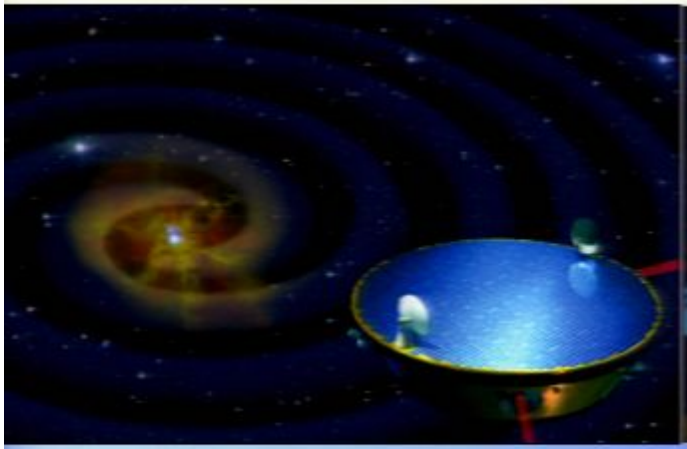
Title: Gravitational Wave Detection: Past, Present and Future

Date: Jun 26, 2010 09:00 AM

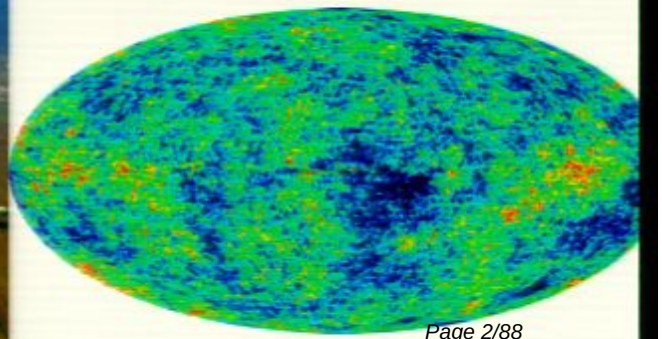
URL: http://pirsa.org/10060082

Abstract: Direct detection of gravitational wave stands at a cross roads; the first generation of interferometric detectors will soon be decommissioned and the second generation projects are underway. In this talk, I will describe the Initial LIGO and VIRGO generation of instruments, the techniques required to achieve a strain sensitivity of 3 x 10^{-23} and an NS / NS inspiral range of 15 Mpc. I'll follow with a description of the Advanced detectors and the differences that should improve the sensitivity by a factor of ten. Finally, I will describe projects from radio and microwave astronomy to measure gravitational waves using pulsar timing and the CMB B-mode polarization.

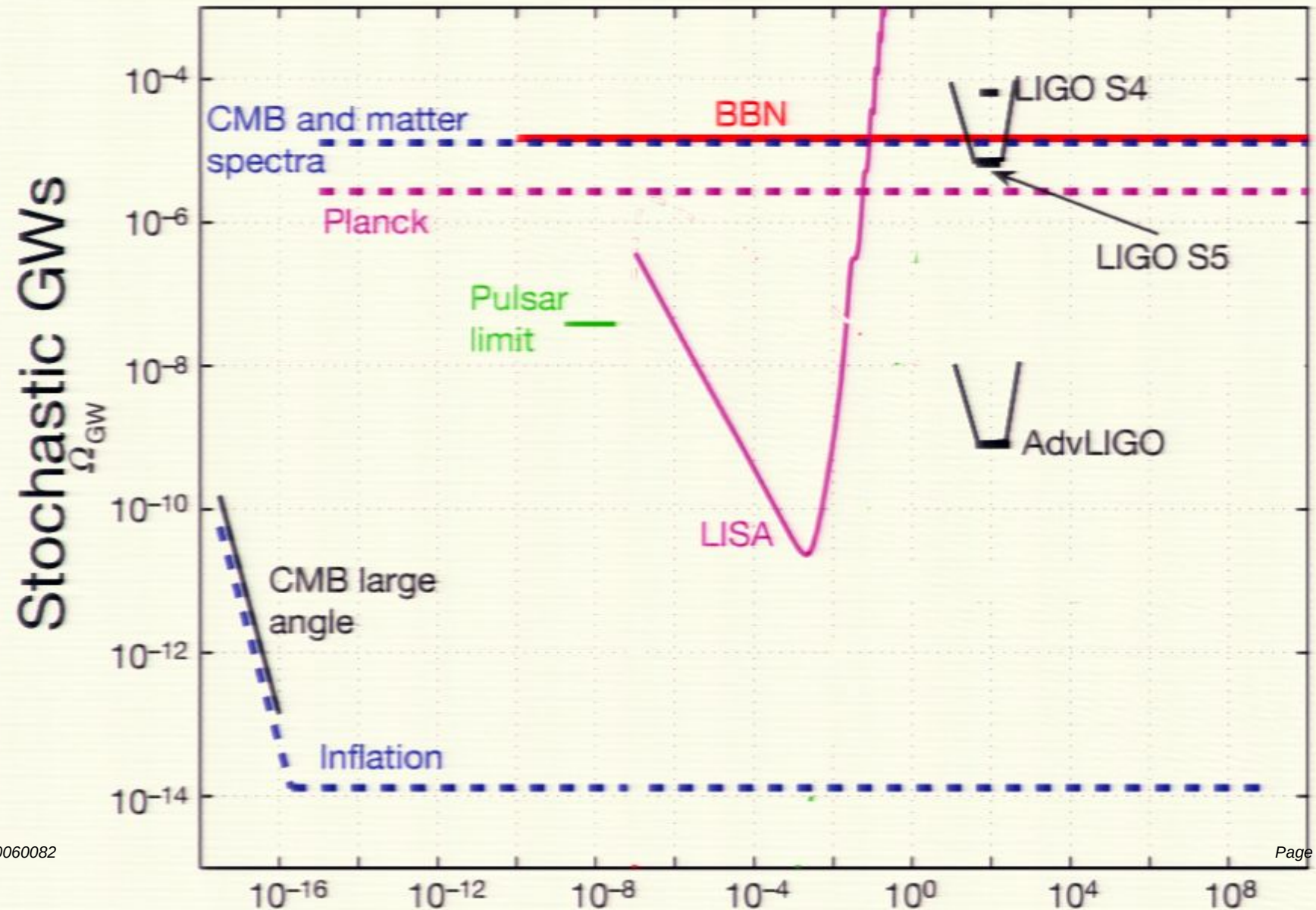
Gravitational wave detection



Sam Waldman (MIT)
June 25, 2010
NRDA @ Perimeter Institute



"you are representing the topic beyond your group"
-- Luis Lehner 2010



Lessons from Wile E.

VIRGO LSC

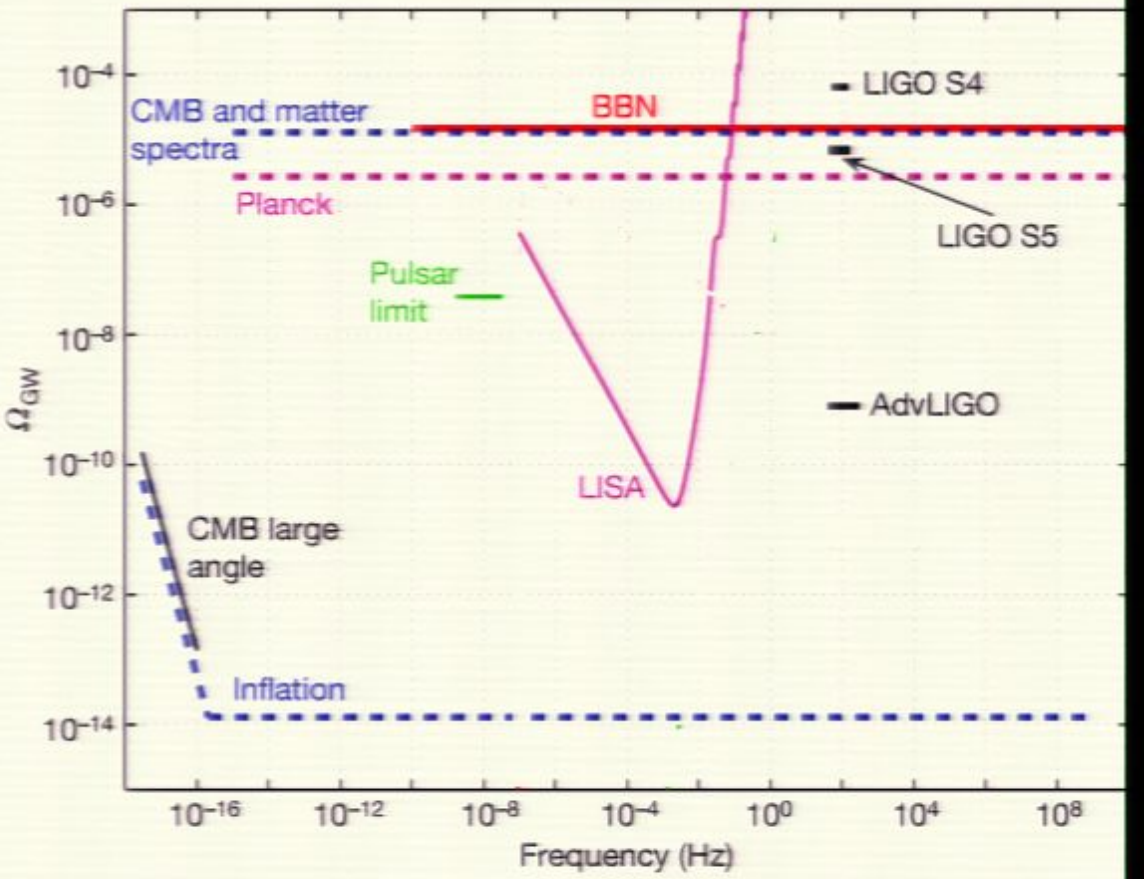
CMB

Pulsar

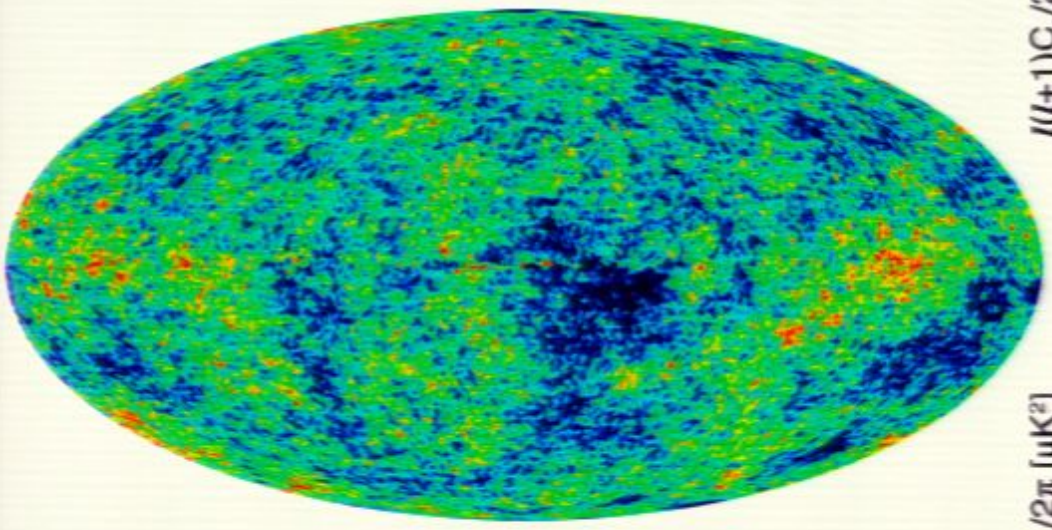
LISA/LPF/GRACE-C

LIGO/Virgo

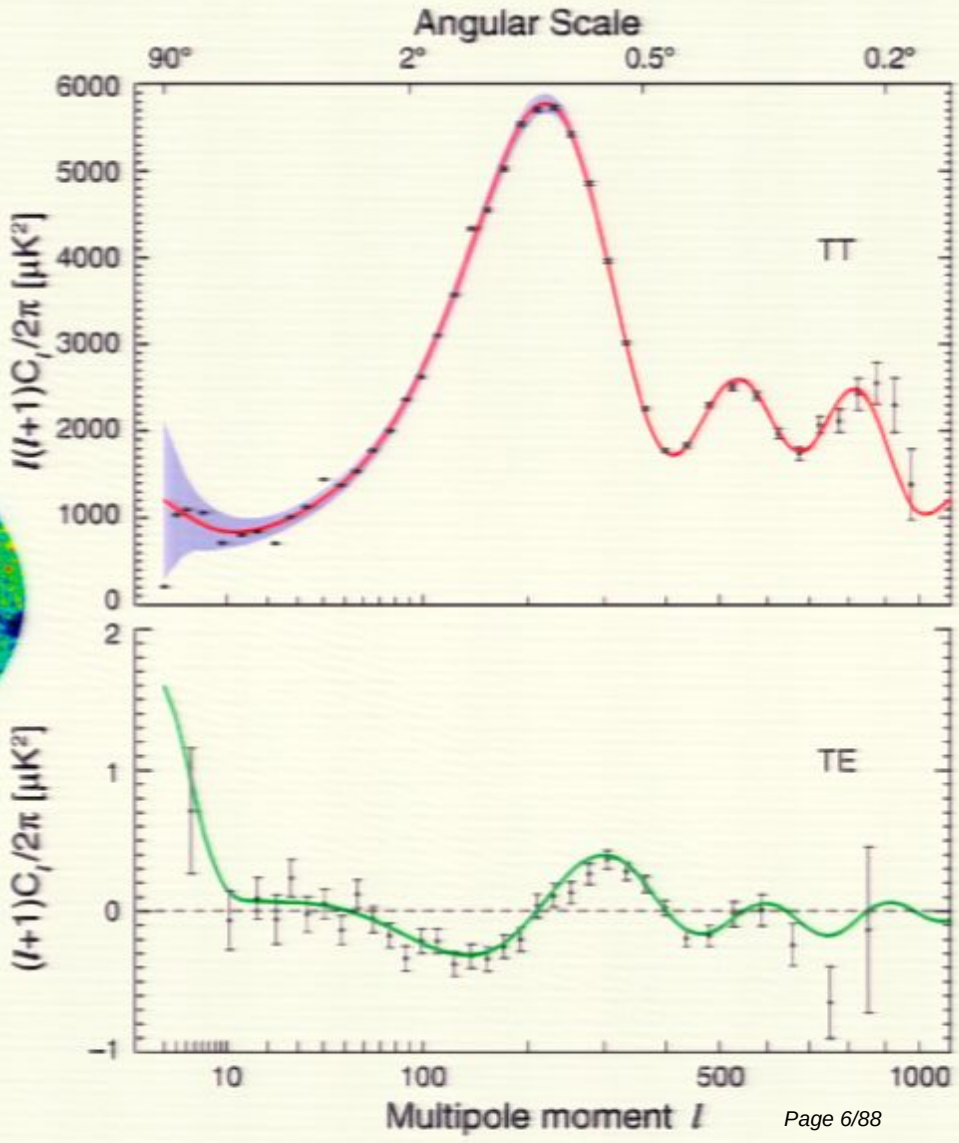
Future Detectors



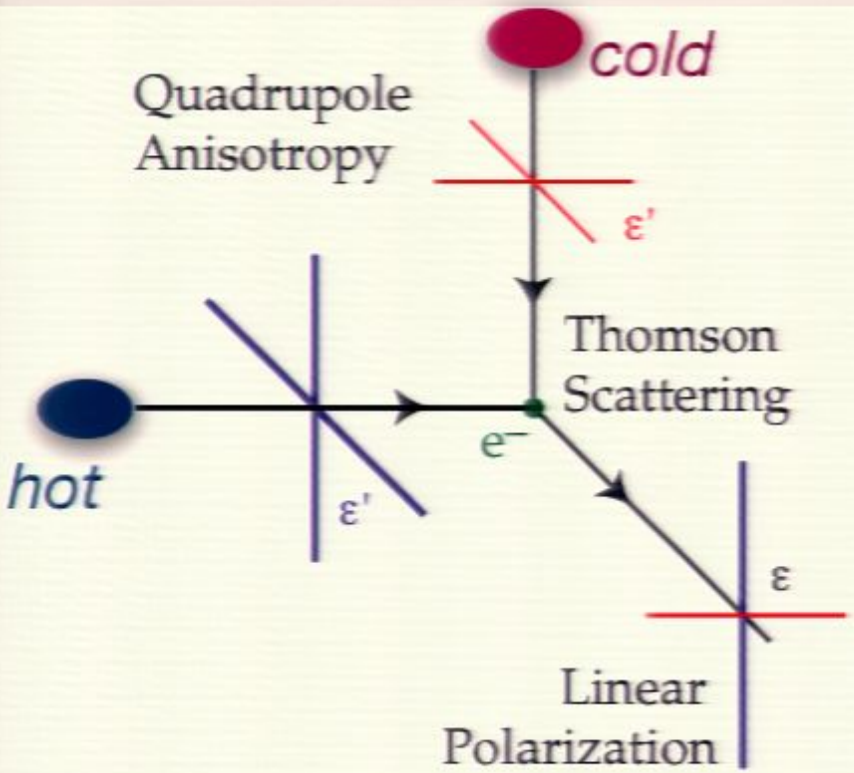
Special thanks to: A. Lommen, R. Weiss, P. Saulson, F. Fidecaro, O. Jennrich, P. McNamara, and G. Heinzel



WMAP 5 year

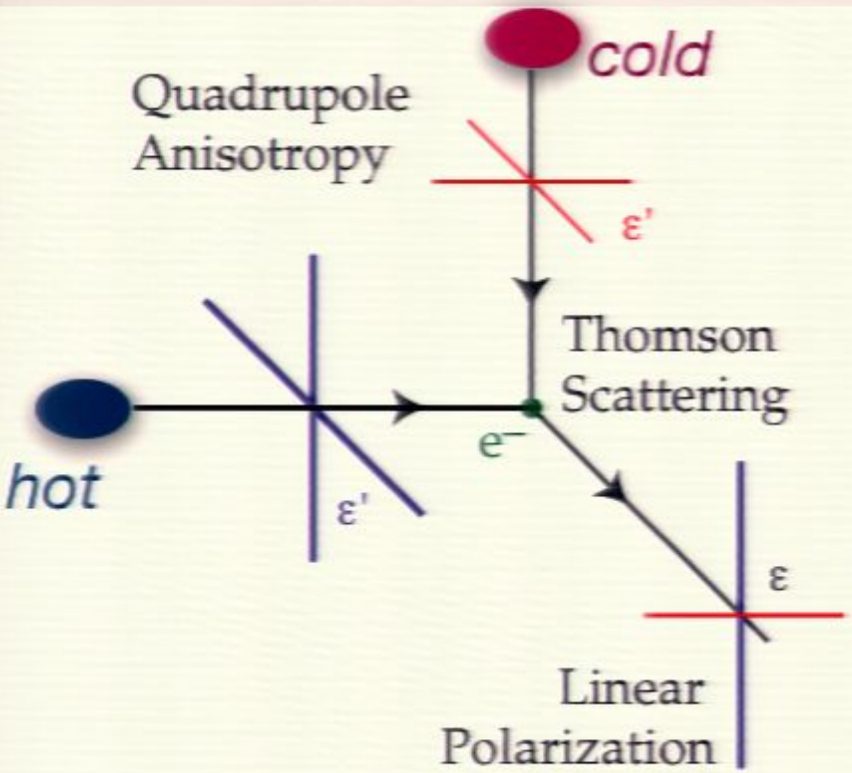

Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ [μK^2]
TT
2
1
0
−1
$(l+1)C_l/2\pi$ [μK^2]
TE
10
100
500
1000
Multipole moment l

Thomson scattering

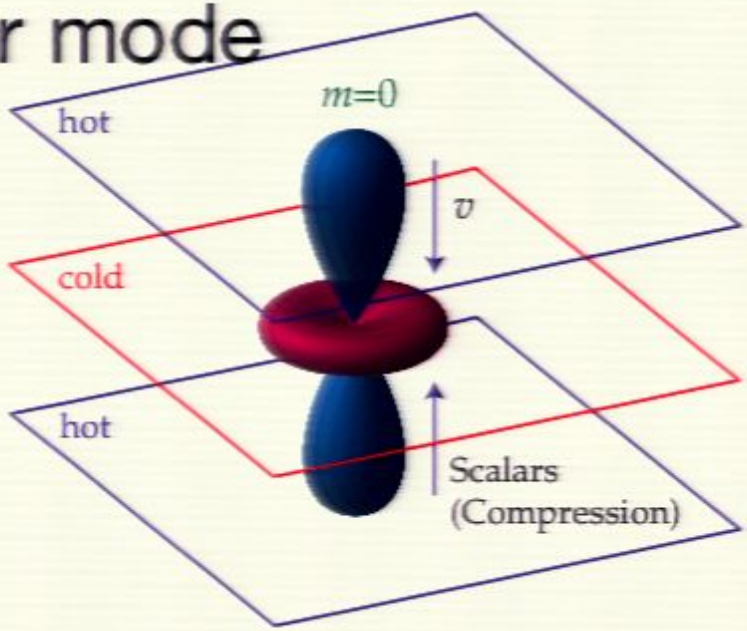


from: W Hu and M White **astro-ph/9706147**

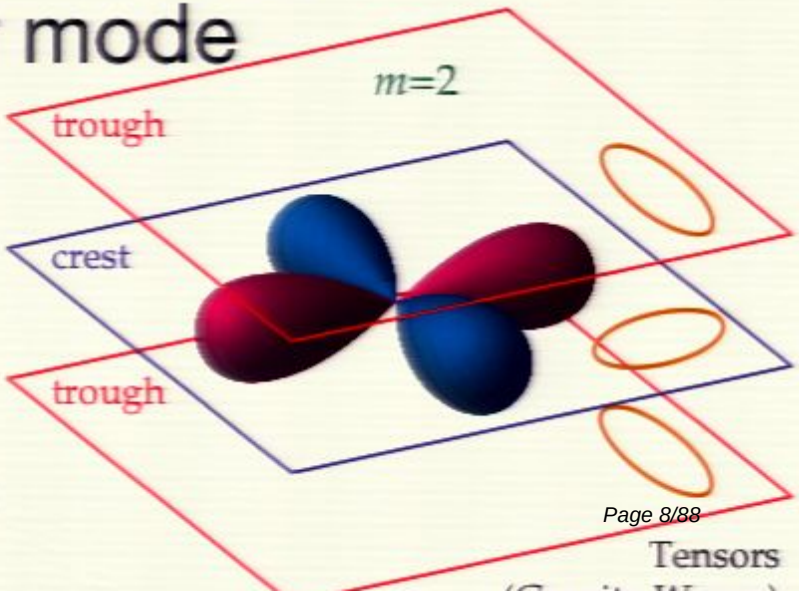
Thomson scattering



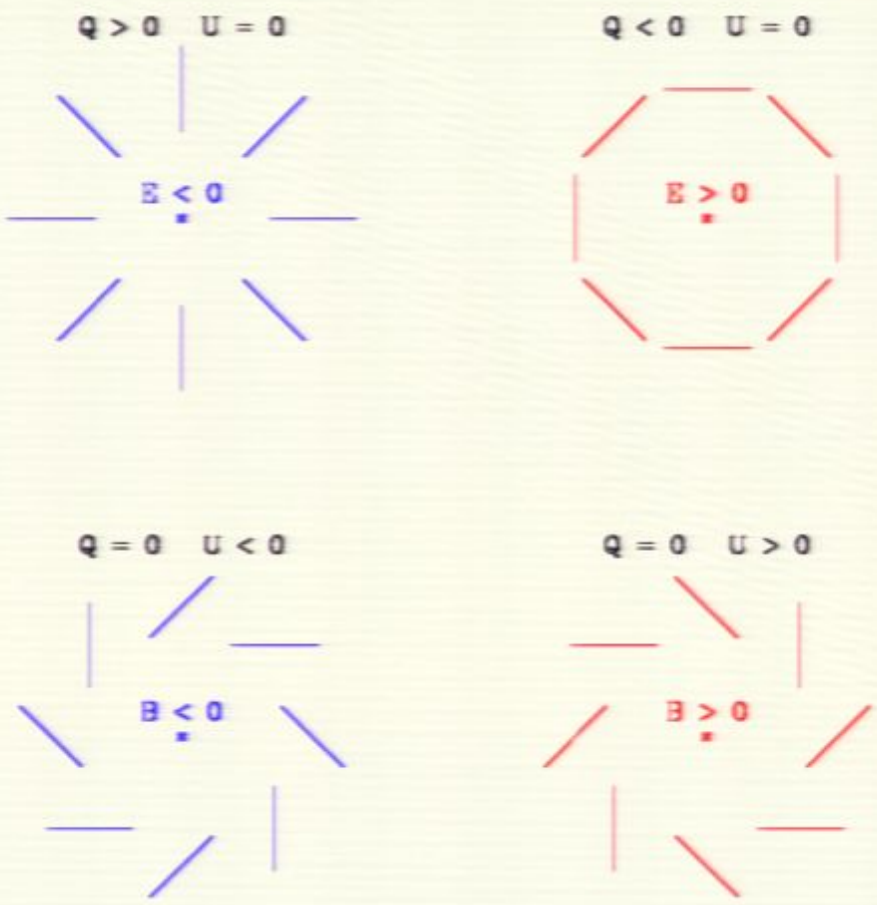
scalar mode

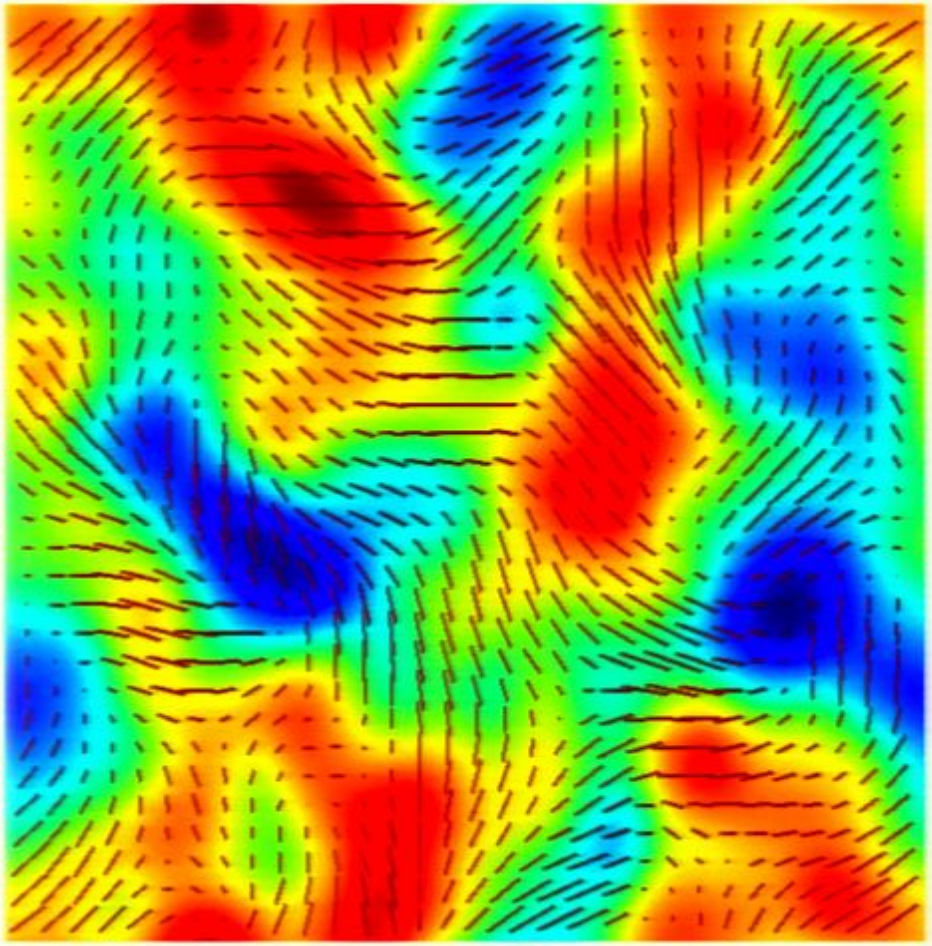


tensor mode

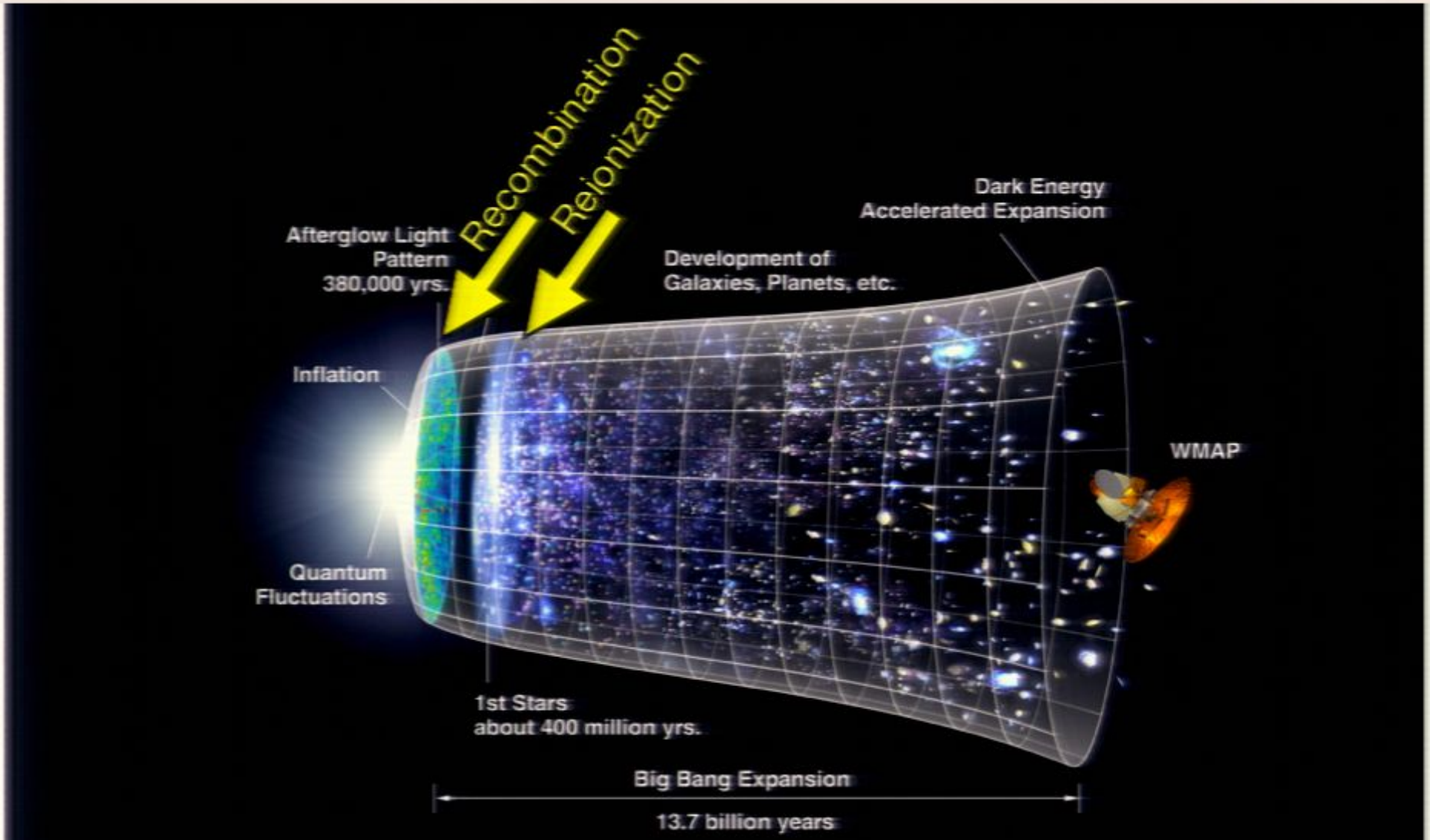


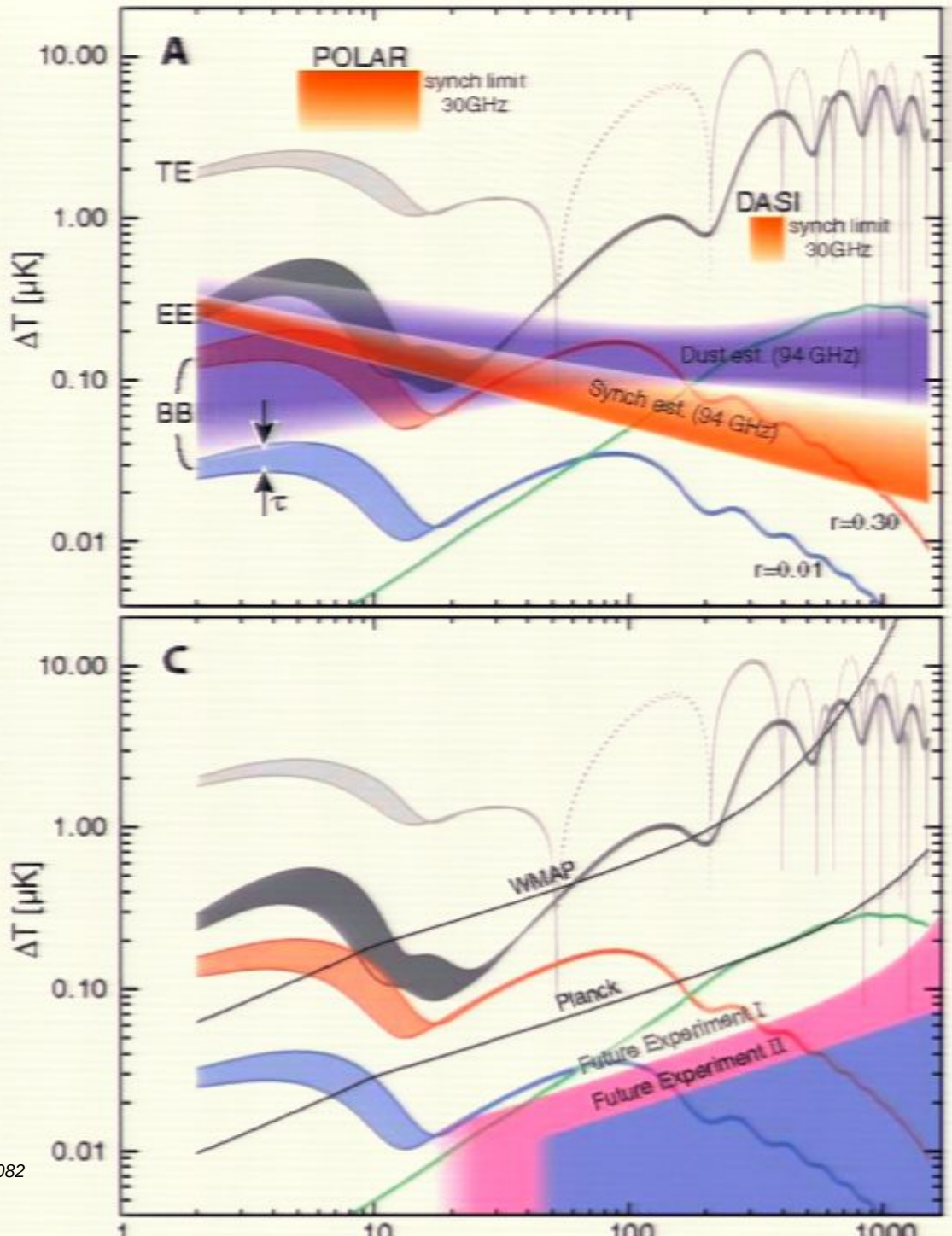
from: W Hu and M White **astro-ph/9706147**





M. Zaldarriaga

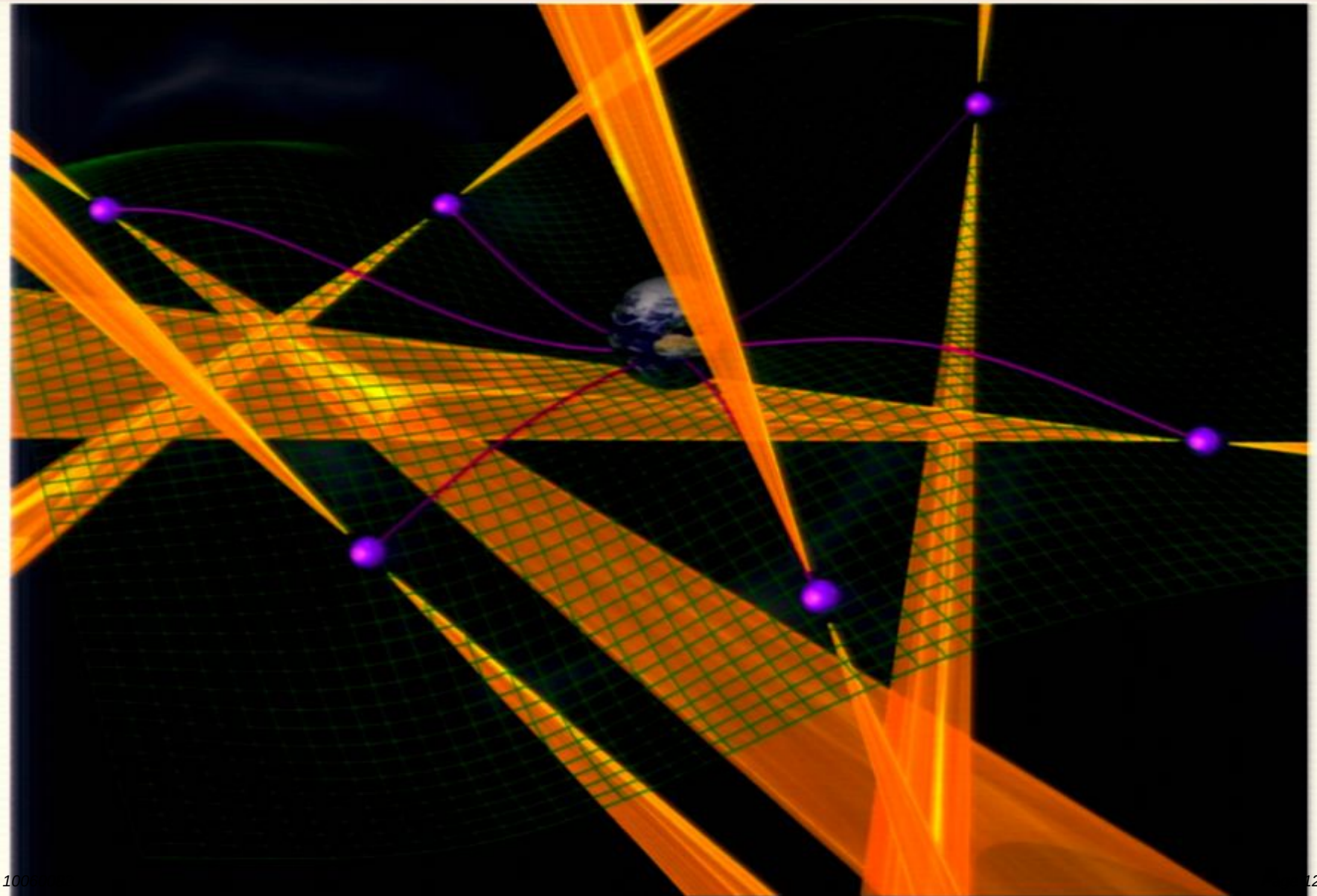

Recombination
Reionization
Afterglow Light Pattern 380,000 yrs.
Dark Energy Accelerated Expansion
Development of Galaxies, Planets, etc.
Inflation
WMAP
Quantum Fluctuations
1st Stars about 400 million yrs.
Big Bang Expansion
13.7 billion years



Planck, QUIET, SPT, ALMA-B, WMAP, Quad, BICEP, Spider, BOOMERanG, DASI, KUPID, POLARBeaR, ...

Planck at L2 until 2011, skymaps in 2012

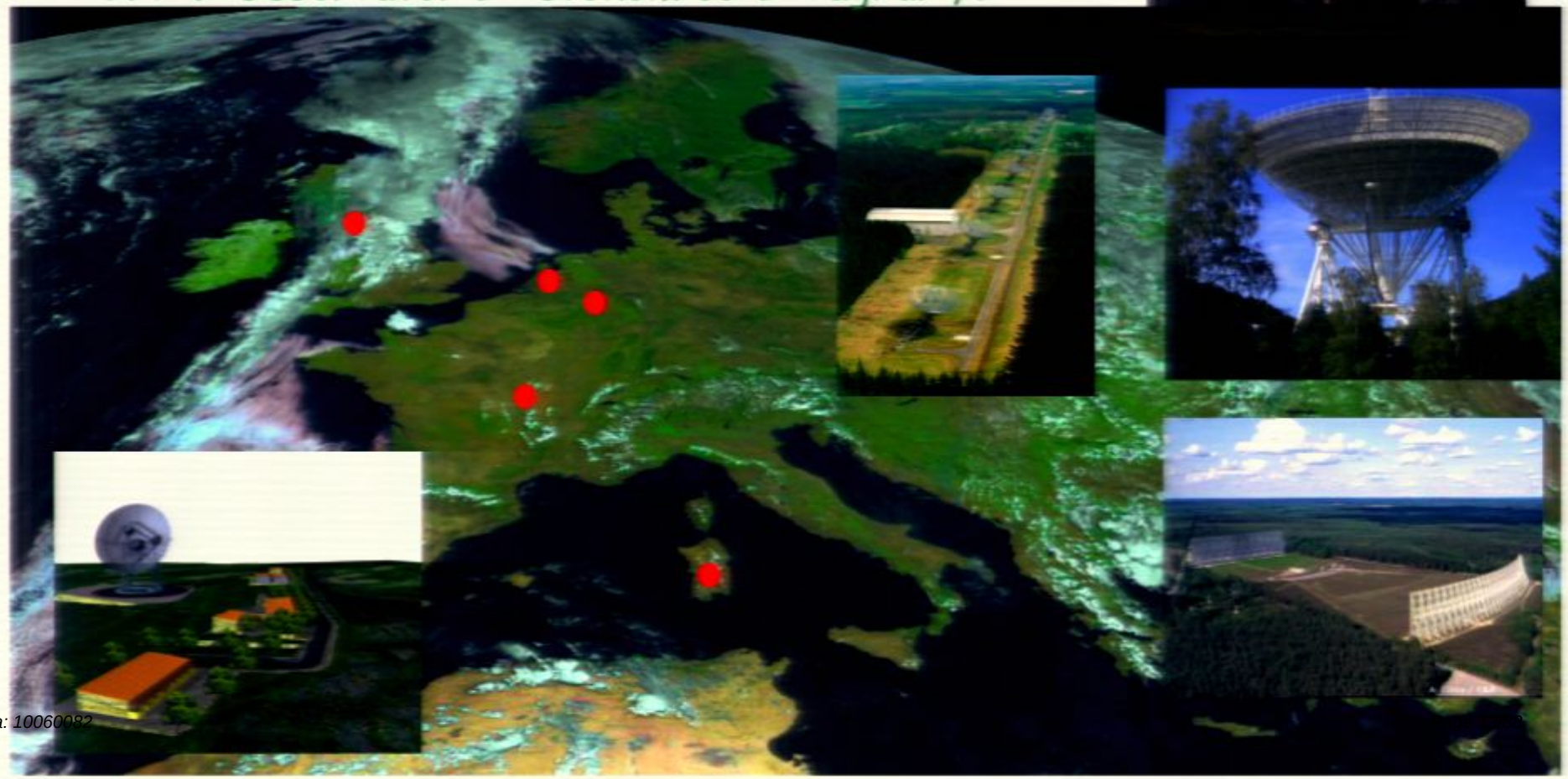
Pulsar timing



European PTA

VIRGO LSC

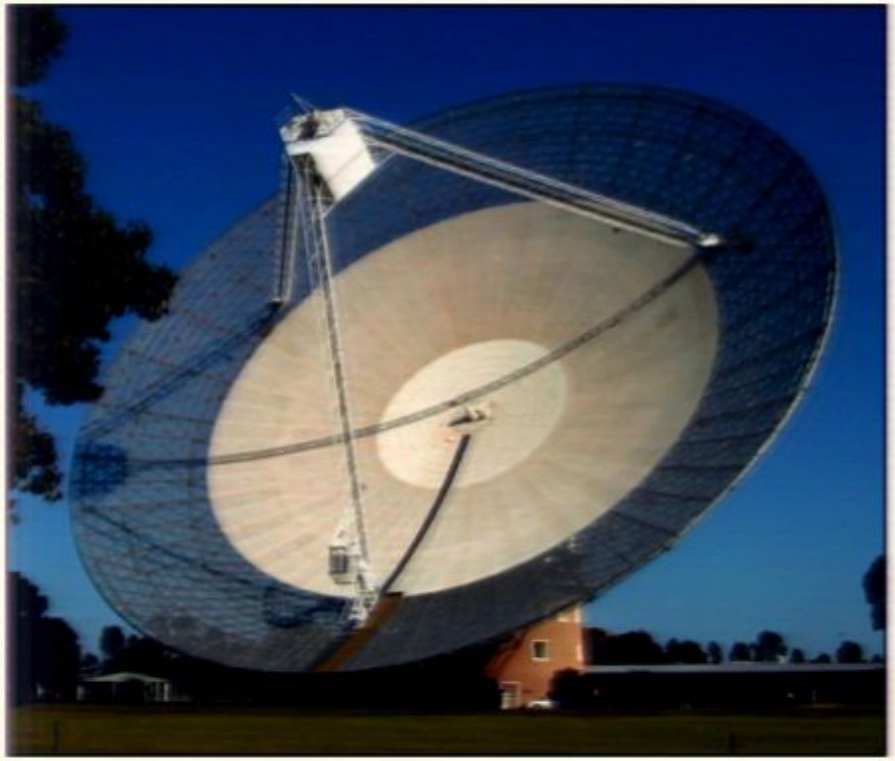
University of Manchester, JBO, UK
ASTRON, NL
Max-Planck Insitut fur Radioastronomie, GER
Nancay Observatory, FR
INAF Osservatorio Astonomico di Cagliari, IT



Pirsa: 10060082

Parkes PTA

- Australia Telescope National Facility, CSIRO, Sydney
  Dick Manchester, George Hobbs, David Champion, John Sarkissian, John Reynolds, Mike Kesteven, Grant Hampson, Andrew Brown, David Smith, Jonathan Khoo, (Russell Edwards)
- Swinburne University of Technology, Melbourne
  Matthew Bailes, Ramesh Bhat, Willem van Straten, Joris Verbiest, Sarah Burke, Andrew Jameson
- University of Texas, Brownsville
  Rick Jenet
- Franklin & Marshall College, Lancaster
  Andrea Lommen
- University of Sydney, Sydney
  Daniel Yardley
- National Observatories of China, Beijing
  Johnny Wen
- Peking University, Beijing
  Kejia Lee
- Southwest University, Chongqing
  Xiaopeng You
- Curtin University, Perth
  Aidan Hotan



Pirsa: 10060082

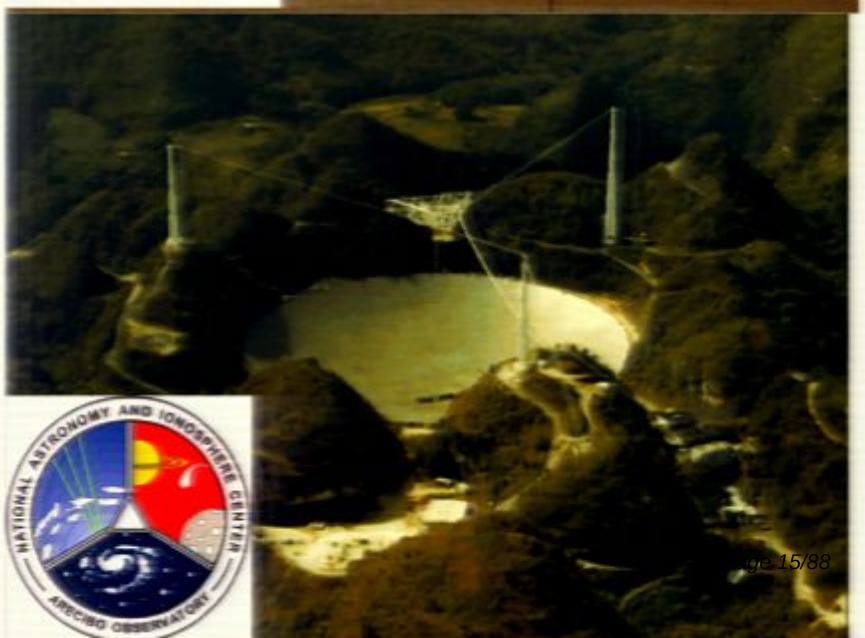
NanoGrav

Waldma
NRD
June 201

VIRGO LSC

- Anne Archibald, McGill University
- Zaven Arzoumanian, Goddard Space Flight Center
- Don Backer, University of California, Berkeley
- Adam Brazier, Cornell University
- Jason Boyles, West Virginia University
- Brian Burt, Franklin and Marshall College
- Jim Cordes, Cornell University
- Paul Demorest, National Radio Astronomy Observatory
- Justin Ellis, West Virginia University
- Rob Ferdman, CNRS, France
- L. Samuel Finn, Center of Gravitational Physics at Penn State Univer
- Paulo Freire, National Astronomy and Ionospheric Center
- Alex Garcia, University of Texas, Brownsville
- Marjorie Gonzalez, University of British Columbia
- Rick Jenet, University of Texas, Brownsville, CGWA
- Victoria Kaspi, McGill University
- Joseph Lazio, Naval Research Laboratories
- Andrea Lommen, Franklin and Marshall College
- Duncan Lorimer, West Virginia University
- Ryan Lynch, University of Virginia
- Maura McLaughlin, West Virginia University
- Jonathan Nelson, Oberlin College
- David Nice, Bryn Mawr College
- Nipuni Palliyaguru, West Virginia University
- Delphine Perrodin, Franklin and Marshall College
- Scott Ransom, National Radio Astronomy Observatory
- Ryan Shannon, Cornell University
- Xavi Siemens, University of Wisconsin
- Ingrid Stairs, University of British Columbia
- Dan Stinebring, Oberlin College
- Kevin Stovall, University of Texas, Brownsville

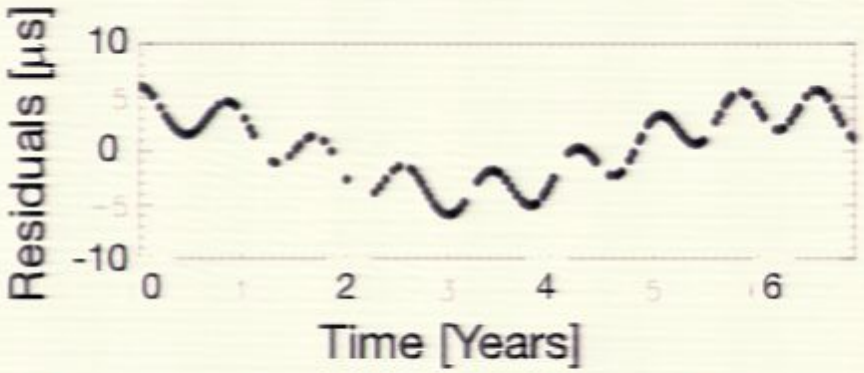
NRAO



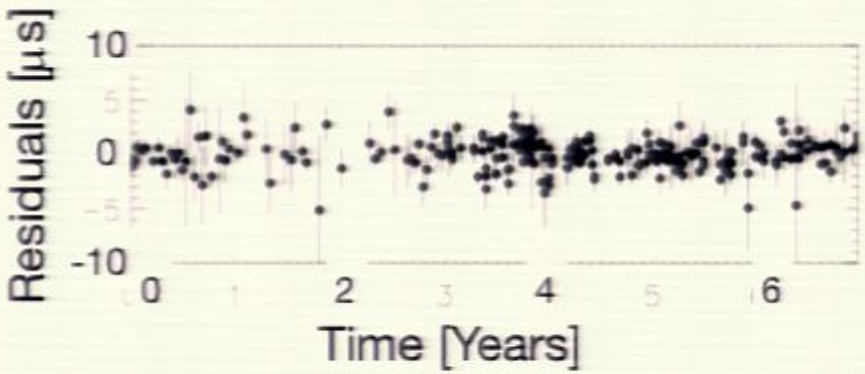
$$\frac{\nu_0 - \nu_{SS}(t)}{\nu_0} = \left[\left(\alpha^2 + \beta^2\right) H_+(t) + 2\alpha\beta\, H_\times(t)\right] / 2\,(1+\gamma)$$

Orbital Motion in the Radio Galaxy 3C 66B: Evidence for a Supermassive Black Hole Binary **Sudou, Iguchi, Murata, Taniguchi (2003) Science 300: 1263-1265.**

Constraining the Properties of Supermassive Black Hole Systems Using Pulsar Timing: Application to 3C 66b**, Jenet, Lommen, Larson and Wen (2004) ApJ 606:799-803.**



Simulated residuals due to 3c66b



Data from Kaspi, Taylor, Ryba 1994

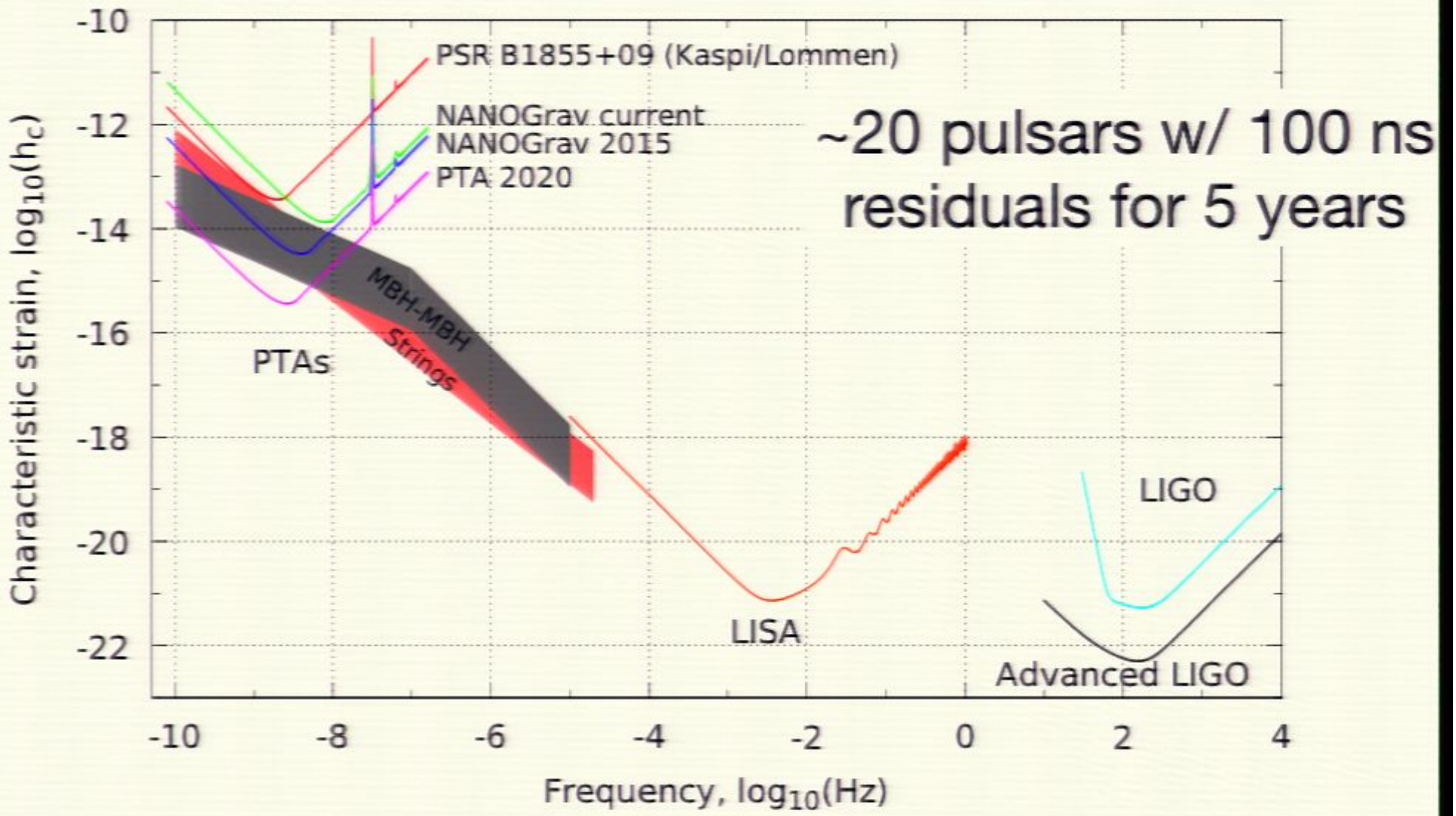
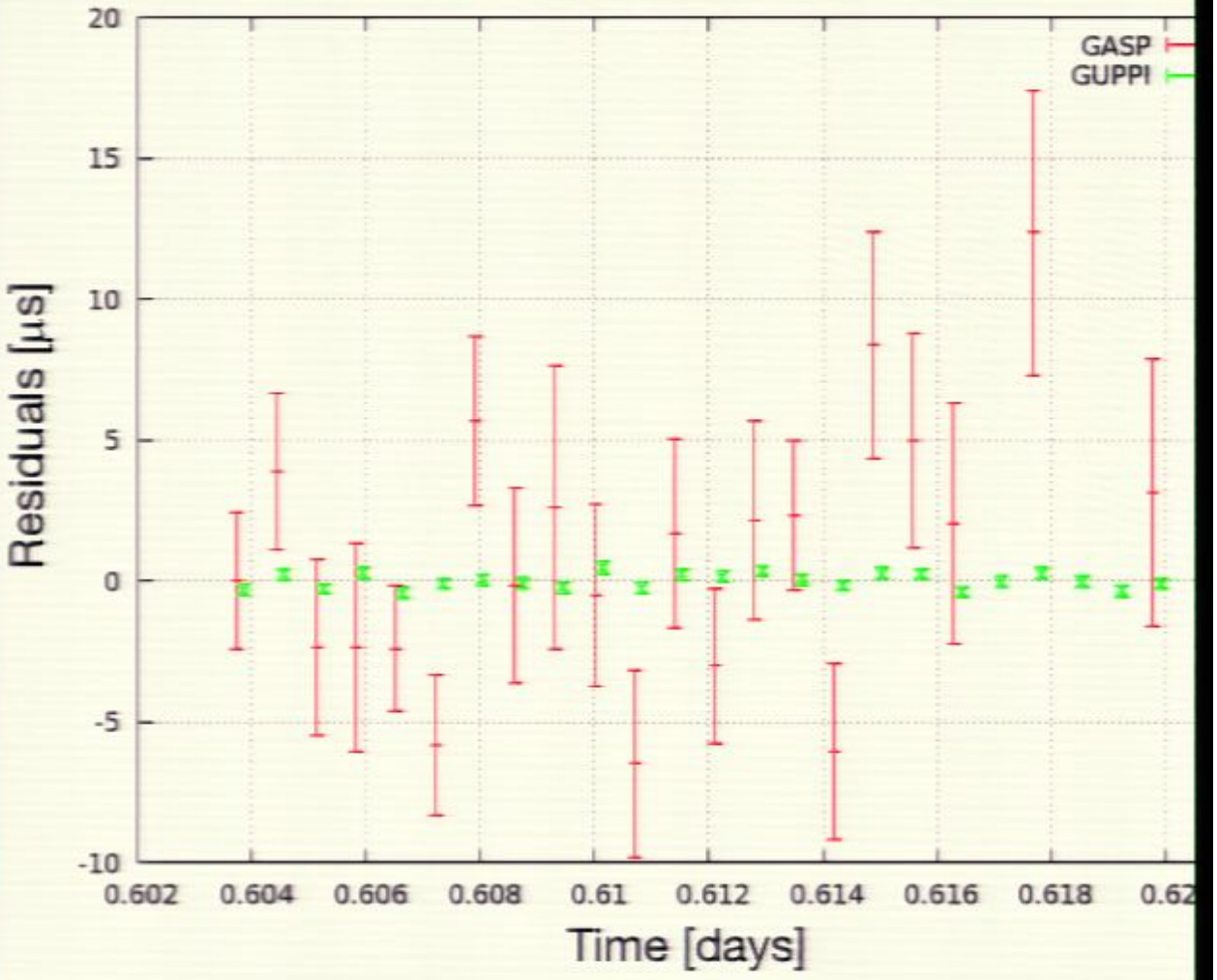


Figure by Paul Demorest (see arXiv:0902.2968)

GUPPI @ Green Bank

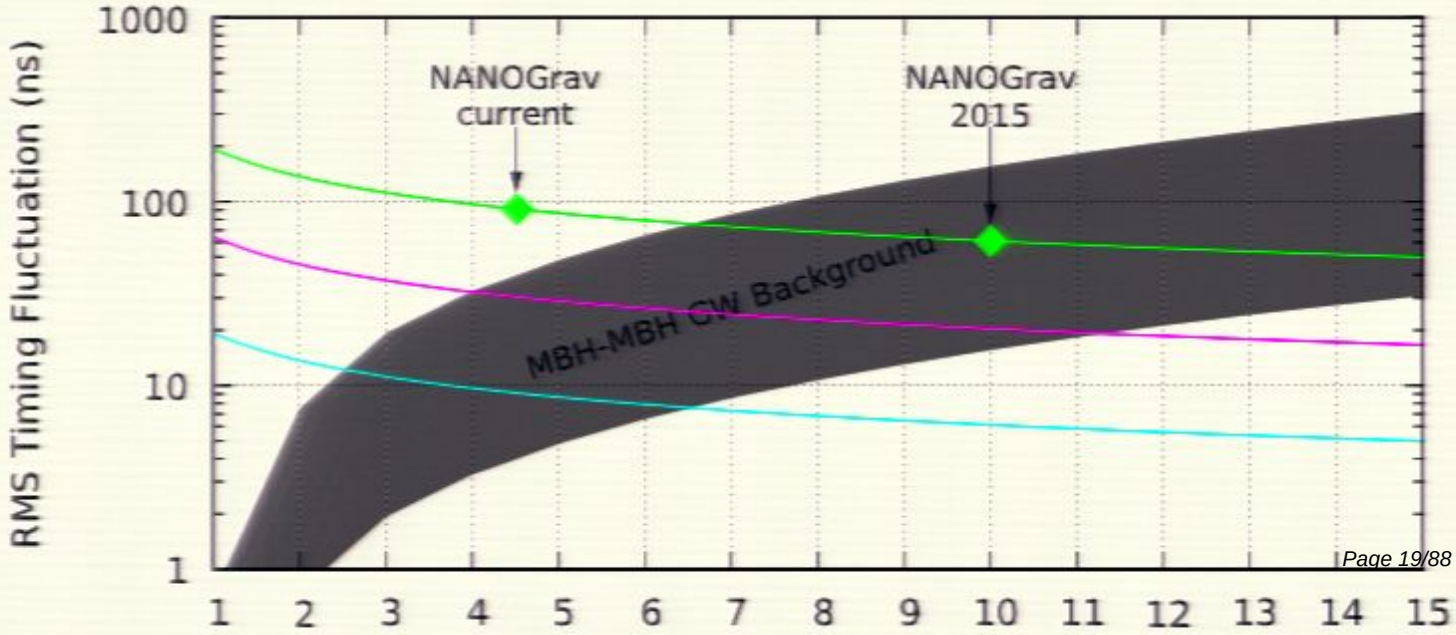


PTA punchline

Requires 20 pulsars with 100 ns timing

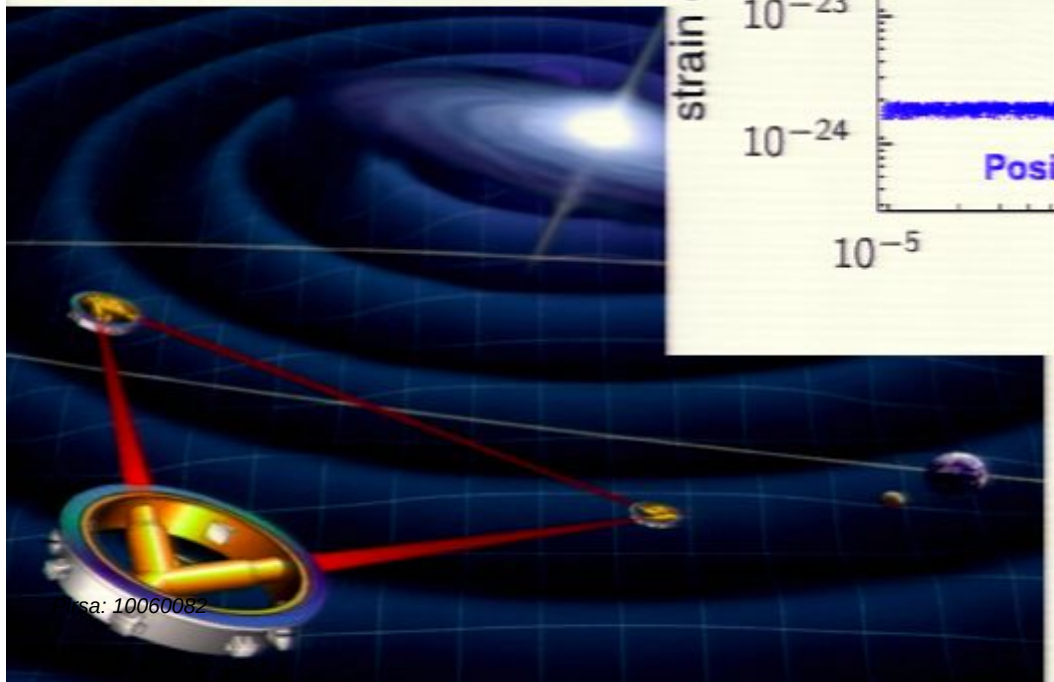
2 week cadence, 3 hours each at 4 frequencies

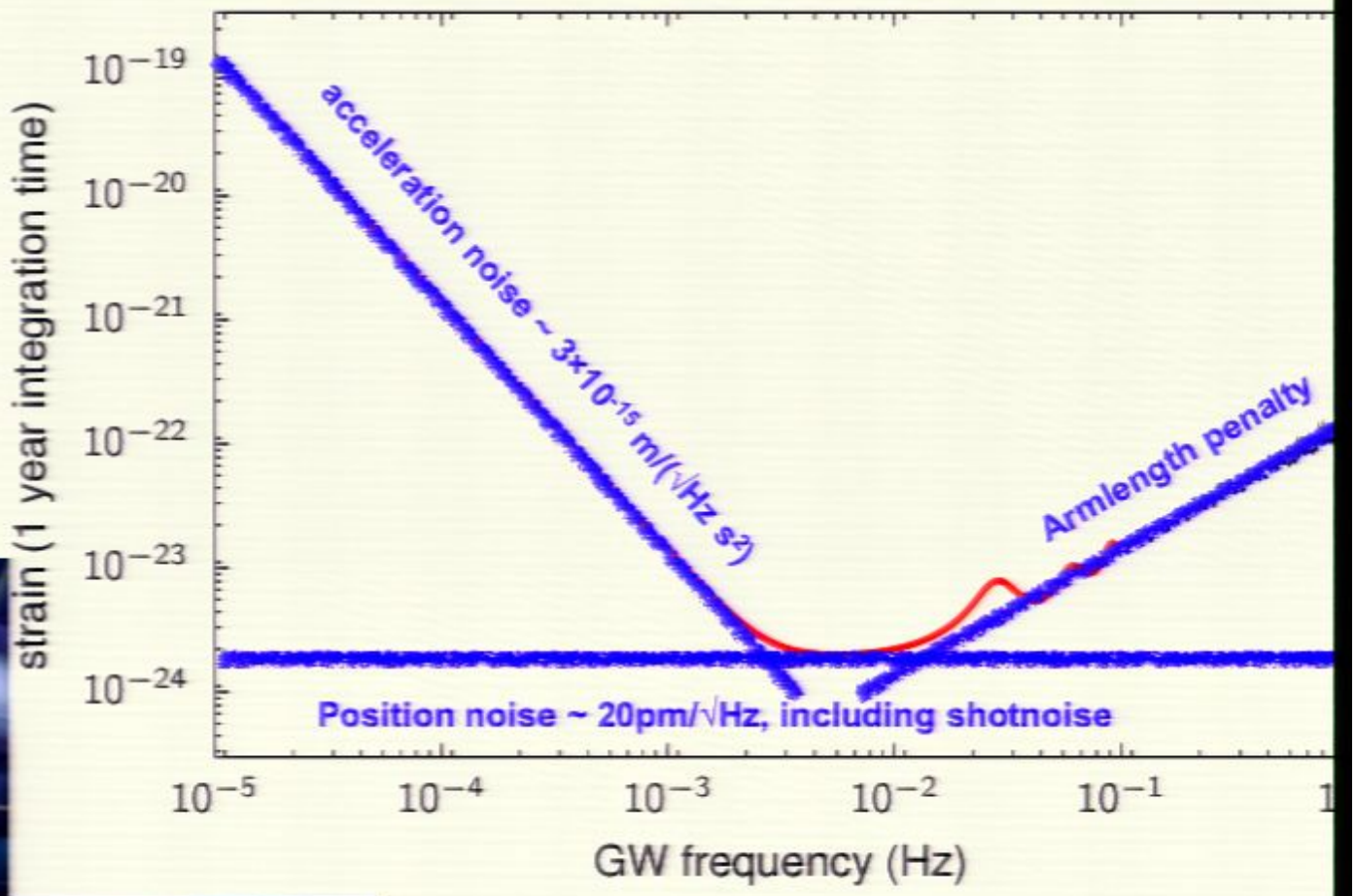
5 year observation to detect MBH/ MBH gravitational waves

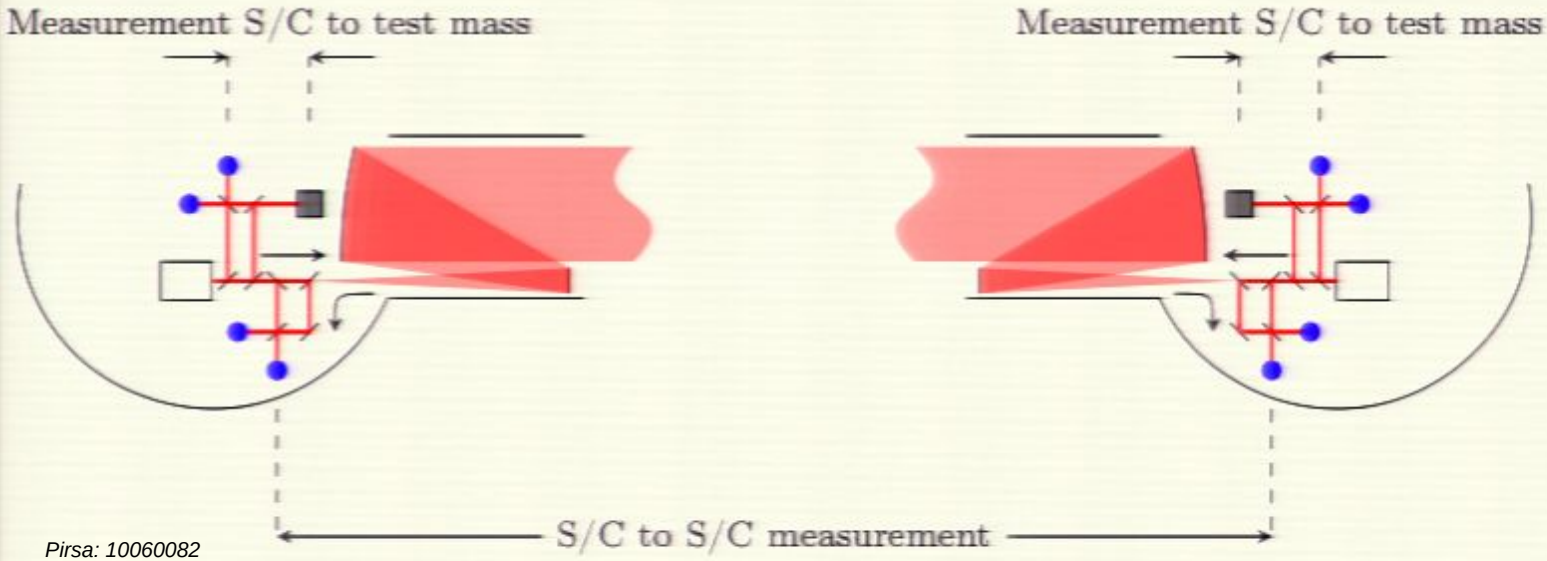


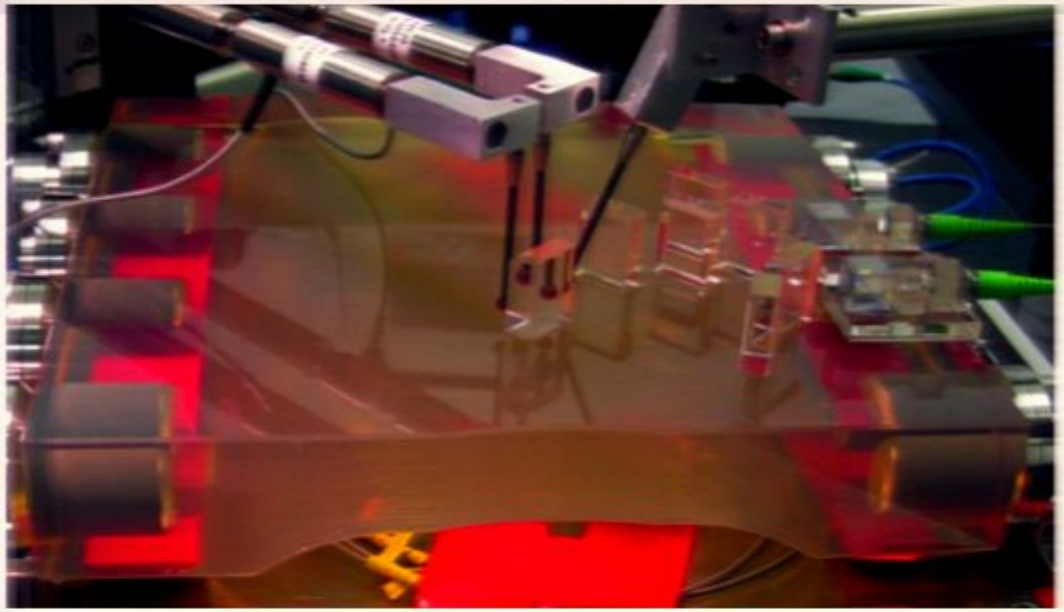
LISA

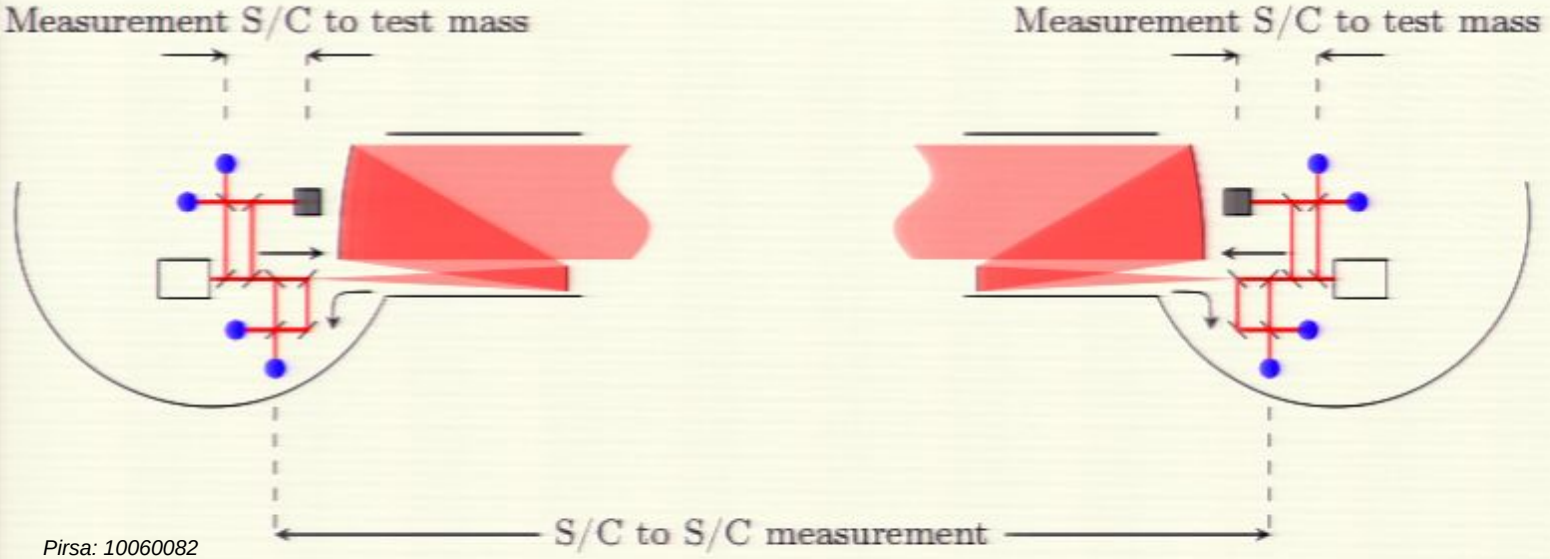
VIRGO LSC






Measurement S/C to test mass
Measurement S/C to test mass
S/C to S/C measurement




Measurement S/C to test mass
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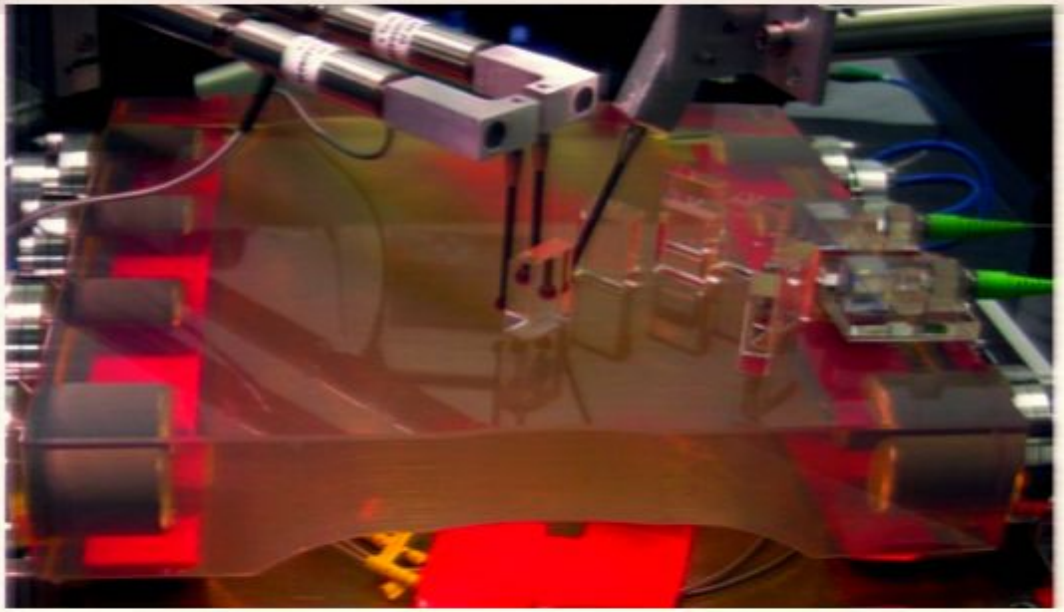
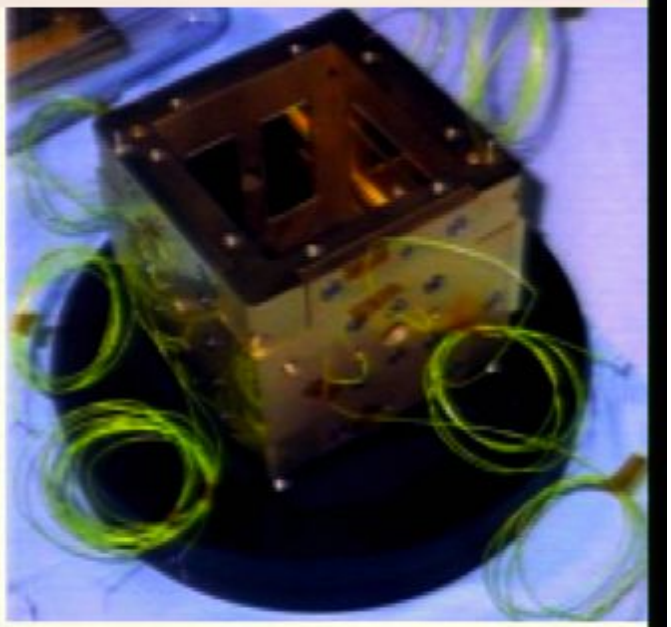
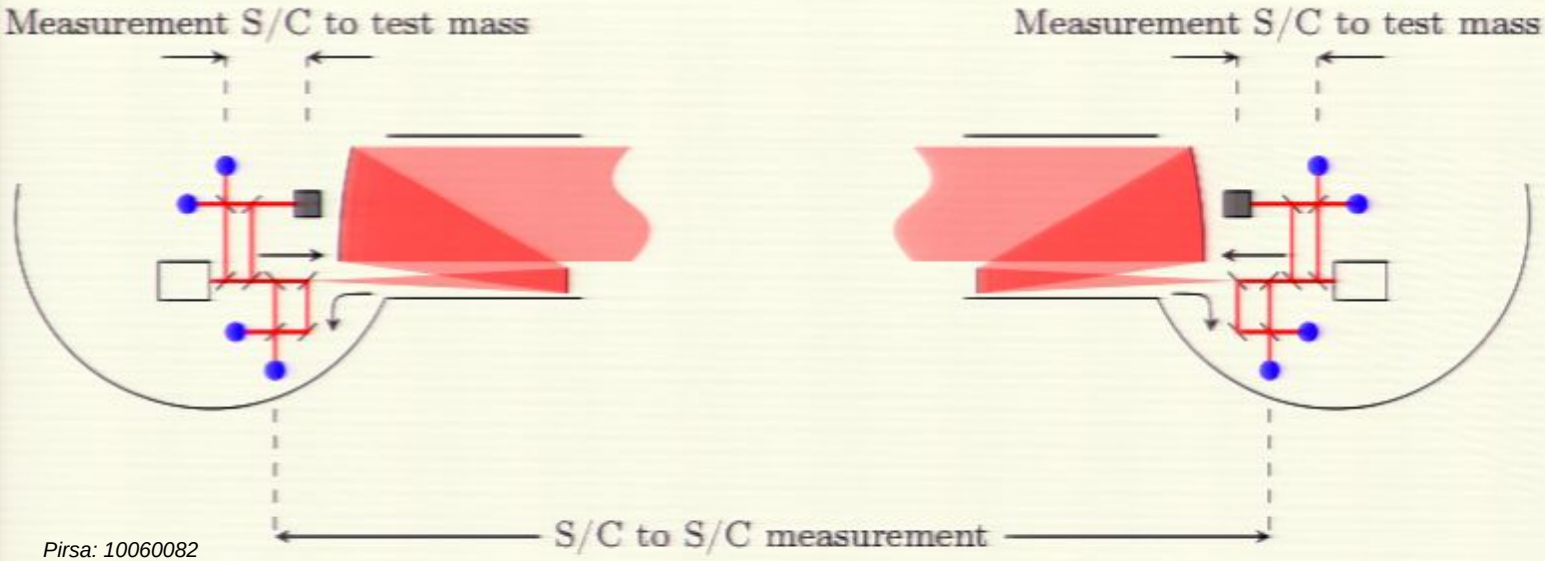
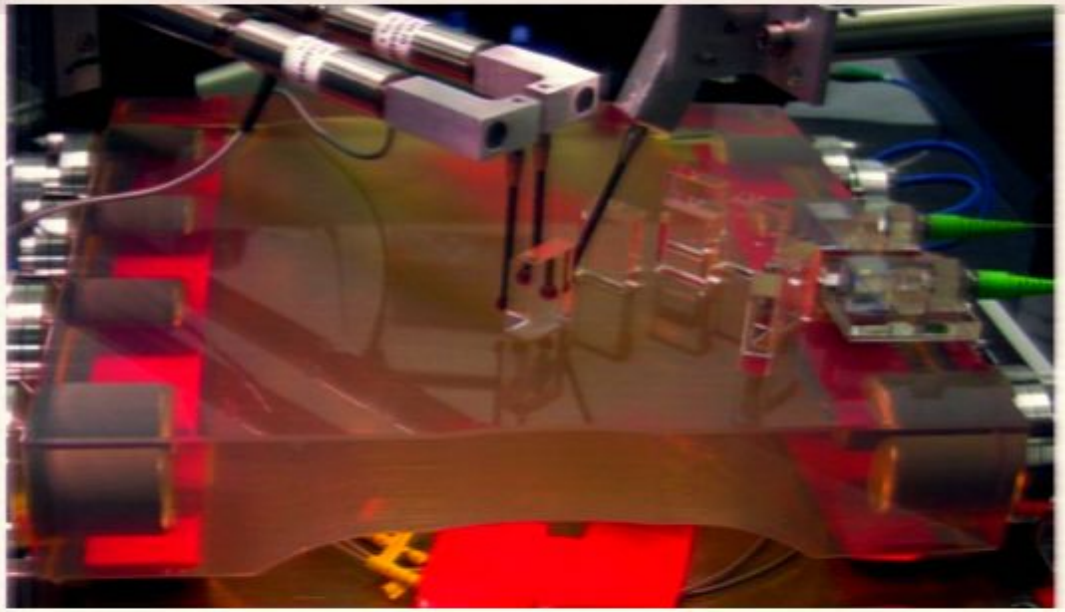
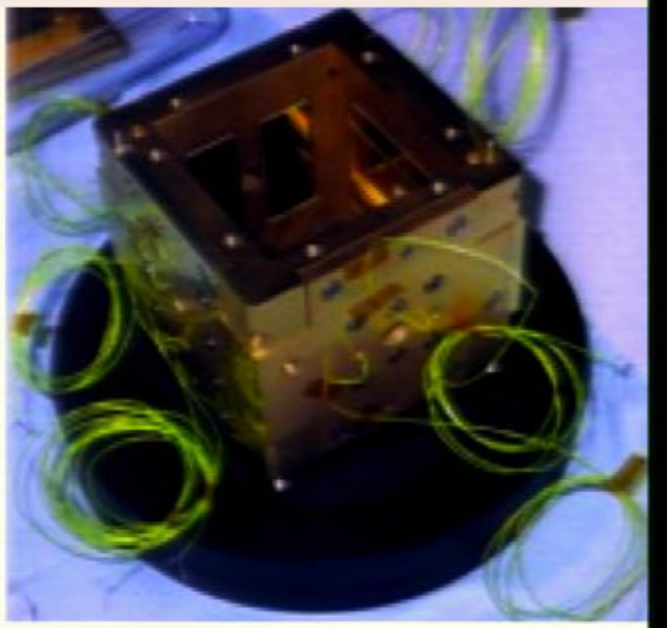
S/C to S/C measurement

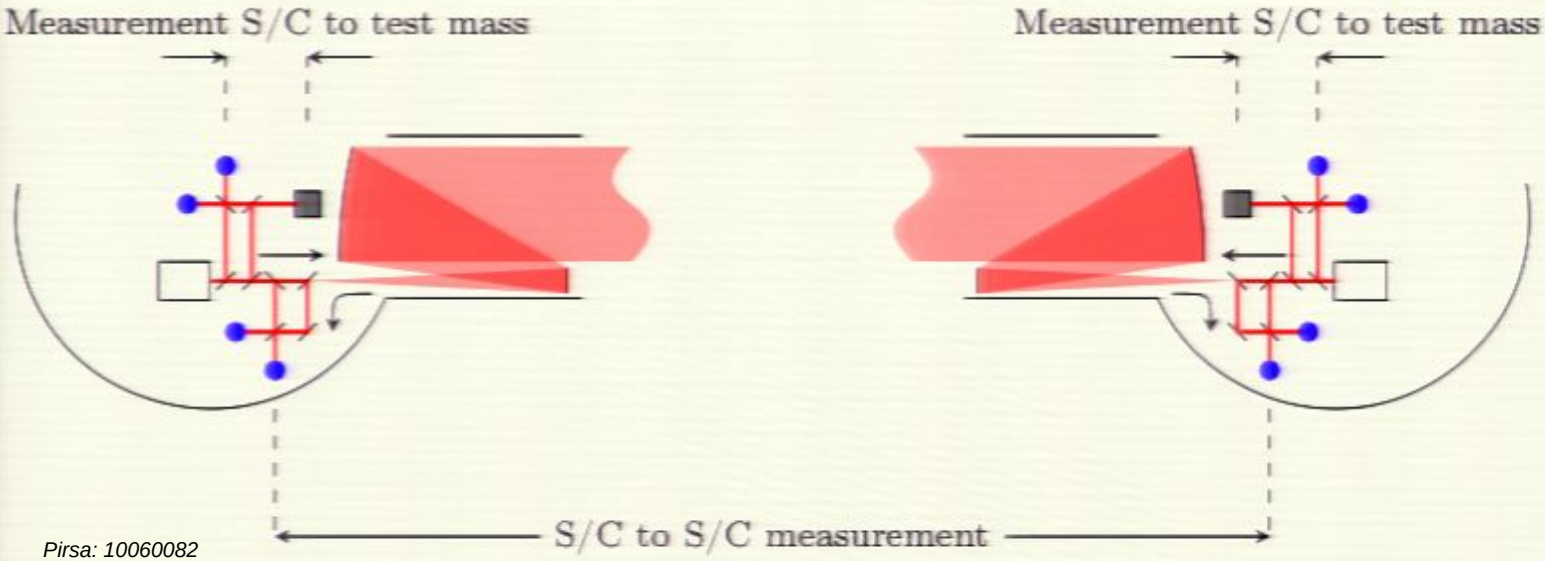




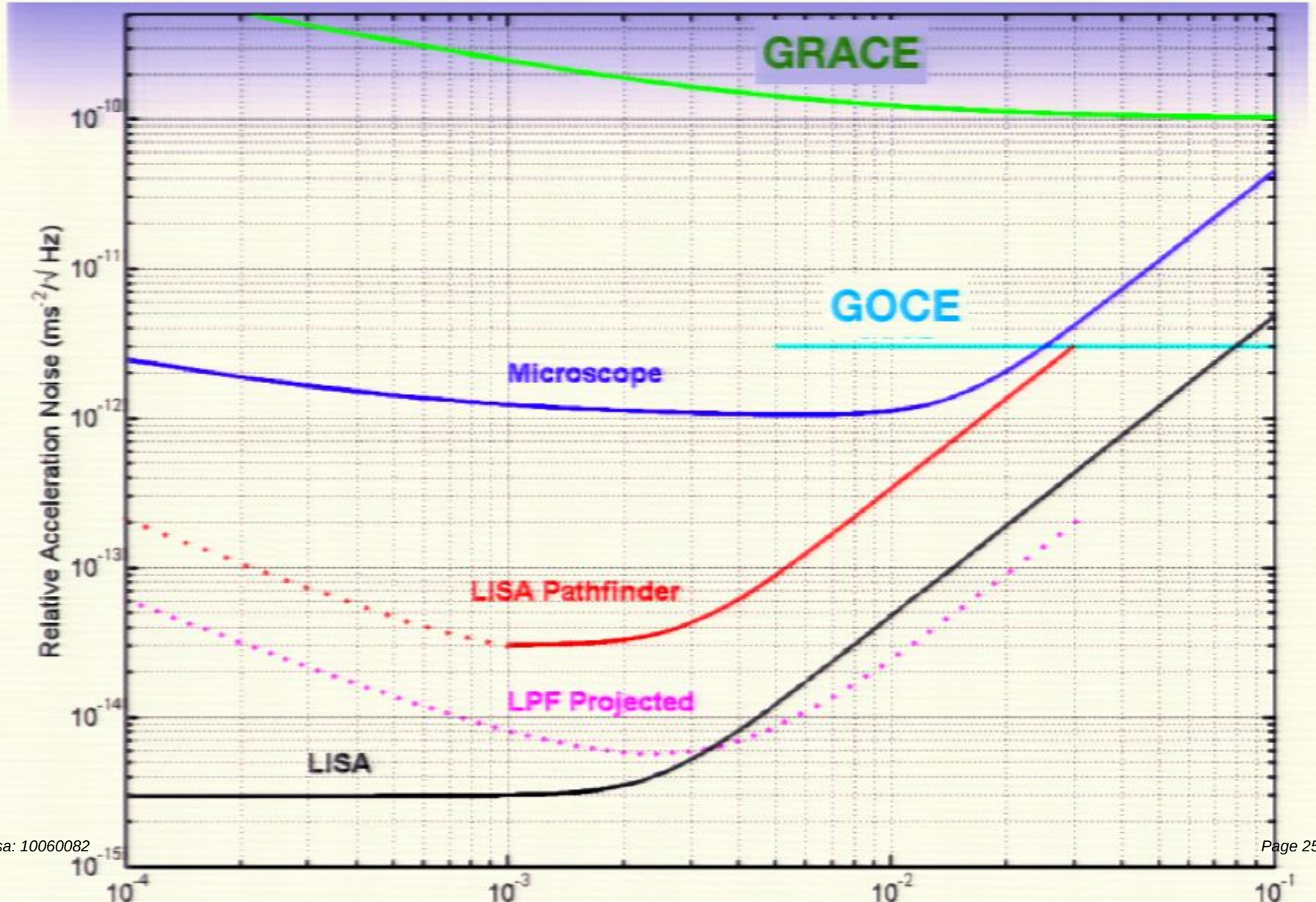

Measurement S/C to test mass
Measurement S/C to test mass
S/C to S/C measurement



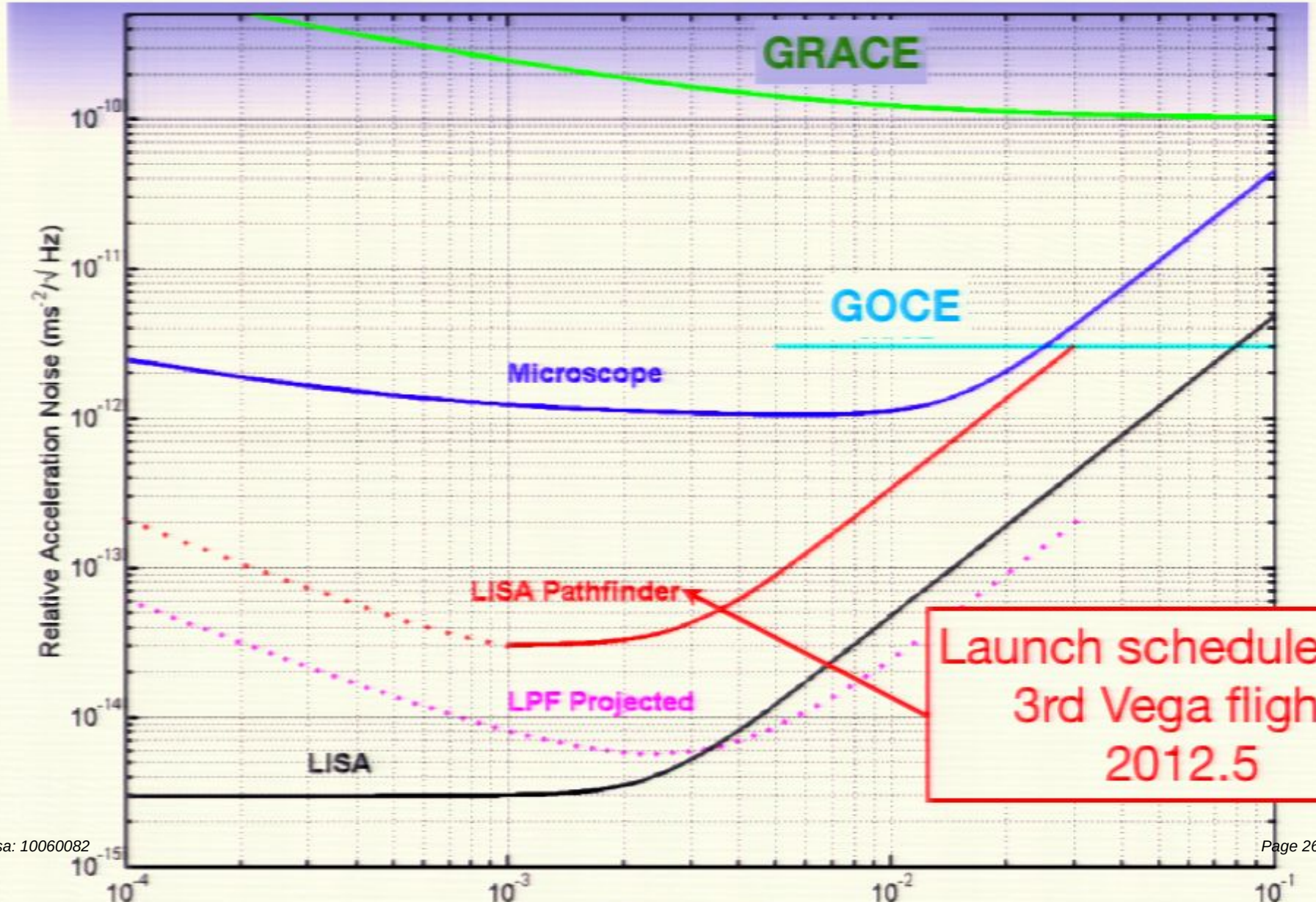


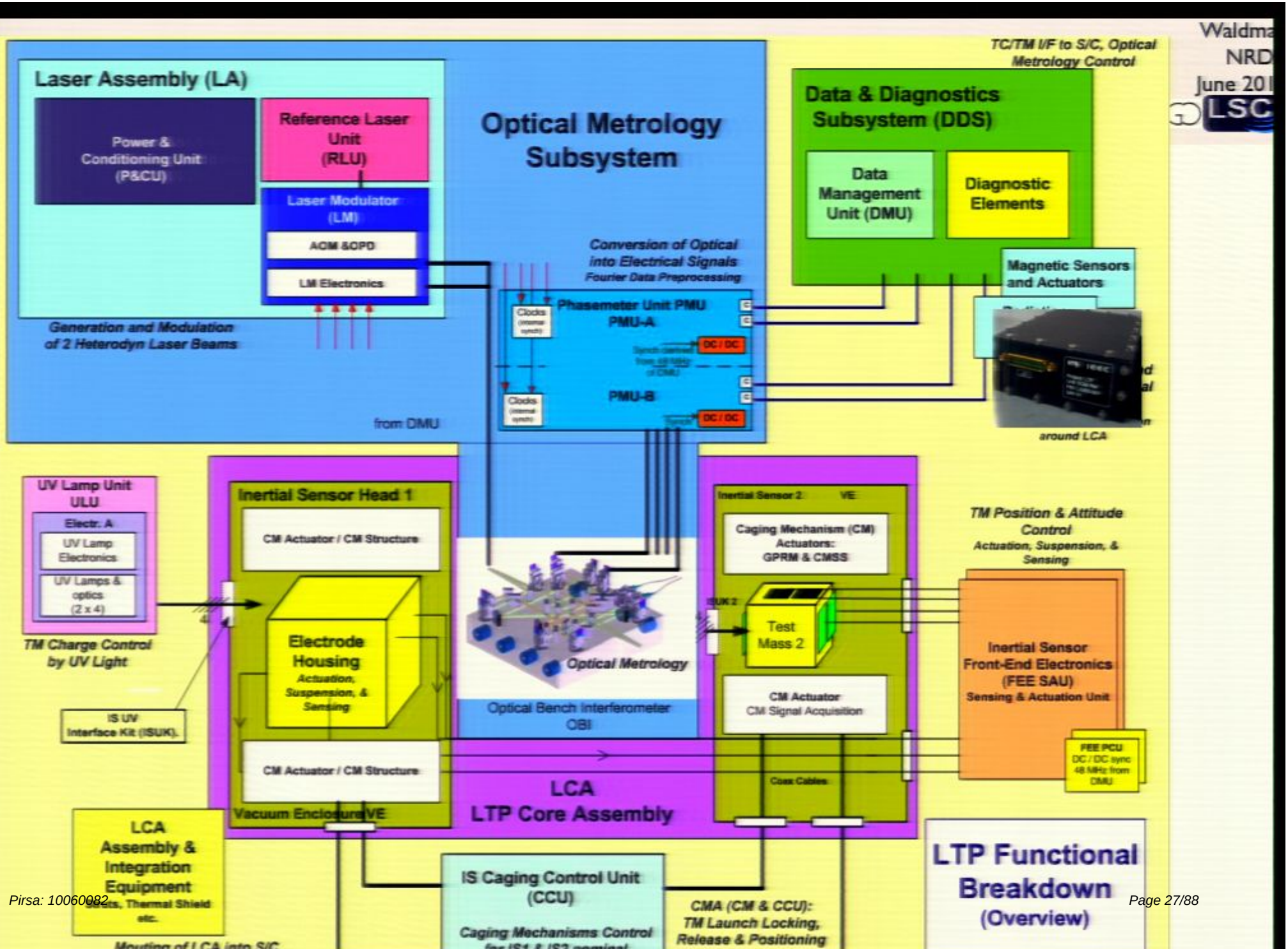

Measurement S/C to test mass
Measurement S/C to test mass
S/C to S/C measurement

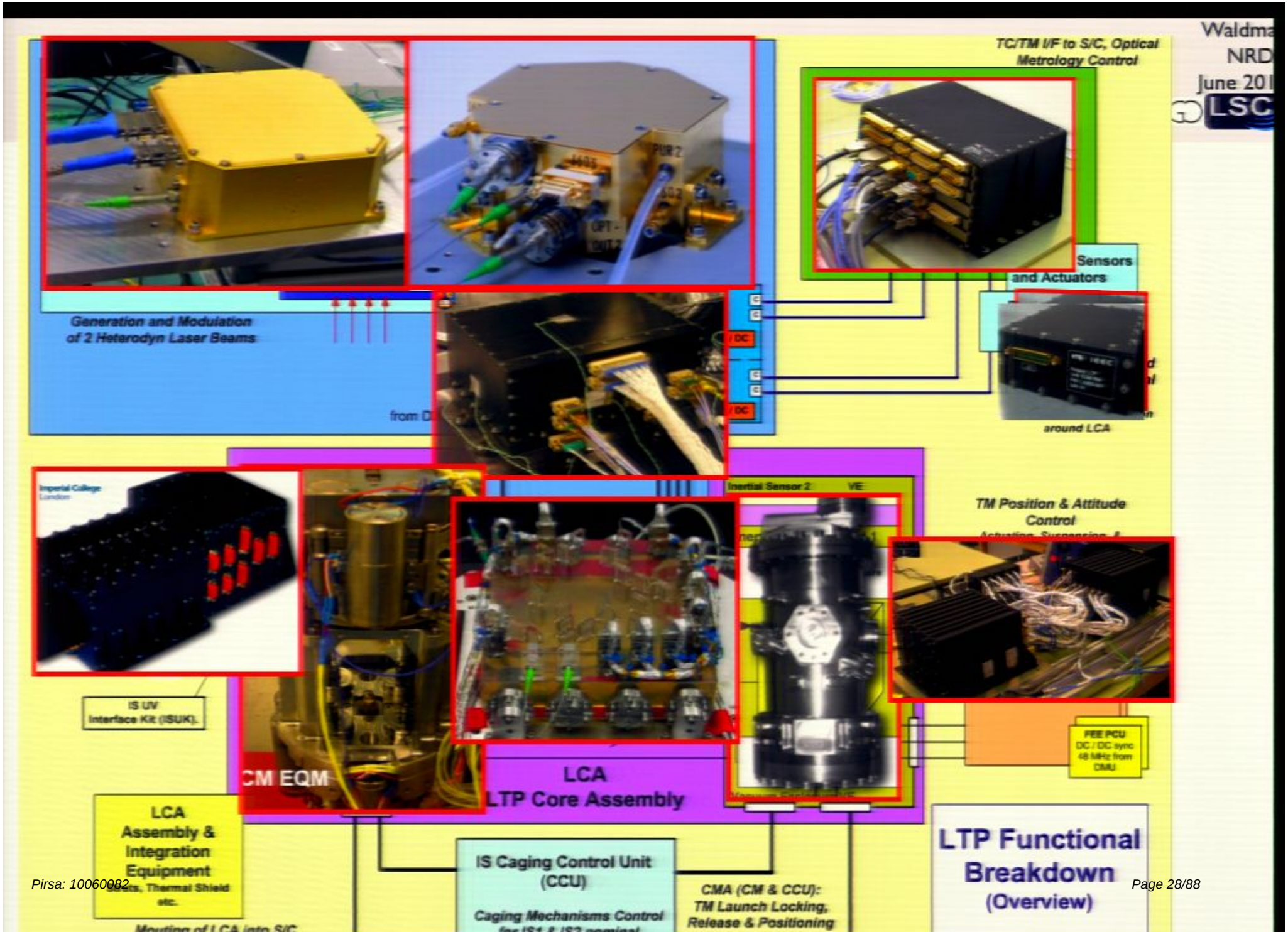
LISA Pathfinder

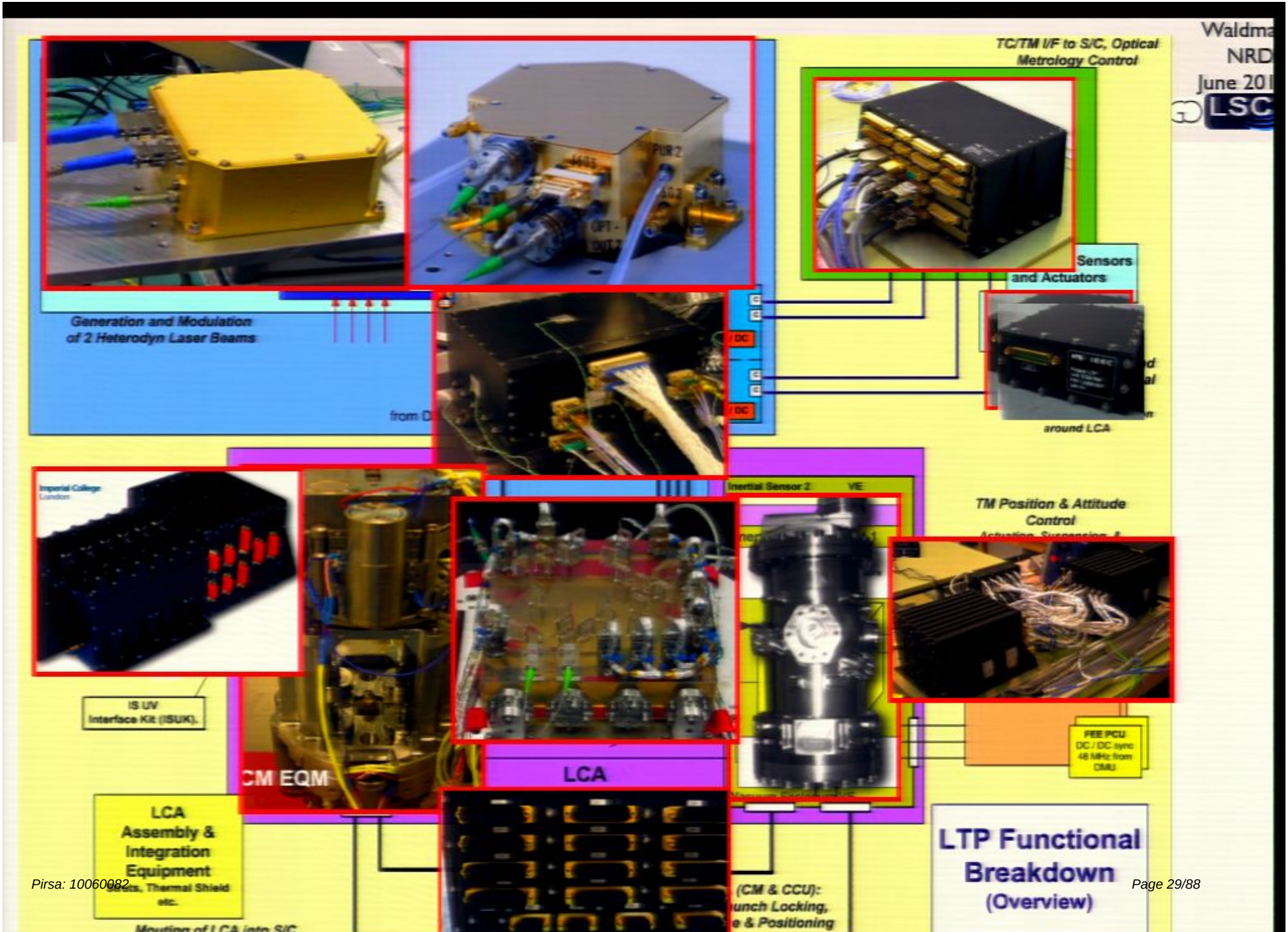


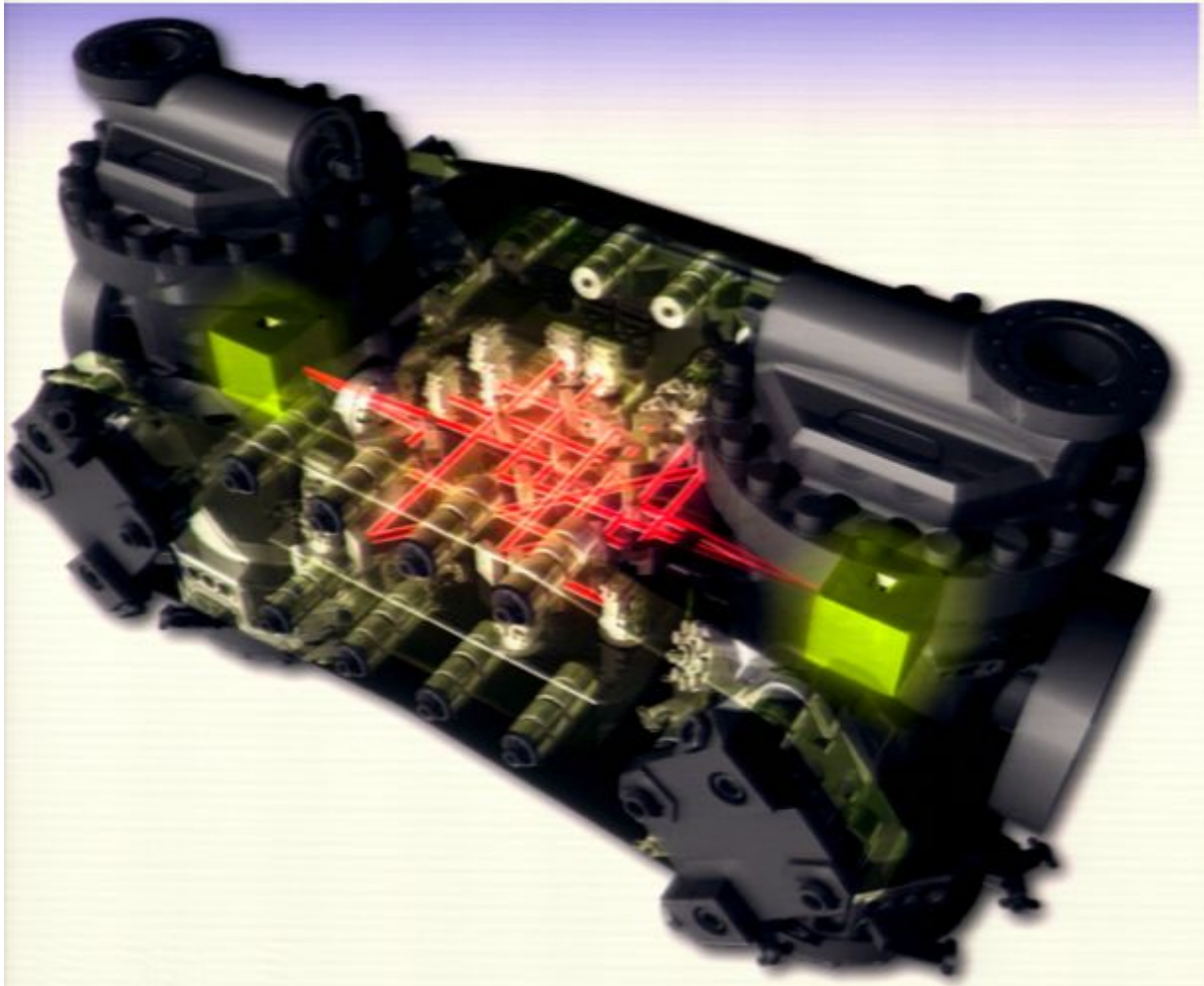
LISA Pathfinder




Laser Assembly (LA)
Power & Conditioning Unit (P&CU)
Reference Laser Unit (RLU)
Laser Modulator (LM)
AOM &OPD
LM Electronics
Generation and Modulation of 2 Heterodyn Laser Beams
Optical Metrology Subsystem
Conversion of Optical into Electrical Signals
Fourier Data Preprocessing
Phasemeter Unit PMU
PMU-A
PMU-B
Clocks
DC / DC
from DMU
TC/TM I/F to S/C, Optical Metrology Control
Data & Diagnostics Subsystem (DDS)
Data Management Unit (DMU)
Diagnostic Elements
Magnetic Sensors and Actuators
around LCA
UV Lamp Unit ULU
Electr. A
UV Lamp Electronics
UV Lamps & optics (2 x 4)
TM Charge Control by UV Light
IS UV Interface Kit (ISUK)
Inertial Sensor Head 1
CM Actuator / CM Structure
Electrode Housing
Actuation, Suspension, & Sensing
CM Actuator / CM Structure
Vacuum Enclosure VE
Optical Metrology
Optical Bench Interferometer OBI
Inertial Sensor 2
Caging Mechanism (CM) Actuators: GPRM & CMSS
Test Mass 2
CM Actuator
CM Signal Acquisition
Coax Cables
TM Position & Attitude Control
Actuation, Suspension, & Sensing
Inertial Sensor Front-End Electronics (FEE SAU)
Sensing & Actuation Unit
FEE PCU
DC / DC sync 48 MHz from DMU
LCA
LTP Core Assembly
LCA Assembly & Integration Equipment
Mounting of LCA into S/C
IS Caging Control Unit (CCU)
Caging Mechanisms Control
CMA (CM & CCU): TM Launch Locking, Release & Positioning
LTP Functional Breakdown
(Overview)


Waldma
NRD
June 201
LSC
TC/TM I/F to S/C, Optical Metrology Control
Sensors and Actuators
Generation and Modulation of 2 Heterodyn Laser Beams
around LCA
Imperial College London
IS UV Interface Kit (ISUK).
Inertial Sensor 2
VE
TM Position & Attitude Control
FEE PCU
DC / DC sync
48 MHz from DMU
CM EQM
LCA
LTP Core Assembly
LCA Assembly & Integration Equipment
Thermal Shield etc.
IS Caging Control Unit (CCU)
Caging Mechanisms Control
CMA (CM & CCU): TM Launch Locking, Release & Positioning
LTP Functional Breakdown
(Overview)


Waldma
NRD
June 201
LSC
TC/TM I/F to S/C, Optical Metrology Control
Sensors and Actuators
Generation and Modulation of 2 Heterodyn Laser Beams
around LCA
TM Position & Attitude Control
IS UV Interface Kit (ISUK).
CM EQM
LCA
FEE PCU
DC / DC sync
48 MHz from DMU
LCA Assembly & Integration Equipment
LTP Functional Breakdown
(Overview)

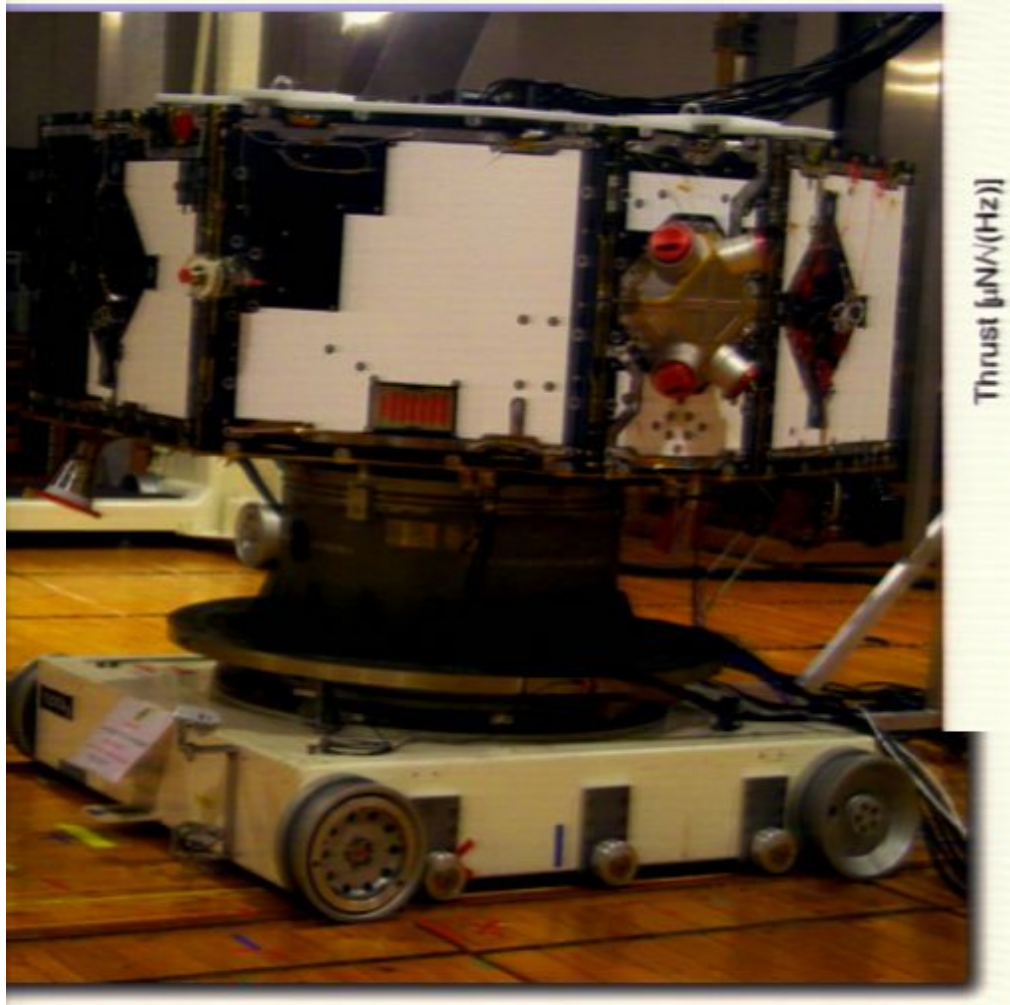


- Caging mechanism key critical path for LTP
- Same flight hardware as LISA

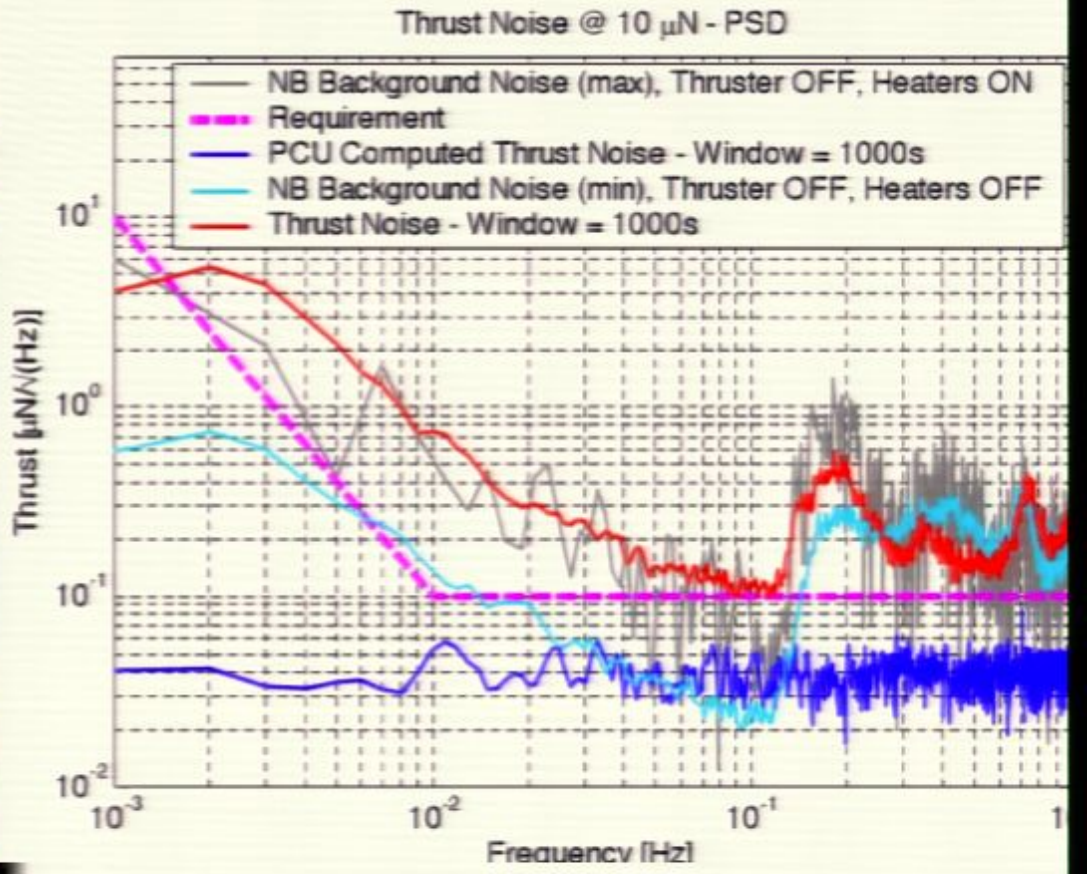
Micro-thrusters

VIRGO LSC

Flight hardware at Astrium UK



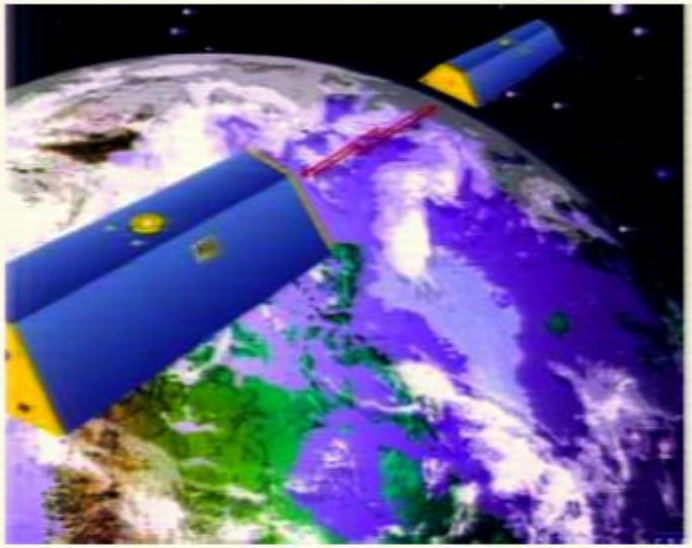
Colloidal Thrusters mounted on s/c during magnetic test

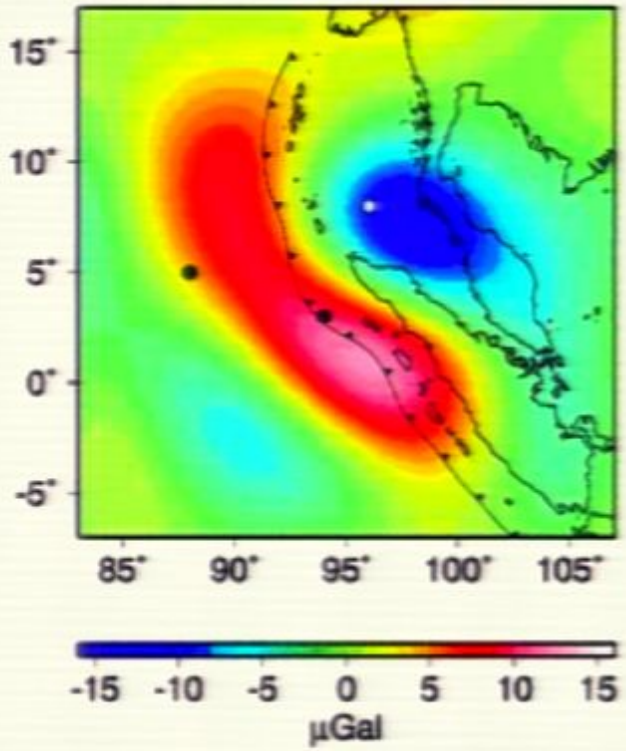


LISA inertial sensor will launch in ~ 2 years

GRACE-C

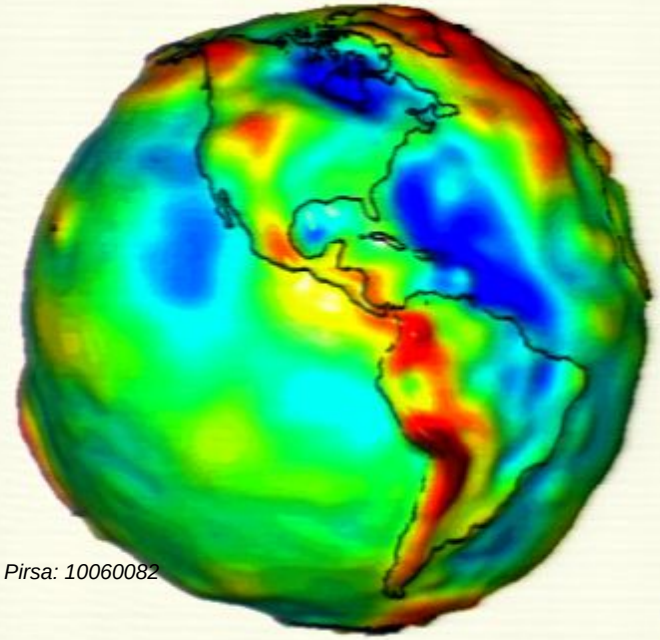
VIRGO LSC

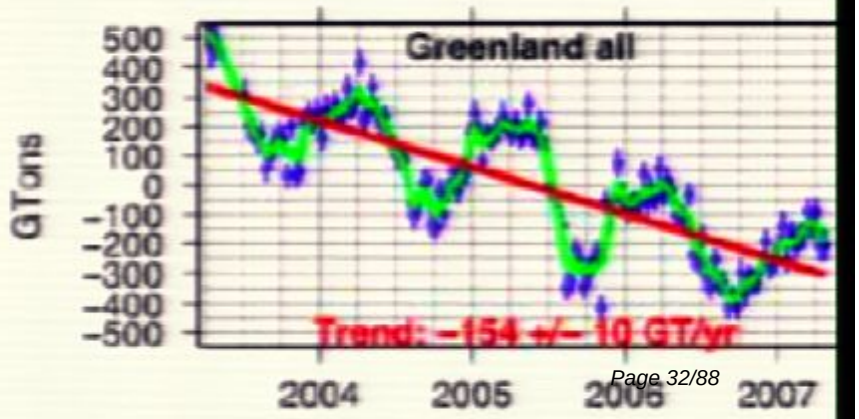


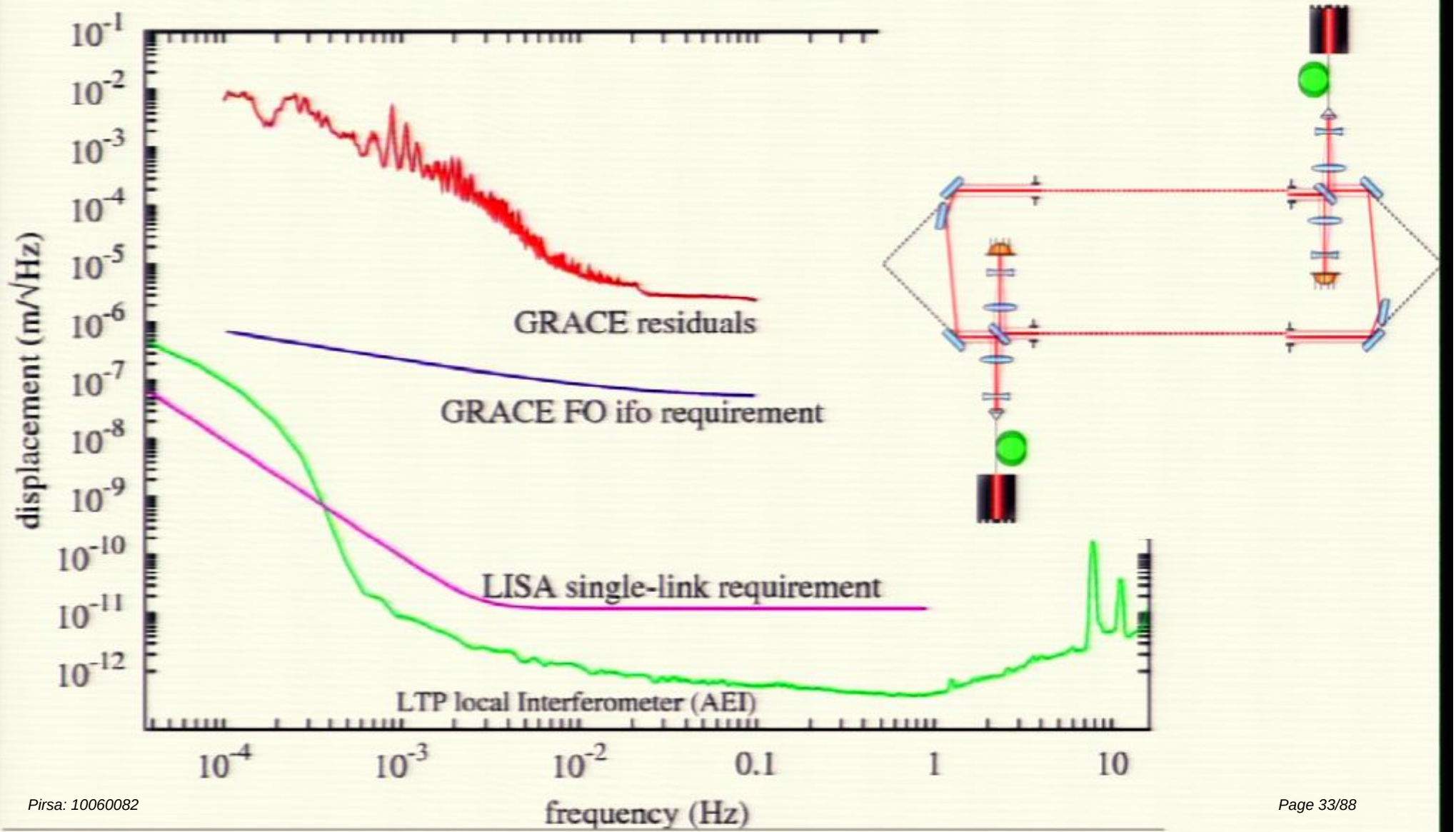


Sumatra earthquake

Gravity
Recovery
And
Climate
Explorer



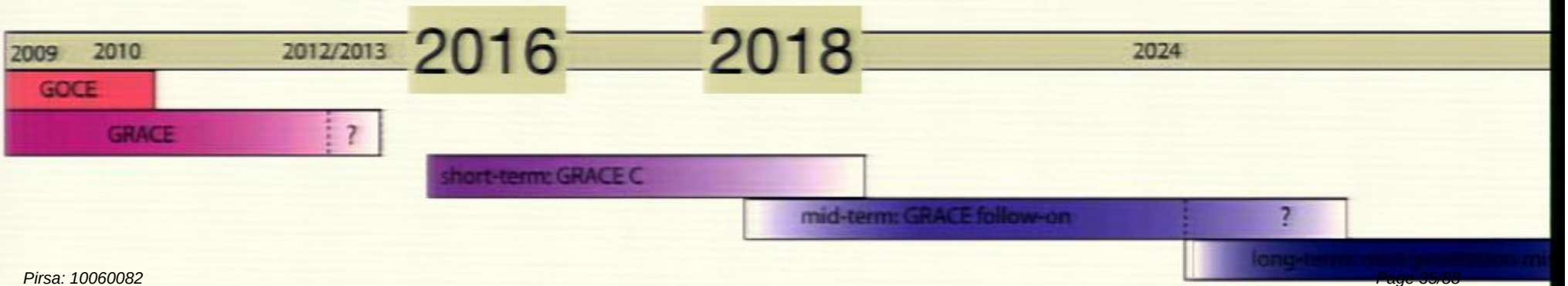



displacement (m/√Hz)
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
GRACE residuals
GRACE FO ifo requirement
LISA single-link requirement
LTP local Interferometer (AEI)
10^-4
10^-3
10^-2
0.1
1
10
frequency (Hz)

Satellite to Satellite Interferometery

	LISA	Laser interferometer SST (preliminary)
Inter-satellite distance	5 million km	≈200 km
Orbit	Heliocentric (1 a.u., triangular constellation)	LEO (≈400 km, Pendulum configuration)
Orbit environment	No atmospheric drag, stable thermal environment	Atmospheric drag, large thermal disturbances
Attitude and Orbit Control System	Drag-free	Partial drag compensation (?)
Single-link noise	12 pm/√Hz (× freq. dep.)	≈50 nm/√Hz (× freq. dep.)
Telescope aperture	38 cm	1.5 cm
Transmit power	1 W	0.03 W
Received power (at telescope)	360 pW	2000 pW
Phase measurement bandwidth	20 MHz	40 MHz

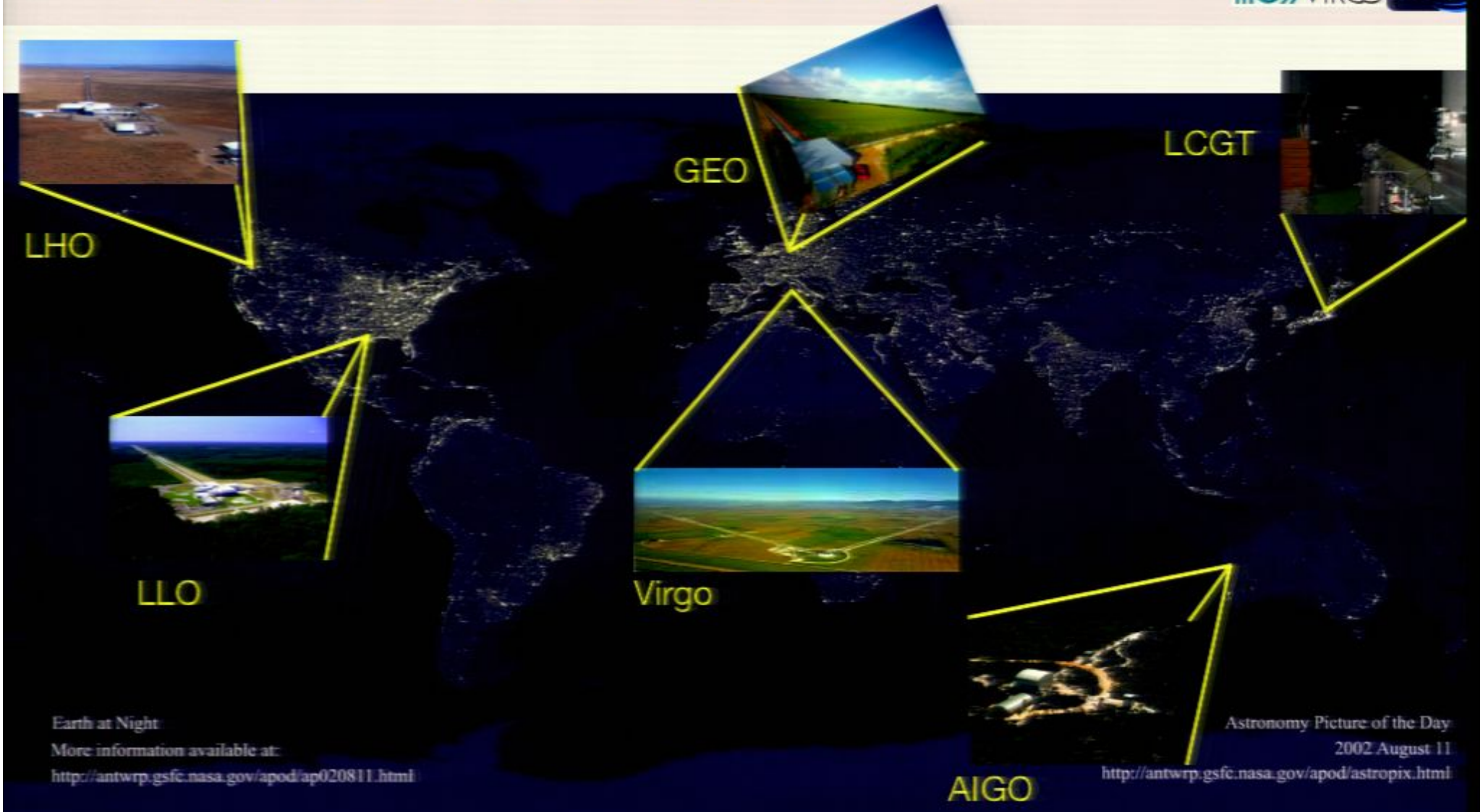
- Users want continued data and better data
- Several constellations under intensive discussions, nothing decided yet
- Best value from Sat-Sat ranging (GRACE concept) with
  - Laser interferometer: 2 µm/√Hz → 50 nm /√Hz or better
  - Pendulum orbit helps aliasing problem
  - More than one pair also helps
- GRACE-C : Grace copy plus laser interferometer demonstrator, NASA + Germany ? + Australia ??, launch 2015 !!!.
- Proposal to ESA under preparation
- Big interest in China and elsewhere
- All GRACE follow-on missions will carry laser interferometer, direct application of LISA technology!



Worldwide network

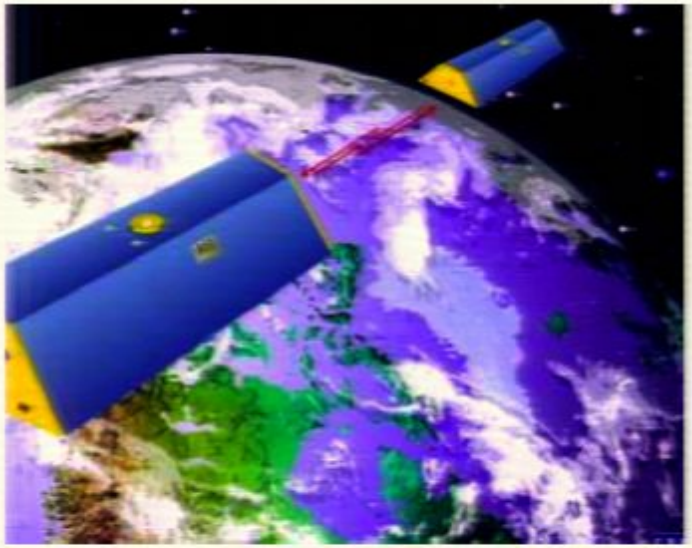
Waldma
NRD
June 201

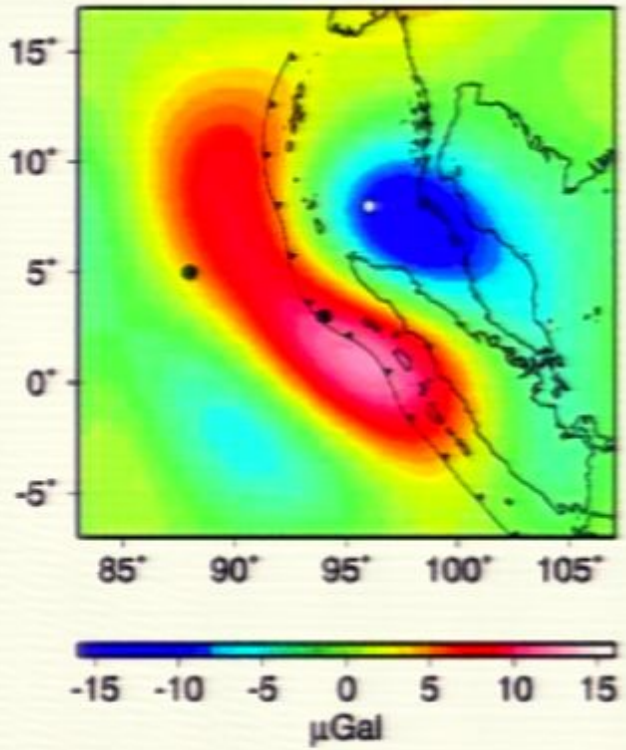
VIRGO LSC



GRACE-C

VIRGO LSC





Sumatra earthquake

Gravity
Recovery
And
Climate
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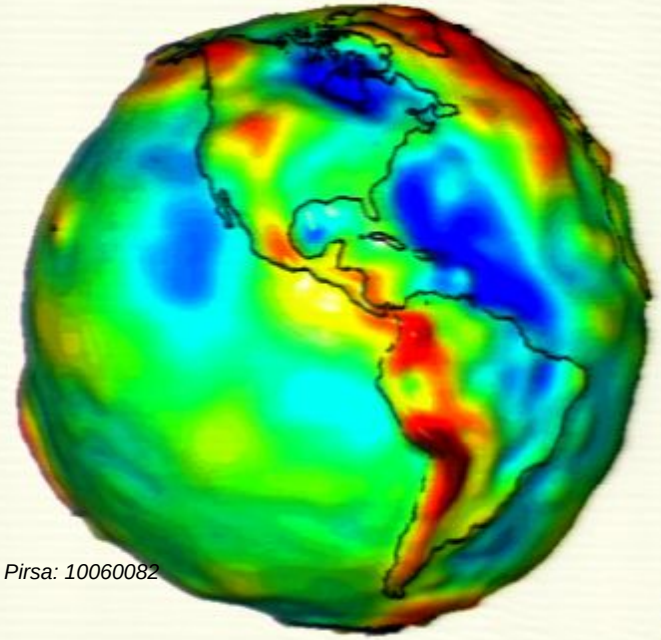
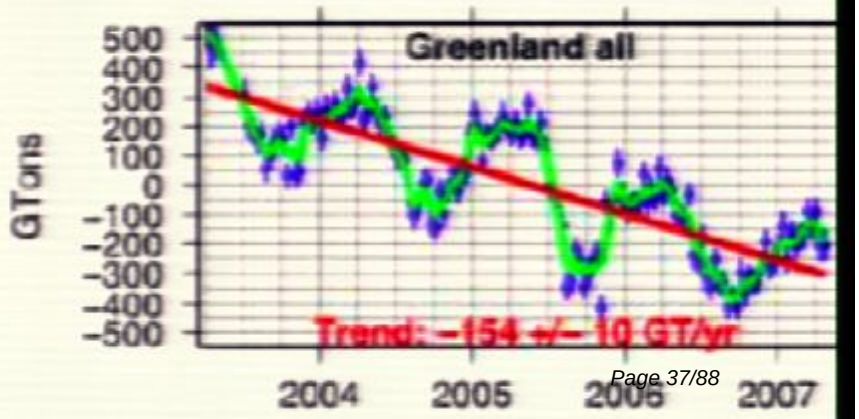
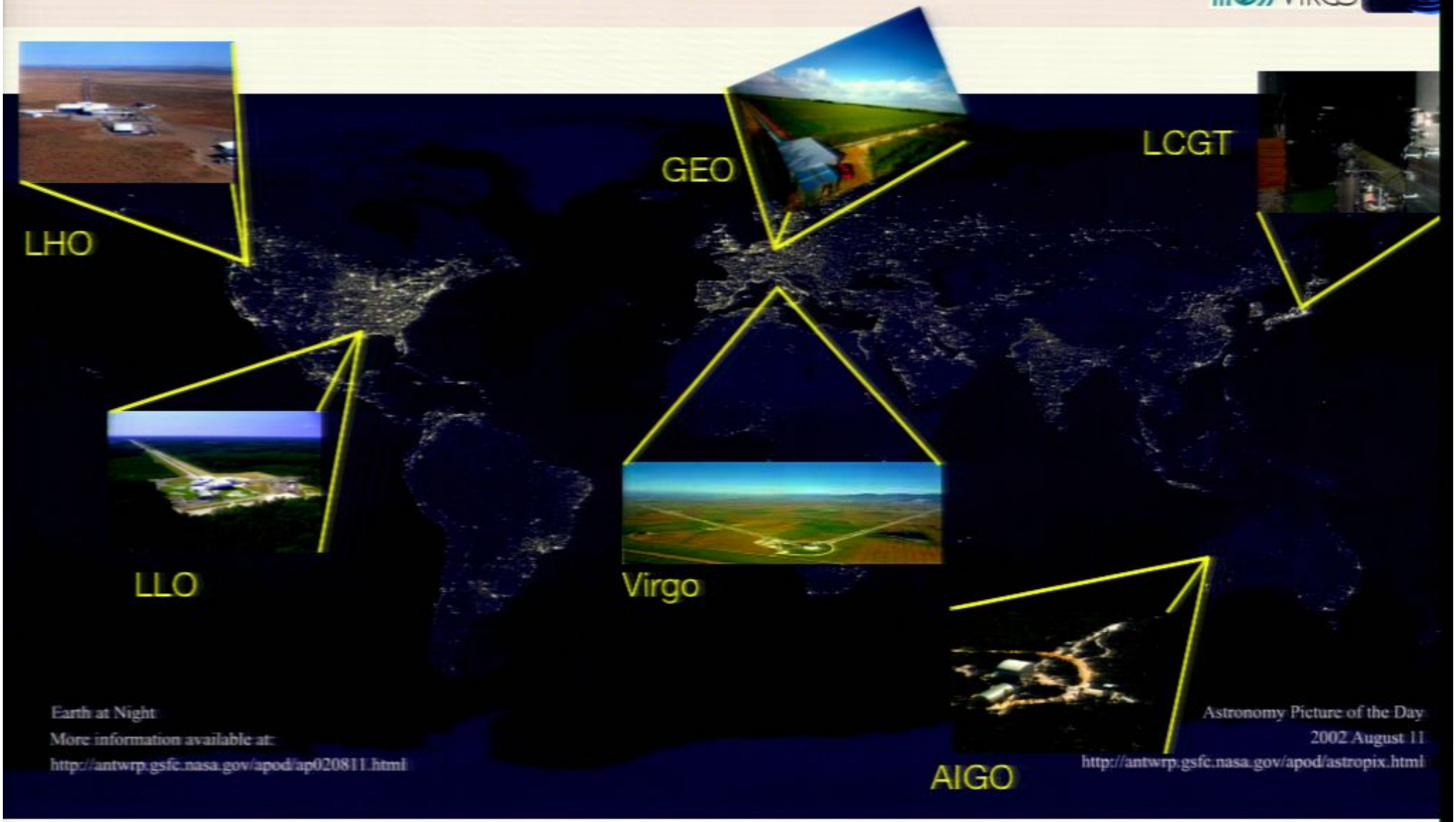
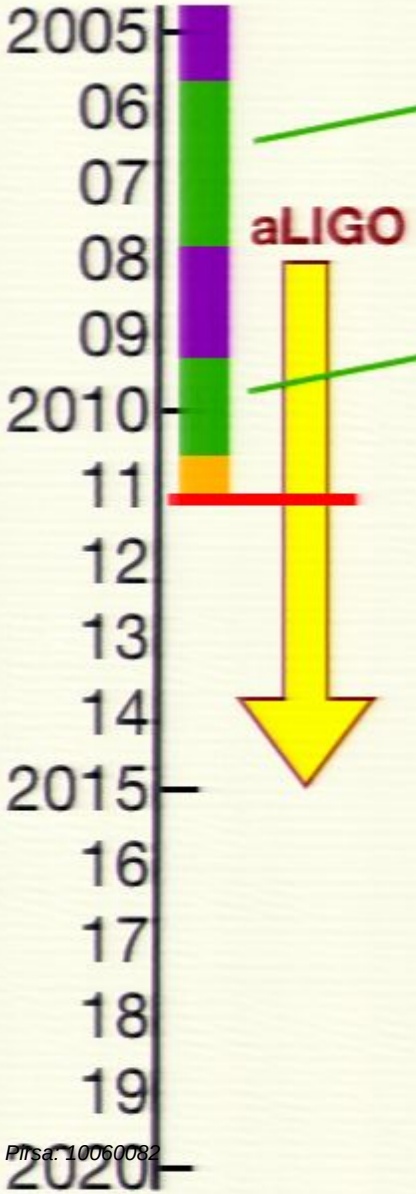




Worldwide network



LIGO/Virgo/GEO

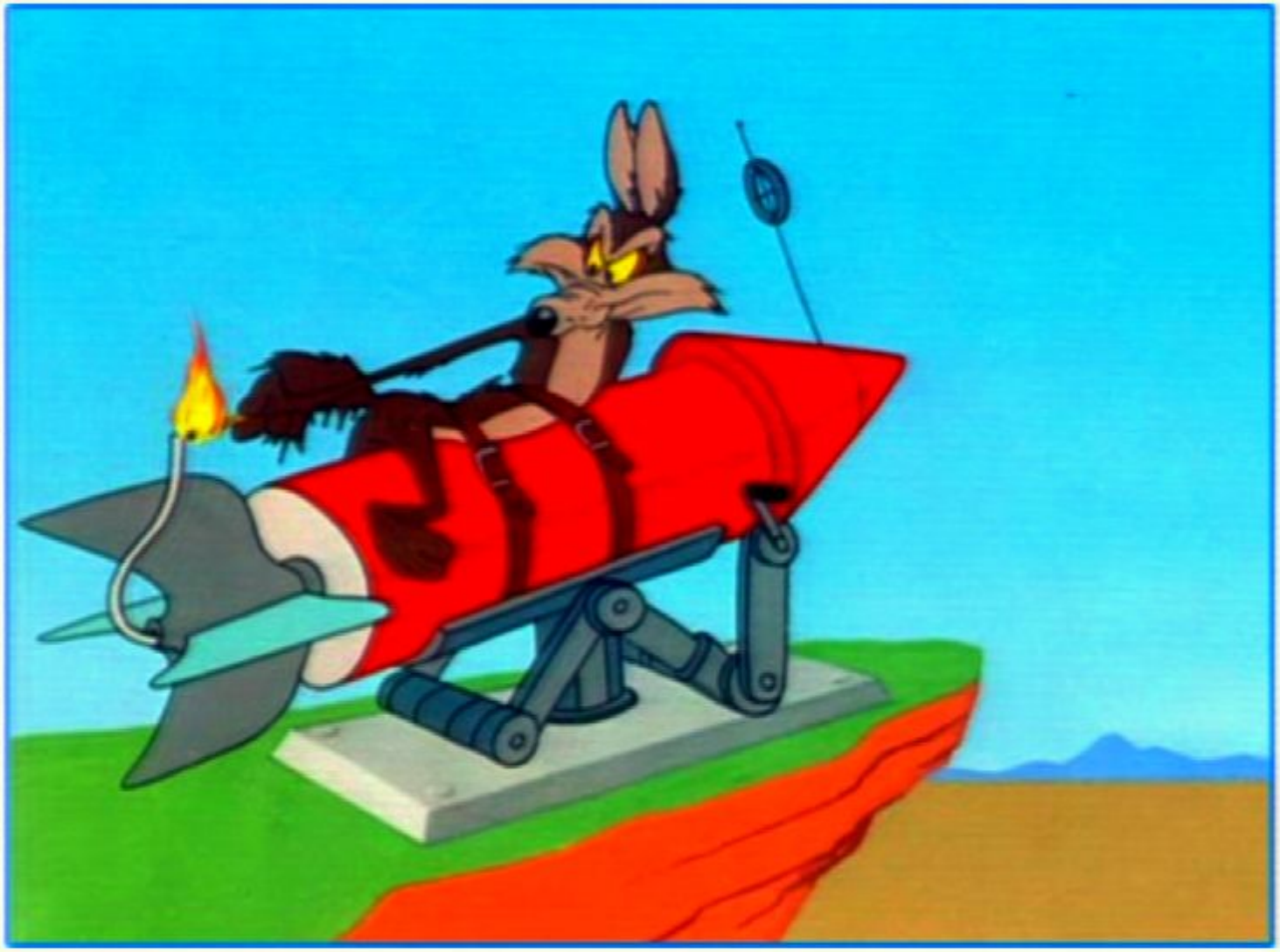


S5/VSR1: max(R) = 15 Mpc, 1 yr triple coincidence
cooperative run with GEO600 and Virgo

S6/VSR2: max(R) = 20 Mpc, 0.3 yr H1/L1 coincidence
few months w/ Virgo+ to begin mid July 201

Detector Handoff: October 20, 2010 aLIGO takes over
July 2011, AdV takes over

Ballistic Wile E.



+ Detectors

GEO-HF

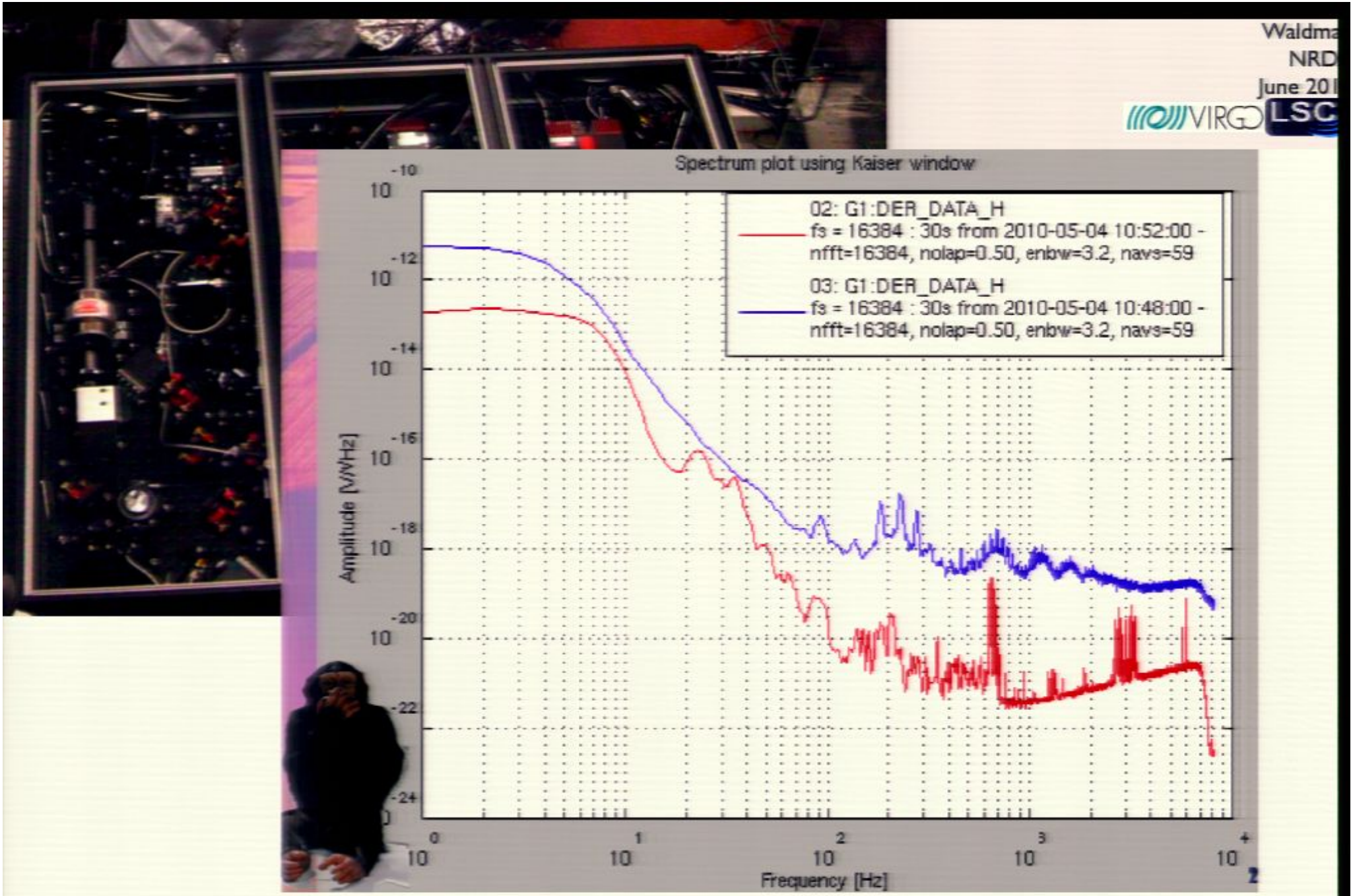
- Increase laser power
- High frequency tuning
- Squeezed light injection

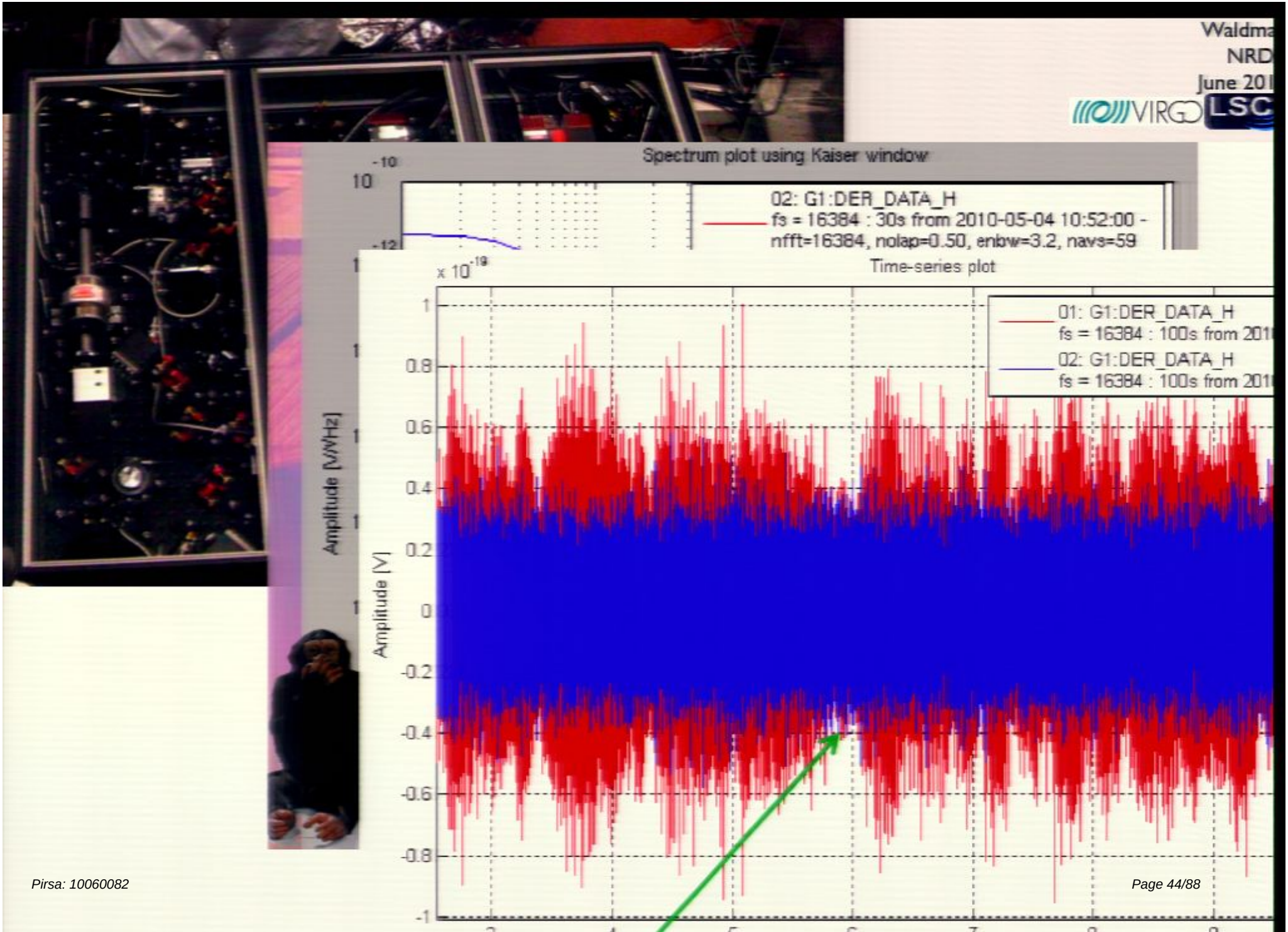
Virgo+

- Increased laser power, higher finesse
- Monolithic suspension

Enhanced LIGO

- In-vacuum, seismically isolated DC readout
- Increased laser power to 35W
- New magnets, EQ stops,
- aLIGO DAQ system, thermal compensation

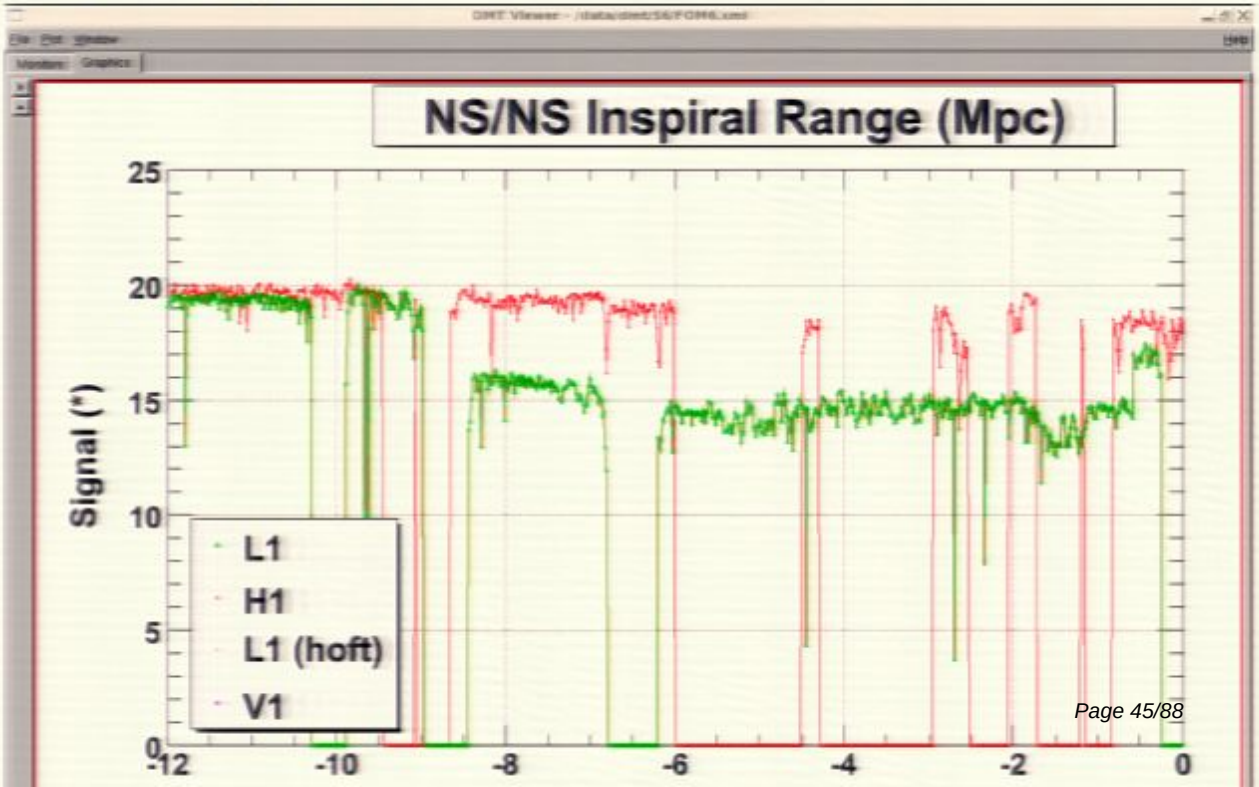

Spectrum plot using Kaiser window
02: G1:DER_DATA_H
fs = 16384 : 30s from 2010-05-04 10:52:00 -
nfft=16384, nolap=0.50, enbw=3.2, navs=59
03: G1:DER_DATA_H
fs = 16384 : 30s from 2010-05-04 10:48:00 -
nfft=16384, nolap=0.50, enbw=3.2, navs=59
Amplitude [V/rHz]
Frequency [Hz]


Waldma
NRD
June 201
VIRGO
LSC
Spectrum plot using Kaiser window
02: G1:DER_DATA_H
fs = 16384 : 30s from 2010-05-04 10:52:00 -
nfft=16384, nolap=0.50, enbw=3.2, navs=59
Amplitude [V/rtHz]
Time-series plot
x 10^-19
01: G1:DER_DATA_H
fs = 16384 : 100s from 201
02: G1:DER_DATA_H
fs = 16384 : 100s from 201
Amplitude [V]
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1

eLIGO and Virgo+

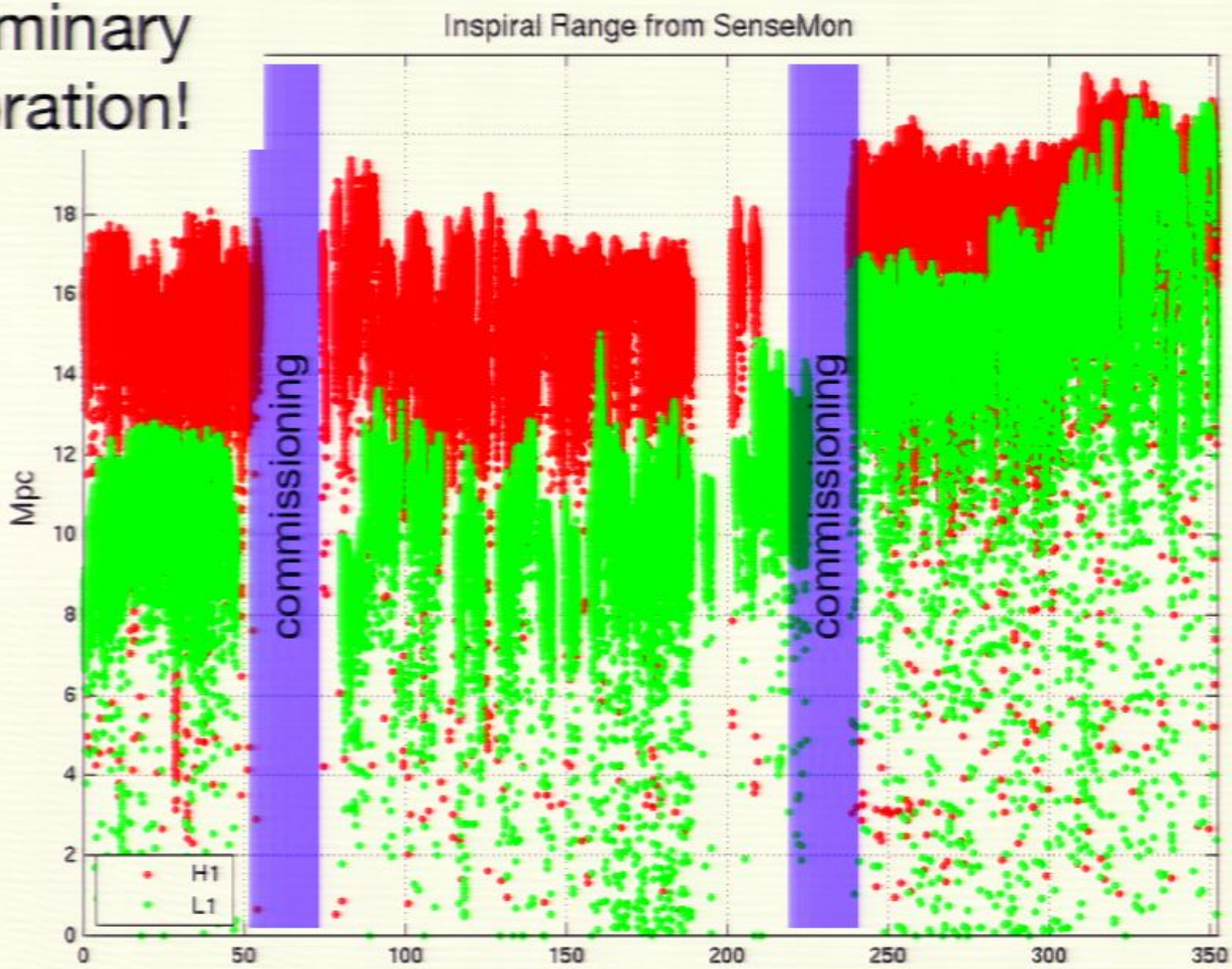
Virgo+ on schedule for mid-July VSR3
- Test masses monolithically suspended
- ITF robustly locked
- Final tuning and noise-hunting remains

eLIGO running in S6 since July 7, 2009
- DC readout
- High power



VIRGO LSC

Preliminary calibration!

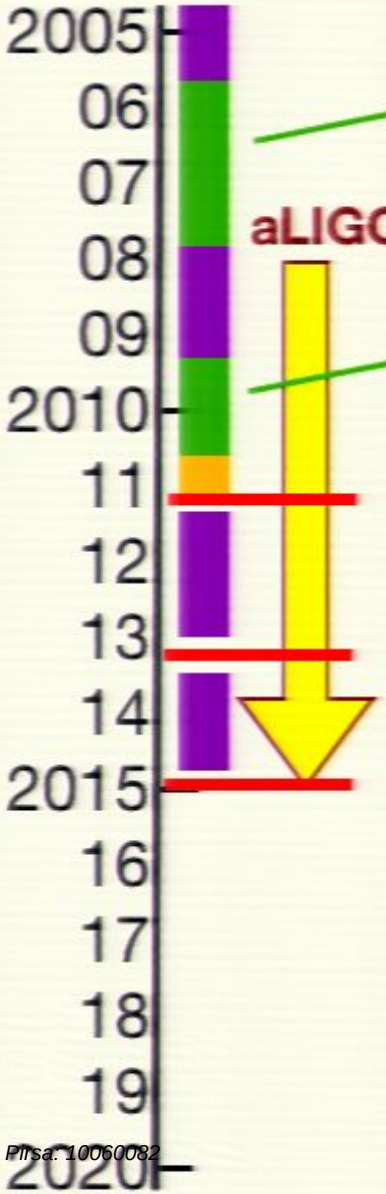


aLIGO commissioning

Have already commissioned:

- DC readout (OMC alignment)
- Thermal Compensation System
- aLIGO DAQ and control
- HAM seismic isolation system
- 35 W of upgraded laser power
- High-power modulator and Faraday
- Feedforward seismic isolation

LIGO/Virgo/GEO



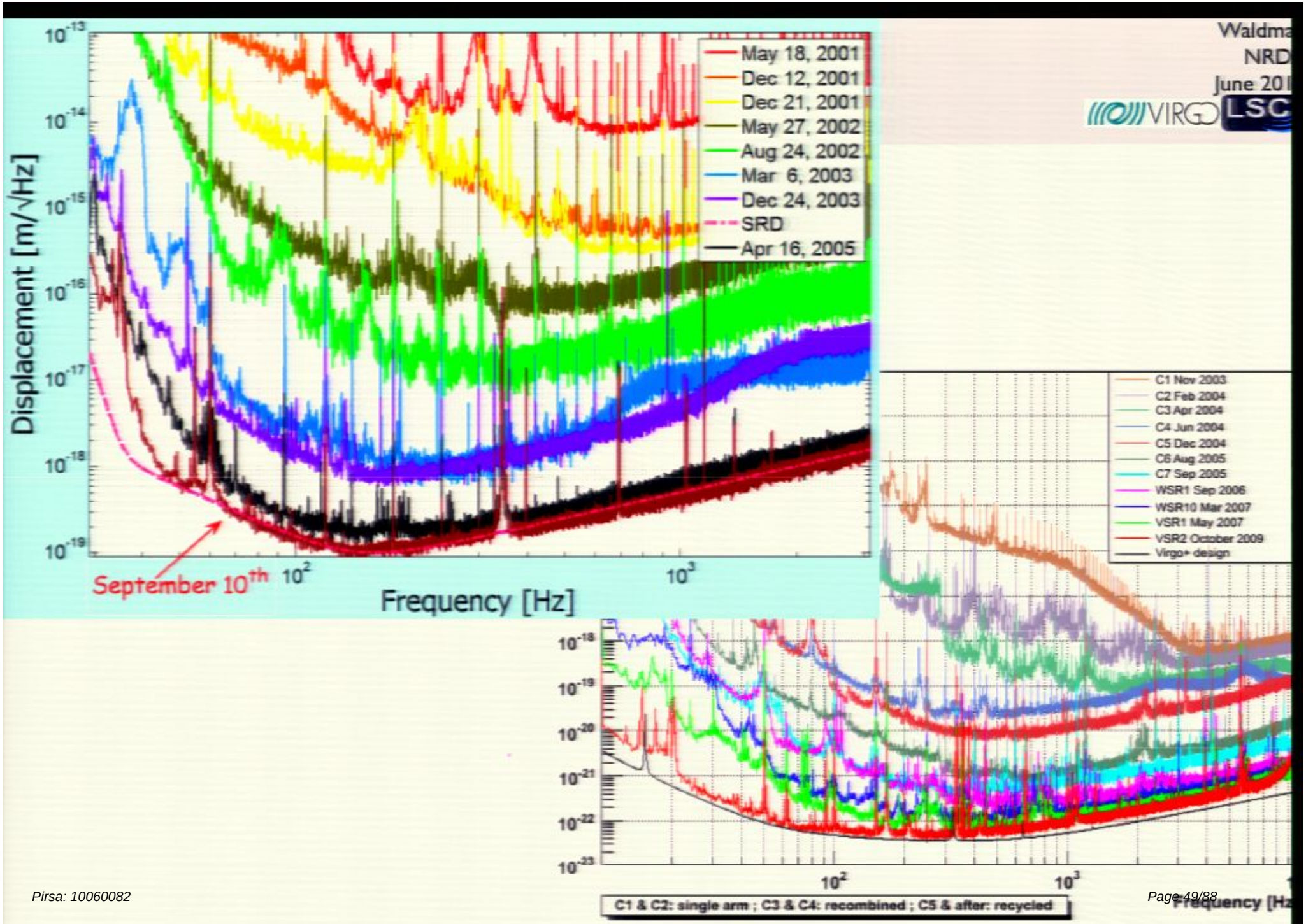
S5/VSR1: *max(R)* = 15 Mpc, 1 yr triple coincidence cooperative run with GEO600 and Virgo

S6/VSR2: max(R) = 20 Mpc, 0.3 yr H1/L1 coincidence
Virgo+ to begin mid July 2010

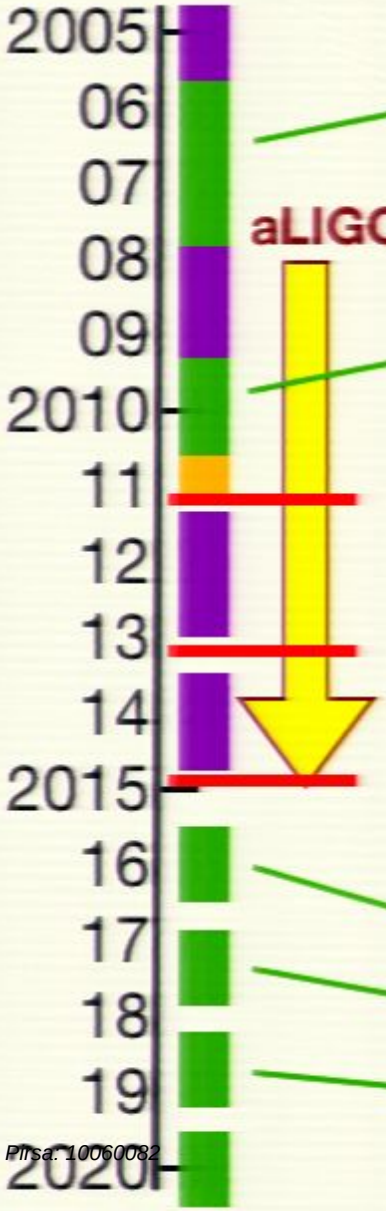
Detector Handoff: October 20, 2010 aLIGO takes over
July 2011, AdV takes over

Installation complete: Project milestone April 2013

Acceptance Review: *Locked in all DOF* Nov. 2014
Similar for AdVirgo


Waldma
NRD
June 201
VIRGO
LSC
Displacement [m/√Hz]
Frequency [Hz]
May 18, 2001
Dec 12, 2001
Dec 21, 2001
May 27, 2002
Aug 24, 2002
Mar 6, 2003
Dec 24, 2003
SRD
Apr 16, 2005
September 10th
C1 Nov 2003
C2 Feb 2004
C3 Apr 2004
C4 Jun 2004
C5 Dec 2004
C6 Aug 2005
C7 Sep 2005
WSR1 Sep 2006
WSR10 Mar 2007
VSR1 May 2007
VSR2 October 2009
Virgo+ design
C1 & C2: single arm ; C3 & C4: recombined ; C5 & after: recycled
Frequency [Hz]

LIGO/Virgo/GEO



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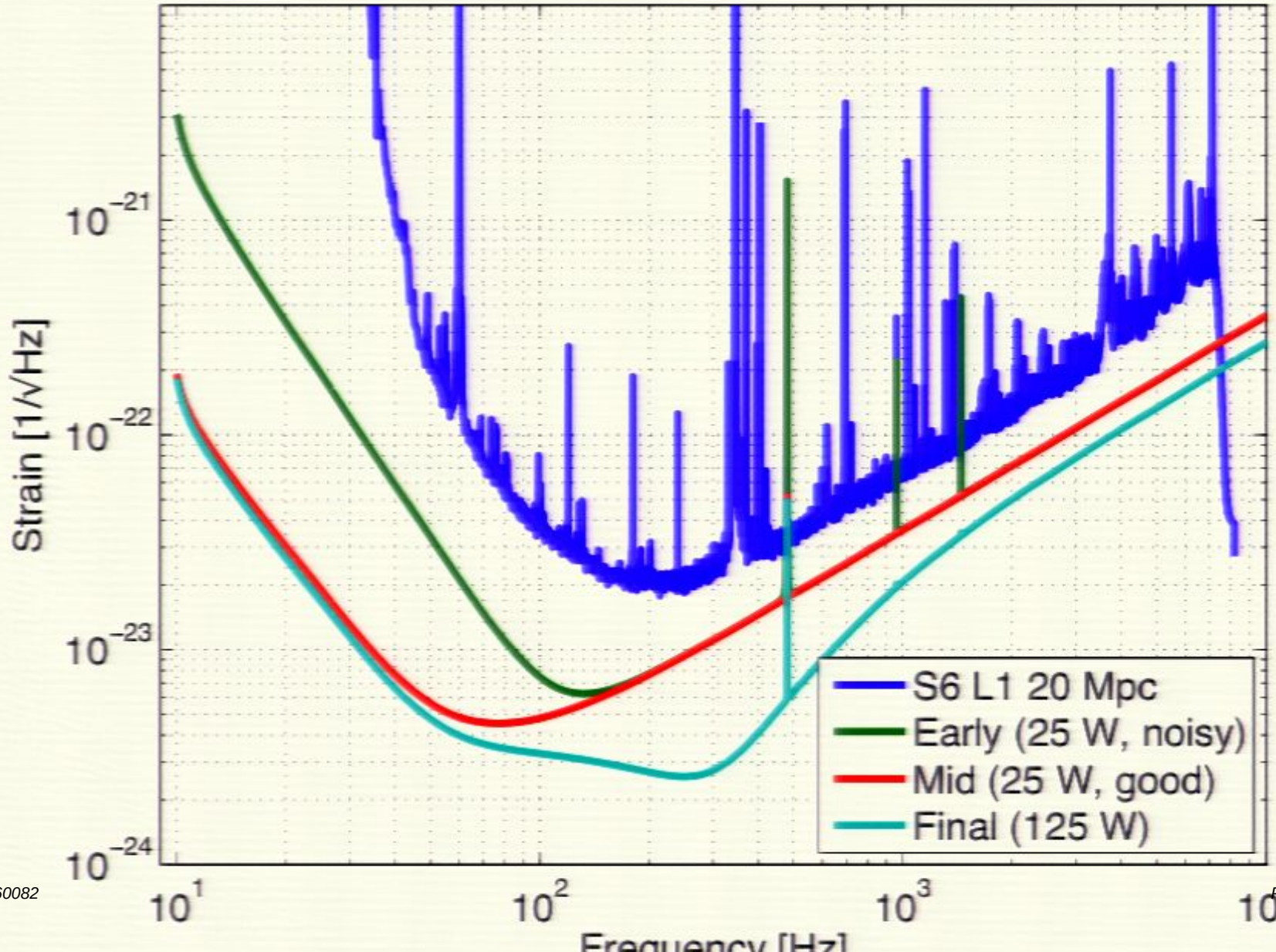
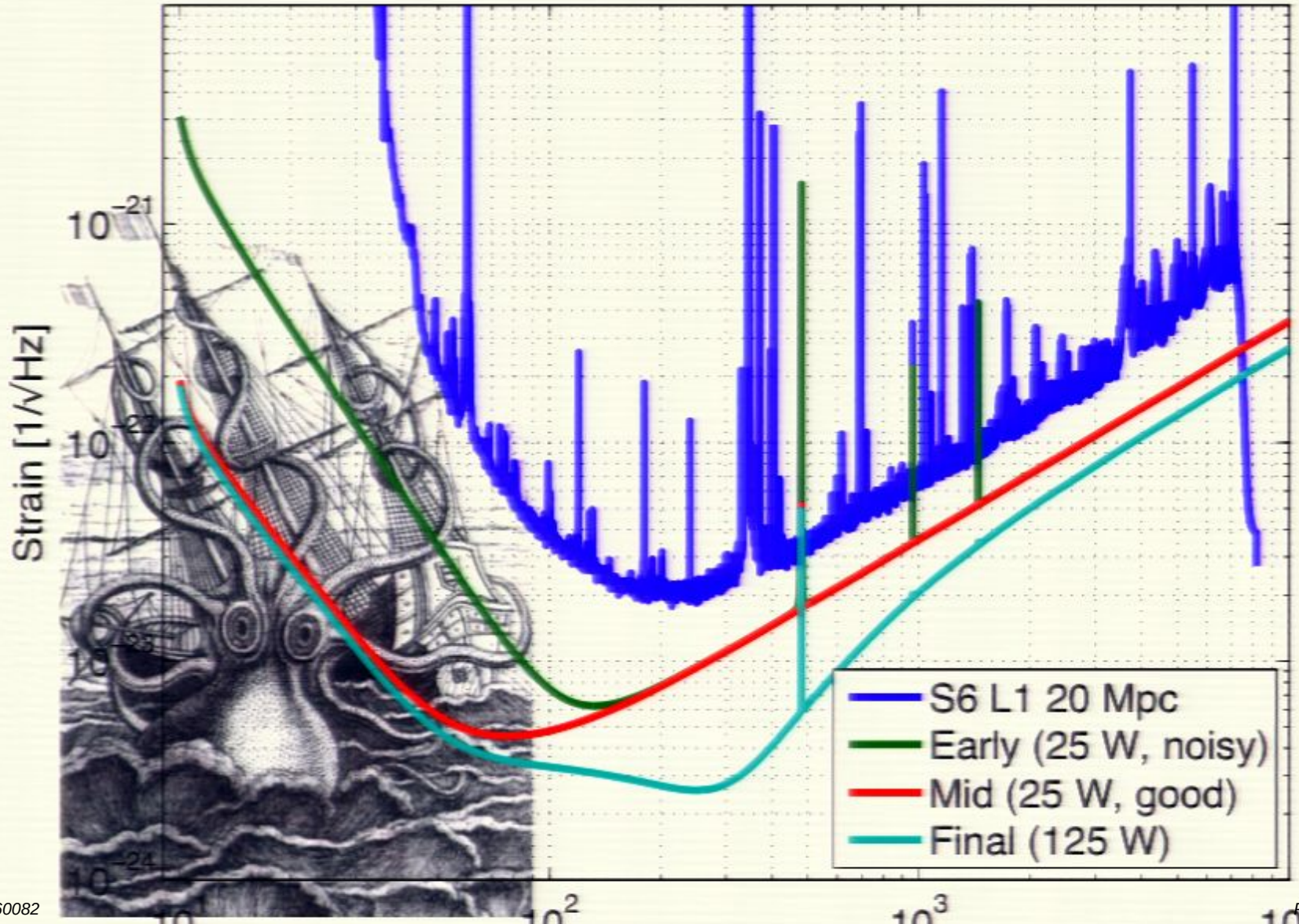
Installation complete: Project milestone April 2013

Acceptance Review: *Locked in all DOF* Nov. 2014
Similar for AdVirgo

S7/VSR3: max(R) = 60 Mpc??
S8/VSR4: max(R) = 140 Mpc??
S9/VSR5: max(R) = 200 Mpc??
S10.....

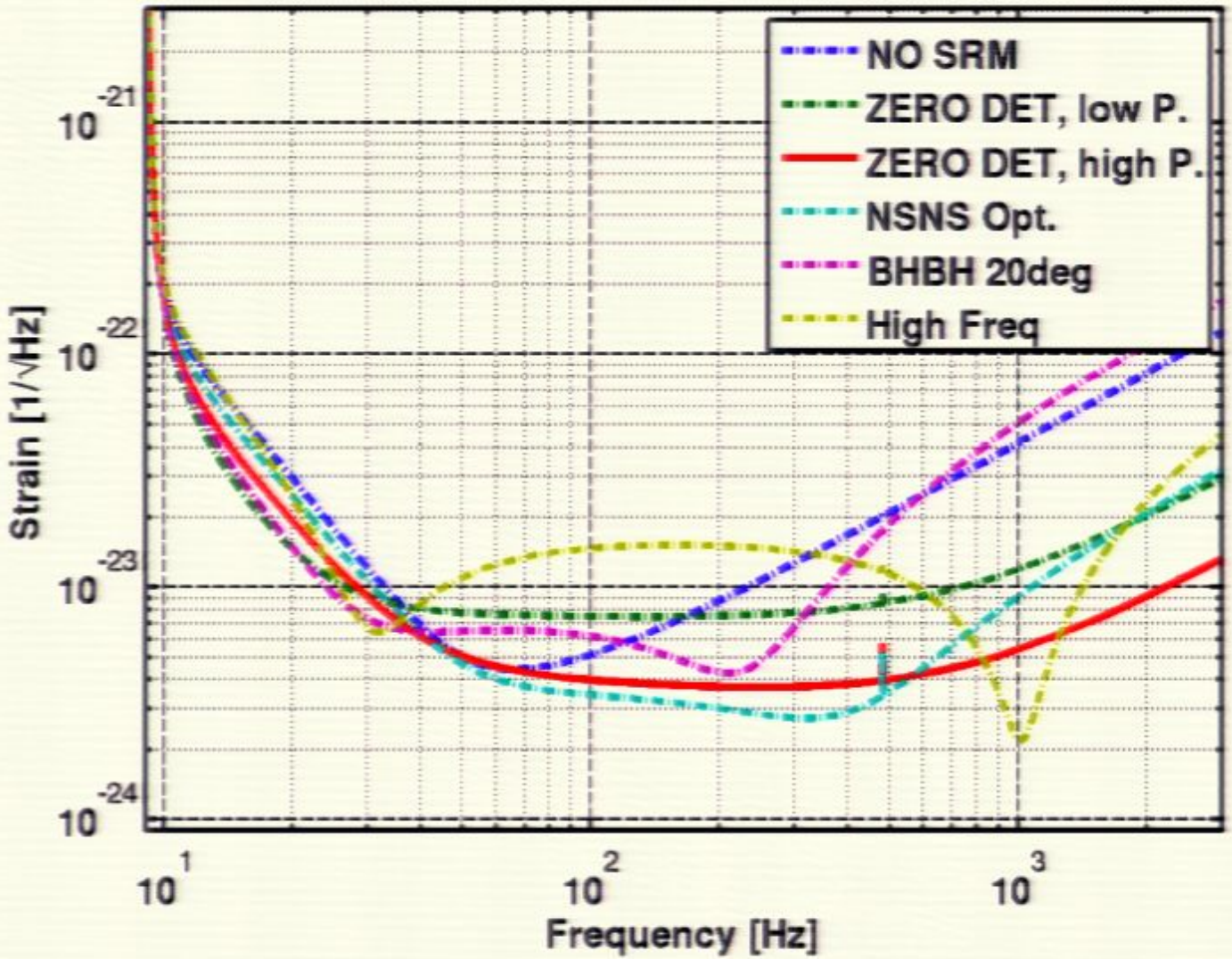
SPECULATIVE!


Strain [1/√Hz]
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency [Hz]
S6 L1 20 Mpc
Early (25 W, noisy)
Mid (25 W, good)
Final (125 W)

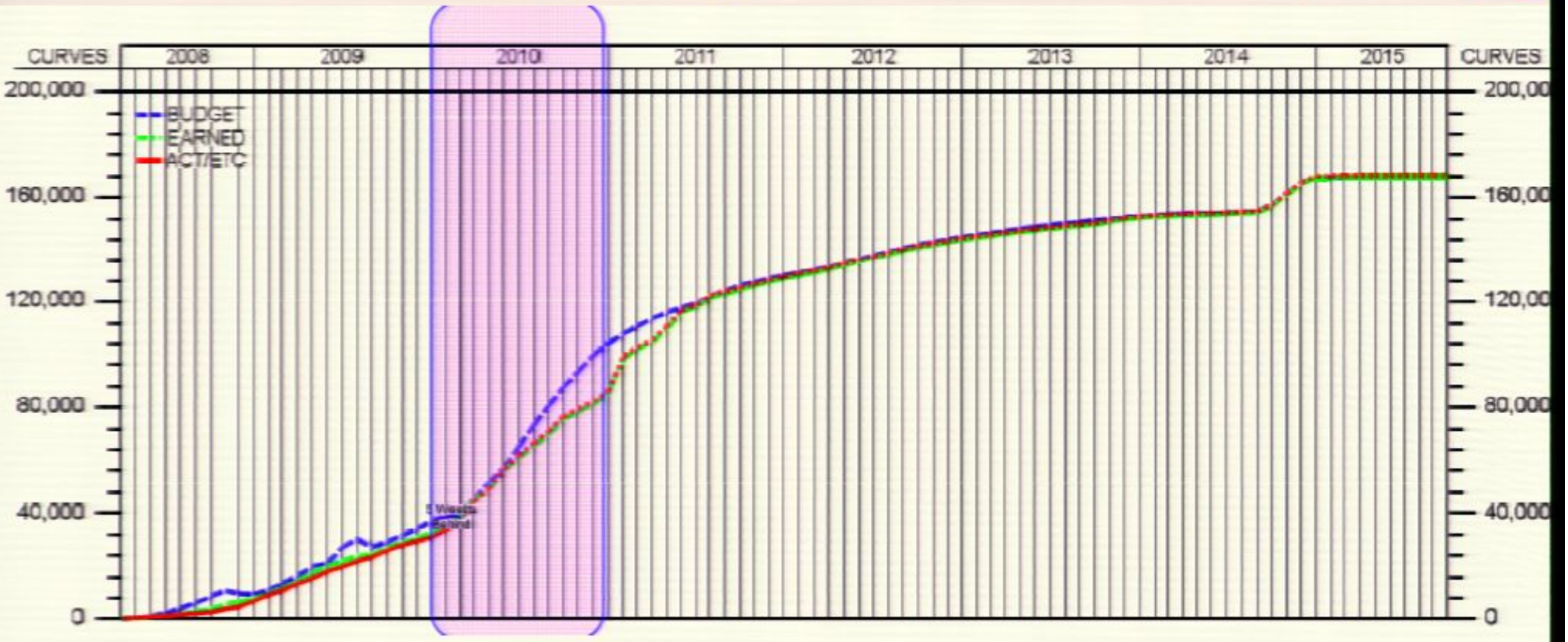

Strain [1/√Hz]
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{2}
10^{3}
10^{4}
Frequency [Hz]
S6 L1 20 Mpc
Early (25 W, noisy)
Mid (25 W, good)
Final (125 W)

LIGO-T0900288-v3

https://dcc.ligo.org/cgi-bin/DocDB/ShowDocument?docid=2974



aLIGO progress



On target to meet all NSF milestones

2 years in, we're 26% complete, 6% *under* budget

Most subsystems in fabrication or EDR

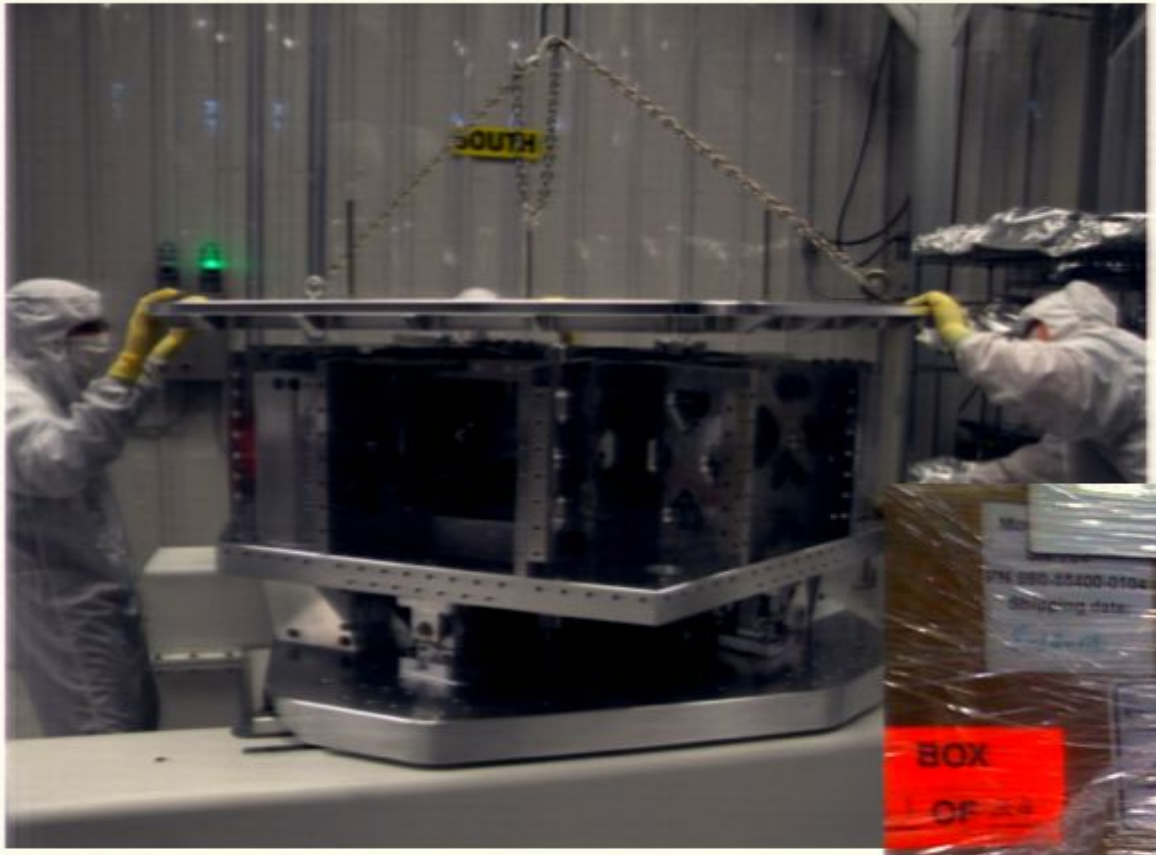
Standing army

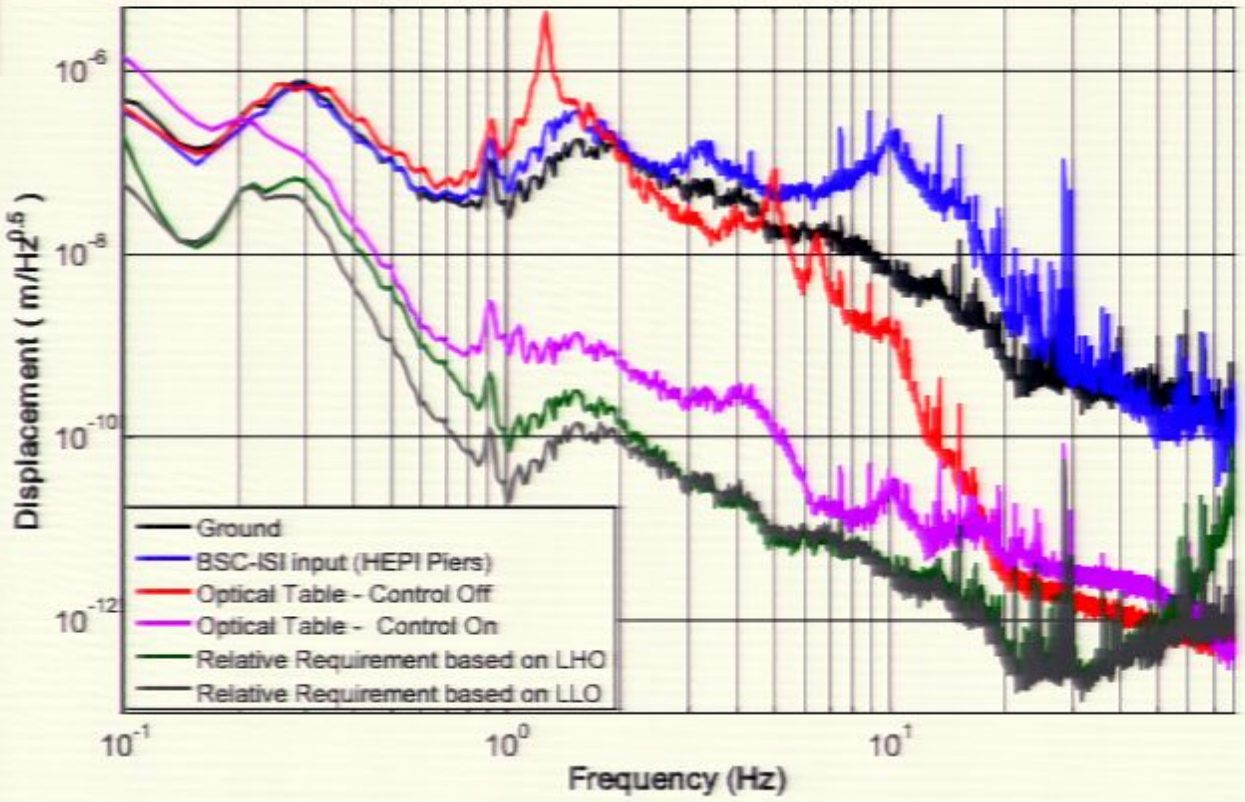
Waldma
NRD
June 201

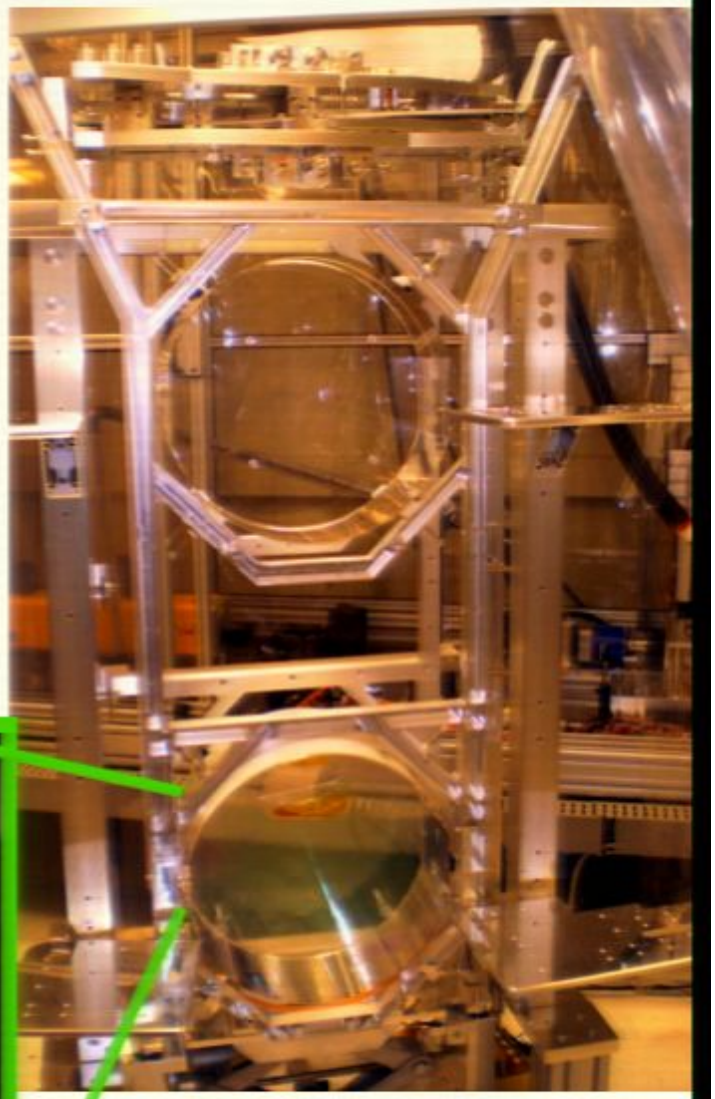
VIRGO LSC

Procurement pains

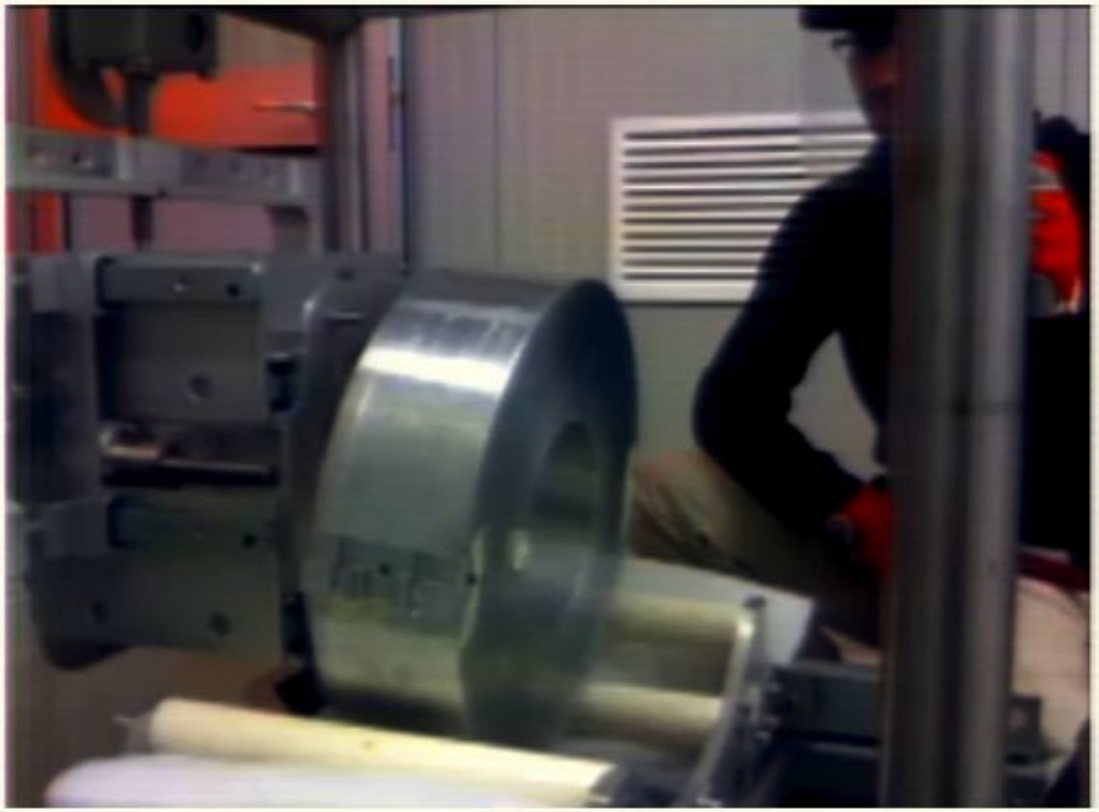
VIRGO LSC




Displacement (m/Hz^0.5)
10^-6
10^-8
10^-10
10^-12
10^-1
10^0
10^1
Frequency (Hz)
Ground
BSC-ISI input (HEPI Piers)
Optical Table - Control Off
Optical Table - Control On
Relative Requirement based on LHO
Relative Requirement based on LLO



Non-destructive testing



Test of Virgo monolithic suspension

Non-destructive testing

Test of Virgo monolithic suspension

Non-destructive testing

Test of Virgo monolithic suspension

Non-destructive testing

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Non-destructive testing

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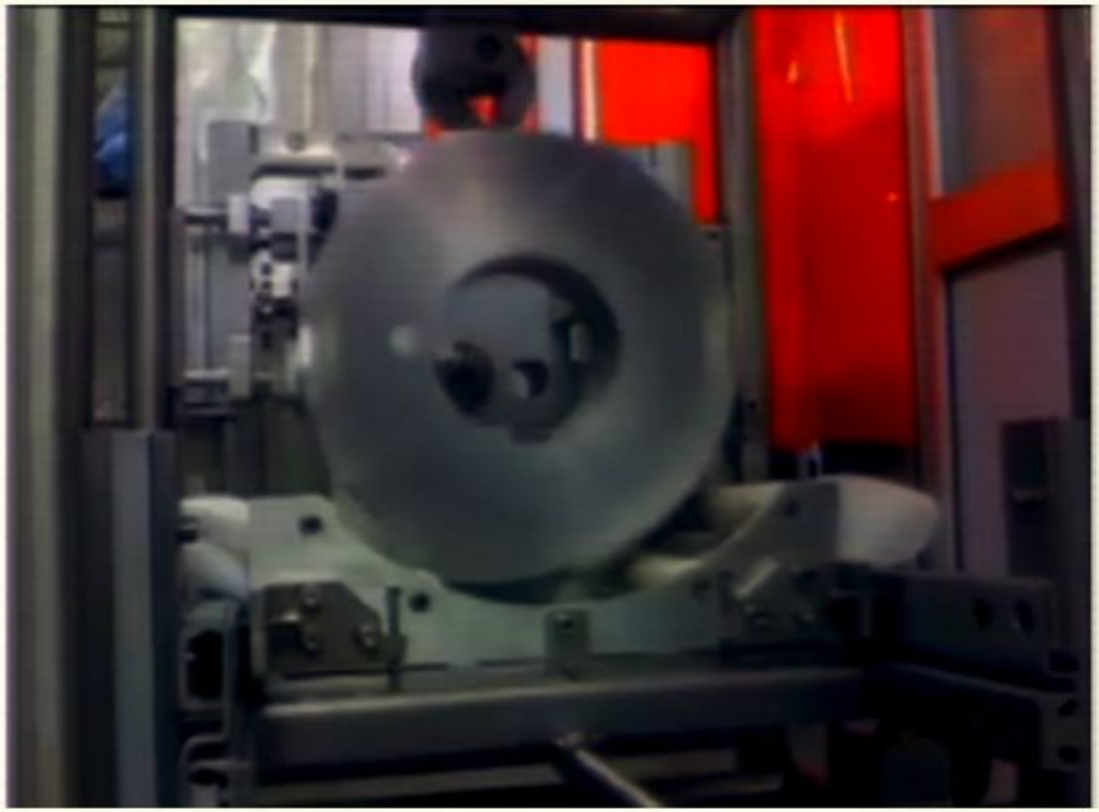
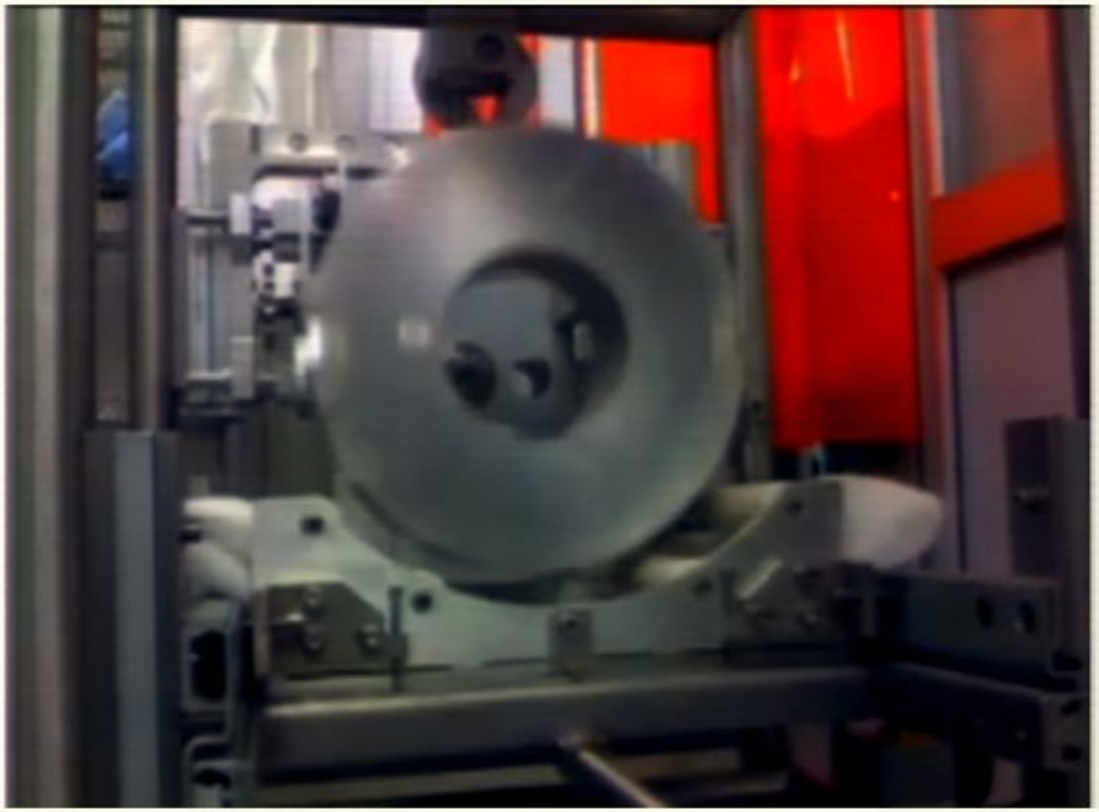


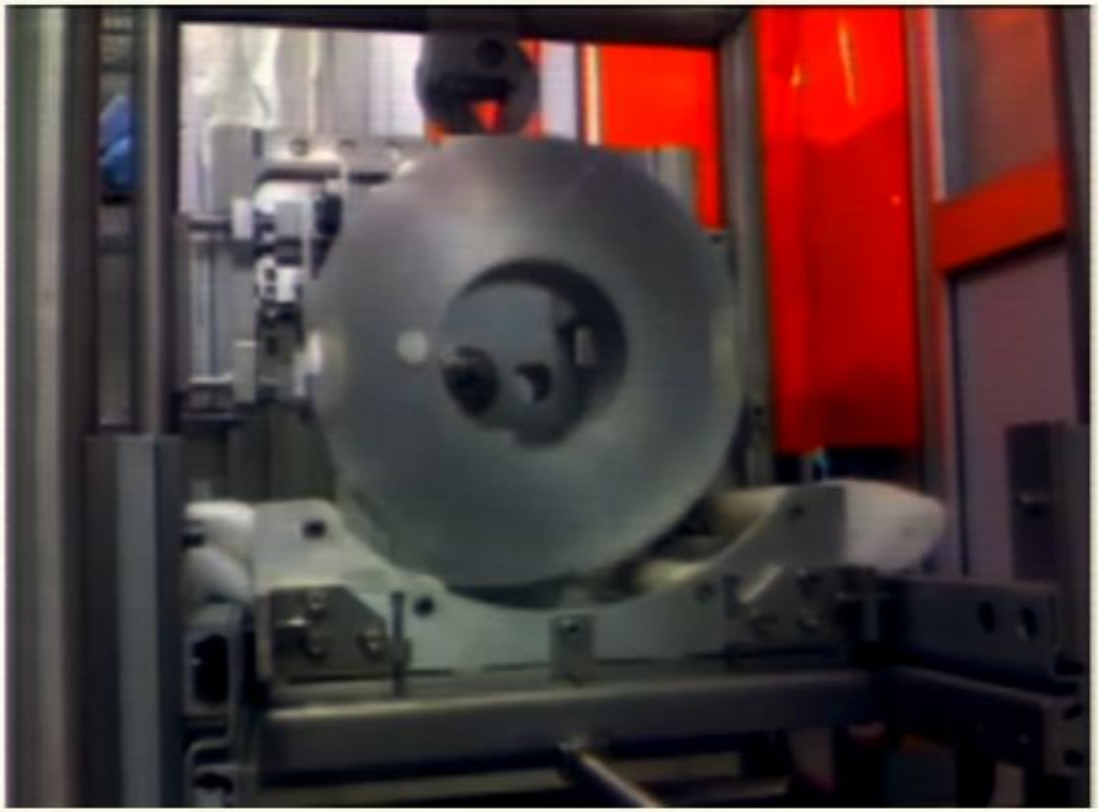
Test of Virgo monolithic suspension

Non-destructive testing



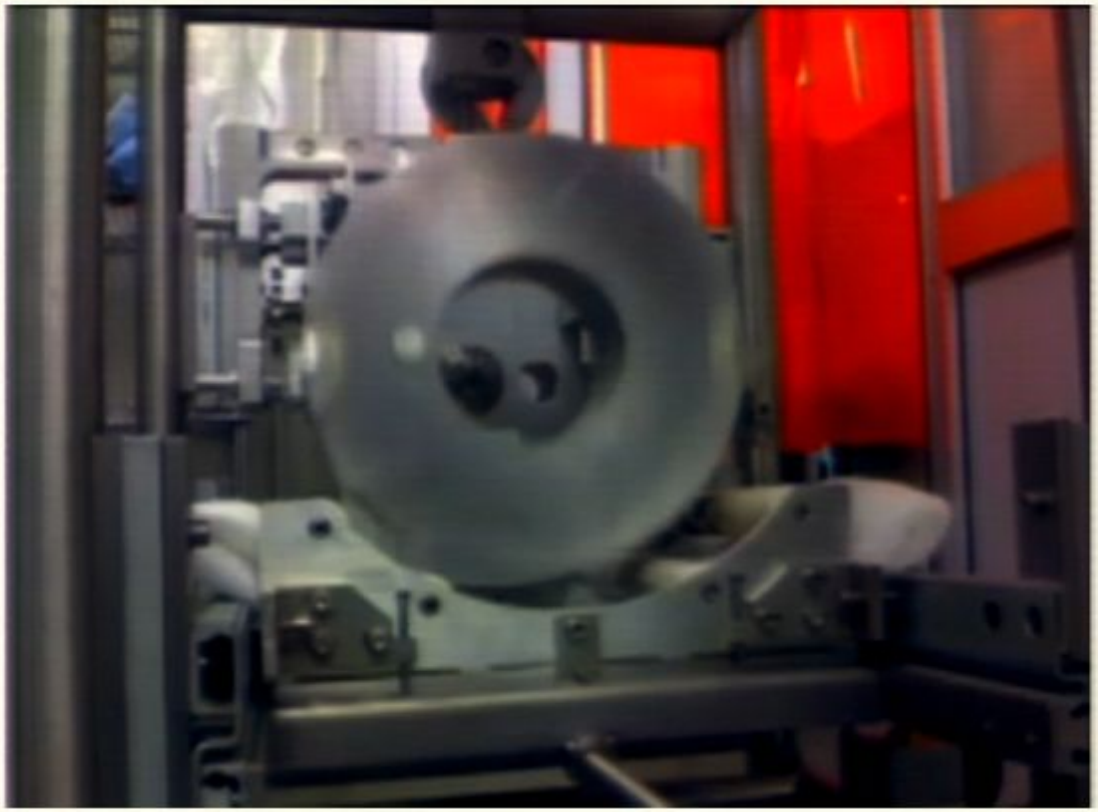
Test of Virgo monolithic suspension

Non-destructive testing



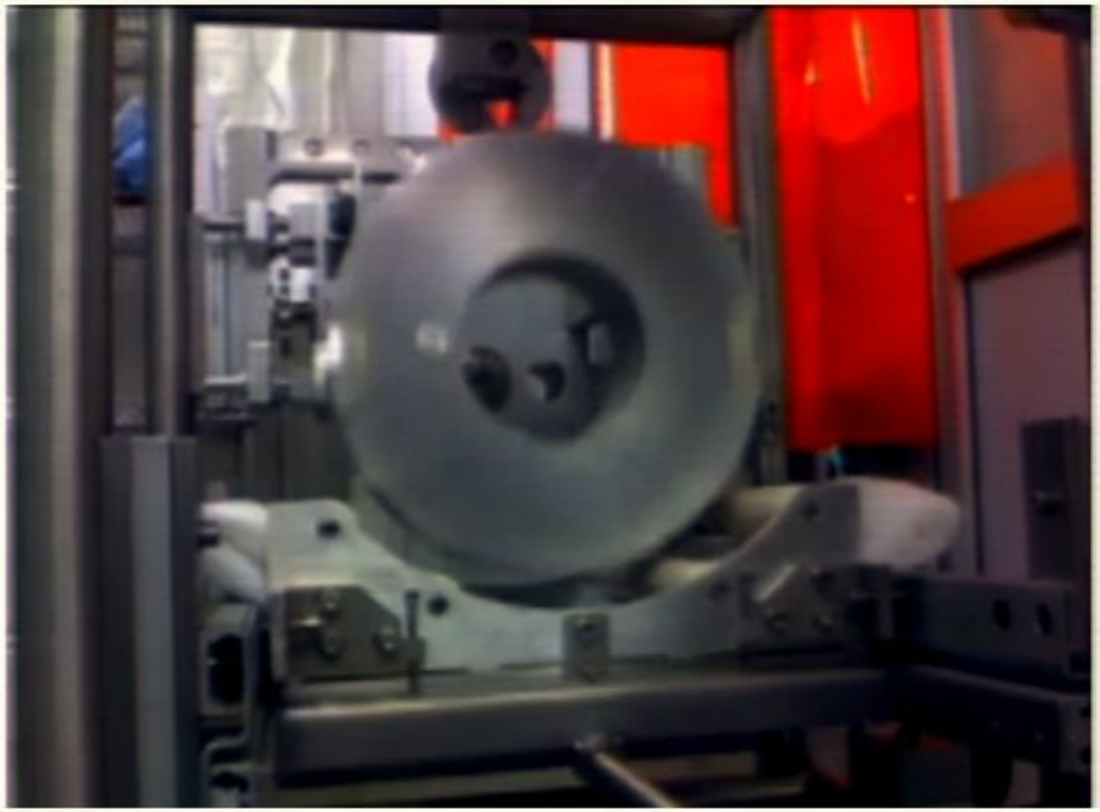
Test of Virgo monolithic suspension

Non-destructive testing



Test of Virgo monolithic suspension

Non-destructive testing



Test of Virgo monolithic suspension

Non-destructive testing

Test of Virgo monolithic suspension

Worldwide network

Waldma
NRD
June 201

VIRGO LSC

LHO

GEO

LCGT

LLO

Virgo

AIGO

Earth at Night
More information available at:
http://antwrp.gsfc.nasa.gov/apod/ap020811.html

Astronomy Picture of the Day
2002 August 11
http://antwrp.gsfc.nasa.gov/apod/astropix.html

Australian Advanced LIGO

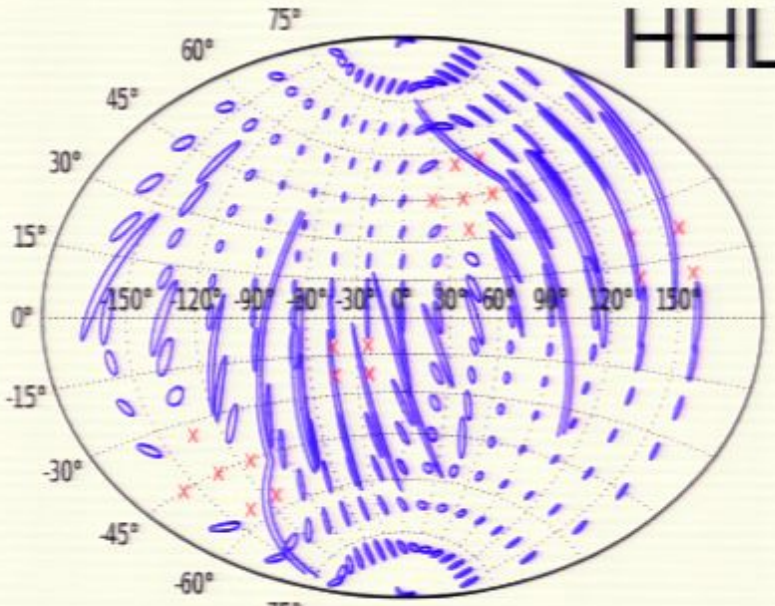
VIRGO LSC

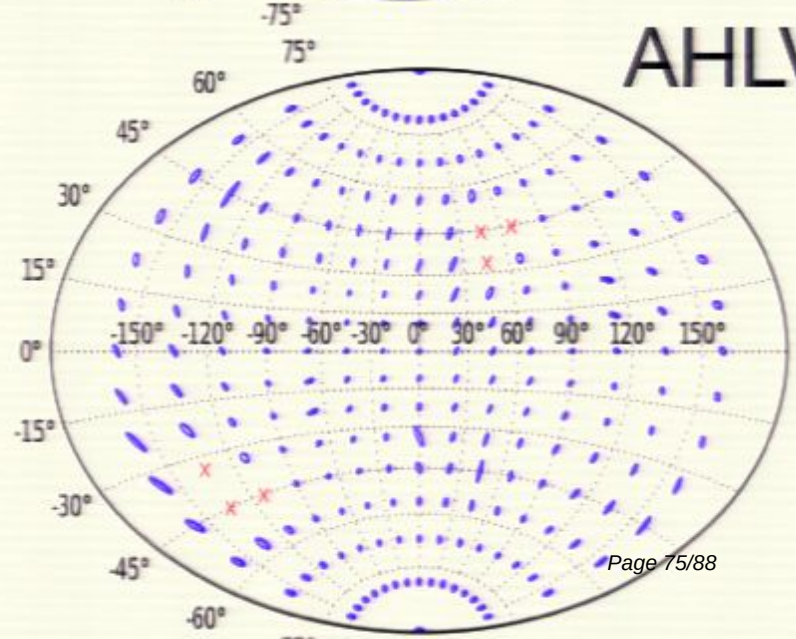
Locate 3rd aLIGO detector in Western Australia

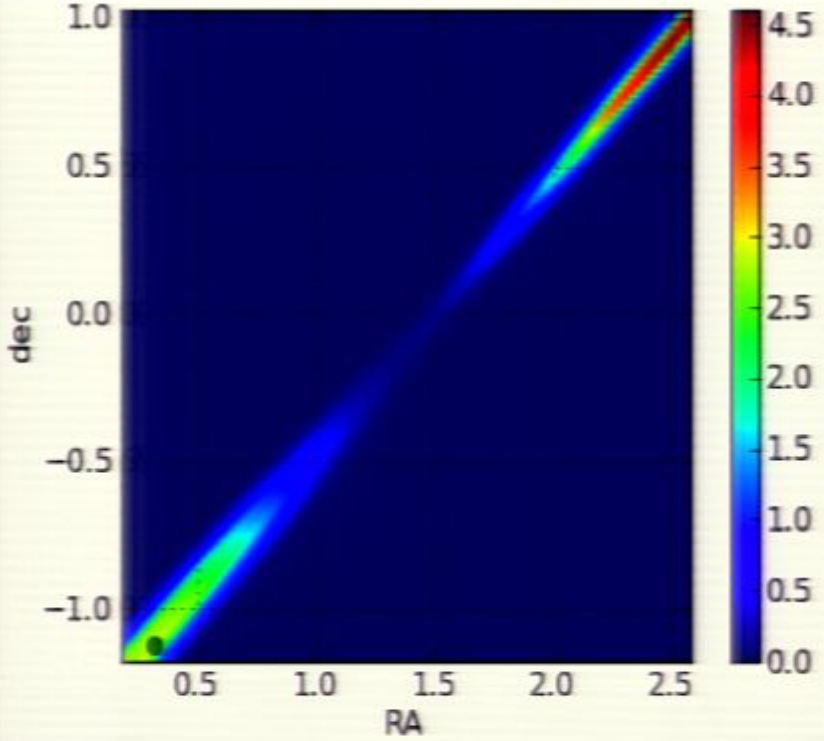
Australia (ACIGA) provides all the infrastructure - buildings, vacuum, clean rooms and staff

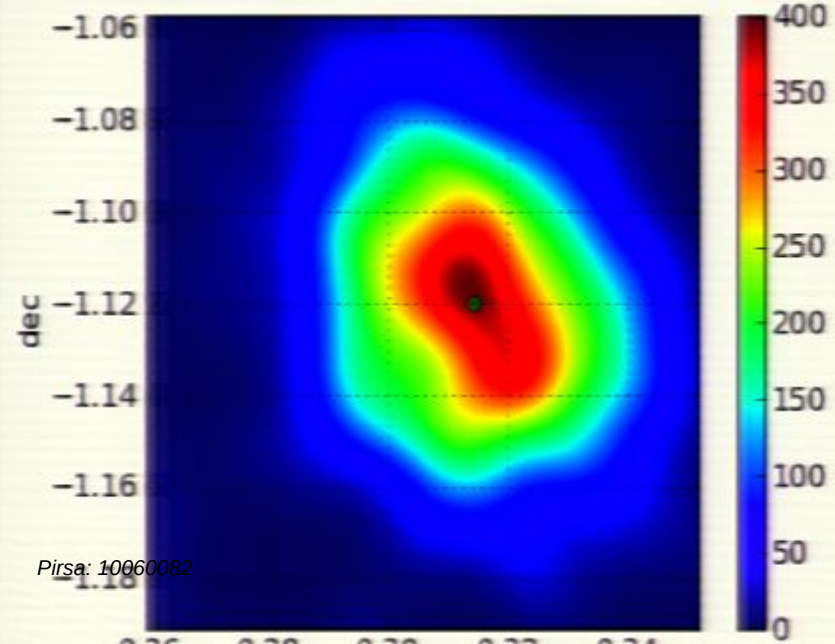
No new cost or delay to NSF/LIGO project

LIGO South online 2017









Waldma
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June 201

VIRGO LSC

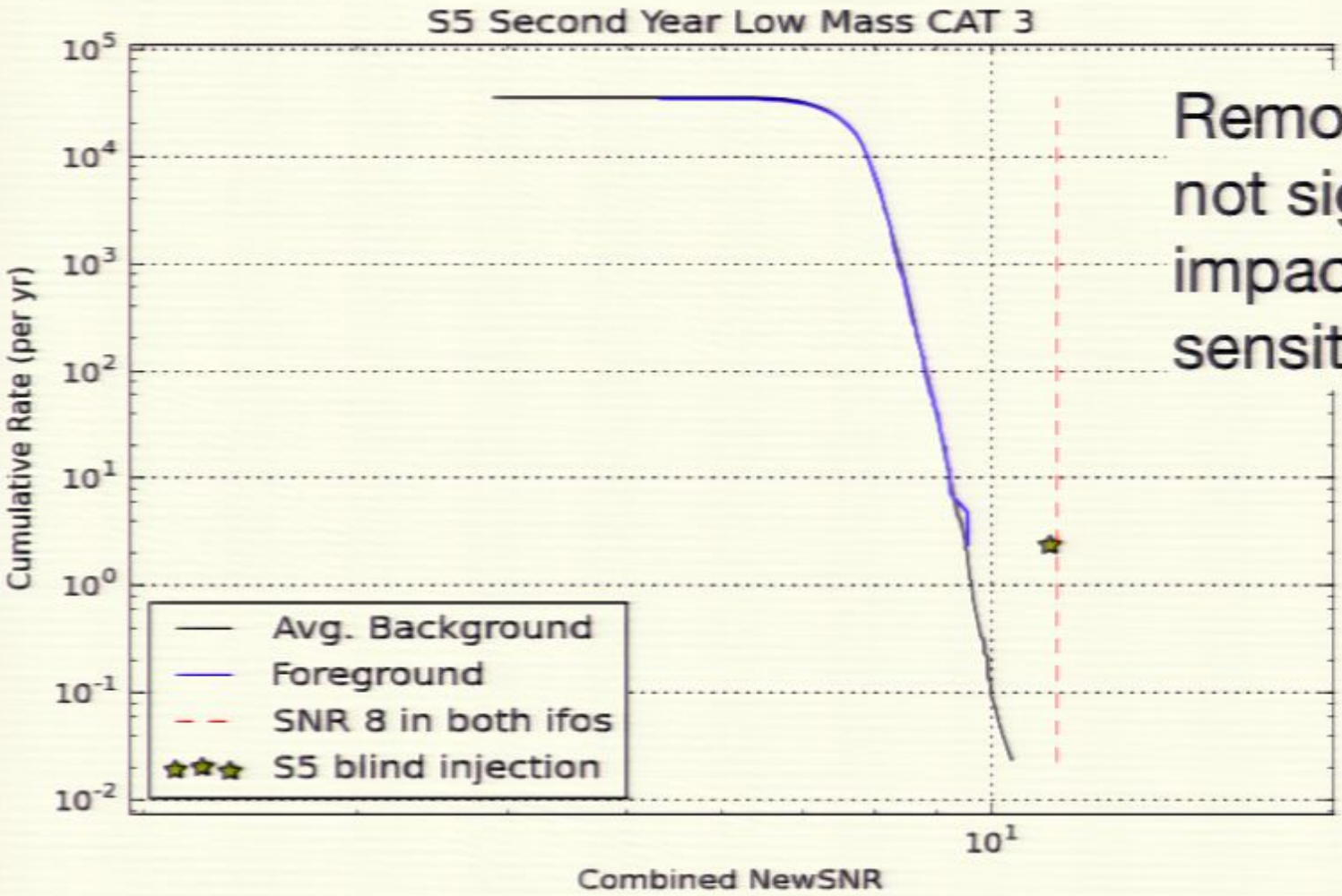
Ad Hoc LSC review Committee

Sam Finn	Pennsylvania State
Peter Fritschel	LIGO-MIT
Sergey Klimenko	University of Florida
Fred Raab	LIGO-Hanford
B. Sathyaprakash	Cardiff University
Peter Saulson	Syracuse University
Rainer Weiss	LIGO-MIT (chair)

Charge:

Compare AHLV (2017) to HHLV (2015) assuming H,L, & V at similar performance in 2015

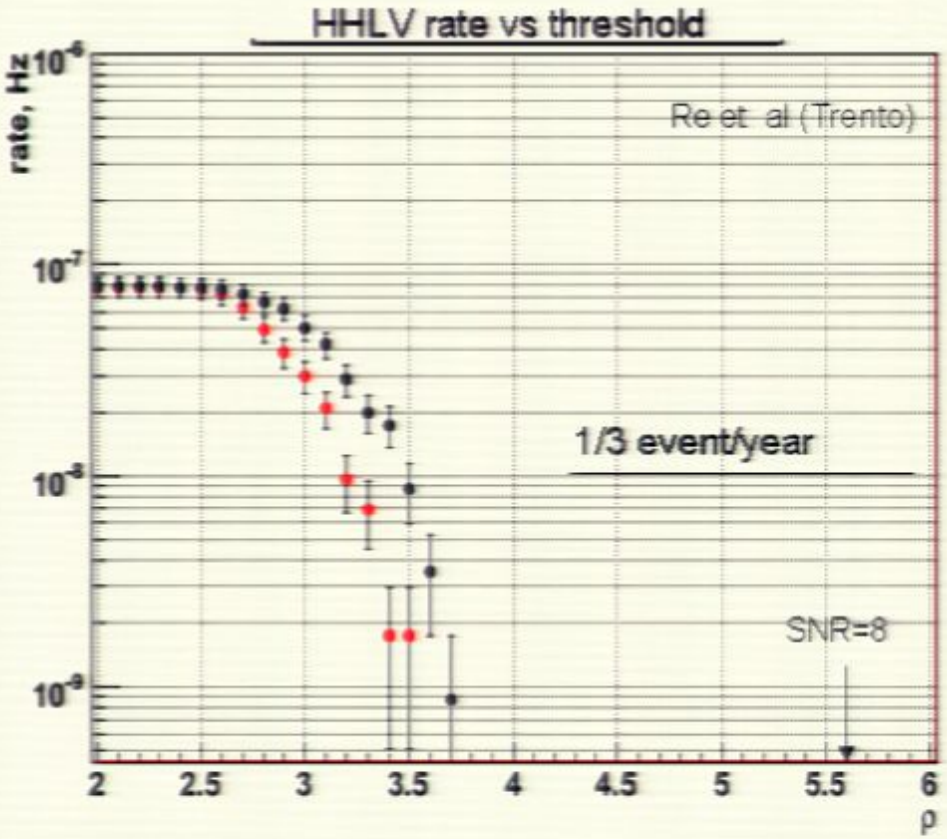
Enabled by improved analysis

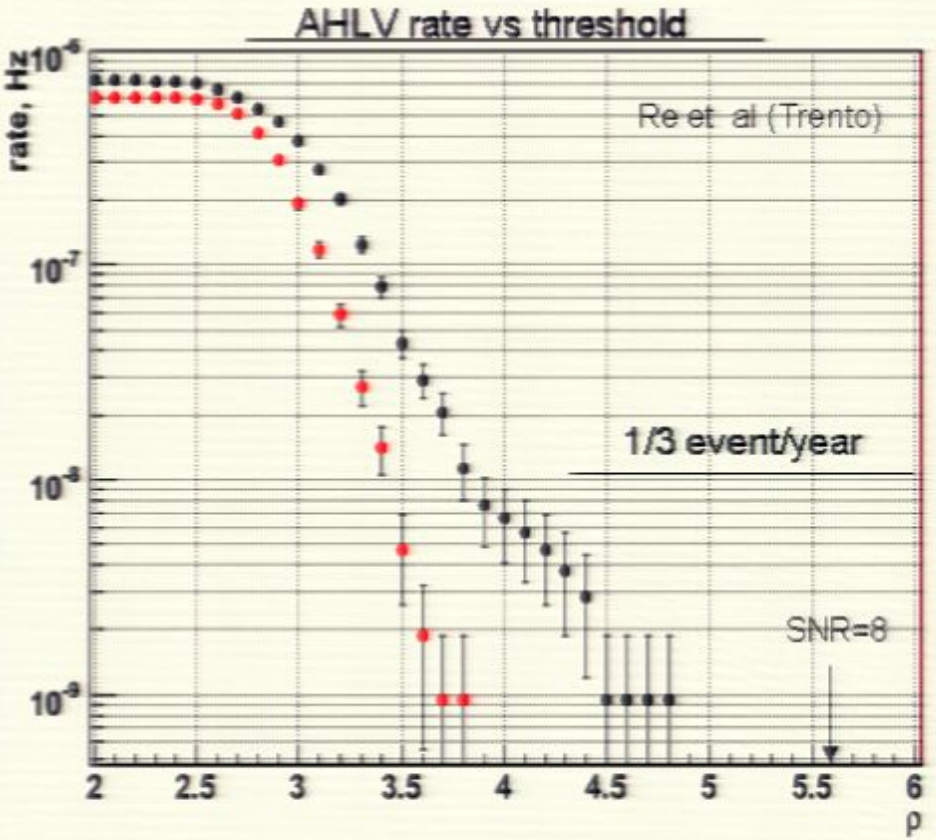


Removal of H2 does not significantly impact network sensitivity

C. Capano *et al.* Syracuse

The penalty


HHLV rate vs threshold
rate, Hz
Re et al (Trento)
1/3 event/year
SNR=8
ρ


AHLV rate vs threshold
rate, Hz
Re et al (Trento)
1/3 event/year
SNR=8
ρ

to NSF & ACIGA

NSF review committee met June 16-17

Iff they return a positive report, proposal goes to the NSB

Simultaneous effort in Australia by ACIGA

AU$85 million, funded in part by *Education Investment Fund*

To avoid impacting aLIGO, agreement deadline by Sept. 30 2011

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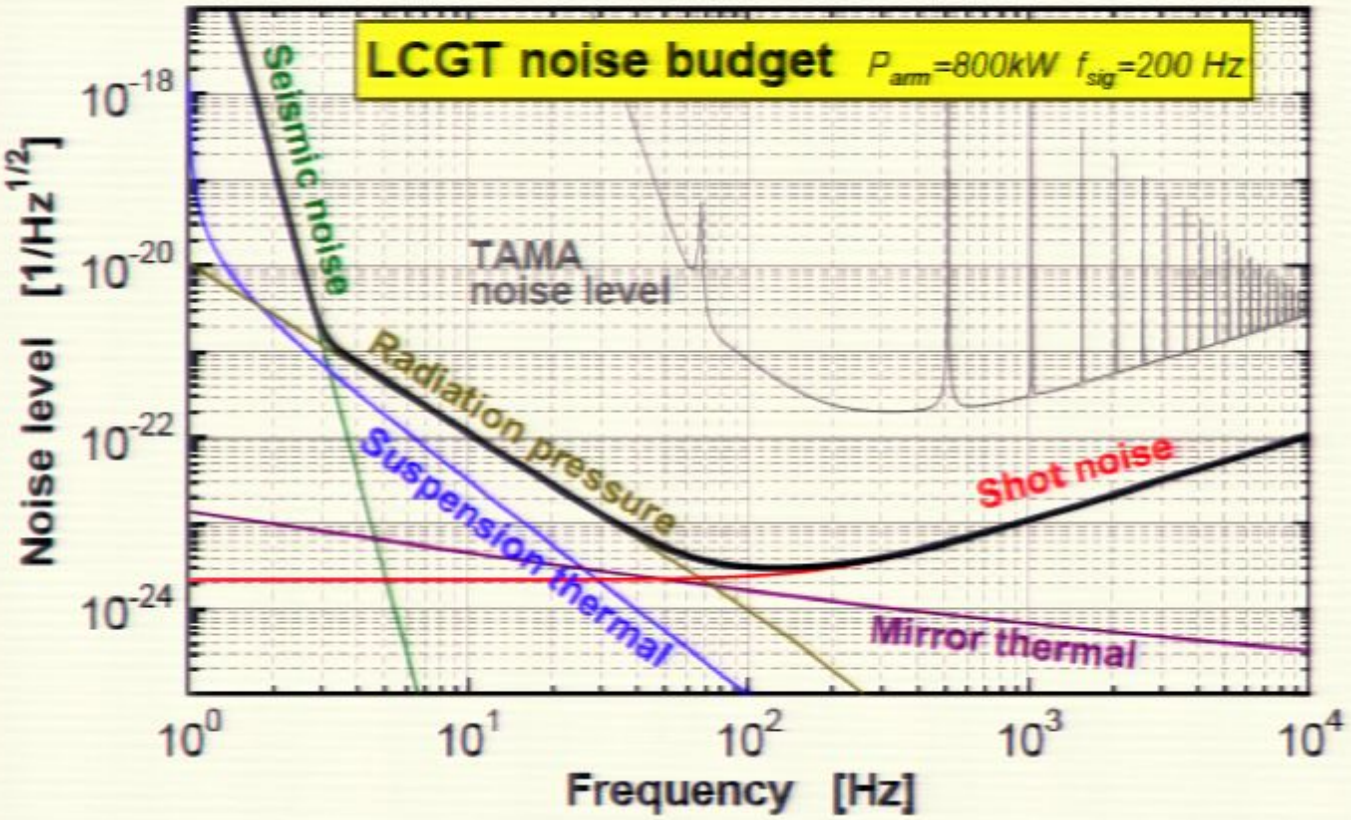
VIRGO LSC

LCGT Funded!

Project led by ICRR @ U Tokyo

3 km, cryogenic, underground detector

Proposal based on experience with L=100m, T=20K CLIO prototype



Funded $109M,
3 years

http://gw.icrr.u-tokyo.ac.jp/lcgt/

Future is bright

Chance for 6 (!!) advanced interferometric detectors online by -- *say* -- 2018 with 100+ Mpc NS/NS range

LISA technology on orbit in 2012, space interferometry in 2015

With 20 pulsars and 50 ns timing, MBH/MBH GW's could be detected by Int'l Pulsar Timing Array within 5 years

If nature is kind, could see B-mode polarization from GW's

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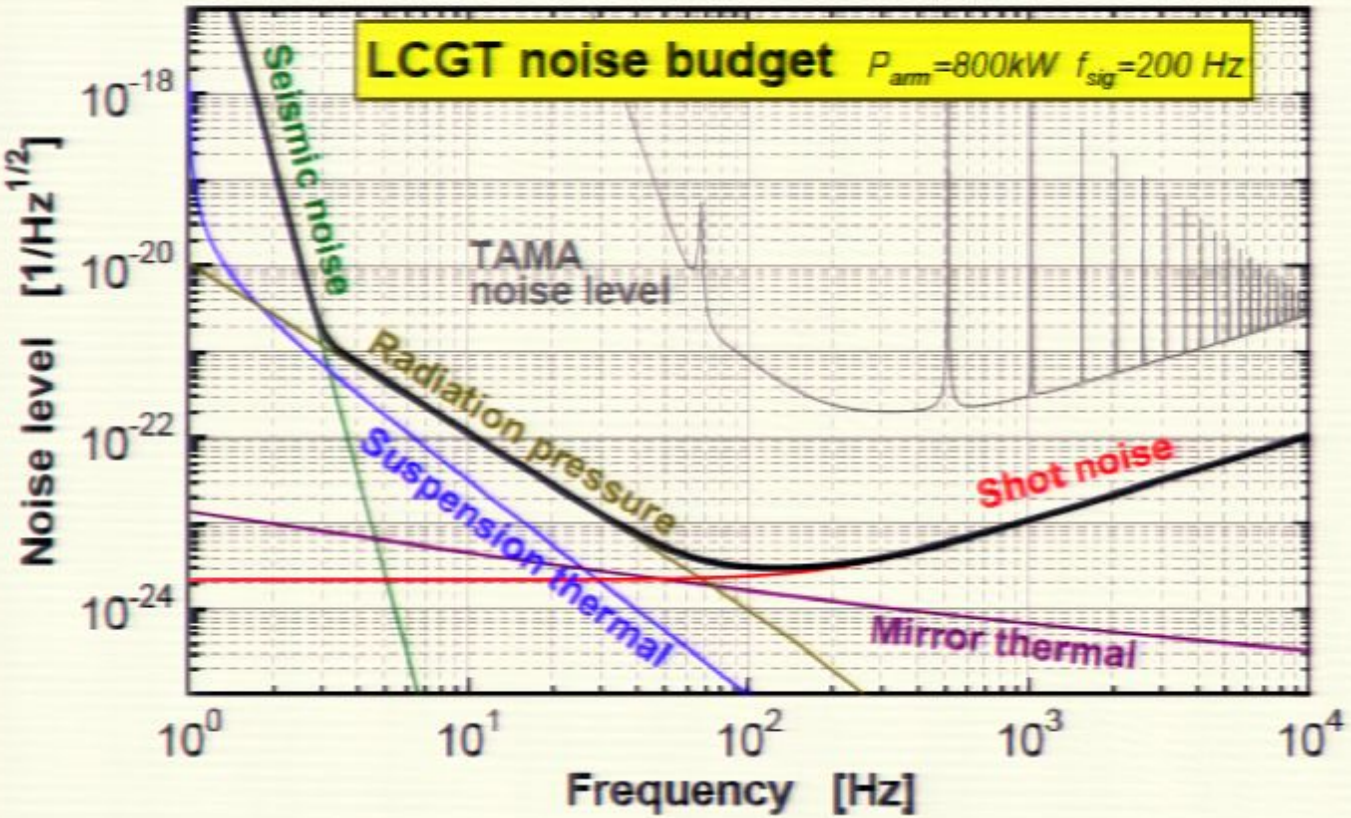

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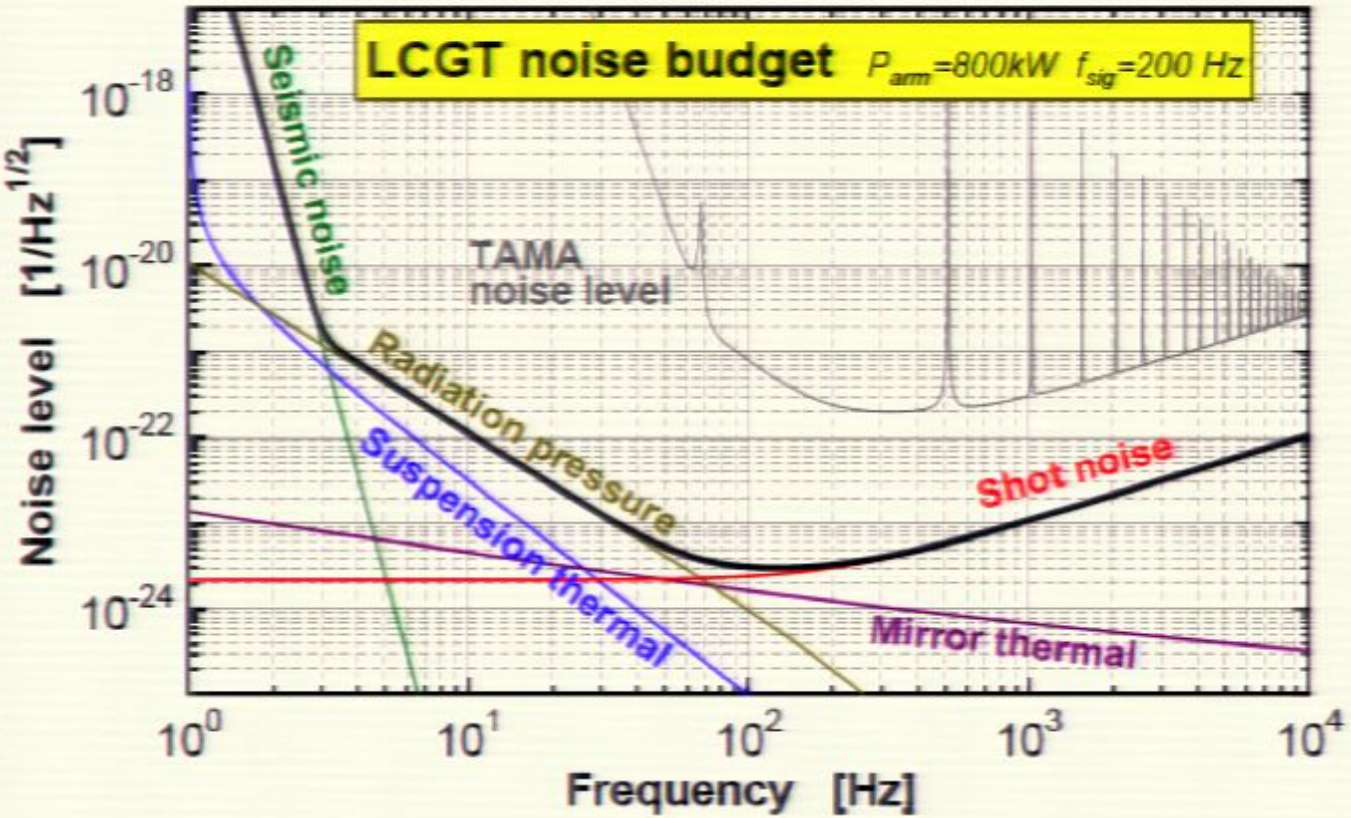

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