学術創成研究費
超弦理論と宇宙の創成
2011
Cosmology & String

Status of LCGT
and
the Prospect of Gravitational Wave Observation

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Summer Institutae 2011
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Plan of Talk

----- Basics -----

- **Gravitational Wave - What ? Why? Where? and How?**
- **Basic of Gravitational Wave Detectors**

  Ground-based Detectors

----- Status of LCGT -----

- **LCGT**

  Large-scale Cryogenic Gravitational wave Telescope

  Project outline, Status of Construction, Science Target,

----- Prospects of GW detectors -----

- **Global Network of GW Detectors**

  What can be derive from GW detectors.

- **Mutually Follow-ups with non-GW observations**

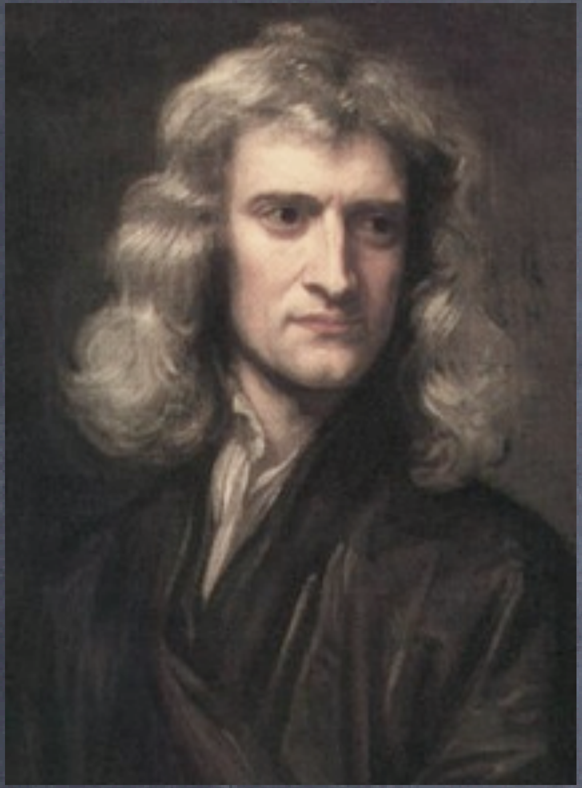
  Counterpart by/for Electromagnetic, high-energy particles, etc.

- Basics -

Gravitational Waves

How to detect

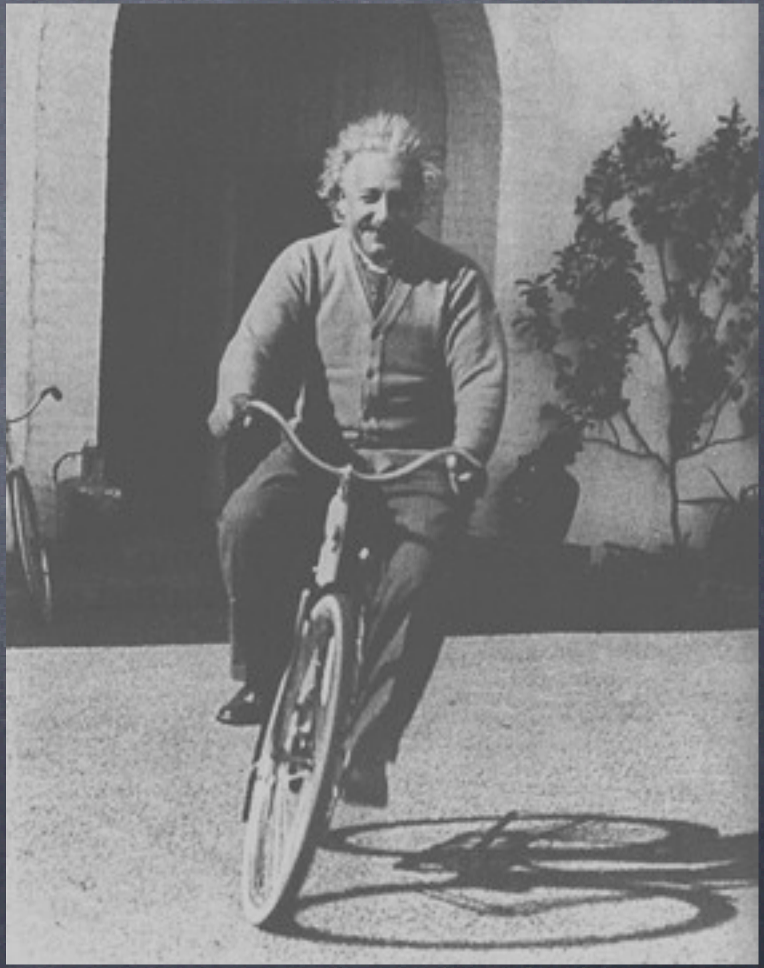
Gravity --> Gravitational Wave



Discover of Gravity

by Newton

“action at a distance”



General Relativity

by Einstein

“distortion of space-time”

What is Gravitational Wave ?

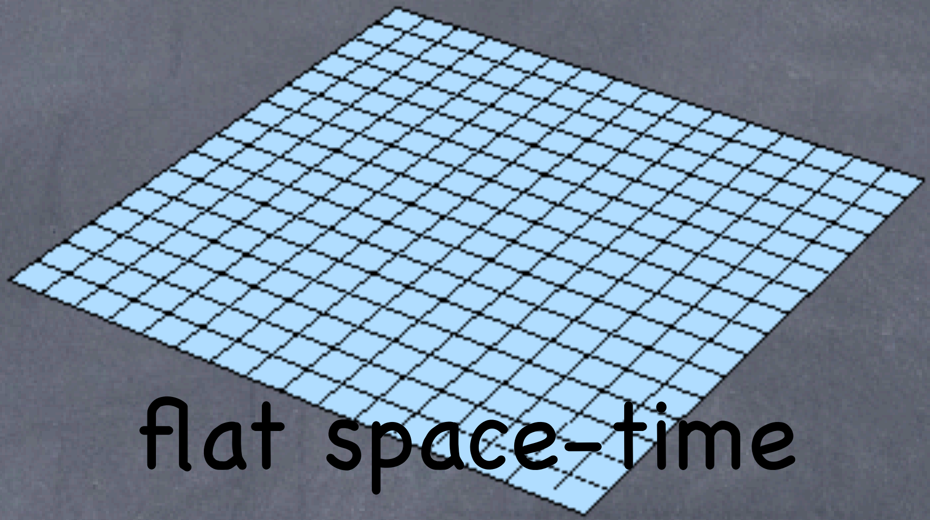
Einstein's Equation

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

metric tensor

"flat" space-time (Minkowski)

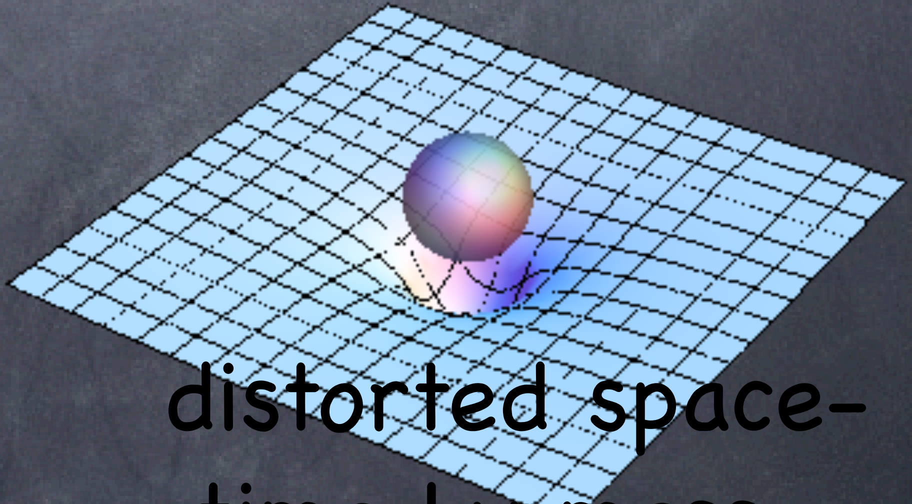
$$g_{\mu\nu} = \eta_{\mu\nu} = \begin{array}{cc} \begin{array}{cccc} ct & x & y & z \end{array} & \\ \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} & \begin{array}{c} ct \\ x \\ y \\ z \end{array} \end{array}$$



flat space-time

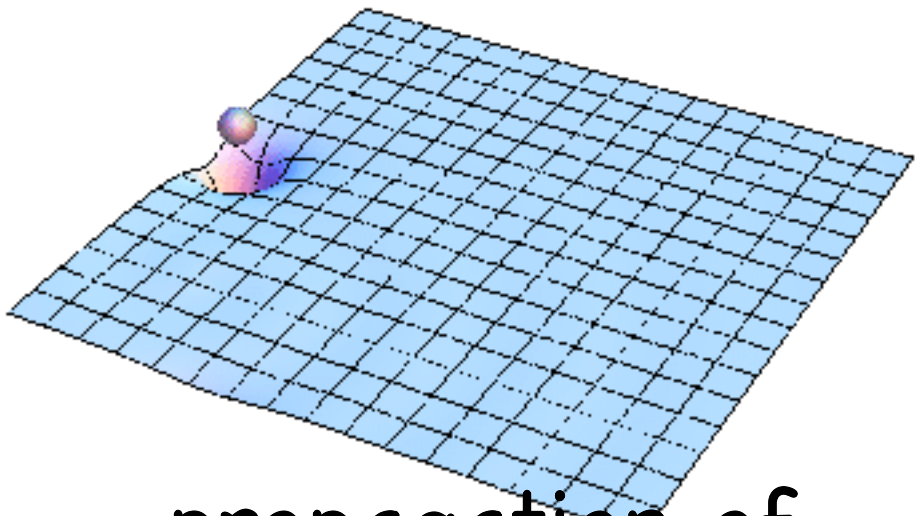
"curved (distorted)" space-time

$$g_{\mu\nu} \neq \eta_{\mu\nu}$$



distorted space-time by mass = gravity

Gravitational Waves



propagation of distortion

- **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 equation !

--> Wave of strain 'h'

- **Gravitational Wave**

light speed

transverse

quadrupole

(tidal force)

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

GW characteristics
& Force on Free masses

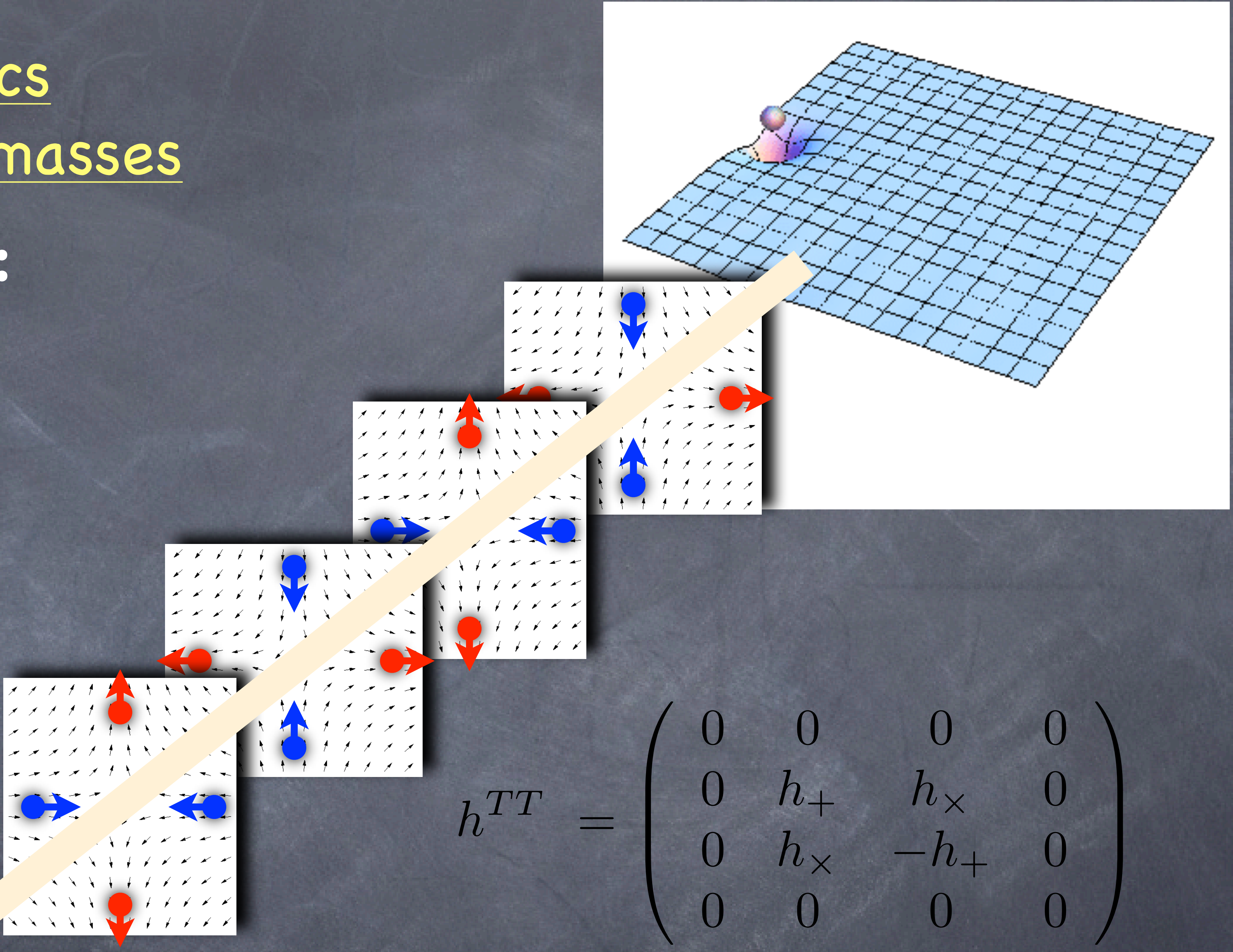
- **Characteristics:**

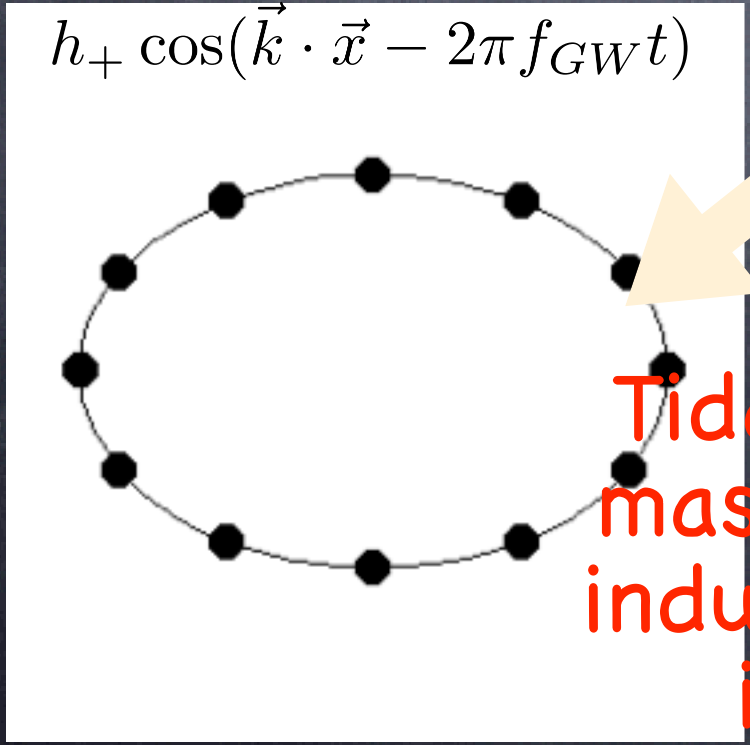
  light speed

  transverse

  quadrupole

  (tidal force)





Tidal force on masses will be induced by GW incident.

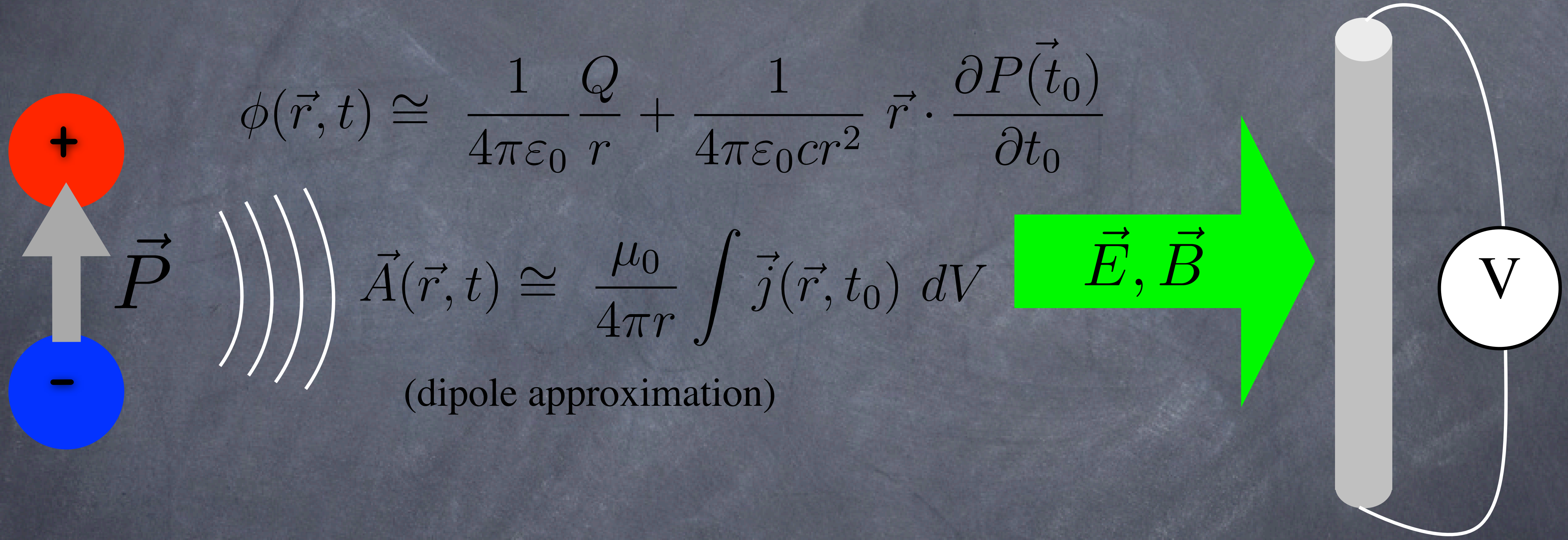
$$h^{TT} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

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

	Electromagnetic Wave	Gravitational Wave
Theory	Electromagnetism (Maxwell Equation)	General Relativity (Perturbation of Einstein Equation)
Field	Electric filed, Magnetic Field (Vector/Scalar potential) $\vec{E}, \vec{B}\ (\mathrm{or}\, \vec{A}, \phi)$	Metric (distortion of the space-time) $h^{TT} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$
Coupled Charge	Electric Charge, Current $e, \vec{i}$	Mass (Quadrupole moment) $m \quad (\ddot{I}_{\mu\nu})$
Strength (=Coupling Constant of the interaction)	$\alpha = \frac{e^2}{4\pi\hbar c} \sim \frac{1}{137}$	$\frac{G_N m^2}{\hbar c} \sim 10^{-39}$ for protons
Character	Speed of light	speed of light
	transverse	transverse
Note:	easily interact with materials, can shield	very small loss passing the materials, cannot shield

in case of EM (Electromagnetic waves) .....

Motion of electric charge (dipole,...) will radiate the EM waves.



$$\phi(\vec{r}, t) \cong \frac{1}{4\pi\varepsilon_0}\frac{Q}{r} + \frac{1}{4\pi\varepsilon_0 c r^2}\ \vec{r} \cdot \frac{\partial P(\vec{t_0})}{\partial t_0}$$

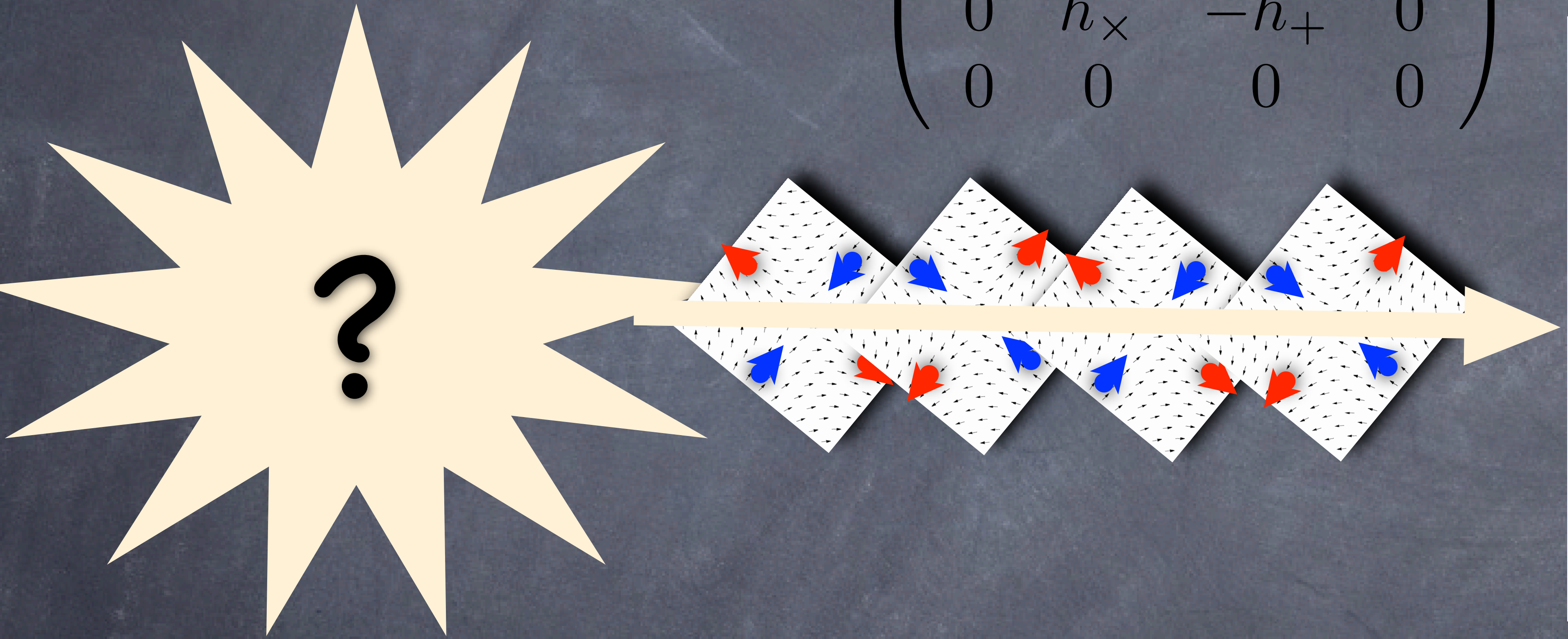
$$\vec{A}(\vec{r}, t) \cong \frac{\mu_0}{4\pi r}\int \vec{j}(\vec{r}, t_0)\ dV$$

(dipole approximation)

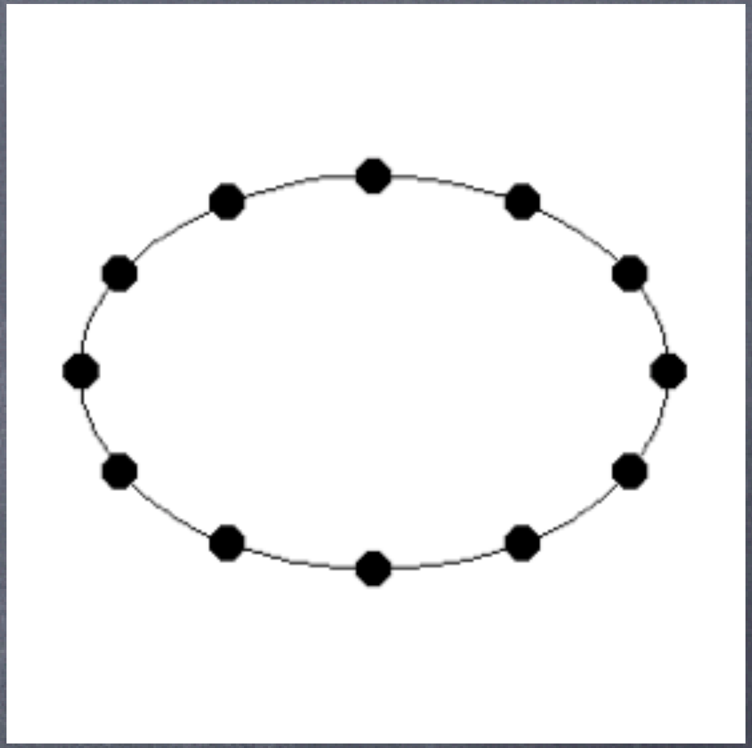
Metal antenna (or test charge) can receive the EM waves with induced current/voltage difference by E or B filed.

in case of GW

$$h^{TT} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$



GW source



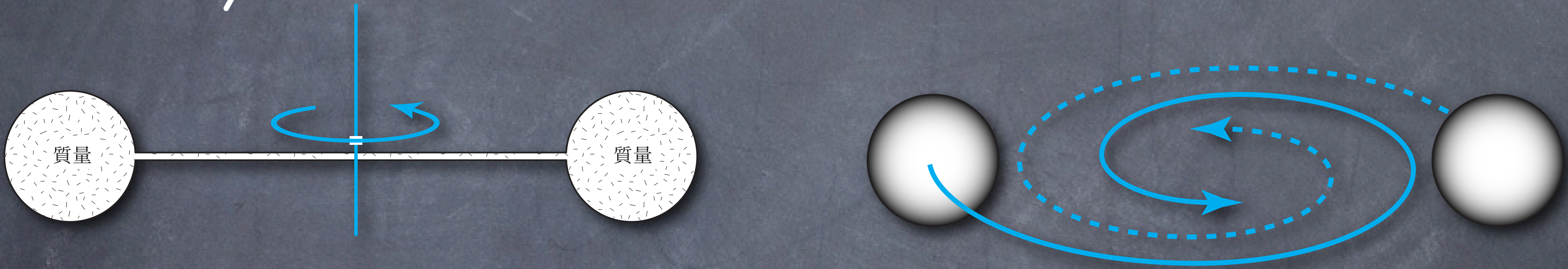
tidal force

Where ? - Fundamental Source of GW radiation -

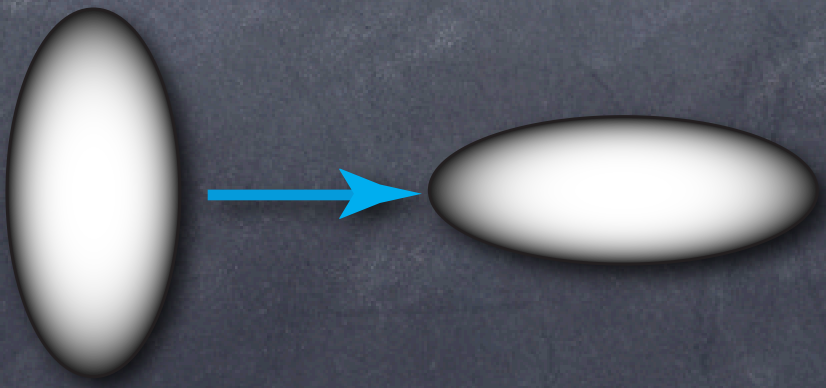
- **Changing a quadrupole moment of mass** $\ddot{I}_{\mu\nu},\ \dddot{I}_{\mu\nu}$

$$I_{\mu\nu} = \int dV (x_\mu x_\nu - \frac{1}{3}\delta_{\mu\nu} r^2)\rho(\vec{r})$$

Two symmetric masses which rotate the axis



Quadrupole deformation of mass distribution (shape)



GW radiation

- **Source**

  change (time derivative) of quadrupole moment of mass distribution

$$I_{\mu\nu} = \int dV (x_\mu x_\nu - \frac{1}{3}\delta_{\mu\nu} r^2)\rho(\vec{r})$$

- **Amplitude**

  inversely proportional to the distance between source and observer

$$h_{\mu\nu} = \frac{2G}{Rc^4}\ddot{I}_{\mu\nu}$$

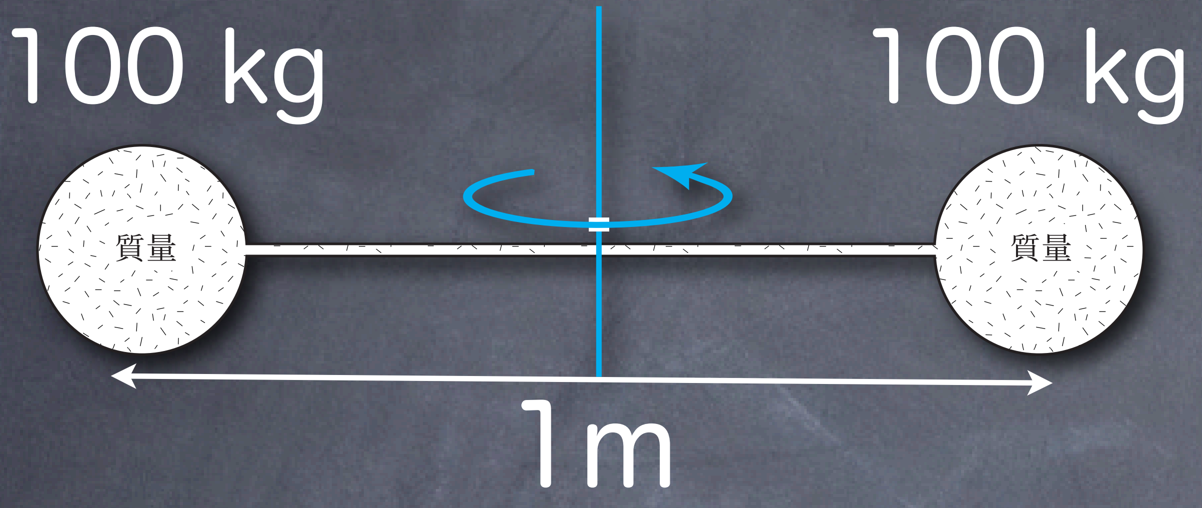
- **Energy**

  total energy is given as :

$$E_{GW} \sim \frac{G}{5c^5} < \dddot{I}_{\mu\nu}\dddot{I}^{\mu\nu} >$$

GW by artificial source .....

$$h_{\mu\nu} = \frac{2G}{Rc^4}\ddot{I}_{\mu\nu}$$



1000rotation/sec
(2kHz GW)

distance : 10m

--> $h \sim 10^{-35}$

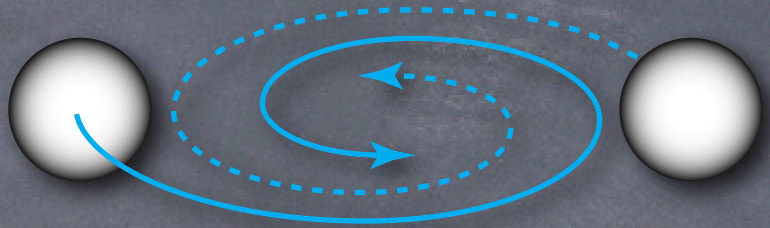
=1m ruler change as

$$\frac{1}{100000000000000000000000000000000000} \text{ m.}$$

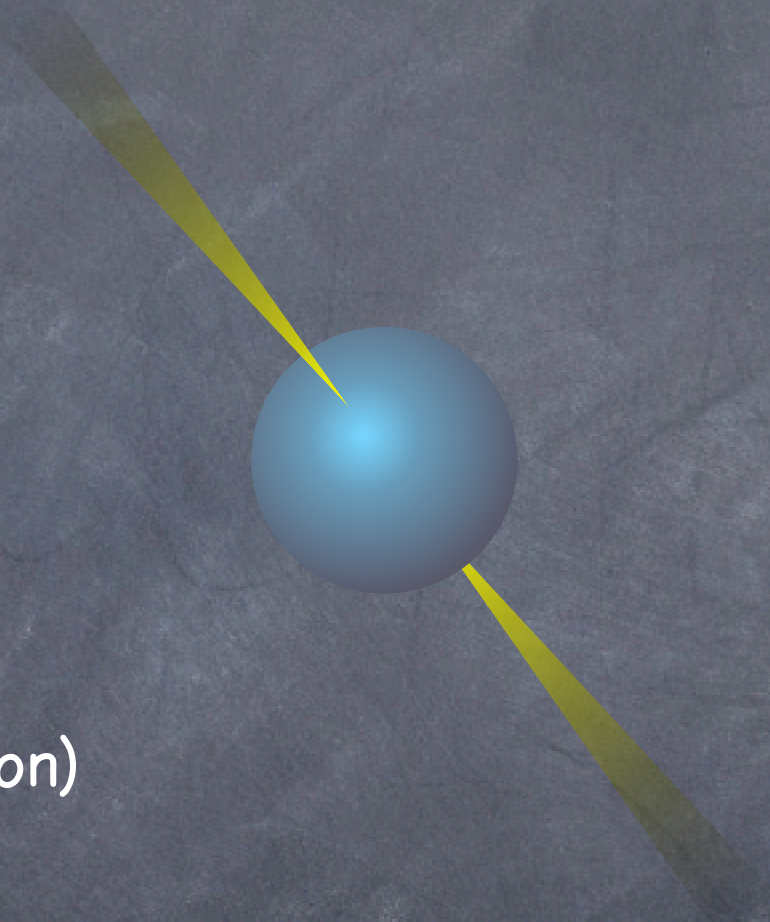
(note: we need more than 150km distance for wavezone of 2kHz GW.

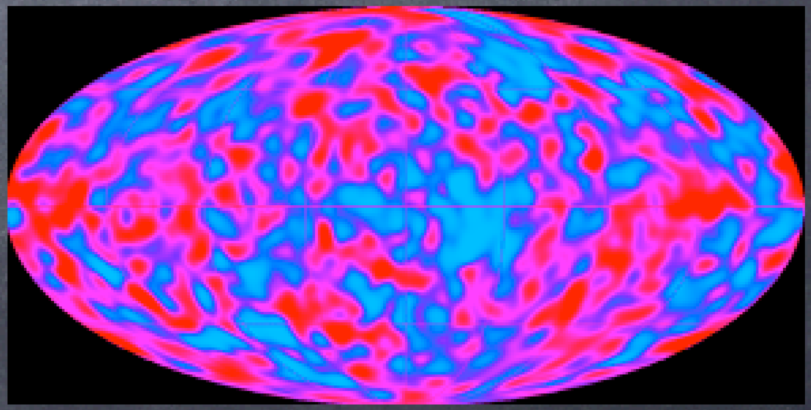
Artificial source is very difficult ...

Where ? - possible sources of GWs -



- **Event like:**
  - Compact Binary Coalescence (NS-NS, NS-BH, BH-BH)
  - neutron star (NS), black-hole (BH)
  - Supernovae
  - BH ringdown
  - Pulsar glitch
- **Continuous waves:**
  - Pulsar rotation
  - Binaries
- **Stochastic Background**
  - Early universe (i.e. Inflation)
  - Cosmic string
  - Astronomical origin (e.g. many NS in galaxy cluster)
- **(& Unknown sources...)**





typical target : $h \lesssim 10^{-22} - 10^{-24}$

Why ? - direct detection / measurement of GW -

GW is not directory detected yet now (2011), but is expected to open new window of physics and astronomy.

- **Physics**

  TEST of general relativity in strong field.

- **Astronomy, Astrophysics**

  Radiation from compact / massive objects.

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

  --> Gravitational Wave Astronomy

- **Cosmology**

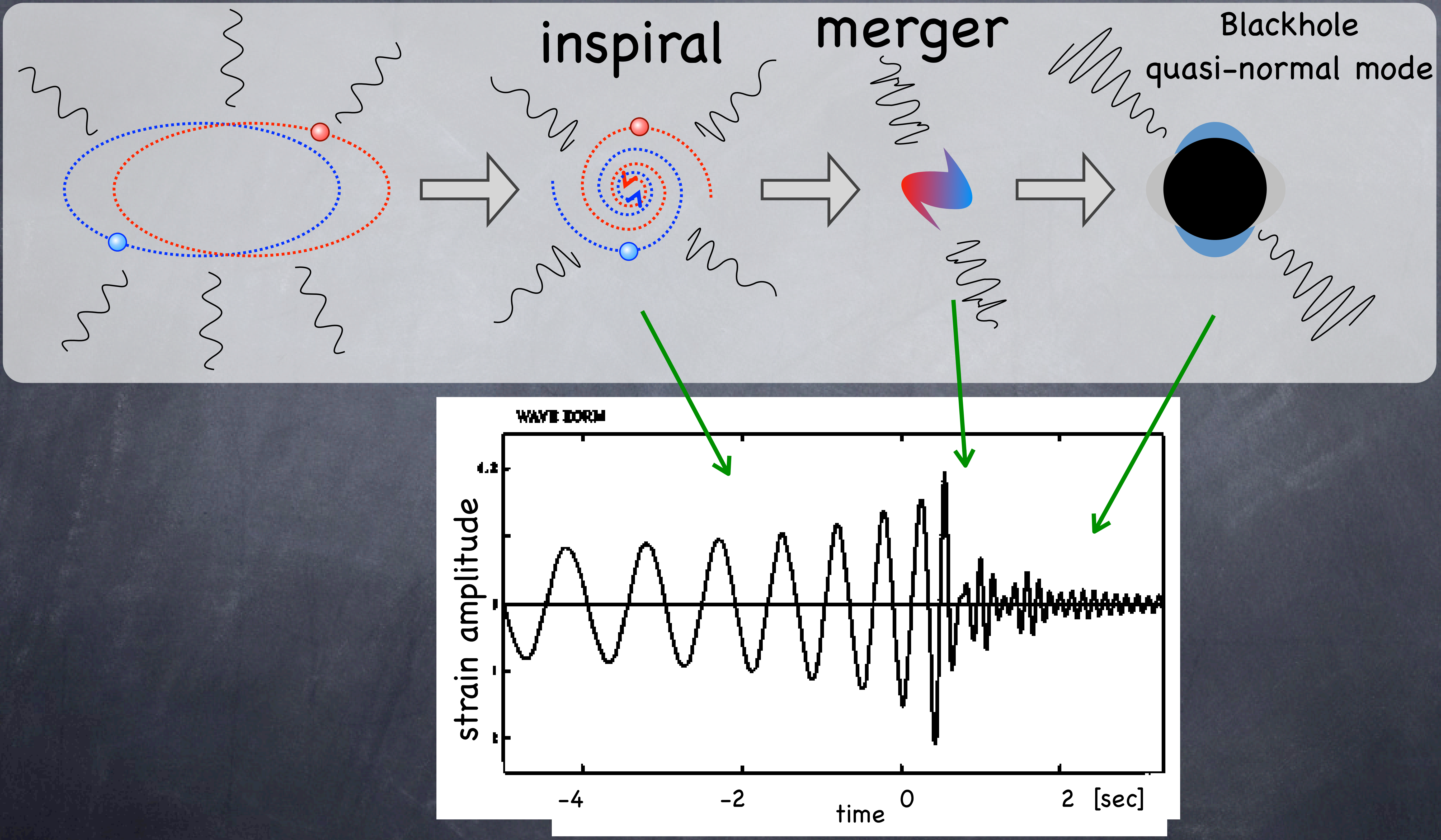
  Cosmic background radiation of GW

  POP-III stars, star formation, etc...

  Physics of early universe.

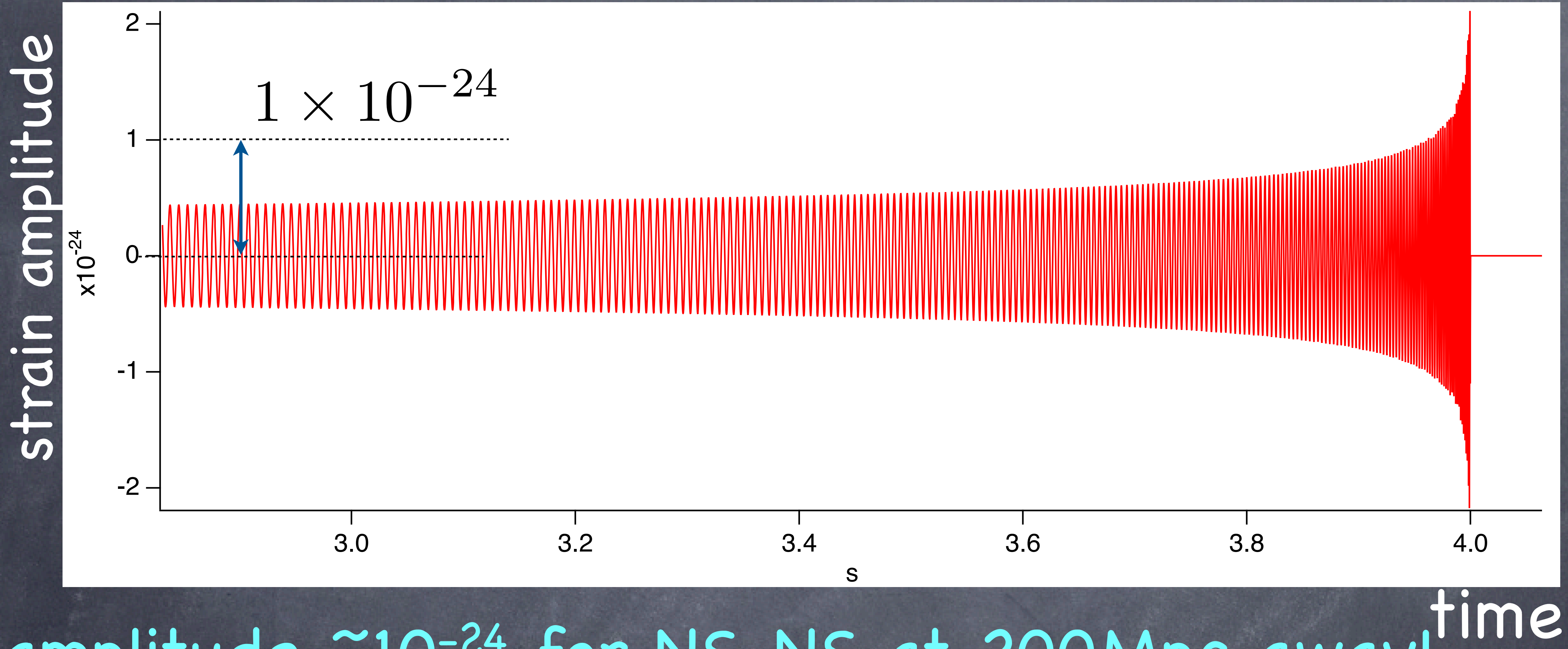
typical source : Coalescence of Neutron Star Binaries

- **NS-NS --> Merge -->(SMNS)--> BH?**



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

--> **'standard candle'**

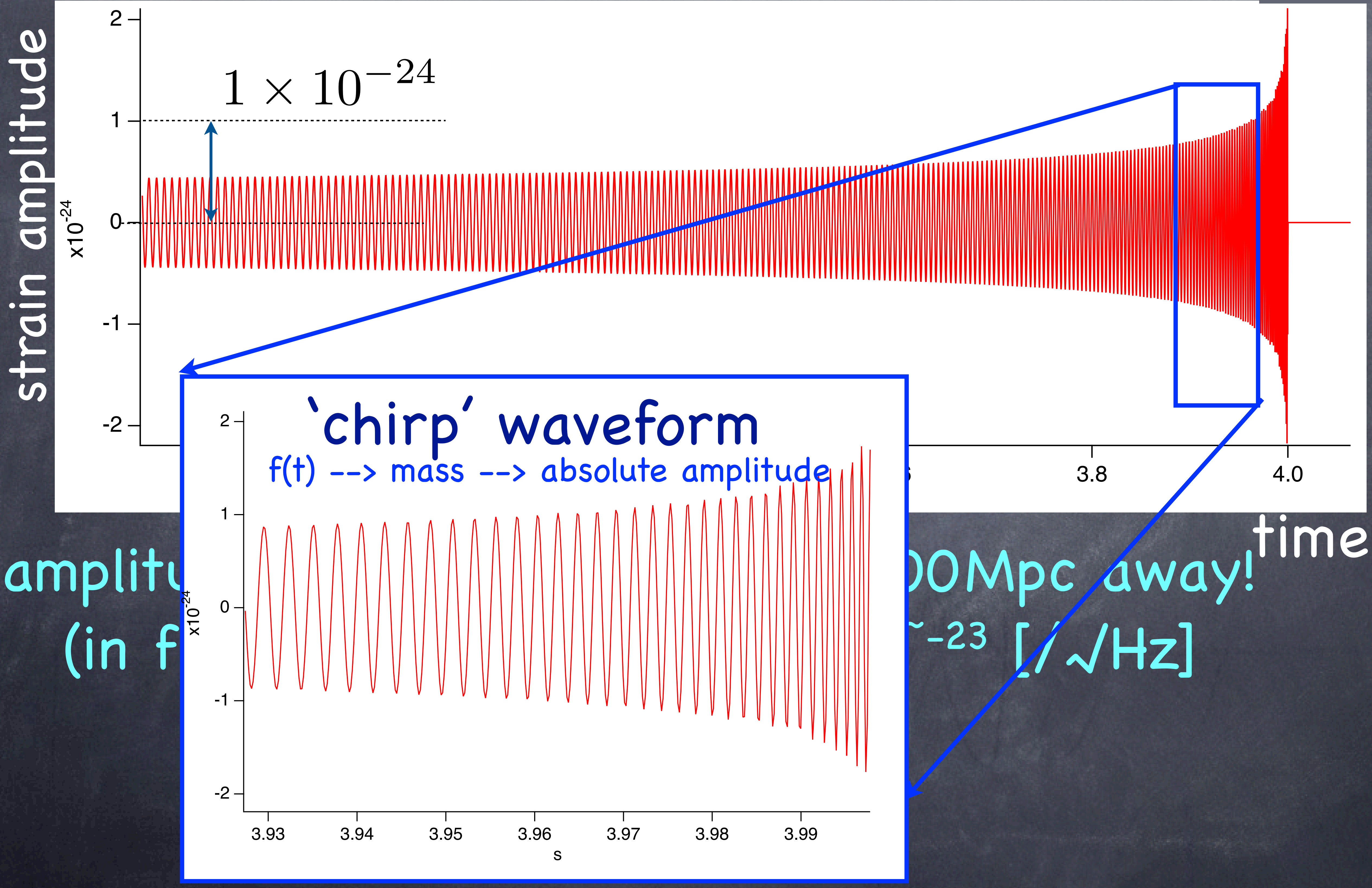


amplitude ~10^{-24} for NS-NS at 200Mpc away!

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

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

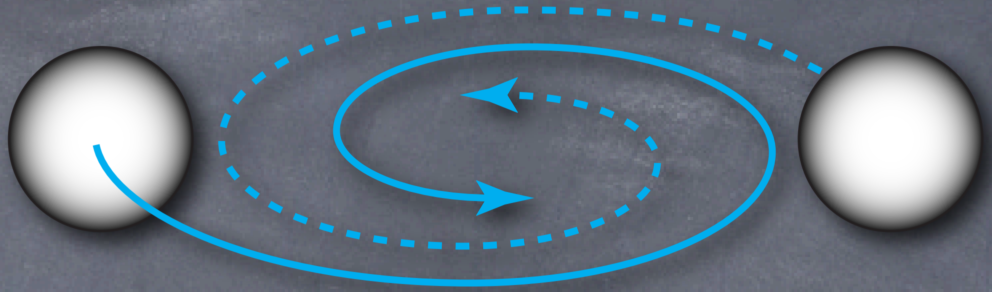
--> 'standard **siren**'

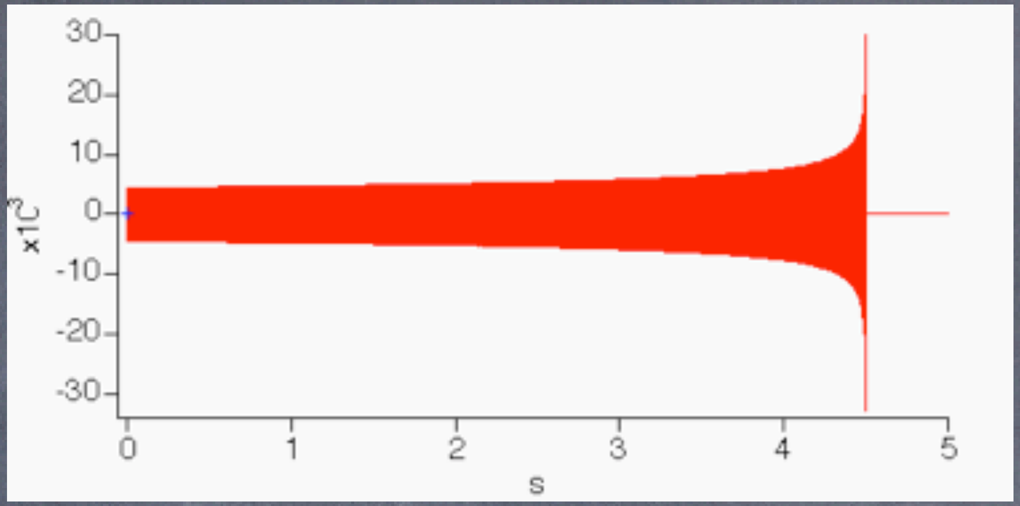


amplitu … 00Mpc away!

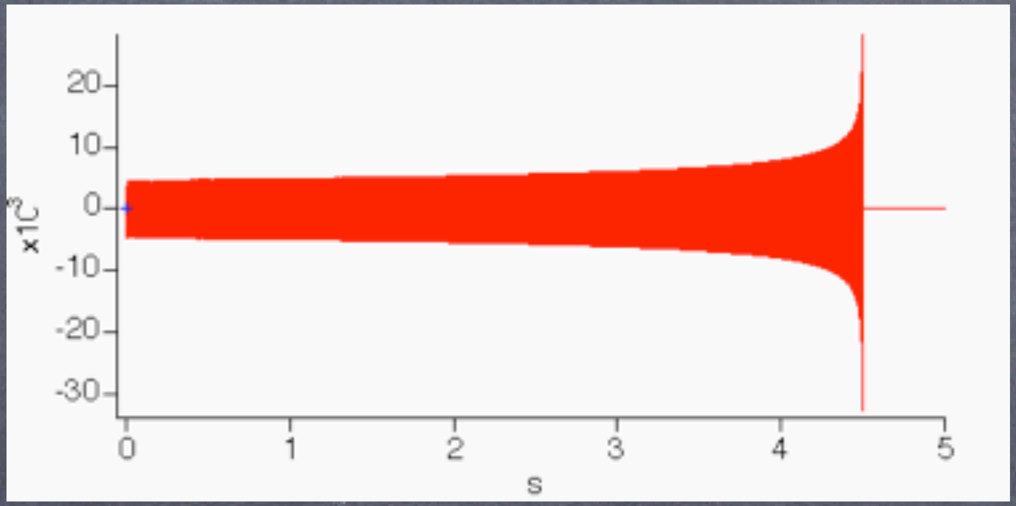
(in f … $^{-23}$ [/√Hz]

"Chirp" of mass

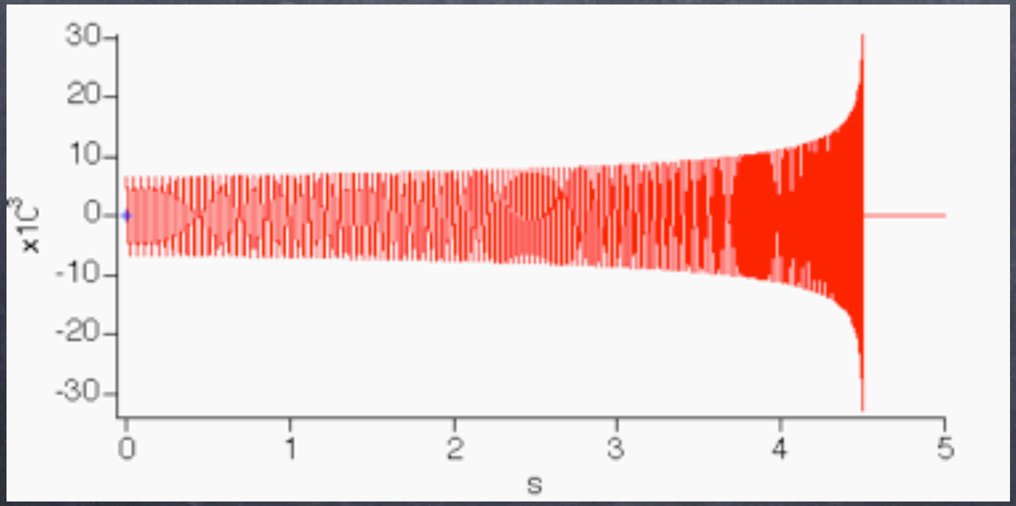




0.5-0.5 M_{solar}



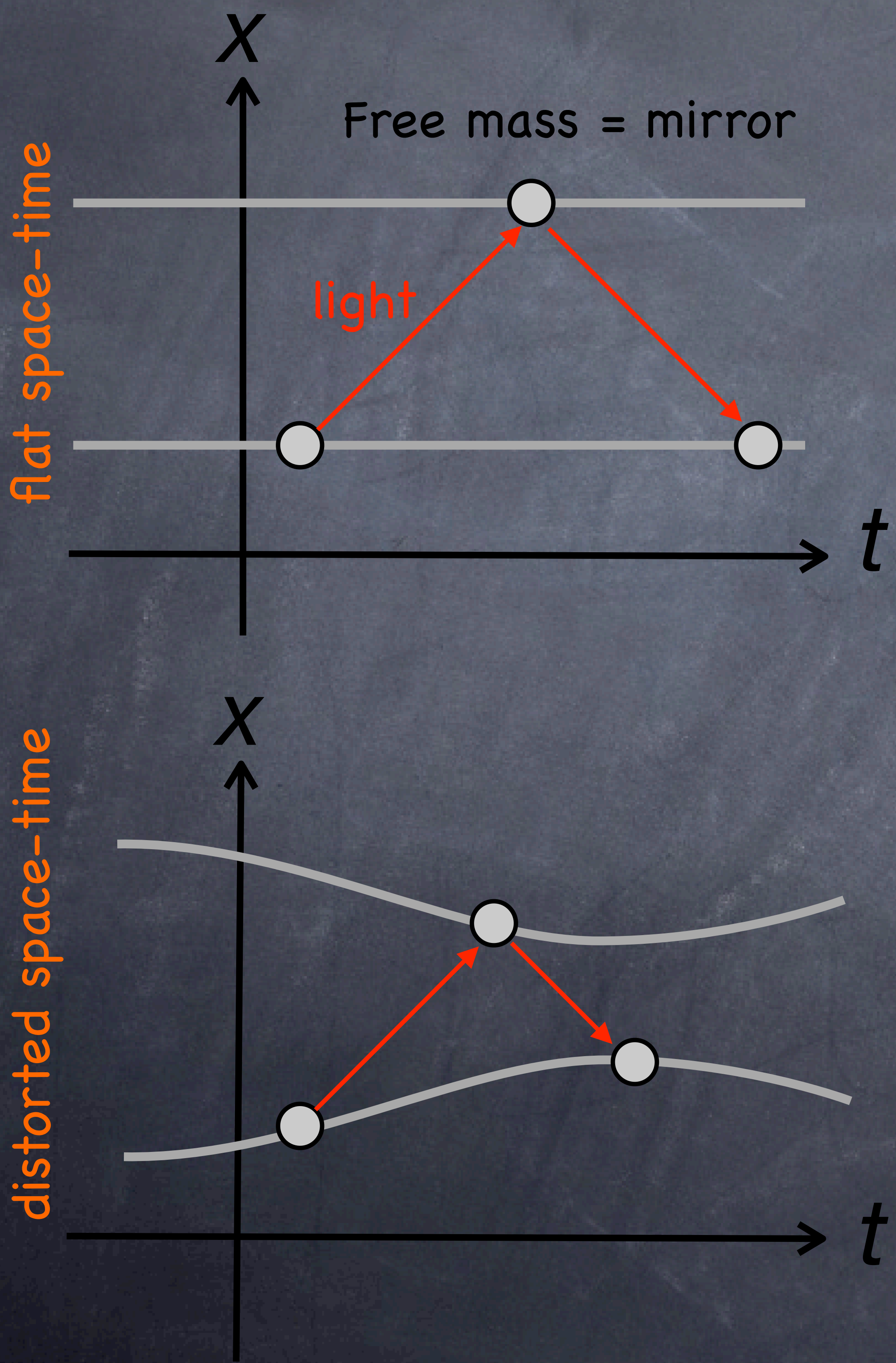
1.4-1.4 M_{solar}

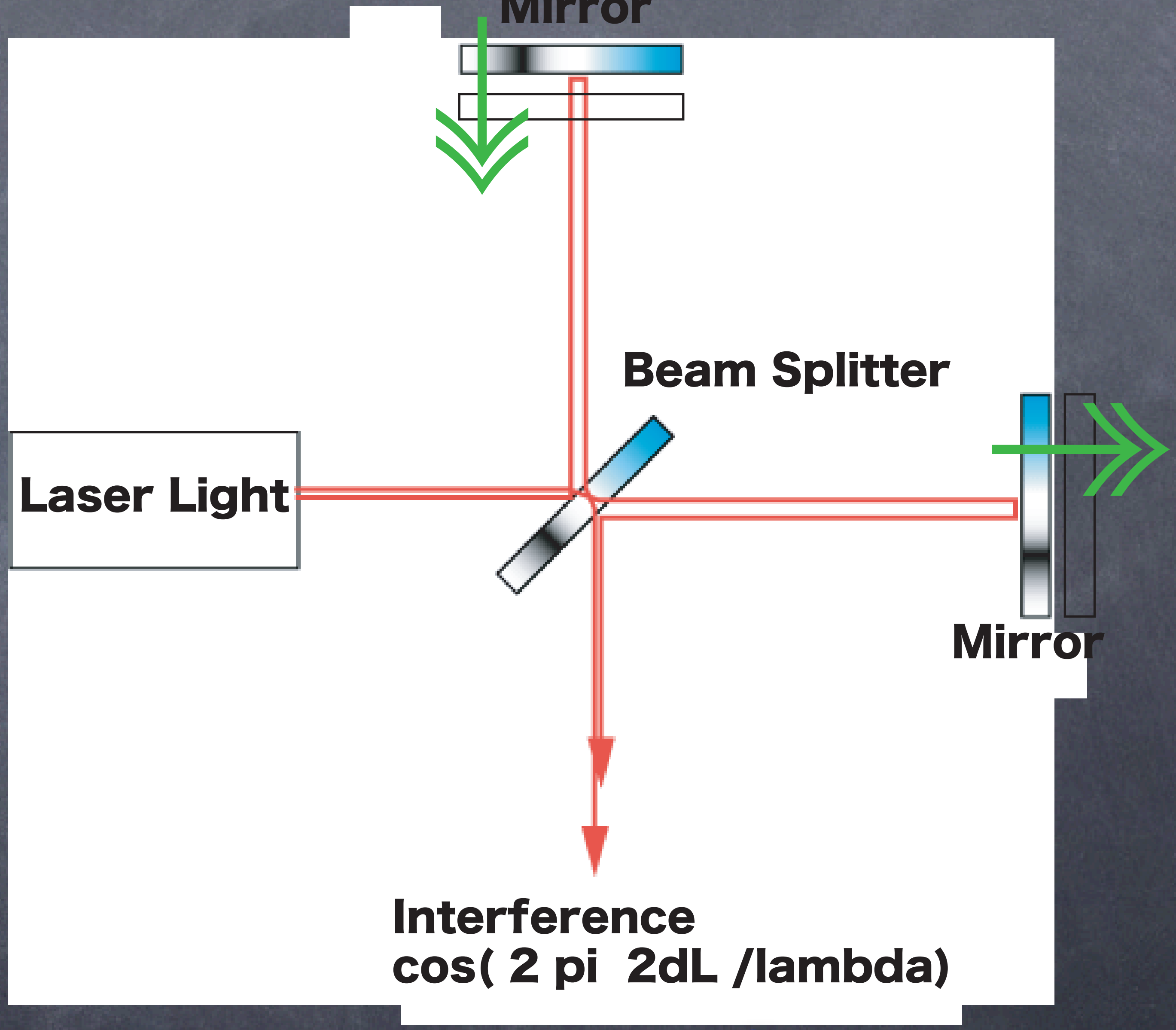


10-10 M_{solar}

How to detect GW

- Free Test Masses & Laser interferometer

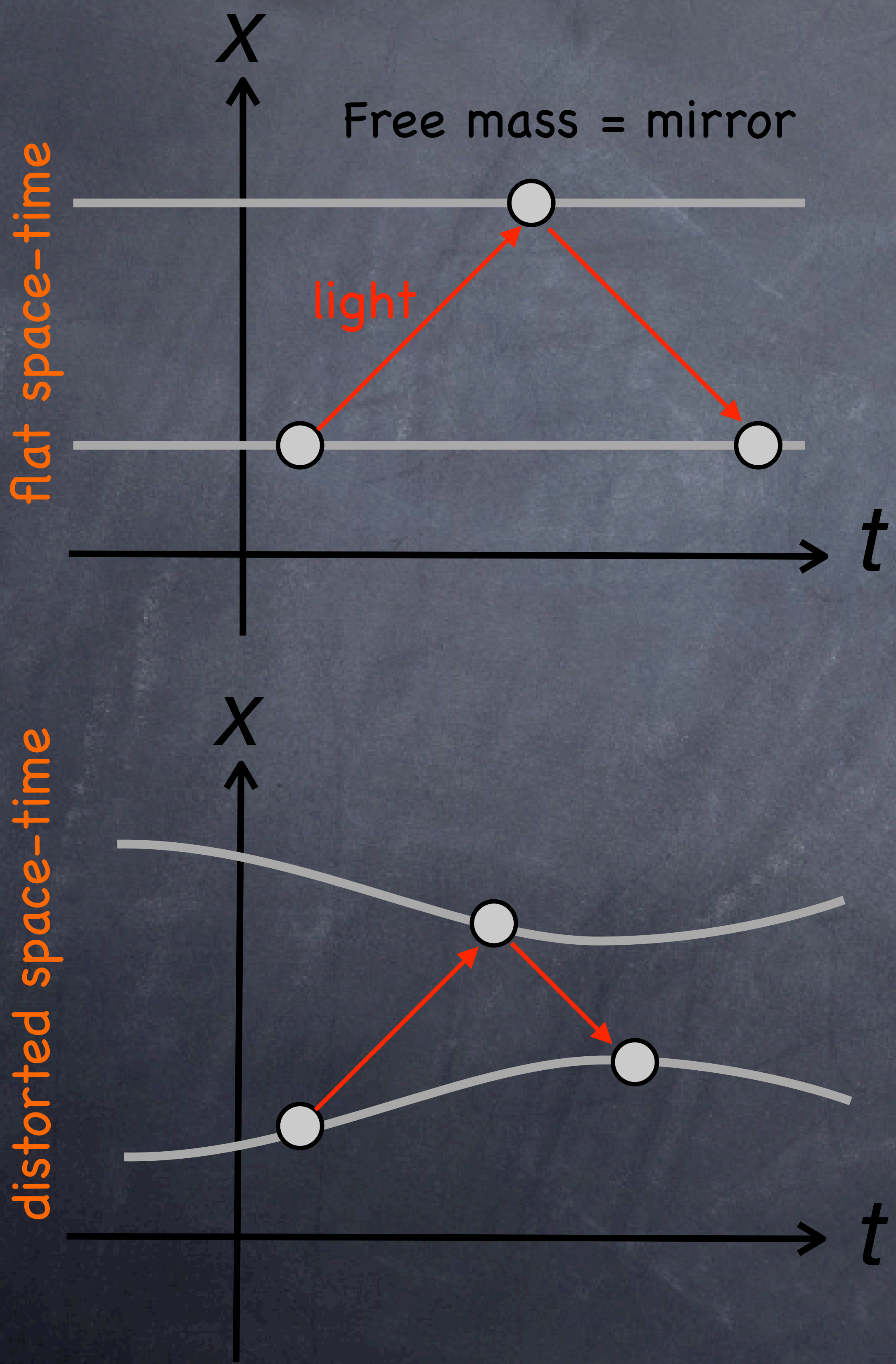


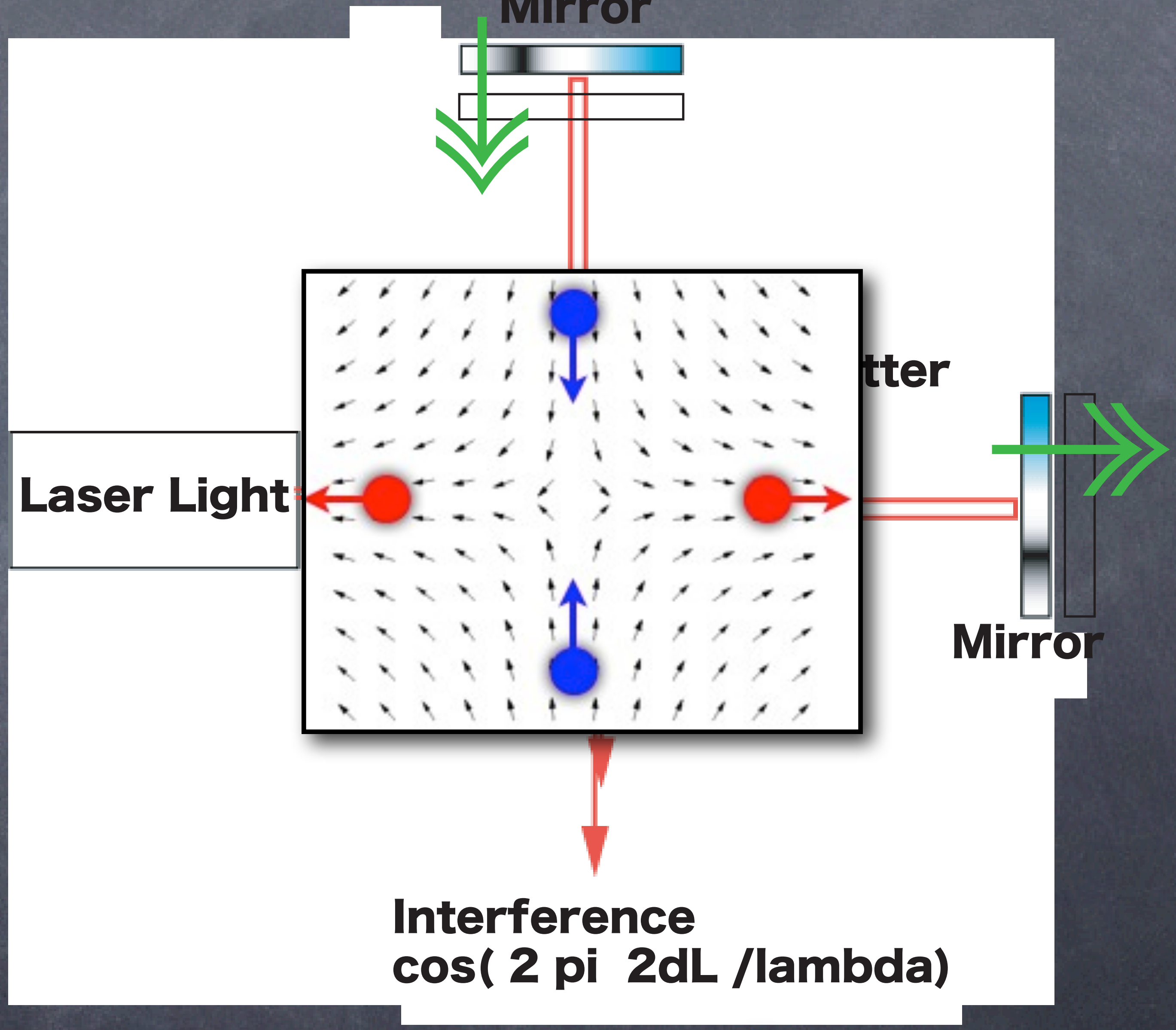


Michelson Interferometer

How to detect GW

- Free Test Masses & Laser interferometer





Interference
cos(2 pi 2dL /lambda)

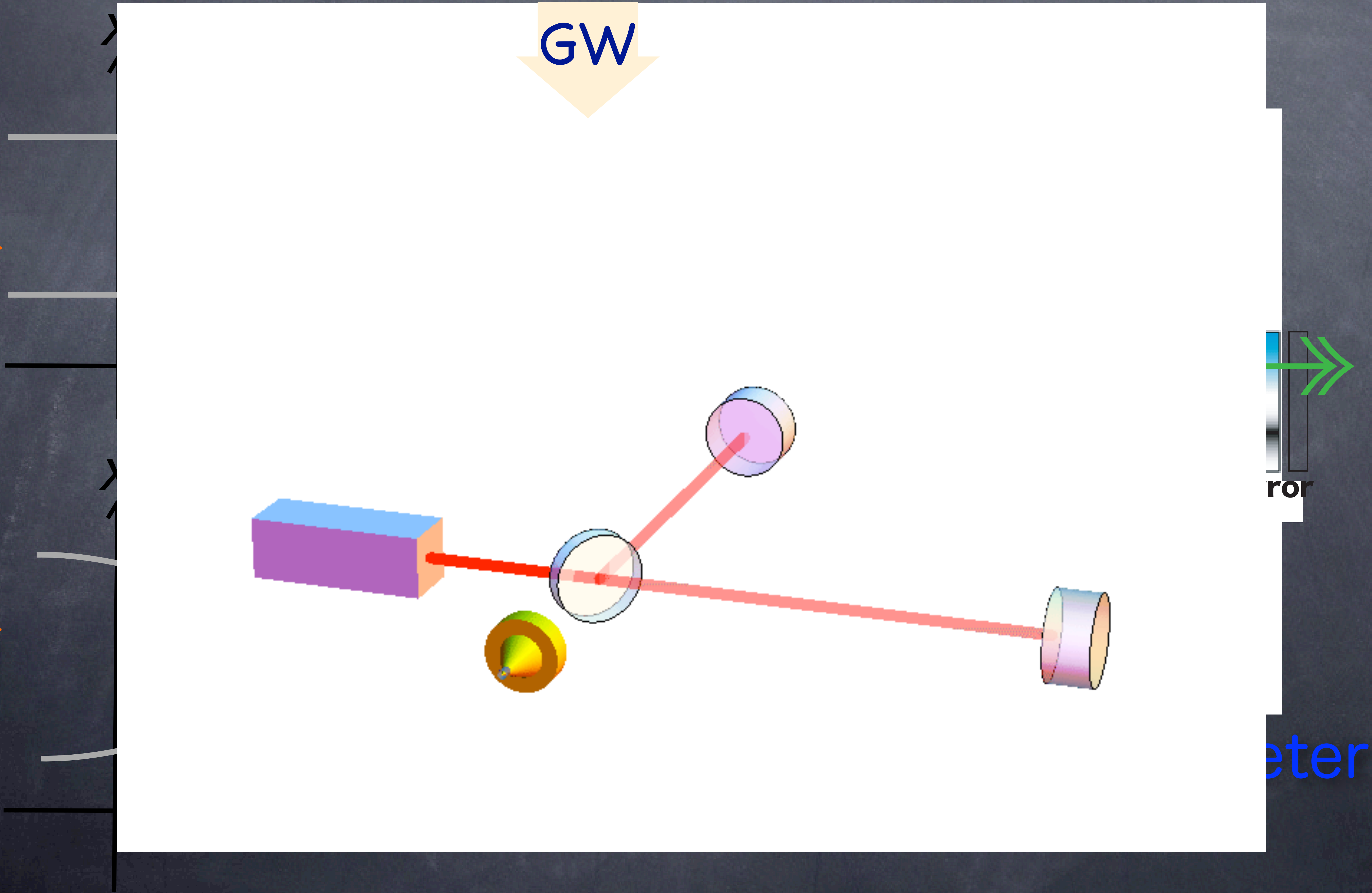
Michelson Interferometer

How to detect GW

- Free Test Masses & Laser interferometer

flat space-time

distorted space-time



Confused Question

- **Q : I'm afraid that both space and laser wavelength will change. Might them cancel out each other ?**
  (change of laser wavelength = change of time, with the rule of 'principle of constancy of light velocity')
- **A : No, don't worry!**

  (for non-physicist) You can see the behavior as "space-distorted" or as "time-distorted" as you like.

  But in any view, you cannot vanish the wave.

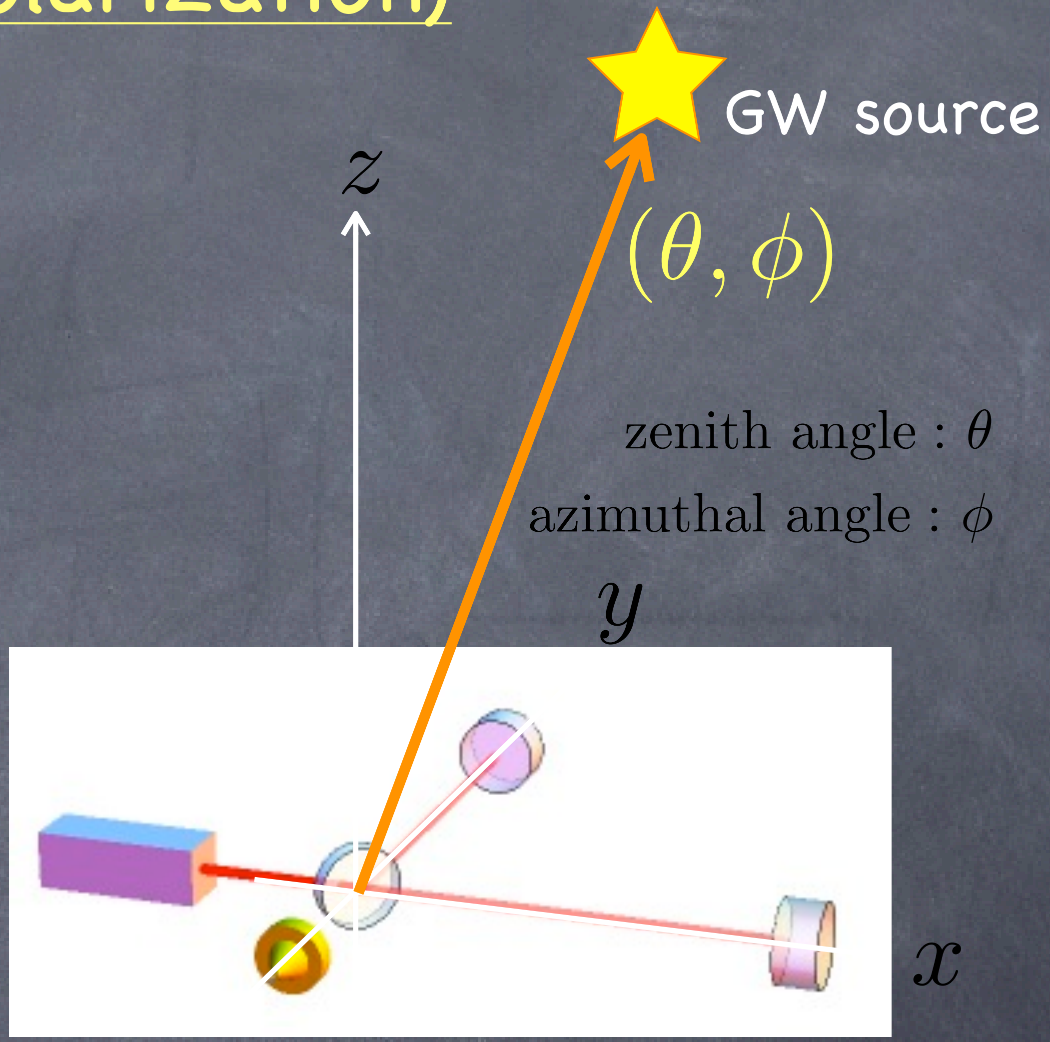
  We explain with 'stable clock' to image easily as in laboratory where we are living :-).

  (for physicist) You should learn classical electromagnetism in undergraduate cause !

  This is problem of "Gauge". Waves will not disappear with Gauge tarnsform.

Antenna Pattern
(Response for source direction and polarization)

Interferometer's antenna pattern is widely spread as almost 'omni-directional'.



Antenna Pattern
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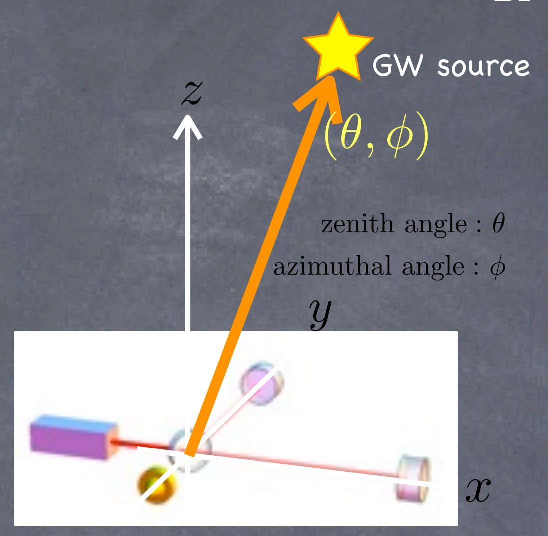

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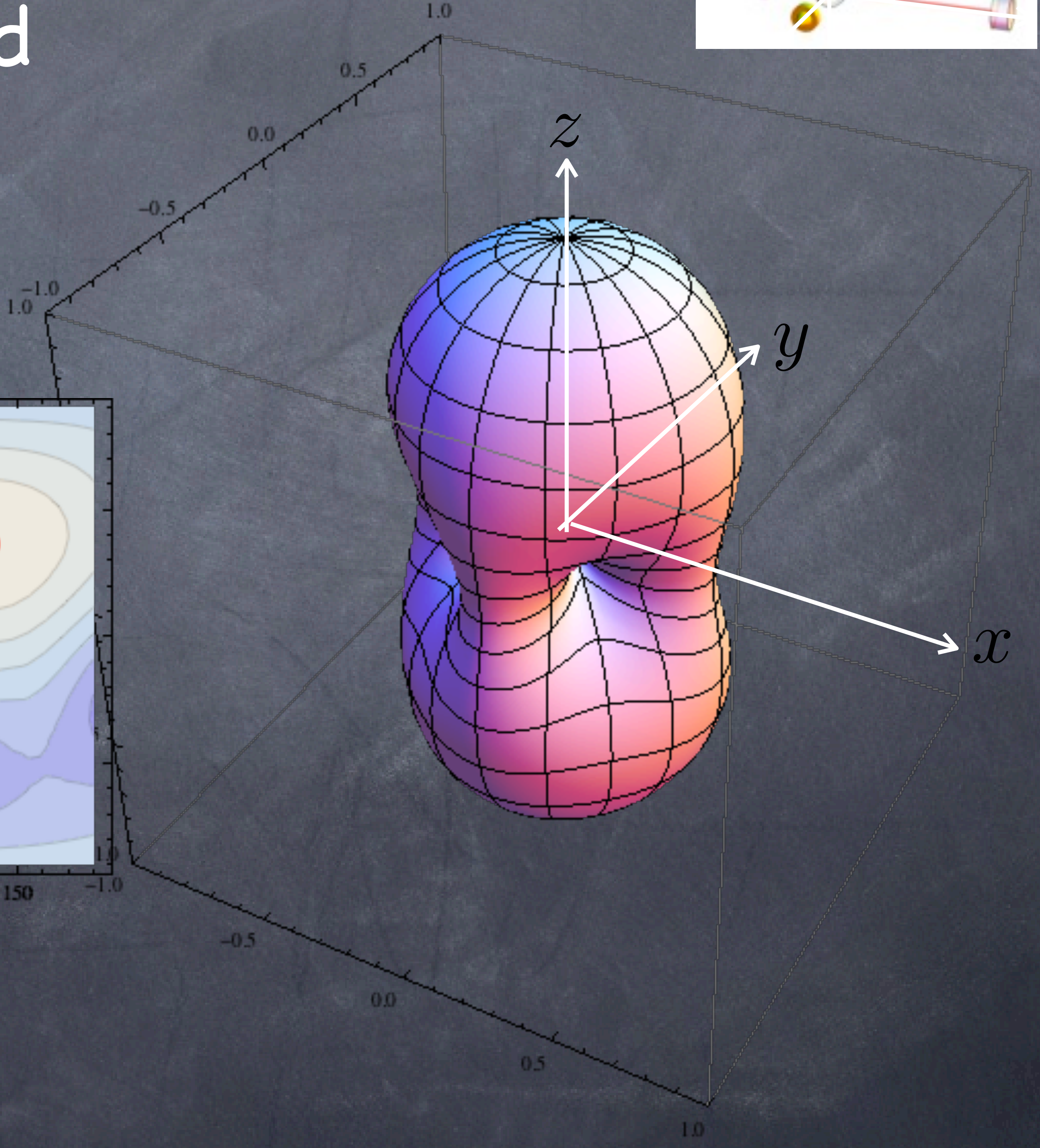
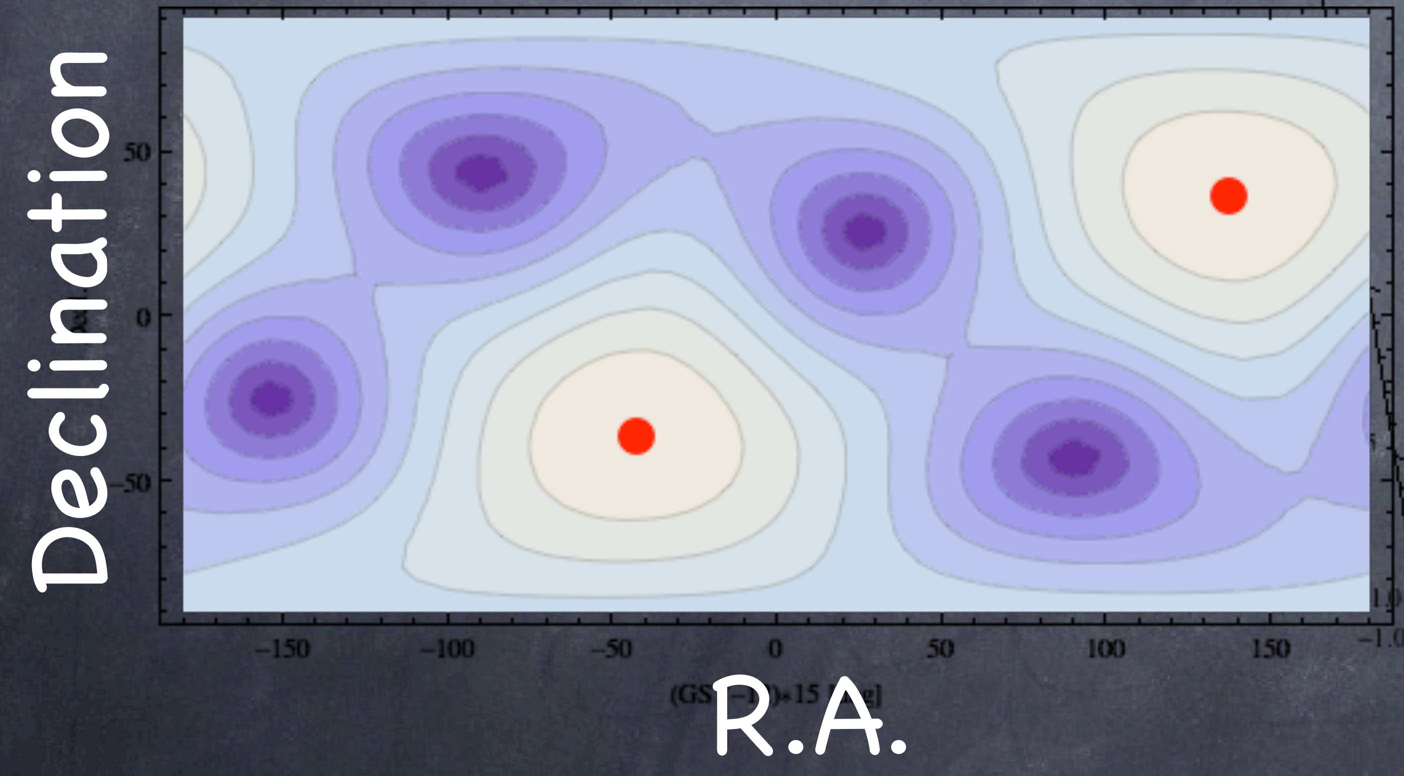
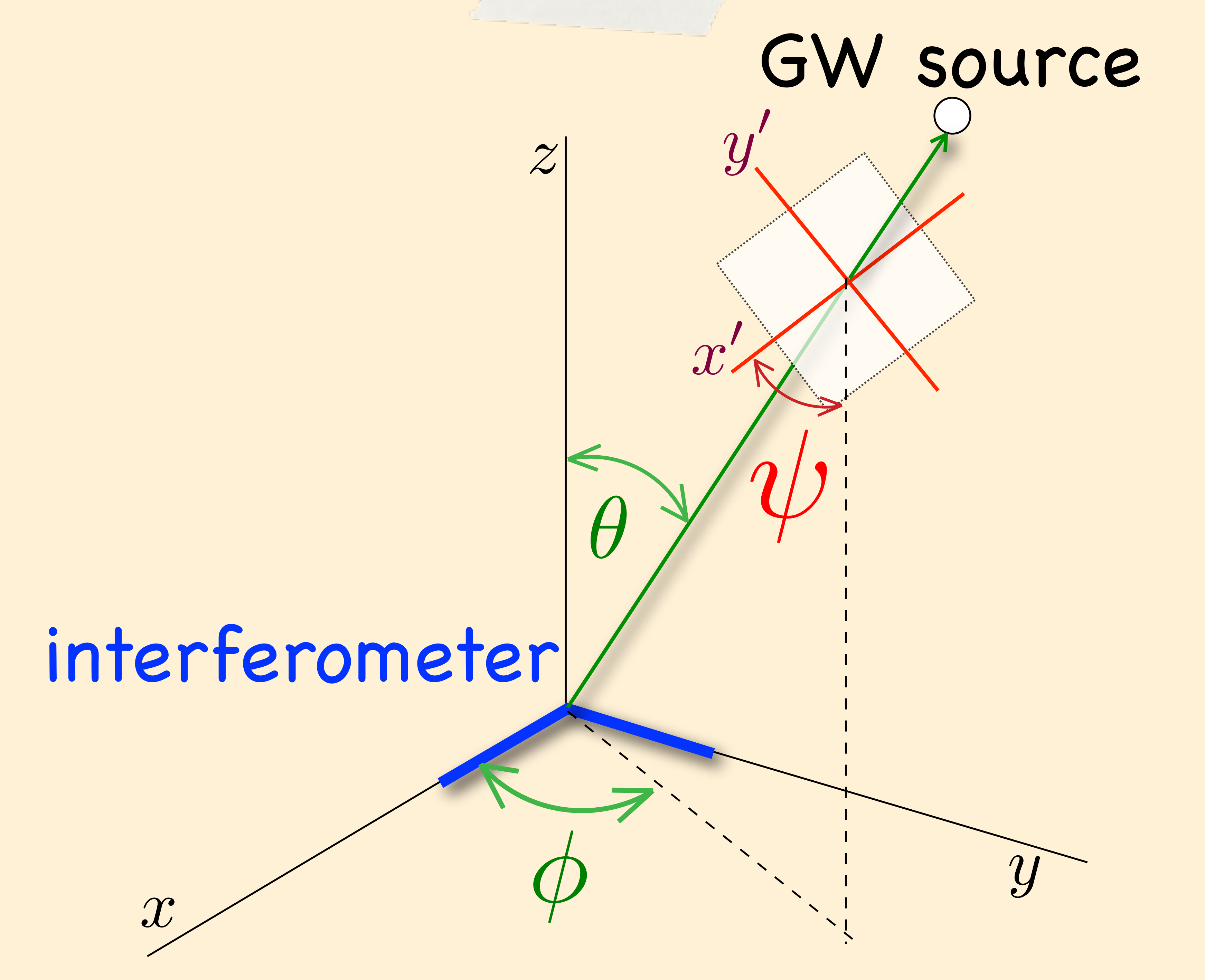
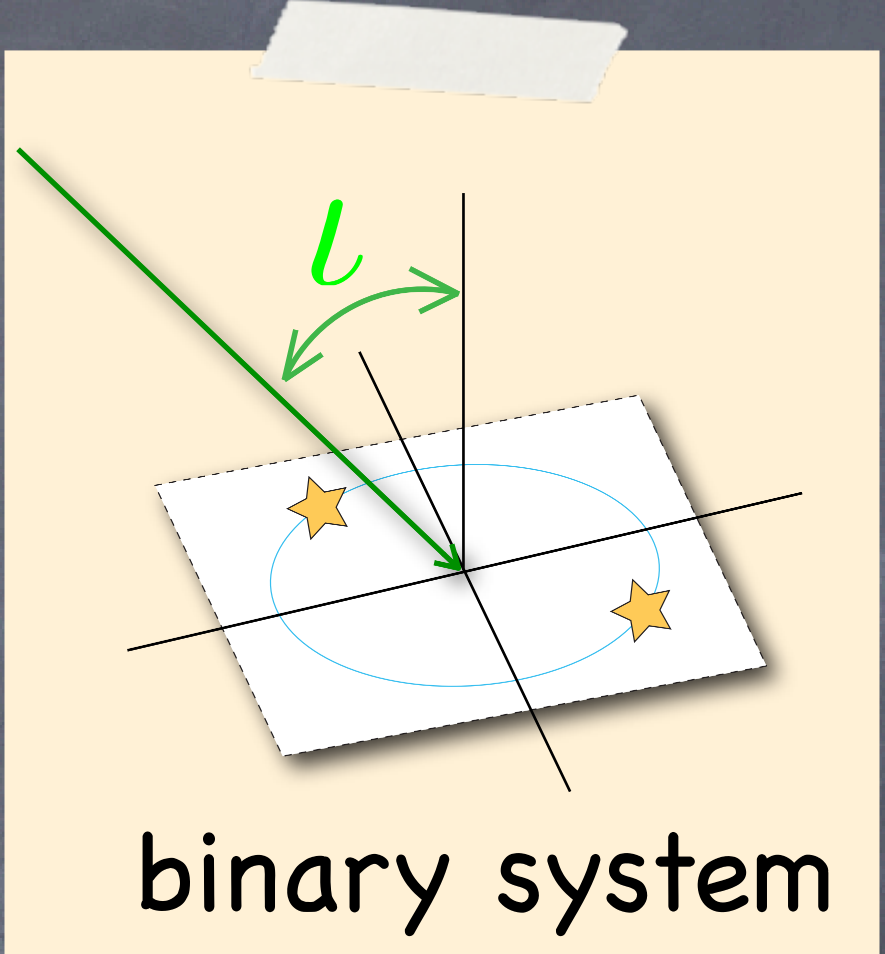




Antenna Pattern

Notation

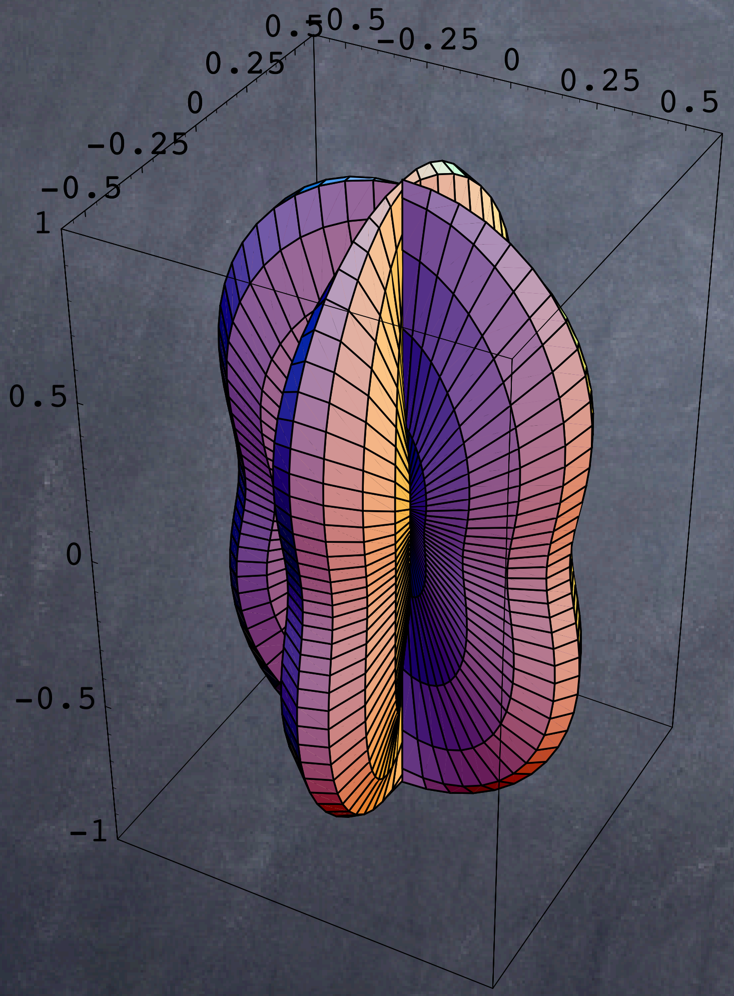




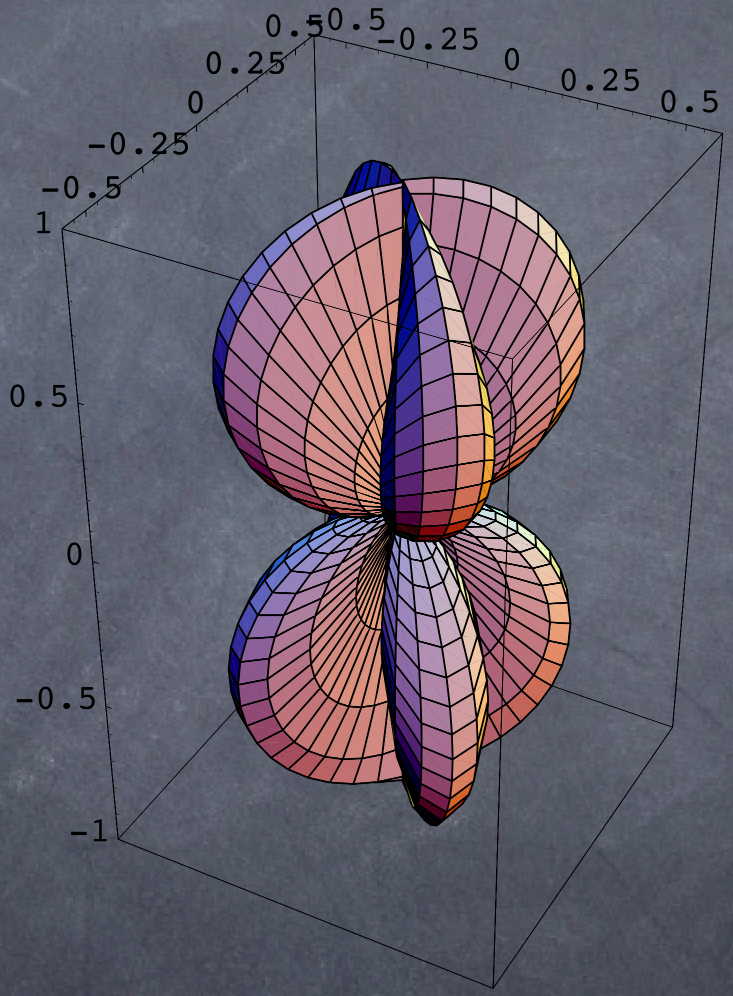
Antenna Pattern

$$F_+(\theta, \phi, \psi) = \frac{1}{2}(1 + \cos^2\theta)\cos 2\phi \cos 2\psi - \cos\theta \sin 2\phi \sin 2\psi$$

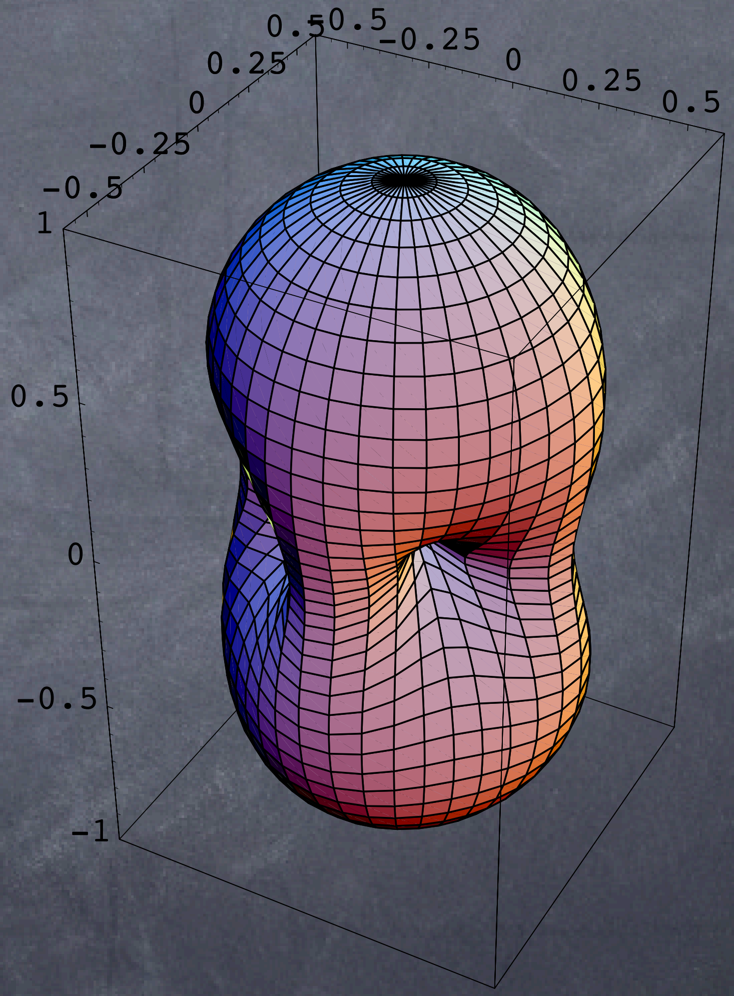
$$F_\times(\theta, \phi, \psi) = \frac{1}{2}(1 + \cos^2\theta)\cos 2\phi \sin 2\psi + \cos\theta \sin 2\phi \cos 2\psi$$



$F_+(\theta, \phi, 0)$



$F_\times(\theta, \phi, 0)$



$\sqrt{F_+(\theta, \phi, \psi)^2 + F_\times(\theta, \phi, \psi)^2}$

$$h_{det} = F_+ h_+ + F_\times h_\times$$

Schematic Figure

- Free mass --> suspended mirror
- To integrate strain 'h' --> long baseline arms.
- Limited size --> Folding arms / Storage cavity
- Against noises -->

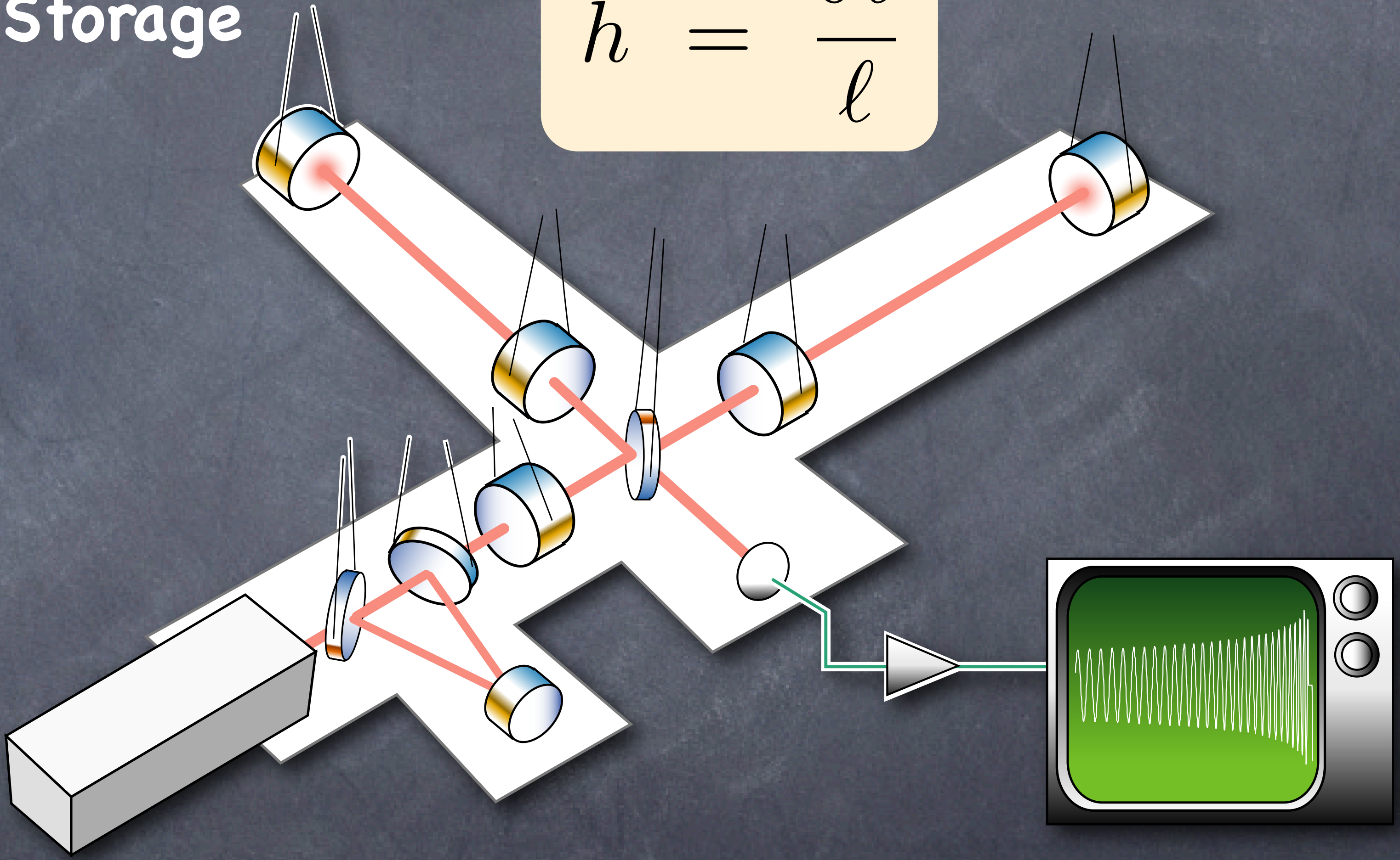
  high power laser

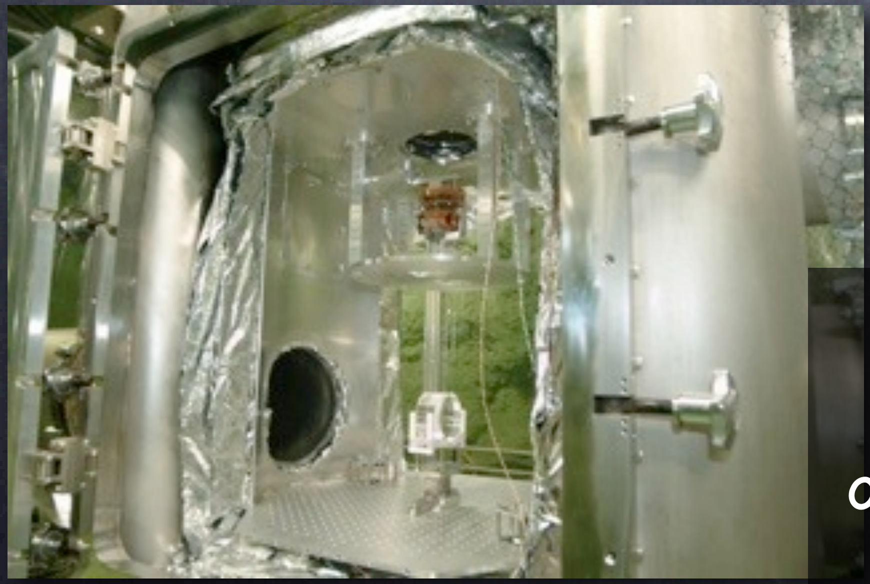
  Cooling

  etc..

merit on long base-line

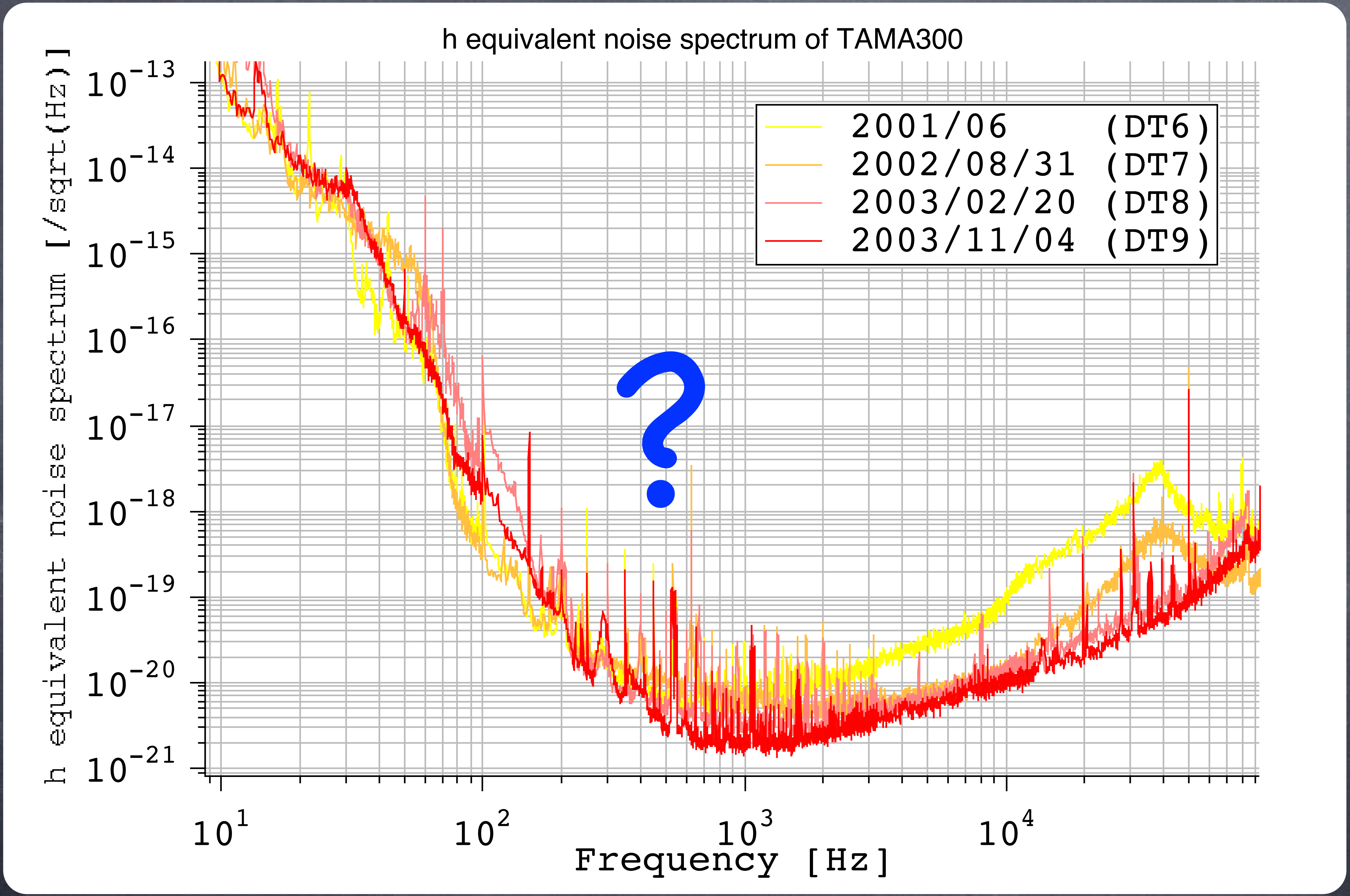
$$h = \frac{\delta \ell}{\ell}$$



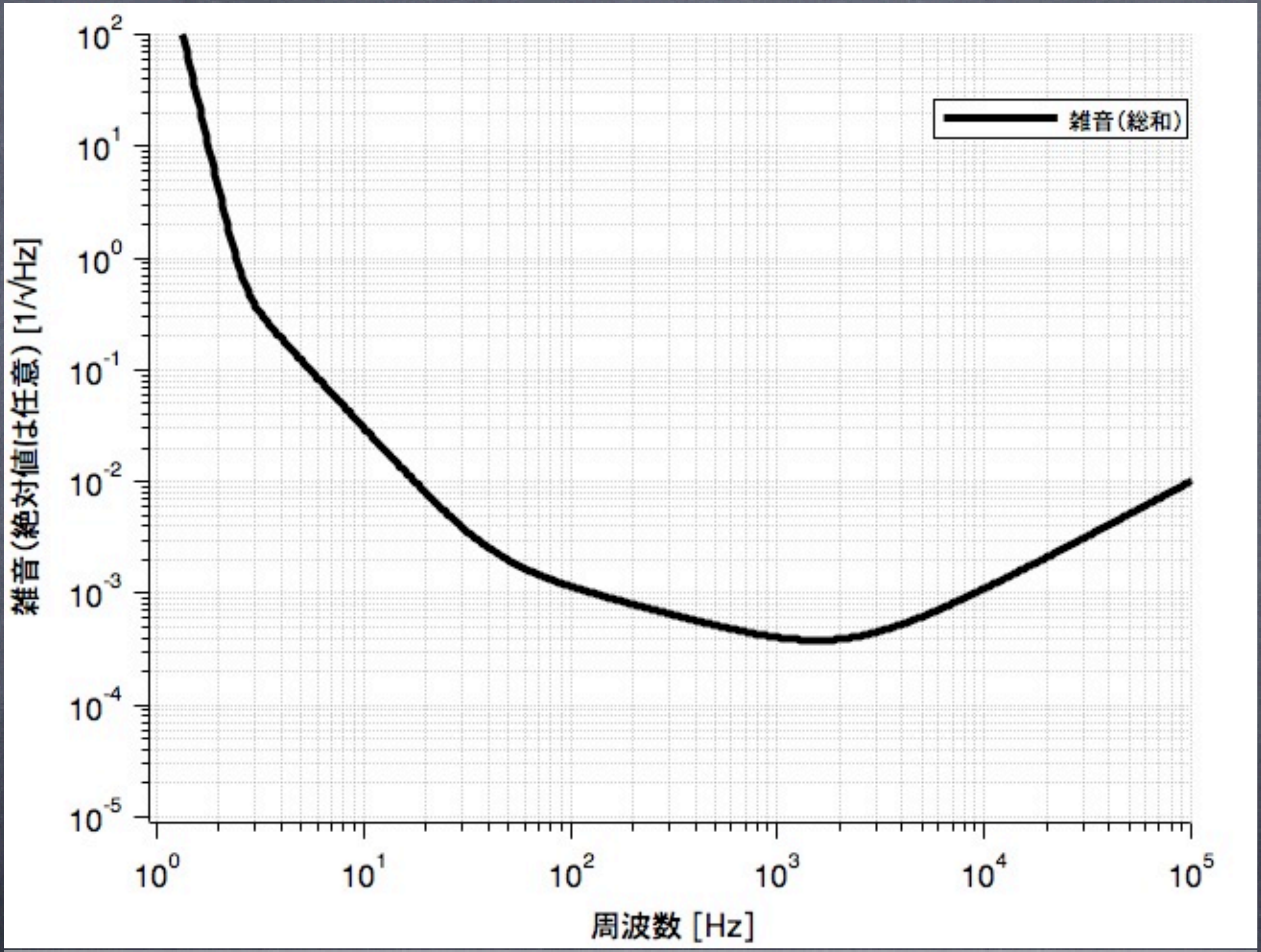


<-- mirror and suspension of CLIO interferometer (prototype of LCGT)

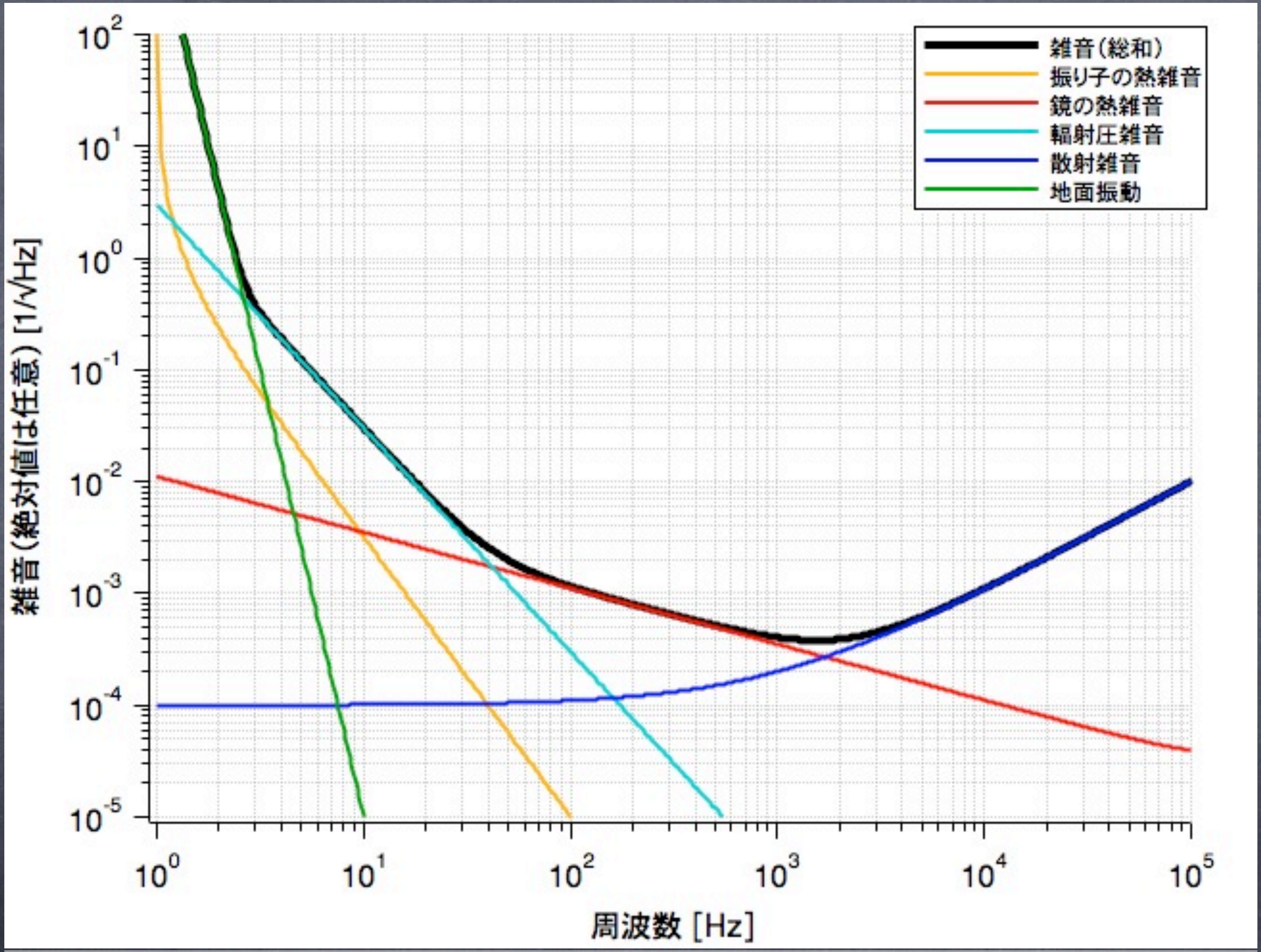
Detector Noise



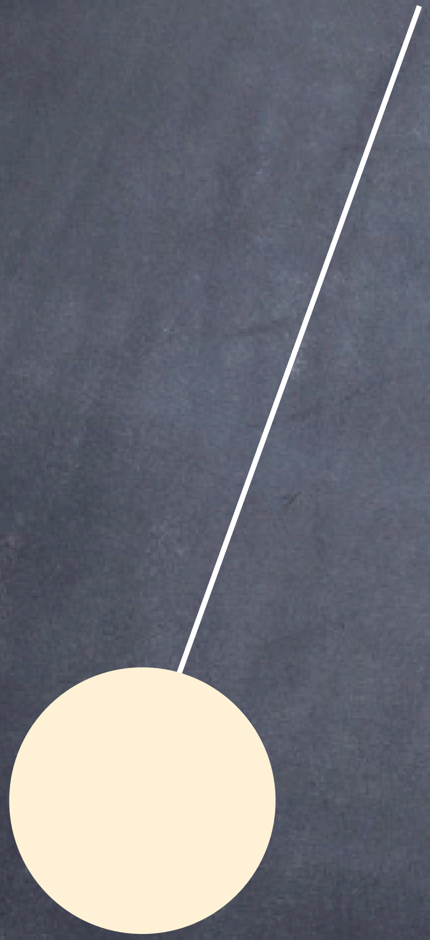
Fundamental Noises



Fundamental Noises



Brownian motion of macroscopic instruments : Pendulum, Mirror ...



$$K = \frac{1}{2}mv^2 \qquad U = -\frac{1}{2}kx^2$$

$$K + U = k_B T$$

$$< K >=< U >= \frac{1}{2}k_B T$$

$$x^2_{RMS} = \frac{k_B T}{m\omega_0^2}$$

Thermal Noise

- **Fluctuation-dissipation theorem**

$$m\frac{d^2x}{dt^2}+\gamma\frac{dx}{dt}+kx=f_N(t)$$

:Langevin Eq.

$$<f_N(t)f_N(t')>=2\gamma k_BT\delta(t-t')$$

$$<x(\omega)^2>=\frac{4\gamma k_BT}{|-m\omega^2+i\omega\gamma+k|^2}$$

: Power spectrum of Brownian motion

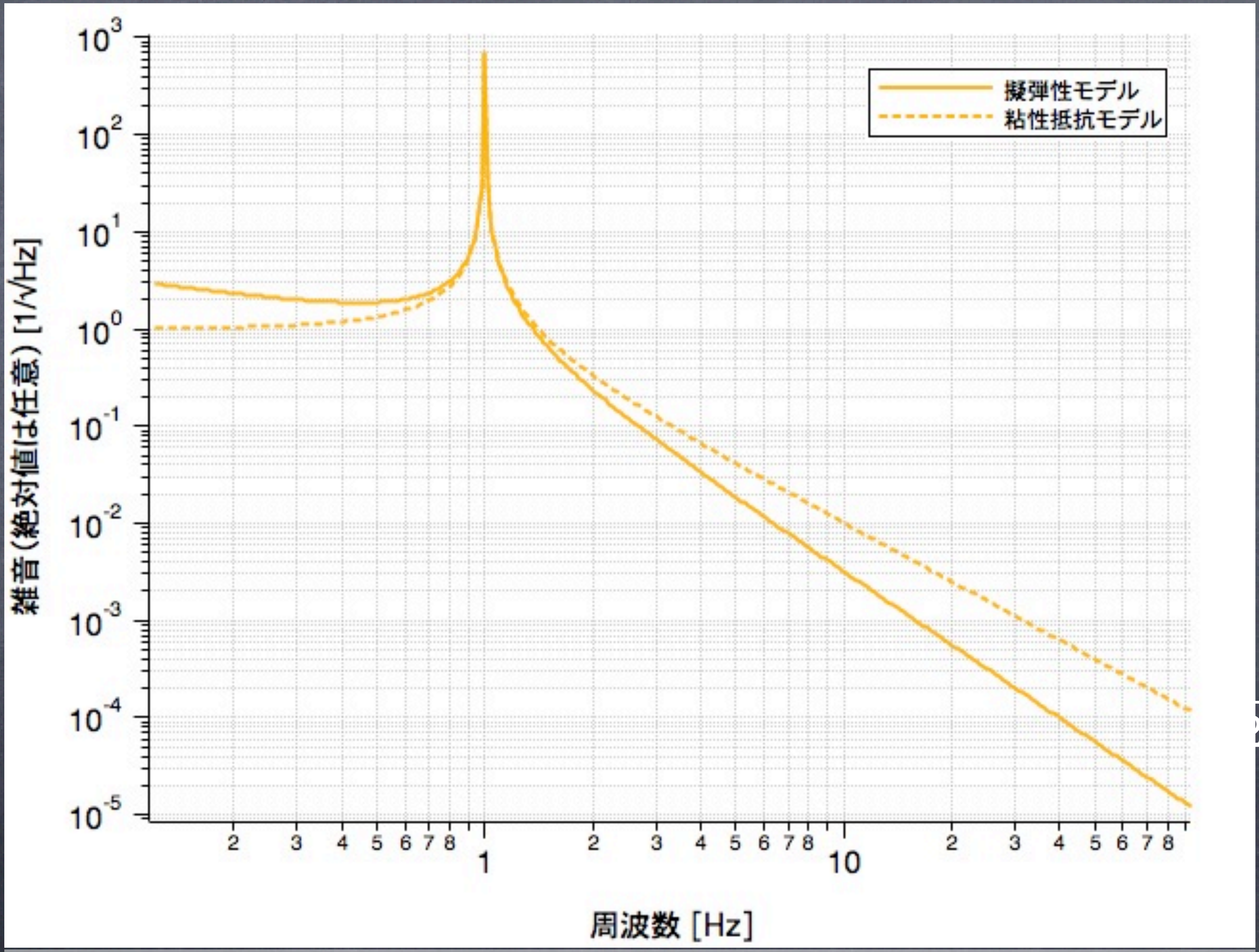
Spectrum

$$k \to k[1 + i\phi]$$

$$m(-\omega^2 + \omega_0\,[1 + i\phi(\omega)])x(\omega) = f(\omega)$$

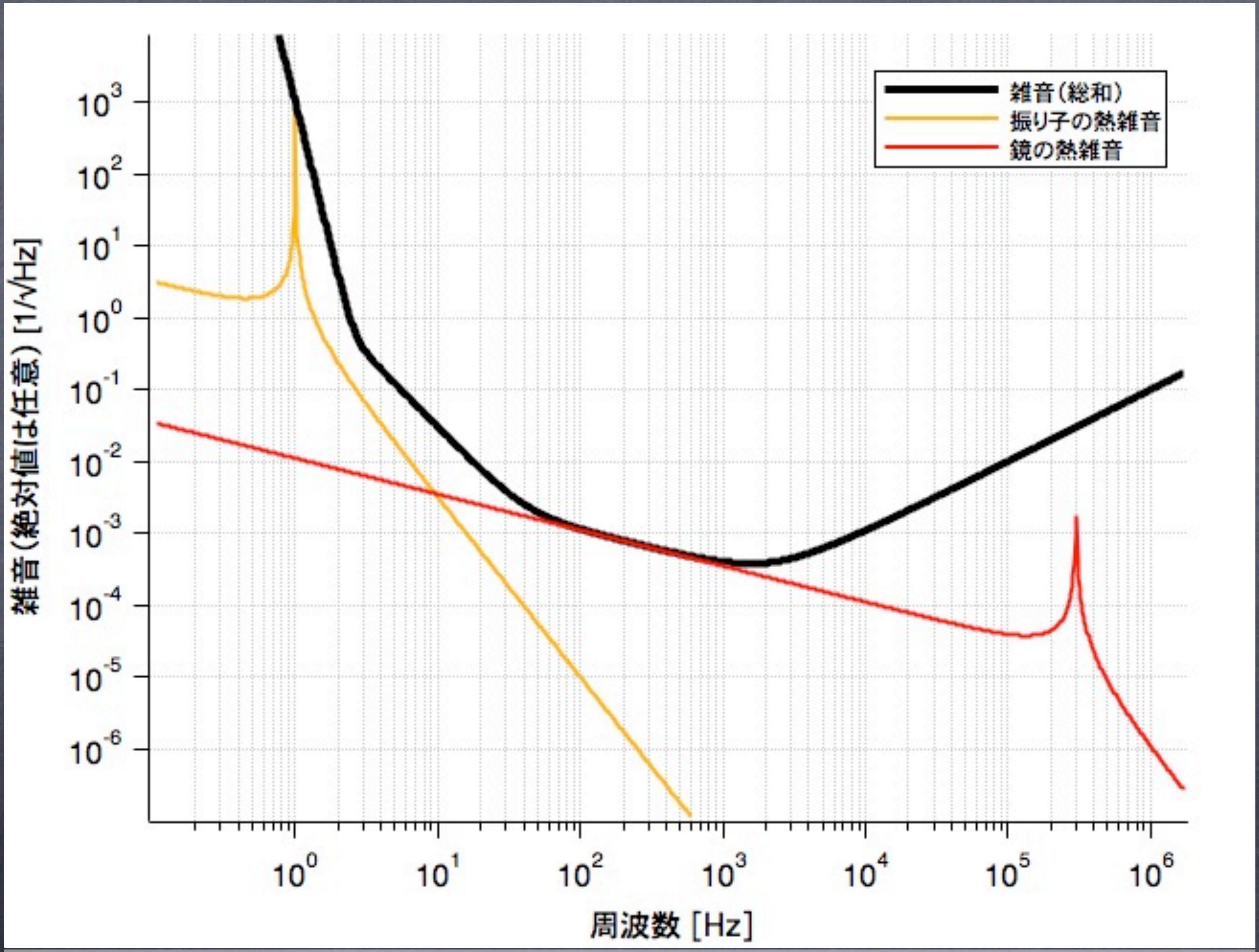
$$< x(\omega)^2 >= \frac{4\gamma k_B T}{\omega} \frac{\omega_0^2 \phi(\omega)}{m \mid -\omega^2 + i\omega^2[1 + i\phi]|^2}$$

Spectrum


10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
雑音（絶対値は任意）[1/√Hz]
擬弾性モデル
粘性抵抗モデル
2 3 4 5 6 7 8
1
2 3 4 5 6 7 8
10
2 3 4 5 6 7 8
周波数 [Hz]

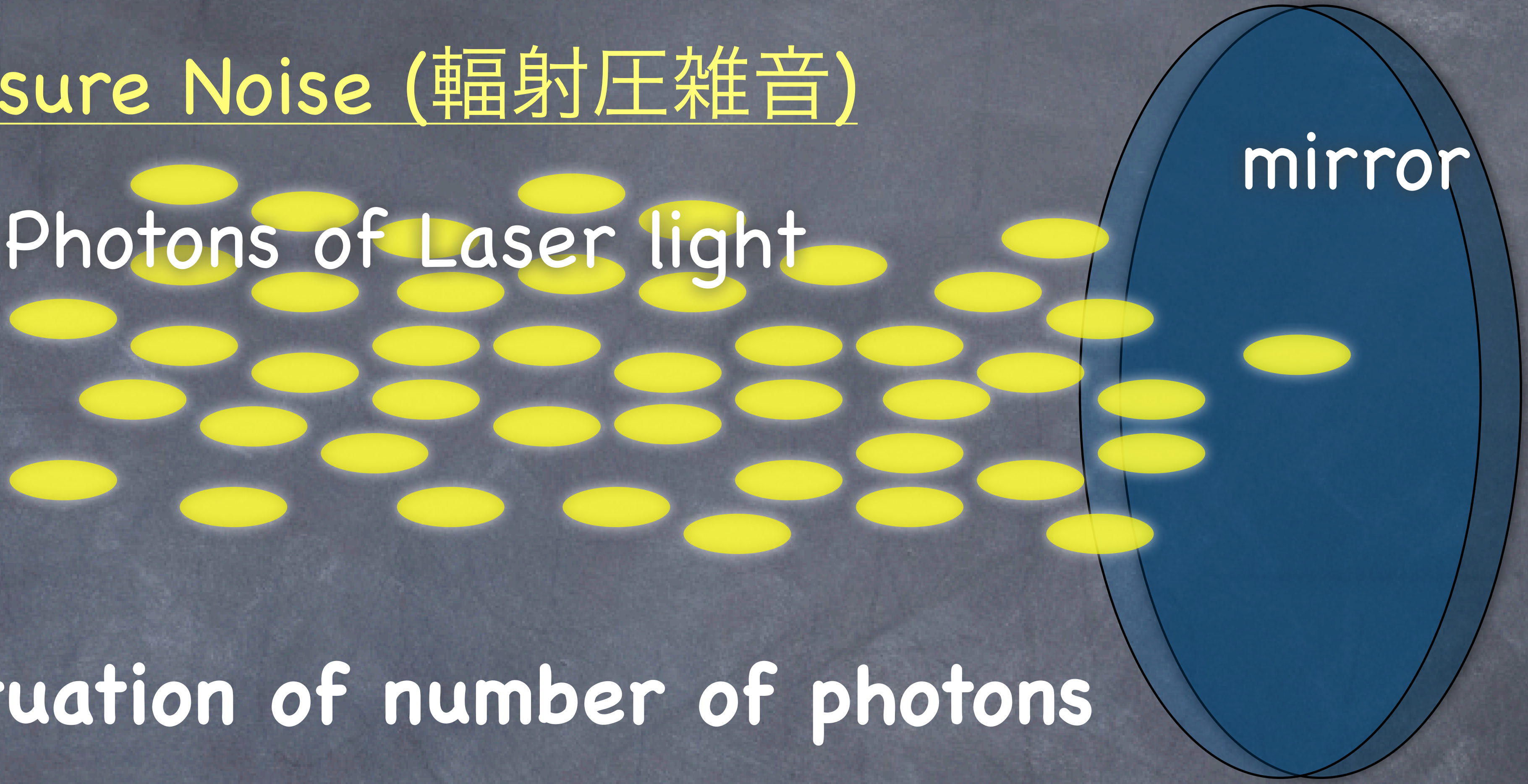
<

in GW detector,



Shot Noise (散射雑音)

Radiation Pressure Noise (輻射圧雑音)

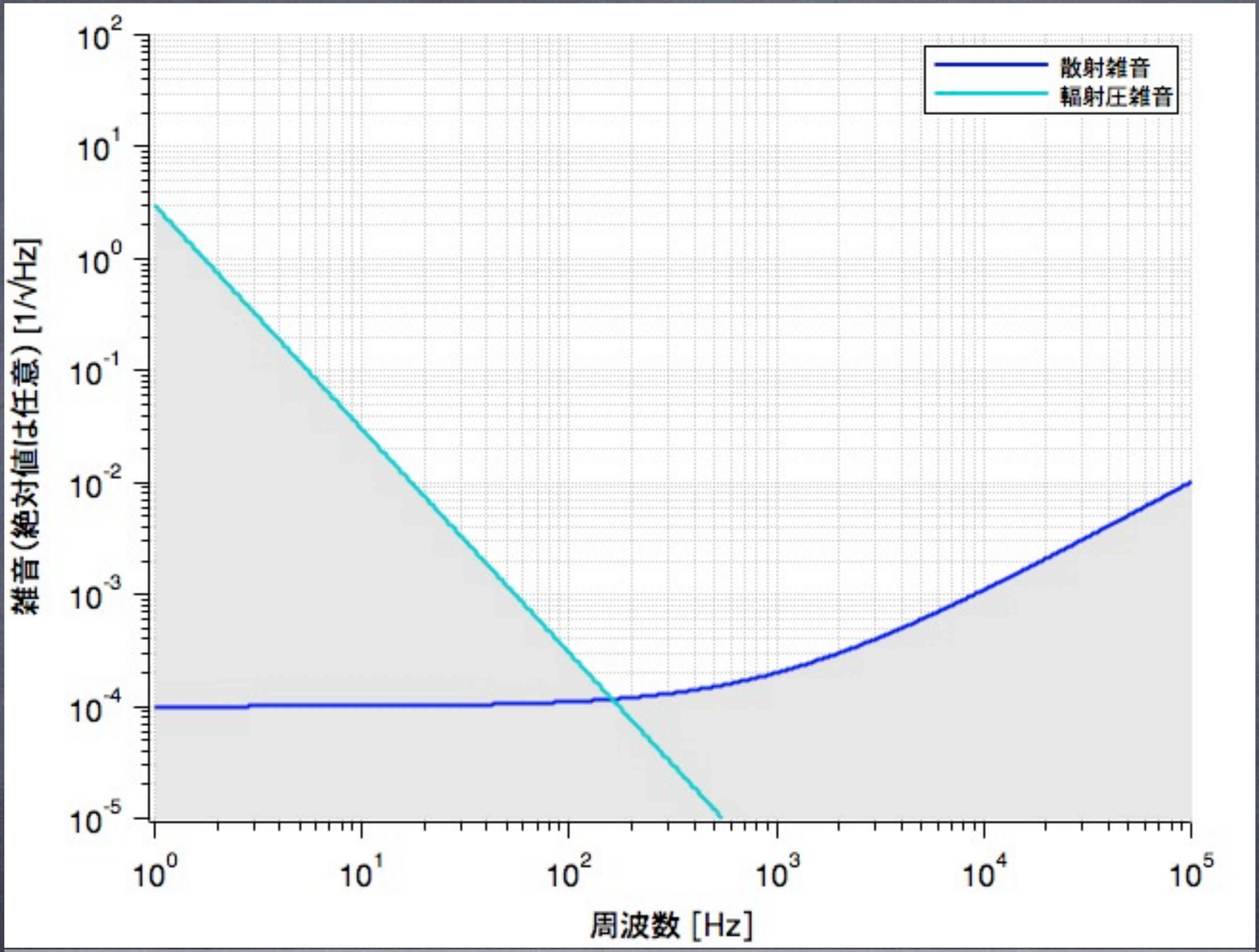


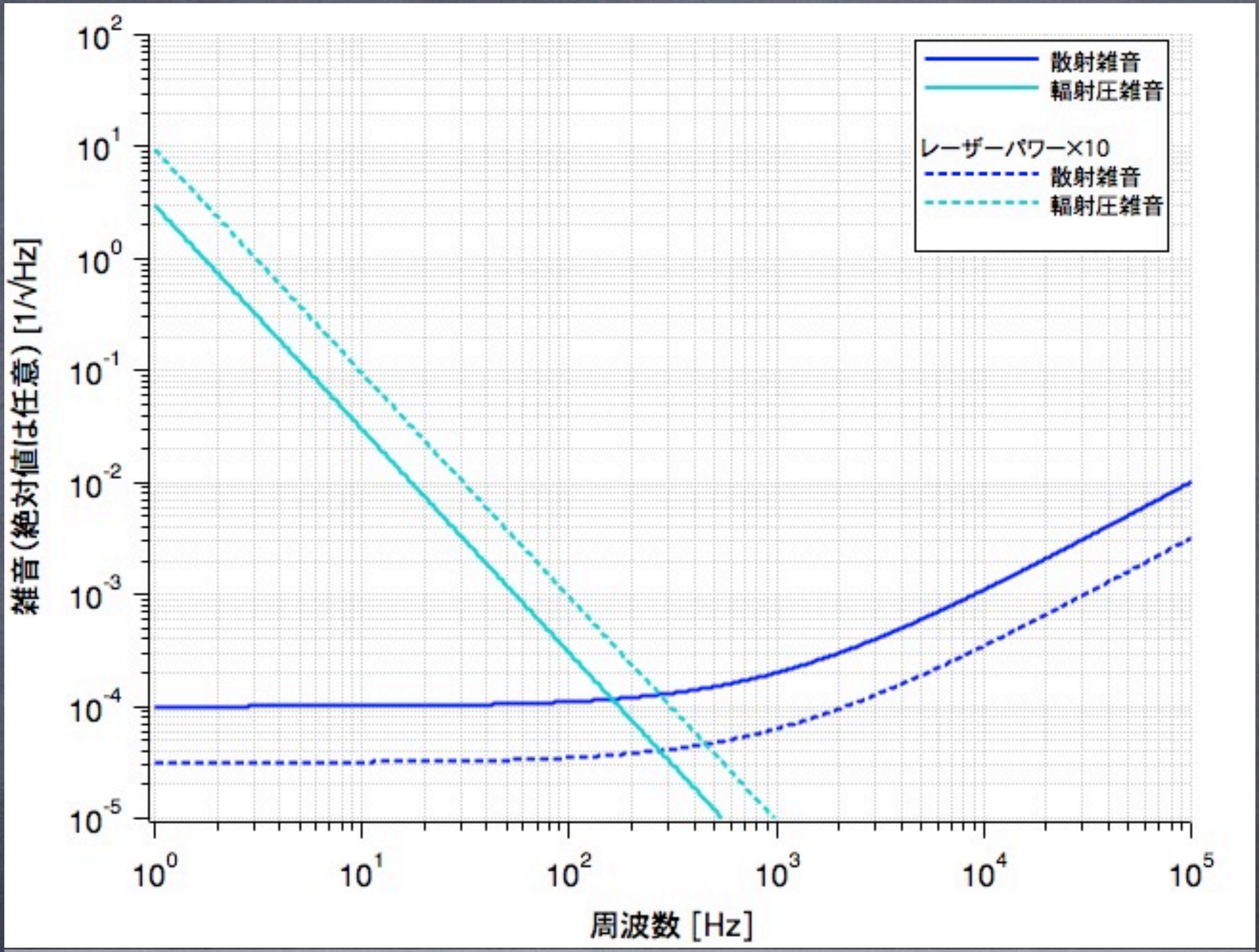
- **Fluctuation of number of photons**

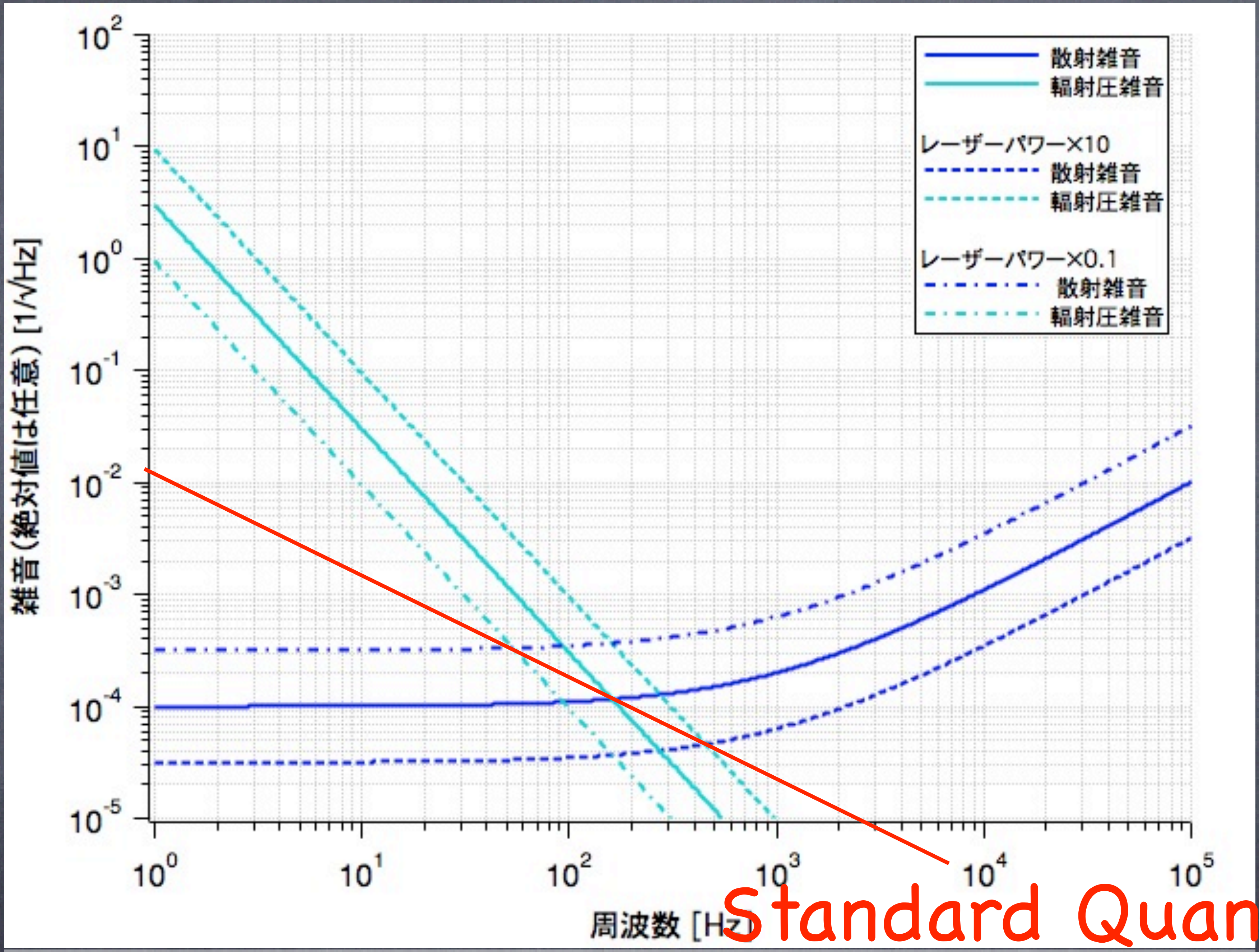
Shot Noise $x_{shot}(f) \propto \sqrt{\frac{\hbar c \lambda}{P}}$

Radiation Pressure Noise $x_{rp}(f) \propto \frac{1}{mf^2}\sqrt{\frac{\hbar P}{c\lambda}}$

High Power ? or Low Power ?

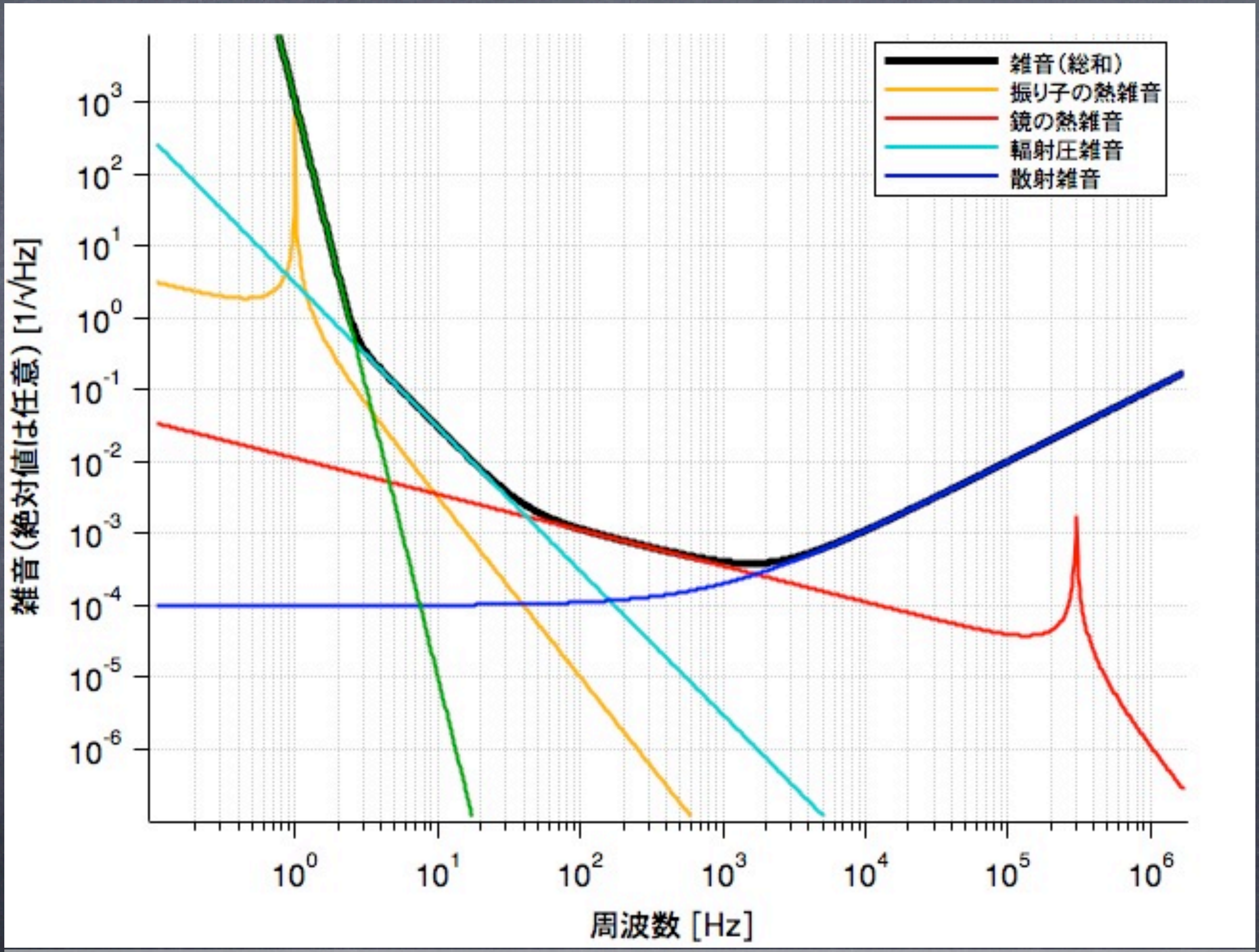

散射雑音
輻射圧雑音
雑音(絶対値は任意) [1/√Hz]
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^0
10^1
10^2
10^3
10^4
10^5
周波数 [Hz]


散射雑音
輻射圧雑音
レーザーパワー×10
散射雑音
輻射圧雑音
雑音（絶対値は任意）[1/√Hz]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
周波数 [Hz]



Standard Quantum limit

Noises !


雑音(総和)
振り子の熱雑音
鏡の熱雑音
輻射圧雑音
散射雑音
雑音(絶対値は任意) [1/√Hz]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
周波数 [Hz]

long base line

- **long L is better**

  noise on mirror : dx

  gravitational wave : h --> signal = h L

  signal-to-noise ratio : S/N = hL / dx

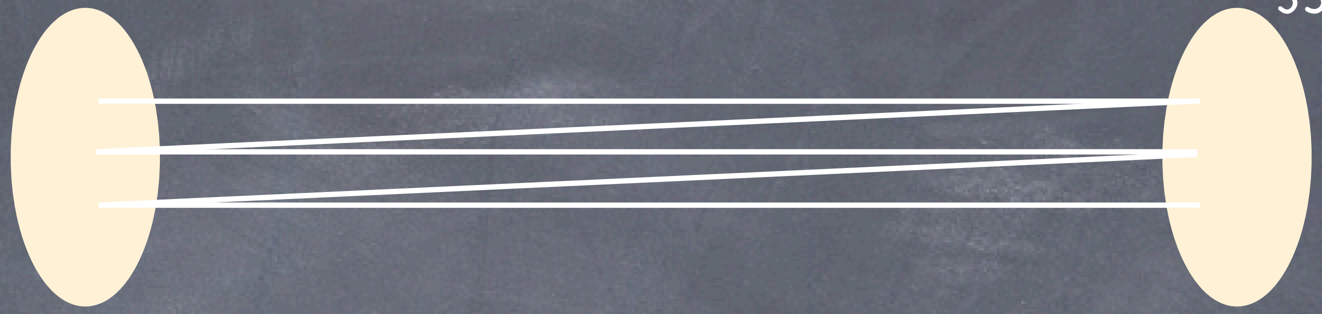
… limite of some pragmatic reasons …

- **---> N turn**

  noise on mirror : N dx

  signal : N L h

  S/N = L h /dx



mirror displacement noise : dx_{mirror}

noises from other instruments
(e.g. electric circuit) : dx_{other}

signal : h

- **by L and N-turns,**

noise average --> $\{ (N\, dx_{mirror})^2 + (dx_{other})^2 \}^{1/2}$

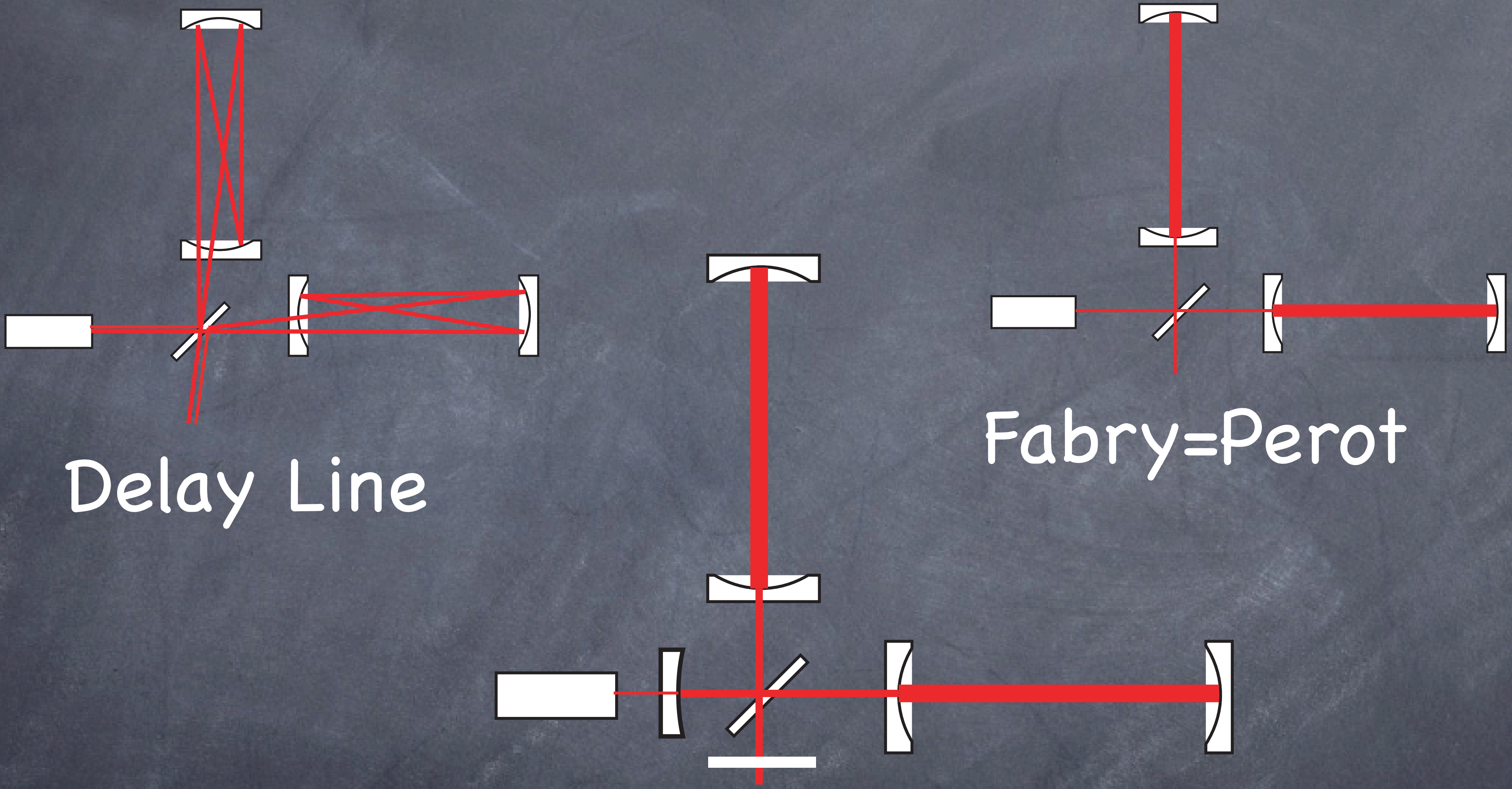
signal --> N L h

$(S^2/N^2)^{1/2} = N L h / \{ (N\, dx_{mirror})^2 + (dx_{other})^2 \}^{1/2}$

Thus, we gain S/N by L against mirror displacement noise and by N L against other noises.

Folding Arms

- 1kHz GW --> Optimal arm length = 75 km ! ...



Delay Line

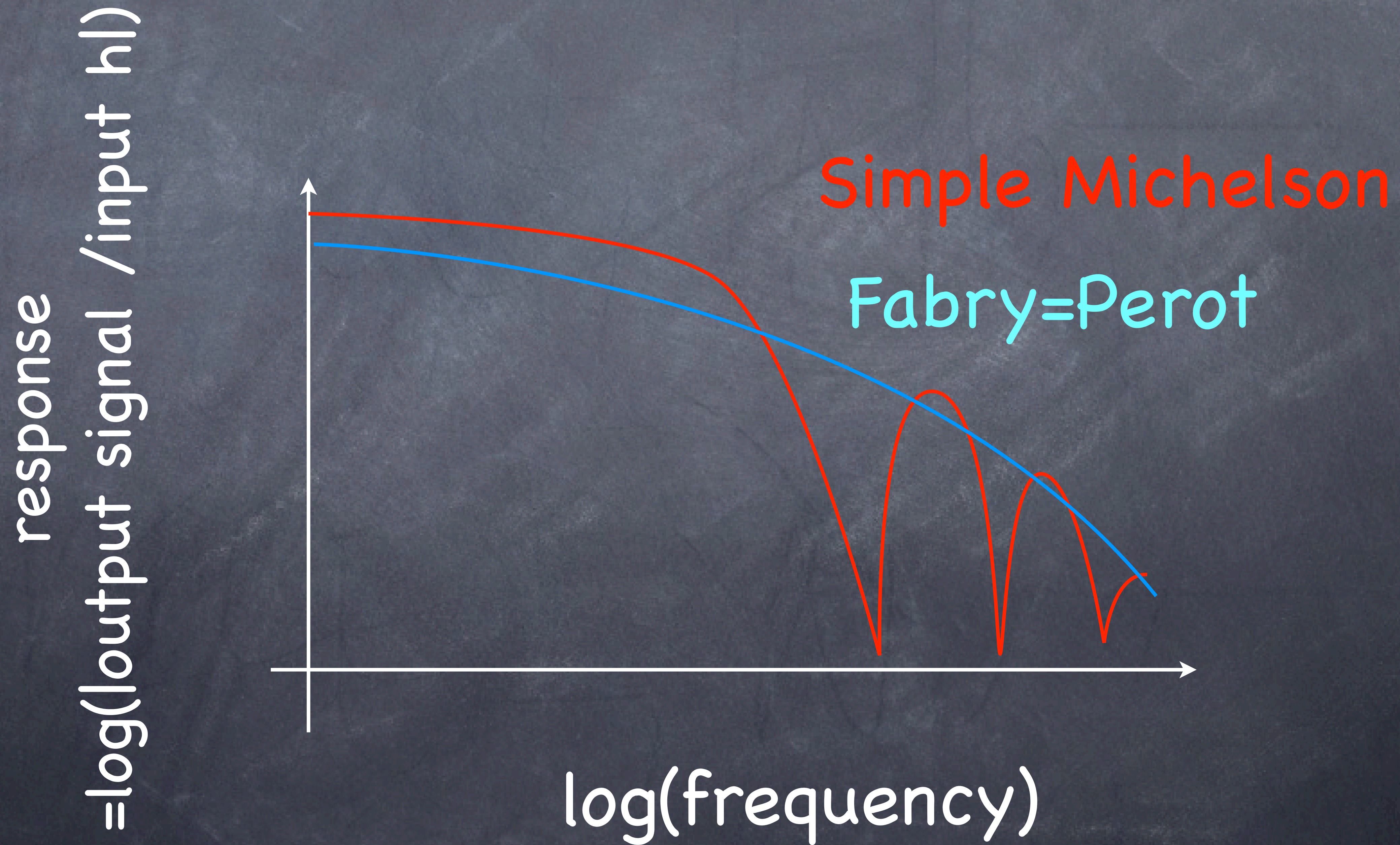
Fabry=Perot

Recycled Fabry=Perot
+signal recycling

LCGT is designed with 3km arms.

Q: As long as possible ?

- **Ans : NO!**
- **Reason : Light Speed**



Fight it out ! , Noises !!

Thermal noises

--> cryogenic

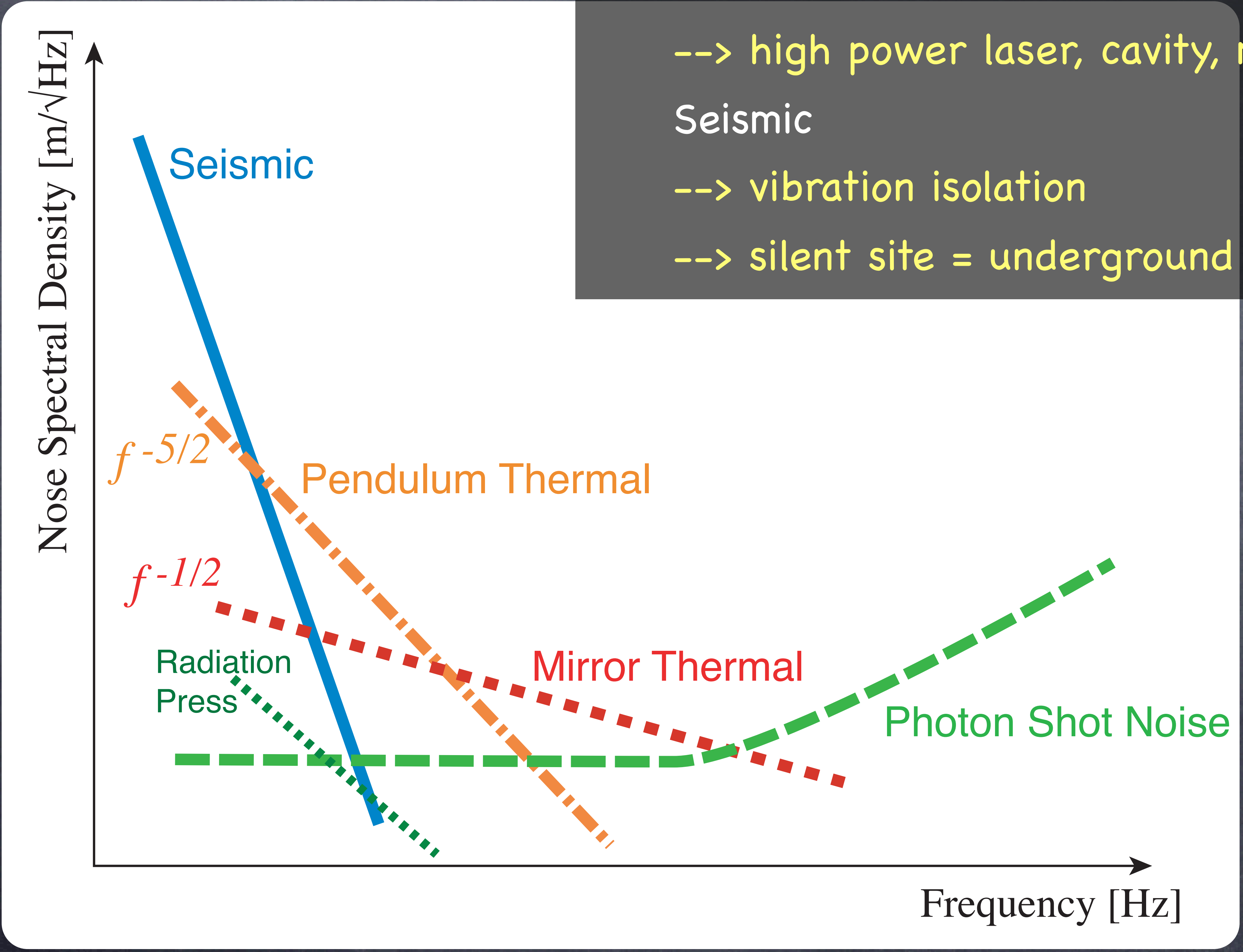
Photon Shot Noise & Radiation Pressure Noise

--> high power laser, cavity, massive mirror

Seismic

--> vibration isolation

--> silent site = underground

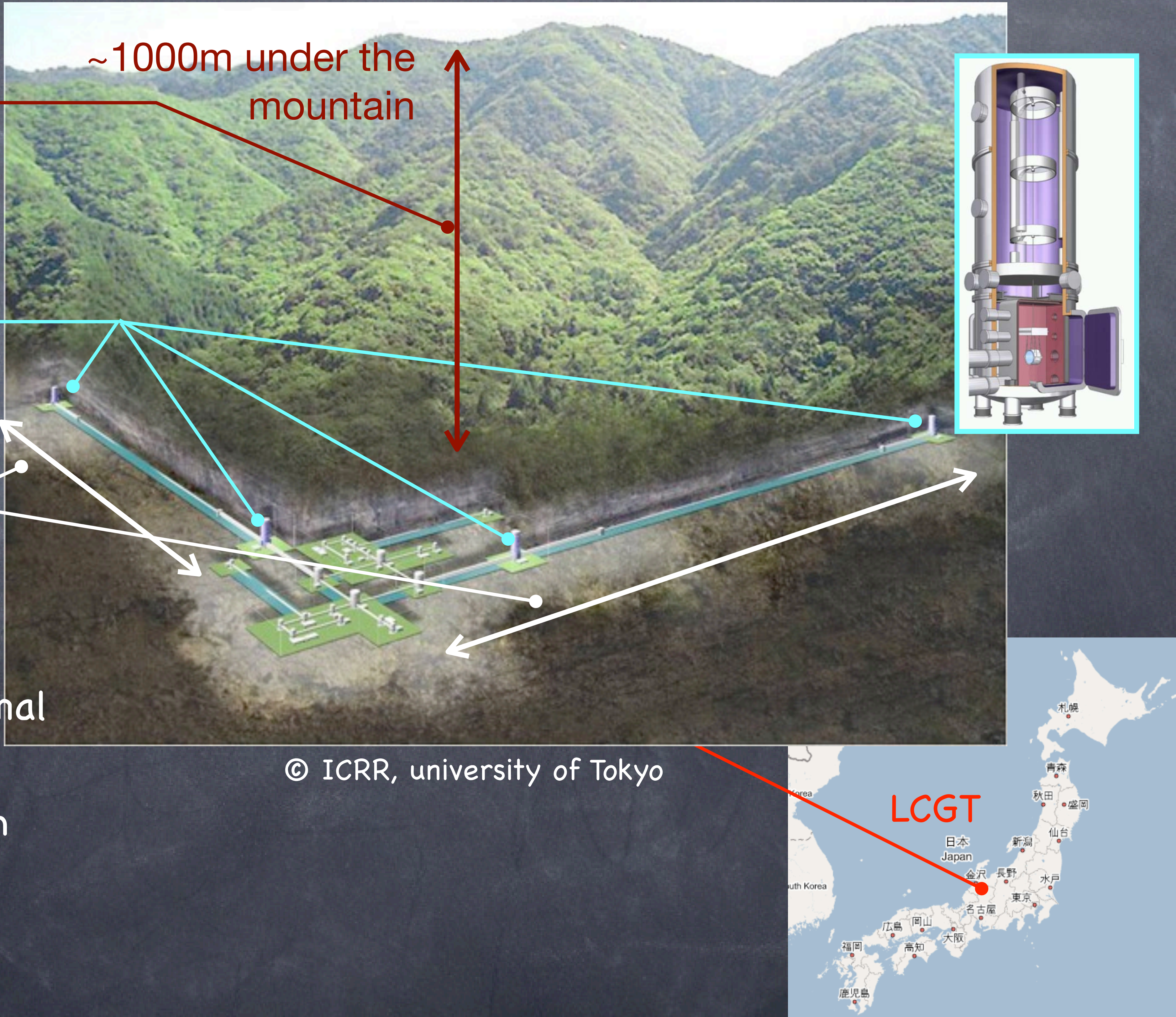


- Status of LCGT -

Large-scale Cryogenic Gravitational wave Telescope

LCGT (Large-scale Cryogenic Gravitational wave Telescope)

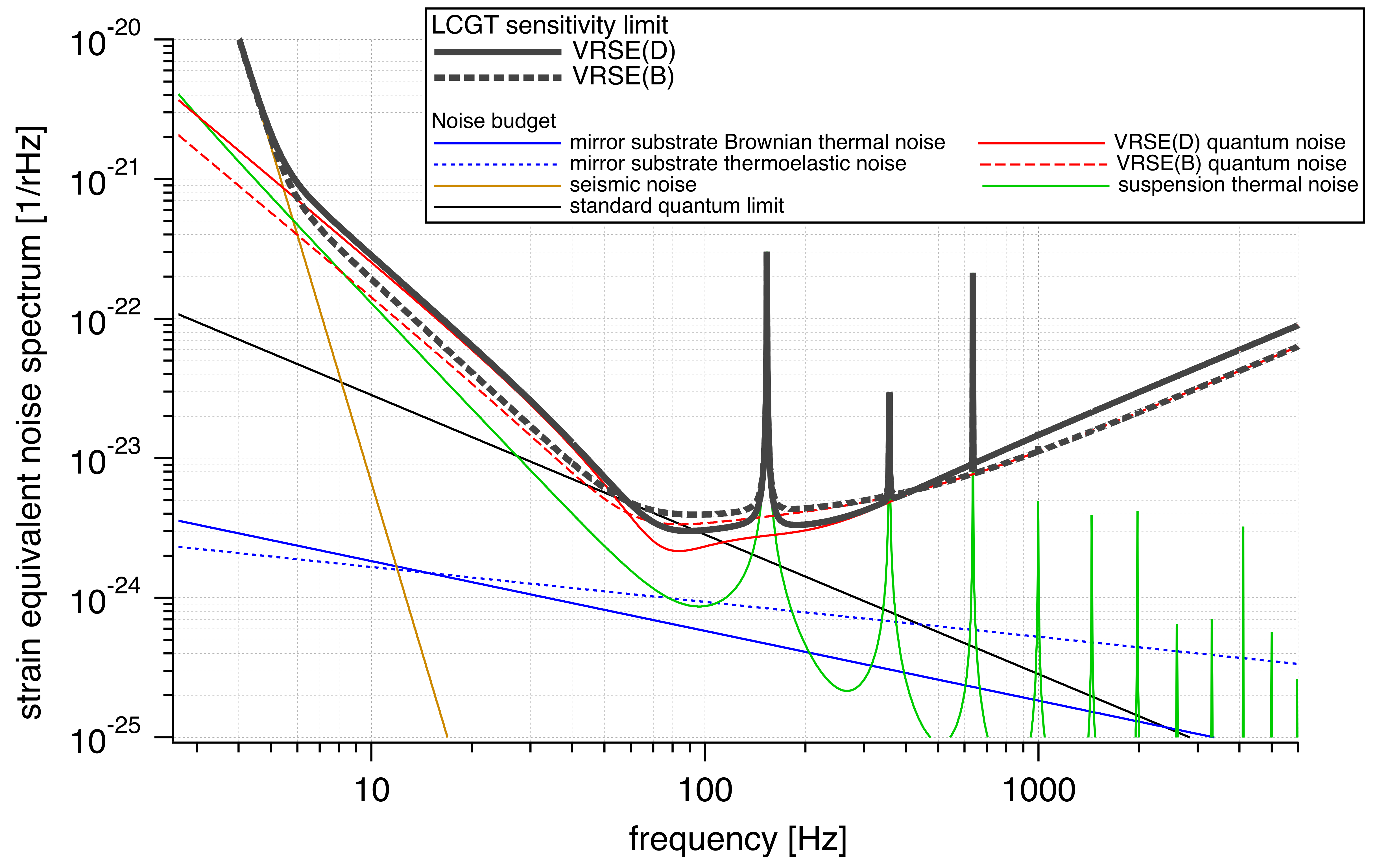
- **Underground**
  - in Kamioka, Japan
  - Silent & Stable environment
- **Cryogenic Mirror**
  - 20K
  - sapphire substrate
- **3km baseline**
- **Plan**
  - 2010 : construction started
  - 2014 : first run in normal temperature
  - 2017- : observation with cryogenic mirror



© ICRR, university of Tokyo

Sensitivity Limit of LCGT

h ~ factor x 10^{-24} [/√Hz]
for observation band

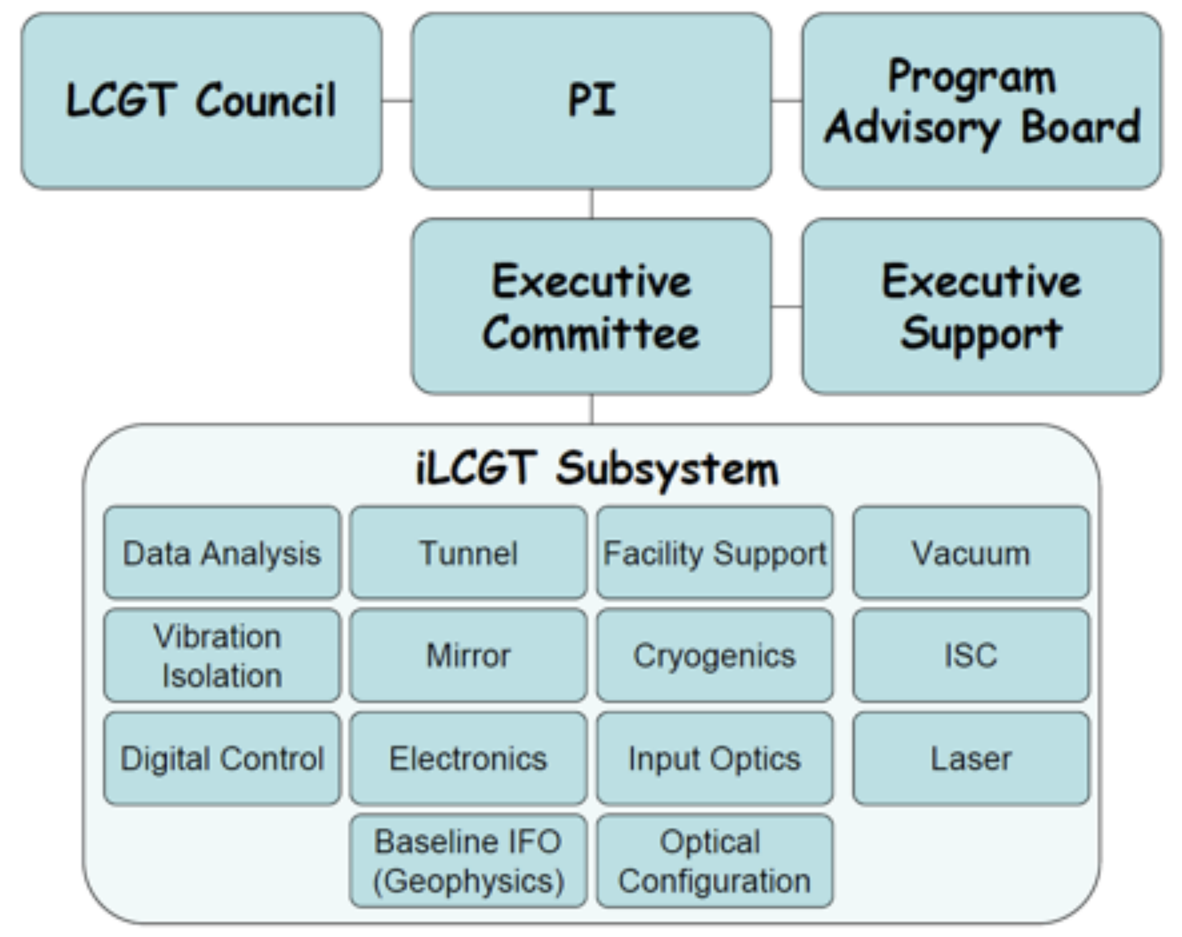


LCGT Collaboration

- Total 124 Collaborators
- (including 25 overseas members)
- 23 Japanese organizations of universities and/or research laboratories
- +
- 15 organizations abroad

(May 2011)

New members are welcome!


LCGT Council

PI

Program Advisory Board

Executive Committee

Executive Support

iLCGT Subsystem

Data Analysis	Tunnel	Facility Support	Vacuum
Vibration Isolation	Mirror	Cryogenics	ISC
Digital Control	Electronics	Input Optics	Laser
	Baseline IFO (Geophysics)	Optical Configuration	


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]

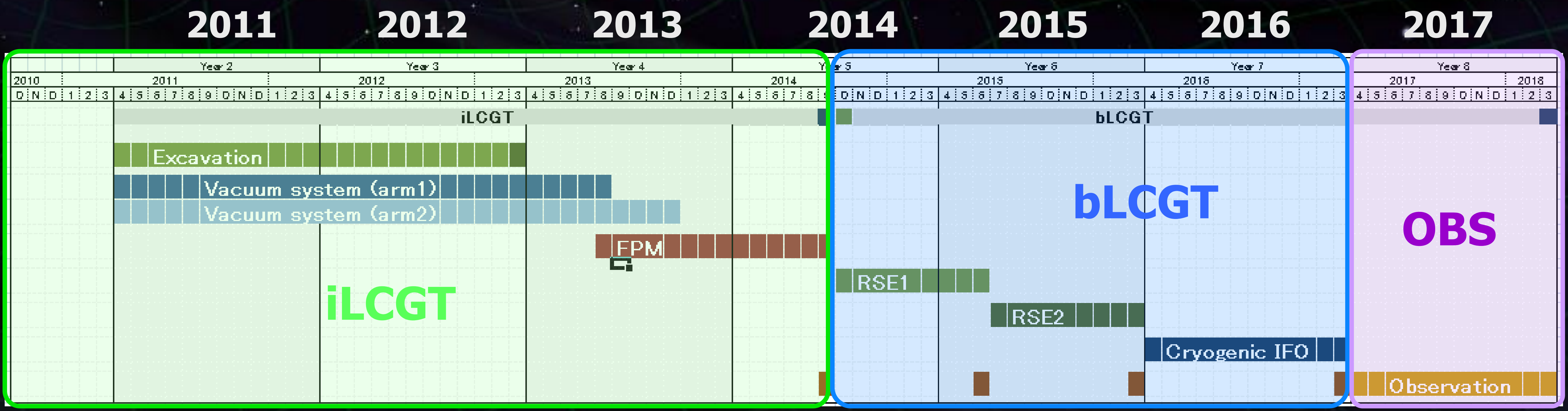
Master Schedule

- **iLCGT** : Stable operation with a large-scale IFO (2010.10 - 2014.9)

  → 3km FPM interferometer at room temperature,
  with simplified vibration isolation system
  ~1 month (TBD) observation run
- **bLCGT** : Operation with the final configuration (2014.10 – 2017.3)

  → RSE, upgraded seismic isolator, cryogenic operation
- **OBS** : Long-term observation and detector tuning (2017.4 -)

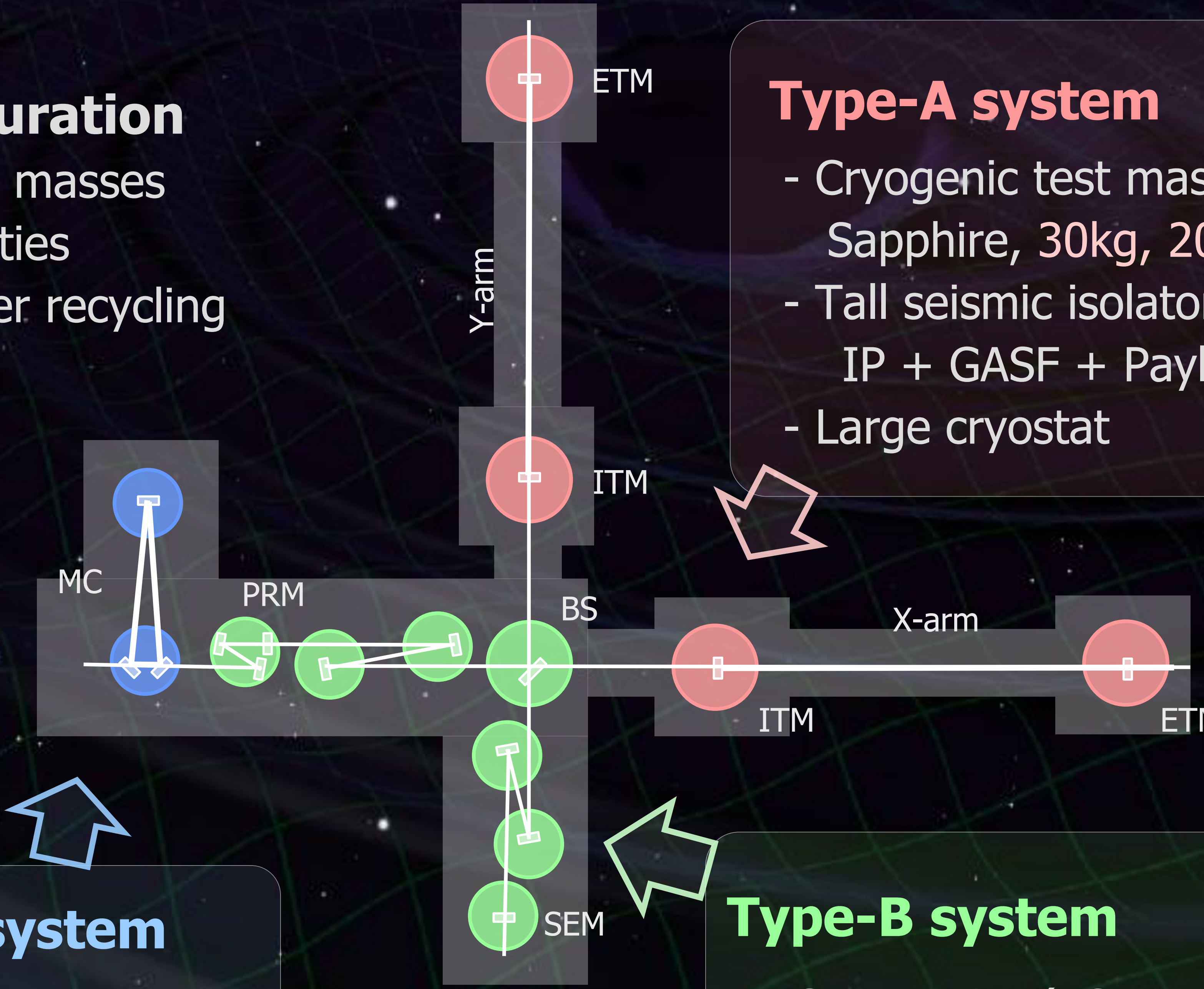
Delay in excavation start → schedule should be updated

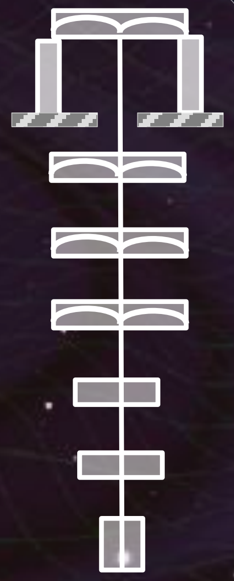


bLCGT configuration

bLCGT configuration

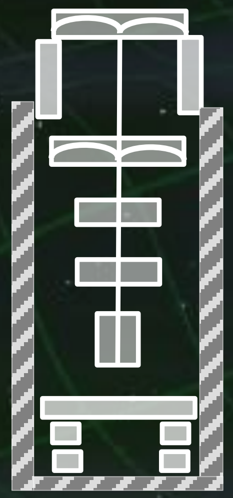
- Cryogenic test masses
- 3 km arm cavities
- RSE with power recycling





Type-A system

- Cryogenic test mass
  Sapphire, 30kg, 20K
- Tall seismic isolator
  IP + GASF + Payload
- Large cryostat



Type-B system

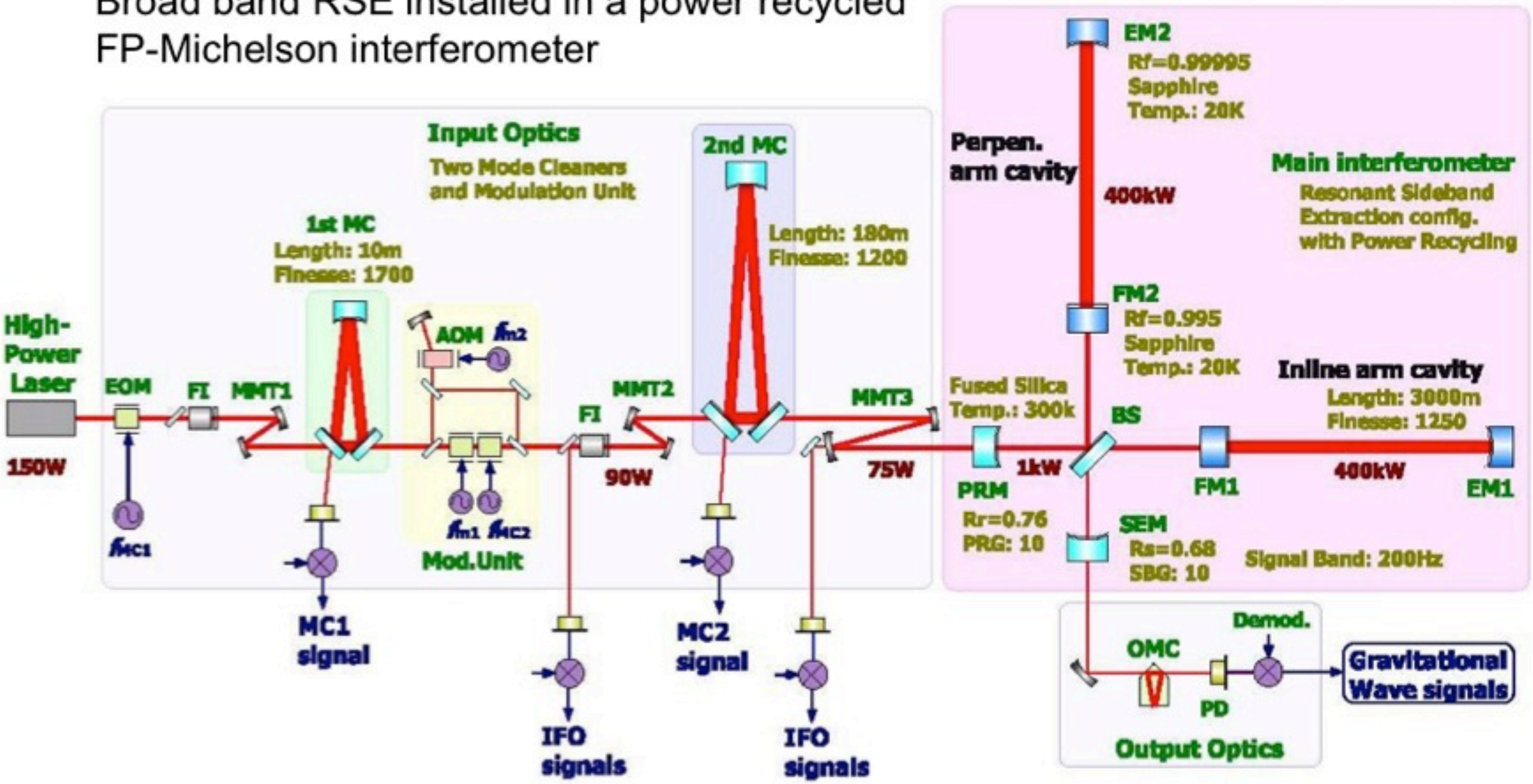
- Core optics (BS, RM ,...)
  Silica, 10kg, 290K
- IP + GASF + Payload
- Stack for aux. optics

Type-C system

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

Optical design

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

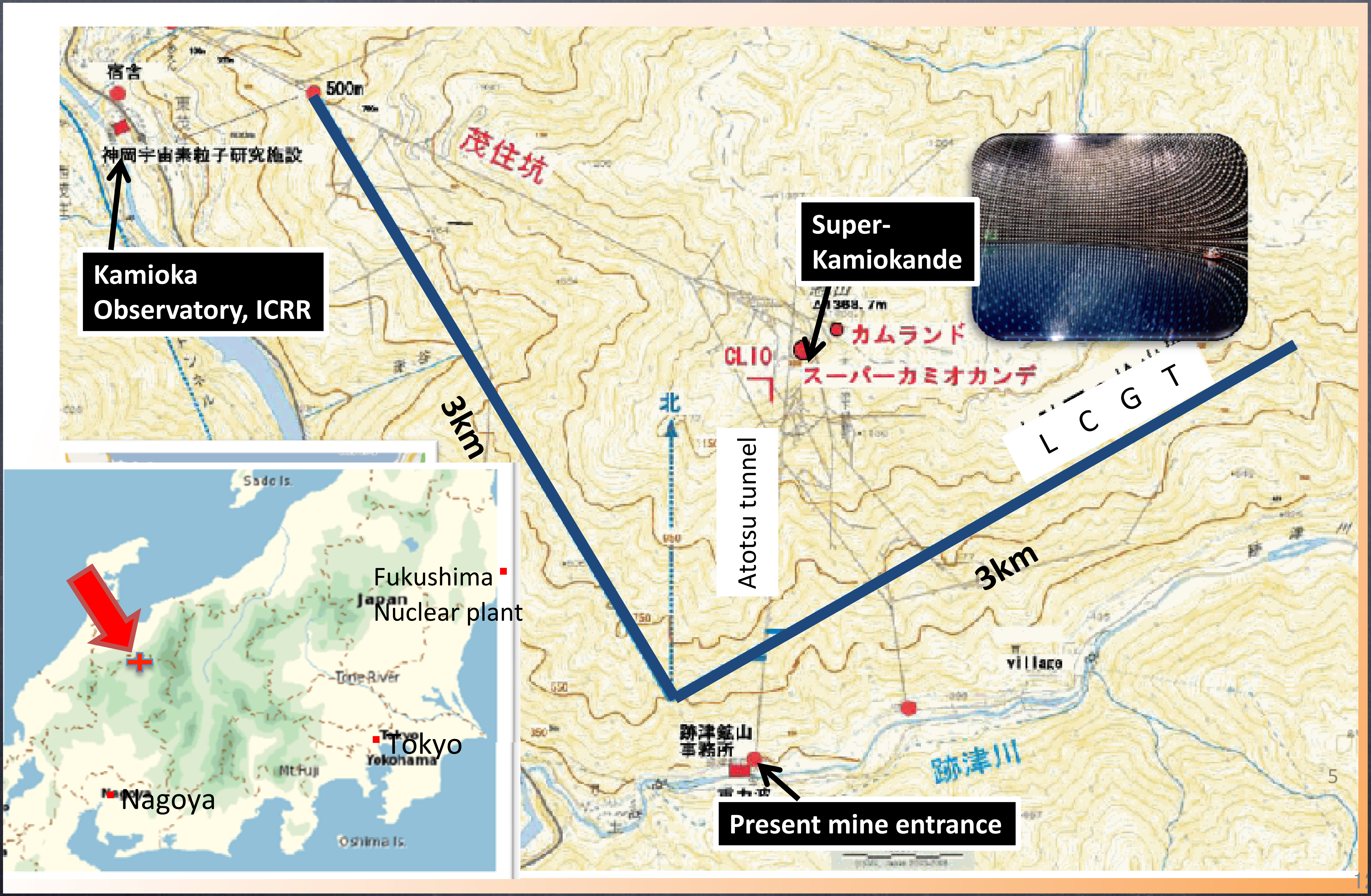


Re-design is under going ;for example

---removing the 180 m long mode cleaner cavity

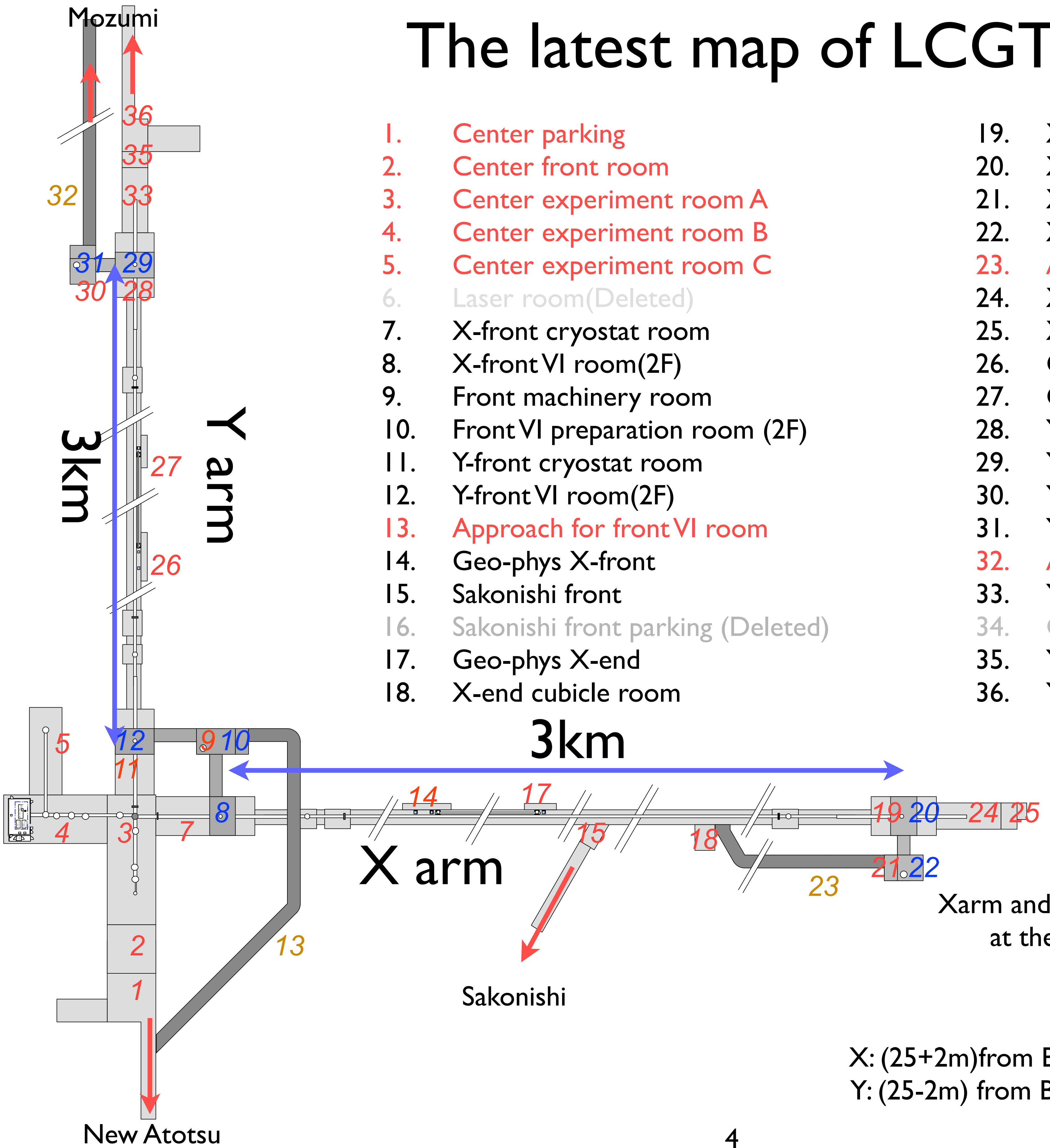
---flexibility change of possible adoption of detuned RSE

Site


宿舎
500m
神岡宇宙素粒子研究施設
茂住坑
Kamioka Observatory, ICRR
Super-Kamiokande
カムランド
CLIO
スーパーカミオカンデ
北
3km
Atotsu tunnel
L C G T
3km
village
跡津鉱山事務所
跡津川
Present mine entrance
Sado Is.
Fukushima Nuclear plant
Japan
Tone River
Tokyo
Yokohama
Mt.Fuji
Nagoya
Oshima Is.
5

Tunnel

The latest 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 (Deleted)
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 (Deleted)
35. Y-end staff room
36. Y-end parking

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

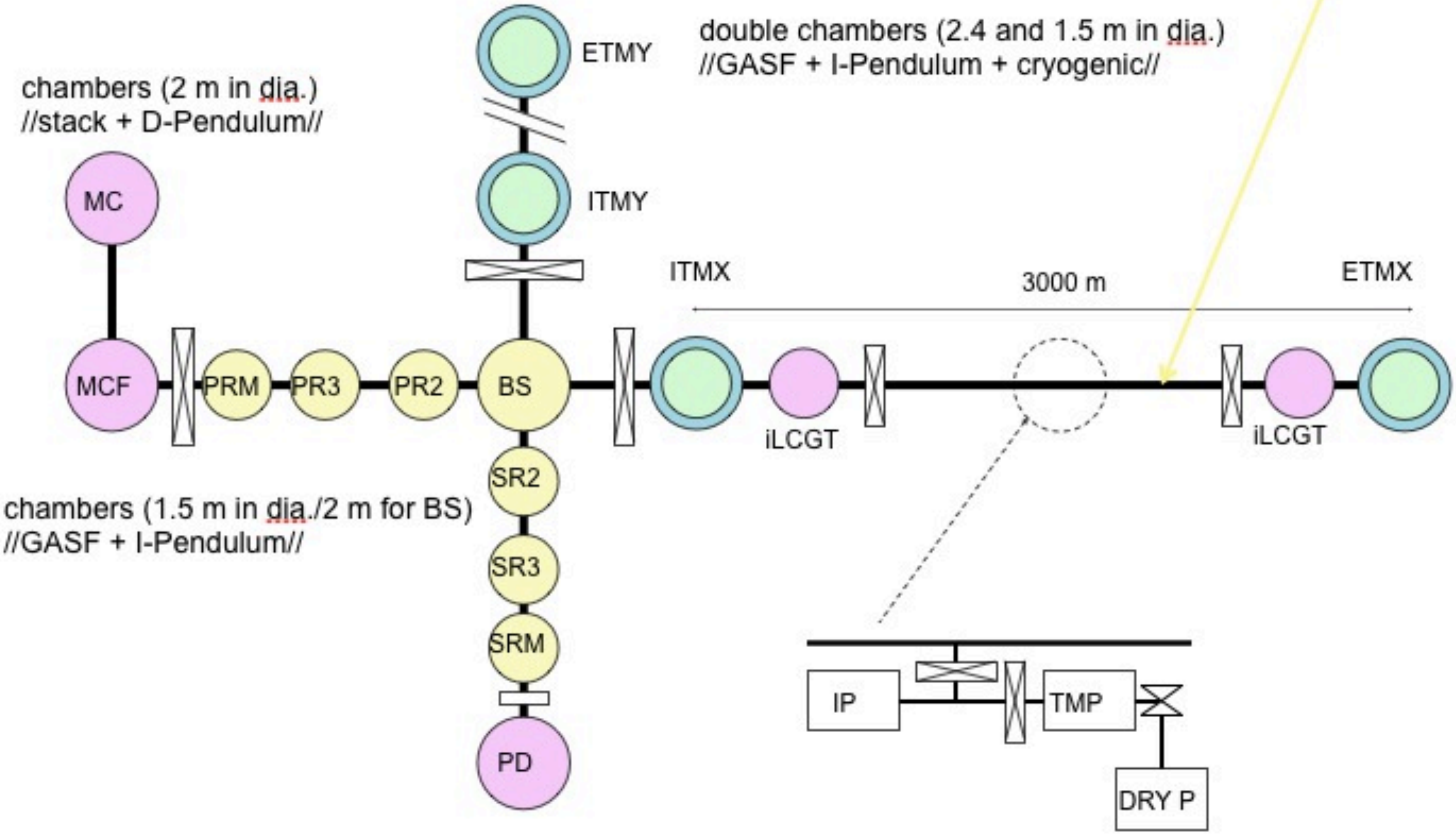
3km:

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

110804 VAC (YS)

LCGT Vacuum System

○ a unit tube (12 m long and 0.8 m in diameter);
production of the first lot (120 of 500 tubes) was started in this July.



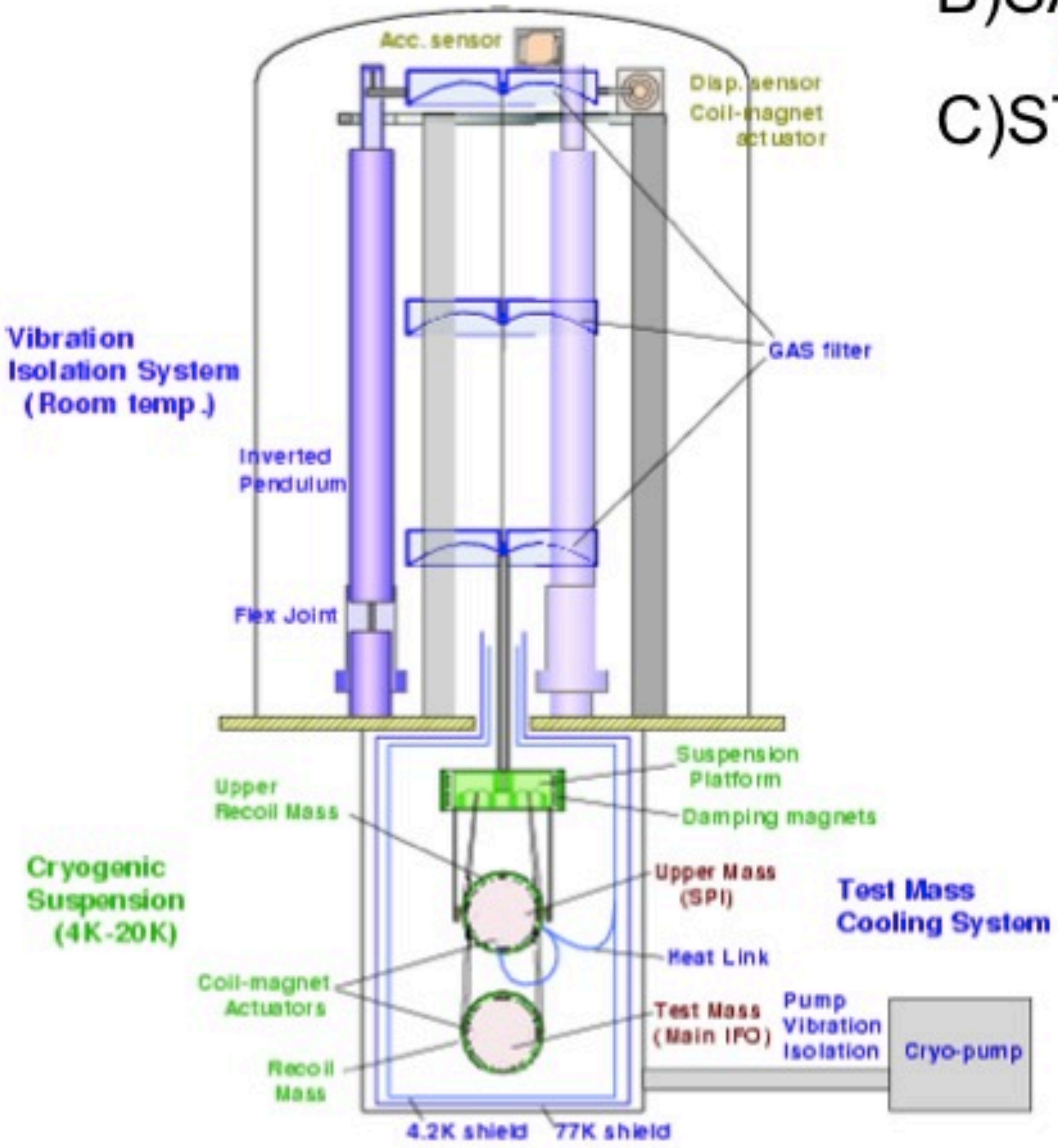
chambers (2 m in dia.)
//stack + D-Pendulum//

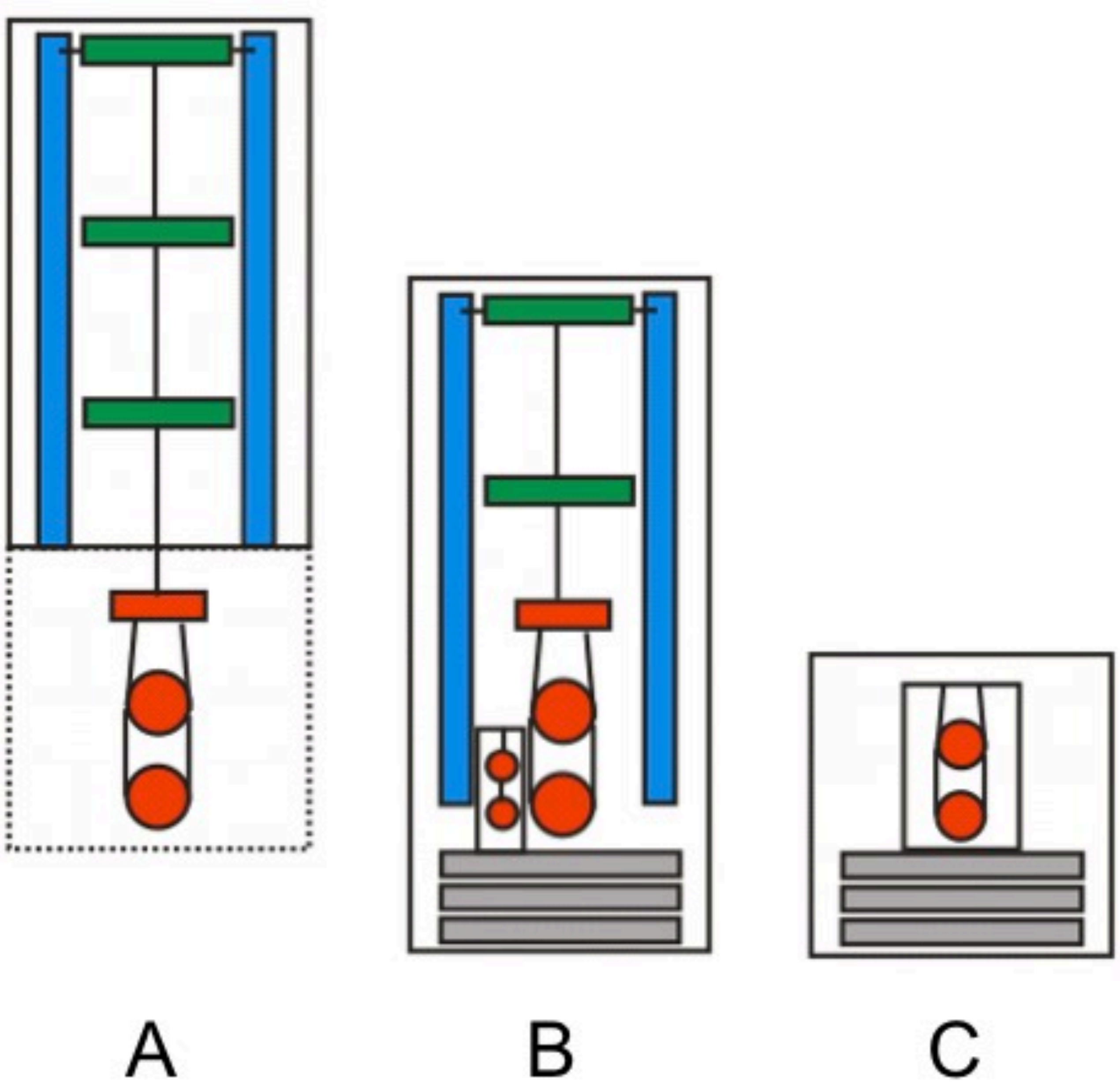
double chambers (2.4 and 1.5 m in dia.)
//GASF + I-Pendulum + cryogenic//

chambers (1.5 m in dia./2 m for BS)
//GASF + I-Pendulum//

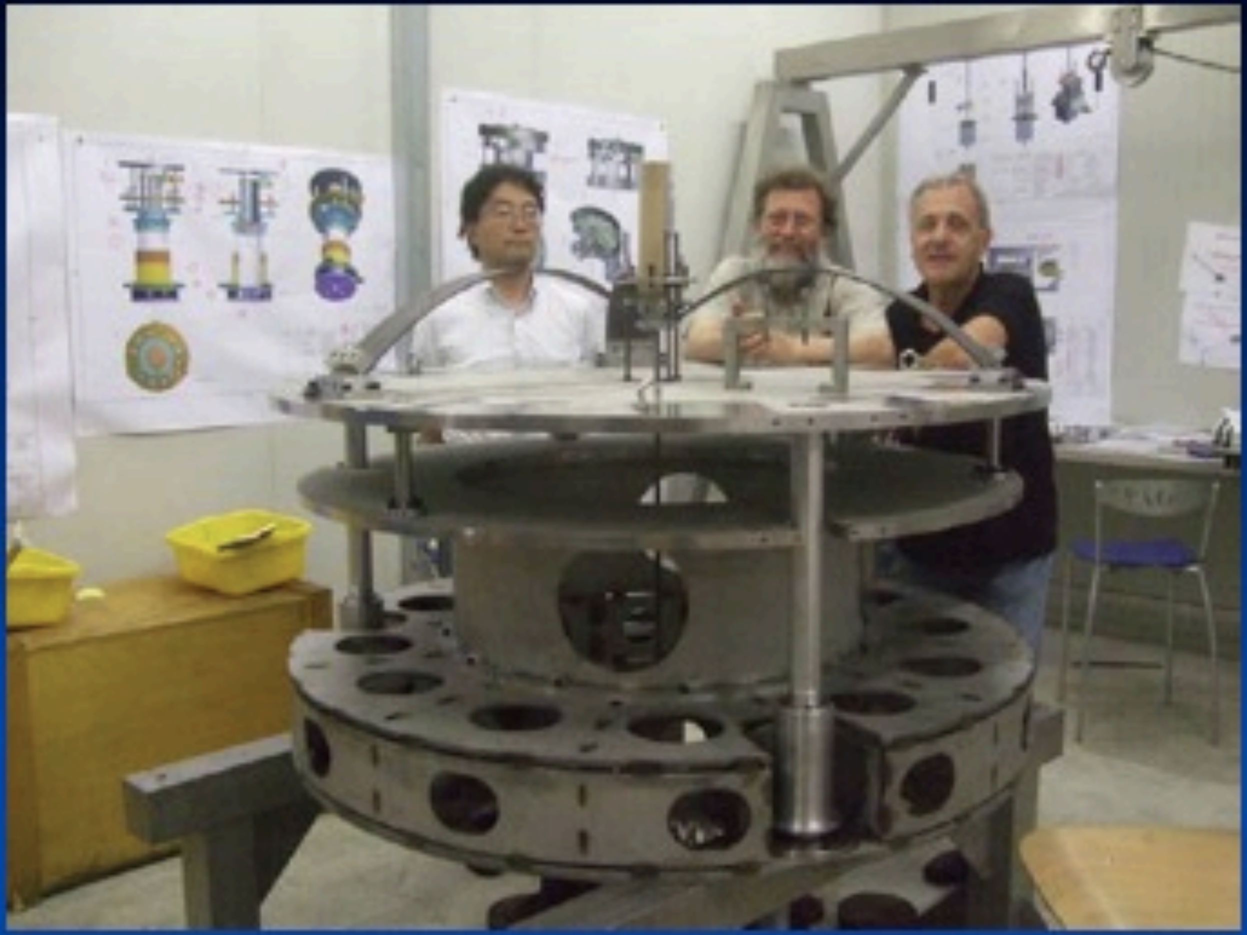
Suspension and Anti-Vibration System

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





Test and Manufacturing



Standard GAS filter

Prototype test: 2011.2- (@NIKHEF)

19 units order: 2011FY

Pre-isolator

Prototype test: 2011.8- (@ICRR)

11 units order: 2012FY

Type-B payload

Prototype test: 2011.8- (@NAOJ)

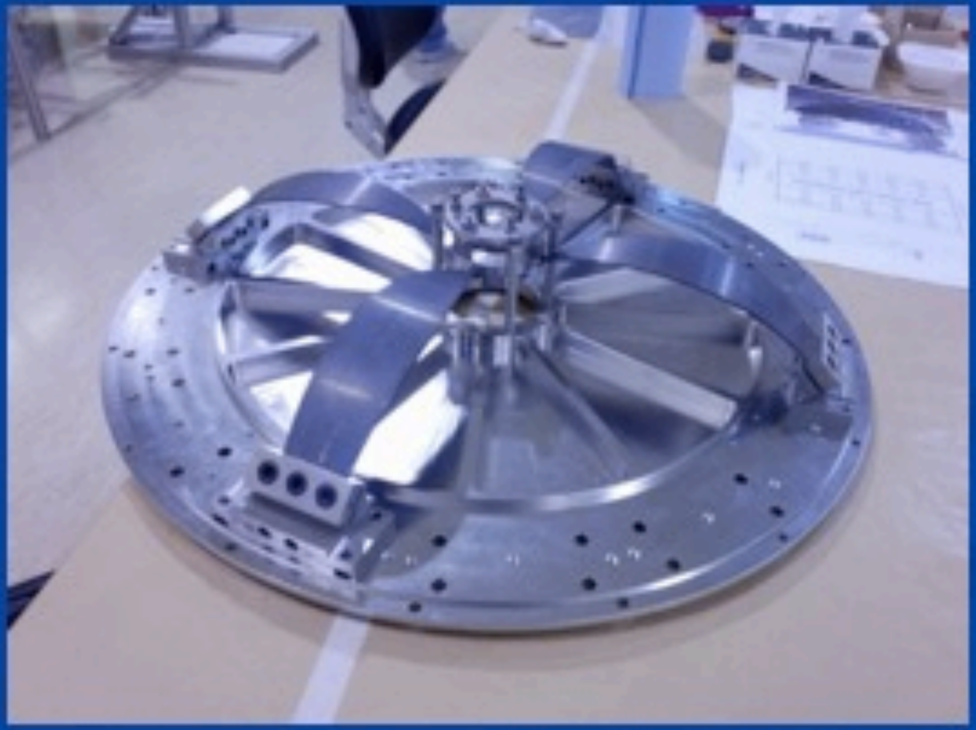
11 units order: 2012FY

Type-B full-system

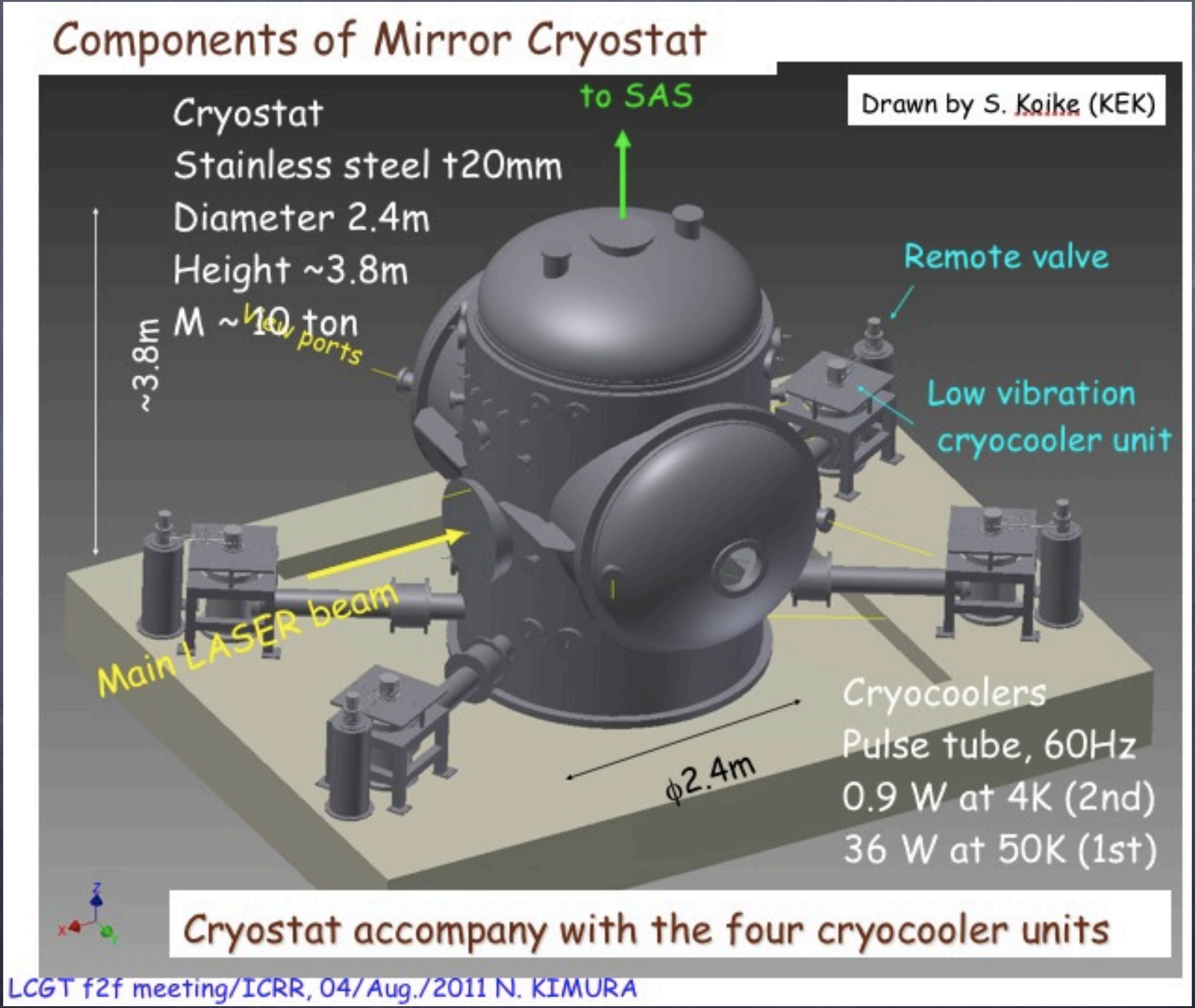
Test in TAMA: 2012FY

Stack

15 units order: 2011FY



Cryostat



Components of Mirror Cryostat

Drawn by S. Koike (KEK)

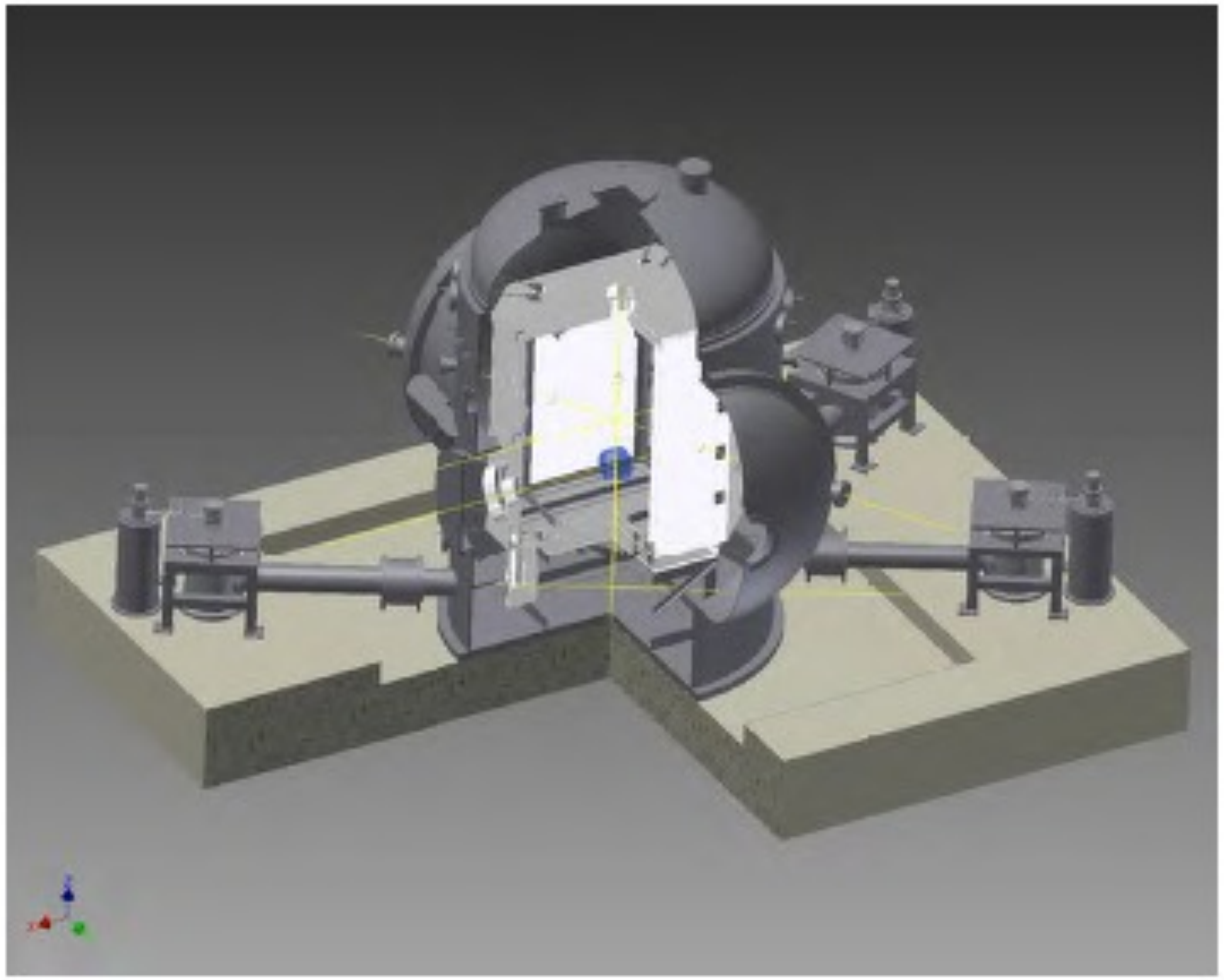
Cryostat
Stainless steel t20mm
Diameter 2.4m
Height ~3.8m
M ~10 ton

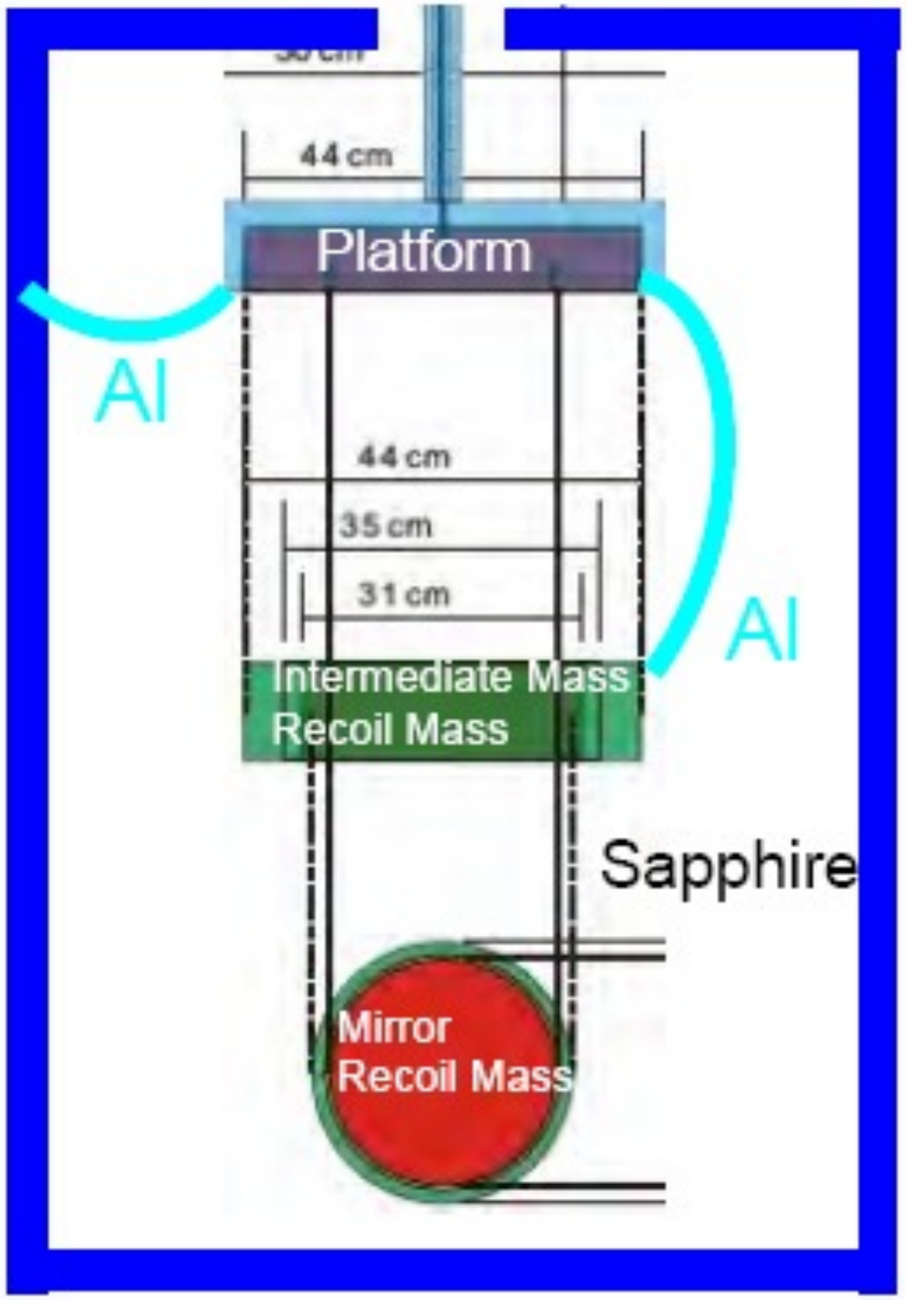
Cryocoolers
Pulse tube, 60Hz
0.9 W at 4K (2nd)
36 W at 50K (1st)

Cryostat accompany with the four cryocooler units

LCGT f2f meeting/ICRR, 04/Aug./2011 N. KIMURA

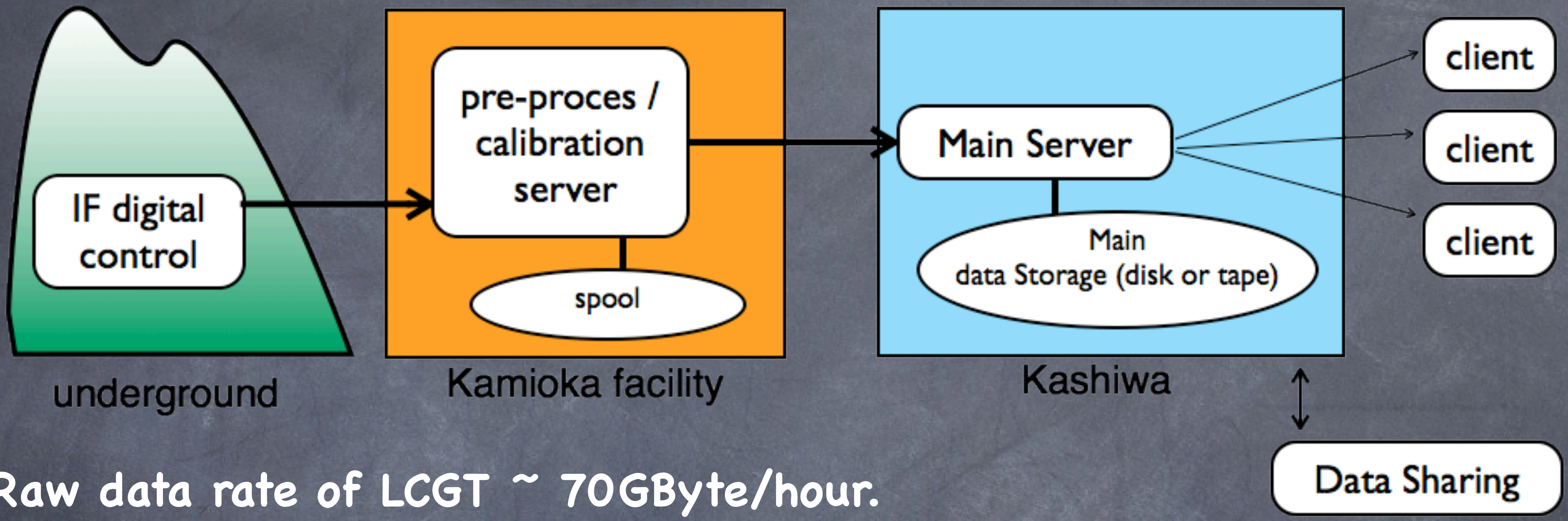
Cooling of payload





Double radiation shield
Low vib. PTC units
Pure Al heat path

Data Storage and Analysis



- **Raw data rate of LCGT ~ 70GByte/hour.**

  The spool storage at Kamioka > 500TByte

- **storage of raw and calibrated data**

  Main data storage at Kashiwa ICRR site.

  ~30PByte for five years observation

  For LCGT data only, it is roughly 1PByte/year.

- **International data sharing**

  5sites (= LCGT + LIGO*2 +Virog +LIGOaustralia) will reach to 5PB/year.

- **Big computing (calculation) power is needed.**

Science Target of LCGT

In general, direct measurement of GW aims :

- **1. Fundamental Physics**

  TEST of Einstein's general relativity in **strong field**.

- **2. Astronomy, Astrophysics**

  Radiation from compact / massive objects.

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

  Gravitational Wave Astronomy

- **3. Cosmology**

  Cosmic background radiation of GW

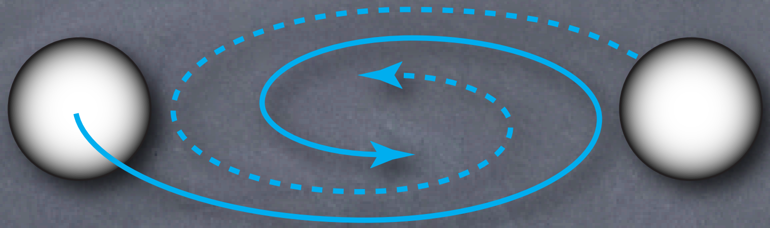
  POP-III stars, star formation, etc...

  Physics on early universe.

LCGT's targets are 1 & 2 mainly .

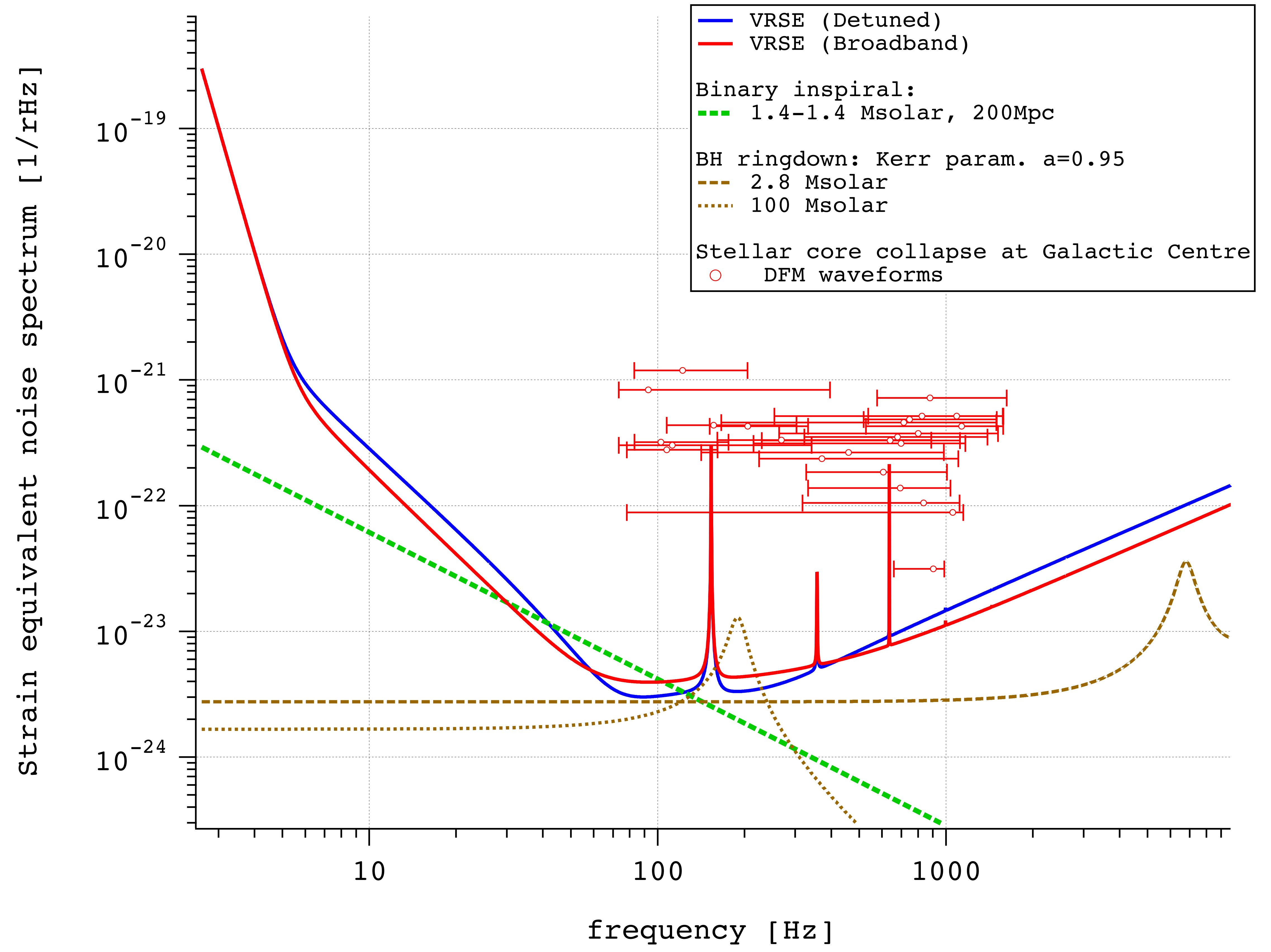
Remind : GW sources that possible to be detected by LCGT

- **Event like:**
  - Compact Binary Coalescence
    - neutron star (NS)
    - black-hole (BH)
  - Supernovae
  - BH ringdown

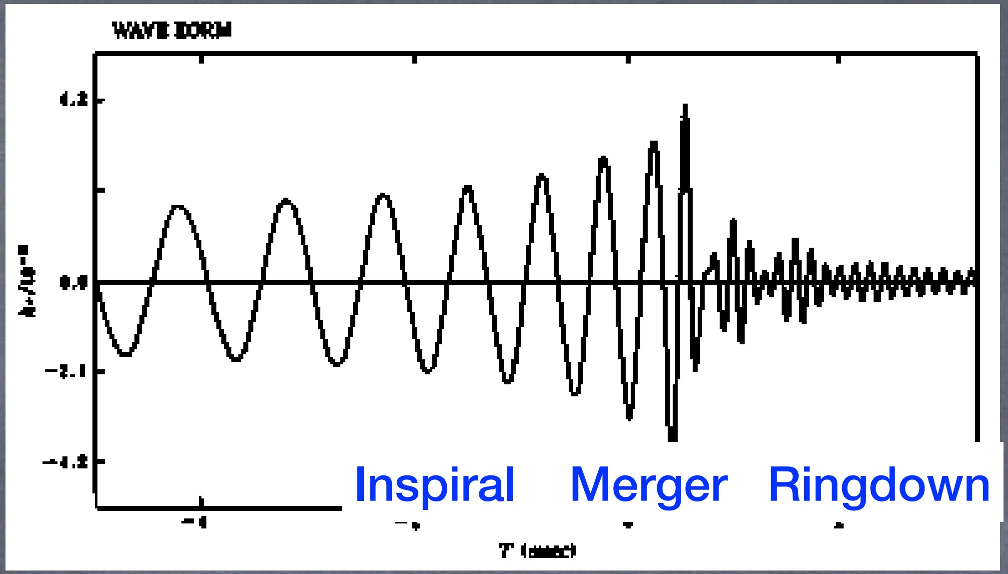


- **Continuous waves:**
  - Pulsar rotation
  - Binaries
- **Stochastic Background**
  - Cosmic string
  - Astronomical origin (i.e. many NS in galaxy cluster)
- **(& Unknown sources...)**

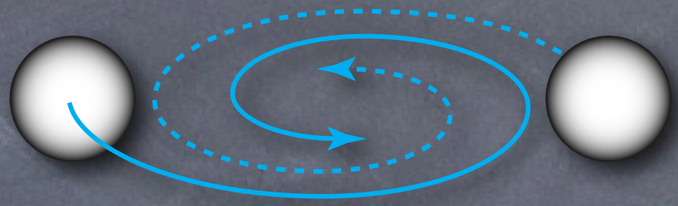
Design Sensitivity of LCGT with GW



CBC (Compact Binary Coalescence)



NS-NS, NS-BH, BH-BH



A few number PSR binaries are found.

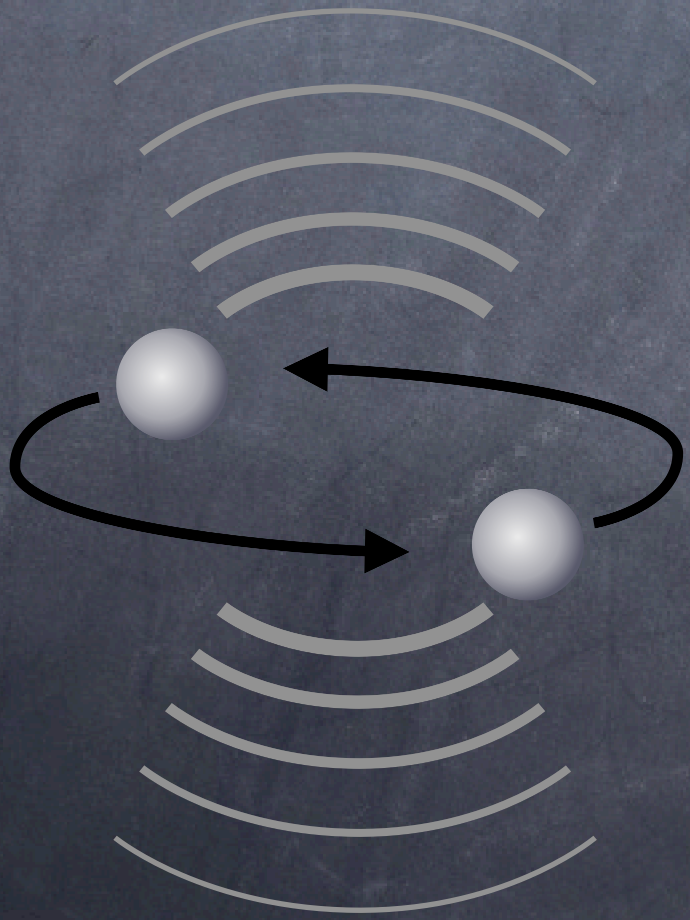
PSR name	P_s (ms)	P_b (hr)	e	$\tau_{\rm life}$ (Gyr)
B1913+16[a]	59.03	7.75	0.617	0.37
B1534+12[a]	37.90	10.10	0.274	2.93
J0737-3039A[a]	22.70	2.45	0.088	0.23
J1756-2251[a]	28.46	7.67	0.181	2.03
J1906+0746[b]	144.14	3.98	0.085	0.082
J2127+11C[bcd]	32.76	8.047	0.681	0.32

Proof of GW (indirect)

- **Binary Pulsar PSR1913+16 observation (Hulse & Taylor)**

  Pulsar is very stable clock.

  Change of orbital period according to a lost of kinetic energy by GW radiation.



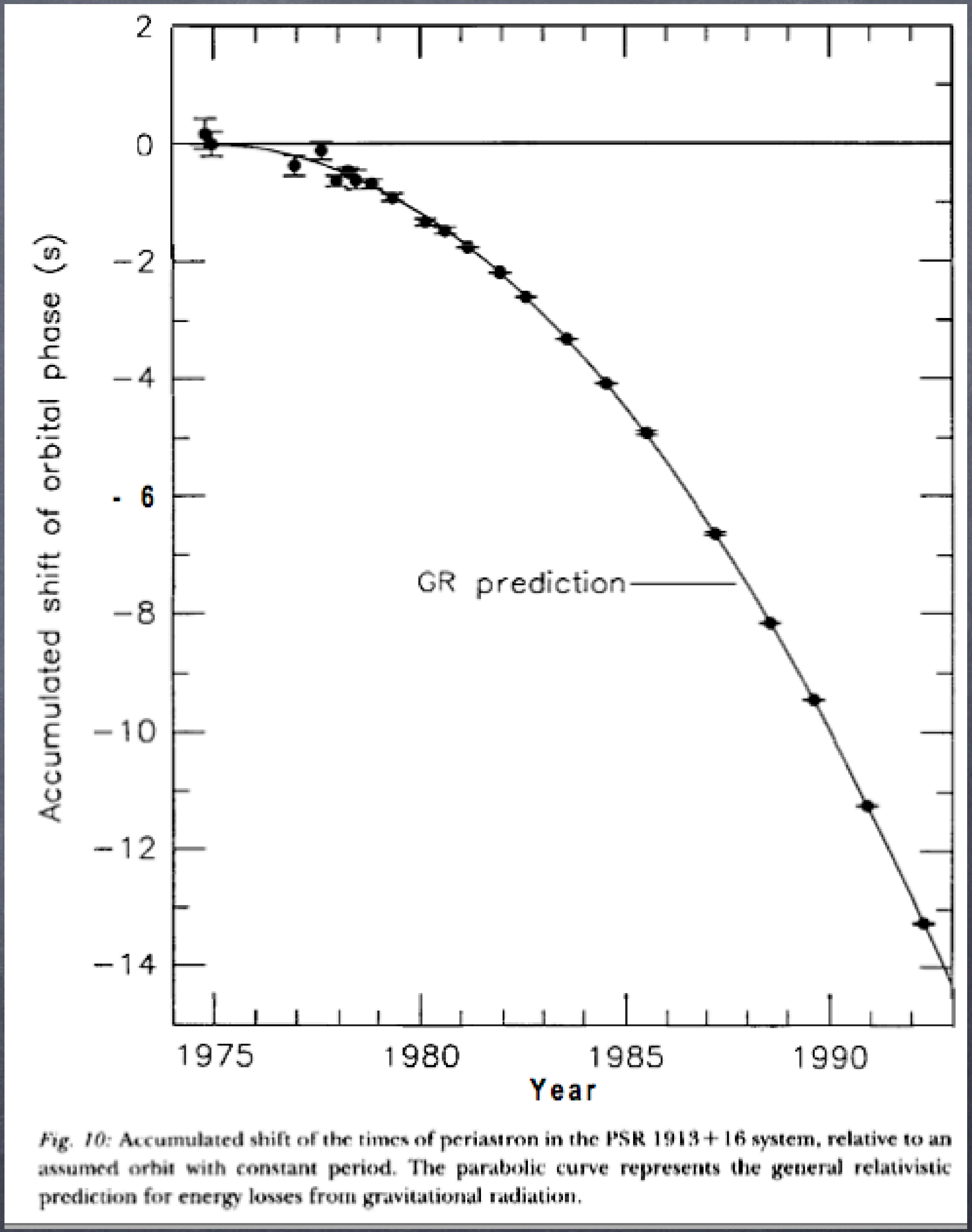
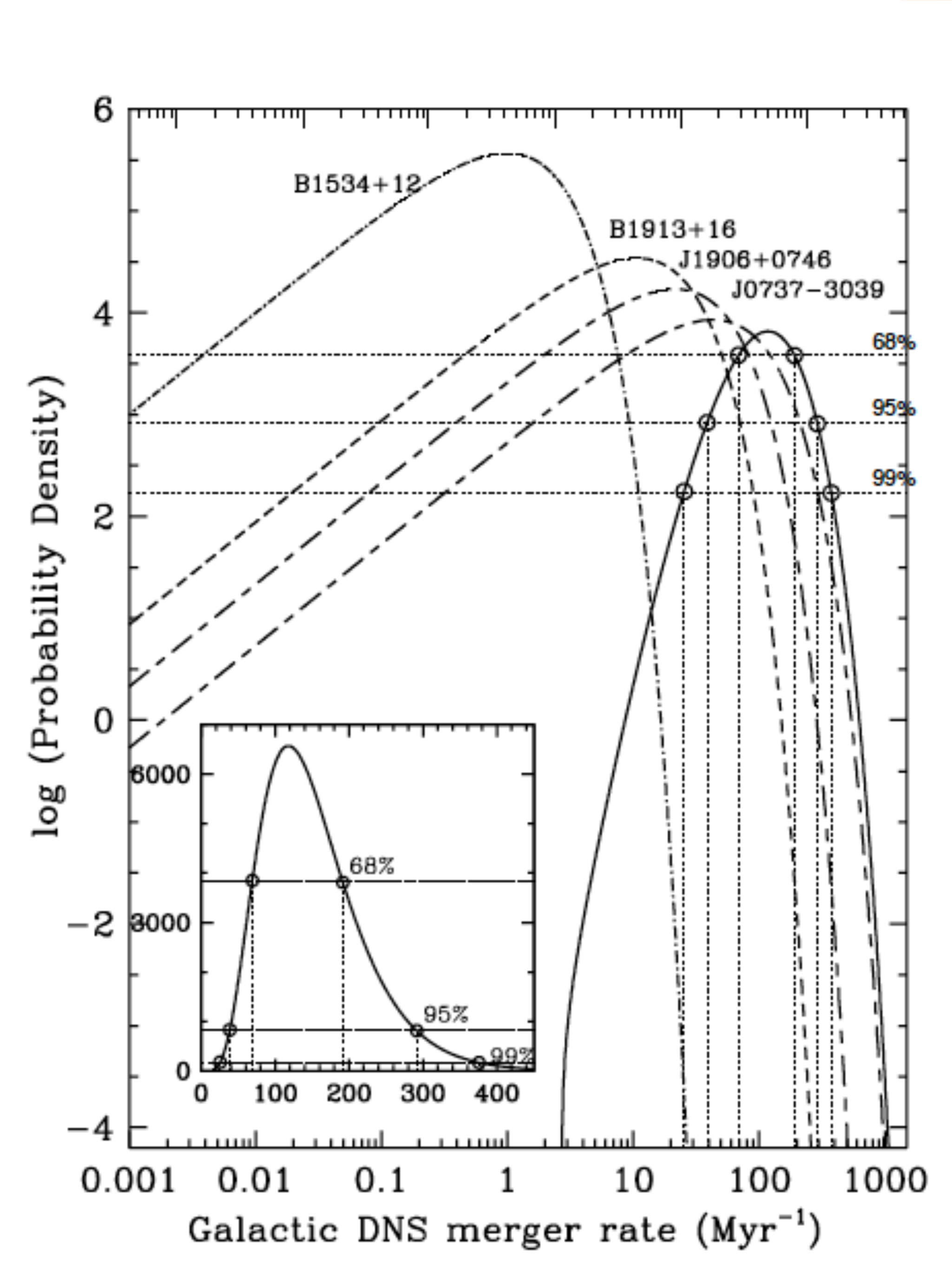


Fig. 10: Accumulated shift of the times of periastron in the PSR 1913+16 system, relative to an assumed orbit with constant period. The parabolic curve represents the general relativistic prediction for energy losses from gravitational radiation.

Taylor, 1993
(ノーベル賞講演より抜粋)

NS-NS merger rate



(Kim ('08), Lorimer ('08))

Galactic merger rate $118^{+174}_{-79}\,\mathrm{Myr}^{-1}$

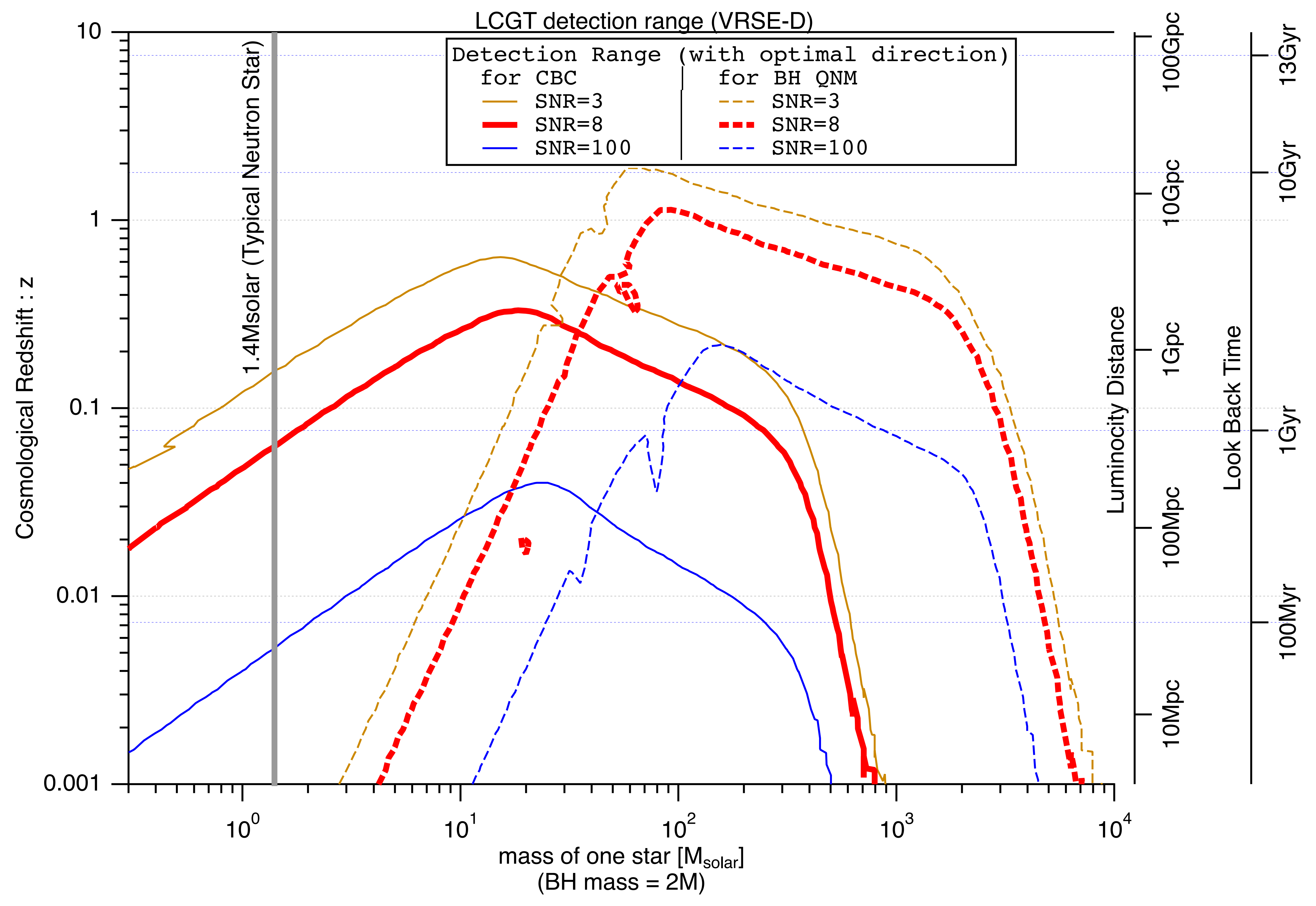
Current standard LCGT design (VRSE-D)
gives horizon distance (@ρ=8)
= 282Mpc (z=0.065)

Event rate for LCGT : $9.8^{+14}_{-6.6}\,\mathrm{yr}^{-1}$

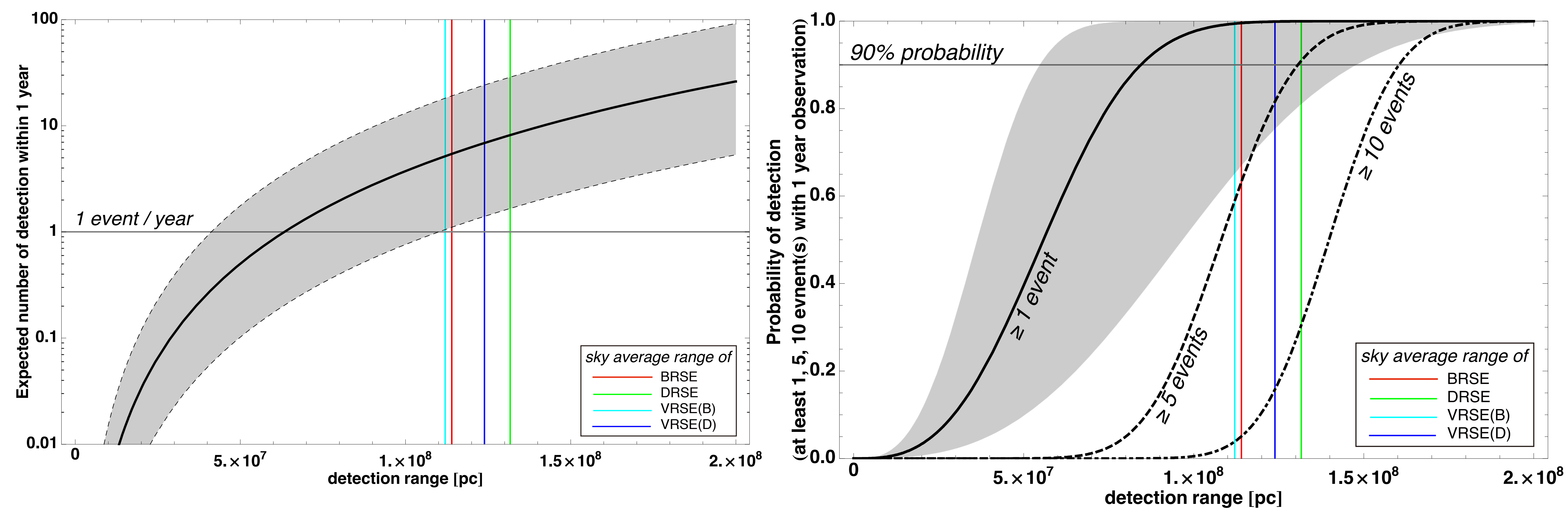
However, systematic errors which are not included in this evaluation will be large.

See also Abadie et al. CQG27, 173001(2010)

Detection Range for Compact Binary (and Blackhole QNM)

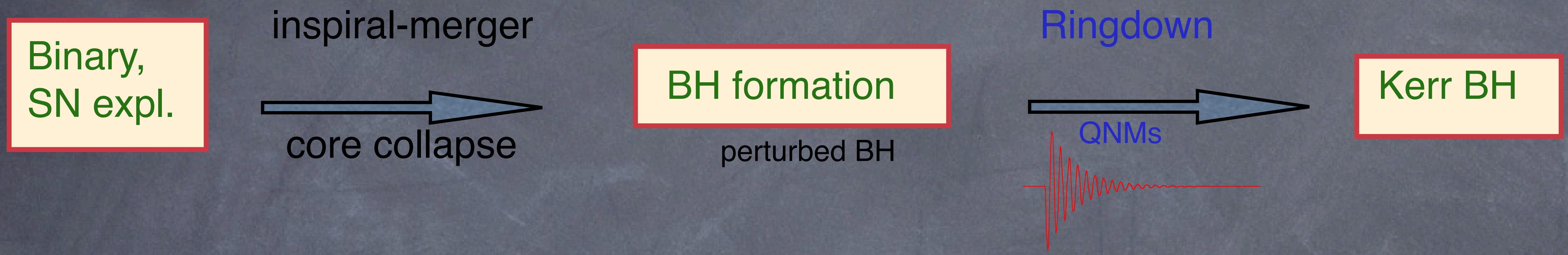


Probability of Detection (NS-NS)



NS-NS Detection Range (sky average)	123 Mpc	
(optimal direction)	**281 Mpc**	
Expected # of events	6.9 $^{+17.3}_{-5.5}$ events/year	(9.8 $^{+14}_{-6.6}$ ev./yr)
Probability of detection at least one event	99.9 % for one year	
90% for 1st event	4 months	
(Galactic Merger Rate)	83 $^{+209}_{-66}$ ev./Myr	(118 $^{+174}_{-79}$ ev./Myr)

Ringdown GW from Blackhole Quasi-Normal Mode



Binary, SN expl.

inspiral-merger

core collapse

BH formation

perturbed BH

Ringdown

QNMs

Kerr BH

Waveform: Damped sinusoid (Quasi-normal modes)

$$h(t) = \exp(-\pi f_c t/Q)\sin(2\pi f_c t)$$

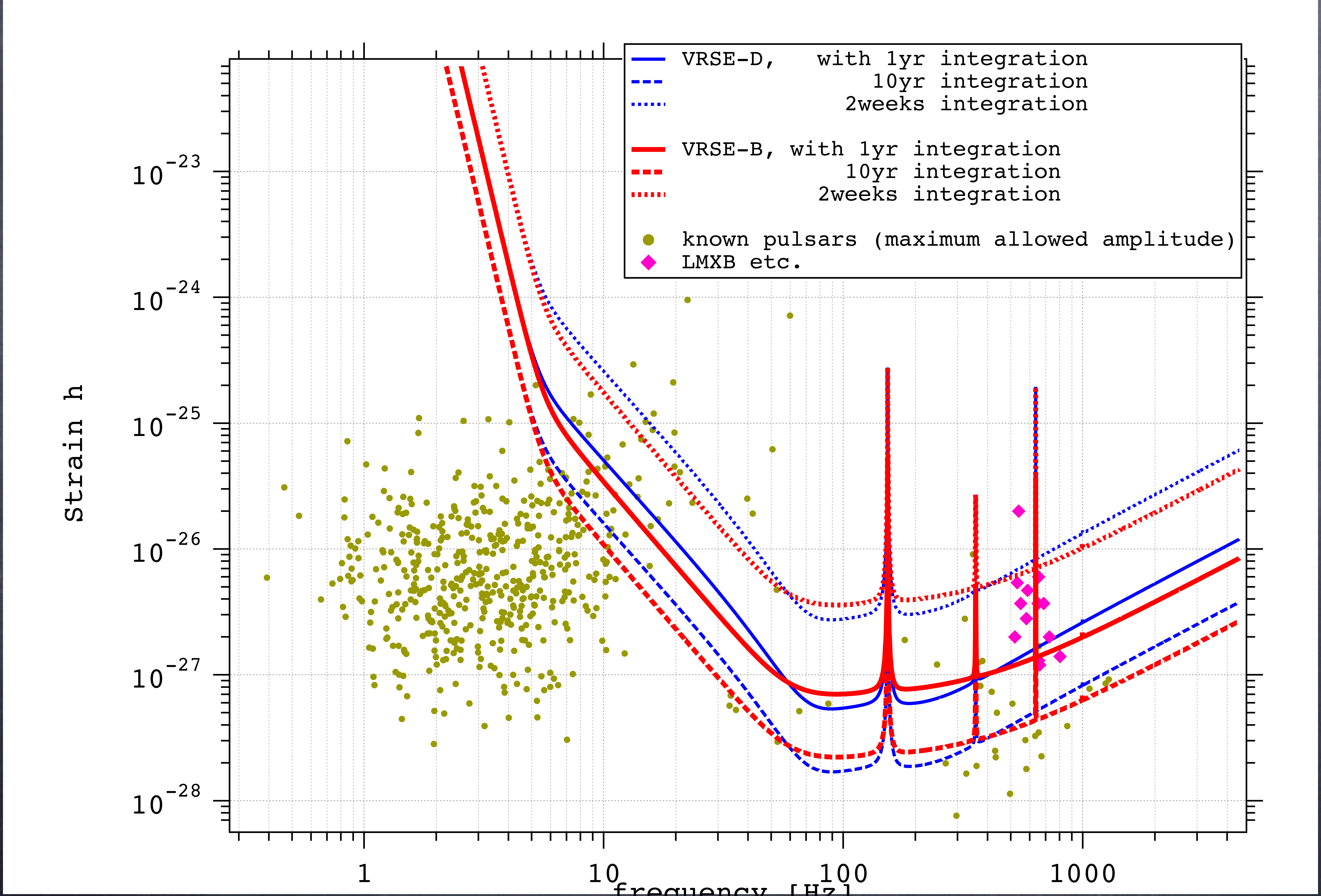
central frequency $$f_c = \frac{3.2\times 10^4[\mathrm{Hz}]}{M/M_\odot}\left[1-(1-a)^{0.3}\right]$$ Echeverria (1989)

Quality factor $$Q = 2.0(1-a)^{-0.45}$$

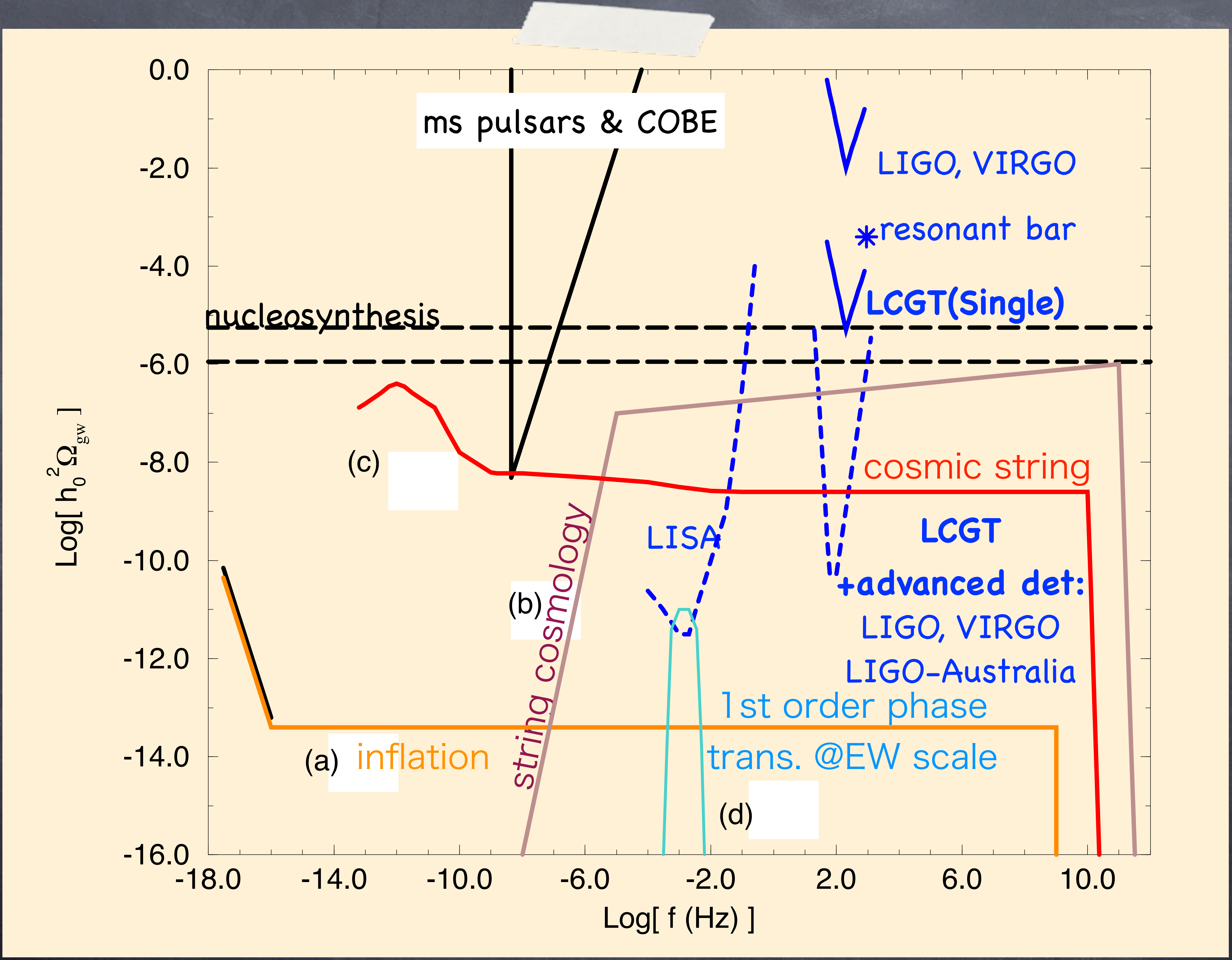
M: Mass
a: Spin

* Probe for BH direct observation
* BH physics in inspiral-merger, core collapses, ...
* Good SNR expected

Sensitivity for Continuous GW



Stochastic GW



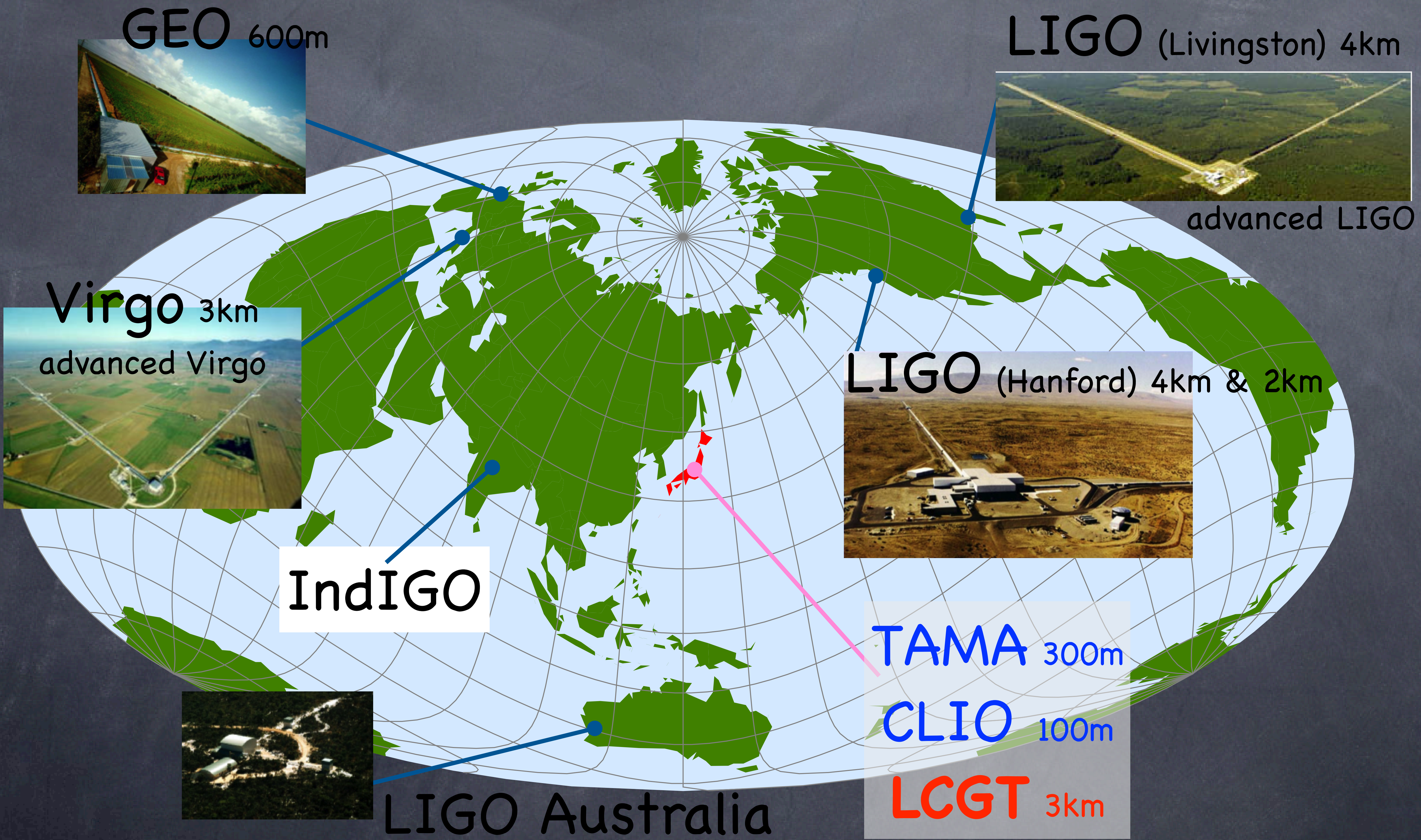
modify the figure of M.Maggiore, gr-qc/0008027

- Prospects of GW detectors -

Gravitational Waves

How to detect

Ground-based GW Detectors



GEO 600m

LIGO (Livingston) 4km

advanced LIGO

Virgo 3km

advanced Virgo

LIGO (Hanford) 4km & 2km

IndIGO

TAMA 300m

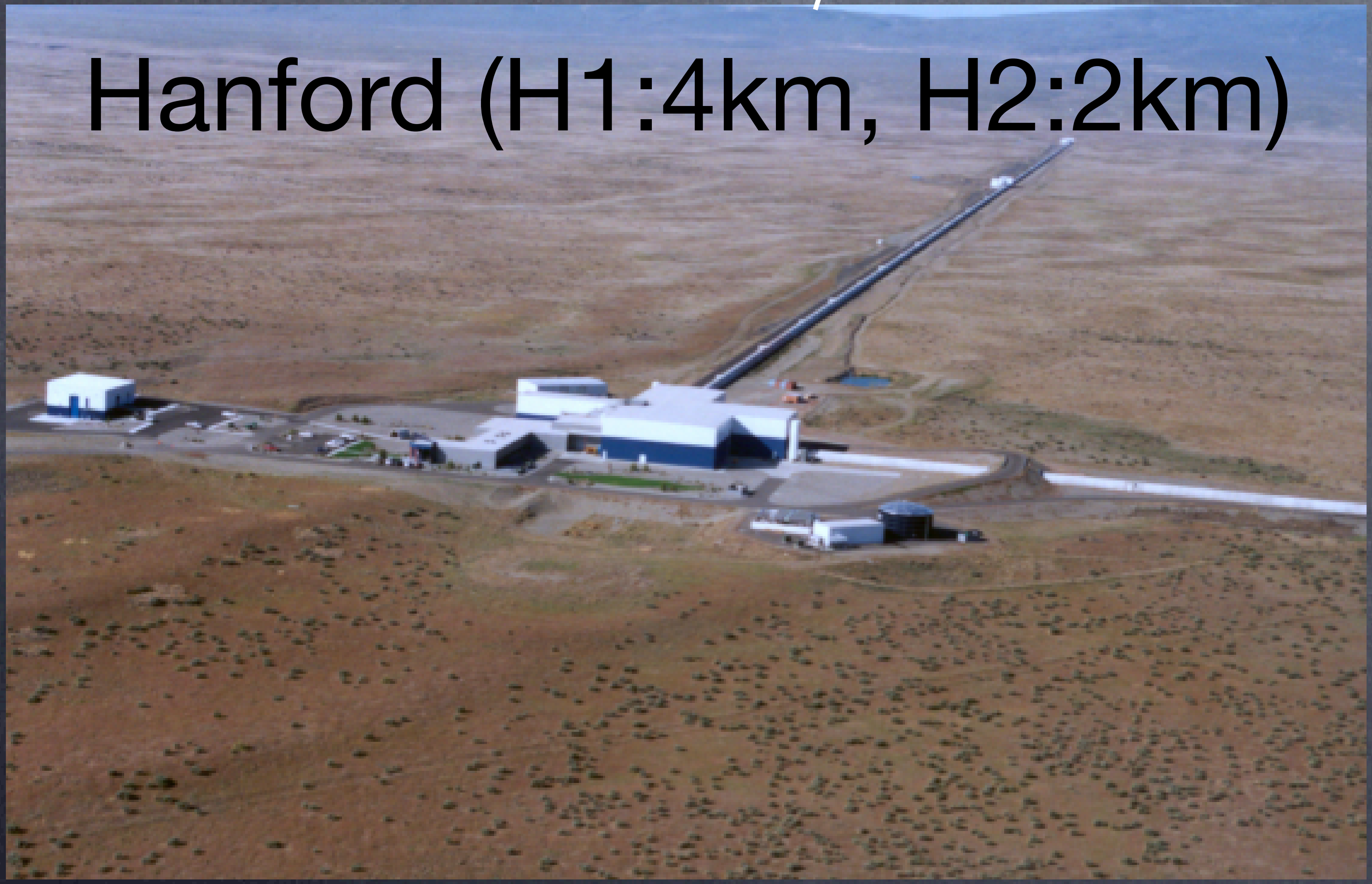
CLIO 100m

LCGT 3km

LIGO Australia

LIGO

US project
Two dislocated
site



They achieved science runs :
S2 (2003)
S3 (2003)
S4 (2004)
S5 (Nov.2005 - Oct.2007)
S6 (July 2009 - Oct.2010)

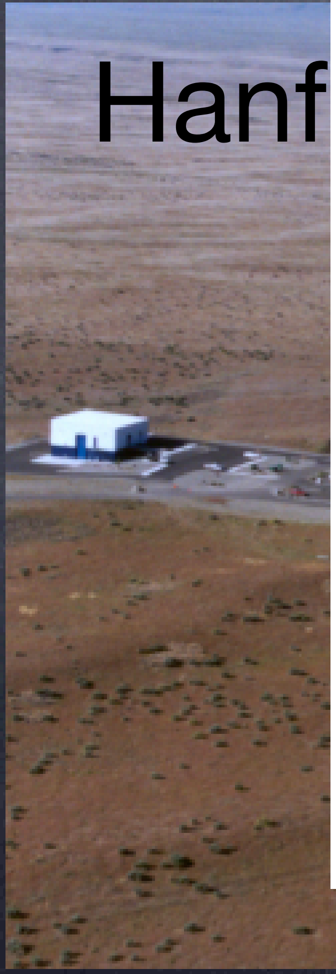
http://www.ligo.org/
https://www.advancedligo.mit.edu/summary.html

LIGO

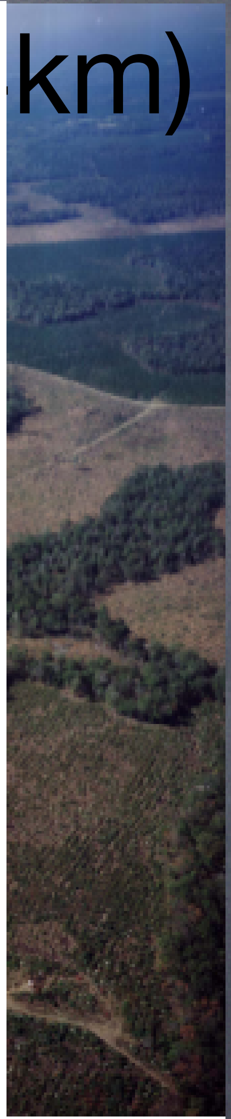
km)

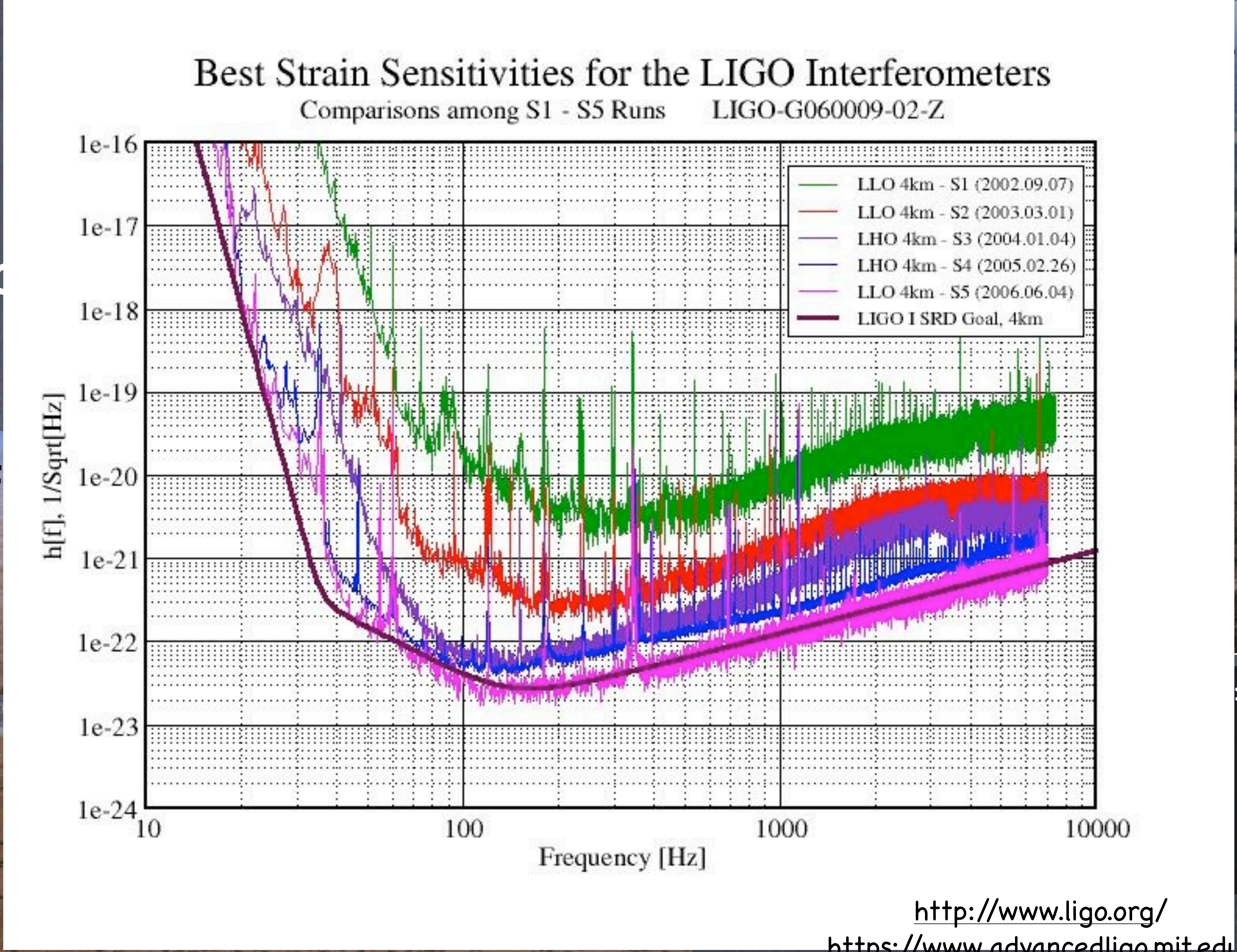
US

Two c



Hanf





http://www.ligo.org/

https://www.advancedligo.mit.edu/summary.html

VIRGO

site : Pisa (Italy)

European Project

Mainly from Italy & France

https://wwwcascina.virgo.infn.it/

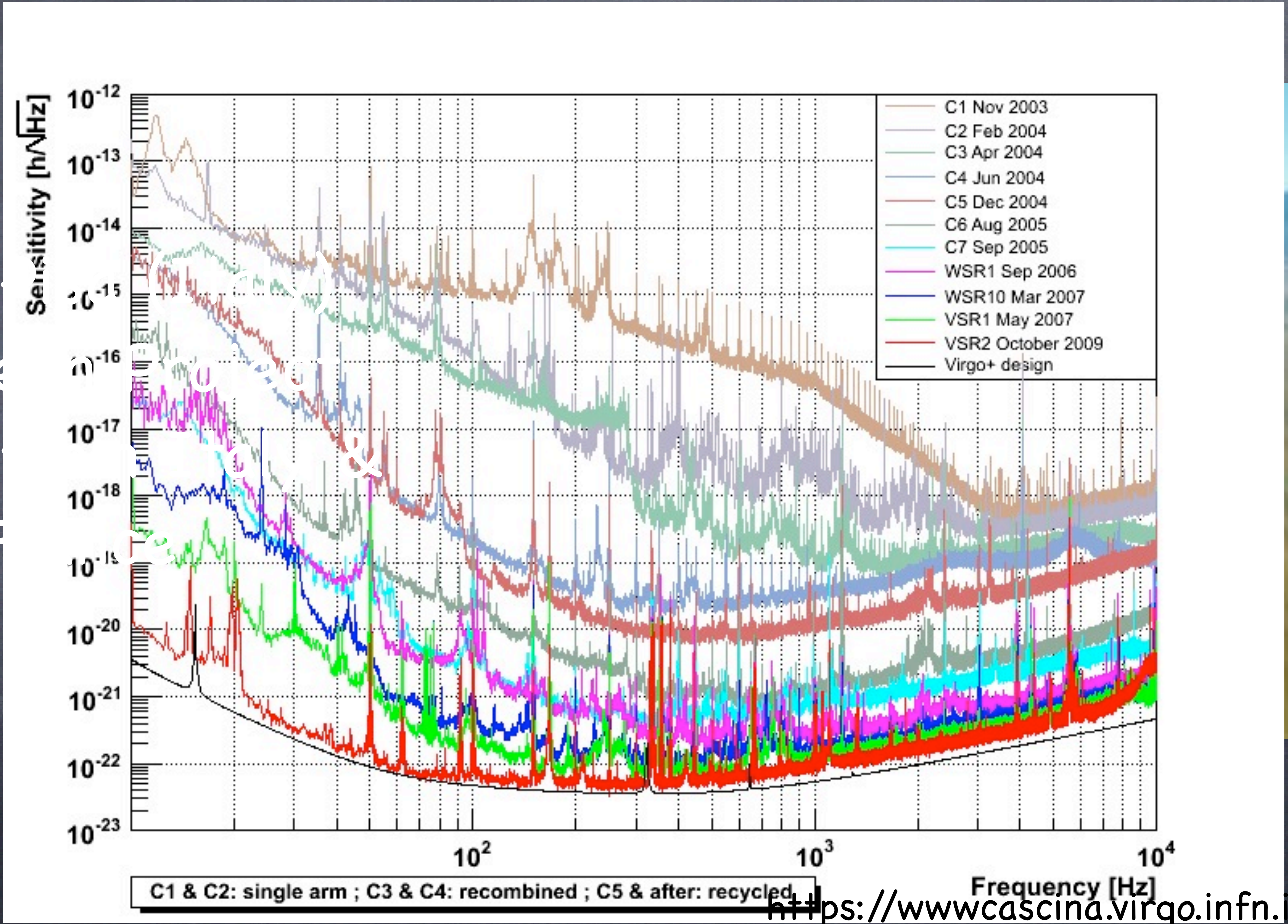
VIRGO

site :

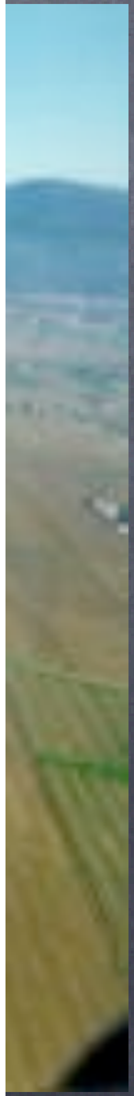
Europe

Mainly

F

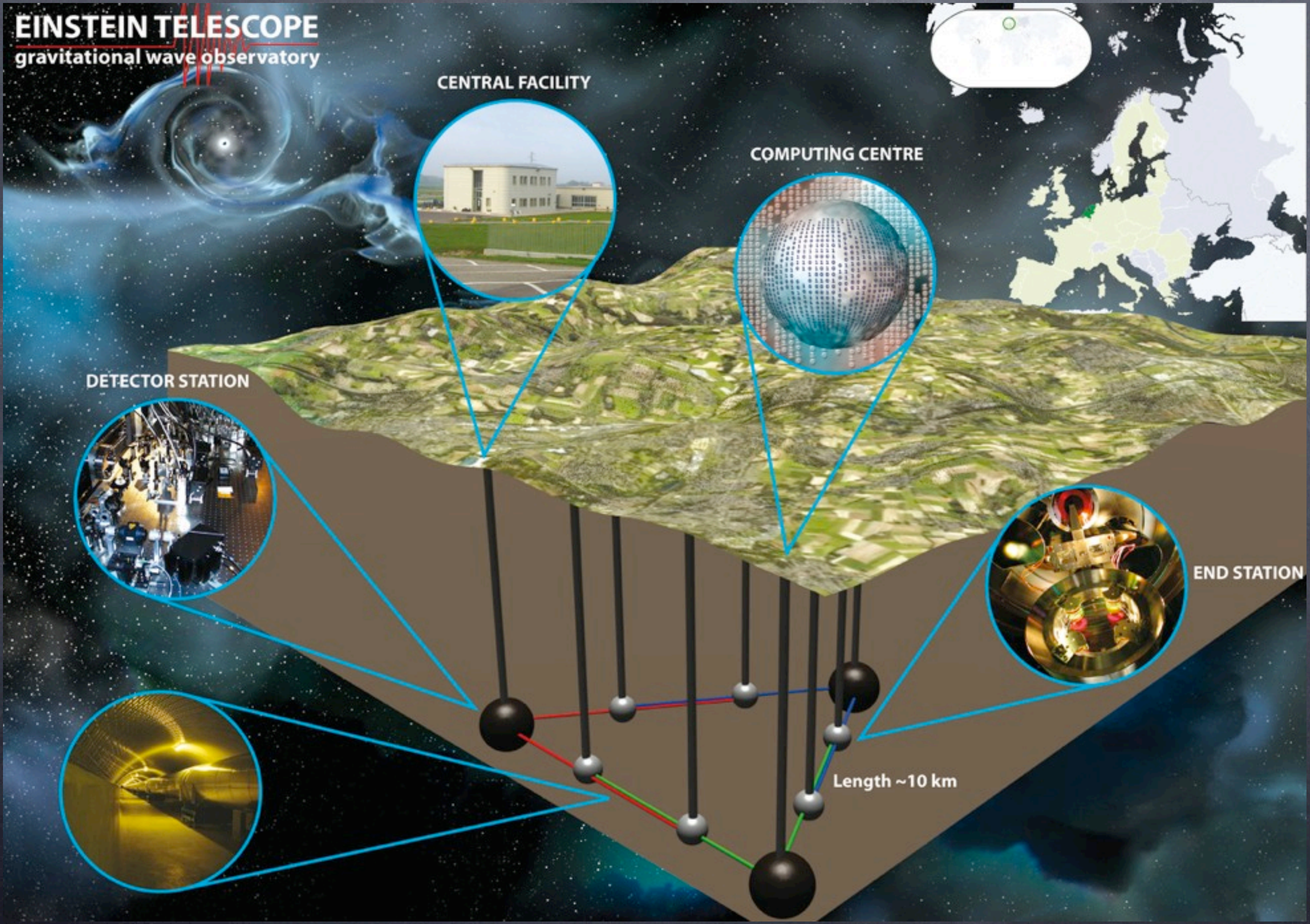


https://wwwcascina.virgo.infn.it/

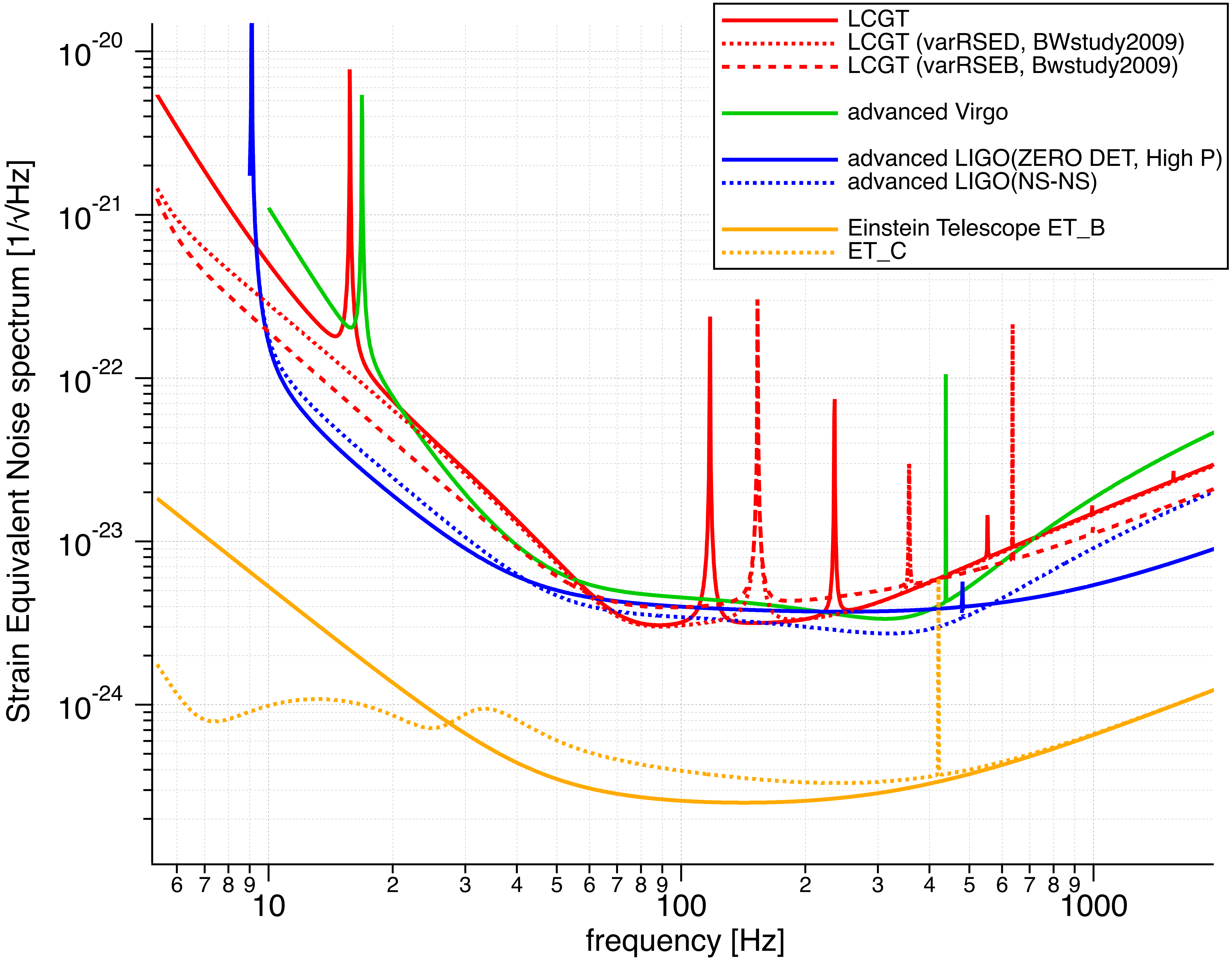


Einstein Telescope (Future Plan)

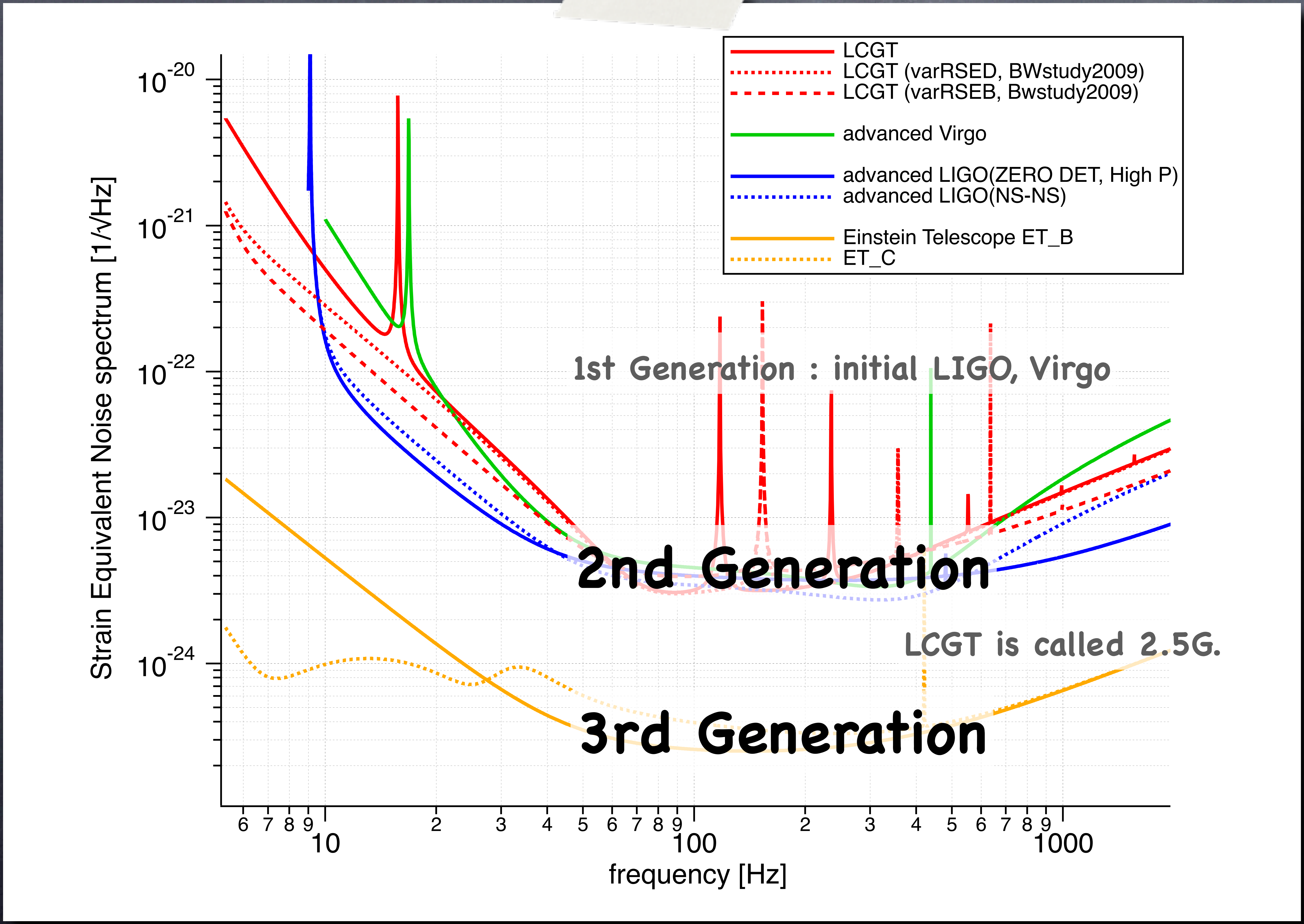
European future project with more one order better sensitivity of aLIGO/aVirgo/LCGT.



Comparison


Strain Equivalent Noise spectrum [1/√Hz]
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
6 7 8 9 10 2 3 4 5 6 7 8 9 100 2 3 4 5 6 7 8 9 1000
frequency [Hz]
LCGT
LCGT (varRSED, BWstudy2009)
LCGT (varRSEB, Bwstudy2009)
advanced Virgo
advanced LIGO(ZERO DET, High P)
advanced LIGO(NS-NS)
Einstein Telescope ET_B
ET_C

Comparison



1st Generation : initial LIGO, Virgo

2nd Generation

LCGT is called 2.5G.

3rd Generation

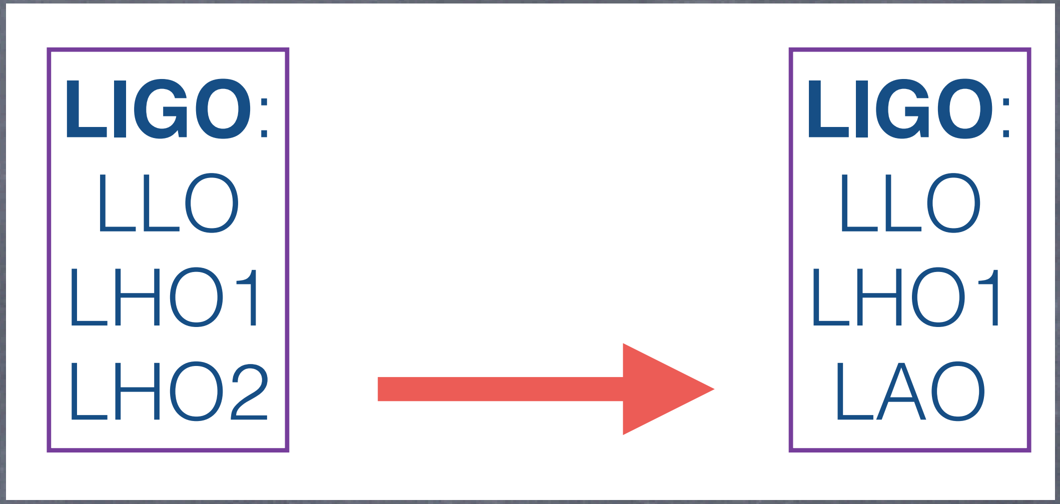
LIGO Australia

The Australian Consortium for Interferometric Gravitational wave Astronomy

The University of Adelaide
The University of Western Australia
The University of Melbourne
Monash University
The Australian National University

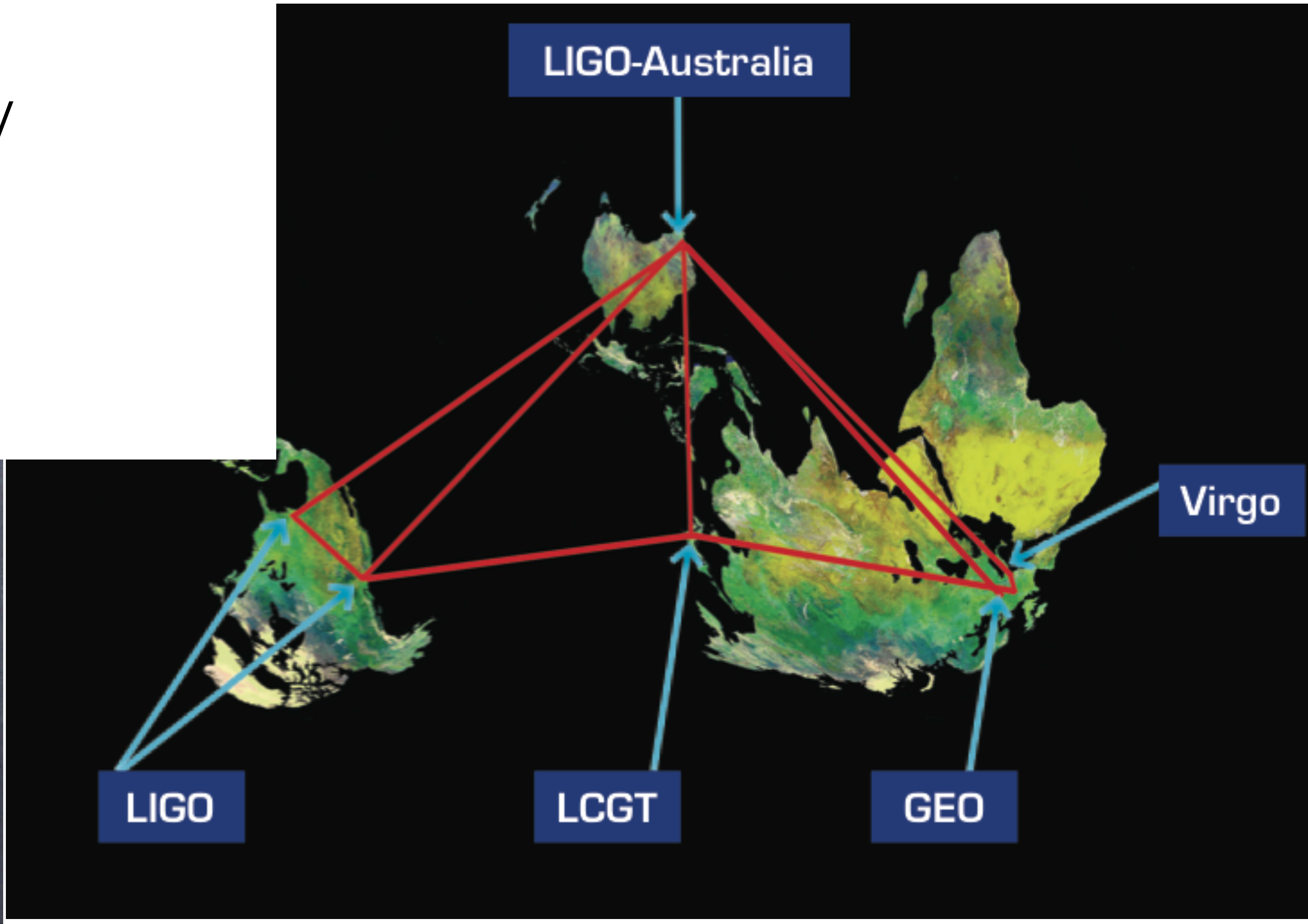
with Charles Sturt University

Over 50 members



LIGO:
LLO
LHO1
LHO2

LIGO:
LLO
LHO1
LAO



viewgraph by David McClelland

IndIGO

Multi-Institutional, Multi-disciplinary Consortium (Aug. 2009)

Nodal Institutions

1. CMI, Chennai
2. Delhi University
3. IISER Kolkata
4. IISER Trivandrum
5. IIT Madras (EE)
6. IIT Kanpur (EE)
7. IUCAA, Pune
8. RRCAT, Indore
9. TIFR, Mumbai
10. IPR, Bhatt

Others

- *RRI*
- *Jamia Milia Islamia*
- *Tezpur Univ*

The IndIGO Consortium

IndIGO Council

1.	Bala Iyer	(Chair)	RRI, Bangalore
2.	Sanjeev Dhurandhar	(Science)	IUCAA, Pune
3.	C. S. Unnikrishnan	(Experiment)	TIFR, Mumbai
4.	Tarun Souradeep	(Spokesperson)	IUCAA, Pune

Instrumentation & Experiment

1.	**C. S. Unnikrishnan**	**TIFR, Mumbai**
2.	G Rajalakshmi	TIFR, Mumbai
3.	P.K. Gupta	RRCAT, Indore
4.	Sendhil Raja	RRCAT, Indore
5.	S.K. Shukla	RRCAT, Indore
6.	Raja Rao	ex RRCAT, Consultant
7.	Anil Prabhakar,	EE, IIT M
8.	Pradeep Kumar,	EE, IIT K
9.	Ajai Kumar	IPR, Bhatt
10.	S.K. Bhatt	IPR, Bhatt
11.	Ranjan Gupta	IUCAA, Pune
12.	Bhal Chandra Joshi	NCRA, Pune
13.	Rijuparna Chakraborty,	Cote d'Azur, Grasse
14.	Rana Adhikari	Caltech, USA
15.	Suresh Doravari	Caltech, USA
16.	Biplab Bhawal	(ex LIGO)

Data Analysis & Theory

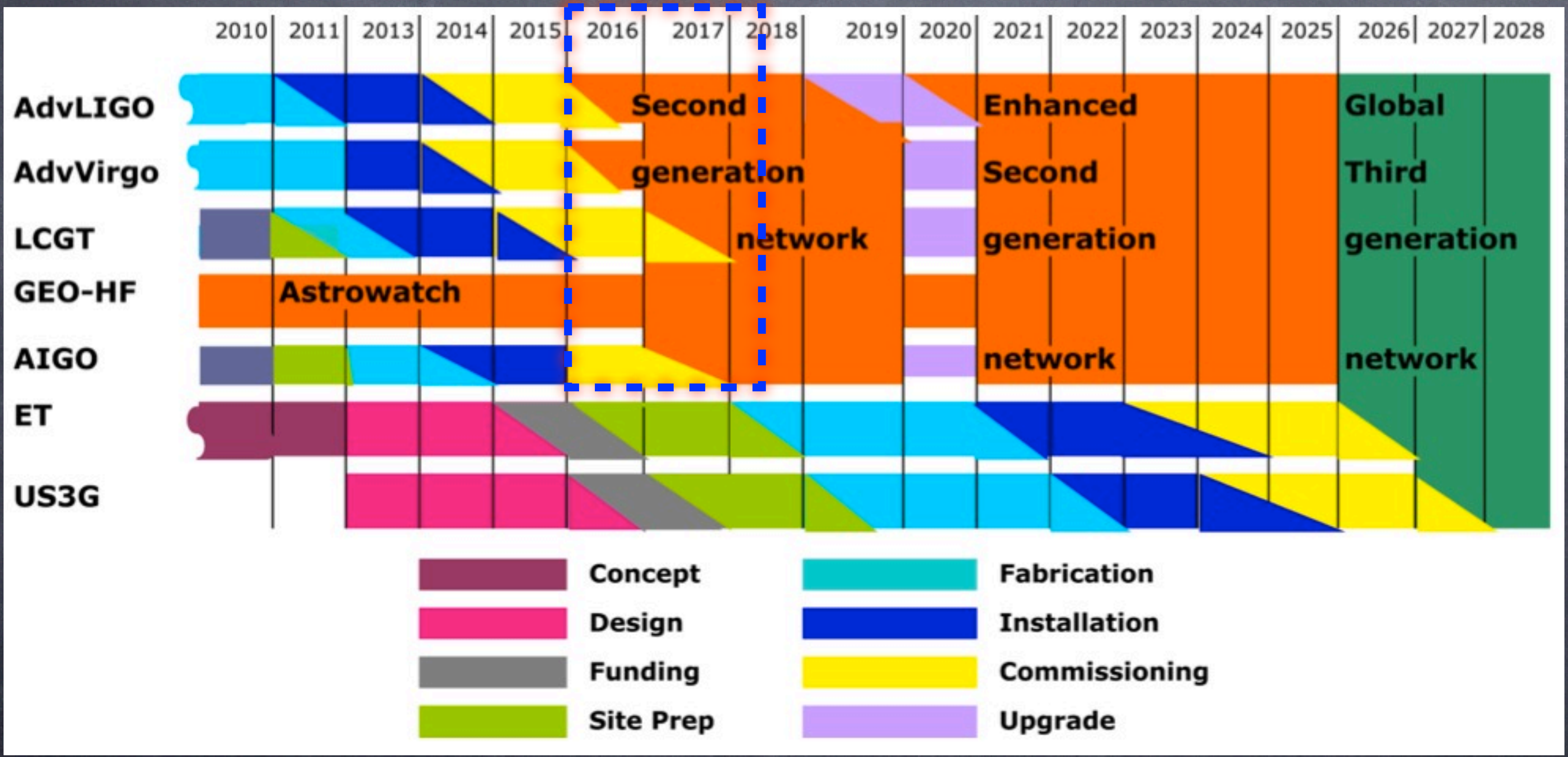
1.	**Sanjeev Dhurandhar**	**IUCAA**
2.	**Bala Iyer**	**RRI**
3.	**Tarun Souradeep**	**IUCAA**
4.	Anand Sengupta	Delhi University
5.	Archana Pai	IISER, Thiruvananthapuram
6.	Sanjit Mitra	JPL , IUCAA
7.	K G Arun	Chennai Math. Inst., Chennai
8.	Rajesh Nayak	IISER, Kolkata
9.	A. Gopakumar	TIFR, Mumbai
10.	T R Seshadri	Delhi University
11.	Patrick Dasgupta	Delhi University
12.	Sanjay Jhingan	Jamila Milia Islamia, Delhi
13.	L. Sriramkumar,	Phys., IIT M
14.	Bhim P. Sarma	Tezpur Univ .
15.	Sanjay Sahay	BITS, Goa
16.	P Ajith	Caltech , USA
17.	Sukanta Bose,	Wash. U., USA
18.	B. S. Sathyaprakash	Cardiff University, UK
19.	Soumya Mohanty	UTB, Brownsville , USA
20.	Badri Krishnan	Max Planck AEI, Germany

Global Network of GW Detectors

- **Aim (Science Target)**
- **Merits, Prospects**

1. The **coincidence** of event candidates convince us the 'true detection'.
2. Global network detectors will make possible to **determine some parameters** of GW sources, direction, inclination, etc...
3. Complemental **sky coverage** and duty time of observation.

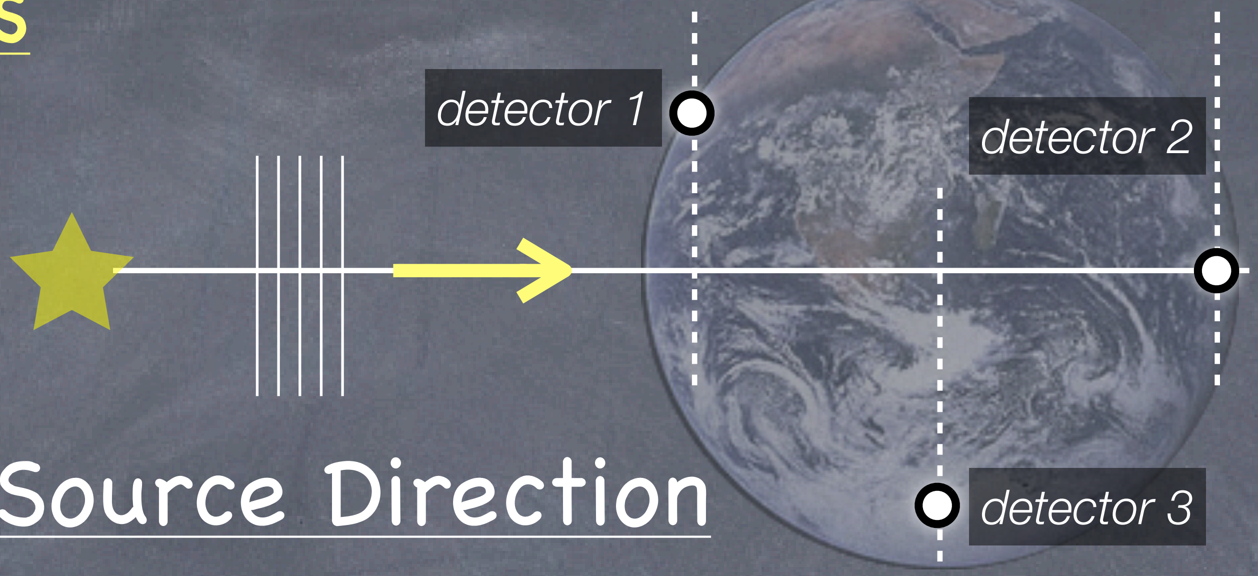
GWIC (Gravitational Wave International Committee) RoadMap



https://gwic.ligo.org/

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

Merit of Network GW detectors



- **Determination of**

  Arrival Direction of GW = Source Direction

  Polarization of GW

  (in case of Compact Binary) Absolute Amplitude & Inclination angle of orbit plane will be determined.

  to be the "Standard Siren"!

- **Sky coverage**

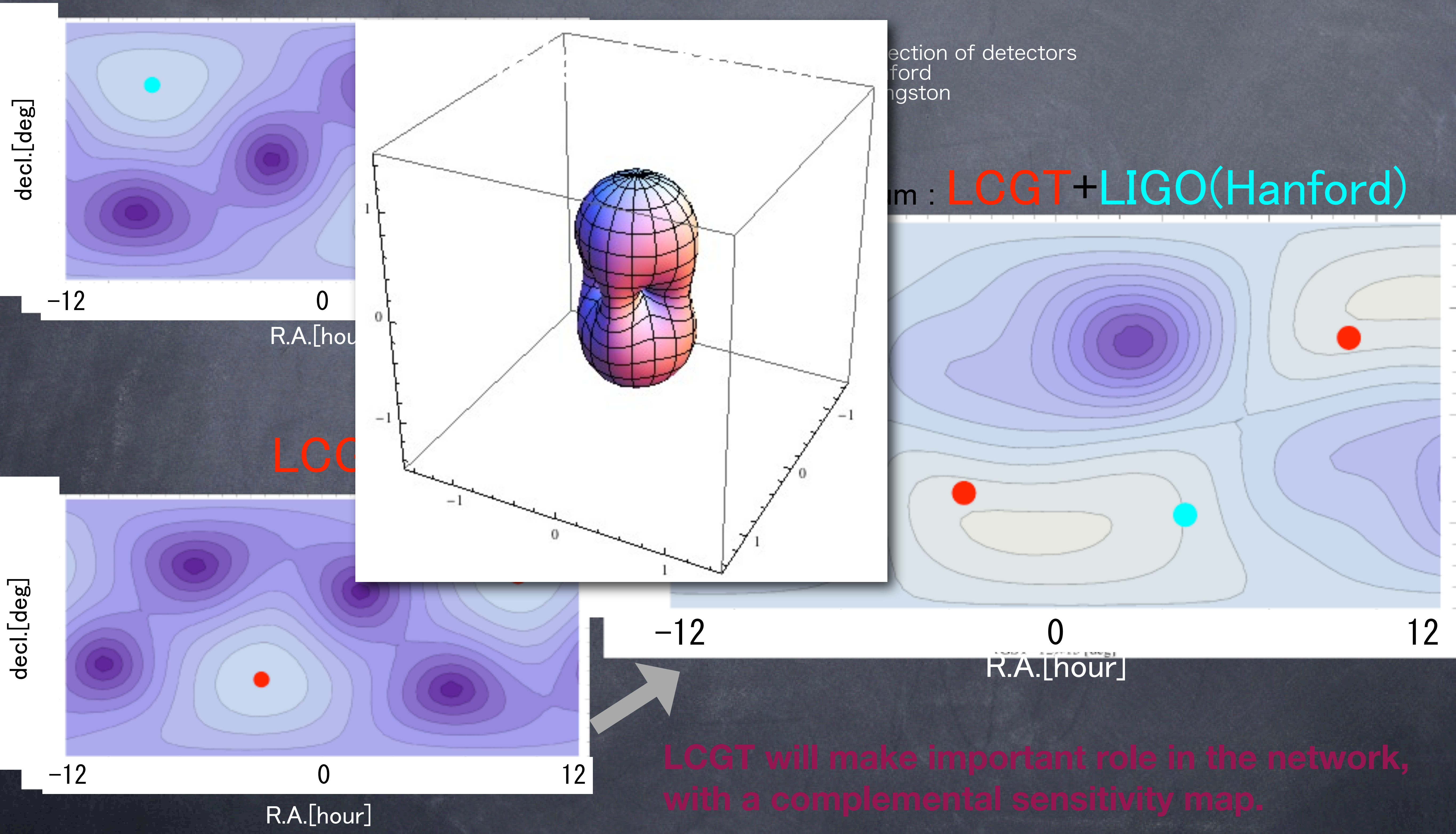
- **Duty Time of Observation**

  More GW events

  Chance for follow-up observations

Sky coverage by detector network

LIGO (Hanford)

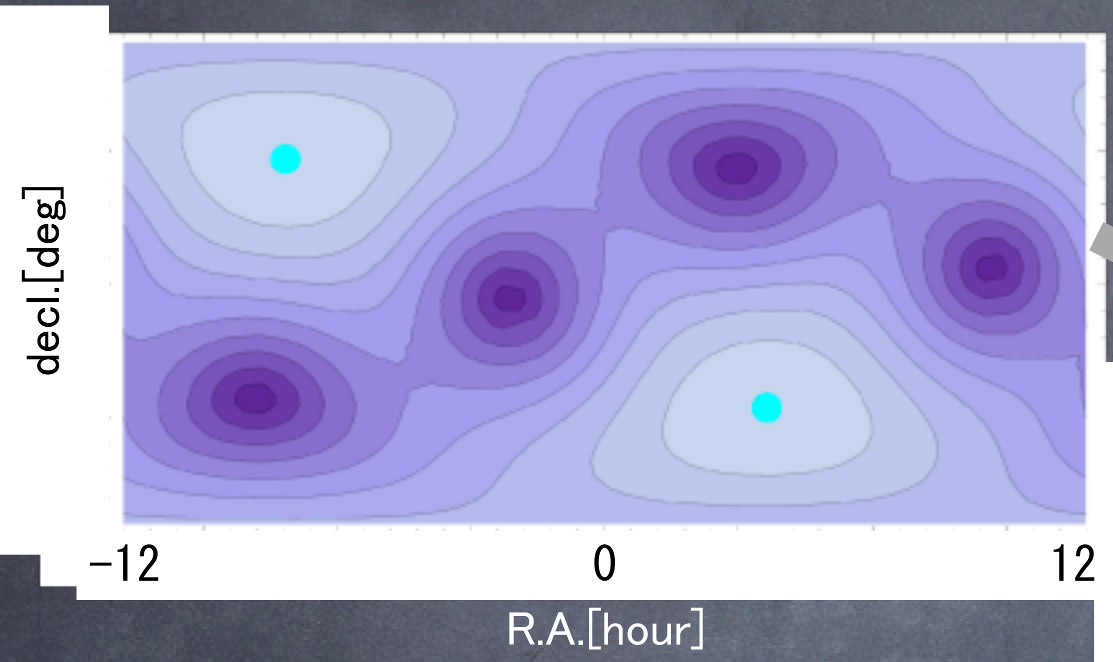


m : LCGT+LIGO(Hanford)

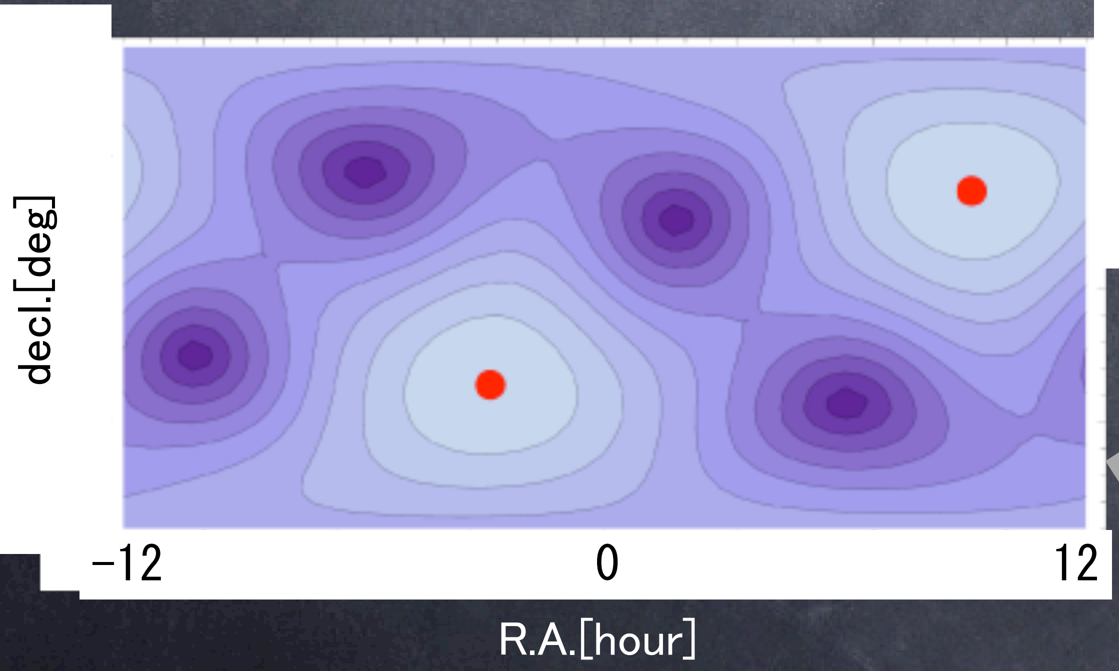
LCGT will make important role in the network, with a complemental sensitivity map.

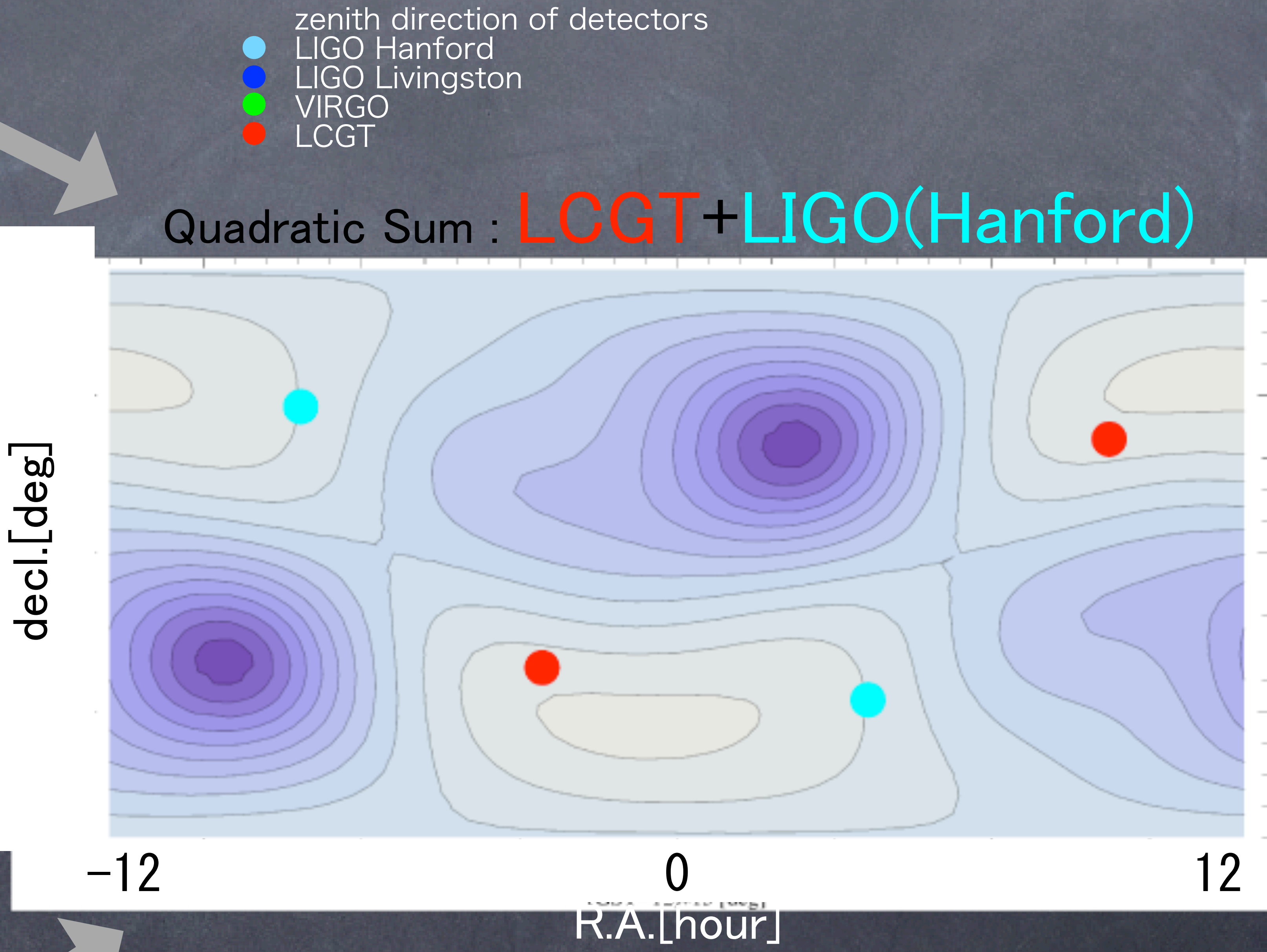
Sky coverage by detector network

LIGO (Hanford)



LCGT

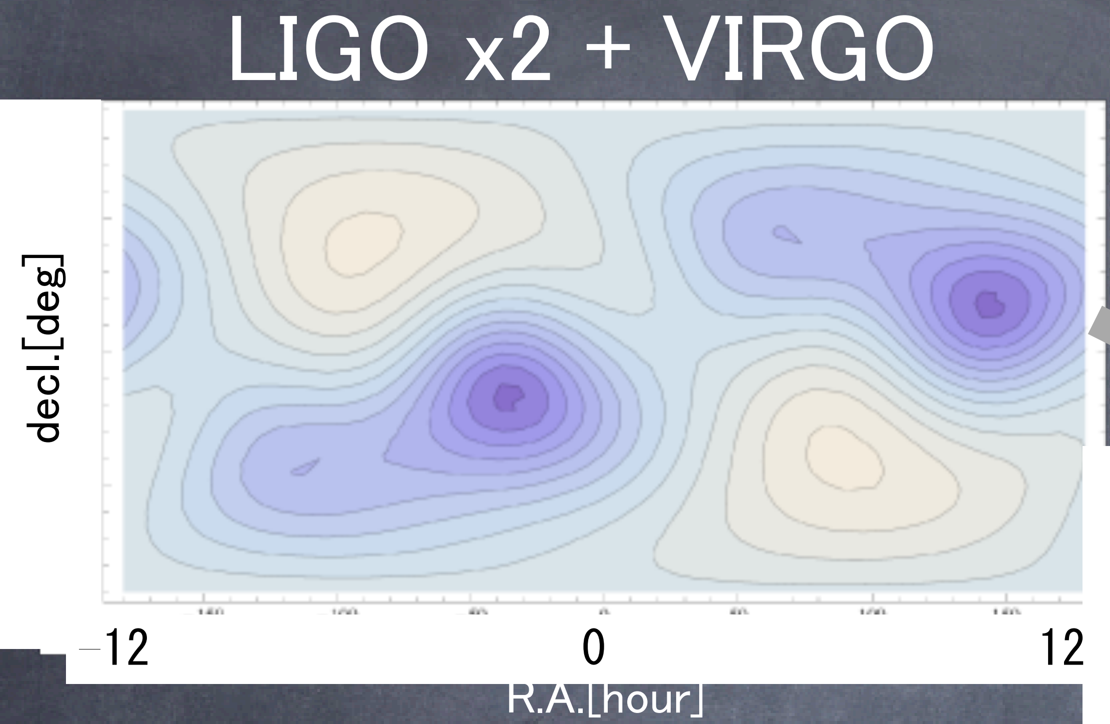


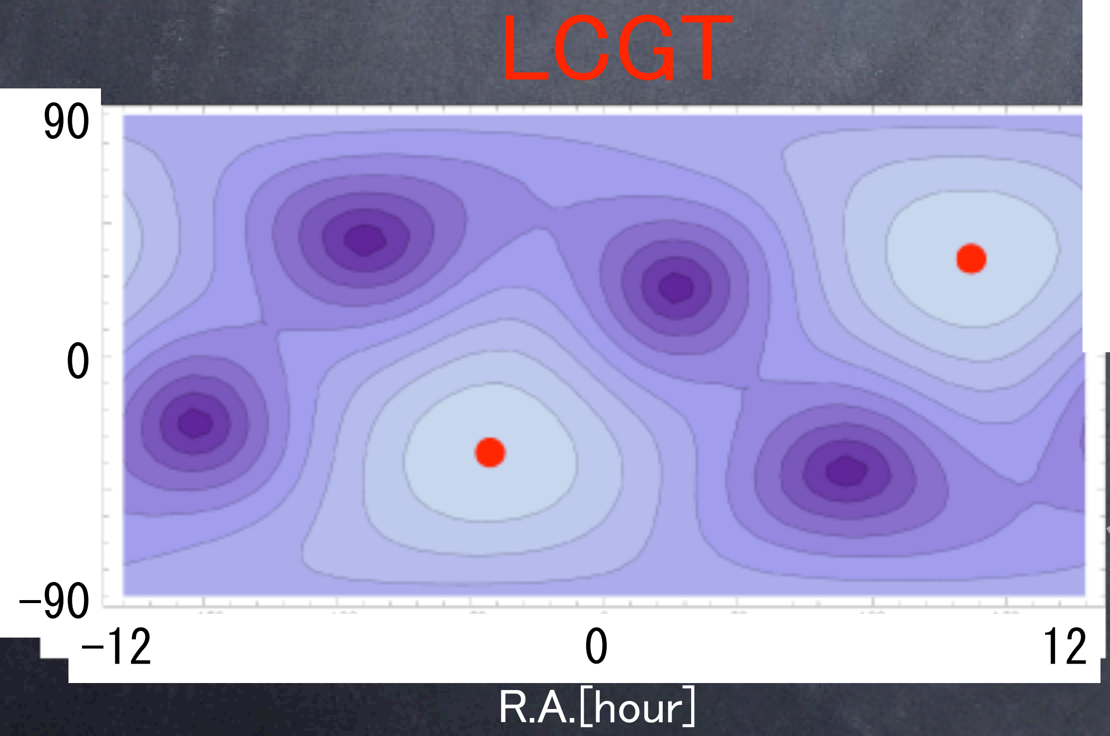


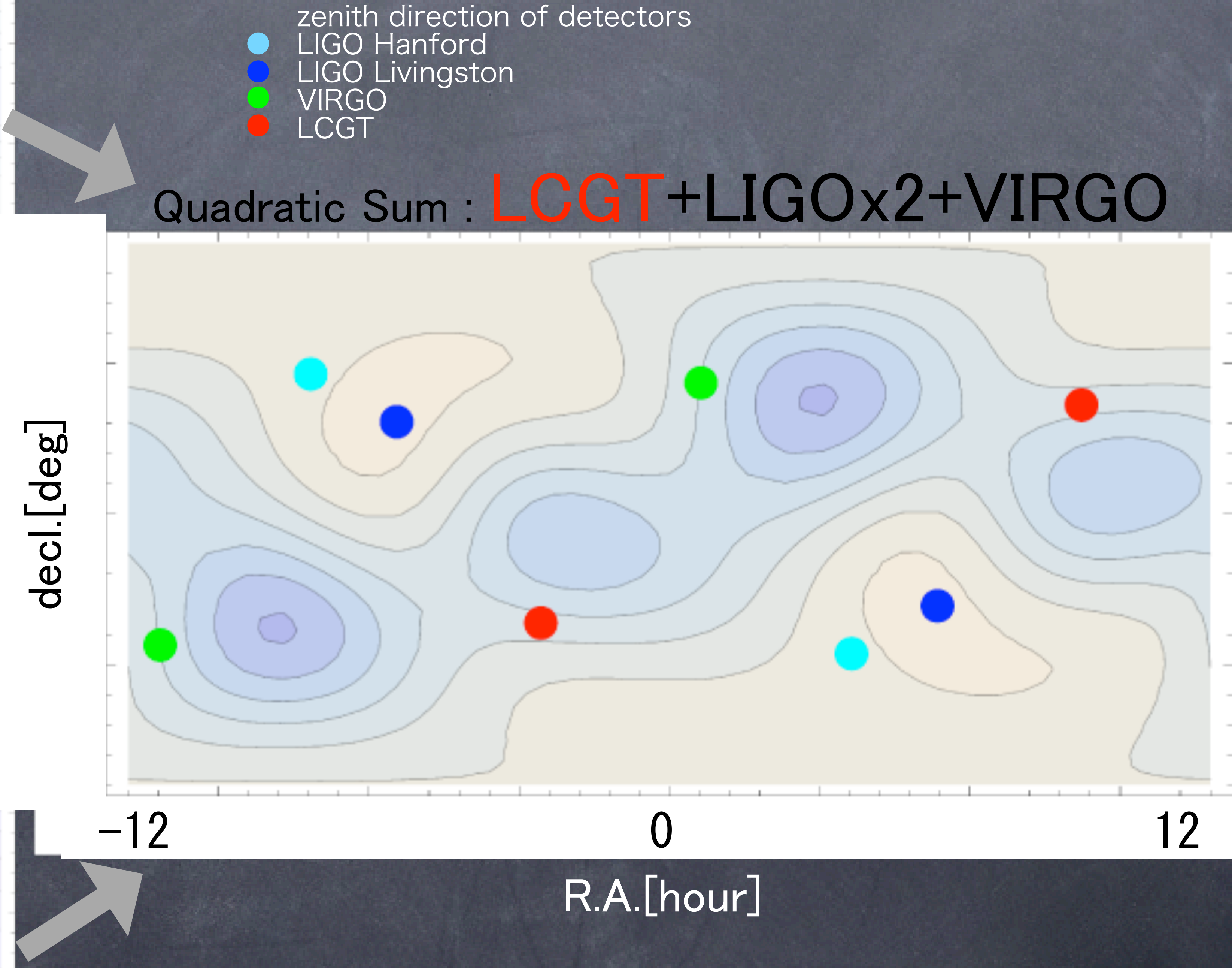
Quadratic Sum : LCGT+LIGO(Hanford)

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

Sky coverage by detector network



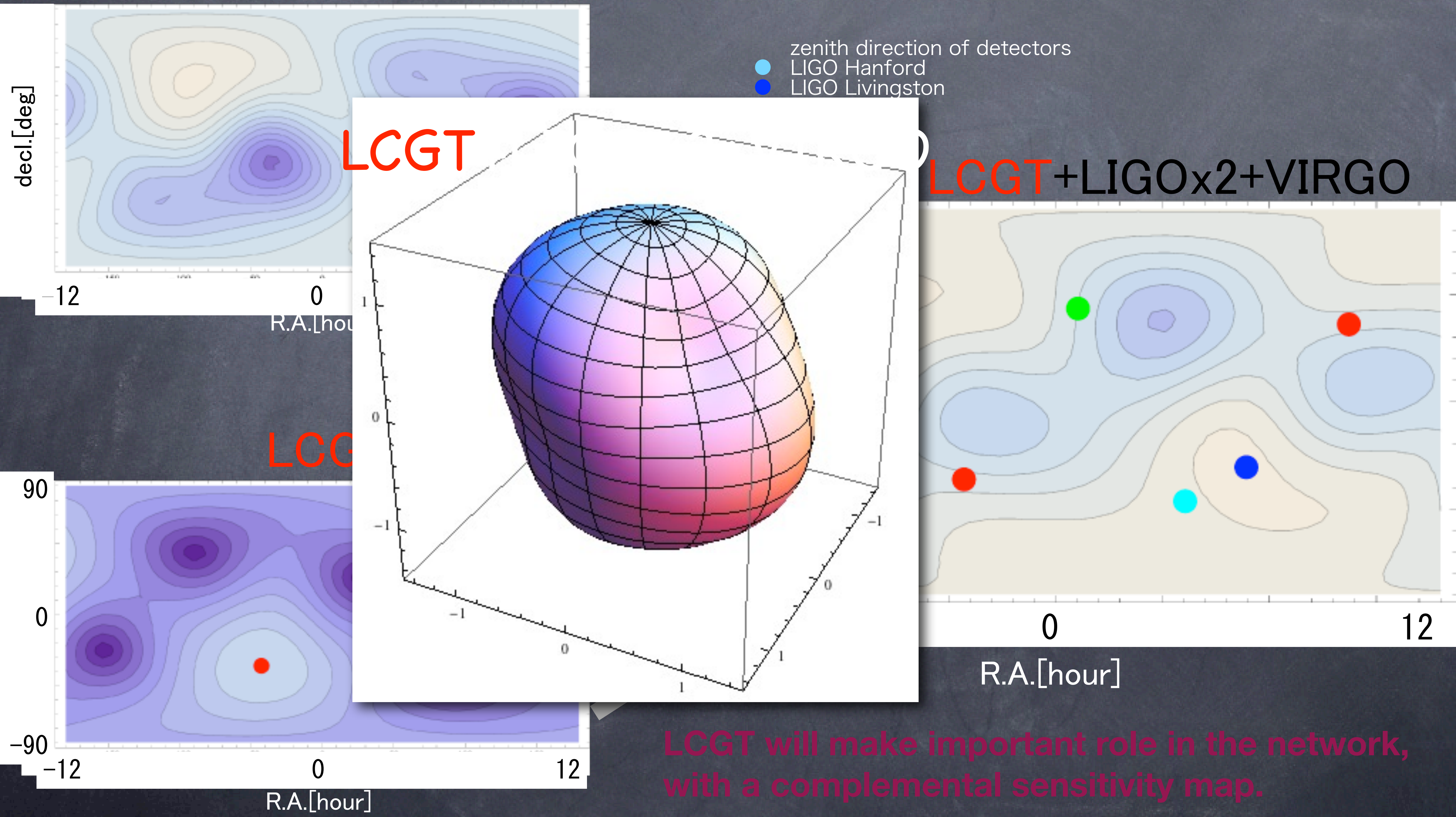




LCGT will make important role in the network, with a complemental sensitivity map.

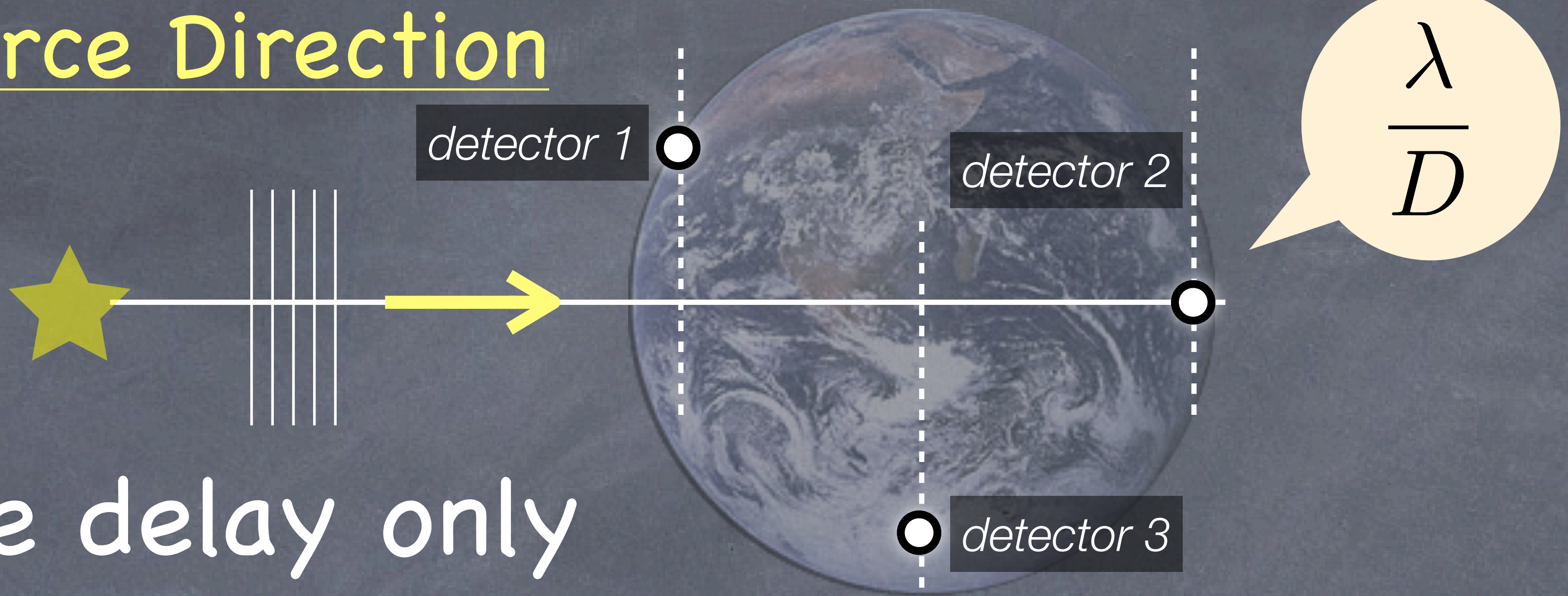
Sky coverage by detector network

LIGO x2 + VIRGO



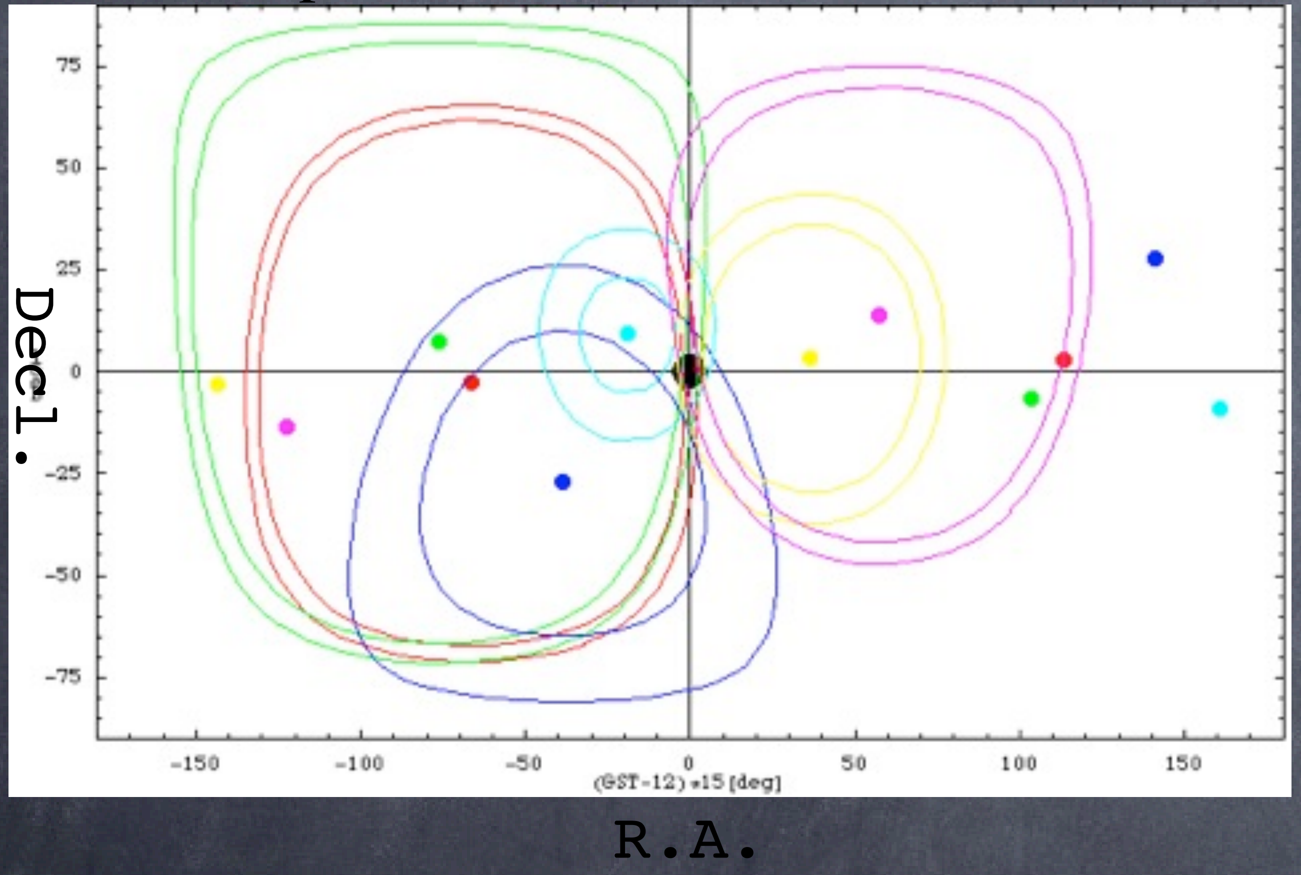
LCGT will make important role in the network, with a complemental sensitivity map.

Determination of Source Direction

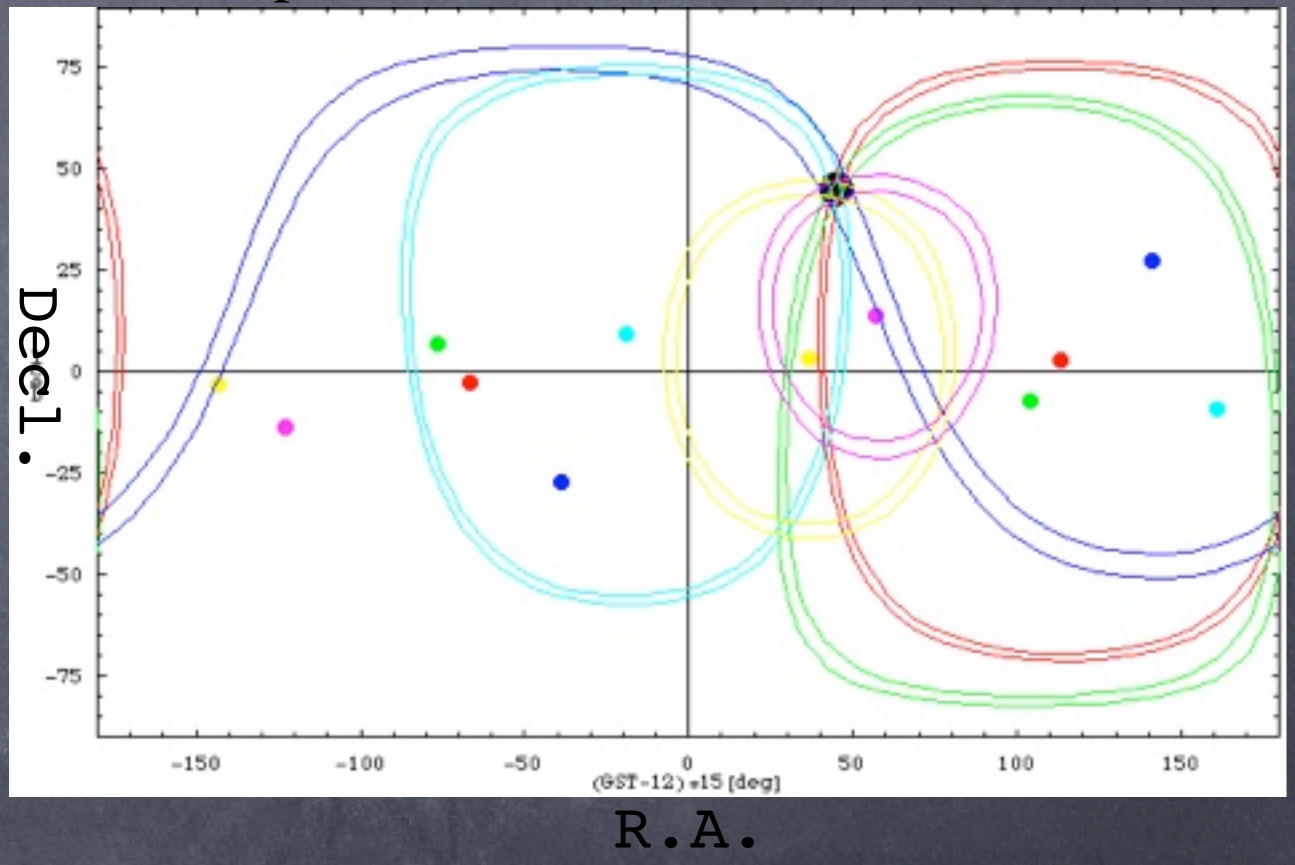


example with time delay only

Example with ΔT=1 msec

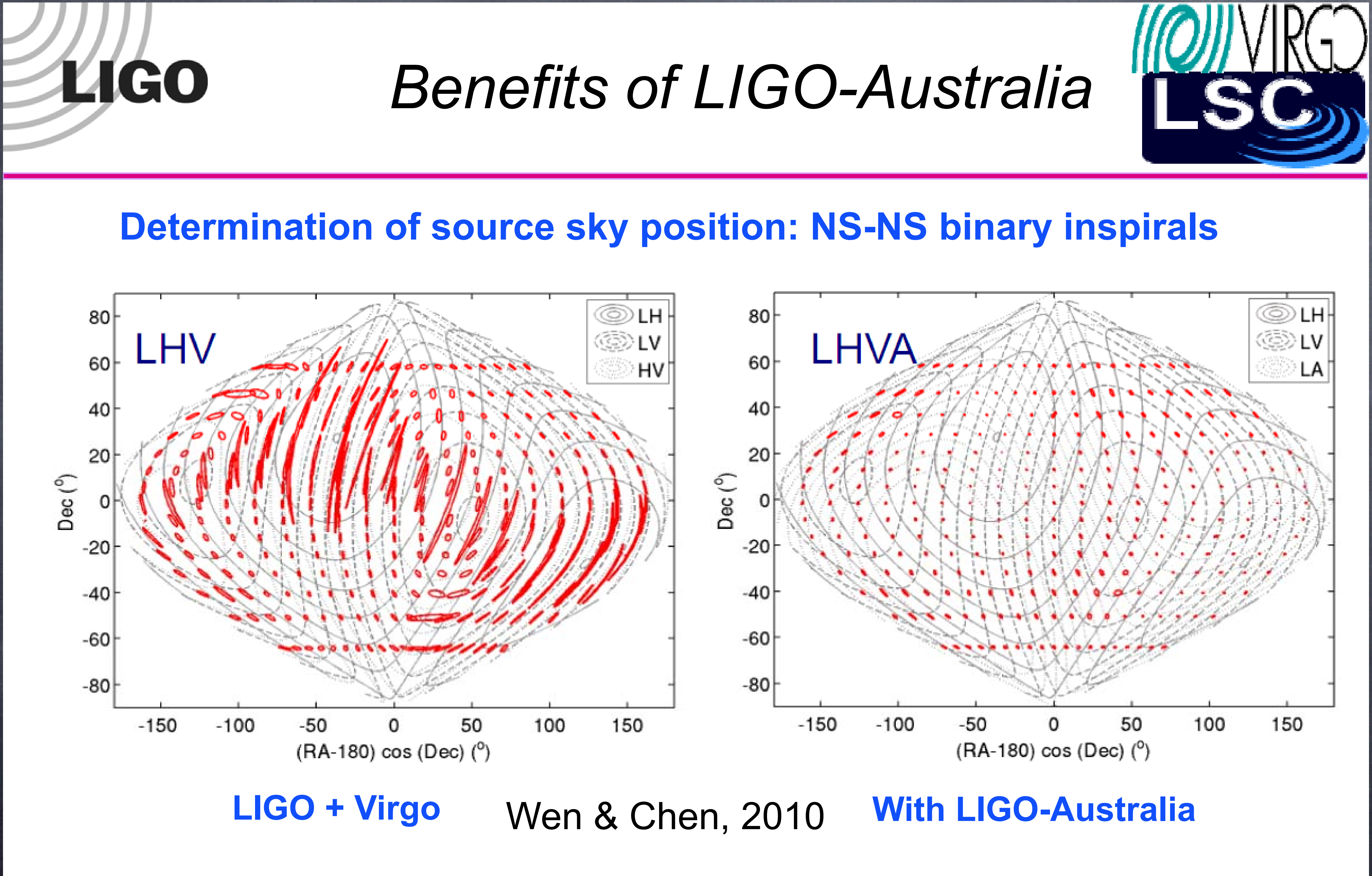


Example with ΔT=0.5 msec



We need to take care also for antenna response dependency of incident direction, polarization, etc..

Source Direction (Reconstruction of Sky Position)



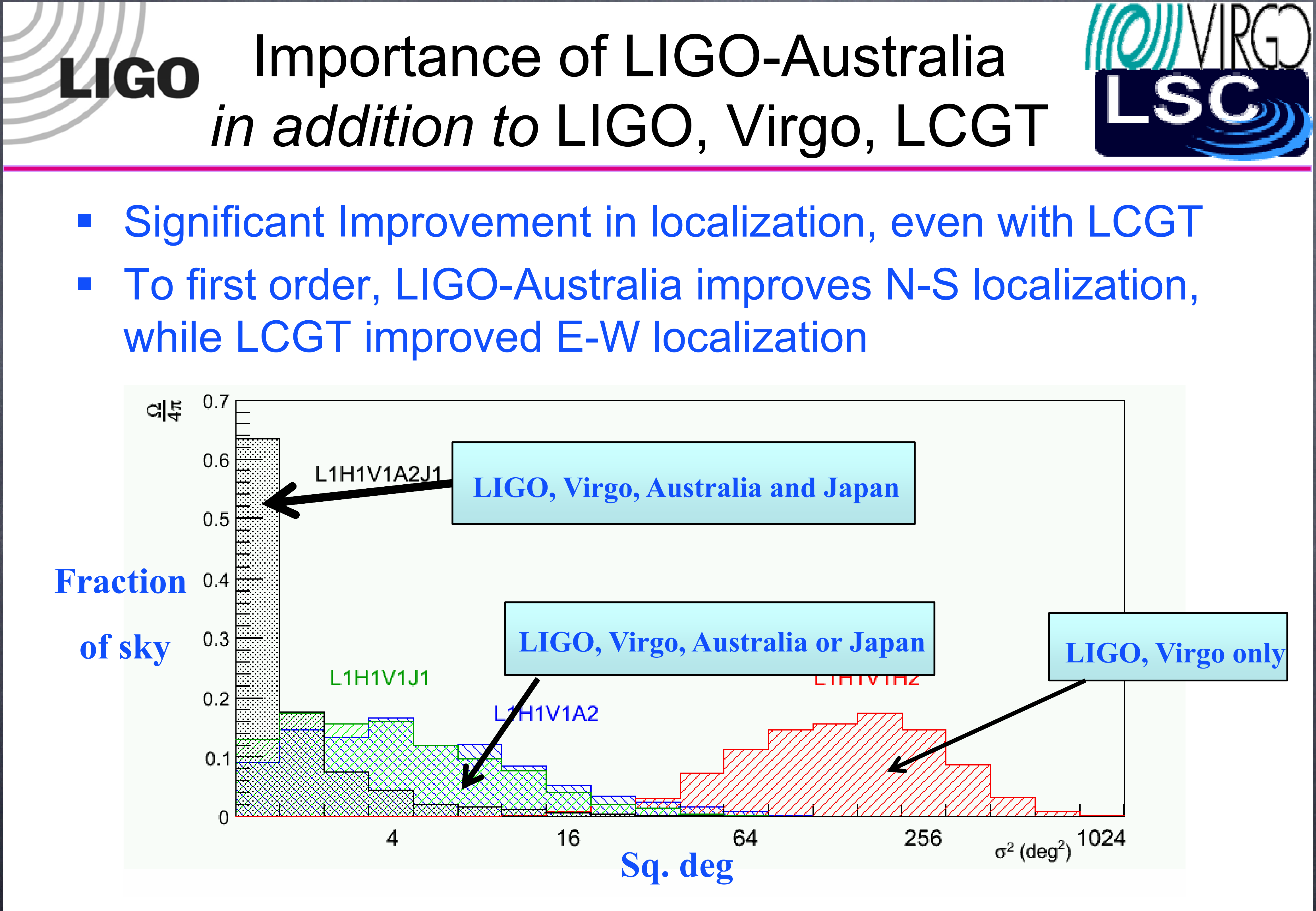
Benefits of LIGO-Australia

Determination of source sky position: NS-NS binary inspirals

LIGO + Virgo Wen & Chen, 2010 **With LIGO-Australia**

viewgraph by Alan Weinstein

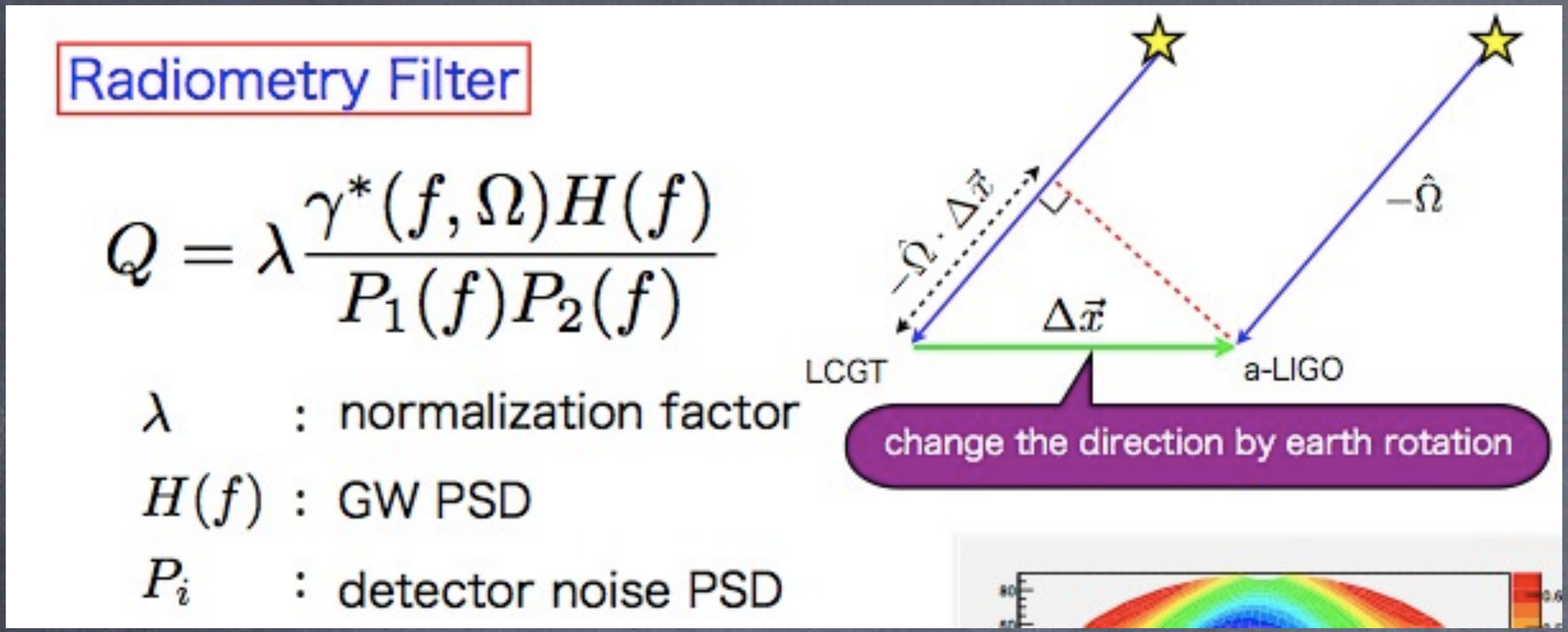
Source Direction (Reconstruction of Sky Position)



Importance of LIGO-Australia *in addition to* LIGO, Virgo, LCGT

- Significant Improvement in localization, even with LCGT
- To first order, LIGO-Australia improves N-S localization, while LCGT improved E-W localization

Radiometry Search for point sources



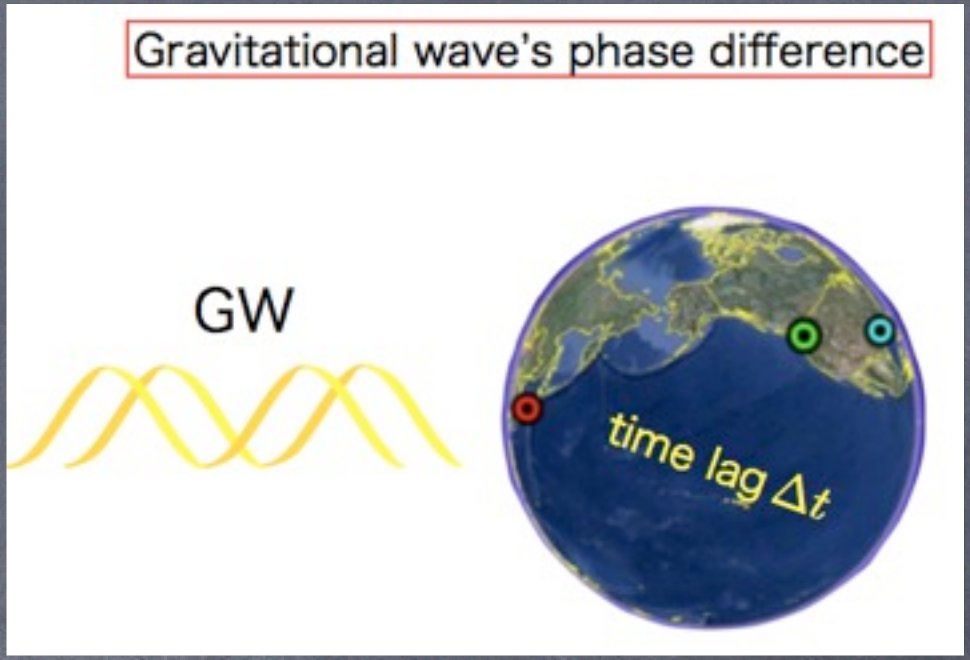
Radiometry Filter

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

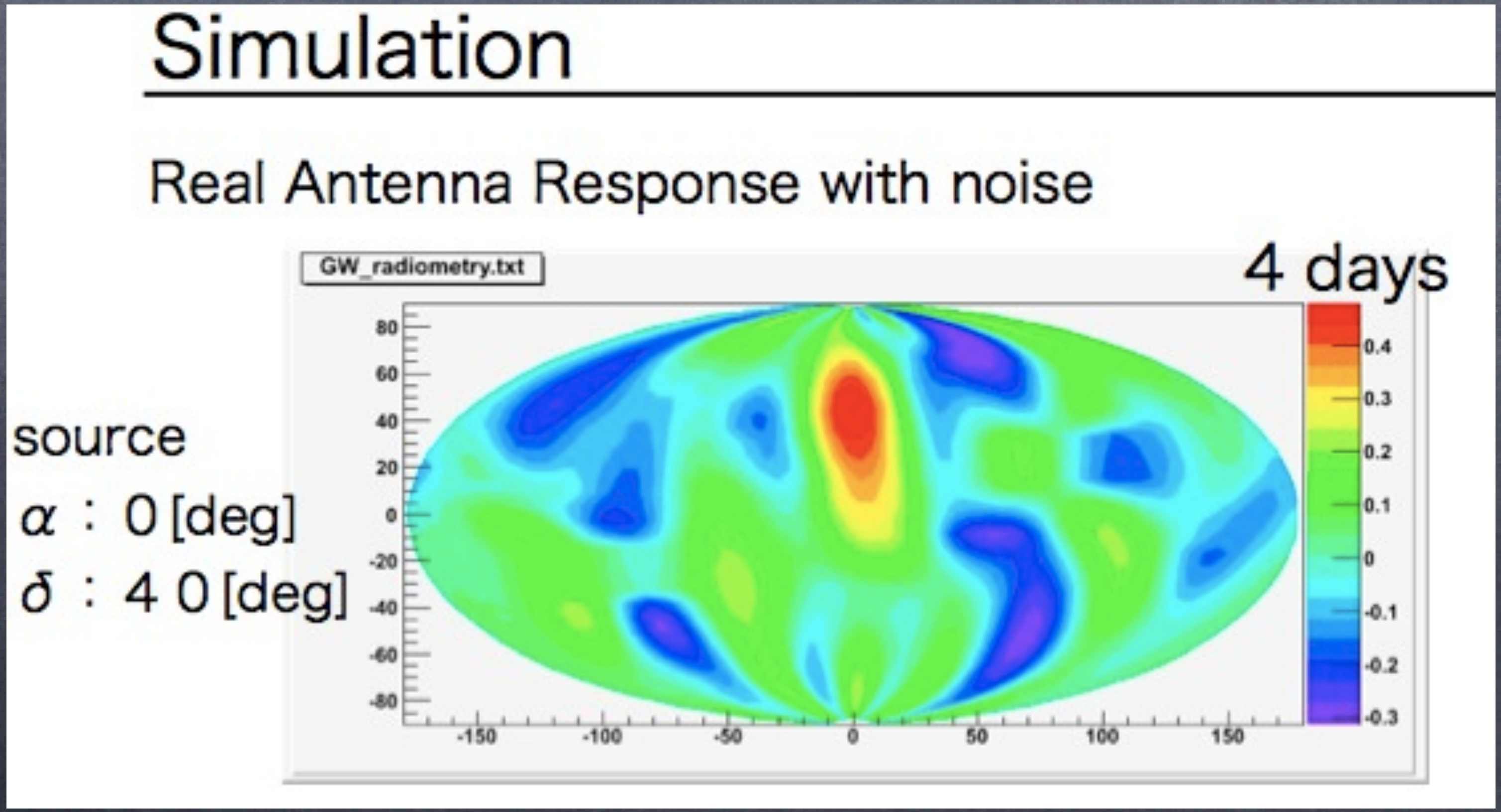
λ : normalization factor

$H(f)$: GW PSD

P_i : detector noise PSD



Gravitational wave's phase difference



Simulation

Real Antenna Response with noise

4 days

source

α : 0 [deg]

δ : 4 0 [deg]

by Y.Okada

Astronomy and Astrophysics with GW

- **Event like:**

  Compact Binary Coalescence (NS-NS, NS-BH, BH-BH)

  neutron star (NS), black-hole (BH)

  Supernovae

  BH ringdown

  Pulsar glitch

- **Continuous waves:**

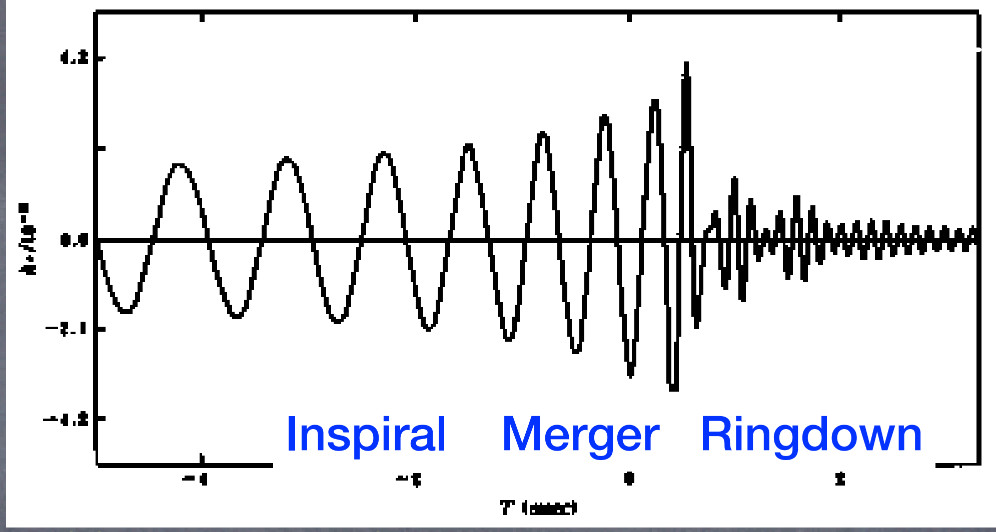
  Pulsar rotation

  Binaries

- **(Unexpected)**

There are many interest !
(I can introduce only a few today.
Thus, join us -LCGT 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, tidal effect (disruption, deformation) ...

- **Ringdown (Perturbation)**

  BH quasi-normal mode

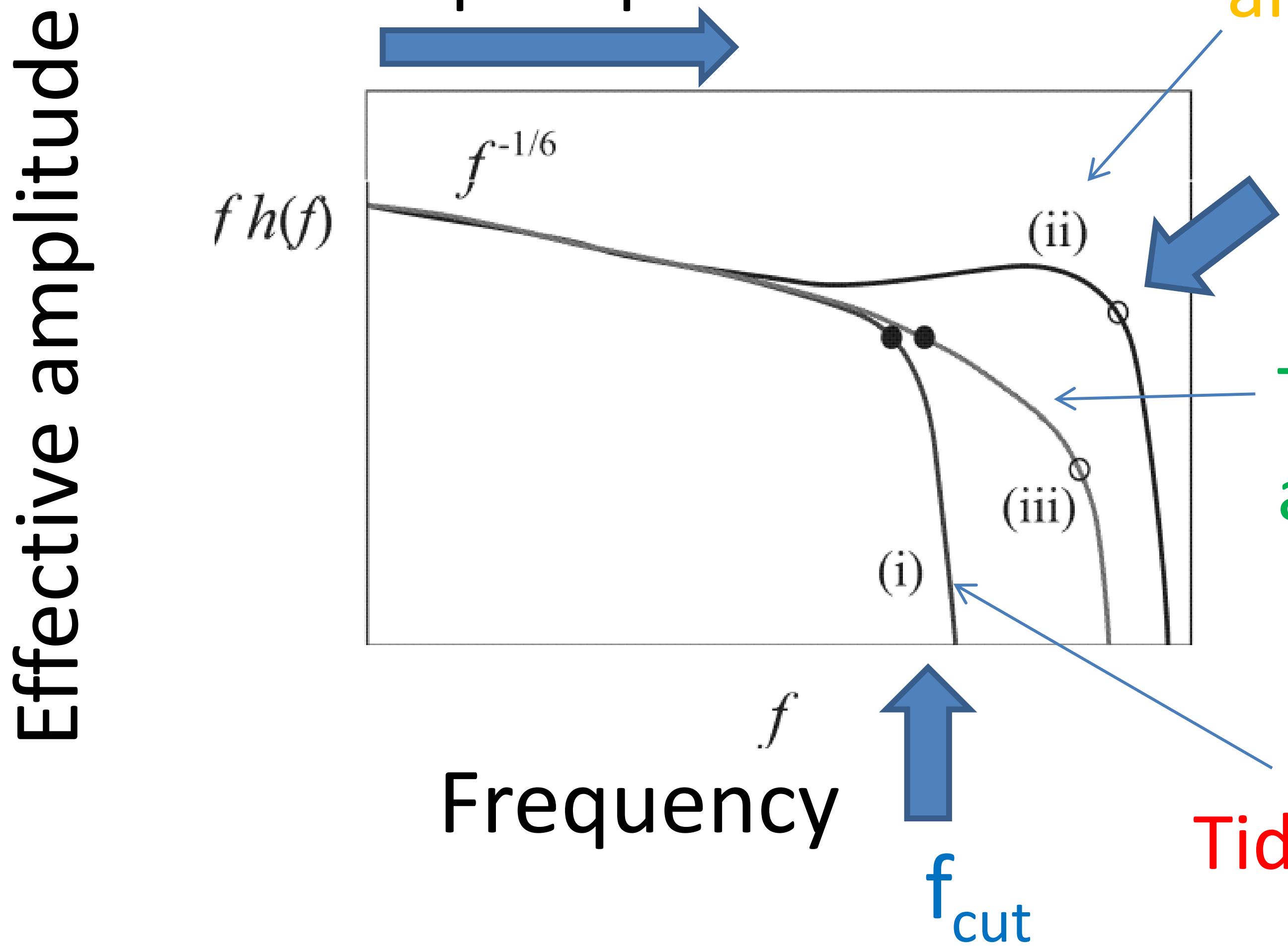
  frequency ---> mass

  decay time ---> spin (Kerr parameter) *What a fruitful source is it !*

Tidal disruption on NS-BH merger

Gravitational wave Spectrum

Schematic picture



Inspiral phase

Effective amplitude

Frequency

f_{cut}

f_{QNM}

No tidal disruption and QNM case

Tidal disruption and QNM case

Tidal disruption case

We extract f_{cut} by fitting the spectrum and calculate f_{QNM} from final BH mass and spin

viewgraph by Kenta Kiuchi

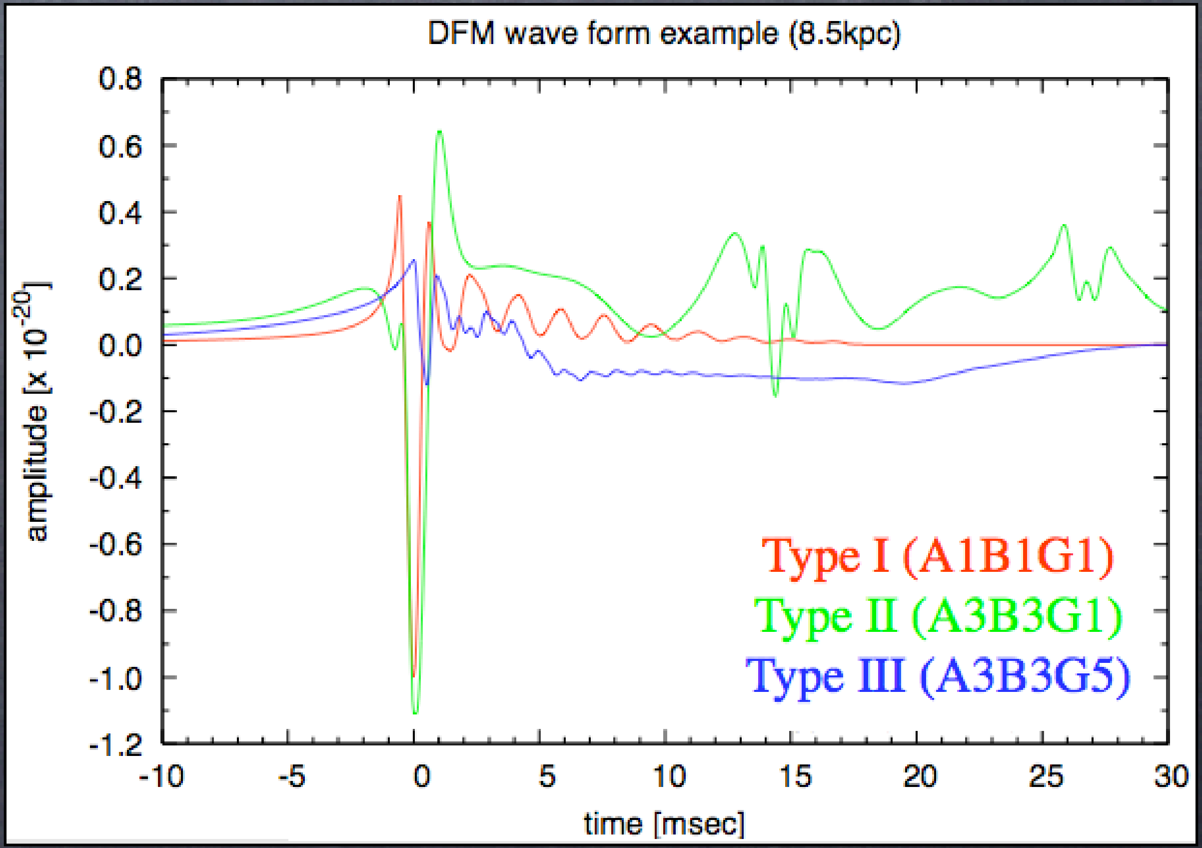
Burst GW from Supernovae (stellar-core collapse)

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

- core bounce
- convection
- formation of proto-neutron star

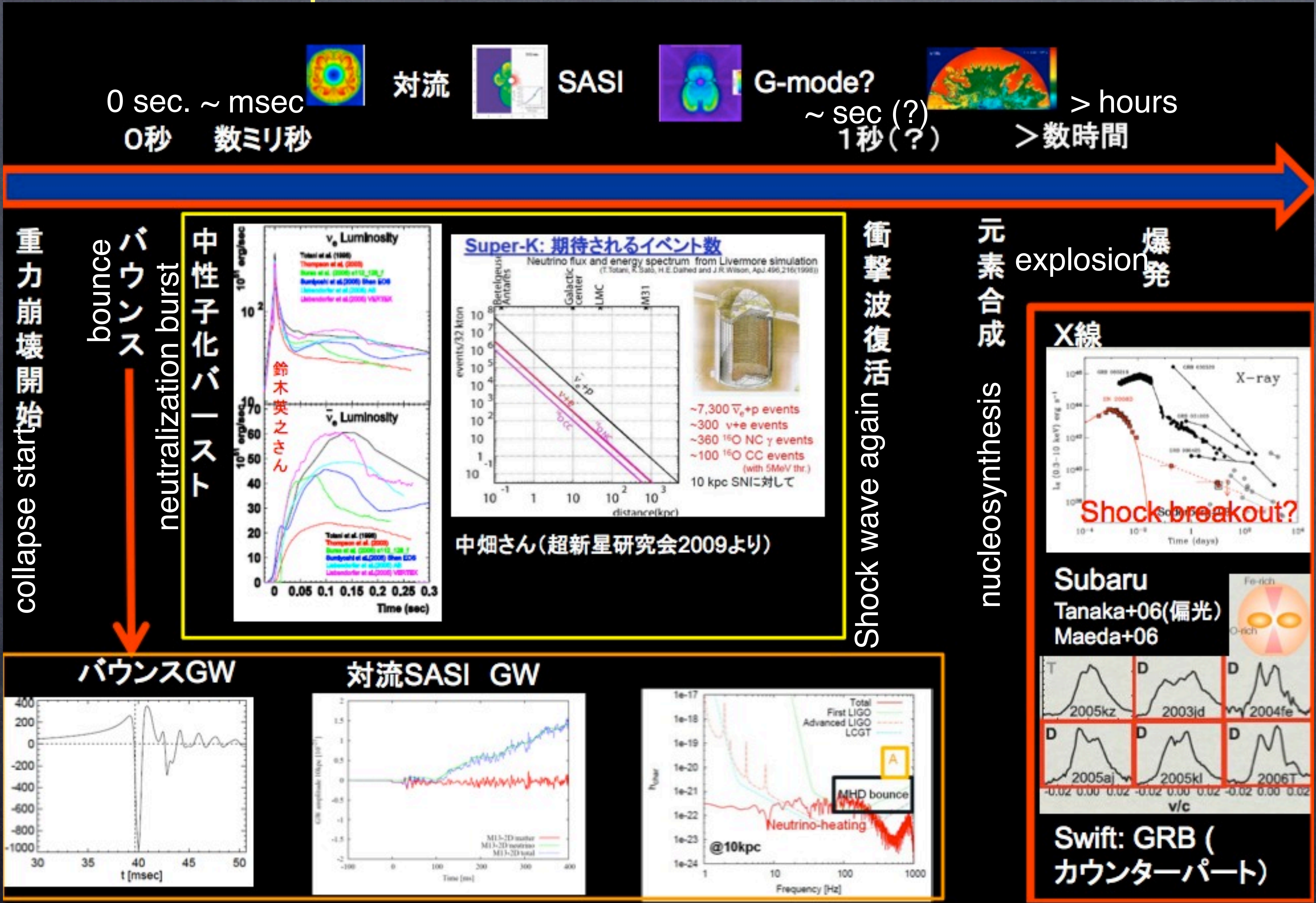
  g-mode oscillation
- neutrino emission
- accretion

  cf: SASI (standing-accretion-shock instability)



Evolution of Supernova and GW

viewgraph by K.Kotake



0 sec. ~ msec
0秒　数ミリ秒

対流

SASI

G-mode?

~ sec (?)
１秒（？）

> hours
＞数時間

重力崩壊開始 collapse start

バウンス bounce

中性子化バースト neutralization burst

鈴木英之さん

Super-K: 期待されるイベント数

Neutrino flux and energy spectrum from Livermore simulation (T.Totani, K.Sato, H.E.Dalhed and J.R.Wilson, ApJ.496,216(1998))

~7,300 $\bar{\nu}_e$+p events
~300 ν+e events
~360 ^{16}O NC γ events
~100 ^{16}O CC events
(with 5MeV thr.)
10 kpc SNに対して

中畑さん（超新星研究会2009より）

衝撃波復活 Shock wave again

元素合成 nucleosynthesis

爆発 explosion

X線

Shock breakout?

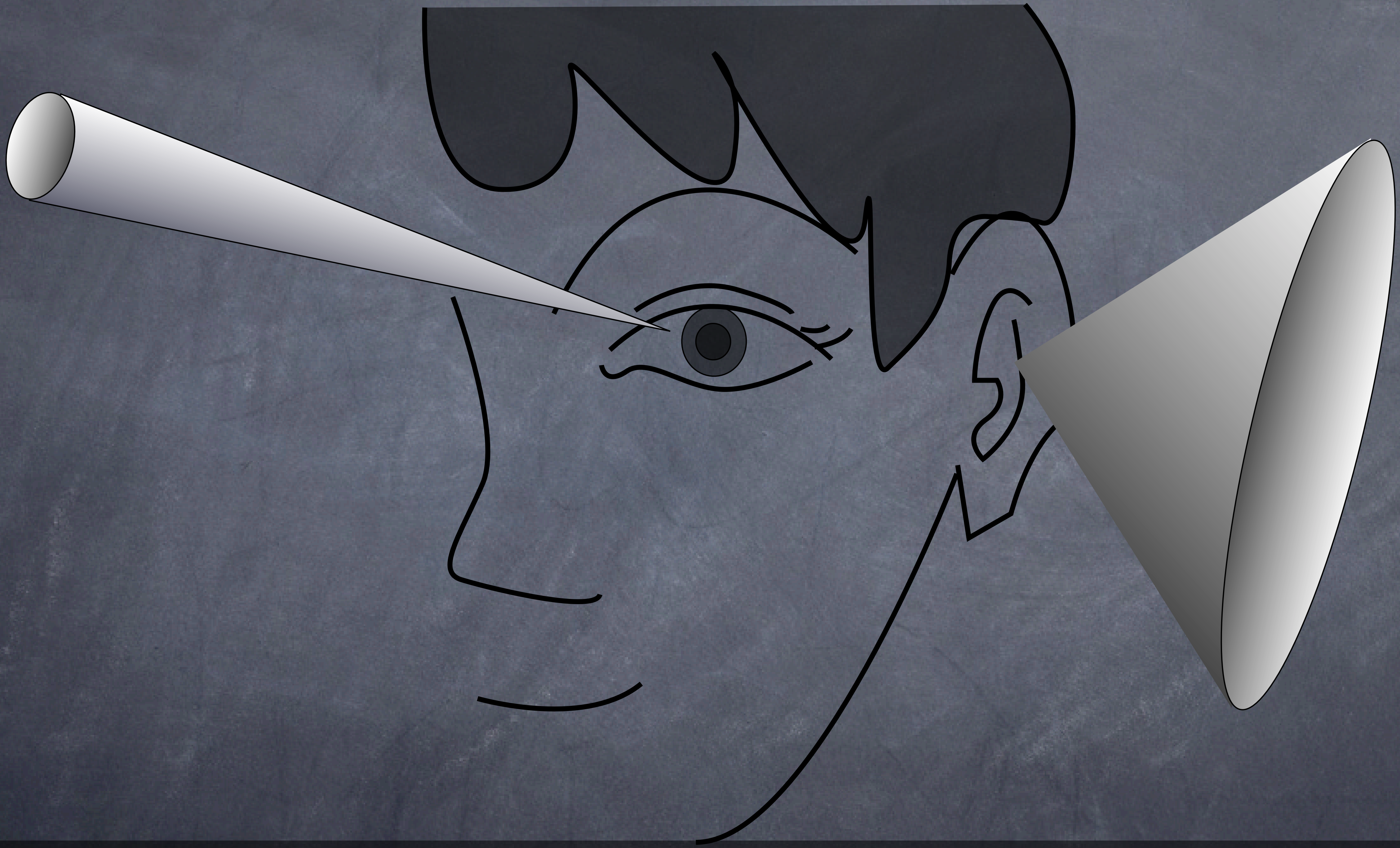
Subaru
Tanaka+06(偏光)
Maeda+06

Swift: GRB (
カウンターパート)

バウンスGW

対流SASI GW

Eye and Ear



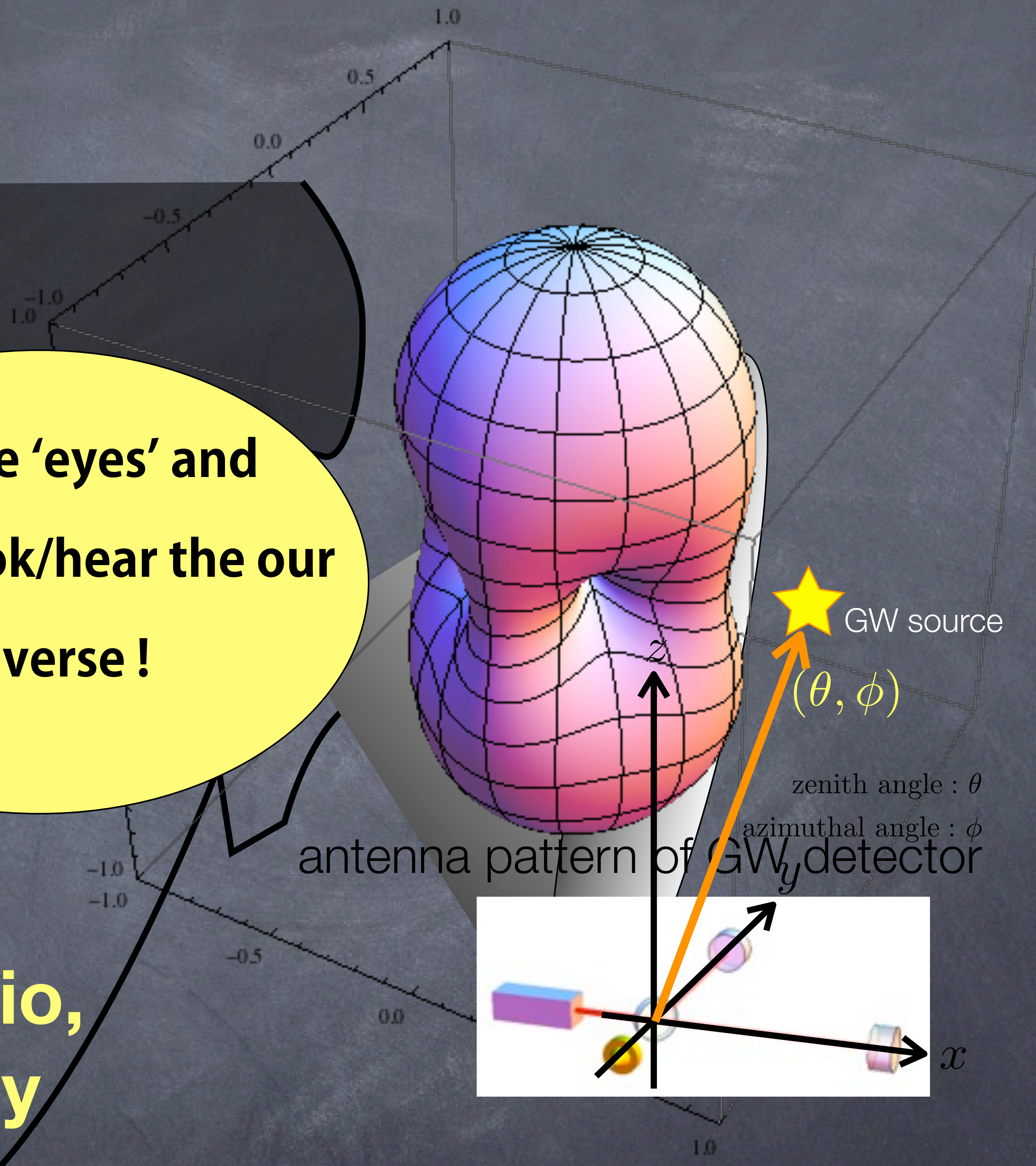
Eye and Ear complete the information from outside.

Eye : fine spatial resolution, good to see the surface of object, hard to see the hidden inside...

Ear : widely angle receiver, bad spatial resolution, suggestion for inside structure...

Eye and Ear

Let's use 'eyes' and 'ears' to look/hear the our universe !



antenna pattern of GW detector

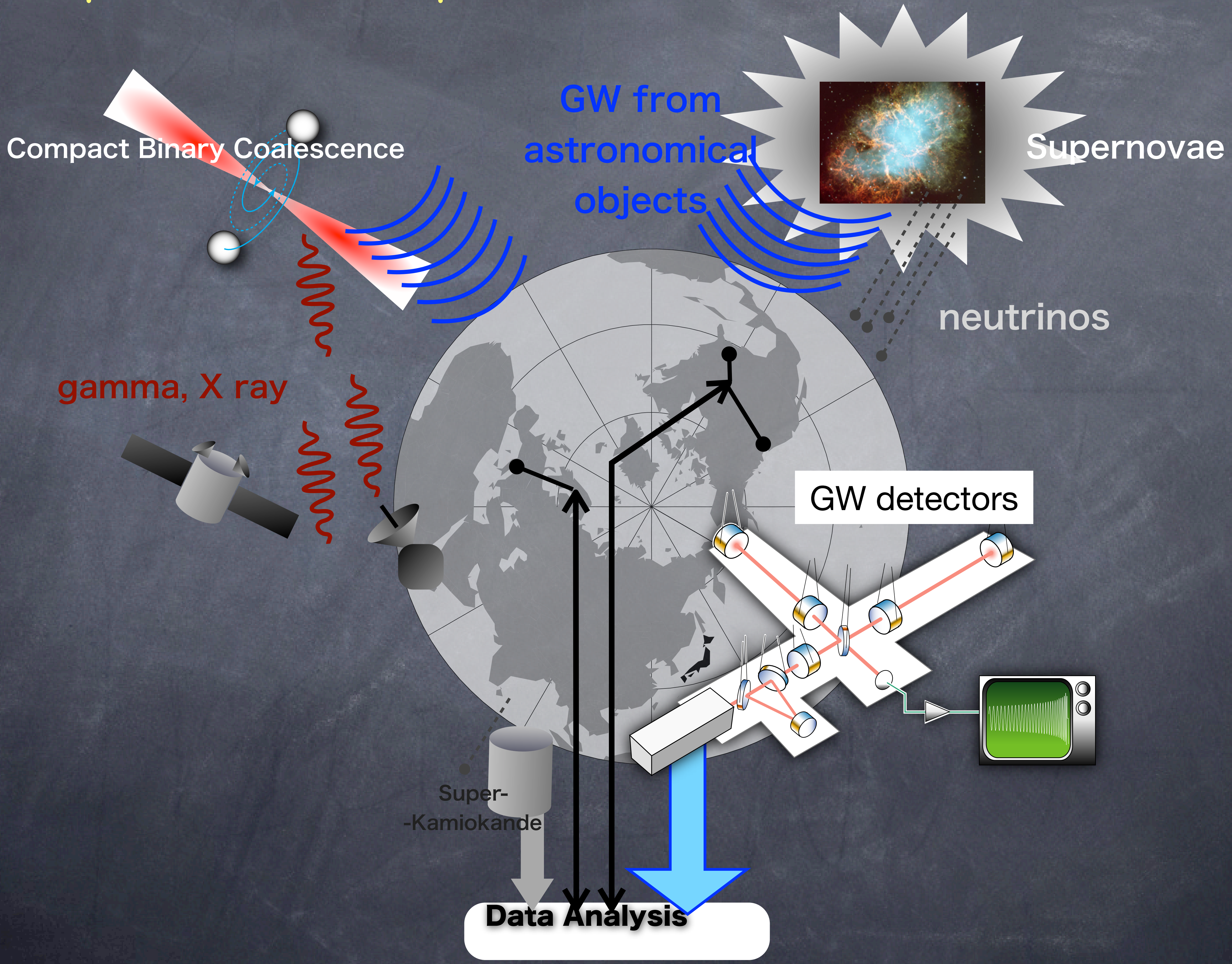
Optical (visible - infrared), Radio, X-ray, Gamma-ray, Cosmic-Ray

Eye and Ear complete the information from outside.

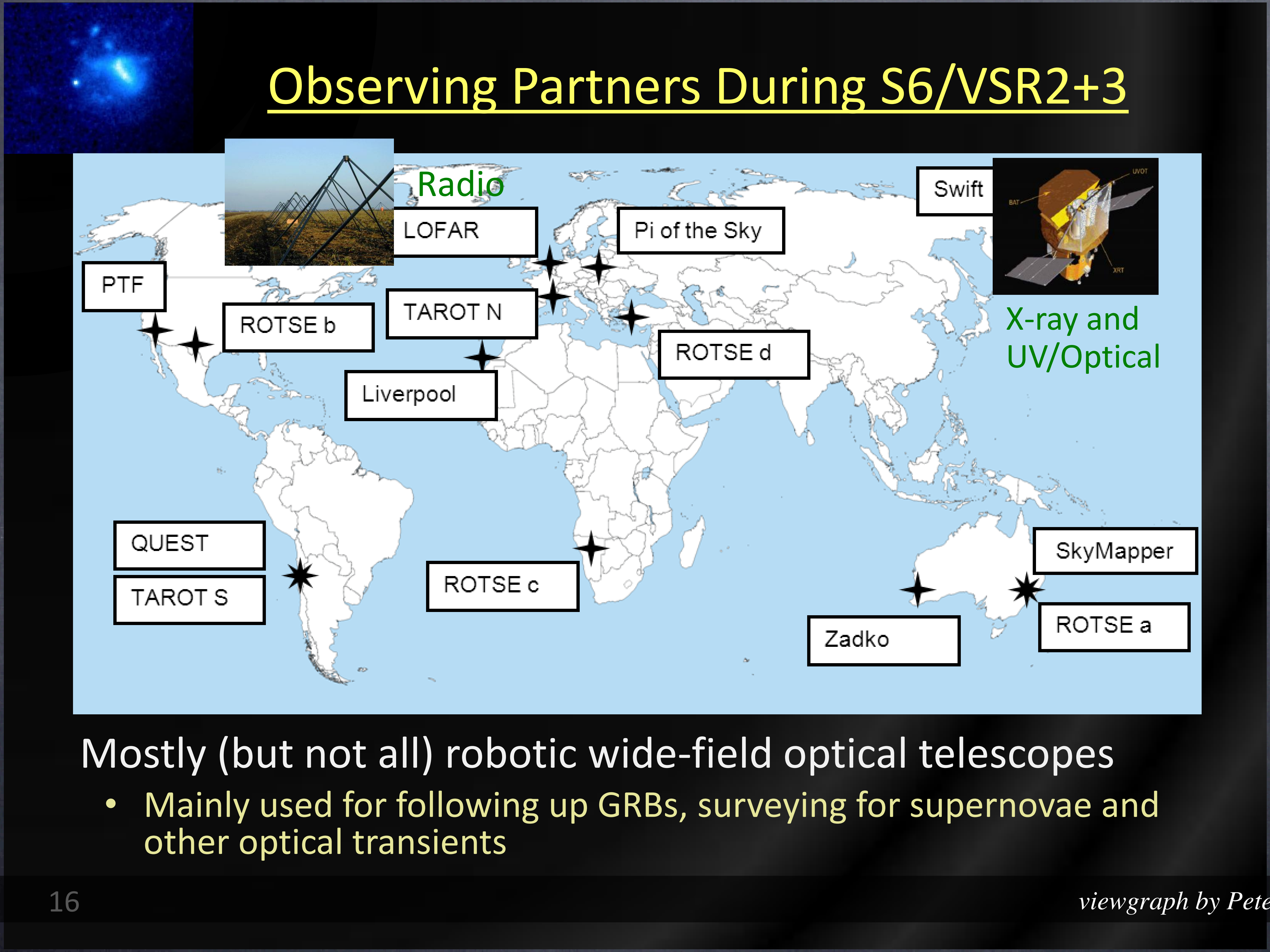
Eye : fine spatial resolution, good to see the surface of object, hard to see the hidden inside...

Ear : widely angle receiver, bad spatial resolution, suggestion for inside structure...

Counterpart / Follow-up Observations



in case of present LIGO-Virgo collaboration



Observing Partners During S6/VSR2+3

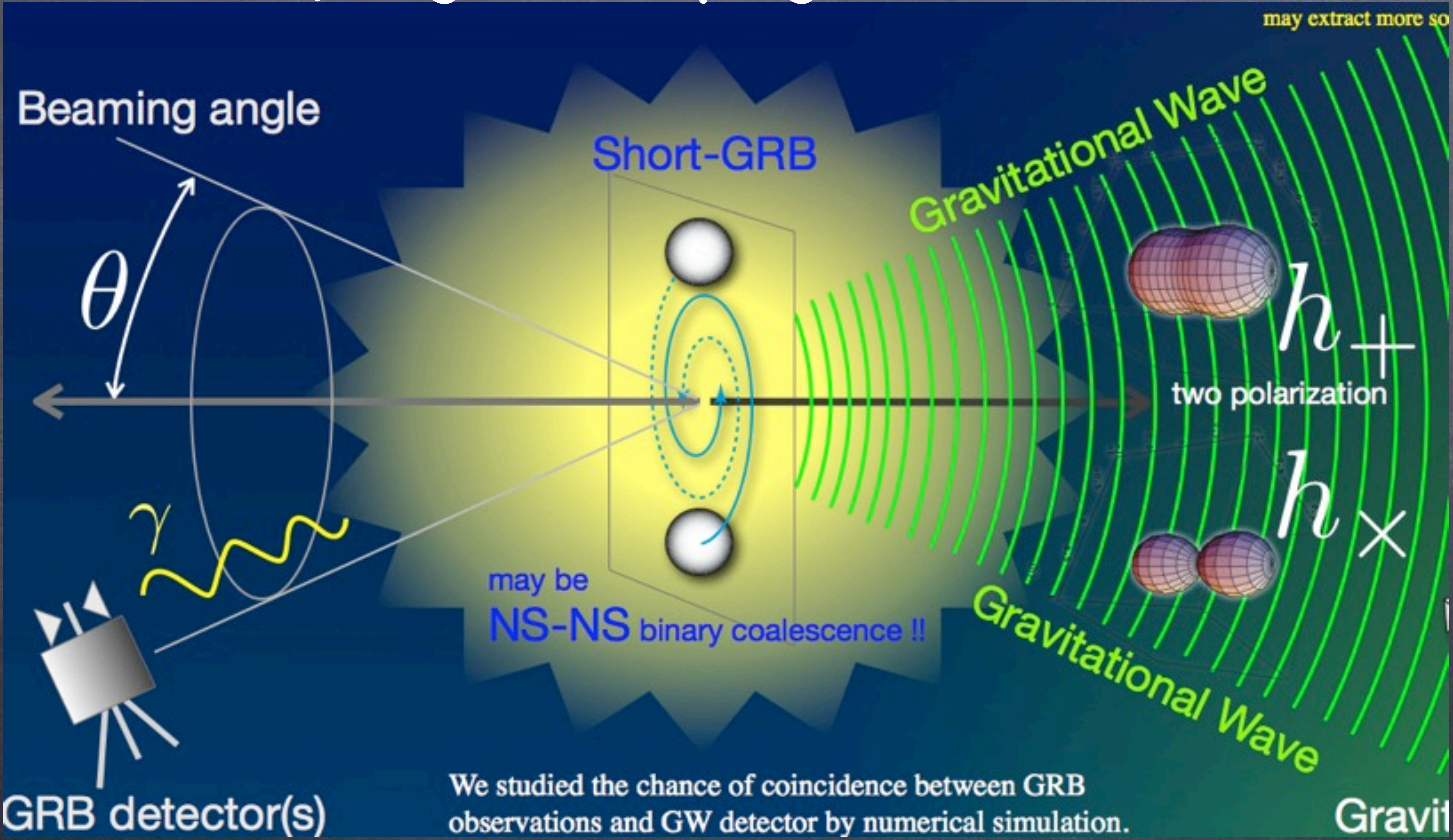
Mostly (but not all) robotic wide-field optical telescopes

- Mainly used for following up GRBs, surveying for supernovae and other optical transients

viewgraph by Peter Shawhan

Compact Binary Coalescences

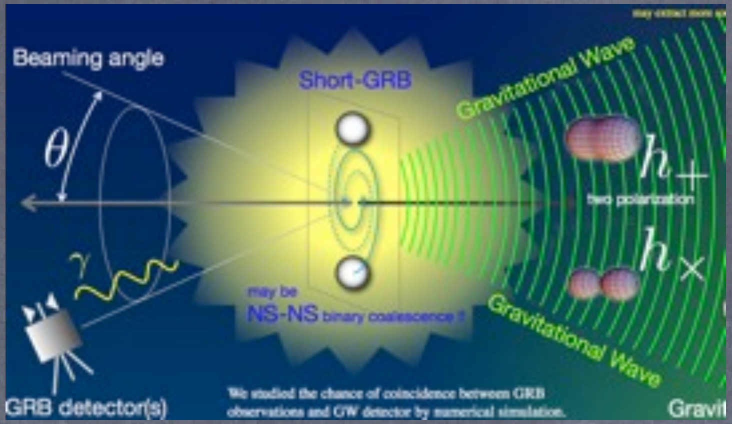
- **NS-NS binary might be a progenitor of Short-GRB.**



We studied the chance of coincidence between GRB observations and GW detector by numerical simulation.

Follow-up obs. between GW and Gamma, X, optical will confirm.

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

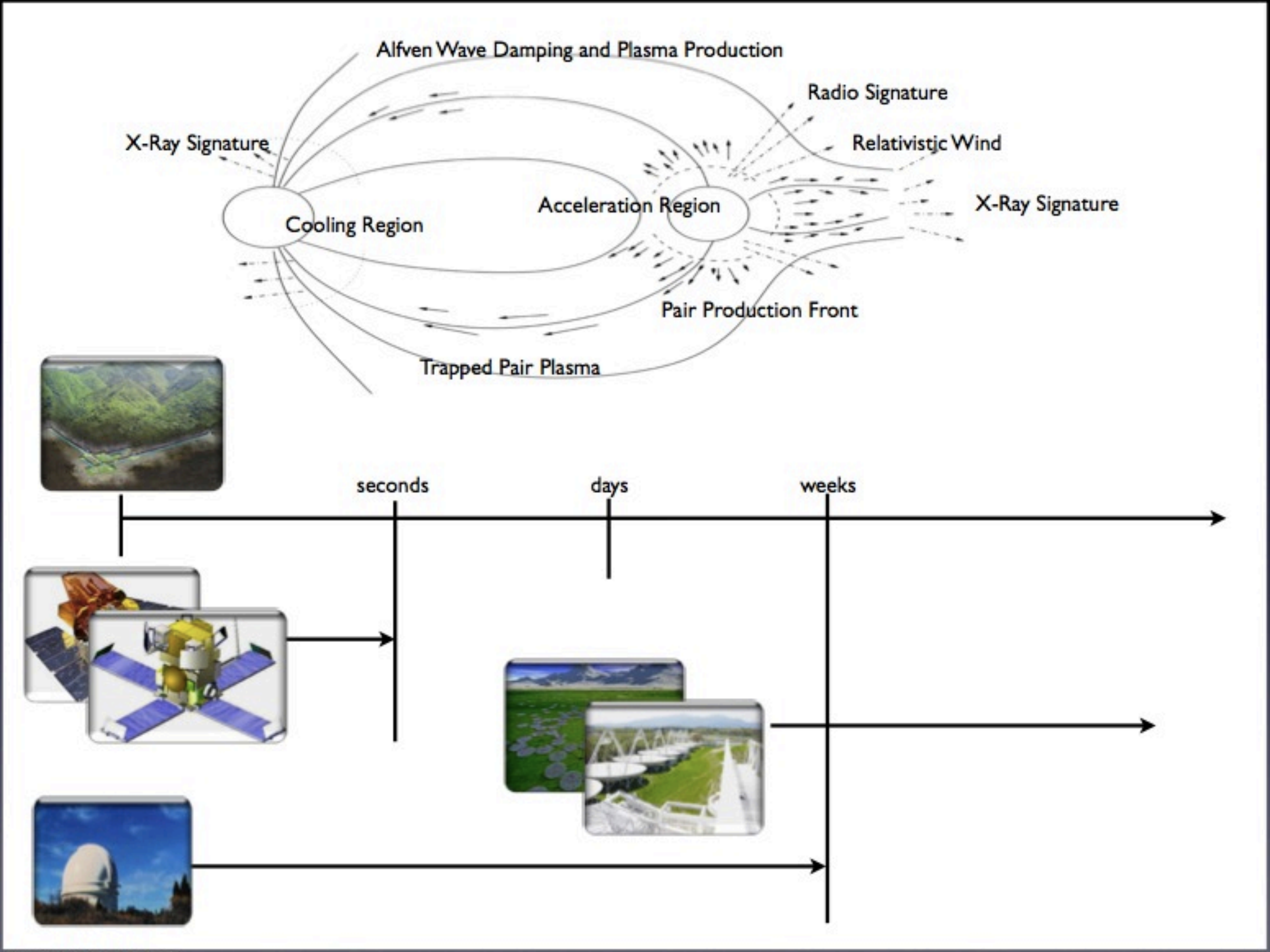
X, Gamma, Optical

Confirmation of Afterglow

[Alert]

date, direction, distance,...

CBC

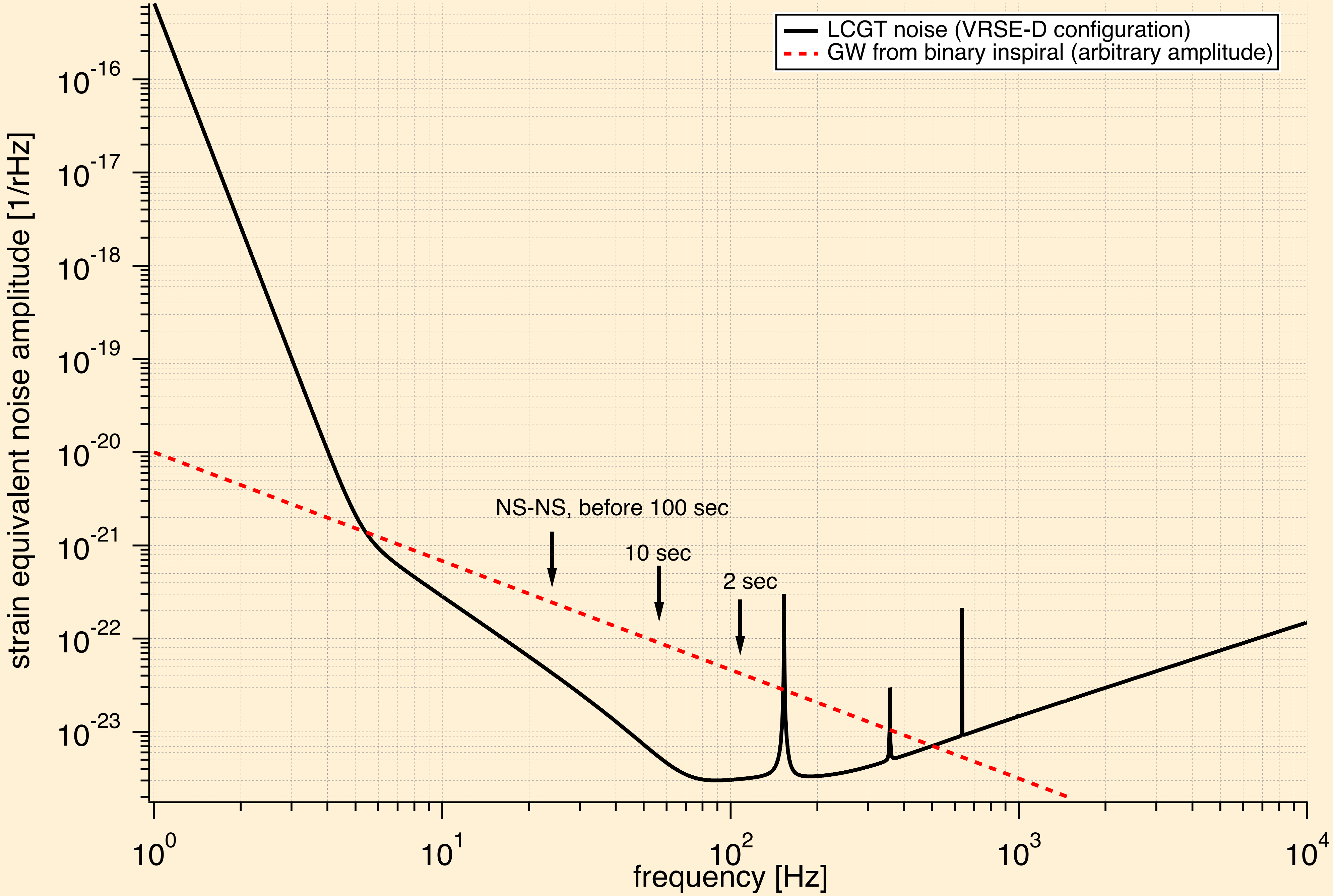


2010年8月11日水曜日

arranged by K.Hayama

Forecast !?

- GW are emitted continuously before coalescence.



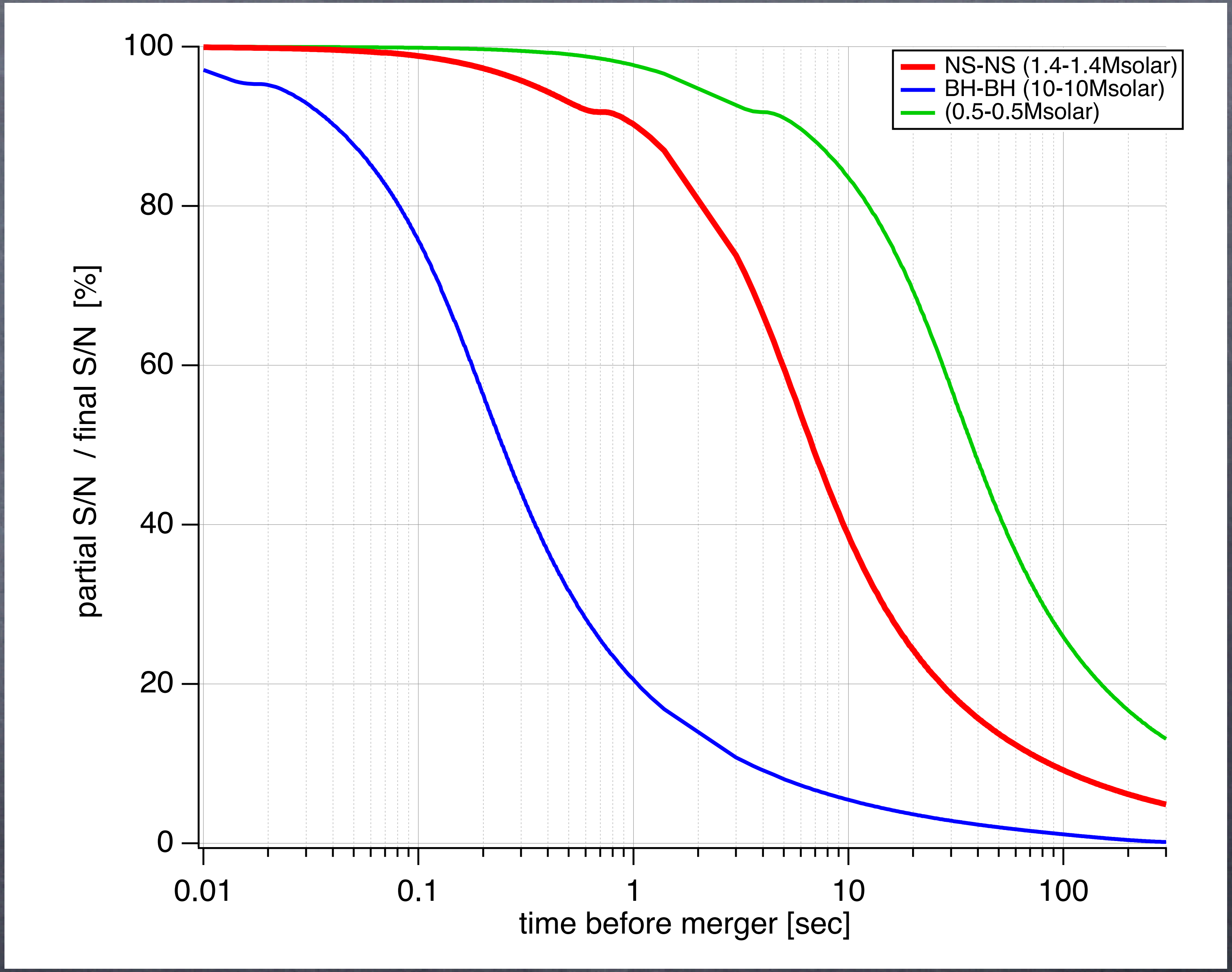
Example of Practical Issue : NS-NS forecast

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.)

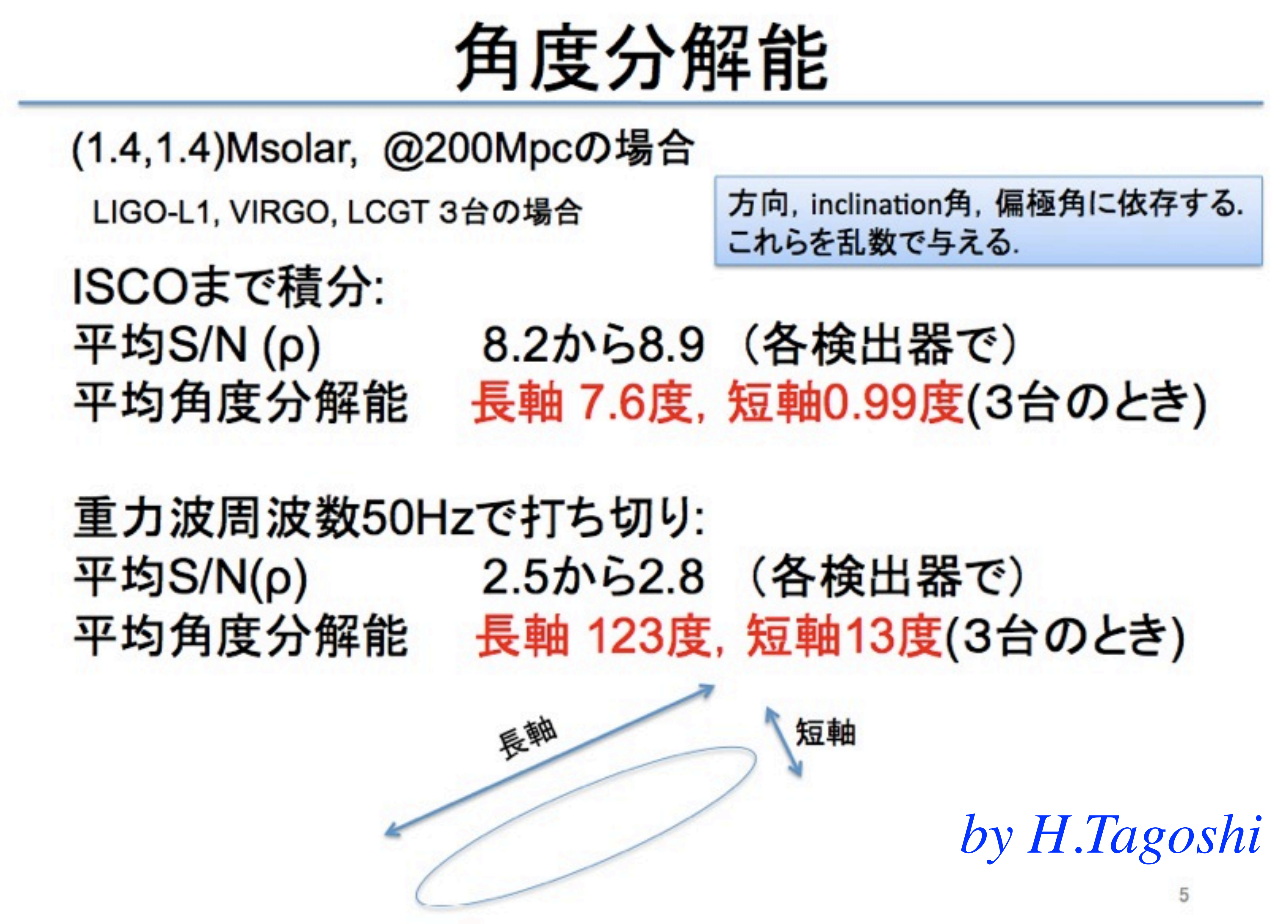
Forecast by GW is not easy, however it is not impossible in principle.

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)

長軸

短軸

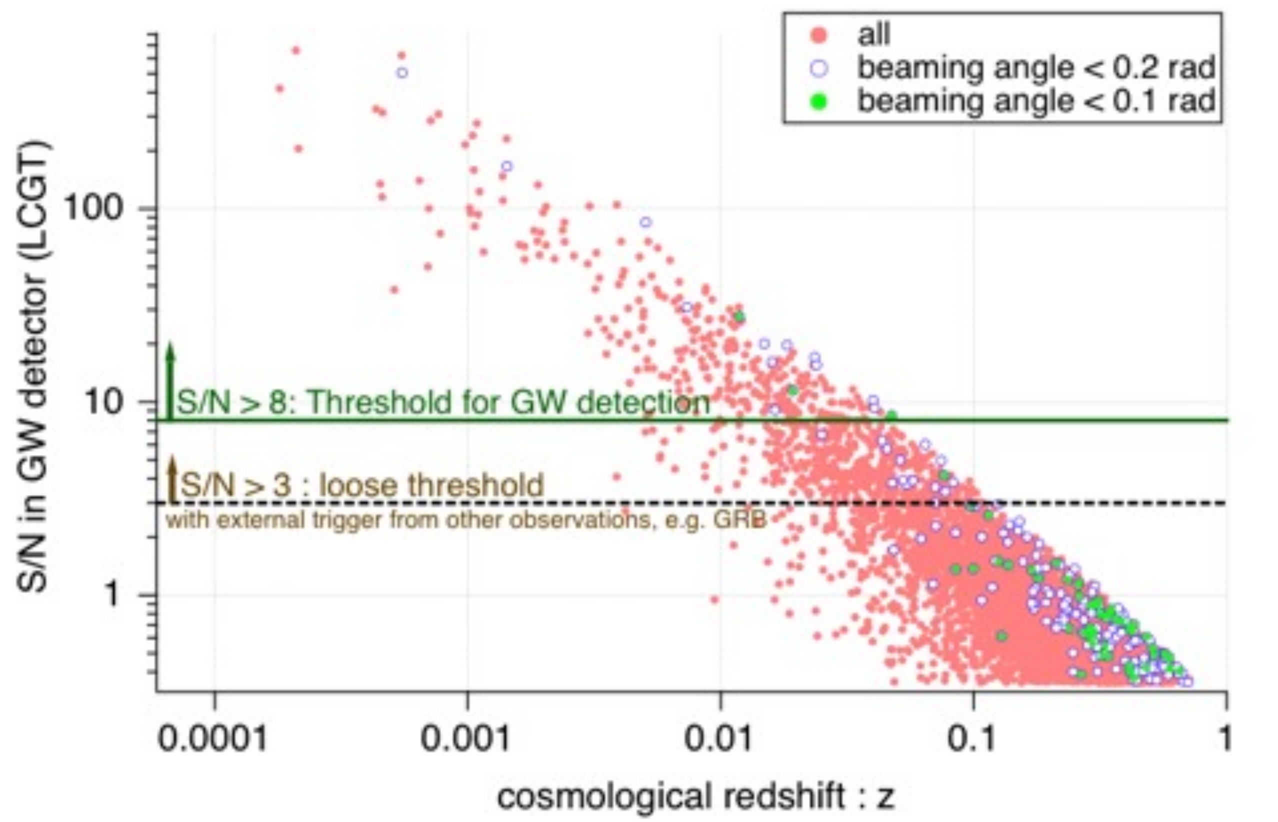
by H.Tagoshi

5

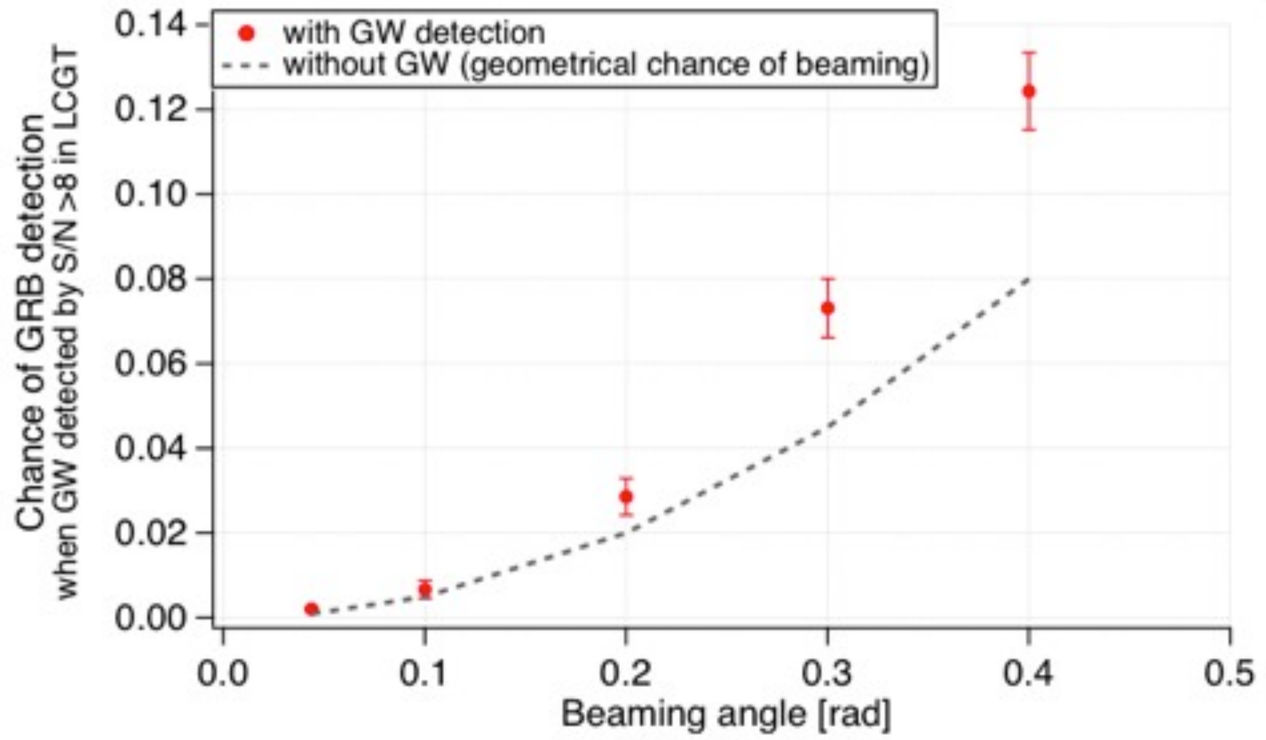
Coincidence chance between GW and GRB

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.



S/N for GW event VS. distance to the source



GRB chance probability , when GW is detected.

GRB 070201 <--> LIGO

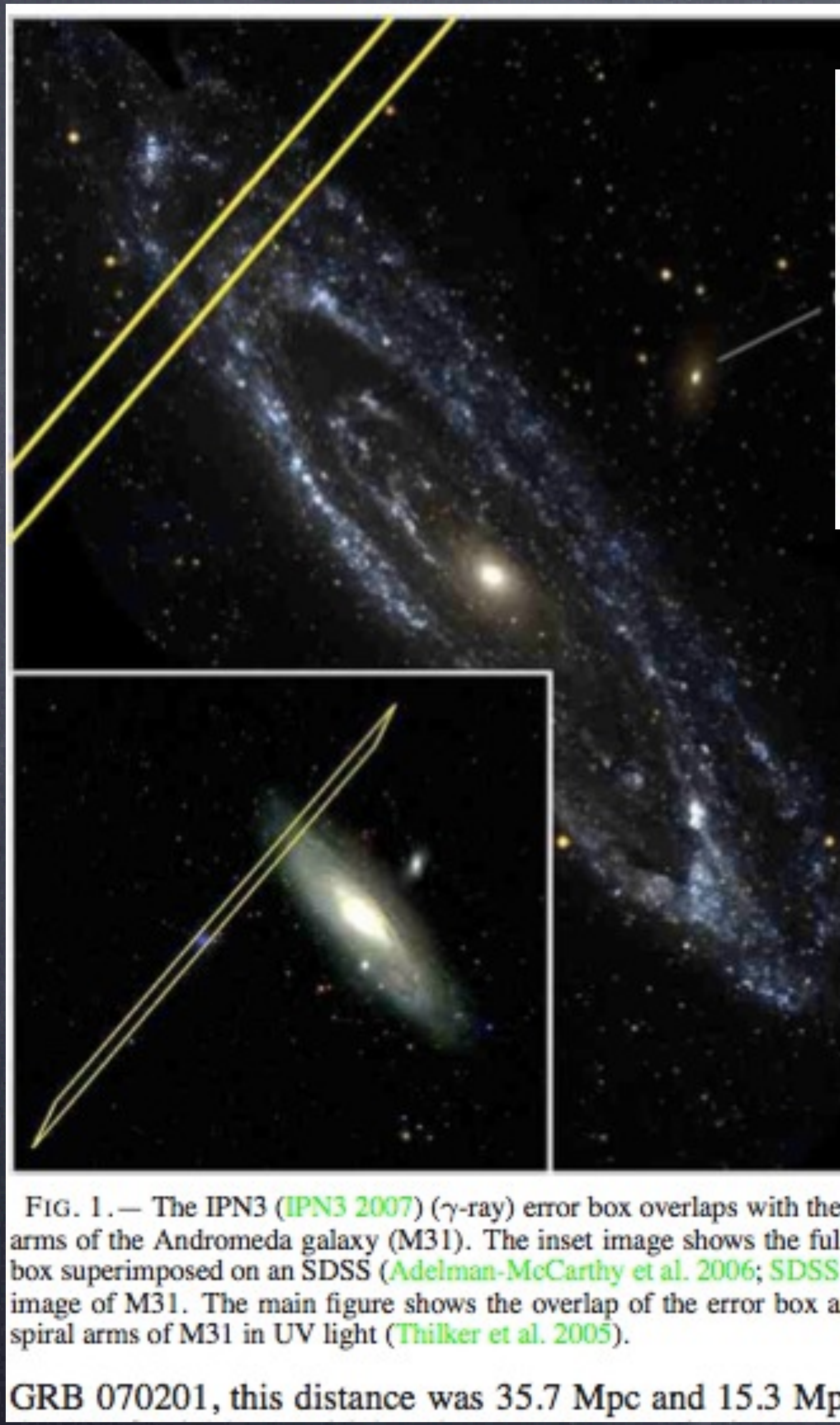
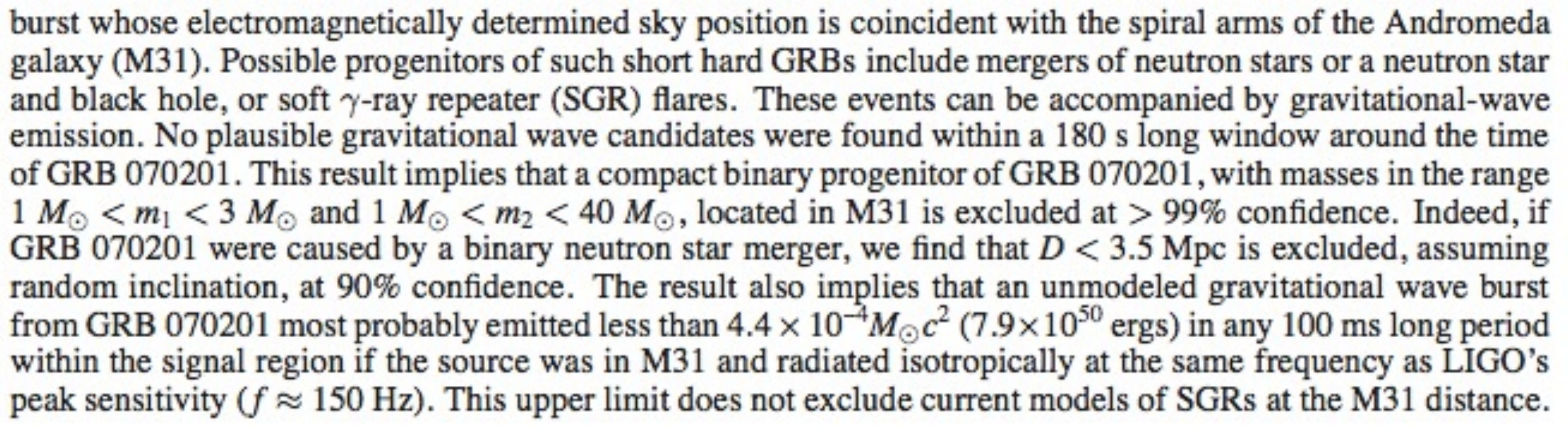


FIG. 1.— The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (Adelman-McCarthy et al. 2006; SDSS 2007) image of M31. The main figure shows the overlap of the error box and the spiral arms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

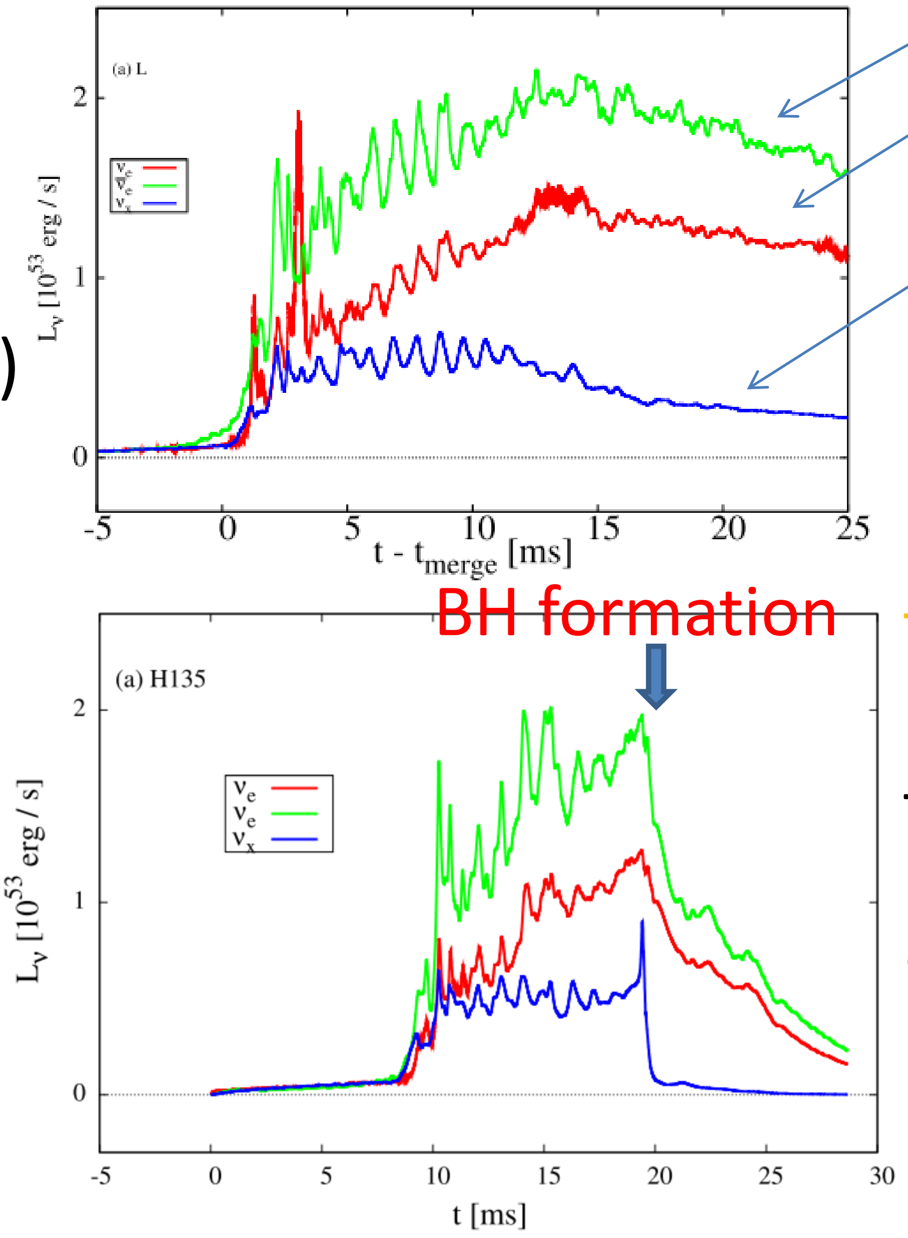
Astrophys.J.681:1419-1428,2008 LIGO collab.

It was NOT CBC. (excluded 99%)

Neutrino Emission from NS-NS merger

- There are few fully GR numerical simulations incorporating microphysics. (e.g., Magneto Hydro Dynamics, EOS with neutrino cooling)
- These results suggest that NS-NS might emit much neutrinos.

Neutrino Luminosity



Shen ($\underline{2.7\ }M_\odot$)

Shen+ Hyperon ($\underline{2.7\ }M_\odot$)

Anti electron neutrino

Electron neutrino

μ, τ neutrino

BH formation

○ Huge luminosity ~ 10^{53} erg/s even after BH formation

○ Neutrino cooling timescale ~ 2-3 second

○ Could be detected if it happened within 10 Mpc for Hyper Kamiokande

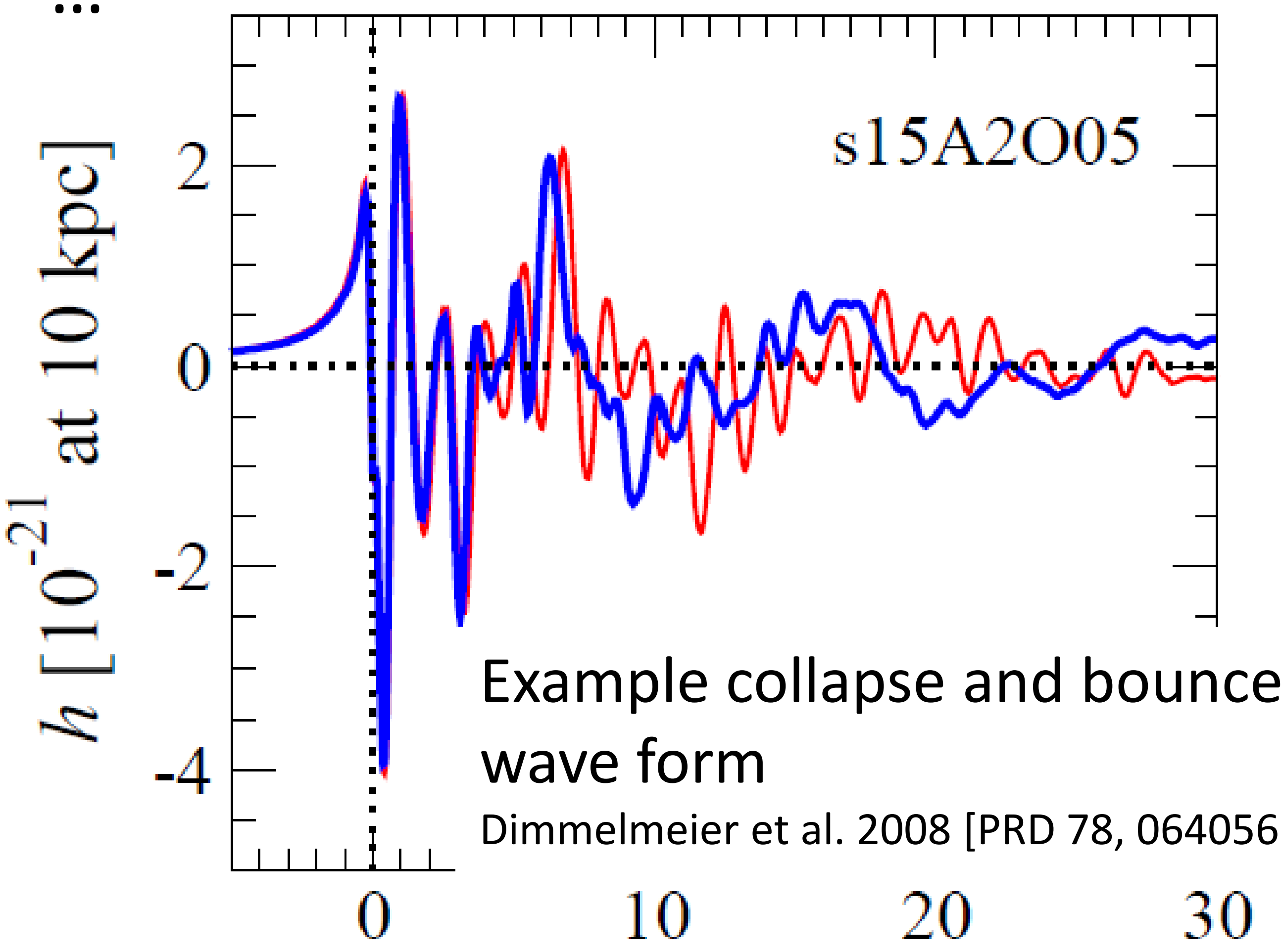
viewgraph by Kenta Kiuchi

Supernovae

may be more promising source for both neutrino and GW.

Various possible gravitational wave emission mechanism:

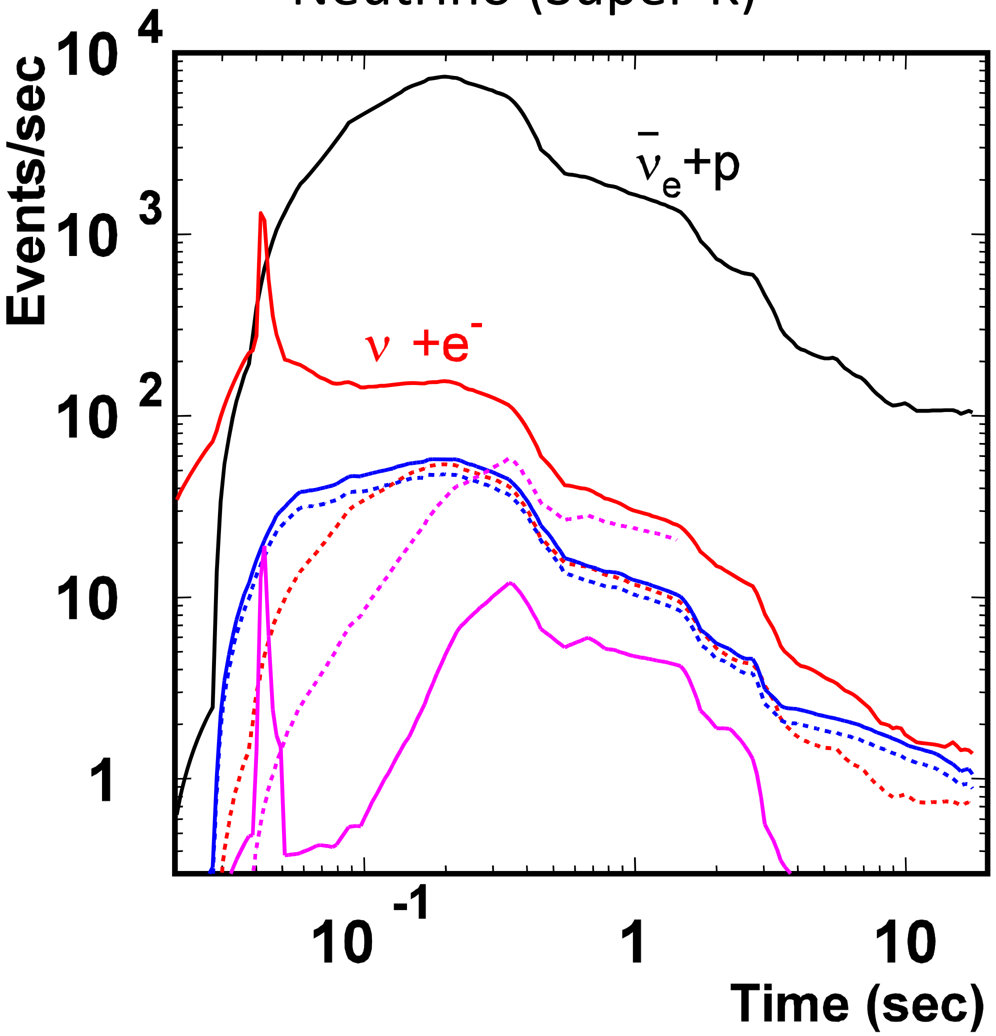
- Core collapse and bounce
- Rotational non-axisymmetric instabilities of proto-neutron star
- Post-bounce convection
- …



Example collapse and bounce wave form

Dimmelmeier et al. 2008 [PRD 78, 064056]

Neutrino (Super-K)



viewgraph by Takaaki Kajita

Neutrino and GW from Supernovae

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

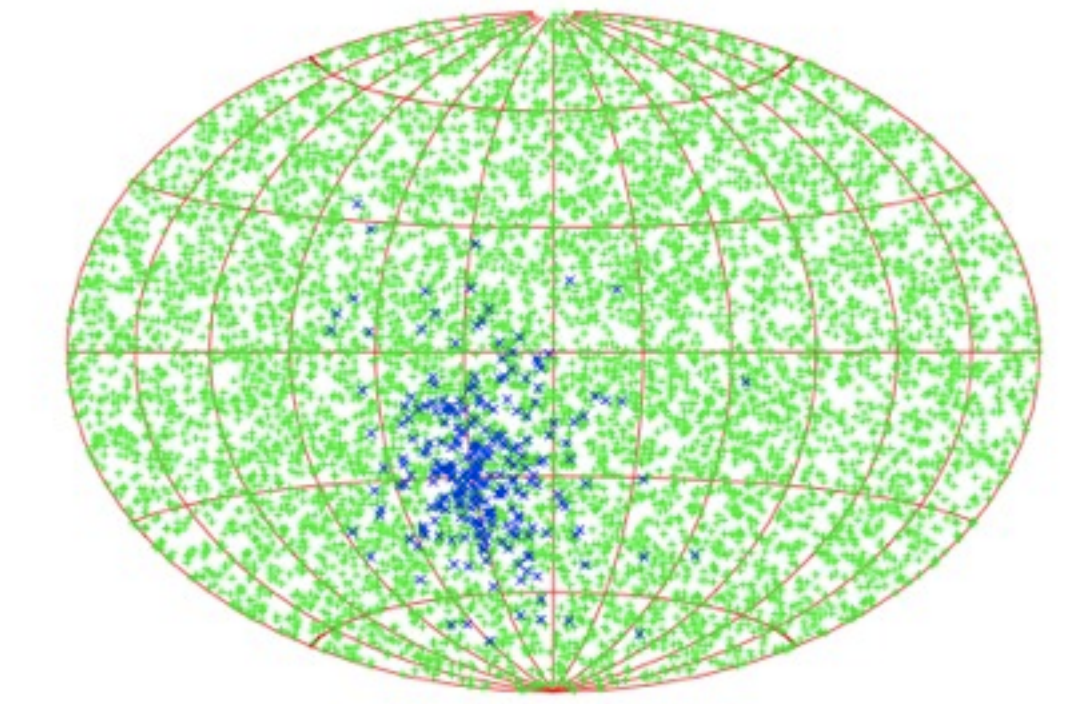
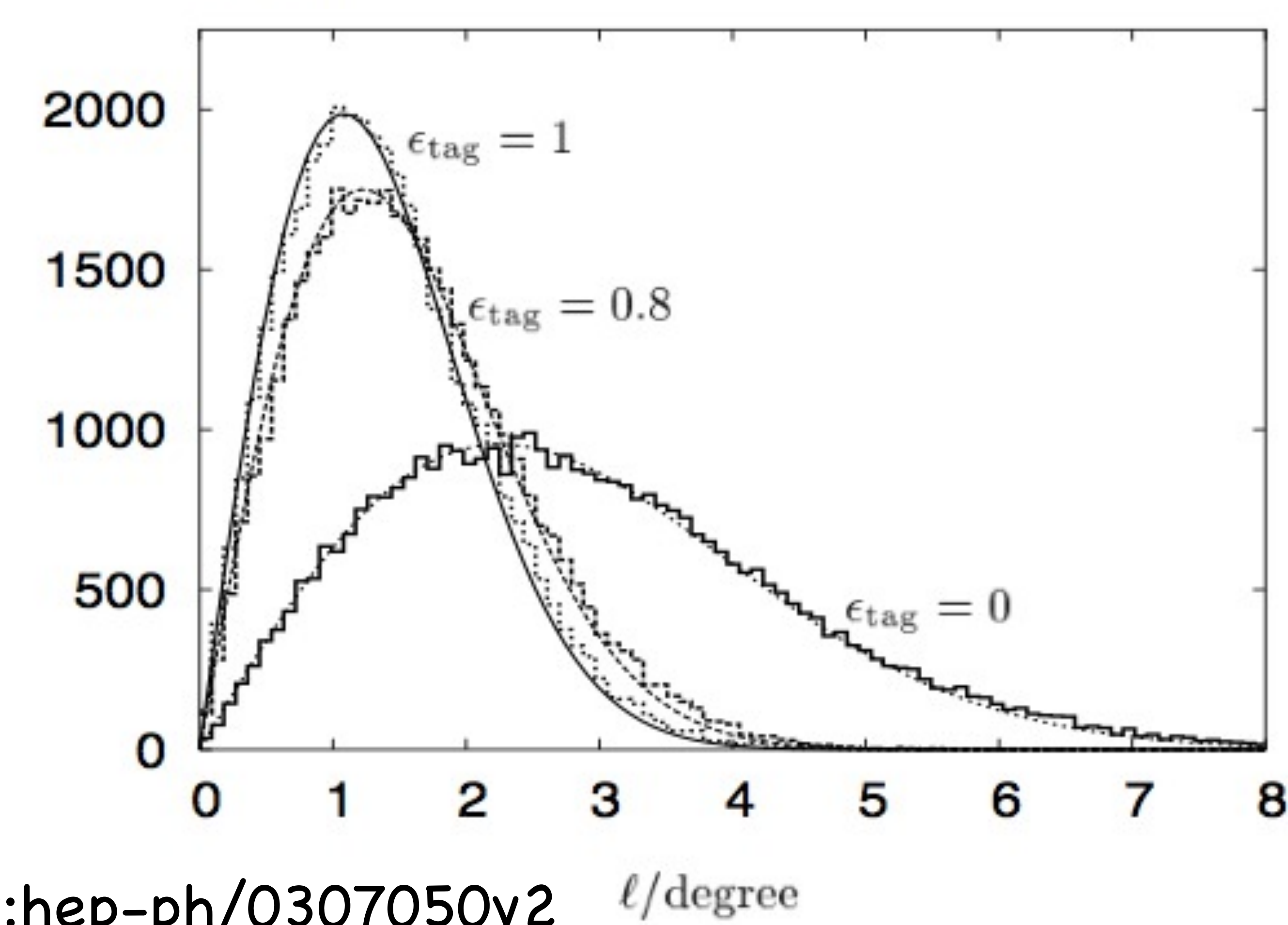


FIG. 4: Angular distribution of $\bar{\nu}_e p \to n e^+$ events (green) and elastic scattering events $\nu e^- \to \nu e^-$ (blue) of one simulated SN.

- **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

Other Possible Sources

- Cusp/Kink of Cosmic String
- LMXB (Wagoner star)
- SMBH, IMBH
- Pulser (Continuous, Pulser glitch)

Summary & Future

- **Gravitational Waves !!!**
- **LCGT**

  has been funded partially, and its construction started !

  (First run will be 2014.)

  Full observation will start at late 2016 or early 2017 with world network of GW observatories.

  It will be an important part of global network.

  We are looking forward the **first detection** !

- **Science of GW is fantastic !**
- **Global Network of GW Detectors and Follow-up Observations**

  will bring fruitful results for

  'Gravitational Wave Astronony'.