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

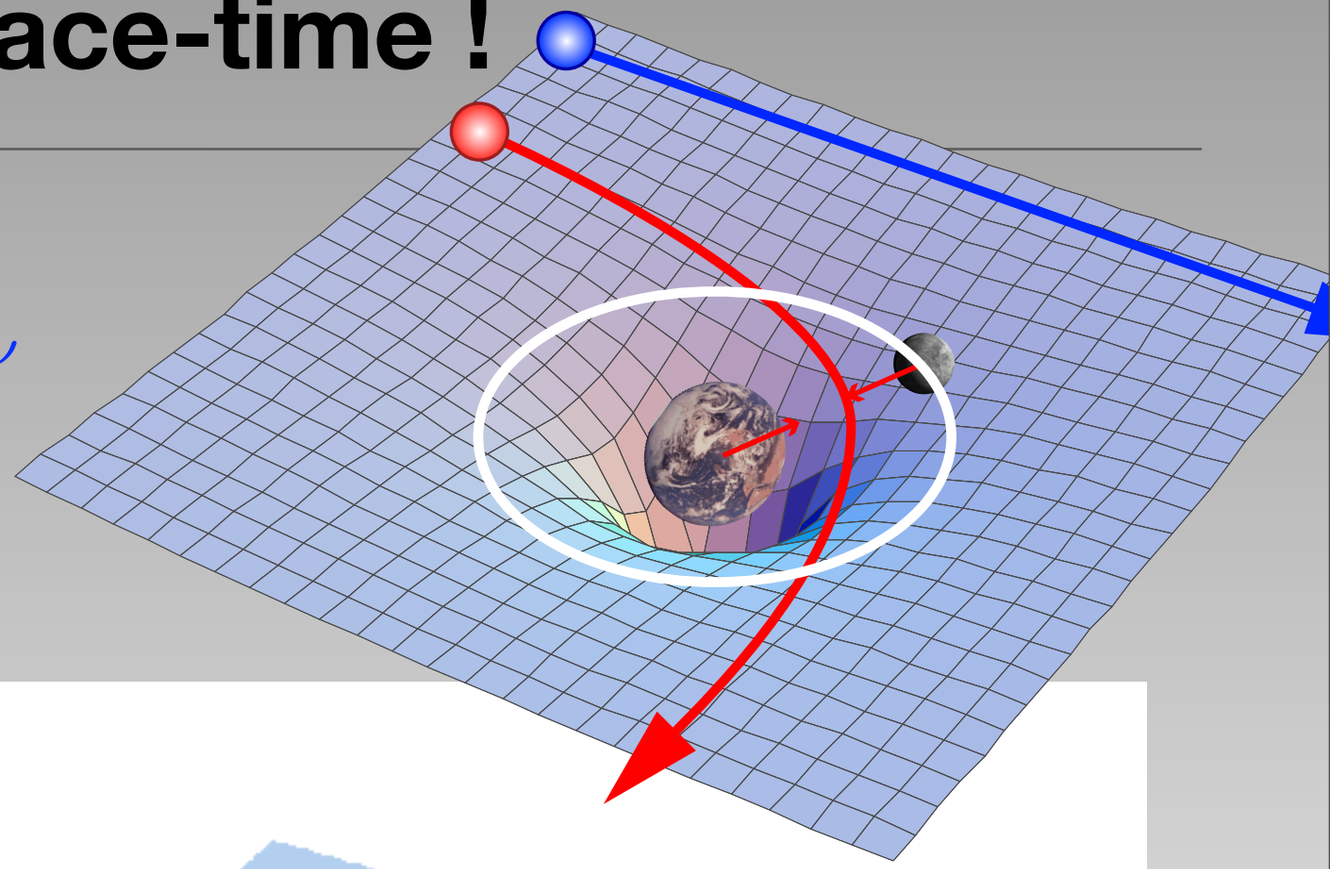
- Overview
- Construction Schedule
- Detection Range for GWs

Counterpart / Follow-up observations

- Possible Sources
- Science (Physics) outcome

Gravity distorts the space-time !

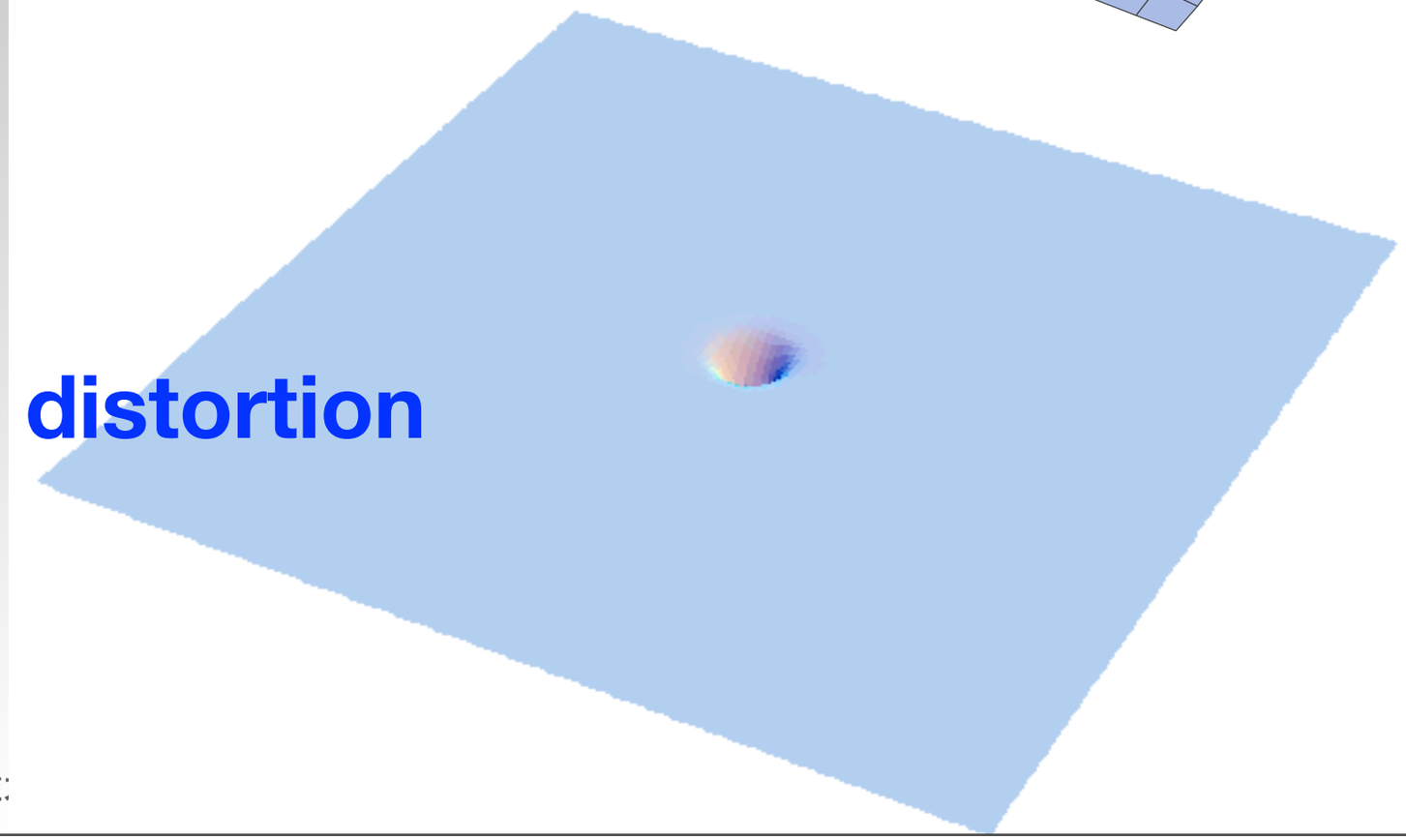
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\kappa T_{\mu\nu}$$



Curved space-time

Propagation of the distortion

- --> Waves !



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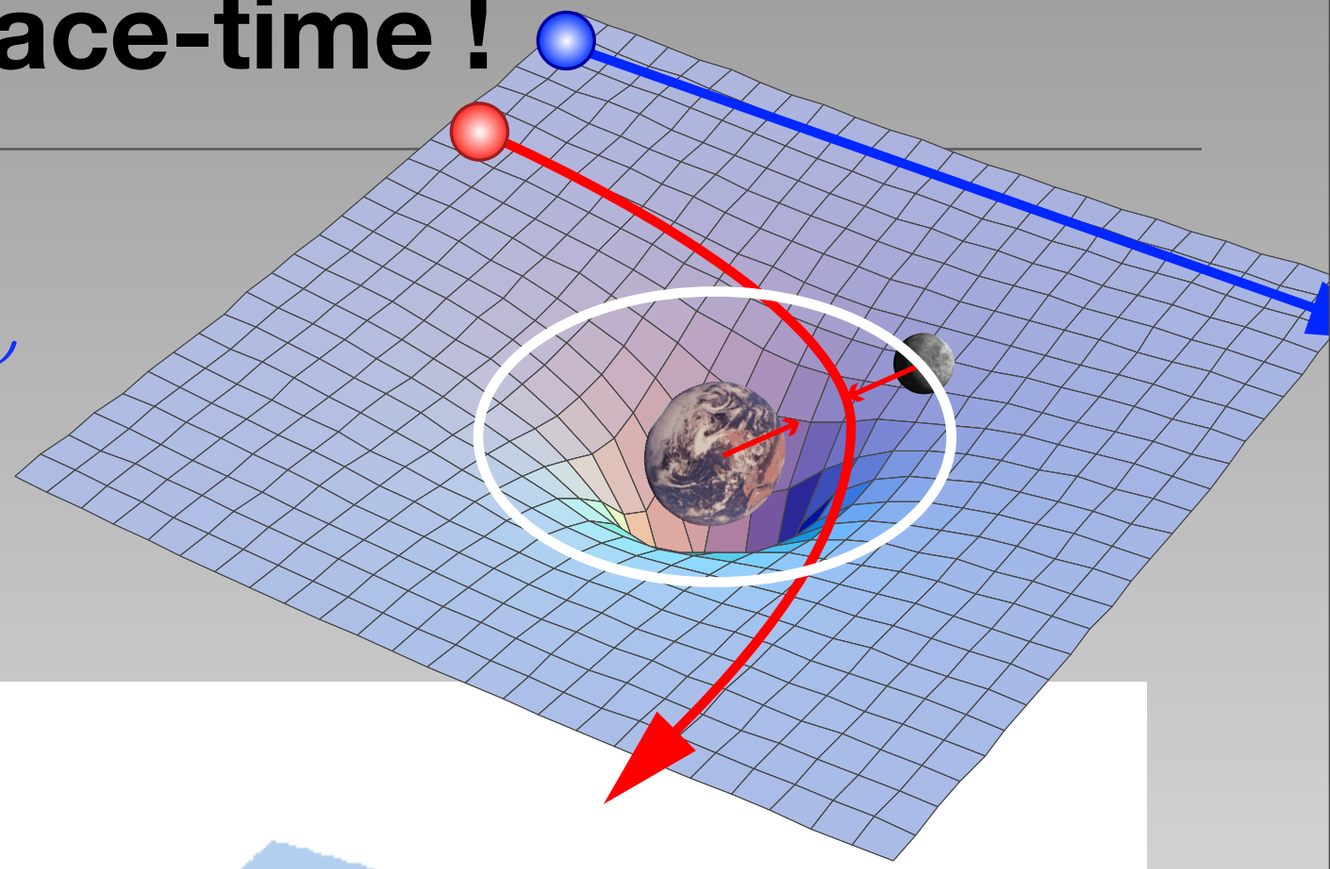

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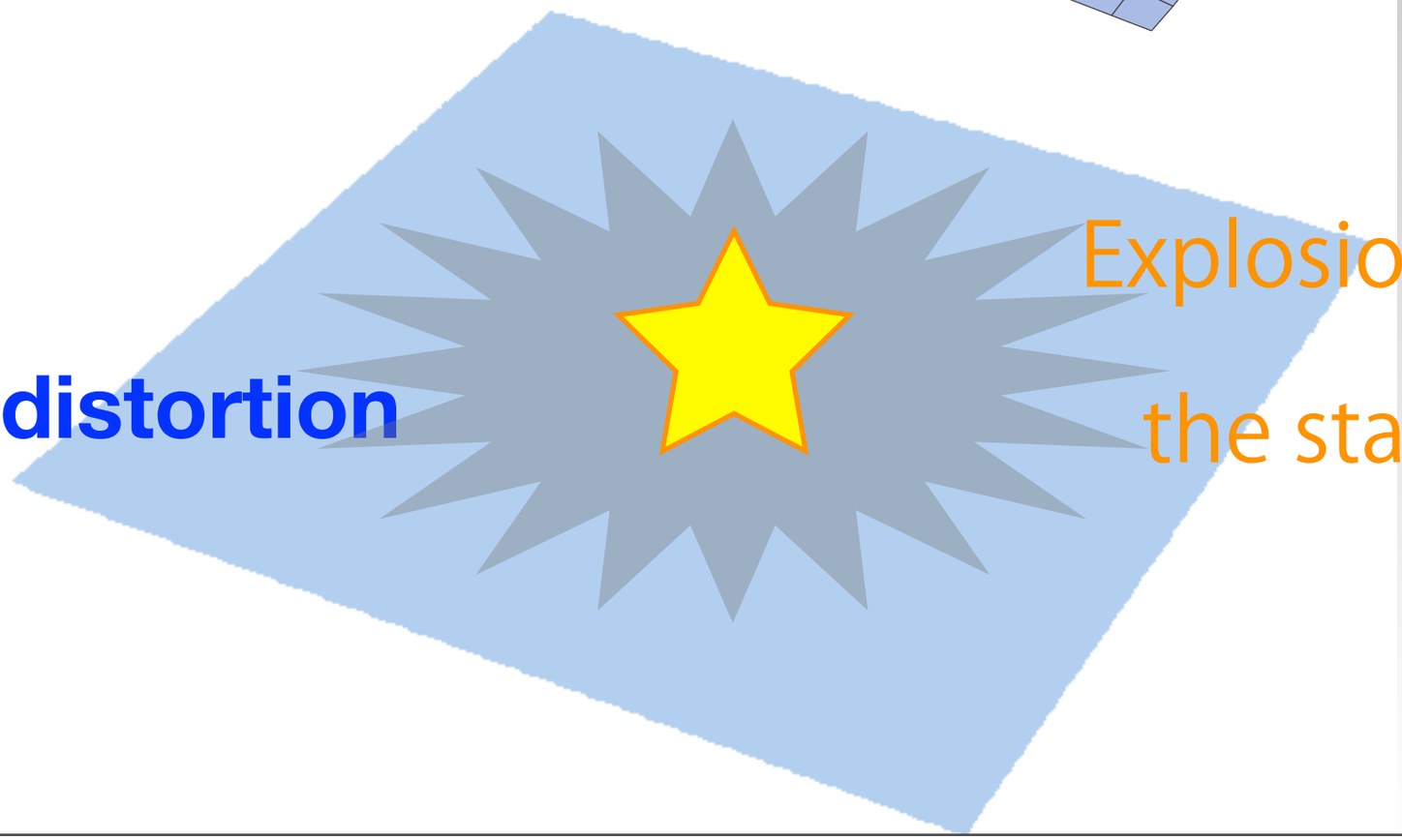


Gravitational Waves

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;

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

--> Wave of strain ‘h’

Gravitational Wave

- light speed
- transverse
- quadrupole
  (tidal force)

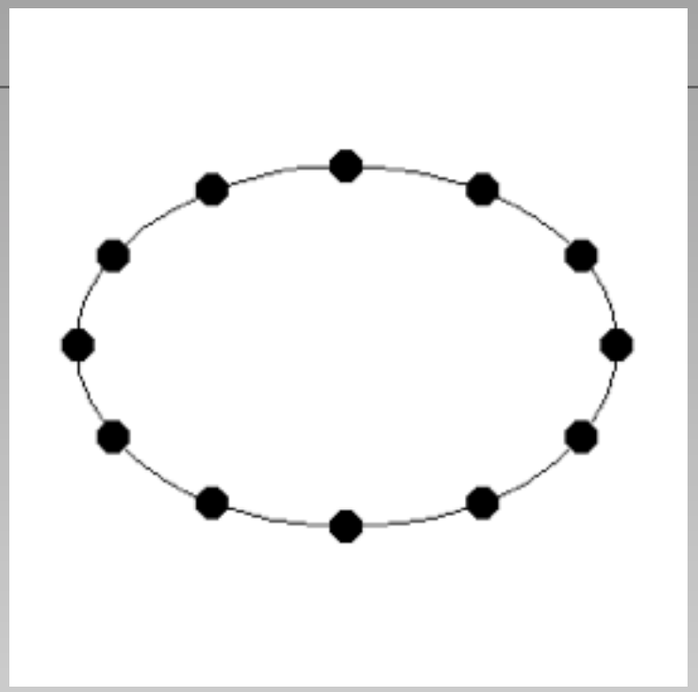
$$h_+ = h \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad h_\times = h \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

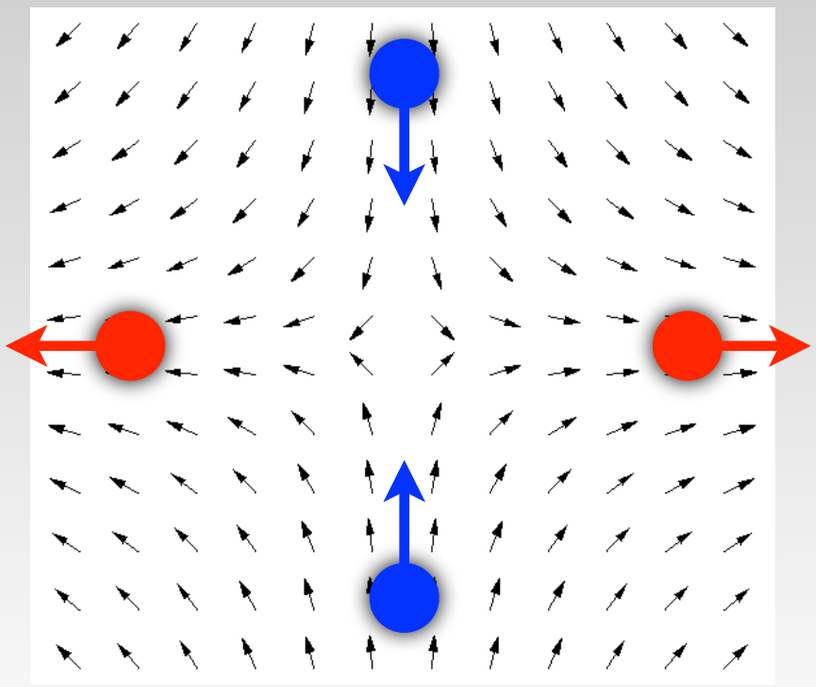
Force (Displacement) by GW

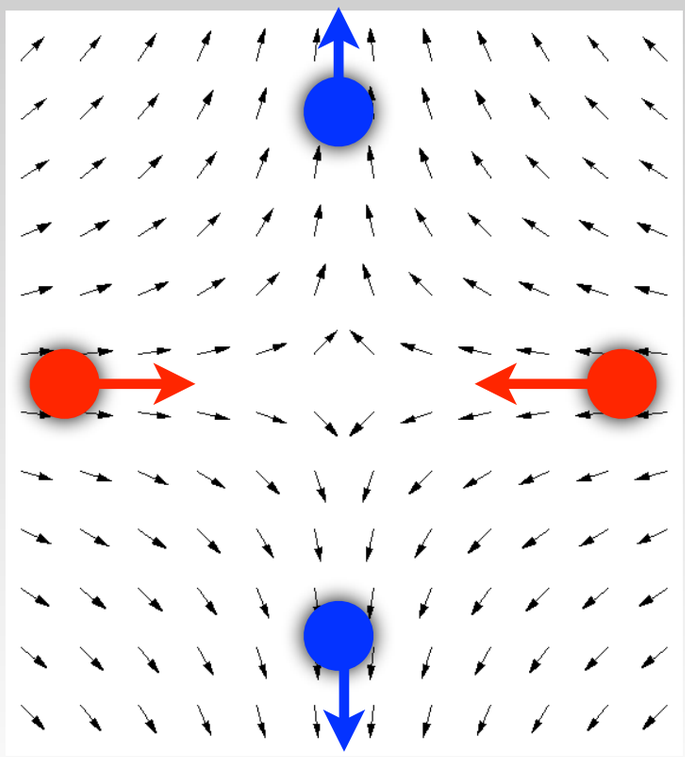
Tidal force on masses

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

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







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

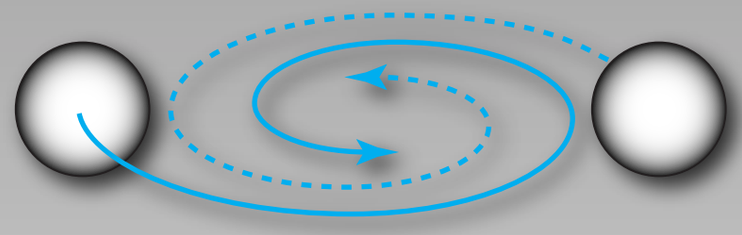
- Cosmic background radiation of GW
- POP-III stars, star formation, etc...

Physics on early universe.

Expected GW sources

Event like:

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

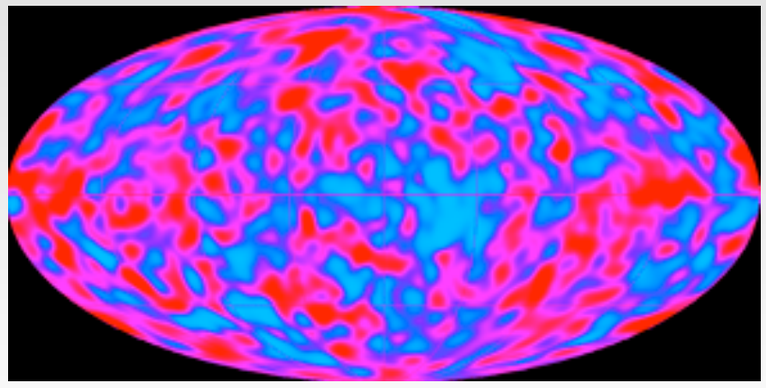


Continuous waves:

- Pulsar rotation
- Binaries

Stochastic Background

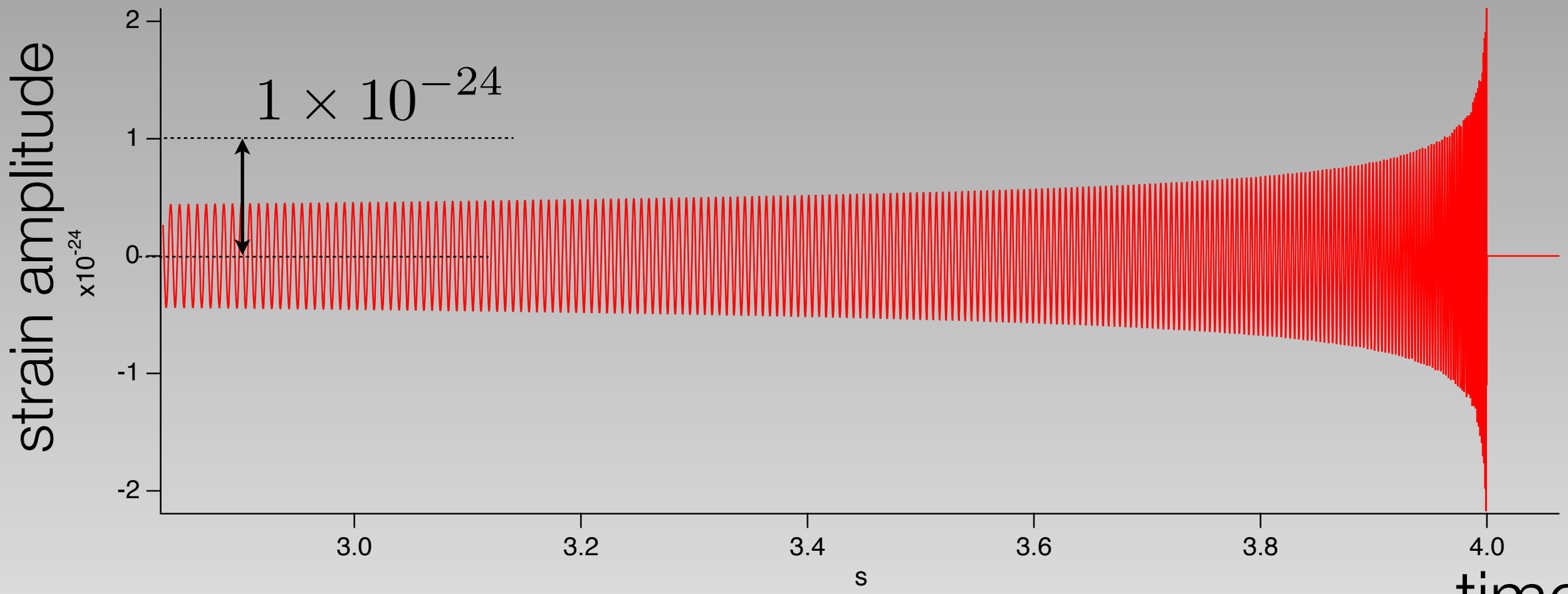
- Early universe (i.e. Inflation)
- Cosmic string



(& Unknown sources...)

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

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

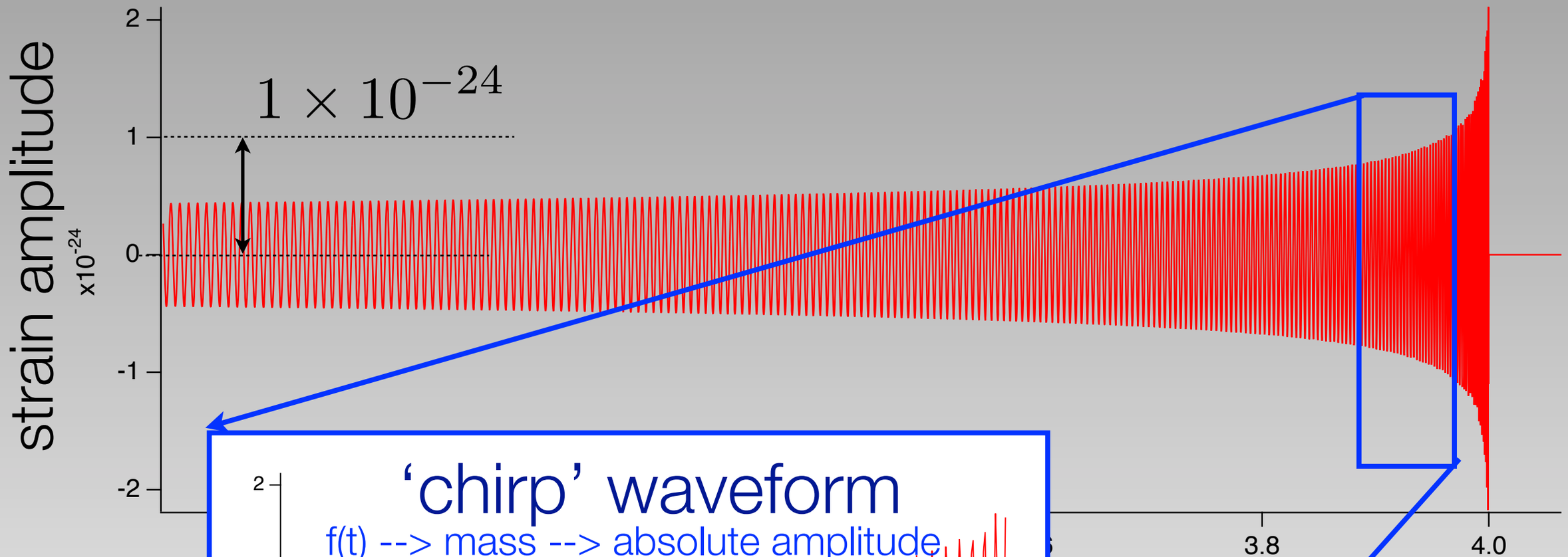


amplitude ~10^{-24} for NS-NS at 200Mpc away!

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

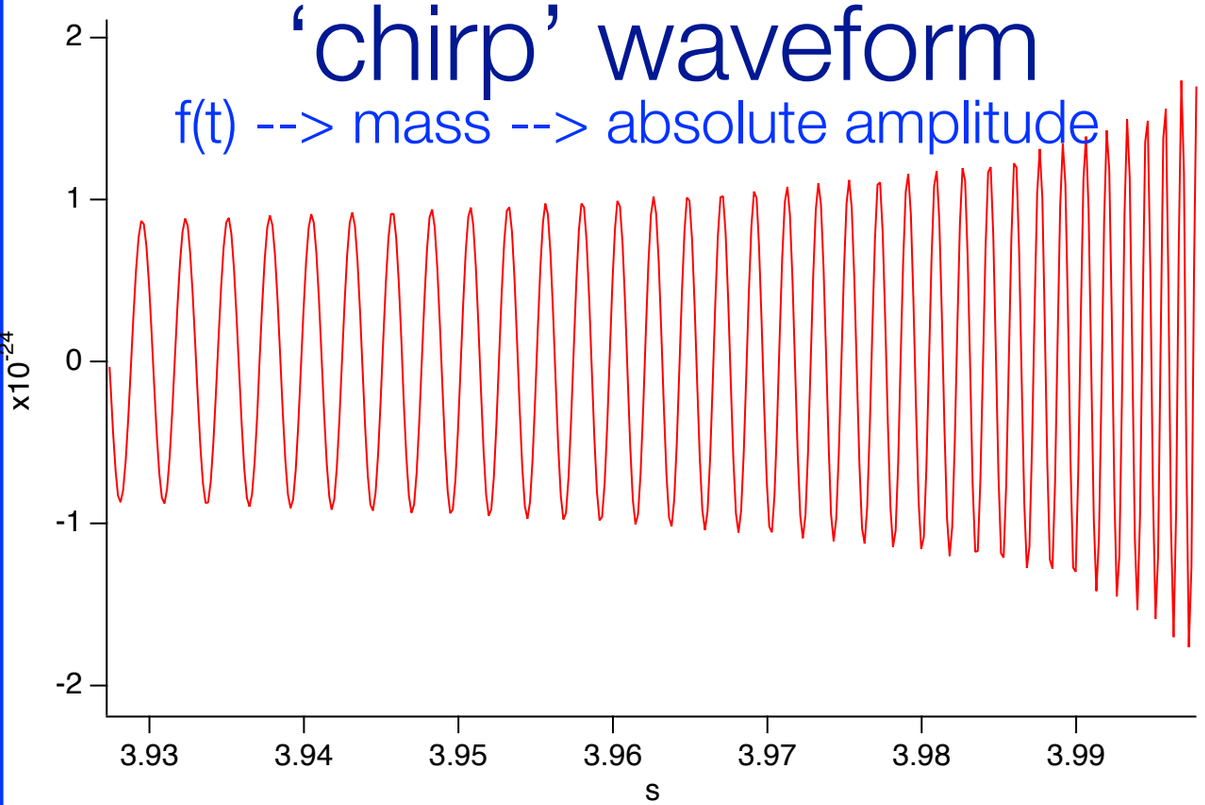
- small amplitude
- Waveform can determine masses and absolute amplitude.

--> ‘***standard candle***’



‘chirp’ waveform

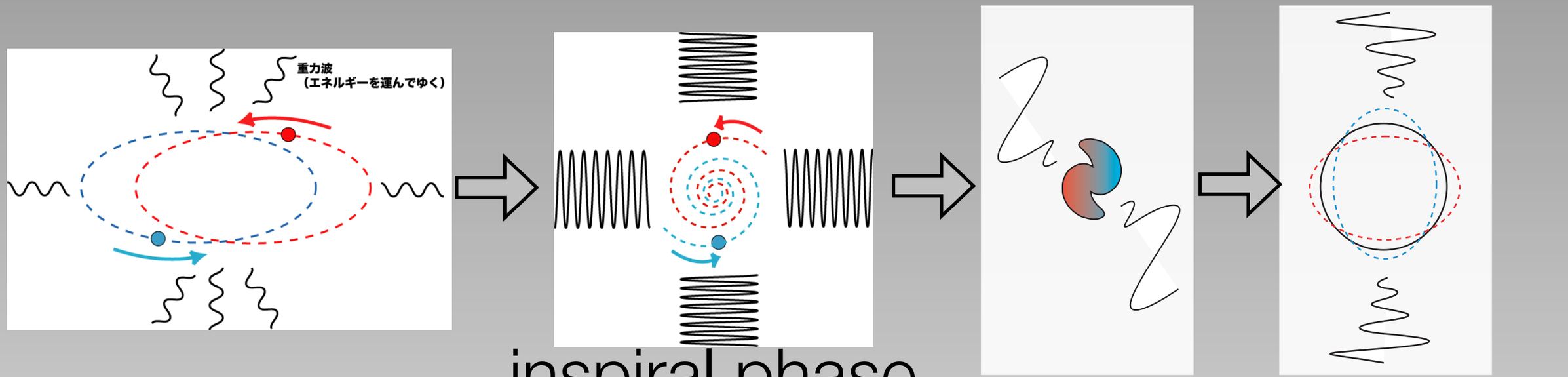
f(t) --> mass --> absolute amplitude



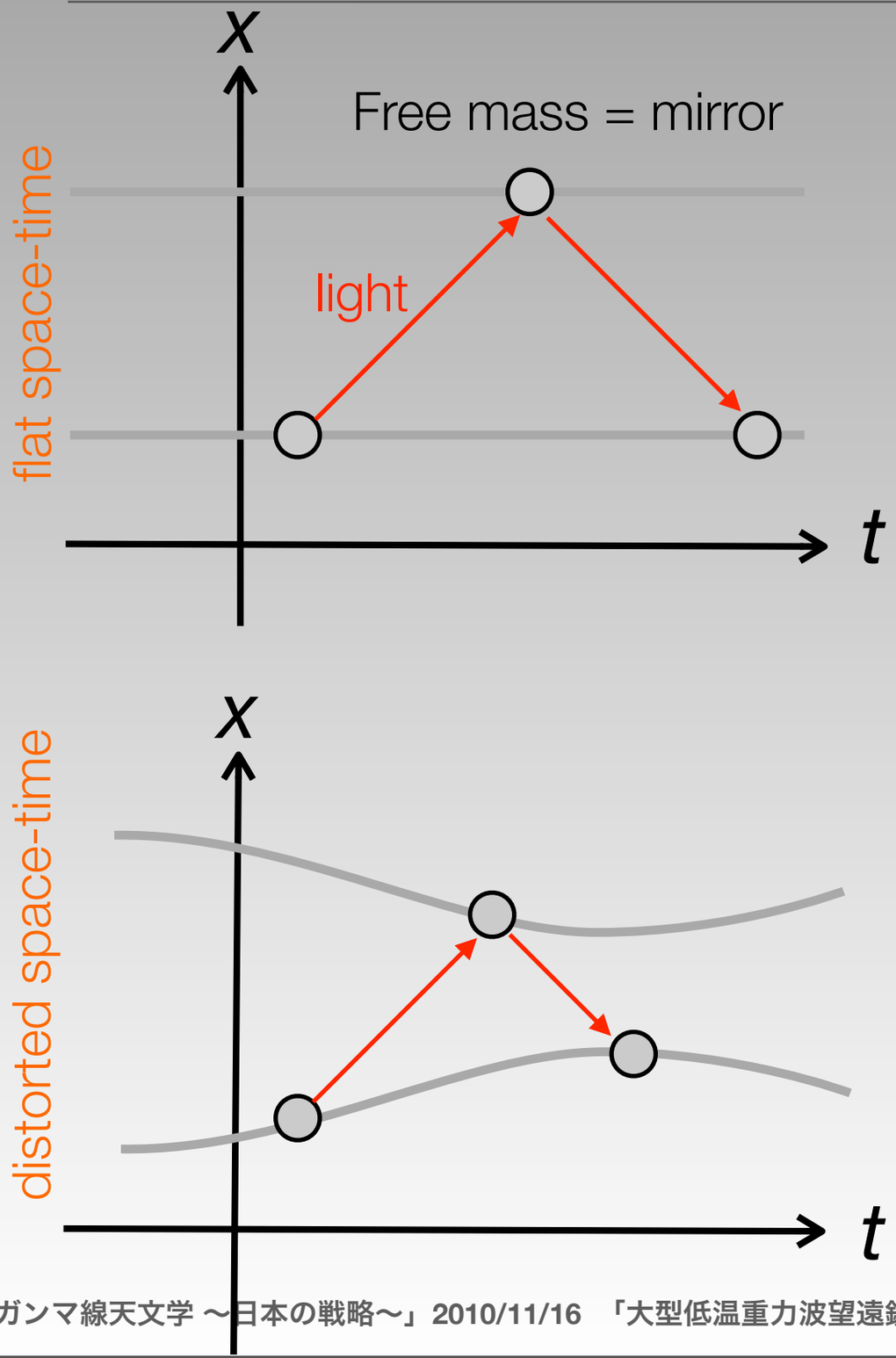
ar t 200Mpc away!

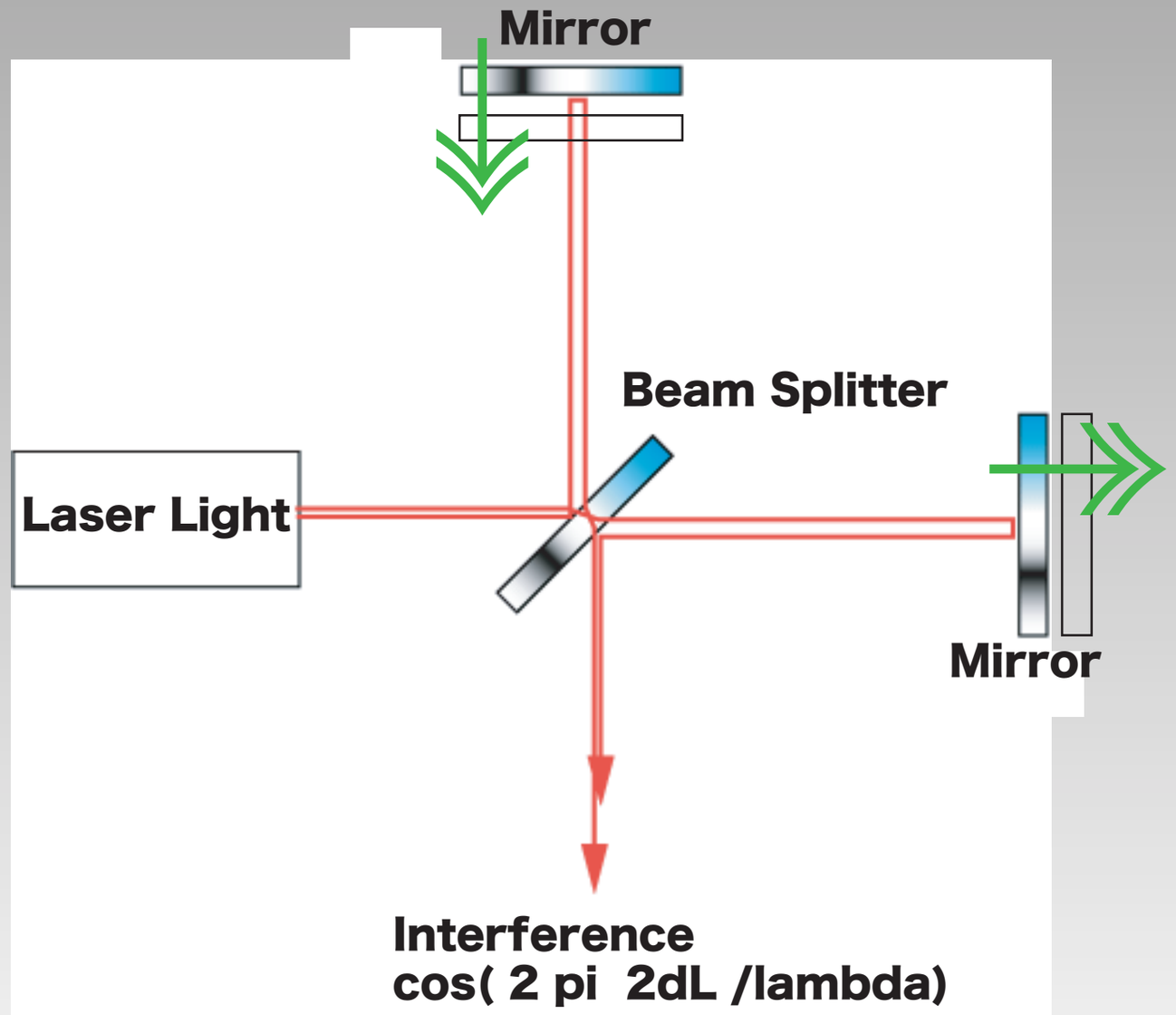
(in frec [/√Hz] @10~100Hz)

Coalescence of neutron star binary (NS-NS)



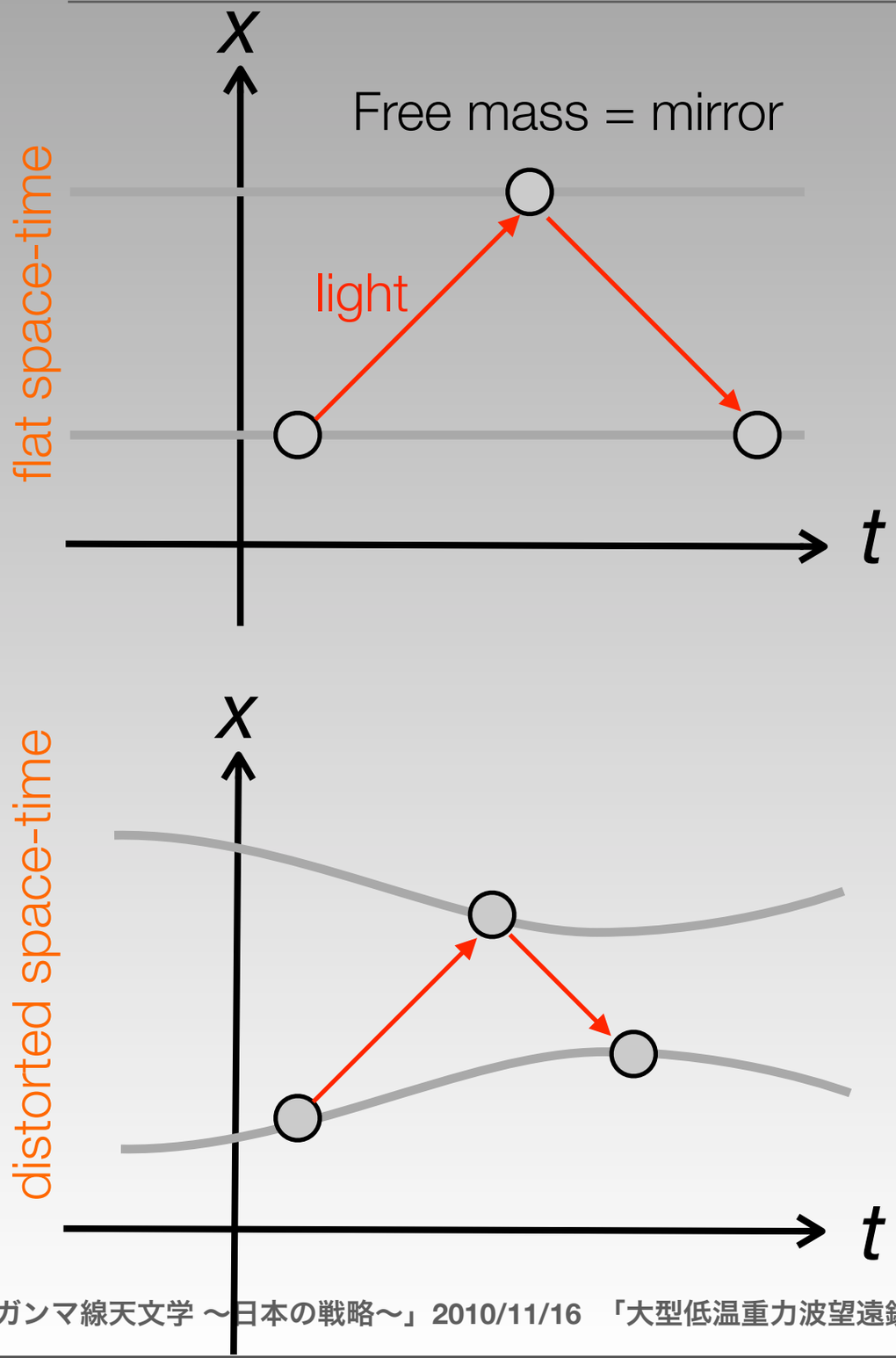
How to detect GW :
Free Test Masses & Laser Interferometer

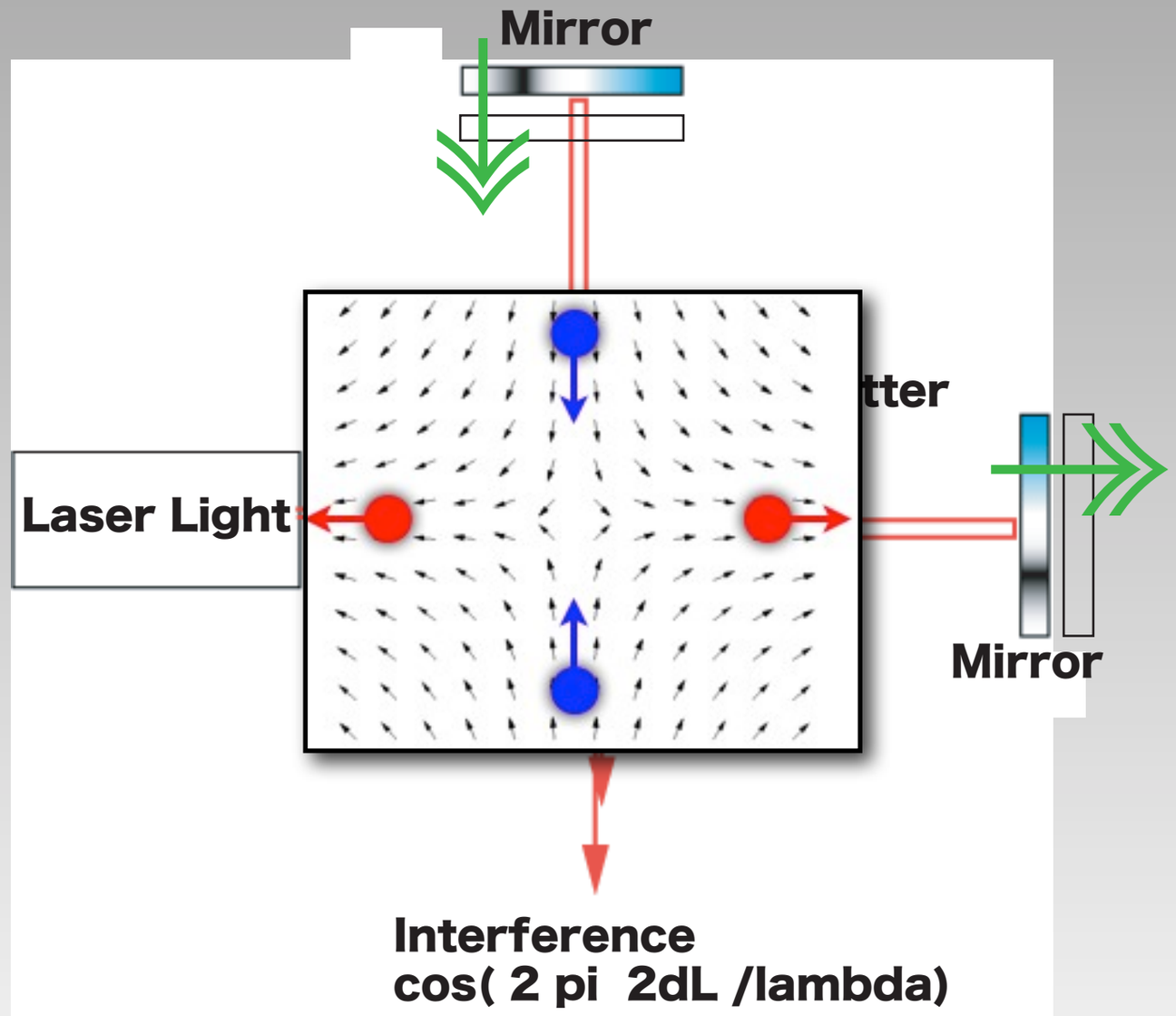




Michelson Interferometer

How to detect GW :
Free Test Masses & Laser Interferometer





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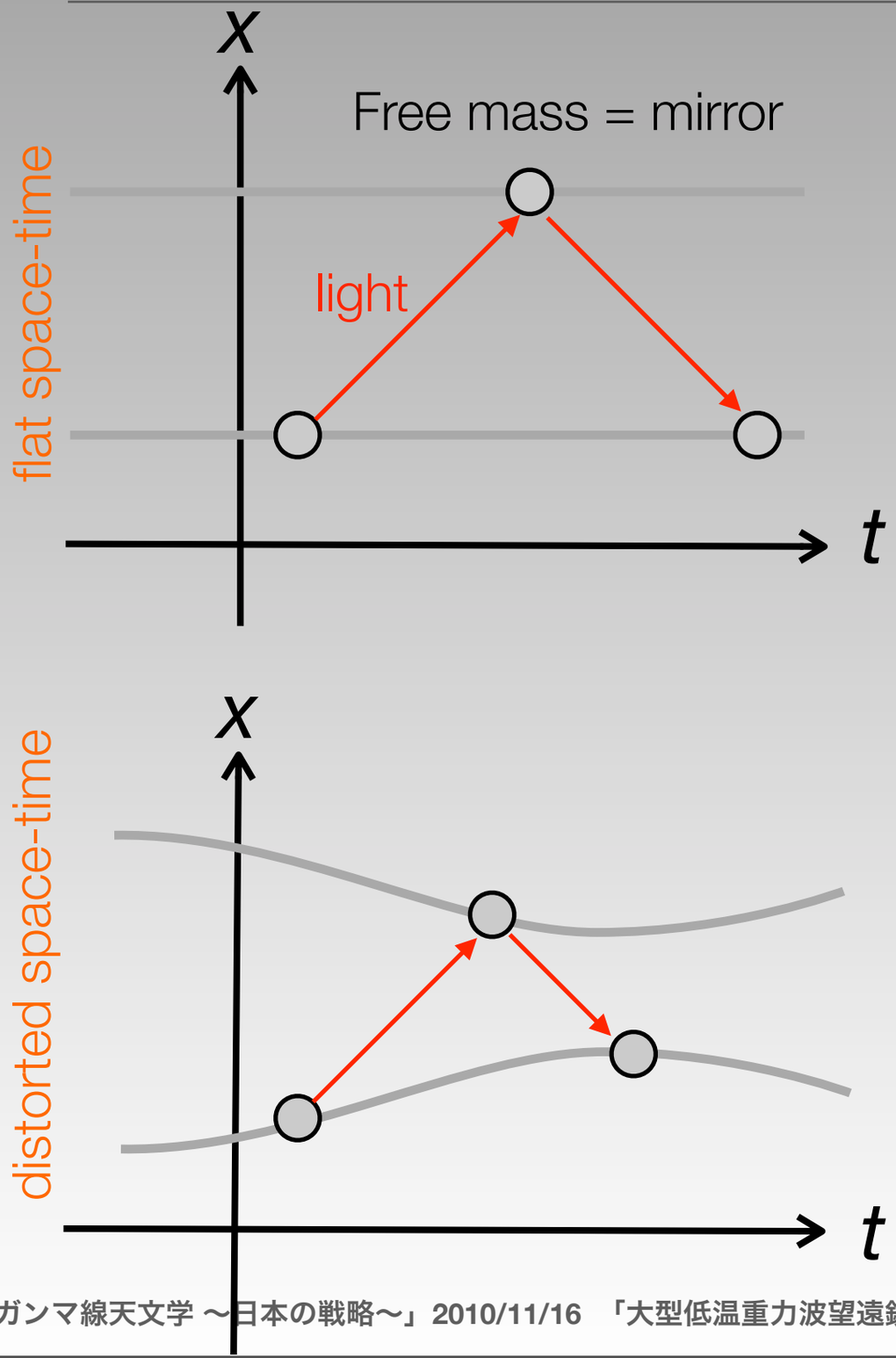
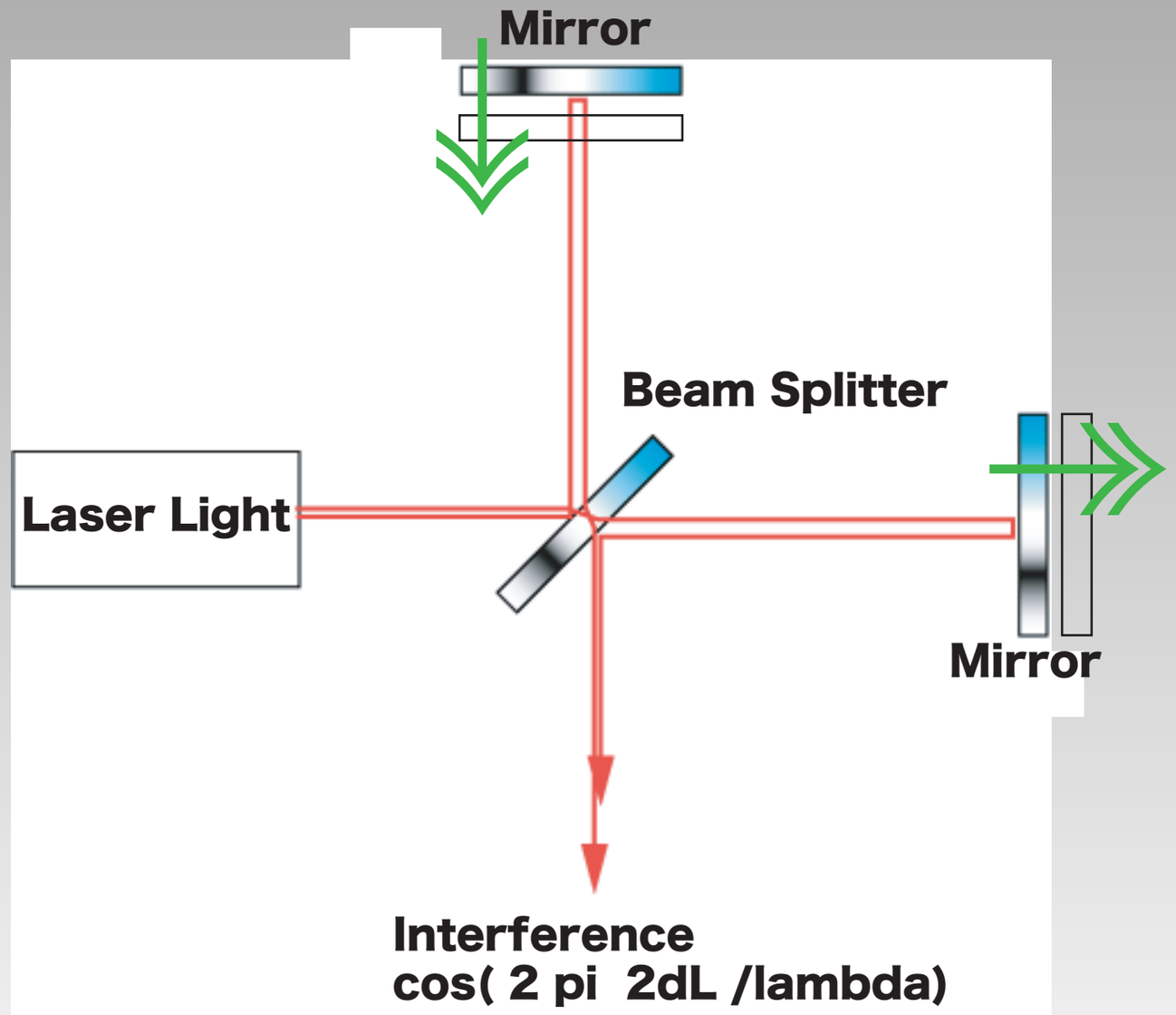




Michelson Interferometer

Schematic Figure

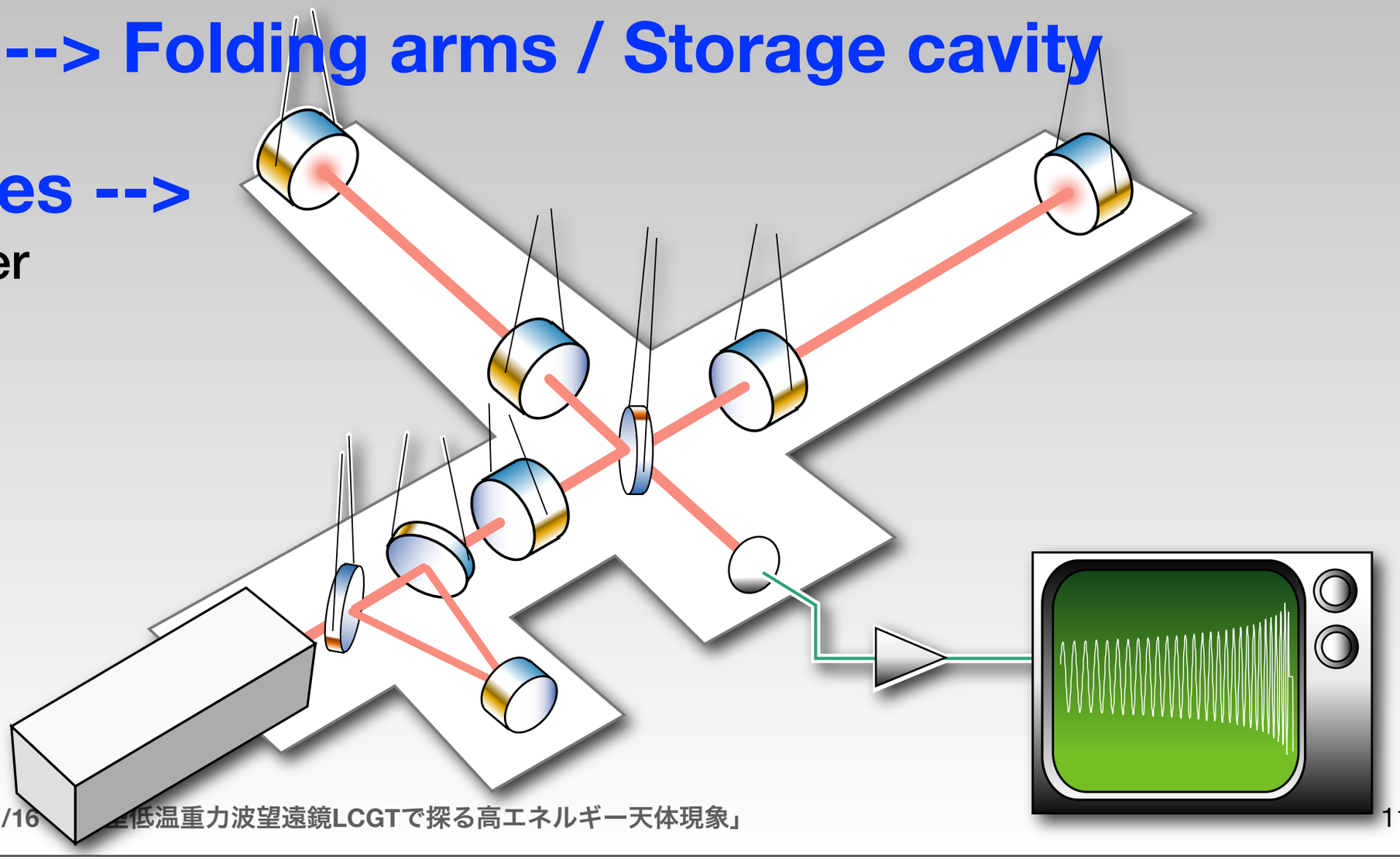
Free mass --> suspended mirror

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!*

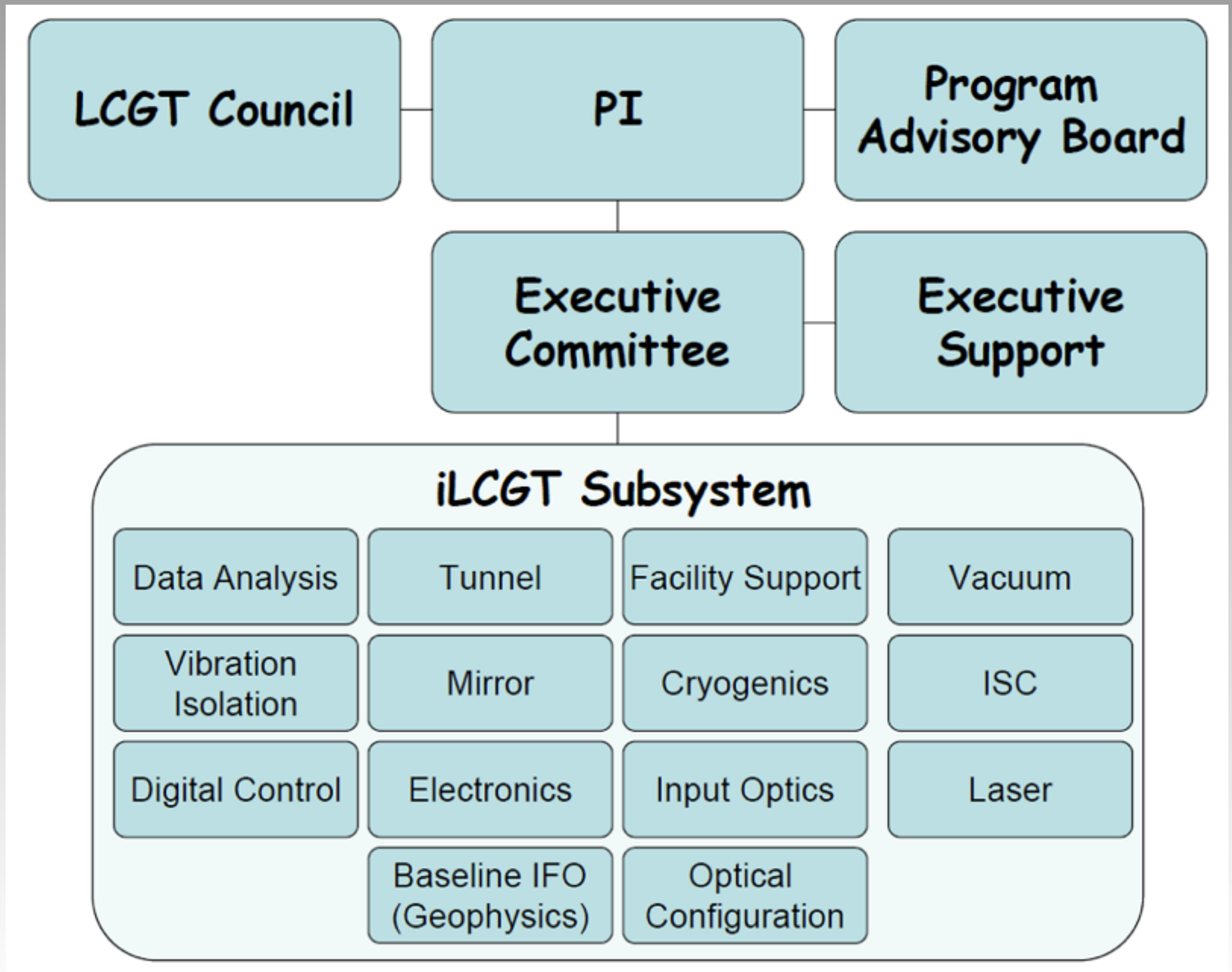
2014 : first run in normal temperture

2017- : observation with cryogenic mirror

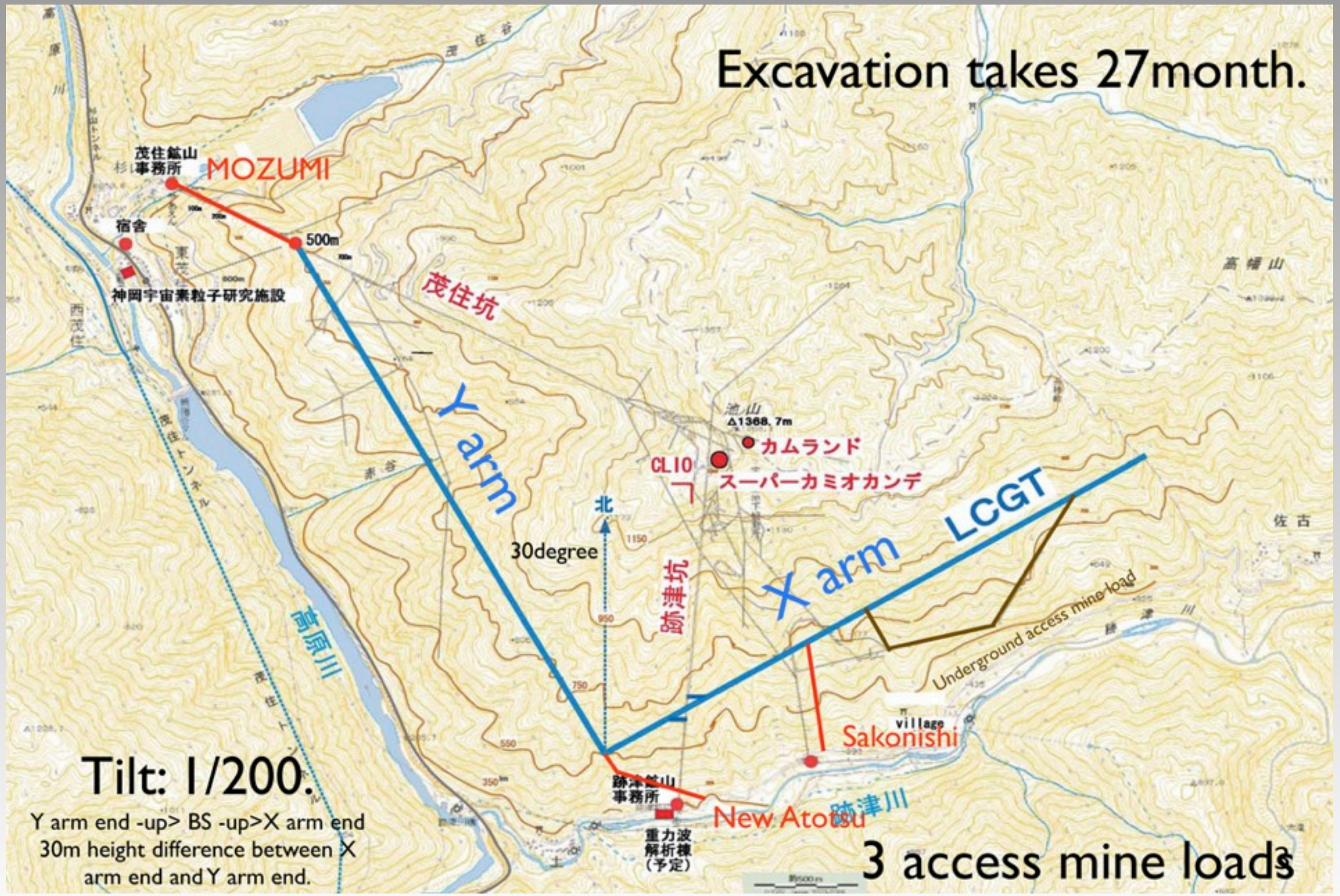
LCGT collaboration

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

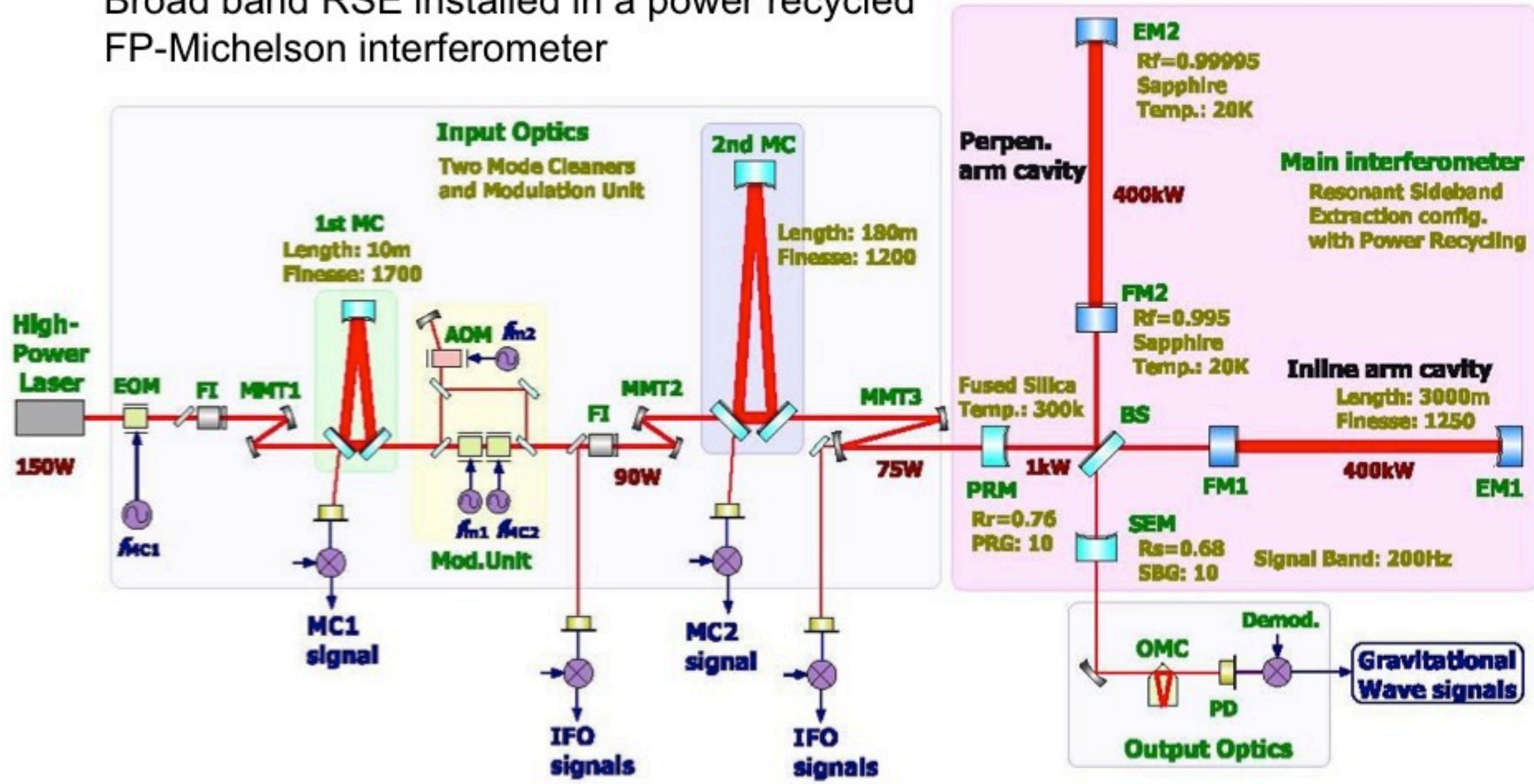


Site


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
北
30degree
跡津坑
X arm
LCGT
池山
△1368. 7m
カムランド
CLIO
スーパーカミオカンデ
高幡山
佐古
高原川
Underground access mine load
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



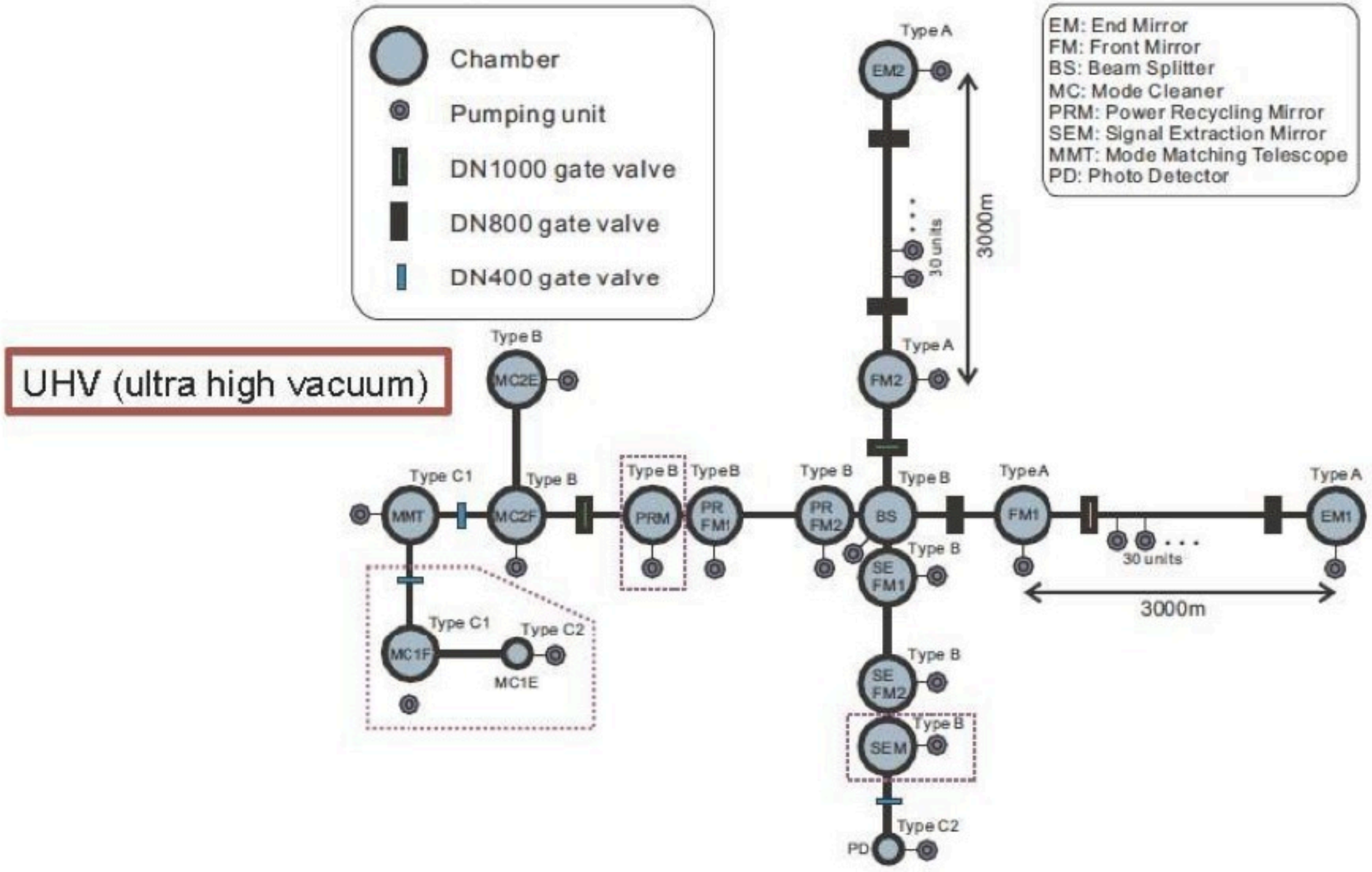
Re-design is under going ;for example

---removing the 180 m long mode cleaner cavity

---flexibility change of possible adoption of detuned RSE

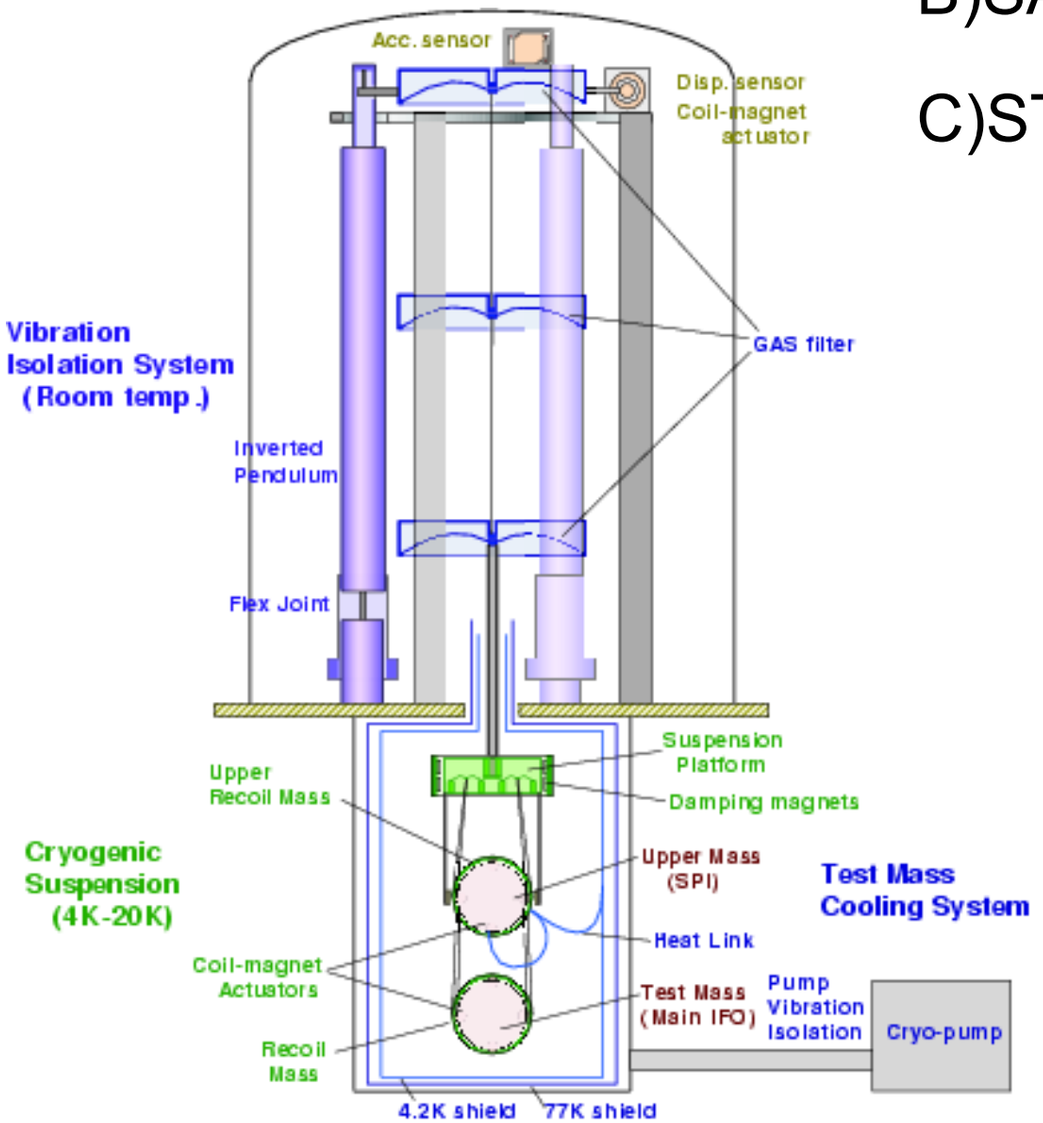
Vacuum System

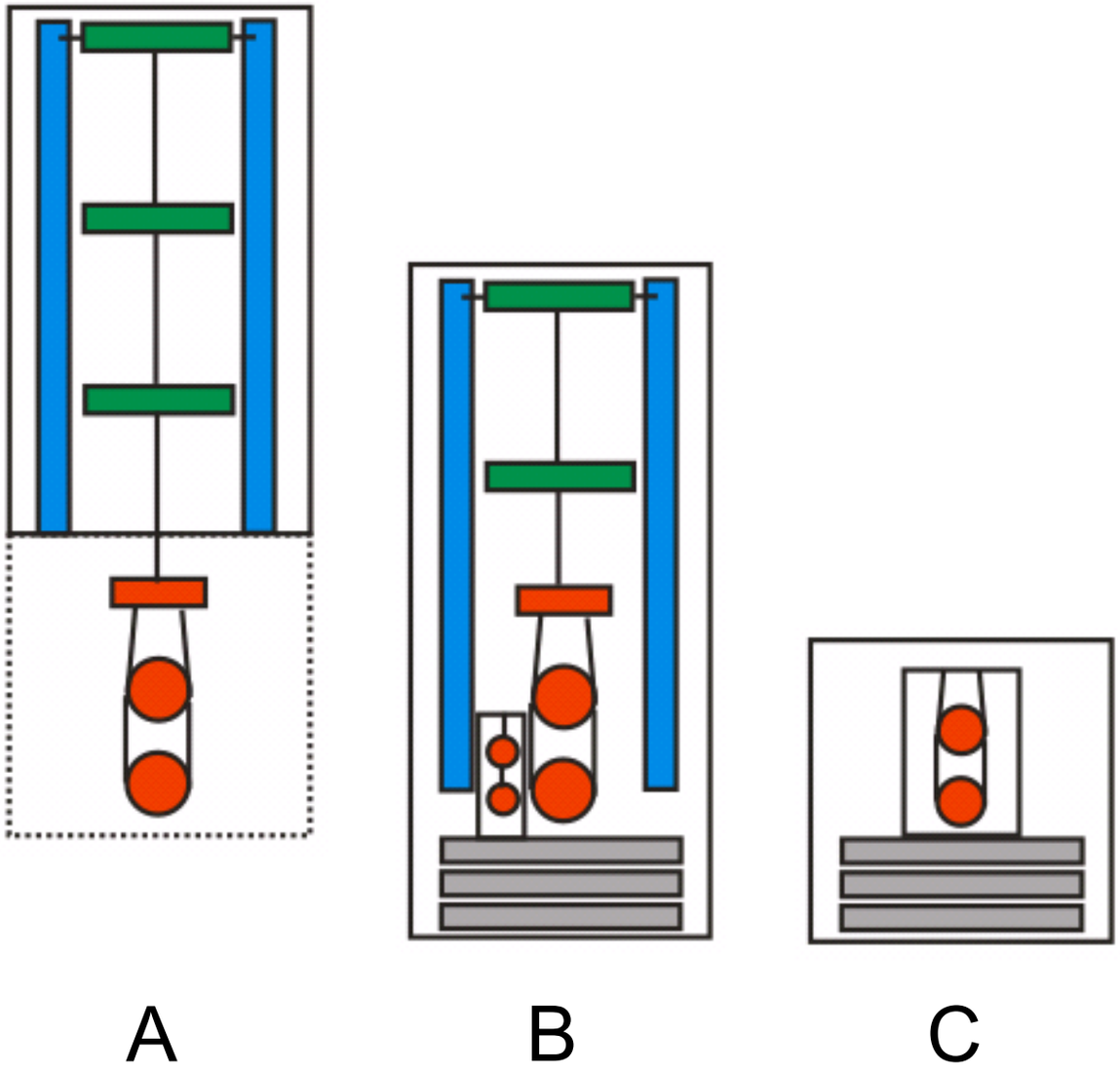
** for reducing noise due to a residual gas effect
** for maintenance minimizing



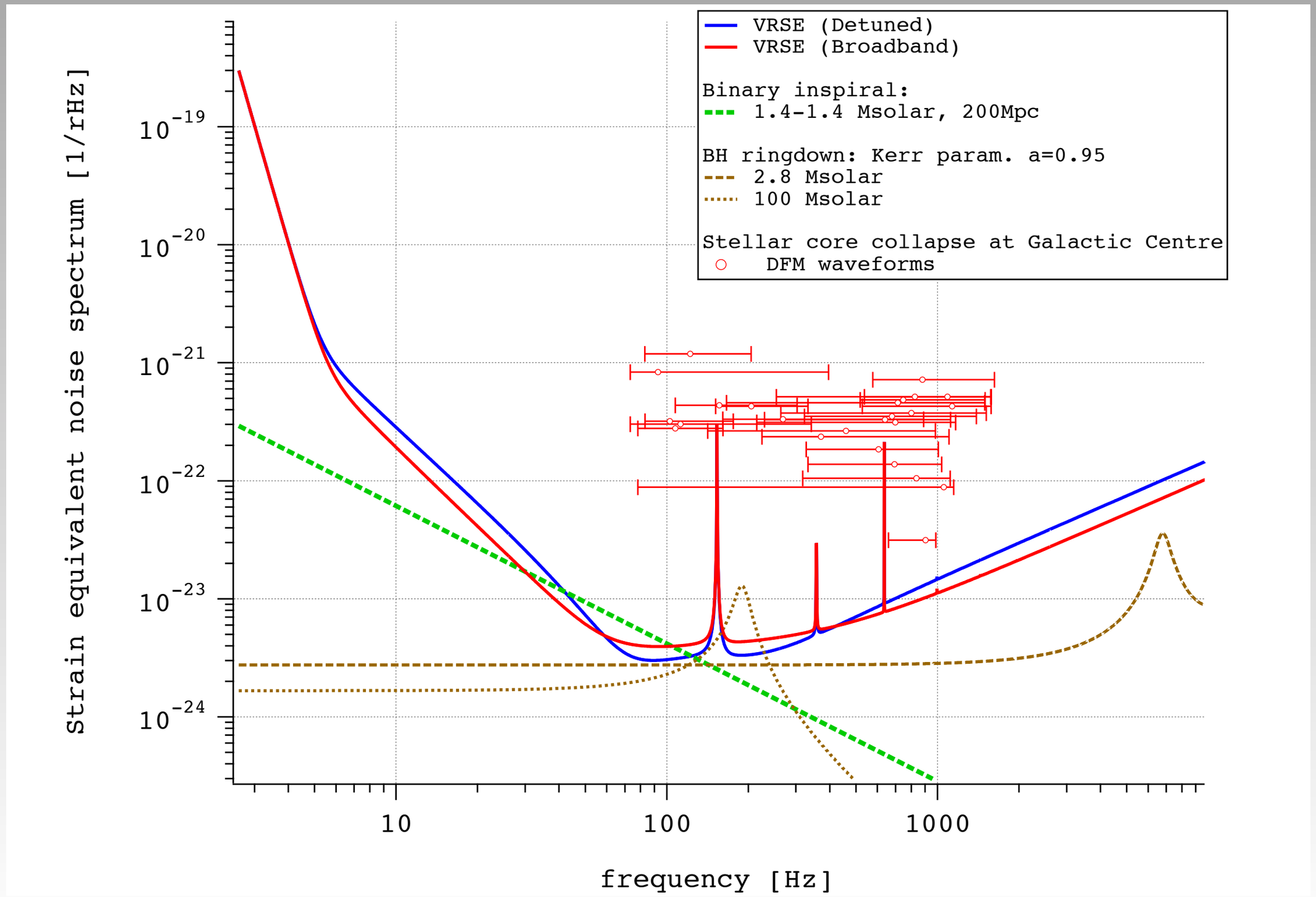
Design of anti-vibration system

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

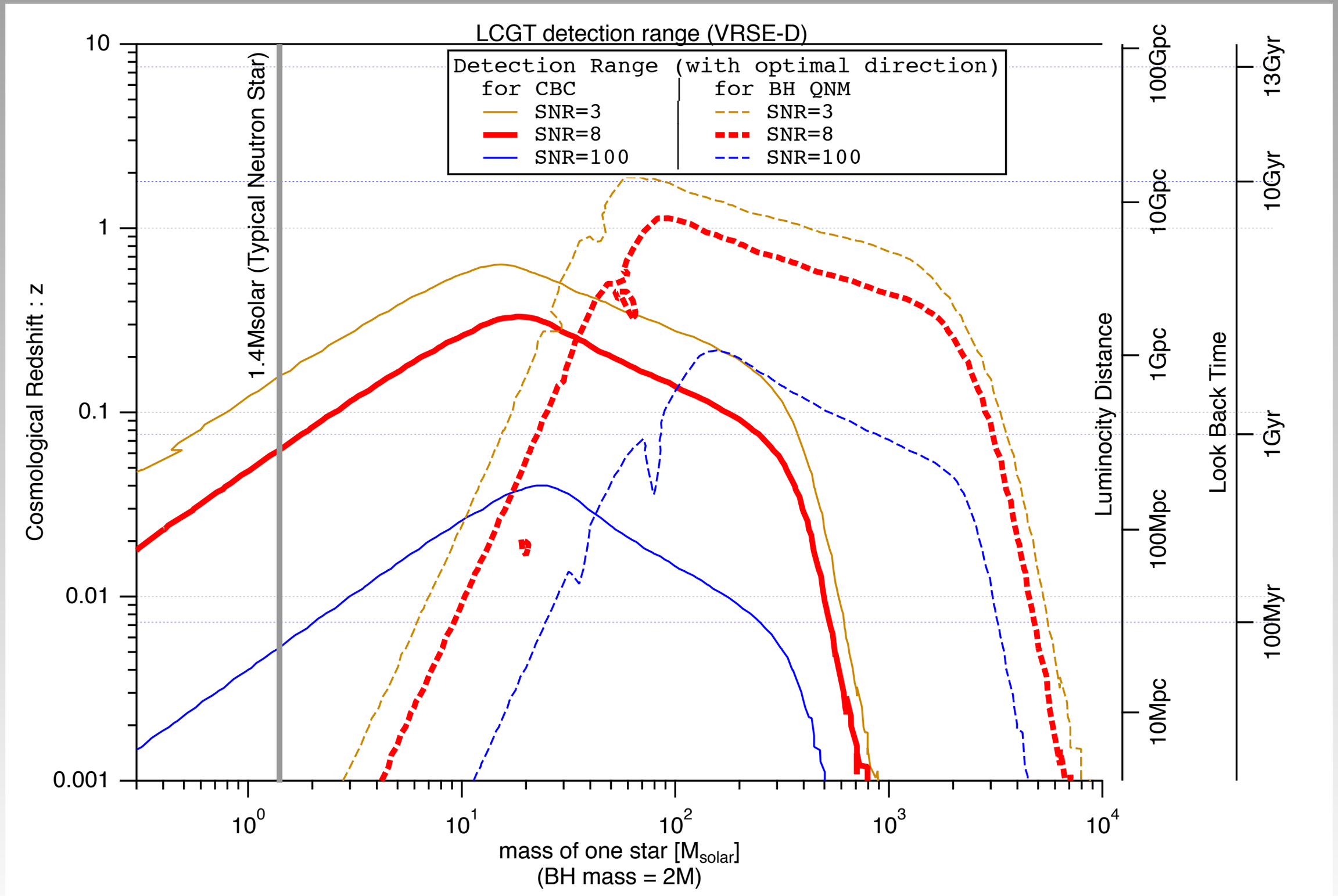




Design Sensitivity of LCGT

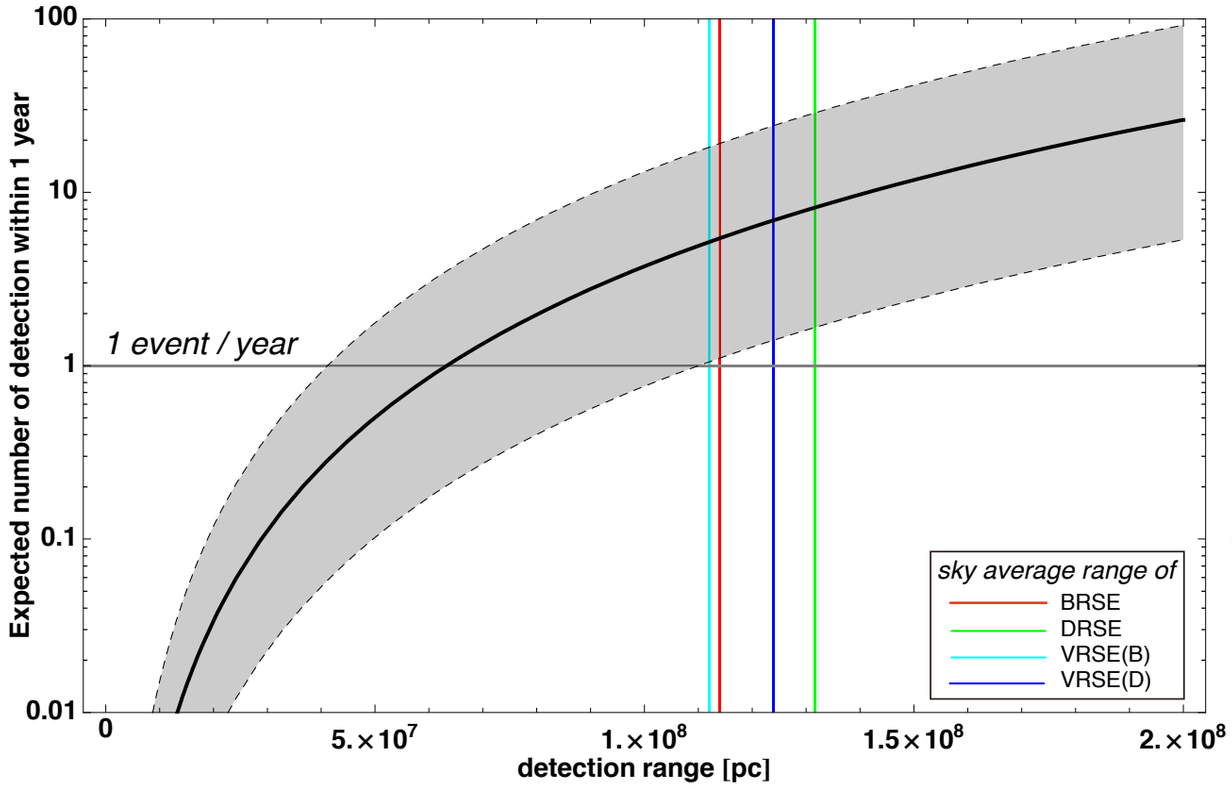


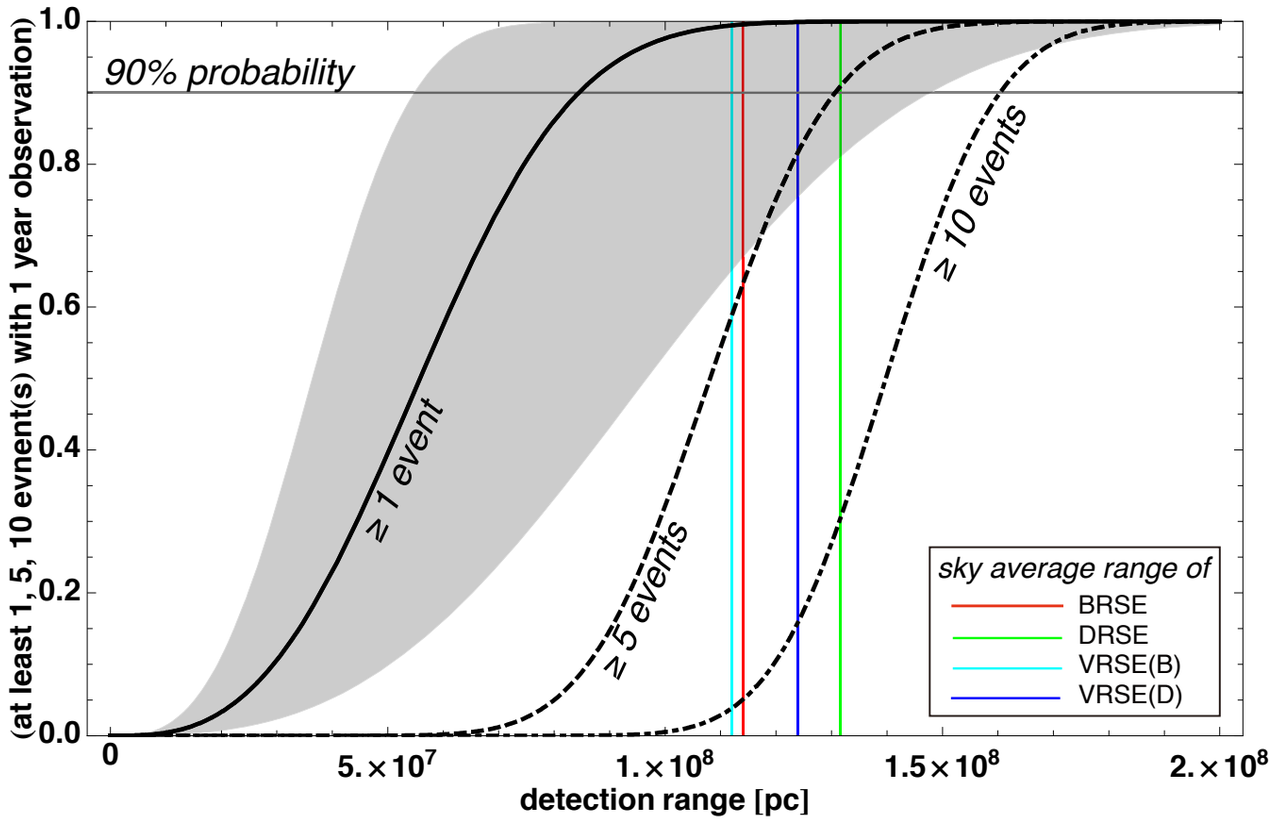
Detection Range for Compact Binary and BH QNM



Probability of Detection

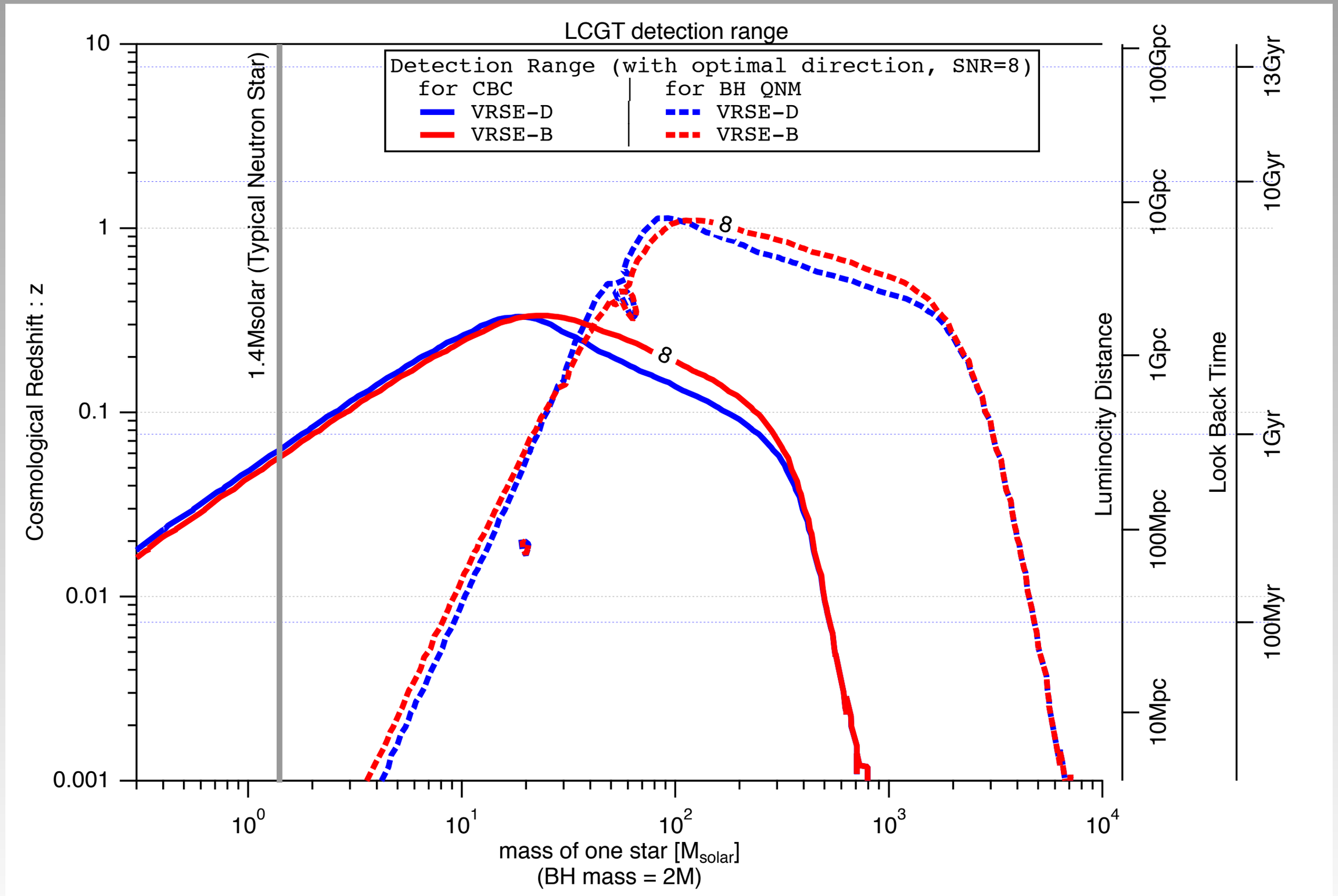
BW working group



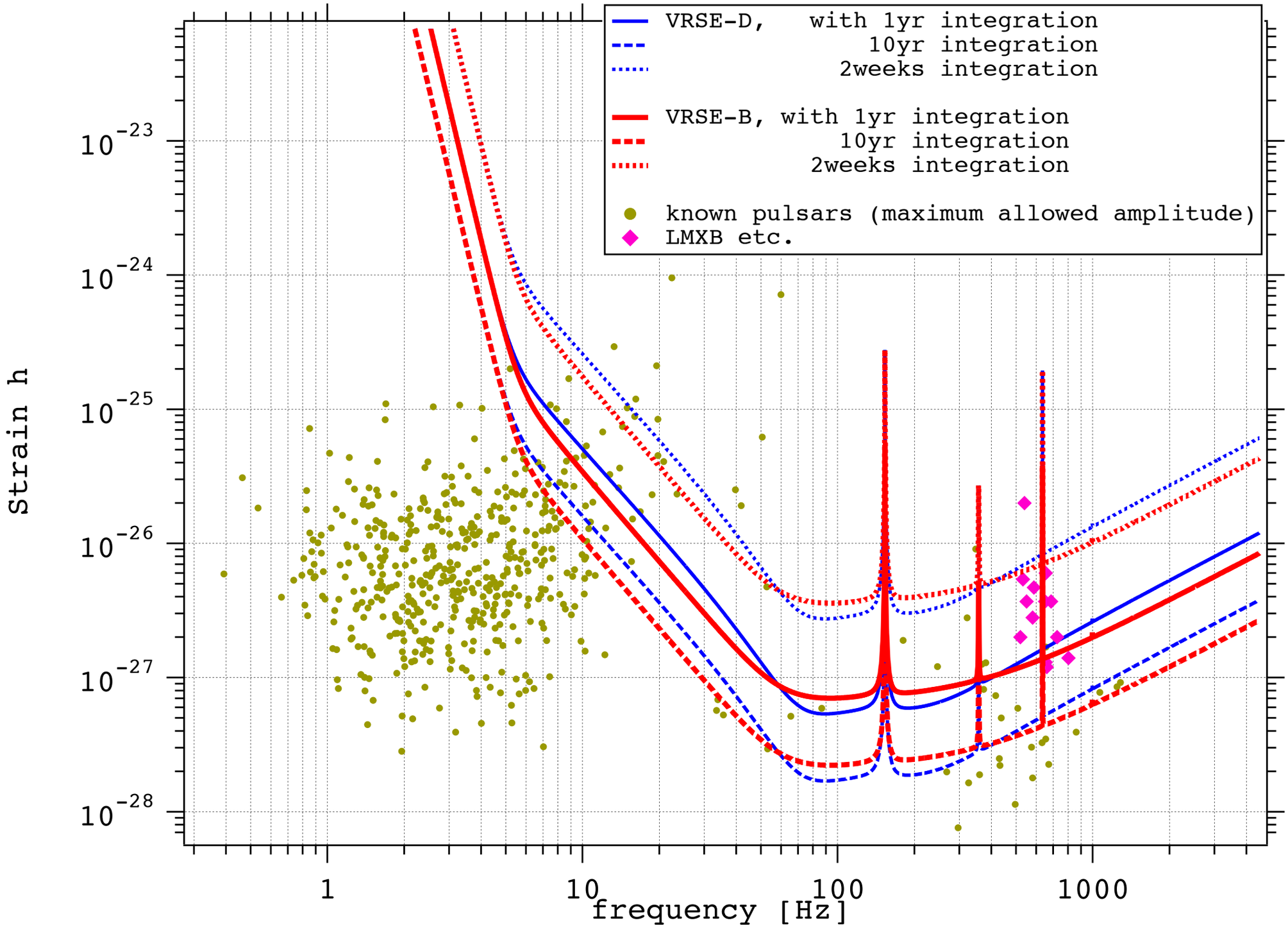


NS-NS Detection Range	(sky average)	123 Mpc
	(optimal direction)	281 Mpc
Expected # of events		6.9 $^{+17.3}_{-5.5}$ events/year
Probability of detection	at least one event	99.9 % for one year
	90% for 1st event	4 months

VRSE-D vs VRSE-B



Sensitivity for Continuous GW



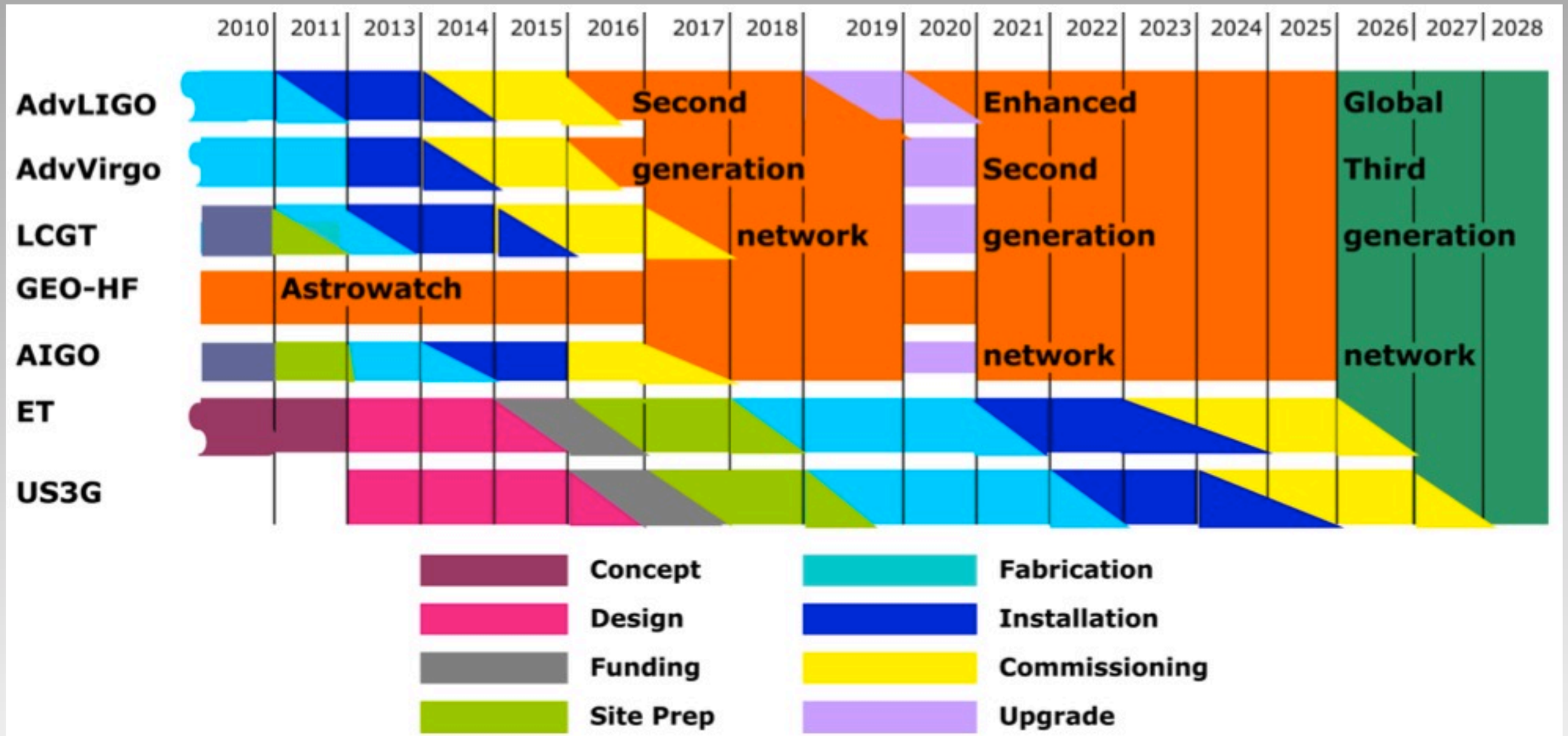
Schedule (Construction & Observation)

item	Japanease FY							
	2010	2011	2012	2013	2014	2015	2016	2017
Excavation								
vacuum system								
Optical system								
Laser ssytem								
suspension								
Anti Vibration								
2nd phase (Cryogenic system)								
Geophysics interferometer								
digital system								
control room (building)								
system tuning								
observation								

construction (off-site)
construction (on-site)
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

GEO 600m

LIGO (Livingston) 4km

VIRGO 3km

EGO

eLIGO (current upgarading)
adv.LIGO

LIGO (Hanford) 4km & 2km

TAMA 300m

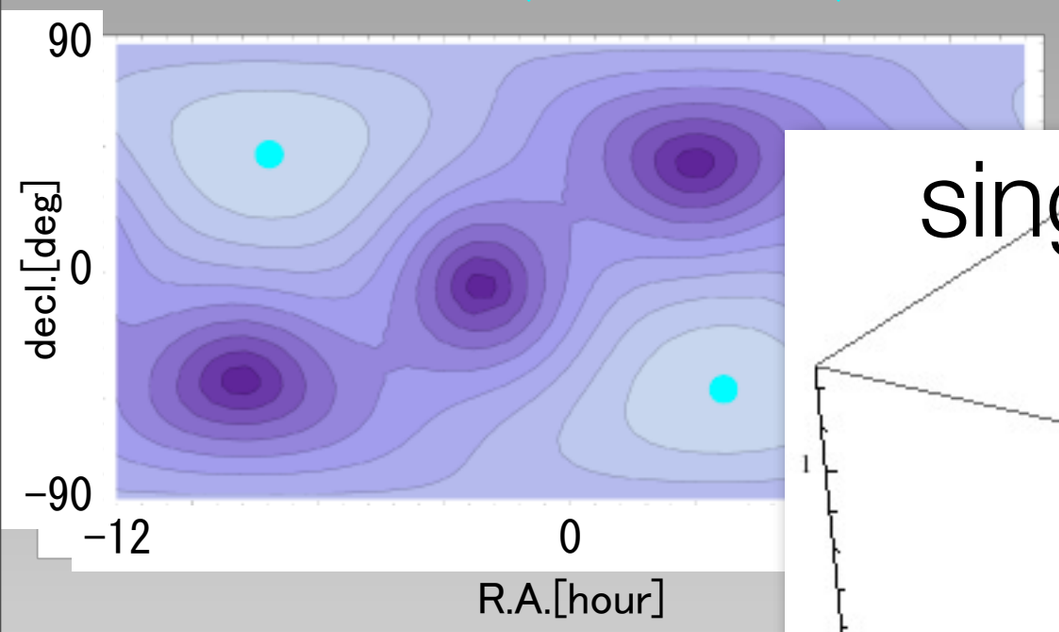
CLIO 100m

LCGT 3km

AIGO

Sky coverage by detector network

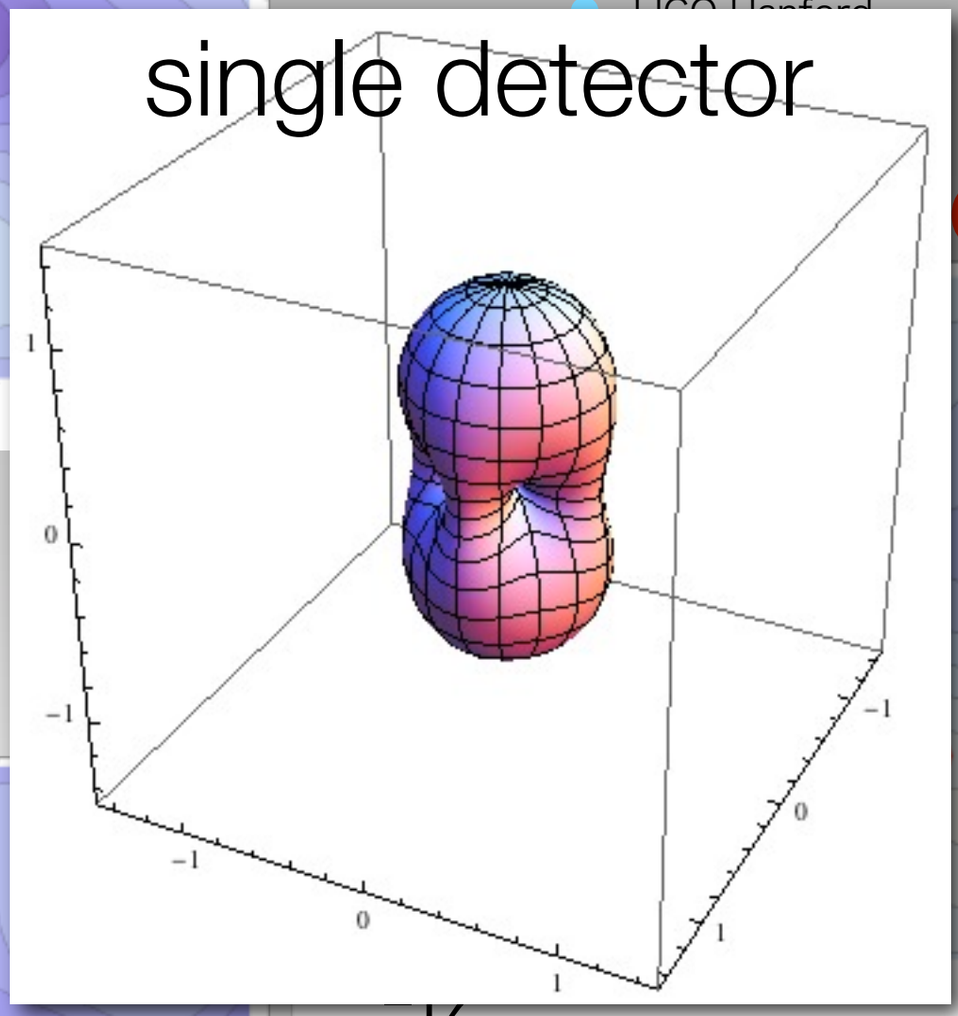
LIGO (Hanford)



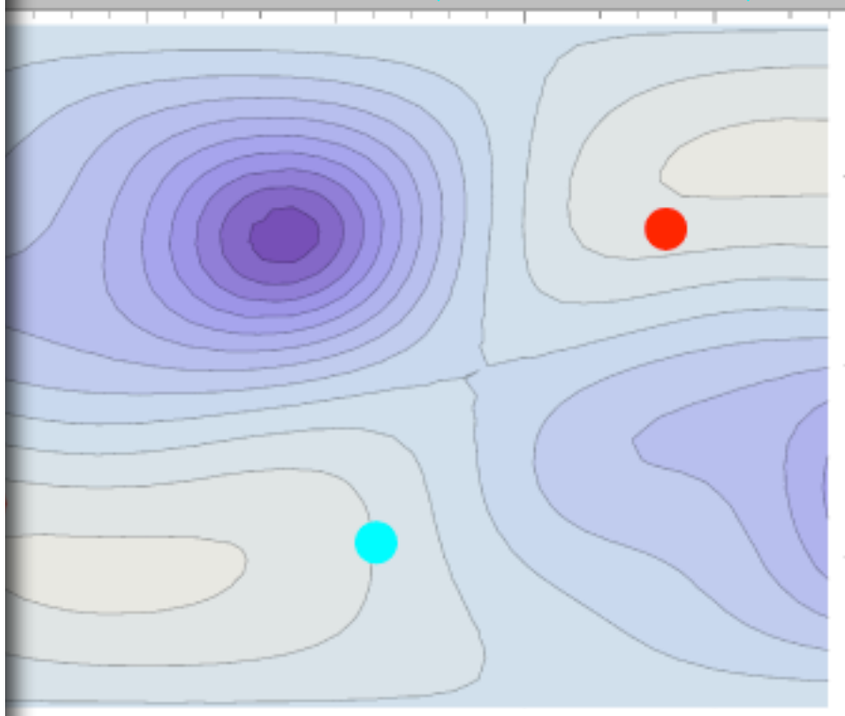
zenith direction of detectors

LIGO Hanford

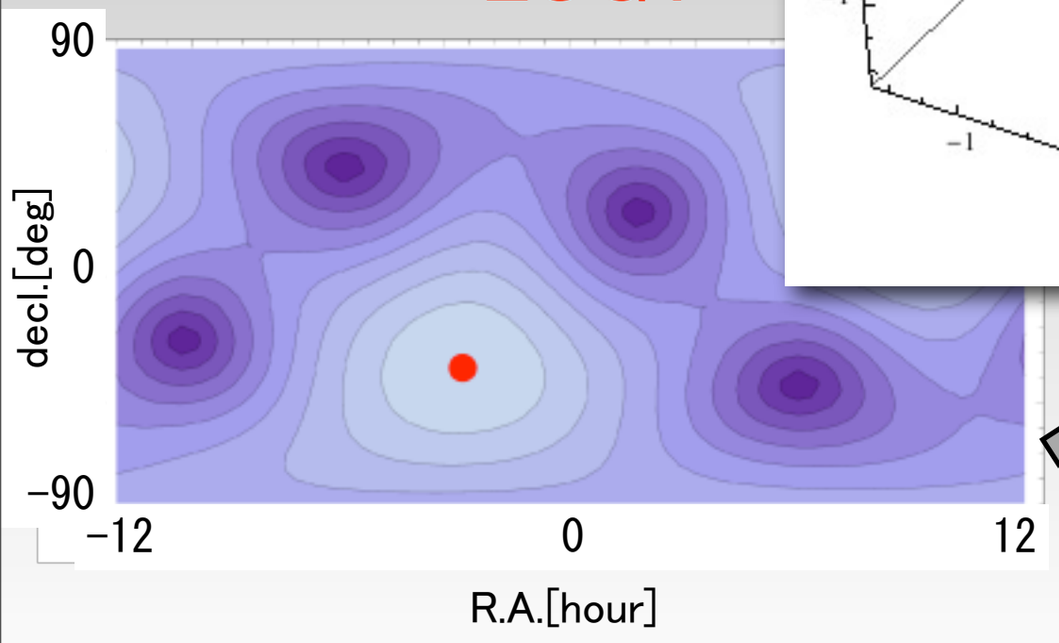
single detector



CGT+LIGO(Hanford)



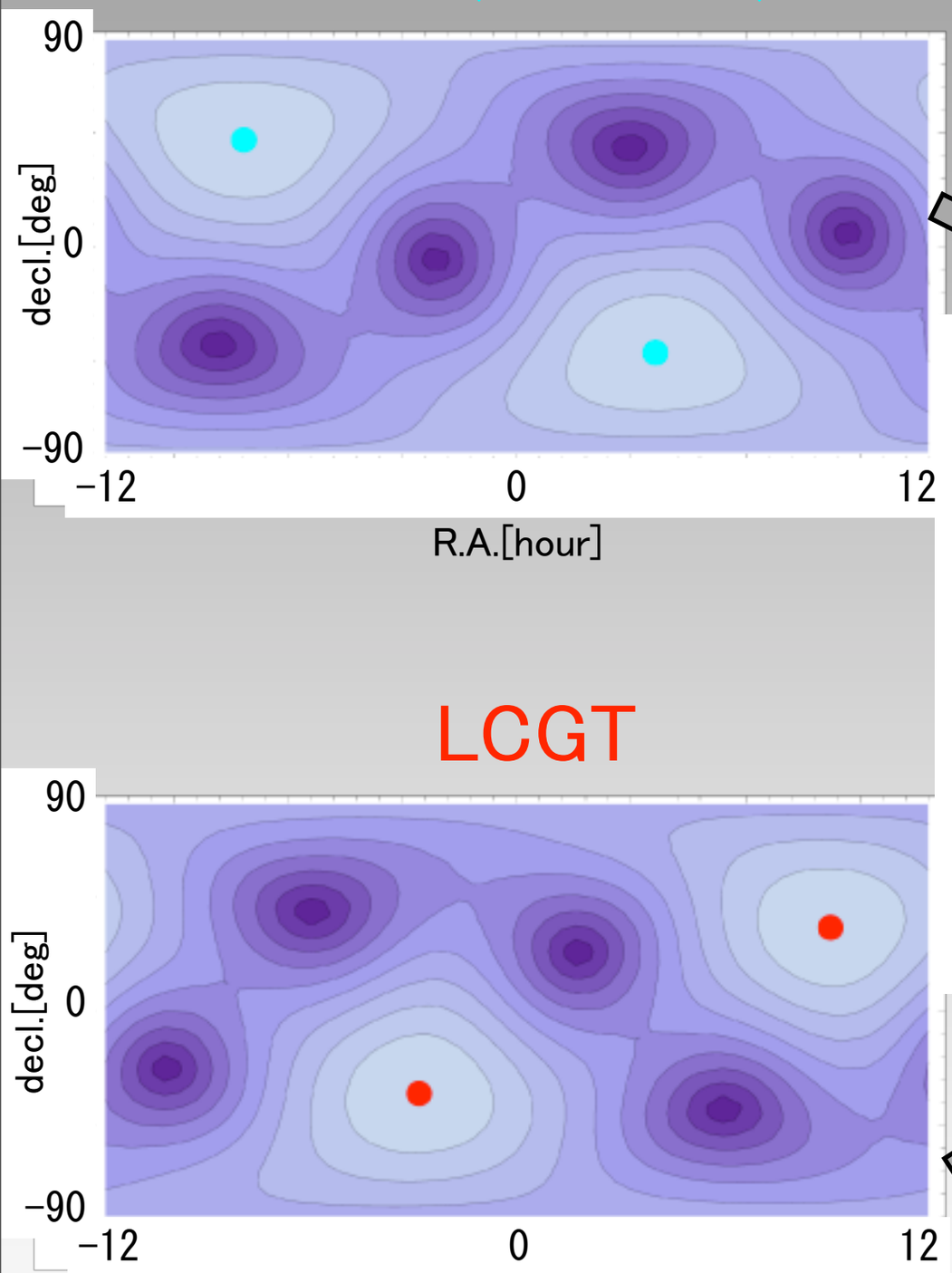
LCGT



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

Sky coverage by detector network

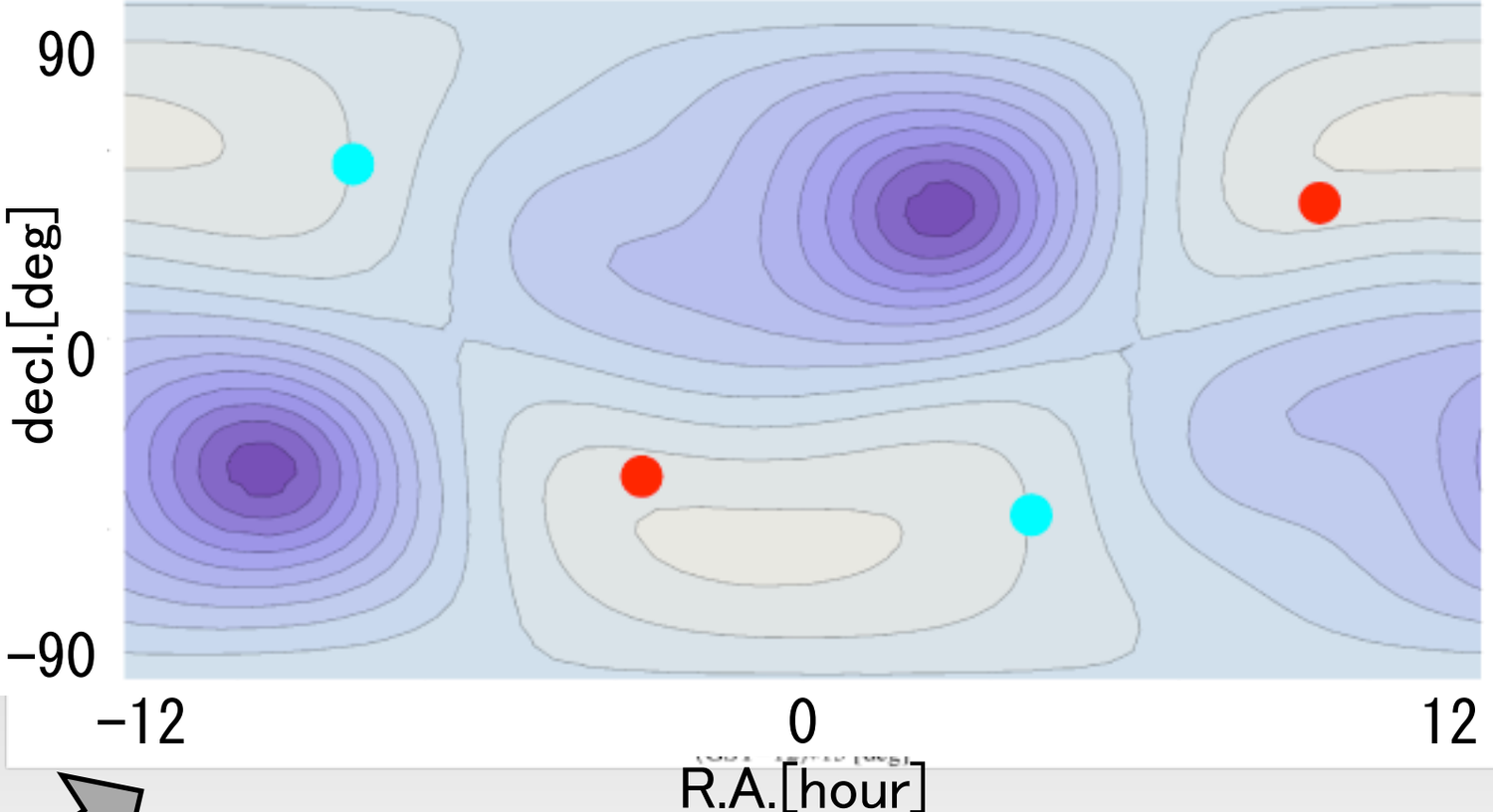
LIGO (Hanford)



LCGT

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

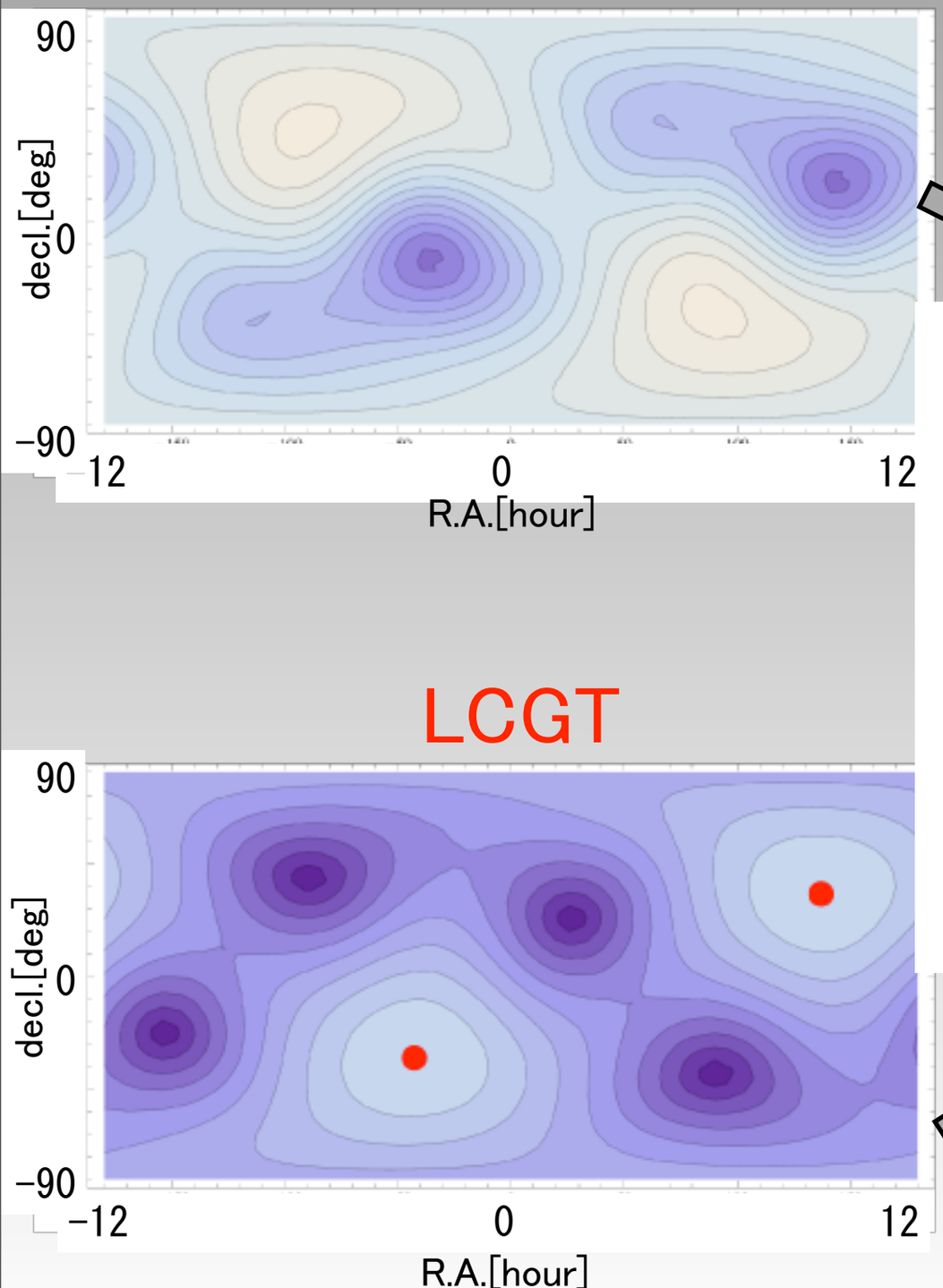
Quadratic Sum : LCGT+LIGO(Hanford)



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

Sky coverage by detector network

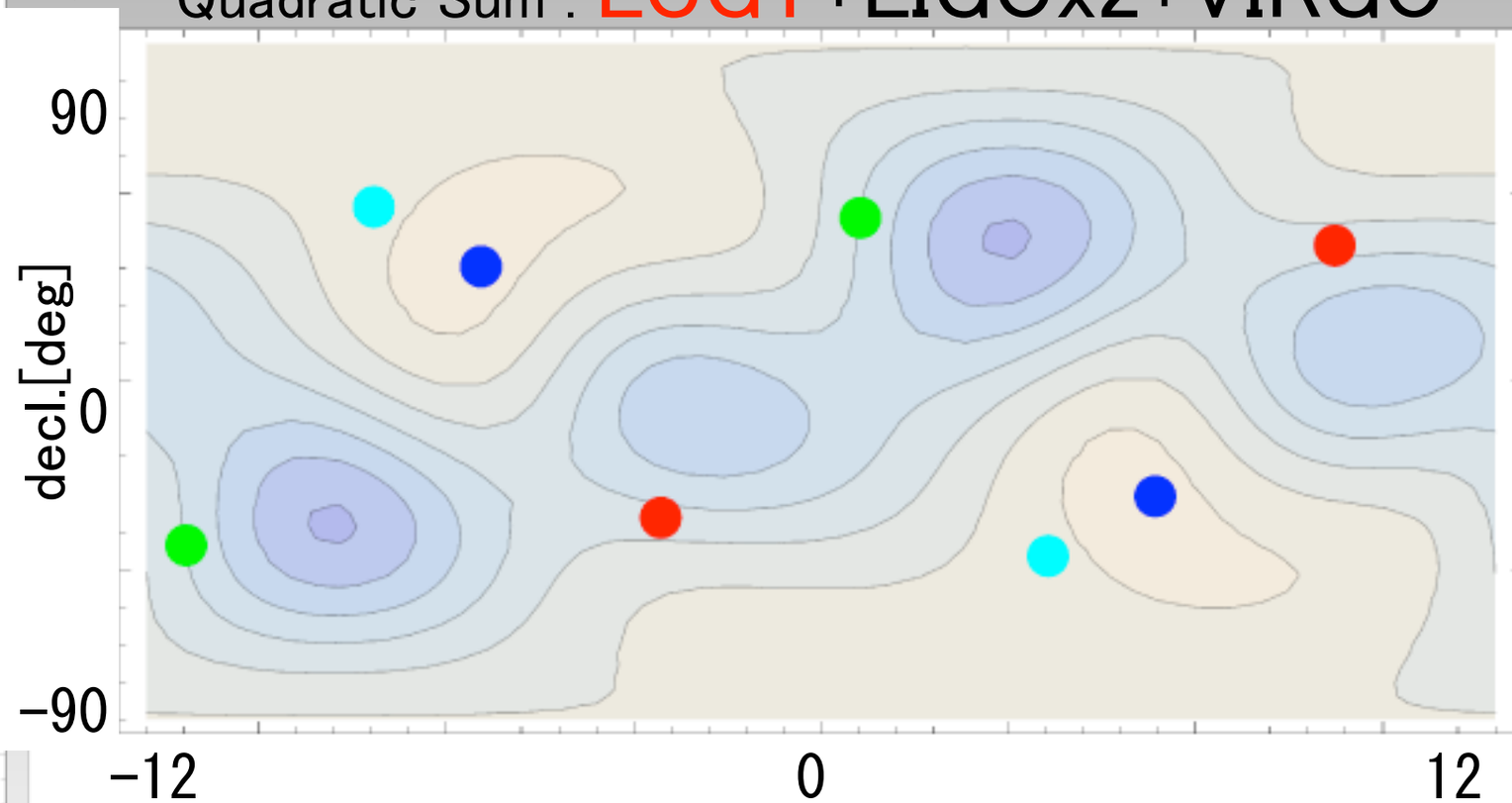
LIGO x2 + VIRGO



LCGT

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

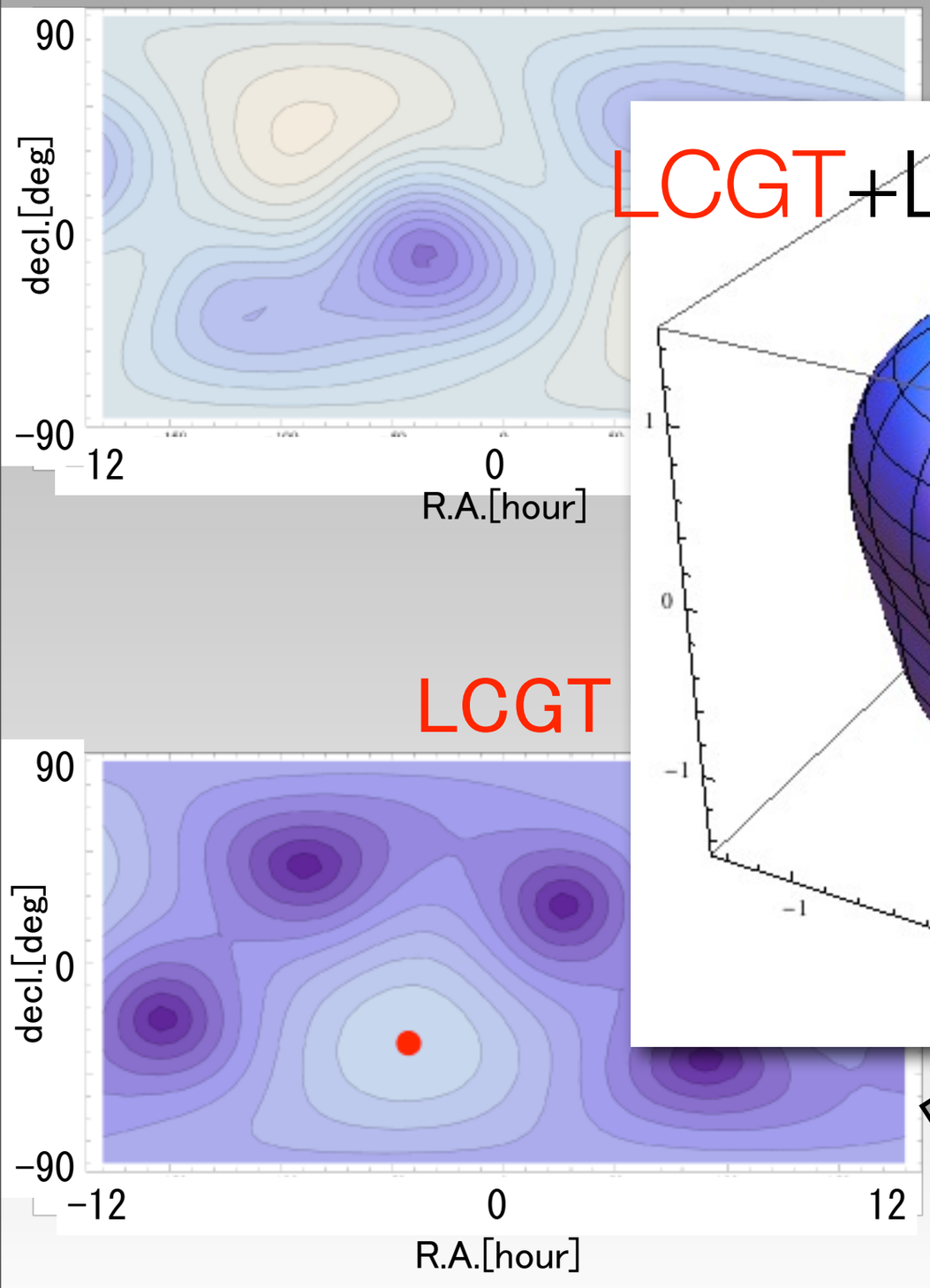
Quadratic Sum : LCGT+LIGOx2+VIRGO



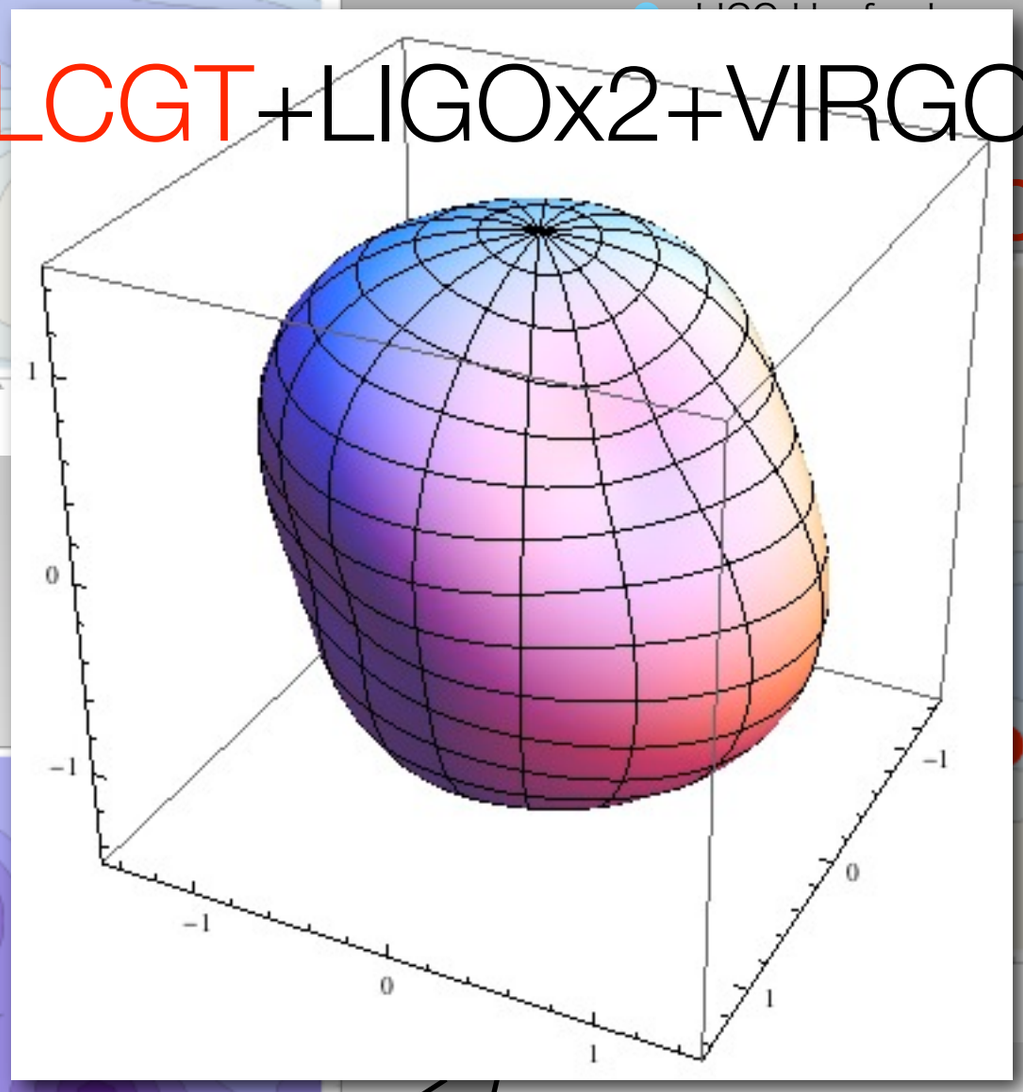
LCGT will make important role in the network, with a complemental sensitivity map.

Sky coverage by detector network

LIGO x2 + VIRGO

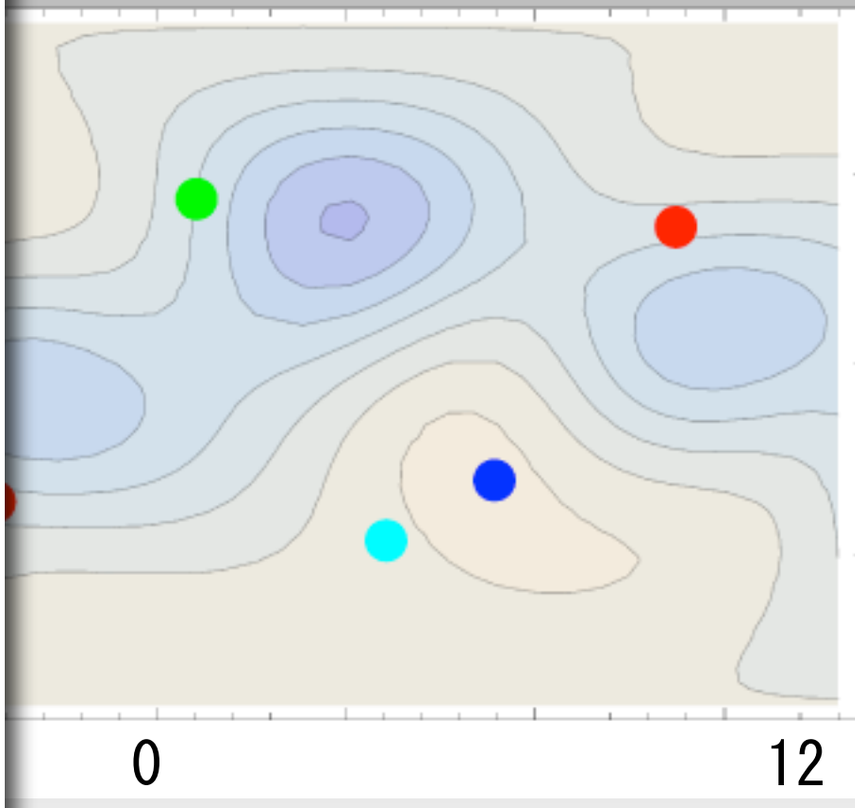


LCGT+LIGOx2+VIRGO



zenith direction of detectors

CGT+LIGOx2+VIRGO

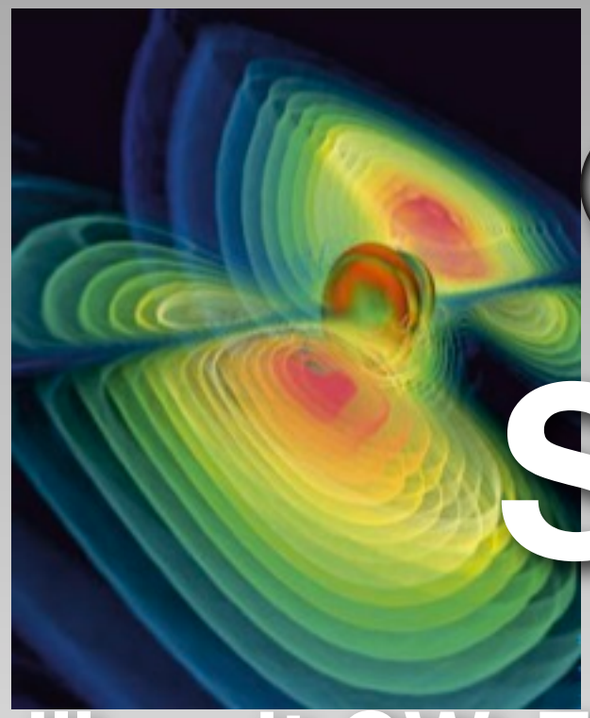


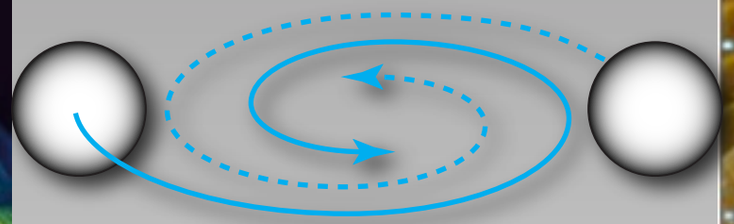
LCGT

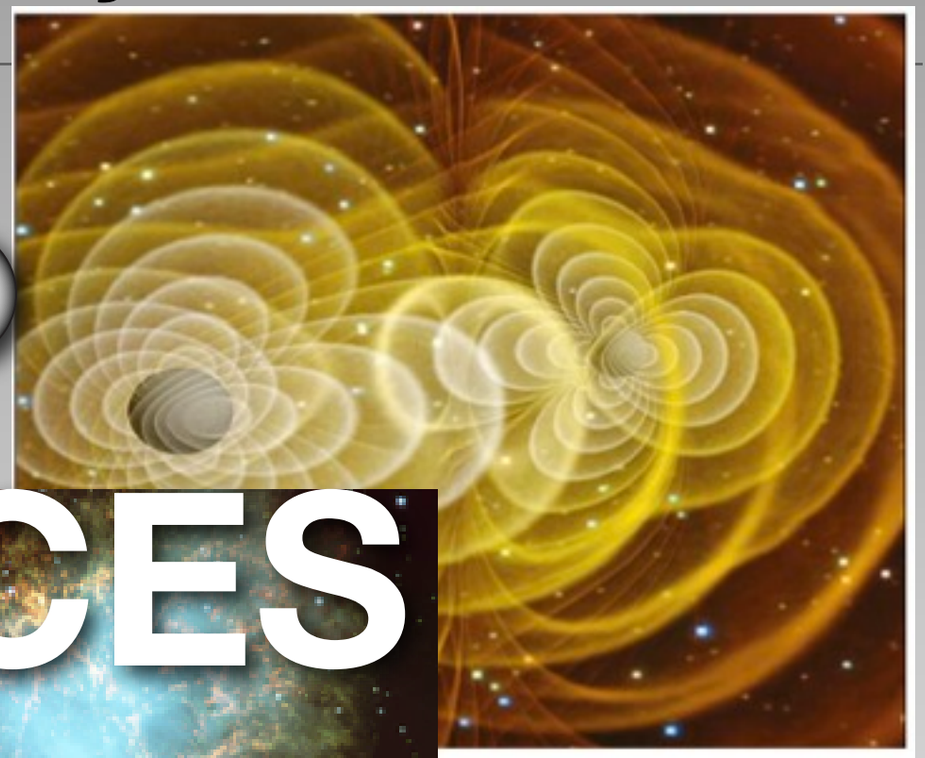
LCGT will make important role in the network, with a complemental sensitivity map.

High Energy Astrophysical Objects and GW

High Energy Astrophysical Objects and GW



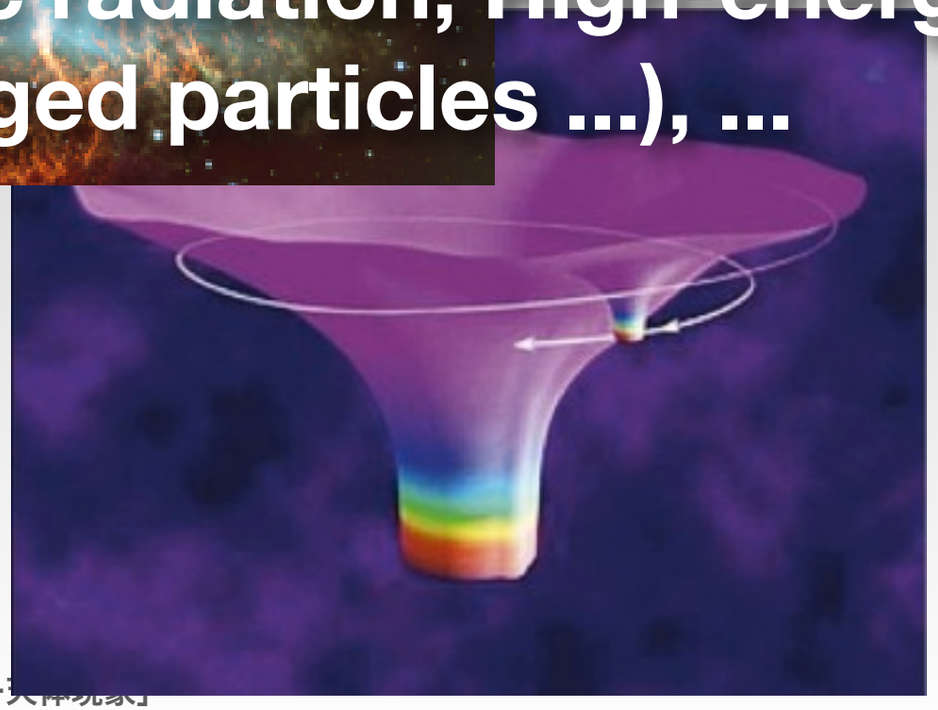




SOURCES

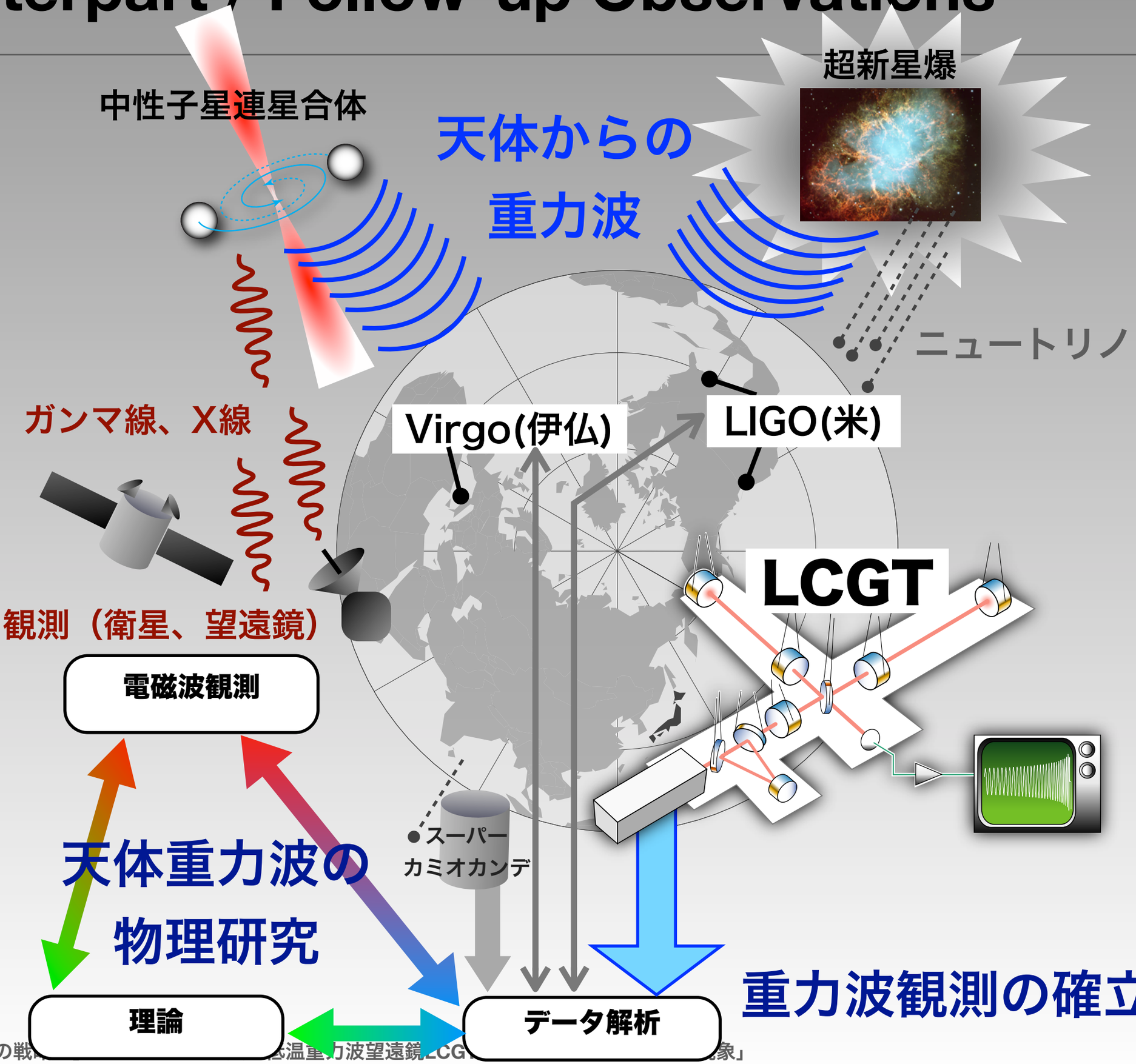
will emit GW, Electromagnetic radiation, High-energy particles (neutrino, charged particles ...), ...

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



of merging black holes (Credit: Henze, NASA)

Counterpart / Follow-up Observations

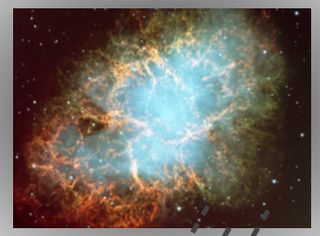


Counterpart / Follow-up Observations

中性子星連星合体

天体からの
重力波

超新星爆



ニュートリノ

ガンマ線、X線

観測（衛星、望遠鏡）

Virgo(伊仏)

LIGO(米)

LCGT

スーパー
カミオカンデ

電磁波観測

CTA も？

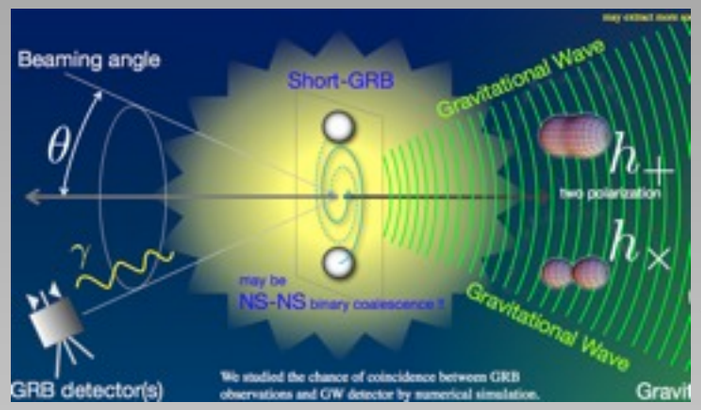
天体重力波の
物理研究

理論

データ解析

重力波観測の確立

Mutually Followup Observations



If NS-NS = Short-GRB,

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

GW by LCGT etc.
Real time analysis

[Aux trigger]
Date, direction, ...

Delayed precise analysis

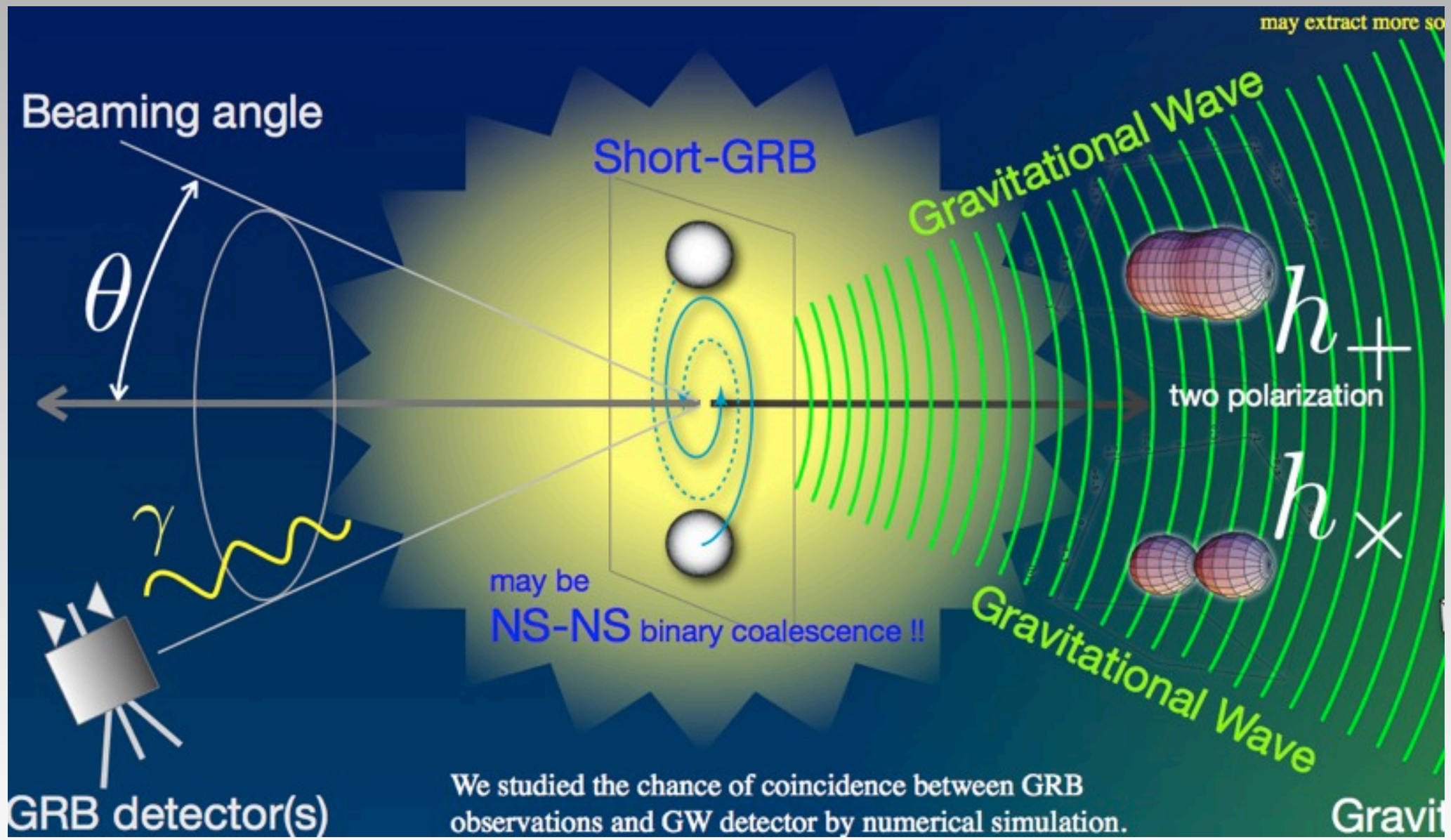
Followup by
X, Gamma, Optical

Confirmation of Afterglow

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

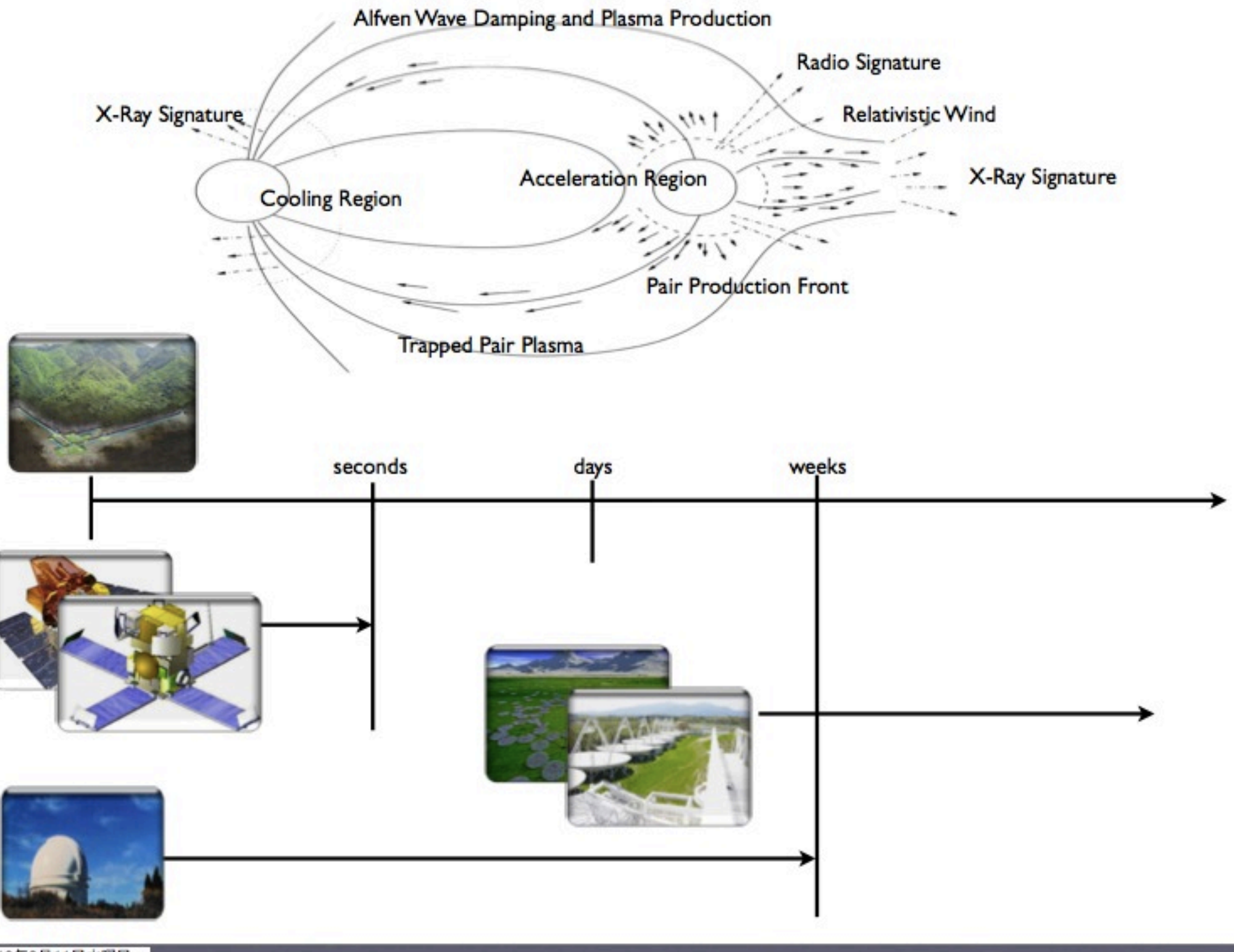
Compact Binary Coalescences

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



CBC

drawn by K.Hayama

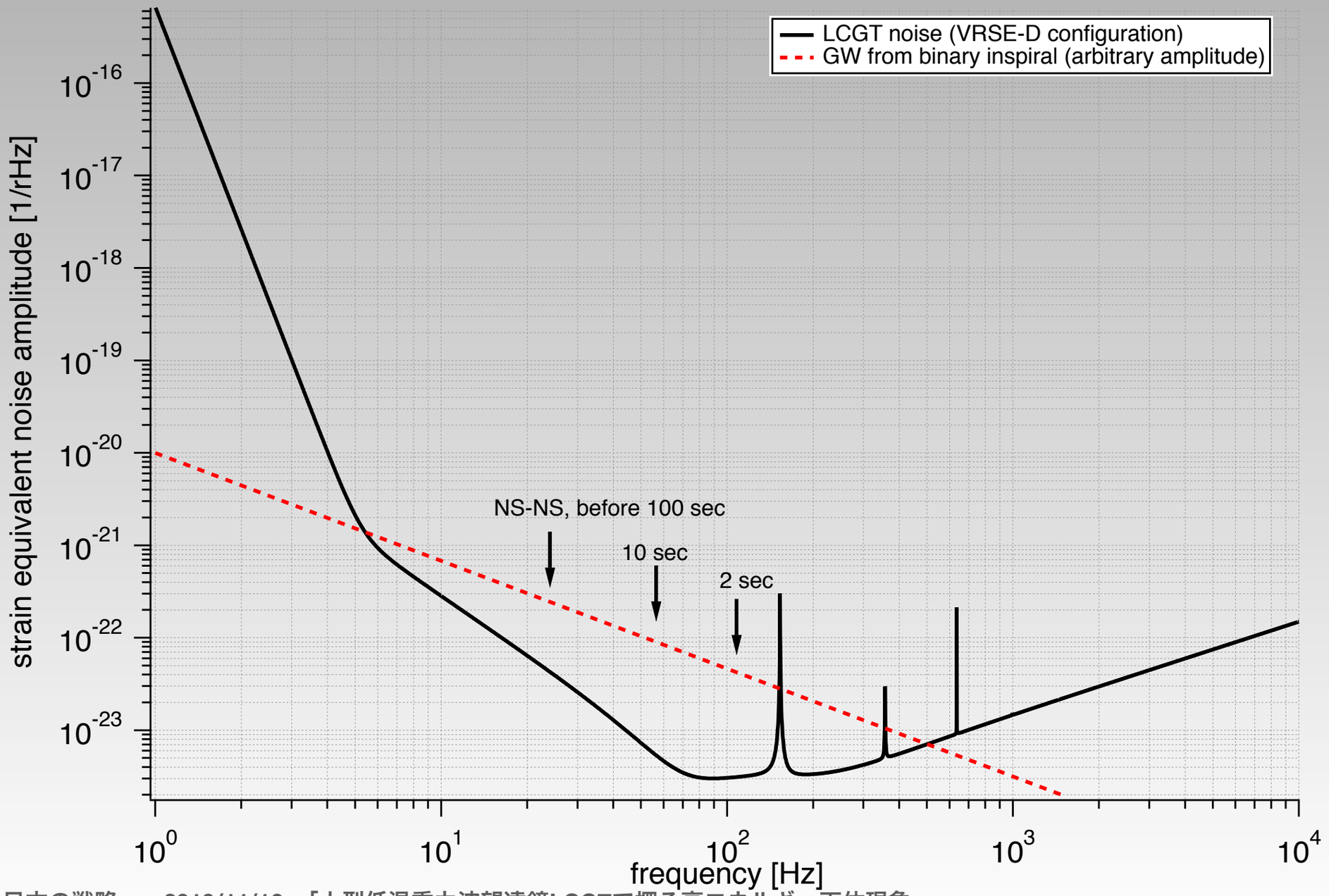


2010年8月11日水曜日

「

Forecast !?

GW are emitted continuously *before* coalescence.

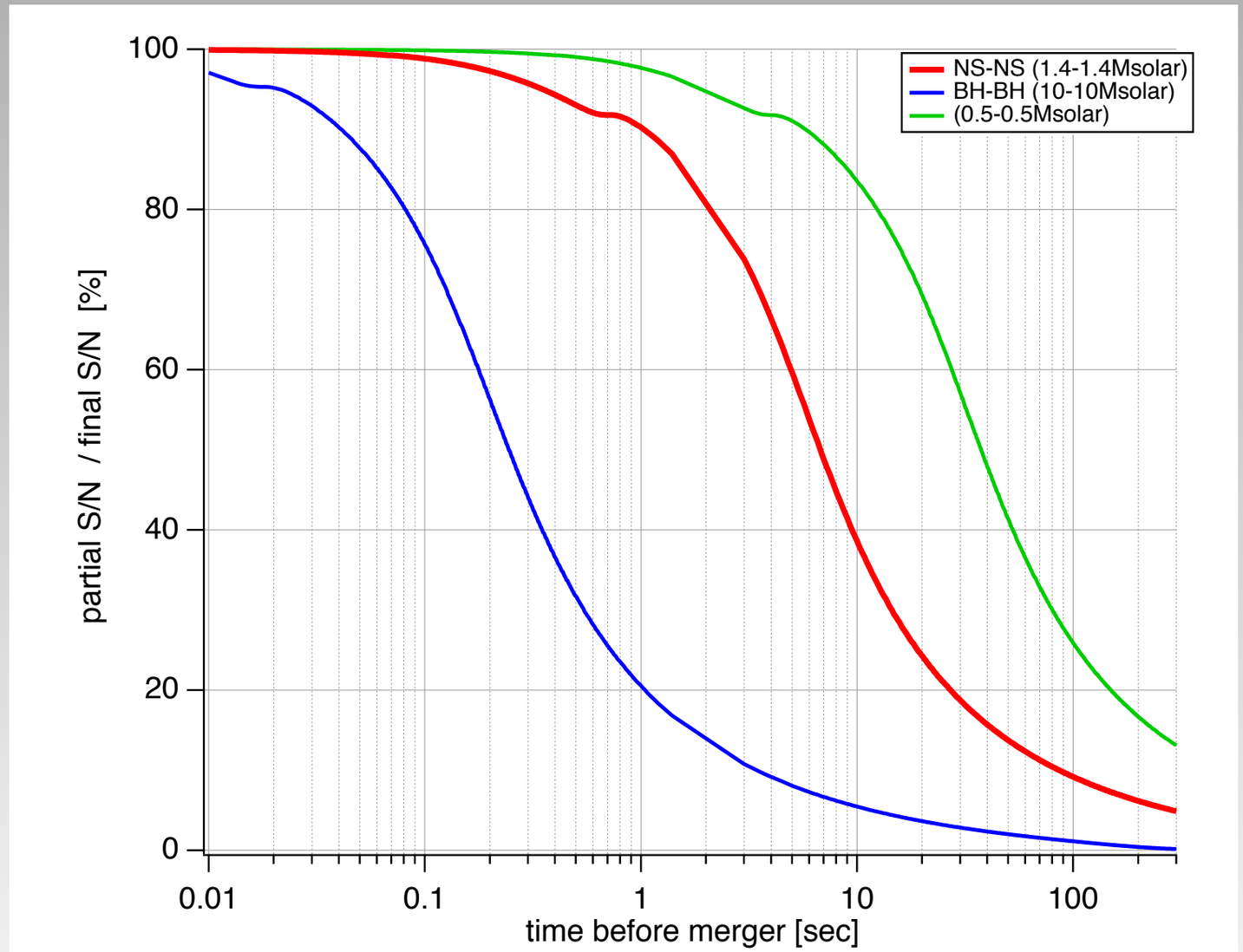


Example of Practical Issue : NS-NS forecast

- 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:

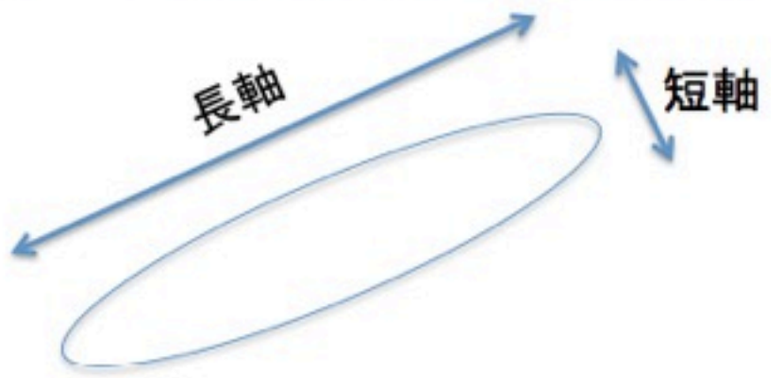
平均S/N (ρ)　　8.2から8.9 （各検出器で）

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)



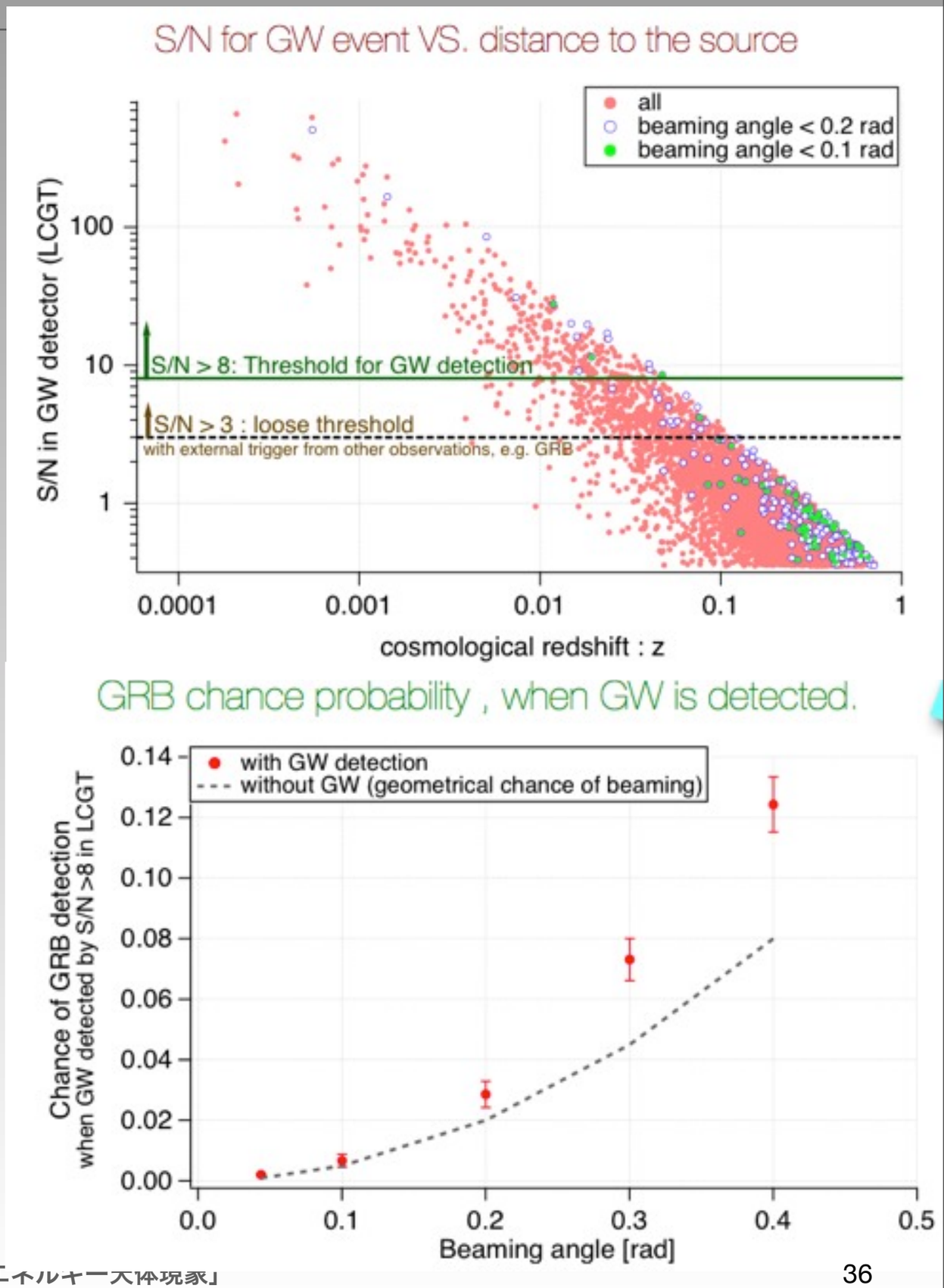
by H.Tagoshi

5

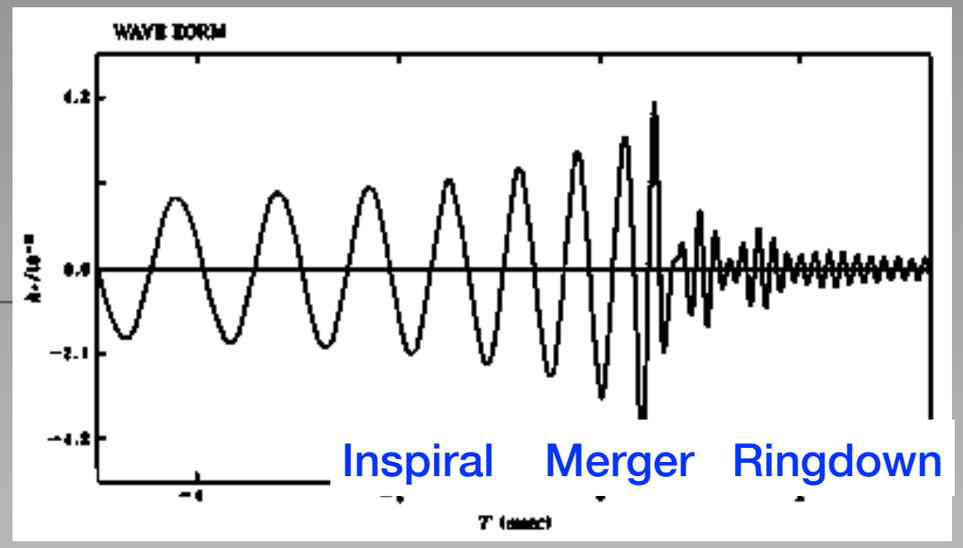
Coincidence chance between GW and GRB

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

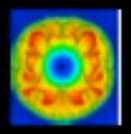
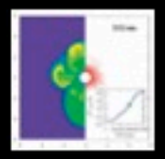
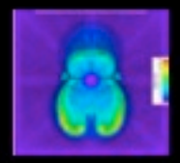
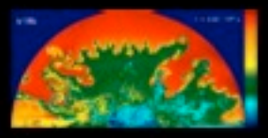
neutrino emission

accretion

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

Evolution of Supernova and GW

by K.Kotake

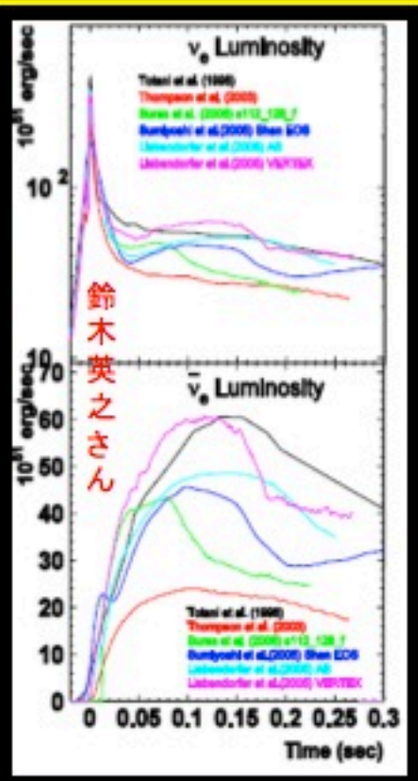

対流

SASI

G-mode?


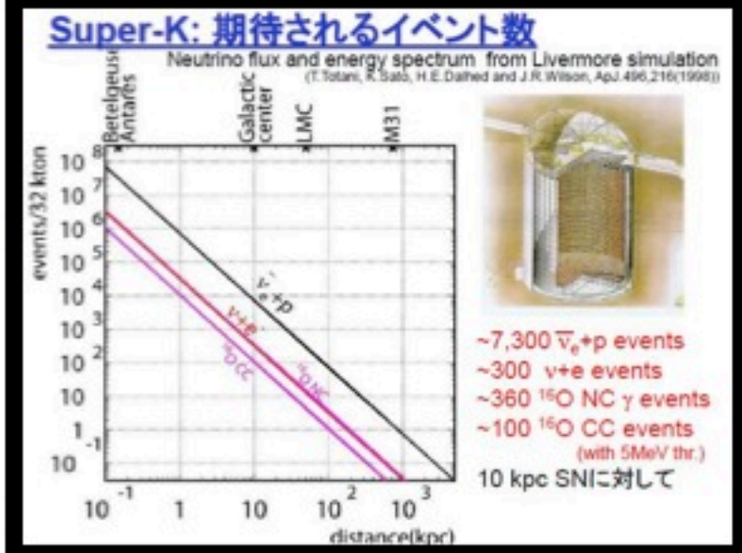
0秒　数ミリ秒　1秒（？）　＞数時間

重力崩壊開始

バウンス

中性子化バースト





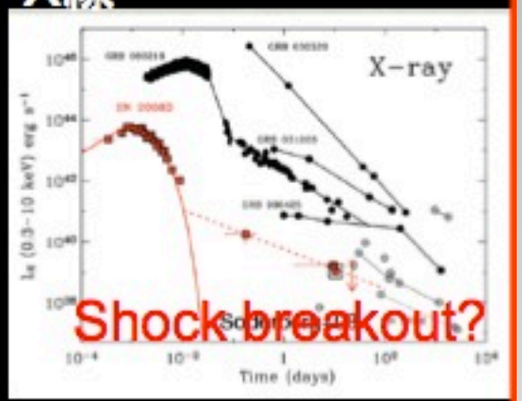
中畑さん（超新星研究会2009より）

衝撃波復活

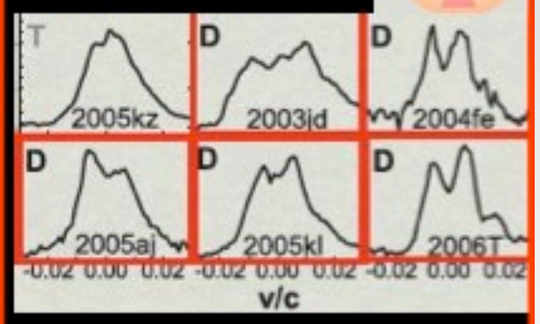
元素合成

爆発

X線

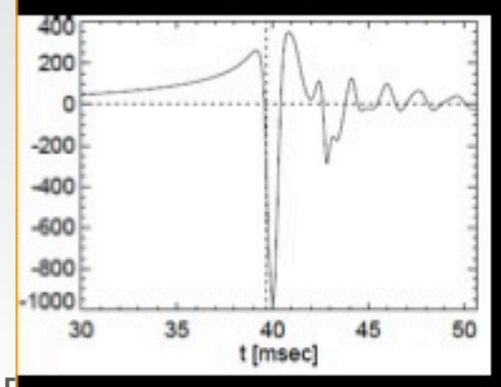


Subaru
Tanaka+06(偏光)
Maeda+06

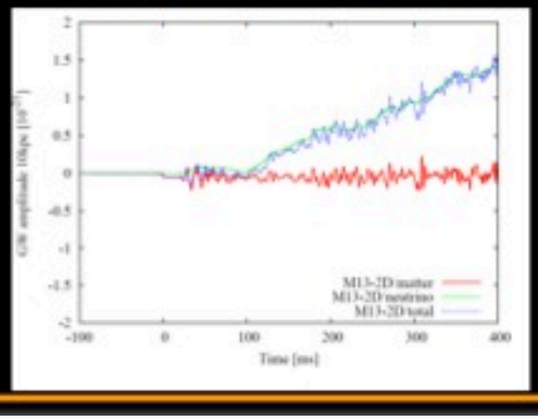


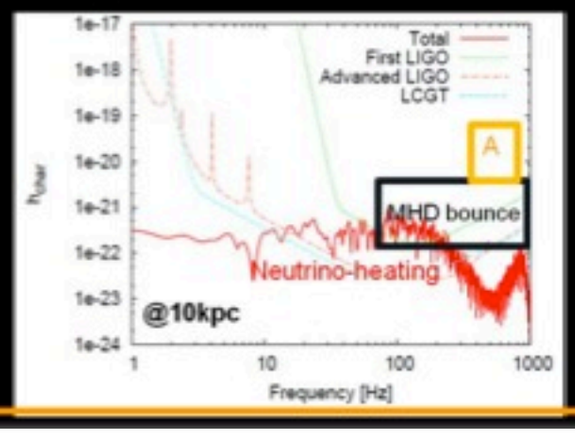
Swift: GRB（カウンターパート）

バウンスGW



対流SASI GW





Neutrino and GW from Supernovae

GW

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

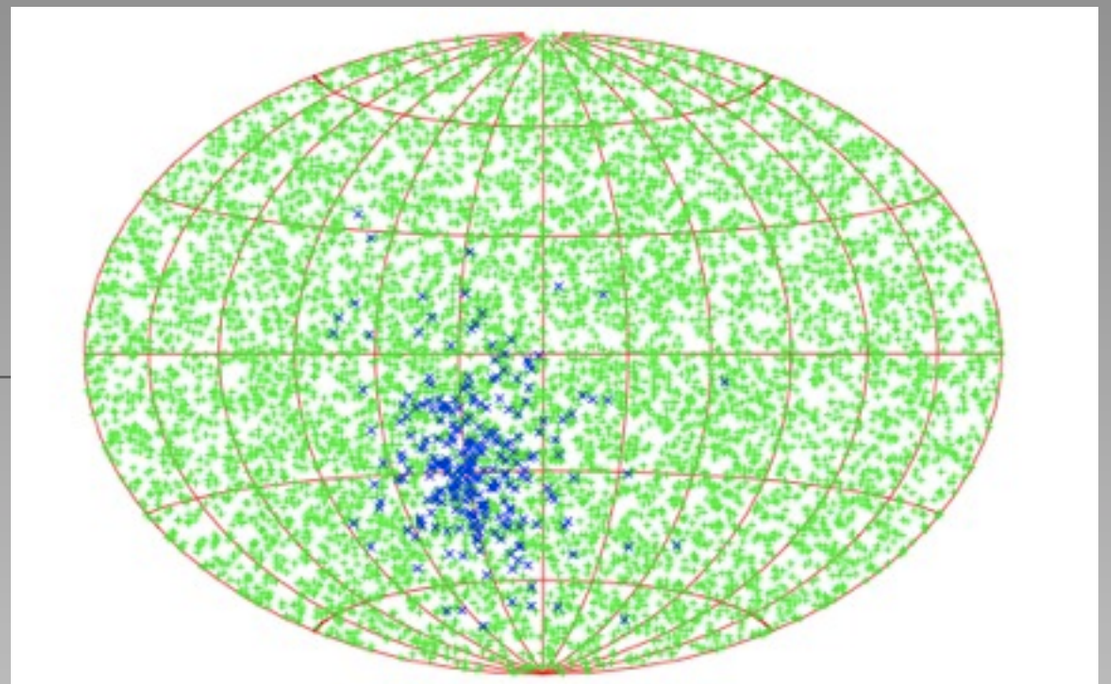
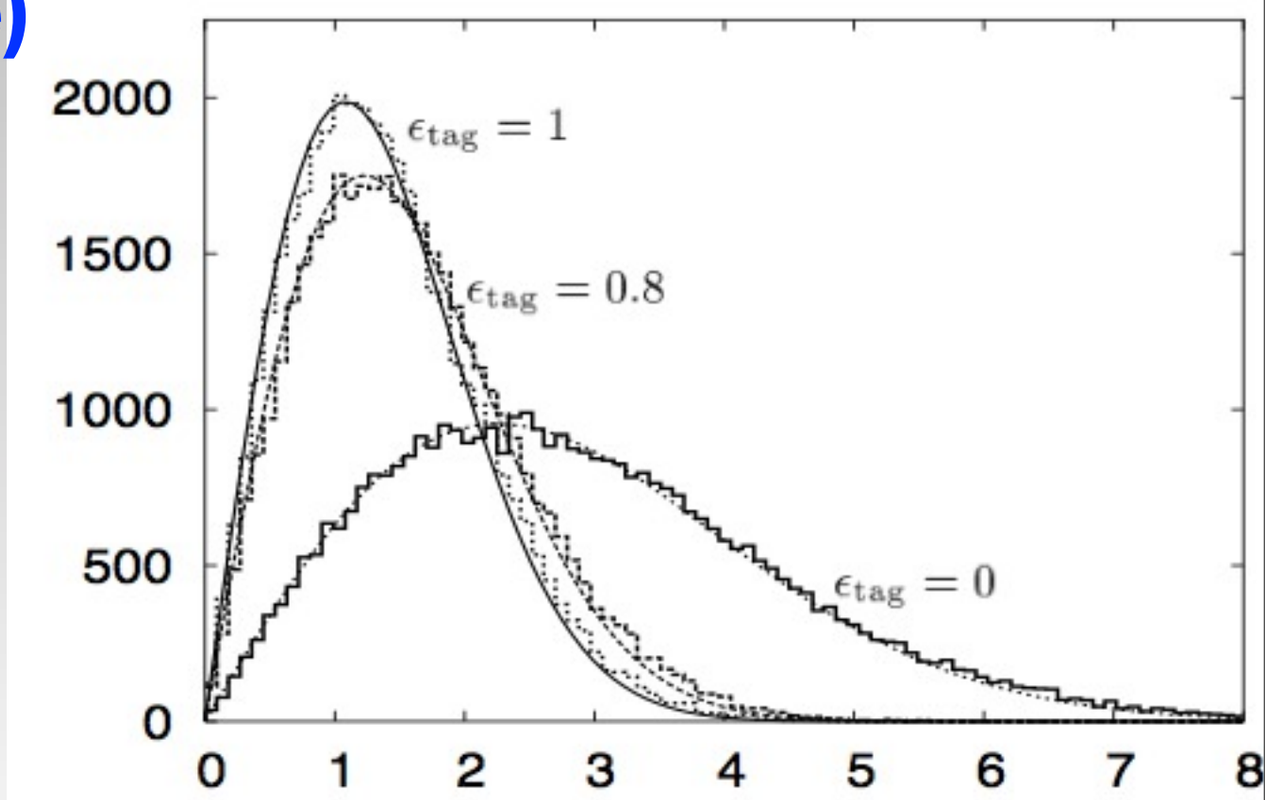


FIG. 4: Angular distribution of $\bar{\nu}_e p \rightarrow n e^+$ events (green) and elastic scattering events $\nu e^- \rightarrow \nu e^-$ (blue) of one simulated SN.

Neutrino (Super-Kamiokande)

- Typical Range ~ 1Mpc
- 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

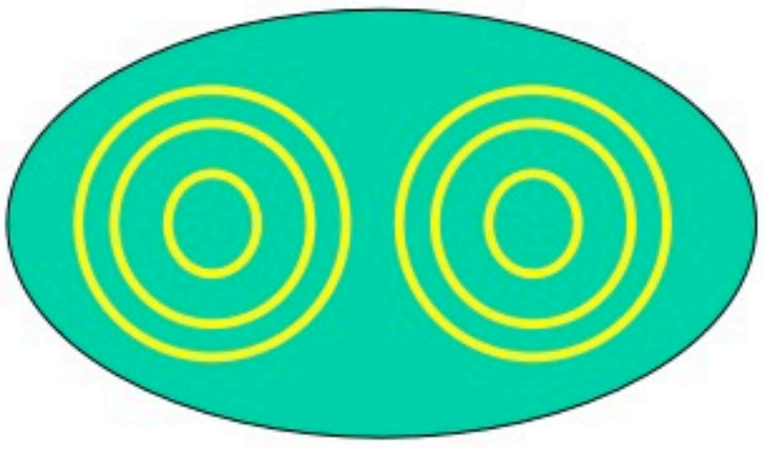
by K.Ioka

Magnetar

Super strongly magnetized neutron star

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

⇨ 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)

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 in late 2016 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.