Gravitational-Wave (GW) Spectrum Middle-Frequency GW Detection and AMIGO (the Astodynamical Middle-frequency Interferometric Gw Observatory)

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Refs: (i) WTN, GW classification, space GW detection sensitivities and AMIGO arXiv:1709.05659 [gr-qc] July 4, 2017 Plenary talk at ICGAC-IK15

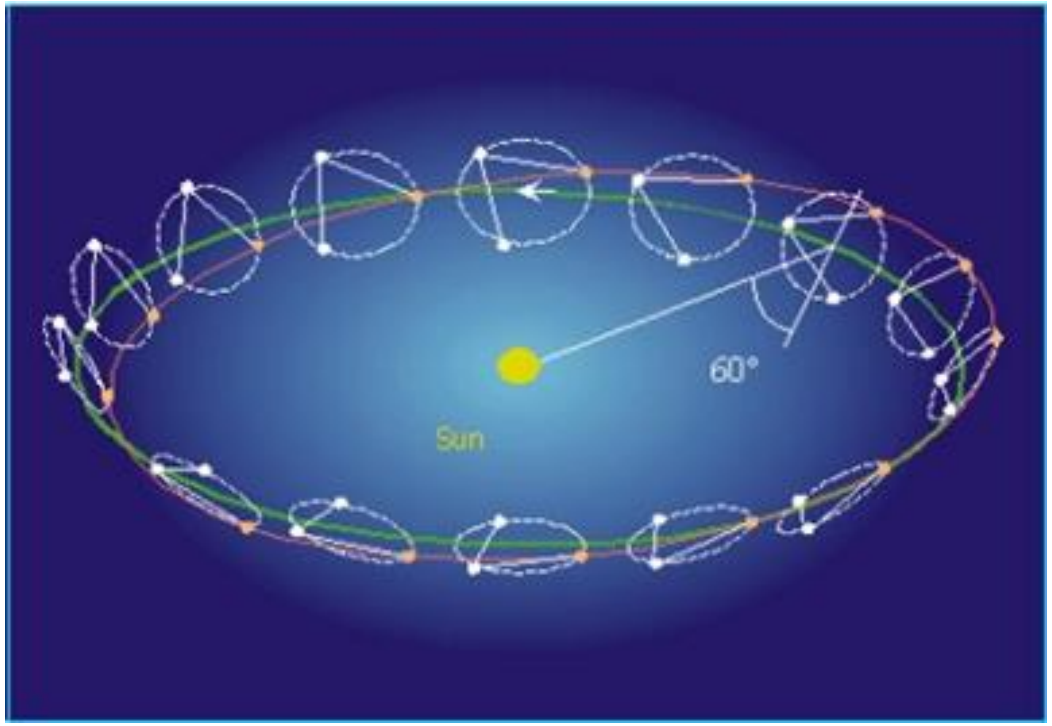
(ii) WTN, G. Wang and A.-M. Wu, AMIGO: Mission Concept and Orbit Design

(iii) S. Kuroyanagi, L-W Luo and WTN, GW sensitivities over all frequency band

(iv) WTN, GW detection in space IJMPD 25 (2016) 1530002

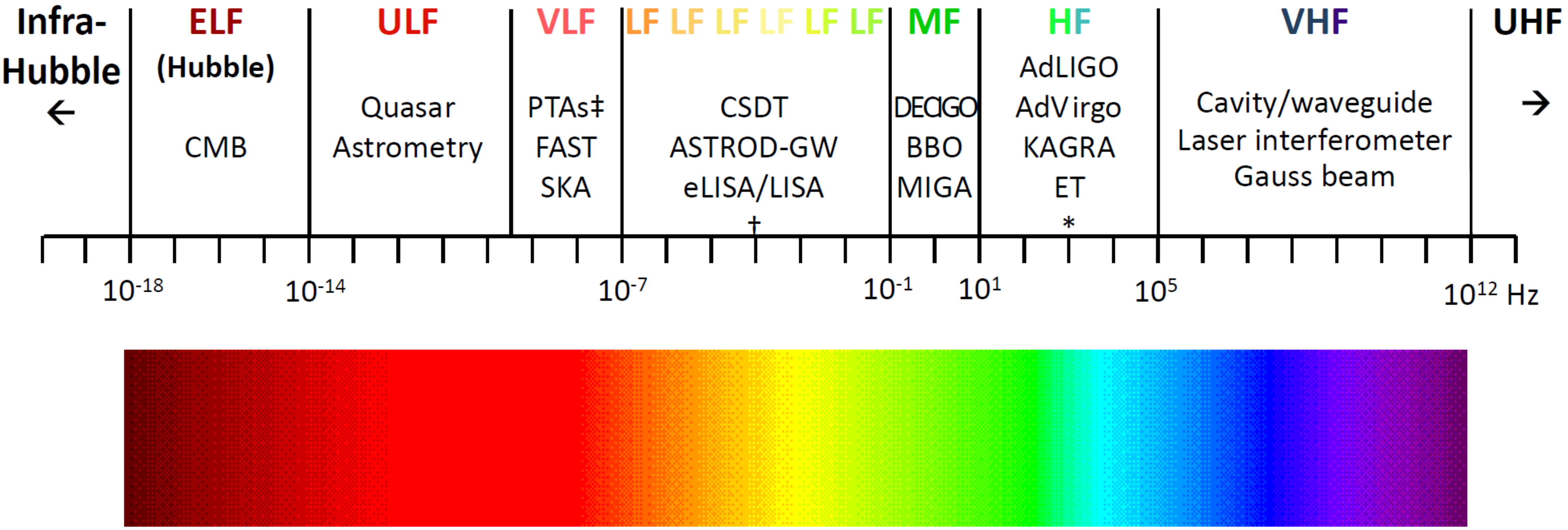
Outline

- GW spectrum and detection sensitivities
- Earth-Based detection
- Middle-Frequency Band
- AMIGO Mission Concept
- AMIGO Orbit Design



- Space GW detection, new LISA, TAIJI, TianQin, ……
- Cosmic Band, Quaser Astrometry Band and PTA band
- Outlook

引力波谱分类 The Gravitation-Wave (GW) Spectrum Classification



* AIGO, AURIGA, EXPLORER, GEO, NAUTILUS, MiniGRAIL, Schenberg.

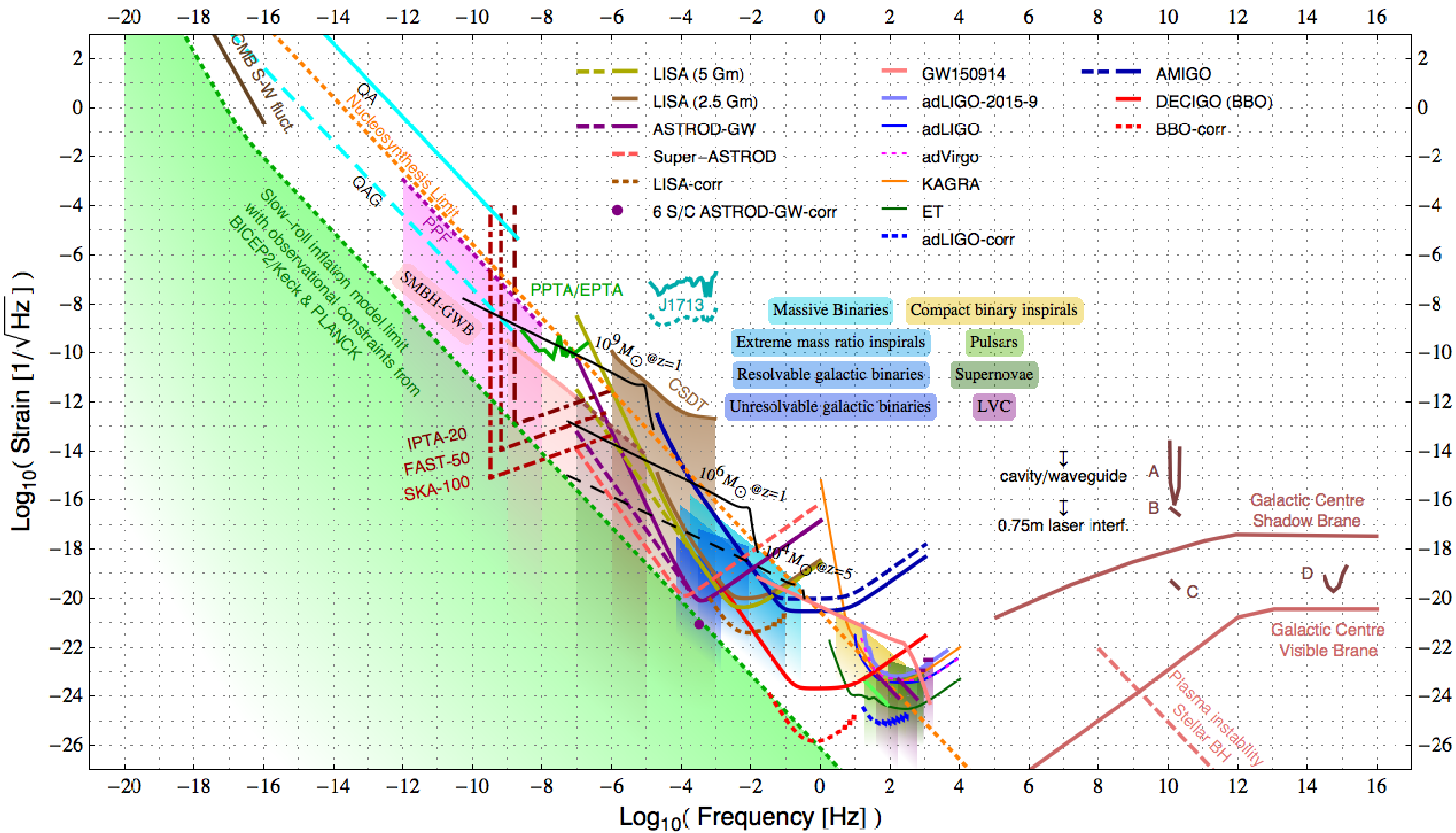
† OMEGA, gLISA/GEOGRAWI, GADFLI, TIANQIN, ASTROD-EM, LAGRANGE, ALIA, ALIA-descope.

‡ EPTA, NANOGrav, PPTA, IPTA.

Scope: Goals –GW Astronomy & Fundamental Physics

Frequency band	GW sources / Possible GW sources	Detection method
Ultrahigh frequency band: above 1 THz	Discrete sources, Cosmological sources, Braneworld Kaluza-Klein (KK) mode radiation, Plasma instabilities	Terahertz resonators, optical resonators, and magnetic conversion detectors
Very high frequency band: 100 kHz – 1 THz	Discrete sources, Cosmological sources, Braneworld Kaluza-Klein (KK) mode radiation, Plasma instabilities	Microwave resonator/wave guide detectors, laser interferometers and Gaussian beam detectors
High frequency band (audio band)*: 10 Hz – 100 kHz	Compact binaries [NS (Neutron Star)-NS, NS-BH (Black Hole), BH-BH], Supernovae	Low-temperature resonators and Earth-based laser-interferometric detectors
Middle frequency band: 0.1 Hz – 10 Hz	Intermediate mass black hole binaries, massive star (population III star) collapses	Space laser-interferometric detectors of arm length 1,000 km – 60,000 km
Low frequency band (milli-Hz band)†: 100 nHz – 0.1 Hz	Massive black hole binaries, Extreme mass ratio inspirals (EMRIs), Compact binaries	Space laser-interferometric detectors of arm length longer than 60,000 km
Very low frequency band (nano-Hz band): 300 pHz – 100 nHz	Supermassive black hole binary (SMBHB) coalescences, Stochastic GW background from SMBHB coalescences	Pulsar timing arrays (PTAs)
Ultralow frequency band: 10 fHz – 300 pHz	Inflationary/primordial GW background, Stochastic GW background	Astrometry of quasar proper motions
Extremely low (Hubble) frequency band: 1 aHz–10 fHz	Inflationary/primordial GW background	Cosmic microwave background experiments
Beyond Hubble-frequency band: below 1 aHz	Inflationary/primordial GW background	Through the verifications of primordial cosmological models

Strain power spectral density (psd) amplitude vs. frequency for various GW detectors and GW sources

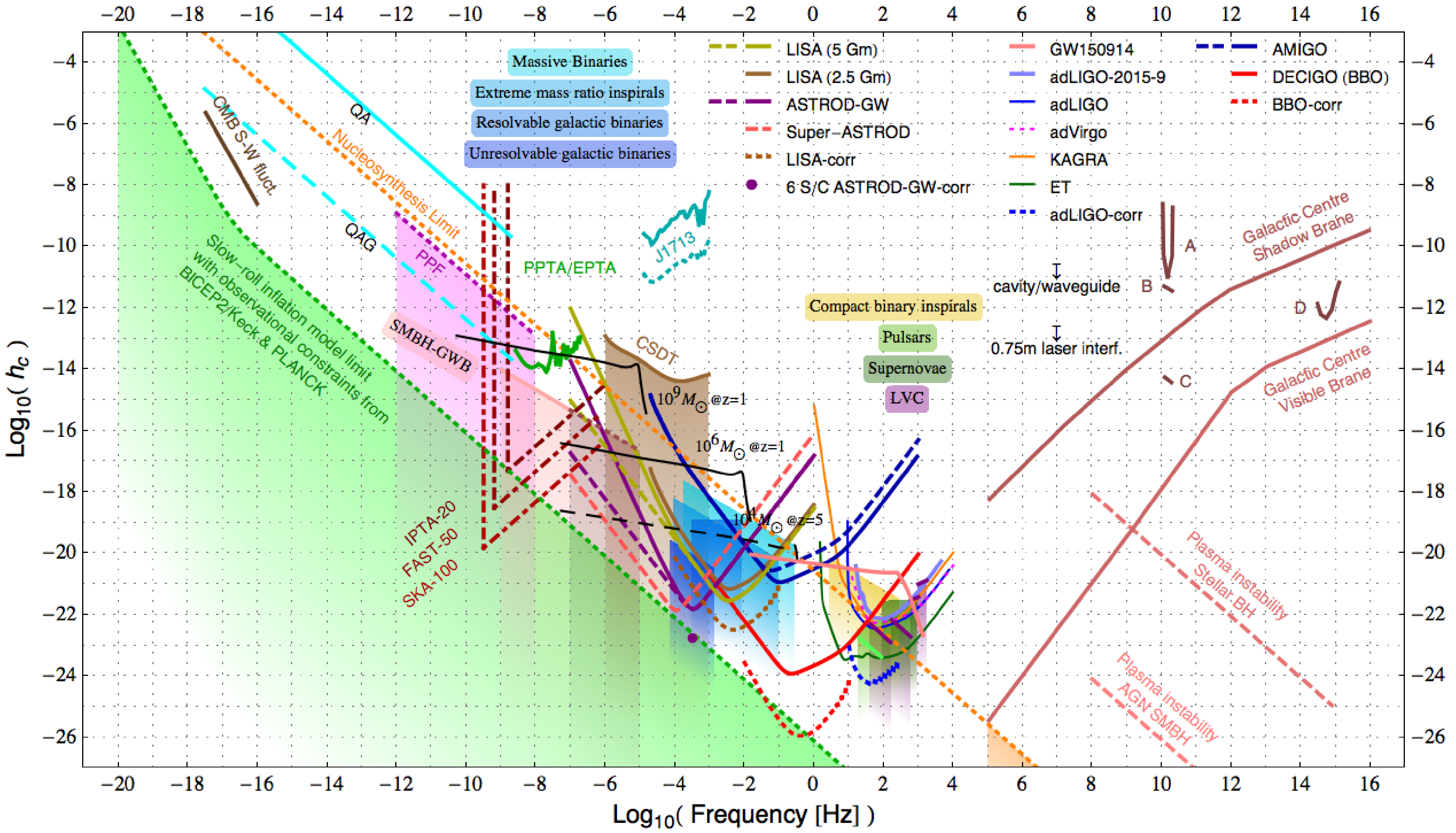


Conversion factors among: the characteristic strain $h_c(f)$, the strain psd (power spectral density) $[S_h(f)]^{1/2}$ the normalized spectral energy density $\Omega_{gw}(f)$

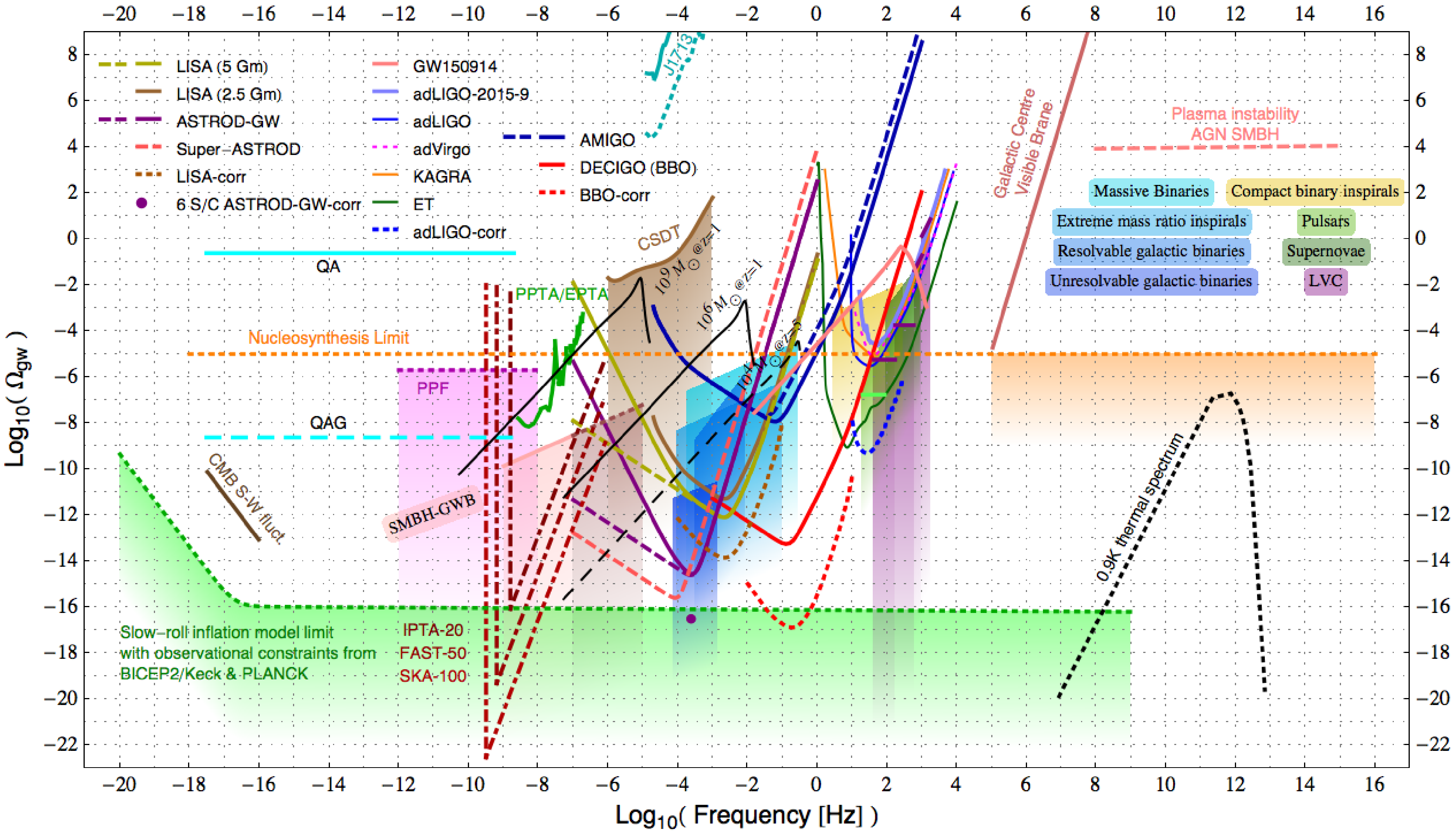
- $h_c(f) = f^{1/2}\,[S_h(f)]^{1/2}$;
- *normalized GW spectral energy density* $\Omega_g(f)$: GW spectral energy density in terms of *the energy density per logarithmic frequency interval divided by the cosmic closure density* ρ_c for a cosmic GW sources or background, i.e.,
- $\Omega_{gw}(f) = (f/\rho_c)\, d\rho(f)/df$
- $\Omega_{gw}(f) = (2\pi^2/3H_0^2)\, f^3\, S_h(f) = (2\pi^2/3H_0^2)\, f^2\, h_c^2(f)$.

	Characteristic strain $h_c(f)$	Strain psd $[S_h(f)]^{1/2}$	Normalized spectral energy density $\Omega_{gw}(f)$
$h_c(f)$	$h_c(f)$	$f^{1/2}\,[S_h(f)]^{1/2}$	$[(3H_0^2/2\pi^2 f^2)\Omega_{gw}(f)]^{1/2}$
Strain psd $[S_h(f)]^{1/2}$	$f^{-1/2} h_c(f)$	$[S_h(f)]^{1/2}$	$[(3H_0^2/2\pi^2 f^3)\Omega_{gw}(f)]^{1/2}$
$\Omega_{gw}(f)$	$(2\pi^2/3H_0^2)\, f^2\, h_c^2(f)$	$(2\pi^2/3H_0^2)\, f^3\, S_h(f)$	$\Omega_{gw}(f)$

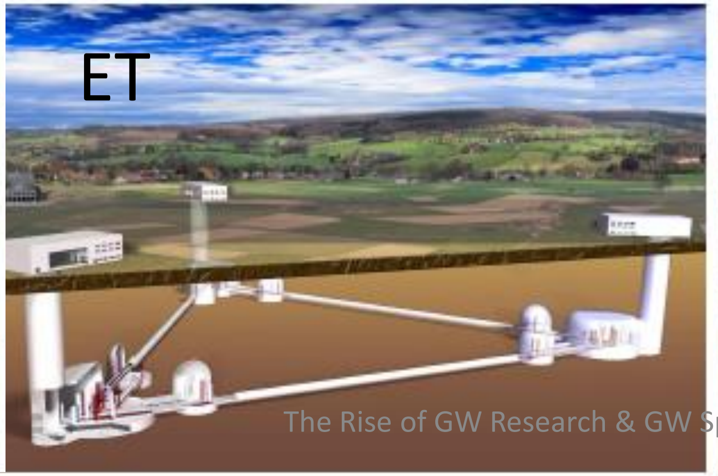
Characteristic strain h_c vs. frequency for various GW detectors and sources. [QA: Quasar Astrometry; QAG: Quasar Astrometry Goal; LVC: LIGO-Virgo Constraints; CSDT: Cassini Spacecraft Doppler Tracking; SMBH-GWB: Supermassive Black Hole-GW Background.]



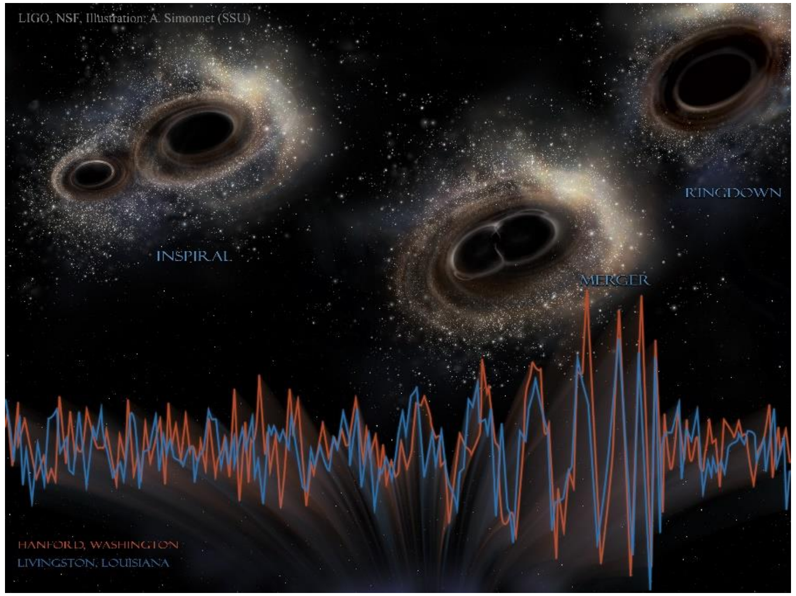
Normalized GW spectral energy density Ω_{gw} vs. frequency for GW detector sensitivities and GW sources

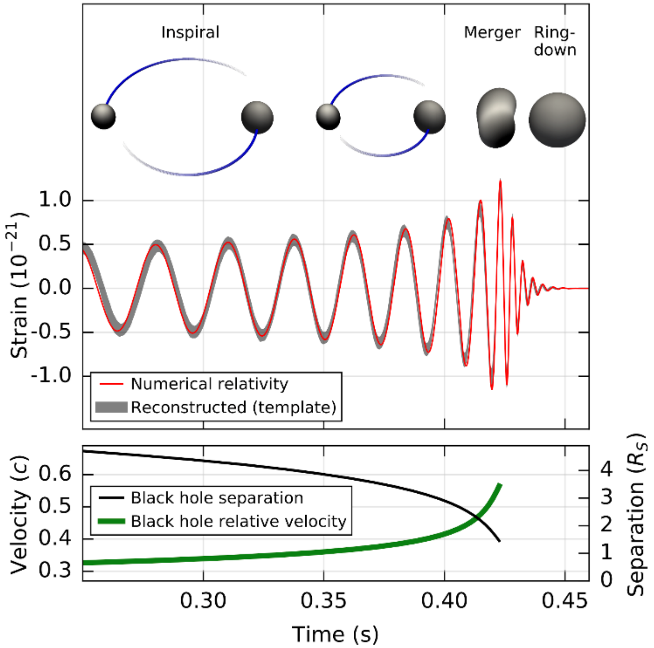


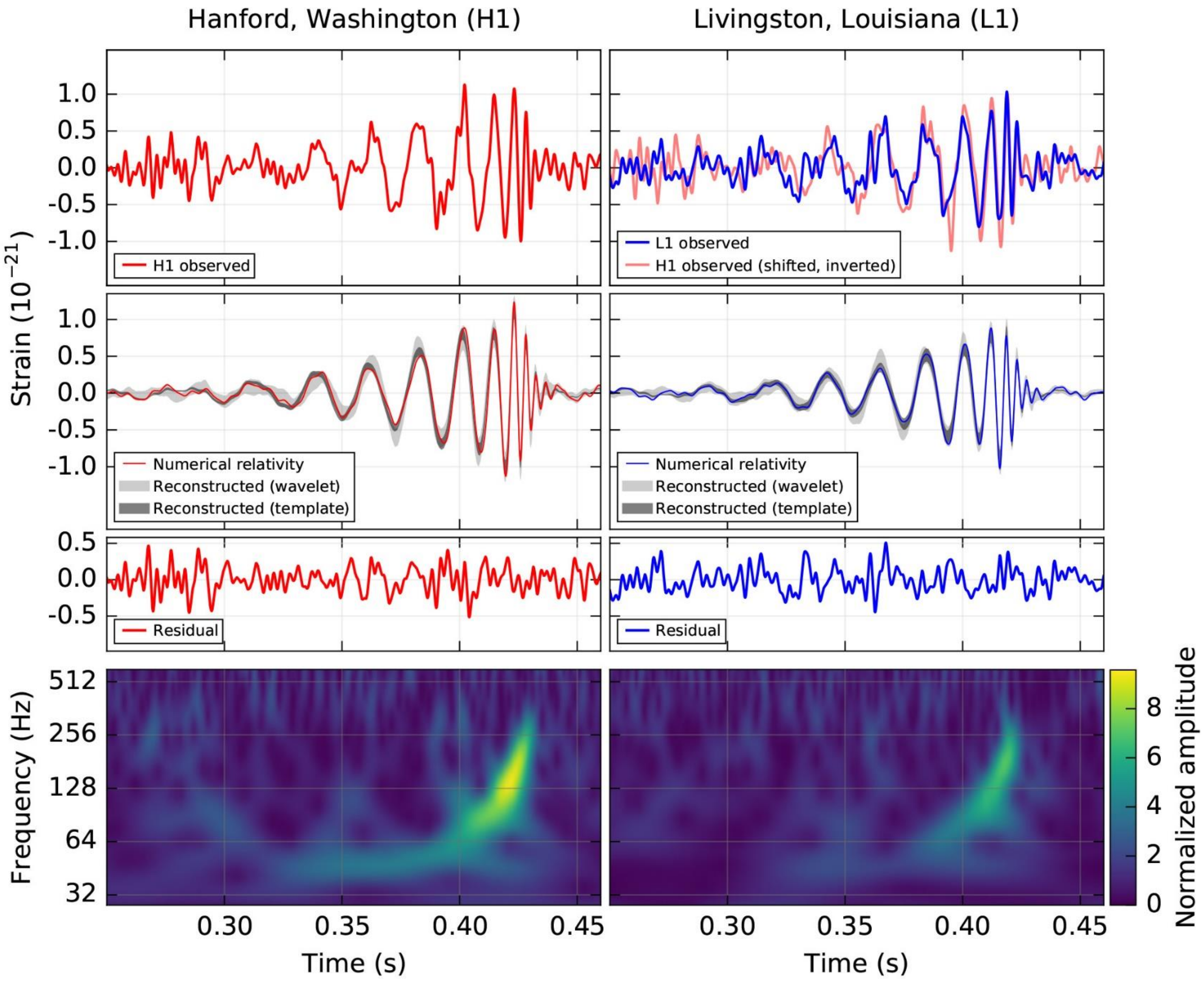
Ground-based GW detectors



2016年2月11日宣布首探 Announcement of first detection

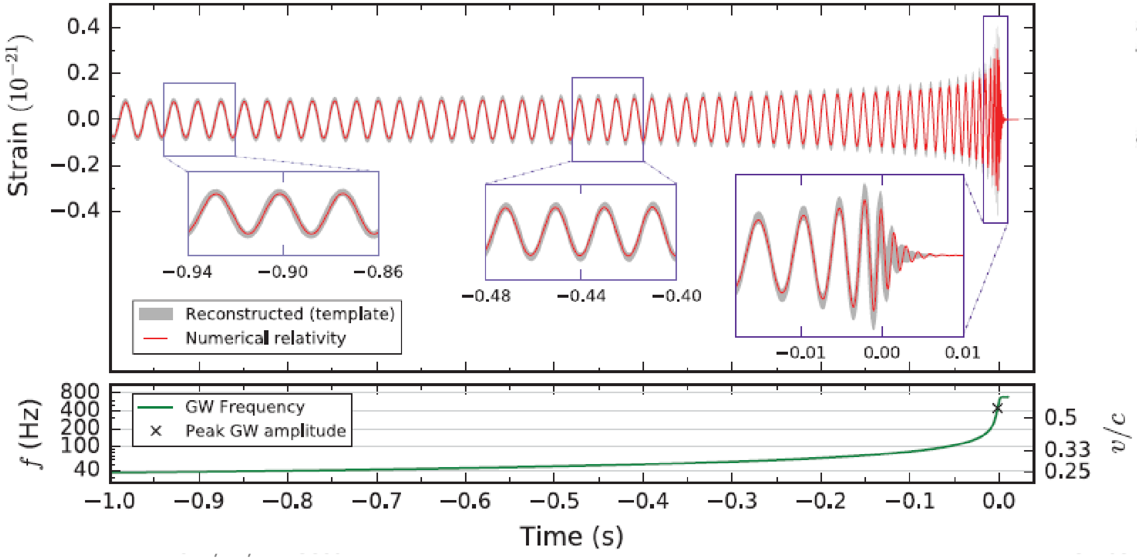


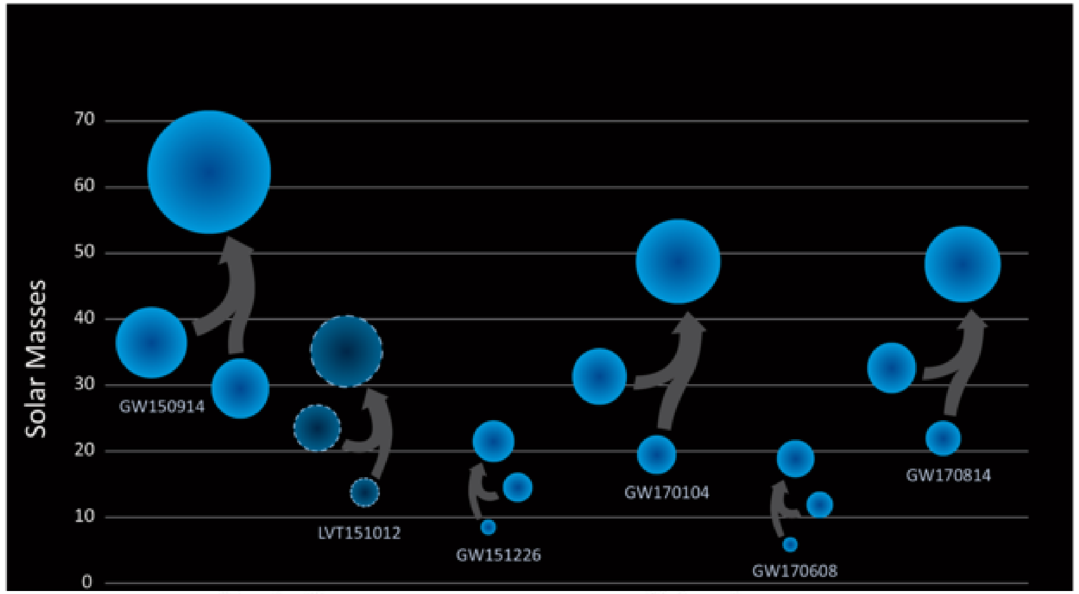


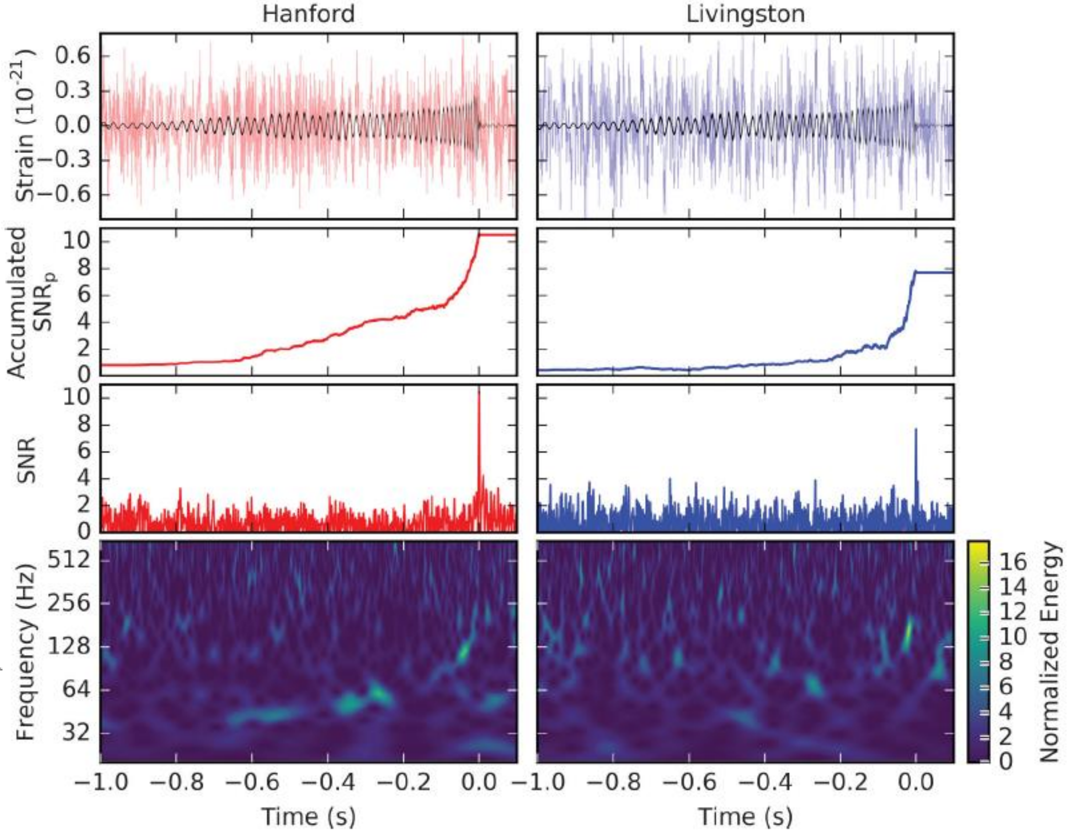


2016年6月15日宣布二探 Announcement of second detection

- GW151226 detected by the LIGO on December 26, 2015 at 03:38:53 UTC.
- identified within 70 s by an online matched-filter search targeting binary coalescences.
- GW151226 with S/N ratio of 13 and significance > 5σ.
- The signal ~ 1 s, about 55 cycles from 35 to 450 Hz, reached 3.4 (+0.7,−0.9) × 10^(−22). source-frame initial BH masses: 14.2 (+8.3,−3.7)$M_\odot$ and 7.5 (+2.3,−2.3)$M_\odot$, the final BH mass is 20.8 (+6.1,−1.7)$M_\odot$.
- 1 BH has spin greater than 0.2. luminosity distance 440 (+180,−190) Mpc redshift of 0.09 (+0.03,−0.04). **2σ**
- improved constraints on stellar populations and on deviations from general relativity.





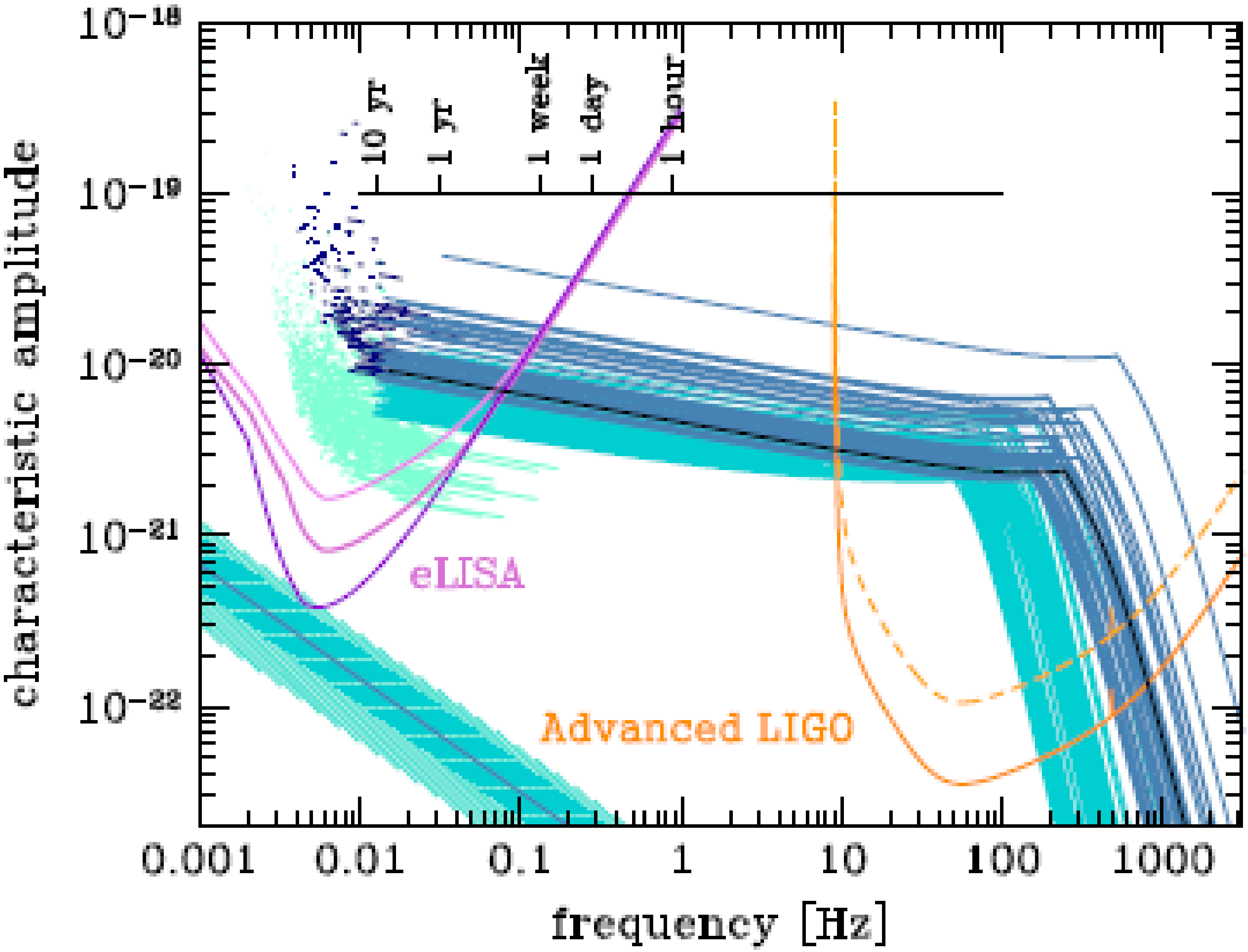


GW20150914

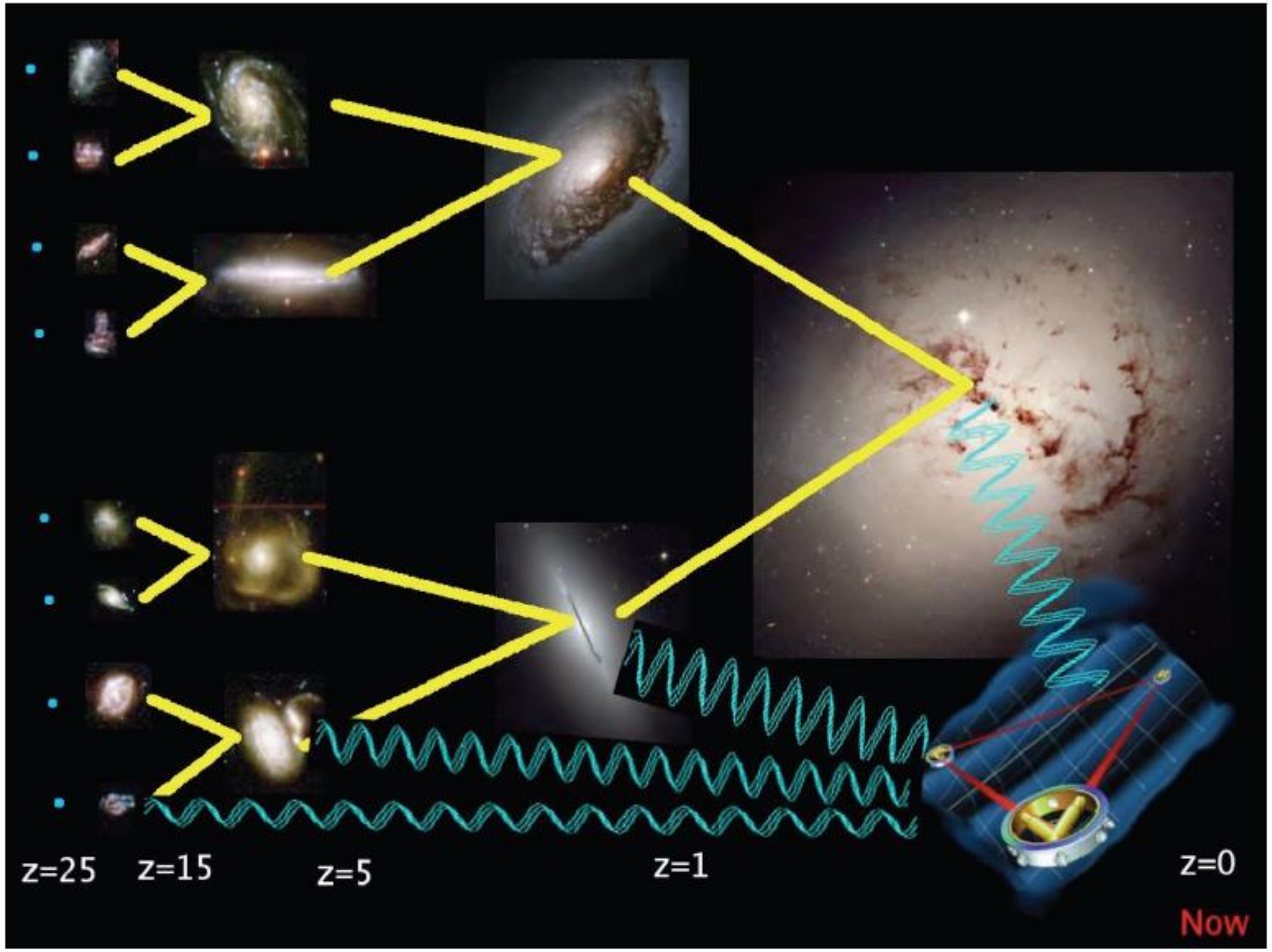
LIGO

LISA

(from Sesana 2017 prl)



Massive Black Hole Systems: Massive BH Mergers & Extreme Mass Ratio Mergers (EMRIs)



Middle frequency GW Detection Science Goals

- **The science goals are the detection of GWs from**
- **(i) Intermediate-Mass Black Holes; could detect IMBH binaries at a few billion light years away or further**
- **(ii) Galactic Compact Binaries as well as stellar mass BH binaries, like GW150914;**
- **(iii) could alert laser interferometers days before merger by detecting inspiral phase and predict time of binany black hole coalescence & neutron star coalescence for ground interferometers**
- **(iv) Relic/Inflationary GW Background.**

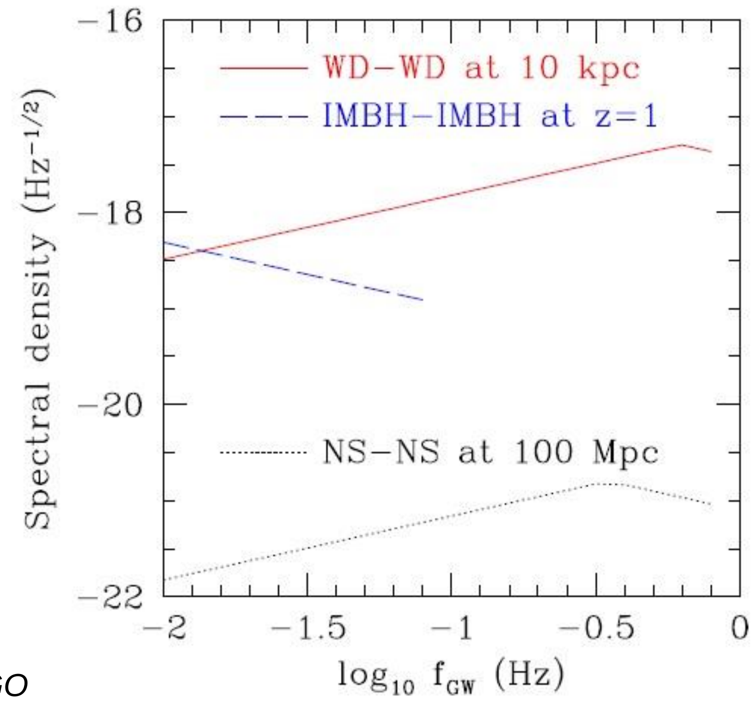
PHYSICAL REVIEW D **88**, 122003 (2013)

Low-frequency terrestrial gravitational-wave detectors

Jan Harms,[1] Bram J. J. Slagmolen,[2] Rana X. Adhikari,[3] M. Coleman Miller,[4,5] Matthew Evans,[6]
Yanbei Chen,[7] Holger Müller,[8] and Masaki Ando[9,10]

Direct detection of gravitational radiation in the audio band is being pursued with a network of kilometer-scale interferometers (LIGO, Virgo, KAGRA). Several space missions (LISA, DECIGO, BBO) have been proposed to search for sub-hertz radiation from massive astrophysical sources. Here we examine the potential sensitivity of three ground-based detector concepts aimed at radiation in the 0.1–10 Hz band. We describe the plethora of potential astrophysical sources in this band and make estimates for their event rates and thereby, the sensitivity requirements for these detectors. The scientific payoff from measuring astrophysical gravitational waves in this frequency band is great. Although we find no fundamental limits to the detector sensitivity in this band, the remaining technical limits will be extremely challenging to overcome.

- **Analyzed three detector options:**
  1. **Atom-laser interferometer**
  2. **TOBA with laser interferometer**
  3. **Michelson interferometer**
- **Would be astrophysically interesting, if one can reach $S_h^{1/2}(f) = 10^{-20}\ \mathrm{Hz}^{-1/2}$ in 0.1-10 Hz band.**
- **Detecting and removing NN appears to be *extremely challenging*.**



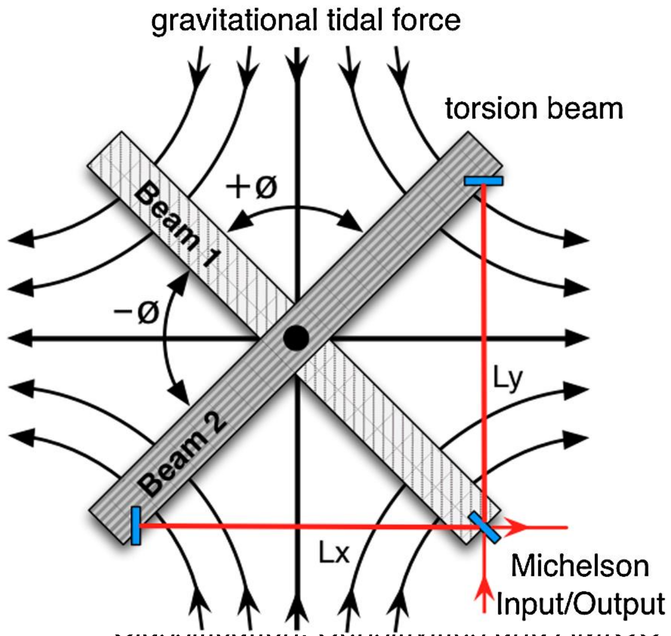
Proposed Detection Methods for Middle-frequency GWs

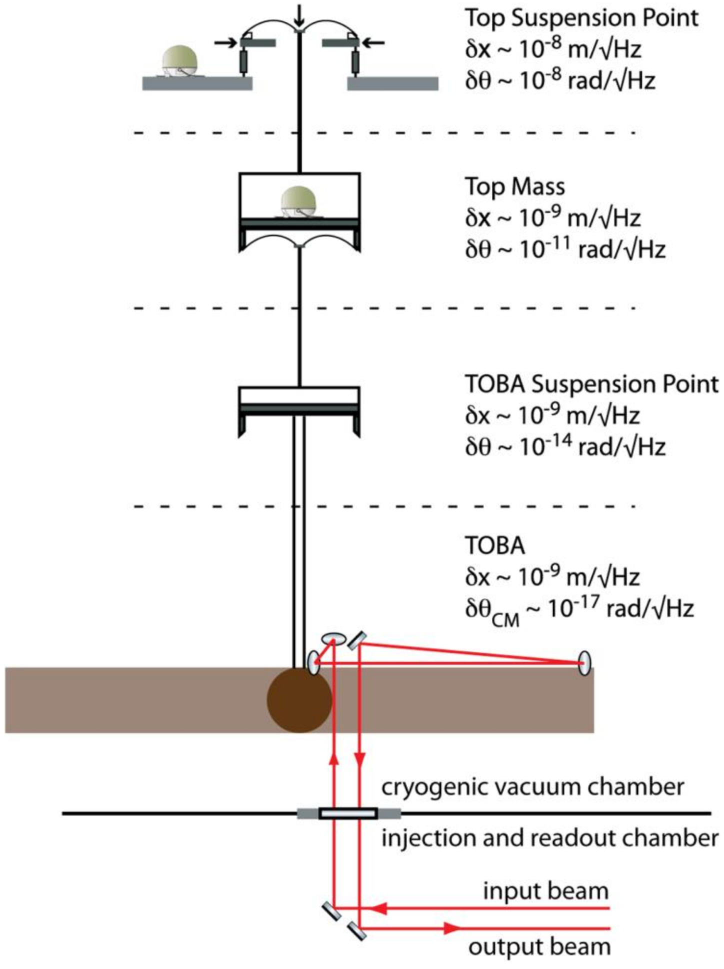
- TOBA – The torsion bar antenna
- SOBRO -- Superconducting Omni-directional Gravitational Radiation Observatory
- Michelson Interferometer on Earth and in space
- Atom Interferometry involving repeatedly imprinting the phase of optical field onto the motional degrees of freedom of the atoms using light propagating back and forth between the spacecraft.
- Resonant Atom Interferometry detection
- Radio-wave Doppler frequency tracking
- GW detection with optical lattice atomic clocks

Torsion-Bar Antenna for Low-Frequency Gravitational-Wave Observations

Masaki Ando,[1,*] Koji Ishidoshiro,[2,†] Kazuhiro Yamamoto,[3] Kent Yagi,[1] Wataru Kokuyama,[2]
Kimio Tsubono,[2] and Akiteru Takamori[4]

- **TOBA – The torsion bar antenna; PRL2010, PRD2013**
- **10 m x 0.6 m ϕ quartz/Al 5056**
- **10 ton each**
- **Fundamental torsion frequency 30 μHz**





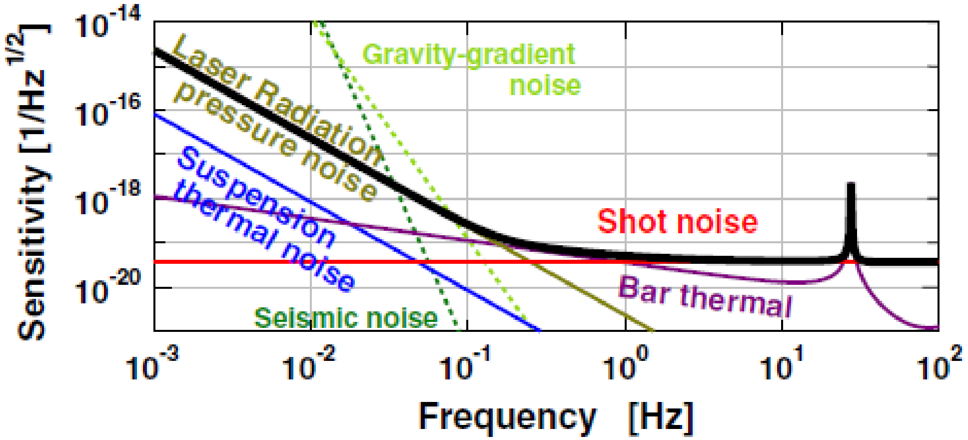
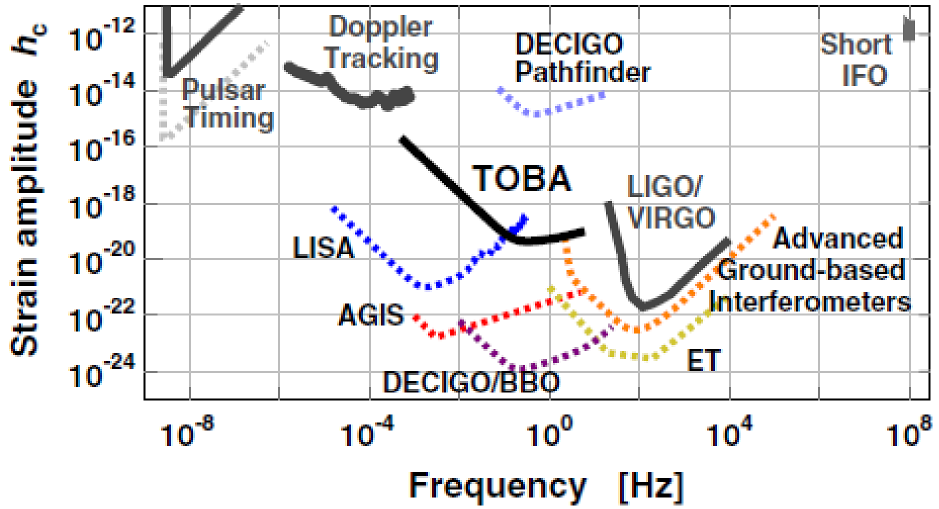
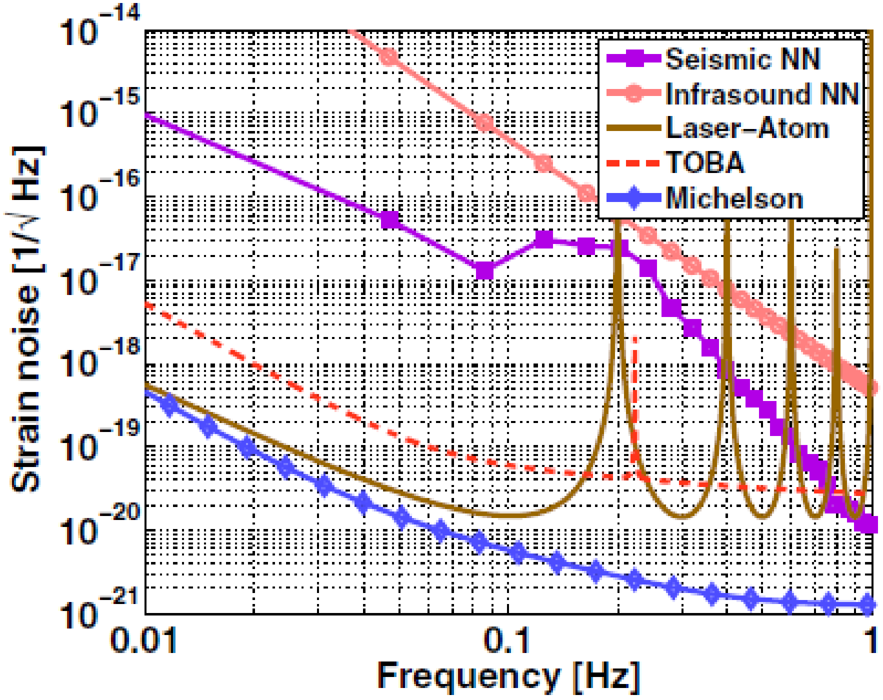


FIG. 2 (color online). Estimated sensitivity of a torsion-bar antenna (thick black curve). Limitations by fundamental noises are shown together.



Newtonian Noise – seismic and atmospheric NN would have to be reduced by large factors to achieve sensitivity goals with respect of NN

It is uncertain whether sufficiently sensitive seismic and infrasound sensors can be provided. It will be very challenging to achieve sufficient NN subtraction. A suppression of the NN by about 4 or 5 orders of magnitude at 0.1 Hz would be needed to make it comparable to the instrument noise limit. A larger number of more sensitive sensors will be required.



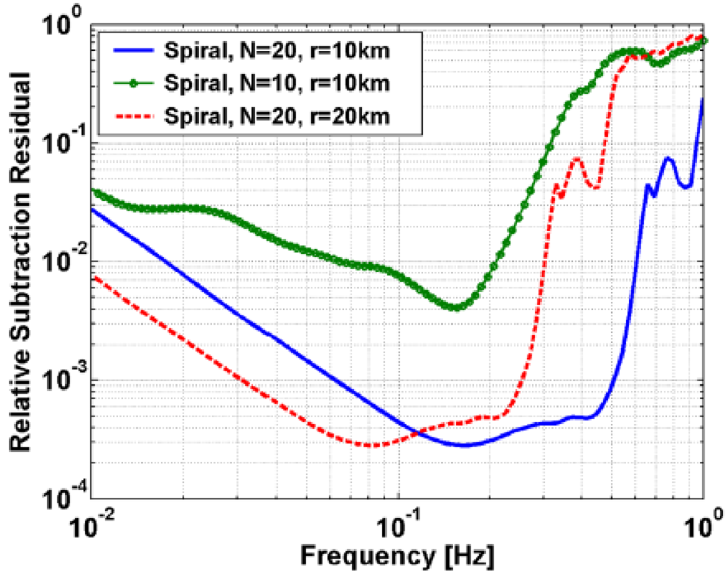


FIG. 10 (color online). Residuals of Rayleigh-wave gradient NN subtraction for double-wound spiral arrays using seismometers with SNR = 1000. Results are presented for different numbers N of seismometers and different array radii r.

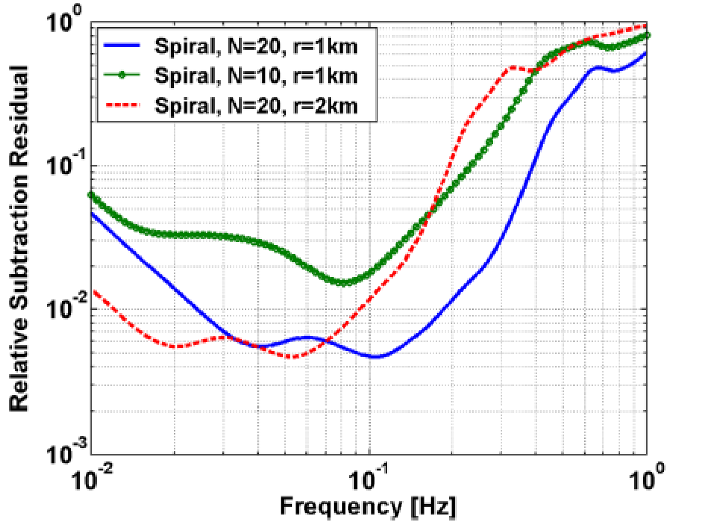


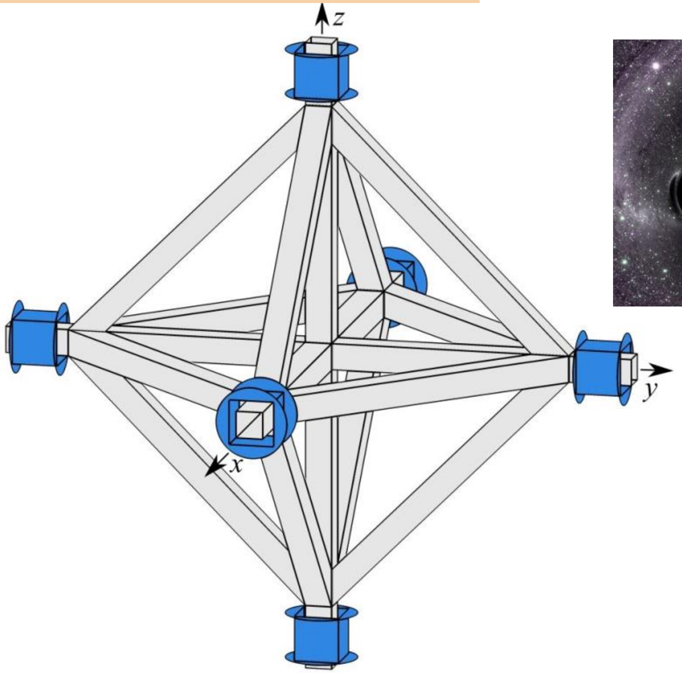
FIG. 11 (color online). Residuals of infrasound gradient NN subtraction for double-wound spiral arrays using microphones with SNR = 1000. Results are presented for different numbers N of microphones and different array radii r.

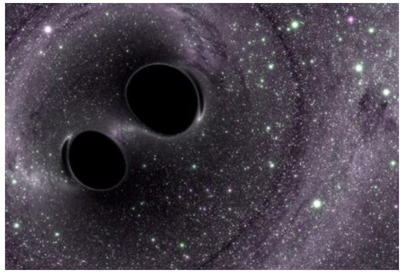
SOGRO (Paik et al 2016) **(Superconducting Omni-directional Gravitational Radiation Observatory)**

A design concept that could reach a strain sensitivity of 10^{-19}–10^{-20} Hz$^{-1/2}$ at 0.2–10 Hz

the range of the WD–WD binary from 0.1 Hz for one year with a SNR of 10 is 1.2 Mpc, assuming one solar mass (M⊙) for the WD mass. Within this horizon, there are two massive galaxies: the Milky Way Galaxy and Andromeda (M31). The WD–WD merger rate of ~1.4×10^{-13} yr^{-1}M$_\odot^{-1}$ has been estimated, corresponding to 0.01 per year for our Galaxy. With M31 about 0.03 per year. Probability of finding a WD–WD binary merger during one-year operation of SOGRO is ~30% since each event is expected to persist for ~10 years in the detector.

Binary mergers composed of IMBHs can be detected by SOGRO up to several Gpc (see figure 1). The estimated rates of mergers are very uncertain, but up to a few tens of IMBH mergers can be detected per year by SOGRO [7].





Each test mass M	5 ton	Nb square tube
Arm length L	30-50 m	Over a ‘rigid’ platform
Antenna temperature T	1.5 K	Superfluid helium or cryocoolers
DM quality factor	5×10^8	Surface-polished pure Nb
Signal frequency f	0.1–10 Hz	

Ho Jung Paik
Department of Physics, University of Maryland
ICGAC-XIII, Seoul, July 4, 2017

AMIGO: Astrodynamical Middle-frequency Interferometric GW Observatory

- Arm length: 10,000 km (or a few times)
- Laser power: 2-10 W (or more)
- Acceleration noise: assuming LPF noise
- Orbit: 4 options (all LISA-like formations):

    (i) Earth-like solar orbit (3-20 degrees behind the Earth orbit)

    (ii) 600,000 km high orbits around the

    (iii) 100,000 km-250,000 high orbits around the Earth

    (iv) near Earth-Moon L4 and L5 orbits
- Scientific Goal: to bridge the gap between high-frequency and low-frequency GW sensitivities. Detecting intermediate mass BH coalescence. Detecting inspiral phase and predict time of binary black hole coalescence together with neutron star coalescence for ground interferometers, detecting compact binary inspirals for studying stellar evolution and galactic poulation

GW Sensitivities of AMIGO

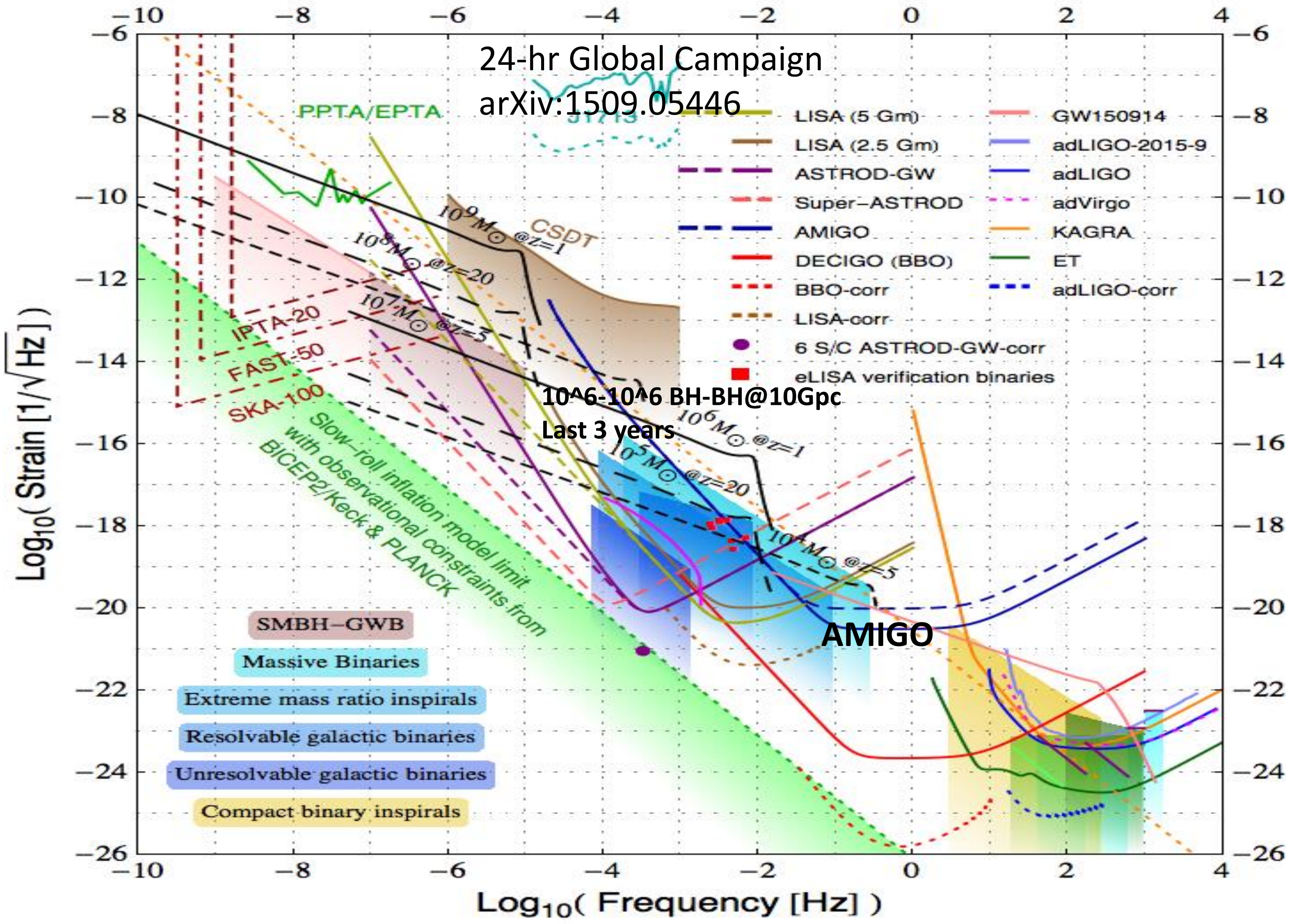
- Baseline Sensitivity: 2 W emitting laser power, 300 mm ϕ telescope
- $S_{\text{AMIGOn}}^{1/2}(f)=(20/3)^{1/2}(1/L_{\text{AMIGO}})\times[(1+(f/(1.29f_{\text{AMIGO}}))^2)]^{1/2}\times[(S_{\text{AMIGOp}}+4S_a/(2\pi f)^4)]^{1/2}\text{Hz}^{-1/2}$,
- over the frequency range of 20 μHz < f < 1 kHz. Here $L_{\text{AMIGO}} = 0.01 \times 10^9$ m is the AMIGO arm length, $f_{\text{AMIGO}} = c/(2\pi L_{\text{AMIGO}})$ is the AMIGO arm transfer frequency, $S_{\text{AMIGOp}} = 1.424 \times 10^{-28}$ m^2 Hz^{-1} is the (white) position noise level due to laser shot noise which is 16×10^{-6} (=0.004^2) times that for new LISA. $S_a(f)$ is the same colored acceleration noise level in (2)
- Design Sensitivity: 10 W emitting laser power, 360 mm ϕ telescope

Shot noise for strain to gain a factor of

10 [≈ (10W/2W)×(360mm/300mm)^4]

AMIGO solid curve by using $S_{\text{AMIGOp}} = 0.1424 \times 10^{-28}$ m^2 Hz^{-1}.

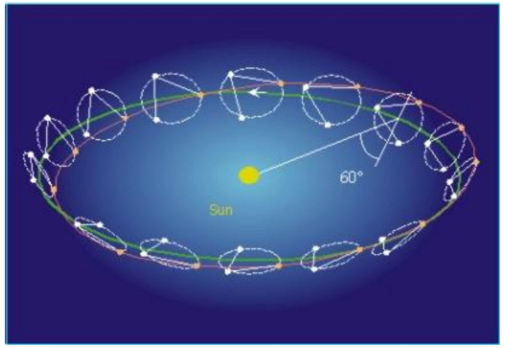
Strain power spectral density (psd) amplitude vs. frequency for various GW detectors and GW sources. [CSDT: Cassini Spacecraft Doppler Tracking; SMBH-GWB: Supermassive Black Hole-GW Background.]



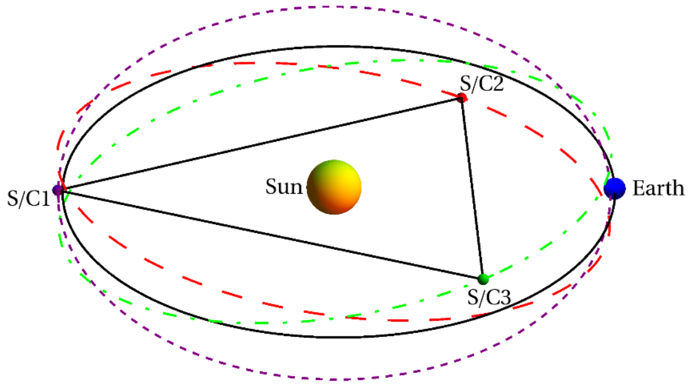
Space GW Detection Science Goals

- The science goals are the detection of GWs from

- (i) Supermassive Black Holes;
- (ii) Extreme-Mass-Ratio Black Hole Inspirals;
- (iii) Intermediate-Mass Black Holes;
- (iv) Galactic Compact Binaries;
- (v) Detecting inspiral phase and predict time of binary black hole coalescence for ground interferometers
- (vi) Relic/Inflationary GW Background.

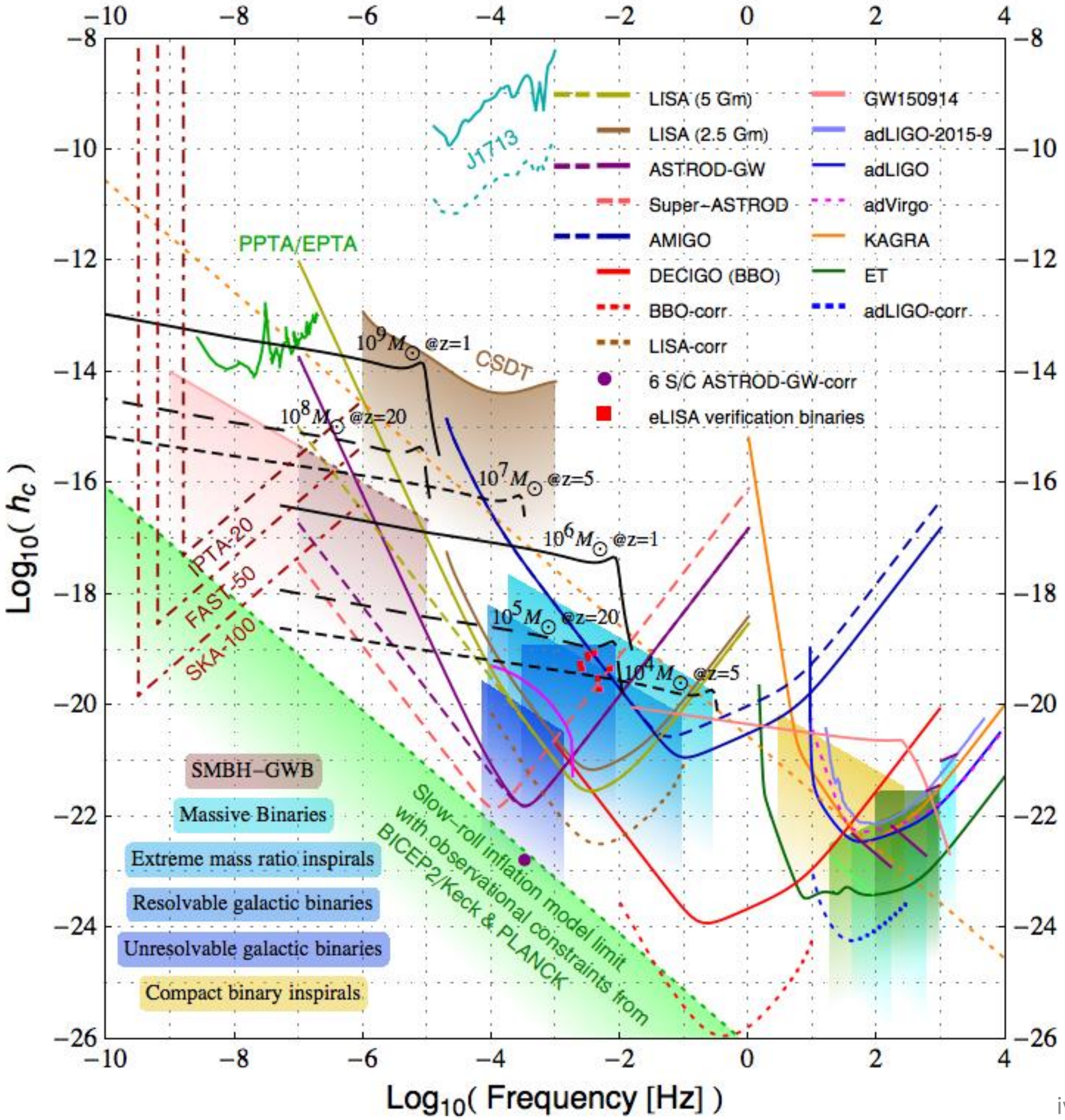


空间引力波探测
A Compilation of GW Mission Proposals LISA Pathfinder Launched on December 3, 2015

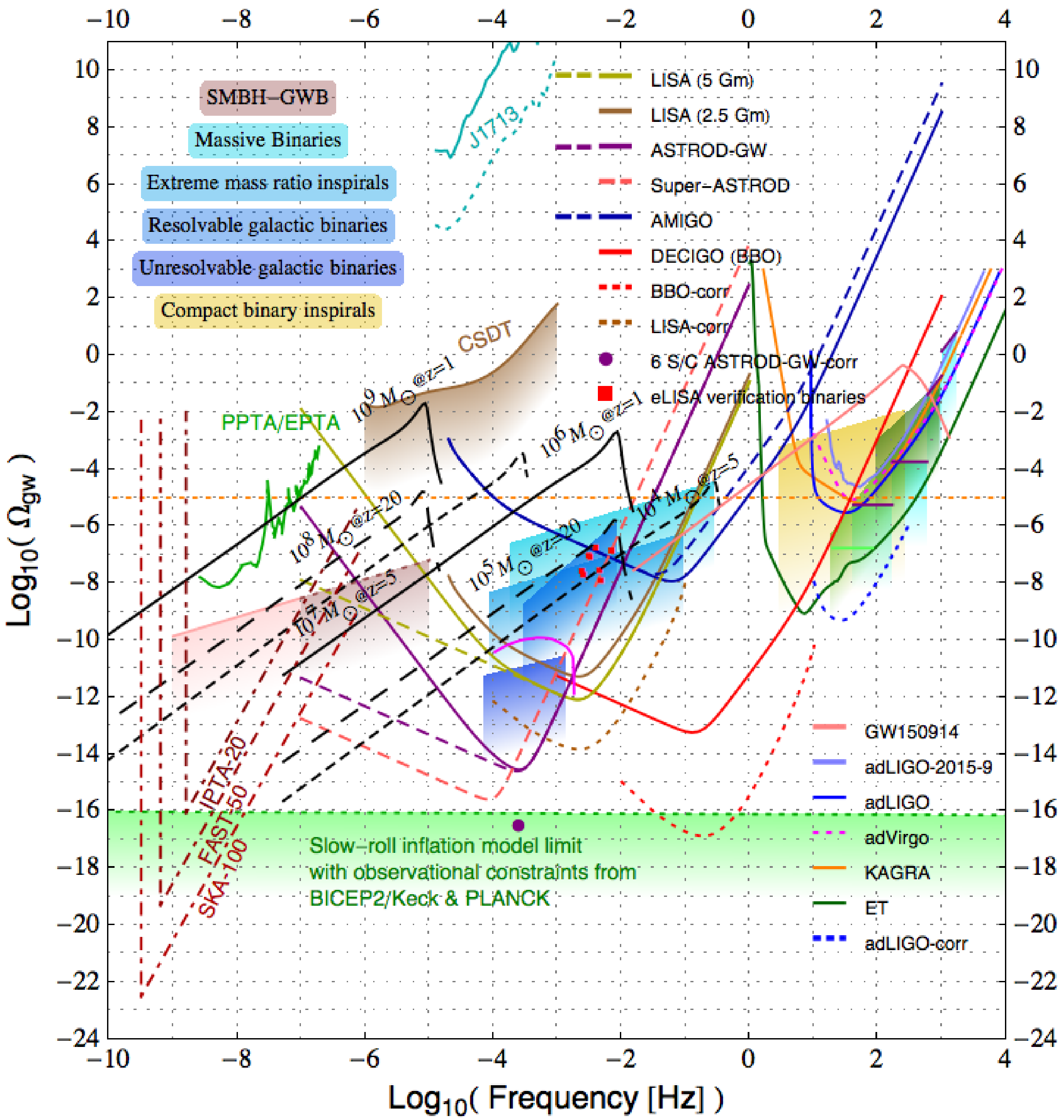


Mission Concept	S/C Configuration	Arm length	Orbit Period	S/C #
Solar-Orbit GW Mission Proposals				
LISA[65]	Earth-like solar orbits with 20° lag	5 Gm	1 year	3
eLISA[64]	Earth-like solar orbits with 10° lag	1 Gm	1 year	3
ASTROD-GW[68]	Near Sun-Earth L3, L4, L5 points	260 Gm	1 year	3
Big Bang Observer[73]	Earth-like solar orbits	0.05 Gm	1 year	12
DECIGO[72]	Earth-like solar orbits	0.001 Gm	1 year	12
ALIA[74]	Earth-like solar orbits	0.5 Gm	1 year	3
ALIA-descope[75] 太极	Earth-like solar orbits	3 Gm	1 year	3
Super-ASTROD[71]	Near Sun-Jupiter L3, L4, L5 points (3 S/C), Jupiter-like solar orbit(s)(1-2 S/C)	1300 Gm	11 year	4 or 5
Earth-Orbit GW Mission Proposals				
OMEGA[81]	0.6 Gm height orbit	1 Gm	53.2 days	6
gLISA/GEOGRAWI[76-78]	Geostationary orbit	0.073 Gm	24 hours	3
GADFLI[79]	Geostationary orbit	0.073 Gm	24 hours	3
TIANQIN[82] 天琴	0.057 Gm height orbit	0.11 Gm	44 hours	3
ASTROD-EM[69,70]	Near Earth-Moon L3, L4, L5 points	0.66 Gm	27.3 days	3
LAGRANGE[80]	Near Earth-Moon L3, L4, L5 points	0.66 Gm	27.3 days	3

Mission concept	S/C configuration	Arm length	Orbit period	S/C #	Acceleration noise [$\mathrm{fm/s^2/Hz^{1/2}}$]	Laser metrology noise [$\mathrm{pm/Hz^{1/2}}$]
Solar-Orbit GW Mission Proposals						
LISA[9]	Earthlike solar orbits with 20° lag	5 Gm	1 year	3	3	20
eLISA[21]	Earthlike solar orbits with 10° lag	1 Gm	1 year	3	3	12(10)
ASTROD-GW[36–40]	Near Sun–Earth L3, L4, L5 points	260 Gm	1 year	3	3	1000
Big Bang Observer[45]	Earthlike solar orbits	0.05 Gm	1 year	12	0.03	1.4×10^{-5}
DECIGO[44]	Earthlike solar orbits	0.001 Gm	1 year	12	0.0004	2×10^{-6}
ALIA[47]	Earthlike solar orbits	0.5 Gm	1 year	3	0.3	0.6
TAIJI (ALIA-descope)[48]	Earthlike solar orbits	3 Gm	1 year	3	3	5–8
Super-ASTROD[42]	Near Sun–Jupiter L3, L4, L5 points (3 S/C), Jupiterlike solar orbit(s)(1–2 S/C)	1300 Gm	11 year	4 or 5	3	5000
Earth-Orbit GW Mission Proposals						
OMEGA[54,55]	0.6 Gm height orbit	1 Gm	53.2 days	6	3	5
gLISA/GEOGRAWI[49–51]	Geostationary orbit	0.073 Gm	24 h	3	3, 30	0.3, 10
GADFLI[52]	Geostationary orbit	0.073 Gm	24 h	3	0.3, 3, 30	1
TIANQIN[19]	0.057 Gm height orbit	0.11 Gm	44 h	3	1	1
ASTROD-EM[43]	Near Earth–Moon L3, L4, L5 points	0.66 Gm	27.3 days	3	1	1
LAGRANGE[53]	Earth–Moon L3, L4, L5 points	0.66 Gm	27.3 days	3	3	5



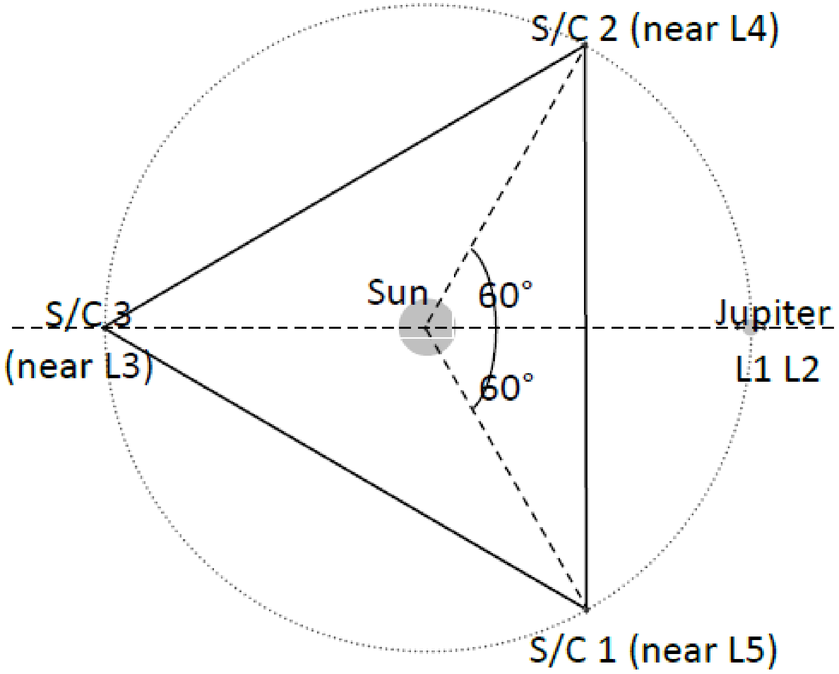
LISA (5 Gm)
LISA (2.5 Gm)
ASTROD-GW
Super-ASTROD
AMIGO
DECIGO (BBO)
BBO-corr
LISA-corr
6 S/C ASTROD-GW-corr
eLISA verification binaries
GW150914
adLIGO-2015-9
adLIGO
adVirgo
KAGRA
ET
adLIGO-corr
J1713
PPTA/EPTA
CSDT
IPTA-20
FAST-50
SKA-100
SMBH-GWB
Massive Binaries
Extreme mass ratio inspirals
Resolvable galactic binaries
Unresolvable galactic binaries
Compact binary inspirals
Slow-roll inflation model limit with observational constraints from BICEP2/Keck & PLANCK
$\log_{10}(h_c)$
$\log_{10}$(Frequency [Hz])

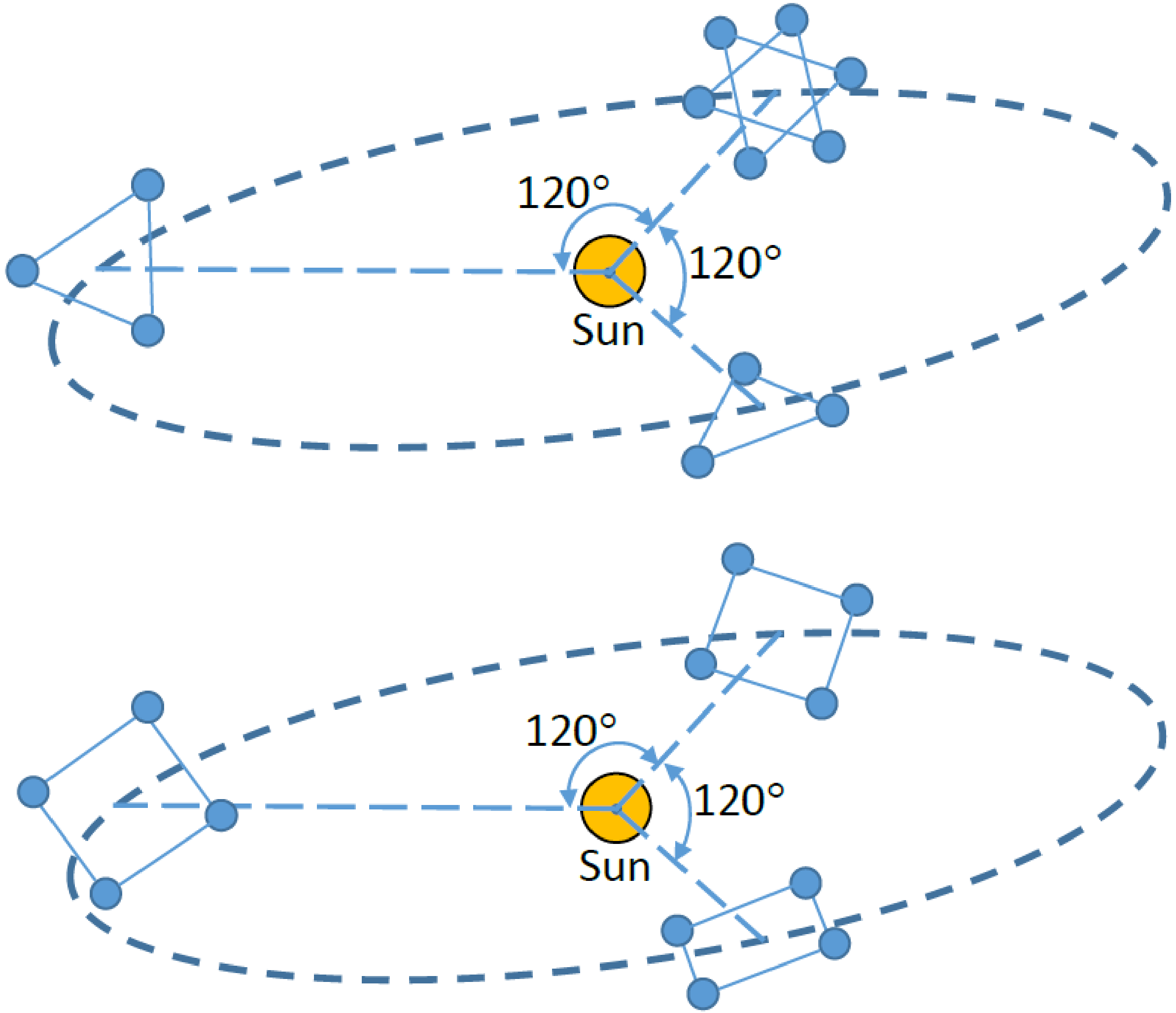


SMBH-GWB
Massive Binaries
Extreme mass ratio inspirals
Resolvable galactic binaries
Unresolvable galactic binaries
Compact binary inspirals
LISA (5 Gm)
LISA (2.5 Gm)
ASTROD-GW
Super-ASTROD
AMIGO
DECIGO (BBO)
BBO-corr
LISA-corr
6 S/C ASTROD-GW-corr
eLISA verification binaries
GW150914
adLIGO-2015-9
adLIGO
adVirgo
KAGRA
ET
adLIGO-corr
J1713
CSDT
PPTA/EPTA
IPTA-20
FAST-50
SKA-100
Slow-roll inflation model limit with observational constraints from BICEP2/Keck & PLANCK
$\log_{10}(\Omega_{gw})$
$\log_{10}$(Frequency [Hz])

Second Generation GW Mission Concepts

- DECIGO
- BBO
- Super-ASTROD

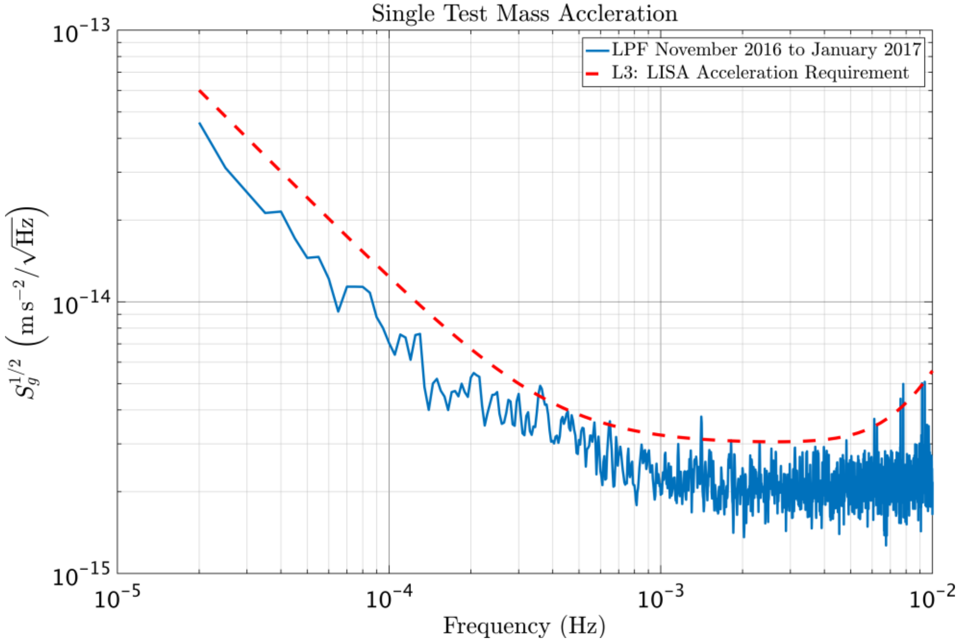


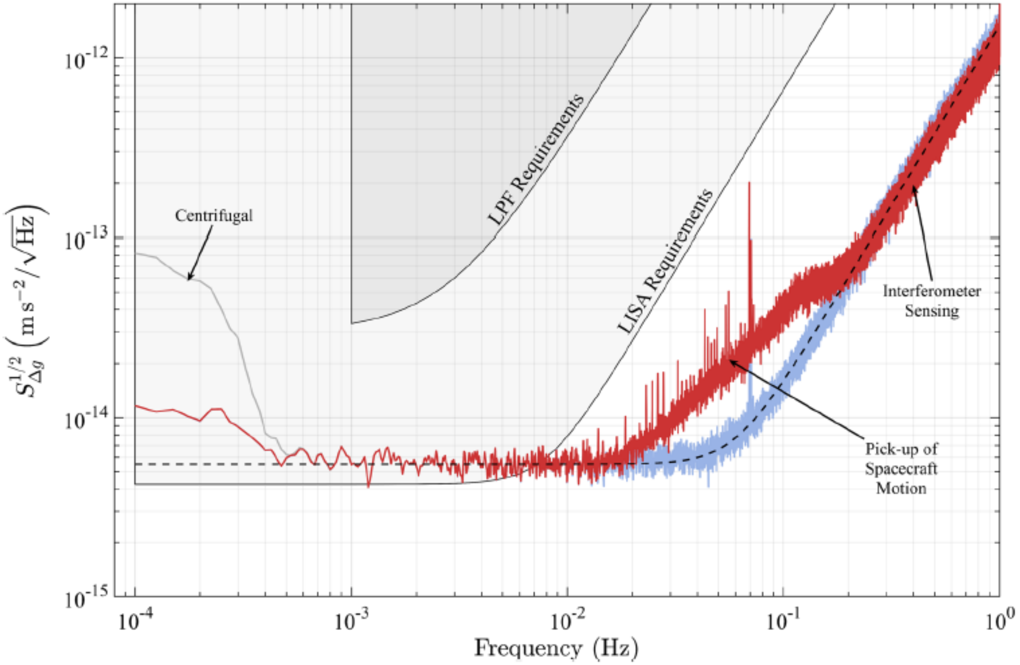


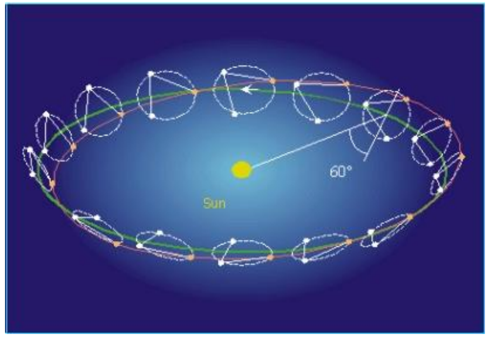
10^(-15) Source-Observation Gap largely bridged

92 days
1440 orbits
83.60 kg mass

- In 1915, white dwarf already discovered, the technology reached 10^(-5). First artificial satellite Sputnik launched in 1957.
- First GW space mission proposed in public in 1981 by Faller & Bender
- LISA proposed as a joint ESA-NASA mission; LISA Pathfinder successfully performed. The drag-free tech is fully demonstrated paving the road for GW space missions.







Weak-light phase locking and manipulation technology

- Weak-light phase locking is crucial for long-distance space interferometry and for CW laser space communication. For LISA of arm length of 5 Gm (million km) the weak-light phase locking requirement is for 70 pW laser light to phase-lock with an onboard laser oscillator. For ASTROD-GW arm length of 260 Gm (1.73 AU) the weak-light phase locking requirement is for 100 fW laser light to lock with an onboard laser oscillator.
- Weak-light phase locking for 2 pW laser light to 200 μW local oscillator is demonstrated in our laboratory in Tsing Hua U.[6]
- Dick *et al.*[7] from their phase-locking experiment showed a PLL (Phase Locked Loop) phase-slip rate below one cycle slip per second at powers as low as 40 femtowatts (fW).
- Shaddock et al: tracking 30 fW free-running laser (2015-2016)

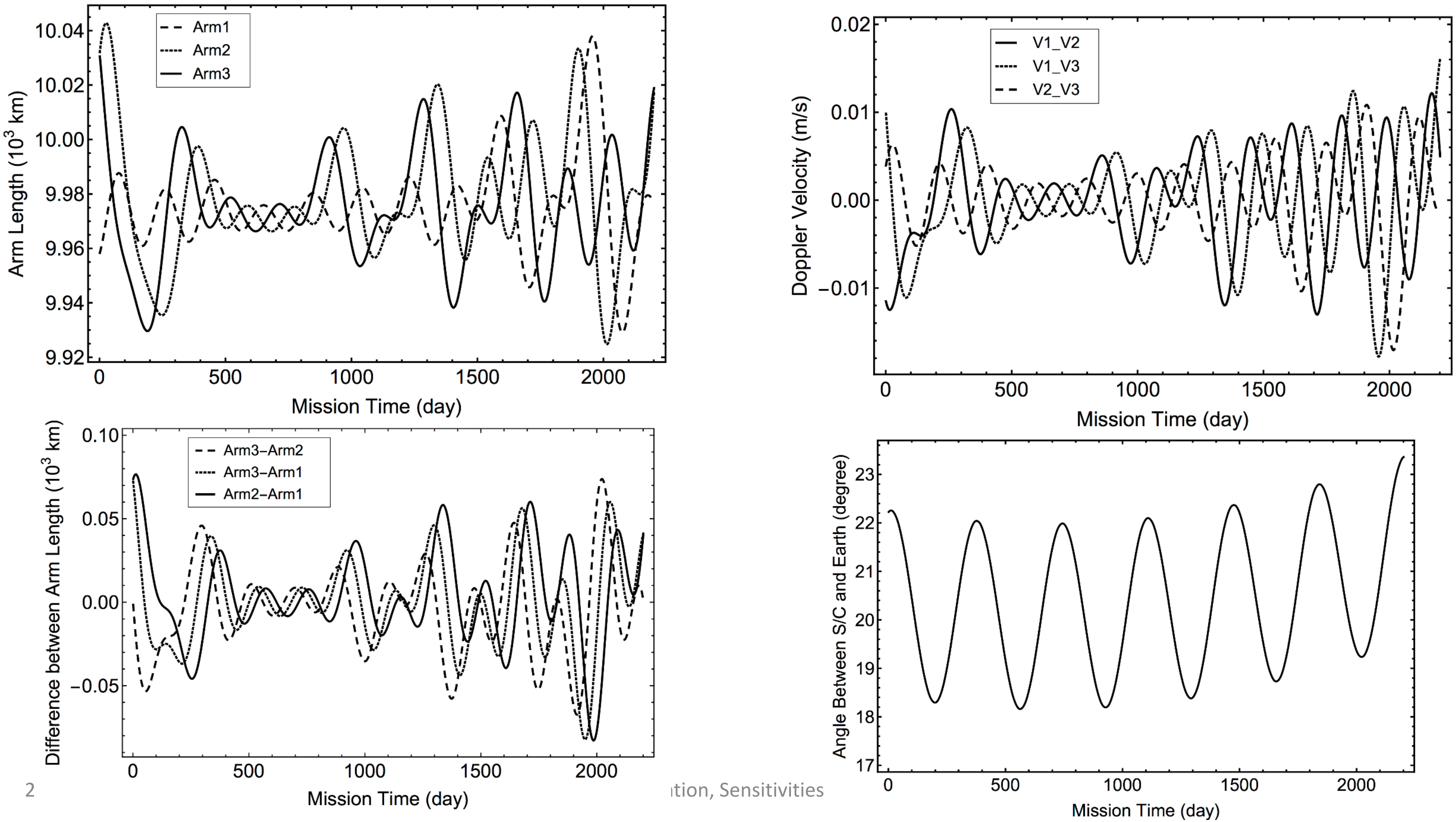
The present laser stability (16 orders) alone does not meet the GW strain sensitivity requirement (21 orders)

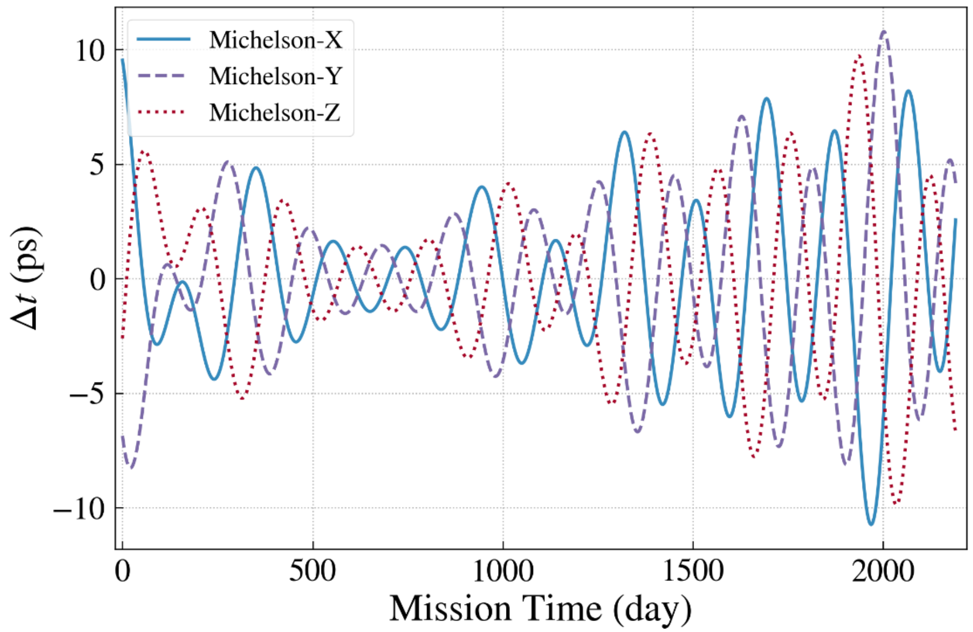
- For space laser-interferometric GW antenna, the arm lengths vary according to solar system orbit dynamics.
- In order to attain the requisite sensitivity, laser frequency noise must be suppressed below the secondary noises such as the optical path noise, acceleration noise etc.
- For suppressing laser frequency noise, it is necessary to use TDI in the analysis to match the optical path length of different beam paths closely.
- The better match of the optical path lengths is, the better cancellation of the laser frequency noise and the easier to achieve the requisite sensitivity. In case of exact match, the laser frequency noise is fully canceled, as in the original Michelson interferometer.

LISA 2.5 Gm Sensitivity

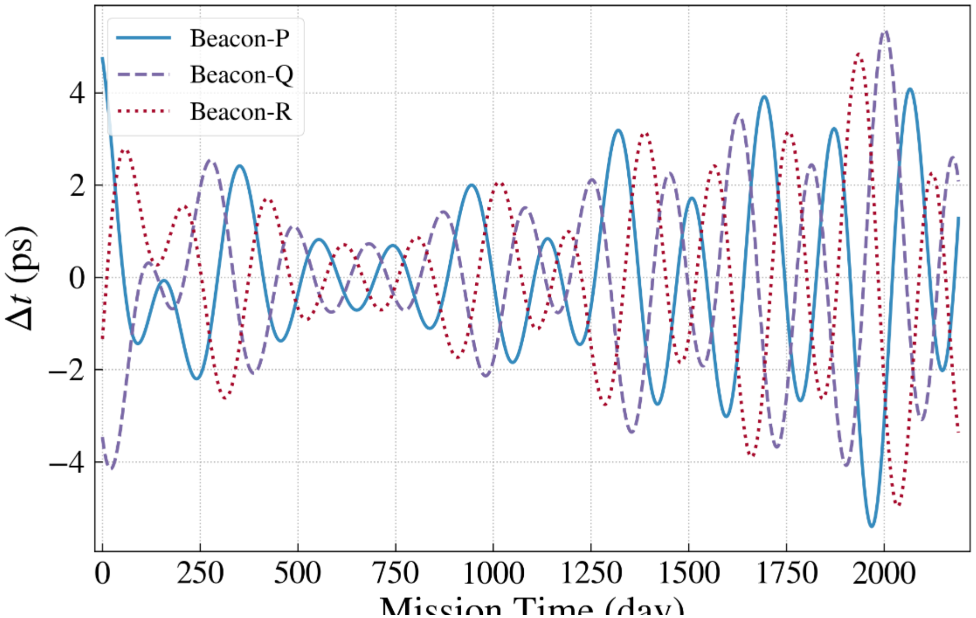
- The new LISA design sensitivity is in [10, 11]. A simple analytical approximation of the design sensitivity is in Petiteau et al. [10] and used by Cornish and Robson [26]:
-
- $S_{\mathrm{Ln}}{}^{1/2}(f) = (20/3)^{1/2}\ (1/L_{\mathrm{L}}) \times [(1 + (f\,/\,(1.29f_{\mathrm{L}}))^2\ )]^{1/2} \times [(S_{\mathrm{Lp}} + 4S_{\mathrm{a}}/(2\pi f)^4)]^{1/2}\ \mathrm{Hz}^{-1/2}$, (1)
-
- over the frequency range 20 μHz < f < 1 Hz. Here L_{L} = 2.5 Gm is the LISA arm length, $f_{\mathrm{L}} = c\,/\,(2\pi L_{\mathrm{L}})$ is the LISA arm transfer frequency, $S_{\mathrm{Lp}} = 8.9 \times 10^{-23}\ \mathrm{m}^2\ \mathrm{Hz}^{-1}$ is the white position noise, and
-
- $S_{\mathrm{a}}(f) = 9 \times 10^{-30}\ \ [1 + (10^{-4}\ \mathrm{Hz}/\,f\,)^2 + 16\ (2 \times 10^{-5}\ \mathrm{Hz}/\,f\,)^{10}\ ]\ \mathrm{m}^2\ \mathrm{s}^{-4}\ \mathrm{Hz}^{-1}$, (2)
-
- is the colored acceleration noise level. This new LISA design sensitivity curve shows in both Fig. 1 and Fig. 2.

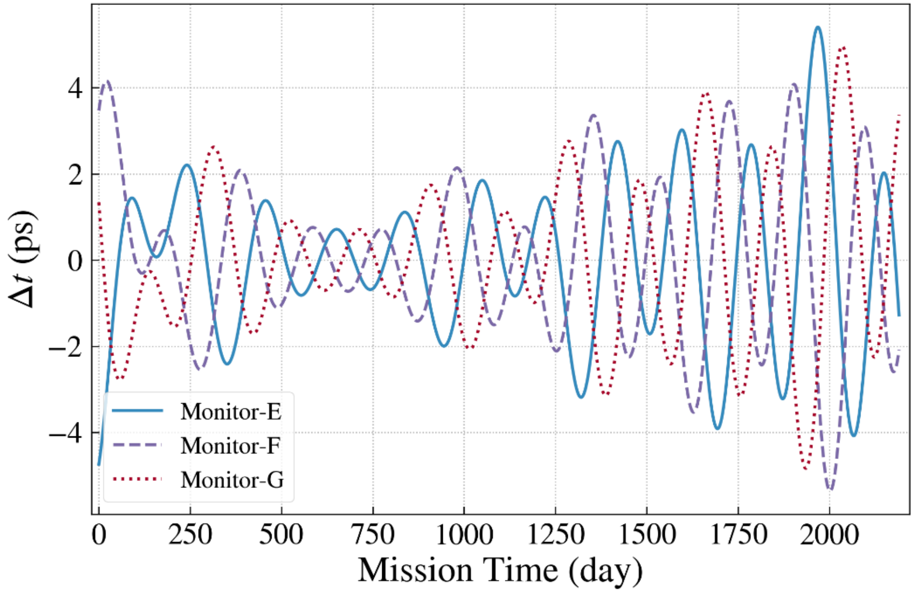
AMIGO Orbit design: Earth-like solar orbits

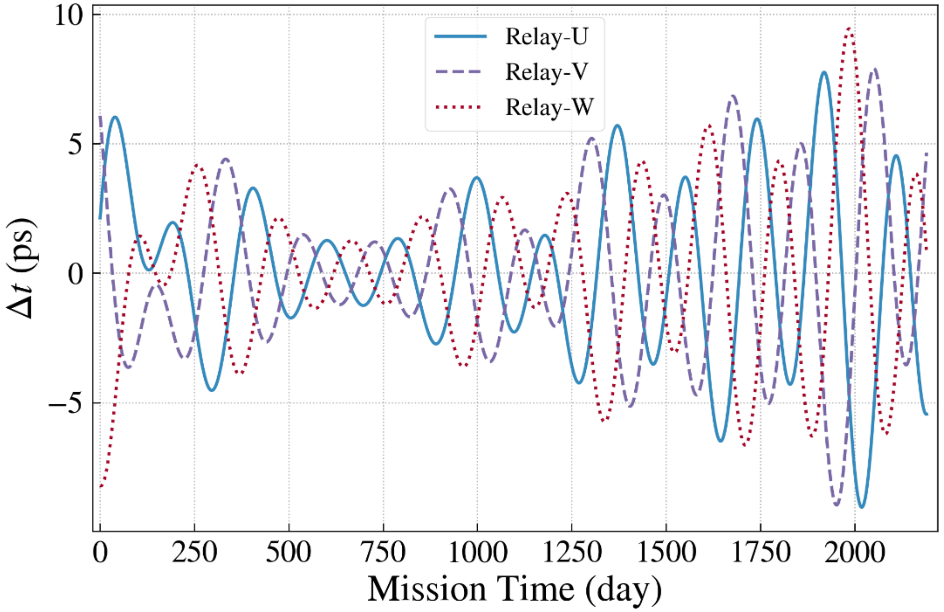



Michelson-X
Michelson-Y
Michelson-Z
10
5
0
−5
−10
Δt (ps)
0
500
1000
1500
2000
Mission Time (day)

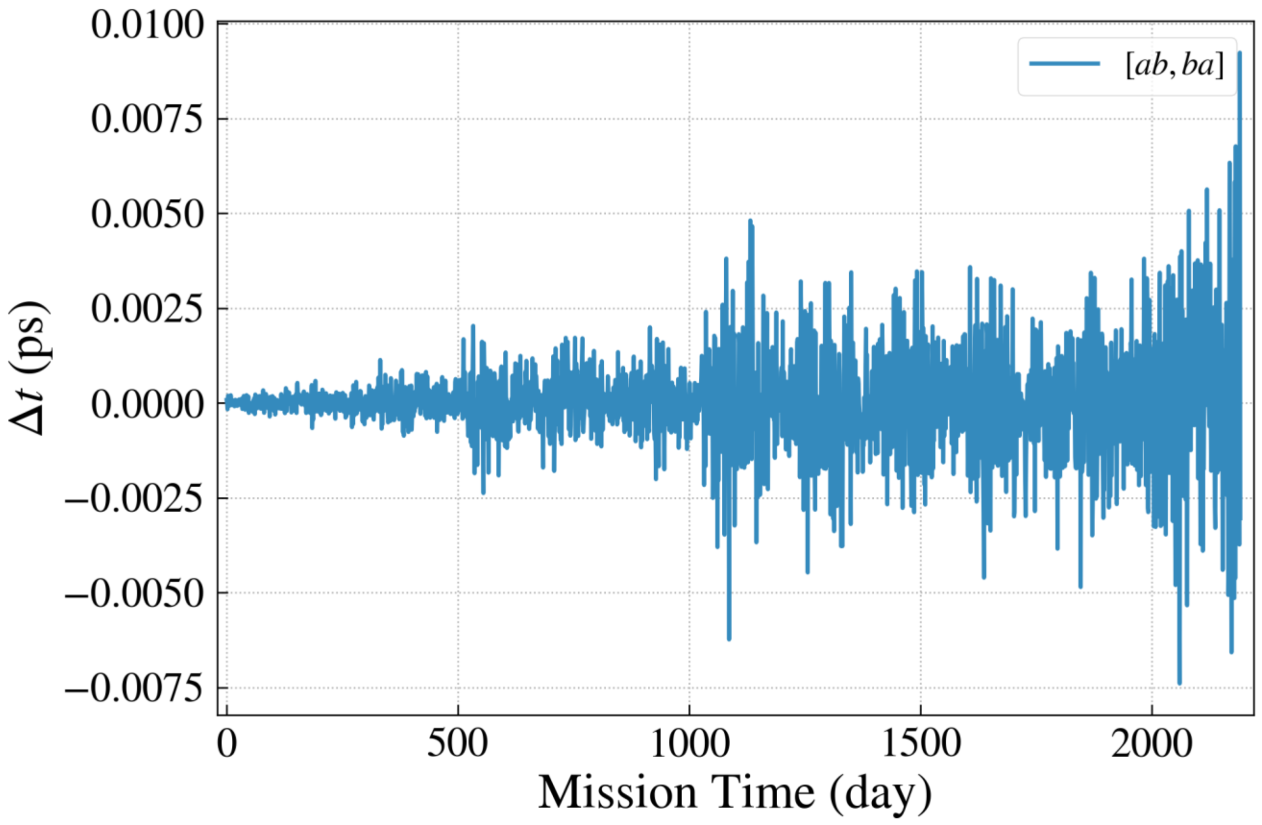
T
D
I

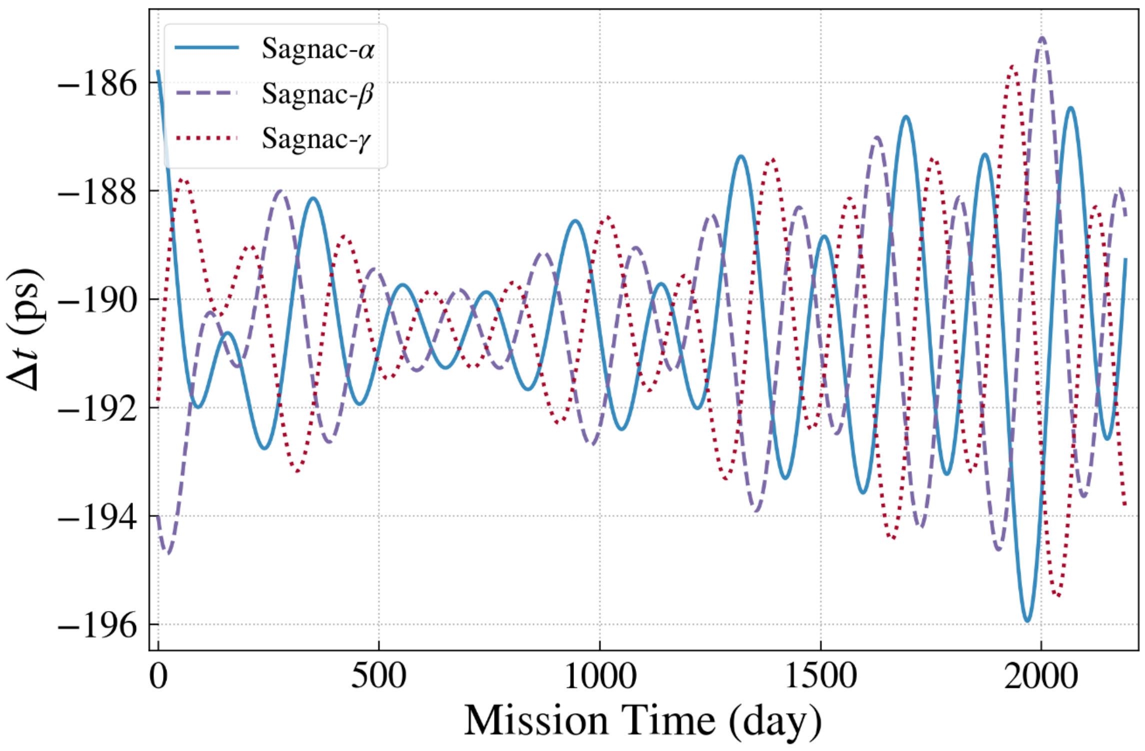

Beacon-P
Beacon-Q
Beacon-R
4
2
0
−2
−4
Δt (ps)
0
250
500
750
1000
1250
1500
1750
2000
Mission Time (day)


4
2
0
−2
−4
Δt (ps)
Monitor-E
Monitor-F
Monitor-G
0
250
500
750
1000
1250
1500
1750
2000
Mission Time (day)


10
5
0
−5
Δt (ps)
Relay-U
Relay-V
Relay-W
0
250
500
750
1000
1250
1500
1750
2000
Mission Time (day)

Time Delay Interferometry





Summary

- Currently, a number of detection methods are proposed and under active research to bridge the middle-frequency band gap between Earth-based and space-borne GW observations with important science goals. In this band, technical limits will be extremely challenging to overcome for Earth-based due to Newtonian noises. In this paper, we propose a first-generation middle-frequency mission concept AMIGO with 10,000 km arm length. The technical readiness level is high. The sensitivity is good to reach science goals considered in the last section.
- If a pathfinder mission is desired with 2-spacecraft demonstration of ranging in the solar-system for a LISA-like mission, the case with 2-5 degrees lagging behind the Earth of the first orbit choice in the last section could be considered. Just take one arm of this AMIGO case, it would be good to test many things in the solar system: deployment, both radio and laser communications, noise budget, and drag-free system together with a concentrated effort on distance metrology. It might be simpler than go to L1 or L2 Sun-Earth Lagrange point.

Space Detection Methods other than Laser Interferometry for Low-frequency and Middle-frequency GWs

- Radio-wave Doppler frequency tracking
- Atom Interferometry involving repeatedly imprinting the phase of optical field onto the motional degrees of freedom of the atoms using light propagating back and forth between the spacecraft.
- Resonant Atom Interferometry detection
- GW detection with optical lattice atomic clocks

Very low frequency band (300 pHz – 100 nHz)

$$h_c(f) = A_{\mathrm{yr}}\,[f/(1\ \mathrm{yr}^{-1})]^{\alpha}$$

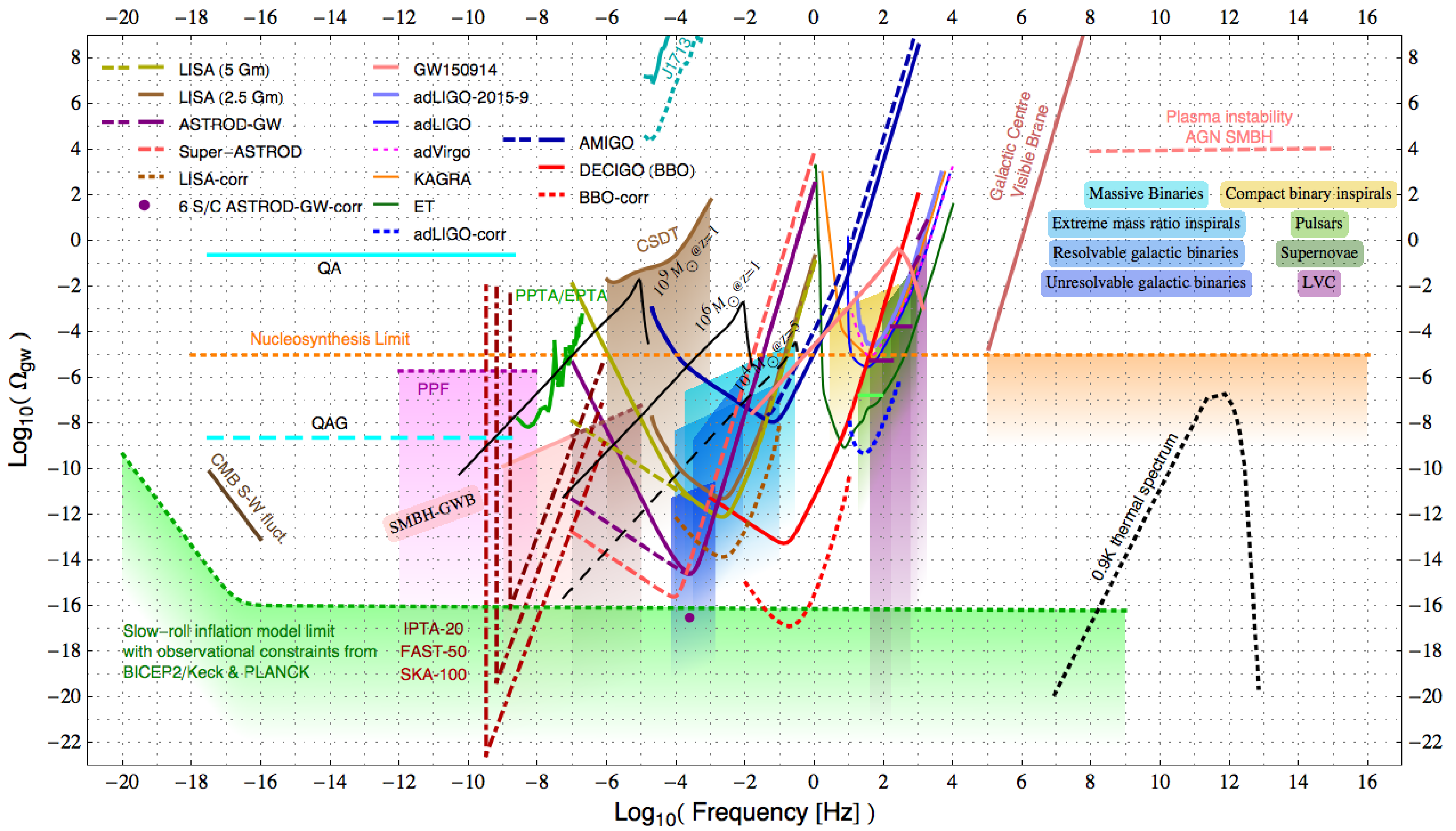
Table 4. Upper limits on the isotropic stochastic background from 3 pulsar timing arrays.

	No. of pulsars included	No. of years observed	Observation radio band [MHz]	Constraint on characteristic strain $h_c(f)$ [$= A_{\mathrm{yr}}\,[f/(1\mathrm{yr}^{-1})]^{-(2/3)}$, ($f = 10^{-9}$-$10^{-7}$ Hz)]
EPTA[102]	6	18	120-3000	$A_{\mathrm{yr}} < 3 \times 10^{-15}$
PPTA[103]	4	11	3100	$A_{\mathrm{yr}} < 1 \times 10^{-15}$
NANOGrav[104]	27	9	327-2100	$A_{\mathrm{yr}} < 1.5 \times 10^{-15}$

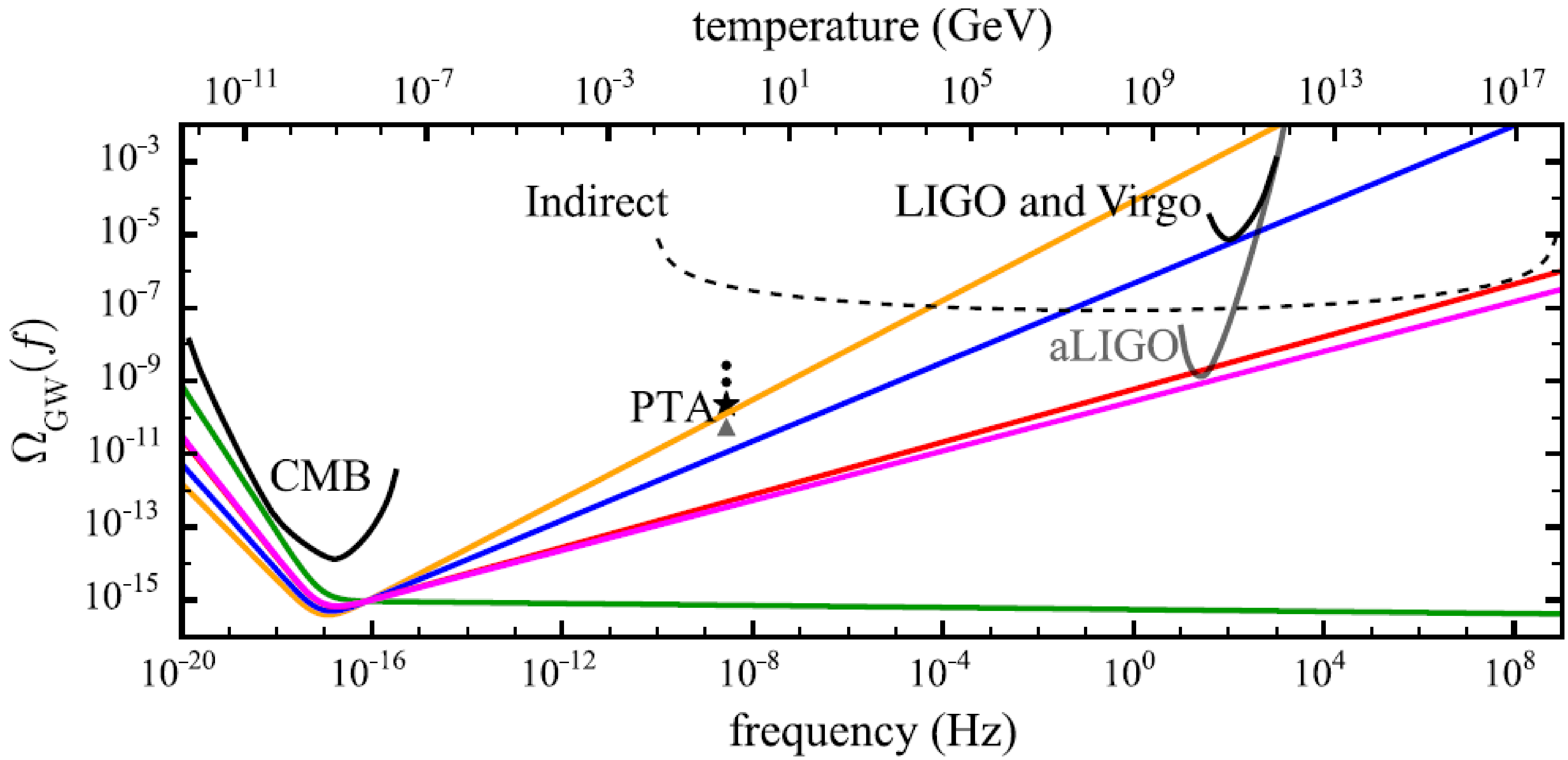
Table 5. Sensitivities of IPTA, FAST and SKA to monochromatic GWs.

	No. of pulsars	No. of years of observation	Timing accuracy (ns)	Sensitivity in characteristic strain $h_c(f)$ [$= B_{\mathrm{yr}}\,(f\,/\,\mathrm{yr}^{-1})$] for monochromatic GWs
IPTA[106]	36	20	100	$B_{\mathrm{yr}} = 1 \times 10^{-16}$
FAST[107]	50	50	50	$B_{\mathrm{yr}} = 1.5 \times 10^{-17}$
SKA[108]	100	100	20	$B_{\mathrm{yr}} = 1.5 \times 10^{-18}$

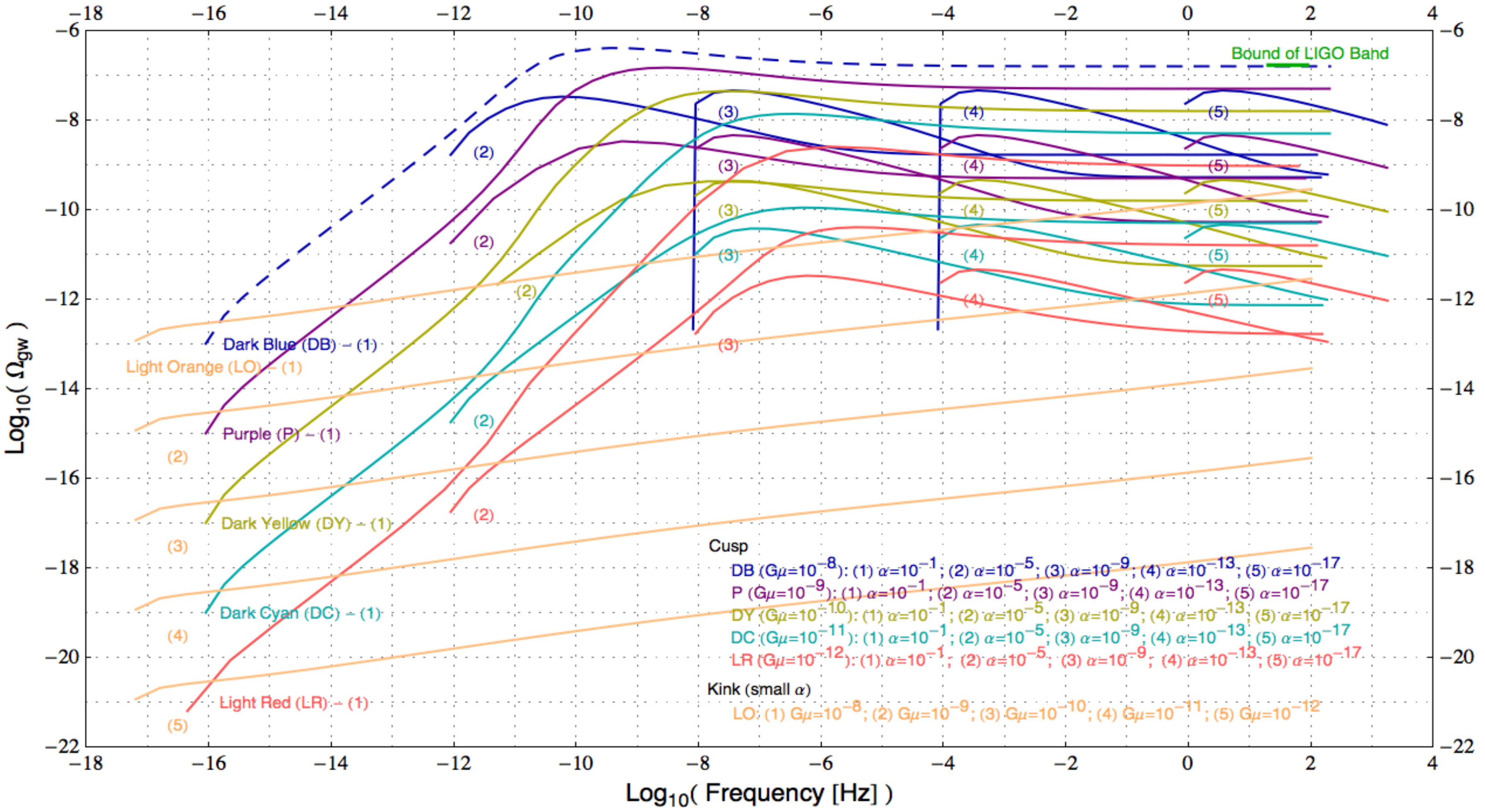
Normalized GW spectral energy density Ω_{gw} vs. frequency for GW detector sensitivities and GW sources



Cosmic band slow-roll model r=0.07, n_t=-r/8



Normalized GW background spectral energy density Ω_{gw} from **cosmic string** cusps and kinks: (i) cusps with $G\mu = 10^{-8}$ [(1)-(5)] in dark blue; (ii) cusps with $G\mu=10^{-9}$ [(1)-(5)] in purple; (iii) cusps with $G\mu = 10^{-10}$ [(1)-(5)] in dark yellow; (iv) cusps with $G\mu = 10^{-11}$ [(1)-(5)] in dark Cyan; (v) cusps with $G\mu = 10^{-12}$ [(1)-(5)] in dark yellow; (iii) kinks with small α [(1)-(5); $G\mu = 10^{-8}$-10^{-12}] in light red.



Outlook

- GW Spectrum is classified fully
- Detection efforts are being made in all frequency bands
- GW detection will play a dominating role in Astronomy and Cosmology in next 50 years


Thank you