Gravitational-wave physics and astronomy: the next ten years

Stan Whitcomb

GWPAW

26 January 2011

LIGO-G1100073-v1

The Next Ten Years?

Research with gravitational waves will be instrument-driven for the next decade

- What makes gravitational waves *as a field* different?
- Prospects for the next “ten” years
  - (›› Cosmic microwave background)
  - » Pulsar timing for nanoHz waves
  - » LISA!
  - » Ground-based interferometers—news and possibilities
- Concluding remarks

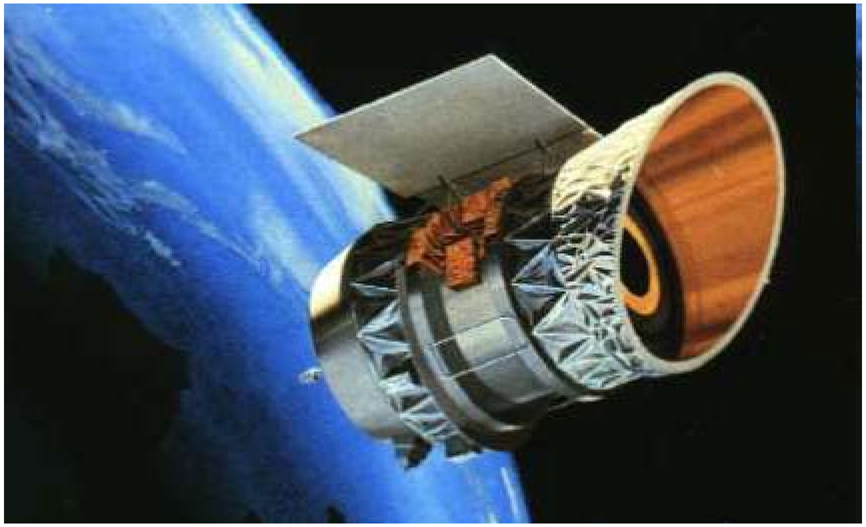
A Very Short (and Over-simplified) History of Far-Infrared Astronomy

- Fundamental problem for Far-Infrared Astronomy:
  Atmosphere is both opaque and hotter than the sources one wants to observe
- NASA-operated Learjet used with 30 cm telescope1969

Balloons and Sounding Rockets in the 1970’s

A Very Short (and Over-simplified) History of Far-Infrared Astronomy

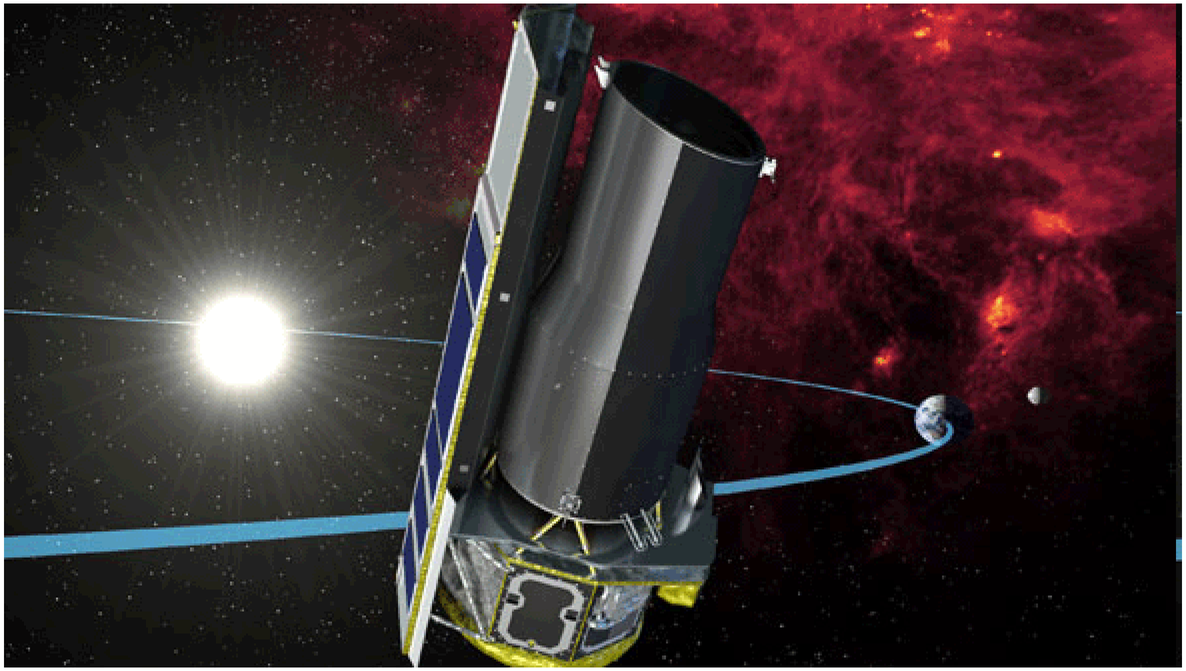
- Kuiper Airborne Observatory
- C141 Transport with 91 cm telescope
- Operated 1975-1995



- IRAS
- Netherlands, US, UK
- Launched 1983
- 11 month lifetime

A Very Short (and Over-simplified) History of Far-Infrared Astronomy

- Spitzer Infrared Telescope Facility (SIRTF)
- Launched 2003
- Last of NASA's "Great Observatories" series of telescopes



A Very Short (and Over-simplified) History of Far-Infrared Astronomy

- Herschel Space Observatory
- ESA, launched 2009
- 3.5 m telescope

- SOFIA, 2010
- 747 with 2.7 m telescope
- DLR and NASA

A Very Short (and Over-simplified) History of Far-Infrared Astronomy

History

- Decades of development
- Very productive and less productive paths pursued

Current state:

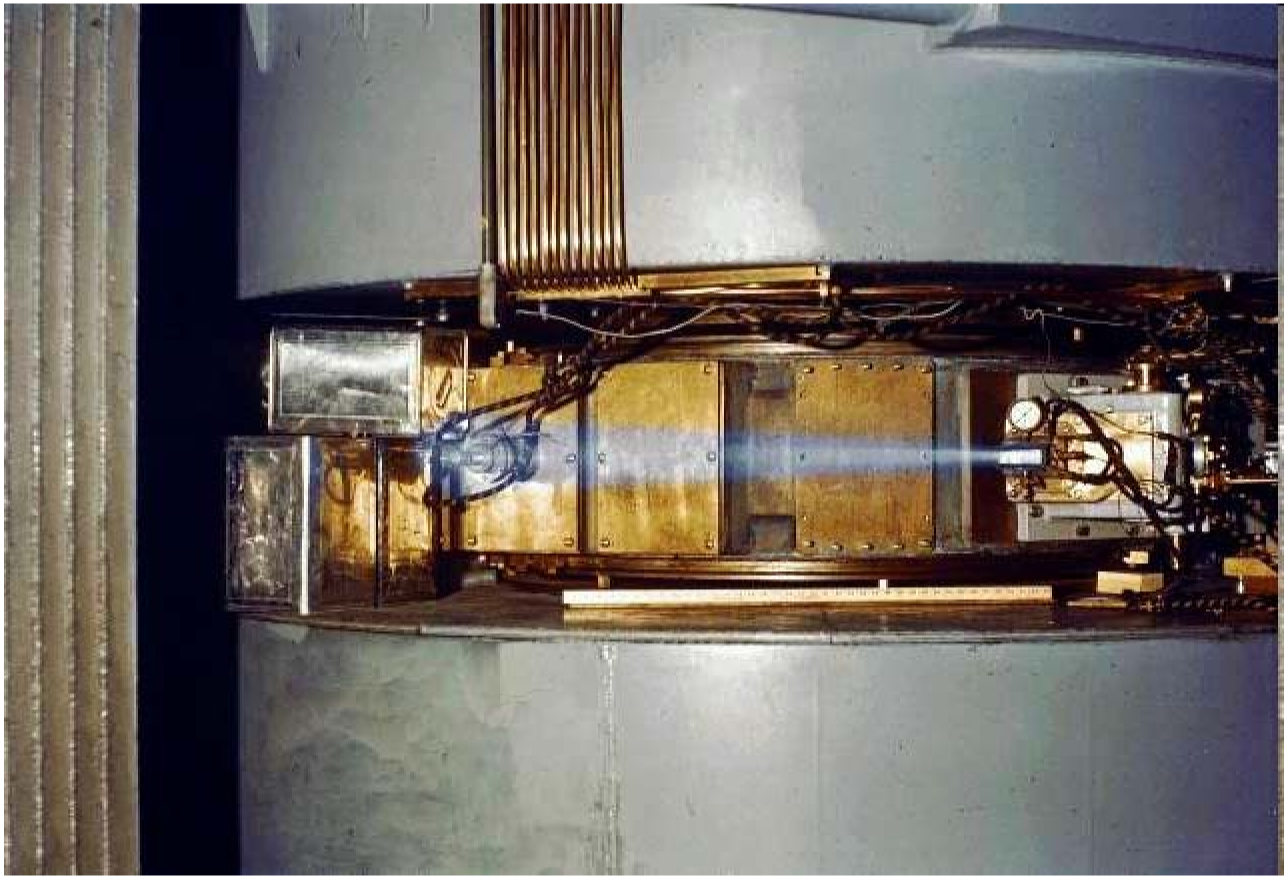
- Multiple large facilities (~$1B-class)
- Serving large user communities
- Instrument development and community growth guided by a series of discoveries

A Very Short (and Over-simplified) History of Particle Accelerators

- First particle accelerator: Cockcroft-Walton 1932
- ~ 1 Mev
- Able to induce nuclear reactions

A Very Short (and Over-simplified) History of Particle Accelerators

- Soon followed by Cyclotron (Ernest Lawrence)
- Increasing energy, flux



A Very Short (and Over-simplified) History of Particle Accelerators

- Synchrotrons
- Example:
  Bevatron (Lawrence Berkeley Lab) 6.3 GeV
- Anti-proton, other exotic baryons, mesons

A Very Short (and Over-simplified) History of Particle Accelerators

- Colliders
- Example: Tevatron (Fermilab)
- Electroweak, Standard Model

A Very Short (and Over-simplified) History of Particle Accelerators

- Large Hadron Collider (LHC), CERN
- Higgs boson?

A Very Short (and Over-simplified) History of Particle Accelerators

History
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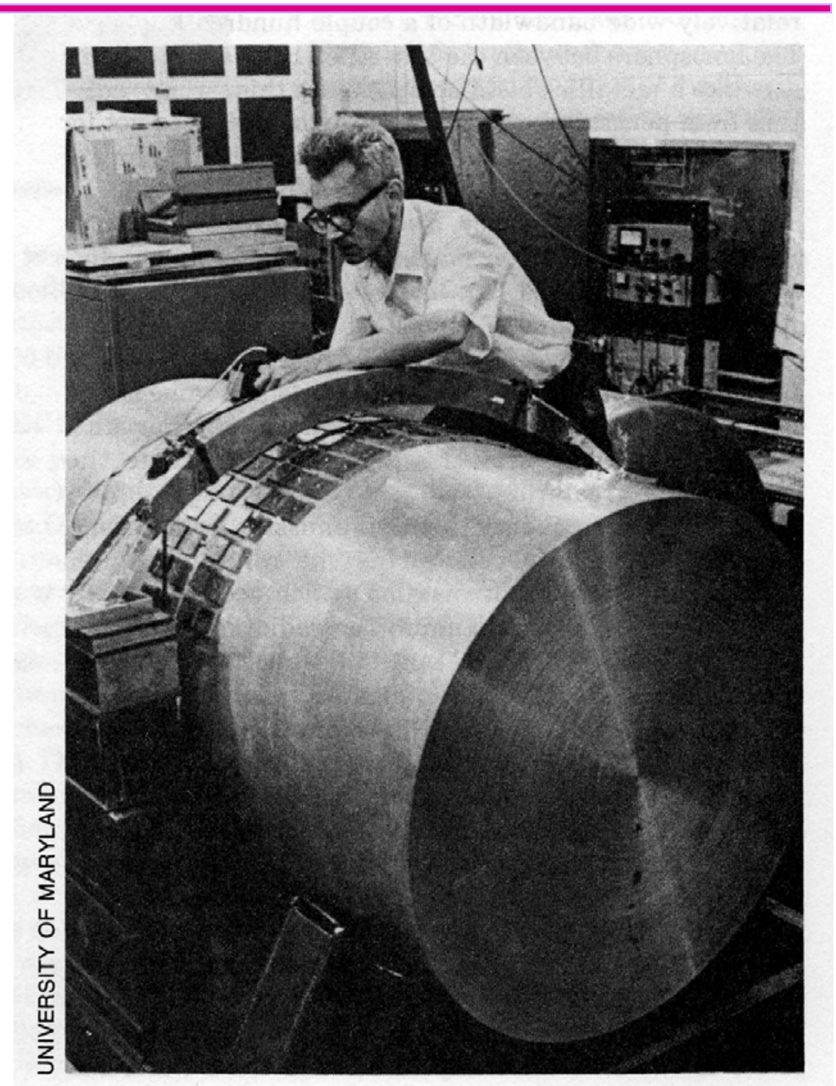
A Very Short (and Oversimplified) History of Gravitational Wave Detection

- Joseph Weber invents the bar detector (1960’s)
- Limited theoretical basis for estimating possible sources at the time, but eventually understood that MUCH more sensitive detectors would be required



A Very Short (and Oversimplified) History of Gravitational Wave Detection

- Led to projects of scale >$100M
- Example: Virgo, construction completed 2003

Gravitational Waves: Similarities and Differences

Similarities

- Decades of development
- Leading to \$100M - \$B -scale projects

Differences

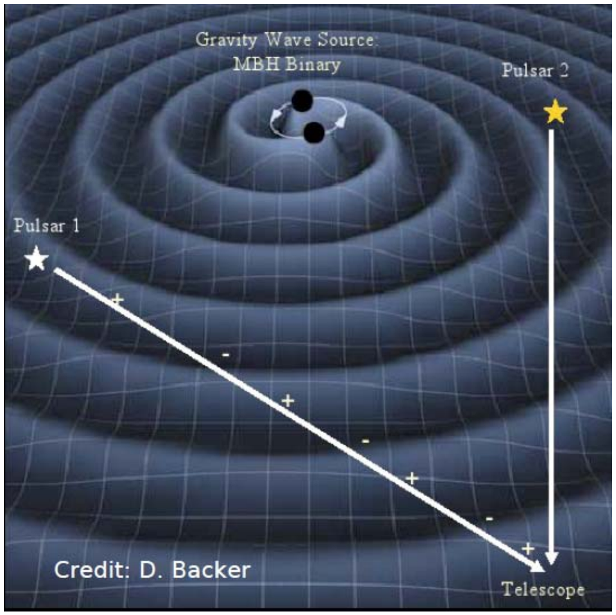
- No observations to guide our future
- Small number of large projects

Differences make this meeting so important

- Have to imagine a high-stakes future without the aid of observations
- Have to sell projects and grow communities without the benefits of intermediate (positive) results

Prospects for the Next Ten Years

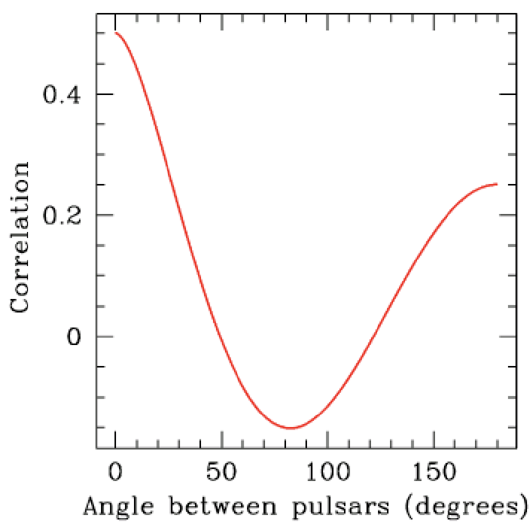
The Big Picture

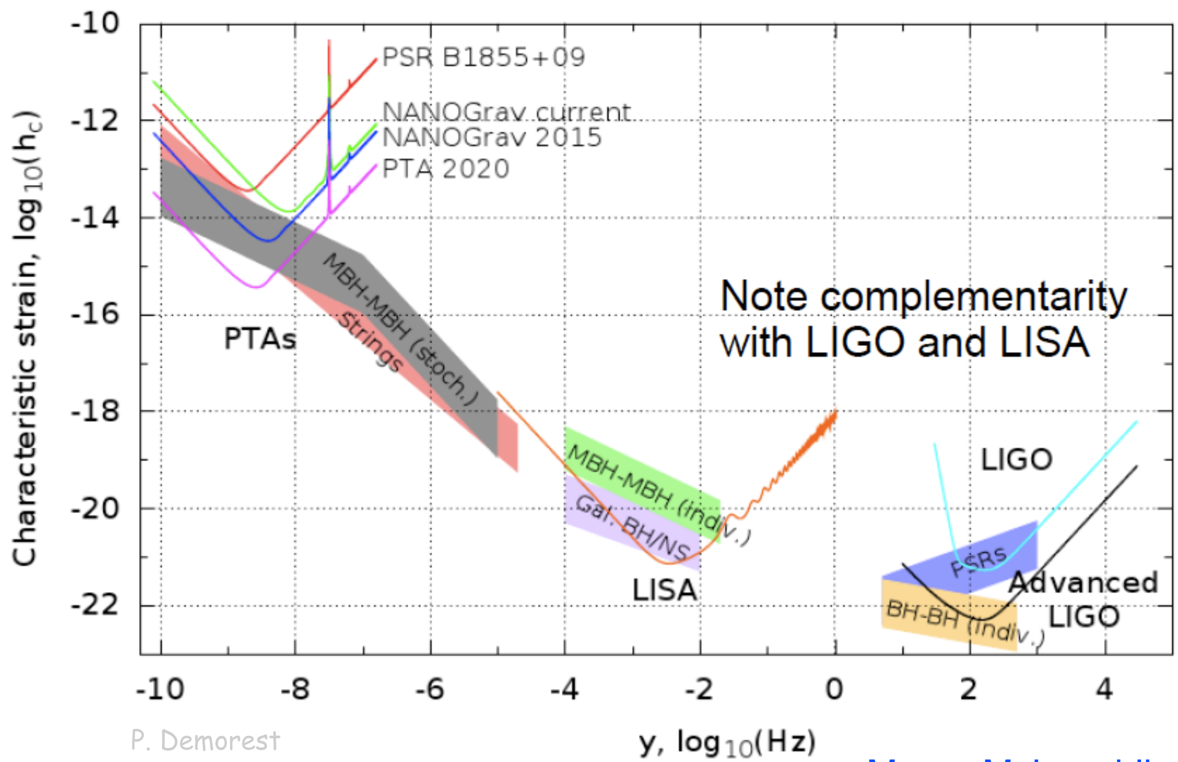


$f \sim$ 1/weeks to 1/years
(10^{-6} - 10^{-9} Hz)

$h \sim \sigma_{rms}/T$
$\sim$ 100 ns/5 years $\sim 10^{-15}$

$\Delta t \sim h/2\pi f \sim$ tens of ns

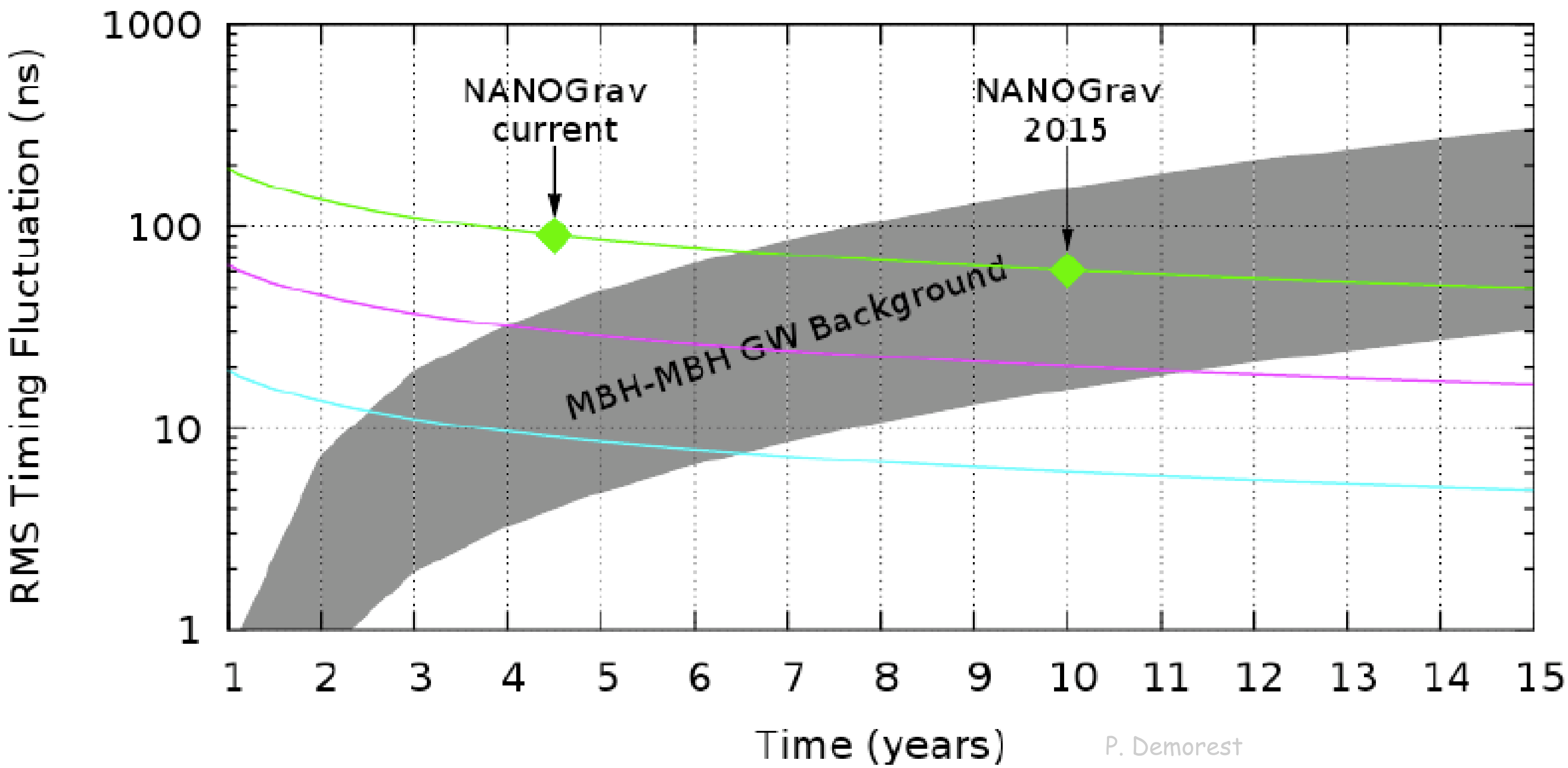




Maura McLaughlin

Time to Detection

We need long observation spans, high-precision timing, and a large number of pulsars.



$$h_{c,min} \propto \frac{\sigma_{rms}}{T\sqrt{N_{TOAs}N_{PSR}}} \sim \frac{\sigma_{rms}}{T^{3/2}\sqrt{N_{PSR}}}$$

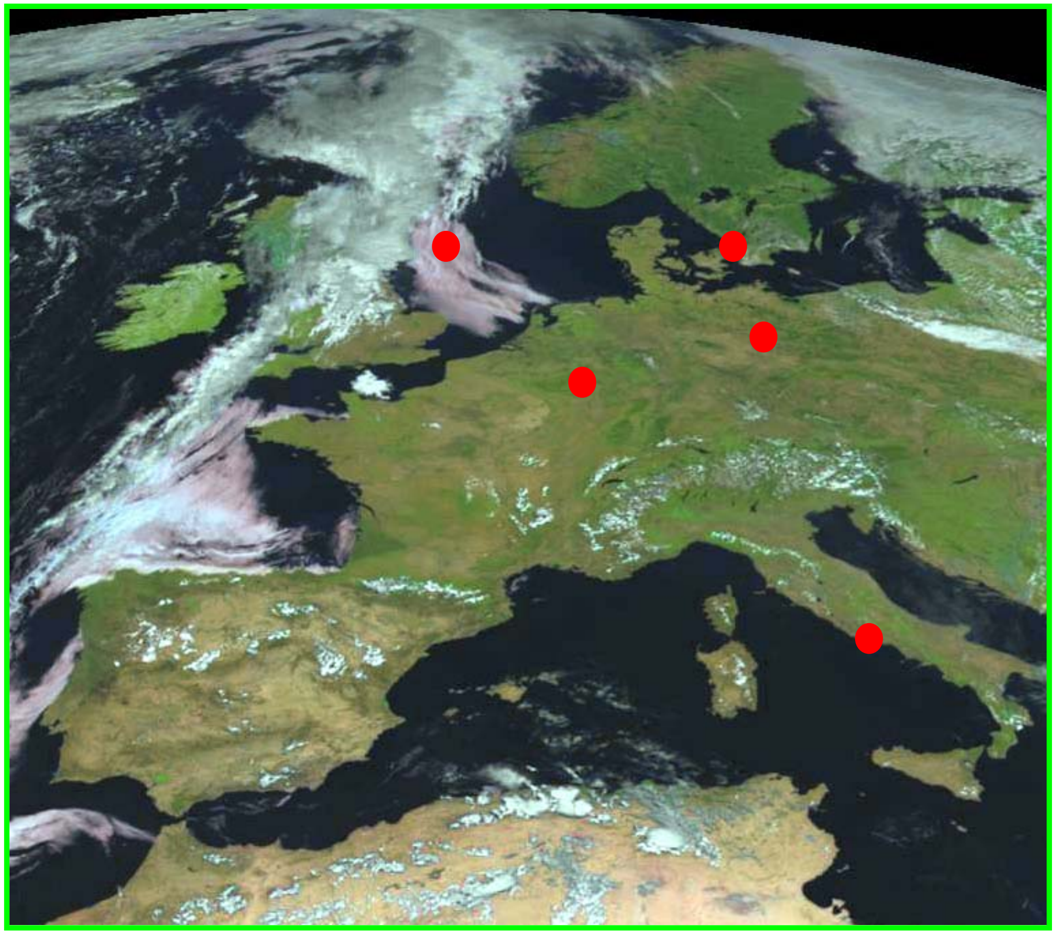
Maura McLaughlin

The Parkes Pulsar Timing Array Project

- Using the Parkes 64-m radio telescope to observe 20 MSPs
- ~25 team members – principal groups: Swinburne University (Melbourne; Matthew Bailes), University of Texas (Brownsville; Rick Jenet), University of California (San Diego; Bill Coles), ATNF (Sydney; RNM)
- Observations at 2 – 3 week intervals at three frequencies: 732 MHz, 1400 MHz and 3100 MHz
- New digital filterbank systems and baseband recorder system
- Regular observations commenced in mid-2004
- Timing analysis – PSRCHIVE and TEMPO2
- GW simulations, detection algorithms and implications, galaxy evolution studies

Dick Manchester

EPTA : the European Pulsar Timing Array



- **Unique feature: 5 100-m class radio-telescopes:**
  - **- Effelsberg (100 m)**
  - **- Westerbork (96 m)**
  - **- Nancay (92 m)**
  - **- Lovell (76 m)**
  - **- Sardinia (64 m)**
- **Commensurate scheduling will offer a better binary and yearly phase coverage**

Andrea Possenti

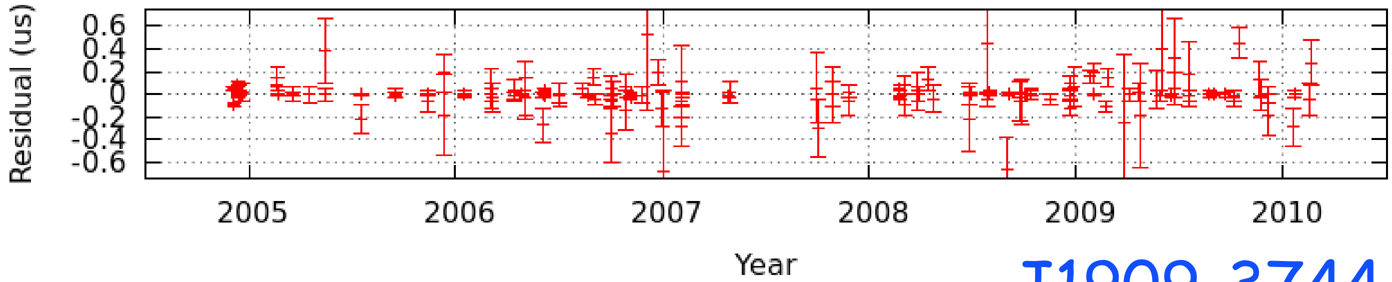
NANOGrav Overview

NANOGrav (North American Nanohertz Observatory of Gravitational Waves) is a consortium of US and Canadian researchers dedicated to GW detection through pulsar timing. Formed in October 2007.

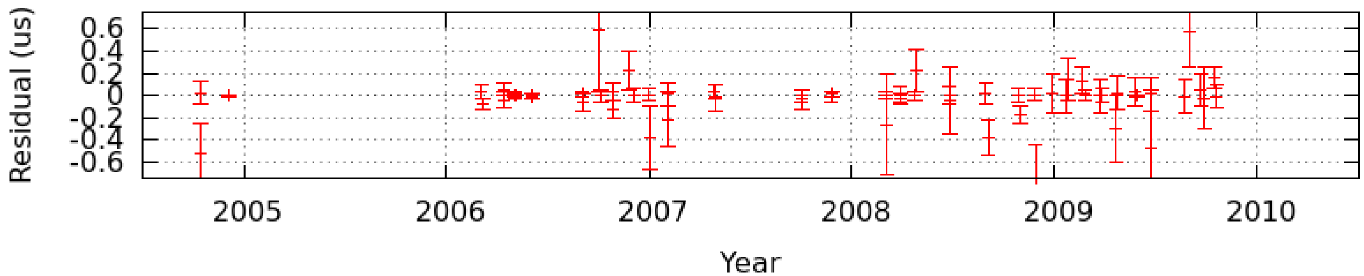
Cornell University – Jim Cordes, Ryan Shannon
Franklin & Marshall College – Andrea Lommen
Goddard Space Flight Center – Zaven Arzoumanian
Lafayette College – David Nice
McGill University – Vicky Kaspi, Anne Archibald
Oberlin College – Dan Stinebring, Johnathan Nelson, Willie Kunert
NRAO/UVA – Scott Ransom, Paul Demorest, Ryan Lynch, Tim Pennucci
Jet Propulsion Laboratory – Joseph Lazio
Penn State University – Sam Finn
University of British Columbia – Ingrid Stairs
University of Texas, Brownsville – Rick Jenet
University of Wisconsin, Wilwaukee – Xavier Siemens, Sydney Chamberlain, Chris Biwer, David Day
West Virginia University – Duncan Lorimer, Maura McLaughlin, Justin Ellis, Nipuni Palliyaguru, Tess Senty, Joe Swiggum

Current results

J1713+0747



J1909-3744

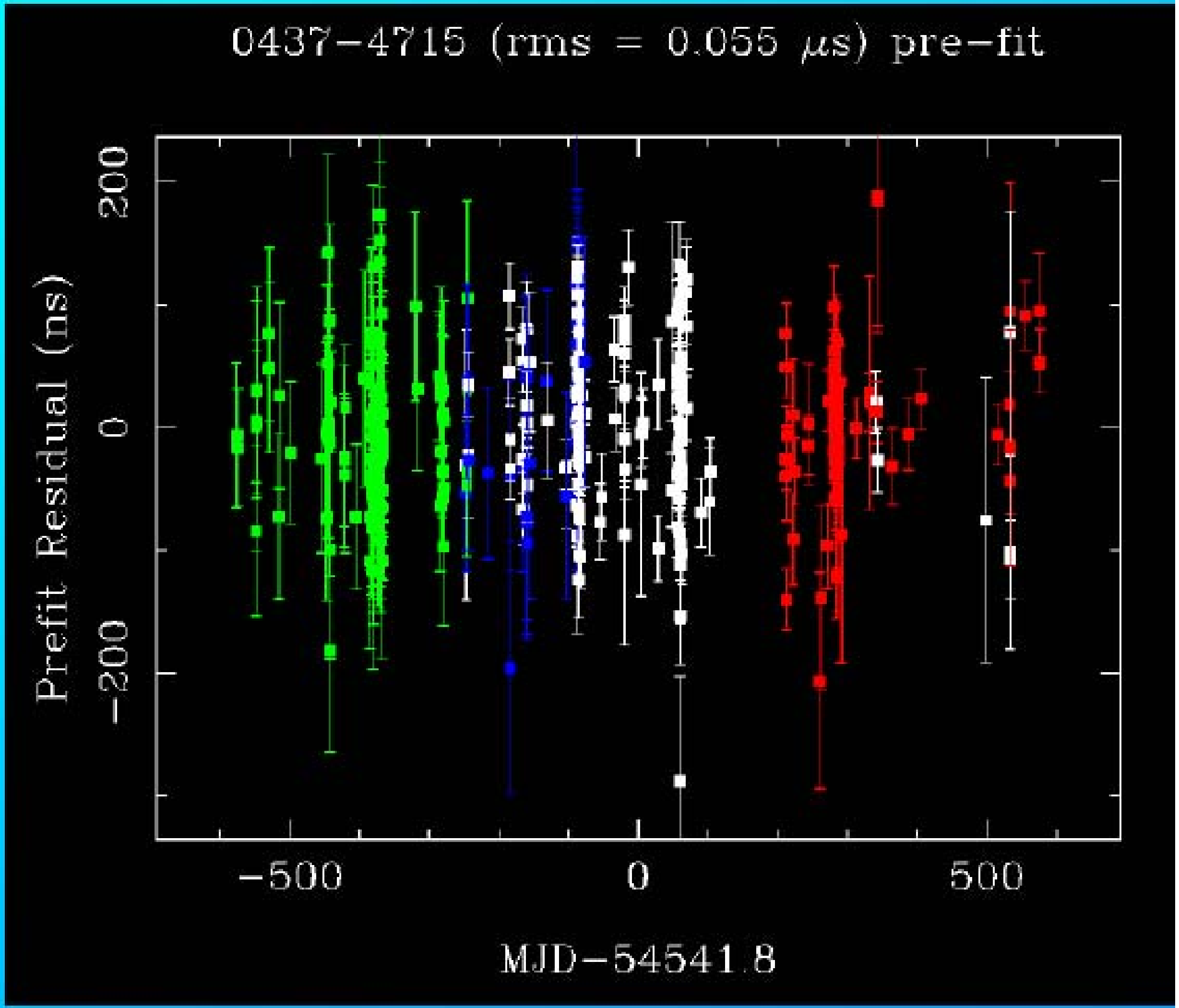


We are timing 26 pulsars with Arecibo and Green Bank. Two pulsars have RMS residuals less than 100 ns. We require at least 20 pulsars being timed at this level for GW detection.

Maura McLaughlin

Best result so far – PSR J0437-4715 at 10cm

- Observations of PSR J0437-4715 at 3100 MHz
- 1 GHz bandwidth with digital filterbank systems (PDFB1, 2 and 4)
- 3.1 years data span
- 374 ToAs, each 64 min observation time
- Weighted fit for 12 parameters using TEMPO2
- No dispersion correction
- Reduced $\chi^2 = 2.46$

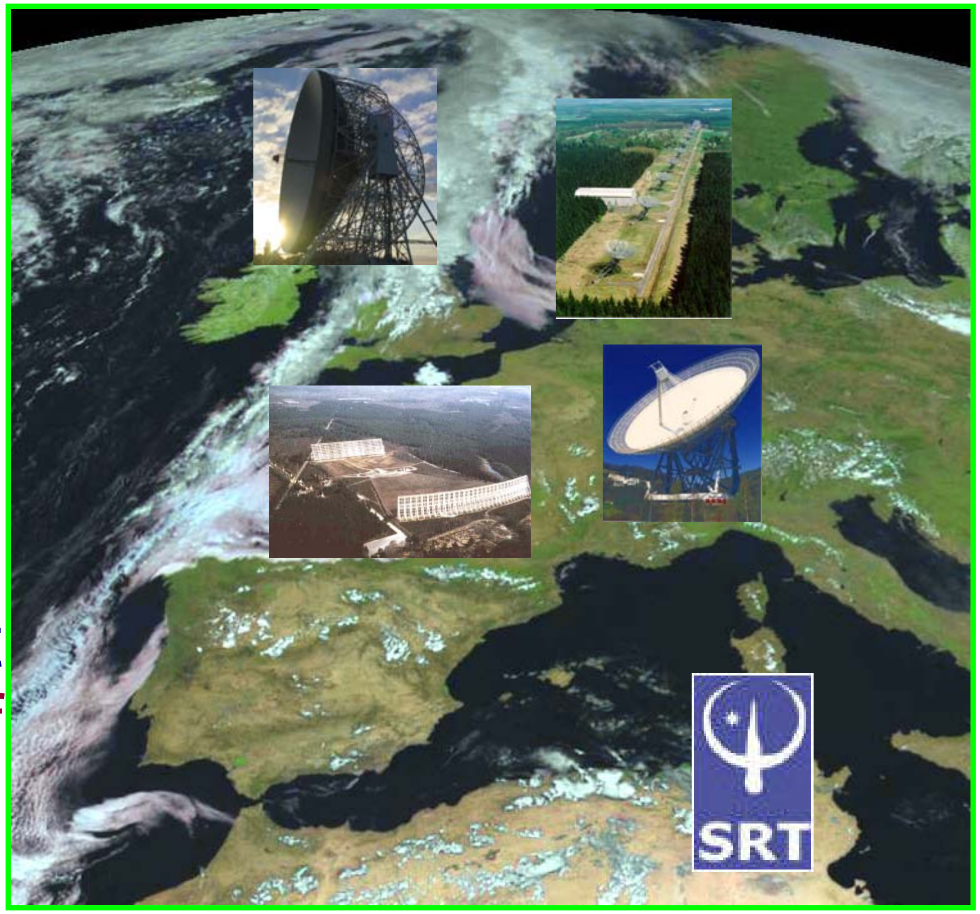


Rms timing residual 55 ns!!

Dick Manchester

LEAP : Large European Array for Pulsars

- ✓ To achieve even better sensitivity to GWs we are planning on combining all the telescopes "coherently"
- ✓ That gives a telescope with a sensitivity equivalent to Arecibo, but able to see much more of the sky
- ✓ It will test limits of sensitivity and pulse jitter



It also provides excellent tests of SKA-like pulsar observing

PIRE Funding

PIRE is the Partnerships for International Research and Education program, funded by NSF OISE. Our $6.5M award is largest ever funded. This is the first joint funding source for NANOGrav.

The goal of the PIRE program is (broadly) to establish the infrastructure for and ensure the success of the International Pulsar Timing Array (IPTA).

For a five year period, PIRE will fund **five postdocs**, eight graduate students, seven undergraduate students, nine senior personnel, and a part-time administrative assistant. WVU will fund a cyber-infrastructure expert for the project over that same period.

It will also fund **a yearly international student workshop** and science workshop, student exchanges, and research and observing trips. Our aim is to have seven undergraduate research-and-study abroad experiences yearly and for the research of each graduate student and postdoc to have a significant international component.

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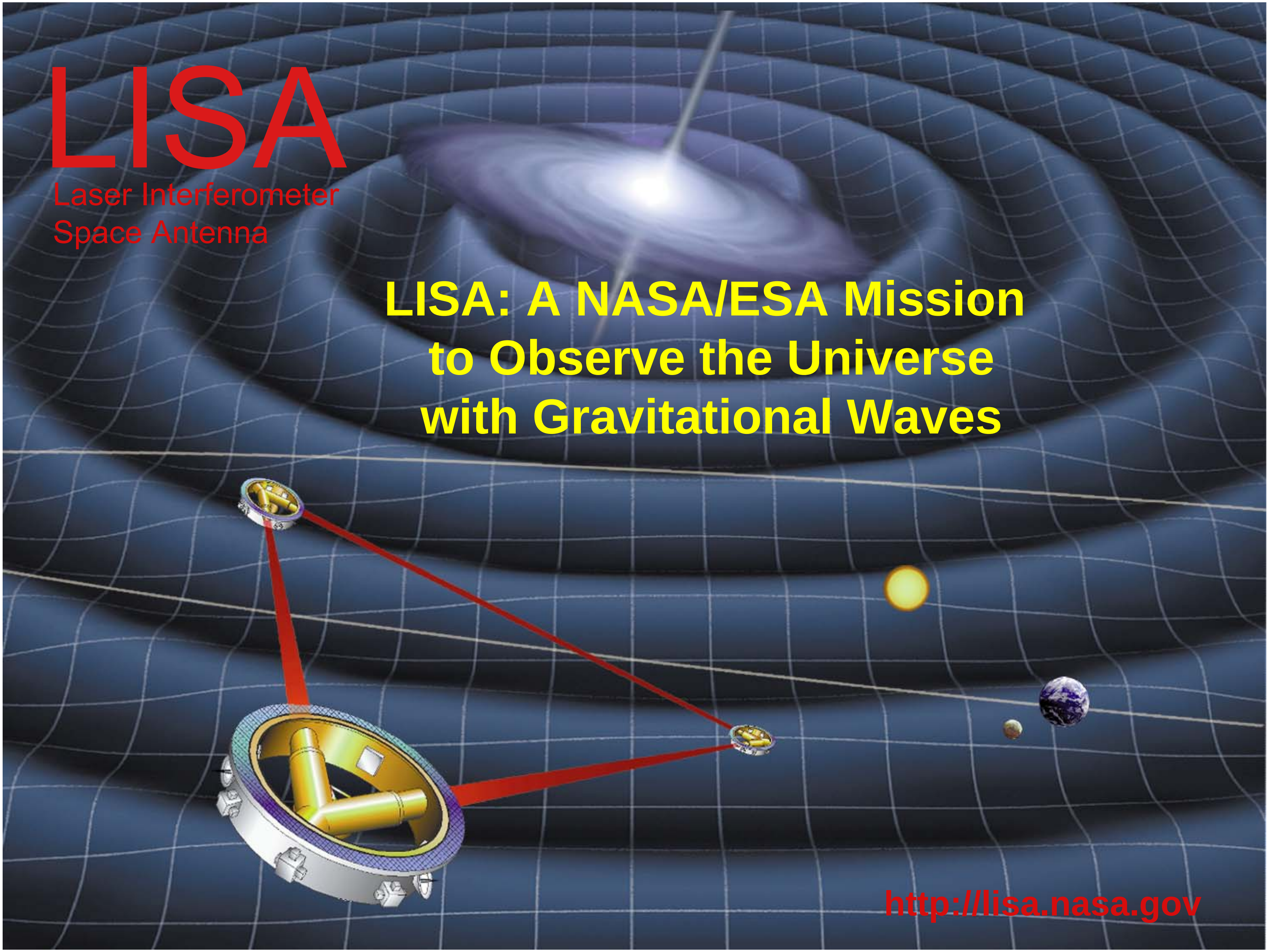
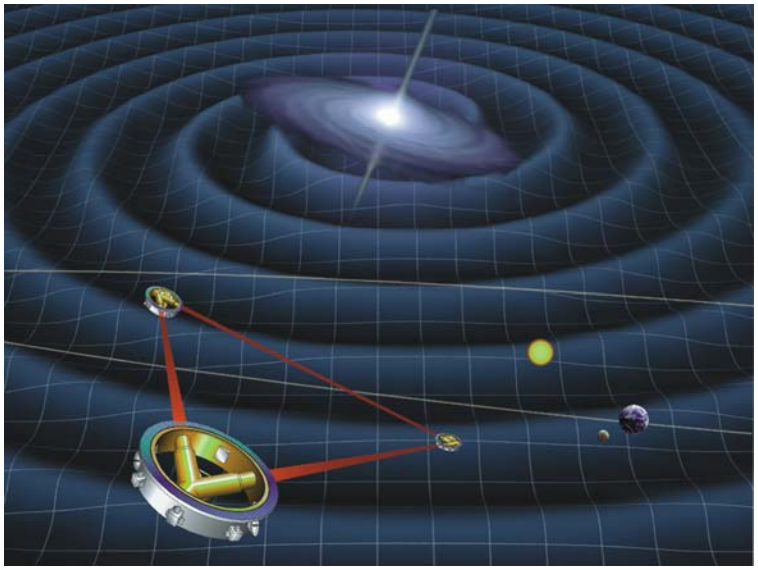

LISA
Laser Interferometer
Space Antenna
LISA: A NASA/ESA Mission
to Observe the Universe
with Gravitational Waves
http://lisa.nasa.gov

LISA - Laser Interferometer Space Antenna



Observational Targets

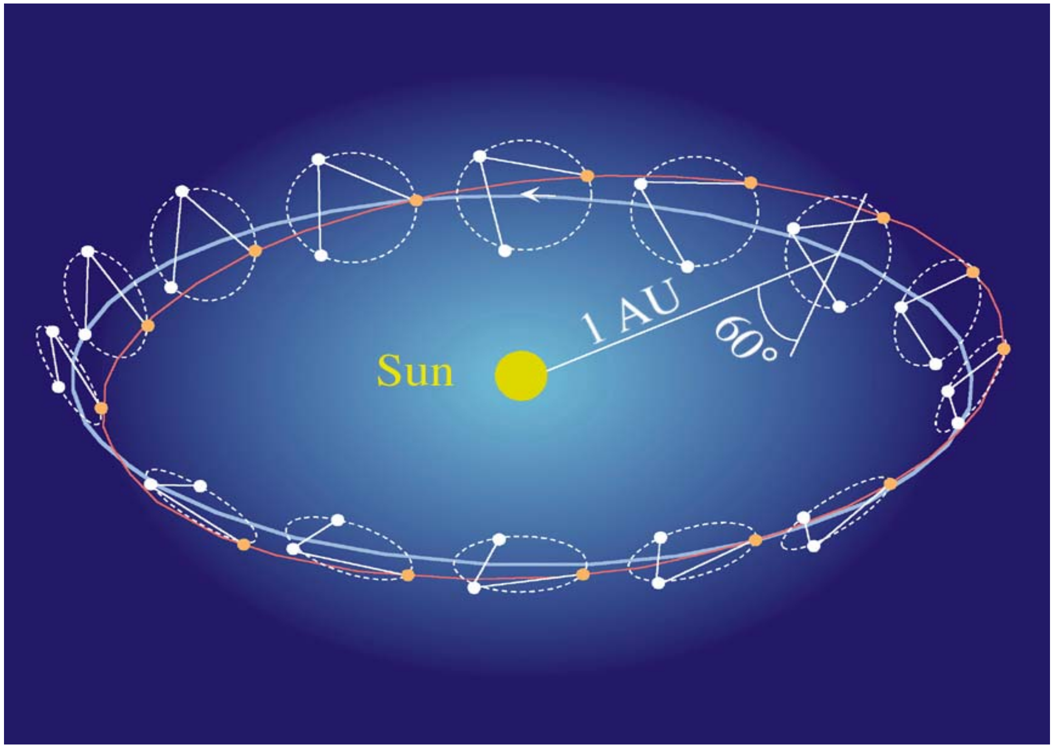
- *Mergers of massive black holes (BHs)*
- *Capture of stellar-mass BHs by massive BHs*
- *Ultra-compact binary systems in our galaxy*
- *Relic gravitational radiation from the early universe*

Mission Description

- *3 spacecraft in Earth-trailing solar orbit separated by 5 x10^6 km.*
- *Gravitational waves are detected by measuring changes in distance between fiducial masses in each spacecraft using laser interferometry*
- *Partnership between NASA and ESA*

LISA Orbits

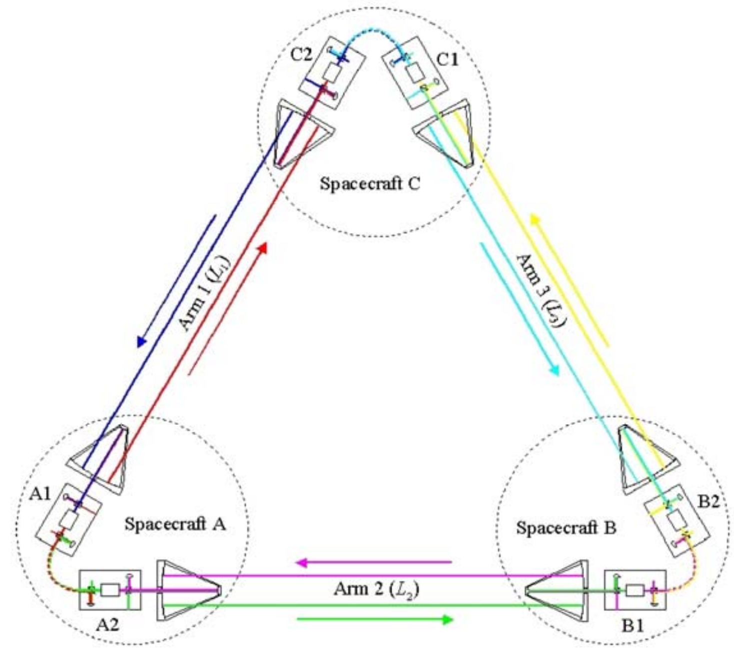
- Three spacecraft in triangular formation; separated by 5 million km
- Spacecraft have constant solar illumination
- Formation trails Earth by 20°; approximately constant arm-lengths

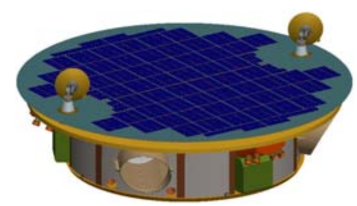


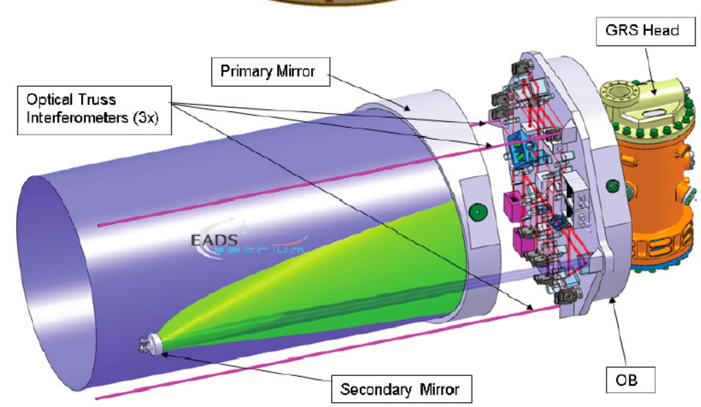
LISA Architecture

- Payload Components
  - 1 W lasers (diode-pumped 1064 nm Nd:YAG)
  - 40 cm telescopes
  - Drag-free proof masses
- Measurements
  - 6 laser Doppler signals between S/C
  - 6 reference beams between S/C assemblies

The LISA architecture is very well-studied and has been stable for almost a decade. Prototype subsystems are being fabricated.

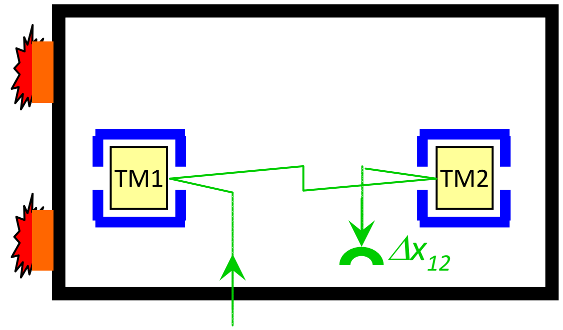


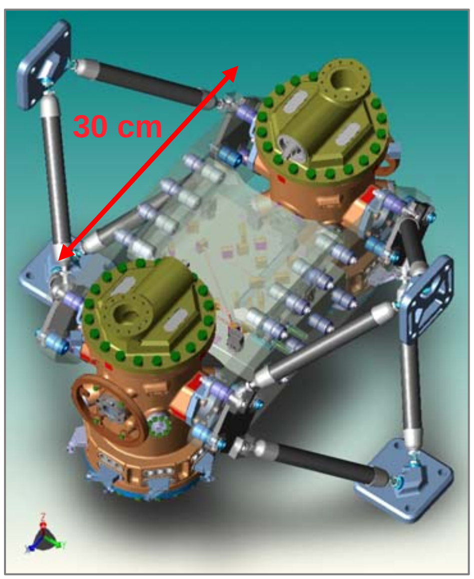


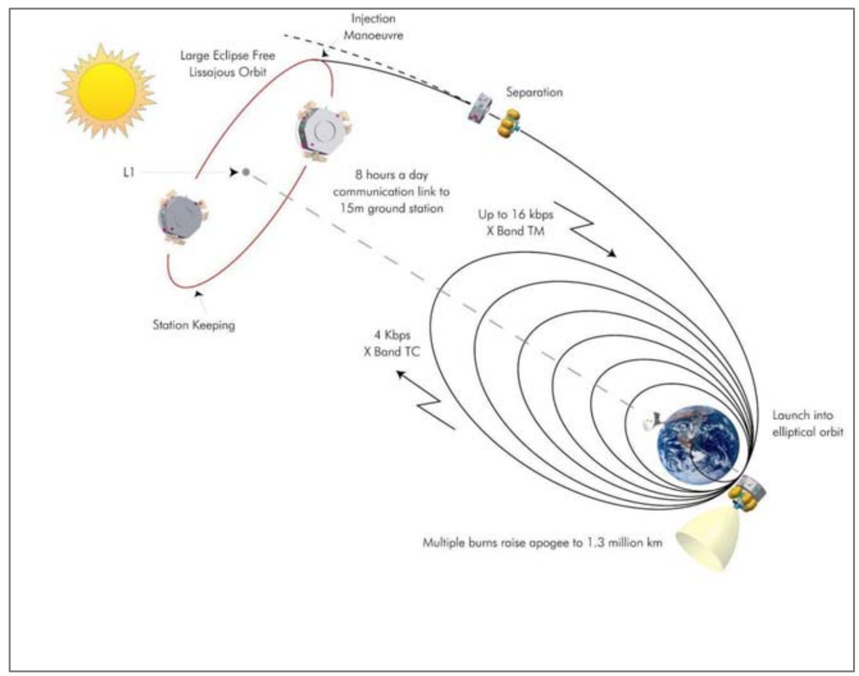


LISA Pathfinder

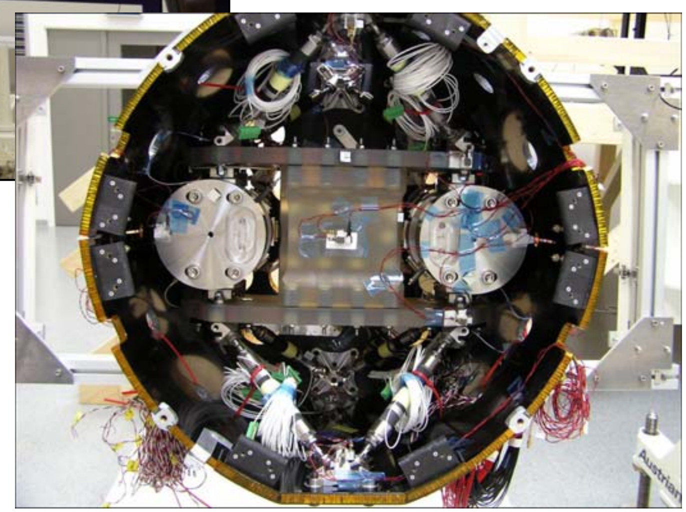
- The European Space Agency (ESA) is developing a mission to validate LISA flight subsystems with launch in 2013 or 2014.
- Two proof mass enclosures + optical bench/interferometer + micro-newton thrusters
- Hardware exists for all major LISA Pathfinder sub-systems: proof masses, optical bench, lasers, thrusters, etc.







LISA Pathfinder: Advanced Development

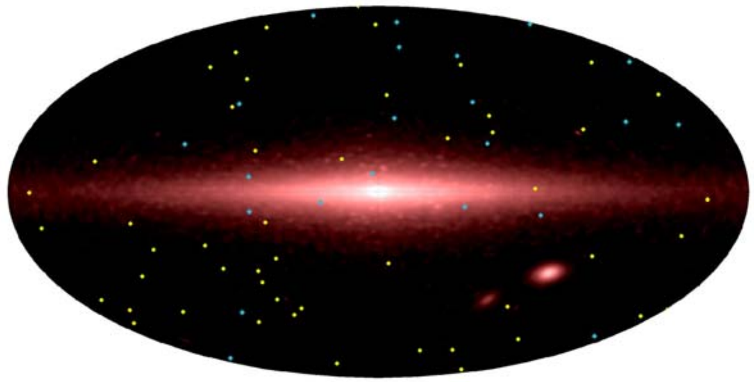


Astrium/ESA

LISA Status

- Gravitational wave astronomy, and LISA in particular, were strongly endorsed in the Astro2010 decadal survey
  - Ready to proceed after LPF and CV selection (see below)
- Cosmic Vision L-Mission down-select currently underway in Europe – includes LISA
  - LISA, IXO (International X-ray Observatory), & Laplace (mission to Jovian moons) are being considered
  - Nominally will select two with later choice of L1 to be launched 2020+
- LISA Pathfinder (LPF) including NASA ST-7/DRS (Disturbance Reduction System)
  - Undergoing integration and test
  - Launch in 2013-2014 time frame
  - 80 days of operation dedicated to experiments using NASA DRS
- US activities continuing on technology readiness and risk reduction

"LISA is an extraordinarily original and technically bold mission concept. The first direct detection of low-frequency gravitational waves will be a momentous discovery, of the kind that wins Nobel Prizes. The mission will open up an entirely new way of observing the universe, with immense potential to enlarge our understanding of both physics and astronomy in unforeseen ways."
- National Research Council (BEPAC 2007) -



LISA highly ranked in all major reviews:

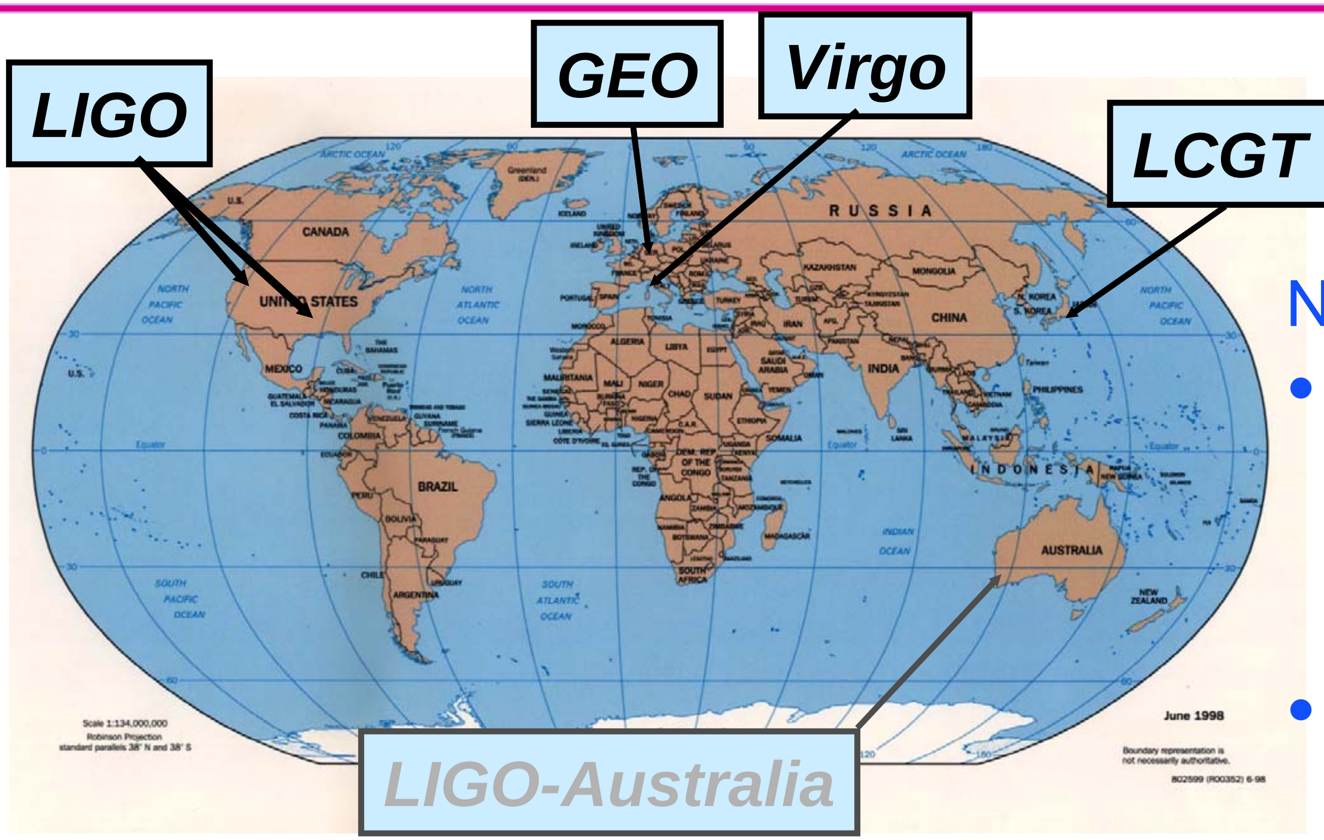
2000 Decadal Review, 2003 Quarks to Cosmos,
2005 Mid-Course Decadal Update, 2007 Beyond Einstein Review,

2010 Astro2010 Decadal Review

LISA Pathfinder: ~2014 launch
LISA: 202x (?)

http://www.lisa-science.org/resources/mission

Ground-based Interferometers

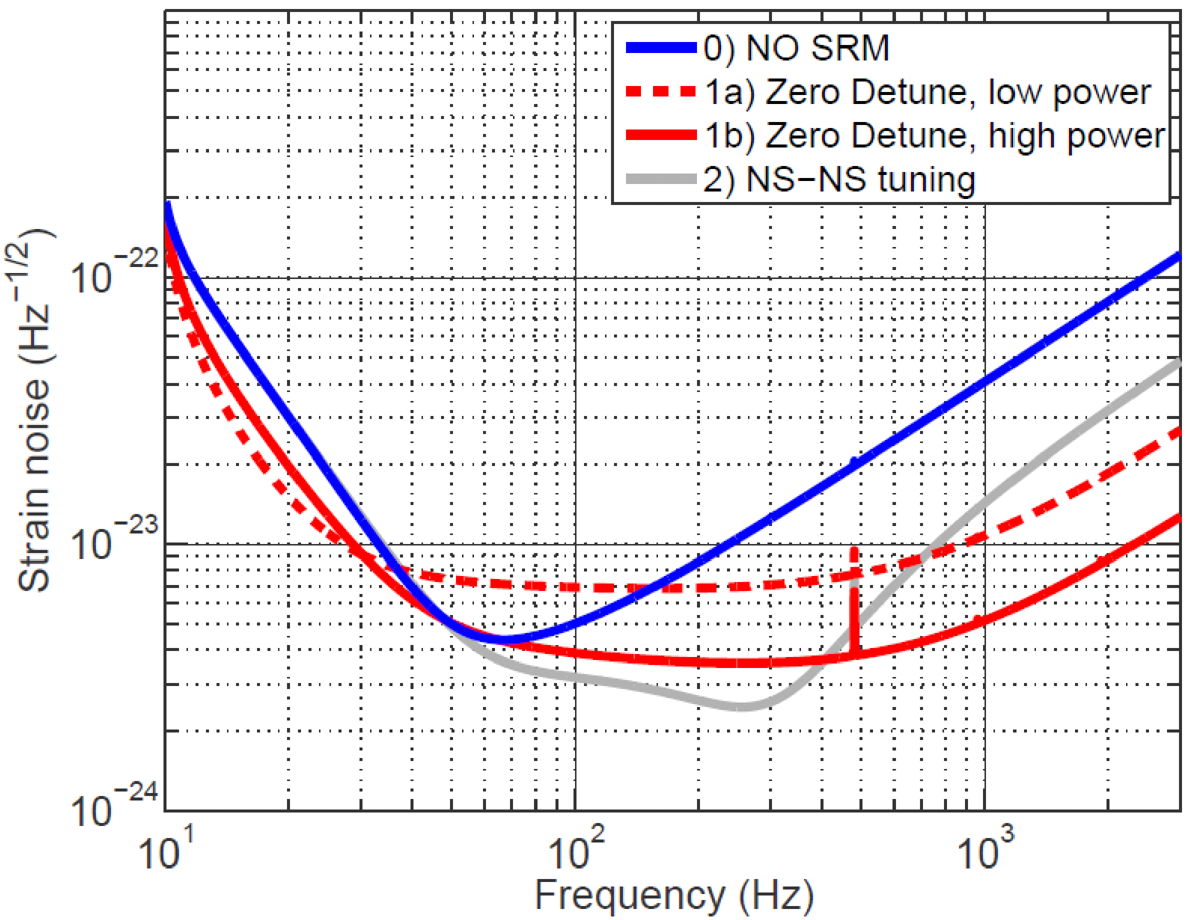


Next 10 years:

- Stop thinking of them as individual detectors
- Start thinking of the array as a single telescope

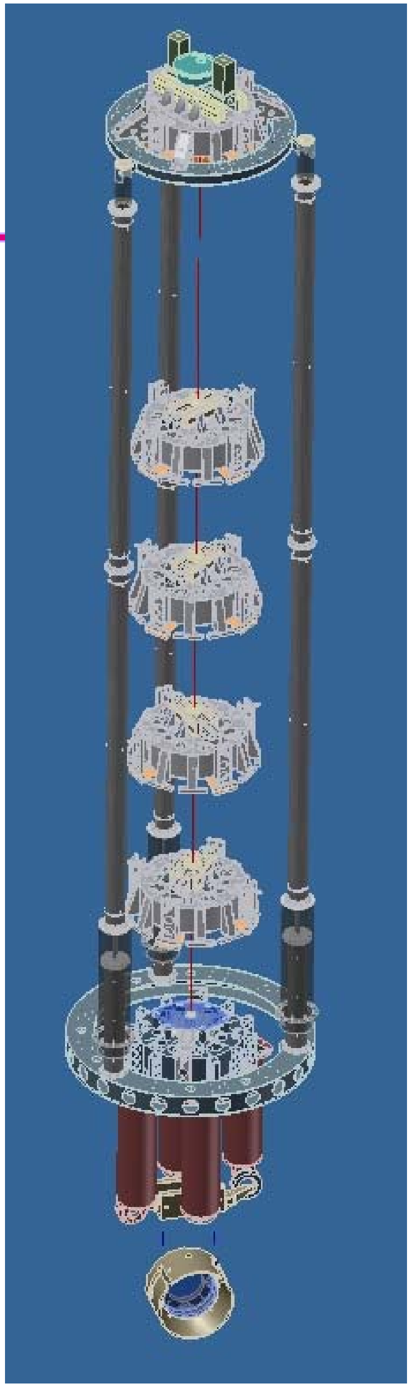
Advanced LIGO

- 10 times sensitivity improvement
- Fabrication began May 2008
- Shutdown initial LIGO and install Adv. LIGO on October 2010
- Hope for initial science data in 2015; will take additional time to reach full performance goals



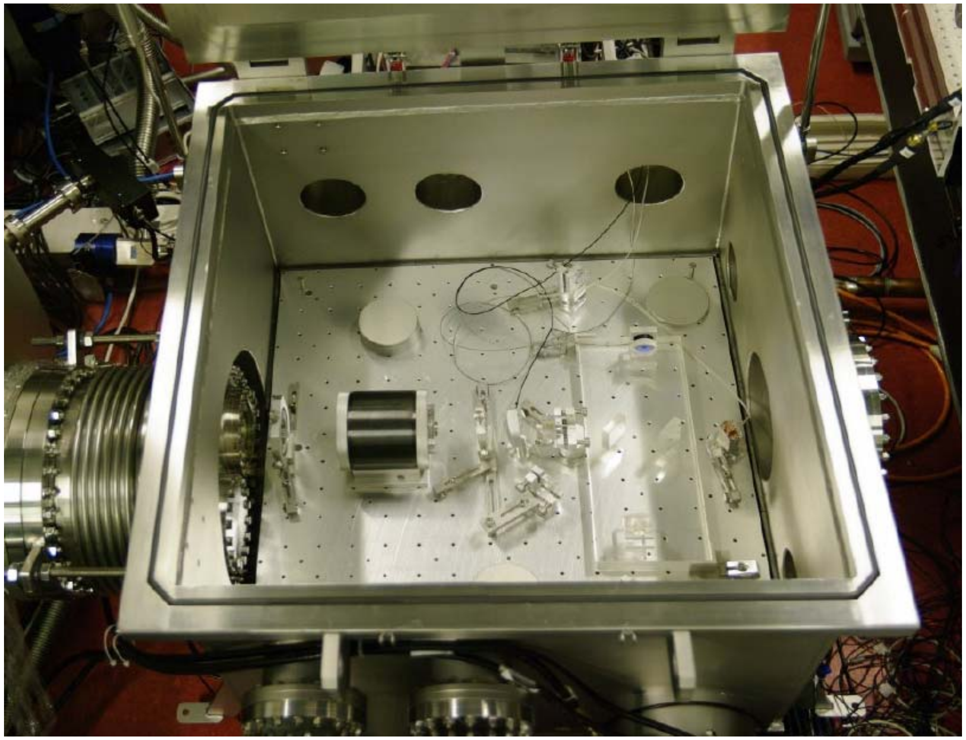
Advanced Virgo

- Comparable performance to Advanced LIGO
- Fabrication began 2009
- Installation planned to begin July 2011
- Current commissioning activities on Virgo+ testing monolithic suspensions (important Advanced Virgo technique)

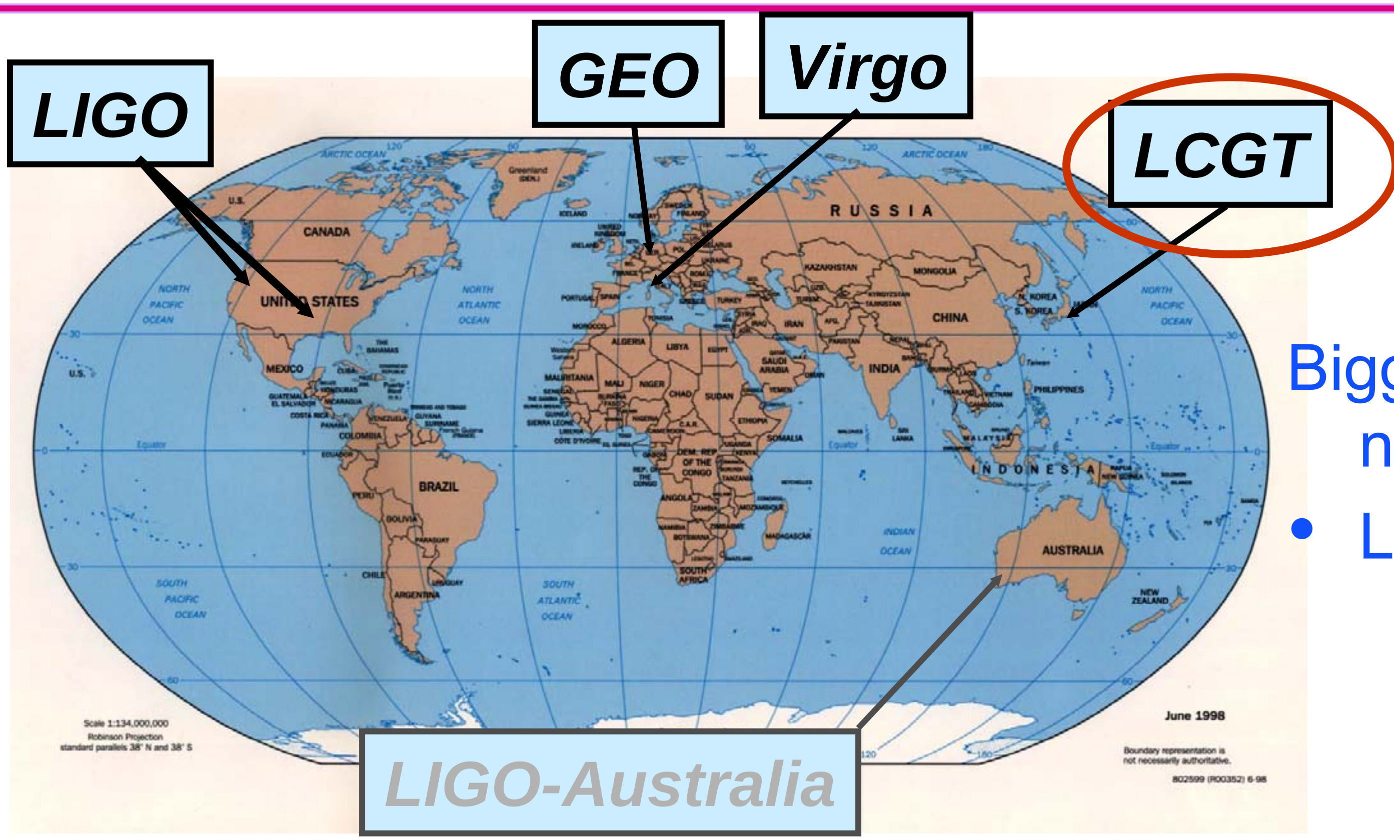


GEO-HF

- Testing techniques for Advanced Detector upgrades
  - » Squeezing
  - » Increased bandwidth for Signal Recycling
  - » Higher power operation
- Data-taking as much as possible during Advanced LIGO/ Advanced Virgo construction



Ground-based Interferometers



Biggest news for network:

- LCGT approved

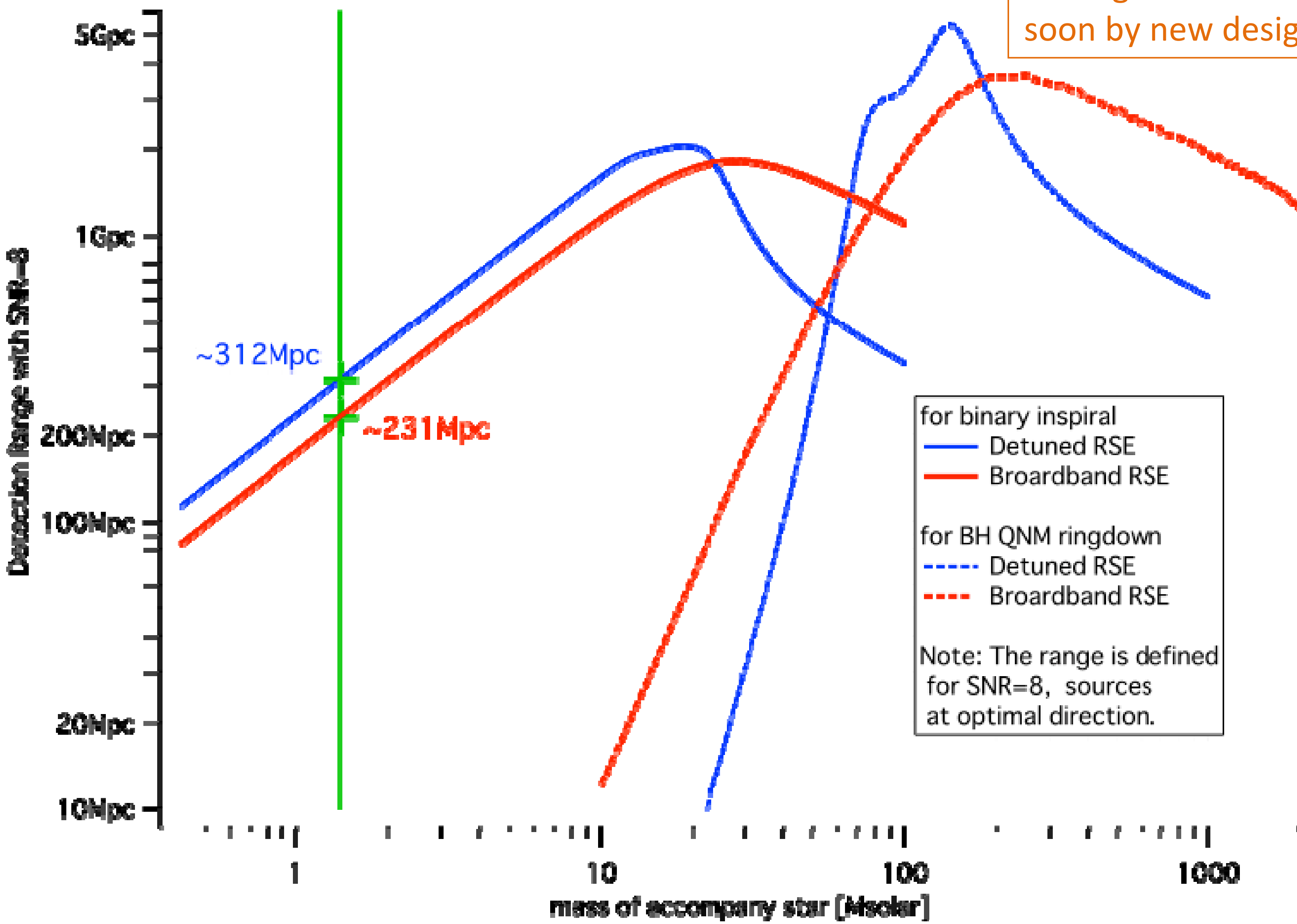
Status of LCGT project

Kazuaki Kuroda
On behalf of LCGT Collaboration

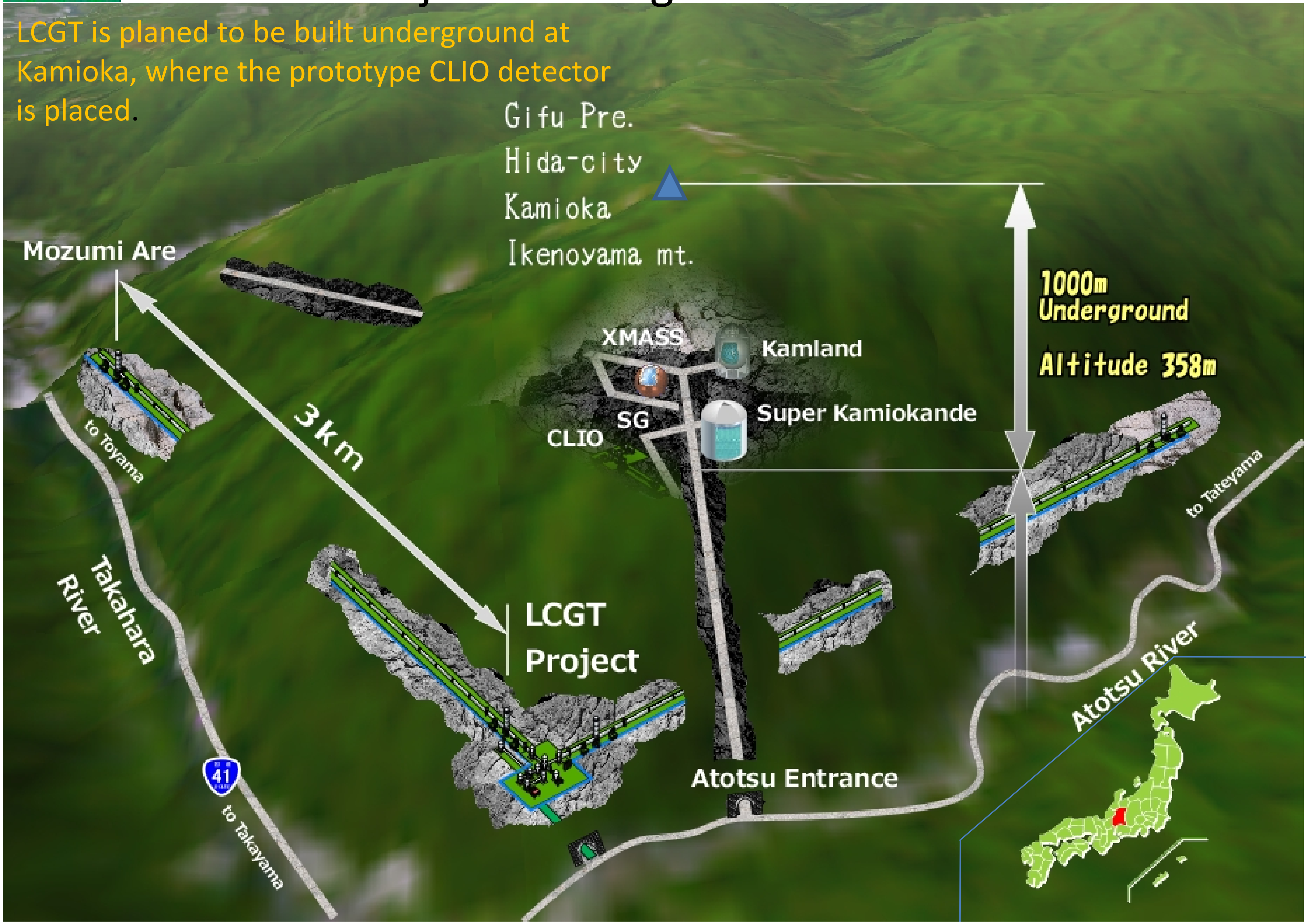
3rd ET meeting@Budapest
23-November, 2010

Sensitivity of LCGT and future improvement

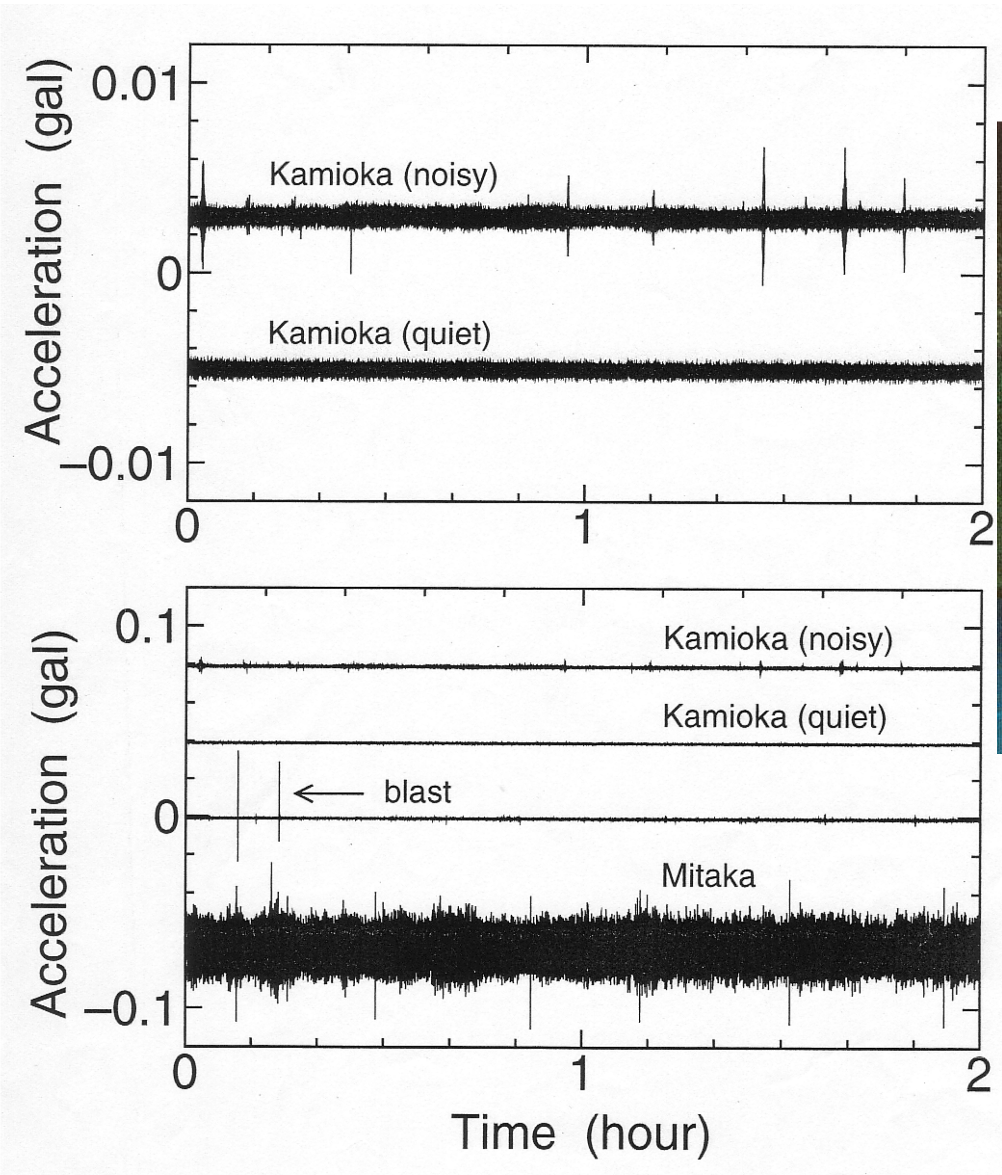
This figure will be revised soon by new design



Projects underground at Kamioka



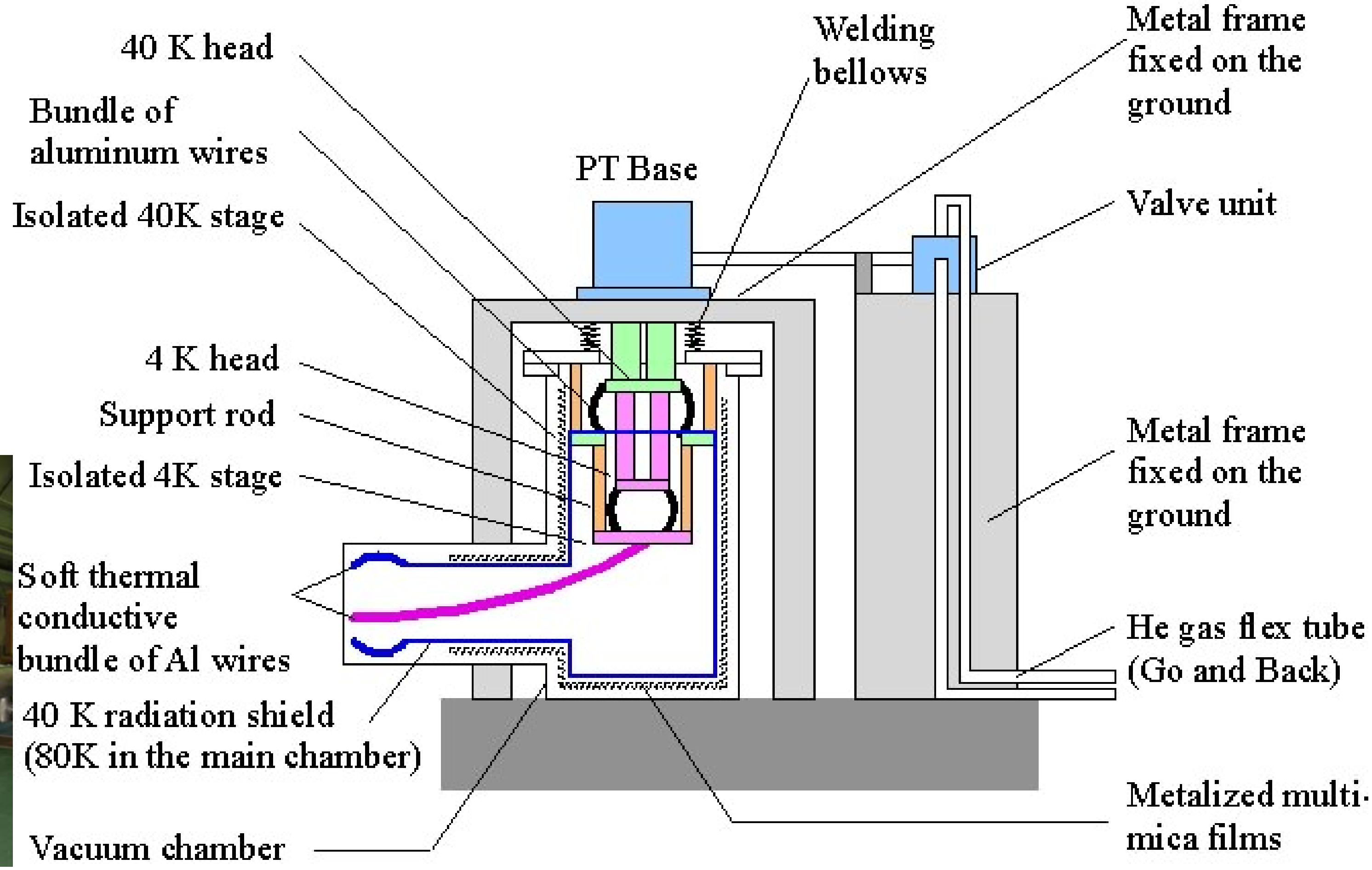
The merit of underground. At Kamioka low frequency noise is less than TAMA site of Mitaka by 30 times.



20m Prototype detector installed

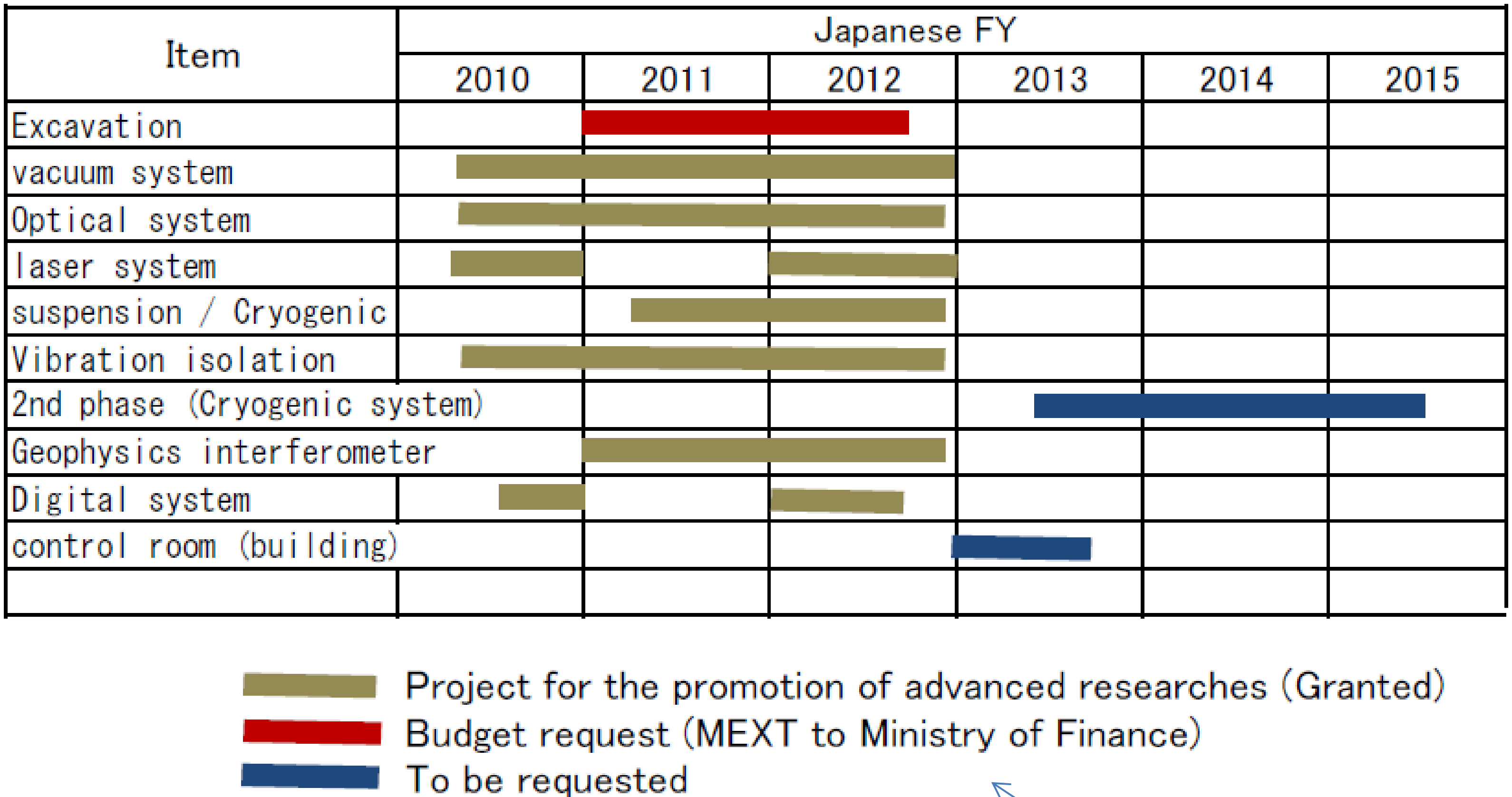
The seismic noise of Mitaka is equivalent to continuous blast-ing in Kamioka underground.

Quiet Refrigerator system with anti-vibration system



Cryostat used in CLIO
at the factory of Toshiba
(in 2003)

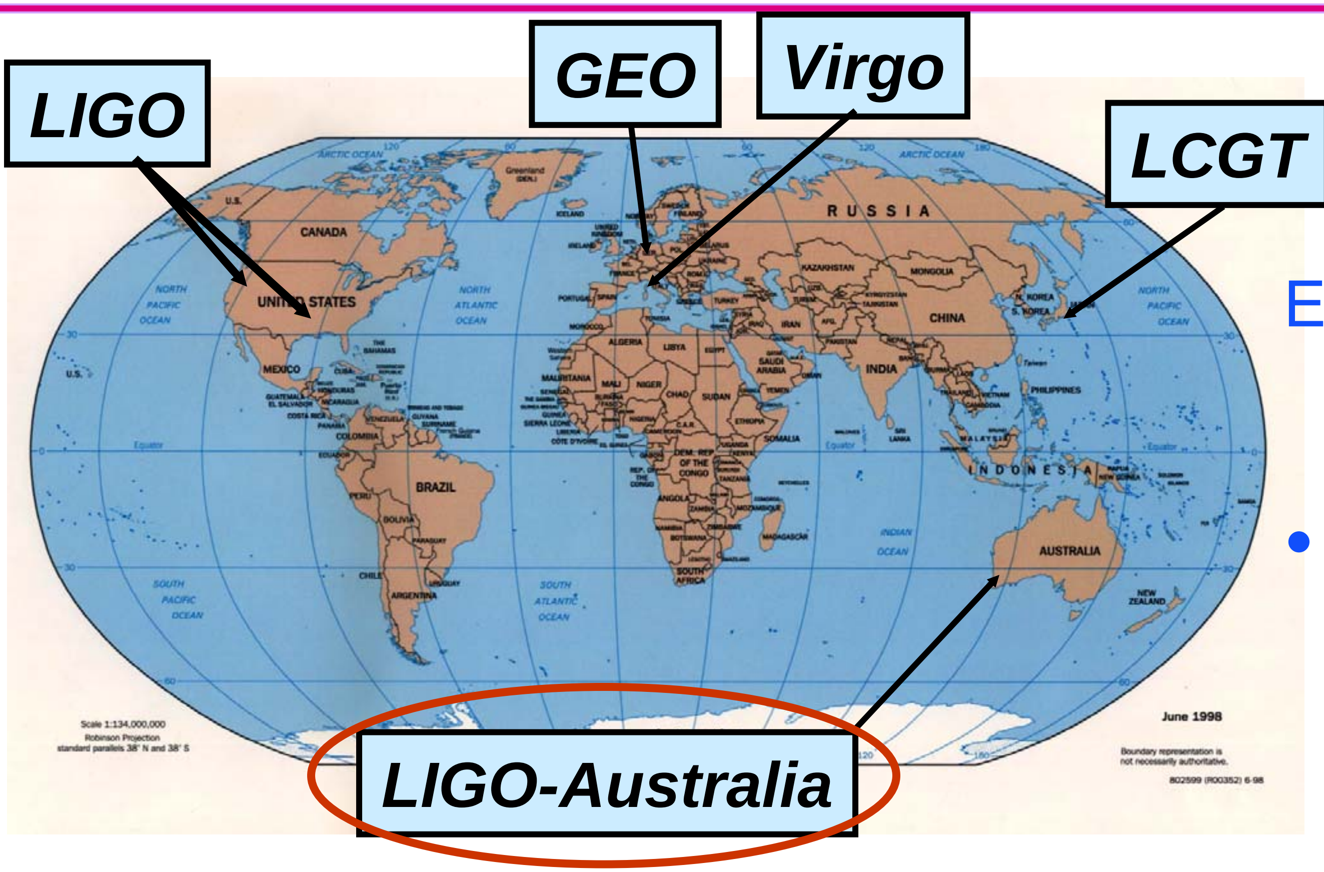
LCGT: Time line (Budget)



~~We will hear the final decision at the end of 2010.~~

Approved

LIGO-Australia



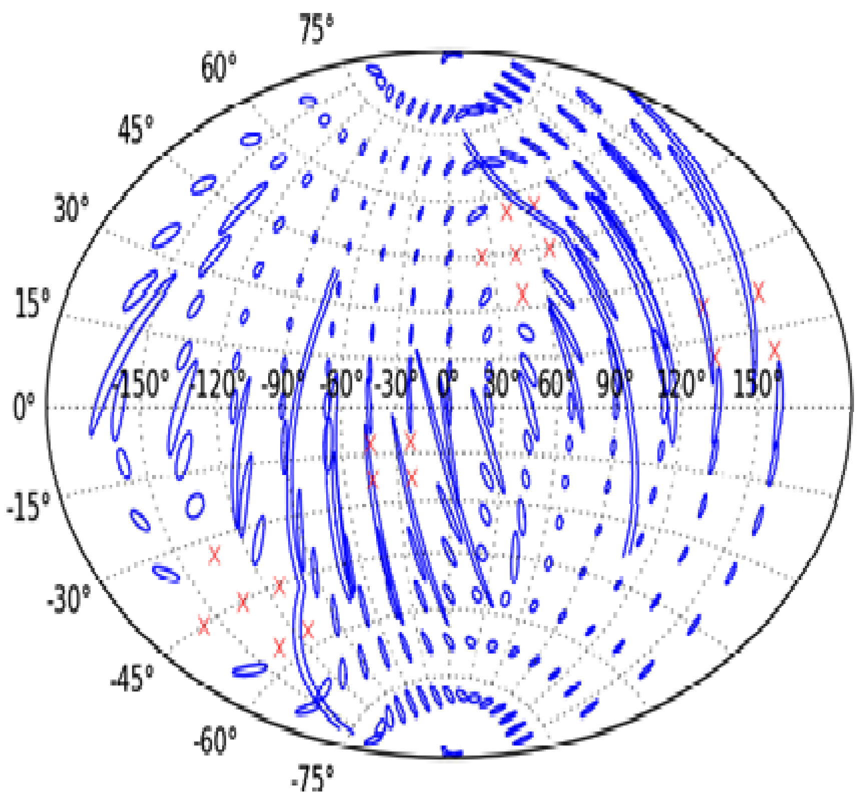
- Even with LCGT, network is incomplete
- Good all-sky angular resolution requires a 3D array

LIGO-Australia Concept

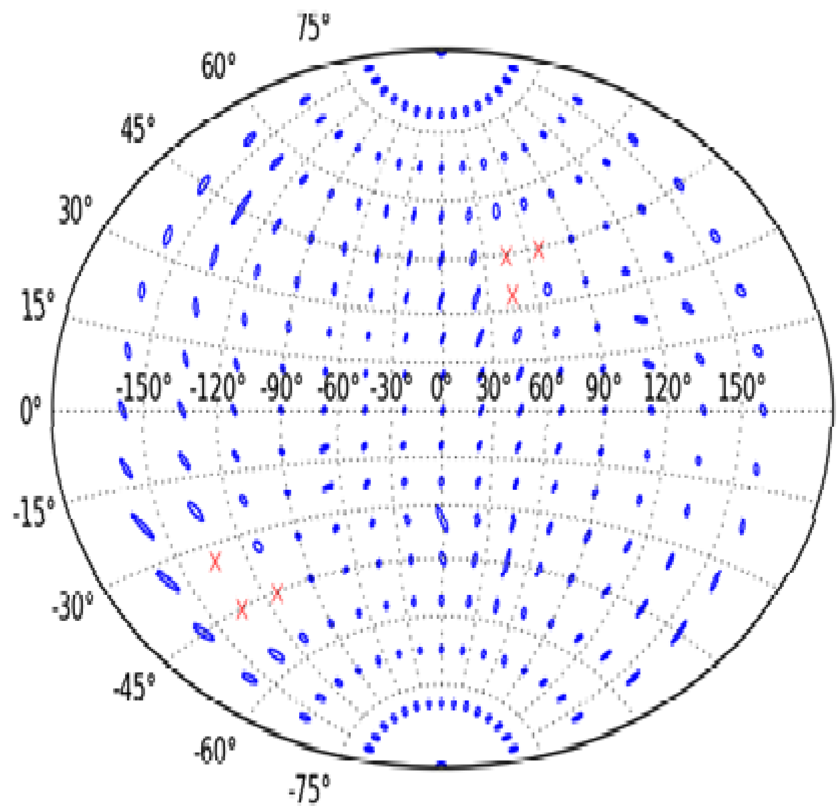
- A direct partnership between LIGO Laboratory and Australian collaborators to build an Australian interferometer
  - » LIGO Lab (with its UK, German and Australian partners) provides components for one Advanced LIGO interferometer, unit #3, from the Advanced LIGO project
  - » Australia provides the infrastructure (site, roads, building, vacuum system), "shipping & handling," staff, installation & commissioning, operating costs
- The interferometer, the third Advanced LIGO instrument, would be operated as part of LIGO to maximize the scientific impact of LIGO-Australia
- Key deadline: LIGO needs a commitment from Australia by October 2011—otherwise, must begin installation of the LIGO-Australia detector at LHO

Benefits of LIGO-Australia

Determination of source sky position: NS-NS binary inspirals



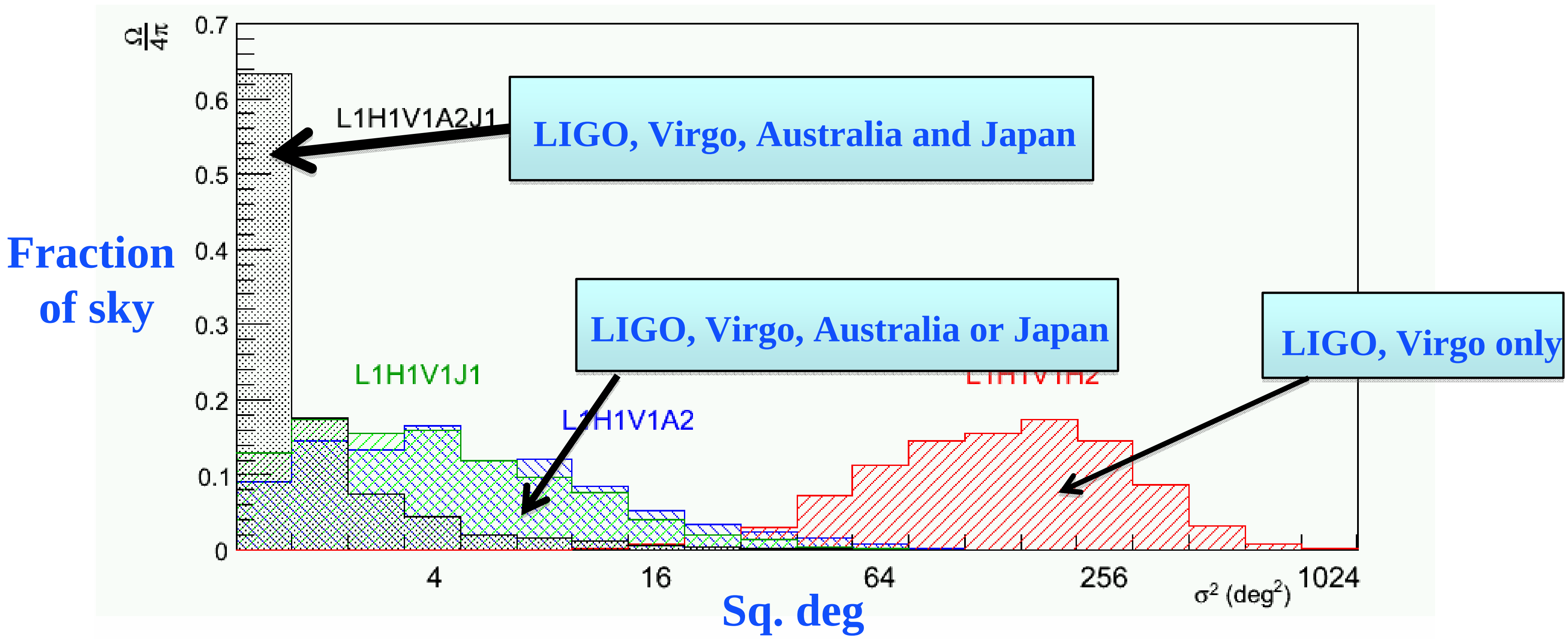
LIGO + Virgo



With LIGO-Australia

Importance of LIGO-Australia Reduced Because of LCGT?

- Improvement in localization is ~independent of LCGT
- To first order, LIGO-Australia improves N-S localization, while LCGT improved E-W localization



LIGO-Australia Site

- Australian Consortium for Interferometric Gravitational Astronomy (Australian National University, University of Western Australia, University of Adelaide, University of Melbourne, Monash University)
- 80 m facility located at Gingin (about 100 km from Perth)
- Operated as a high power test bed for LIGO
- Site expandable to 4 km
- Site also contains 1m robotic optical telescope and an award-winning science education centre

Progress toward LIGO-Australia

- Australian population and economy ~7% of US => Project >$100M is a BIG project
  - » One year isn't a lot of time to react
- LIGO Laboratory proposed it to NSF
  - » Reviewed by NSF panel—strong endorsement
  - » NSF informed National Science Board and received approved
- Five ACIGA universities have signed MOU for project
  - » Five of the "Group of Eight" major research universities
  - » "Acting" Project Director (SW) appointed
- Indian Collaboration (IndIGO) planning to ask for ~$20M from Indian government to participate

What Needs to be Done?

- Scale of Australian investment (“Landmark” scale) will require partnership among Universities, State Government, Federal Government
- Formal proposal in final stages
- Will almost certainly require Australian Government Cabinet action to create funding line
  - » Political considerations will be as important as scientific ones
- Prospects still very uncertain

Final Remarks

- The unique history of the field of gravitational wave science gives great importance to meetings like this one
  - » Bring together GW specialist with the broader community
- Keep your eyes on pulsar timing—
  it could surprise us!
- LISA offers superb science, but faces tough competition for limited resources
- LCGT is an important step on the way to the ground-based gravitational wave telescope that we want,
  but we need LIGO-Australia!