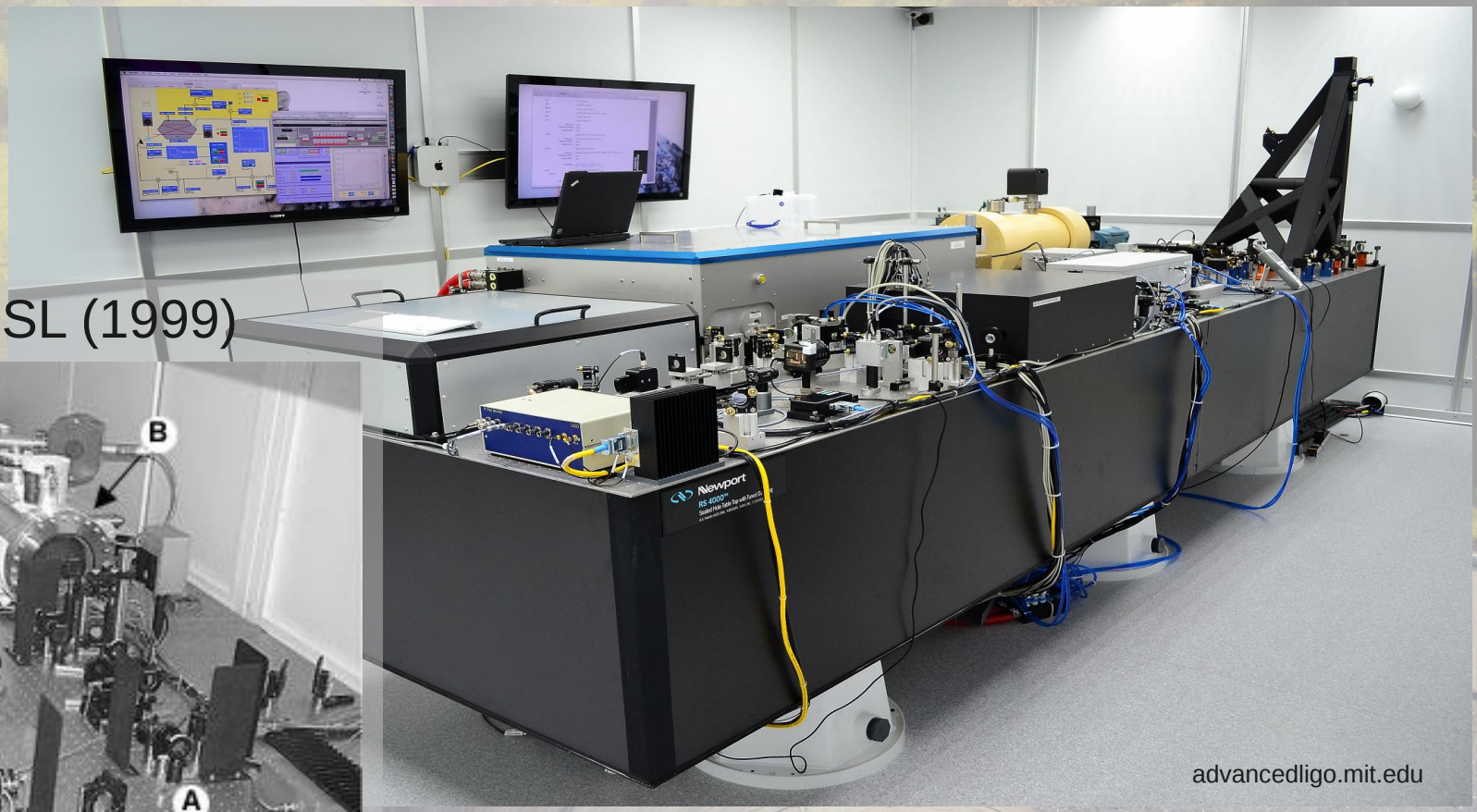
- Step One: Prove feasibility of extra-galatic sensitivity, iLIGO
- Step Two: Secure funding for construction of advanced detector, we'd like to acknowledge our NSF funding.
- Step Three: Do so many upgrades and modifications the finished instrument appears brand new, resulting in an Advanced Era Detector
- Step Four: Done!

Comparing Initial to Advanced Detectors



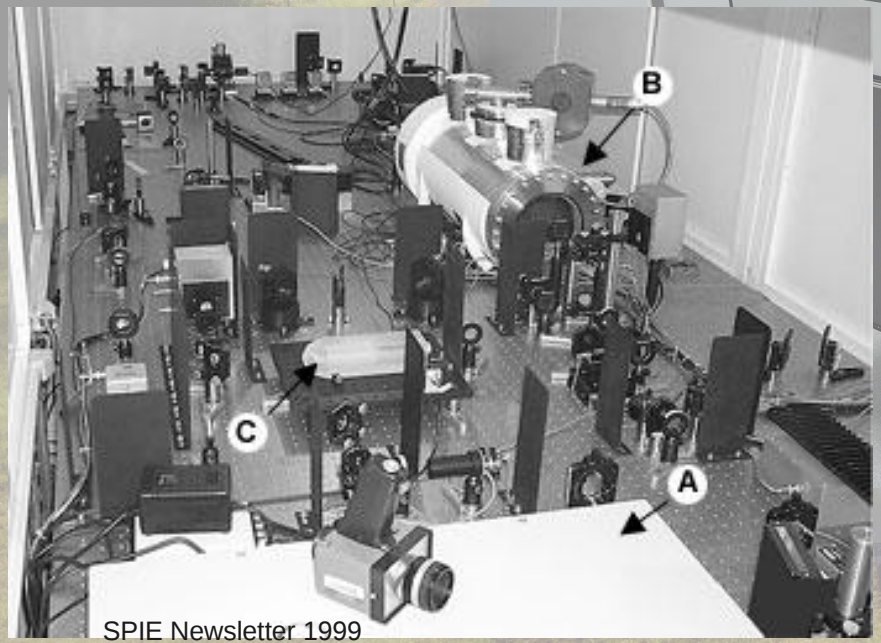
	Laser	Mirrors	Layout	Readout	Seismic	Software
iLIGO	10 W 10 kW	10 kg	Power Recycling	Hetero-dyne RF	Single Pendulum	Off-line analysis
aLIGO	180 W 700 kW	40 kg	Dual Recycling	Homo-dyne DC	FF + Multi Pendulum	Real-time^{+} analysis

Livingston 2k PSL (2011)



advancedligo.mit.edu

Hanford 2k PSL (1999)



SPIE Newsletter 1999

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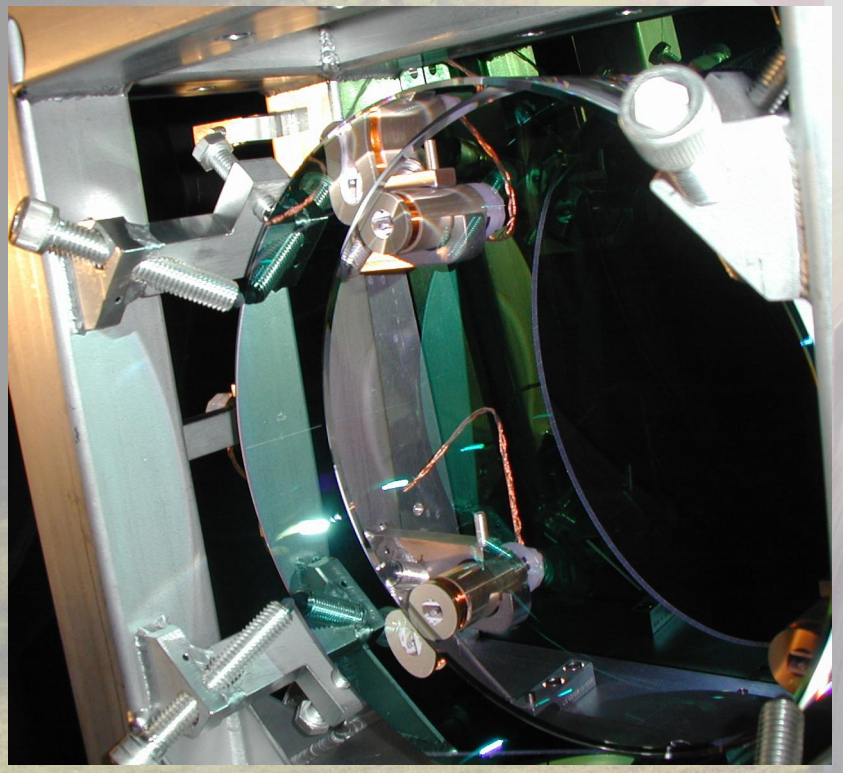
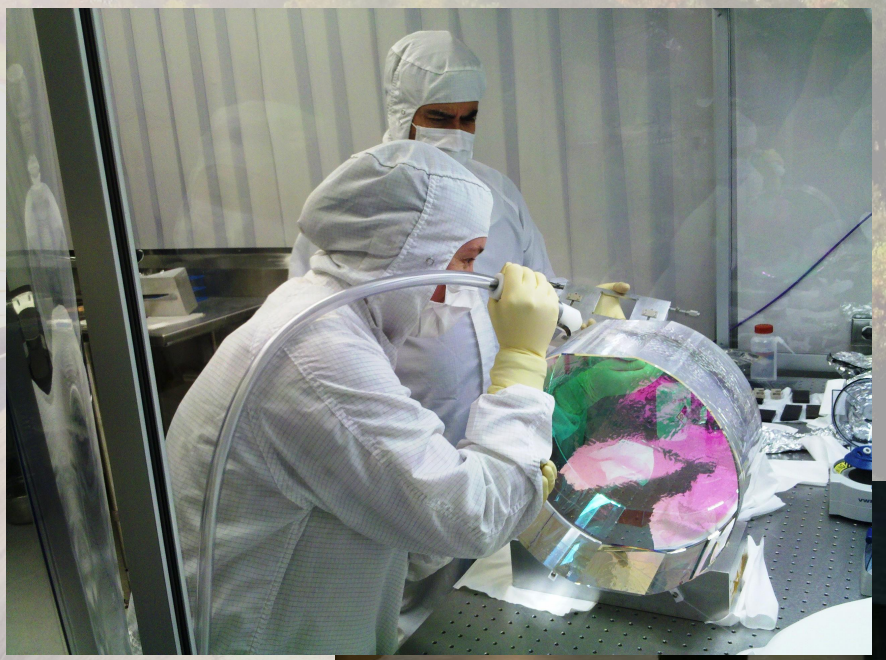
ITM Hanford iLIGO



aLIGO ETM Livingston



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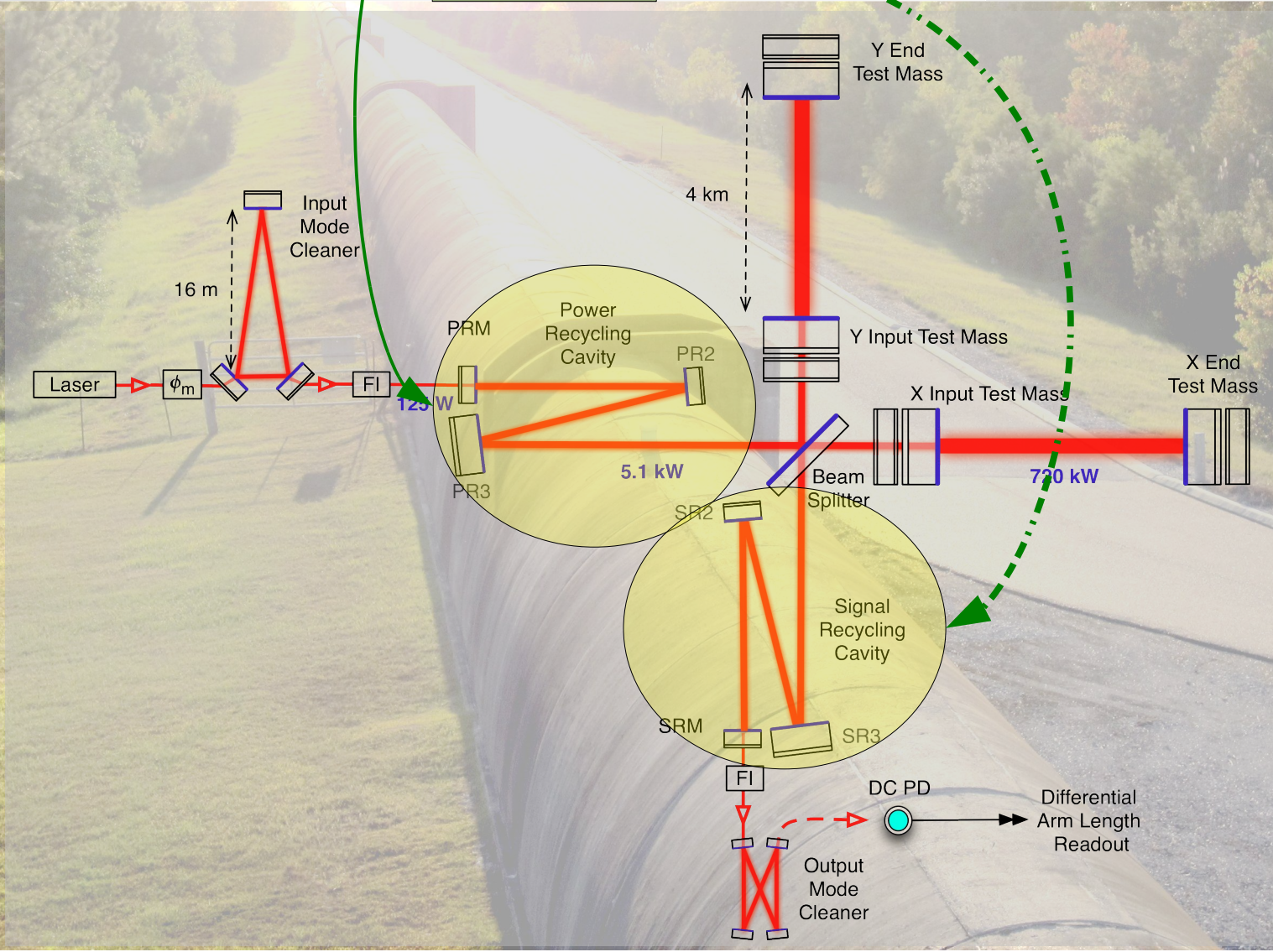

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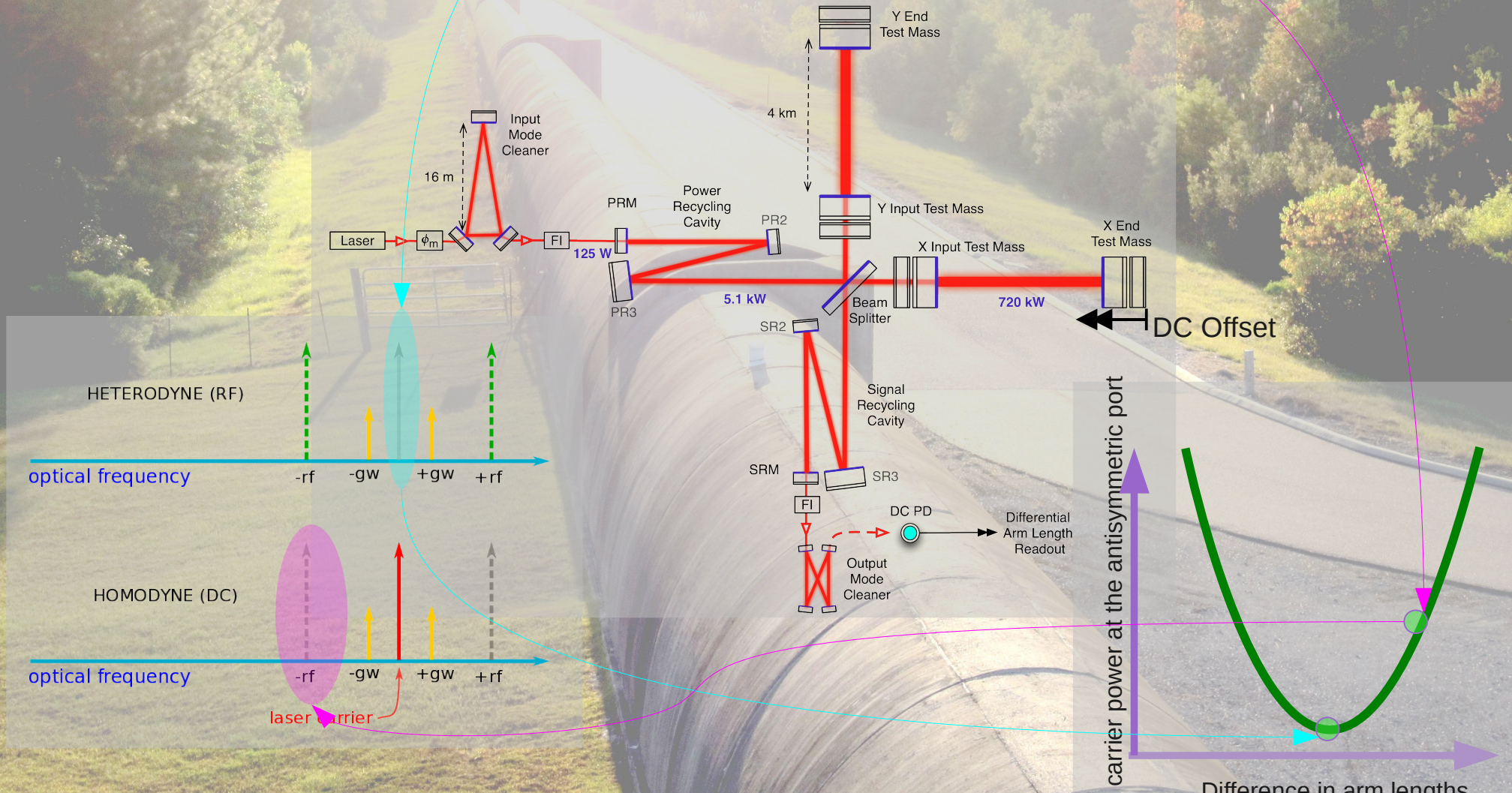

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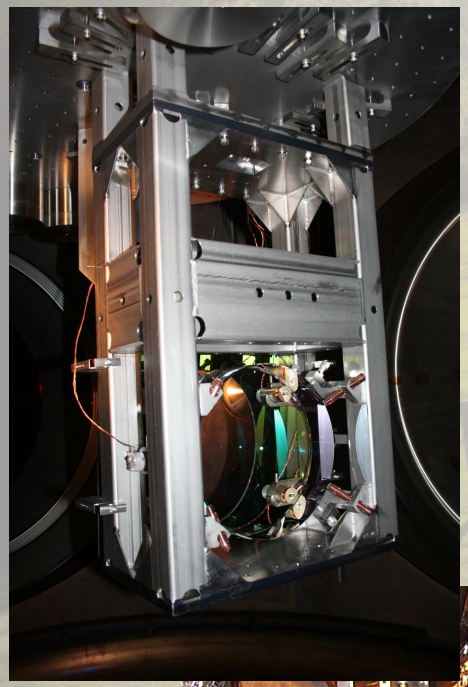
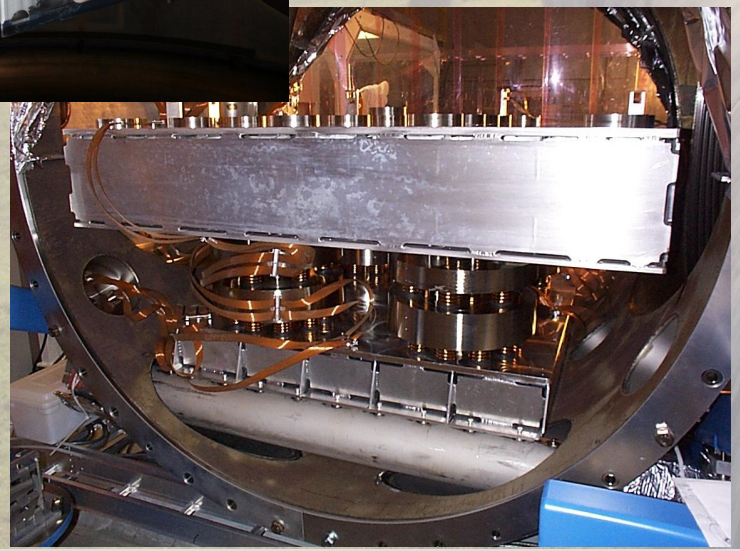


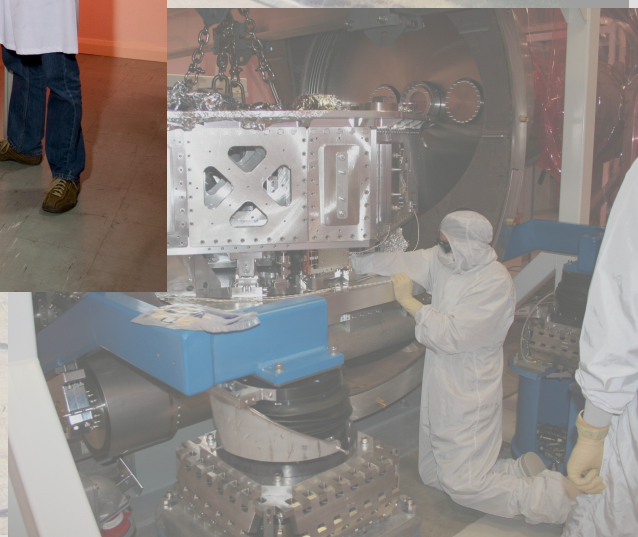
Single Stage Pendulum Active Control $\propto \frac{1}{f}$

Passive Mass Spring Damping Stacks



4 Stage Pendulum Mixed Control $\propto \frac{1}{f^4}$

Active Payload Isolation Table



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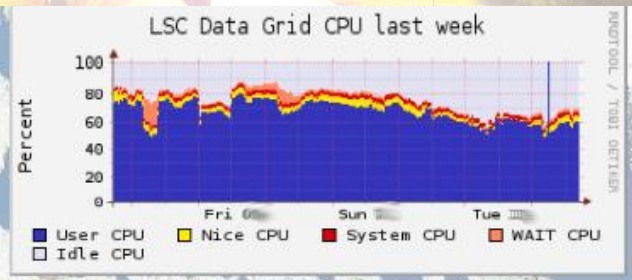
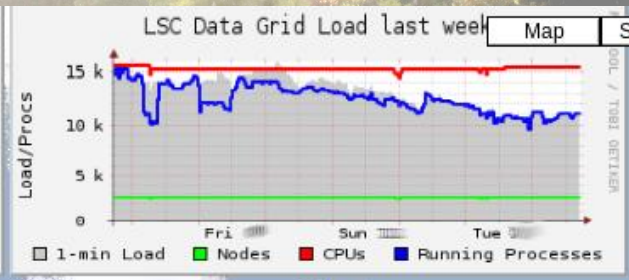
Search Groups (4), Detector Characterization (1), Instrument Groups(3+)





KW

MVSC

. . .

cWB

CW

Ω

hVeto

iHope

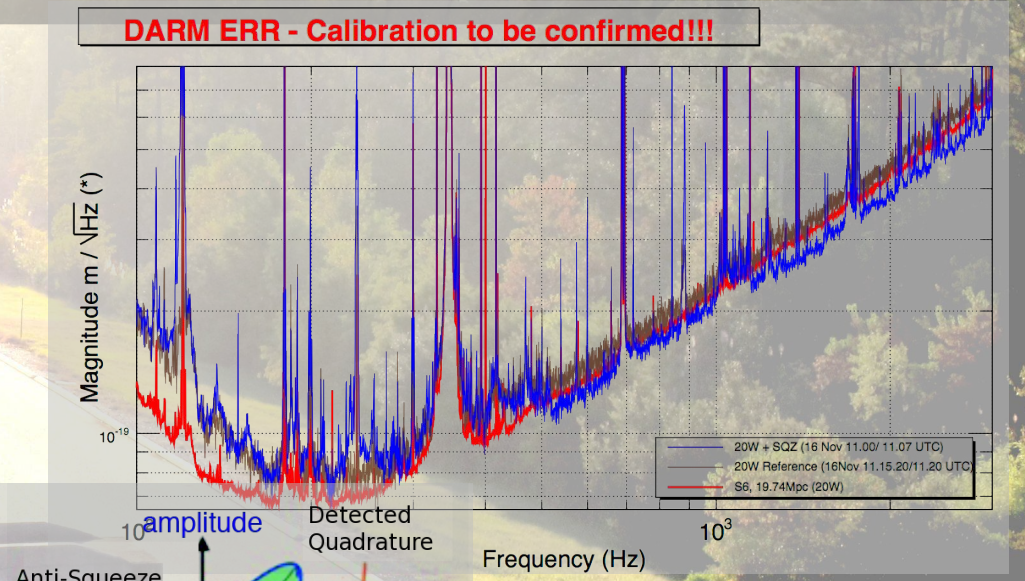
Ann

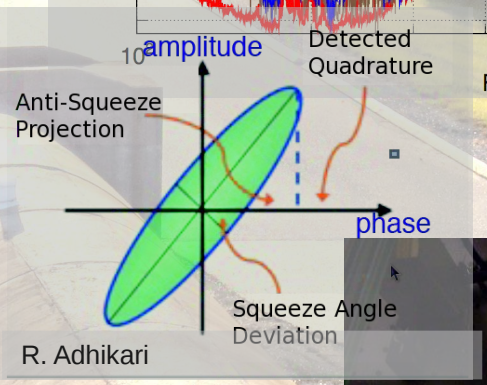
Tweaking the Detectors

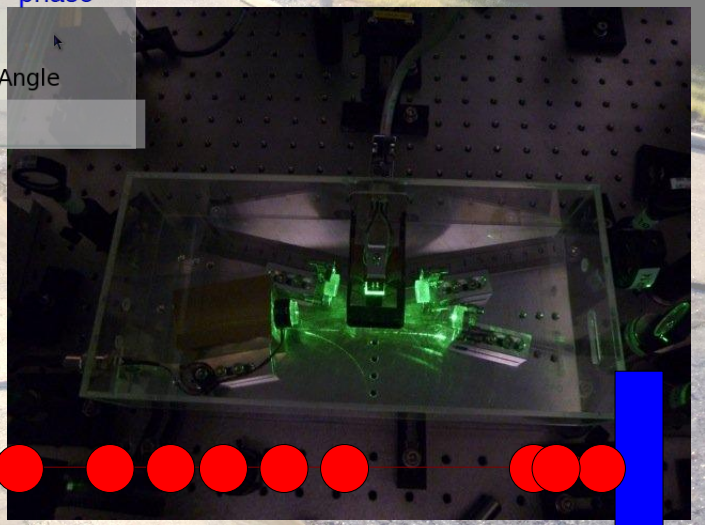
- Squeezing

  Nature Physics 7,962–965 (2011)

  - Suppress Counting Noise (Poisson)
  - Overcome quantum uncertainties; trading
    - Phase noise
    - Amplitude noise
    - Requires 2nd laser
- Tested at 600m GEO observatory



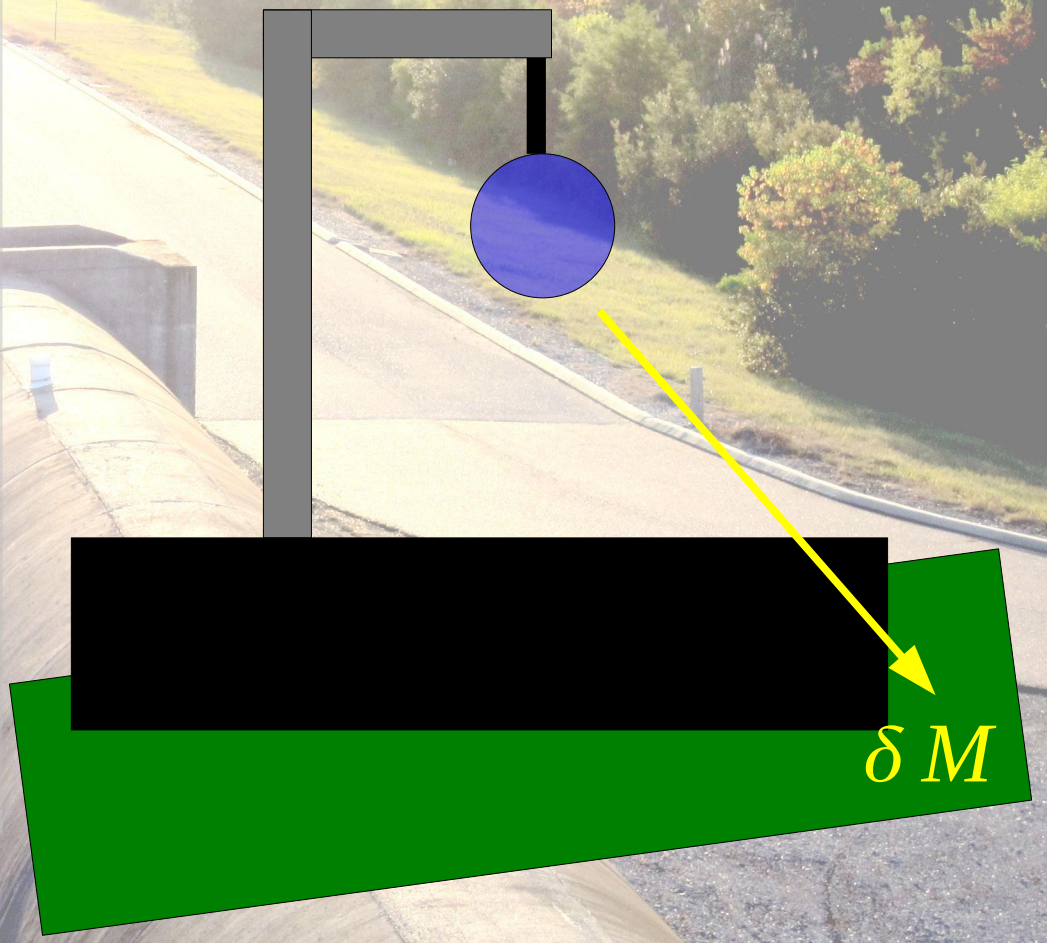




Tweaking the Detectors

- Newtonion Noise
  - Noise from localized mass distributions (not gravitational radiation)
  - Control systems reflexively feed back to optics suspensions
- Not an issue for beginning of aLIGO, but maybe later

$$x(f) \propto \frac{\delta M(f)}{r^9 f^9}$$



The road ahead!

S5

S6

iLIGO

aLIGO Era Begins

Dark Era!

1st IFO Done

2st IFO Done

3rd IFO Done

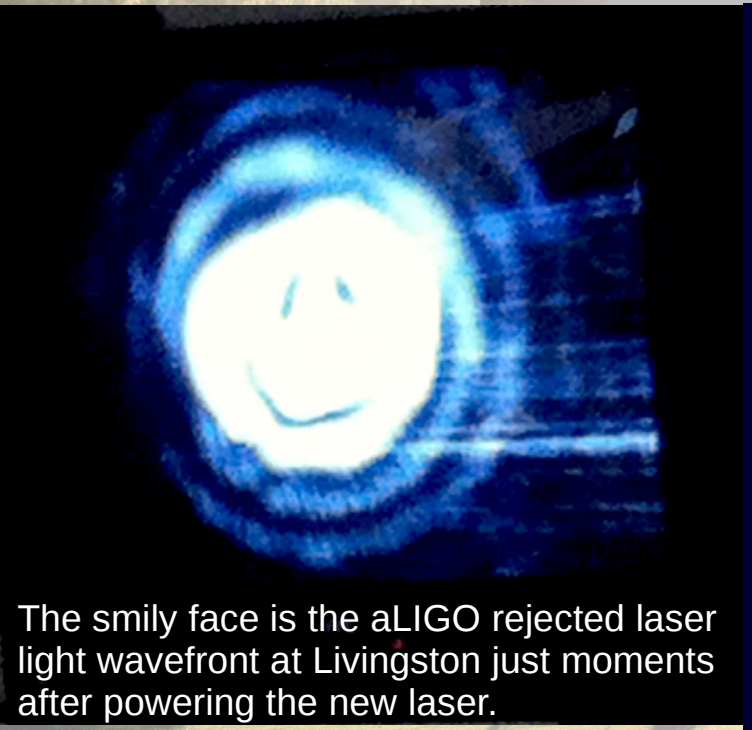
GW Astronomy Begins!

Multi-Messenger Astronomy

Some items already completed!

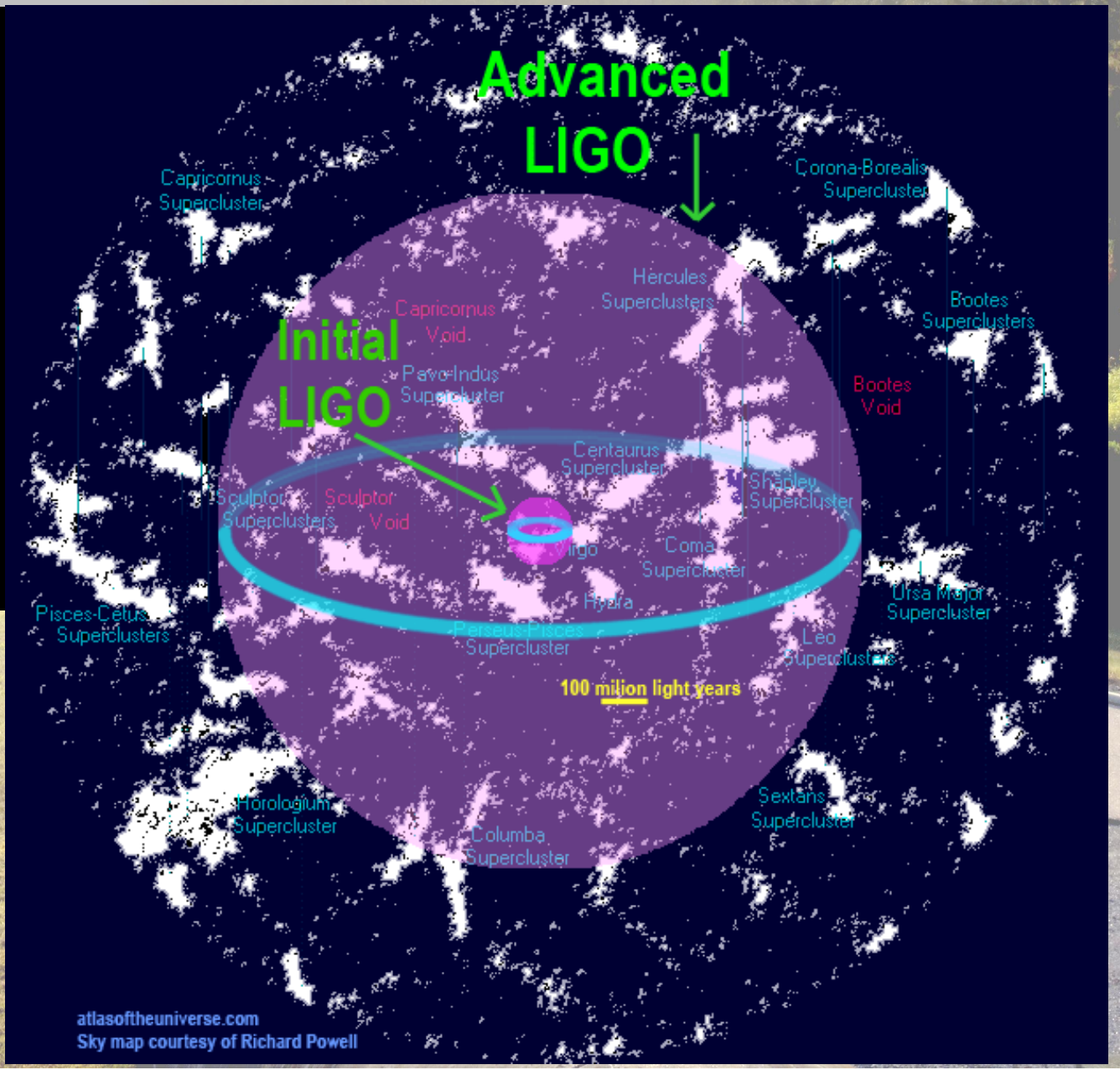
iLIGO component removal
aLIGO components under construction
DAQ system installed and running
Major components being installed
Seismic,Tubes,Laser,...
Cleaning of components and chambers

What awaits us in the future!



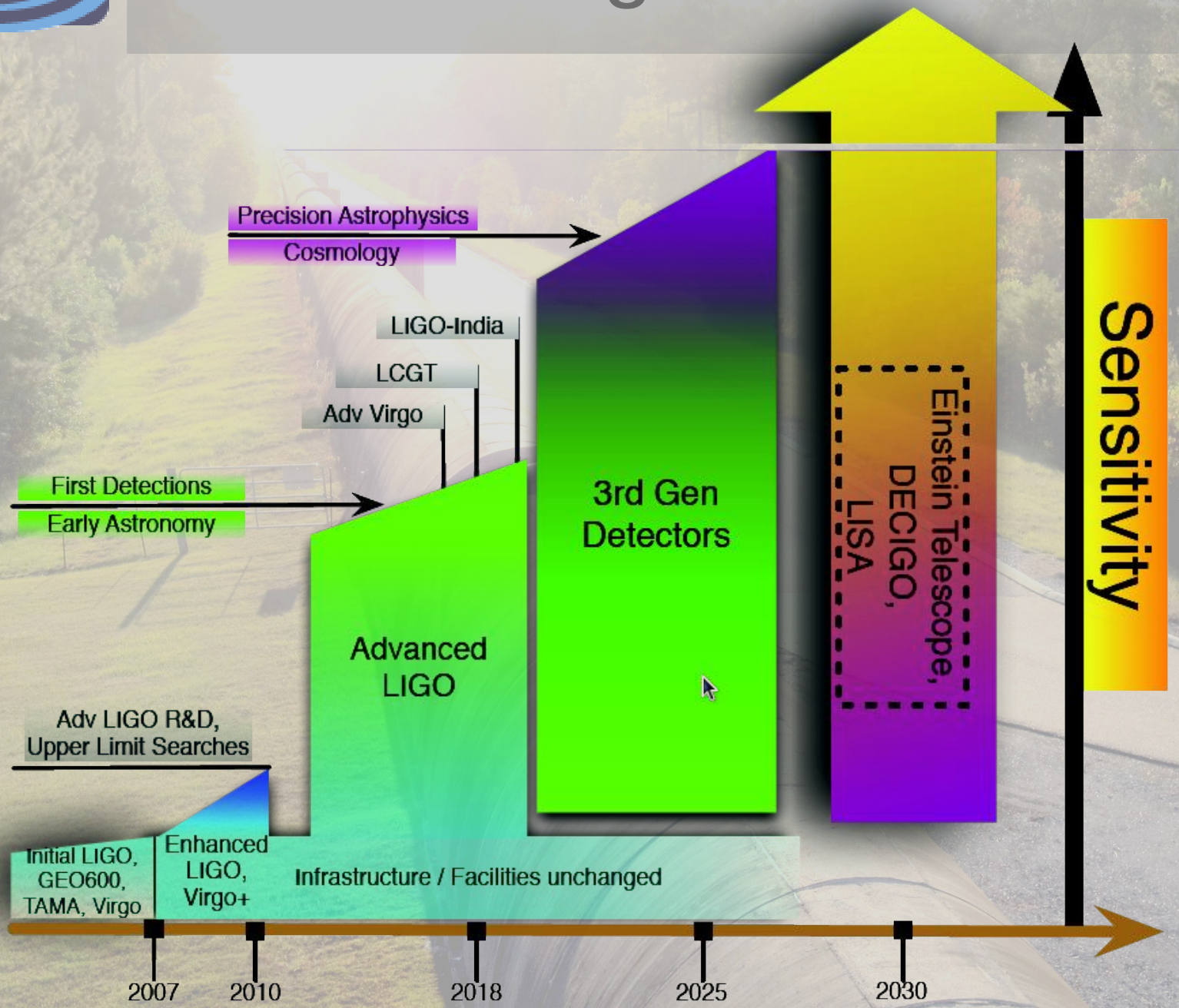
The smily face is the aLIGO rejected laser light wavefront at Livingston just moments after powering the new laser.

This is an exciting time with a bright future for the LIGO project.

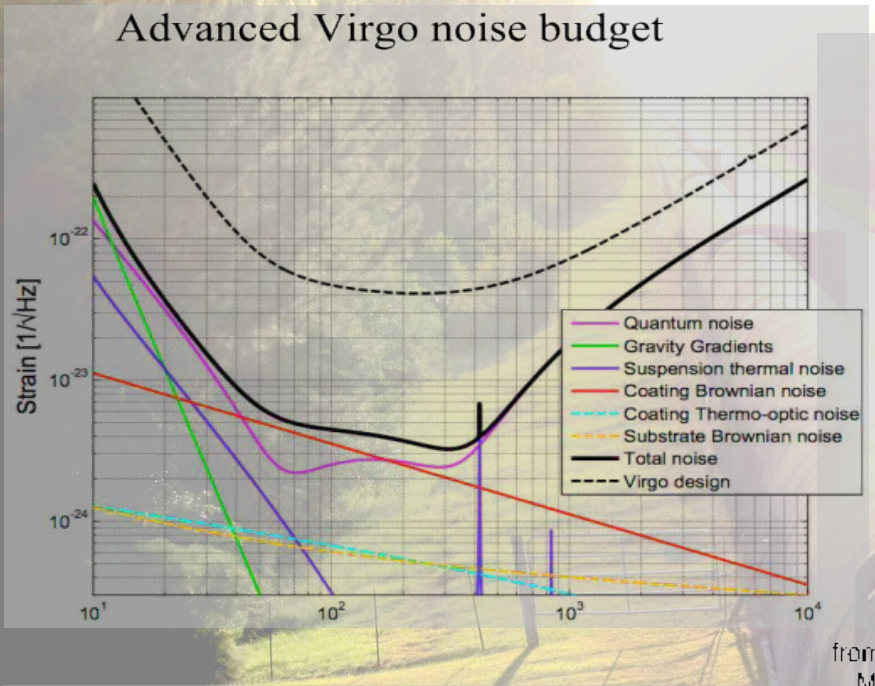


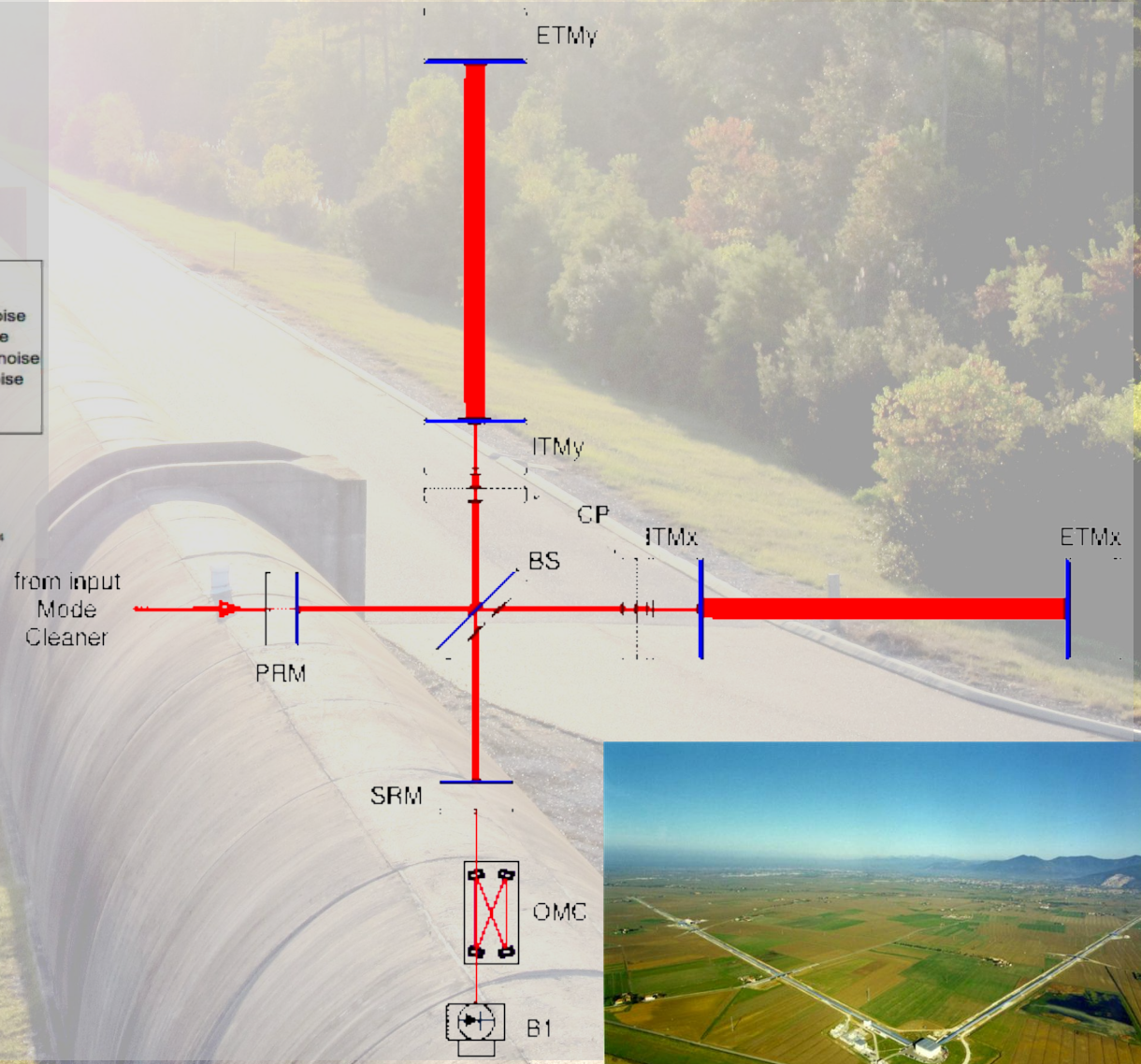
Extra Slides

Looking Far Ahead



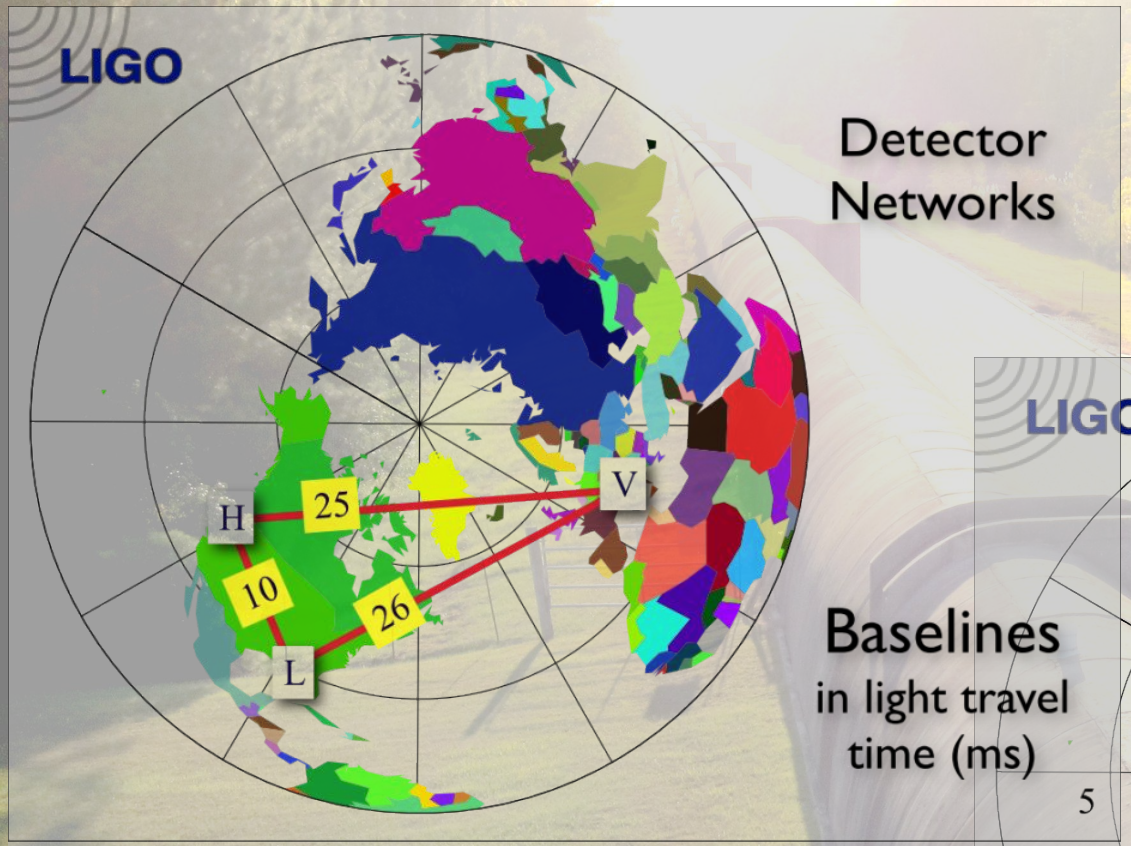
AdVirgo





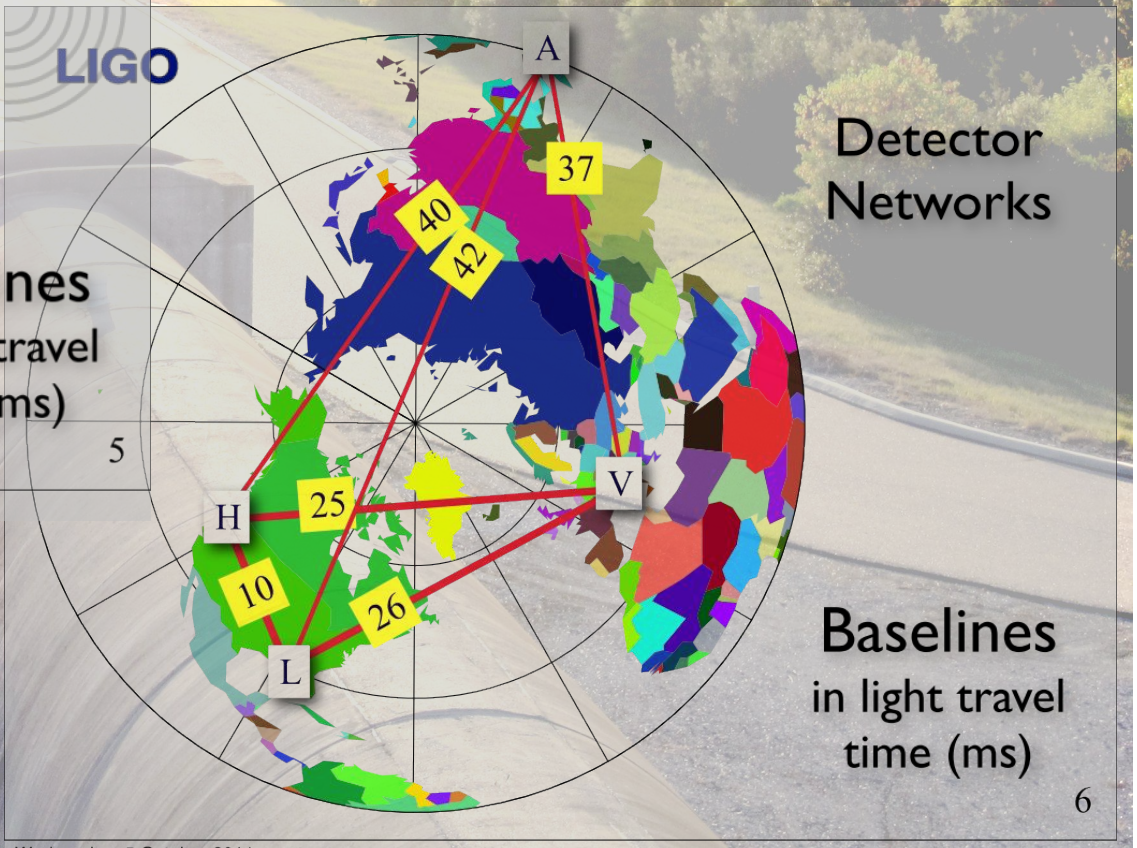
- Located in Italy
- Operated by European Consortium
- 3 km arm length
- Similar design to aLIGO:
- Expected online in 2015

GW Detector Networks

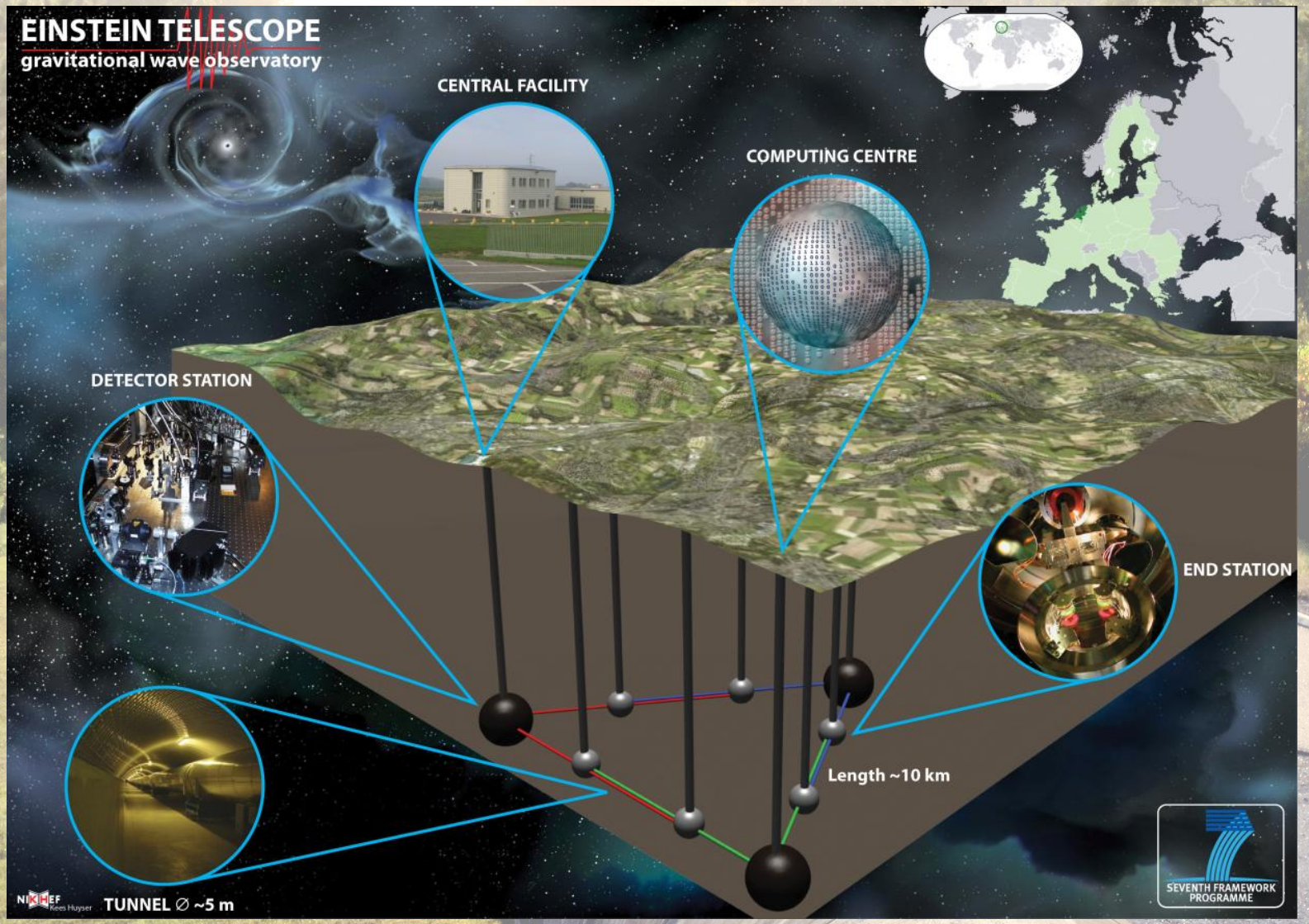


Current GW Detector Network

Proposed Improved Detector Network



Einstein Telescope



“Einstein gravitational wave Telescope conceptual design study”
https://tds.ego-gw.it/itf/tds/index.php?callContent=2&callCode=8709

LIGO Scientific Collaboration

LIGO

LSC

- Australian Consortium for Interferometric Gravitational Astronomy
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Univ. of Cambridge
- Canadian Institute for Theoretical Astrophysics and Perimeter Institute for Theoretical Physics
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- CSU Fullerton
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd Univ.
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Hanyang University
- Korea Institute of Science and Tech Information
- Leibniz Universität Hannover
- Lund University
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola Univ. of New Orleans
- University of Maryland
- Max Planck Institute for Gravitational Physics
- McNeese State University
- Univ. of Melbourne
- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- National Inst. of Mathematical Sciences
- University of New Hamshire
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Pusan National University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- Seoul National University
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- USC - Information Sciences Institute
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Tsinghua University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

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