Precision Cosmology from Gravitational Waves

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National Tsing Hua Univ.

Dark energy, co-evolution of massive black holes with galaxies, and ASTROD-GW, *Adv. Space Res.* **51** (2013) 525,
Int. J. Mod. Phys. D **22** (2013) 1341004.

Outline

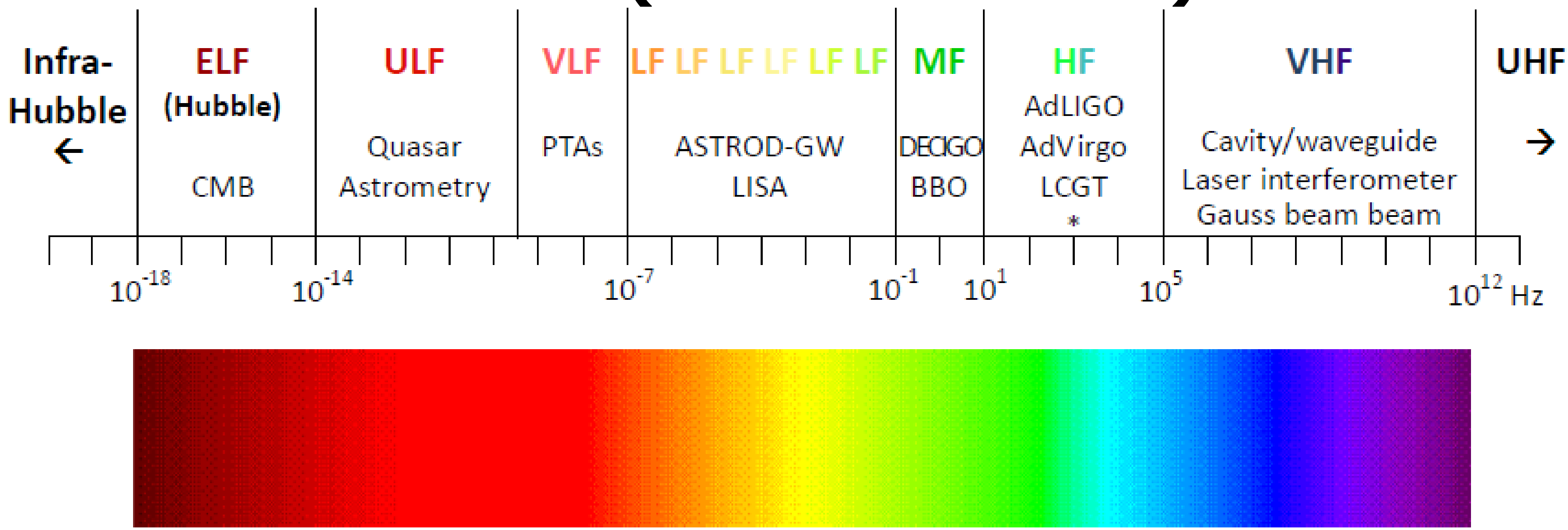
- Complete GW Classification and present detector status
- Galaxy co-evolution of Black Holes, PTA's, and space detectors
- Dark energy and precision cosmology using space detectors BBO/DECIGO and ASTROD-GW
- Primordial GWs and its possible detection
- Summary and outlook

Complete GW Classification

http://astrod.wikispaces.com/file/view/GW-classification.pdf

(MPLA 25 [2010] pp. 922-935; arXiv:1003.3899v1 [astro-ph.CO])

Space Detection: LF (100 nHz- 100 mHz) & MF (100 mHz- 10 Hz)



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

Complete GW Classification (I)

- Ultra high frequency band (above 1 THz): Detection methods include Terahertz resonators, optical resonators, and ingenious methods to be invented.
- Very high frequency band (100 kHz – 1 THz): Microwave resonator/wave guide detectors, optical interferometers and Gaussian beam detectors are sensitive to this band.
- High frequency band (10 Hz – 100 kHz): Low-temperature resonators and laser-interferometric ground detectors are most sensitive to this band.
- Middle frequency band (0.1 Hz – 10 Hz): Space interferometric detectors of short armlength (1000-100,000 km).
- Low frequency band (100 nHz – 0.1 Hz): Laser-interferometer space detectors (1Gm-1Tm) are most sensitive to this band.

Gravitational Wave Astronomy is Being Born

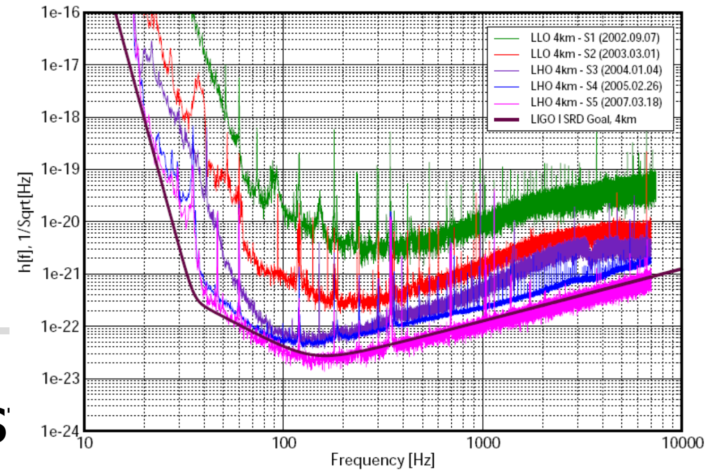
- LIGO, VIRGO, GEO, TAMA …
  - 4000m, 3000m, 2000m, 600m, 300m interferometers built to detect gravitational waves from compact objects

In addition to adLIGO and adVirgo, KAGRA(LCGT) construction started in 2010

Led by ICRR (Kajita, Kuroda, Kawamura)

- Proposed 1999: 3 km Resonant Sideband Extraction (RSE) interferometer: with the cryogenic mirrors (sapphire substrates & fibers, 20 K) suspended from the Seismic Attenuation System (SAS), underground in the Kamioka mine
- inspiral range for binary neutron star coalescences: 176 Mpc sensitivity limit
- Status: beam tubes and cryostats manufactured & delivered, cryogenic and mechanical characterization performed. Two sapphire mirrors delivered: optical parameters measured.
- After tunnel excavation completed in March of 2014: initial KAGRA 2015 and baseline KAGRA 2017/2018.

Second Generation Detectors

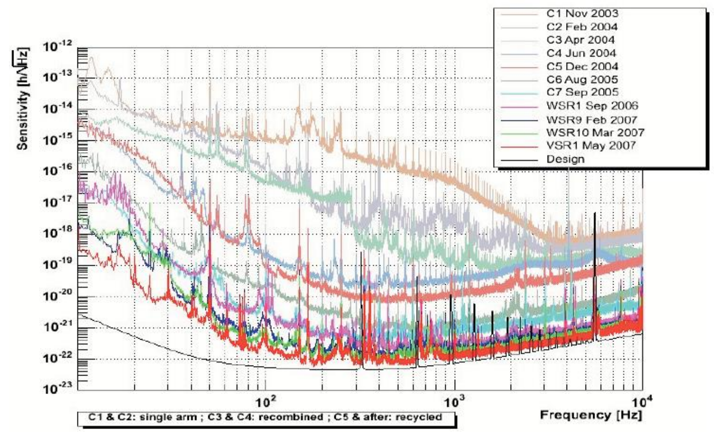


- AdLIGO 10 times enhancement in s LIGO → 10 times reach in distance

  → 1000 times in volume (2015+)

  GW detection from ns-ns merging:

  1 per 10-20 yrs → 50-100 per year

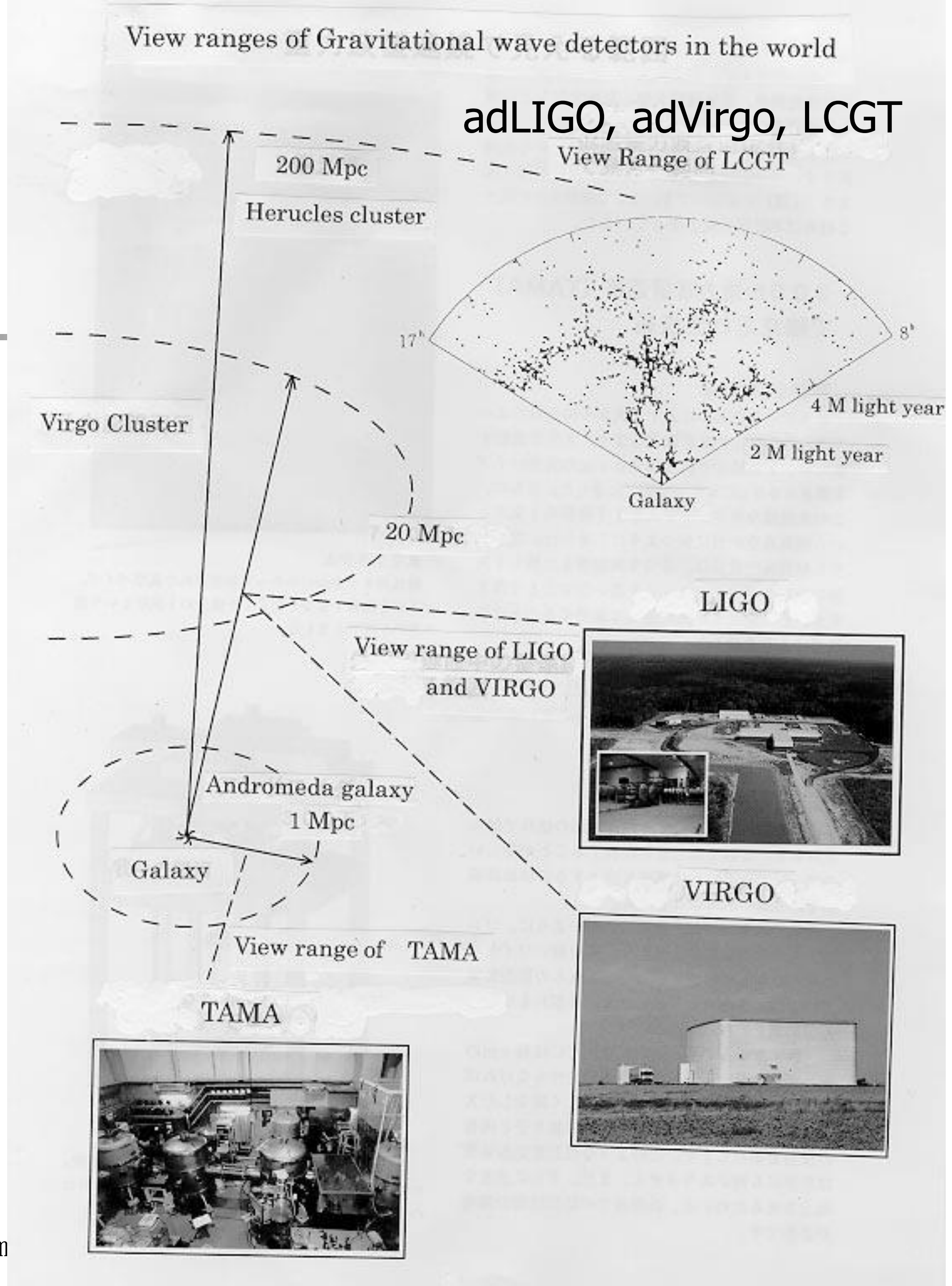


- AdVIRGO (2015+)
- KAGRA/LCGT: underground and with cryogenic mirrors of 3^{rd} generation requirement(2017/2018)
- INDIGO/LIGO South: pending grant approval
- Expecting DETECTION around 2020!!

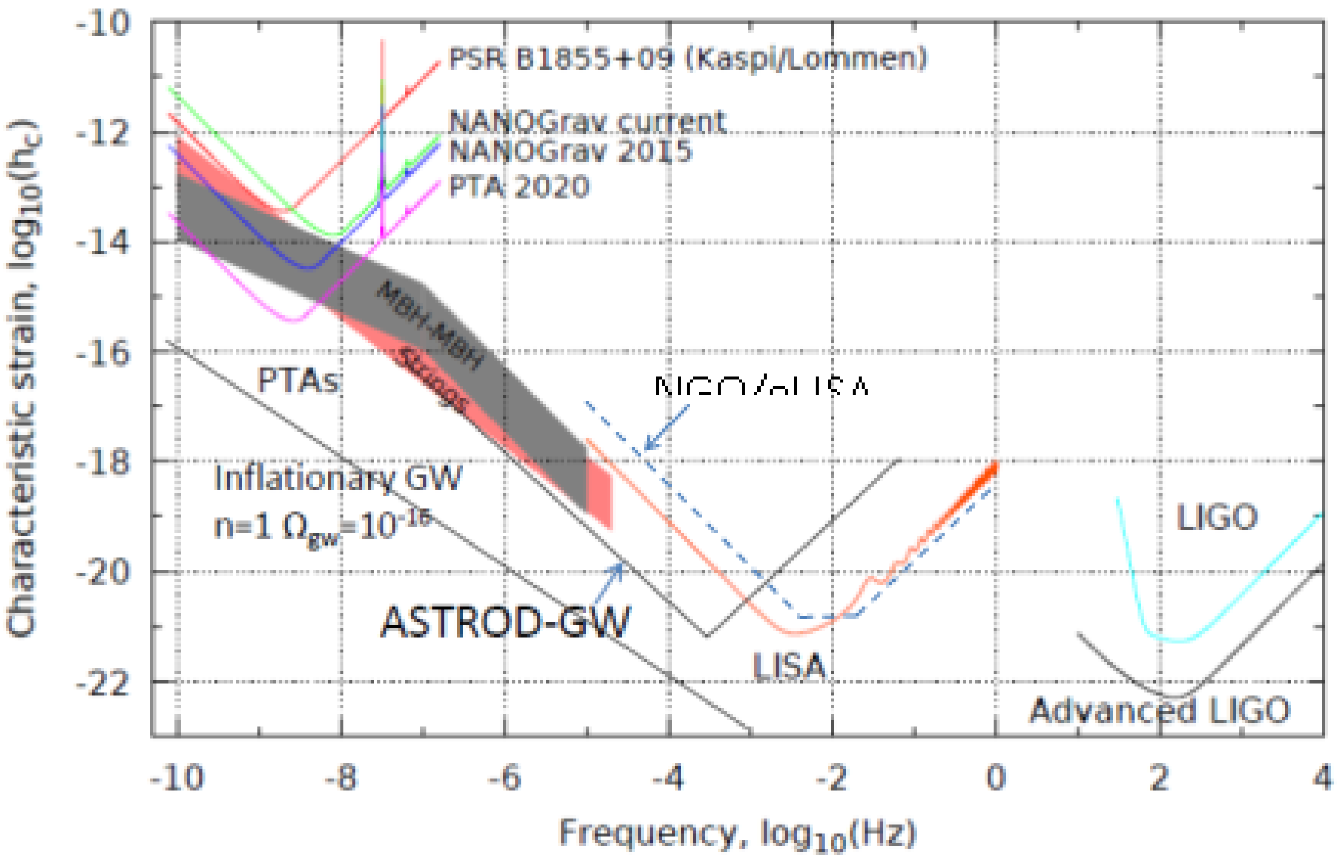
View ranges for GW sources for ground detectors

(Kuroda et al. LCGT paper, IJMPD 1999)

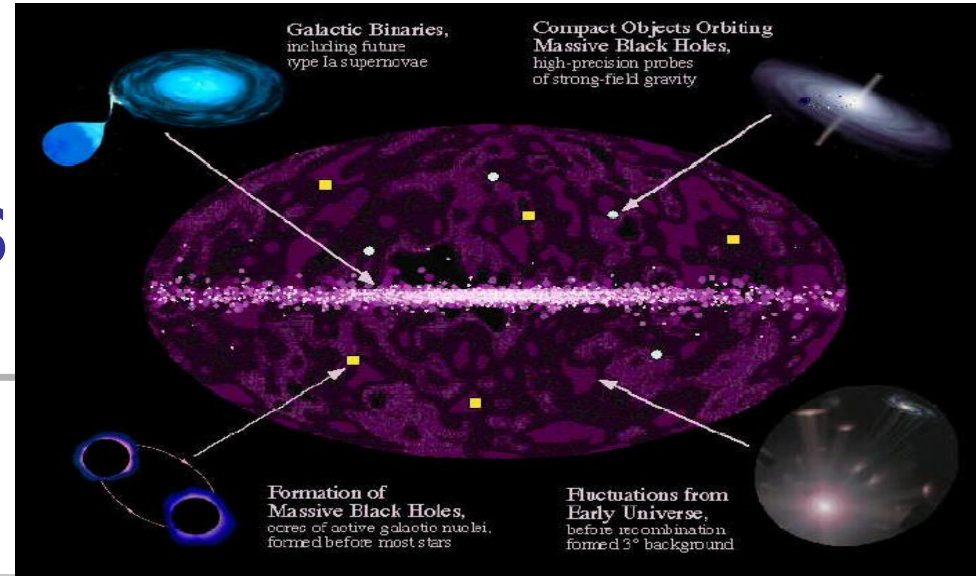
- Ground GW detectors will most likely start direct detection GW astronomy
- However, to do prec. cosmology, one has to go into space for lower frequency and longer wavelength

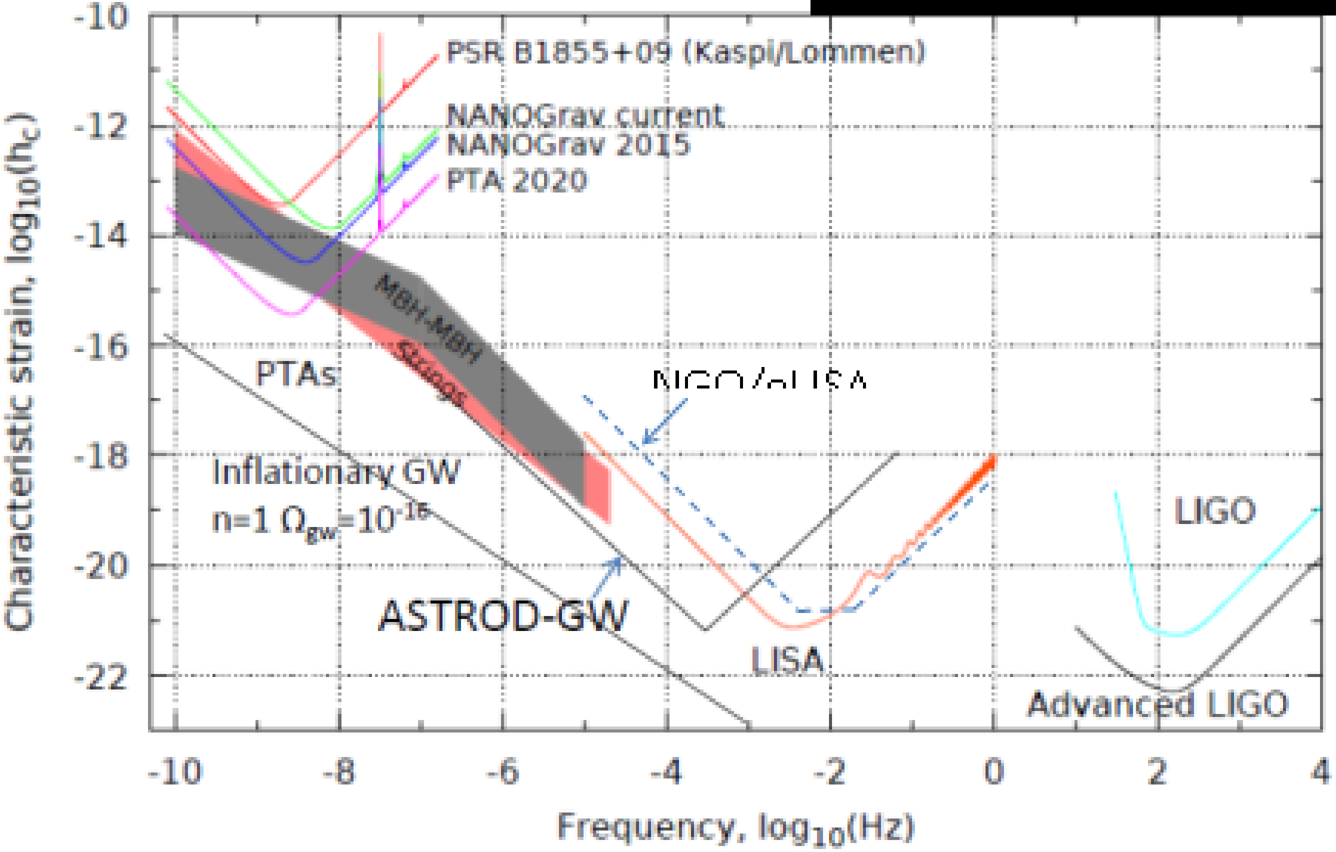


Comparison of current and planned GW detectors

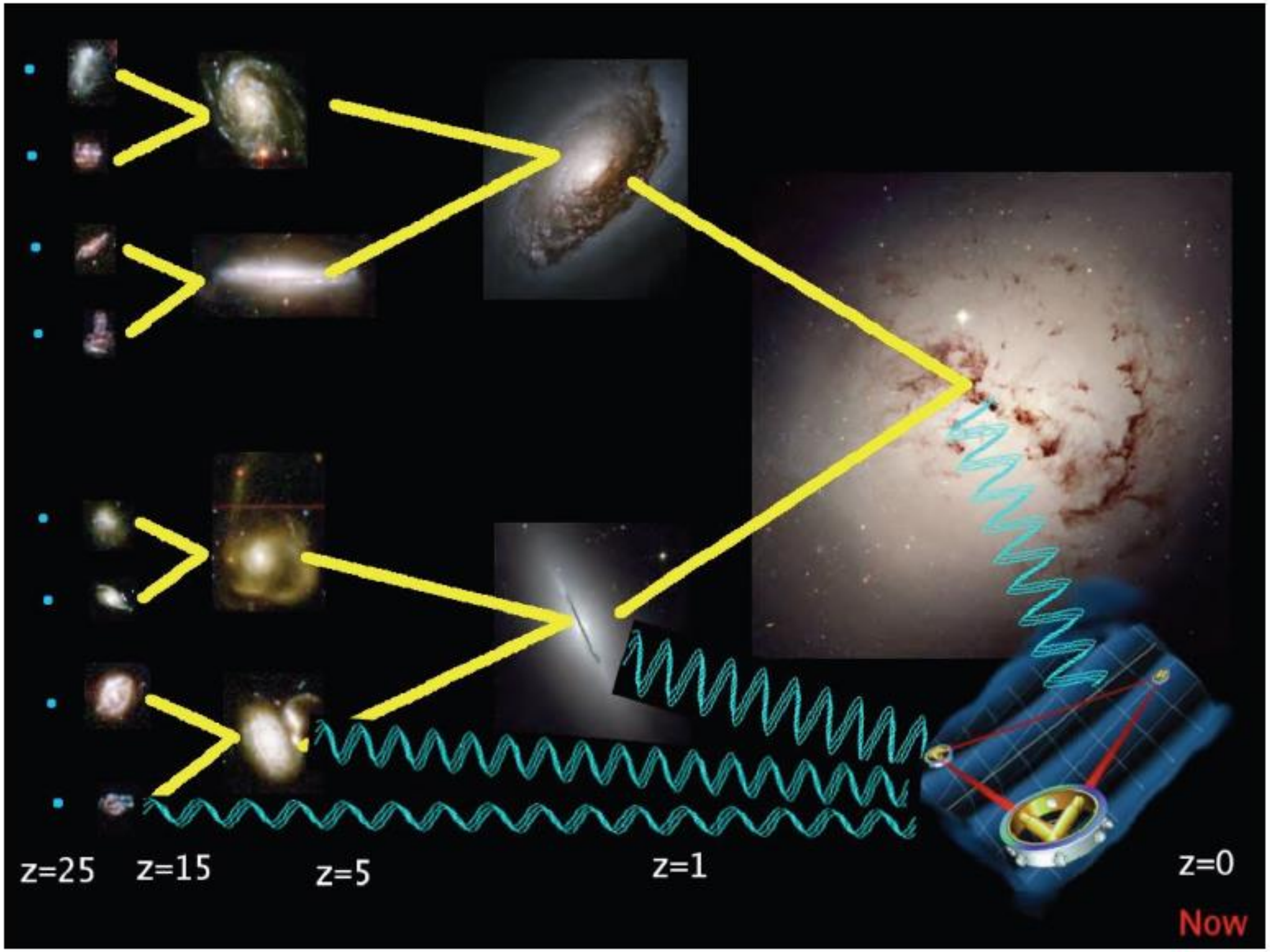


Scientific goals





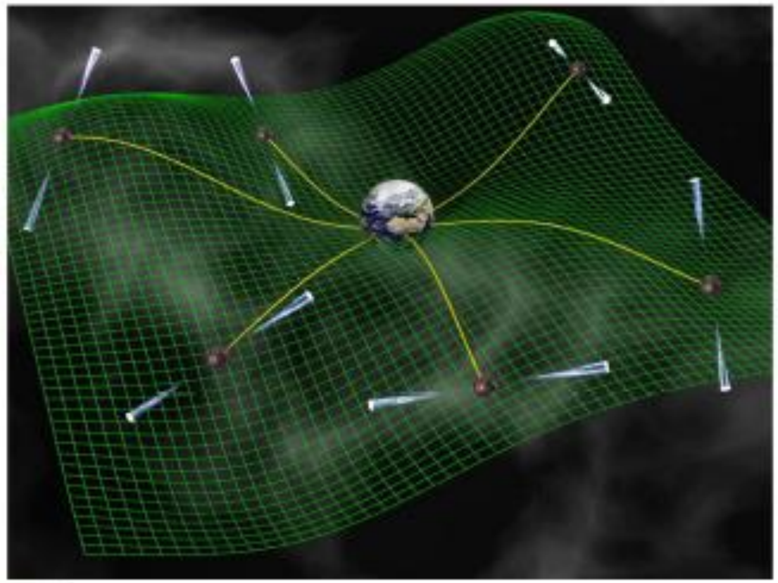
Massive Black Hole Systems: Massive BH Mergers & Extreme Mass Ratio Mergers (EMRIs)

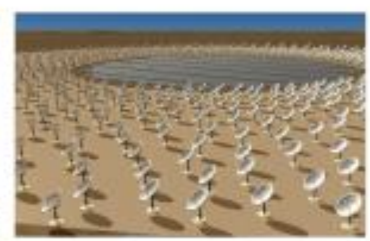


Gravitational Wave Astronomy Using Pulsars: Massive Black Hole Mergers & the Early Universe

A White Paper for the Astronomy & Astrophysics Decadal Survey

NANOGrav:





Complete GW Classification

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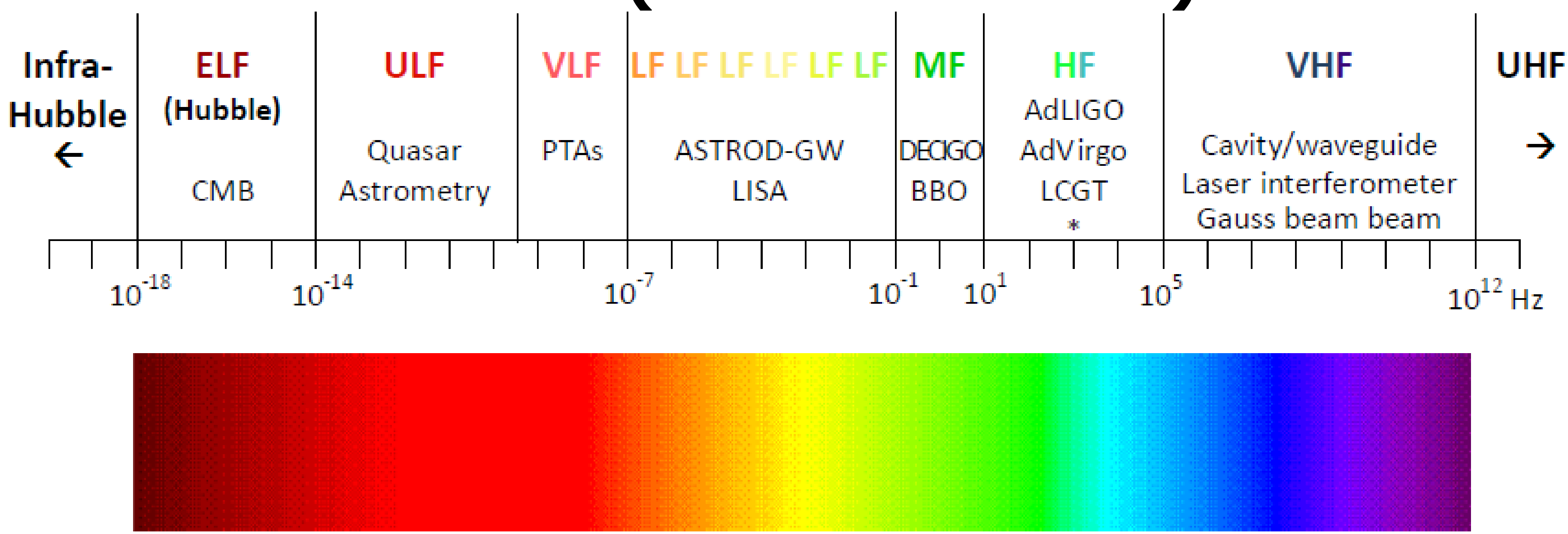


* AIGO, AURIGA, ET, EXPLORER, GEO, NAUTILUS, MiniGRAIL, Schenberg.

Complete GW Classification (II)

- Very low frequency band (300 pHz – 100 nHz): Pulsar timing observations are most sensitive to this band.
- Ultra low frequency band (10 fHz – 300 pHz): Astrometry of quasar proper motions are most sensitive to this band.
- Extremely low (Hubble) frequency band（1 aHz – 10 fHz): Cosmic microwave background experiments are most sensitive to this band.
- Beyond Hubble frequency band (below 1 aHz): Inflationary cosmological models give strengths of GWs in this band. They may be verified indirectly through the verifications of inflationary cosmological models.

Dark energy

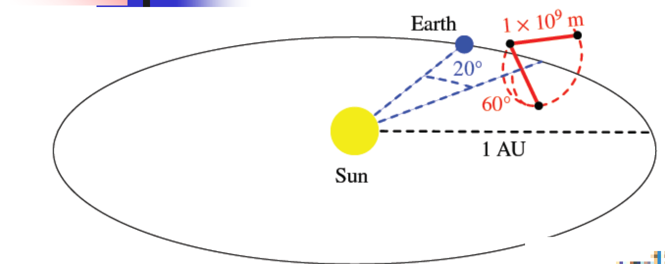
and

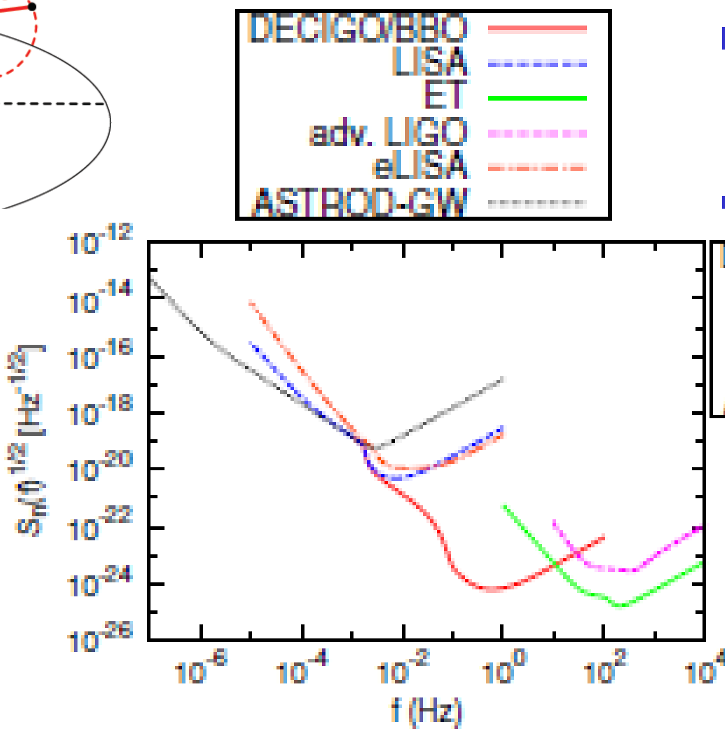
precision cosmology

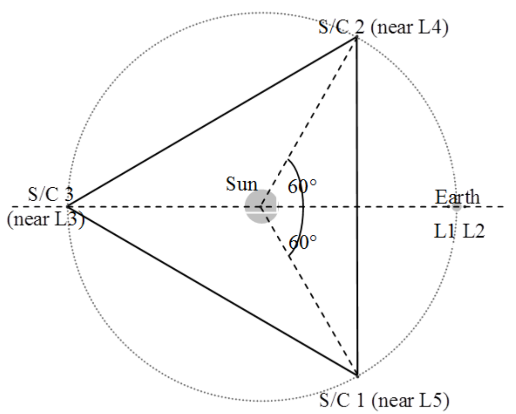
using

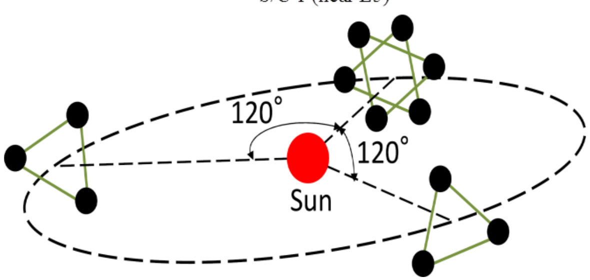
space detectors

Sensitivity, Angular resolution & Deployment









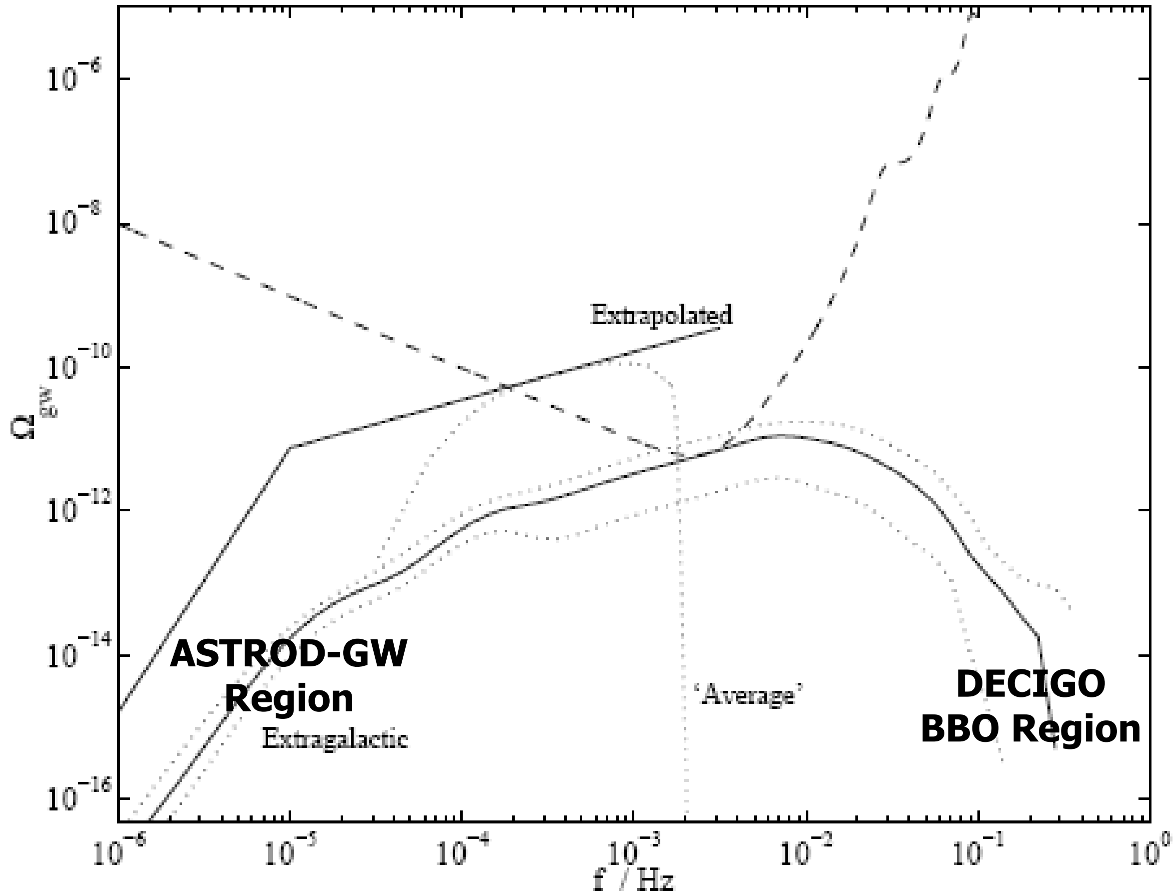
From Yagi 2013
(left & above)

- Angular resolution ~ S/N ratio
- Solar orbit Deployment after separation of launcher:
- 1-2 years with propellent mass ratio 0.25 to 0.55
- Using near Hohmann orbit and Venus flyby

The Gravitational Wave Background from Cosmological Compact Binaries

Alison J. Farmer and E. S. Phinney (Mon. Not. RAS [2003])

Optimistic (upper dotted), fiducial (Model A, lower solid line) and pessimistic (lower dotted) extragalactic backgrounds plotted against the LISA (dashed) single-arm Michelson combination sensitivity curve. The‘unresolved’ Galactic close WD–WD spectrum from Nelemans et al. (2001c) is plotted (with signals from binaries resolved by LISA removed), as well as an extrapolated total, in which resolved binaries are restored, as well as an approximation to the Galactic MS–MS signal at low frequencies.



Comparison of Sensitivities for LISA/eLISA, BBO/DECIGO and ASTROD-GW

Mission under planning	Detection frequency range	Arm length Gm (Mkm)	Acceleration noise goal	Power
LISA	10 μHz - 1 Hz	5 Gm (Mkm)	3×10^{-15} m s^{-2} Hz$^{-1/2}$	1-2 W
eLISA	10 μHz - 1 Hz	1 Gm (Mkm)	3×10^{-15} m s^{-2} Hz$^{-1/2}$	1-2 W or less
ASTROD-GW	100 nHz -1 Hz	260 Gm (Mkm)	3×10^{-15} m s^{-2} Hz$^{-1/2}$	1-2 W
BBO	30 mHz – 10 Hz	0.05 Gm	3×10^{-17} m s^{-2} Hz$^{-1/2}$	300 W
DECIGO	30 mHz – 10 Hz	0.001 Gm	3×10^{-17} m s^{-2} Hz$^{-1/2}$	100 W

Space GW Detectors

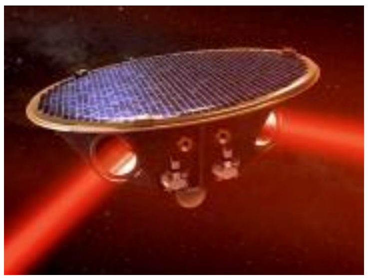
- Space interferometers (eLISA, ASTROD-GW, BBO/DECIGO) for gravitational-wave detection hold the most promise with signal-to-noise ratio.
- eLISA (evolved Laser Interferometer Space Antenna) is aimed at detection of low-frequency (10^{-4} to 1 Hz) gravitational waves with a strain sensitivity of $4 \times 10^{-21}/(\mathrm{Hz})^{1/2}$ at 1 mHz.
- There are abundant sources for LISA, and ASTROD-GW: galactic binaries (neutron stars, white dwarfs, etc.). Extra-galactic targets include supermassive black hole binaries, supermassive black hole formation, and cosmic background gravitational waves.
- LISA Pathfinder will Launch in 2015; DECIGO Pathfinder will bid for a selection in 2016.
- A date of eLISA launch is hoped for 2028. LPF: 2015 launch

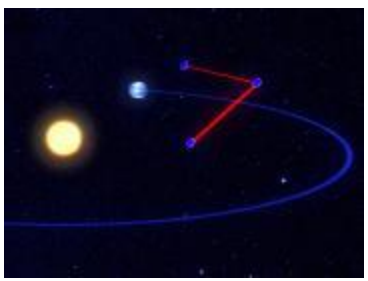
Space offers revolutionary GW science

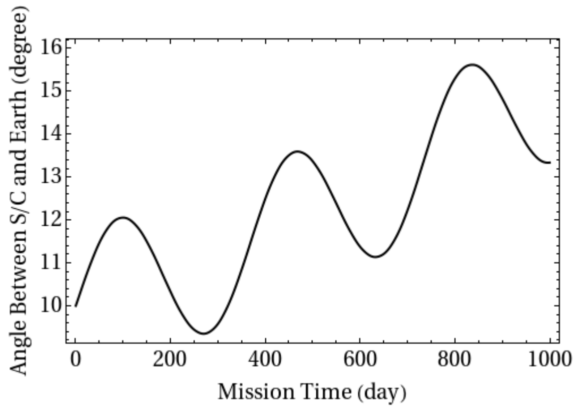
- **Massive BHs (10^3--10^8 M_o)**
  - Mass function, spin evolution as function of redshift z, sample central black holes in ordinary galaxies, search for intermediate mass BHs (IMBH).
- **Evolution of the Cosmic Web at high redshift**
  - Observation of objects before re-ionisation: BH mergers at $z >> 10$.
  - Test models of how massive BHs formed and evolved from seeds.
- **Compact WD binaries in the Galaxy**
  - Catalogue white-dwarf binary systems in the Galaxy, compare with GAIA.
  - Precise masses & distances for many WD/NS/BH binaries.
- **Fundamental physics and testing GR**
  - Ultra-strong GR: Prove horizon exists; test no-hair theorem, cosmic censorship; search for scalar gravitational fields, other GR breakdowns.
  - Fundamental physics: look for cosmic GW background, test the order of the electroweak phase transition, search for cosmic strings.

eLISA/NGO:

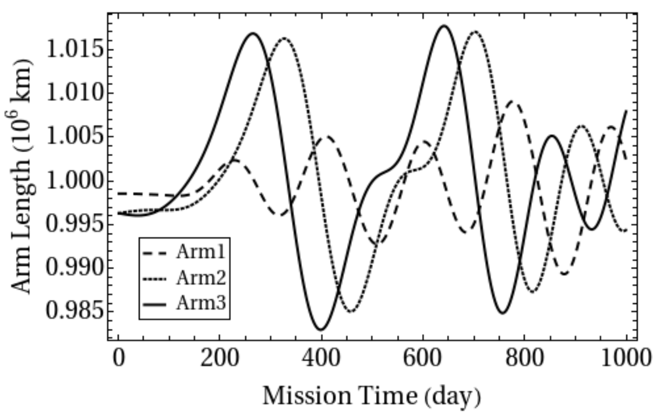
evolved Laser Interferometer Space Antenna / New Gravitational Wave Observatory

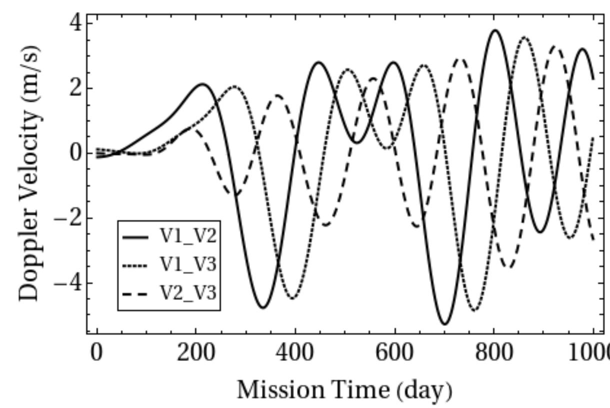






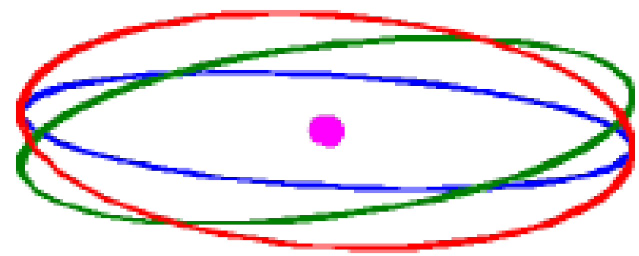
Variations of the arm lengths, the velocities in the line of sight direction, and the angle between barycentre of S/Cs and Earth in 1000 days for the S/C configuration

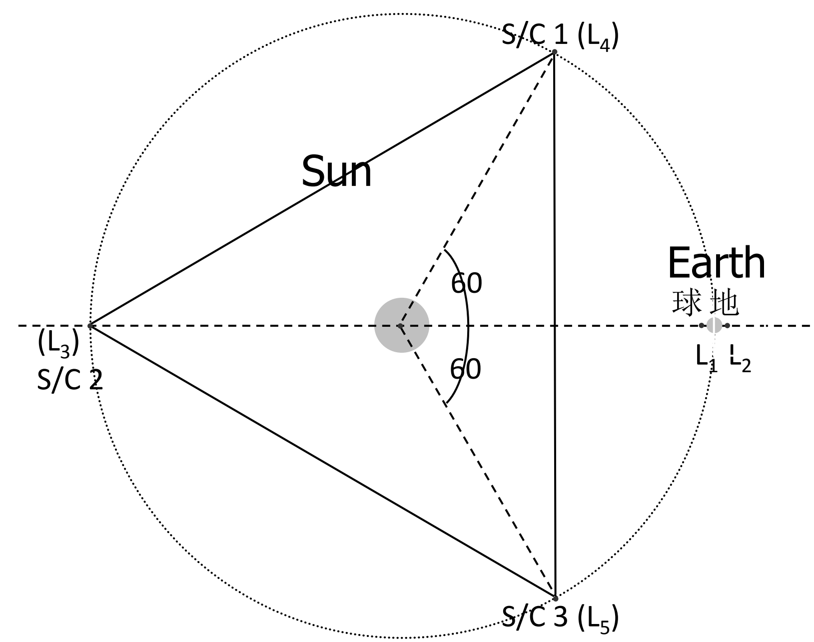




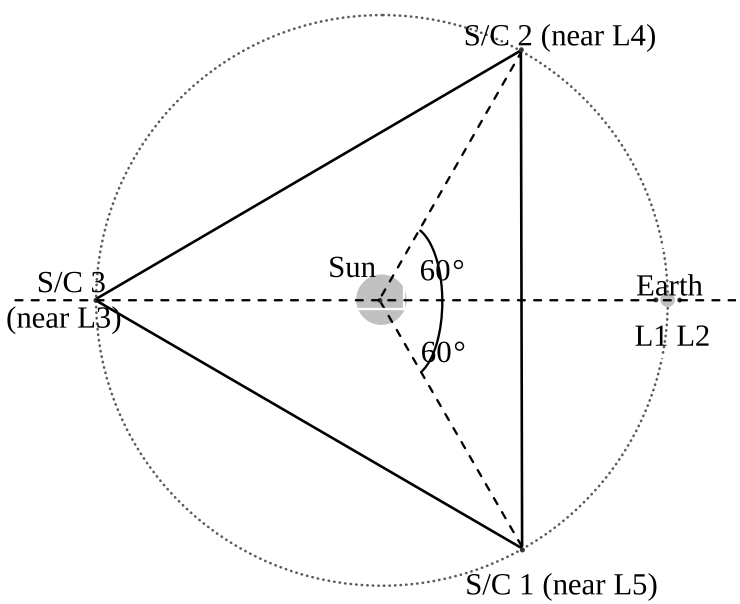
ASTROD-GW Mission Orbit

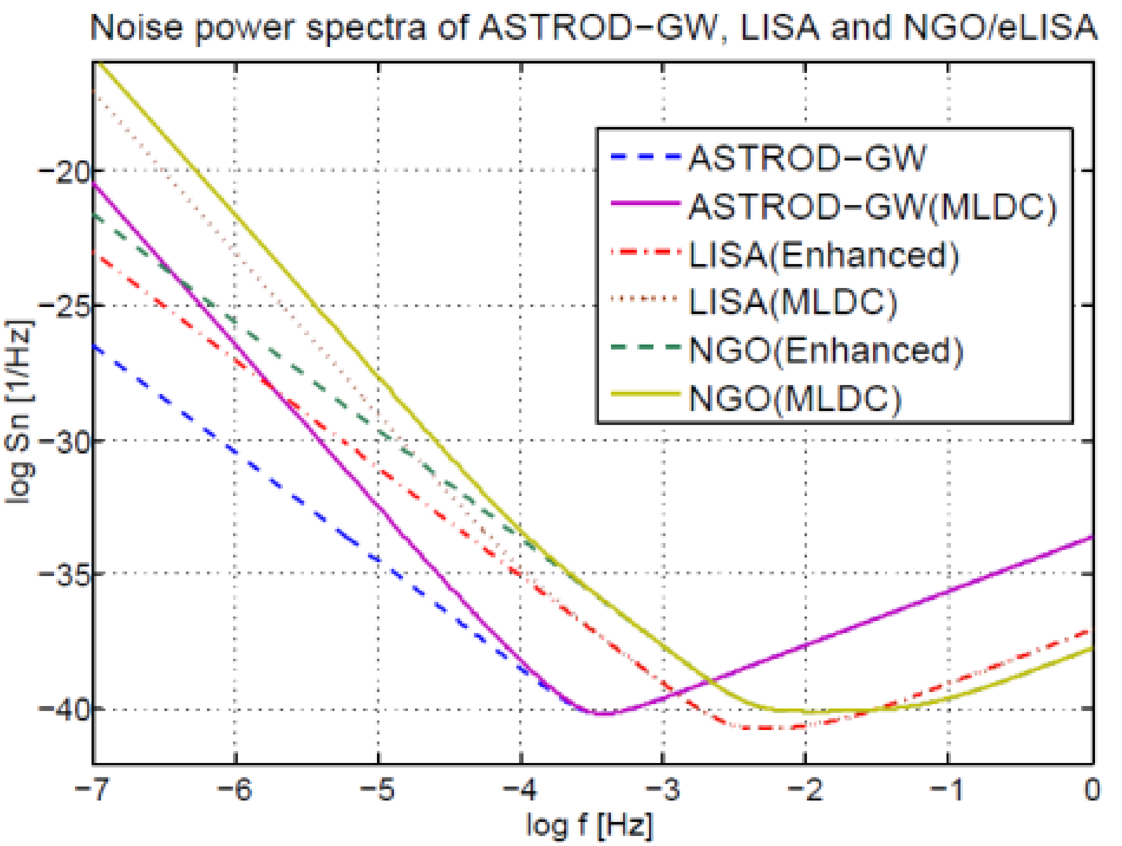
- Considering the requirement for optimizing GW detection while keeping the armlength, mission orbit design uses nearly equal arms.
- 3 S/C are near Sun-Earth Lagrange points L3、L4、L5，forming a nearly equilateral triangle with arm length 260 million km (1.732 AU) with formation inclined to the ecliptic plane 1-3 degree with half year precession period.
- 3 S/C ranging interferometrically to each other.





Strain noise power spectra of ASTROD-GW as compared with LISA and NGO/eLISA





INSTITUTE OF PHYSICS PUBLISHING CLASSICAL AND QUANTUM GRAVIT
Class. Quantum Grav. 23 (2006) S125–S131 doi:10.1088/0264-9381/23/8/S1

The Japanese space gravitational wave antenna—DECIGO

Table 1. Fundamental specifications of DECIGO.

Item	Value
Distance between satellites	1000 km
Effective laser power	10 W
Wavelength of light	532 nm
Mass of the mirror	100 kg
Diameter of the mirror	1 m
Finesse of cavity	10

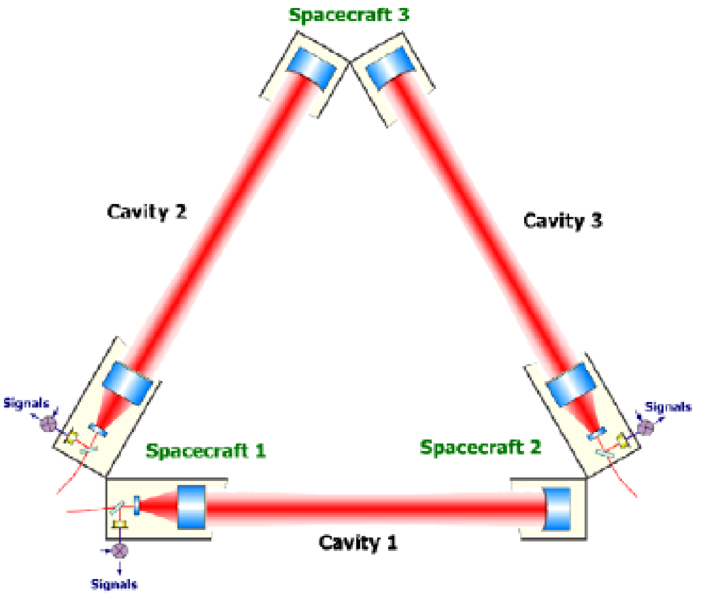
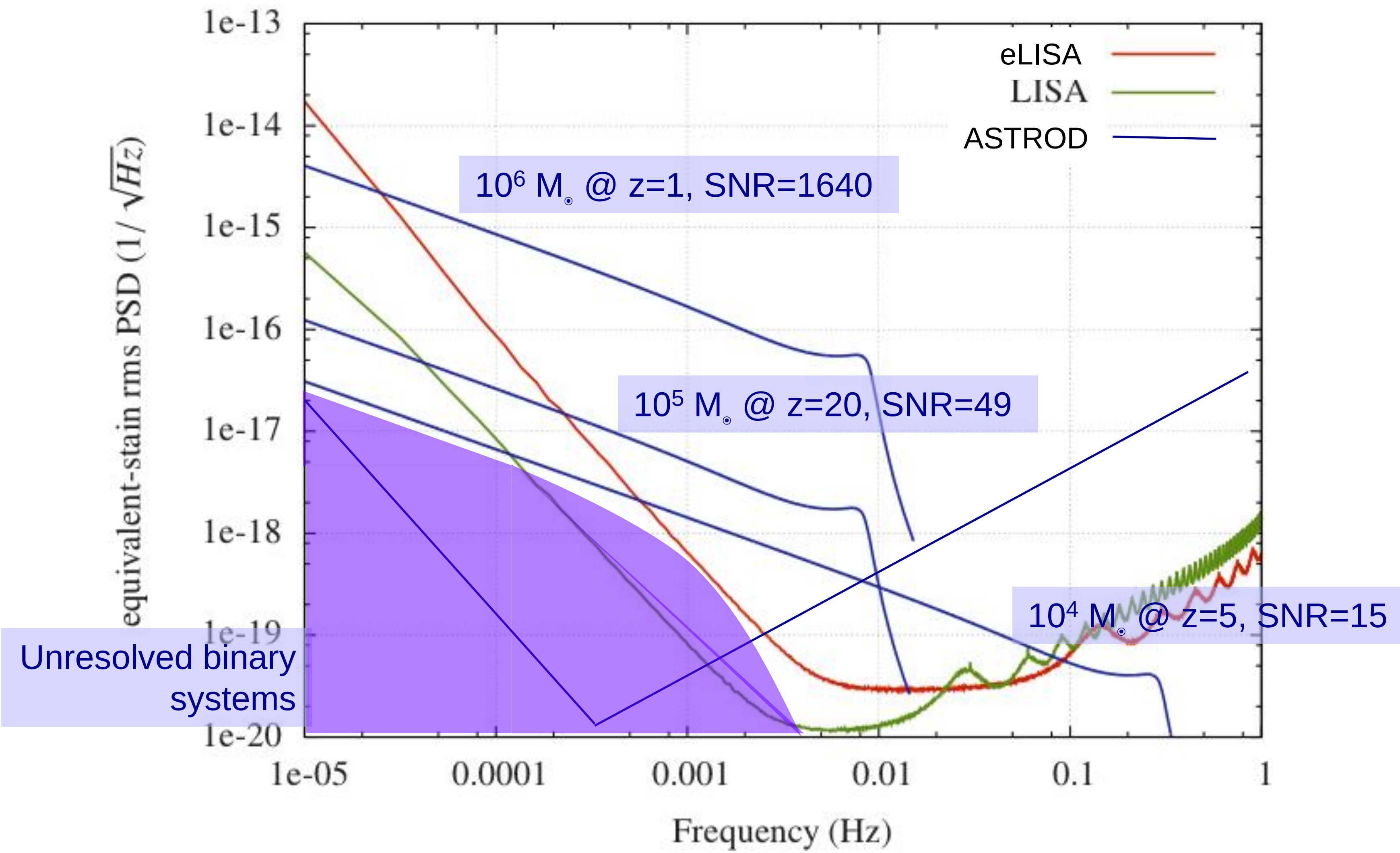


Table 2. Important requirements of DECIGO.

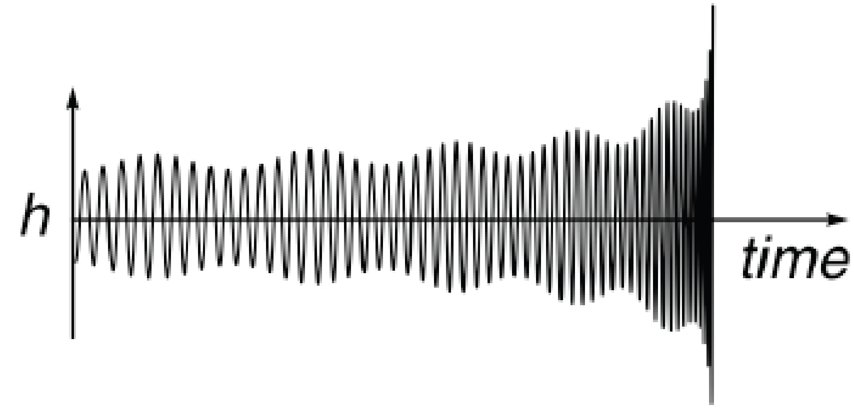
Item	Value
Acceleration noise per mirror	4×10^{-19} m s^{-2} Hz$^{-1/2}$
Total acceleration noise	8×10^{-19} m s^{-2} Hz$^{-1/2}$
Frequency stability of a laser with the first-stage frequency stabilization	1 Hz Hz$^{-1/2}$ (at 1 Hz)
Frequency stabilization gain by the common-mode arm length	10^5 (at 1 Hz)
Common-mode rejection ratio	10^5
Intensity stability of a laser with the intensity stabilization	10^{-8} Hz$^{-1/2}$ (at 1 Hz)
Residual rms motion of the differential arm length	2×10^{-11} m

Sensitivity and BH Science



Absolute Distances from Black Hole Binaries

Waveforms of black hole binaries give precise, gravitationally calibrated distances to high redshift



Absolute luminosity distances can be derived *directly* from

- amplitude
- orbital frequency
- chirp time

$$\text{Distance} \cong c \frac{1}{\text{frequency}^2 \times t_{\text{chirp}} \times \text{amplitude}}$$

1. Distances accurate to 0.1% to ~10% per event
2. Absolute, physical calibration using only gravitational physics

Space GW detectors and Dark energy

- In the solar system, the equation of motion of a celestial body or a spacecraft is given by the astrodynamical equation

$$\mathbf{a} = \mathbf{a}_{\mathrm{N}} + \mathbf{a}_{\mathrm{1PN}} + \mathbf{a}_{\mathrm{2PN}} + \mathbf{a}_{\mathrm{Gal\text{-}Cosm}} + \mathbf{a}_{\mathrm{GW}} + \mathbf{a}_{\mathrm{non\text{-}grav}}$$

- In the case of scalar field models, the issue becomes what is the value of $w(\phi)$ in the scalar field equation of state:

$$w(\phi) = p(\phi) / \rho(\phi),$$

where p is the pressure and ρ the density.

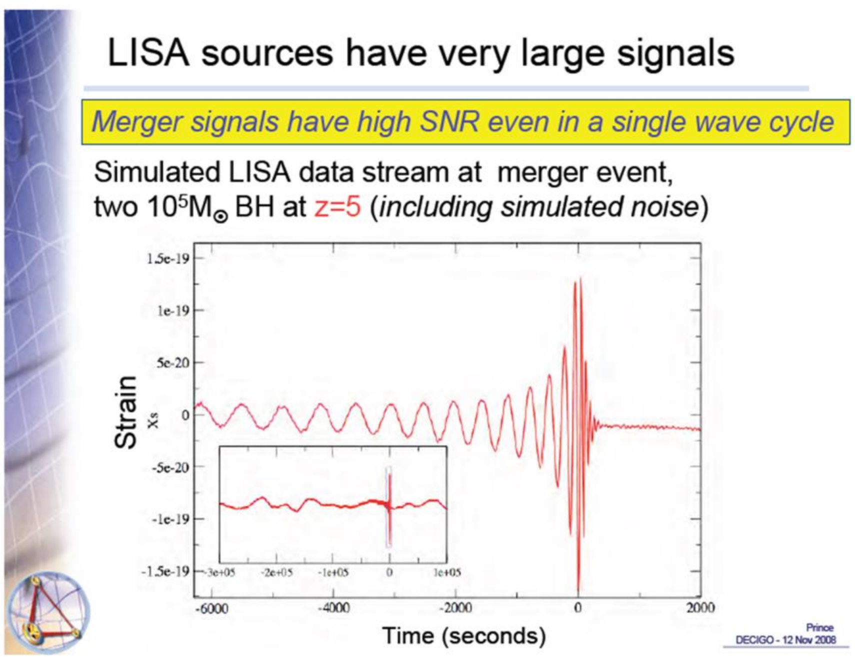
- For cosmological constant, $w = -1$.
- From cosmological observations, our universe is close to being flat. In a flat Friedman Lemaître-Robertson-Walker (FLRW) universe, the luminosity distance is given by

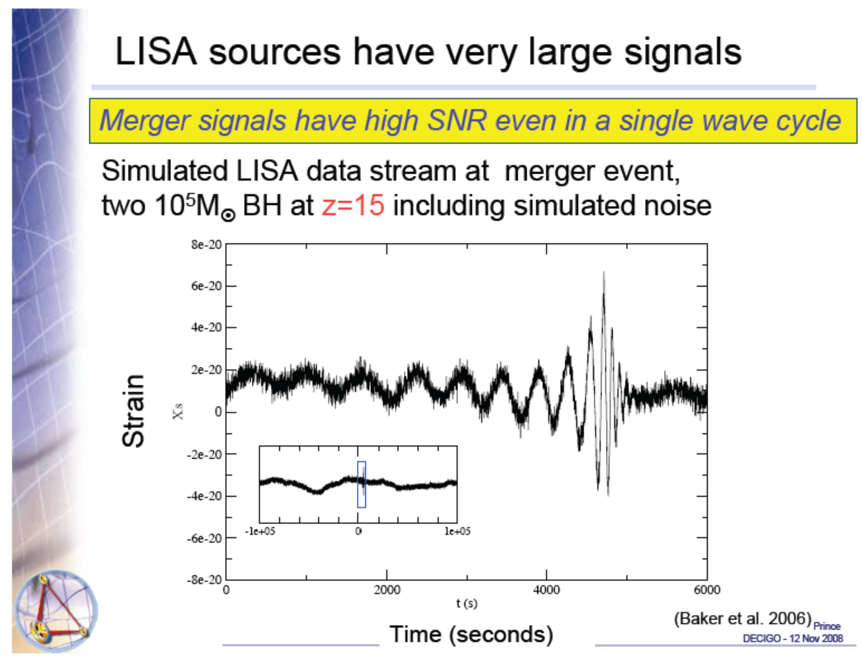
$$d_L(z) = (1+z) \int_{0\rightarrow z} (H_0)^{-1} [\Omega_m(1+z')^3 + \Omega_{\mathrm{DE}}(1+z')^{3(1+w)}]^{-(1/2)} dz',$$

where w is assumed to be constant.

Space GW detectors as dark energy probes

- Luminosity distance determination to 0.1 % or better
- Measurement of redshift by association
- From this, obtain luminosity distance vs redshift relation, and therefore equation of state of dark energy





Determination of Dark Energy Equation is limited by gravitational lensing

Cutler & Holz PRD 80, 104009 (2009)

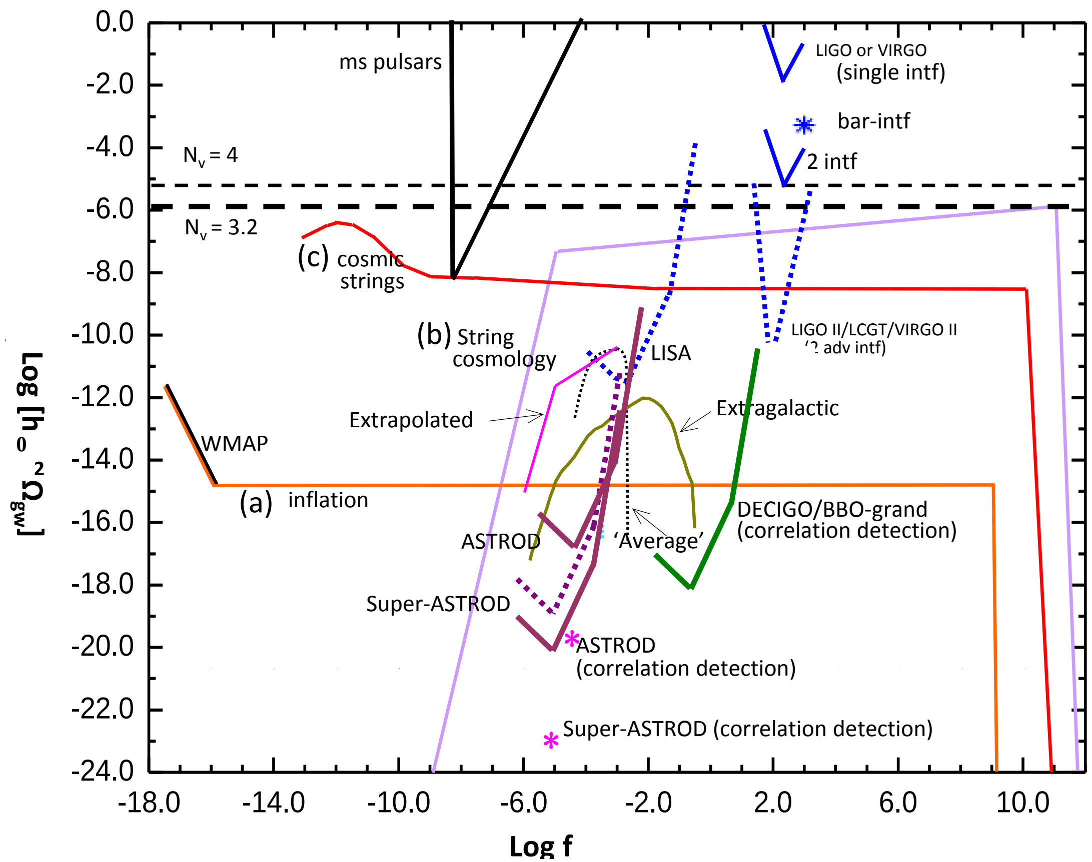
- Standard error σ in the luminosity distance:

  $\sigma/D_L = (\eta_{weak}^2 + \eta_{lensing\ instrument}^2)^{1/2}$ for $z < 5$
- $\eta_{weak}(z) = 0.042\, z$, $\eta_{weak}(z=5) = 0.21$
- Cutler & Holz 2009: BBO 3 year observations → about 300,000 compact star binaries → $H_0 \sim 0.1\,\%$; $w_0 \sim 0.01$; $w_a \sim 0.1$
- Specifically, NS-NS binary at z=1.5, median distance error ~2% due to detector; ~7% due to weak lensing
- BH-BH rate: a factor ~20 smaller than the NS-NS rate
- NS-NS typical S/N ratio for each measurement is 3.4
- BH-BH S/N ratio for each measurement is 5.3 × 3.4
- S/N ratio for whole NS population is $3.4 \times (300{,}000)^{1/2} \sim 2000$
- Lensing S/N ratio for whole BH population is ~2200

Determination of Dark Energy Equation from ASTROD-GW is limited by Gravitational Lensing

- BBO angular resolution for NS-NS, BH-NS, BH-BH: 0.01-100 $arcsec^2$; ASTROD-GW resolution in the $arcmin^2$ range
- For z=4, the noise/signal ratio for luminosity distance is 0.168 (4.2z) due to lensing for the detection of massive BH binary mergers (rate 10-1000 per year).
- Suppose rate is 10-1000 per year, for 3 years, N/S ratio is 0.01
- Determination of luminosity distance-redshift relation limited only by weak lensing and number of events will extend to higher redshift (z = 20) the determination of dark energy equation.

Primordial Gravitational Waves
[strain sensitivity → (ω^2) energy sensitivity]



Summary

- The dominant GW sources in the most-sensitive BBO/DECIGO frequency band (30 mHz – 3 Hz) are compact binary mergers consisted of NSs and stellar-sized BHs.
- The angular resolution for these sources will be measured by BBO/DECIGO to high precision. The redshift measurement of GP ('gold-plated') sources with only single galaxies in the narrow angular resolution cone will give the redshifts of the sources.
- With about 3 x 10^5 compact star binaries, the covariance of weak lensing as a function of redshift could be measured to unprecedented precision, and Hubble constant and the dark energy equation of state could be determined, to high accuracy.

Summary II

- ASTROD-GW frequency band (100 nHz – 1 mHz): massive black hole binary (MBHB) mergers, with rate estimate 10-1000 yr^{-1}, and the MBHB background.
- A similar determination of luminosity distance-redshift relation limited only by weak lensing and number of events will extend to higher redshift (z = 20) the determination of dark energy equation.
- The measurement of the MBHB background together with single event detections will track the galaxy evolution history and test various evolution models

Summary III

- BBO/DECIGO could detect all NS-NS mergers up to z = 5 and subtract them to probe the primordial (inflationary) GWs to 10^{-17} critical density of the universe.
- With correlated detection of background and subtractions, we are currently studying whether ASTROD-GW would reach this sensitivity or better. Issues mainly concern with the magnitudes of the MBHB background, and the single event rate/spectrum.

Thank You！