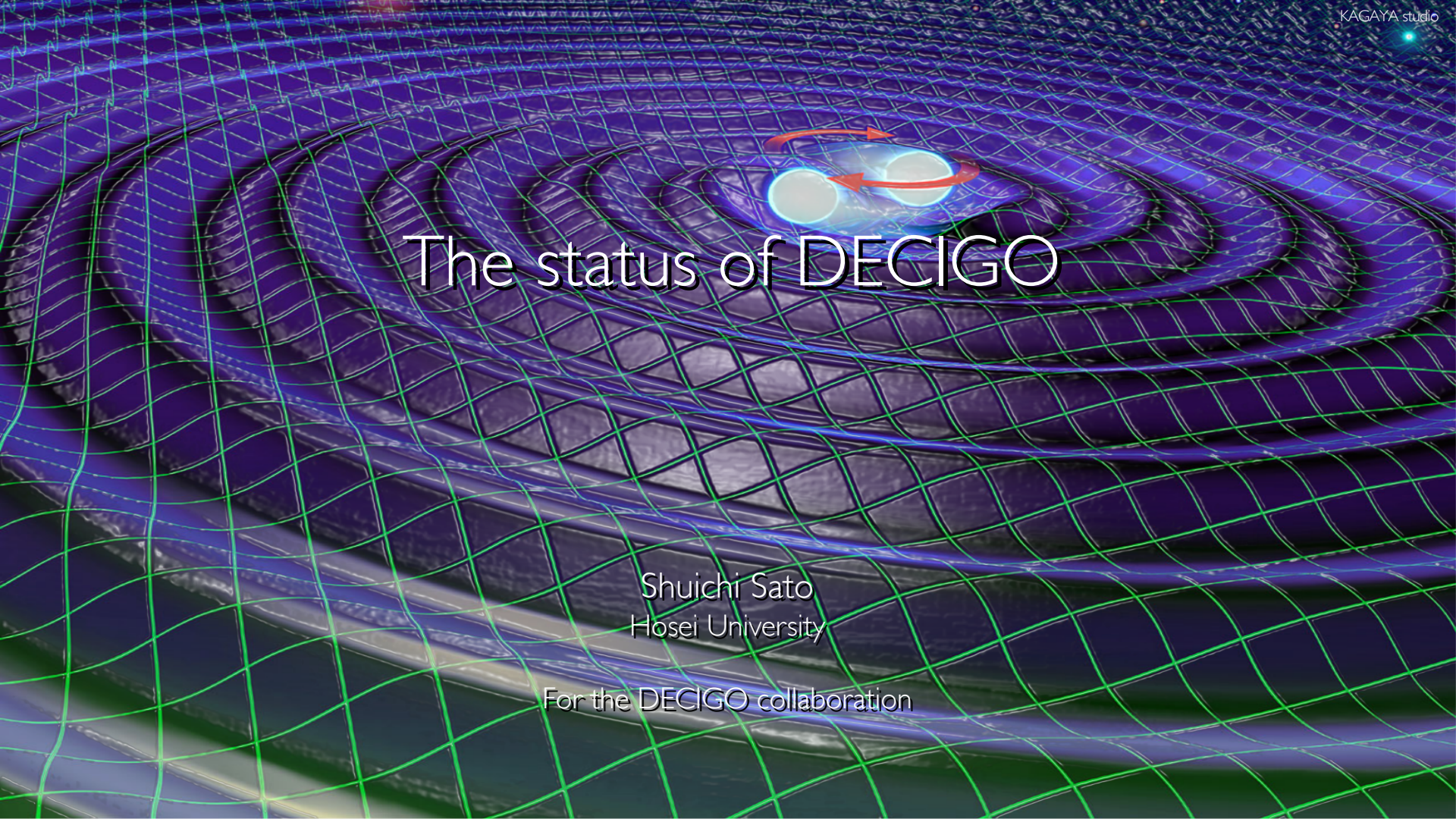


The status of DECIGO

Shuichi Sato
Hosei University

For the DECIGO collaboration

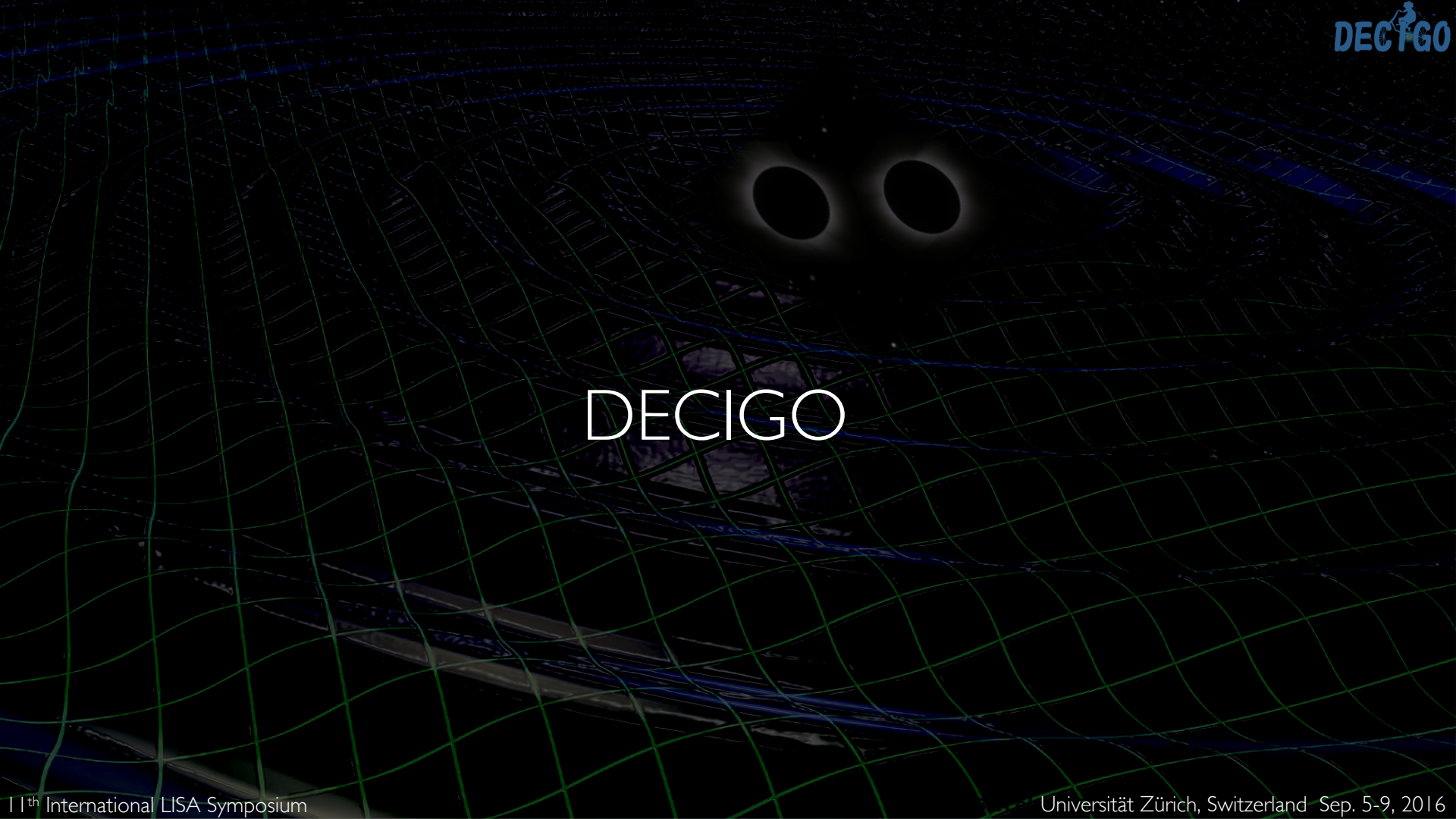
DECIGO working group

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, Hideki Ishihara, 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, 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 1st, 2016)

Outline

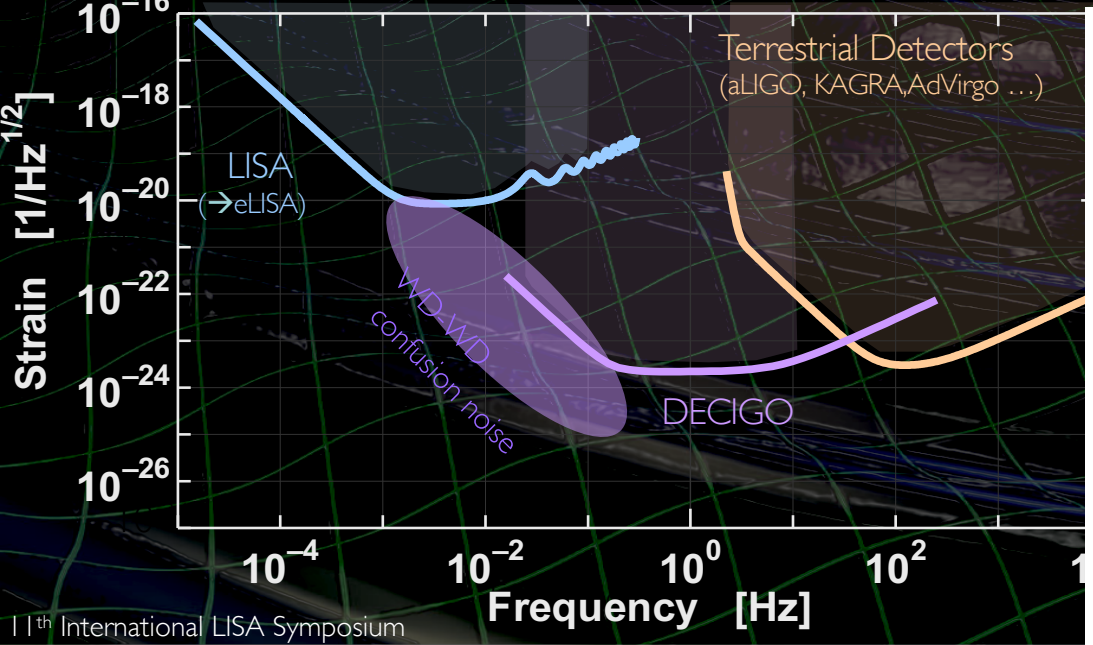
- DECIGO
- Pre-DECIGO
- Summary


DECIGO

DECIGO – *The idea* –

- DECi-hertz Interferometer Gravitational wave Observatory
  - Seto, Kawamura and Nakamura, PRL87, 221103(2001)
  - Bridges the gap between LISA and terrestrial detector
  - Low confusion noise → Potentially high sensitive instruments

Fig. by Ando



VOLUME 87, NUMBER 22 PHYSICAL REVIEW LETTERS 26 NOVEMBER 2001

Possibility of Direct Measurement of the Acceleration of the Universe Using 0.1 Hz Band Laser Interferometer Gravitational Wave Antenna in Space

Naoki Seto,[1] Seiji Kawamura,[2] and Takashi Nakamura[3]
[1]*Department of Earth and Space Science, Osaka University, Toyonaka 560-0043, Japan*
[2]*National Astronomical Observatory, Mitaka 181-8588, Japan*
[3]*Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*
(Received 4 June 2001; published 9 November 2001)

It may be possible to construct a laser interferometer gravitational wave antenna in space with $h_{\rm rms} \sim 10^{-27}$ at $f \sim 0.1$ Hz in this century. Using this antenna, (1) typically 10^5 chirp signals of coalescing binary neutron stars per year may be detected with S/N $\sim 10^4$; (2) we can directly measure the acceleration of the universe by a 10 yr observation of binary neutron stars; and (3) the stochastic gravitational waves of $\Omega_{\rm GW} \gtrsim 10^{-20}$ predicted by the inflation may be detected by correlation analysis. Our formula for phase shift due to accelerating motion might be applied for binary sources of LISA.

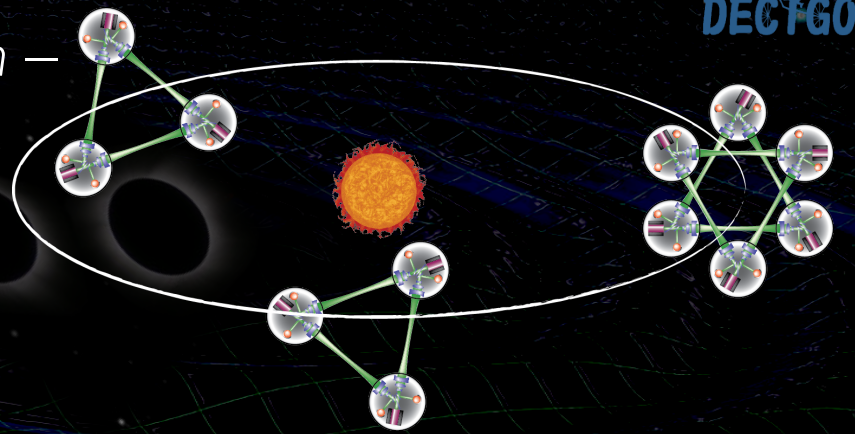
DOI: 10.1103/PhysRevLett.87.221103 PACS numbers: 95.55.Ym, 04.80.Nn, 98.80.Es

I. Introduction.—There are at least four methods to detect gravitational waves: (1) resonant type antenna covering ~kHz band; (2a) laser interferometers on the ground covering 10 Hz–kHz band; (2b) laser interferometers in space like LISA [1] covering 10^{-4}–10^{-2} Hz band; (3) residuals of pulsar timing covering $\sim 10^{-8}$ Hz band; (4) Doppler tracking of the spacecraft covering 10^{-4}–10^{-2} Hz band. It is quite interesting to note that little has been discussed on possible detectors in 10^{-2}–10 Hz band. In this Letter we consider the possible specification of such a detector, which we call DECIGO (Decihertz Interferometer Gravitational Wave Observatory). We argue that the direct measurement of the acceleration of the universe is possible using DECIGO.

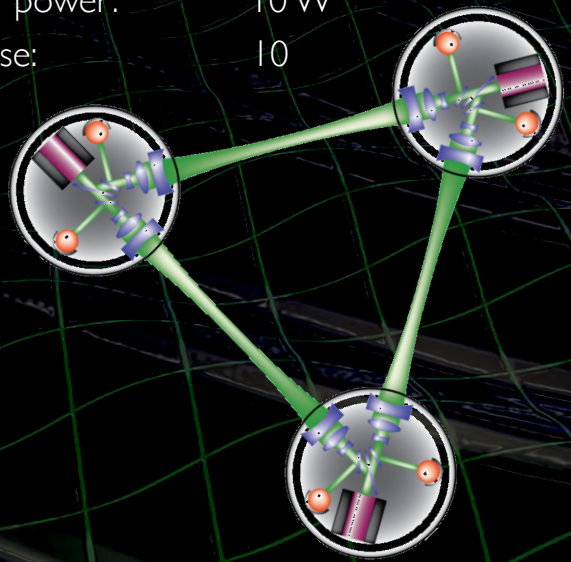
II. Specification of DECIGO.—The sensitivity of a space antenna with an arm length of 1/10 of LISA and yet the same assumption of the technology level, such as a laser power of 1 W, the optics of 30 cm, etc., will sooner. Note here that when the pioneering efforts to detect the gravitational waves started in the last century using resonant-type detectors as well as laser interferometers, few people expected the present achievement in resonant-type detectors such as IGEC (bar) [3] and in laser inteferometers such as TAMA300 [4], LIGO, GEO600, and VIRGO (for these detectors see [5]). Therefore all the experimentalists and the theorists on gravitational waves should not be restricted to the present levels of the detectors. Our point of view in this Letter is believing the proverb "Necessity is the mother of the invention" so that we argue why a detector like DECIGO is necessary to measure some important parameters in cosmology.

The sensitivity of DECIGO, which is optimized at 0.1 Hz, is assumed to be limited only by radiation pressure noise below 0.1 Hz and shot noise above 0.1 Hz. The contributions of the two noise sources are equal to each other at 0.1 Hz, giving the quantum limit sensitivity at this

DECIGO – *Pre-conceptual design* –



- Interferometer parameters
  - Arm length: 1000 km
  - Mirror diameter: 1 m
  - Mirror mass: 100 kg
  - Laser wavelength : 515 nm
  - Laser power: 10 W
  - Finesse: 10

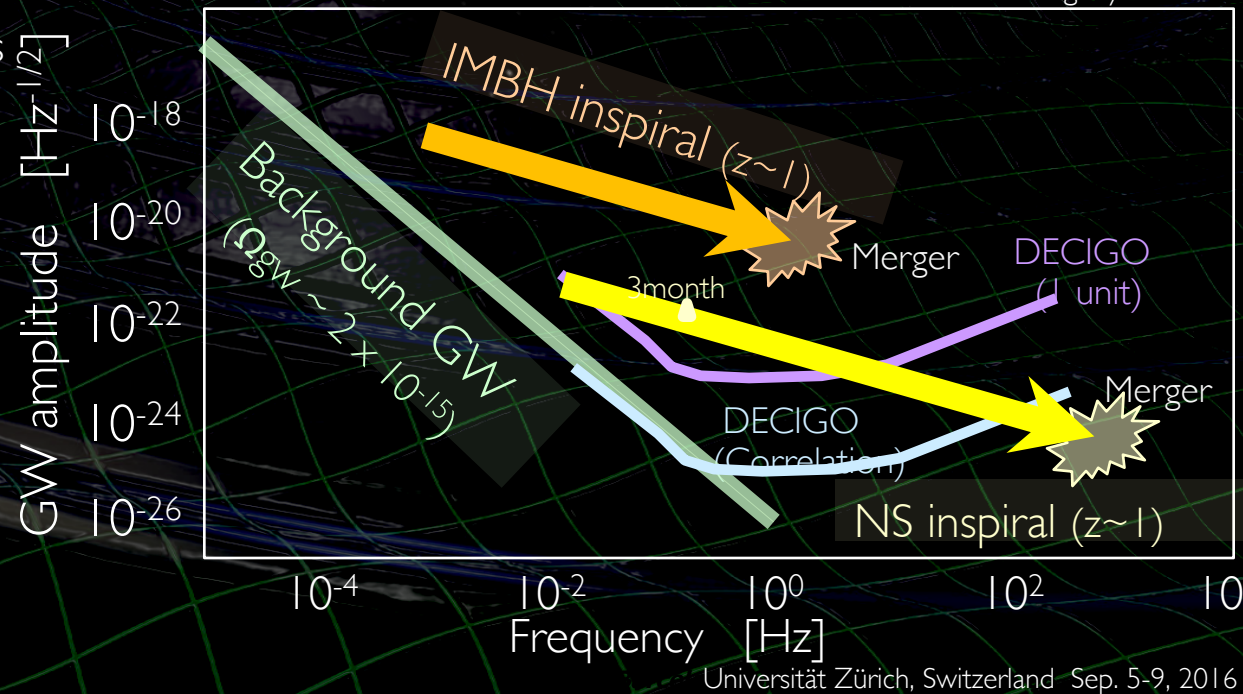


- Interferometer topology
  - Differential FP interferometer
  - Three interferometers for redundancy
  - Drag-free controlled S/Cs
- Constellation
  - 4 interferometer units
  - 2 overlapped units → Cross correlation
  - 2 separated units → Angular resolution

DECIGO – *Science case* –

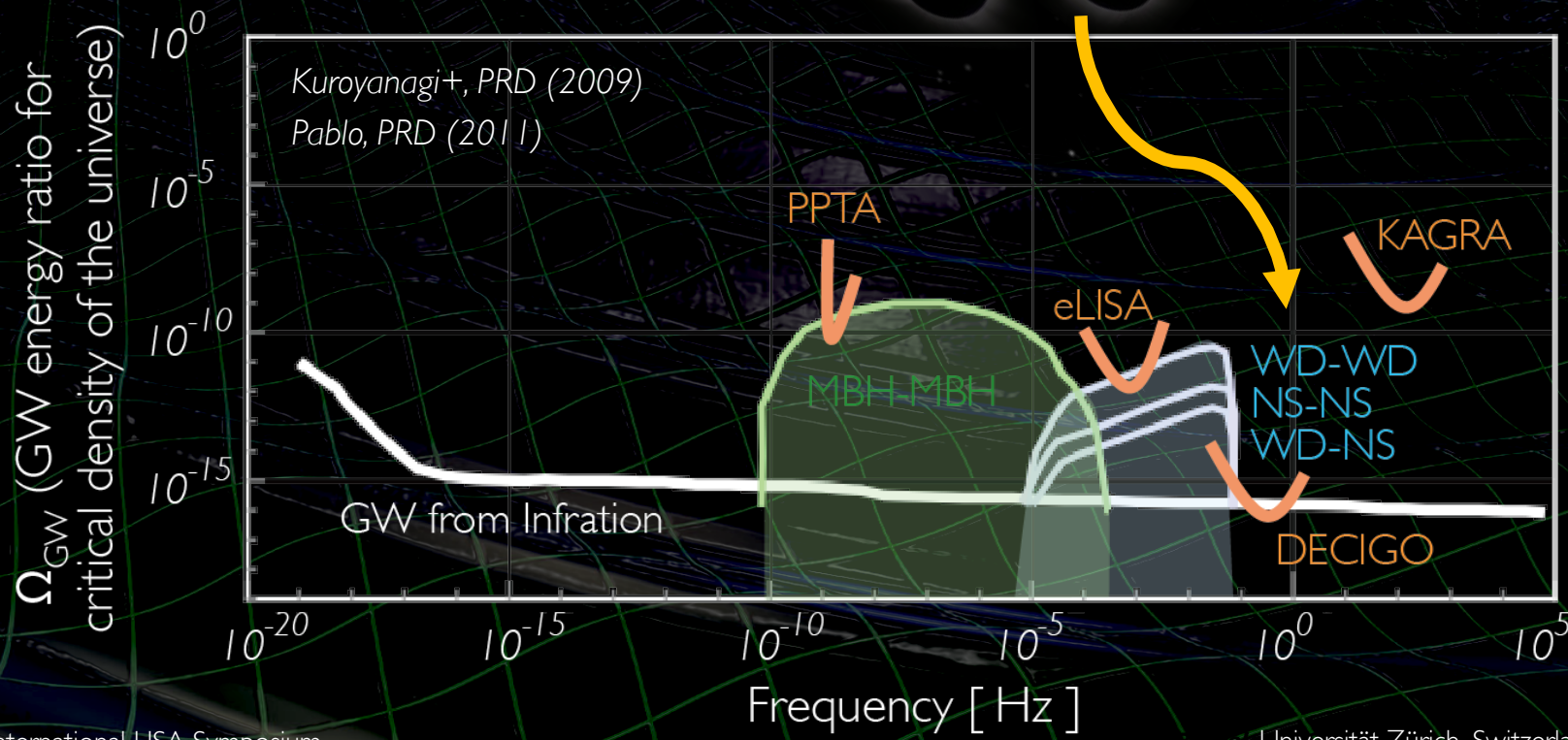
- BNS Inspirals
  - From cosmological distance
  - Cosmology (Inflation, Dark energy)
- IMBH Inspirals and Mergers
  - Formation history of SMBH
  - Galaxy formation
- Stochastic background
  - Fundamental physics

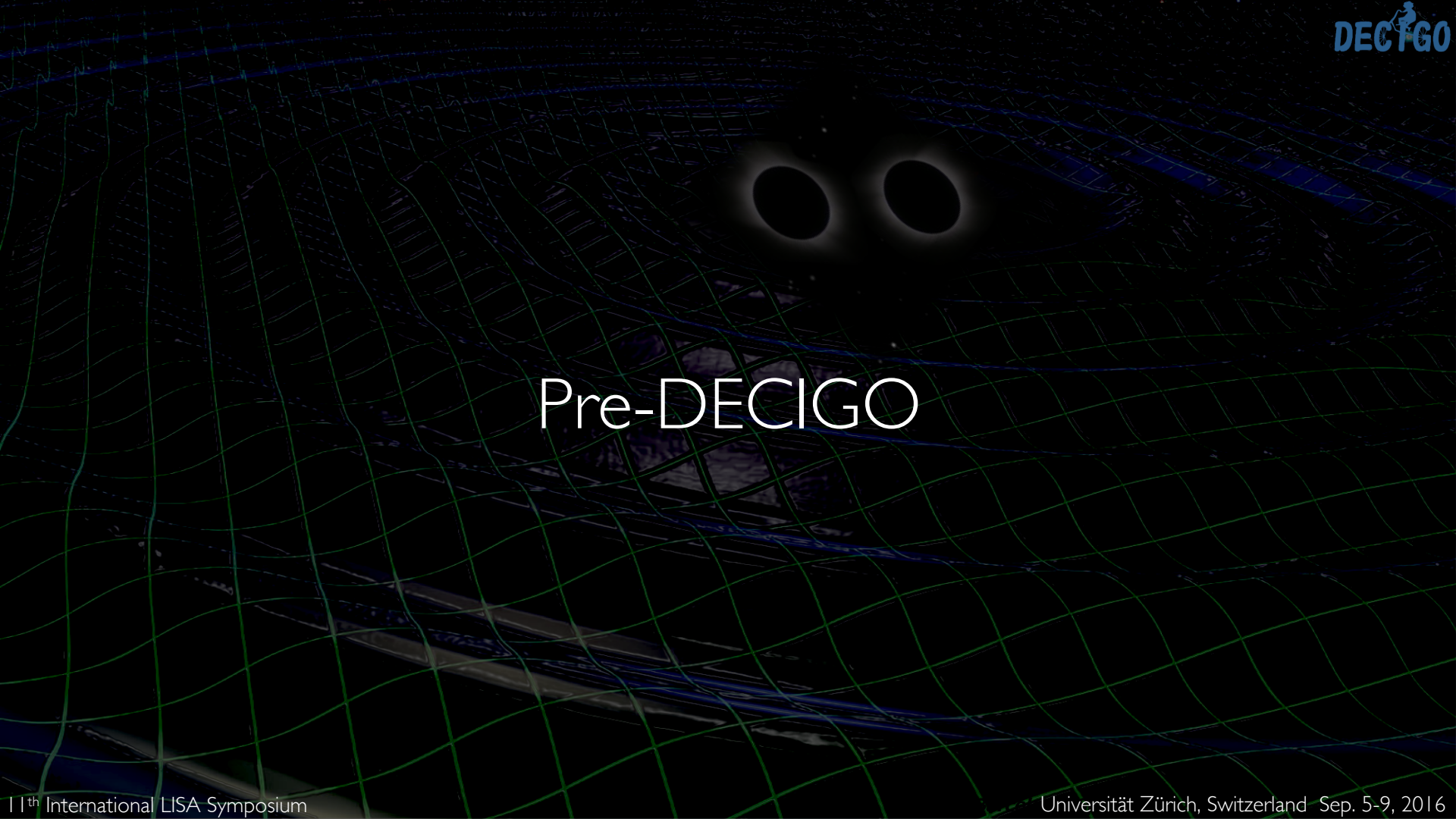
Fig. by Ando



DECIGO – *Access to very beginning of the Universe* –

DECIGO band is open window
for direct observation of the early universe.

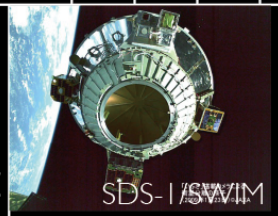


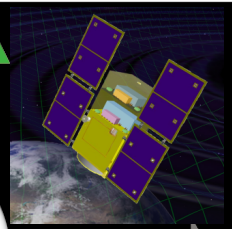

DECIGO
Pre-DECIGO

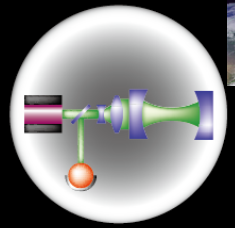
Pre-DECIGO – *Roadmap* –

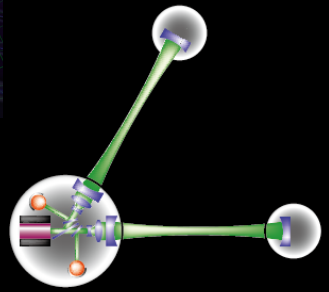
Fig. by Kawamura, rev.

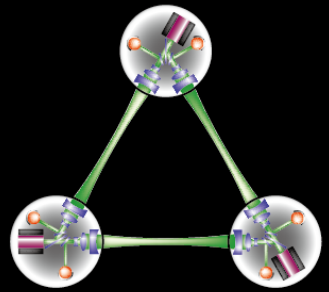
	2012	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Mission																											
Objectives																											
Scope																											











DECIGO Pathfinder

Pre-DECIGO

DECIGO

Test of key tech. in orbit
GW detection
Earth gravity observation

Detection of GW
w/ min. spec.
FP cavities between S/Cs

GW astronomy

Single small S/C
Short FP interferometer

3 S/Cs, single IFO
Single unit

3 S/Cs, 3 IFOs
3 or 4 units

Pre-DECIGO – *DECIGO pathfinder plan* –

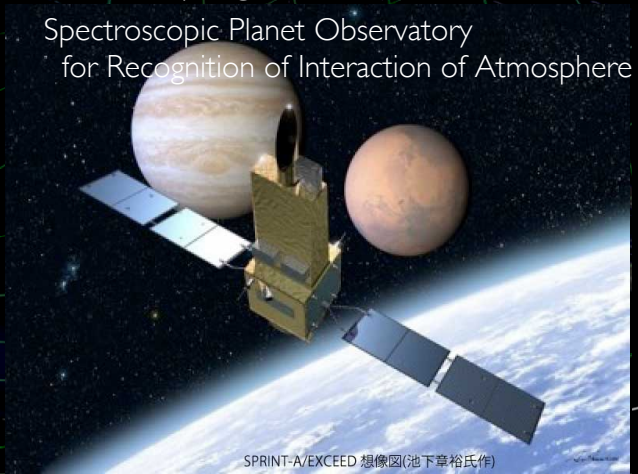
- JAXA's "Small science satellite series" program

  "At least 3 satellites in 5 years with
  Standard Bus + M-V follow-on rocket"

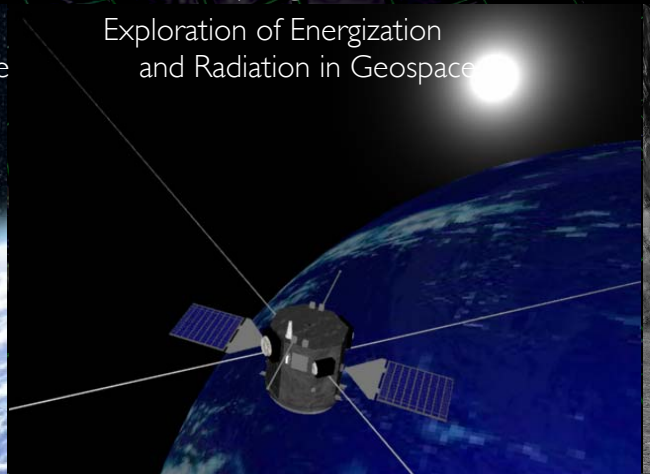
  - 1st mission (2013.9): SPRINT-A /EXCEED
  - 2nd mission (~2016) : SPRINT-B /ERG
  - 3rd mission (~2019/20) : SPRINT-C ? /SLIM

EPSIRON : Solid rocket booster (M-V FO)
Fig. by JAXA

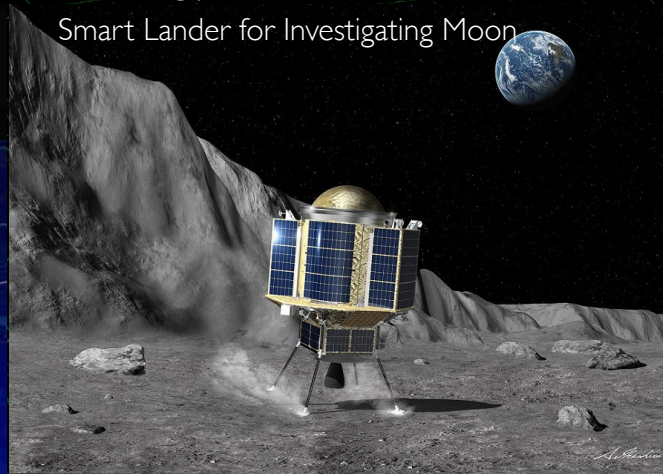
SPRINT-A /EXCEED
Spectroscopic Planet Observatory
for Recognition of Interaction of Atmosphere



SPRINT-B /ERG
Exploration of Energization
and Radiation in Geospace

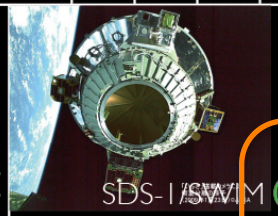


SPRINT-C /SLIM
Smart Lander for Investigating Moon



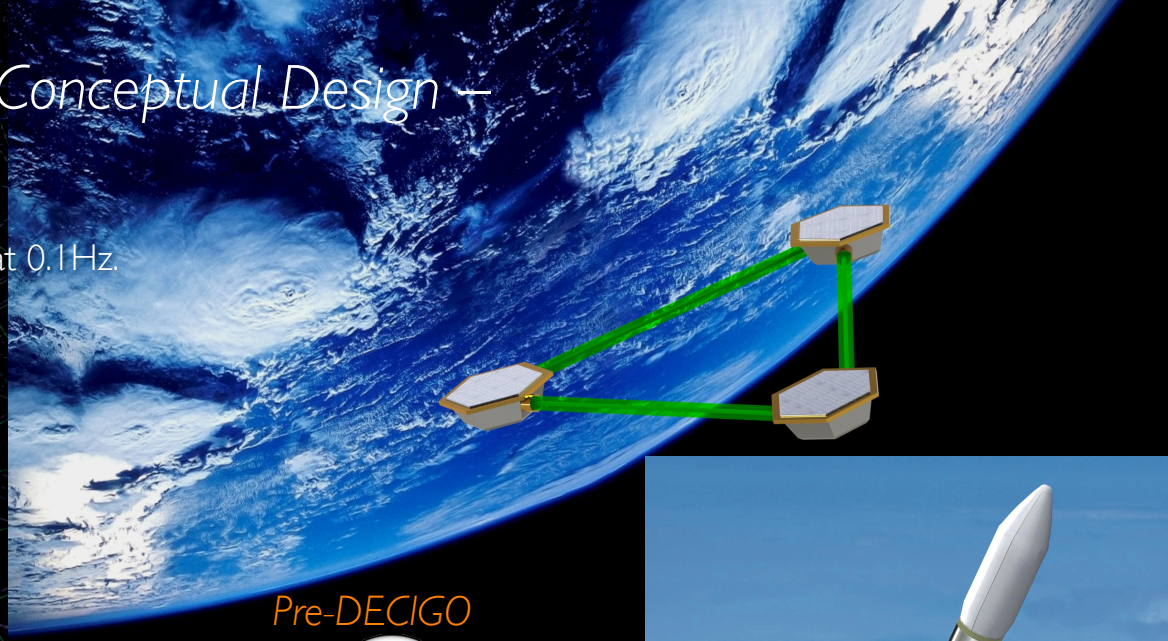
Pre-DECIGO – *Revised Roadmap* –

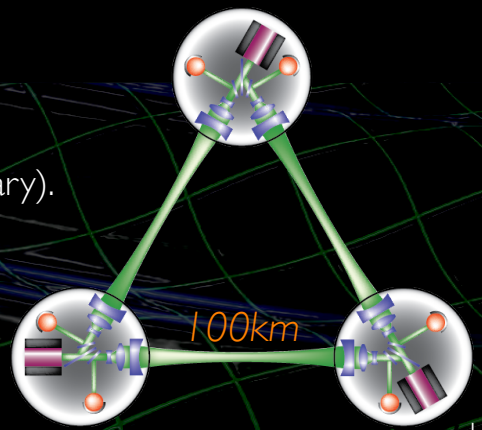
Fig. by Kawamura, rev.

	2012	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Mission	 SDS-1/SWIM					Ground test + Piggy back									Pre-DECIGO						DECIGO					
Objectives						*Technology demonstration of Space IFO technique*									*Detection of GW in orbit Original Sciences*						*GW astronomy and Cosmology*					
Scope						*Micro-g experiment Short FP cavity + Dragfree*									*3 S/Cs, 3 IFO Single unit*						*3 S/Cs, 3 IFOs 3 or 4 units*					

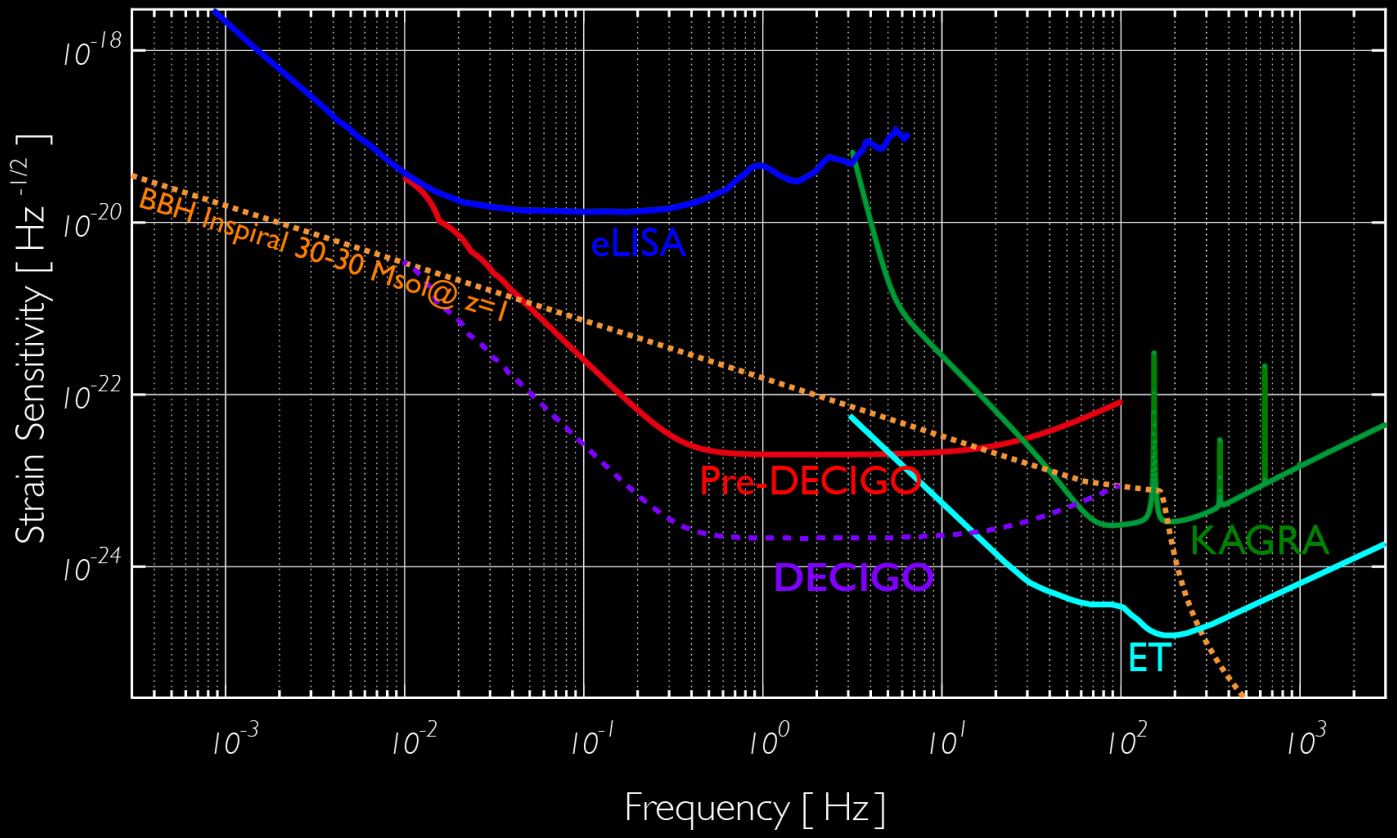
Pre-DECIGO – *Pre Conceptual Design* –

- Mission Requirement
  - Strain sensitivity of 2×10^{-23} $Hz^{-1/2}$ at 0.1Hz.
  - 3-years observation period.
- Conceptual Design
  - Laser interferometer by 3 S/C
  - Baseline : 100 km
  - Laser source : 1W, 515nm
  - Mirror : 300mm, 30kg
  - Drag-free and Formation flight.
  - Record-disk orbit around the earth:
  - Altitude 2000km, Period ~120min (Preliminary).



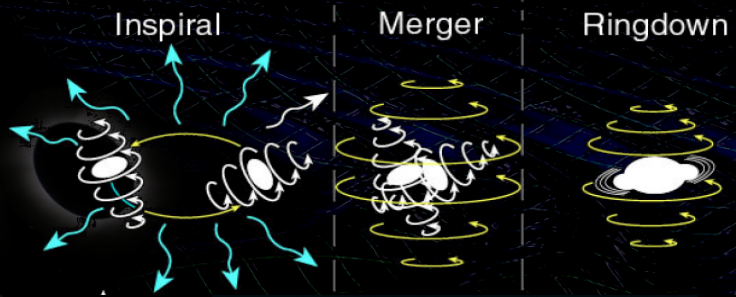


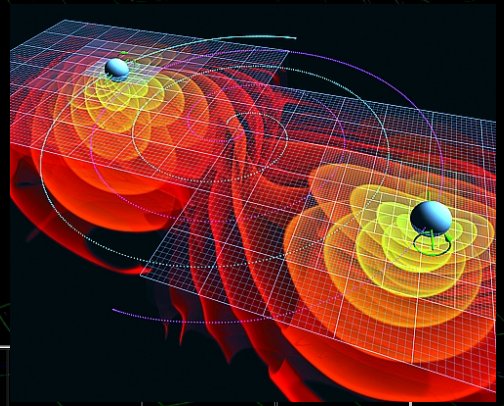
Pre-DECIGO – *Sensitivity Curve* –

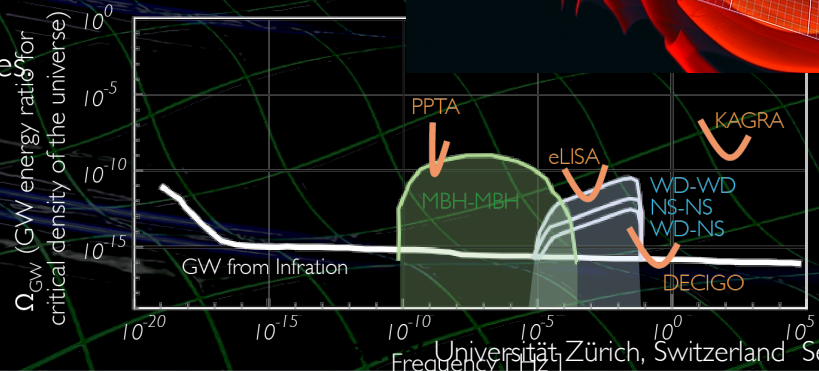


Pre-DECIGO – *Science Case* –

- Inspiral of Compact Binaries
  - High rate ~10^6 binaries/yr.
  - Estimation of binary parameters and merger time.
  - Astronomy by GW only and GW-EM observations.
- Inspirals and Mergers of IMBHs
  - Cover most of the universe.
  - Formation history of SMBH and galaxies.
- Foreground Understandings for DECIGO
  - Parameter estimation and subtraction of binaries.
  - Characteristics of foreground
  - Is the any eccentric binaries?

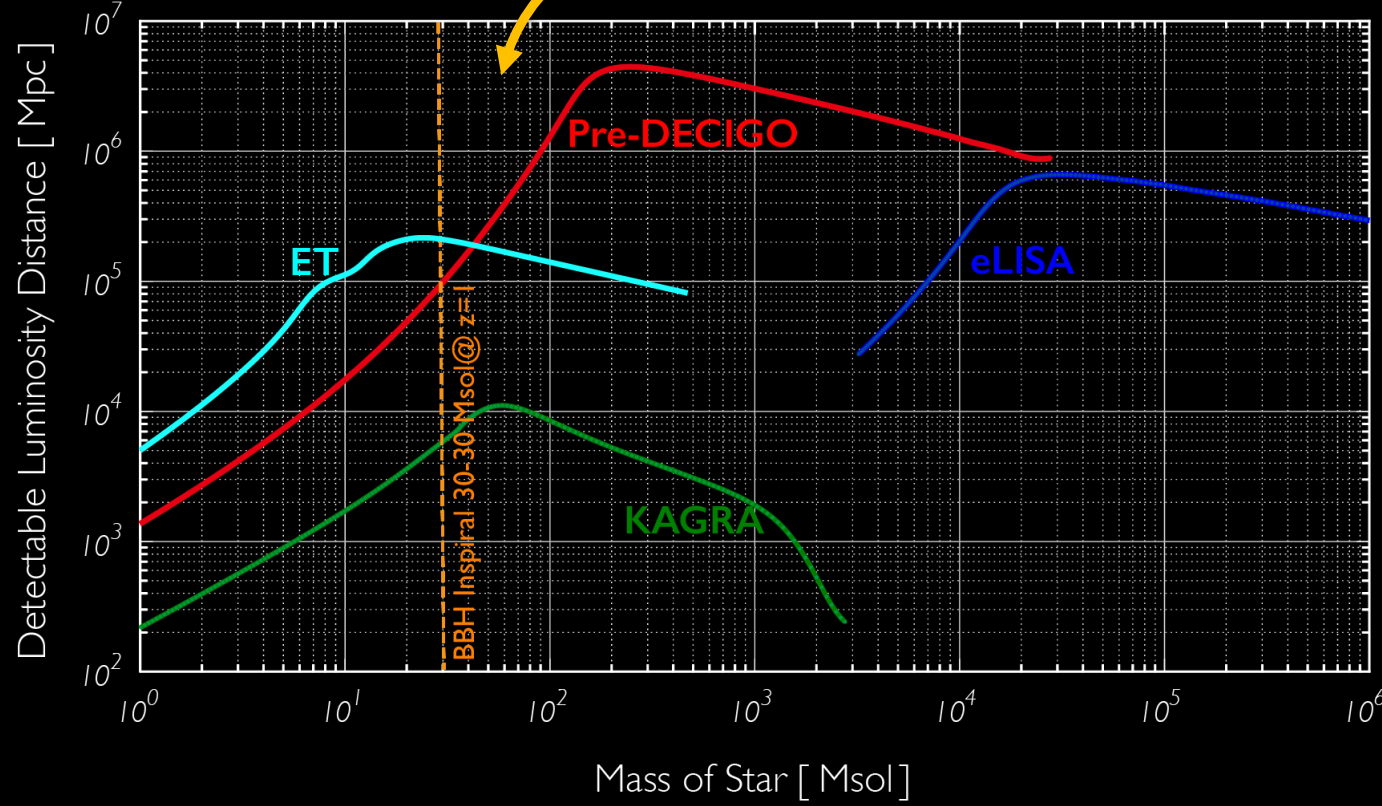






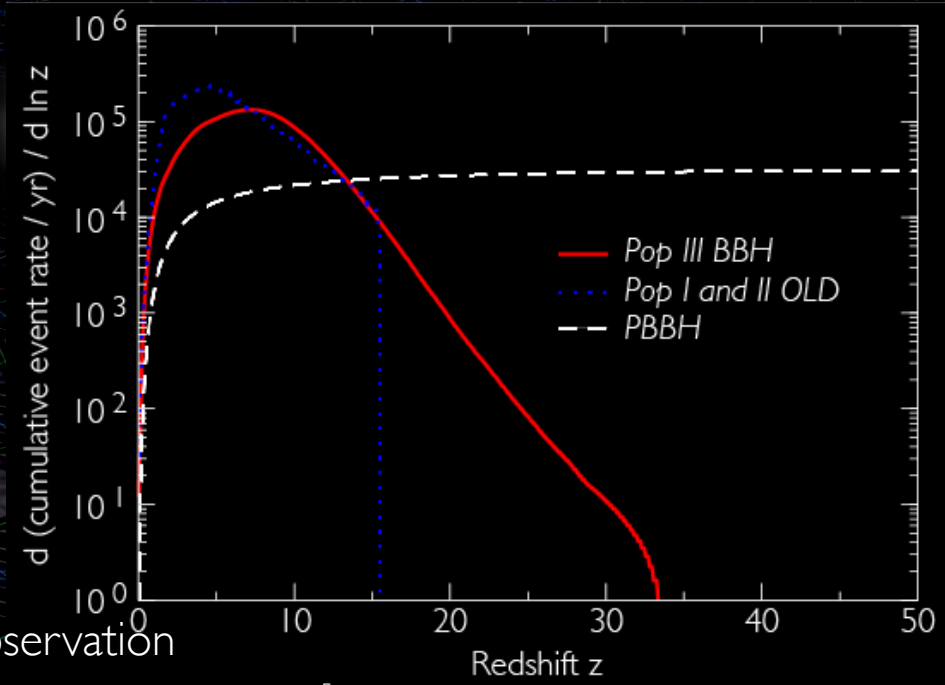
Pre-DECIGO – *Observable Range* –

$30M_{\odot}$ BBH Merger : 100 Gpc (z>10) range
with SNR~8 (optimal direction/polarization).



Pre-DECIGO – *Compact Binaries* –

- BBH
  - Observable range ~Tpc
  - Detection Rate will be ~ 4×10^4 - 10^6 evevts/yr
  - Possible to identify the origin of BBH
    - Pop-III, Pop-I/II, or Primordial BH.
- BNS
  - Range for BNS is ~2Gpc
  - Higher rate expected.



- With low-freq. GW observations, longer observation
  - Improved parameter estimation accuracy with lager cycle number (~10^5) :
  - Localization, Merger time → Alerts for GW-EM.
  - Mass, Distance, Spin → Origin and nature of BBH.

arXiv : http://arxiv.org/abs/1607.00897
PTEP : accepted on 10Aug.2016

PTEP

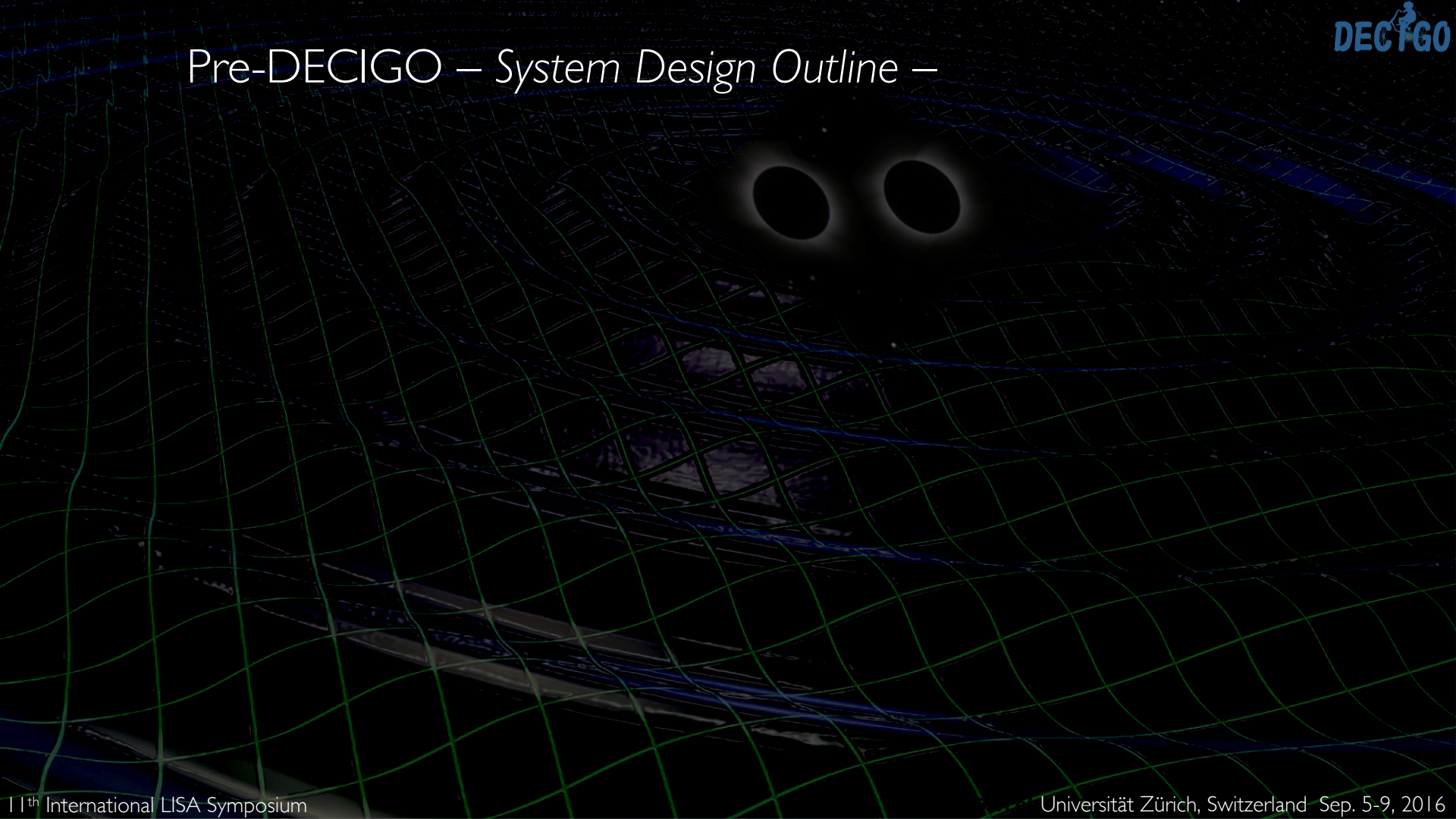
Prog. Theor. Exp. Phys. **2015**, 00000 (17 pages)
DOI: 10.1093/ptep/0000000000

Pre-DECIGO can get the smoking gun to decide the astrophysical or cosmological origin of GW150914-like binary black holes

Takashi Nakamura[1], Masaki Ando[2,3,5], Tomoya Kinugawa[4], Hiroyuki Nakano[1], Kazunari Eda[2,5], Shuichi Sato[6], Mitsuru Musha[7], Tomotada Akutsu[3], Takahiro Tanaka[1,8], Naoki Seto[1], Nobuyuki Kanda[9], Yousuke Itoh[5]

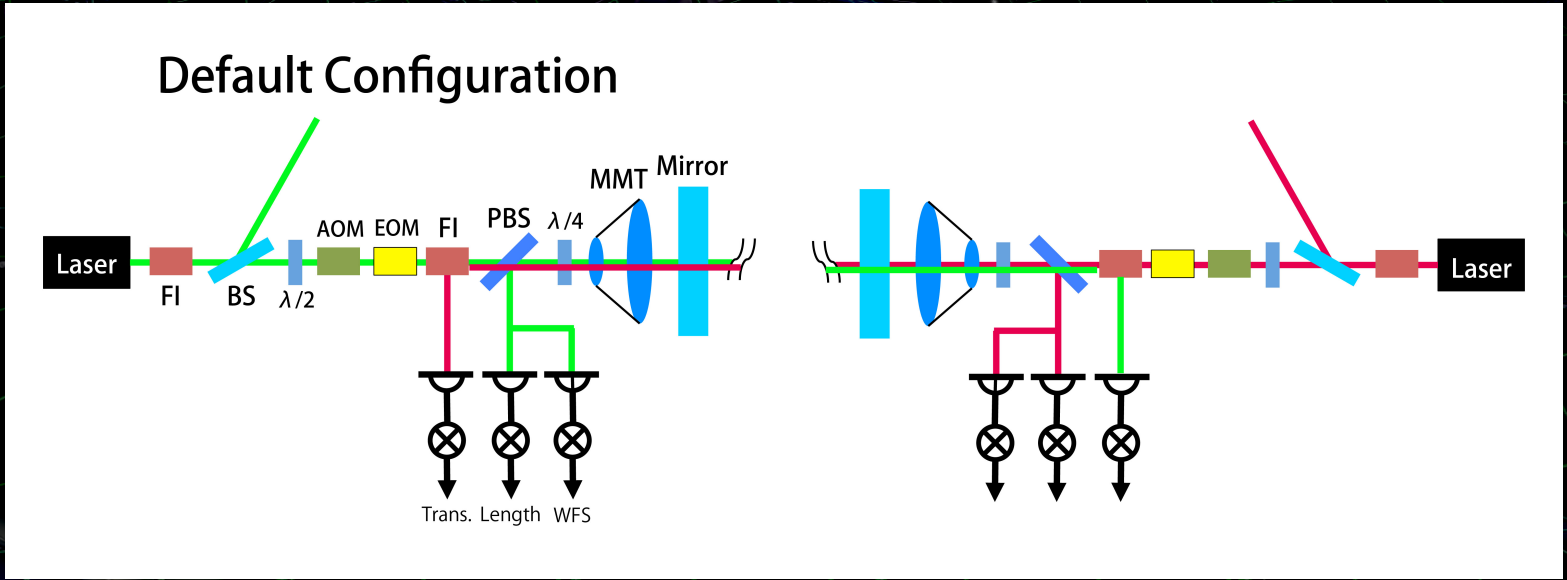
[1] *Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[2] *Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan*
[3] *National Astronomical Observatory of Japan, Tokyo 181-8588, Japan*
[4] *Institute for Cosmic Ray Research, The University of Tokyo, Chiba 277-8582, Japan*
[5] *Research Center for the Early Universe (RESCEU), The University of Tokyo, Tokyo 113-0033, Japan*
[6] *Department of Advanced Sciences, Hosei University, Tokyo 184-8584 Japan*
[7] *Institute for Laser Science, University of Electro-Communications, Tokyo 182-8585, Japan*
[8] *Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*

Pre-DECIGO – *System Design Outline* –



Pre-DECIGO – *Interferometer topology* –

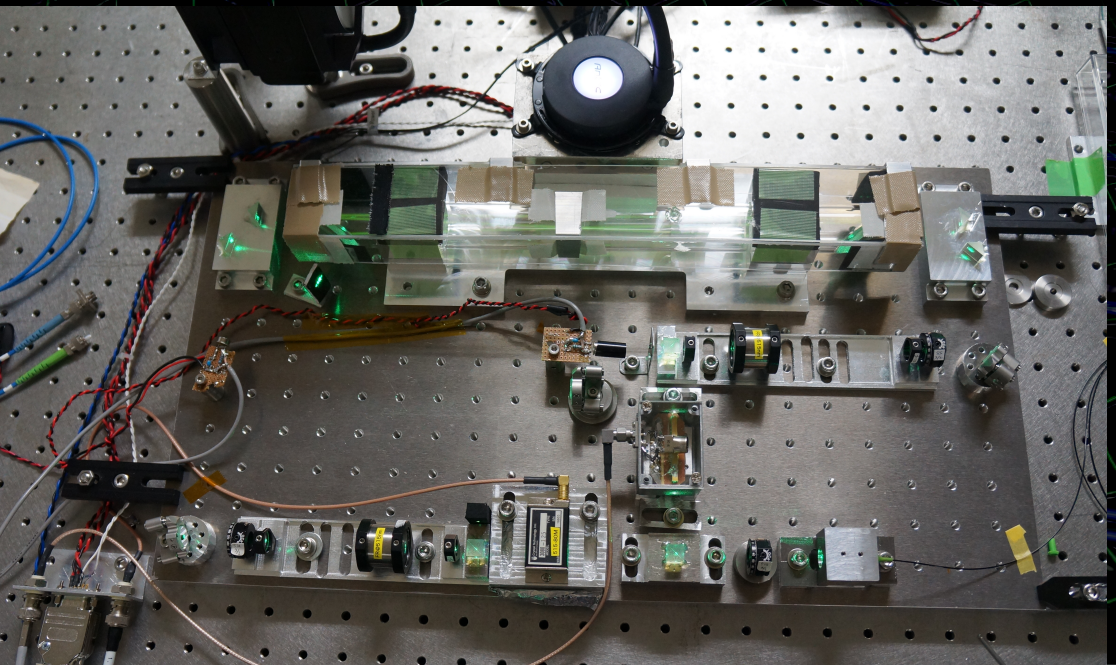
- Optical layout (Very Preliminary)
  - Differential FP interferometer : Opening angle~60deg
  - Critical coupled FP cavities : r = 0.95
  - Feeding back to TMs and laser wavelength via AOM



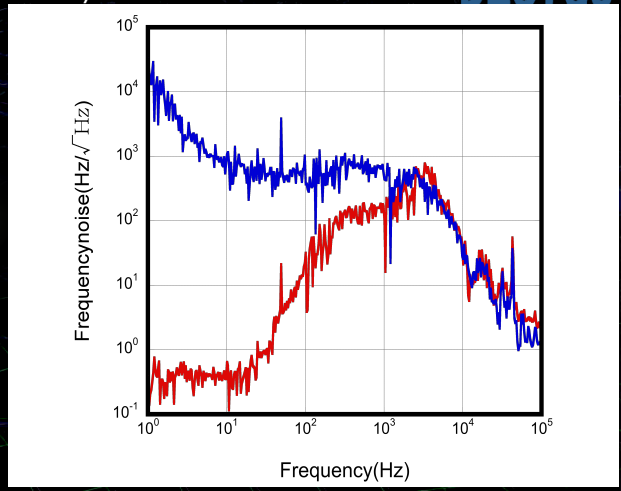
Pre-DECIGO – *Light Source* –

- Frequency doubled Yb:DFB fiber laser (λ=1030 nm)
- Iodine-stabilized
- 1W input to cavities

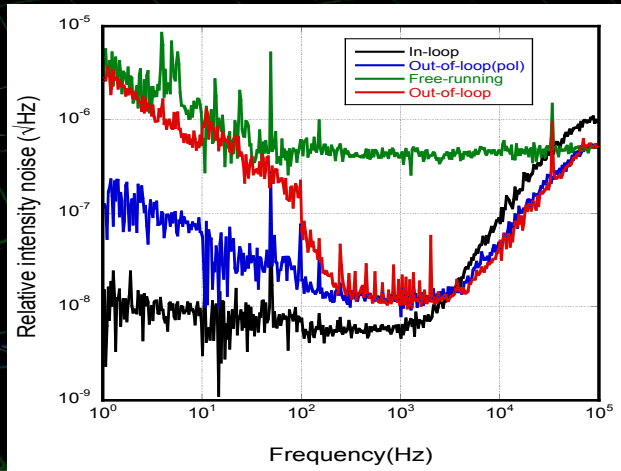
Poster : Suemasa "Developments of highly-stabilized lasers for DECIGO/Pre-DECIGO"



Frequency noise

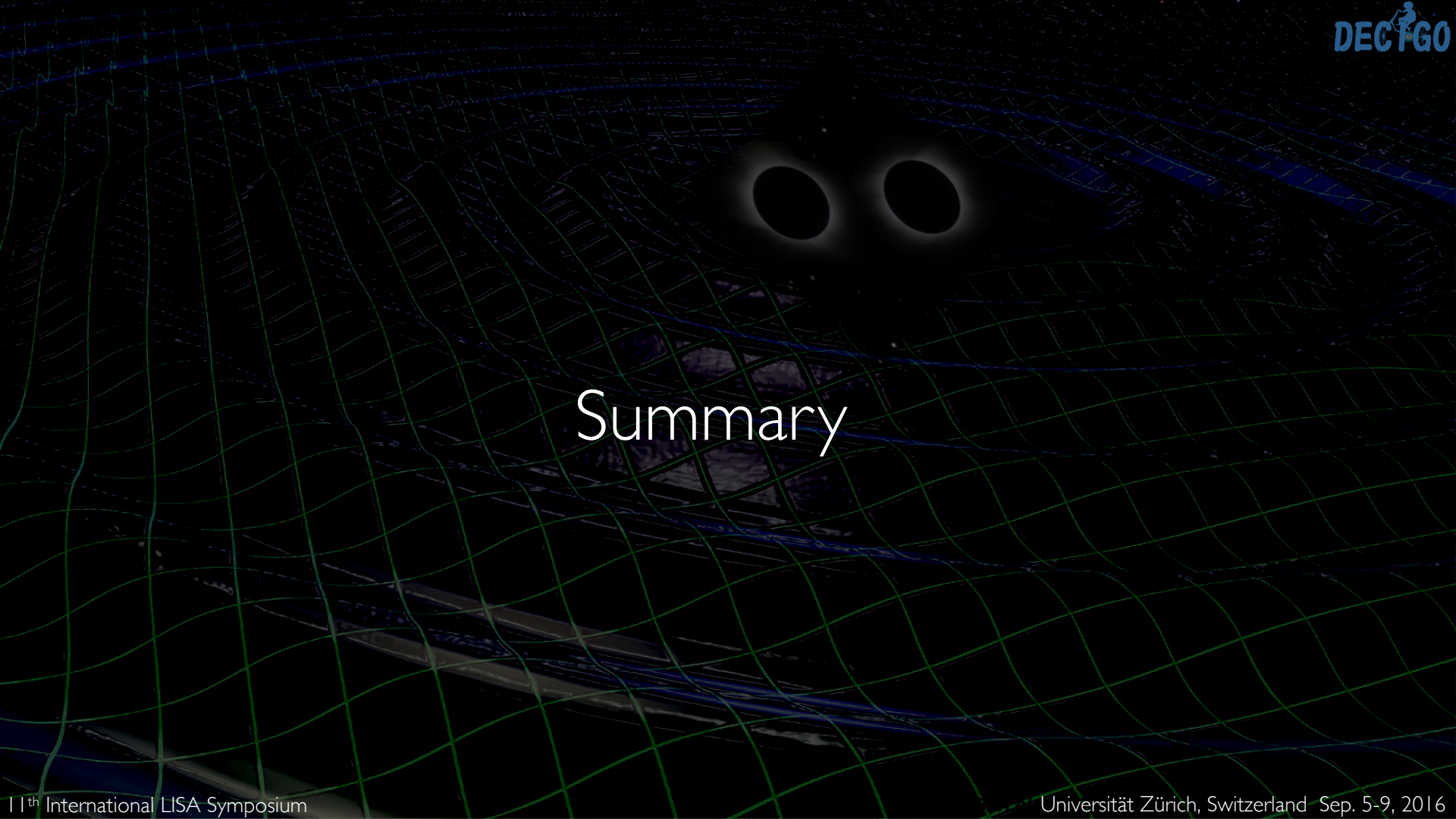


Intensity noise



Pre-DECIGO – *Orbit Design* –

- Sun-Synchronous (Dawn-dusk) orbit
- Cartwheel(Record-disk) orbit around the earth
  - Altitude 2000 [km]
  - Inclination angle : 99.49 [deg]
  - Period ~127 [min.] (Preliminary).

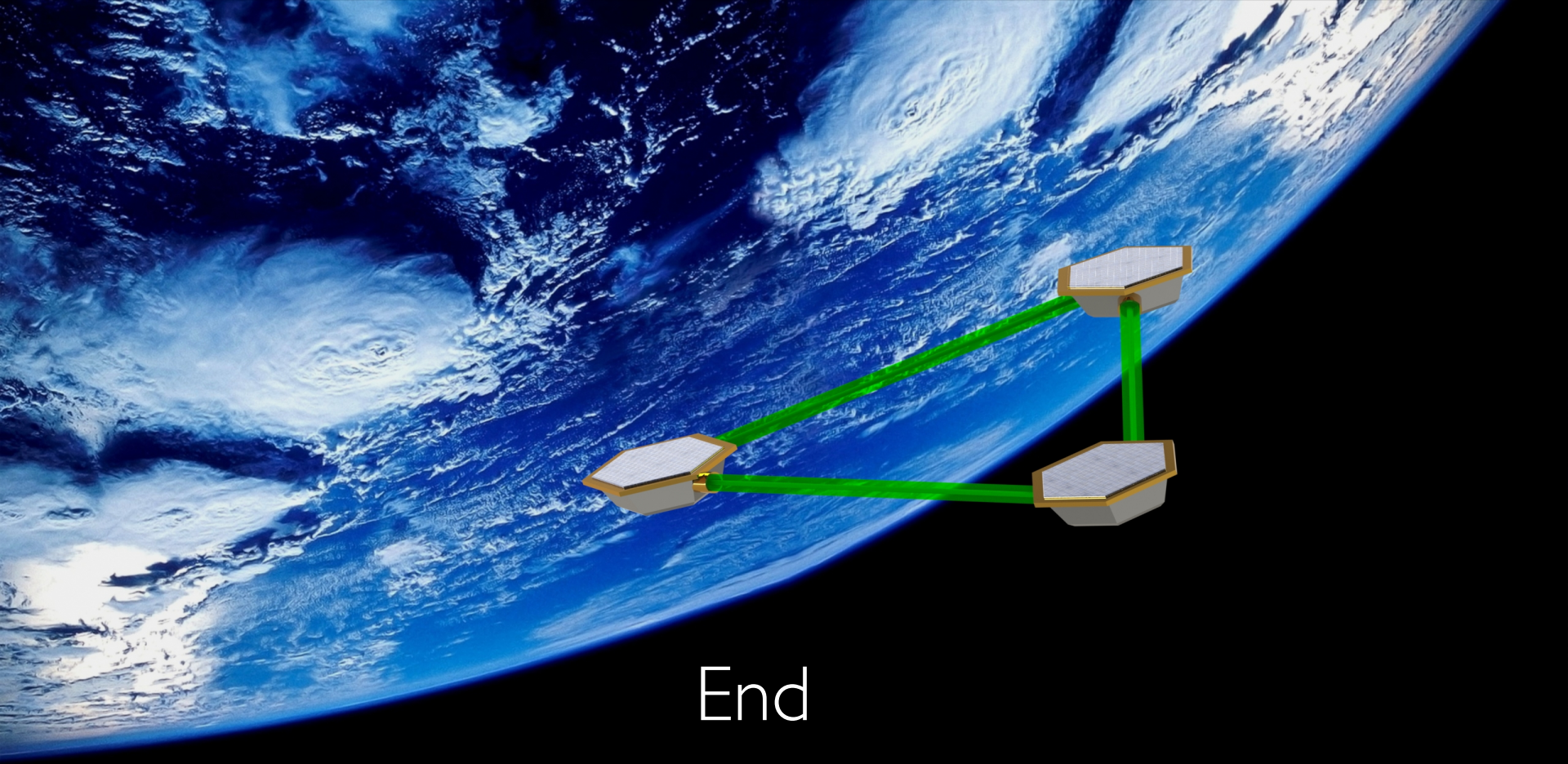


Summary

Summary

- DECIGO : Great Sciences
  - Direct observation of very beginning of the Universe
  - Dark energy, Dark matter
  - Galaxy formation

- Pre-DECIGO : Fruitful and Original Sciences
  - Compact Binary Coalescences : GW150914-like BBH, and BNS
  - Observation of IMBH mergers
  - Understandings of foreground for DECIGO



End