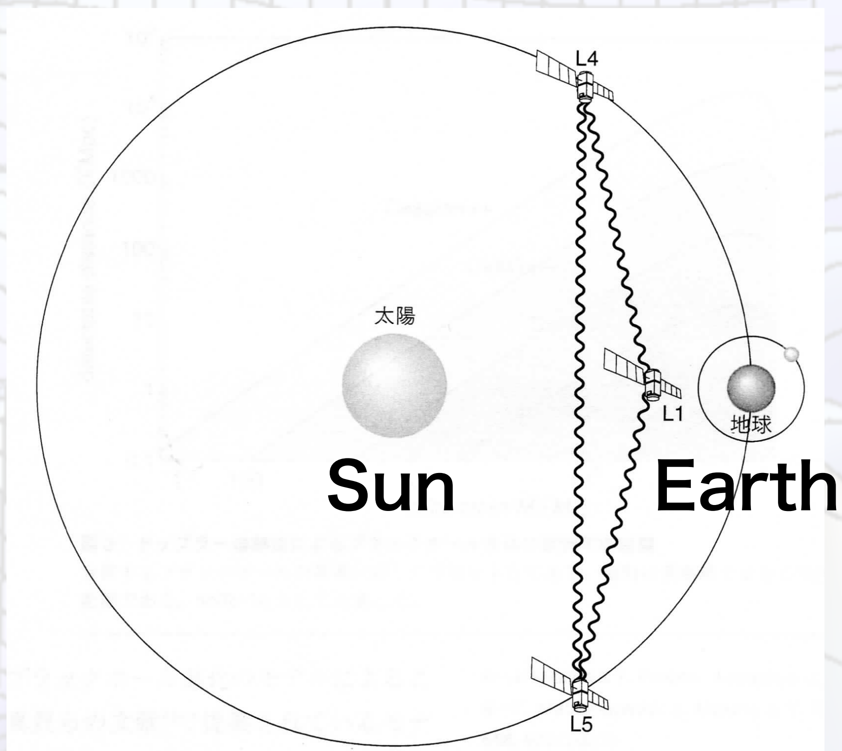
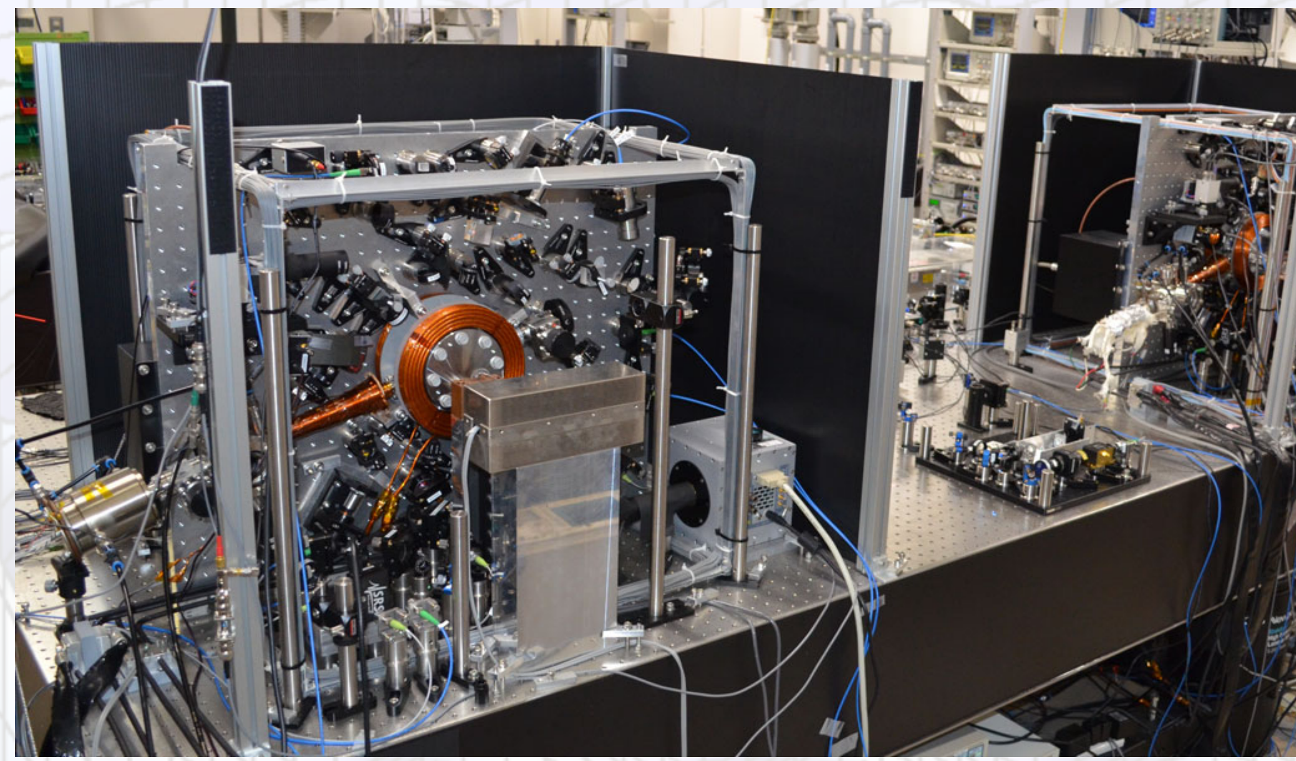
Gravitational-wave detector using Optical Lattice Clocks in Space

Hisaaki Shinkai (Osaka Inst. Tech) , Toru Tamagawa (RIKEN) , Atsushi Noda (JAXA) ,
Hidetoshi Katori (U Tokyo/RIKEN) , Jun'ichiro Makino (Kobe U/RIKEN) ,
Toshikazu Ebisuzaki (RIKEN)





- **Cassini's Doppler tracking (2001-2002) can be improved 3-order mag. with current technologies**
- **"Cassini+++", "Cassini++++" : sensitivity curve, detectable distance *D***
- **Event rate by hierarchical formation model of SMBH**

2018/7/3 Marcel Grossmann 15@Rome

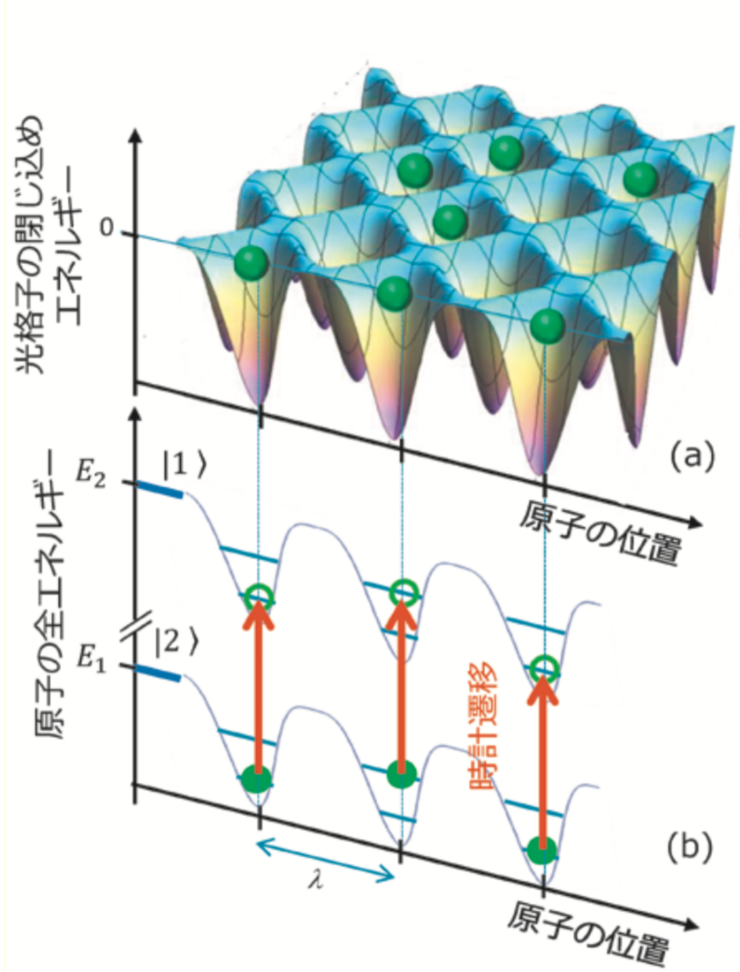
1. Introduction : Optical Lattice Clock

"Optical Lattice Clock"

H. Katori (JPS Journal, 2002, p754)

trap atoms at standing laser wave

read frequency of transient phase



JPS J, 2017, p84

Cs atomic clock $\Delta t/t = 5\times10^{-16}$

Optical Lattice Clock (2015) 10^{-18}

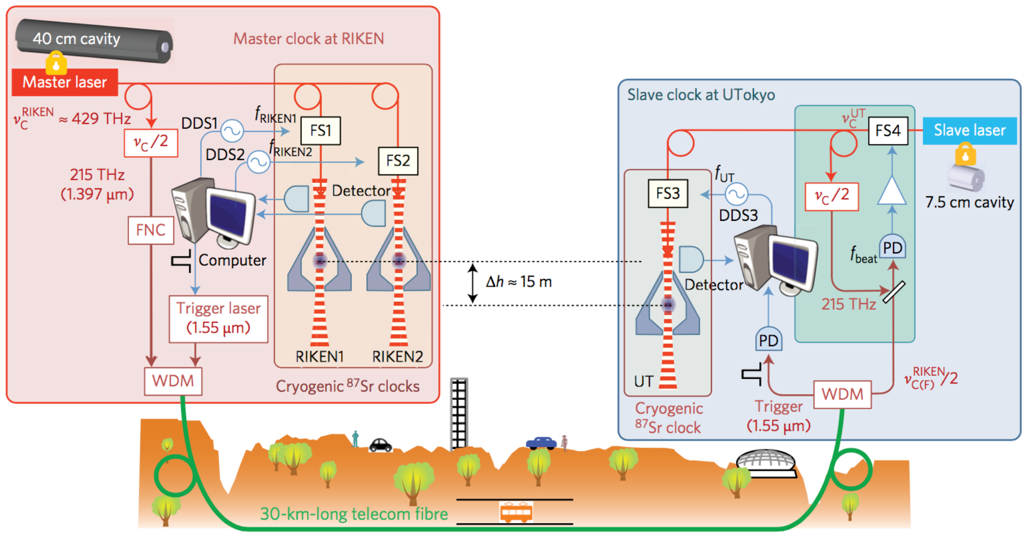
magic freq. compensates multi-polarization

OLC targets $\Delta t/t = 10^{-19}$

LETTERS nature photonics
PUBLISHED ONLINE: 15 AUGUST 2016 | DOI: 10.1038/NPHOTON.2016.159

Geopotential measurements with synchronously linked optical lattice clocks

Tetsushi Takano[1,2], Masao Takamoto[2,3,4], Ichiro Ushijima[2,3,4], Noriaki Ohmae[1,2,3], Tomoya Akatsuka[2,3,4], Atsushi Yamaguchi[2,3,4], Yuki Kuroishi[5†], Hiroshi Munekane[5], Basara Miyahara[5] and Hidetoshi Katori[1,2,3,4*]

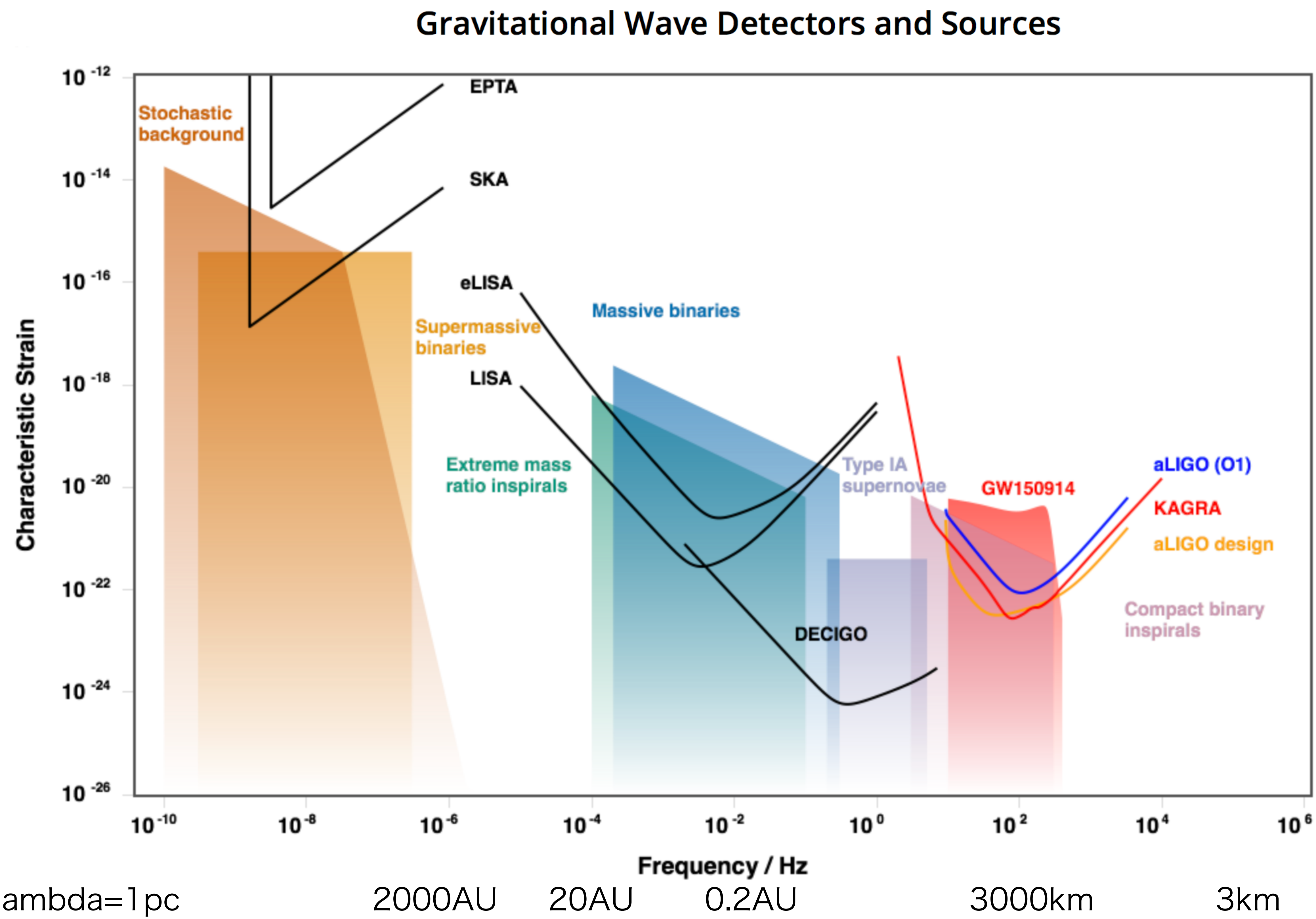


grav. potential of 15m difference

relativistically measured ± 5cm

(1 cm on the Earth $\Delta t/t = 1.1\times10^{-18}$)

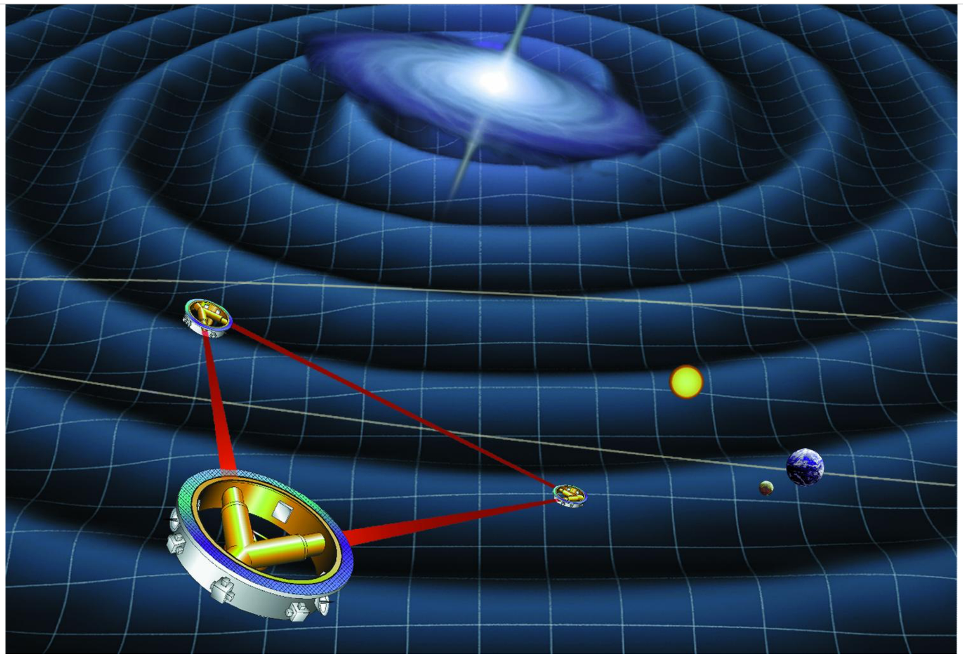
1. Introduction

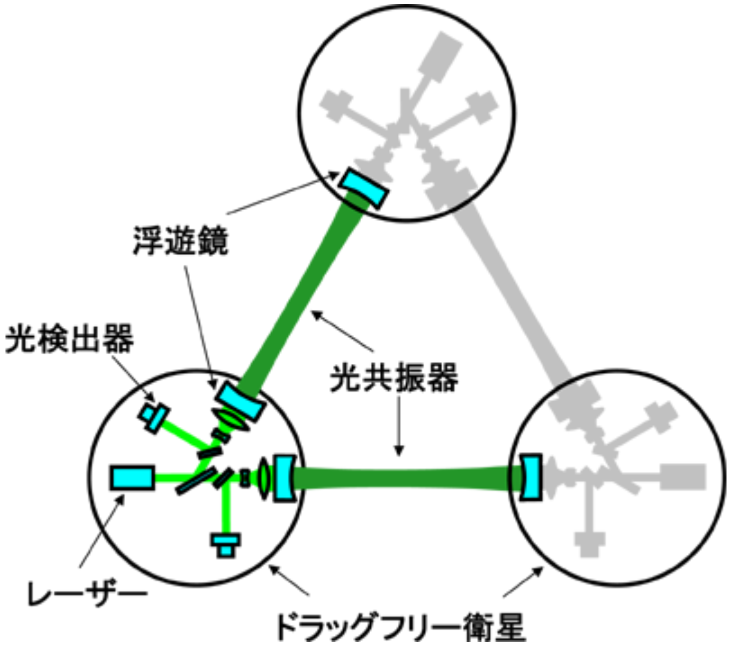


http://rhcole.com/apps/GWplotter/

1. Introduction : Existing plans for space GW observatories

LISA (ESA/NASA)	B-DECIGO ⇒ DECIGO (Japan)
Laser Interferometer Space Anntena	**Deci-hertz Interferometer GW Observatory**
mHz range	0.1Hz range
2030 launch	proposed
3 satellites at L4 of Sun-Earth	around earth 2000km 3 sattelites ⇒ Sun orbit
2.50×10^6 km	100 km ⇒ 1000 km
robust to acceleration noise	
light transponder	**Fabry-Perot interferometer**
	robust to shot-noises
drag-free flight	**drag-free flight**
Doppler tracking with Laser beam	same as ground interferometer



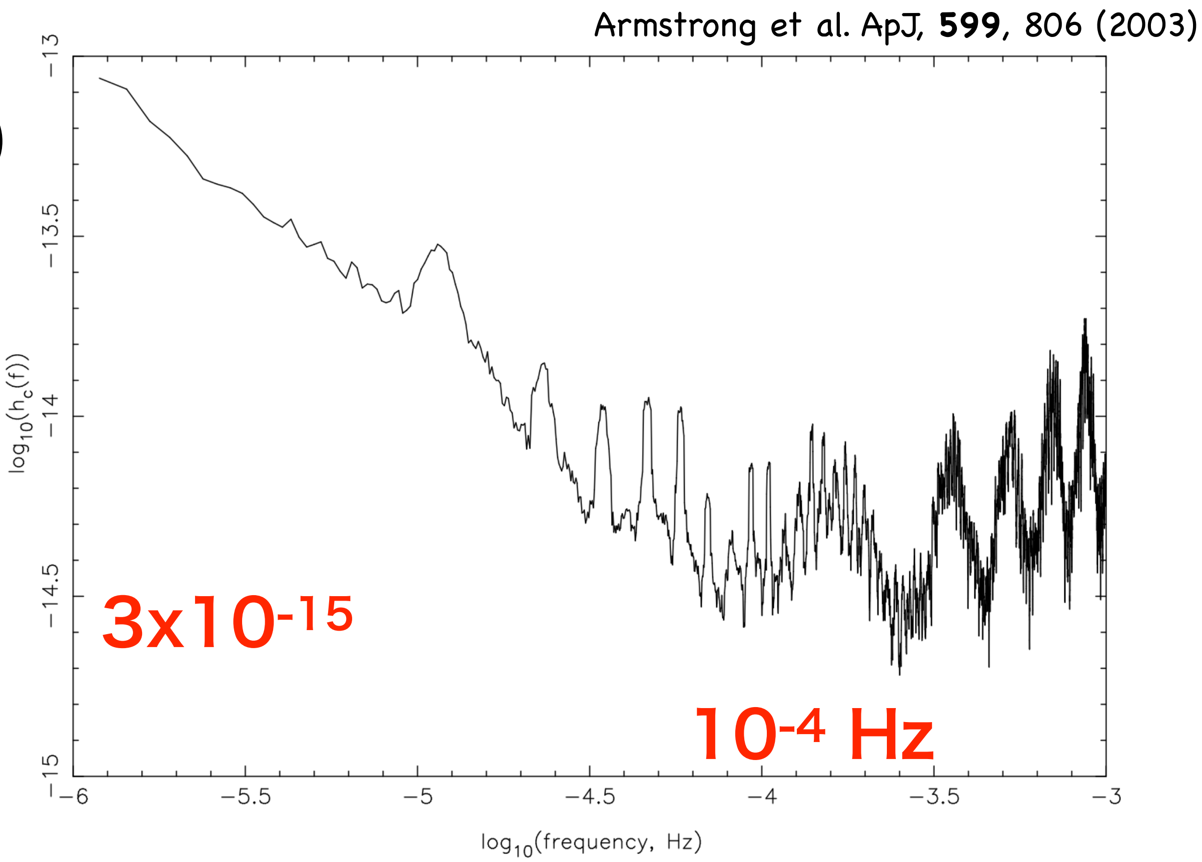


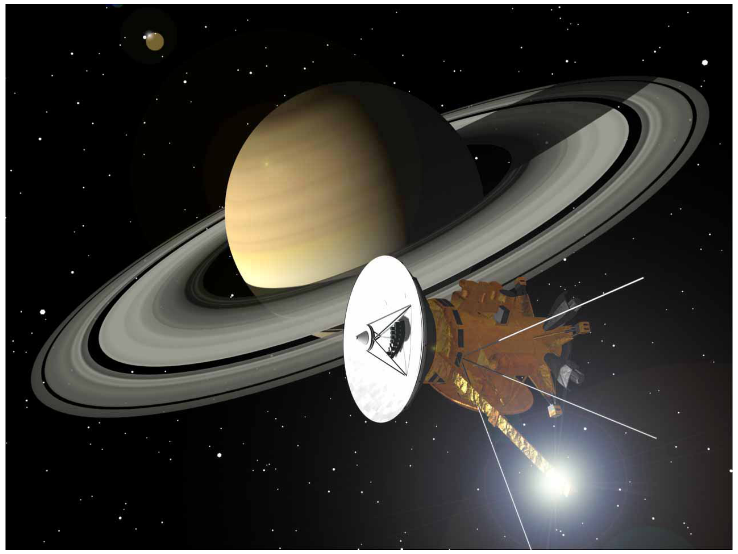
2. Doppler tracking of Cassini Saturn Explorer

Cassini 2001-2002 (Armstrong, LRR 2006)

G. Cassini (1625-1712)

$h_c(f)$



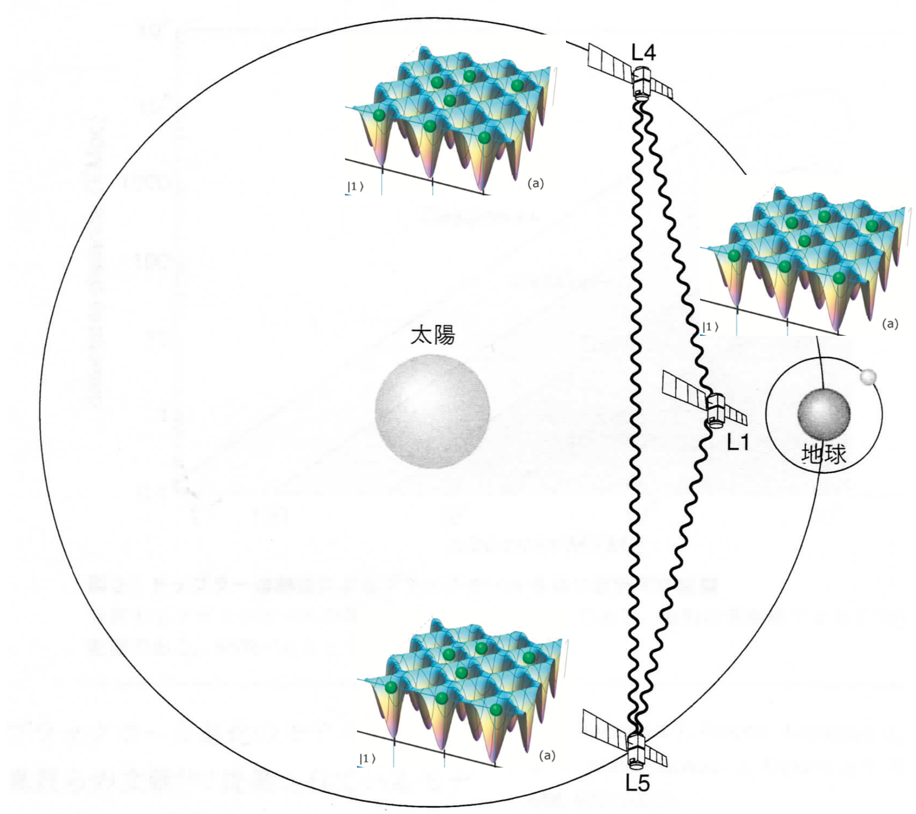


Cassini (1997-2017)

Table 4: Required improvement in subsystems to improve overall Doppler sensitivity by a factor of 10 relative to Cassini-era performance.

Noise source	Comment (σ_y at $\tau = 1000$ s)	Required improvement	
Frequency standard	currently FTS + distribution $\simeq 8 \times 10^{-16}$	$\simeq$ 8X	**atomic clock**
Ground electronics	currently $\simeq 2 \times 10^{-16}$	$\simeq$ 2X	
Tropospheric scintillation	currently $\simeq 10^{-15}$ under favorable conditions	$\simeq$ 10X	**troposphere**
Plasma scintillation	Cassini-class radio system probably adequate for calibration to $\simeq 10^{-16}$	$\simeq$ 1X	**plasma**
Spacecraft motion	currently $\simeq 2 \times 10^{-16}$	$\simeq$ 2X	**radiation pressure of Sun**
Antenna mechanical	currently $\simeq 2 \times 10^{-15}$ under favorable conditions	$\simeq$ 20X	**control technology**

2. Improvement of Doppler sensitivity（1）



1 AU baseline ▶ 10^{-5}Hz

▶ **monitor the time by Opt Lattice Clocks in 3 satellites** — need to make it portable

If radio transmission,
use two frequency ranges（double tracking)
to check phase differences due to interplanetary plasma

▶ **If light transmission,**
no effects from plasma. — need R&D

Table 4: Required improvement in subsystems to improve overall Doppler sensitivity by a factor of 10 relative to Cassini-era performance.

Noise source	Comment (σ_y at $\tau = 1000$ s)	Required improvement
Frequency standard	currently FTS + distribution $\simeq 8 \times 10^{-16}$	$\simeq$ 8X
Ground electronics	currently $\simeq 2 \times 10^{-16}$	$\simeq$ 2X
Tropospheric scintillation	currently $\simeq 10^{-15}$ under favorable conditions	$\simeq$ 10X
Plasma scintillation	Cassini-class radio system probably adequate for calibration to $\simeq 10^{-16}$	$\simeq$ 1X
Spacecraft motion	currently $\simeq 2 \times 10^{-16}$	$\simeq$ 2X
Antenna mechanical	currently $\simeq 2 \times 10^{-15}$ under favorable conditions	$\simeq$ 20X

atomic clock ▶ Opt. Lattice Clock

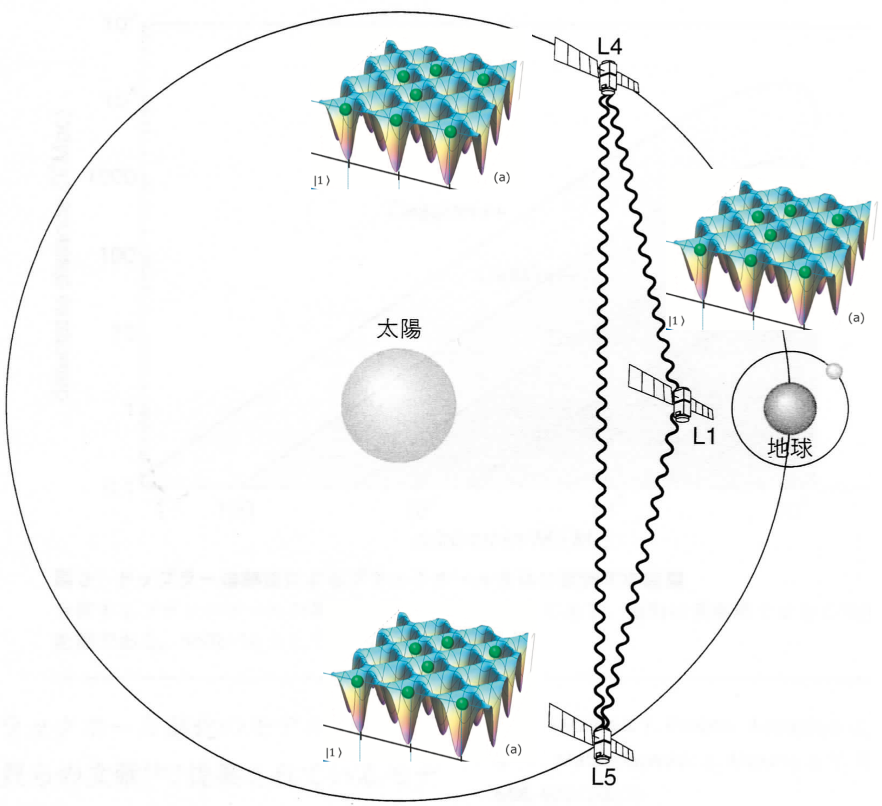
troposphere ▶ in space

plasma ▶ light transmission

rad. pressure ▶ solar panel parasol

control technology

2. Improvement of Doppler sensitivity（2）



1 AU baseline ▶ 10^{-5}Hz

rad. press. F=P/c

P=1.3 kW/m²

1000 kg, 10 m²

acceleration

a=5x10^{-8} m/s²

ΔP/P ≒ 1/1000

Δa/a ≒ 10^{-11}

▶ solar panel parasol

Δg/g ≒ 10^{-12}

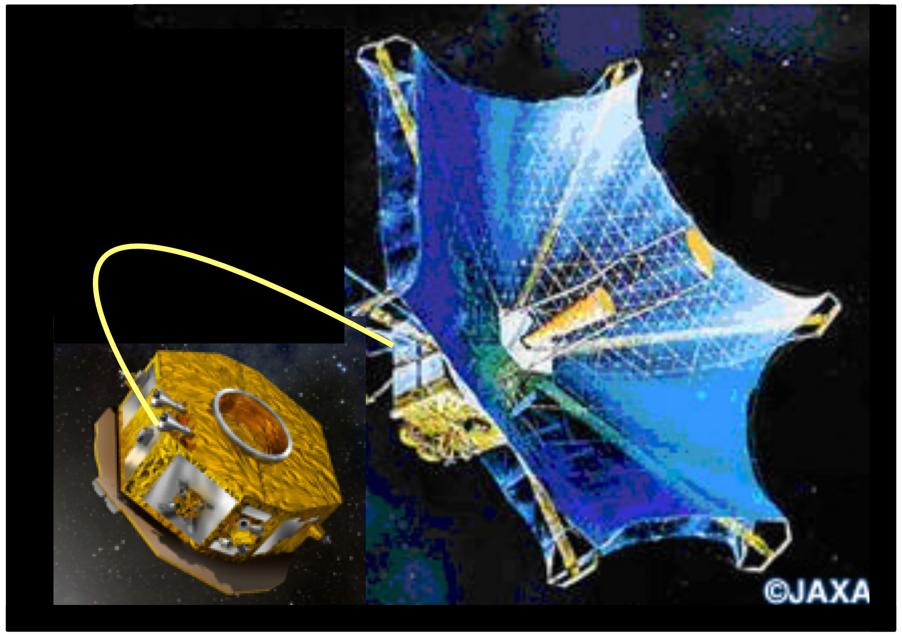


Table 4: Required improvement in subsystems to improve overall Doppler sensitivity by a factor of 10 relative to Cassini-era performance.

Noise source	Comment (σ_y at $\tau = 1000$ s)	Required improvement
Frequency standard	currently FTS + distribution $\simeq 8 \times 10^{-16}$	$\simeq$ 8X
Ground electronics	currently $\simeq 2 \times 10^{-16}$	$\simeq$ 2X
Tropospheric scintillation	currently $\simeq 10^{-15}$ under favorable conditions	$\simeq$ 10X
Plasma scintillation	Cassini-class radio system probably adequate for calibration to $\simeq 10^{-16}$	$\simeq$ 1X
Spacecraft motion	currently $\simeq 2 \times 10^{-16}$	$\simeq$ 2X
Antenna mechanical	currently $\simeq 2 \times 10^{-15}$ under favorable conditions	$\simeq$ 20X

atomic clock ▶ **Opt. Lattice Clock**

troposphere ▶ **in space**

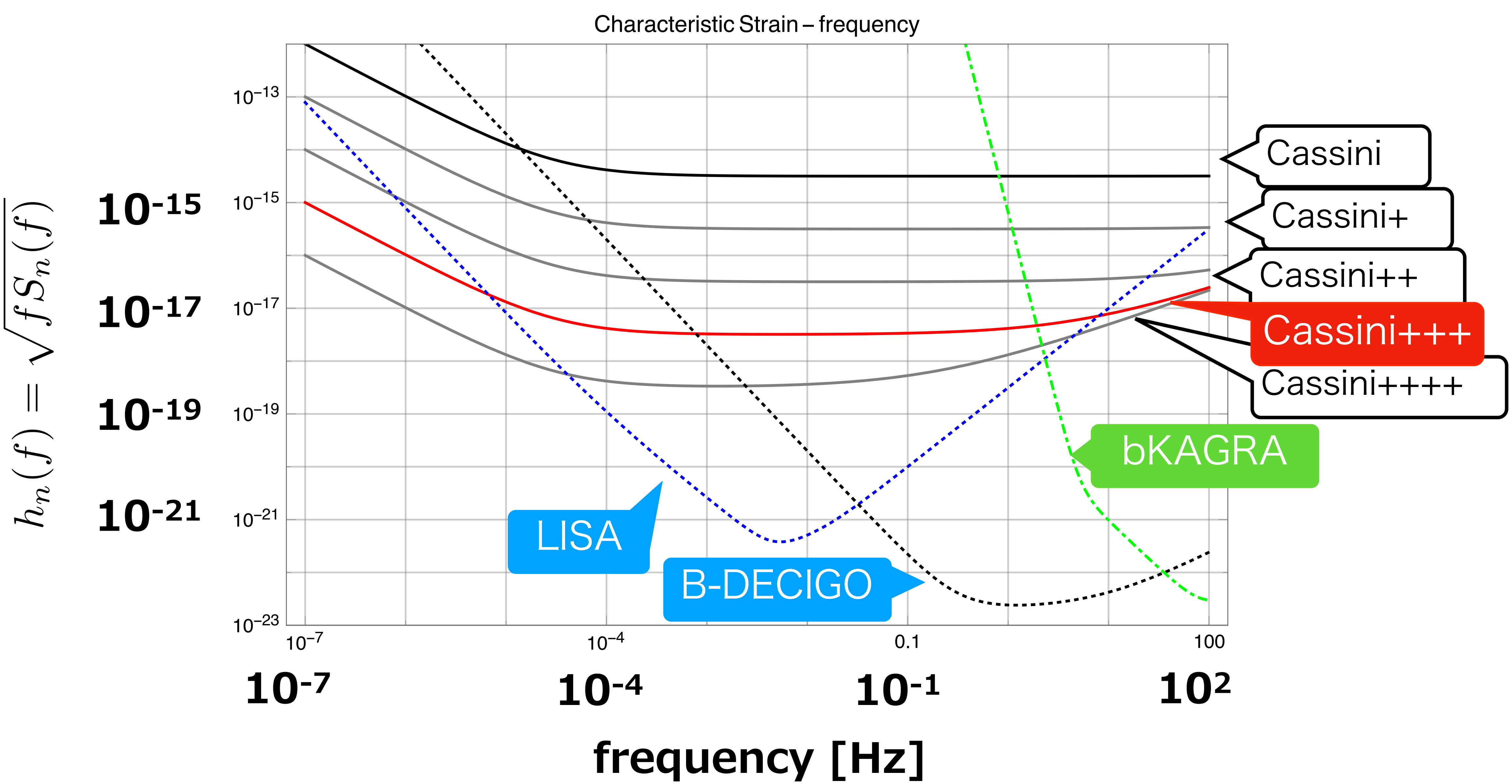
plasma ▶ **light transmission**

rad. pressure ▶ **solar panel parasol**

control technology

2. Improvement of Doppler sensitivity（3）

With current technologies, we can obtain 3-order less than Cassini !



sensitivity f^{-1}
satellite control perturbation

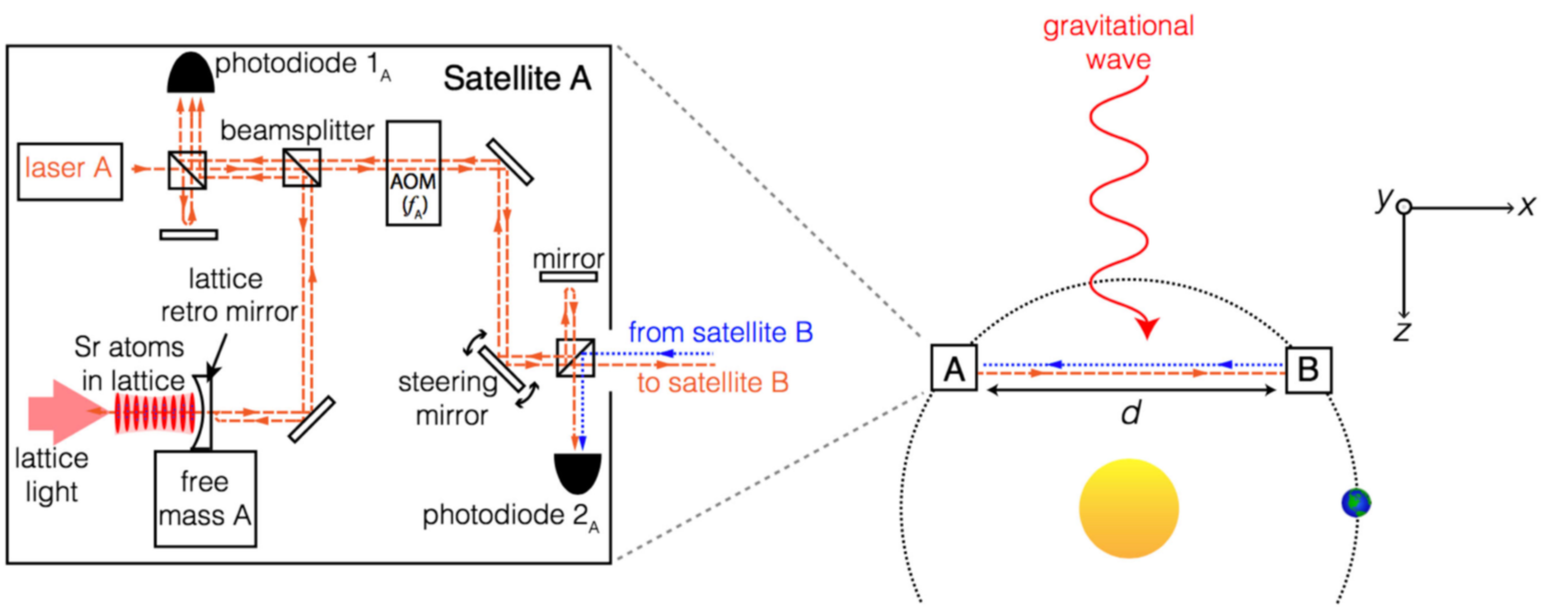
sensitivity $f^{2/3}+10^{-18}$
Opt. Lattice Clock limitation

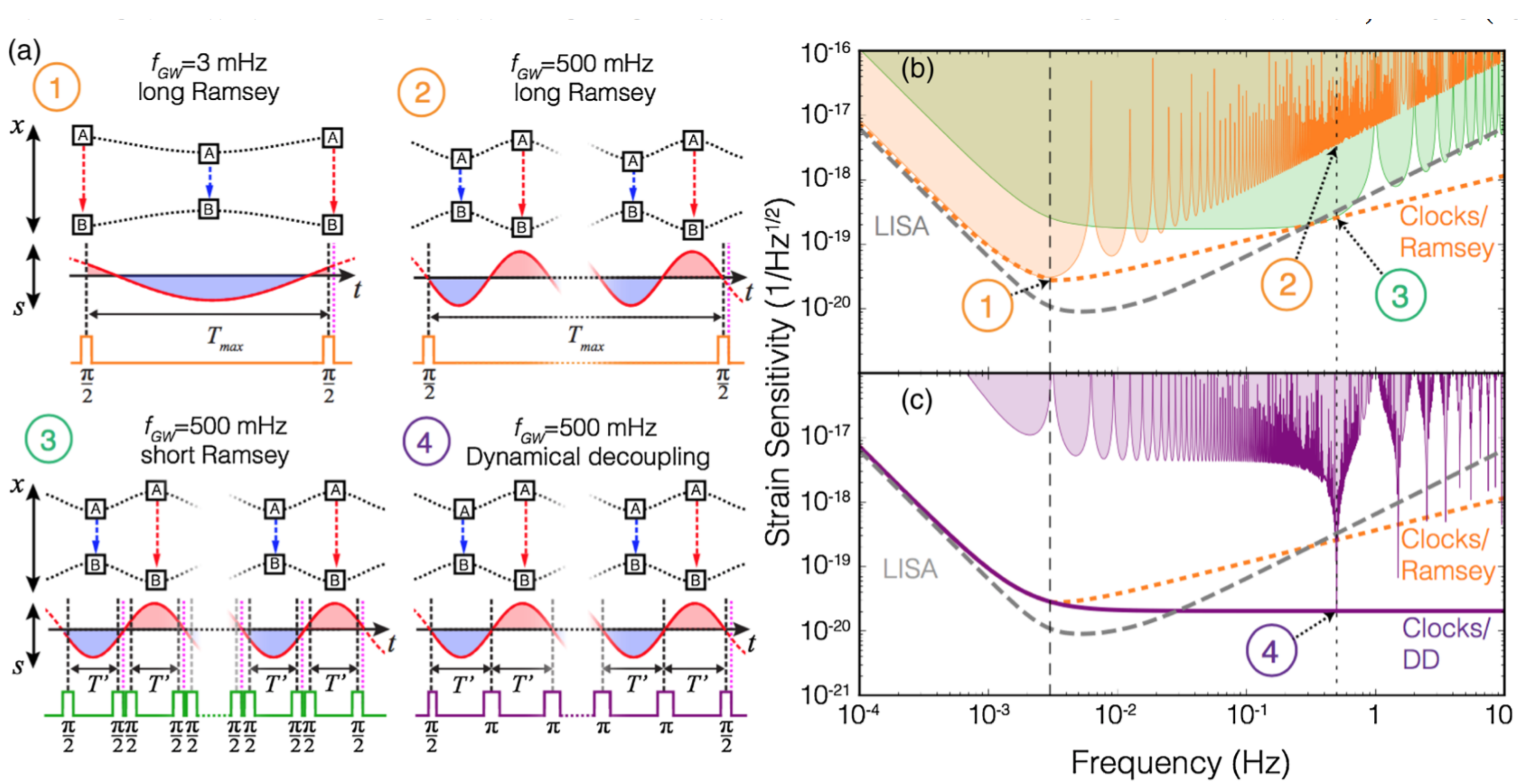
3. Previous proposals（Kolkowitz+ 2016)

PHYSICAL REVIEW D **94,** 124043 (2016)

Gravitational wave detection with optical lattice atomic clocks

S. Kolkowitz,[1,*] I. Pikovski,[2,3] N. Langellier,[2] M. D. Lukin,[2] R. L. Walsworth,[2,4] and J. Ye[1,†]

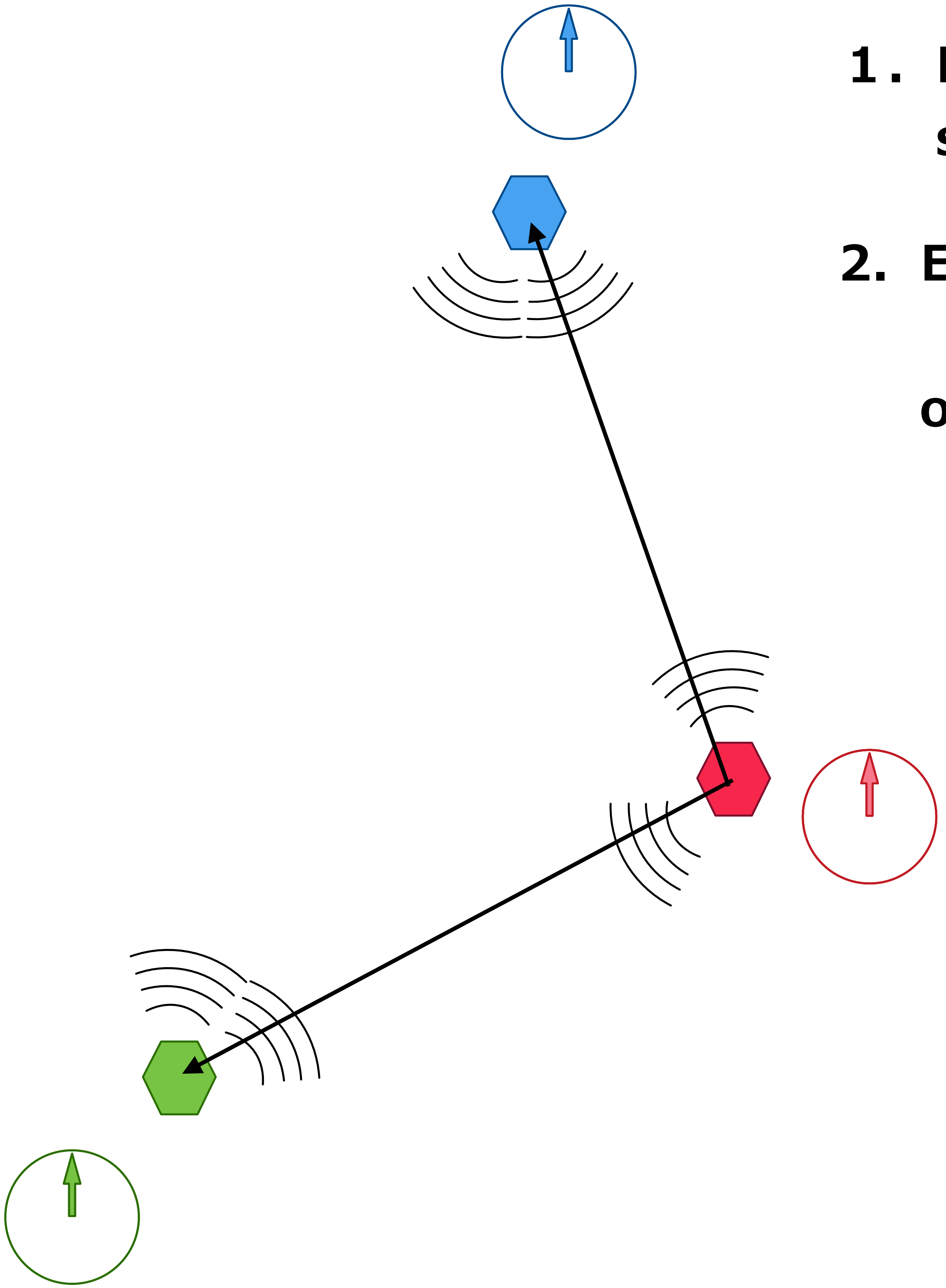




Kolkowitz +
PRD94(2016)124043
3 mHz or 30 mHz –10 Hz
5x10⁷ km or 5x10⁶ km
2 satellites, laser link
compare freq. w Opt Lattice Clock
drag-free flight
Doppler shift with Laser beam

see also
Loeb, Maoz, 1501.00996
Vutha, New J. Phys. 17, 063030

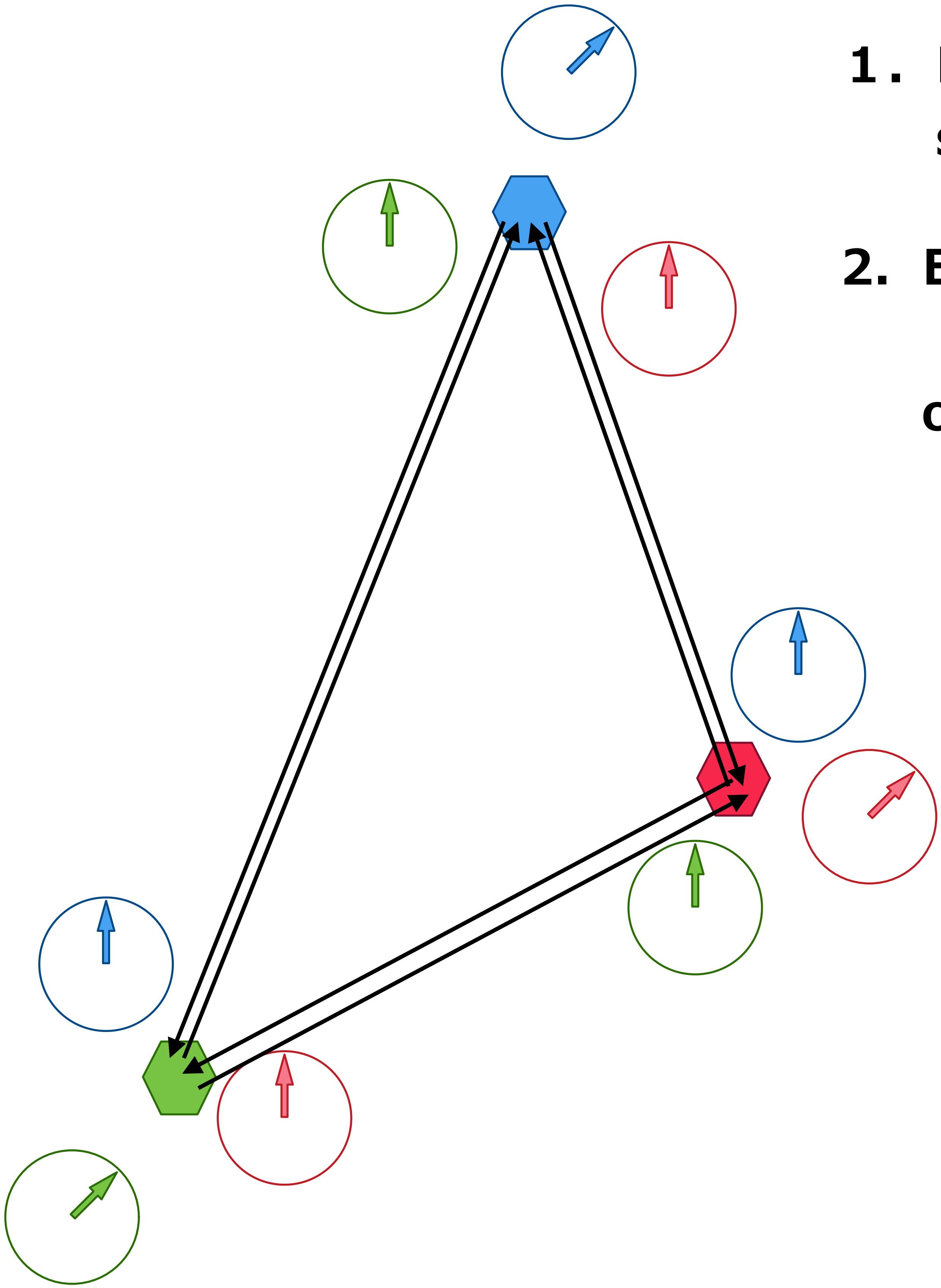
3. Principle of GW detection



1. Each satellite has Opt Lattice Clock, send out each time to others.

2. Each satellite recognizes **direction・distance・velocity** of others, and we know all of them.

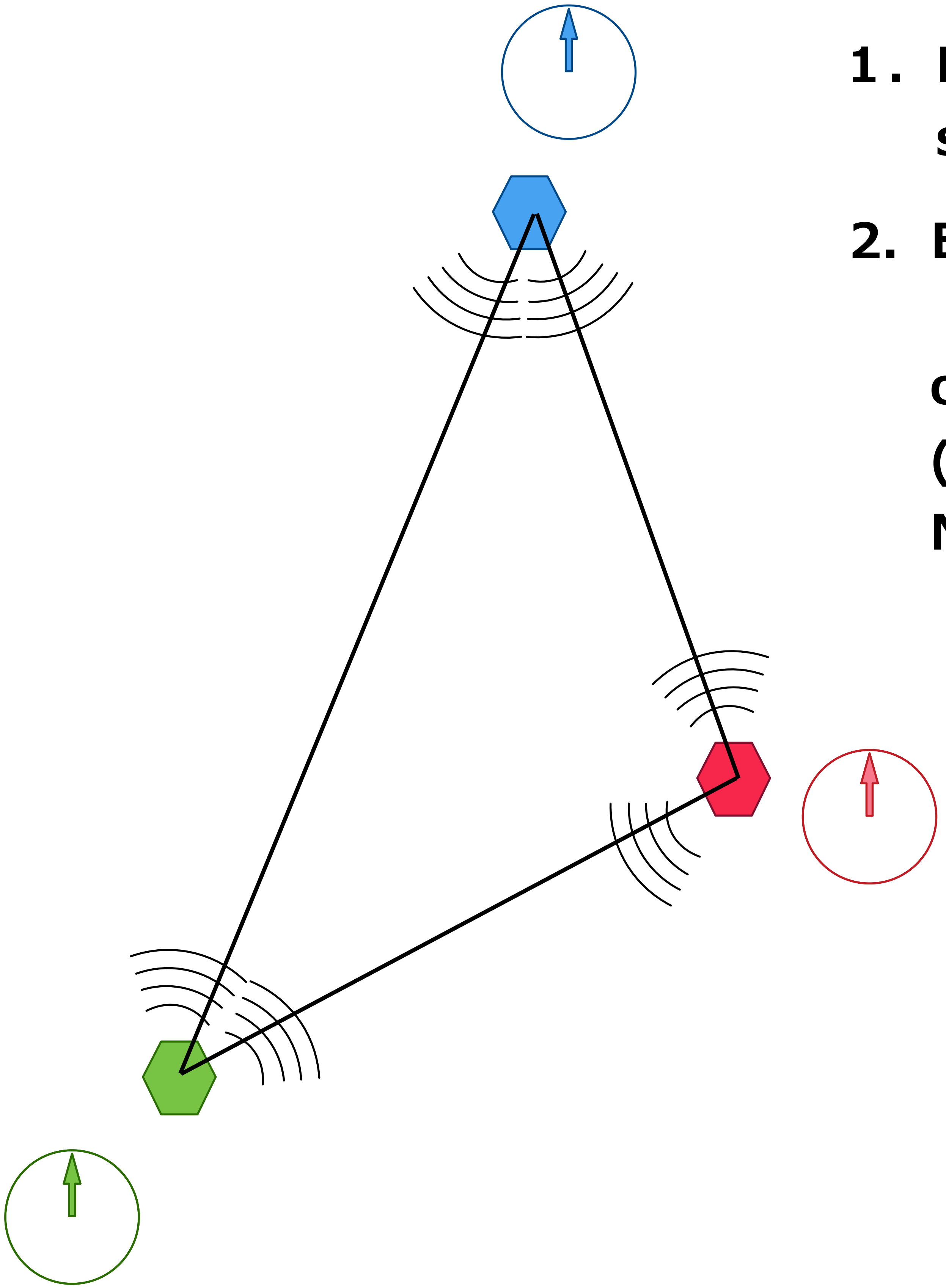
3. Principle of GW detection



1. Each satellite has Opt Lattice Clock, send out each time to others.

2. Each satellite recognizes direction・distance・velocity of others, and we know all of them.

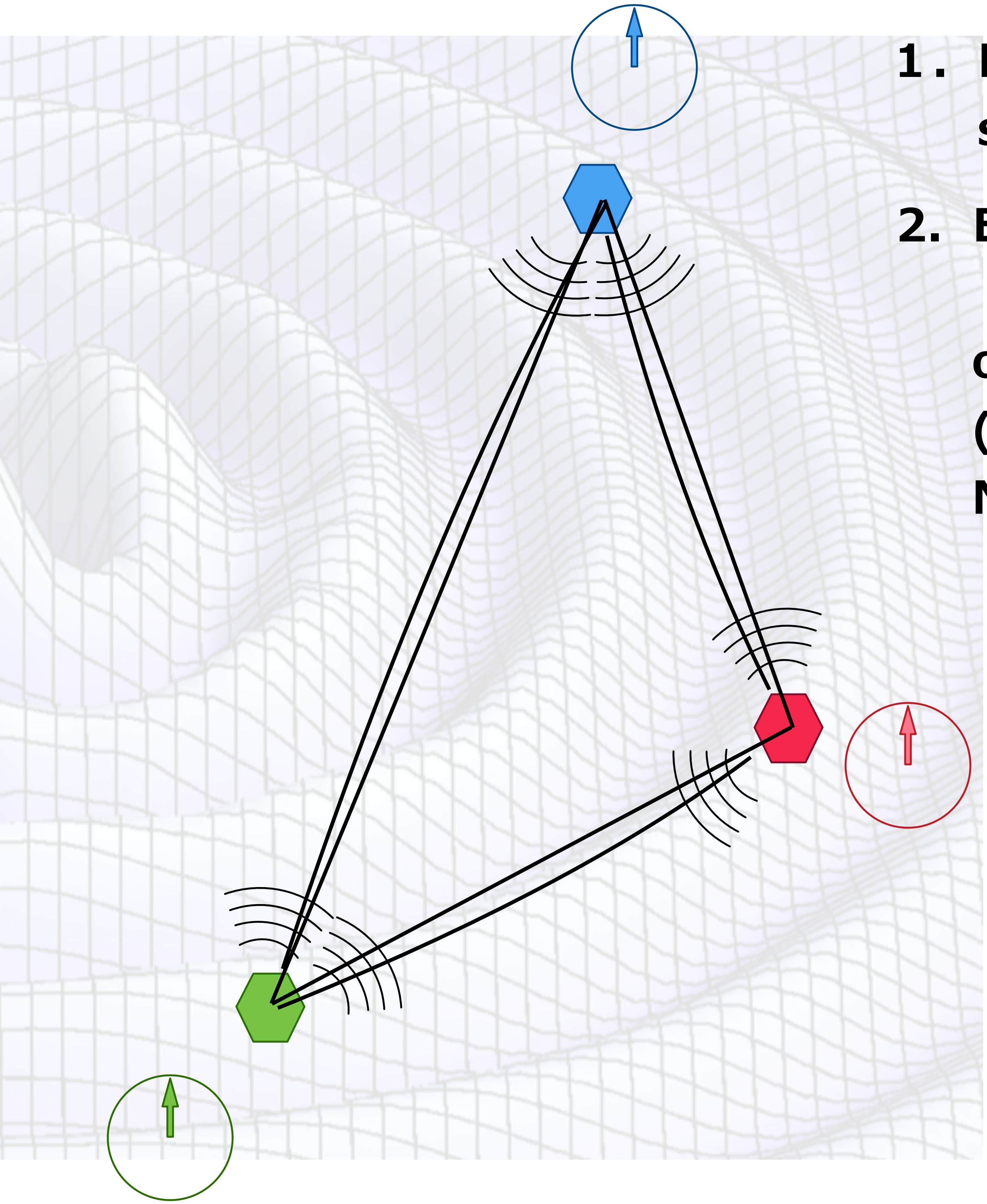
3. Principle of GW detection



1． **Each satellite has Opt Lattice Clock, send out each time to others.**

2. **Each satellite recognizes**
   direction・distance・velocity
   of others, and we know all of them (including the potentioal of the Sun.)
   Note: effects of planets are *O*(month).

3. Principle of GW detection



1. Each satellite has Opt Lattice Clock, send out each time to others.

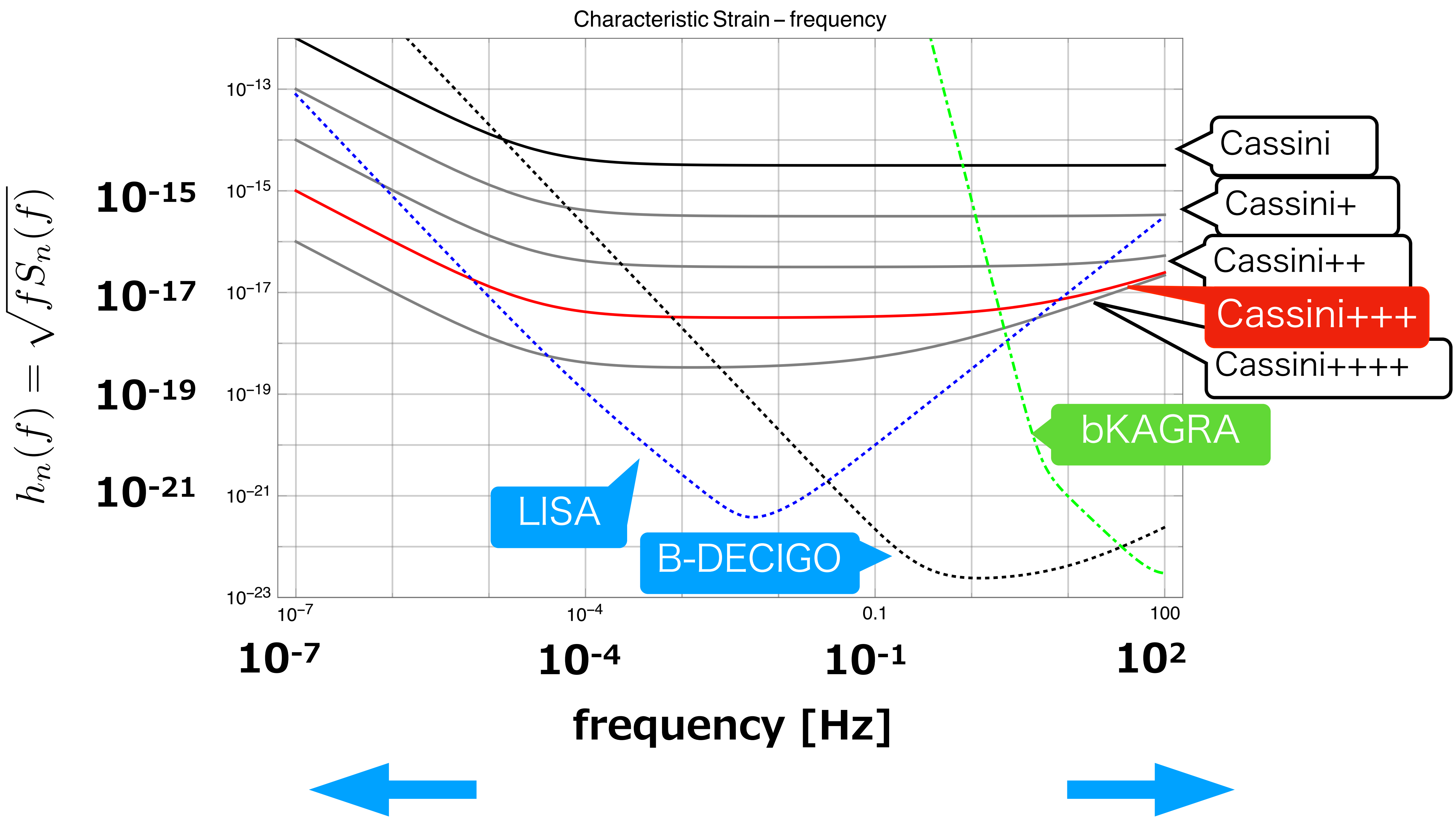
2. Each satellite recognizes
   direction · distance · velocity
   of others, and we know all of them (including the potentioal of the Sun.)
   Note: effects of planets are O(month).

3. When GW passes, we know its differences.

   If the events are ～10s (/yr), then we can calibrate them well.

2. Improvement of Doppler sensitivity（3）

With current technologies, we can obtain 3-order less than Cassini !

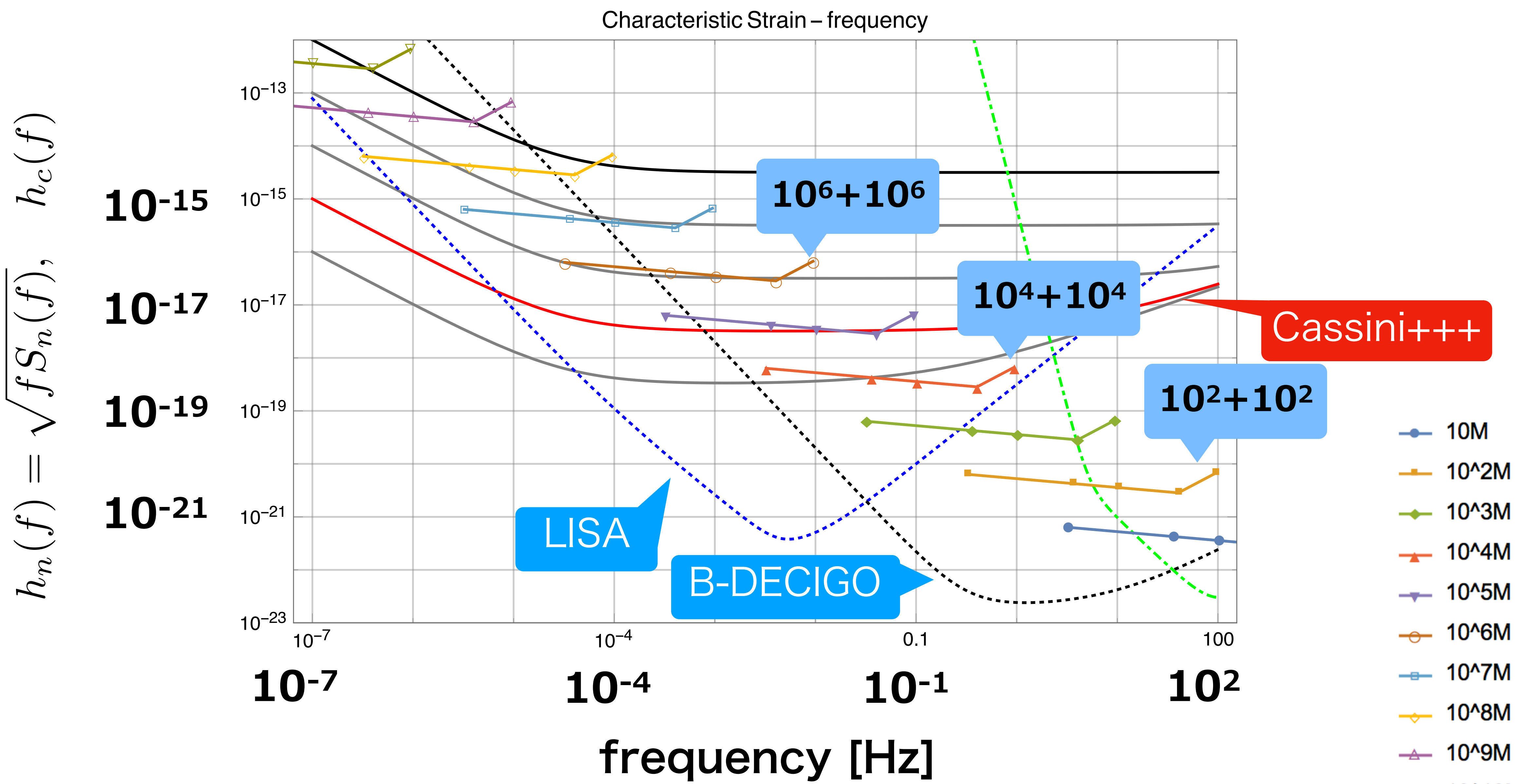


sensitivity f^{-1}
satellite control perturbation

sensitivity $f^{2/3}+10^{-18}$
Opt. Lattice Clock limitation

3. GW obs. using Optical Lattice Clocks : target sources

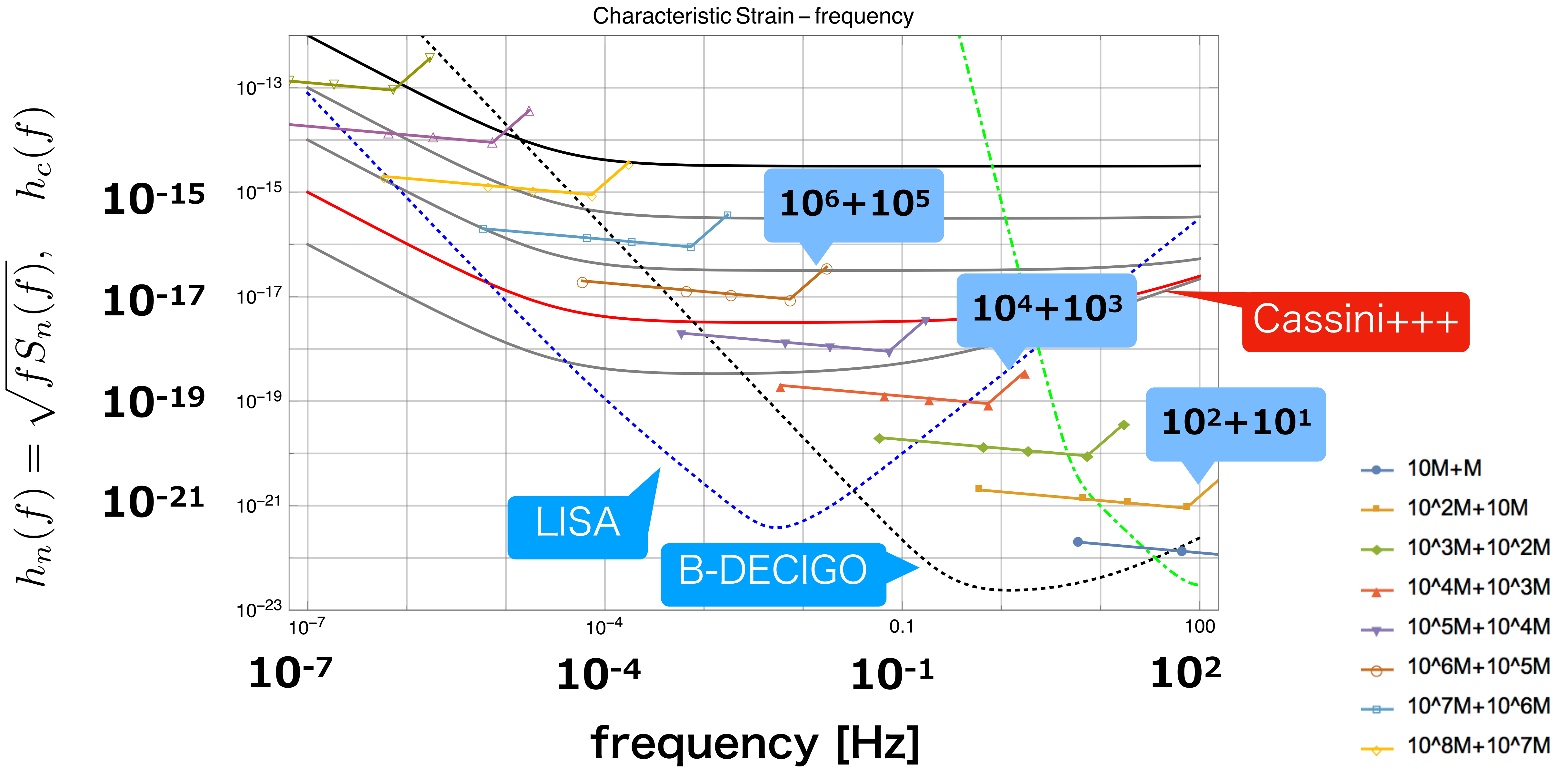
equal-mass Binary BH inspiral at 1Gpc



3. GW obs. using Optical Lattice Clocks : target sources

unequal-mass Binary BH inspiral at 1Gpc

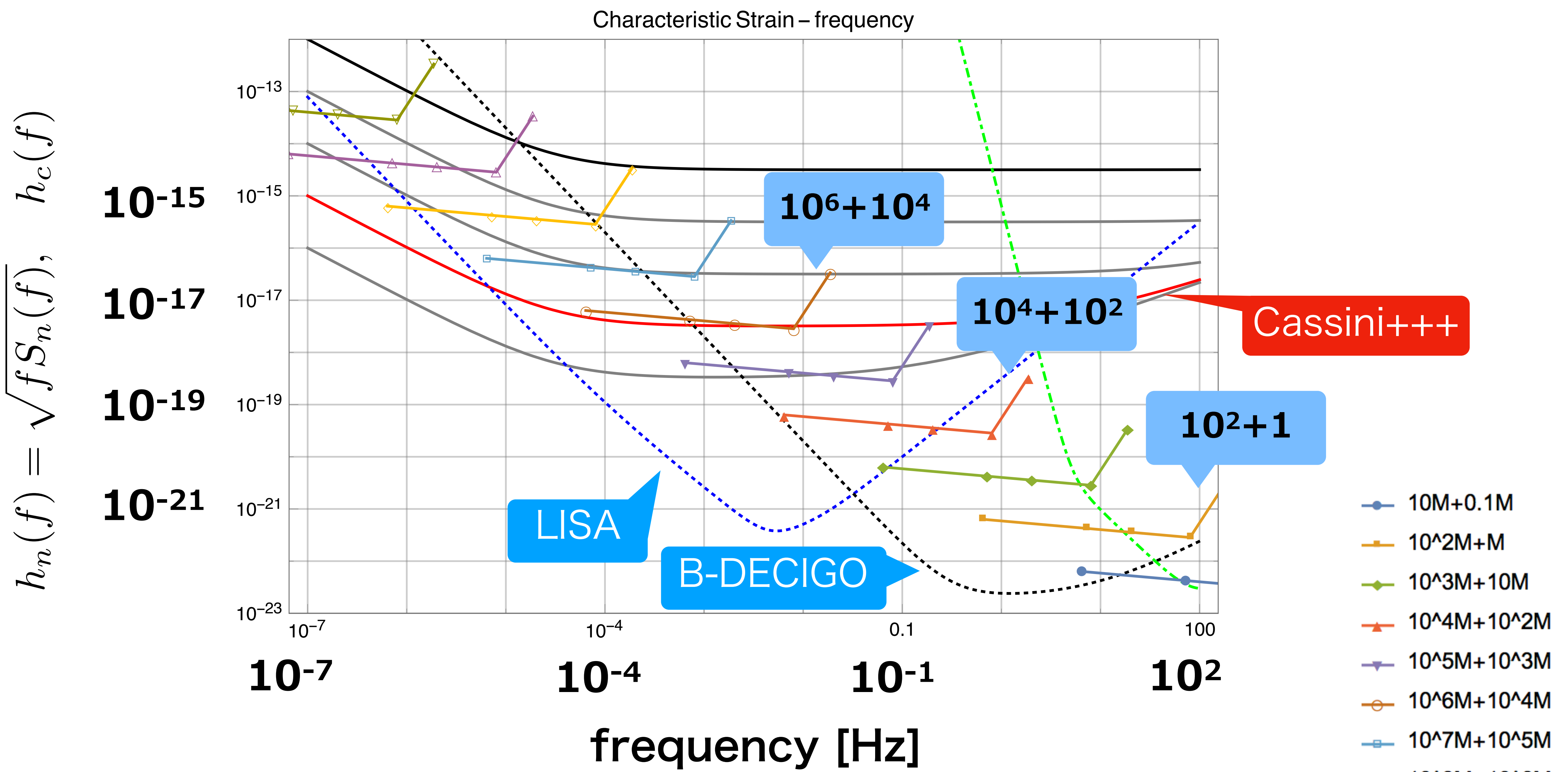
mass ratio q=0.1



3．GW obs. using Optical Lattice Clocks : target sources

unequal-mass Binary BH inspiral at 1Gpc

mass ratio q=0.01

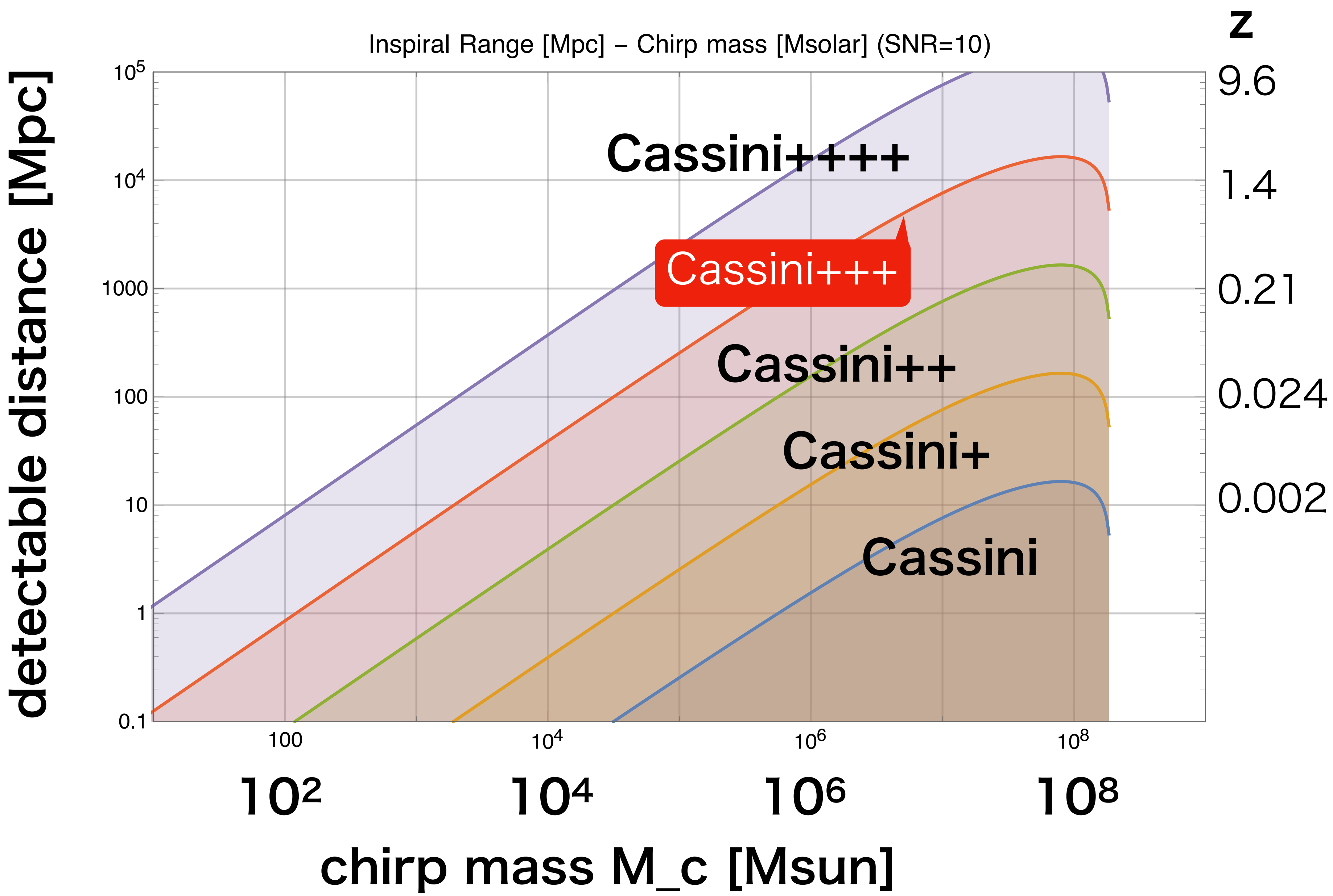


1 day=8.6x10^4 s

1 month=2.6x10^6 s

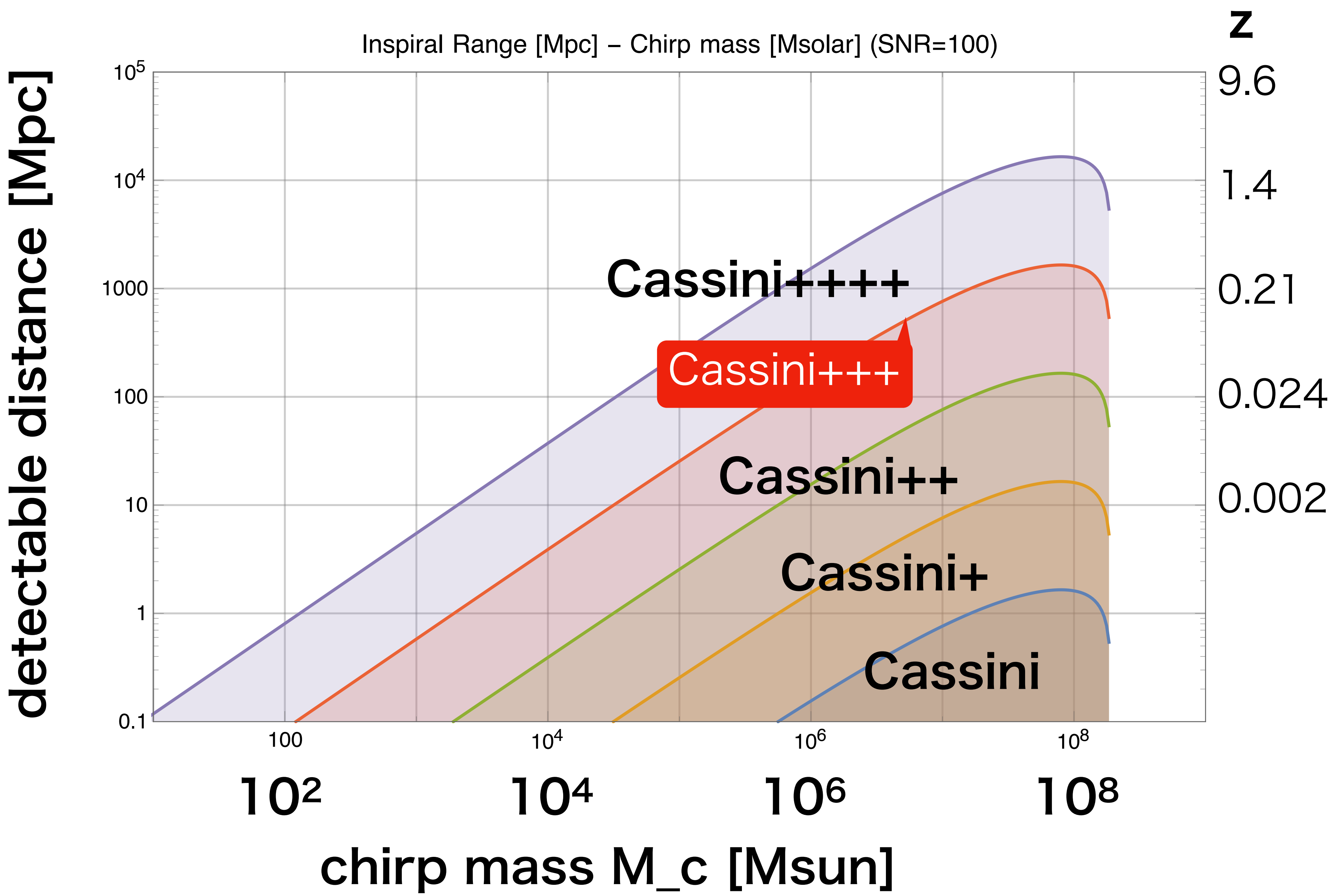
3．GW obs. using Optical Lattice Clocks : detectable distance

S/N=10



3． GW obs. using Optical Lattice Clocks : detectable distance

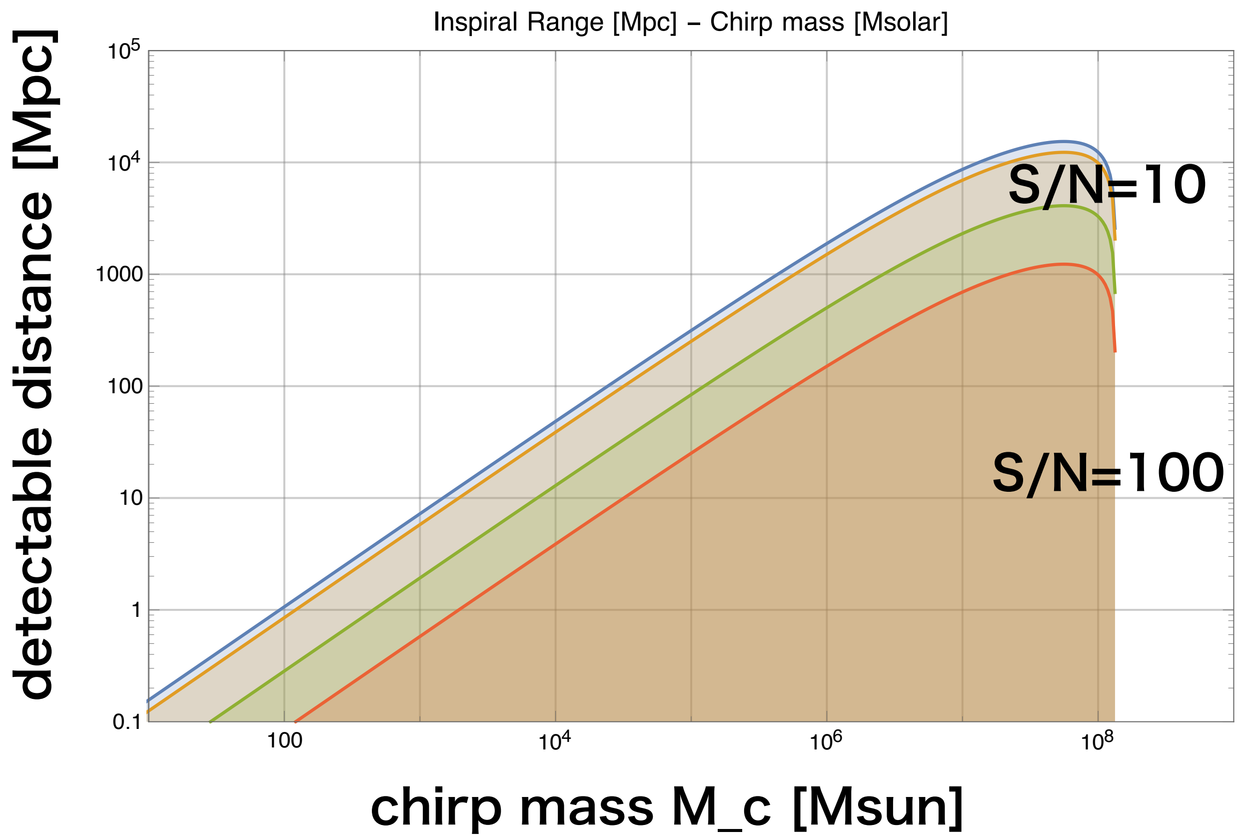
S/N=100



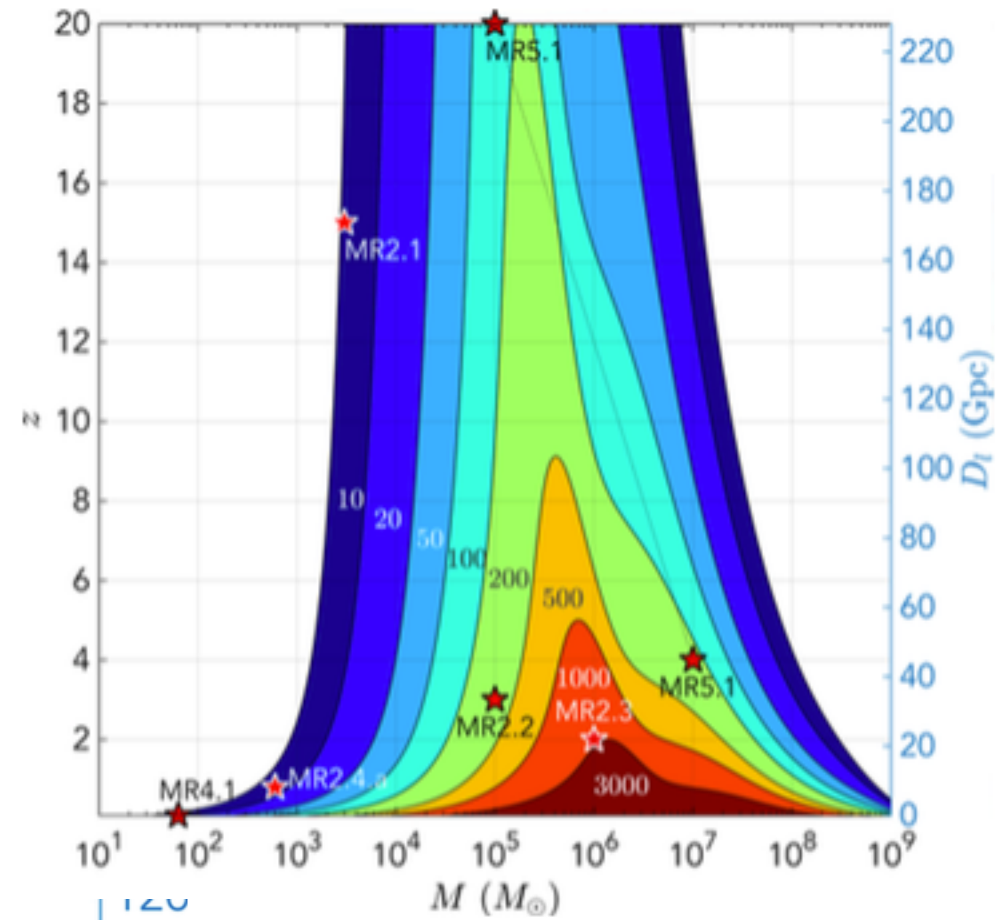
3. GW obs. using Optical Lattice Clocks : detectable distance q=0.2

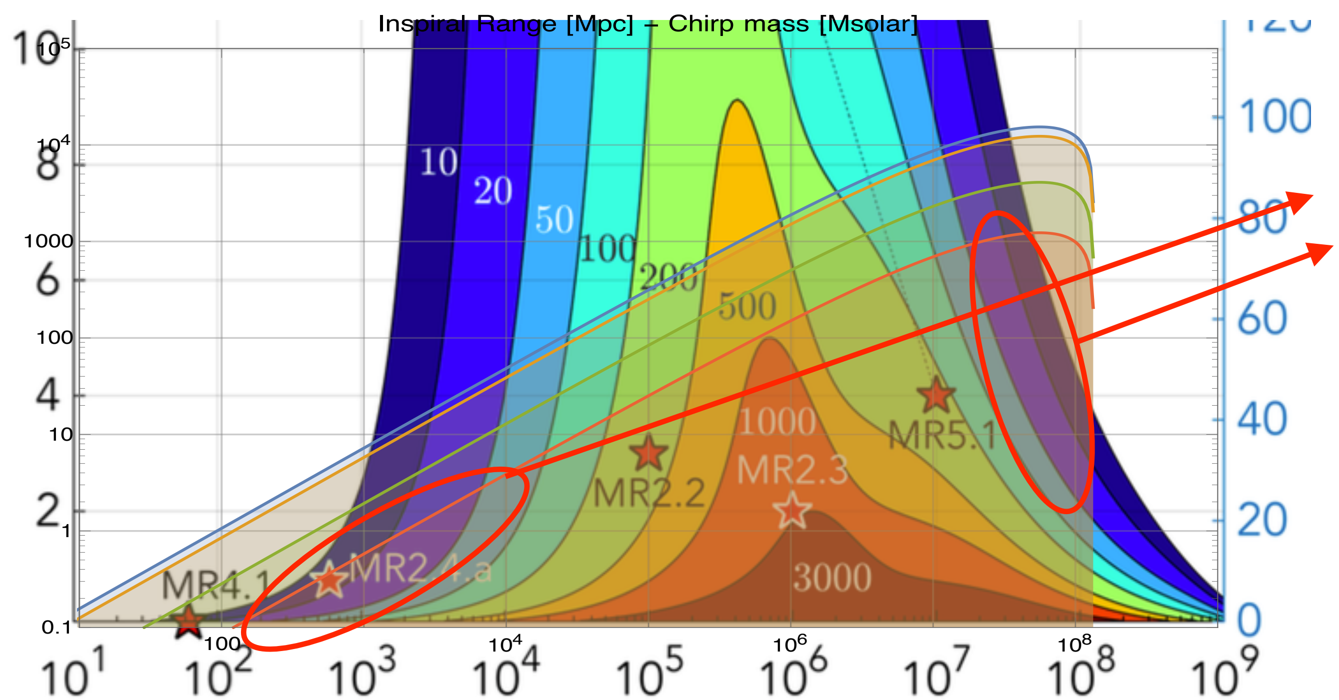
mass ratio q=0.2

Cassini+++



LISA 1702.00786



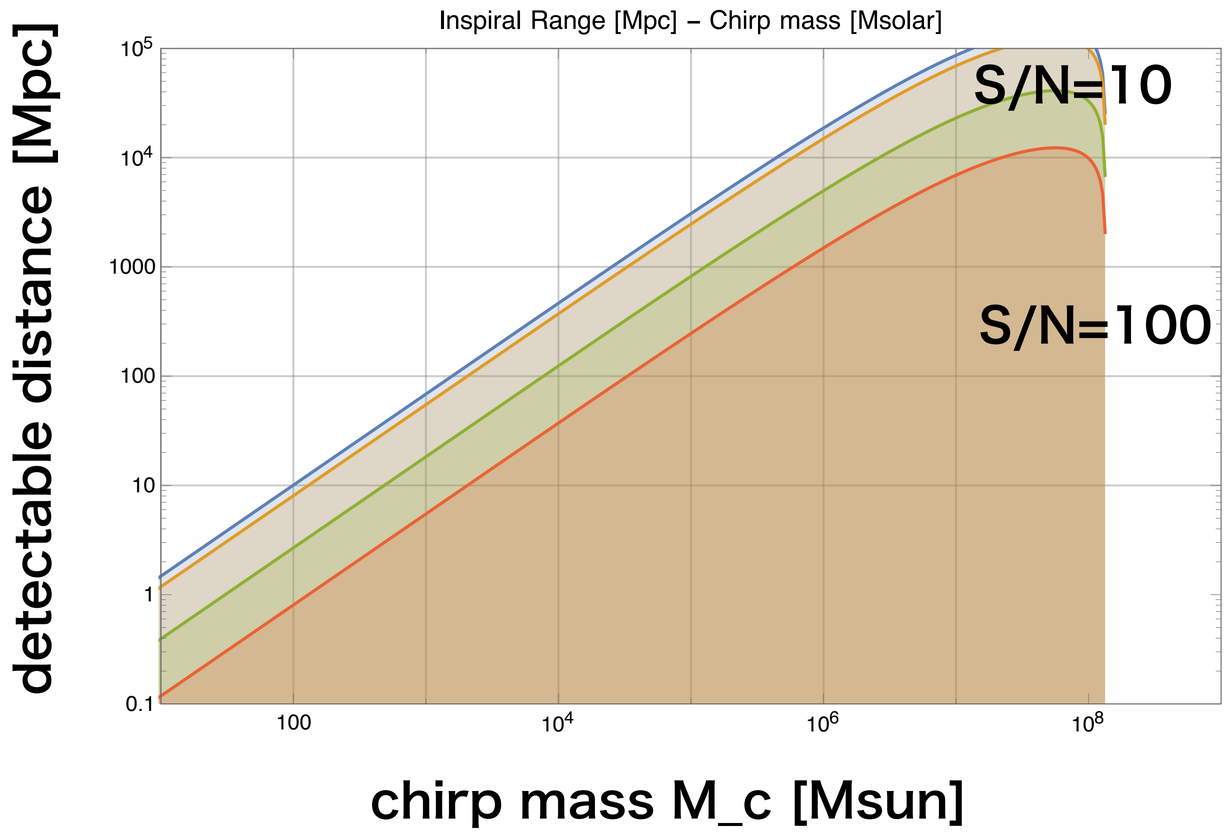


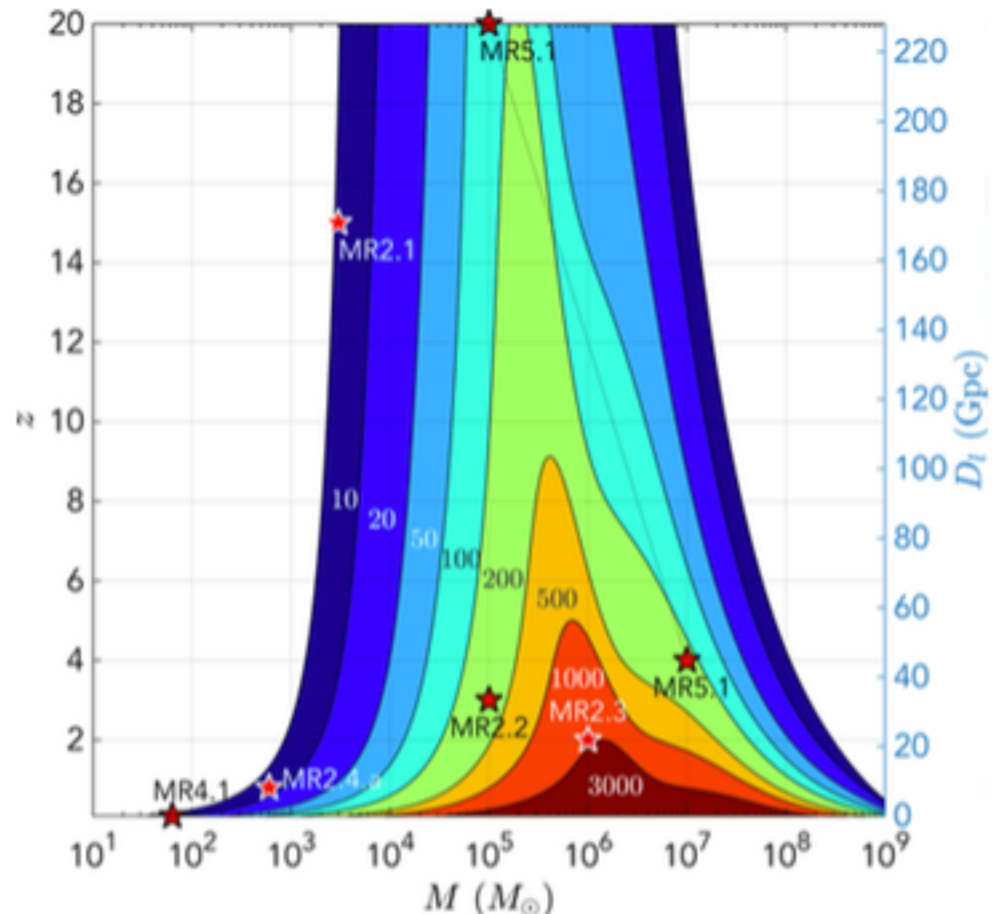
Cassini+++
is better than LISA

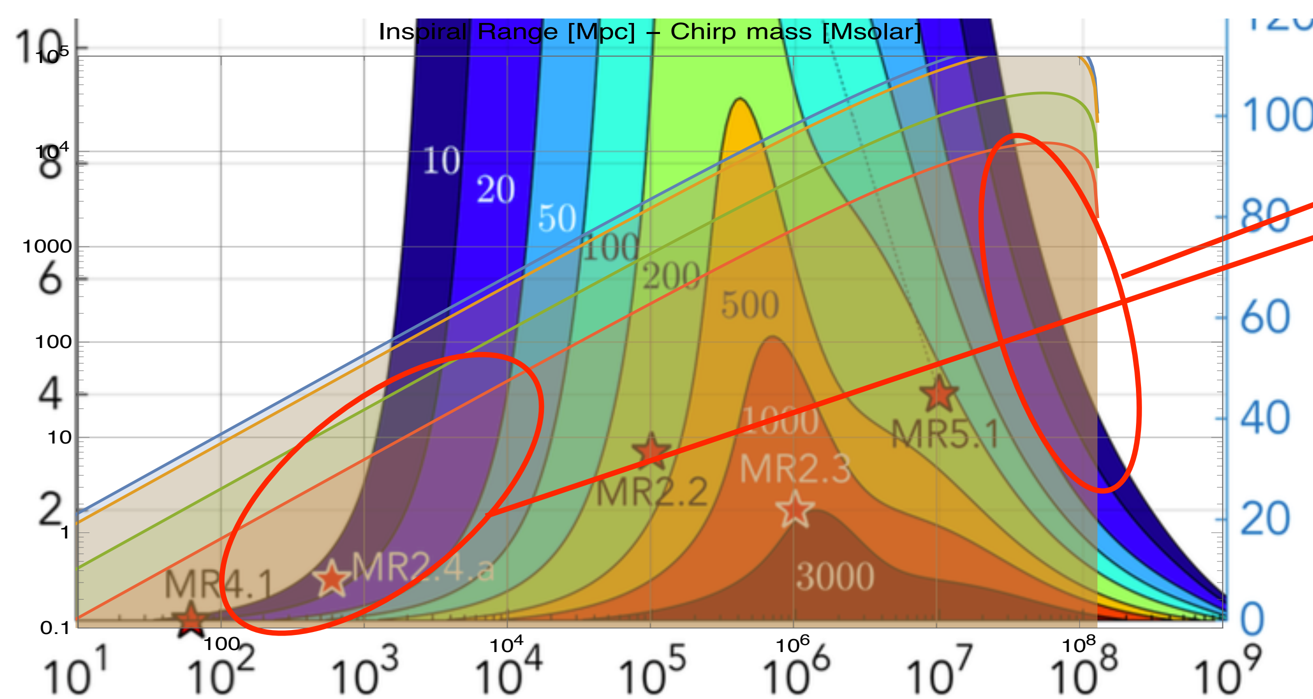
3. GW obs. using Optical Lattice Clocks : detectable distance q=0.2

mass ratio q=0.2 Cassini++++

LISA 1702.00786



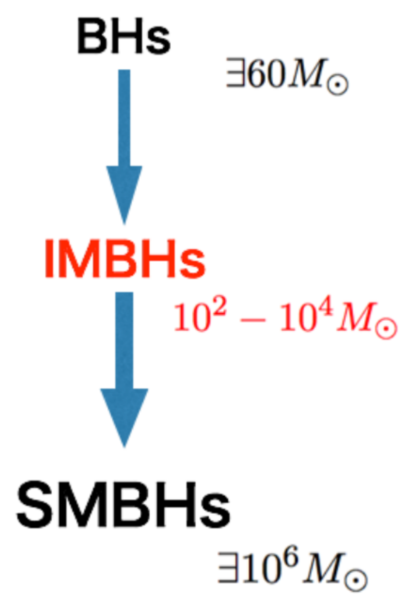




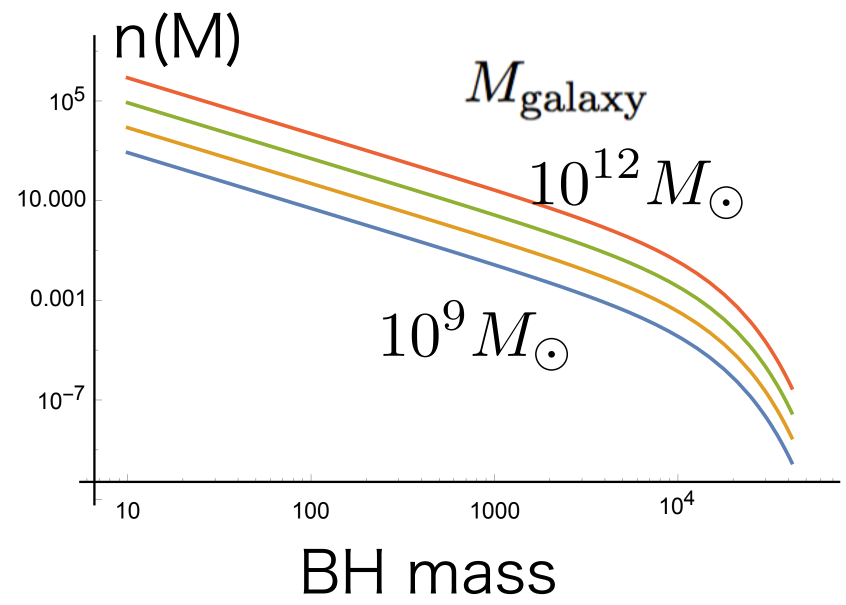
Cassini+++
is better than LISA

4. SMBH formation model : IMBHs' hierarchical mergers

HS, Kanda, Ebisuzaki, ApJ, 835 (2017) 276 [arXiv:1610.09505]

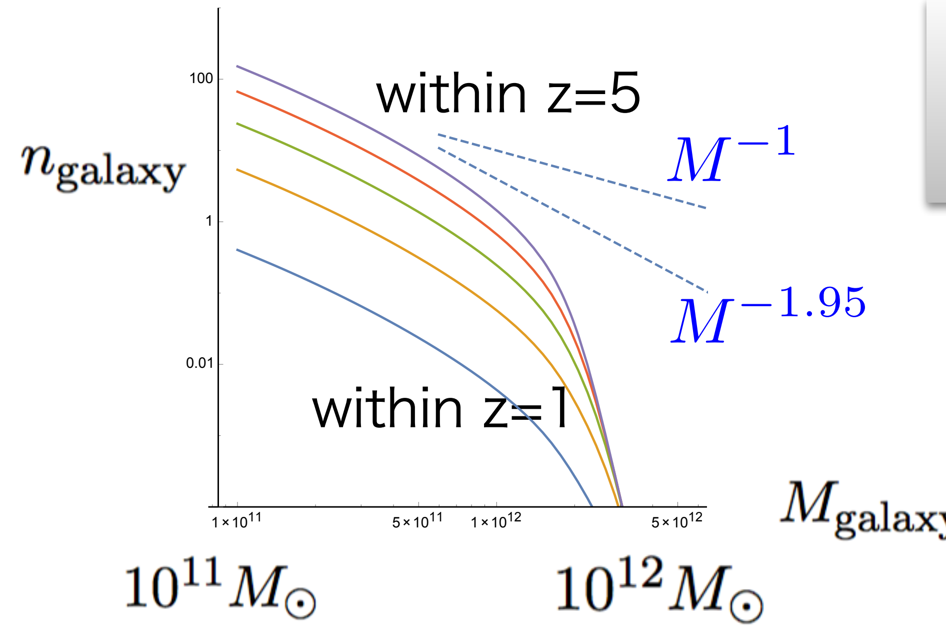


How many BHs in a Galaxy?

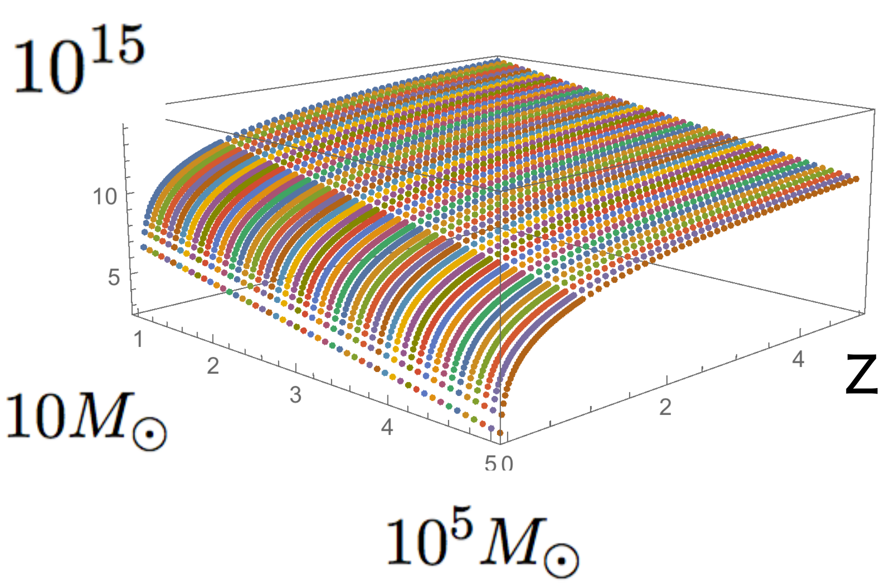


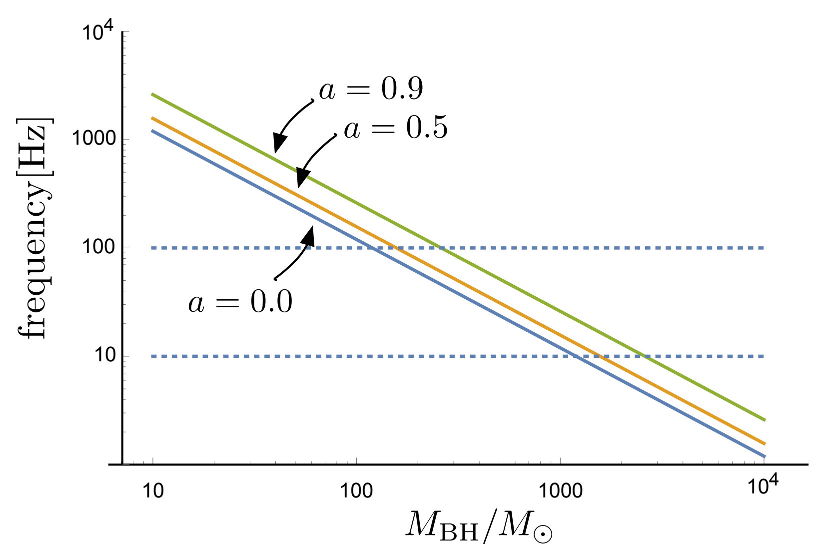
How many Galaxies in the Universe?

z<3
10^{12}



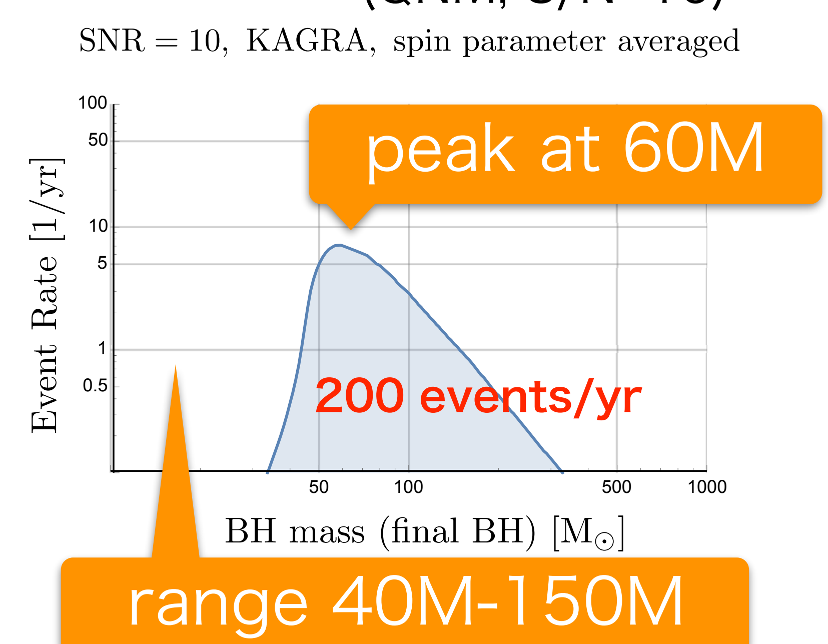
How many BH mergers in the Universe?



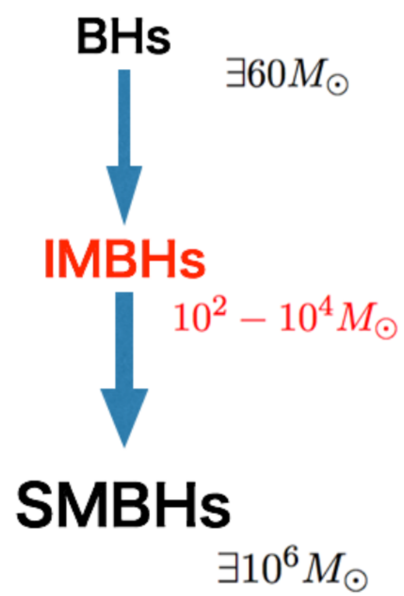


Event Rates at bKAGRA

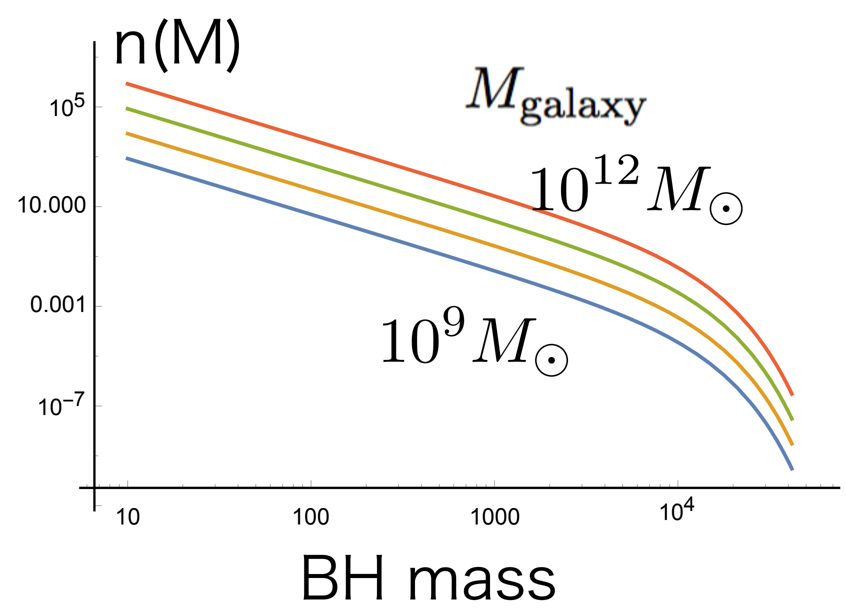
(QNM, S/N=10)



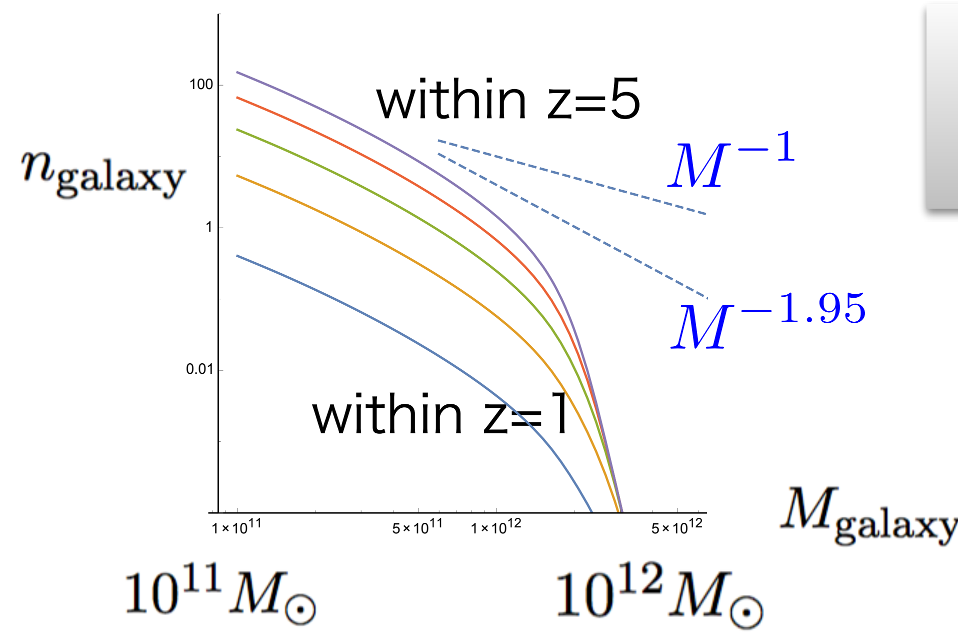
4. SMBH formation model : IMBHs' hierarchical mergers



How many BHs in a Galaxy?

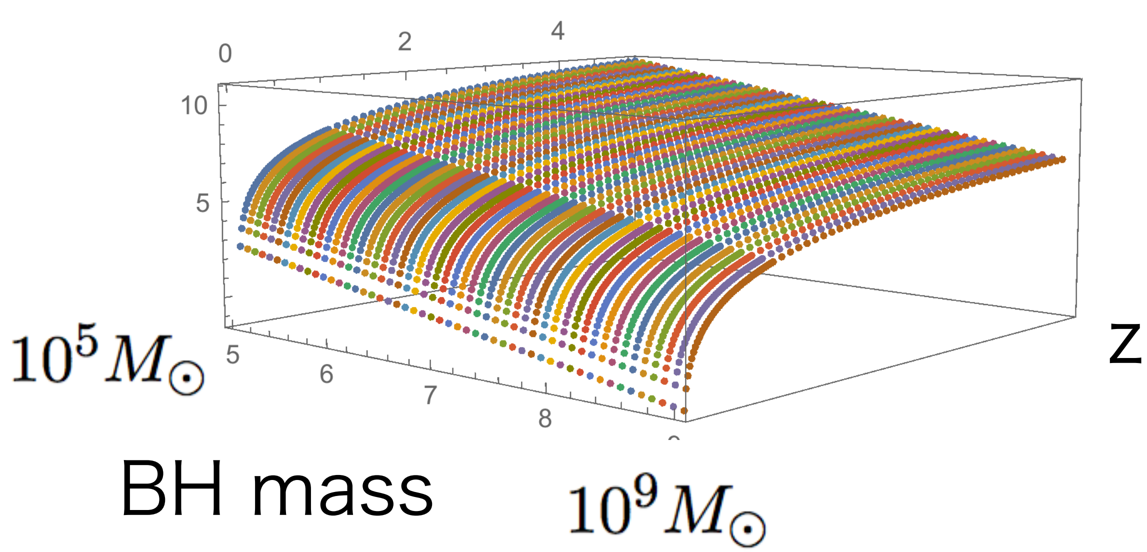


How many Galaxies in the Universe?



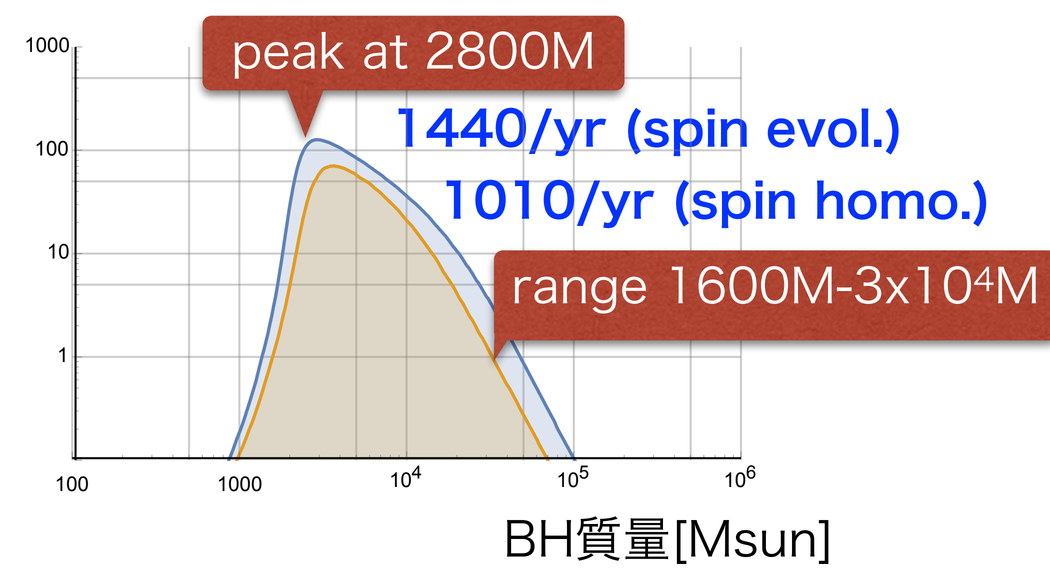
z<3
10^{12}

How many BH mergers in the Universe?



Event Rates at B-DECIGO

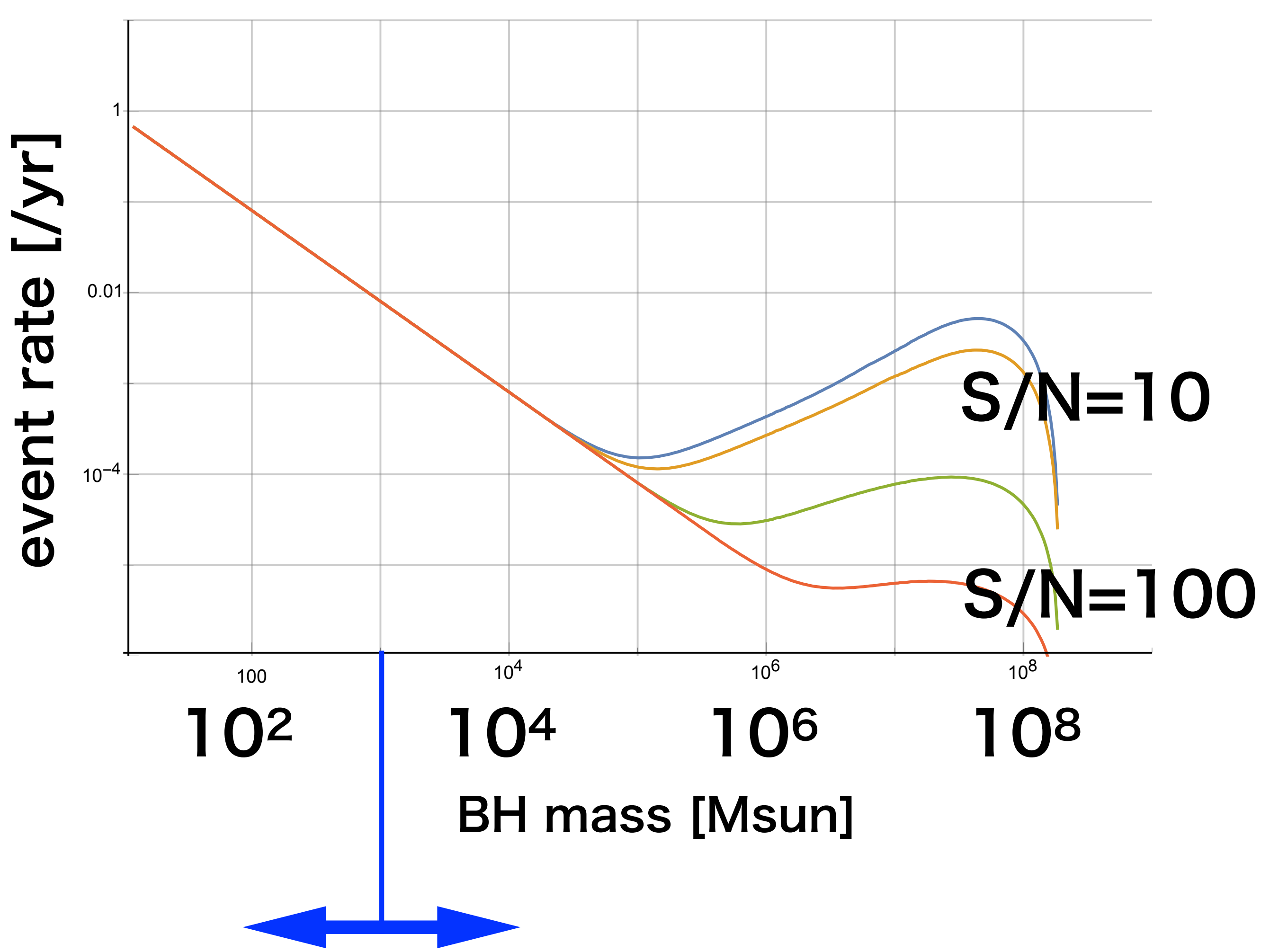
(QNM, S/N=30)



4. SMBH formation model : IMBHs' hierarchical mergers

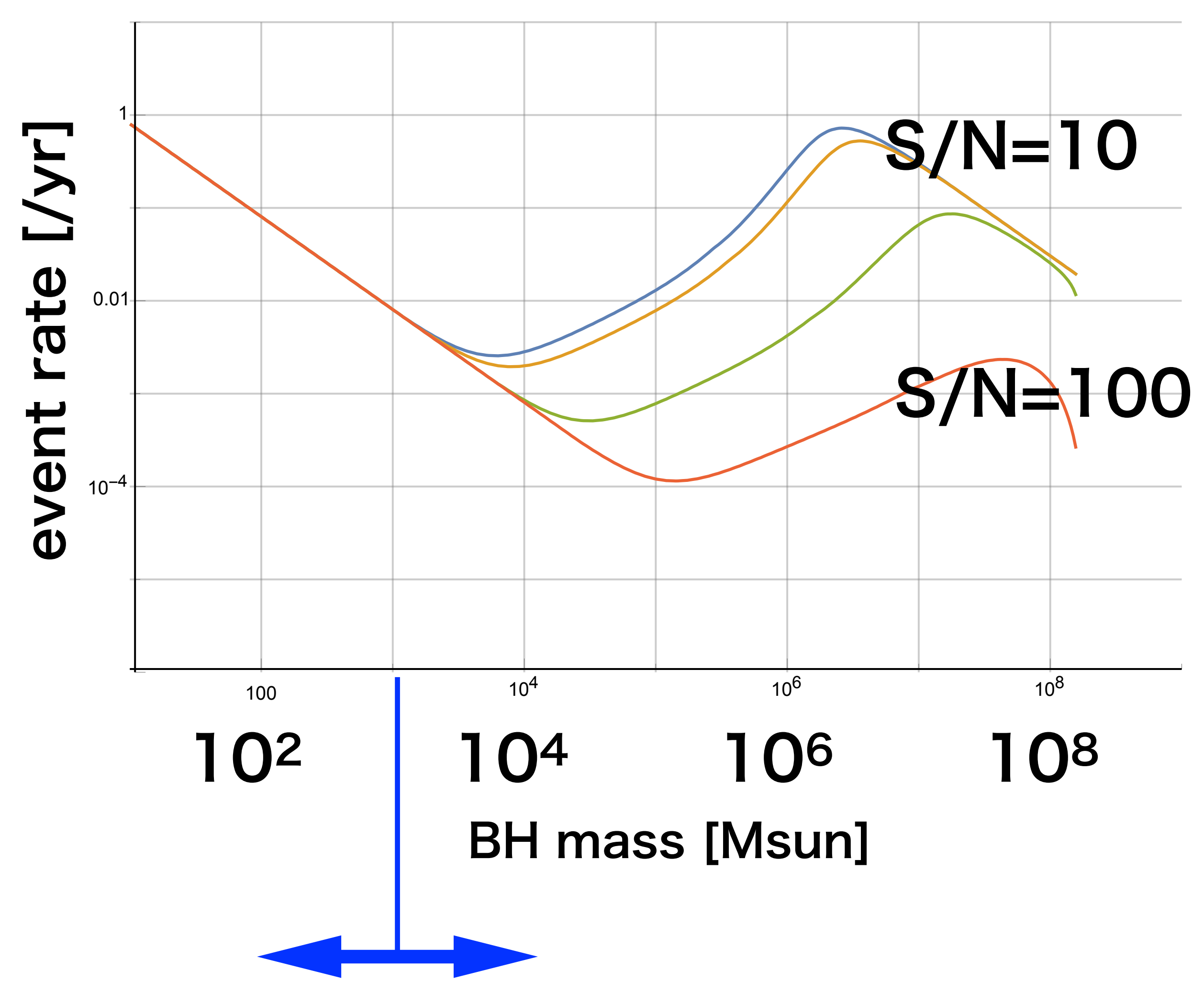
Event Rate

Cassini+++



19.1/yr 0.35/yr for S/N=10

Cassini++++



19.2/yr 29.8/yr for S/N=10

Summary

LISA (ESA/NASA)	B-DECIGO ⇒ DECIGO (Japan)	Kolkowitz +	Our Proposal
mHz range	0.1Hz range	3 mHz or 30 mHz −10 Hz	0.1 mHz —1 Hz
3 satellites at L4 of Sun-Earth	around earth 2000km 3 sattelites ⇒ Sun orbit	2 satellites	Sun-Earth L1-L4-L5
2.50×10^6 km	100 km ⇒ 1000 km	5×10^7 km or 5×10^6 km	1 AU
		laser link	light or radio link
light transponder	**Fabry-Perot interferometer**	**compare freq. w Opt Lattice Clock**	**monitor time w Opt Lattice Clocks**
drag-free flight	**drag-free flight**	**drag-free flight**	**no drag-free**
Doppler tracking with Laser beam	same as ground interferometer	Doppler shift with Laser beam	Doppler tracking
robust to accel. noise	**robust to shot-noise**		**available at current tech**

⭐Cassini's Doppler tracking (2001-2002) can be improved 3-order mag. with current technologies
Opt Lattice Clocks, 3 satellites in space, Solar panel parasol
⭐ "Cassini+++", some range is better than LISA sensitivity
⭐ "Cassini+++", stellar-mass BH merger prediction 20 events/yr
"Cassini++++", + IMBH inspiral 30 events/yr

backup

原子時計を宇宙空間に設置する計画

The Space-Time Explorer and QUantum Equivalence Principle Space Test (STE-QUEST)
ESA, 2024年打ち上げ予定．地球周回軌道にルビジウム同位体原子干渉計．等価原理検証など．

Primary Atomic Reference Clock in Space (PARCS)
NASAが2008年にセシウム原子時計をISSに搭載しようと計画したものだが，Bushの政策Vision for Space Exploration (VSE) により中止．

Galileo Global Navigation Satellite System
European GNSS Agency とESAが2019年完成目指して，構築しているヨーロッパ発の非軍事GPS．各衛星は，水素メーザーとルビジウム原子時計を持つ．

Atomic Clock Ensemble in Space (ACES)
ESAによる計画．　ISSに，セシウム原子時計(PHARAO)と水素メーザー(SHM) の２つの原子時計を設置するもの．
2018年に日本のHTVによって打ち上げ予定．

Deep Space Atomic Clock (DSAC)
NASA JPLが計画する，水銀イオン原子時計を用いて，ナビゲーションの精度を高めようとする計画．
2018年，SpaceX Falcon で地球周回軌道に打ち上げ予定．

光格子時計を宇宙空間に設置する計画

space optical clock mission (SOC)
ESA. ISSに光格子時計を搭載して，地球重力赤方偏移，太陽重力，等価原理検証を目指そうとするもの．
2010年からスタート．10年後（もうすぐ？）にISS搭載を目指す．