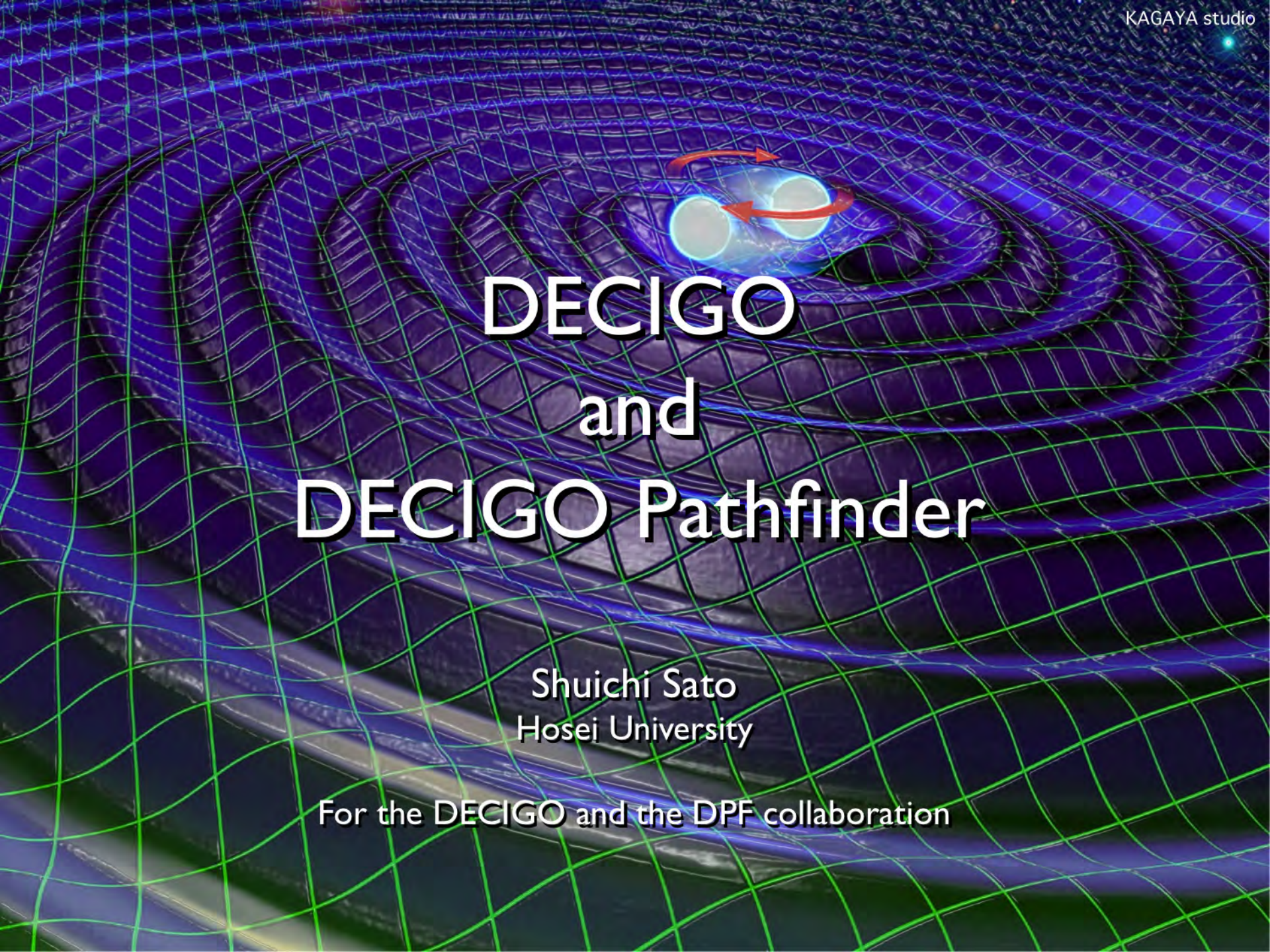


DECIGO and DECIGO Pathfinder

Shuichi Sato
Hosei University

For the DECIGO and the DPF collaboration

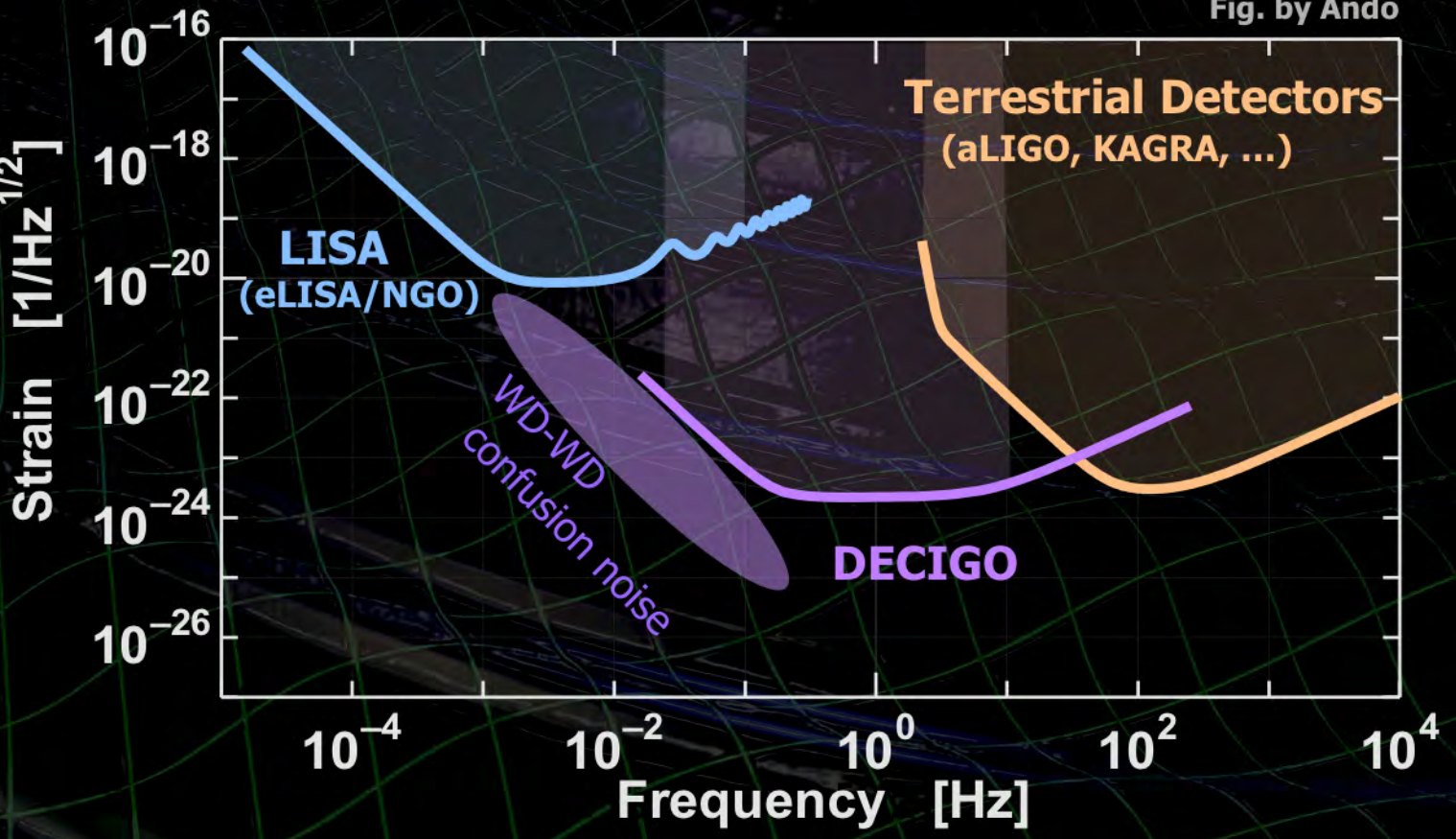
Outline

- DECIGO
  - Overview
- DECIGO pathfinder
  - Overview
  - Mission status
  - Subsystem status
- Summary

Idea of DECIGO

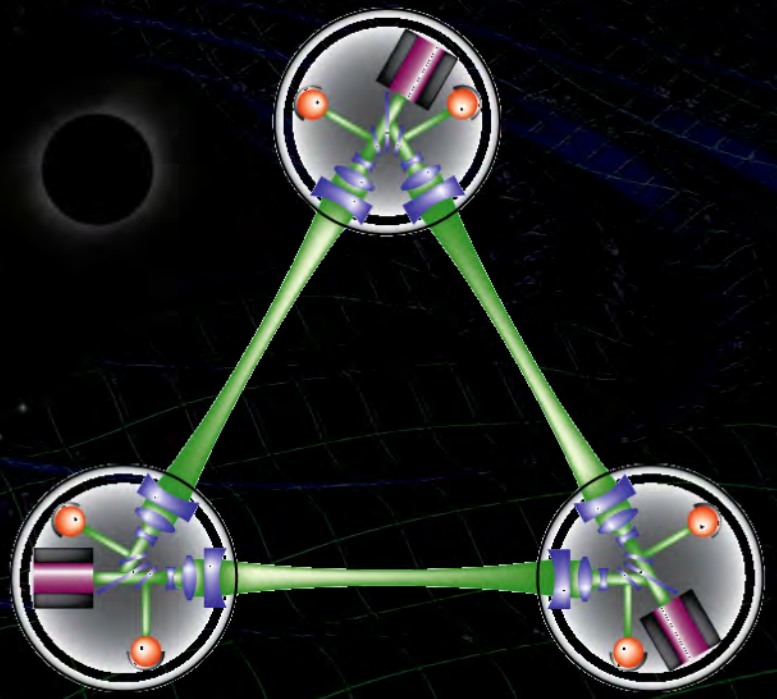
- DECi-hertz Interferometer Gravitational wave Observatory
  - Seto, Kawamura and Nakamura, *PRL87, 221103(2001)*
  - Bridges the gap between LISA and terrestrial detector
  - Low confusion noise → Potentially high sensitive instruments

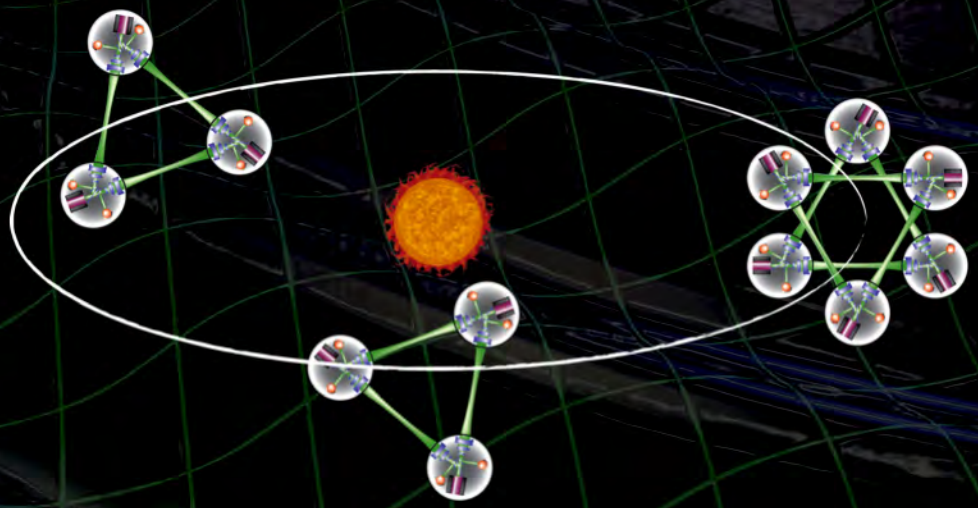
Fig. by Ando



Pre-conceptual design

- 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





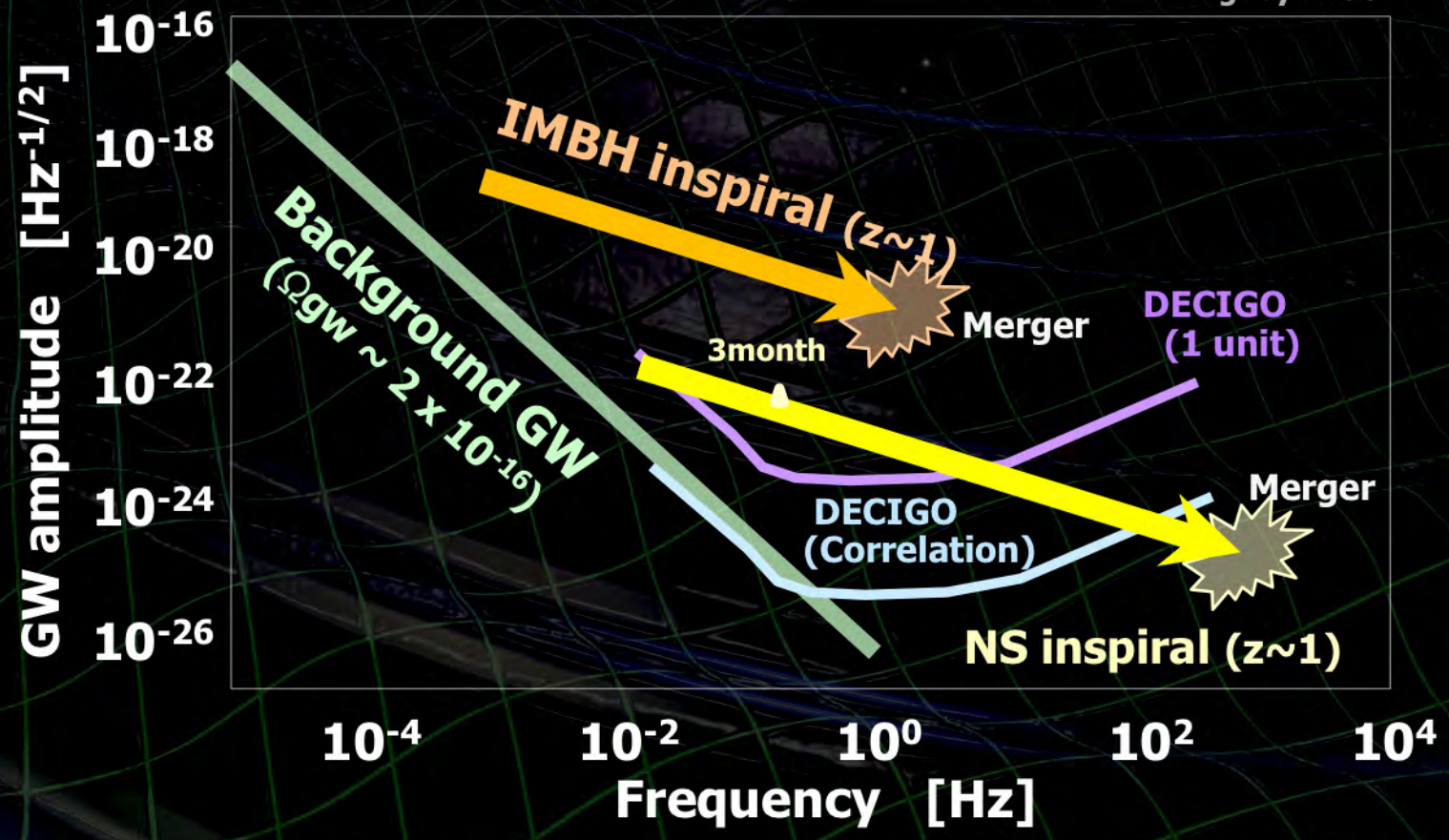
Arm length:	1000 km
Mirror diameter:	1 m
Mirror mass:	100 kg
Laser wavelength :	532 nm
Laser power:	10 W
Finesse:	10

Science of DECIGO

- IMBH binary inspiral
- NS binary inspiral
- Stochastic background

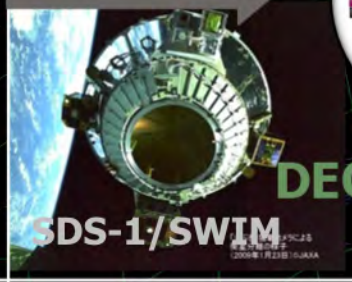
- Galaxy formation (Massive BH)
- Cosmology (Inflation, Dark energy)
- Fundamental physics

Fig. by Ando



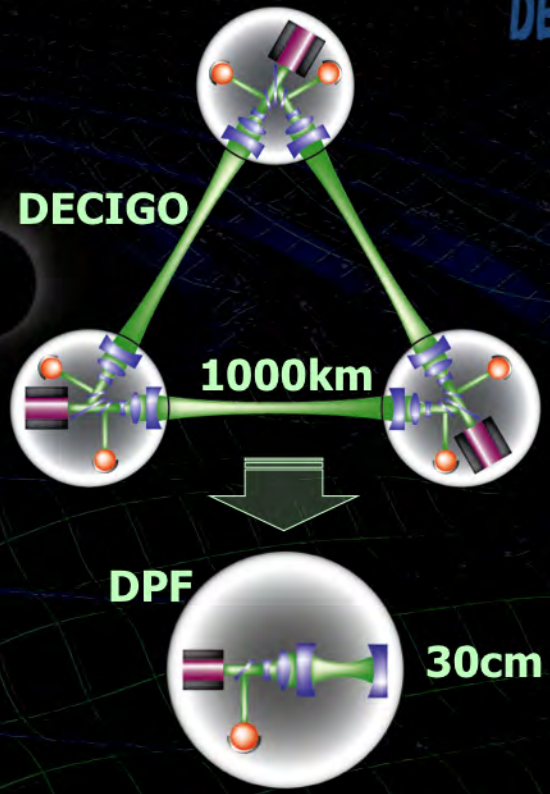
Roadmap

Fig. by Kawamura, rev.

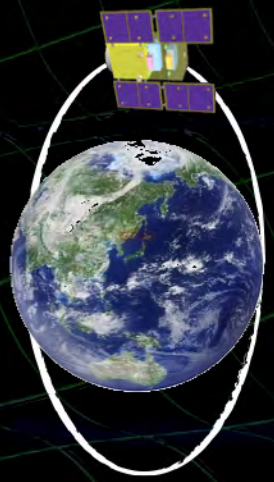
	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Mission	R&D Fabrication								R&D Fabrication							R&D Fabrication				
	 SDS-1/SWIM								DECIGO Pathfinder (DPF)							Pre-DECIGO				DECIGO
Objectives	Test of key tech. in orbit GW detection Earth gravity observation										Detection of GW w/ min. spec. FP cavities between S/Cs						GW astronomy			
Scope	Single small S/C Short FP interferometer										3 S/Cs, single IFO Single unit						3 S/Cs, 3 IFOs 3 or 4 units			

DECIGO pathfinder (DPF)

- First precursor satellite for DECIGO
  - DECIGO: 1000km baseline
    Formation flying S/Cs
  - DPF: 30cm baseline
    Single satellite



- Mission scale: ~350kg
- Orbit: Low earth orbit, 500km
  (sun synchronous polar orbit)
- Launch vehicle: Next-generation
  Solid rocket booster (M-V FO)
- Apply for JAXA's
  "Small science satellite series" program



Mission status of DECIGO pathfinder

- JAXA's "Small science satellite series" program

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

1st mission (2012): SPRINT-A /EXCEED
2nd mission (~2014/15) : SPRINT-B /ERG
3rd mission (~2016/17) : SPRINT-C? /TBD
Call for proposal : 2012!

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

SPRINT-A /EXCEED
UV telescope mission

SPRINT-B /ERG
Plasma observing mission

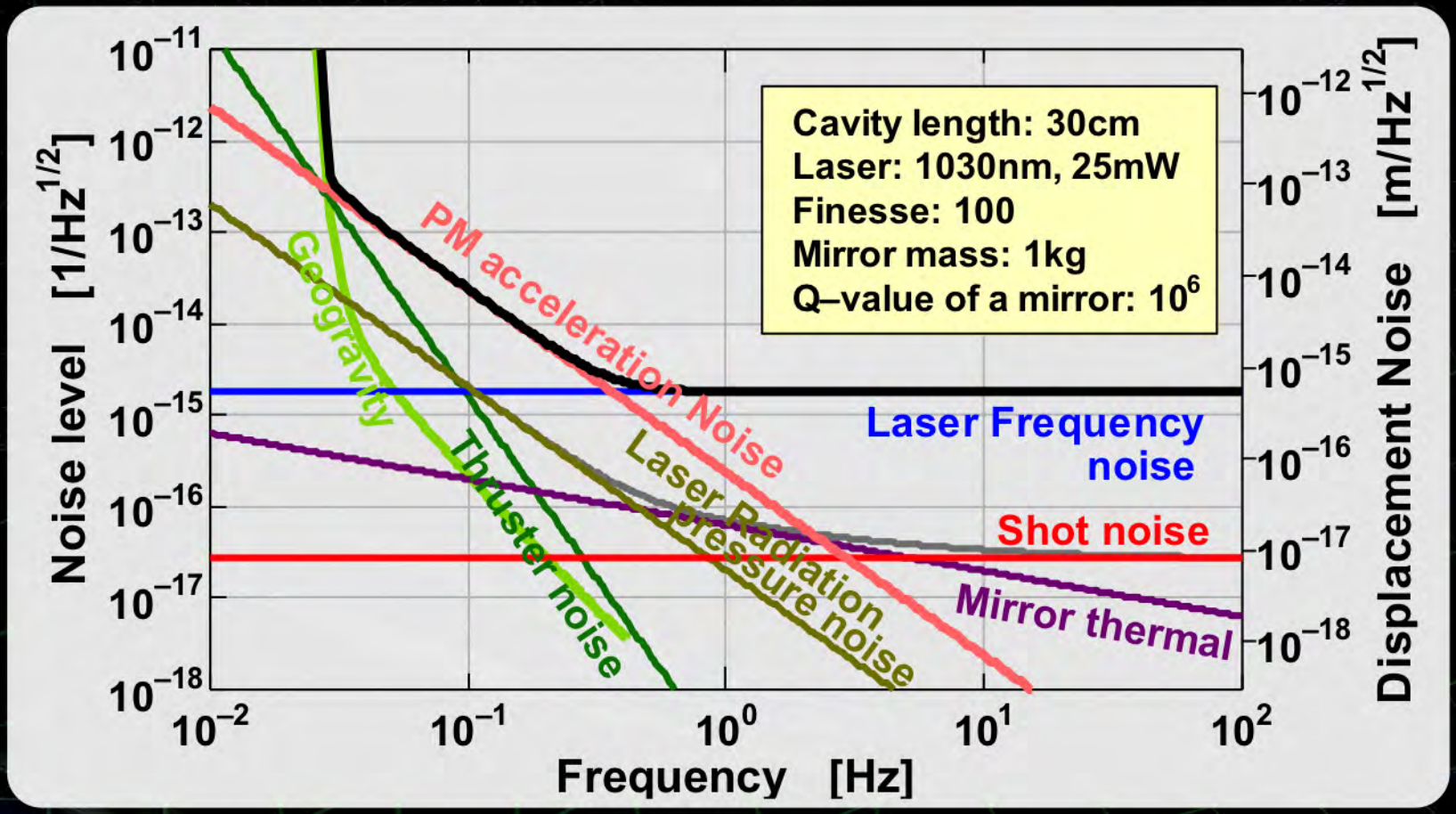
Sensitivity of DECIGO pathfinder

Laser source : 1030nm, 25mW
IFO length : 30cm
Finesse : 100, Mirror mass : 1kg
Q-factor : 10^5, Substrate: TBD
Temperature : 293K

Satellite mass : 350kg, Area: $2m^2$
Altitude: 500km
Thruster noise: $0.1\mu N/Hz^{1/2}$

(Preliminary parameters)

Fig. by Ando



Target of DECIGO pathfinder

- Technical demonstration for DECIGO in orbit
  - Laser interferometry
  - Stabilized laser system
  - Drag-free control system
  - Data acquisition and analysis
- Scientific observations
  - Gravitational Waves form BH mergers
    → BH formation mechanism
  - Gravity of the Earth
    → Geophysics, Earth environment

Fig. by KAGAYA

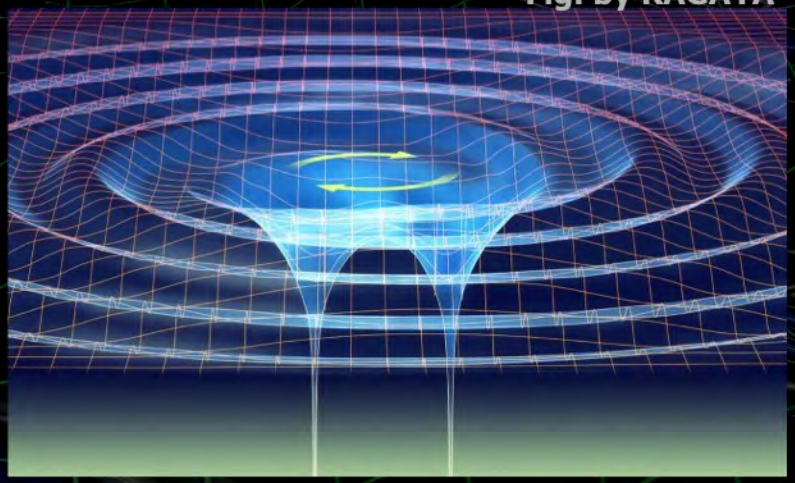
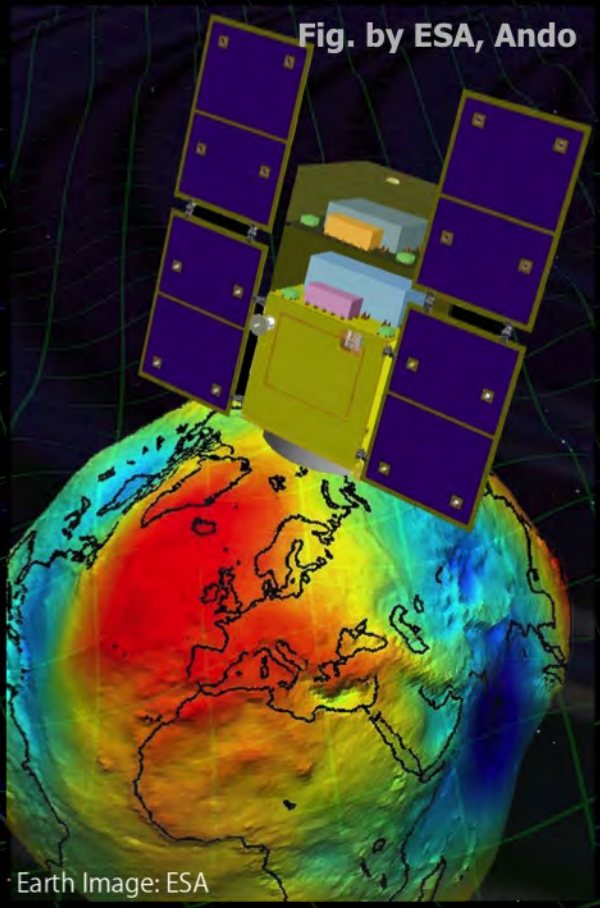


Fig. by ESA, Ando

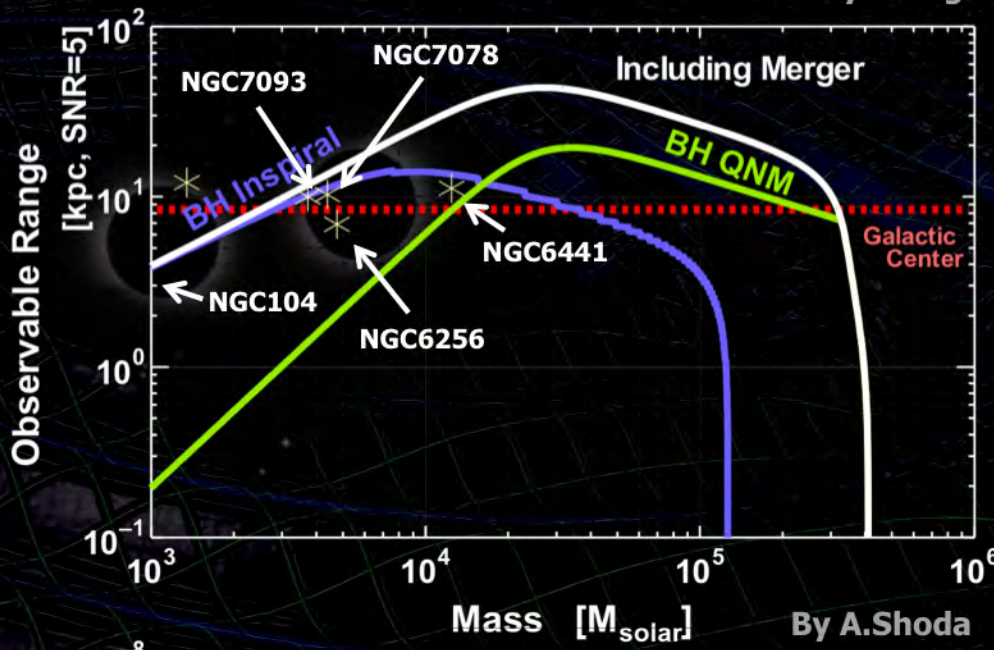


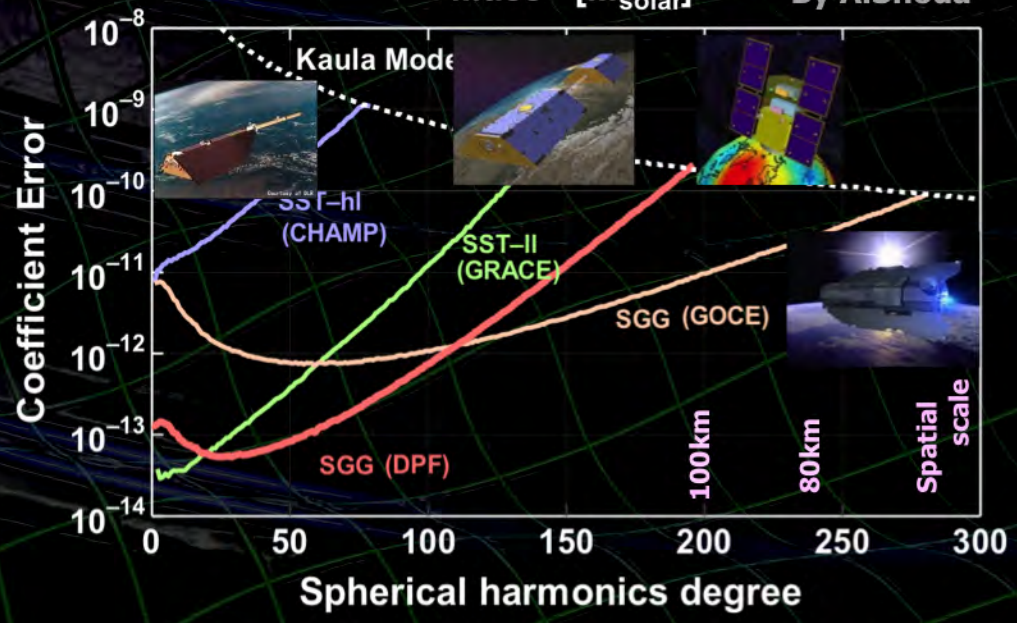
Science of DECIGO pathfinder

- Detection of gravitational wave
  - IMBH merger in our galaxy
    - → Formation mechanism of supermassive BHs
  - ~30 globular clusters in range

K. Yagi, 2012 *Class. Quantum Grav.* 29 075005
"Gravitational wave observations of galactic intermediate-mass black hole binaries with DECIGO Path Finder"

- Observing earth gravity
  - Gravitational potential
    - → Shape of the earth
    - → Environment monitor
  - Comparable to GOCE, GRACE
  - Could join to the network





DPF satellite overview

DPF Payload

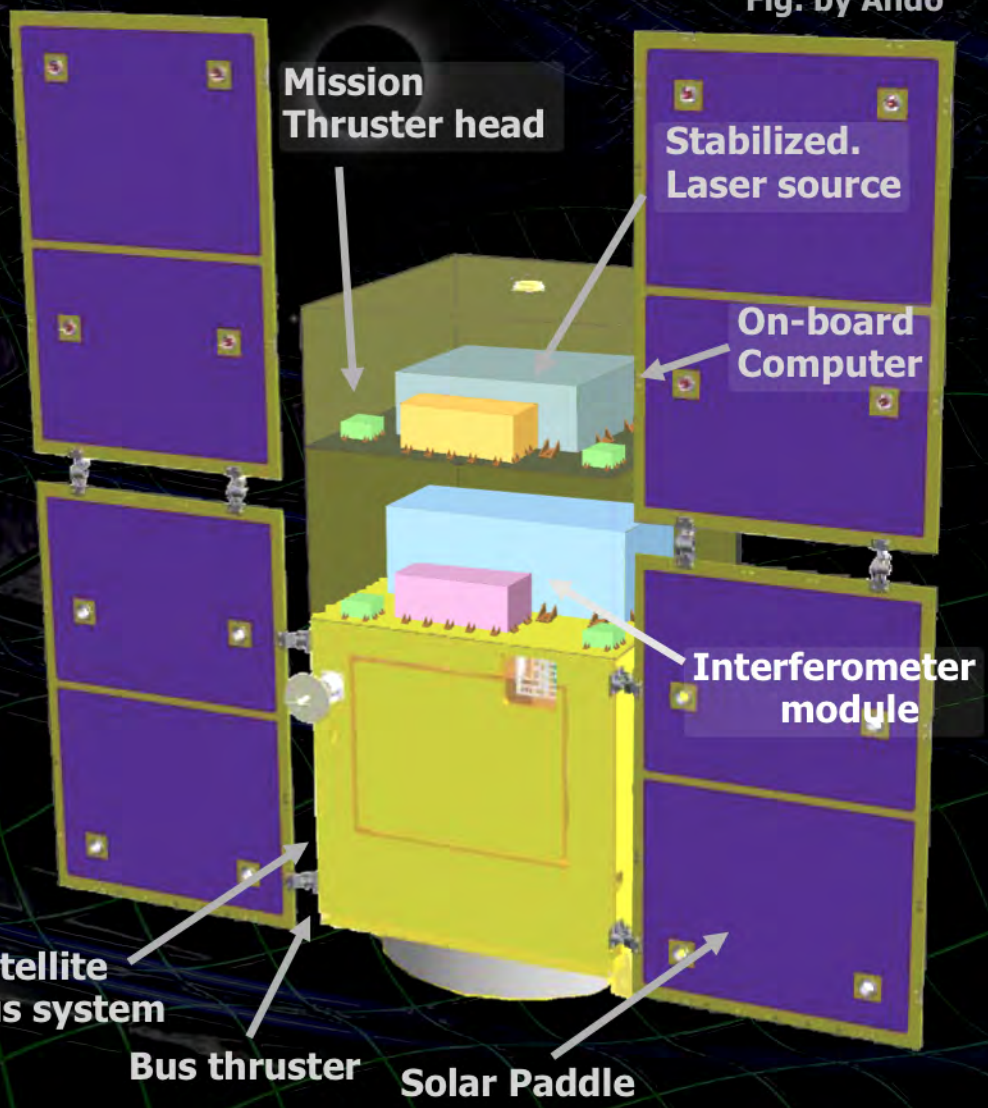
Size : 950mm cube
Weight : 150kg
Power : 130W
Data Rate: 800kbps
Mission thruster x12

Power Supply
SpW Comm.

Satellite Bus

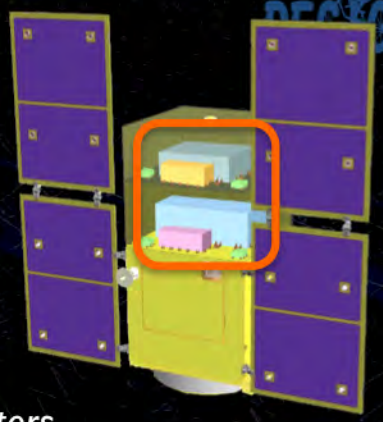
('Standard bus' system)
Size : 950x950x1100mm
Weight : 200kg
SAP : 960W
Battery: 50AH
Downlink : 2Mpbs
DR: 1GByte
3N Thrusters x 4

Fig. by Ando



DPF mission system (schematic)

Mission weight : ~150kg (200kg for bus)
Mission space : ~95 x 95 x 90 cm



Drag-free control
Local sensor signal
→ Feedback to thrusters

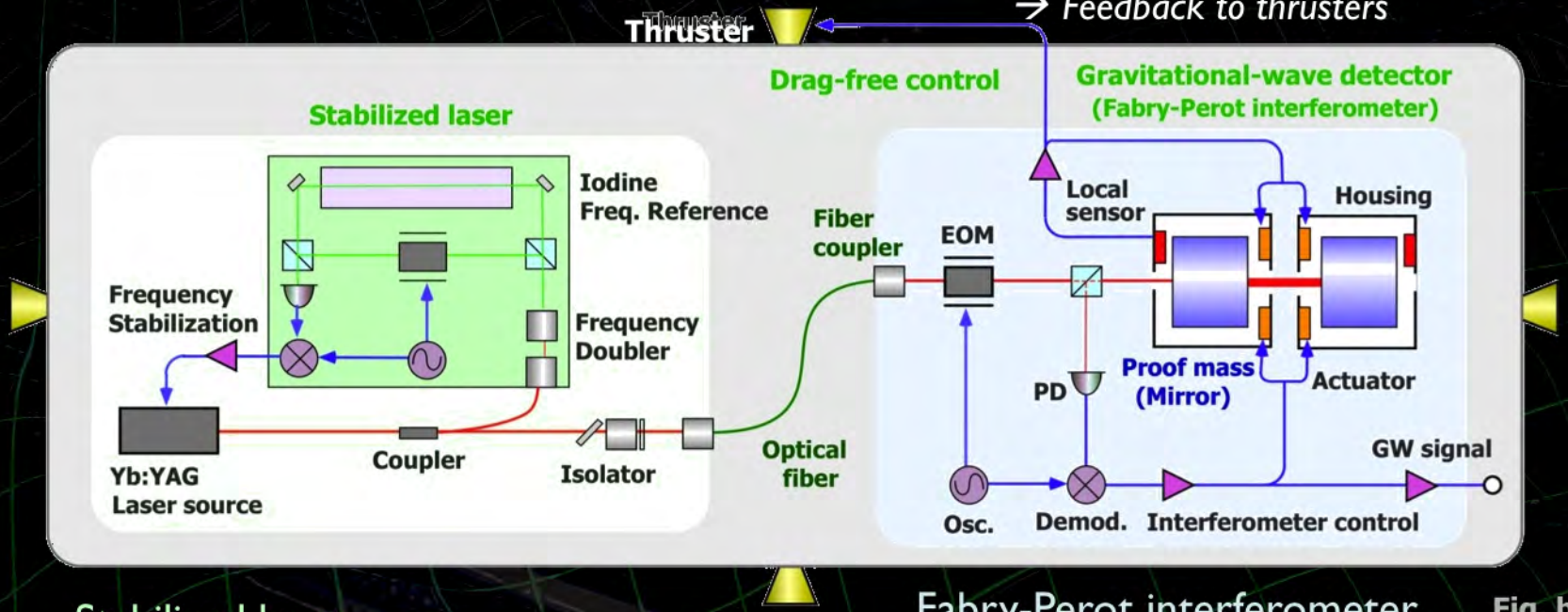


Fig. by Ando

Stabilized laser

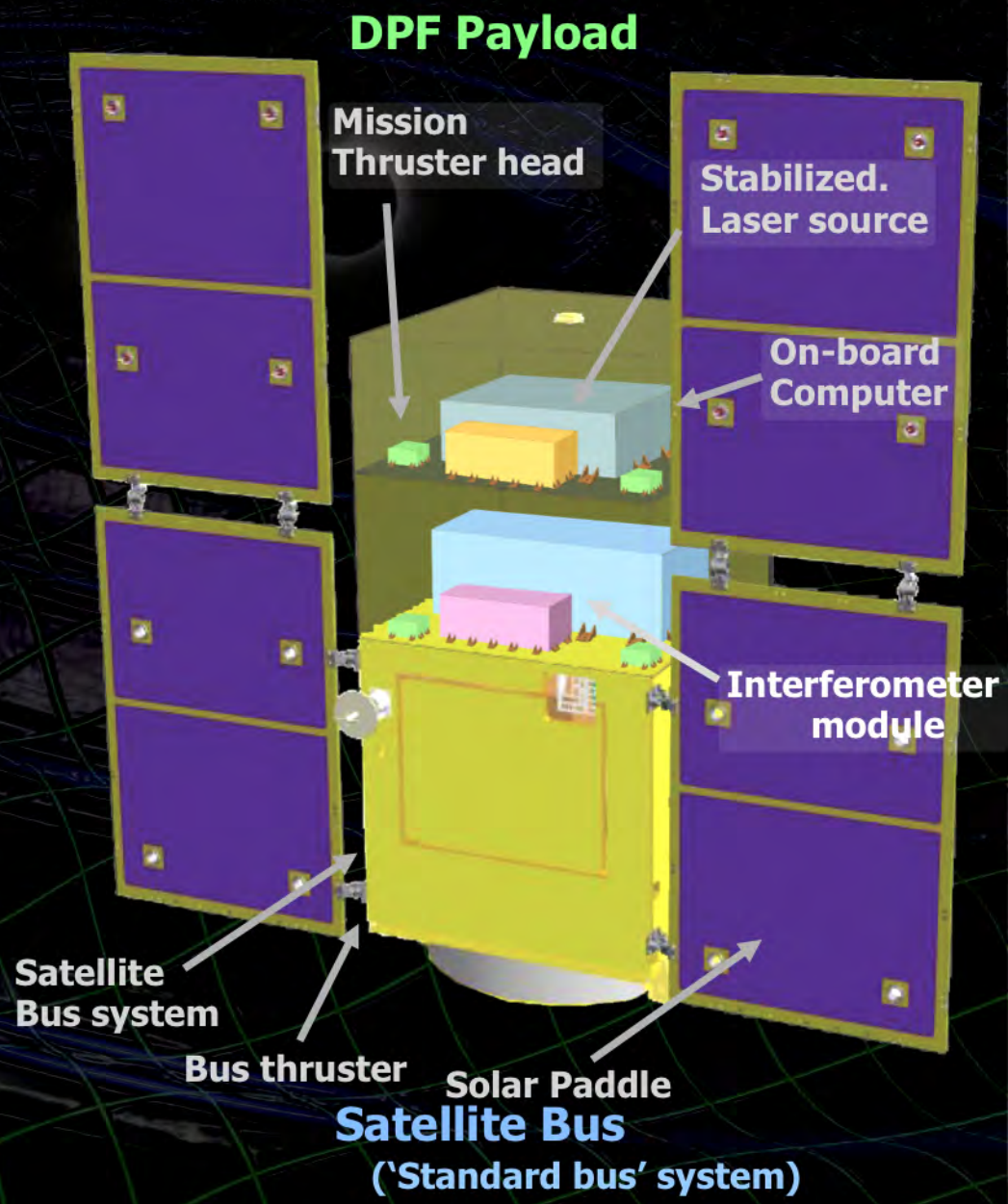
Yb:YAG laser (1030nm)
Power : 25mW
Freq. stab. by Iodine absorption line

Fabry-Perot interferometer

Finesse : 100
Length : 30cm
Test mass : ~1kg
Signal extraction by PDH

Mission module/system on-board

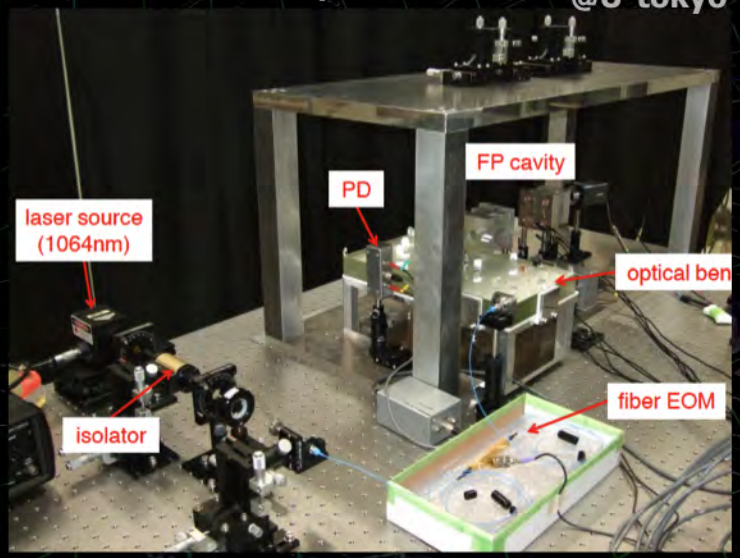
- Interferometer module
  - Test mass module
    Test mass, caging frame, laser sensor, Electro static sensor/actuator, Test mass lock mechanism, Charge management system
  - Input/output optics
    Monolithic optical bench, PDH control, WFSs, MMT
  - Structure/shielding system
    Support frame, thermal shielding, Vacuum enclosure
- Stabilized laser module
- Attitude/drag-free control system
- Signal processing/control system

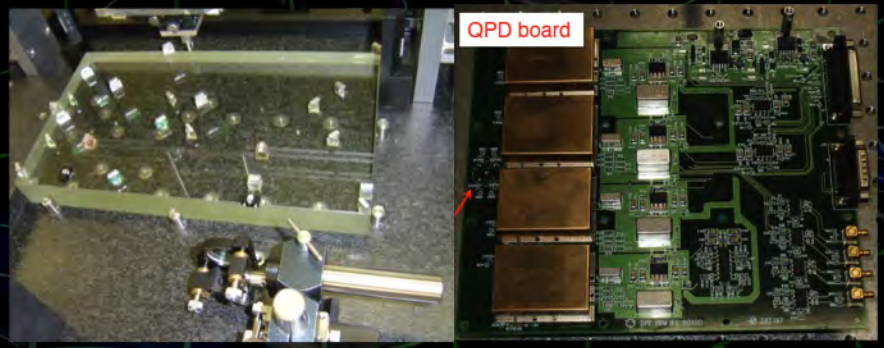


Interferometer module

- BBM
  - Assembly of components
    Test mass, Electronics,
    Monolithic optical bench,…
- FP functionality test

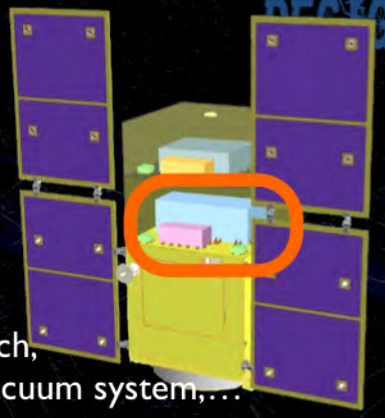
@U-tokyo

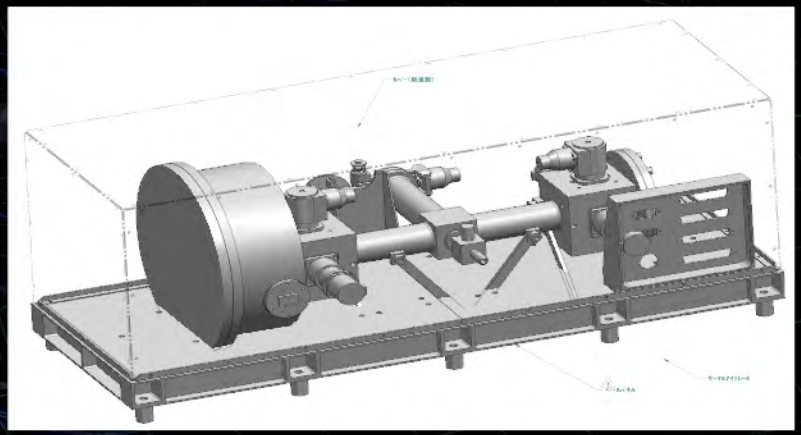


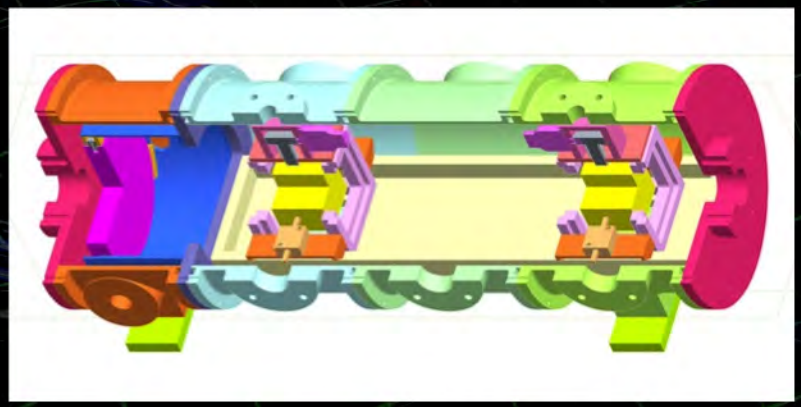


- BBM2 design
  - As complete module
    Test mass module,
    Monolithic optical bench,
    30cmIFO, Structure, vacuum system,…
  - Compatible with mission

@NAOJ



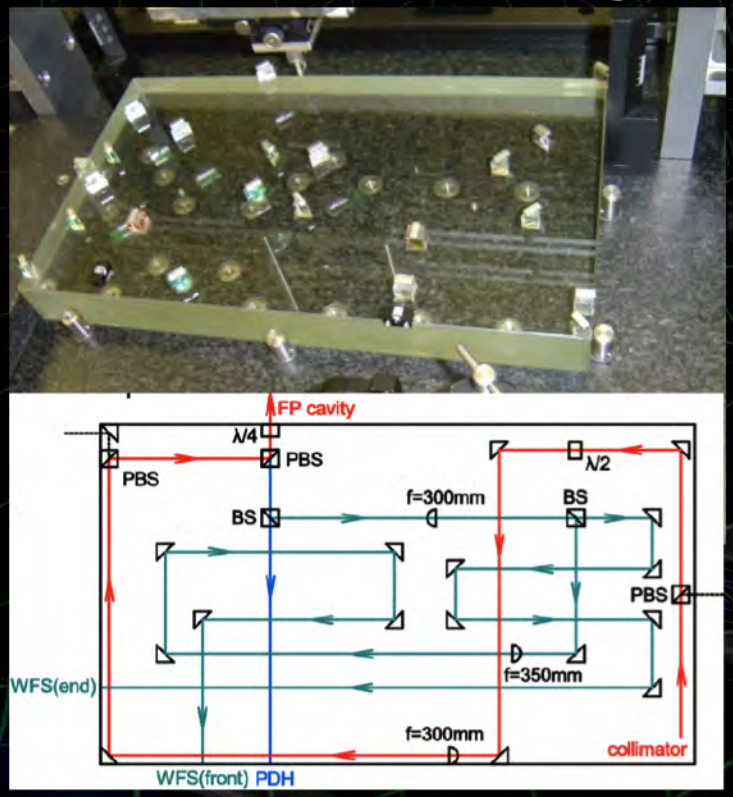




Input/output optical system

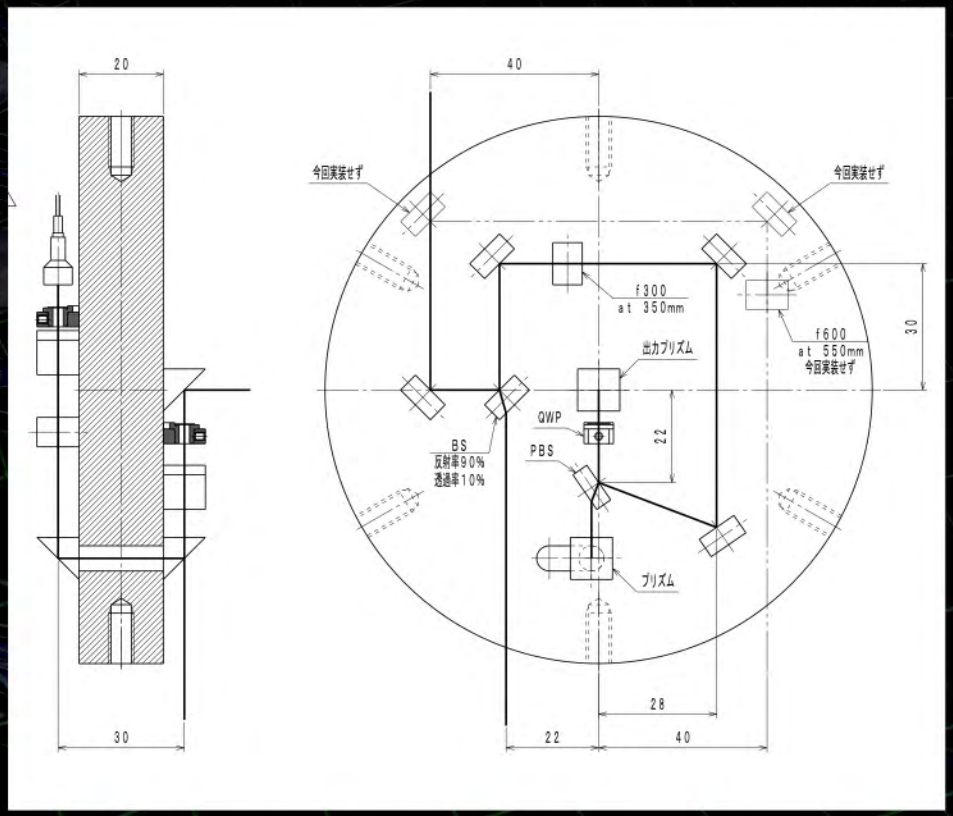
- IOO BBM
  - Optical design
    Mode matching, WFSs, GPTs,…
  - Monolithic optical bench
  - Silicate bonding
  - 350x200mm size

@NAOJ

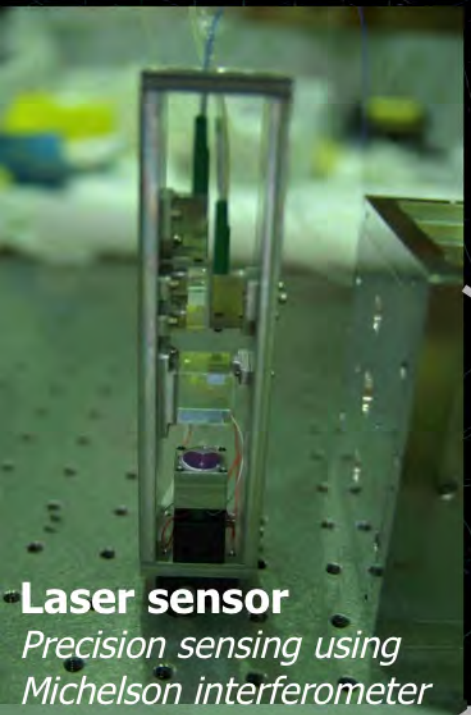


- IOO BBM2 design
  - Compactify for IFO BBM, 120mmø
  - Optics bonded on both sides
  - I/F mechanics to IFO frame

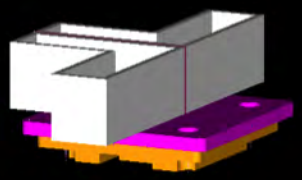
@NAOJ



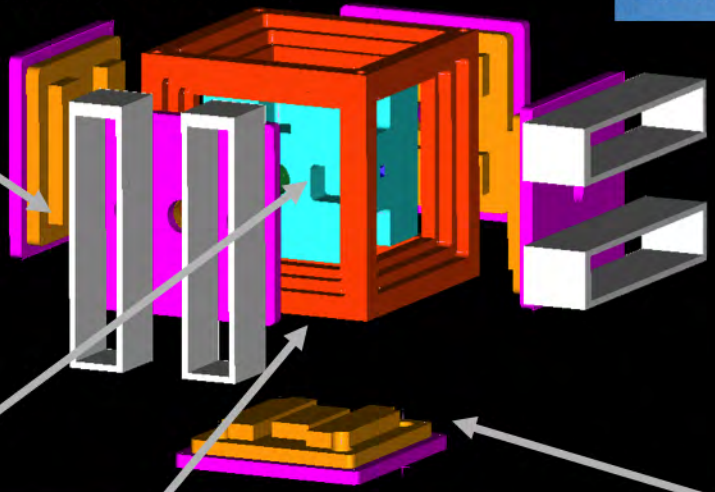
Test-mass module (1)

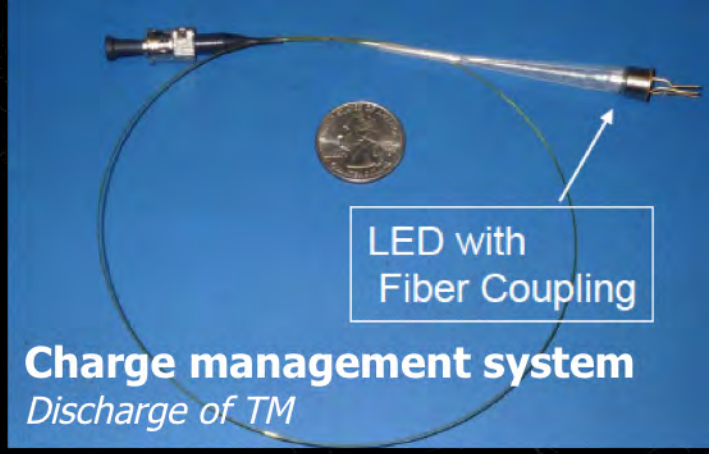


Laser sensor
Precision sensing using Michelson interferometer



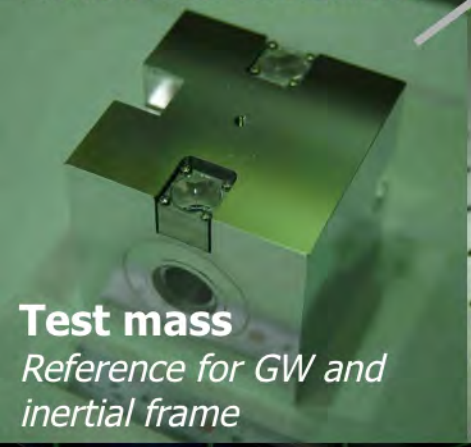
Test mass module



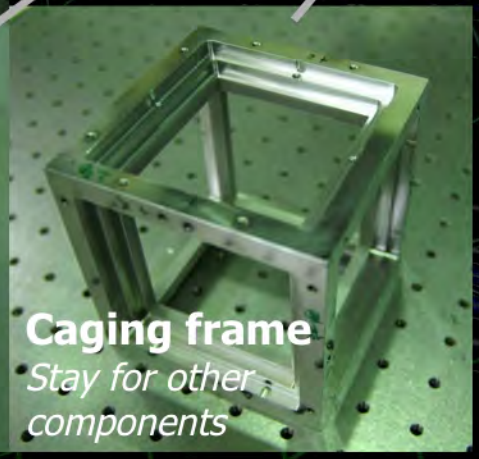


Charge management system
Discharge of TM

Clump release/ Launch lock mechanism



Test mass
Reference for GW and inertial frame

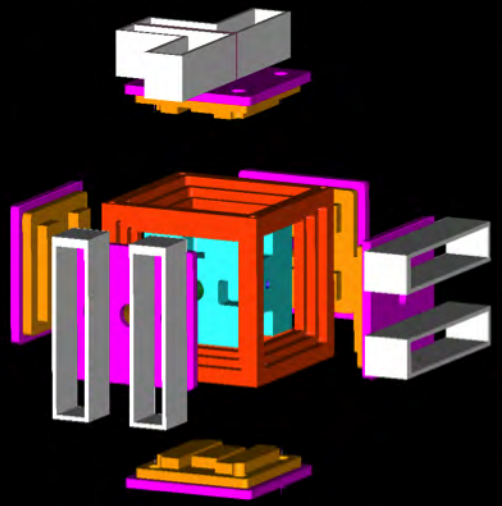


Caging frame
Stay for other components

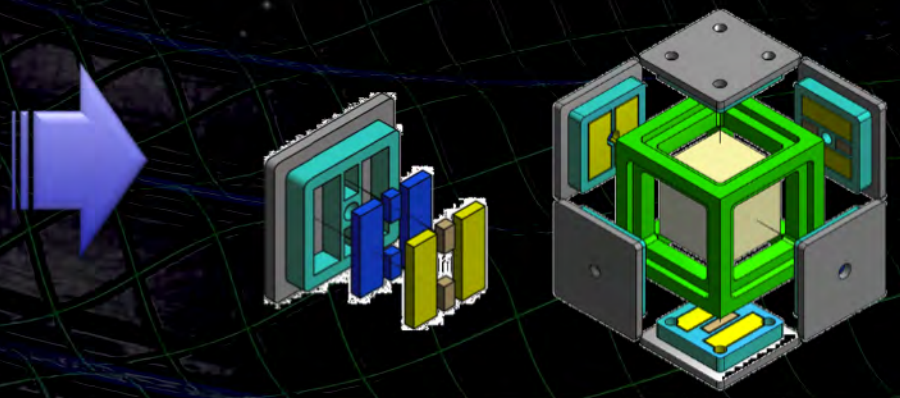
Electrodes for electrostatic sensor/actuator
Local sensing actuation of TM

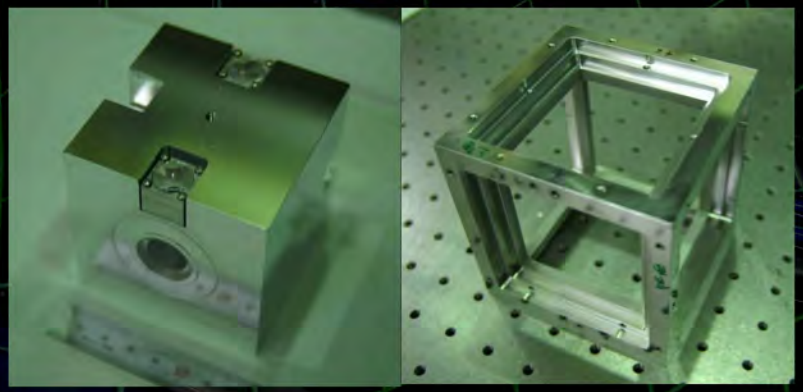
Test-mass module (2)

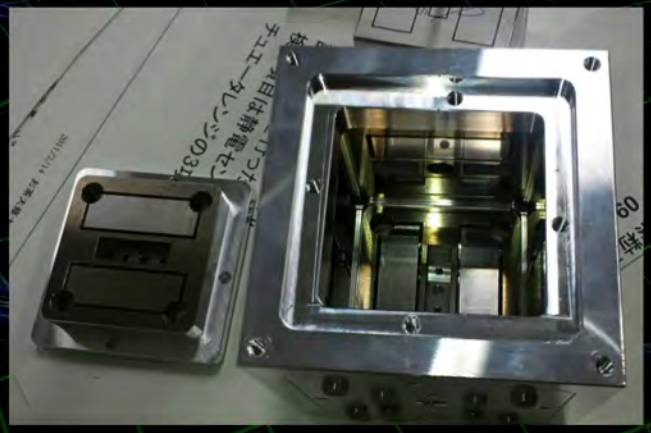
- TM-module BBM @NAOJ
  - Test mass: 70mm cube
  - Al, ~2kg
  - HR mirror for FP cavity
  - 6 corner-cube reflector



- TM-module BBM2 @NAOJ
  - Test mass: 50mm cube
  - Redesigned ES sensor property
  - Optimized electrode design

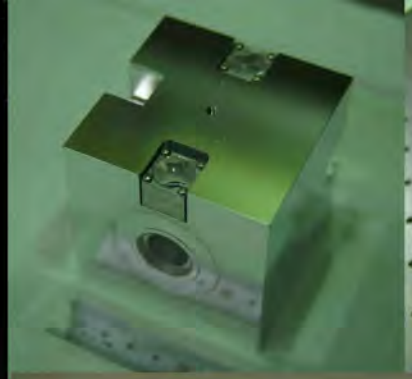


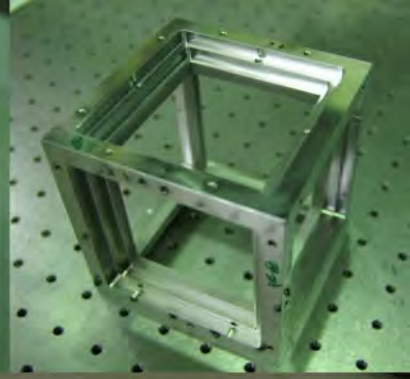




Test-mass

- Test mass
  - Low susceptibility (10^{-6}[SI])
  - High density material
  - Mass ~1kg
- Exploring material
  - Alloy of paramagnet / diamagnet
  - Reasonable combination of elements
  - Hopefully not precious metals





Al-Cu case

Al-Sn case

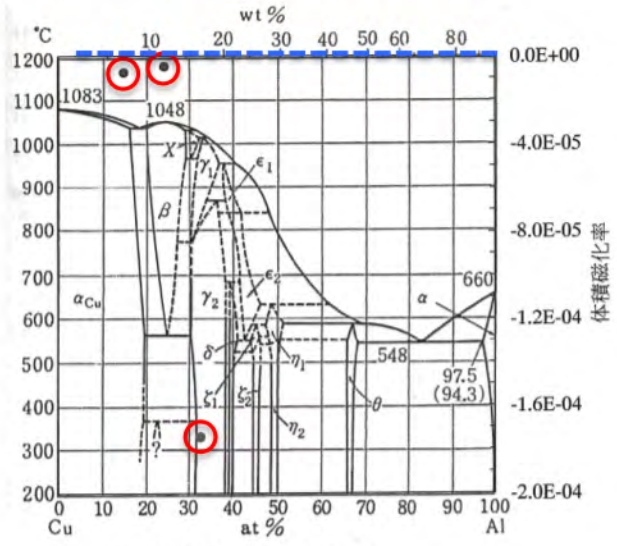


図 3・91 Al—Cu（解説：右段）

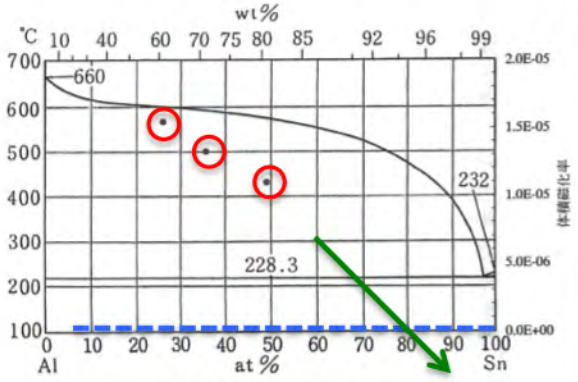


図3・114 Al—Sn

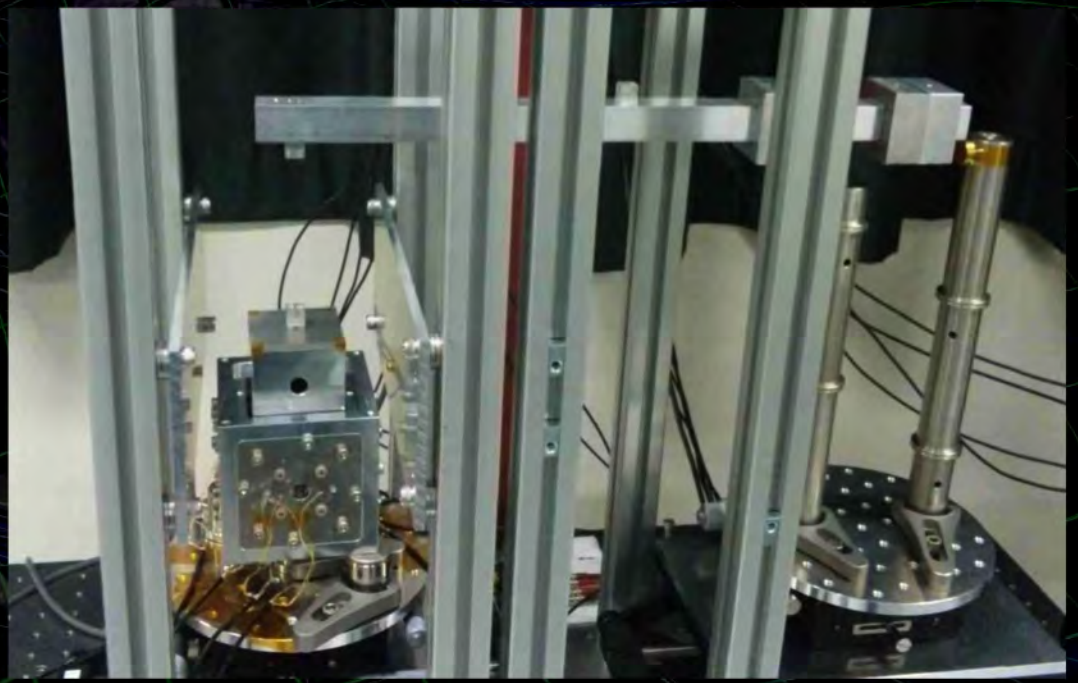
表－3

合番	主な成分	磁化率
1	Be-Cu(ALLOY17410)	9.94×10^{-5}
2	Be-Cu(BRUSH60)	2.26×10^{-5}
3	7wt%Al-93wt%Cu	-7.04×10^{-6}
4	12wt%Al-88wt%Cu	-4.34×10^{-6}
5	17wt%Al-83wt%Cu	-1.74×10^{-4}
6	19wt%Al-81wt%Sn	1.10×10^{-5}
7	29wt%Al-71wt%Sn	1.33×10^{-5}
8	39wt%Al-61wt%Sn	1.55×10^{-5}

Test-mass module test

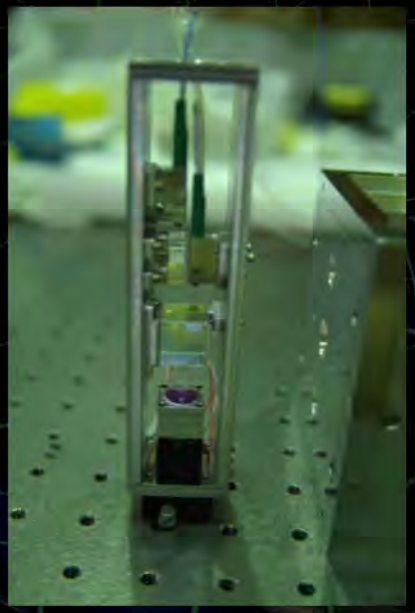
- ES sens./act. test @NAOJ
  - Assembly of components
  - Double pendulum
  - BBM electrode
  - Sense/actuate 2 dof
- Combination test with digital control
  - FPGA+SpC sytem

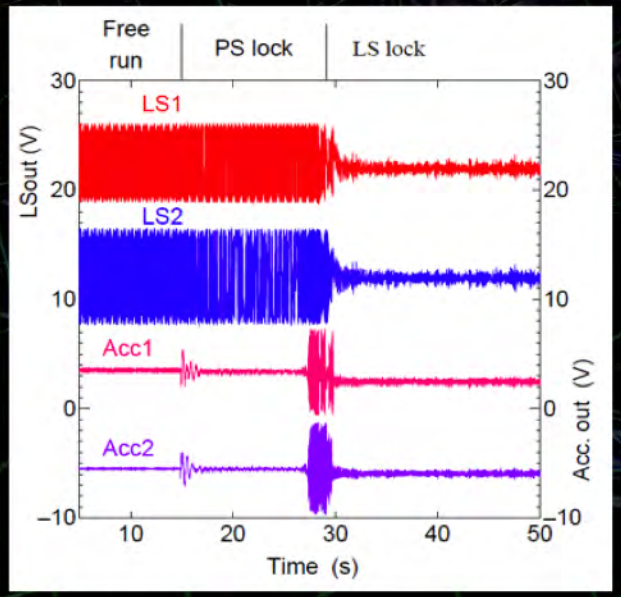
- BBM2 test @NAOJ
  - Test mass module BBM2
  - Double torsion pendulum
  - 2 dof control

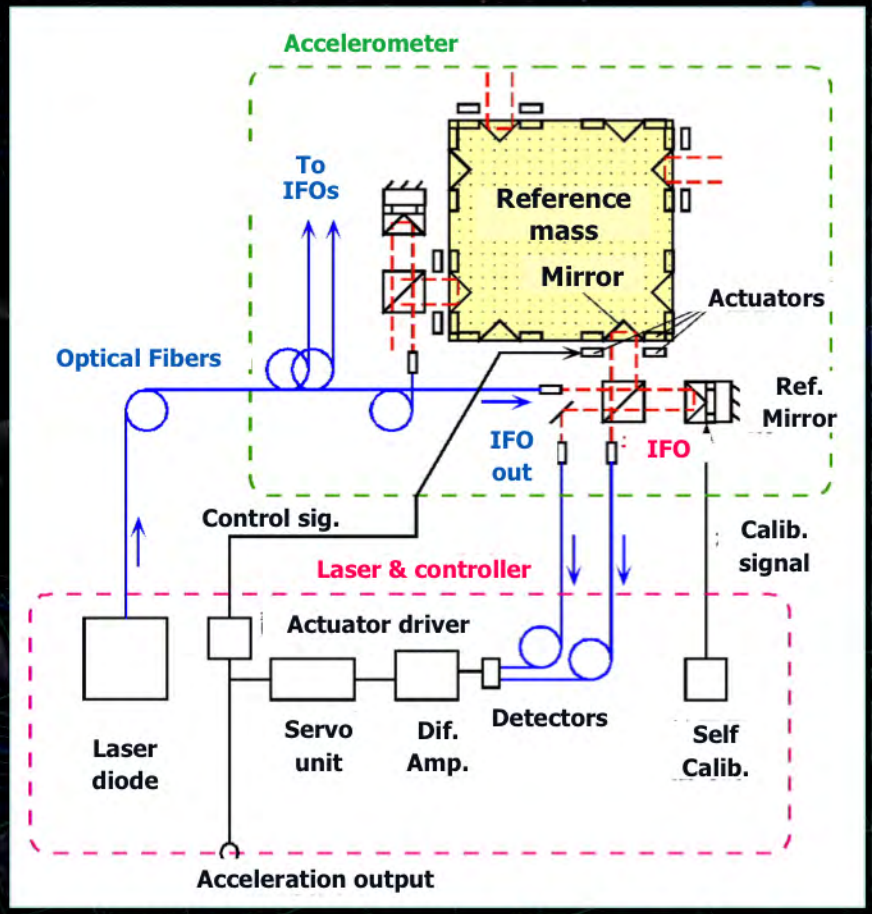


Laser sensor

- Precision displacement sensor for earth gravity measurement
- Michelson laser interferometry
  - Light source : fiber-coupled DFB laser
  - Offset layout using corner cube reflector
- 6 modules on 3 faces : for 6 d.o.f. sensing
- BBM: 30x30x130mm module
- Initial functionality test
- Control demonstration /characterization

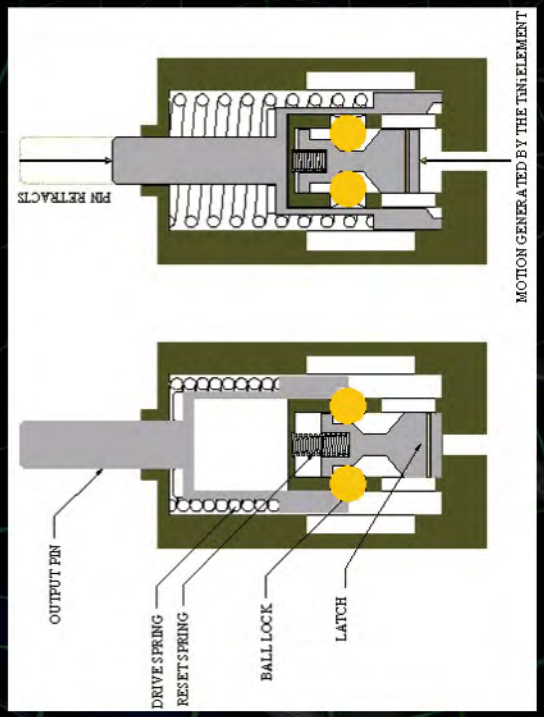


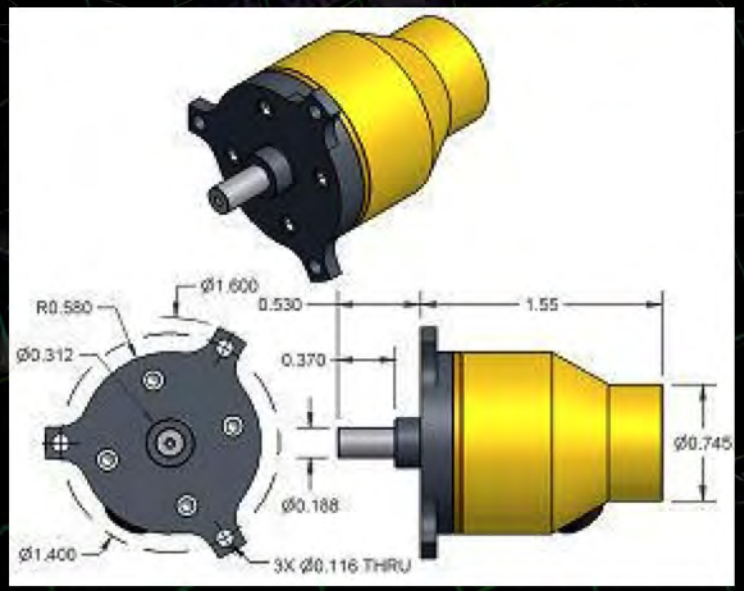


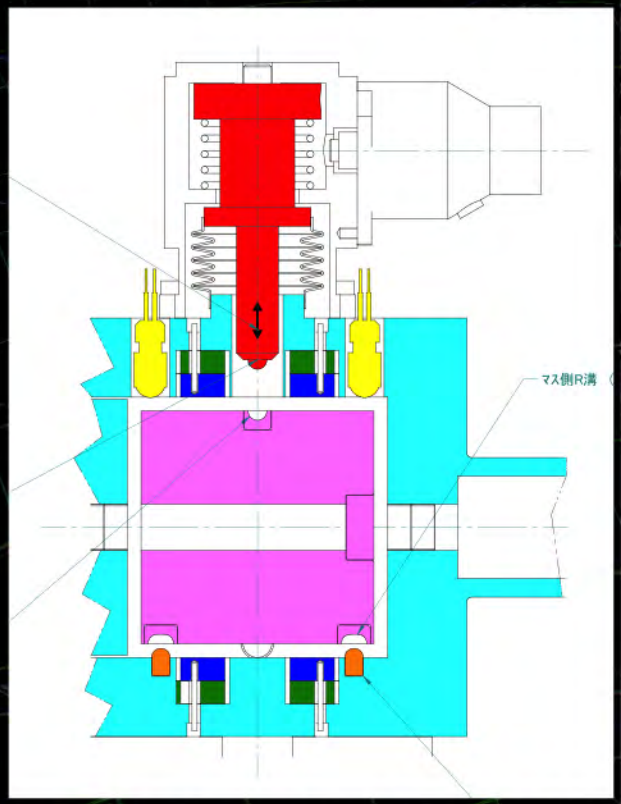


Test-mass lock mechanism

- Cramp-release @NAOJ
  - Piezo motor / Shielded stepping motor
  - Kick velocity measurement ongoing
- Launch-lock
  - Active actuator: Hydraulic motor (LPF)
  - Passive mechanism: Finger + release spring
  - "Pin-puller" triggered

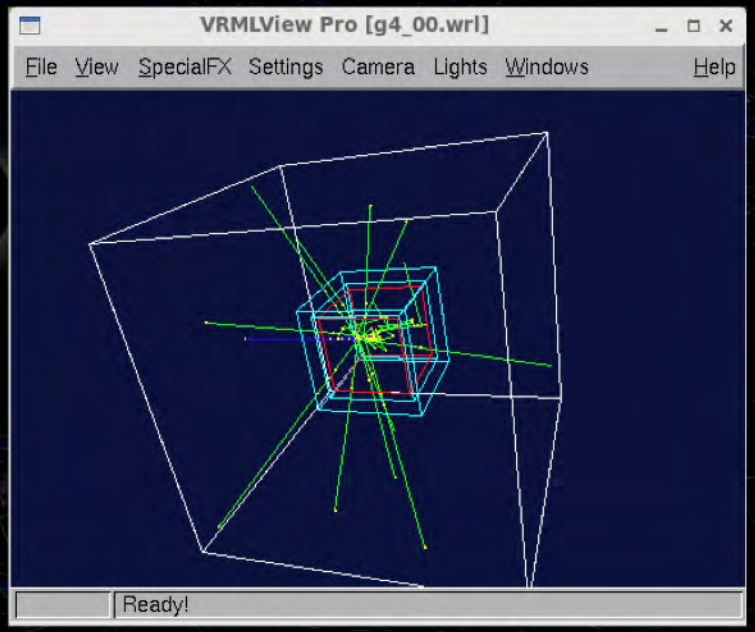






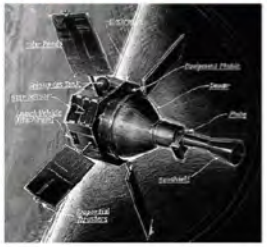
Charge management system

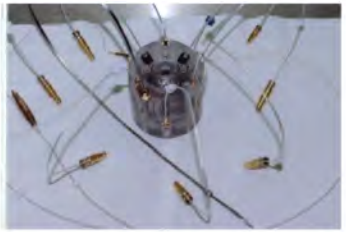
- Charge management system @stanford
  - UV-LED based system
  - Collaboration with stanford SSGD
  - I/F design for DPF BBM
- Functional test @NAOJ
  - Simulation of charge-up in DPF orbit
  - Experiment setup ongoing



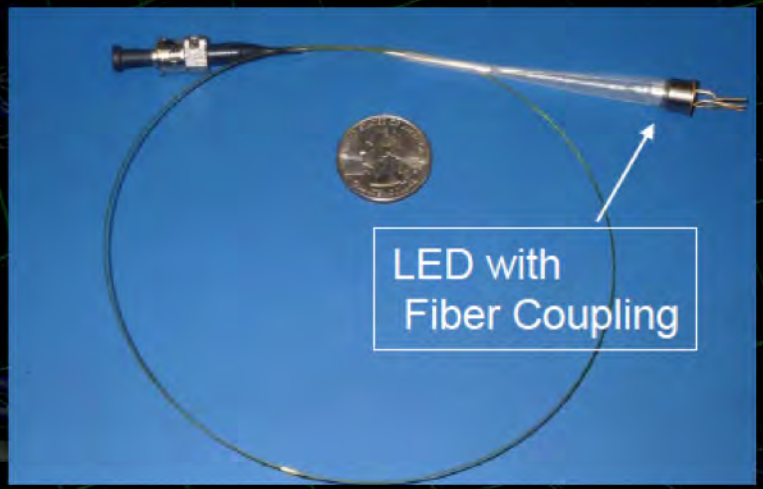
GP-B Charge Management R&D Heritage at Stanford

GP-B charge management
R&D since 1990's
- **Non-contact charge transfer by UV light**
- **Critical to GP-B mission success**
  - > **Initial gyro lifting-off**
  - > **Continuous charge management during science measurement**



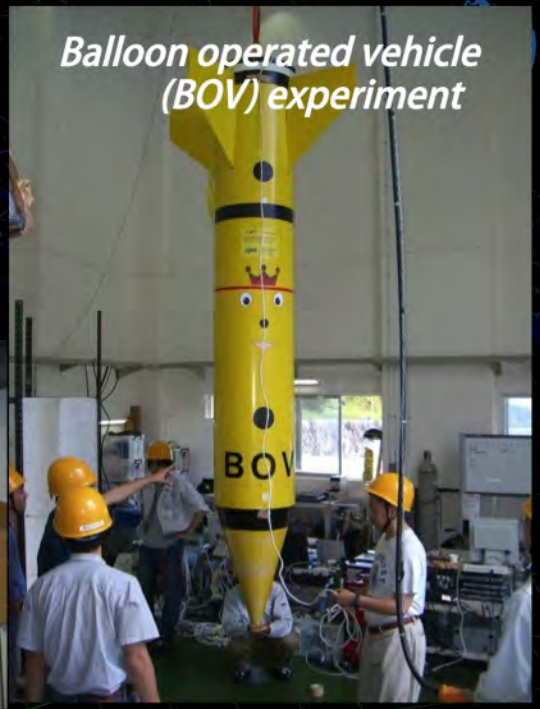


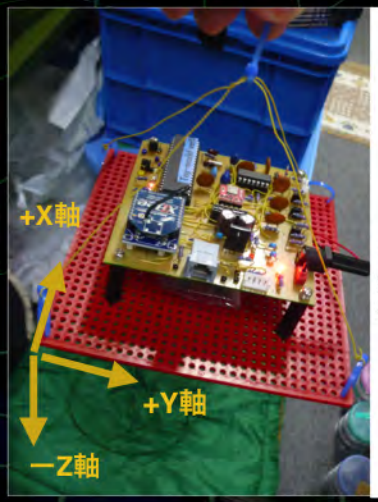
Saps Buchman, Theodore Quinn, G. M. Keiser, and Dale Gill, "*Gravity Probe B Gyroscope charge control using field-emission cathodes,*" J. Vac. Sci. Technol. B 11 (2) 407-411 (1993)

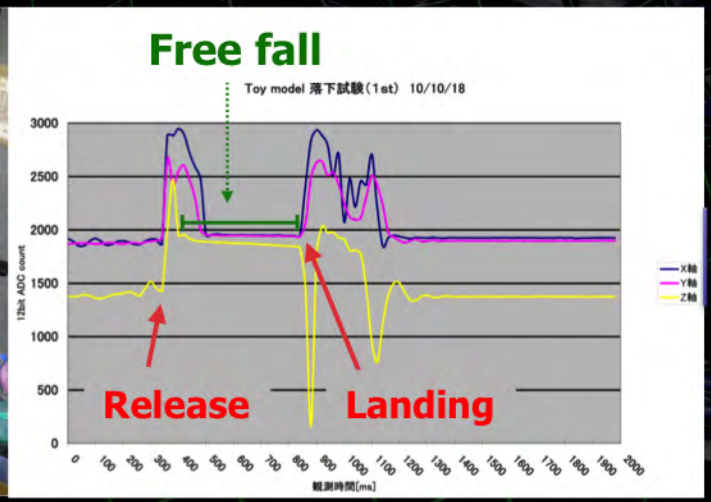


Free fall test

- μ-Gravity experiment @SWIM
  - μ-G environment with "free fall"
    - *Free fall tower*
    - *Balloon experiment*
    - *Parabolic flight*
- μ-Gravity experiment @NAOJ
  - All 6 DOF control demonstration
  - Single TMmodule as an accelerometer
  - Cramp-release test
  - Extend to FP interferometer control



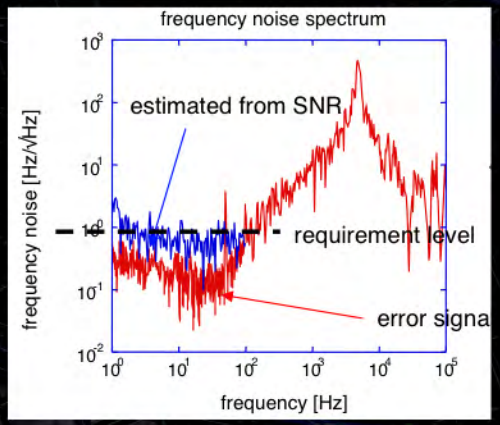


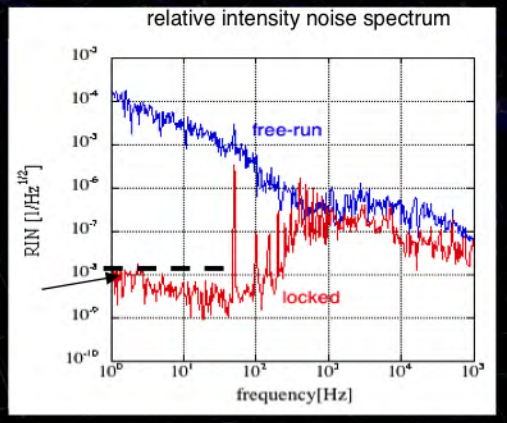


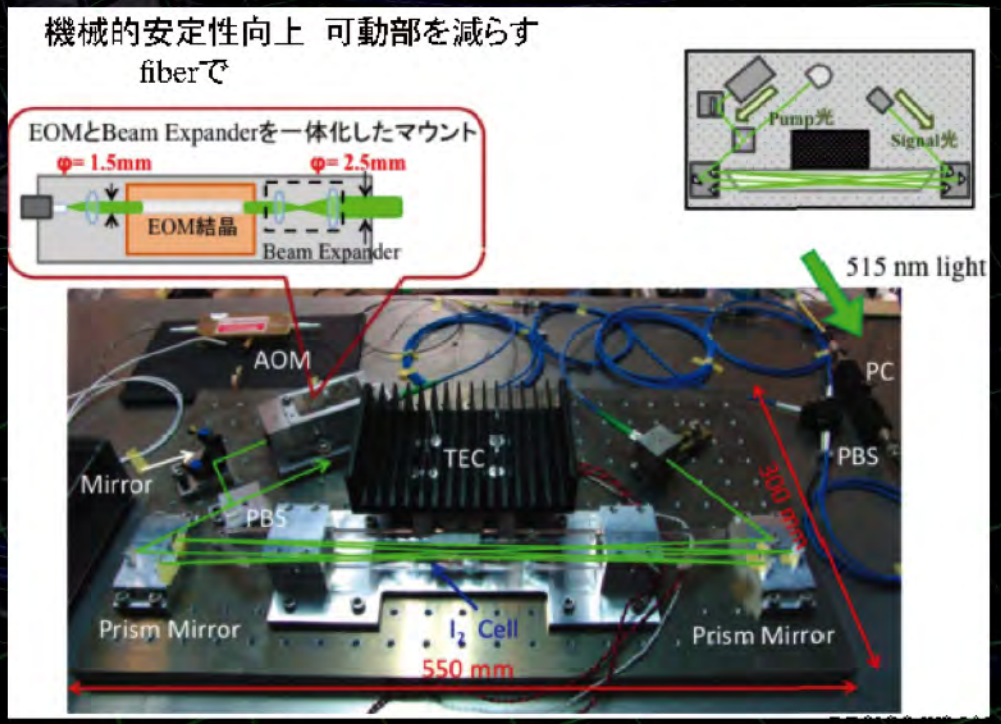
Stabilized laser module

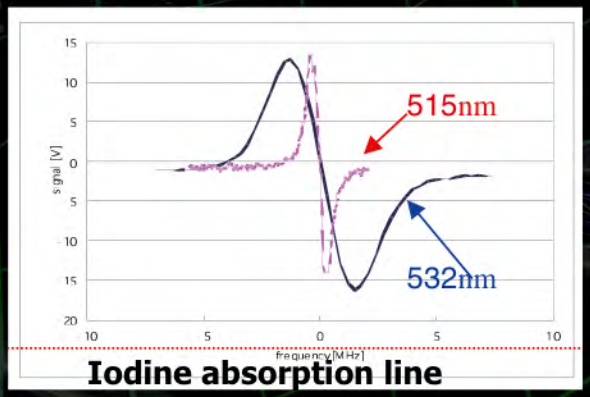
ILS, NICT, NASA/GSFC

- Laser source
  - Yb:YAG 1030nm
  - NPRO or Fiber laser/amplifier
    - *Compact and light*
    - *Vibration resistant*
  - BBM2 test
- Frequency stabilization
  - Iodine absorption line: 515nm
    - *Vibration resistant*
  - BBM2 test ongoing
  - Stability check



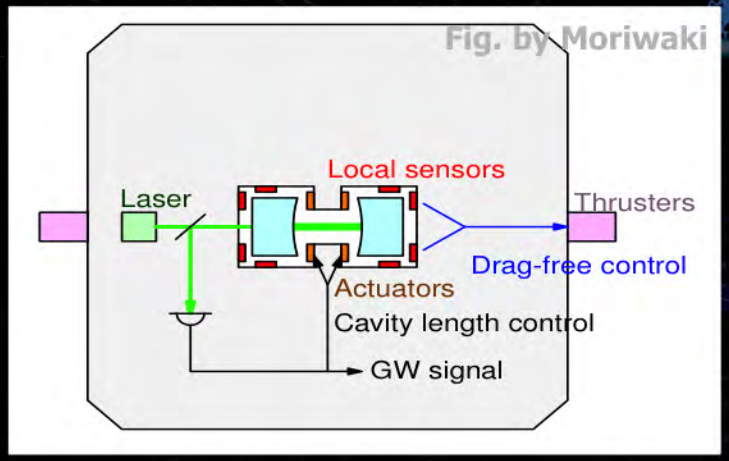


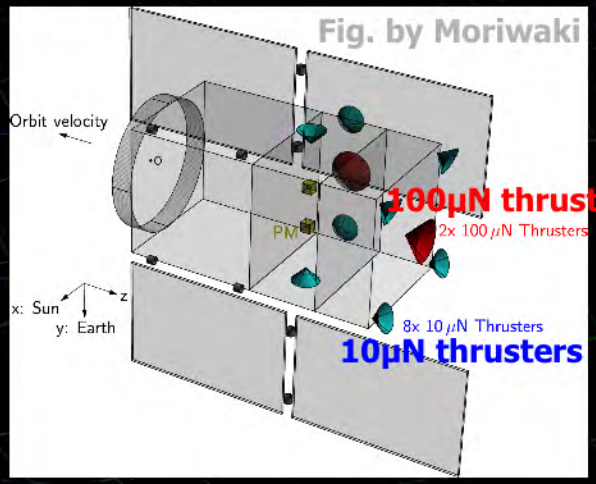


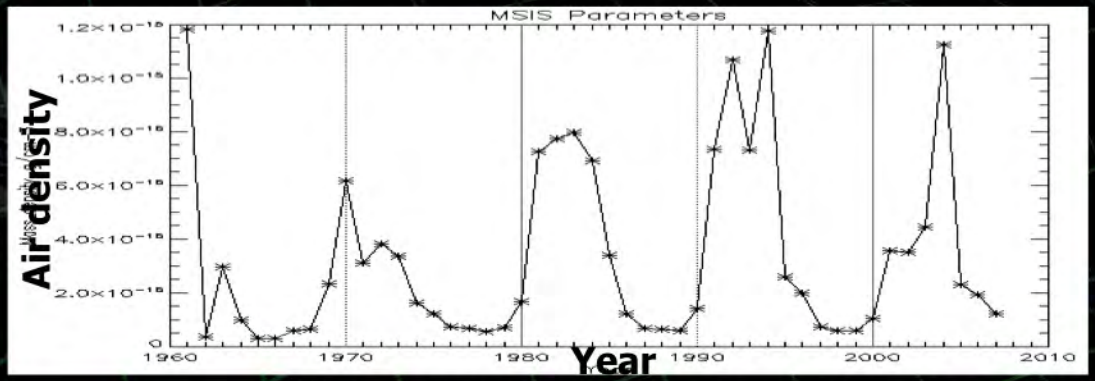


Drag free control

- Concept
  - Control S/C with reference to TMs
  - Diff. modes to TMs
  - Comm. modes to S/C
  - Using hierarchical control
- Disturbance source @LEO500km
  - Solar radiation pressure: 20μN@DC
  - Air drag: typ.100μN@DC
    Annual/season dependent
- Thruster dynamic range
  - 10μN thruster x8 for drag free control
  - 100μN thruster x2 for DC drag cancellation
- Attitude control
  - Should work w/o thrusters
  - Passive: owing to S/C shape
  - Active: MTQ control

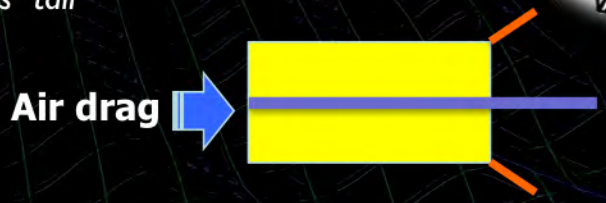


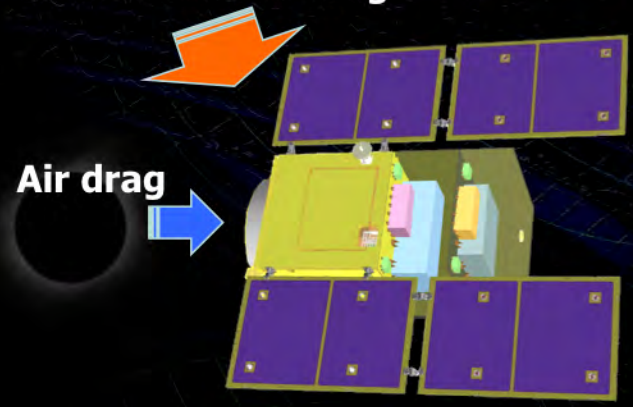




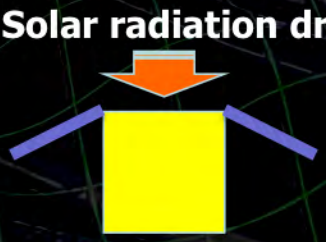
Attitude/Drag free control

- Passive control
  - "weathercock" stability (for air drag)
    - *SAP as "wing"*
    - *Fin as "tail"*





  - Cant for SAPs (for solar radiation drag)
    - *Cant angle*
    - *SAP position to the S/C frame*

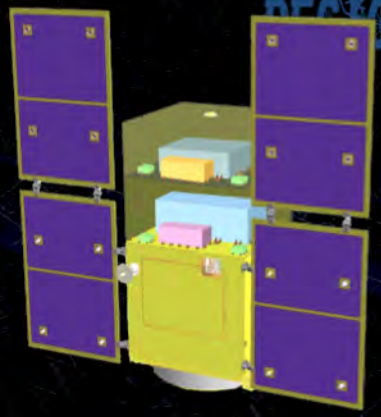


- Time domain simulation ongoing
  - Attitude control
  - Drag free control
  - Air drag, Solar radiation drag and earth gravity

Attitude/drag-free control system

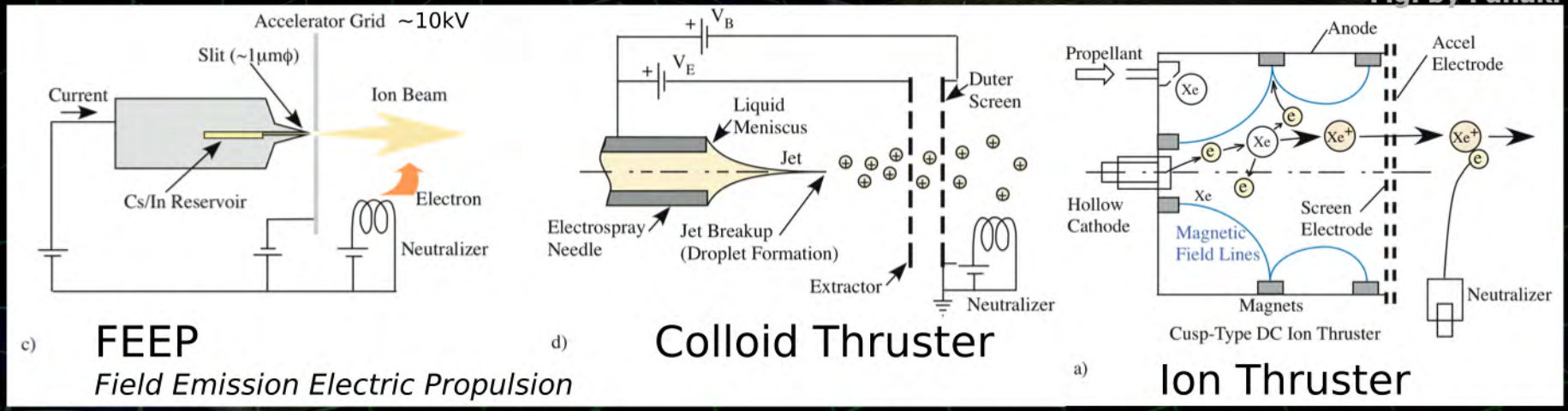
- Micro thruster
  - Actuators for satellite control
  - Wide-range throttling capability: 0-100μN
  - Low thrust noise: 0.1μN/rHz
  - Fast control: >10Hz
  - Long life: >0.5year
- Candidates: Electrostatic micro-thrusters
  - FEEP
  - Colloid thruster
  - Ion thruster
- BBM test and characterization ongoing

U-Tokyo, JAXA



JAXA, U-Tokai, Nat'l Def. Acad.

Fig. by Funaki



c) FEEP

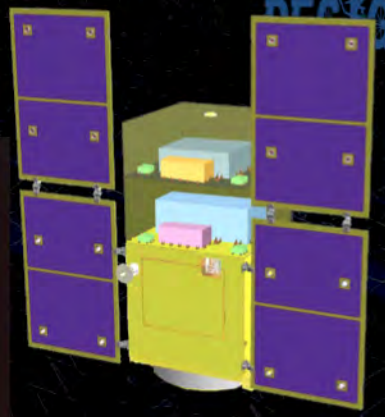
Field Emission Electric Propulsion

d) Colloid Thruster

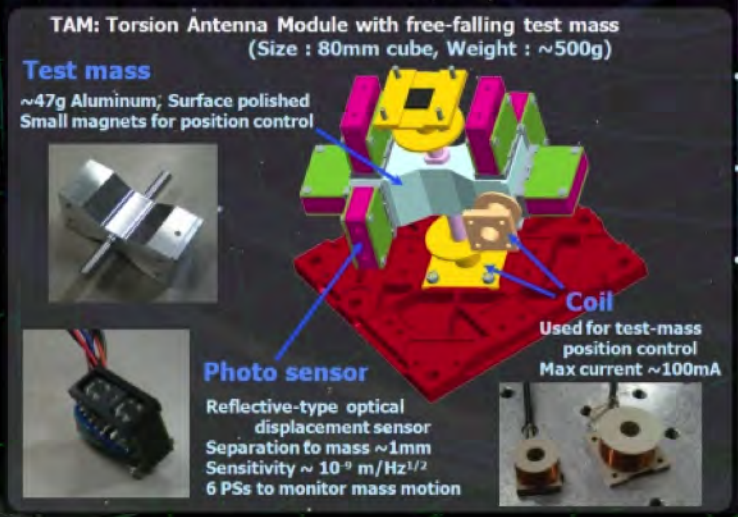
a) Ion Thruster

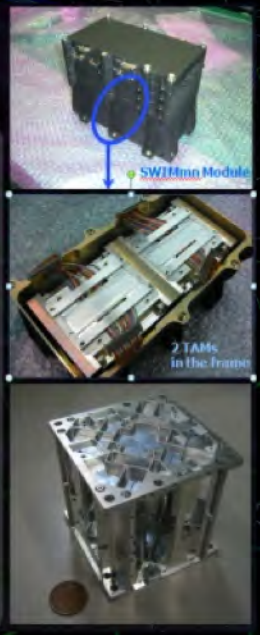
Signal process/control system

- Space Wire -based system
  - Demonstration in orbit
    SWIM on SDS-1
    Space Cube 2 (SpC2))+Spacw Wire (SpW) system

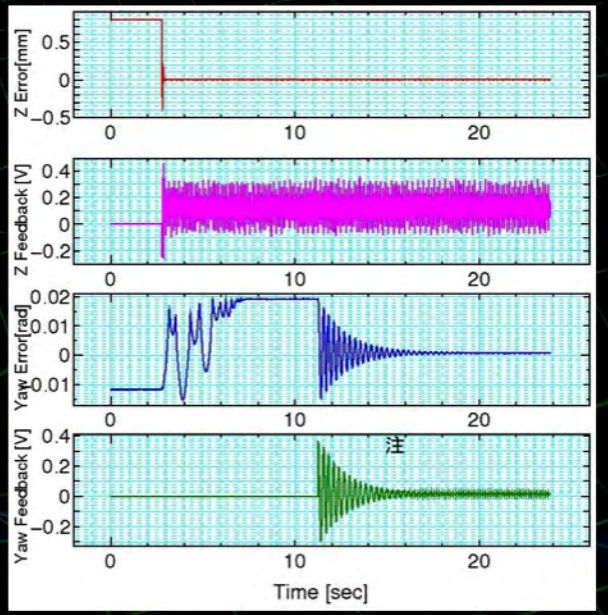


  - Control and precision measurement
    SWIM demonstration in orbit (2009)





JAXA, U-Tokyo, Kyoto-U



Summary

DECIGO : Sciences !

- Very beginning of the Universe
- Dark energy
- Galaxy formation

DECIGO Pathfinder : Important milestone !

- Technical demonstration in orbit
- Detection of GW
- Earth's gravity observation

Apply for JAXA's small science satellite series this year!!!

International/Domestic collaboration

- Supports from LISA
  - Technical advices from LISA/LPF experiences
  - Support Letter for DECIGO/DPF, Joint workshop (2008.11)
- Collab. with Stanford univ. group
  - Drag-free control of DECIGO/DPF
  - UV LED Charge Management System for DPF
- Collab. with NASA/GSFC
  - Fiber Laser , Earth's gravity observation
- Collab. with JAXA navigation-control section
  - → Formation flight of DECIGO, DPF drag-free control
- Geophysics group (Kyoto, ERI, UEC, NAOJ)
- Advanced technology center (ATC) of NAOJ
- JAXA's fund for small satellite development
- Research Center for the Early Universe (RESCEU), Univ. of Tokyo