PB21

INO: Interplanetary Network of Optical Lattice Clocks

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Outline & Summary

The new technique of measuring frequency by optical lattice clocks now approaches to the relative precision of $(\Delta f/f)=O(10^{-18})$.
We propose to place such precise clocks in space and to use Doppler tracking method for detecting low-frequency gravitational wave below 1 Hz.
Our idea is to locate three satellites at one A.U. distance (say at L1, L4 & L5 of the Sun-Earth orbit), and apply the Doppler tracking method by communicating “the time” each other. Applying the current available technologies, we obtain the sensitivity for gravitational wave with three or four-order improvement ($h_n \sim 10^{-17}$ or 10^{-18} level in 10^{-5} Hz -- 1 Hz) than that of Cassini satellite in 2001.
This sensitivity enables us to observe black-hole mergers of their mass greater than 10^5 Msun in the cosmological scale.
Based on the hierarchical growth model of black-holes in galaxies, we estimate the event rate of detection will be 20-50 a year.
We nickname "INO" , named after Tadataka Ino (1745--1818), a Japanese astronomer, cartographer, and geodesist. [arXiv:1809.10317]

伊能忠敬　没後 200 年

Improvement of Doppler-tracking sensitivity

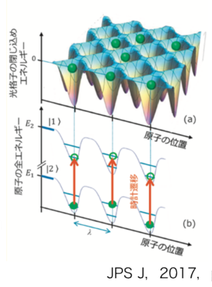
1. Introduction : Optical Lattice Clock

“Optical Lattice Clock”
H. Katori (JPS Journal, 2002, p754)
trap atoms at standing laser wave
read frequency of transient phase

Cs atomic clock　$\Delta t/t = 5\times10^{-16}$
Optical Lattice Clock (2015)　10^{-18}

magic freq. compensates multi-polarization

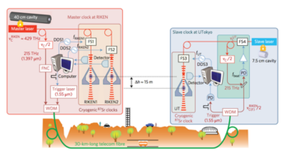
OLC targets　$\Delta t/t = 10^{-19}$



JPS J, 2017, p84

Geopotential measurements with synchronously linked optical lattice clocks

Tetsushi Takano[1], 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[6], Basara Miyahara[1] and Hidetoshi Katori[1,2,3,4]*

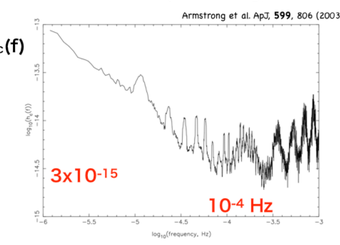


grav. potential of 15m difference
relativistically measured　± 5cm

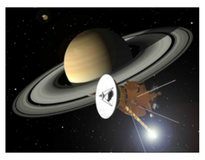
（1 cm on the Earth　$\Delta t/t = 1.1\times10^{-18}$ ）

2. Doppler tracking of Cassini Saturn Explorer

Cassini 2001-2002 (Armstrong, LRR 2006)



G. Cassini (1625-1712)

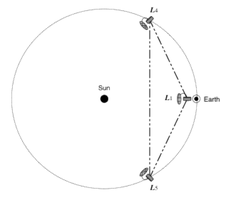


Cassini (1997-2017)

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 $\simeq 8\times10^{-16}$	$\simeq$ 8X	atomic clock
Ground electronics	currently $\simeq 2\times10^{-16}$	$\simeq$ 2X	troposphere
Tropospheric scintillation	currently $\simeq 10^{-15}$ under favorable conditions	$\simeq$ 10X	plasma
Plasma scintillation	Cassini-class radio system probably adequate for calibration to $\simeq 10^{-16}$	$\simeq$ 1X	radiation pressure of Sun
Spacecraft motion	currently $\simeq 2\times10^{-16}$	$\simeq$ 2X	control technology
Antenna mechanical	currently $\simeq 2\times10^{-15}$ under favorable conditions	$\simeq$ 20X	

2. Improvement of Doppler sensitivity（1）



▶ 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

1 AU baseline ▶ 10^{-5}Hz

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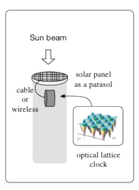
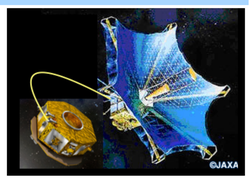
▶ Opt. Lattice Clock
▶ in space
▶ light transmission
▶ solar panel parasol

2. Improvement of Doppler sensitivity（2）



rad. press. F=P/c
P=1.3 kW/m²
1000 kg, 10 m²

acceleration
$a=5\times10^{-8}$ m/s²
$\Delta P/P \fallingdotseq 1/1000$
$\Delta a/a \fallingdotseq 10^{-11}$
$\Delta g/g \fallingdotseq 10^{-12}$



▶ solar panel parasol

1 AU baseline ▶ 10^{-5}Hz

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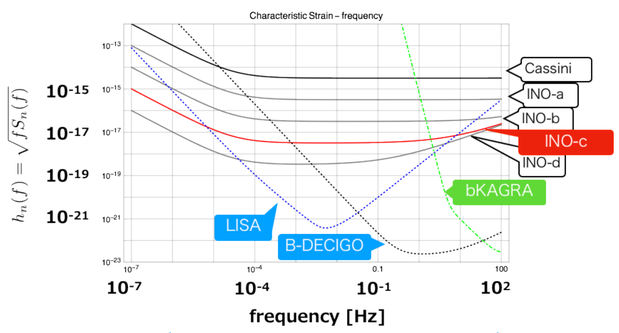
▶ Opt. Lattice Clock
▶ in space
▶ light transmission
▶ solar panel parasol

2. Improvement of Doppler sensitivity（3）

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

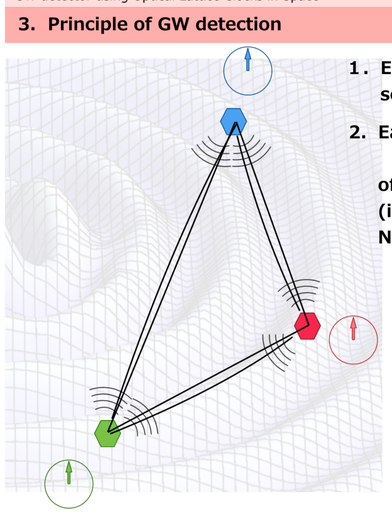


sensitivity f^{-1}
satellite control perturbation

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

GW detector using Optical Lattice Clocks in Space

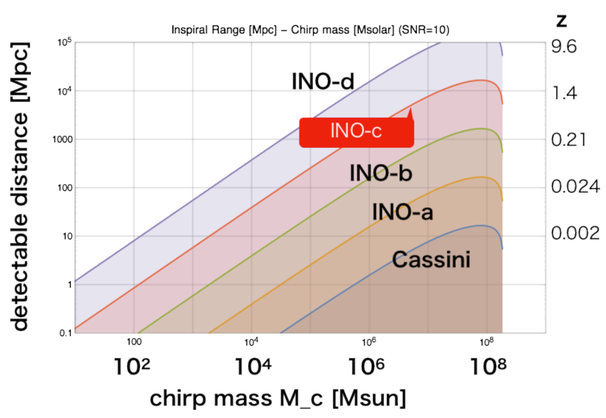
3. Principle of GW detection



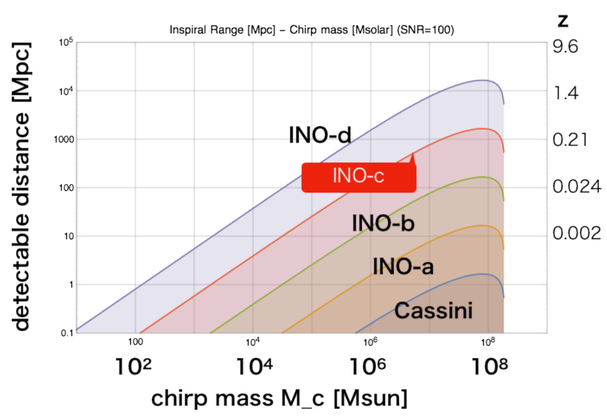
1. Each satellite has Opt Lattice Clock, send out each time to others.
2. Each satellite recognizes
direction・distance・velocity
of others, and we know all of them
(including the potentioal of the Sun.)
Note: effects of planets are *O*(month).
3. When GW passes, we know its differences.
If the events are ~10s (/yr),
then we can calibrate them well.

Detectble Distance

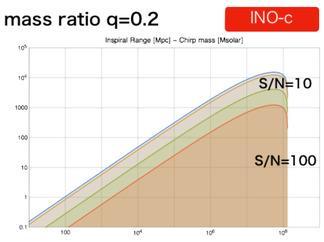
S/N=10

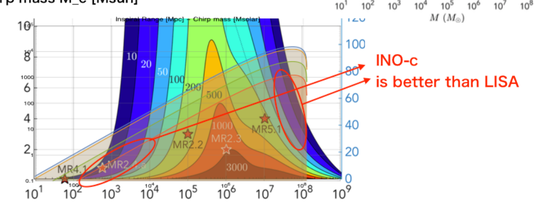


S/N=100

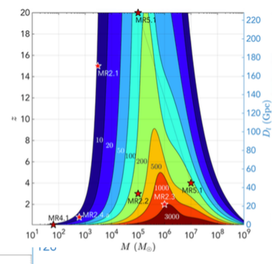


mass ratio q=0.2　INO-c



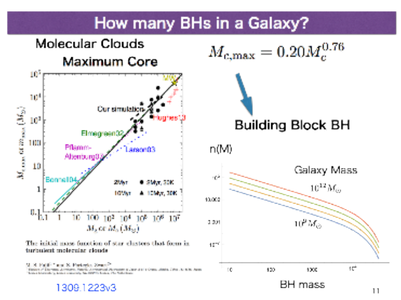


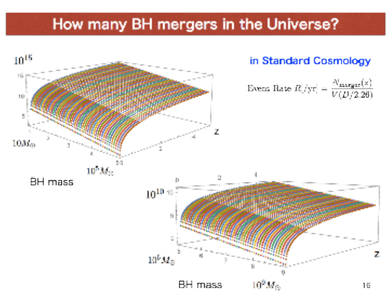
LISA　1702.00786



Hierarchical growth model of SMBH

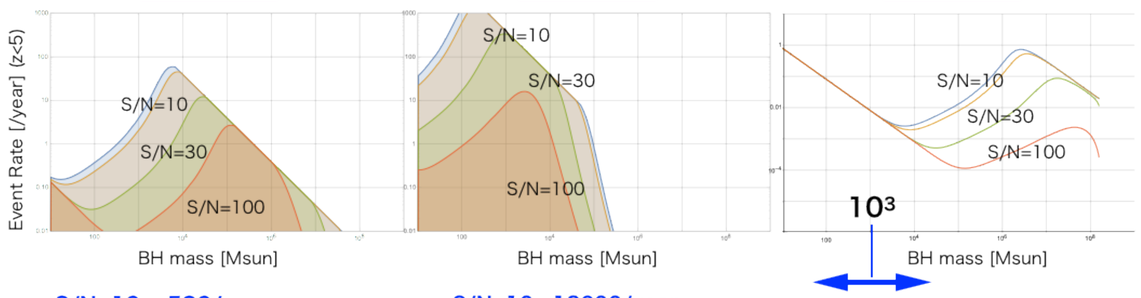
BHs　$\exists 60 M_\odot$
↓
IMBHs　$10^2 - 10^4 M_\odot$
↓
SMBHs　$\exists 10^6 M_\odot$





ApJ. 835 (2017) 276

How many BH mergers ?



S/N=10　520/year
(range: 550M-3.8x10⁵M)
S/N=30　6/year
(range: 5.5x10³M-3.3x10⁴M)

S/N=10　18000/year
(range: 10M-7.9x10⁴M)
S/N=30　4300/year
(range: 10M-3.3x10⁴M)

19.2/yr　29.8/yr
S/N=10