大型低温重力波望遠鏡LCGT
かぐら (KAGRA)

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On behalf of
the KAGRA Collaboration

おしらせ

・大型低温重力波望遠鏡 LCGT

(Large Cryogenic Gravitational-wave Telescope)

に愛称がつきました.

かぐら　KAGRA

- 一般公募された候補の中から
有識者による選定委員会で決定
(選定委員長: 作家・小川洋子さん)

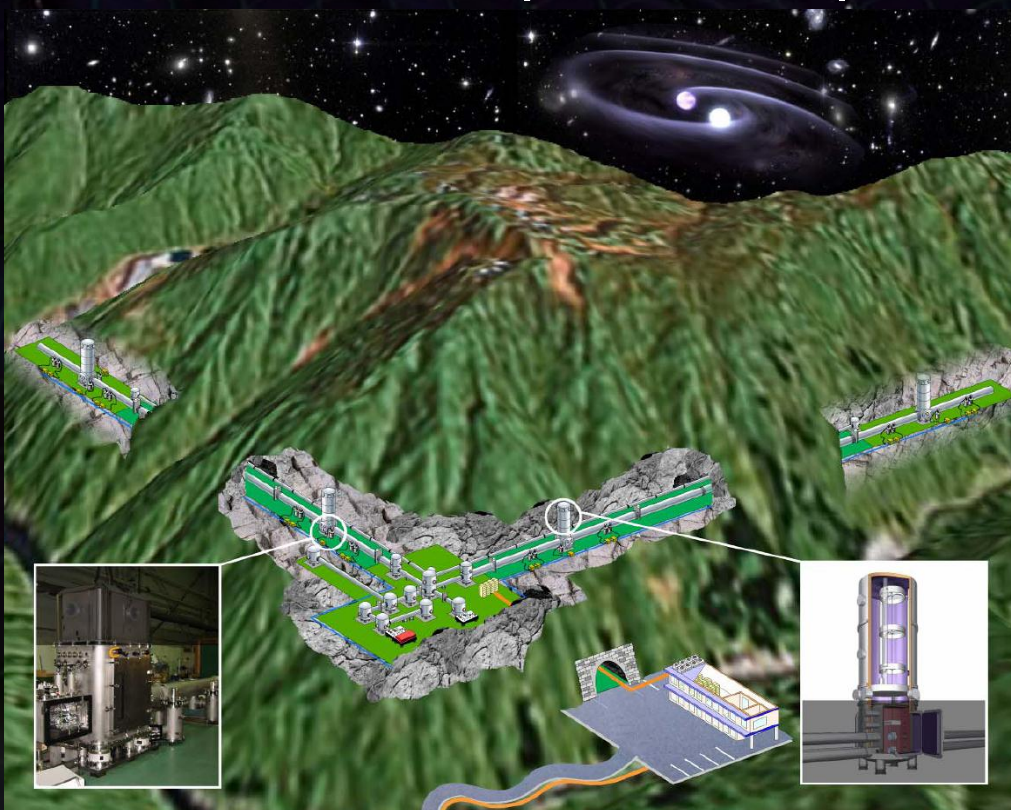
- かぐら (神楽) : 神に奉げる歌や踊り.
- Acronymではないが、
KA (Kamioka) + GRA (Gravitational Wave Antenna)
の意味合いもある.

大型低温重力波望遠鏡

かぐら (KAGRA)

(LCGT: Large-scale Cryogenic Gravitational-wave Telescope)

日本の次世代重力波検出器 (本格観測　2017年 -)
海外の望遠鏡 (Ad. LIGOなど) と同等の感度 → 国際観測網.



大規模な重力波天文台
- Baseline length: 3km
- High-power Interferometer

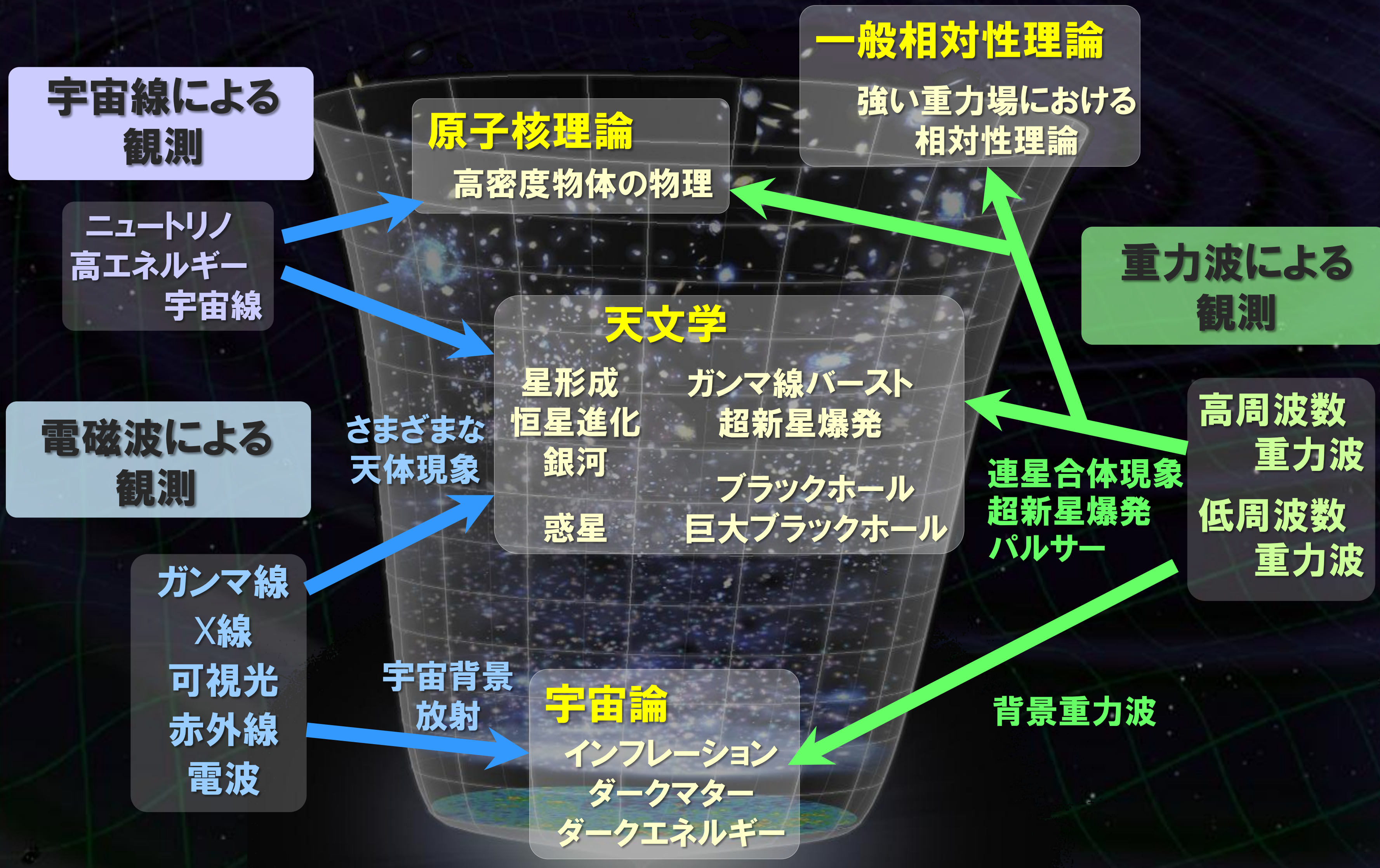
低温干渉計
- Mirror temperature: 20K

地下の安定・静寂な環境
- Kamioka mine,
  1000m underground

- 背景とKAGRAの意義
- KAGRAの概要
- KAGRAの設計と現状
- まとめ

背景とKAGRAの意義

重力波で宇宙を探る



背景画: NASA/WMAP Science Team

地上重力波望遠鏡のターゲット

地上重力波望遠鏡 -- 10Hz – 1kHz の観測周波数帯

⇨ コンパクト天体, 高エネルギー天体現象

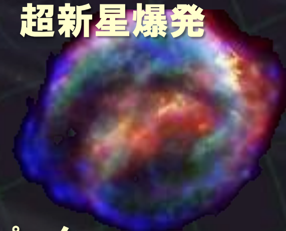
中性子星

ブラックホール

初期宇宙

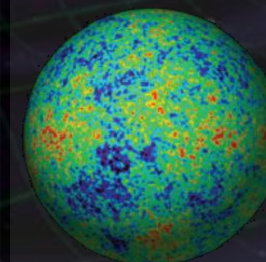
パルサー

超新星爆発

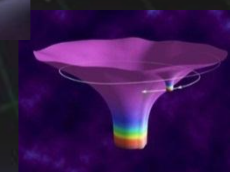


連星合体

背景重力波



EMRI



準固有
振動

軟ガンマ線リピーター

星の
振動
モード

長ガンマ線
バースト

短ガンマ線
バースト

電磁波
ニュートリノ
高エネルギー宇宙線

同時観測
数値相対論

高エネルギー天体
現象の総合的理解

高密度天体の状態方程式
原子核物理

相対性理論の検証
強い重力場での物理法則

宇宙重力波望遠鏡のターゲット

宇宙重力波望遠鏡 -- 0.1mHz – 1 Hz の観測周波数帯

⇨ 中間/巨大ブラックホール, 初期宇宙

中性子星・白色矮星

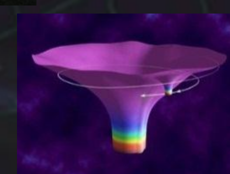
連星

定常的・準静的な自転・公転運動

ブラックホール

巨大ブラックホールの合体

EMRI

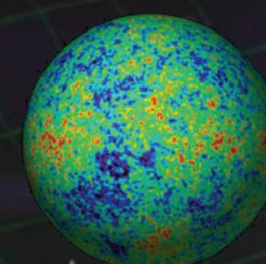


準固有振動

初期宇宙

多数天体の重ね合わせ

背景重力波



電磁波
ニュートリノ

同時観測
数値相対論

重力理論の検証

超巨大BHの形成過程
銀河形成史

宇宙論, 宇宙の誕生と発展
ダークエネルギー・ダークマター

第1世代 重力波検出器

検出の試み：1960年代より行われる
2000年前後より、大型干渉計型検出器が観測を開始
レーザー干渉計型：5台, 共振型検出器：3台

国際的観測ネットワーク ： 1年を超える観測データ
→ 科学的成果（上限値, 理論モデルへの制約など）

連星中性子星合体イベント：50kpc~20Mpcの観測レンジ
→ 我々の銀河, 近傍銀河でイベントがあれば検出可能

本格的な天文学

現在の検出器 --- 近傍銀河までの観測範囲を持つ

ただ… そのような重力波イベントは稀　(10^{-4}-10^{-2} event/yr)

⇨ 約1桁感度を向上した 第2世代の重力波望遠鏡

高感度化→より多くの銀河をカバーする

(重力波の振幅)　∝ 1/(波源までの距離)

⇩

感度が10倍向上 → イベントレートは 10^3倍

得られるサイエンス

Initial LIGO 1年間の観測

~ Advanced LIGO 9時間の観測

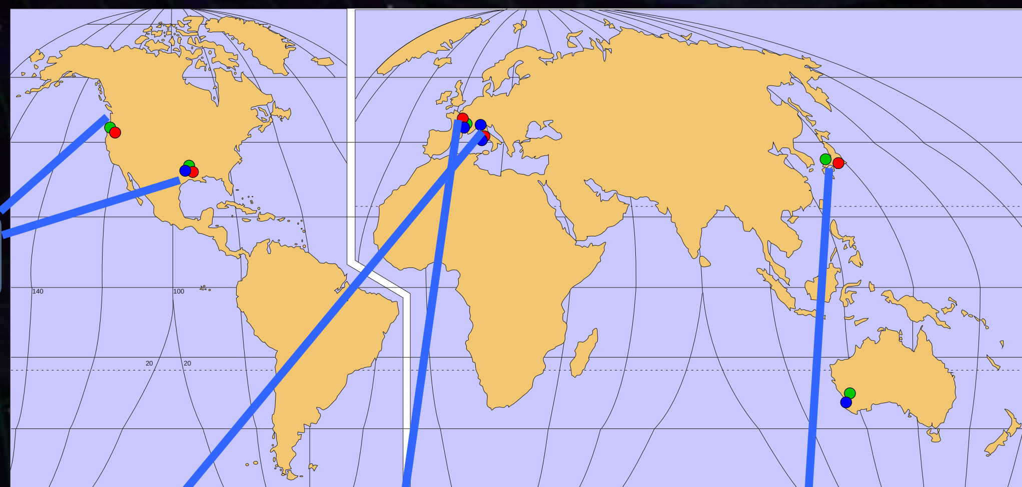
第2世代望遠鏡では、検出頻度 ~ 10 event/year

第2世代 重力波望遠鏡

国際観測ネットワークが形成される　(現在から 約5年後)

→ 重力波天文学
(重力波の検出, 波源位置の特定, 波源の物理情報, …)

aLIGO (USA)
4km x 2 (or3)

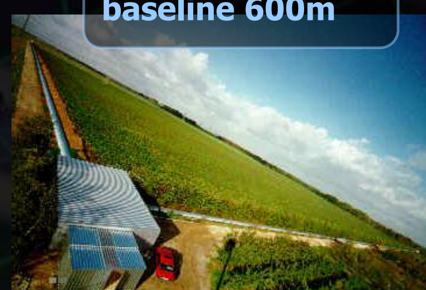


LIGO-Austreria
in proposal

LIGO-India
in proposal

indigo

GEO-HF (GER-UK)
baseline 600m



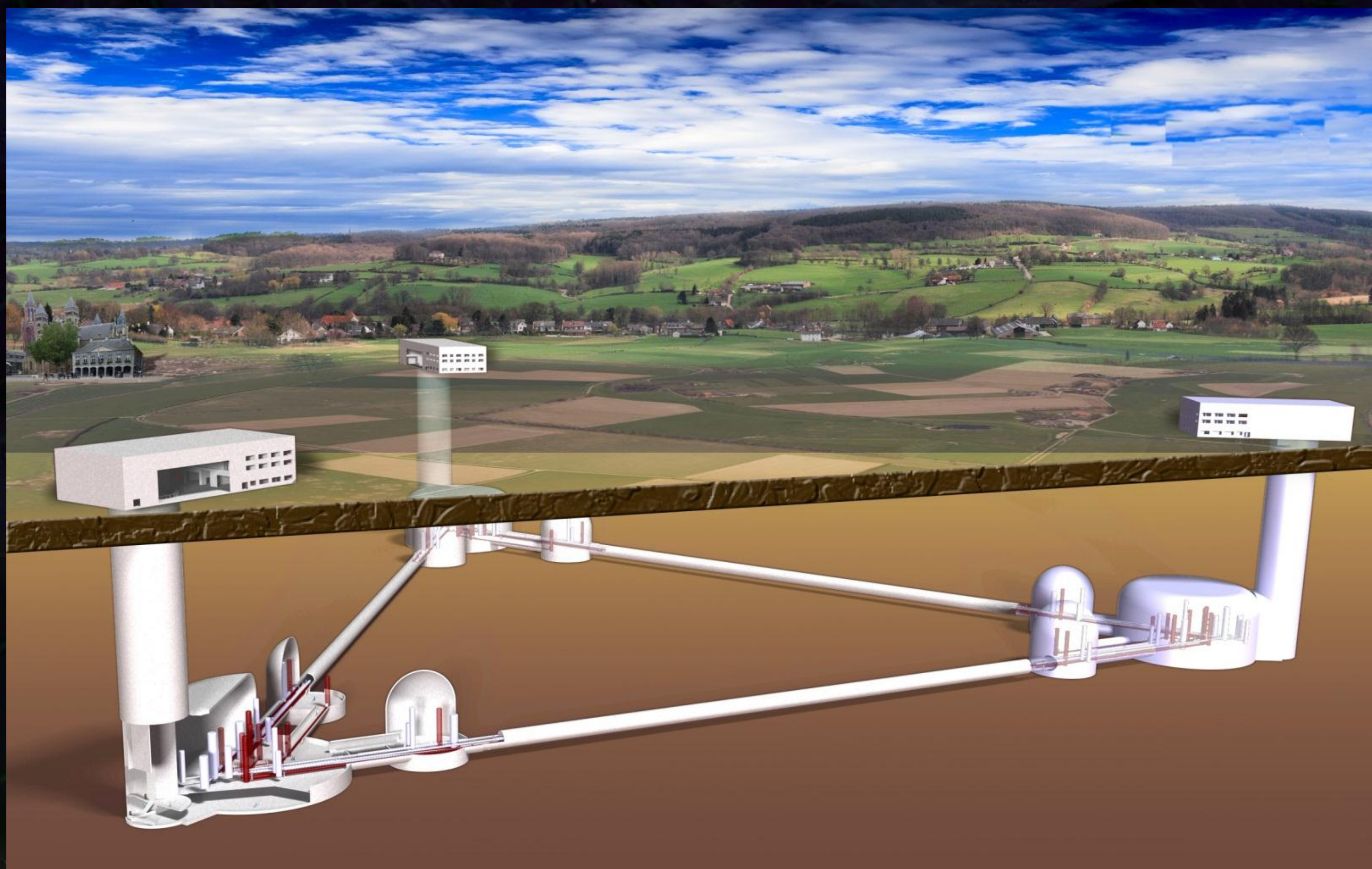
KAGRA (JPN)
baseline 3km

Adv.VIRGO (ITA-FRA)
baseline 3km

第3世代 重力波望遠鏡

3rd-generation detector : ET (Einstein Telescope)

感度：さらに一桁の改善, 2026年頃観測開始.
長基線長 ~10km, 地下サイトに建設, 低温干渉計



地上重力波望遠鏡のロードマップ

- **1st Generation detector**
  - Obs. range: ~20Mpc
  - Rate: 10^{-4} – 10^{-2} event/yr
  - → 幸運なイベント, 上限値

- **2nd Generation detector**
  - Obs. Range: ~200Mpc
  - Rate: ~10 event/yr
  - → 確実な検出, 天体物理

- **3rd Generation detector**
  - Obs. Range ~3 Gpc
  - Dairy detection
  - → 宇宙論

海外望遠鏡との比較

	2nd-generation detectors			3rd generation
	aLIGO	Ad. VIRGO	KAGRA	ET
観測開始	~ 2016	~ 2016	~ 2017	~ 2026
サイト	地上 Hanford 2台 Livingstone 1台	地上 Pisa 1台	地下 Kamioka 1台	地下 3 台
基線長	4 km	3 km	3 km	10 km
観測レンジ (*1)	306 Mpc	243 Mpc	273 Mpc (*2)	3 Gpc
干渉計方式	RSE広帯域	RSE狭帯域	RSE可変帯域	RSE Xylophone
熱雑音の低減	大ビーム径, 低機械損失鏡 熱レンズ効果の補正		低温化	低温化
防振系	能動防振系	受動防振系	受動防振系	受動防振系

(*1) 連星中性子性合体現象に対する観測可能距離, 最適方向, 最適偏波, SNR>8.
(*2) 現在、設計の更新作業が進められており, 変更の可能性がある.

KAGRAの意義

・重力波の検出と重力波天文学の創生

- 1年間の観測で複数回の重力波信号の検出が期待できる.
  → 重力波天文学の幕開け, 相対性理論の検証.
- 国際観測網における重要な拠点
  波形, 偏波などの情報 → 天体現象の情報.
  波源の位置の特定 → 電磁波観測も含めた波源の理解.

・先進的な干渉計技術の実証

- KAGRAの特徴：低温干渉計, 地下サイトに設置.
  → 第3世代望遠鏡 (Einstein Telescope) に必須の技術.

⇨ KAGRAには、**第2.5世代の望遠鏡**としての役割もある.

KAGRAの概要

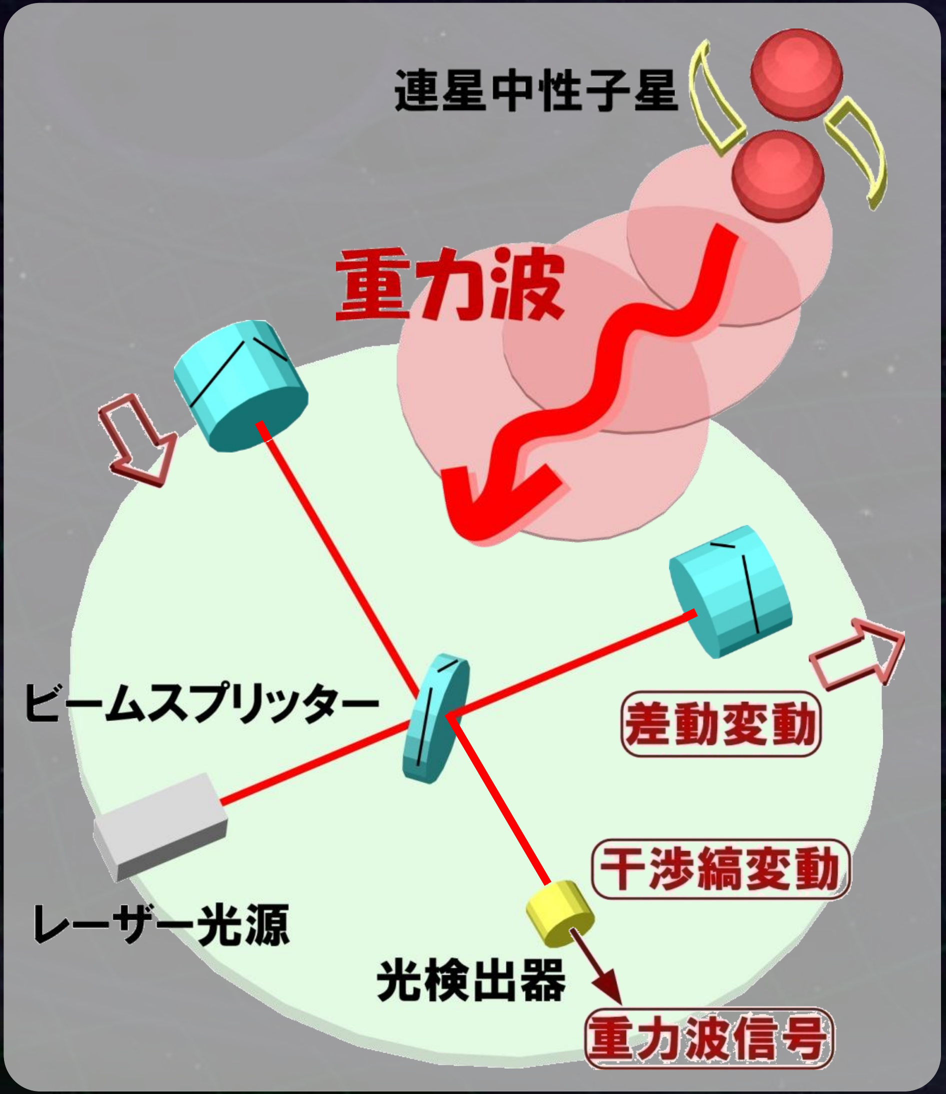
レーザー干渉計型重力波検出器

マイケルソン干渉計が基本
レーザー光源からの光を
直交する2方向に分岐

それぞれ、懸架された鏡で打ち返し
干渉させる → 光検出器で観測.

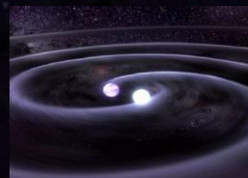
重力波が入射

腕の長さの差動変動を
干渉光量の変動として検出

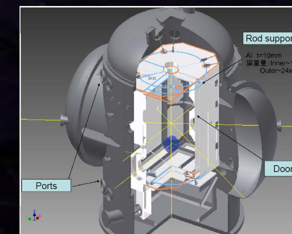


重力波望遠鏡の高感度化

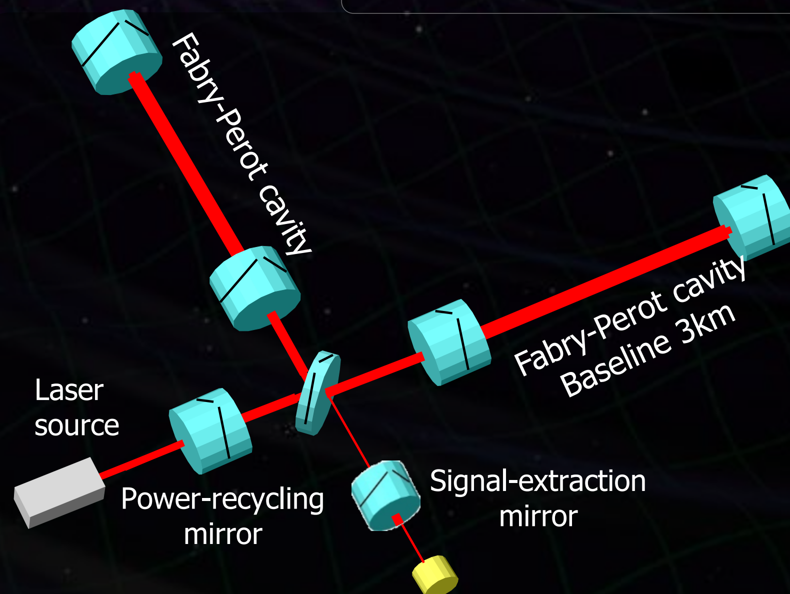
- **重力波源の理解**
  - 理論・解析的計算
  - 数値相対論
  - データ解析手法



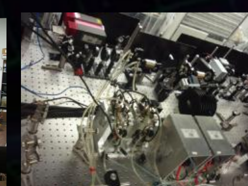
- **鏡・振り子の熱雑音**
  - 鏡・振り子の低温化
  - 材質の機械損失



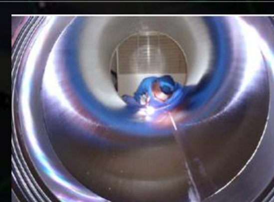
- **地面振動の影響**
  - 静寂な地下サイト
  - 高性能防振装置



- **光の量子雑音**
  - 大型干渉計
  - 干渉計方式の工夫
  - 高出力レーザー光源
  - 高性能鏡

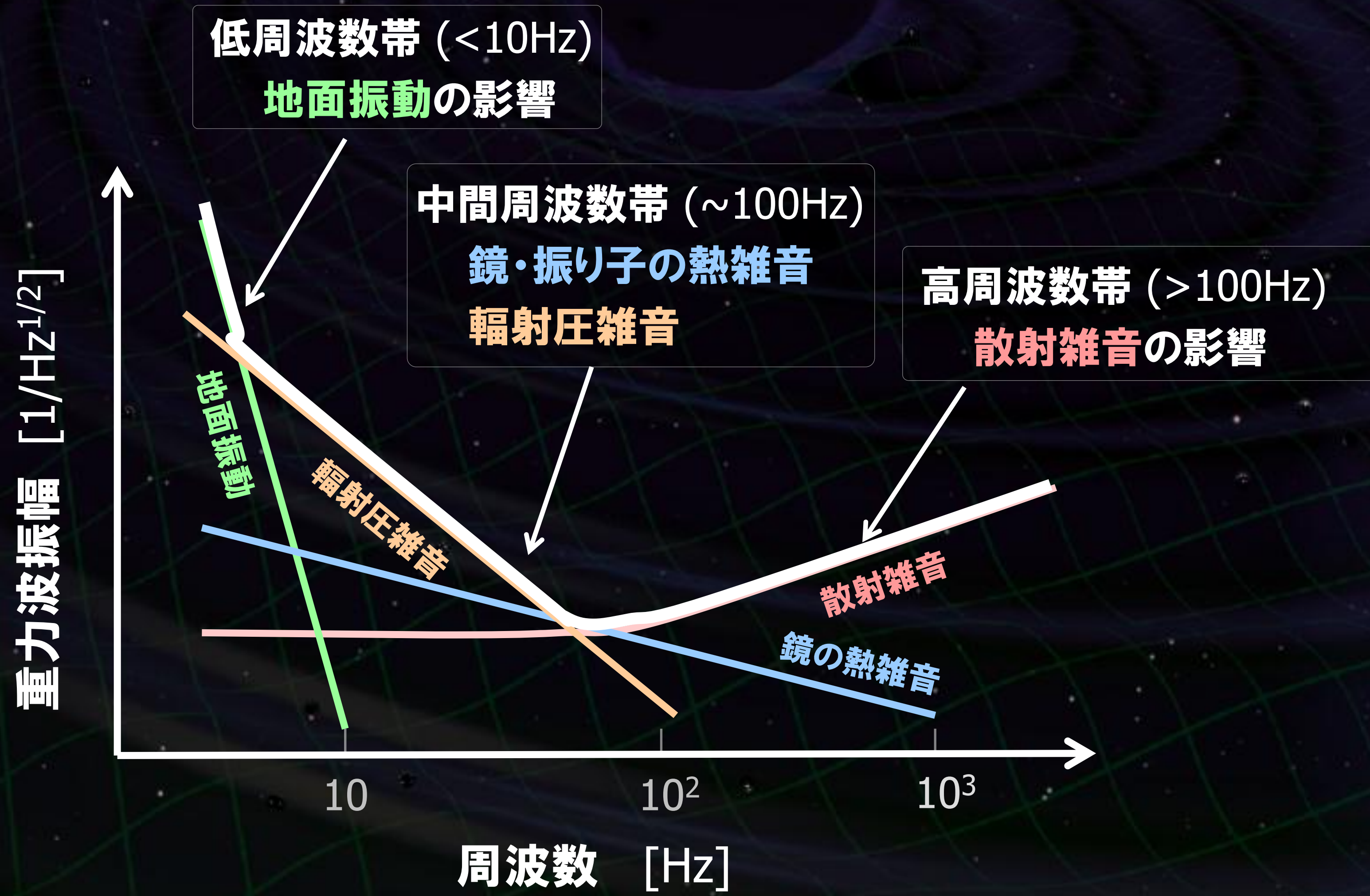


- **真空システム**
  - 光路長の揺らぎ
  - 音響雑音などの低減



- **長期・連続観測**
  - デジタル制御・データ取得系
  - 環境モニタ, データ保管・分配

重力波検出器の感度



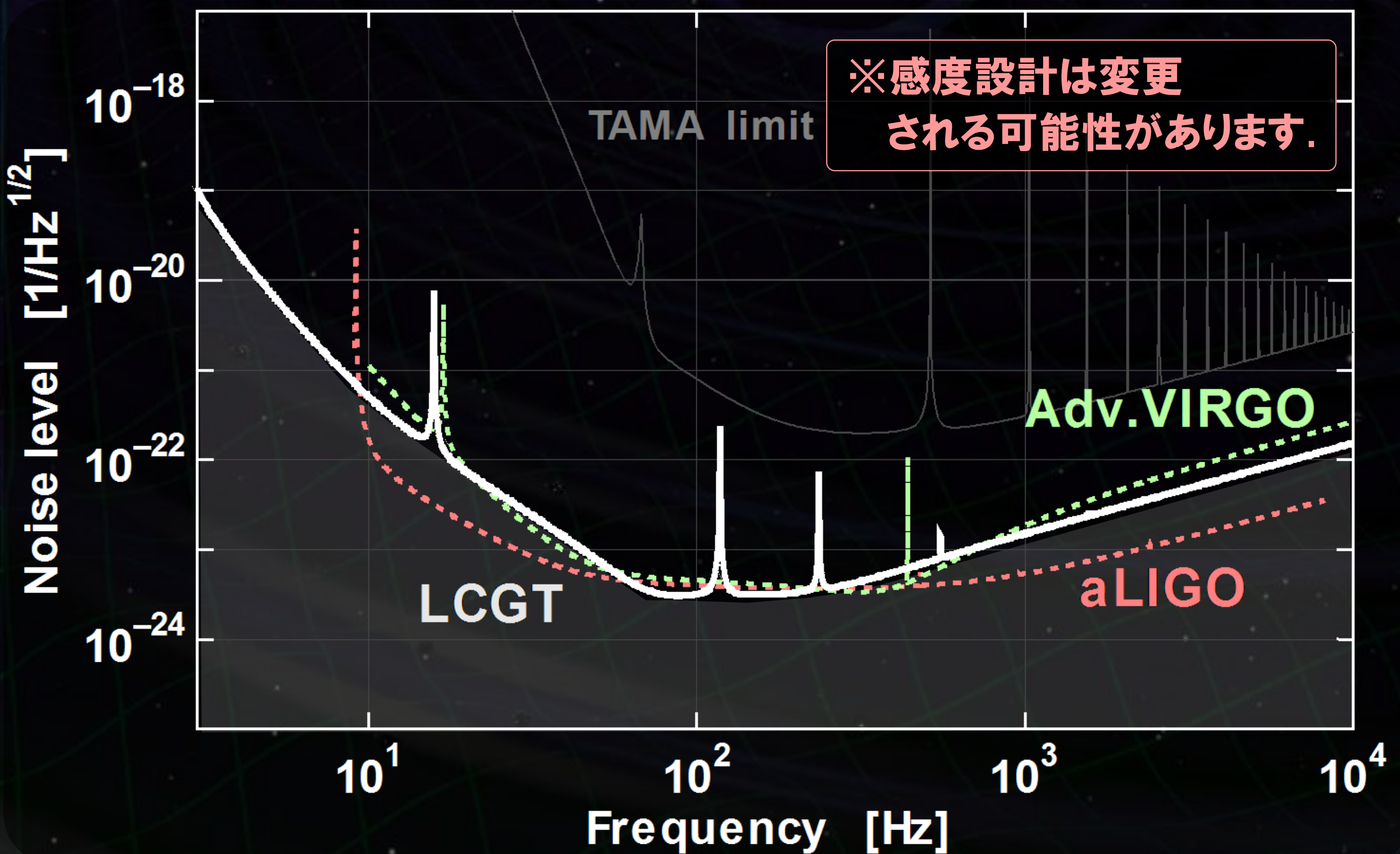
低周波数帯 (<10Hz)
地面振動の影響
中間周波数帯 (~100Hz)
鏡・振り子の熱雑音
輻射圧雑音
高周波数帯 (>100Hz)
散射雑音の影響
重力波振幅 [1/Hz1/2]
地面振動
輻射圧雑音
散射雑音
鏡の熱雑音
10
10²
10³
周波数 [Hz]

KAGRAの感度限界

主要な雑音源で決まる限界感度
aLIGO や Ad.VIRGOと同等

⇒

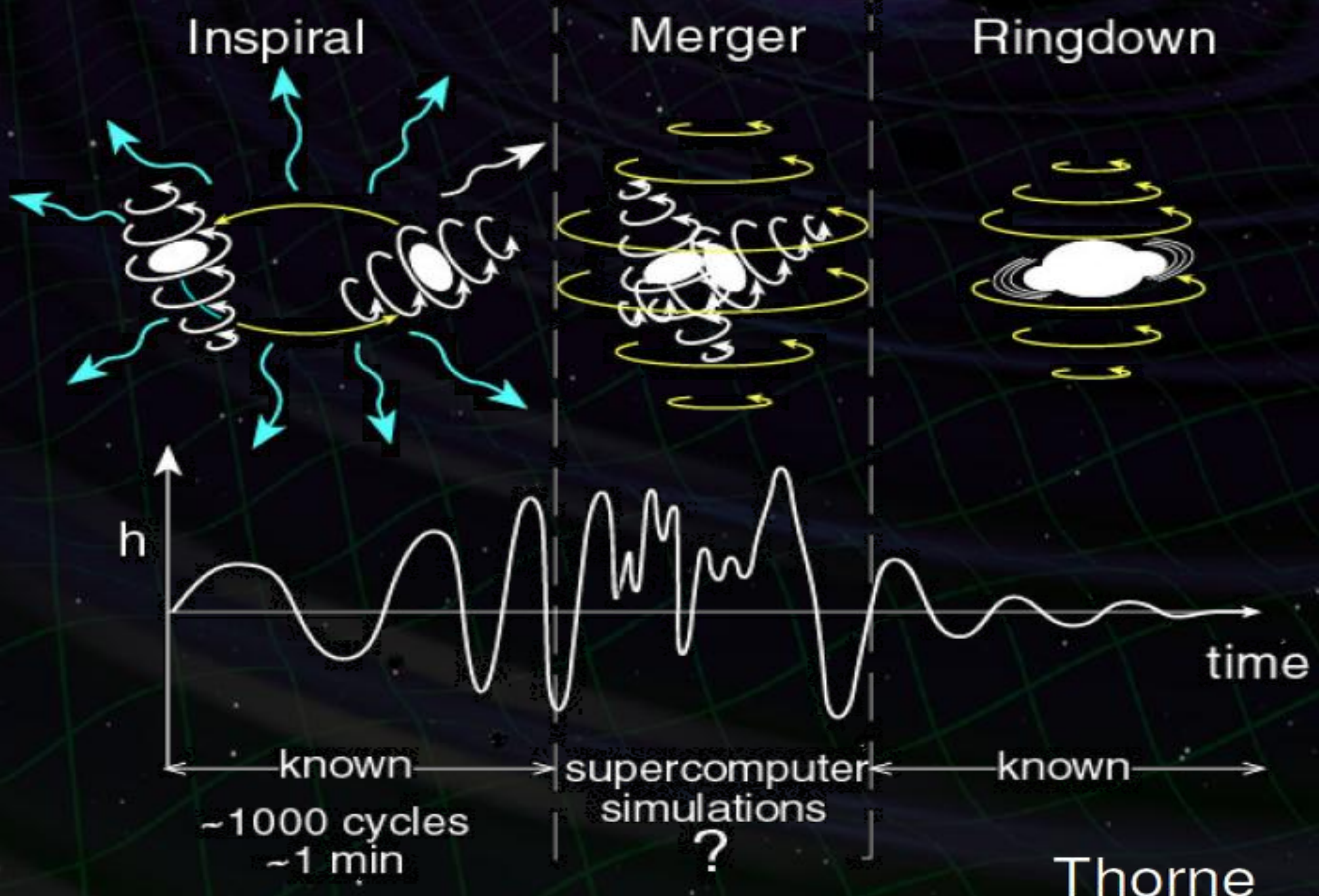
国際観測網を形成
年間数回以上の重力波信号検出

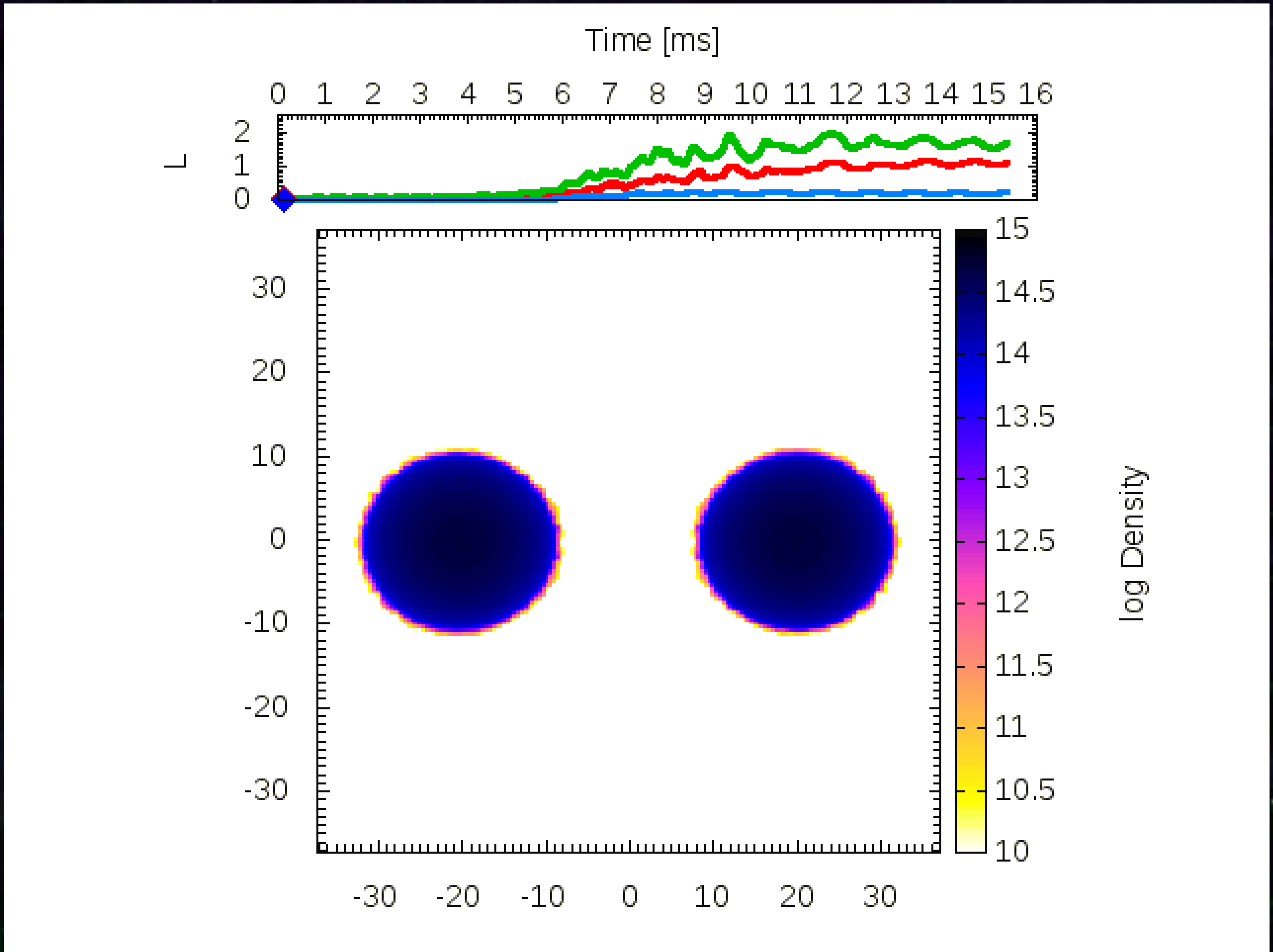


連星合体現象からの重力波

・連星合体からの重力波の波形

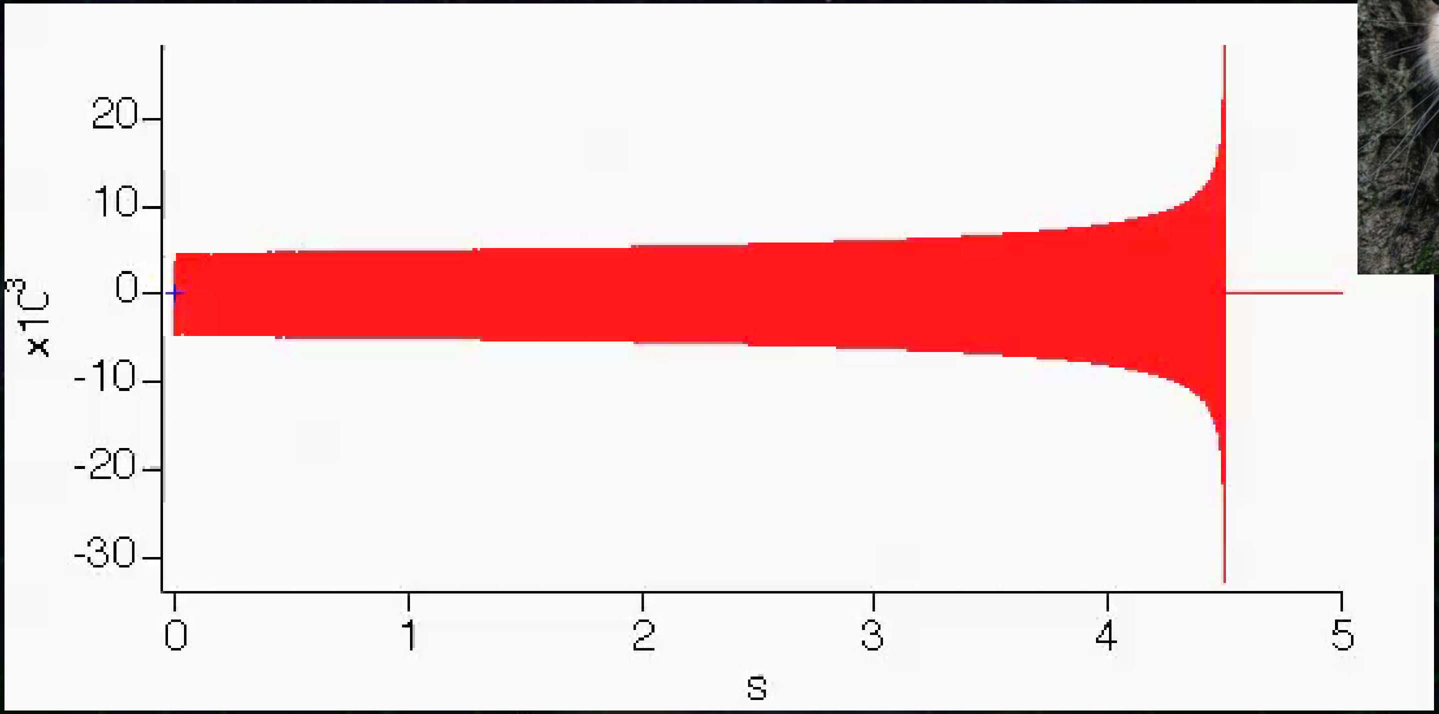
インスパイラル　合体　リングダウン





連星中性子星の合体数値シミュレーション by 関口氏

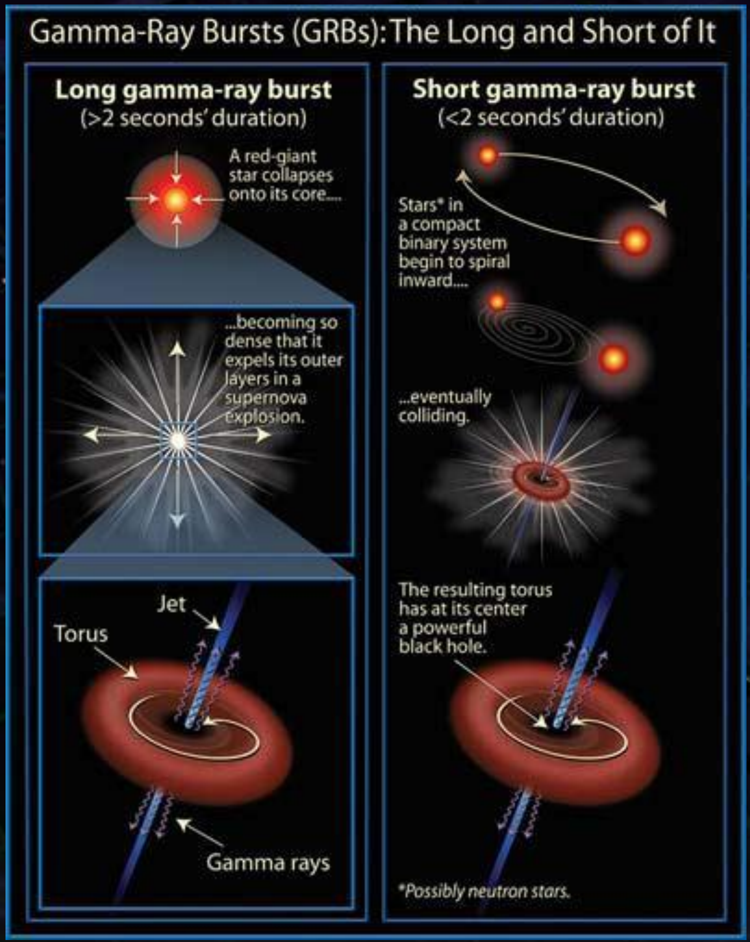
「耳をすます」



重力波の音 by 神田氏

連星合体観測による知見

- 重力波の初検出
  - 連星中性子星：存在が確実, 波形が予測できる.
  - 相対性理論/重力法則の検証.
  - 新しい天文学の創生,
  - ガンマ線バーストの起源, 未知の発見.
- 高密度核物質の直接探査
  - 中性子星の状態方程式の情報.
  - 潮汐変形/破壊, HMNSの形成など.
- 宇宙論・銀河形成史に対する知見
  - 宇宙論パラメータへの制限.
  - 超巨大ブラックホールの形成過程
  - 連星の進化や分布の情報.



From encyclopedia of science

中性子星連星合体の数値シミュレーション

Hotokezaka+, PRD (2011)

等質量連星
中性子星合体

HMNS形成

遠心力によって
$M > M_{\mathrm{max}}$
を支える中性子星

Type Ⅰ

BHへ崩壊

Type Ⅱ
寿命 < 5ms

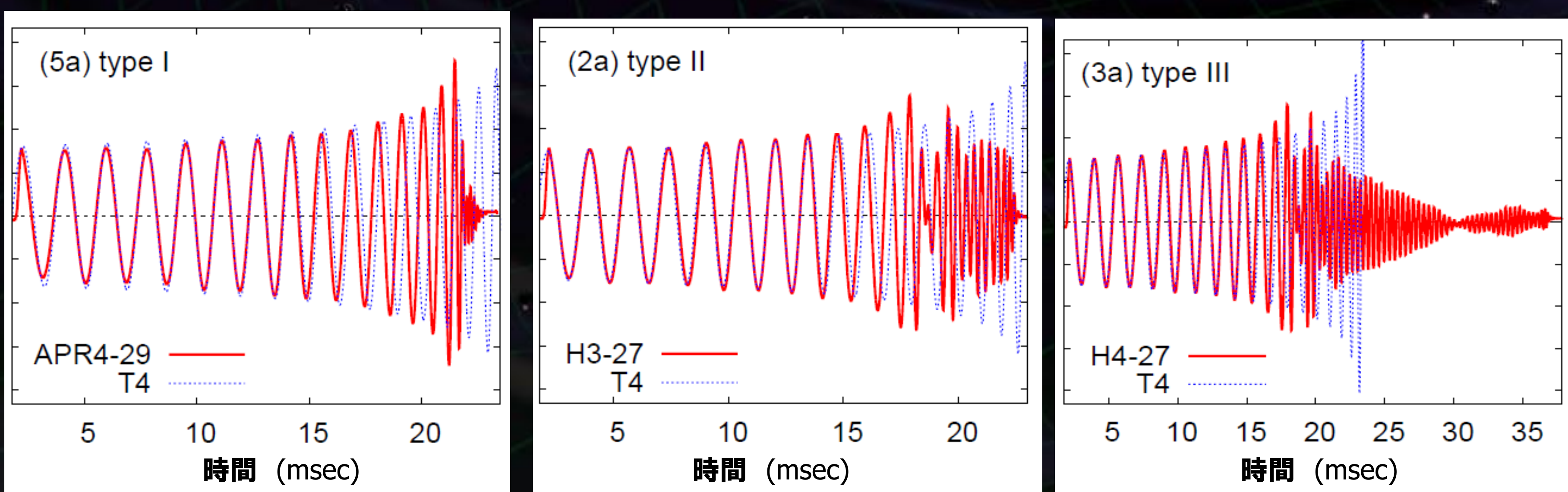
Short lived

BHへ崩壊

Type Ⅲ
寿命 > 5ms

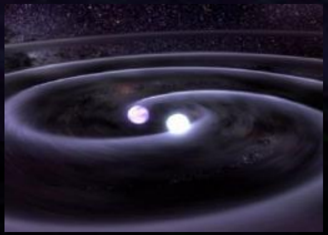
Long lived

BHへ崩壊



KAGRAの観測確率

第一目標: **連星中性子星合体**からの重力波の検出



観測レンジ

感度曲線 → 観測可能距離 270 Mpc

(SNR 8, 最適方向・偏波)

銀河の個数密度：

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

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

銀河あたりのイベントレート:

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

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

⇨ KAGRAの観測レート **9.8 events/yr**

(1年間の観測での検出確率 99.9%以上)

KAGRAの設計と現状

KAGRA サイト

岐阜県・神岡町 の地下サイトに建設

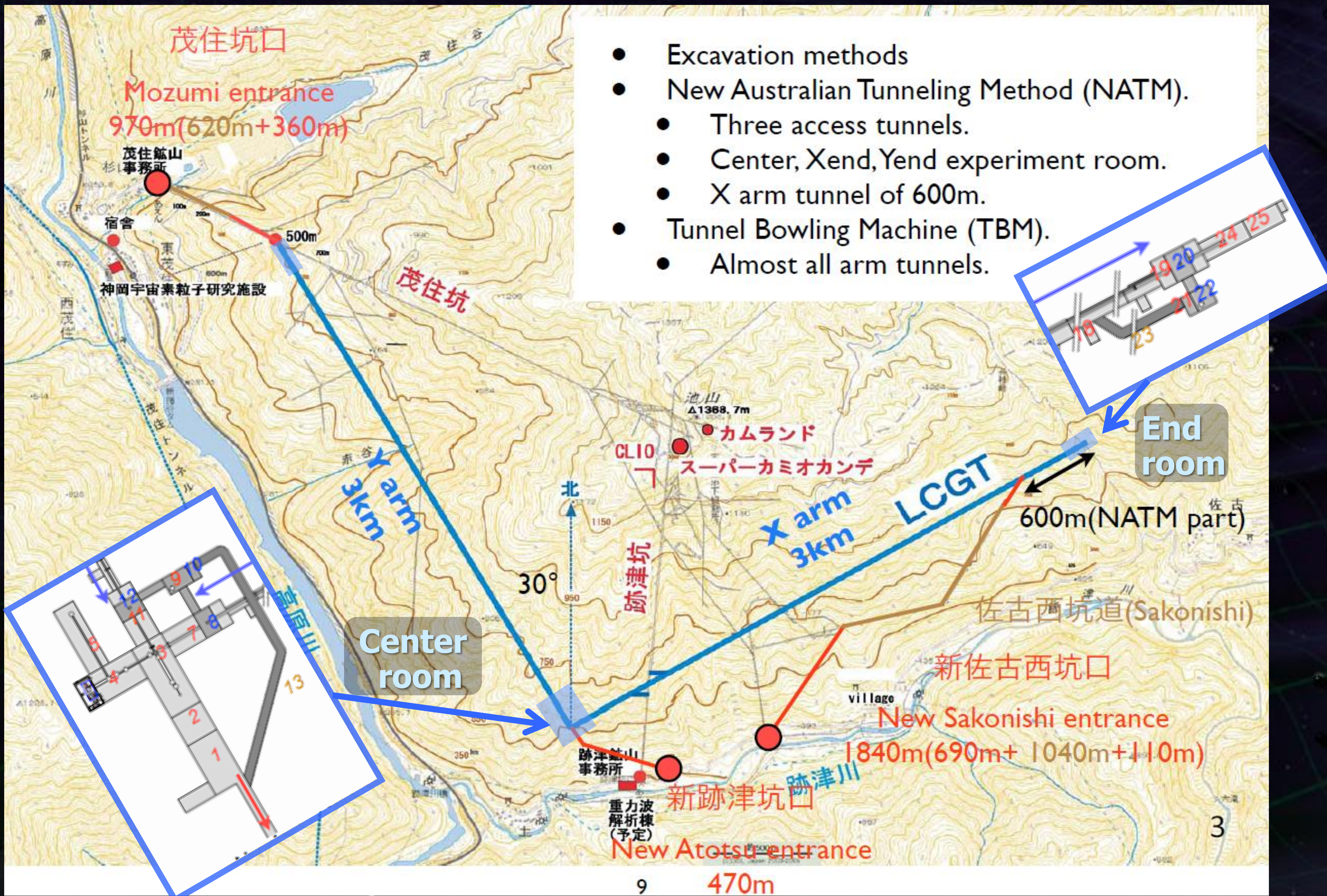
Facility of the Institute of Cosmic-Ray Research (ICRR), Univ. of Tokyo.

Neutrino
  Super Kamiokande, Kamland
Dark matter
  XMASS
Gravitational wave
  CLIO, KAGRA
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)

KAGRAトンネル設計

- 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.



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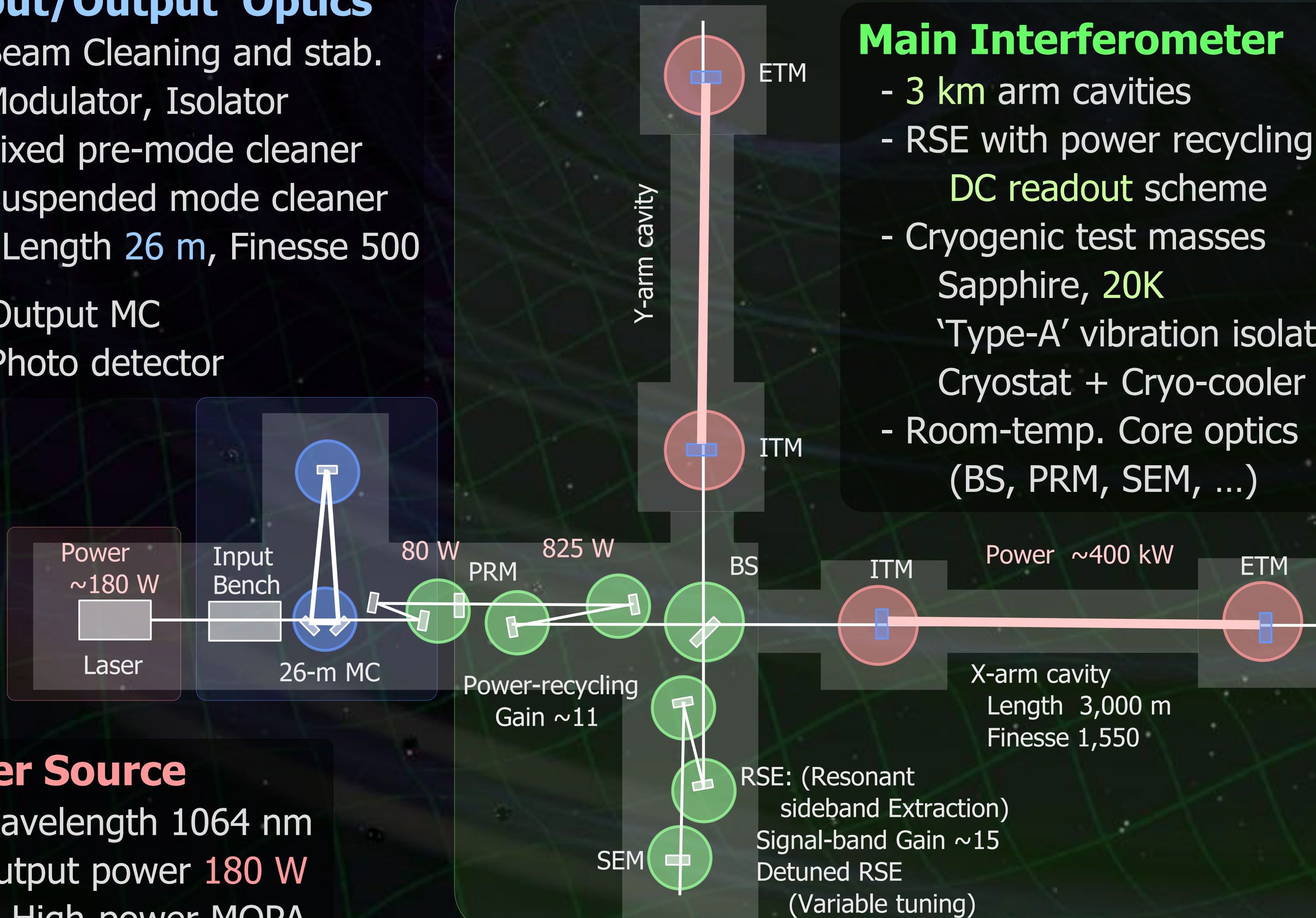
KAGRA 干渉計構成

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

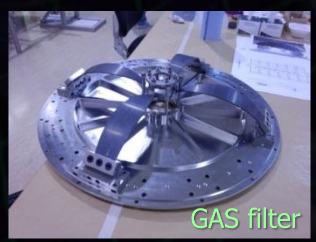


Main Interferometer
- 3 km arm cavities
- RSE with power recycling
  DC readout scheme
- Cryogenic test masses
  Sapphire, 20K
  'Type-A' vibration isolator
  Cryostat + Cryo-cooler
- Room-temp. Core optics
  (BS, PRM, SEM, ...)

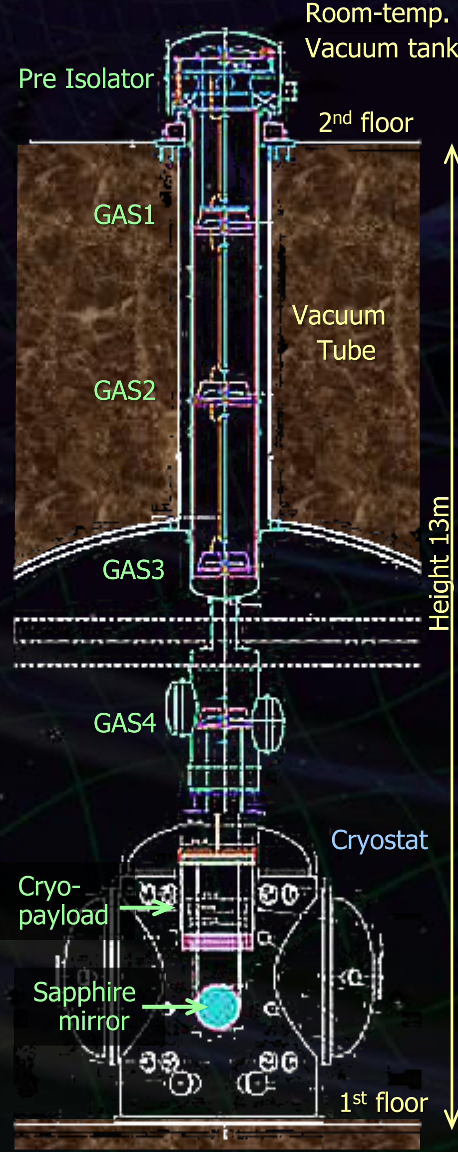
Laser Source
- Wavelength 1064 nm
- Output power 180 W
  High-power MOPA

KAGRA鏡懸架・冷却系

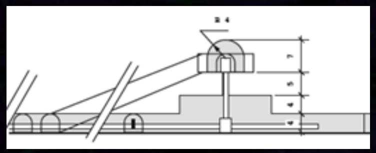
- **高性能防振装置** (Type-A SAS)
  - 上層部の岩盤より懸架された多段の受動防振装置.
  - 常温の真空槽内に収められる.
  - ローカル制御とダンピング機構.
  - 最下段に低温ペイロード, サファイヤ鏡を懸架.



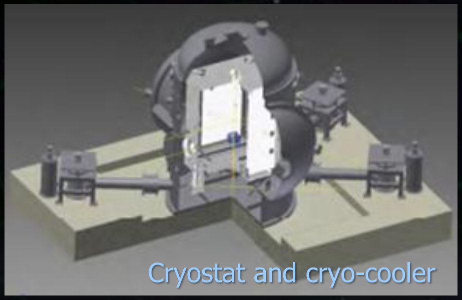
- **低温ペイロード**
  - サファイヤ鏡を懸架する2段振り子.
    - サファイヤ鏡 20K
    - 振り子部 16K
  - 鏡の変位・角度用アクチュエータ.
  - 低温シールド部とヒートリンク接続.



- **トンネル**： 2層構造
  - 上部 高さ 7m
  - 中間岩盤 厚さ 5m
  - 下部 高さ 8m



- **クライオスタット・冷却系**
  - 外形：Φ2.4m, 高さ 3.8m
  - 二重の輻射シールド (80K, 8K)
  - 4台の低雑音PT冷凍機
    - 1st stage 36 W at 50K
    - 2nd stage 0.9 W at 4K

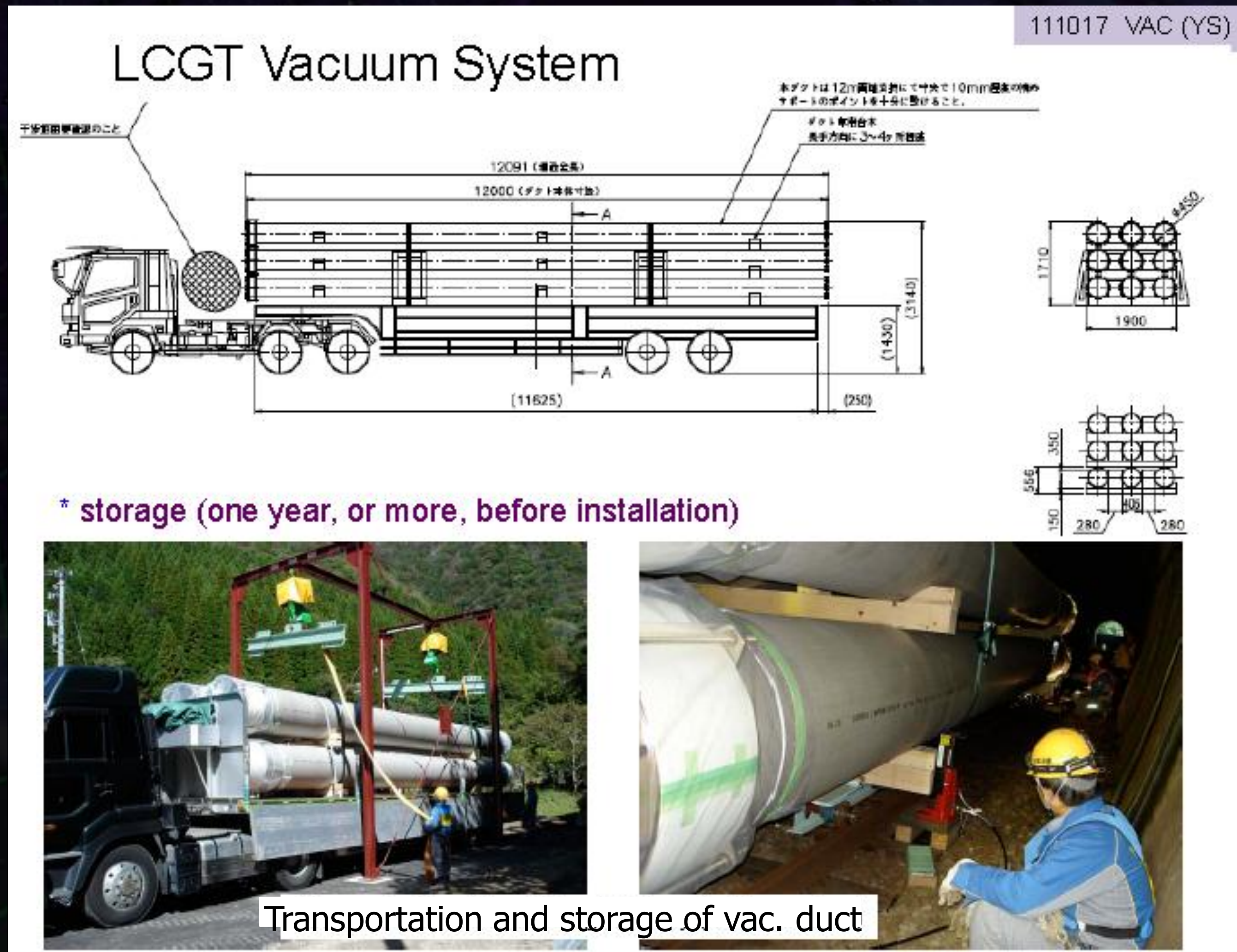


安全祈願祭・着工式

KAGRA安全祈願祭・着工式・祝賀会
岐阜県・神岡 (2012年1月20日)

KAGRA Vacuum duct

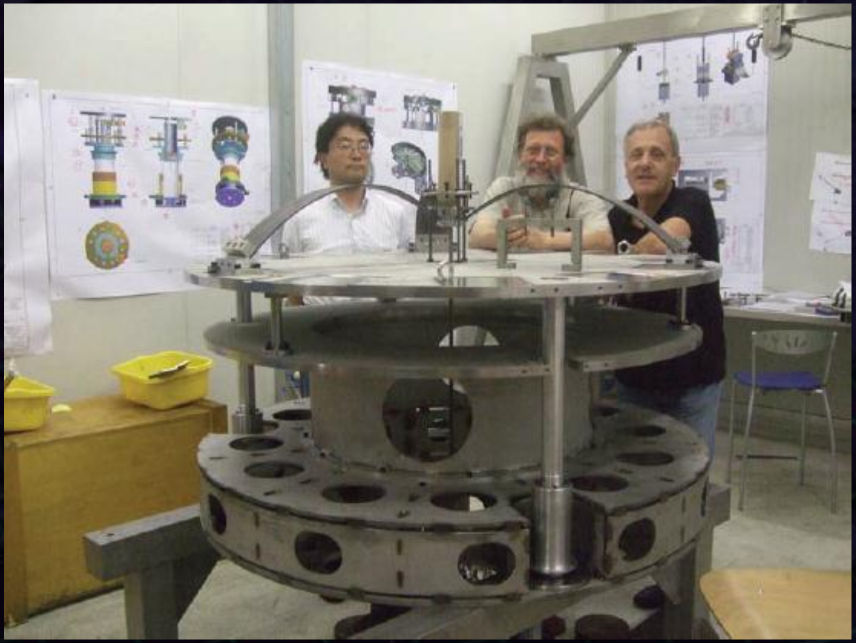
12-m ducts are being delivered: ~100 of 500 ducts

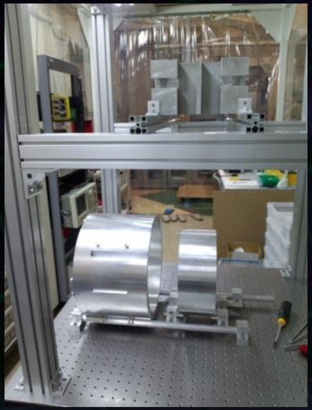


Transportation and storage of vac. duct

Presentation
By Y.Saito (KEK)

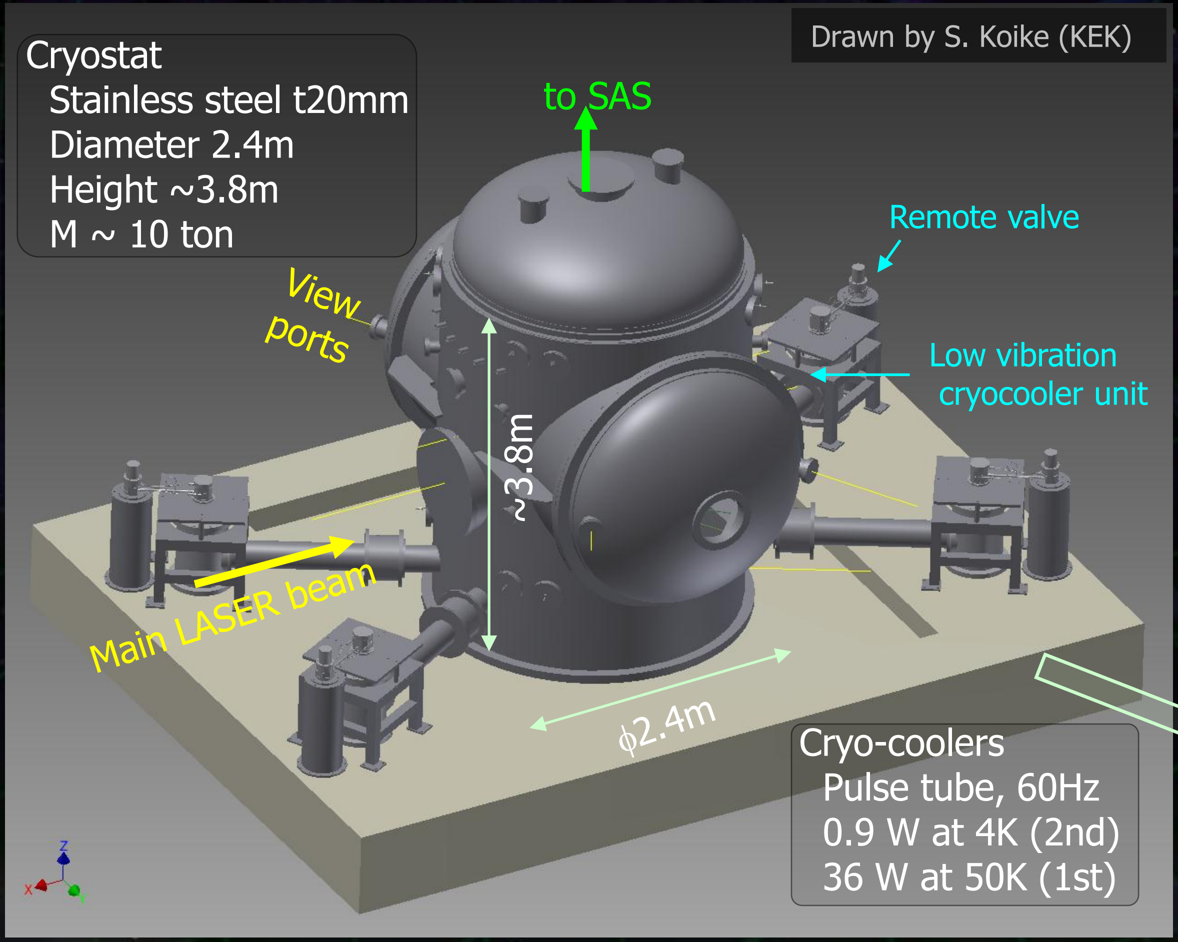
防振装置

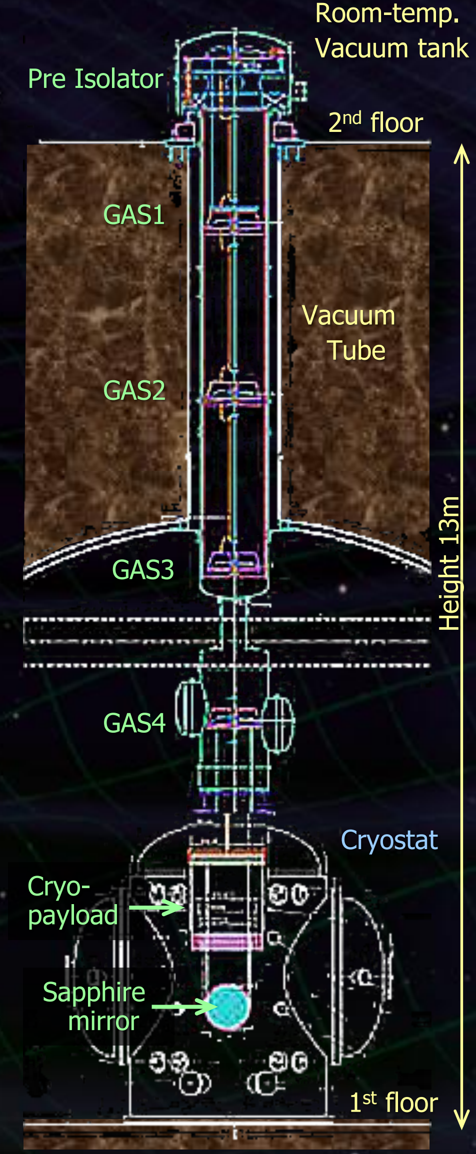




クライオスタット

- CLIO等の経験を生かして設計 (構造解析, 熱解析)
  → 2012年度中頃に1台目評価試験.

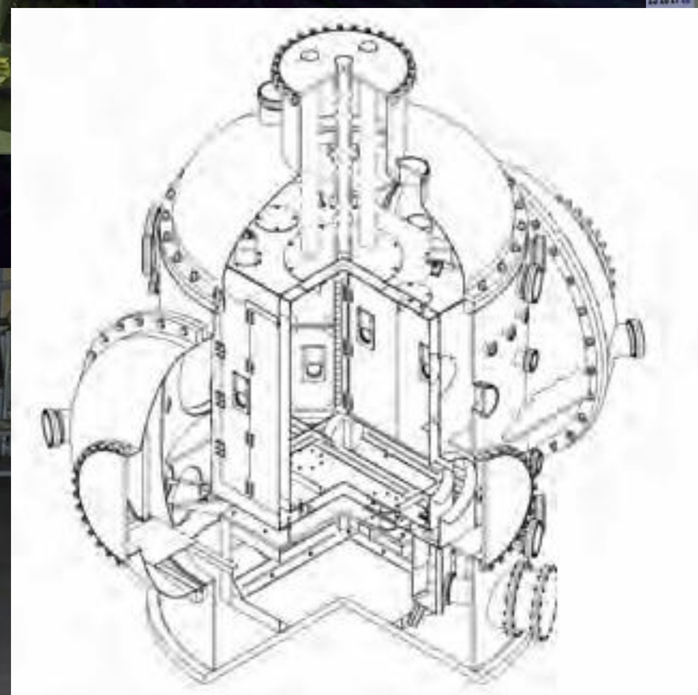




クライオスタット

Ribs inside cryostat

Welding on the connection port



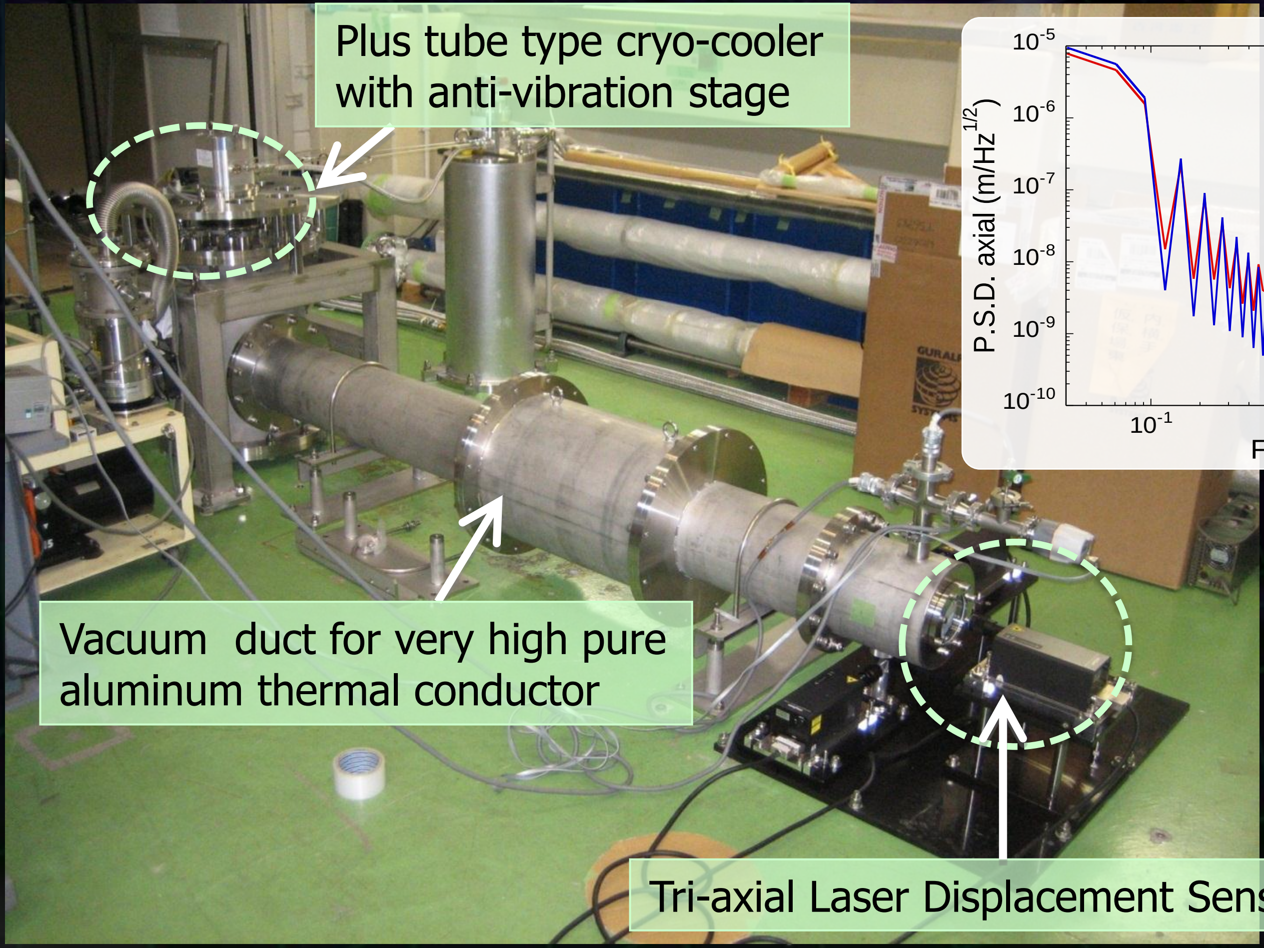
Connection port
to cryo-cooler unit

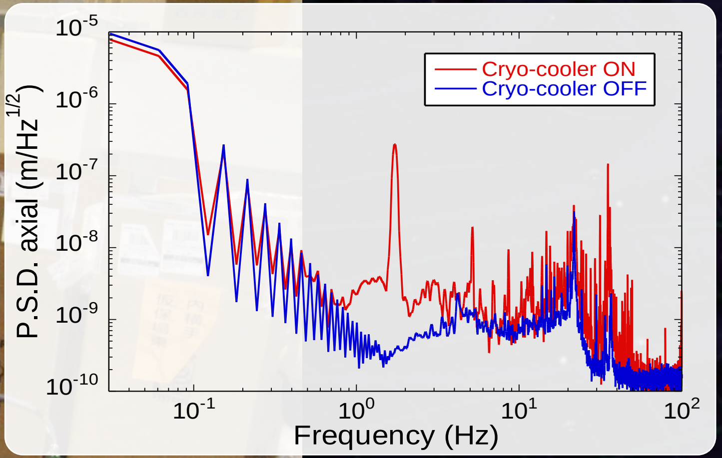
Pipes

at Toshiba Keihin Factory

低振動冷凍機

- CLIOなどの経験・実績を生かして製作.
  - → プロトタイプを用いた評価試験進行中 (KEK)
    冷却能力, 伝熱系を含めた振動など.

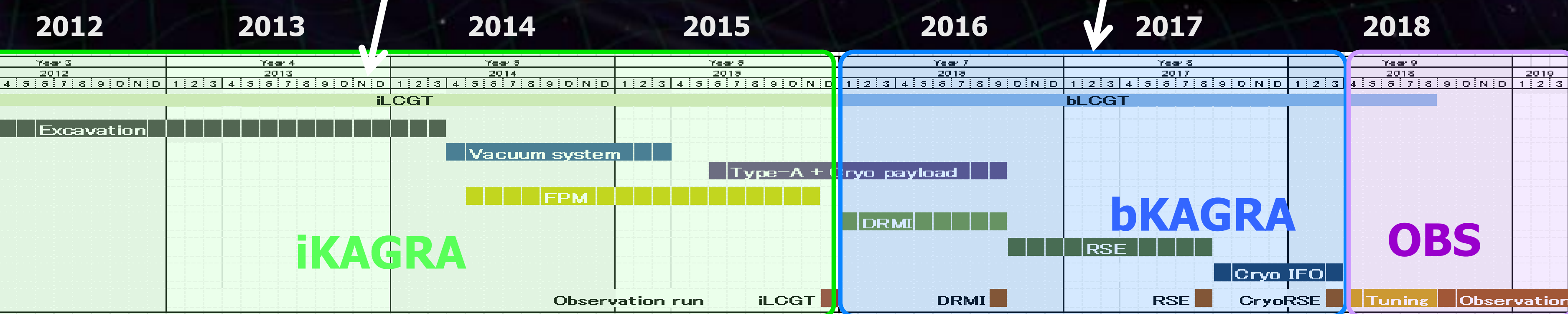




KAGRA全体スケジュール

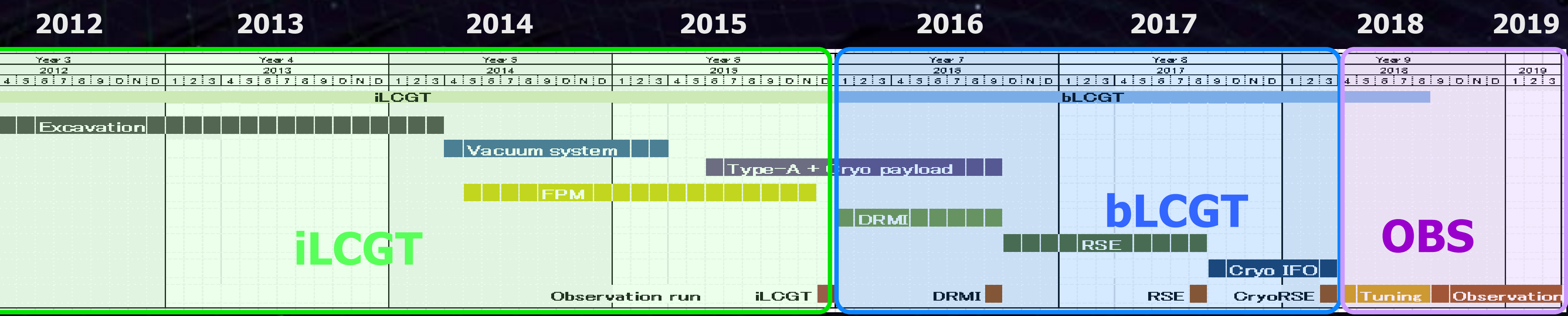
- **iKAGRA** (2010.10 – 2015.12)
  大型干渉計の安定動作を実現
  - 基線長3kmの常温干渉計を動作.
  - 比較的シンプルな光学系・防振系構成で総合システムとしての動作.

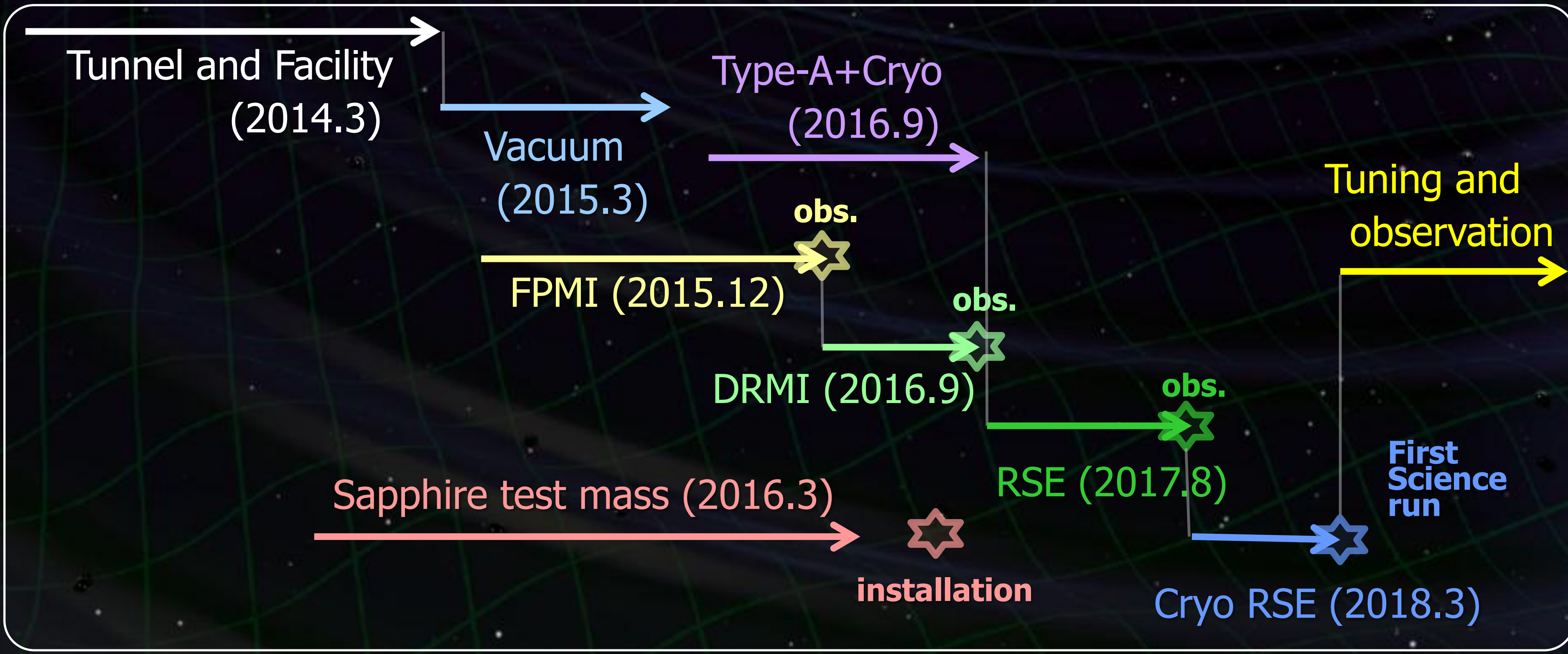
- **bKAGRA** (2016.1 – 2018.3)
  最終構成での動作
  - 干渉計構成, 防振系最終形
  - 低温干渉計としての動作.



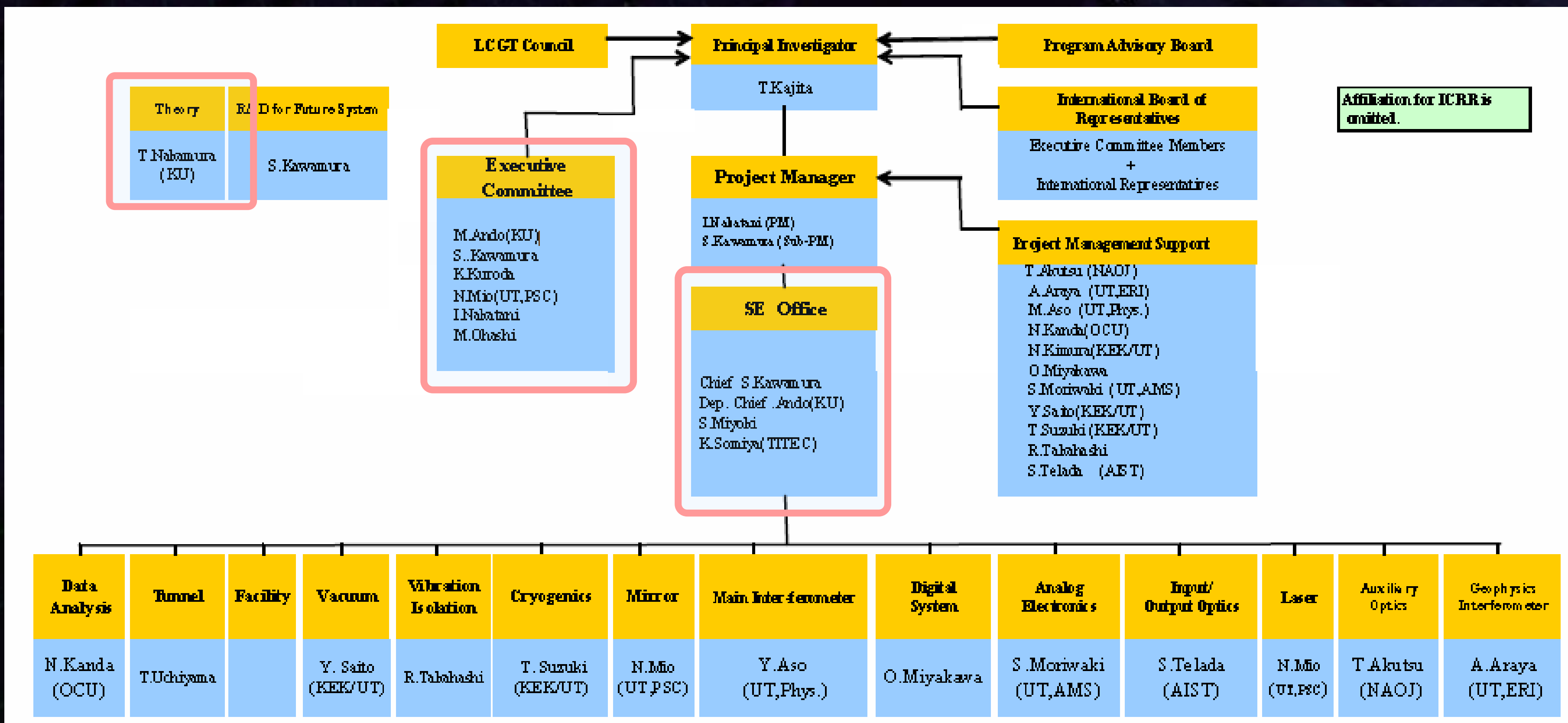
- **OBS** (2018.4 -)
  長期間観測運転と干渉計チューニング.

KAGRAスケジュール





KAGRA組織図



KAGRA System Engineering Management Plan
(ver 2a, Feb. 17, 2012)

まとめ

まとめ

KAGRA： プロジェクト進行中

- 観測可能距離 200Mpc以上 → 年間数回以上の重力波検出.
- 海外の望遠鏡とともに 第2世代の観測ネットワークを形成

⇨ 重力波天文学の分野を切り開く.

- KAGRAでは, 世界に先駆けて第3世代の技術も実証.

低温干渉計技術, 地下サイト

設計と開発

- TAMA と CLIO などの経験・実績を生かして設計.
- 実機プロトタイプ試験, シミュレーションによる詳細設計・検討が進行中.

2010年代後半には、
重力波天文学が幕を開けているだろう!

新しい重力波望遠鏡方式

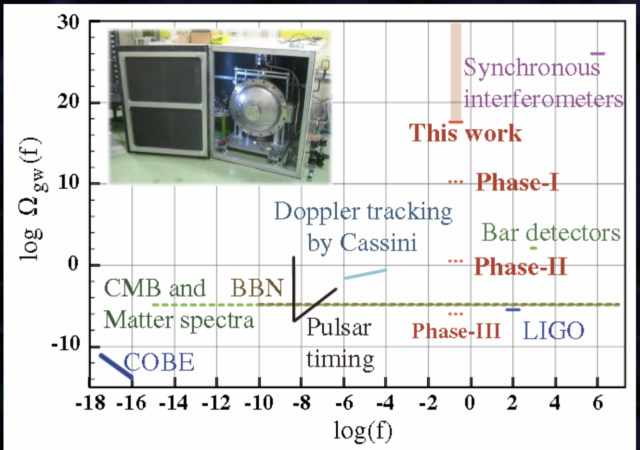
ねじれ型重力波望遠鏡 (TOBA: Torsion-Bar Antenna)

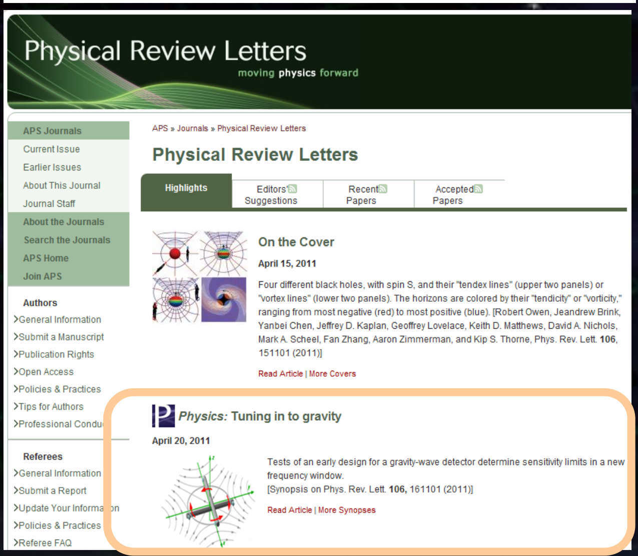
- 新しいアイデアによる重力波望遠鏡方式.
- 低周波数・極低周波数の観測を可能にする.

☆設計検討・プロトタイプ開発.

- 小型TOBAの開発と観測運転.
  → 0.2Hz帯の背景重力波に初めての上限値.
- 東京-京都2台での同時観測運転.
- 超小型宇宙実証モジュールSWIM
  → 世界初の宇宙重力波検出器 (2009年)

MA+, PRL (2010), 物理学会誌 (2010)
K.Ishidoshiro MA+, PRL (2011) → ハイライト記事に選ばれる.
石徹白晃治 博士論文 (2009) → 物理学会若手奨励賞 (2011年度)
穀山渉 修士論文 → 東京大学 奨励賞 (2008年度)
A.Shoda GWPAW Poster Award (2010)　　　など



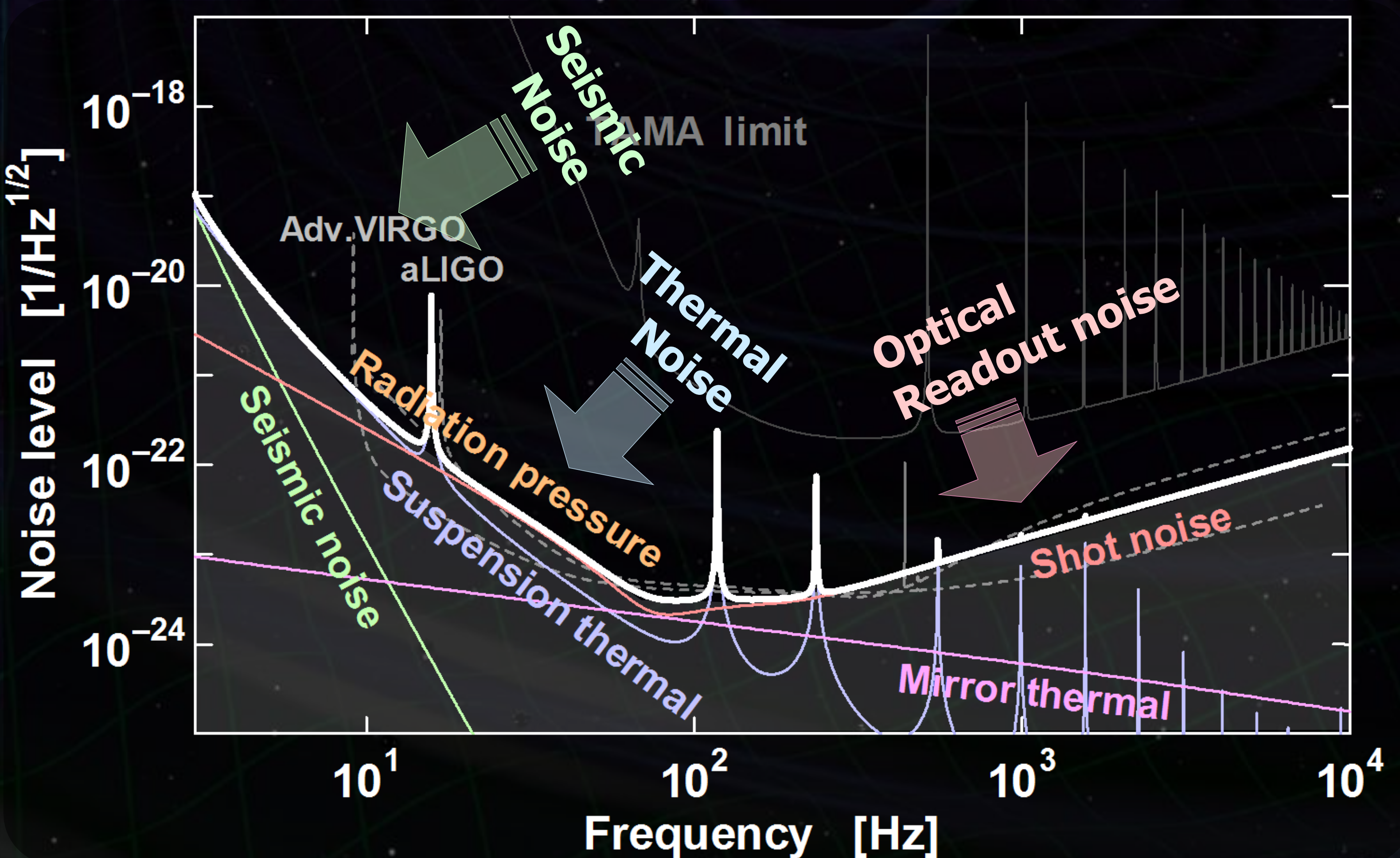


Phys. Rev. Lett.誌 Highlight記事 (April 2011)

終わり

感度の向上

本格的な天文学を目指す → 原理的な雑音源を低減する必要.



光の量子雑音

- 光の量子雑音 --- 干渉計における原理的な雑音
  - 散射雑音 (Shot Noise)
    光検出時の光子数計数誤差
  - 輻射圧雑音 (Radiation Pressure Noise)
    鏡での反射時の光子反跳雑音

$$h_{\mathrm{shot}} \propto 1/\sqrt{P}$$

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

［P：干渉計入射光パワー］

標準量子限界 (Standard Quantum Limit)

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

［M：鏡の質量
L：基線長］

⇨ 長い干渉計基線長
大質量鏡

LCGT：大型・大光量干渉計

基線長 3km, 鏡質量 22kg, 干渉計内光パワー ~800kW

熱雑音の低減

- 熱雑音 --- 干渉計の原理的雑音

  干渉計の構成コンポーネントに 機械損失 → 揺動力 (揺動散逸定理)

  - 鏡の熱雑音　　: 鏡基材, コーティング面などでの損失.
  - 振り子の熱雑音 : 鏡の懸架ワイヤ等での損失.

熱雑音

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

T : 温度 [K]
Q : 機械損失の逆数

⇒ 温度を下げる
良い材質を選ぶ
低減する干渉計構成

LCGT : 低温干渉計 → 熱雑音を低減するクリアな方法.

- 鏡 ~20K, 振り子 ~16K
- 付加的な効果 : 機械損失の低減, 熱レンズ効果の低減,
  パラメトリック不安定性の低減.

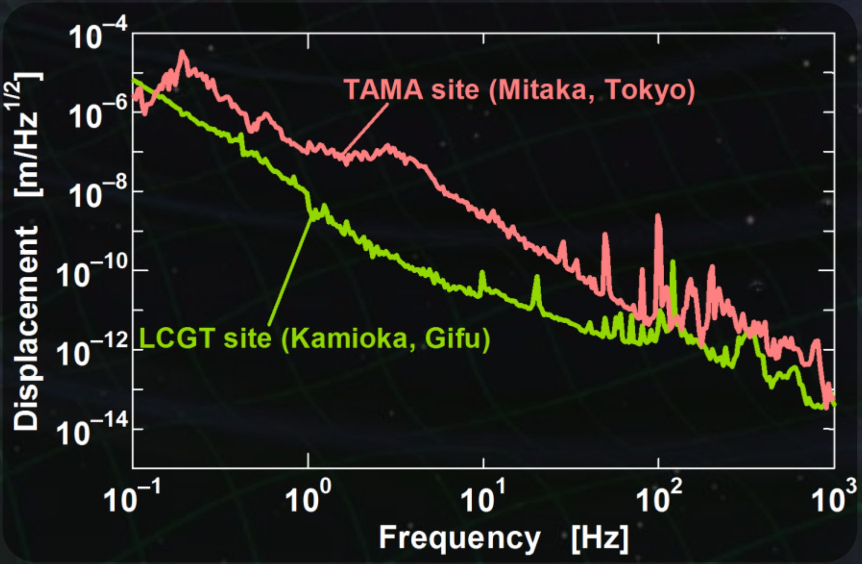
地面振動の影響低減

- 地面振動 --- 地上干渉計の低周波観測帯域と安定度を制限
  - 常微動　　：準定常的な変動. 干渉計の観測帯域を制限.
  - 非定常変動：地震, 気象変動, 人工的な励起など.
    干渉計の安定度, 観測のデューティサイクルに影響.

地面振動レベル
- 地下サイトでは2-3桁小さい
- 高周波数で低減.

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

（神岡サイトでの値, f：周波数, ）



LCGT：地下サイトに建設 → 2-3桁小さい常微動, 長期安定な環境.

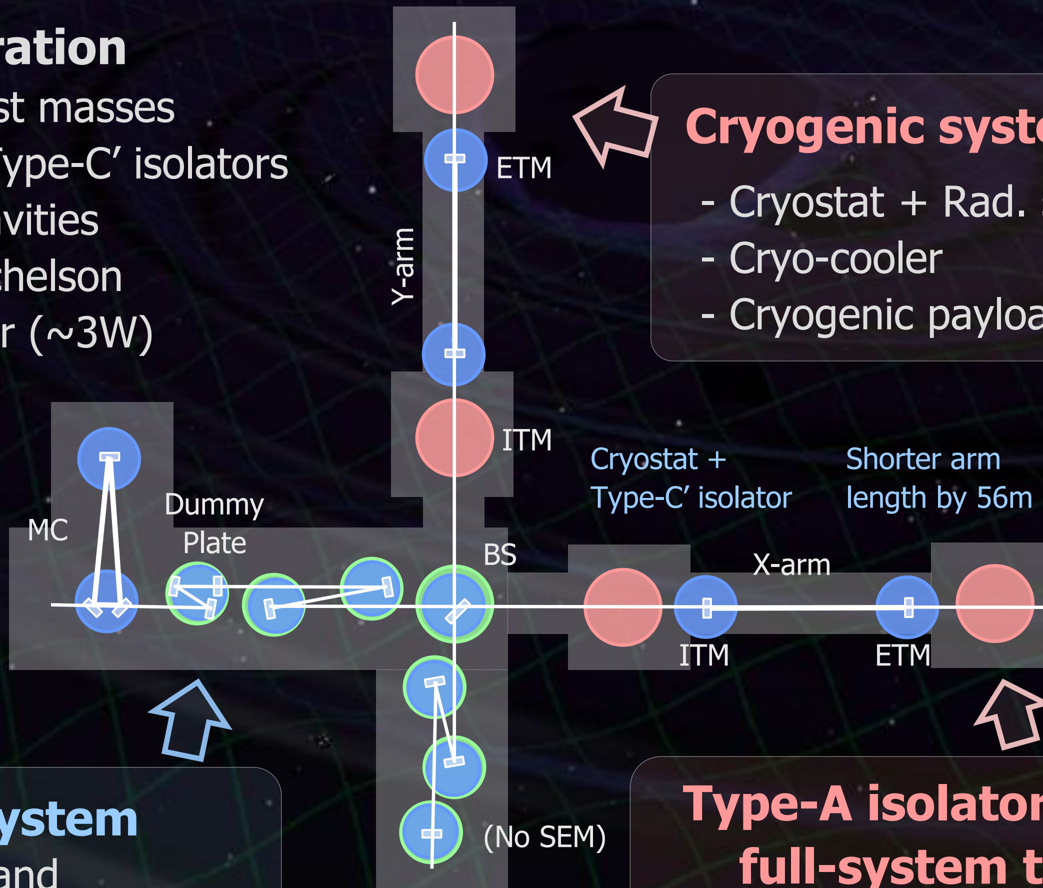
高性能防振装置 SAS：多段・低周波の防振装置.

LCGTスケジュール

iLCGT コミッショニング

iLCGT configuration

- Room-temp. test masses suspended by Type-C′ isolators
- 2.94 km arm cavities
- Fabry-Perot Michelson
- Low laser power (~3W)



Cryogenic system test

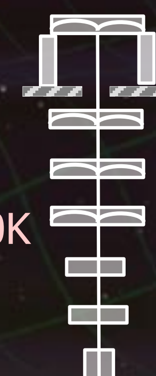
- Cryostat + Rad. shield duct
- Cryo-cooler
- Cryogenic payload (optional)

Type-C′ system

- Test mass and
  Core optics (BS, FM,..)
  Silica, 10kg, 290K
- Seismic isolator
  Stack + Type-B Payload

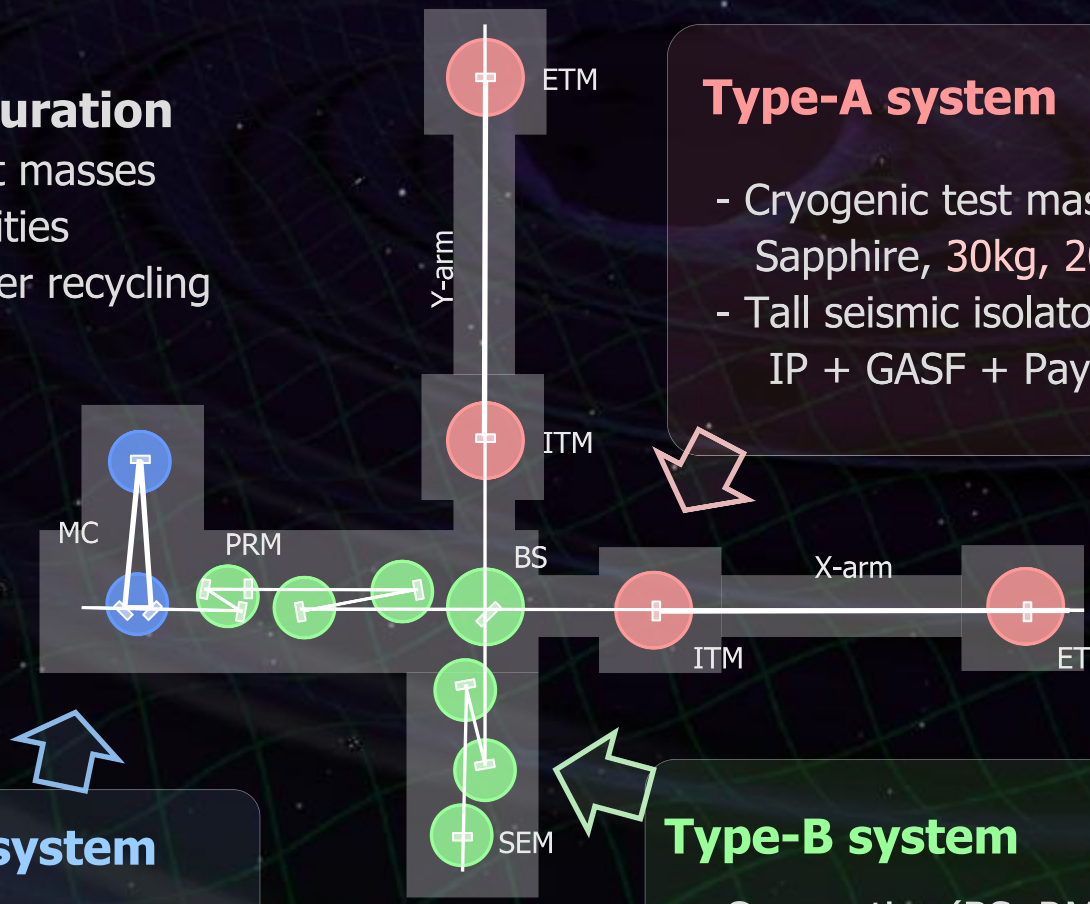
Type-A isolator full-system test

- Room-temp. test
  Sapphire (?), 30kg, 290K
- Tall seismic isolator
  IP + GASF + Payload



bLCGT 干渉計構成

bLCGT configuration
- Cryogenic test masses
- 3 km arm cavities
- RSE with power recycling



Type-A system
- Cryogenic test mass
  Sapphire, 30kg, 20K
- Tall seismic isolator
  IP + GASF + Payload

Type-C system

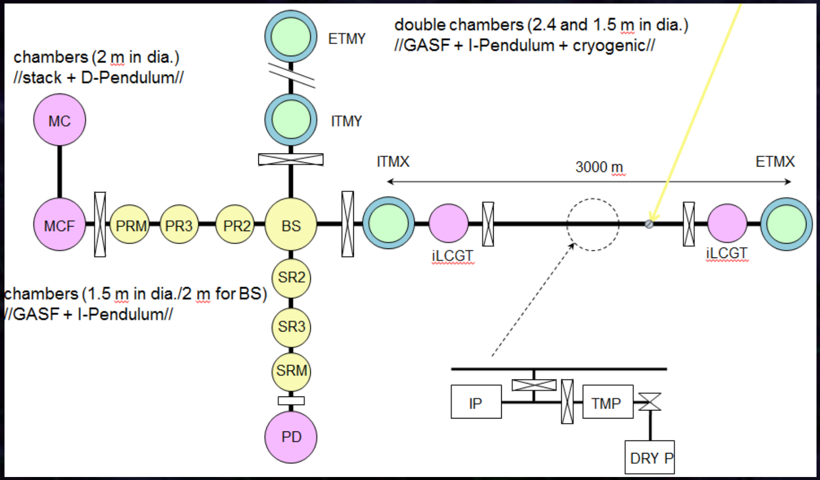
- Mode cleaner
  Silica, 1kg, 290K
- Stack + Payload

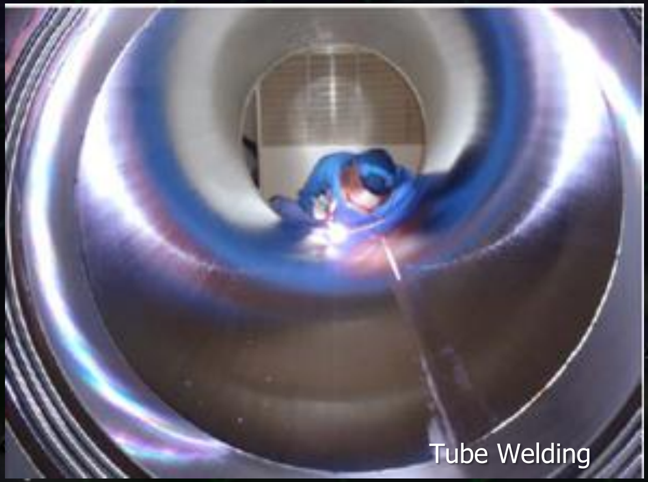
Type-B system
- Core optics (BS, RM ,...)
  Silica, 10kg, 290K
- IP + GASF + Payload
- Stack for aux. optics

真空系

- 真空ダクト
  長さ 12m, Φ80cmのダクトを500本接続.

  - 最初の120本を製作開始.
    24か月ですべてを製作予定.
  - 乾燥空気を密封
    → 廃線になった鉄道トンネルに保管.




Tube Welding


Furnace
(200℃, ～3days)

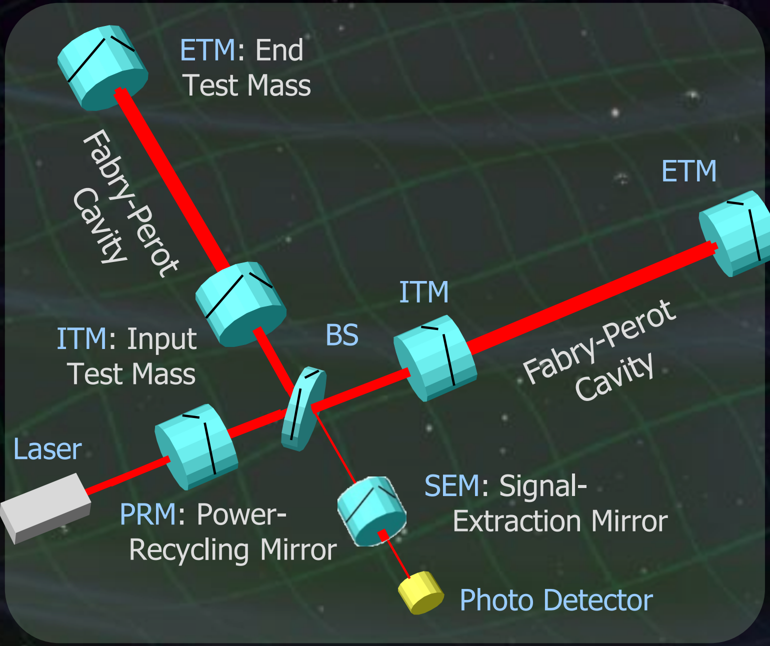

Mozumi tunnel of Kamioka Mining Railway (not in service)

干渉計方式

- RSE干渉計方式 (Resonant-Sideband Extraction)

  マイケルソン干渉計に鏡を追加
  - 腕に ITM　　　: 基線長3kmの Fabry-Perot共振器を構成.
  - 入射部に PRM : 干渉計内の光量を増大させる.
  - 出射部に SEM : 干渉計ないから信号成分を取り出す.

- RSE方式の利点
  - 信号のキャンセルを避けつつ、大光量を腕共振器に蓄えることが可能.
  - 鏡基材を透過する光量を相対的に低減.
    → 鏡の冷却にとって必須.
  - 観測周波数帯が変更可能.
    → 観測対象に応じて最適化が可能.



干渉計の開発研究

TAMA300および プロトタイプ干渉計による豊富な経験と実績.

・TAMA300の動作・長時間観測運転
- PRFPMI方式 での動作.
- 第1世代干渉計としての実績.
  2000-2002年 世界最高感度
  3000時間を超える観測データの蓄積

TAMA300

・プロトタイプ干渉計によるRSE方式の研究
- NAOJ 4m干渉計, Caltech 40m干渉計

⇨ RSE干渉計の安定動作の実現.
RSEの原理を実証.
（信号成分の取り出し, 観測帯域の調整）

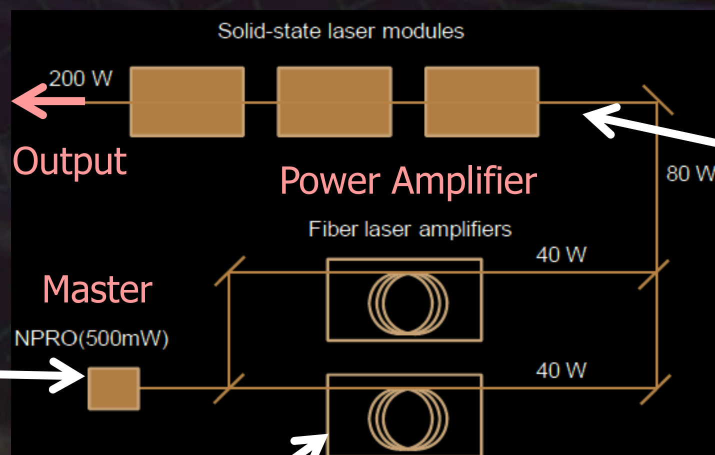
4m RSE prototype at NAOJ

⇨ RSE干渉計技術は確立されている.
シミュレーション等を用い, 光学設計・制御性設計進行中.

レーザー光源

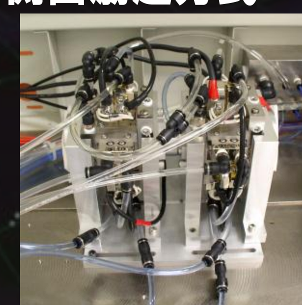
干渉計内の光量を増加させるためには、
高出力レーザー光源と低光損失鏡が必要.

- LCGT用の光源：出力180W の Nd:YAG レーザー
  MOPA (Master Oscillator Power Amplifier) 方式



マスターレーザー
Nd:YAG, 500mW
NPRO方式固体レーザー

固体レーザーアンプ
市販モジュール 50W
側面励起方式



ファイバーアンプ
市販モジュール 40W
単モード, 偏波面保存

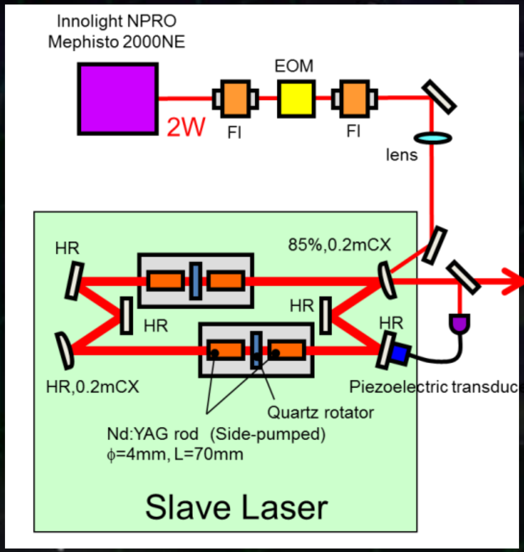
高出力光源の開発

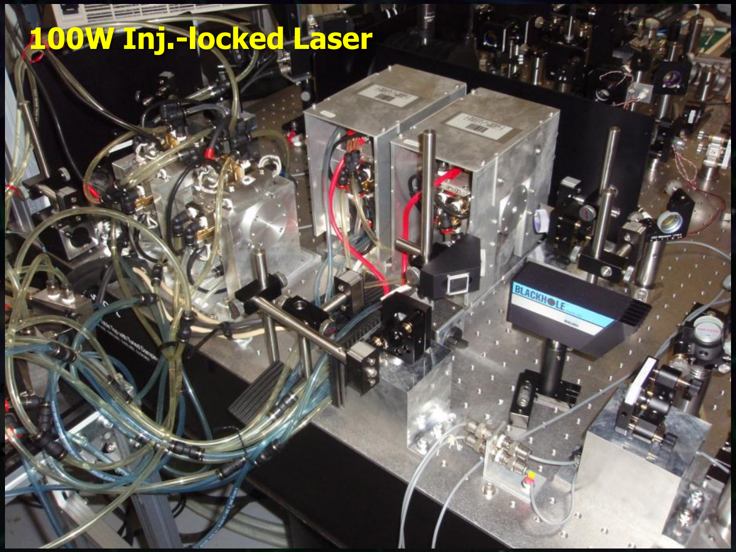
100Wレーザープロトタイプの開発・試験　(東京大・新領域)

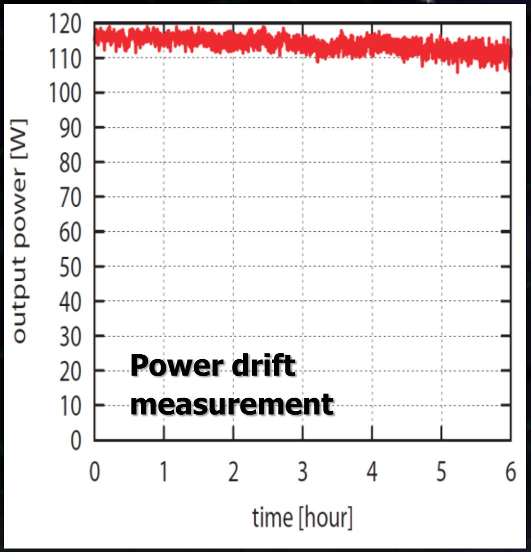
・固体レーザーモジュール 2台により注入同期レーザー

- 長時間安定動作を確認, 出力光の品質評価.
- 外部共振器レファレンスを用いた周波数安定化 → 要求値を満たす.
- 強度安定化実験　→ 制御性を確認.

⇨ 基本特性を確認. 実機の手配進行中.







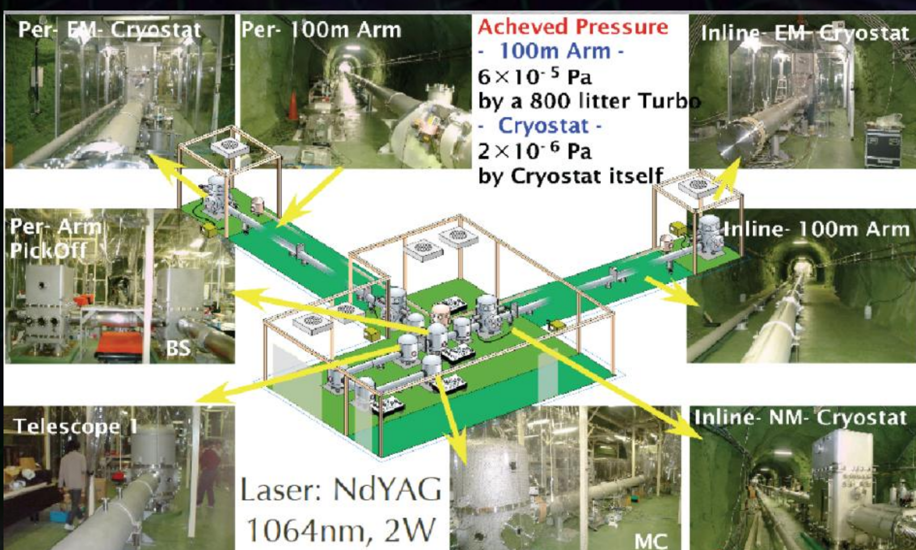
低温干渉計の動作実証

- CLIO --- 基線長100mの低温干渉計
  - 神岡の地下サイトに設置されている
  - 鏡・振り子を 約16K まで冷却した状態で動作.
    サファイヤ鏡, 低温懸架装置, 低雑音冷凍機など.

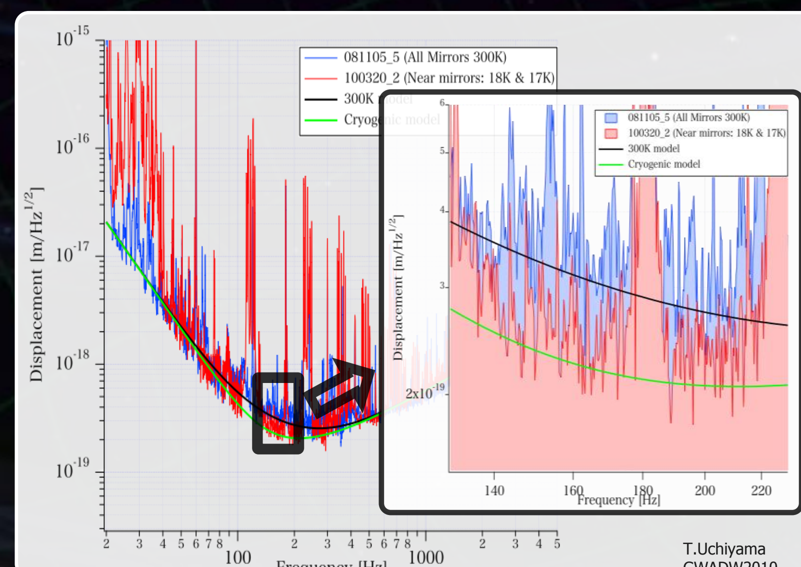
低温工学・超電導学会誌
「低温工学」7月号でLCGT特集

⇨ 冷却運転時に感度の向上を確認.
低温干渉計の動作実証を達成.

詳細は宮川氏講演にて.

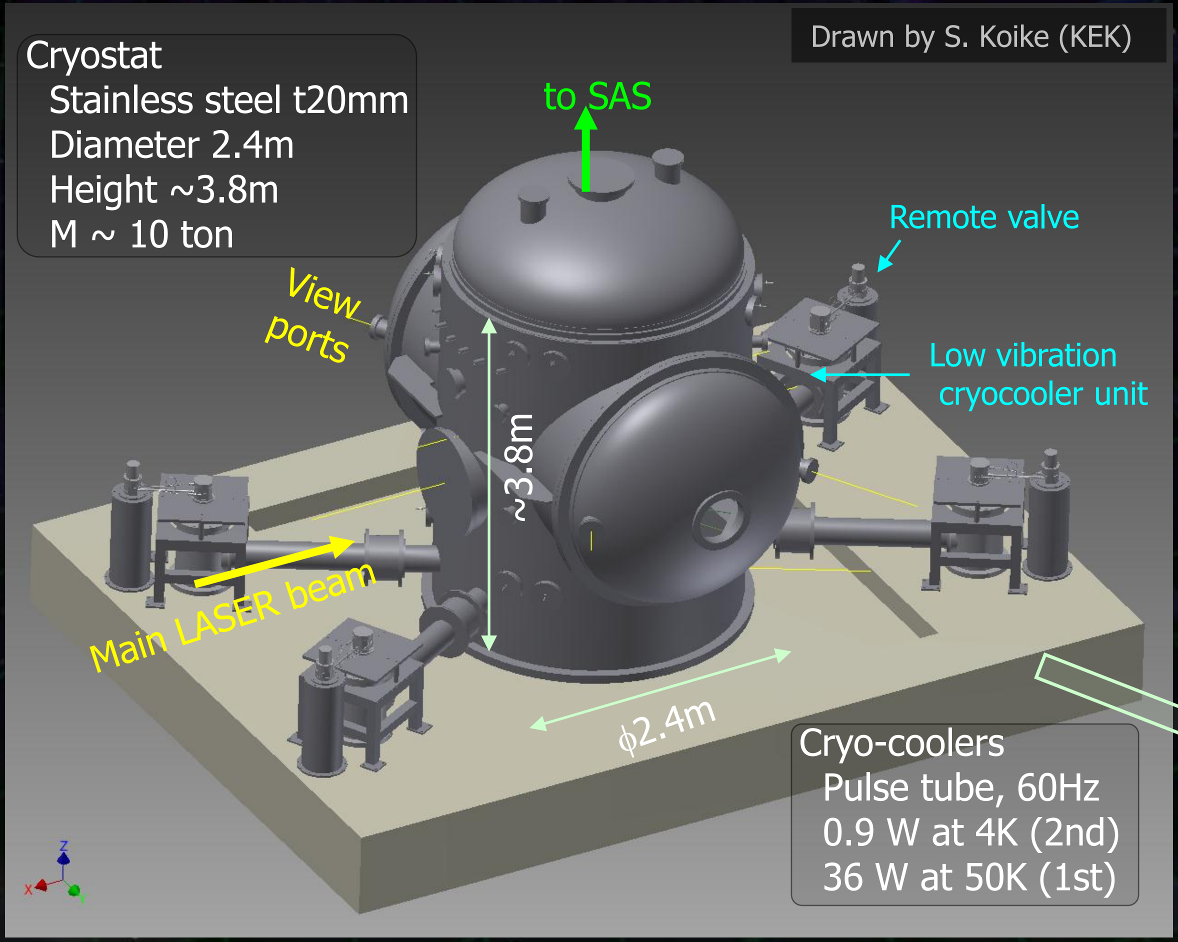


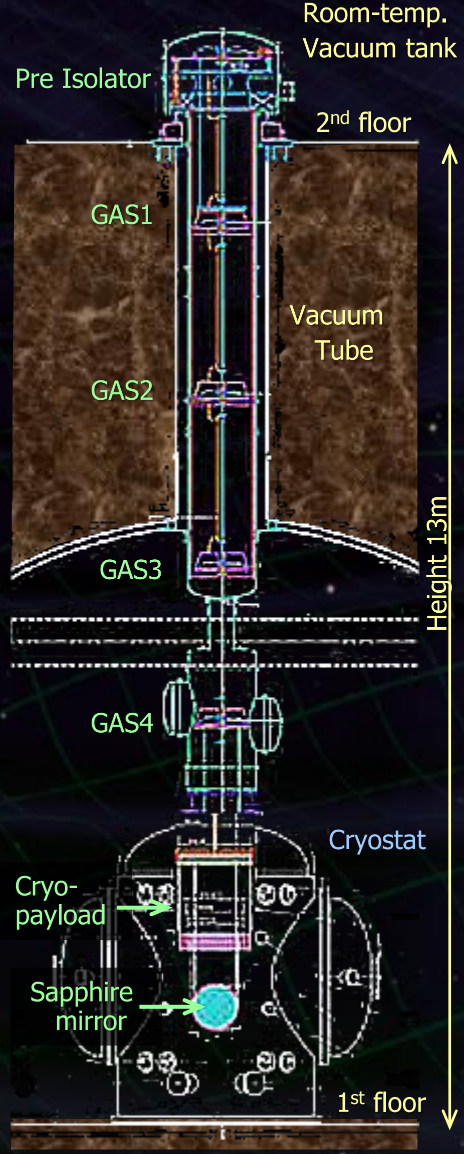
CLIO : 100-m cryogenic interferometer



クライオスタット

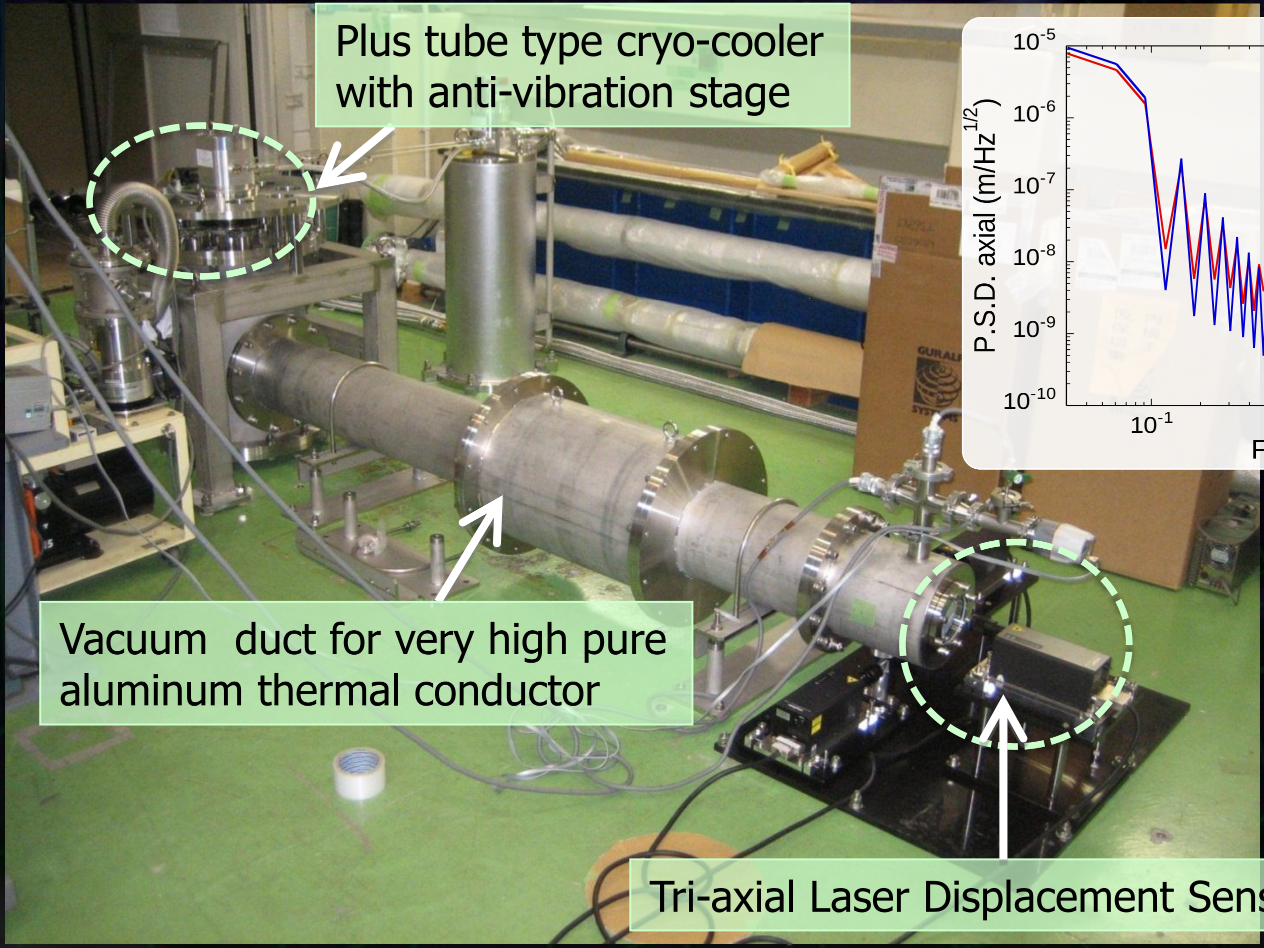
- CLIO等の経験を生かして設計 (構造解析, 熱解析)
  → 2012年度中頃に1台目評価試験.

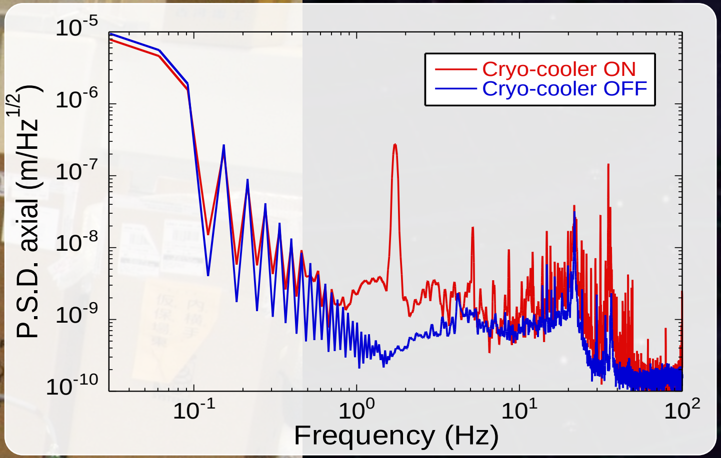




低振動冷凍機

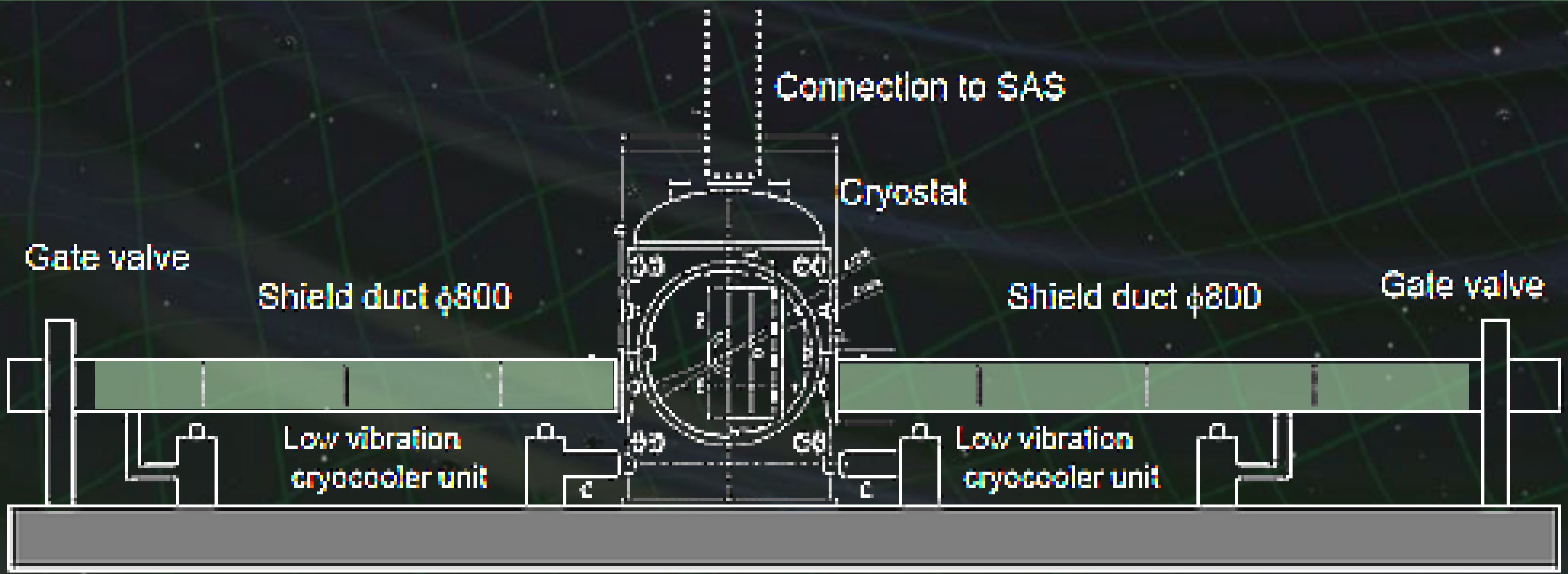
- CLIOなどの経験・実績を生かして製作.
  → プロトタイプを用いた評価試験進行中 (KEK)
  冷却能力, 伝熱系を含めた振動など.





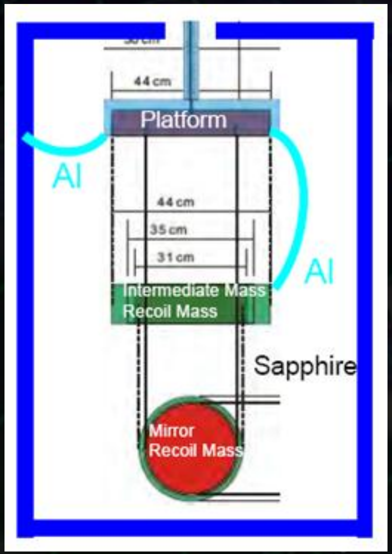
シールドダクト

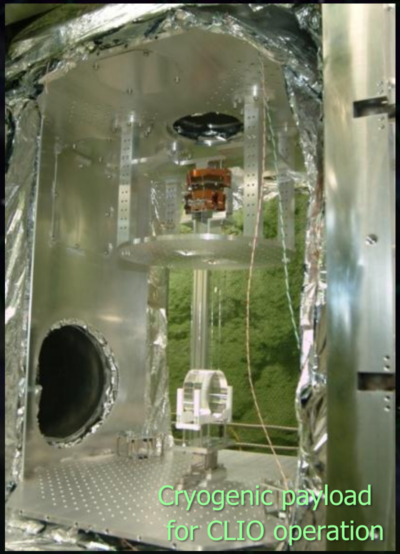
- 光軸方向 (3kmダクト部) からの
  熱流入を低減するための輻射シールド.
- CLIOを用いた評価結果をもとに設計.
  → バッフル・シールド内面処理などの詳細検討進行中.
  シミュレーション等による評価 (ICRR).
  ⇨ 2012年度より実機試験.

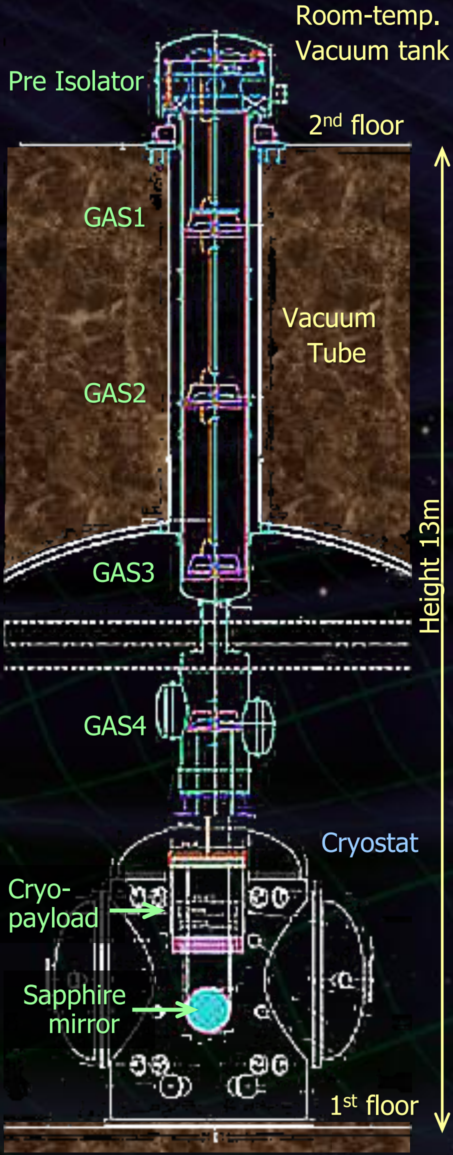


低温ペイロード

- これまでの干渉計での実績を用いて設計.
  - CLIO　　：サファイヤ鏡, 熱伝導系の設計.
  - TAMA300：防振特性, 制御用アクチュエータ構成.
- 設計と評価試験.
  - 熱設計 – 有限要素法シミュレーション (KEK, ICRR)
  - サファイヤファイバー懸架 (KEK, U-Tokyo)
  - コーティングの熱雑音 (ICRR, KEK)





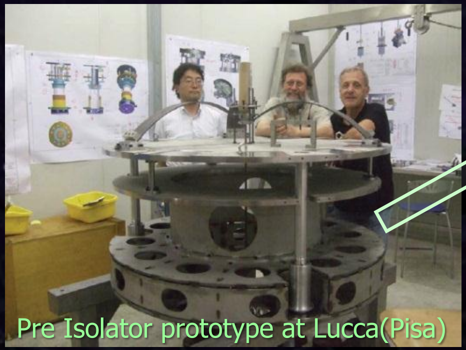


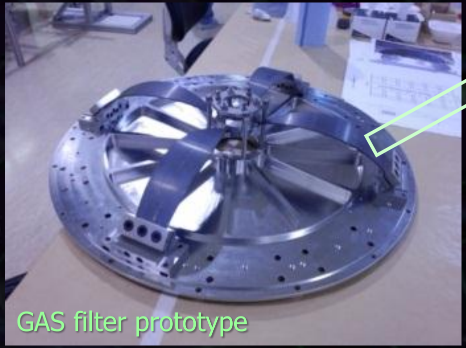
試験マス防振系

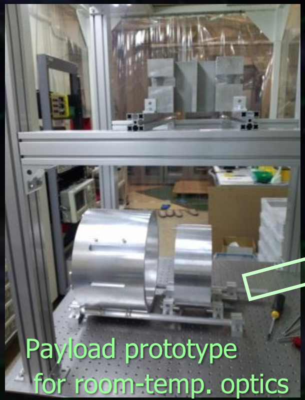
- TAMA300に導入された
  TAMA-SASをもとに設計.
  → シミュレーションにより防振
  性能・低周波安定性など評価.

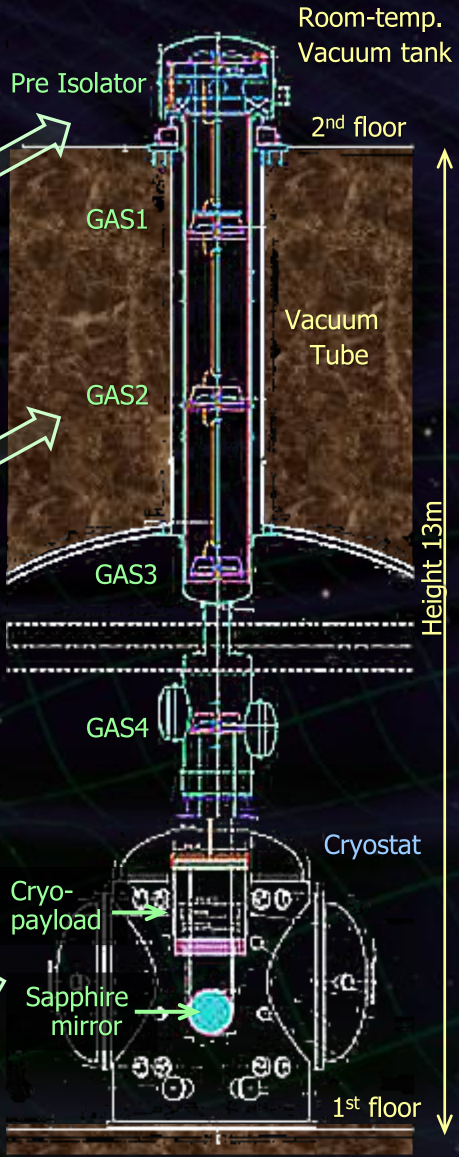
- 構成要素のプロトタイプ試験進行中.
  - Pre-isolator (ICRR)
  - 常温ペイロード (NAOJ)

- 2012年度よりTAMAサイトで
  Type-B SAS 防振系 (常温用)
  の総合プロトタイプ試験.


Pre Isolator prototype at Lucca(Pisa)


GAS filter prototype


Payload prototype
for room-temp. optics

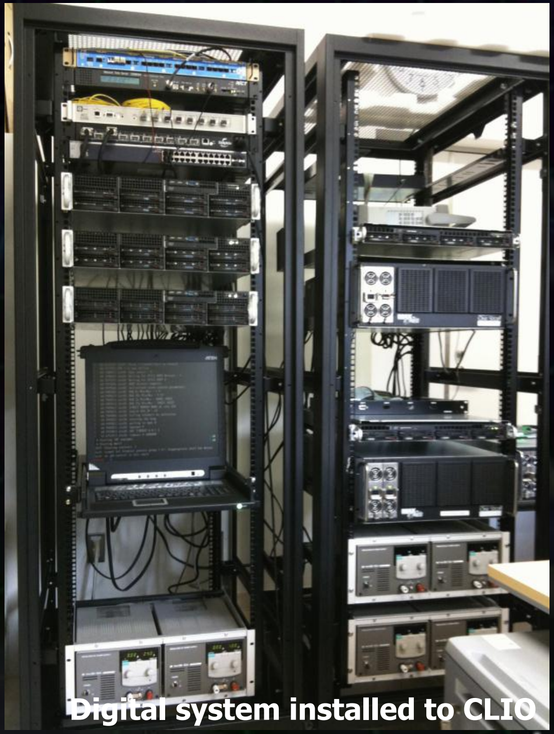


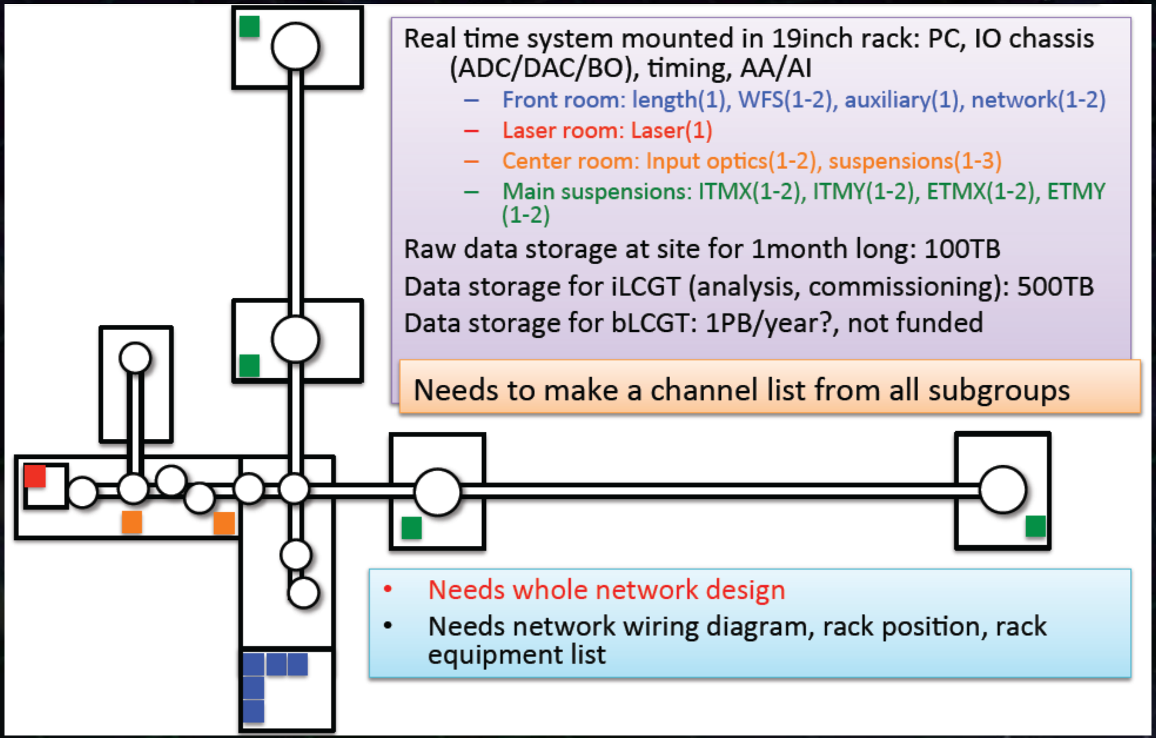
干渉計制御・データ取得系

・デジタルシステム

- 干渉計の制御とデータの取得・記録.
  ADC/DAC, アナログフロントエンドを備えたデジタル制御系をネットワーク接続.
  Fast loop : 16 kHz, 64channel

- aLIGOと同等のシステム
  → LIGOの協力のもとCLIOで実証試験.
  今年度中に5セットを調達.



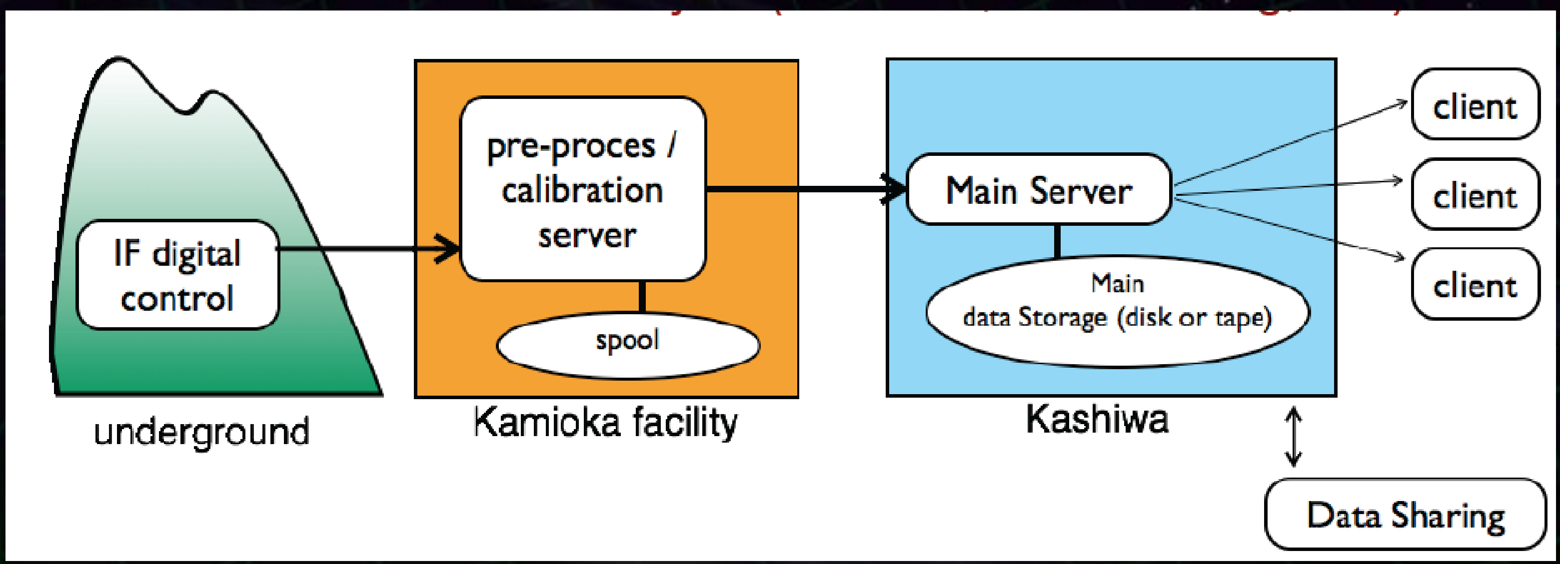


データ処理・解析

- データの記録と分配
  - データ取得系：干渉計制御システムと統合.
  - 神岡施設で、前処理とスプール.
  - 宇宙線研究所でデータの保管と解析.

  - 国際協力体制については、議論中.

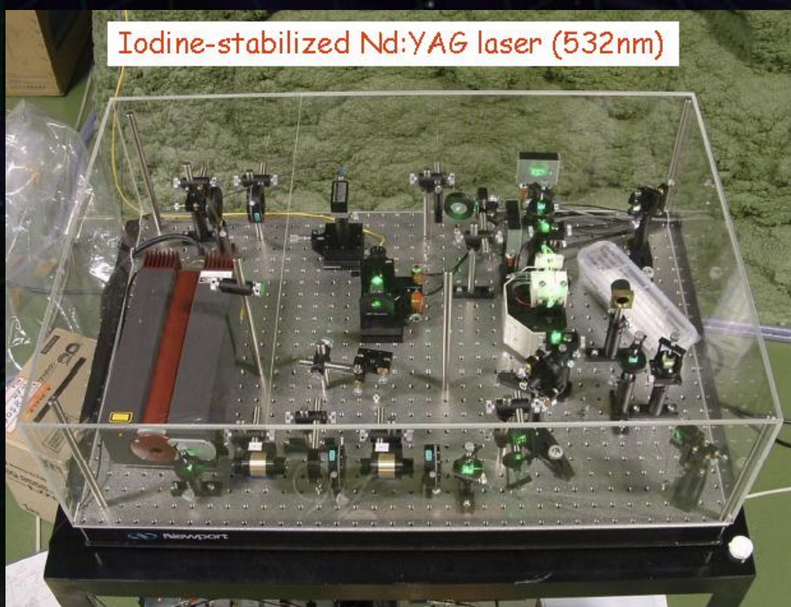
データレート　：70 GByte/hour
計算処理能力：数 TFlops.
記録容量　：30 PByte



Computing platform and Network

地殻歪み干渉計

- 地殻歪み観測用の干渉計型.
  - LCGTの腕に沿って設置, 基線長 1.5 km
  - 光源：ヨウ素吸収線を用いて周波数安定化.
  - **歪み感度**：10^{-13}

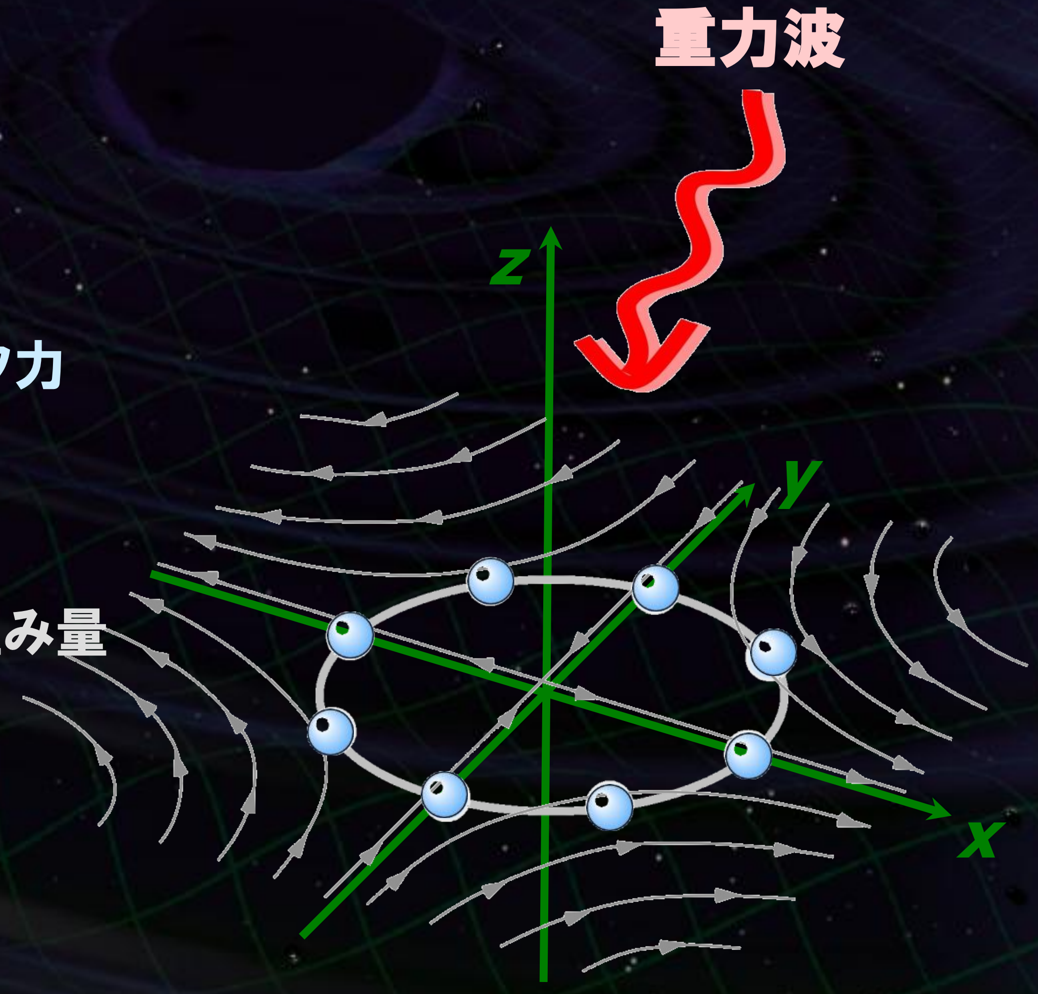


重力波の効果

重力波の効果

　自由質点間の距離の変化

　大きさを持った物体への潮汐力



重力波の振幅 h ：無次元の歪み量

$h = 10^{-21}$

→ 1mの距離が 10^{-21}m 伸縮する

宇宙重力波望遠鏡のターゲット

宇宙重力波望遠鏡 -- 0.1mHz – 1 Hz の観測周波数帯

⇨ **中間/巨大ブラックホール, 初期宇宙**

中性子星・白色矮星

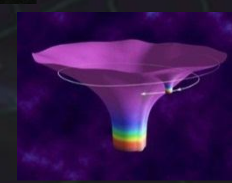
連星

定常的・
準静的
な自転・
公転運動

ブラックホール

巨大ブラック
ホールの合体

EMRI

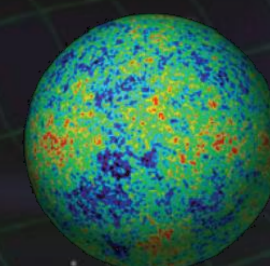


準固有振動

初期宇宙

多数天体の
重ね合わせ

背景重力波



電磁波
ニュートリノ

同時観測
数値相対論

重力理論の検証

超巨大BHの形成過程
銀河形成史

宇宙論, 宇宙の誕生と発展
ダークエネルギー・ダークマター

TAMA300 と CLIO

TAMA300 (1995~)

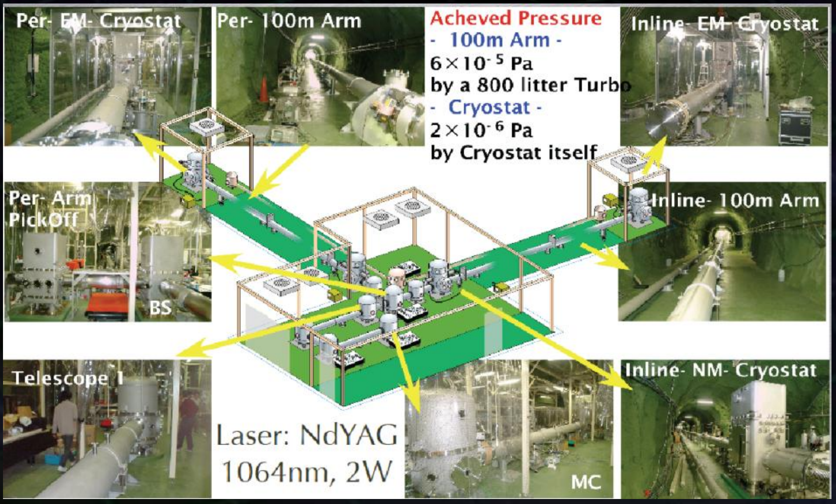
基線長300mの 重力波検出器

銀河系内を見渡せる感度
(世界最高感度 2000-2002年)
他の干渉計に先駆けた観測運転
(3000時間を超える観測データ)

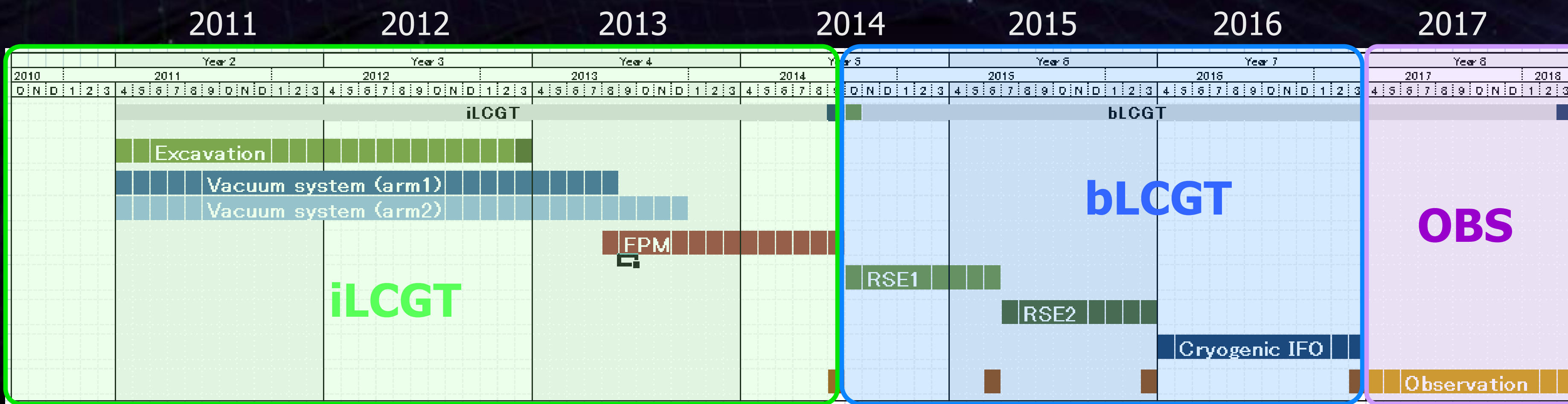
CLIO (2002~)

基線長100mの
低温・地下レーザー干渉計

地下環境を生かした安定な動作
20K以下の低温での動作
→ 冷却による感度向上を確認



Schedule



iLCGT laser preparation

Installation and operation

bLCGT laser operation

Half-cryogenic operation

Full-cryogenic operation

Observation and tuning

MC installation and operation

Room-temperature IFO commissioning

iLCGT commissioning

RSE implementation

Cryostat + Cryo-payload Prototype test

Cryogenic full system installation and shakedown

Observation runs

- **Step-by-step commissioning plan**

  → Observation or engineering run is planed at each step.

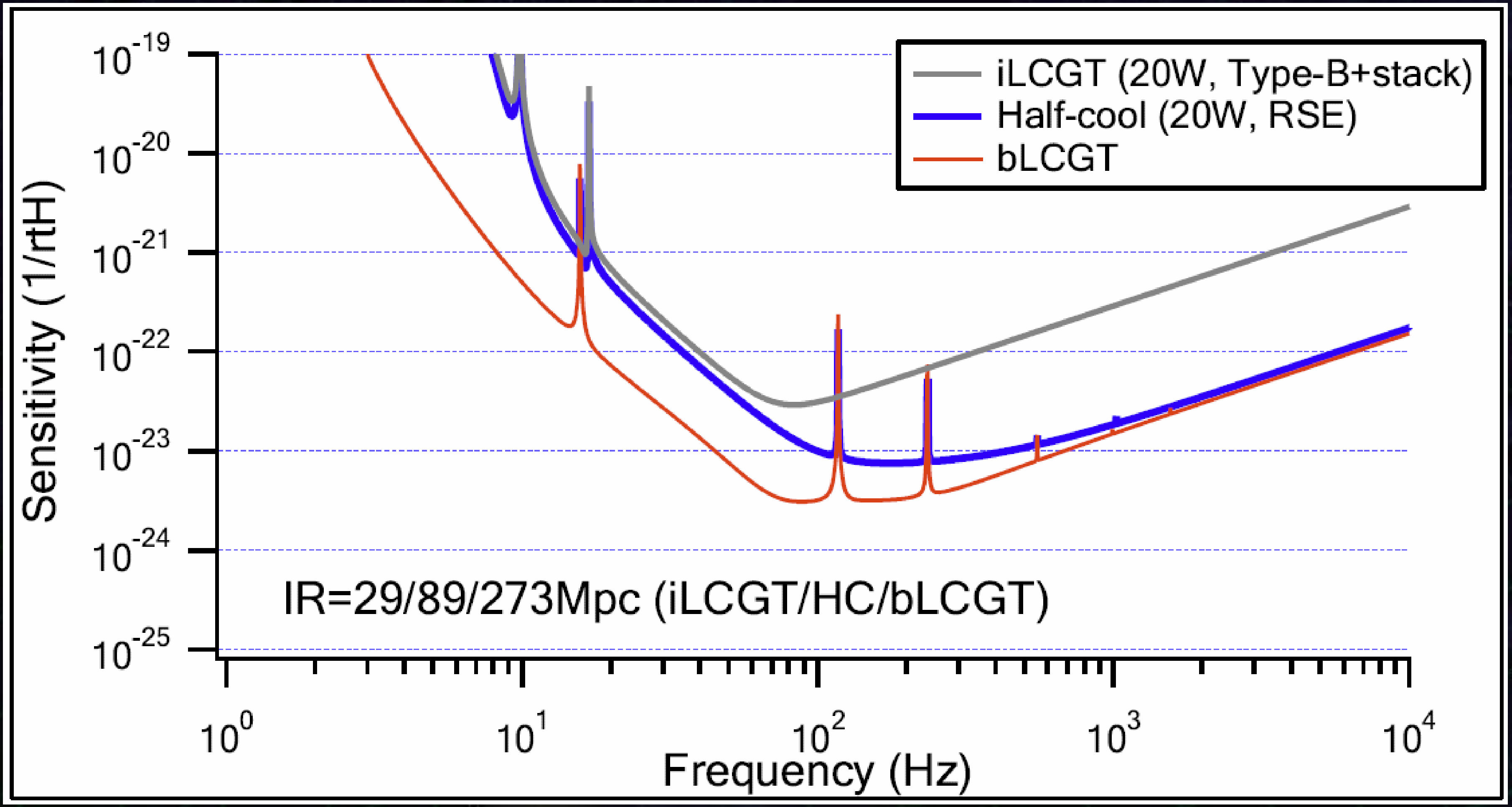
  - Test of full detector system including a data-processing.
  - Detector characterization on long-term stability.
  - Development of data-analysis pipelines.

Observable range for NS binary inspiral		Fundamental noise limit
iLCGT	29 Mpc	FPM, Low power, 10kg Silica, Temp: 300K
Half cryogenic	89 Mpc	RSE, Low power, 10kg Silica, Temp: 20K + 300K
Final bLCGT	273 Mpc	RSE, High power, 30kg Sapphire, Temp: 20K

(Source at optimal direction, Threshold : SNR 8)

- **Tight schedule**
  - First priority is to operate LCGT with the final configuration.
  - Refrain from spending too much time for the intermediate runs.

Sensitivity



By K.Somiya

国際協力

複数台での同時観測の意義

(Ad. LIGO, Ad. VIRGOとの同時観測)

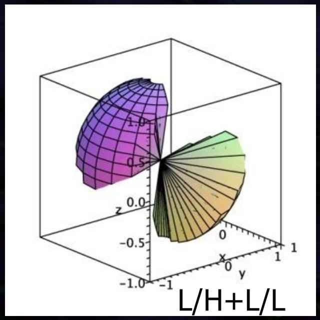
天文的な意義

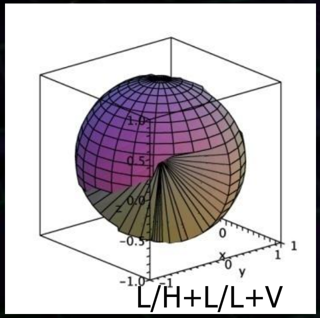
天球のカバー　←　干渉計は 弱い指向性を持つ

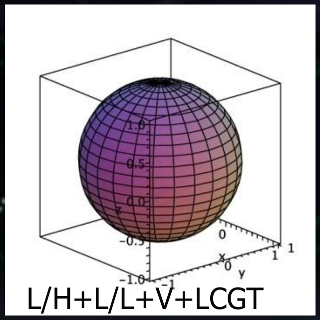
検出された場合　--- 天文的情報の取得

波源の位置, 偏波　の情報の取得

→ 最低3台, 指向性を考慮するとさらに必要







実際上の意義

重力波信号は微弱

→ 多くの Fake event が現れる

複数台での同時検出

→ 検出の信頼度の向上, 偽イベントの除去

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

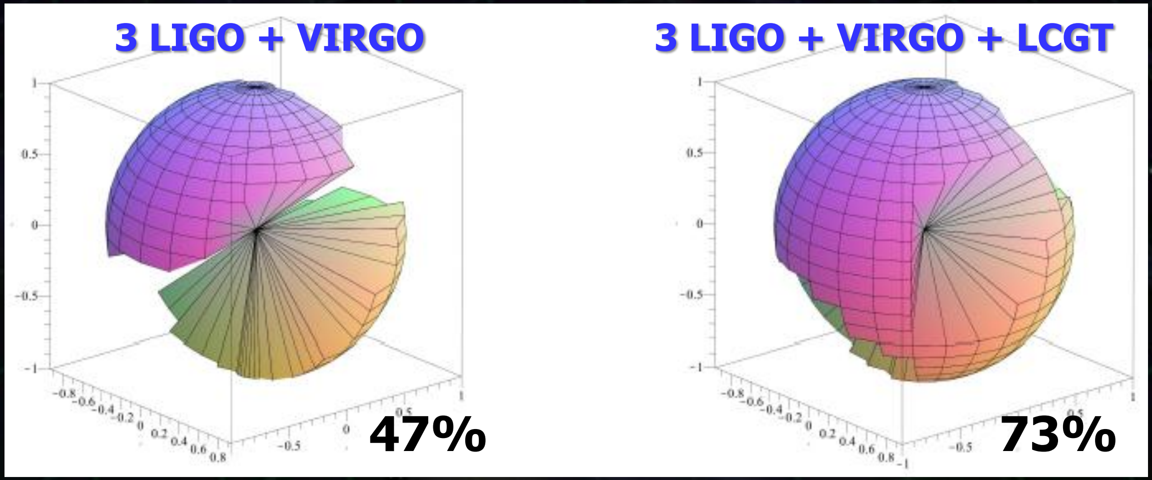
Gamma-ray, X-ray, optical/IR, Radio, Neutrino, ….

- 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



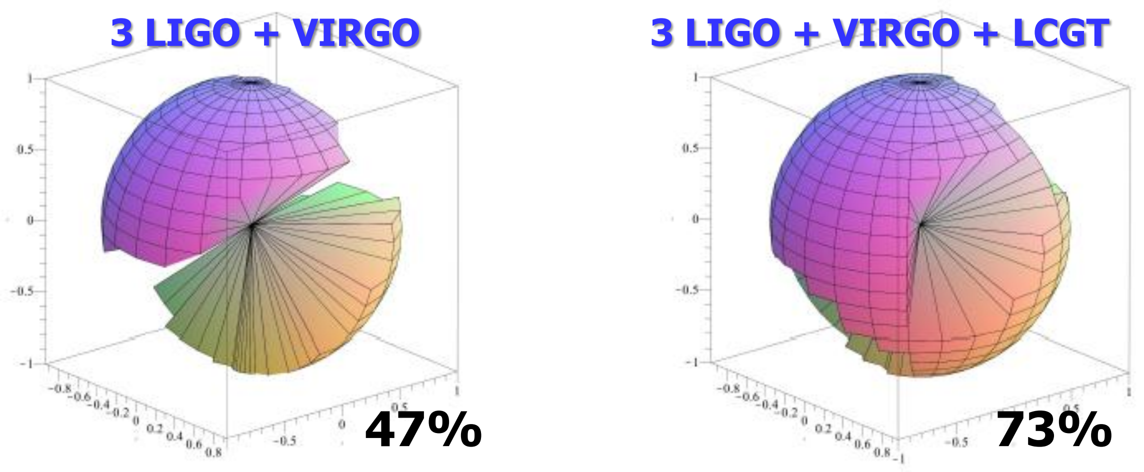
Sky-coverage pattern
(0.707 of max. range)

B.Schutz
arXiv:1102.5421

Network Observation

LCGT will be one of key stations in the world-wide observation network

- **Detection**
  Increase : Triple-detection rate, Detection volume.
  Reduce : Fake events, Event-detection threshold.
- **Astrophysics**
  Increase : Sky coverage, Directional precision.
  Waveform reconstruction.



Sky-coverage pattern
(0.707 of max. range)

B.Schutz
arXiv:1102.5421

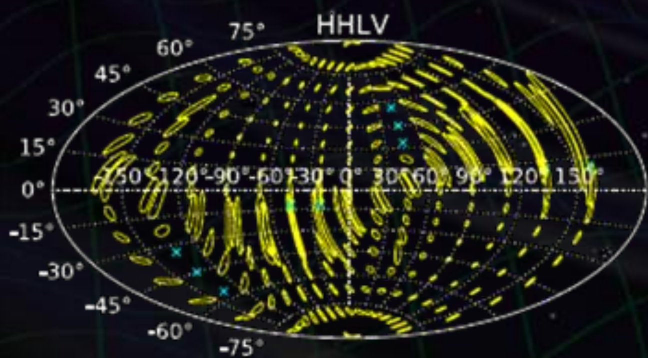
Parameter estimation

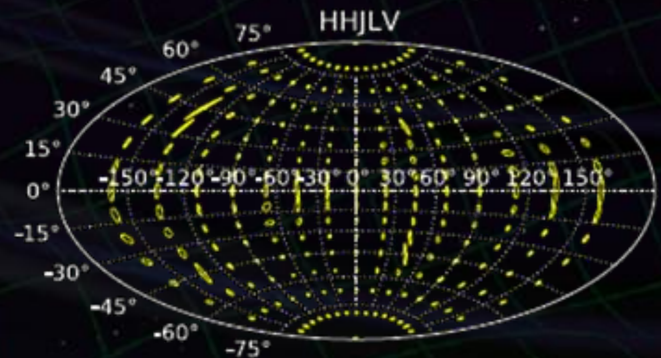
Angular resolution for the source

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

Why LCGT?

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.

Conclusion

LCGT project has started. But we have serious problems in our country.

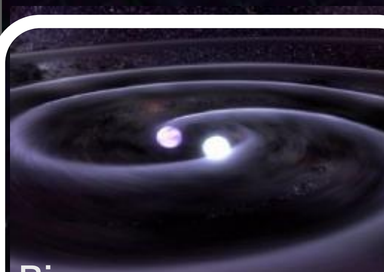
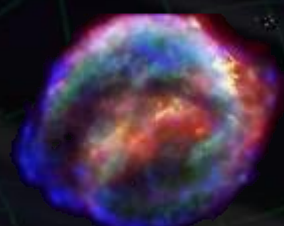
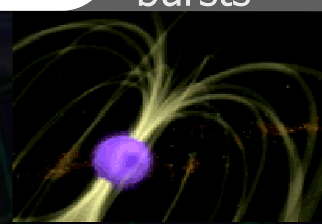
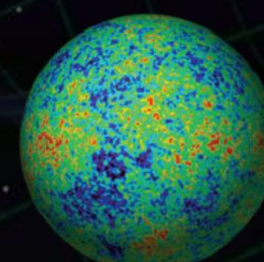
We will do our best for life of people and science.

We already receive kind supports.
We greatly appreciate them!

Backups

GW targets and data analysis

Signal duration

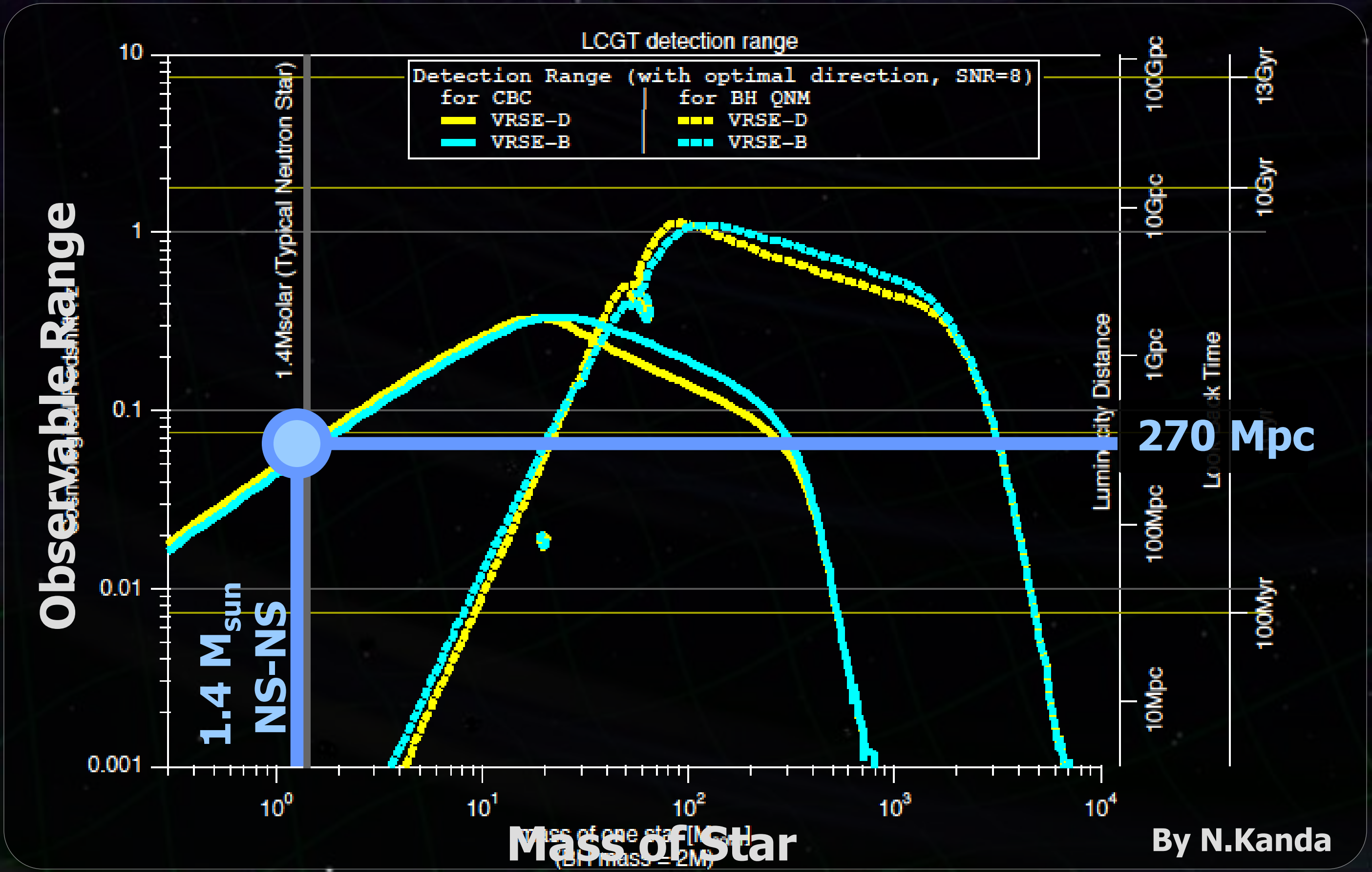
Waveform	Short (bursts)		Long (stationary)
Known	 Binary merger → Chirp wave, Ringdown wave	Gamma-ray bursts	 Pulsar, LMXB → Continuous
Unknown	 Stellar core collapse → burst wave	 Soft gamma-ray repeater	 Stochastic background → Random wave

Observable range

Primary purpose of LCGT : Detection of GW

→ First target : Neutron-star binary inspirals

⇨ Obs. Range 270Mpc (SNR=8, Optimal sky pos. an pol.)



LCGTの観測確率

第一目標: **連星中性子星合体**からの重力波の検出

観測レンジ

Sensitivity curve → 120 Mpc　(SNR 8, 天球上の位置・偏波平均)

銀河の個数密度：

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

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

銀河あたりのイベントレート:

$$\mathcal{R} = 83.0^{+209.1}_{-66.1} [\mathrm{events/Myr}]$$

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

⇨ LCGTの観測レート　**6.9 events/yr**

その他: 超新星爆発, パルサー, 背景重力波

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**

成功確率

1年間の観測で, 少なくとも1回以上
重力波を検出できる確率: 99.9%

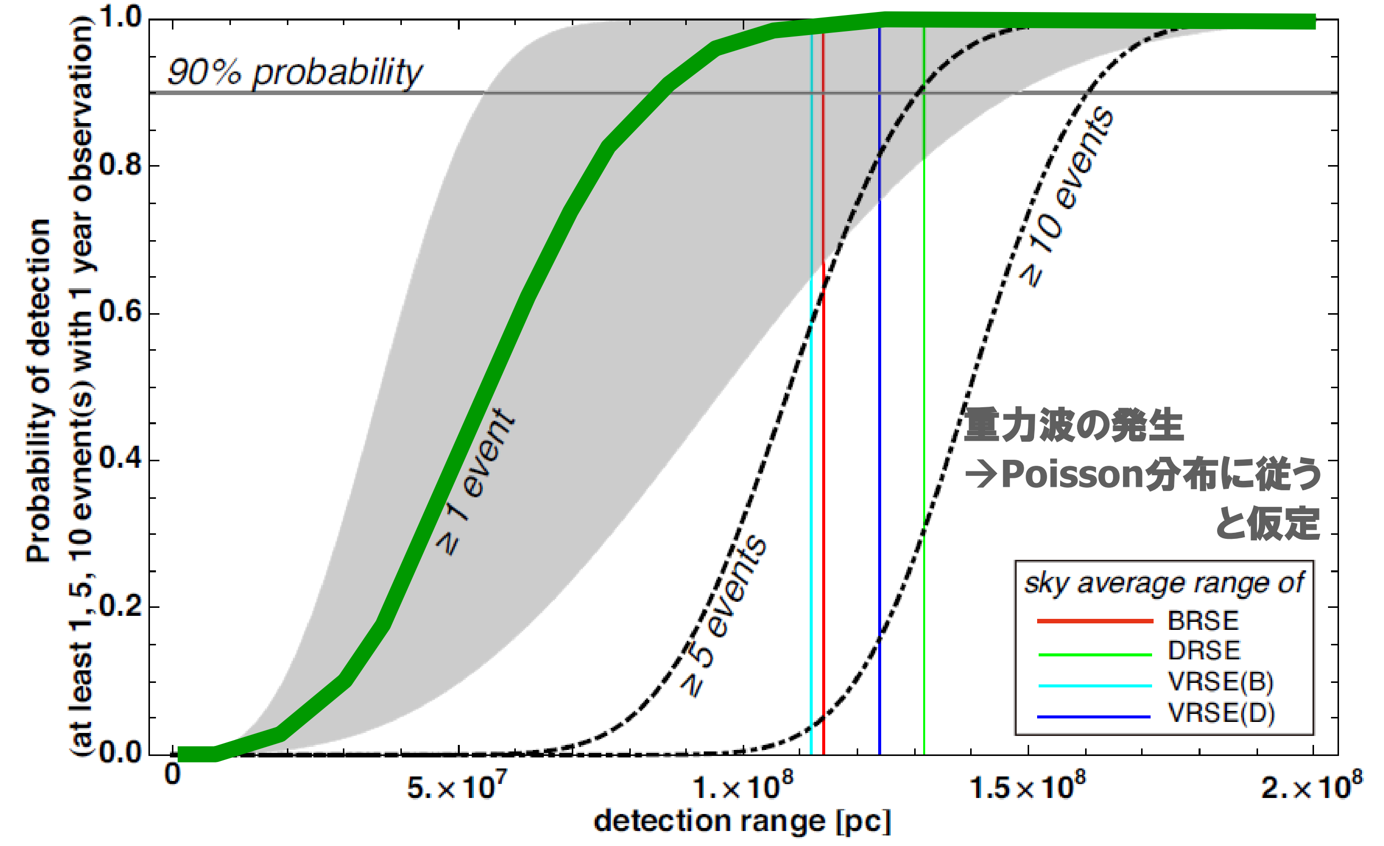


Figure
N.Kanda

TAMA300 and CLIO

TAMA300 (1995~)

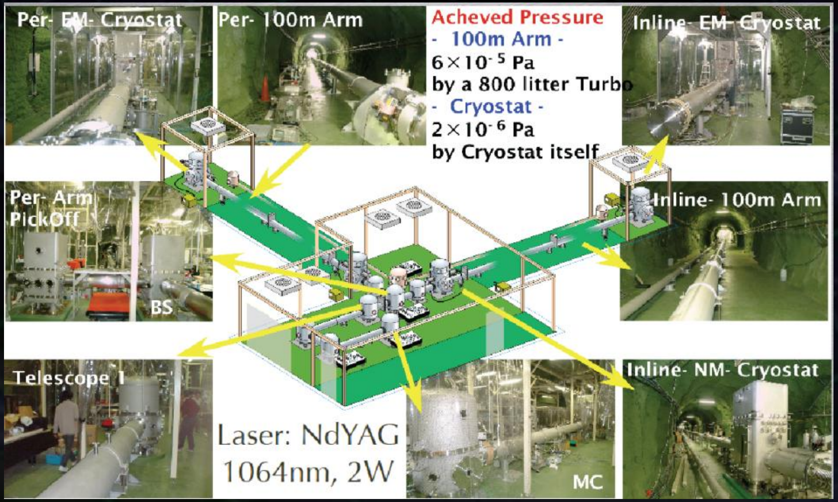
GW detector with a baseline of 300m

Sensitivity to cover our galaxy
(World best in 2000-2002)
Earlier observation runs
(Obs. data over 3000hours)

CLIO (2002~)

Cryogenic interferometer (Kamioka)
with 100m baseline length

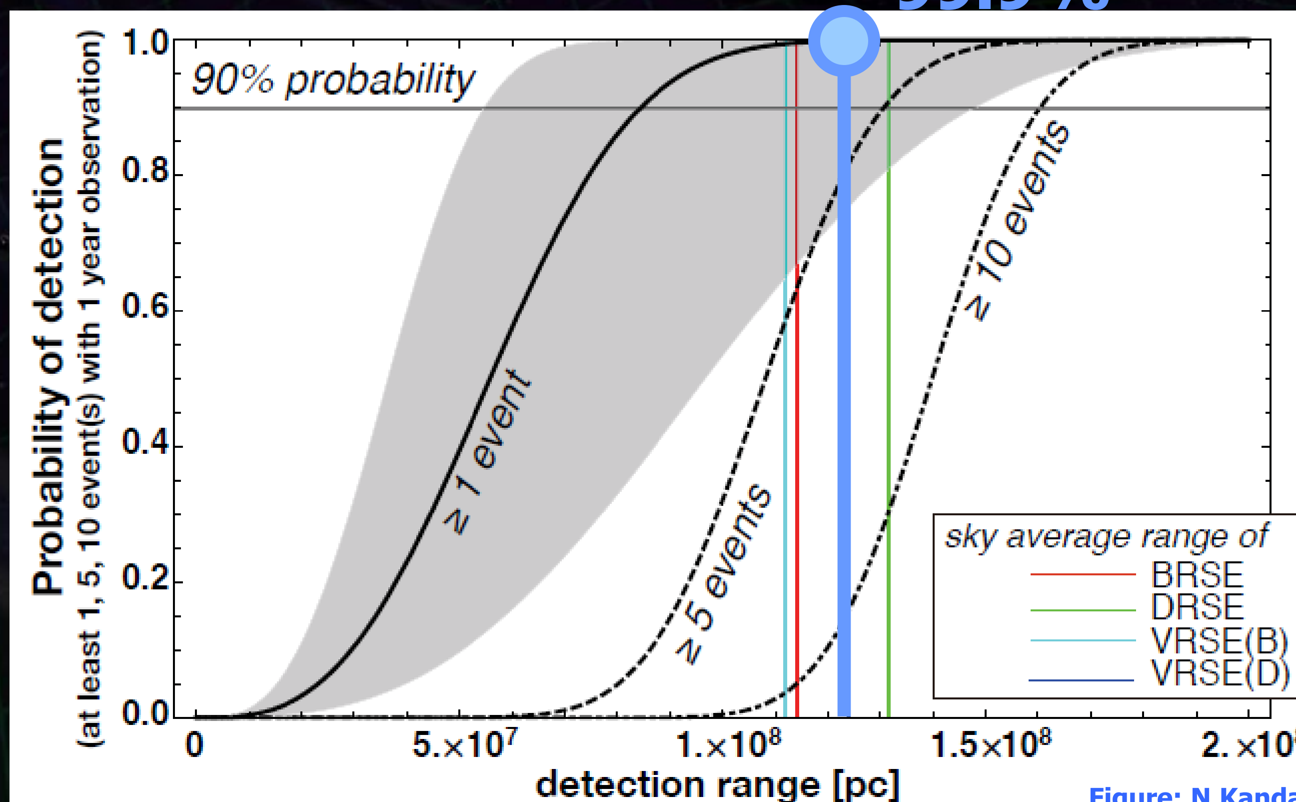
Stable operation taking
advantage of underground site
Cryogenic operation below 20K
→ Improved sensitivity



Detection probability

Probability to detect at least one event in one-year observation ⇨ **Success probability of the LCGT project**

99.9%

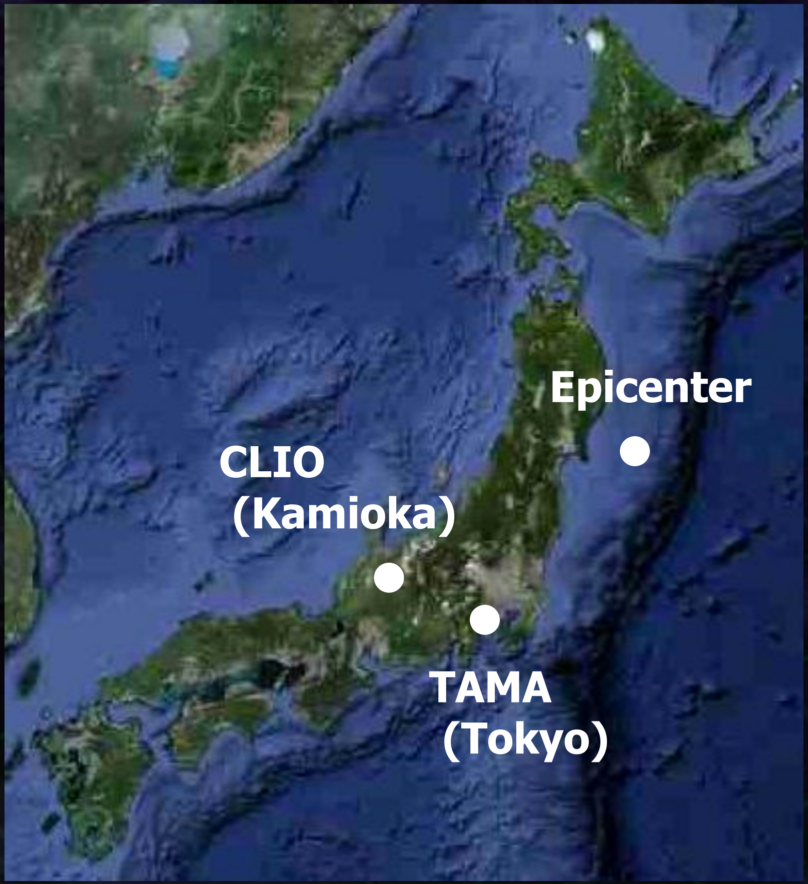


Assume Poisson distribution

•CLIO (Kamioka, Gifu ~500km away from epicenter)

- Two people (Miyakawa, Saito) were working at CLIO site.
  → did not noticed the shake.
- MC couldn’t be kept locked more than a few seconds. This condition continues >1 hour.

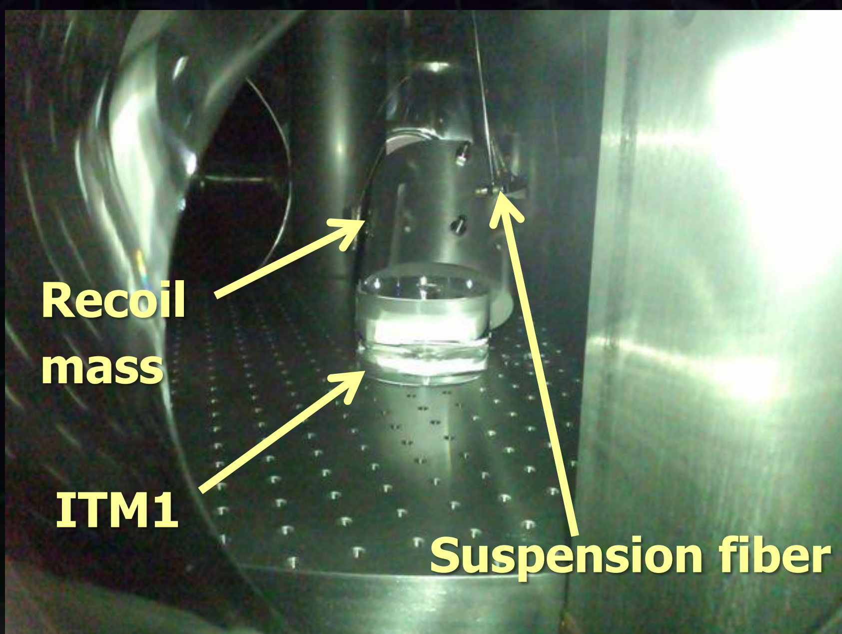
- No serious damages: mirror, suspension, cryostat system, vacuum system.
- Small misalignment in suspended optics.

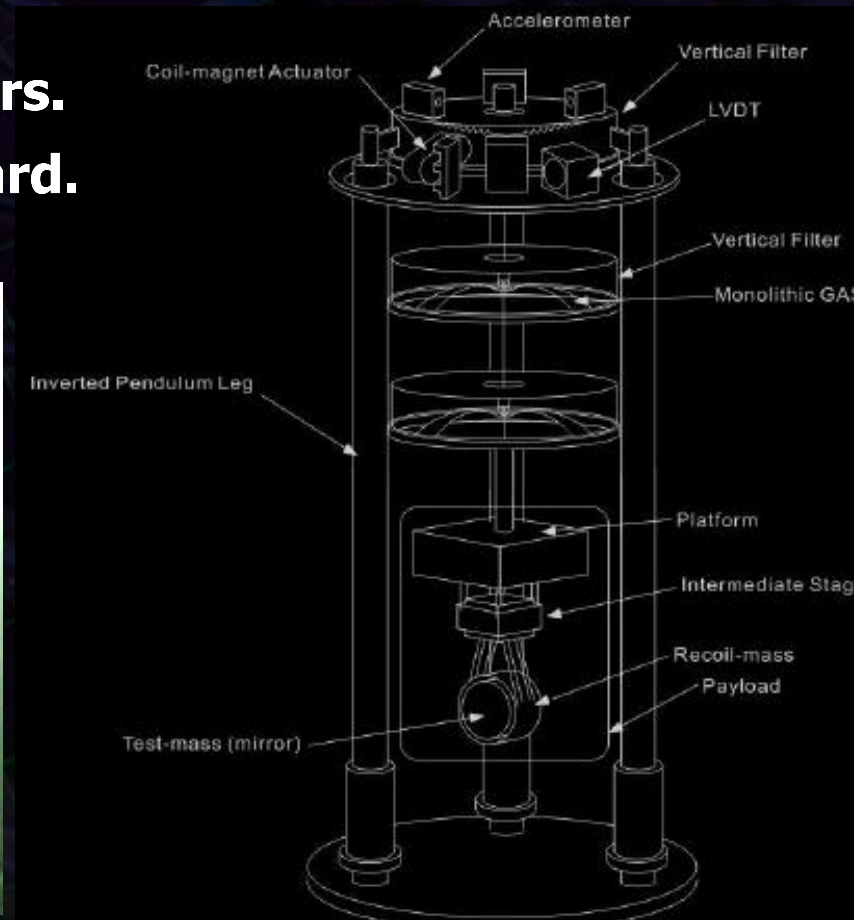


• **TAMA** (NAOJ, Tokyo ~400km away from epicenter)

Serious damages in suspensions and mirrors.

Three TMs fell onto breadboard.





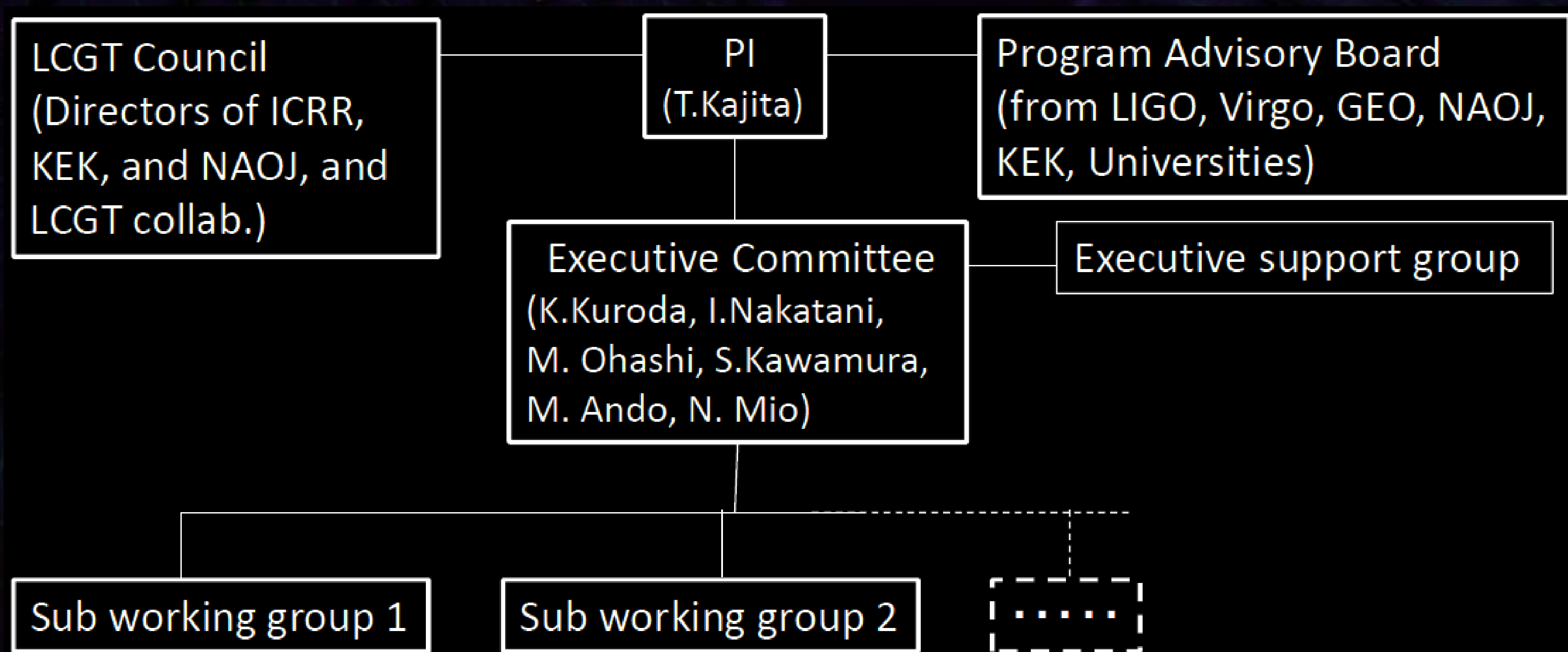
Main Concerns

Personal point of view

- Tight schedule, under-estimated cost
  - Excavation takes ~2 years
  - Short commissioning period for iLCGT
- Vibration isolation tuning
  - 14 isolators needed in early period
- Cryogenic suspension
  - Coupling from vertical DoF
- Sapphire substrate
  - with good optical properties
- Thermal noise of mirror coating

Organization

Organization of LCGT during construction



14 subsystems

Tunnel, Facility, Vacuum, Vibration Isolation, Cryogenics, Main interferometer, Input/Output optics, Laser, Mirror, Data analysis, Digital system, Analog electronics, Detector configuration, Geophysics interferometer

Design Reviews

- **Internal review**
  - Review design, schedule, etc. of each subsystem
    by the subsystem leaders, Ando, and Kawamura
  - We had 15 internal reviews for the last three months
- **External review** ← 2/28 - 3/4, summary report 3/12
  - Review design, schedule, etc. of each subsystem
    by external experts in the GW field
  - The most important review
    for the technical aspects of LCGT
    Special thanks to Reviewers:
    M.Zucker (chair), S.Ballmer, A.Bertolini,
    R.Flaminio, A.Freise, W.Johnson D.Ottaway, B.Willke
- **Program advisory board**
  - Review management, progress, design, etc. of LCGT
    by senior (management) people in the GW and neighboring fields
  - The first PAB will be held in June

International Collaborations

- with LIGO laboratory
  Attachment agreed under existing MOU between ICRR (represents LCGT Collaboration) and LIGO laboratory.
  → Manpower, software & technique exchanged, Mirror
- with VIRGO
  MOU with Attachment between VIRGO (EGO + Virgo Collaboration) and ICRR was signed.
- with GEO
  MOU between ICRR and GEO people is also conceived.
- with ET
  Collaboration with ET → Cooperative research on cryogenics and vibration isolation.
- with SUCA (China)
  MOU between ICRR and Shanghai Normal University, SUCA is on the process of agreement.
- with Korea
  Collaboration with Korean researchers is conceived.

By the way…

LCGT will have a new Nickname soon…

- Invite candidates from the public
  → over 600 applications (already closed)
- Naming committee with 6 peoples
  Chair: Y. Ogawa (Novelist)
- Will be announced in a few month (?)

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 almost approved.

Baseline design is not changed:
Requesting the additional cost for
full construction of LCGT.

Detailed Specifications

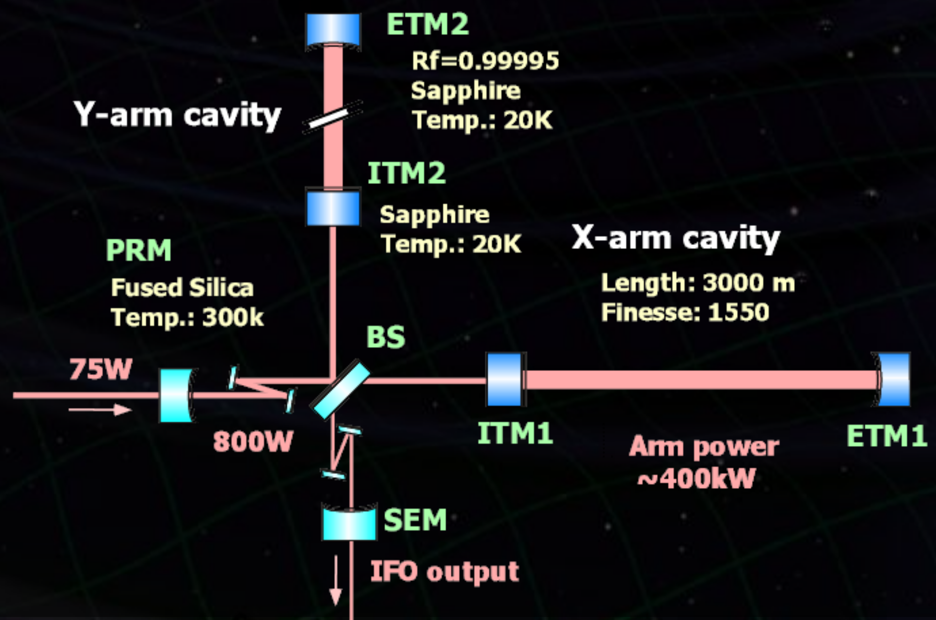
LCGT interferometer

High-power RSE interferometer with cryogenic mirrors

Resonant-Sideband Extraction
- Input carrier power : >85W
- DC readout
- PRC, SEC :Folded for stability

Main IFO mirror
- 20K, 30kg (Φ250mm, t150mm)
- Mech. Loss : 10^{-8}
- Opt. Absorption 20ppm/cm

Suspension
- Sapphire fiber 16K
- Mech. Loss : 2×10^{-7}



Main parameters

Detector parameters

Laser
- Nd:YAG laser (1064nm)
- Master Laser + Power Amplifier
  - Power : 180 W

Main Interferometer
- Broad band RSE configuration
  - Baseline length : 3km
  - Beam Radius : 3-5cm
  - Arm cavity Finesse : 1550
  - Power Recycling Gain : 11
  - Signal Band Gain : 15
  - Stored Power : 771kW
  - Signal band : 230Hz

Vacuum system
- Beam duct diameter : 80cm
- Pressure : 10^{-7} Pa

Mirror
- Sapphire substrate + mirror coating
- Diameter : 25cm
- Thickness : 15cm
- Mass : 30 kg
- Absorption Loss : 20ppm/cm
- Temperature : 20 K
- $Q = 10^8$
- Loss of coating : 10^{-4}

Final Suspension
- Suspension + heat link with 4 Sapphire fibers
- Suspension length : 30cm
- Fiber diameter : 1.6mm
- Temperature : 16K
- Q of final suspension : 10^8

Main Interferometer (1/2)

LCGT Main interferometer

- Sufficient sensitivity and stability to detect GWs
  - Inspiral range >250Mpc (Optimal direction and polarization, SNR>8)
  - Duty cycle > 90%

- **Optical design**
  - Dual-recycled Fabry-Perot-Michelson interferometer in RSE mode
  - Variable RSE between Detuned and Broadband operation
  - Inspiral range : 275Mpc
- **Arm cavity**
  - Baseline length : 3000 m
  - Sapphire test masses at cryogenic temperature of 20K
  - Finesse : 1546
  - ITM reflectivity : 99.6%
  - Round-trip loss < 100ppm
  - Accumulated power: ~400kW/arm
  - ROC : Flat (ITM), 7km (ETM)
  - g-factor : $g_1=1$, $g_2=0.572$
  - Beam size : 3.43cm (ITM), 4.53cm (ETM)

- **Central interferometer**
  - Power recycling gain : ~11
  - Signal band gain : ~15
  - PRM, SEM ROC : 300m
  - Folded cavities for stability
    - Length : 66.62m
    - ROC : -3.251m, 27.26m
    - Gouy phase shift : 20deg
  - MI Asymmetry : 3.33 m
  - RF sideband condition
    - f1 (PM 16.875 MHz)
      - Resonant with PRC-SRC
    - f2 (PM 45 MHz)
      - Resonant with PRC
      - Full reflectivity by MI part
    - f3 (AM 56.25MHz)
      - Non-resonant to PRC

Main Interferometer (2/2)

- **Length signal sensing and control**
  - Frontal modulation
    - for 5 length DoF for MIF control

	Signal port	UGF
DARM	ASDC	200 Hz
CARM	REFL 1I	10 kHz
MICH	REFL 1Q	10 Hz
PRCL	POP 2I	50 Hz
SRCL	POP 1I	50 Hz

Feed forward gain : 100
Non-linear factor : 10^9 m^{-1}
PD dynamic range : 160dB
Variable RSE by SRC tuning :
Offset addition to control signal

- **Alignment signal sensing and control**
  - Wave front sensing and optical lever
  - Details : TBD

- **Lock acquisition**
  - Pre-lock of arm cavities with auxiliary green laser beams
    - Beam injection from folding mirrors in PRC and SEC
    - Arm finesse to green beam : ~10

Third-harmonic demodulation
(Beat between 2*f1 and f1)

Non-resonant sideband

Tunnel

LCGT underground site

Ikenoyama mountain >200m from the ground level
Tunnel tilt : 1/300 for natural water drain
(Experimental rooms : leveled)

- Location
  Latitude 36 deg N , Longitude 137 deg E
  Height : 372 m above the sea level
  Arm direction: X-arm 300 deg, Y-arm 30 deg (from North)
  → height difference of 20m between X and Y end rooms
- 3 access tunnels from the ground level
- 2 water drain points
- Arm tunnels
  Excavation by TBM
  (Tunnel Bowling Machine)
  Tunnel Width 4m, Height 3.8m
- Experimental rooms
  Center and end rooms
  Excavation by NATM
  (New Australian Tunneling Method)
  Height : 4.2 m
- Test mass area
  20m x 12 m room
  2 layer structure
  1st floor height 8m
  2nd floor height 7m
  5m bedrock between them
  130m approach tunnel for 2nd floor

Vacuum

LCGT vacuum system

Vacuum pressure : < 1×10^{-7} Pa ← Ion pump lifetime (5 years)

< 2×10^{-7} Pa ← Residual gas noise (safety margin 10)

Scattered light suppression

- Beam tube for two 3km arms
  - Diameter : 0.8 m
  - Material : Stainless steel
  - Outgas rate : 10^{-8} Pa•m/s
  - Inner surface : Electro polishing
  - Pre-baking and dry-air seal before installation
  - Flange Connection of 500 tubes with 12-m length
- Optical baffle
  - 500 optical baffles at every 12-m inside the vacuum tube
  - Diamond-like Carbon (DLC) coating
  - Height : 40 mm (Saw-tooth edge, 45deg. tilted)
- Chamber (14 chambers)
  - 4 chambers with cryogenic system
    - Diameter : 2.4 m
    - Type-A vibration isolation for test mass
    - Aluminum-coated PET (polyethylene terephtalate) for thermal insulation
  - 7 chambers (BS, PRM, SEM, folding)
    - Diameter : 1.5 m (2 m for BS)
    - Type-B vibration isolation
  - 3 chambers (MC, PD)
    - Diameter : 2 m
    - Type-C vibration isolation
- Pumping system
  - Every 100m along the tube
  - Pumping unit with dry-pump + TMP + ion-pump

Cryogenics

Cryogenic System for test-mass mirror

Temperature of test mass : 20 K
Avoid excess vibration and mirror contamination

- **Test-mass suspension**
  - Cool mirror by thermal conduction
  - Sapphire suspension from upper mass
    - Cooling power : 1 W
    - 4 sapphire fibers
    - Diameter : ϕ1.6 mm
    - Length : 300 mm
  - Heat link : pure Aluminum (6N) wires (Upper Mass – CM – Cryo-shield)
- **Cryostat**
  - Vacuum chamber with cryo-shield (radiation shield)
  - Access to inside from both sides
  - Mechanical resonance >30 Hz
  - Inner shield : 10 K, 2W
  - Outer shield : 80 K, 90W
    - Insulator: Low-outgas MLI (or SI)
    - Size : 1990 x 1220 x 1500? mm
    - Mechanical resonance > 22 Hz
- **Low-vibration cryocooler**
  - Pulse-tube cryocooler
    - Cold head temperature : 4 K
  - Vibration isolated cold head
    - Separated valve unit
    - Flexible link to heat bath
    - Rigid frame for supporting stage
  - Acoustic shield
    - Compressor placed in a separated room with acoustic shield
- **Shield duct**
  - to avoid incoming residual gas and thermal radiation
  - Length : 20 m (TBD)
  - Diameter : ϕ500 mm, t 10 mm
  - Baffle aperture: ϕ250 mm
  - Temperature : 65 - 77 K
  - Cryocooler : 50K, 150W

Vibration Isolation (1/2)

Vibration isolation system

- Reduce the seismic noise level below optical-readout noise at 10 Hz
  - Displacement noise < 4×10^{-20} m/Hz$^{1/2}$ at 10Hz,
  - Residual RMS fluctuation < 0.1μm, < 0.1 μm/s

- **Type-A system for cryogenic test mass**
  Low-frequency, multi-stage vibration-isolation system with cryogenic compatibility

Room-temperature isolator part

Pre-Isolator

- Inverted Pendulum (IP) and GASF
- IP Length : 50 cm
- Resonant frequency : 30mHz
- Sensor : 4 Geophones (L4-C), 4 LVDTs
- Actuator : Magnet-coil
  Stepping motor, Pico motor

GAS (Geometric Anti-Spring) filter

- 3-stage filters suspended by a single wire
- Resonant frequency : ~ 350 mHz
- Yaw-mode damping onto the first stage

Cryogenic Payload

3-stage suspension (PF-IM-TM)

Test mass (TM)

- Sapphire mirror, Temp: 20K
- Weight : 30kg
- Recoil mass (RM) for actuation

Intermediate mass (IM)

- Suspend TM with sapphire fibers
- Damping from Magnet Box (MB)

Platform (PF)

- Suspended from room-temp. part by a single wire with low-thermal conductivity
- Actuated from CB (Control box)

Heat link

- Pure Aluminum wire
- Link between IM-PF and PF-Radiation shield

Vibration Isolation (2/2)

- **Type-B system for room-temp. optics**
  Low-frequency, multi-stage
  vibration-isolation system
  Used for BS, PRM, SEM, Folding mirrors
  Based on TAMA-SAS

  Pre-Isolator
  Inverted Pendulum (IP) and GASF
  IP Length : 50 cm
  Resonant frequency : 30mHz
  Sensor : 4 Geophones (L4-C), 4 LVDTs
  Actuator : Magnet-coil
  Stepping motor, Pico motor

  GAS (Geometric Anti-Spring) filter
  Vertical filter
  suspended by a single wire
  Resonant frequency : ~ 350 mHz
  Yaw-mode damping

  Payload
  3-stage suspension (PF-IM-TM)
  Test-mass weight : 10kg

- **Type-C system**
  Double pendulum on
  Multi-layer stacks
  Used for MC, PD
  Based on original TAMA isolation
  Suspended optics : 1kg

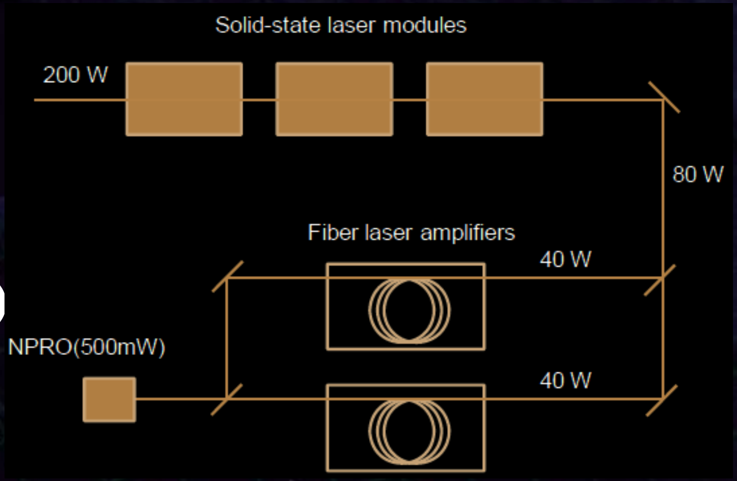
  Multi-layer stack

  Double pendulum

Laser

High-power and stable laser source

Wavelength : 1064nm
Output Power 180 W
Single mode, Linear polarization
Line width < a few kHz
Frequency noise < 100 Hz/Hz$^{1/2}$ (100Hz)
Freq. Control band ~ 1 MHz
Intensity noise < 10^{-4} Hz$^{-1/2}$ (100Hz)
Int. control band > 100 kHz



High-power MOPA laser

→ Easy assembly and maintenance

- Seed laser
  NPRO (Nonplanar Ring Oscillators)
  Power 500mW
- Fiber amplifier
  Commercial fiber amp.
  NUFERN Single Freq. PM amp.
  Output power ~40W
  Coherent addition with two units
- Solid-state laser module
  Side pump + diffusive reflector
  Laser module by Mitsubishi
- Frequency stabilization
  PZT of the master laser
  External wideband EOM
  Stoichiometric $LiNbO_3$
- Intensity stabilization
  Current shunt control
  on power amplifier

Core Optics

Cryogenic test mass --- Sapphire

Temperature : 20 K
Absorption Loss < 20ppm/cm
Optical loss < 45ppm
Mechanical loss < 10^{-8}

- **Substrate**
  - Diameter : 25cm
  - Thickness : 15cm
  - Mass : 30 kg
  - ITM: c-axis, ETM: a-plane (TBD)
  - Heat Exchange Method (HEM) by Crystal Systems Inc.
- **Polish**
  - ROC ITM: Flat, ETM: 7km
  - ROC Error : 100m (Error $\lambda/40$)
  - Scattering < 30ppm
- **Coating**
  - Absorption < 0.5ppm
  - Mechanical Loss < 10^{-4}
  - Moderate reflectivity for green beam

Room-temp. optics --- Fused Silica

Temperature : 290 K
Absorption Loss < 1ppm/cm
Homogeneity < 10^{-7}

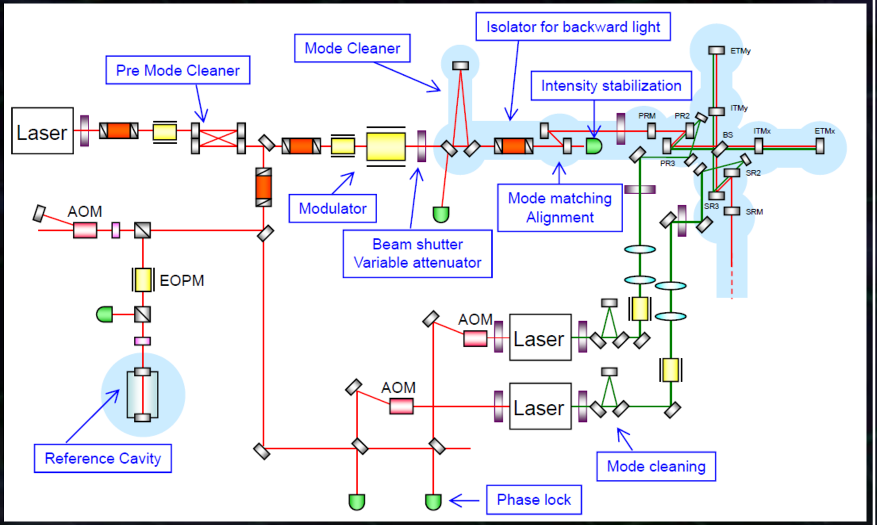
- **Main interferometer** (PRM, SEM, Folding Mirror)
  - Diameter : 25cm
  - Thickness : 10cm
  - Mass : 10 kg
  - *also used for iLCGT test mass
  - AGC or Heraeus (ITM)
  - LIGO TM substrates (other)
- **Beam splitter**
  - Diameter : 38cm
  - Thickness : 12cm
  - Mass : 30 kg
- **Input optics (MC, MMT)**
  - Diameter : 10 cm
  - Thickness : 3 cm
  - Mass : 0.5 kg

Input/Output Optics (1/3)

Input Optics between the laser source and the main interferometer

Frequency stability < 3×10^{-8} Hz/Hz$^{1/2}$
Intensity stability < 2×10^{-9} Hz$^{-1/2}$
RF intensity noise < 1×10^{-9} Hz$^{-1/2}$ (>10MHz)
Beam jitter : ---
RF modulation : 16.875 MHz 45 MHz (optional 56.25 MHz)
TEM_{00} power throughput >50 % (?)

- Mode Cleaner
  Suspended triangle cavity
  for spatial MC, reduction of beam jitter, and freq. stabilization
  Transmission of RF sidebands for main interferometer control
  Round-trip length : 53.333 m
  Finesse : ~500
  FSR : 5.625 MHz
  Mirror dimension : ϕ100mm, t30mm
  ROC : Flat (In and Out)
  40 m (End)
  Beam radius : ~2.5mm at waist



Input/Output Optics (2/3)

Input Optics between the laser source and the main interferometer

- **Pre Mode Cleaner (PMC)**
  2 or 3 PMCs in series for
  RF noise reduction and spatial MC
  Monolithic 4-mirror bow-tie cavity
  Roundtrip length : 1.95 m
  Finesse : 155
  Cutoff freq. : 154 MHz
  Length control :
  PZT (<1kHz) and heat expansion
  Spacer material : Aluminum
  Placed in air-enclosed case

- **Reference cavity**
  Low-frequency reference at DC - 10Hz
  Linear cavity in vacuum,
  supported by a vibration isolator
  Length : 15cm
  Finesse : 10^5
  Cutoff freq. : 50kHz
  Spacer material : ULE or Silica

- **Modulator**
  RF sidebands for MIF control
  16.875 MHz (PM), 45 MHz (PM)
  56.25 MHz (AM optional)
  Mach-Zender IFO for 2 PMs
  EOM : RTP or MgO-doped $LiNbO_3$
  4x4 (or 5x5) mm^2 for PM
  2x2 mm^2 for ~1MHz control
  4x4 mm^2 for >100kHz control
  Crystal length : 20 – 40 mm

- **Isolator**
  Suspended Faraday isolator
  between MC and MIF
  Details : TBD

- **Mode-matching telescope**
  Suspended folded telescope
  between MC and MIF
  Length : ~5.6 m
  Mirror size : ϕ100mm, t30mm
  ROC : ~20.6m, 26.1 m

Input/Output Optics (3/3)

Output Optics

between the main interferometer
and analog electronics

OMC throughput : TBD
Photo detection power : ~100mW

- **Output Mode Cleaner**
  4-mirror bow-tie cavity for
  beam cleaning at dark port
  Round-trip length : 1.52 m (TBD)
  Finesse : 1000 (TBD)
  Cutoff freq. : 98 kHz
  Spacer material : TBD
  Actuator and control : TBD

- **Output Telescope**

- **Photo Detection**
  Main PD in vacuum tank
  DC/RF PD
  Wave Front Sensor
  Beam Shutter

Others

- **Green beam** injection
  for lock-acquisition of MIF
  Phase-locked to the main beam
  Injected to MIF from
  PRC and SEC folding mirror

- **Optical lever** for test masses
  Details TBD

- **Laser room facility**
  for optical benches of laser
  source and input optics
  Clean room : Class TBD
  Temp. control : +/- 1K
  Acoustic shield

Digital System

LCGT digital observation system

Data acquisition and control system

Observation bandwidth >5 kHz, Dynamic range >120 dB

Control bandwidth > 200 Hz, Signal number > 1024 channels

Observation system

Human interface , Observatory monitor, Detector diagnosis

- **Control system**

  Network of ~12 real-time systems and client workstations

  Sampling rate : 16,384 Hz

  ADC resolution : 16 bit

  Input

  ADC range : +/- 15 V

  Signal number : 2048 ch

  Output

  DAC range : +/- 10 V

  Signal number : 512 ch

  Binary Output : 2048 ch

  DAC/DAC noise : $<3\ \mu V/Hz^{1/2}$

  Delay $< 100\ \mu$sec

- **Timing system**

  GPS-based timing distribution system

  Ground-level GPS antenna

  → Timing master in the center room

  Real-time modules are synchronized using 1 PPS signal

  Recorded with data as IRIG-B format

  Timing accuracy : ???

- **Environment monitor**

  RT system or

  EPICS-based system (TBD)

- **Data Storage**

  Recorded in frame format

  300 TByte/year

  (16kHz : 64ch, 2kHz : 512ch, 64Hz : 1024ch, 16 Hz : 10000ch)

Analog electronics

Analog electronics

- **DC power supply**
  - Low-voltage power supply
    - Bipolar : 24V
    - Distributed by D-Sub 3W3
    - 24-to-15 V series regulator
  - High-voltage power supply
    - Bias voltage for QPD : 180 V
    - Power supply for
      - Coil driver, PZT actuator,
      - LD driver, TEC driver
- **Conditioning filter** for digital system
  - Anti-aliasing and Whitening filter for ADCs
  - Anti-imaging and de-whitening filter for DACs
- **High-speed controls**
  - High-speed servo, Feedaround,
  - Threshold detector for digital I/F
- **Actuator drivers**
- **Photo detector**
  - Quantum efficiency > 0.9
  - DC photo detector for MIF DC readout
    - Input power : 100 mW
    - PD diameter : ϕ3 mm
  - RF photo detector
    - Input power : 100 mW
    - PD diameter : ϕ3 mm
    - Frequency : 16.875MHz, 45 MHz
  - RF-QPD for wave front sensors (WFS)
  - AF-QPD for beam position sensing
  - Optical lever sensors
  - CCD imaging monitors
- **RF system**
  - Low-noise oscillator synchronized to 10MHz standard
  - RF distributor
  - Modulator resonant driver
  - Demodulator
    - Noise level : 1nV/Hz$^{1/2}$
    - Range : 100 mV

Data Analysis

Data analysis

- **DAQ**
  - Data acquisition, low-latency transfer
  - Data storage
  - Data characterization
- **Analysis**
  - Search for GW signals, and extract scientific outcomes
  - Cooperate with other GW experiments

• Data acquisition and storage
(by digital subsystem)
Raw-data rate : 70 GByte/hour
Data spool storage
at Kamioka > 500 TByte

• Calibration and data characterization
Pre-processing for calibrated data
Data and detector characterization
Recorded in frame format
at the ICRR Kashiwa site
Total storage : 30 PByte

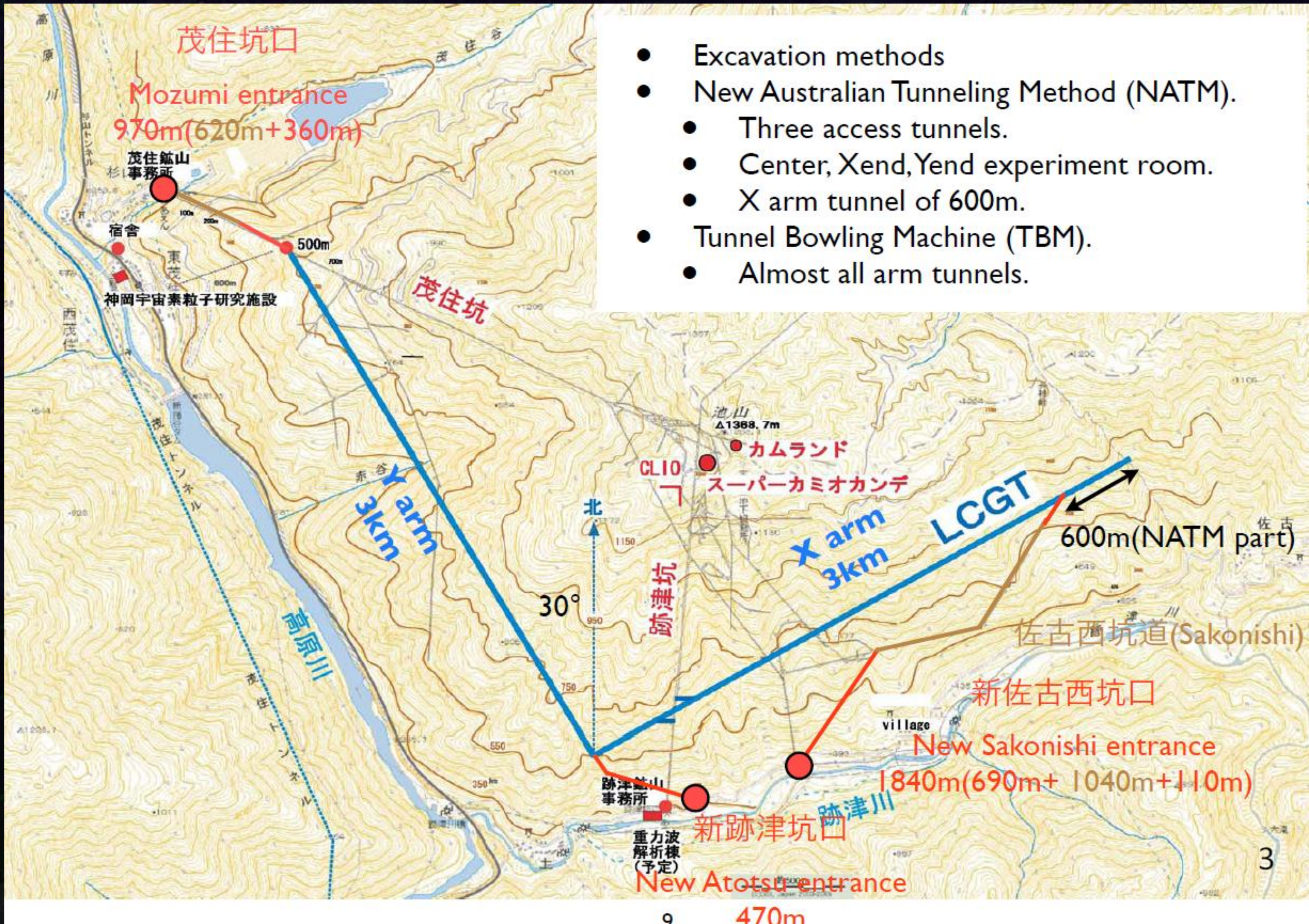
• Computing platform
Main computing platform at Kashiwa
Computation power > a few TFlops
Software libraries in cooperation
with world-wide network
Distribution of
data subset to collaborators

• Network observation
Low-latency data processing
for follow-up observations
GW observatories
Counterpart observations
X-ray, Gamma-ray, Radio afterglow
Neutrino

Materials

Tunnel

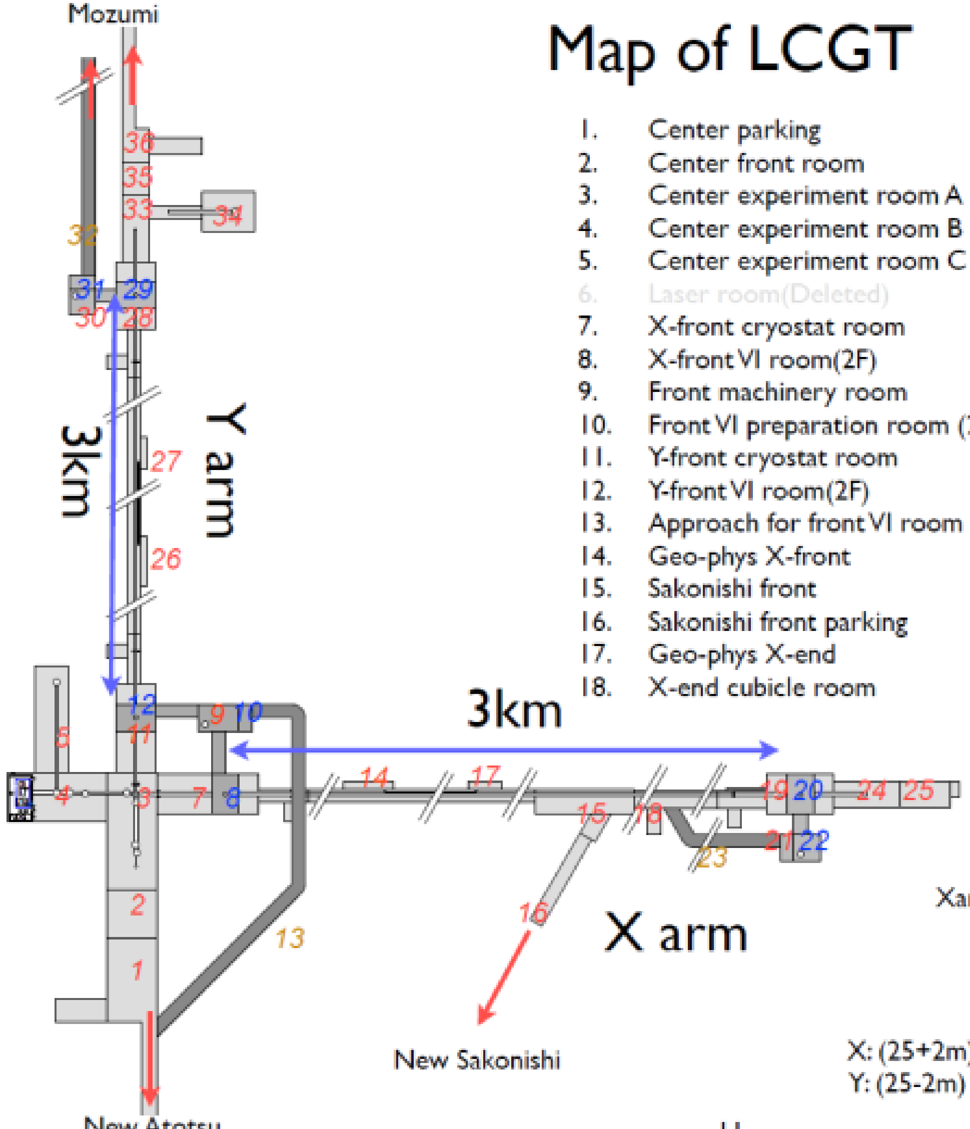
- Excavation methods
- New Australian Tunneling Method (NATM).
  - Three access tunnels.
  - Center, Xend, Yend experiment room.
  - X arm tunnel of 600m.
- Tunnel Bowling Machine (TBM).
  - Almost all arm tunnels.



3

Tunnel

Map of LCGT



1. Center parking
2. Center front room
3. Center experiment room A
4. Center experiment room B
5. Center experiment room C
6. Laser room(Deleted)
7. X-front cryostat room
8. X-front VI room(2F)
9. Front machinery room
10. Front VI preparation room (2F)
11. Y-front cryostat room
12. Y-front VI room(2F)
13. Approach for front VI room
14. Geo-phys X-front
15. Sakonishi front
16. Sakonishi front parking
17. Geo-phys X-end
18. X-end cubicle room
19. X-end cryostat room
20. X-end VI room(2F)
21. X-end machinery room
22. X-end VI preparation room (2F)
23. Approach for X-end VI room
24. X-end experiment room
25. X-end staff room
26. Geo-phys Y-front
27. Geo-phys Y-end
28. Y-end cryostat room
29. Y-endVI room(2F)
30. Y-end machinery room
31. Y-end VI preparation room (2F)
32. Approach for Y-end VI room
33. Y-end experiment room
34. Cryogenic experiment room
35. Y-end staff room
36. Y-end parking

Xarm and Yarm cross perpendicularly
at the center of BS chamber.

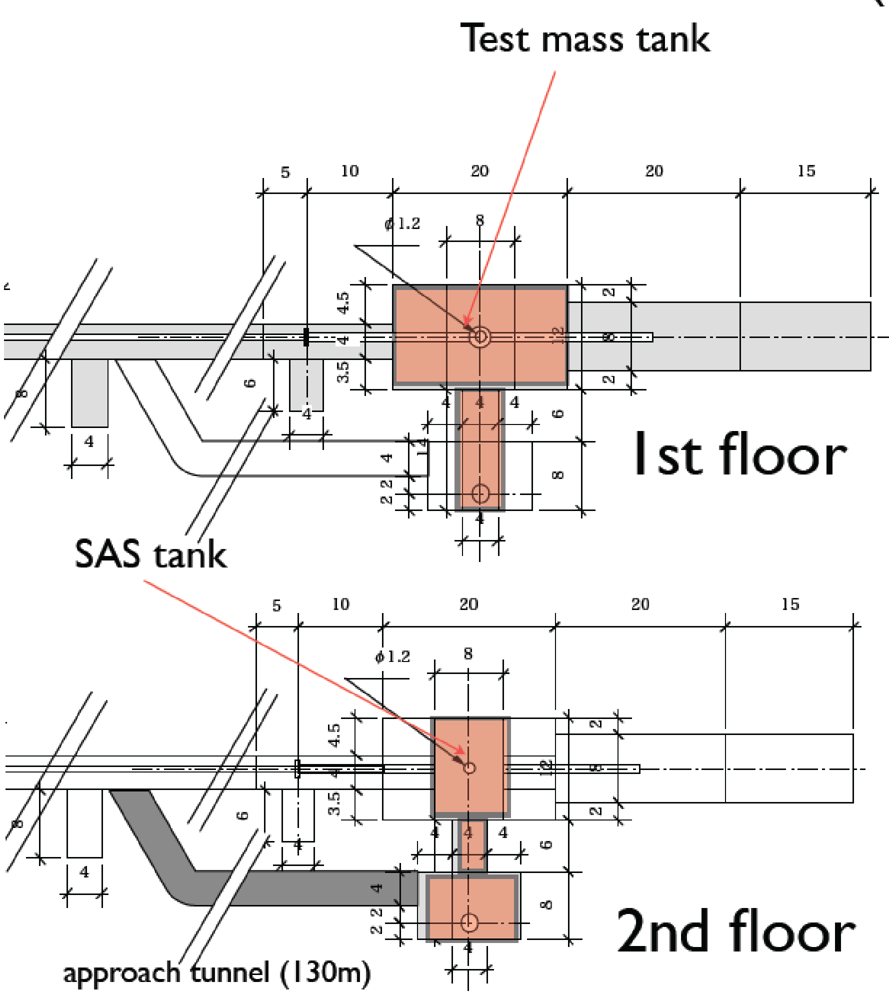
3km:

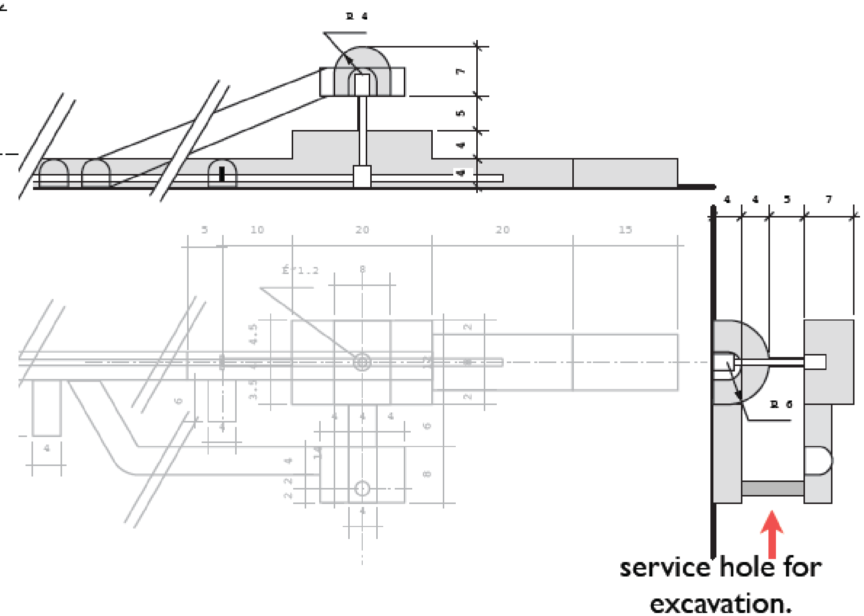
X: (25+2m)from BS - Center of X end cryostat room
Y: (25-2m) from BS - Center of Y end cryostat room

11

Tunnel

X end (2layer)





Compare with 1 layer (20×20×H15m)

Floor area：400m² → 512m²

Volume：5140m³ → 2860m³

Approach tunnel(130m)：1860m³.

Vertical hole: about 2,500,000Yen.

Vacuum system

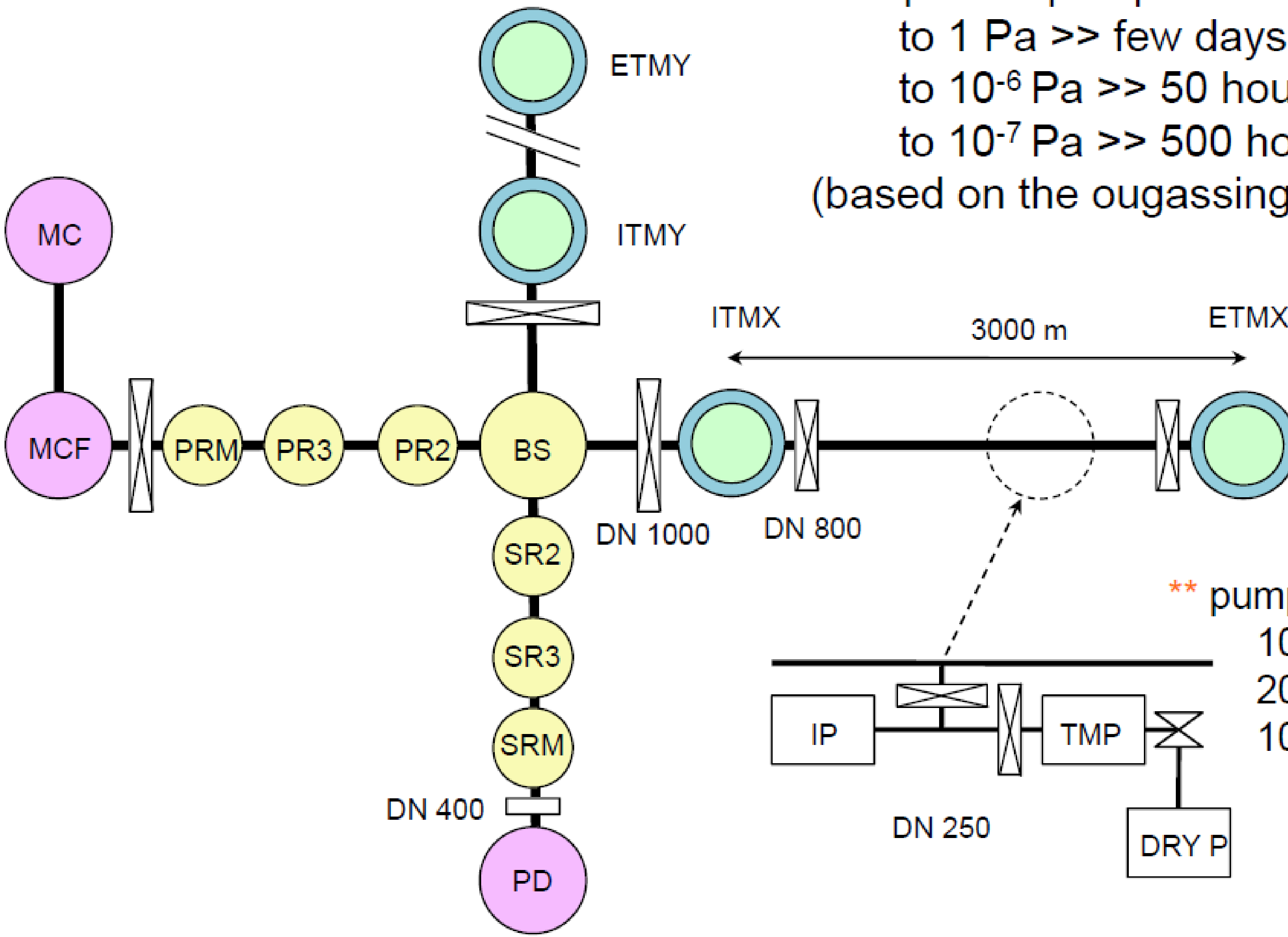
** expected pump-down scheme

to 1 Pa >> few days by dry-pump

to 10^{-6} Pa >> 50 hours by TMP

to 10^{-7} Pa >> 500 hours by IP

(based on the ougassing rate in test tube)



** pumping speed of the unit

$100\ m^3/h$ >> dry-pump

2000 L/s >> TMP

1000 L/s >> IP

Vacuum system

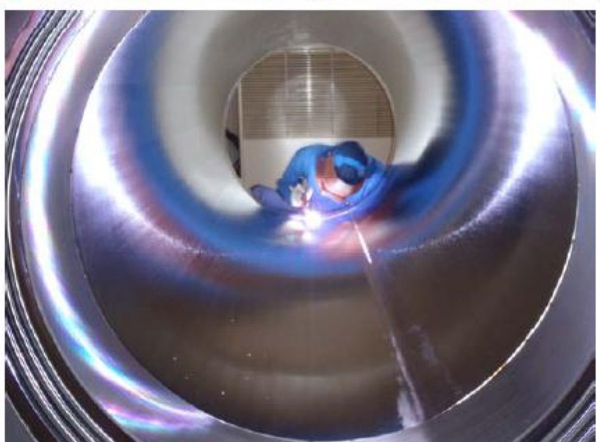
110302 VAC (YS)

LCGT Vacuum System

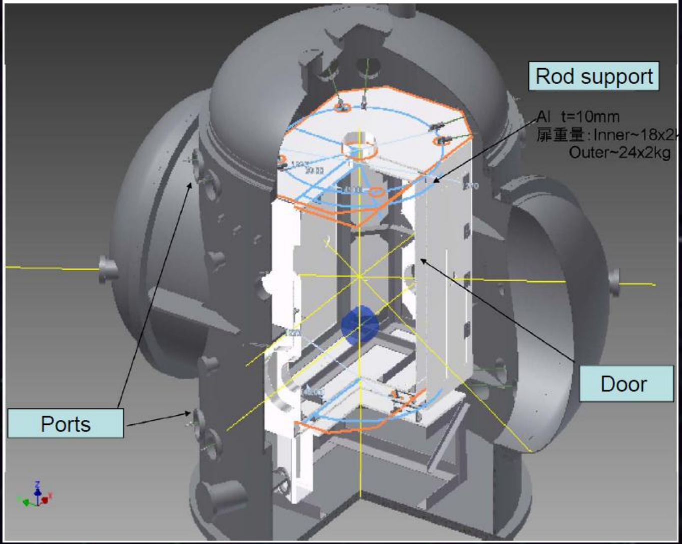
** test product of the tube

* A 4-m long tube was manufactured and a half of the inner surface was electro polished.

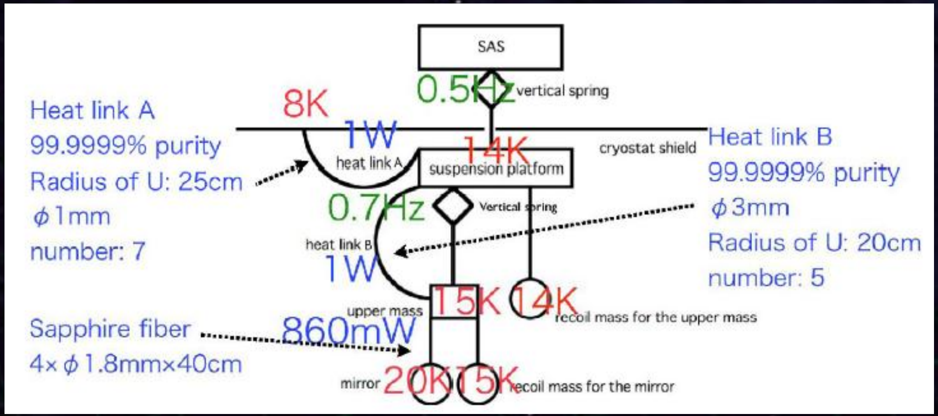
* A flange with a bellows (one convolution) was manufactured.



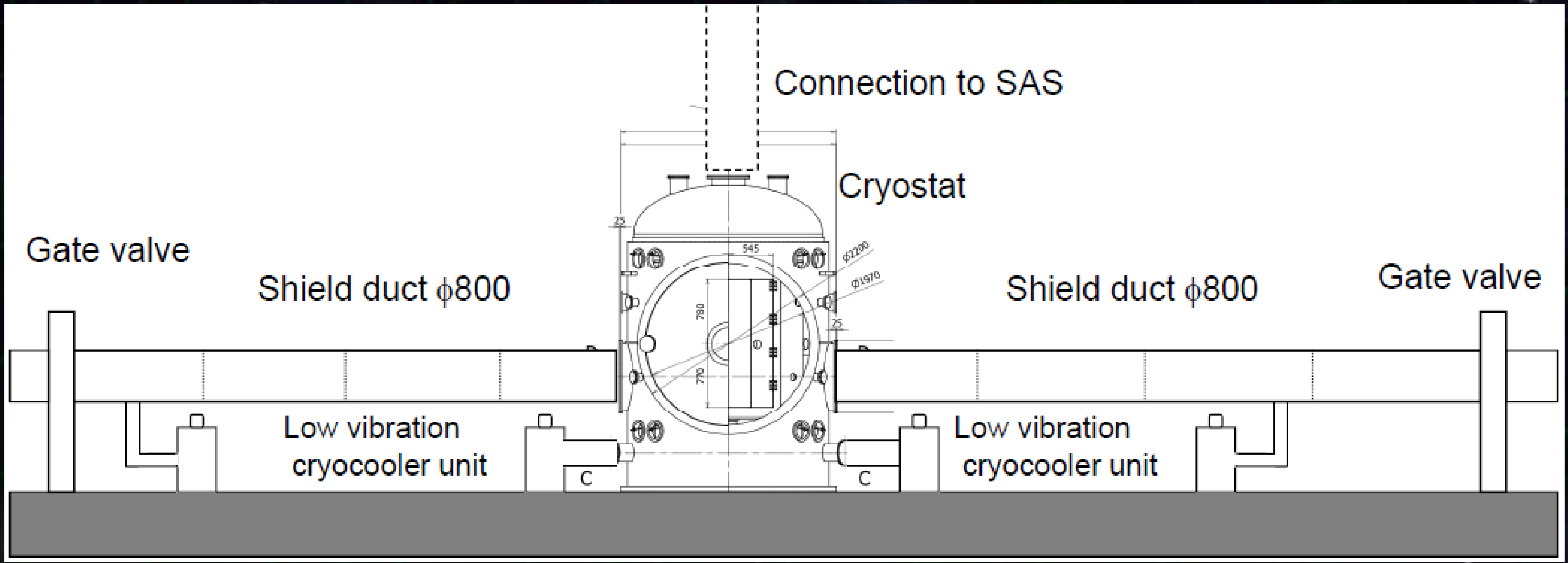
Cryogenics



Rod support
Al t=10mm
扉重量: Inner~18x2kg
Outer~24x2kg
Ports
Door

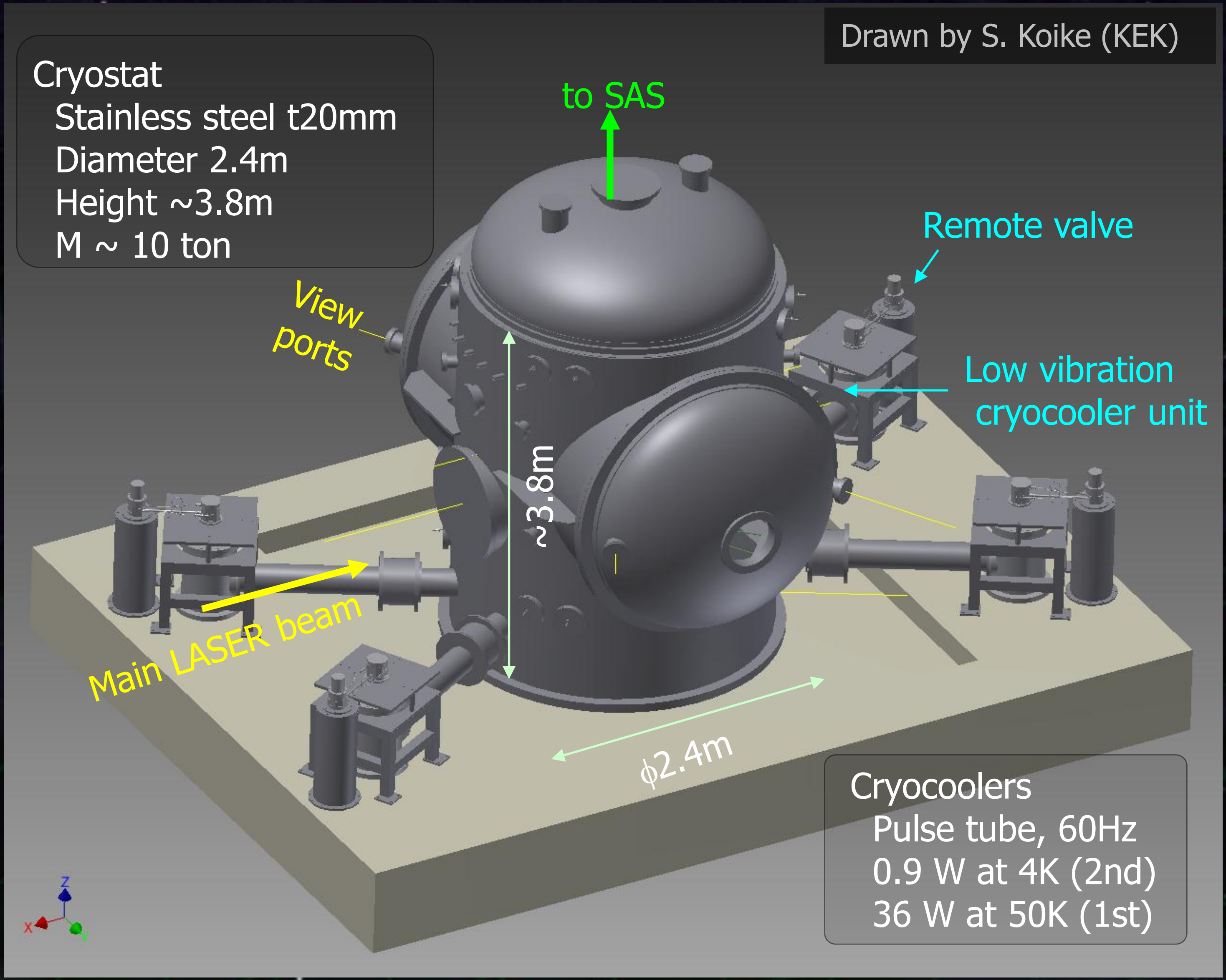


SAS
0.5Hz vertical spring
8K
1W
heat link A
14K
suspension platform
cryostat shield
0.7Hz
Vertical spring
heat link B
1W
upper mass
15K
14K
recoil mass for the upper mass
860mW
mirror
20K
15K
recoil mass for the mirror
Heat link A
99.9999% purity
Radius of U: 25cm
ϕ1mm
number: 7
Heat link B
99.9999% purity
ϕ3mm
Radius of U: 20cm
number: 5
Sapphire fiber
4×ϕ1.8mm×40cm

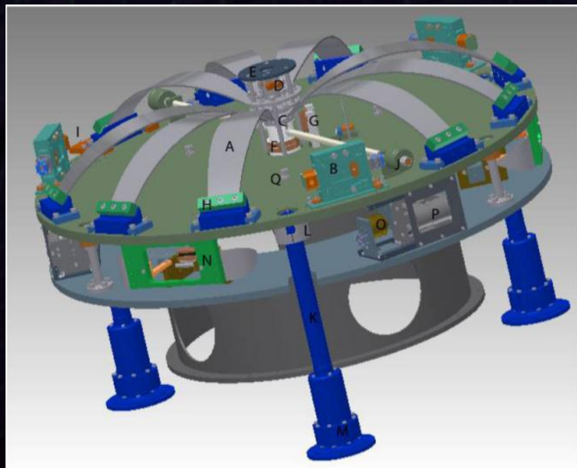


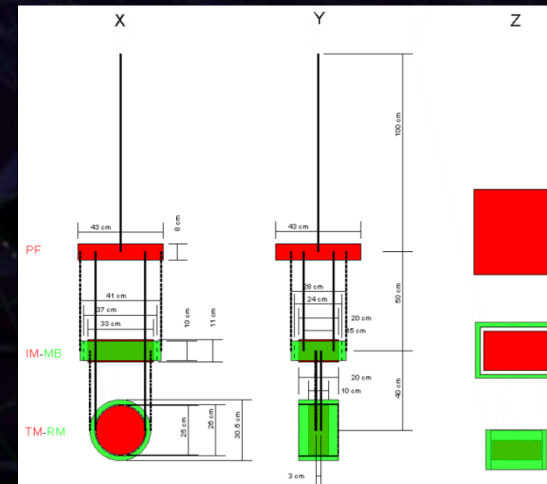
Connection to SAS
Cryostat
Gate valve
Shield duct ϕ800
Shield duct ϕ800
Gate valve
Low vibration
cryocooler unit
Low vibration
cryocooler unit

クライオスタットデザイン

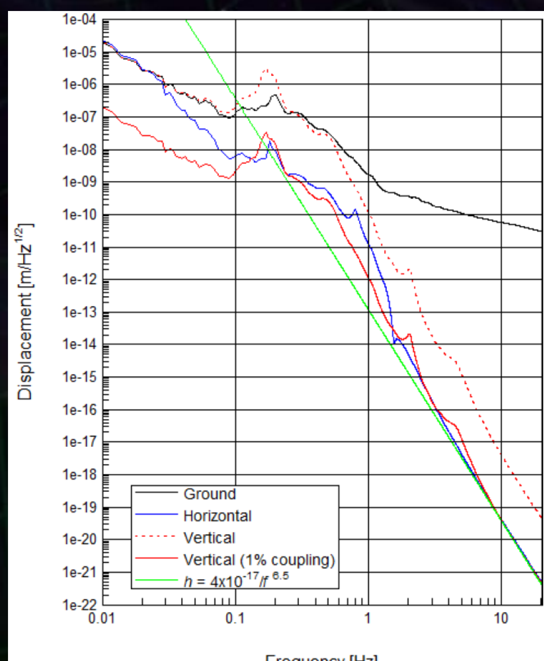


Vibration Isolation

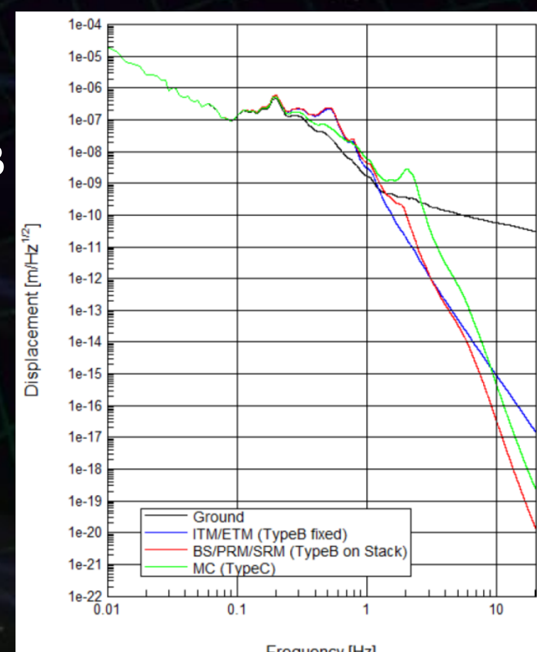




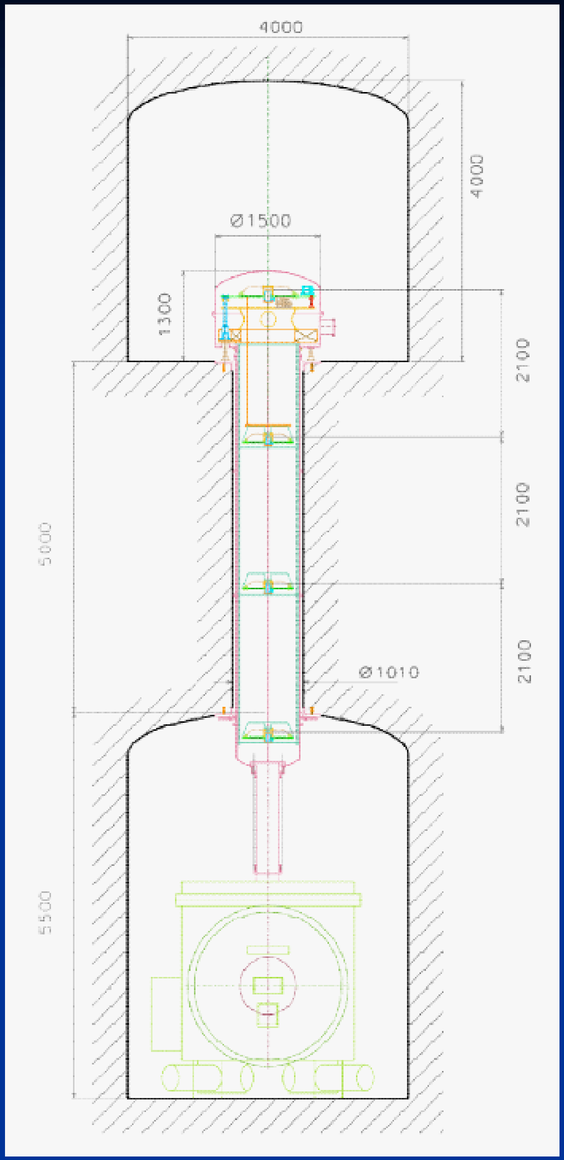
Type-A



Type-B



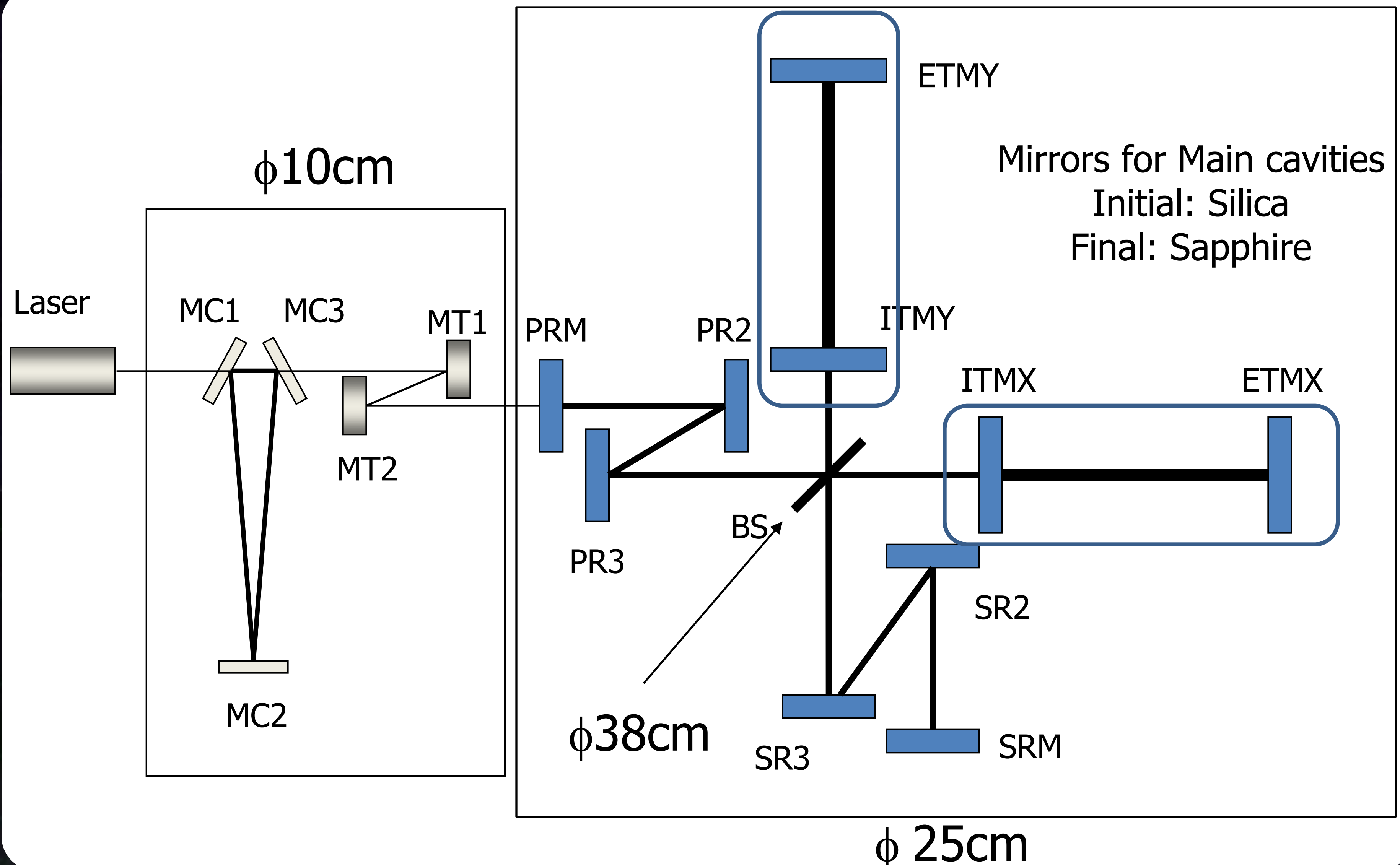
Vibration Isolation



Type-A (2-layer structure)

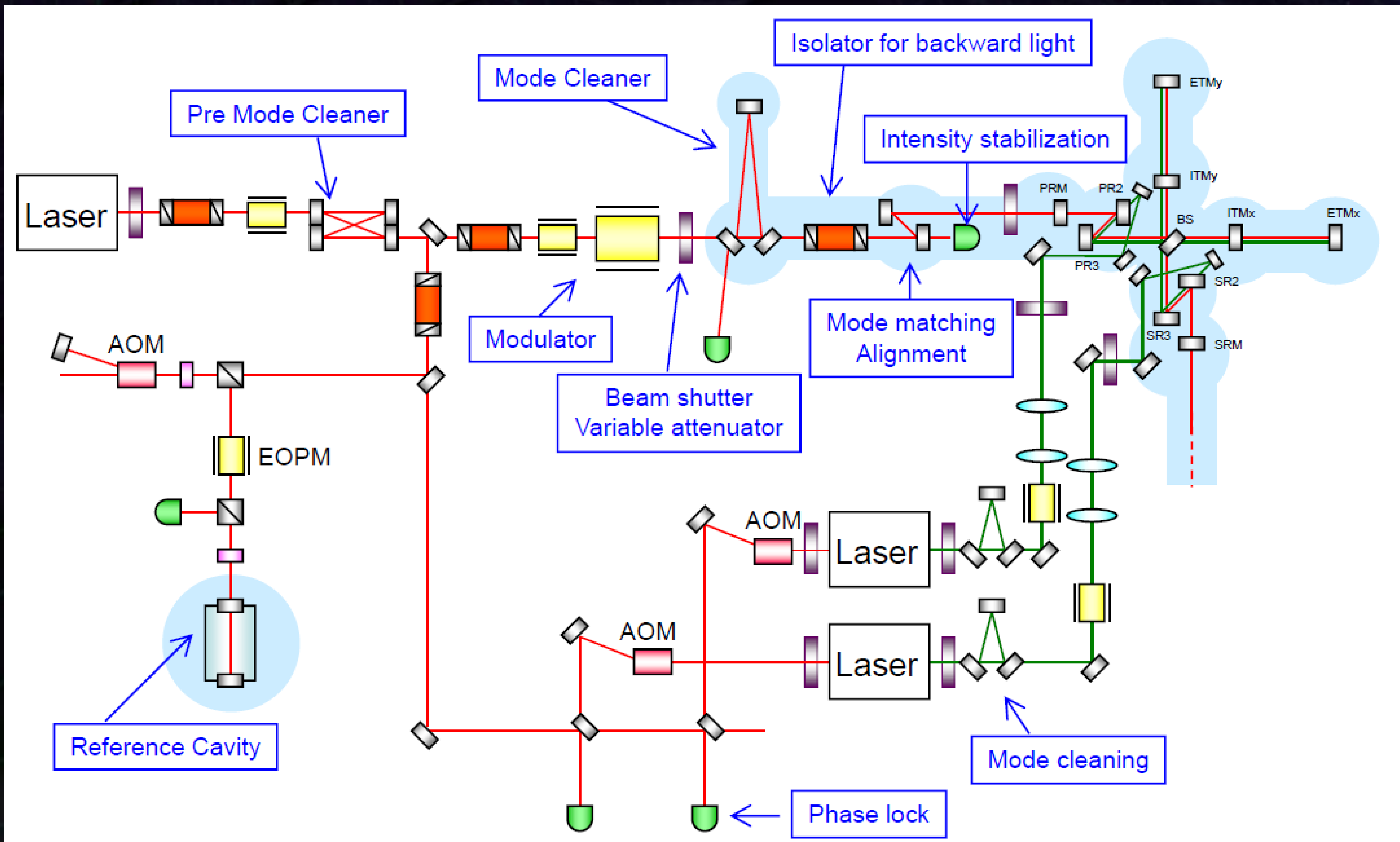
- Upper tunnel containing pre-attenuator (short IP and top filter)
- 1.2m diameter 5m tall borehole containing standard filter chain
- Lower tunnel containing cryostat and payload

Core Optics

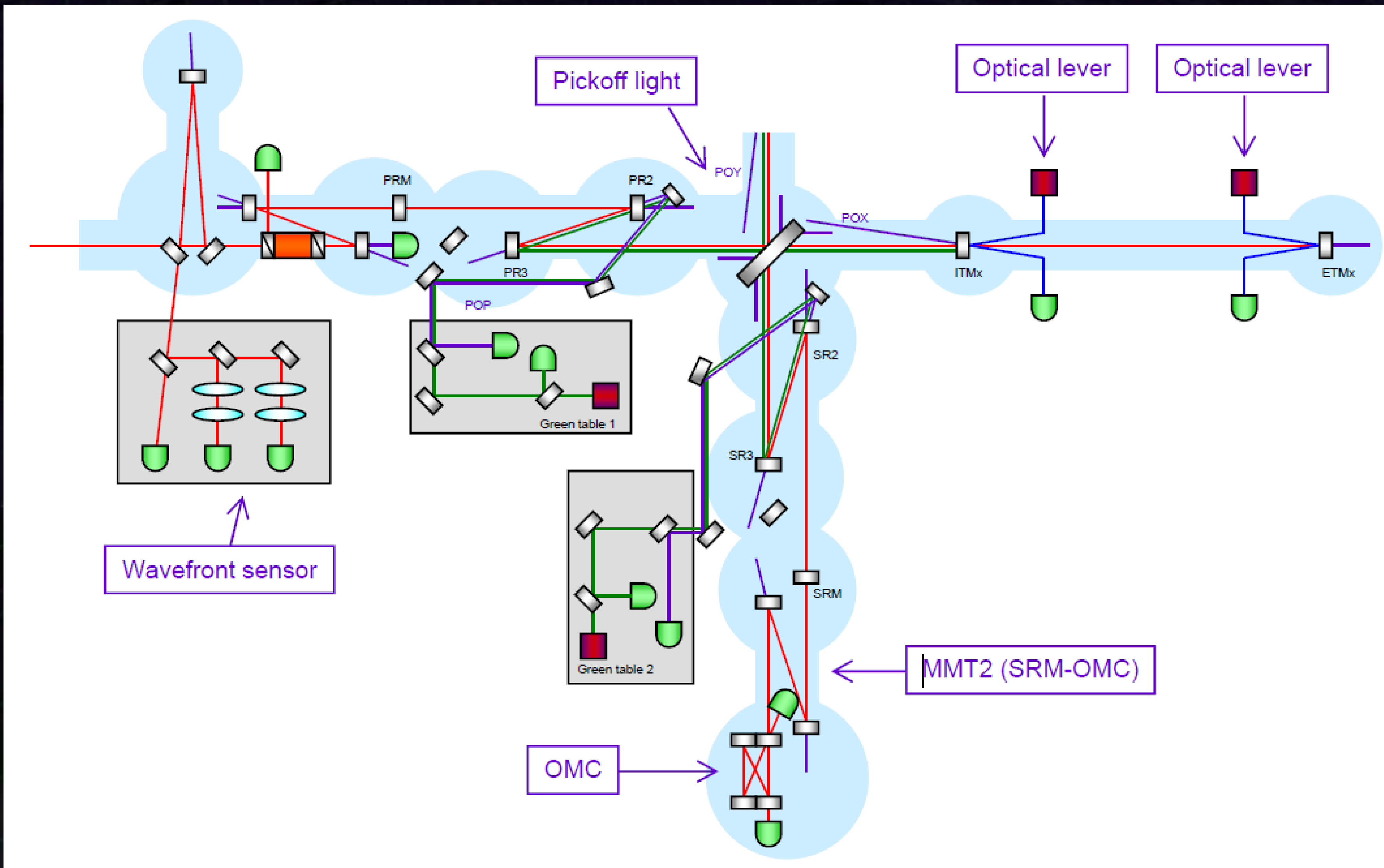


ϕ10cm
Laser
MC1
MC3
MT1
MT2
MC2
PRM
PR2
PR3
BS
ϕ38cm
ETMY
ITMY
ITMX
ETMX
SR2
SR3
SRM
Mirrors for Main cavities
Initial: Silica
Final: Sapphire
ϕ 25cm

Input/Output Optics

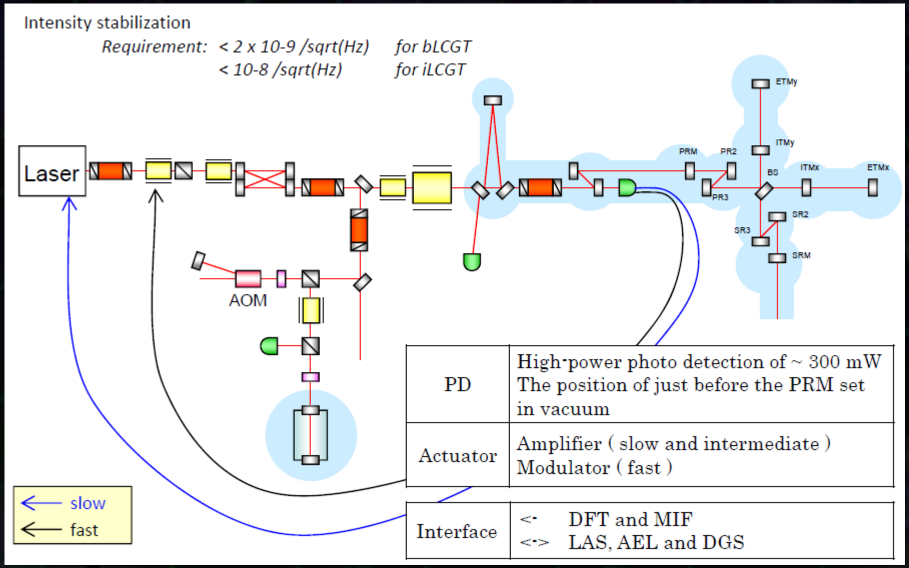


Output Optics

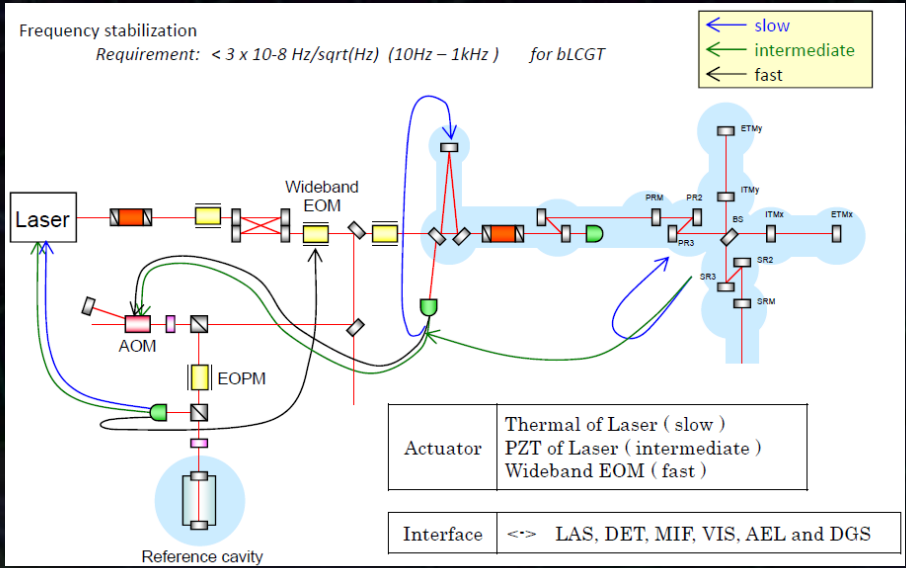


Freq. and Int. stabilization

- **Intensity stabilization**
- **Frequency stabilization**

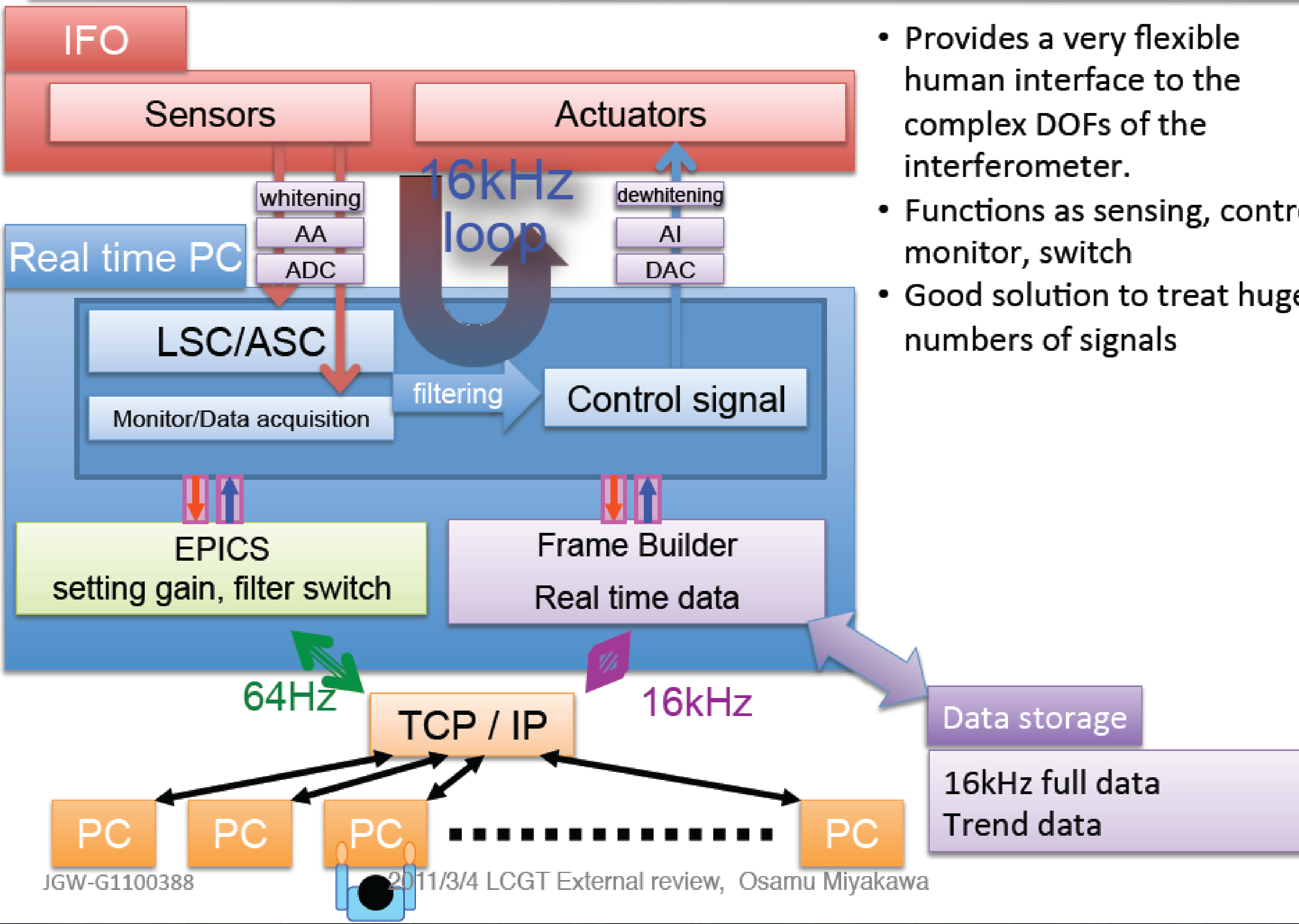


PD	High-power photo detection of ~ 300 mW The position of just before the PRM set in vacuum
Actuator	Amplifier (slow and intermediate) Modulator (fast)
Interface	<- DFT and MIF <-> LAS, AEL and DGS



Actuator	Thermal of Laser (slow) PZT of Laser (intermediate) Wideband EOM (fast)
Interface	<-> LAS, DET, MIF, VIS, AEL and DGS

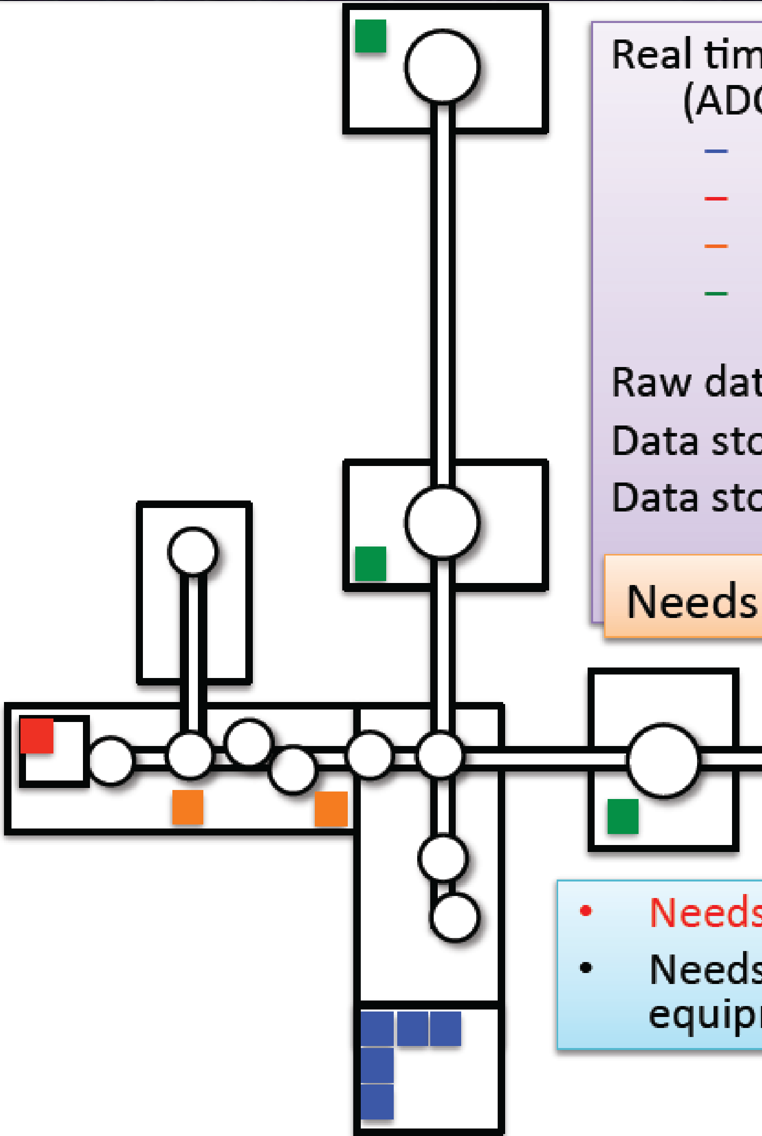
Digital System



- Provides a very flexible human interface to the complex DOFs of the interferometer.
- Functions as sensing, control, monitor, switch
- Good solution to treat huge numbers of signals

JGW-G1100388 2011/3/4 LCGT External review, Osamu Miyakawa

Digital System



Real time system mounted in 19inch rack: PC, IO chassis (ADC/DAC/BO), timing, AA/AI

- Front room: length(1), WFS(1-2), auxiliary(1), network(1-2)
- Laser room: Laser(1)
- Center room: Input optics(1-2), suspensions(1-3)
- Main suspensions: ITMX(1-2), ITMY(1-2), ETMX(1-2), ETMY(1-2)

Raw data storage at site for 1month long: 100TB

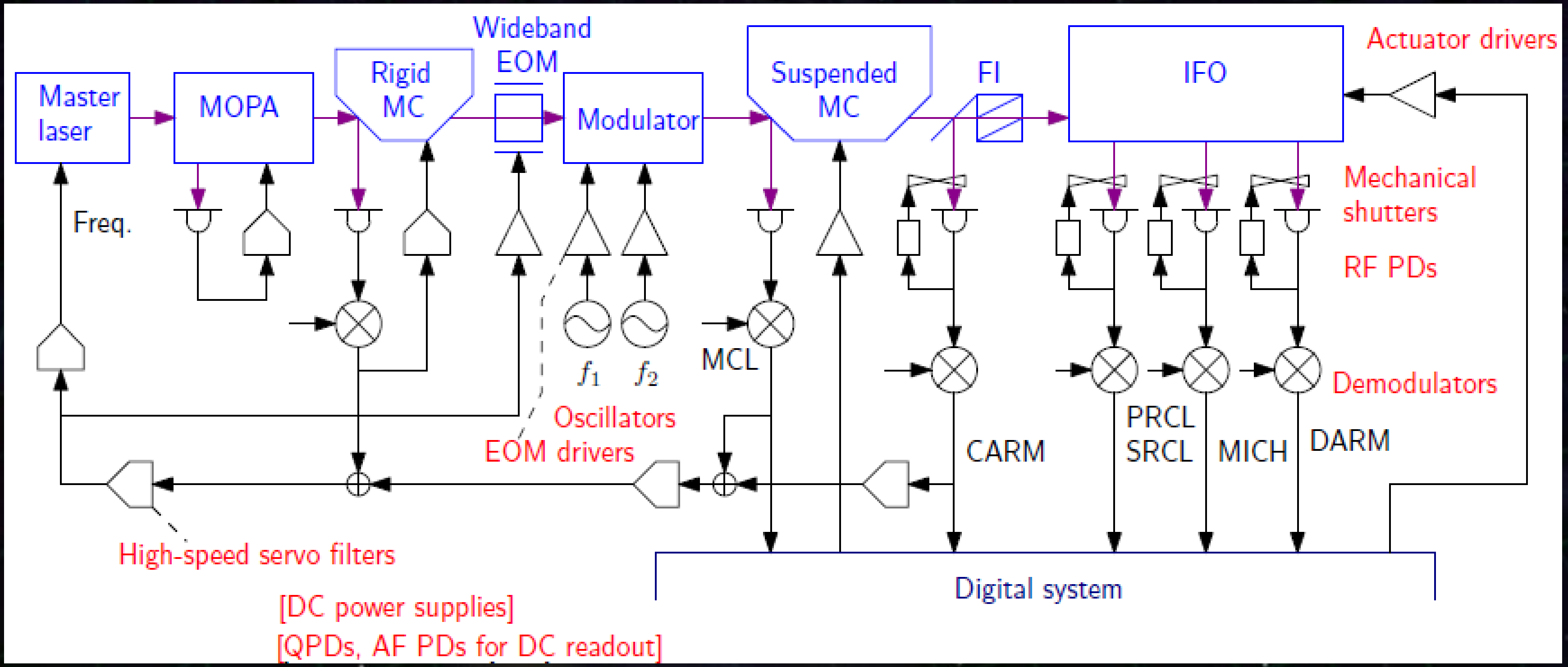
Data storage for iLCGT (analysis, commissioning): 500TB

Data storage for bLCGT: 1PB/year?, not funded

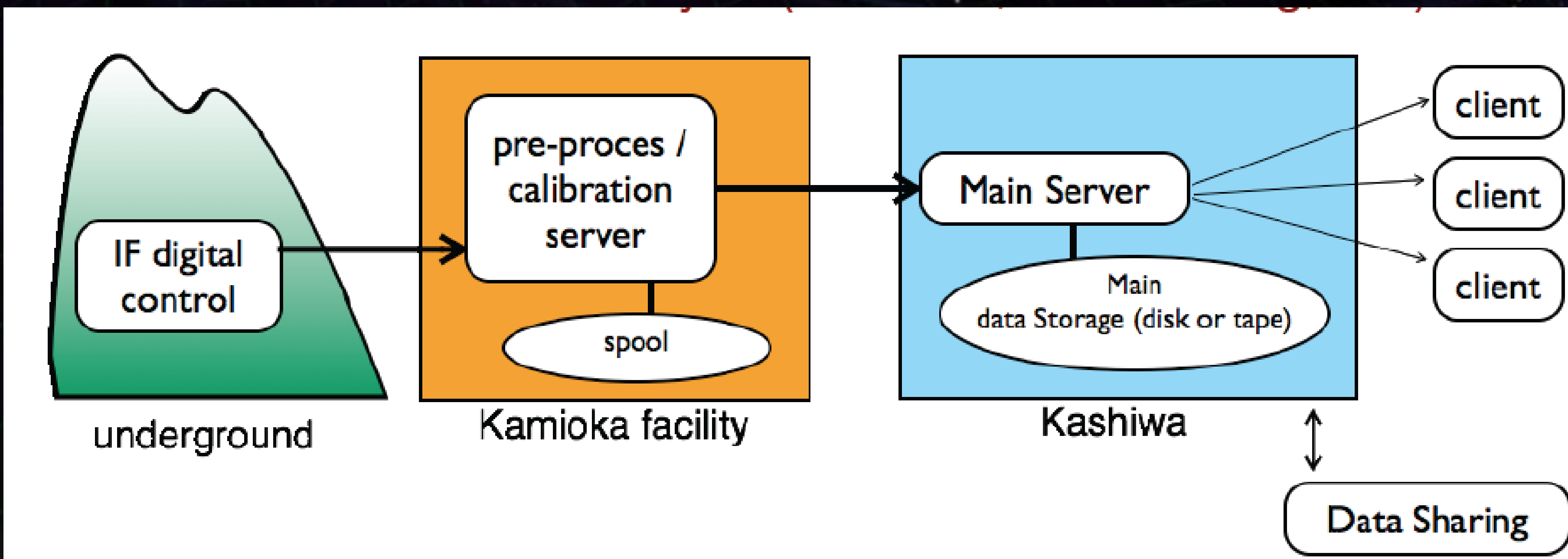
Needs to make a channel list from all subgroups

- Needs whole network design
- Needs network wiring diagram, rack position, rack equipment list

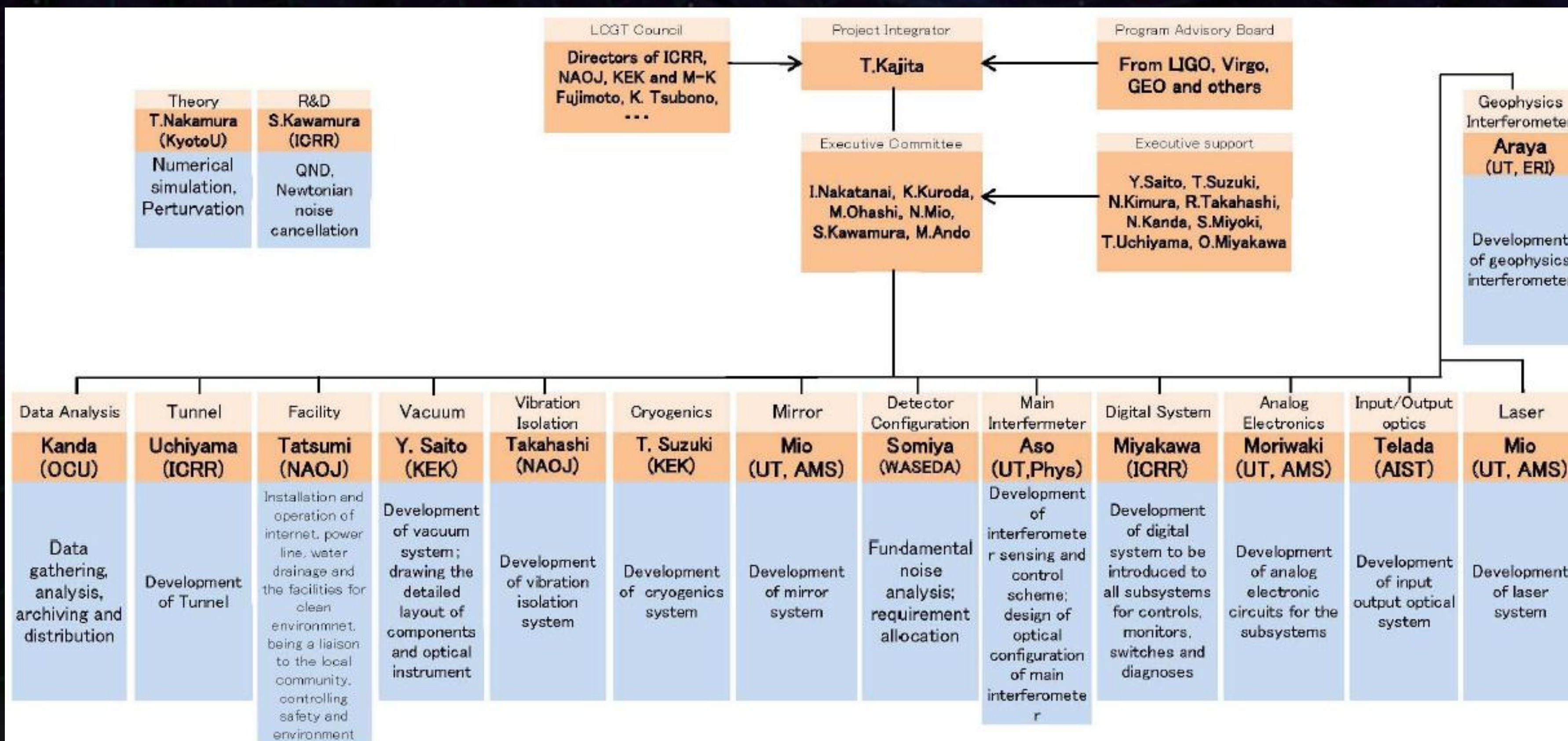
Analog electronics



Data Analysis



Organization



LCGTとAd. LIGO

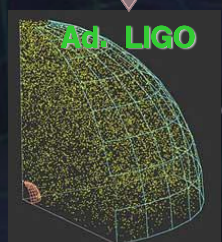
LCGT (JPN)		Advanced LIGO (USA)
1 detector (3km)	**Scale**	3 detectors (4km) (2 close, 1 separated)
Long baseline Better seismic attenuation system Underground site	**Seismic noise reduction**	Long baseline Better seismic attenuation system Suburban site
Low-mechanical-loss mirrors and suspensions Cryogenic (20k)	**Thermal noise reduction**	Low-mechanical-loss mirrors and suspensions Large beam size
High-power laser source Low-loss optics Variable RSE config.	**Quantum noise reduction**	High-power laser source Low-loss optics Detuned RSE config.

Roadmap of GW detectors

Ground based detectors

Improved sensitivities (10-1kHz)

LIGO
Enhanced LIGO
Advanced LIGO



TAMA CLIO
LCGT

Virgo/GEO
Advanced Virgo

ET

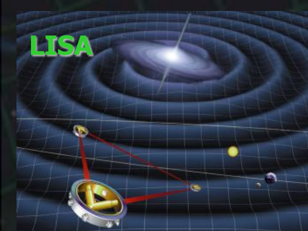
2010
2015
2020
2025

Detection Rate
~10 event/yr

Space-borne detectors

Low-frequency sources
(0.1mHz – 1Hz)

LPF



LISA

Guaranteed source
0.1mHz-10mHz

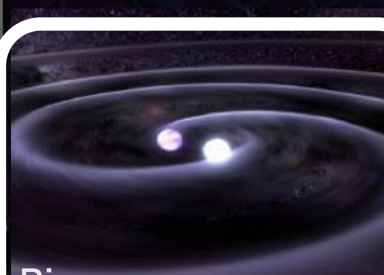
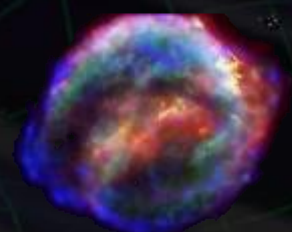
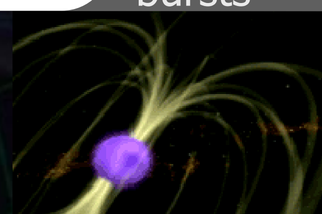
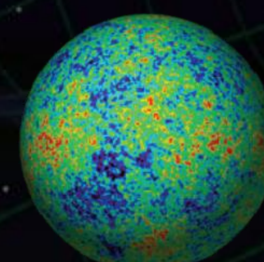
BBO

Cosmological GWs
around 0.1Hz

DECIGO
DPF
Pre-DECIGO
DECIGO

GW targets and data analysis

Signal duration

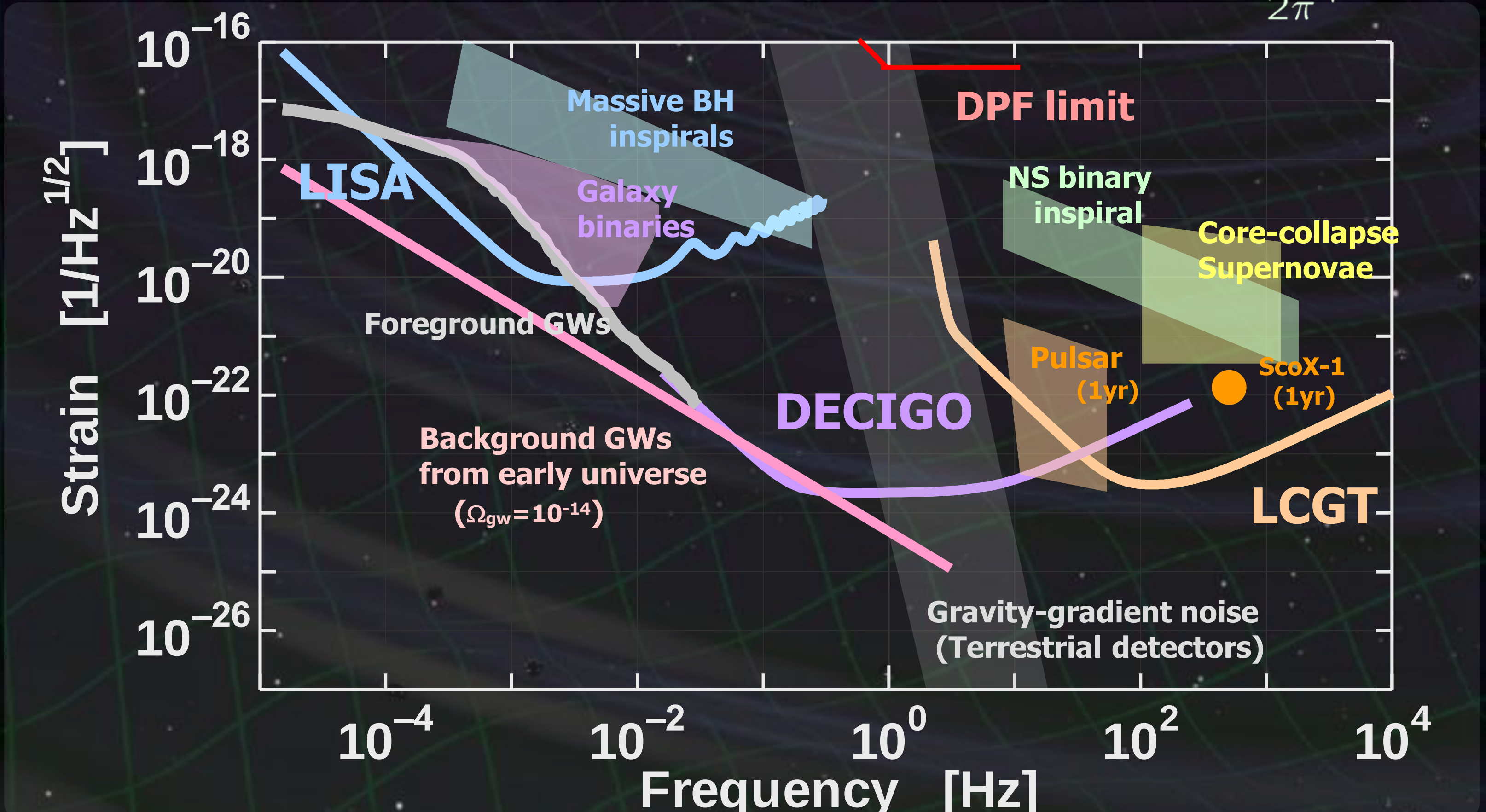
Waveform	Short (bursts)		Long (stationary)
Known	 Binary merger → Chirp wave, Ringdown wave	Gamma-ray bursts	 Pulsar, LMXB → Continuous
Unknown	 Stellar core collapse → burst wave	 Soft gamma-ray repeater	 Stochastic background → Random wave

DPF sensitivity

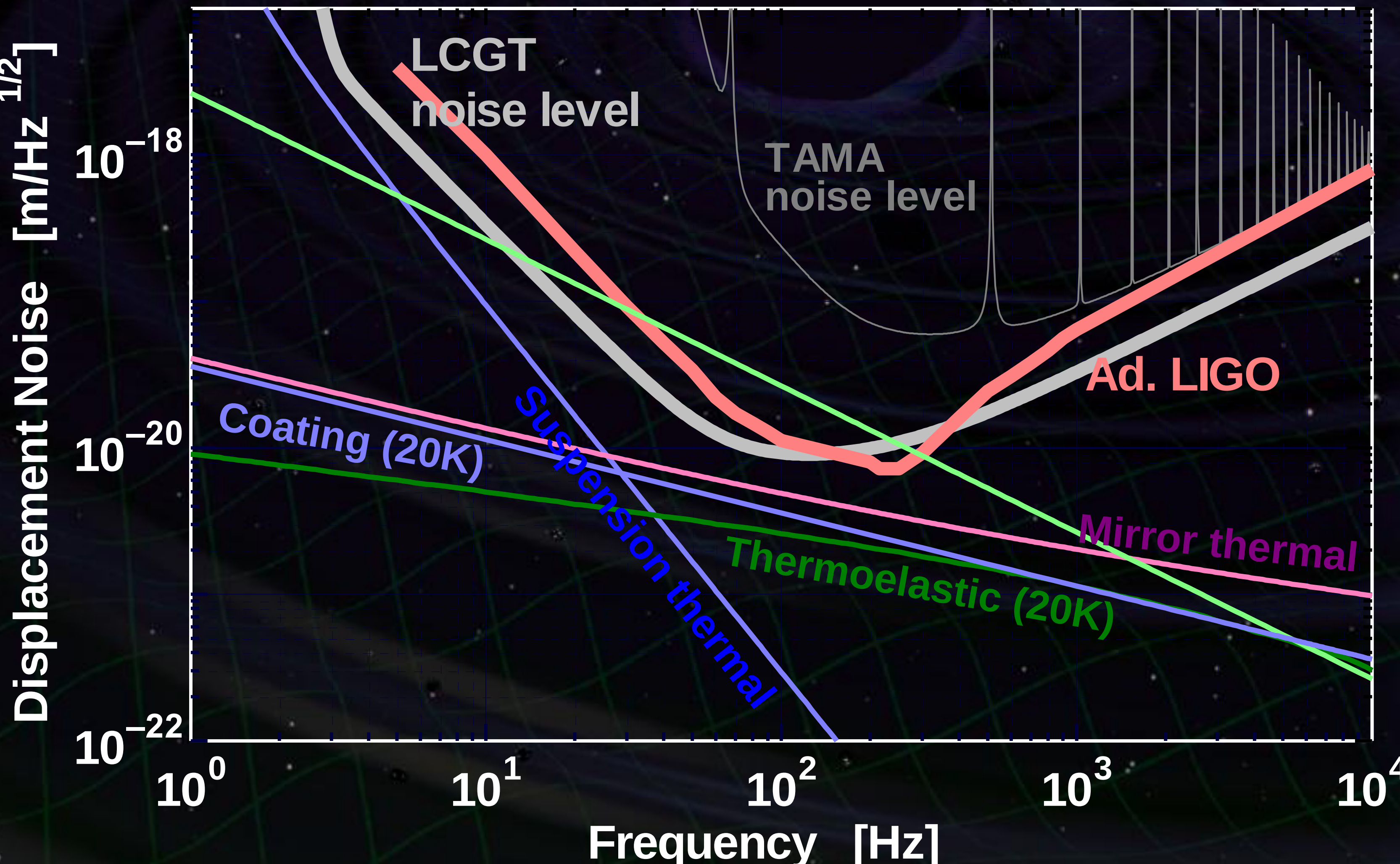
DPF sensitivity $h \sim 2\text{x}10^{-15}\ \text{Hz}^{1/2}$

(x10 of quantum noises)

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



LCGTとAd. LIGO



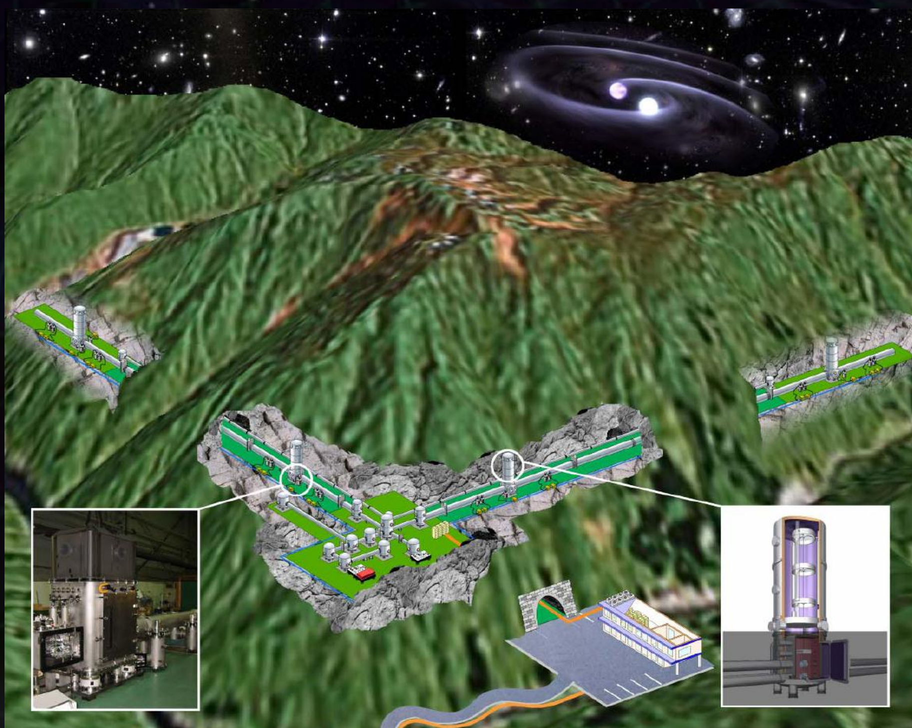
LCGT and DECIGO

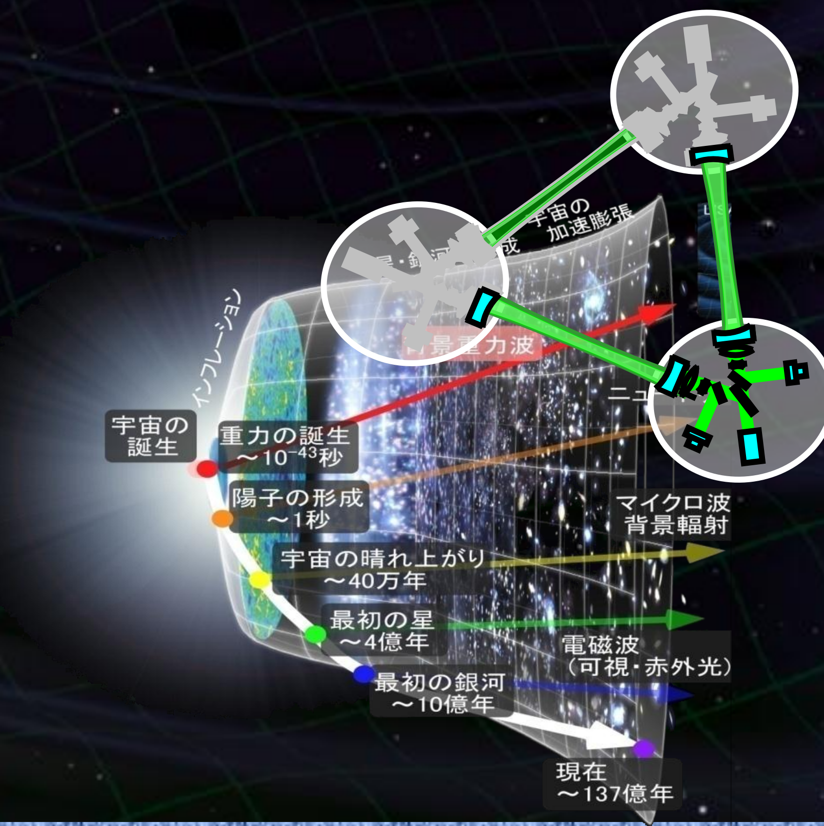
LCGT (~2017)
Terrestrial Detector
→ High frequency events

Target: GW detection

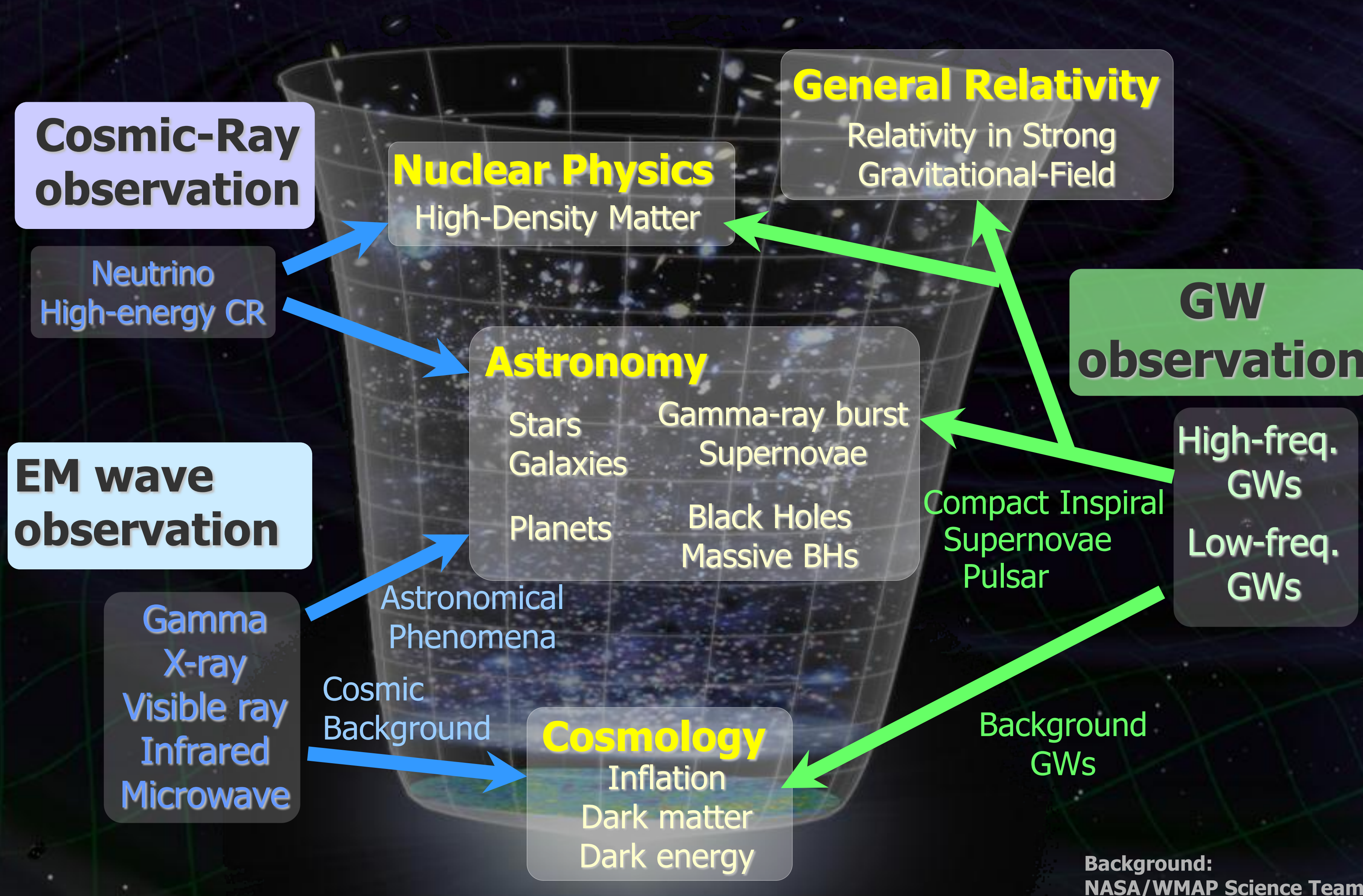
DECIGO (~2027)
Space observatory
→ Low frequency sources

Target: GW astronomy





Observation of the Universe



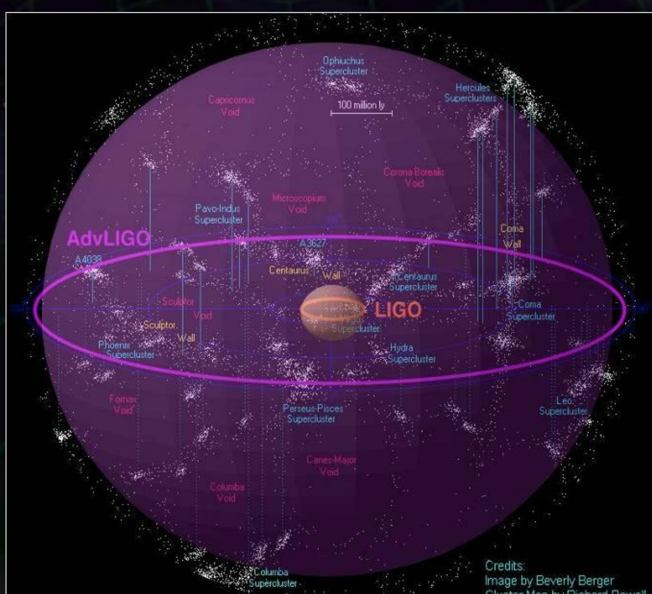
Expanding the Horizon

Current GW detectors : <20Mpc obs. range

However... we can expect only rare events (10^{-5}-10^{-3} event/yr)

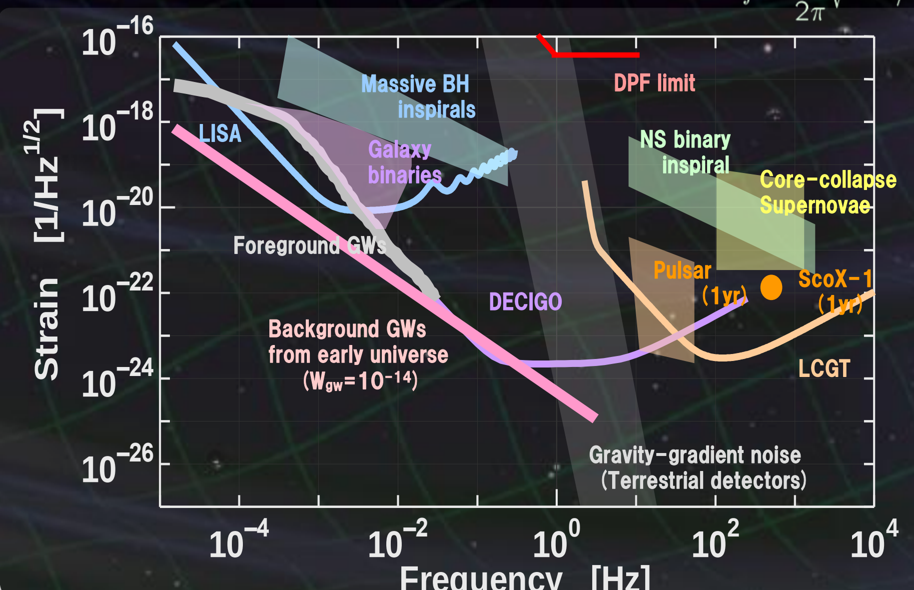
⇨ **Next generation detectors**

Better sensitivity to cover more galaxies



Wider observation band for various sources

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

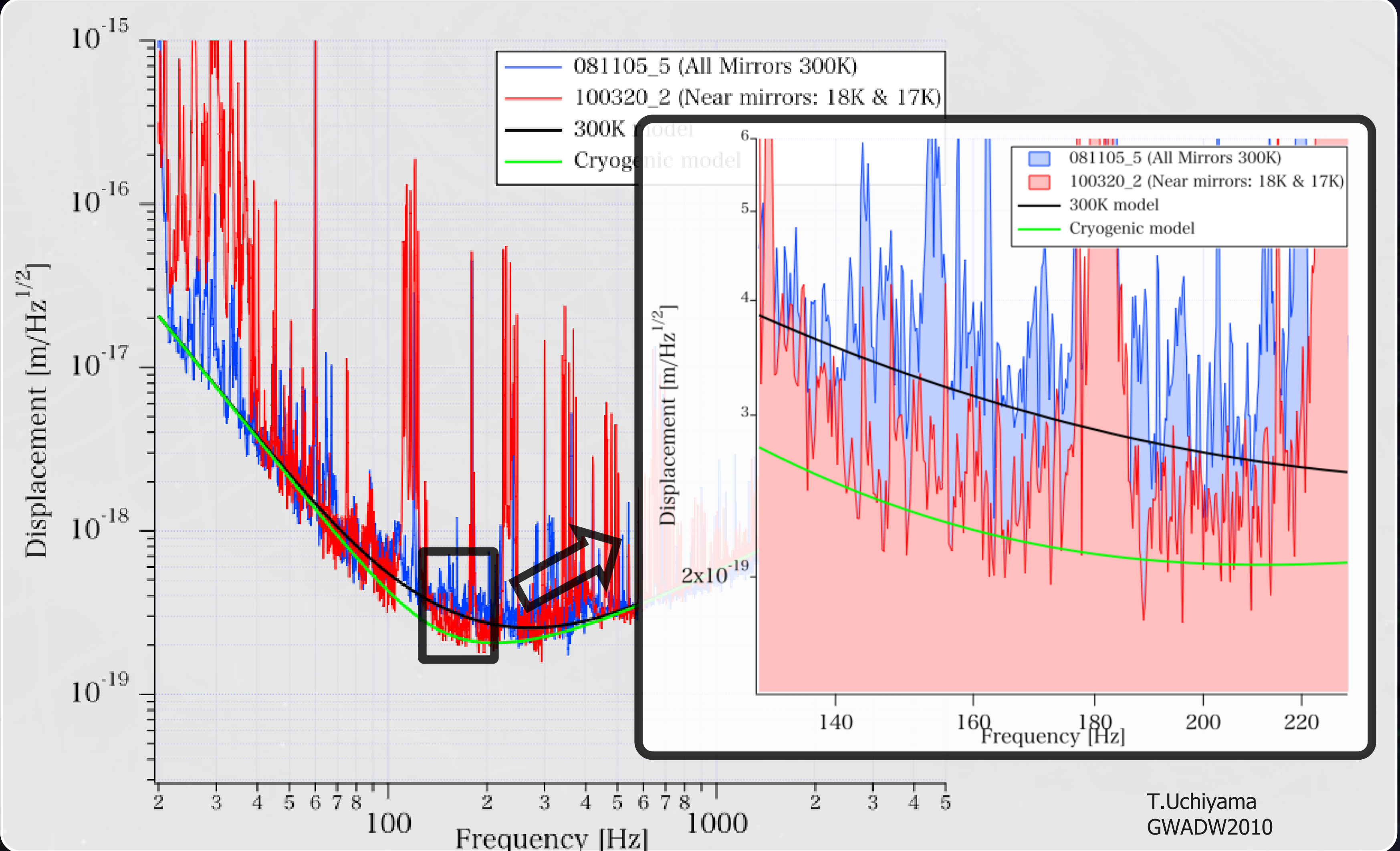


CLIO


T.Uchiyama
March 29, 2009 JPS Meeting
CLIO
Per- EM- Cryostat
Per- 100m Arm
Acheved Pressure
- 100m Arm -
6×10-5 Pa
by a 800 litter Turbo
- Cryostat -
2×10-6 Pa
by Cryostat itself
Inline- EM- Cryostat
Per- Arm PickOff
BS
Inline- 100m Arm
Telescope 1
Laser: NdYAG
1064nm, 2W
MC
Inline- NM- Cryostat

CLIO sensitivity

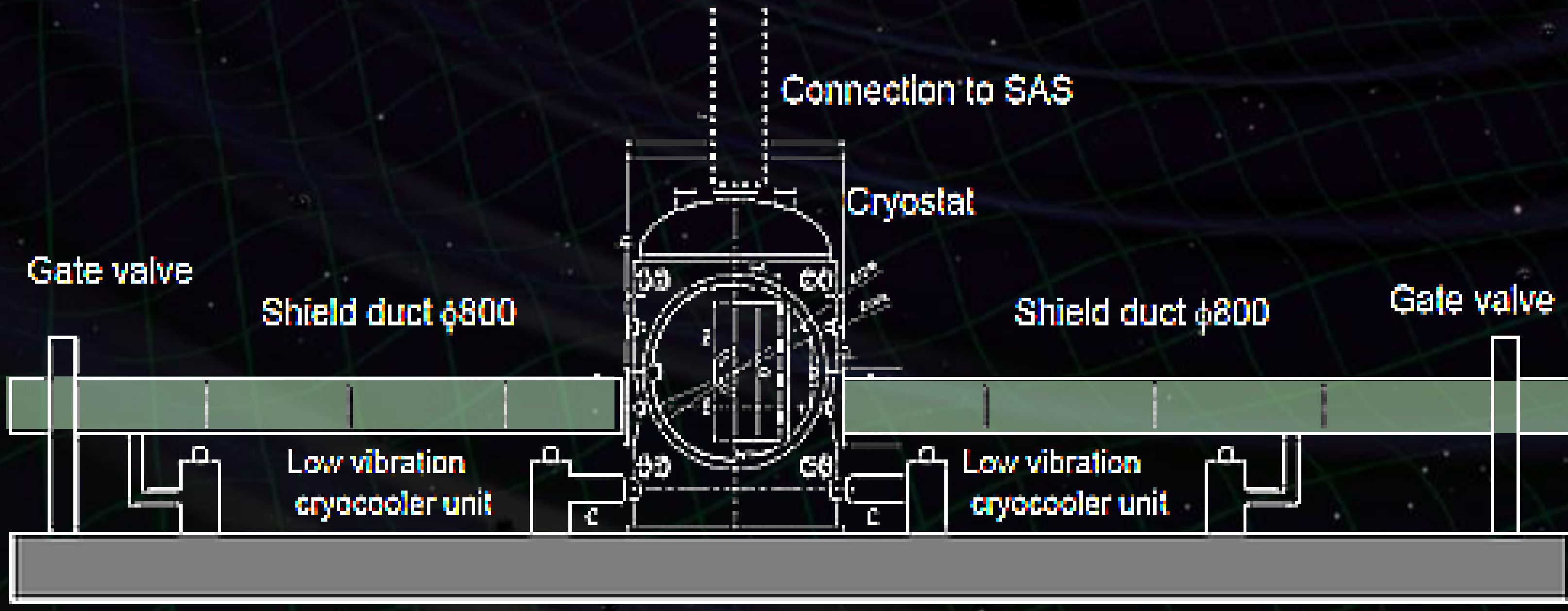
Sensitivity improvement with cryogenic operation



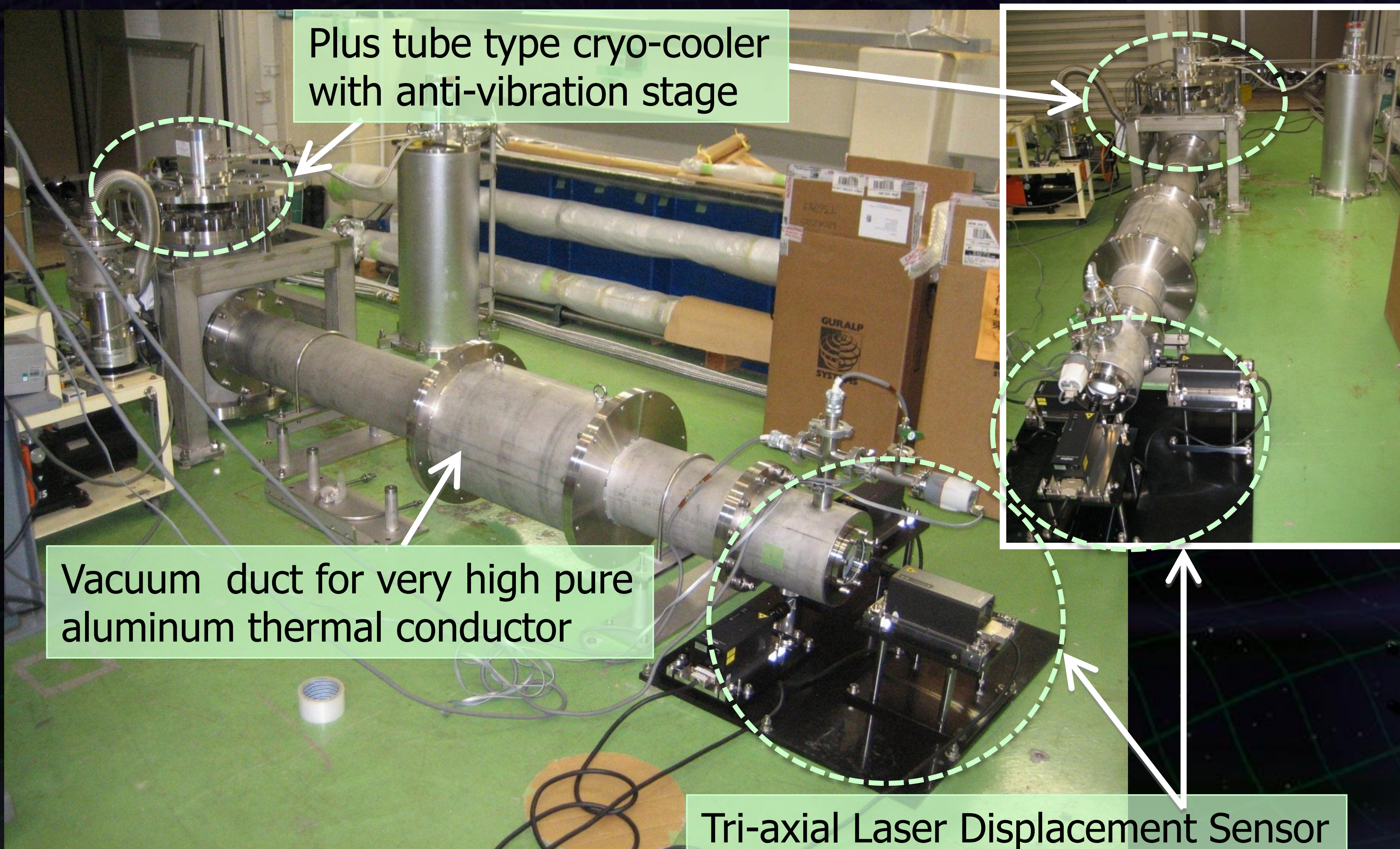
T.Uchiyama
GWADW2010

シールドダクト

・光軸方向 (3kmダクト部) からの
熱流入を低減するための輻射シールド.



低振動冷凍機


Plus tube type cryo-cooler
with anti-vibration stage
Vacuum duct for very high pure
aluminum thermal conductor
Tri-axial Laser Displacement Sensor