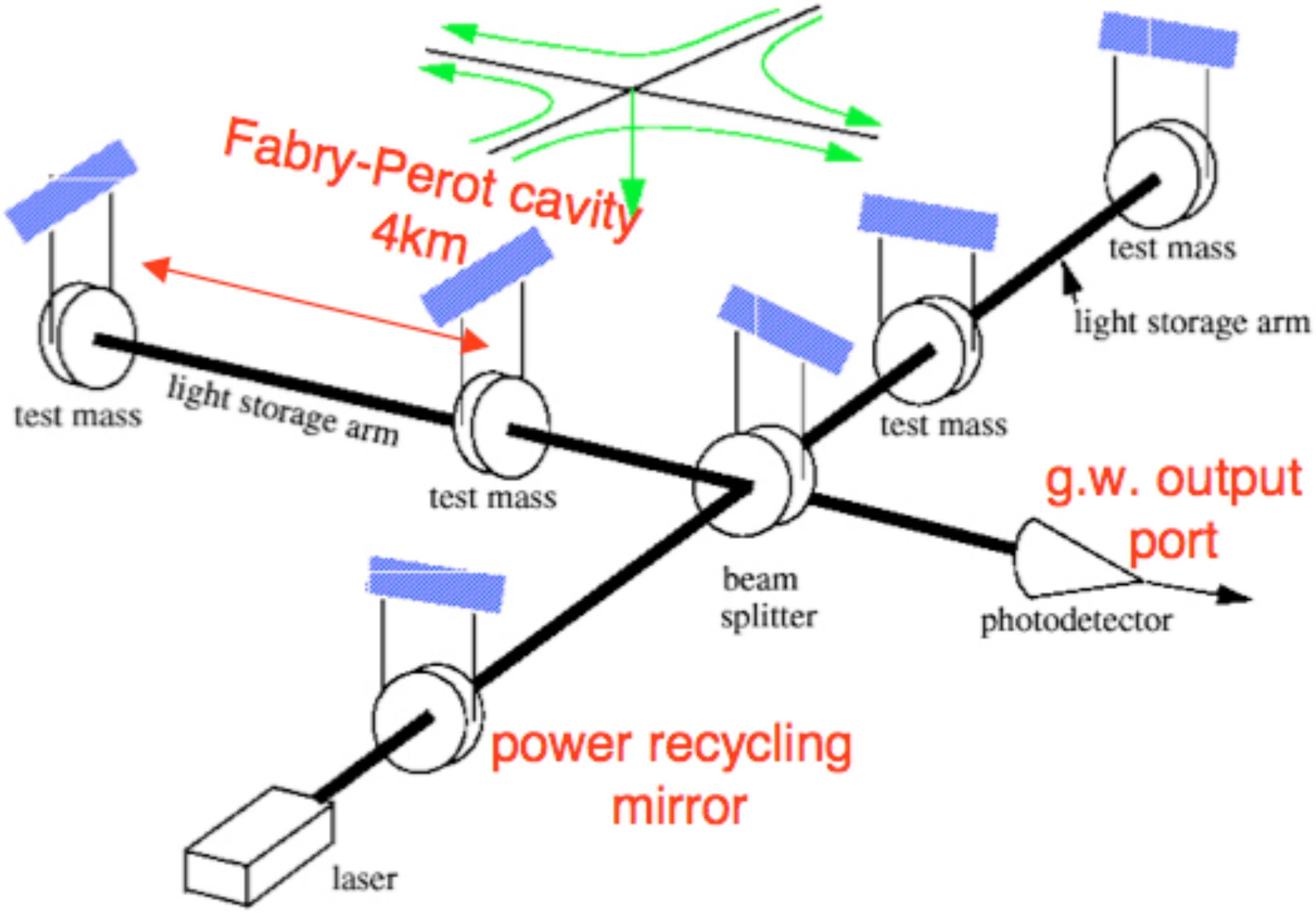
LISA Project

이형목
2020년 12월 20일
우주기반 기초 연구 워크숍

Plan

- Present and Future Ground-based detectors
- Why we need space based detectors
- LISA Projects

Laser Interferometers (LIGO/Virgo)



- 2002-2010 Initial LIGO
- 2015.9 ~ Advanced LIGO (10times better sensitivity)

Simple Estimates of Sensitivity of Interferometers

- If the length measurement is limited by the wavelength of the laser

$$h \equiv \frac{\Delta l}{l} = \frac{\lambda_{laser}}{l} = \frac{10^{-6}\mathrm{m}}{10^{3}\mathrm{m}} = 10^{-9}$$

- Optical path length can be significantly increased by adopting optical cavity, but should be smaller than GW wavelength (~1000 km for 300 Hz)

$$h \sim \frac{\Delta l}{l_{eff}} \sim \frac{\lambda_{laser}}{\lambda_{GW}} \sim \frac{10^{-6}\mathrm{m}}{10^{6}\mathrm{m}} = 10^{-12}$$

- However, due to quantum nature of the photons, the length resolution coud be as small as $N^{-1/2}_{photons}\lambda_{laser}$. Thus sensitivity could reach

$$h \sim N_{photons}^{-1/2} \frac{\lambda_{laser}}{\lambda_{GW}}$$

Shot noise limit

Shot Noise

- Collect photons for a time of the order of the period of GW wave $\tau \sim 1/f_{GW}$

$$N_{photons} = \frac{P_{laser}}{hc/\lambda_{laser}}\tau \sim \frac{P_{laser}}{hc/\lambda_{laser}}\frac{1}{f_{GW}}$$

- For 1W laser with λ_{laser}=1 μm, f_{GW}=300Hz, $N_{photons}$=10^{16}

$$h \sim \frac{\Delta l}{l_{eff}} \sim \frac{N_{photons}^{-1/2}\lambda_{laser}}{\lambda_{GW}} \sim \frac{10^{-8}\times 10^{-6}\mathrm{m}}{10^{6}\mathrm{m}} = 10^{-20}$$

- By adopting high power laser (20W for O1) and power recycling, we can reach ‘astrophysical sensitivity’ of ~10^{-22}.

Radiation Pressure Noise

- Rms momentum to the test mass given by photon number fluctuation

$$\delta P = \delta N \frac{2h\nu}{c} = \sqrt{N}\frac{2h\nu}{c} = \sqrt{\frac{I_0\tau}{h\nu}\frac{2h\nu}{c}}$$

- The fluctuation in force

$$\delta f = \frac{\delta P}{\tau} = \sqrt{\frac{4h\nu I_0}{c^2\tau}}$$

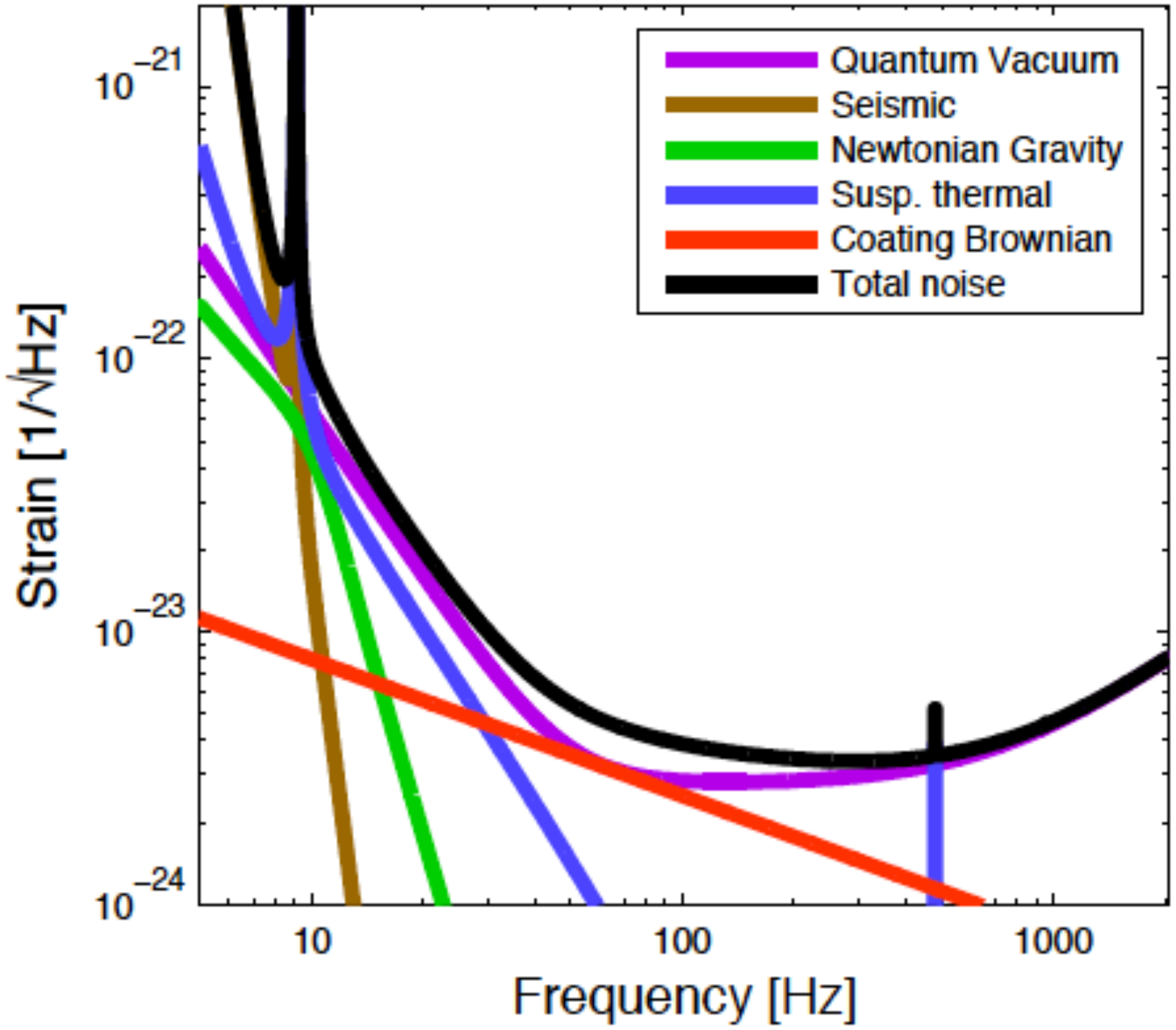
- Strain noise spectral density

$$\sqrt{S_h} = \frac{1}{mf^2L}\sqrt{\frac{4h\nu I_0}{c^2}}$$

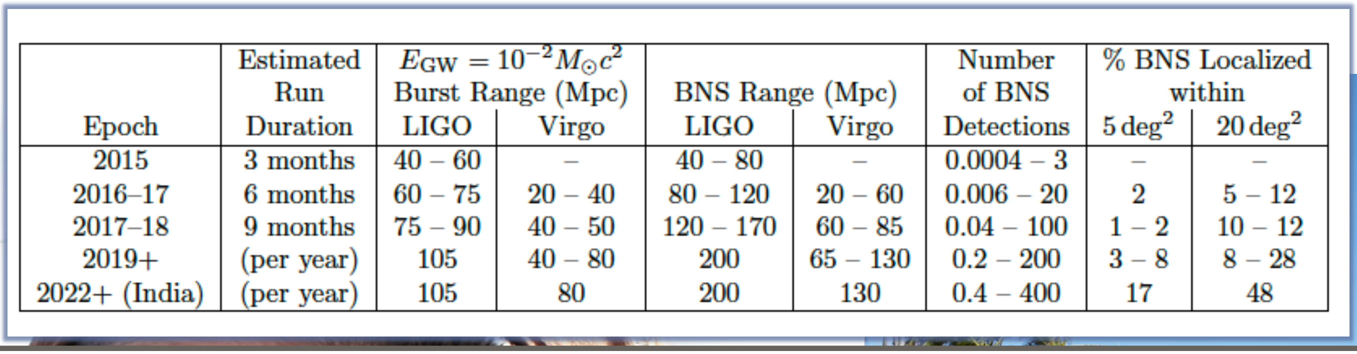
ν : laser frequency
I_0 : laser power
τ : time for measurement ($\sim 1/f$)
L : arm length
m : mass of the mirror

Other Noises

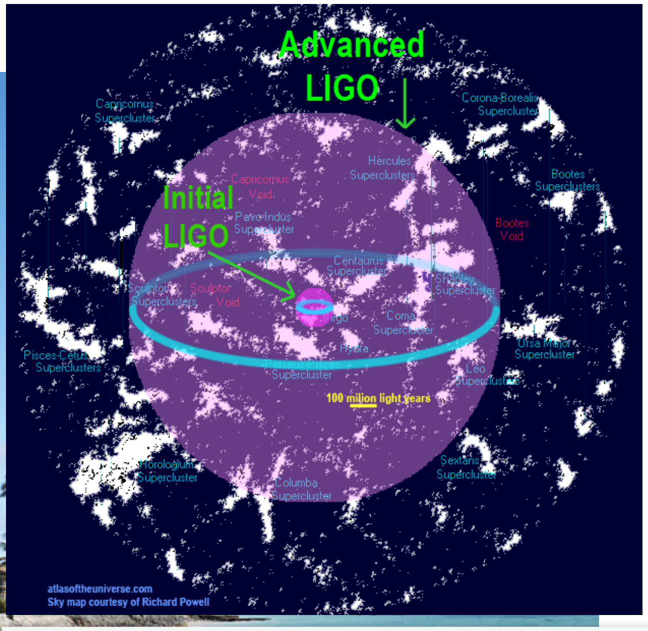
- Suspension thermal noise/ mirror coating brownian noise
    - Increase beam size, monolithic suspension structure
- Seismic noise
    - Multi-stage suspension, underground
- Newtonian Noise
    - So far difficult to avoid.
    - Seismic and wind measurement and careful modeling



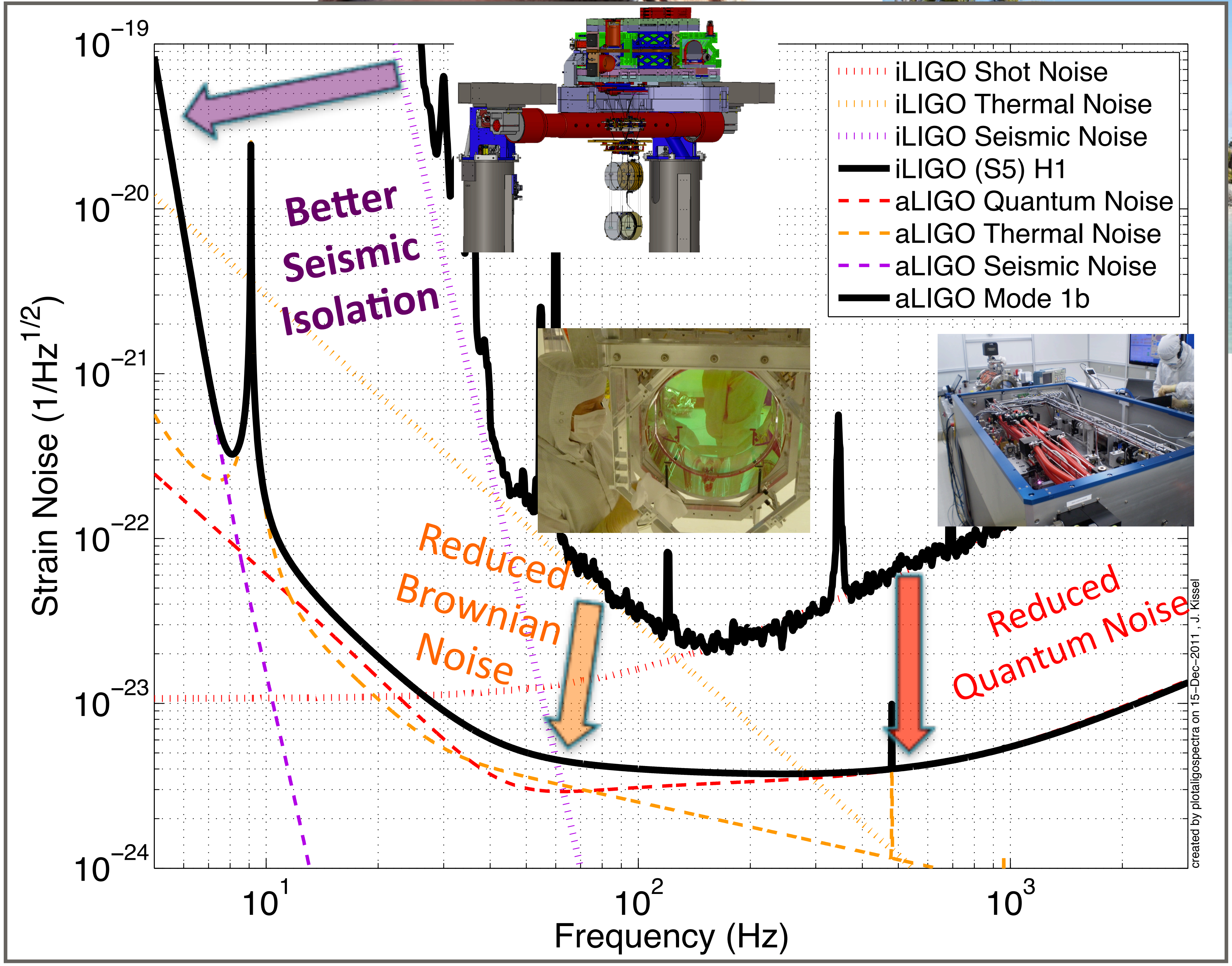
Goal of aLIGO

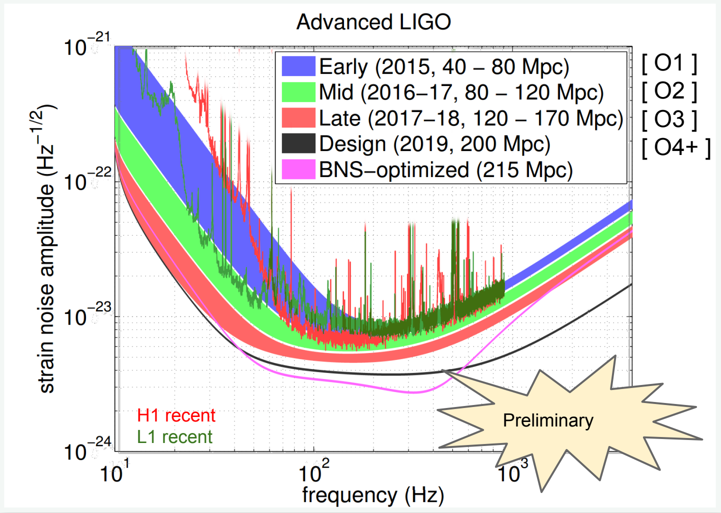


Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

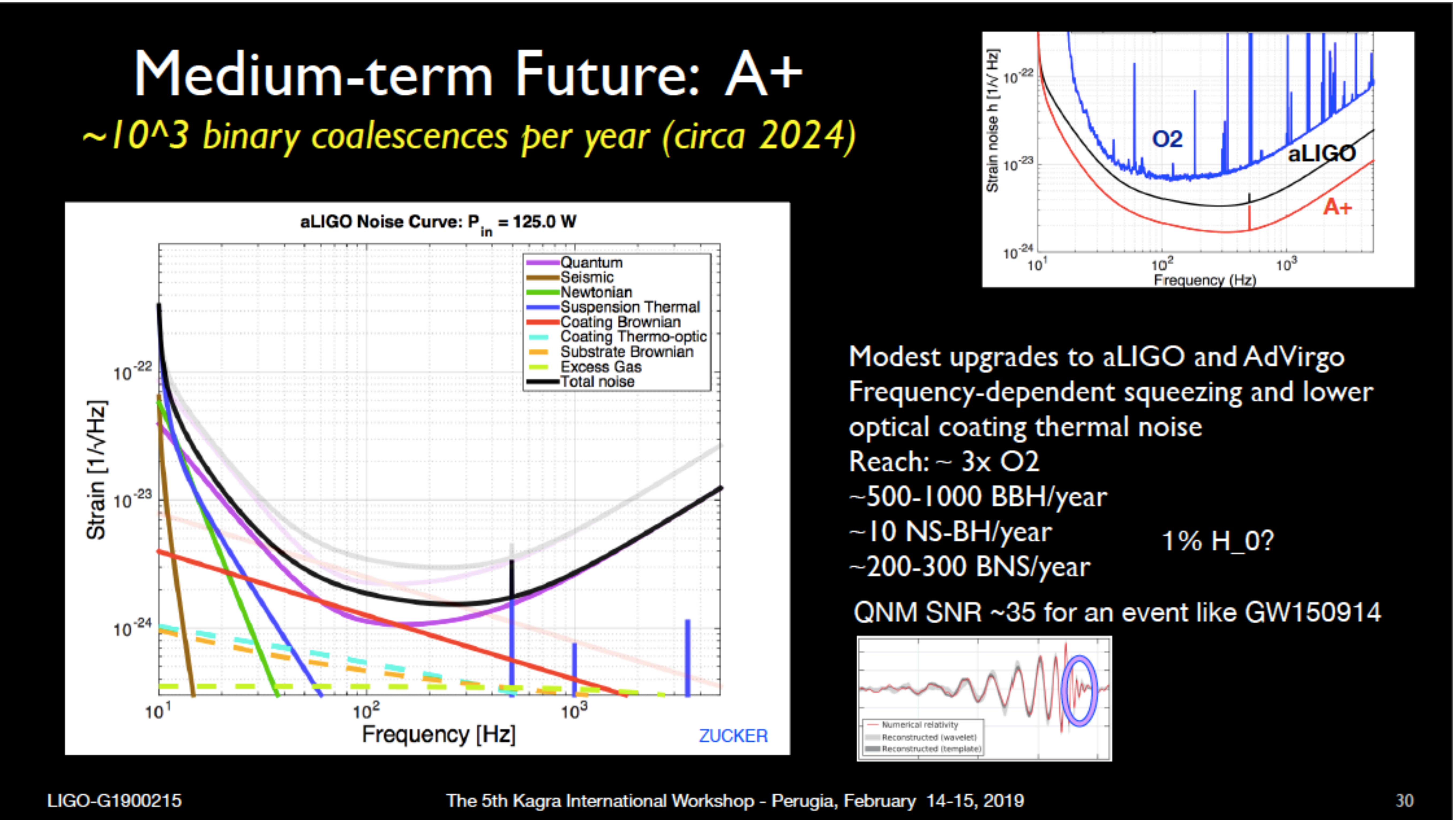


atlasoftheuniverse.com
Sky map courtesy of Richard Powell





Upgrade: 2.5G



Medium-term Future: A+

~10^3 binary coalescences per year (circa 2024)

Modest upgrades to aLIGO and AdVirgo
Frequency-dependent squeezing and lower optical coating thermal noise
Reach: ~ 3x O2
~500-1000 BBH/year
~10 NS-BH/year
~200-300 BNS/year

1% H_0?

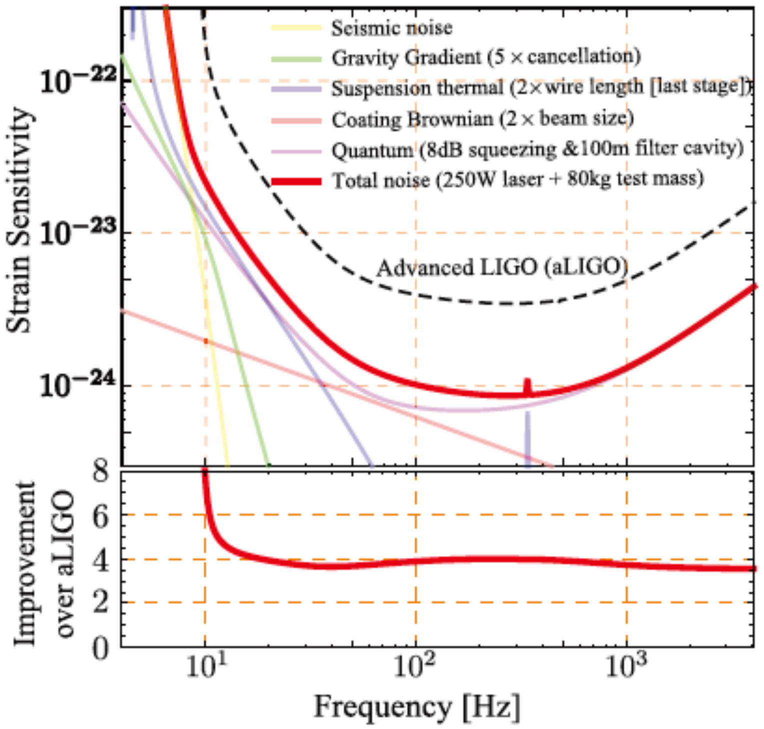
QNM SNR ~35 for an event like GW150914

LIGO-G1900215 The 5th Kagra International Workshop - Perugia, February 14-15, 2019 30

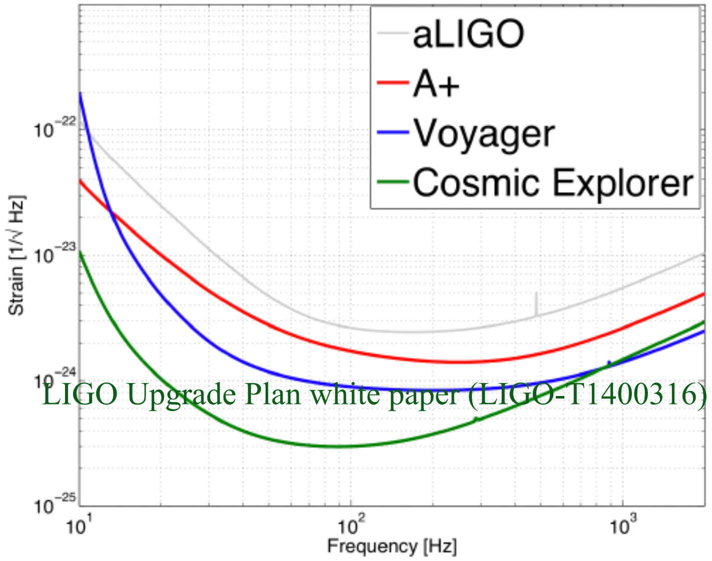
Slide by L. Cadonati

Third Generation (3G) detectors

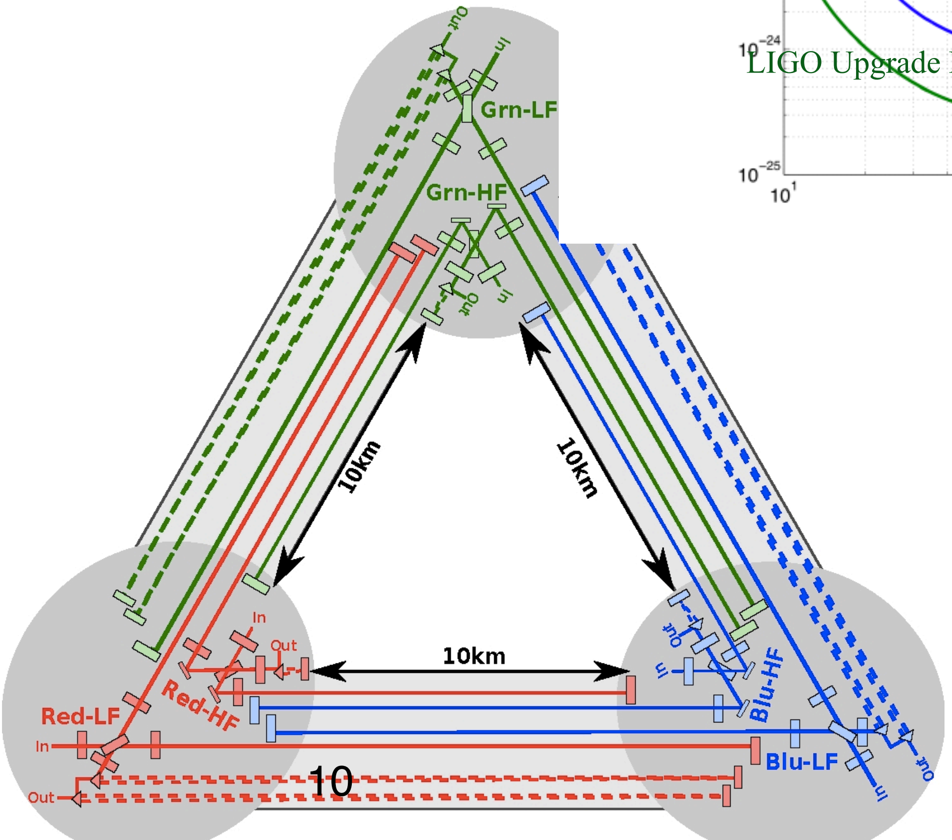
- 8 km detectors in Australia (and p
- Cosmic Explorer (order of magnitude)
- Einstein Telescope
  - 10 km baselines
  - underground
  - cryogenic



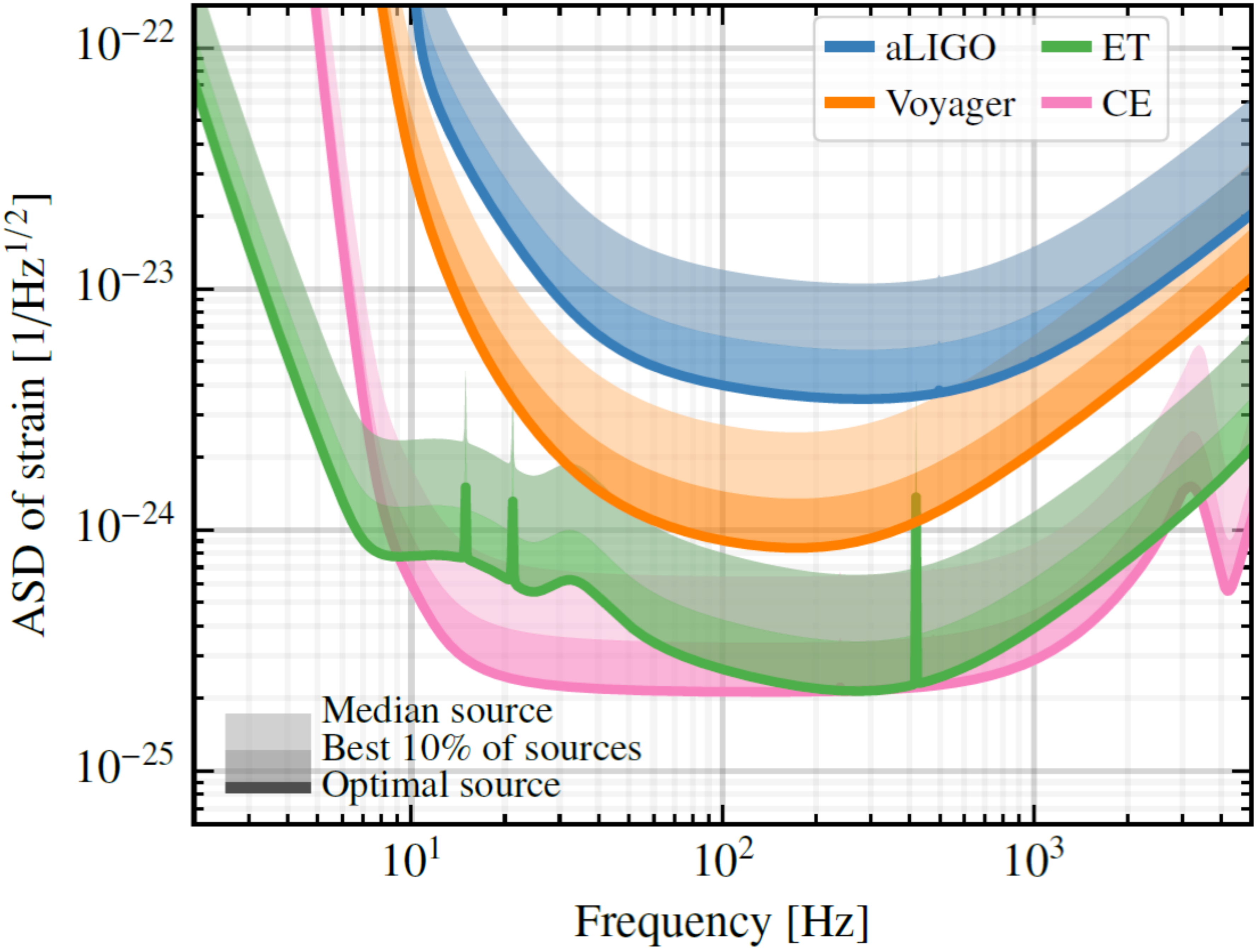
Blair et al. 2015, Science China Physics, Mechanics, and Astronomy, 58, 5747



LIGO Upgrade Plan white paper (LIGO-T1400316)



The Goal of 3G Detectors

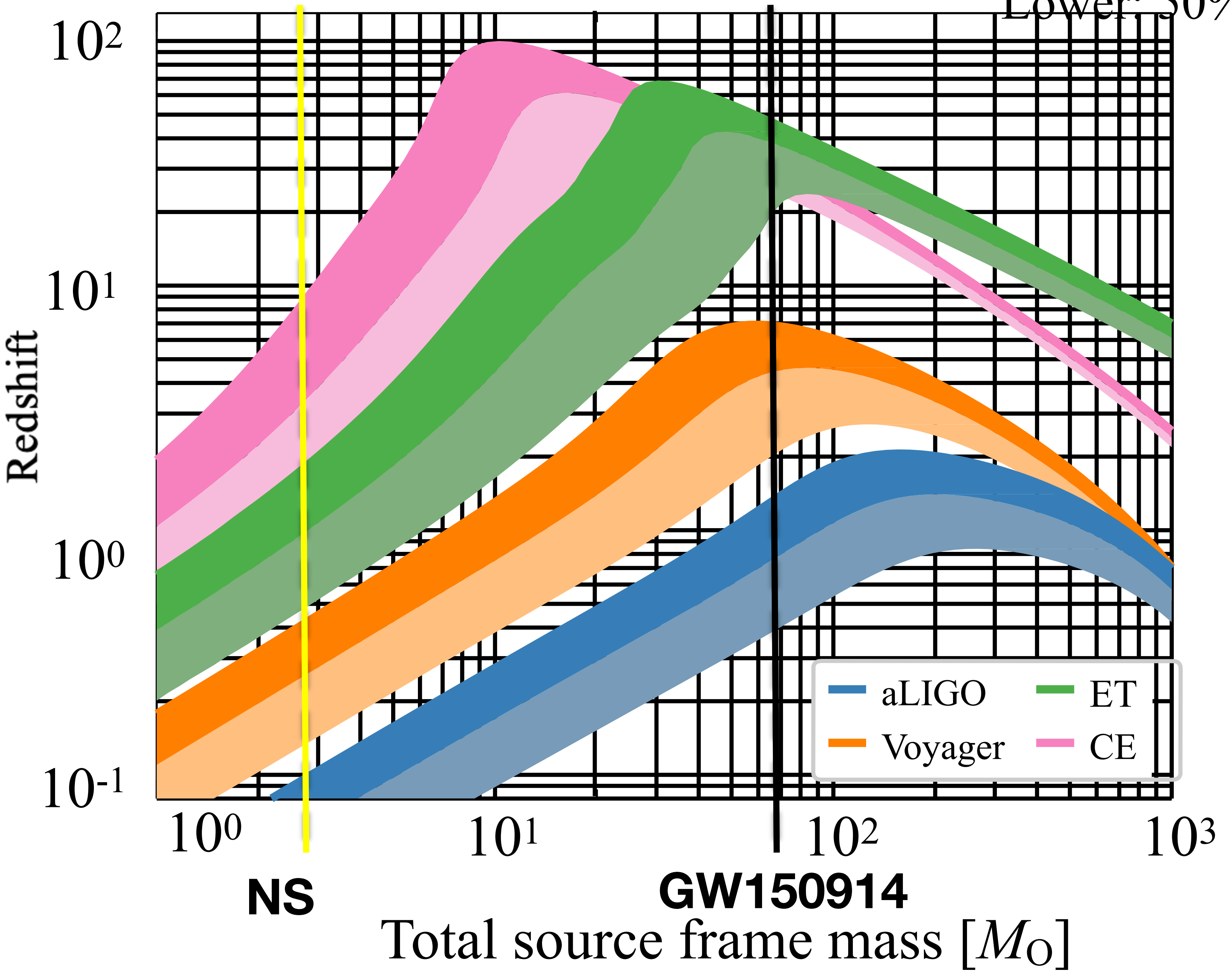


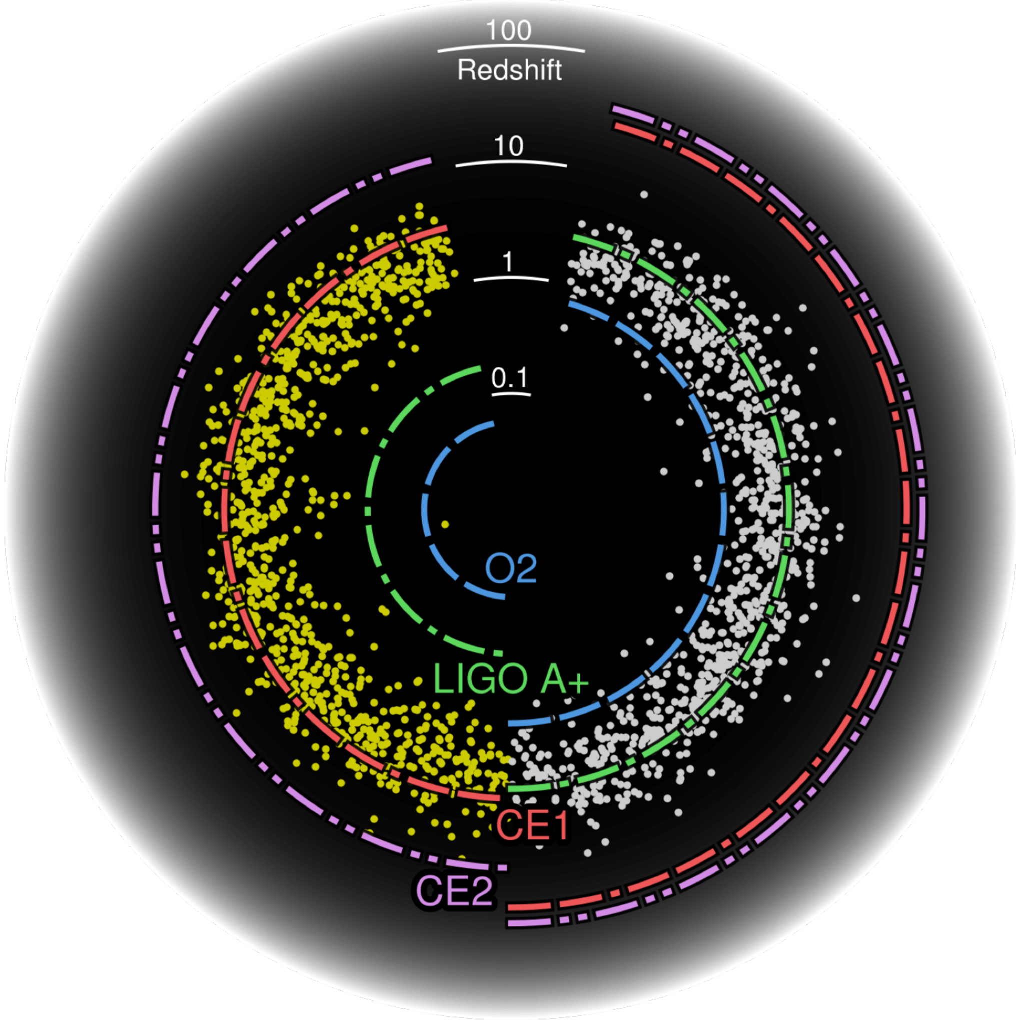
Next several slides by Harald Luck
in the 5th KAGRA International Workshop
https://indico.ego-gw.it/event/12/

How far we can reach?

Credit: E. Hall, J. Miller

Boundary: Horizon
Upper: 10% detection
Lower: 50% detection



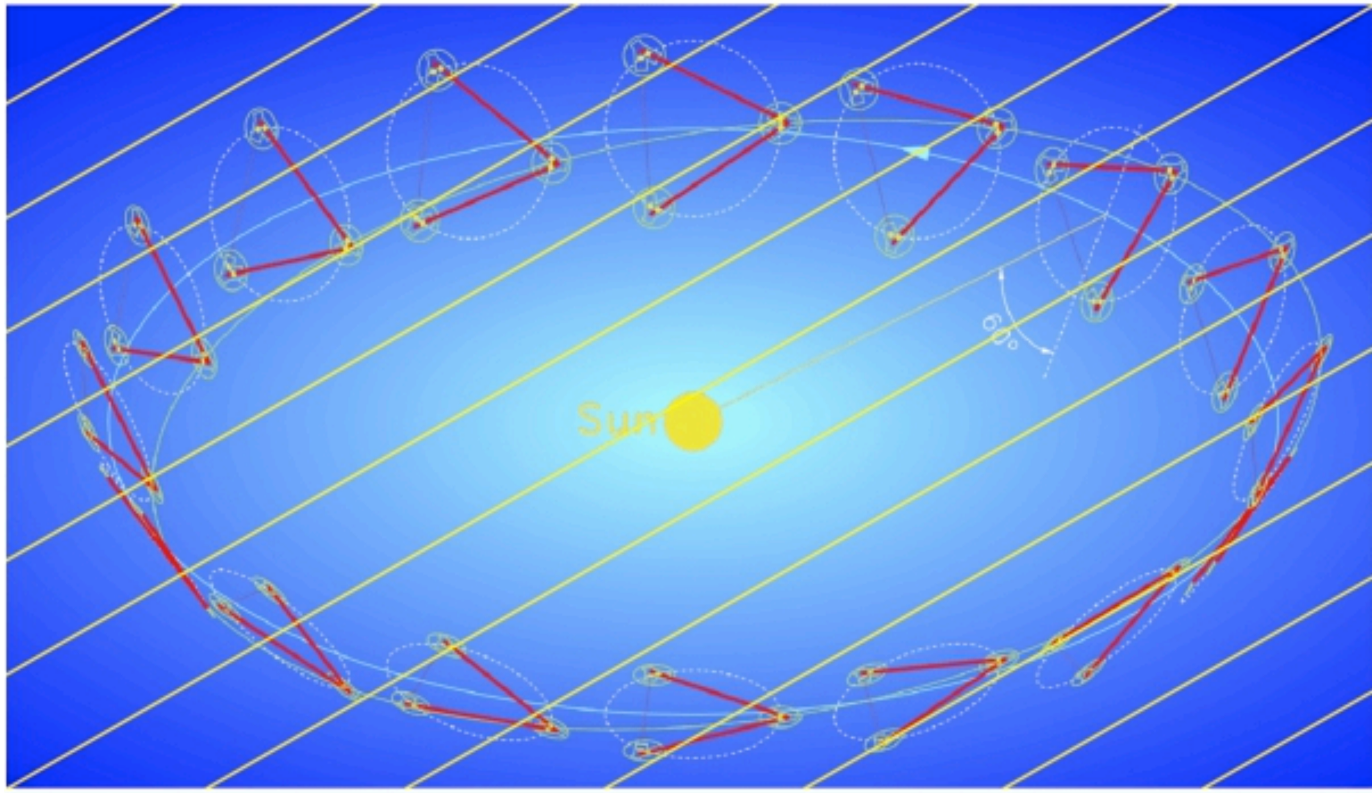


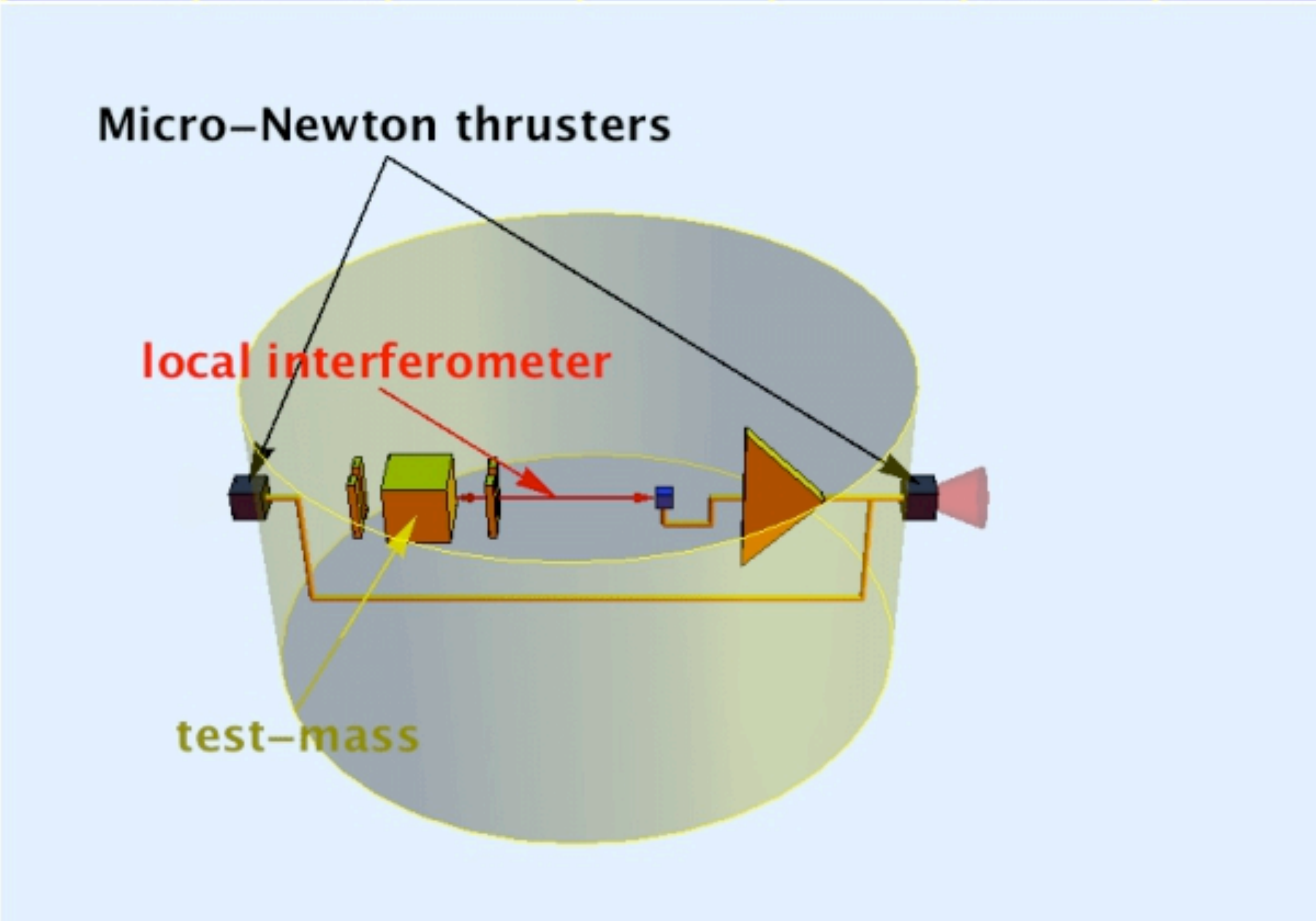
Why do we need space based detectors

- Baseline cannot be longer that ~10 km
- Seismic and Newtonian noises limit the sensitivities at lower frequencies than 1 Hz
  - There are large variety of low frequency GW sources
    - Intermediate mass black holes, massive black holes, white dwarf binaries

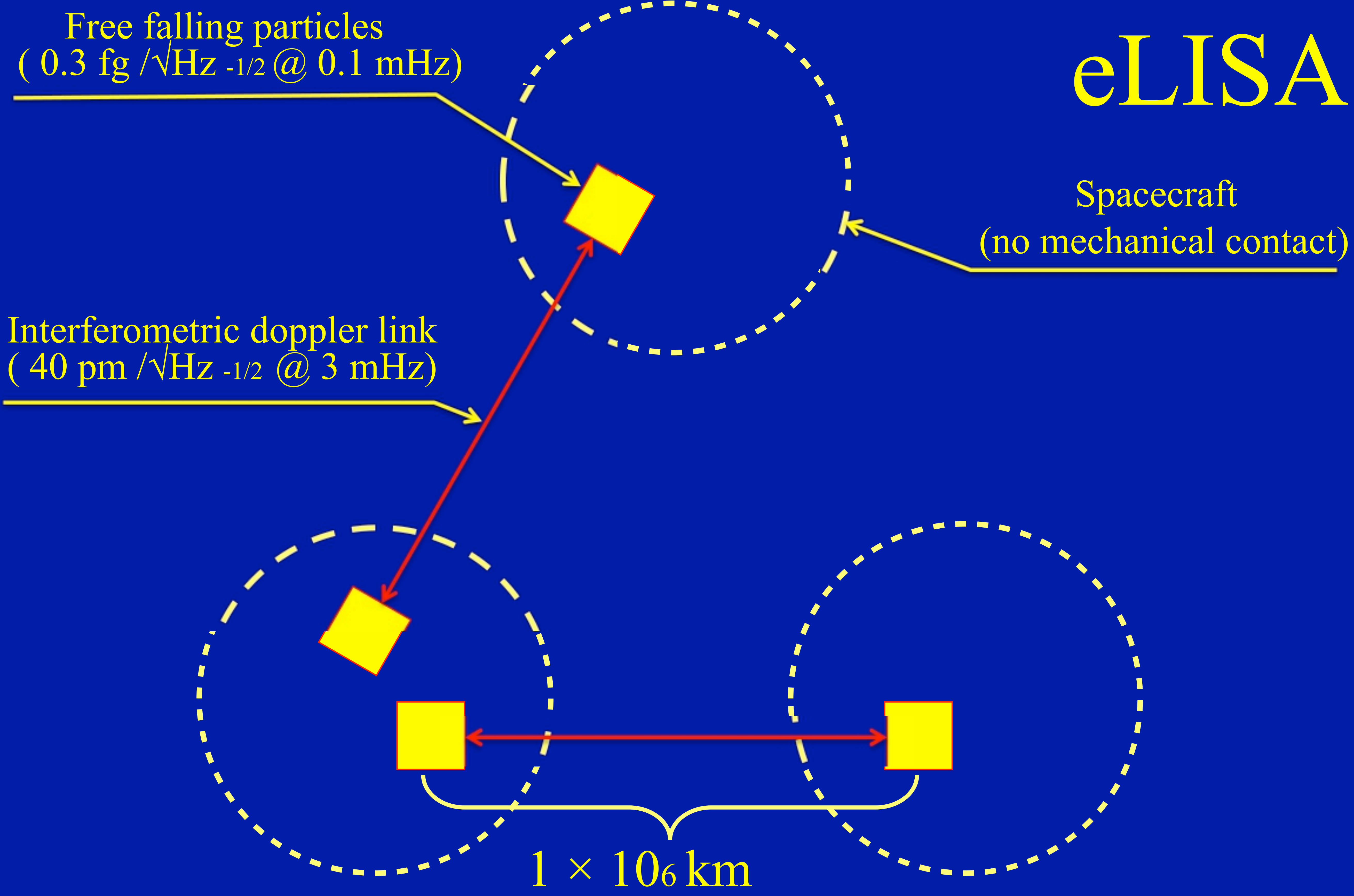
Basic concept of LISA/ eLISA

- Orbits:
  - Satellites follow independent heliocentric orbits. No formation keeping needed
  - Constellation rotates within waves and give source location (and distance)
- Non contacting spacecraft
  - Position of spacecraft relative to test-mass is measured by local interferometer
  - Spacecraft is kept centered on test-mass by acting on micro-Newton thrusters.





eLISA



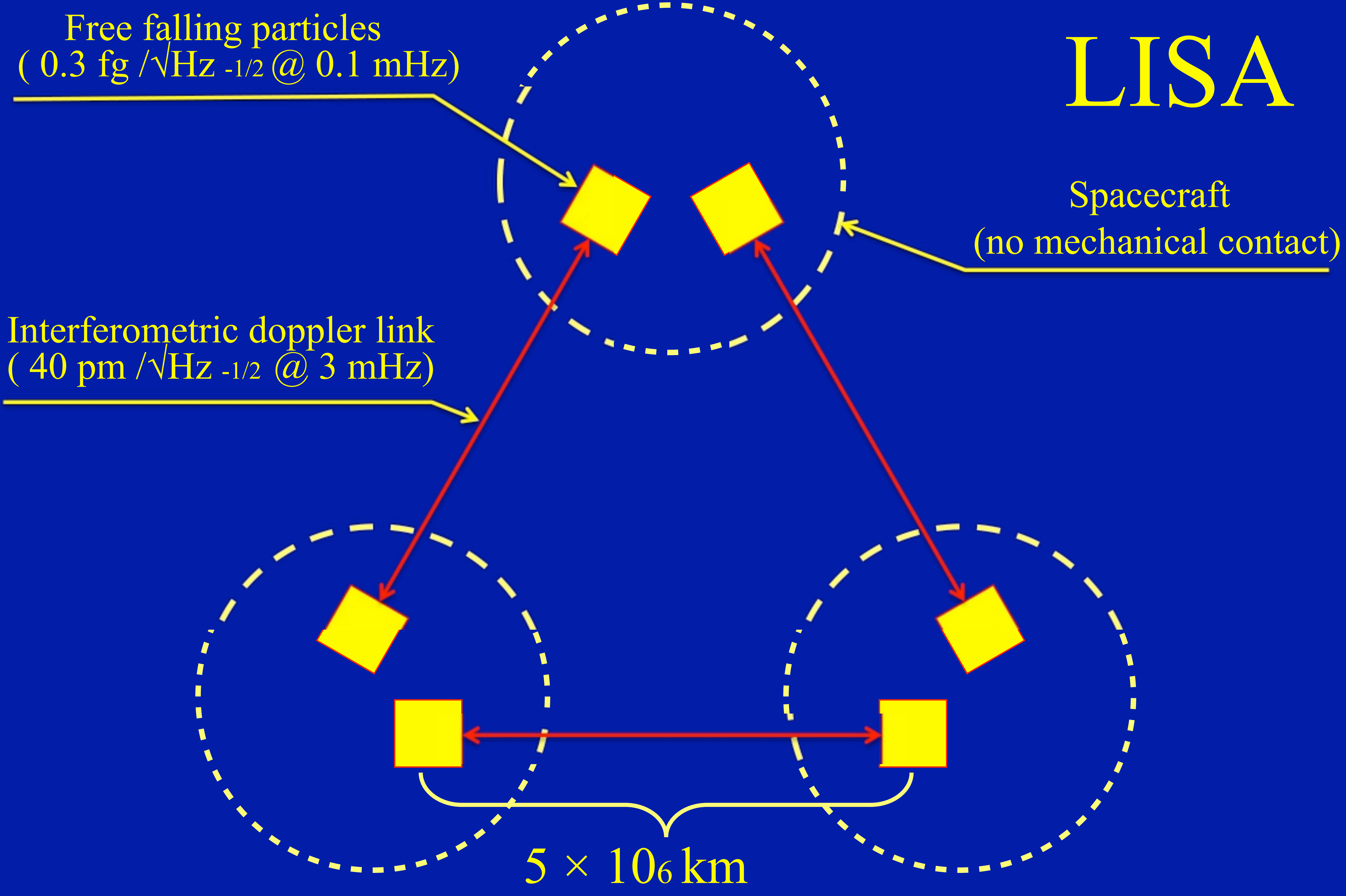
Free falling particles
(0.3 fg /√Hz $_{-1/2}$ @ 0.1 mHz)

Spacecraft
(no mechanical contact)

Interferometric doppler link
(40 pm /√Hz $_{-1/2}$ @ 3 mHz)

$1 \times 10_6$ km

LISA



Free falling particles
(0.3 fg /√Hz $_{-1/2}$ @ 0.1 mHz)

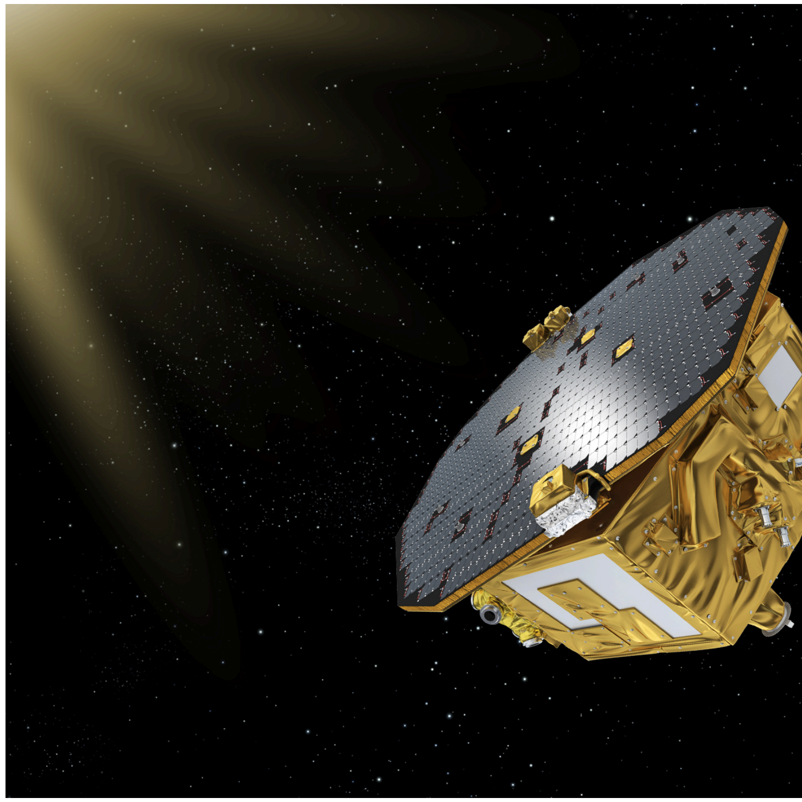
Spacecraft
(no mechanical contact)

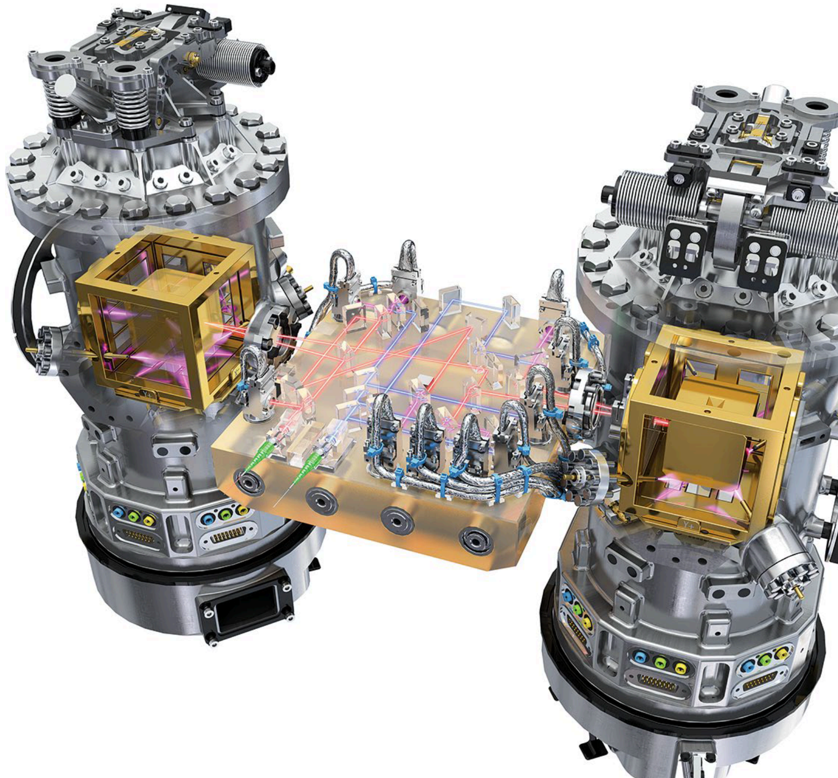
Interferometric doppler link
(40 pm /√Hz $_{-1/2}$ @ 3 mHz)

$5 \times 10_{6}$ km

LISA Pathfinder

- An ESA spacecraft that was launched on 3 December 2015
- The mission tested technologies needed for the LISA
- It placed two test masses in a nearly perfect gravitational free-fall, and controlled and measured their relative motion with unprecedented accuracy.
- Overall, it verified
  - Drag-free attitude control of a spacecraft with two proof masses,
  - The feasibility of laser interferometry in the desired frequency band (which is not possible on the surface of Earth), and
  - The reliability and longevity of the various components—capacitive sensors, microthrusters, lasers and optics.





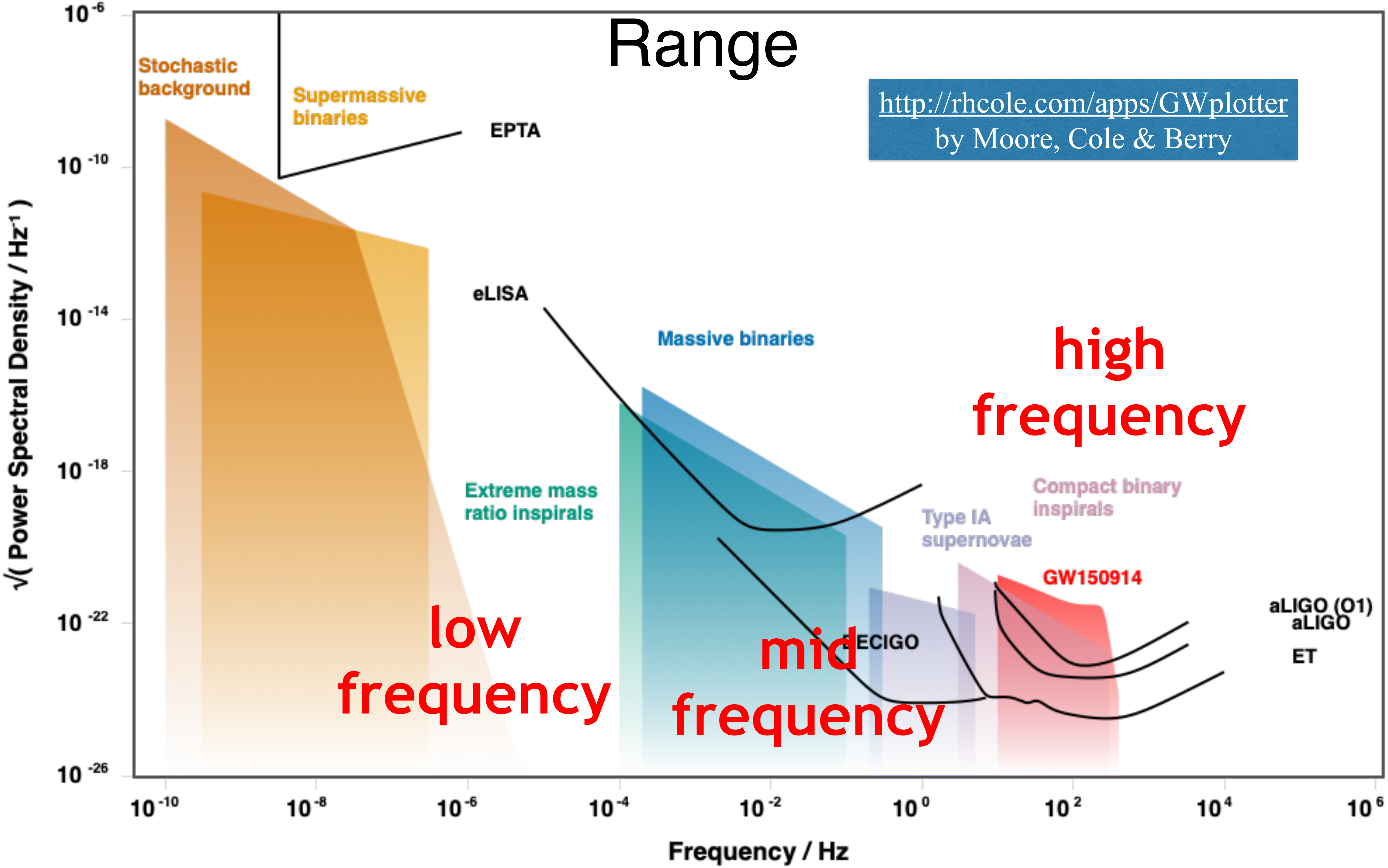
LISA Sensitivity

- There are no seismic, Newtonian, and suspension noises
- Dominant noises are due to photon fluctuations and spurious acceleration of test masses
    - Acceleration noise due to residual forces on the proof masses, like Coulomb forces induced from imperfect cancellation of charges, surface effects, residual gas pressure, etc

$$\delta f \sim 3 \times 10^{-15}\ \mathrm{m/s^2/\sqrt{Hz}}$$

$$\to \tilde{x}_{acc}(f) \approx 3 \times 10^{-15}\ \mathrm{m/s^2/\sqrt{Hz}} \times \frac{1}{(2\pi f)^2}$$

Gravitational Waves in Wide Spectral Range

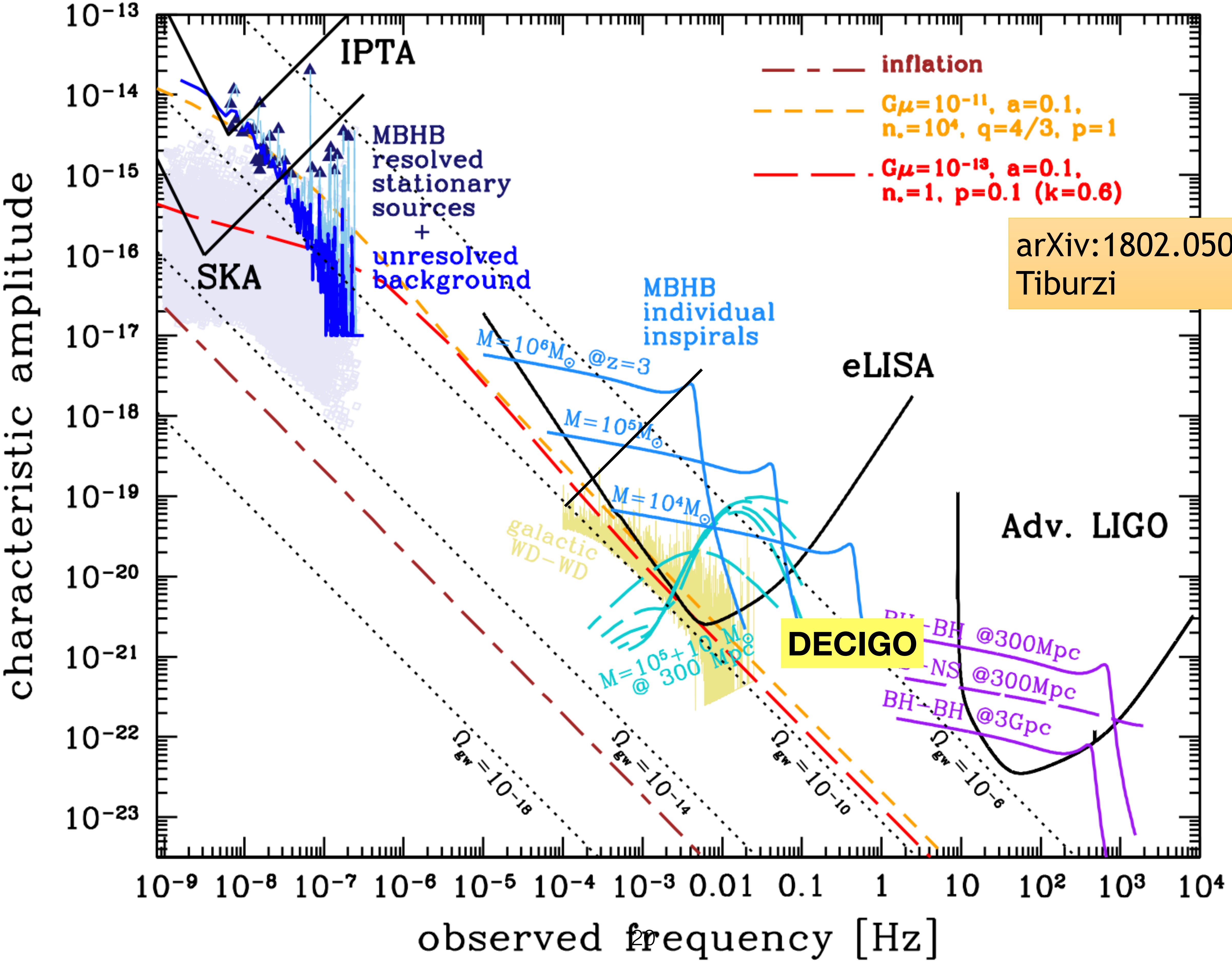


http://rhcole.com/apps/GWplotter
by Moore, Cole & Berry

high frequency

low frequency

mid frequency



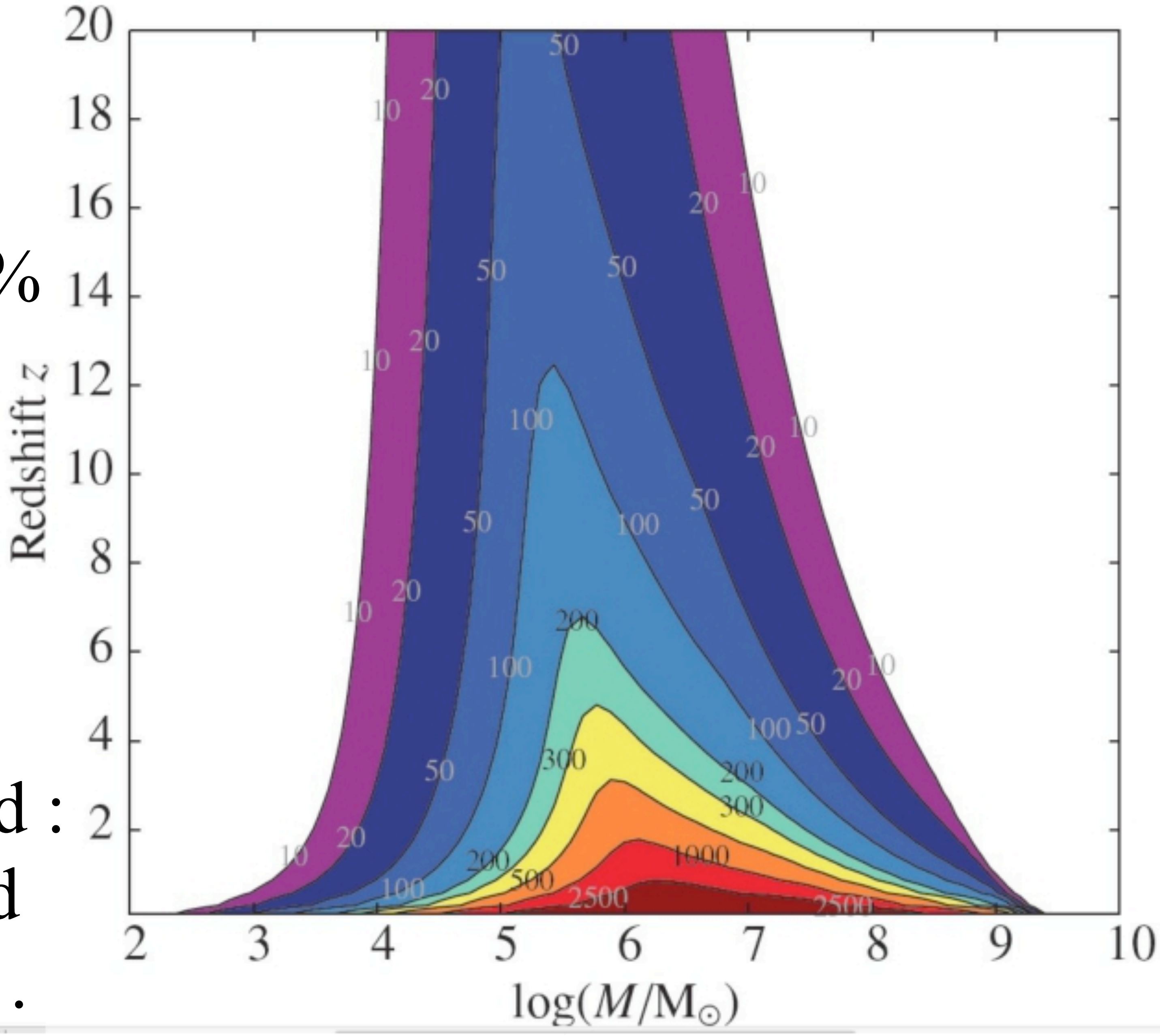
arXiv:1802.05076
Tiburzi

LISA Sciences

- Survey compact stellar-mass binaries and study the structure of the Galaxy
- Trace the formation, growth and merger history of massive black holes.
- Explore stellar populations and dynamics in galactic nuclei
- Confront General Relativity with observations
- Probe new physics and cosmology with gravitational waves

Observing the entire universe

- ELISA will detect ALL the mergers in the universe in its frequency band, even out to z=15 and beyond if they are happening.
- BBH rest mass 10 $_4$ – 10 $_7$
- Luminosity distance 1 – 50 %
- Sky location 3° - 10 °
- Masses to ±0.5%
- Spin magnitudes to ±0.01.
- Spin alignments
- No complex modeling needed : these data are directly encoded in phase of inspiral waveform .



Current Status of LISA

- LISA is currently developed with contributions from the ESA member states and NASA as an international partner
- Target launch:before 2034.
- Anybody can apply for a consortium membership
  - https://www.elisascience.org/articles/lisa-consortium
  - Consortium member: commits to contribute directly to the work of the consortium.
  - Consortium Associate: interested in the science of LISA, working group members expressing willingness to participate, on request, to short- or long-term tasks of the consortium, as organised by the working group chairs.
  - Ex-Officio members, appointed directly by the Consortium board on suggestion by Consortium members, by ESA, by NASA or by any of the National Agencies involved in LISA.
- https://signup.lisamission.org/docs/LISA-LCST-MIS-PL-001_i1.7_ConsortiumManagementPlan.pdf
- Japan
  - Two groups from Japan began participating in the consortium with the goal of making significant scientific contributions to LISA in 2018.
    - *Japan instrument group*,
    - *Japanese working group for LISA science (Associate member)*