Gravitational Wave Detectors: Back to the Future

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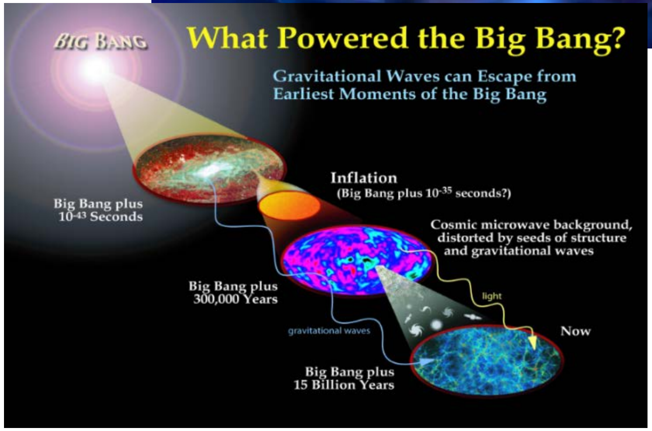
Summary

- Short introduction to gravitational waves (GW)
  - GW sources and amplitudes
  - Laser interferometer gravitational wave detectors
- The LIGO-Virgo experience
  - Initial detectors
  - Advanced detectors
- Perspectives in the US and in Europe
  - Advanced LIGO+, Voyager, Cosmic Explorer
  - Einstein Telescope
  - LISA

Gravitational waves

- Many of the most energetic phenomena in the Universe are expected to be source of gravitational waves

- Merger of compact stars
  - ◆ Black holes and neutron stars
- Massive star explosions
  - ◆ Supernovae, Gamma ray bursts
- The Big Bang
  - ◆ Universe is transparent to GW



- Their detection is shedding light on the Dark Universe

Gravitational waves amplitude

- Gravitational wave amplitudes on Earth are tiny

- Two examples:

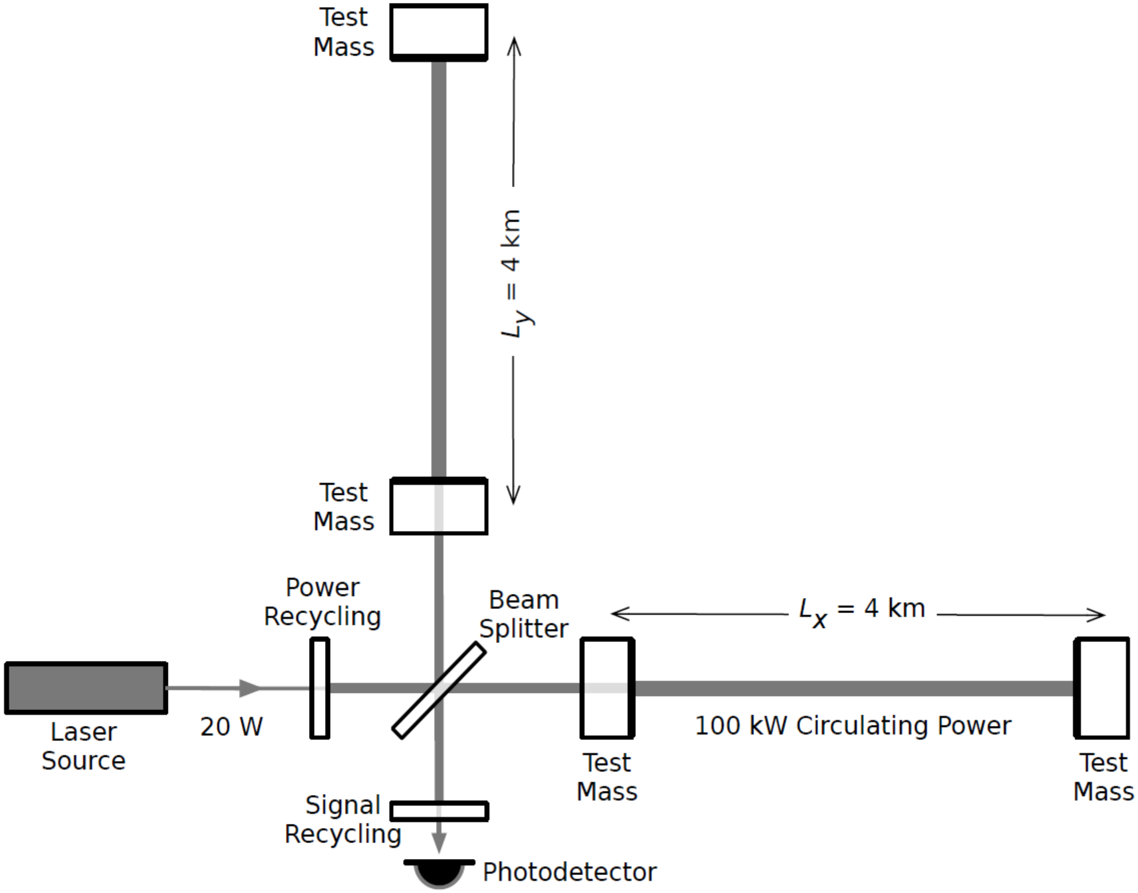
  - Coalescence of two stellar mass black holes at a distance of 1 Gpc

  - Explosion of Supernovae in the Virgo cluster (converting 10^{-2} solar mass into GW)

  - Expected GW amplitude at the Earth $dL/L \sim 10^{-21}$

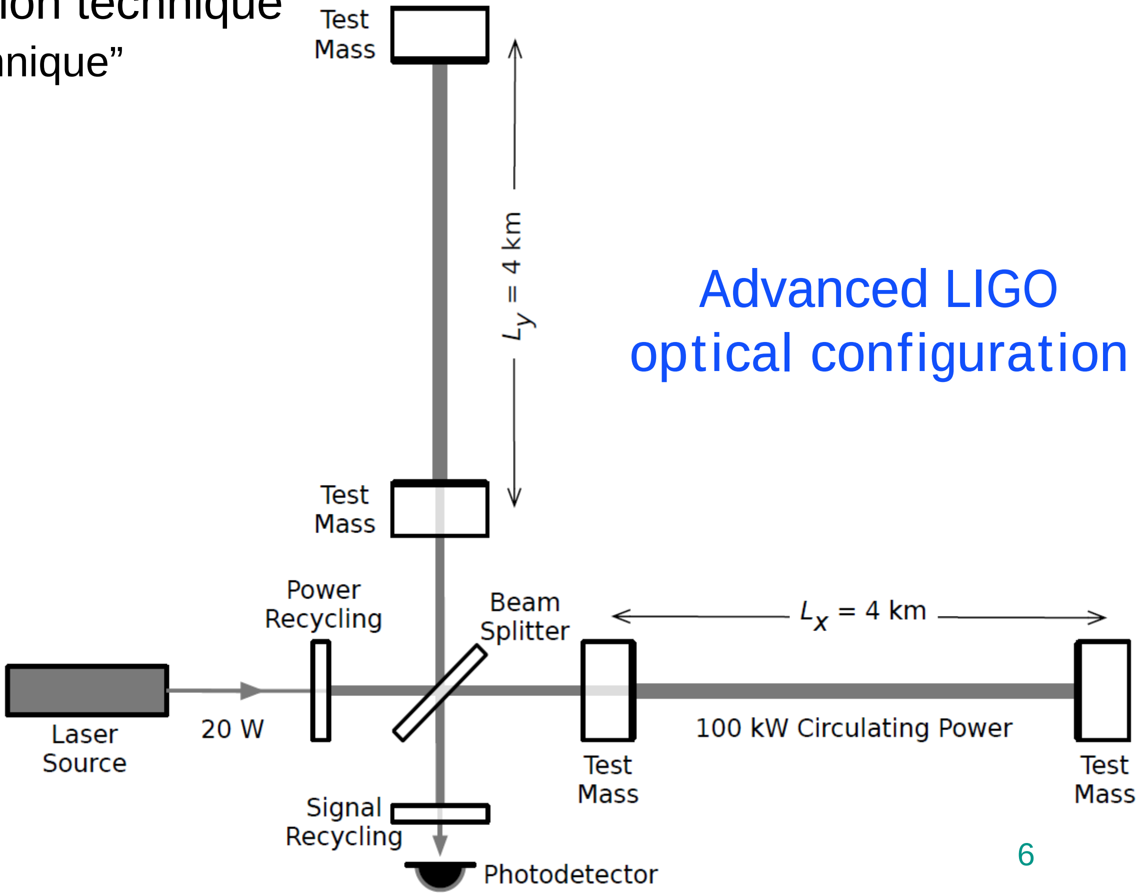
GW detection with laser interferometers

- In the 80’s it became clear that the detection of GW amplitudes of the order of 10^{-21} was possible
  - km-scale laser interferometers were needed



Ronald W. P. Drever

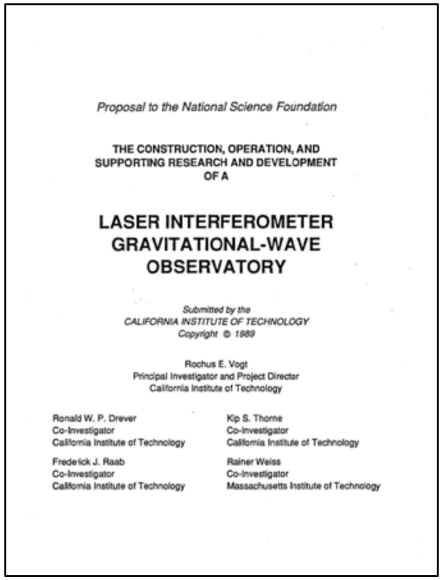
- The inventor of nowadays interferometer optical configurations
  - Fabry Perot cavities in the arms
  - Power recycling technique
  - Signal recycling technique
  - Laser frequency stabilization technique
    - » "Pound-**Drever**-Hall technique"



Advanced LIGO optical configuration

End of the 80's

- Proposals to build km-scale laser interferometers
  - Required investment ~ 100 M$ / interferometer + salaries
- LIGO (US)
  - Two interferometers, 4km long
  - Approved in 1990, construction started in 1994
- Virgo (France-Italy)
  - One interferometer, 3km long
  - Approved in 1993, construction started in 1996
- GEO (Germany-UK)
  - One interferometer, 3km long
  - Not approved (effect of German reunification)
  - GEO600 (600m long) funded by Lower Saxony



Proposal to the National Science Foundation

THE CONSTRUCTION, OPERATION, AND SUPPORTING RESEARCH AND DEVELOPMENT OF A

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

Submitted by the CALIFORNIA INSTITUTE OF TECHNOLOGY
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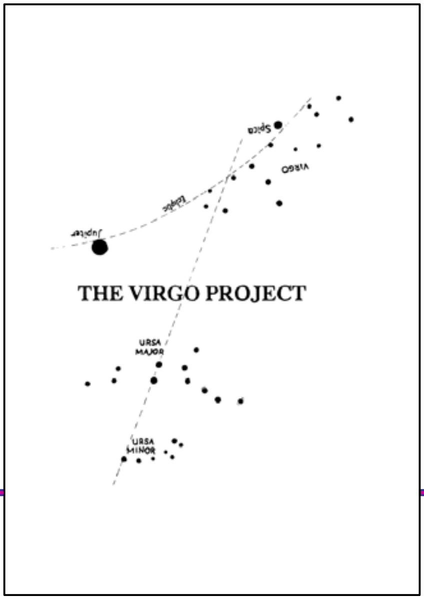
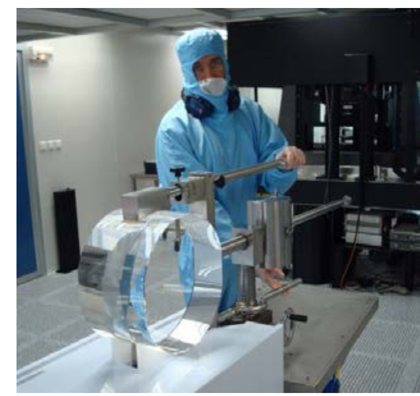
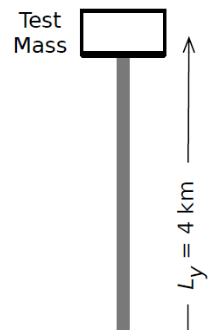
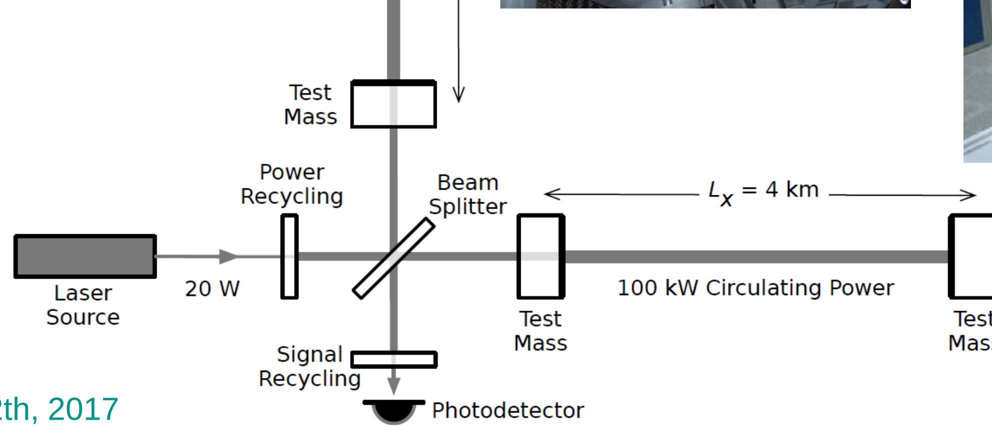


More than a supreme laser interferometer

- Many challenges: vibration isolation, lasers, coatings, vacuum, electronics, signal processing, …
  - An additional challenge: have all these experts working together in the same project!



Initial LIGO/Advanced LIGO timeline

1986 Physics Decadal Survey endorses LIGO
1990 National Science Board (NSB) approves LIGO construction proposal
1992 NSF selects LIGO sites in Washington and Louisiana states.
1994 Site construction begins
1997 The LIGO Scientific Collaboration (LSC) is established
2002 First coincident operation of initial LIGO interferometers and GEO600
2004 NSB approves Advanced LIGO
2006 LIGO design sensitivity achieved.
2007 Joint data analysis agreement ratified between LIGO and Virgo.
Joint observations with LIGO and Virgo starts.
2008 Construction of Advanced LIGO components begins
2014 Advanced LIGO installation complete

September 14, 2015 First GW detection!

Initial Virgo/Advanced Virgo timeline

1989 Virgo proposal

1993 Virgo approved by France and Italy

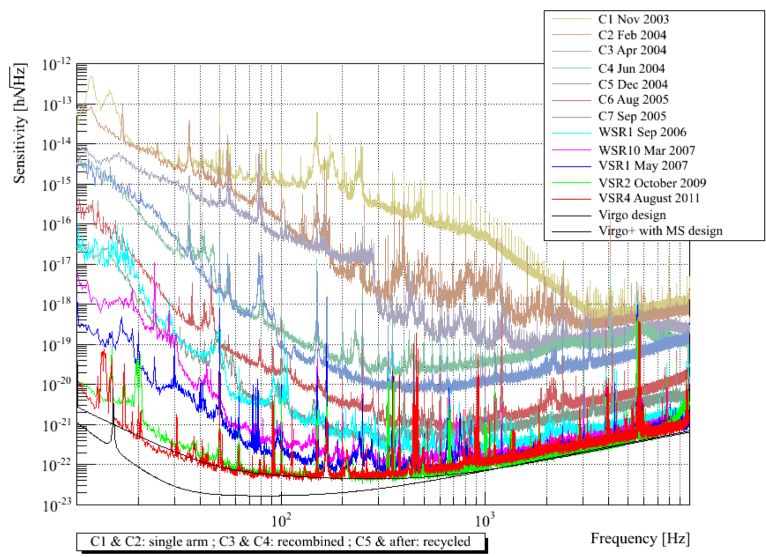
1996 Site construction begins

2003 Installation completed

2007 Joint data analysis agreement ratified between LIGO and Virgo. Joint observations with LIGO and Virgo starts

2009 Construction of Advanced Virgo starts

2016 Advanced Virgo installation completed

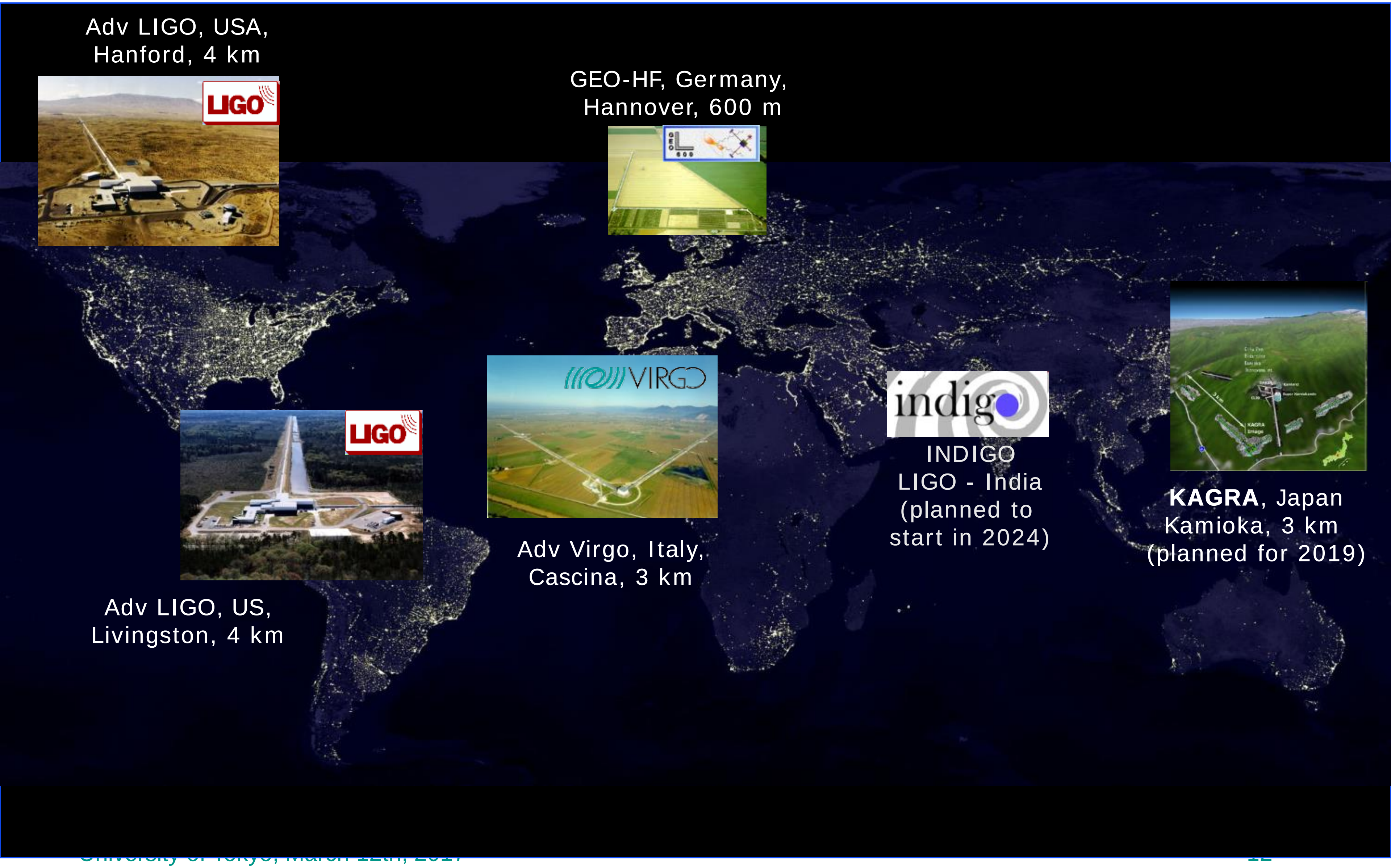


LIGO/Virgo projects and collaboration

- Large projects
  - > 100 M$
  - Several 100's scientists (LIGO+Virgo = 1000 people)
  - Project management culture required
    - » Already common in large astronomy projects, had just entered the field of particle physics in the 90's
  - Unite scientists from different fields
    - » astrophysics, particle physics, optics, general relativity, signal processing, etc.

- LIGO-Virgo collaboration model
  - Independent projects
    - » Independent detector funding and construction
  - Joint operation planning
  - Full data sharing
  - Joint data analysis groups and internal review
  - Joint publications
    - » Common publication policy
    - » Typical of large collaborations

A world-wide network of detectors



Source localization

- LIGO and INDIGO consortium agreed to install the 3rd Advanced LIGO detector in India
  - LIGO-India
  - Larger baseline
  - Better source localization

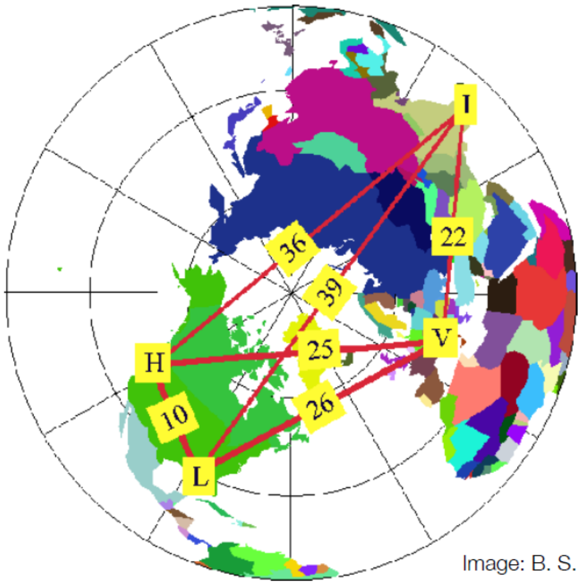
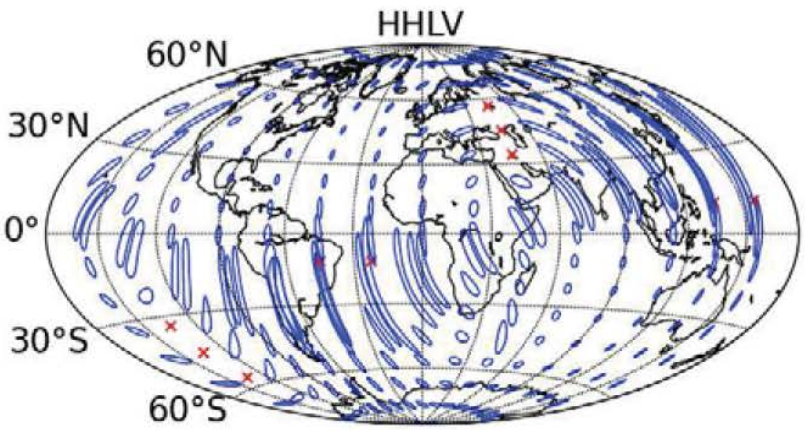
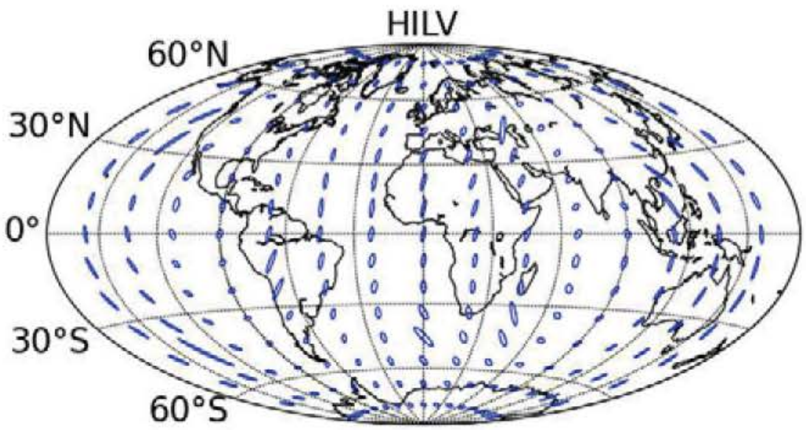


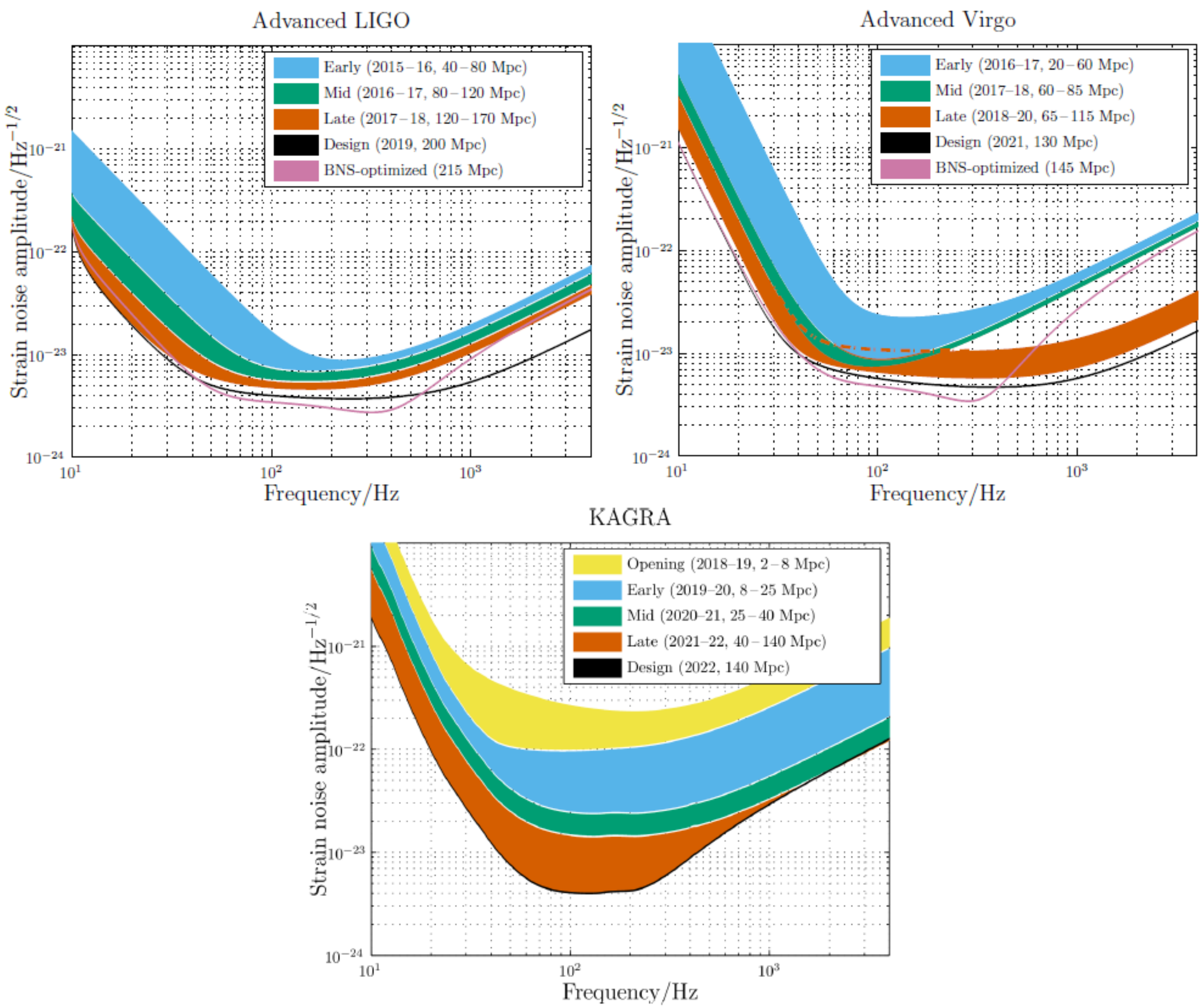
Image: B. S. Sathyaprakash





Observing scenario

- Under discussion



Observing scenario

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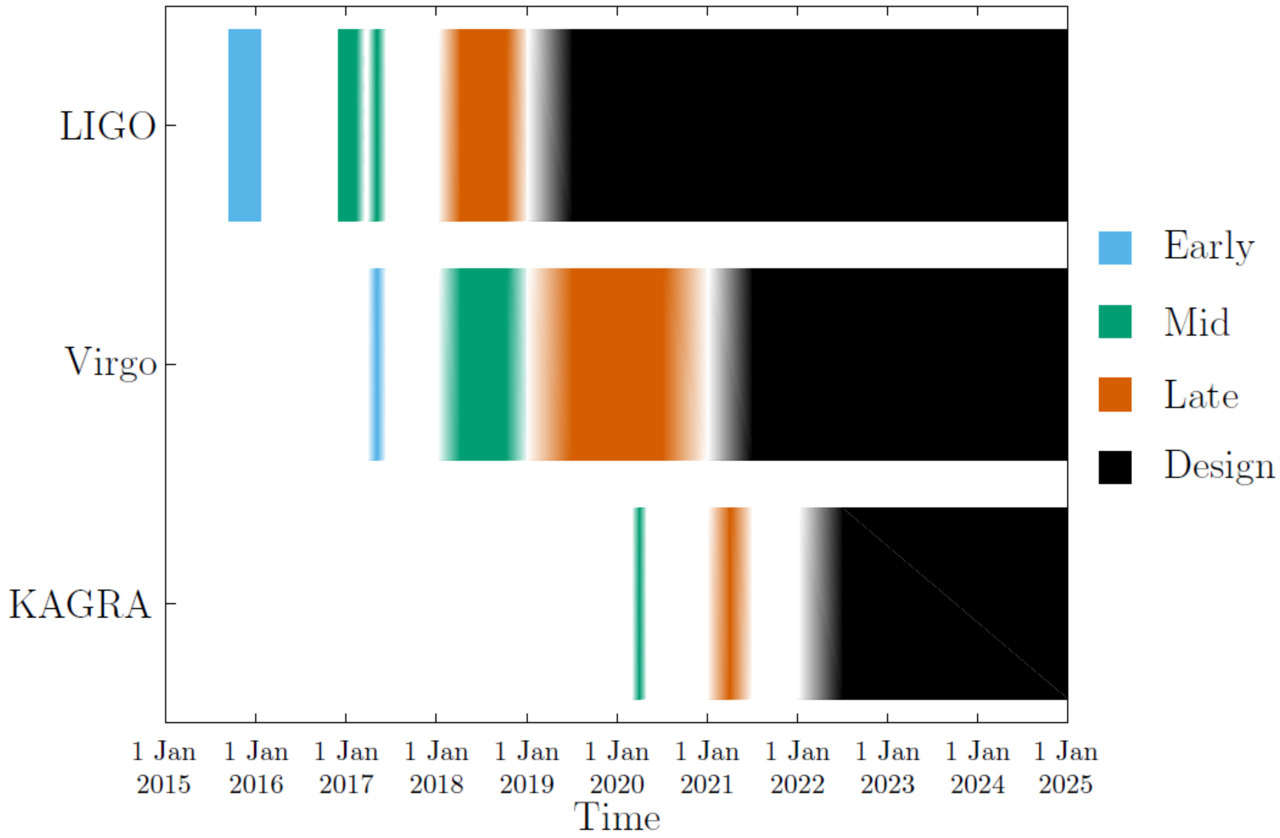
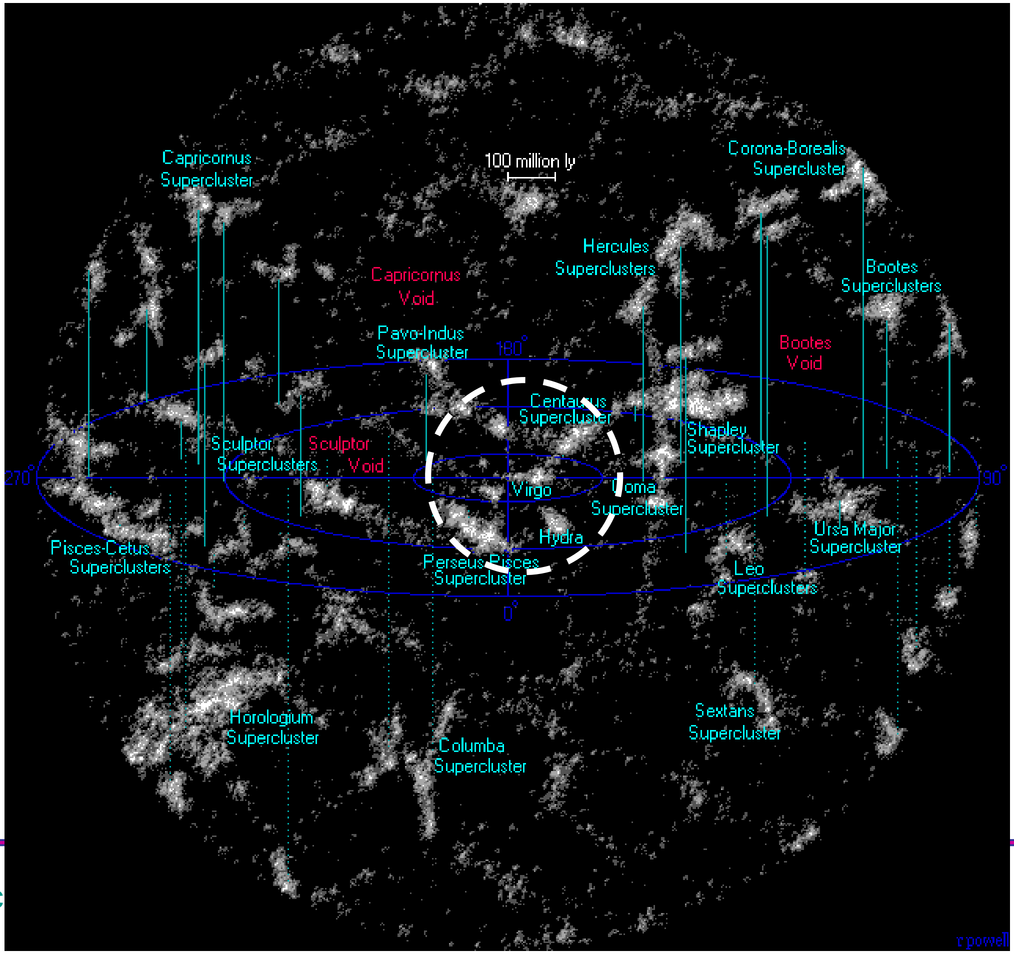


Perspectives

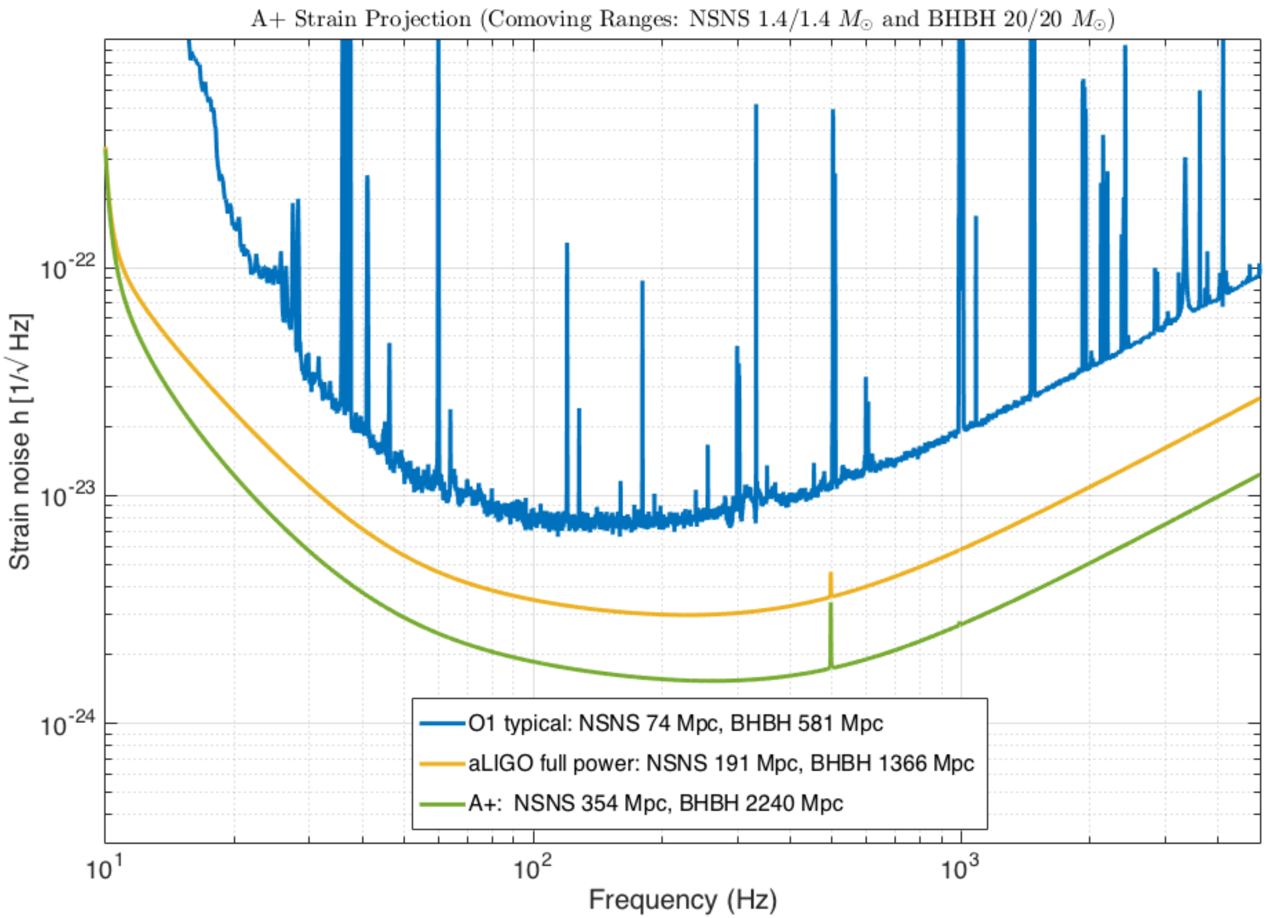
- IMPORTANT:
  - GW detectors sense amplitude
    => a factor of 2 improvement in sensitivity increase rate of events by 8



Credit: R. Powell

Perspective in the US: A+

- Advanced Virgo +
  - Cost: “a small fraction of Advanced LIGO”
  - Improve sensitivity by 1.7 and so event rates by 5

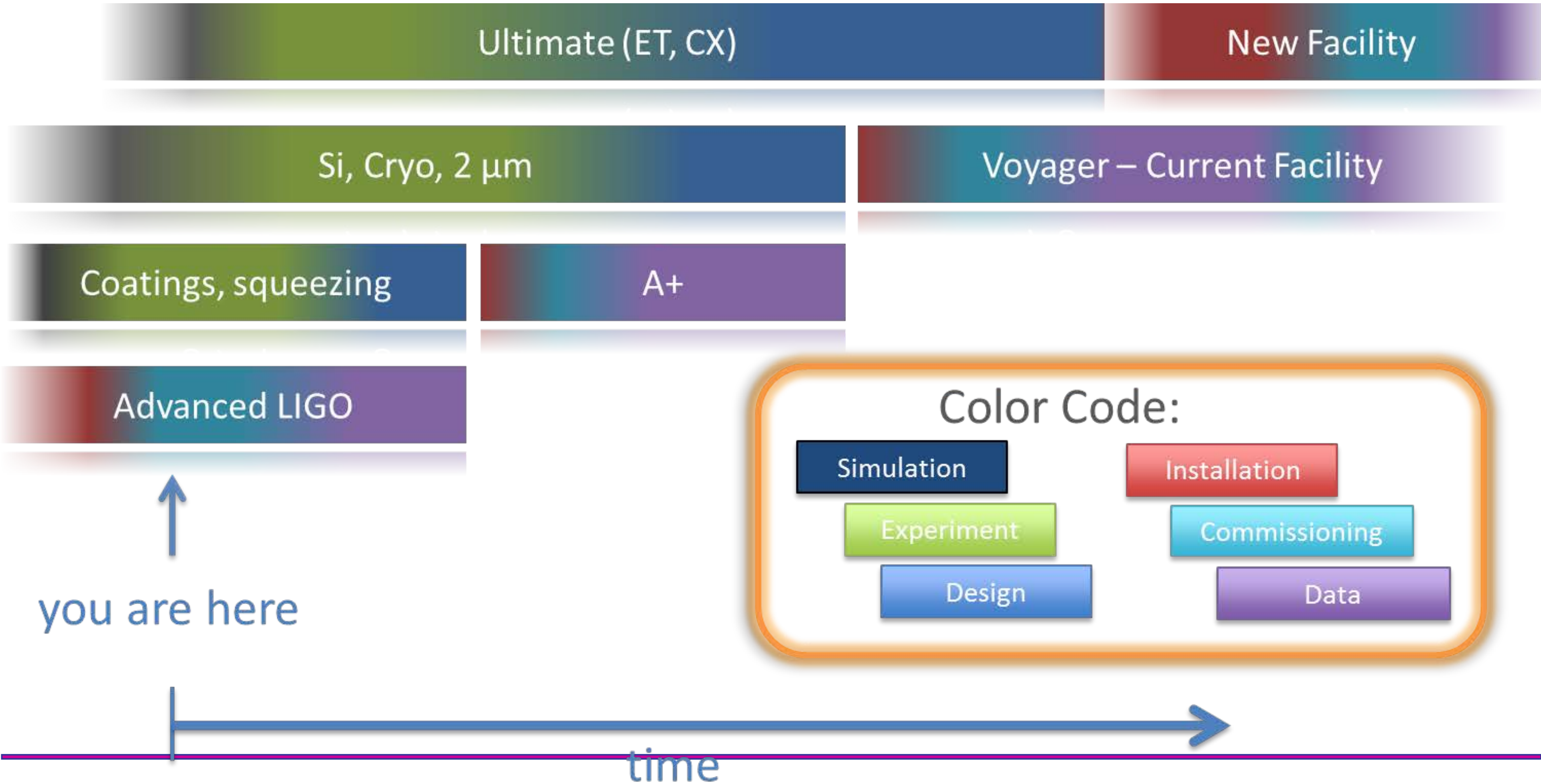


A+ key parameters:

12dB injected squeezing
15% readout loss
100 m filter cavity
20 ppm RT FC loss
CTN half of aLIGO

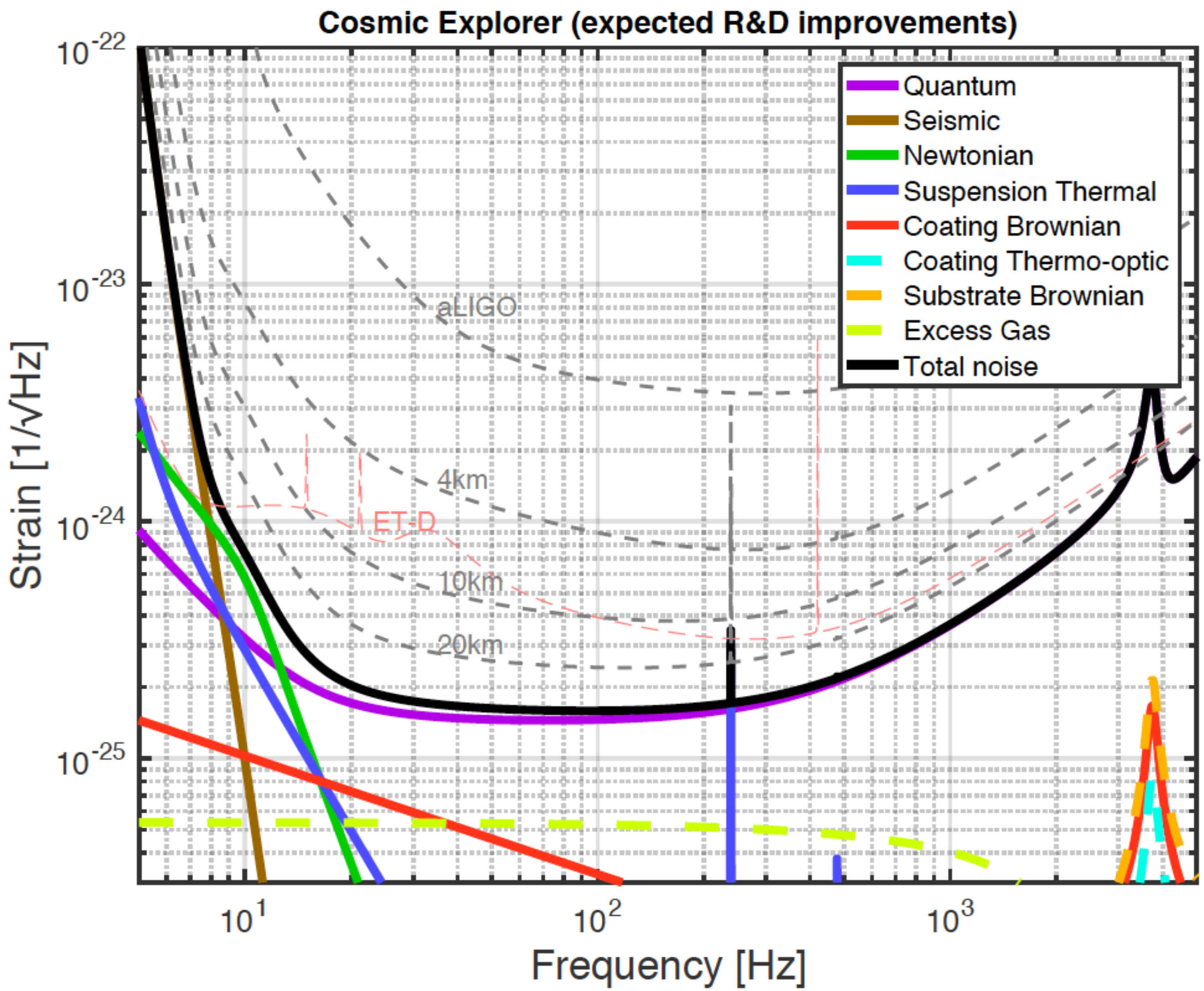
Perspectives in the US

- Under discussion



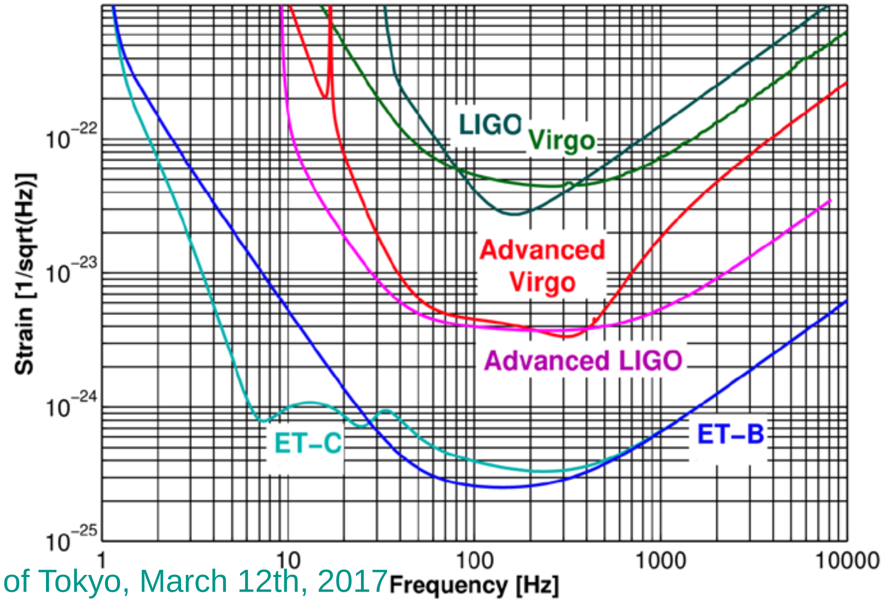
Perspectives in the US: Cosmic Explorer

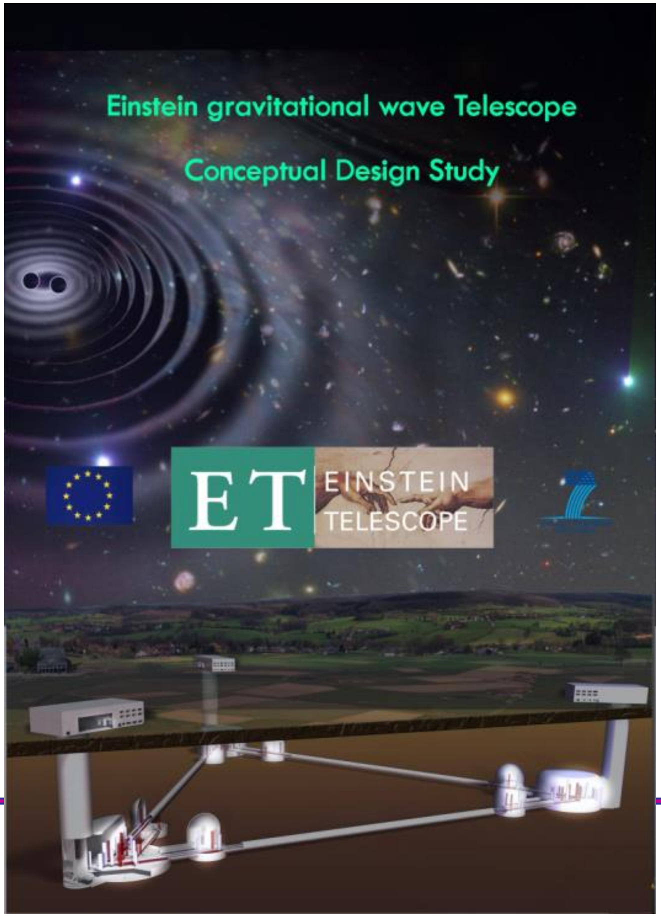
- A new facility: 40 km long?



Perspectives in Europe: Einstein Telescope

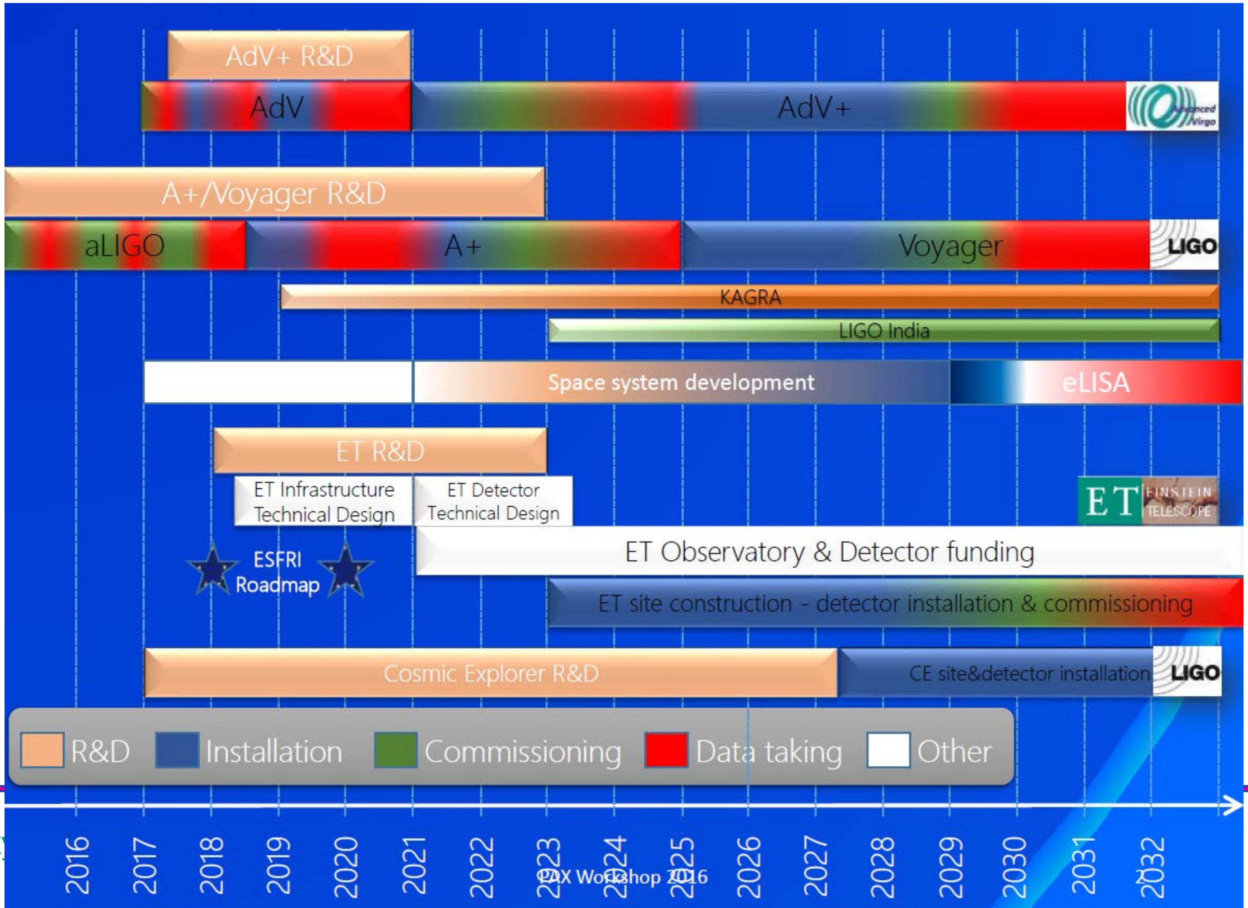
- Proposal for a new European infrastructure devoted to GW astronomy
  - Design study financed by the EU. Released in 2011
  - Goal: x10 better sensitivity compared to advanced detectors
- Keywords:
  - Underground
  - 10 km triangle
  - Cryogenic





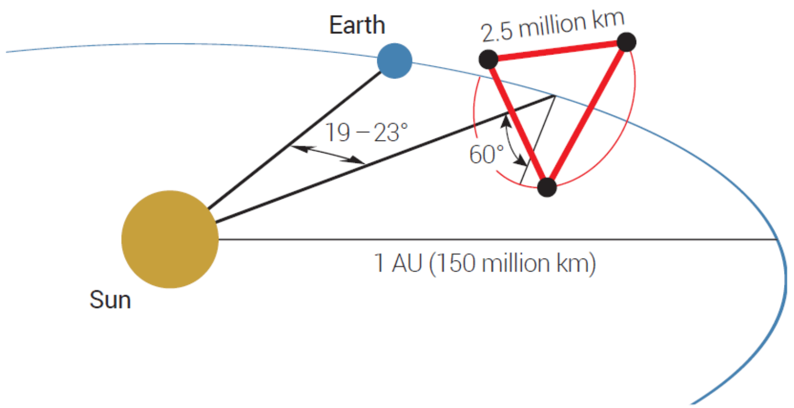
Perspectives in Europe: Einstein Telescope

- Several countries involved in Europe (DE, FR, IT, GB, NL, …)
- Important to get on the ESFRI Roadmap
  - European Strategy Forum for Research Infrastructures
- Possible timeline

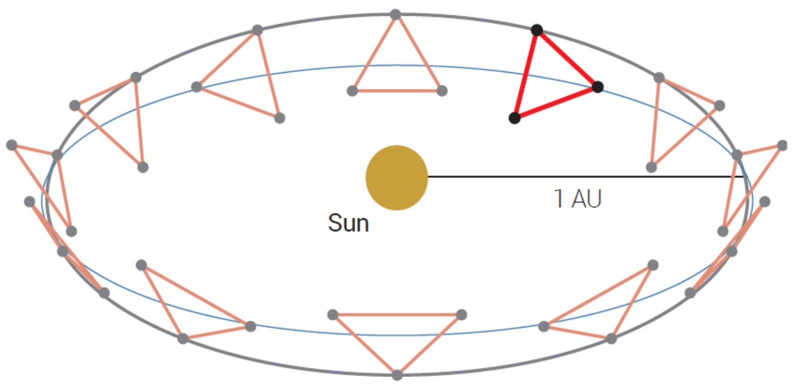


Laser Interferometer Space Antenna

- Laser Interferometer Space Antenna: LISA
  - ◆ 3 Michelson interferometers
    - » L = 2.5 million km
  - ◆ 3 S/C in heliocentric orbit
  - ◆ 20 degrees behind the earth
  - ◆ Plane inclined by 60 degrees



- Sensitive to low frequencies
  - ◆ 10^{-3} – 10^{-1} Hz

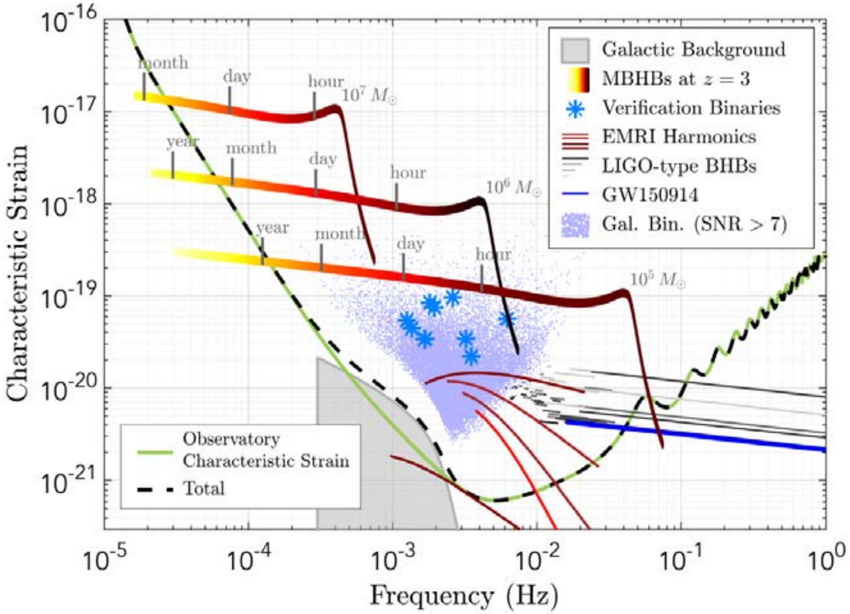


- Complementary to ground-based detectors

- Selected as L3 mission by ESA
  - ◆ Launch planned in 2034
  - ◆ Possible to anticipate after the LISA Pathfinder results
  - ◆ Contribution from NASA under discussion

Laser Interferometer Space Antenna

- Massive black hole binary inspiral and merger
  - ◆ Dynamical behavior of space-time
  - ◆ Growth of massive black holes
  - ◆ Absolute distances
- Ultra compact binaries
  - ◆ Extreme degenerate stars (mainly WD, NS, BH, …)
- Extreme mass ratio inspirals
  - ◆ Test Kerr black hole solution of GR
  - ◆ Study galaxy nuclei
- Cosmological backgrounds



Worldwide strategy setting

- Signal coincidence in different detectors will continue to be crucial for GW astronomy
  => International coordination is mandatory

- Gravitational Wave International Committee (GWIC)
  - ◆ Representative from all detectors/projects
    - » LIGO, Virgo, KAGRA, GEO, LISA, …

- Gravitational Wave Agency Committee (GWAC)
  - ◆ Promoted by NFS
  - ◆ Representatives from funding agencies in several countries
    - » US, Canada, Germany, France, Italy, Spain, UK, Australia
    - » Japan is missing so far

Conclusion

- First gravitational wave detection achieved!
- Gravitational wave astronomy started!
- 20 years of effort with Initial detectors and Advanced detectors
  - 10 year cycles
- Advanced LIGO/Virgo upgrades being prepared
- LISA on track to be launched in 2034 (earlier launch technically possible)
- New ground based facilities discussed in Europe and in the US
- GW science has a bright future