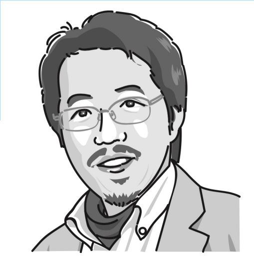
Interplanetary Network of Optical Lattice Clocks

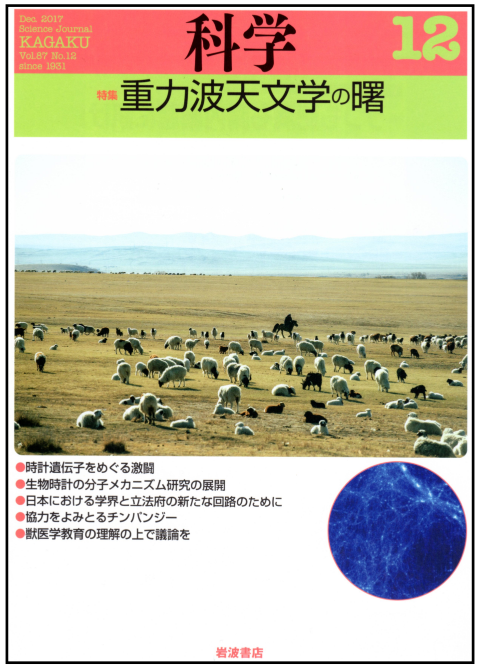
Hisaaki Shinkai (Osaka Inst. Tech.)
真貝寿明（大阪工大）

http://www.oit.ac.jp/is/shinkai



Proposal of new GW detection method, using the world-recording precise clocks in space, and current-ready techniques.

数理科学
12
2018
特集
重力波の衝撃
新時代の物理学の幕開け
巻頭言 重力波天文学・物理学・宇宙論の夜明け 佐々木 節
アインシュタインの予言 須山 輝明
ブラックホールと重力波 真貝 寿明
連星中性子星合体からの重力波と多粒子天文学 久徳浩太郎
重力子 中山 和則
インフレーションと原始重力波 重力波でみる「宇宙のはじまり」 齊藤 遼
重力波検出の歴史と現状 大橋 正健
重力波がもたらす新しい物理学と天文学 田中 貴浩
［コラム］重力波検出古事記 佐藤 文隆
〈連載〉例題形式で探求する集合・位相 その10 丹下 基生
例題形式で探求する複素解析の幾何学 その9 志賀 啓成
No.666
サイエンス社



Dec. 2017
Science Journal
KAGAKU
Vol.87 No.12
since 1931
科学
12
特集 重力波天文学の曙
●時計遺伝子をめぐる激闘
●生物時計の分子メカニズム研究の展開
●日本における学界と立法府の新たな回路のために
●協力をよみとるチンパンジー
●獣医学教育の理解の上で議論を
岩波書店

work with
Toshikazu Ebisuzaki 戎崎俊一（RIKEN）
Hidetoshi Katori 香取秀俊 (RIKEN, UTokyo)
Jun Makino 牧野淳一郎 (Kobe U, RIKEN)
Atsushi Noda 野田篤司 (JAXA)
Toru Tamagawa 玉川徹（RIKEN）

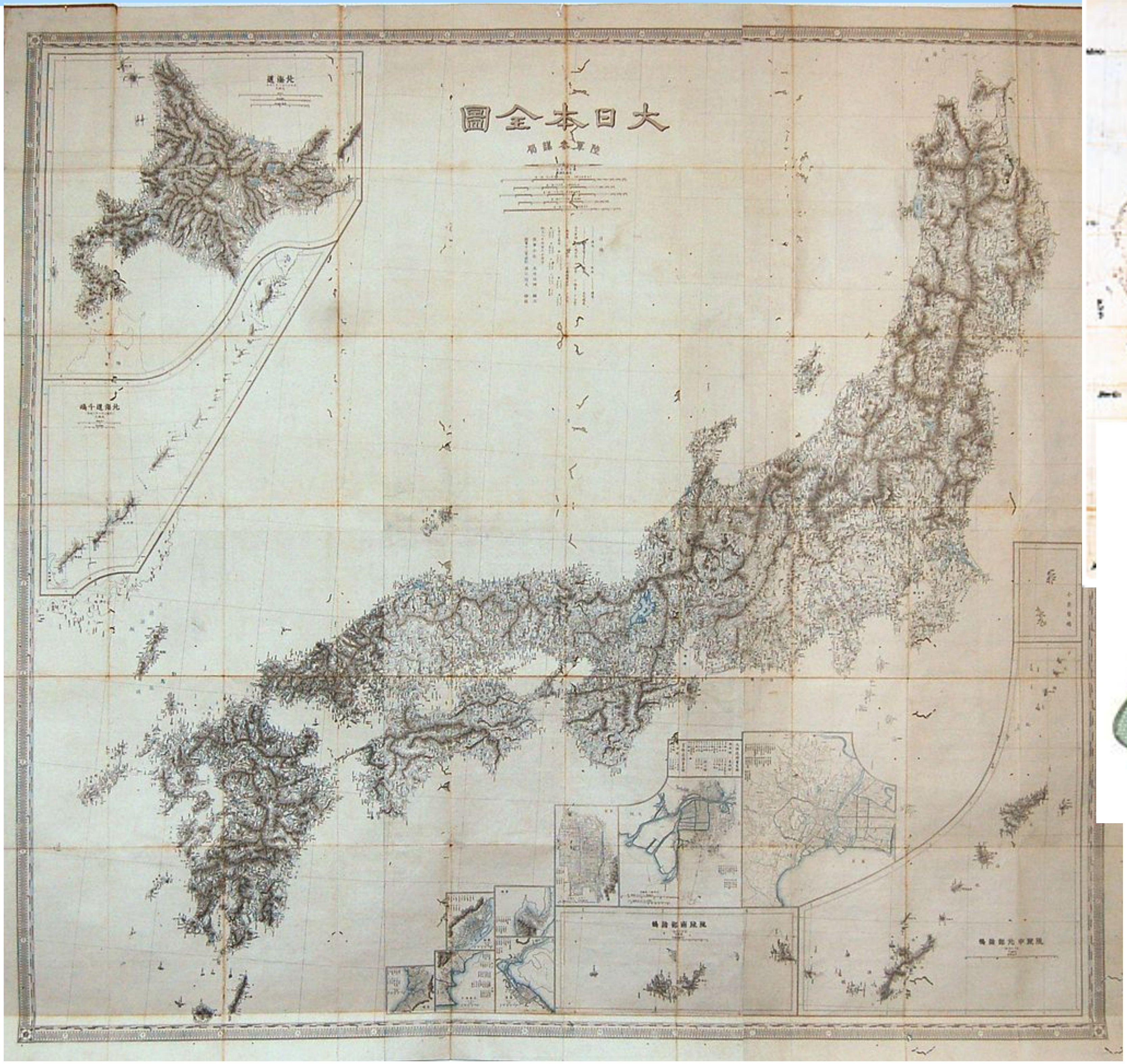
「数理科学」2018-12
「科学」2017-12
Int. J. Mod. Phys. D 28 (2019) 1940002

https://doi.org/10.1142/S0218271819400029 or arXiv:1809.10317

2019 June 14 @ GW-Research Exchanging Meeting

Interplanetary Network of Optical Lattice Clocks

Hisaaki Shinkai (Osaka Inst. Tech.)

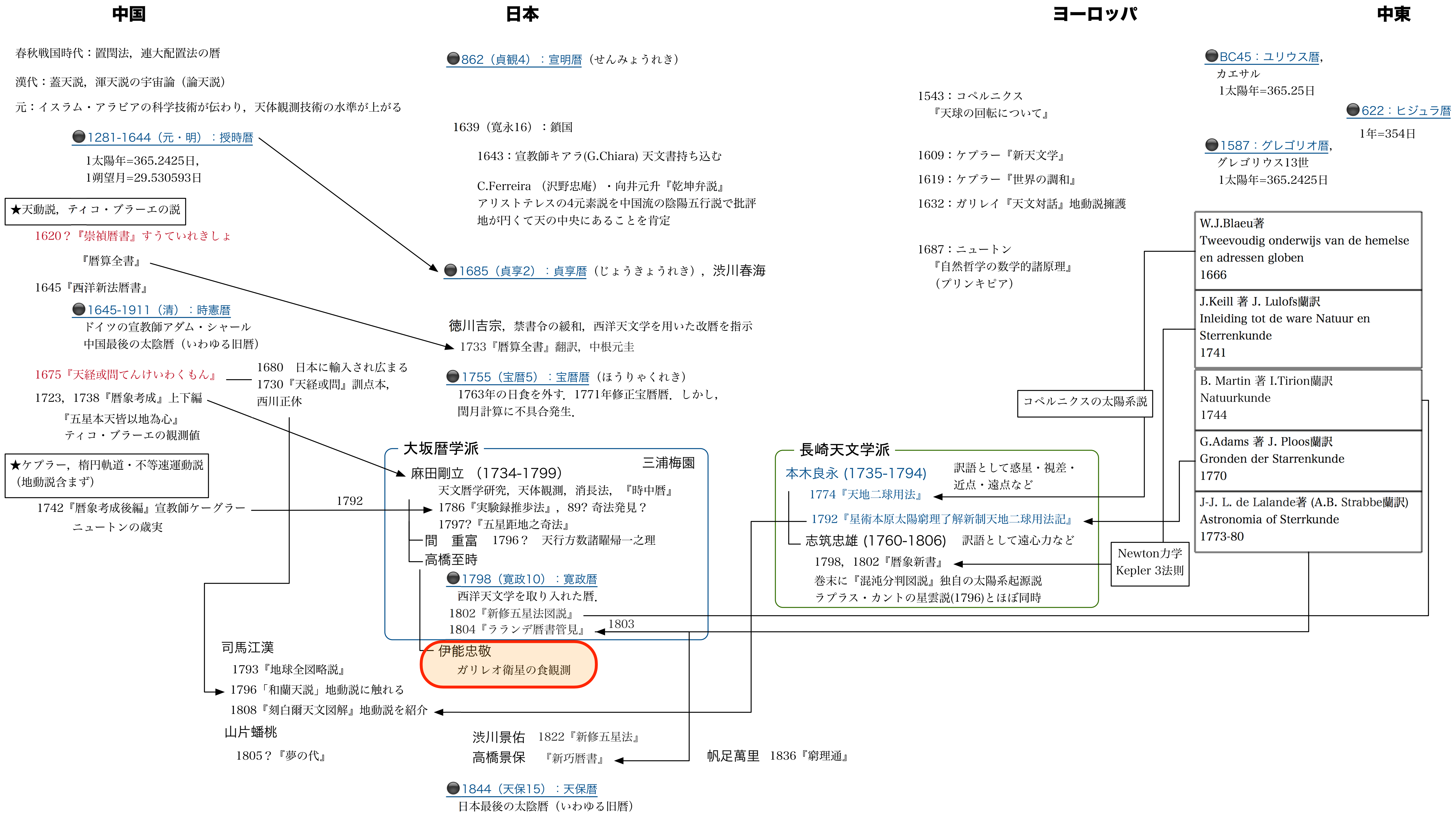


伊能忠敬

Tadataka Ino (1745-1818)

a Japanese astronomer,
cartographer, and geodesist.

天文学・物理学の受容



中国

春秋戦国時代：置閏法，連大配置法の暦

漢代：蓋天説，渾天説の宇宙論（論天説）

元：イスラム・アラビアの科学技術が伝わり，天体観測技術の水準が上がる

● 1281-1644（元・明）：授時暦
1太陽年=365.2425日，
1朔望月=29.530593日

★天動説，ティコ・ブラーエの説

1620？『崇禎暦書』すうていれきしょ

『暦算全書』

1645『西洋新法暦書』

● 1645-1911（清）：時憲暦
ドイツの宣教師アダム・シャール
中国最後の太陰暦（いわゆる旧暦）

1675『天経或問てんけいわくもん』

1680　日本に輸入され広まる
1730『天経或問』訓点本，
西川正休

1723，1738『暦象考成』上下編
『五星本天皆以地為心』
ティコ・ブラーエの観測値

★ケプラー，楕円軌道・不等速運動説
（地動説含まず）

1742『暦象考成後編』宣教師ケーグラー
ニュートンの歳実

1792

司馬江漢
1793『地球全図略説』
1796「和蘭天説」地動説に触れる
1808『刻白爾天文図解』地動説を紹介

山片蟠桃
1805？『夢の代』

日本

● 862（貞観4）：宣明暦（せんみょうれき）

1639（寛永16）：鎖国

1643：宣教師キアラ(G.Chiara) 天文書持ち込む

C.Ferreira （沢野忠庵）・向井元升『乾坤弁説』
アリストテレスの4元素説を中国流の陰陽五行説で批評
地が円くて天の中央にあることを肯定

● 1685（貞享2）：貞享暦（じょうきょうれき），渋川春海

徳川吉宗，禁書令の緩和，西洋天文学を用いた改暦を指示
1733『暦算全書』翻訳，中根元圭

● 1755（宝暦5）：宝暦暦（ほうりゃくれき）
1763年の日食を外す．1771年修正宝暦暦．しかし，
閏月計算に不具合発生．

大坂暦学派

三浦梅園

麻田剛立　(1734-1799)
天文暦学研究，天体観測，消長法，『時中暦』
1786『実験録推歩法』，89? 奇法発見？
1797?『五星距地之奇法』

間　重富　1796？　天行方数諸曜帰一之理

高橋至時

● 1798（寛政10）：寛政暦
西洋天文学を取り入れた暦．
1802『新修五星法図説』
1804『ラランデ暦書管見』

1803

伊能忠敬
ガリレオ衛星の食観測

渋川景佑　1822『新修五星法』
高橋景保　『新巧暦書』

帆足萬里　1836『窮理通』

● 1844（天保15）：天保暦
日本最後の太陰暦（いわゆる旧暦）

渋川景佑　1846『新法暦書続編』

● 1873（明治6）：太陽暦・グレゴリオ暦

長崎天文学派

本木良永 (1735-1794)
1774『天地二球用法』
1792『星術本原太陽窮理了解新制天地二球用法記』

訳語として惑星・視差・
近点・遠点など

志筑忠雄 (1760-1806)　訳語として遠心力など
1798，1802『暦象新書』
巻末に『混沌分判図説』独自の太陽系起源説
ラプラス・カントの星雲説(1796)とほぼ同時

ヨーロッパ

1543：コペルニクス
『天球の回転について』

1609：ケプラー『新天文学』

1619：ケプラー『世界の調和』

1632：ガリレイ『天文対話』地動説擁護

1687：ニュートン
『自然哲学の数学的諸原理』
（プリンキピア）

コペルニクスの太陽系説

Newton力学
Kepler 3法則

W.J.Blaeu著
Tweevoudig onderwijs van de hemelse en adressen globen
1666

J.Keill 著 J. Lulofs蘭訳
Inleiding tot de ware Natuur en Sterrenkunde
1741

B. Martin 著 I.Tirion蘭訳
Natuurkunde
1744

G.Adams 著 J. Ploos蘭訳
Gronden der Starrenkunde
1770

J-J. L. de Lalande著 (A.B. Strabbe蘭訳)
Astronomia of Sterrkunde
1773-80

● BC45：ユリウス暦，
カエサル
1太陽年=365.25日

● 1587：グレゴリオ暦，
グレゴリウス13世
1太陽年=365.2425日

中東

● 622：ヒジュラ暦
1年=354日

T. INO learned astronomical positioning method.
He observed the eclipse of Io.

麻田剛立とケプラーの惑星運動第3法則
真貝寿明
大阪工業大学紀要61巻 (2016) 2号 27-36

Interplanetary Network of Optical Lattice Clocks

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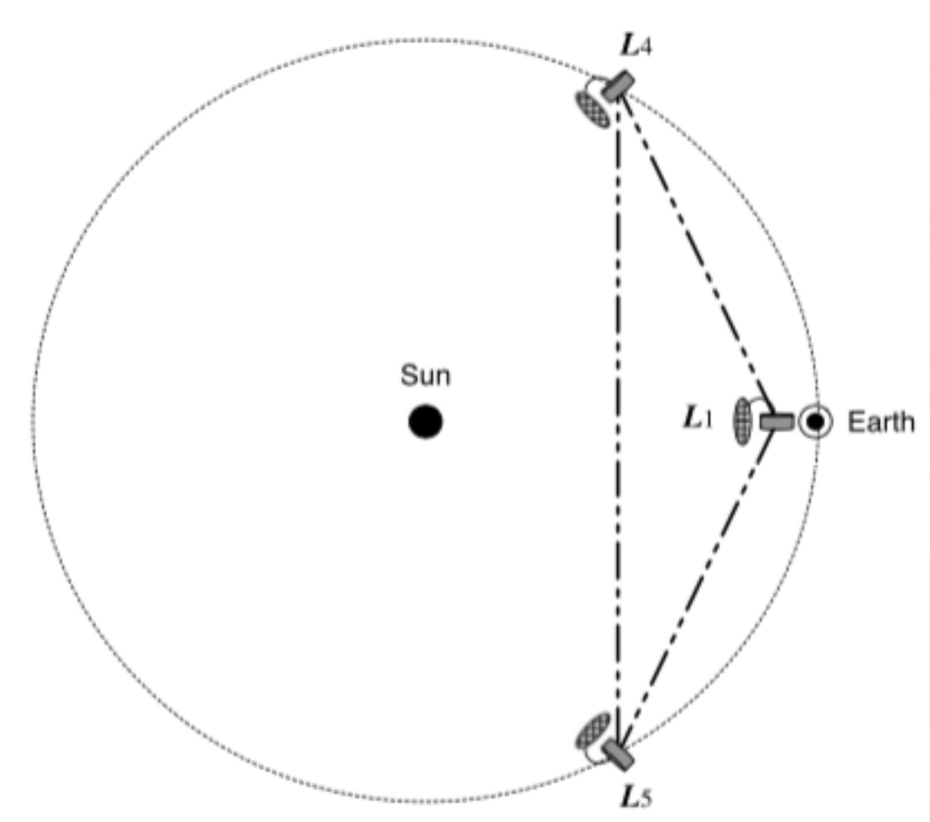
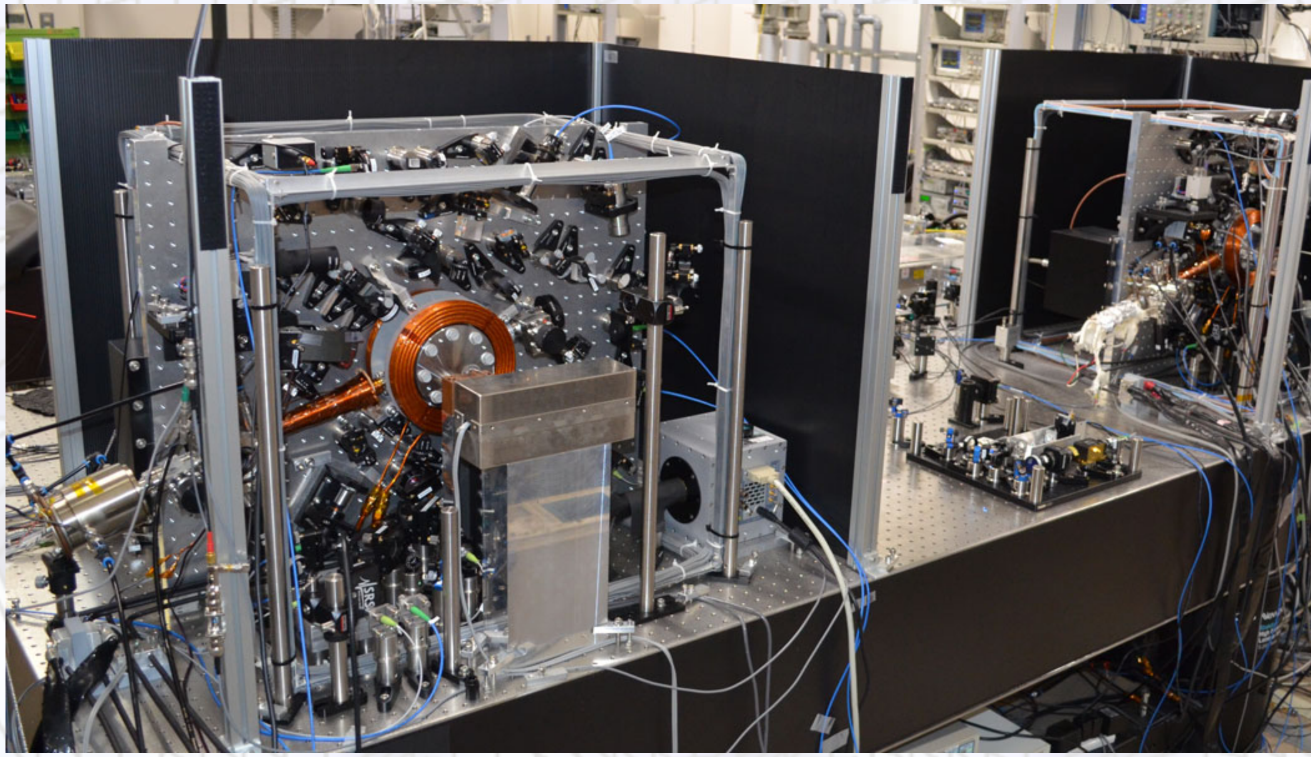
Int. J. Mod. Phys. D 28 (2019) 1940002 https://doi.org/10.1142/S0218271819400029 or arXiv:1809.10317





◆Cassini’s Doppler tracking (2001-2002) can be improved 3-order mag. with current technologies

◆“INO-c”, “INO-d” : sensitivity curve, detectable distance *D*

◆ Event rate by hierarchical formation model of SMBH

- ◆ One satellite costs 50 billion yen (500億円).

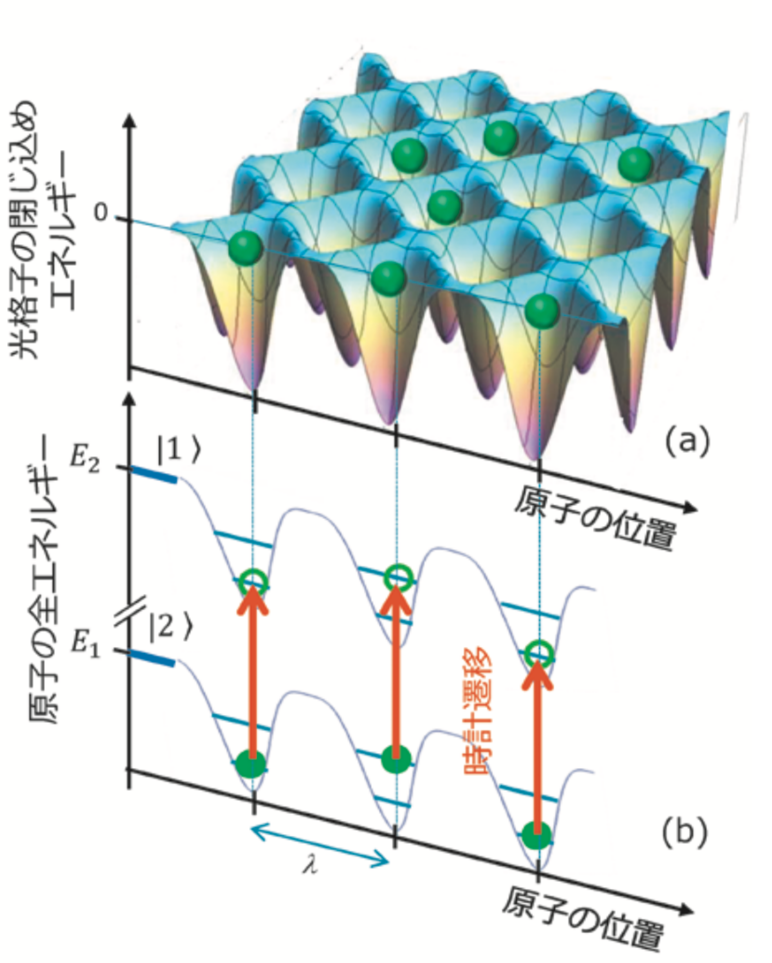
1. Introduction : Optical Lattice Clock

“Optical Lattice Clock”

H. Katori (JPS Journal, 2002, p754)

trap atoms at standing laser wave

read frequency of transient phase



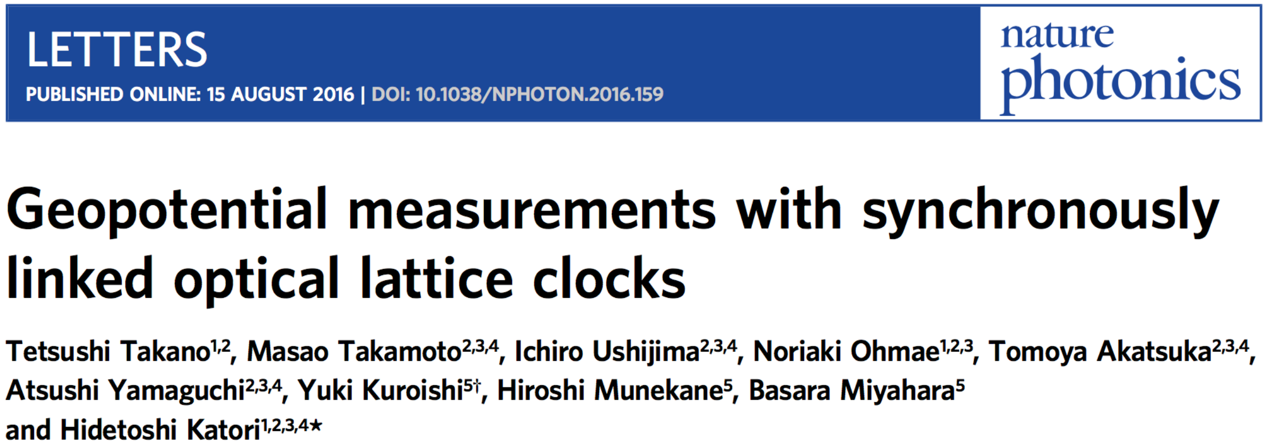
JPS J, 2017, p84

Cs atomic clock $\Delta t/t = 5\mathrm{x}10^{-16}$

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

magic freq. compensates multi-polarization

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



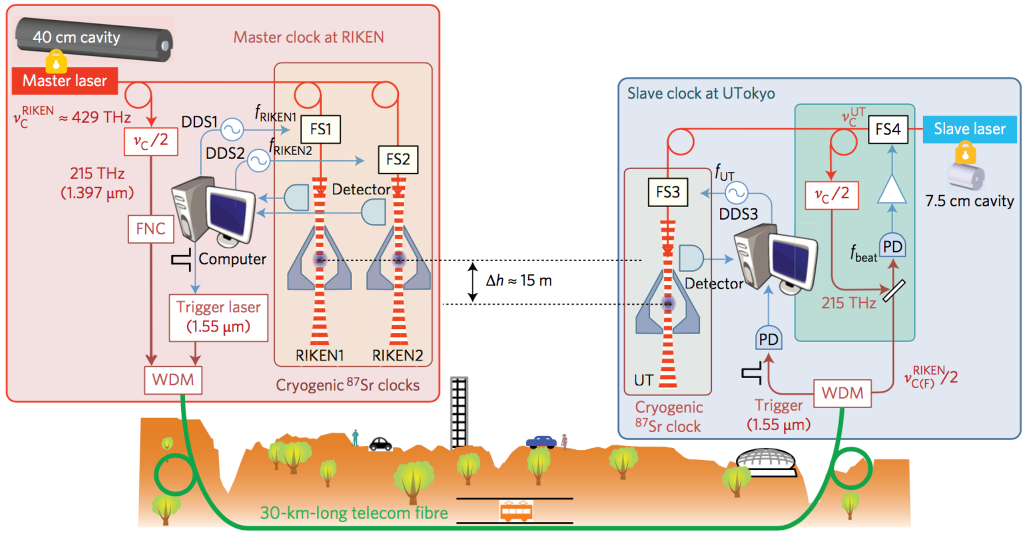
LETTERS

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

nature photonics

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*]

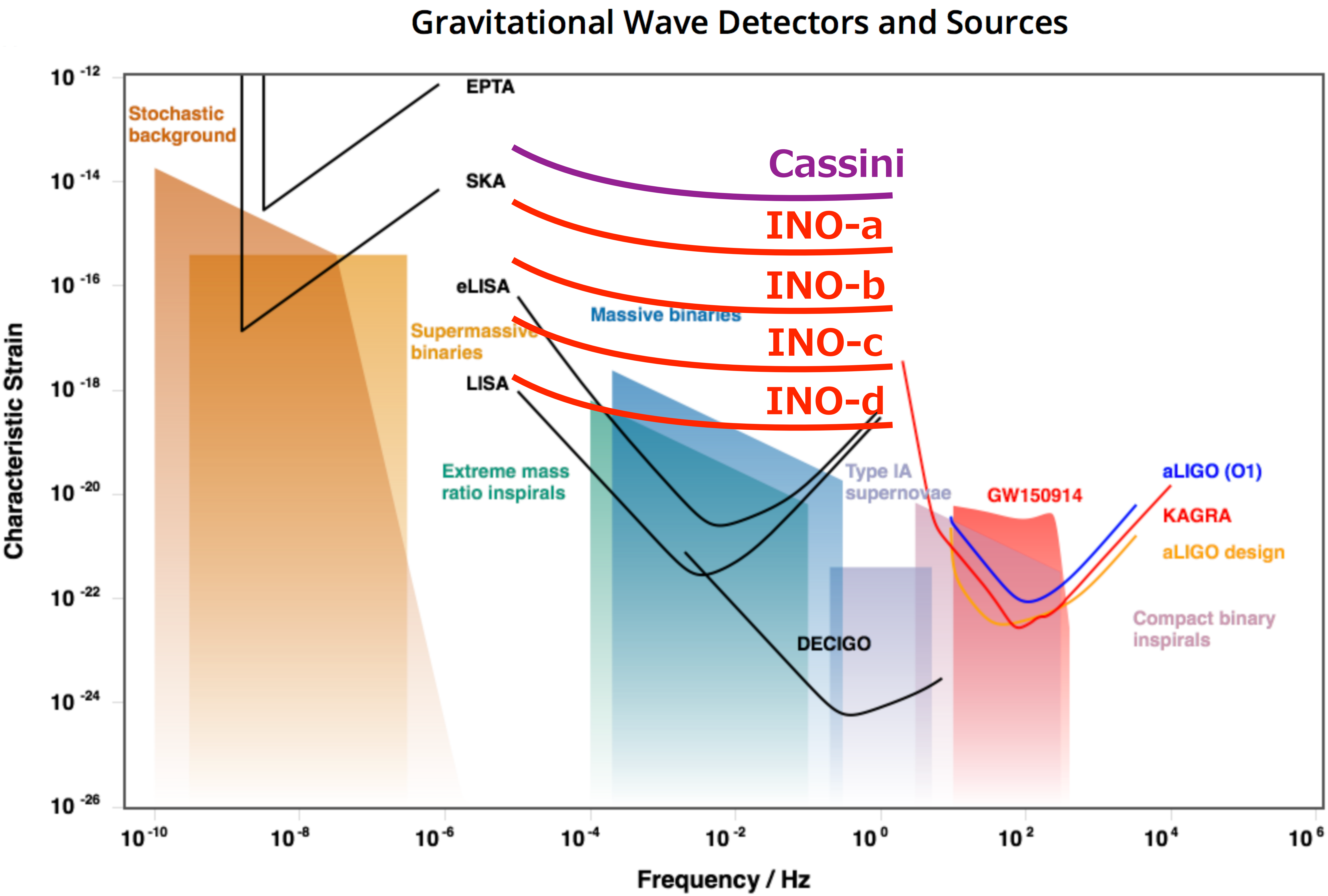


grav. potential of 15m difference

relativistically measured ± 5cm

(1cm on the Earth $\Delta t/t= 1.1\ \mathrm{x}10^{-18}$)

1. Introduction

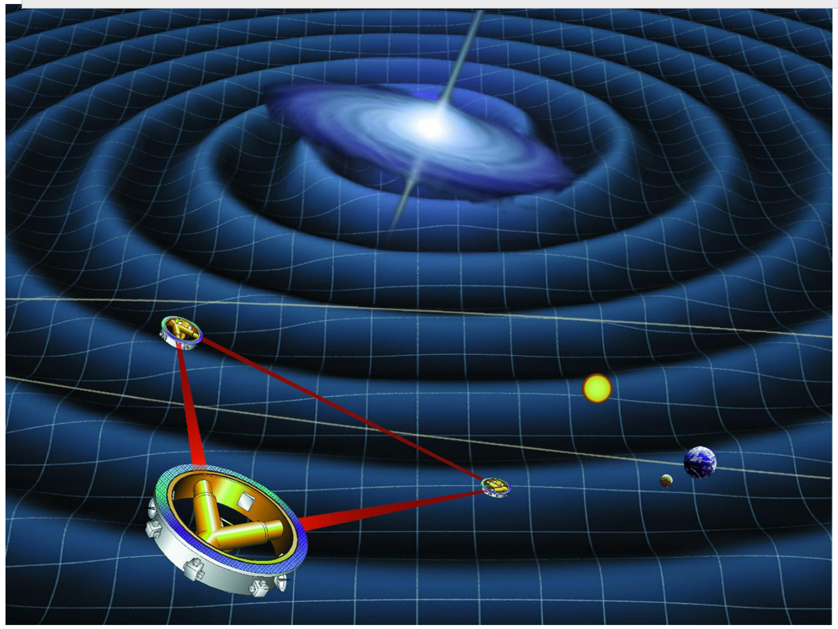


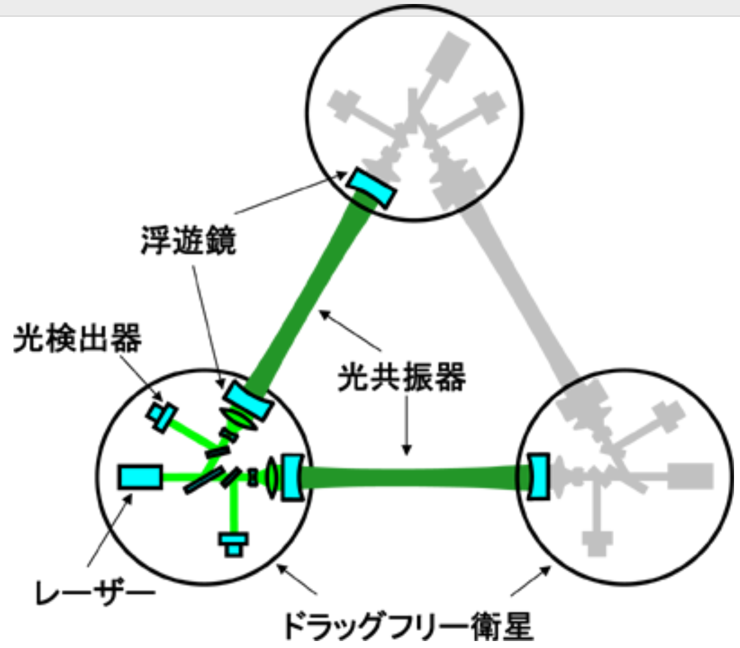
lambda=1pc 2000AU 20AU 0.2AU 3000km 3km

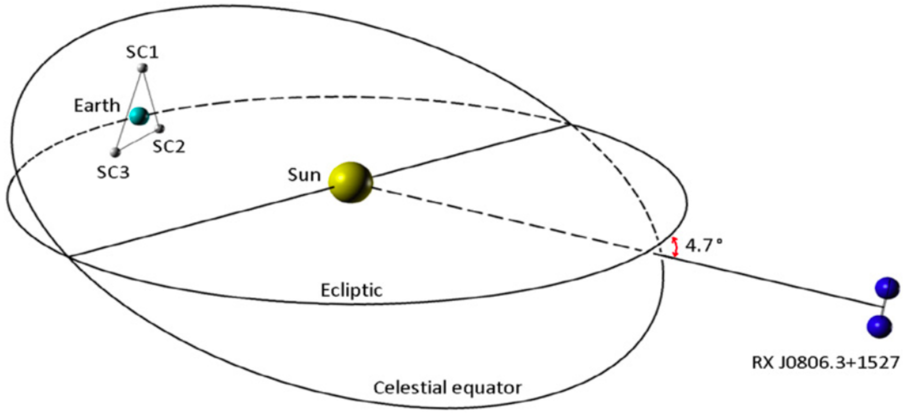
http://rhcole.com/apps/GWplotter/

1. Introduction : Existing plans for space GW observatories

LISA (ESA/NASA)	B-DECIGO ⇒ DECIGO（Japan）	TianQin 天琴 (China)
Laser Interferometer Space Anntena	**Deci-hertz Interferometer GW Observatory**	
mHz range	0.1Hz range	0.1 - 100 mHz range
2030 launch	proposed	2025−2030
3 satellites at L4 of Sun-Earth	around earth 2000km 3 sattelites ⇒ Sun orbit	3 satellites around the Earth
2.50 x 10^6 km	100 km ⇒ 1000 km	10^5 km
robust to acceleration noise		
light transponder	**Fabry-Perot interferometer**	**Fabry-Perot interferometer**
	robust to shot-noises	
drag-free flight	**drag-free flight**	**drag-free flight**
Doppler tracking with Laser beam	same as ground interferometer	same as ground interferometer
1702.00786	CQG 28 (2011) 094011	CQG 33 (2016) 035010



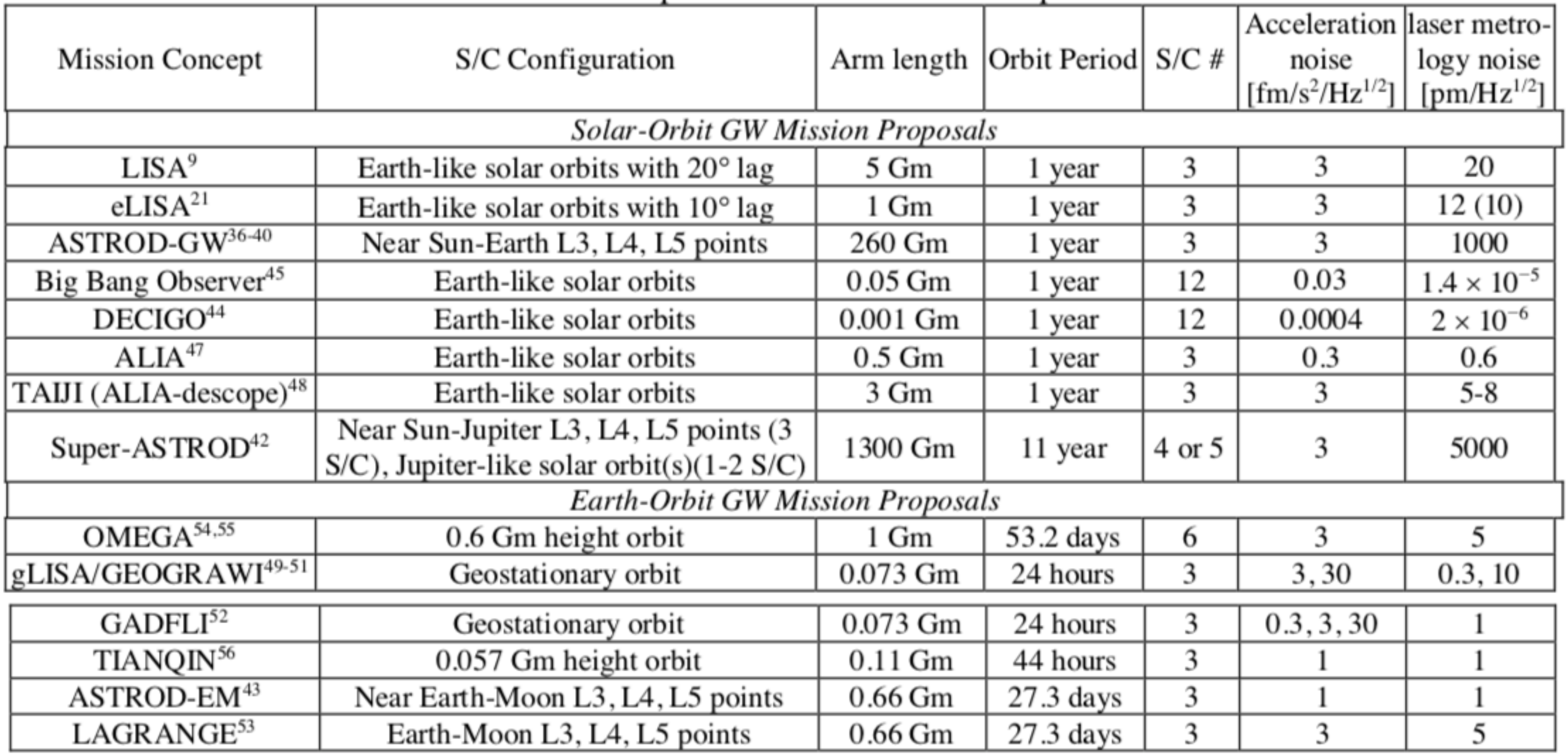




1. Introduction : Existing plans for space GW observatories

Ni, arXiv:1610.01148

Table 1. A Compilation of GW Mission Proposals



Mission Concept	S/C Configuration	Arm length	Orbit Period	S/C #	Acceleration noise [fm/s^2/Hz$^{1/2}$]	laser metrology noise [pm/Hz$^{1/2}$]
Solar-Orbit GW Mission Proposals						
LISA[9]	Earth-like solar orbits with 20° lag	5 Gm	1 year	3	3	20
eLISA[21]	Earth-like 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]	Earth-like solar orbits	0.05 Gm	1 year	12	0.03	1.4×10^{-5}
DECIGO[44]	Earth-like solar orbits	0.001 Gm	1 year	12	0.0004	2×10^{-6}
ALIA[47]	Earth-like solar orbits	0.5 Gm	1 year	3	0.3	0.6
TAIJI (ALIA-descope)[48]	Earth-like solar orbits	3 Gm	1 year	3	3	5-8
Super-ASTROD[42]	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	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 hours	3	3, 30	0.3, 10
GADFLI[52]	Geostationary orbit	0.073 Gm	24 hours	3	0.3, 3, 30	1
TIANQIN[56]	0.057 Gm height orbit	0.11 Gm	44 hours	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

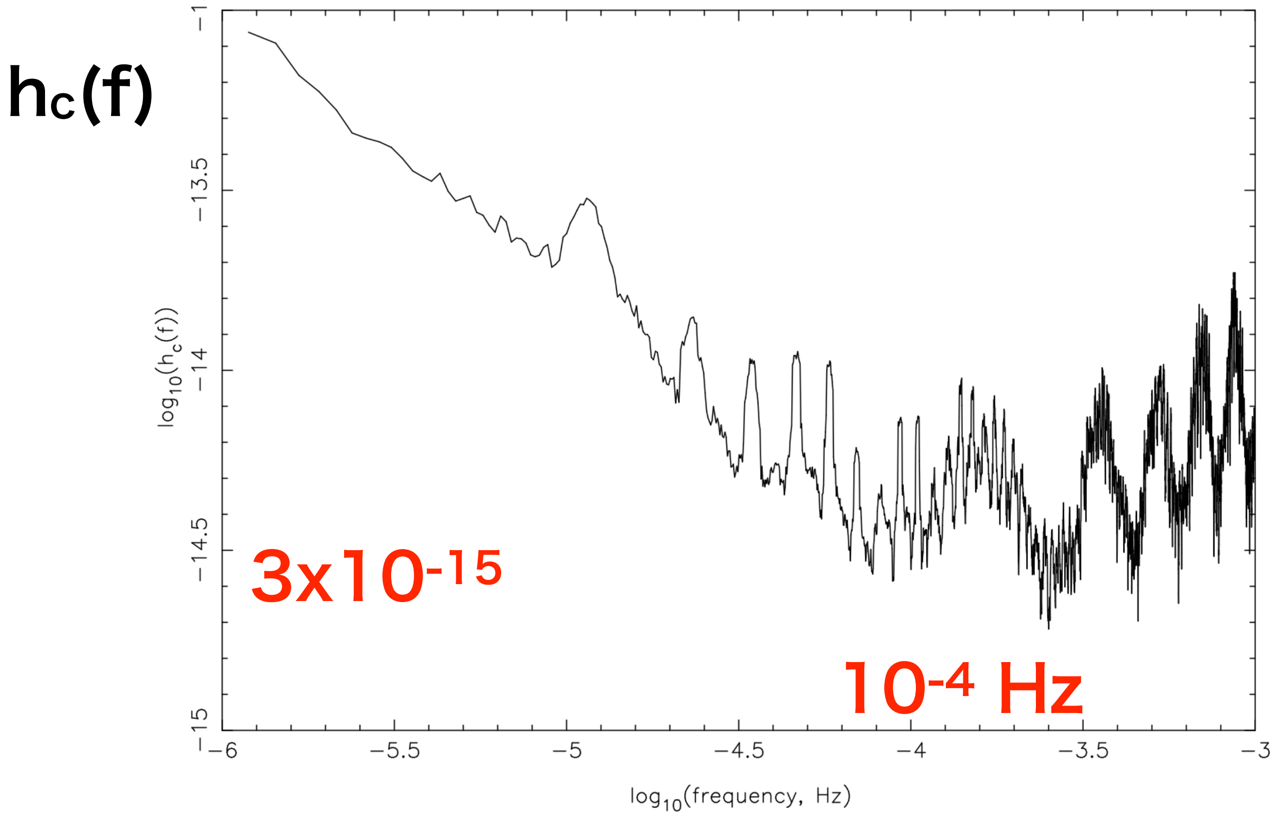
ASTROD=Astrodynamical Space Test of Relativity using Optical Devices

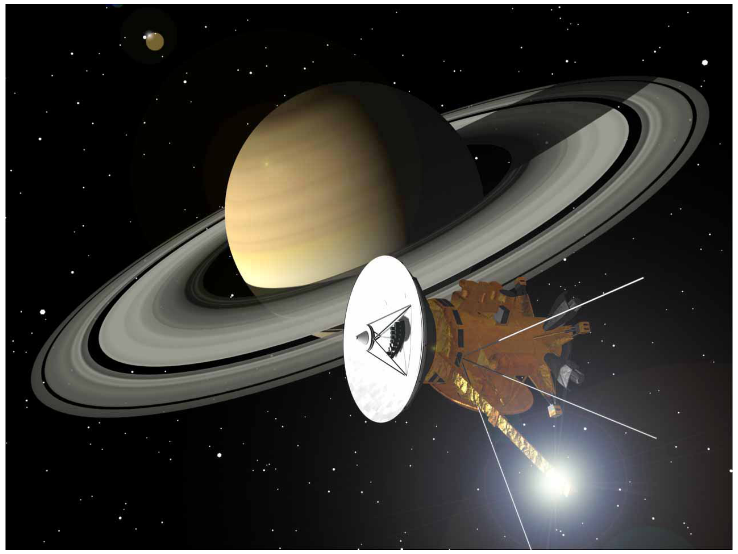
2. Doppler tracking of Cassini Saturn Explorer

G. Cassini (1625-1712)

Cassini 2001-2002 (Armstrong, LRR 2006)

Armstrong et al. ApJ, **599**, 806 (2003)





Cassini (1997-2017)

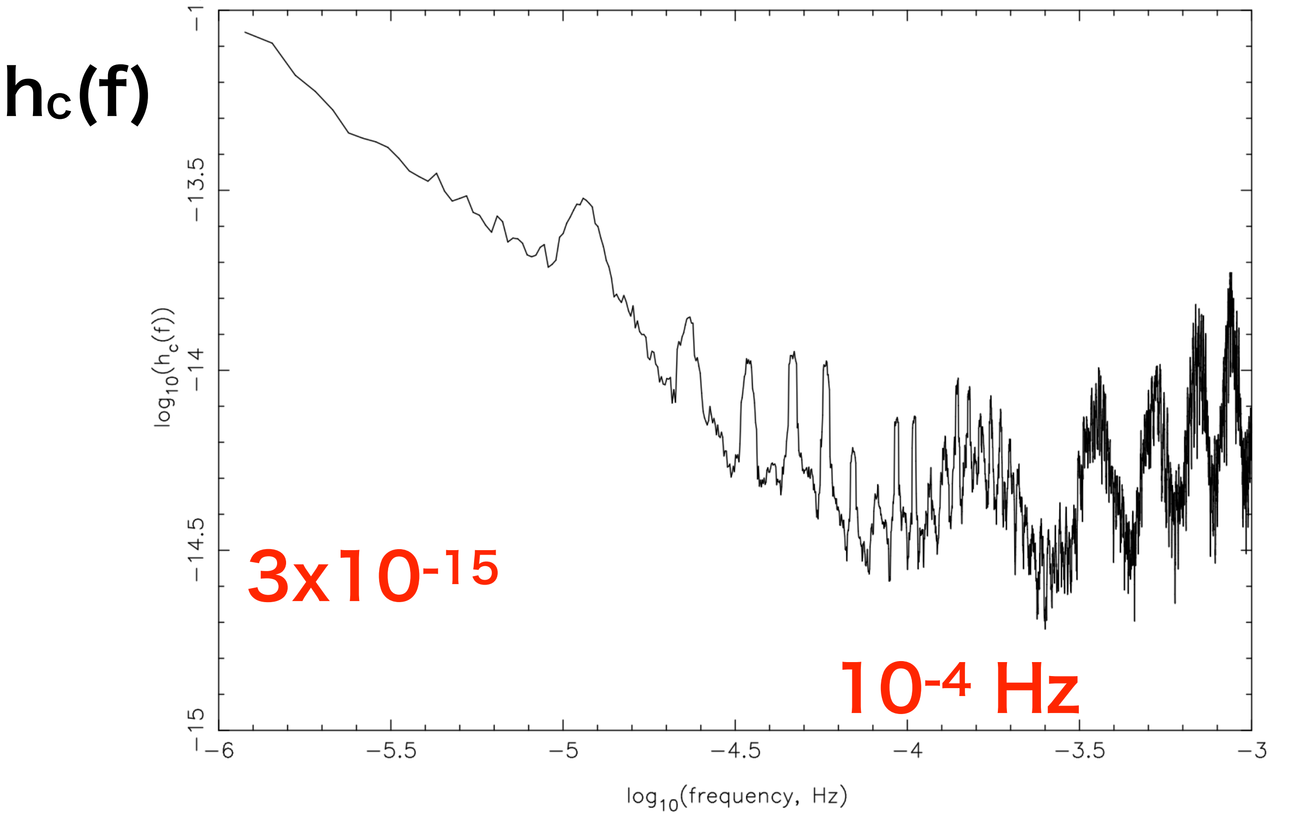
Table 4: Required improvement in subsystems to improve overall Doppler sensitivity by a factor of 10 relative to Cassini-era performance.

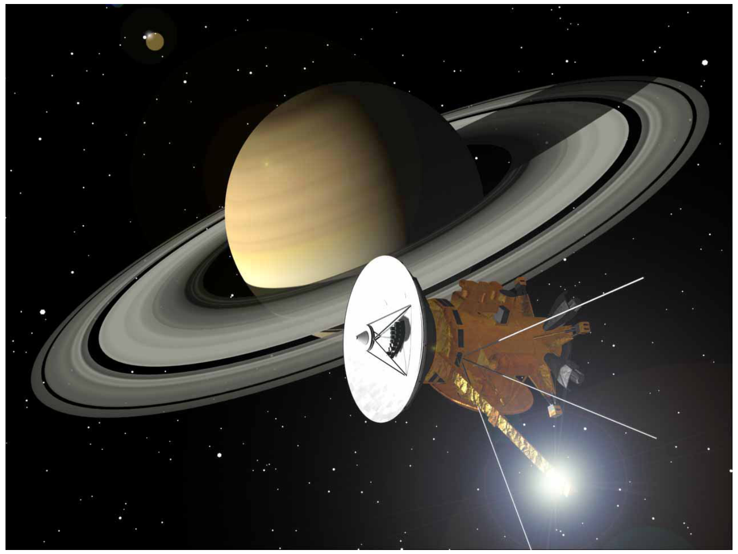
Noise source	Comment (σ_y at $\tau = 1000$ s)	Required improvement	
Frequency standard	currently FTS + distribution $\simeq 8 \times 10^{-16}$	$\simeq$ 8X	**atomic clock**
Ground electronics	currently $\simeq 2 \times 10^{-16}$	$\simeq$ 2X	
Tropospheric scintillation	currently $\simeq 10^{-15}$ under favorable conditions	$\simeq$ 10X	**troposphere (対流圏)**
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）

Cassini 2001-2002 (Armstrong, LRR 2006)

Armstrong et al. ApJ, **599**, 806 (2003)





Cassini (1997-2017)

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Antenna mechanical	currently $\simeq 2 \times 10^{-15}$ under favorable conditions	$\simeq$ 20X

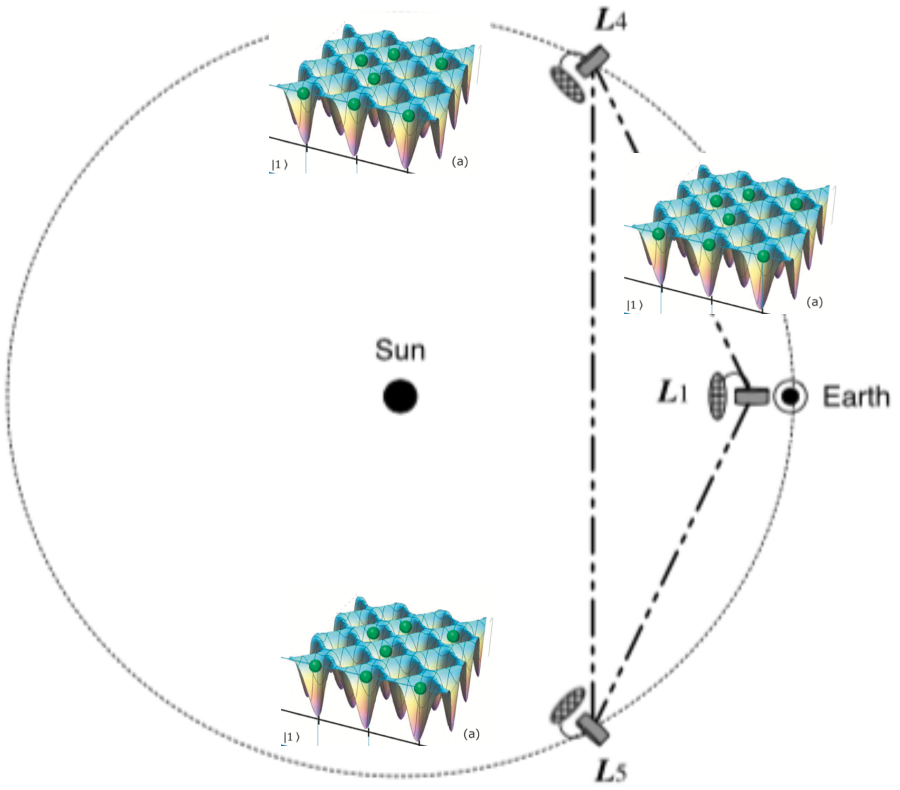
atomic clock

troposphere (対流圏) ▶ **in space**

plasma

radiation pressure of Sun
control technology

2. Improvement of Doppler sensitivity（2）



1 AU baseline ▶ 10^{-5}Hz

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

longer baseline is better to track Doppler shift

- ▶ fuel, power
- ▶ L1, L4, L5 of Sun-Earth orbit
  L1=unstable point
  L4, L5 = stable point

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**

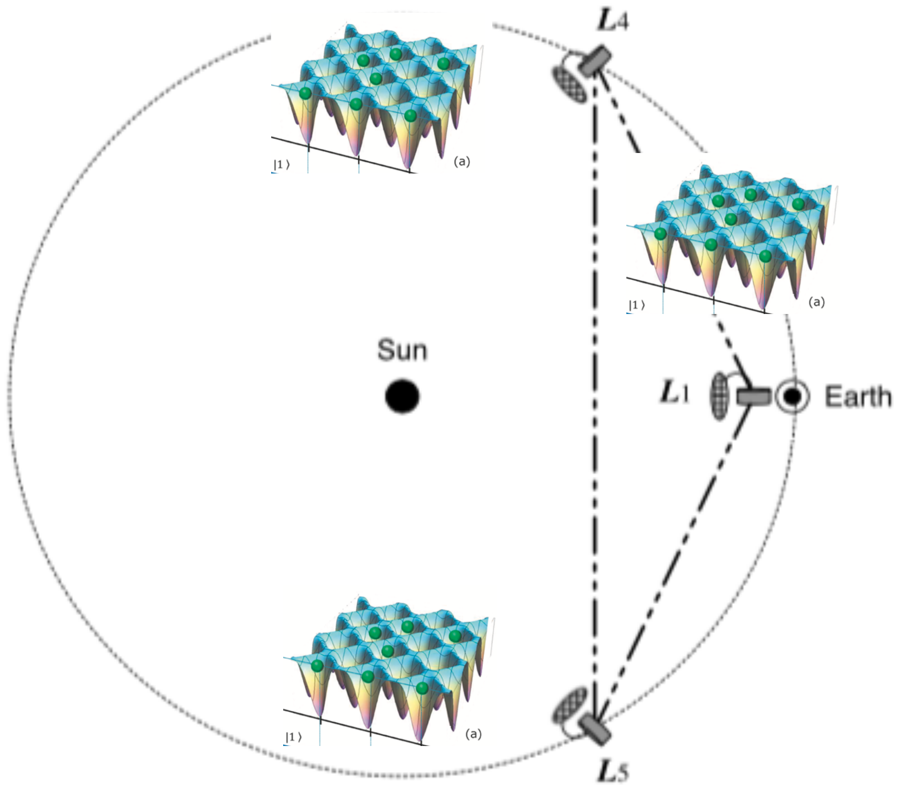
troposphere (対流圏) ▶ **in space**

plasma

radiation pressure of Sun

control technology

2. Improvement of Doppler sensitivity（3)



1 AU baseline ▶ 10^{-5}Hz

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 **> 10^7km**

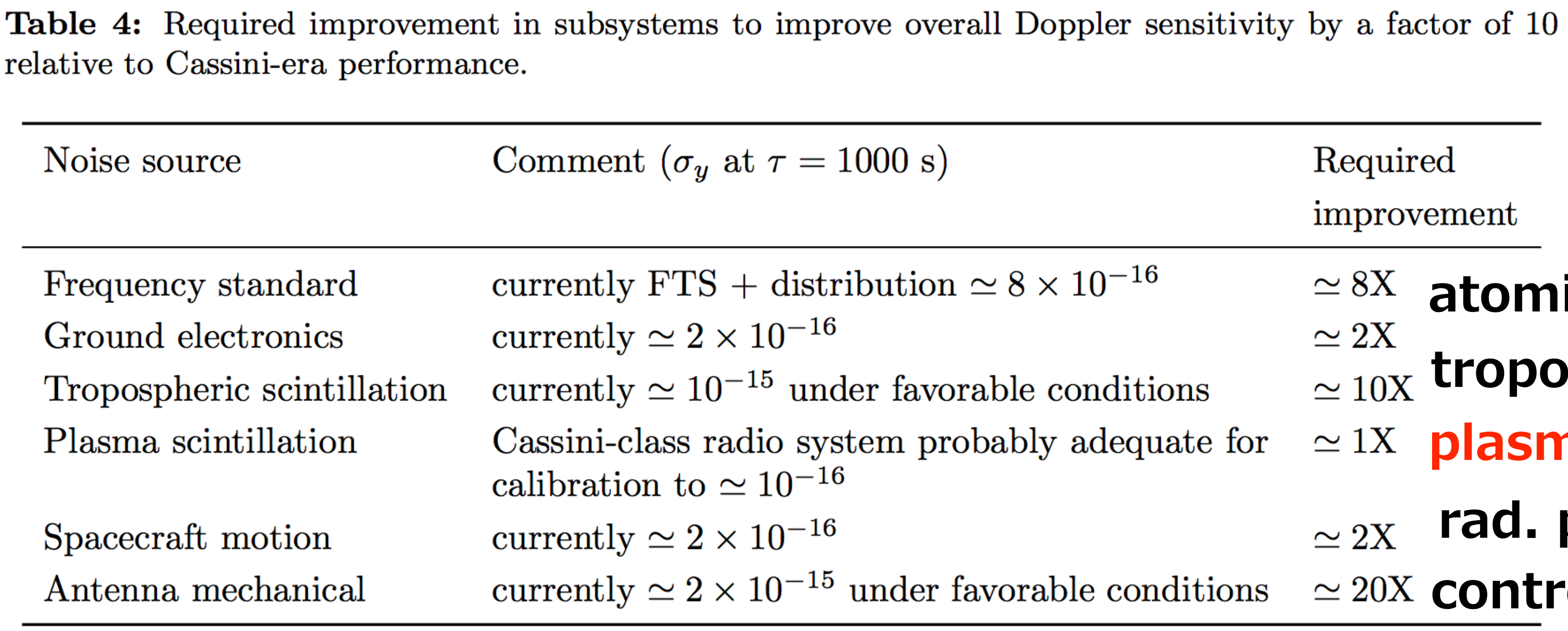
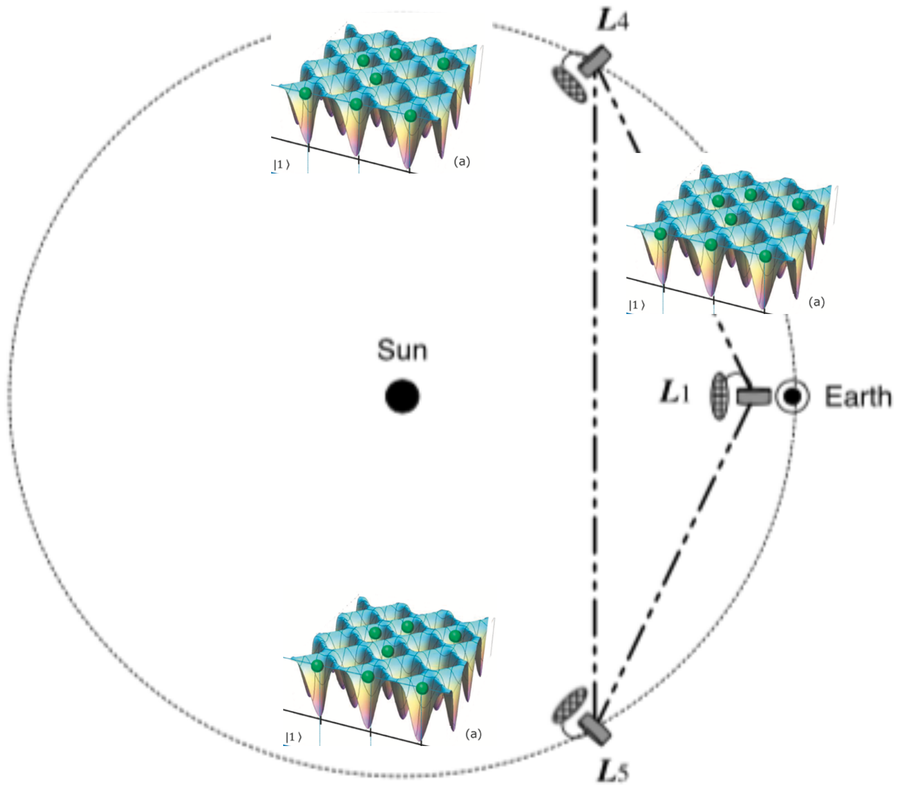


Table 4: Required improvement in subsystems to improve overall Doppler sensitivity by a factor of 10 relative to Cassini-era performance.

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
control technology

2.　Improvement of Doppler sensitivity（4）



1 AU baseline ▶ 10^{-5}Hz

required level

$h=10^{-17}=0.7\,\mathrm{mm}=2\mathrm{x}10^{-8}\,\mathrm{m/s}$　$\Delta g/g \fallingdotseq 10^{-12}$

rad. press. $F=P/c$

$P=1.3\ \mathrm{kW/m^2}$

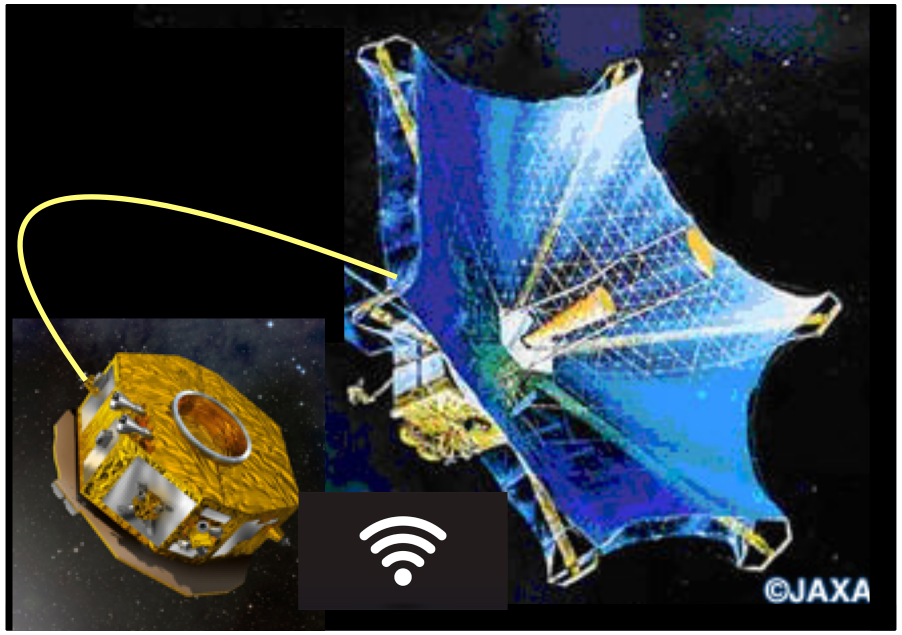
$\Delta P/P \fallingdotseq 1/1000$

acceleration

$a=5\mathrm{x}10^{-8}\ \mathrm{m/s^2}$

$\Delta a/a \fallingdotseq 10^{-11}$

$< 10^{-12}$



1000 kg, 10 m^2

10cm 12kW wireless

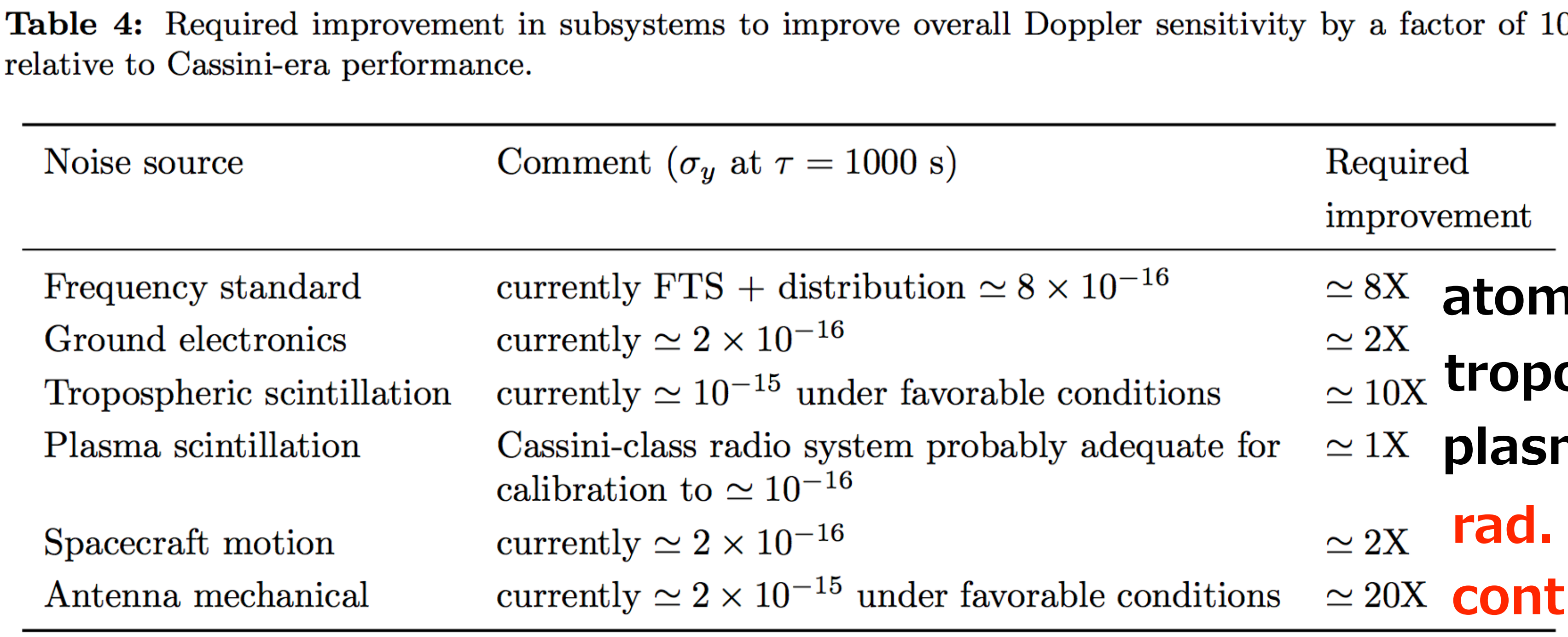


Table 4: Required improvement in subsystems to improve overall Doppler sensitivity by a factor of 10 relative to Cassini-era performance.

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

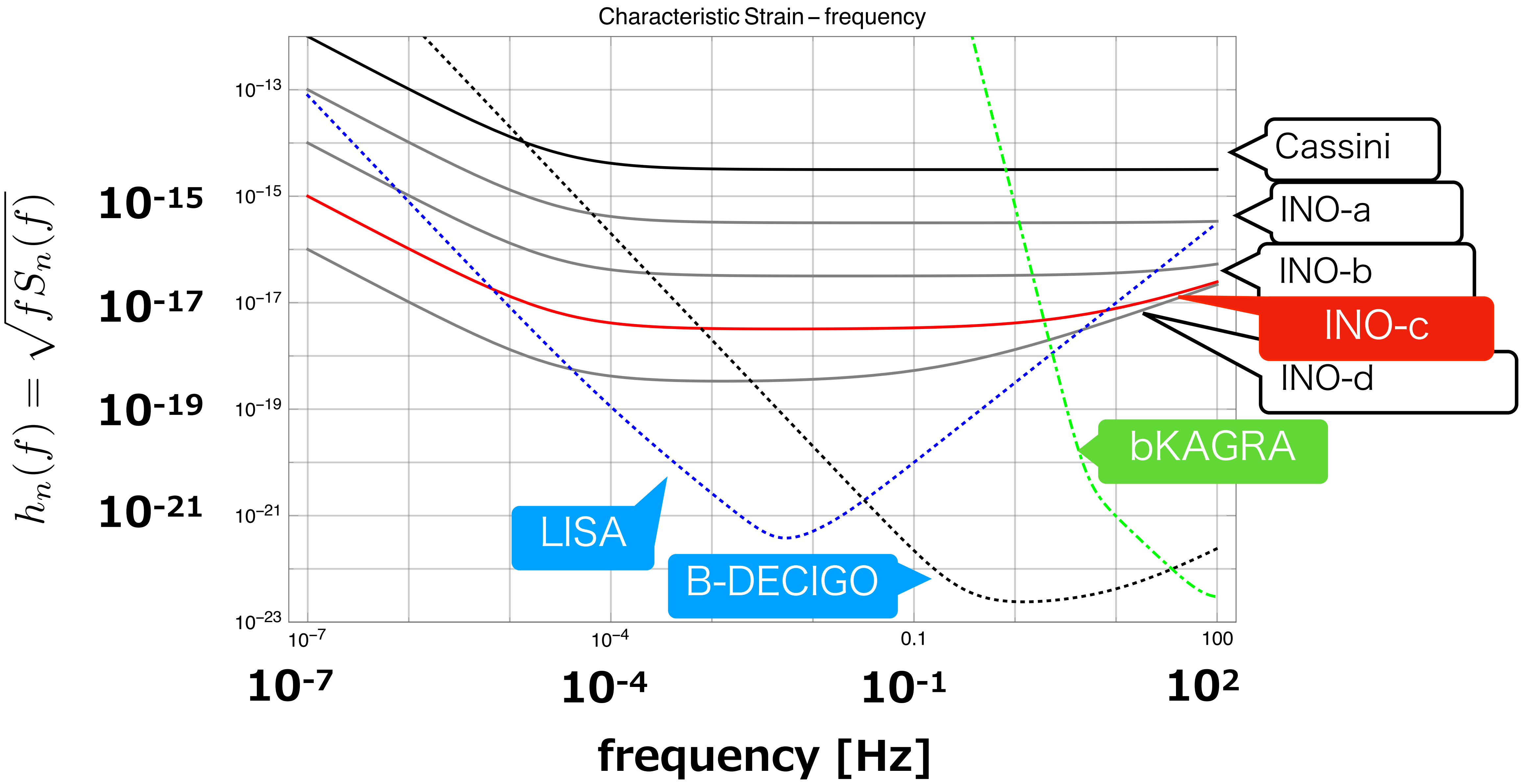
plasma ▶ light transmission

rad. pressure ▶ solar panel parasol

control technology ▶ no drag-free

2. Improvement of Doppler sensitivity（5）

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



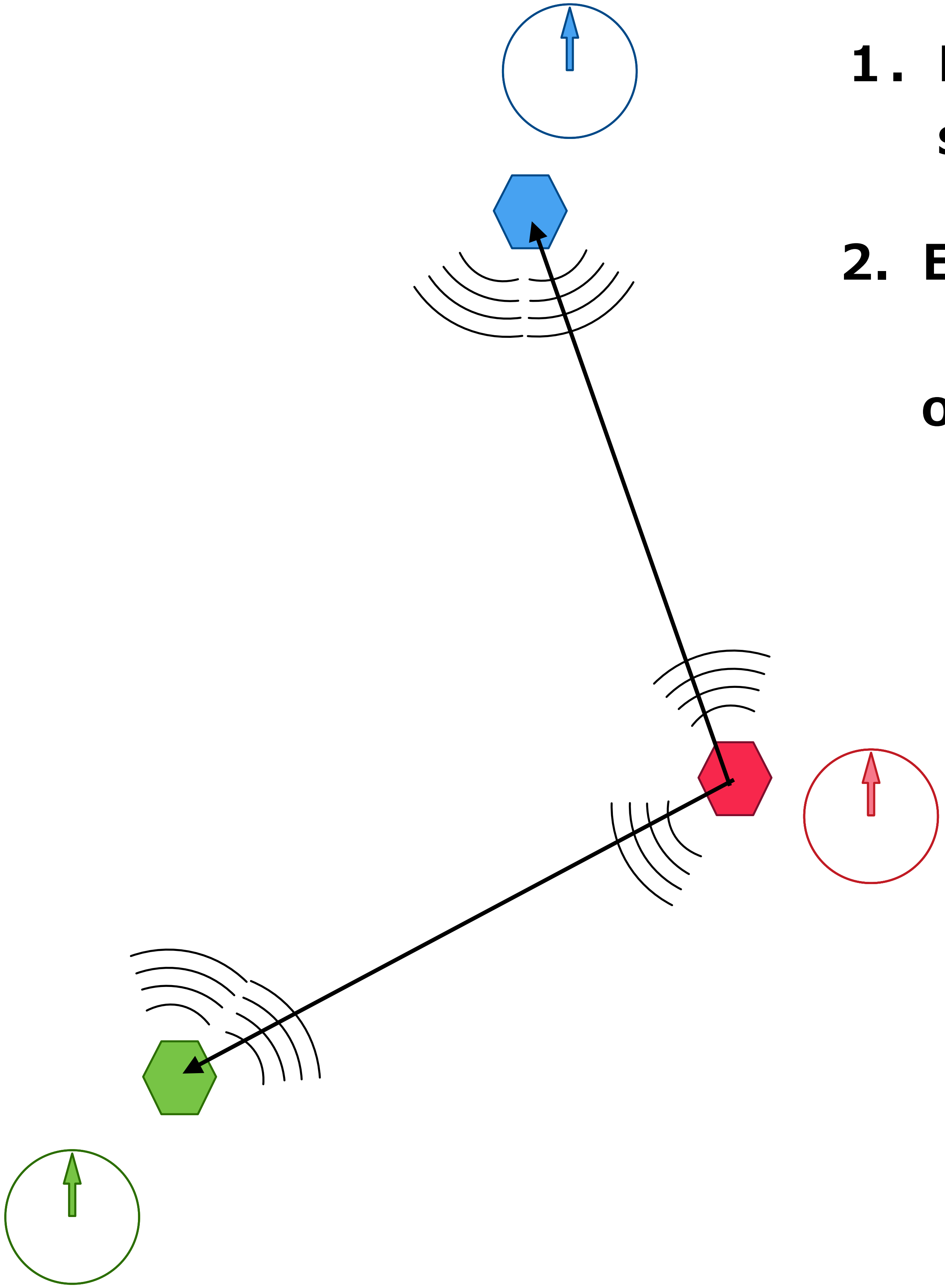
sensitivity f^{-1}

satellite control perturbation

sensitivity $f^{2/3}+10^{-18}$

Opt. Lattice Clock limitation

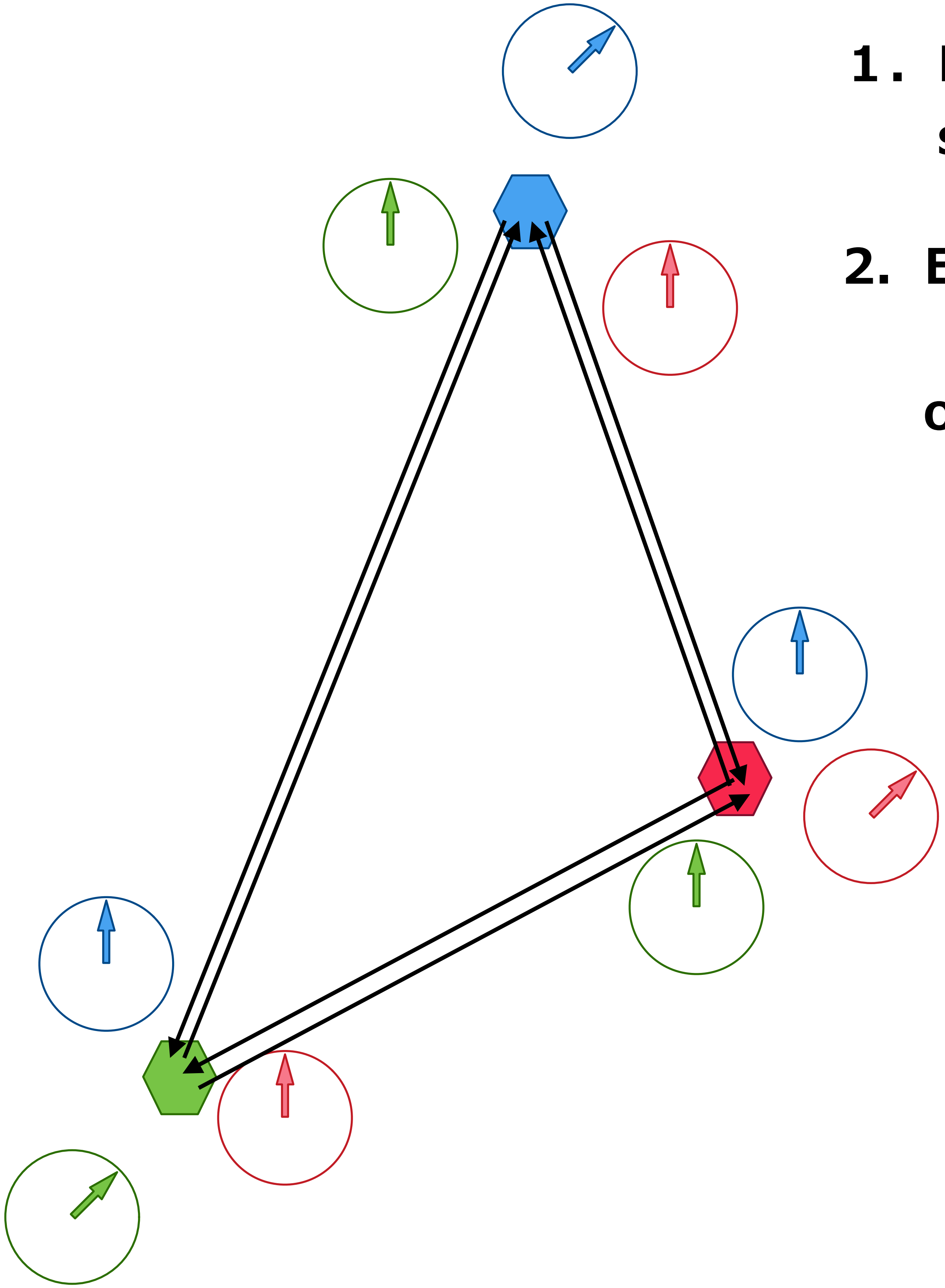
3. Principle of GW detection



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.

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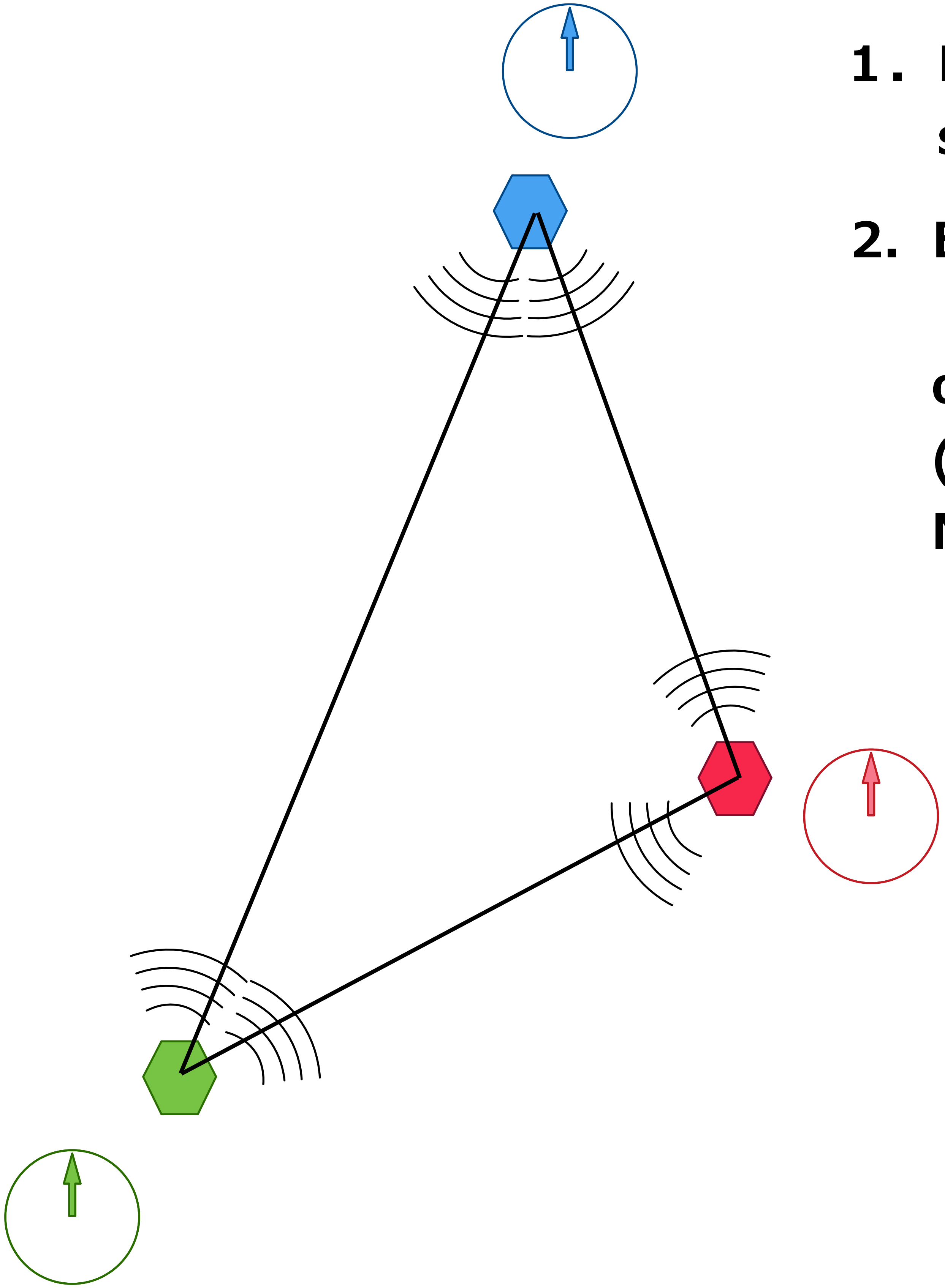


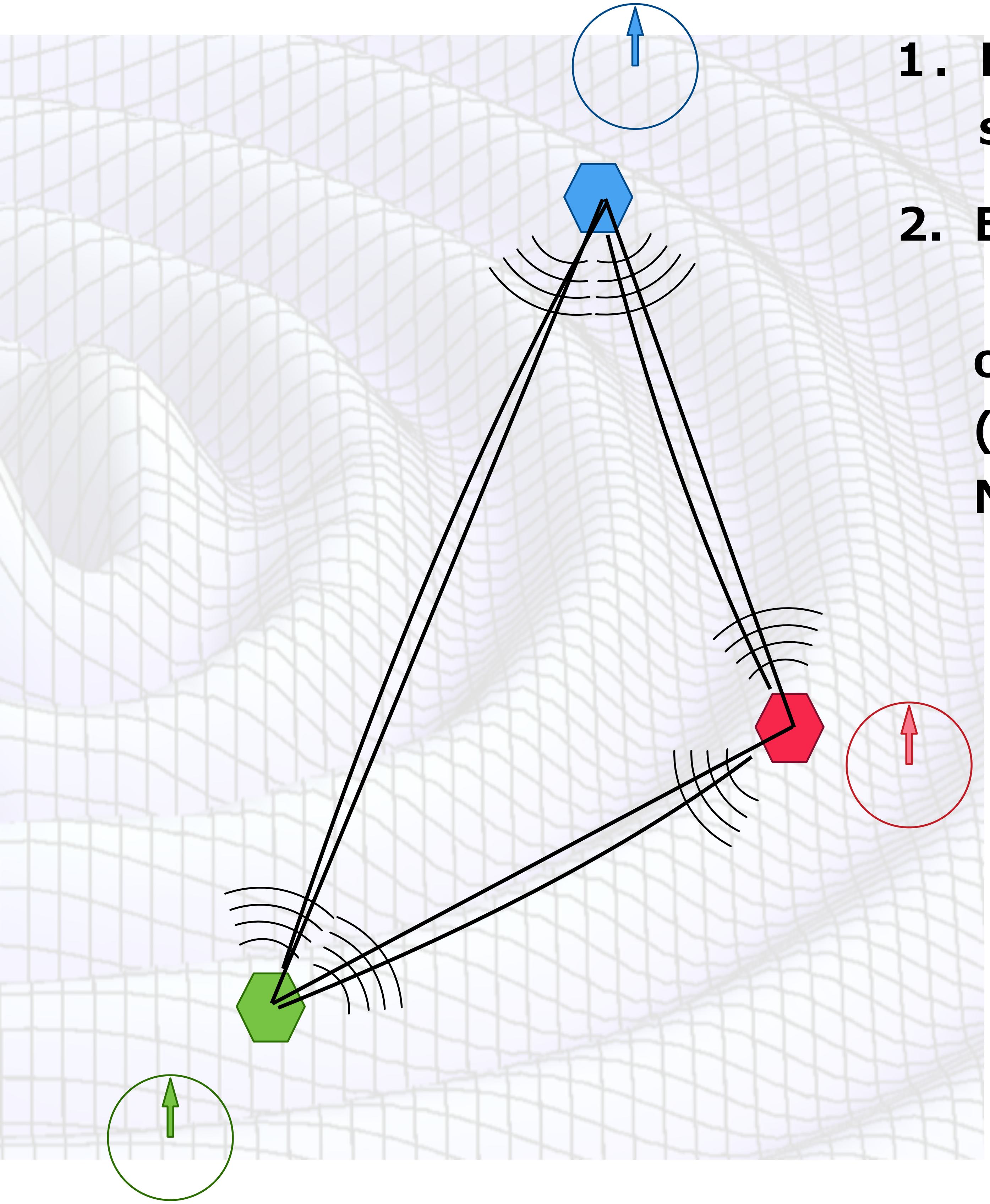
1. **Each satellite has Opt Lattice Clock, send out each time to others.**
2. **Each satellite recognizes**

   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

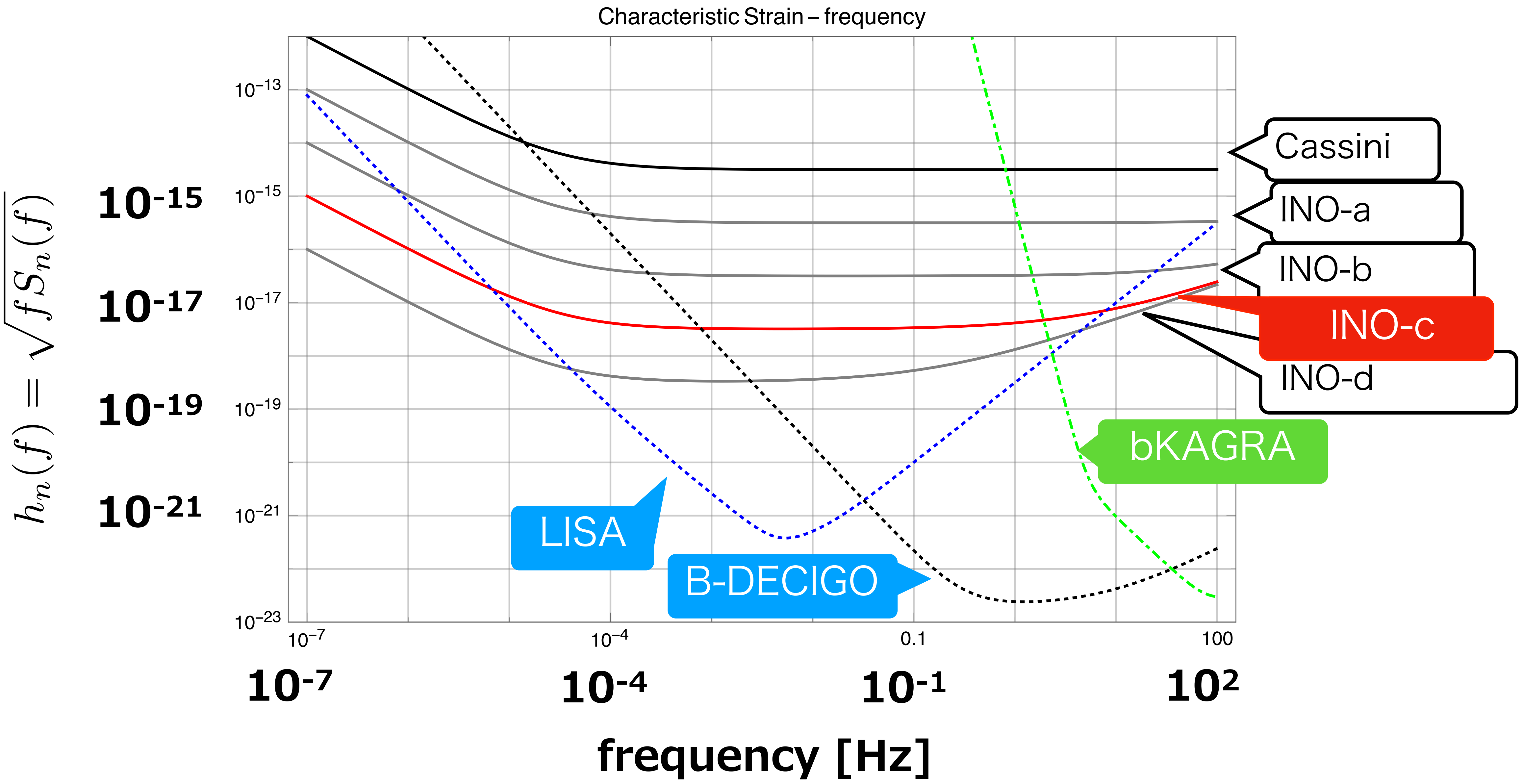


1. **Each satellite has Opt Lattice Clock, send out each time to others.**
2. **Each satellite recognizes**
   direction・distance・velocity
   of others, and we know all of them (including the potentioal of the Sun.)
   Note: effects of planets are *O*(month).
3. **When GW passes, we know its differences.**

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

2. Improvement of Doppler sensitivity（5）

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

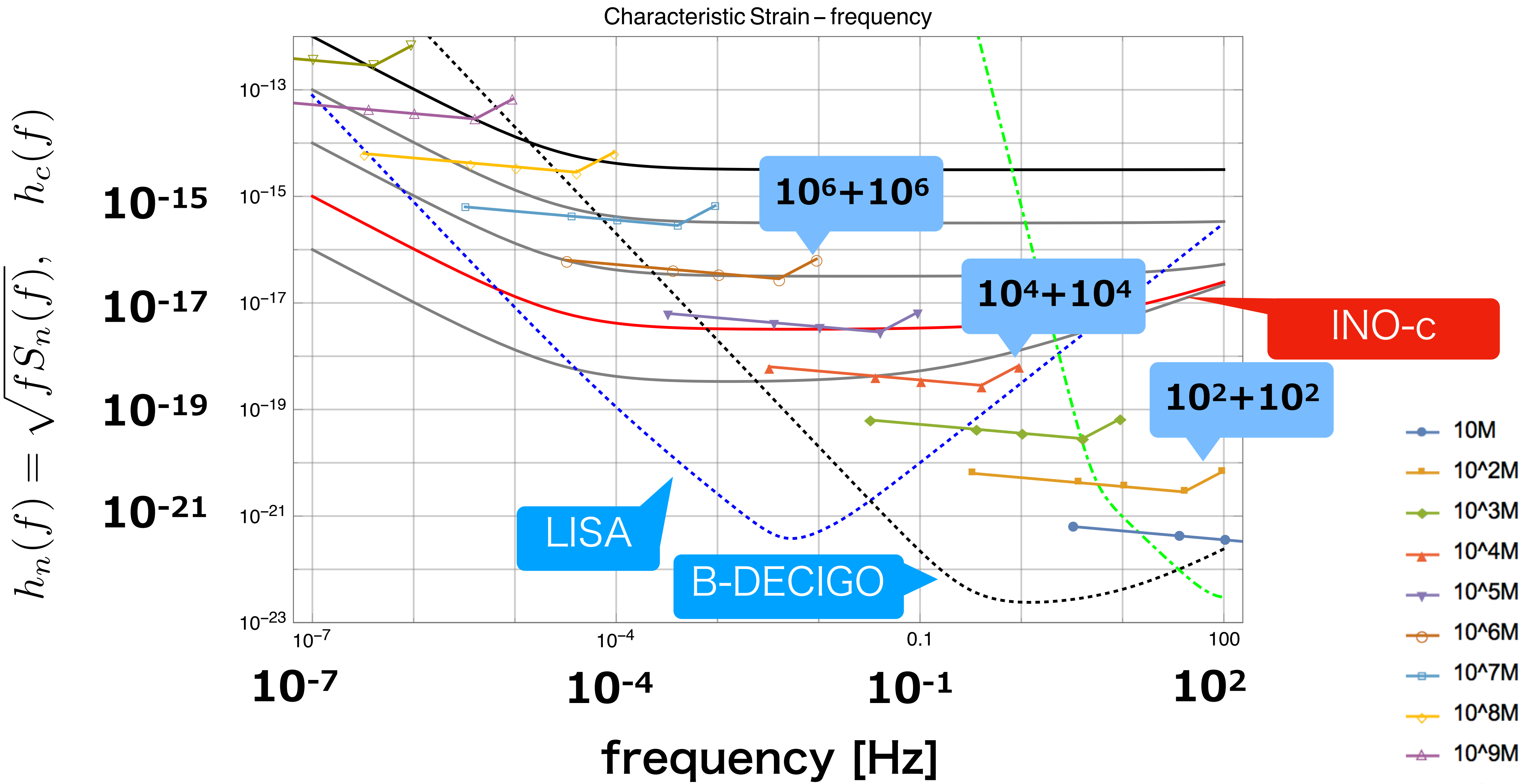


sensitivity f^{-1}
satellite control perturbation

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

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

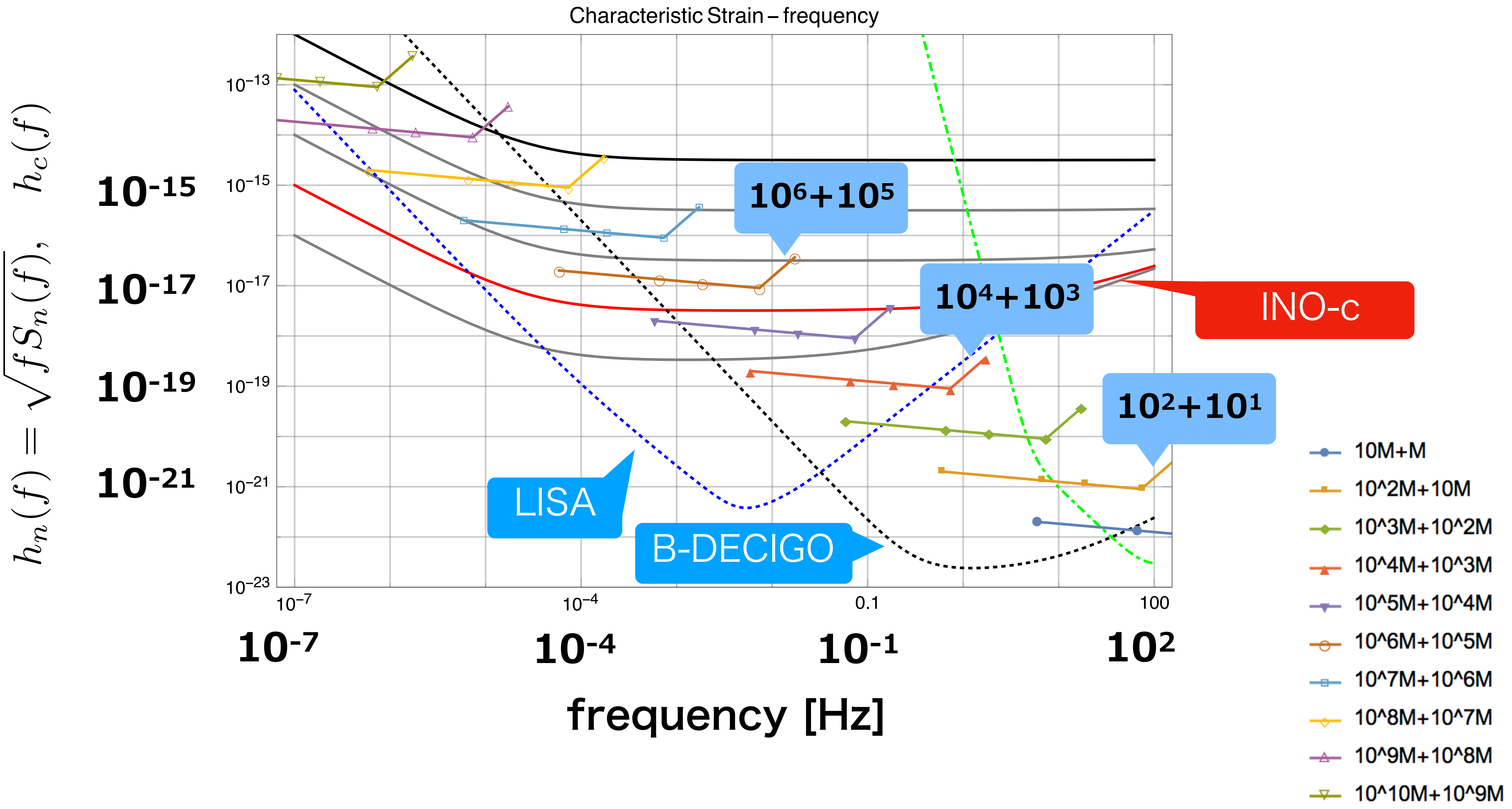
equal-mass Binary BH inspiral at 1Gpc



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

unequal-mass Binary BH inspiral at 1Gpc

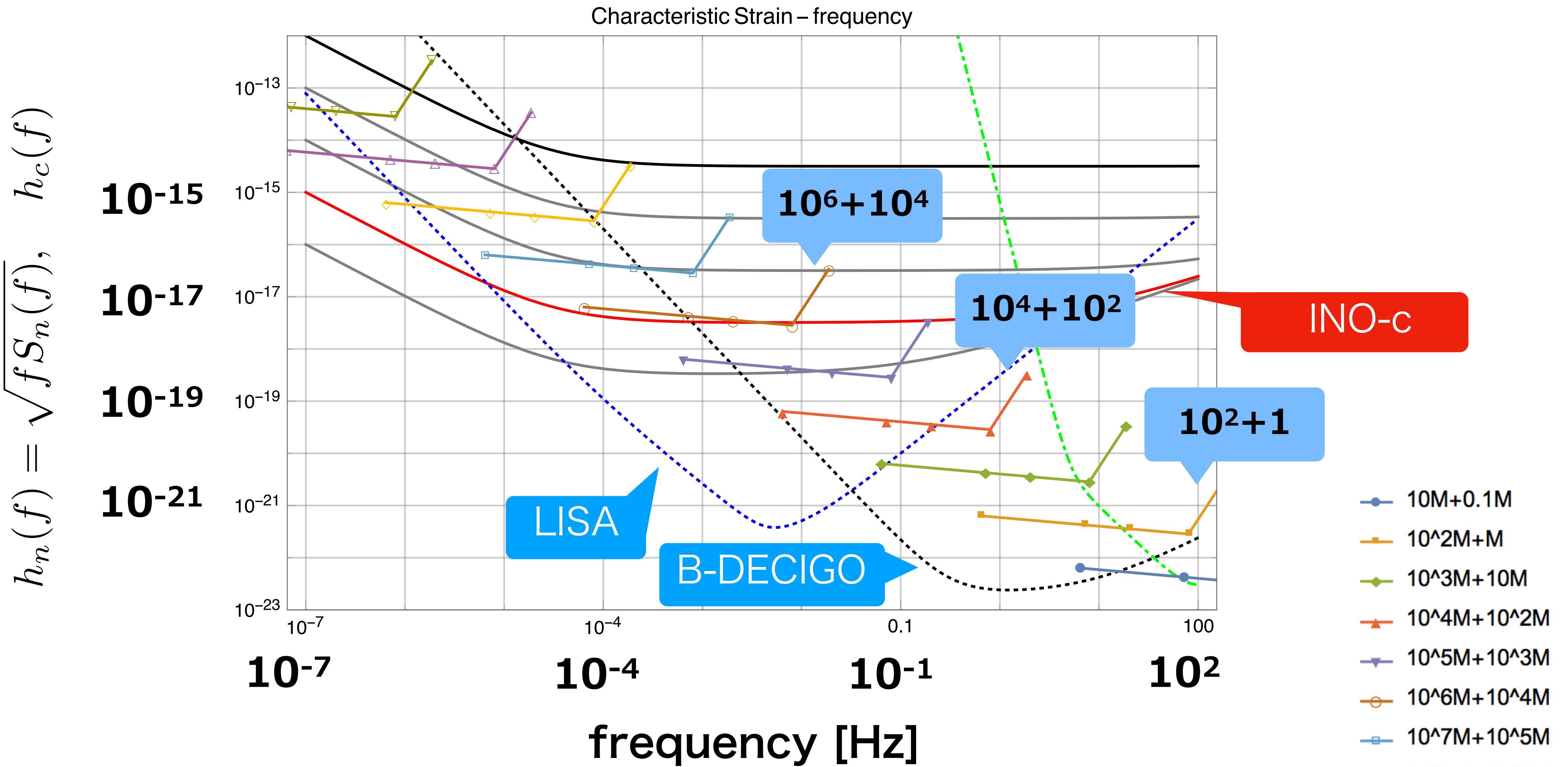
mass ratio q=0.1



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

unequal-mass Binary BH inspiral at 1Gpc

mass ratio q=0.01

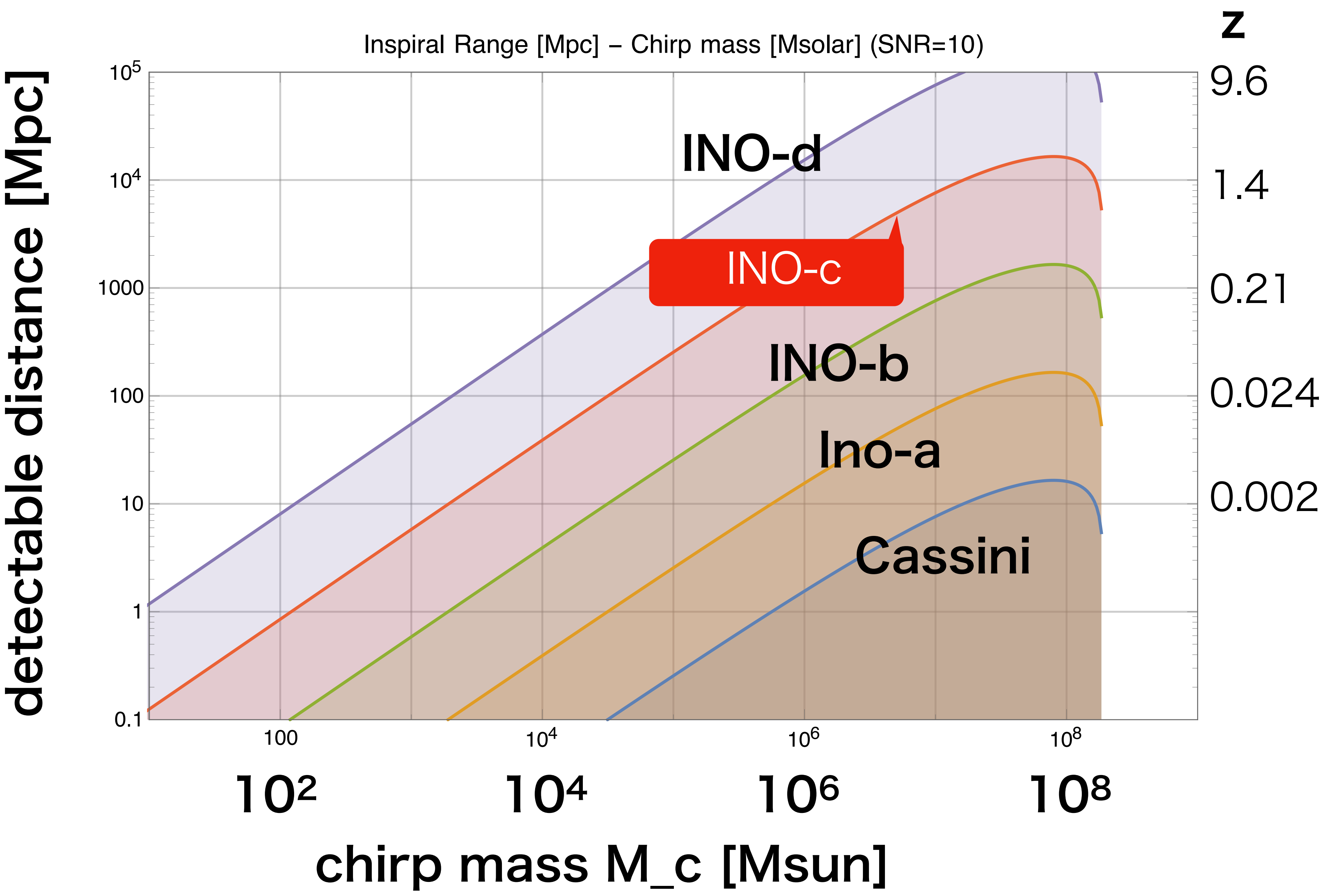


1 day=8.6x10^4 s

1 month=2.6x10^6 s

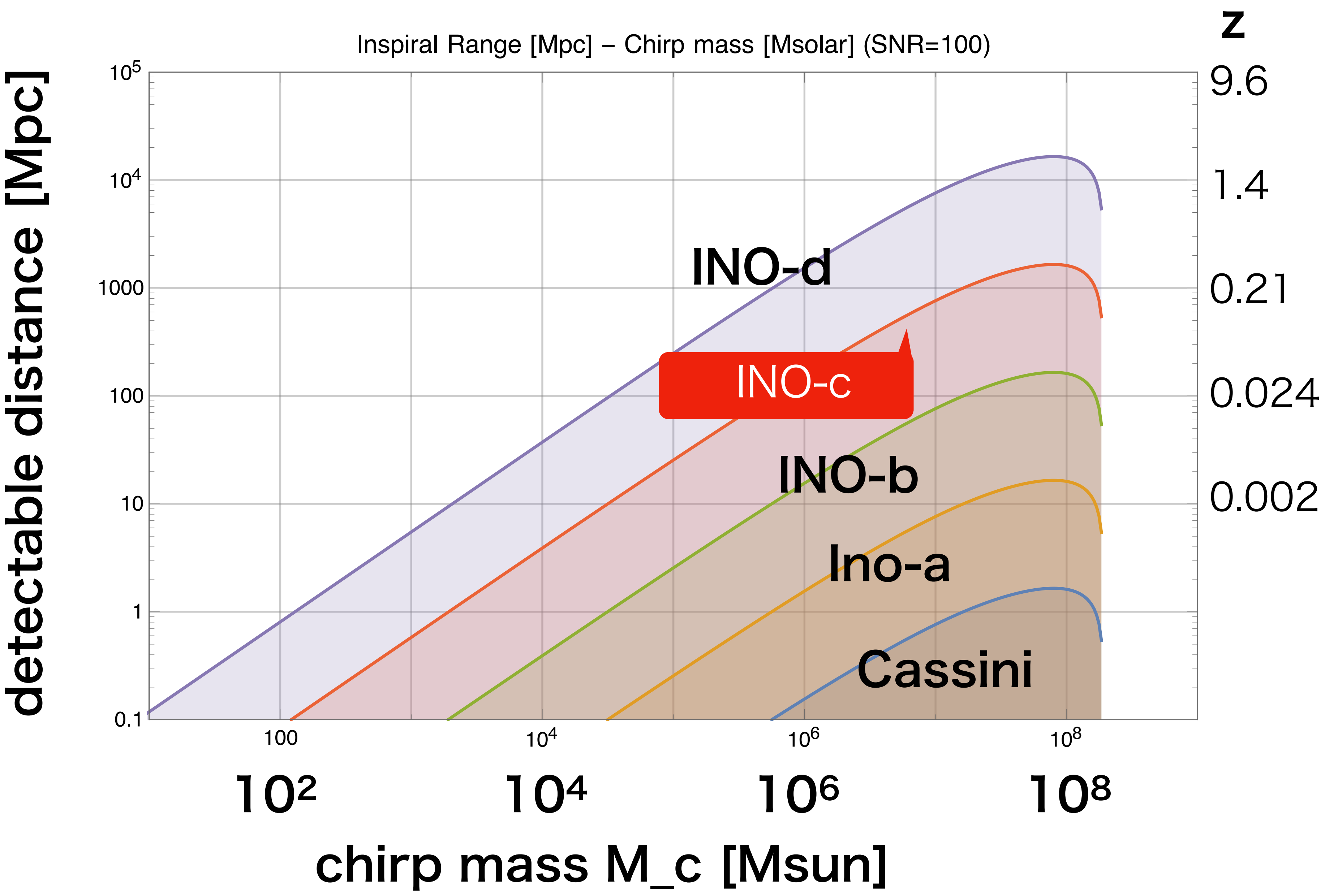
3. GW obs. using Optical Lattice Clocks : detectable distance

S/N=10



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

S/N=100

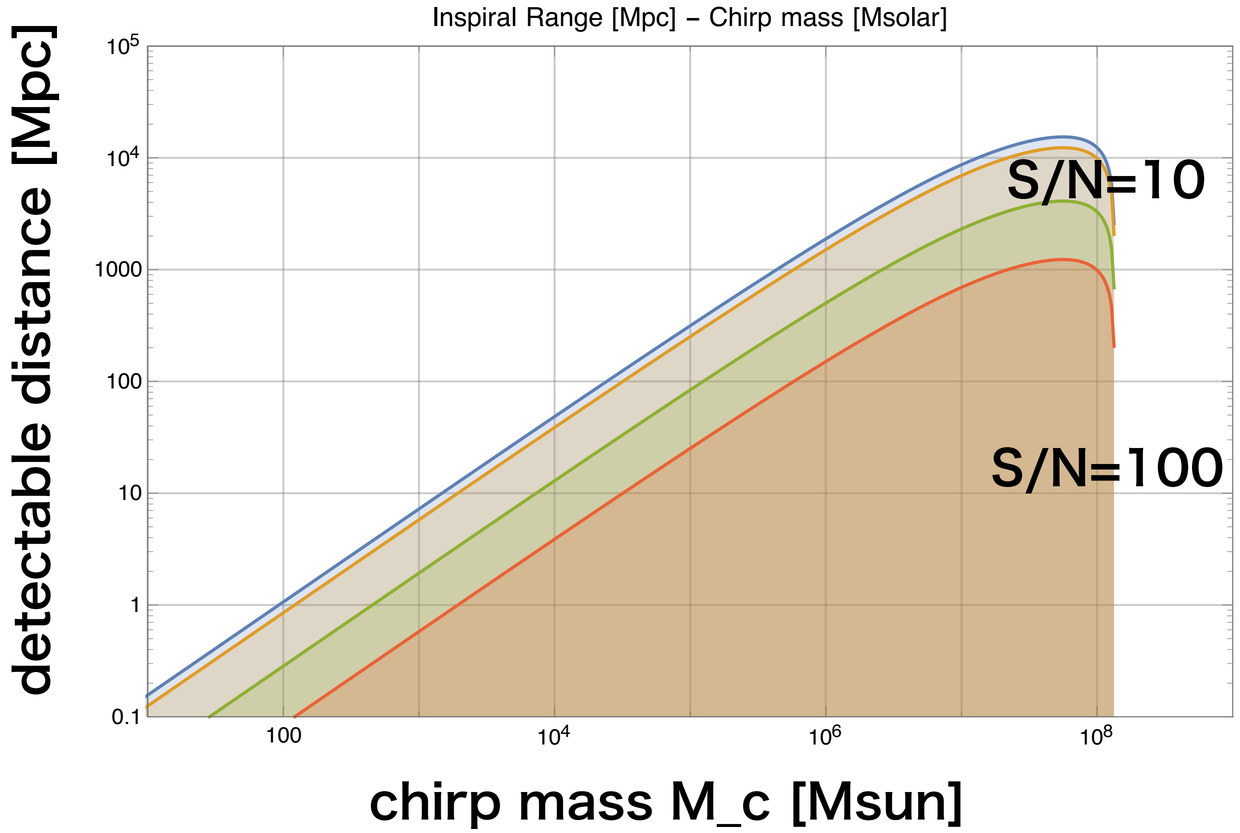


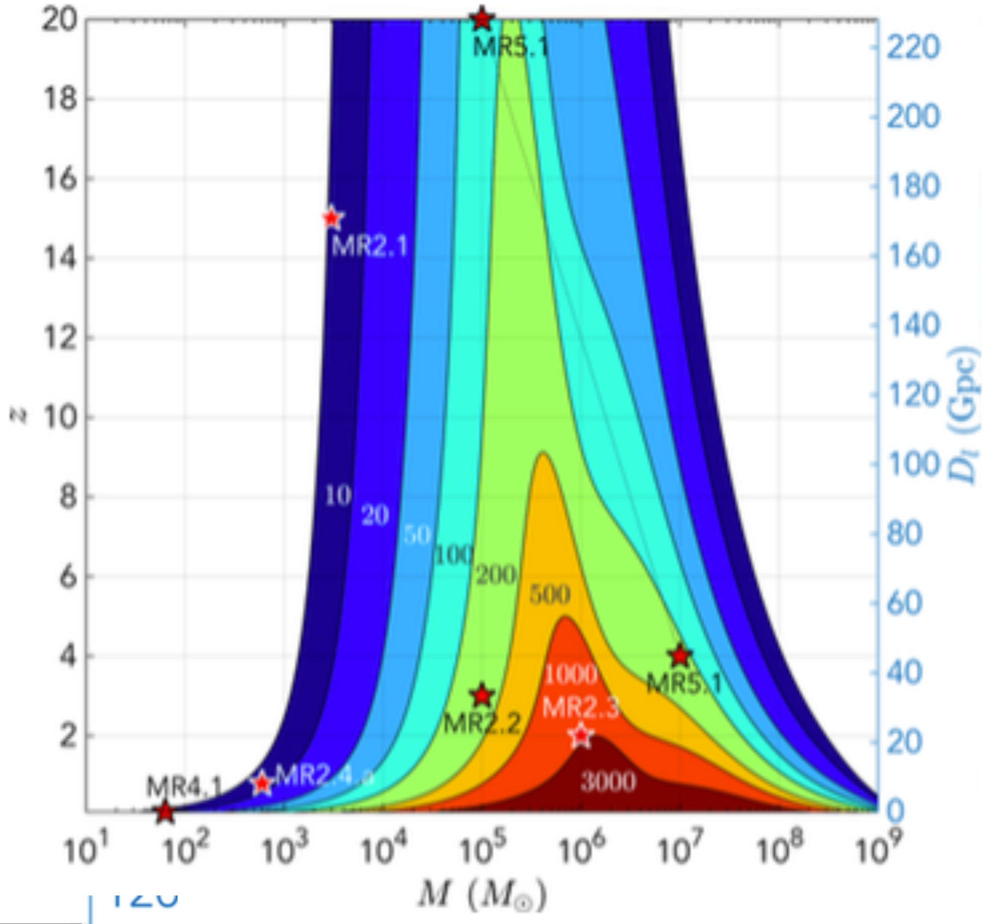
3．GW obs. using Optical Lattice Clocks : detectable distance q=0.2

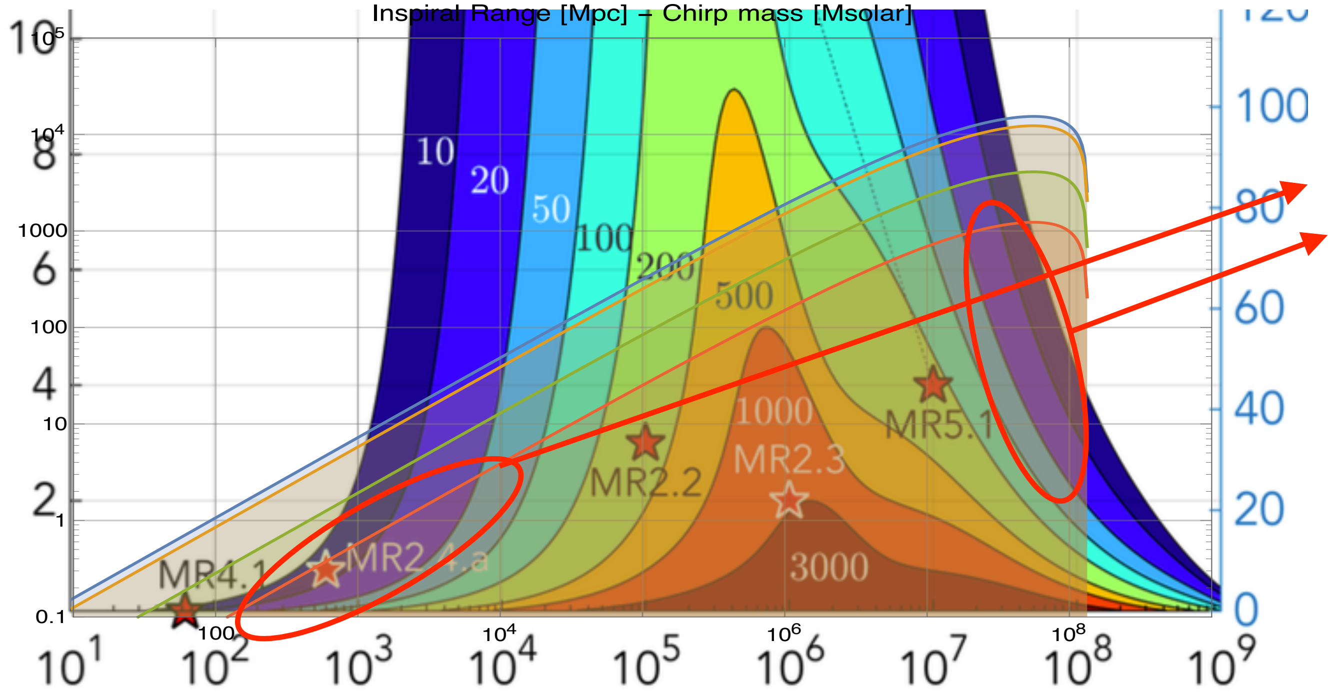
mass ratio q=0.2

INO-c

LISA 1702.00786





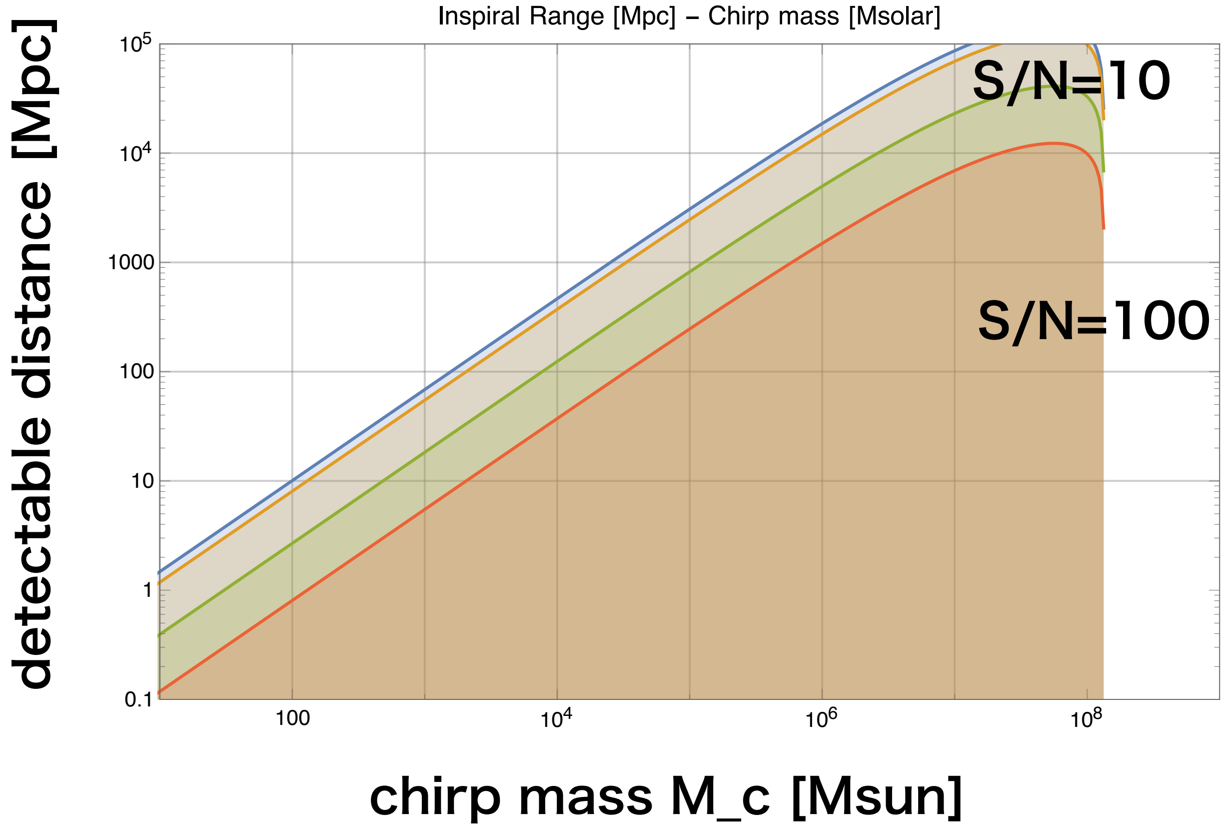


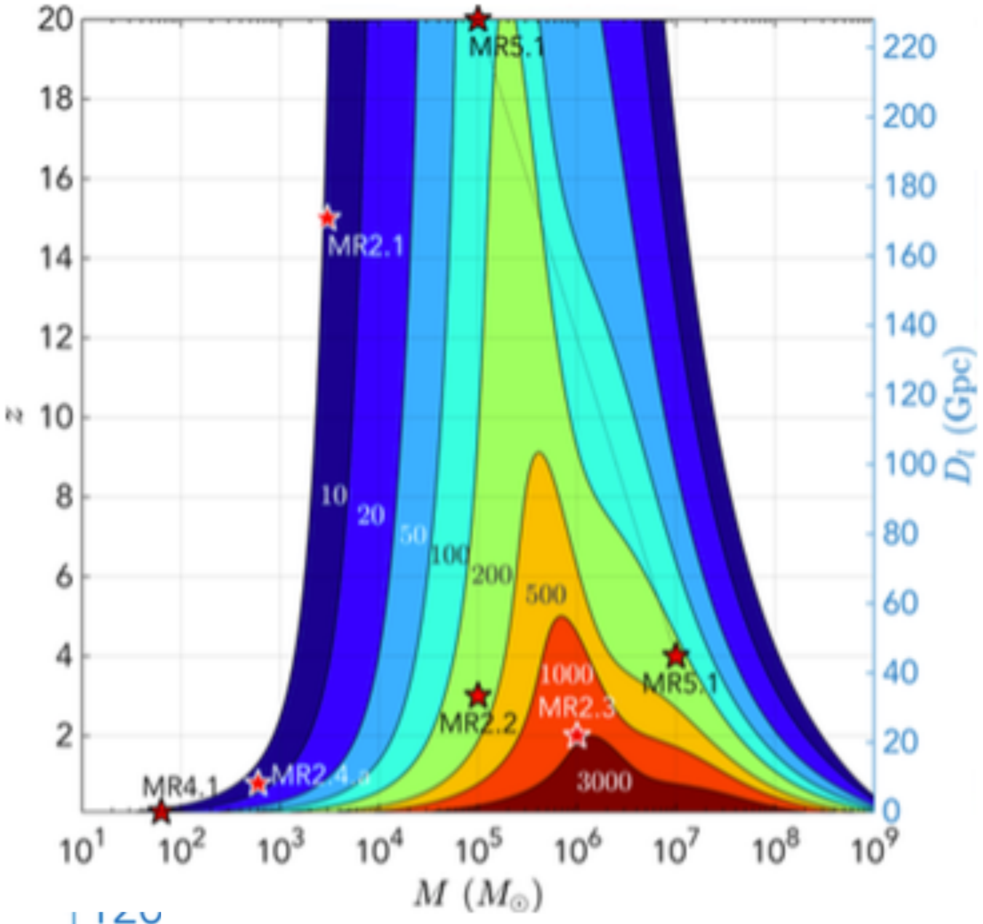
INO-c
is better than LISA

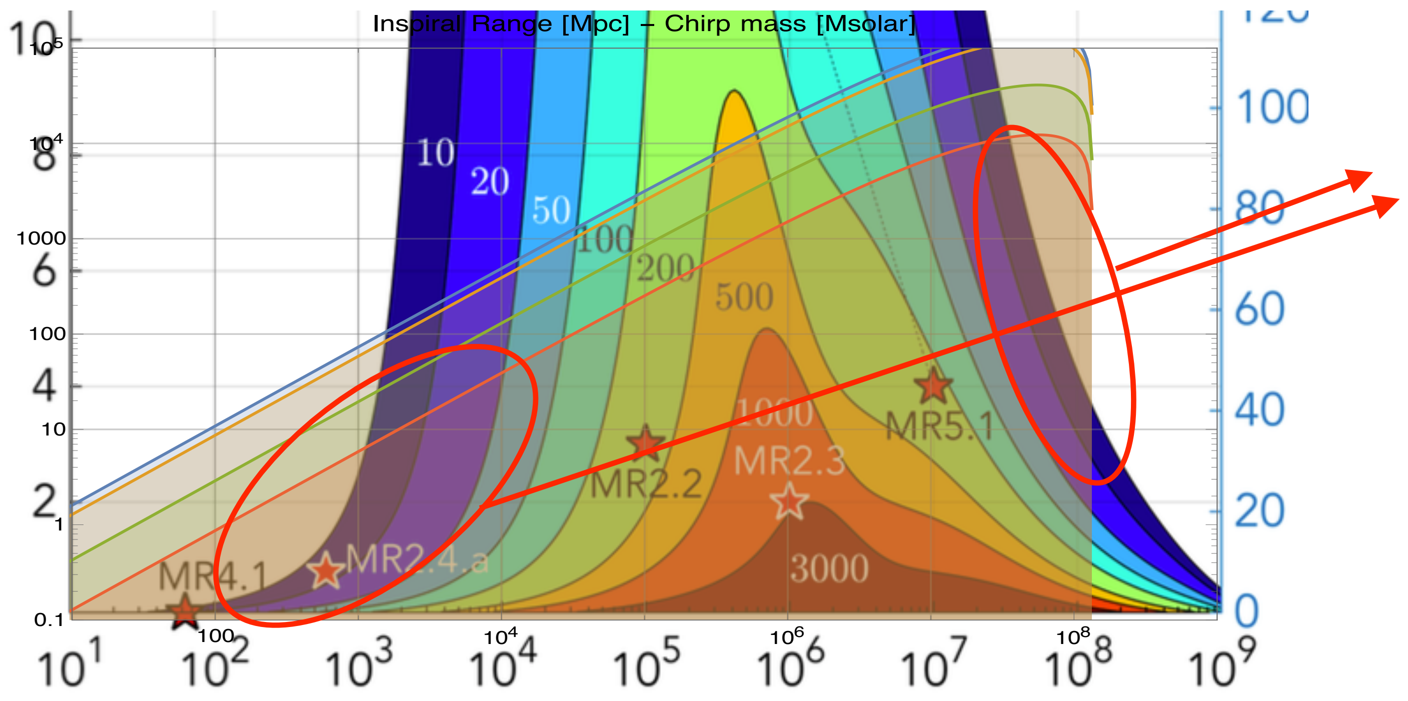
3. GW obs. using Optical Lattice Clocks : detectable distance q=0.2

mass ratio q=0.2 **INO-c**

LISA 1702.00786

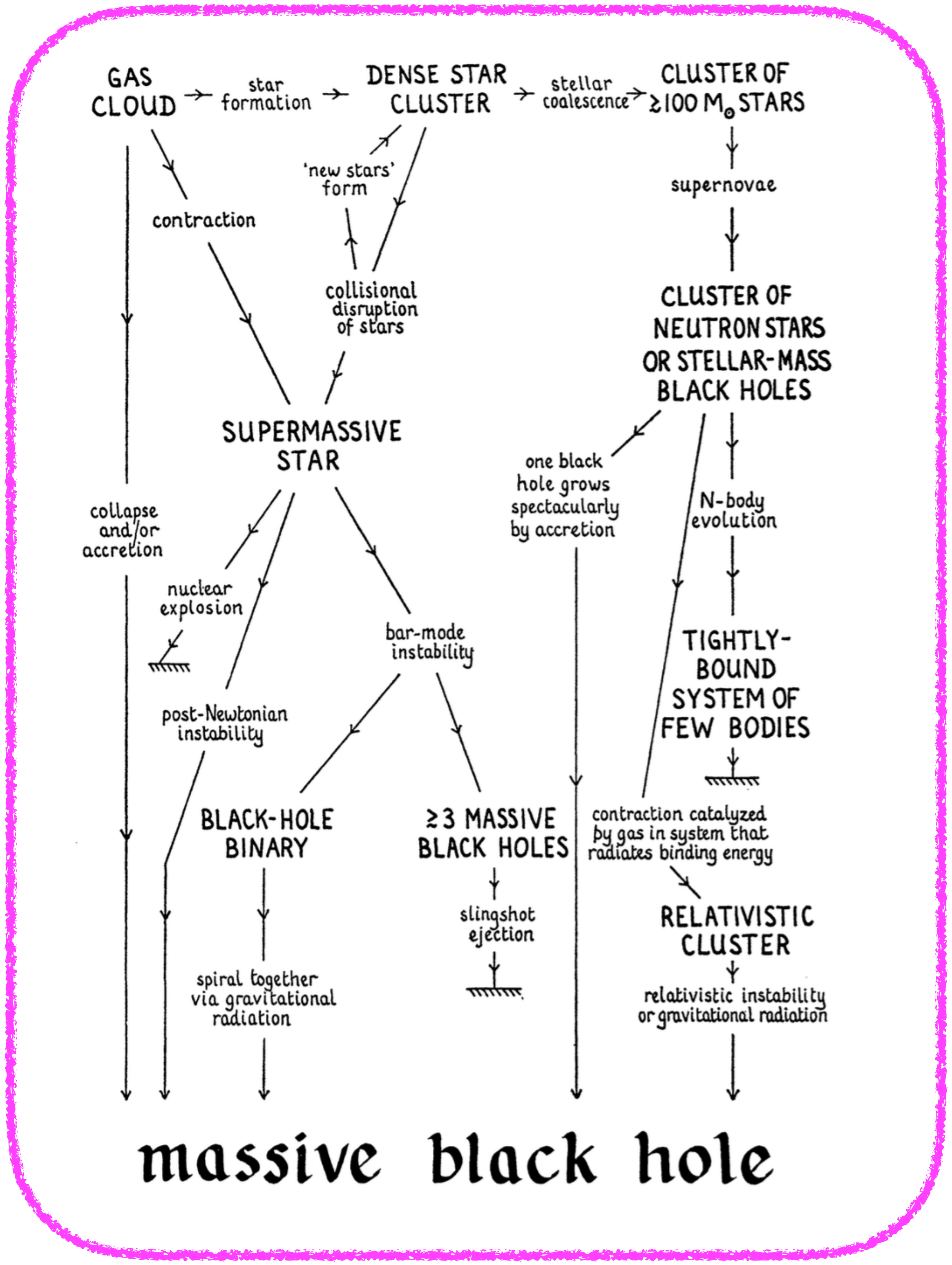




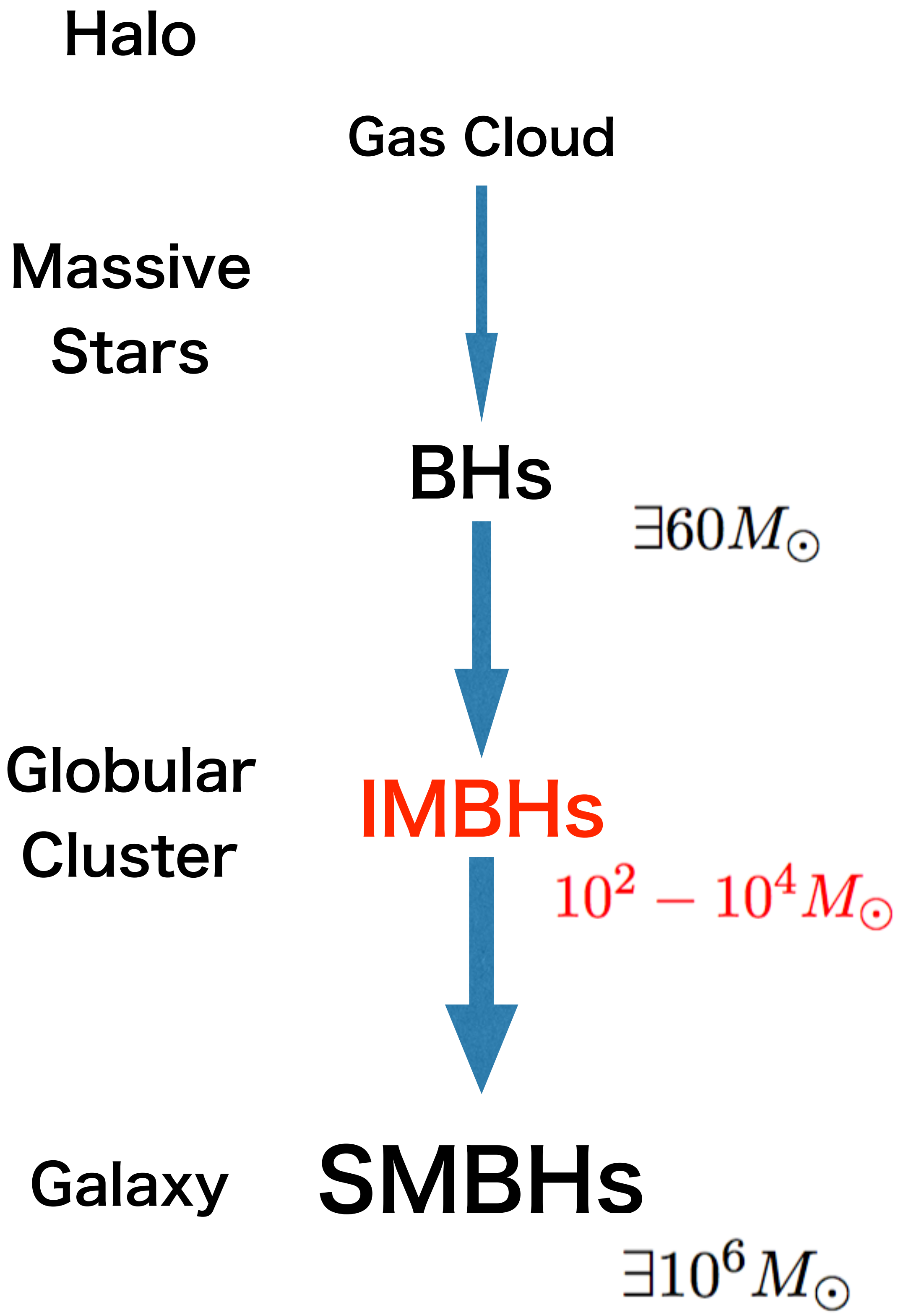


INO-c
is better than LISA

4. SMBH formation model : IMBHs' hierarchical mergers



Rees, M.J. 1978. Observatory 98: 210



Halo

Gas Cloud

Massive Stars

BHs

$\exists 60 M_\odot$

Globular Cluster

IMBHs

$10^2 - 10^4 M_\odot$

Galaxy

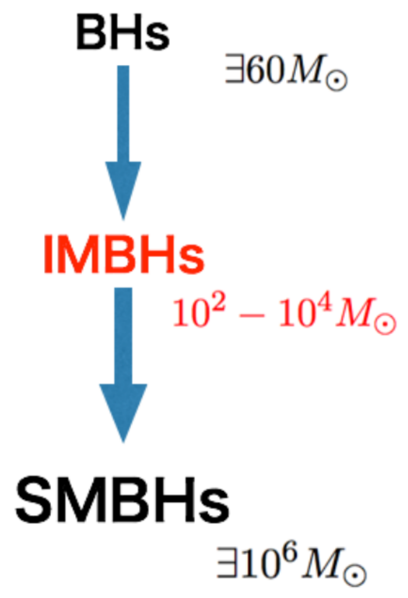
SMBHs

$\exists 10^6 M_\odot$

Ebisuzaki +, ApJ, 562, L19 (2001)

4. SMBH formation model : IMBHs' hierarchical mergers

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

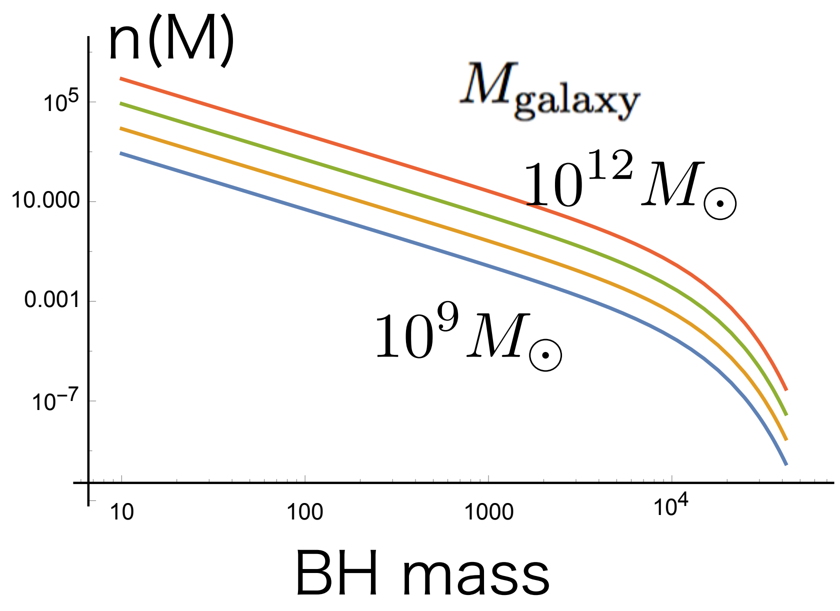


BHs $\exists 60 M_\odot$

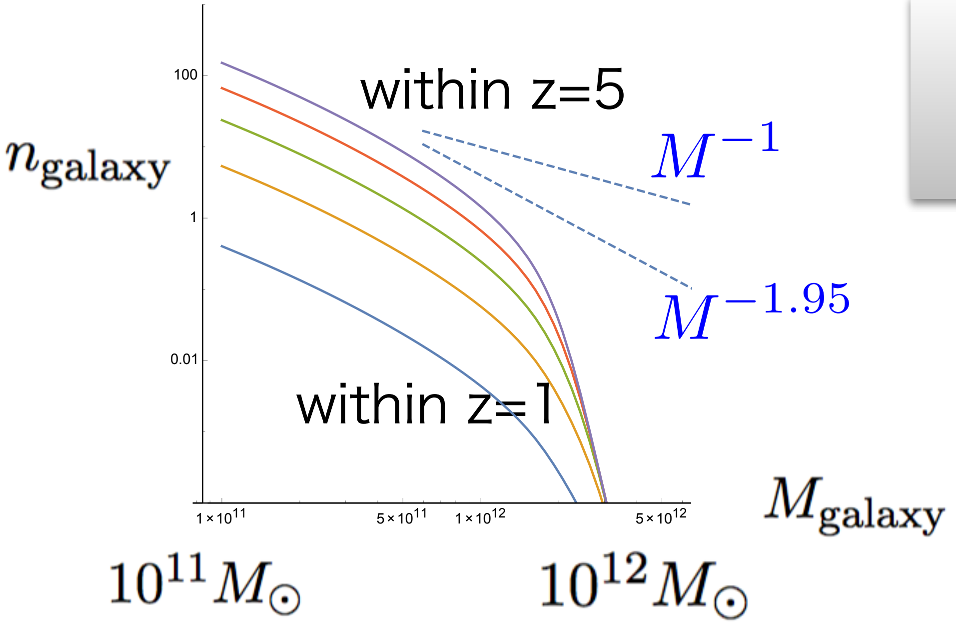
IMBHs $10^2 - 10^4 M_\odot$

SMBHs $\exists 10^6 M_\odot$

How many BHs in a Galaxy?



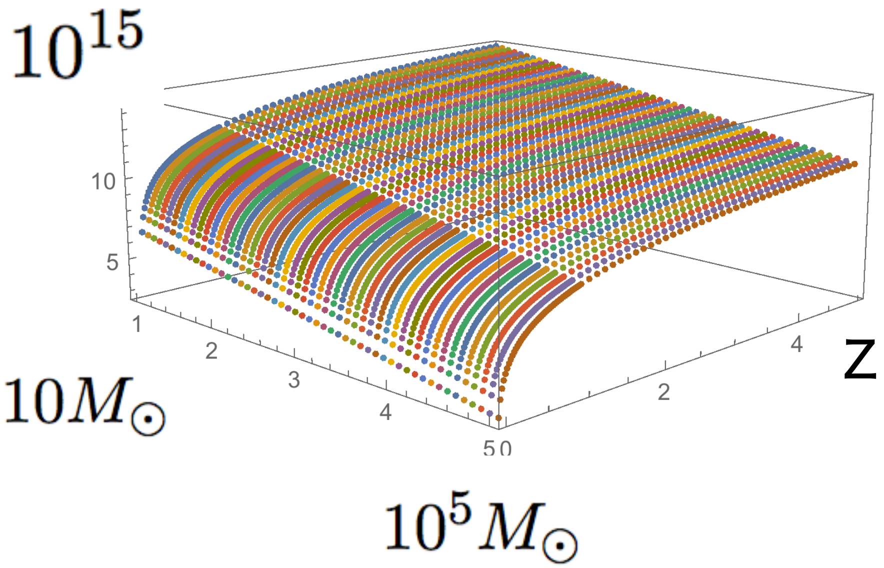
How many Galaxies in the Universe?

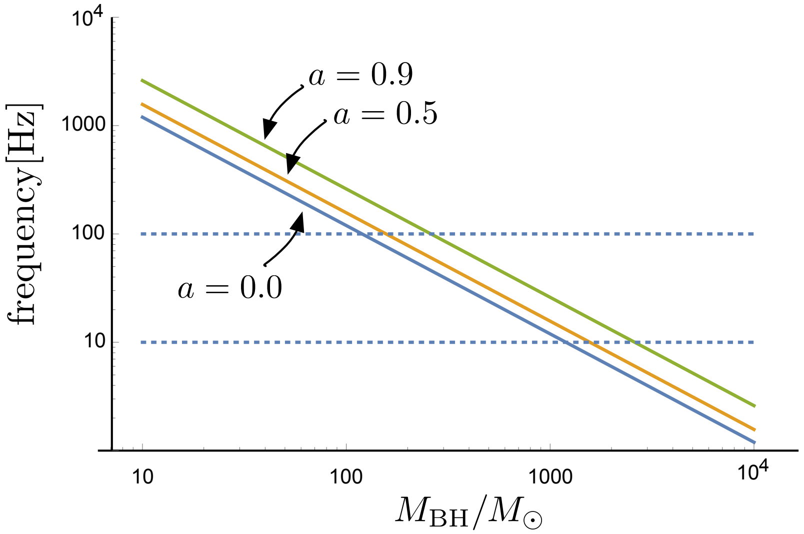


z<3

10^{12}

How many BH mergers in the Universe?

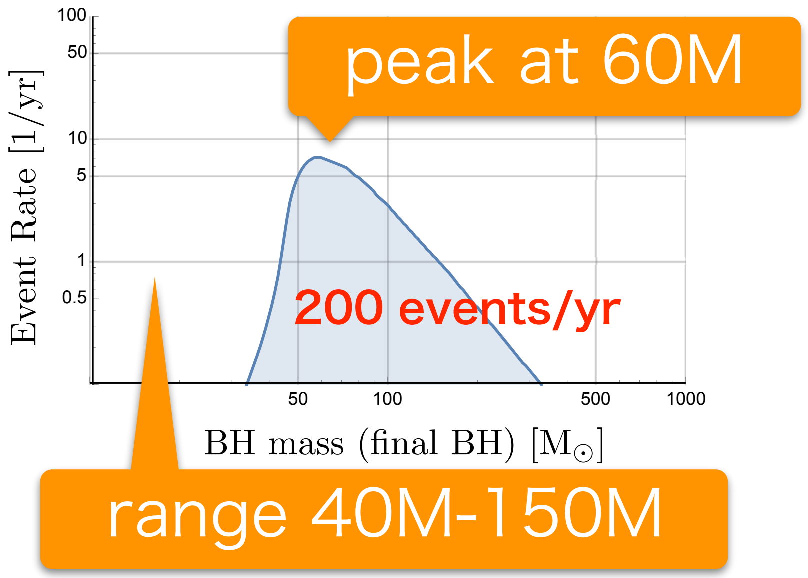




Event Rates at bKAGRA

(QNM, S/N=10)

SNR = 10, KAGRA, spin parameter averaged



peak at 60M

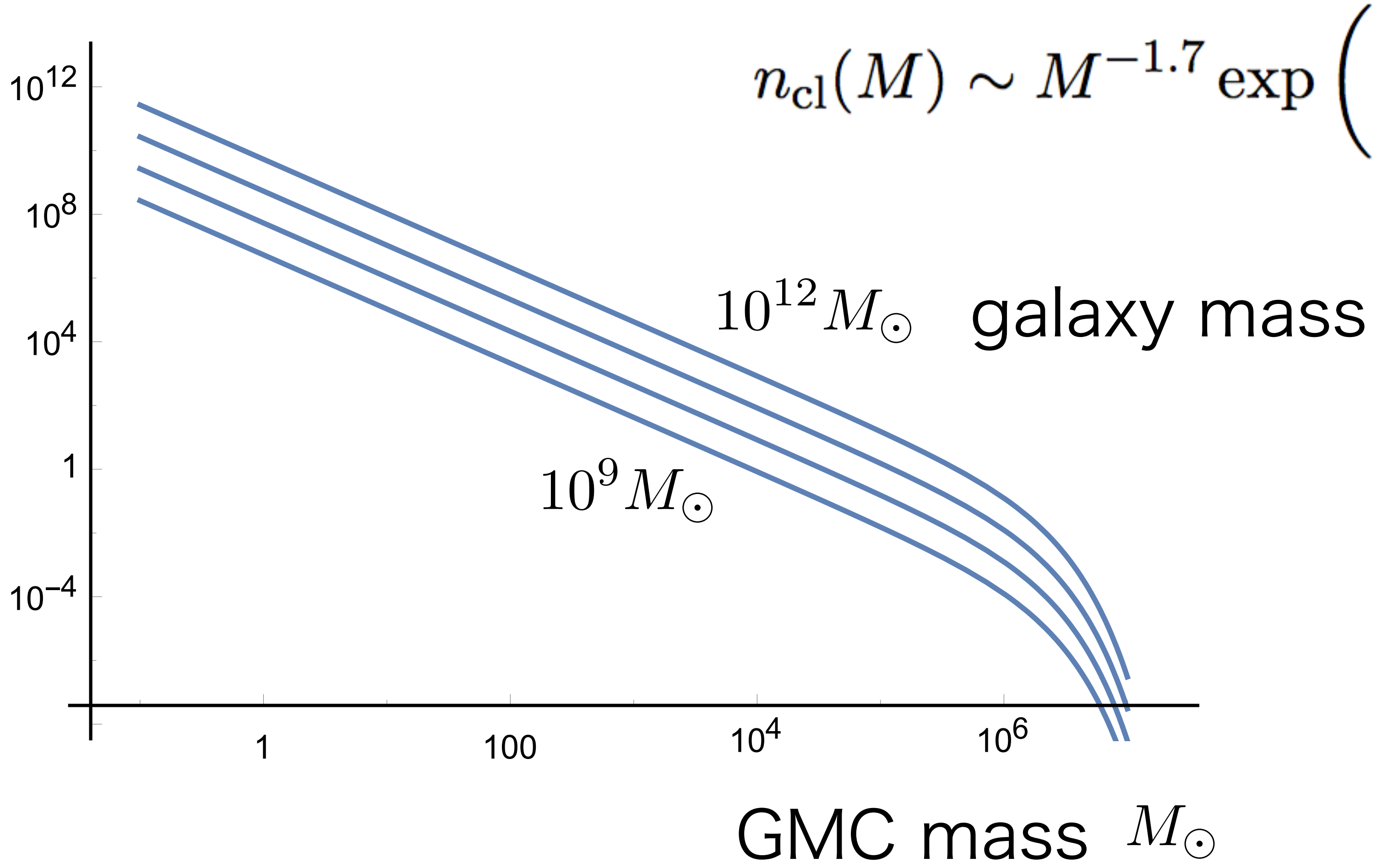
200 events/yr

range 40M-150M

How many BHs in a Galaxy?

Mass Function of Giant Molecular Clouds

$$n_{\rm cl}(M) \sim M^{-1.7} \exp\left(-\frac{M}{M_{\rm cut}}\right), \qquad M_{\rm cut} = 10^6 M_\odot$$



$$\boxed{\frac{\partial n_{\rm cl}}{\partial t} + \frac{\partial}{\partial M}\left(n_{\rm cl}\frac{dM}{dt}\right) = -\frac{n_{\rm cl}}{T_{\rm d}},}$$

The Formation and Destruction of Molecular Clouds and Galactic Star Formation

An Origin for The Cloud Mass Function and Star Formation Efficiency

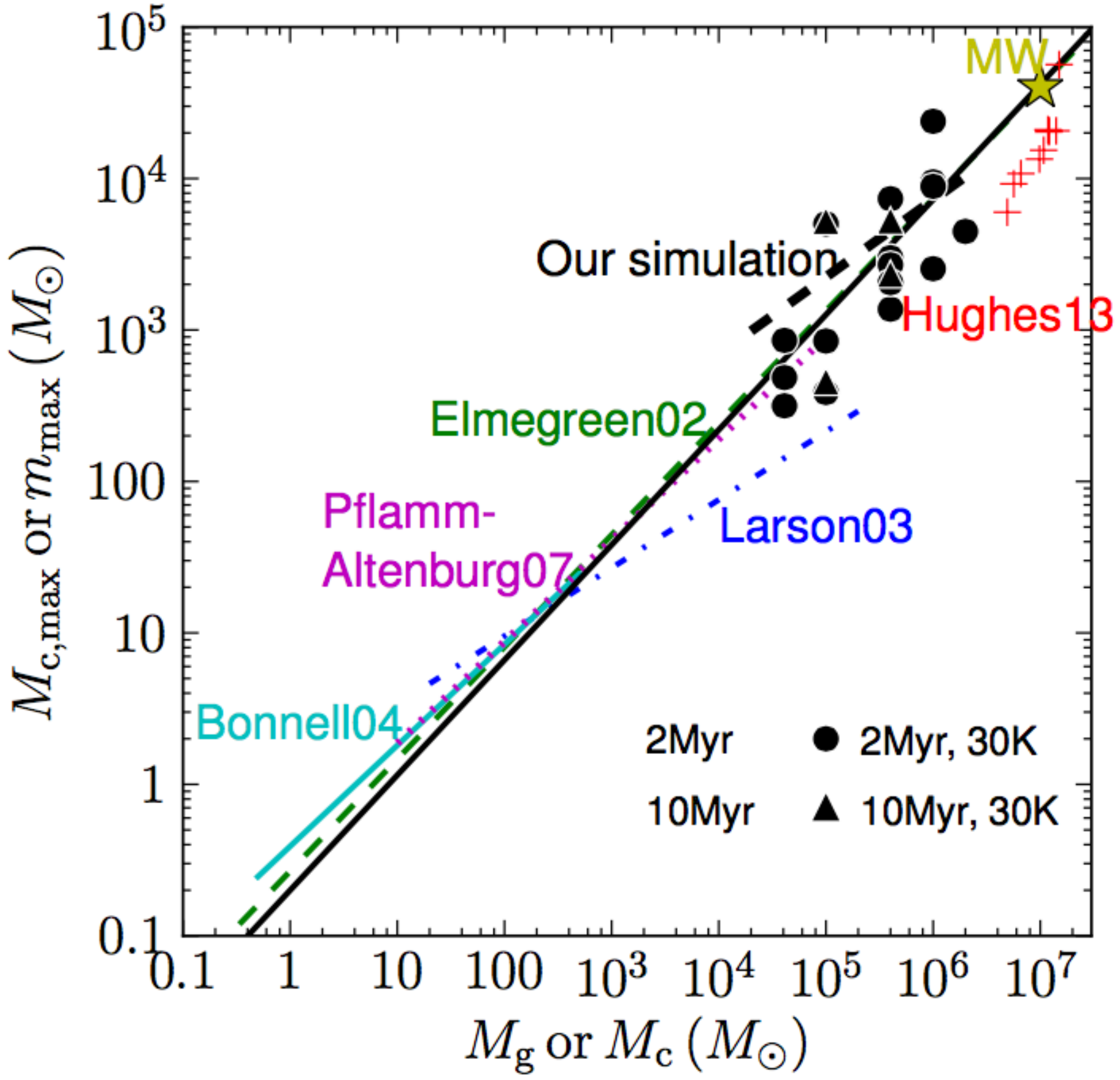
Shu-ichiro Inutsuka[1], Tsuyoshi Inoue,[2], Kazunari Iwasaki[1, 3], and Takashi Hosokawa[4]

A&A 580, A49 (2015) [arXiv:1505.04696]

How many BHs in a Galaxy?

Molecular Clouds

Maximum Core



The initial mass function of star clusters that form in turbulent molecular clouds

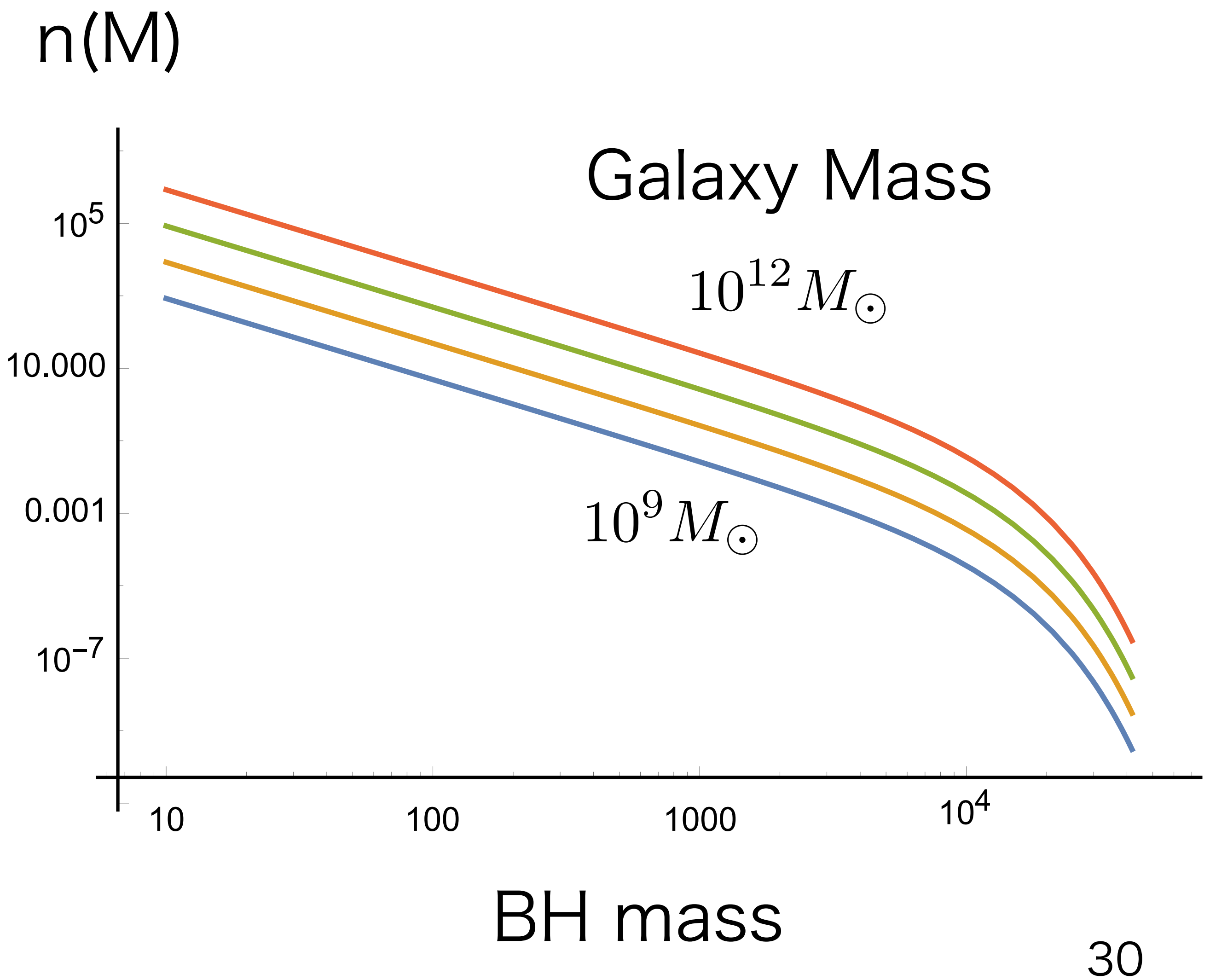
M. S. Fujii[1] ⋆ and S. Portegies Zwart[2]⋆

[1] *Division of Theoretical Astronomy, National Astronomical Observatory of Japan 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan*
[2] *Leiden Observatory, Leiden University, NL-2300RA Leiden, The Netherlands*

1309.1223v3

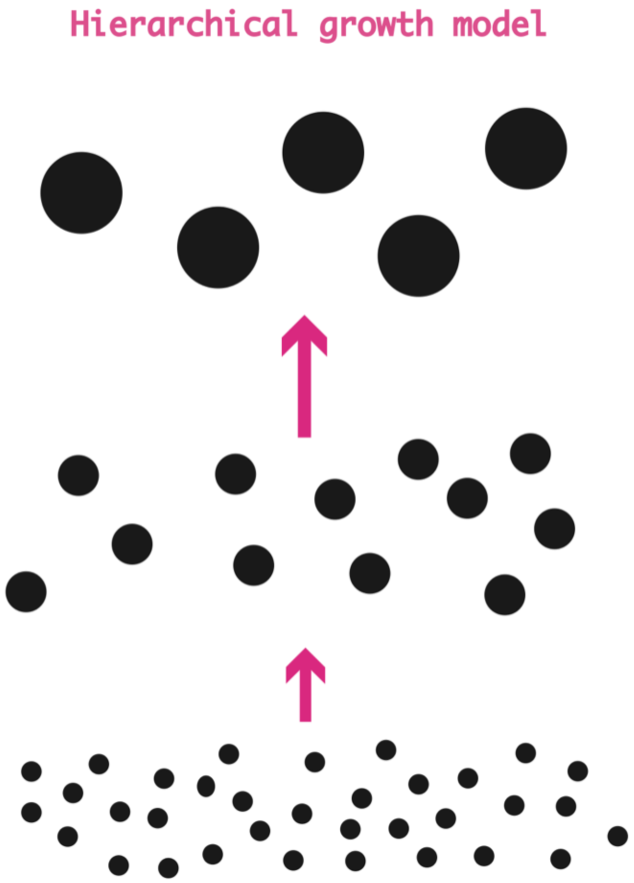
$$M_{c,\max} = 0.20 M_c^{0.76}$$

Building Block BH

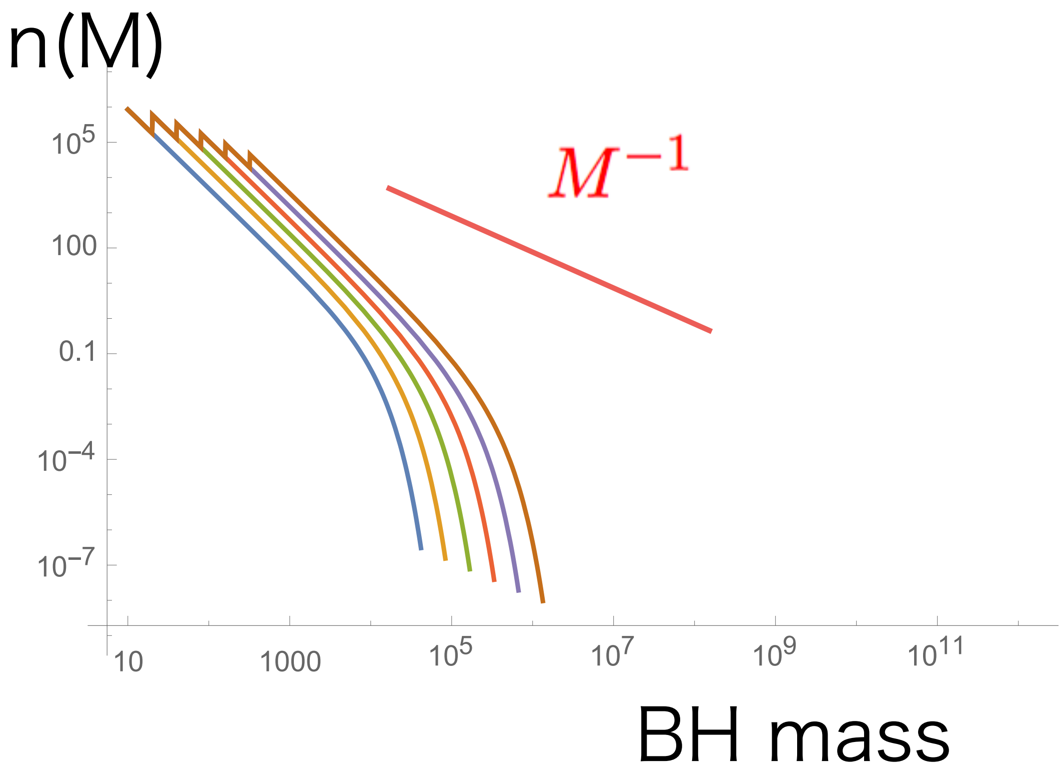


How many BHs in a Galaxy?

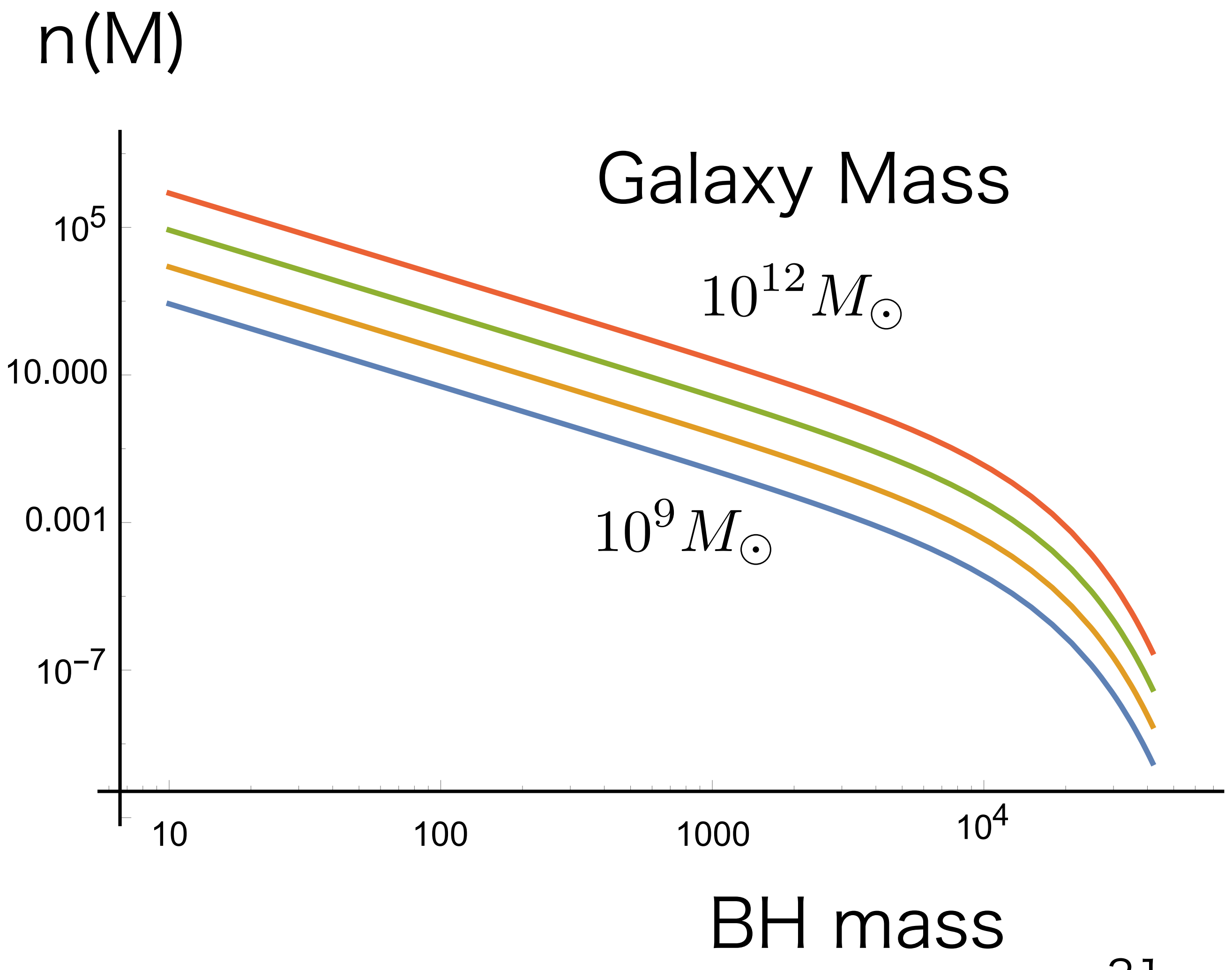
Count BHs to form a SMBH



$$\begin{aligned} M_{k+1} &= 2M_k \\ N_{k+1} &= N_k/2 \end{aligned}$$



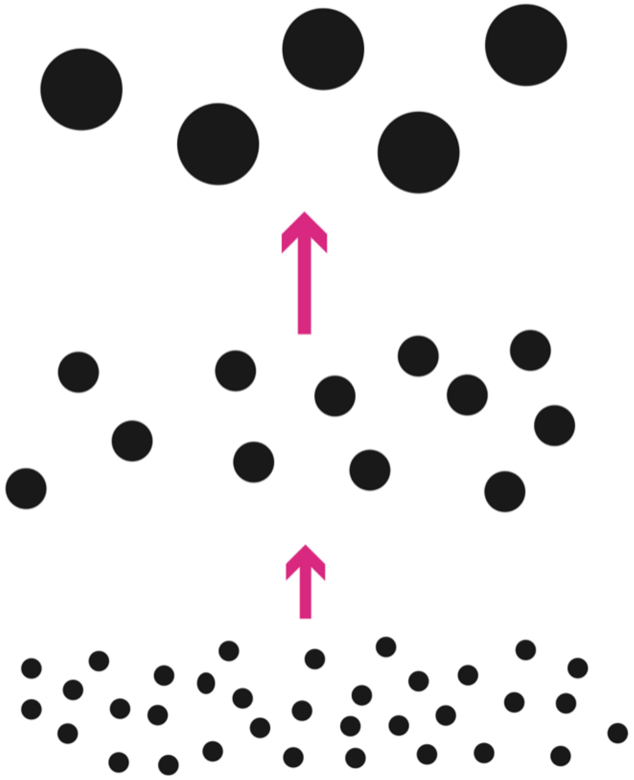
Building Block BH



How many BHs in a Galaxy?

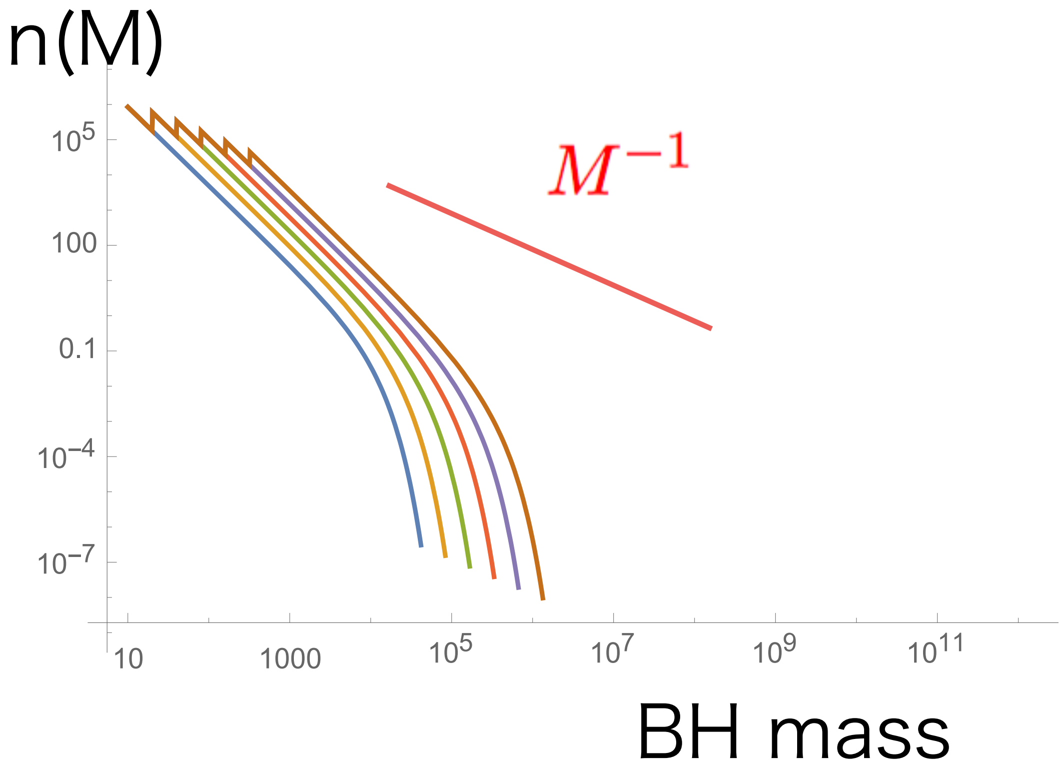
Count BHs to form a SMBH

Hierarchical growth model



$$\begin{aligned} M_{k+1} &= 2M_k \\ N_{k+1} &= N_k/2 \end{aligned}$$

dynamical friction



How many Galaxies in the Universe?

Count BHs to form a SMBH

$$
\begin{aligned}
M_{\rm SMBH} &= 2\times10^{-4} M_{\rm galaxy} \\
&= 10^{-3} M_{\rm bulge}
\end{aligned}
$$

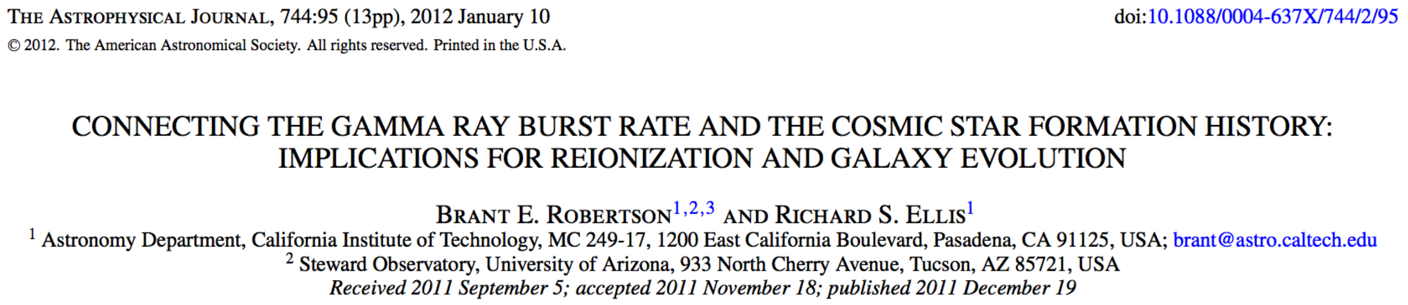
(sub-)Galaxy
from Halo model

Mon. Not. R. Astron. Soc. **371,** 1173–1187 (2006) doi:10

The non-parametric model for linking galaxy luminosity with halo/subhalo mass

A. Vale[1]★ and J. P. Ostriker[1,2]

[1] *Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA*
[2] *Princeton University Observatory, Princeton University, Princeton, NJ 08544, USA*



The Astrophysical Journal, 744:95 (13pp), 2012 January 10 doi:10.1088/0004-637X/744/2/95
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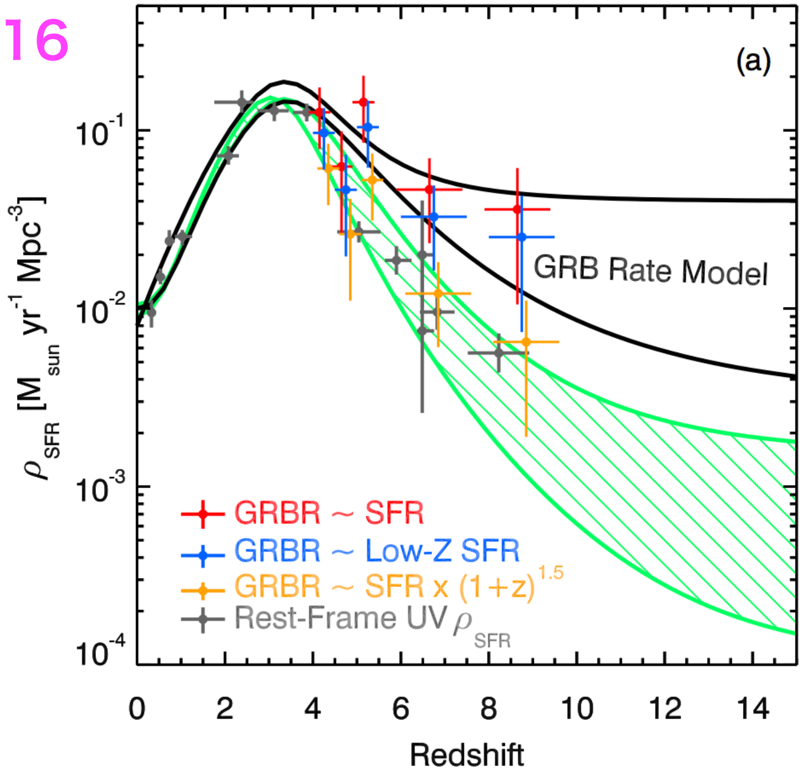
CONNECTING THE GAMMA RAY BURST RATE AND THE COSMIC STAR FORMATION HISTORY: IMPLICATIONS FOR REIONIZATION AND GALAXY EVOLUTION

Brant E. Robertson[1,2,3] and Richard S. Ellis[1]

[1] Astronomy Department, California Institute of Technology, MC 249-17, 1200 East California Boulevard, Pasadena, CA 91125, USA; brant@astro.caltech.edu
[2] Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA
Received 2011 September 5; accepted 2011 November 18; published 2011 December 19

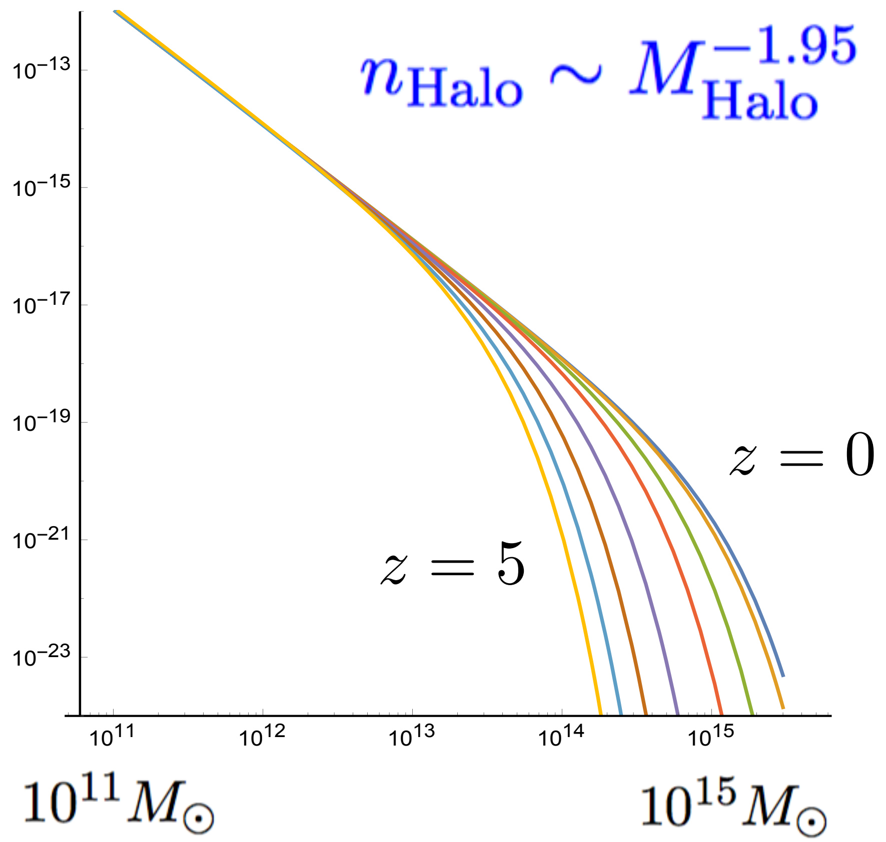
Star Formation Rate

peak z=3.16

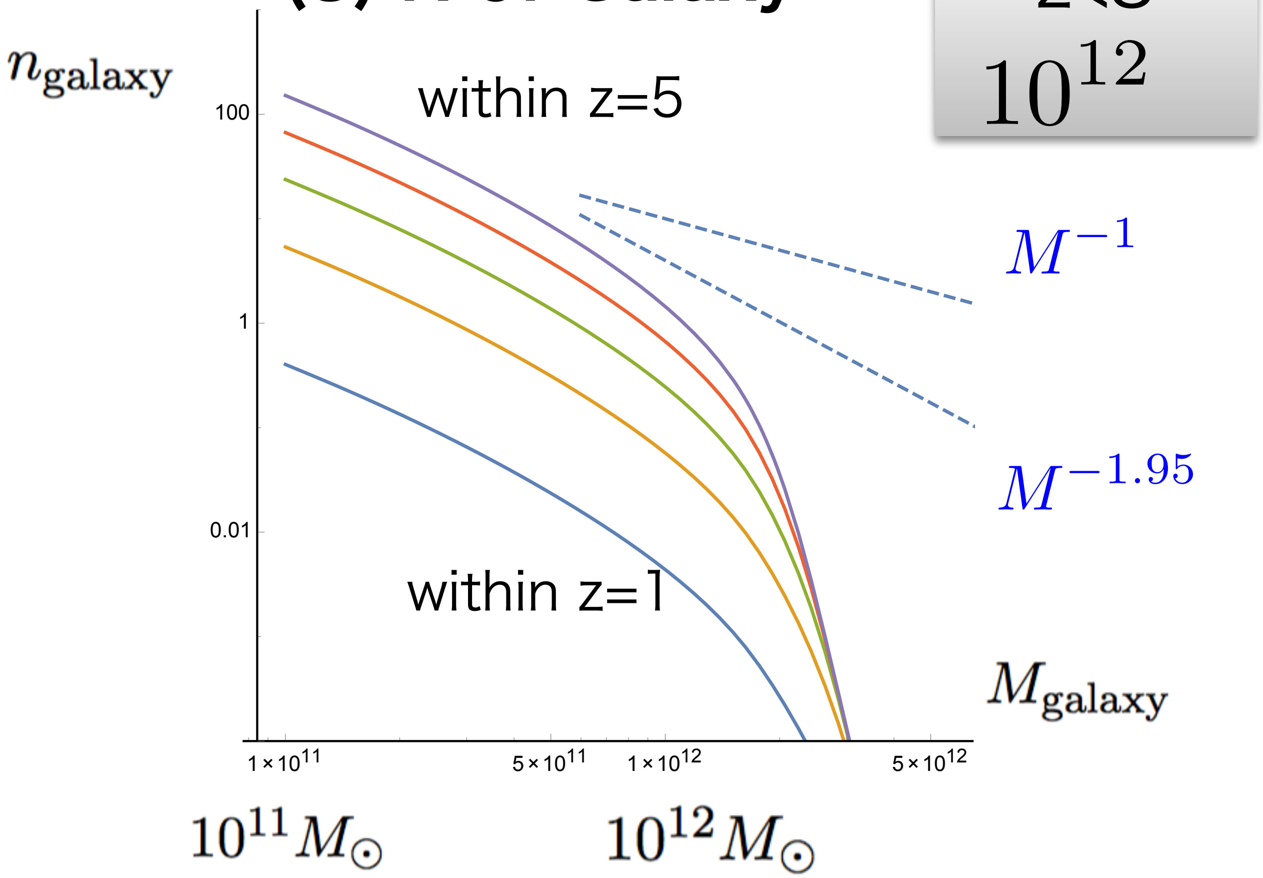


How many Galaxies in the Universe?

(1) Halo number density



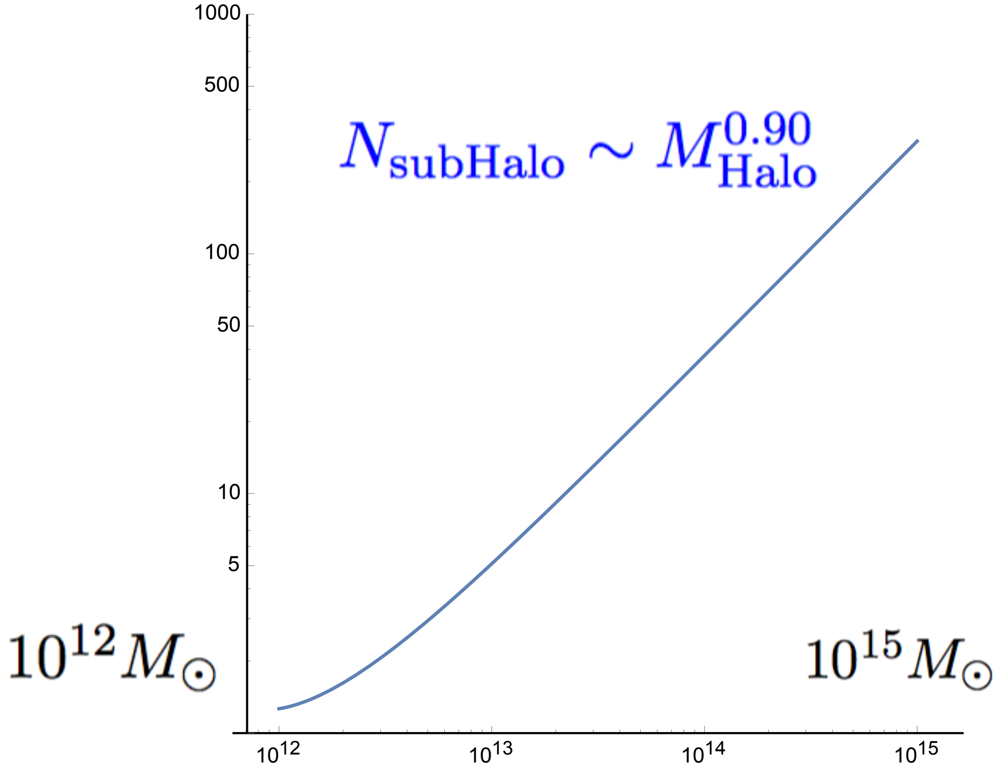
(3) N of Galaxy

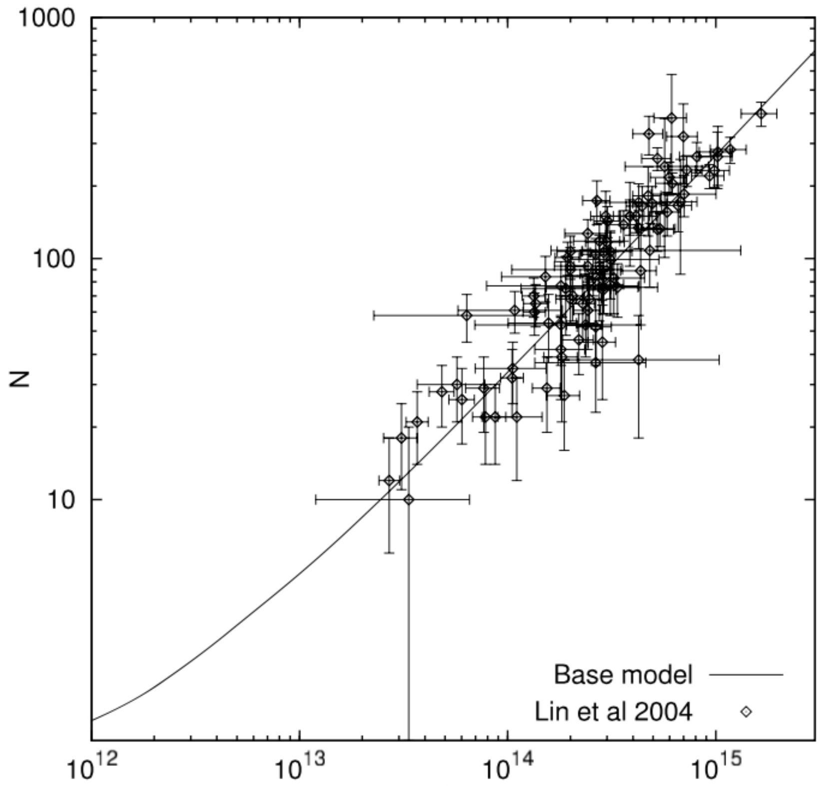


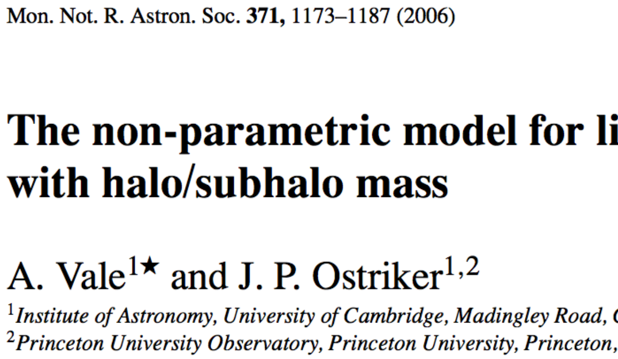
z<3

10^{12}

(2) N of seeds of Galaxy (subHalo)







Mon. Not. R. Astron. Soc. **371,** 1173–1187 (2006)

The non-parametric model for li
with halo/subhalo mass

A. Vale[1]★ and J. P. Ostriker[1,2]

[1]*Institute of Astronomy, University of Cambridge, Madingley Road,*
[2]*Princeton University Observatory, Princeton University, Princeton,*

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Advancing Astronomy and Geophysics

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NEWS & PRESS

A universe of two trillion galaxies

Last Updated on Monday, 24 October 2016 11:26
Published on Thursday, 13 October 2016 14:00

An international team of astronomers, led by Christopher Conselice, Professor of Astrophysics at the University of Nottingham, have found that the universe contains at least two trillion galaxies, ten times more than previously thought. The team's work, which began with seed-corn funding from the Royal Astronomical Society, appears in the Astrophysical Journal today.

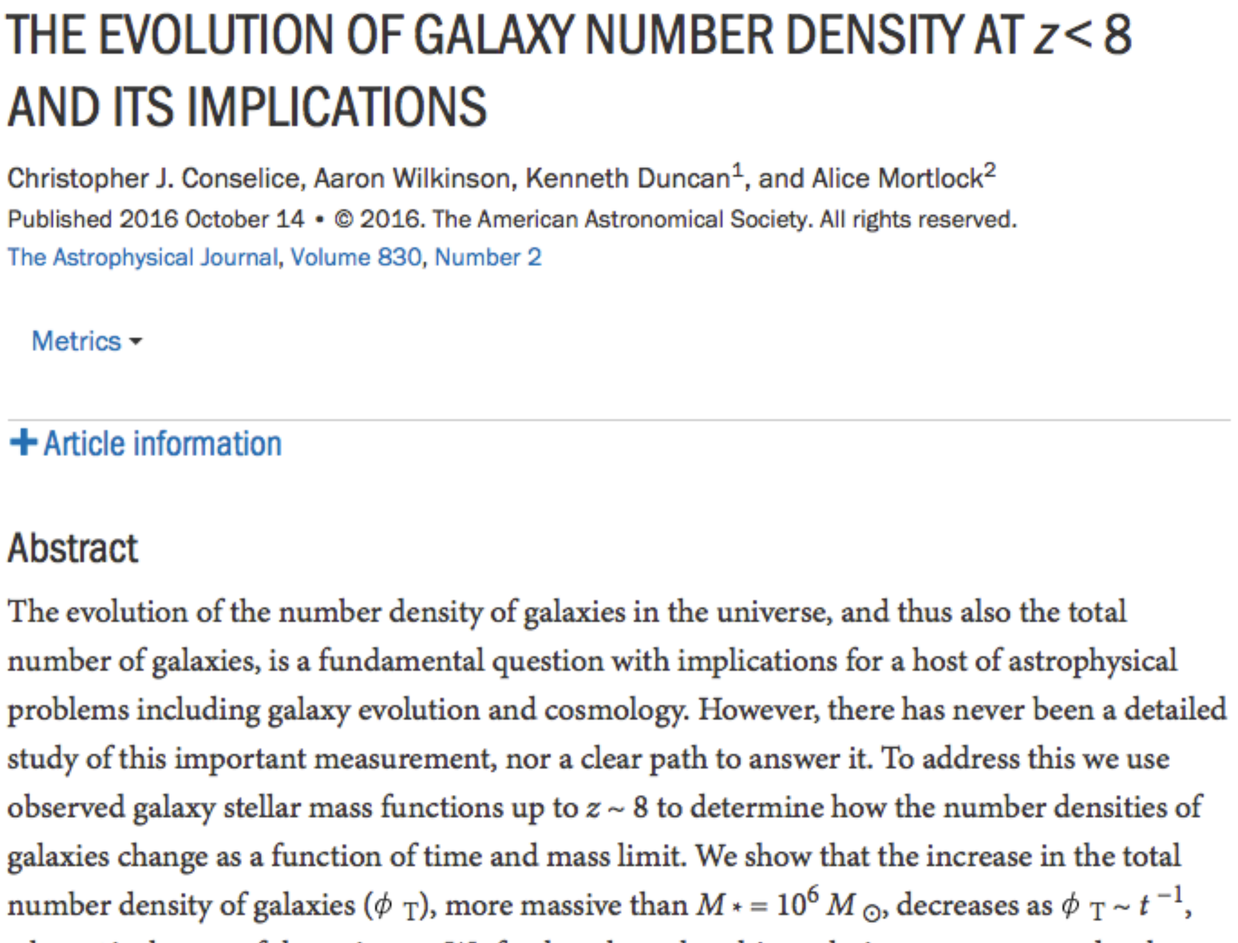
http://iopscience.iop.org/article/10.3847/0004-637X/830/2/83

https://www.ras.org.uk/news-and-press/2910-a-universe-of-two-trillion-galaxies

x10 more than before

# of galaxy (z<8) : 2×10^{12}

# of galaxy 10^6>Msun
reduces in evolution



THE EVOLUTION OF GALAXY NUMBER DENSITY AT $z<8$ AND ITS IMPLICATIONS

Christopher J. Conselice, Aaron Wilkinson, Kenneth Duncan[1], and Alice Mortlock[2]
Published 2016 October 14 • © 2016. The American Astronomical Society. All rights reserved.
The Astrophysical Journal, Volume 830, Number 2

Abstract

The evolution of the number density of galaxies in the universe, and thus also the total number of galaxies, is a fundamental question with implications for a host of astrophysical problems including galaxy evolution and cosmology. However, there has never been a detailed study of this important measurement, nor a clear path to answer it. To address this we use observed galaxy stellar mass functions up to $z\sim8$ to determine how the number densities of galaxies change as a function of time and mass limit. We show that the increase in the total number density of galaxies (ϕ_T), more massive than $M_* = 10^6 M_\odot$, decreases as $\phi_T \sim t^{-1}$,

How many Galaxies in the Universe?

Count BHs to form a SMBH

$$\begin{aligned} M_{\rm SMBH} &= 2\times10^{-4} M_{\rm galaxy} \\ &= 10^{-3} M_{\rm bulge} \end{aligned}$$

(sub-)Galaxy
from Halo model

Mon. Not. R. Astron. Soc. **371,** 1173–1187 (2006) doi:10

The non-parametric model for linking galaxy luminosity with halo/subhalo mass

A. Vale[1]★ and J. P. Ostriker[1,2]

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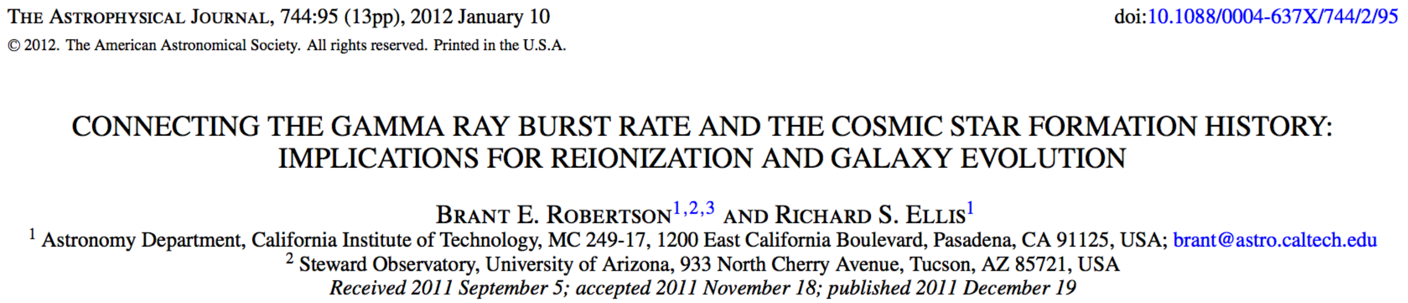

THE ASTROPHYSICAL JOURNAL, 744:95 (13pp), 2012 January 10 doi:10.1088/0004-637X/744/2/95
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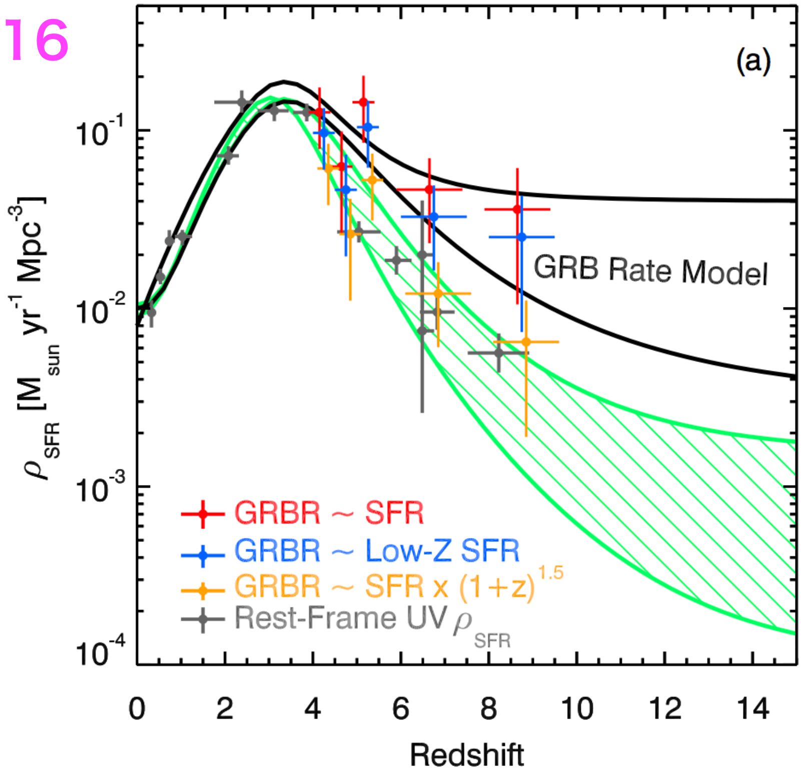
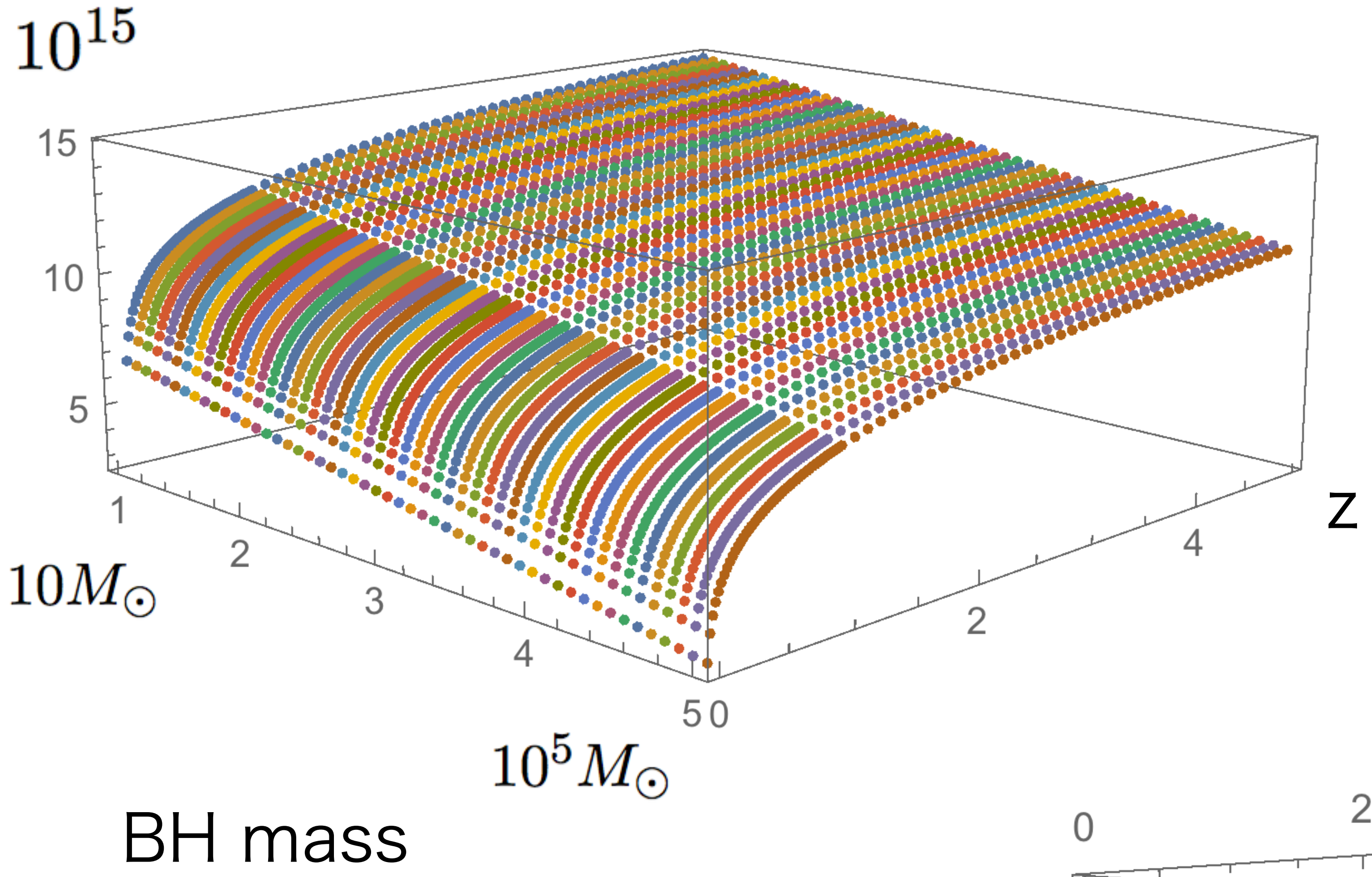
BRANT E. ROBERTSON[1,2,3] AND RICHARD S. ELLIS[1]
[1] Astronomy Department, California Institute of Technology, MC 249-17, 1200 East California Boulevard, Pasadena, CA 91125, USA; brant@astro.caltech.edu
[2] Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA
Received 2011 September 5; accepted 2011 November 18; published 2011 December 19

Star Formation Rate

peak z=3.16



How many BH mergers in the Universe?

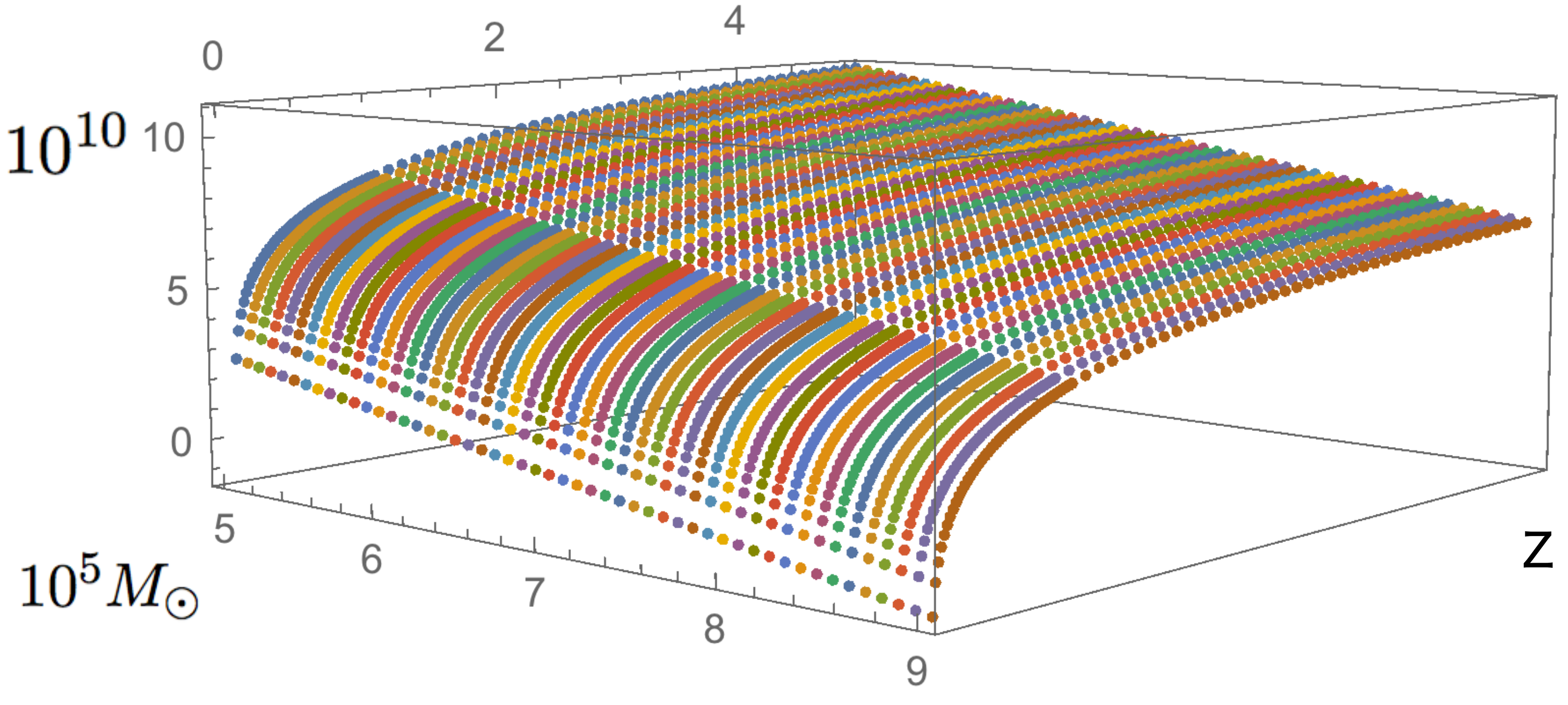


in Standard Cosmology

$$\text{Event Rate } R[/\text{yr}] = \frac{N_{\text{merger}}(z)}{V(D/2.26)}$$

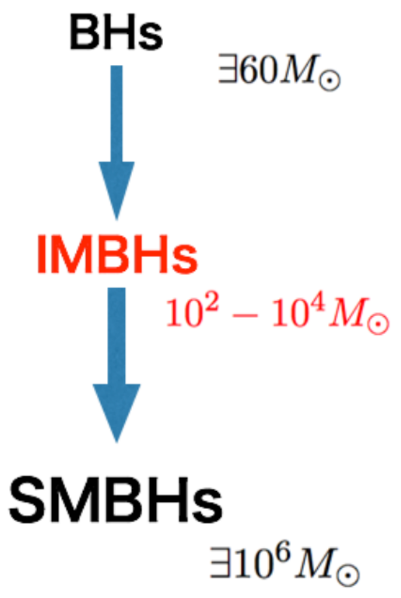
Standard Cosmology

averaging distances
for all directions



4. SMBH formation model : IMBHs' hierarchical mergers

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

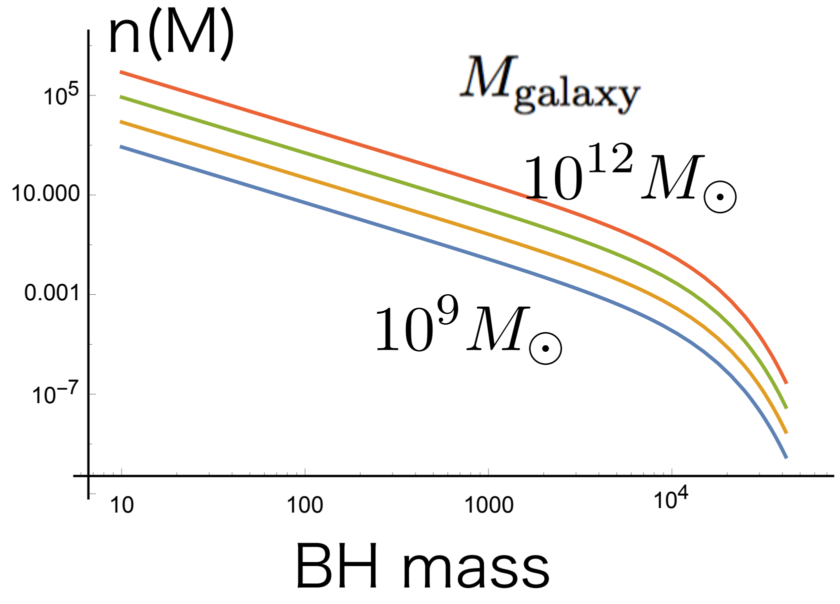


BHs $\exists 60 M_\odot$

IMBHs $10^2 - 10^4 M_\odot$

SMBHs $\exists 10^6 M_\odot$

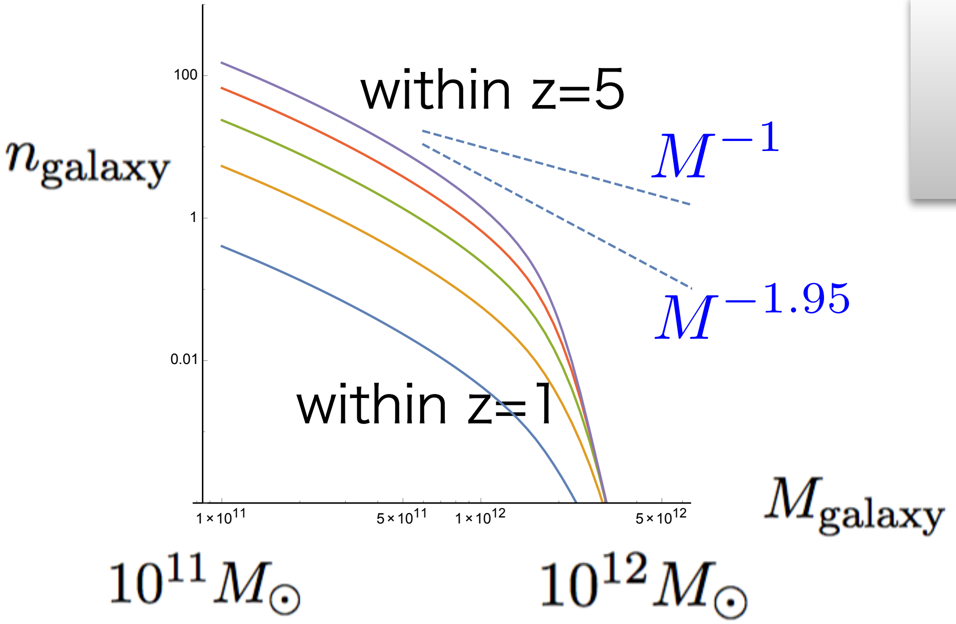
How many BHs in a Galaxy?



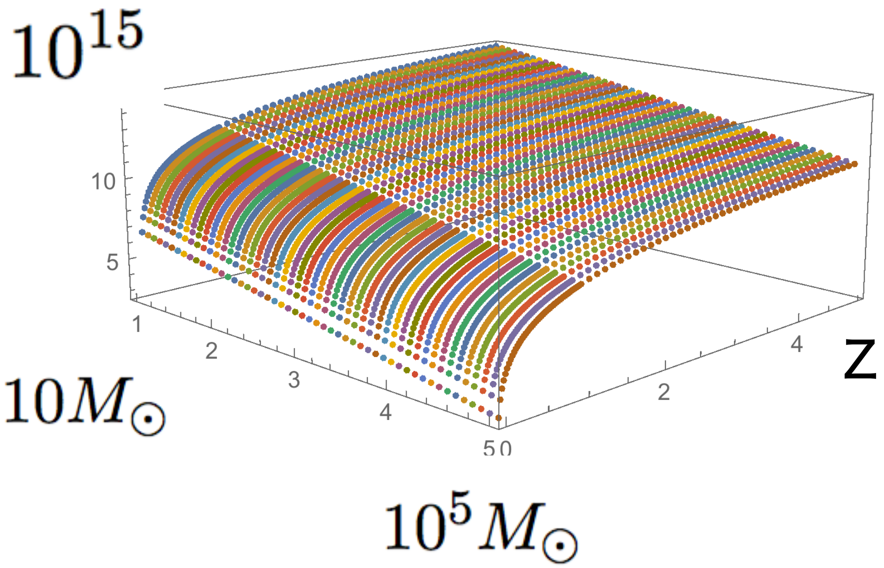
How many Galaxies in the Universe?

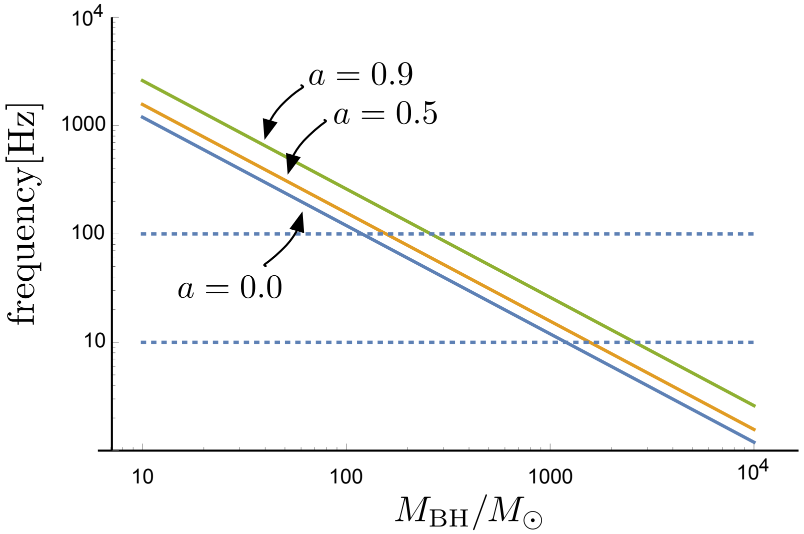
z<3

10^{12}



How many BH mergers in the Universe?

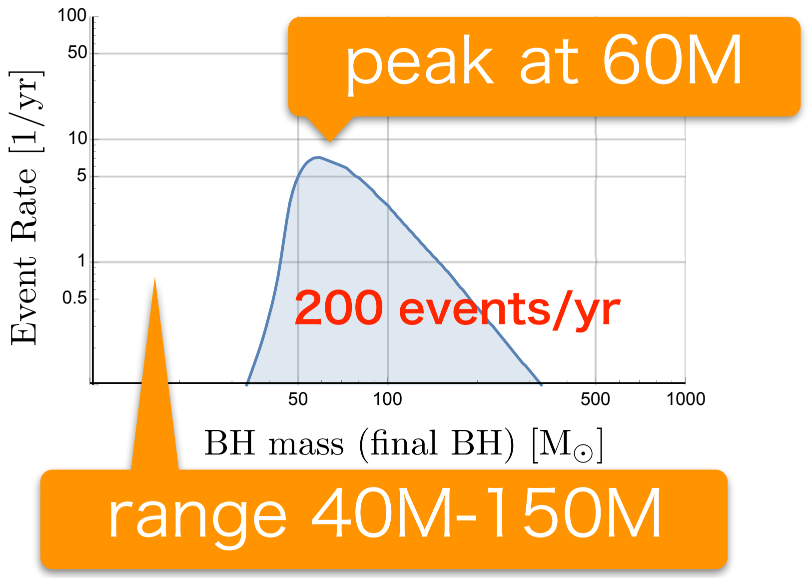




Event Rates at bKAGRA

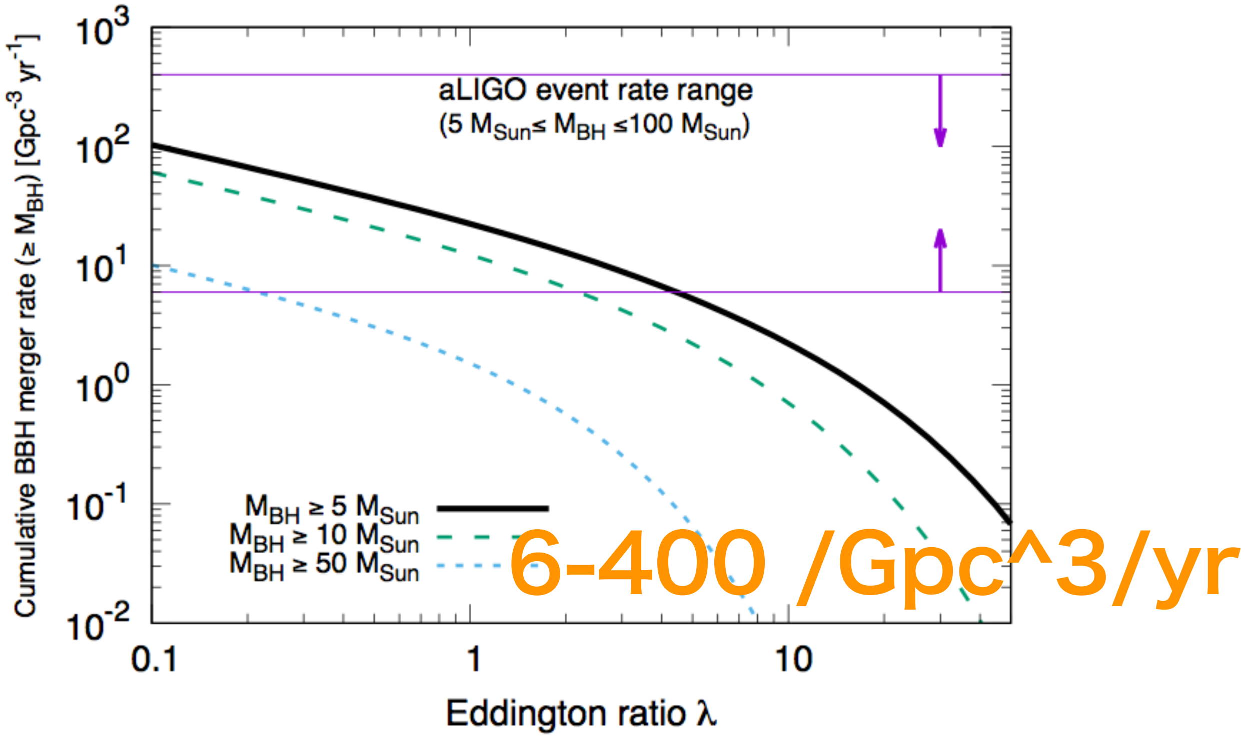
(QNM, S/N=10)

SNR = 10, KAGRA, spin parameter averaged



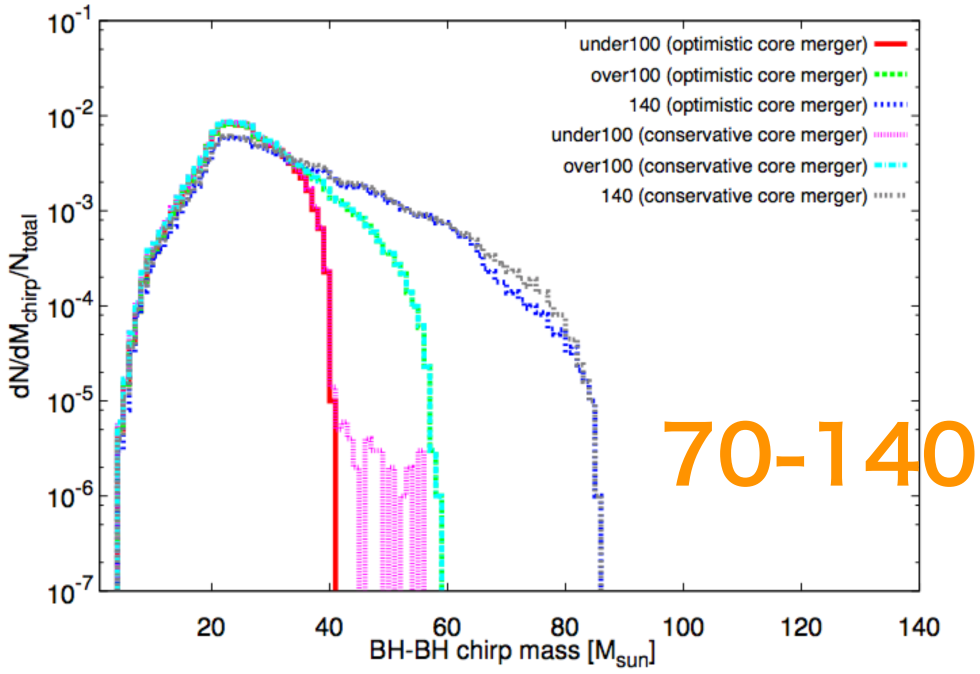
Event Rates at bKAGRA/aLIGO

Inoue+ MNRAS461(16)4329

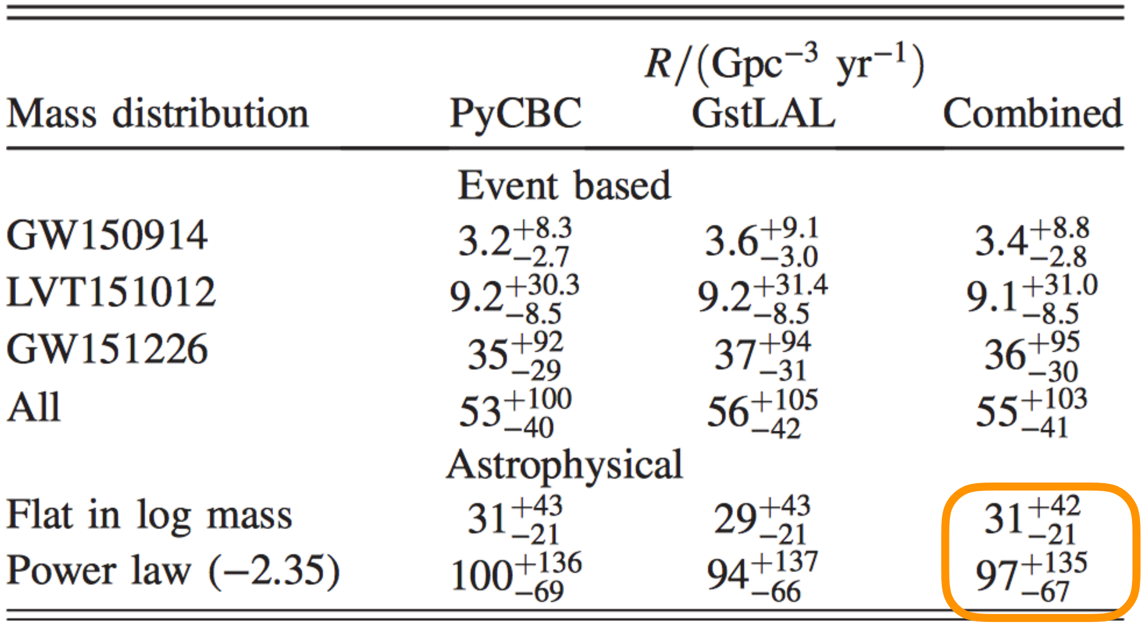


6-400 /Gpc^3/yr

Kinugawa+ MNRAS456(15)1093



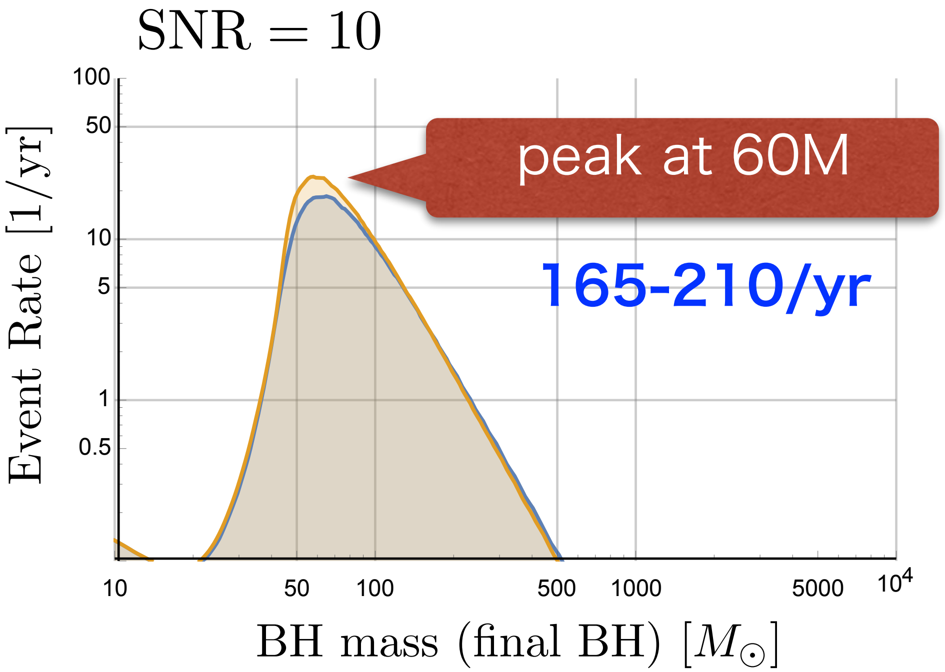
70-140 /yr



	$R/(\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1})$		
Mass distribution	PyCBC	GstLAL	Combined
	Event based		
GW150914	$3.2^{+8.3}_{-2.7}$	$3.6^{+9.1}_{-3.0}$	$3.4^{+8.8}_{-2.8}$
LVT151012	$9.2^{+30.3}_{-8.5}$	$9.2^{+31.4}_{-8.5}$	$9.1^{+31.0}_{-8.5}$
GW151226	35^{+92}_{-29}	37^{+94}_{-31}	36^{+95}_{-30}
All	53^{+100}_{-40}	56^{+105}_{-42}	55^{+103}_{-41}
	Astrophysical		
Flat in log mass	31^{+43}_{-21}	29^{+43}_{-21}	31^{+42}_{-21}
Power law (−2.35)	100^{+136}_{-69}	94^{+137}_{-66}	97^{+135}_{-67}

LIGO group PRX6(2016)041015

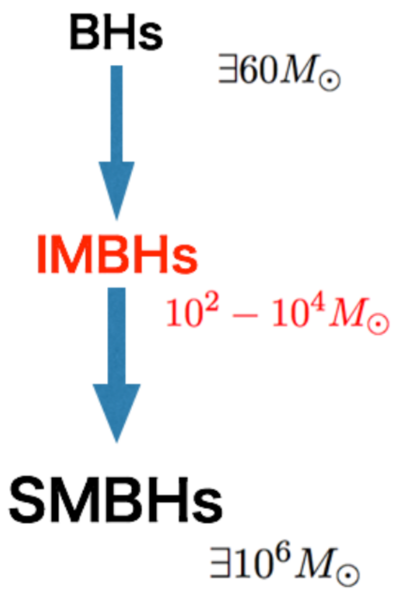
HS+ ApJ 835(17)276



peak at 60M

165-210/yr

4. SMBH formation model : IMBHs' hierarchical mergers


BHs $\exists 60 M_\odot$

IMBHs $10^2 - 10^4 M_\odot$

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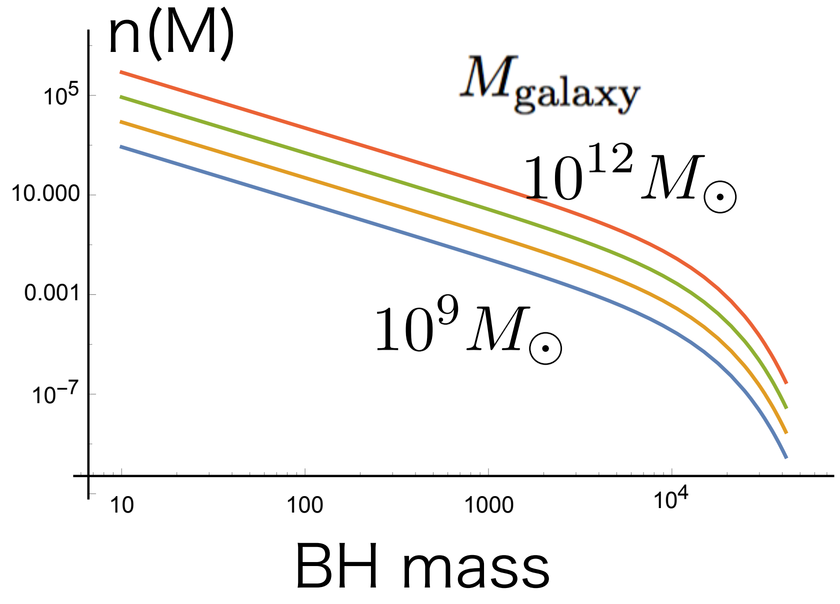
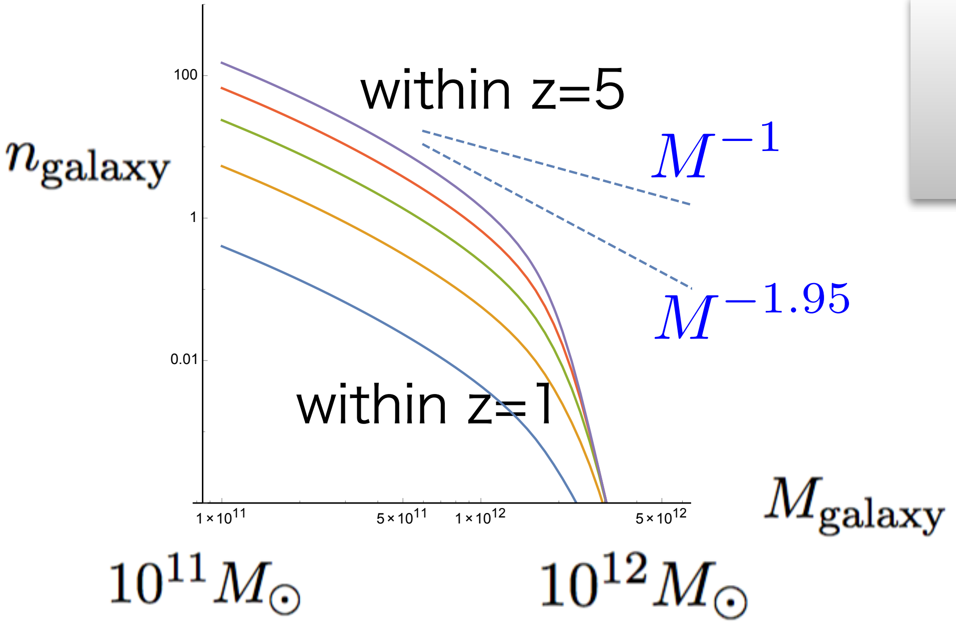
How many BHs in a Galaxy?

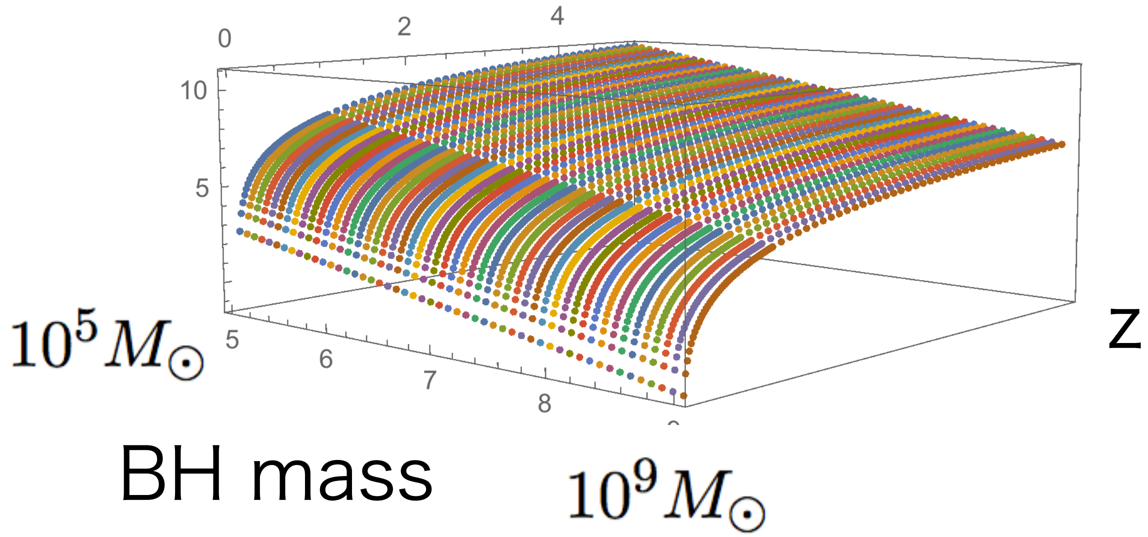


How many Galaxies in the Universe?



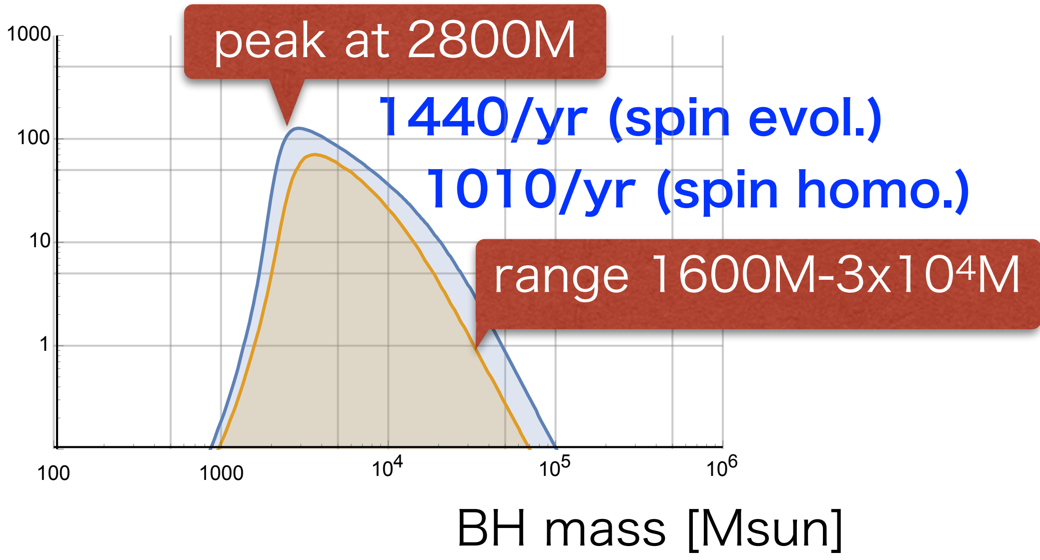
z<3
10^{12}

How many BH mergers in the Universe?



Event Rates at B-DECIGO

(QNM, S/N=30)


peak at 2800M

1440/yr (spin evol.)

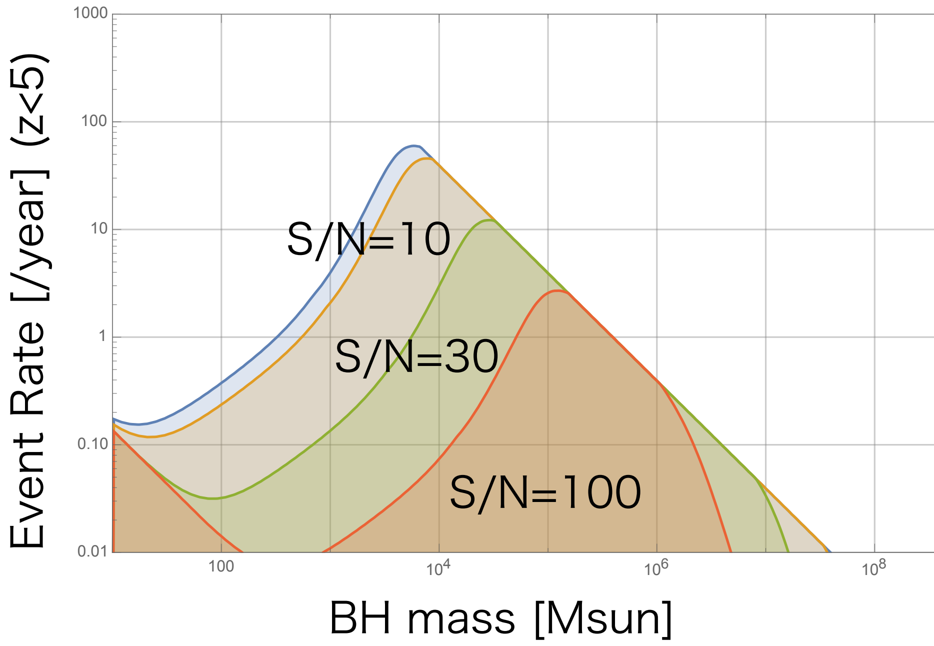
1010/yr (spin homo.)

range 1600M-3x10⁴M

4. SMBH formation model : IMBHs’ hierarchical mergers

SMBH形成をIMBHを経たヒエラルキー合体成長モデルと考え，宇宙空間での
イベント数，観測される質量プロファイルを計算した.

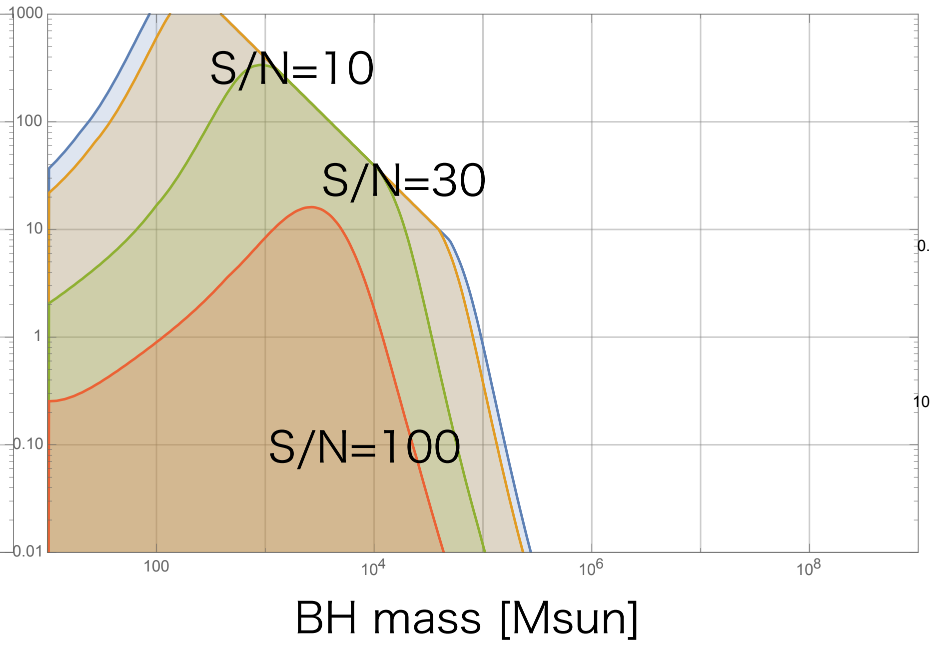
eLISA



S/N=10 520/year
(range: 550M-3.8x10^{5}M)
S/N=30 6/year
(range: 5.5x10^{3}M-3.3x10^{4}M)

inspiral+ringdown

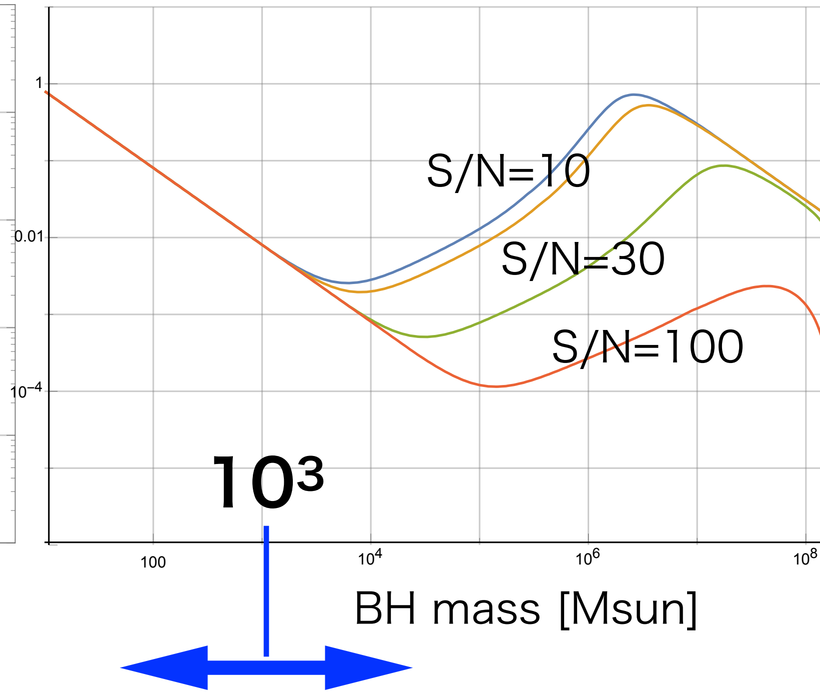
B-DECIGO



S/N=10 18000/year
(range: 10M-7.9x10^{4}M)
S/N=30 4300/year
(range: 10M-3.3x10^{4}M)

inspiral+ringdown

INO-d



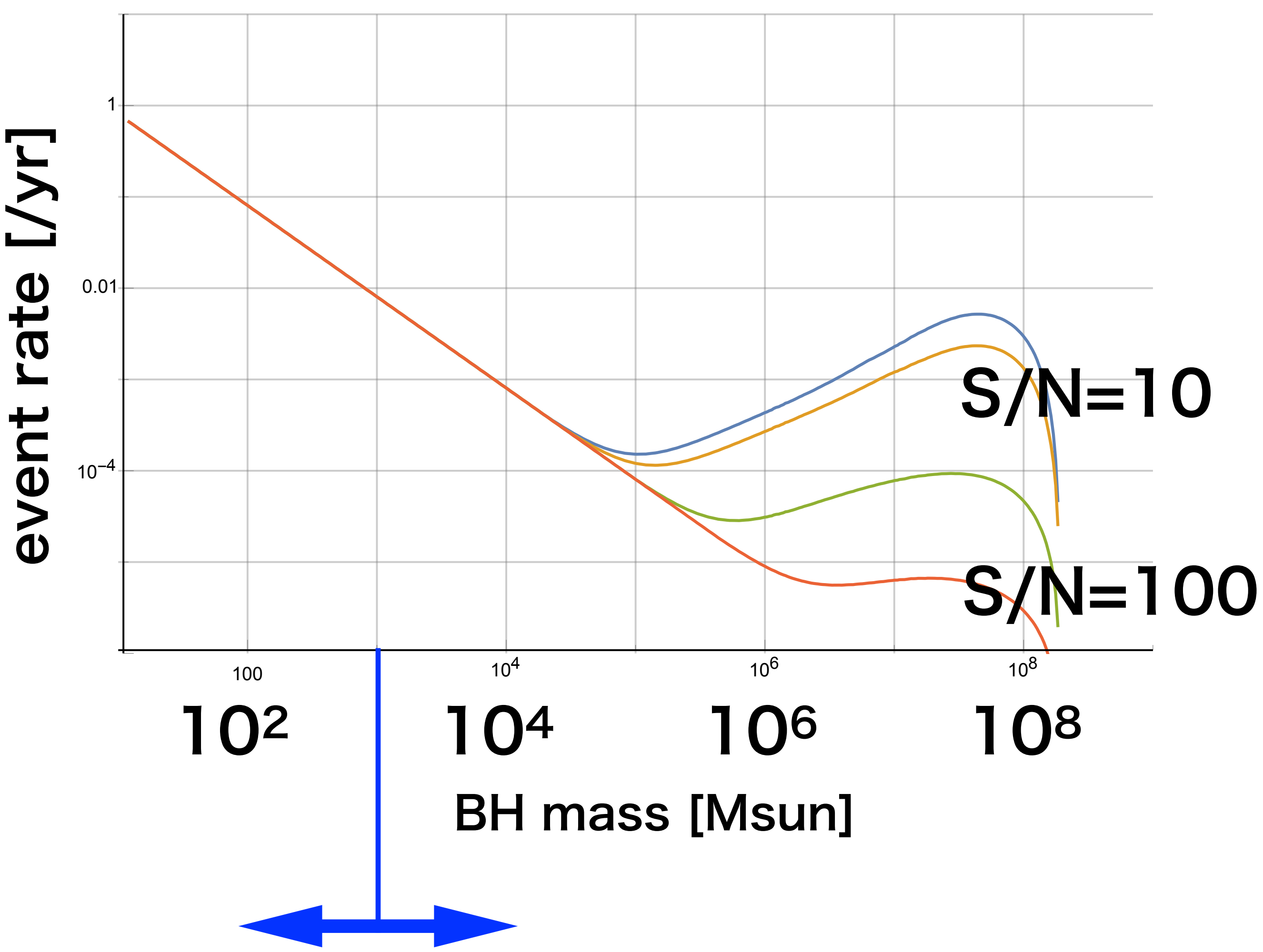
19.2/yr **29.8/yr**
S/N=10

inspiral+ringdown

4. SMBH formation model : IMBHs’ hierarchical mergers

Event Rate

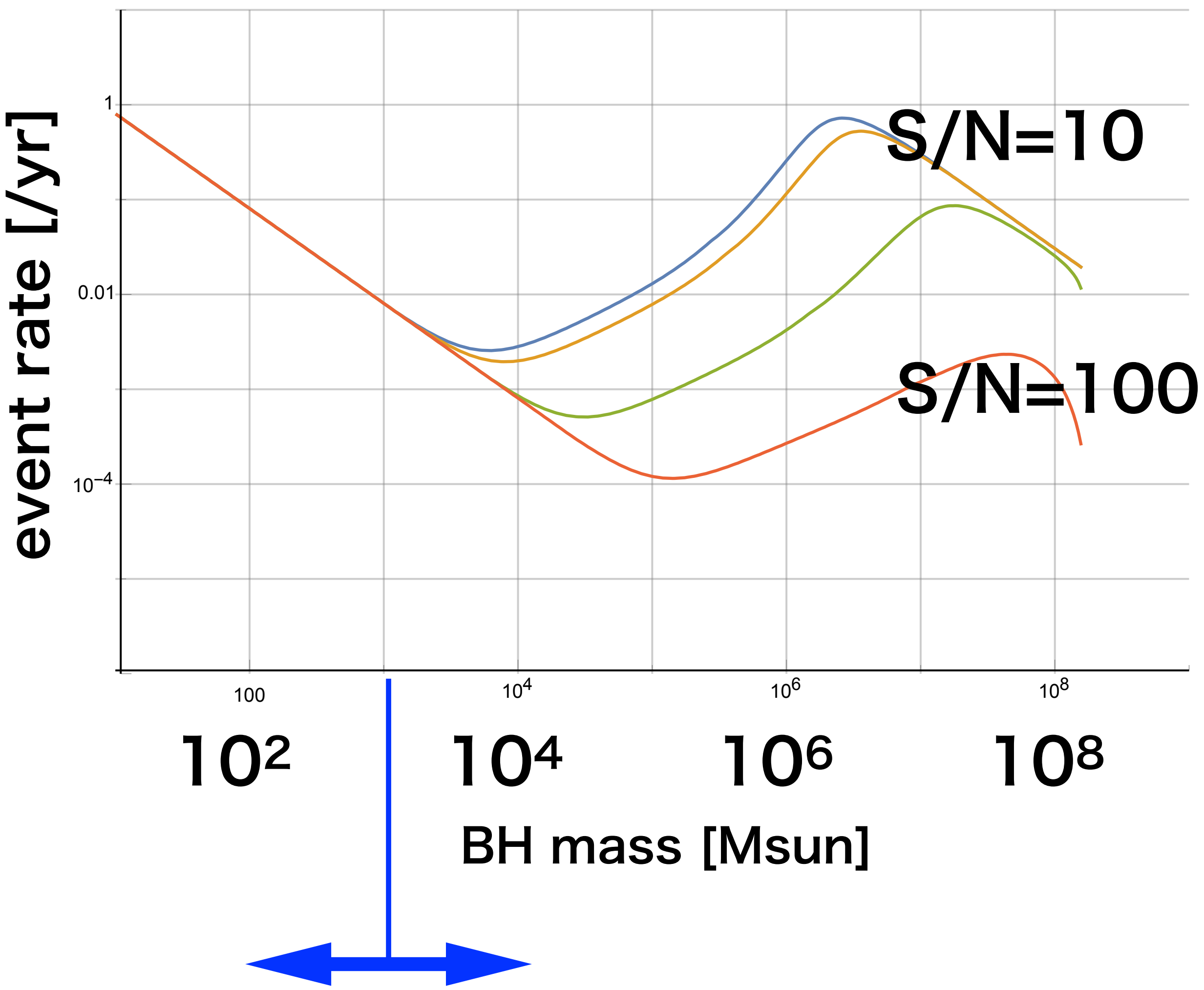
INO-c



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

inspiral+ringdown

INO-d



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

inspiral+ringdown

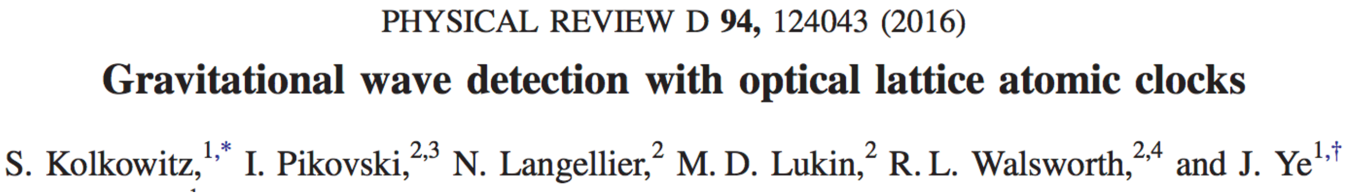
Summary

LISA (ESA/NASA)	**B-DECIGO ⇒ DECIGO (Japan)**	**TianQin 天琴 (China)**	**INO**
mHz range	0.1Hz range	0.1 - 100 mHz range	0.1 mHz —1 Hz
3 satellites at L4 of Sun-Earth	around earth 2000km 3 sattelites ⇒ Sun orbit	3 satellites around the Earth	Sun-Earth L1-L4-L5
2.50 x 10^6 km	100 km ⇒ 1000 km	10^5 km	1 AU
			light or radio link
light transponder	**Fabry-Perot interferometer**	**Fabry-Perot interferometer**	**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 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
⭐ "INO-c", some range is better than LISA sensitivity
⭐ "INO-c", stellar-mass BH merger prediction 20 events/yr
"INO-d", + IMBH inspiral 30 events/yr

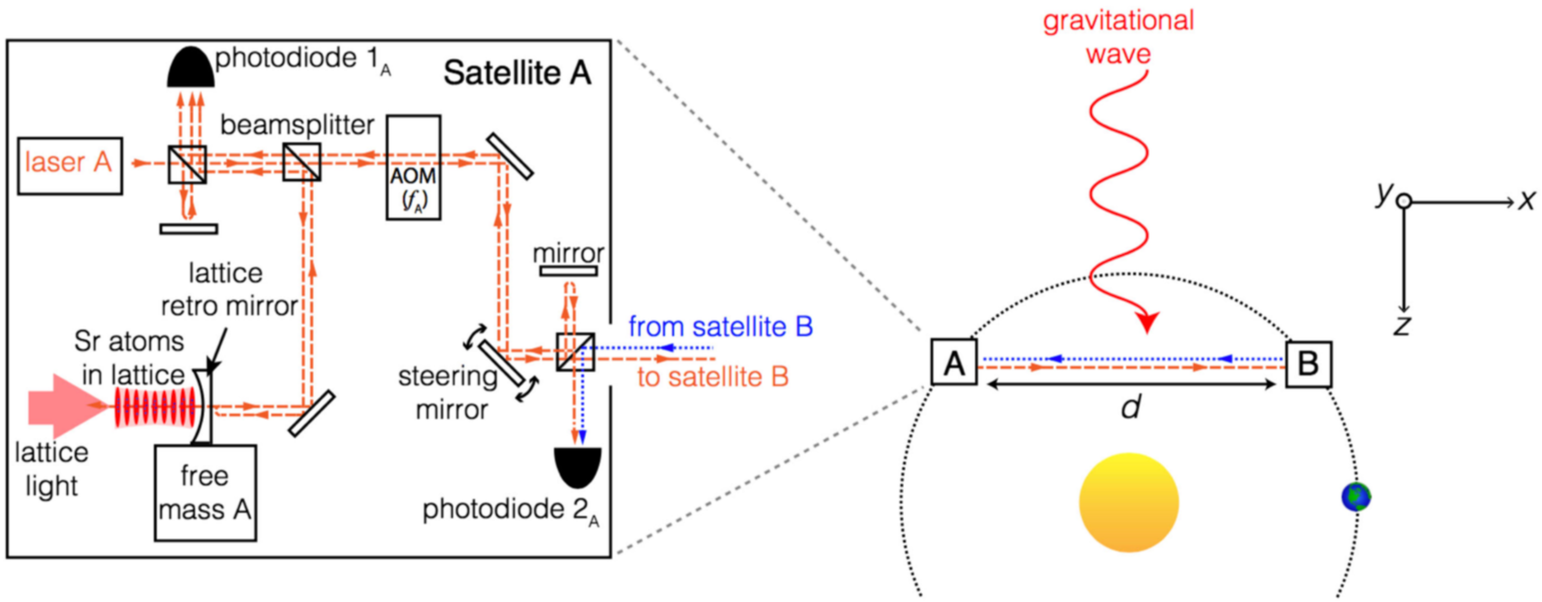
backup

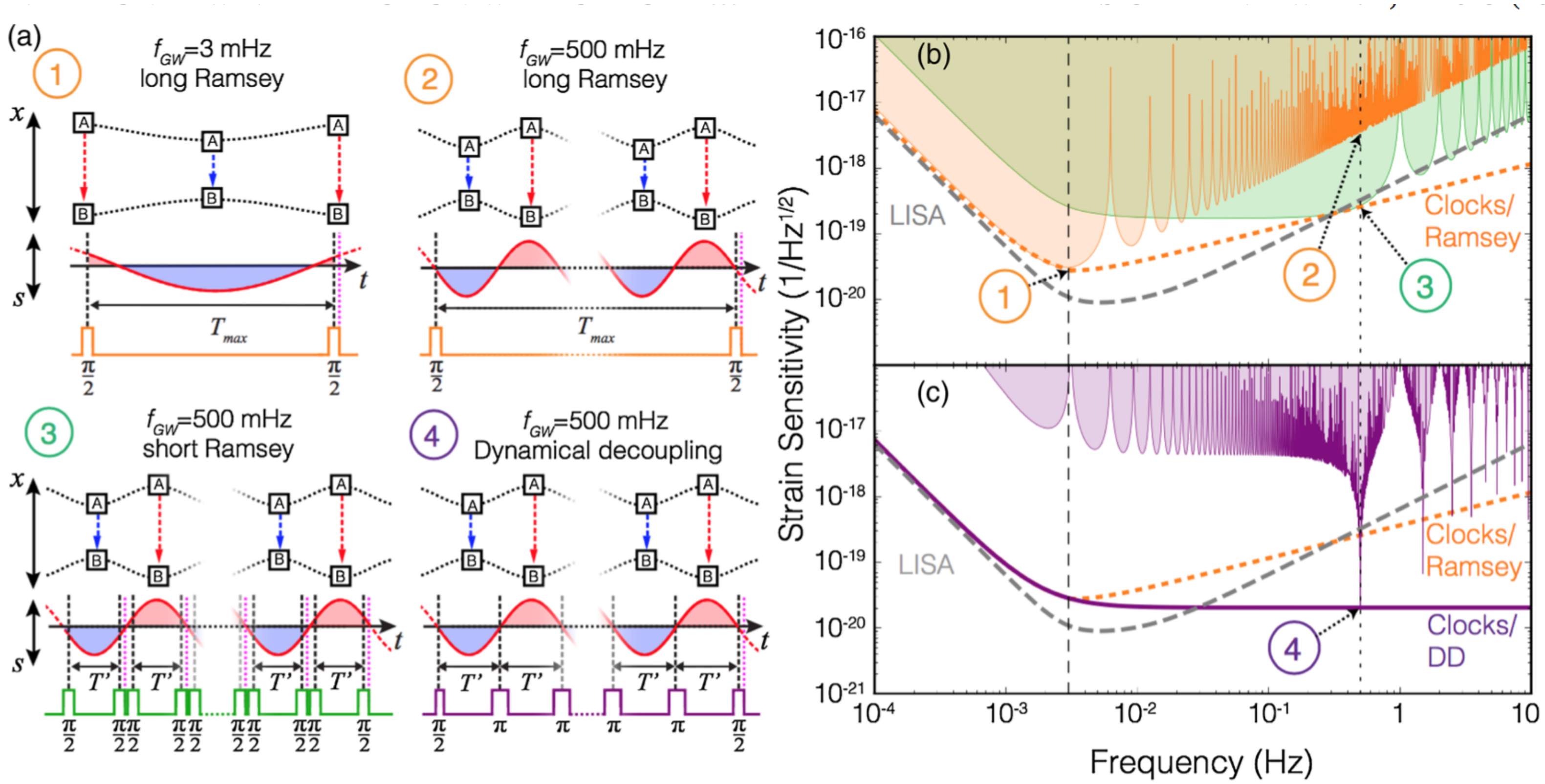
3. Previous proposals（Kolkowitz+ 2016)


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,†]





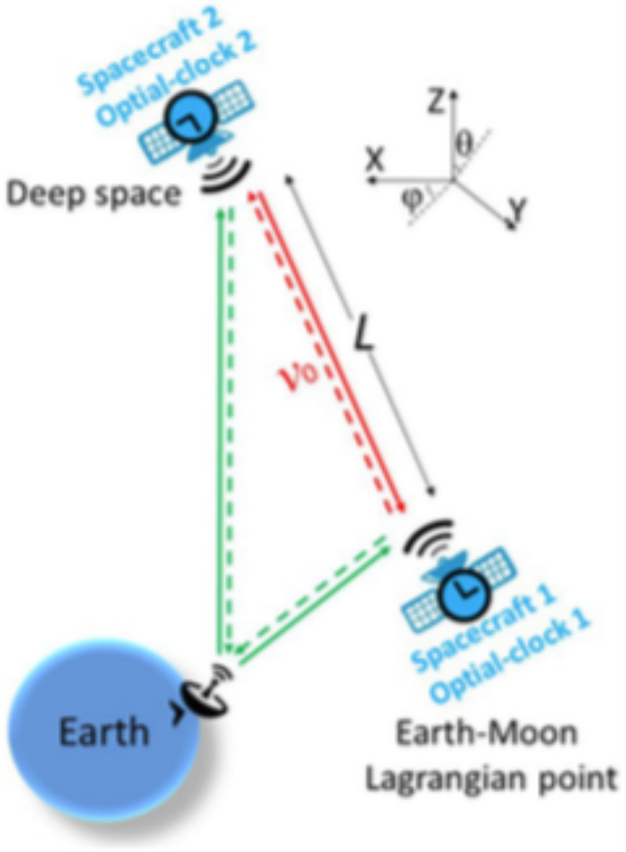
Kolkowitz +
PRD94(2016)124043
3 mHz or 30 mHz –10 Hz
5x10^7 km or 5x10^6 km
2 satellites, laser link
compare freq. w Opt Lattice Clock
drag-free flight
Doppler shift with Laser beam

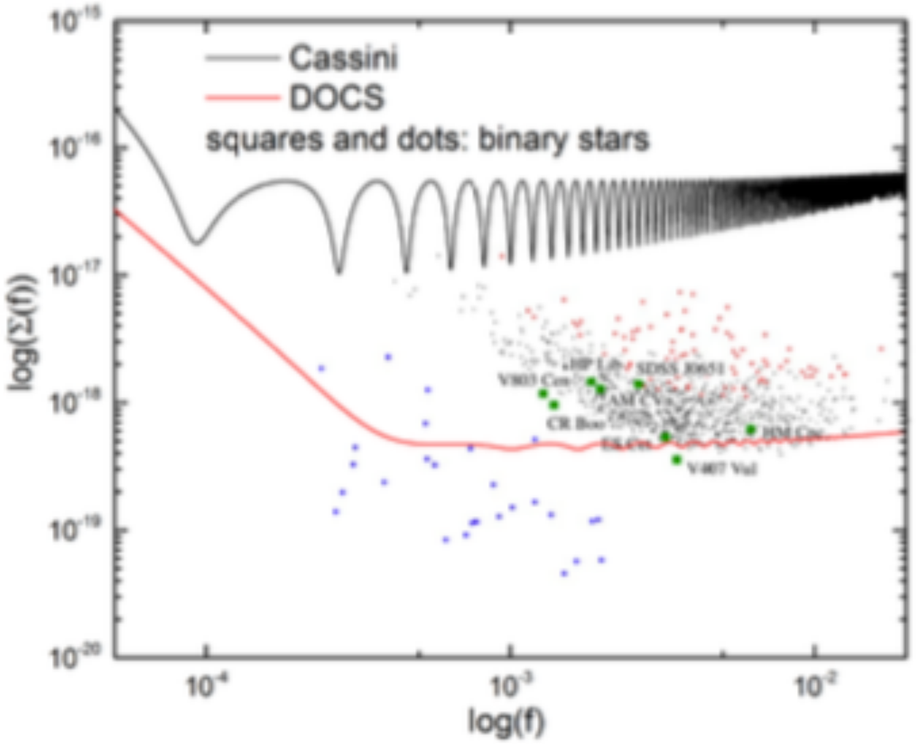
drag-free flight
vs. photoelectric charge by cosmic ray

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

3. Previous proposals（Su+ 2018)

DOCS=Double Optical Clocks in Space





Su, Wang, Wang, Philippe
CQG35 (2018) 05010
0.1 mHz –10 mHz
Earth-Moon Lagrange its
2 satellites, laser link
compare freq. w Opt Lattice Clock
drag-free flight

at Lagrange points of Earth-Moon orbit, link them with the Earth by radio

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．2020年に打ち上げ予定．

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．

INO-ISS (INO at ISS)
ISSに光格子時計を搭載して，地球重力赤方偏移，等価原理検証を目指そうとするもの．2018年から検討スタート．2019年JAXA内部検討プログラム．3年後にISS搭載を目指す．