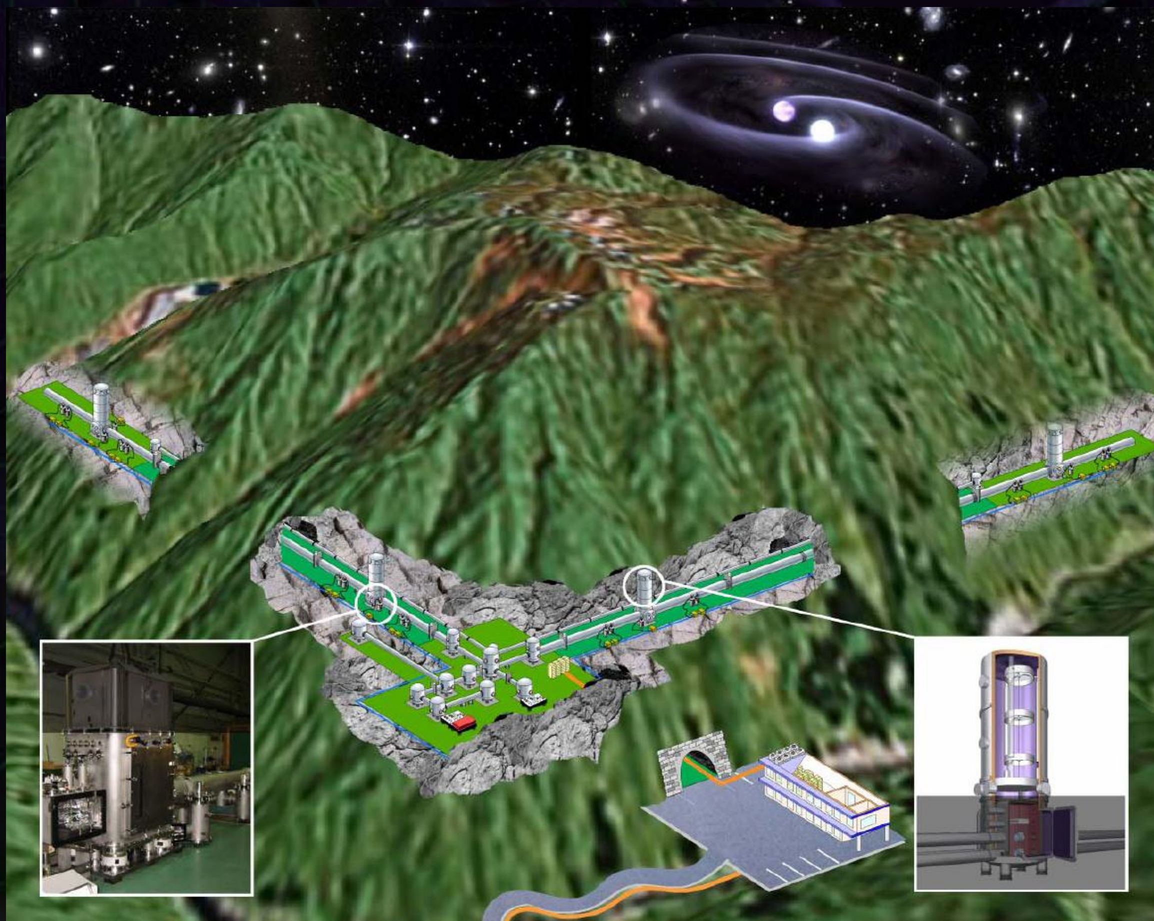
Gravitational Wave Experiment



Masaki Ando
(Department of Physics,
Kyoto University)

1. Introduction

2. Ground-based detectors

   Overview and design of LCGT

3. Space detectors

   Overview and status of DECIGO

4. Summary

Introduction

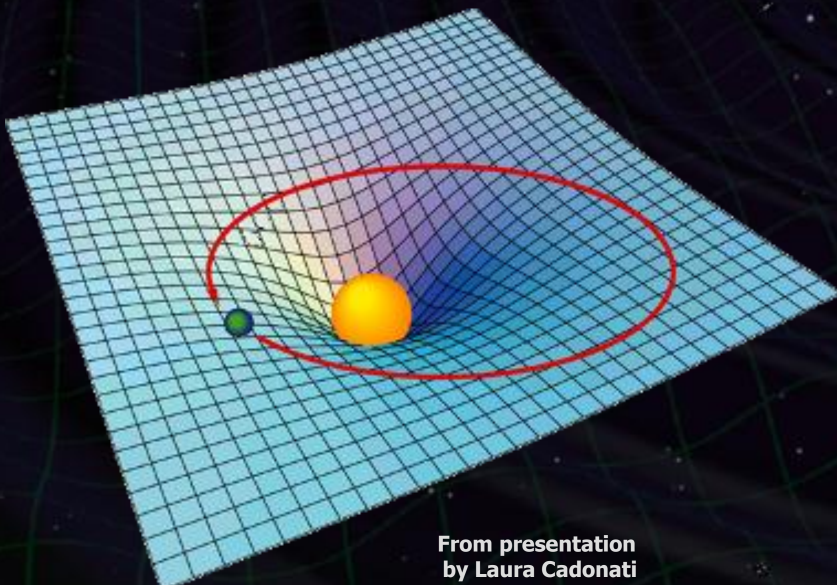
From presentation by B Schutz

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

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

Curvature ($G_{\mu\nu}$)

Mass (Energy momentum) ($T_{\mu\nu}$)

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

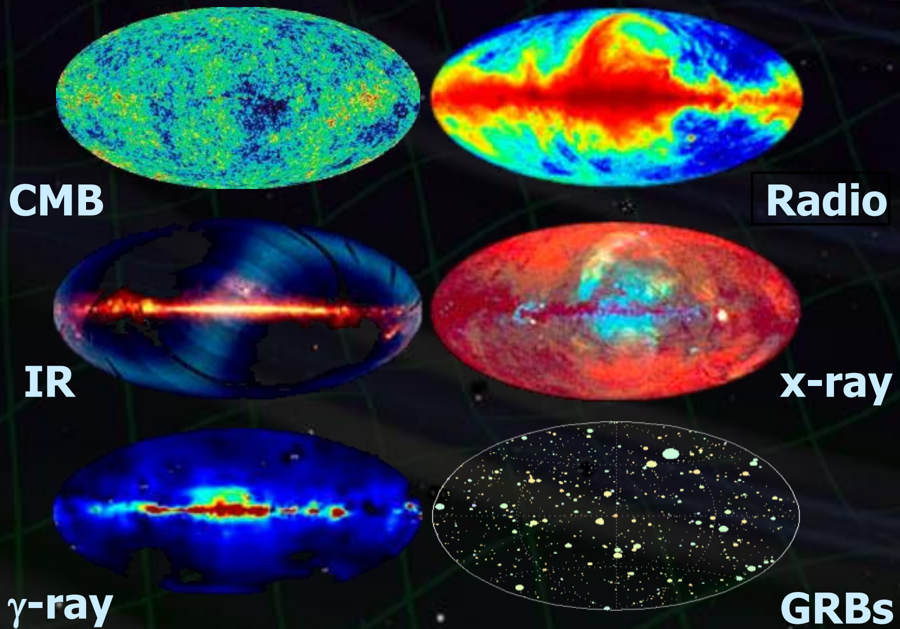
⇒ Gravitational Wave

Gravitational-wave astronomy

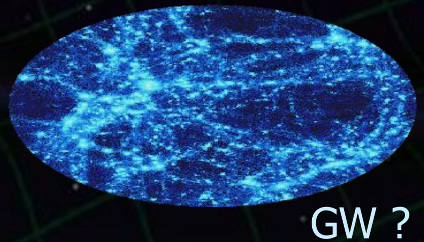
Reveal the universe by Gravitational Waves.

Nature of GWs
- Radiated by accelerated masses
- Strong transmissivity

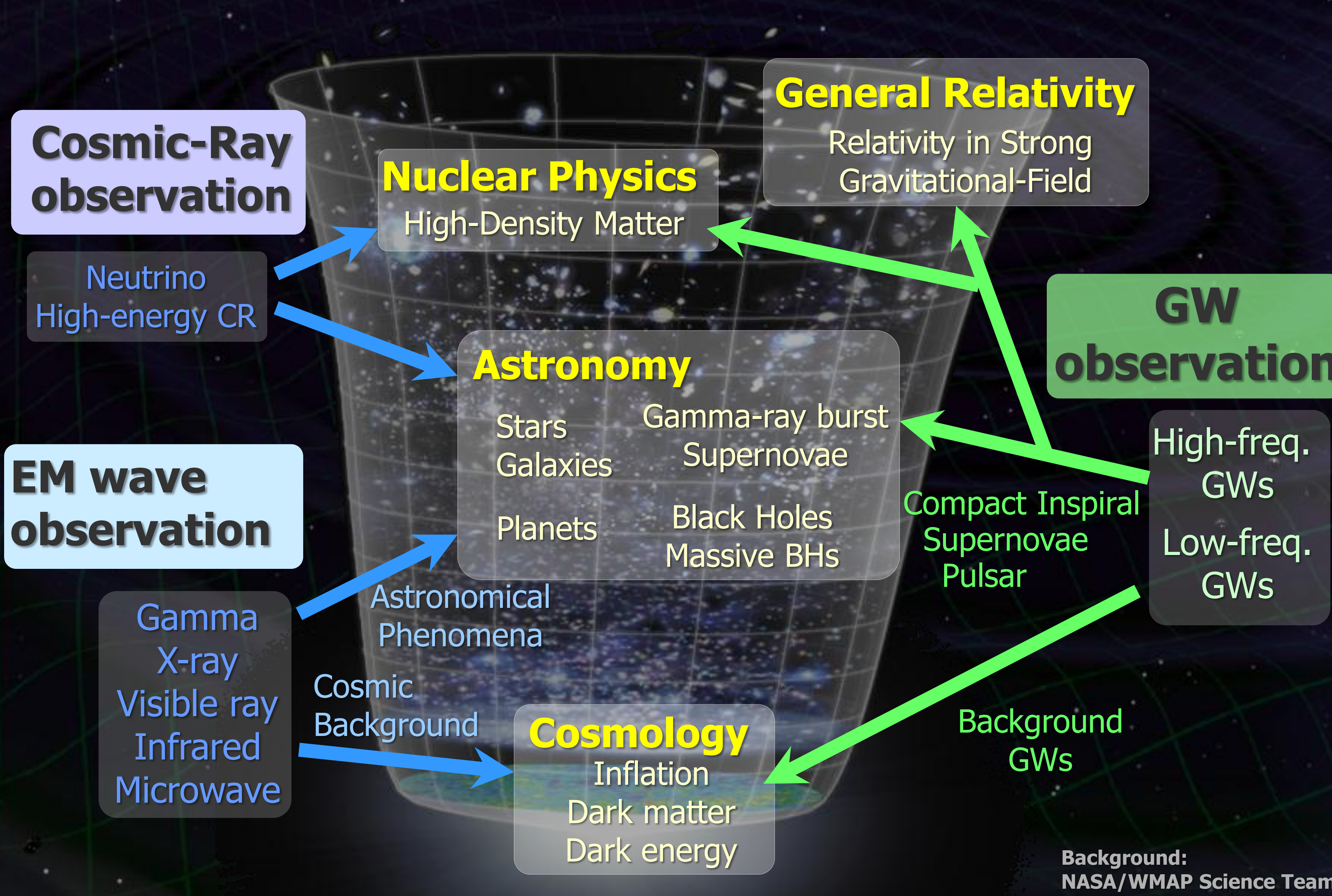
New probe to the universe
- Complementary with EMWs.
- Unique sciences
  - Early universe before CMB era
  - Central part of violent phenomena



+



Observation of the Universe



Background: NASA/WMAP Science Team

High-frequency GW targets

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

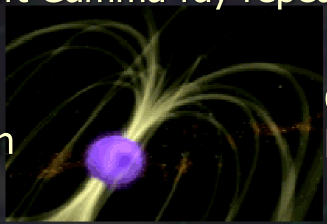
⇨ Compact, High-energy phenomena

Neutron star

Pulsar

Supernova

Soft Gamma-ray repeater



Star Vibration mode

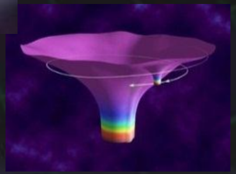
Long Gamma-ray burst

Black hole

Binary inspiral

Short Gamma-ray burst

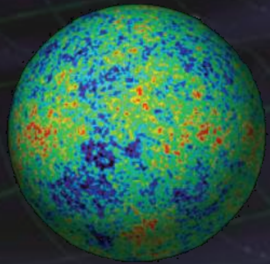
EMRI



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

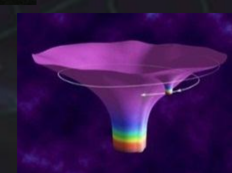
Pulsar

Stationary Orbital / spin motion

Black hole

Merger of Supermassive Black holes

EMRI



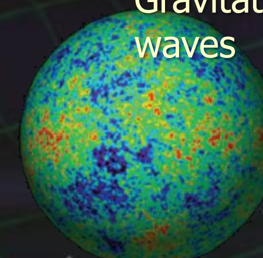
Quasi-normal mode

Early Universe

Superposition of many sources

GW background

Primordial Gravitational waves



EM Waves
Neutrino

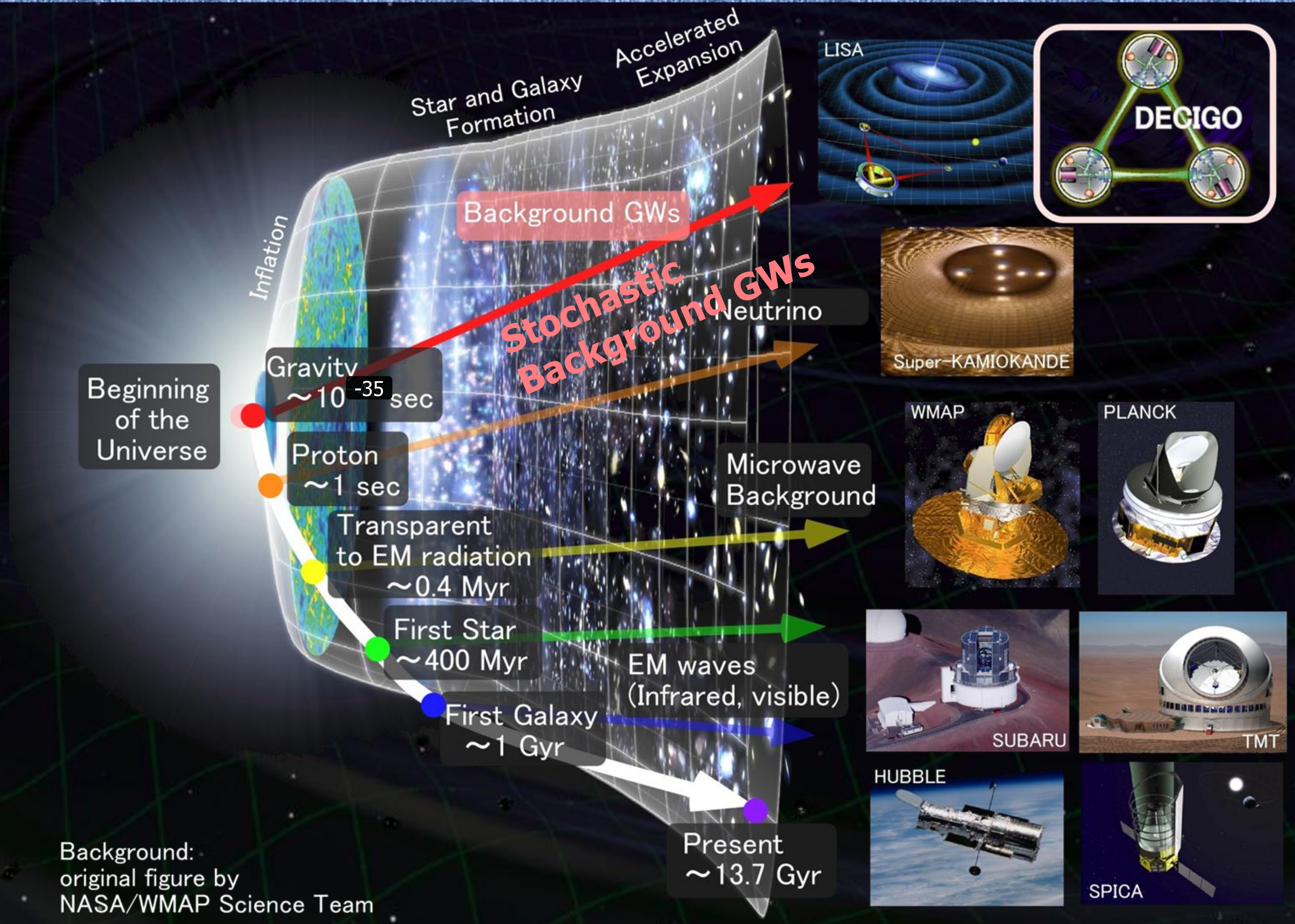
Multi-messenger
Numerical relativity

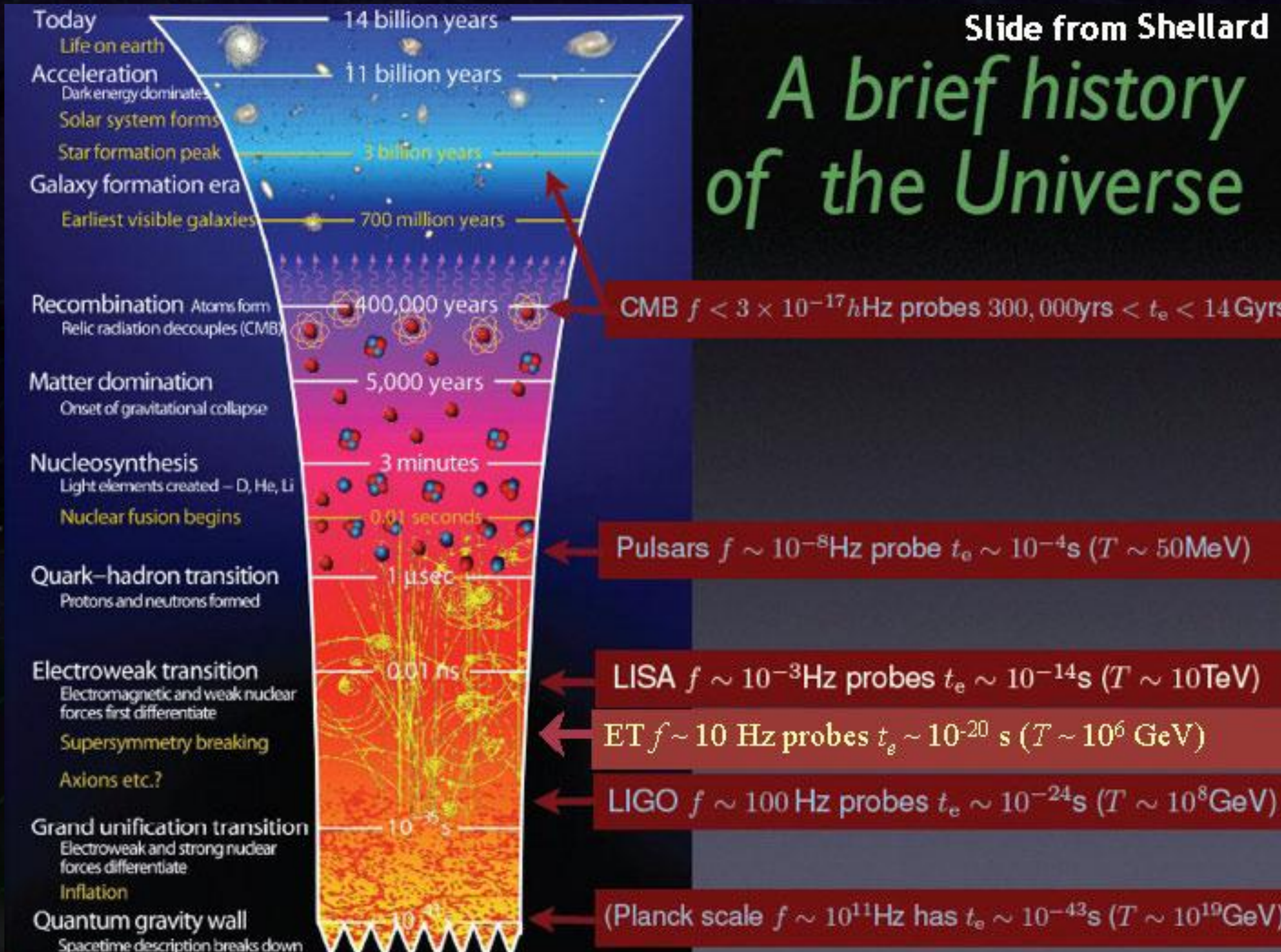
Test of Gravity theories

Formation scenario of Super-massive BHs

Cosmology, Universe
Dark energy, Dark matter

Stochastic Background GWs



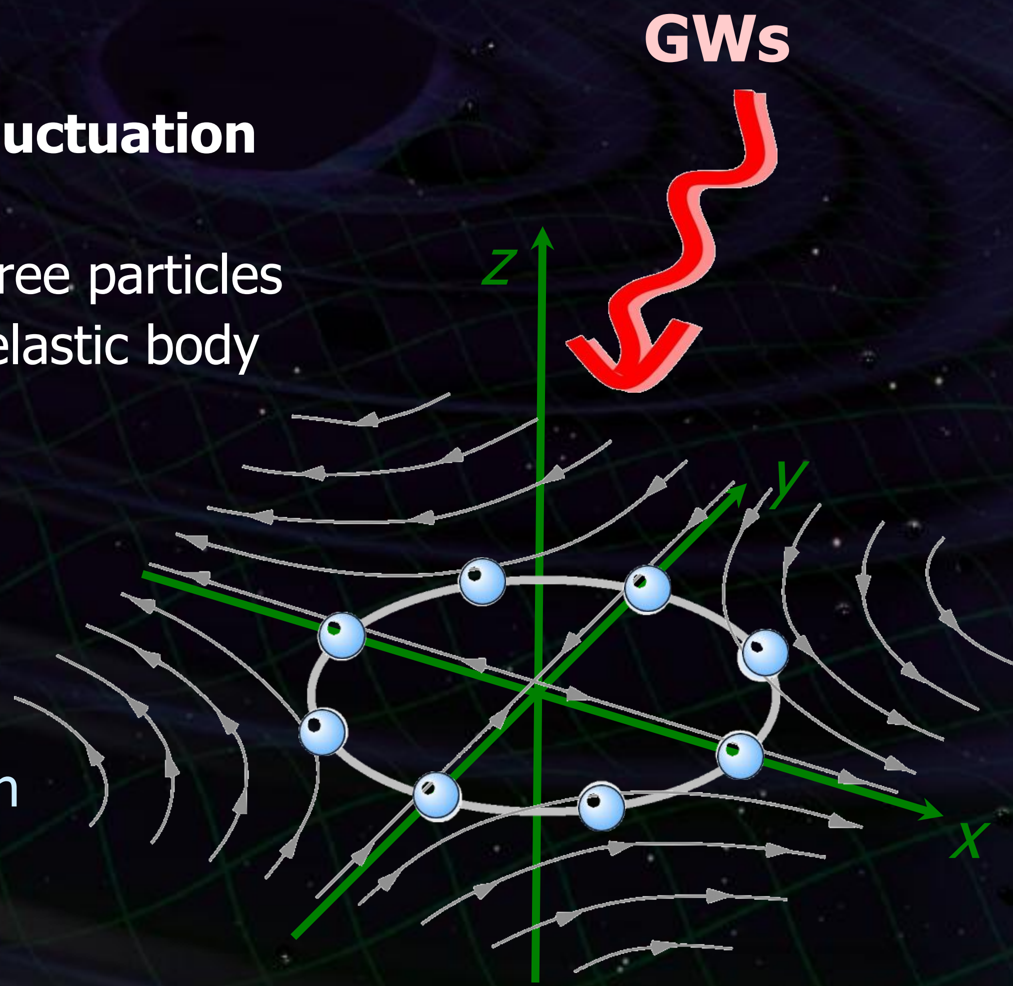

Slide from Shellard
A brief history of the Universe
Today
Life on earth
14 billion years
Acceleration
Dark energy dominates
11 billion years
Solar system forms
Star formation peak
3 billion years
Galaxy formation era
Earliest visible galaxies
700 million years
Recombination Atoms form
Relic radiation decouples (CMB)
400,000 years
CMB $f < 3\times10^{-17}h$Hz probes $300,000$yrs $< t_e < 14$Gyrs
Matter domination
Onset of gravitational collapse
5,000 years
Nucleosynthesis
Light elements created – D, He, Li
3 minutes
Nuclear fusion begins
0.01 seconds
Pulsars $f \sim 10^{-8}$Hz probe $t_e \sim 10^{-4}$s ($T \sim 50$MeV)
Quark–hadron transition
Protons and neutrons formed
1 μsec
Electroweak transition
Electromagnetic and weak nuclear forces first differentiate
0.01 ns
LISA $f \sim 10^{-3}$Hz probes $t_e \sim 10^{-14}$s ($T \sim 10$TeV)
Supersymmetry breaking
ET $f \sim 10$ Hz probes $t_e \sim 10^{-20}$ s ($T \sim 10^6$ GeV)
Axions etc.?
LIGO $f \sim 100$ Hz probes $t_e \sim 10^{-24}$s ($T \sim 10^8$GeV)
Grand unification transition
Electroweak and strong nuclear forces differentiate
Inflation
Quantum gravity wall
Spacetime description breaks down
(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

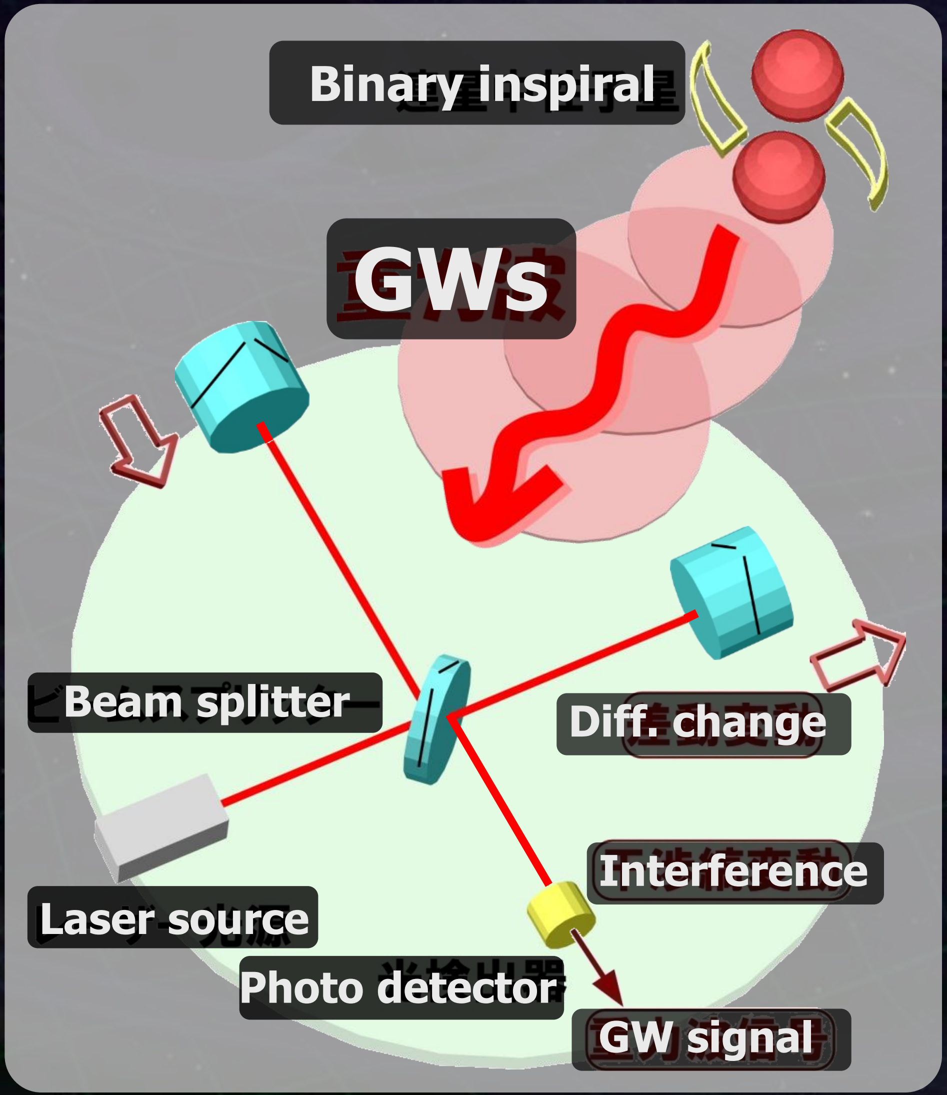
Laser interferometric detector

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

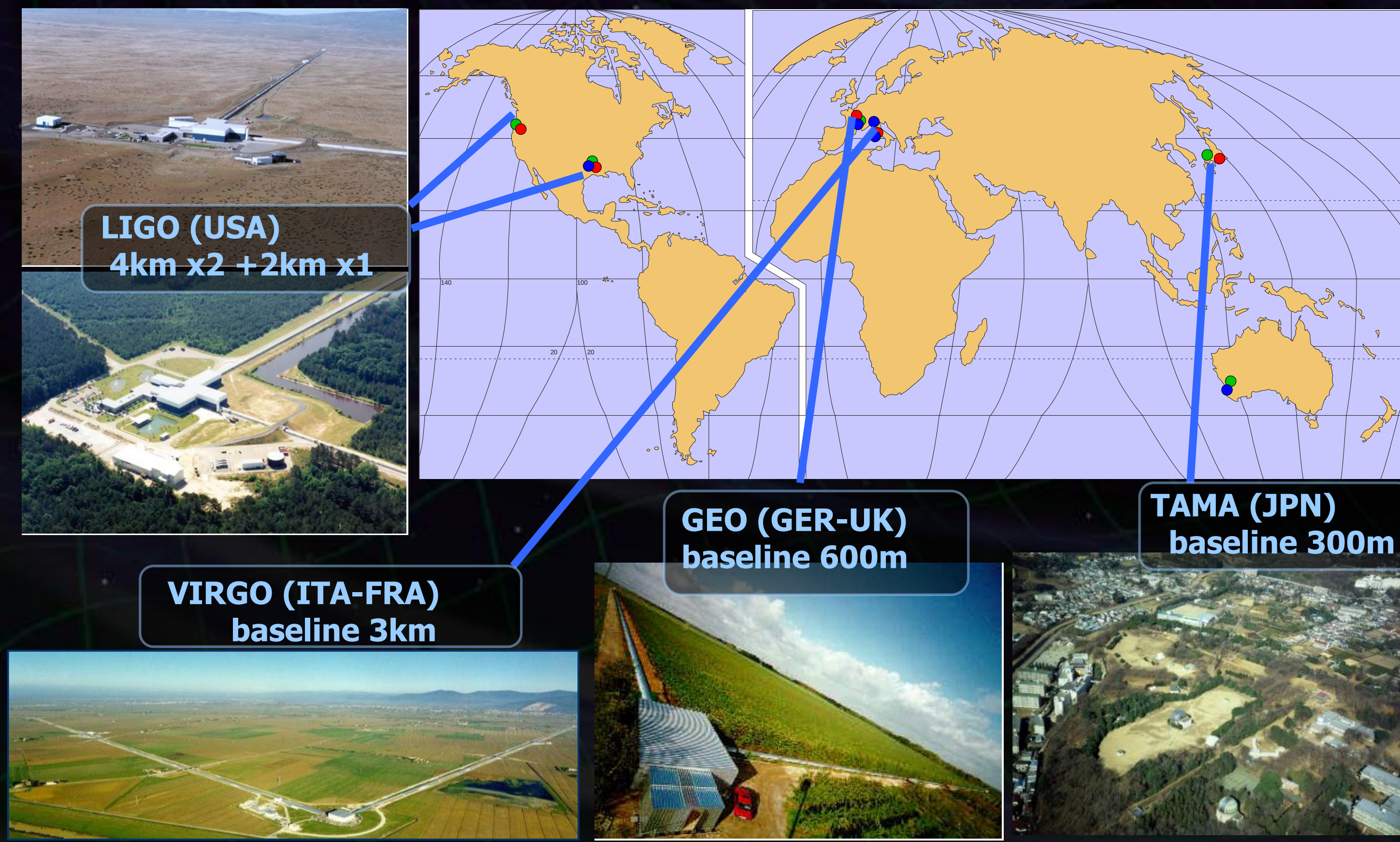


First generation detectors

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

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

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



First generation 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

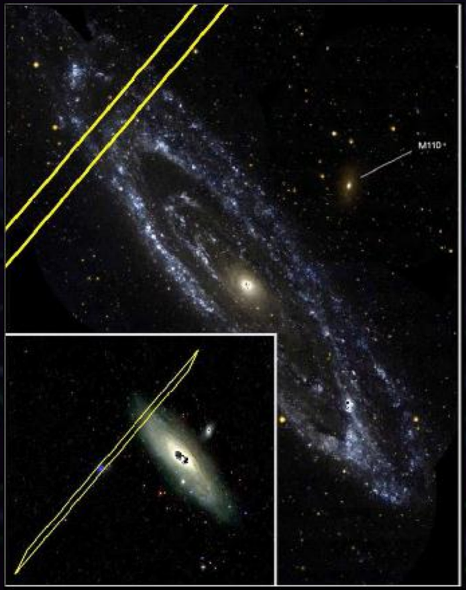
→ Cover our galaxy and nearby galaxies

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

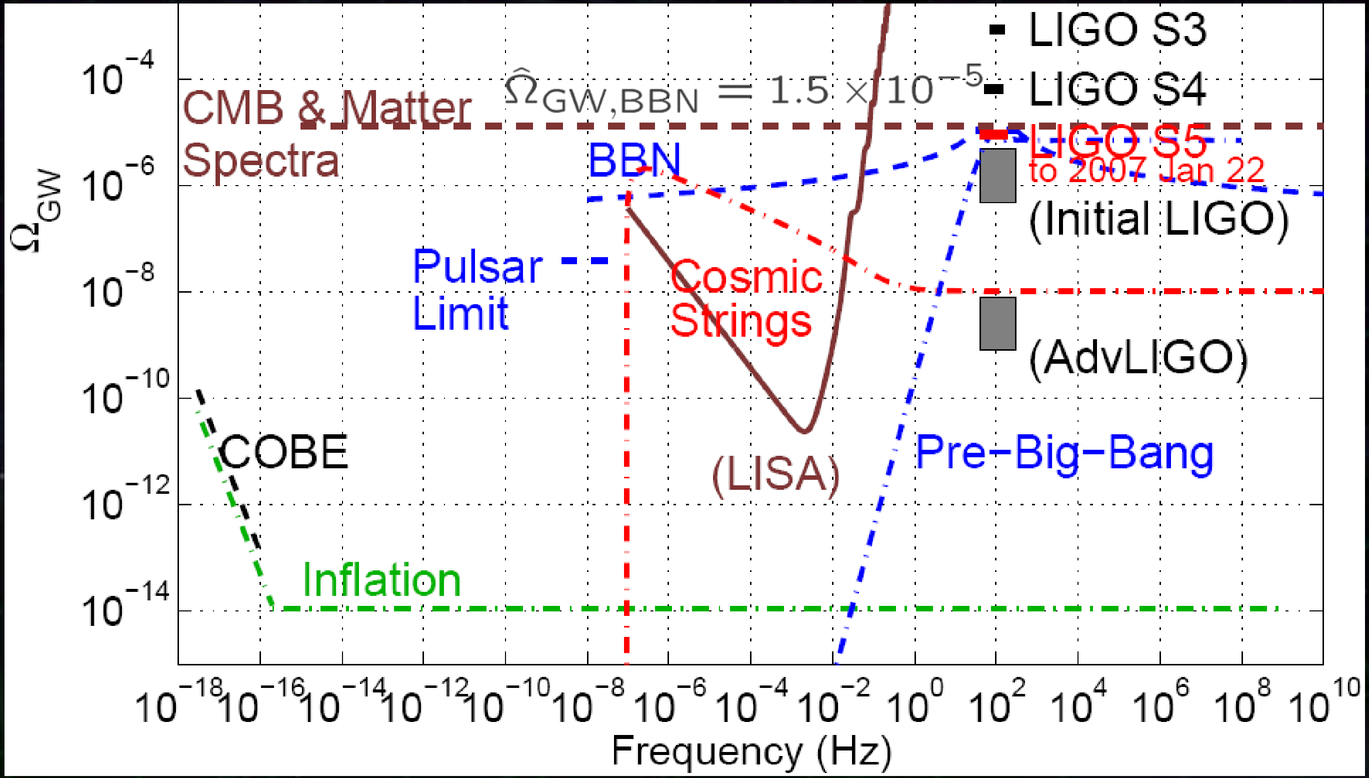
LIGO S5

Use good-quality data around 41.5-177.5Hz

→ Better upper limit for GWB than BBN

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

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



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

Next-generation detectors

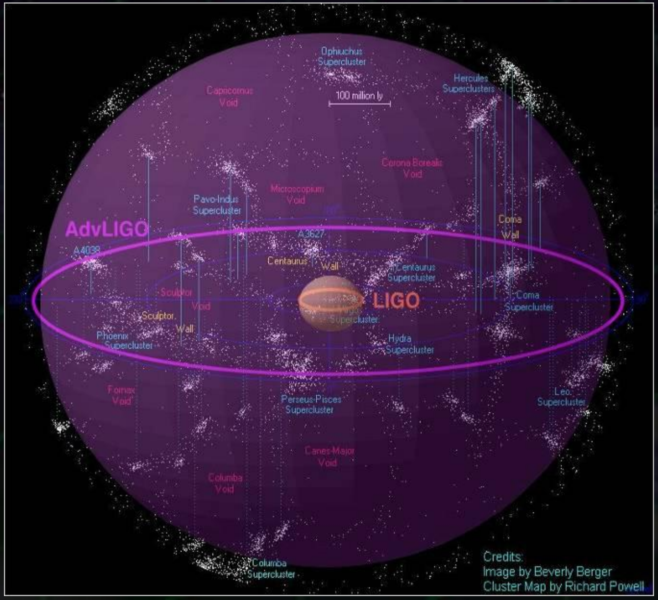
Expanding the Horizon

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

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

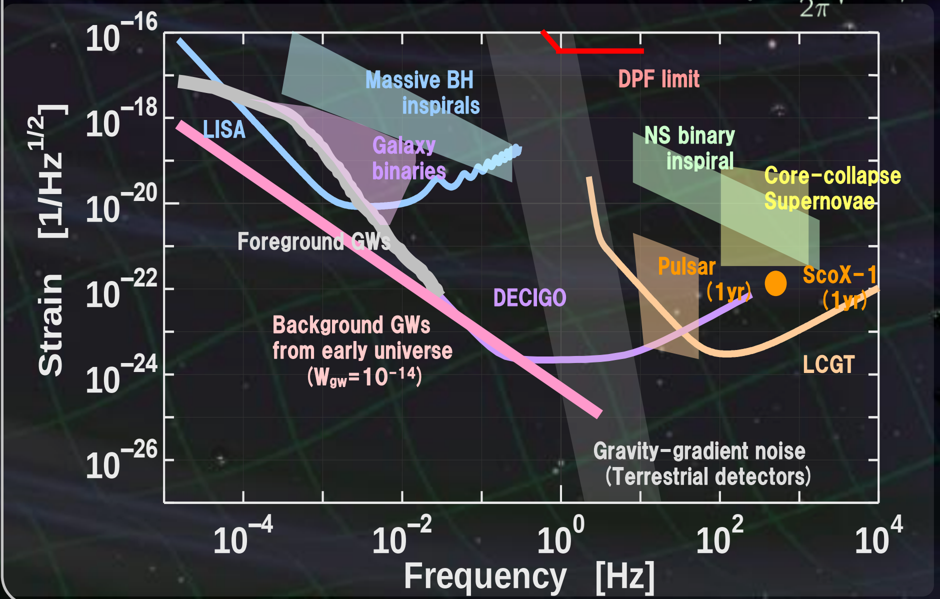
⇨ **Next generation detectors**

Better sensitivity to cover more galaxies



Wider observation band for various sources

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



Improving the sensitivity

2nd-generation detectors --- x10 sensitivity

GW amplitude $\propto$ 1/(distance)

⇩

Sensitivity x10

→ GW event rate x10^3

Expected science

1-year obs. by 1st-gen. detector

~ 9-hour obs. by 2nd-gen. detector

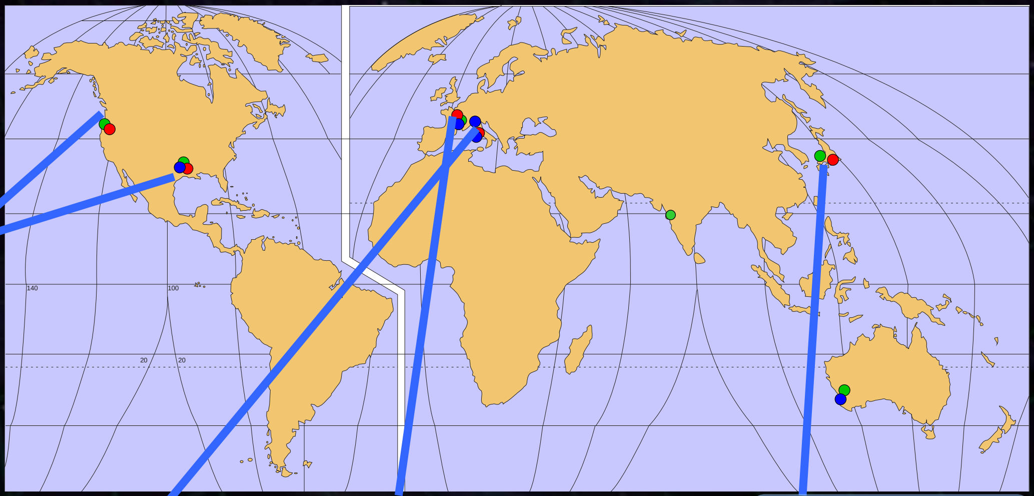
Event rate > 1 event/year in 2nd-generation detectors

Second generation detectors

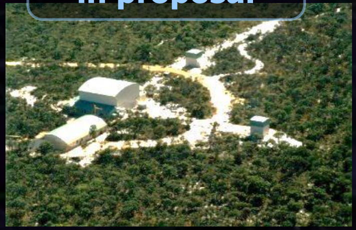
2nd-generation detector network (~5 years from now)

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


aLIGO (USA)
4km x 2 (or3)



LIGO-Austreria
in proposal



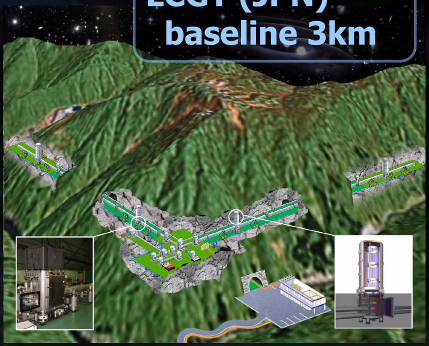
LIGO-India
in proposal

indigo

Adv.VIRGO (ITA-FRA)
baseline 3km

GEO-HF (GER-UK)
baseline 600m

LCGT (JPN)
baseline 3km



2nd generation detectors

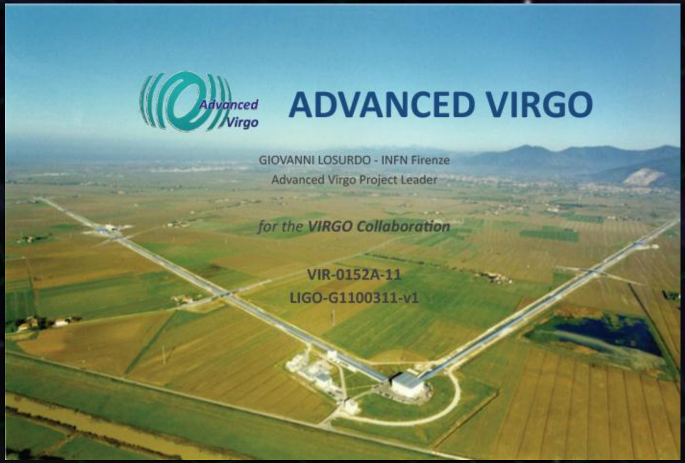
David Shoemaker, LV meeting March 2011

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

Under installation procedure

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

Under installation procedure



G. Losurdo LV meeting March 2011

2nd generation detectors

Hartmut Grote, LV meeting March 2011

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

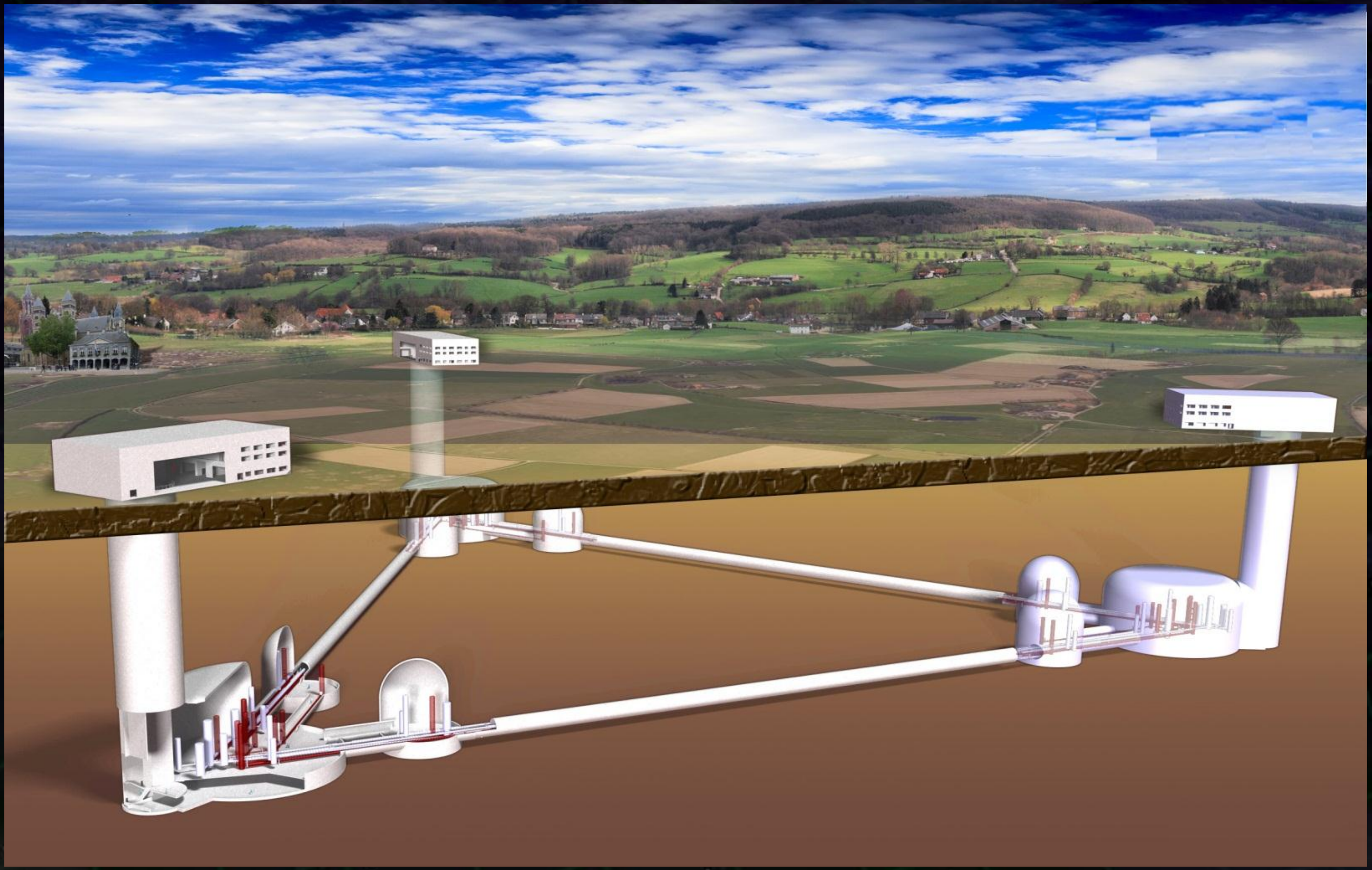
AstroWatch and upgrade

- 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.

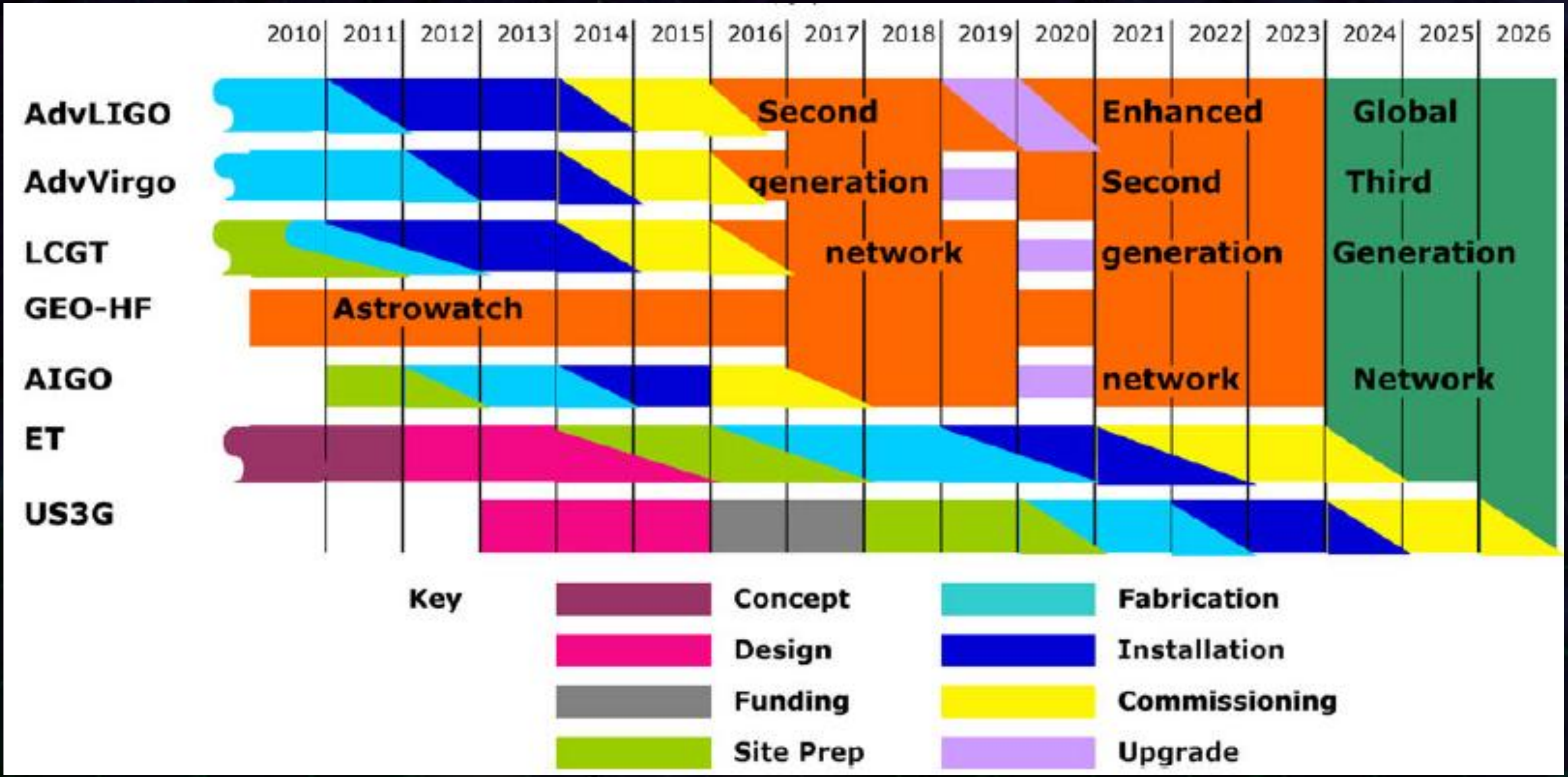
Third generation detectors

3rd-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/

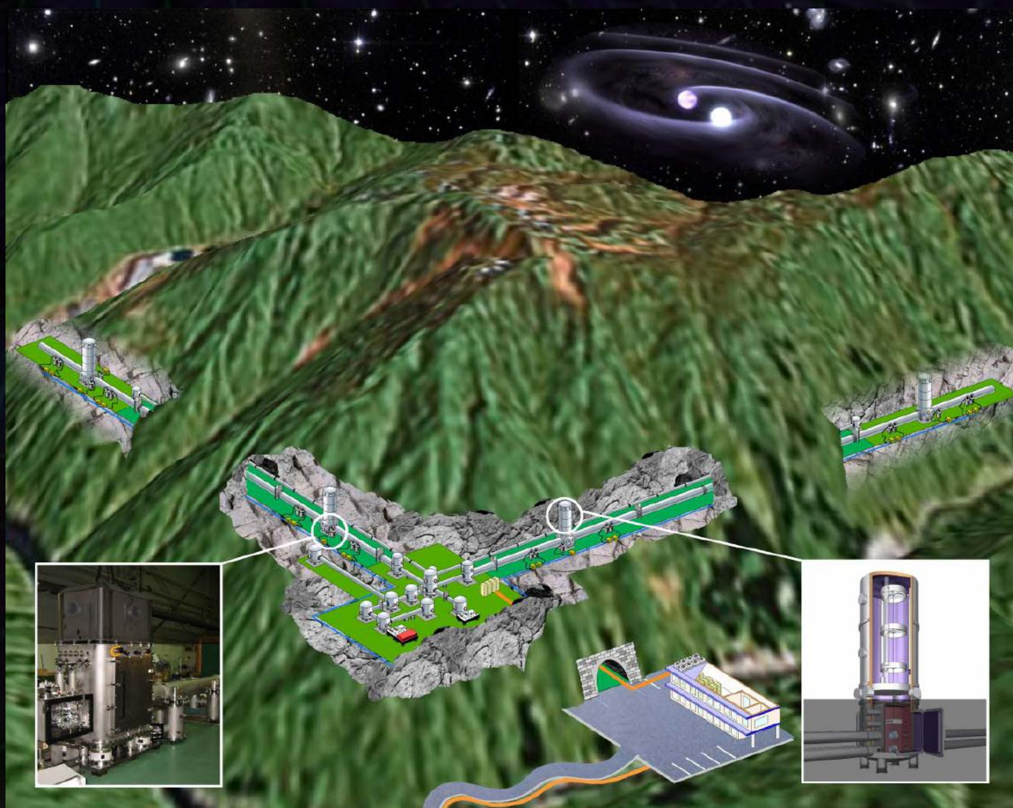
LCGT

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).

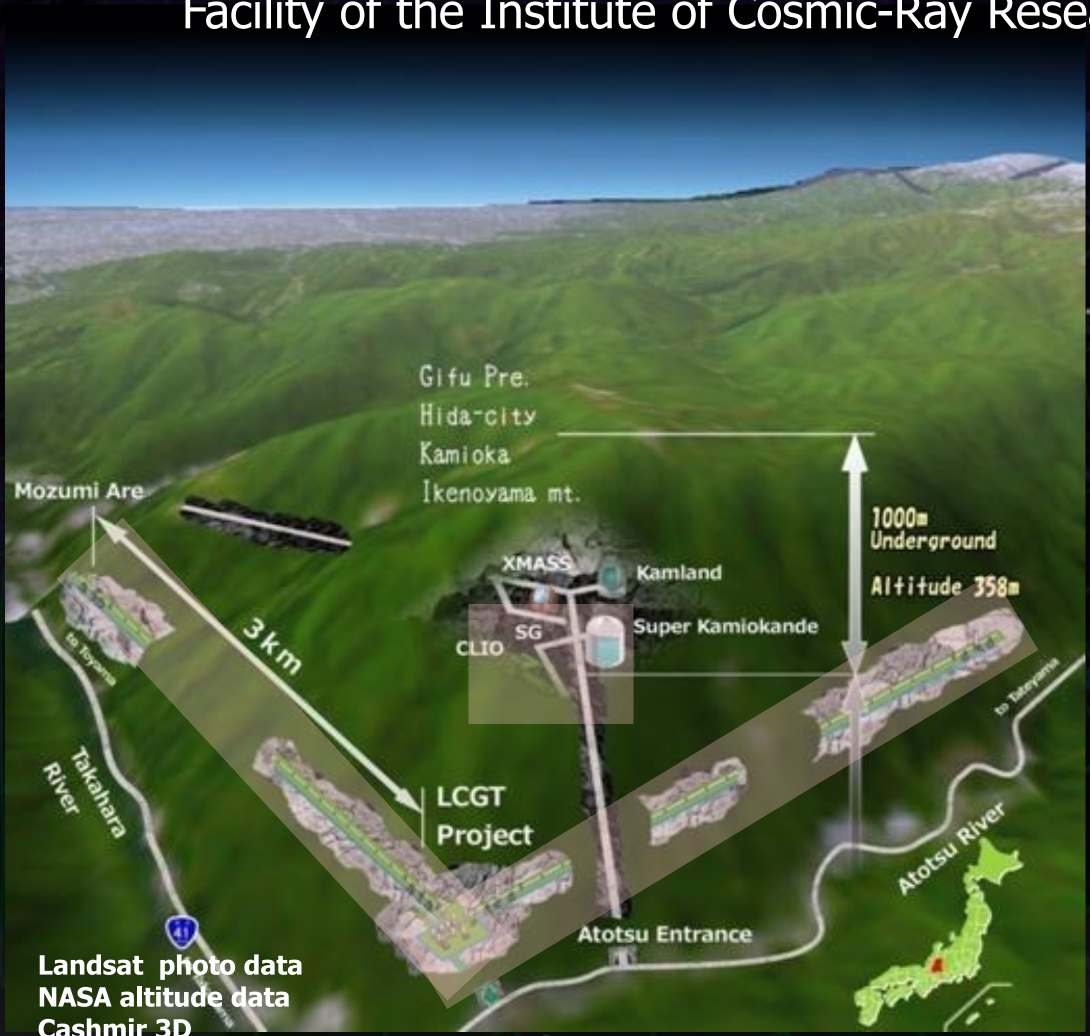
Construction cost is partially approved:
9.8 BYen for first 3-year construction.
(Original request: 15.5 BYen for 7 years.)

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.



Neutrino
- Super Kamiokande, Kamland

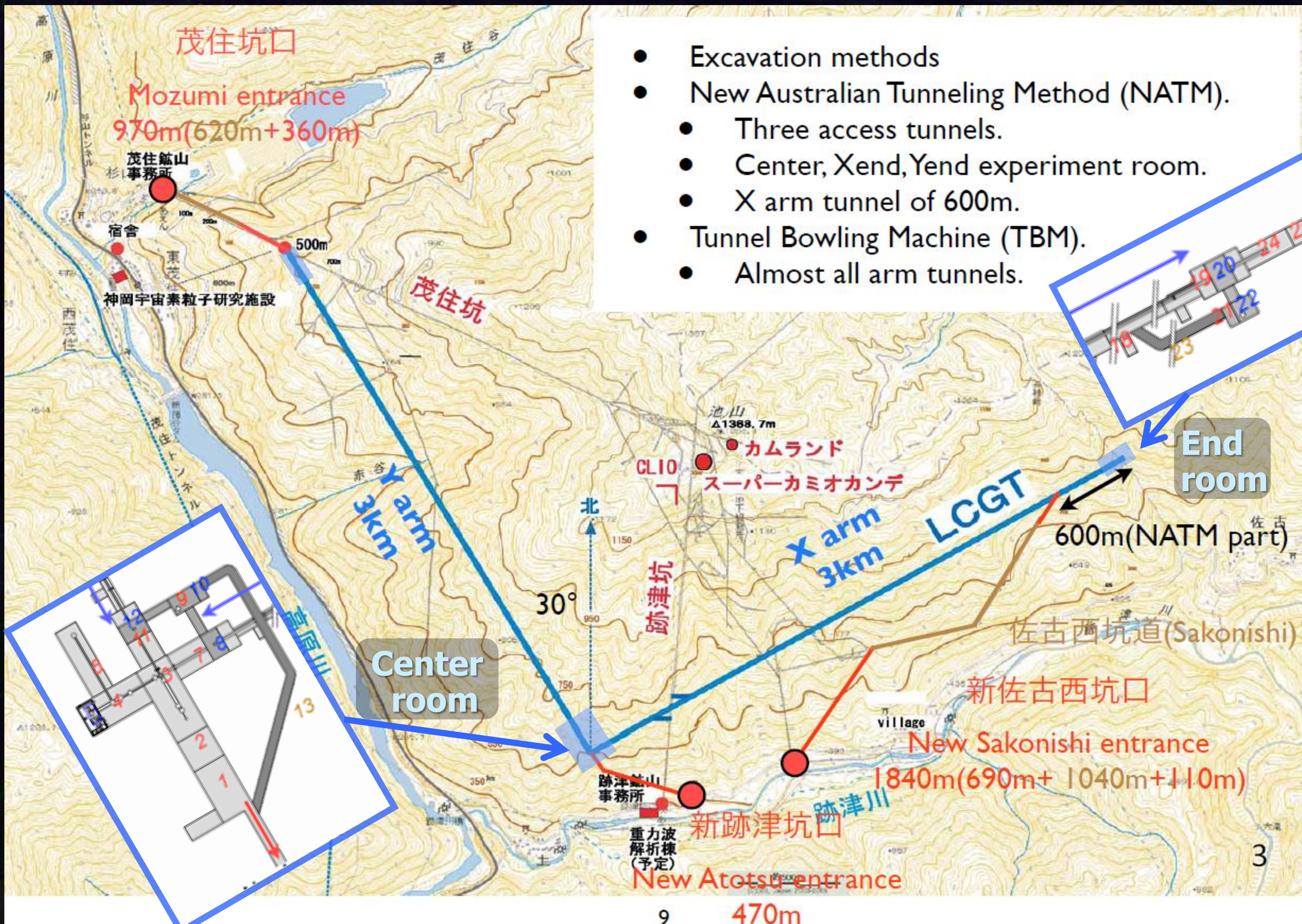
Dark matter
- XMASS

Gravitational wave
- CLIO, LCGT

Geophysics
- Strain meter

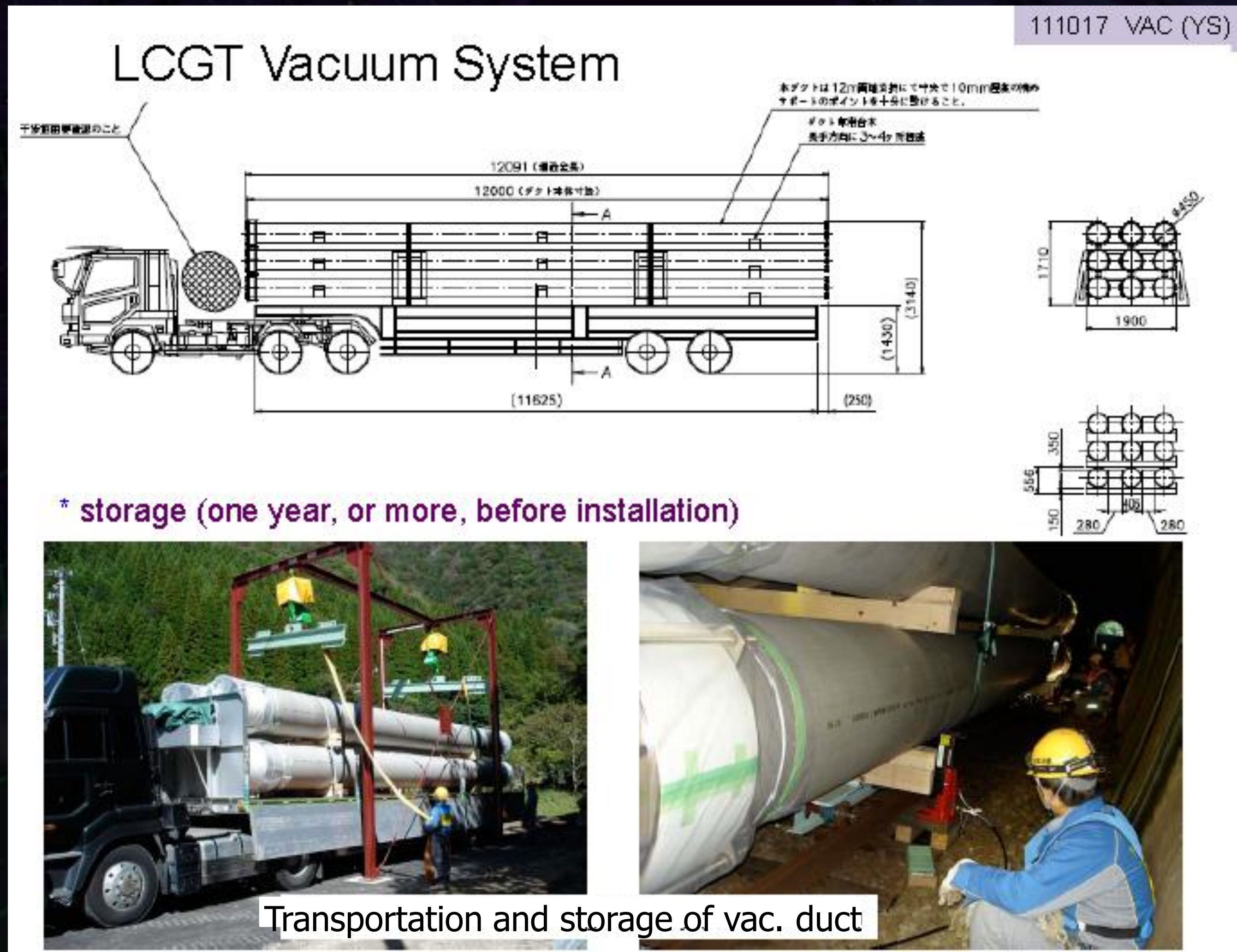
- 220km away from Tokyo
- 1000m underground from the top of the mountain. (Near Super Kamiokande)
- 360m altitude
- Hard rock of Hida gneiss (5 [km/sec] sound speed)

LCGT tunnel design



LCGT Vacuum duct

12-m ducts are being delivered: ~100 of 500 ducts

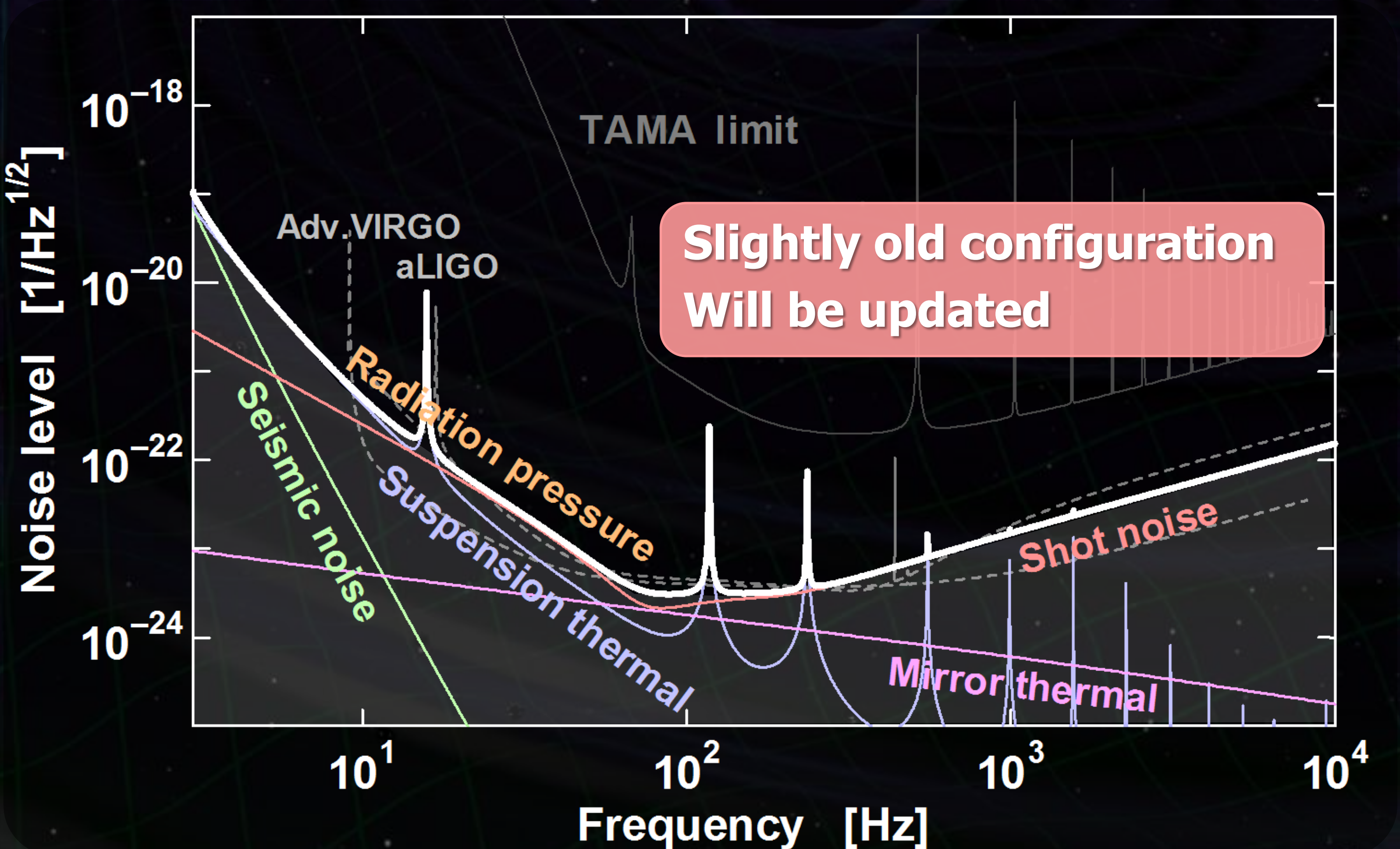


Presentation
By Y.Saito (KEK)

Sensitivity Limit

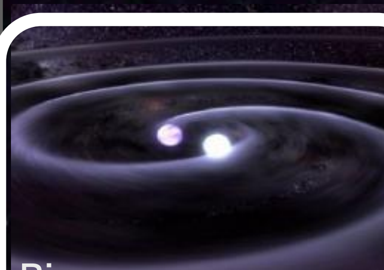
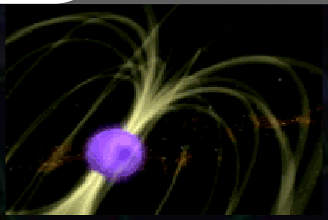
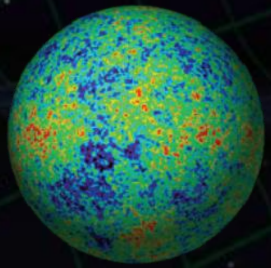
Comparable with aLIGO Ad.VIRGO

→ Global observation network



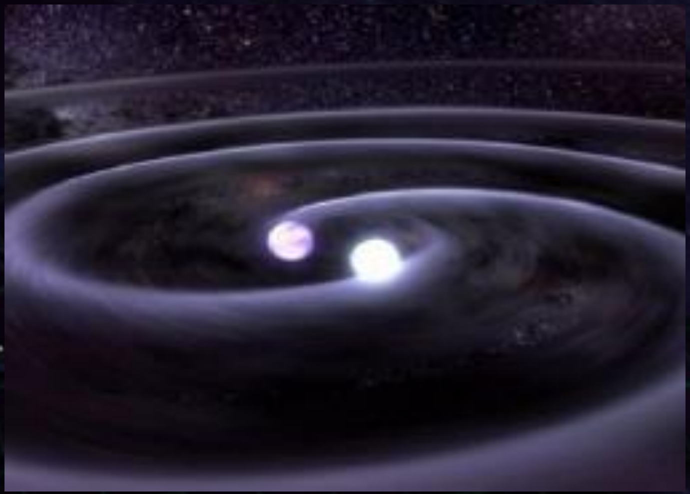
GW targets and data analysis

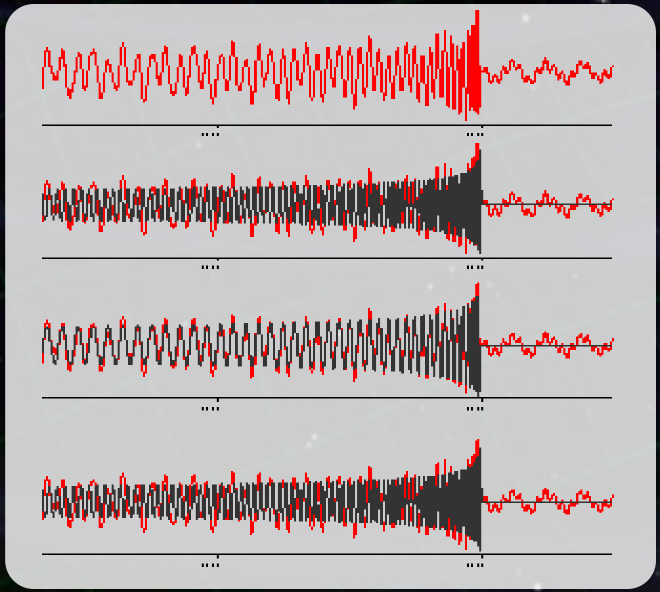
Signal duration

Waveform	Short (bursts)		Long (stationary)
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

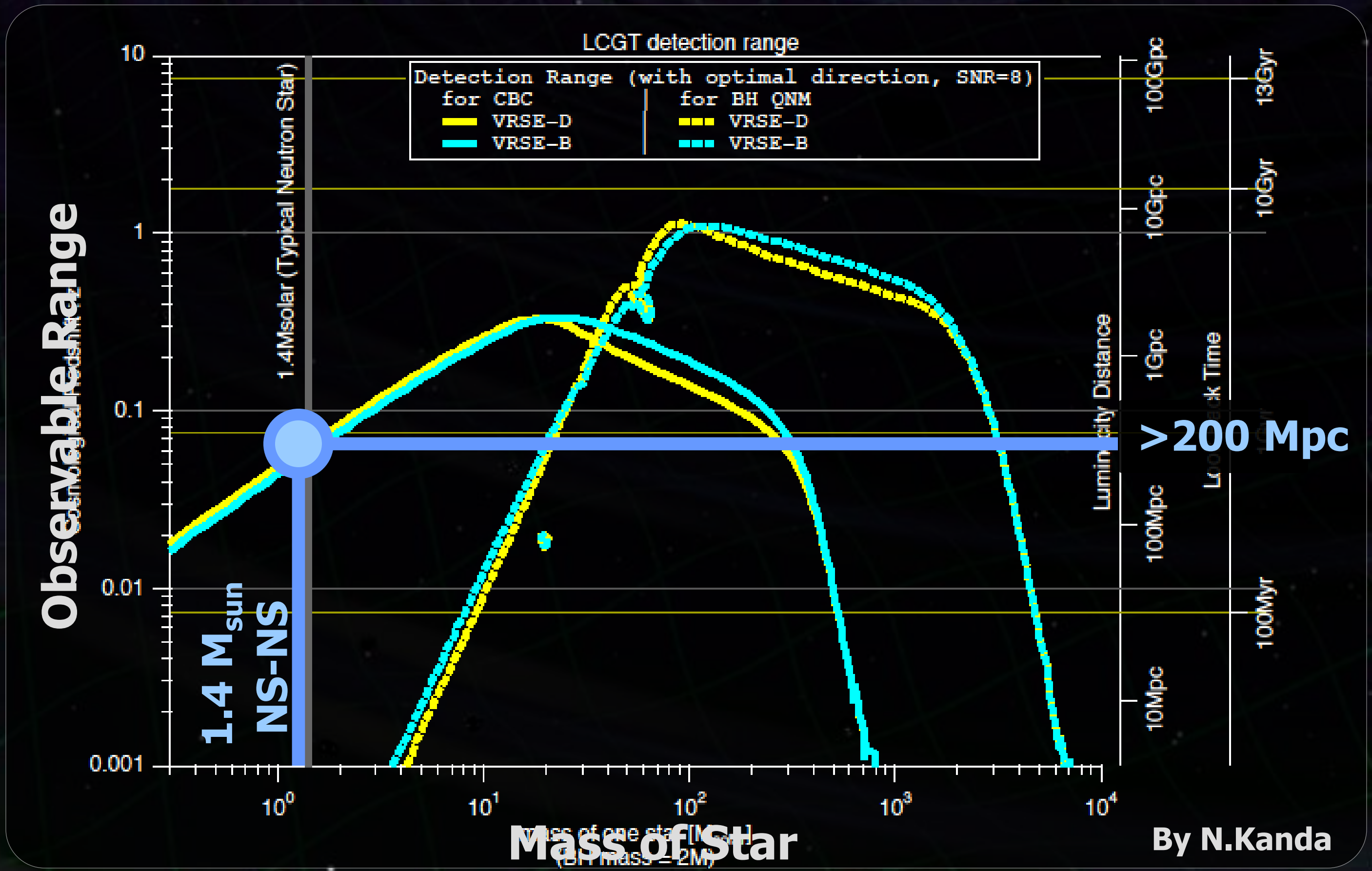
- EoS of neutron star.
- Formation and evolution of stars.
- Origin of high-energy phenomena.

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.)



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)

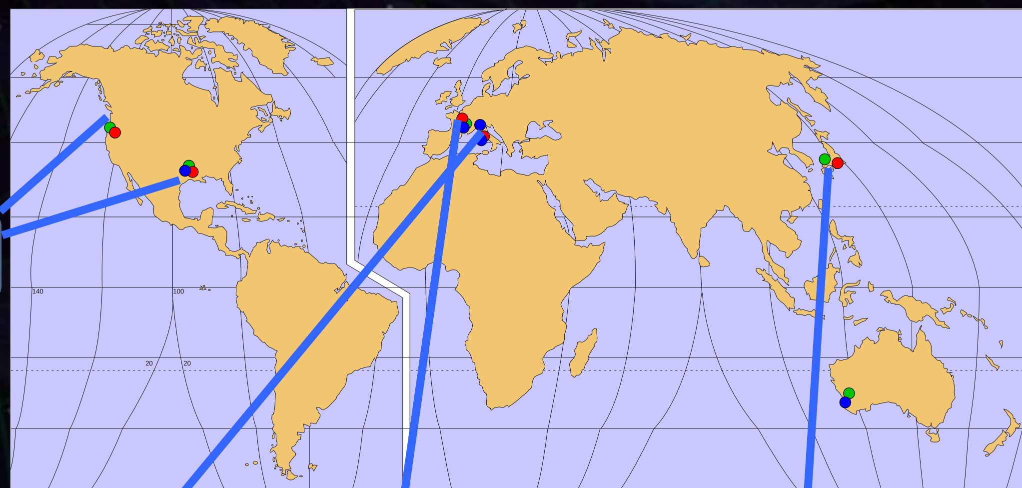
⇨ **LCGT Detection rate 9.8 events/yr**

Second generation detectors

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

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

aLIGO (USA)
4km x 2 (or3)

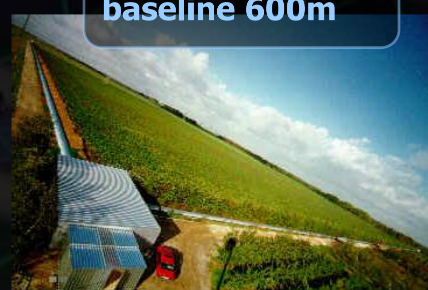


LIGO-Austreria
in proposal

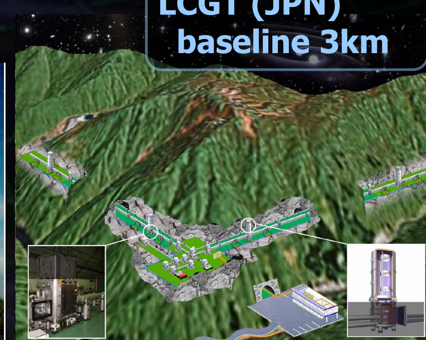
LIGO-India
in proposal

indigo

GEO-HF (GER-UK)
baseline 600m



LCGT (JPN)
baseline 3km



Adv.VIRGO (ITA-FRA)
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

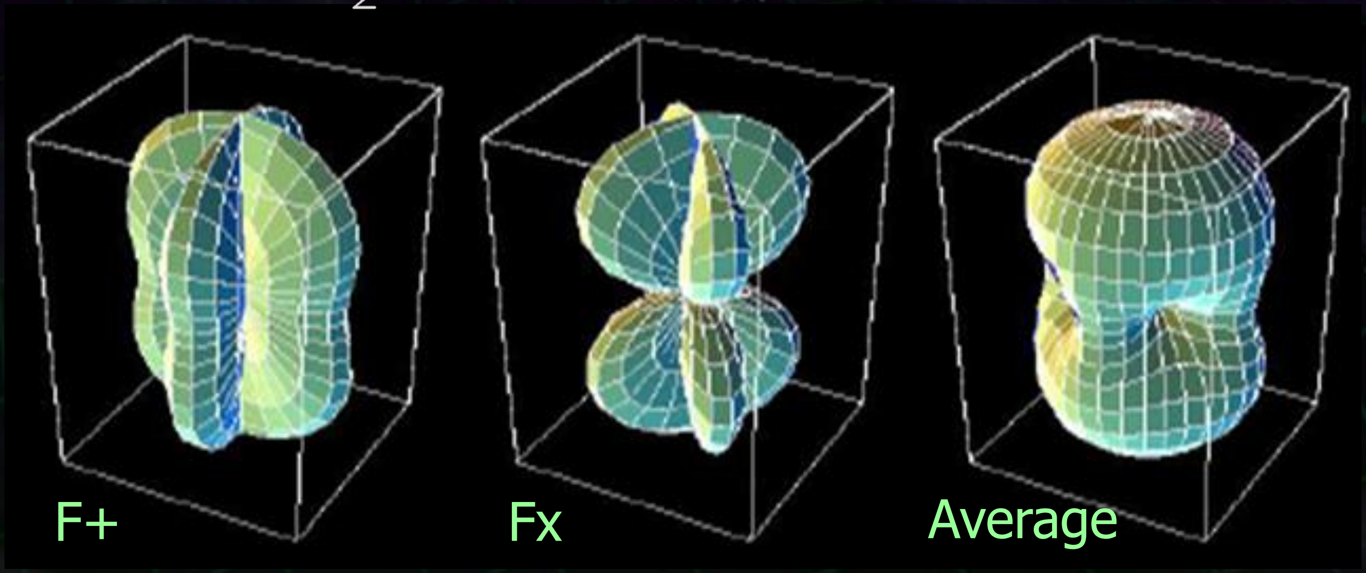
- Interferometric detector response

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

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

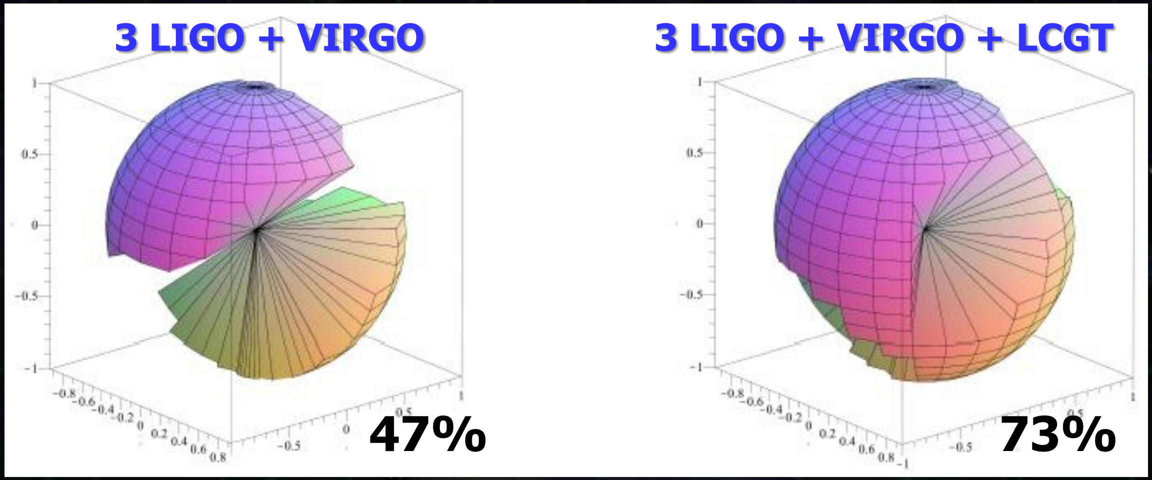
Gamma-ray, X-ray, optical/IR, Radio, Neutrino, ….

- 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

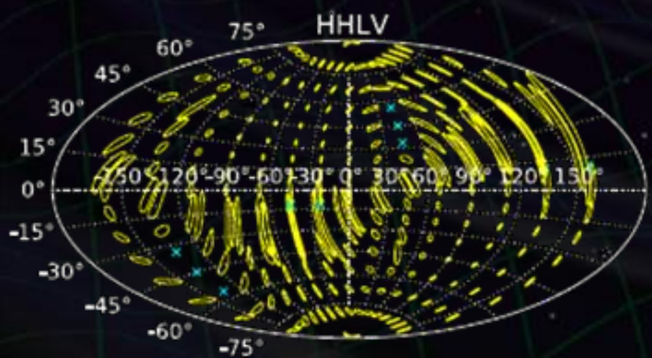
Parameter estimation

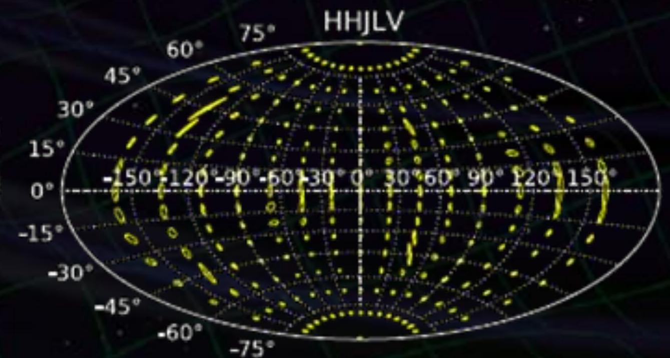
Angular resolution for the source

By H. Tagoshi

	LHV	LHVJ	LHVA	LHVJA
average of δΩ [Deg²]	34.4	7.26	4.20	2.78
median of δΩ [Deg²]	10.8	3.54	2.20	1.46

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



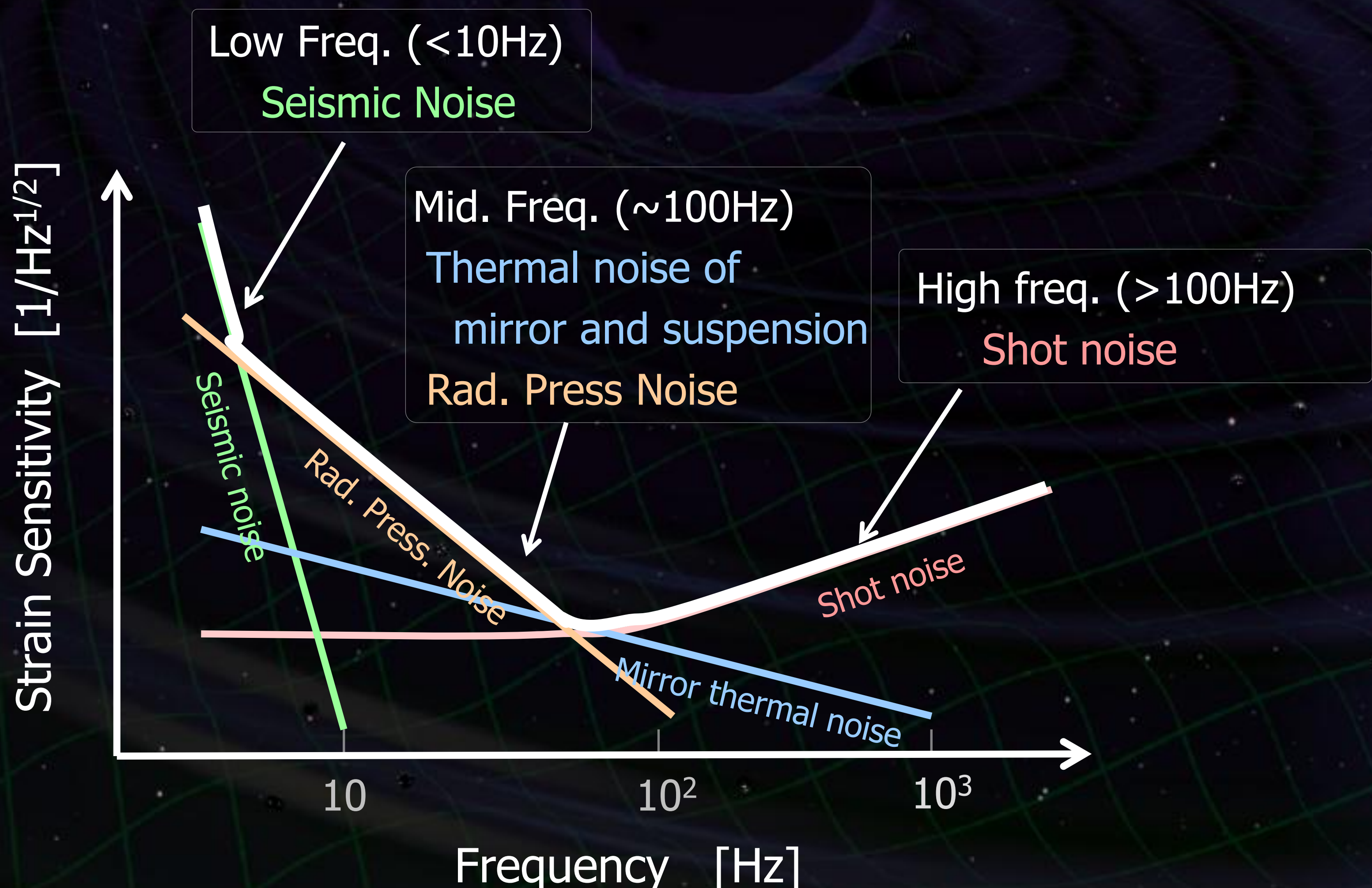


S.Fairhaurst
CQG 28(2011) 105021

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

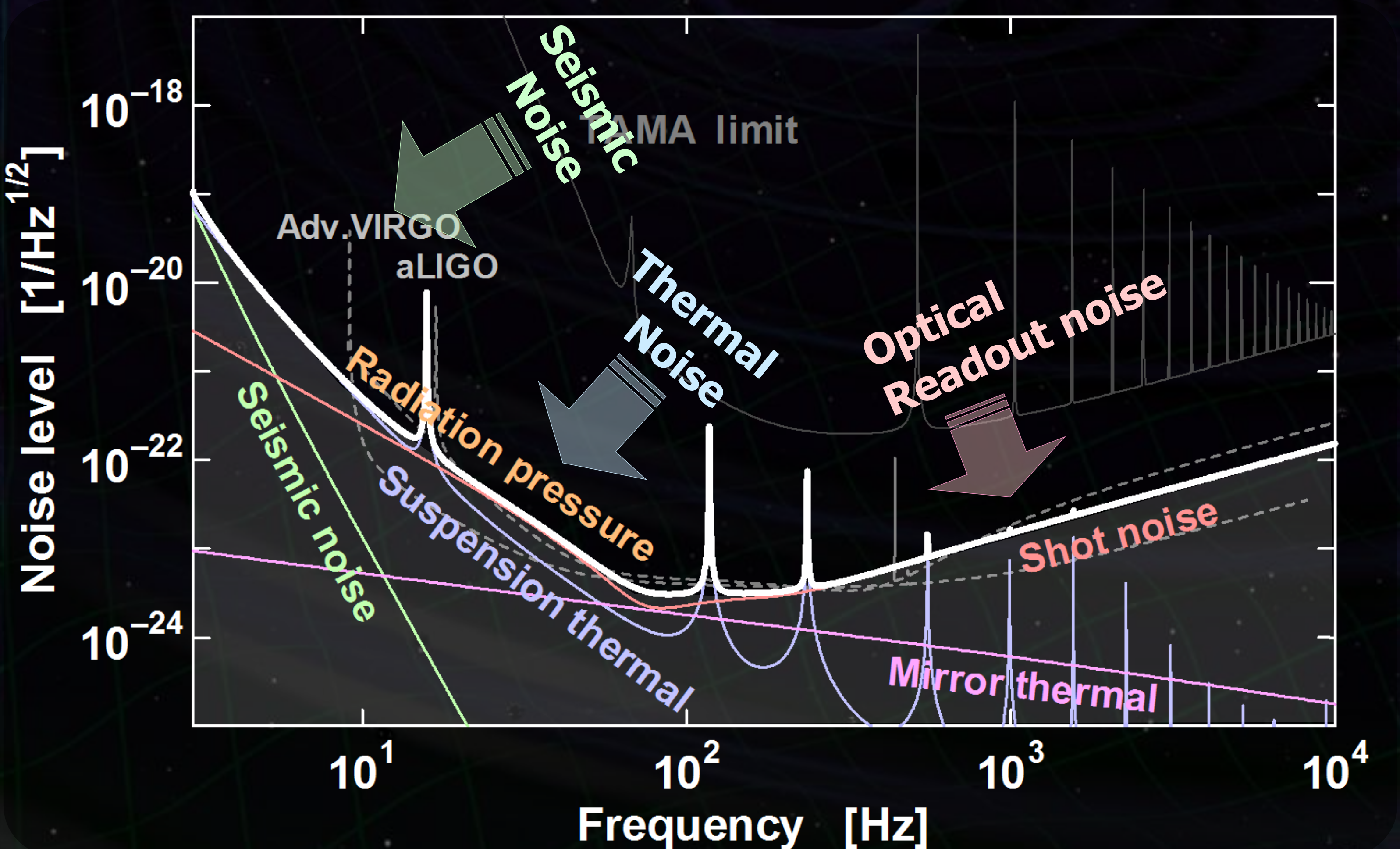
LCGT design

Fundamental Noise Sources



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

    Fluctuation of momentum on reflection $h_{\text{RPN}} \propto \sqrt{P}$

    P : Laser power

Standard Quantum Limit

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

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

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

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, ….

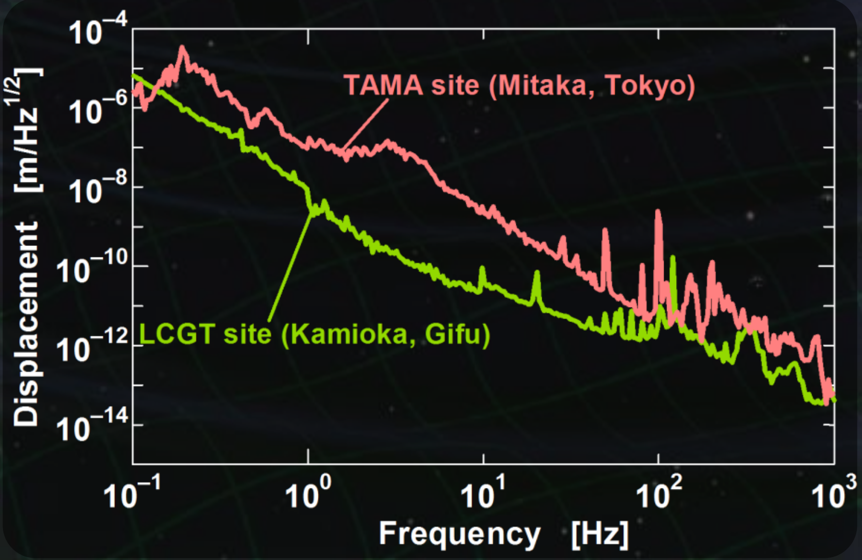
    → Affect detector stability, duty cycle of operation.

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)



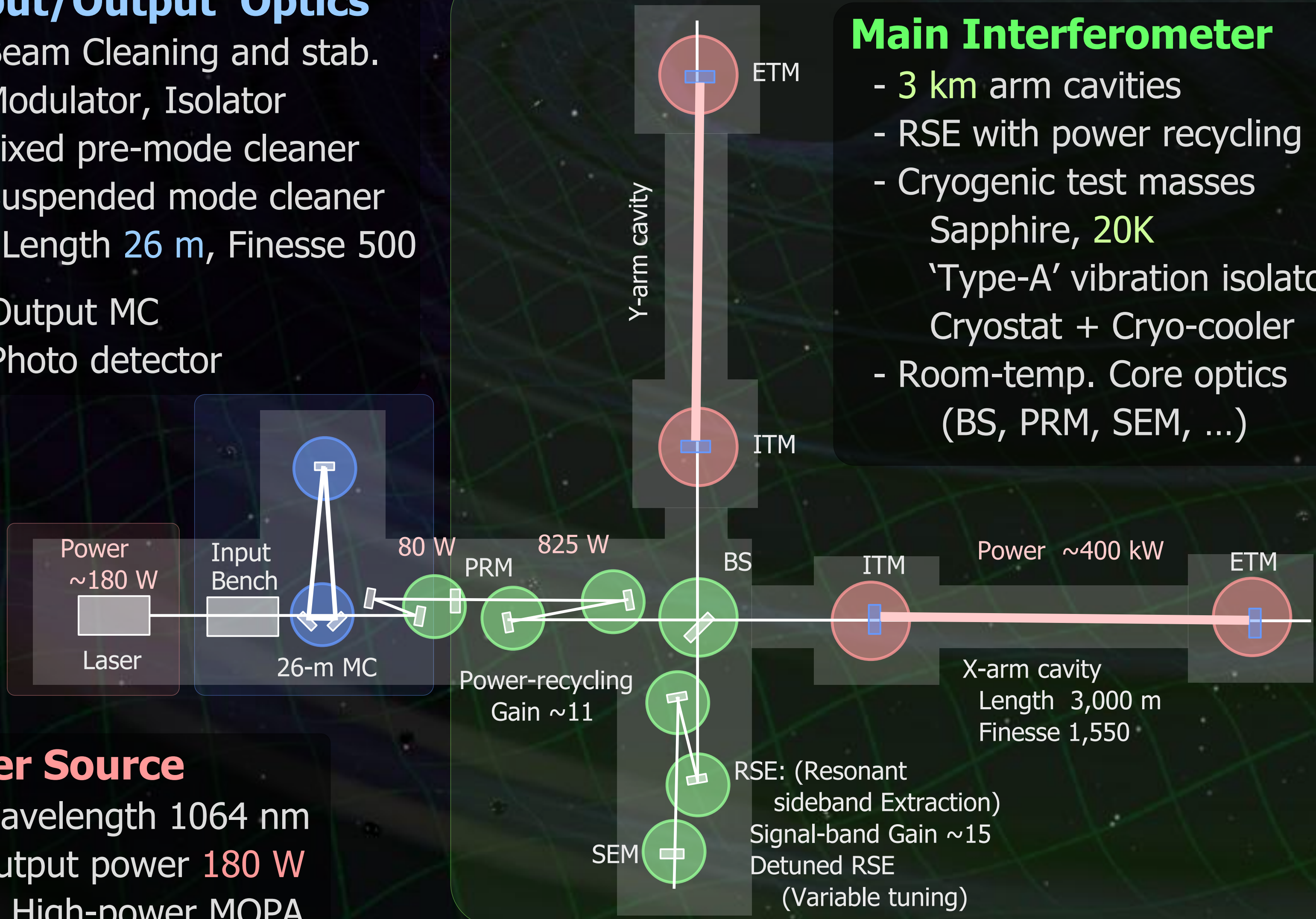
LCGT : Underground site → Low-seismic noise, Long-term stability.

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, ...)

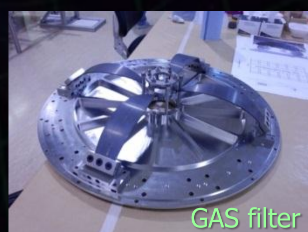


Laser Source
- Wavelength 1064 nm
- Output power 180 W
  High-power MOPA

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.

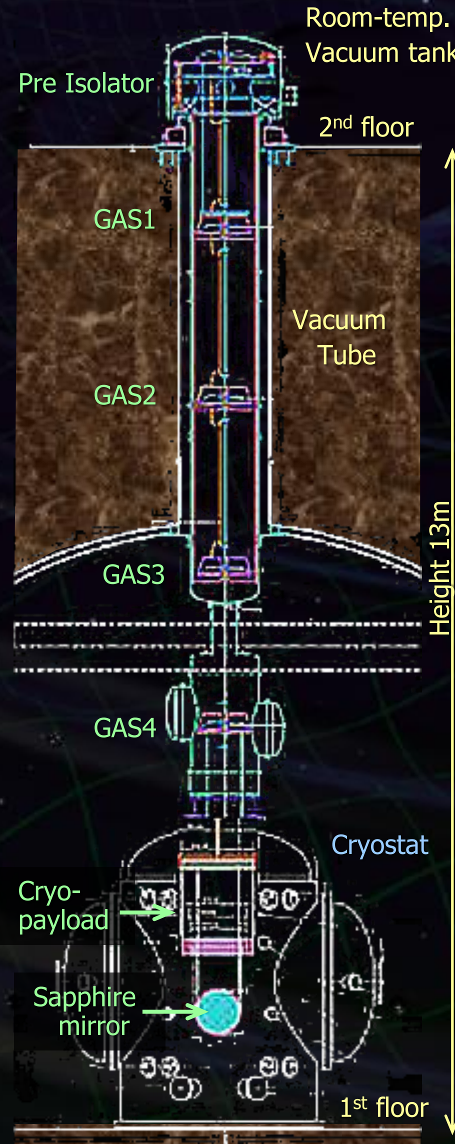

Pre Isolator


GAS filter

- Cryo-payload
  - Double pendulum

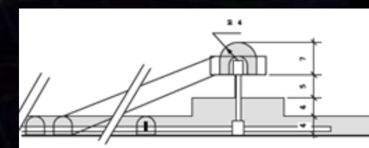
Sapphire test mass	20K
Suspension	16K

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



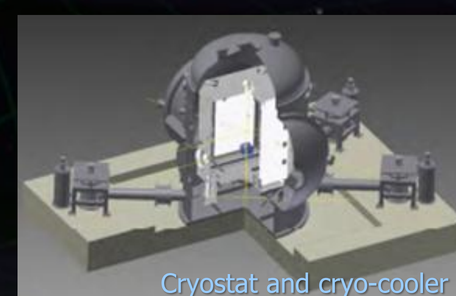
- Tunnel : 2 layer structure

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

	2nd-generation detectors			3rd 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 Jan. 28, 2012.

DECIGO

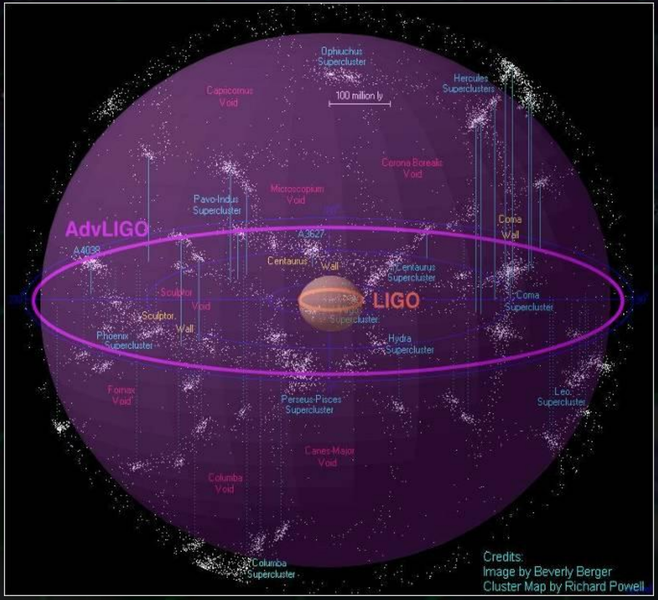
Expanding the Horizon

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

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

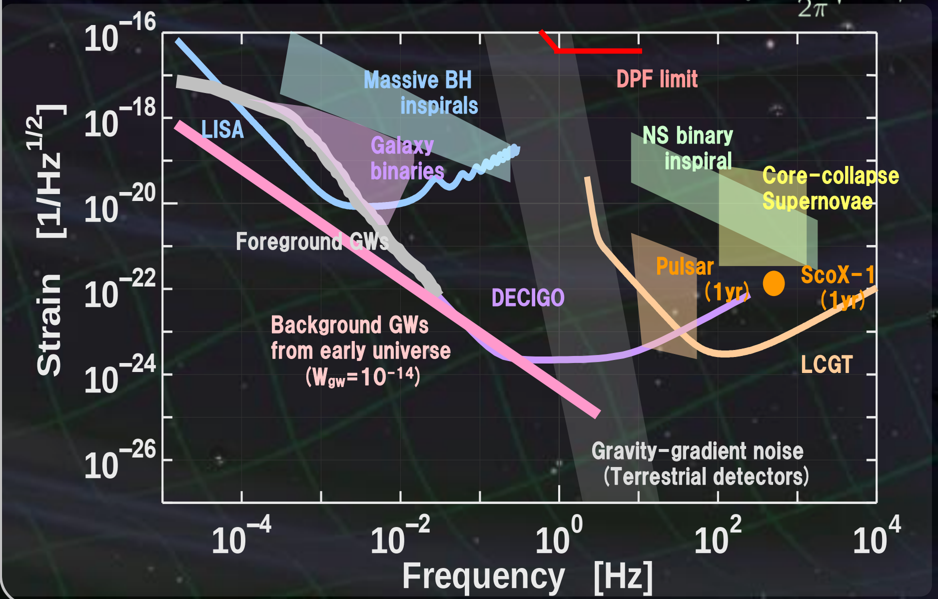
⇨ **Next generation detectors**

Better sensitivity to cover more galaxies



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

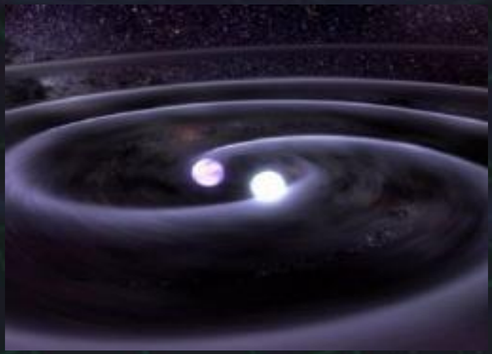
- Larger-mass events → larger amplitude GW
- (Almost) stationary source → Do not have to wait for 'events'

➡ **Different or complementary science**

(Example) GW from compact binary inspiral

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

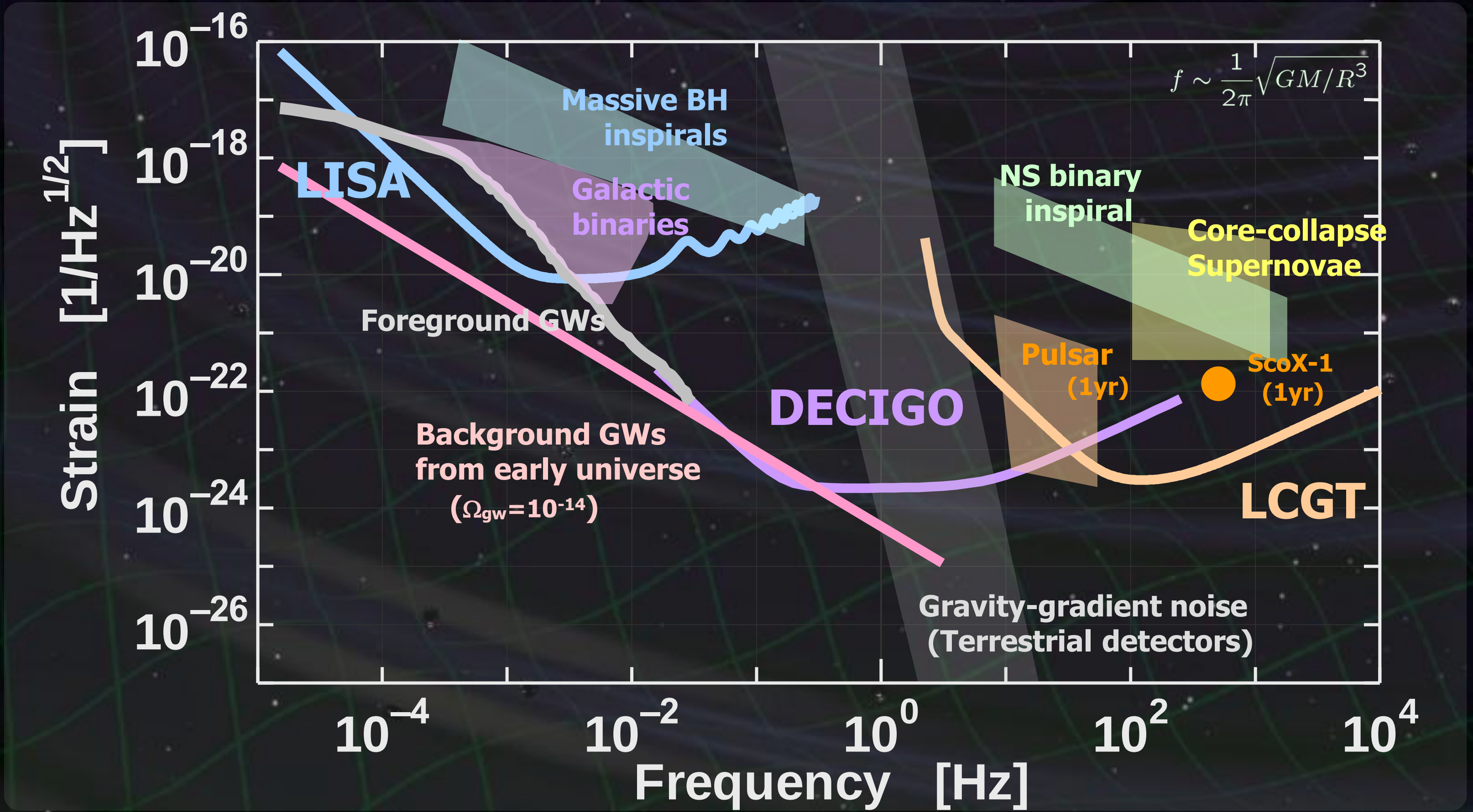
Separation (R) Mass ($m_1 m_2$)



- Large separation
  → stationary, low-freq. GWs
- Just before merger ($R_{\rm ISCO} \propto M$)
  → 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

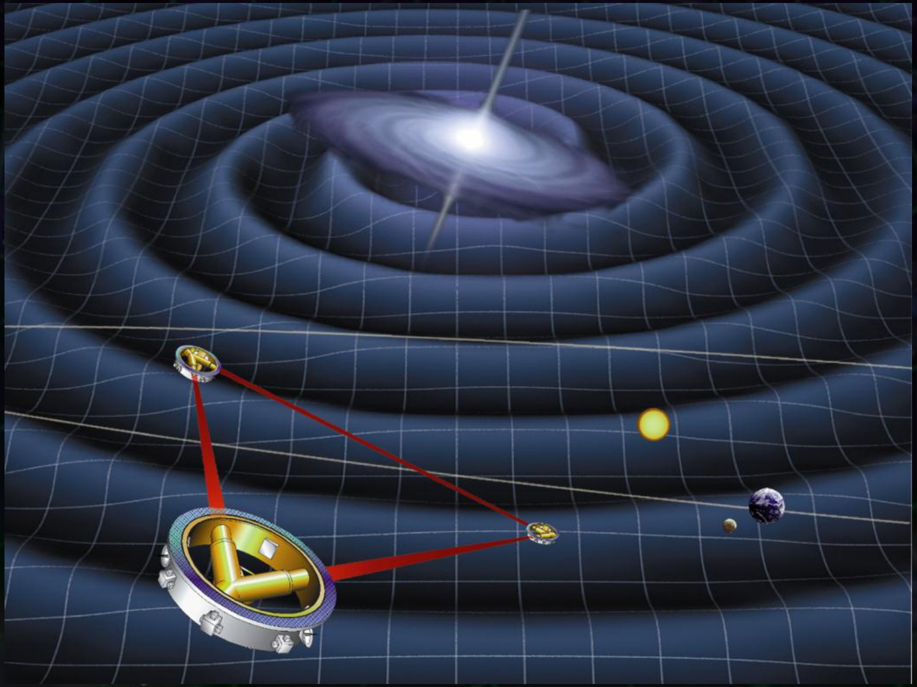
LISA (Laser Interferometer Space Antenna)

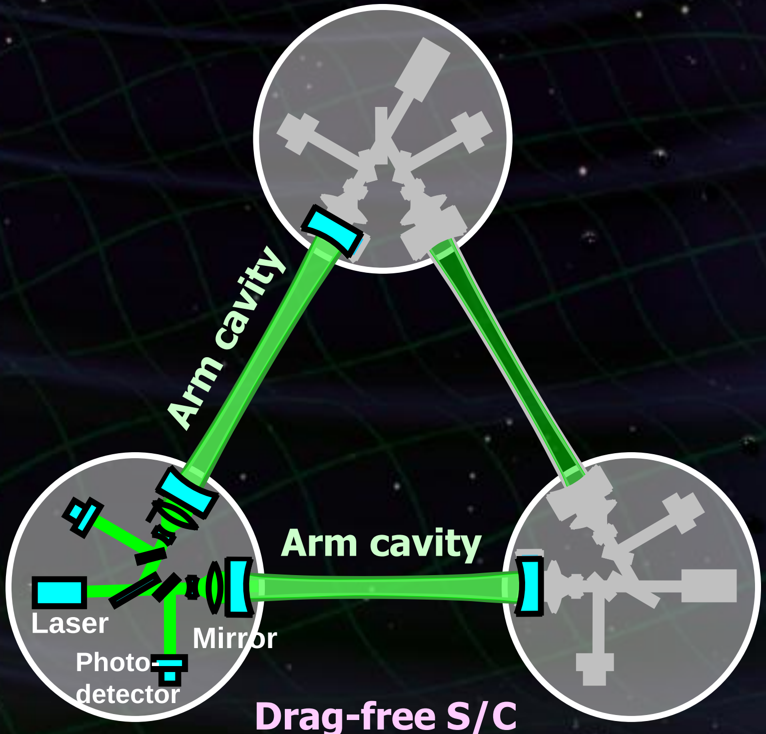
Obs. band around 1mHz
~Million km baseline length
Recent change : ESA/NASA → ESA mission
Design updates underway
→ changing name to
NGO (New Gravitational-wave Observatory)

DECIGO

(Deci-hertz Interferometer Gravitational Wave Observatory)

Obs. Band around 0.1Hz
1000km baseline length



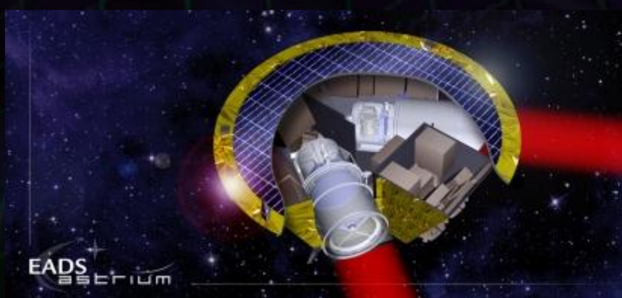


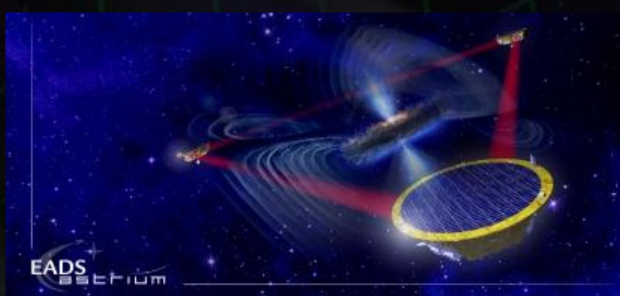
NGO (LISA) Interferometry

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





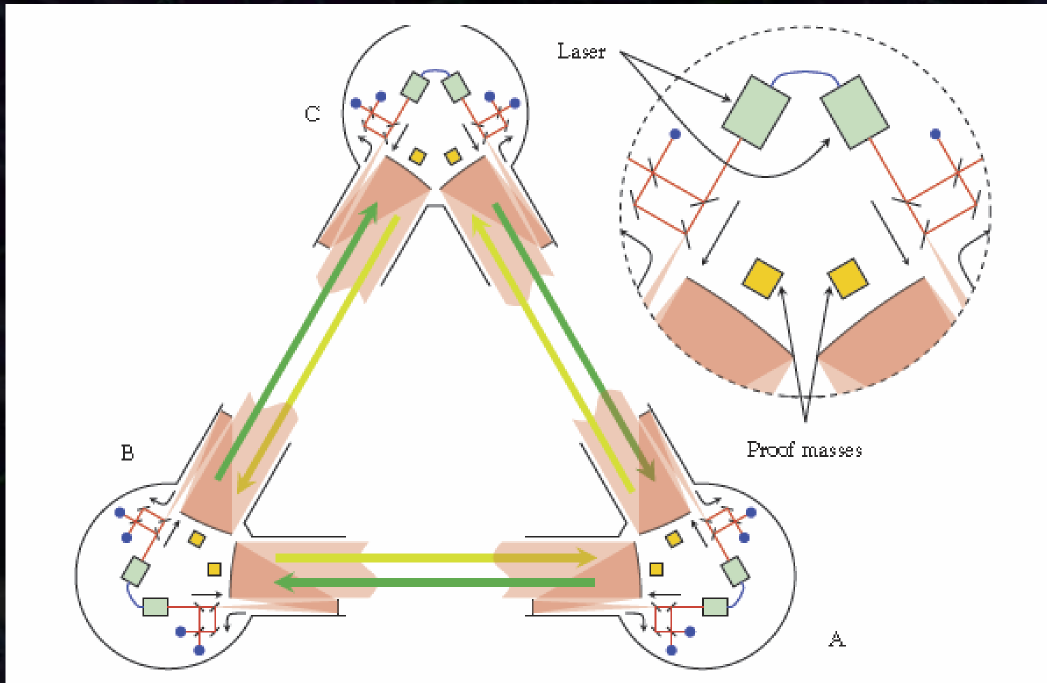


Figure 3.2.: A constellation of three identical LISA spacecraft constitutes the science instrument. There are six identical, send/receive laser ranging terminals (two per S/C) with associated test masses and a comparison of signals at each apex. The sketch leaves out the test mass interferometers for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

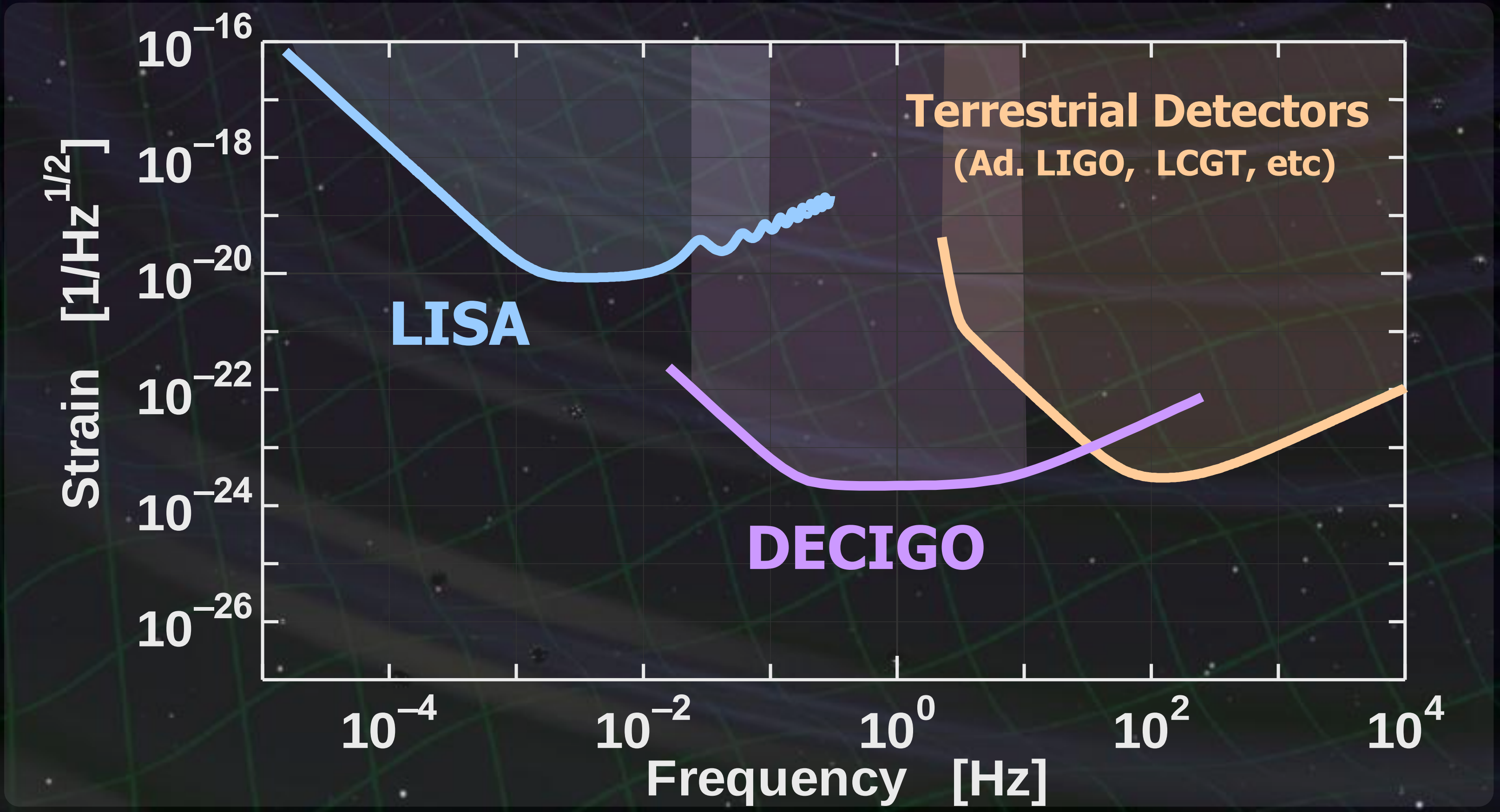
M Hewitson for the LPF team, AMALDI, July 15th 2011

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



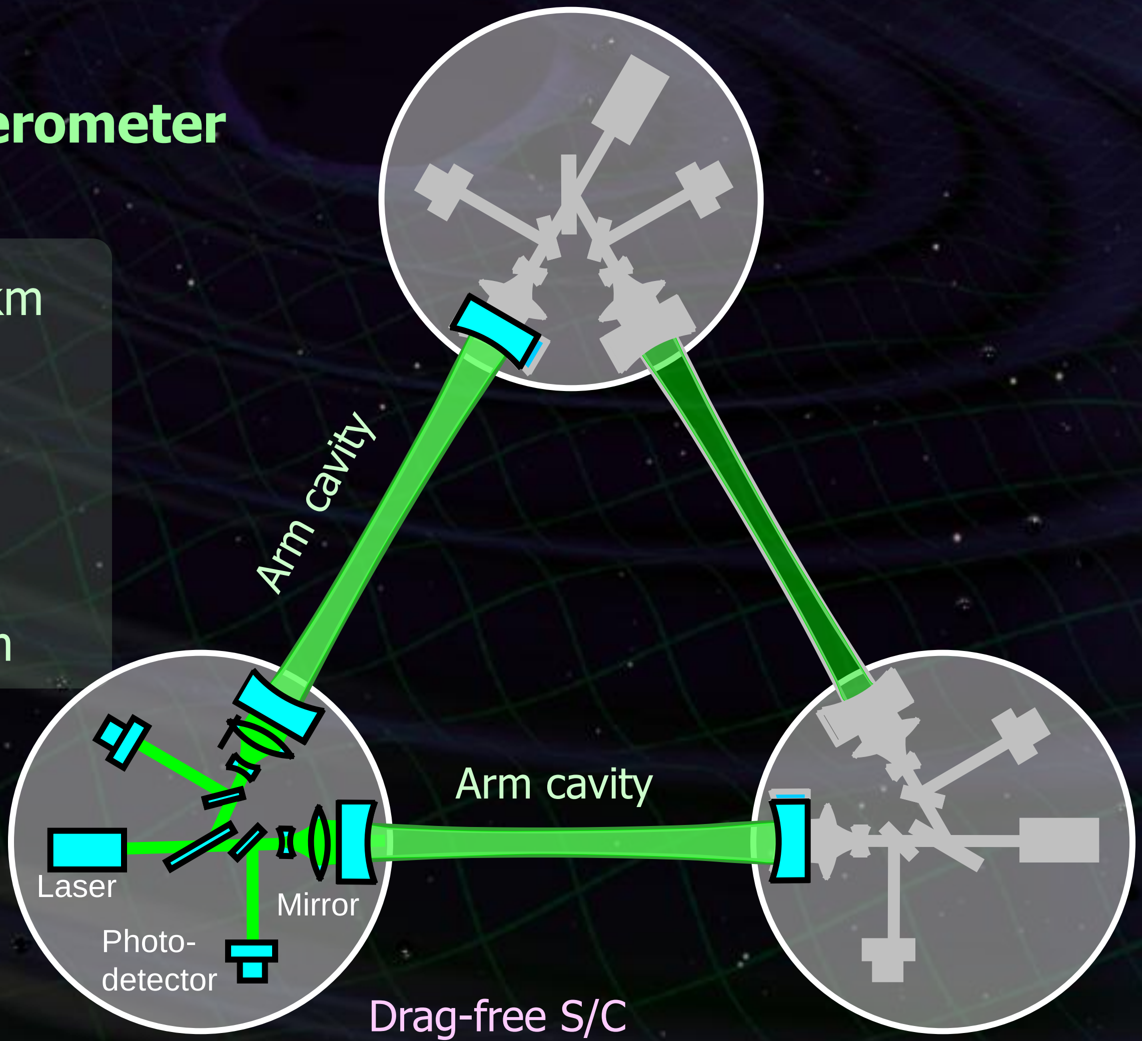
Pre-Conceptual Design

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

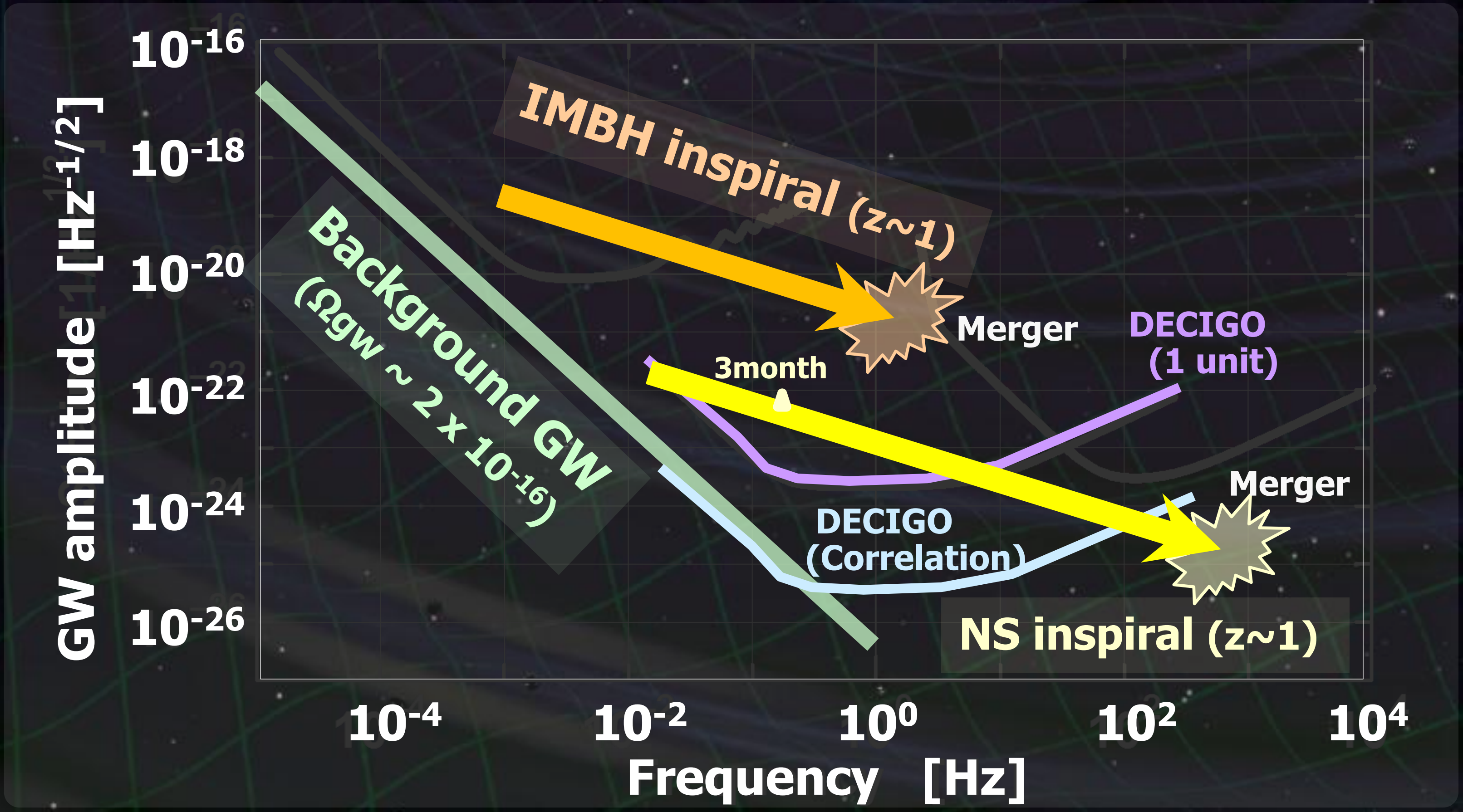


Targets and Science

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)

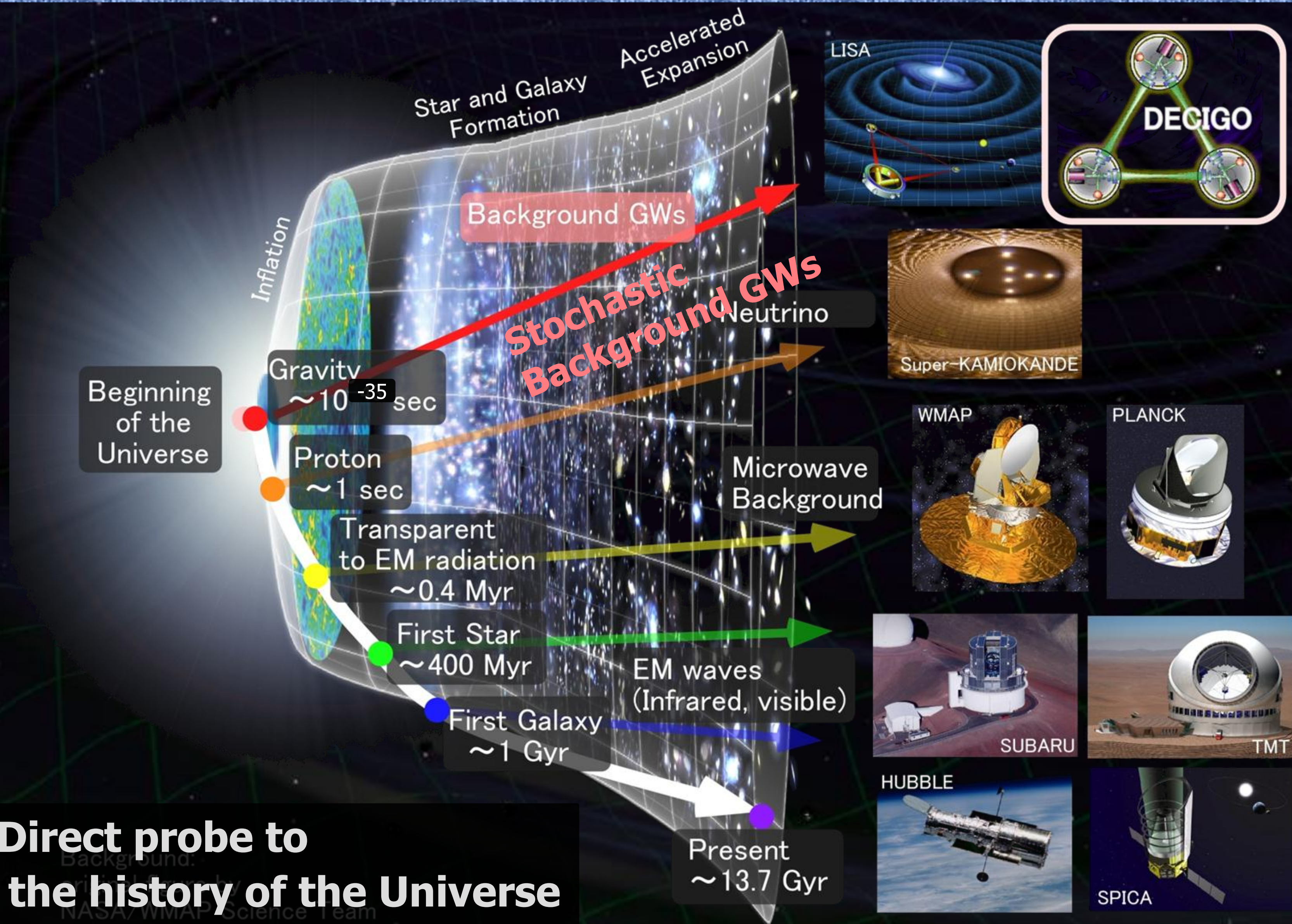
- **Neutron-star physics**

  Determine masses of 10^5 NSs per year

  → Constrain the EoS of NS

  Formation process of NS from the spectrum

Characterization of inflation

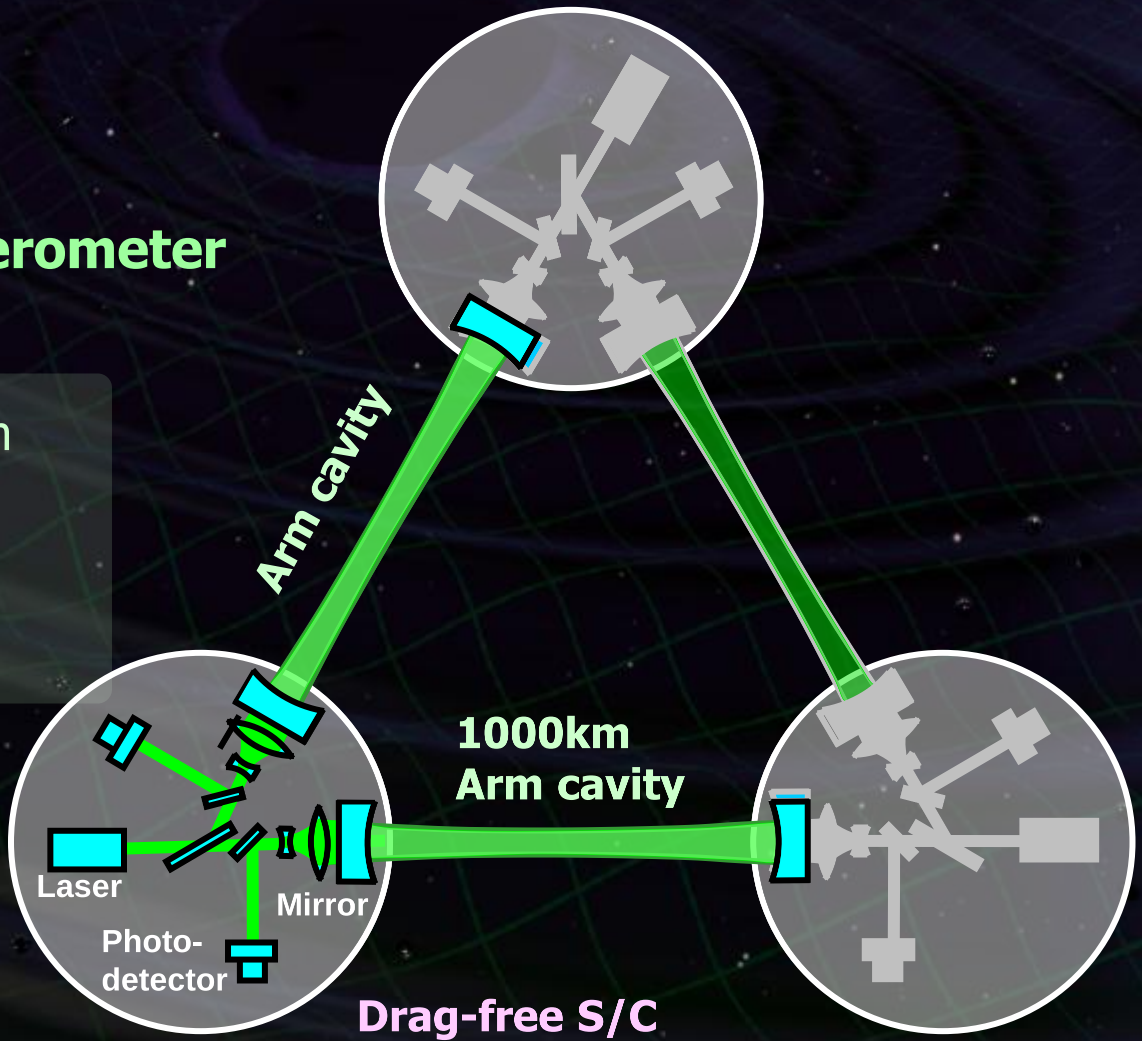


Direct probe to the history of the Universe

DECIGO Interferometer

Interferometer Unit:
Differential FP interferometer

Baseline length: 1000 km
3 S/C formation flight
3 FP interferometers
Drag-free control

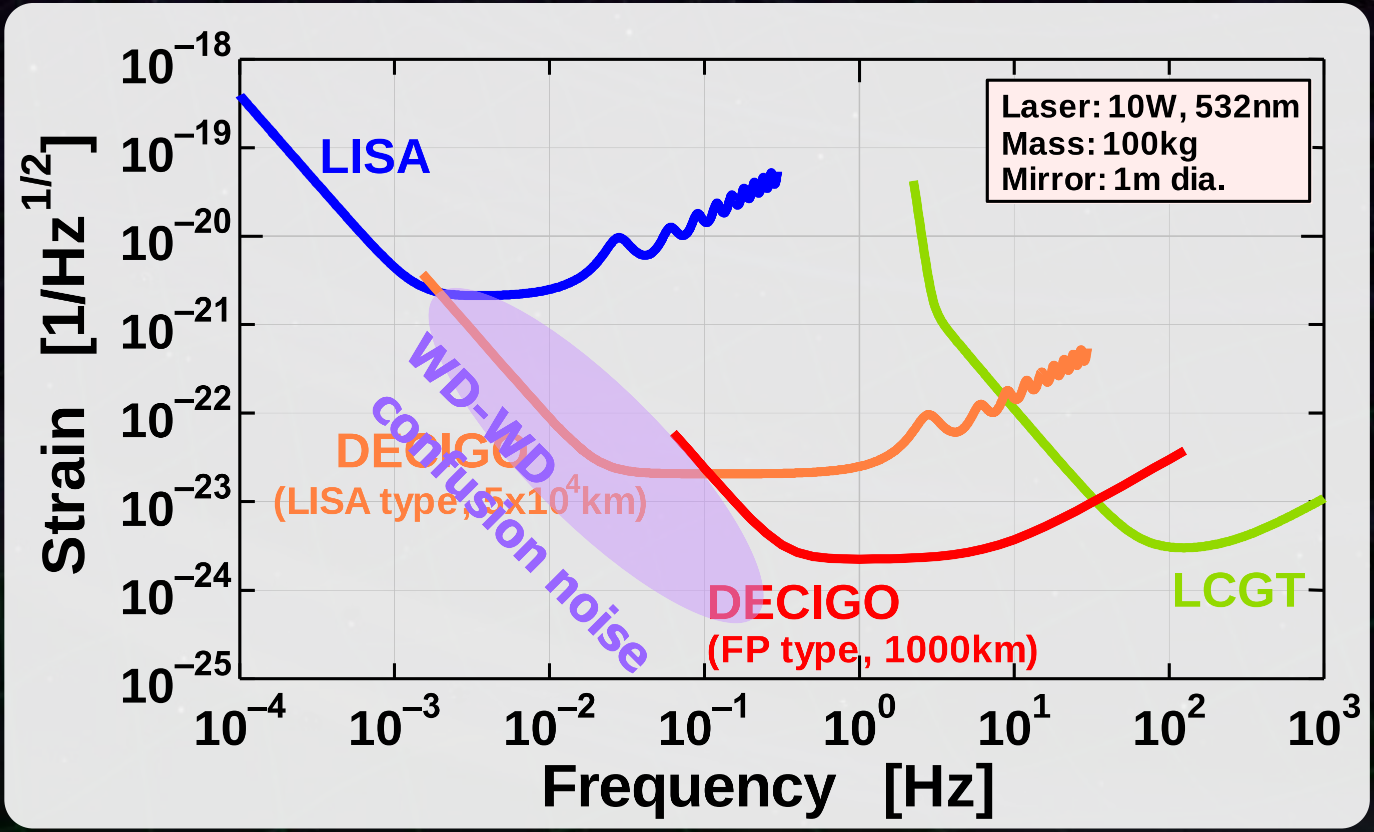


Interferometer Design

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

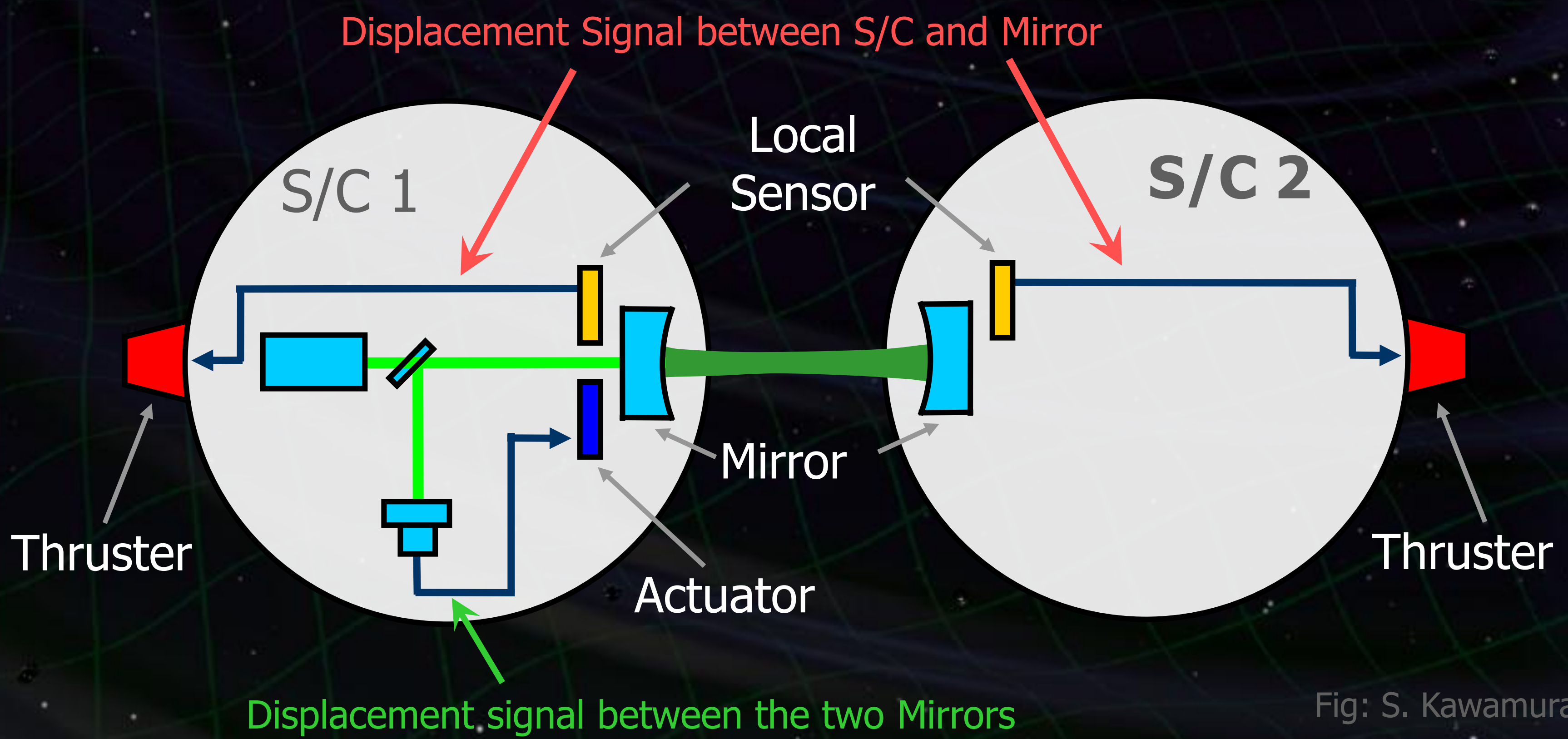


Fig: S. Kawamura

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.

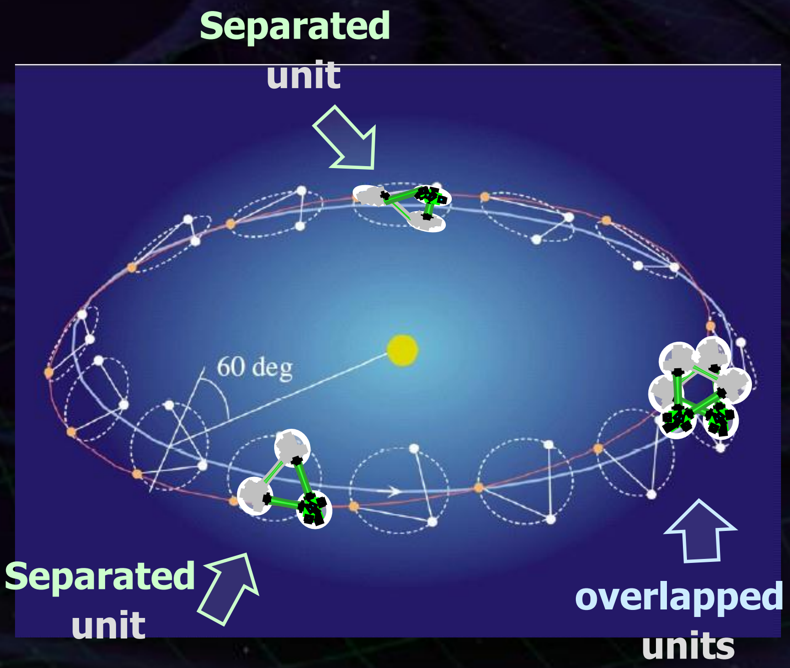
Orbit and Constellation

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

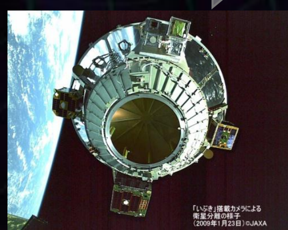
Roadmap

Figure: S.Kawamura

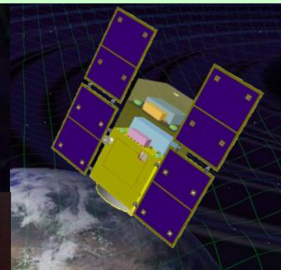
	2010	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29

Mission

R&D Fabrication

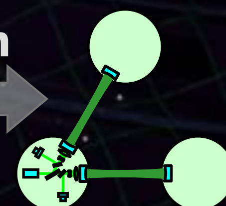


SDS-1/SWIM



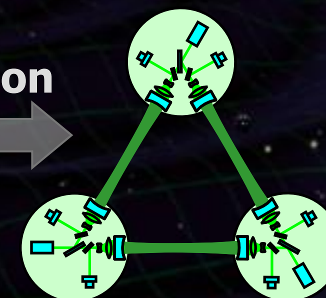
DECIGO Pathfinder (DPF)

R&D Fabrication



Pre-DECIGO

R&D Fabrication



DECIGO

	SDS-1/SWIM, DPF	Pre-DECIGO	DECIGO
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

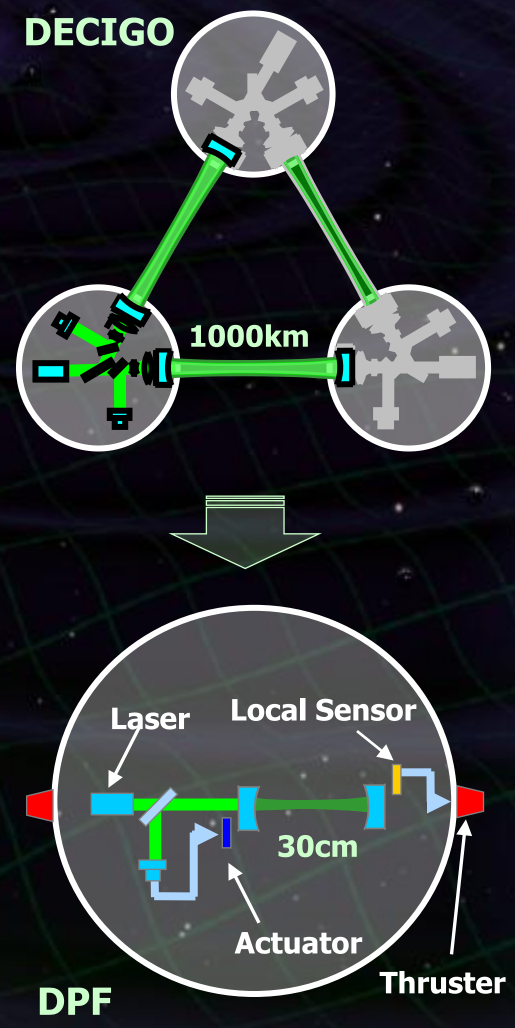
DECIGO-PF

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

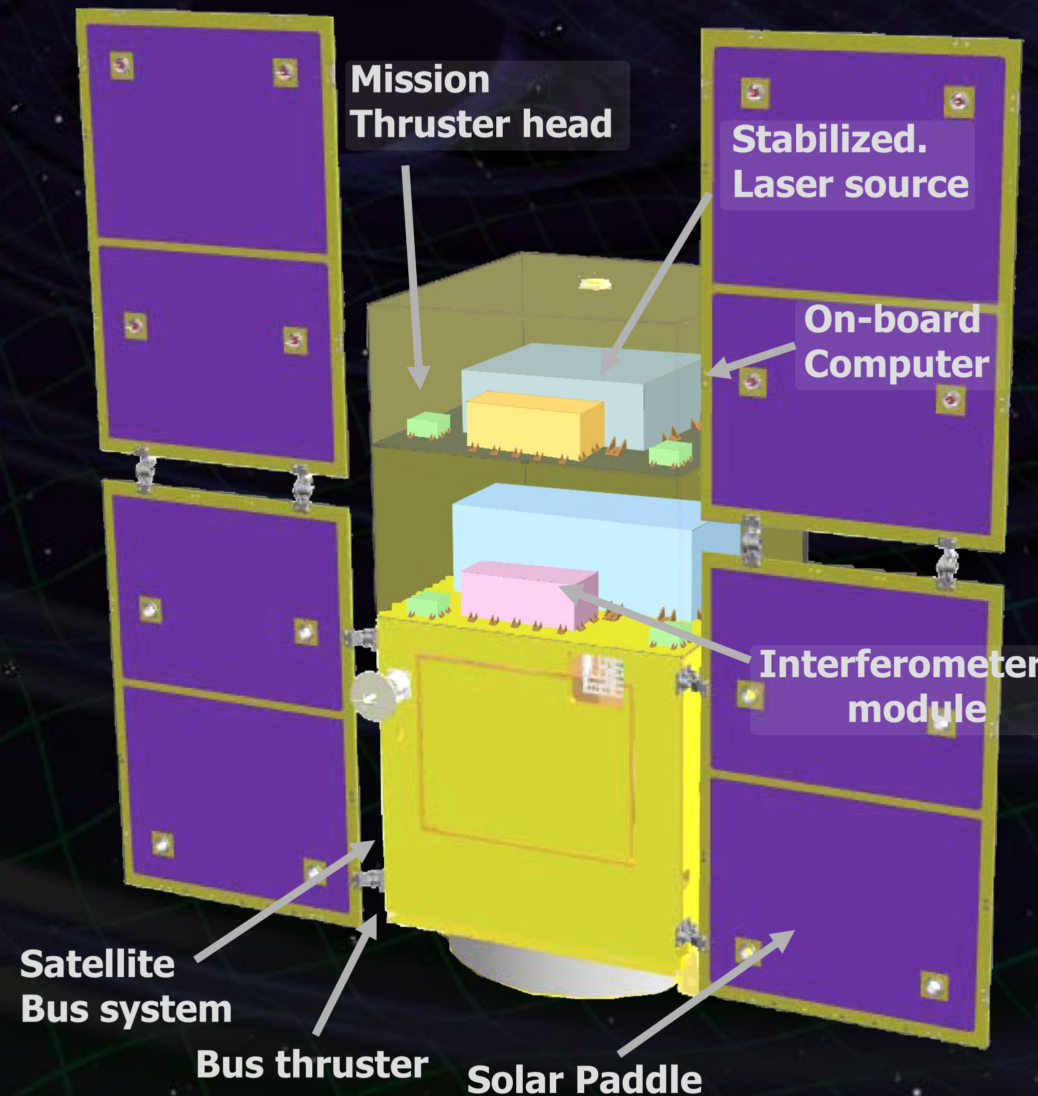
Size : 950mm cube
Weight : 150kg
Power : 130W
Data Rate: 800kbps
Mission thruster x12

Power Supply
SpW Comm.

Satellite Bus

('Standard bus' system)

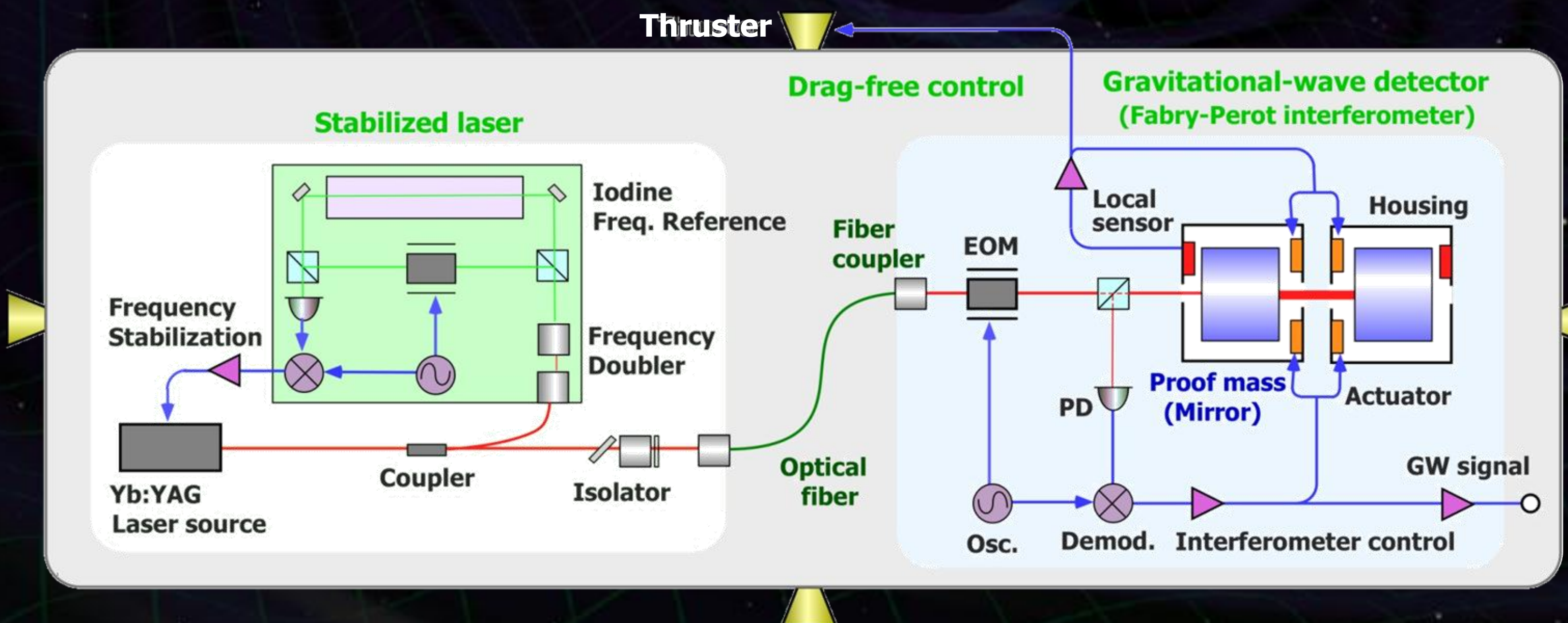
Size :
950x950x1100mm
Weight : 200kg
SAP : 960W
Battery: 50AH
Downlink : 2Mpbs
DR: 1GByte
3N Thrusters x 4



DPF mission payload

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

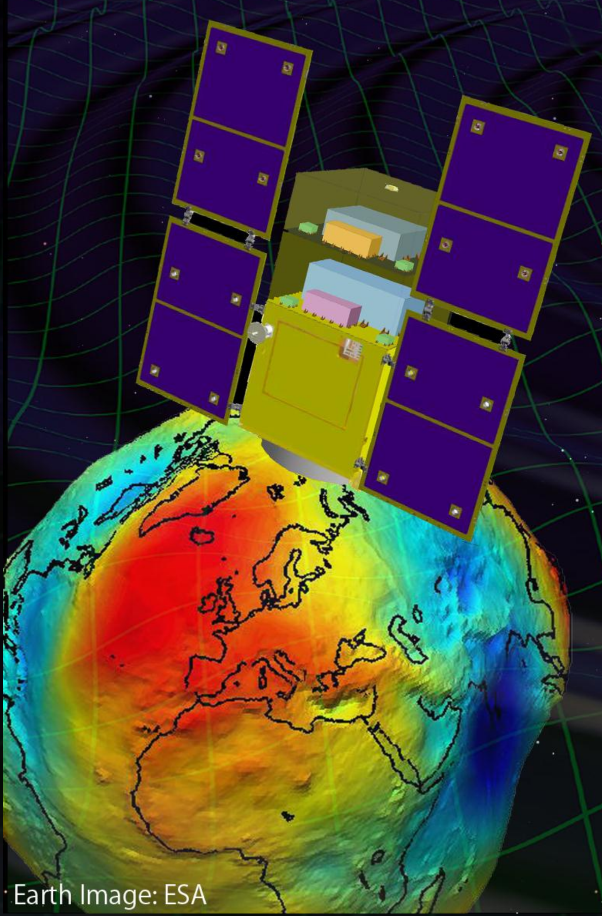
Drag-free control
Local sensor signal
→ Feedback to thrusters



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 P**DH**

Targets of DPF



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

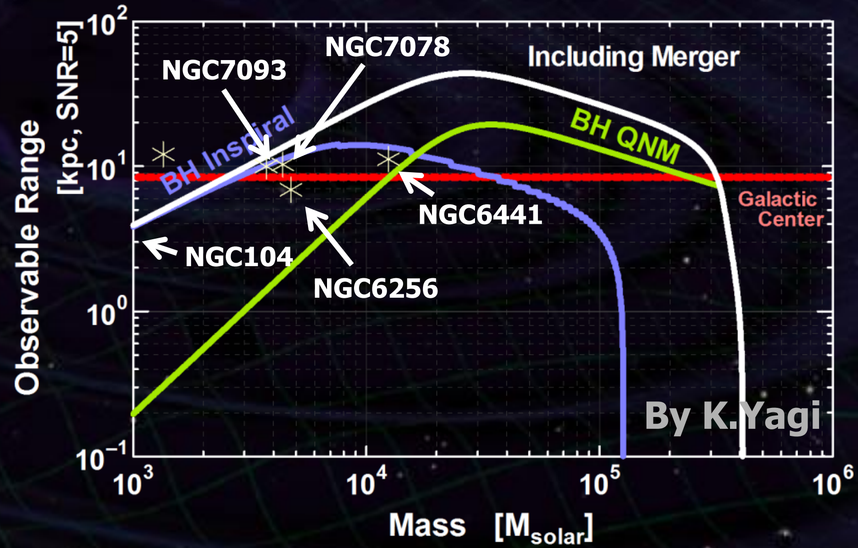
DPF Science

Astronomical observation

GW from merger of IMBHs

→ Formation mechanism of supermassive BHs

~30 GCs within DPF range



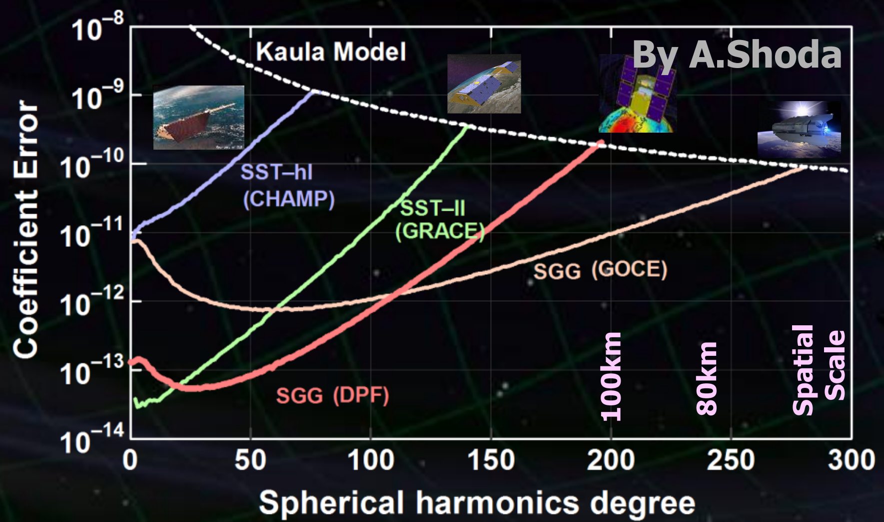
Observation of the earth

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

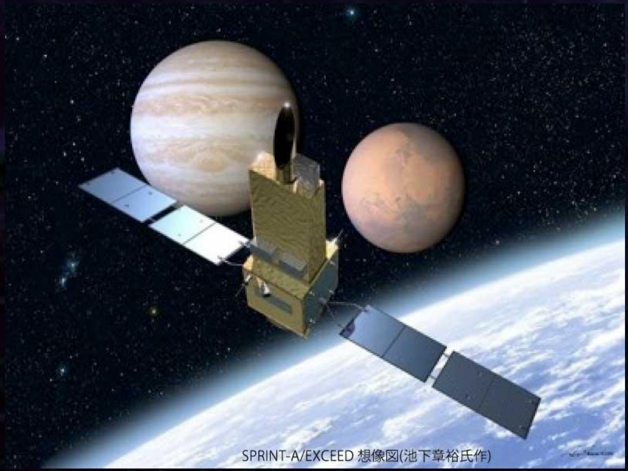
2nd mission (~2014/15) : SPRINT-B/ERG

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

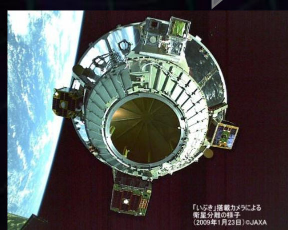
Next-generation Solid rocket booster (M-V FO) Fig. by JAXA

SWIM

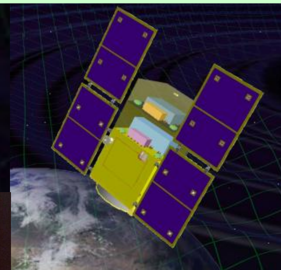
Roadmap

Figure: S.Kawamura

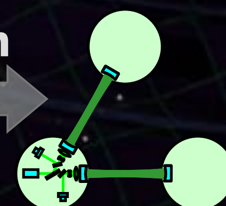
	2010–16	17–22	23–29
Years	2010 11 12 13 14 15 16	17 18 19 20 21 22	23 24 25 26 27 28 29
Mission	R&D Fabrication → SDS-1/SWIM; DECIGO Pathfinder (DPF) (launch: 15)	R&D Fabrication → Pre-DECIGO (launch: 21)	R&D Fabrication → DECIGO (launch: 27)
Objective	Space test of key tech. GW observation	Detect GW 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



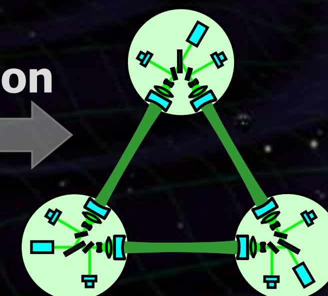
SDS-1/SWIM



DECIGO Pathfinder (DPF)



Pre-DECIGO



DECIGO

SWIM launch and operation

Tiny GW detector module

Launched in Jan. 23, 2009

⇨ In-orbit operation

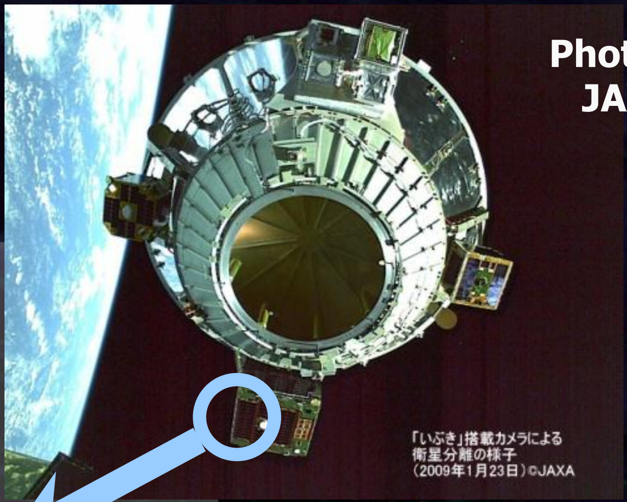
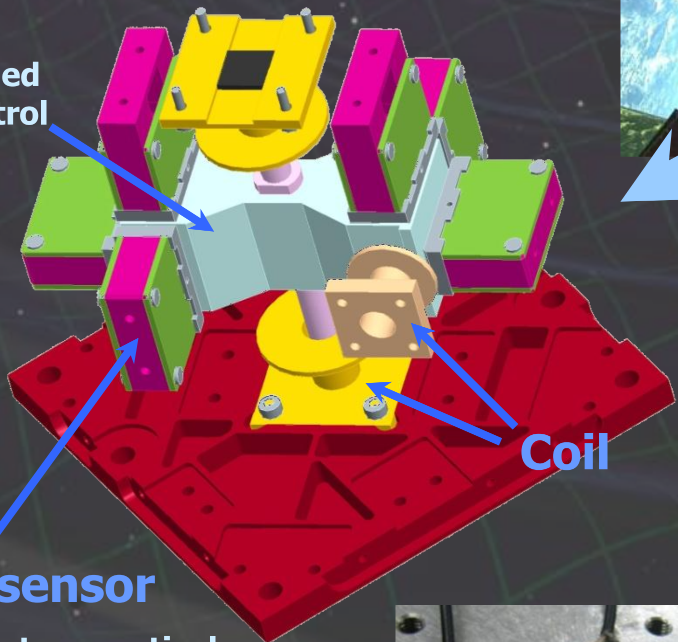


Photo: JAXA

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

Test mass

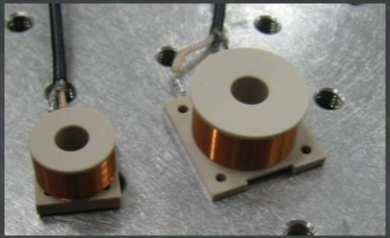
~47g Aluminum, Surface polished
Small magnets for position control

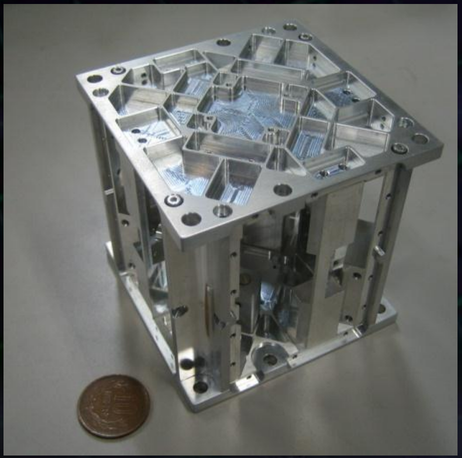


Coil

Photo sensor

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



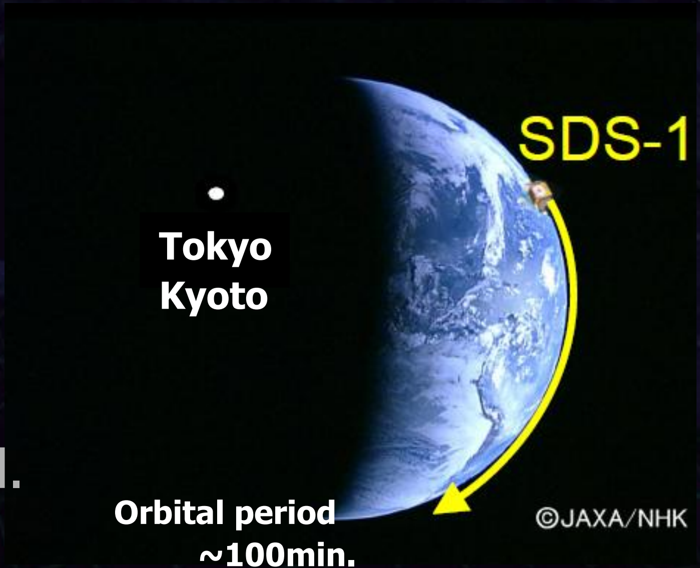


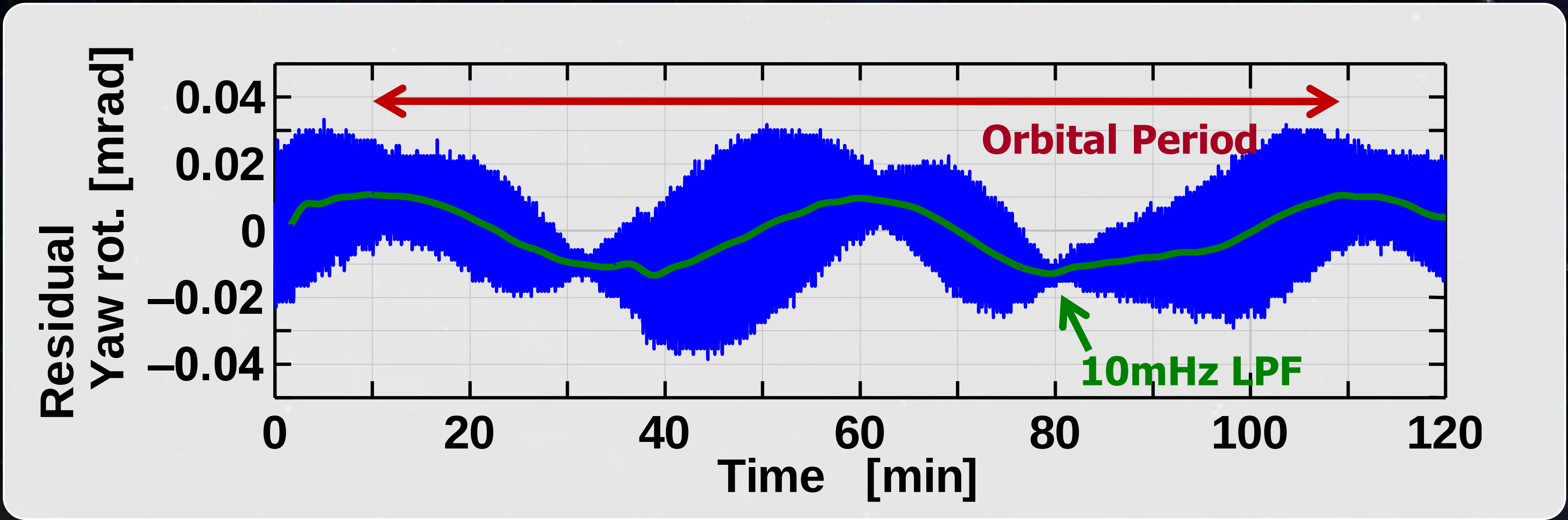
SWIM observation

Observation by SWIM

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

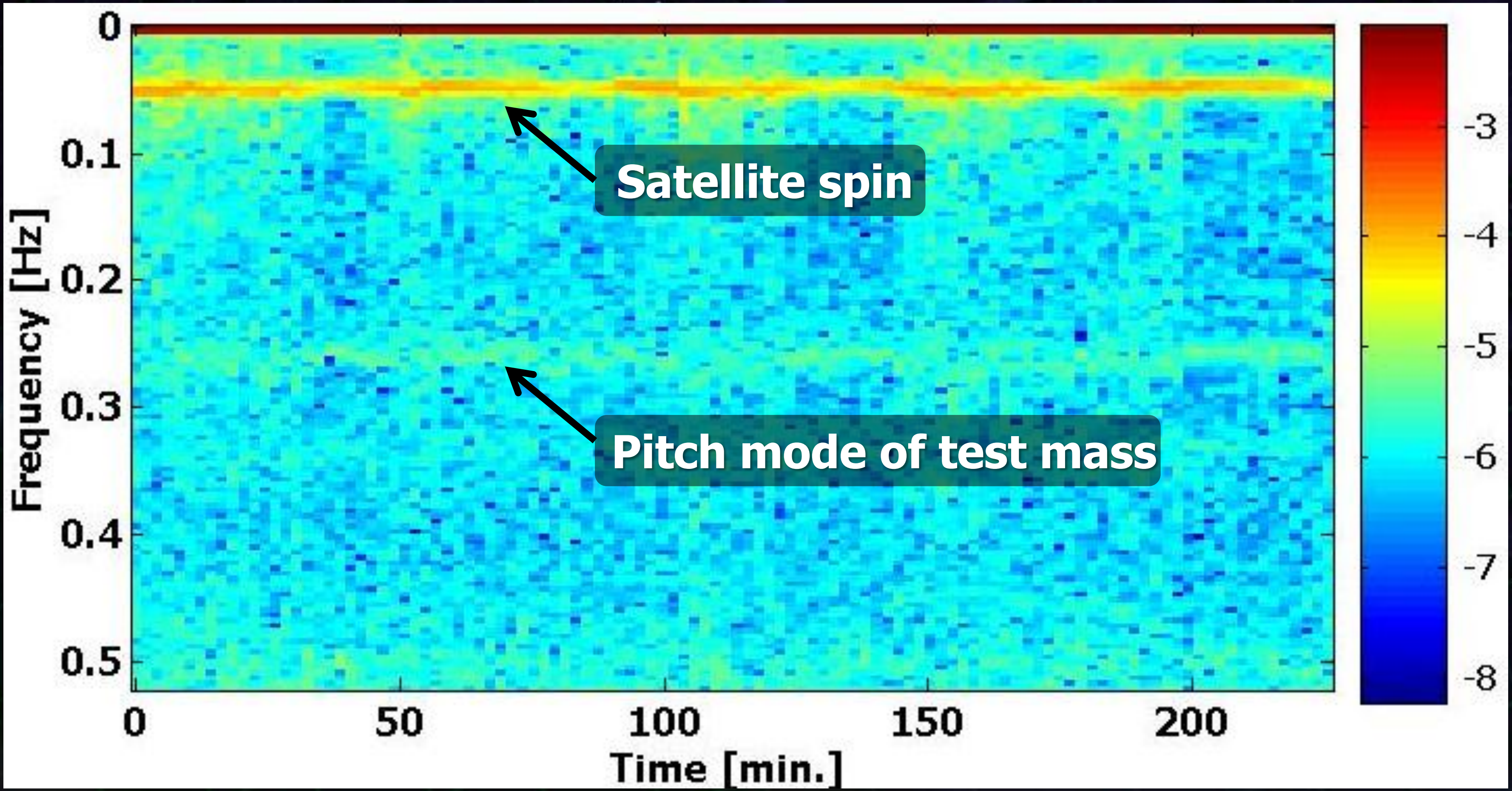
Ground-based detectors were operated at the same period.





SWIM observation

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



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

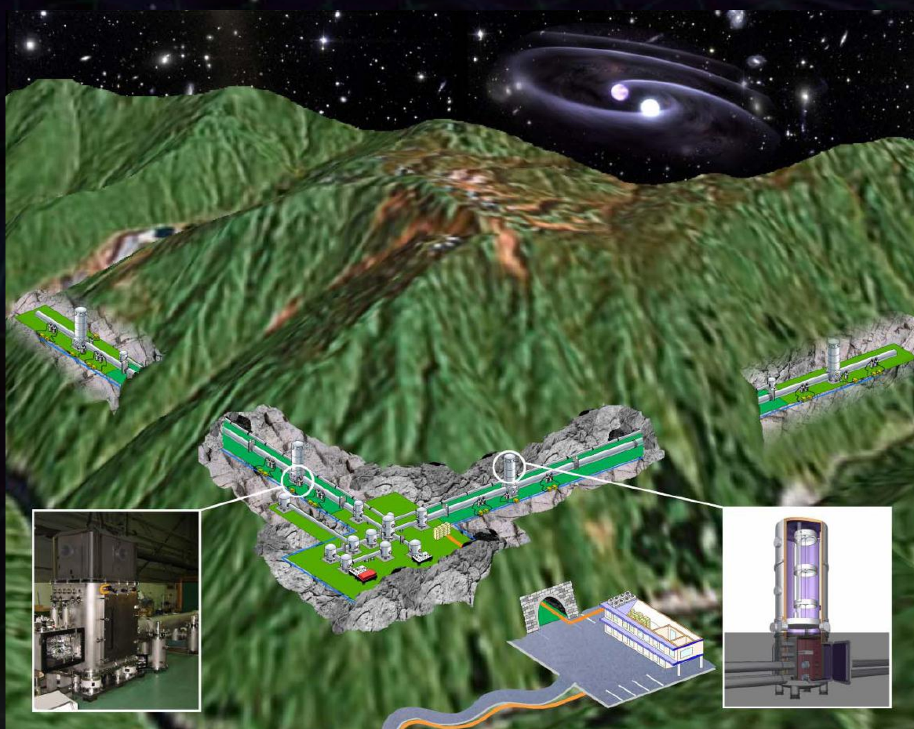
Target: GW detection

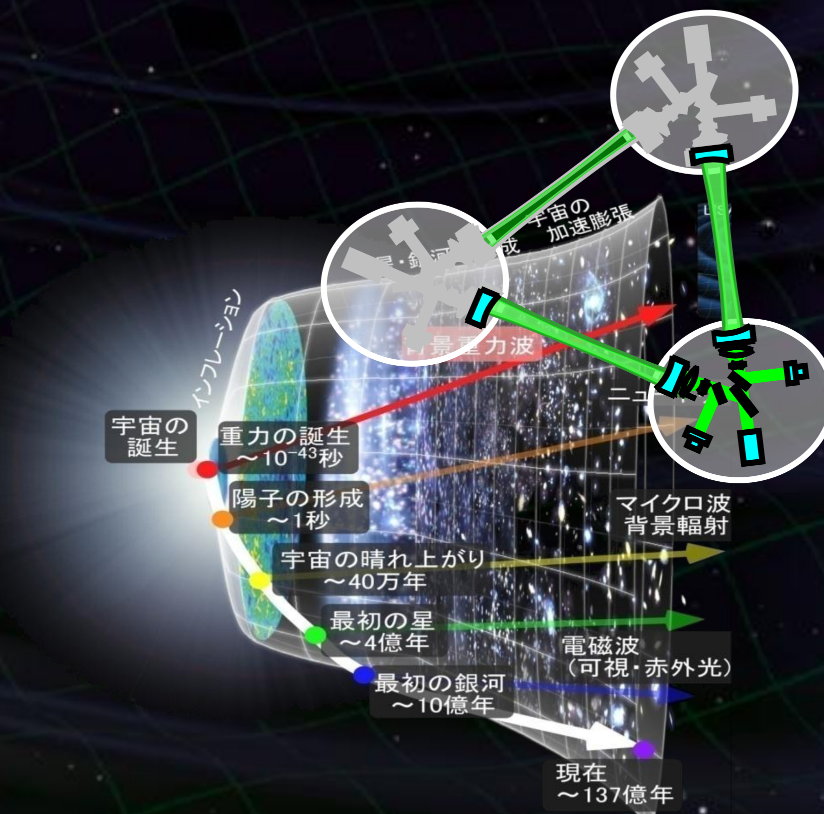
DECIGO (~2027)

Space observatory

→ Low frequency sources

Target: GW astronomy





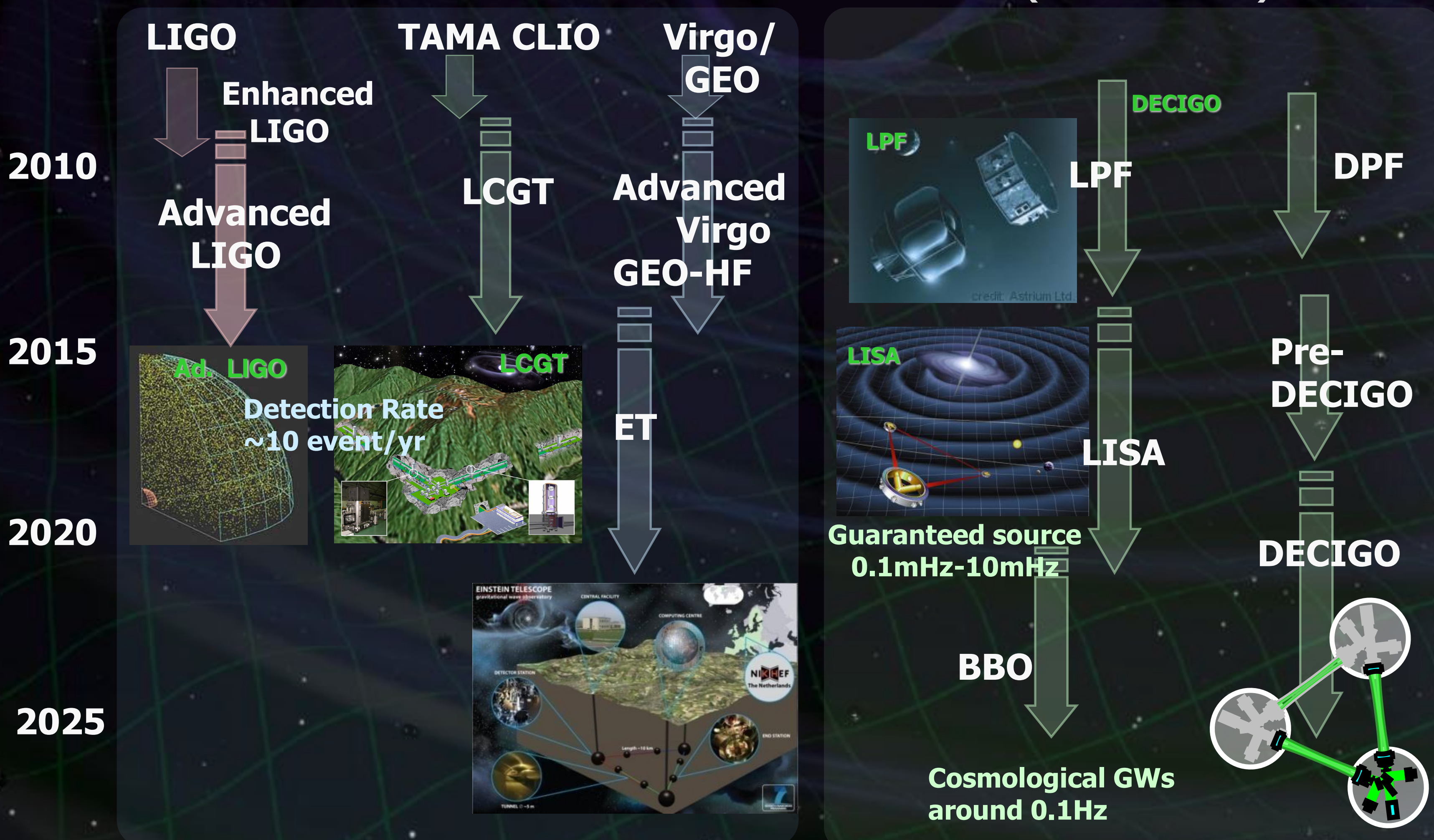
Roadmap of GW detectors

Ground based detectors

Improved sensitivities (10-1kHz)

Space-borne detectors

Low-frequency sources
(0.1mHz – 1Hz)



End