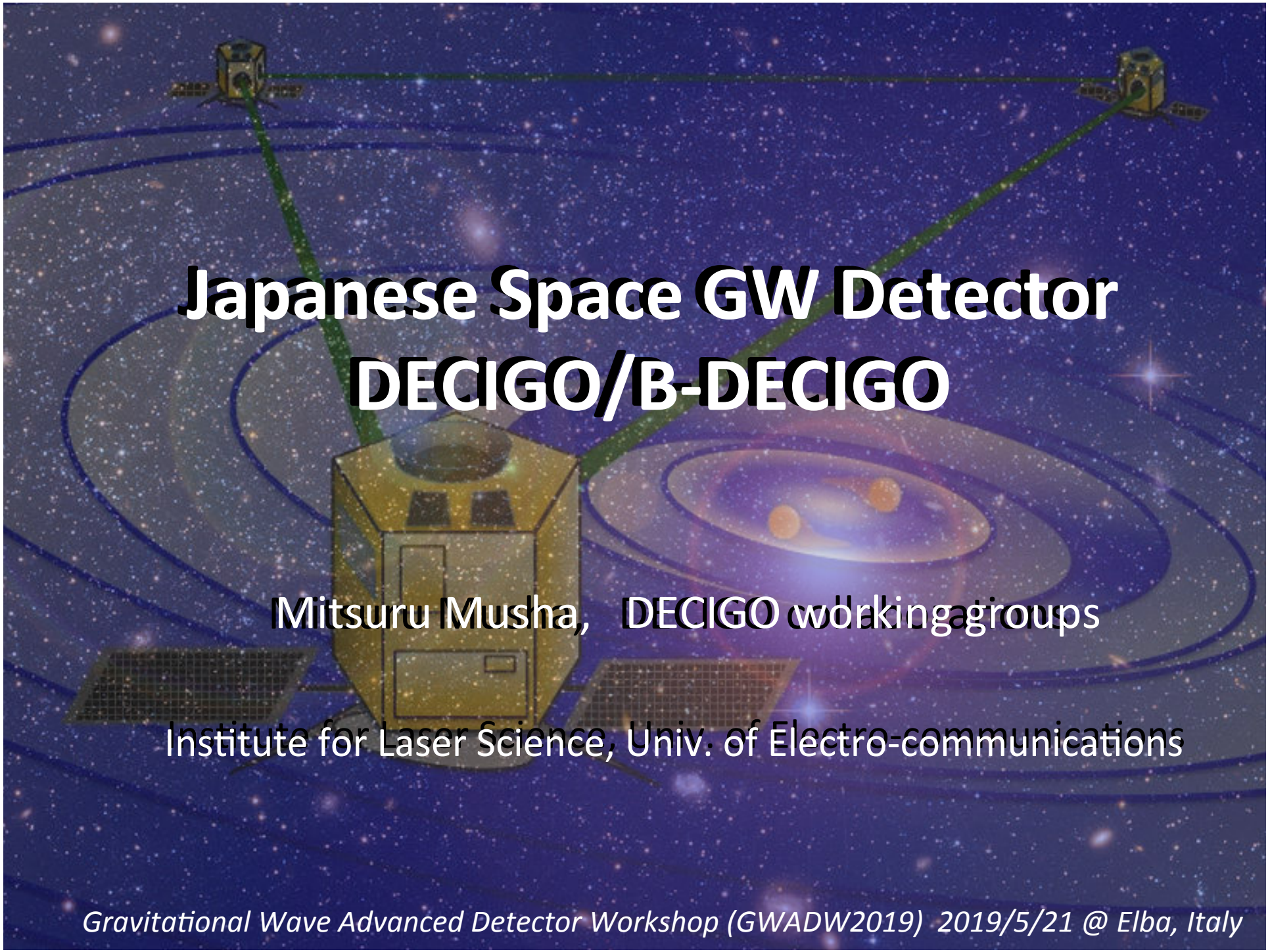


# Japanese Space GW Detector DECIGO/B-DECIGO

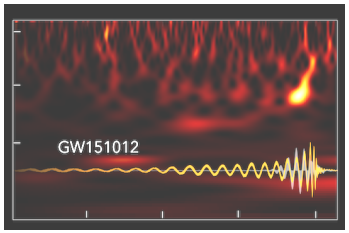
Mitsuru Musha, DECIGO working groups

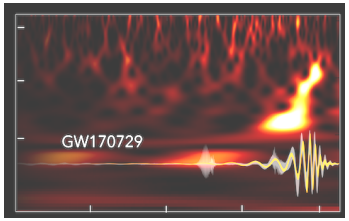
Institute for Laser Science, Univ. of Electro-communications

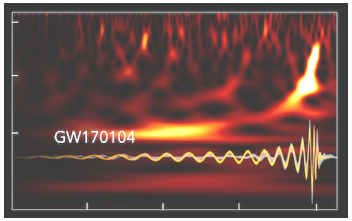
*Gravitational Wave Advanced Detector Workshop (GWADW2019) 2019/5/21 @ Elba, Italy*

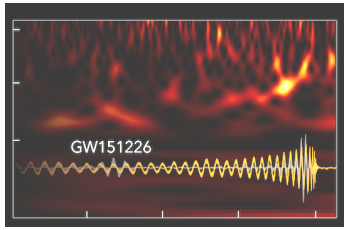

DECIGO working group
Masaki Ando, Seiji Kawamura, Naoki Seto, Takashi Nakamura, Kimio Tsubono, Shuichi Sato, Takahiro Tanaka, Ikkoh Funaki, Kenji Numata,Nobuyuki Kanda, Kunihito Ioka, Takeshi Takashima, Jun'ichi Yokoyama, Tomotada Akutsu, Mitsuru Musha, Akitoshi Ueda, Koh-suke Aoyanagi, Kazuhiro Agatsuma, Hideki Asada, Yoichi Aso, Koji Arai, Akito Araya, Takeshi Ikegami, Takehiko Ishikawa, Hideharu Ishizaki, HidekiIshihara, Kiwamu Izumi, Kiyotomo Ichiki, Hiroyuki Ito, Yousuke Itoh, Kaiki T. Inoue, Ken-ichi Ueda, Takafumi Ushiba, Masayoshi Utashima, Satoshi Eguchi, Yumiko Ejiri, Motohiro Enoki, Toshikazu Ebisuzaki, Yoshiharu Eriguchi, Naoko Ohishi, Masashi Ohkawa, Masatake Ohashi, Kenichi Oohara, Yoshiyuki Obuchi, Kenshi Okada, Norio Okada, Koki Okutomi, Nobuki Kawashima, Fumiko Kawazoe, Isao Kawano, Kenta Kiuchi, Naoko Kishimoto, Hitoshi Kuninaka, Hiroo Kunimori, Kazuaki Kuroda, Sachiko Kuroyanagi, Hiroyuki Koizumi, Feng-Lei Hong, Kazunori Kohri, Wataru Kokuyama, Keiko Kokeyama, Yoshihide Kozai, Yasufumi Kojima, Kei Kotake, Shiho Kobayashi, Rina Gondo,Motoyuki Saijo, Ryo Saito, Shin-ichiro Sakai, Masaaki Sakagami, Shihori Sakata, Norichika Sago, Misao Sasaki, Takashi Sato, Masaru Shibata, Kazunori Shibata, Ayaka Shoda, Hisaaki Shinkai, Ayumi Shimo-oku, Aru Suemasa, Naoshi Sugiyama, Rieko Suzuki, Yudai Suwa, Kentaro Somiya, Hajime Sotani, Tadashi Takano, Kakeru Takahashi, Keitaro Takahashi, Hirotaka Takahashi, Fuminobu Takahashi, Ryuichi Takahashi, Ryutaro Takahashi, Takamori Akiteru, Hideyuki Tagoshi, Hiroyuki Tashiro, Nobuyuki Tanaka, Keisuke Taniguchi, Atsushi Taruya, Takeshi Chiba, Dan Chen, Shinji Tsujikawa, Yoshiki Tsunesada, Morio Toyoshima, Yasuo Torii, Kenichi Nakao, Kazuhiro Nakazawa, Shinichi Nakasuka, Hiroyuki Nakano, Shigeo Nagano, Kouji Nakamura, Yoshinori Nakayama, Atsushi Nishizawa, Erina Nishida, Yoshito Niwa, Taiga Noumi, Tatsuaki Hashimoto, Kazuhiro Hayama, Tomohiro Harada, Wataru Hikida, Yoshiaki Himemoto, Hisashi Hirabayashi, Takashi Hiramatsu, Mitsuhiro Fukushima, Ryuichi Fujita, Masa-Katsu Fujimoto, Toshifumi Futamase, Mizuhiko Hosokawa, Hideyuki Horisawa, Kei-ichi Maeda, Hideo Matsuhara, Nobuyuki Matsumoto, Yuta Michimura, Osamu Miyakawa, Umpei Miyamoto, Shinji Miyoki, Shinji Mukohyama, Toshiyuki Morisawa, Mutsuko Y. Morimoto, Shigenori Moriwaki, Kent Yagi, Hiroshi Yamakawa, Toshitaka Yamazaki, Kazuhiro Yamamoto, Shijun Yoshida, Taizoh Yoshino, Chul-Moon Yoo,Yaka Wakabayashi
145 (On April, 1, 2016)
DECIGO Working Group

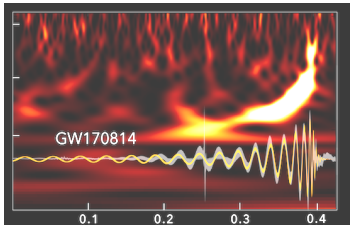
# Gravitational Wave Detection

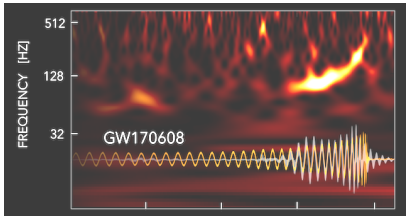


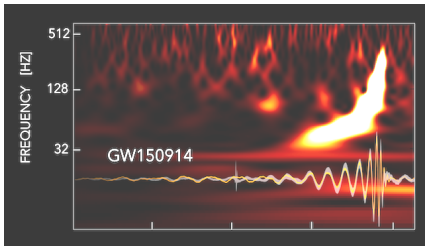



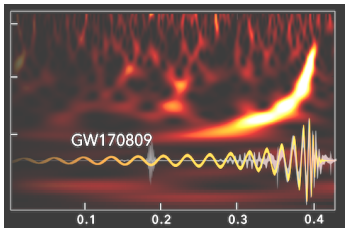



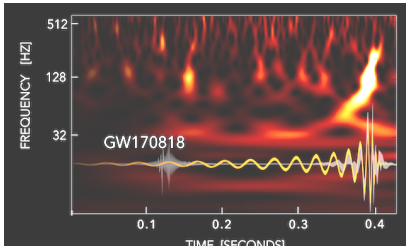



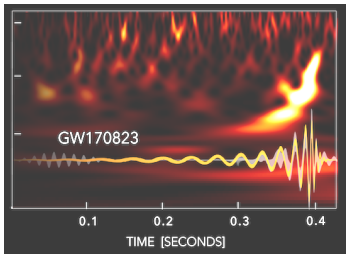



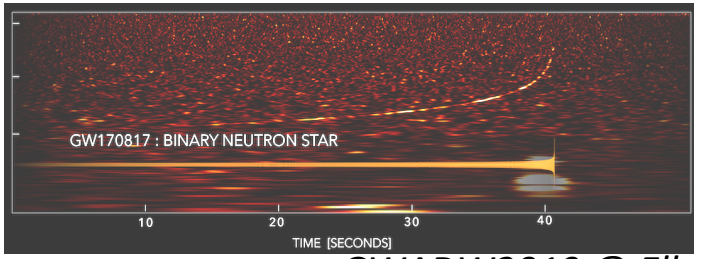

**first detection of GW**



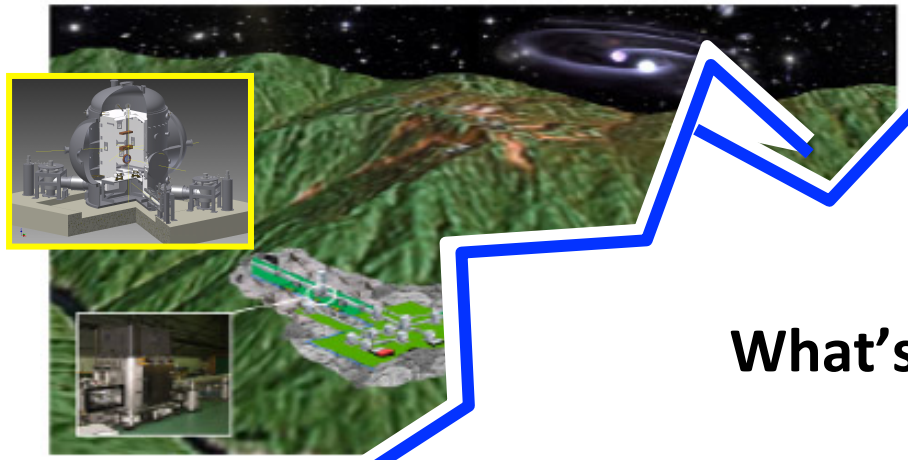



# Japanese GW detector

KAGRA

(*K*amioka *A*dvanced *GR*avitational wave *A*ntenna)



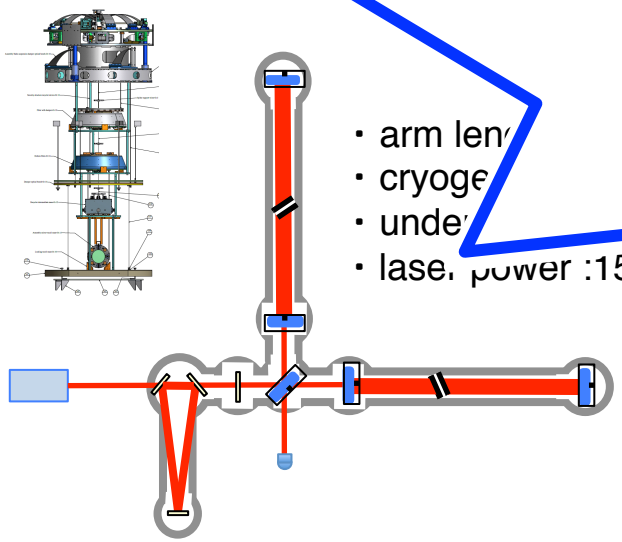
TENKO100

TAMA 300

NAO 20m

**What's Next**

**DECIGO**



- arm len
- cryoge
- unde
- lase. power :150 W

**observat n run will start**

**KAGRA+**

# *outline*

- ***Gravitational Wave Detection***
- ***DECIGO***
- ***B-DECIGO***
- ***Light source for DECIGO/B-DECIGO***
- ***Summary***

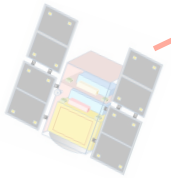
**DECIGO** (**DEC**i-hertz **I**nterferometer **G**ravitational-wave **O**bservatory)

Proposed in 2001 by N.Seto, S.Kawamura, T. Nakamura

Phys.Rev.Lett.81 (2001) 221103

*Acceleration of expansion of Universe*

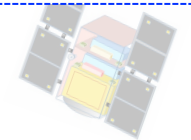
GW from coalescence of distant NSB



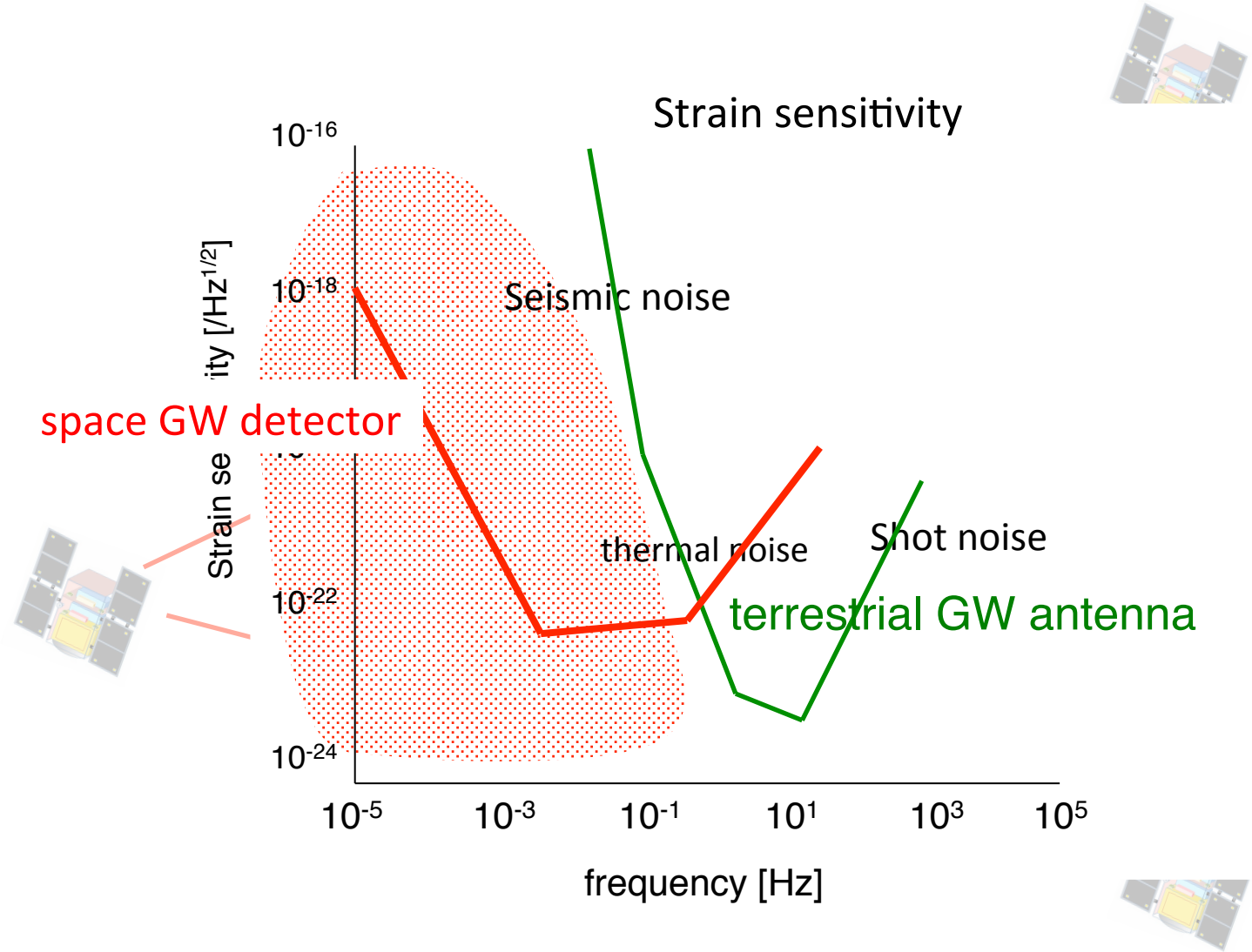
Low-frequency GW detectors

Direct observation of the origin of space-time

primordial GW coming from the inflation

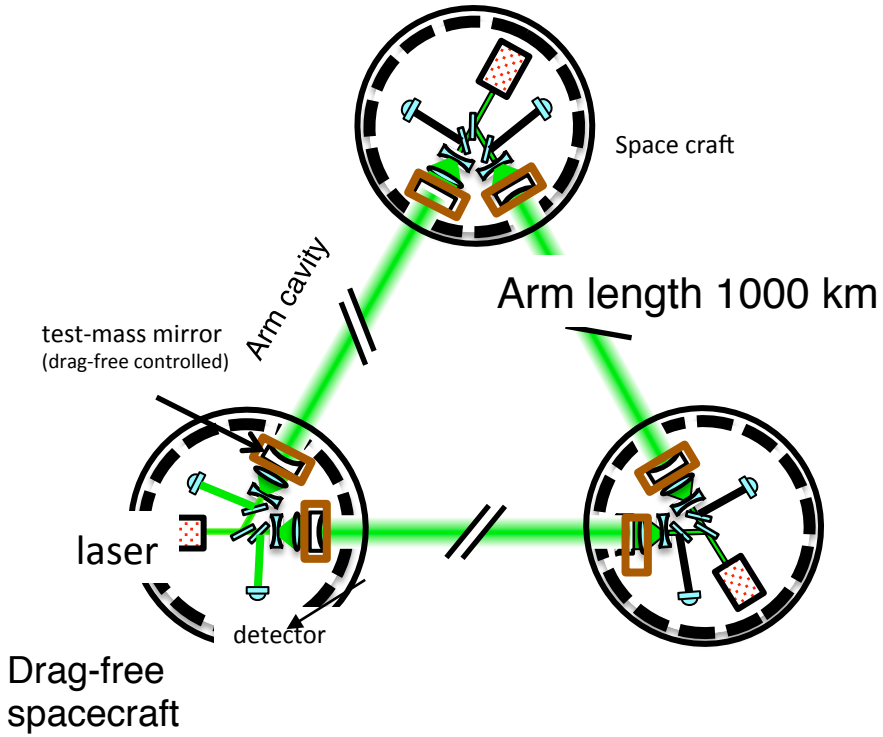


# DECIGO (DECi-hertz Interferometer Gravitational-wave Observatory)



# DECIGO (DECi-hertz Interferometer Gravitational-wave Observatory)

Differential Fabry-Perot interferometer

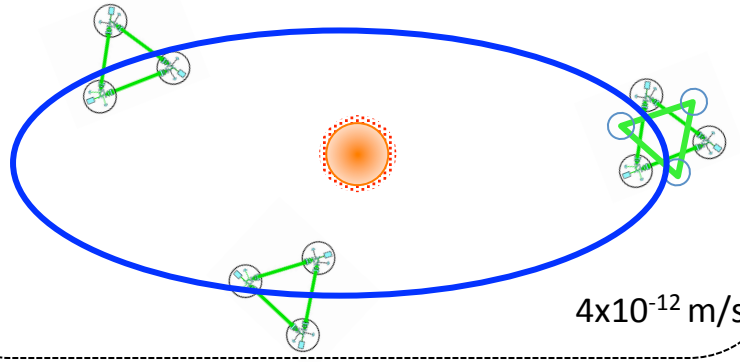



launched: mid 2030s

- 3 S/C formation flight
- 3 Fabry-Perot interferometer
  - $L$=1000 km
  - $F$=10
- mirrors w=100kg.
  - $\Phi$=1m
- drag-free control
- laser power 10W@0.5 μm

**record-disk orbit around sun**

4 interferometer units
- 2 overlapped units -> cross correlation
- 2 separated units -> angular resolution



# *space GW antenna*

## LISA

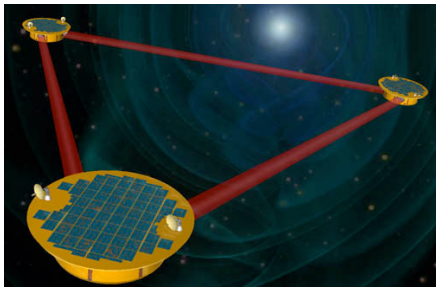
(Laser Interferometer Space Antenna)

baseline 2,500,000 km

laser transponder

constellation flight of 3 S/C

laser wavelength 1μm



**much lower frequency**

## DECIGO

(Deci-hertz Interferometer GW observatory)

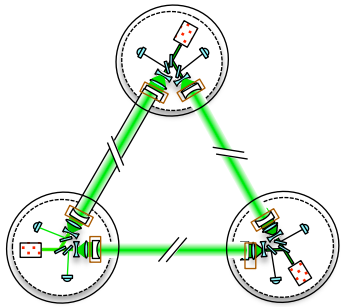
triangle-shaped laser interferometric space GW antenna

baseline 1,000 km

Fabry-Perot interferometer

formation flight of 3 S/C

laser wavelength 0.5 μm



**much photons**

# space GW antenna

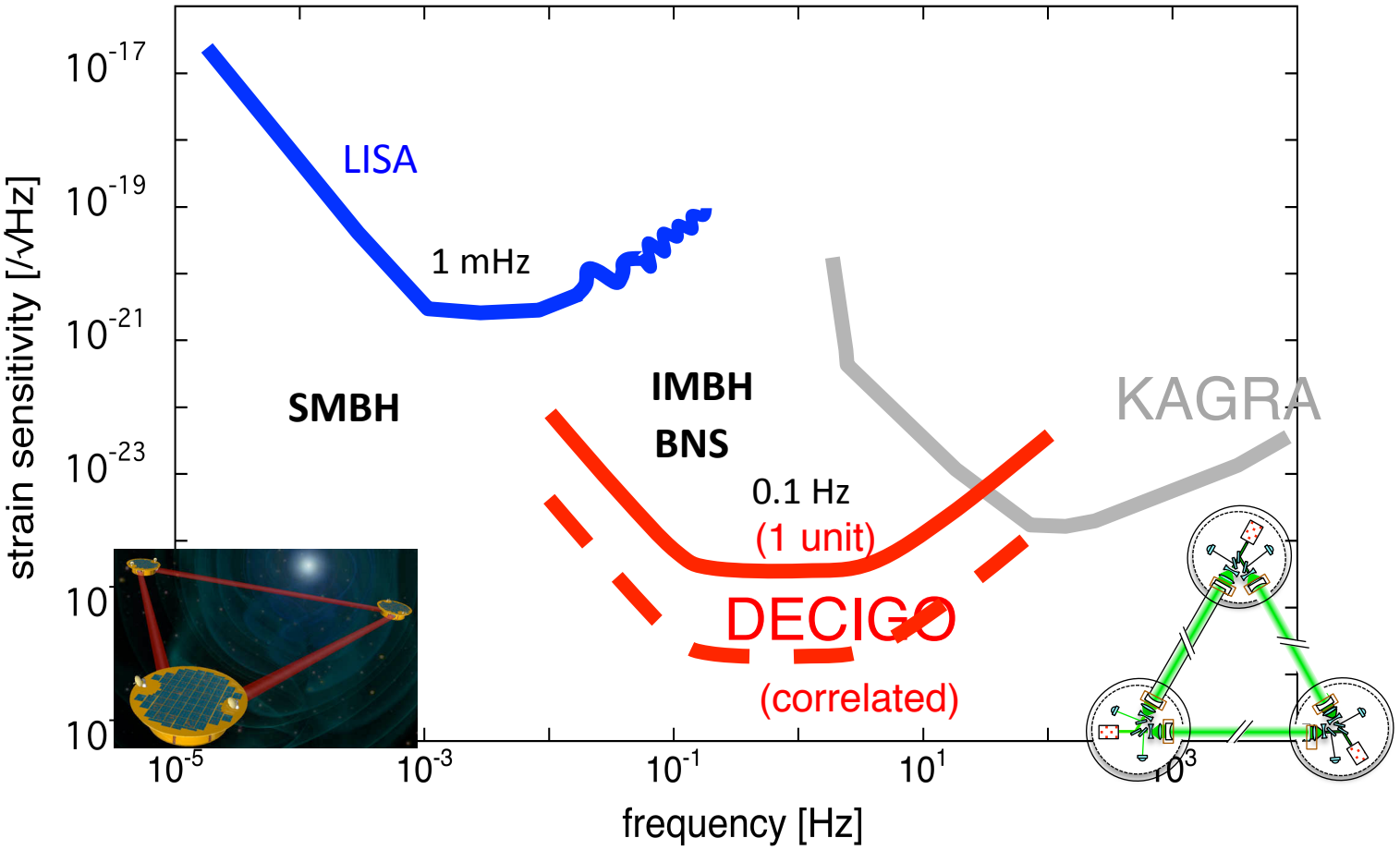
## LISA

(Laser Interferometer Space Antenna)

## DECIGO

(Deci-hertz Interferometer GW observatory)

triangle-shaped laser interferometric space GW antenna



# design concept

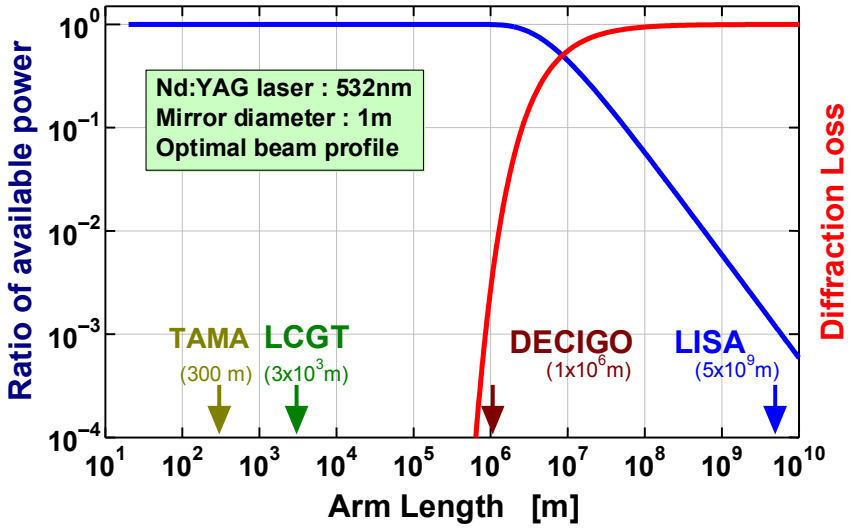
## Cavity arm length

Laser wavelength : **515nm**

Mirror diameter: 1m

Optimal beam size

diffraction loss




1000 km is almost max.

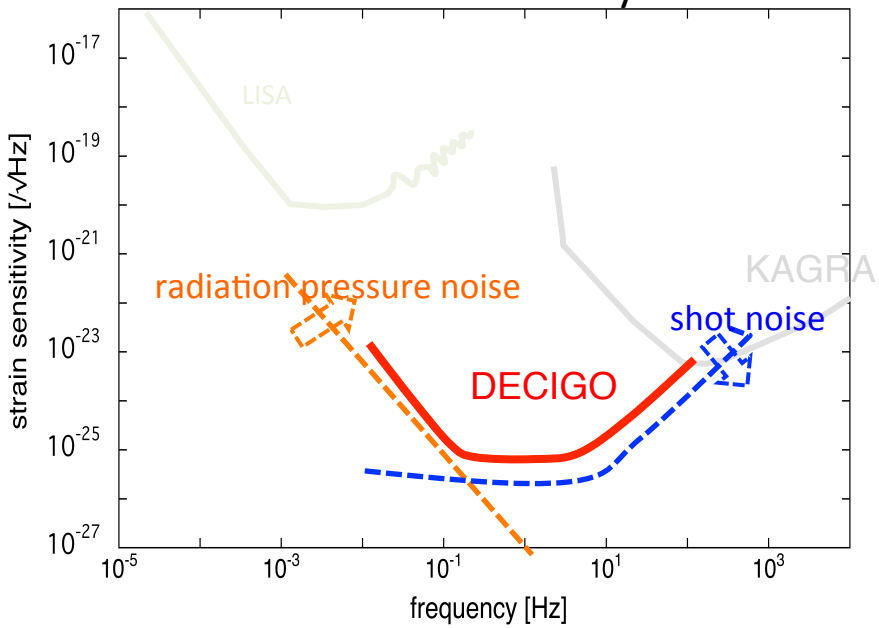
## Laser power

Quantum noise limited

radiation pressure noise

photon shot noise

strain sensitivity




10 W , 515 nm

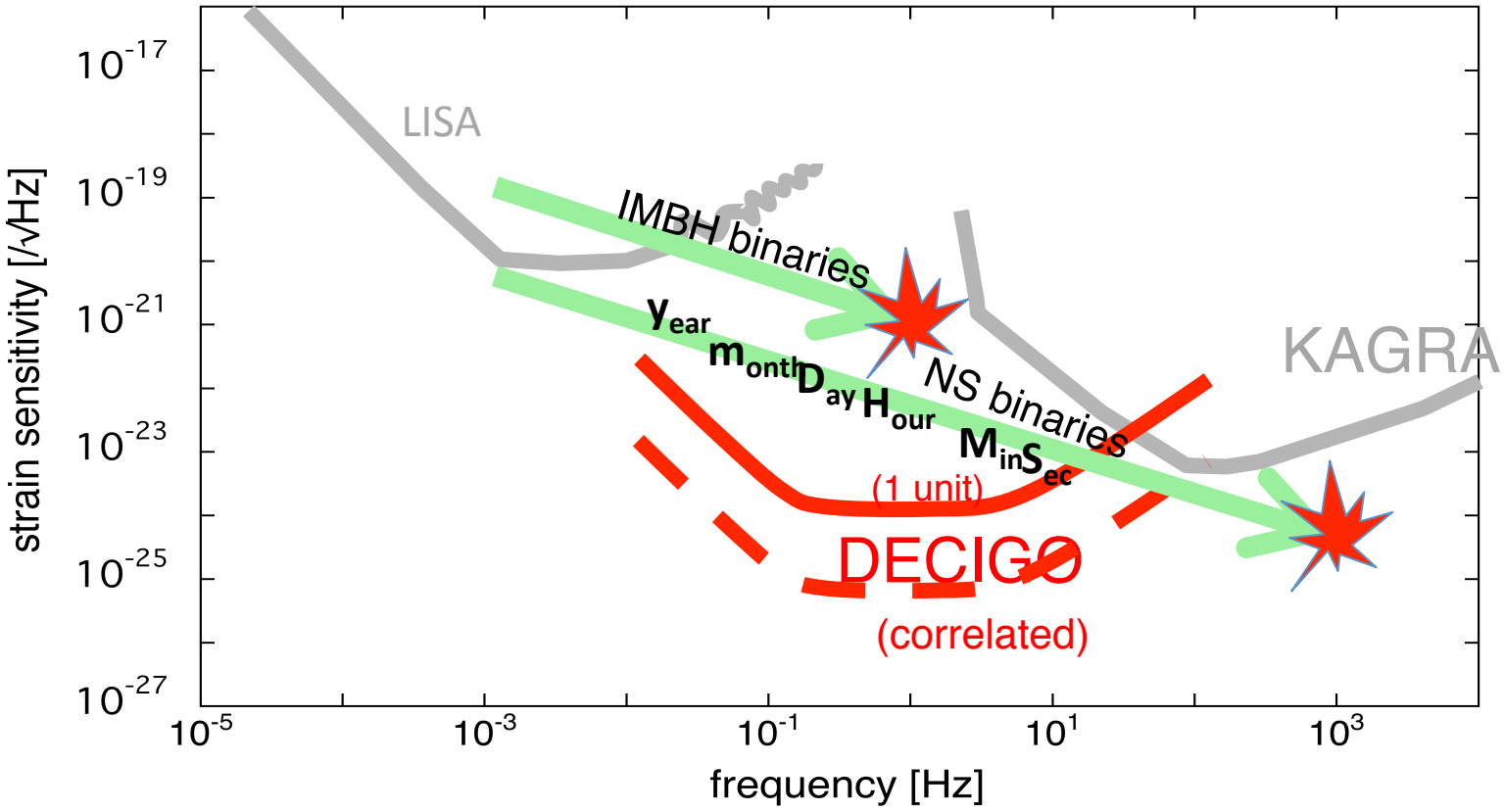
# DECIGO- targets

- NSB-inspiral
- IMBHB-inspiral

⇨ Formation mechanism of SMBH
Galaxy formation
Cosmology (inflation, dark energy)

- 5 years before NS-merger

⇨ Prediction for multi messenger
Improving parameter accuracy

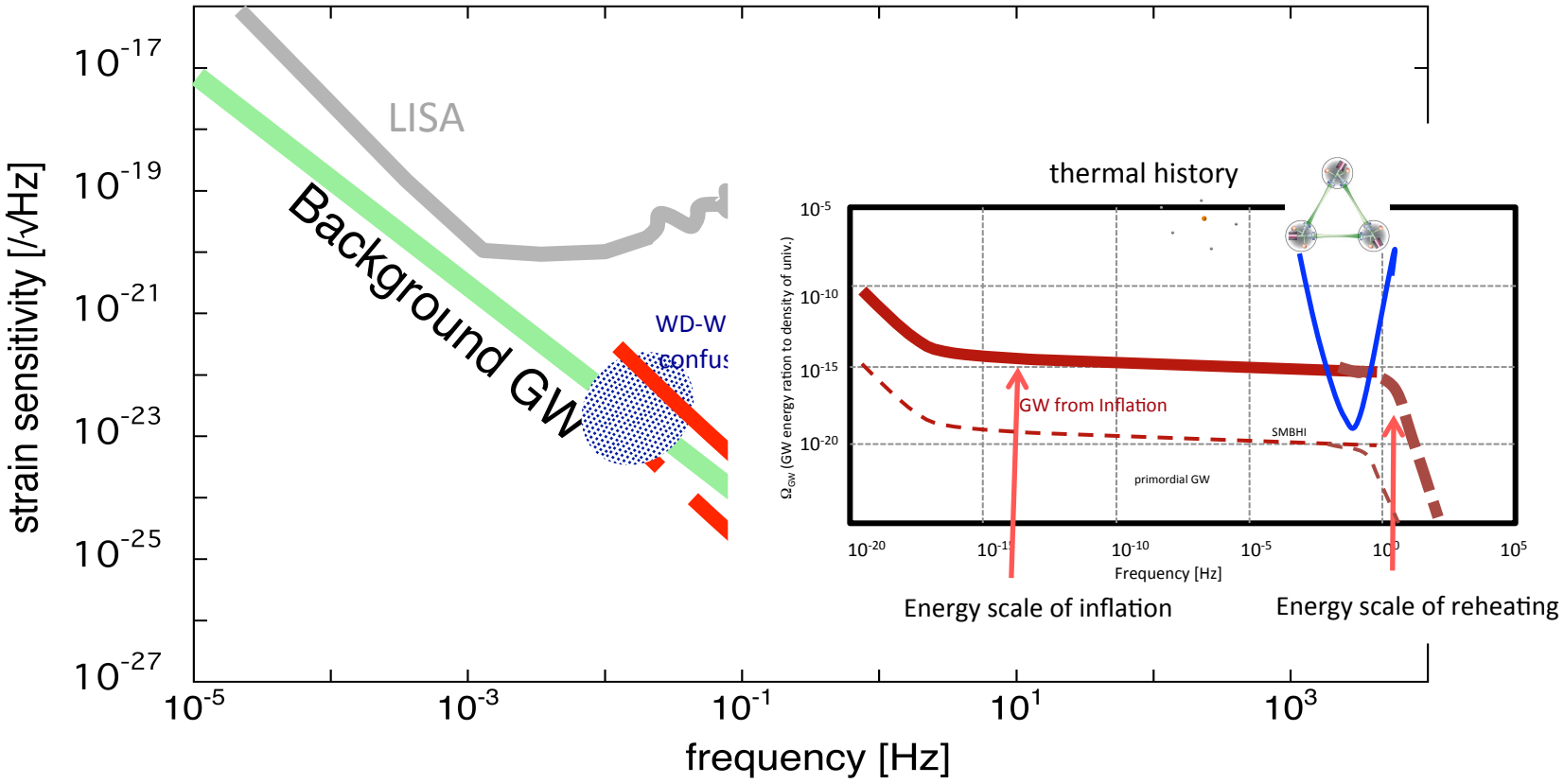


# DECIGO- targets

- Stochastic background ⇨ Birth of Universe

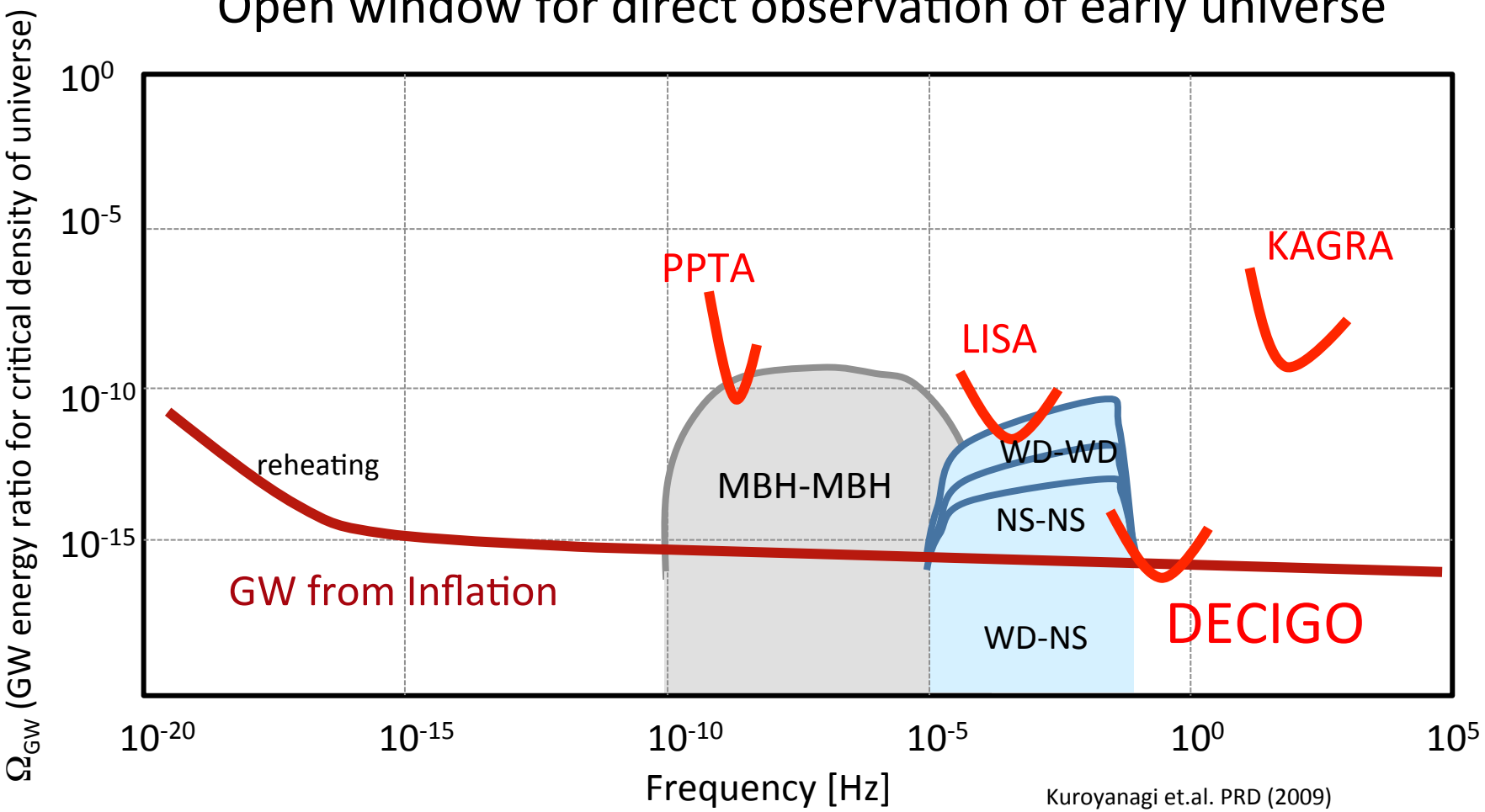
from very early universe

verification & characterization of inflation



# GW from Early Universe

Open window for direct observation of early universe




Kuroyanagi et.al. PRD (2009)
Pablo et.al PRD (2011)

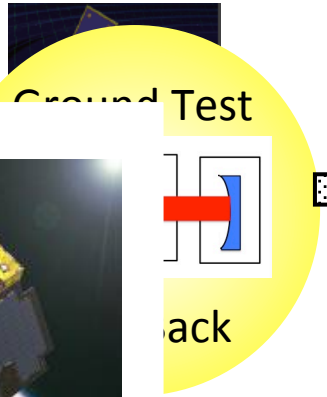
$$h_{GW}^{2}(f) \propto f^{-3}\Omega_{GW}(f)$$

r=0.1, TR=$10^{9}$ GeV

# DECIGO -roadmap

Proposal of DECIGO : Seto et.al PRL 87 (2001)221103

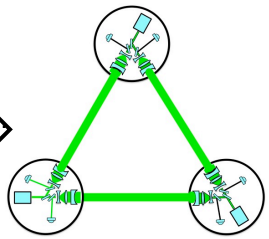
| 2012 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|



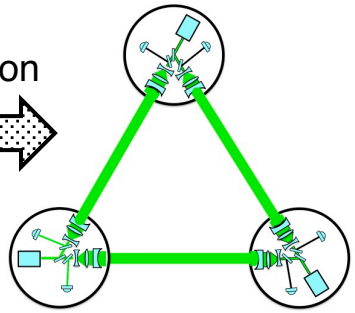
Ground Test

ack

R&D Fabricati



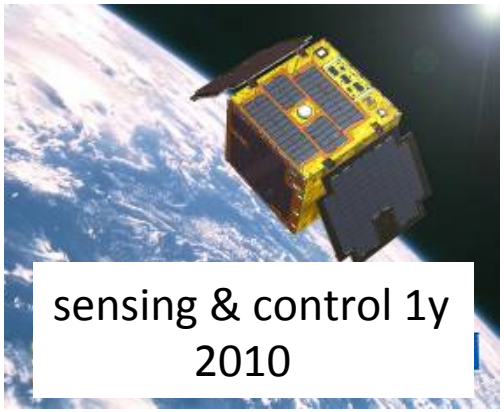
R&D Fabrication



B-DECIGO

DECIGO

SWIM



sensing & control 1y
2010

in orbit

onstration

technique

Earth gravity observation

Detection of GW

Detection of GW

NS-NS binary

Original Science

F.P. cavities between S/Cs

GW astronomy

BH-BH binary

Background GW

M S/C

3 S/Cs, 3 IFO

single unit

M～L S/C

3 S/Cs, 3IFOs

3 or 4 units

Short F.P.cavity drag-ree

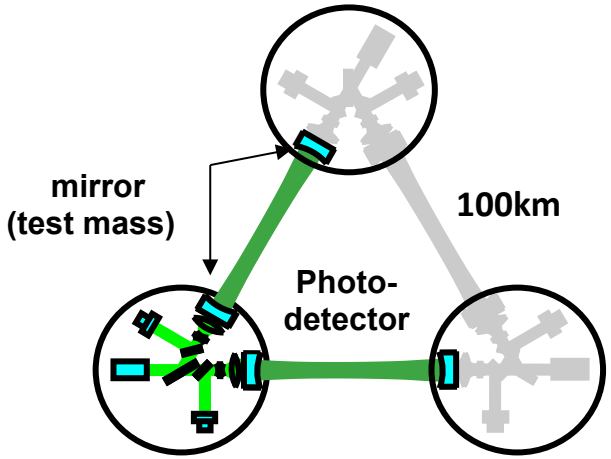
Short F.P. Interferometer

# outline

- *Gravitational Wave Detection*
- *DECIGO*
- ***B-DECIGO***
- *Light source for DECIGO/B-DECIGO*
- *Summary*

# B-DECIGO

Conceptual design




F.P. Michelson interferometer
Triangle 3 S/C
Drag-free, formation flight

3 years operation

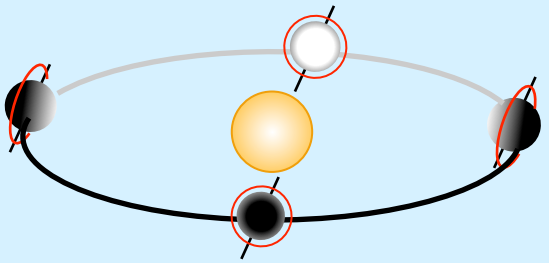
| | armlength (km) | test mass (kg) | mirror diam. (cm) | power (W) | unit |
|---|---|---|---|---|---|
| DECIGO | 1000 | 100 | 100 | 10 | 3～4 |
| B-DECIGO | 100 | 30 | 30 | 1 | 1 |

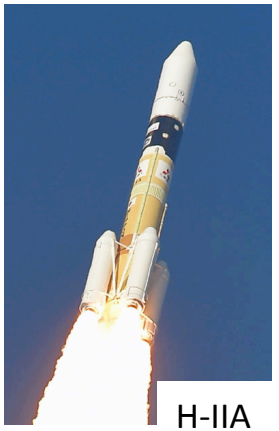


Sun synchronous orbit

Cartwheel orbit around the earth

altitude 2000 km





H-IIA

target: JAXA Strategic Medium-scale mission (2020s).

# B-DECIGO-targets

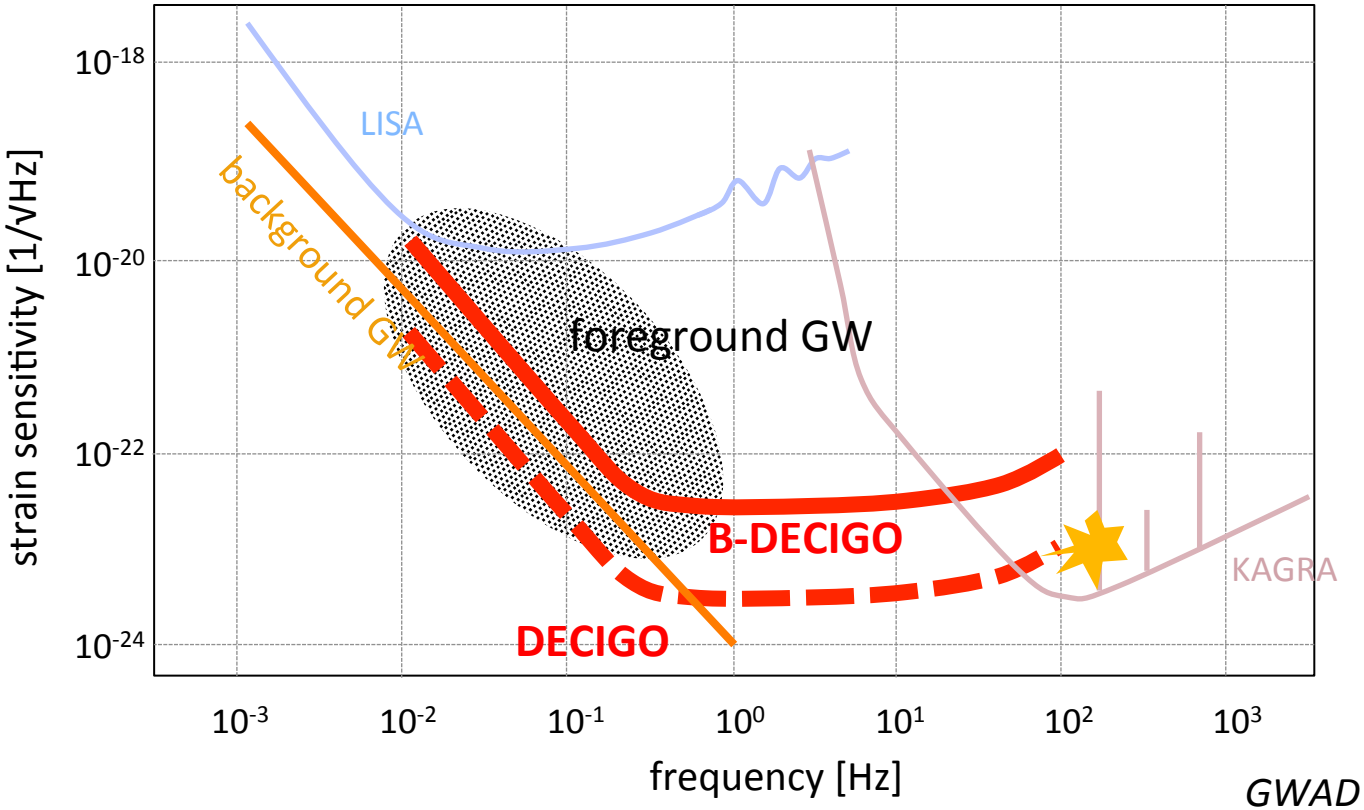
## Feasibility test s for DECIGO

formation flight

drag-free control $\delta F < 10^{-16}$ N/√Hz

precision measurement in space $\delta L < 2\times10^{-18}$ m/√Hz

Optical configuration, Laser



## science targets

(1) **Inspiral of Compact binaries** ['Promised' target]

high rate ~ $10^4$-$10^6$ binaries/yr.

estimation of binary parameters and merger time.

→ Astronomy by GW only and GW-EM observations.

(2) **Inspirals and mergers of IMBHs** [Original science]

- Cover most of the universe.

→ Formation history of SMBH and galaxies.

(3) **Foreground understandings for DECIGO** [Cosmology]

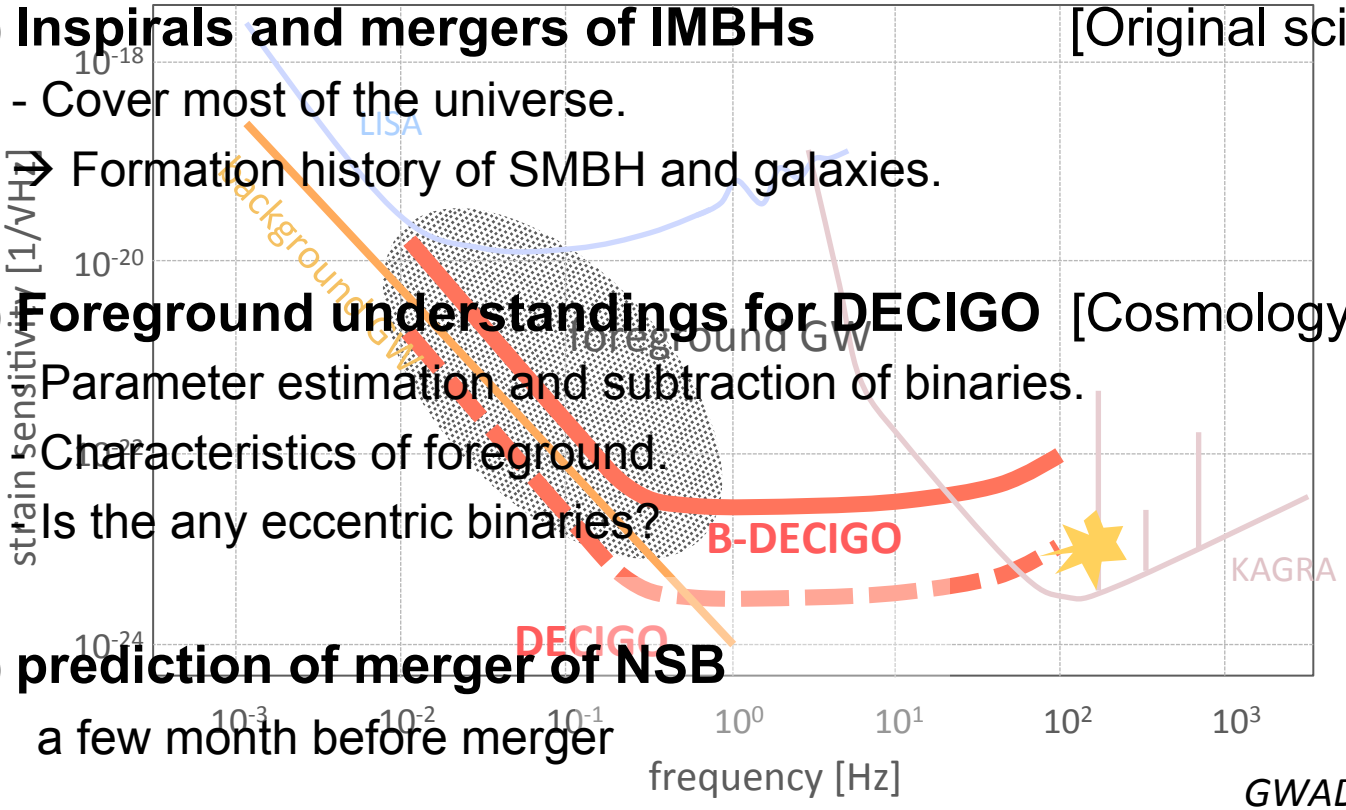
Parameter estimation and subtraction of binaries.

Characteristics of foreground.

Is the any eccentric binaries?

(4) **prediction of merger of NSB**

a few month before merger



# B-DECIGO- science targets

(1) **Inspiral of Compact binaries** ['Promised' target]

high rate ~$10^6$ binaries/yr

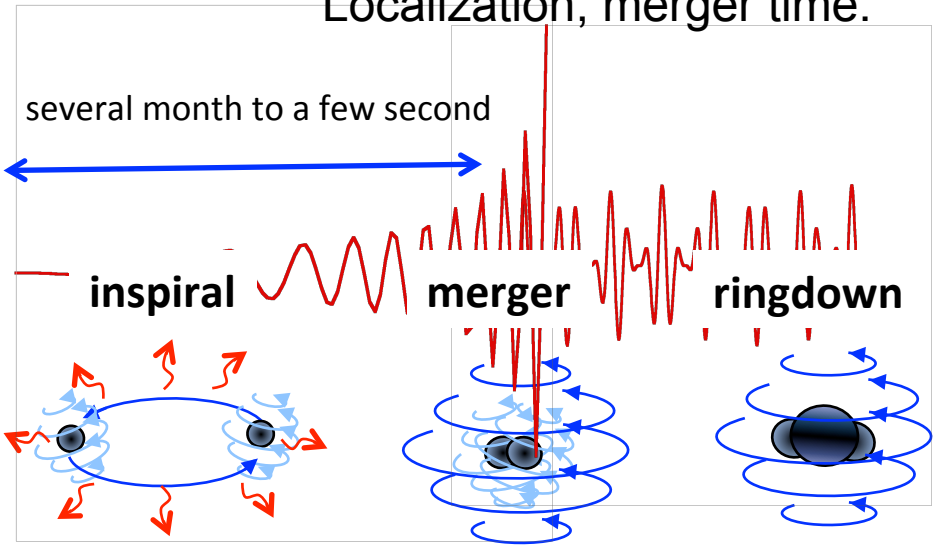
BBH ～Tpc
BNS ～2Gpc

binary NS inspirals : 100/yr

binary BH inspirals : ～$10^6$/yr

accurate estimation of binary parameter -$10^5$cycles

Localization, merger time.




identify origin of BBH (pop-II, pop-III, primordial BH)

# B-DECIGO- science targets

(1) **Inspiral of Compact binaries** ['Promised' target]

high rate ~$10^6$ binaries/yr.

estimation of binary parameters and merger time.

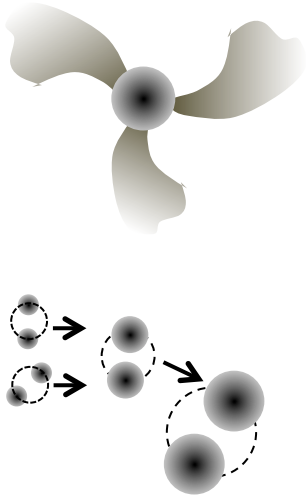
(2) **Inspirals and mergers of IMBHs** [Original science]

cover most of the universe.

formation history of SMBH and galaxies.

How SMBHs evolve @ center of galaxy ?

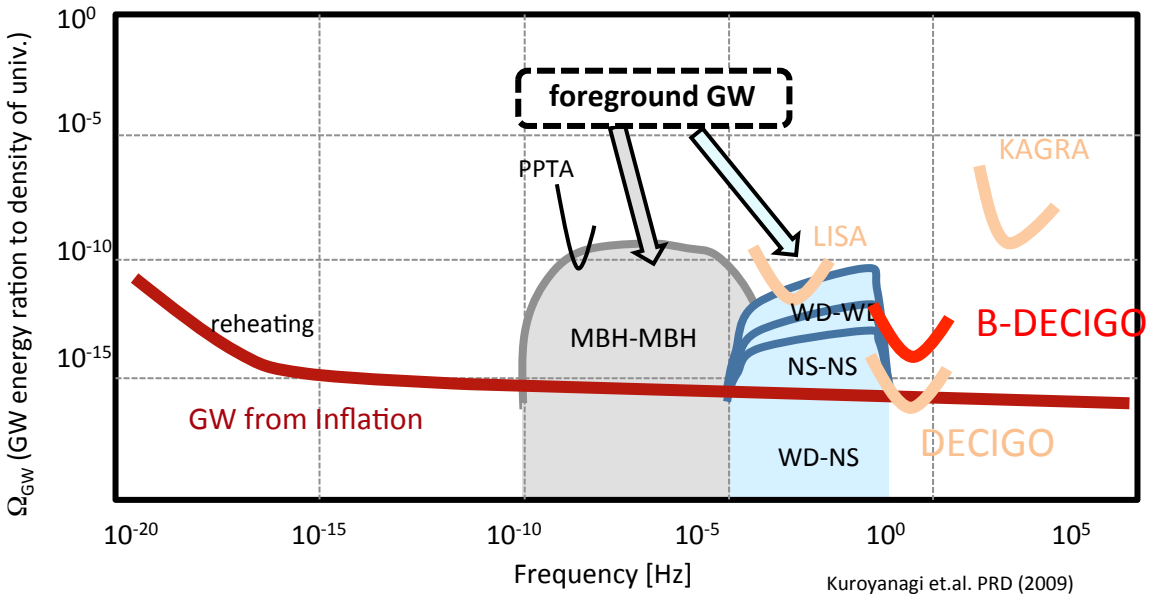
- Large BH + Accretion
- Hierarchical merger



# B-DECIGO- science targets

(1) **Inspiral of Comp**
high rate ~$10^6$ bina
estimation of binary

(2) **Inspirals and me**
cover most of the ur
formation history of




Kuroyanagi et.al. PRD (2009)
Pablo et.al PRD (2011)

(3) **Foreground understandings for DECIGO** [Cosmology]
parameter estimation and subtraction of binaries.
characteristics of foreground.
is the any eccentric binaries?

# technical challenges for B-DECIGO

- **Long-basesline laser interferometer** $\delta L$ <2x10$^{-18}$ m/√Hz @ 0.1 Hz

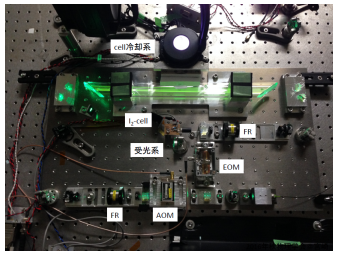
  Control of bidirectional optical cavity

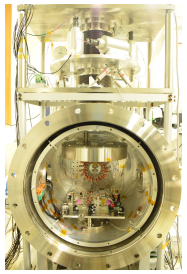
  Mirrors with ROC of 100 km and diameter of 0.3 m

  **Sequence of initial alignment of mirrors**

  Precision cavity control system with large dynamic range

  **Highly-stabilized high power space-borne laser**



- **low force noise** $\delta f < 1x10^{-16}$ N/√Hz

  Fluctuations of gravity and magnetic fields

  Residual gas

  Cosmic ray exposure

  mechanical noise from S/C control $\delta L$ <1x10$^{-9}$ m/√Hz @ 0.1 Hz

  Thermal (EM) Radiation

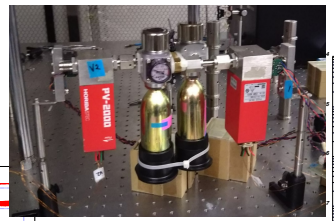
- **Stable condition in S/C**

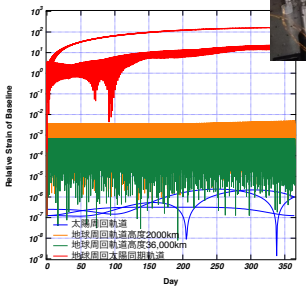
  Drag-free technique

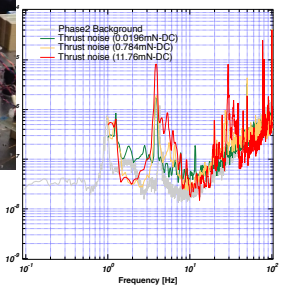
  Low-noise thruster

  Passive external noise suppression

  orbital design






*GWADW2019 @ Elba*

# outline

- *Gravitational Wave Detection*
- *DECIGO*
- *B-DECIGO*
- ***Light source for DECIGO/B-DECIGO***
- *Summary*

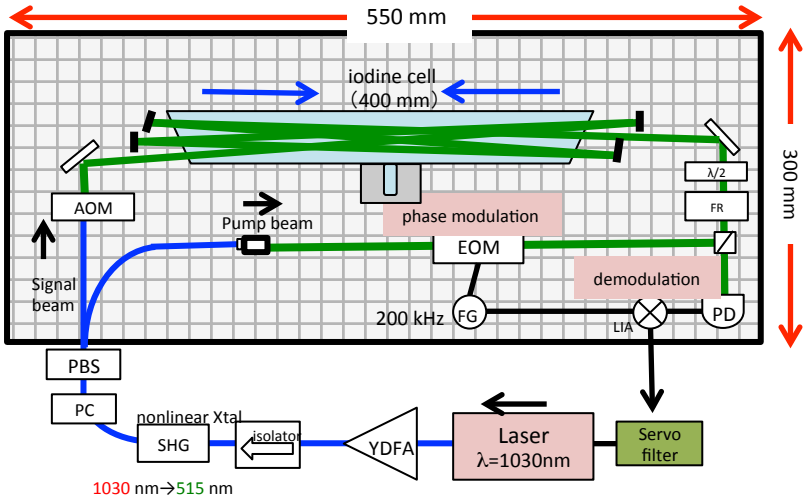
# *Light source for GW-detector*

single-frequency, single transverse mode, CW, linear polarized

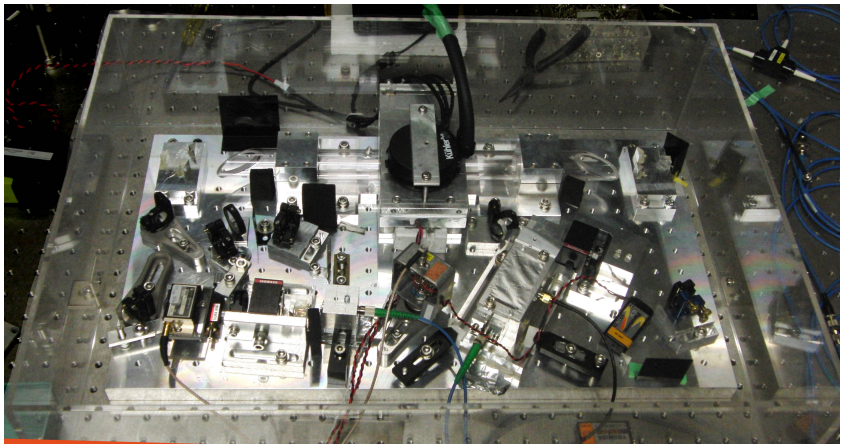
-- Requirements -

| | Wavelength [μm] | frequency noise [Hz/Hz$^{1/2}$] @1Hz | intensity noise [1/Hz $^{1/2}$] | output power [W] |
|---|---|---|---|---|
| **B-DECIGO** | 0.5 | $10^{0}$ | $10^{-8}$ | 1 |
| **DECIGO** | 0.5 | $10^{0}$ | $10^{-8}$ | 10 |

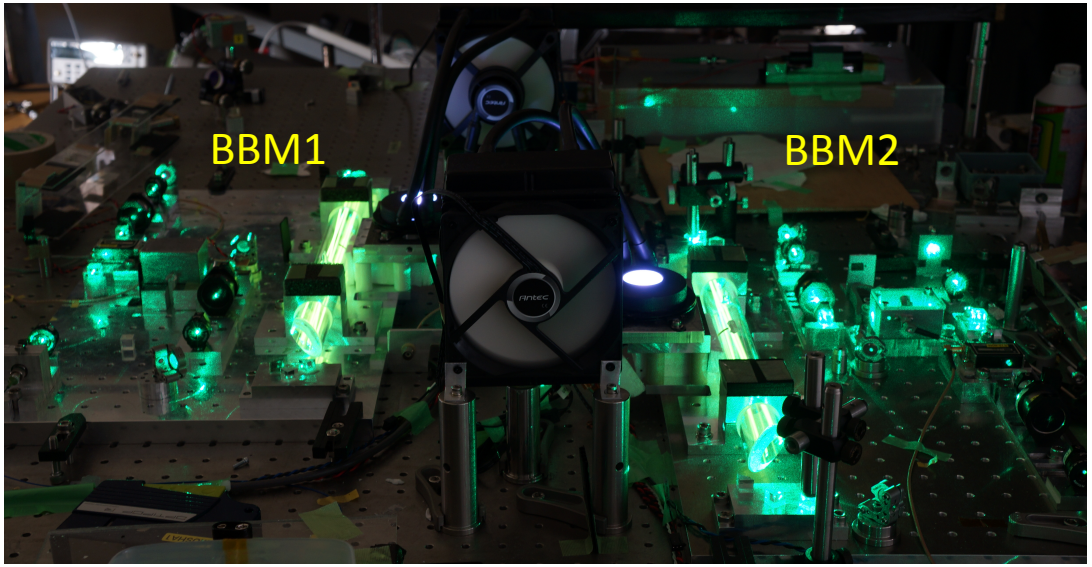
**Iodine-stabilized Yb-doped fiber laser @ 515 nm (SHG)**



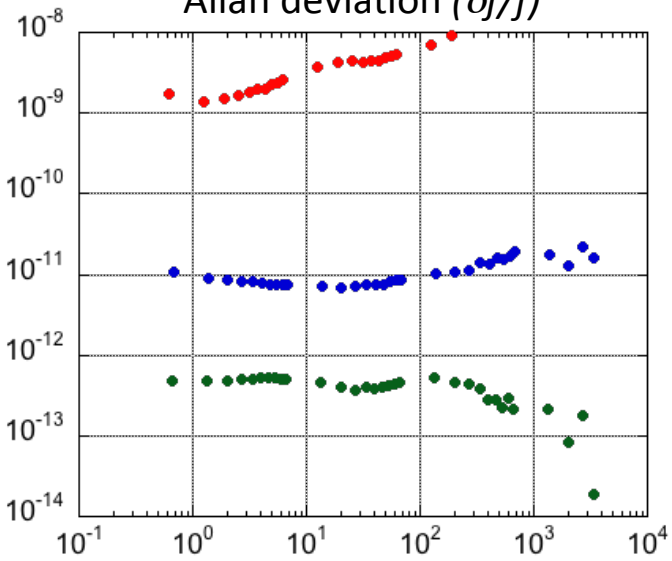

fiber DFB laser



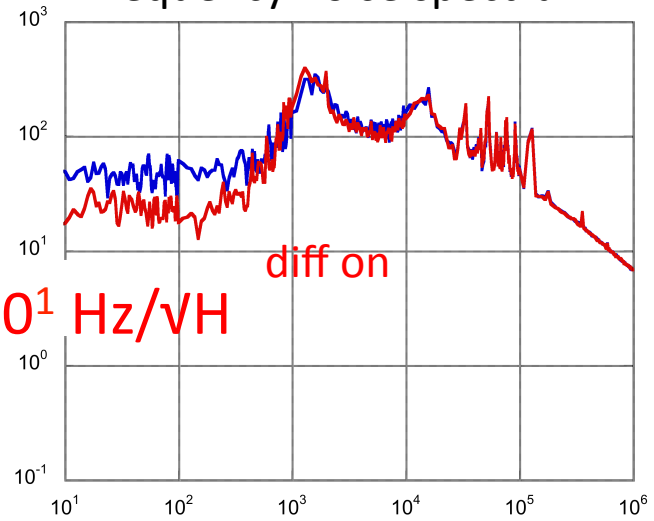
# frequency stabilized laser




Allan deviation ($\delta f/f$)



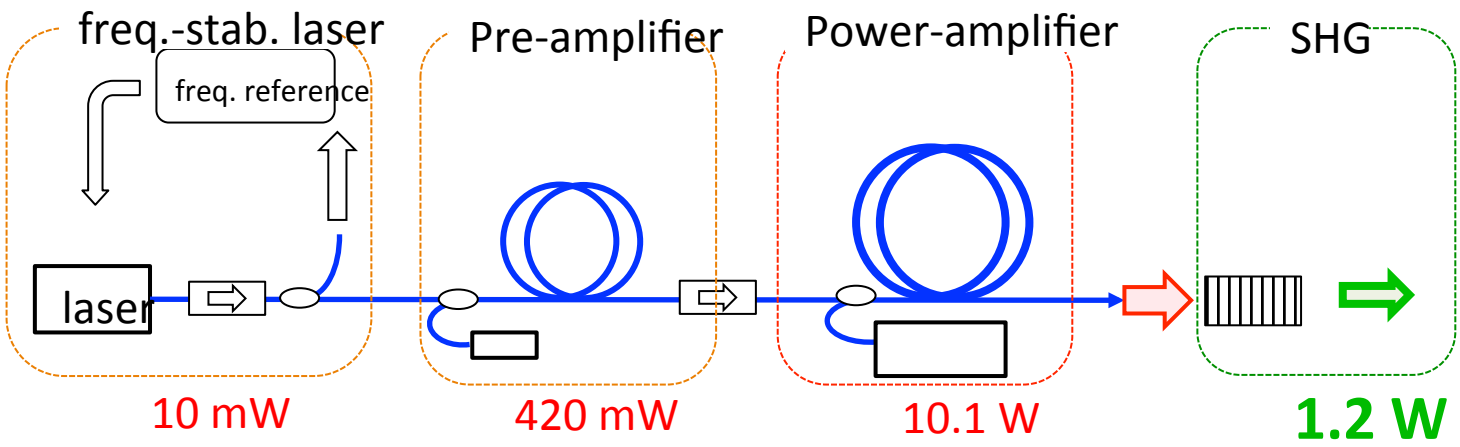

frequency noise spectrum

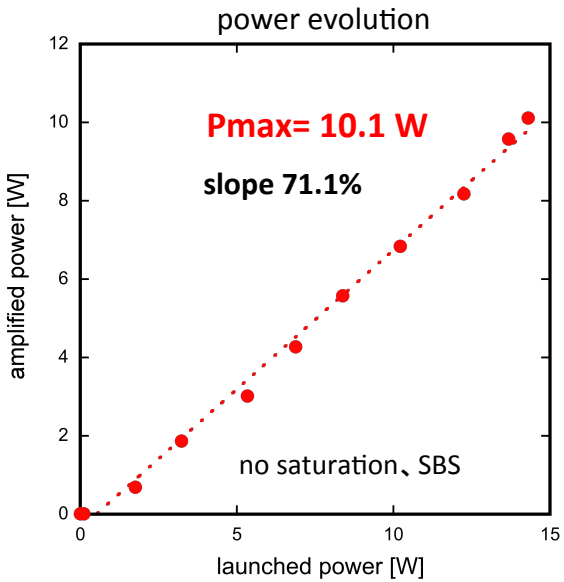


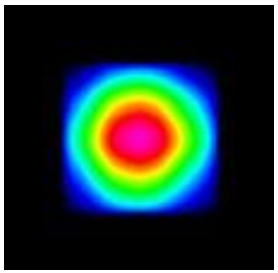

$1.5 \times 10^{1}$ Hz/√H

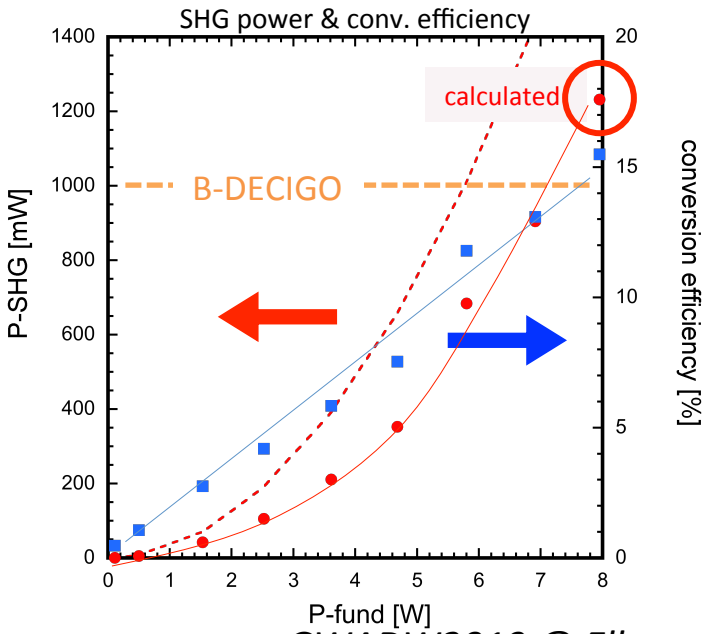
# high power light source

two-stage cascaded Yb:fiber amplifier & SHG

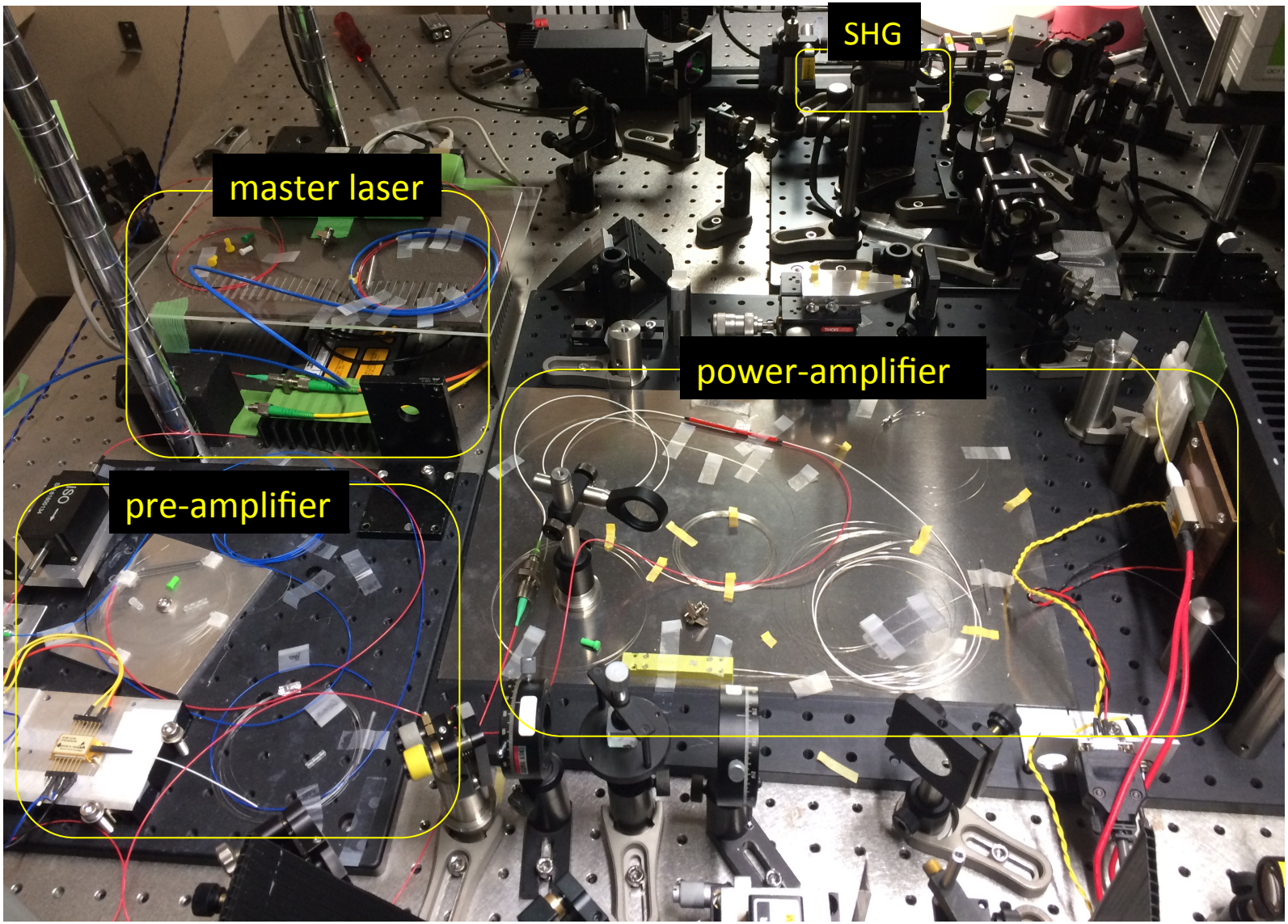


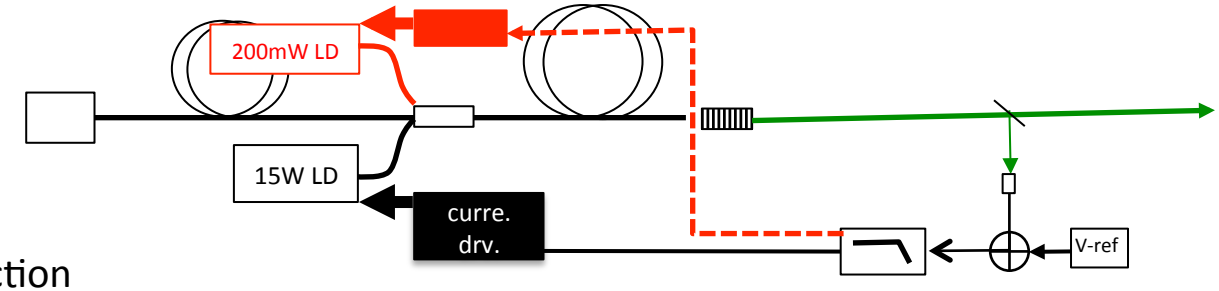


# high power green light

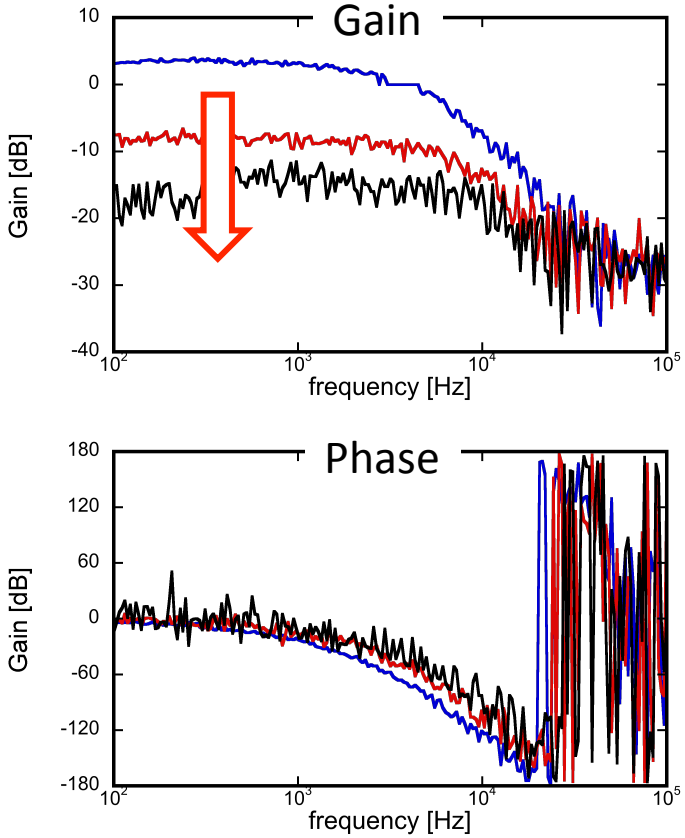


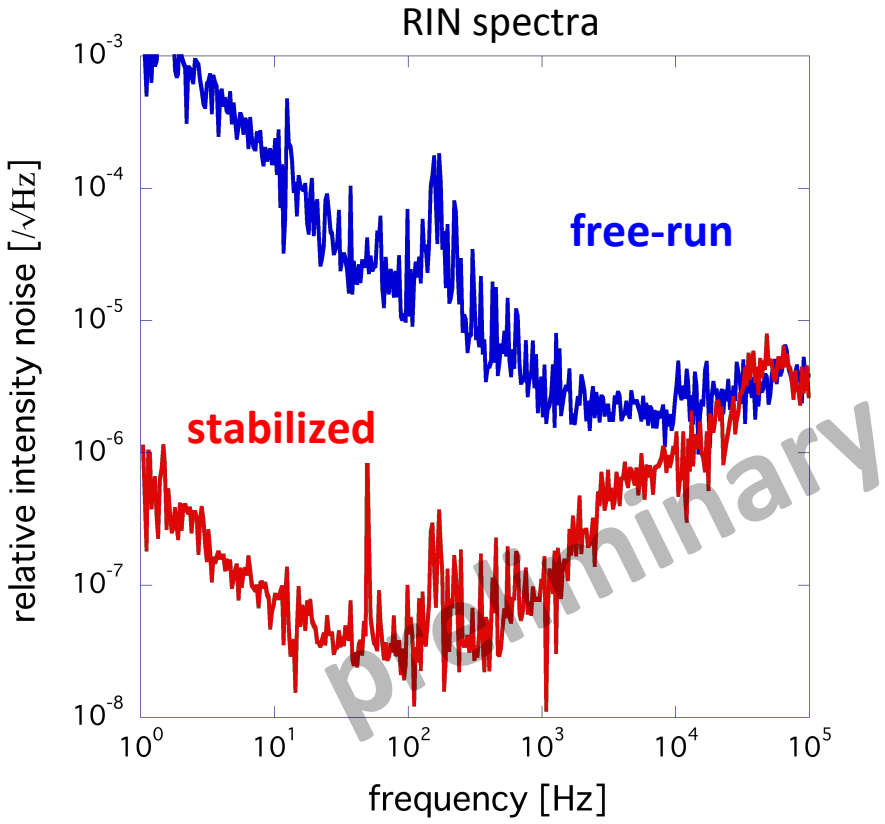
# intensity stabilization of green light

intensity of SHG ⇒ pump LD control




transfer function



# Summary

## B-DECIGO

$l$=100 km, $\delta l/l=10^{-23}$ /√Hz @ 0.1～10Hz

- Milestone mission for DECIGO　Fruitful science　Compact binary coalescences
  - GW150914-like BBH and BNS gravitational wave
  - Observation of IMBH mergers
  - Understanding of foreground GW for DECIGO
- Plan to be launched　late 2020s

## DECIGO

$l$=1000 km, $\delta l/l=10^{-24}$ /√Hz　@ 0.1～10Hz

- Space gravitational wave detector　Rich science
  - Direct detection of very beginning of the Universe
  - Dark energy, Dark matter
  - Galaxy formation
- Plan to be launched　mid 2030s

*Insight of the Universe*

# Acknowledgements

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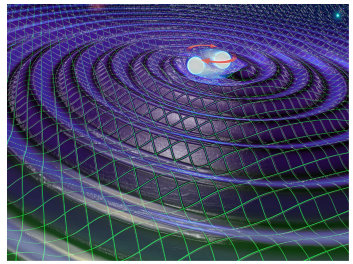

*Grazie per l'attenzione !*