Gravitational Wave Experiment

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Kyoto University)

Asian Winter School on Strings, Particles, and Cosmology (January 17, 2012, Kusatsu, Gunma)

1. Introduction
2. Ground-based detectors
   - Overview and design of LCGT
3. Space detectors
   - Overview and status of DECIGO
4. Summary

Introduction

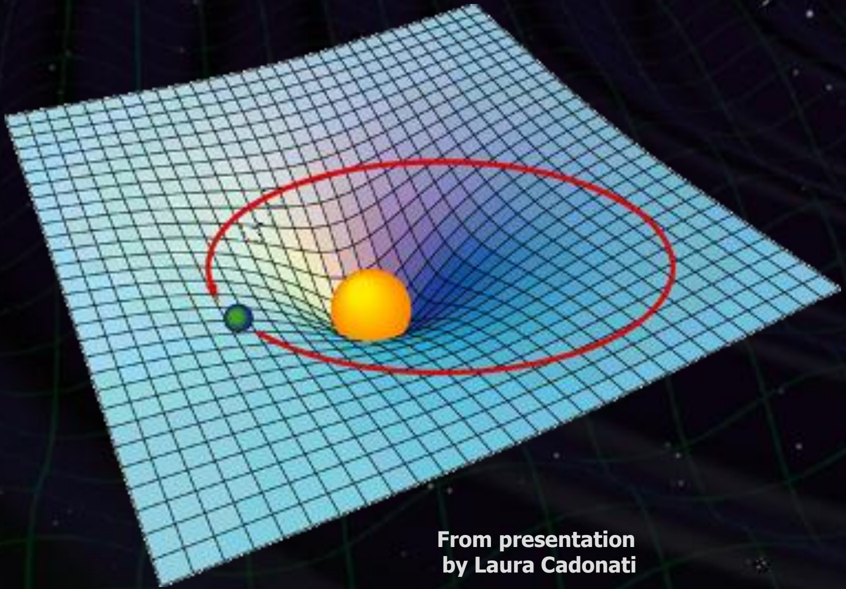
From presentation by B Schutz

Gravitational Wave

General Relativity

Interpret the gravity as a nature of space-time

"Mass tells space-time how to curve,
and space-time tells mass how to move. "
John Archibald Wheeler



From presentation
by Laura Cadonati

Einstein Equation

$$\boxed{G_{\mu\nu}} = \frac{8\pi G}{c^4}\boxed{T_{\mu\nu}}$$

↑ Curvature

↑ Mass (Energy momentum)

Motion of Mass, Change in shape
- → Changes in gravitational field.
- → Propagate as ripples of space-time.

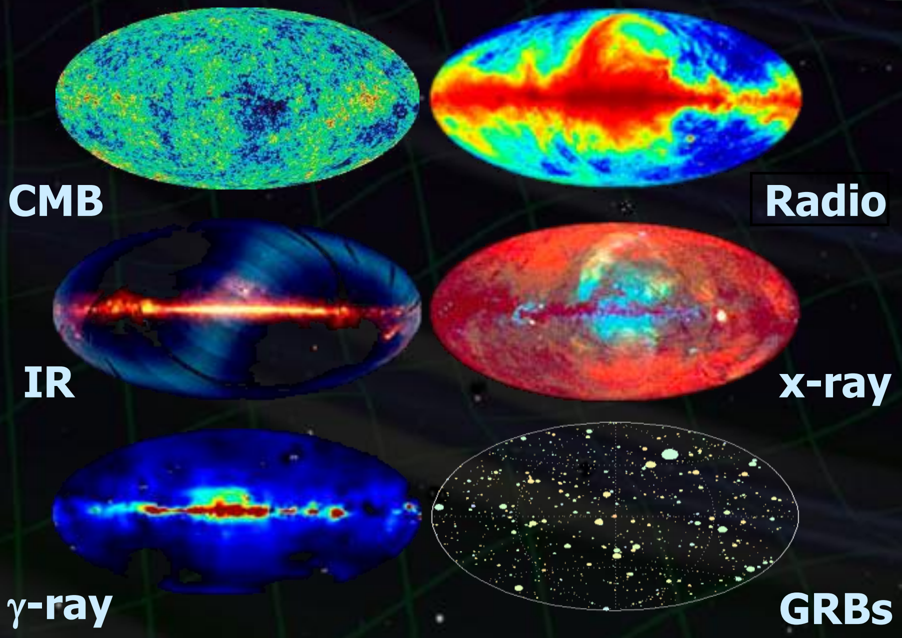
⇨ Gravitational Wave

Gravitational-wave astronomy

Reveal the universe by Gravitational Waves.

Nature of GWs
- Radiated by accelerated masses
- Strong transmissivity

New probe to the universe
- Complementary with EMWs.
- Unique sciences
  - Early universe before CMB era
  - Central part of violent phenomena



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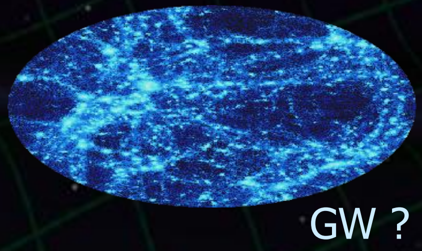
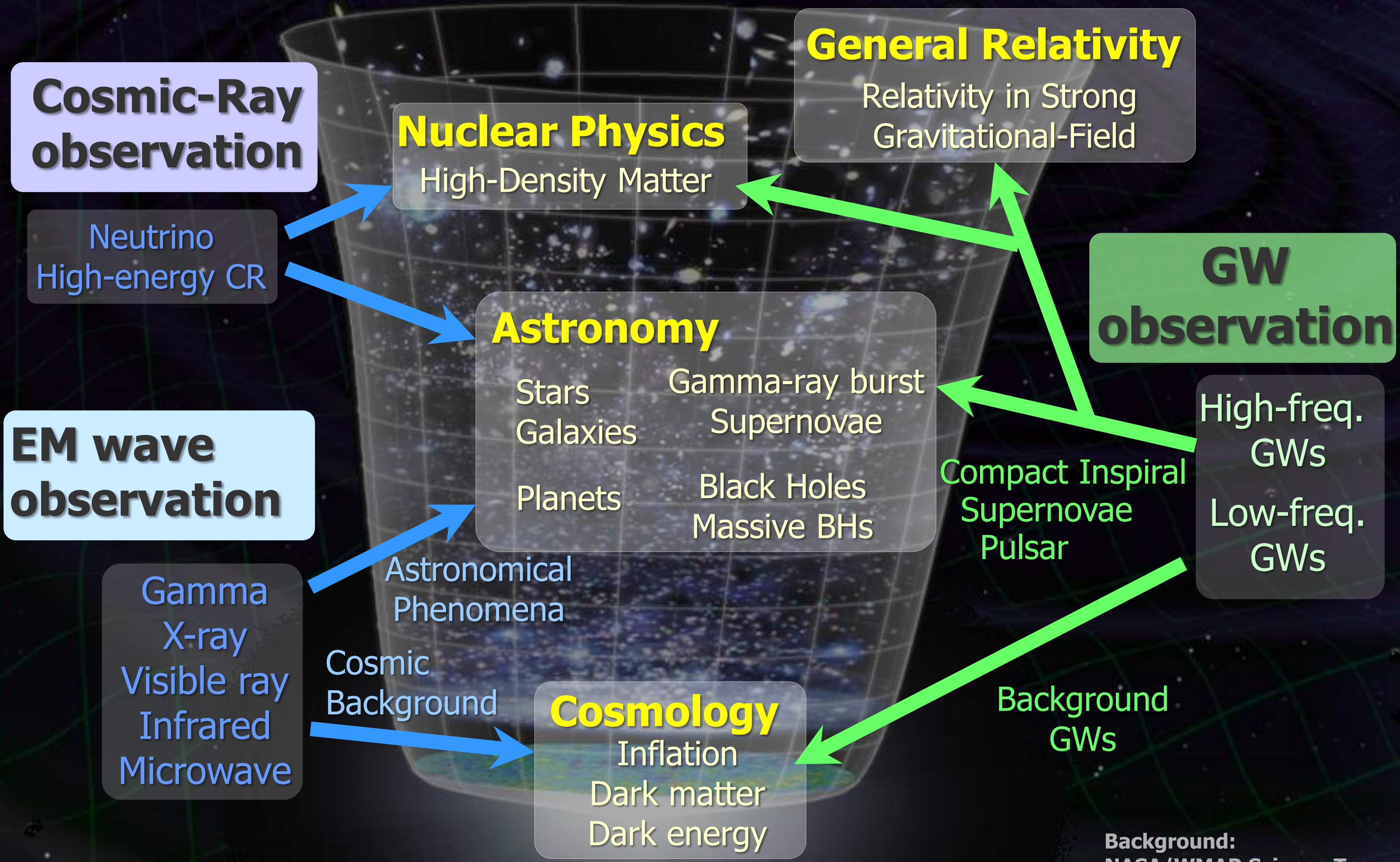


Observation of the Universe



Cosmic-Ray observation

Neutrino
High-energy CR

EM wave observation

Gamma
X-ray
Visible ray
Infrared
Microwave

Astronomical Phenomena

Cosmic Background

Nuclear Physics
High-Density Matter

General Relativity
Relativity in Strong Gravitational-Field

Astronomy

Stars
Galaxies
Planets

Gamma-ray burst
Supernovae
Black Holes
Massive BHs

Cosmology
Inflation
Dark matter
Dark energy

GW observation

High-freq. GWs

Low-freq. GWs

Compact Inspiral
Supernovae
Pulsar

Background GWs

Background:
NASA/WMAP Science Team

High-frequency GW targets

Ground-based detectors -- Obs. band 10Hz – 1kHz

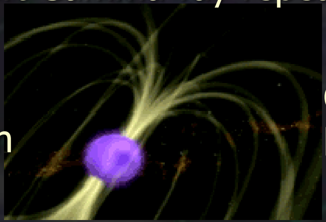
⇨ Compact, High-energy phenomena

Neutron star

Pulsar

Supernova

Soft Gamma-ray repeater



Star Vibration mode

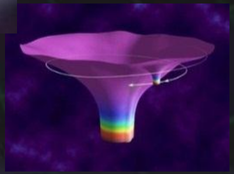
Long Gamma-ray burst

Black hole

Binary inspiral

Short Gamma-ray burst

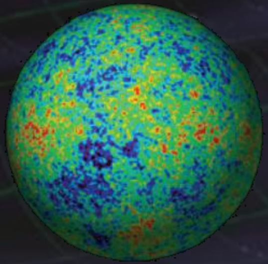
EMRI



Quasi-normal mode

Early Universe

Gravitational-wave background



EM Waves
Neutrino
High-energy CRs

Trigger, Follow-up

Numerical Relativity

Understandings of High-energy pheno.

EoS of high-density matter, Nuclear physics

Test of Relativity, Physics under strong gravity

Low-frequency GW targets

Space detectors -- Obs. band 0.1mHz – 1 Hz

⇨ Super-massive/Intermediate-mass BH, early Universe

Neutron star, White dwarf

Binary system

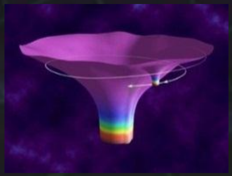
Pulsar

Stationary
Orbital / spin
motion

Black hole

Merger of
Supermassive
Black holes

EMRI



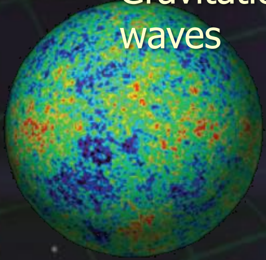
Quasi-normal mode

Early Universe

Superposition of
many sources

GW background

Primordial
Gravitational
waves



EM Waves
Neutrino

Multi-messenger

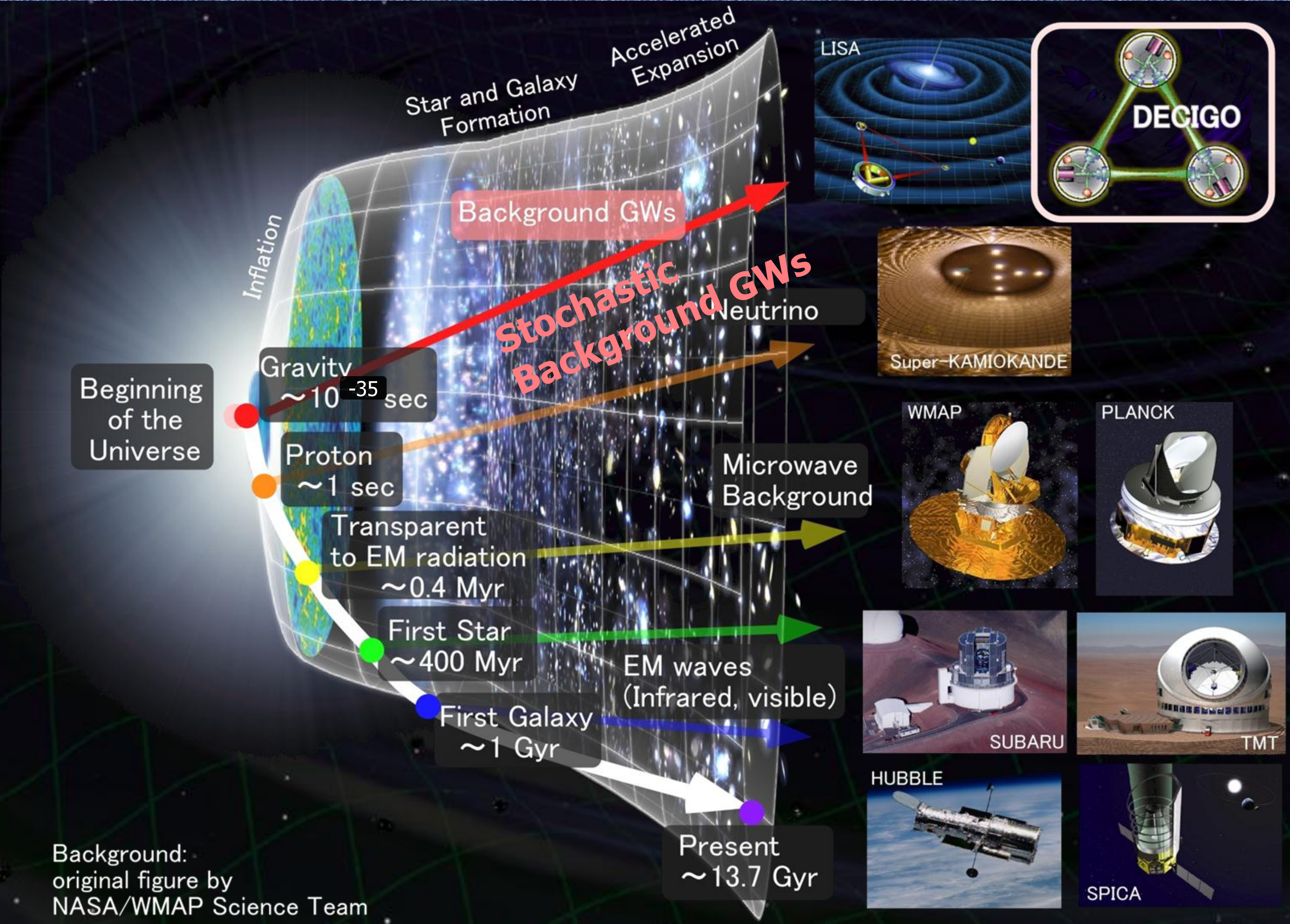
Numerical relativity

Test of
Gravity theories

Formation scenario of
Super-massive BHs

Cosmology, Universe
Dark energy, Dark matter

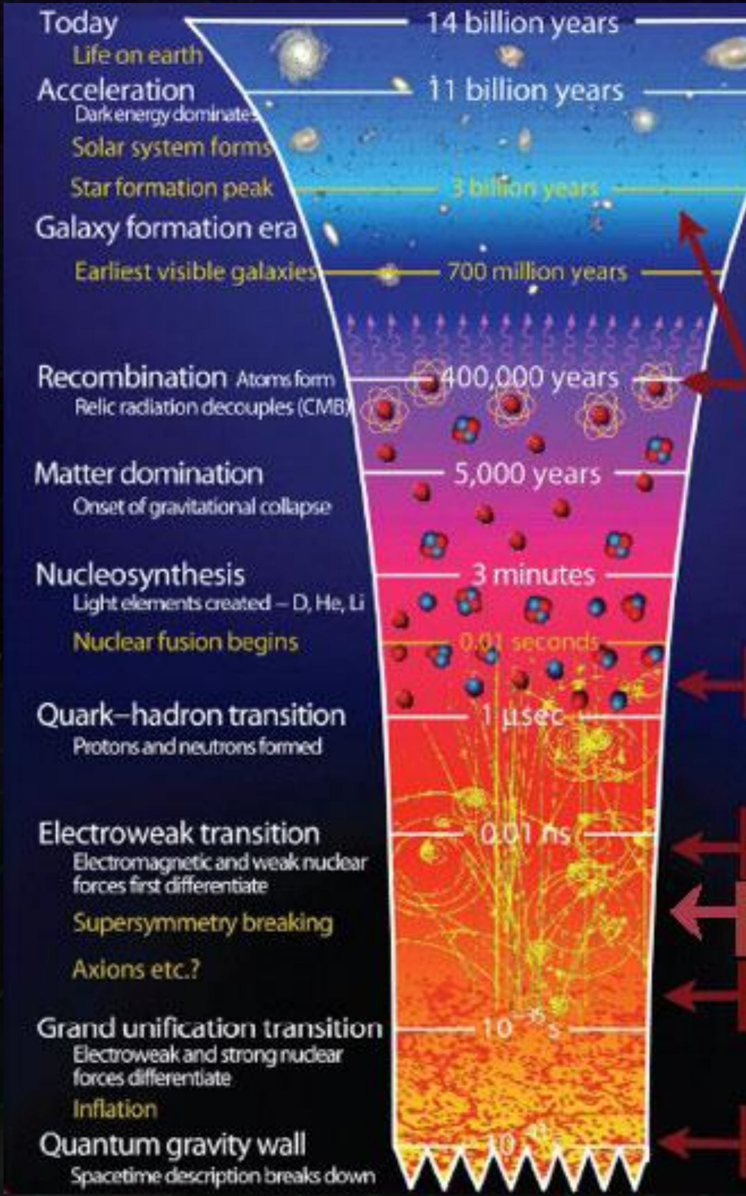
Stochastic Background GWs



Background: original figure by NASA/WMAP Science Team

Slide from Shellard

A brief history of the Universe



CMB $f < 3 \times 10^{-17} h$Hz probes $300,000$yrs $< t_e < 14$Gyrs

Pulsars $f \sim 10^{-8}$Hz probe $t_e \sim 10^{-4}$s ($T \sim 50$MeV)

LISA $f \sim 10^{-3}$Hz probes $t_e \sim 10^{-14}$s ($T \sim 10$TeV)

ET $f \sim 10$ Hz probes $t_e \sim 10^{-20}$ s ($T \sim 10^6$ GeV)

LIGO $f \sim 100$Hz probes $t_e \sim 10^{-24}$s ($T \sim 10^8$GeV)

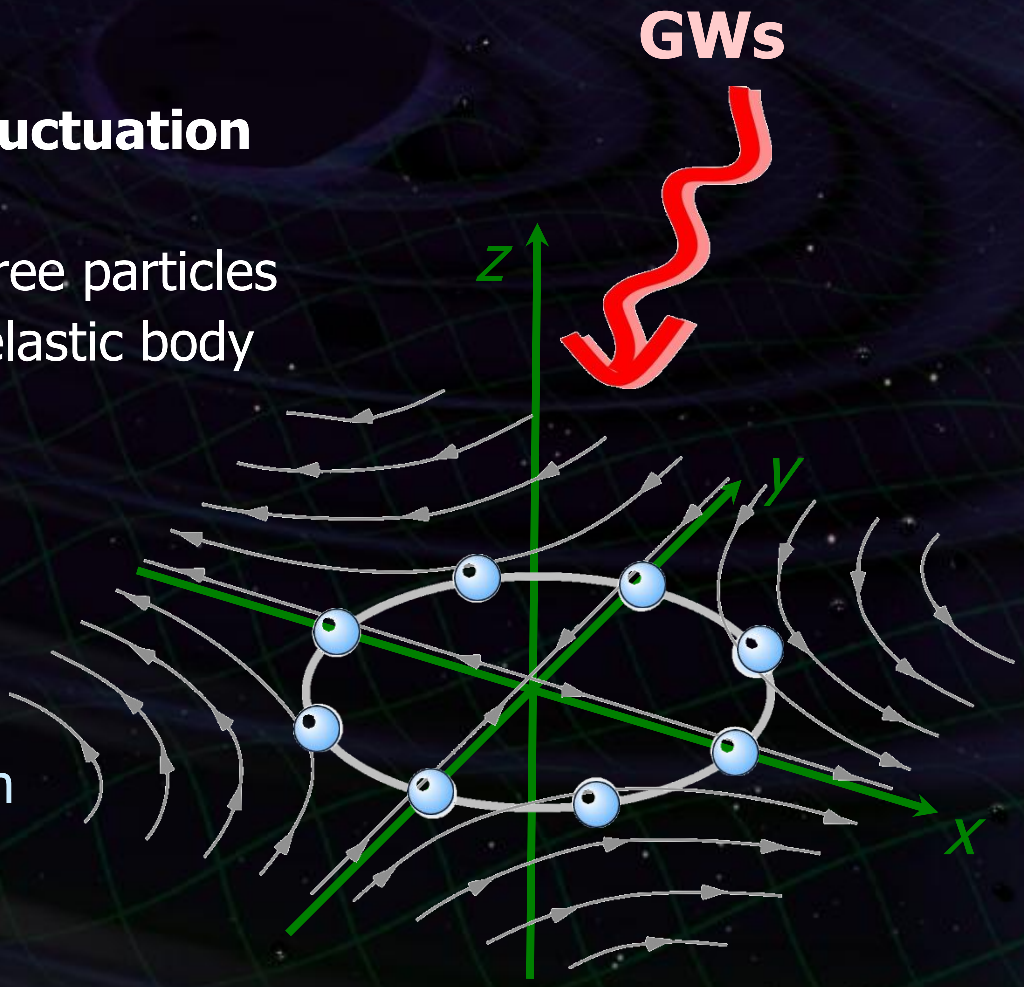
(Planck scale $f \sim 10^{11}$Hz has $t_e \sim 10^{-43}$s ($T \sim 10^{19}$GeV)

Effect of gravitational waves

Effect of GWs : Tidal force fluctuation

appears as …

- Distance change between free particles
- Tidal forces for finite-sized elastic body



GW amplitude h : strain

$h = 10^{-21}$

→ 10^{-21}m length fluctuation for 1-m baseline

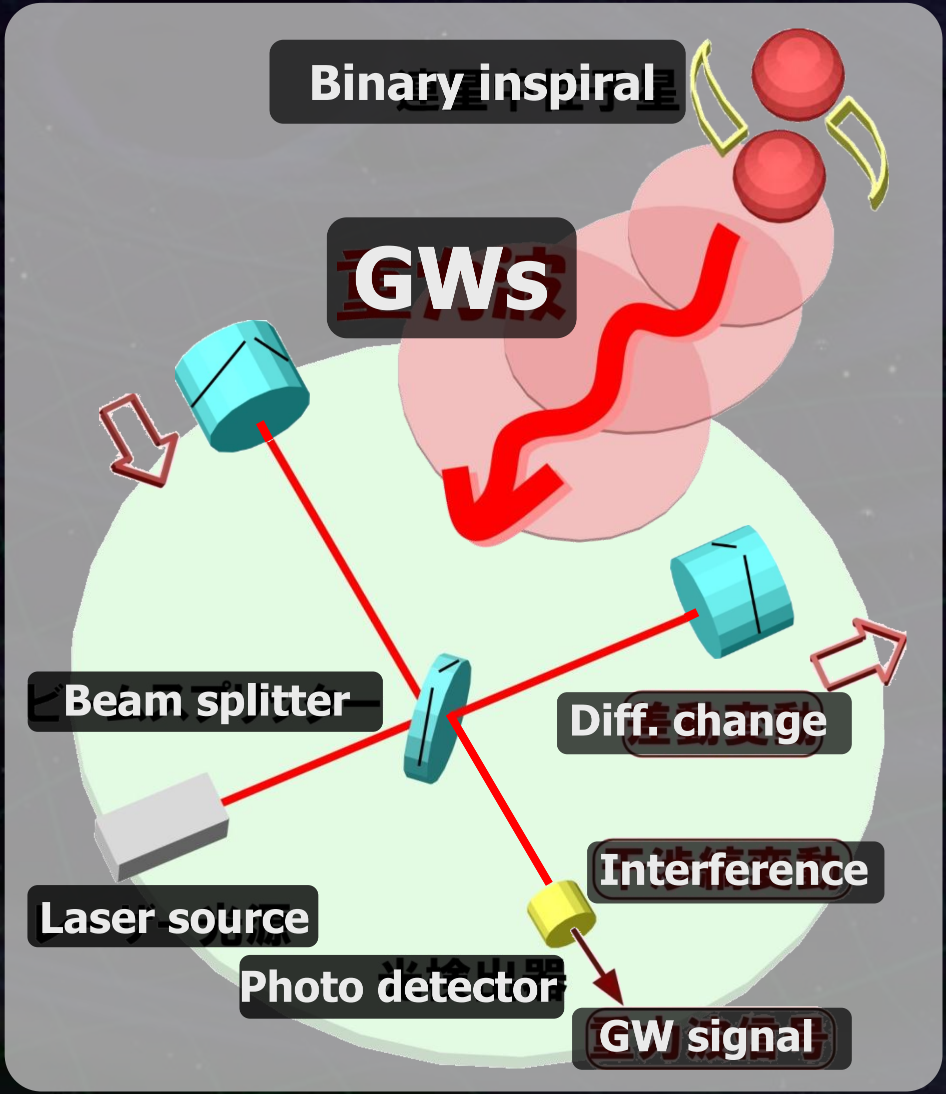
Laser interferometric detector

Michelson interferometer
Separate input beam into
two orthogonal direction

Each beam is reflected back by
a suspended mirror
→ Interference at beam splitter

When GW comes…

Differential length changes are
detected at photo detector

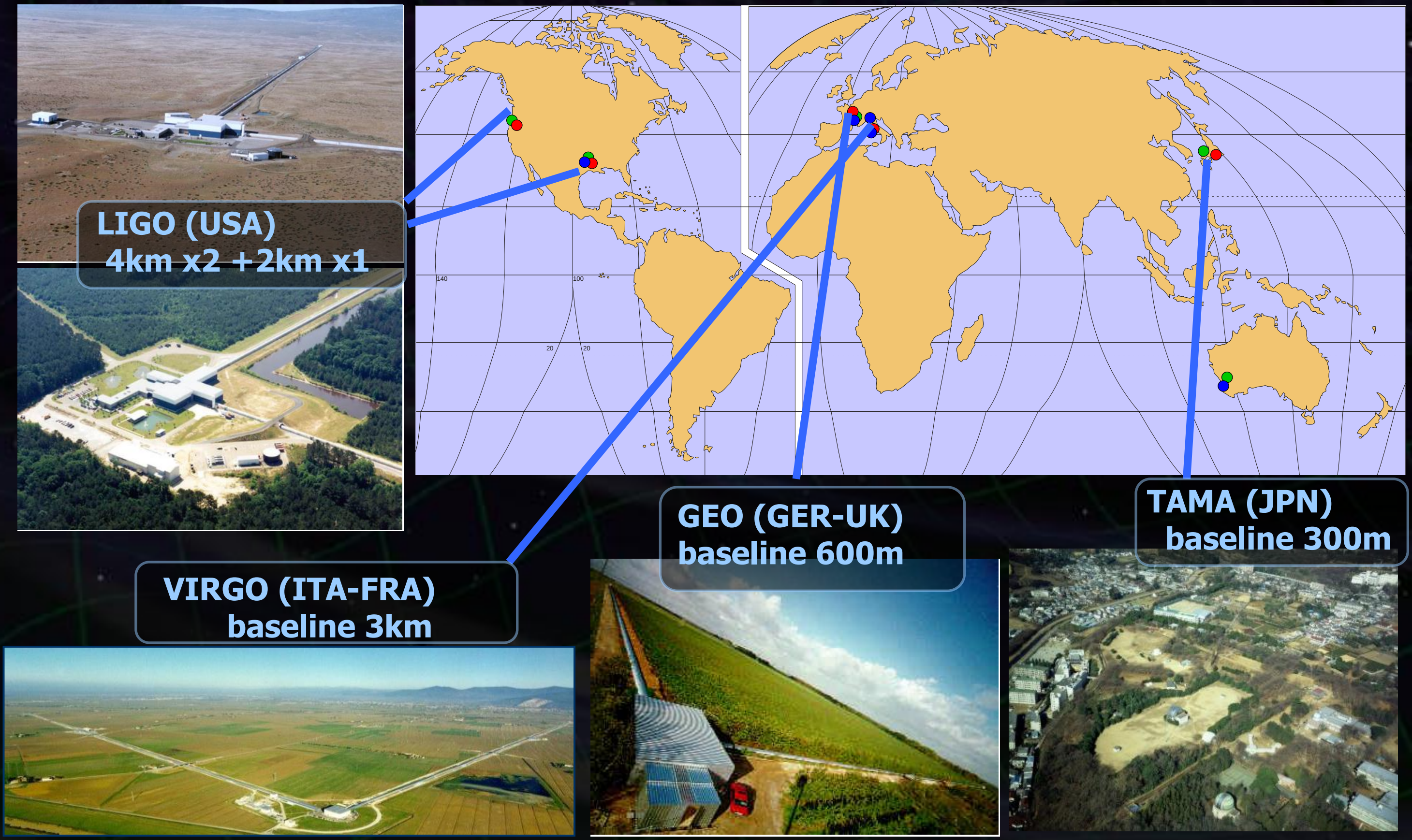


First generation detectors

Trial for GW detection --- Began in 1960s (Bar detectors)

→ First-generation large-scale interferometers (1999-)

LIGO (USA), VIRGO, GEO (Europe), TAMA (JPN)



LIGO (USA)
4km x2 +2km x1

VIRGO (ITA-FRA)
baseline 3km

GEO (GER-UK)
baseline 600m

TAMA (JPN)
baseline 300m

First generation detectors

Trial for GW detection --- Began in 1960s (Bar detectors)

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LIGO (USA), VIRGO, GEO (Europe), TAMA (JPN)

➡ Global observation network

Observation data over 1 year, Scientific outcomes

Neutron-star binary: Observable range ~20Mpc

→ Cover our galaxy and nearby galaxies

Central engine of Short GRB

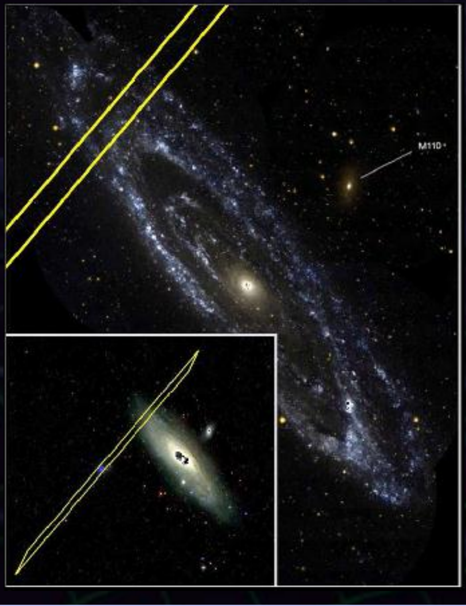
Gamma-ray burst

GRB070201 (found in 2007)

(Konus-Wind, INTEGRAL, MESSENGER)

→ Direction of M31
(Andromeda galaxy, 770kpc)

Origin of short gamma-ray burst
would be a merger
of binary neutron stars.



LIGO was in operation with sufficient sensitivity.

→ As a result of data analysis, no signal was found.
Conclusion: This Short GRB is not coming from
neutron-star merger event at M31.

Abbott et al, axiv:0711.1163.

Stochastic background GWs

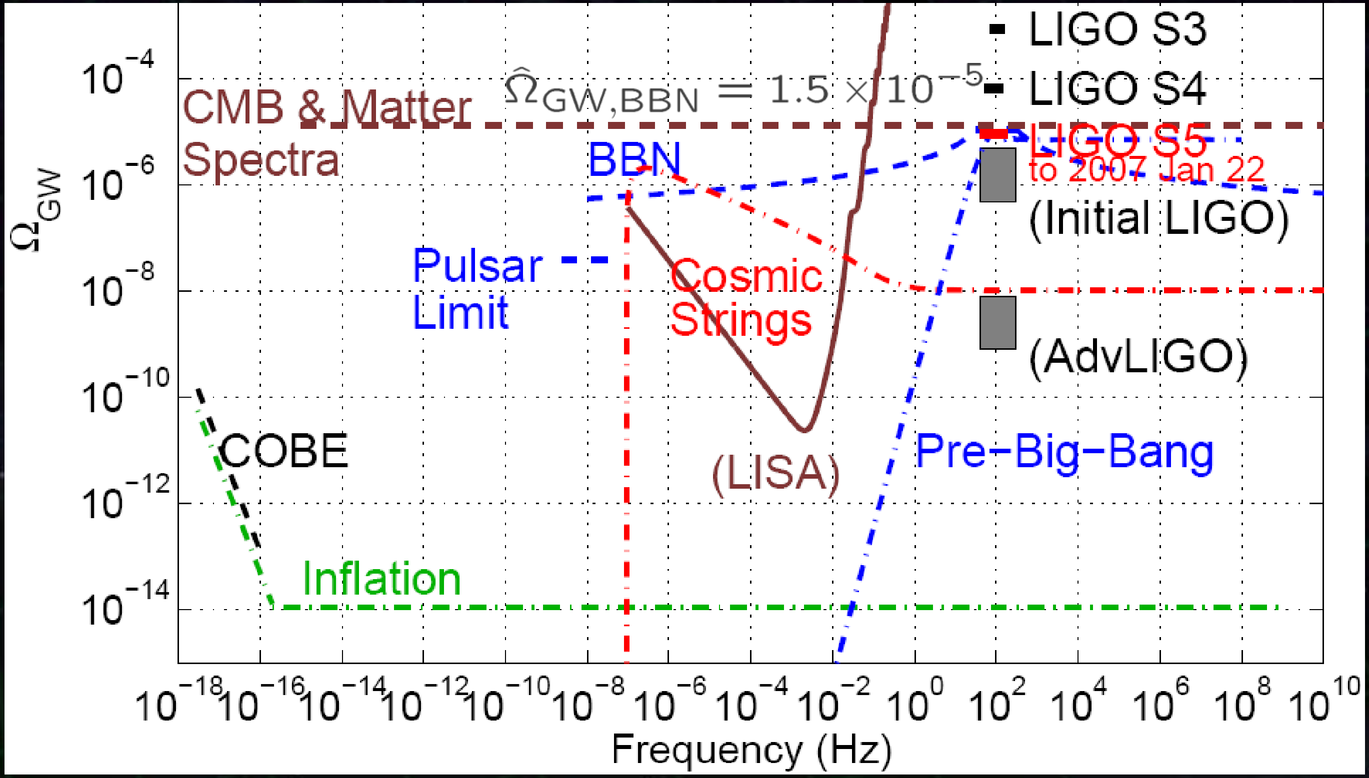
LIGO S5

Use good-quality data around 41.5-177.5Hz

→ Better upper limit for GWB than BBN

$$\hat{\Omega}_{GW} = 6.9 \times 10^{-6} \quad \textbf{(95\% CL)}$$

LIGO and VIRGO collab.,
Nature 460 (2009) 08278.



John T. Whelan for the LSC, AAS Meeting, Jan 2008

Next-generation detectors

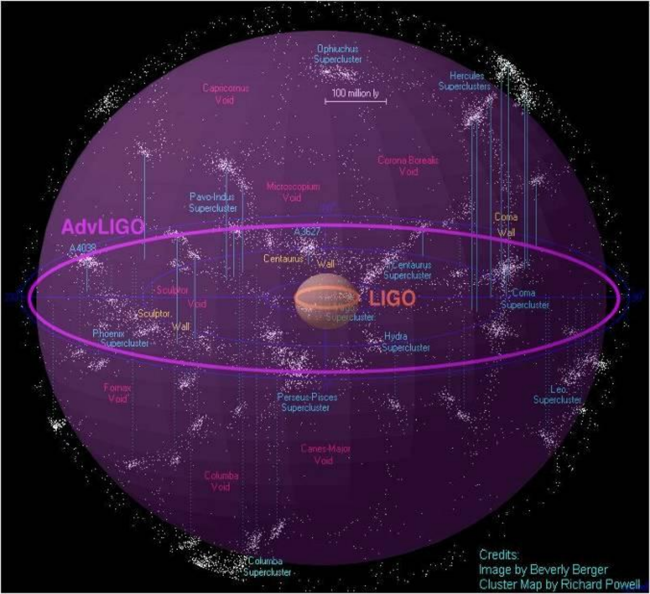
Expanding the Horizon

First-gen. GW detectors : ~ 20Mpc obs. range

However… we can expect only rare events
(10^{-4}-10^{-2} event/yr)

⇨ **Next generation detectors**

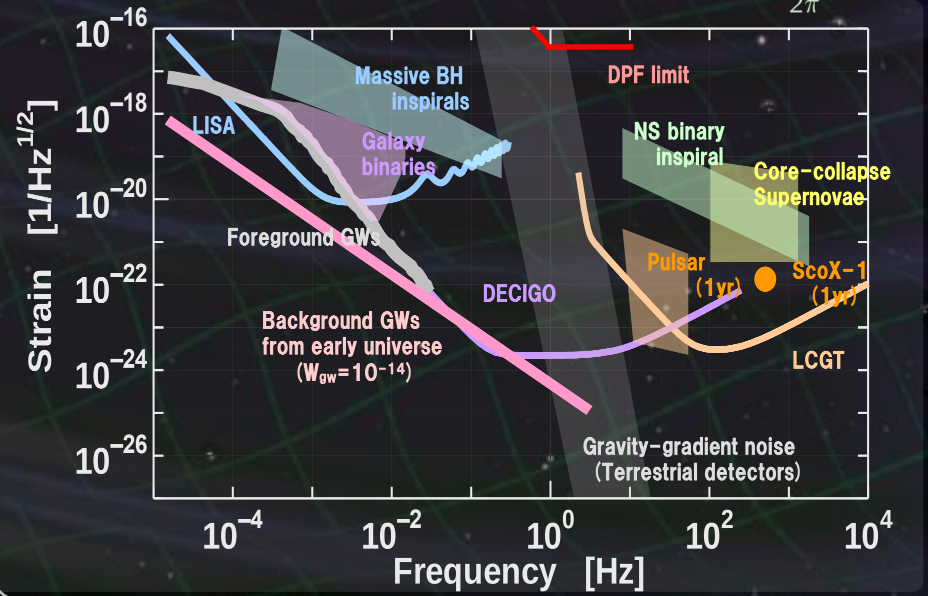
Better sensitivity
to cover more galaxies



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

Wider observation band
for various sources

$$f \sim \frac{1}{2\pi}\sqrt{GM/R^3}$$



Improving the sensitivity

2^{nd}-generation detectors --- x10 sensitivity

GW amplitude $\propto$ 1/(distance)

⇩

Sensitivity x10

→ GW event rate $\times 10^3$

Expected science

1-year obs. by 1^{st}-gen. detector

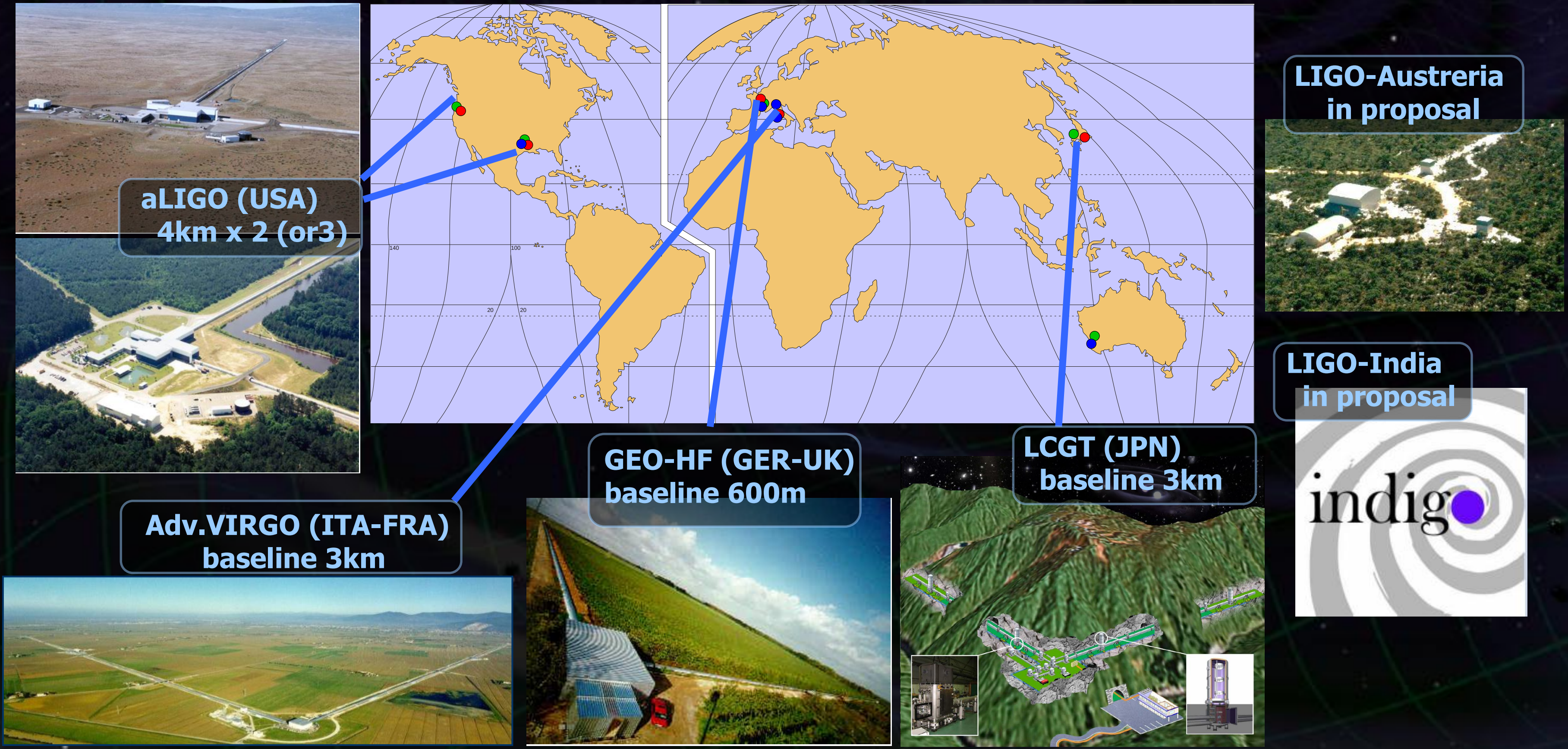
~ 9-hour obs. by 2^{nd}-gen. detector

Event rate > 1 event/year in 2^{nd}-generation detectors

Second generation detectors

2^{nd}-generation detector network (~5 years from now)

GW astronomy : confident detection, source direction,
scientific information on sources



aLIGO (USA)
4km x 2 (or3)

Adv.VIRGO (ITA-FRA)
baseline 3km

GEO-HF (GER-UK)
baseline 600m

LCGT (JPN)
baseline 3km

LIGO-Austreria
in proposal

LIGO-India
in proposal

2^{nd} generation detectors

- aLIGO
  - Baseline 4km, iLIGO Facility and Vacuum
  - Optics, Isolators, Control,… : Replace
  - Squeezing test experiment
    6dB Squeezing → See noise behaivior.

Under installation procedure

David Shoemaker, LV meeting March 2011

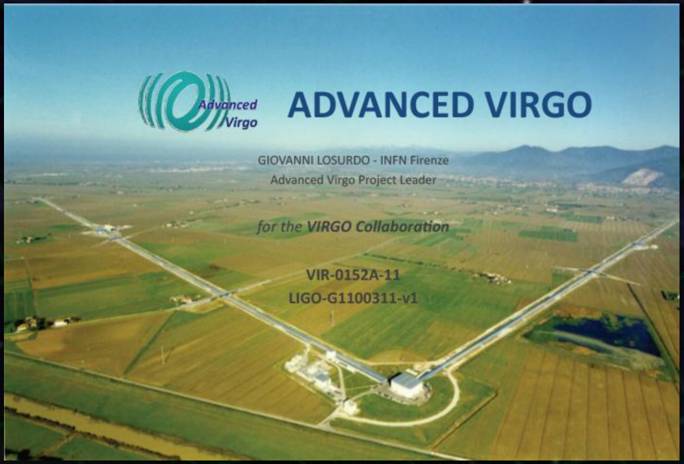
LIGO

Big News since we last met:
The start of Installation

- 20 October 2010: Handoff of Observatories to aLIGO
- A very significant transition for aLIGO
- Most chambers now empty
- First new parts going in now

- Advanced VIRGO
  - Baseline 3km, IFO upgrade to RSE.
  - Laser source upgrade to fiber laser.
  - Thermal compensation, Output MC.

Under installation procedure



Advanced Virgo

ADVANCED VIRGO

GIOVANNI LOSURDO - INFN Firenze
Advanced Virgo Project Leader

for the VIRGO Collaboration

VIR-0152A-11
LIGO-G1100311-v1

G. Losurdo LV meeting March 2011

2nd generation detectors

Hartmut Grote, LV meeting March 2011

GEO 600 STATUS

Hartmut Grote
for the LSC
LSC-Virgo meeting
Arcadia, March. 2011
LIGO-G1100206

- GEO-HF: Upgraded GEO
  - Baseline 600m
    → Sensitivity improvement at igh-freq.
  - High-power laser,
    Squeezing → Achieve 3.5dB improvement.

AstroWatch and upgrade

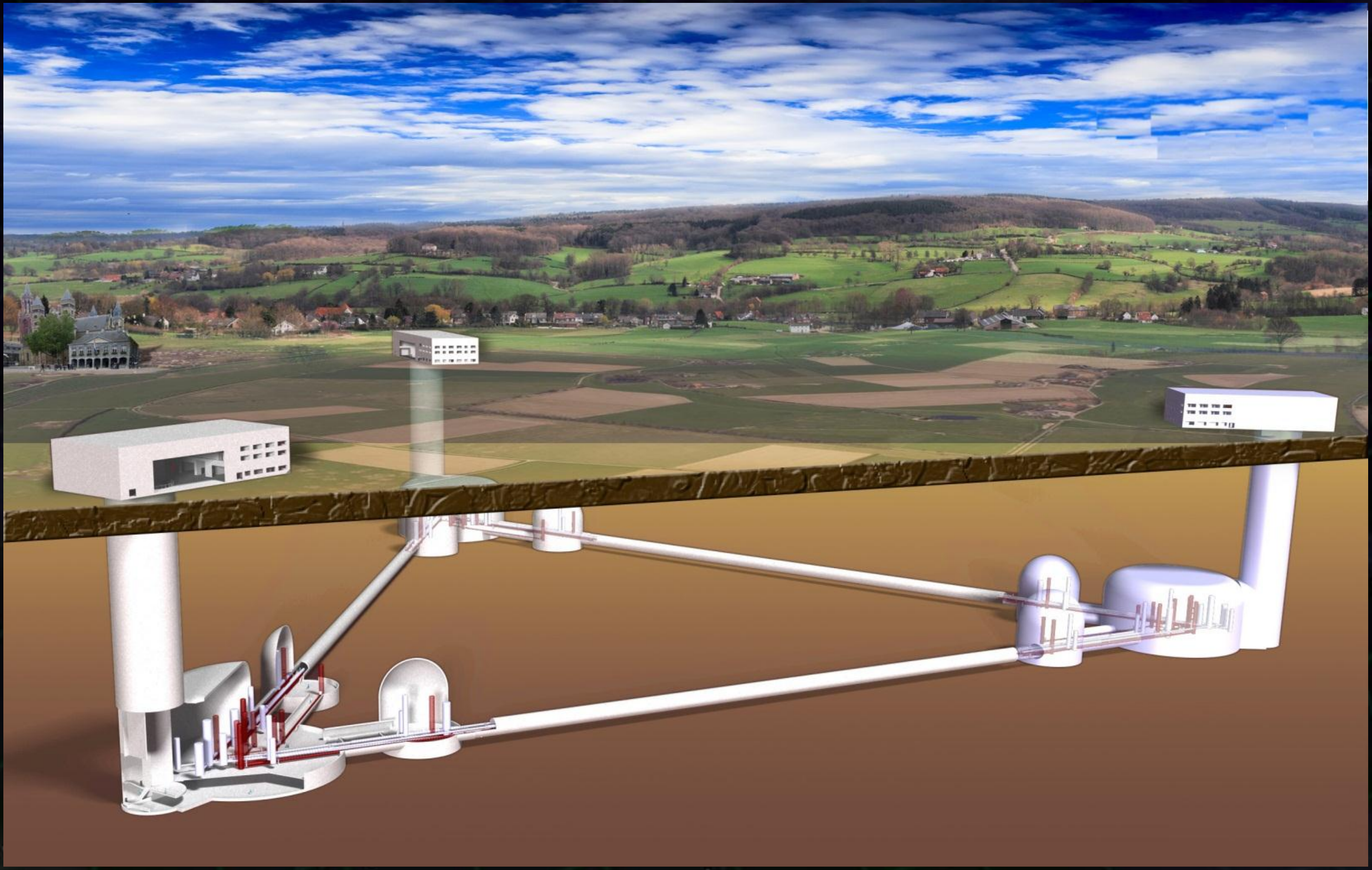
- LIGO-Austreria, LIGO-India
  - Move one detector of aLIGO → Angular resolution.
  - Established in August 2009 to coordinate the Indian GW community to participate in GW research!
  - Funding received for a 3m prototype interferometer at the Tata Institute for Fundamental Research.

indigo

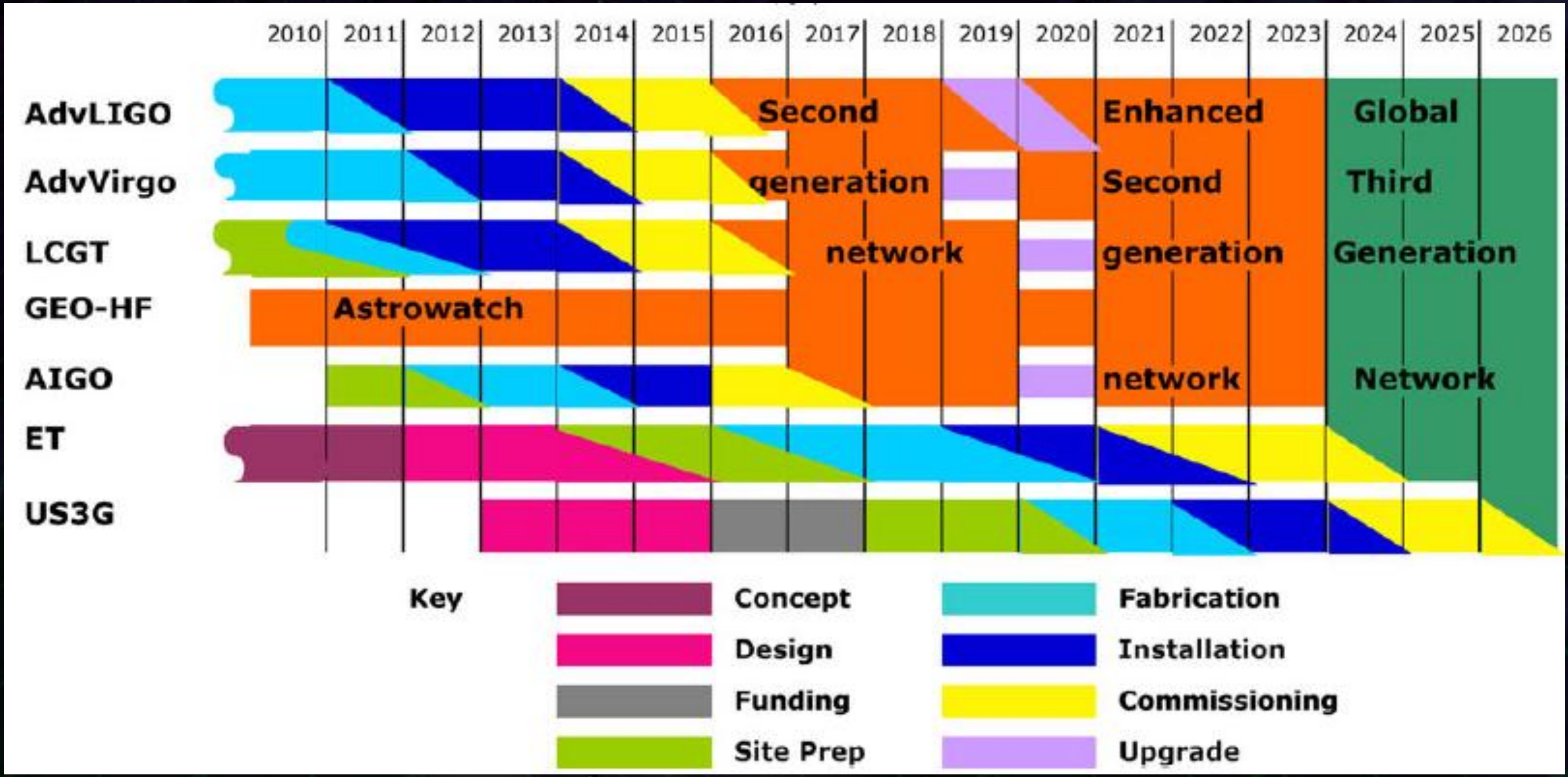
Third generation detectors

3^{rd}-generation detector: ET (Einstein Telescope)

Sensitivity : x 10 improvement
Longer baseline, Underground site, Cryogenic mirrors



GWIC roadmap



Gravitational Waves International Committee Roadmap
http://gwic.ligo.org/roadmap/

LCGT

LCGT

LCGT (Large-scale Cryogenic Gravitational-wave Telescope)

- LCGT

Detect GW signals and open a new field of GW astronomy

Large-scale Detector

Baseline length: 3km

High-power Interferometer

Cryogenic interferometer

Mirror temperature: 20K

Underground site

Kamioka mine,

1000m underground

Start of LCGT project

LCGT project was selected by the
'Facility for the advanced researches'
program of MEXT (June 2010).

Construction cost is partially approved:
9.8 BYen for first 3-year construction.
(Original request: 15.5 BYen for 7 years.)

In addition, request for excavation cost was approved.

LCGT site

Kamioka underground site

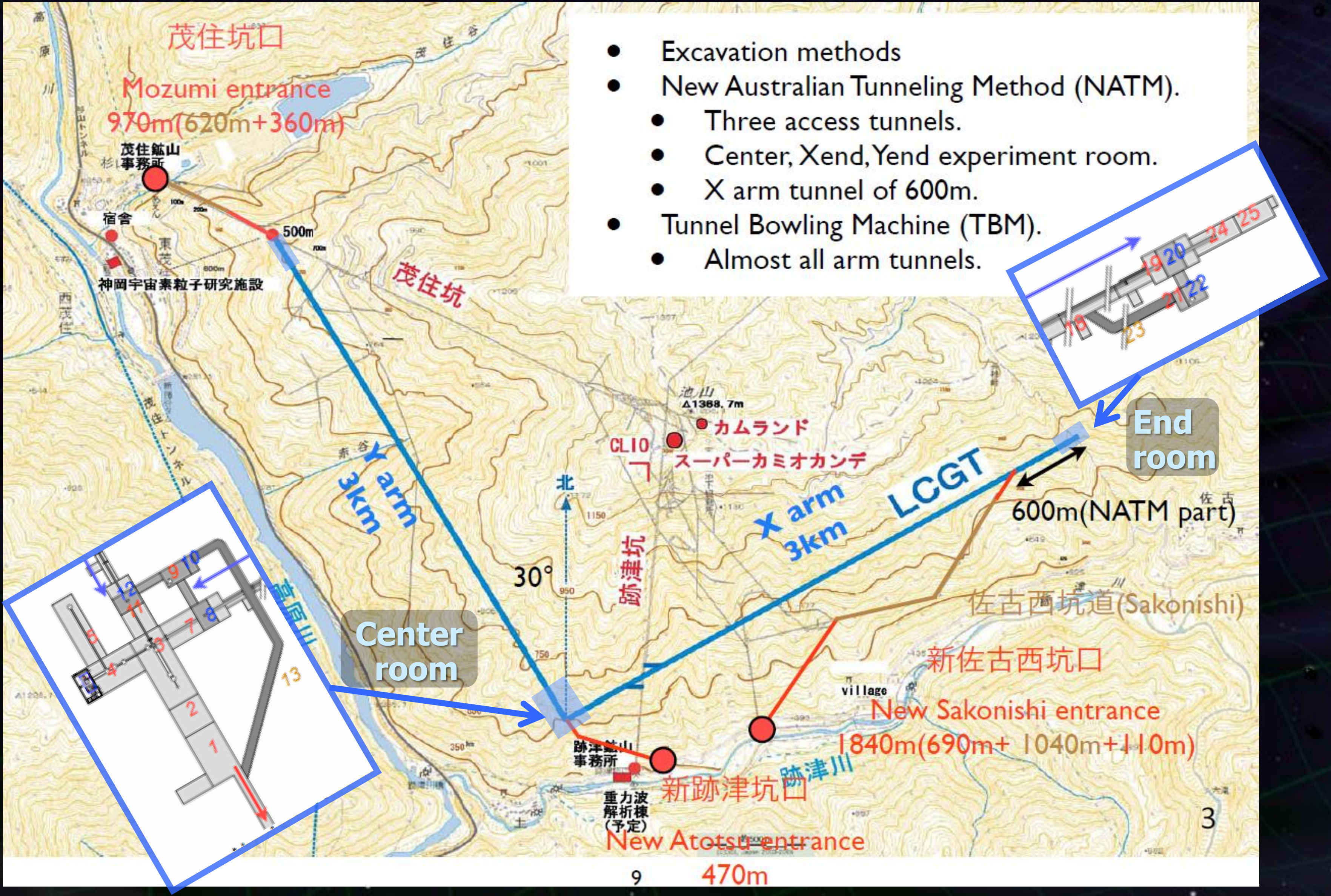
Facility of the Institute of Cosmic-Ray Research (ICRR), Univ. of Tokyo.

Landsat photo data
NASA altitude data
Cashmir 3D

- Neutrino
  - Super Kamiokande, Kamland
- Dark matter
  - XMASS
- Gravitational wave
  - CLIO, LCGT
- Geophysics
  - Strain meter

- 220km away from Tokyo
- 1000m underground from the top of the mountain. (Near Super Kamiokande)
- 360m altitude
- Hard rock of Hida gneiss (5 [km/sec] sound speed)

LCGT tunnel design

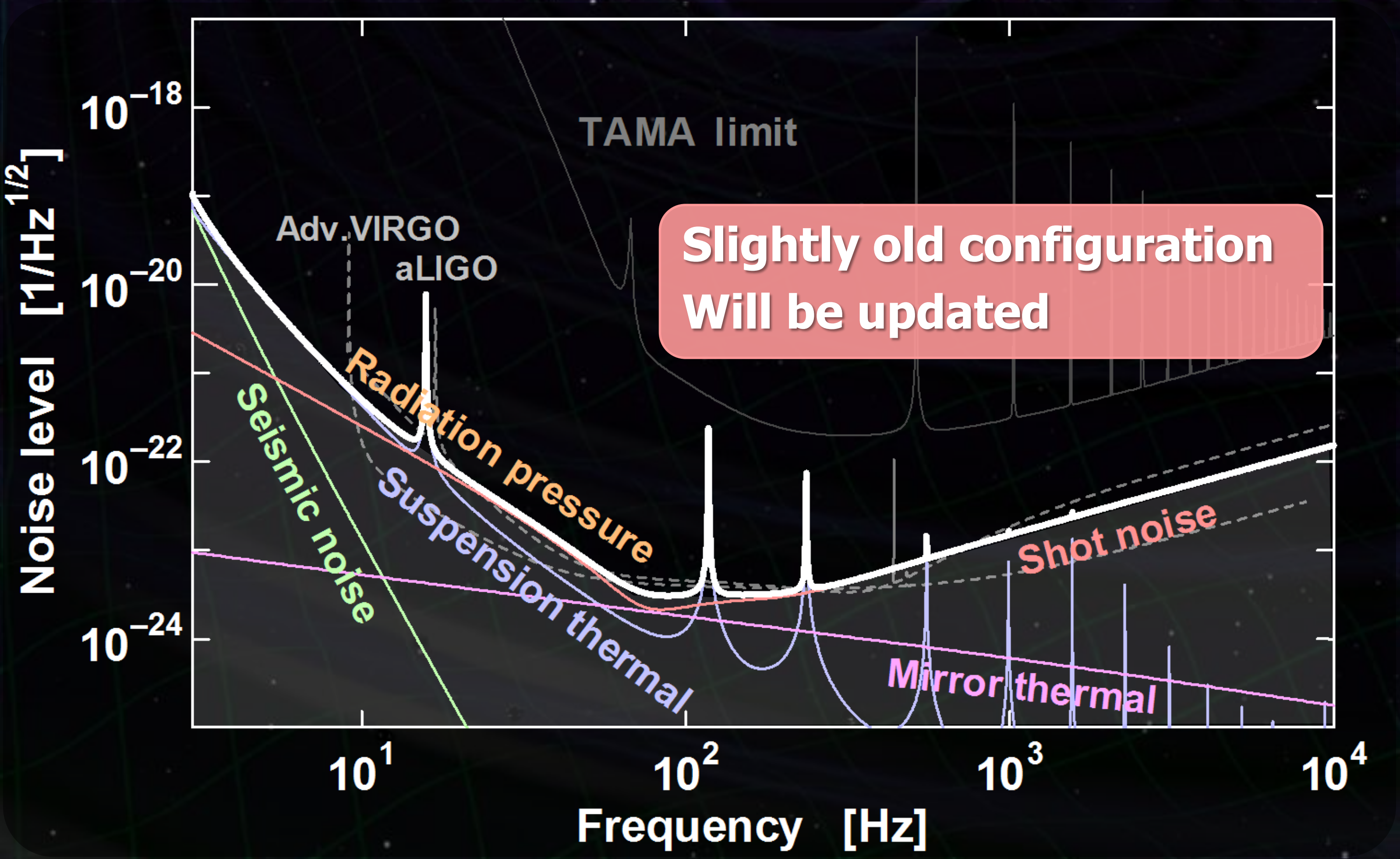


- Excavation methods
- New Australian Tunneling Method (NATM).
  - Three access tunnels.
  - Center, Xend, Yend experiment room.
  - X arm tunnel of 600m.
- Tunnel Bowling Machine (TBM).
  - Almost all arm tunnels.

Sensitivity Limit

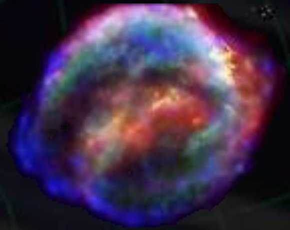
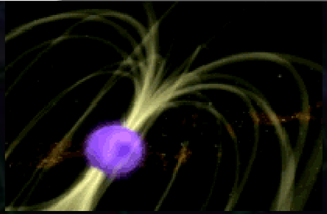
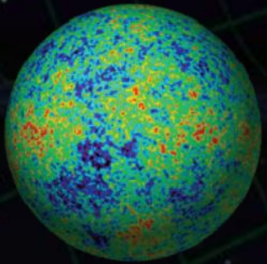
Comparable with aLIGO Ad.VIRGO

→ Global observation network



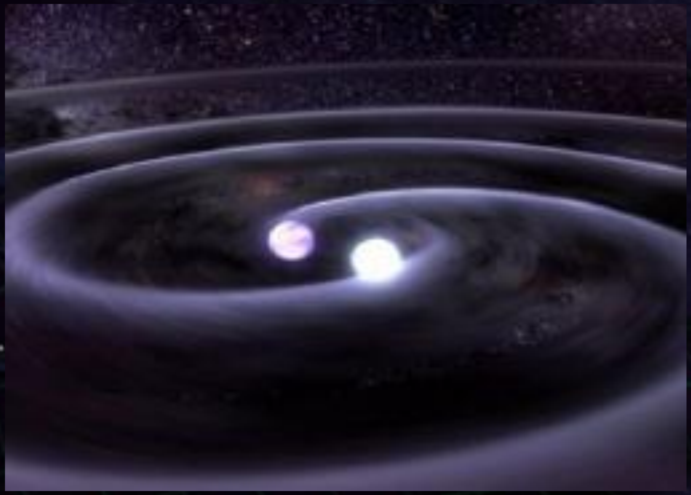
Slightly old configuration
Will be updated

GW targets and data analysis

		Signal duration	
		Short (bursts)	Long (stationary)
Waveform	Known	 Binary merger → Chirp wave, Ringdown wave Gamma-ray bursts	 Pulsar, LMXB → Continuous
	Unknown	 Stellar core collapse → burst wave  Soft gamma-ray repeater	 Stochastic background → Random wave

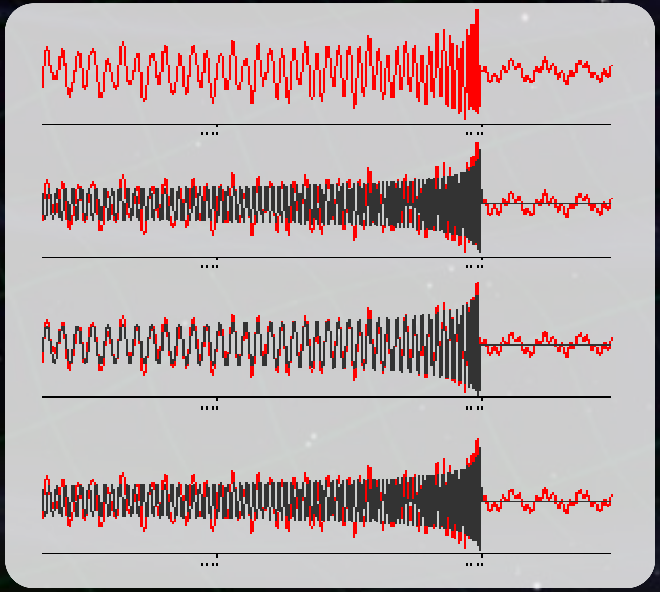
Neutron-star inspiral

Primary target of LCGT:
Inspiral and merger of NS binary



Detectability

- Quantitative estimation of event rate from pulsar observations.
- Precise waveform is predicted.
  → Sophisticated analysis method using an optimal filter.



Scientific outcomes

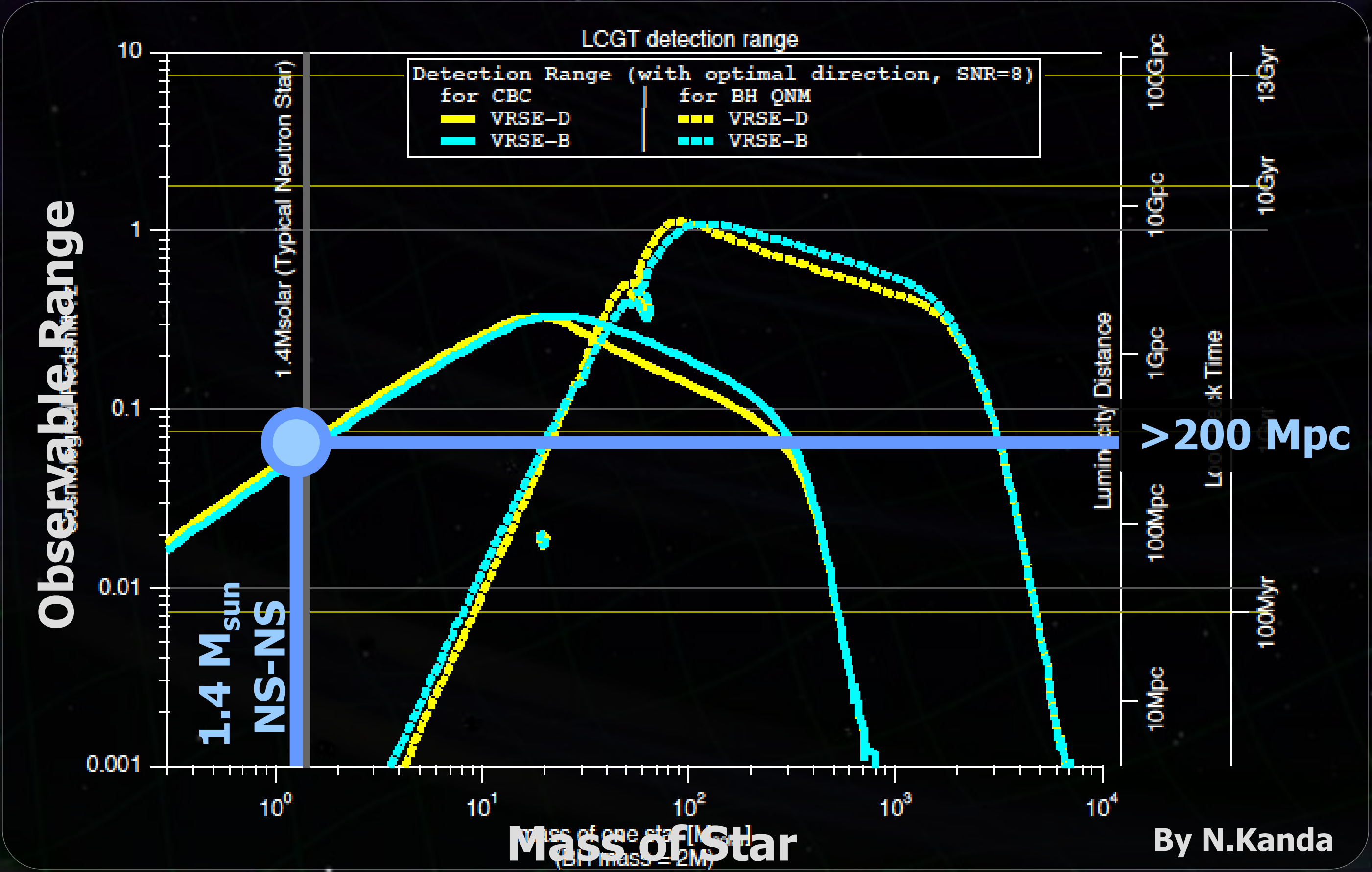
- EoS of neutron star.
- Formation and evolution of stars.
- Origin of high-energy phenomena.

Observable range

Primary purpose of LCGT : Detection of GW

→ **First target : Neutron-star binary inspirals**

⇨ **Obs. Range >200Mpc** (SNR=8, Optimal sky pos. an pol.)



By N.Kanda

Detection rate of LCGT

Neutron-star binary inspirals events

Observable range

sensitivity curve → 270 Mpc

Galaxy number density :

$$\rho = 1.2 \times 10^{-2} \quad [\mathrm{Mpc}^{-3}]$$

R. K. Kopparapu et.al.,
ApJ. 675 1459 (2008)

Event rate :

$$\mathcal{R} = 118^{+174}_{-79} [\mathrm{events/Myr}]$$

V. Kalogera et.al.,
ApJ, 601 L179 (2004)
Kim et al. (2008)

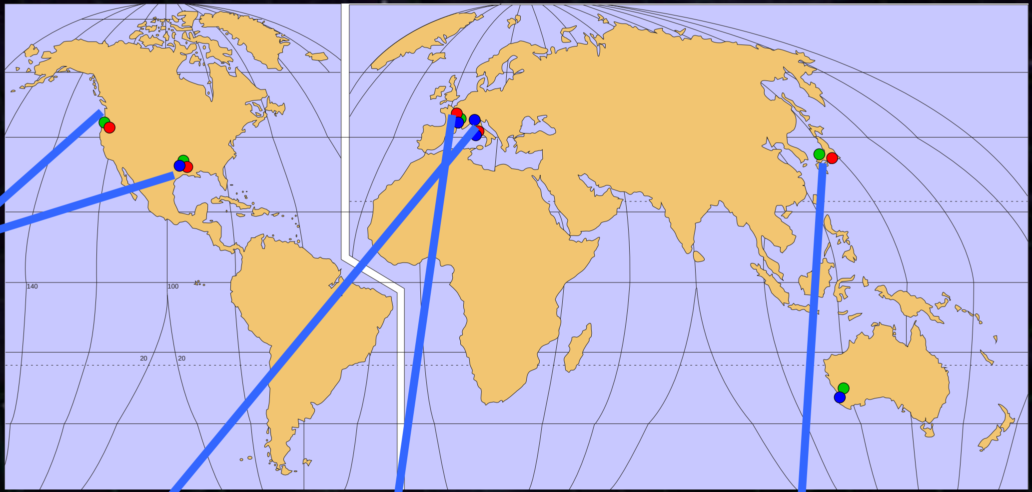
⇨ **LCGT Detection rate 9.8 events/yr**

Second generation detectors

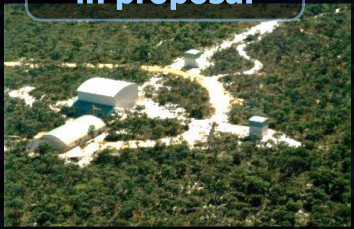
2^{nd}-generation detector network (~5 years from now)

GW astronomy : confident detection, source direction, scientific information on sources

aLIGO (USA)
4km x 2 (or3)



LIGO-Austreria
in proposal



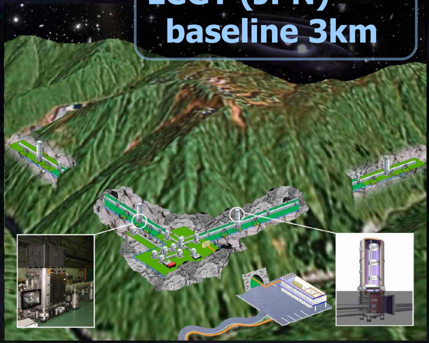
LIGO-India
in proposal

indigo

Adv.VIRGO (ITA-FRA)
baseline 3km

GEO-HF (GER-UK)
baseline 600m

LCGT (JPN)
baseline 3km



LCGT in the global network

One of key observatories in global network

Increase detection rate and scientific outcomes

Advanced technologies

Advanced technologies used for 3rd-generation detectors.

Cryogenics, underground site

→ LCGT is considered as a 2.5-generation detector.

Antenna pattern

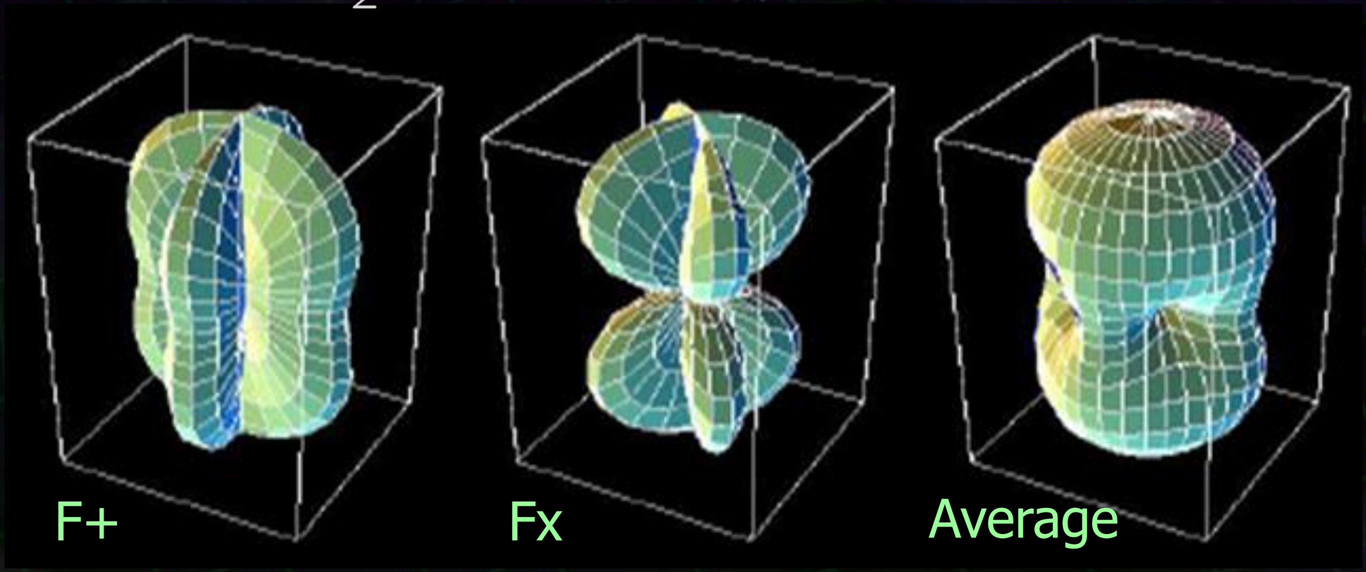
- Interferometric detector response

$$h_{\mathrm{obs}}(t) = F_+ \cdot h_+(t) + F_\times \cdot h_\times(t)$$

Antenna pattern

$$F_+ = -\frac{1+\cos^2\theta}{2}\cos 2\phi \, \cos 2\psi - \cos\theta \, \sin 2\phi \, \sin 2\psi$$

$$F_\times = \frac{1+\cos^2\theta}{2}\cos 2\phi \, \sin 2\psi - \cos\theta \, \sin 2\phi \, \cos 2\psi$$



Network Observation

Network of multiple GW detectors

- Detection

  Increase : Detection rate, Detection volume, Sky coverage.

  Reduce : Fake events, Event-detection threshold.

- Astrophysics

  Increase : Sky position precision of the source,
  Waveform reconstruction.

Multi-messenger astrophysics

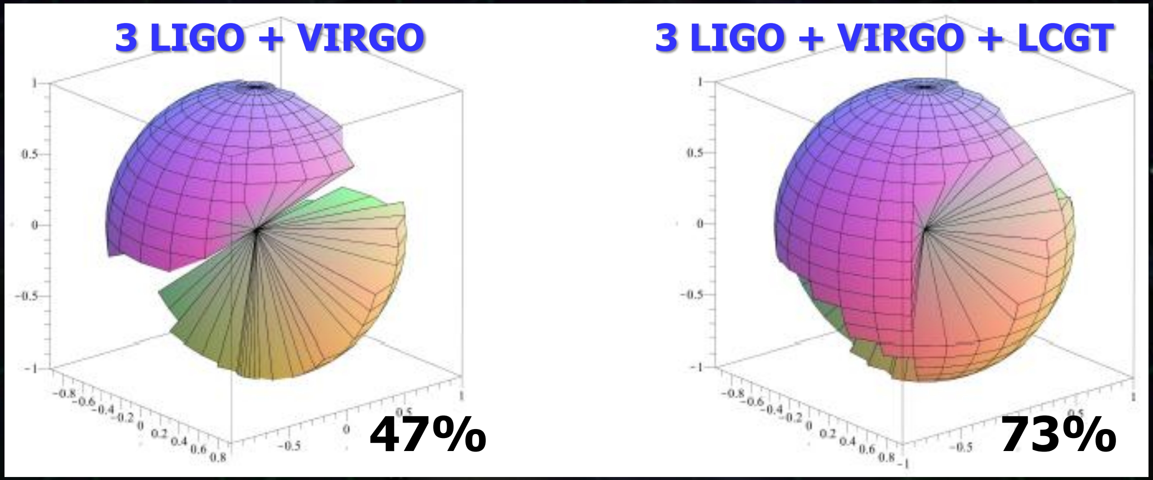
GW source can be central engines of high-energy phenomena
Stellar core collapse, compact binary merger, pulsar, ….
→ Coordinated observation with other telescopes
Gamma-ray, X-ray, optical/IR, Radio, Neutrino, ….

- Triggered search: Other obs. → GW search
- Follow-up search: GW detection → Other telescopes

Increase of detection rate

Increase detection probability

- Increase of sky and time coverage.
- Decrease of fakes by coincidence analysis.
  - → Increase the detection probability



Sky-coverage pattern
(0.707 of max. range)

B.Schutz
arXiv:1102.5421

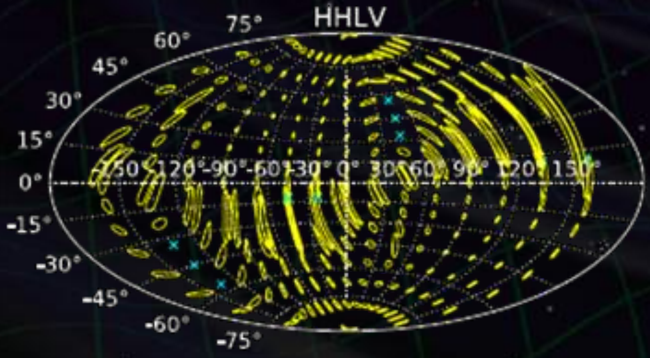
Parameter estimation

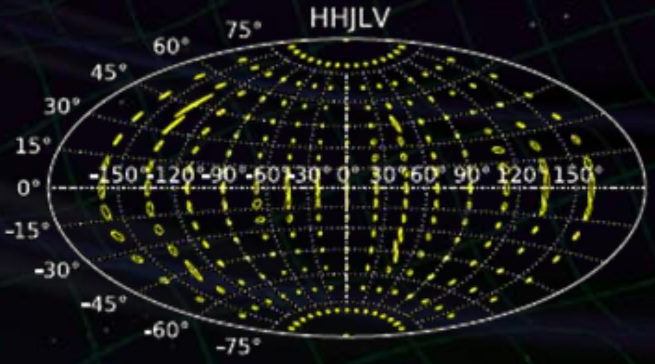
Angular resolution for the source

By H. Tagoshi

	LHV	LHVJ	LHVA	LHVJA
average of $\delta\Omega$ [Deg^2]	34.4	7.26	4.20	2.78
median of $\delta\Omega$ [Deg^2]	10.8	3.54	2.20	1.46

H: LIGO--Hanford
L: LIGO--Livingston
V: Virgo, J: LCGT
A: LIGO--Australia



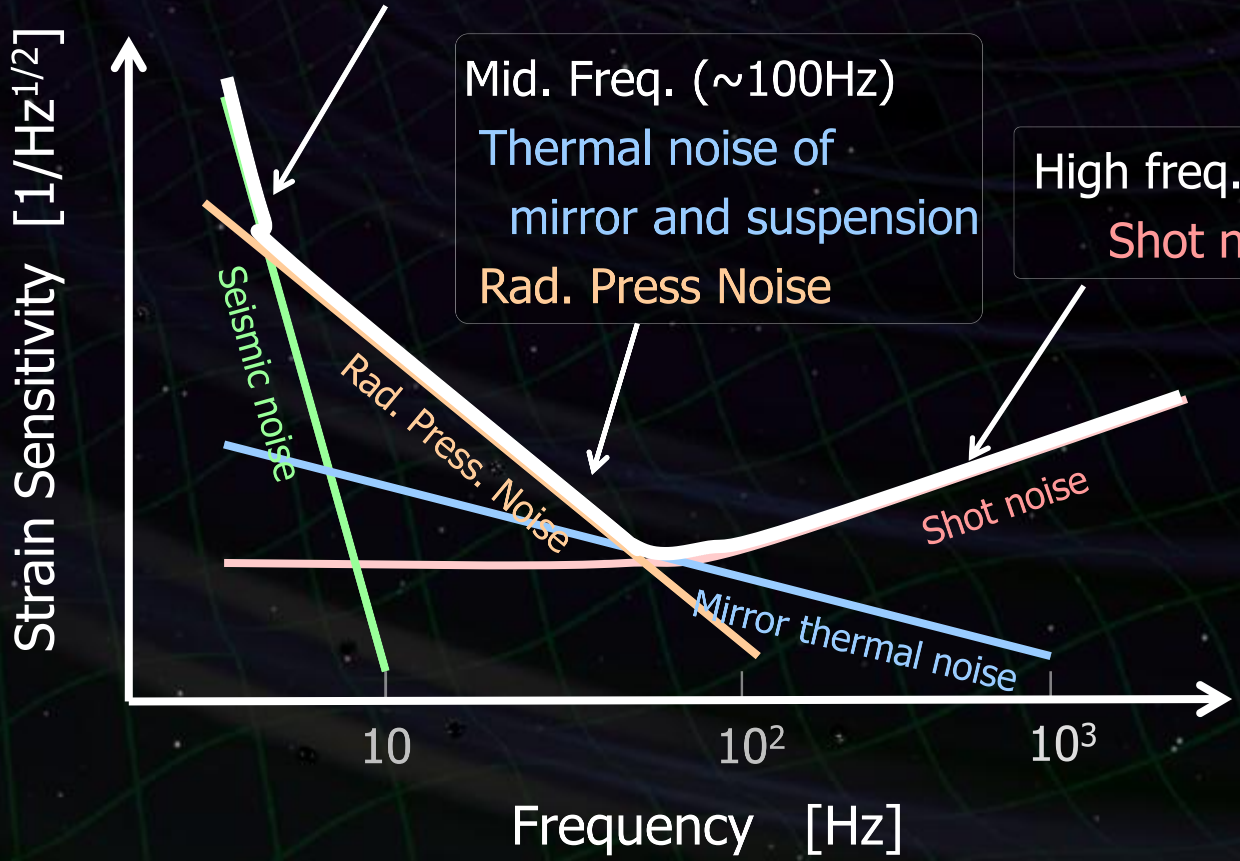


S.Fairhaurst
CQG 28(2011) 105021

Adding LCGT to (aLIGO + adv. VIRGO) network
→ Factor ~3-4 improvement in sky area

LCGT design

Fundamental Noise Sources



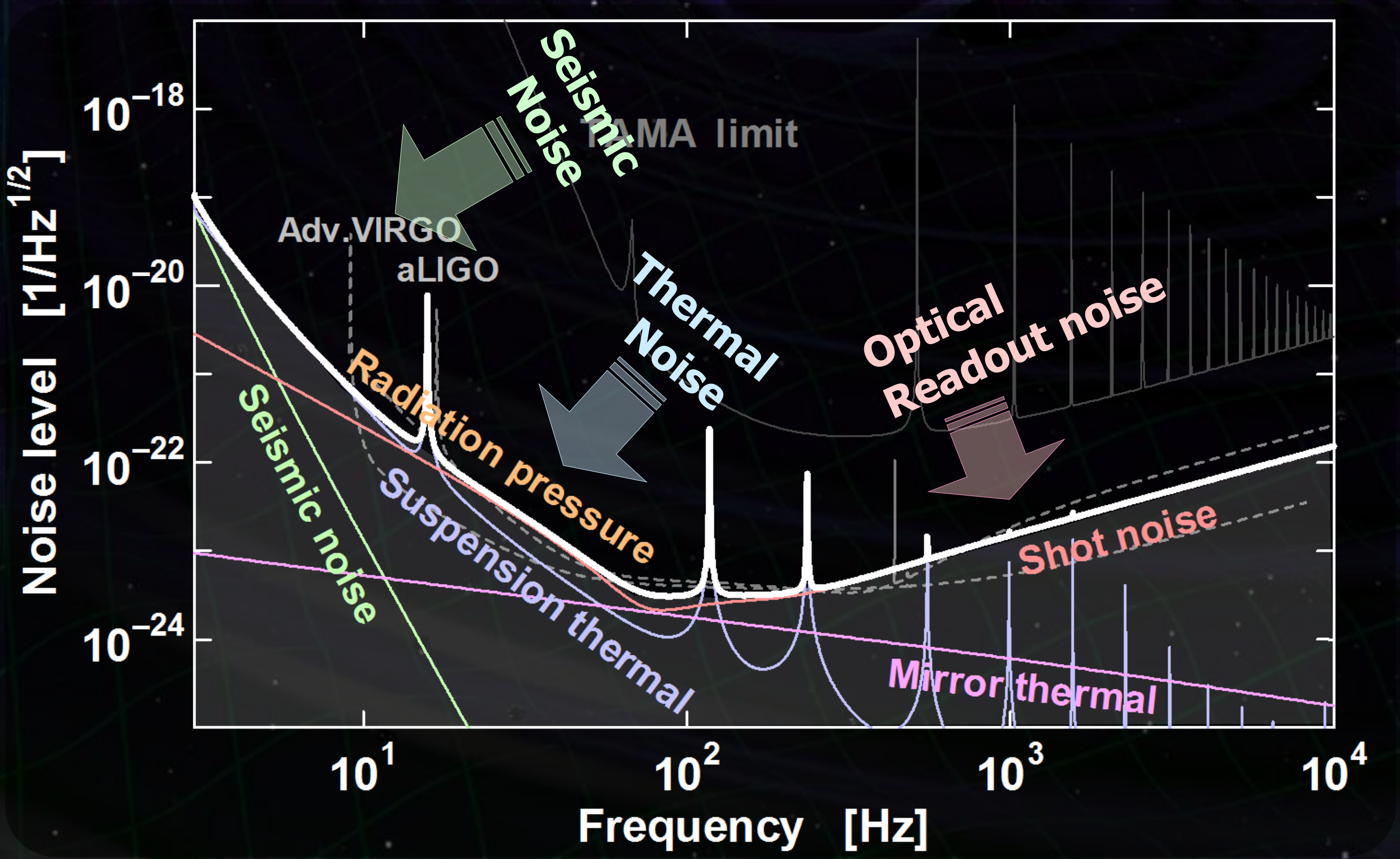
Low Freq. (<10Hz)
Seismic Noise

Mid. Freq. (~100Hz)
Thermal noise of mirror and suspension
Rad. Press Noise

High freq. (>100Hz)
Shot noise

Sensitivity Curve

Improved sensitivity
from the first generation detectors



Optical-readout noise

- Quantum noise in optical readout
  - Shot noise

    Photon counting noise at photo detector

    $h_{\mathrm{shot}} \propto 1/\sqrt{P}$
  - Radiation Pressure noise

    Fluctuation of momentum on reflection

    $h_{\mathrm{RPN}} \propto \sqrt{P}$

    P : Laser power

Standard Quantum Limit

$$h_{\mathrm{SQL}} \propto \frac{1}{\sqrt{M\ L^2}}$$

M : Mirror Mass
L : Baseline l

⇨ Long baseline
Large-mass mirror

LCGT : Large-scale, High-power interferometer

Baseline 3km, Mirror mass 22kg, Laser power in arm ~800kW

Thermal noise

- Thermal fluctuation of components

  Mechanical Loss (Dissipation) → Fluctuation Force (FDT)

  - Mirror thermal noise : Mirror substrate, Coating, ….
  - Suspension thermal noise : Suspension wire, ….

Thermal noise

Thermal noise $\propto \sqrt{\frac{T}{Q}}$

T : Temperature [K]
Q : 1/(Mechanical loss)

⇨

Cryogenic
Low-loss Material
IFO configuration

LCGT : Cryogenic interferometer → Straight forward strategy

- Mirror ~20K, Suspension ~16K
- Additional merit : Low-material loss, No thermal lensing, Relaxed parametric instability.

Seismic noise

- Seismic motion --- Limit sensitivity and stability
  - Stationary vibrations : Low-freq. limit of the observation band.
  - Non-stationary bursts : Earthquake, Weather change, ….

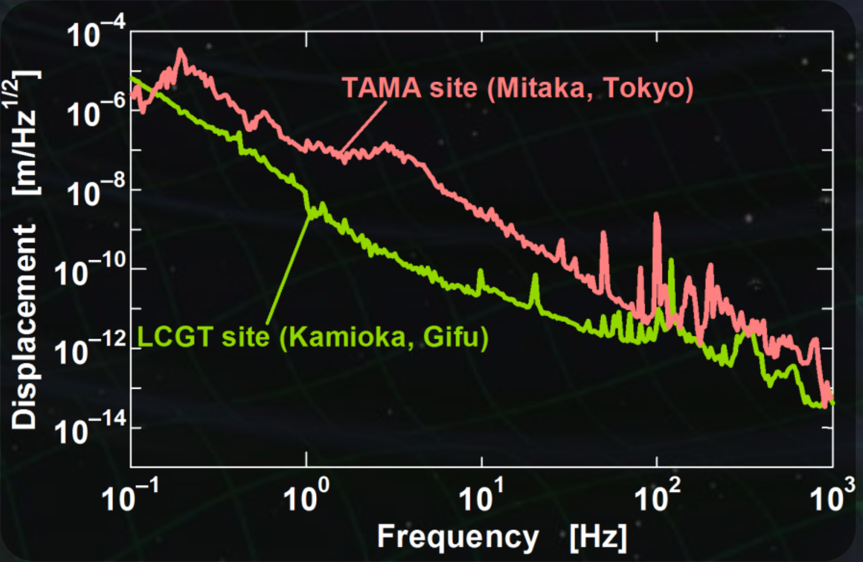
→ Affect detector stability, duty cycle of operation.

Seismic noise level

- Low by 2-3 orders at underground
- Reduces at high freq.

$$\delta x_{\mathrm{seis}} \sim \frac{10^{-9}}{f^2} \quad [\mathrm{m/Hz^{1/2}}]$$

(At Kamioka site, f: Frequency)



LCGT : Underground site → Low-seismic noise, Long-term stability.

High performance isolator SAS : Multi-stage, low-freq. isolator.

Interferometer configuration

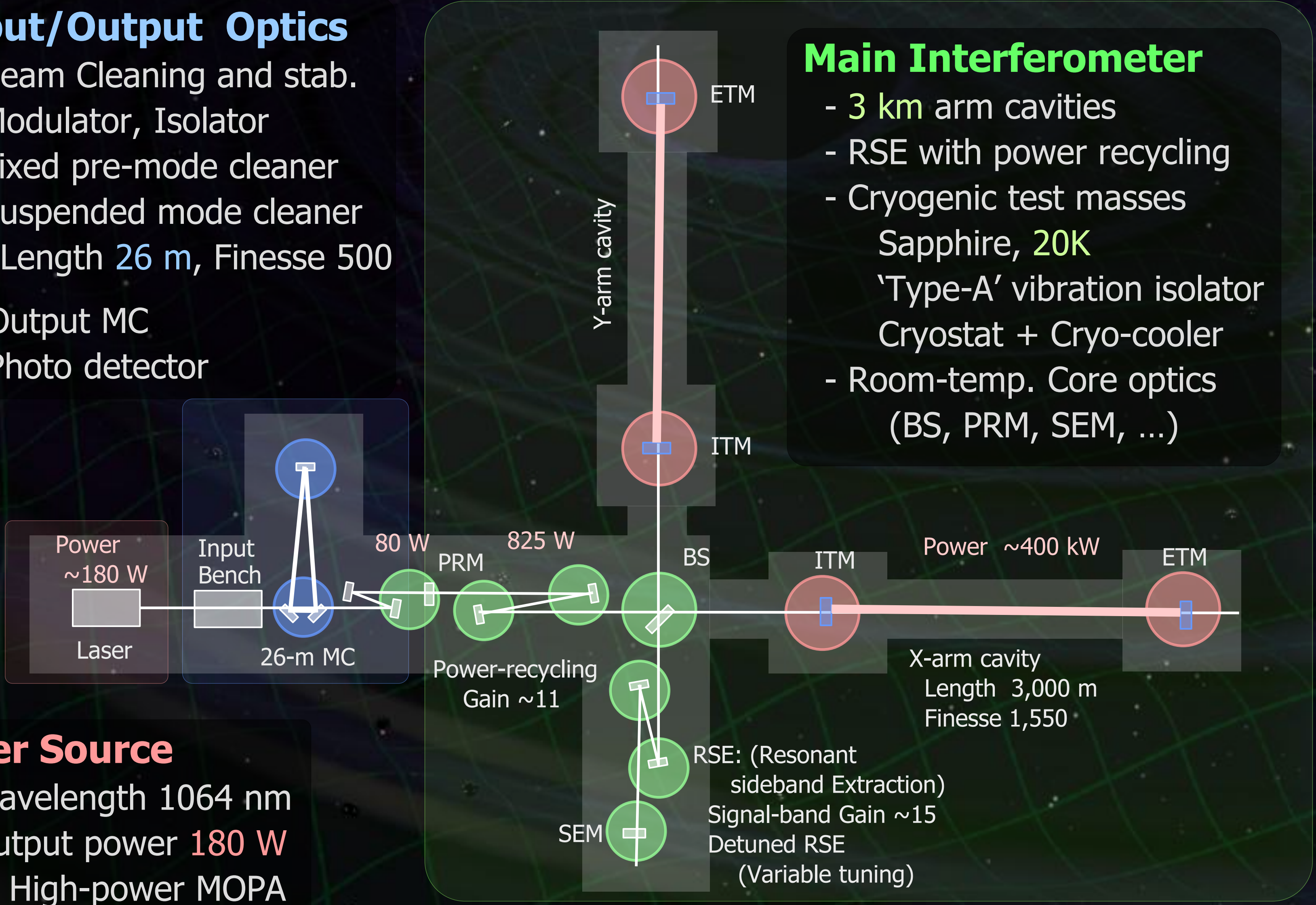
Input/Output Optics

- Beam Cleaning and stab.
- Modulator, Isolator
- Fixed pre-mode cleaner
- Suspended mode cleaner
  Length 26 m, Finesse 500

- Output MC
- Photo detector

Main Interferometer

- 3 km arm cavities
- RSE with power recycling
- Cryogenic test masses
  Sapphire, 20K
  'Type-A' vibration isolator
  Cryostat + Cryo-cooler
- Room-temp. Core optics
  (BS, PRM, SEM, …)



Laser Source

- Wavelength 1064 nm
- Output power 180 W
  High-power MOPA

Suspension, Isolation, and Cryo-system

- Seismic Isolator (Type-A SAS)
  - Multi-stage passive isolator, suspended from hard rock.
  - Housed in vacuum system.
  - Local control and damping.
  - Cryo-payload at bottom, suspend a sapphire test mass.

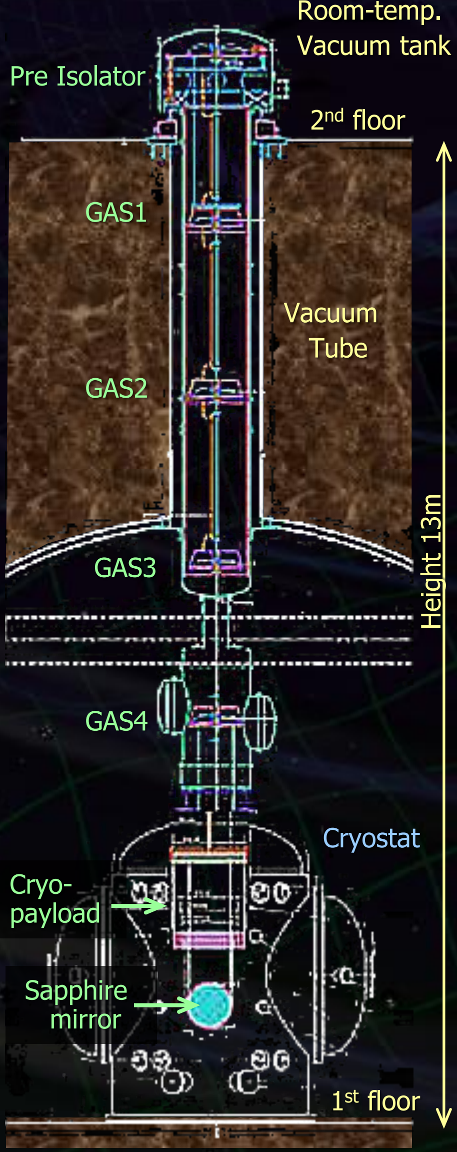

Pre Isolator


GAS filter

- Cryo-payload
  - Double pendulum

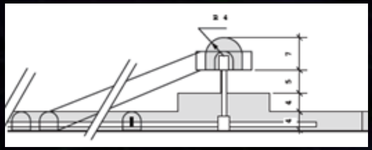
Sapphire test mass	20K
Suspension	16K

  - Actuators for fine control.
  - Heat links to radiation shield.



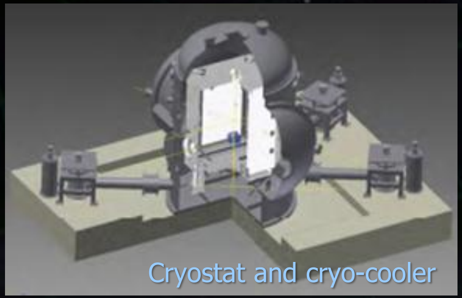
- Tunnel : 2 layer structure

Upper room	7m height
Rock floor	5m height
Lower room	8m height



- Cryostat, cryo-cooler
  - Diameter Φ2.4m, Height 3.8m
  - 2 layer rad. shield (80K, 8K)
  - Low-noise PT cryo-cooler x4

1st stage	36 W at 50K
2nd stage	0.9 W at 4K


Cryostat and cryo-cooler

Comparison of detectors

	2^{nd}-generation detectors			3^{rd} generation
	aLIGO	**Ad. VIRGO**	**LCGT**	**ET**
Obs. start	~ 2016	~ 2016	~ 2017	~ 2026
Site	On ground Hanford 2 IFOs Livingstone 1 IFO	On ground Pisa 1 IFO	Under ground Kamioka 1 IFO	Under ground 3 IFOs
Baseline length	4 km	3 km	3 km	10 km
Obs. range (*1)	306 Mpc	243 Mpc	273 Mpc (*2)	3 Gpc
IFO config.	Broadband RSE	Detuned RSE	Variable RSE	RSE Xylophone
Thermal noise	Large beam diameter, Low-loss mirror, Thermal compensation		Cryogenic	Cryogenic
Seismic isolator	Active isolator	Passive isolator	Passive isolator	Passive isolator

(*1) Observable range for BNS inspiral, Optimal direction, polarization, SNR>8.

(*2) Under discussion, and will be updated.

LCGT schedule

- **We will have an initial-phase operation (iLCGT) as the first 3-year program**

  3km FPM interferometer at room temperature,
  with simplified vibration isolation system (TBD)
  ~1 month (TBD) engineering run in FY2015.

- **Start observation in FY2017 with the baseline design (bLCGT).**

  Cryogenic RSE interferometer
  with originally-designed vibration isolation system.

Note: Details under discussion

Announcement

LCGT will have a new Nickname soon…

- Invite candidates from the public

  → over 600 applications.
- Naming committee with 6 peoples.

  Chair: Y. Ogawa (Novelist)

  → Has been decided in June 2011.

- Will be announced on this Friday (Jan. 20, 2012).

DECIGO

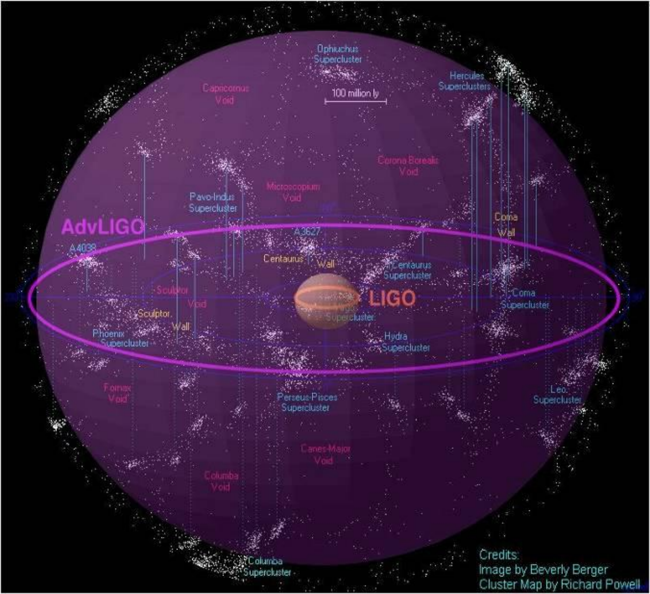
Expanding the Horizon

First-gen. GW detectors : ~ 20Mpc obs. range

However… we can expect only rare events (10^{-4}-10^{-2} event/yr)

⇨ **Next generation detectors**

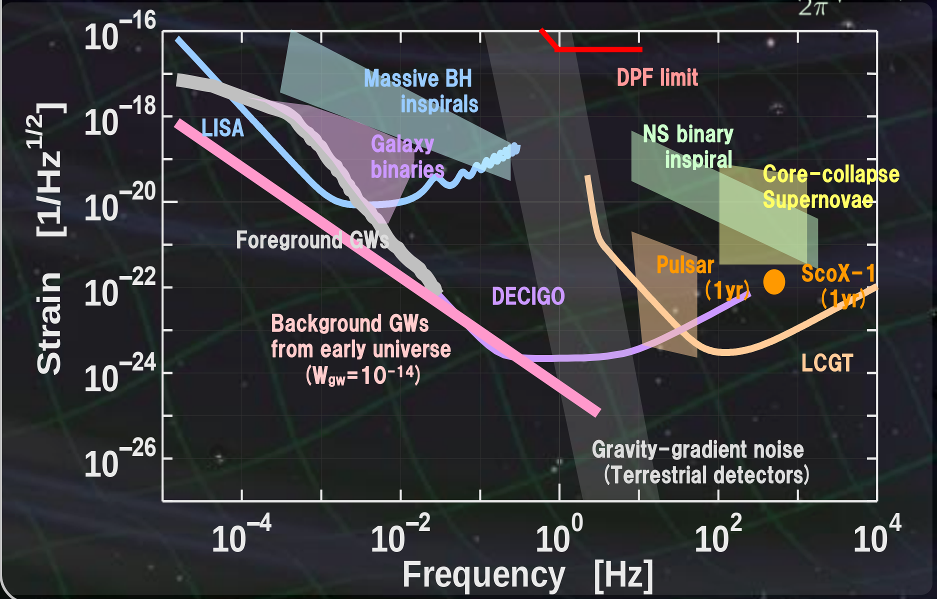
Better sensitivity
to cover more galaxies



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

Wider observation band
for various sources

$$f \sim \frac{1}{2\pi}\sqrt{GM/R^3}$$



Expanding the observation band

GW frequency ~ 1/ (time scale of the source)

Observation at low frequency

- Larger-mass events → larger amplitude GW
- (Almost) stationary source → Do not have to wait for 'events'

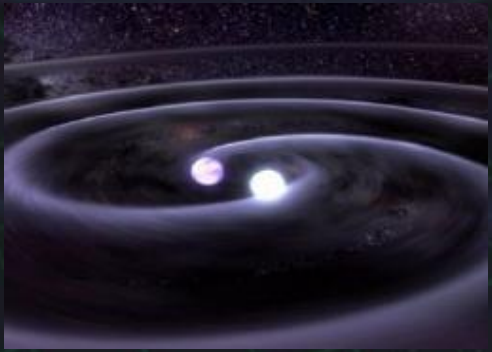
➡ **Different or complementary science**

(Example) GW from compact binary inspiral

$$h \sim \frac{4G^2}{c^4 r} \frac{\boxed{m_1 m_2}}{\boxed{R}} \qquad f \sim \frac{1}{2\pi}\sqrt{\frac{G(m_1+m_2)}{R^3}}$$

Separation

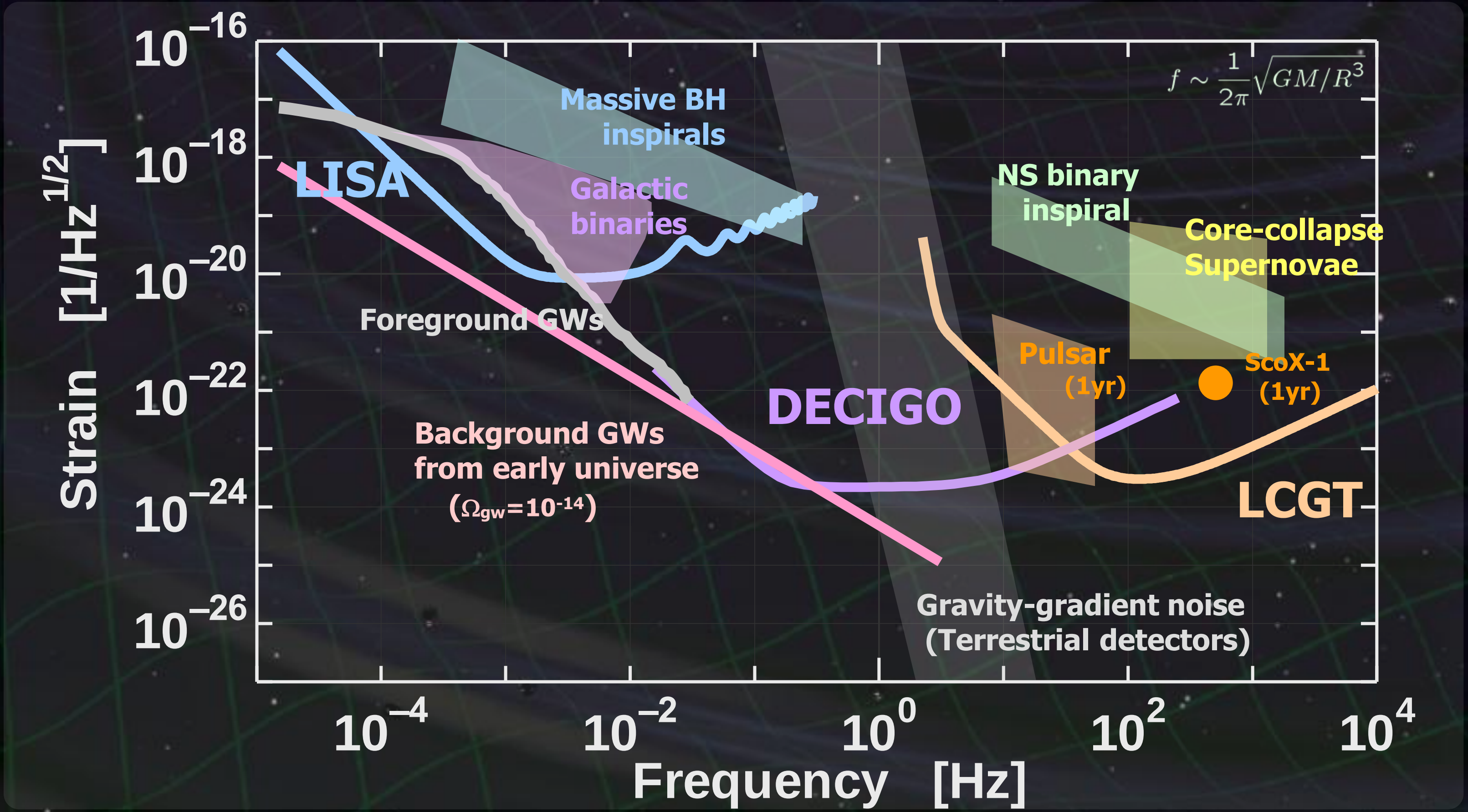
Mass



- Large separation
  → stationary, low-freq. GWs
- Just before merger ($R_{\mathrm{ISCO}} \propto M$)
  → Large mass, large amplitude GWs at low freq.

Sources and detectors

Ground-based detectors : 10Hz - 1kHz → Neutron star, Supernova, …
DECIGO/BBO : 0.1 - 1Hz → IMBH, Background GWs, …
LISA : 1mHz – 0.1Hz → SMBH, Compact binary,...



Space GW detector

Advantages of a space detector for low-freq. observation

- Free from noises by the earth
  - Seismic noise, gravity-gradient noise

- Longer baseline
  - Observation freq. band
    - $\propto$ 1 / (Beam storage time) $\propto$ Baseline length
  - Suppression of displacement noise
    - Strain sensitivity ~ (disp. noise) / (Baseline length)

Disadvantages of a space detector

- Cost, Development time
- Maintenance and upgrade are almost impossible after launch

Space-borne observatories

LISA (Laser Interferometer Space Antenna)

Obs. band around 1mHz

~Million km baseline length

Recent change : ESA/NASA → ESA mission

Design updates underway

→ changing name to

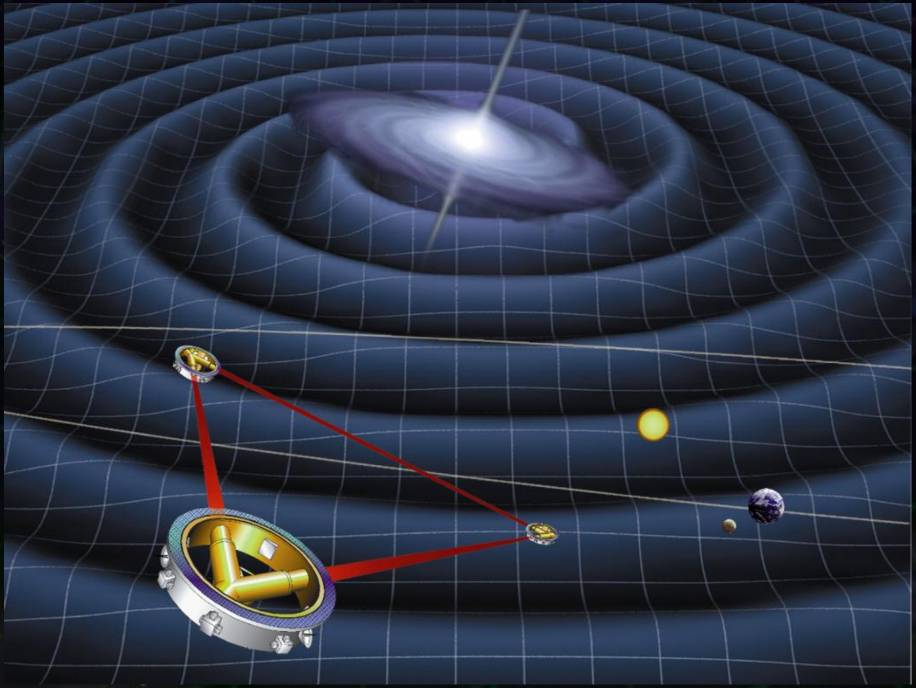
NGO (New Gravitational-wave Observatory)

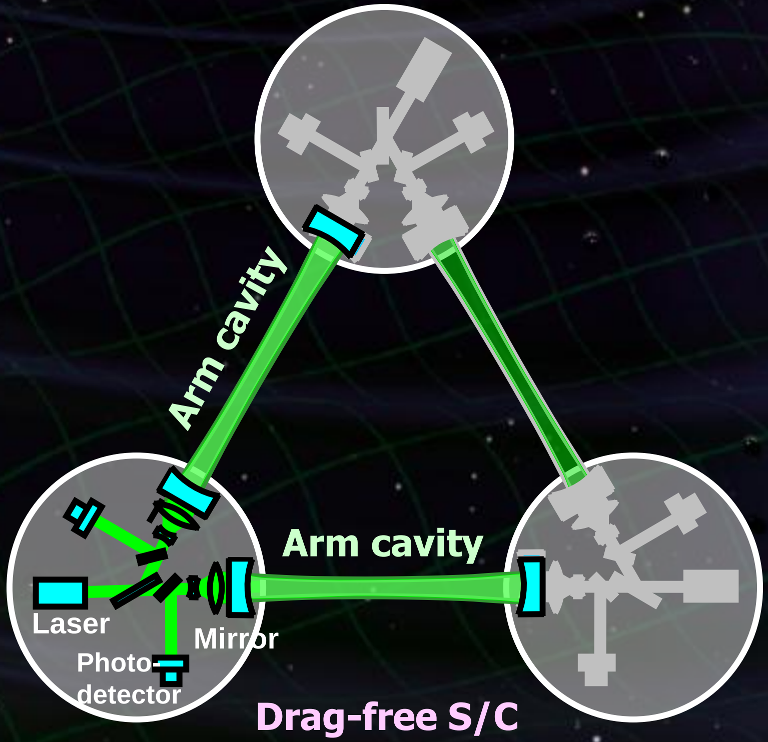
DECIGO

(Deci-hertz Interferometer Gravitational Wave Observatory)

Obs. Band around 0.1Hz

1000km baseline length



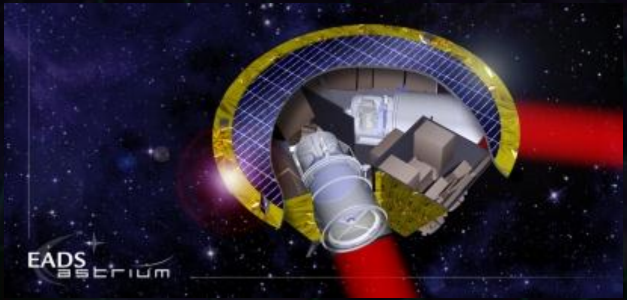


NGO (LISA) Interferometry

Interferometer design

- Optical transponder configuration
  Long baseline (~1 million km) →power loss by diffraction
  Each S/C has laser source →Phase-lock to incoming beam

LISA web page : http://sci.esa.int/lisa



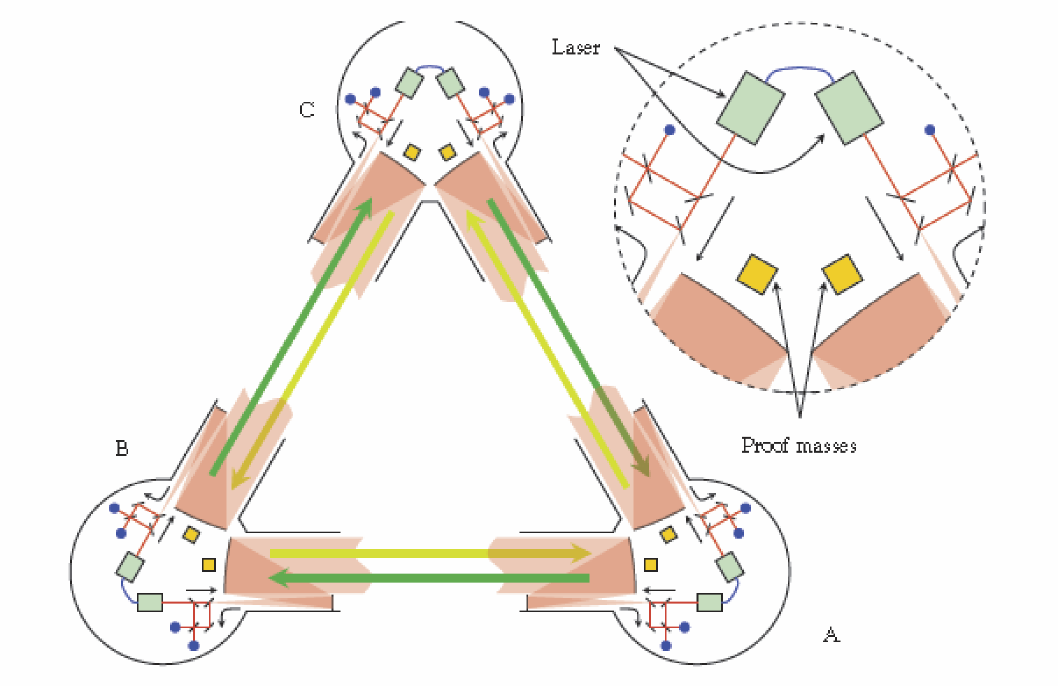


Figure 3.2.: A constellation of three identical LISA spacecraft constitutes the science instrument. There are six identical, send/receive laser ranging terminals (two per S/C) with associated test masses and a comparison of signals at each apex. The sketch leaves out the test mass interferometers for clarity.

LISA assessment study report (Yellow Book), ESA/SRE (2011) 3, February 2011

LISA Pathfinder

LISA Pathfinder

- Technical test for LISA
  - Obtain the best geodesic motion possible
    - Differential acceleration of the two TMs
      - 3×10^{-14} m s^{-2} at 1 mHz
    - Determine best configuration by experiments
  - Develop a noise model of the system
    - Allows the projection of the performance of technologies to LISA

- Status
  - Most of the hardware is there.
  - Awaiting thrusters and launch lock.
  - Most of the experiments are already defined.
- Launch in 2014

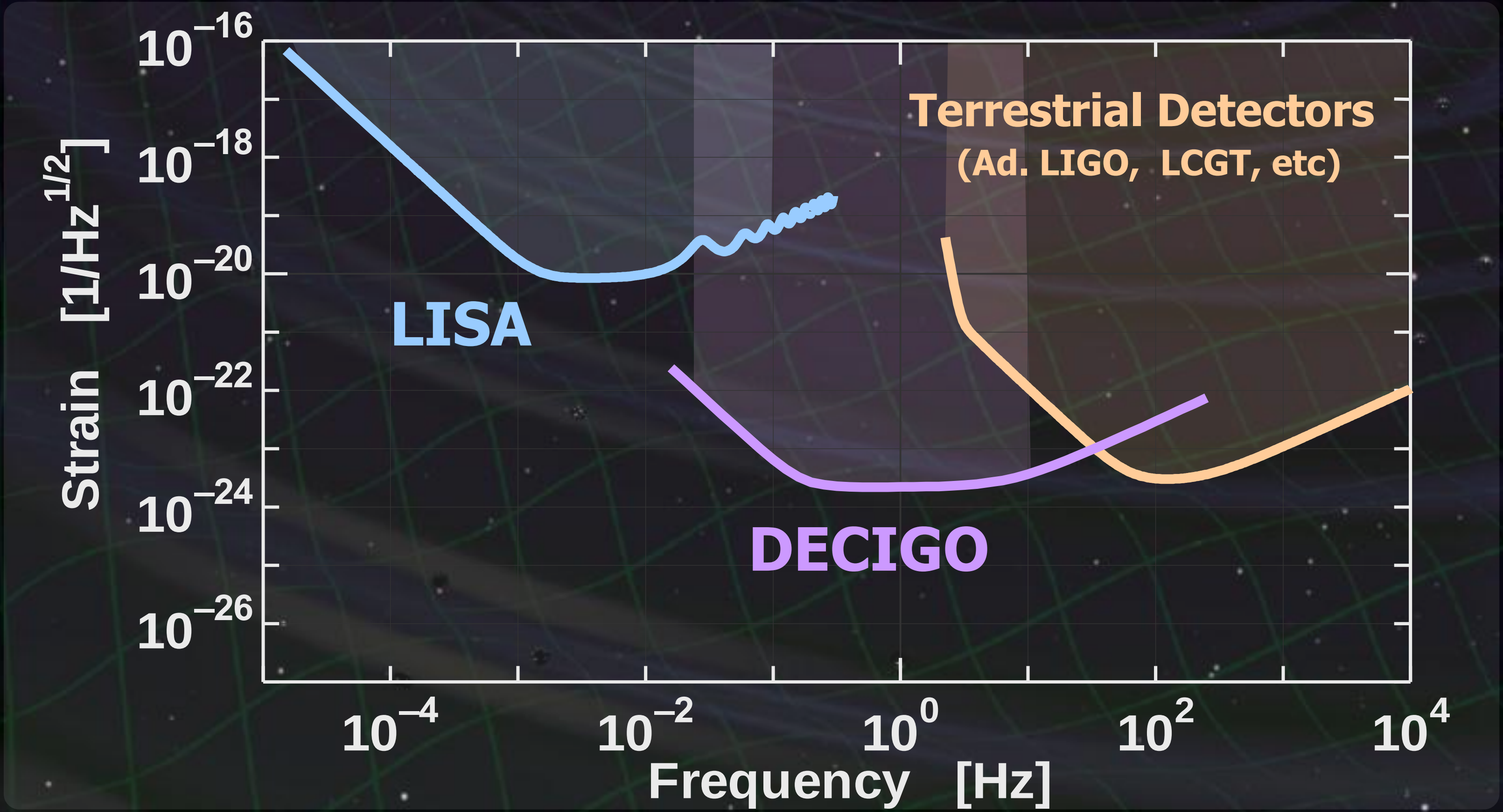
M Hewitson for the LPF team, AMALDI, July 15th 2011

DECIGO

DECIGO (Deci-hertz interferometer Gravitational wave Observatory)

Space GW antenna (~2027)
Obs. band around 0.1 Hz

⇨ 'Bridge' the obs.gap between LISA and Terrestrial detectors



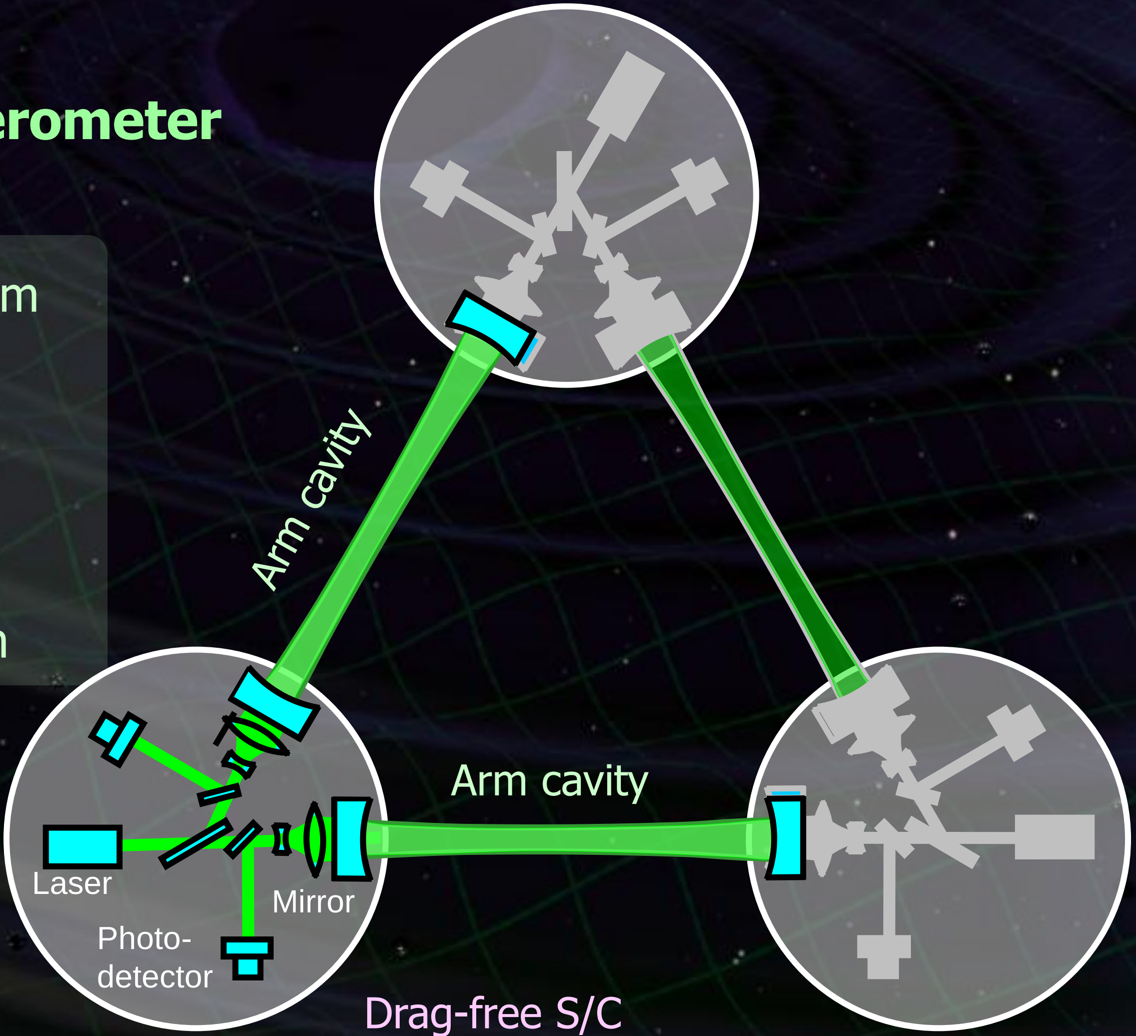
Pre-Conceptual Design

Interferometer Unit:

Differential FP interferometer

Arm length:	1000 km
Finesse:	10
Mirror diameter:	1 m
Mirror mass:	100 kg
Laser power:	10 W
Laser wavelength:	532 nm

S/C: drag free
3 interferometers

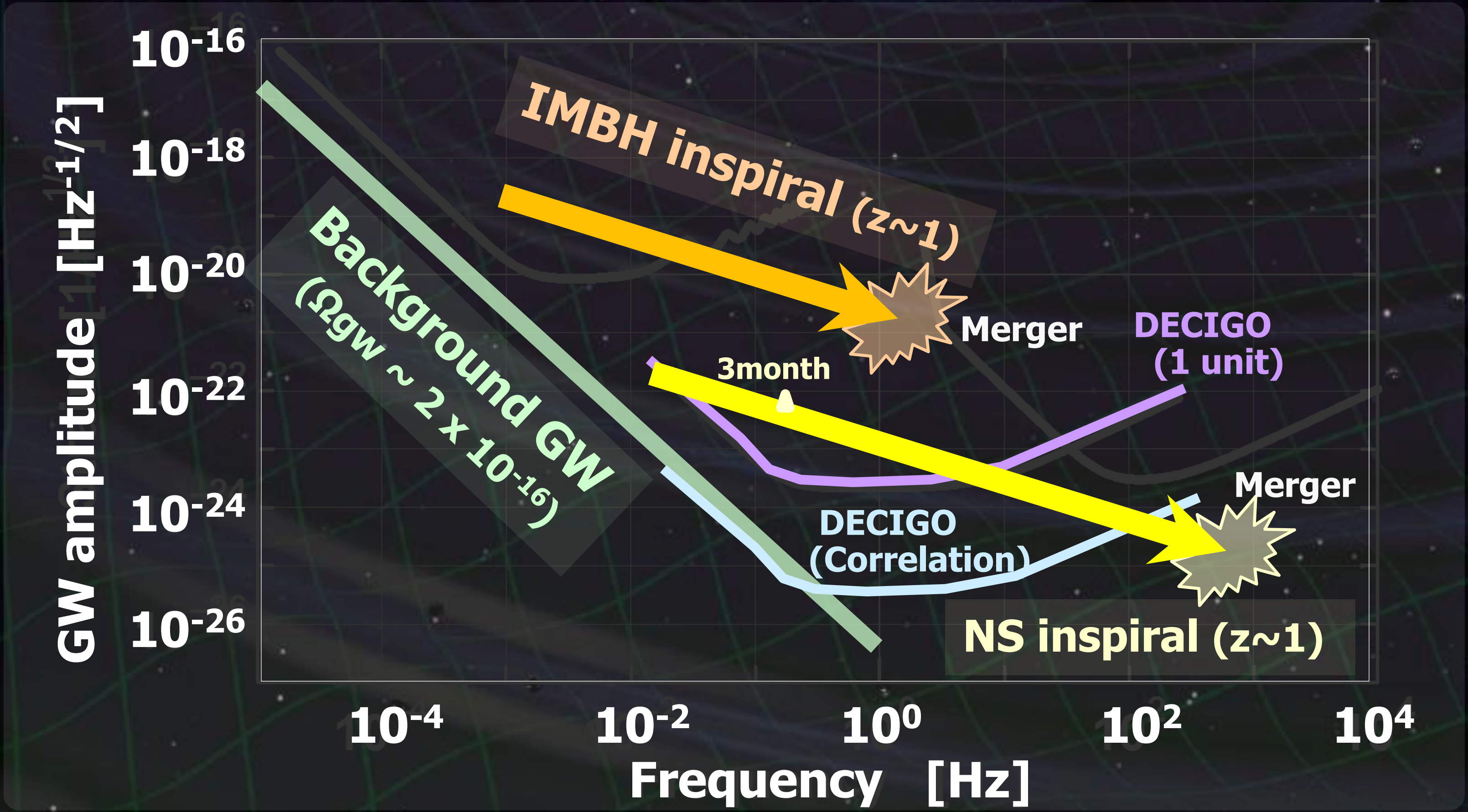


Targets and Science

IMBH binary inspiral
NS binary inspiral
Stochastic background

⇨

Galaxy formation (Massive BH)
Cosmology (Inflation, Dark energy)
Fundamental physics



Astronomy and Cosmology

- **Verification of the alternative theories of gravity**

  Test Brans-Dicke theory by NS/BH binary evolution

  → Stronger constraint by 10^4 times

  K. Yagi and T. Tanaka, Prog. Theor. Phys. 123, 1069 (2010)

- **Black hole dark matter**

  Gravitational collapse of the primordial density fluctuations

  → Primordial black holes (PBHs) as a candidate of dark matter

  R. Saito and J. Yokoyama, Phys. Rev. Lett. 102 161101 (2009)

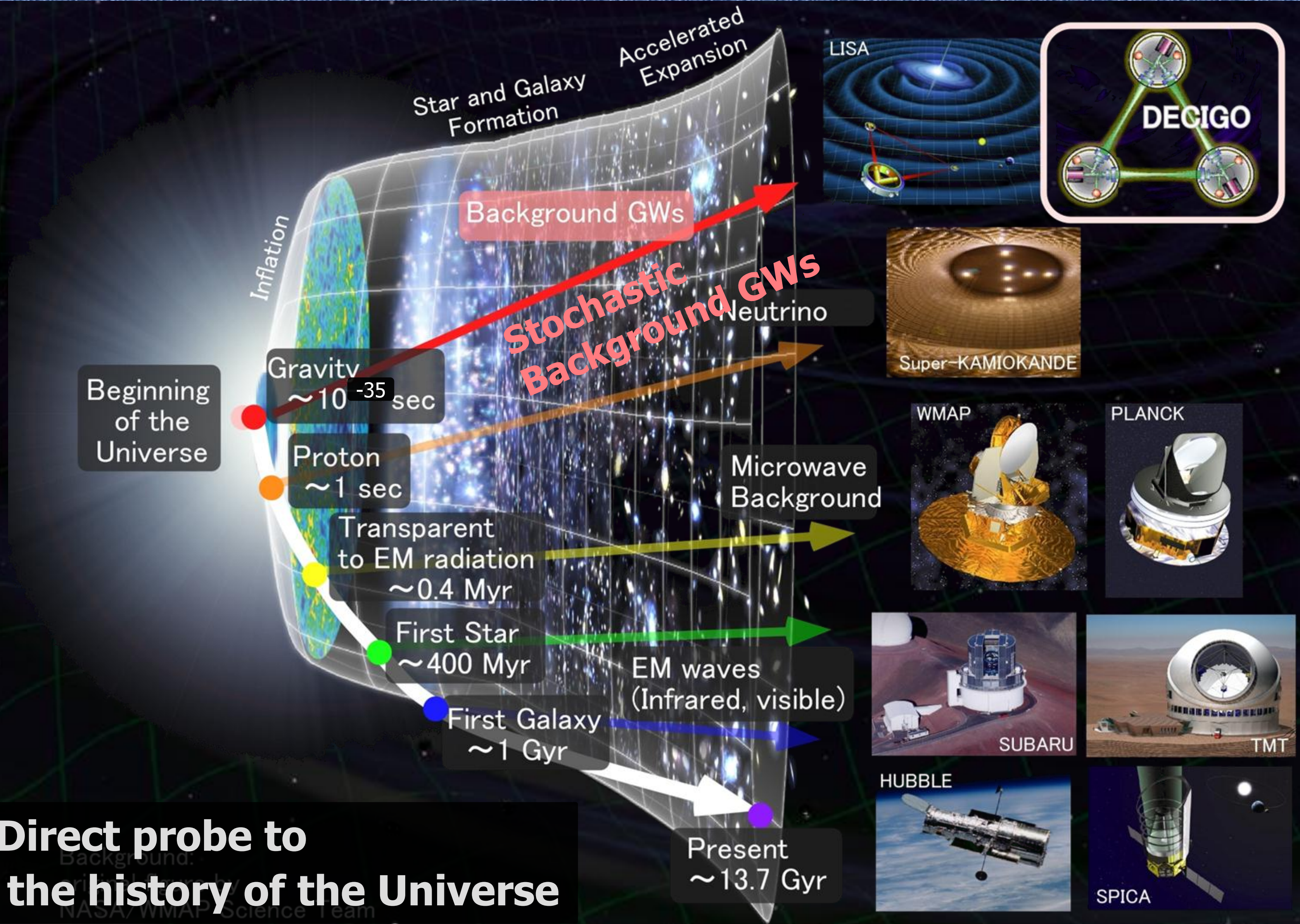
- **Neutron-star physics**

  Determine masses of 10^5 NSs per year

  → Constrain the EoS of NS

  Formation process of NS from the spectrum

Characterization of inflation



Direct probe to the history of the Universe

DECIGO Interferometer

Interferometer Unit:

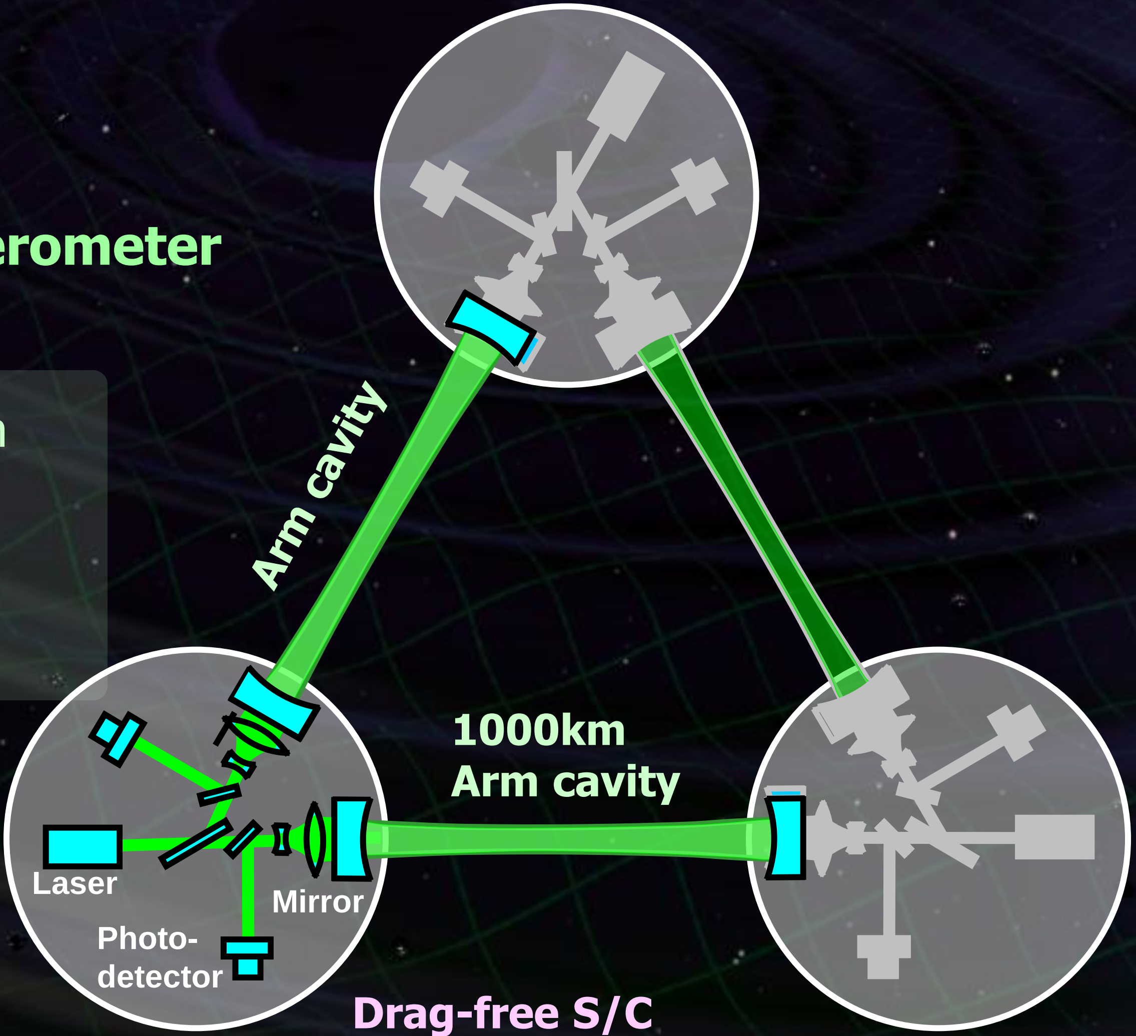
Differential FP interferometer

Baseline length: 1000 km

3 S/C formation flight

3 FP interferometers

Drag-free control

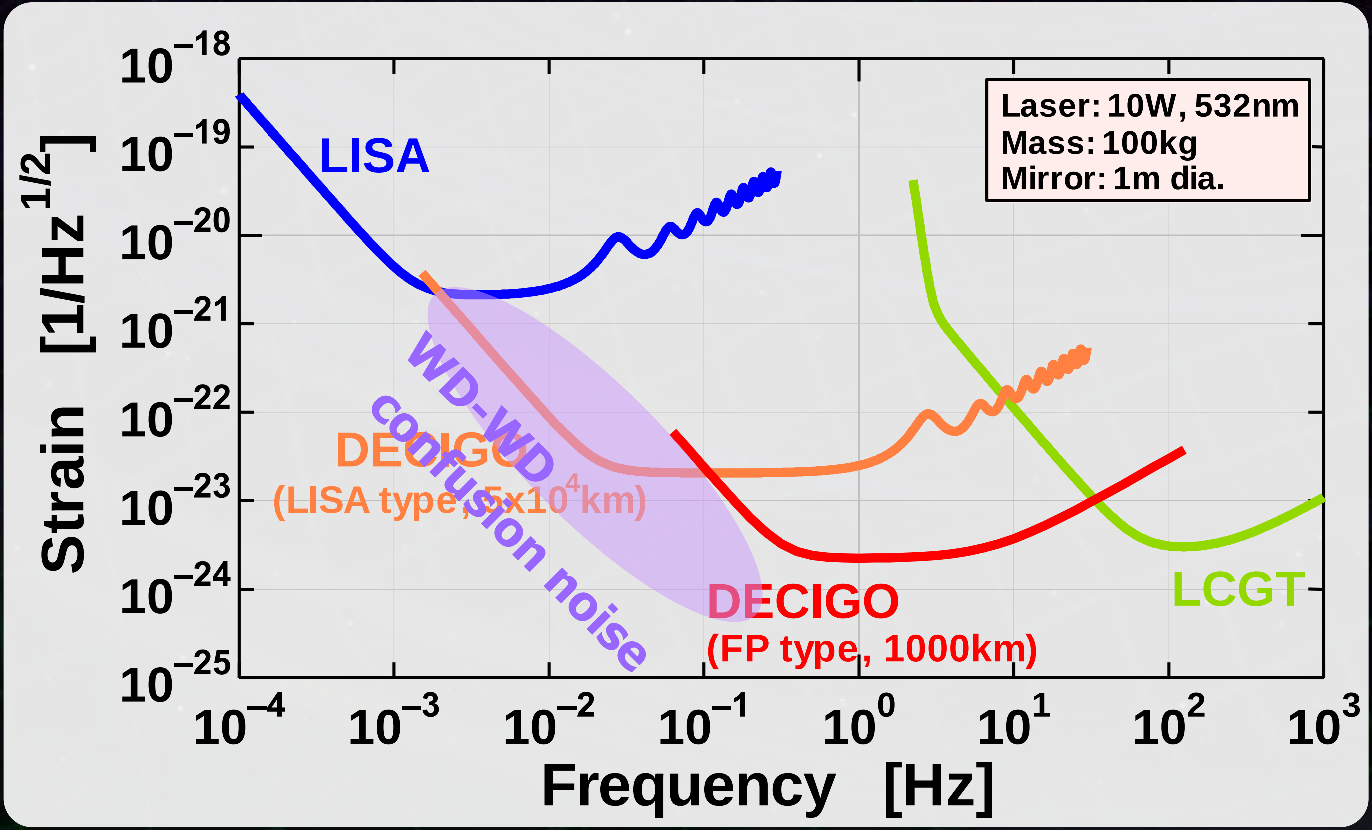


Interferometer Design

Transponder type vs **Direct-reflection type**

Compare : Sensitivity curves and Expected Sciences

⇨ Decisive factor: Binary confusion noise



Cavity and S/C control

Cavity length change

PDH error signal → Mirror position (and Laser frequency)

Relative motion between mirror and S/C

Local sensor → S/C thruster

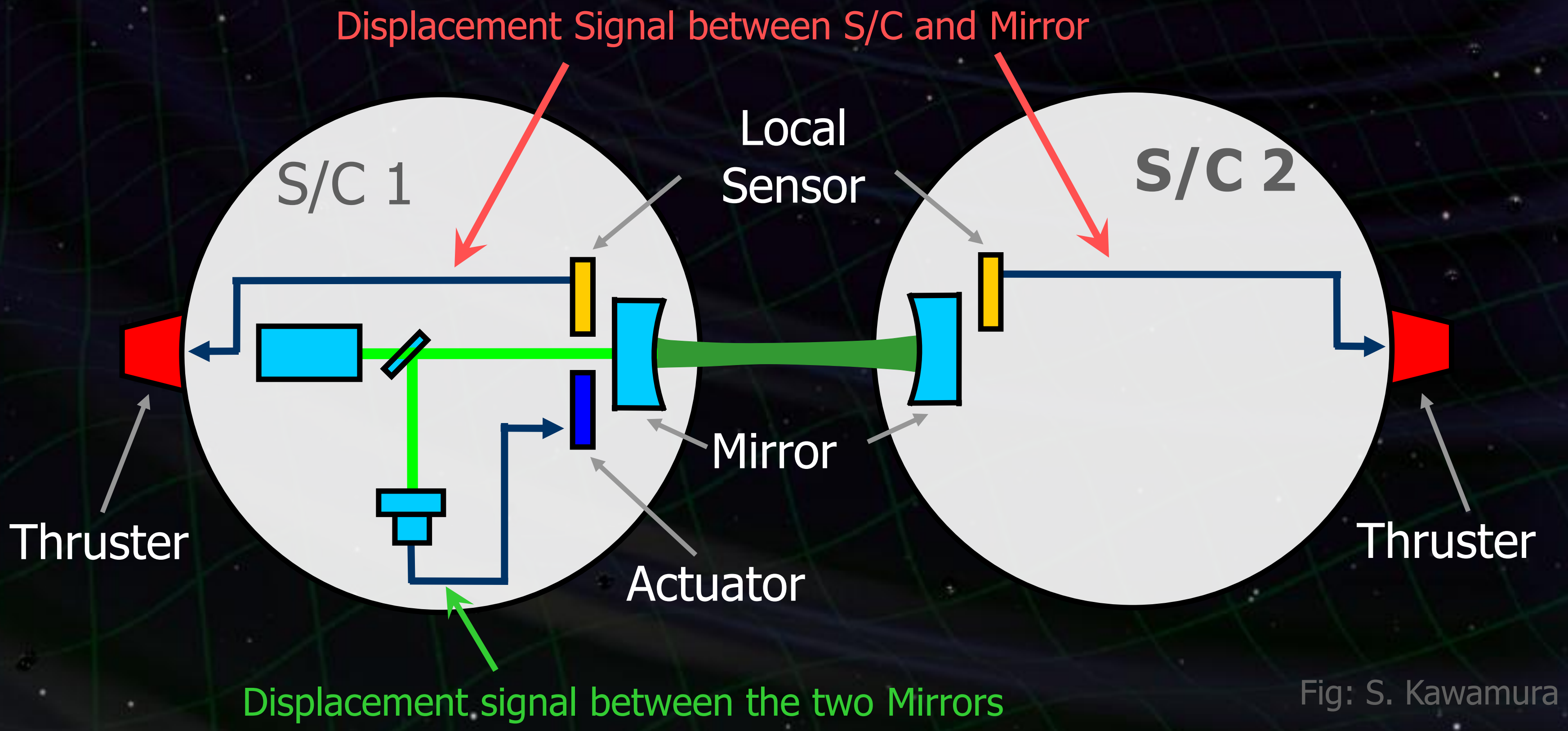


Fig: S. Kawamura

Requirements

Sensor Noise

Shot noise 3×10^{-18} m/Hz$^{1/2}$ (0.1 Hz)

⇨ **x 10 of LCGT in phase noise**

Other noises should be well below the shot noise

Laser freq. noise: 1 Hz/Hz$^{1/2}$ (1Hz)

Stab. Gain 10^5, CMRR 10^5

Acceleration Noise

Force noise 4×10^{-17} N/Hz$^{1/2}$ (0.1 Hz)

⇨ **x 1/50 of LISA**

External force sources

Fluctuation of magnetic field, electric field, gravitational field, temperature, pressure, etc.

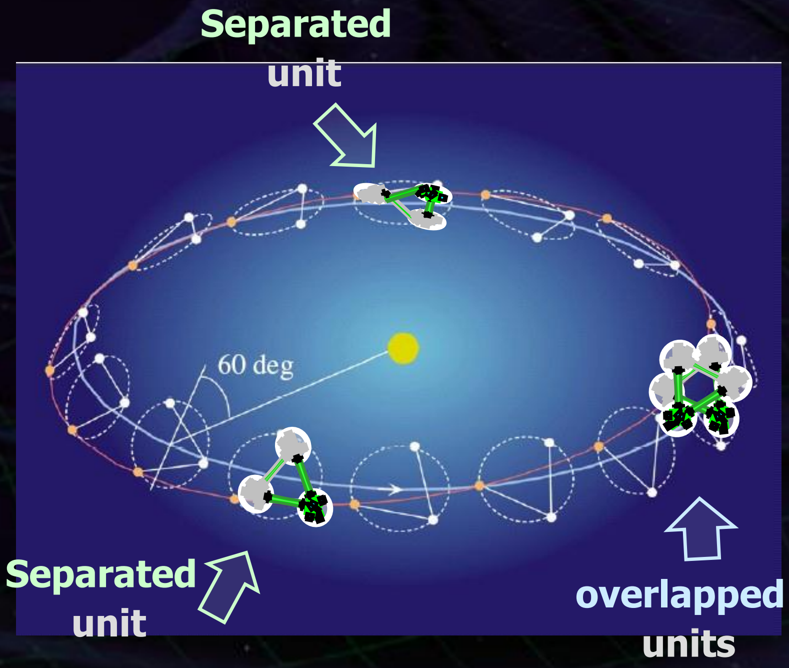
Orbit and Constellation

Candidate of orbit:

Record-disk orbit around the Sun

Relative acc. 4×10^{-12} m/s^2

(Mirror force ~10^{-9} N)



Constellation

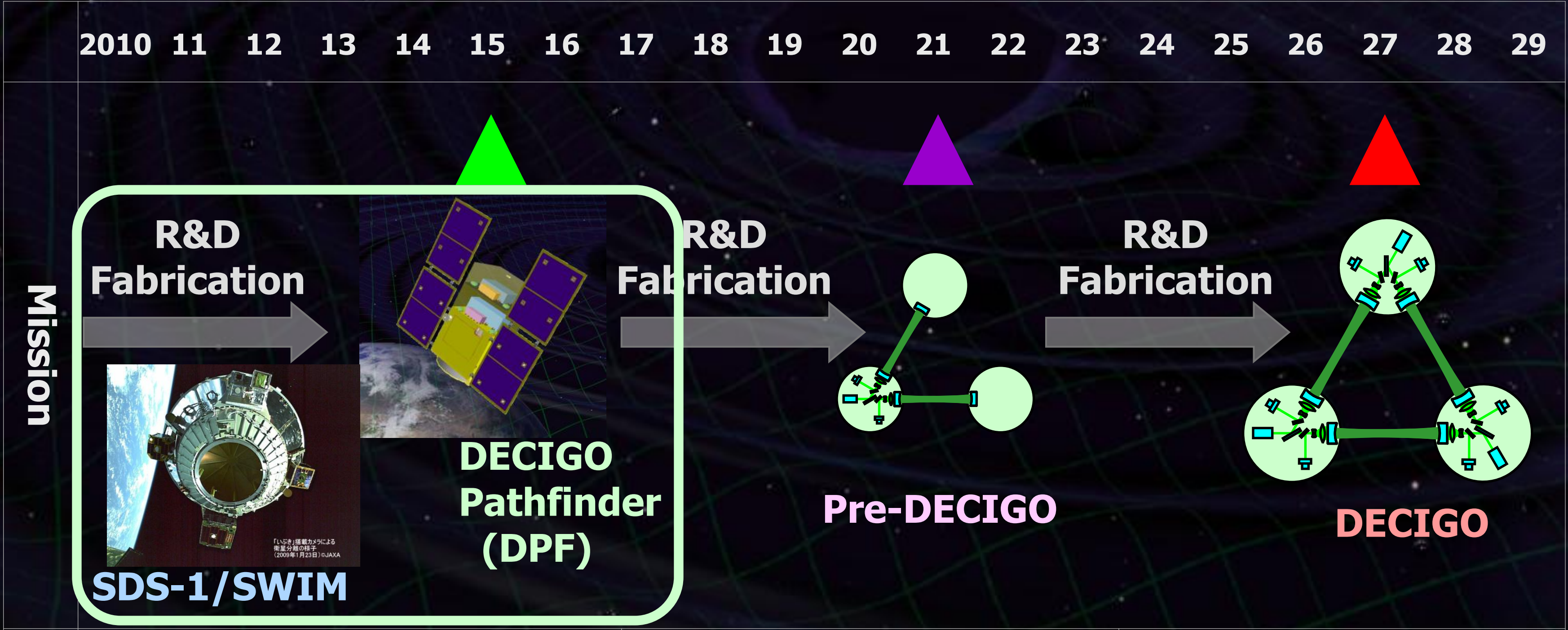
4 interferometer units

2 overlapped units → Cross correlation
2 separated units → Angular resolution

DECIGO Pathfinder

Roadmap

Figure: S.Kawamura



Objective	Space test of key tech. GW observation	Detect GW with min. spec FP between S/C	GW astronomy
Design	Single small satellite Short FP interferometer	3 S/C 1 interferometer unit	3 S/C x 3-4 units

DECIGO-PF

DECIGO Pathfinder (DPF)

First milestone mission for DECIGO

Shrink arm cavity

DECIGO 1000km → DPF 30cm

Single satellite

(Payload ~1m^3 , 350kg)

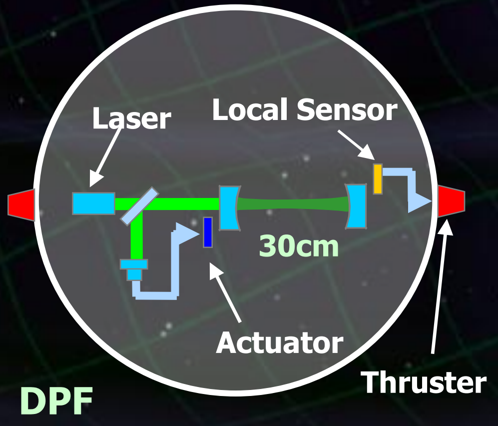
Low-earth orbit

(Altitude 500km, sun synchronous)

30cm FP cavity with 2 test masses

Stabilized laser source

Drag-free control



DPF satellite

DPF Payload

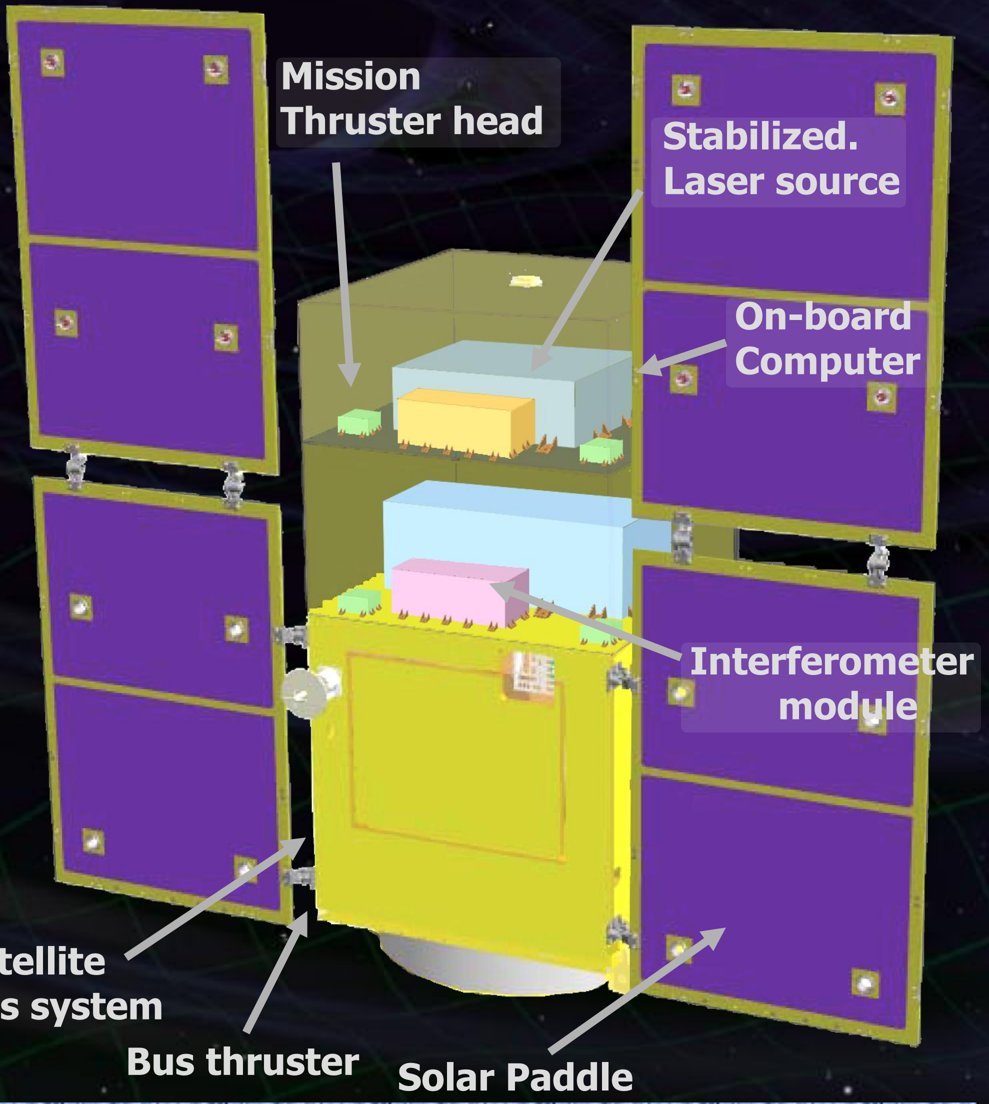
Size :	950mm cube
Weight :	150kg
Power :	130W
Data Rate:	800kbps
Mission thruster x12	

Power Supply
SpW Comm.

Satellite Bus

('Standard bus' system)

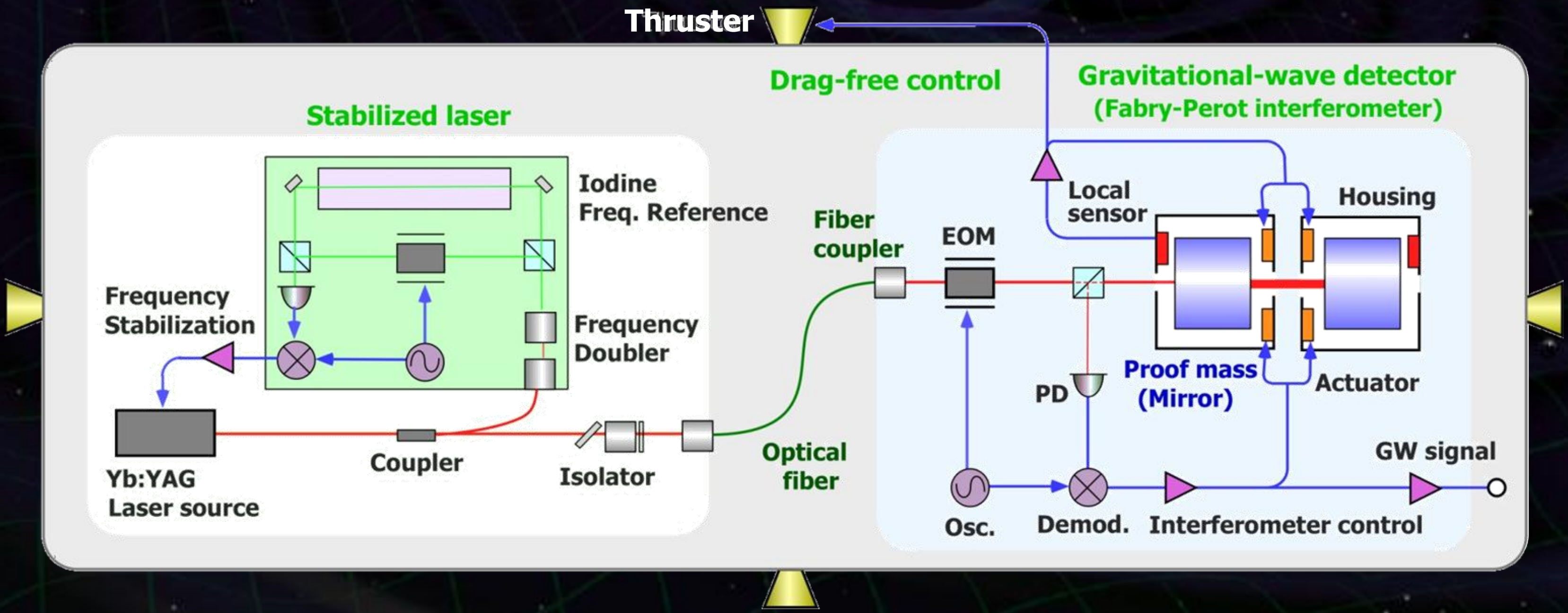
Size :	950x950x1100mm
Weight :	200kg
SAP :	960W
Battery:	50AH
Downlink :	2Mpbs
DR:	1GByte
3N Thrusters x 4	



DPF mission payload

Mission weight : ~150kg
Mission space : ~95 x 95 x 90 cm

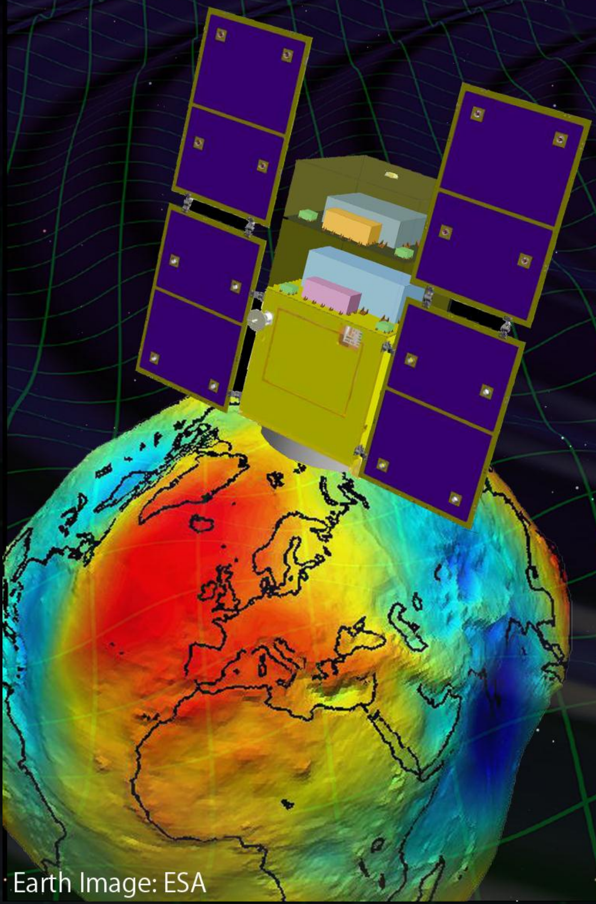
Drag-free control
Local sensor signal
→ Feedback to thrusters



Laser source
Yb:YAG laser (1030nm)
Power : 25mW
Freq. stab. by Iodine abs. line

Fabry-Perot interferometer
Finesse : 100
Length : 30cm
Test mass : ~a few kg
Signal extraction by **PDH**

Targets of DPF



Earth Image: ESA

Scientific observations

Gravitational Waves form BH mergers

→ BH formation mechanism

Gravity of the Earth

→ Geophysics, Earth environment

Science technology

Space demonstration for DECIGO

→ Most tech. with single satellite
(IFO, Laser, Drag-free)

Precision measurement in orbit

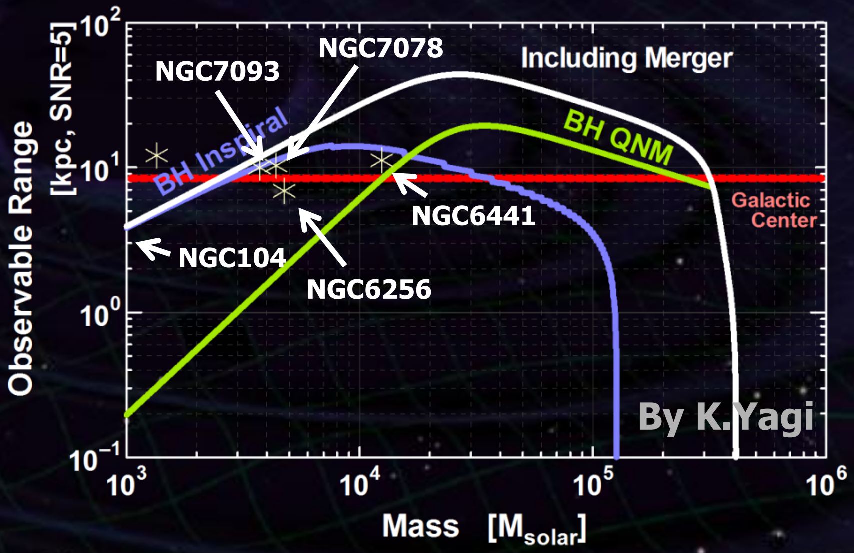
→ IFO measurement
under stable zero-gravity

DPF Science

Astronomical observation

GW from merger of IMBHs
→ Formation mechanism
of supermassive BHs

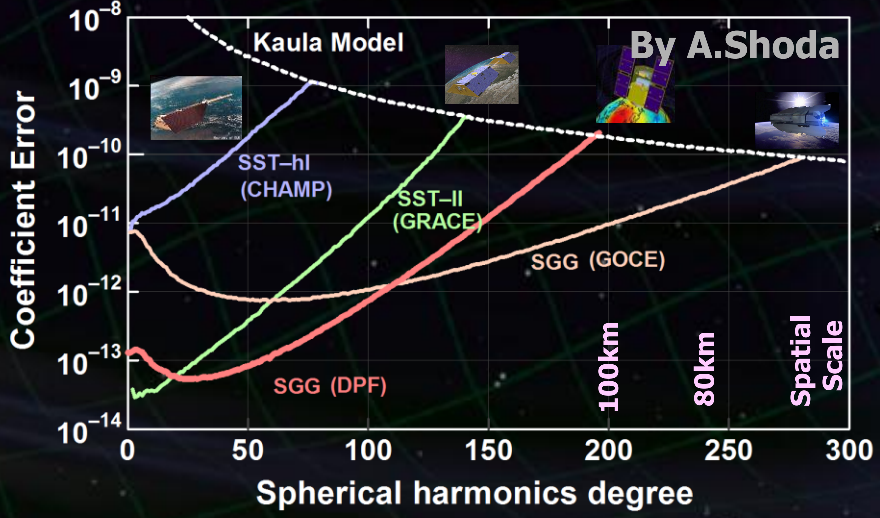
~30 GCs within DPF range



Observation of the earth

Gravitational potential
→ Shape of the earth
Environment monitor

**Comparable sensitivity
with other missions**



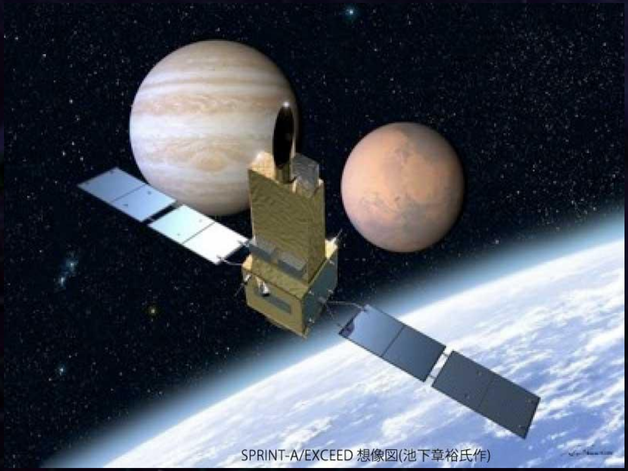
DPF mission status

DPF : One of the candidate of JAXA's small satellite series

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

1st mission (2012): SPRINT-A/EXCEED
2nd mission (~2014/15) : SPRINT-B/ERG
DPF survived until final two
3rd mission (~2016/17) : TBD
Call for proposal : 2012

DPF is one of the strongest candidates of the 3rd mission



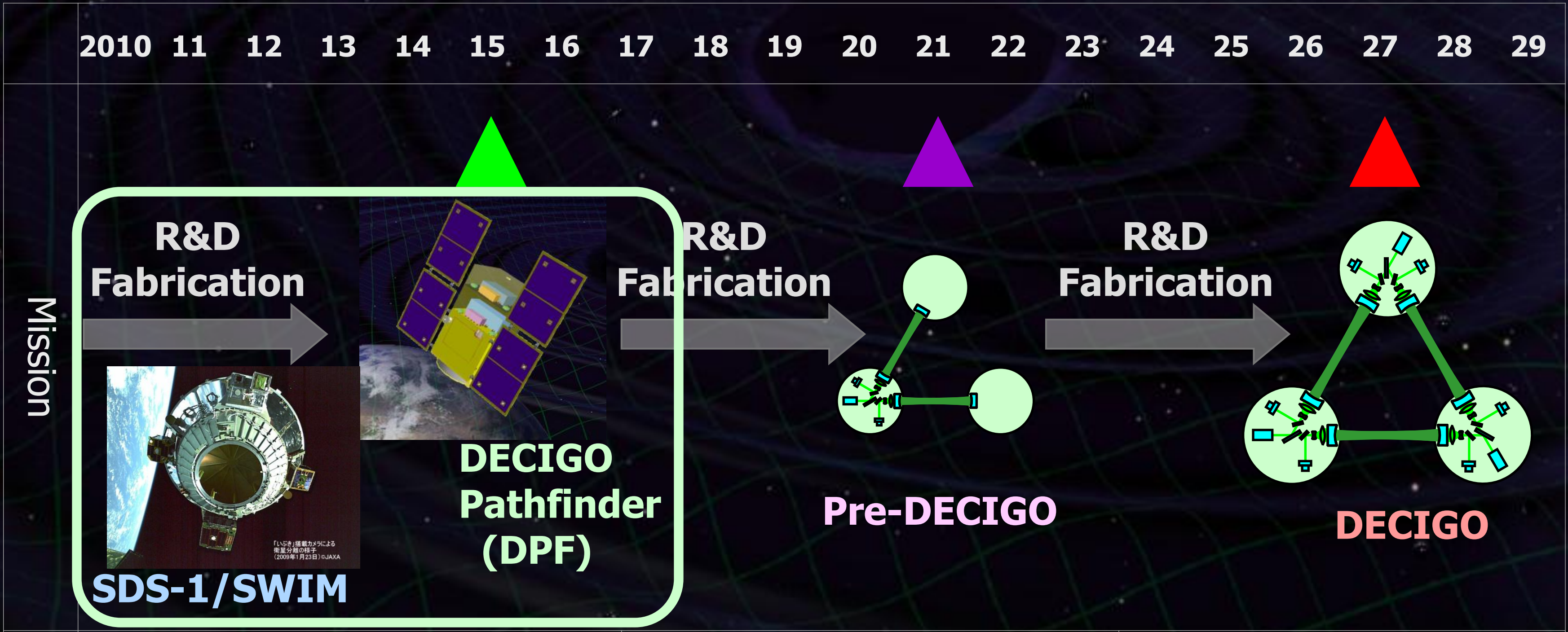
SPRINT-A /EXCEED
UV telescope mission

Next-generation
Solid rocket booster (M-V FO)
Fig. by JAXA

SWIM

Roadmap

Figure: S.Kawamura



Objective	Space test of key tech. GW observation	Detect GW with min. spec FP between S/C	GW astronomy
Design	Single small satellite Short FP interferometer	3 S/C 1 interferometer unit	3 S/C x 3-4 units

SWIM launch and operation

Tiny GW detector module

Launched in Jan. 23, 2009

⇨ In-orbit operation

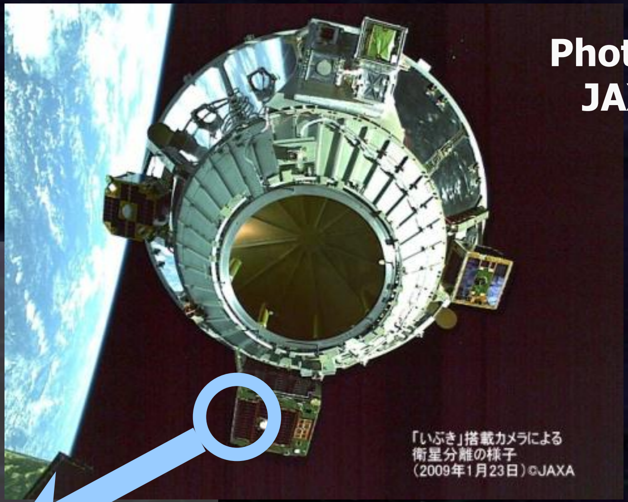
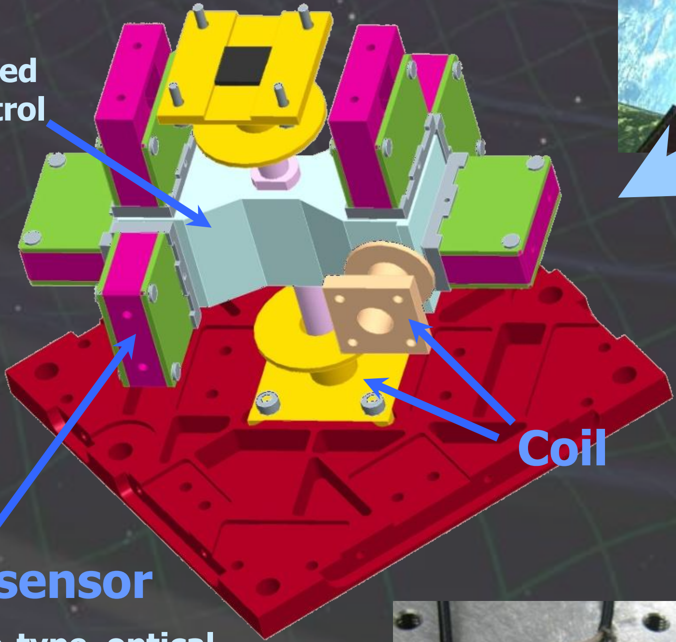


Photo: JAXA

TAM: Torsion Antenna Module with free-falling test mass
(Size : 80mm cube, Weight : ~500g)

Test mass

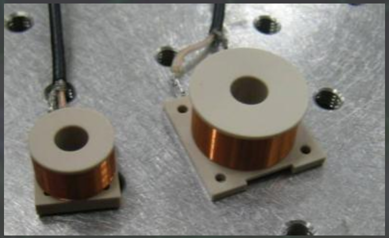
~47g Aluminum, Surface polished
Small magnets for position control

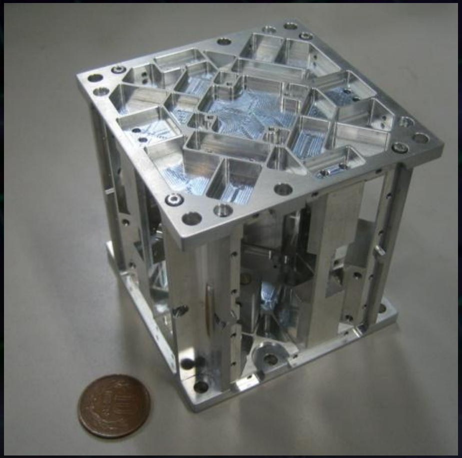


Coil

Photo sensor

Reflective-type optical displacement sensor
Separation to mass ~1mm
Sensitivity ~ 10^{-9} m/Hz$^{1/2}$
6 PSs to monitor mass motion



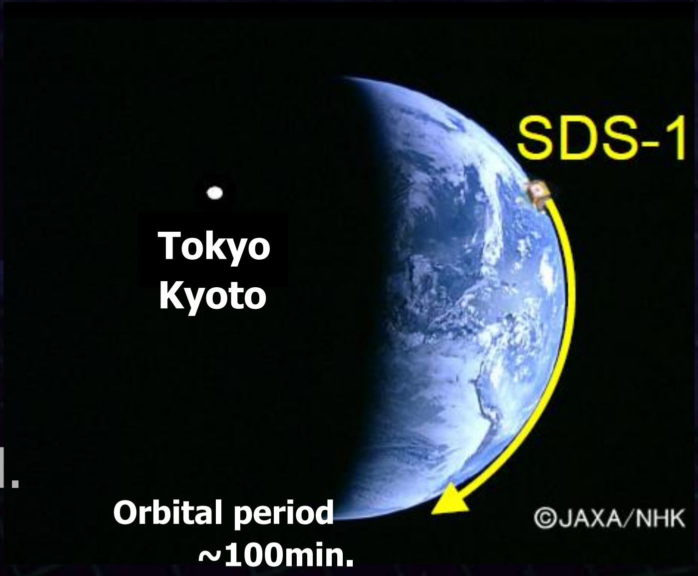


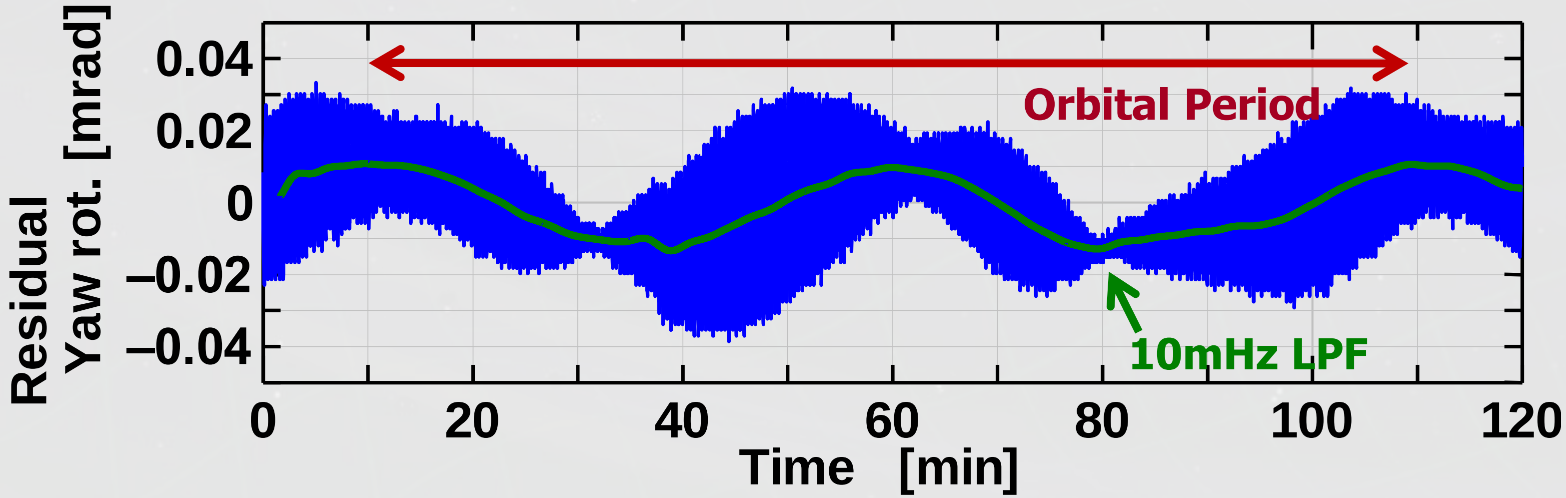
SWIM observation

Observation by SWIM

Jun 17, 2010 ~120 min. operation
July 15, 2010 ~240 min. operation

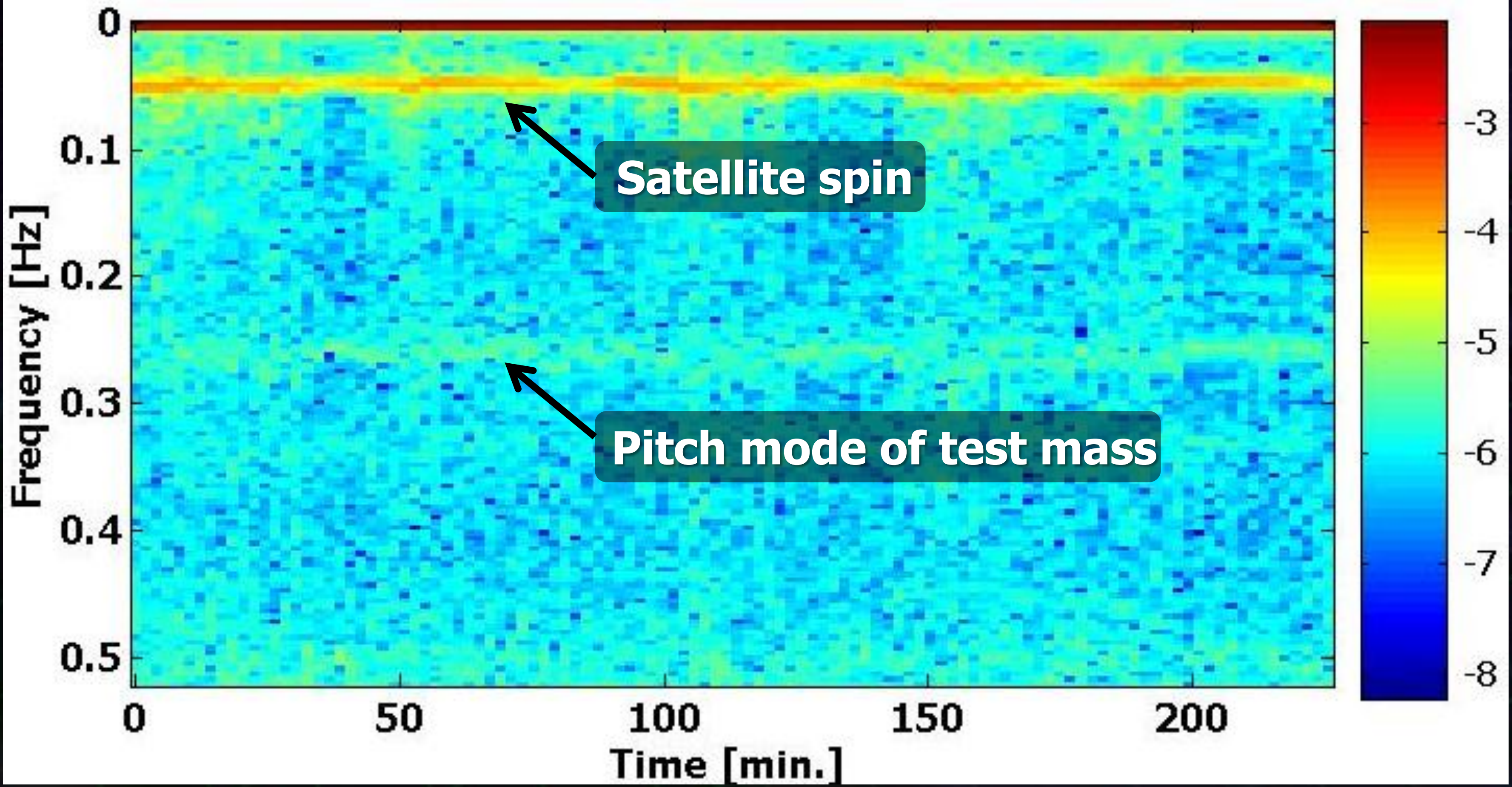
Ground-based detectors were operated at the same period.





SWIM observation

SWIM observation (July 15, 2010 ~240 min.)



Satellite spin

Pitch mode of test mass

Summary

Summary

LCGT : Project started

- Costs have been partially funded
- Form global network as one of the 2nd generation detectors

⇨ Aim to detect GW, and to open new astronomy

- LCGT will demonstrate 3rd generation detector techniques: cryogenics and underground

Design and R&D

- Detailed design underway : internal and external reviews
- TAMA and CLIO experiences

  TAMA : GW observatory, TAMA-SAS

  CLIO : Cryogenic interferometer, underground site
- Prototype developments : SAS, Digital system, Cryostat

Summary

DECIGO : Fruitful Sciences

Very beginning of the Universe

Dark energy

Galaxy formation

DECIGO Pathfinder

Important milestone for DECIGO

Observation of GWs and Earth's gravity

Strong candidate of JAXA's satellite series

SWIM – Operation in orbit

first precursor to space!

LCGT and DECIGO

LCGT (~2017)

Terrestrial Detector

→ High frequency events

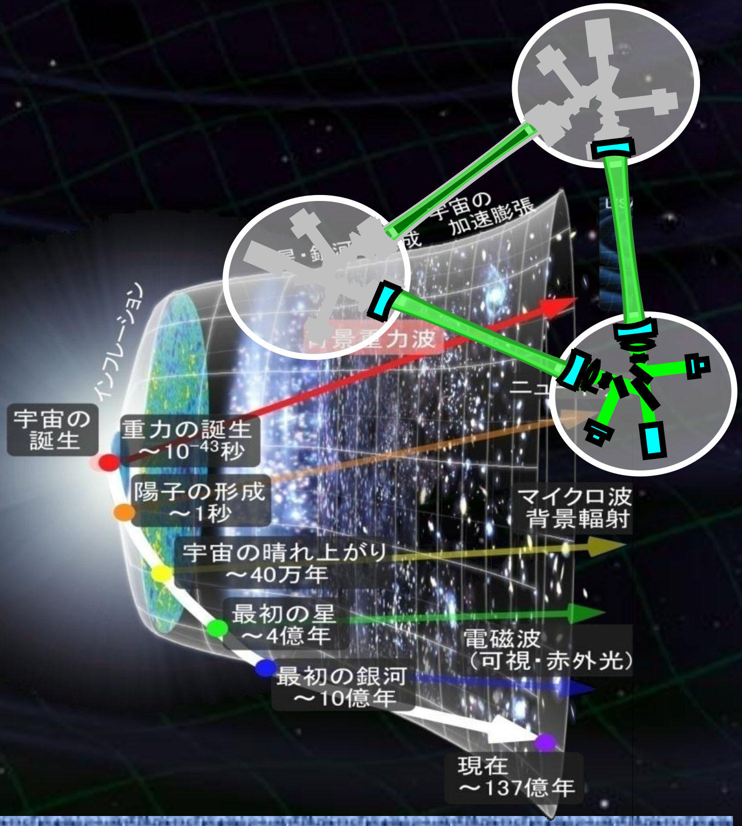
Target: GW detection

DECIGO (~2027)

Space observatory

→ Low frequency sources

Target: GW astronomy



Roadmap of GW detectors

Ground based detectors

Improved sensitivities (10-1kHz)

LIGO

Enhanced LIGO

Advanced LIGO

TAMA CLIO

LCGT

Virgo/ GEO

Advanced Virgo

GEO-HF

ET

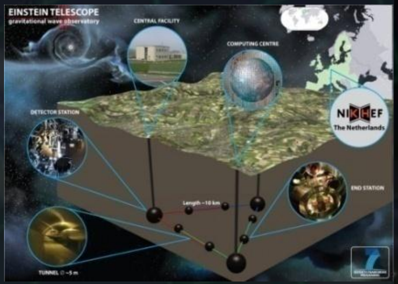
2010

2015

2020

2025

Detection Rate
~10 event/yr



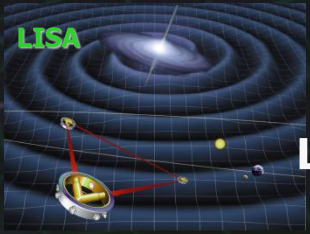
Space-borne detectors

Low-frequency sources
(0.1mHz – 1Hz)

DECIGO

LPF

DPF



LISA

Guaranteed source
0.1mHz-10mHz

Pre-DECIGO

DECIGO

BBO

Cosmological GWs
around 0.1Hz

End