# 大型低温重力波望遠鏡LCGTで探る 高エネルギー天体現象

@宇宙線研究所共同利用研究会「ガンマ線天文学 〜日本の戦略〜」2010/11/16


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Nobuyuki Kanda (Osaka City Univ.)

LCGT collaboration
+ GW&EM followup working group

# Plan of Talk

## Gravitational Waves

- What ?
- Why ?
- Sources

## LCGT

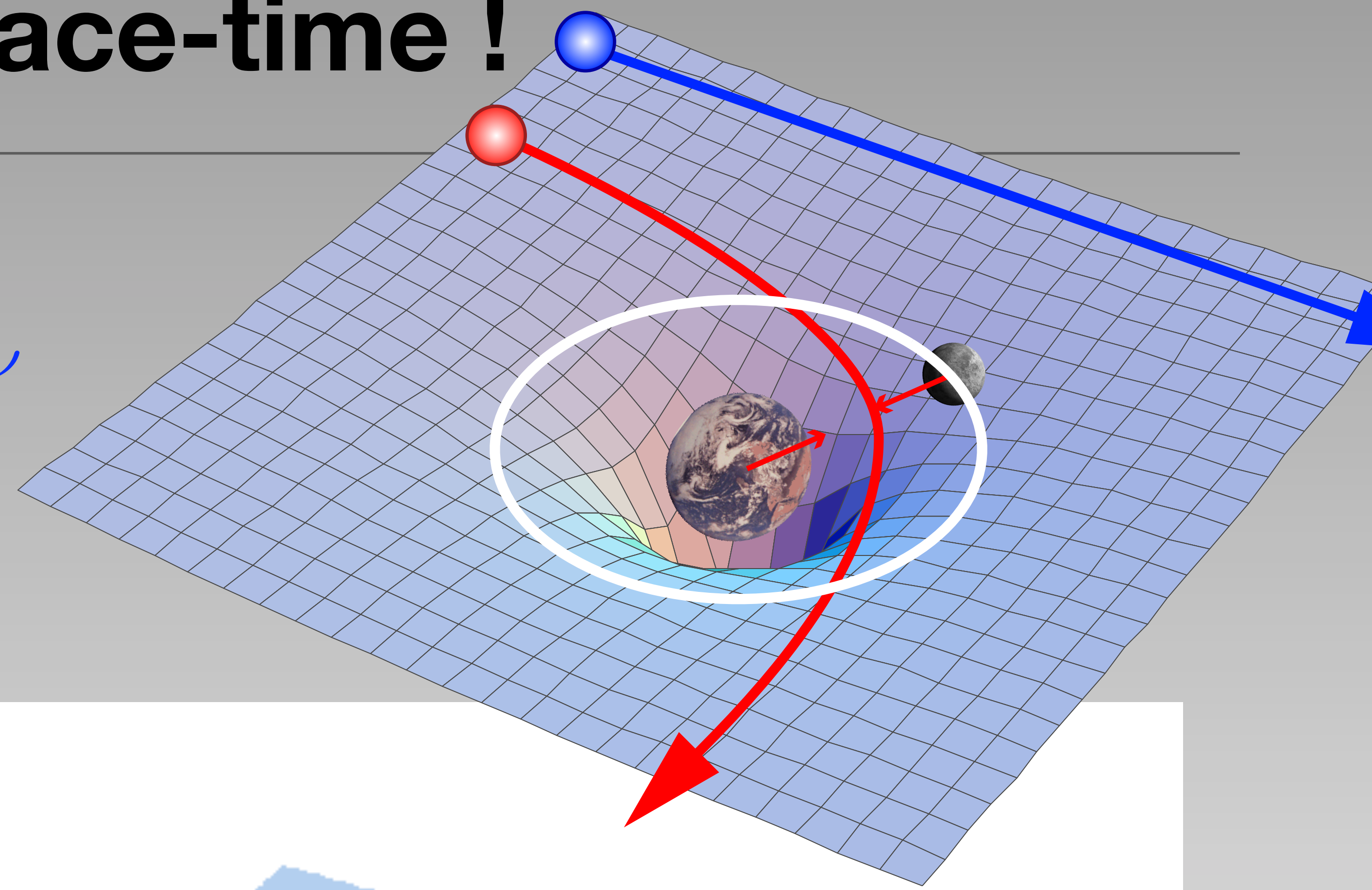
- Overview
- Construction Schedule
- Detection Range for GWs

## Counterpart / Follow-up observations

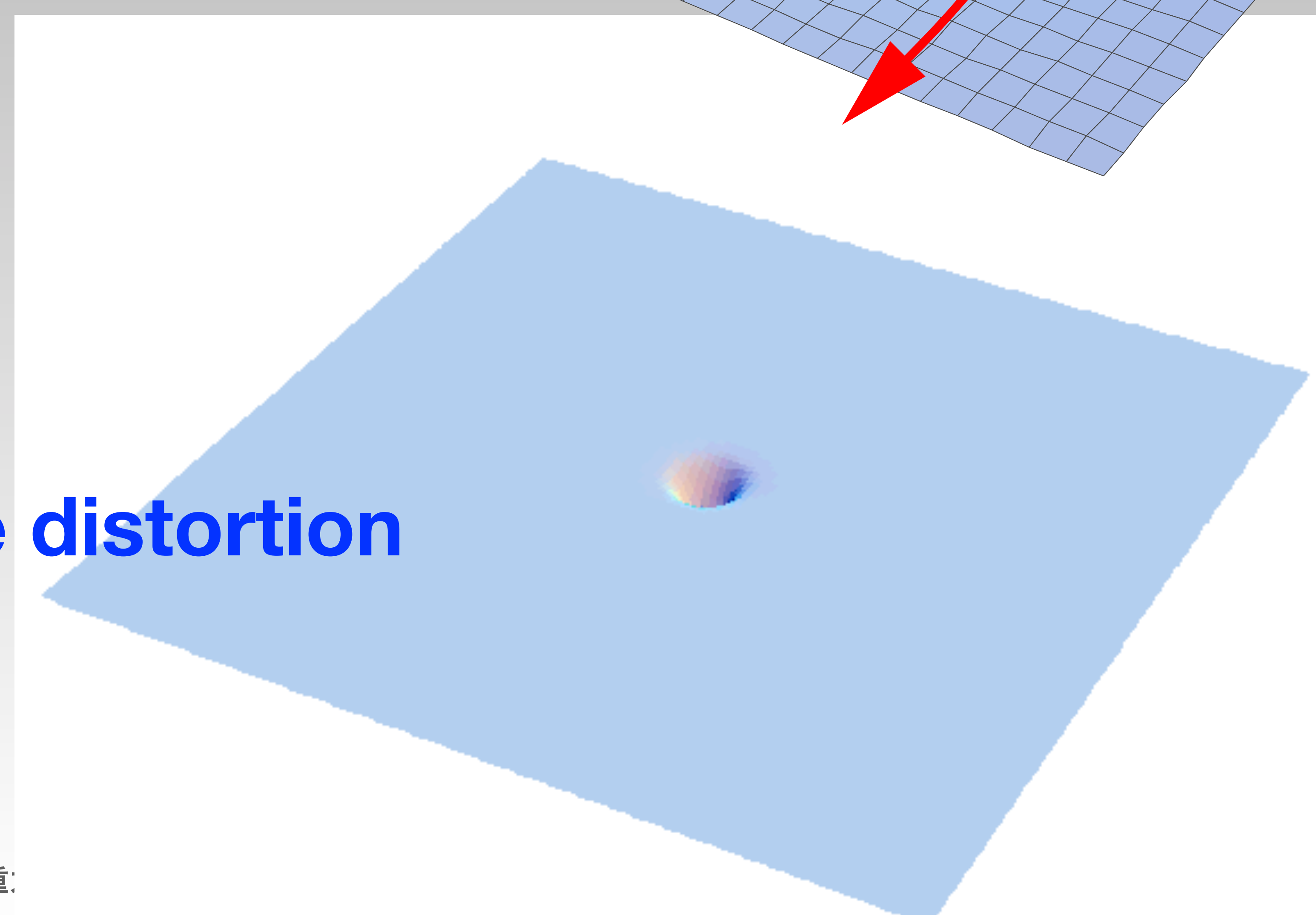
- Possible Sources
- Science (Physics) outcome

# Gravity distorts the space-time !

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\kappa T_{\mu\nu}$$



## Curved space-time

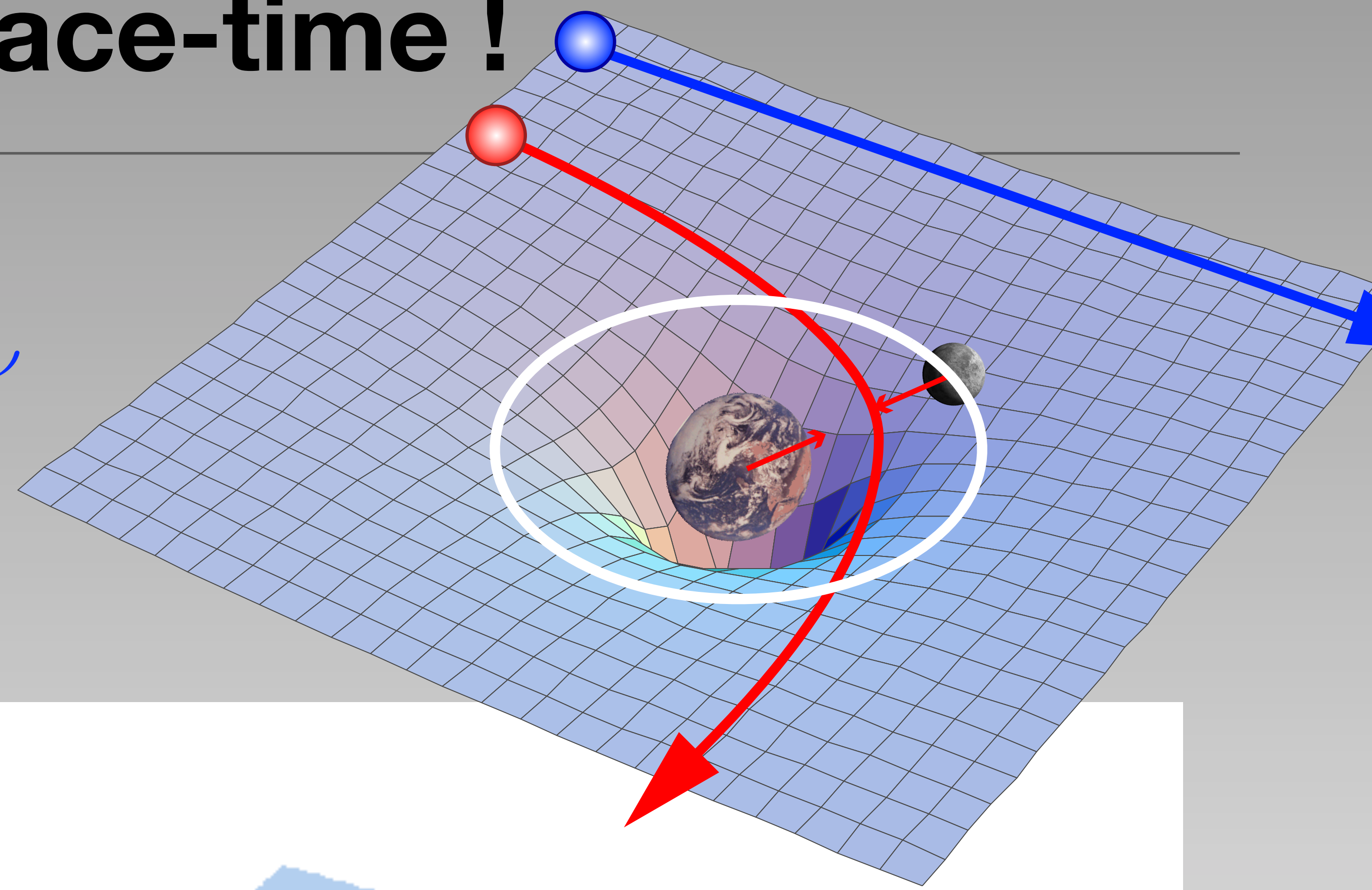


## Propagation of the distortion

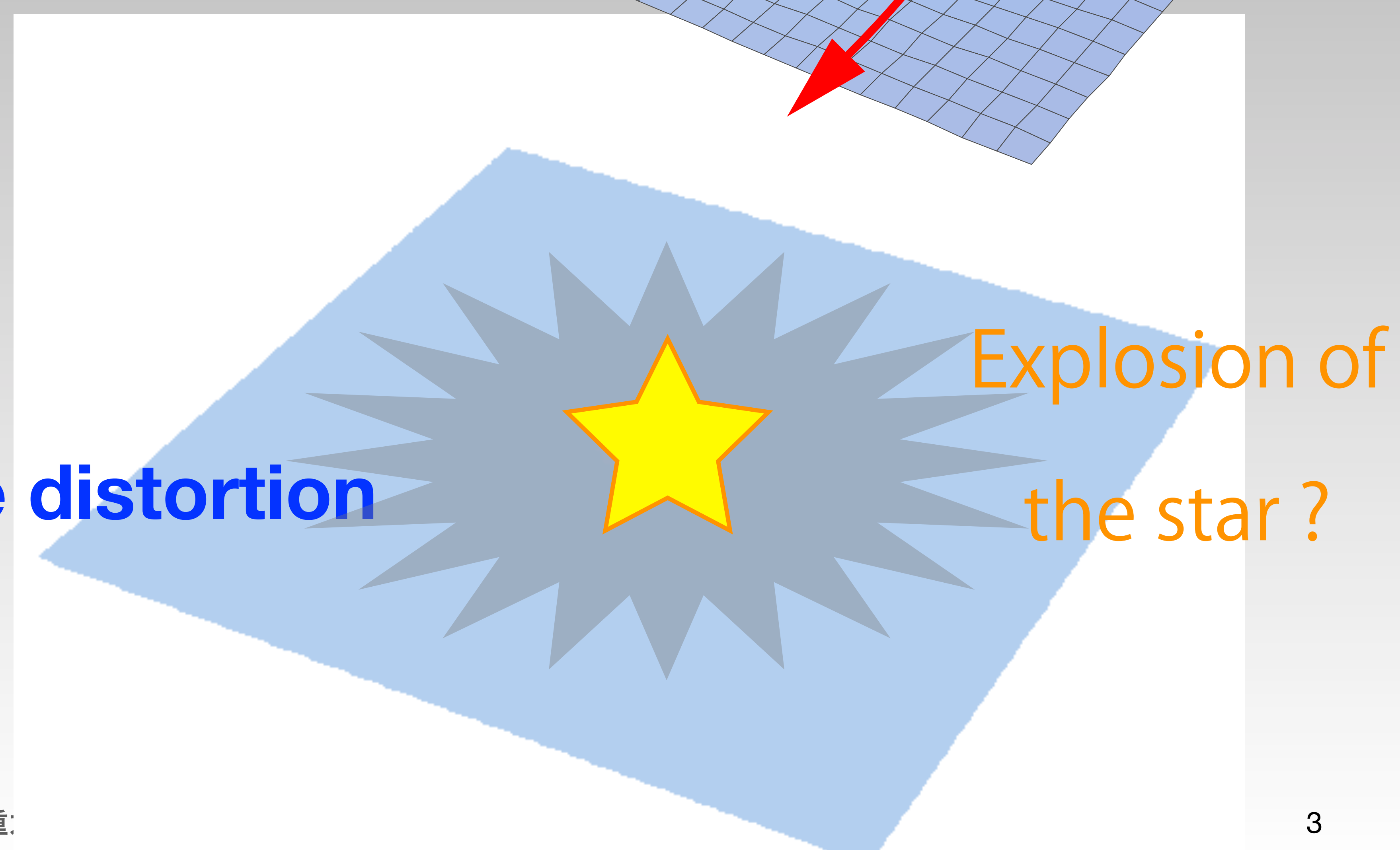
- --> Waves !

# Gravity distorts the space-time !

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\kappa T_{\mu\nu}$$



## Curved space-time




## Propagation of the distortion

- --> Waves !

# Gravitational Waves

**Einstein Equation :** $$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\kappa\, T_{\mu\nu}$$

In case of small perturbation 'h',
a wave equation is derived as;

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\left( \nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = 0$$

--> Wave of strain 'h'

## Gravitational Wave

- light speed
- transverse
- quadrupole
  (tidal force)

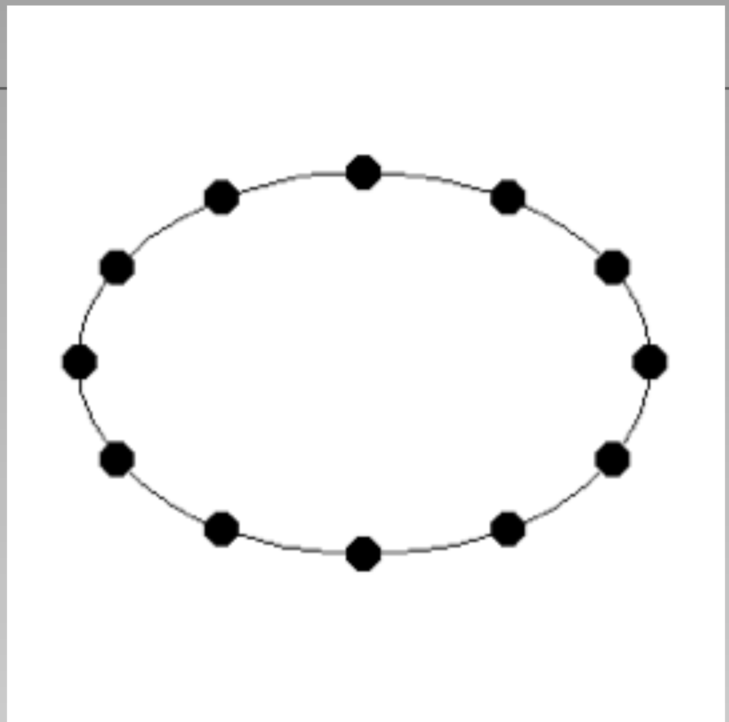
$$h_{+} = h \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad h_{\times} = h \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

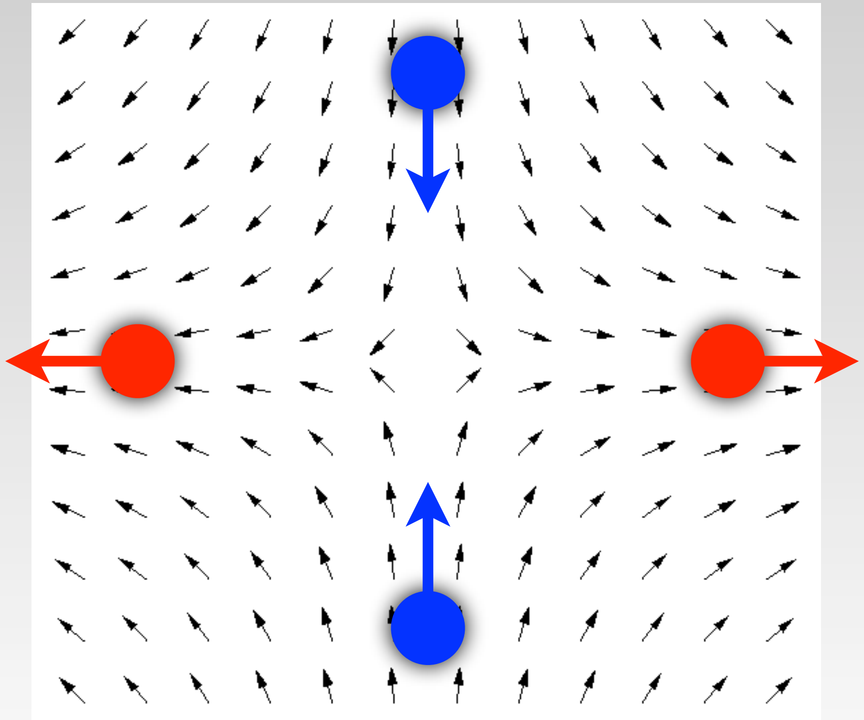
# Force (Displacement) by GW

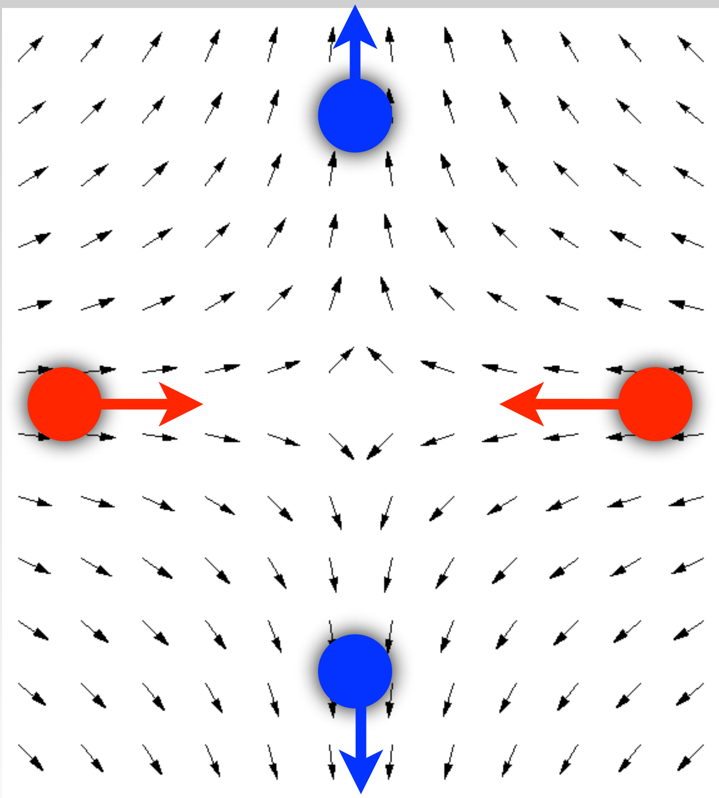
## Tidal force on masses

$$h_+ \cos(\vec{k}\cdot\vec{x} - 2\pi f_{GW} t)$$

$$h_+ = h \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$







# Direct measurements of GW

## Physics

TEST of Einstein's general relativity in strong field.

## Astronomy, Astrophysics

- Radiation from compact / massive objects.

  Physics of black-hole, neuron star, supernovae, etc...

  --> Gravitational Wave Astronomy

## Cosmology

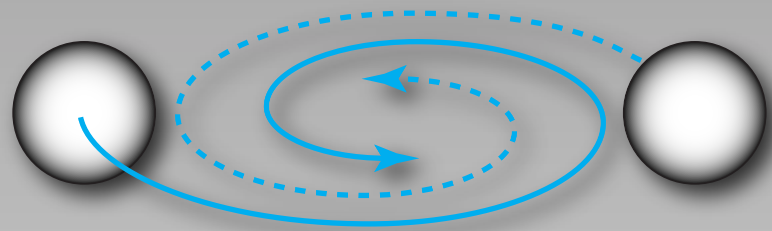
- Cosmic background radiation of GW
- POP-III stars, star formation, etc...

  Physics on early universe.

# Expected GW sources

## Event like:

- Compact Binary Coalescence
  - neutron star (NS)
  - black-hole (BH)
- Supernovae
- BH ringdown

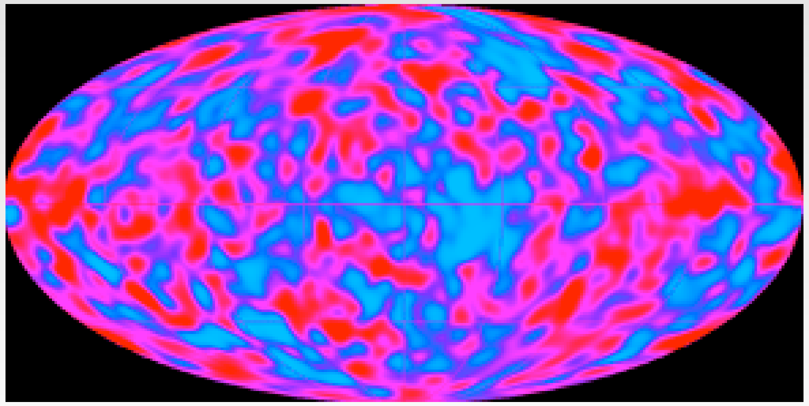


## Continuous waves:

- Pulsar rotation
- Binaries

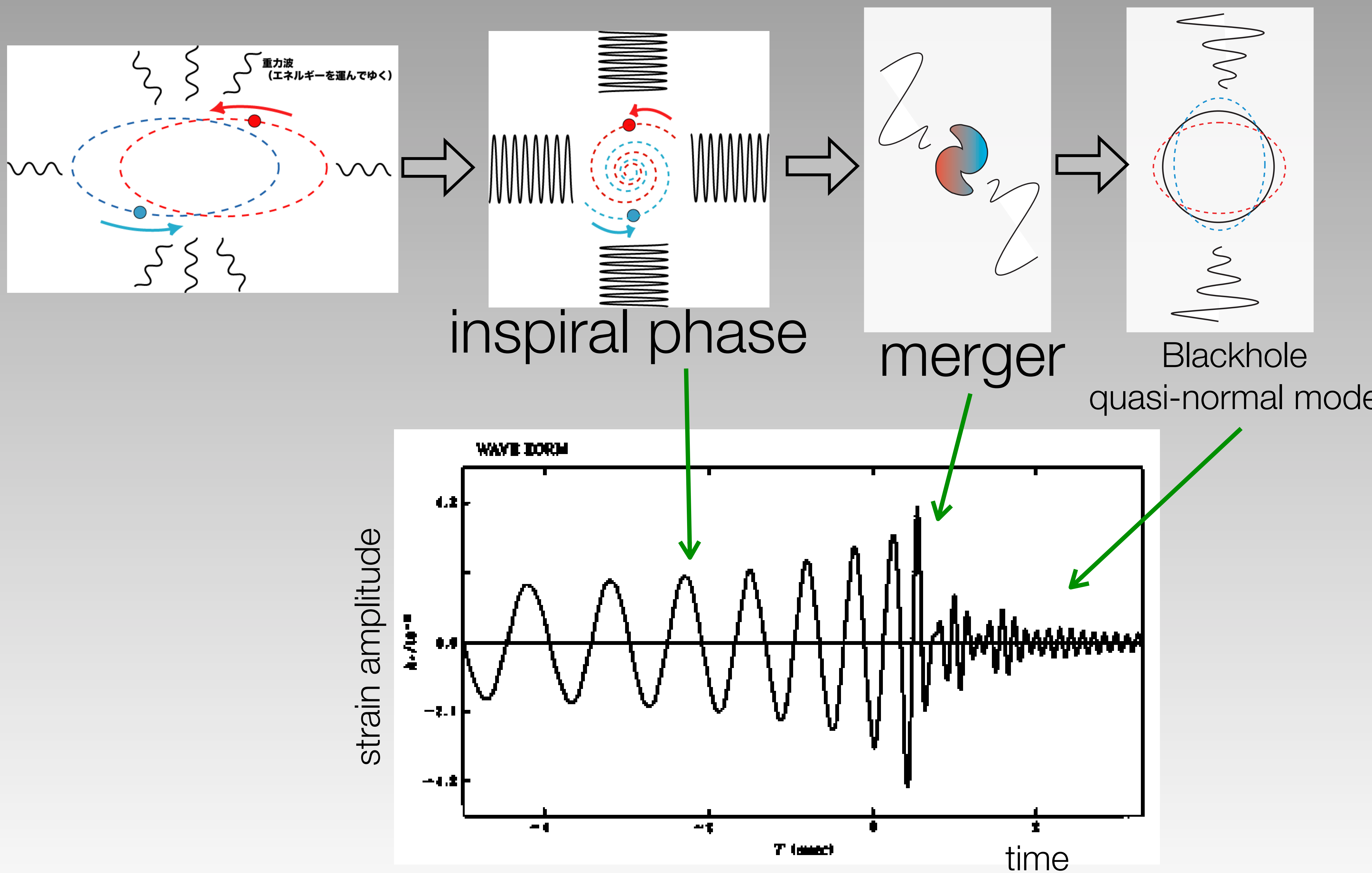
## Stochastic Background

- Early universe (i.e. Inflation)
- Cosmic string



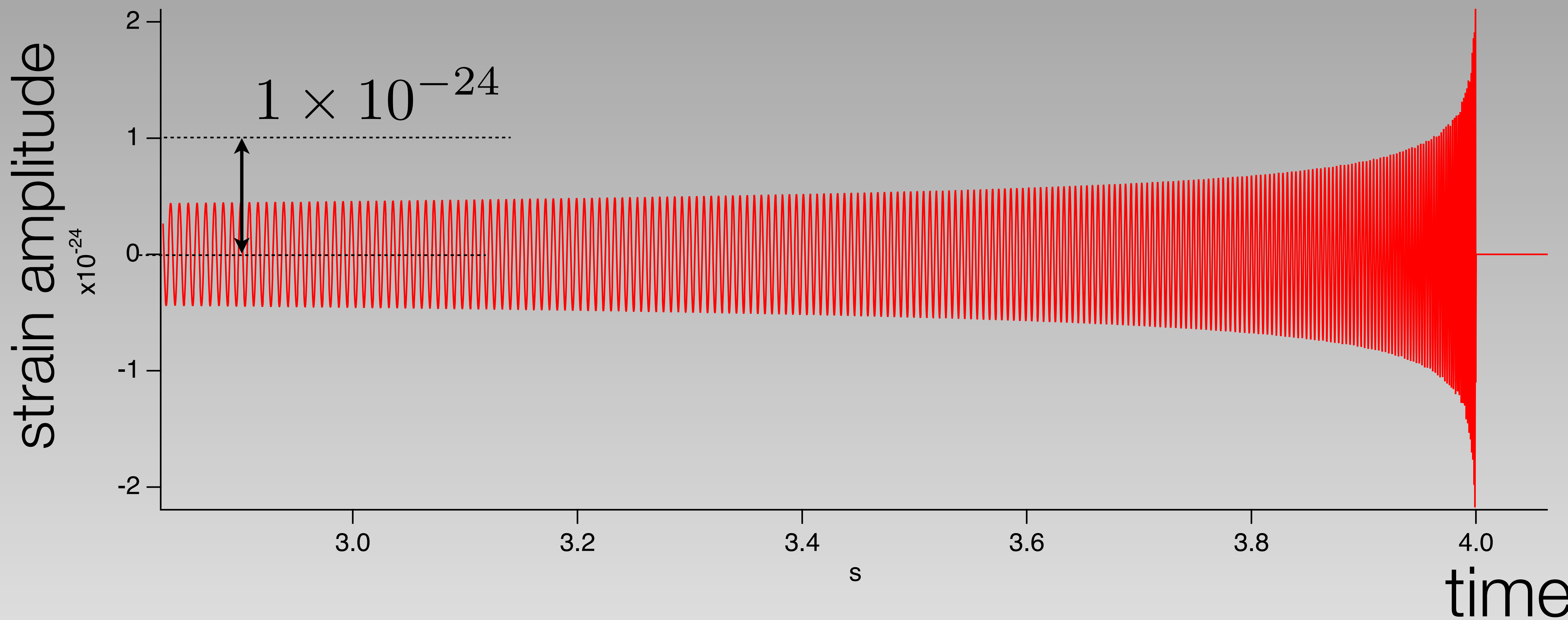
**(& Unknown sources...)**

# Coalescence of neutron star binary (NS-NS)



- small amplitude
- Waveform can determine masses and absolute amplitude.

--> ***'standard candle'***

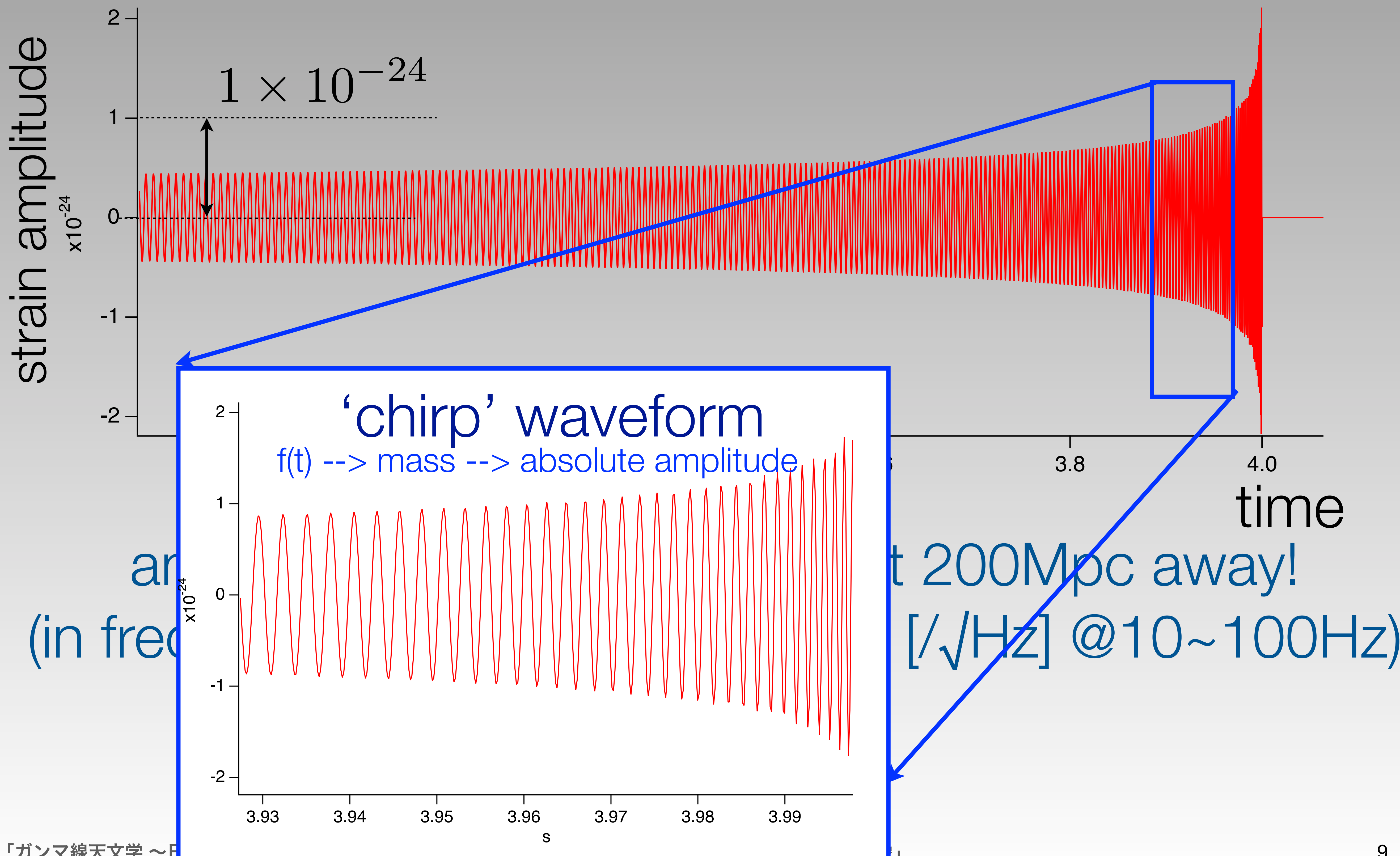



amplitude ~$10^{-24}$ for NS-NS at 200Mpc away!

(in frequency spectrum, ~$10^{-22\sim-23}$ [/√Hz] @10~100Hz)

- small amplitude
- Waveform can determine masses and absolute amplitude.

--> ‘***standard candle***’

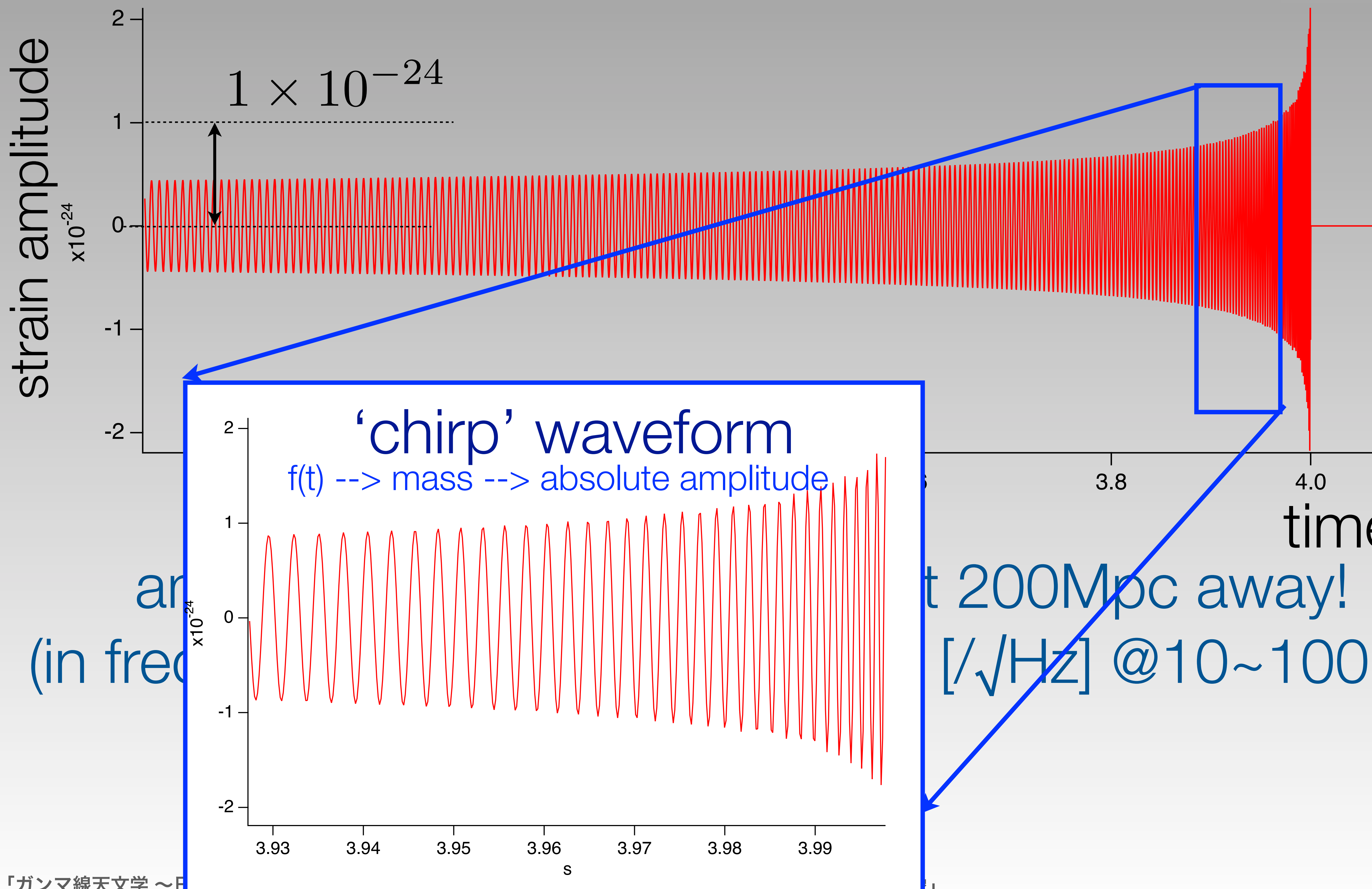



ar... t 200Mpc away!

(in fre... [/√Hz] @10~100Hz)

- small amplitude
- Waveform can determine masses and absolute amplitude.

--> '***standard siren***'




ar… t 200Mpc away!

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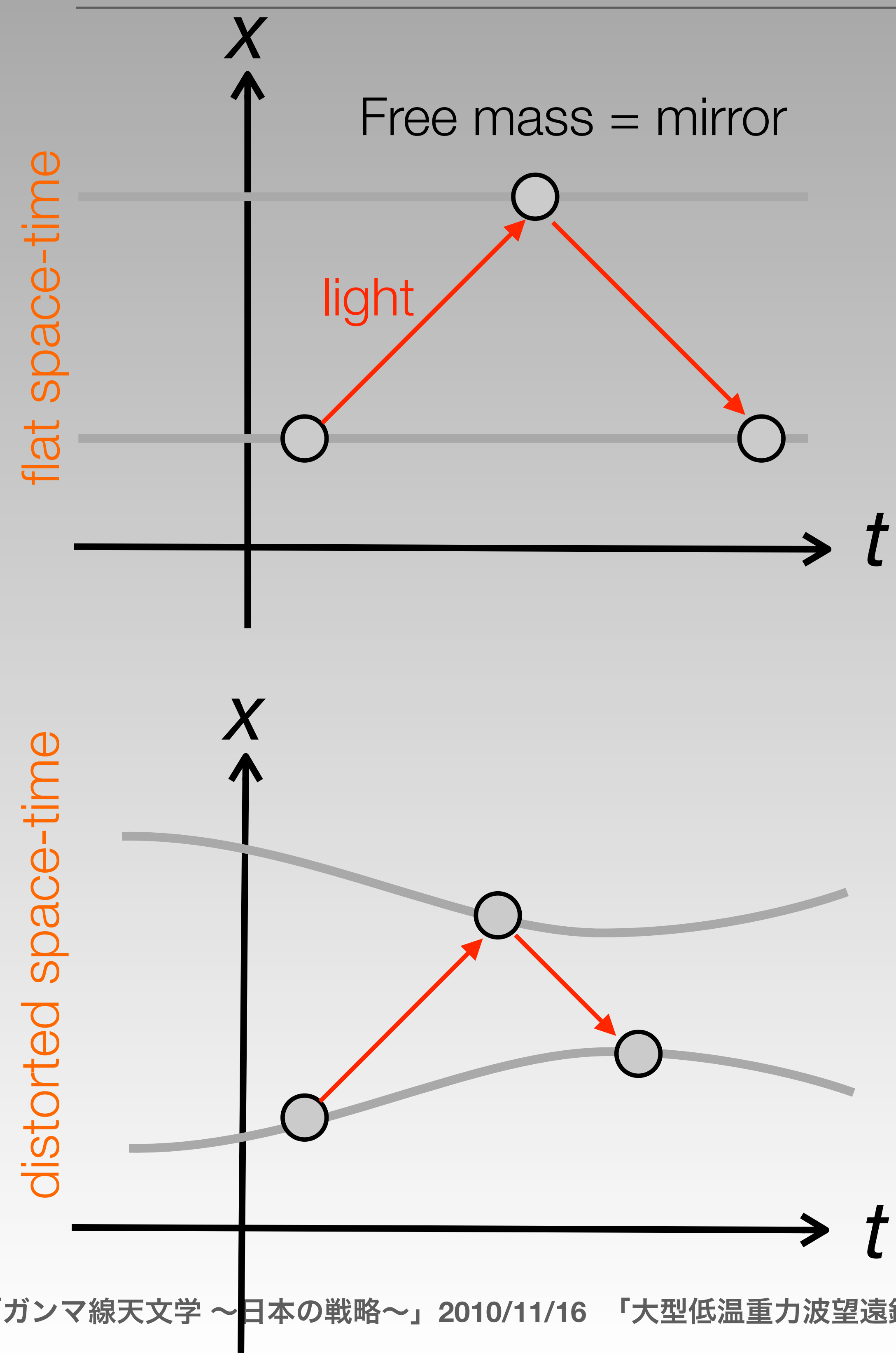
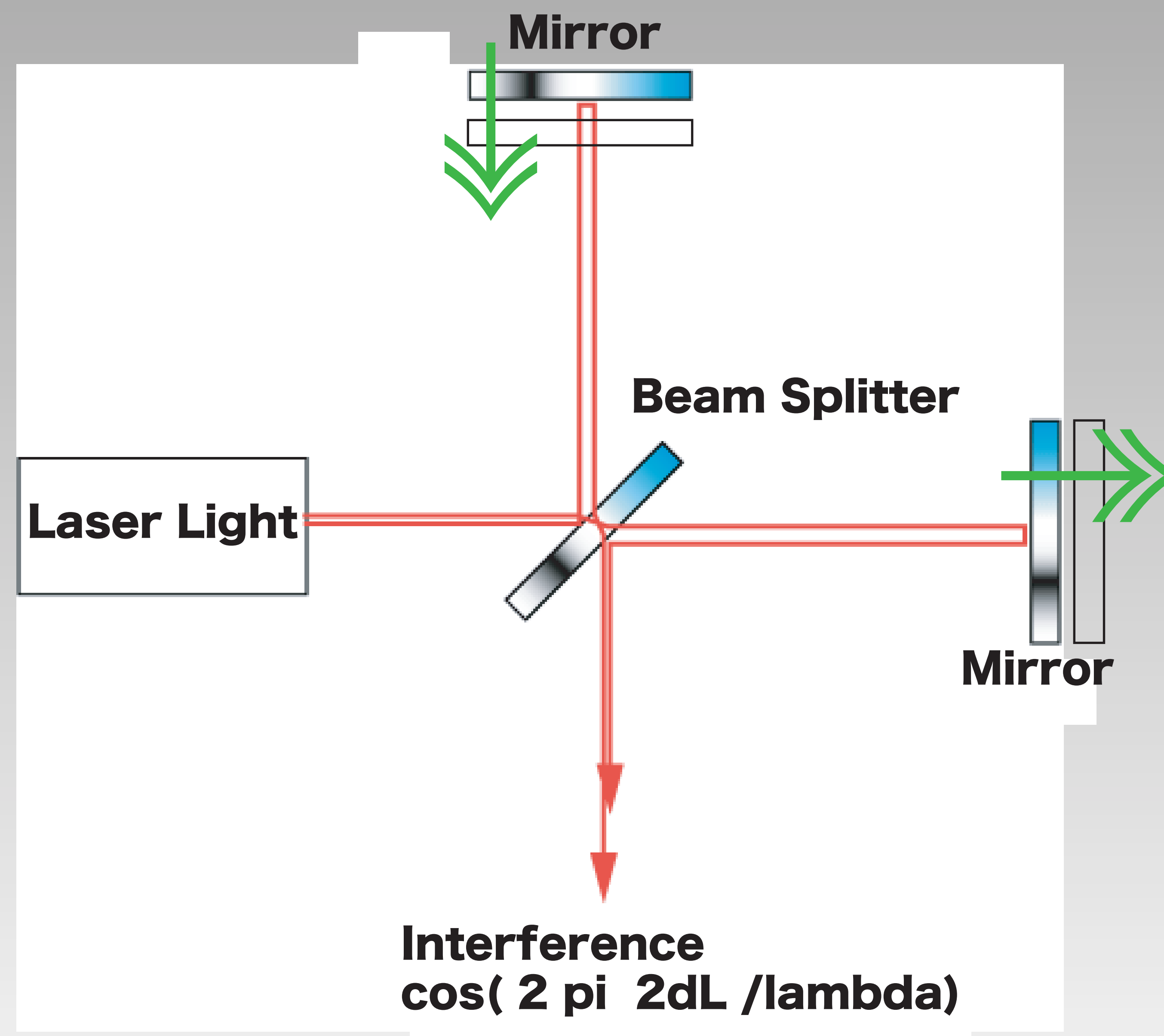
# How to detect GW :
# Free Test Masses & Laser Interferometer




Michelson Interferometer

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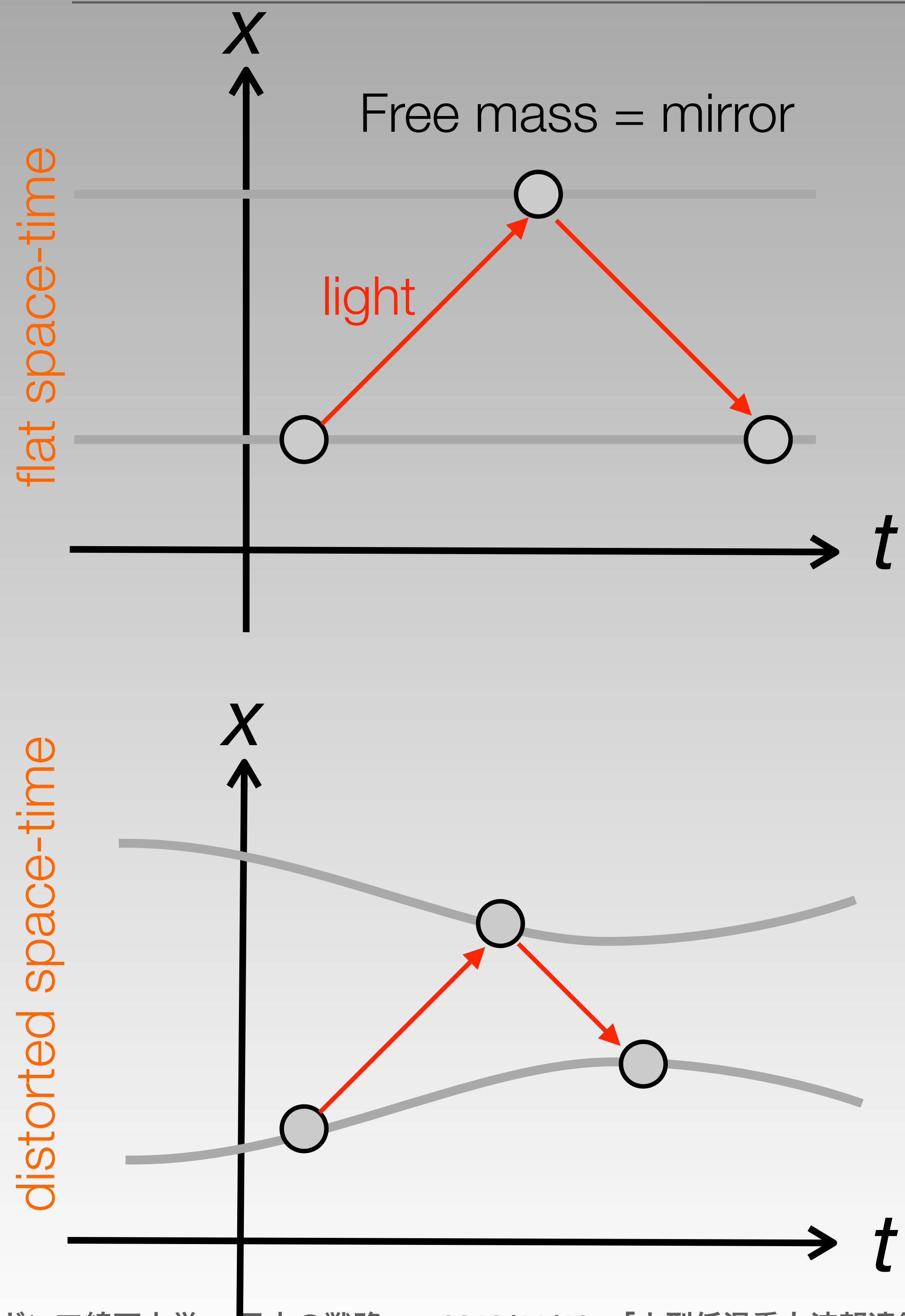


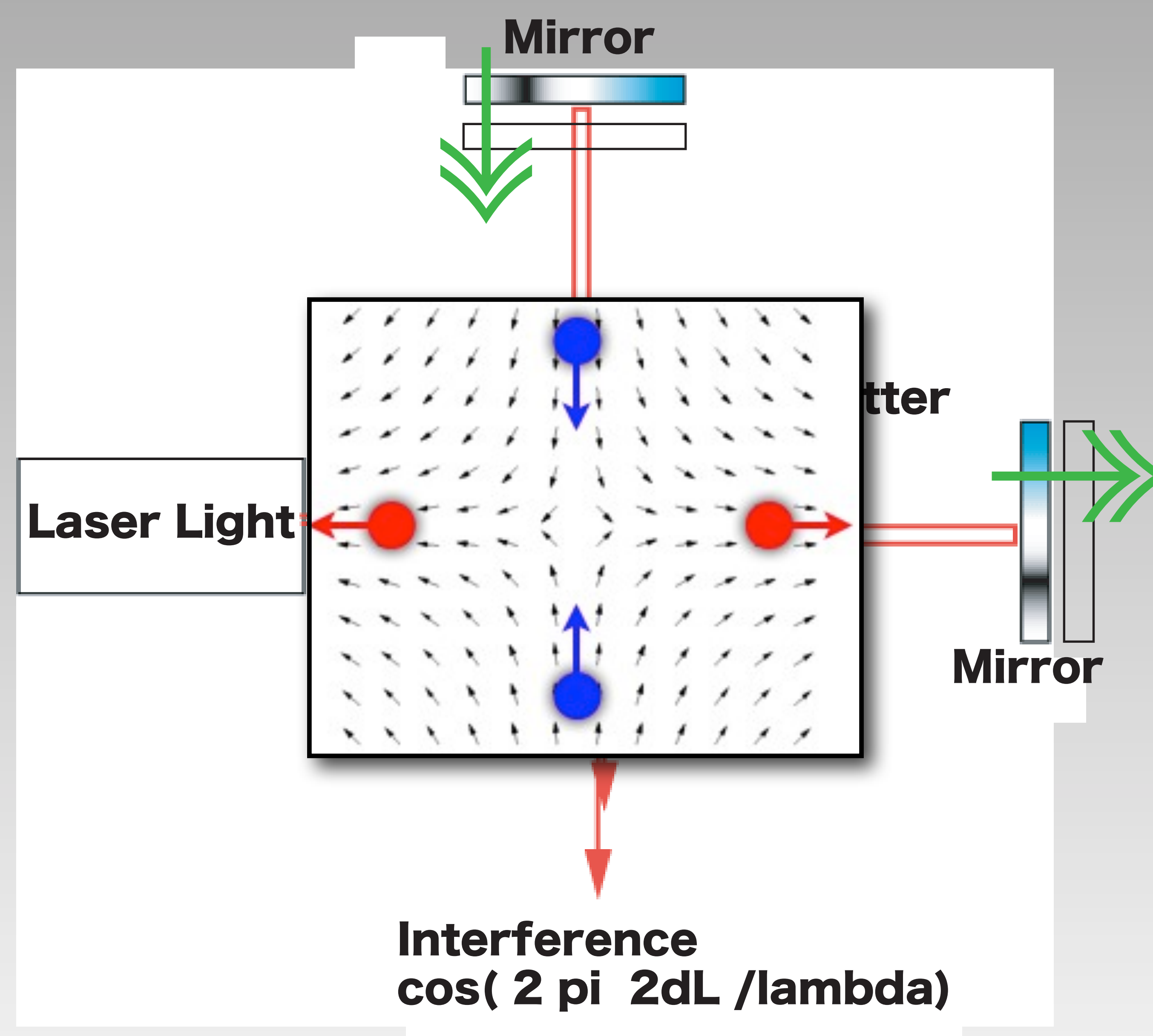


Michelson Interferometer

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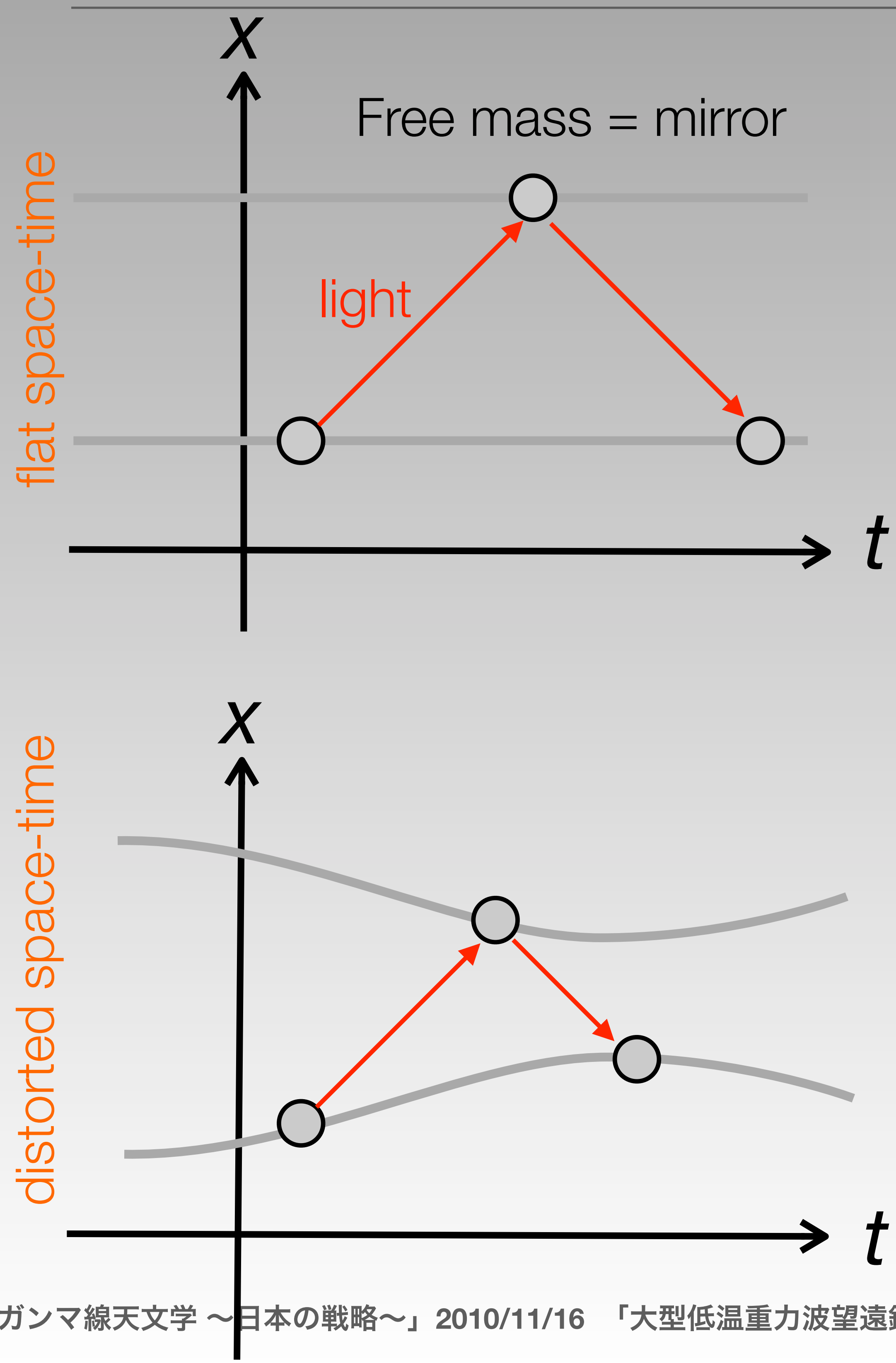
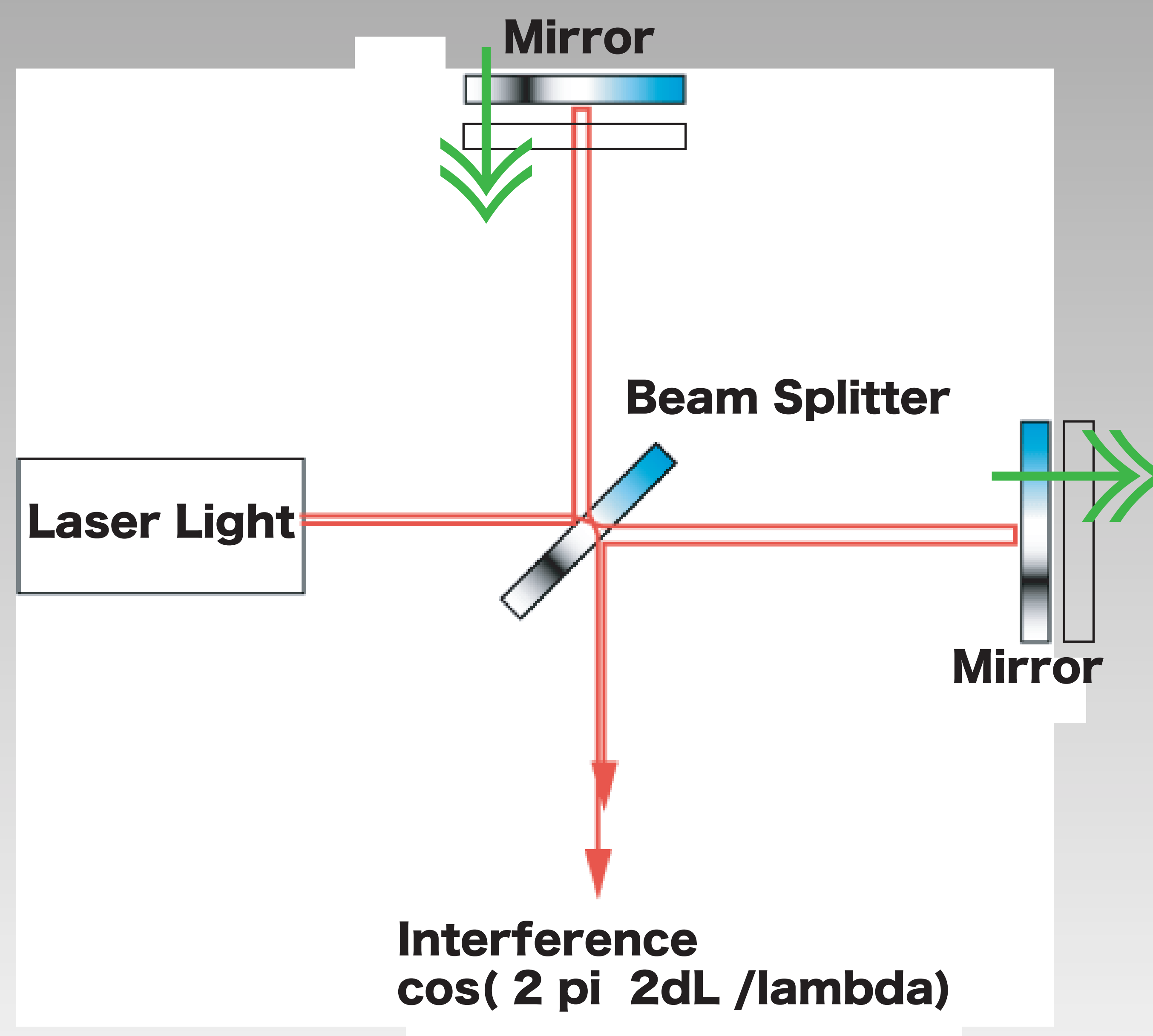



Michelson Interferometer

# Schematic Figure

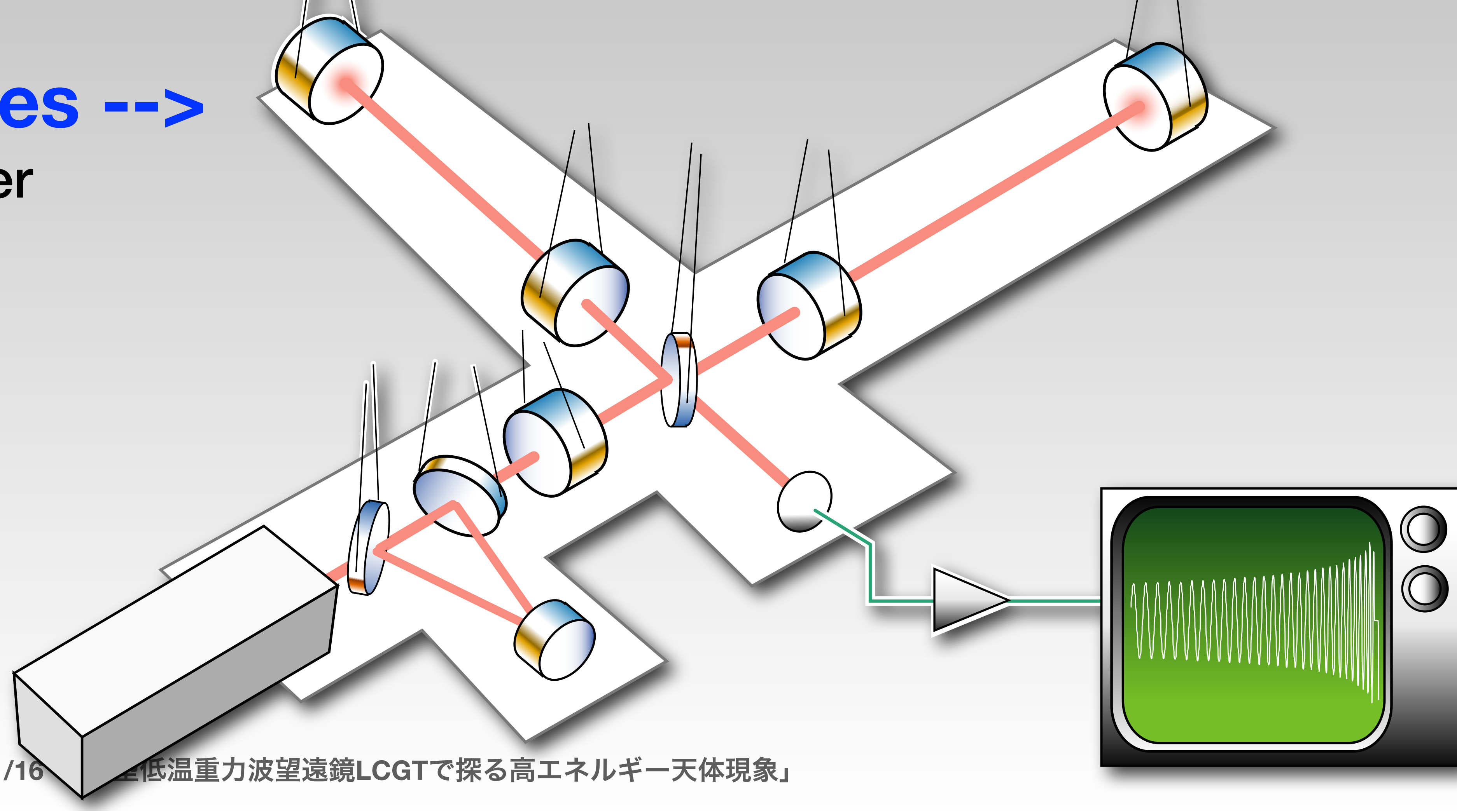
**Free mass --> suspended mirror**

**To integrate strain ‘h’ --> long baseline arms.** $h = \frac{\delta l}{\ell}$

**Limited size --> Folding arms / Storage cavity**

**Against noises -->**

- high power laser
- Cooling
- etc..



# LCGT
# (Large-scale Gravitational wave Telescope)

## Underground
- in Kamioka, Japan

  Silent & Stable environment

## 3km baseline

## Cryogenic Mirror
- 20K
- saffhire substrate


Plan

2010　: construction *start now!*

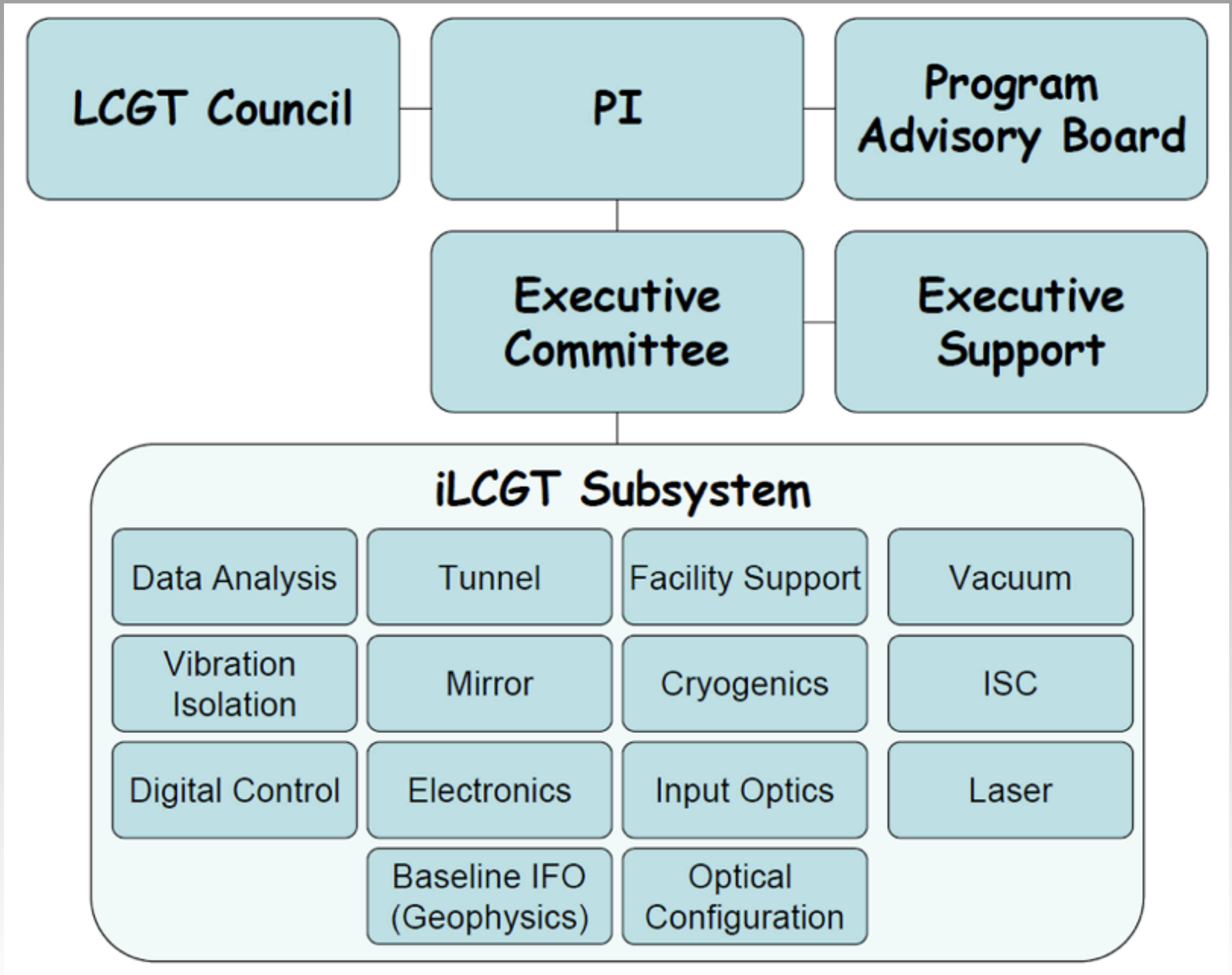
2014　: first run in normal temperture

2017- : observation with cryogenic mirror

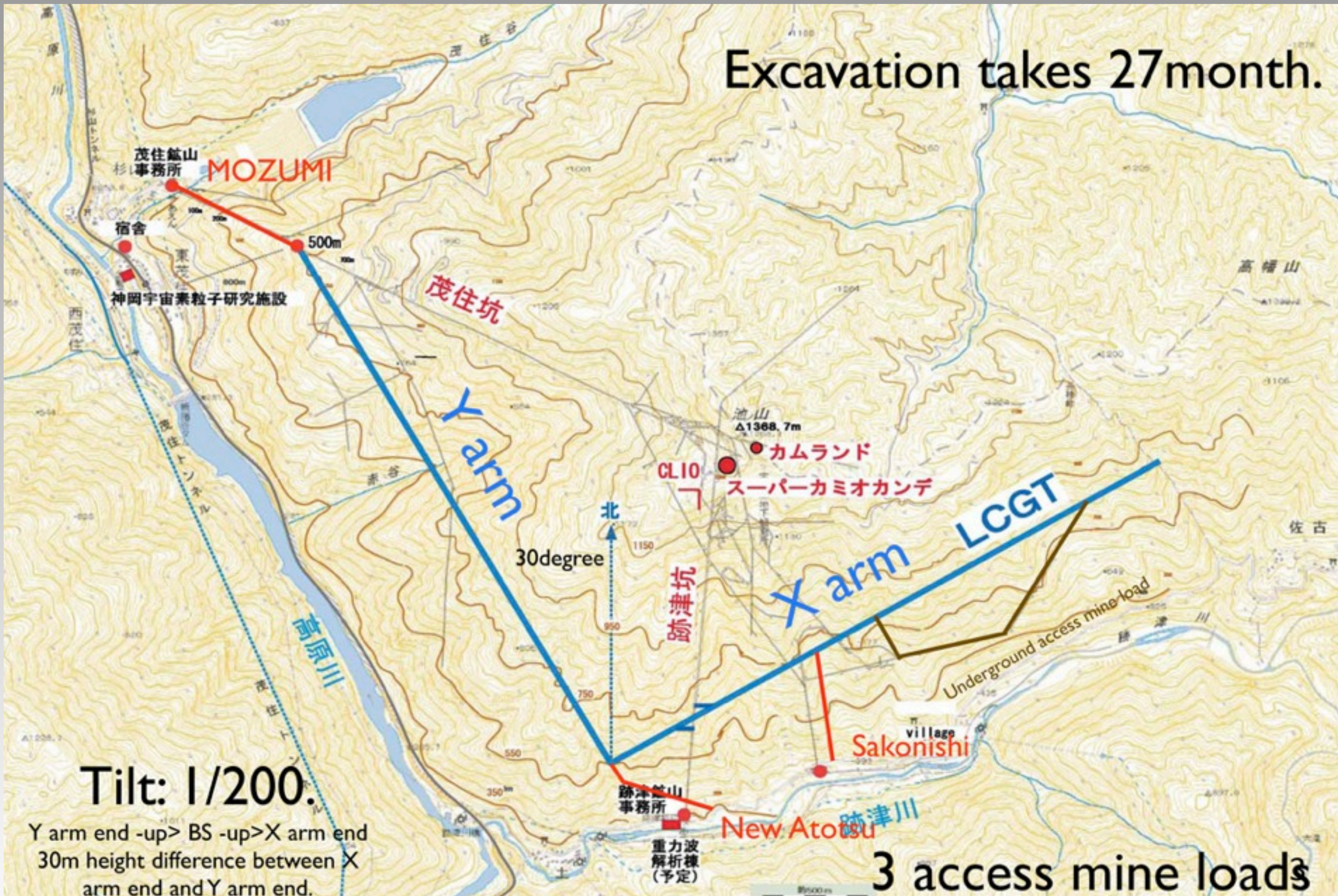
# LCGT collaboration

K Kuroda[1], I Nakatani[1], M Ohashi[1], S Miyoki[1], T Uchiyama[1], O Miyakawa[1], H Ishiduka[1], K Agatsuma[1], T Saito[1], M-K Fujimoto[2], S Kawamura[2], R Takahashi[2], D Tatsumi[2], A Ueda[2], M Fukushima[2], H Ishizaki[2], Y Torii[2], S Sakata[2], A Nishizawa[2], K Kotake[2], Y Sekiguchi[2], A Yamamoto[3], Y Saito[3], T Haruyama[3], T Suzuki[3], N Kimura[3], T Tomaru[3], K Ioka[3], K Tsubono[4], Y Aso[4], K Ishidoshiro[4], K Takahashi[4], W Kokuyama[4], K Okada[4], S Kawara[4], N Matsumoto[4], F Takahashi[4], A Taruie[4], J Yokoyama[4], K Ueda[5], H Yoneda[5], K Nakagawa[5], M Musha[5], N Mio[6], S Moriwaki[6], N Omae[6], T Ogikubo[6], Y Tokuda[6], A Araya[7], A Takamori[7], K Izumi[8], N Kanda[9], K Nakao[9], S Sato[10], S Telada[11], T Takatsuji[11], Y Bito[11], S Nagano[12], H Tagoshi[13], T Nakamura[14], N Seto[14], M Ando[14], M Sasaki[15], M Shibata[15], T Tanaka[15], N Sago[15], E Nishida[16], Y Wakabayashi[16], T Shintomi[17], H Asada[18], Y Itho[19], T Futamase[19], K Oohara[20], M Saijo[21], T Harada[21], S Yamada[22], N Himemoto[23], H Takahashi[24], Y Kojima[25], K Uryu[26], K Yamamoto[27], F Kawazoe[27], A Pai[27], K Hayama[27], Y Chen[28], K Kawabe[28], K Arai[28], K Somiya[28], M.E.Tobar[29], D Blair[29], J Li[29], C Zhao[29], L Wen[29], J Warren[30], H Nakano[31], R Stuart[32], M Szabolcs[33], K Kokeyama[34], Z-H Zhu[35], SDhurandhar[36], S Mitra[36], H Mukhopadhyay[36], V Milyukov[37], L Baggio[38], Y Zhang[39], J Cao[40], C-G Huang[41], W-T Ni[42], S-S Pan[43], S-J Chen[43], K Numata[44]

# LCGT collaboration



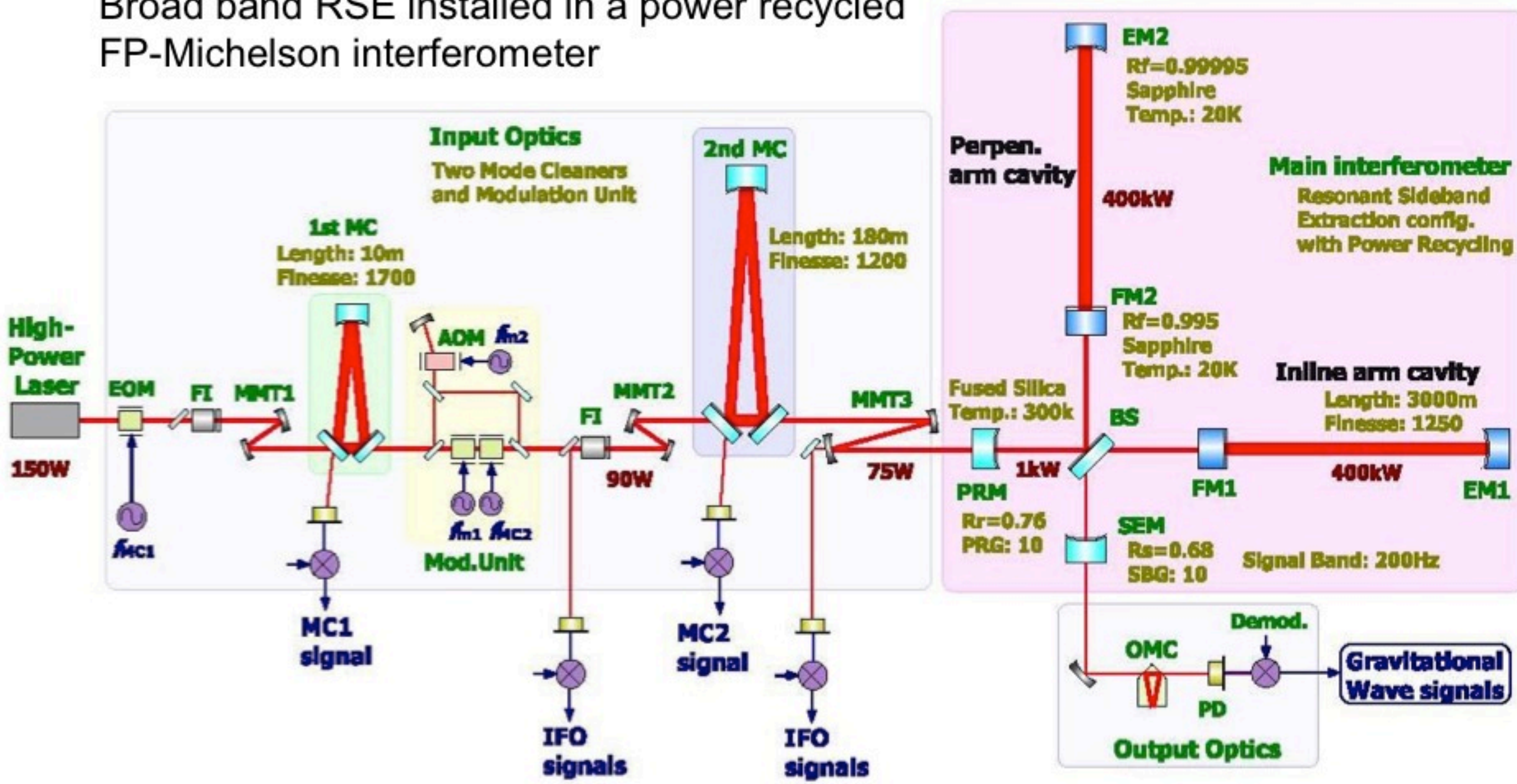
# Site



Excavation takes 27month.
茂住鉱山
事務所
MOZUMI
宿舎
500m
神岡宇宙素粒子研究施設
茂住坑
Y arm
池山
Δ1368. 7m
カムランド
CLIO
スーパーカミオカンデ
北
30degree
跡津坑
X arm
LCGT
Underground access mine load
高原川
village
Sakonishi
跡津鉱山
事務所
New Atotsu
跡津川
重力波
解析棟
(予定)
Tilt: 1/200.
Y arm end -up> BS -up>X arm end
30m height difference between X
arm end and Y arm end.
3 access mine loads

# Optical design

Broad band RSE installed in a power recycled FP-Michelson interferometer

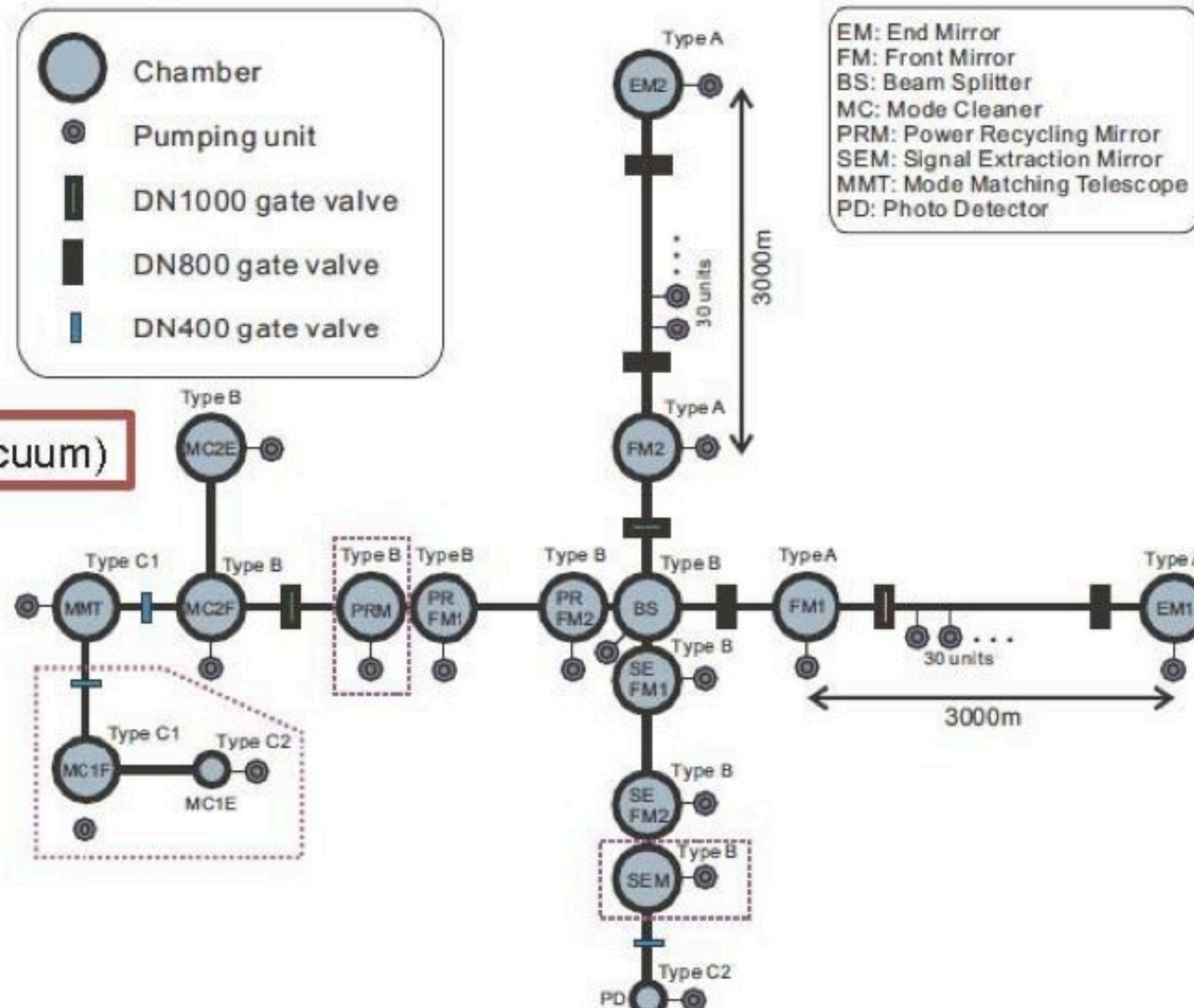



Re-design is under going ;for example
---removing the 180 m long mode cleaner cavity
---flexibility change of possible adoption of detuned RSE

# Vacuum System

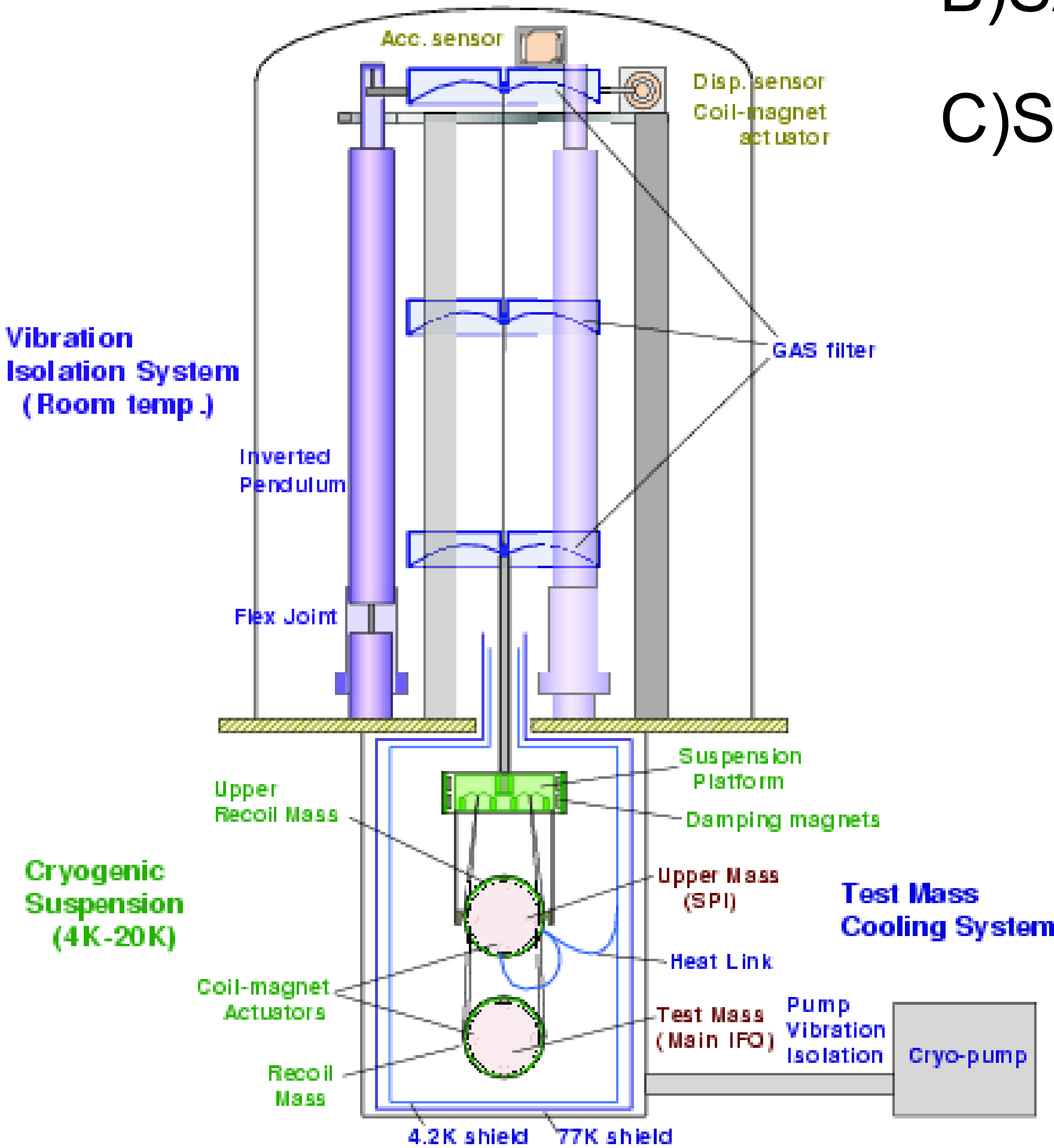
** for reducing noise due to a residual gas effect
** for maintenance minimizing

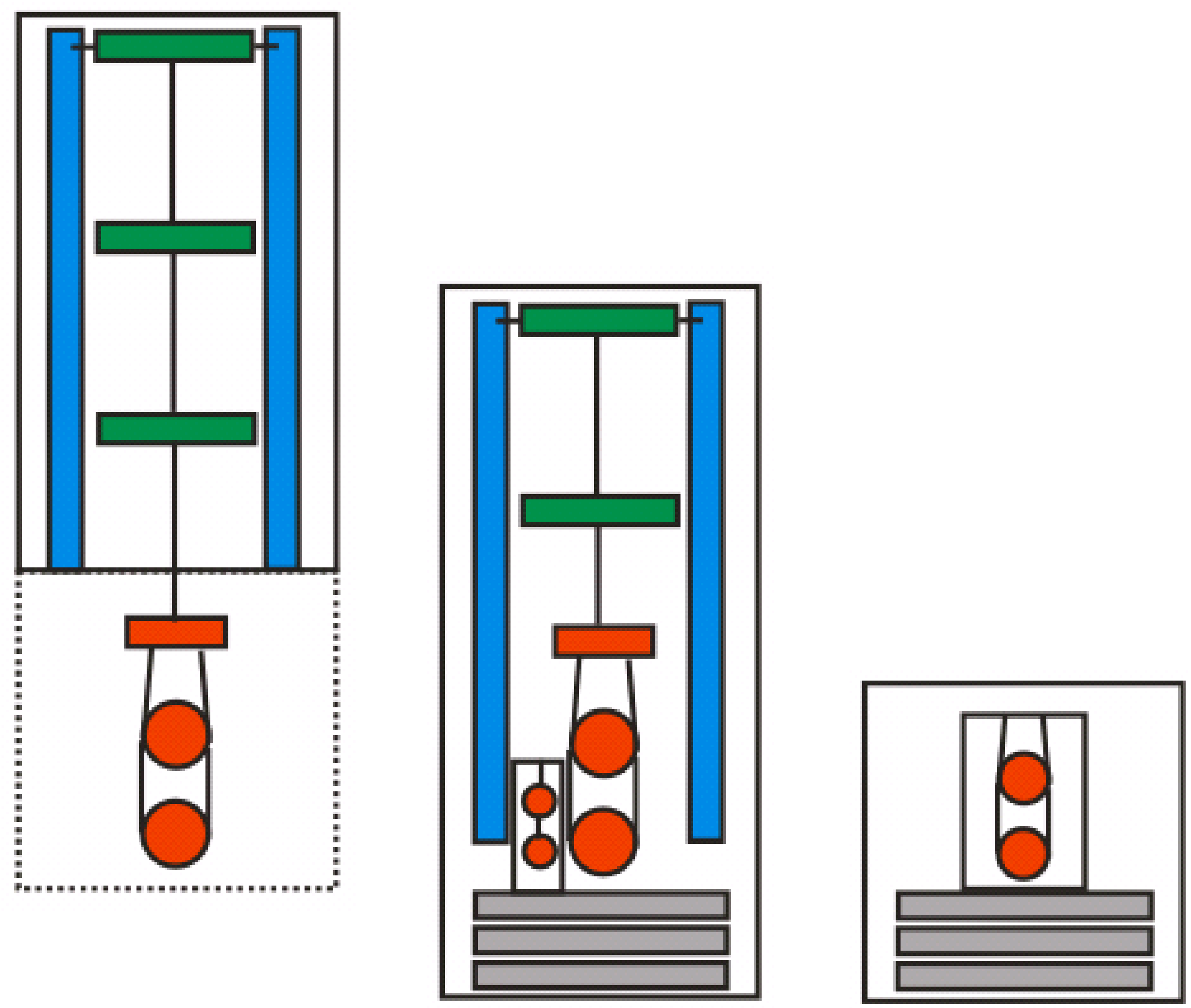
UHV (ultra high vacuum)



# Design of anti-vibration system

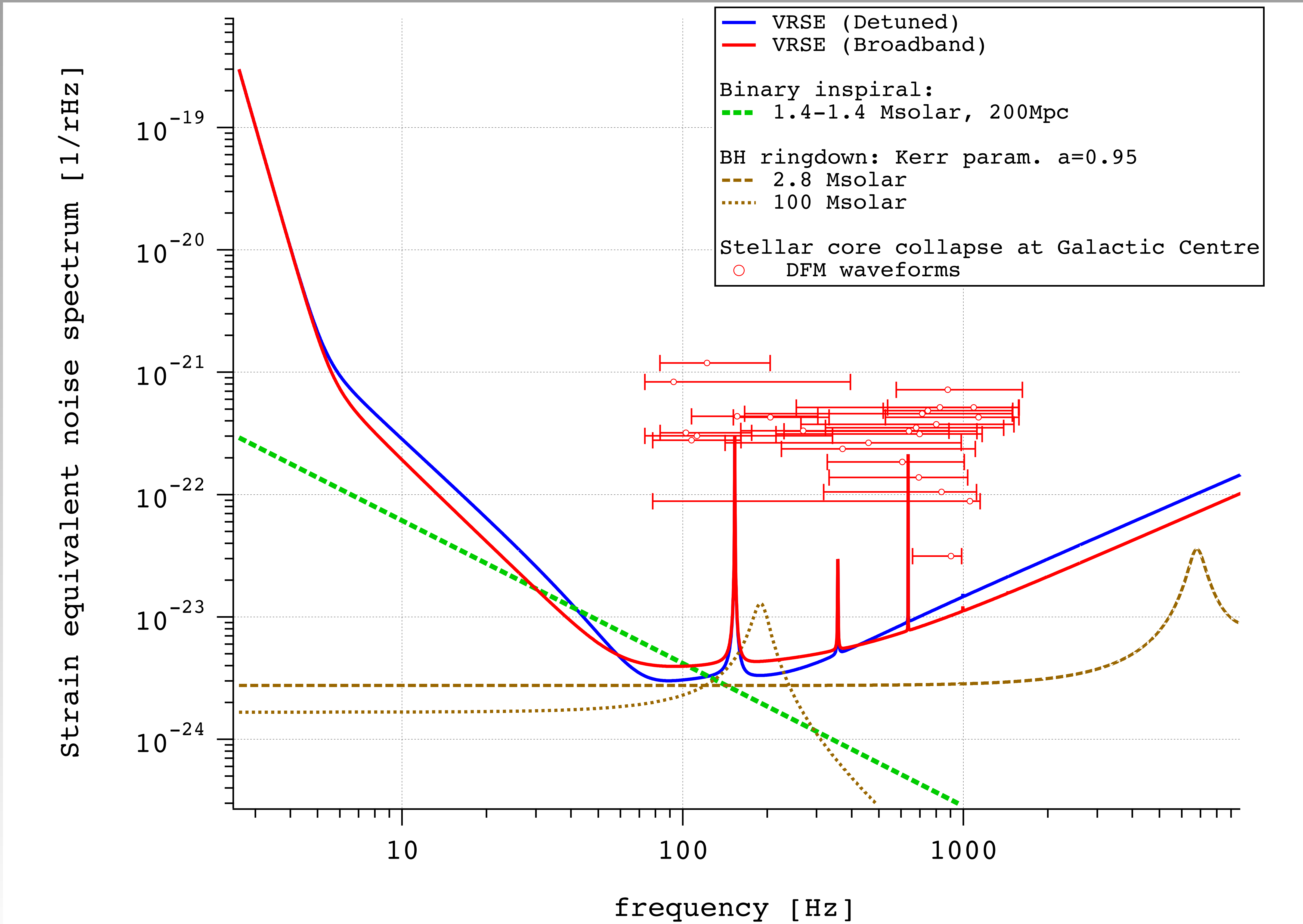
A)SAS(GASF 3stage)+cryo-sus:
FM1、FM2、EM1、EM2
B)SAS(GASF 2stage)+non-cryo:
BS、PRM、SEM、FM、MC2F、MC2E
C)STACK+2stages: MC1F、MC1E、MMT、PD



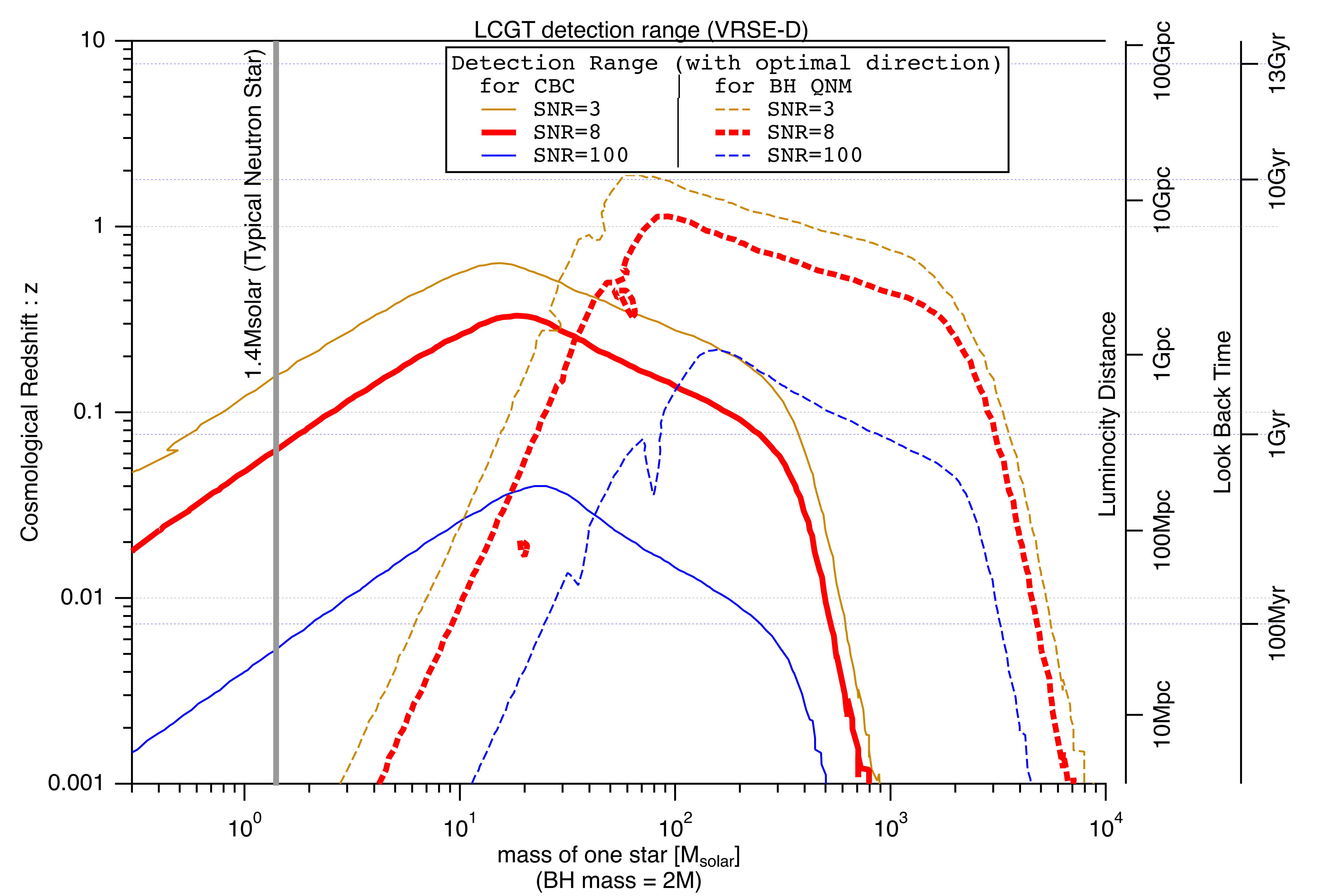



A B C

# Design Sensitivity of LCGT

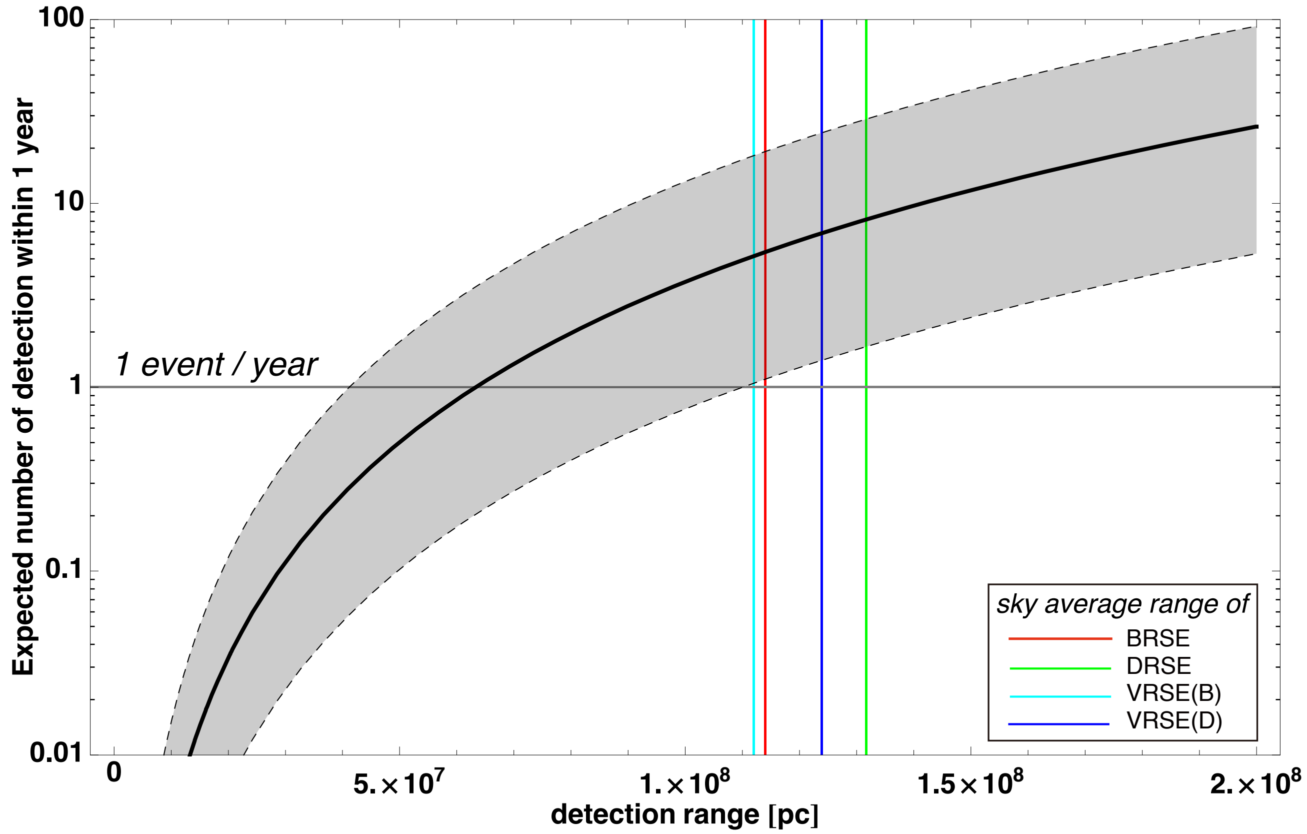


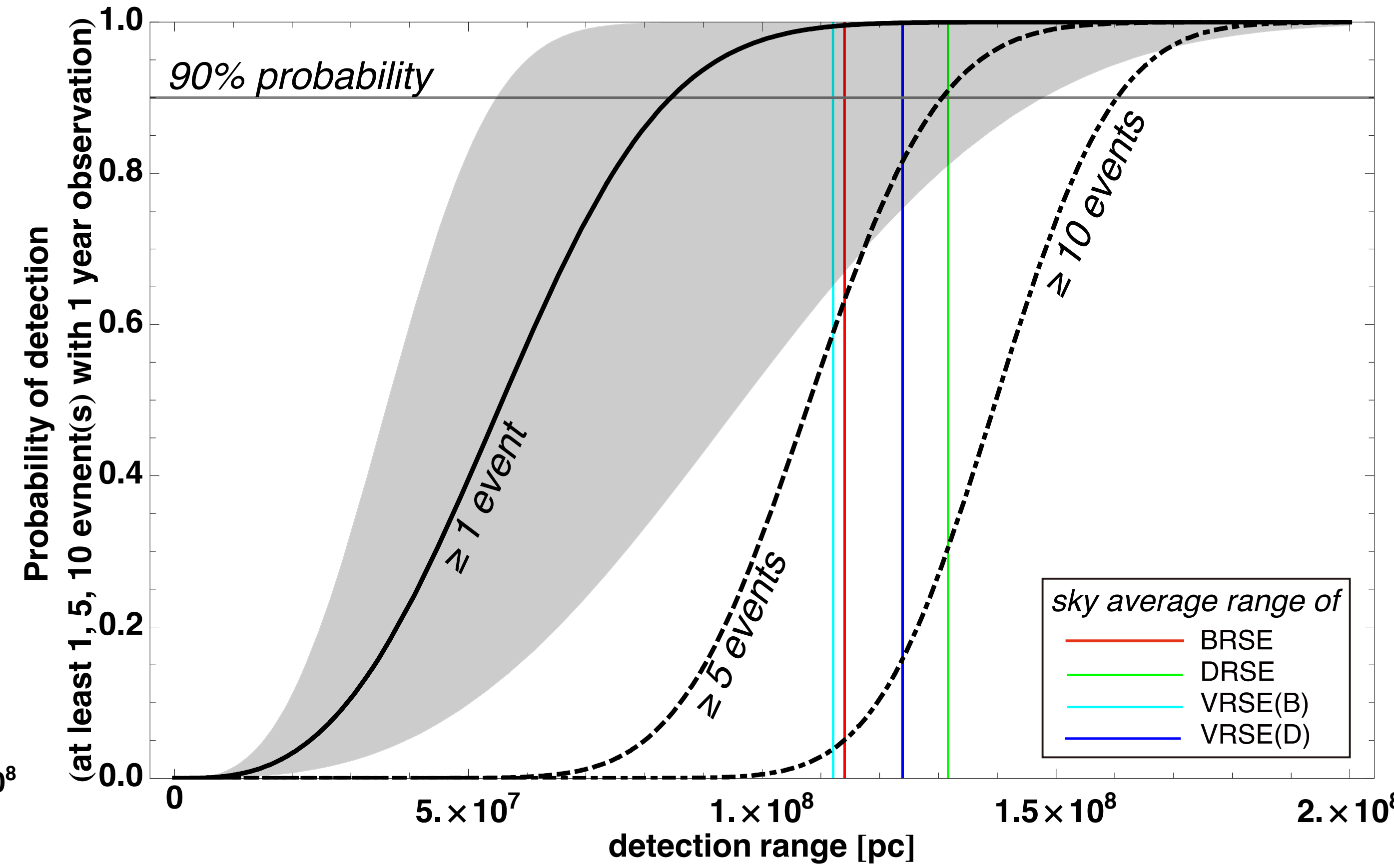
# Detection Range for Compact Binary and BH QNM



# Probability of Detection

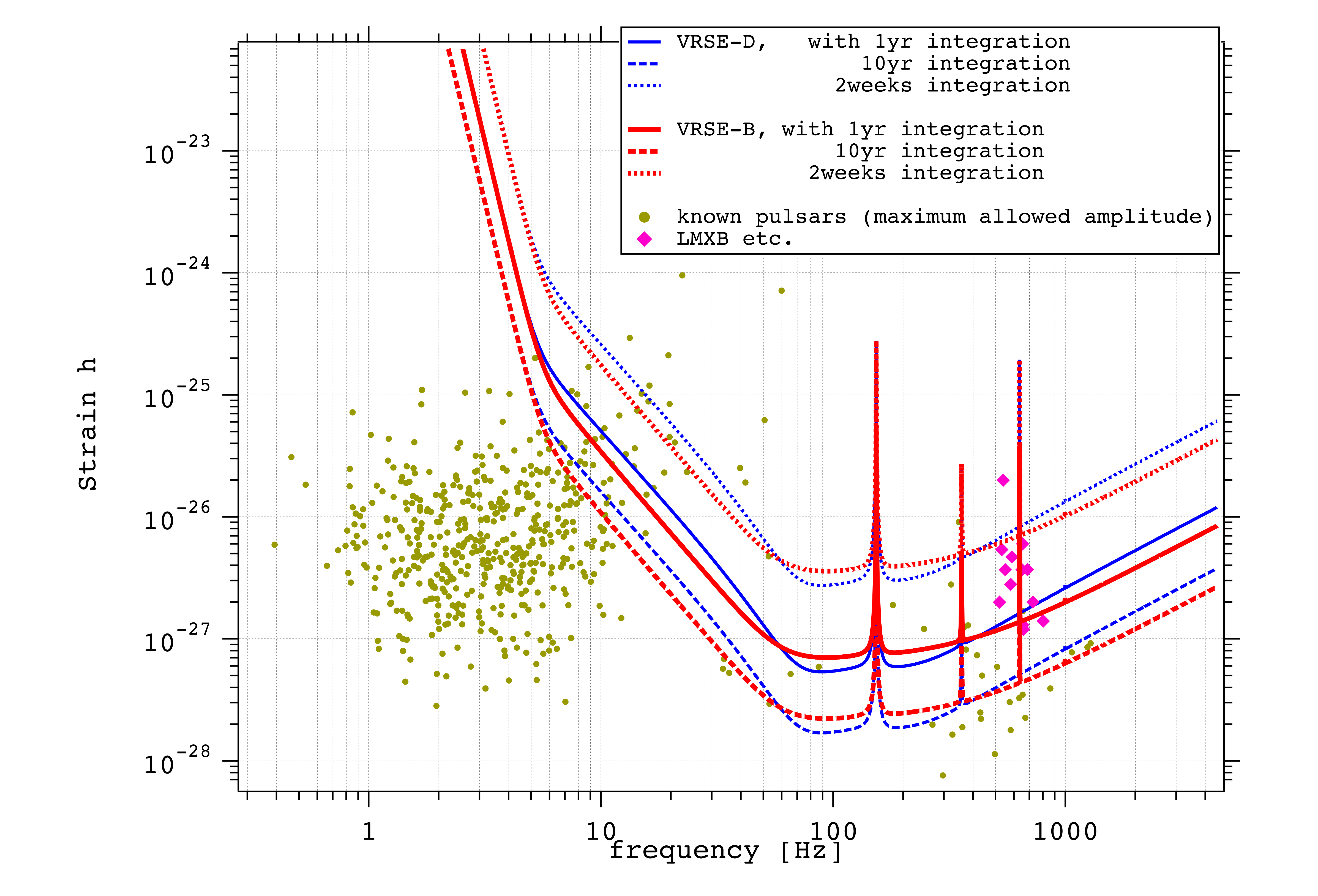
BW working group



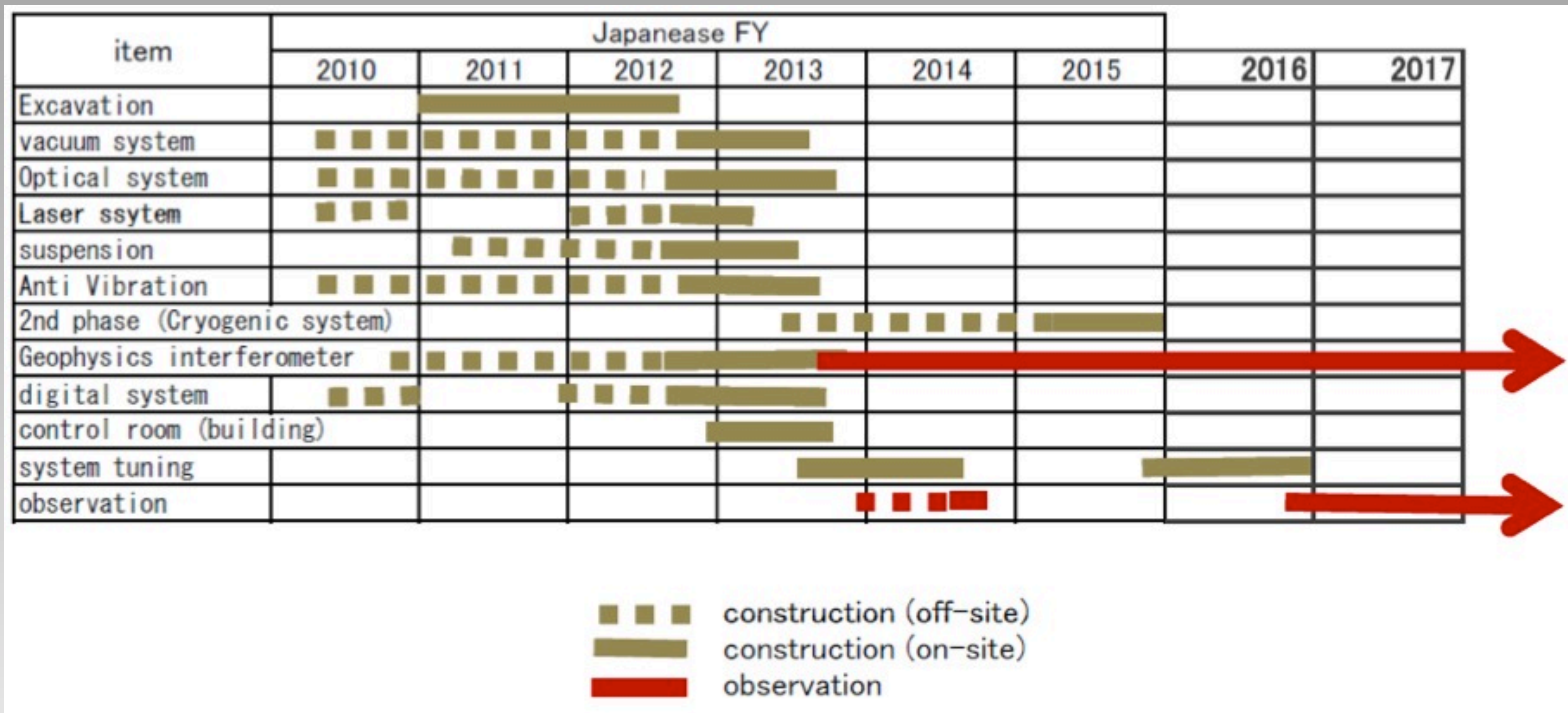




| | |
|---|---|
| NS-NS Detection Range (sky average) | 123 Mpc |
| (optimal direction) | 281 Mpc |
| Expected # of events | 6.9 $^{+17.3}_{-5.5}$ events/year |
| Probability of detection at least one event | 99.9 % for one year |
| 90% for 1st event | 4 months |

# Sensitivity for Continuous GW

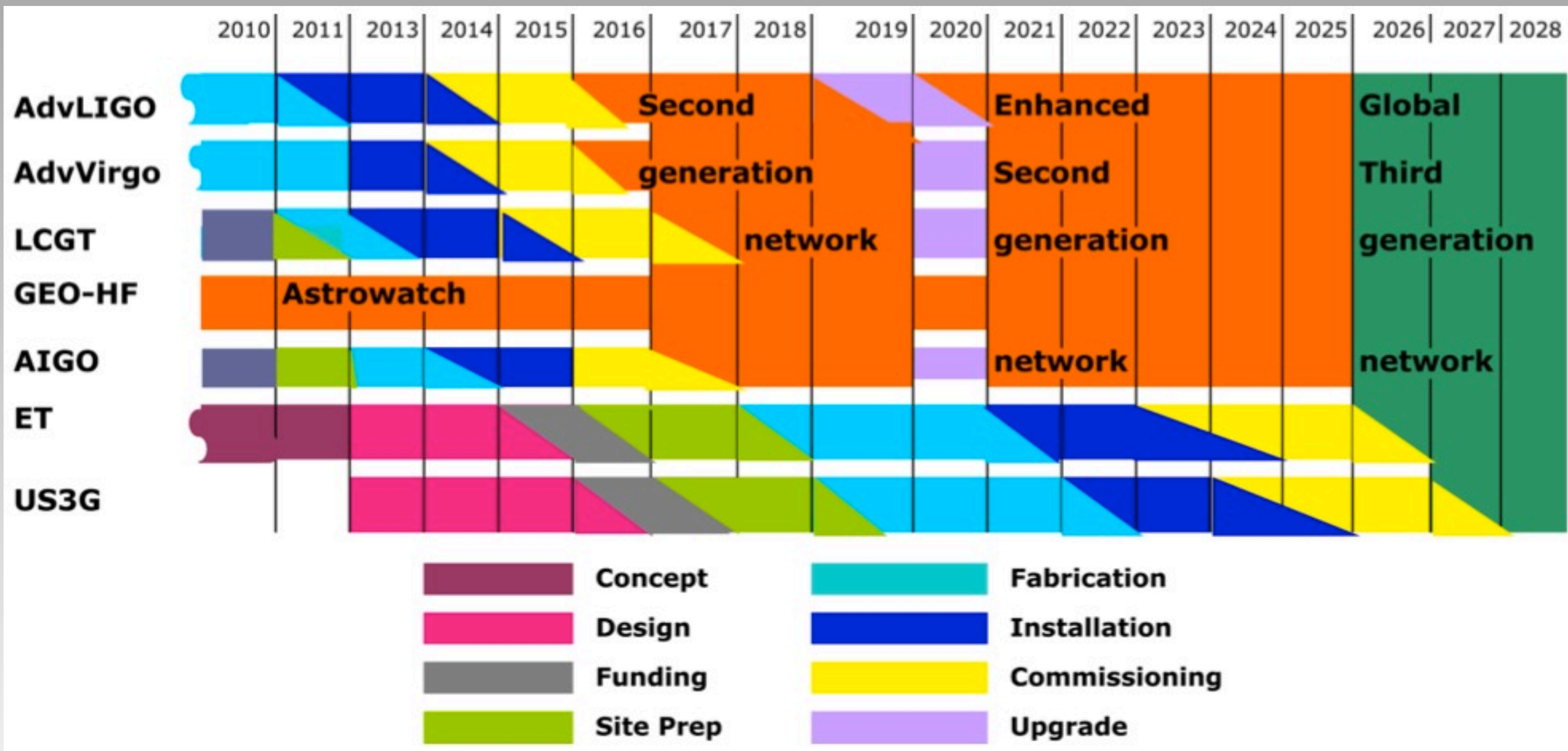


# Schedule (Construction & Observation)




The construction/observation plan is in 2 stages:
In 2014, non-cryogenic observation.
Full observation with the cryogenic system, at the beginning of 2017.

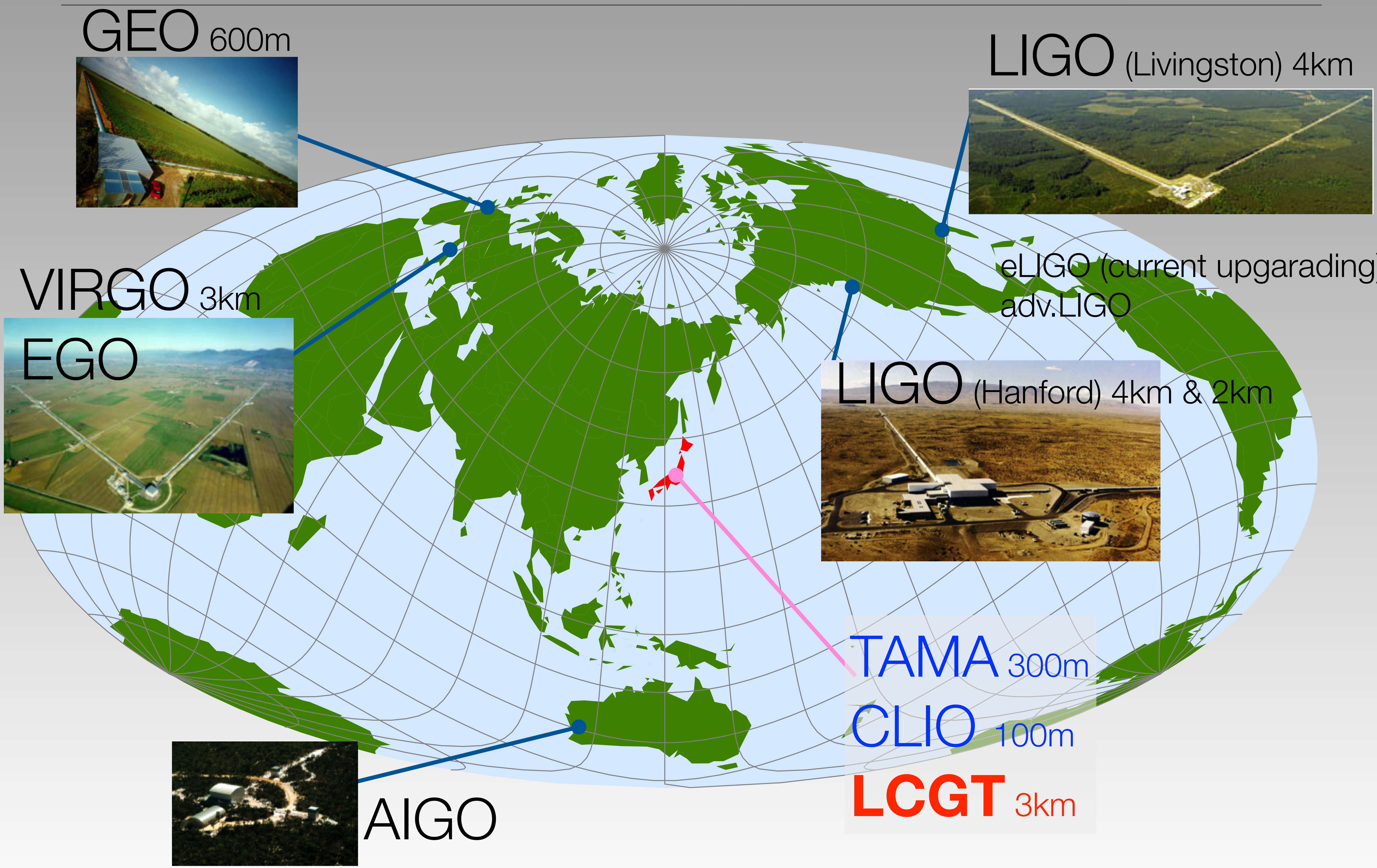
# GWIC (Gravitational Wave International Committee) RoadMap



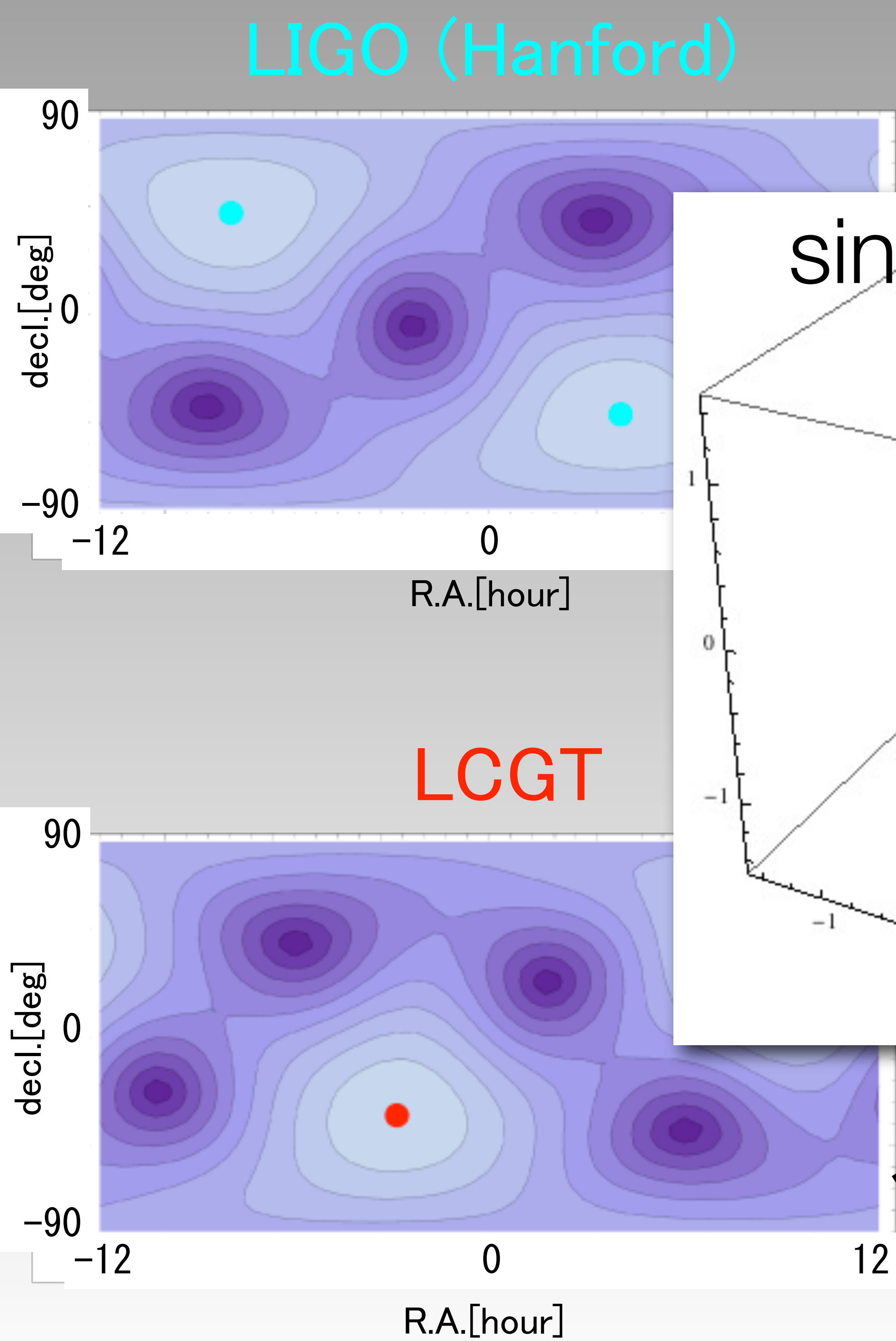

https://gwic.ligo.org/

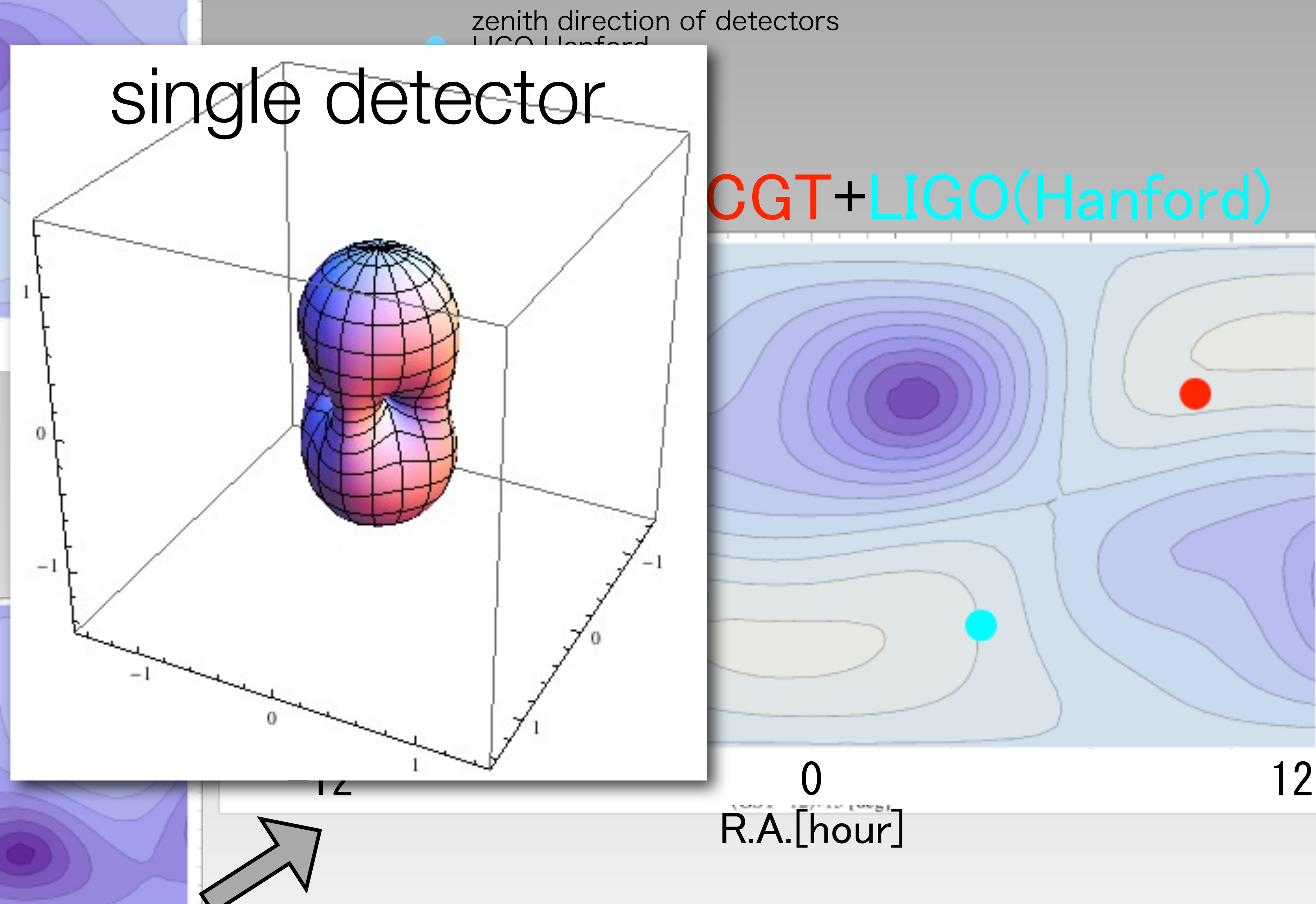
https://gwic.ligo.org/roadmap/Roadmap_100814.pdf

# World Wide Network of GW Observatories



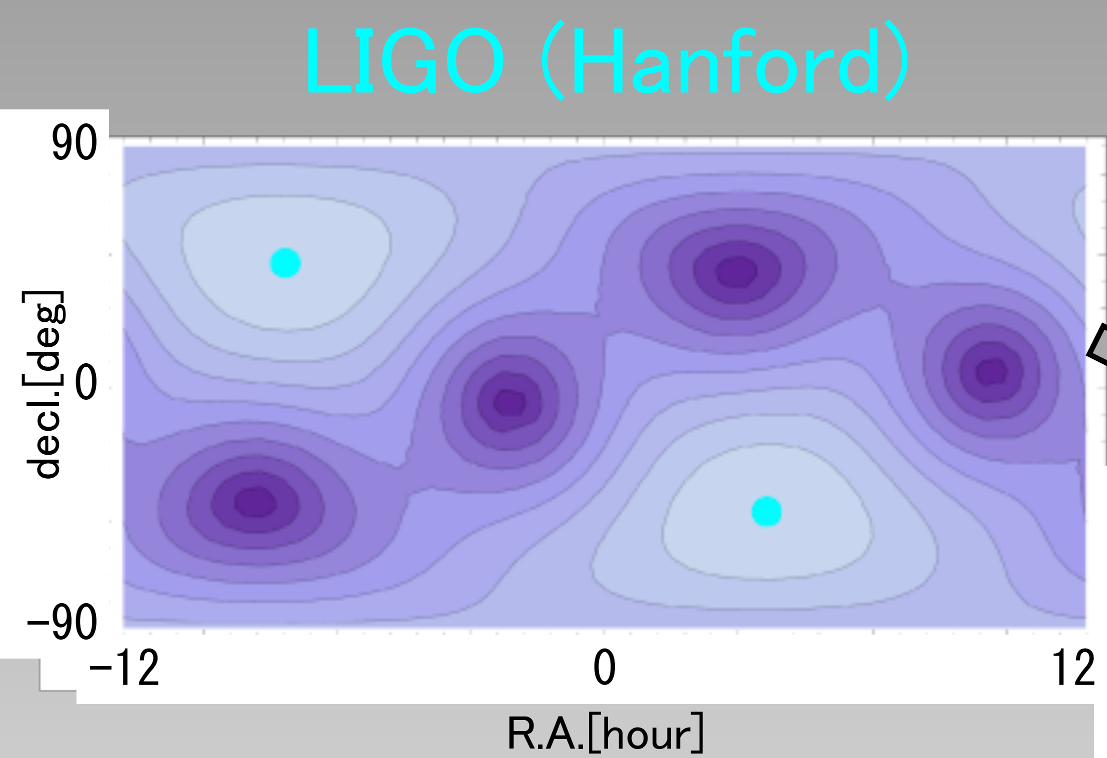
# Sky coverage by detector network

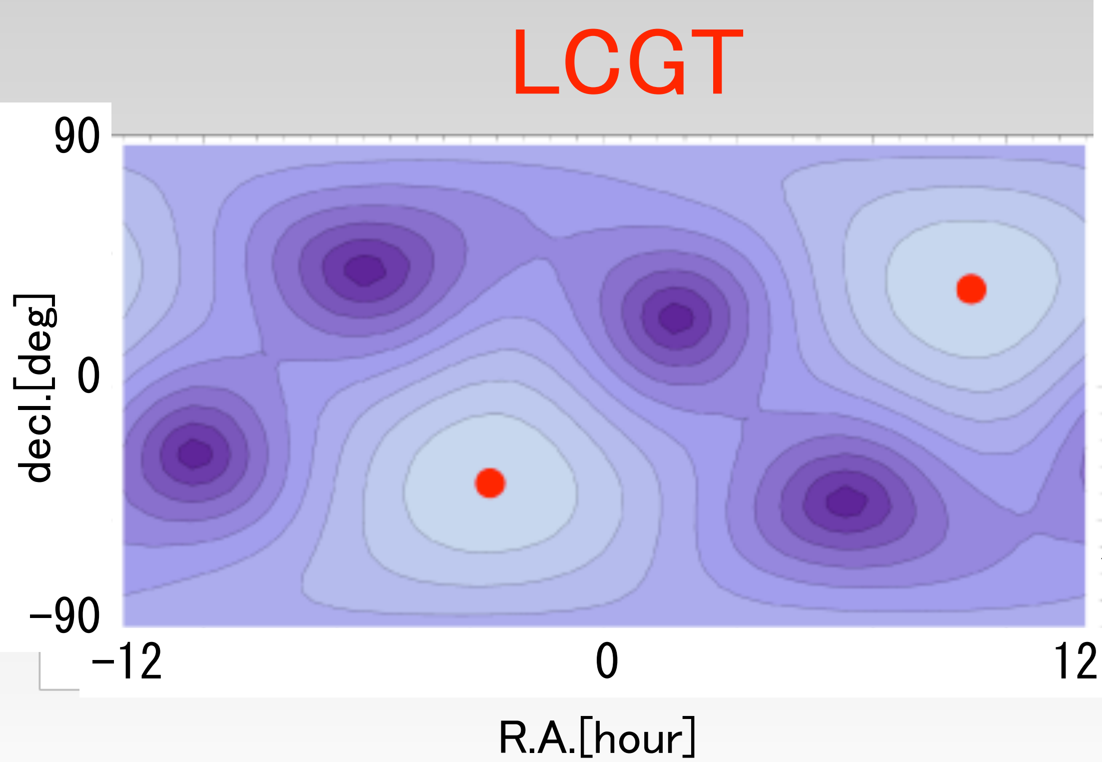


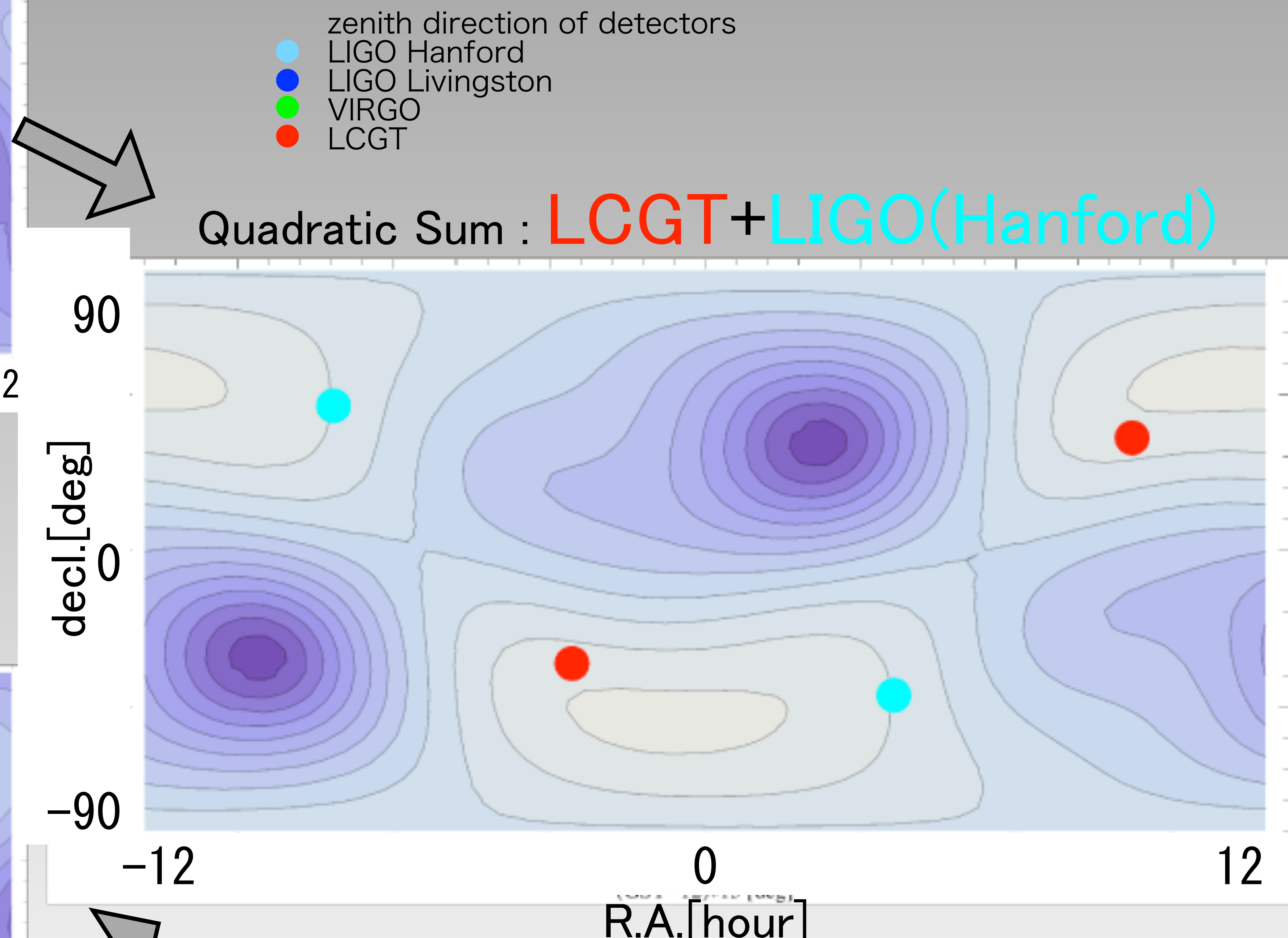




**LCGT will make important role in the network, with a complemental sensitivity map.**

# Sky coverage by detector network

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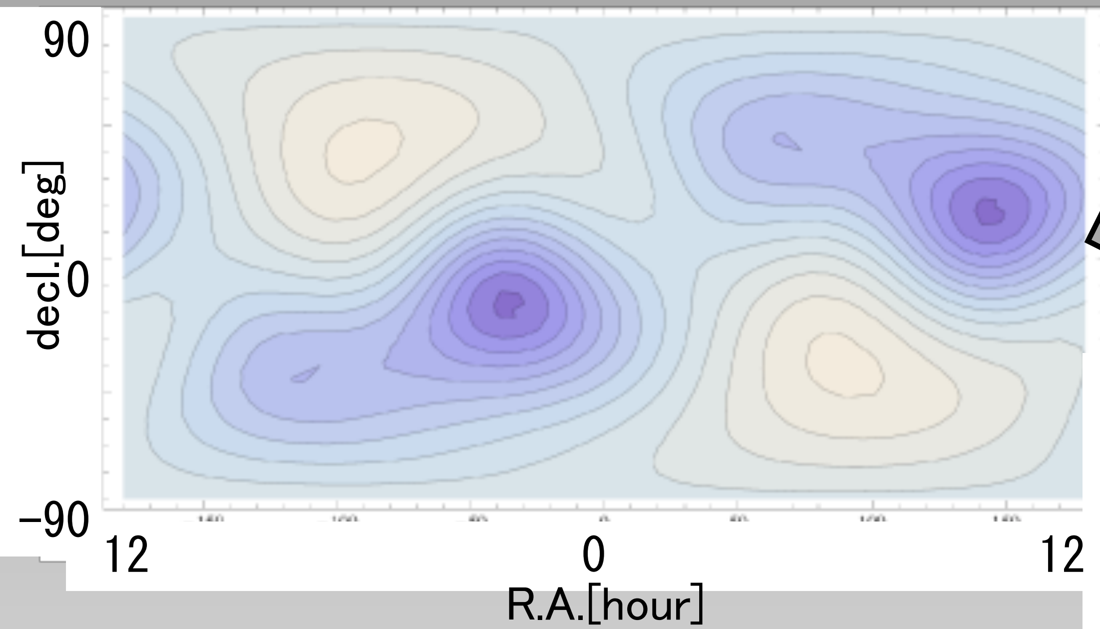
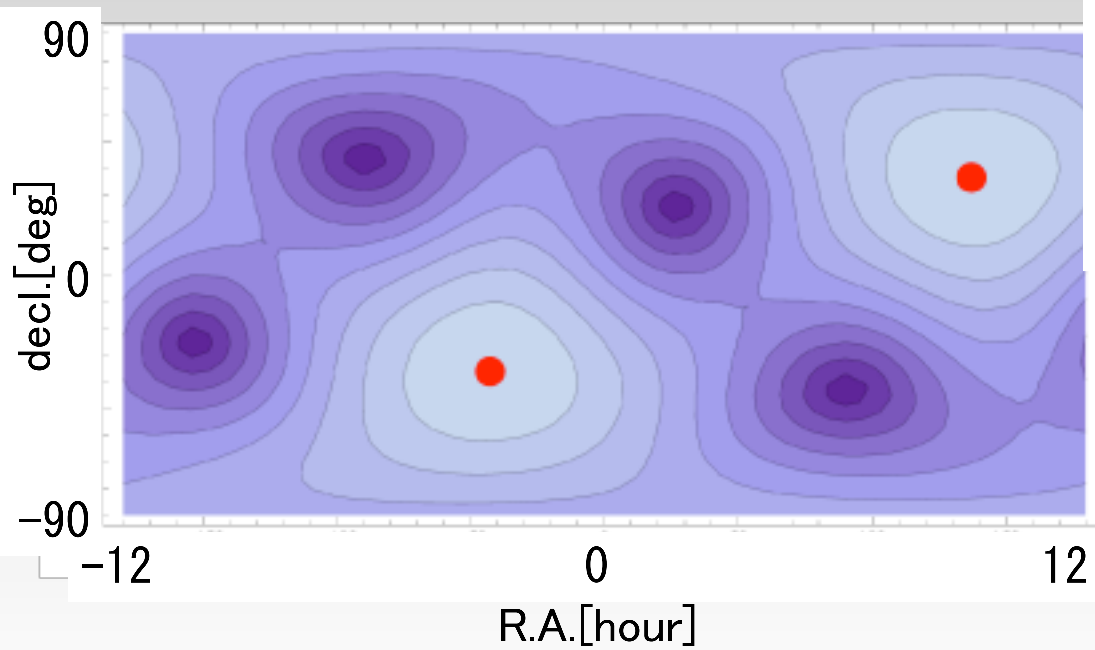
# Sky coverage by detector network

LIGO x2 + VIRGO

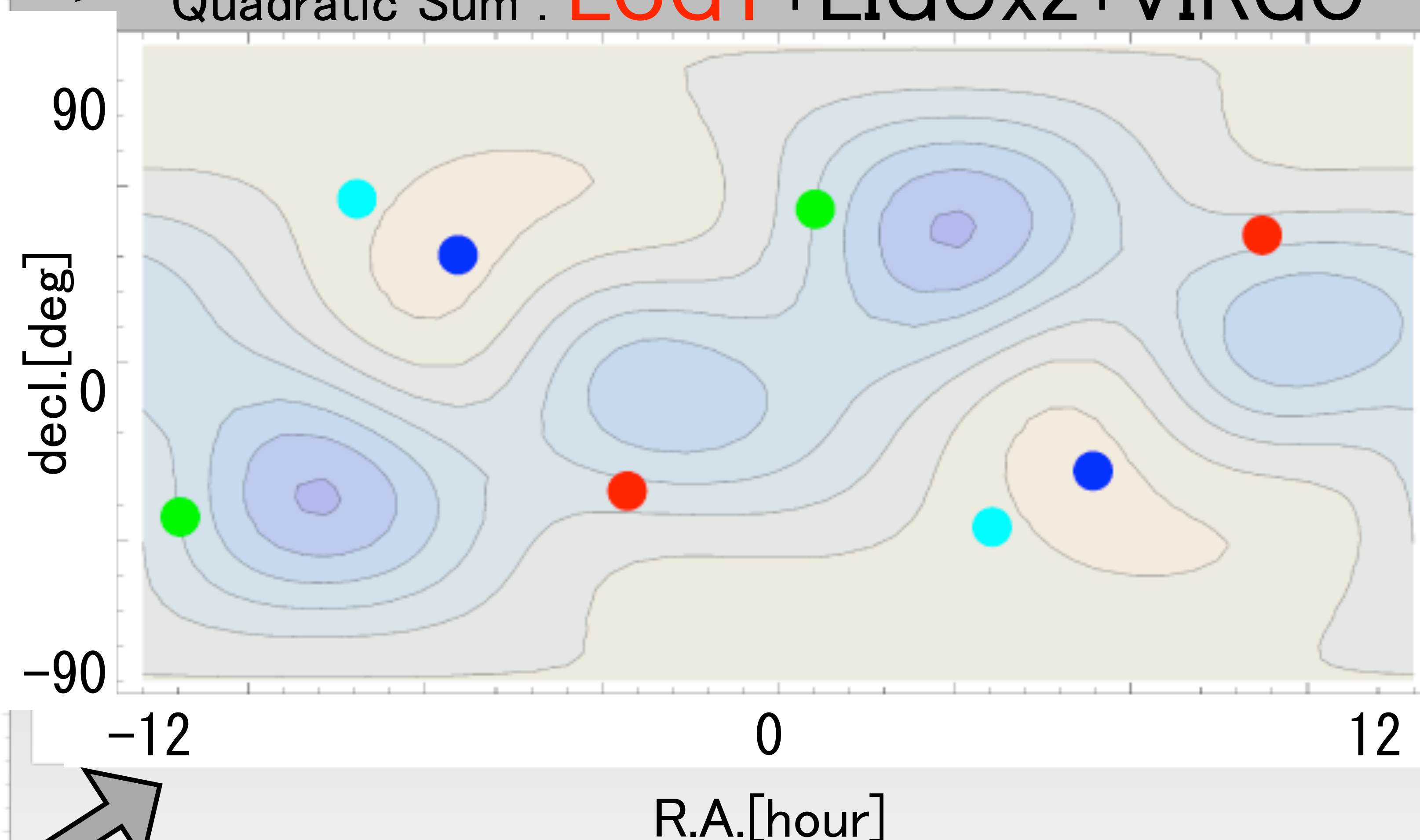



LCGT




zenith direction of detectors
- LIGO Hanford
- LIGO Livingston
- VIRGO
- LCGT

Quadratic Sum : LCGT+LIGOx2+VIRGO

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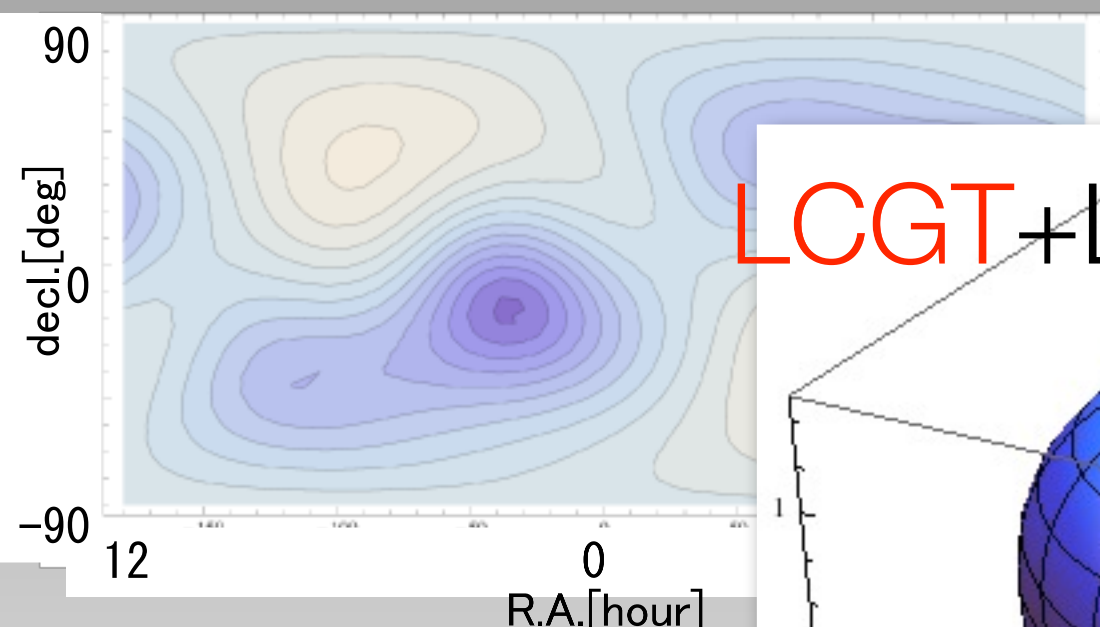
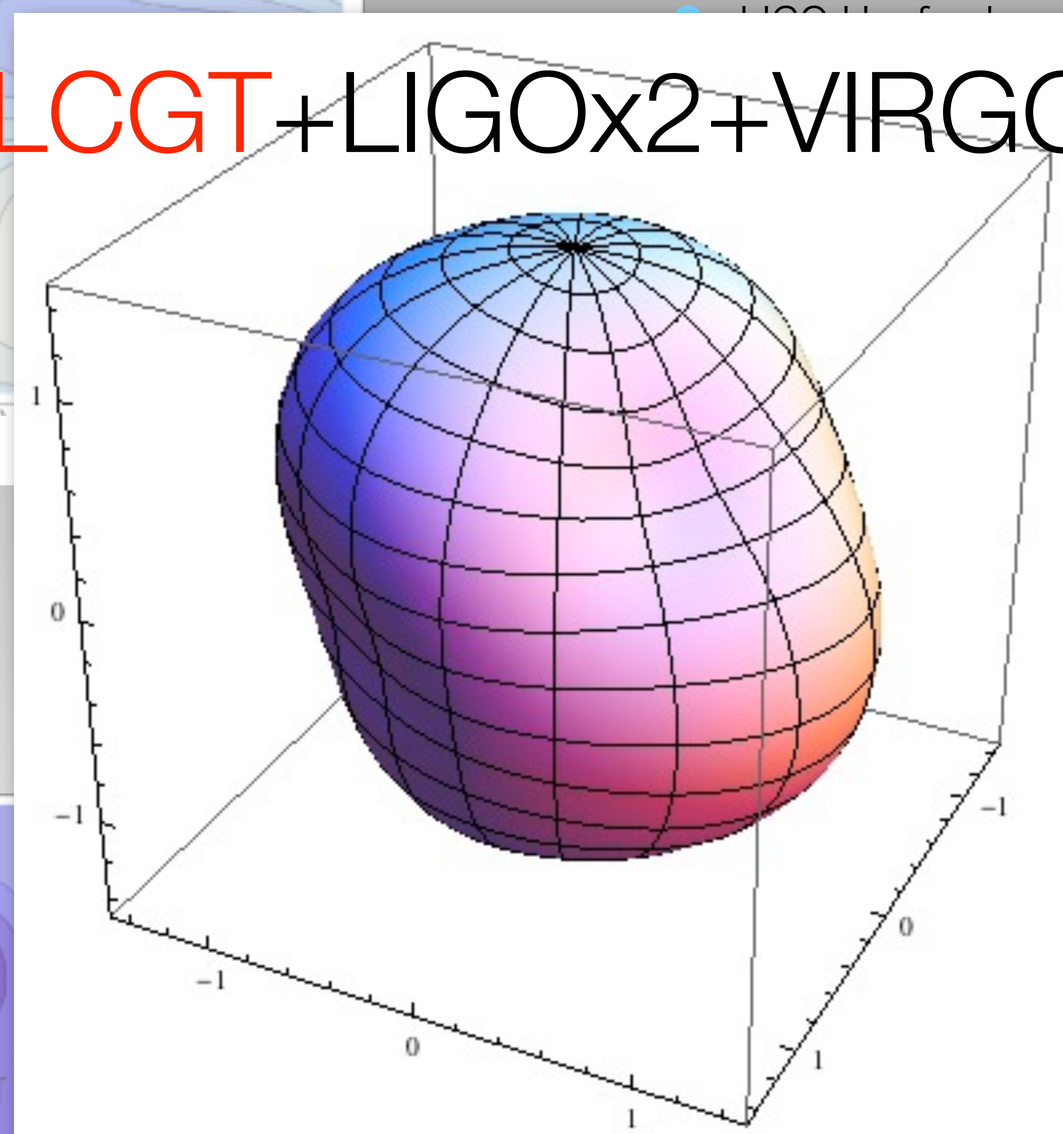
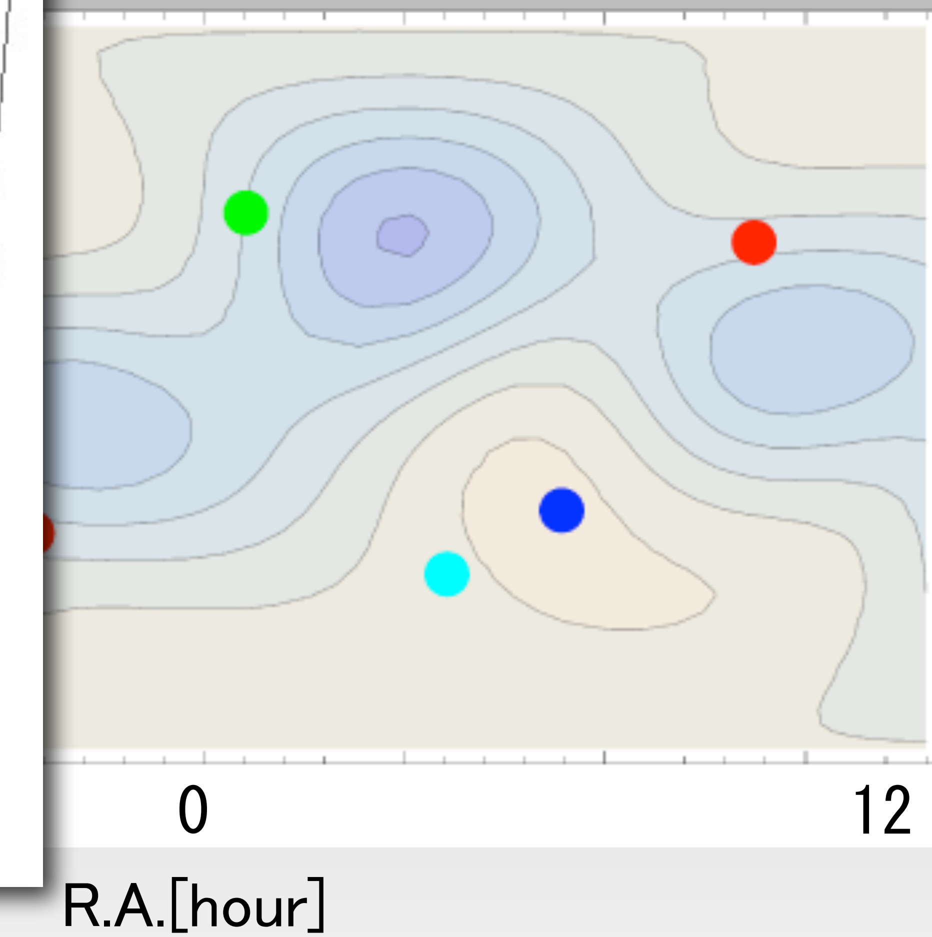



zenith direction of detectors

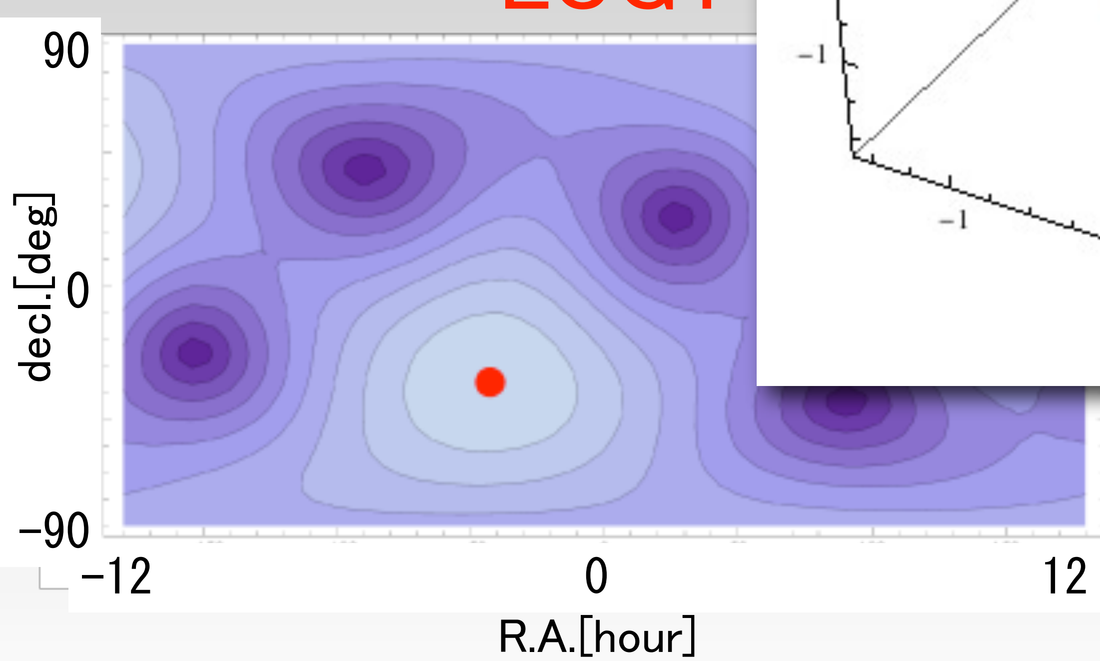
LCGT+LIGOx2+VIRGO



LCGT+LIGOx2+VIRGO




LCGT




**LCGT will make important role in the network, with a complemental sensitivity map.**

# High Energy Astrophysical Objects and GW

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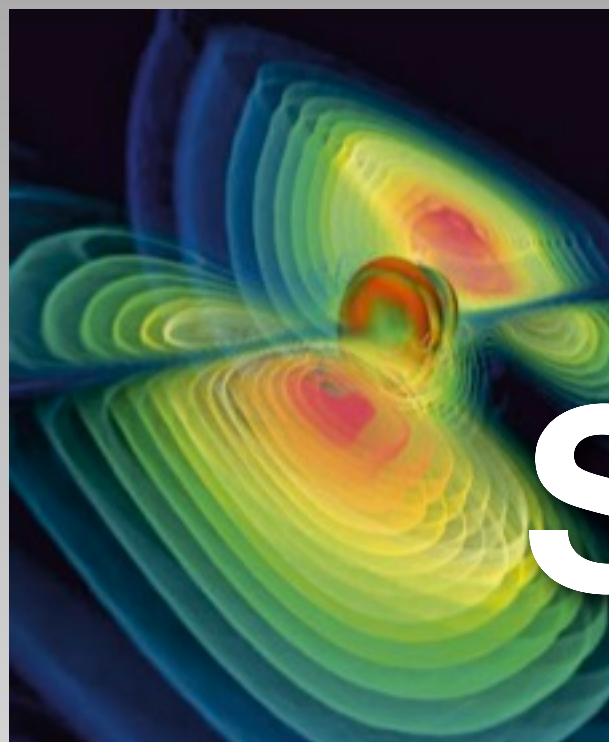
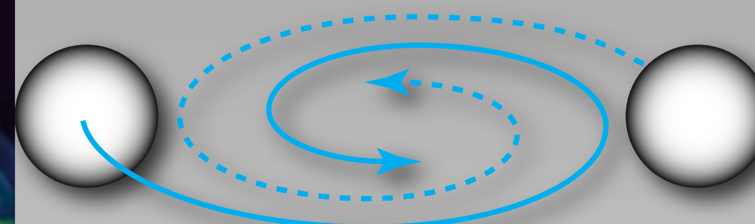
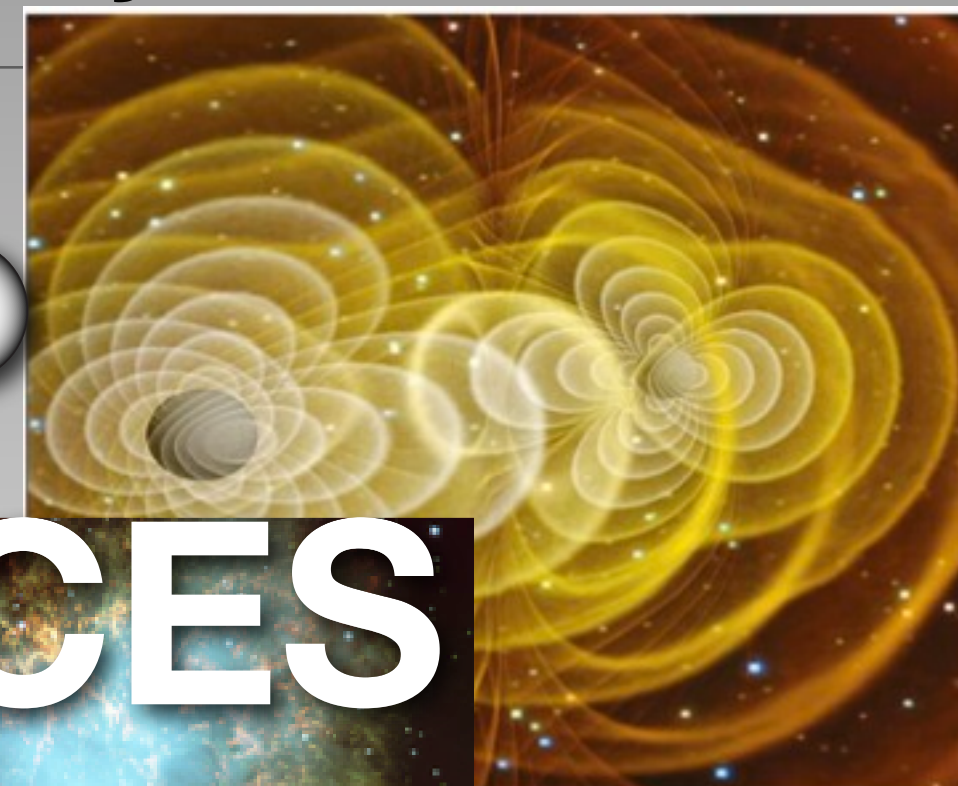
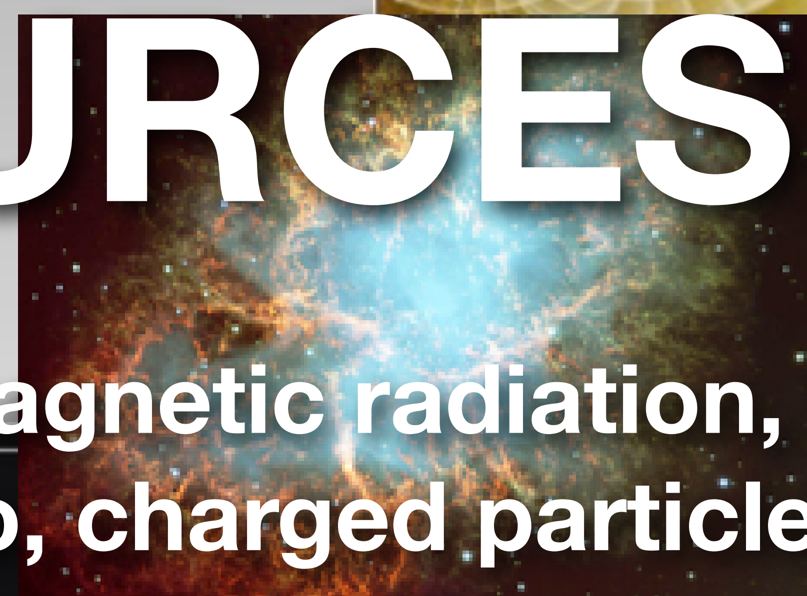






of merging black holes (Credit: Henze, NASA)



**SOURCES**

**will emit GW, Electromagnetic radiation, High-energy particles (neutrino, charged particles ...), ...**

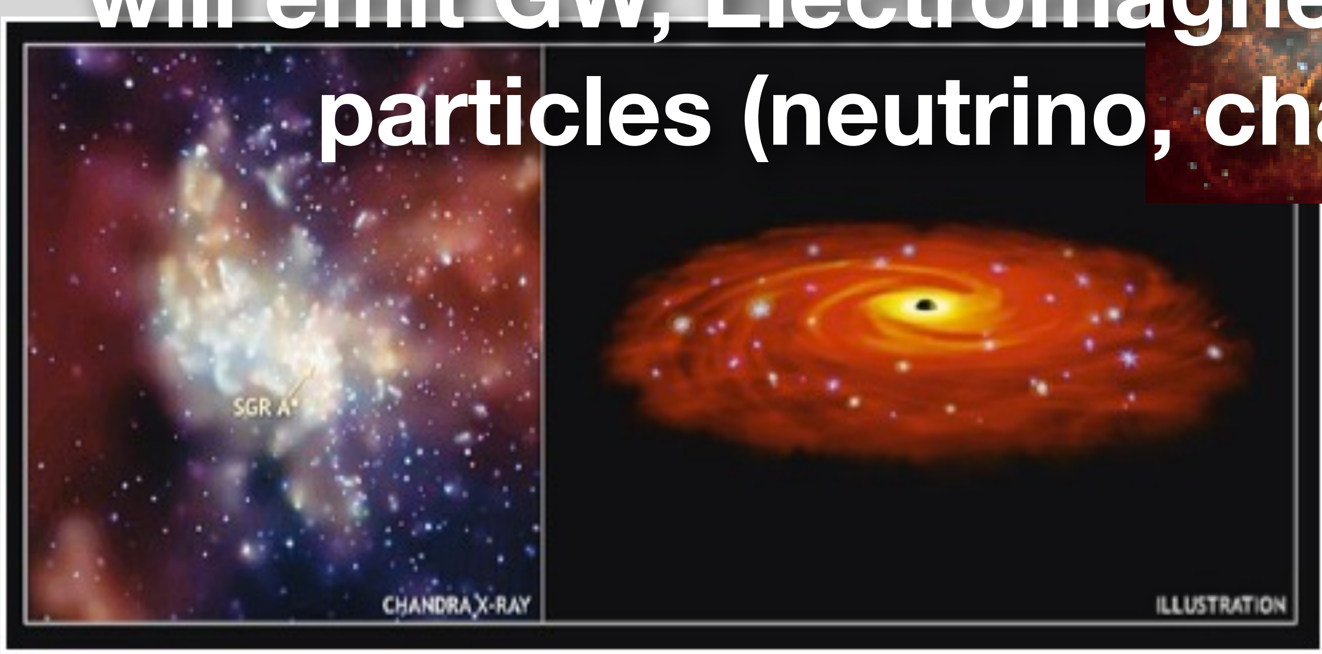
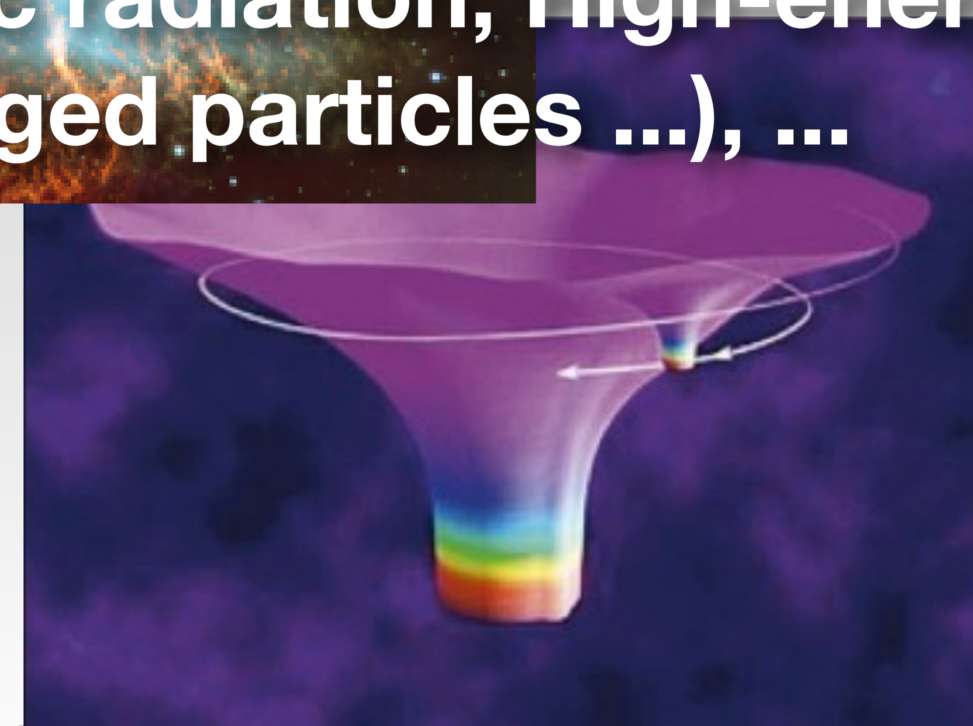
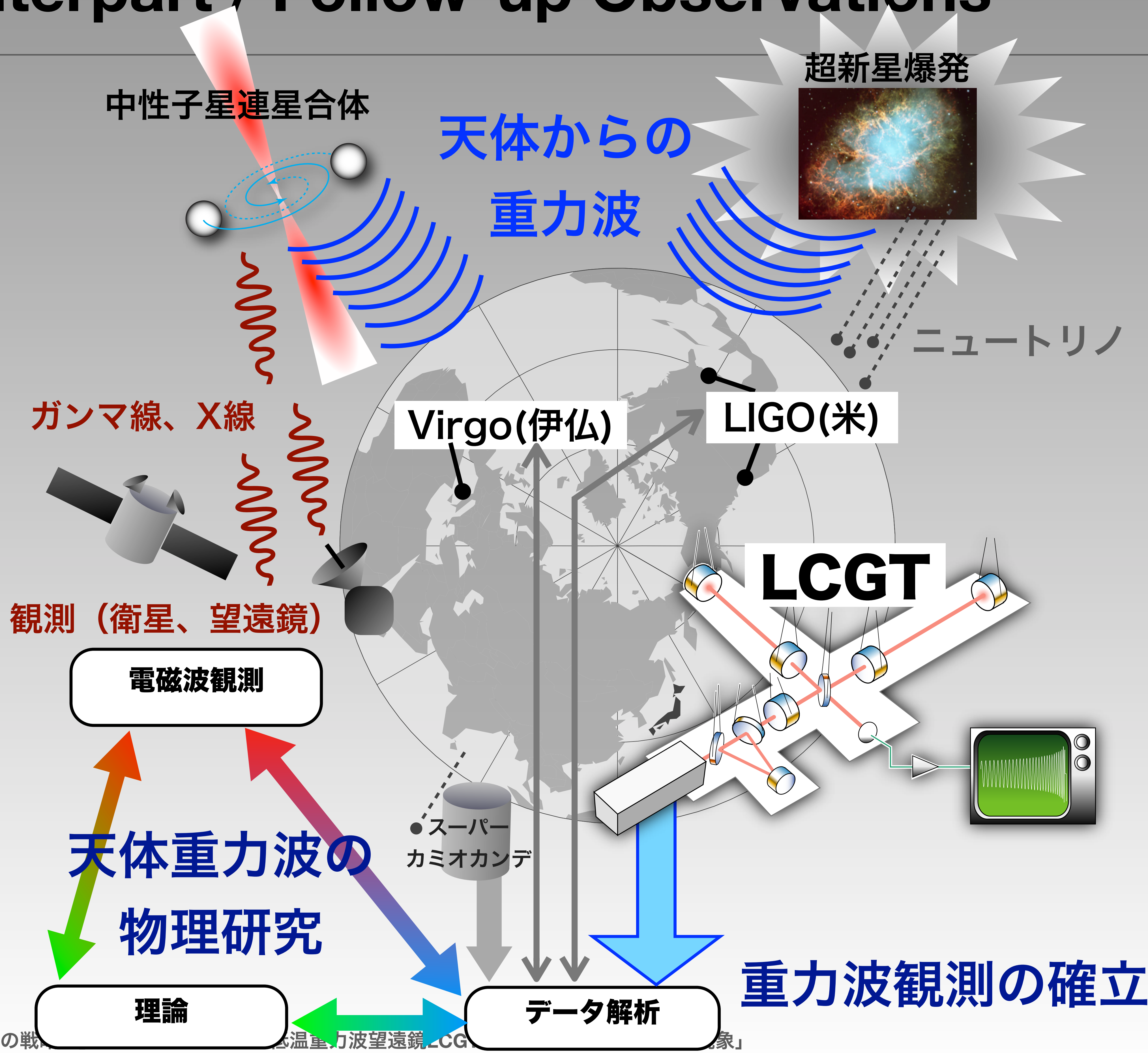


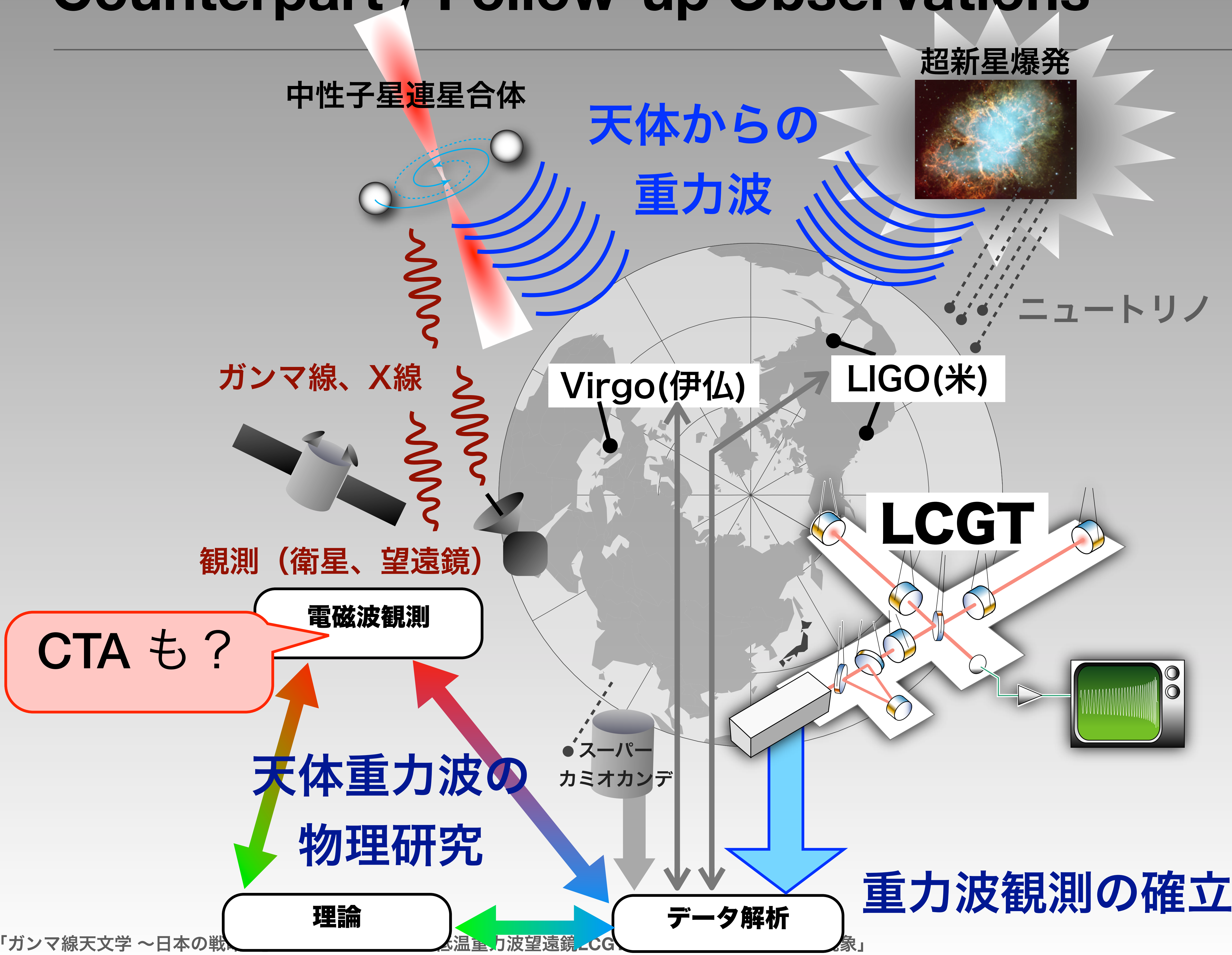

Fig. 4.3 – Chandra image of the Galactic Center (left). Illustration of massive stars formed from a large disk of gas around Sagittarius A*, the Milky Way's central black hole (illustration on right). Credit: X-ray: NASA/CXC/MIT/ F.K.Baganoff et al.; Illustration: NASA/CXC/M.Weiss



# Counterpart / Follow-up Observations

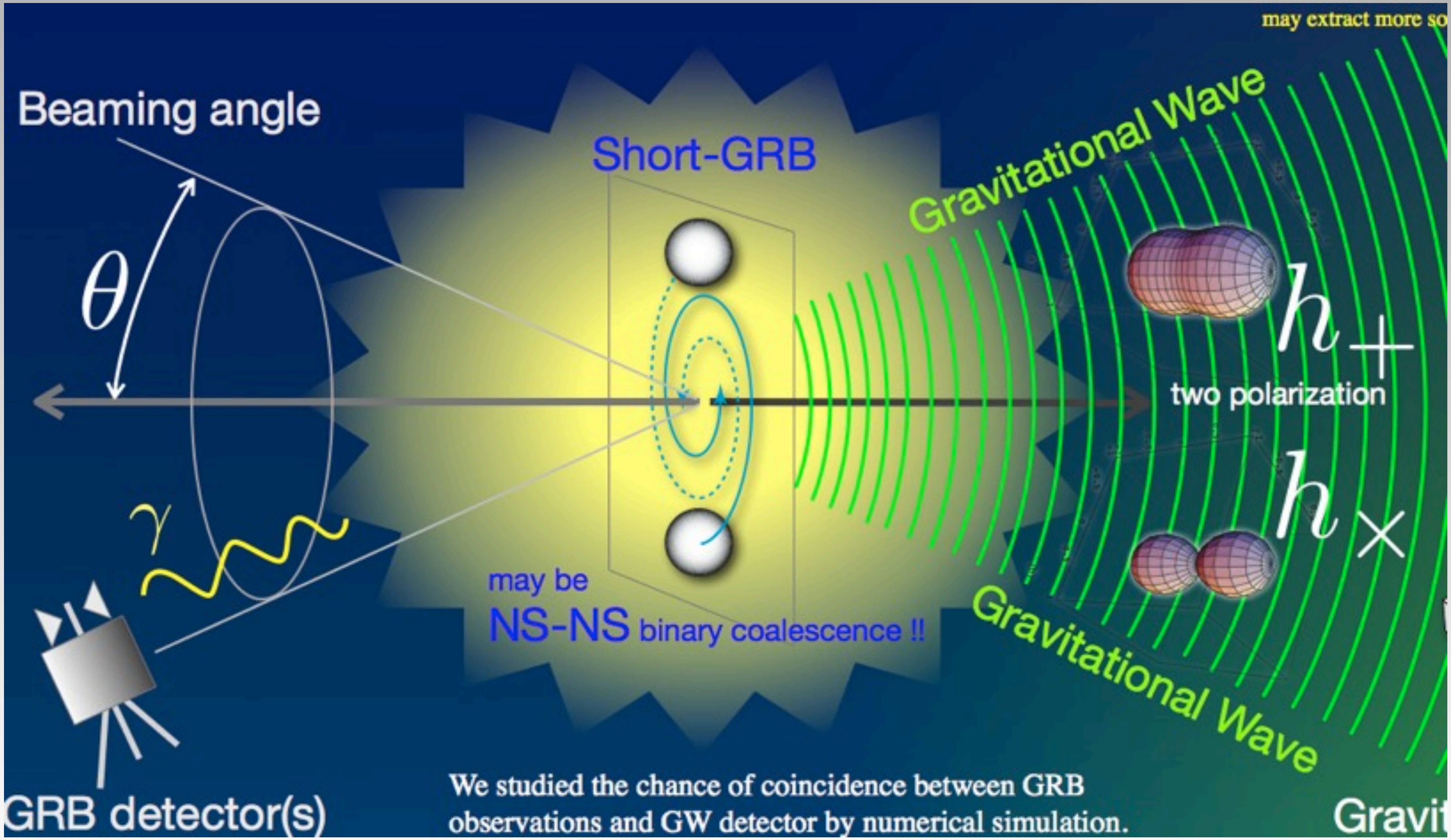


# Counterpart / Follow-up Observations

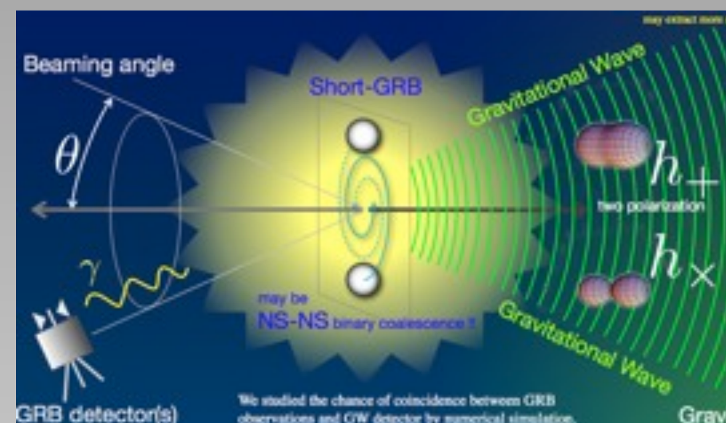


# Compact Binary Coalescences

## NS-NS binary might be a progenitor of Short-GRB.



# Mutually Followup Observations




If NS-NS = Short-GRB,

[Forecast]
merger before 30sec !
direction (xx.xx, yy.yy)

GW by LCGT etc.
Real time analysis

Delayed precise analysis

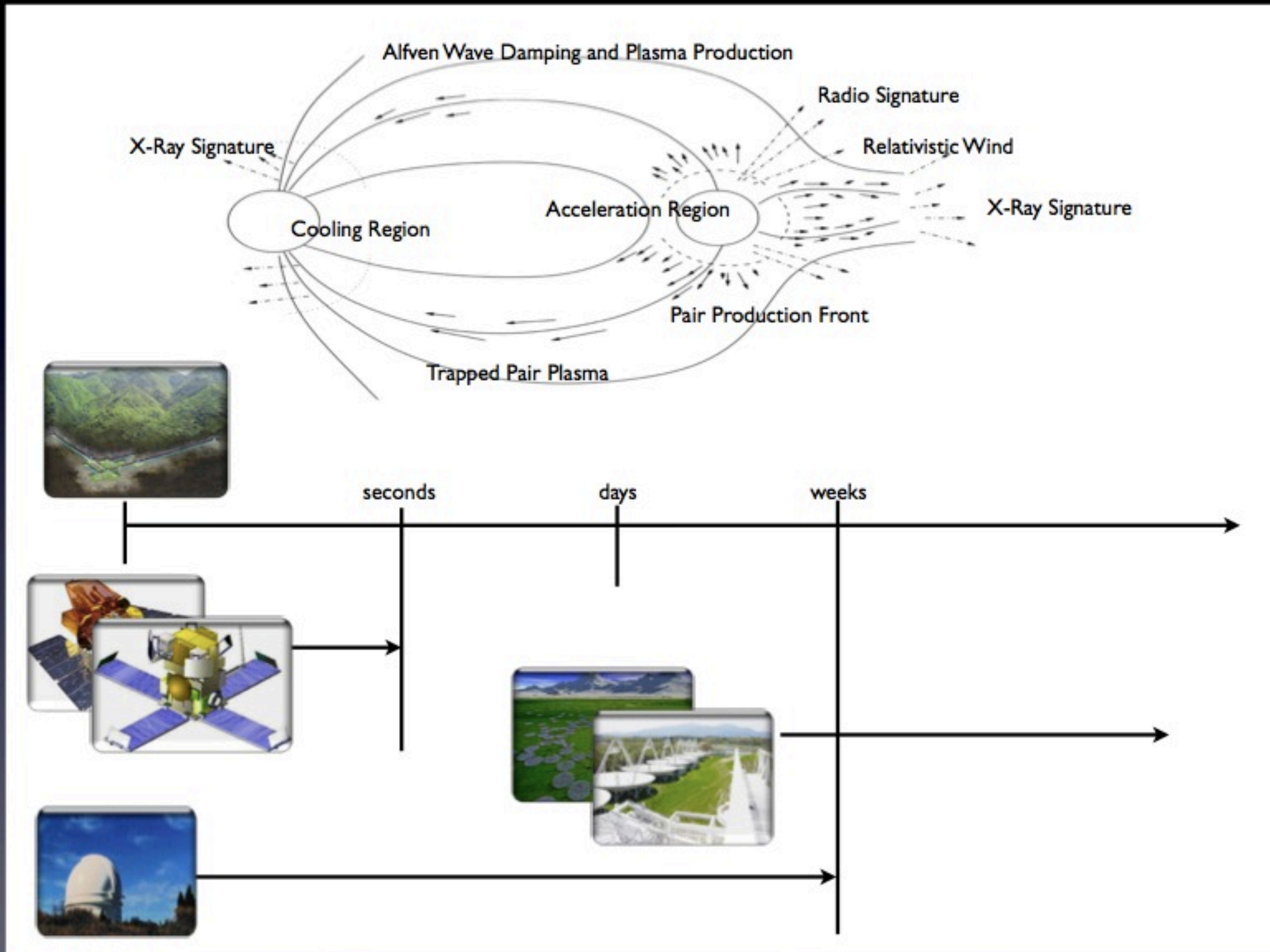
[Aux trigger]
Date, direction, ...

Followup by
**X, Gamma, Optical**

Confirmation of Afterglow

[Alert]
date, direction, distance,...

# CBC

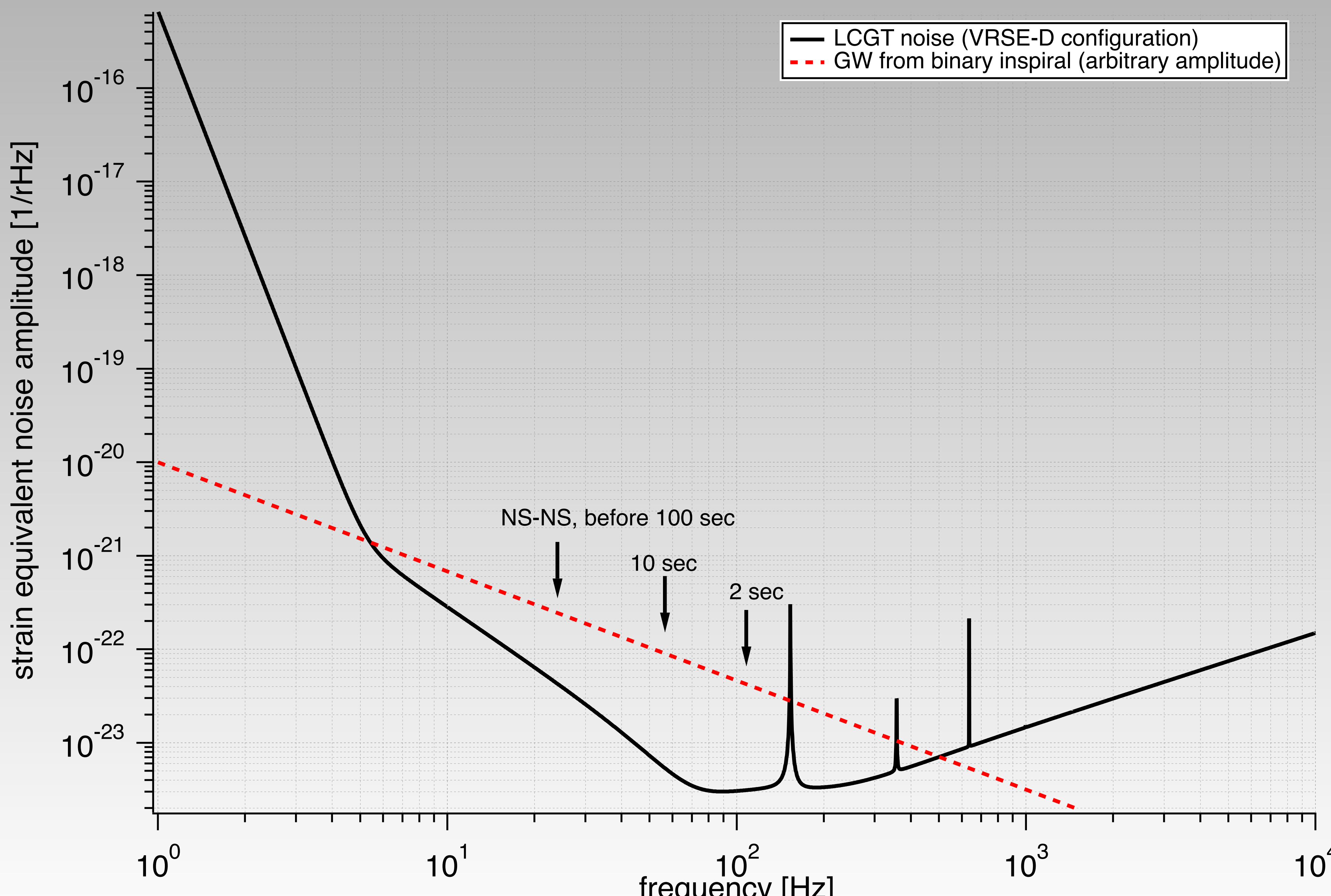



2010年8月11日水曜日

*arranged by K.Hayama*

# Forecast !?

## GW are emitted continuously ***before*** coalescence.

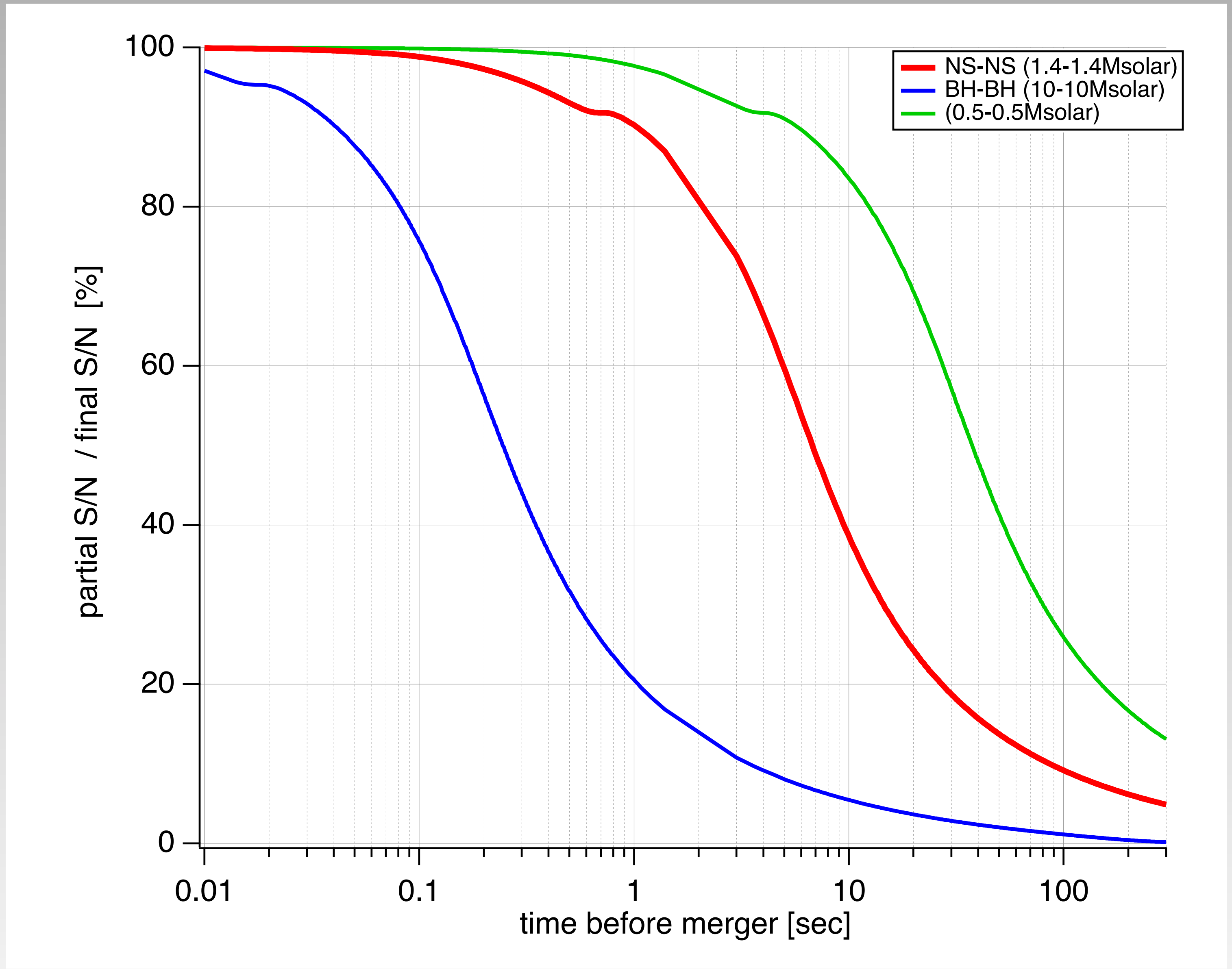


# Example of Practical Issue : NS-NS forecast

- Before merger,
  10% of final S/N before 1 min.
  40% before 10 sec.

  for S/N>8,
  1 min --> 25Mpc
  10 sec --> 80Mpc
  (*optimal direction.)

*Forecast by GW is not easy, however it is not impossible in principle.*
*Even it is not a forecast,*
**faster alert is useful for observe the transient behavior.**



# Direction of Sources

**Since GW observation's error box is wide, it will require large F.O.V. for gamma/X telescopes.**

## 角度分解能

(1.4,1.4)Msolar, @200Mpcの場合

LIGO-L1, VIRGO, LCGT 3台の場合

方向, inclination角, 偏極角に依存する.
これらを乱数で与える.

ISCOまで積分:

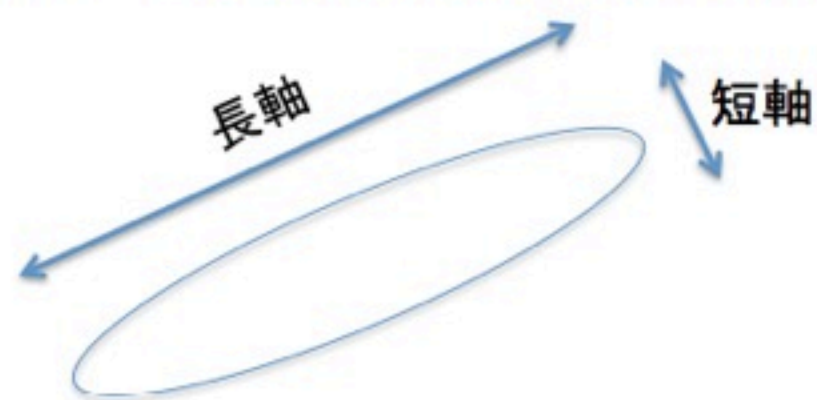
平均S/N (ρ)　　8.2から8.9 （各検出器で）

平均角度分解能　　長軸 7.6度, 短軸0.99度(3台のとき)

重力波周波数50Hzで打ち切り:

平均S/N(ρ)　　2.5から2.8 （各検出器で）

平均角度分解能　　長軸 123度, 短軸13度(3台のとき)

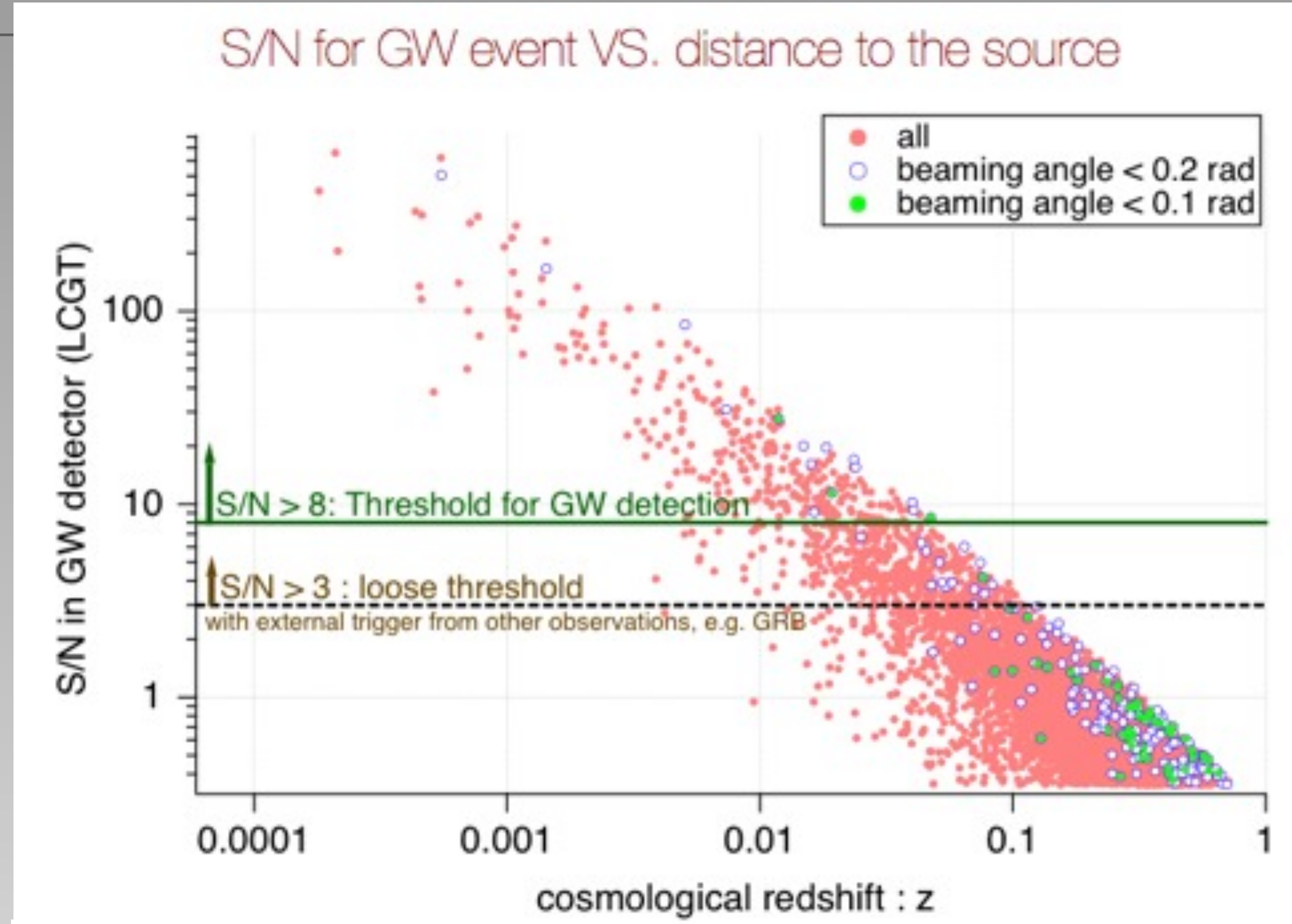


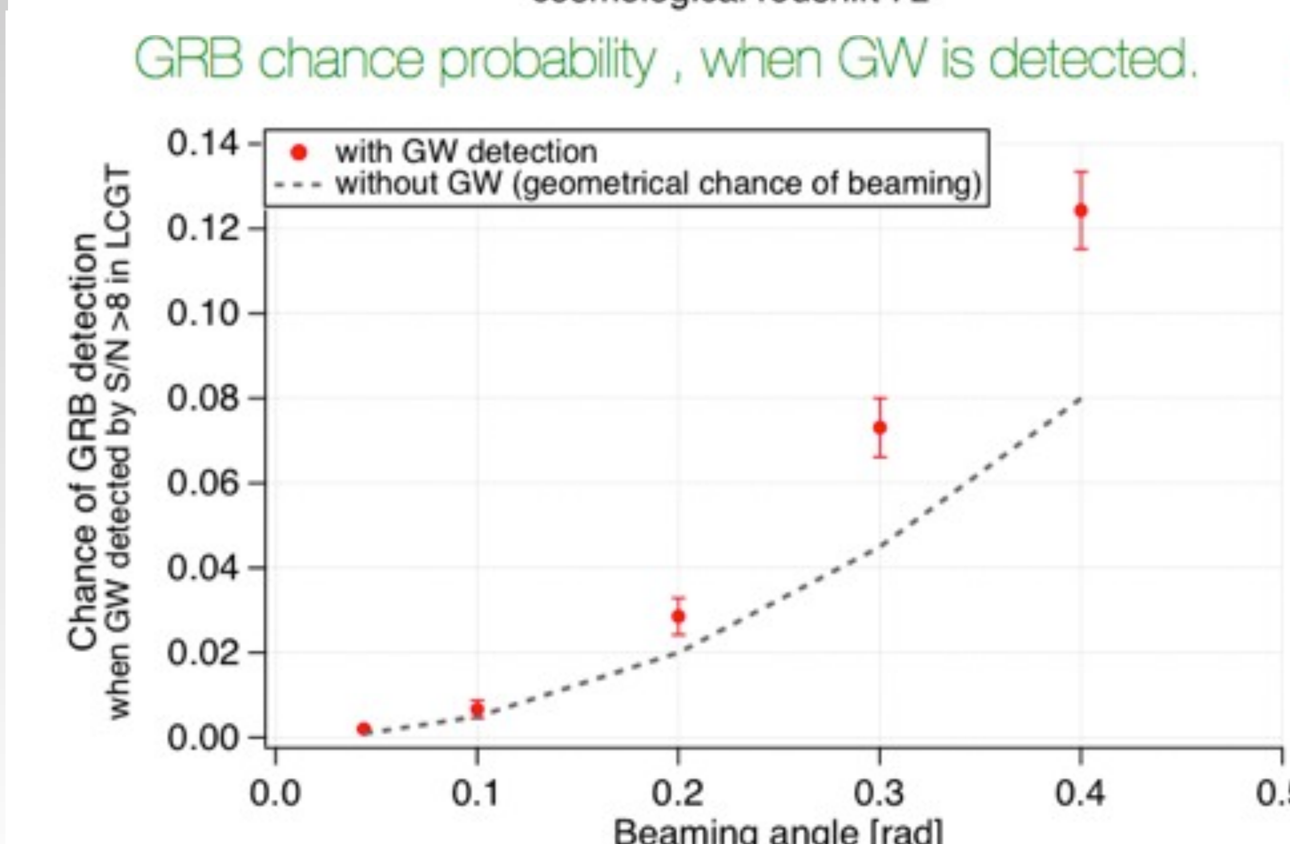

*by H.Tagoshi*

5

# Coincidence chance between GW and GRB

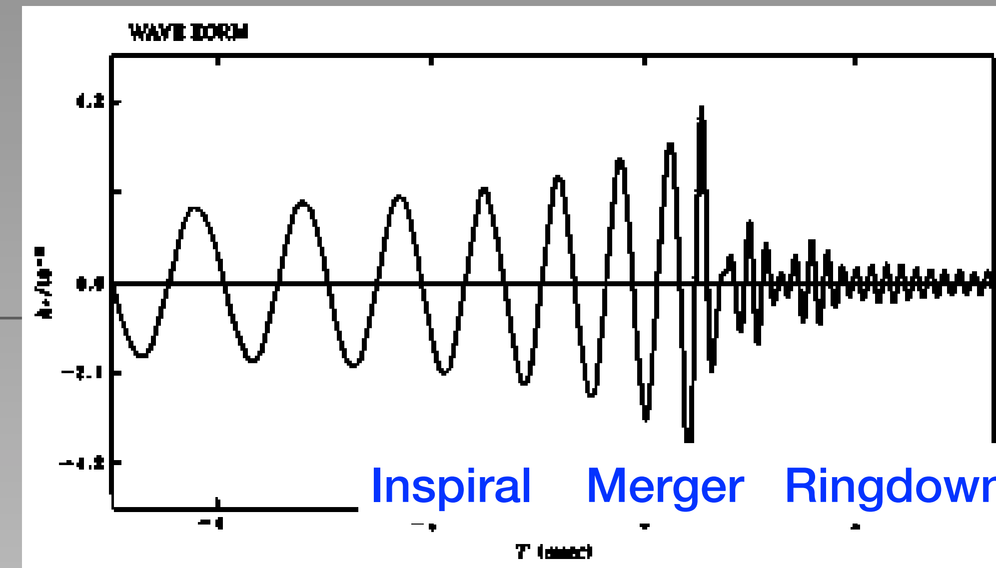
| z distribution | Beaming of GRB | Chance of GRB found |
|---|---|---|
| pre-Swift | 0.2 rad | 2.9% |
| Swift | 2.5 deg | 0.2% |
| | 0.1 rad | 0.7% |
| | 0.2 rad | 2.9% |
| | 0.3 rad | 7.3% |
| | 0.4 rad | 12.4% |




If beaming of GRB is about 0.2 rad, a chance is once for 30 times.

# Physics on CBC waveforms




## NS-NS, NS-BH, BH-BH

GW emissions from different phases carry out different informations.
In case of CBC, methods of waveform prediction are also different.

### Inspiral (Post-Newton)

- frequency development ---> mass of stars, and absolute amplitude
- measured amplitude ---> distance from the earth
- polarization ---> inclination angle of binary orbit

### Merger (Numerical Relativity)

- depends of many (initial/boundary) conditions ---> Complex information of stars , e.g. radius, viscosity, EOS ...

### Ringdown (Perturbation)

BH quasi-normal mode

- frequency ---> mass
- decay time ---> spin (Kerr parameter)

*What a fruitful source is it !*

# Supernovae

Supernova will emit GW also in various phase of its development.

## core bounce

## convection

## formation of proto-neutron star

- g-mode oscillation

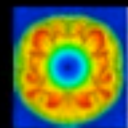
## neutrino emission

## accretion

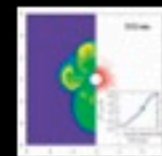
- cf: SASI (standing-accretion-shock instability)

# Evolution of Supernova and GW

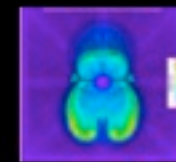
*by K.Kotake*



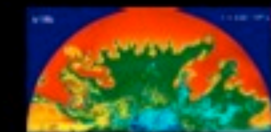
対流



SASI



G-mode?

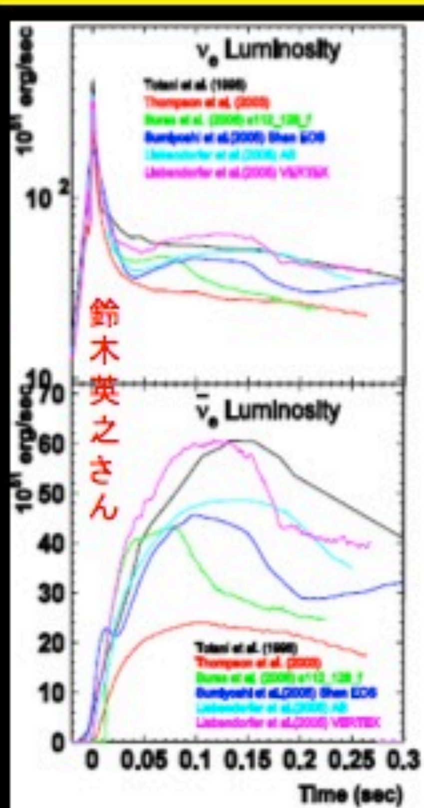


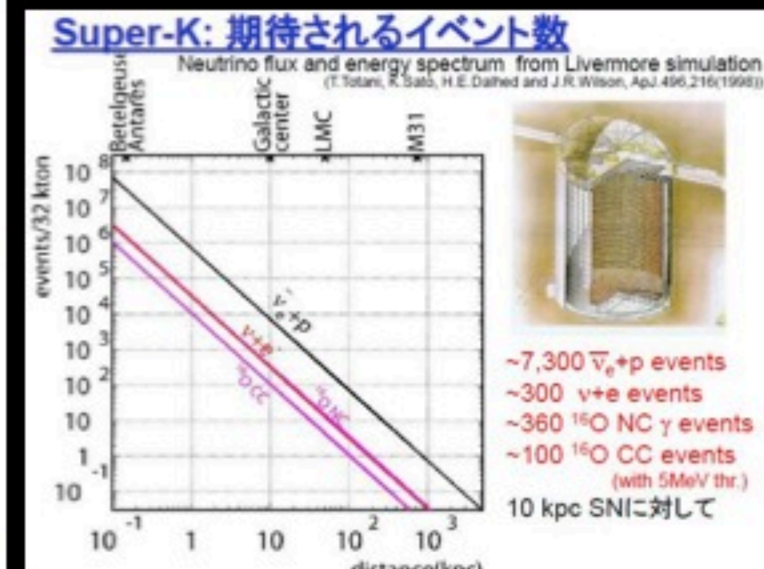
0秒　数ミリ秒　1秒（？）　＞数時間

重力崩壊開始

バウンス

中性子化バースト



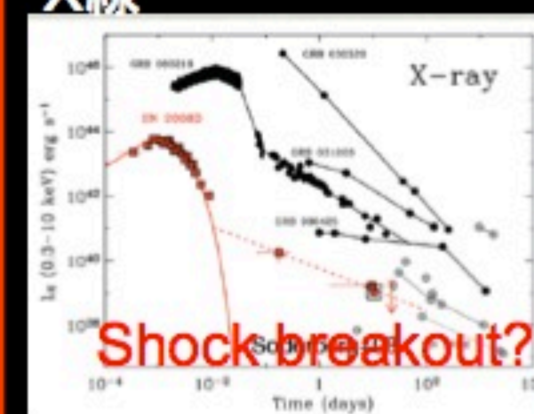

中畑さん（超新星研究会2009より）

衝撃波復活

元素合成

爆発

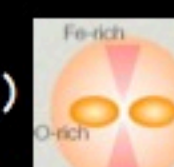
X線

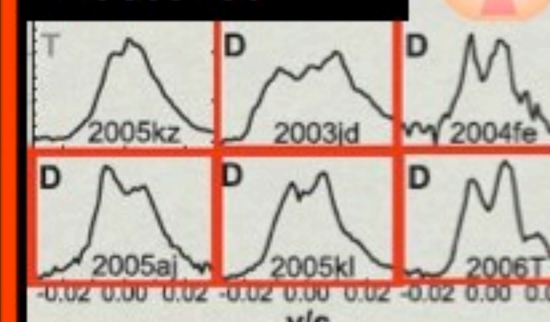



Subaru

Tanaka+06(偏光)

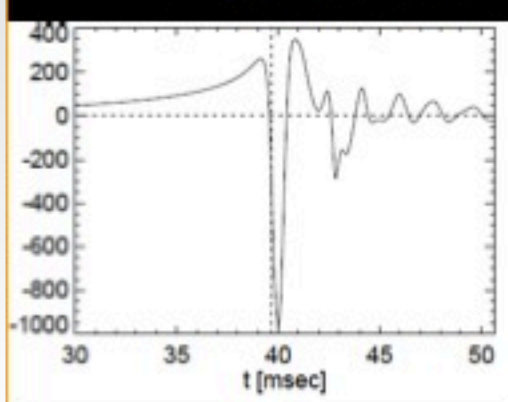
Maeda+06



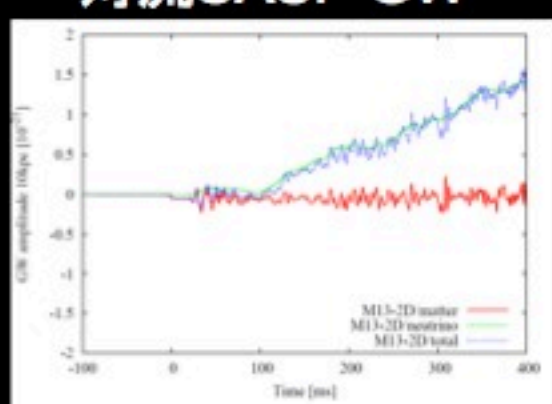



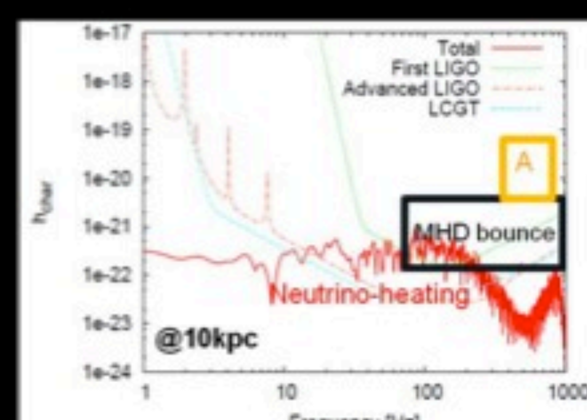

Swift: GRB（カウンターパート）

バウンスGW




対流SASI　GW



# Neutrino and GW from Supernovae

## GW

- Typical Range < 1Mpc
- Typical Angular Resolution ~ 3 degree

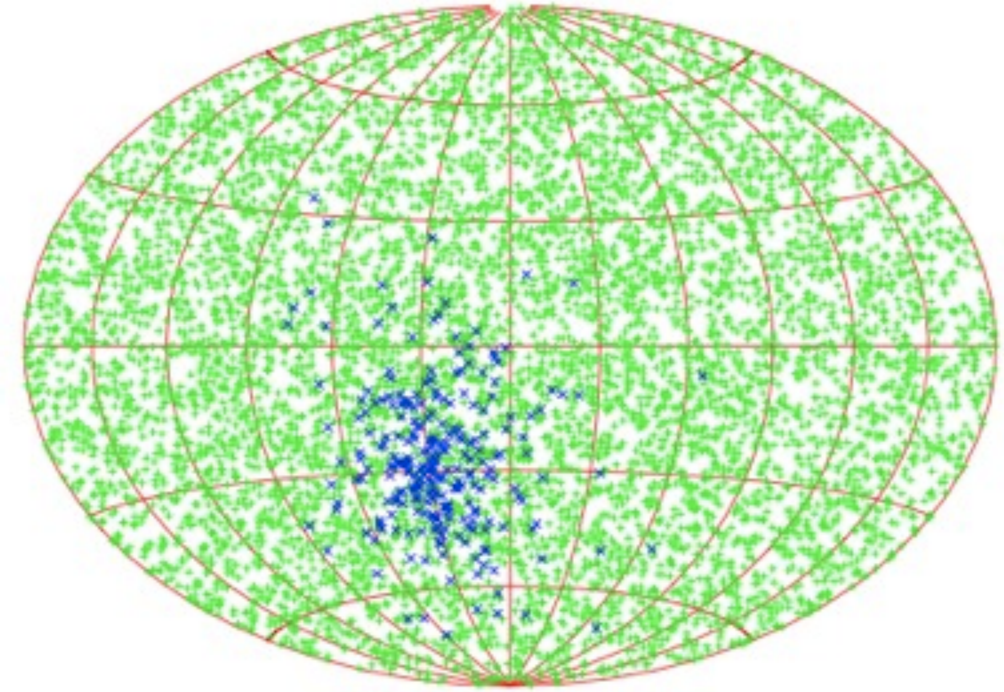


FIG. 4: Angular distribution of $\bar{\nu}_e p \to n e^+$ events (green) and elastic scattering events $\nu e^- \to \nu e^-$ (blue) of one simulated SN.

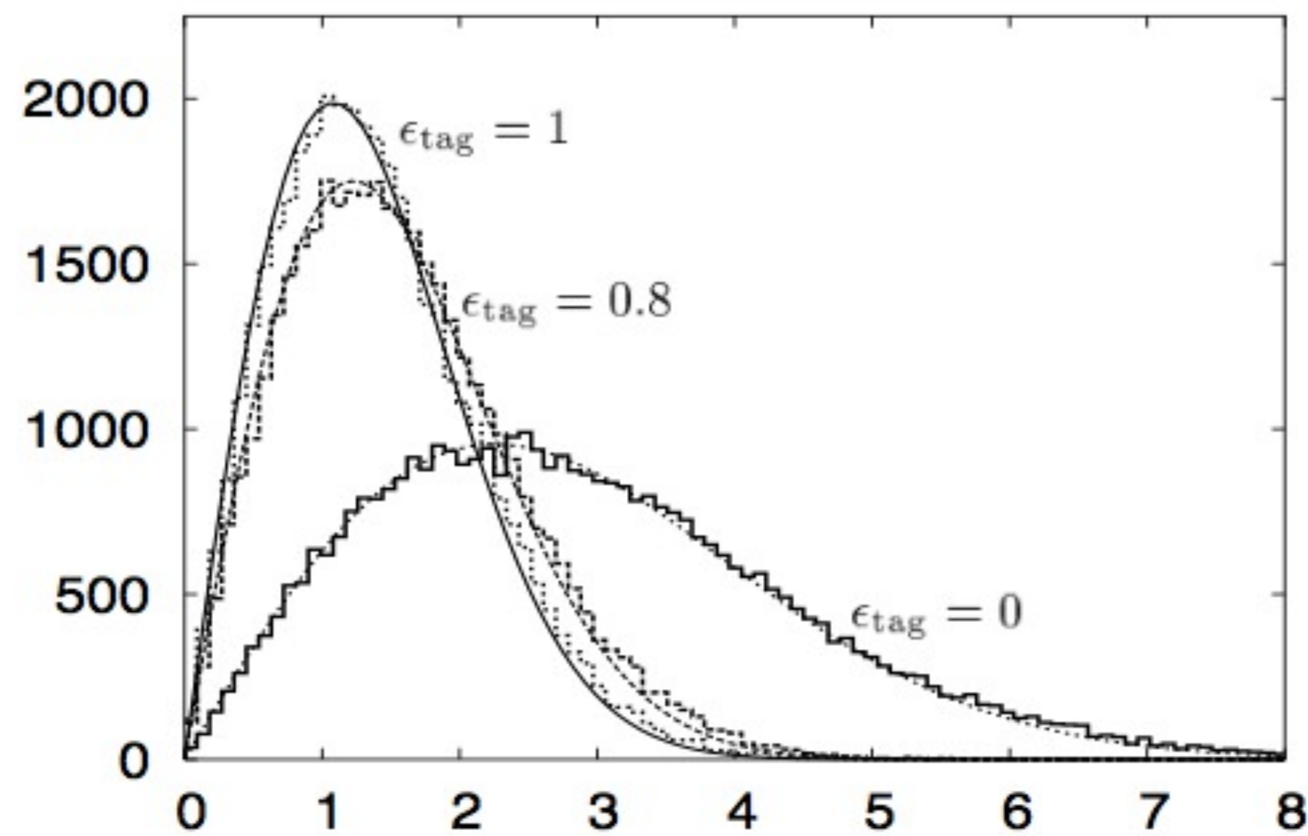
## Neutrino (Super-Kamiokande)

- Typical Range ~ several 100 kpc
- Typical Angular Resolution

  at 10kpc

  C.L.68% (=1 sigma) --> 4.7 degree

  C.L.95% (=2 sigma) --> 7.8 degree




Phys.Rev. D68 (2003) 093013 / arXiv:hep-ph/0307050v2

R. Tomas, D. Semikoz, G. G. Raffelt, M. Kachelriess, A. S. Dighe

# Magnetor

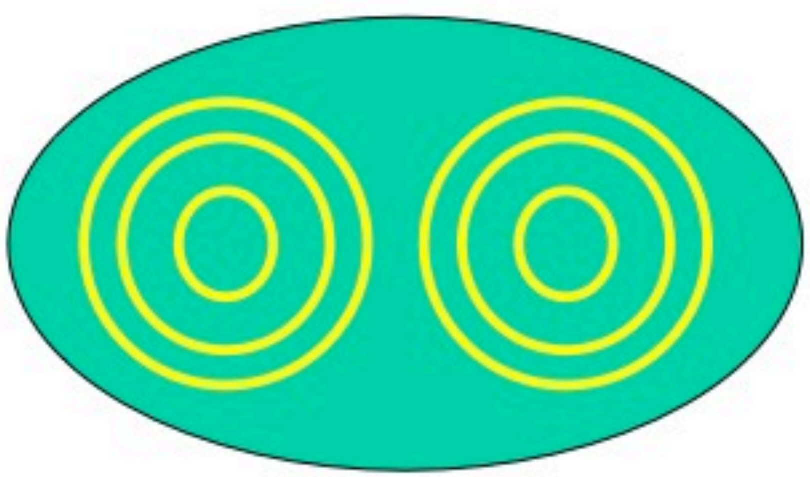
*by K.Ioka*

## Magnetar

Super strongly magnetized neutron star

$$\frac{\text{Magnetic energy}}{\text{Gravitational energy}} \sim \frac{B^2 R_*^3}{G M_*^2 / R_*} \sim 10^{-4} \left( \frac{B}{10^{16}\text{G}} \right)^2$$

⇨ Deformation of neutron stars



1. Precession
2. GW source (e.g., GRB)
3. Influence on the oscillation

Equilibrium of magnetized stars

# Other Possible Sources

Soft Gamma Ray Repeater

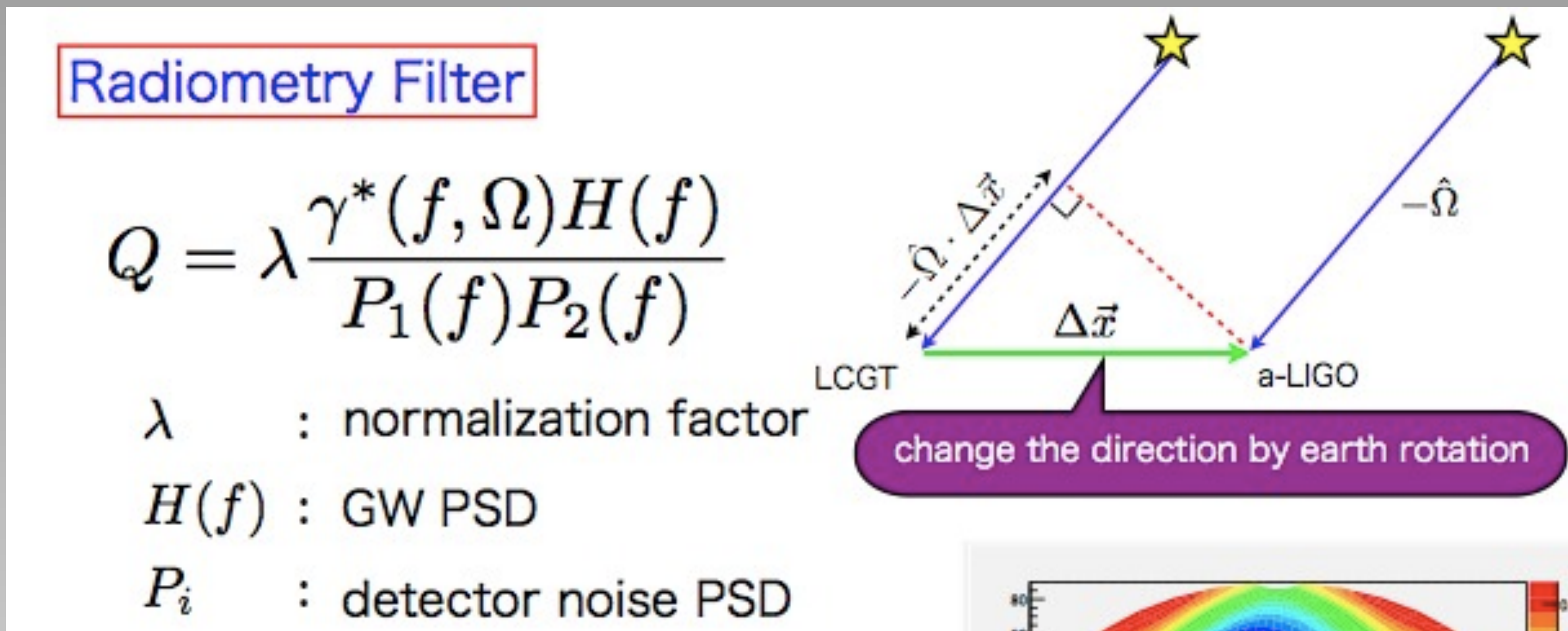
Cusp/Kink of Cosmic String

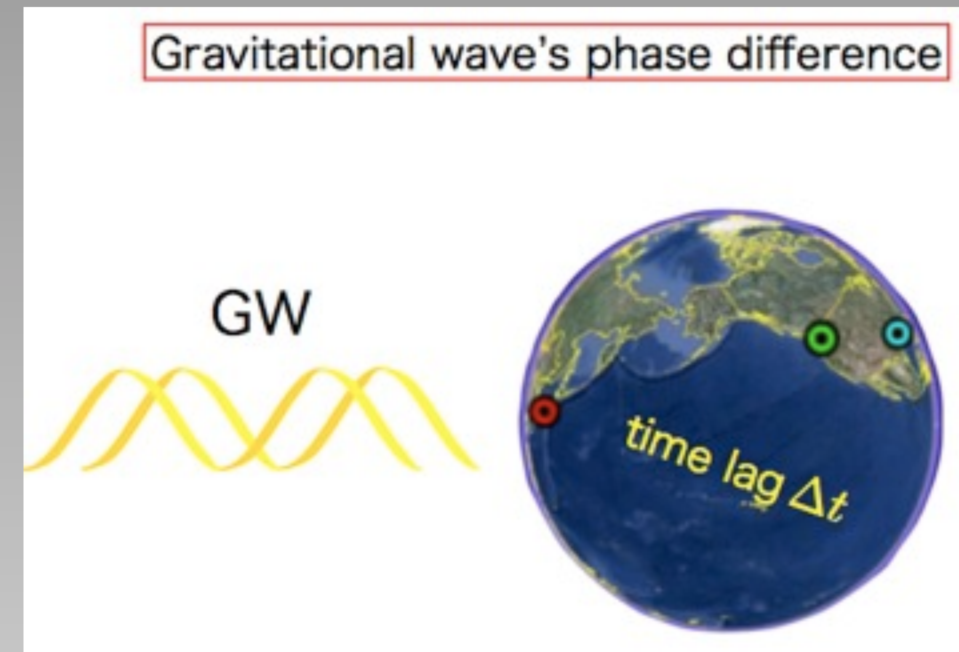
LMXB (Wagoner star)

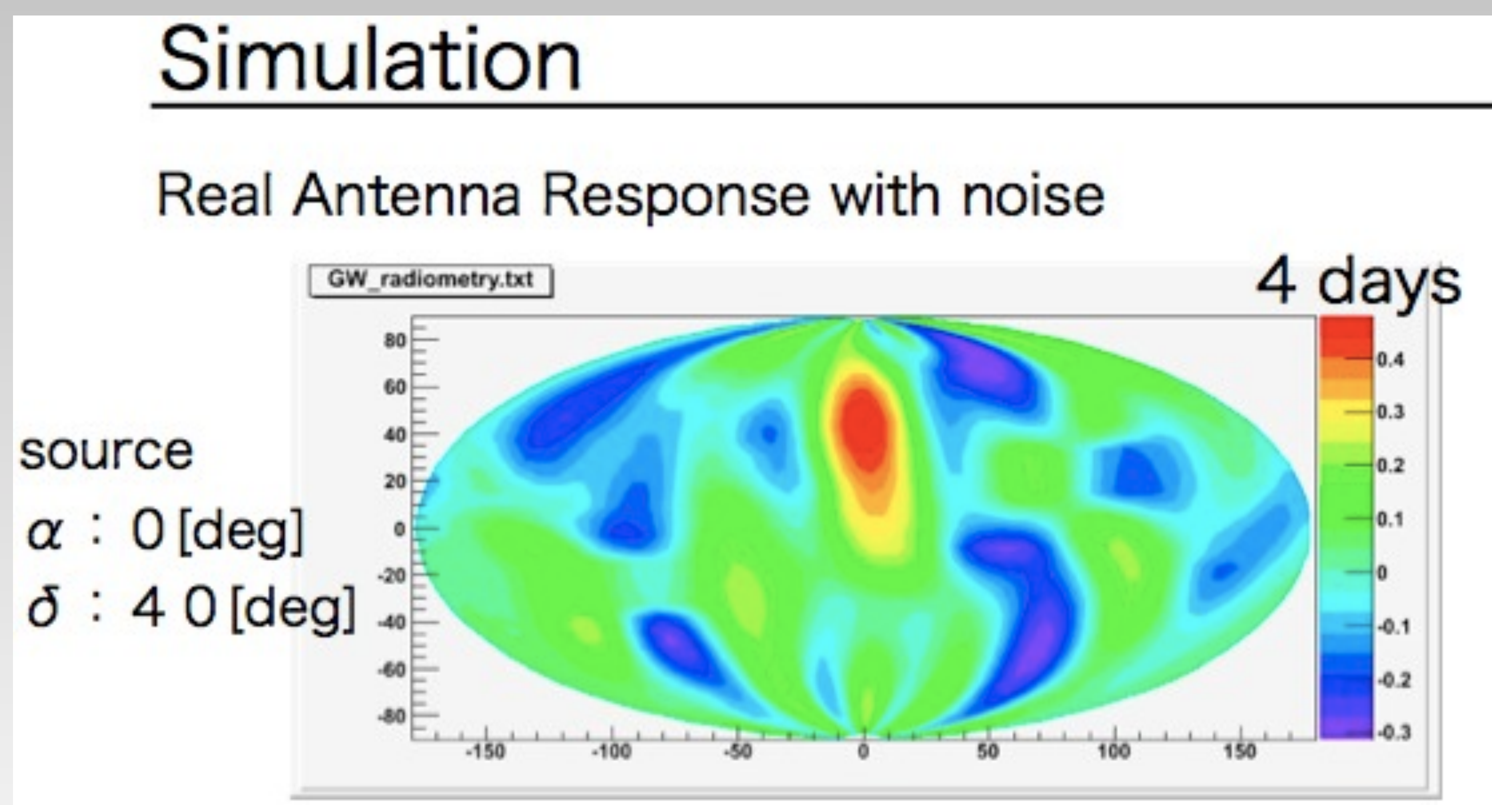
SMBH, IMBH

Pulser (Continuous,  Pulser glitch)

# Radiometry Search for point sources




*by Y.Okada*

**Stochastic GW (convolution of point sources, random phases) will be able to detetect.**

# What’s need for mutually follow up ?

## GW obs.

- fast processing event searches
- reliable alert (low false alarm rate, high efficiency)
- trigger data-base

## EM / high energy particle counterparts

- wider field of view / quick response
- sky coverage

  GW will be detect from whole sky.

# Summary

## LCGT

has been funded partially, and the construction start now!
(First run will be 2014.)
Full observation will start at late 2016 or early 2017 with world network of GW observatories.

## Mutually Follow-up

observations between GW and electromagnetic or high energy particles or both is expected.
Counterpart information will make appear the inside/structure/development of high energy astrophysical objects.