GW Detectors and their targets from 10^{-20} Hz – 10^{3} Hz

Pat Meyers

Caltech

July 11, 2022

VIPER PTA Summer School

The Plan

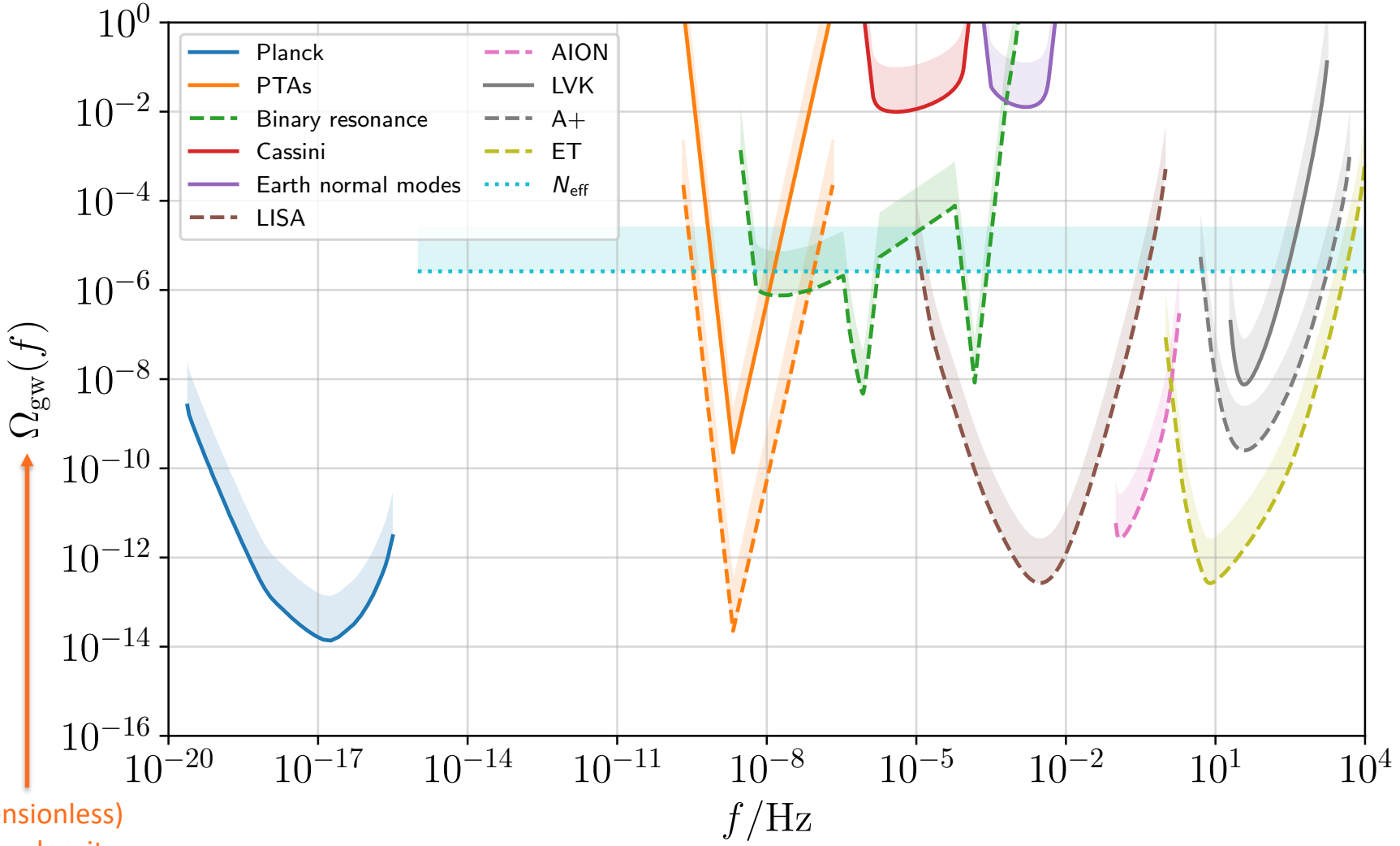
- Name a bunch of detector/methods in different frequency bands for you
  - "The firehose approach"
- Discuss each frequency band in turn
  - Exciting sources (many overlap between bands)
  - What detectors/methods are interesting, who's proposing them
  - Generally how do those detectors work? (non-technical)
  - Will *try* not to editorialize [sometimes I can't help myself]
- I will miss some…feel free to let me know if I do.

Glossary

Some words I'll say and what they mean

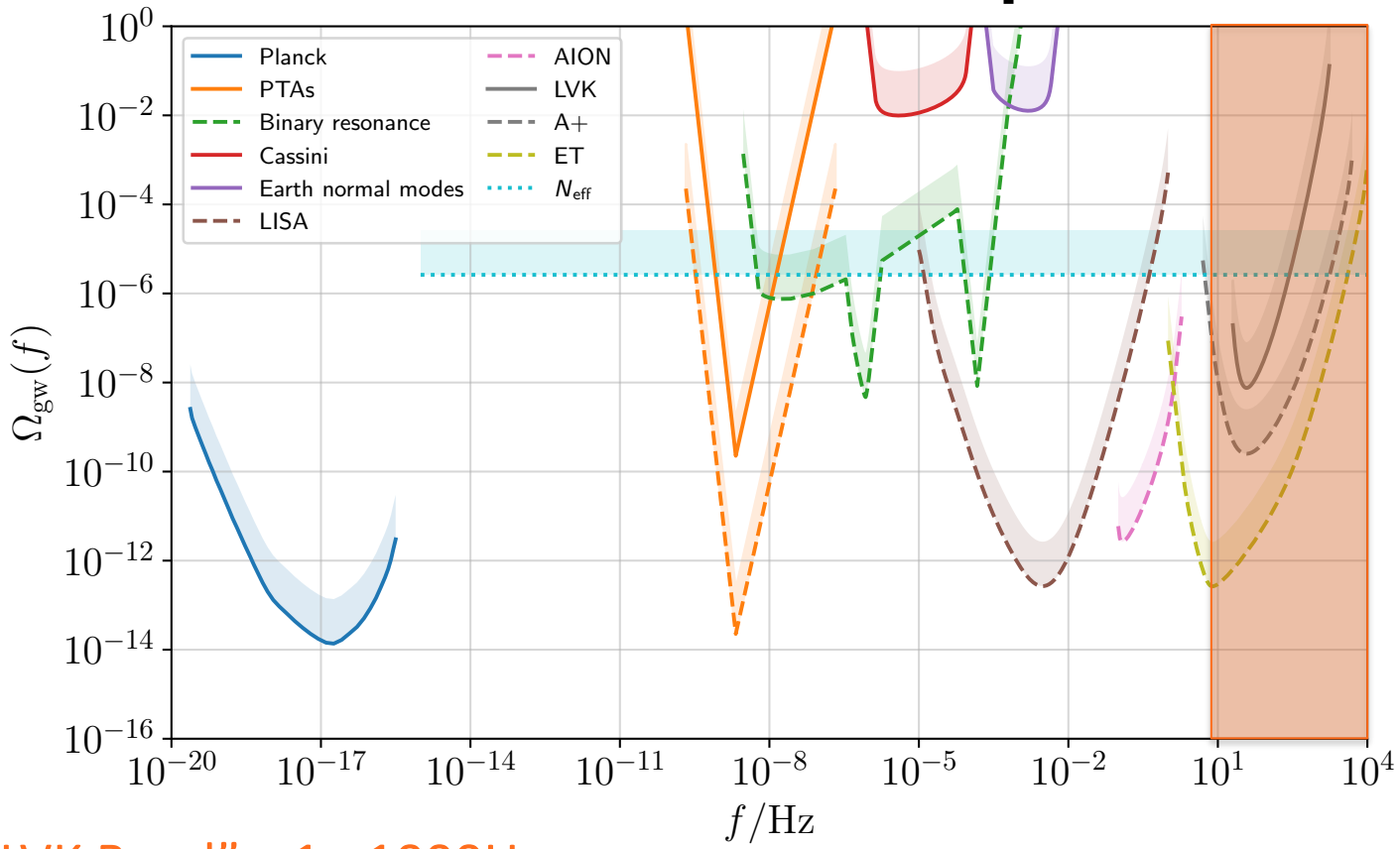
- **Waveform** – the strain vs. time signal for a given individual GW source
- **Matched-filter search** – search method for an individual GW source, done comparing the waveform for a given signal with the data
- **Gravitational-wave background (GWB)** – unresolved sources of GWs
- **Cross-correlation search** – correlate data from multiple detectors to detect a GWB.
- **IFO –** interferometer (probably referring to LIGO-like detectors)
- **I will probably accidentally use some jargon without explaining it. Don't hesitate to stop me and ask.**

The road map



(dimensionless) energy density of GWs

The road map

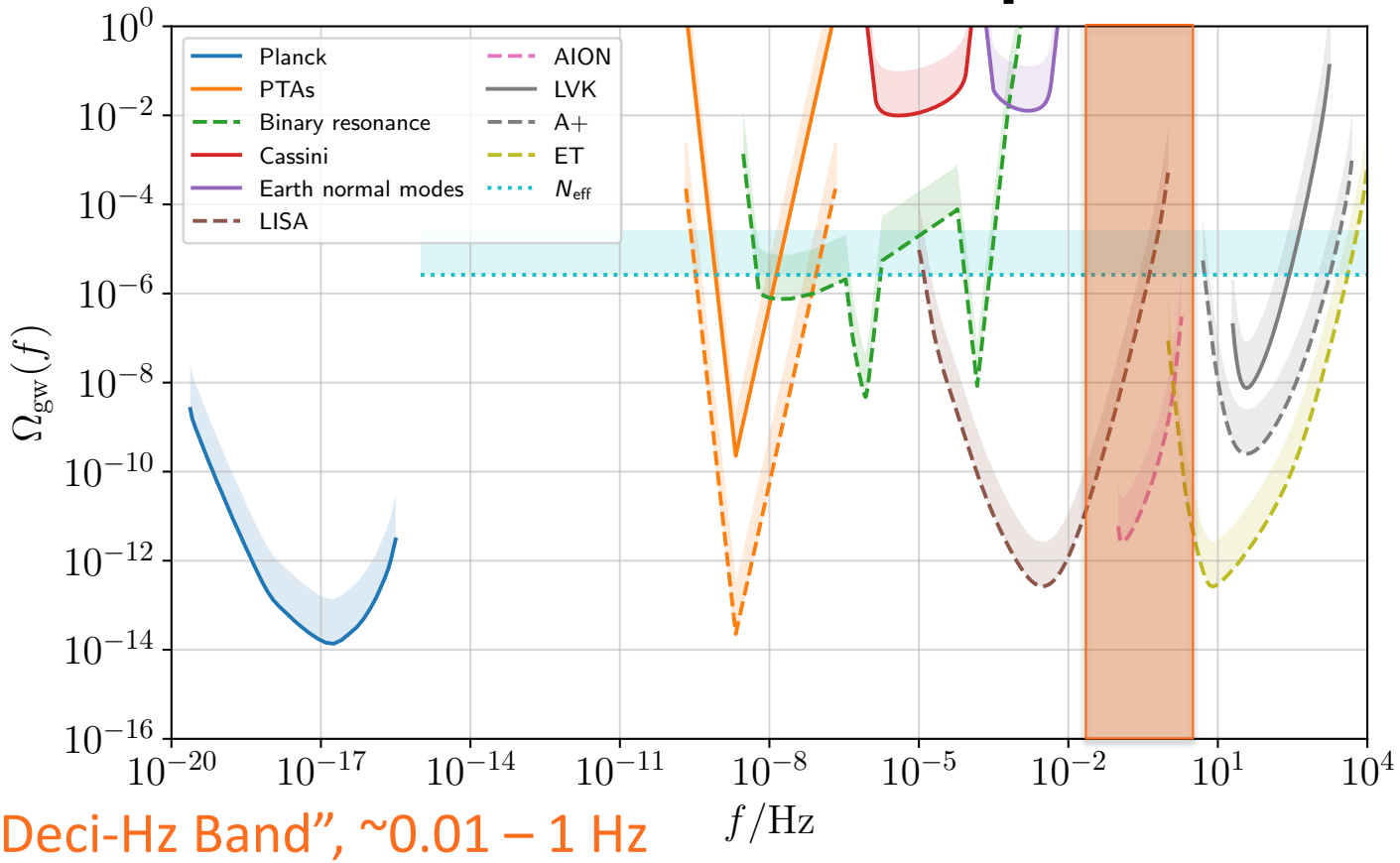


"LVK Band", ~1 - 1000Hz

Earth-based "LIGO-like" detectors

- **Current/Past**: LIGO/Virgo/KAGRA/GEO600/TAMA, resonant mass
- **Proposed:** Einstein Telescope, Cosmic Explorer, NEMO

The road map

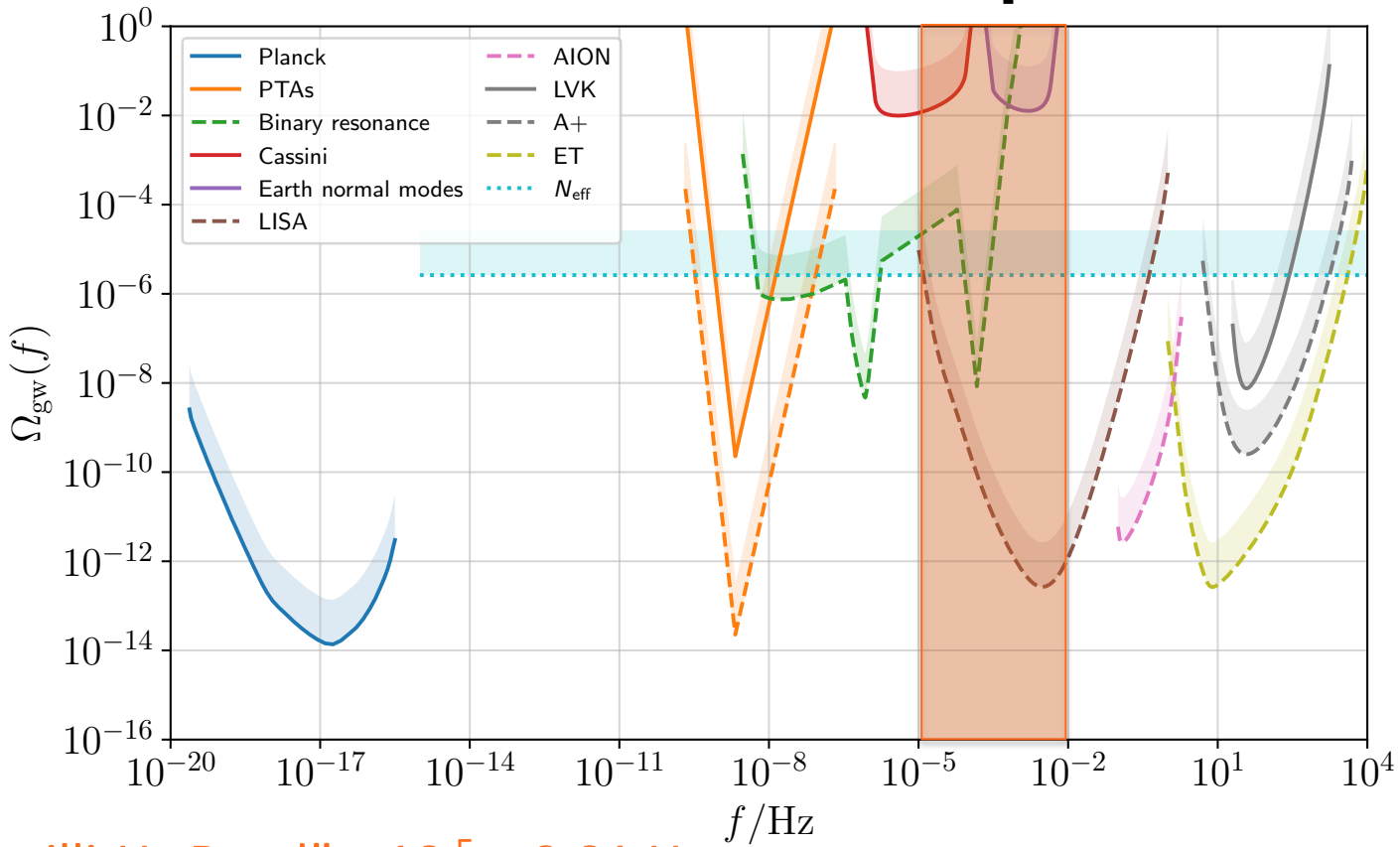


"Deci-Hz Band", ~0.01 – 1 Hz

Space-based detectors, Moon-based detectors

- **Current/Past**: Seismic arrays on Earth/Moon
- **Proposed:** DECIGO, LISA, Tianqin, Taiji, Moon seismometers, Moon interferometer, Atom interferometers

The road map

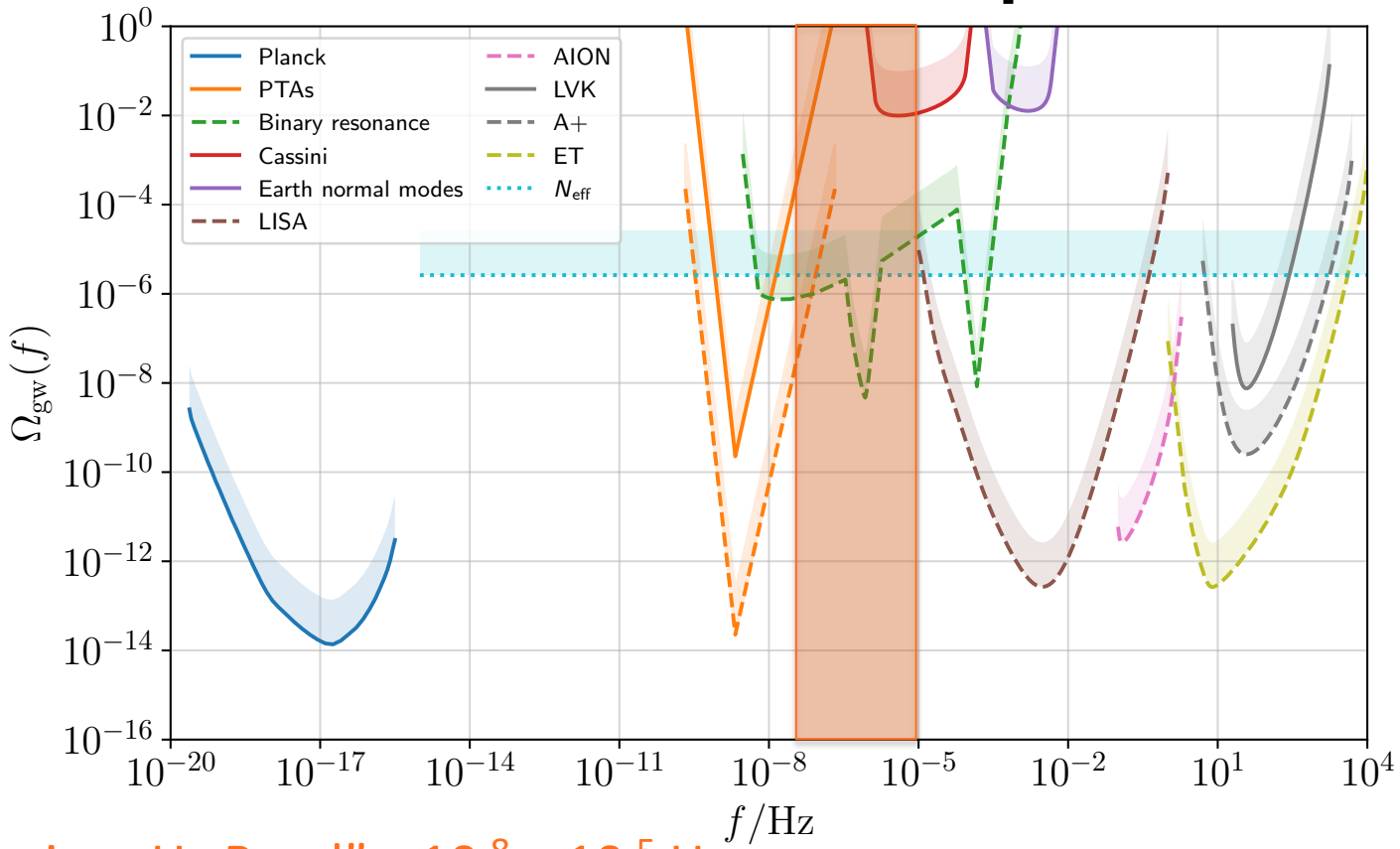


"milli-Hz Band", ~10^{-5} – 0.01 Hz

Space-based detectors

- **Current/Past**: Seismic arrays on Earth/Moon
- **Proposed:** LISA, Tianqin, Taiji, BBO, ALIA,

The road map

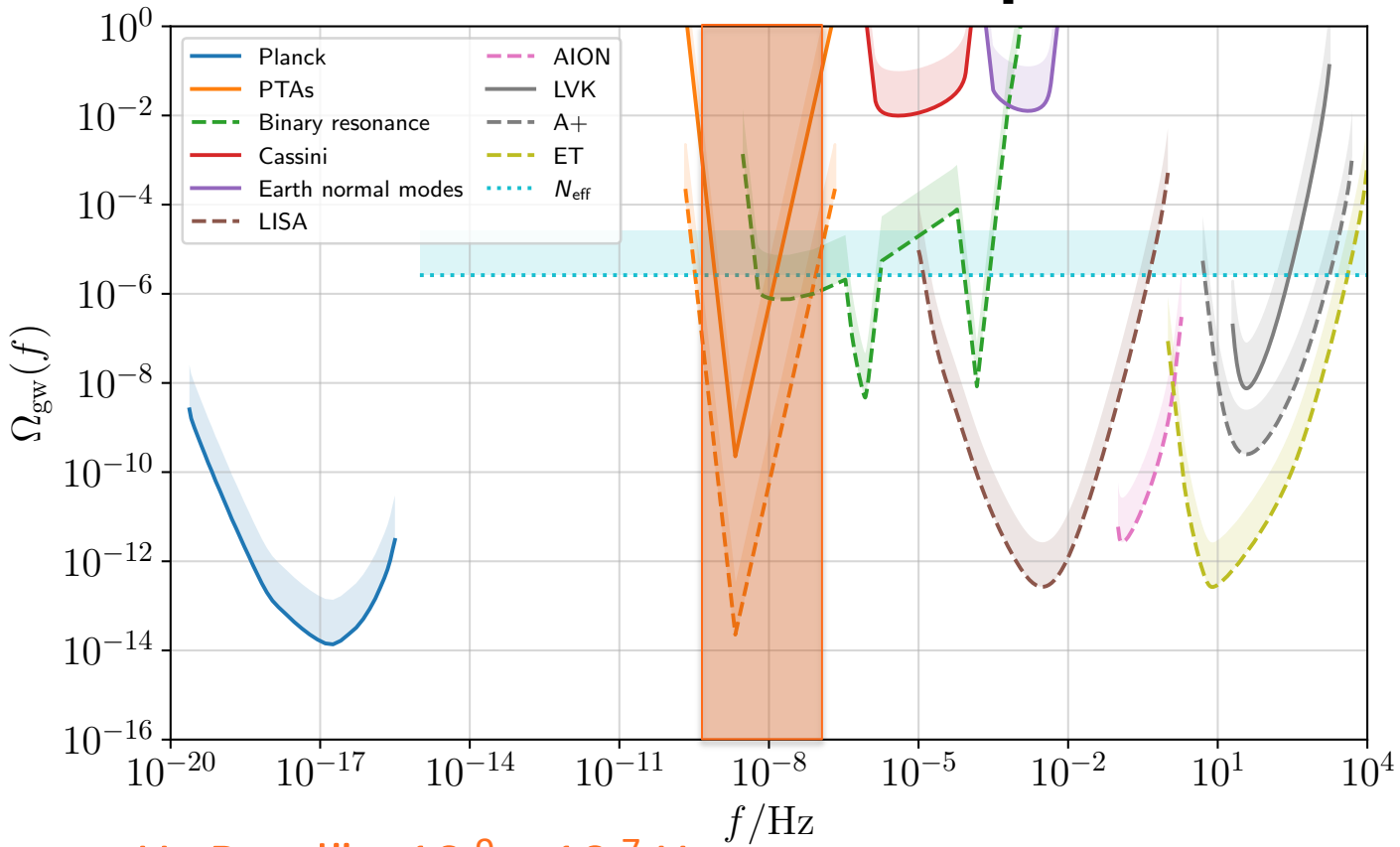


"micro-Hz Band", ~10^{-8} – 10^{-5} Hz

Space-based detectors

- **Current/Past**: None!
- **Proposed:** Binary resonance, astrometry, µAres detector, asteroids, Timing arrays of GW sources

The road map

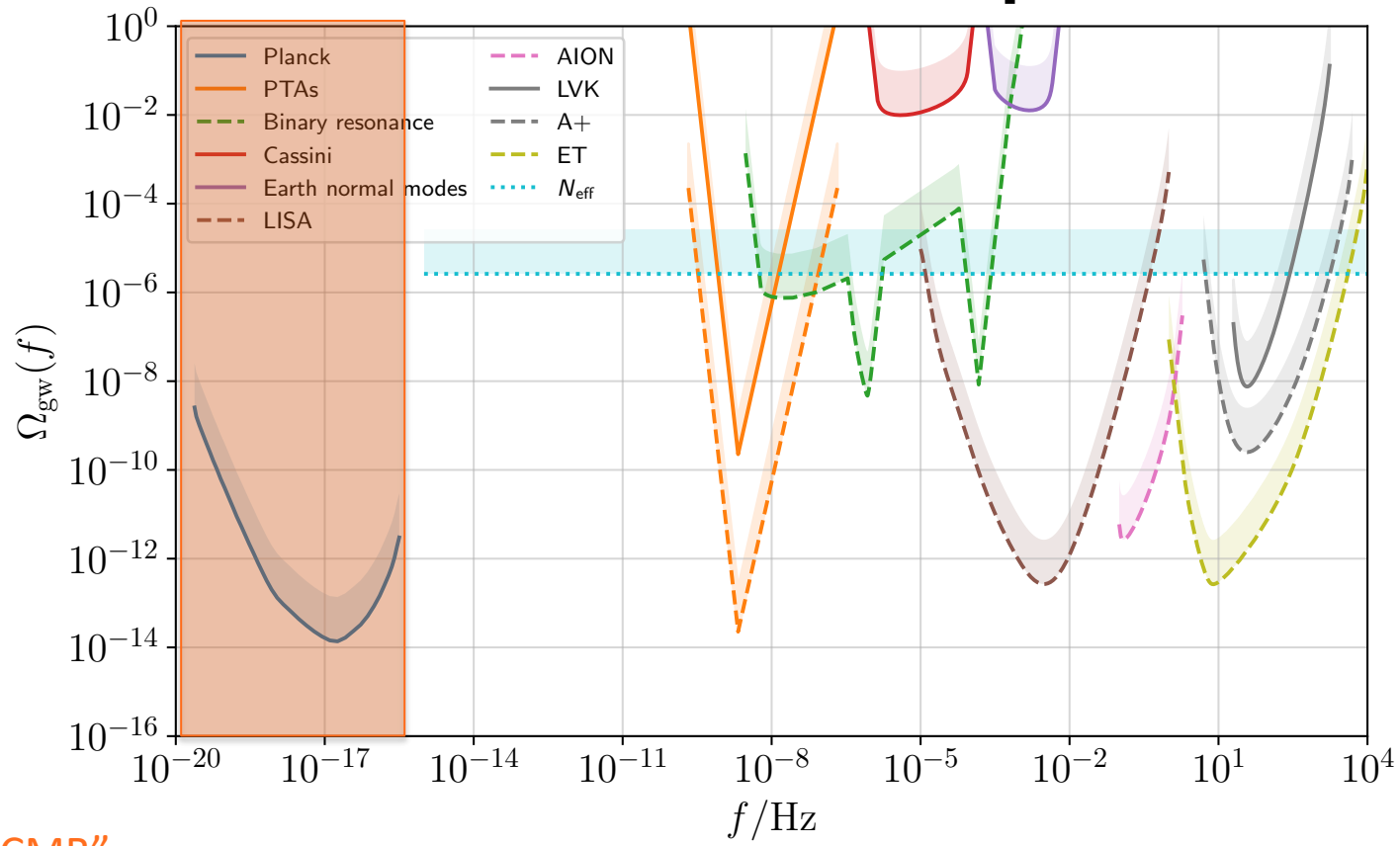


"nano-Hz Band", ~10^{-9} – 10^{-7} Hz

Space-based detectors

- **Current/Past**: Pulsar timing arrays
- **Proposed:** Binary resonance, astrometry, Timing arrays of continuous GW sources

The road map



"CMB"

Imprints of GWs on the CMB…

LVK Band

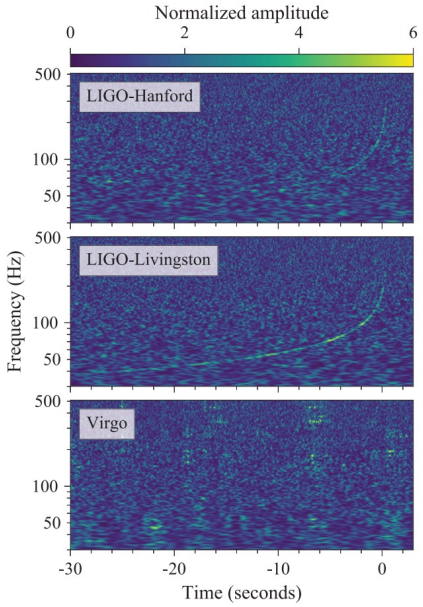
"LVK Band", ~1 - 1000Hz

Earth-based "LIGO-like" detectors

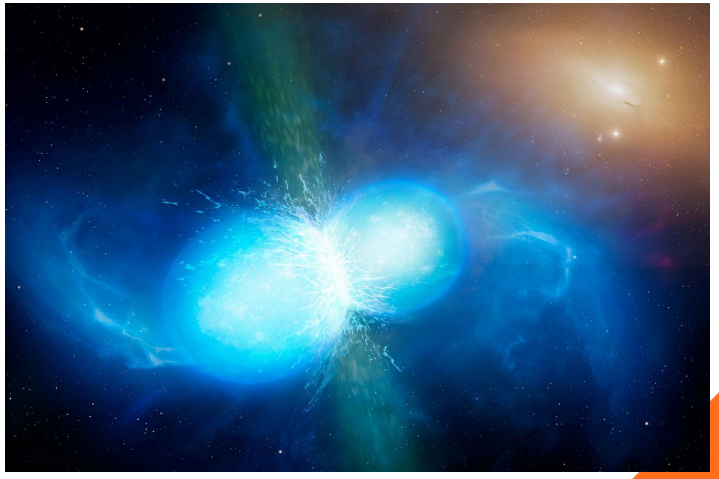
- **Current/Past**: LIGO/Virgo/KAGRA/GEO600/TAMA, resonant mass
- **Proposed:** Einstein Telescope, Cosmic Explorer, NEMO

LVK-band dominant sources

- Stellar-mass Compact Binary Coalescences (CBCs)
  - Binary black holes, Binary neutron stars, Neutron star-black hole mergers
- Continuous GWs from asymmetric neutron stars
- Gravitational-wave background
- Supernovae



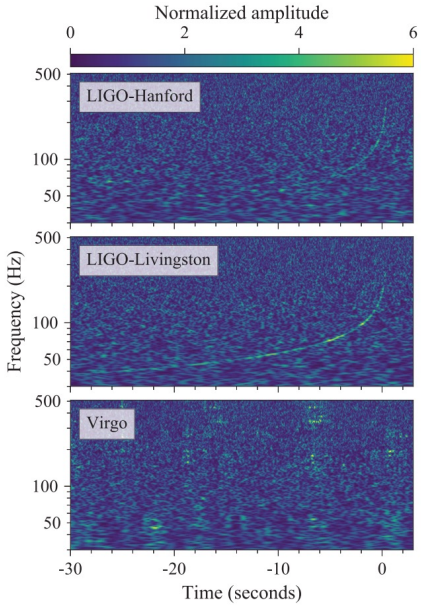
GW 170817 Signal
Phys. Rev. Lett. **119**, 161101



Artist's illustration of BNS
aasnova11

LVK-band dominant sources

- CBC science
  - Constraining neutron star equation of state with mass/radius/tidal deformability measurements.
  - Compiling population information about black holes and neutron stars
  - Trying to understand origin of black hole binaries. How do the form? How many? Where do they form?



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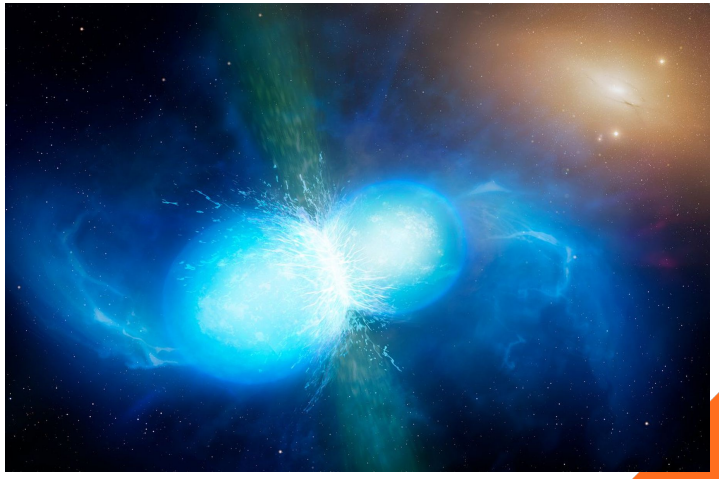
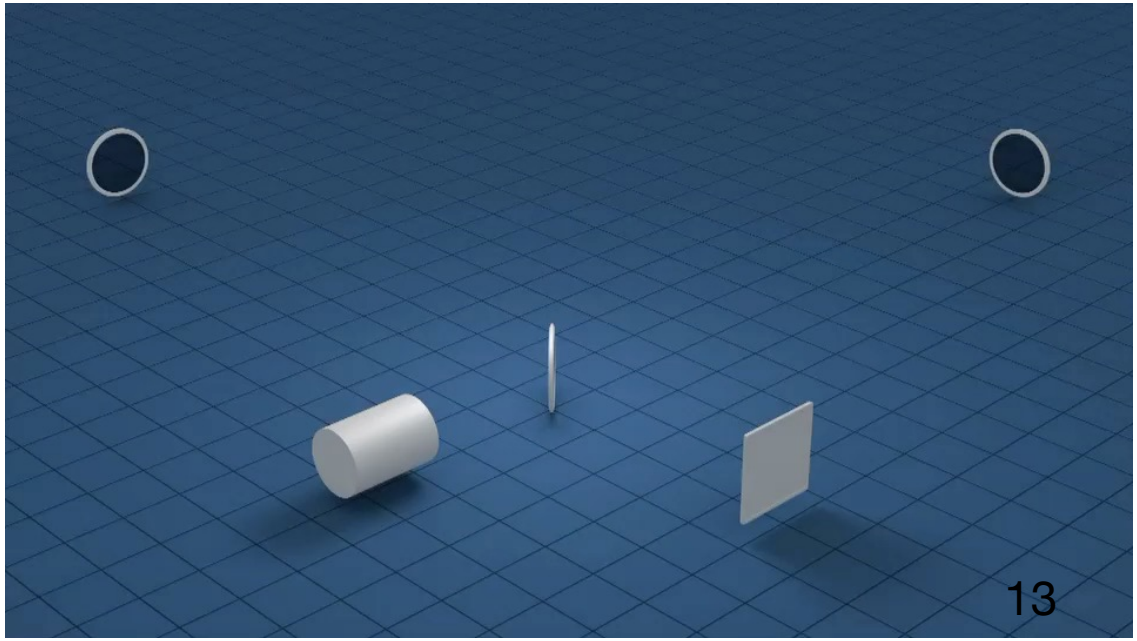


Artist's illustration of BNS
aasnova

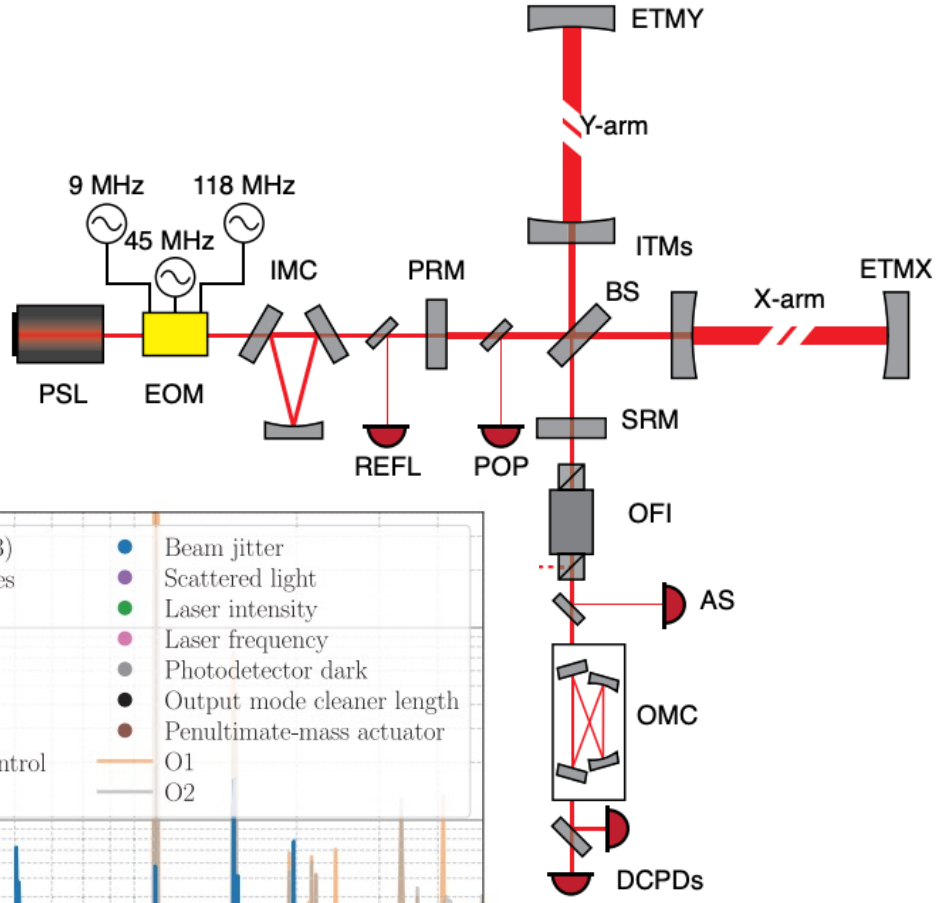
LVK-like Detectors [current]

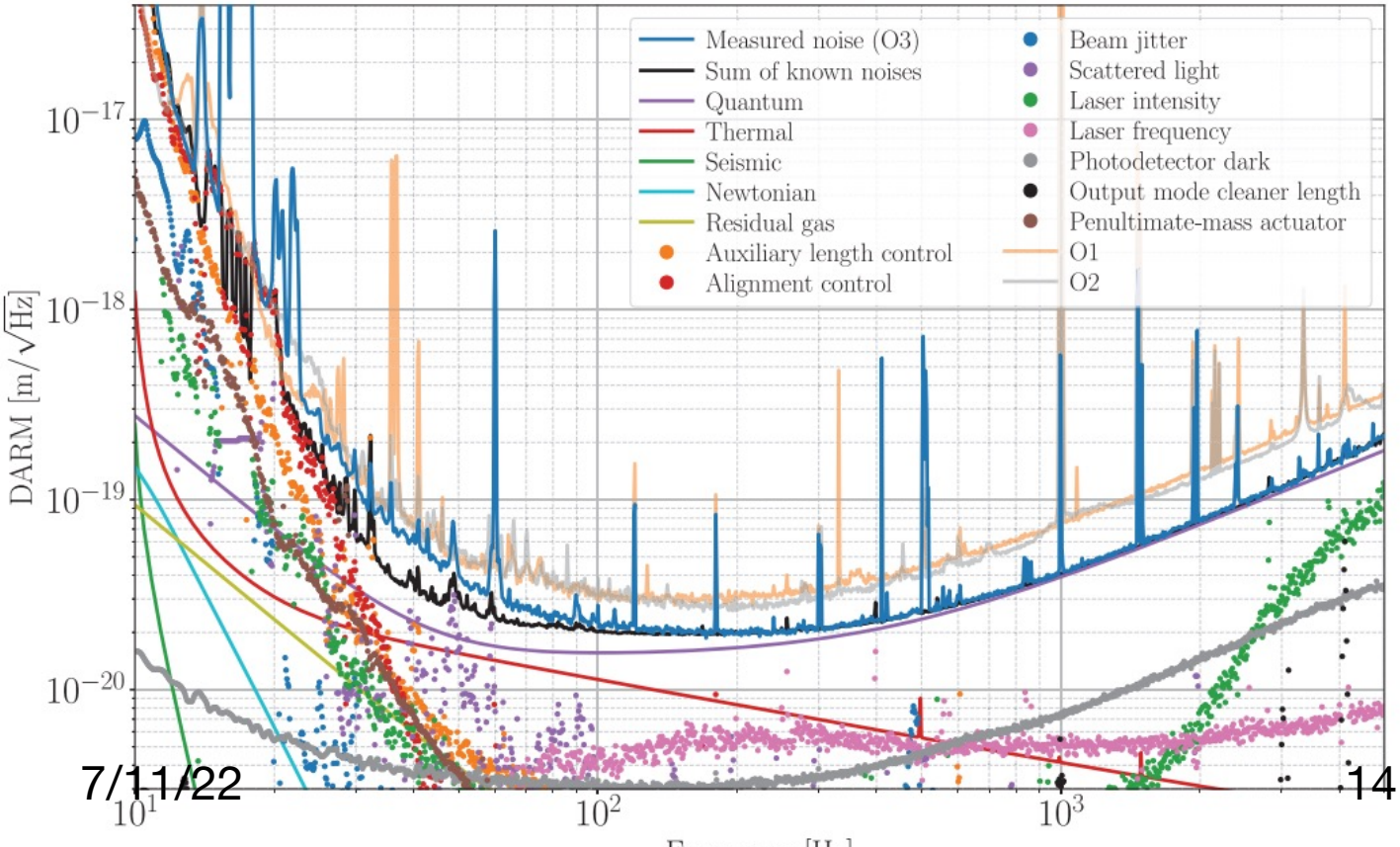
- Current generation of detectors
  - LIGO – Hanford/Livingston, USA, 4km long arms
  - Virgo – Cascina, Italy, 3km arms
  - KAGRA – Kamioka mine, underground, 3km long arms, eventual cryogenic mirrors
  - GEO600 – 600m arms, mostly test facility now.
  - LIGO India – Under construction, similar to USA-based LIGO detectors
- "L"-shaped detectors
  - measure GW effect on mirrors in orthogonal directions
  - Use Laser Interferometry



LVK-like Detectors

2 minutes on How they work





[O3 LIGO sensitivity]

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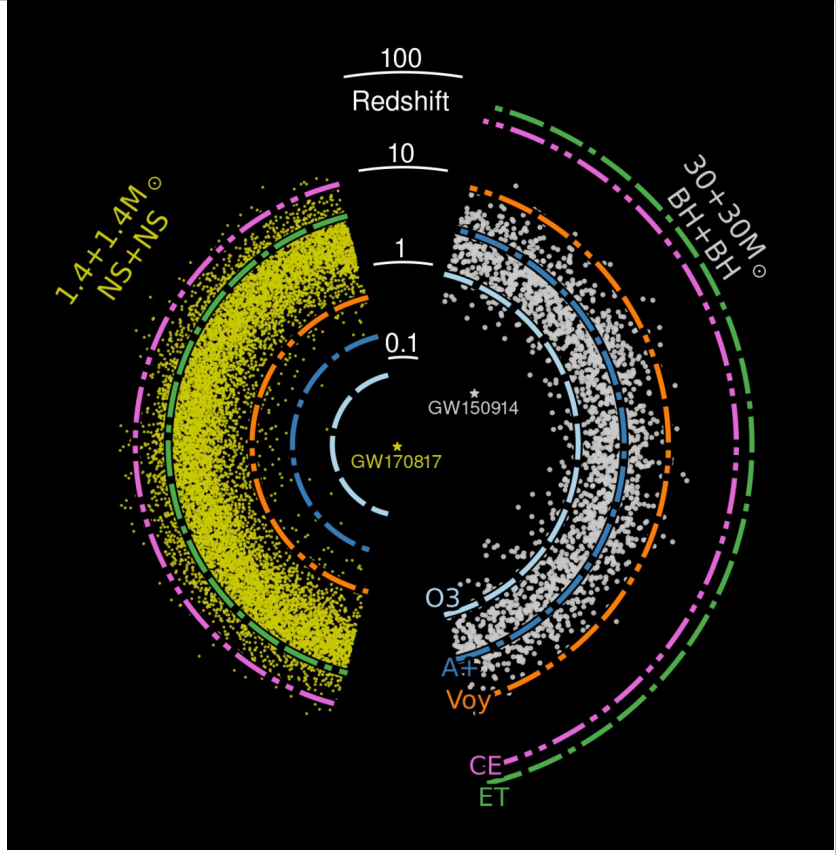
LVK-like Detectors [planned]

- Einstein Telescope – LINK – Europe-based
  - 10km long arms, underground
  - Triangle configuration with 6 separate interferometers in a “xylophone” configuration
  - Pathfinder has been funded
  - Timeline – Construction 2026? Observations 2035?
- Cosmic explorer – LINK – USA-based
  - 2 sites, one with 40km arms, other with 20km arms
  - “L”-shaped design, cryogenic mirrors, etc.
  - Full study here
- NEMO – LINK – 2.5 Generation detector
  - Targeted at neutron star post-merger signal
  - VERY high laser power, test facility for future detectors



CE and ET sensitivity to BHs and NSs
Horizon study

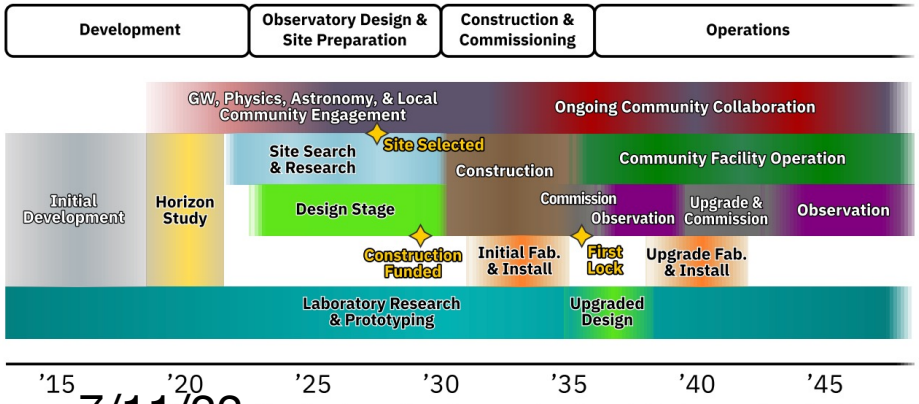


Figure 11.1: A top-level timeline showing a phased approach to Cosmic Explorer, as described in §11.2. The eventual divestment from the facility is not indicated.

Proposed CE timeline
Horizon study

Resonant mass detectors

"The original GW detectors"

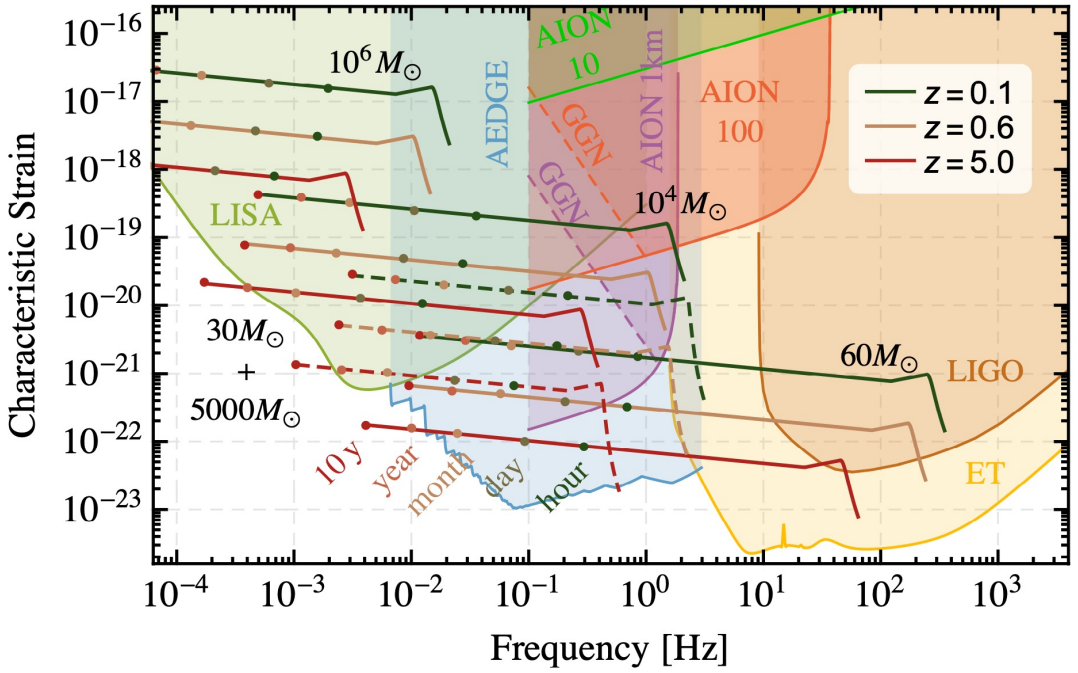
- Resonant mass detectors
  - Cryogenic bar (to reduce thermal noise)
  - GWs excite resonant modes in the bar
- Weber claimed to detect GWs using one
  - Energy in the supposed signal was way (way) too large
- AFAIK, last of these has been decommissioned

Deci-Hz Band
“mid-band”
~0.01 Hz – 10 Hz

- **Current/Past**: Seismic arrays on Earth/Moon
- **Proposed:** DECIGO, LISA, Tianqin, Taiji, Moon gravimeters, Moon interferometer, Atom interferometers

Target sources – deciHz band

- **Intermediate-mass black holes (IMBH)** 10^2 – 10^5 Msun
- **Intermediate-mass ratio inspirals** (ratio of masses ~1000)
- **LIGO CBCs are continuous sources**
- **Multi-band science** of binary black holes, binary neutron stars, neutron star-BH binaries with LVK-band
- **Double White Dwarf** (DWD) mergers
- **Gravitational-wave backgrounds**
  - Unresolved CBCs
  - Inflationary GWs?
  - Cosmic strings?



From AION paper

Past efforts

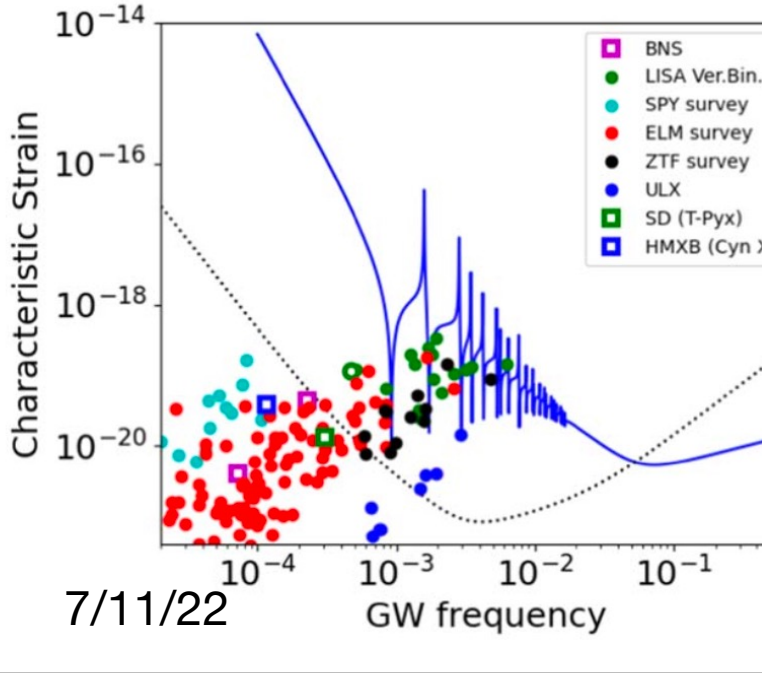
- Upper bounds on GWB using Earth and Moon normal modes
  - Earth or Moon acts as a “resonant mass” detector
    - GWs excite normal modes, detectable with seismometers
    - Can perform matched-filter searches for specific waveforms
    - Papers – Earth I, Earth II, Moon
- Planned detector using same method on the moon. Link to paper

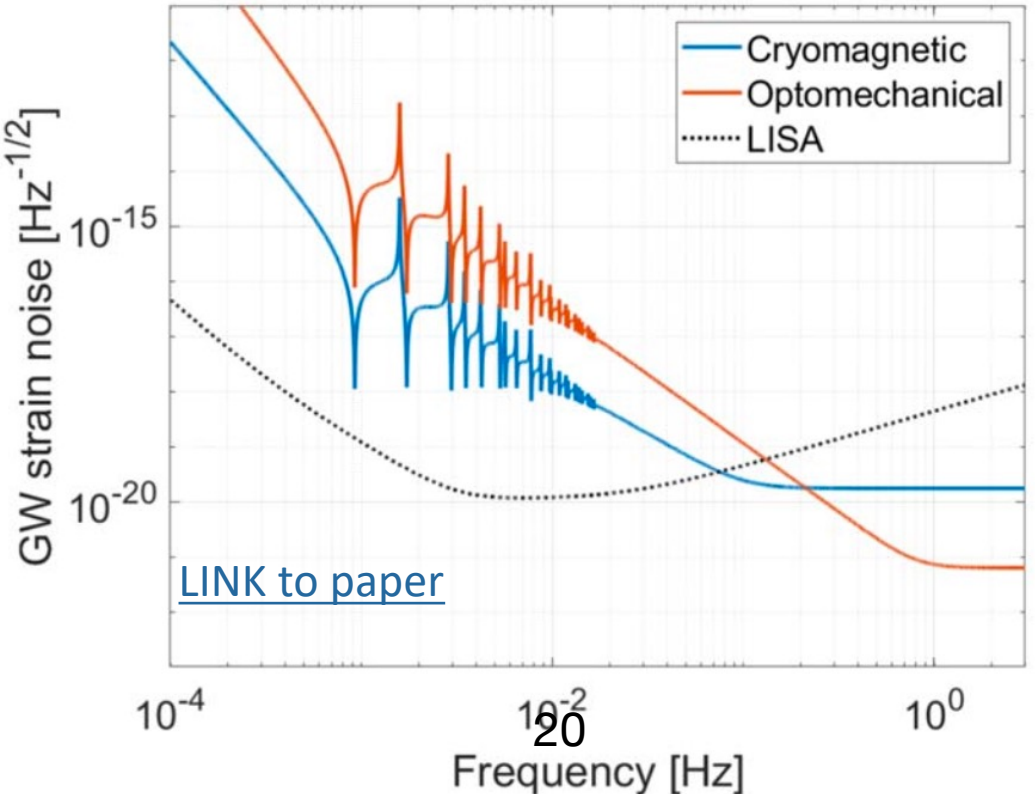
Proposed efforts

- Lunar antenna
  - Similar to Apollo mission
  - Phase 1 – seismometers near poles (away from other missions
  - Phase 2 – antipodal array -> good GW correlations, but minimal seismic correlations from Phase 1 array

Noise sources:

- Normal mode response to GWs (1e-3 – 1e-2 Hz)
- Seismic transients
- Meteroid background
- Seismometer self noise (!!!)





Proposed efforts (deciHz)

- DECIGO – 0.1 – 10 Hz, Japanese-based project
  - 4 clusters of 3 spacecrafts
  - Each cluster = 3 Michelson interferometers
  - 2 clusters collocated for better GWB detection
  - Large potential for multi-band science with LVK-band detectors
  - B-DECIGO (pathfinder) ~2030s

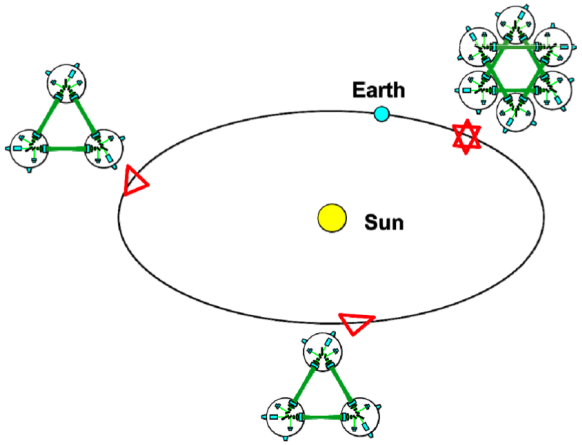


Fig. 1. Orbit of DECIGO. Four clusters of DECIGO are put in the heliocentric orbit: two at the same position and the other two at different positions.

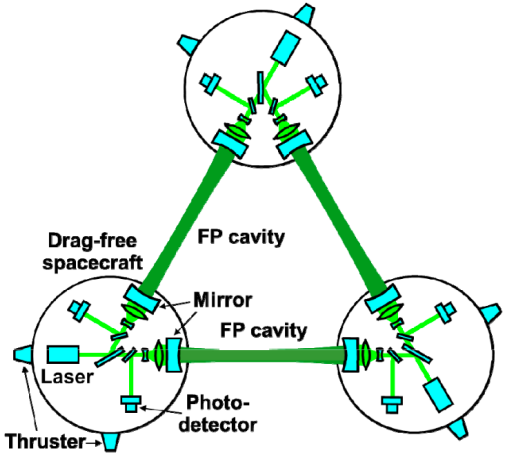
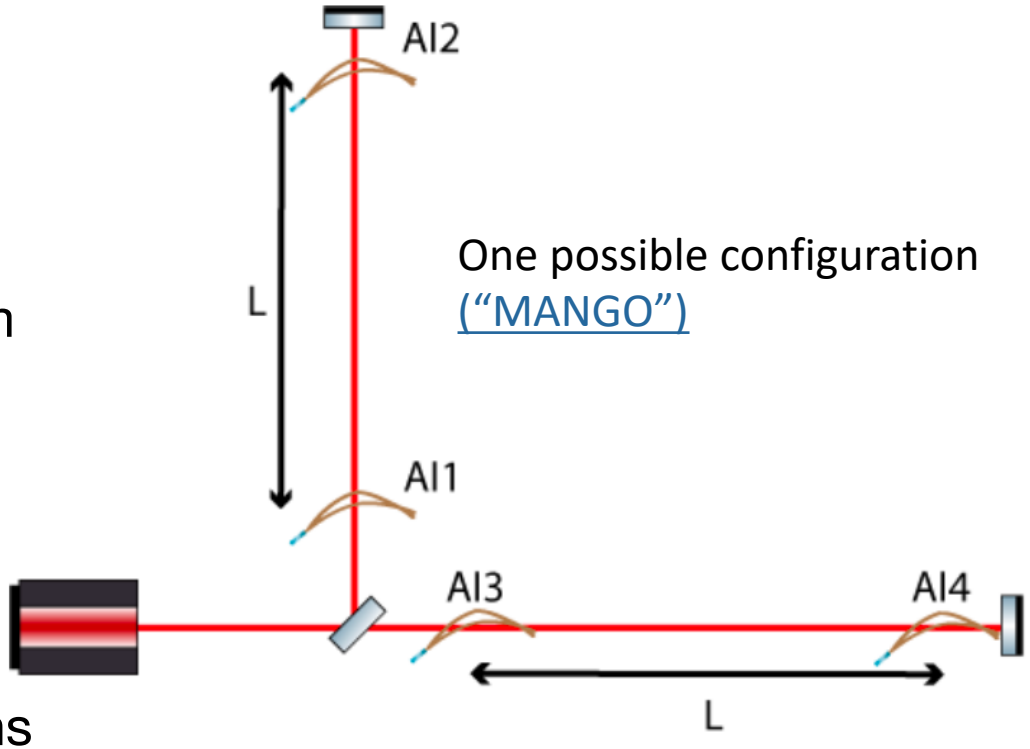


Fig. 2. Conceptual design of DECIGO. One cluster of DECIGO consists of three drag-free spacecraft. FP cavities are used to measure a change in the arm length.

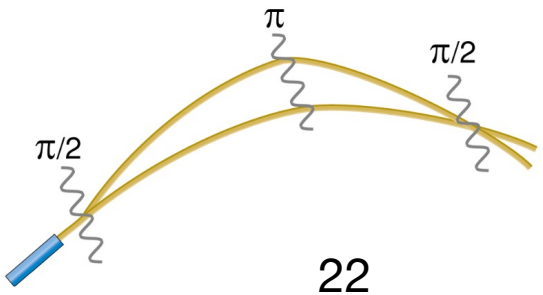
From the DECIGO Status report

Proposed efforts (deciHz)

- Atom Interferometers – ~0.1 – 10 Hz
  - Ultra-cold atoms in free fall
  - Laser pulses -> momentum to atoms
  - Generate quantum superposition of two separate paths
    - "like a beamsplitter"
  - Recombination of two paths measured by lasers again
- Can put multiple AIs in a LIGO-like configuration, using same laser. Each AI = separate phase measurement.



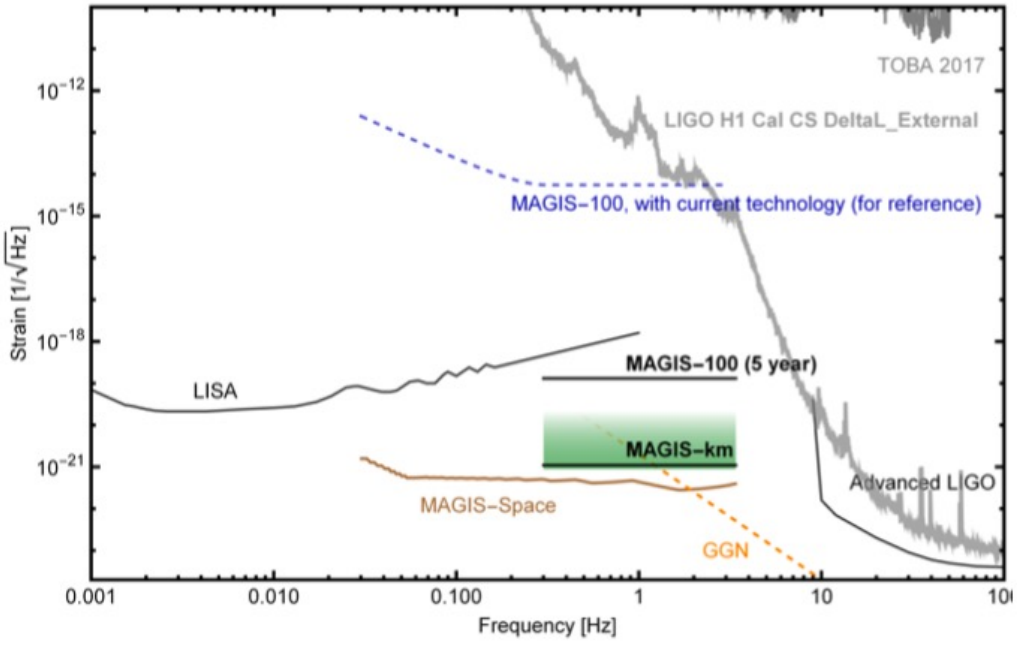
One possible configuration ("MANGO")



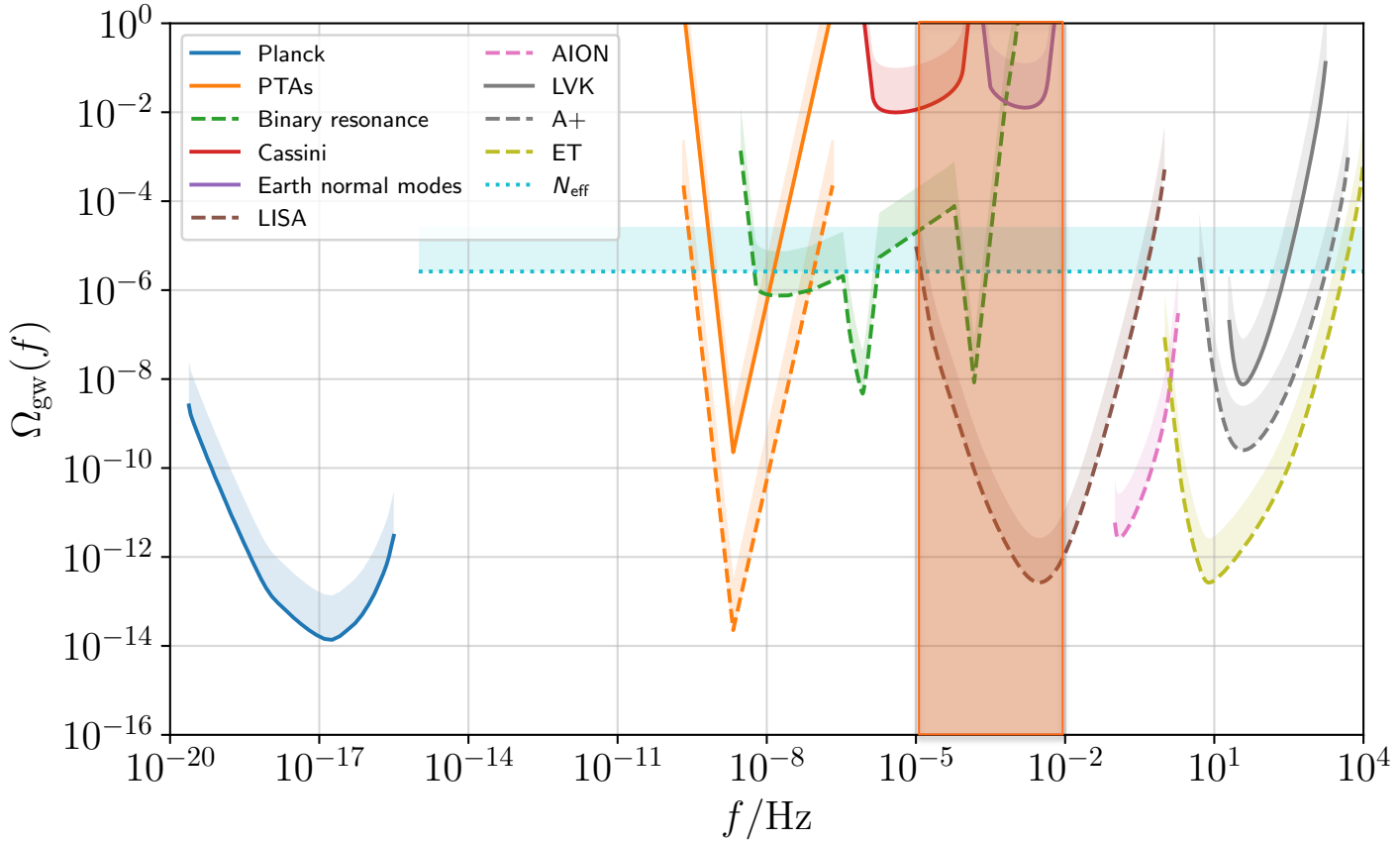
Proposed efforts (deciHz)

- Atom Interferometers – ~0.1 – 10 Hz
  - **Can also probe beyond standard model physics**
  - MAGIS-100, MAGIS-km, MAGIS-Space
  - AION
  - ZAIGA
  - MANGO
  - ELGAR
  - SAGE (not to be confused with SAGE, the cube-sat IFO)
  - I've probably missed 1 or 2

MAGIS Proposal



mHz Band, ~10^{-5} – 0.01 Hz

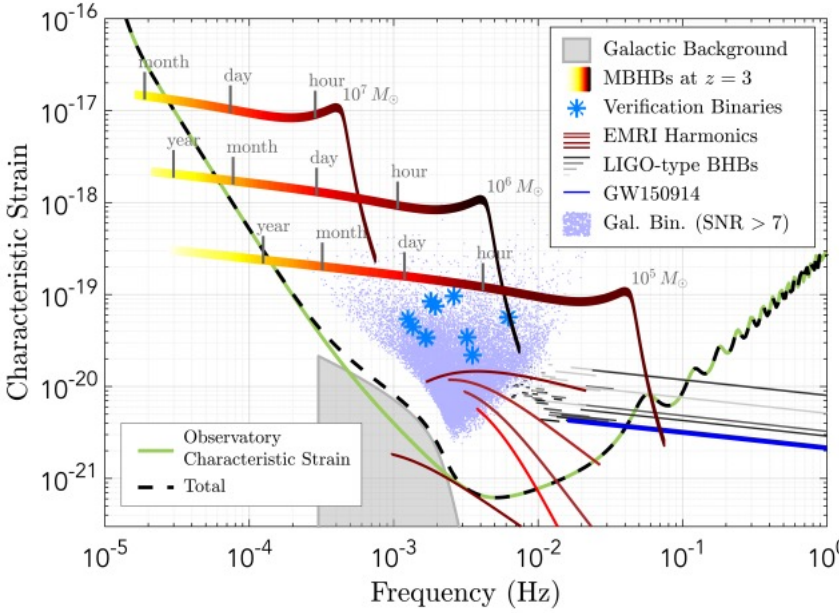


Space-based detectors

- **Current/Past**: Seismic arrays on Earth/Moon
- **Proposed: LISA, Tianqin, Taiji,**

Exciting sources in mHz Band

- Extreme mass ratio inspirals (EMRIs)
  - Stellar-mass black holes around massive black holes
- IMBHs, Massive BHBs
- Galactic DWDs
  - Individual, continuous sources
    - Testing GR (non-interacting sources)
    - Learn about DWD interactions (interacting
  - Confusion background
    - Learn about populations of DWDs
- Multi-band science
  - (very) early warning of BBH mergers for LVK
  - BNSs are continuous signals
- Cosmic GWBs below confusion noise?



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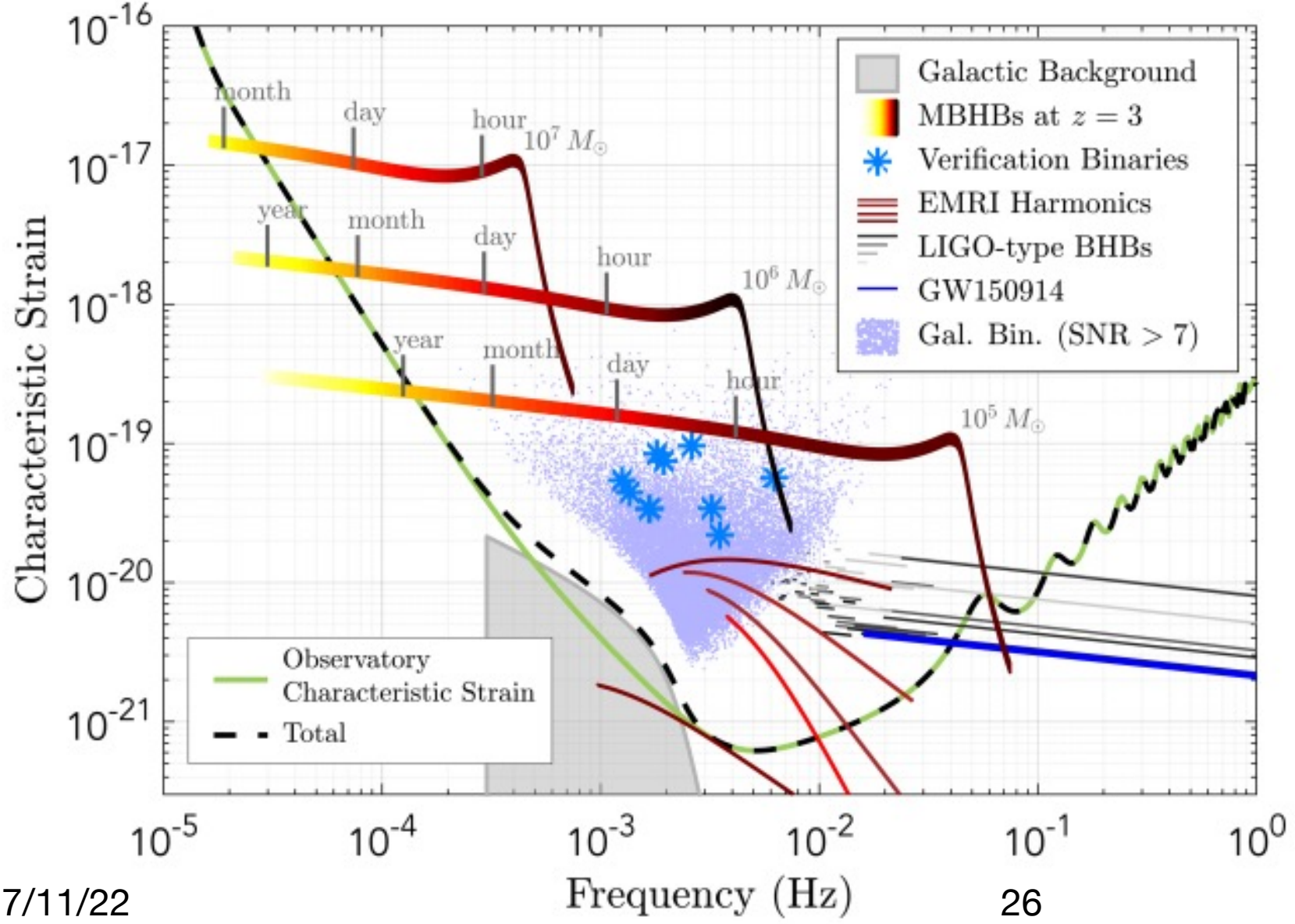
Exciting sources in mHz Band



LISA!

- 3 drag-free space crafts
  - 2.5 million km apart
  - Orbit sun (“cartwheeling”) behind earth
  - 2W lasers linking them together
  - Use “time-delay interferometry”
- Pathfinder mission *very* successful
- LISA Pathfinder was a **proof-of-concept** mission to prove that the two **masses can fly through space, untouched but shielded by the spacecraft**, and maintain their relative positions to the precision needed to realize a full gravitational wave observatory planned for launch in 2037.
- WIKI, PAPER
- AMIGO proposal – Advanced version of LISA.

PROPOSAL, and
LISA SCIENCE PROGRAM

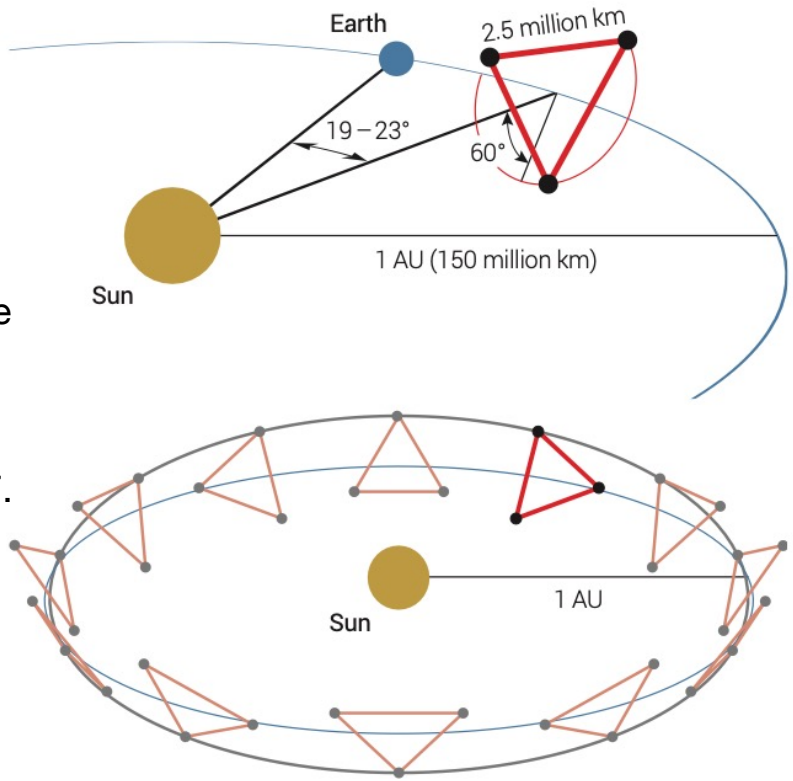


Figure 4: Depiction of the LISA Orbit.

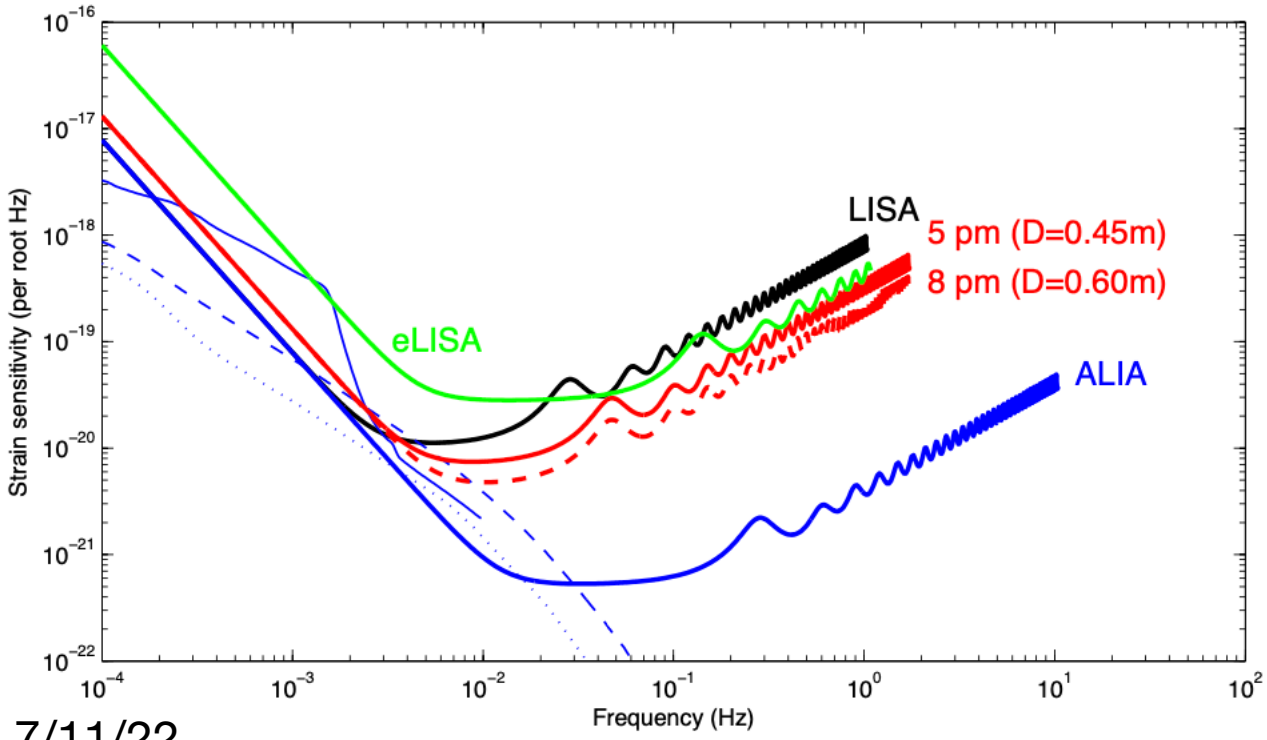
ALIA/TAIJI

- Chinese-based project
  - Space-based
  - Longer arms than LISA
  - Time-delay interferometry (see LISA slides)

Table 1.

Armlength (m)	Telescope diameter (m)	Laser power(W)	1-way position noise ($\frac{\text{pm}}{\sqrt{\text{Hz}}}$)	Acceleration ($\frac{\text{m s}^{-2}}{\sqrt{\text{Hz}}}$)
3×10^9	0.45-0.6	2	5-8	$3 \times 10^{-15}(> 0.1\text{mHz})$
5×10^8 (ALIA)	1.0	30	0.1	$3 \times 10^{-16}(> 1\text{mHz})$
5×10^9 (LISA)	0.4	2	18	$3 \times 10^{-15}(> 0.1\text{mHz})$
1×10^9 (eLISA)	0.2	2	11	$3 \times 10^{-15}(> 0.1\text{mHz})$

ARXIV
(1410.7296)



ARXIV
(1410.7296)

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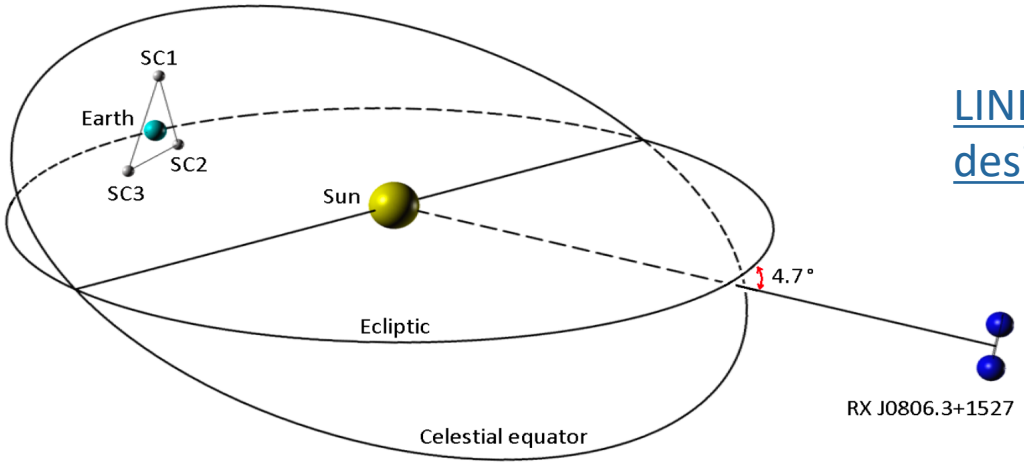
TianQin

- 0.01 – 10 Hz, Chinese-based project
  - Space-based
  - Orbit around the Earth – (grav. Field of earth complicates things)
  - Time-delay interferometry (see LISA slides)
  - Primary target – DWD, but plenty of other proposed science



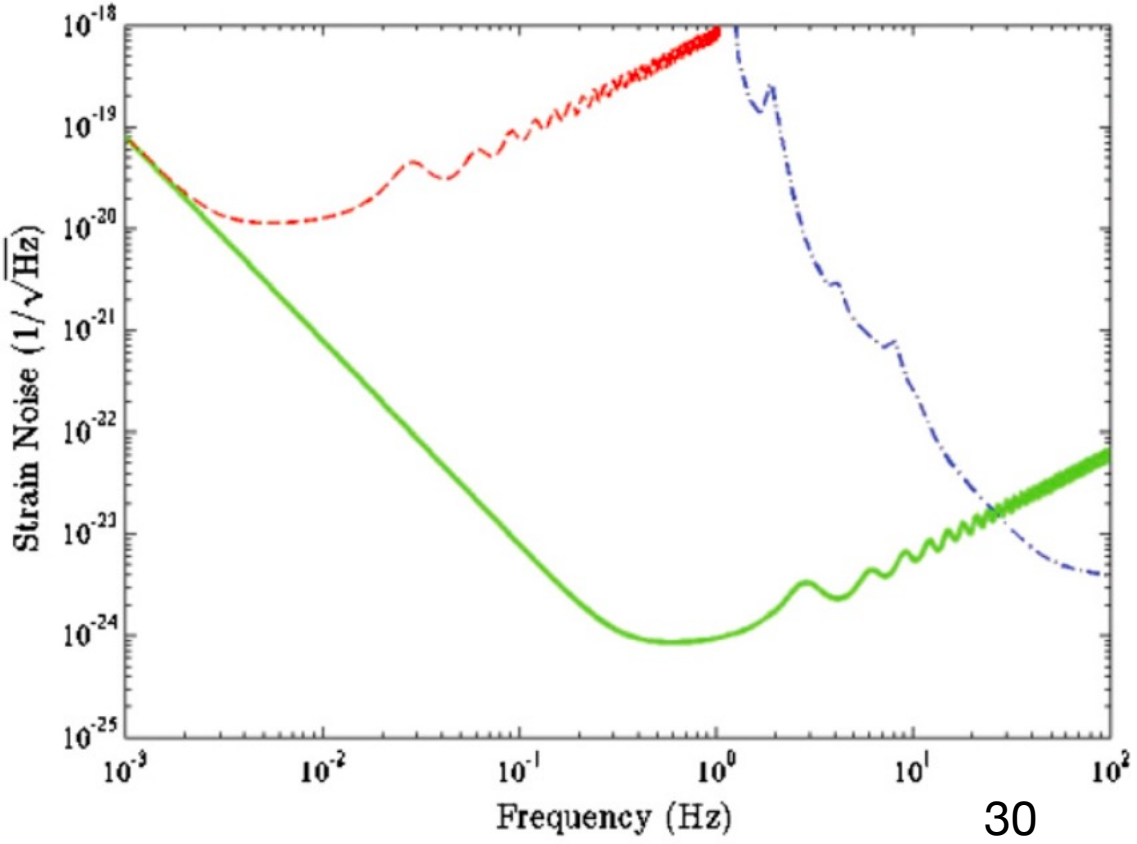
LINK to TianQin design, arxiv

Figure 1: An illustration of the preliminary concept of TianQin, with J0806 being the reference source. The three TianQin spacecraft are denoted as SC1, SC2 and SC3. The plane of the celestial equator is also shown, together with the direction to J0806 in the sky.

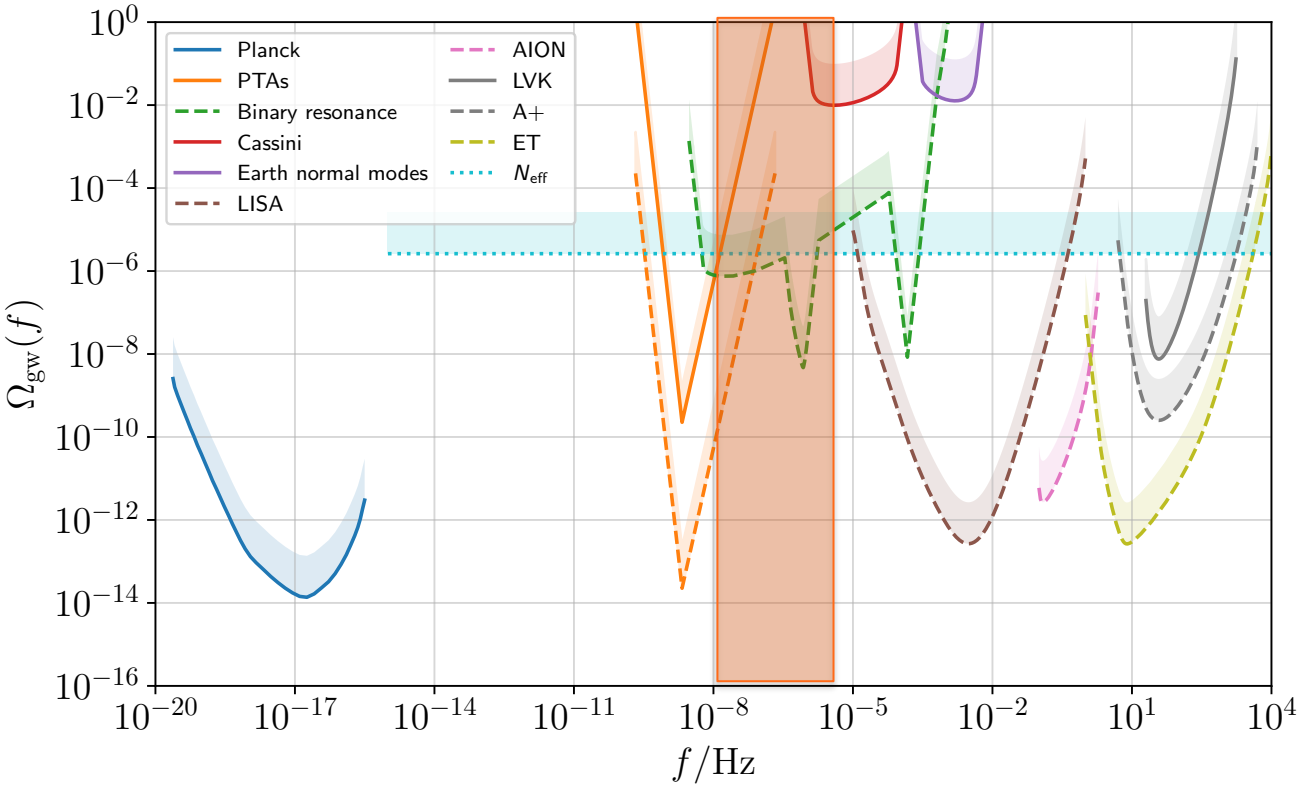
Big Bang Observer (BBO)

- Proposed LISA follow on
- Designed to detect early-universe GWB
- 200-300W power(!!)
- Locked on a dark fringe (more like LIGO than LISA)

Original PAPER



μHz Band



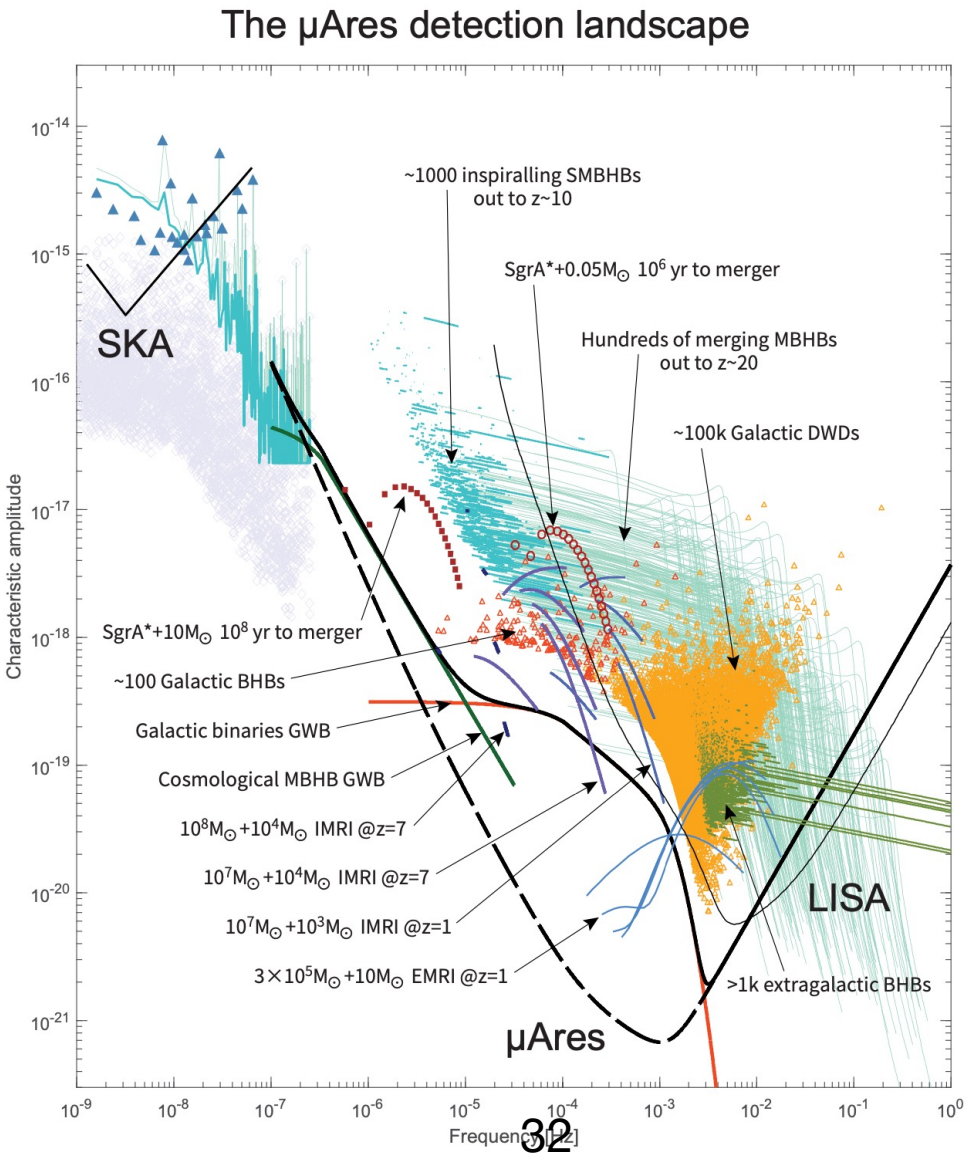
"micro-Hz Band", ~10^{-8} – 10^{-5} Hz

Space-based detectors

- **Current/Past**: Some sensitivity from PTAs
- **Proposed:** Binary resonance, astrometry, μAres detector, asteroids, Timing arrays of GW sources

Exciting sources

- Massive black hole binaries (10^3 – 10^7 solar masses), observed for longer
  - Non-linear GW memory builds up while observing these
- Compact object (CO) – non-CO binaries (e.g. WD + brown dwarf)
- Double neutron stars are continuous sources
- What happens in the galactic center? EMRI/IMRI/Primordial black holes interacting with Sag A?



Binary resonance

- Track binary orbits very precisely
  - Observable binary systems absorb GWs from stochastic GWB.
  - Cause perturbation to measurable binary orbital elements
  - Millisecond pulsars in binary system
  - Laser ranging (lunar or satellite)

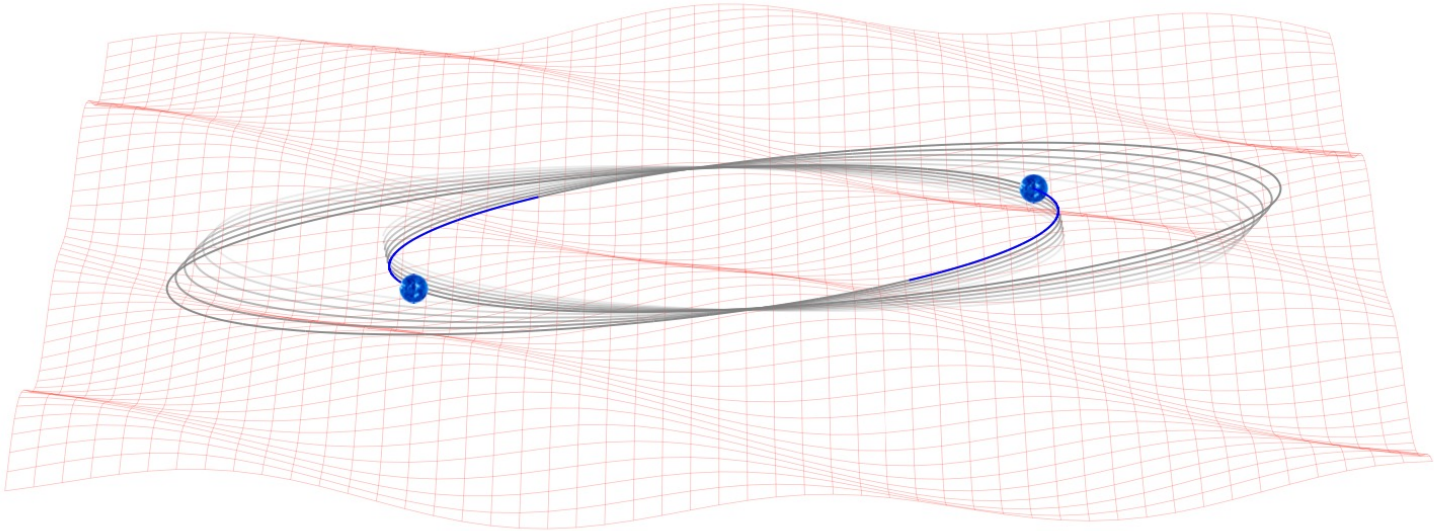


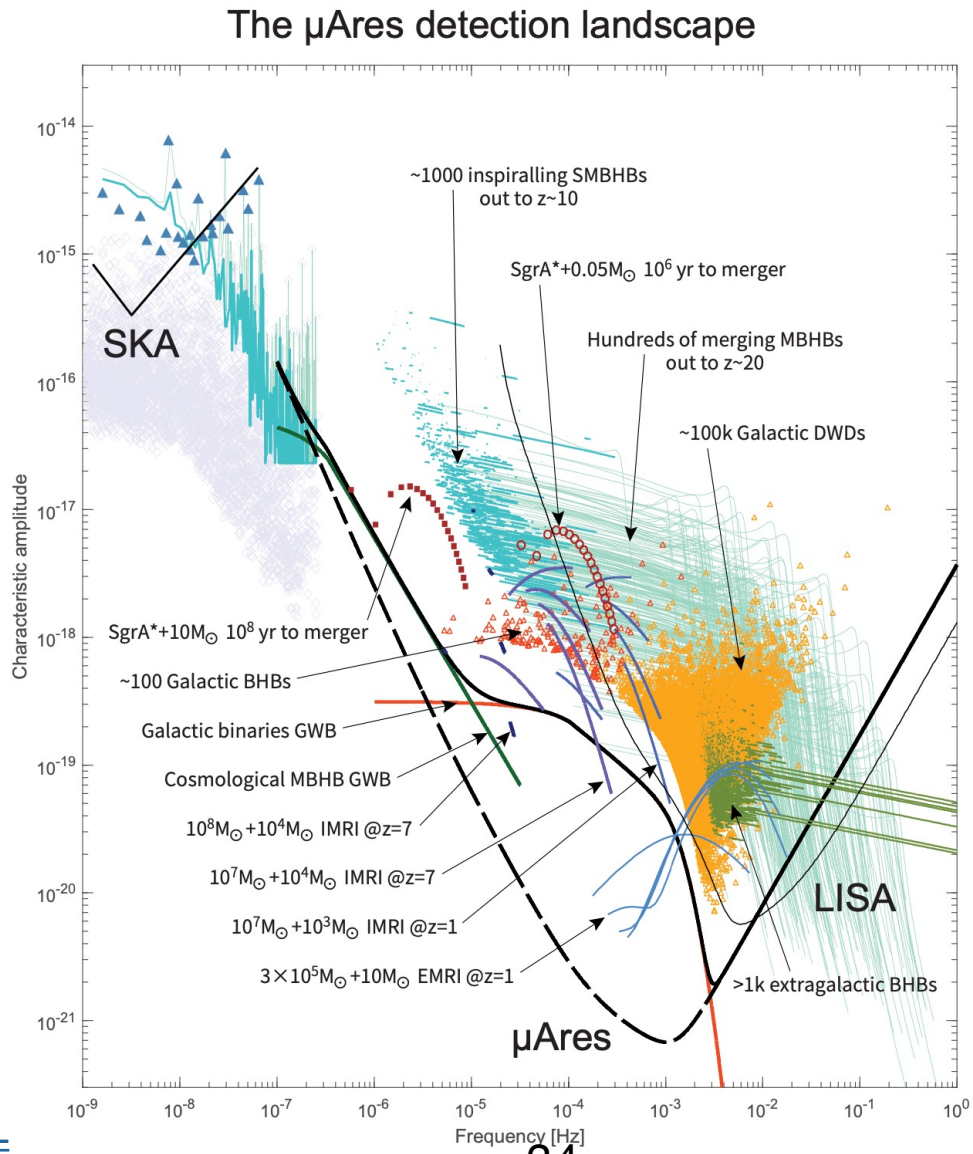
Figure 1: Cartoon illustration of the binary resonance effect. Stochastic fluctuations in the background spacetime geometry due to incoming GWs perturb the trajectories of two orbiting masses, causing cumulative changes to their orbital elements.

Introduction

LINK for image reference and most detailed work on this

μAres

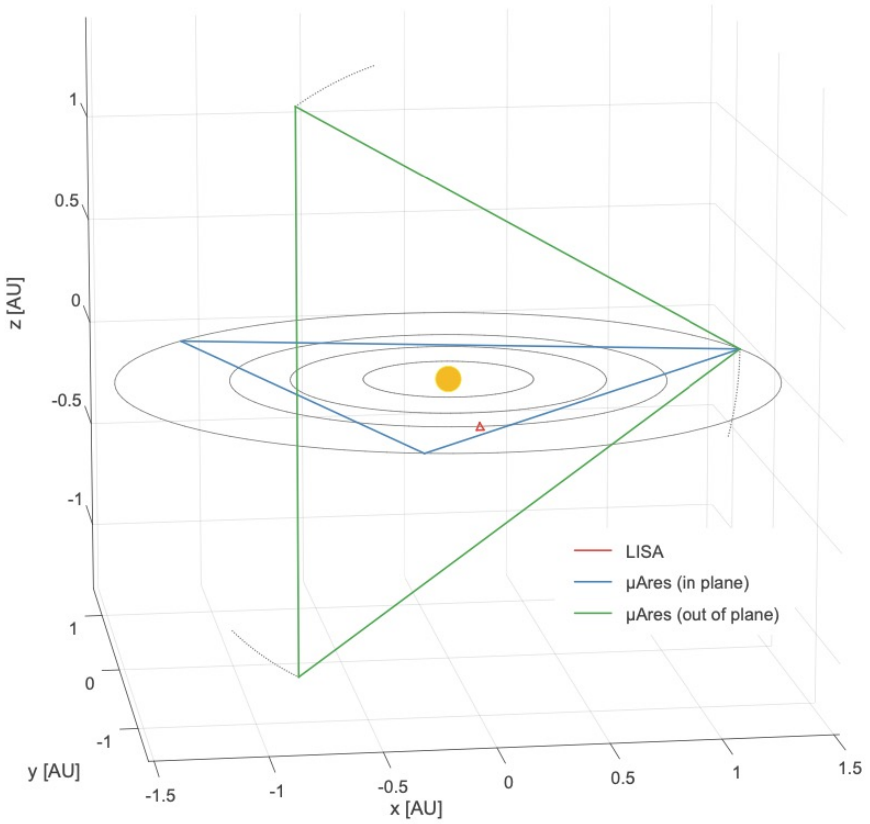
- Proposed LISA follow-on
  - ESA Voyage 2050 Proposal
- Design
  - 100 million km arms (40x LISA)
  - Acceleration noise 2x better than LISA
  - 10W laser



LINK TO PROPOSAL

μAres

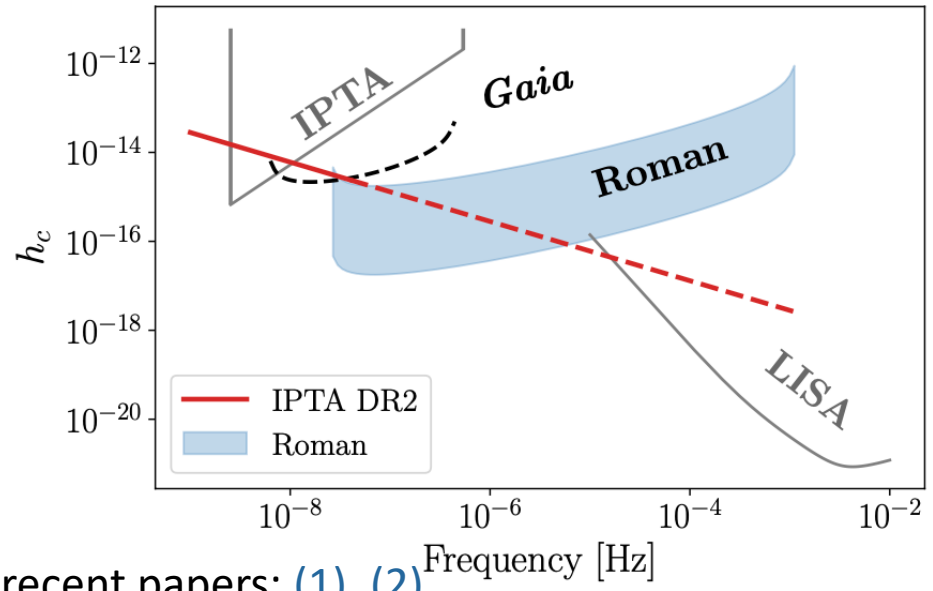
- Proposed LISA follow-on
  - ESA Voyage 2050 Proposal
- Design
  - 100 million km arms (40x LISA)
  - Acceleration noise 2x better than LISA
  - 10W laser



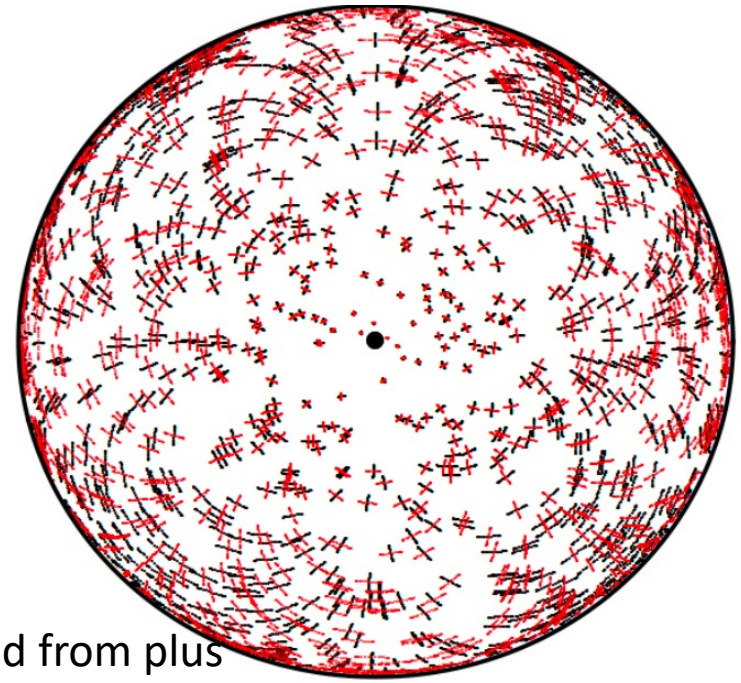
LINK TO PROPOSAL

Detecting GWs using Astrometry

- GWs deflect photons coming from stars
  - Cause deviation in apparent position of star
  - Deviations correlated across the sky due to GWB
  - Cross-correlate data from astrometric meas of many stars
- Can possibly detect individual supermassive black hole binary systems (Moore et al.)



2 recent papers: (1), (2)

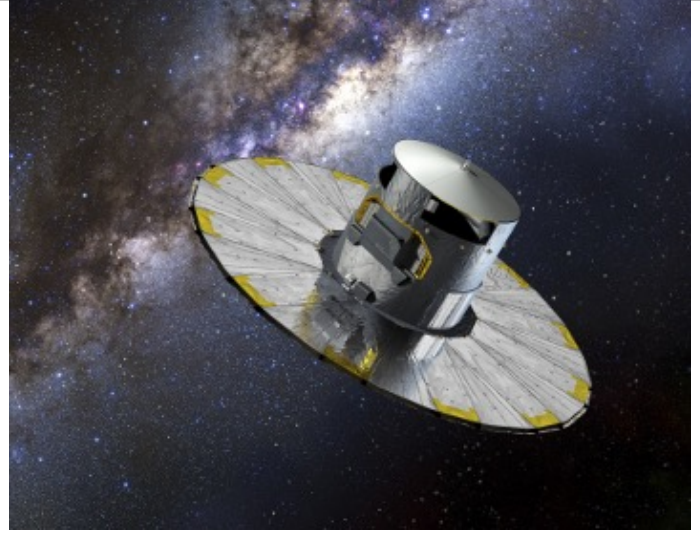


Strain induced from plus (cross) polarizations in red (black) (From Moore et al.)

Diving deep? Book & Flanagan

Detecting GWs using Astrometry

- Gaia – taking data
  - Space telescope for astrometric measurements
- Nancy Grace Roman Telescope (formerly WFIRST) -- planned
  - Space telescope for many things
  - Exoplanet Microlensing survey
- Astrometric measurements of white dwarfs (conceived)



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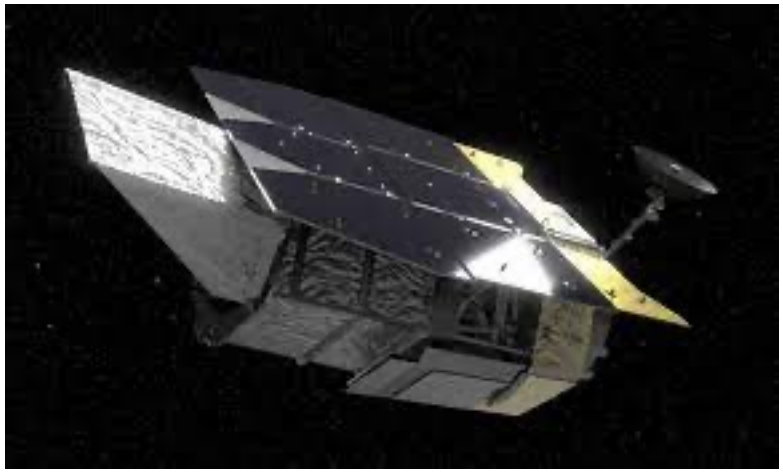
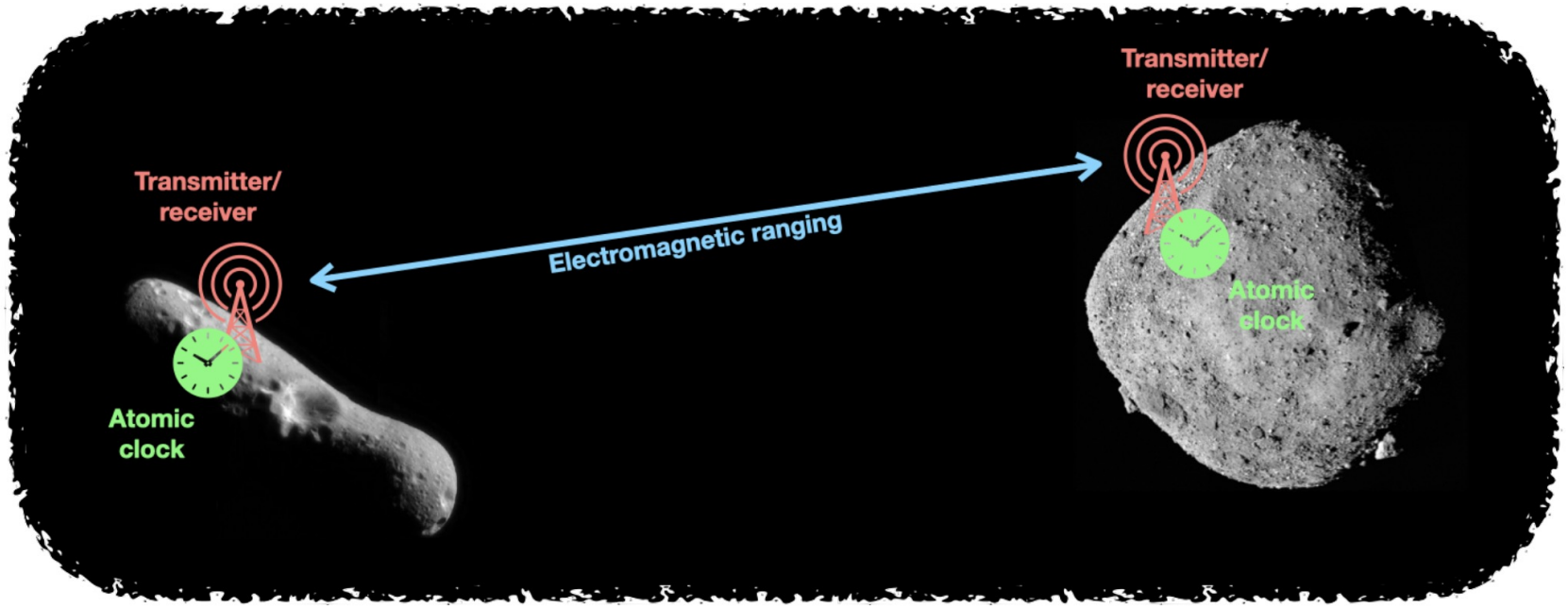


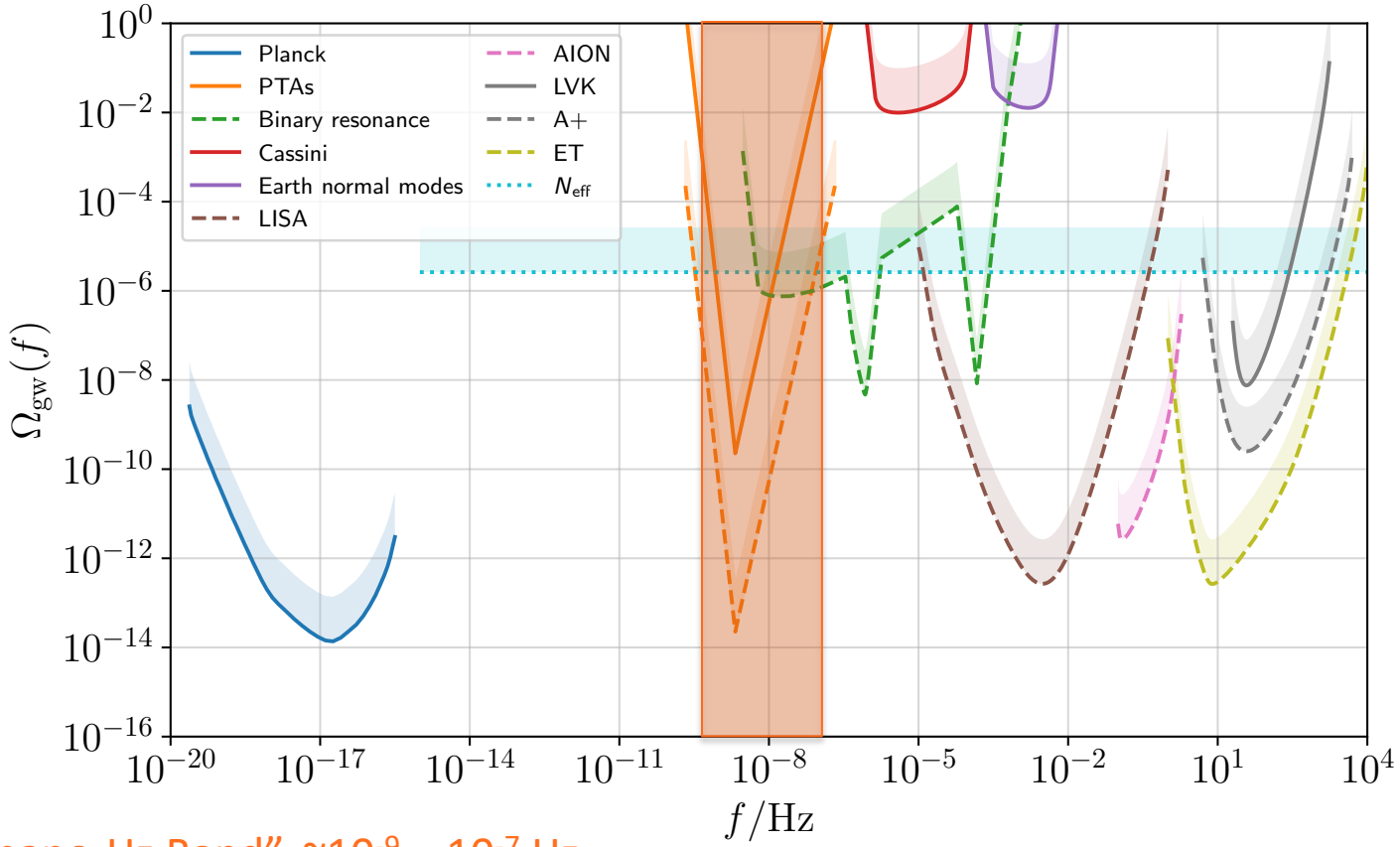
link

Asteroids as test masses



- Put transmitters on asteroids, paired with atomic clocks
  - Send pulse from one asteroid to the other
  - amplify signal, send return pulse
  - Compare arrival time of returned pulse with local clock reference

nHz Band



"nano-Hz Band", ~10^{-9} – 10^{-7} Hz

Space-based detectors

- **Current/Past**: Pulsar timing arrays
- **Proposed:** Binary resonance, astrometry, Timing arrays of continuous GW sources

Exciting sources

- GWB from unresolved Supermassive black hole binaries
- Individual Supermassive black hole binaries
- GW memory
- Other non-astrophysical sources
  - Cosmic strings
  - Phase transitions

Pulsar timing arrays

- Pulsars are neutron stars
- They rotate, emitting pulses
  - Typically in radio and/or X-ray or gamma-ray bands
- Those pulses are very predictable
- GWs change arrival time of pulses

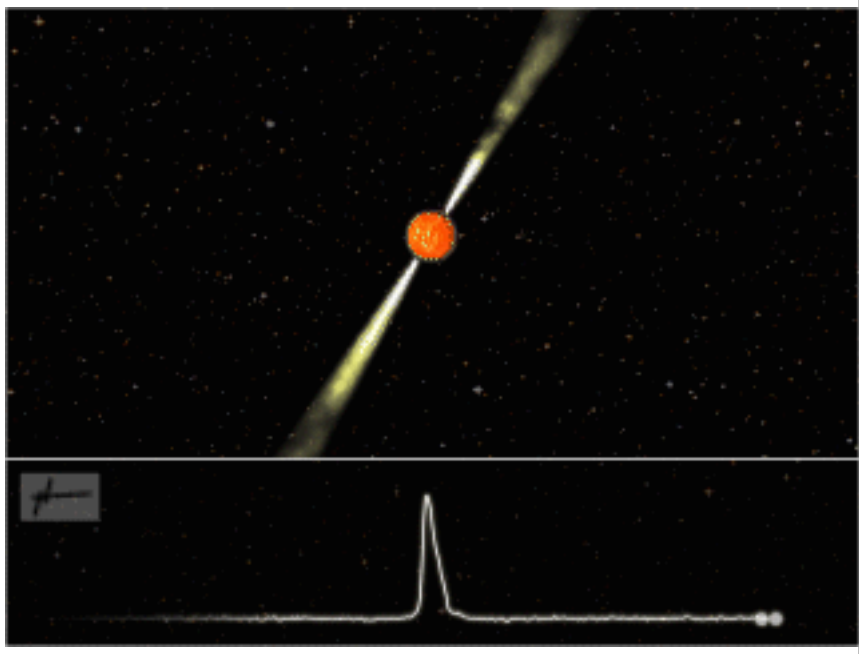
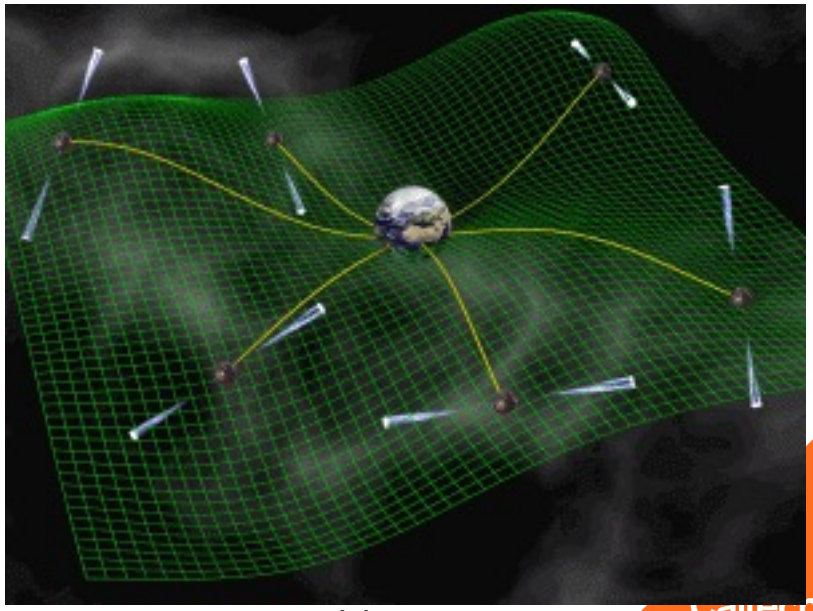


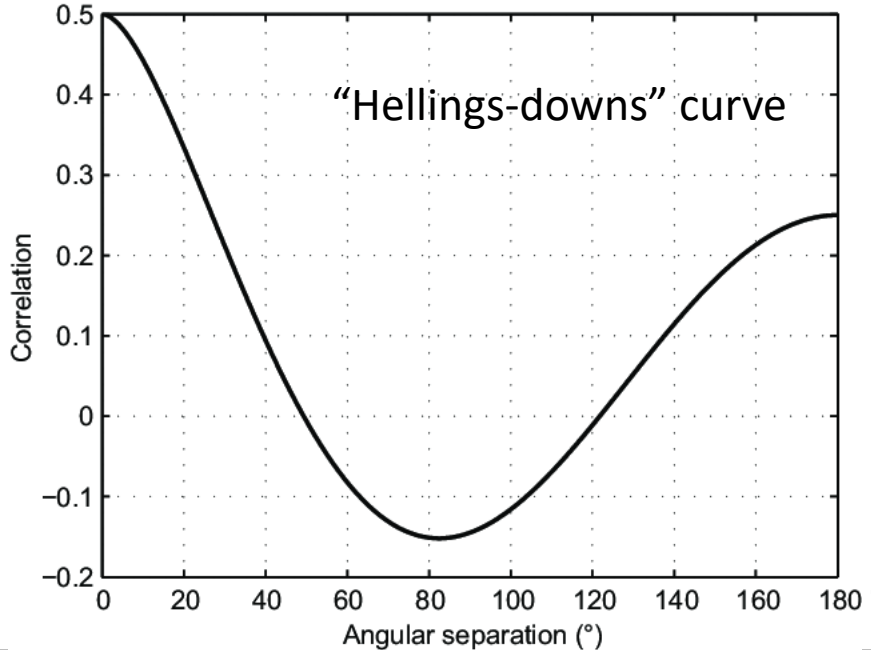
Image credit: Joeri van Leeuwen



[David Champion/NASA/JPL]

Pulsar timing arrays in one slide

- We treat pulsars as very precise clocks
- Gravitational waves will cause slight deviations in the arrival of those pulses
- Those deviations should be correlated between pulsars
- The amplitude of that correlation depends on the separation of the pulsars on the sky



Subject to assumptions like isotropy of the sources, etc.

Current detection efforts

- NANOGrav
  - North America-based collaboration
  - Uses Green Bank Telescope, Arecibo Observatory, CHIME/Pulsar, VLA
  - 12.5 year results (45 pulsars) indicate evidence for “common process”
- Parkes Pulsar Timing Array
  - Uses Parkes (Murriyang) Telescope
  - 15 years of data, 26 pulsars, also indicate evidence for common process

Current detection efforts

- European Pulsar Timing array
  - Use Nançay Radio Telescope, Effelsberg 100m Radio Telescope, Lovell Telescope, and Westerbork Synthesis Radio Telescope
  - 6 pulsars, 24 years of data, evidence for CP
- International Pulsar Timing array
  - PPTA + EPTA + NANOGrav
  - 30 years, 53 pulsars, evidence for CP

Upcoming efforts

Taking data, but no GW searches, or not yet taking data

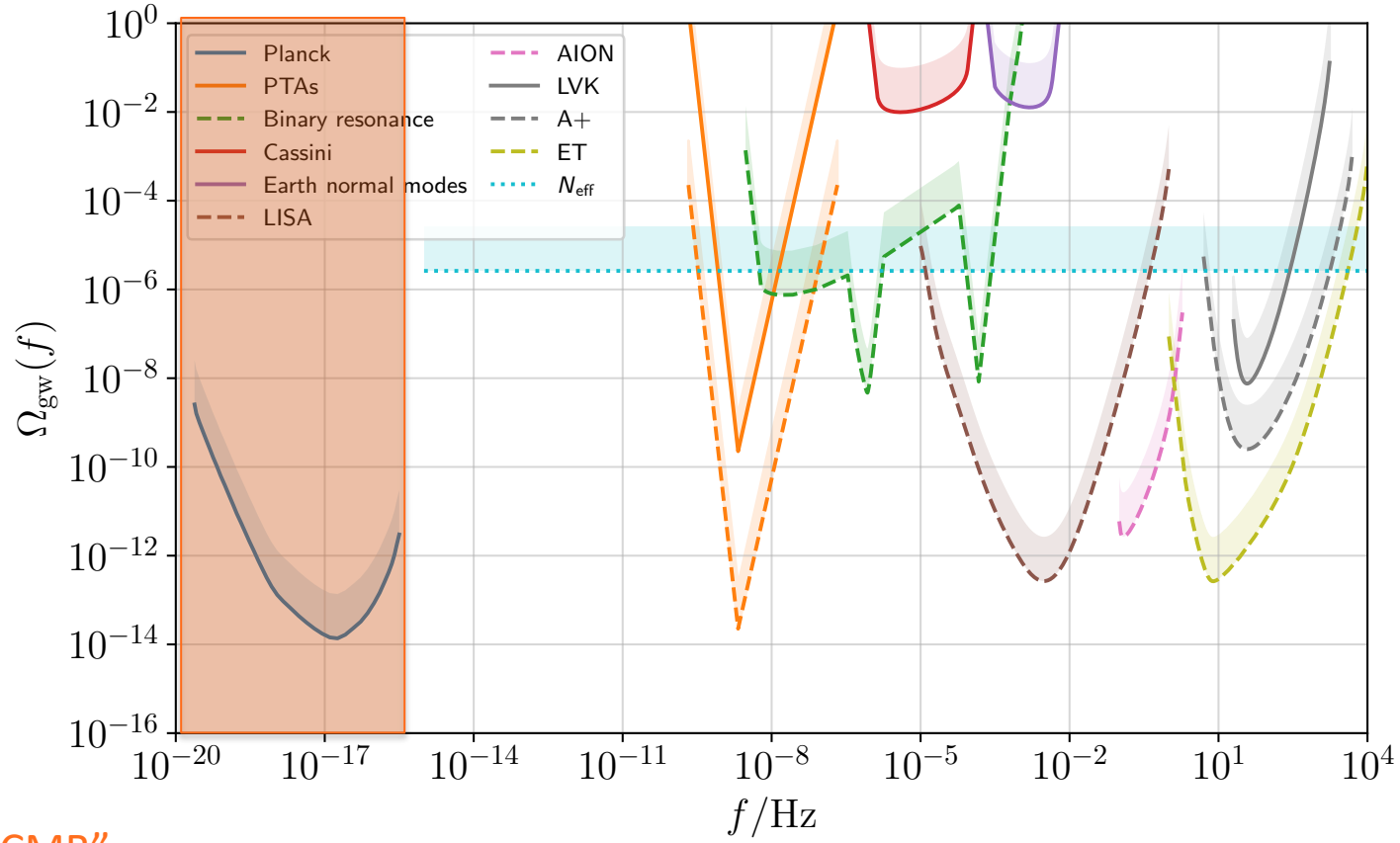
- Meerkat/Meertime
  - Using MeerKAT telescope (SKA pathfinder) in South Africa
  - Currently operating and timing many pulsars
- Five hundred meter Aperture Telescope (FAST)
  - Chinese radio telescope with 500m dish
  - Very (very) sensitive
  - Currently timing pulsars

Upcoming efforts

Taking data, but no GW searches, or not yet taking data

- Indian Pulsar Timing Array
  - First data release just published! Link
  - Likely to be included in IPTA
- Square Kilometer Array (SKA)
  - Wideband, will use aperture synthesis
  - Will be *very* sensitive
- DSA-2000
  - Proposed (conceived?) 2000-dish array, with pulsar science as one of the core components

CMB



"CMB"

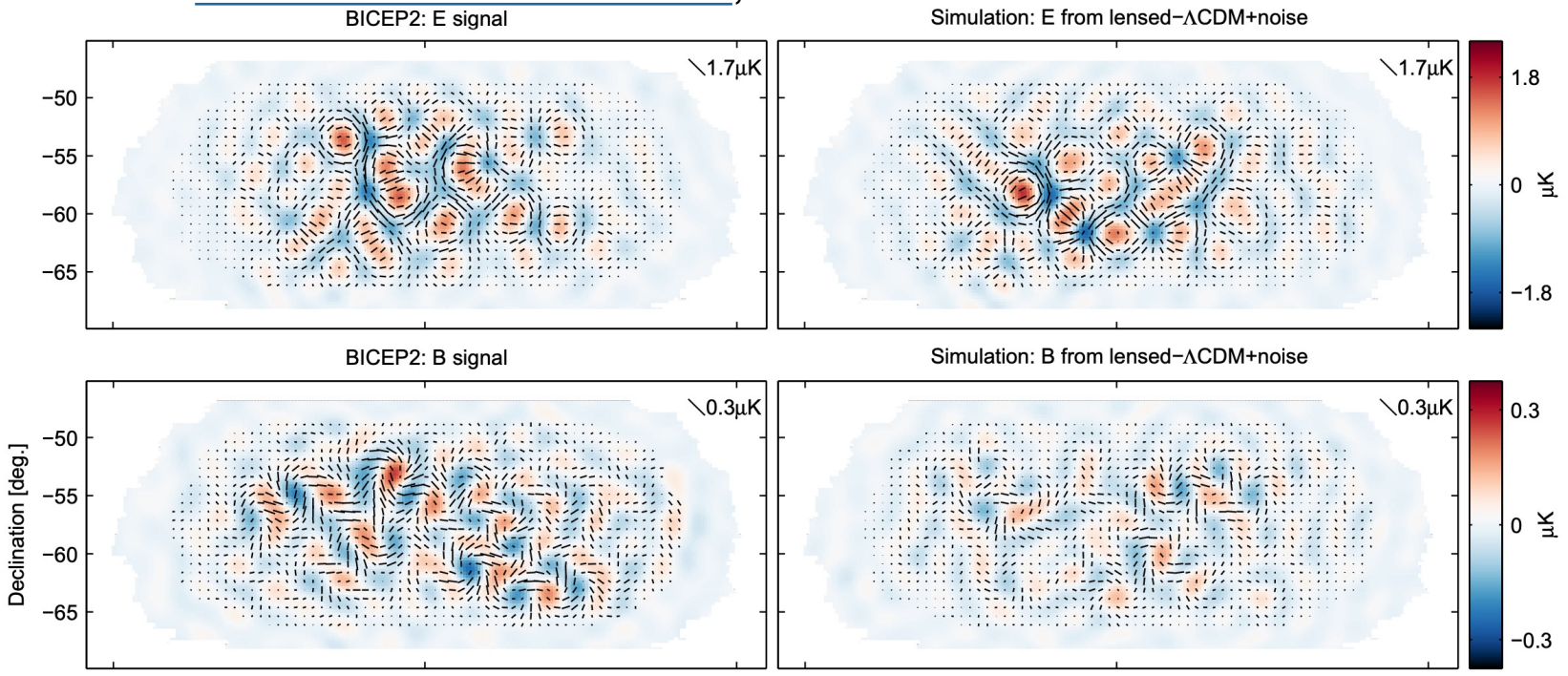
Imprints of GWs on the CMB…

Exciting sources

- GWs from early Universe!

How does it work?

- GWs present at time of last scattering induce specific pattern in polarization of the CMB
  - "B-modes"
  - Characterized in terms of ratio of power spectrum of density perturbations to power spectrum of GWs ("tensor to scalar ratio")
  - Planck+BICEP constraints, r< 0.044



From the ill-fated BICEP2 results

Main experiments

- **Planck** – Space observatories, goal to map anisotropies of cosmic microwave background.
- **Bicep** – South pole radio telescopes. Main goal to measure polarization of CMB.
- **CMB-S4 – ground-based CMB experiment. 21 telescopes (South Pole & Chile, planned for 7 years)**
- **There are a few others (e.g. some balloon experiments), I've just named some of the more famous ones here.**