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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LCGT collaboration
+ GW&EM followup working group

Plan of Talk

Gravitational Waves

- What ?
- Why ?
- Sources

LCGT

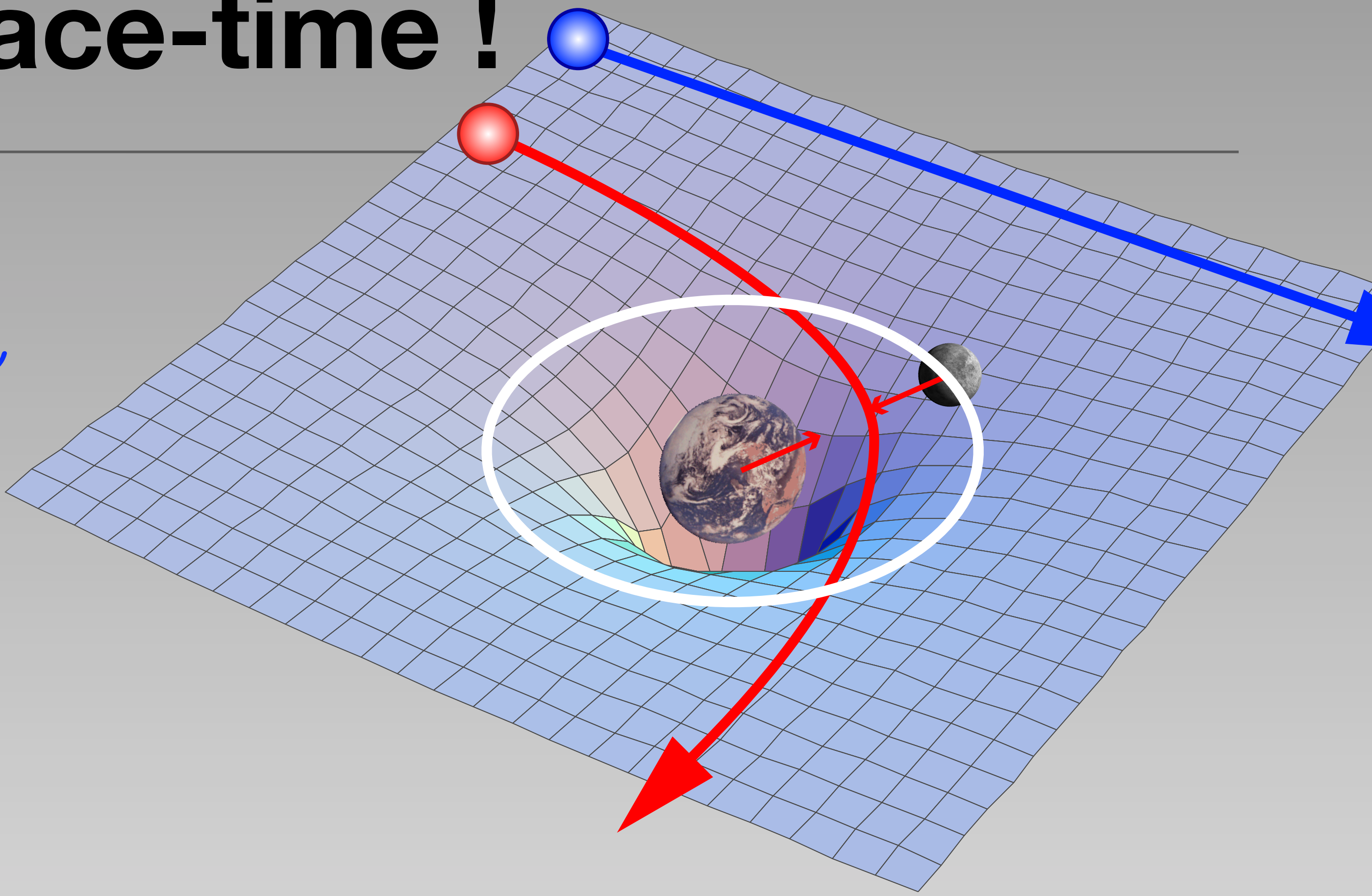
- Overview
- Construction Schedule
- Detection Range for GWs

Counterpart / Follow-up observations

- Possible Sources
- Science (Physics) outcome

Gravity distorts the space-time !

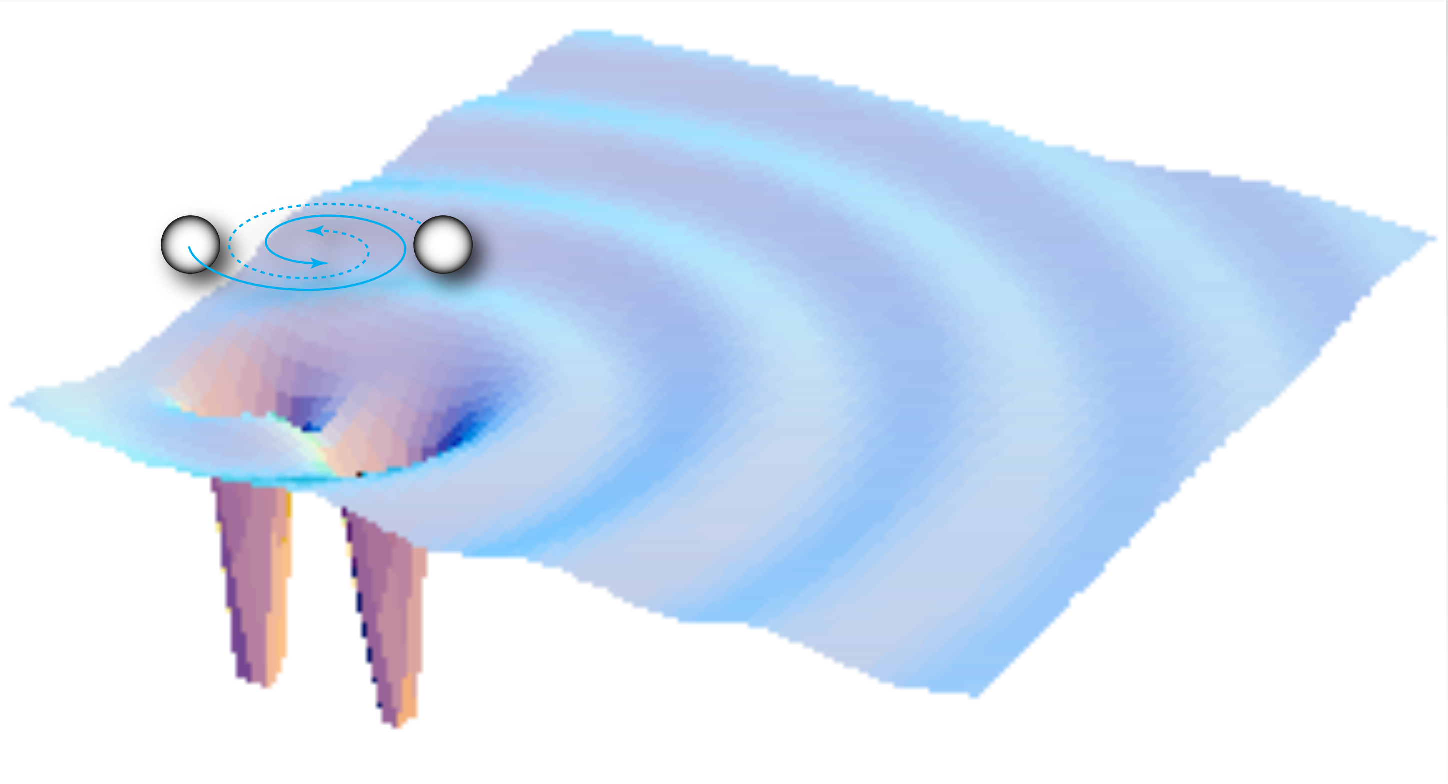
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\kappa T_{\mu\nu}$$



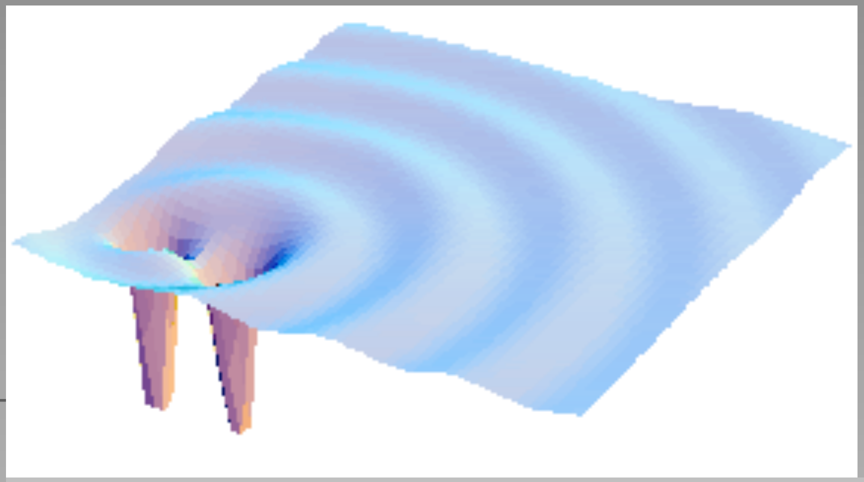
Curved space-time

Propagation of the distortion

- --> Waves !



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)

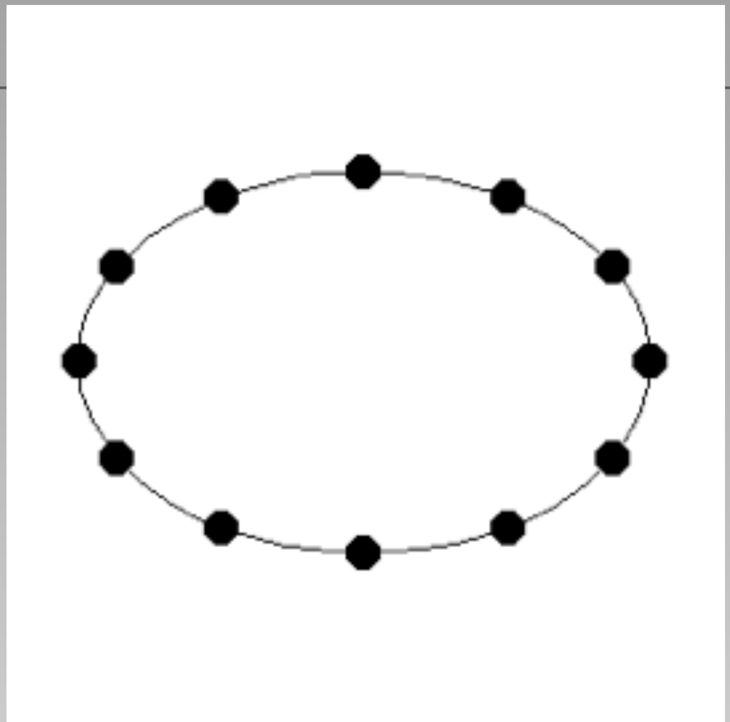
$$h_+ = h \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad h_\times = h \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

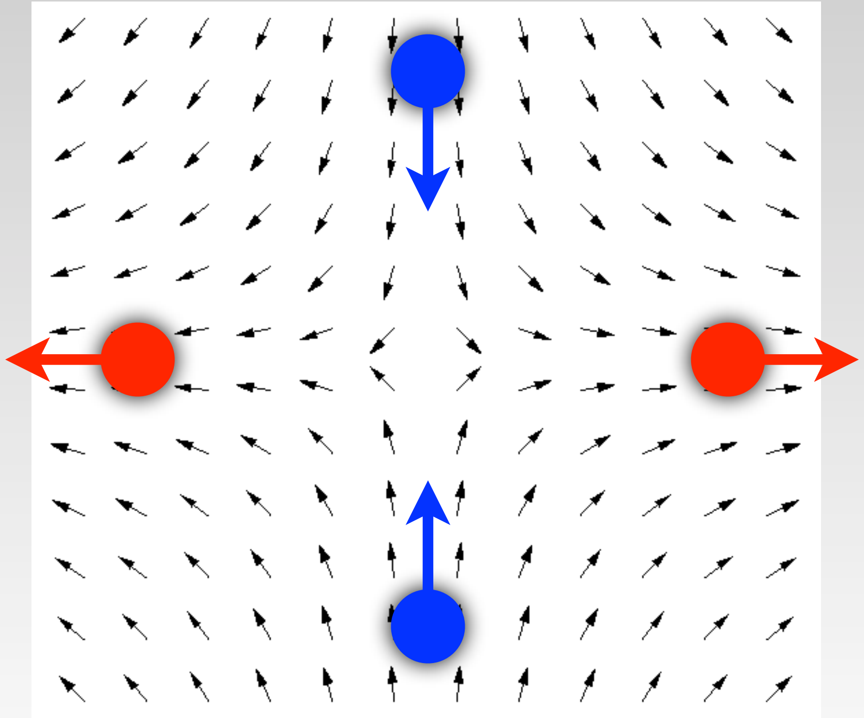
Force (Displacement) by GW

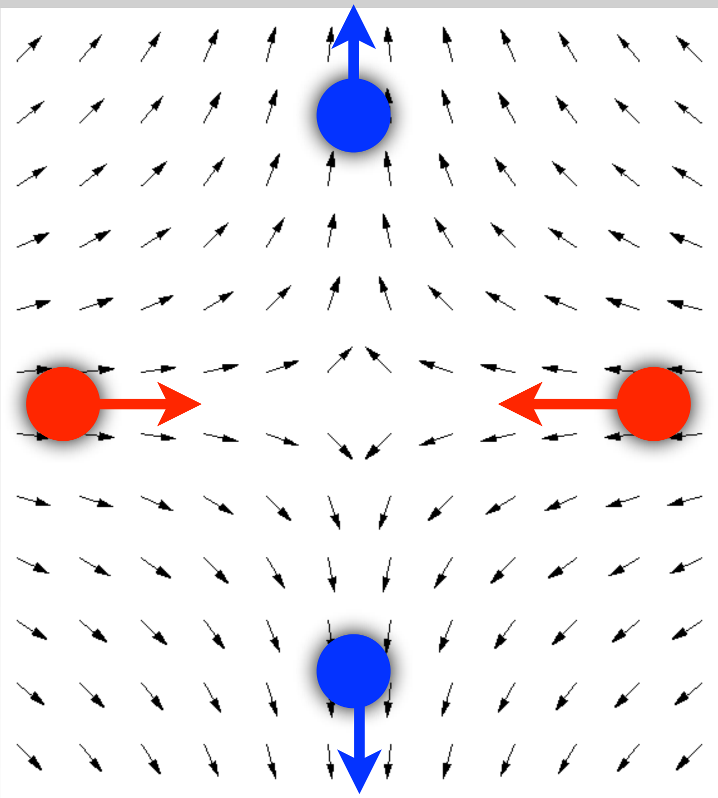
Tidal force on masses

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

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







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

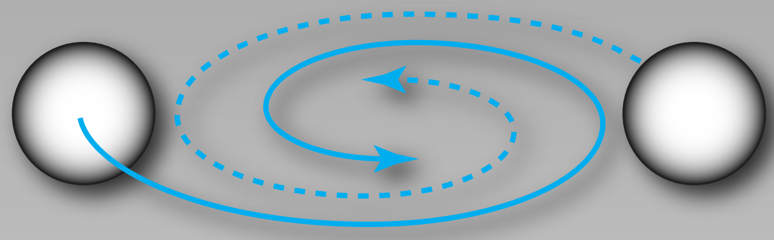
- Cosmic background radiation of GW
- POP-III stars, star formation, etc...

  Physics on early universe.

Expected GW sources

Event like:

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

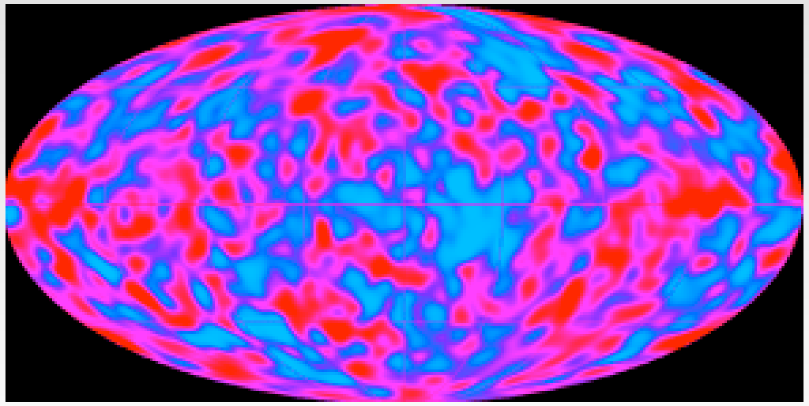


Continuous waves:

- Pulsar rotation
- Binaries

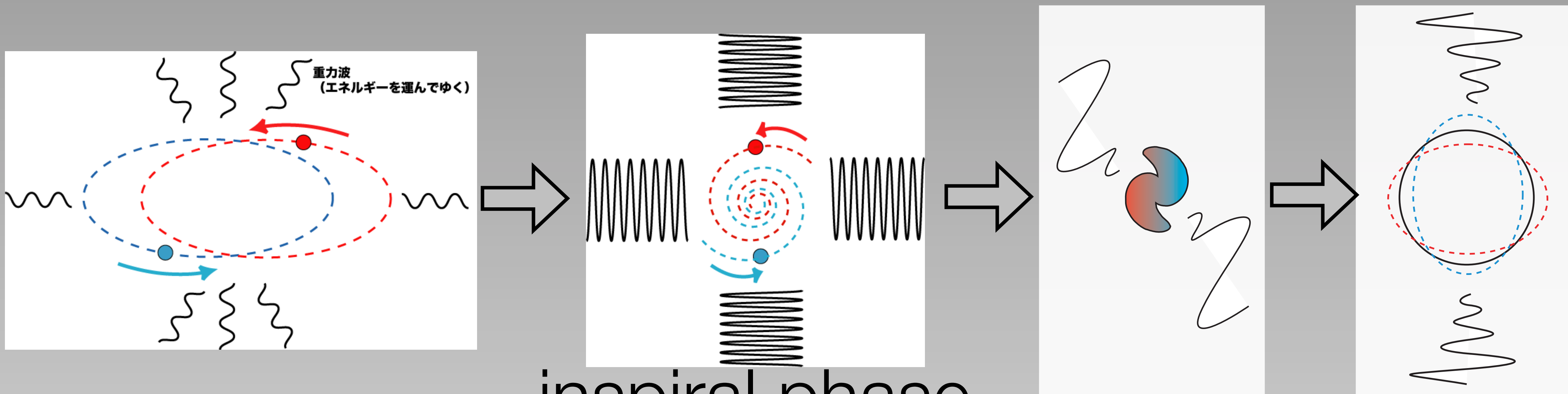
Stochastic Background

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



(& Unknown sources...)

Coalescence of neutron star binary (NS-NS)

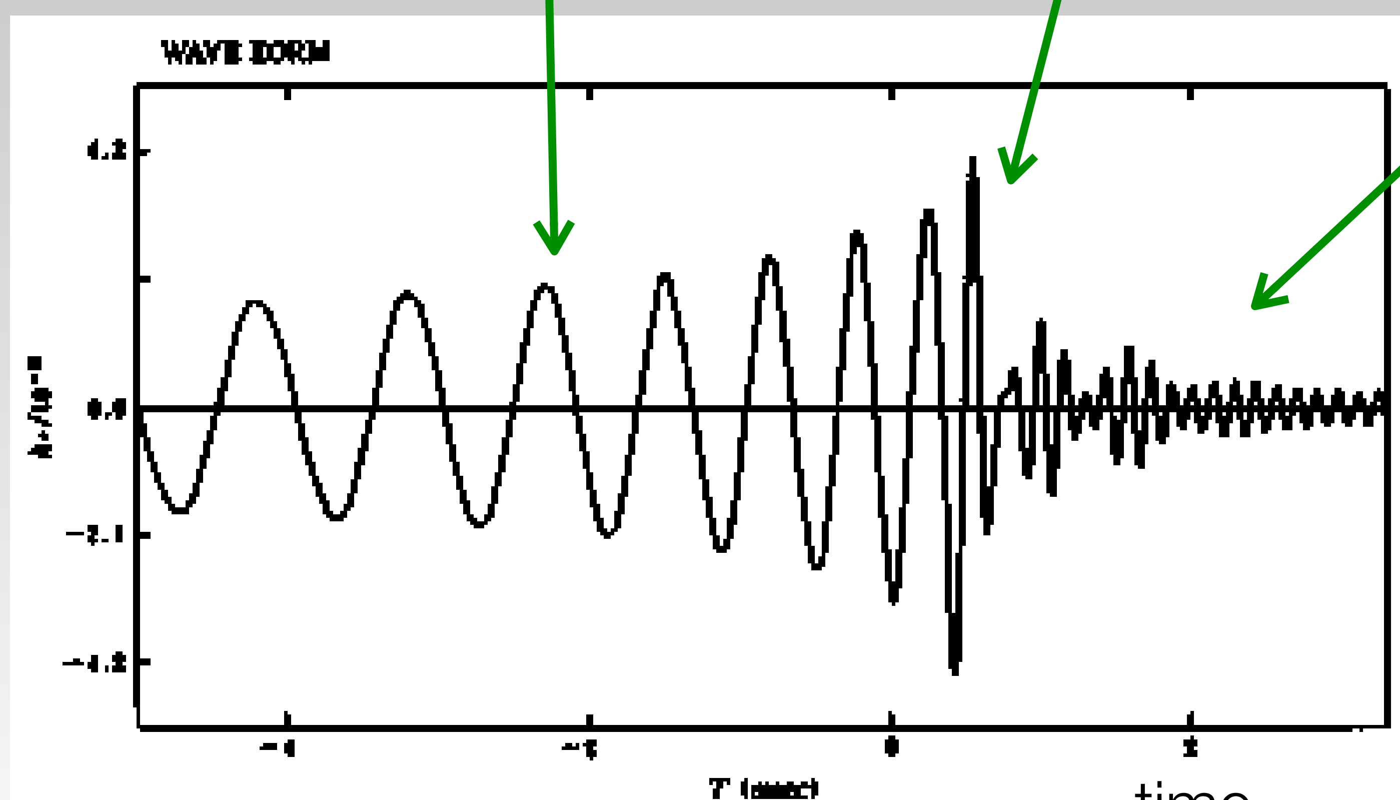


inspiral phase

merger

Blackhole
quasi-normal mode

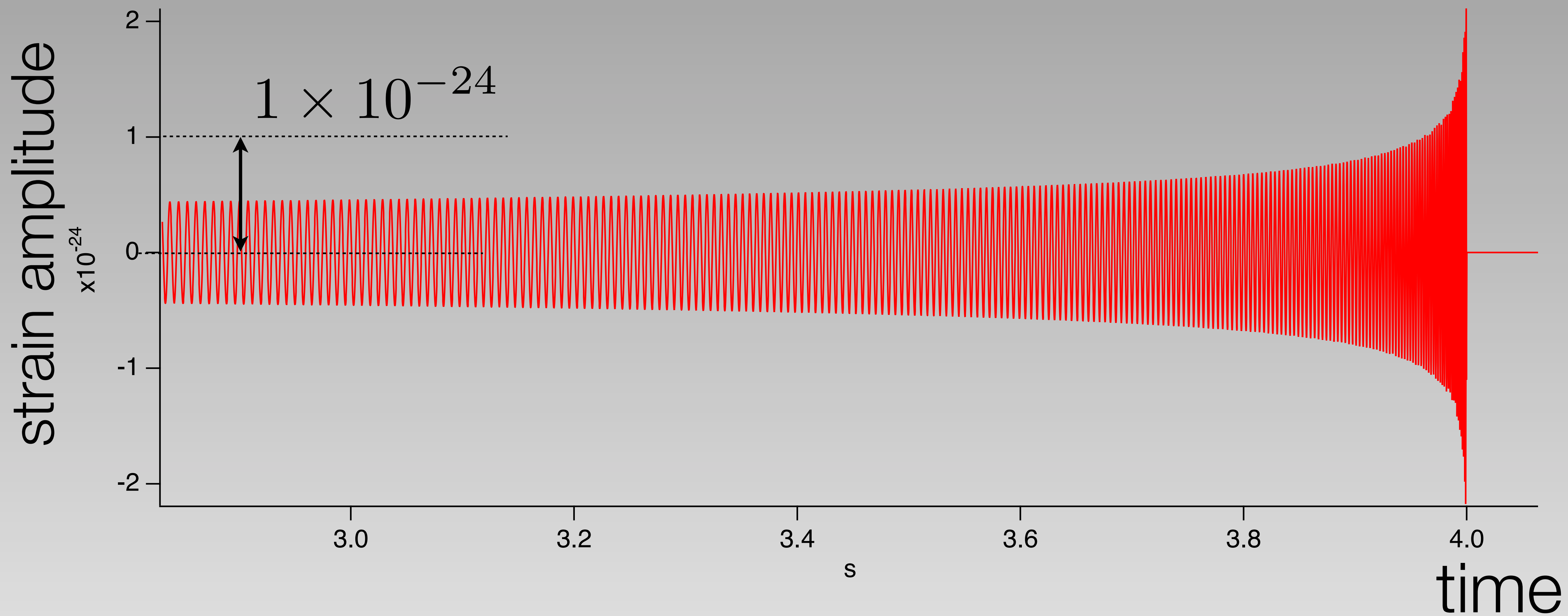
strain amplitude



time

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

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

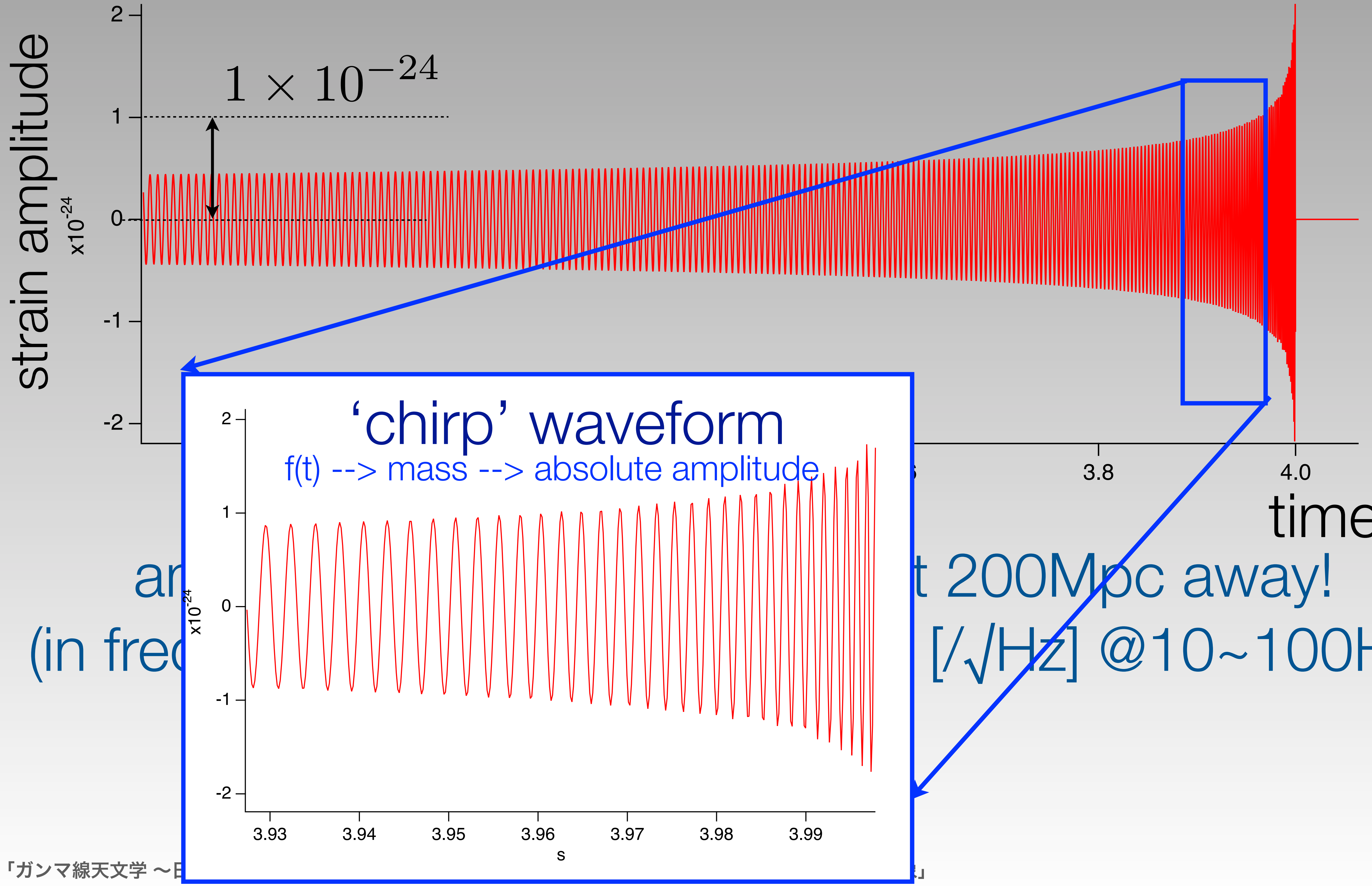


amplitude ~10^{-24} for NS-NS at 200Mpc away!

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

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

--> ***‘standard candle’***

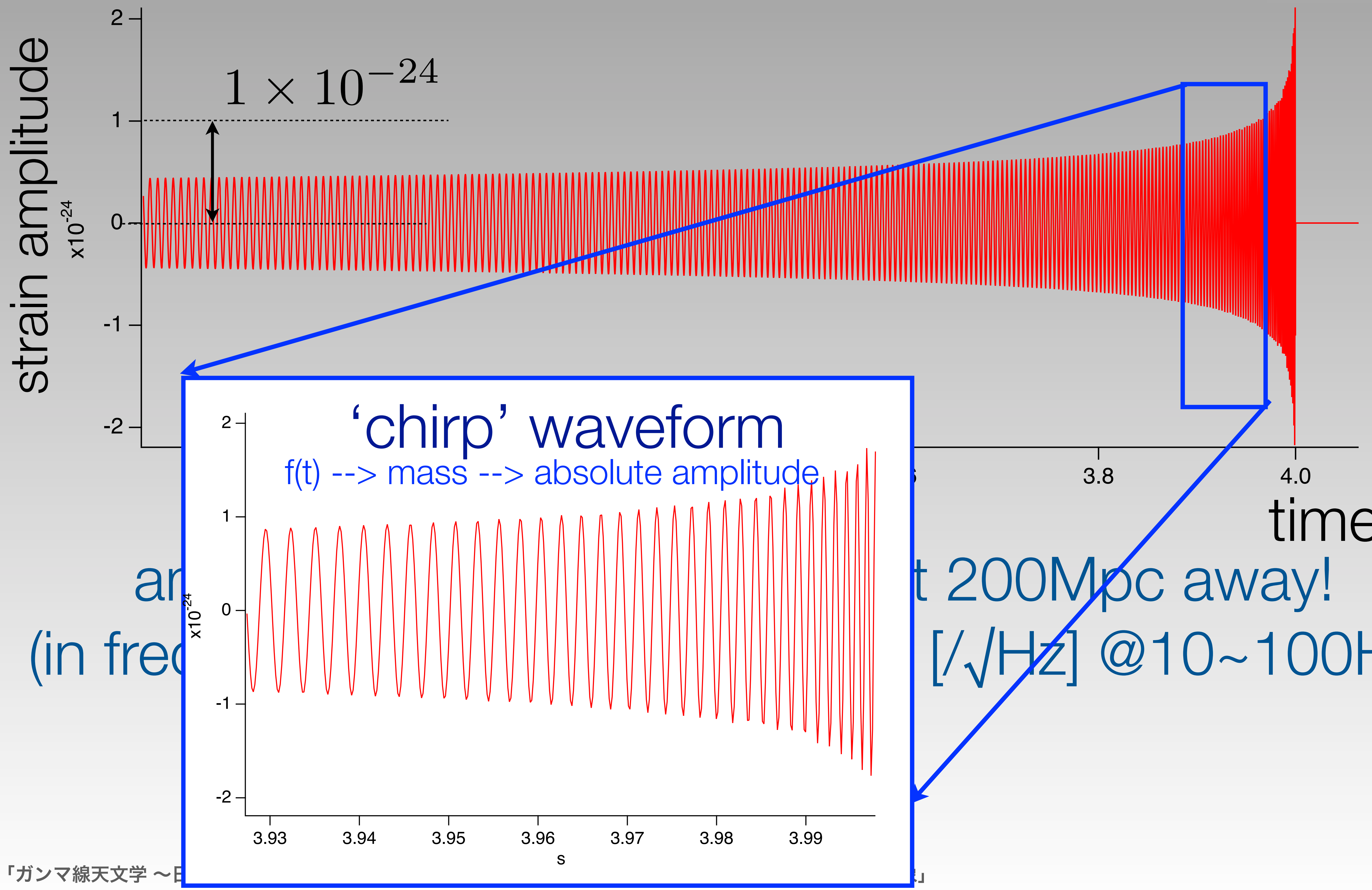


ar… t 200Mpc away!

(in freq… [/√Hz] @10~100Hz)

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

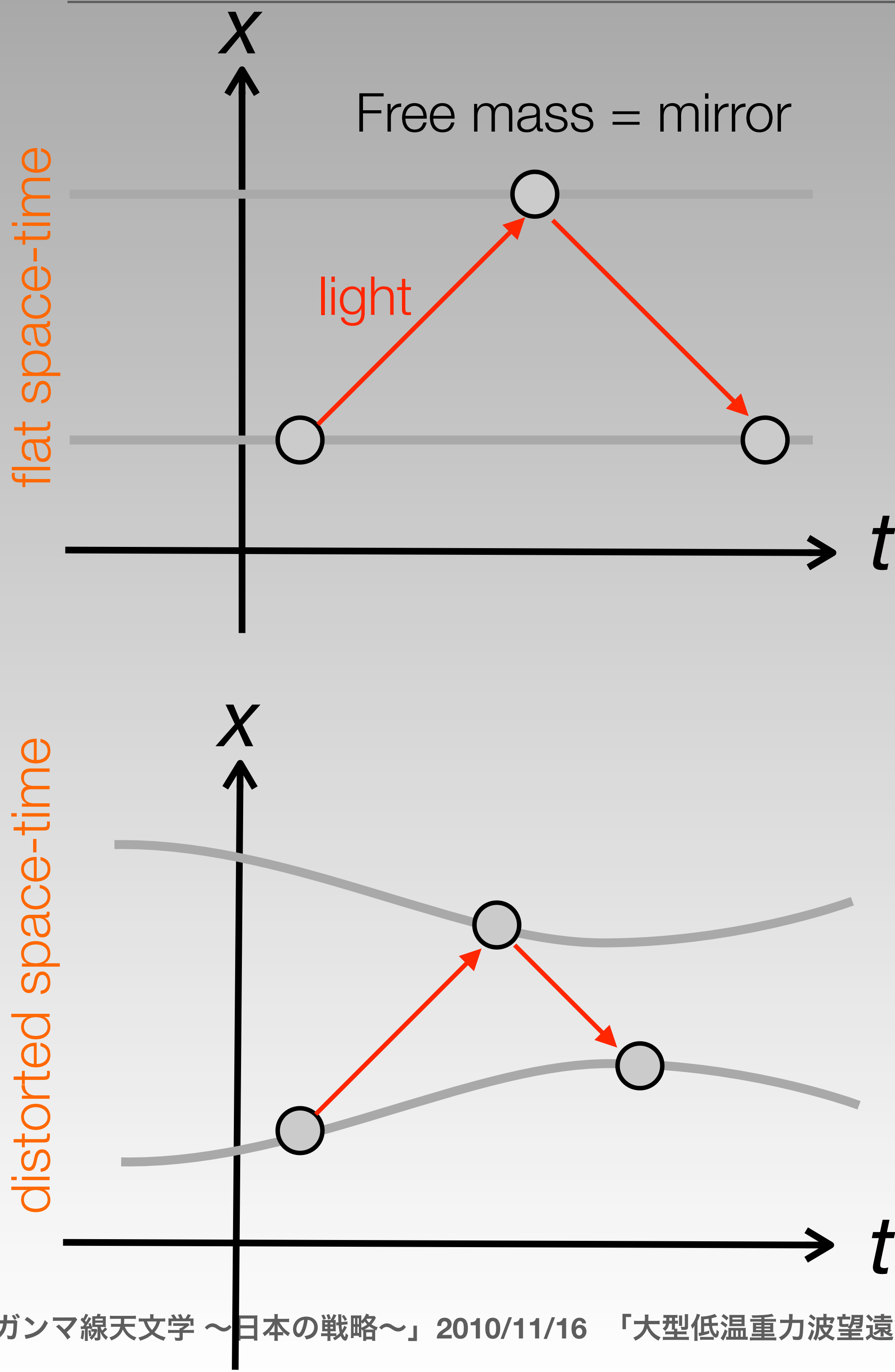
--> ‘***standard siren***’

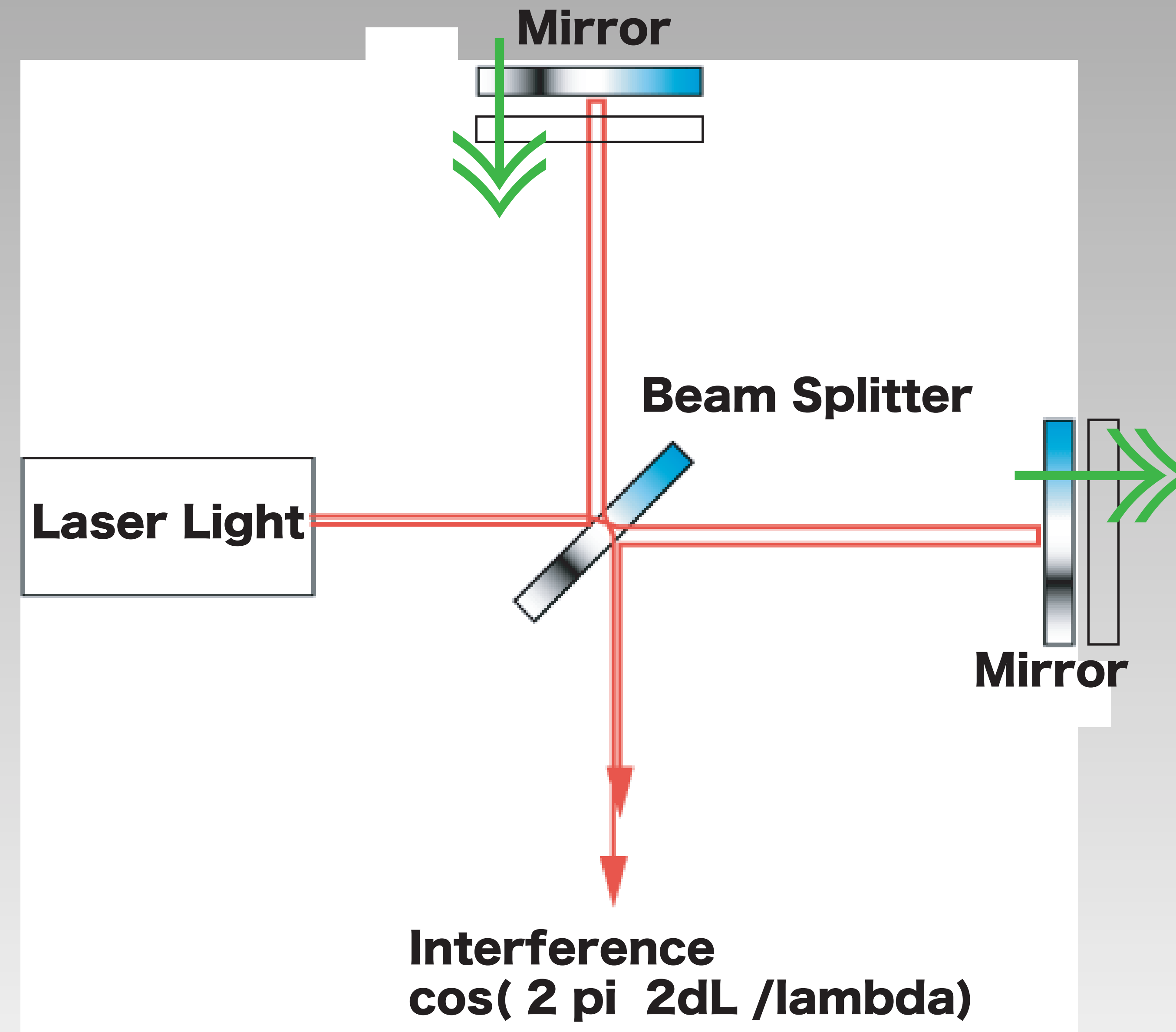


ar … t 200Mpc away!

(in freq … [/√Hz] @10~100Hz)

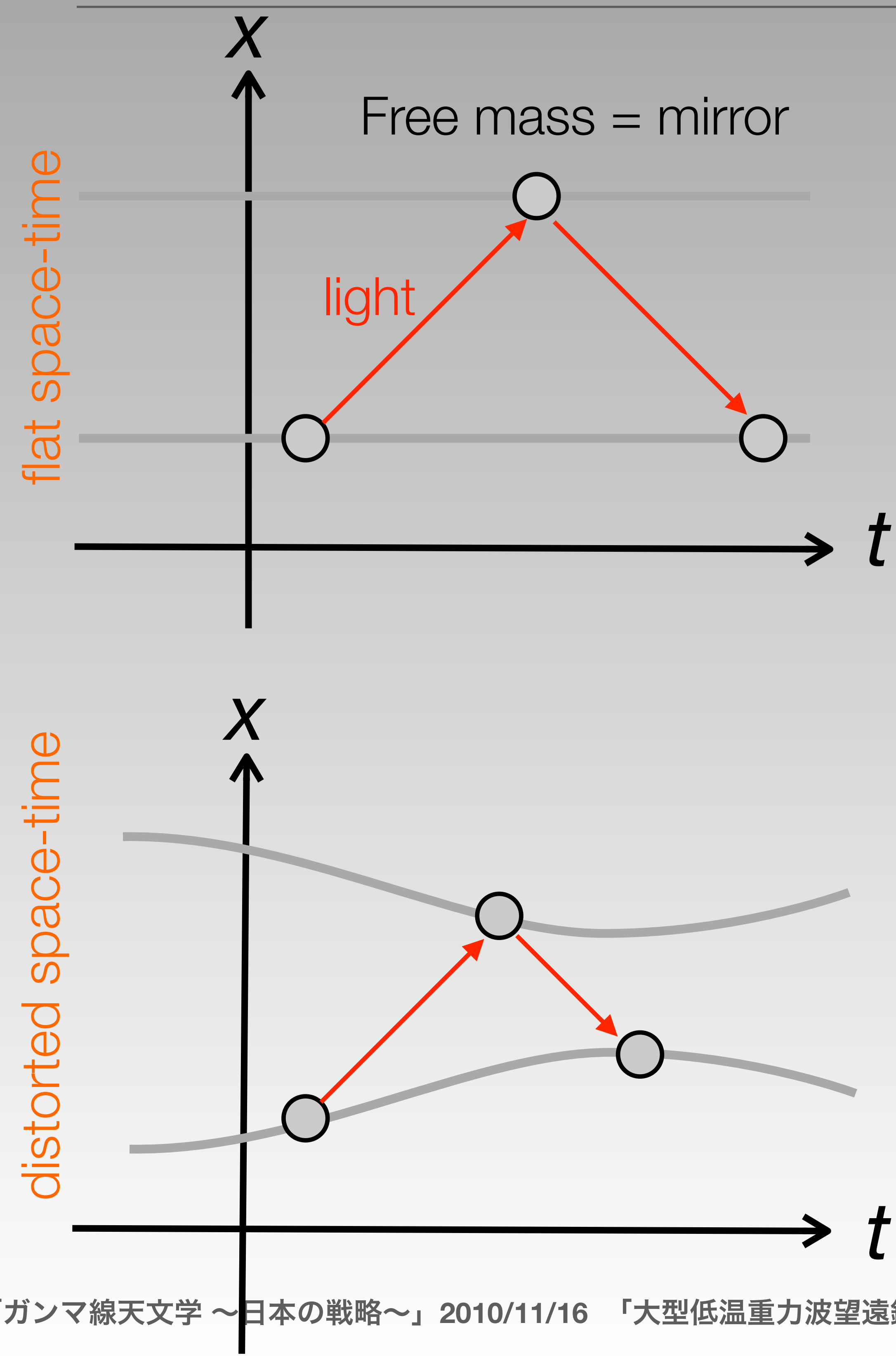
How to detect GW :
Free Test Masses & Laser Interferometer

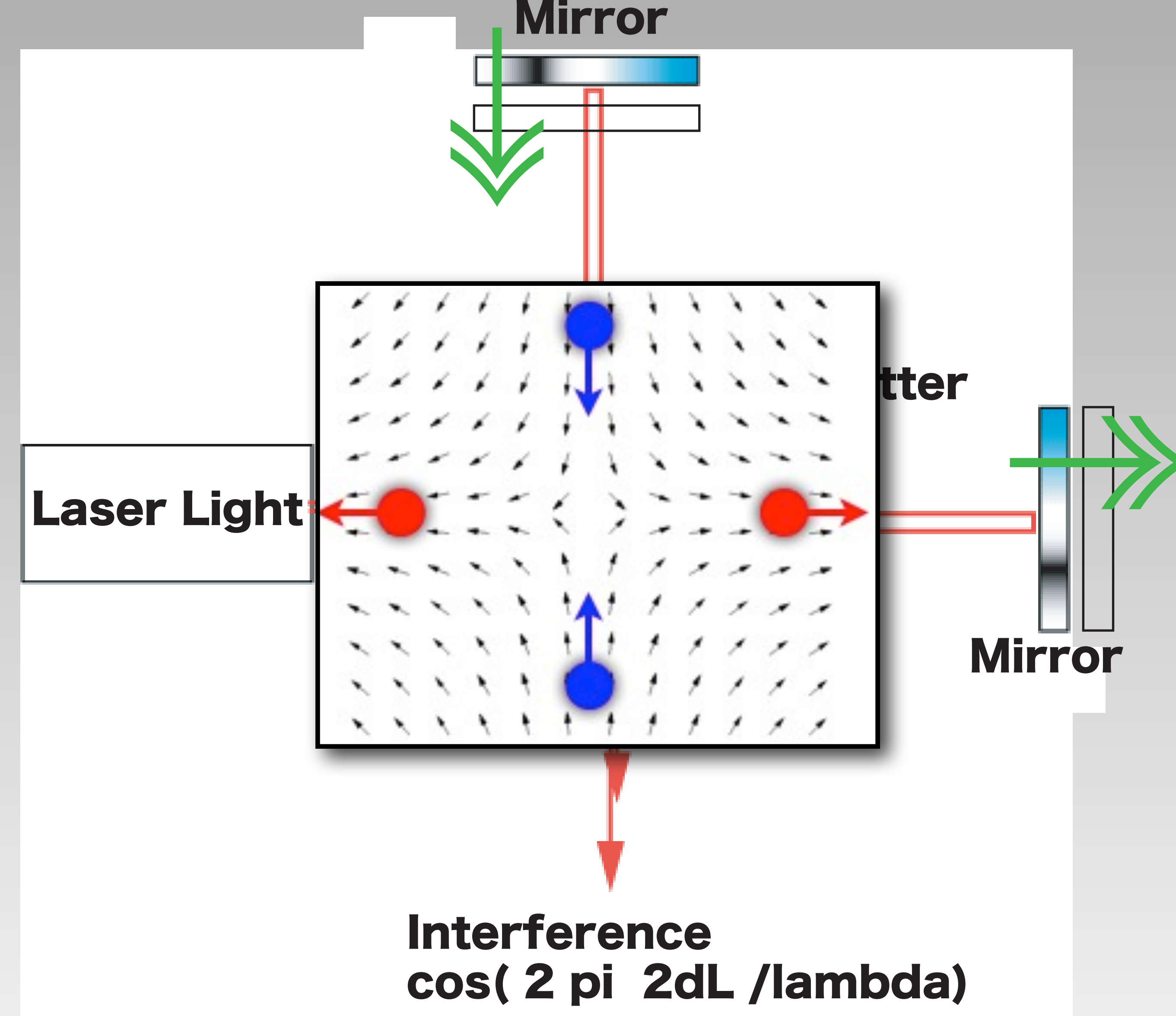




Michelson Interferometer

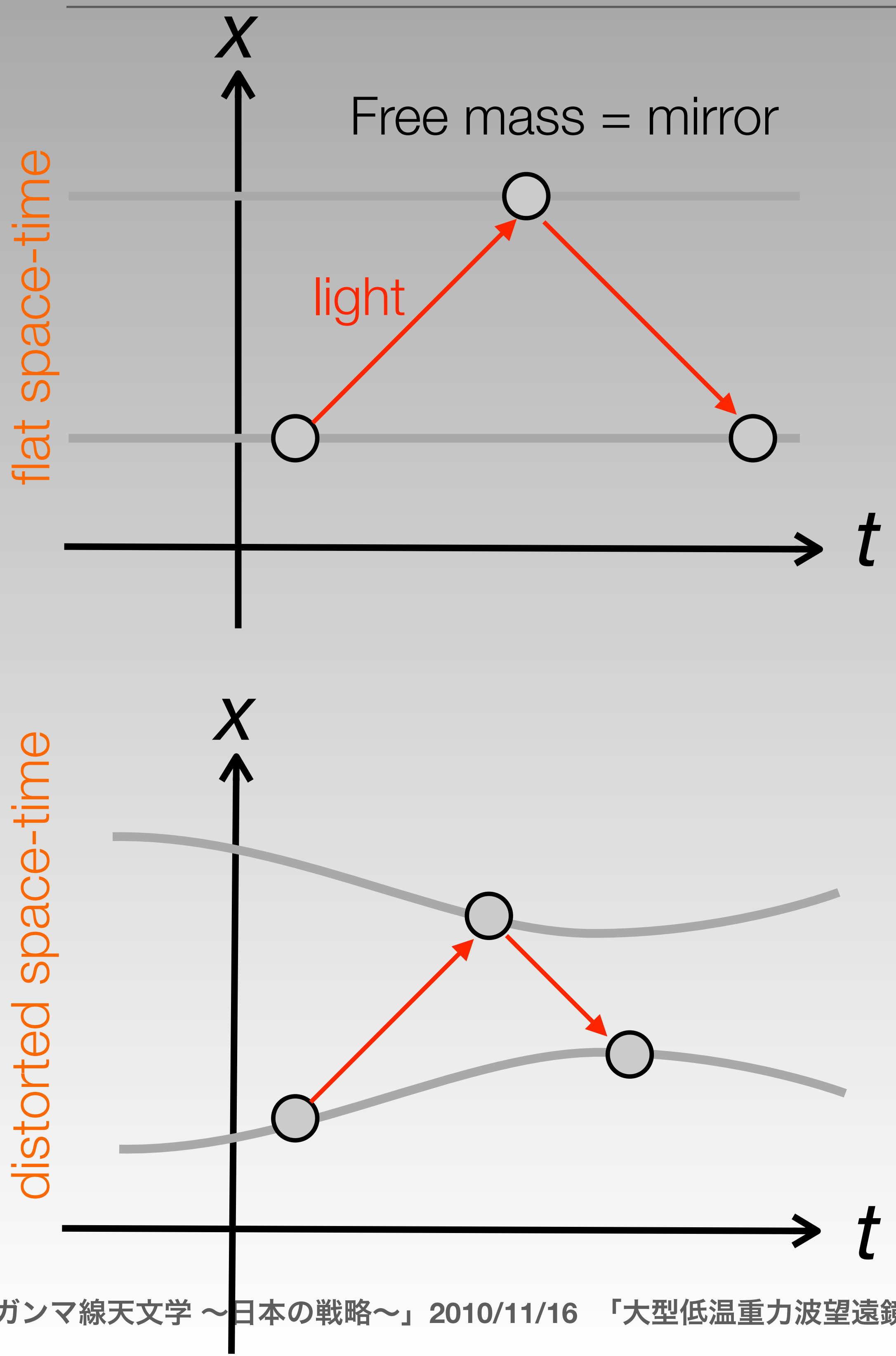
How to detect GW :
Free Test Masses & Laser Interferometer

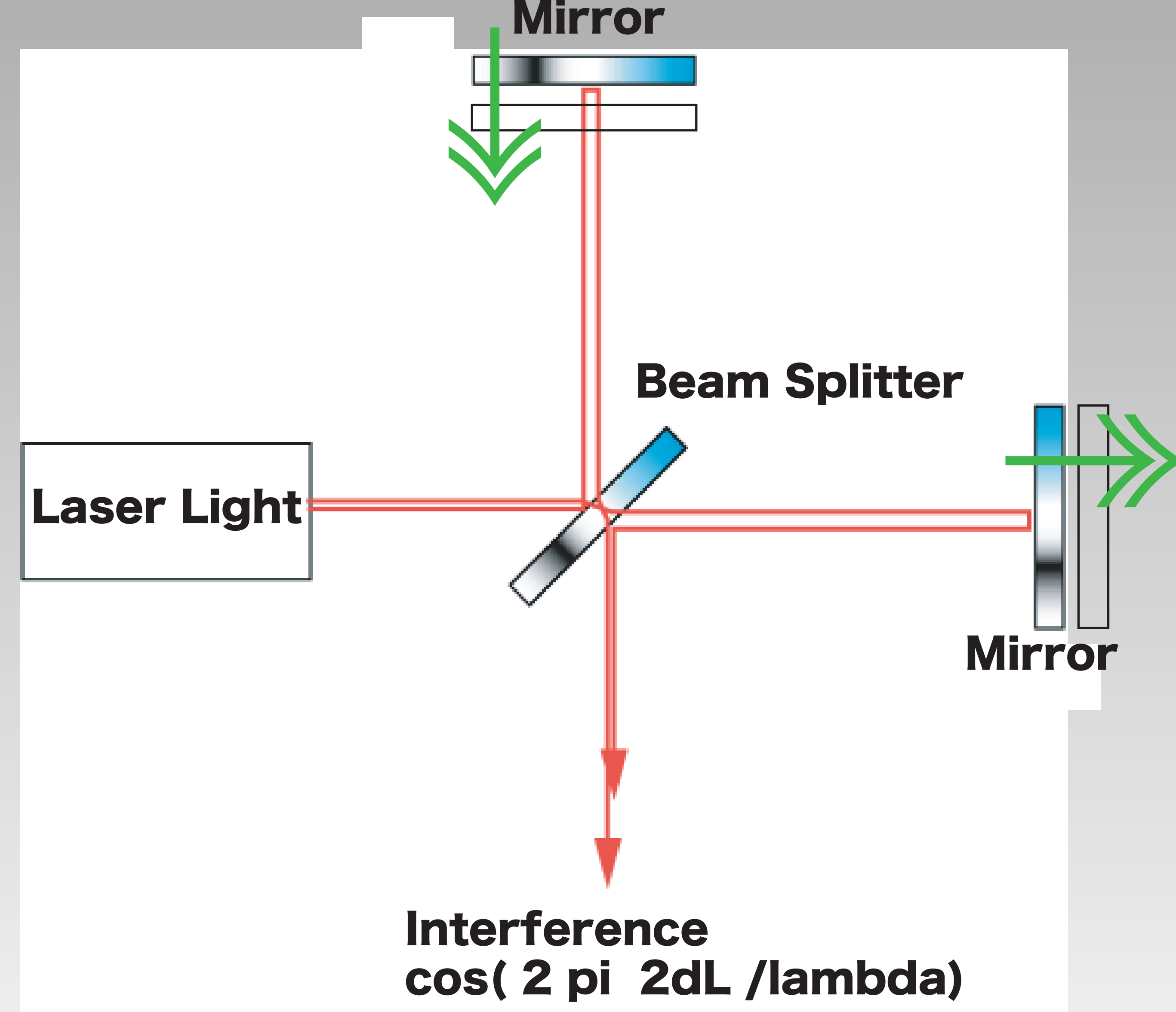




Michelson Interferometer

How to detect GW :
Free Test Masses & Laser Interferometer





Michelson Interferometer

Schematic Figure

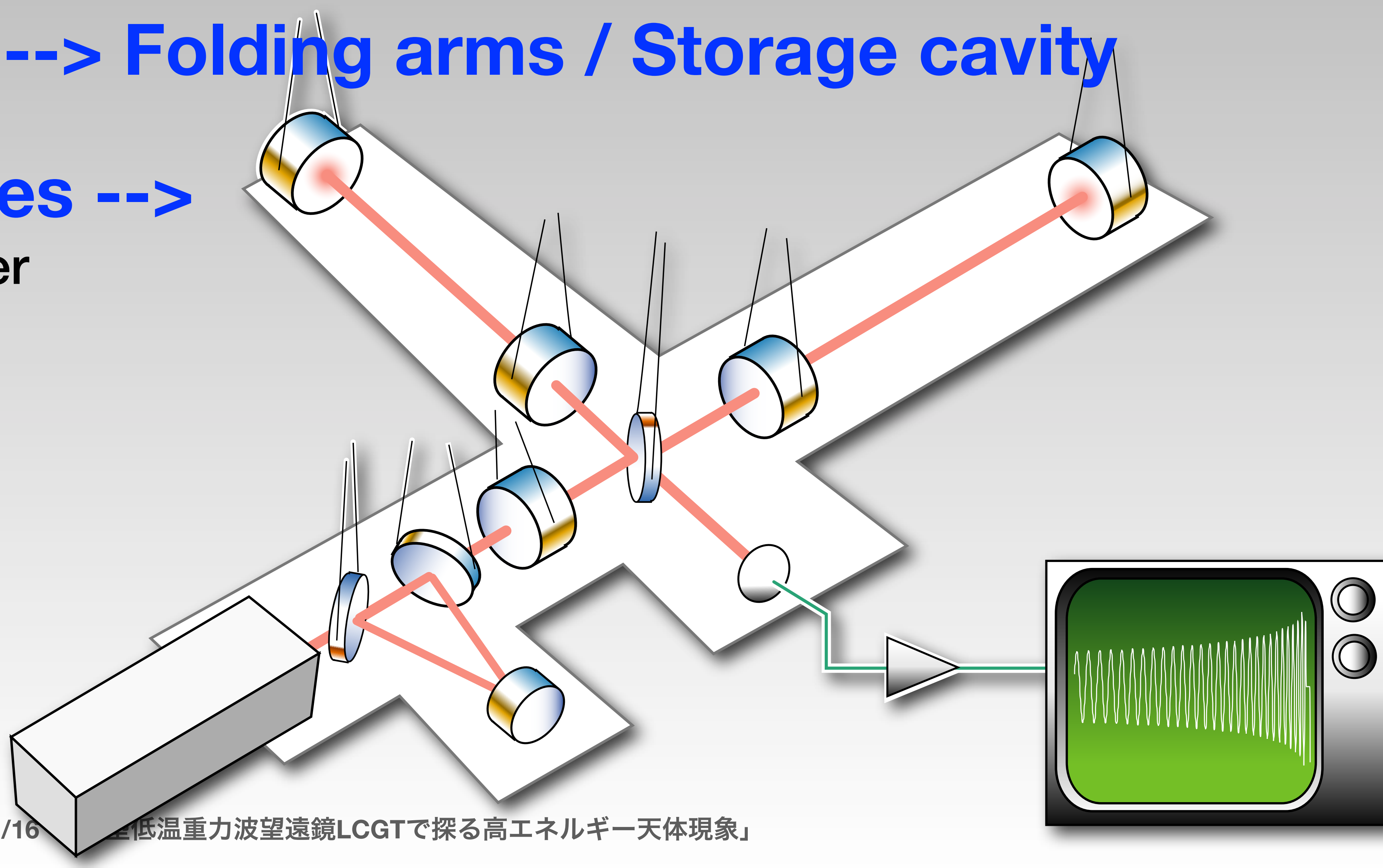
Free mass --> suspended mirror

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 Cryogenic Gravitational wave Telescope)

Underground
- in Kamioka, Japan

  Silent & Stable environment

3km baseline

Cryogenic Mirror
- 20K
- saffhire substrate

Plan

2010 : construction *start now!*

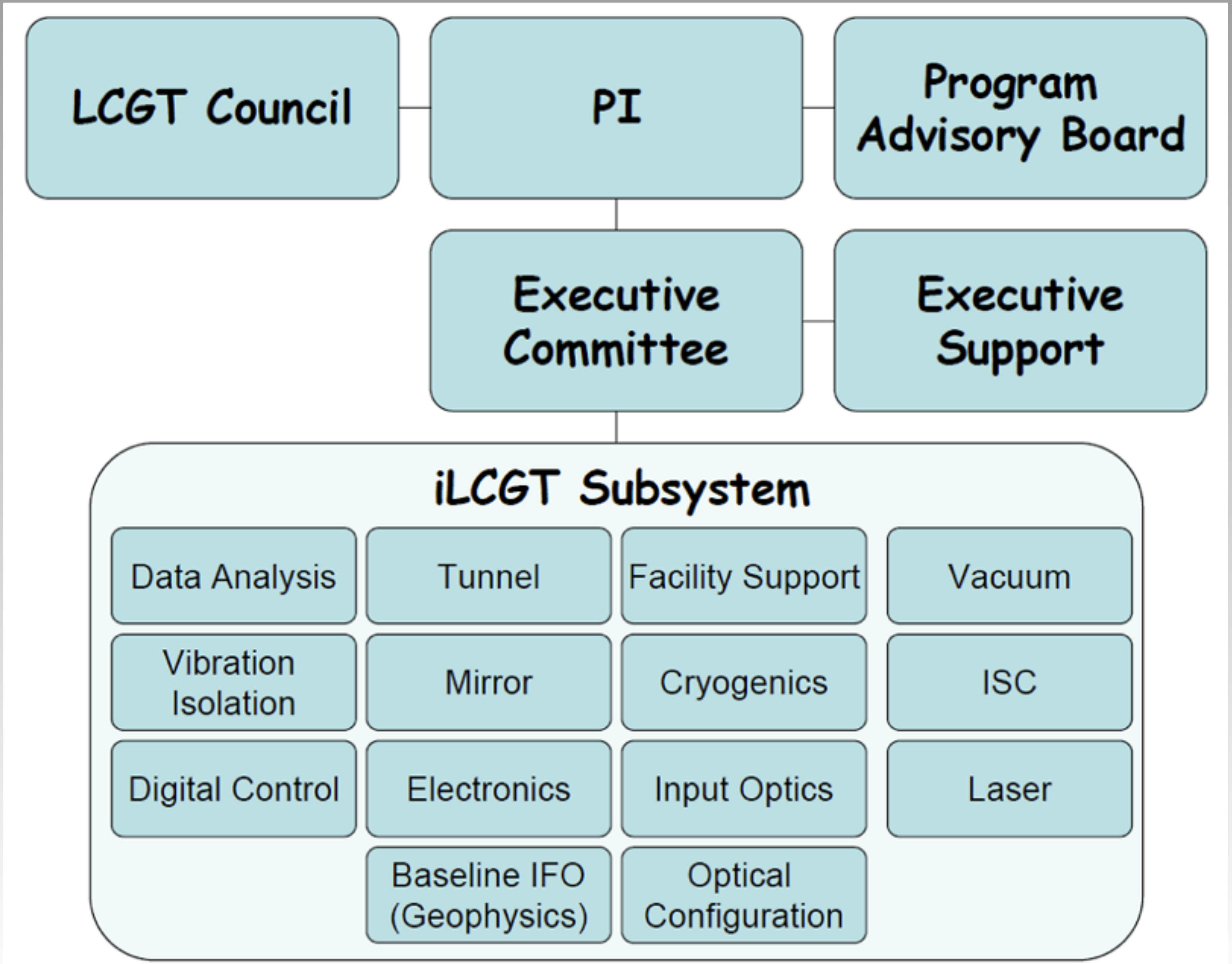
2014 : first run in normal temperture

2017- : observation with cryogenic mirror

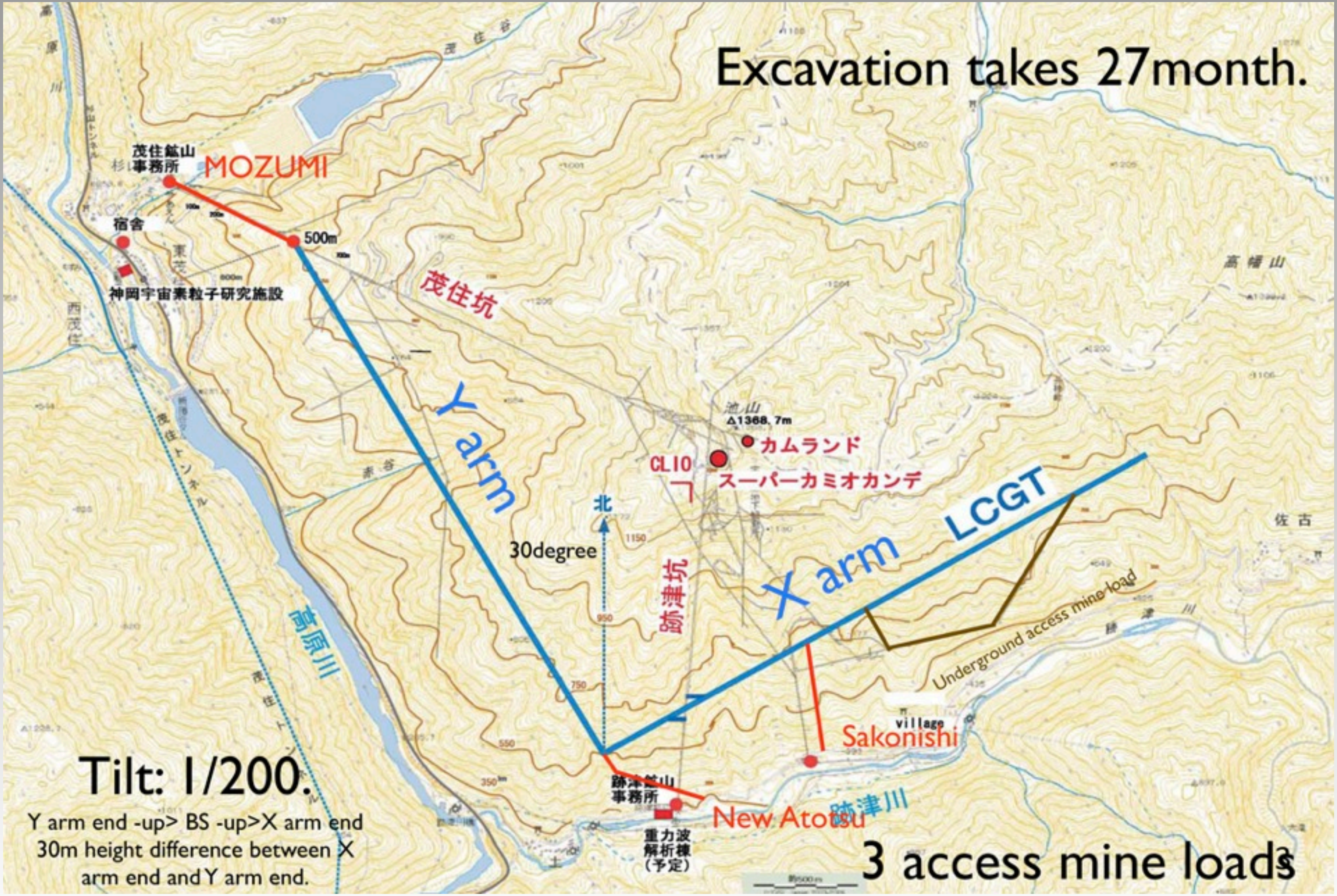
LCGT collaboration

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



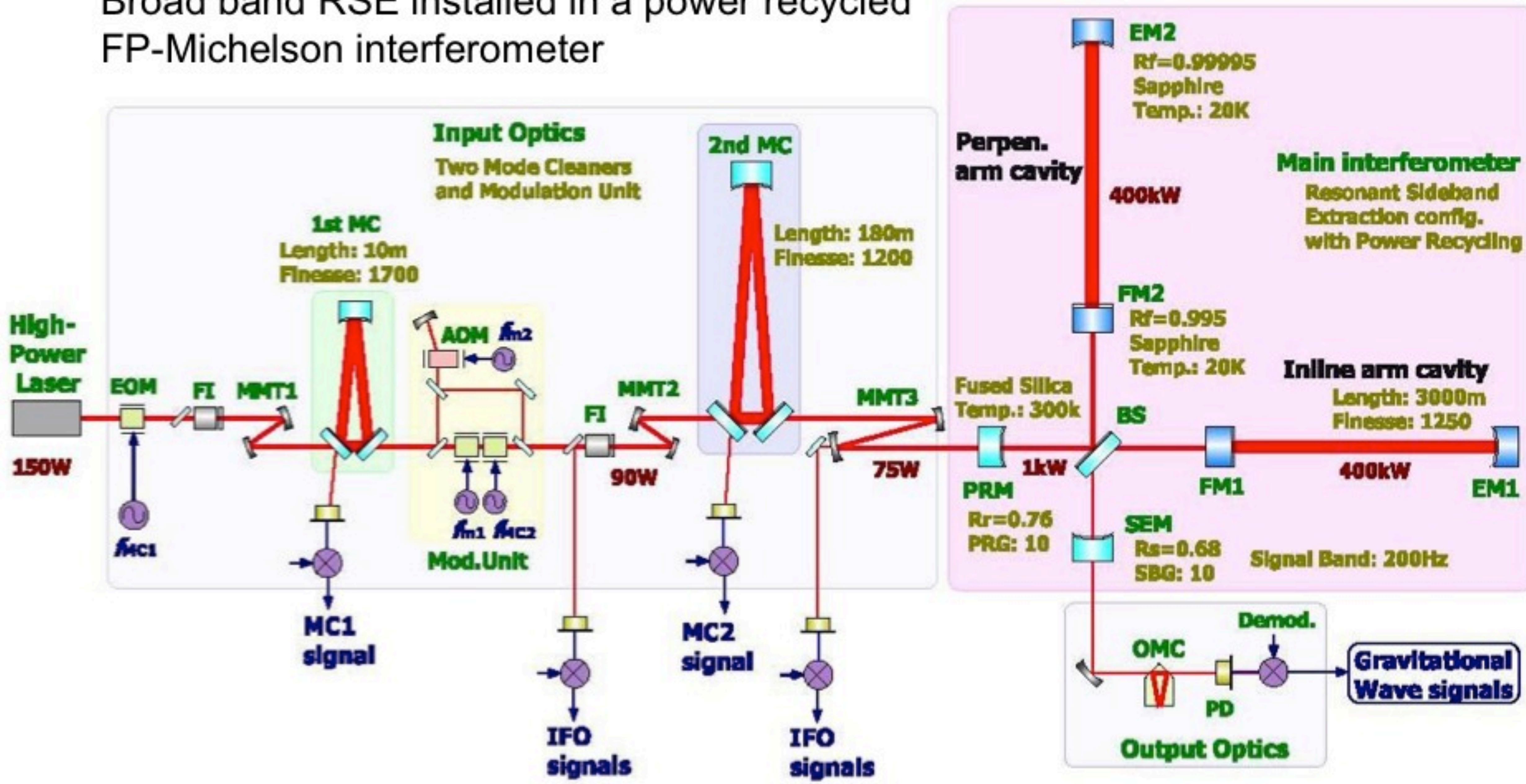
Site



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
CL10
スーパーカミオカンデ
北
30degree
跡津坑
LCGT
X arm
Underground access mine load
高幡山
佐古
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

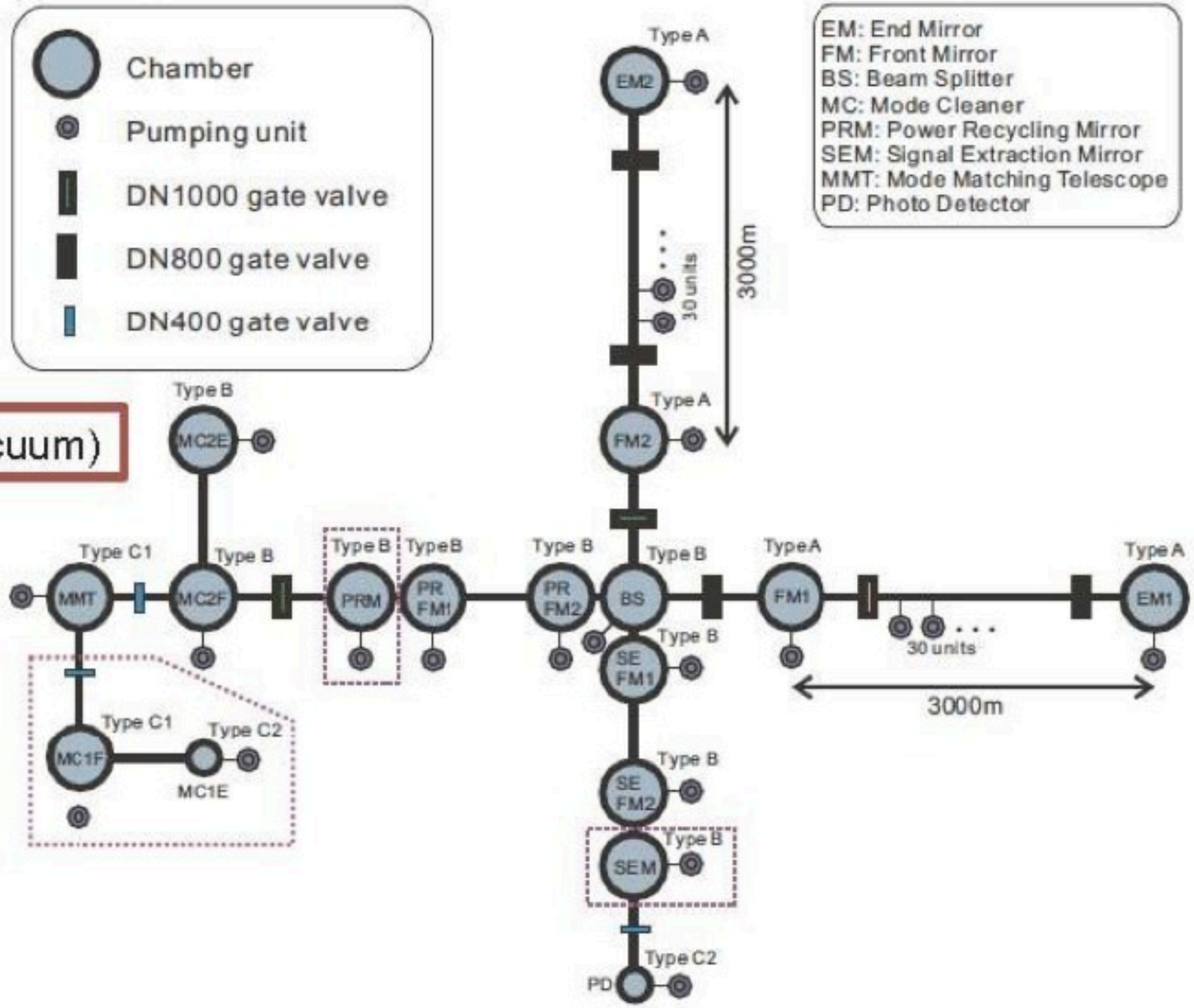
---removing the 180 m long mode cleaner cavity

---flexibility change of possible adoption of detuned RSE

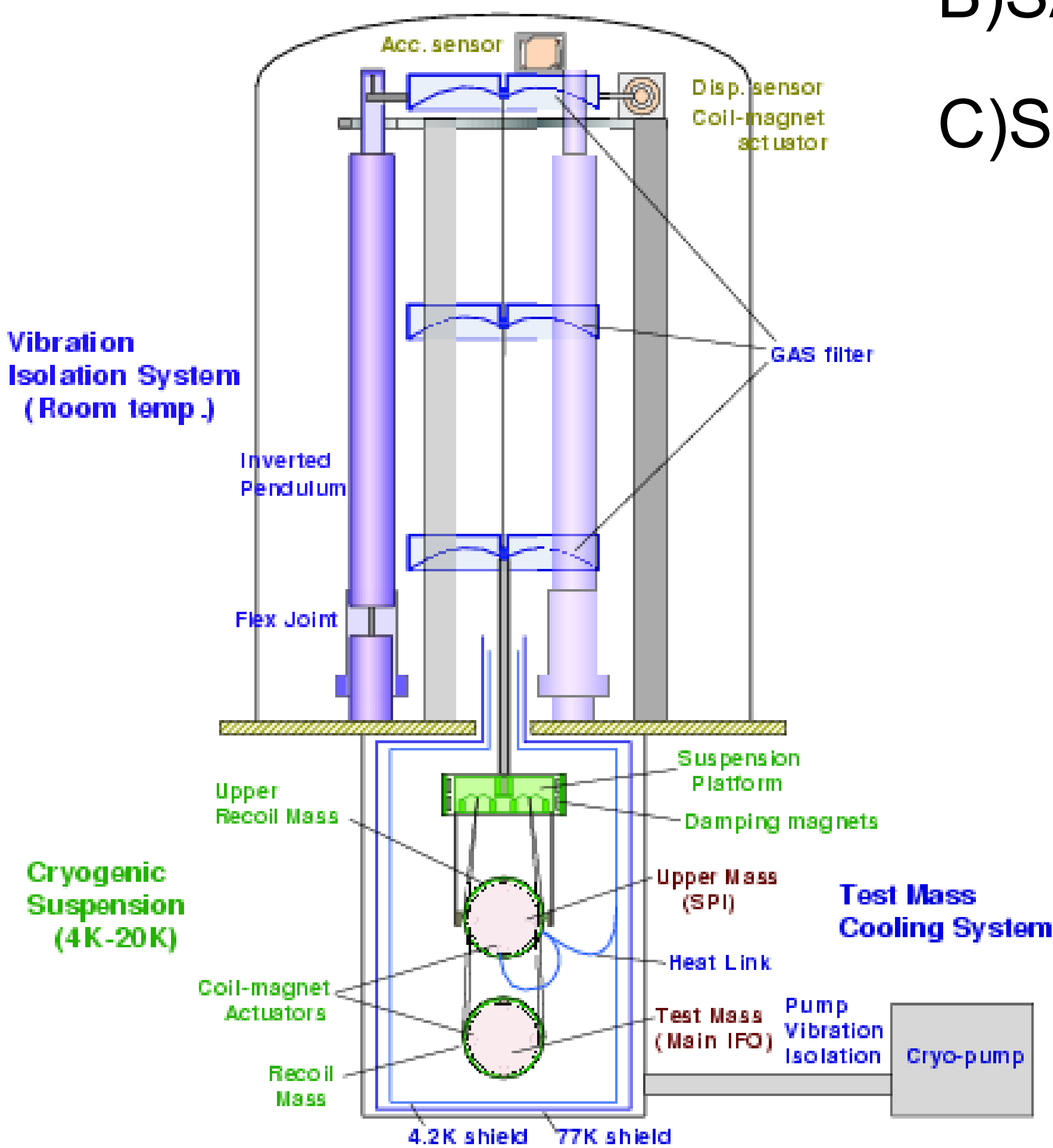
Vacuum System

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

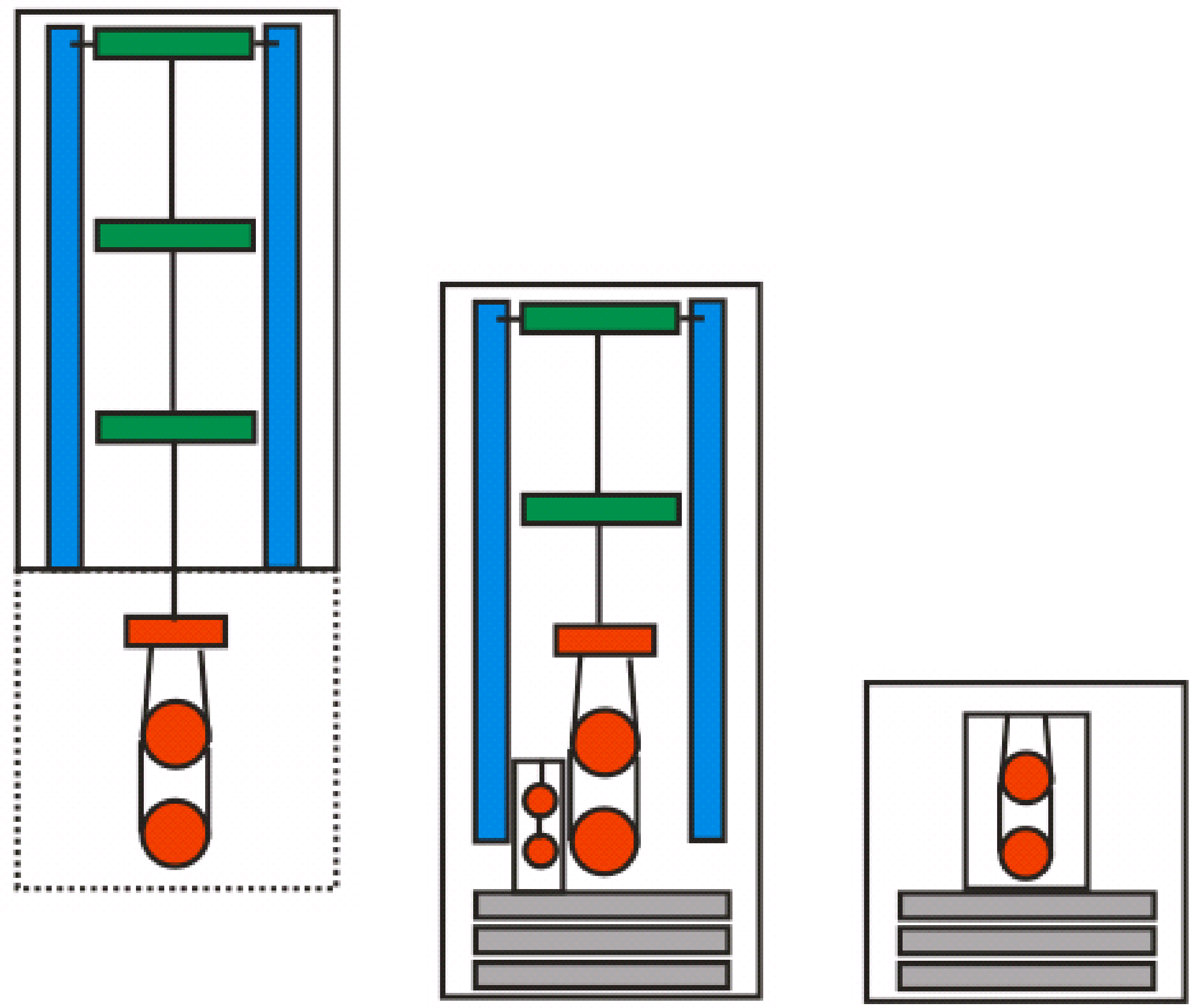
UHV (ultra high vacuum)



Design of anti-vibration system

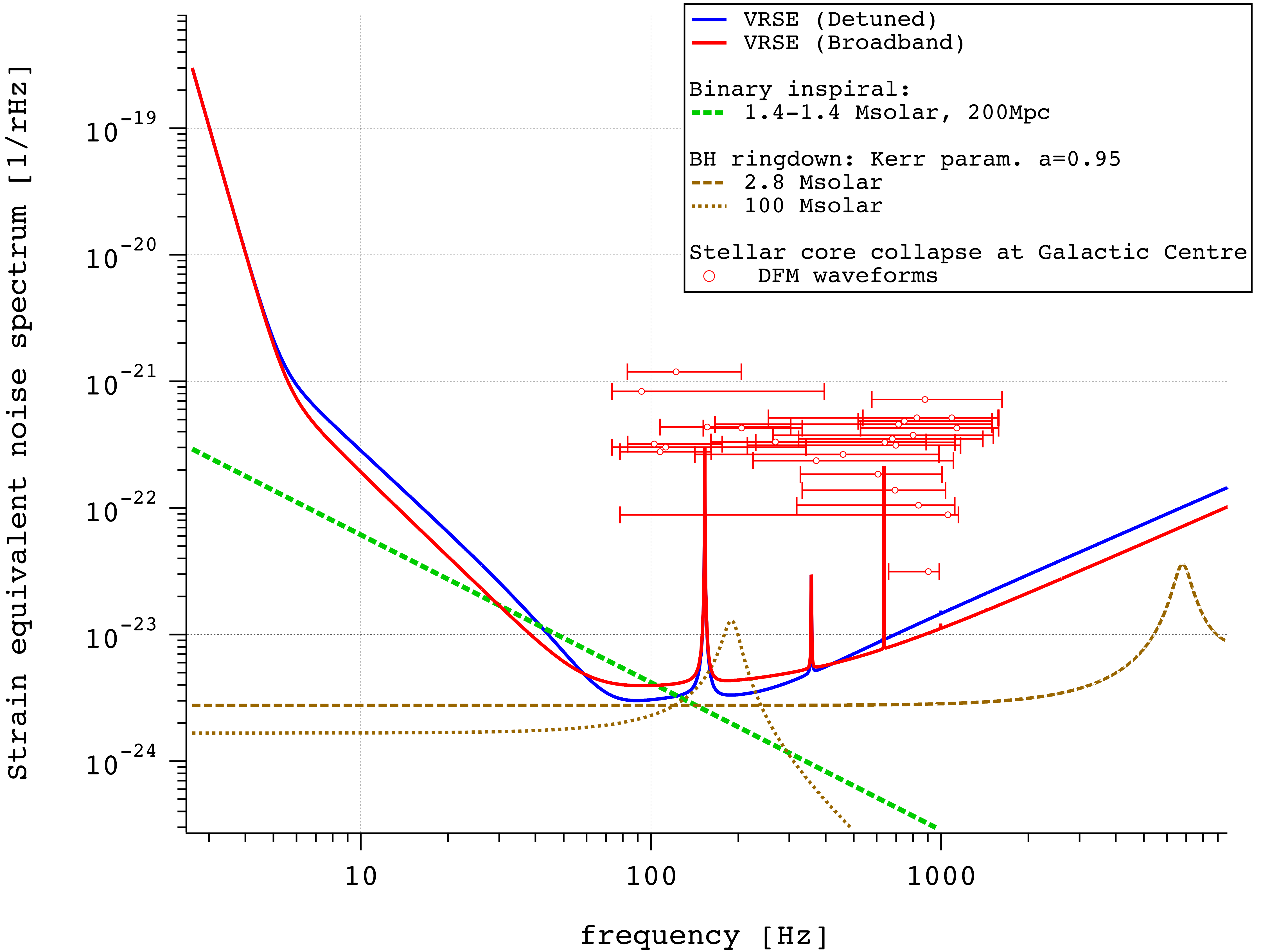


A)SAS(GASF 3stage)+cryo-sus:
FM1、FM2、EM1、EM2
B)SAS(GASF 2stage)+non-cryo:
BS、PRM、SEM、FM、MC2F、MC2E
C)STACK+2stages: MC1F、MC1E、MMT、PD

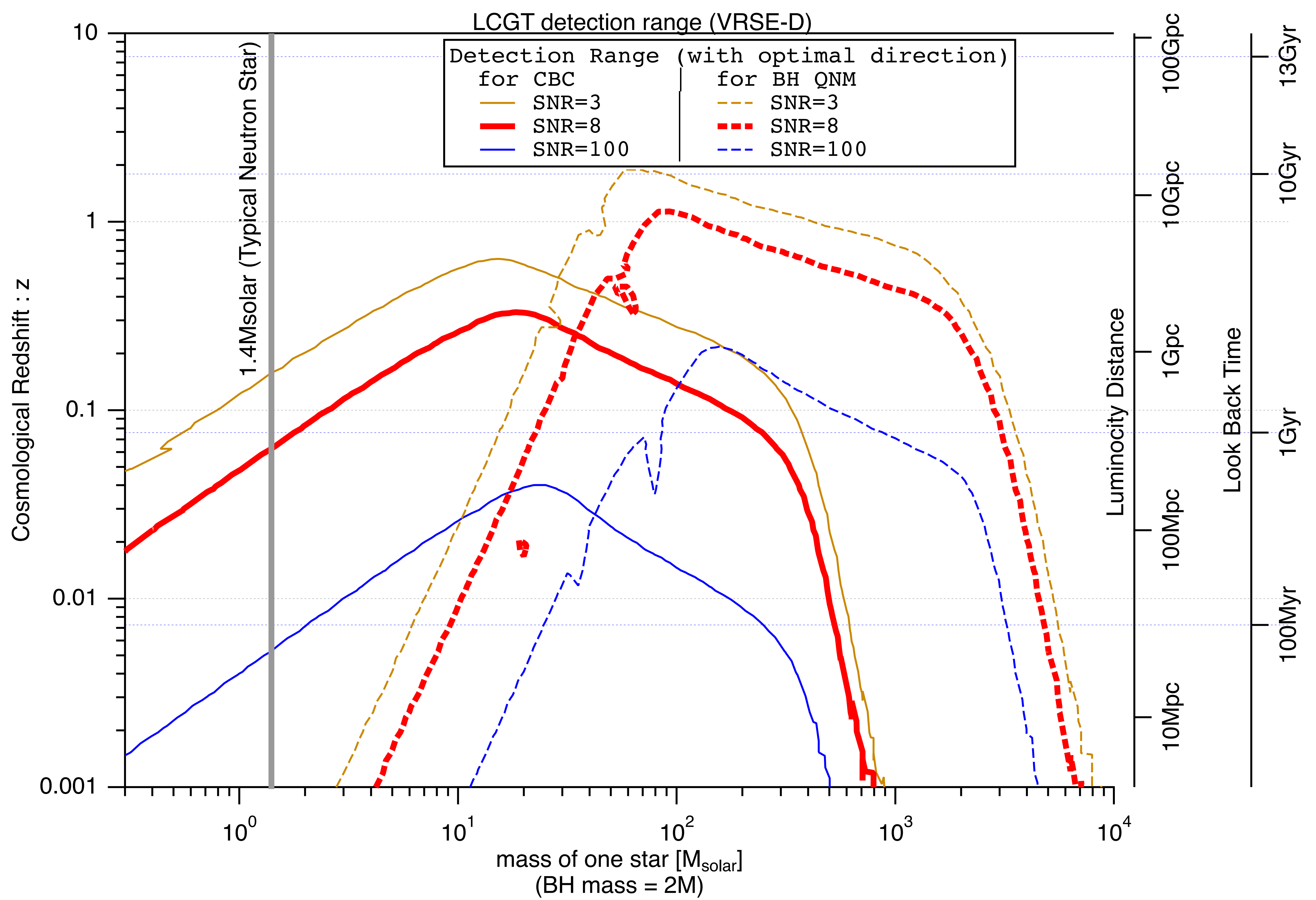


A B C

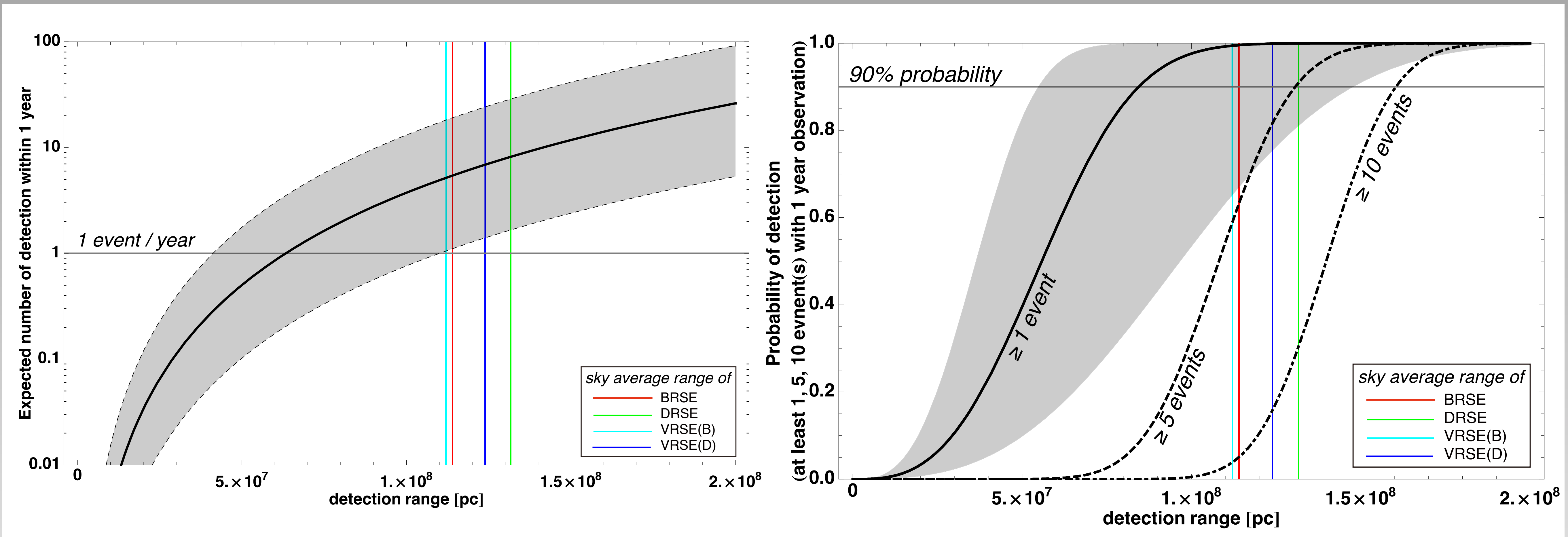
Design Sensitivity of LCGT



Detection Range for Compact Binary and Blackhole QNM

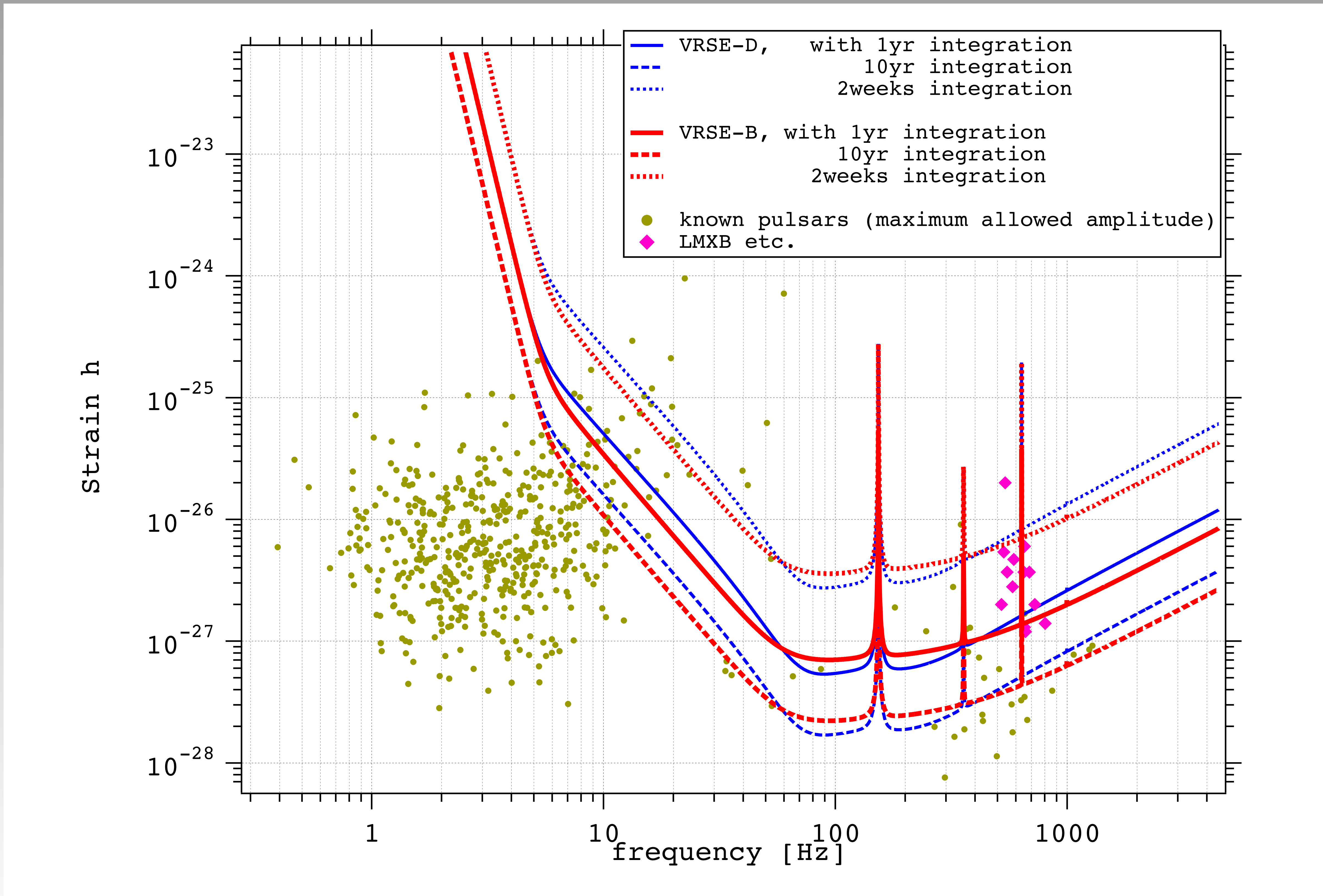


Probability of Detection (NS-NS)

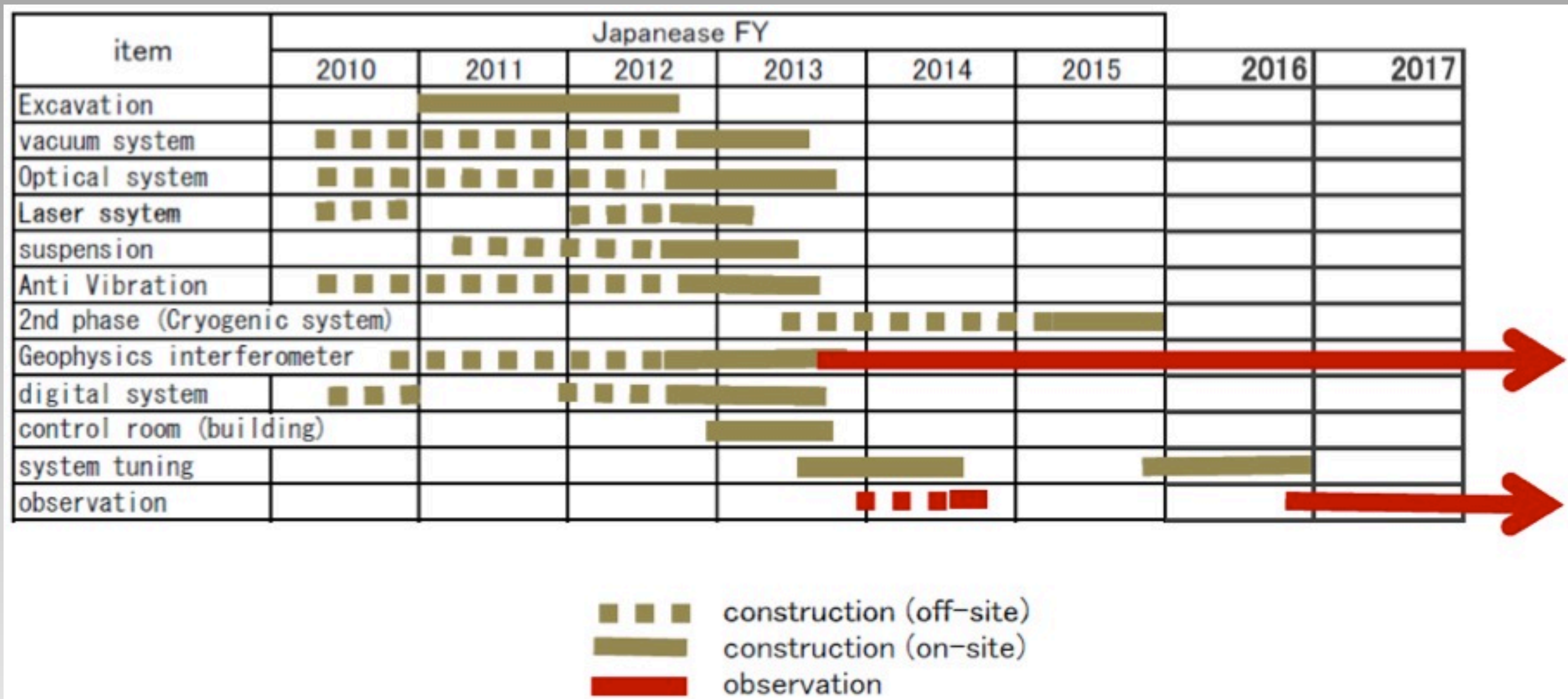


NS-NS Detection Range (sky average)	123 Mpc
(optimal direction)	281 Mpc
Expected # of events	$6.9^{+17.3}_{-5.5}$ events/year
Probability of detection at least one event	99.9 % for one year
90% for 1st event	4 months

Sensitivity for Continuous GW

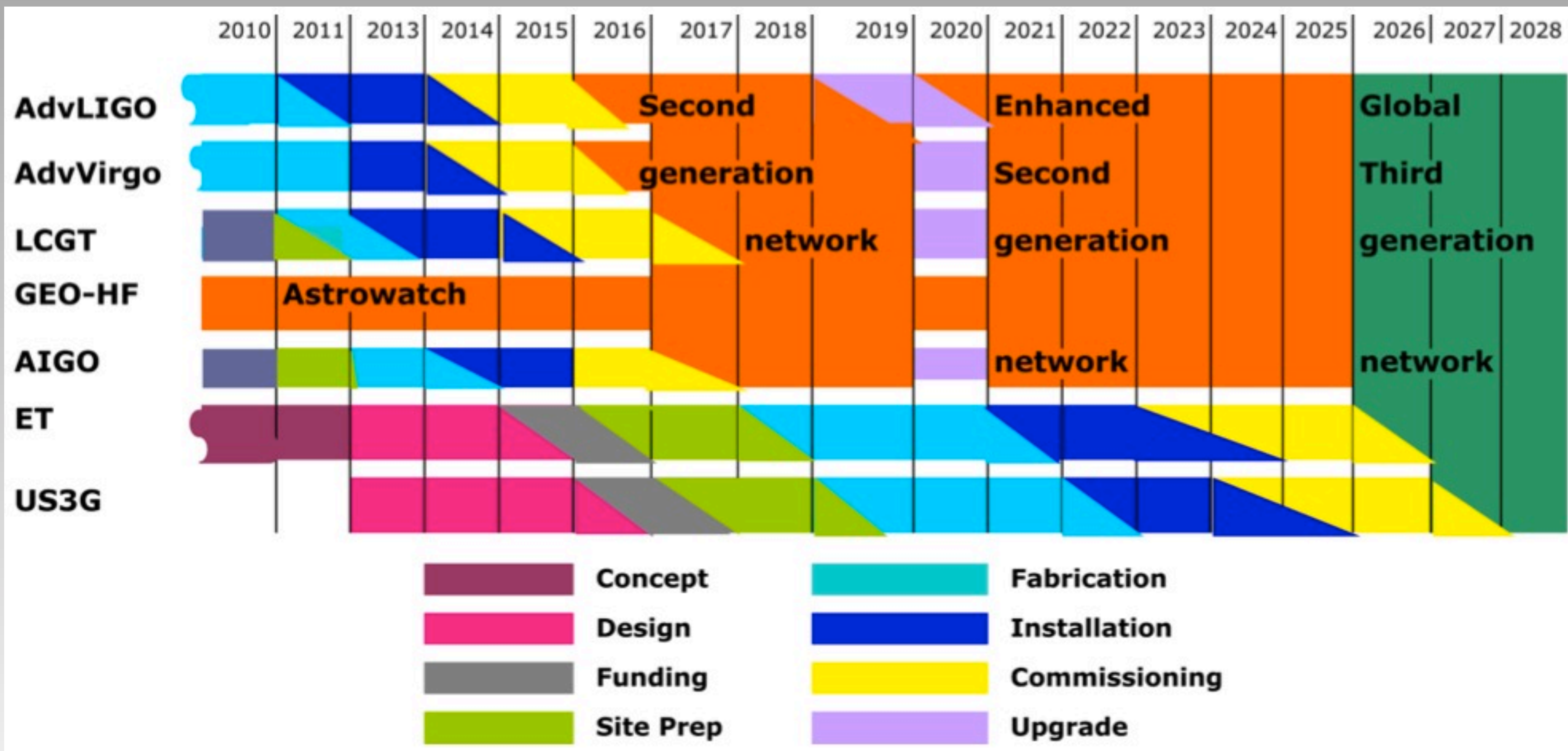


Schedule (Construction & Observation)



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

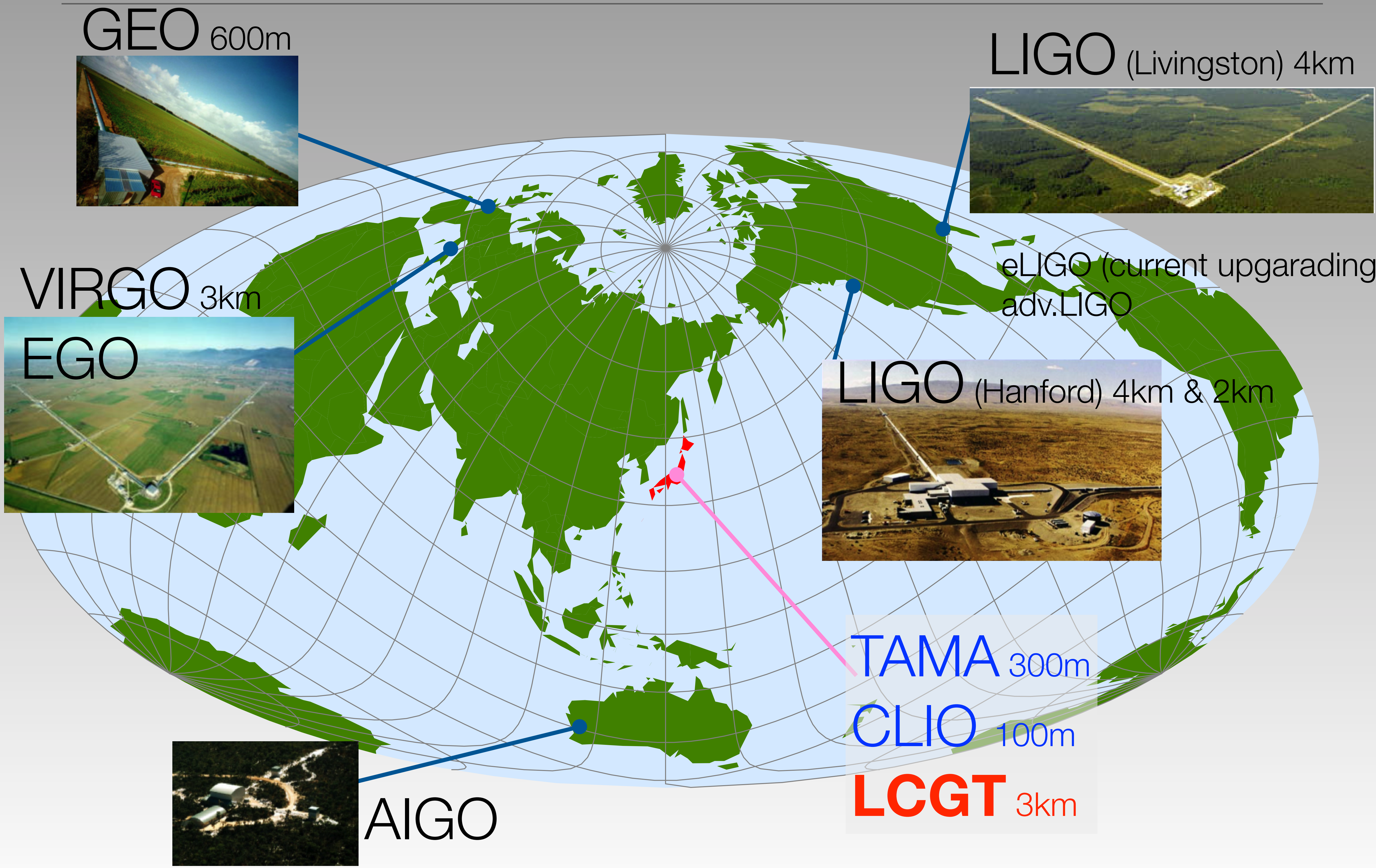
GWIC (Gravitational Wave International Committee) RoadMap



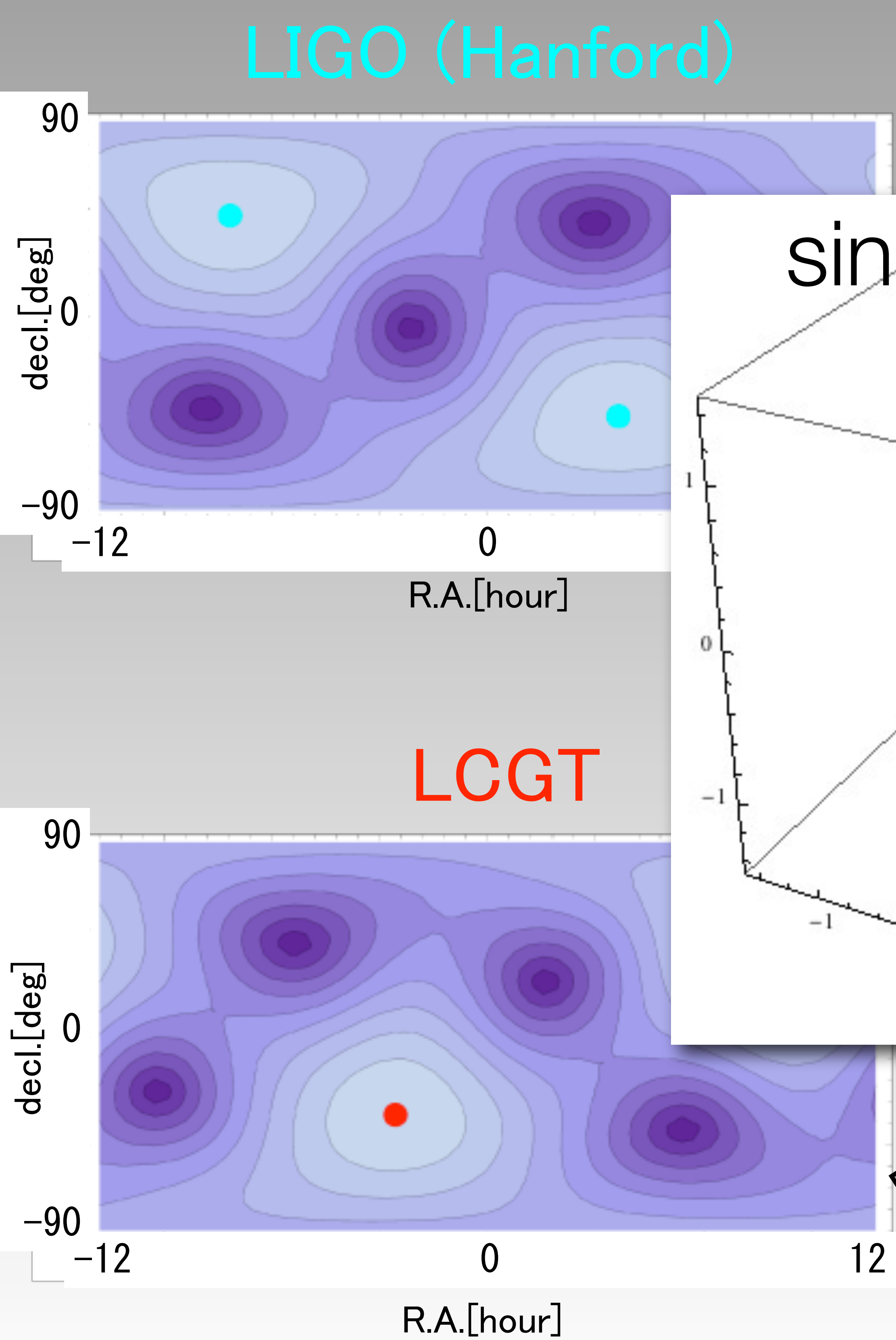
https://gwic.ligo.org/

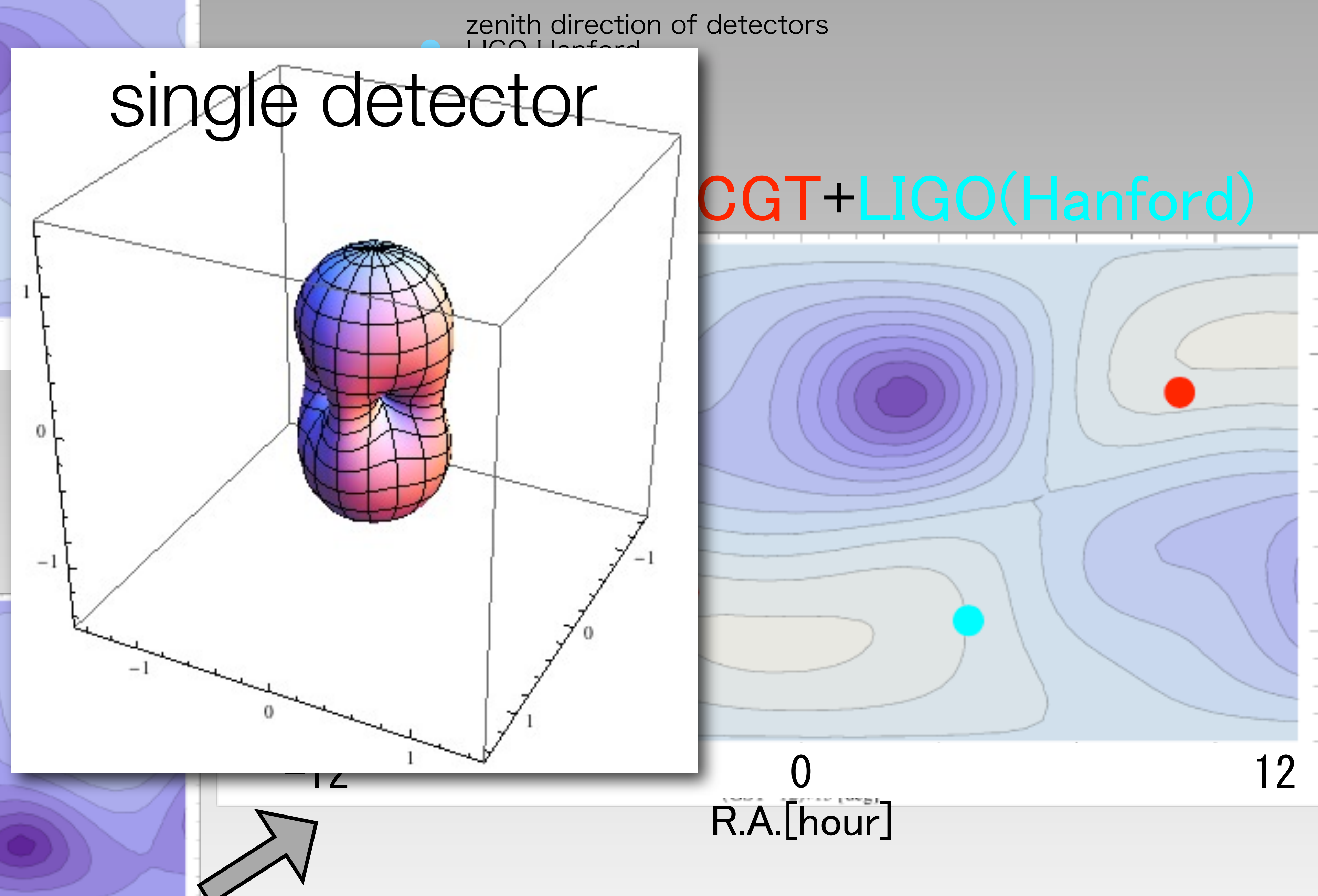
https://gwic.ligo.org/roadmap/Roadmap_100814.pdf

World Wide Network of GW Observatories



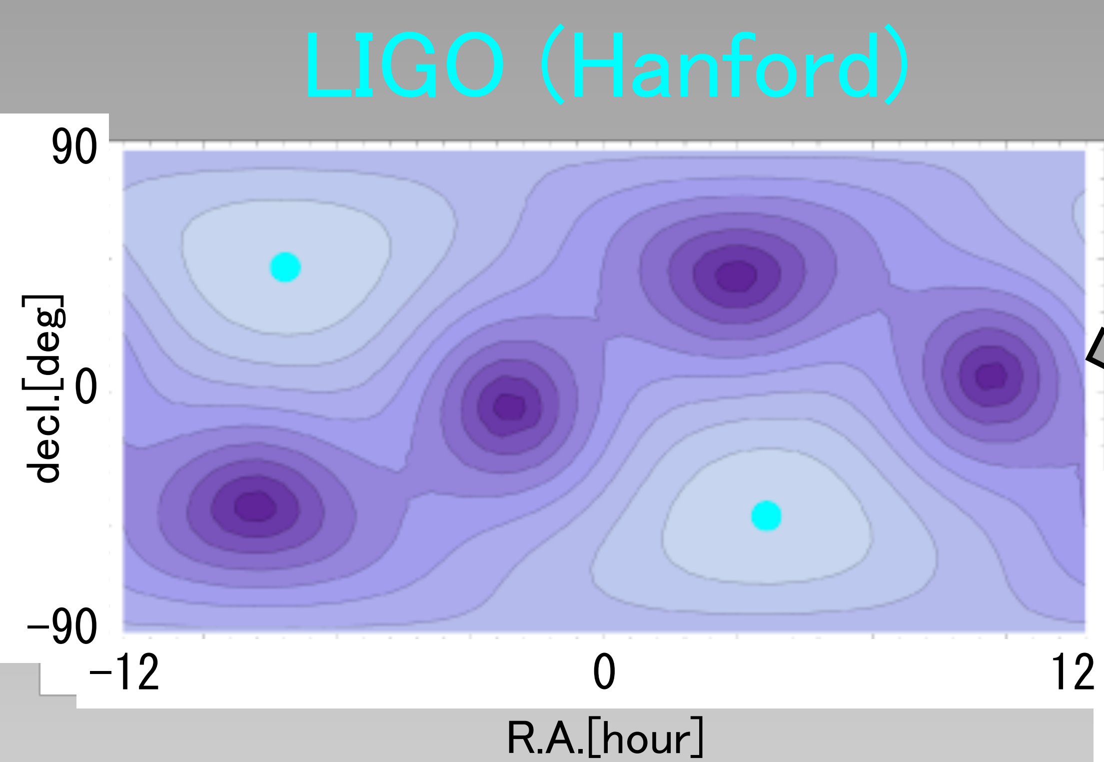
Sky coverage by detector network

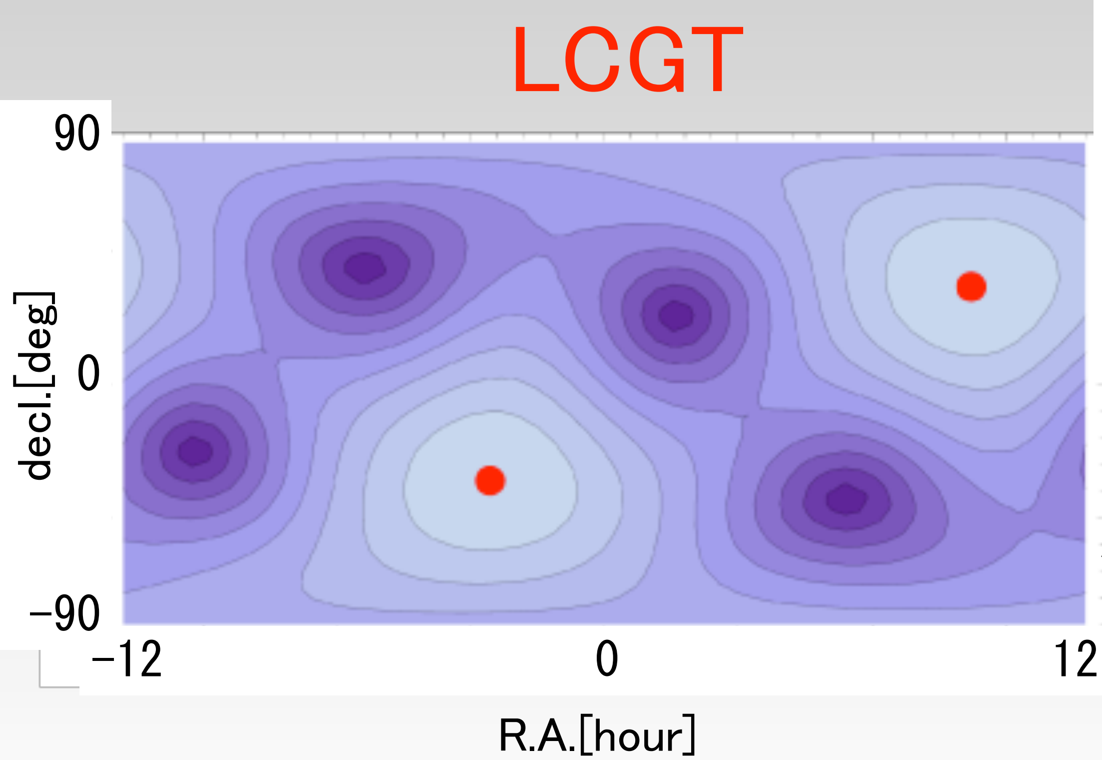


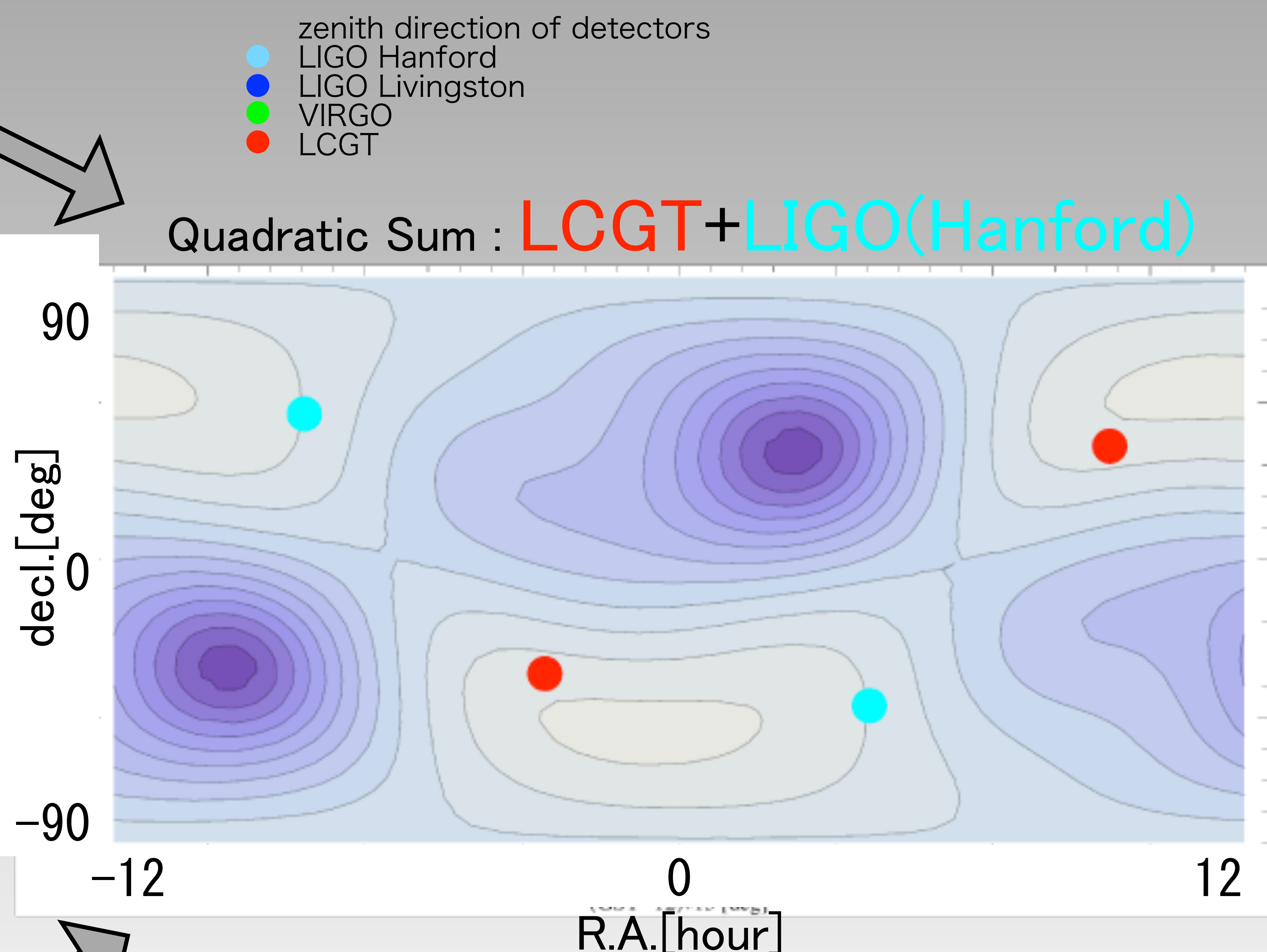


LCGT will make important role in the network, with a complemental sensitivity map.

Sky coverage by detector network



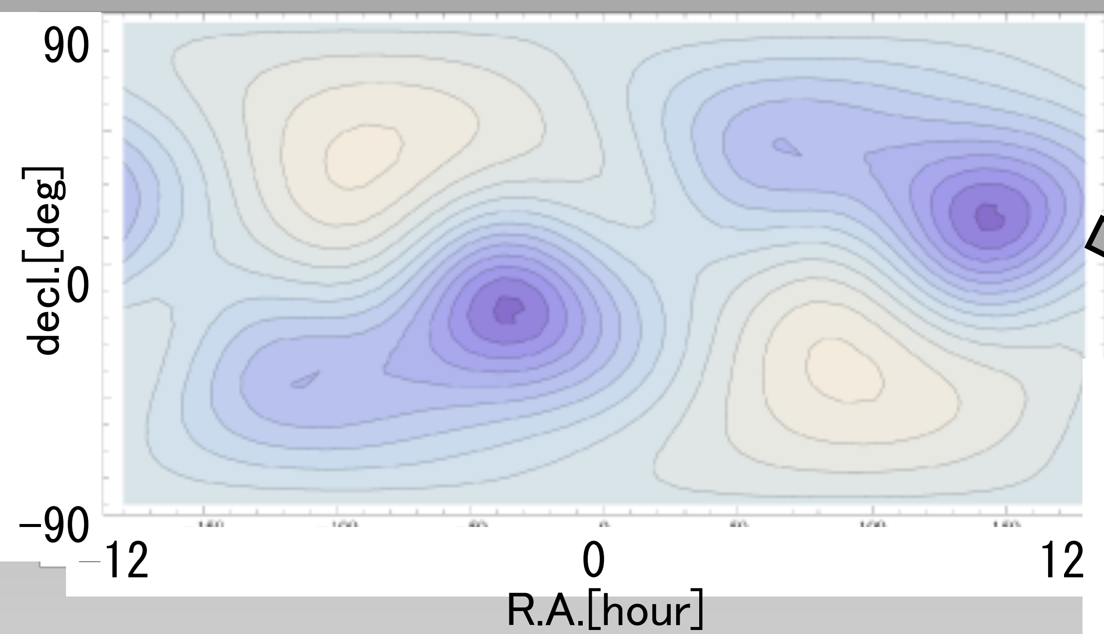




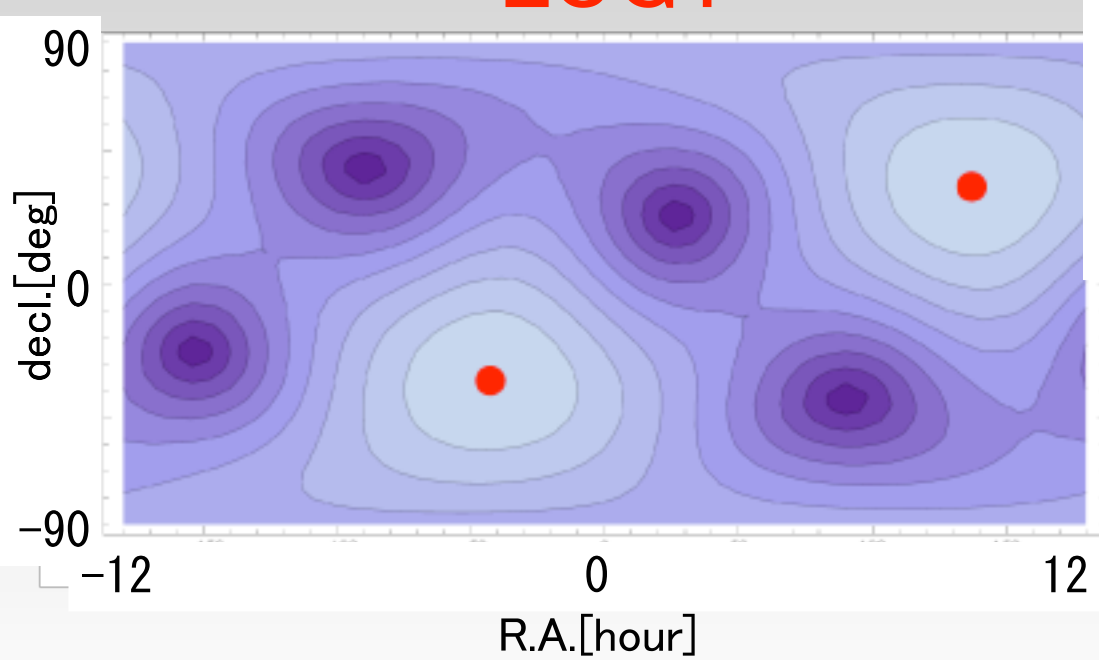
LCGT will make important role in the network, with a complemental sensitivity map.

Sky coverage by detector network

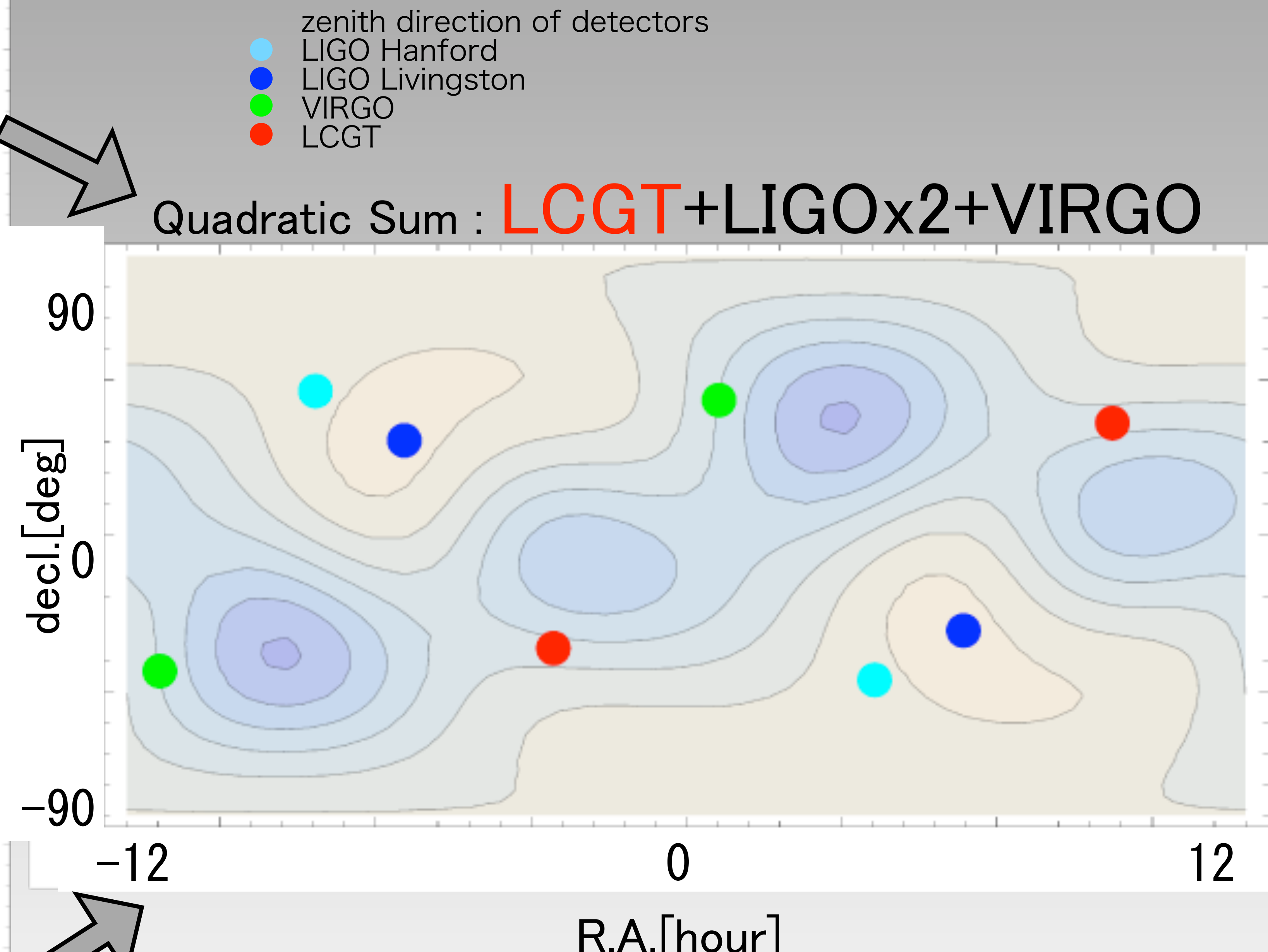
LIGO x2 + VIRGO



LCGT



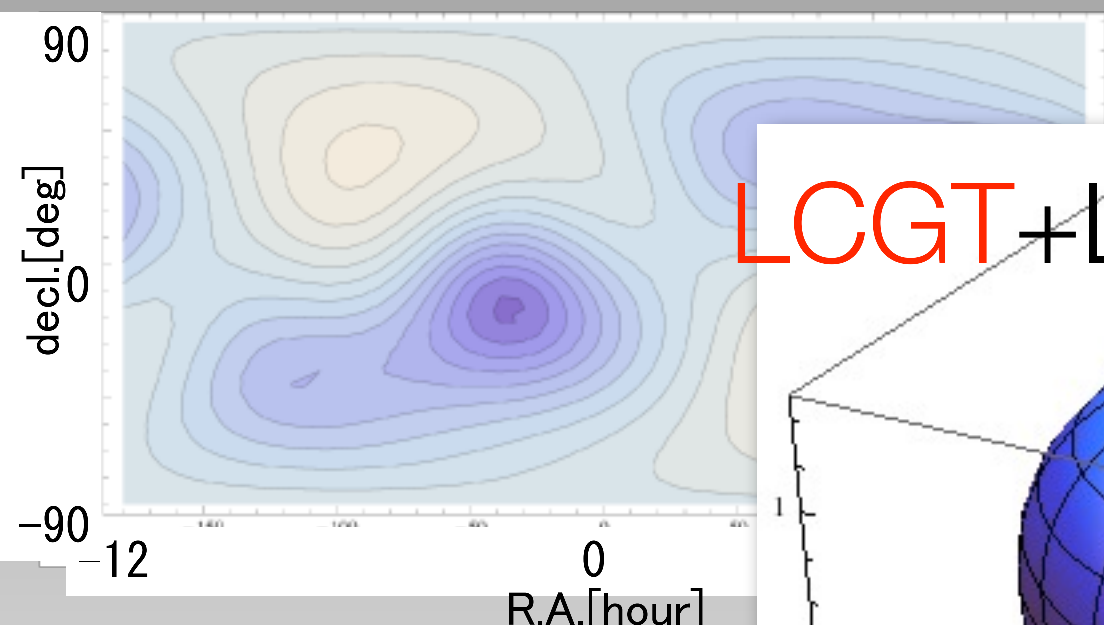
Quadratic Sum : LCGT+LIGOx2+VIRGO



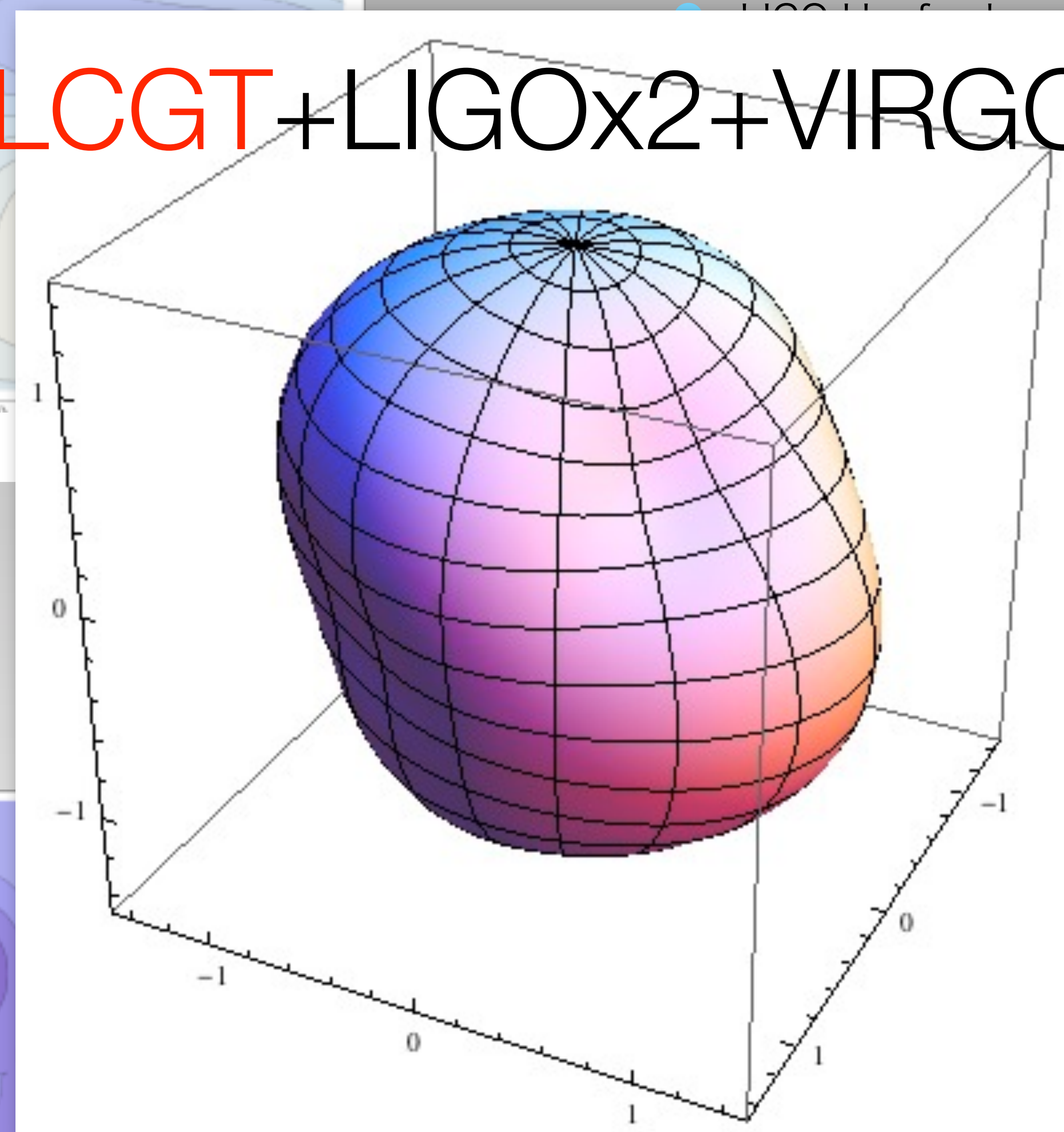
LCGT will make important role in the network, with a complemental sensitivity map.

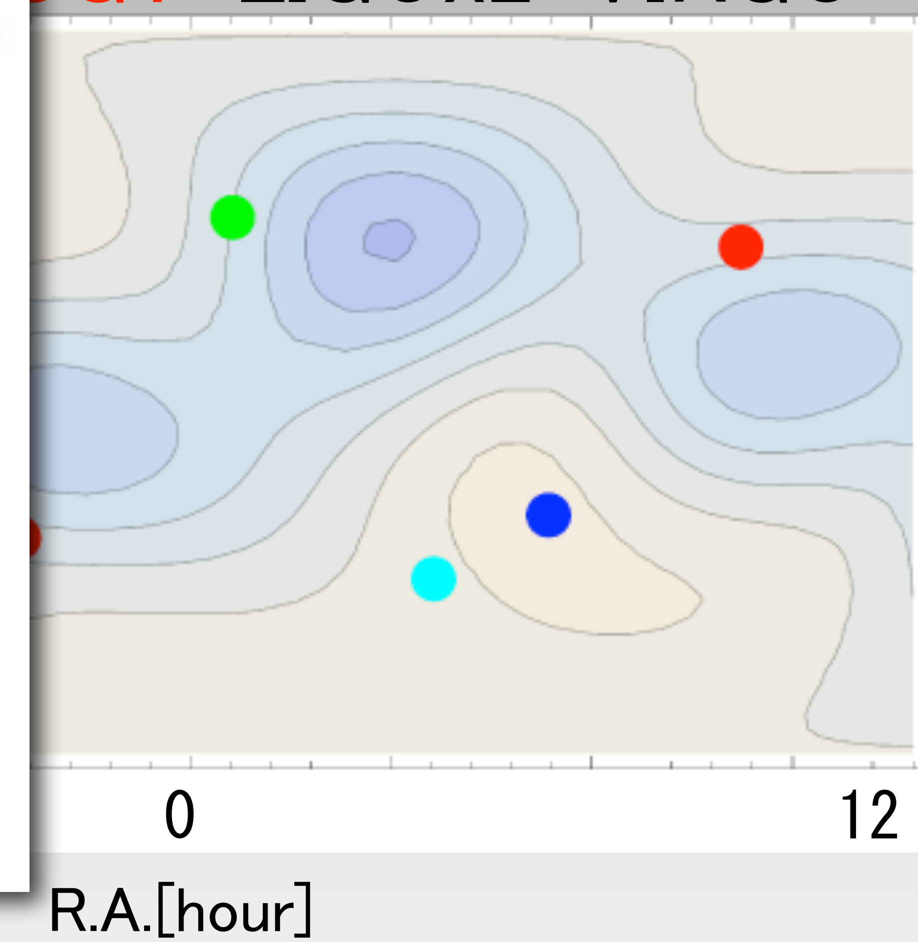
Sky coverage by detector network

LIGO x2 + VIRGO



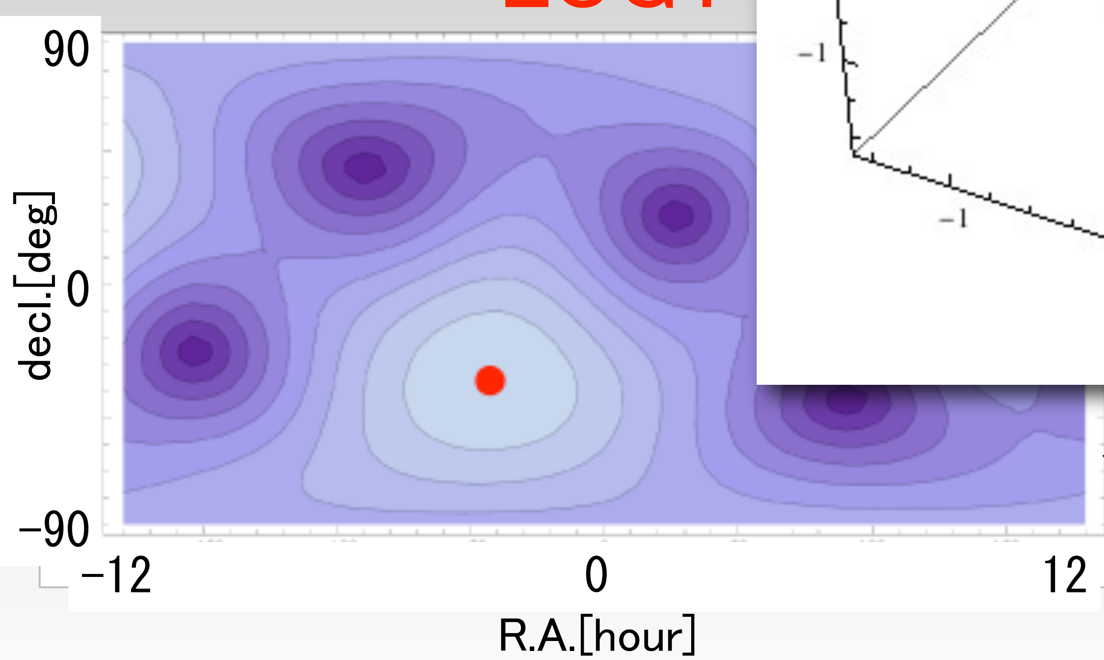
zenith direction of detectors





LCGT+LIGOx2+VIRGO

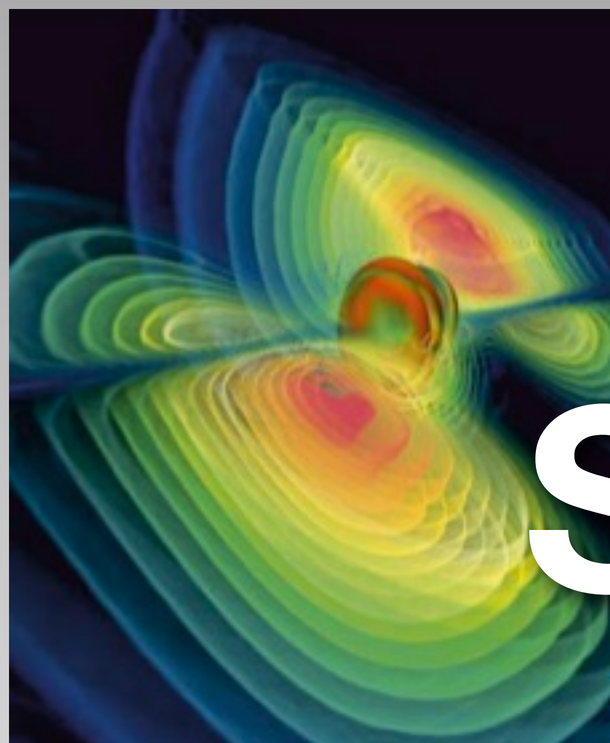
LCGT

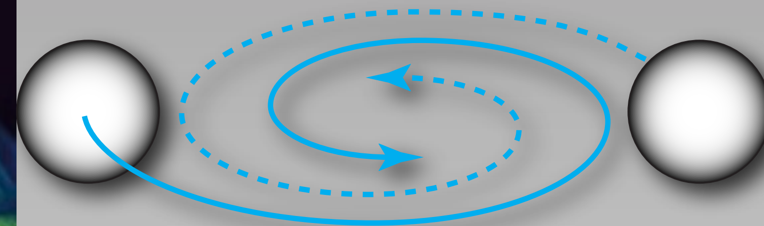


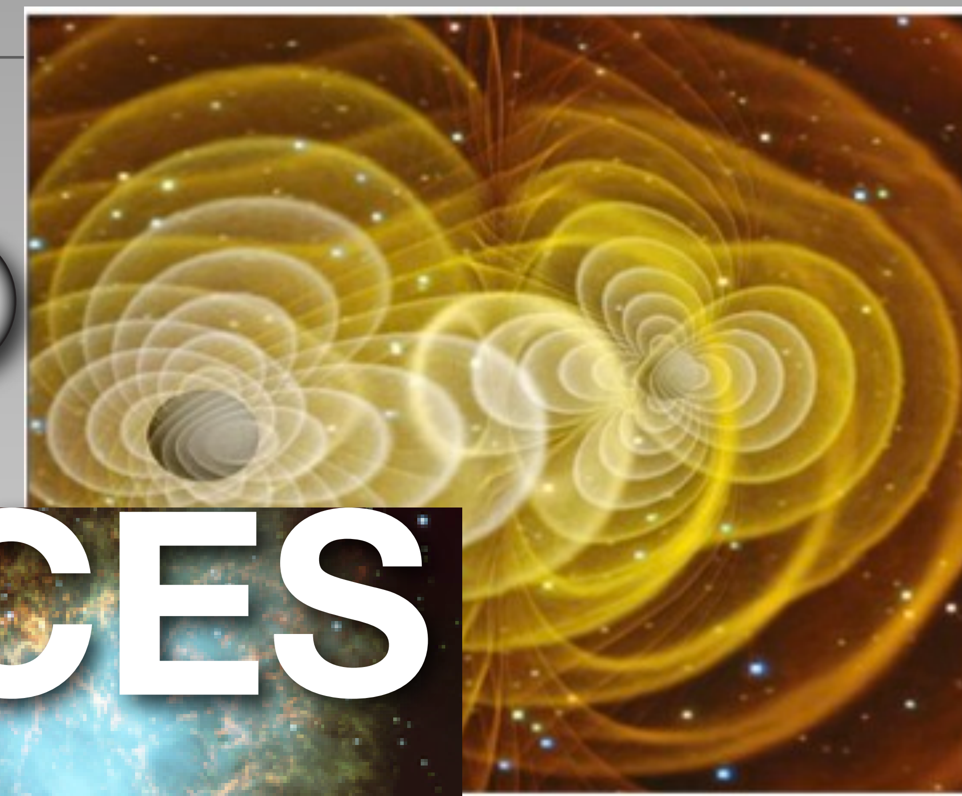
LCGT will make important role in the network, with a complemental sensitivity map.

High Energy Astrophysical Objects and GW

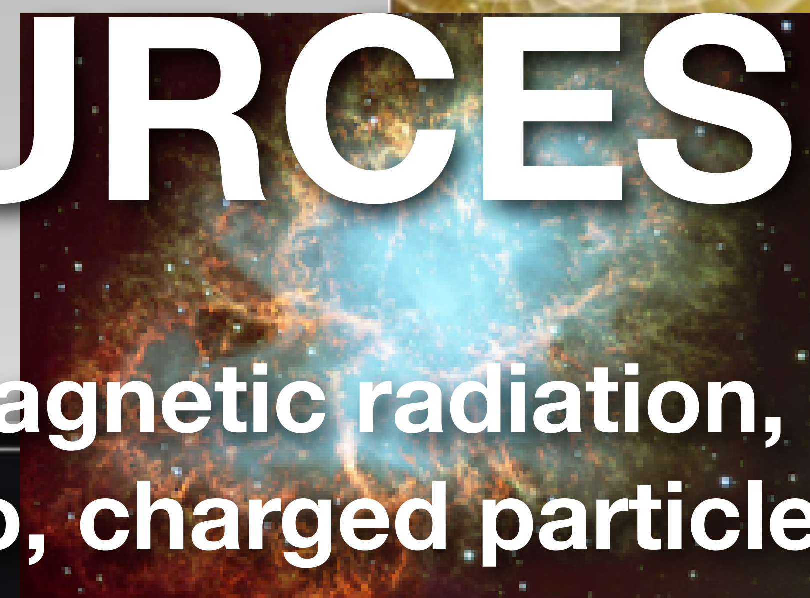
High Energy Astrophysical Objects and GW







...of merging black holes (Credit: Henze, NASA)



SOURCES

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

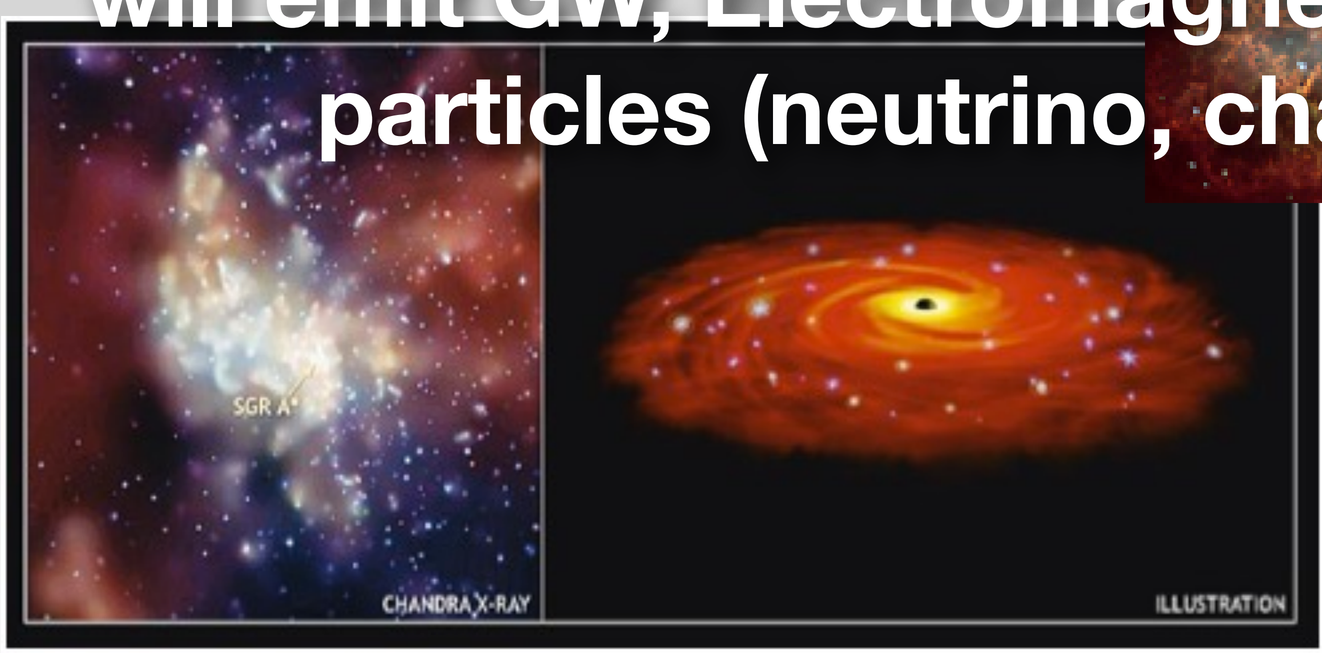
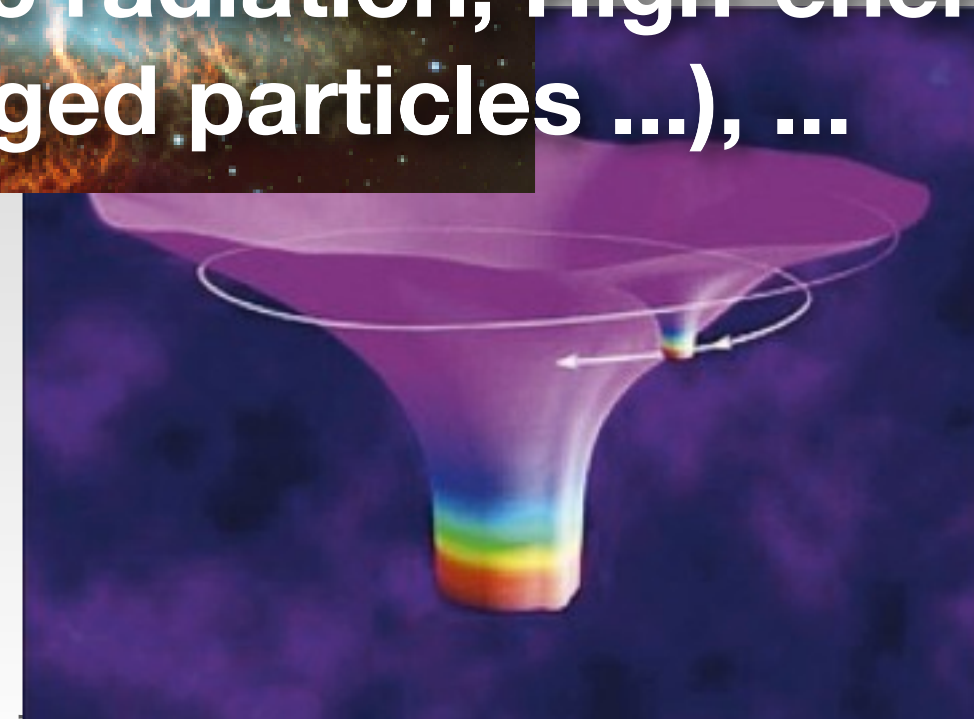
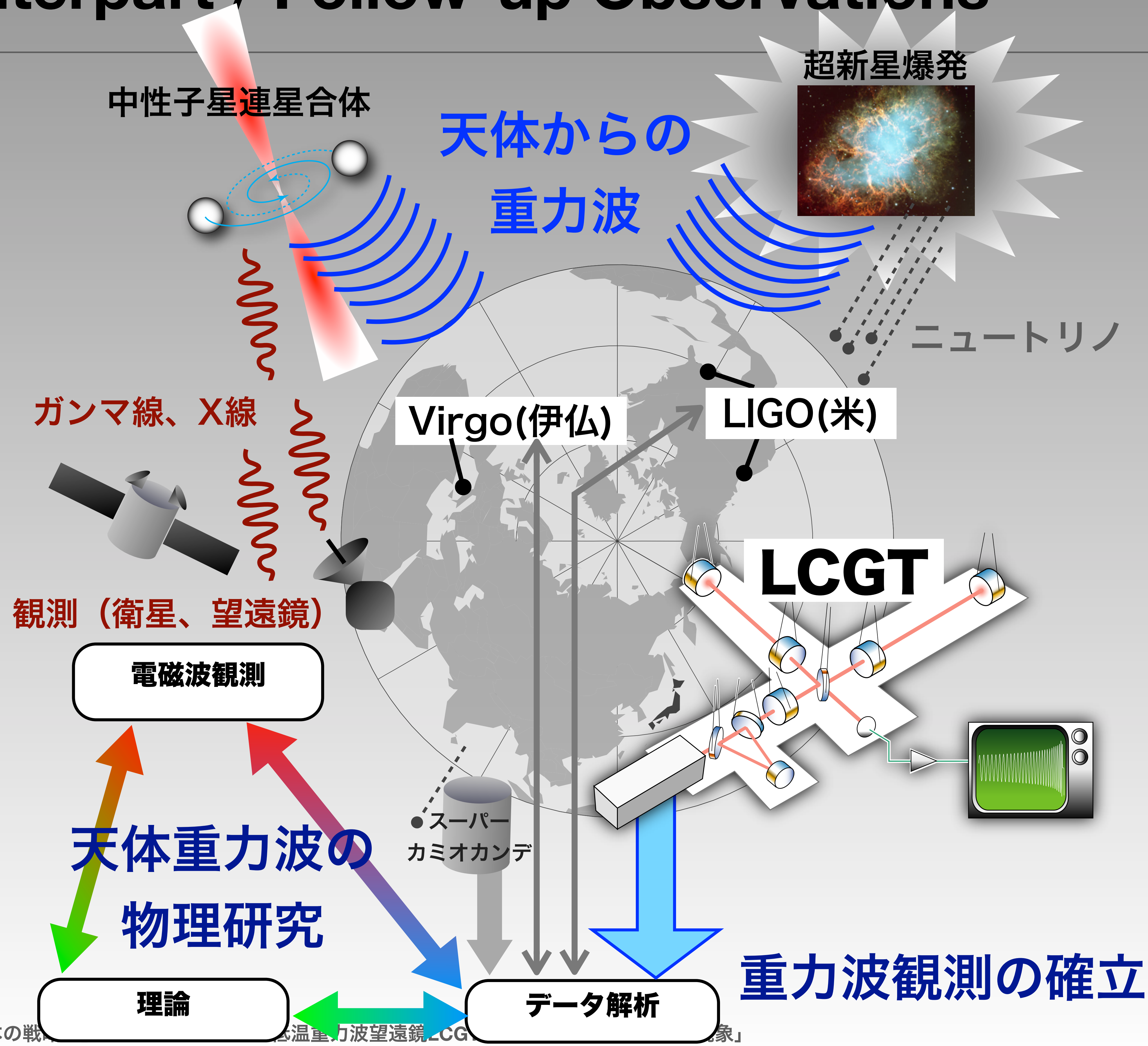


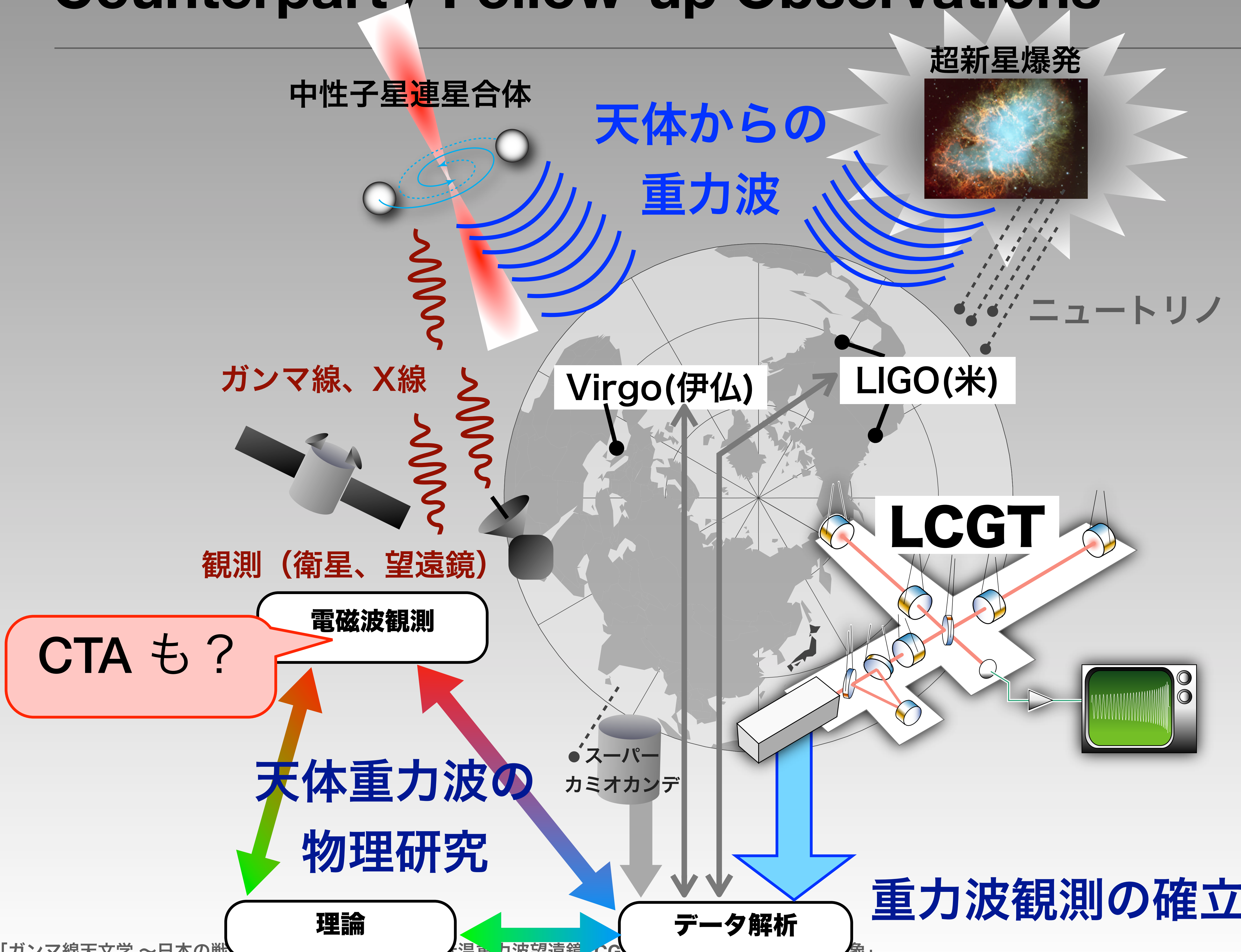
Fig. 4.3 – Chandra image of the Galactic Center (left). Illustration of massive stars formed from a large disk of gas around Sagittarius A*, the Milky Way's central black hole (illustration on right). Credit: X-ray: NASA/CXC/MIT/F.K.Baganoff et al.; Illustration: NASA/CXC/M.Weiss



Counterpart / Follow-up Observations

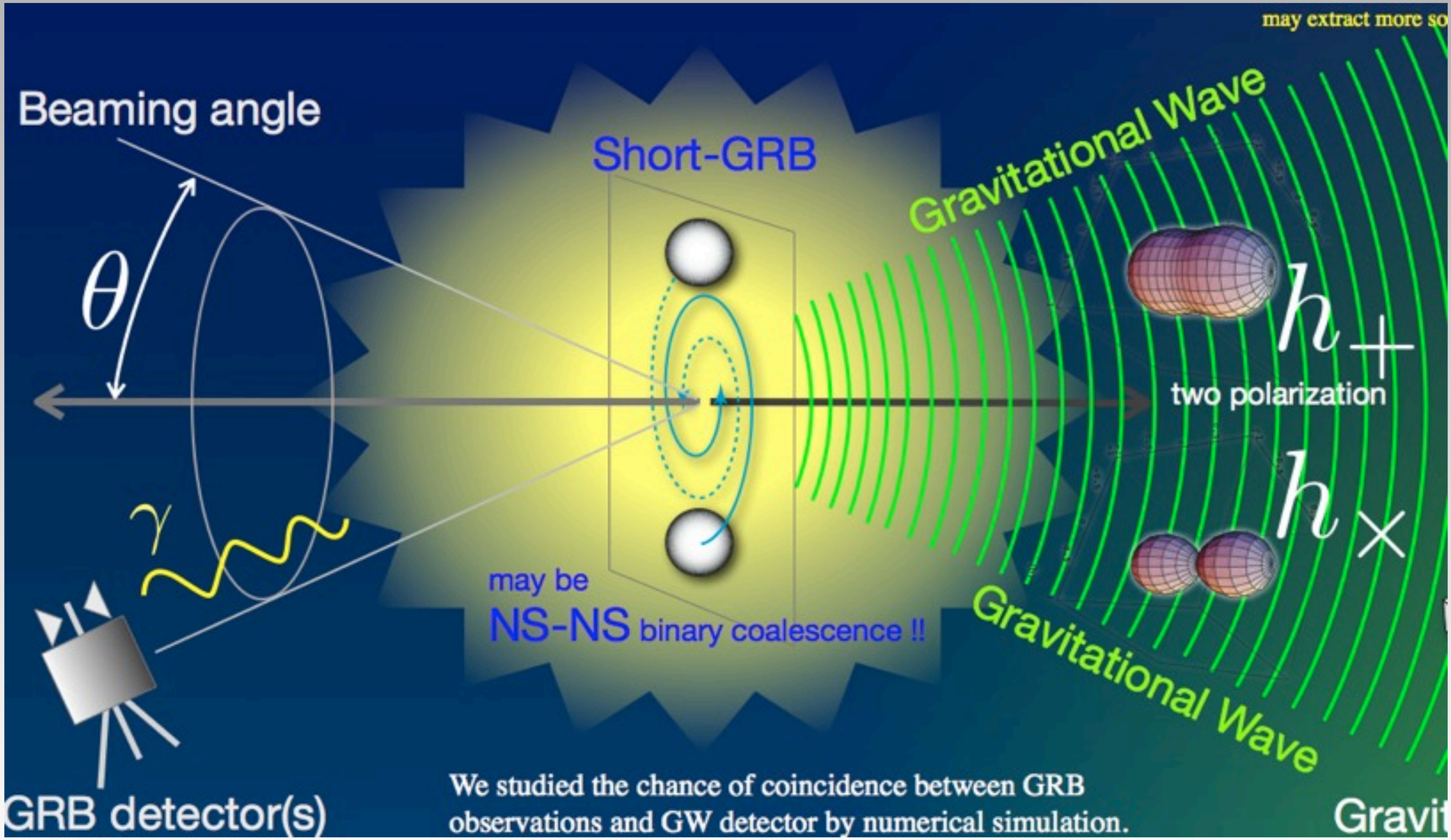


Counterpart / Follow-up Observations

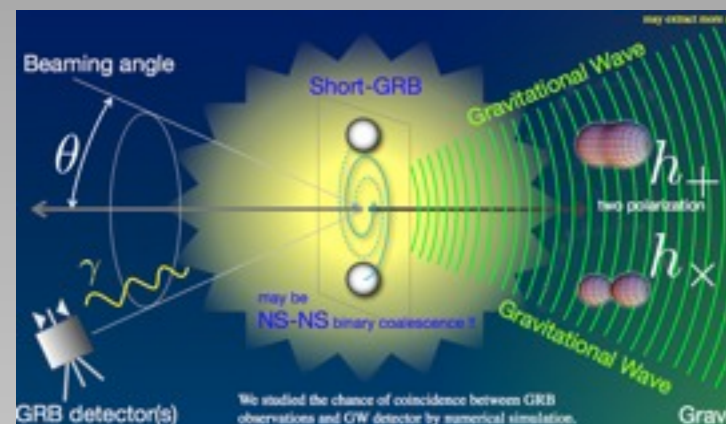


Compact Binary Coalescences

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

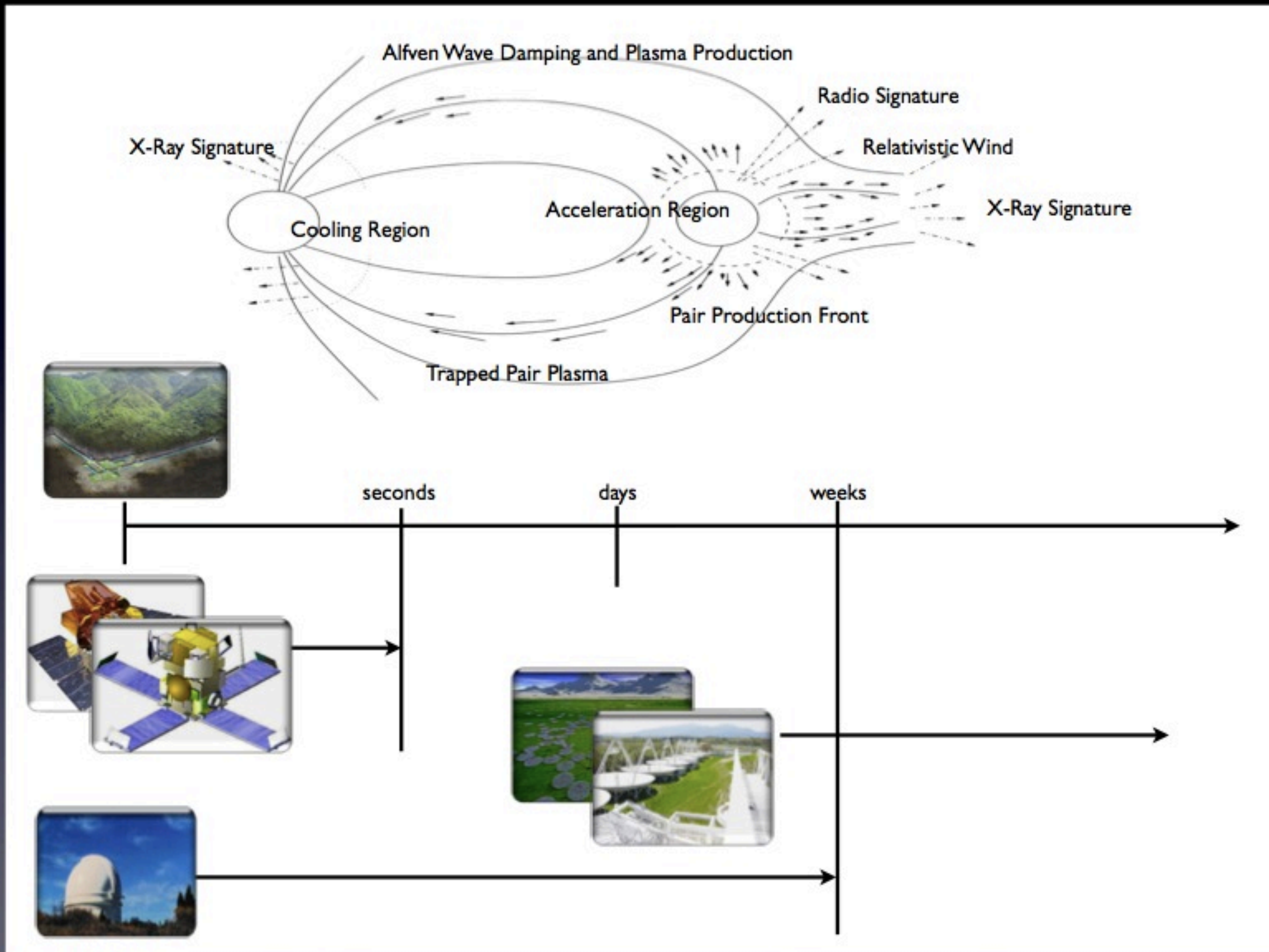
[Aux trigger]
Date, direction, ...

Followup by
X, Gamma, Optical

Confirmation of Afterglow

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

CBC

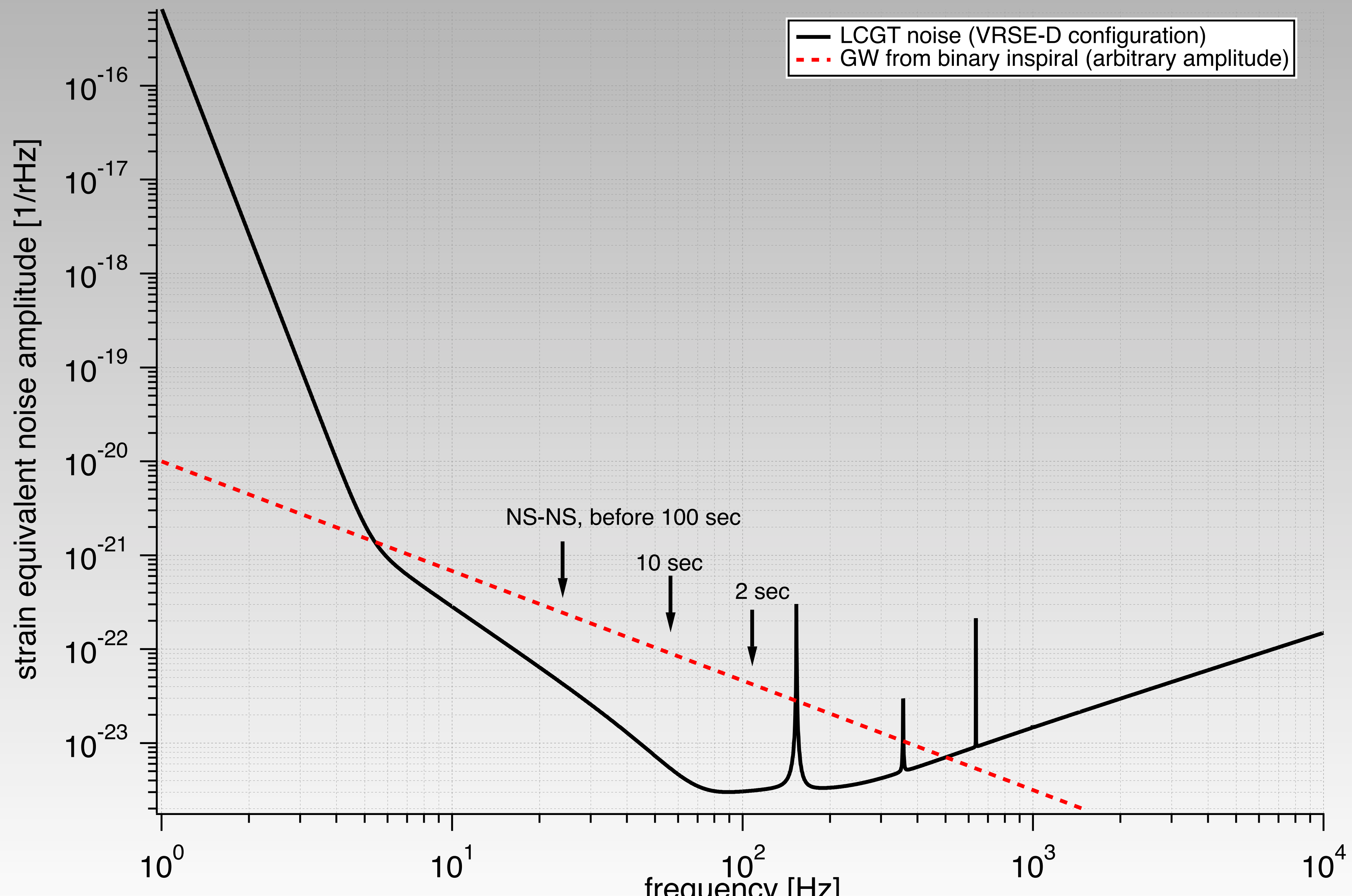


2010年8月11日水曜日

arranged by K.Hayama

Forecast !?

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

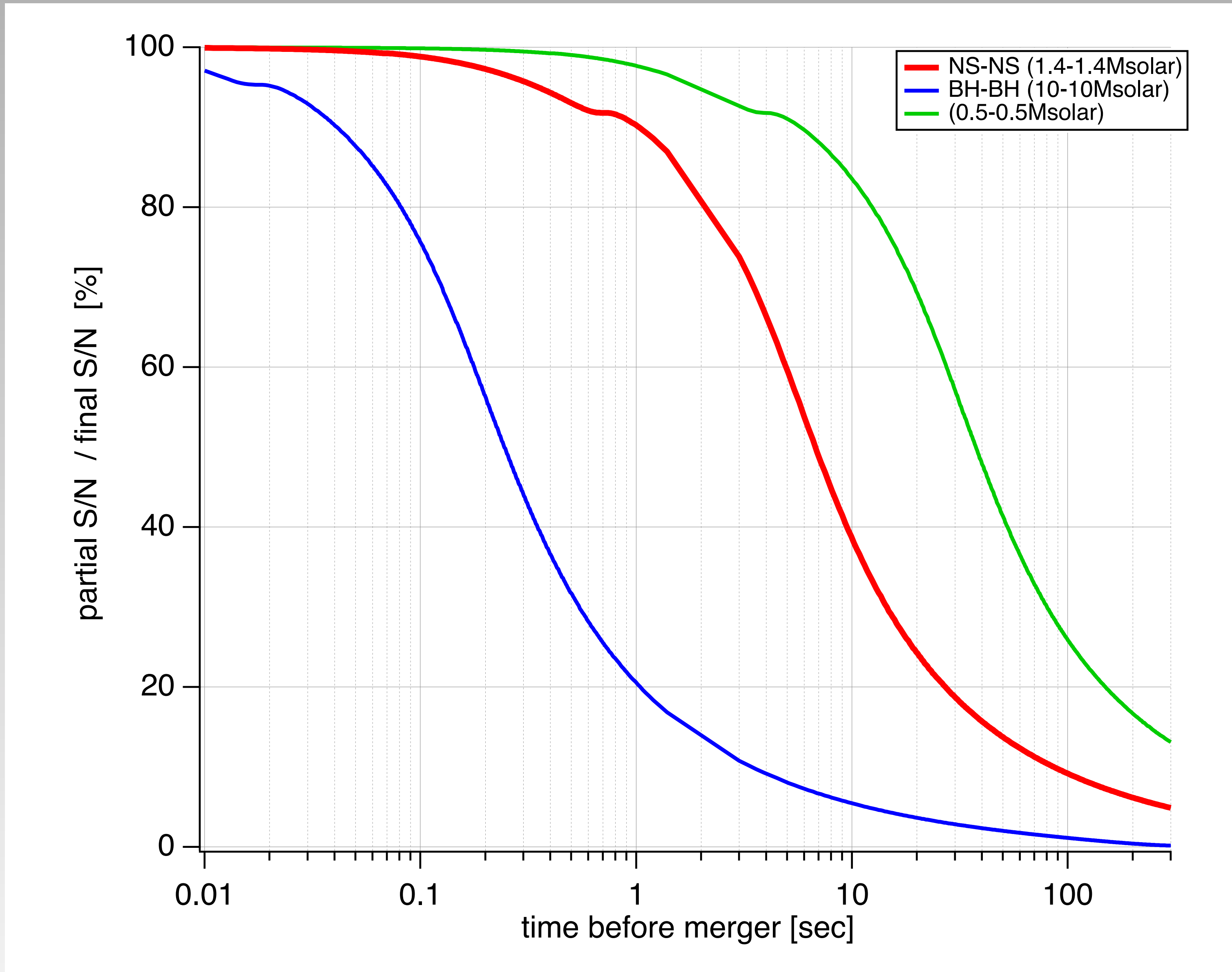


Example of Practical Issue : NS-NS forecast

- 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:

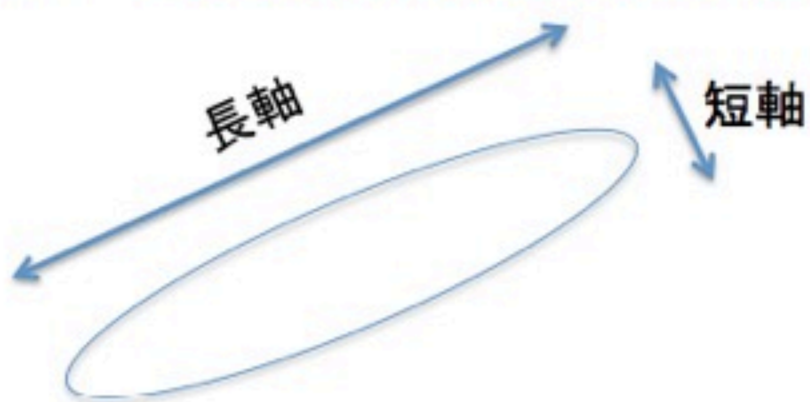
平均S/N (ρ)　　8.2から8.9（各検出器で）

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)



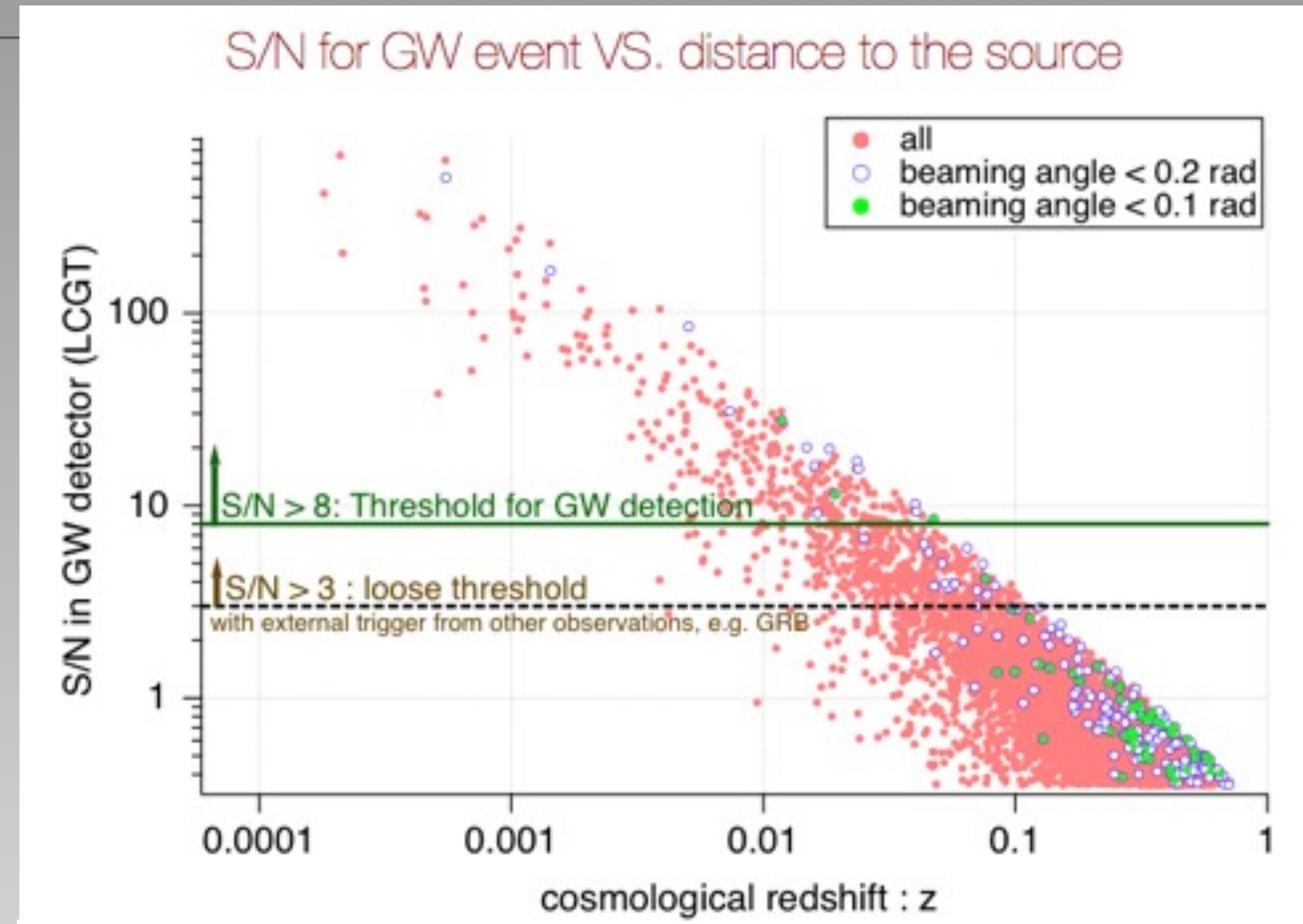
by H.Tagoshi

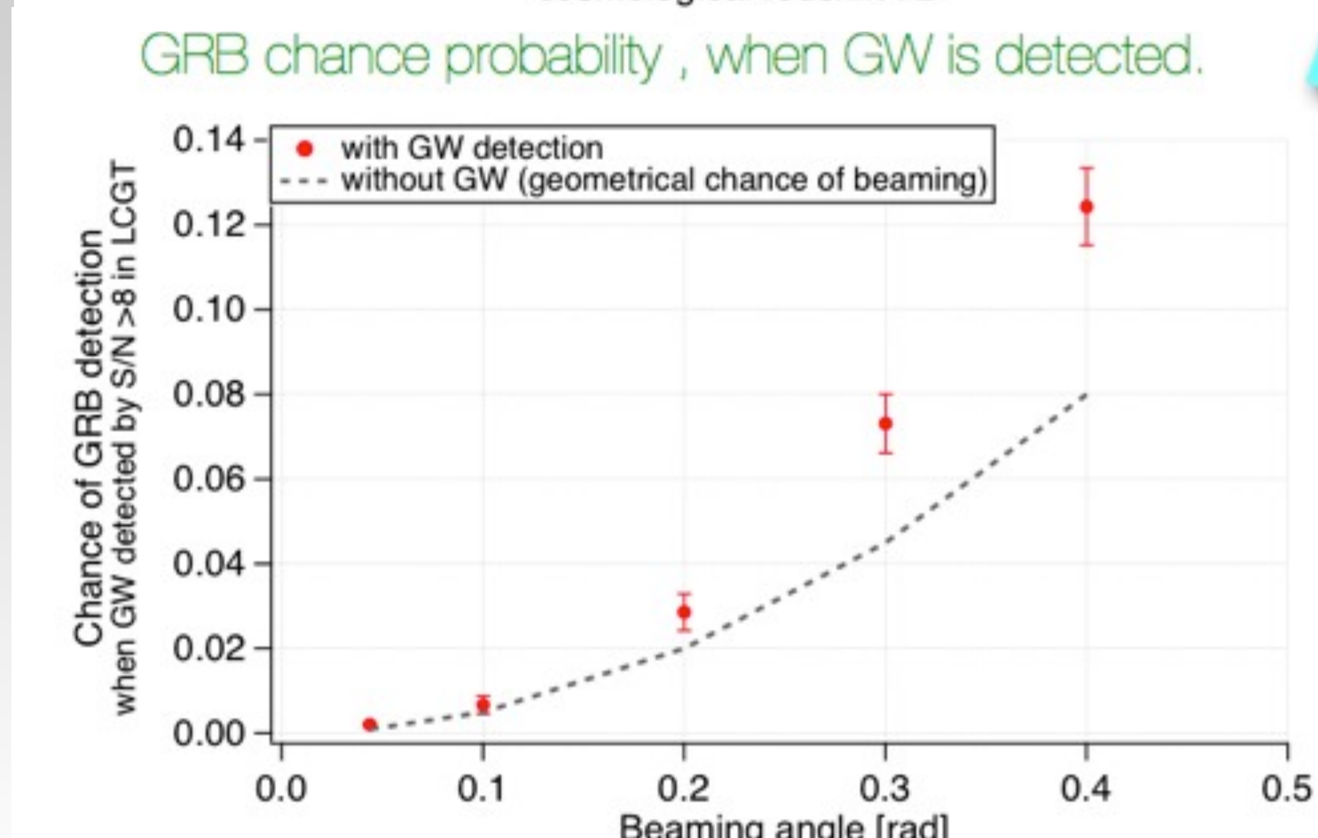
5

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.





GRB 070201 <--> LIGO

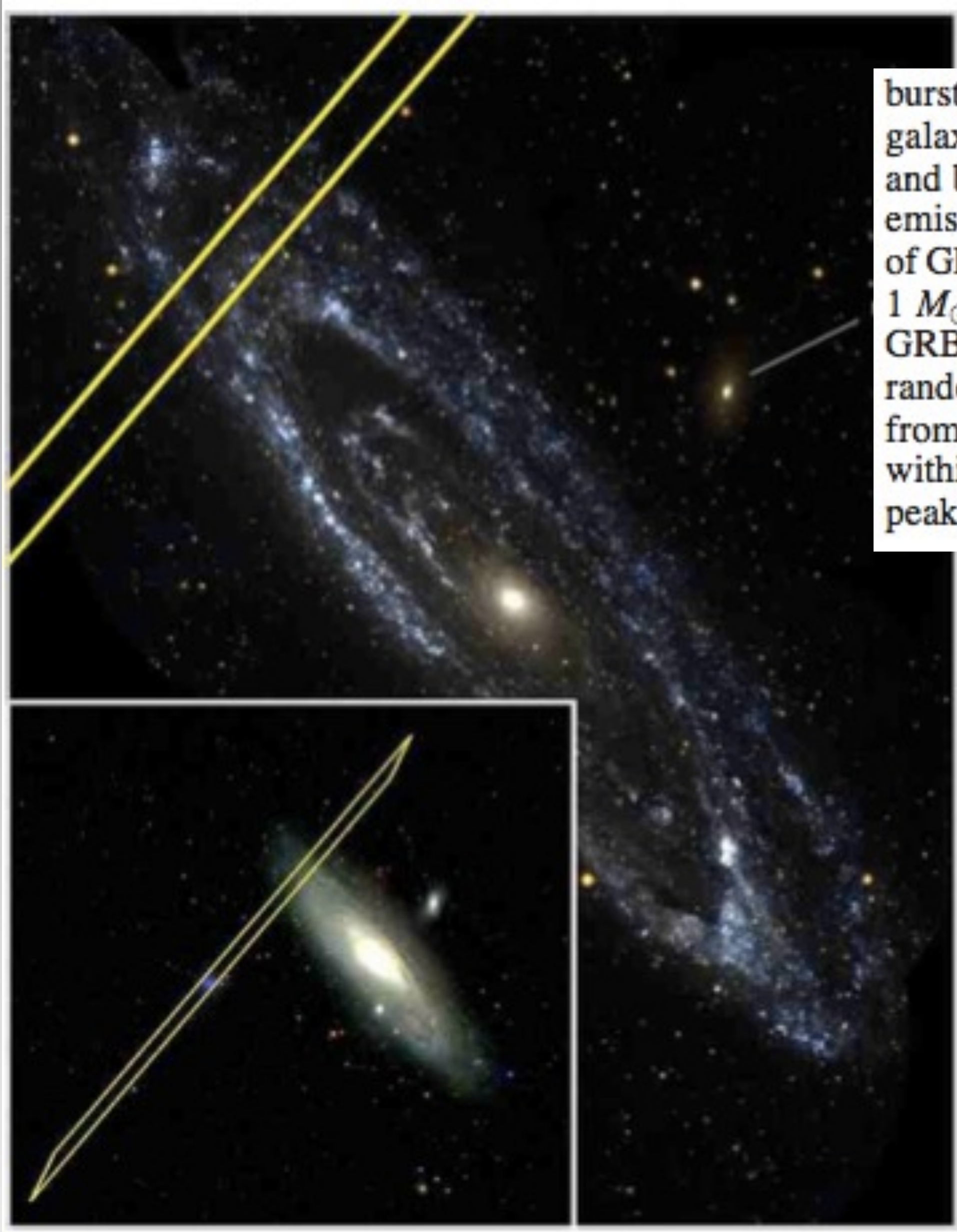


FIG. 1.— The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (Adelman-McCarthy et al. 2006; SDSS 2007) image of M31. The main figure shows the overlap of the error box and the spiral arms of M31 in UV light (Thilker et al. 2005).

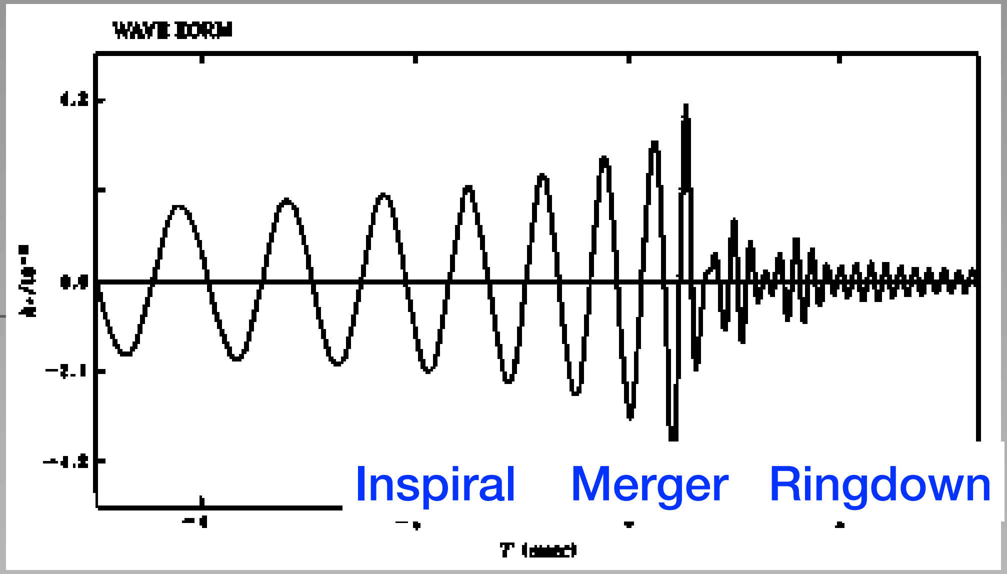
GRB 070201, this distance was 35.7 Mpc and 15.3 Mpc for

burst whose electromagnetically determined sky position is coincident with the spiral arms of the Andromeda galaxy (M31). Possible progenitors of such short hard GRBs include mergers of neutron stars or a neutron star and black hole, or soft γ-ray repeater (SGR) flares. These events can be accompanied by gravitational-wave emission. No plausible gravitational wave candidates were found within a 180 s long window around the time of GRB 070201. This result implies that a compact binary progenitor of GRB 070201, with masses in the range $1\,M_\odot < m_1 < 3\,M_\odot$ and $1\,M_\odot < m_2 < 40\,M_\odot$, located in M31 is excluded at $> 99\%$ confidence. Indeed, if GRB 070201 were caused by a binary neutron star merger, we find that $D < 3.5$ Mpc is excluded, assuming random inclination, at 90% confidence. The result also implies that an unmodeled gravitational wave burst from GRB 070201 most probably emitted less than $4.4 \times 10^{-4} M_\odot c^2$ (7.9×10^{50} ergs) in any 100 ms long period within the signal region if the source was in M31 and radiated isotropically at the same frequency as LIGO's peak sensitivity ($f \approx 150$ Hz). This upper limit does not exclude current models of SGRs at the M31 distance.

It was NOT CBC. (excluded 99%)

Astrophys.J.681:1419-1428,2008　LIGO collab.

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

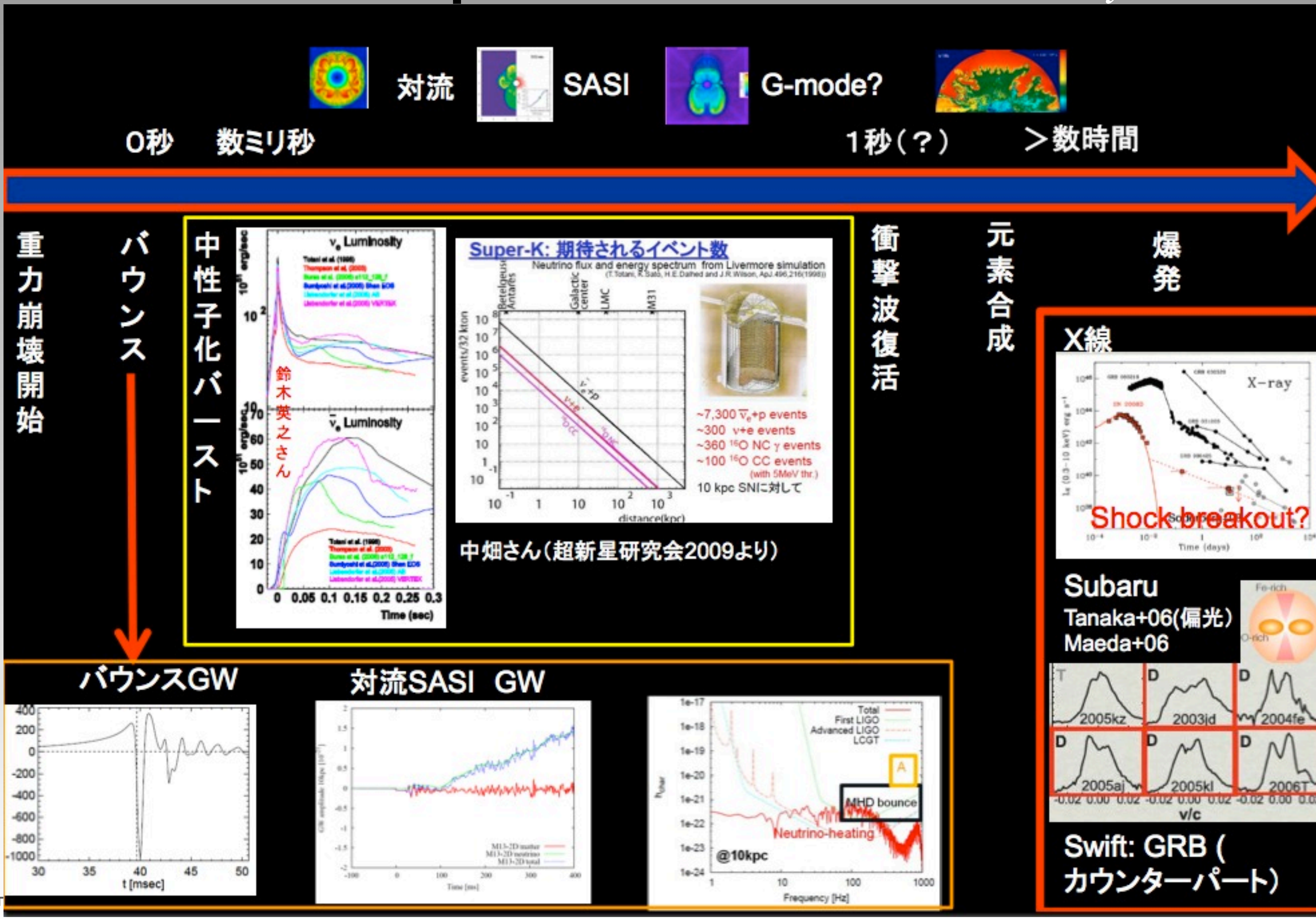
neutrino emission

accretion

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

Evolution of Supernova and GW

by K.Kotake



Neutrino and GW from Supernovae

GW

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

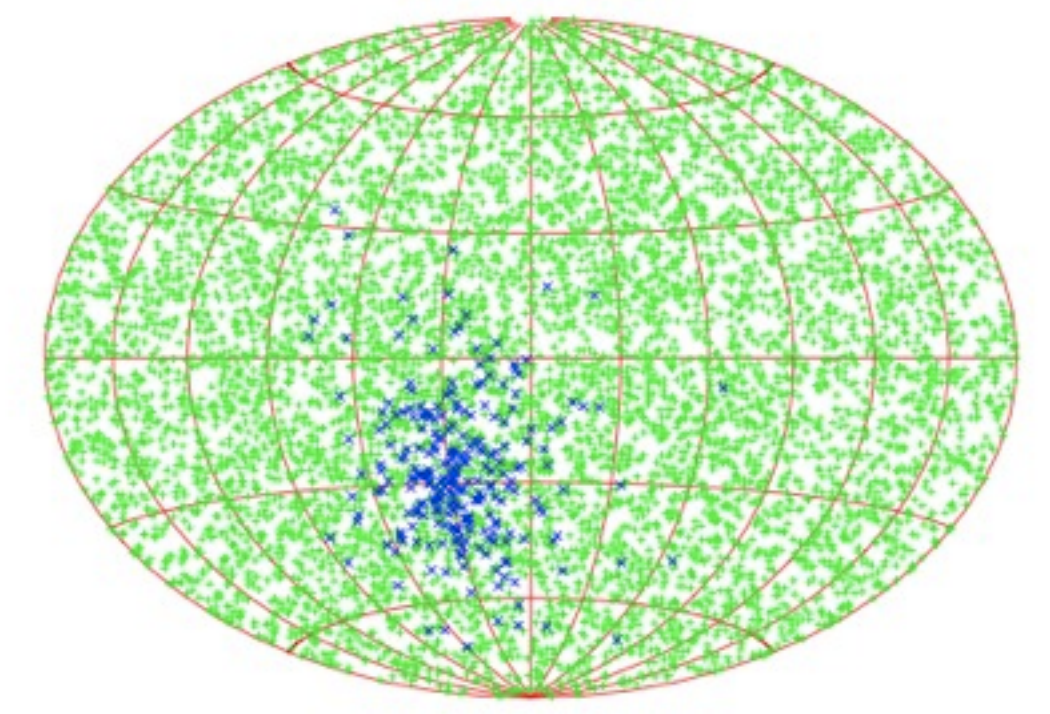


FIG. 4: Angular distribution of $\bar{\nu}_e p \to n e^+$ events (green) and elastic scattering events $\nu e^- \to \nu e^-$ (blue) of one simulated SN.

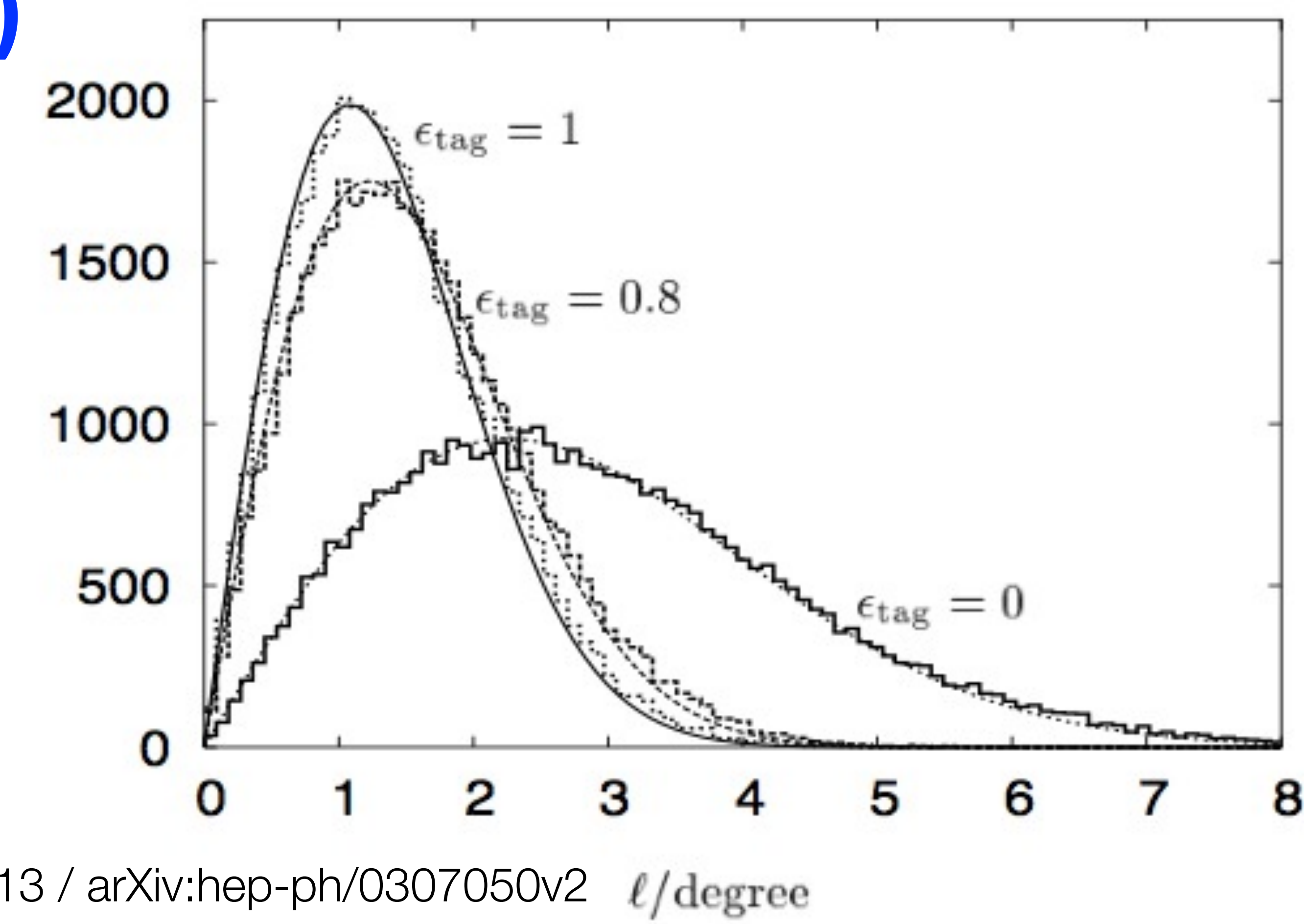
Neutrino (Super-Kamiokande)

- 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

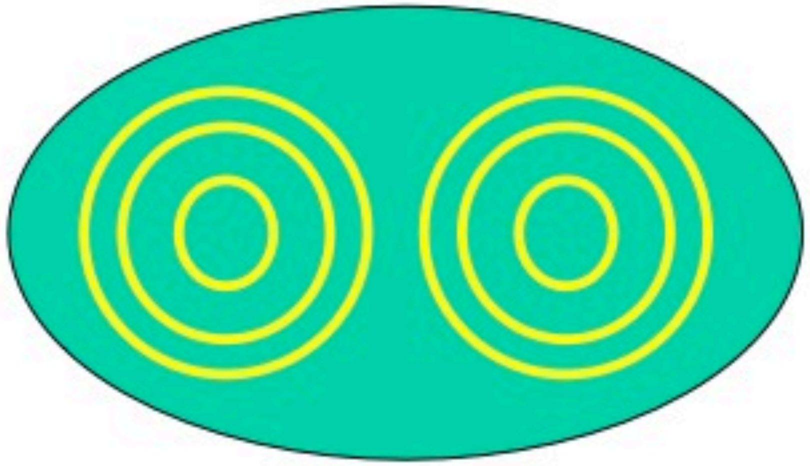
by K.Ioka

Magnetar

Super strongly magnetized neutron star

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

⇨ Deformation of neutron stars



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

Equilibrium of magnetized stars

Soft Gamma Ray Repeater

We present a LIGO search for short-duration gravitational waves (GWs) associated with soft gamma ray repeater (SGR) bursts. This is the first search sensitive to neutron star *f* modes, usually considered the most efficient GW emitting modes. We find no evidence of GWs associated with any SGR burst in a sample consisting of the 27 Dec. 2004 giant flare from SGR 1806−20 and 190 lesser events from SGR 1806−20 and SGR 1900+14. The unprecedented sensitivity of the detectors allows us to set the most stringent limits on transient GW amplitudes published to date. We find upper limit estimates on the model-dependent isotropic GW emission energies (at a nominal distance of 10 kpc) between 3×10^{45} and 9×10^{52} erg depending on waveform type, detector antenna factors and noise characteristics at the time of the burst. These upper limits are within the theoretically predicted range of some SGR models.

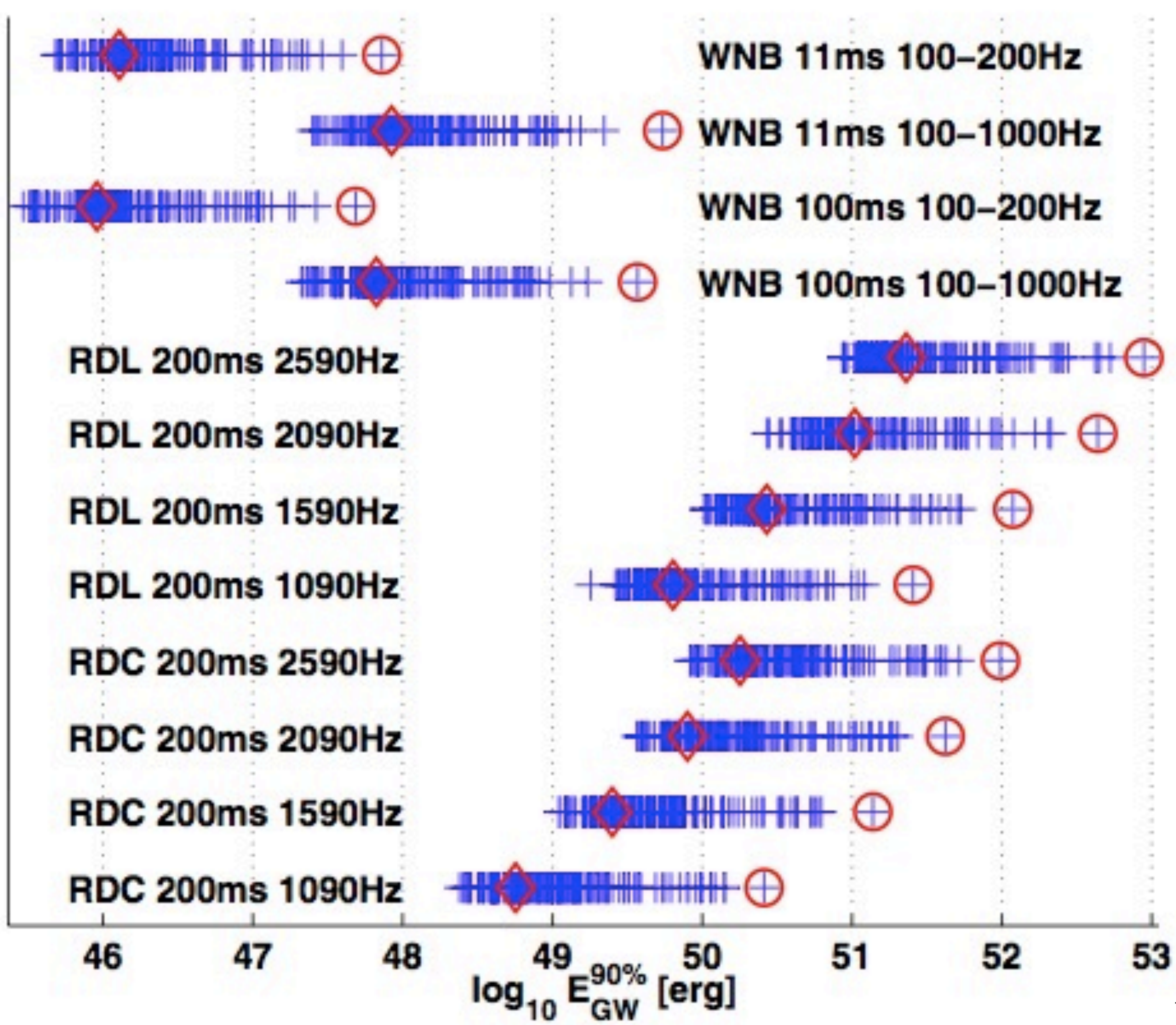


FIG. 1 (color online). $E_{GW}^{90\%}$ upper limits for the entire SGR burst sample for various circularly or linearly polarized RDs (RDC/RDL) and white noise burst (WNB) signals. The limits shown in Table I, for the giant flare and the 060806 event, are indicated in the figure by circles and diamonds, respectively.

PRL 101, 2111102 (2008), LIGO collab.

Radiometry Search for point sources

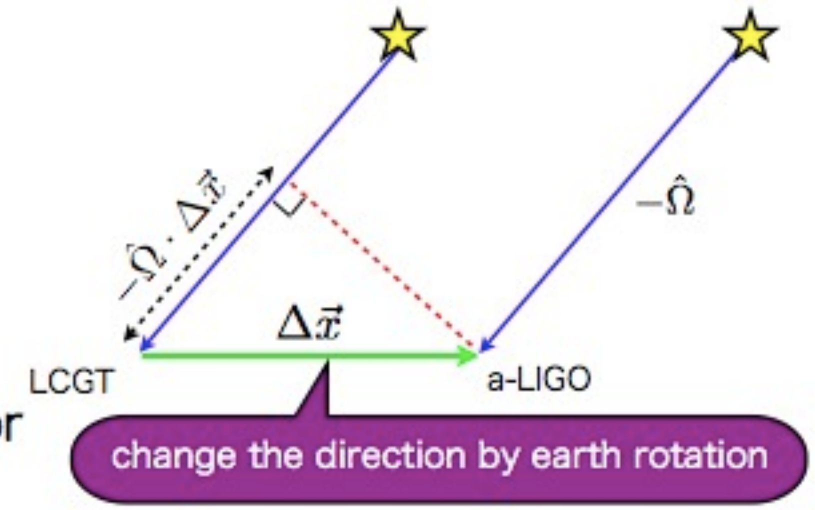
Radiometry Filter

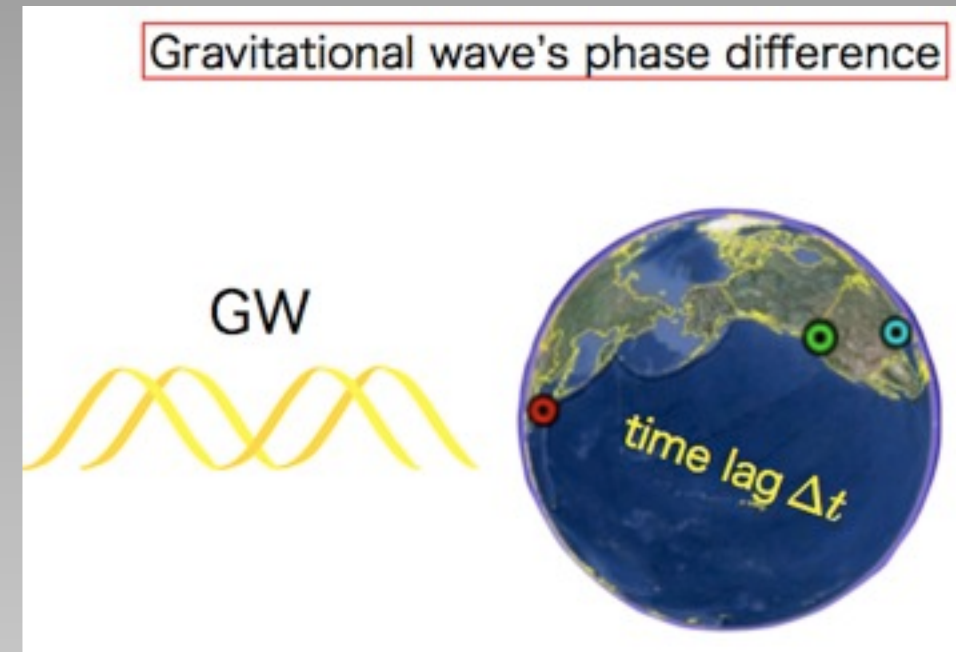
$$Q = \lambda \frac{\gamma^*(f,\Omega)H(f)}{P_1(f)P_2(f)}$$

λ : normalization factor

$H(f)$: GW PSD

P_i : detector noise PSD





by Y.Okada

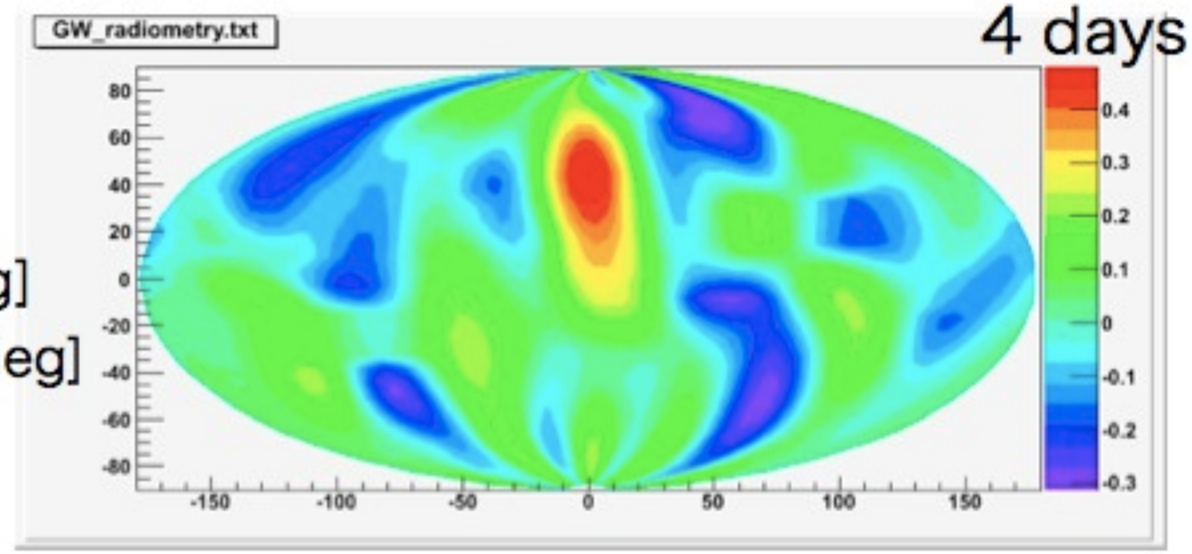
Simulation

Real Antenna Response with noise

source

α : 0 [deg]

δ : 4 0 [deg]



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

Other Possible Sources

Cusp/Kink of Cosmic String

LMXB (Wagoner star)

SMBH, IMBH

Pulser (Continuous, Pulser glitch)

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

- larger 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.