Frontier of Gravitational Wave Astronomy

- Opening New Window of Astrophysics and Cosmology -

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Plan of Lecture

lecture 1 : Fundamentals of Gravitational Wave and its Detection

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

  LCGT, LIGO, Virgo, GEO + Planned (IndIGO, LIGO-Australia)

  Japan project = LCGT (Large-scale Cryogenic Gravitational wave Telescope)

  Project outline, Status of Construction, Science Target,

lecture 2 : Physics, Astrophysics and Cosmology with Gravitational Waves

- **Global Network of GW Detectors**

  What can be derive from GW detectors.

- **Physics of GW Sources**

  Compact Binaries, Supernovae, Black hole, Pulsar, etc.

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

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

Note:

- **Gravitational Wave (GW)**

  is not detected directly yet at Summer 2011.

  In this lecture, we will display figures/sounds of GW by theoretical prediction, simulation etc. mainly (but not all) .

- **Construction/Upgrading of newer detectors**

  are started already.

  Some of them are real photograph, but also include future plans.

lecture 1 : Fundamentals of Gravitational Wave and its Detection

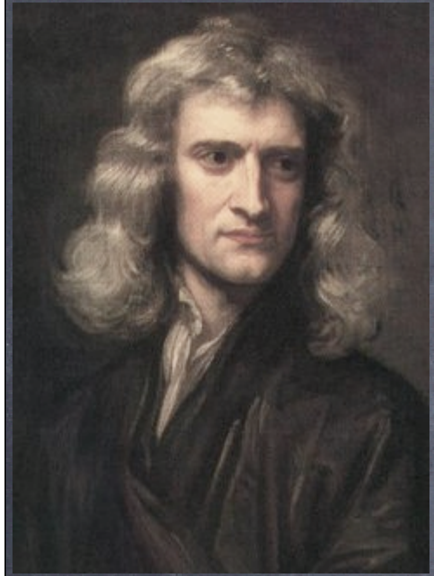
What is Gravitational Waves ?

Where come from ?

Why we would like to measure ?

How to detect it ?

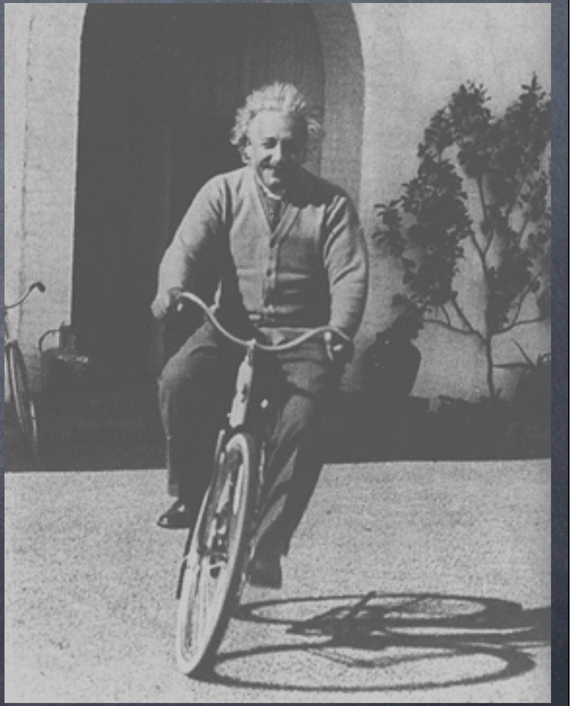
Gravity --> Gravitational Wave



Discover of Gravity

by Newton

"action at a distance"



General Relativity

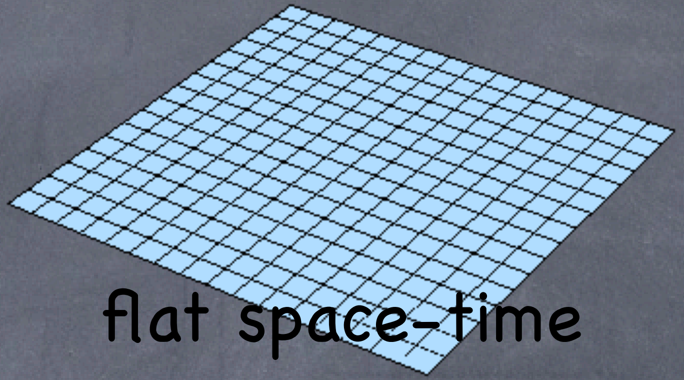
by Einstein

"distortion of space-time"

What is Gravitational Wave ?

Einstein's Equation

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



flat space-time

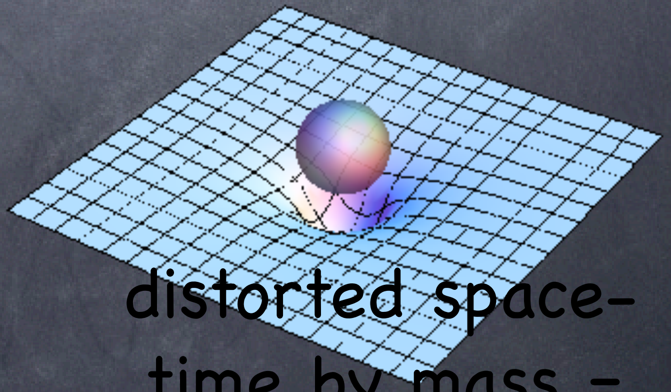
metric tensor

"flat" space-time (Minkowski)

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

"curved (distorted)" space-time

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

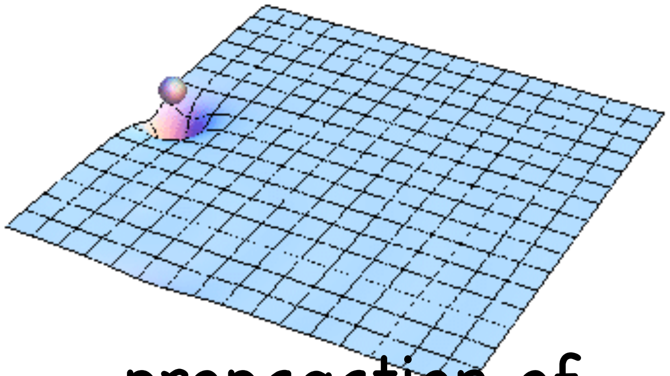


distorted space-time by mass = gravity

Gravitational Waves

- **Einstein Equation :**

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



propagation of distortion

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

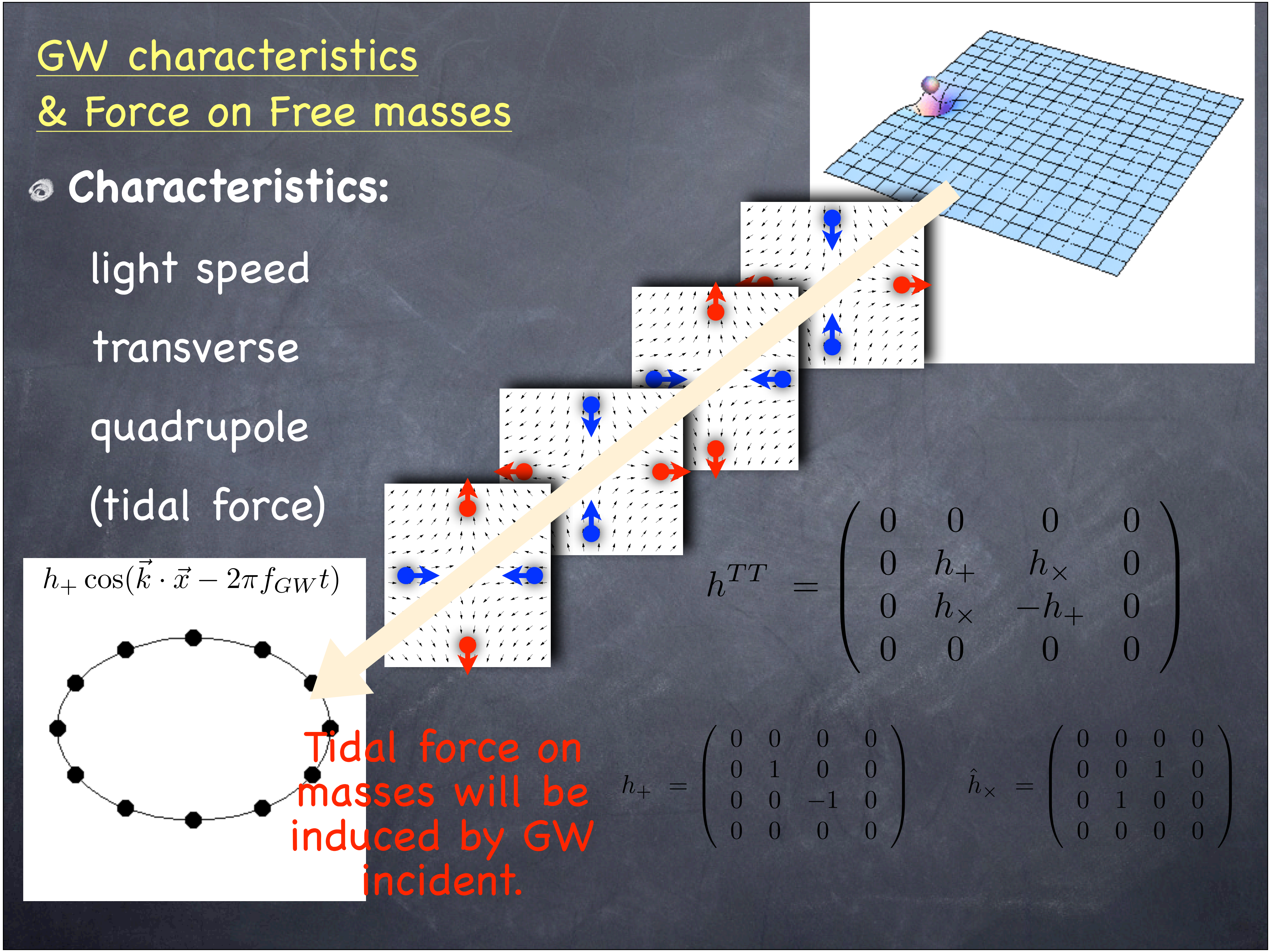
- **Characteristics:**

  light speed

  transverse

  quadrupole

  (tidal force)



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

Tidal force on masses will be induced by GW incident.

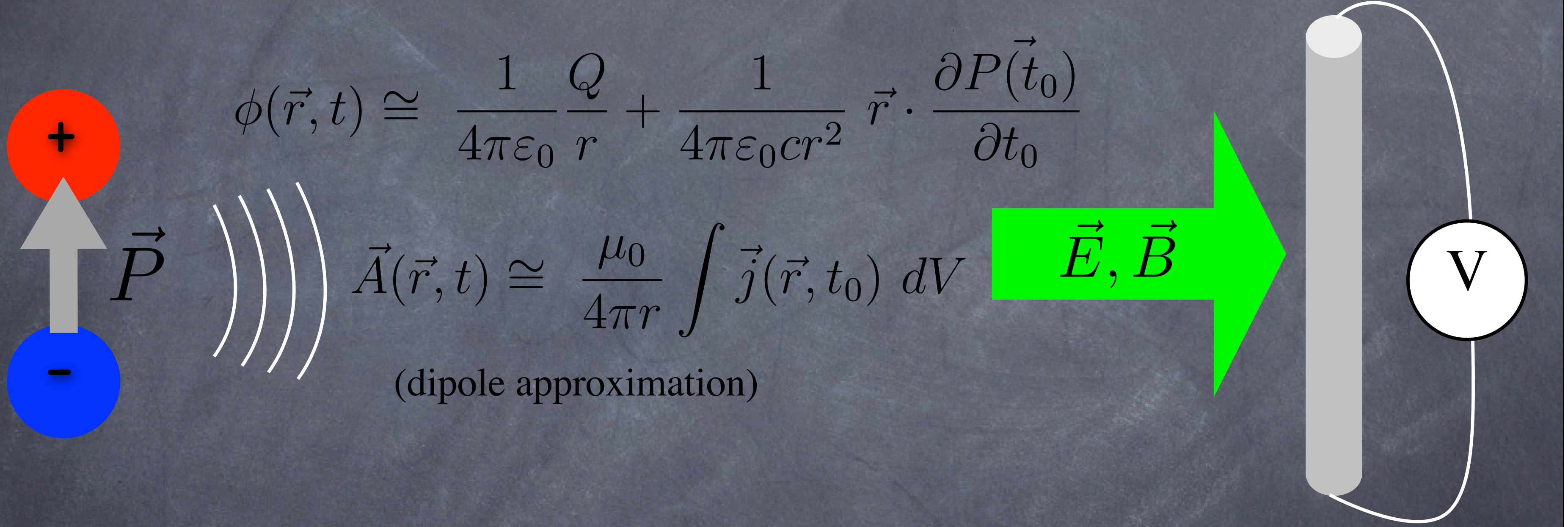
$$h^{TT} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

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

	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.



$$\phi(\vec{r},t) \cong \frac{1}{4\pi\varepsilon_0}\frac{Q}{r} + \frac{1}{4\pi\varepsilon_0 c r^2}\,\vec{r}\cdot\frac{\partial P(\vec{t}_0)}{\partial t_0}$$

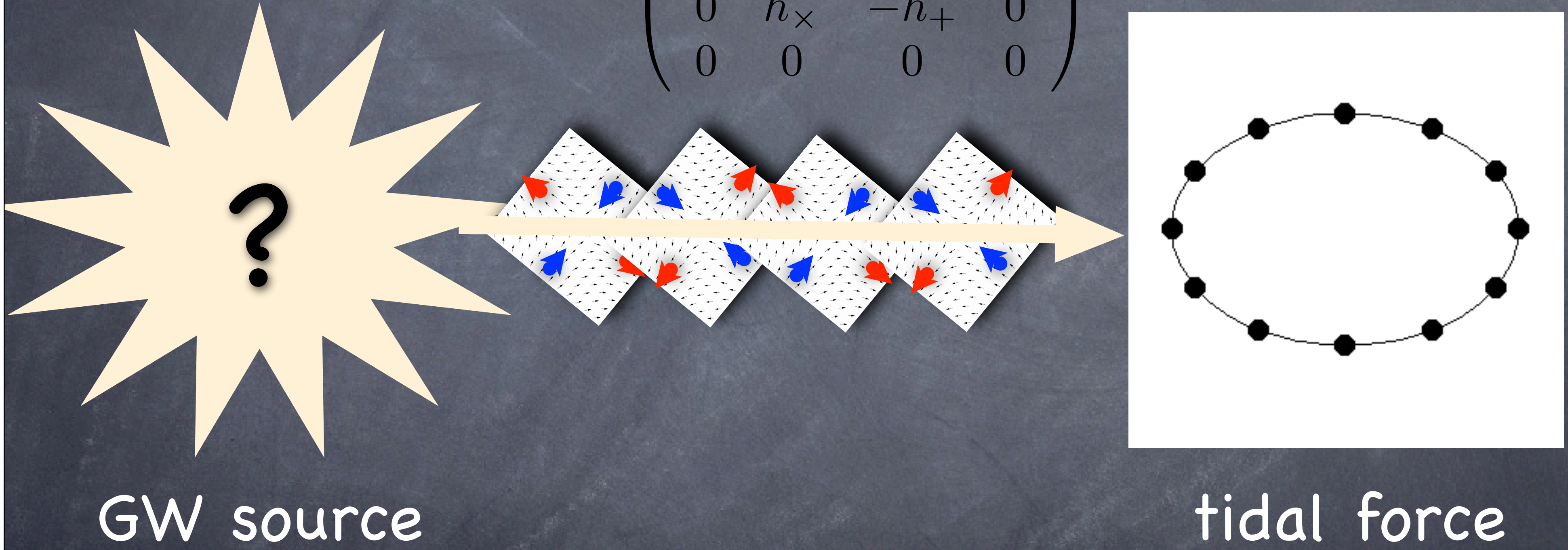
$$\vec{A}(\vec{r},t) \cong \frac{\mu_0}{4\pi r}\int \vec{j}(\vec{r},t_0)\;dV$$

(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

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



Quadrupole Radiation is fundamental in GW.

- **Electro-Magnetic Waves**

  Electric dipole (Charge dipole),

  Magnetic dipole (Current dipole),

  Electric quadrupole, …., …., …., …

- **Graviational Waves**

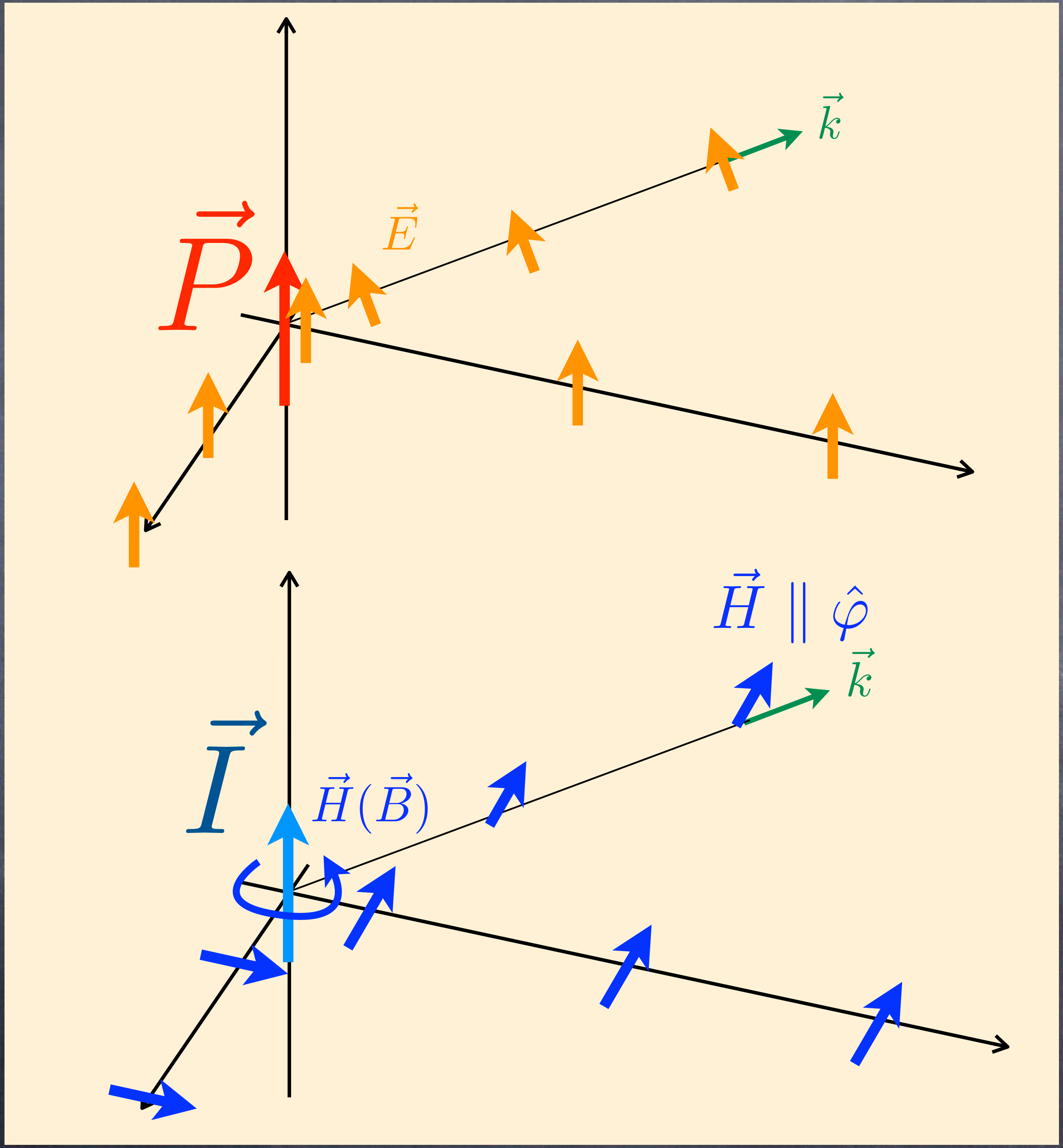
  Quadrupole (Mass),

  Quadrupole (Mass current),

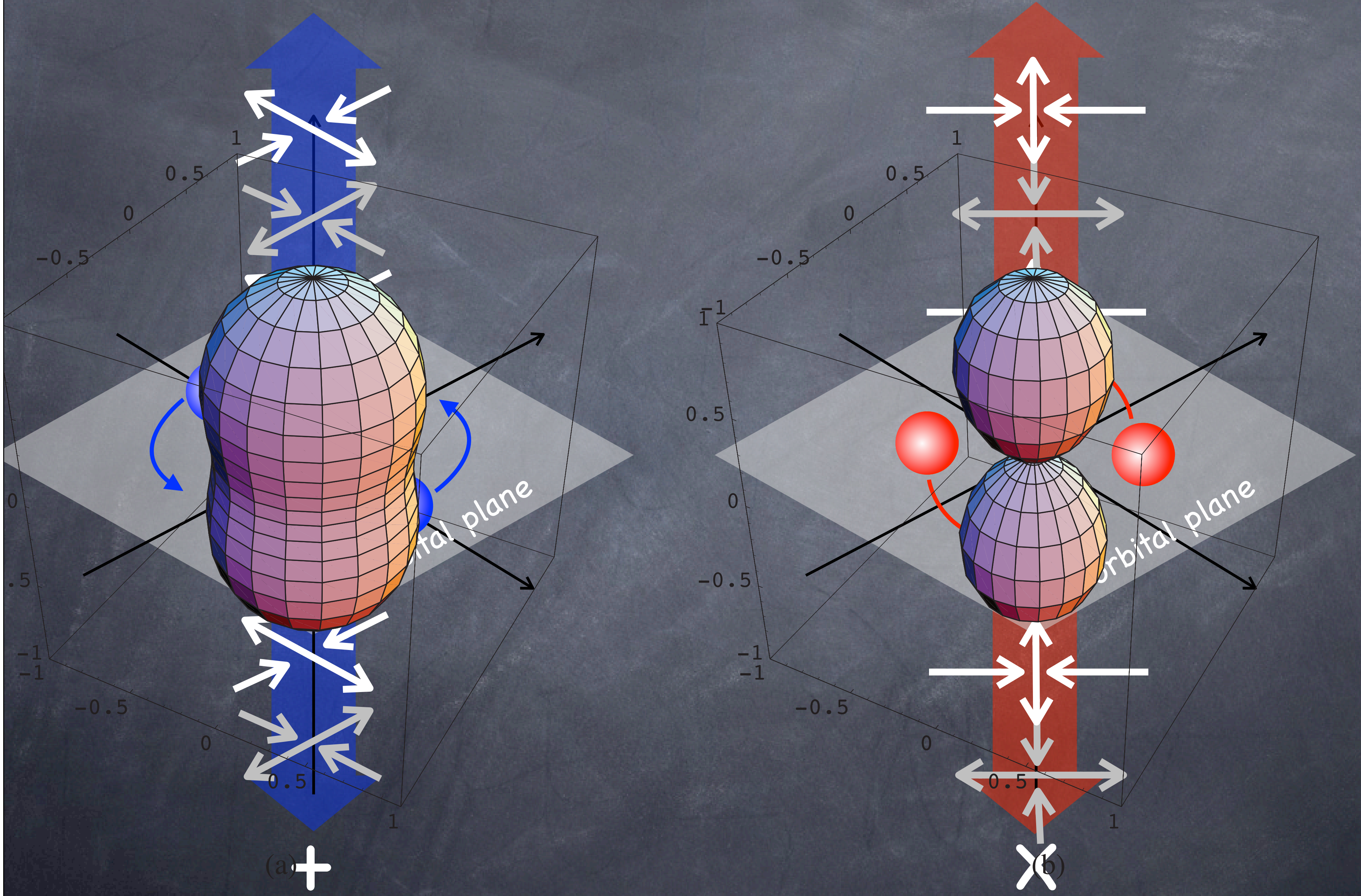
  …., …., …

  Dipole Radiation is inhibited, because ….

Elacromagnetic Wave from Dipole

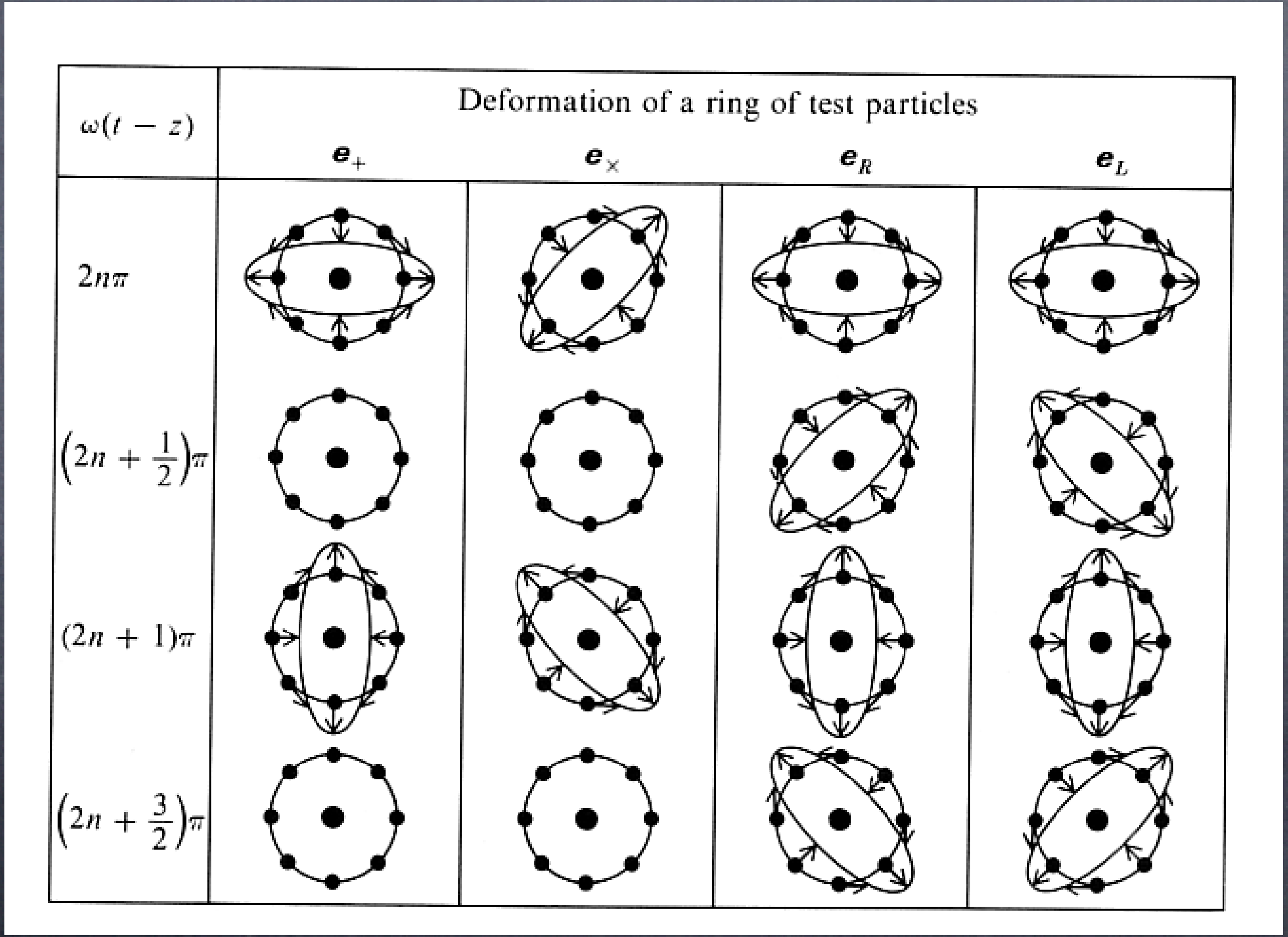


GW from Quadrupole Motion



Polarization

$$\mathbf{e}_+ = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \quad \mathbf{e}_\times = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}.$$



$\omega(t-z)$	Deformation of a ring of test particles			
	$\boldsymbol{e}_+$	$\boldsymbol{e}_\times$	$\boldsymbol{e}_R$	$\boldsymbol{e}_L$
$2n\pi$				
$\left(2n+\frac{1}{2}\right)\pi$				
$(2n+1)\pi$				
$\left(2n+\frac{3}{2}\right)\pi$				

Misner, Thorne, Wheeler
W H Freeman & Co (Sd) (1973/09)

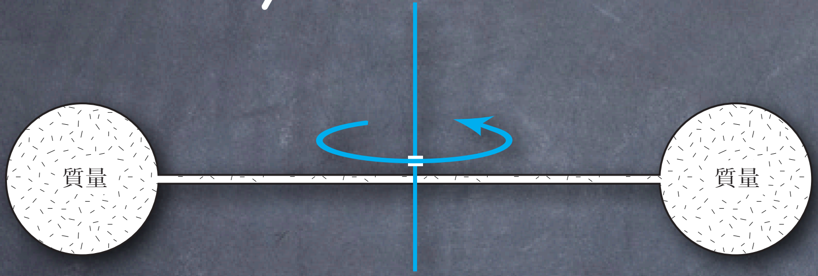
We can choose (e+,ex) or (eR, eL) as independent basis.

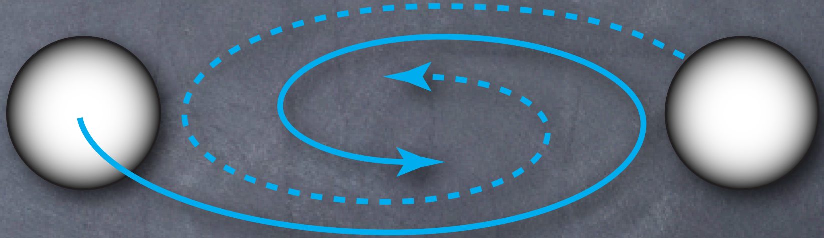
Where ? - Fundamental Source of GW radiation -

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

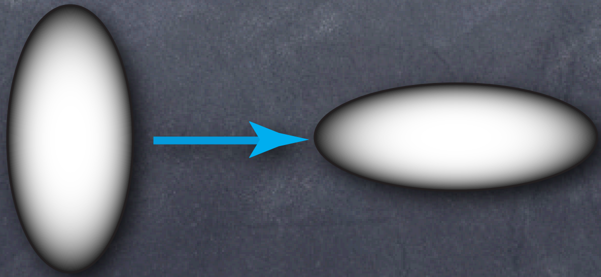
$$I_{\mu\nu} = \int dV(x_\mu x_\nu - \frac{1}{3}\delta_{\mu\nu}r^2)\rho(\vec{r})$$

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

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

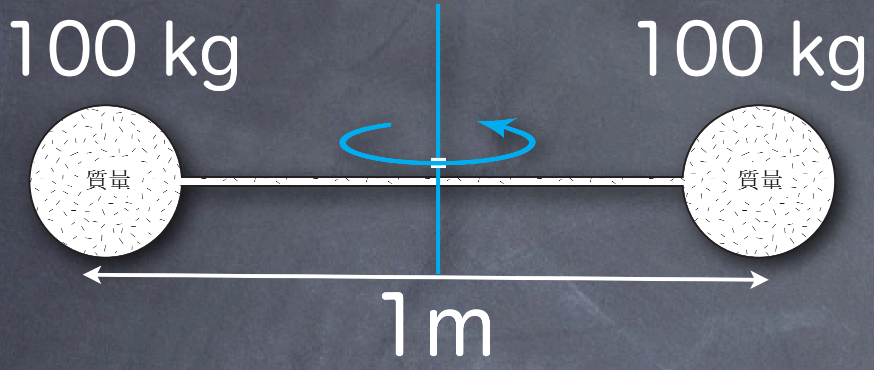
- **Energy**

  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~10^{-35}

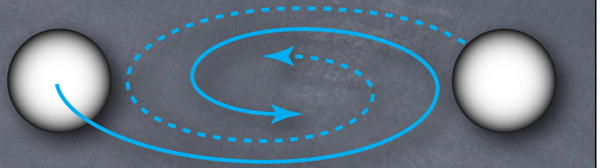
=1m ruler change as

$$\frac{1}{10000000000000000000000000000000000}\ \mathrm{m}.$$

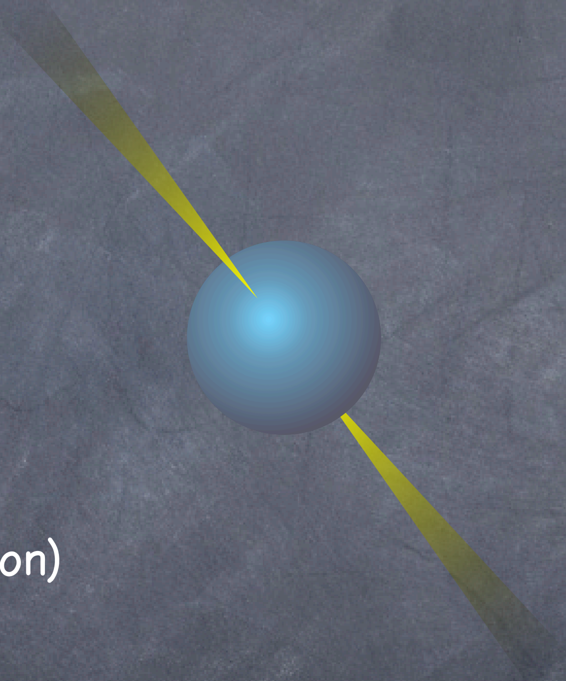
(note: we need more than 150km distance for wavezone of 2kHz GW.

Artificial source is very difficult ...

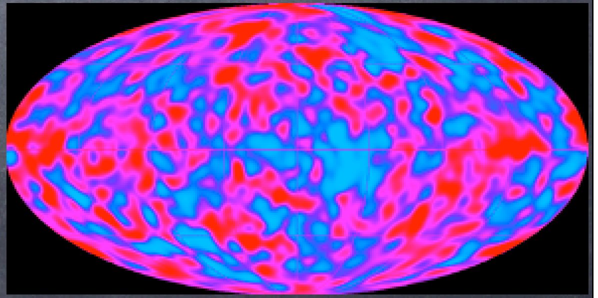
Where ? - possible sources of GWs -



- **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**

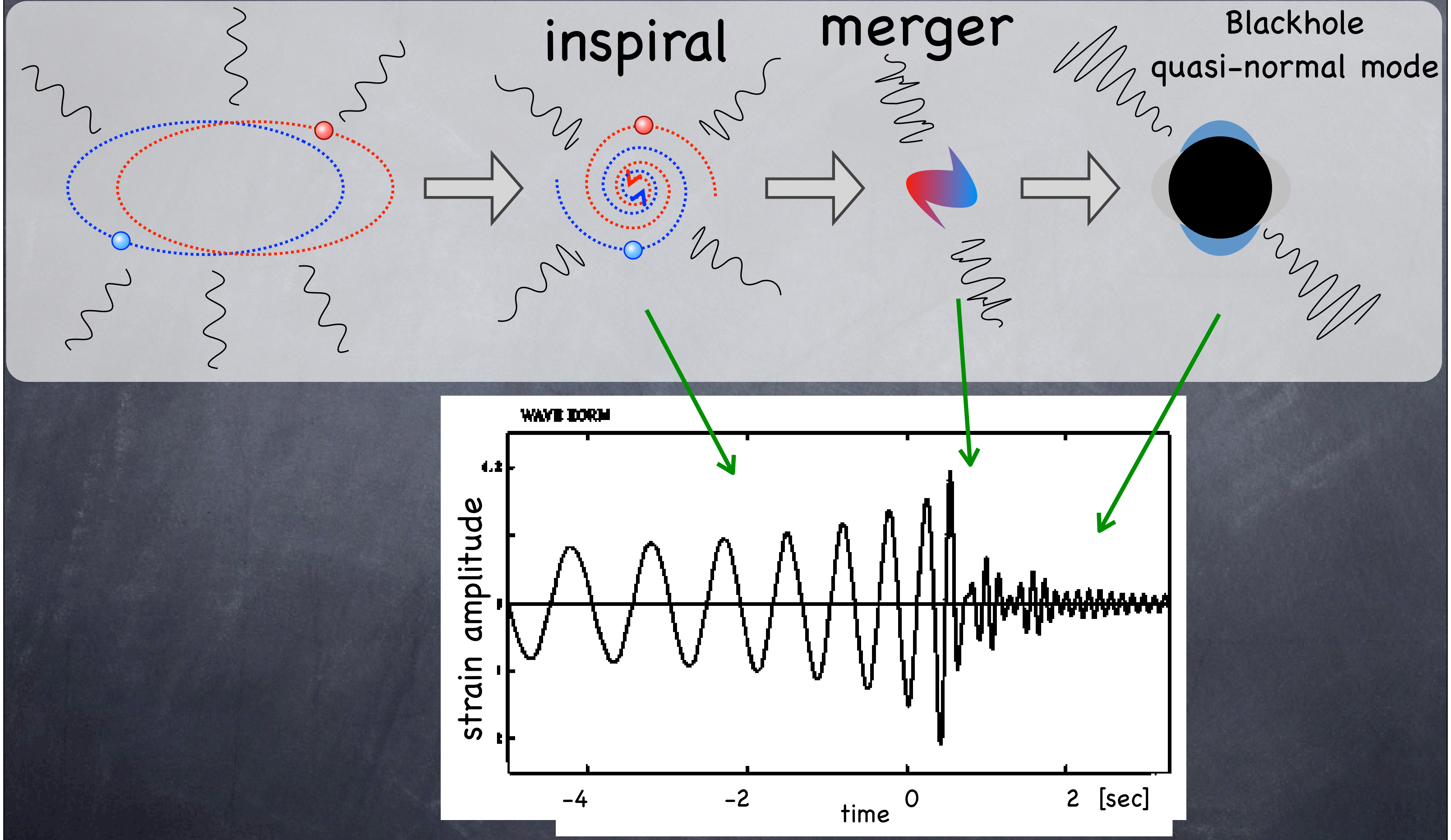
  Cosmic background radiation of GW

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

  Physics of early universe.

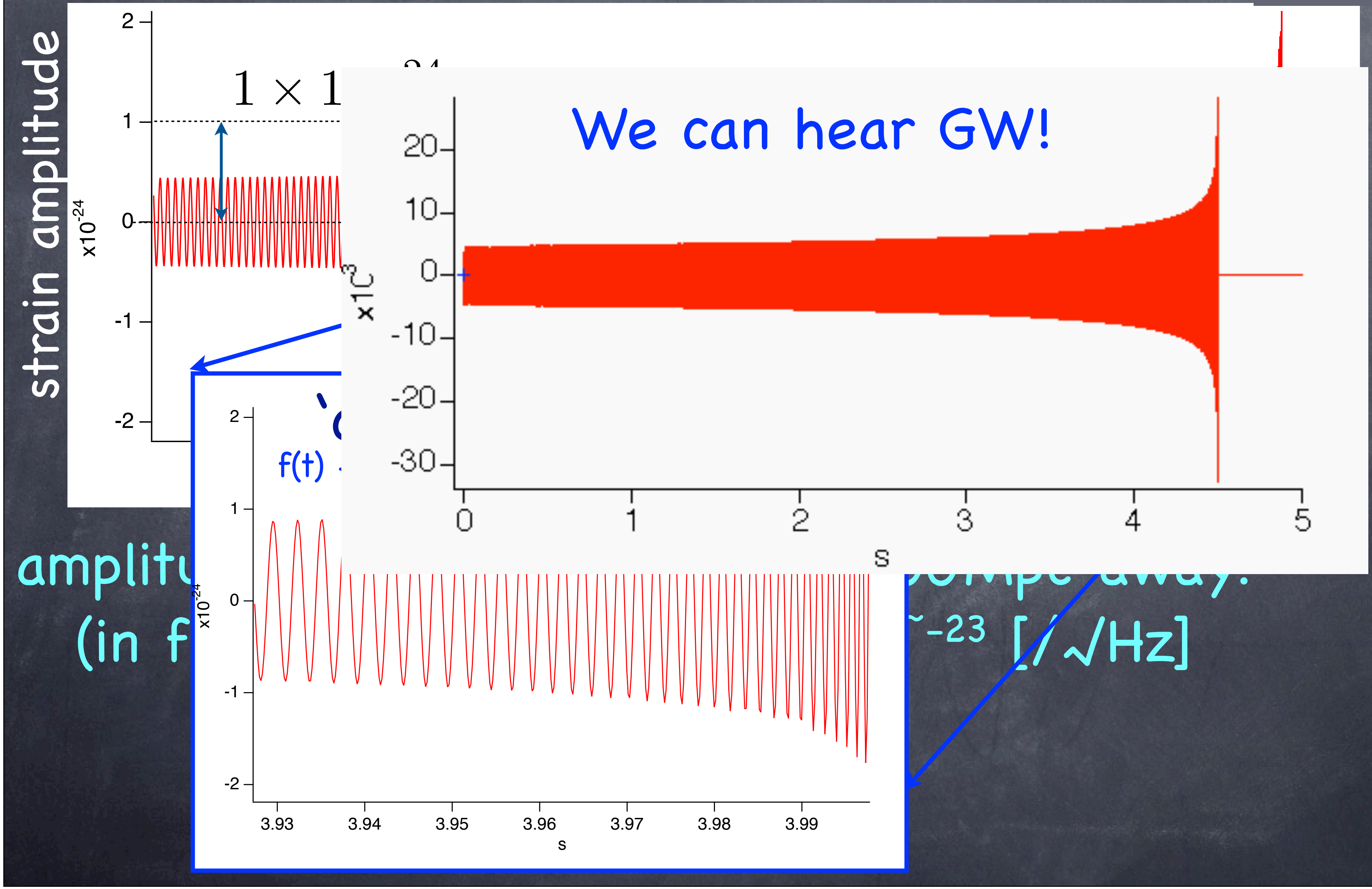
typical source : Coalescence of Neutron Star Binaries

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



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

--> 'standard **siren**'



We can hear GW!

amplitu ompe away.

(in f ~-23 [/√Hz]

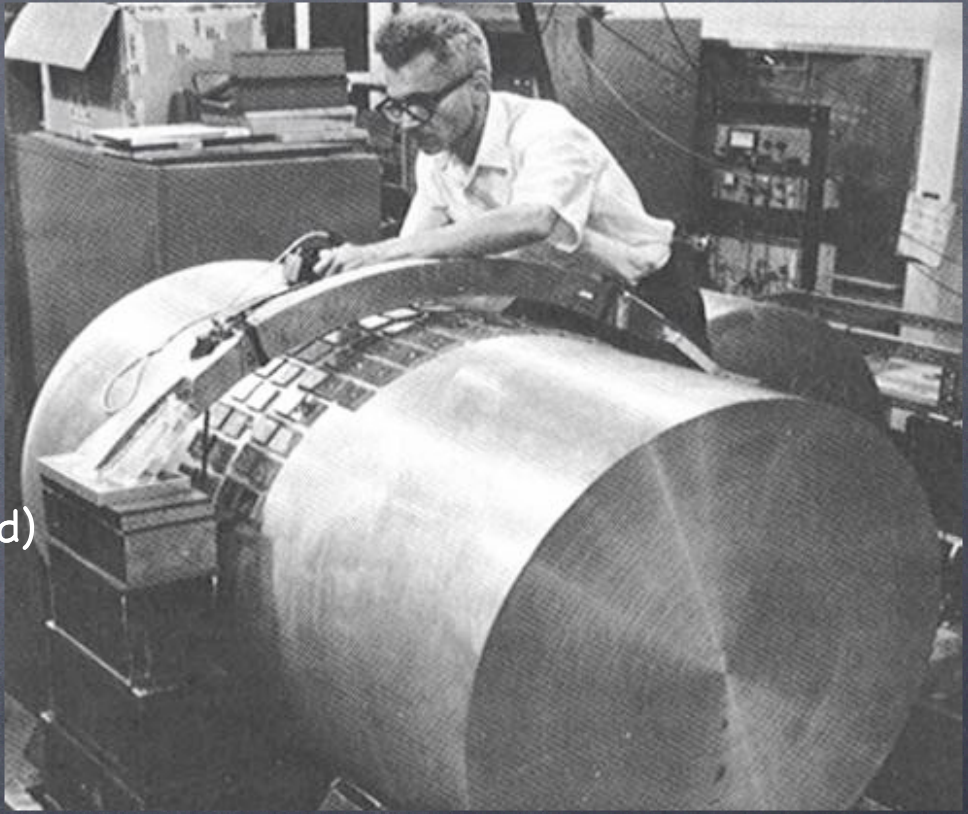
How to detect GW

Resonant mass

$$\mu_n\left[\ddot{x}_n(t)+\frac{\omega_n}{Q_n}\dot{x}_n(t)+\omega_n^2 x_n(t)\right]=\frac{1}{4}\ddot{h}_{\alpha\beta}q_{\alpha\beta}+\ldots$$

merits:
- sensitive on the resonance frequency
- cost

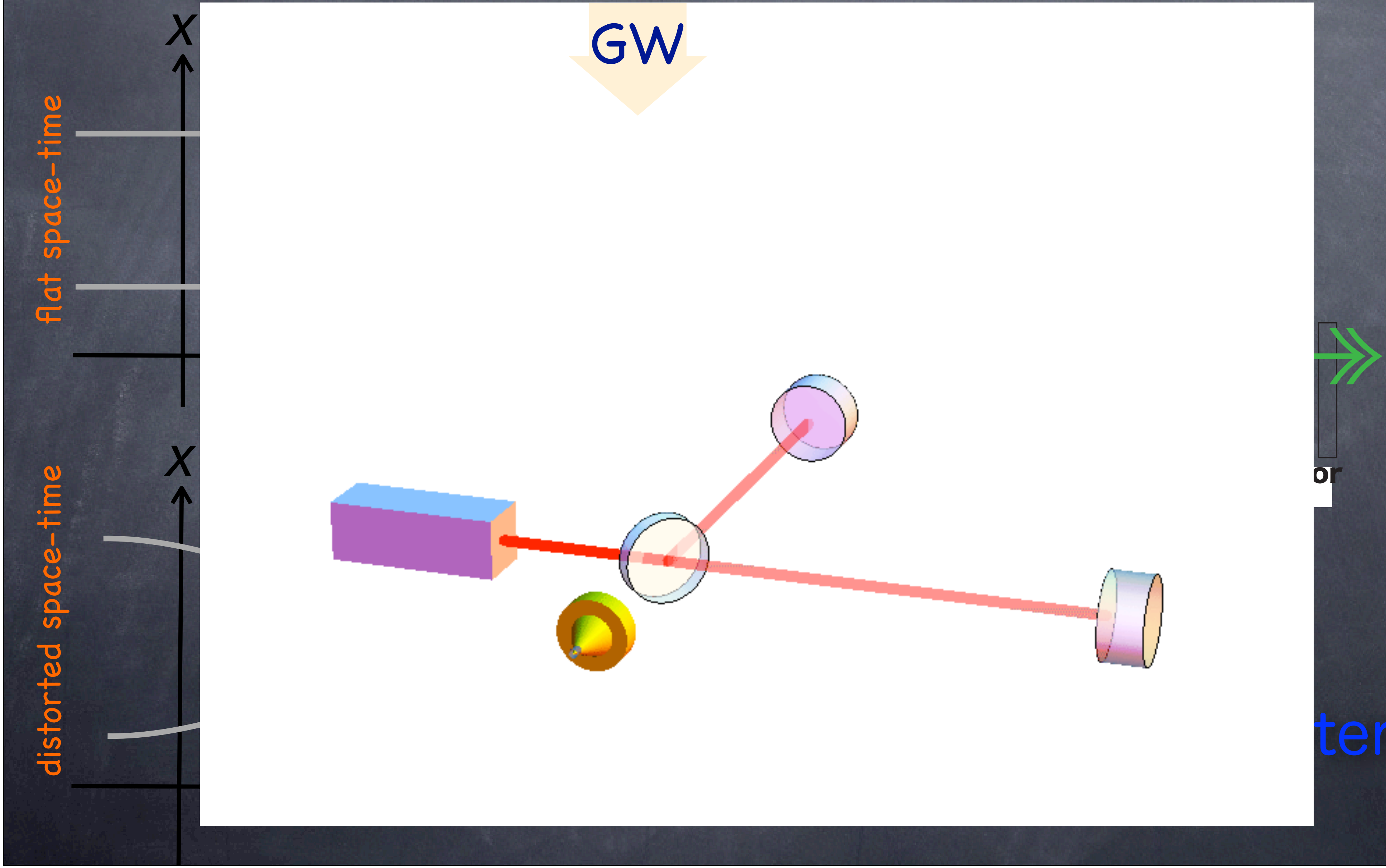
demerits:
- poor waveform reconstruction (narrow band)
- sensitivity limit



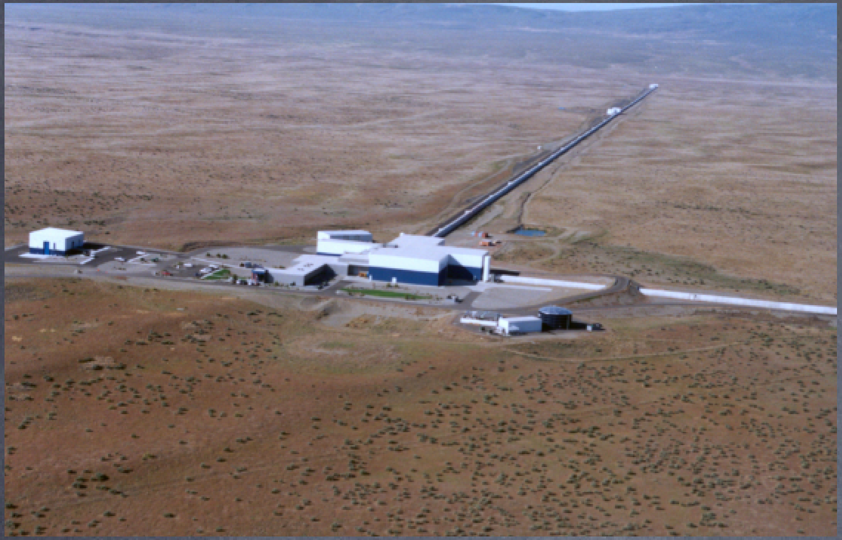
Weber “bar”

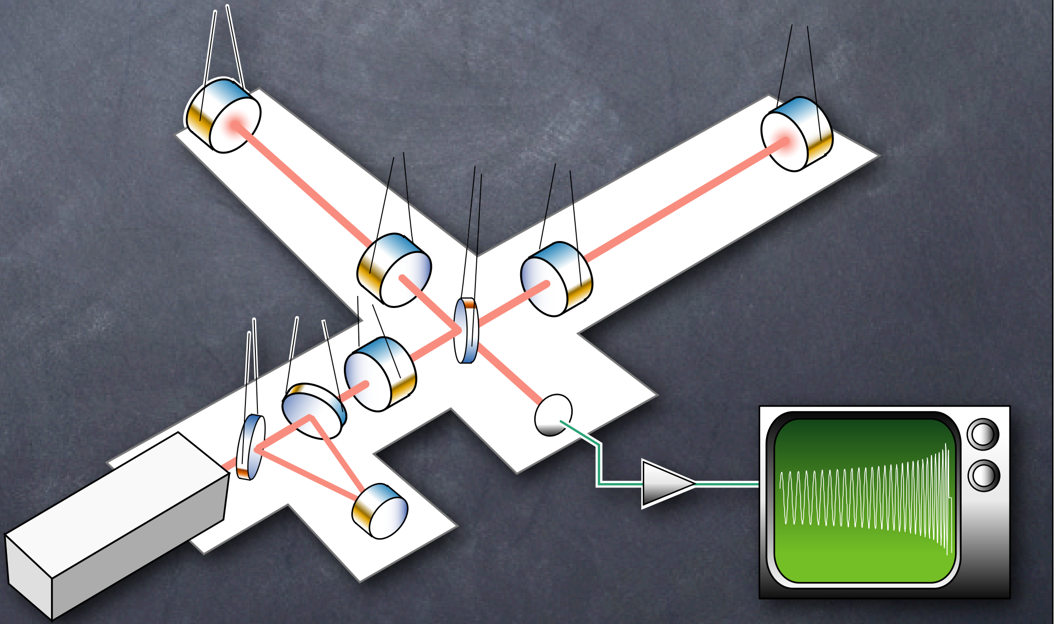
How to detect GW

- **Free Test Masses & Laser interferometer**



Laser Interferometers





http://www.ligo-la.caltech.edu/

Sensitivities of Laser Interferometric GW detectors

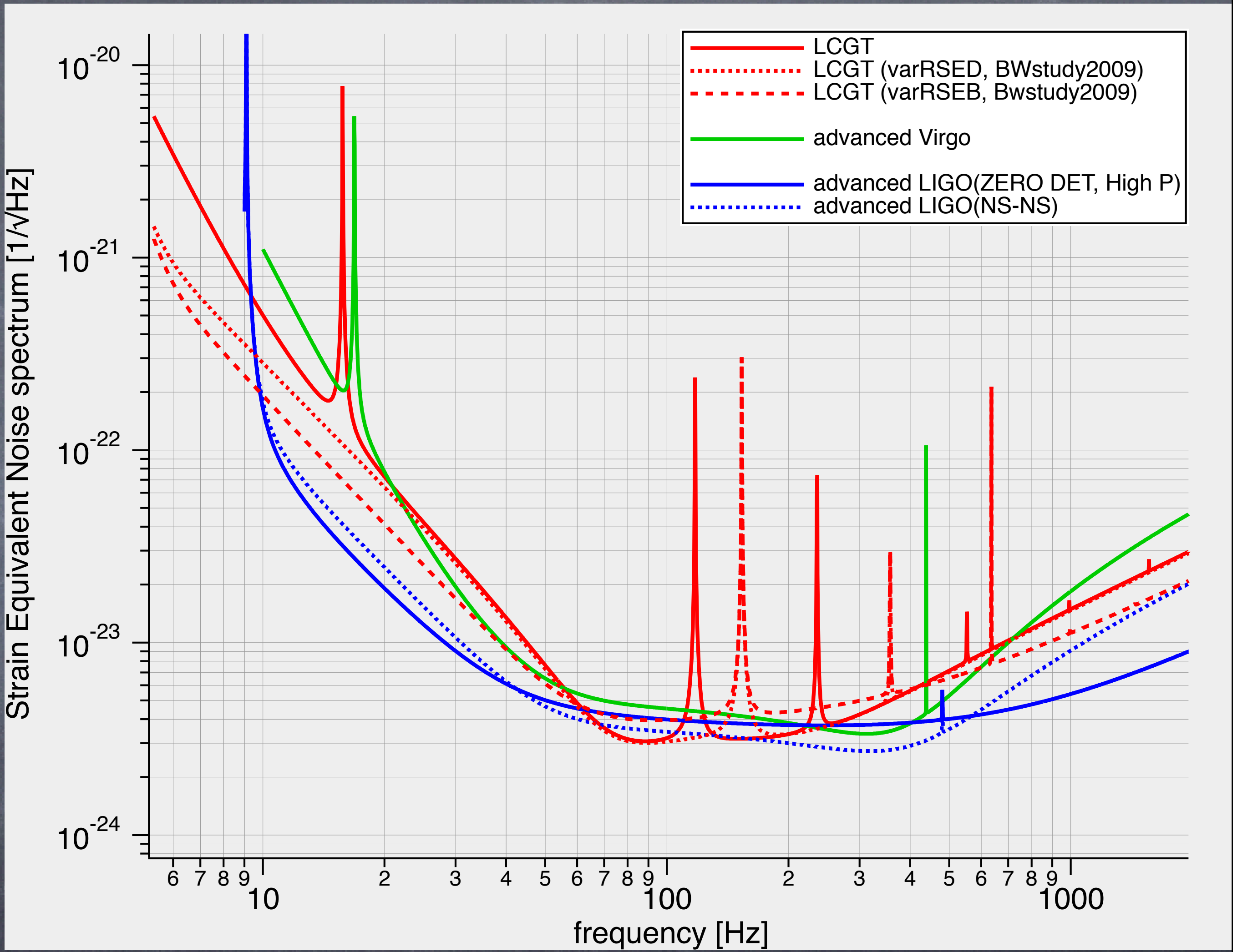
(strain equivalent)

Noise spectrum

||

GW which amplitude larger than it can be measured.

$$[1/\sqrt{\mathrm{Hz}}]$$



Frequency of signal $[\mathrm{Hz}]$

https://wwwcascina.virgo.infn.it/advirgo/docs.htmlhttps://wwwcascina.virgo.infn.it/advirgo/

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.

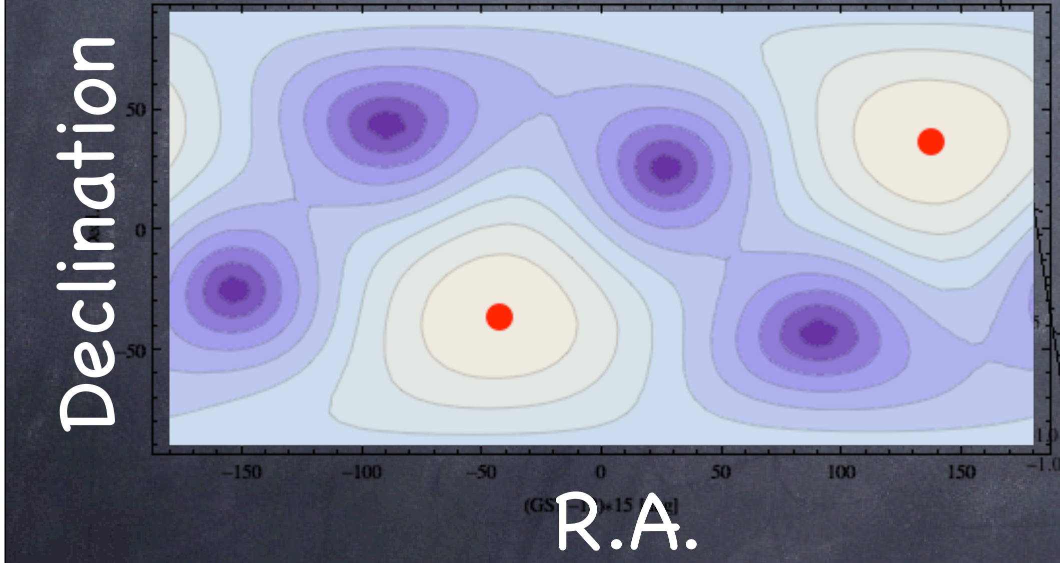
  We explain with 'stable clock' to image easily as in laboratory where we are living :-).

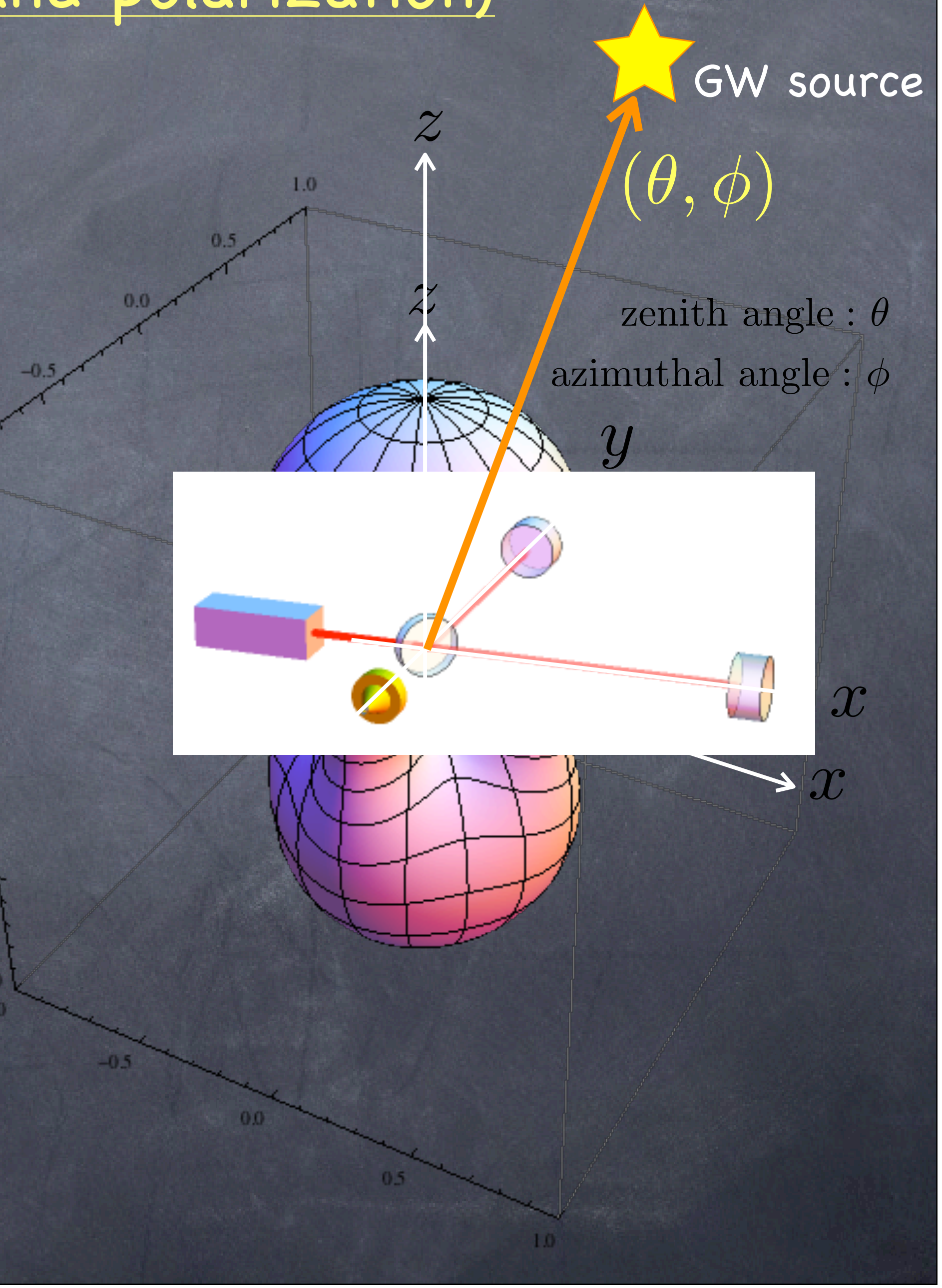
  (for physicist) You should learn classical electromagnetism in undergraduate cause !

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

Antenna Pattern
(Response for source direction and polarization)

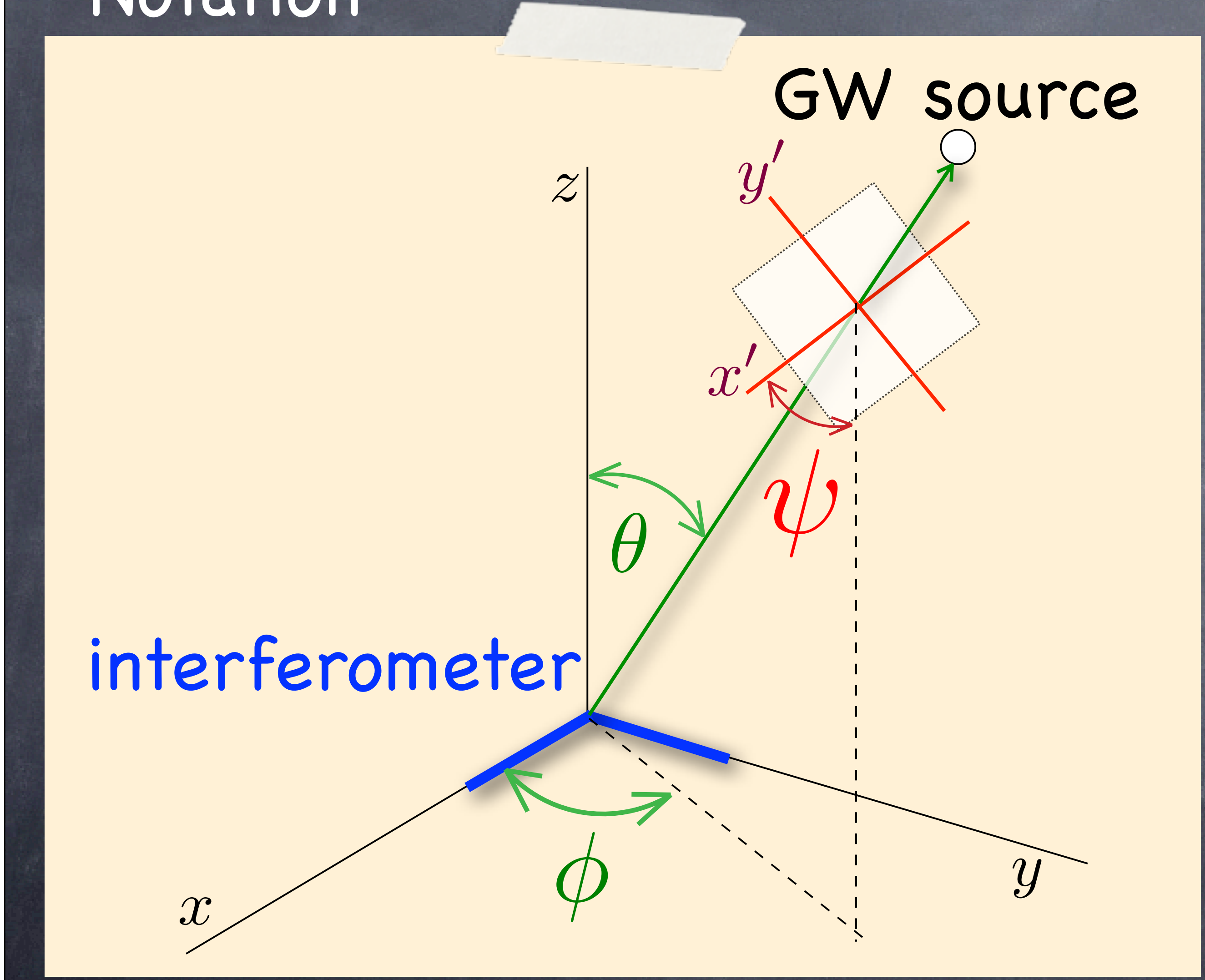
Interferometer's antenna pattern is widely spread as almost 'omni-directional'.

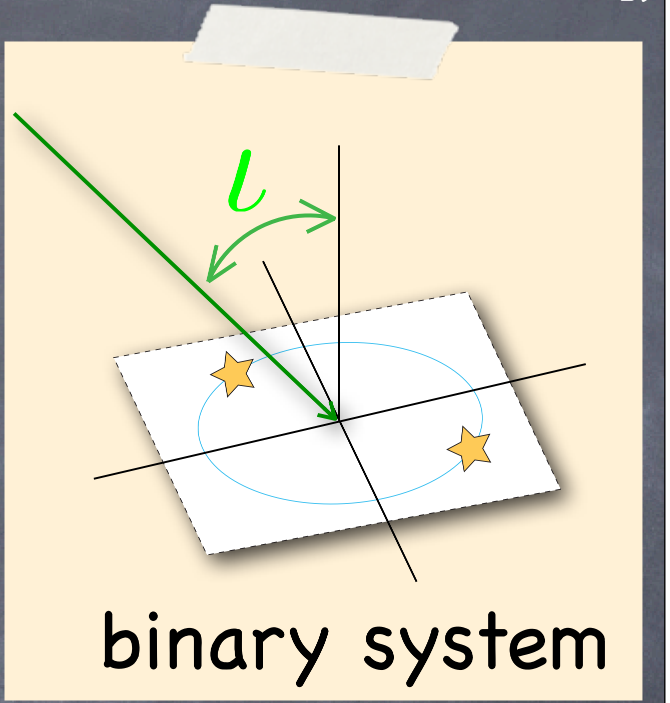




Antenna Pattern

Notation

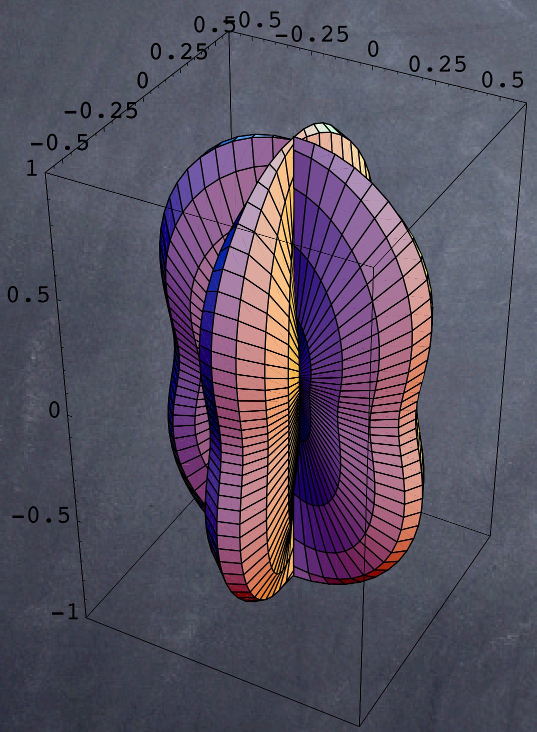




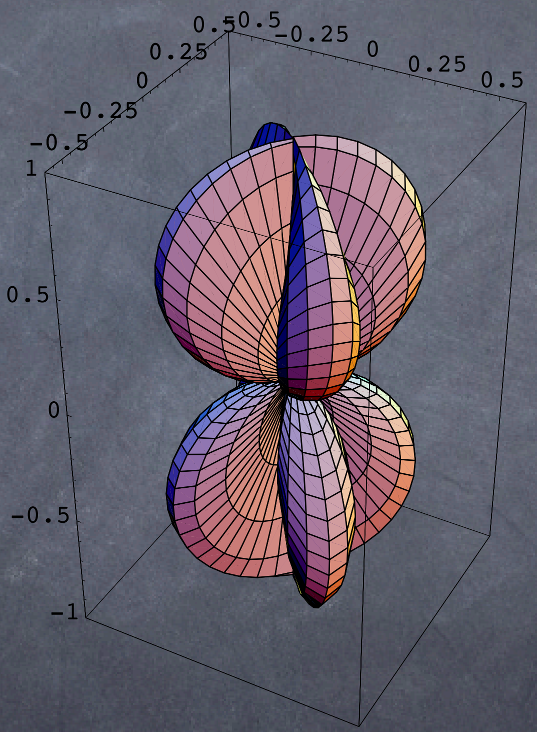
Antenna Pattern

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

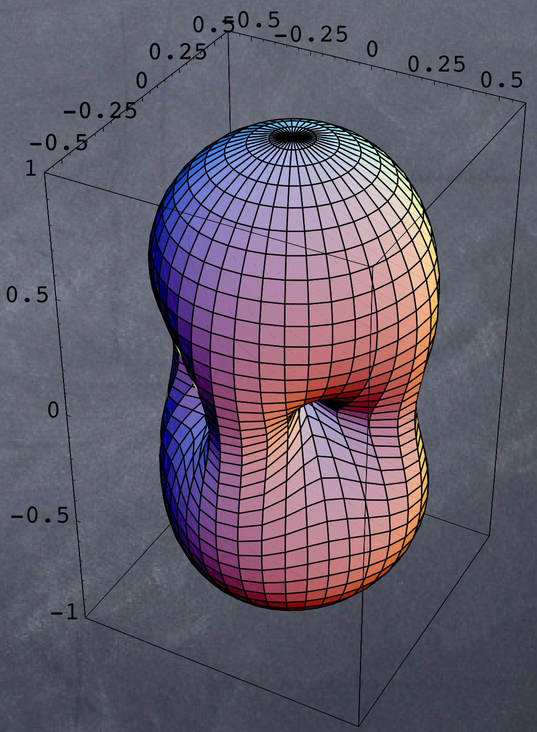
$$F_\times(\theta, \phi, \psi) = \frac{1}{2}(1 + \cos^2\theta)\cos 2\phi \sin 2\psi + \cos\theta \sin 2\phi \cos 2\psi$$



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



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



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

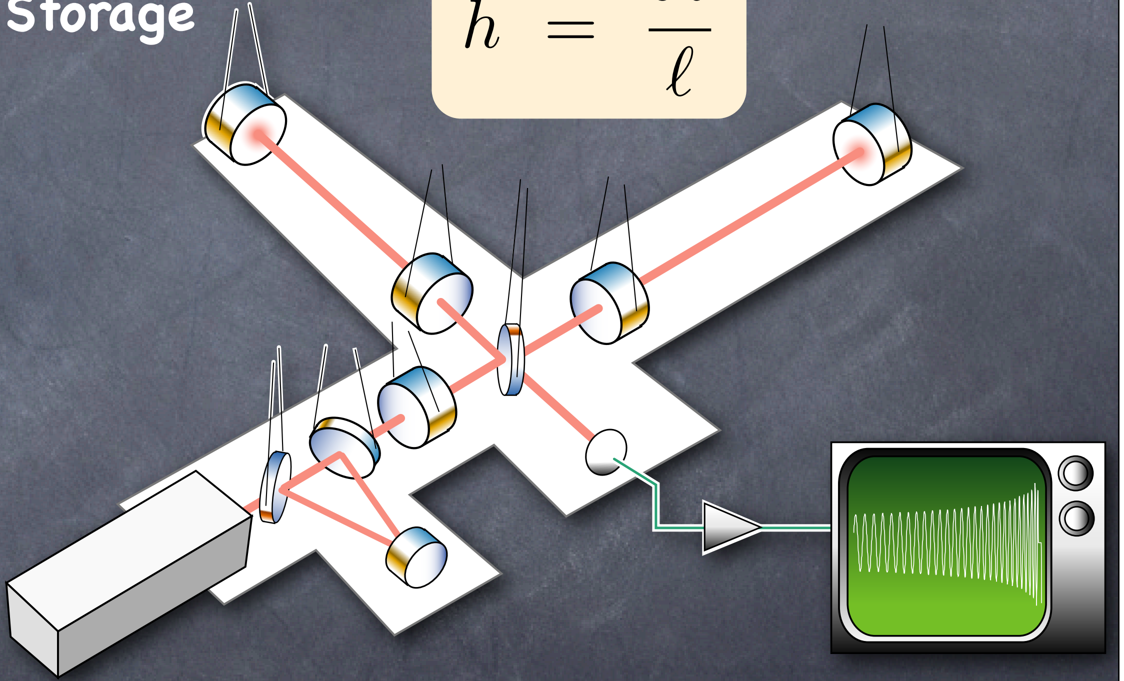
$$h_{det} = F_+ h_+ + F_\times h_\times$$

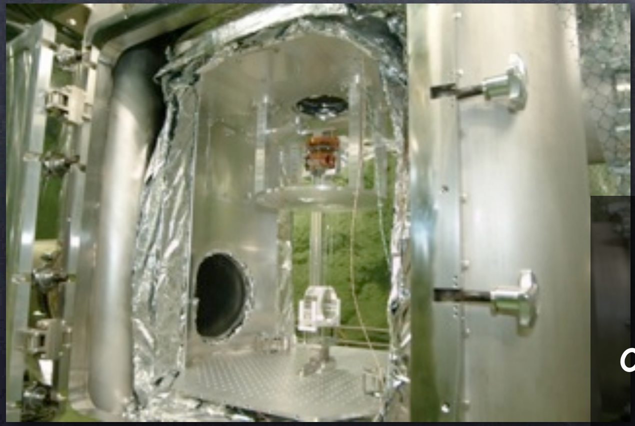
Schematic Figure

- **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

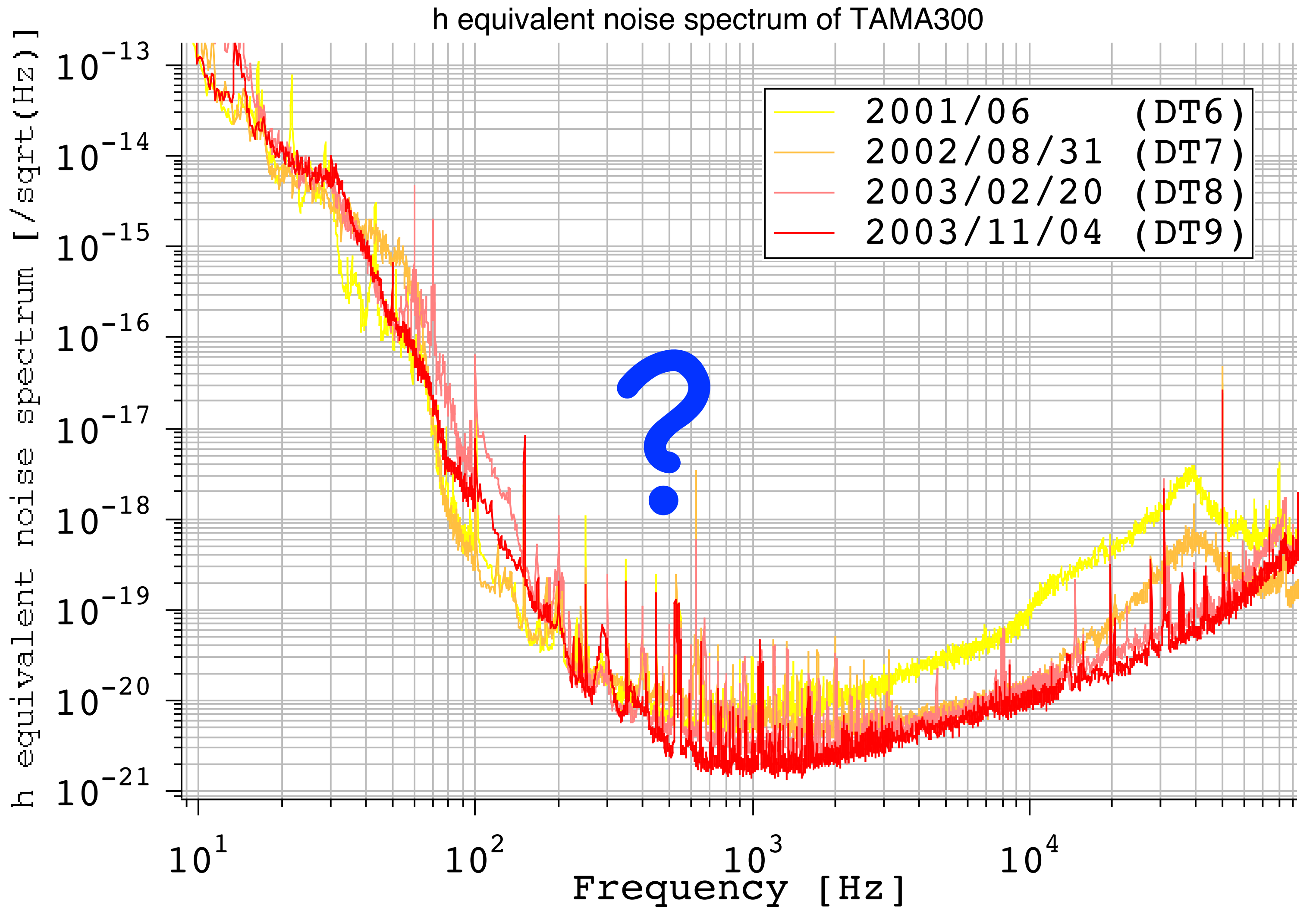
$$h = \frac{\delta \ell}{\ell}$$





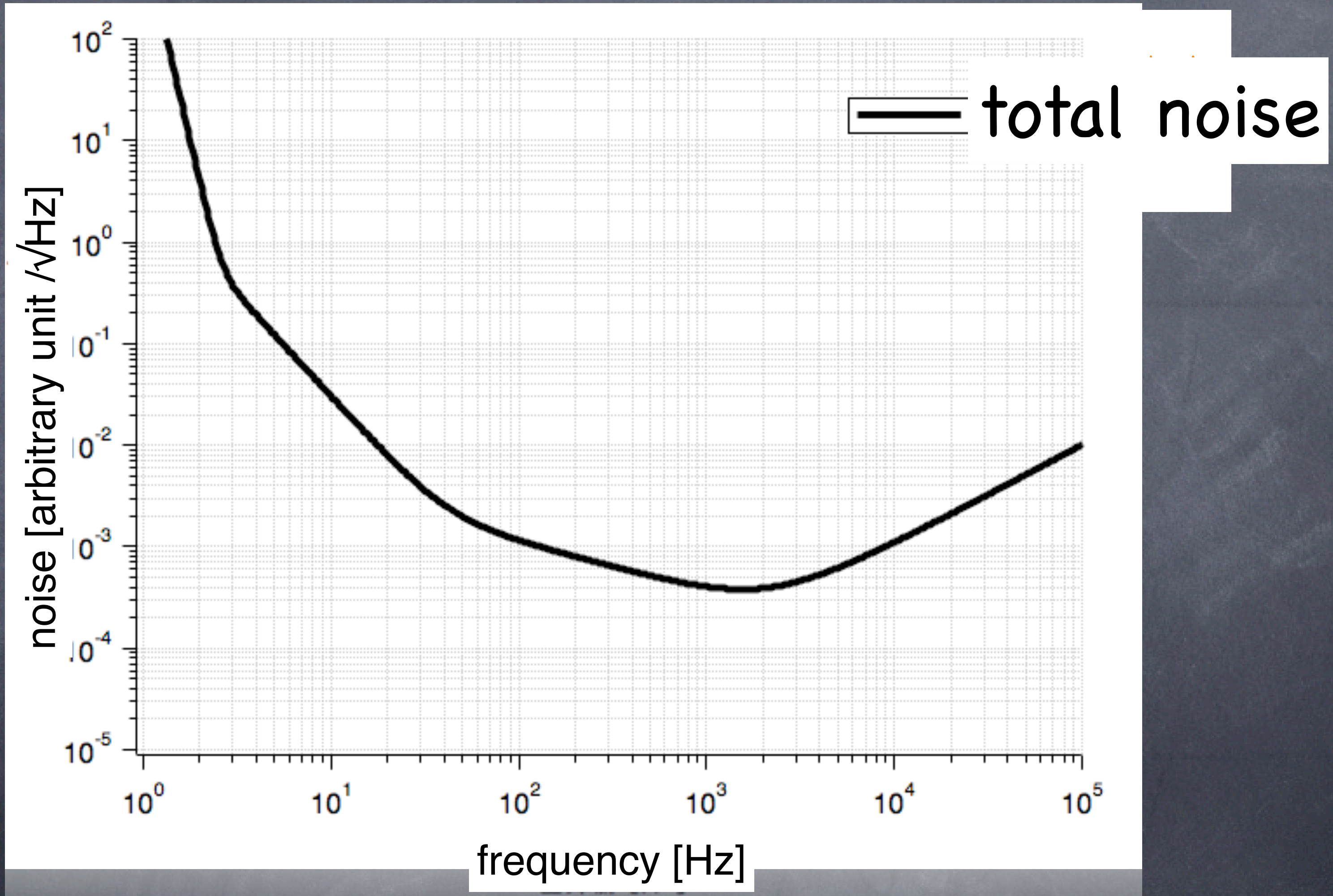
<-- mirror and suspension
of CLIO interferometer
(prototype of LCGT)

Detector Noise



http://tamago.mtk.nao.ac.jp/spacetime/index.html

Fundamental Noises



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

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

$$K + U = k_BT$$

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

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

Thermal Noise

- **Fluctuation-dissipation theorem**

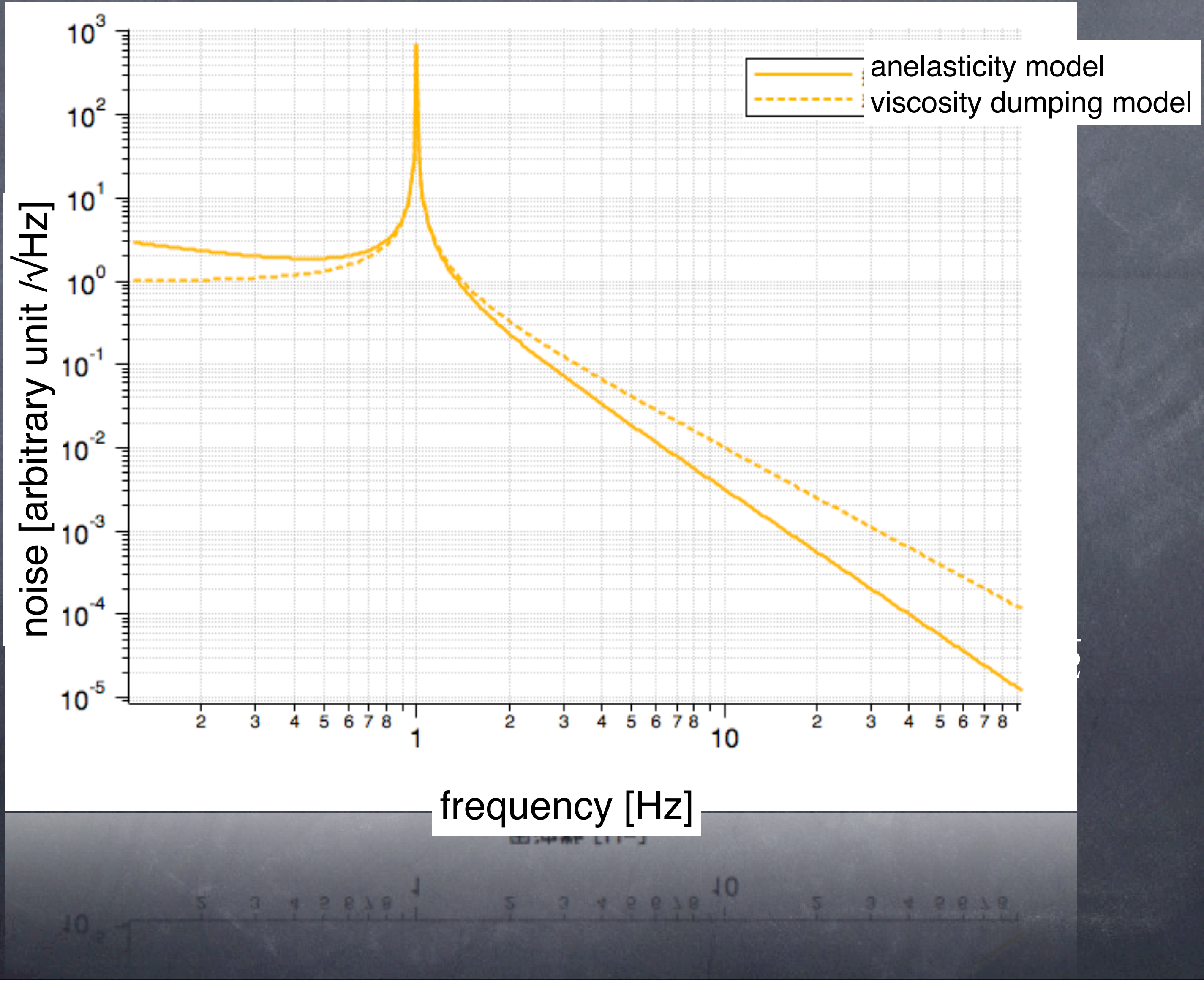
$$m\frac{d^2x}{dt^2} + \gamma\frac{dx}{dt} + kx = f_N(t)$$:Langevin Eq.

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

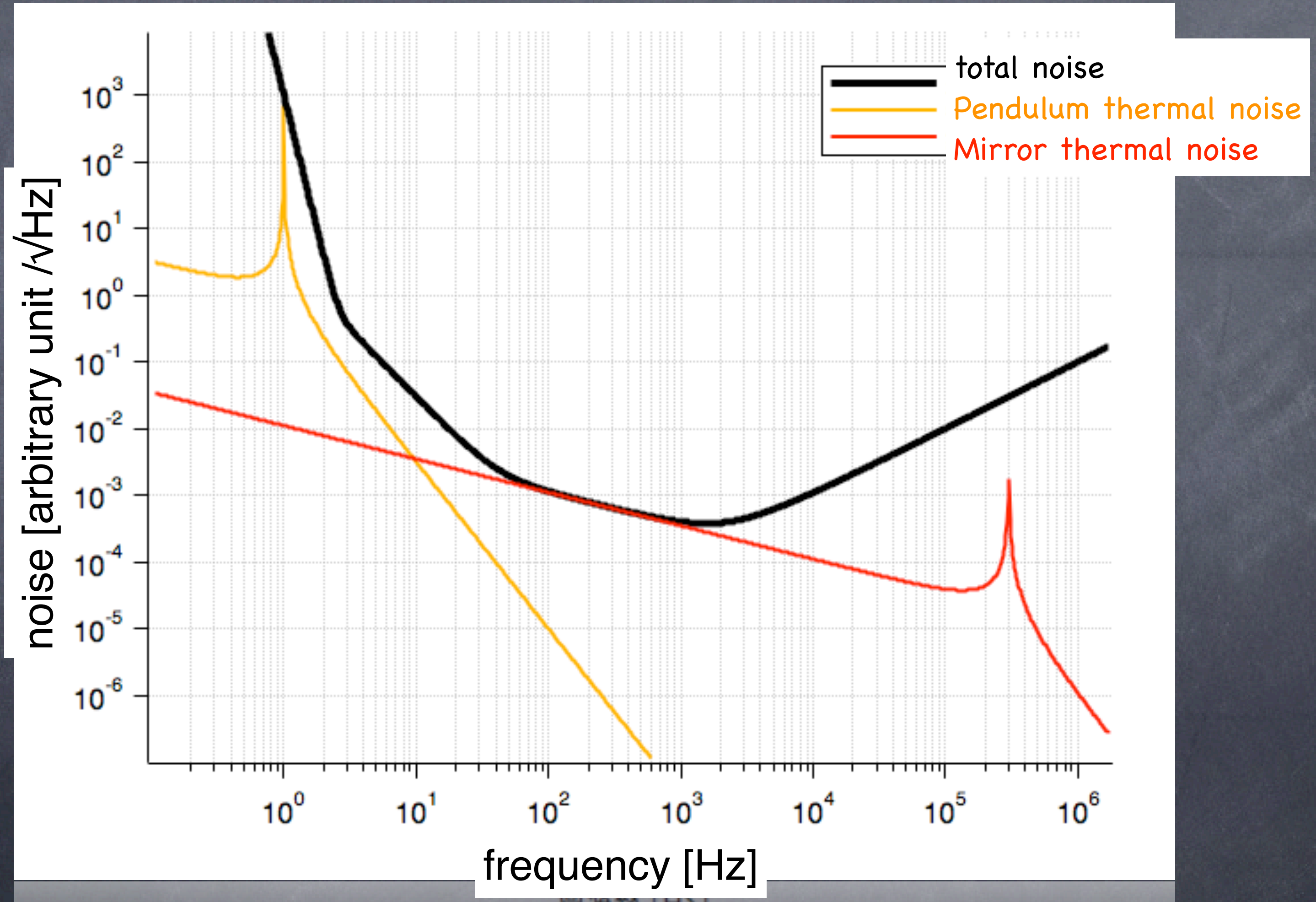
$$< x(\omega)^2 >= \frac{4\gamma k_B T}{|-m\omega^2 + i\omega\gamma + k|^2}$$

: Power spectrum of Brownian motion

Spectrum

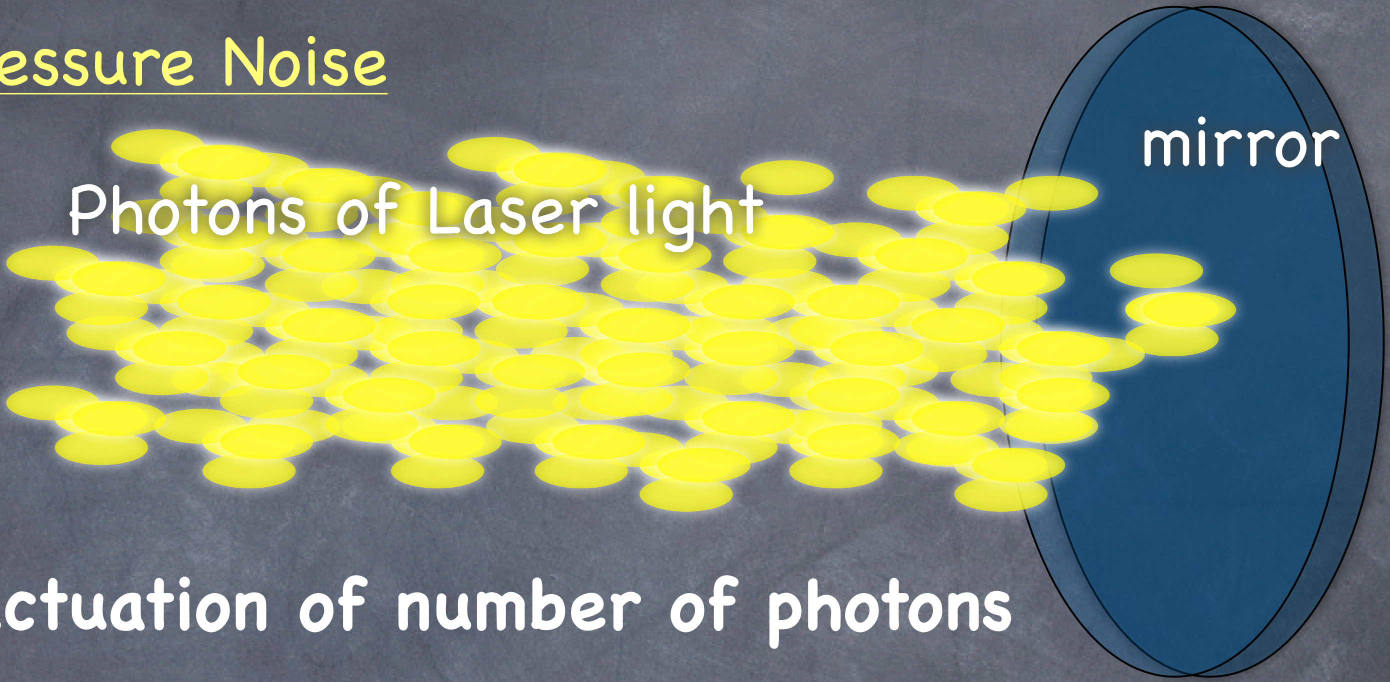

noise [arbitrary unit /√Hz]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
2 3 4 5 6 7 8
1
2 3 4 5 6 7 8
10
2 3 4 5 6 7 8
frequency [Hz]
anelasticity model
viscosity dumping model

in GW detector,



Shot Noise

Radiation Pressure Noise

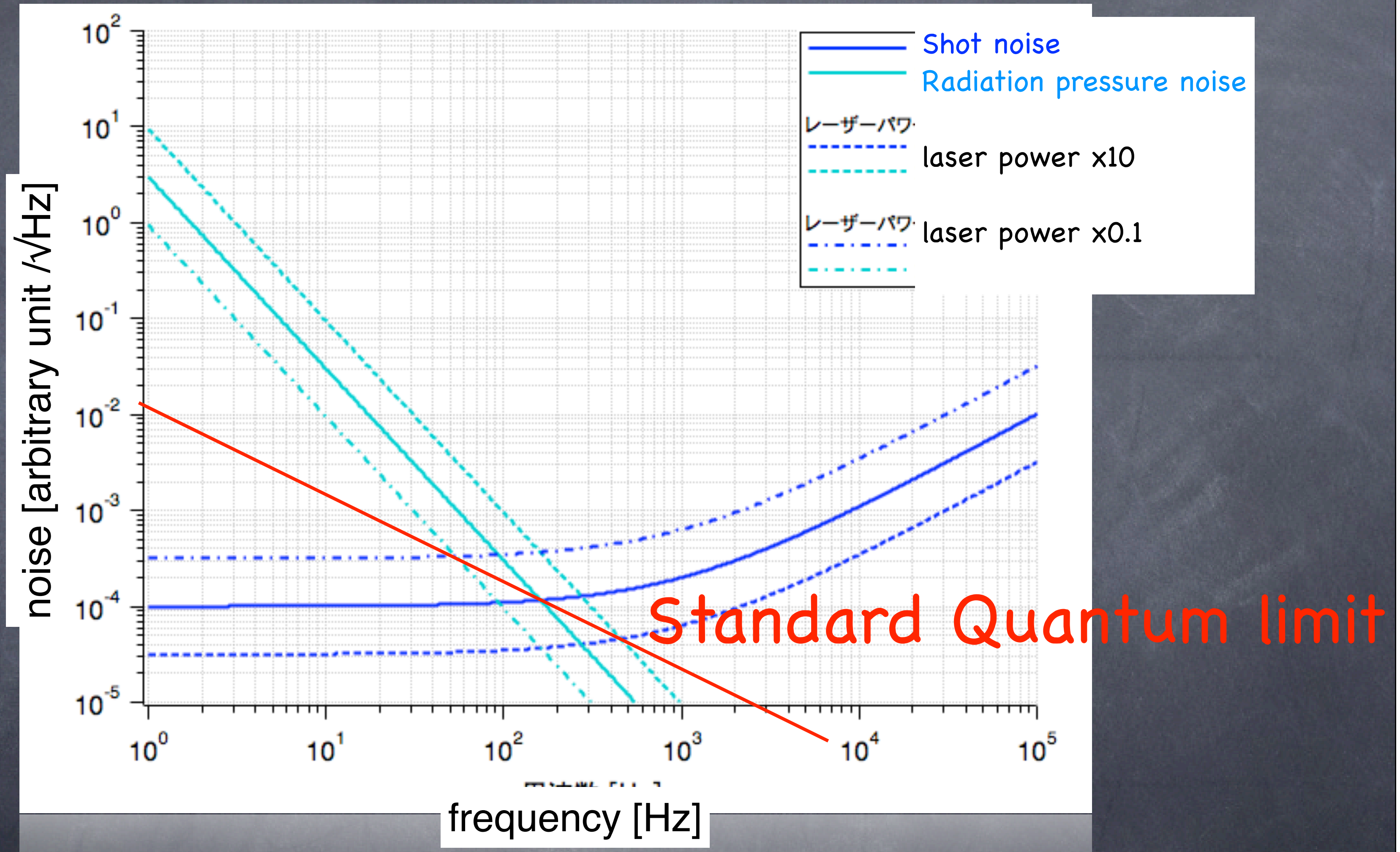


- **Fluctuation of number of photons**

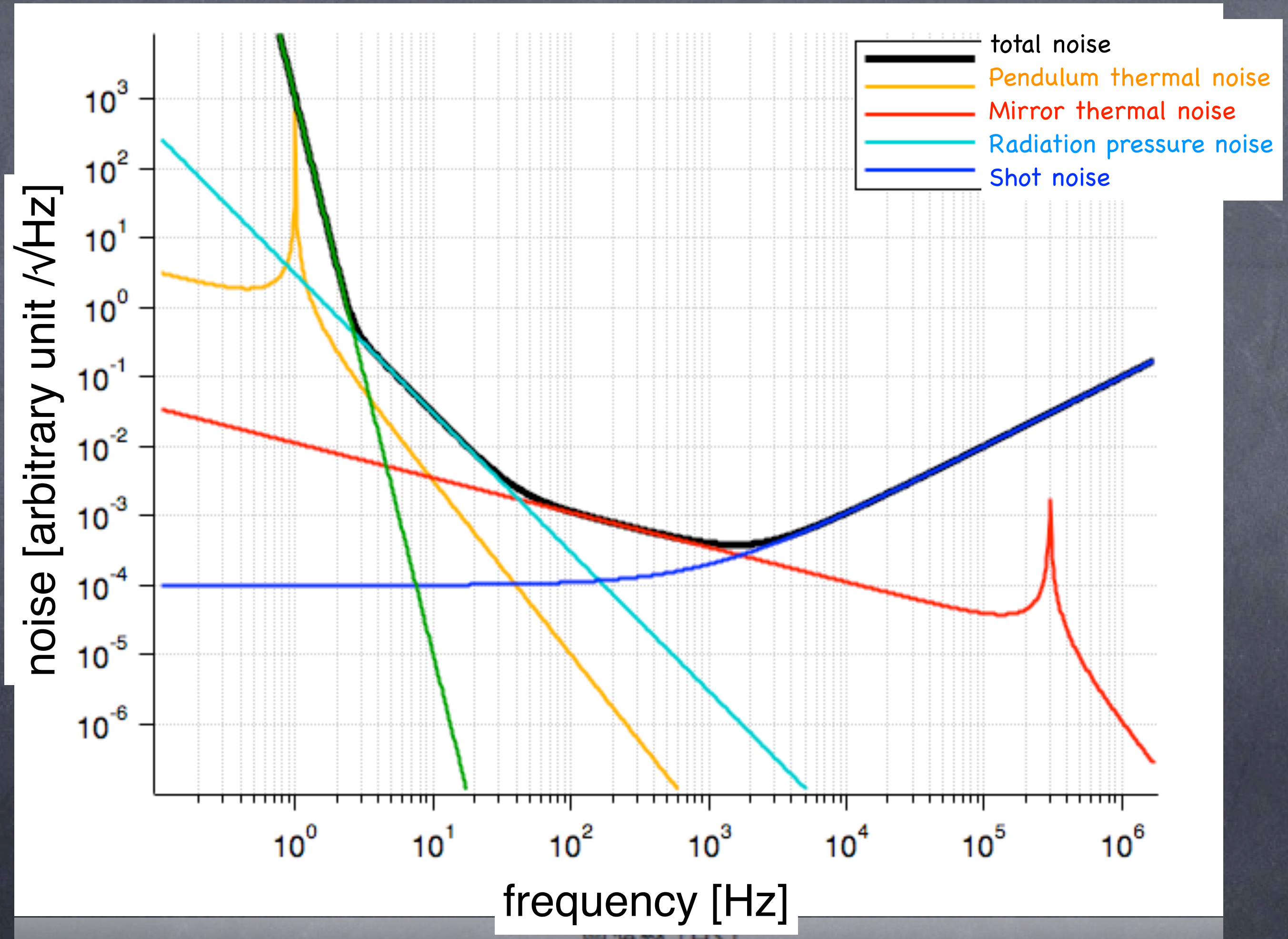
Shot Noise $x_{shot}(f) \propto \sqrt{\frac{\hbar c \lambda}{P}}$

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

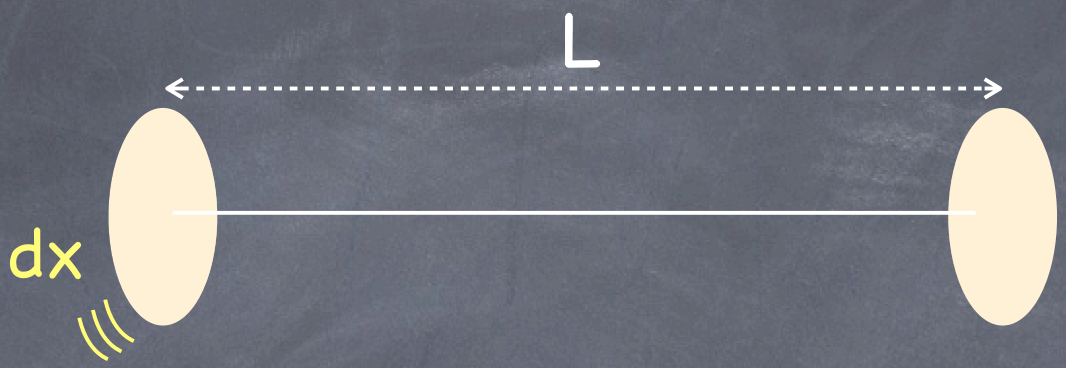
High Power ? or Low Power ?


Shot noise
Radiation pressure noise
レーザーパワ
laser power x10
レーザーパワ
laser power x0.1
Standard Quantum limit
noise [arbitrary unit /√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}
frequency [Hz]

Noises !


total noise
Pendulum thermal noise
Mirror thermal noise
Radiation pressure noise
Shot noise
noise [arbitrary unit /√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
frequency [Hz]

long base line (for enhance GW signal)



- **long L is better !**

  noise on mirror : dx

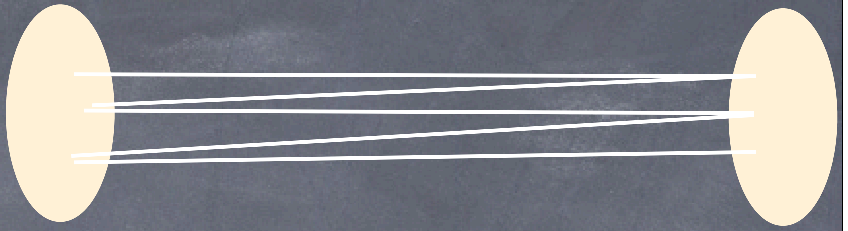
  gravitational wave : h --> signal = h L

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

Baseline length can be extend up to λ/2

... limite of some pragmatic reasons ...

- ---> N turn



signal : N L h

mirror displacement noise : dx_{mirror}

--> N dx_{mirror}

$$S/N_{mirror} = L\ h\ /dx_{mirror}$$

noises from other instruments : dx_{other}

(e.g. from electric circuit)

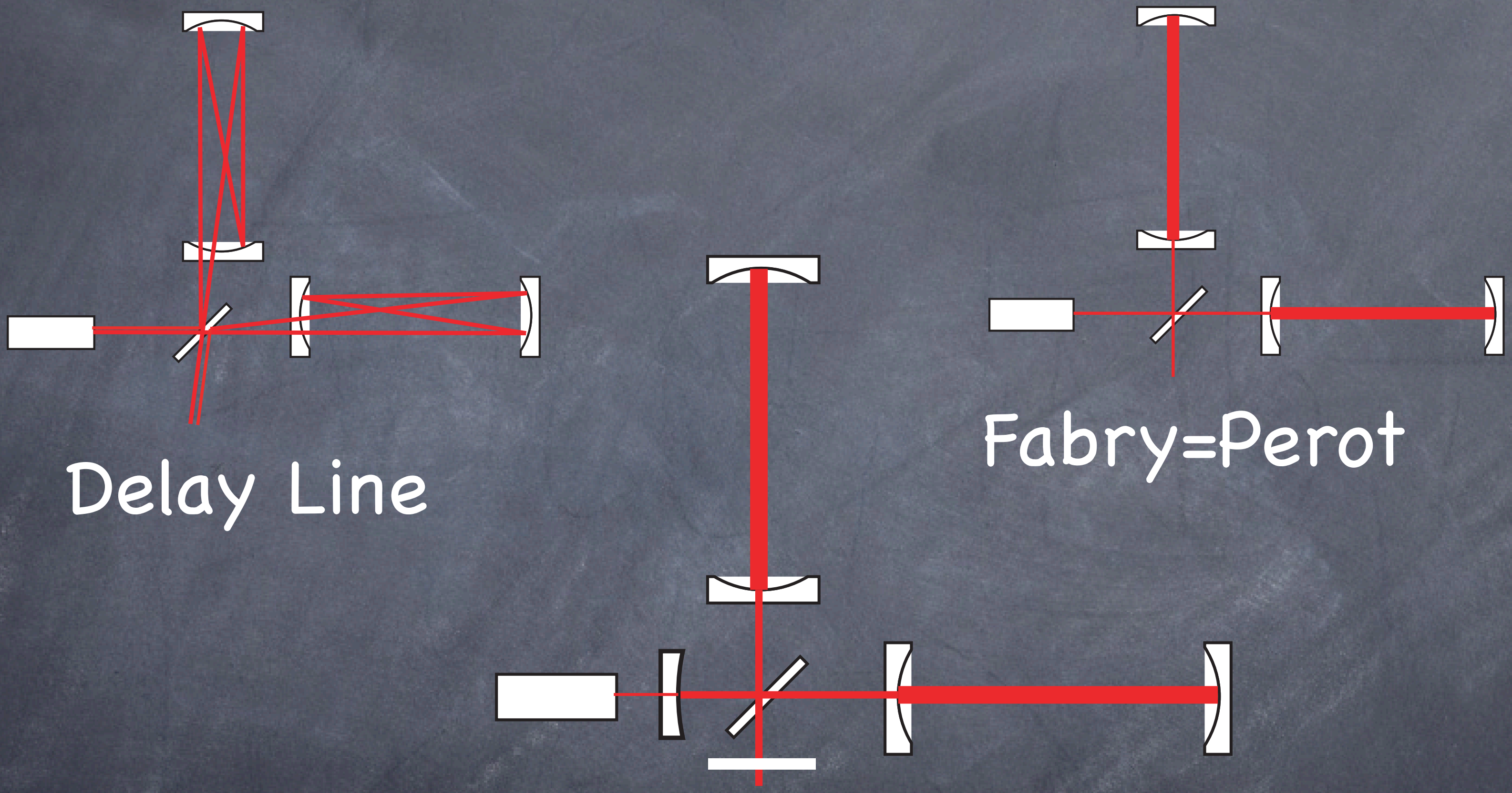
$$S/N_{other} = N\ L\ h\ /\ dx_{other}$$

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

By baseline L and N-turns, S/N gain by L against mirror displacement noise, and by N L against other noises.

Folding Arms

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



Delay Line

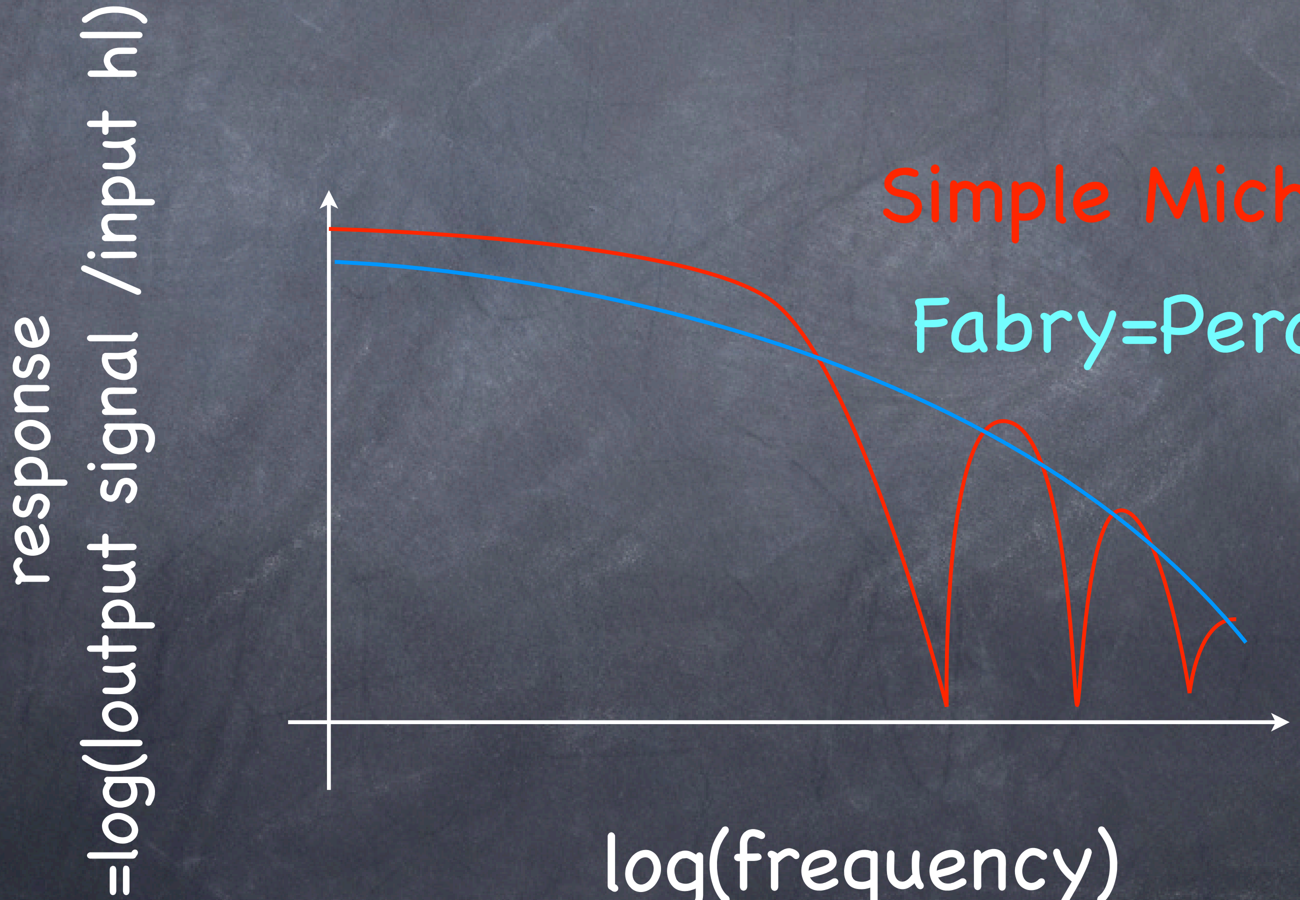
Fabry=Perot

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

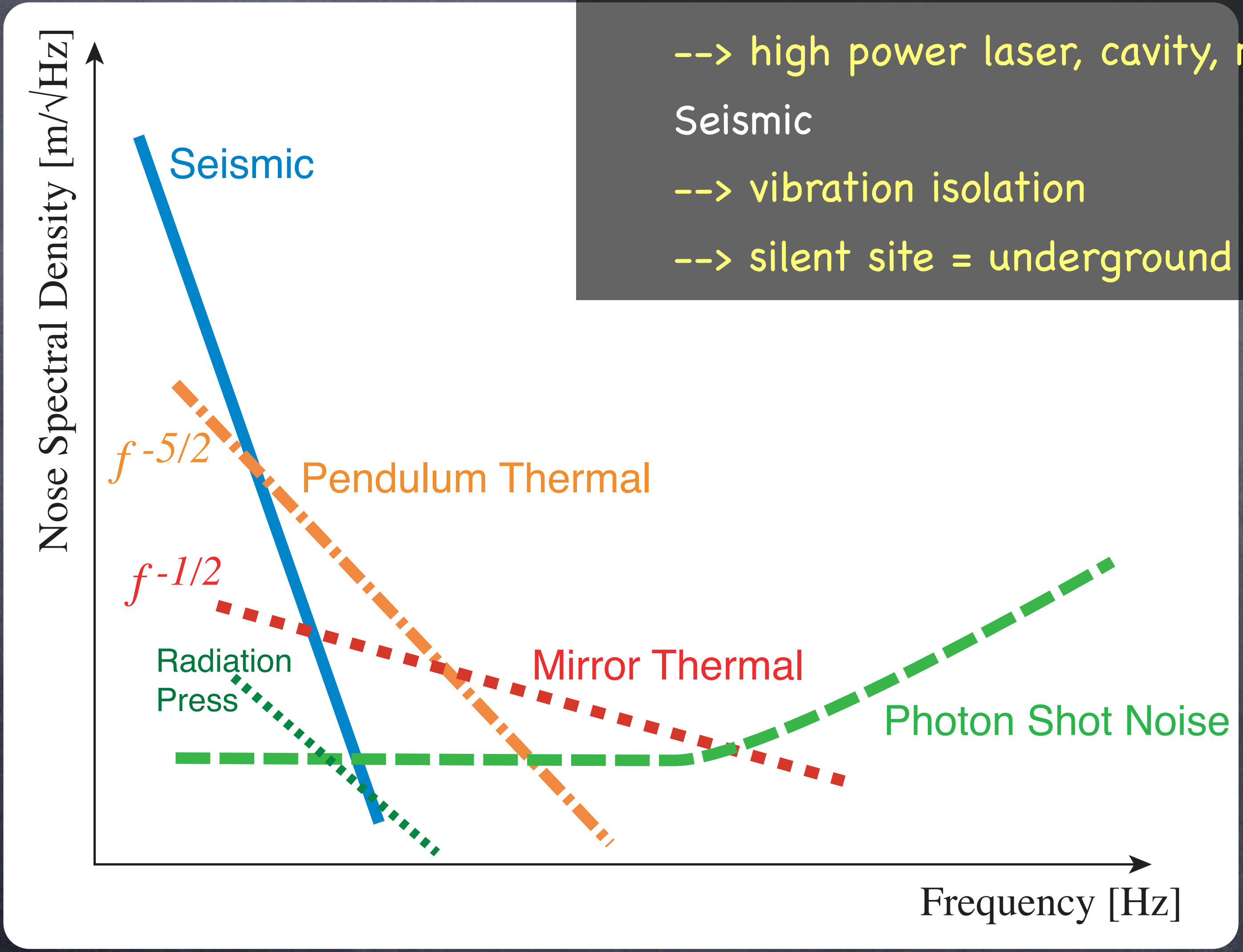
Photon Shot Noise & Radiation Pressure Noise

--> high power laser, cavity, massive mirror

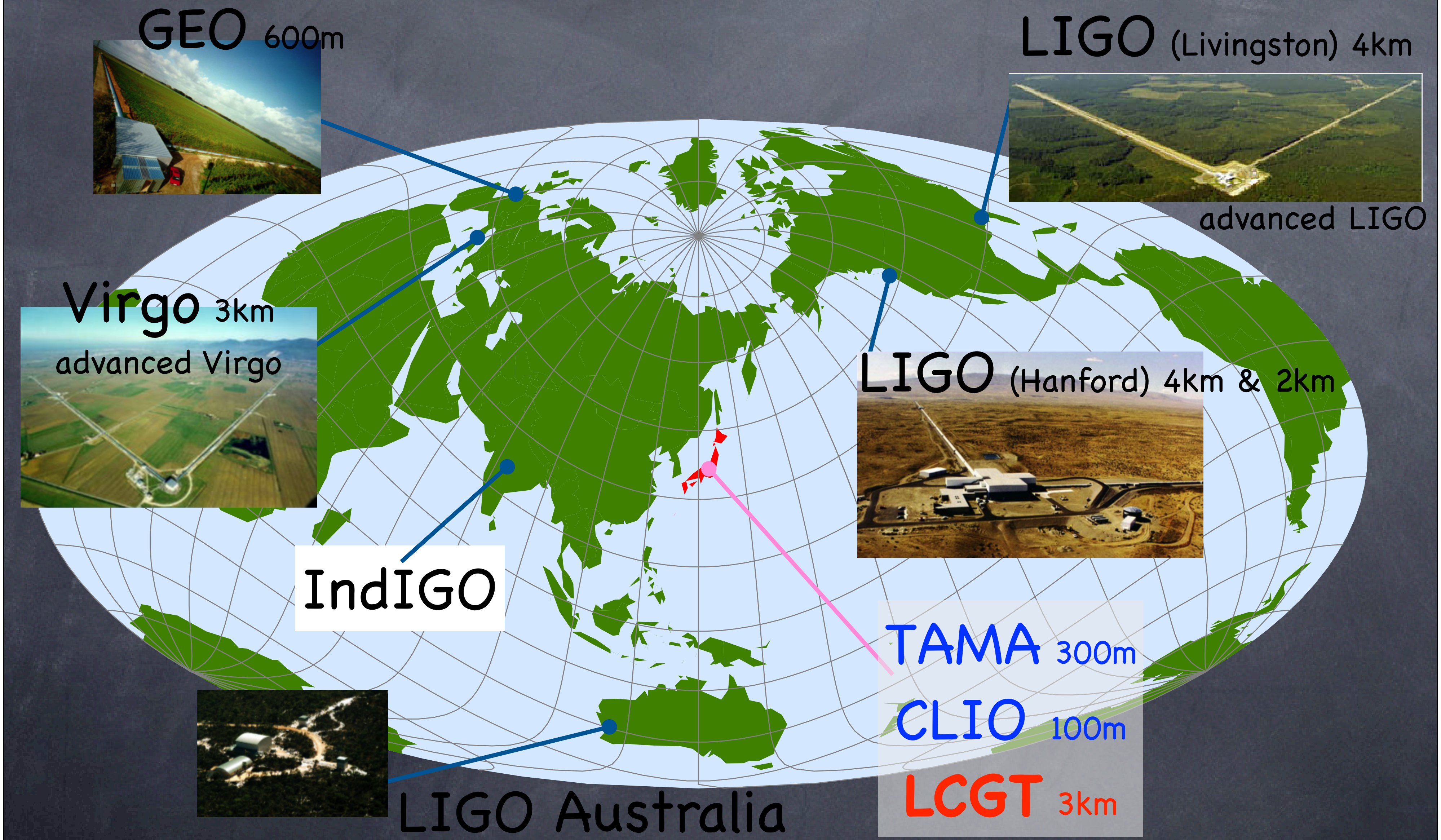
Seismic

--> vibration isolation

--> silent site = underground



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

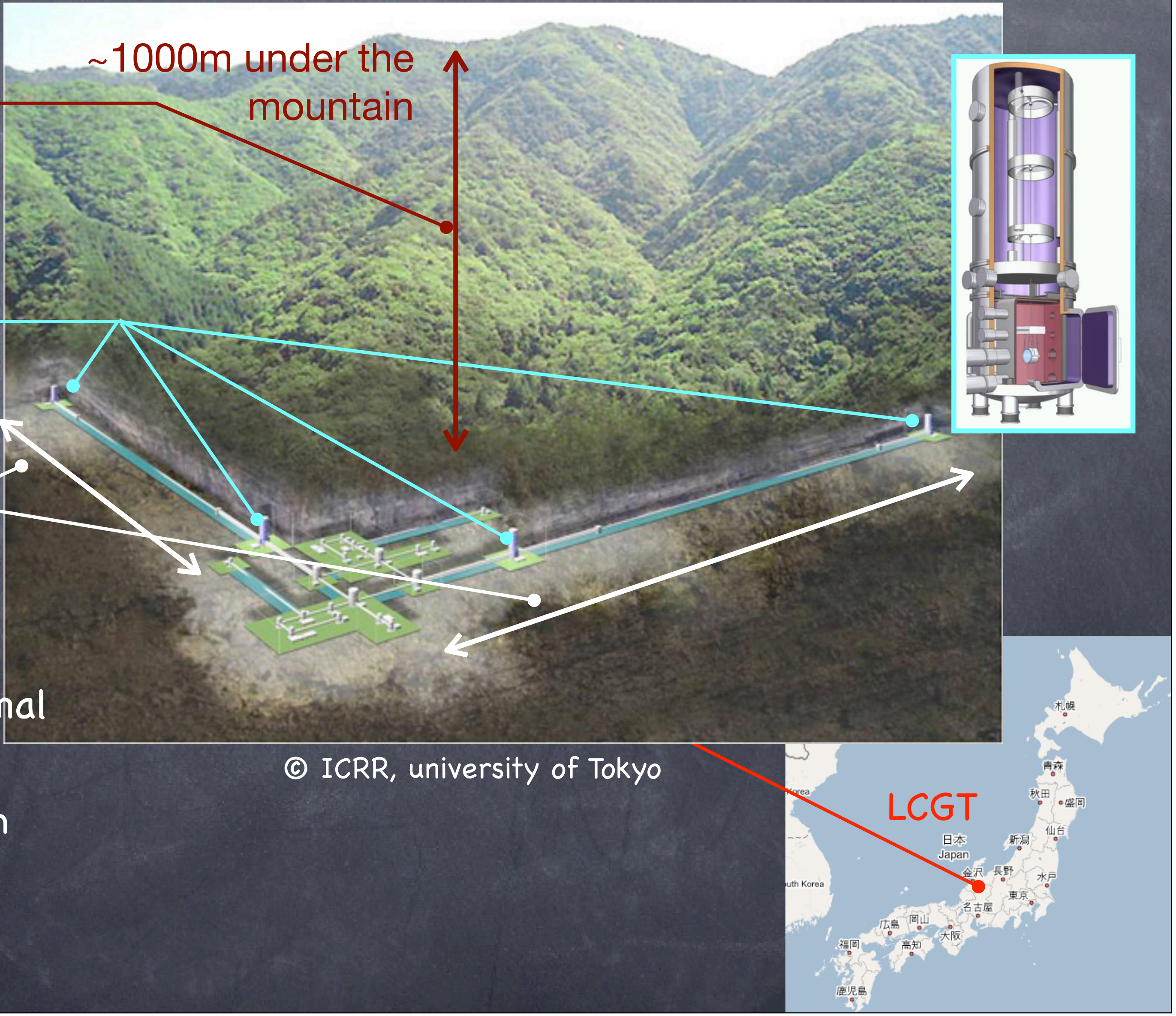
LIGO Australia

- LCGT -

Large-scale Cryogenic Gravitational wave Telescope

LCGT (Large-scale Cryogenic Gravitational wave Telescope)

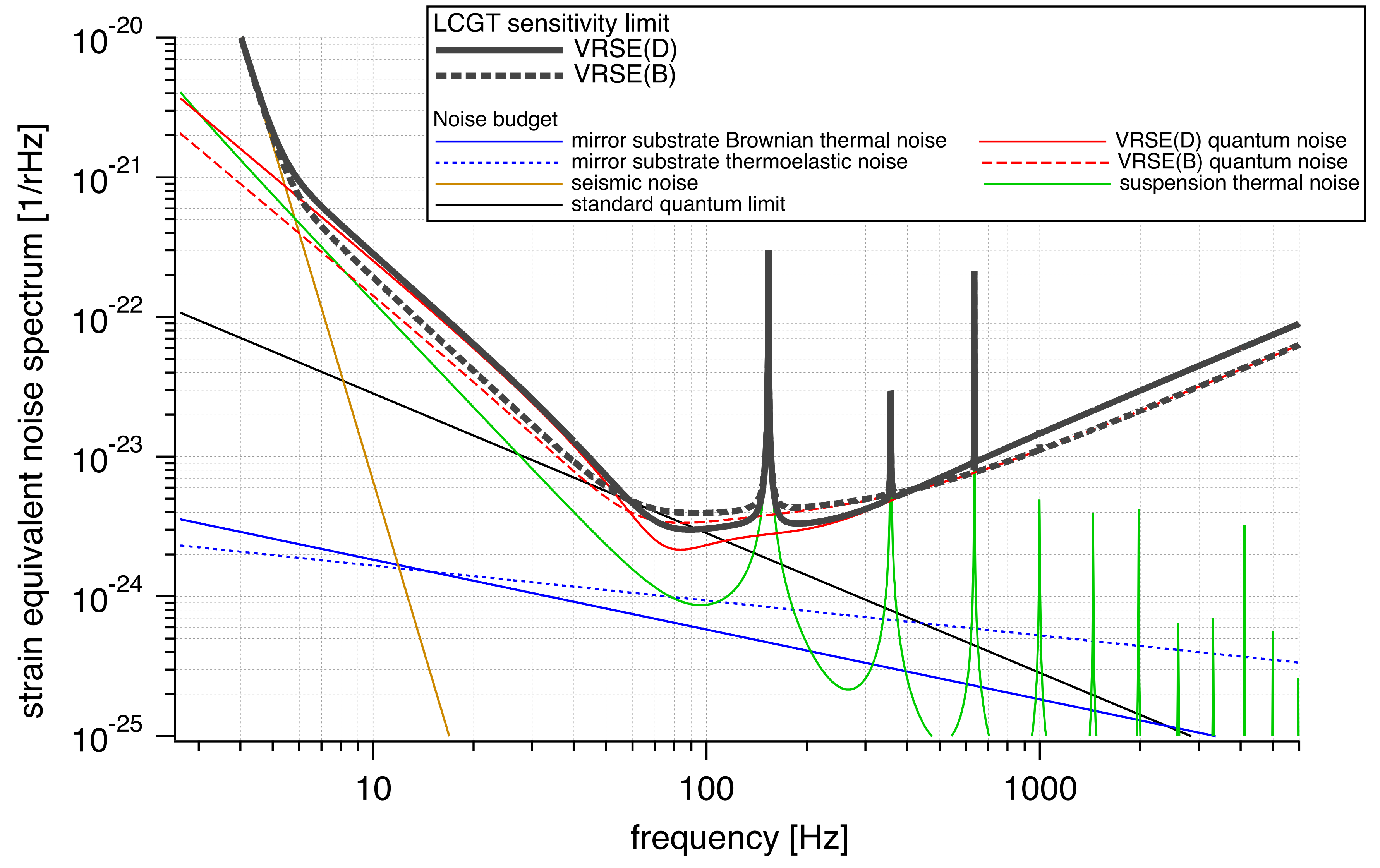
- **Underground**
  - in Kamioka, Japan
  - Silent & Stable environment
- **Cryogenic Mirror**
  - 20K
  - sapphire substrate
- **3km baseline**
- **Plan**
  - 2010 : construction started
  - 2014 : first run in normal temperature
  - 2017- : observation with cryogenic mirror



© ICRR, university of Tokyo

Sensitivity Limit of LCGT

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



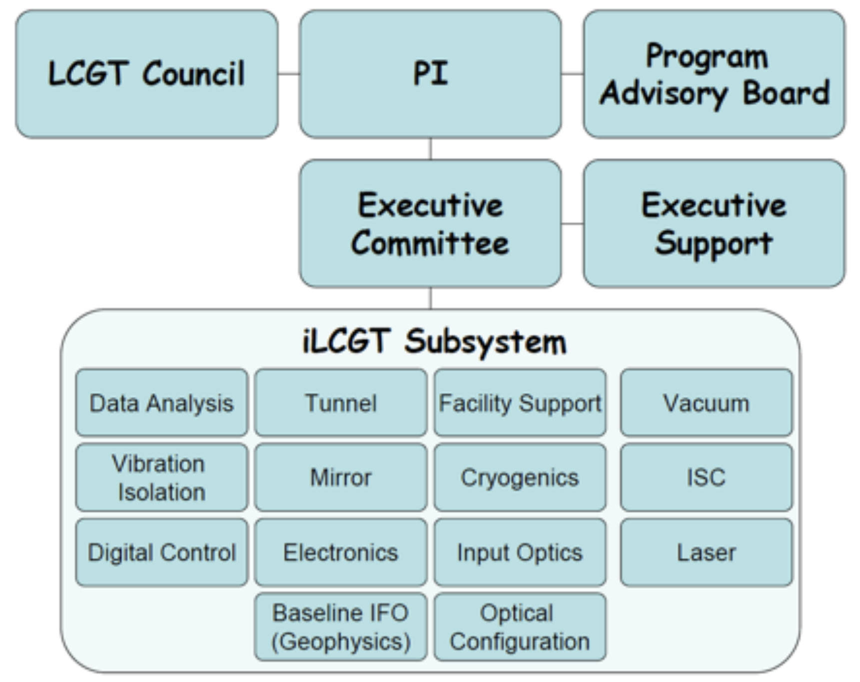
http://gwcenter.icrr.u-tokyo.ac.jp/en/researcher/parameter

LCGT Collaboration

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

  (May 2011)

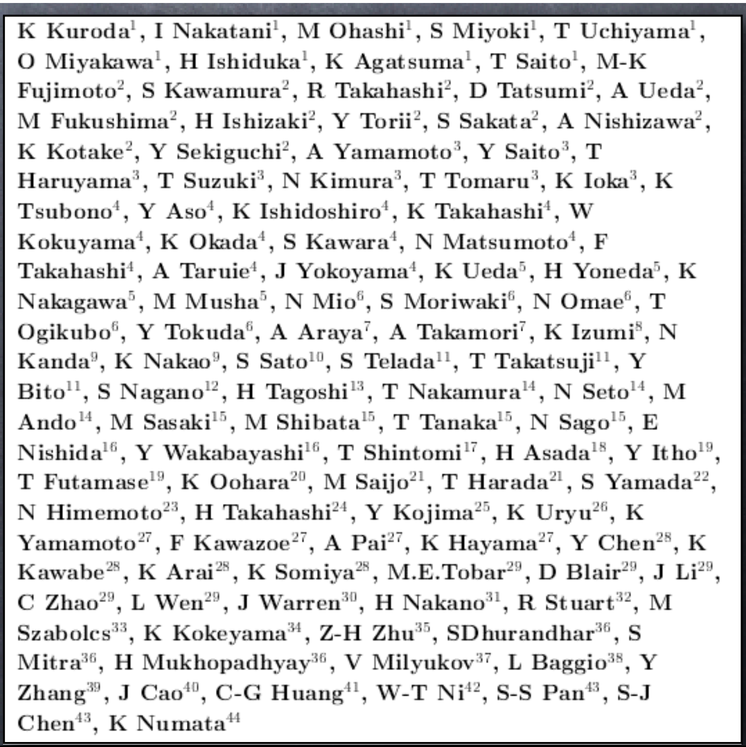
  New members are welcome!



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

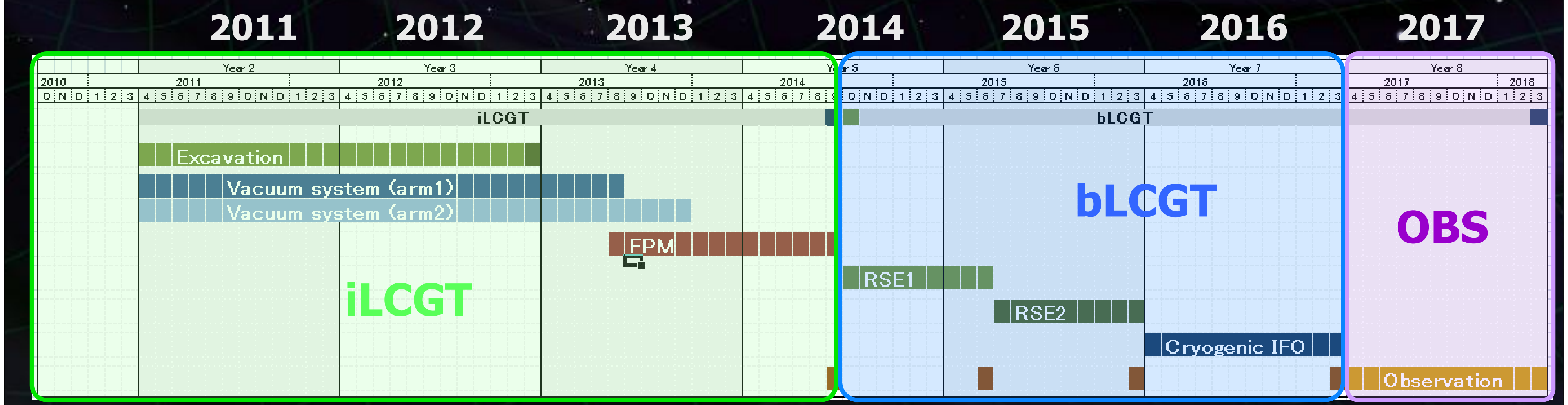


K Kuroda[1], I Nakatani[1], M Ohashi[1], S Miyoki[1], T Uchiyama[1], O Miyakawa[1], H Ishiduka[1], K Agatsuma[1], T Saito[1], M-K Fujimoto[2], S Kawamura[2], R Takahashi[2], D Tatsumi[2], A Ueda[2], M Fukushima[2], H Ishizaki[2], Y Torii[2], S Sakata[2], A Nishizawa[2], K Kotake[2], Y Sekiguchi[2], A 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 -)

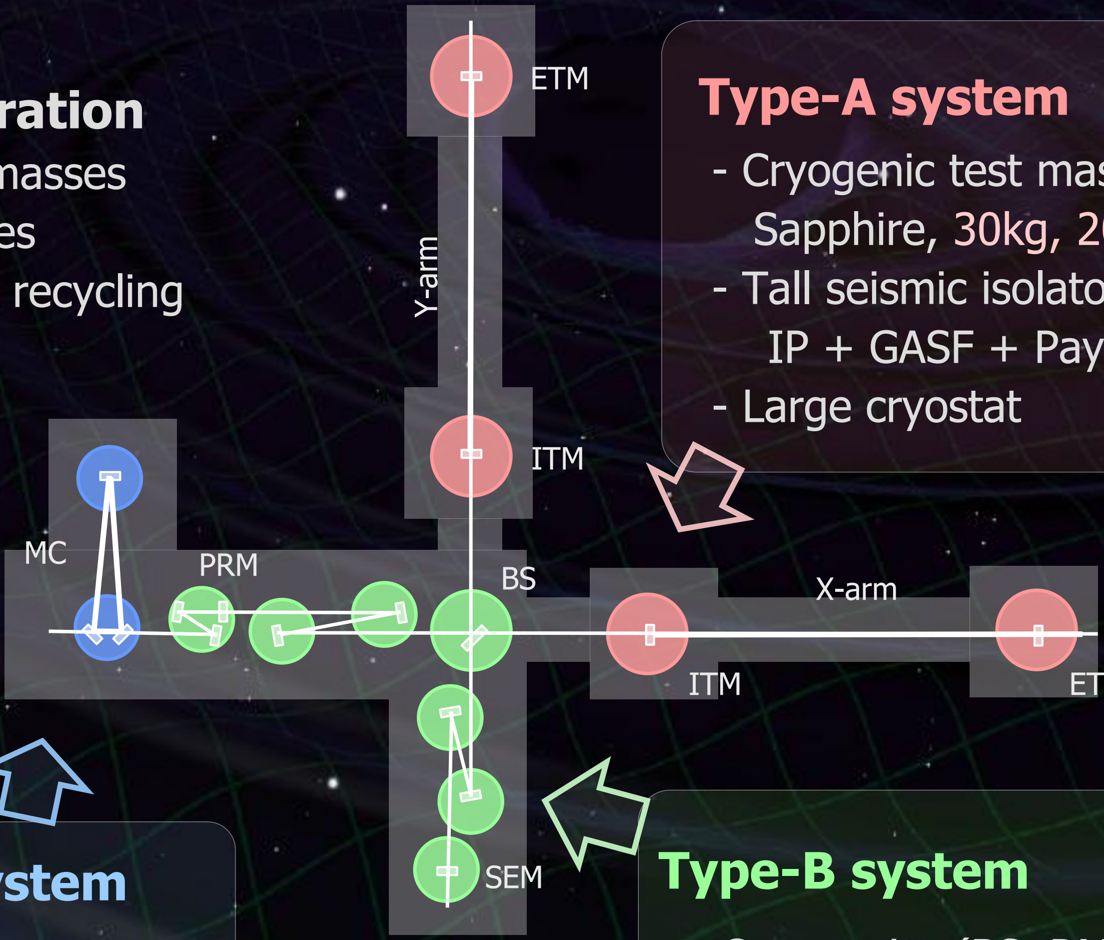
Delay in excavation start → schedule should be updated



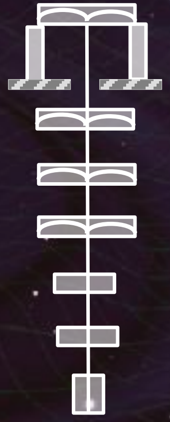
bLCGT configuration

bLCGT configuration

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

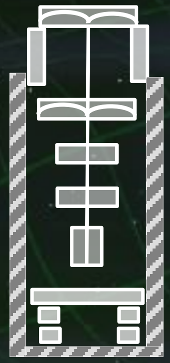


Type-A system



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

Type-B system

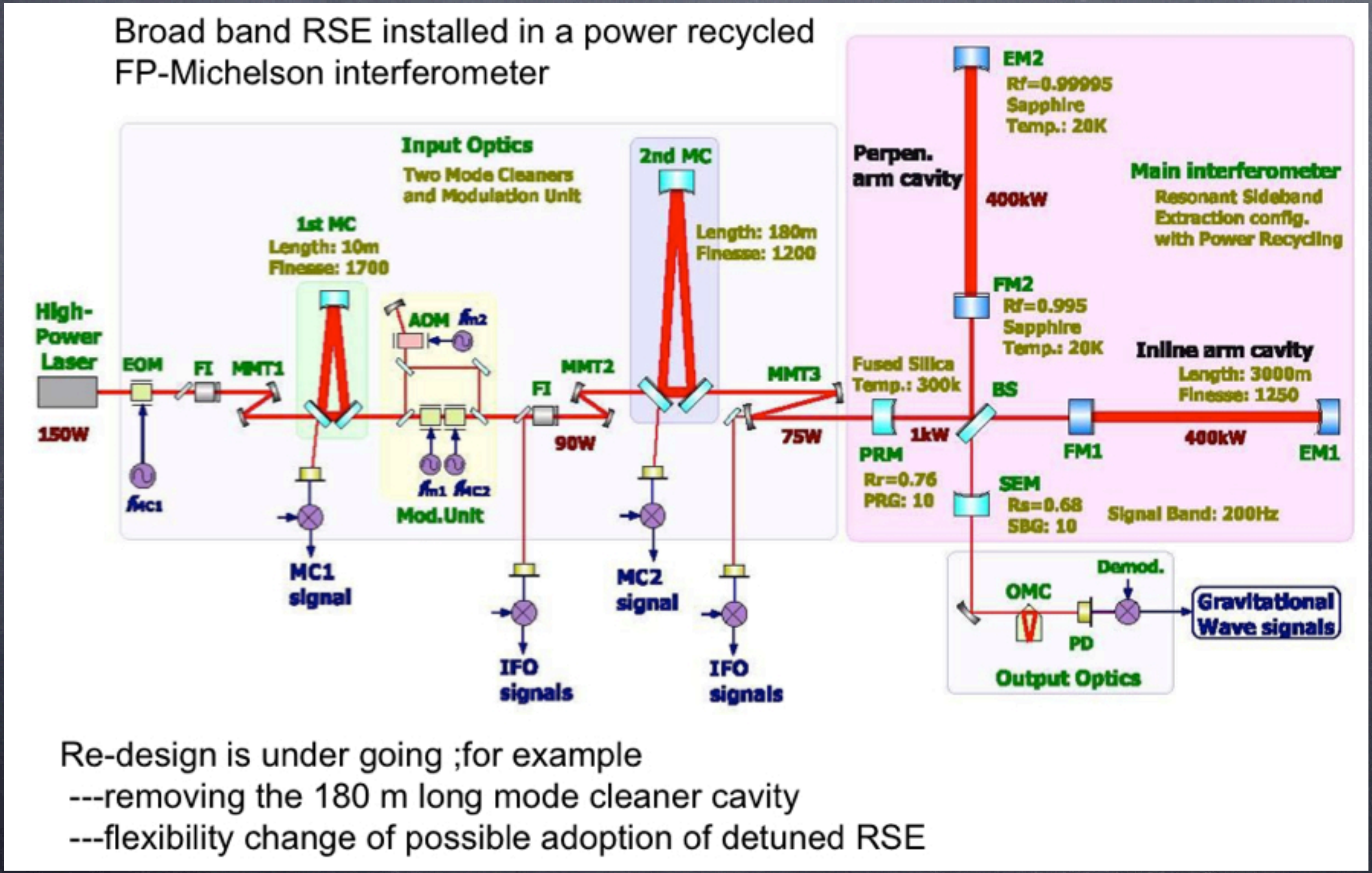


- Core optics (BS, RM ,...)
  Silica, 10kg, 290K
- IP + GASF + Payload
- Stack for aux. optics

Type-C system

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

Optical design



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

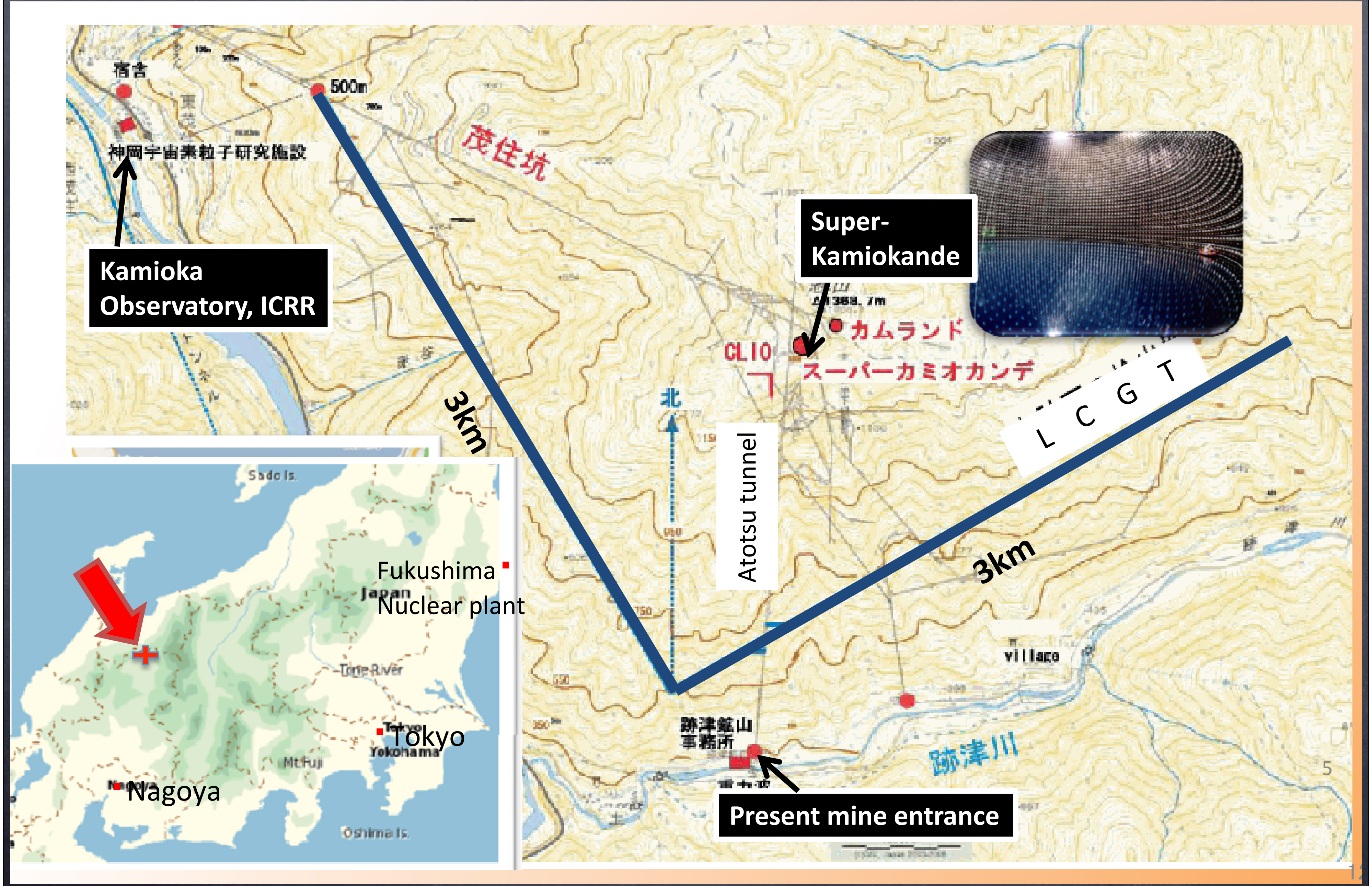
Re-design is under going ;for example

---removing the 180 m long mode cleaner cavity

---flexibility change of possible adoption of detuned RSE

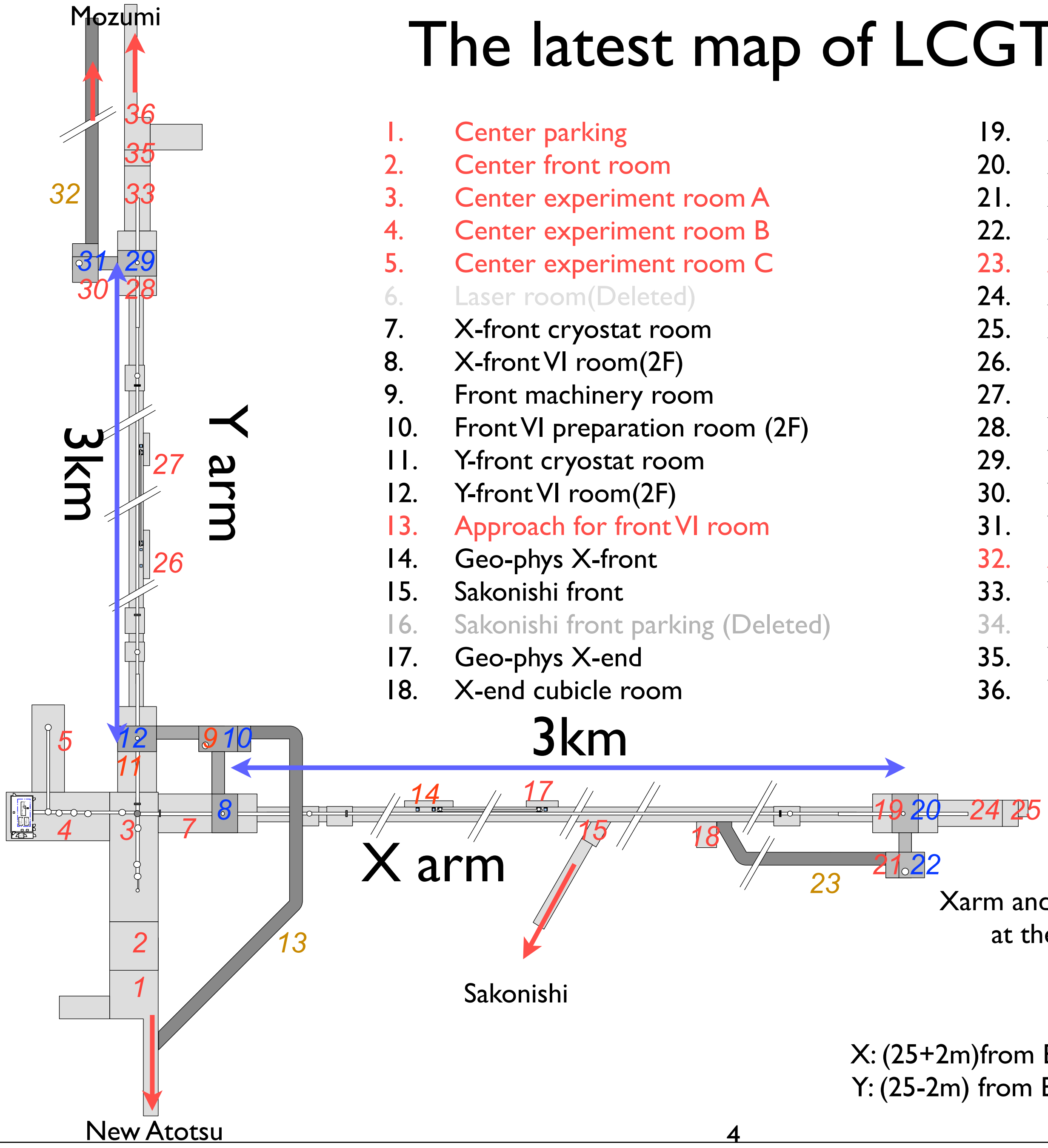
http://www.icrr.u-tokyo.ac.jp/gr/LCGTdoc.pdf

Site


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

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

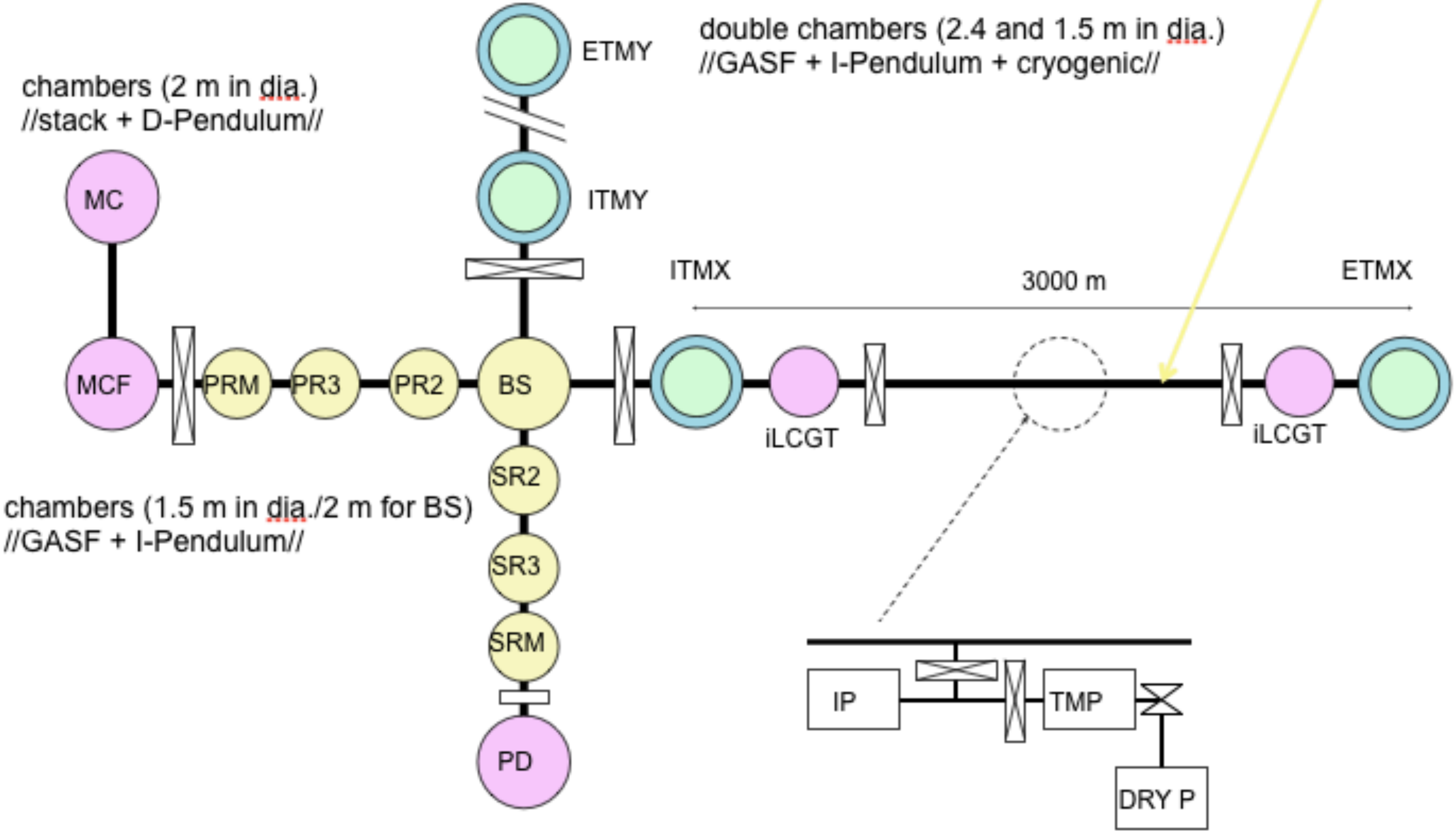
Xarm and Yarm cross perpendicularly
at the center of BS chamber.

3km:

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

LCGT Vacuum System

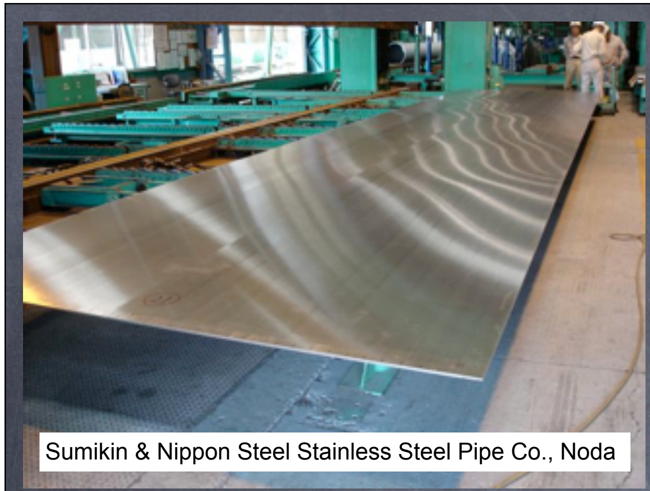
○ a unit tube (12 m long and 0.8 m in diameter);
production of the first lot (120 of 500 tubes) was started in this July.



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

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

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


Sumikin & Nippon Steel Stainless Steel Pipe Co., Noda


Sumikin & Nippon Steel Stainless Steel Pipe Co., Noda

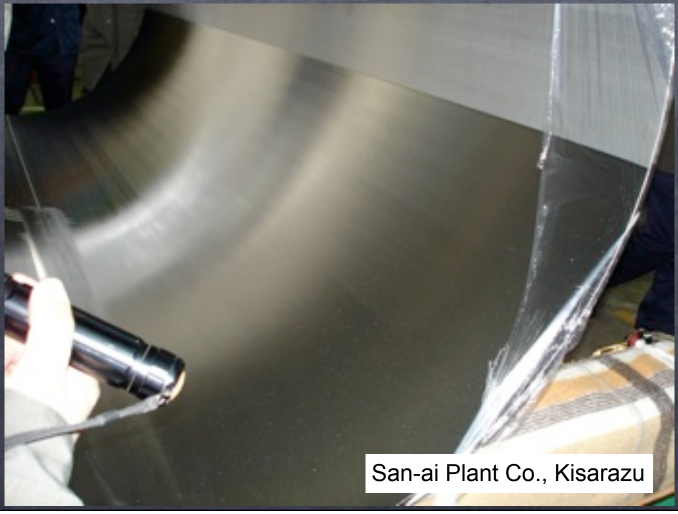

Sumikin & Nippon Steel Stainless Steel Pipe Co., Noda


Nippon Shinshukukan Co., Hosono

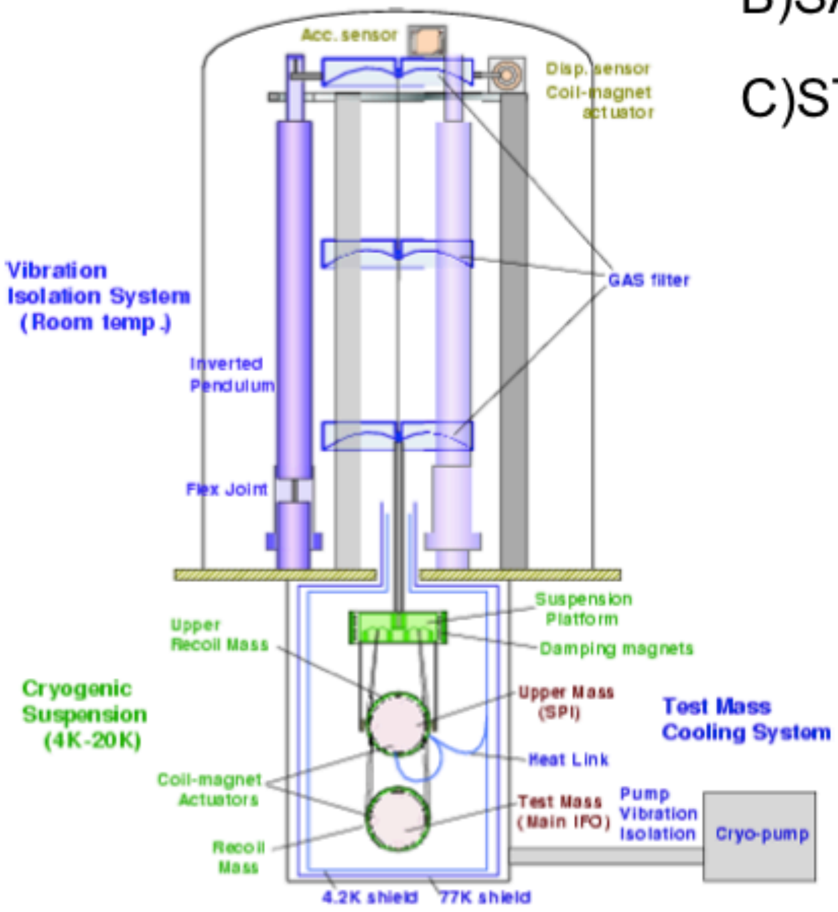

MIRAPRO Co., Noda


MIRAPRO Co./MESCO, Kamioka

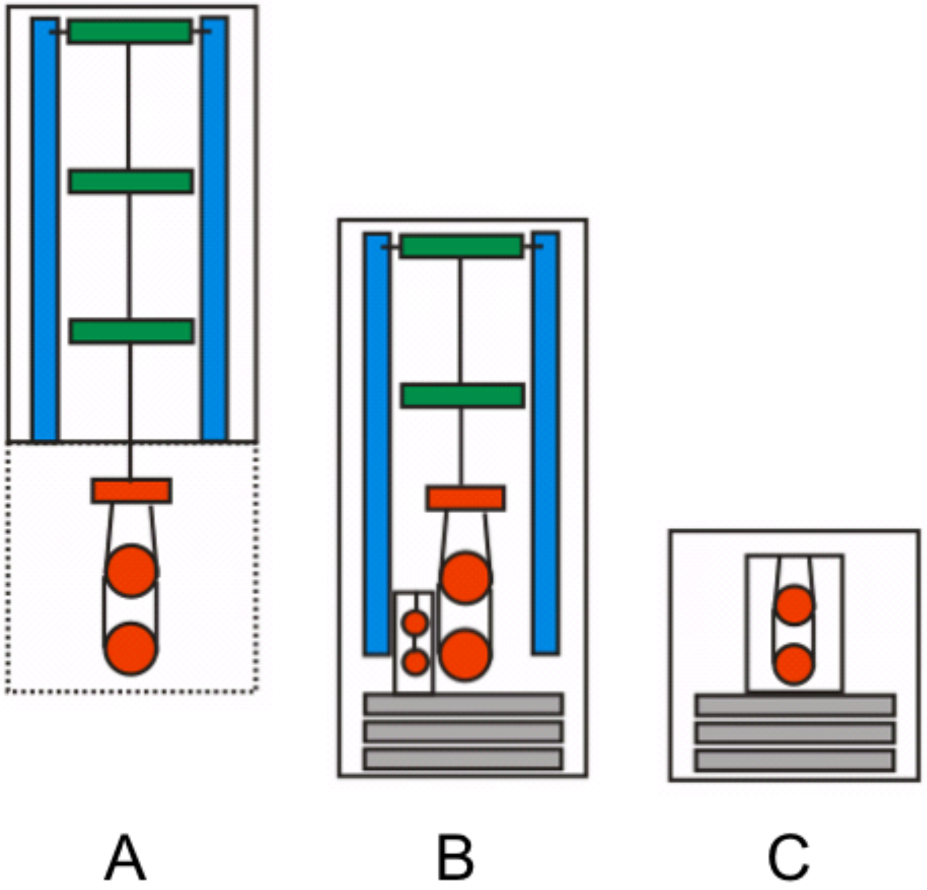

San-ai Plant Co., Kisarazu


San-ai Plant Co., Kisarazu

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



http://www.icrr.u-tokyo.ac.jp/gr/LCGTdoc.pdf

Test and Manufacturing

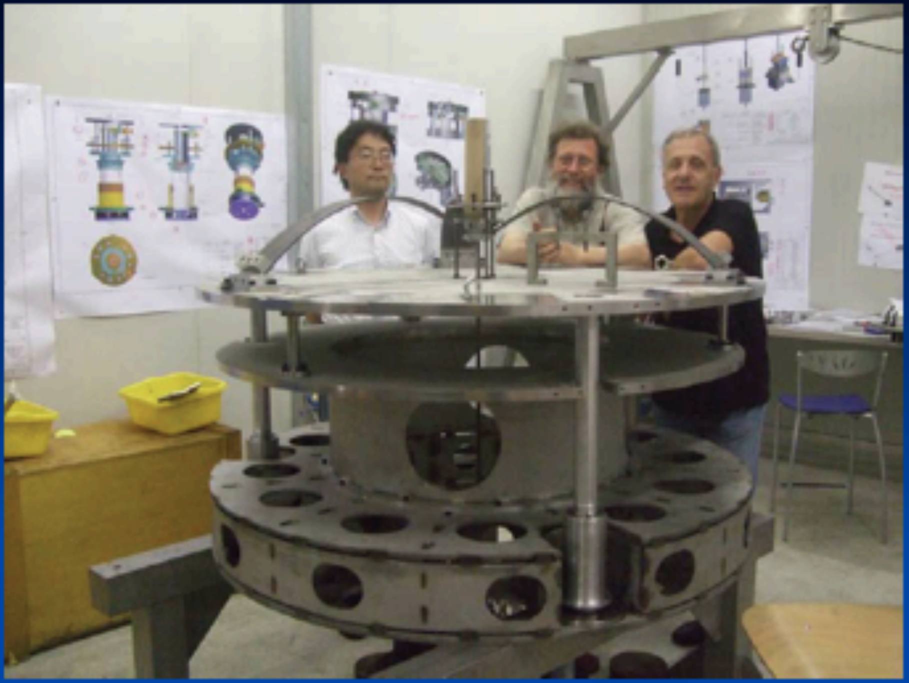
Standard GAS filter
Prototype test: 2011.2- (@NIKHEF)
19 units order: 2011FY

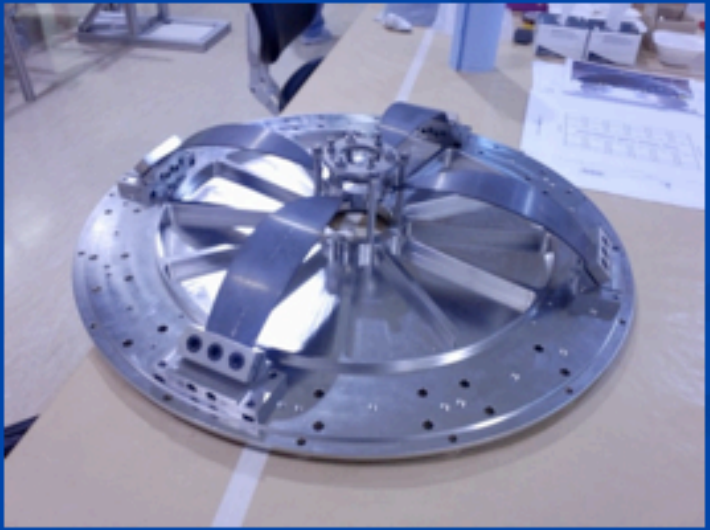
Pre-isolator
Prototype test: 2011.8- (@ICRR)
11 units order: 2012FY

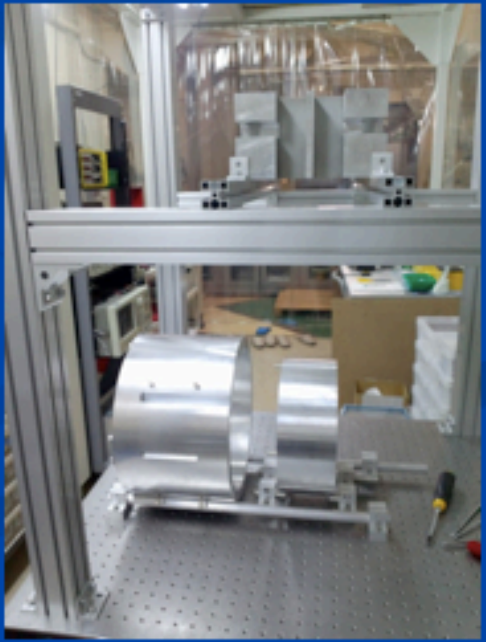
Type-B payload
Prototype test: 2011.8- (@NAOJ)
11 units order: 2012FY

Type-B full-system
Test in TAMA: 2012FY

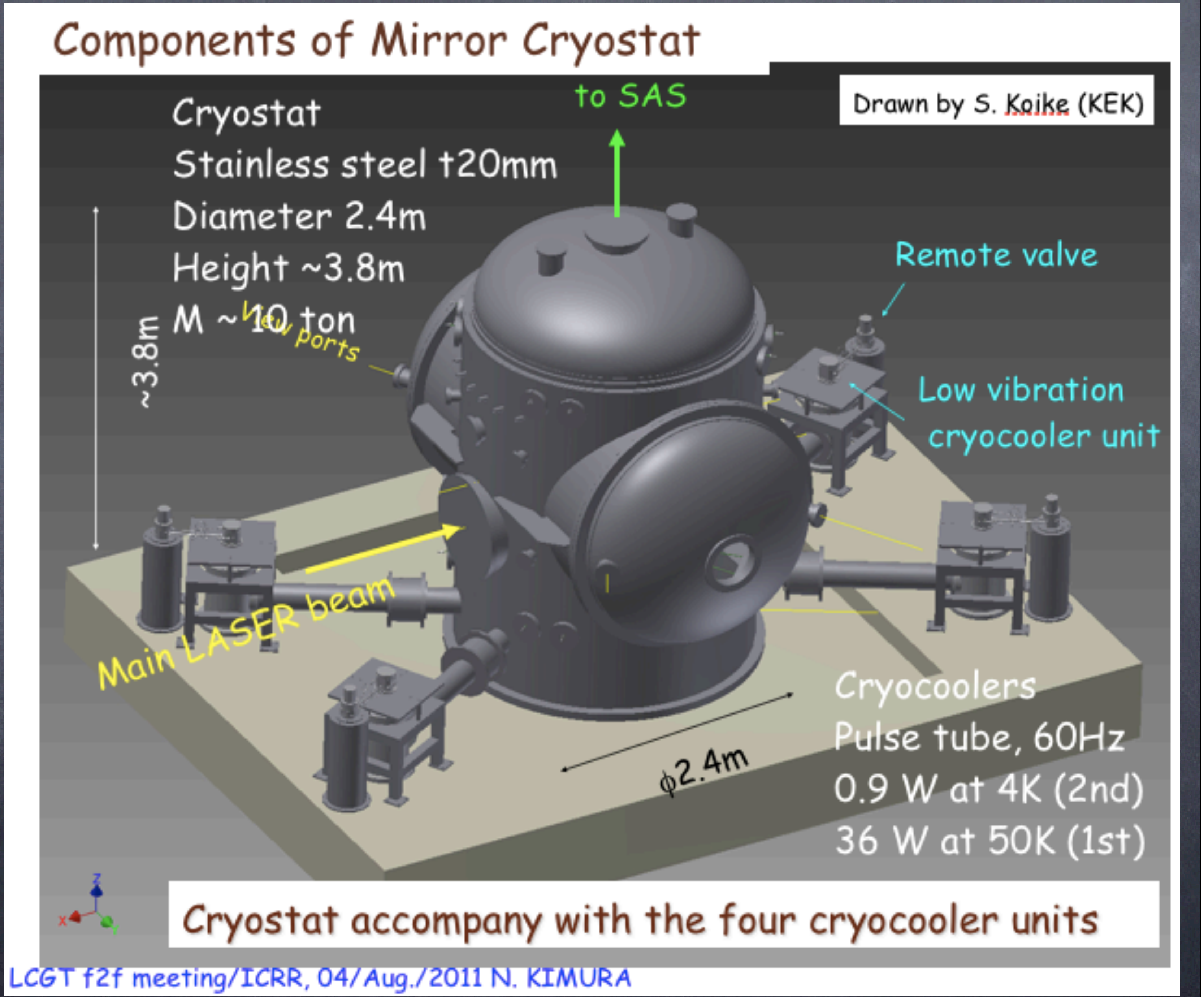
Stack
15 units order: 2011FY







Cryostat



Components of Mirror Cryostat

Drawn by S. Koike (KEK)

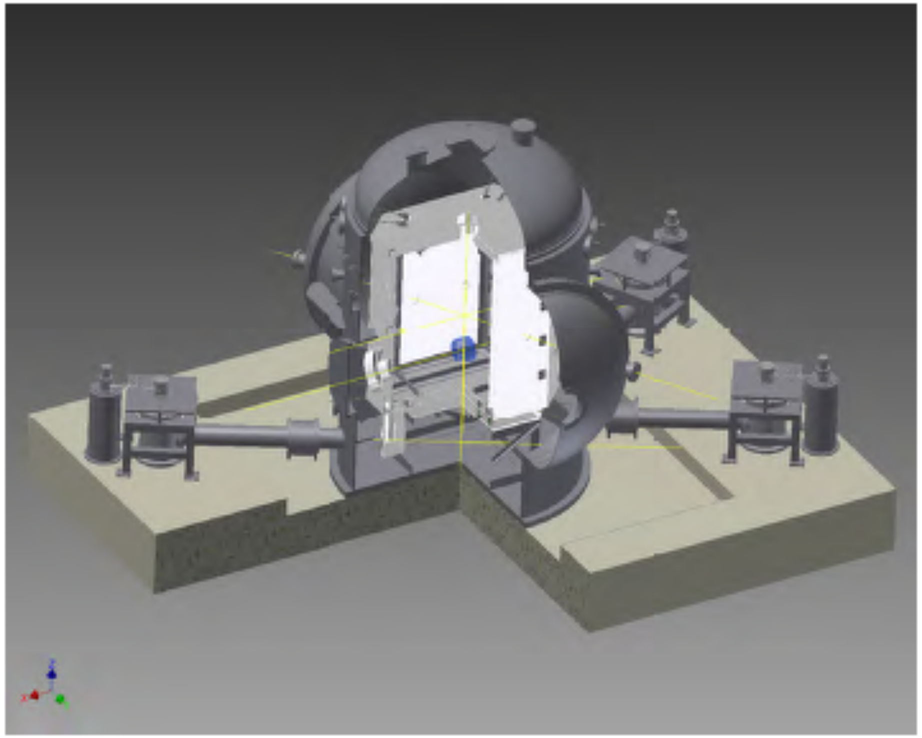
Cryostat
Stainless steel t20mm
Diameter 2.4m
Height ~3.8m
M ~10 ton

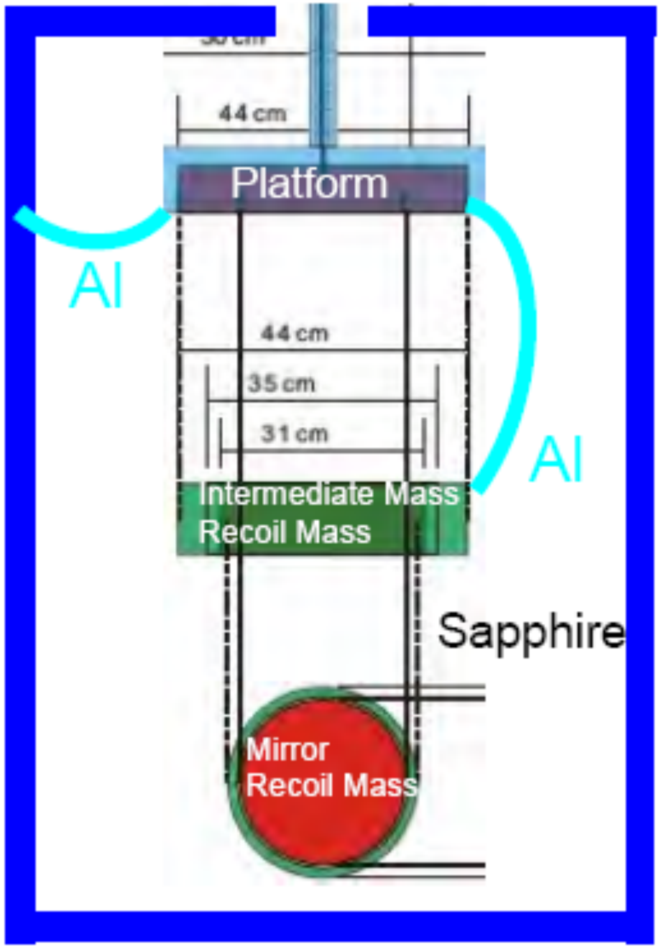
Cryocoolers
Pulse tube, 60Hz
0.9 W at 4K (2nd)
36 W at 50K (1st)

Cryostat accompany with the four cryocooler units

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

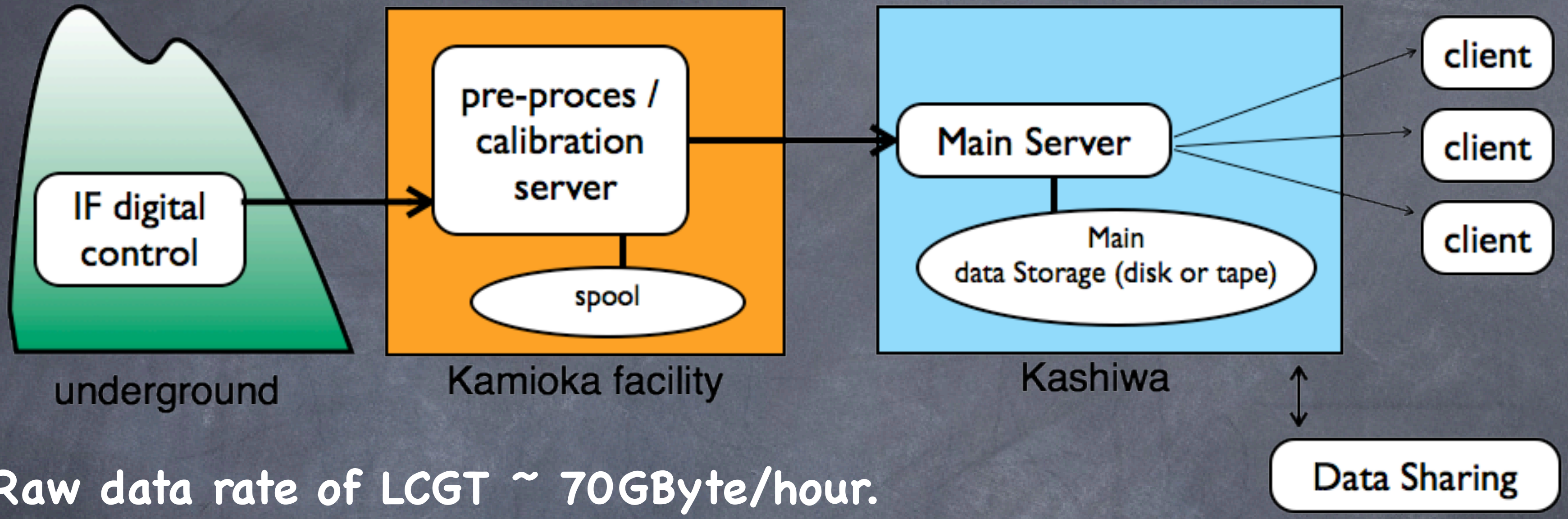
Cooling of payload





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.**

Prototype of LCGT

TAMA

CLIO

TAMA300

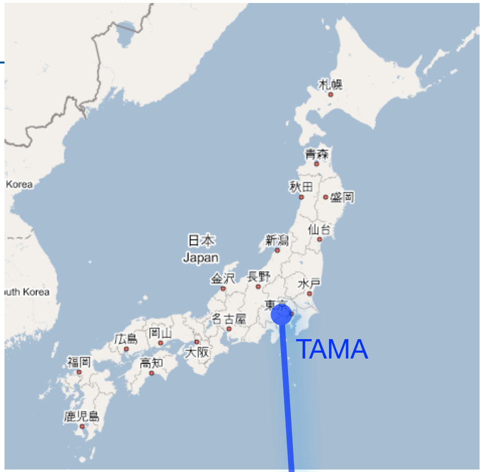
(1995-)
middle size detector

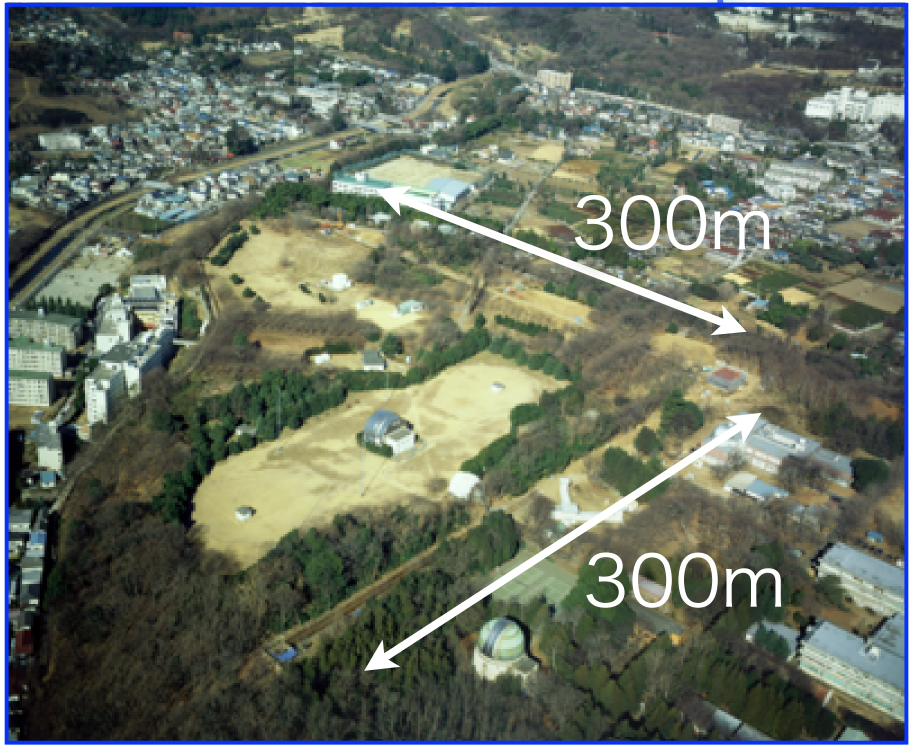
Configuration

- Fabry=Perot=Michelson, with Power Recycling
- baseline: 300m
- laser: Injection-lock Nd:YAG, 10W, 1064nm

Site

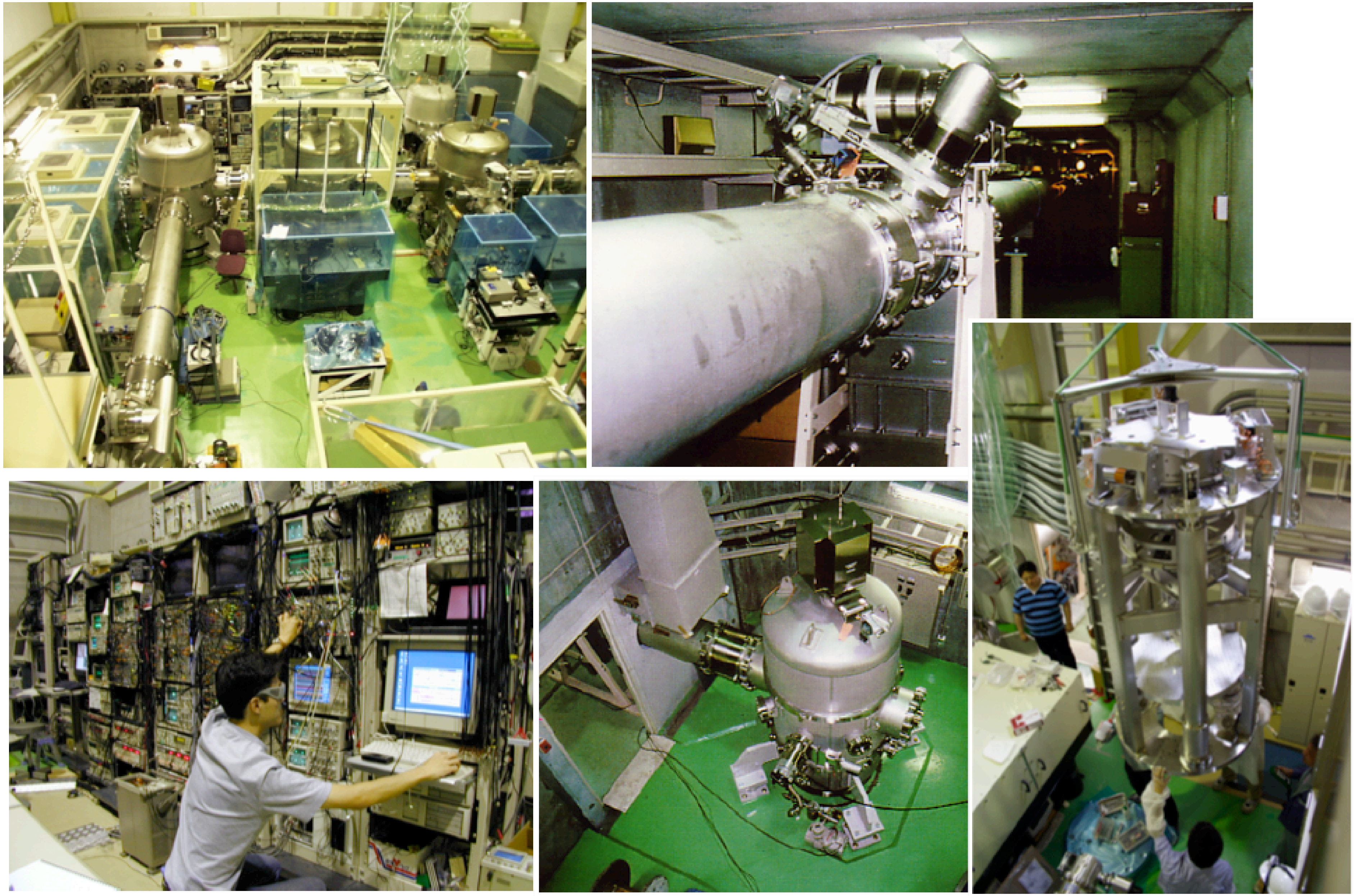
- National Astronomical Observatory,
  Mitaka, Tokyo





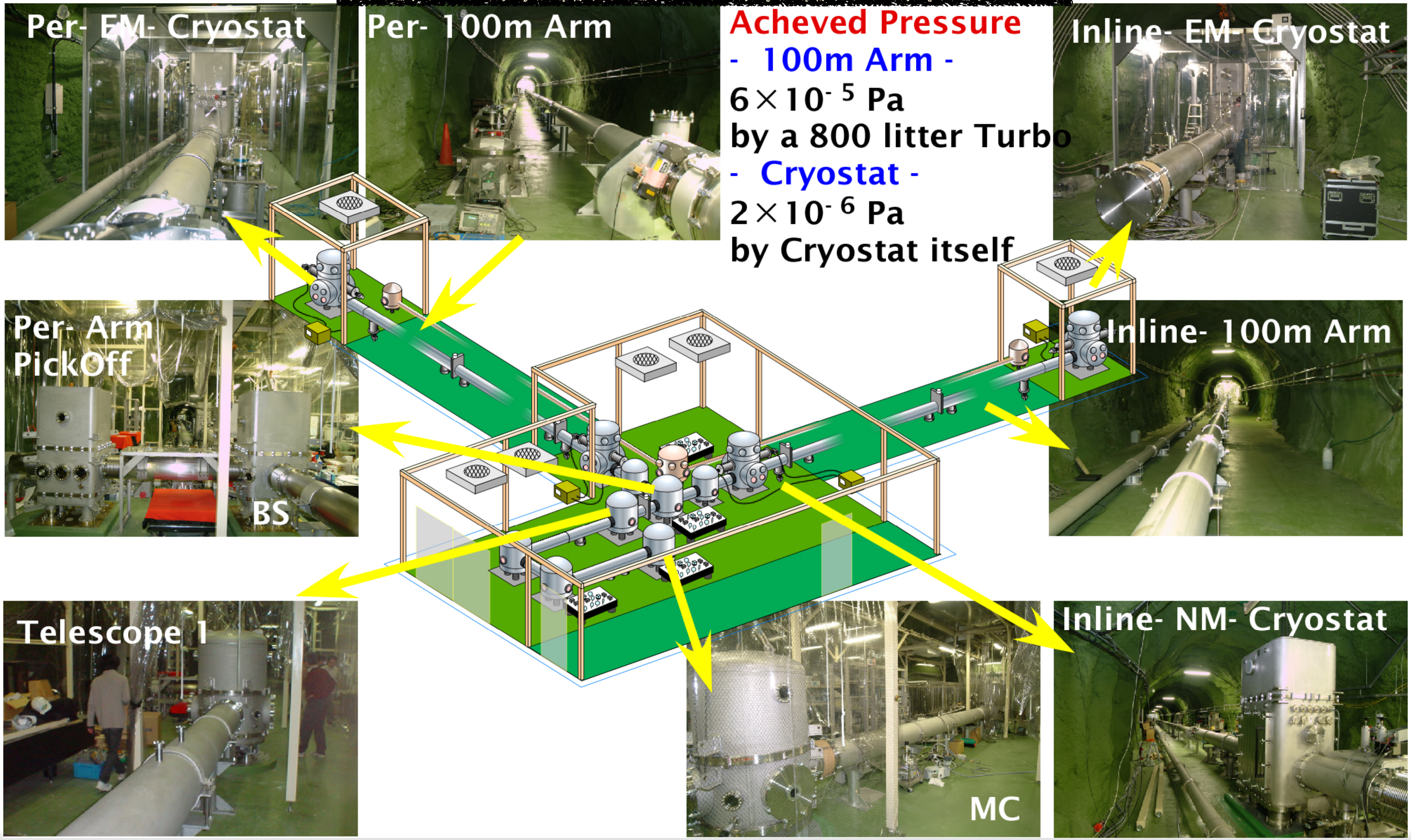
http://tamago.mtk.nao.ac.jp/spacetime/index.html

TAMA300



CLIO (Cryogenic Laser Interferometer Observatory)

Prototype of LCGT at Kamioka
(Look it at Kamioka Tour)



Acheved Pressure

- 100m Arm -

6×10^{-5} Pa
by a 800 litter Turbo

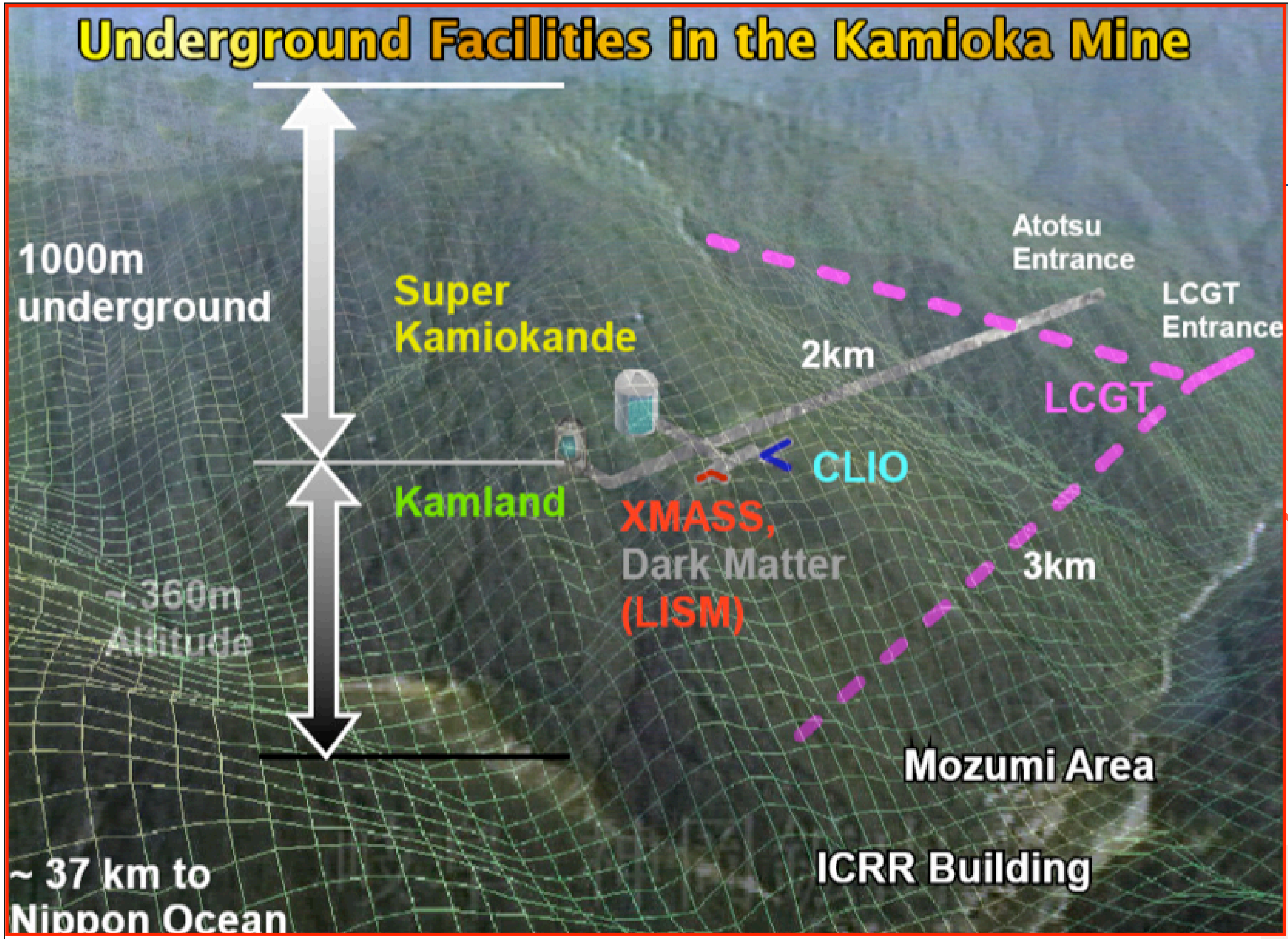
- Cryostat -

2×10^{-6} Pa
by Cryostat itself

http://www.icrr.u-tokyo.ac.jp/gr/homej/grj.html

cooooling !!

Underground Facilities in the Kamioka Mine



Reduction of noises ! http://www-sk.icrr.u-tokyo.ac.jp/aboutus/index.html

Seismic disturbances --> **Underground**

Thermal motion --> **Cryogenic**

enhance GW --> **km baseline**

World Wide GW detectors

LIGO, Virgo, GEO

IndIGO, AIGO(LIGO-Australia)

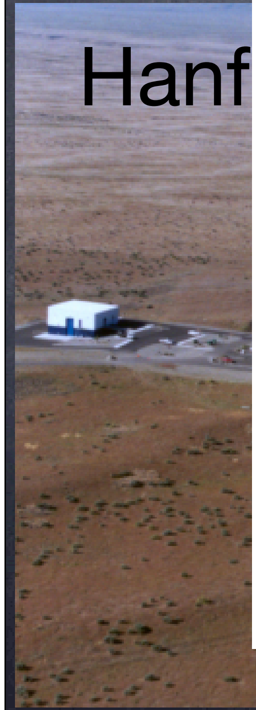
LIGO

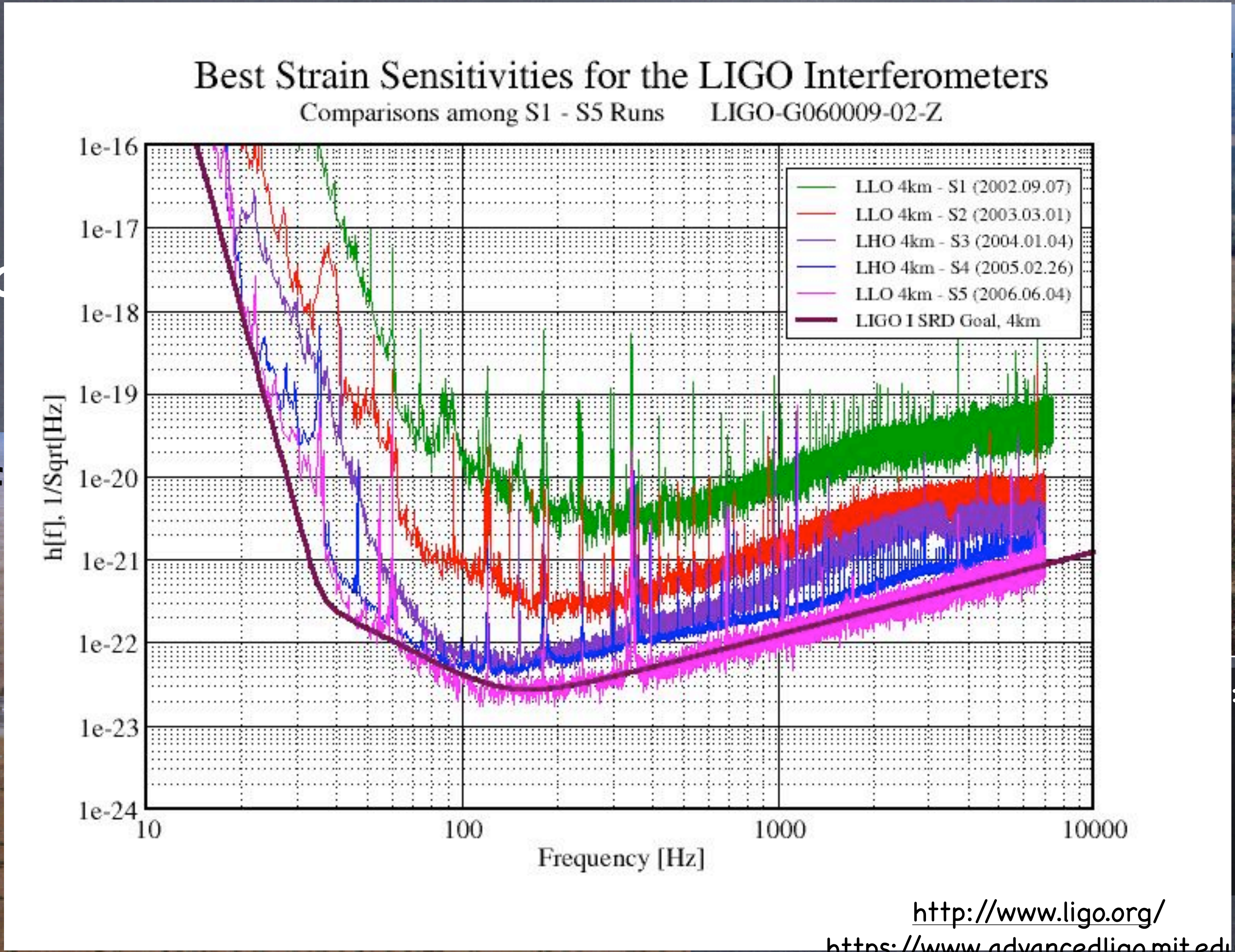
US

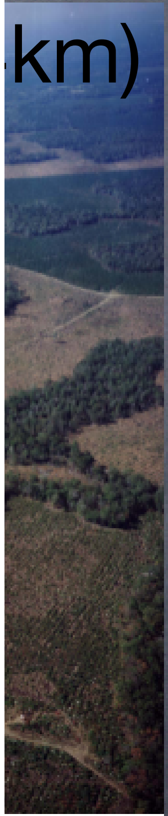
Two c

Hanf

km)







http://www.ligo.org/

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

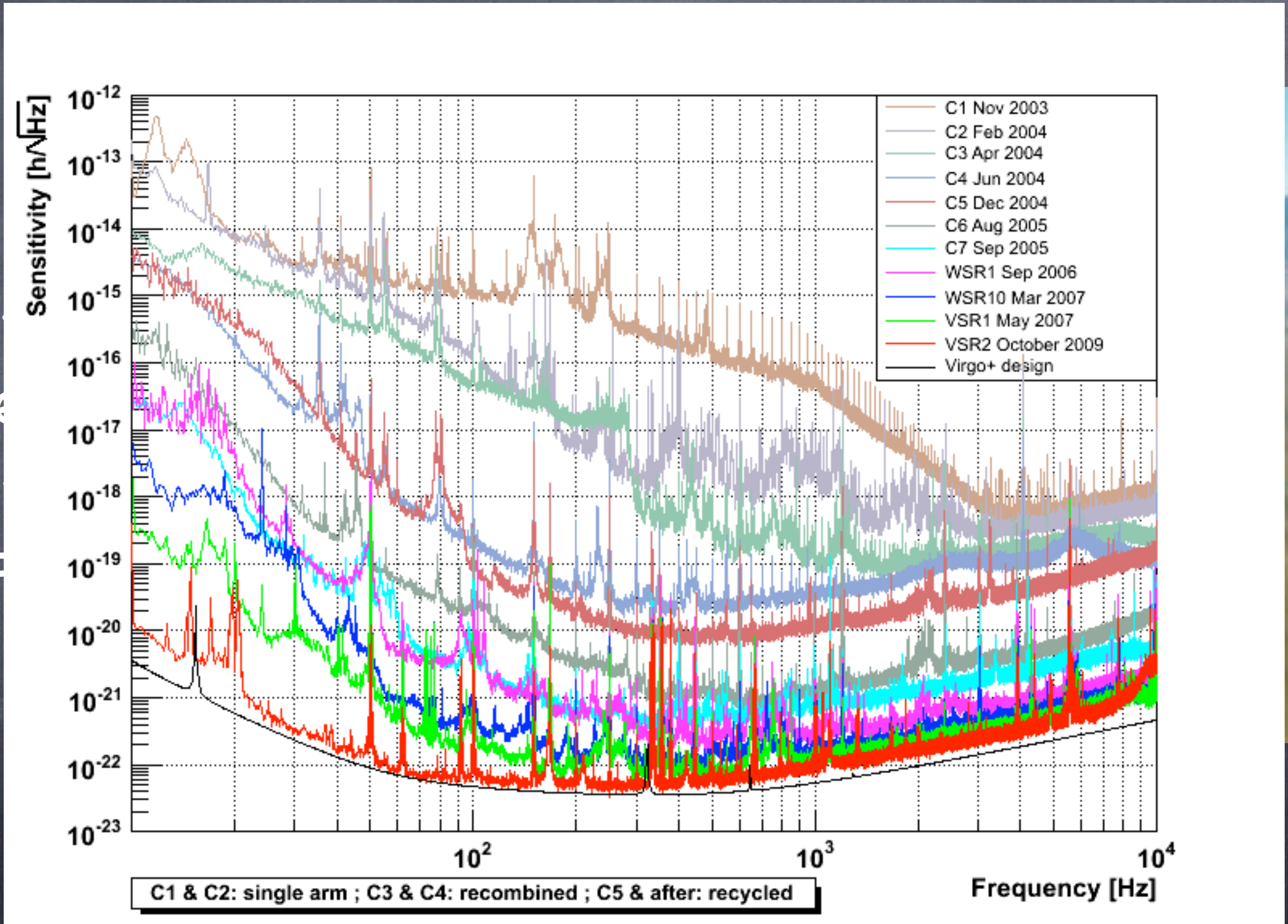
VIRGO

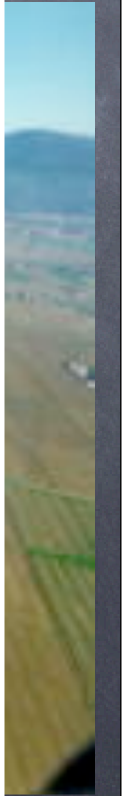
site :

Europe

Mainly

F

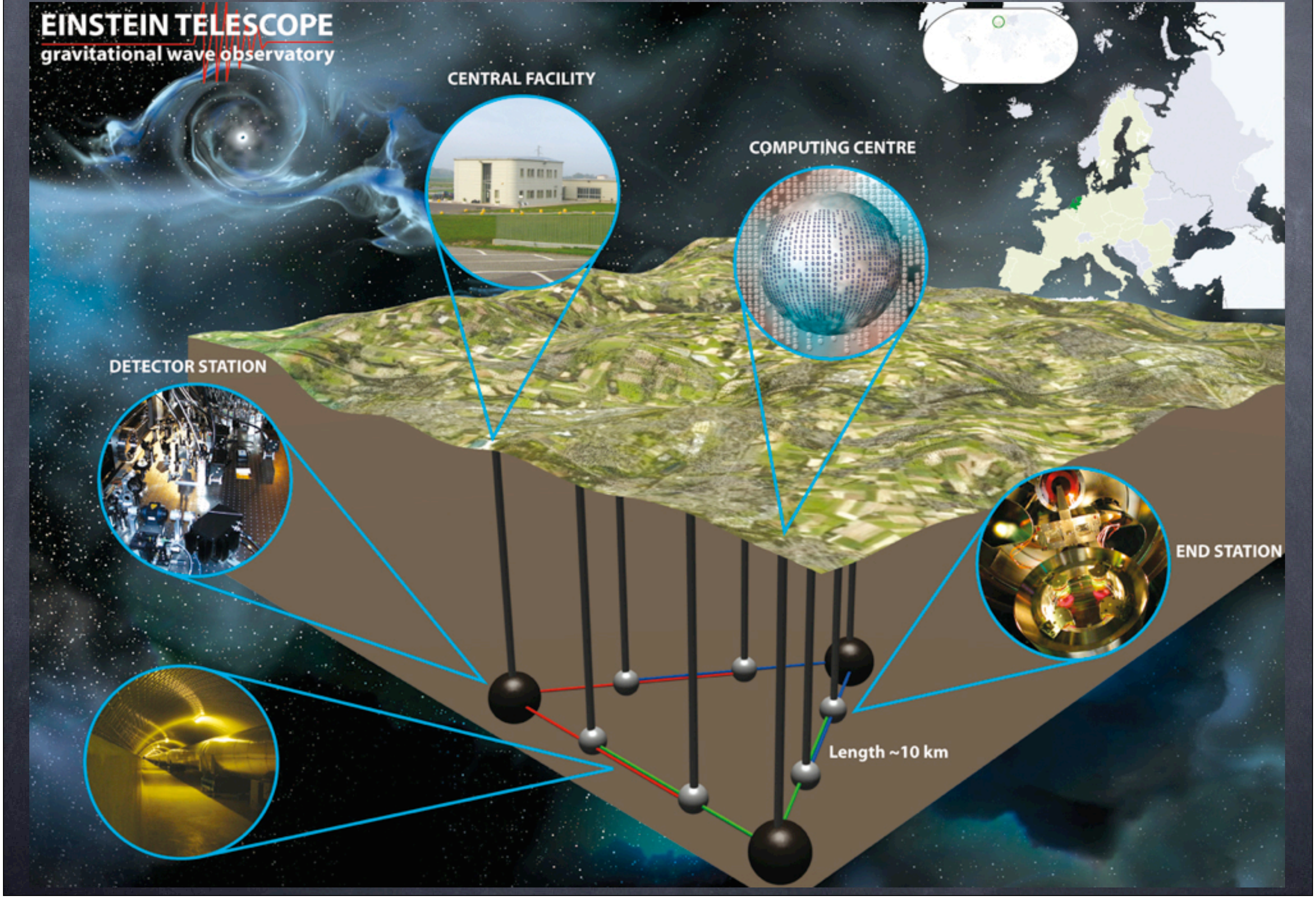




https://wwwcascina.virgo.infn.it/

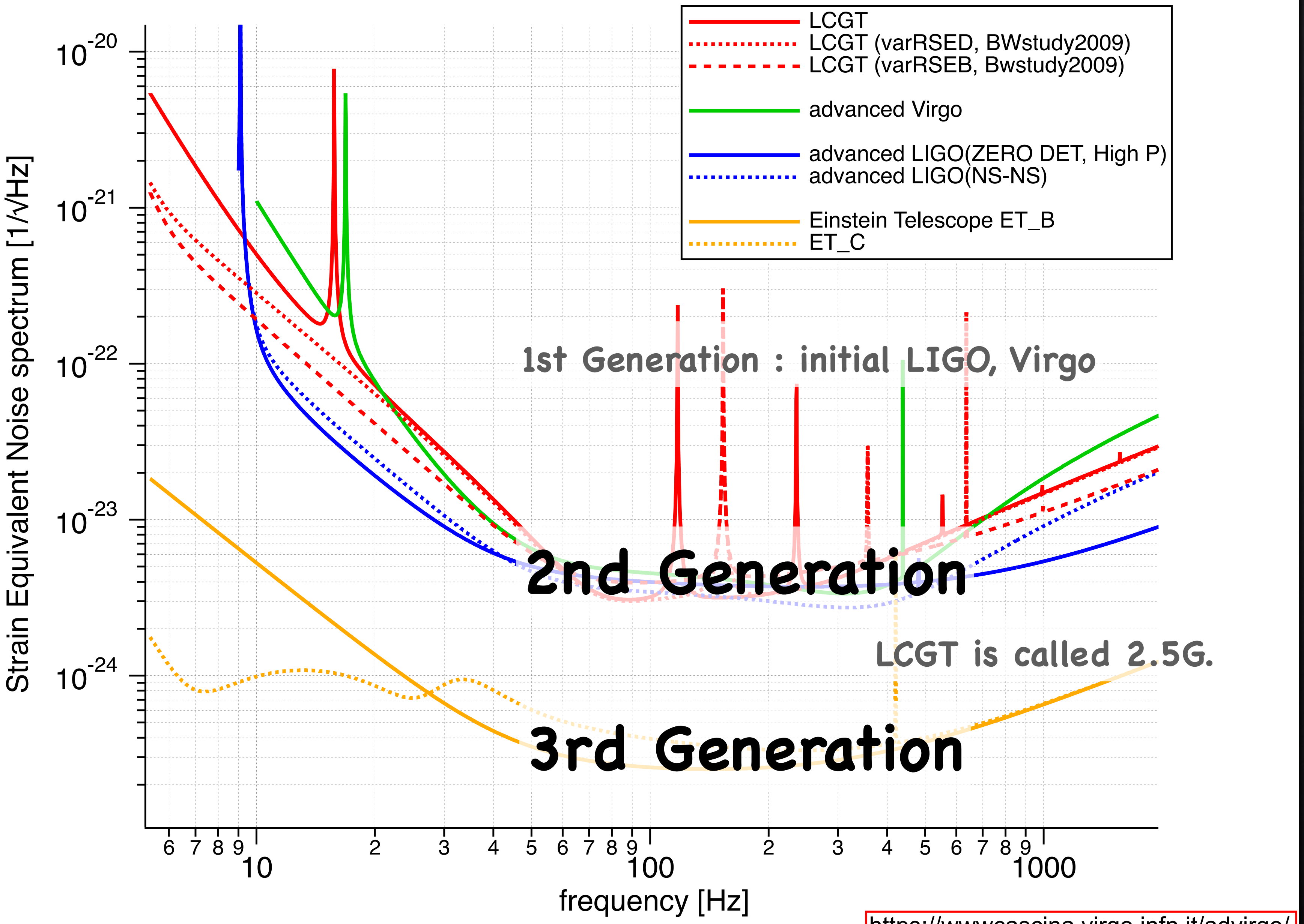
Einstein Telescope (Future Plan)

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



http://www.et-gw.eu/

Comparison



LCGT is called 2.5G.

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

http://www.et-gw.eu/

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

viewgraph by Tarun Souradeep

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

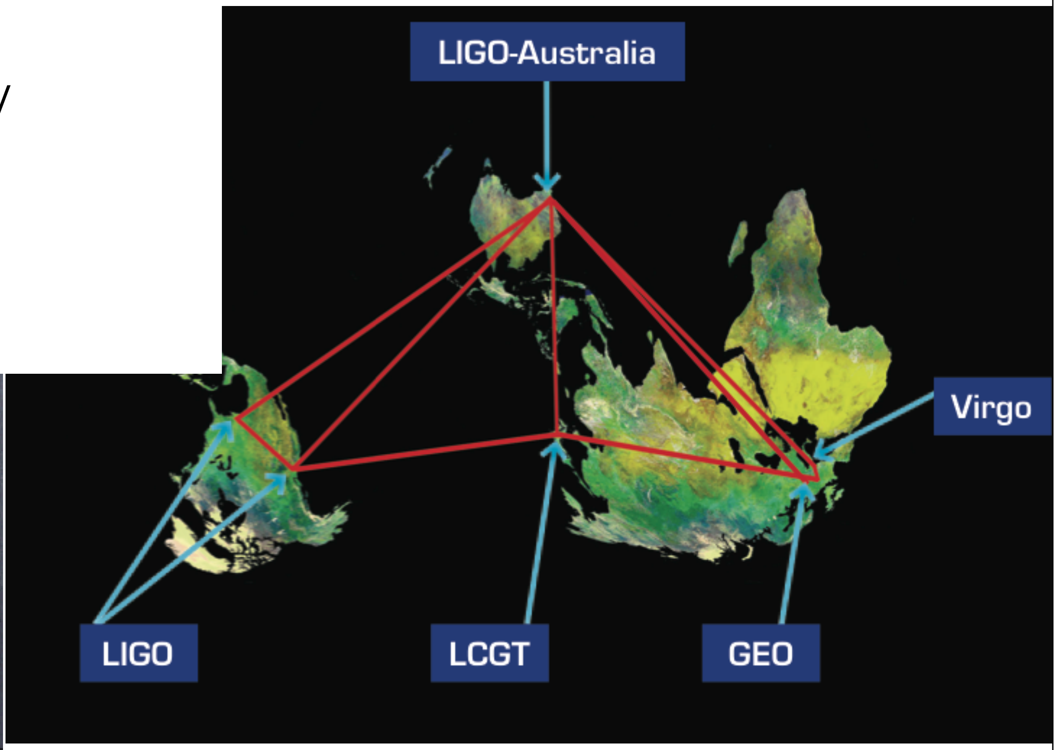
with Charles Sturt University

Over 50 members

LIGO:
LLO
LHO1
LHO2

→

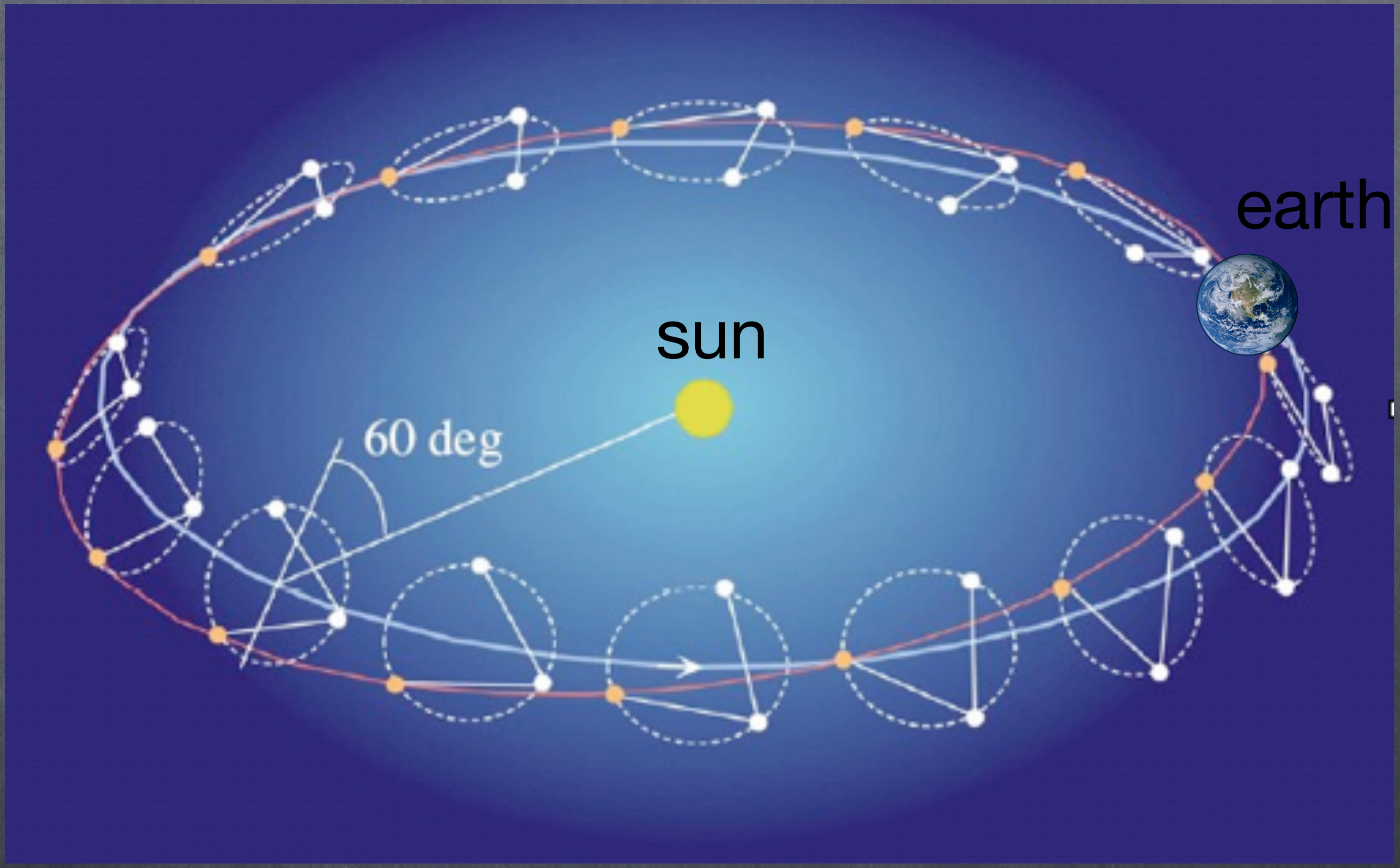
LIGO:
LLO
LHO1
LAO



viewgraph by David McClelland

Space-base projects

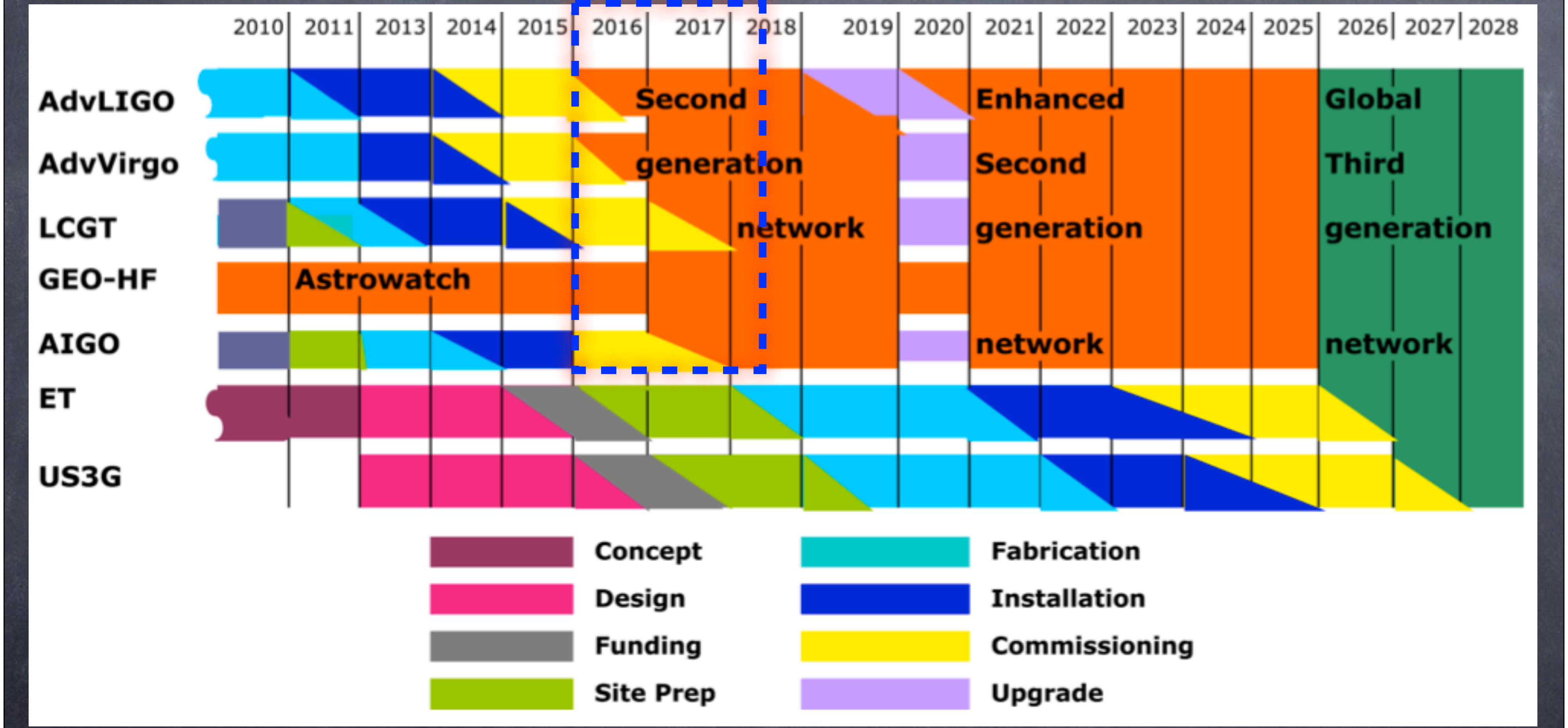
- **LISA** These plans focus on lower frequency band.
- **DECIGO**
- **BBO**



Pulsar Timing Arrays

More lower frequency, for stochastic background GW ...

GWIC (Gravitational Wave International Committee) RoadMap



https://gwic.ligo.org/

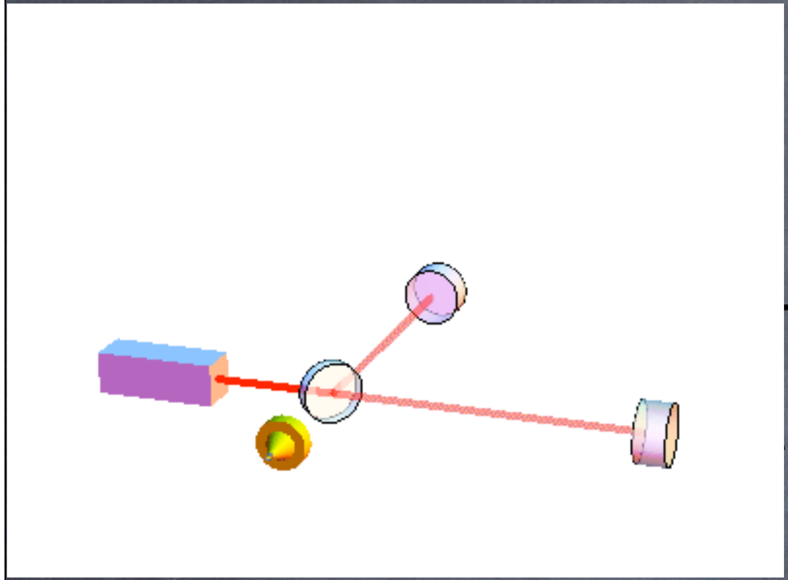
https://gwic.ligo.org/roadmap/Roadmap_100814.pdf

lecture 2 : Phyics, Astrophysics and Cosmology with Gravitational Waves

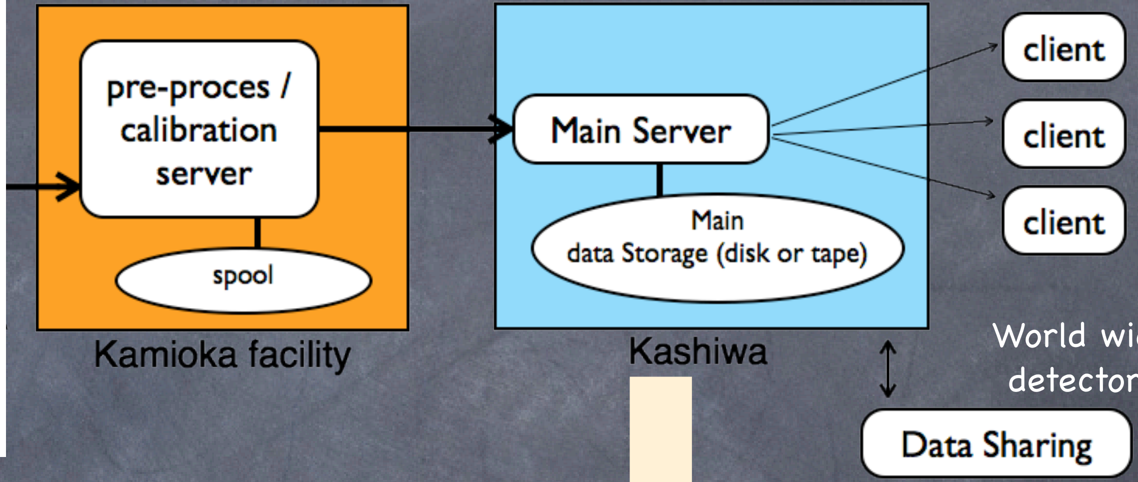
GW detection is a important test of Einstein's general relativity.

GW bring many information of its sources inside.

Interferometer--(signal)-->raw data--**(analysis)-->Science**



raw data ~600TB/year



GW events

Science

Counterpart / Follow up Observations

Science Target of LCGT (and 2nd generation detectors)

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**

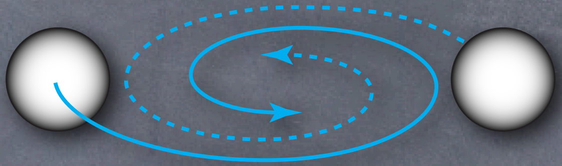
  Cosmic background radiation of GW

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

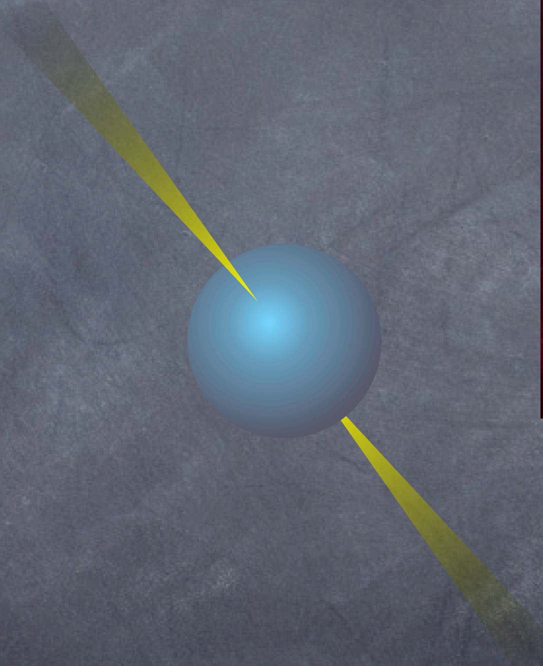
  Physics on early universe.

LCGT's targets are 1 & 2 mainly .

Remind : GW sources that possible to be detected by LCGT



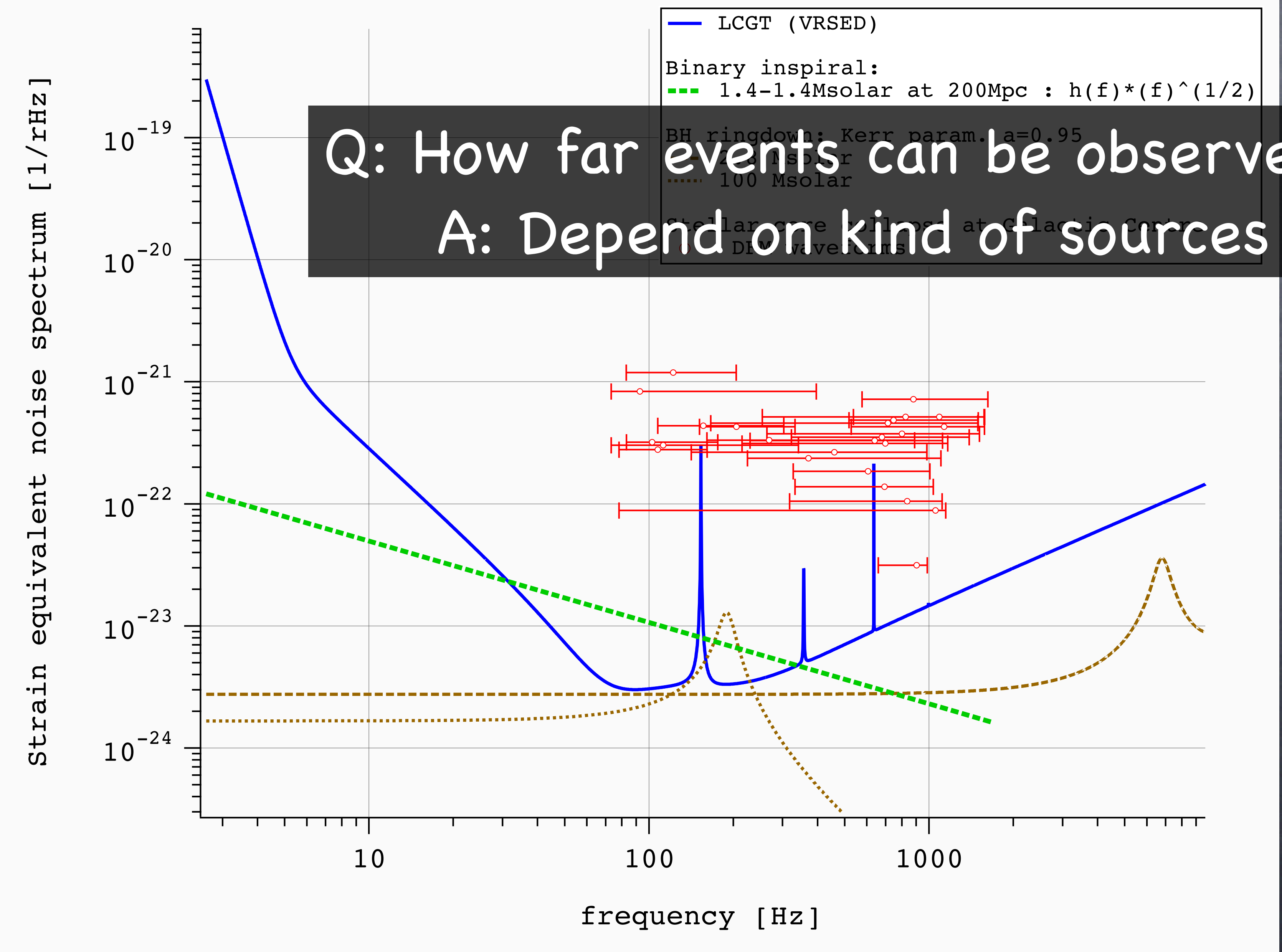
- **Event like:**
  - Compact Binary Coalescence
    - neutron star (NS)
    - black-hole (BH)
  - Supernovae
  - BH ringdown
  - Pulsar glitch
- **Continuous waves:**
  - Pulsar rotation
  - Binaries
- **Stochastic Background**
  - Cosmic string
  - Astronomical origin (i.e. many NS in galaxy cluster)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



Sensitivity limit of LCGT

Typical target :

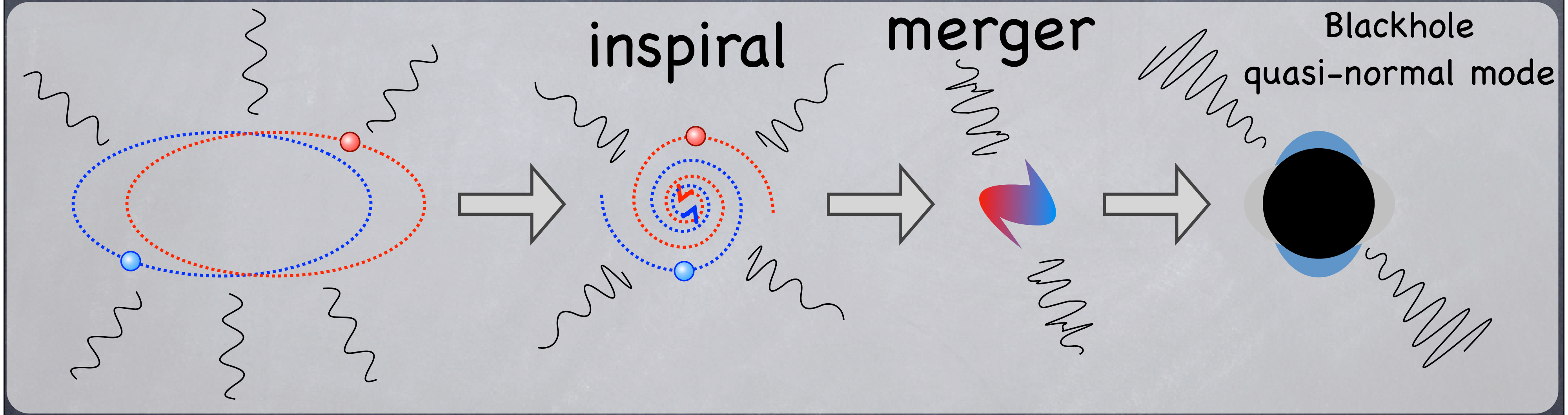
$$h \lesssim 10^{-22} - 10^{-24} [1/\sqrt{\mathrm{Hz}}]$$



Q: How far events can be observed ?

A: Depend on kind of sources

Compacr Binary Coalescences



NS-NS
NS-BH
BH-BH

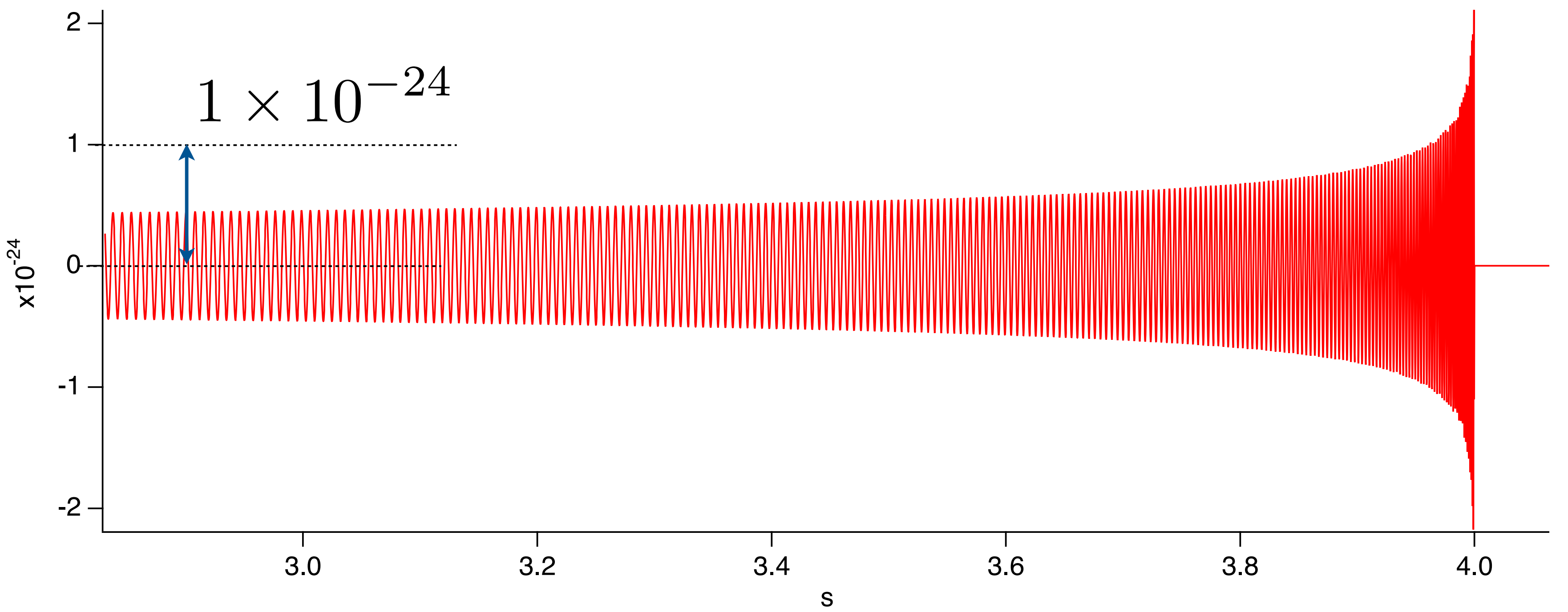
NS(neutron star)-NS binary

Most promising source

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

--> **'standard siren'**

strain amplitude



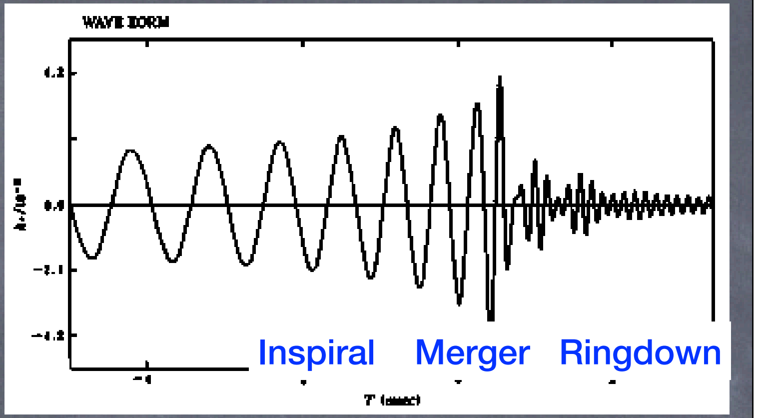
time

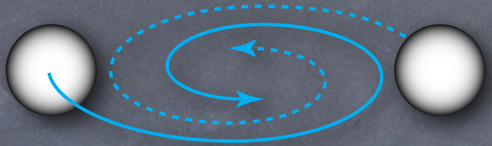
amplitude ~10^{-24} for NS-NS at 200Mpc away!

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

CBC (Compact Binary Coalescence)

NS-NS, NS-BH, BH-BH





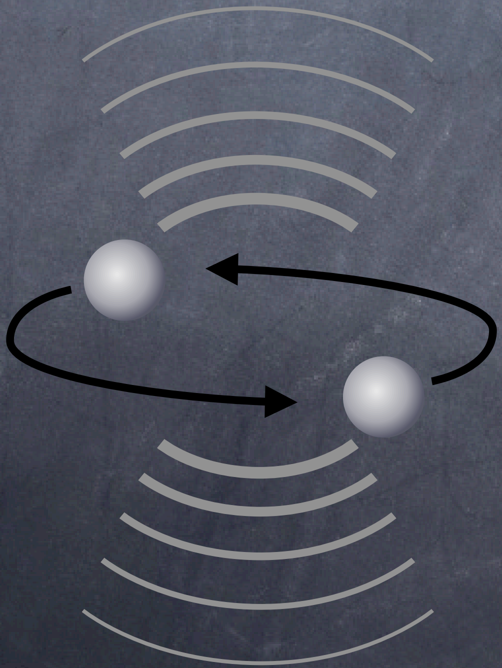
A few number PSR binaries are found.

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

http://relativity.livingreviews.org/Articles/lrr-2008-8/

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.



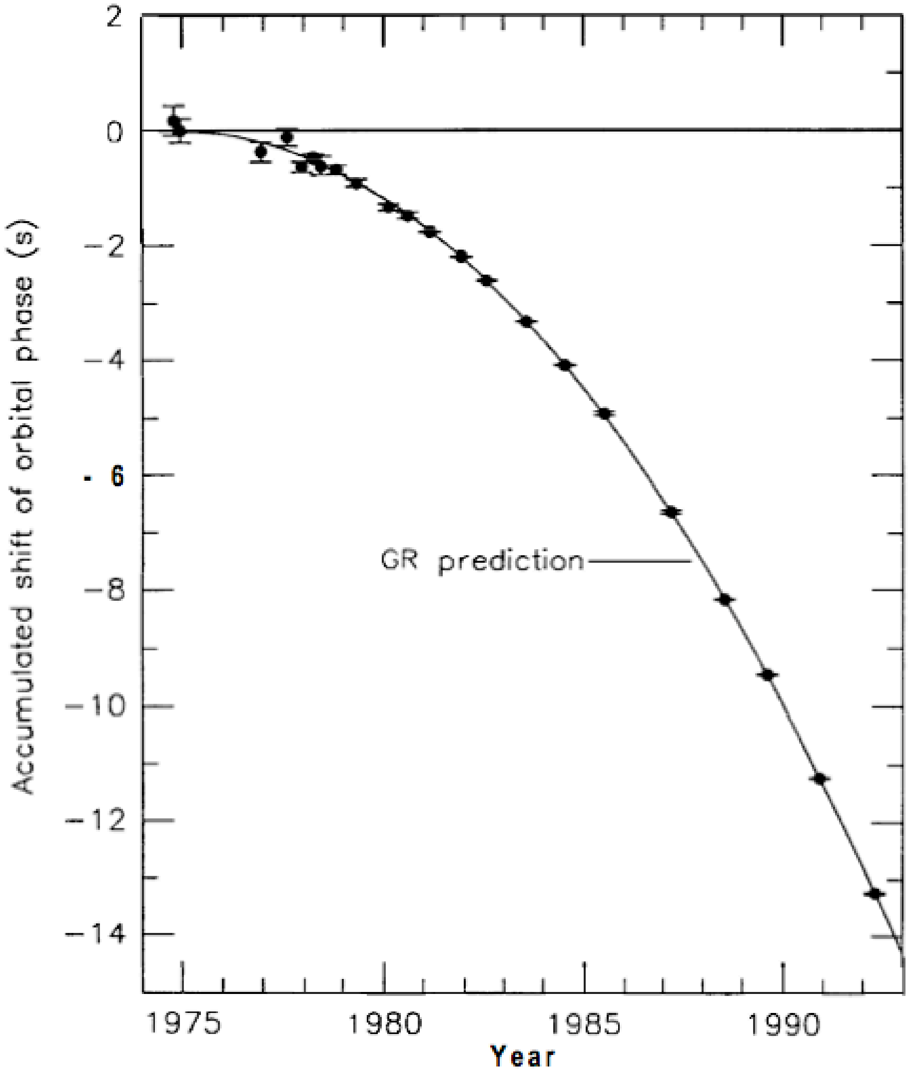
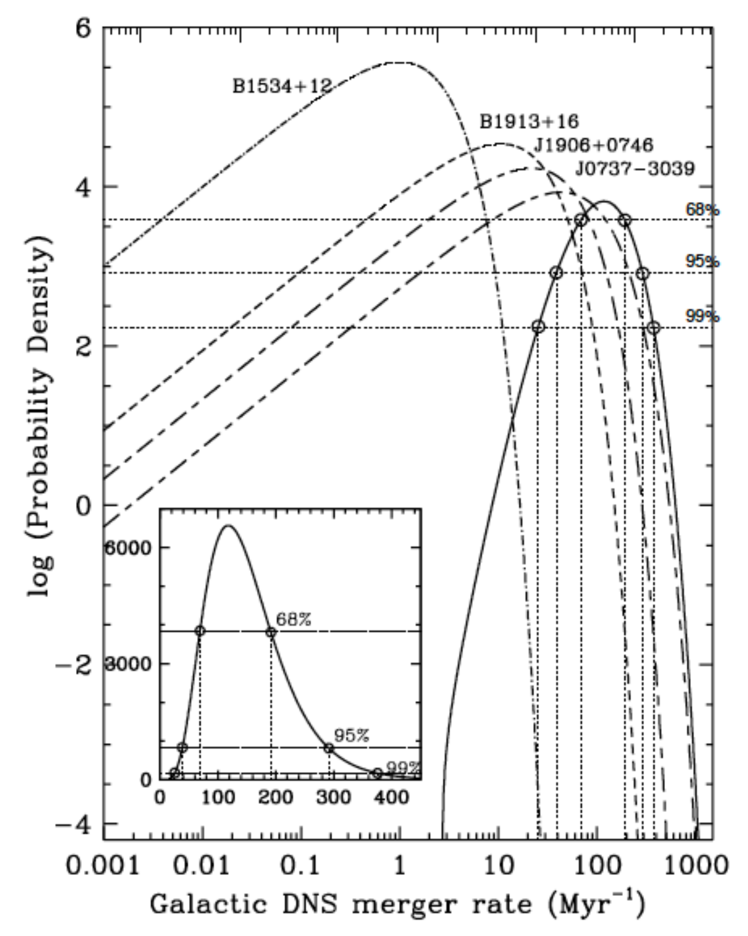


Fig. 10: Accumulated shift of the times of periastron in the PSR 1913+16 system, relative to an assumed orbit with constant period. The parabolic curve represents the general relativistic prediction for energy losses from gravitational radiation.

Taylor, 1993
(ノーベル賞講演より抜粋)

J.H. Taylor 1993

Expected detection rate of NS-NS for LCGT



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

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

Current standard LCGT design (VRSE-D)
gives horizon distance (@S/N=8)
=280Mpc (z=0.065)

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

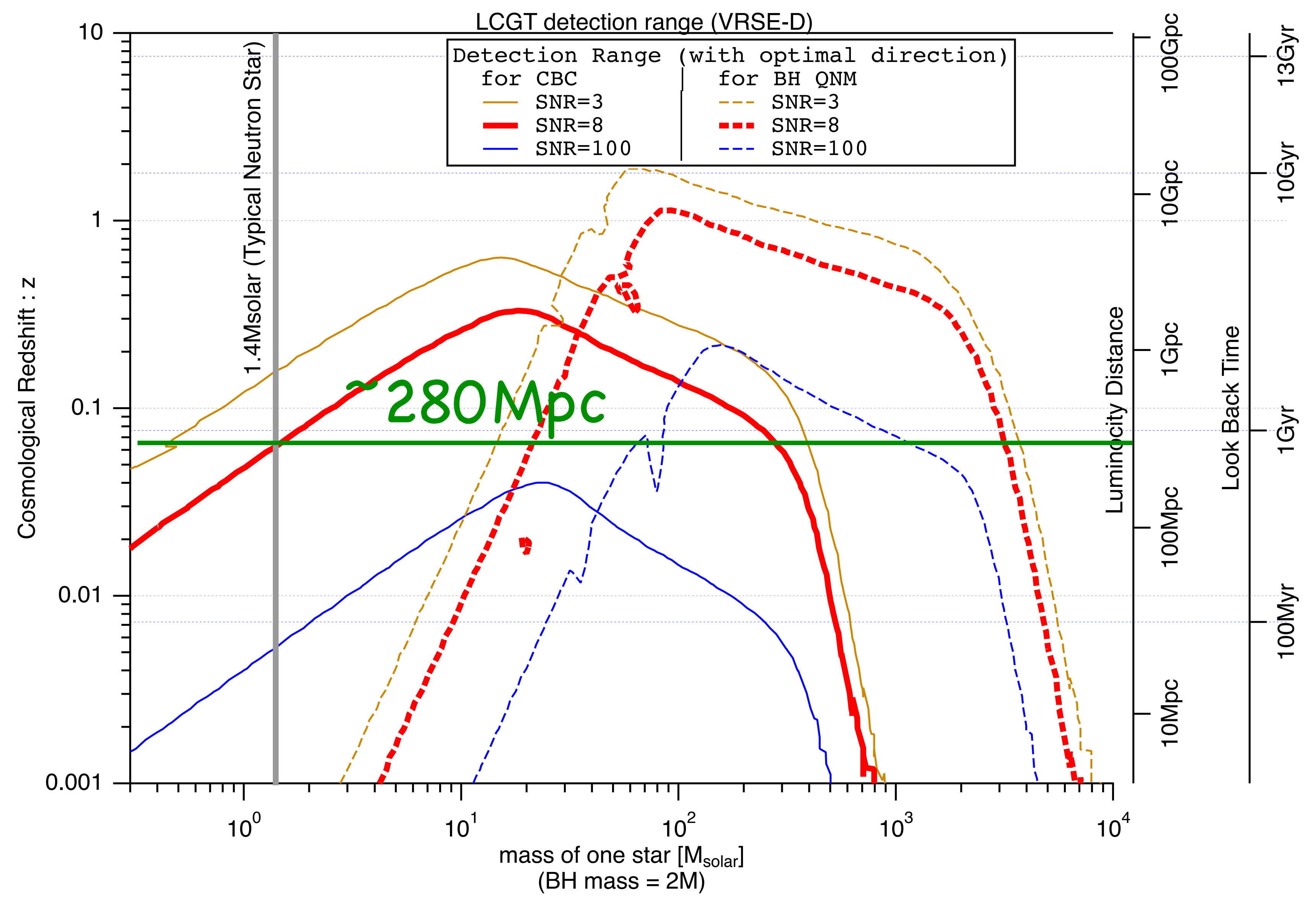
~10 event/year

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

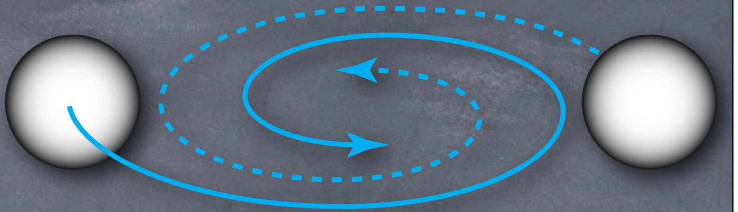
See also Abadie et al. CQG27, 173001(2010)

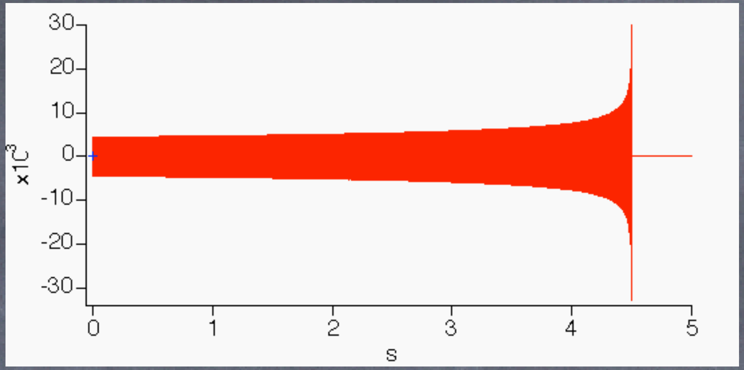
by H.Tagoshi

LCGT's detection range for CBC (+ for Black hole quasi-normal mode oscillation)

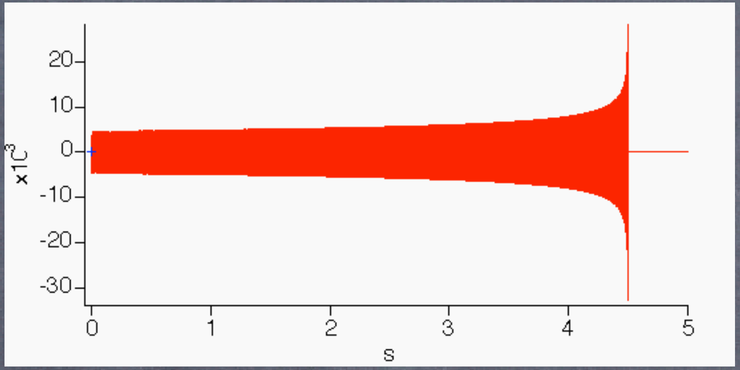


“Chirp” of mass

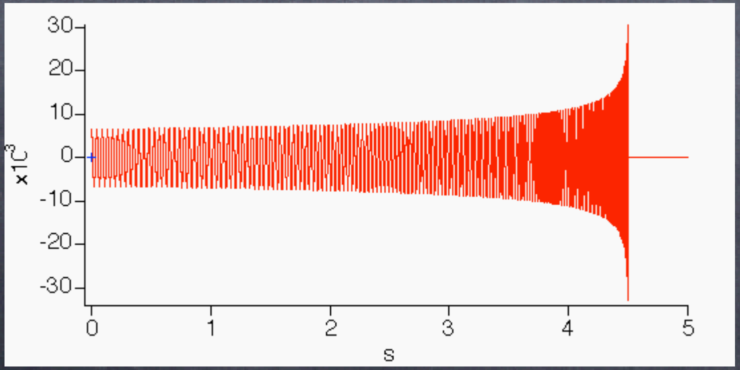




0.5-0.5 Msolar



1.4-1.4 Msolar



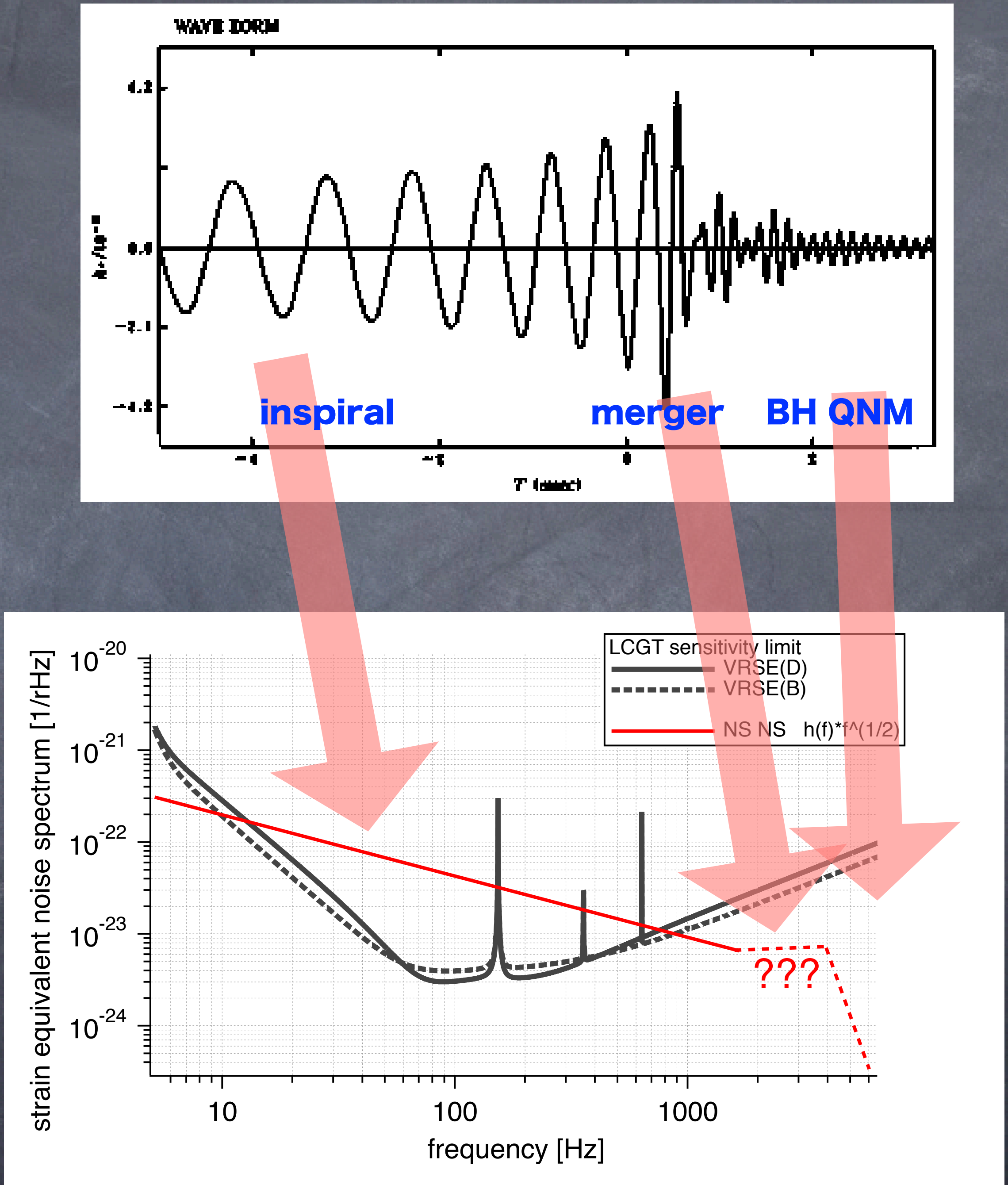
10-10 Msolar

frequency development --> mass of stars

Waveform of CBC

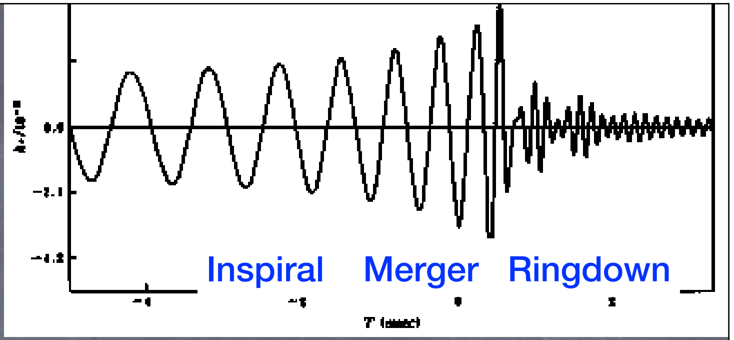
time series

frequency domain
(spectrum)



http://gwcenter.icrr.u-tokyo.ac.jp/researcher/parameters

Physics on CBC waveforms



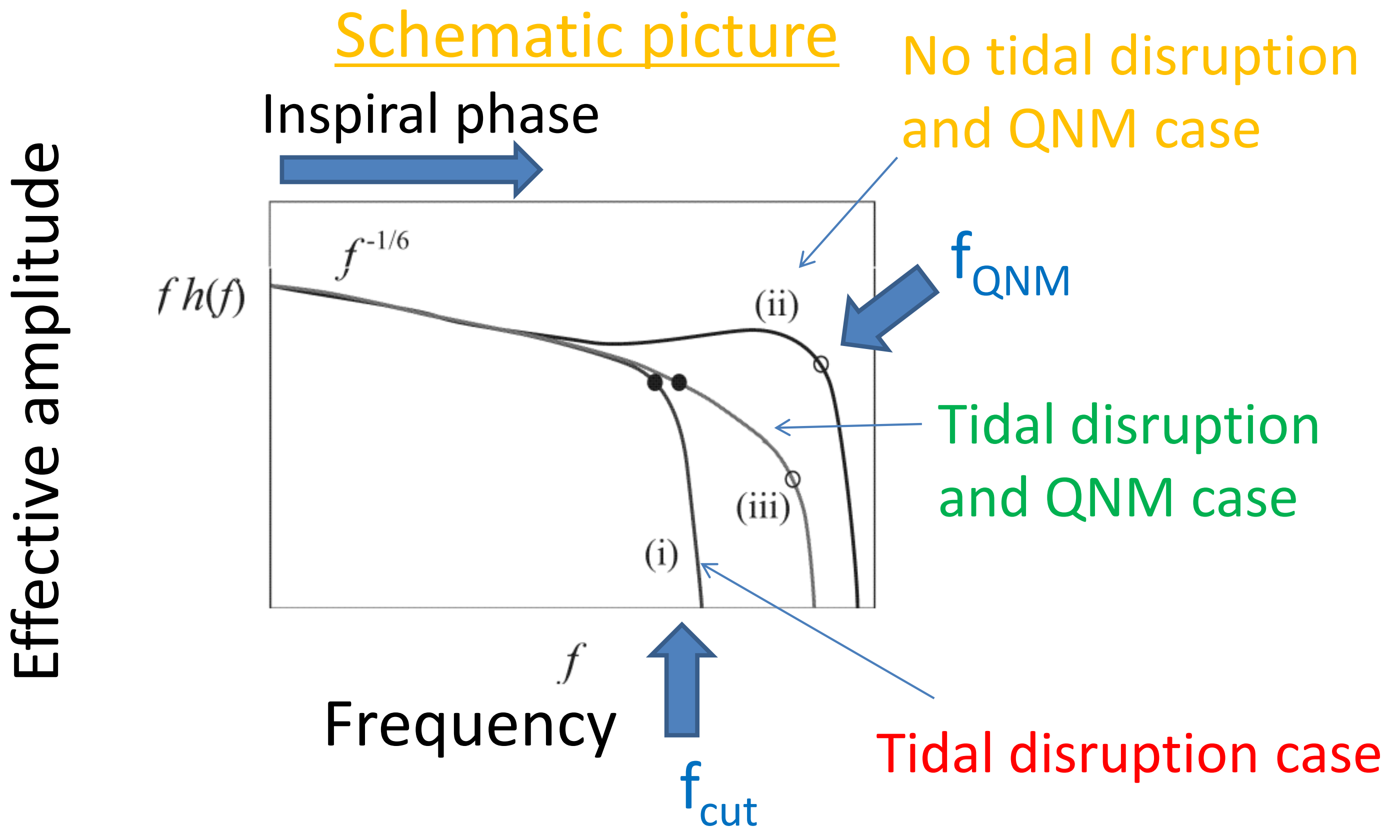
GW emissions from different phases
carry out different informations.
In case of CBC, methods of waveform prediction are also different.

- **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

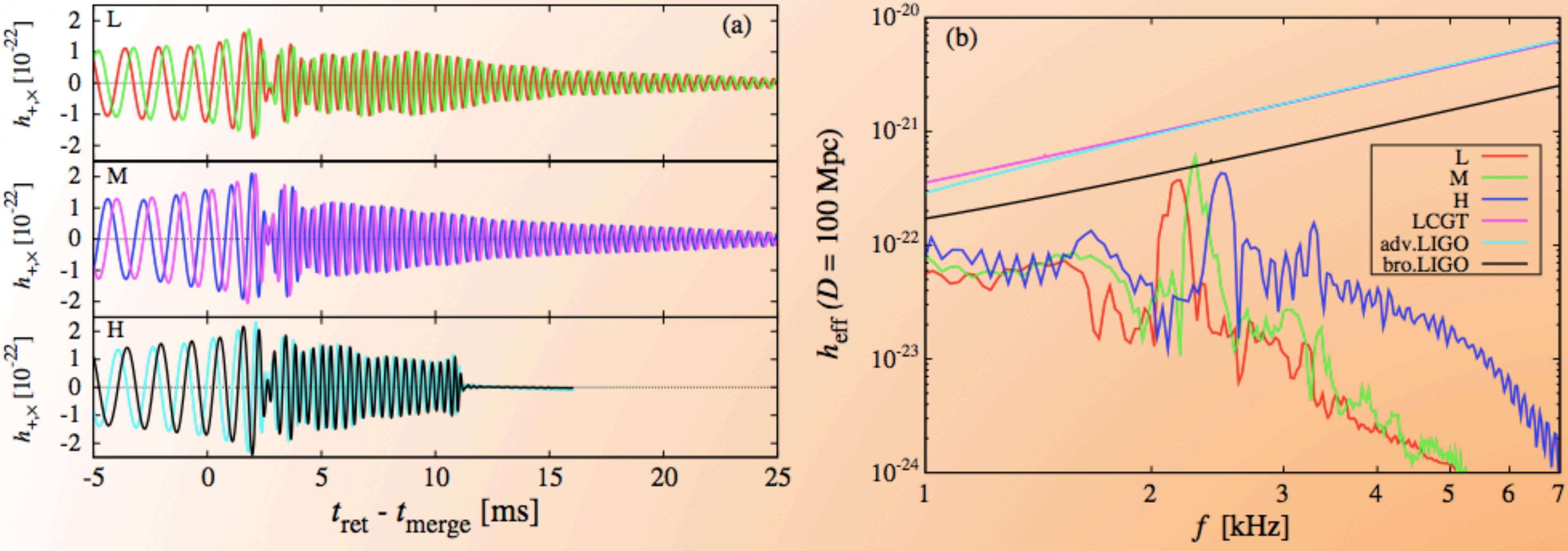
Gravitational wave Spectrum



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

Numerical simulation of NS-NS merger

Sekiguchi, Kiuchi, Kyutoku, Shibata, PRL107, 051102(2011)

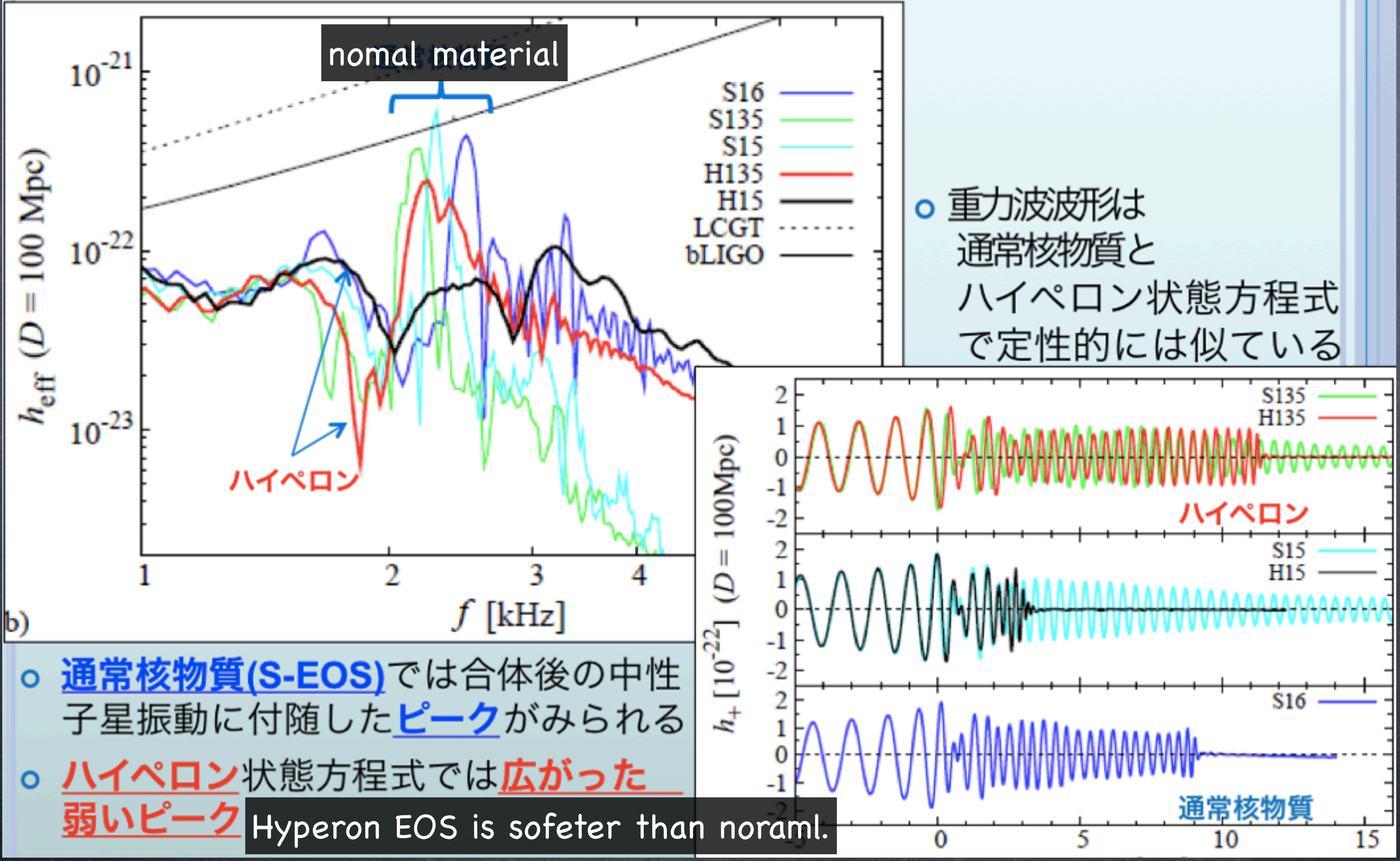


Hyper-massive NS might be formed.

Effect of hyperon in EOS

by Y.Sekiguchi

重力波スペクトルは状態方程式の情報を含む



nomal material

- 重力波波形は通常核物質とハイペロン状態方程式で定性的には似ている

- **通常核物質(S-EOS)**では合体後の中性子星振動に付随した**ピーク**がみられる
- **ハイペロン**状態方程式では**広がった弱いピーク**

Hyperon EOS is sofeter than noraml.

NS mass limit : various EOS

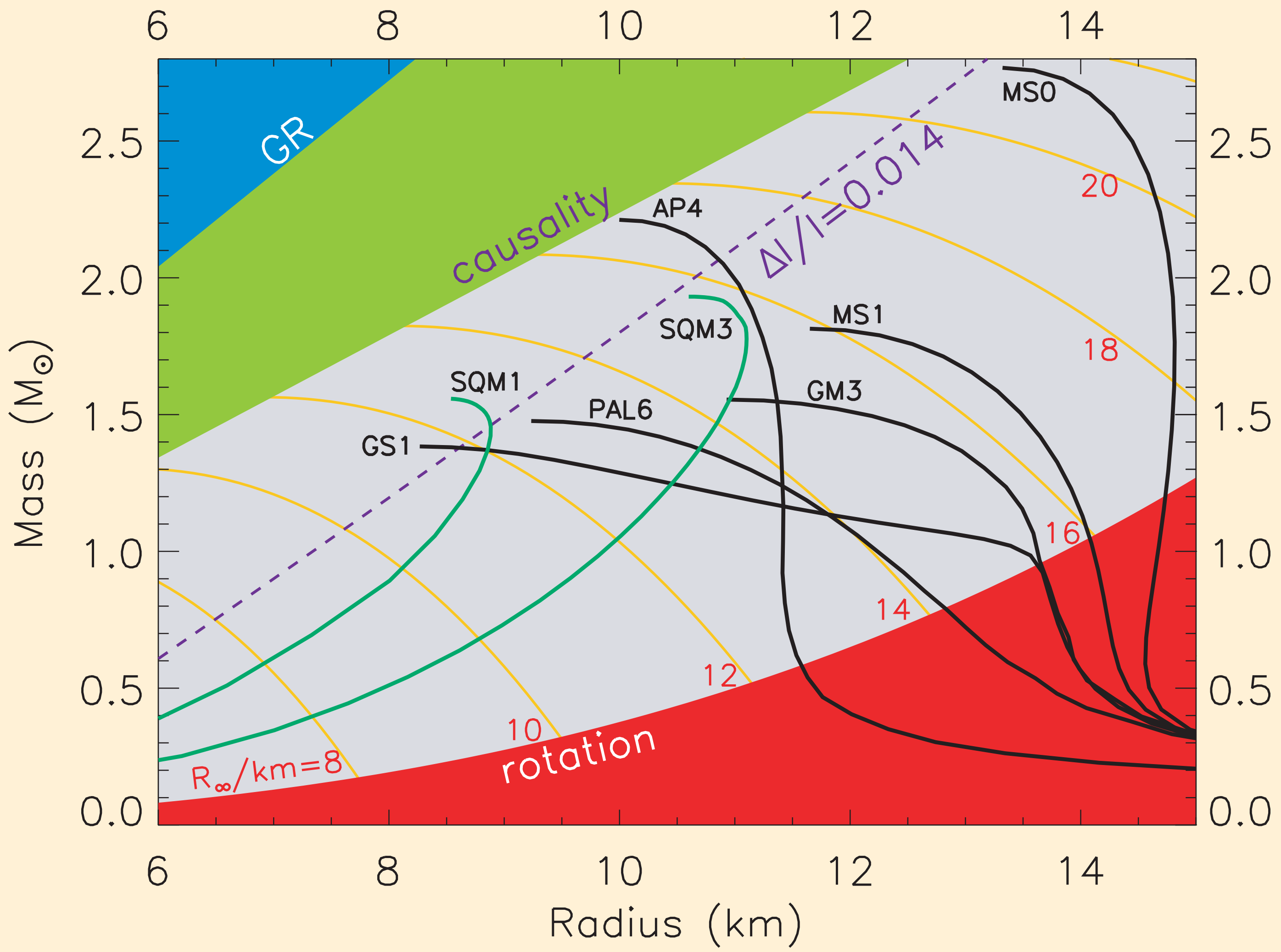


Fig. 2. Mass-radius diagram for neutron stars. Black (green) curves are for normal matter (SQM) equations of state [for definitions of the labels, see (*27*)]. Regions excluded by general relativity (GR), causality, and rotation constraints are indicated. Contours of radiation radii R_∞ are given by the orange curves. The dashed line labeled $\Delta I/I = 0.014$ is a radius limit estimated from Vela pulsar glitches (*27*).

Lattimer, et al.
Science 304, 536
(2004)

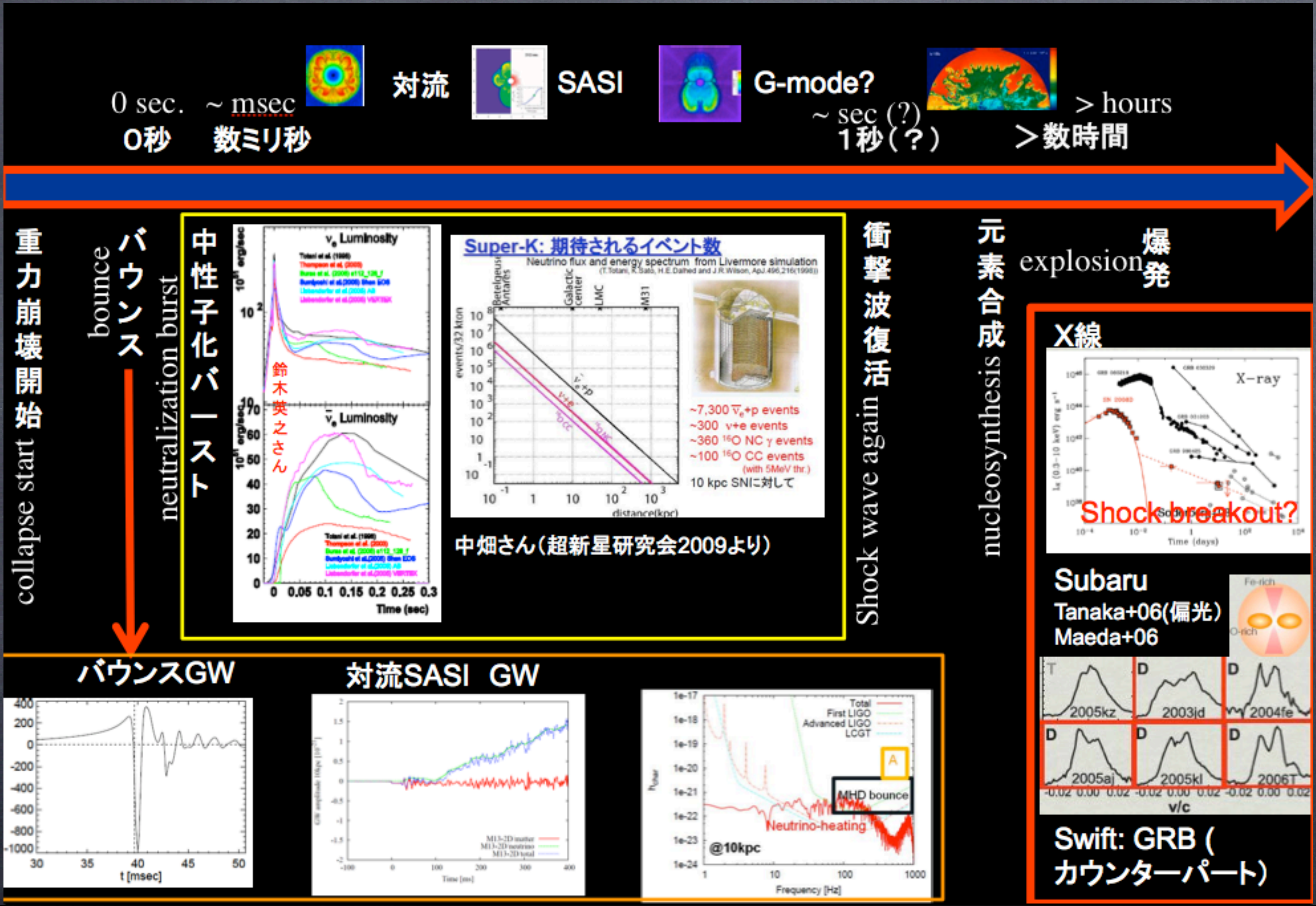
Supernovae

Easy to
find by eyes and telescope
(GW detectors cannot lost the
chance ...)

Supernova will emit GW 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



0 sec. 0秒

~ msec 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

MHD bounce

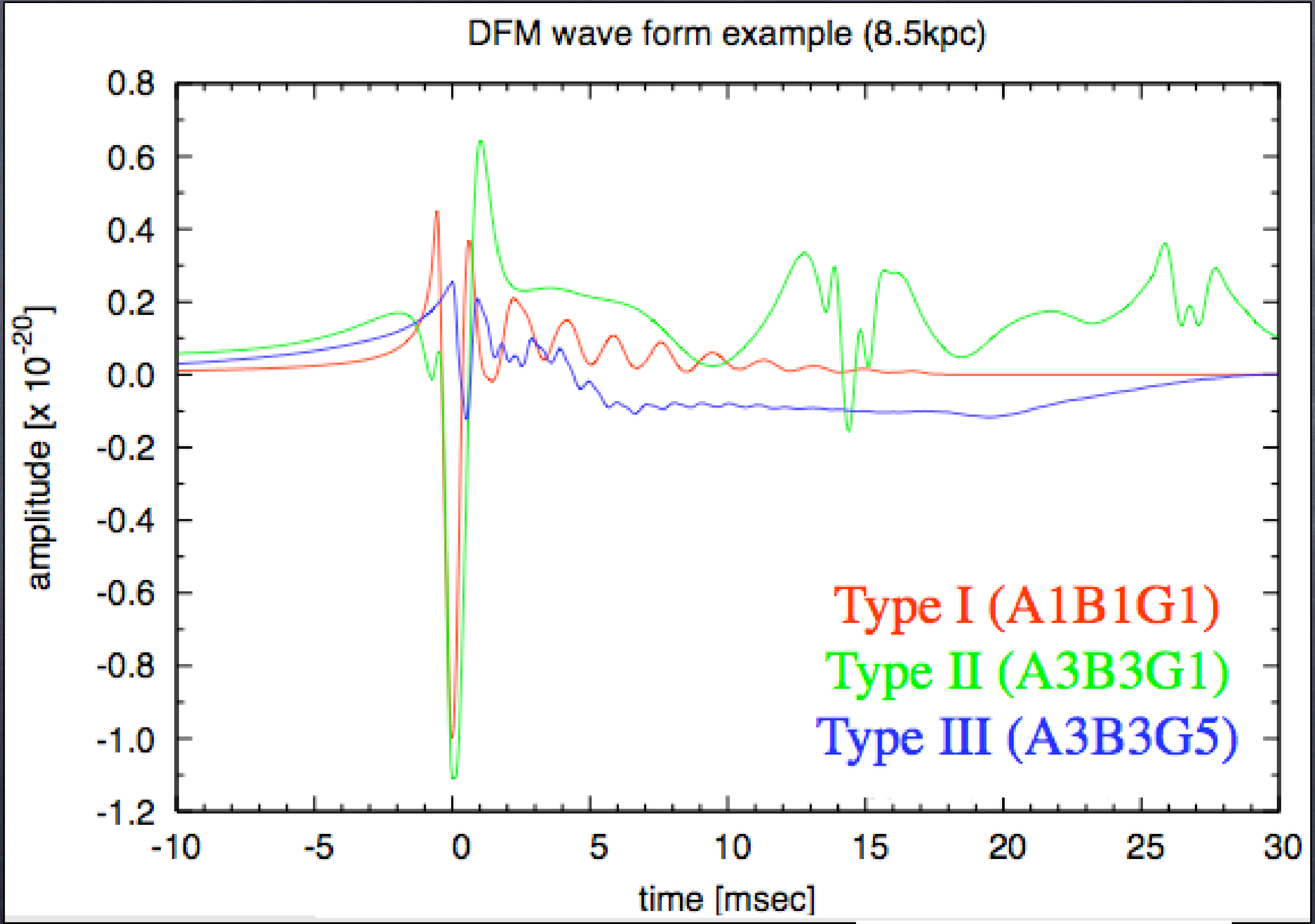
Neutrino-heating

@10kpc

viewgraph by Kei Kotake

Burst Waveform (Short duration wave)

- **Rotating core collapse and bounce will radiate GW.**



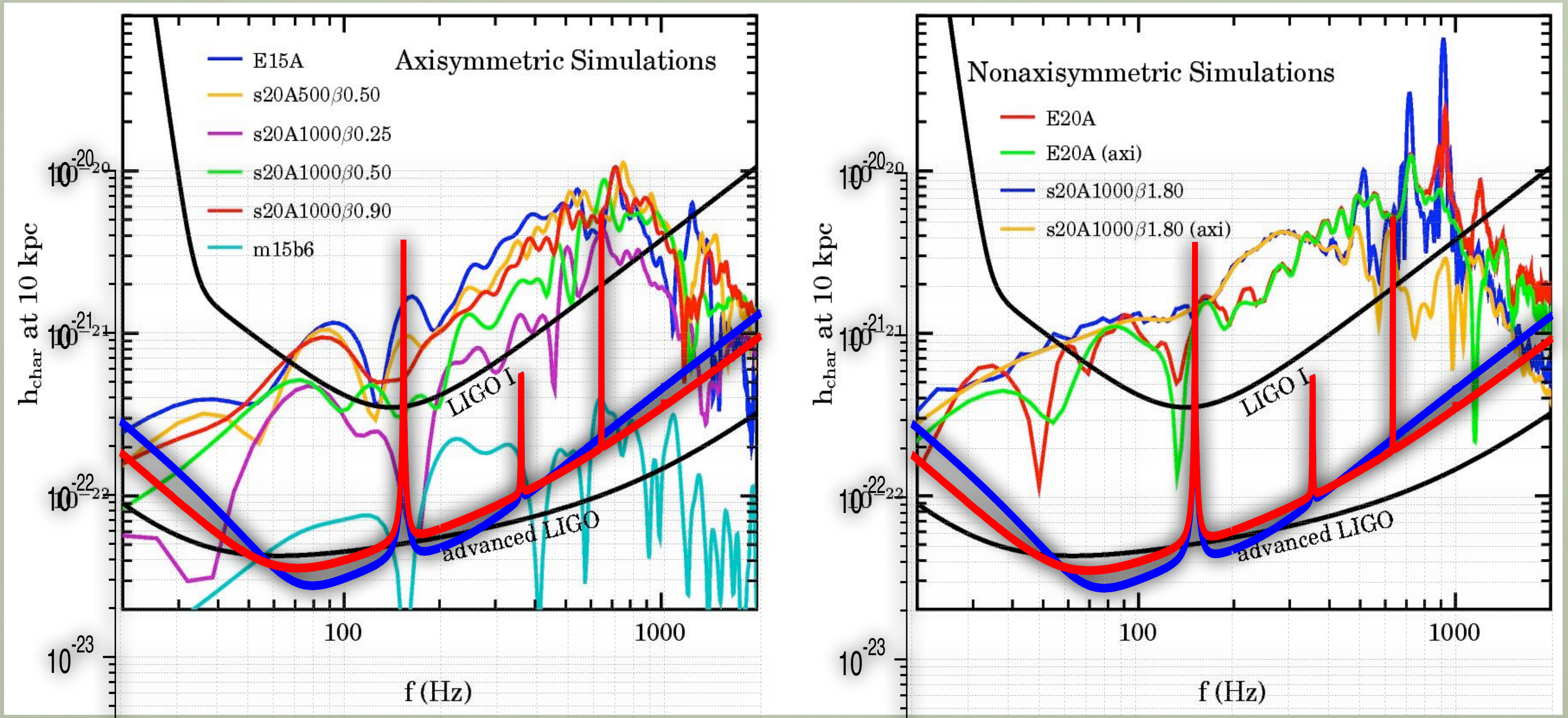
Dimmermeier at al.

GW Emission vs. Detector Noise

$$h_{\rm char} = \sqrt{\frac{2}{\pi^2}\frac{1}{D^2}\frac{G}{c^3}\frac{dE_{\rm GW}}{df}}$$

$$S/N = \sqrt{\int_0^\infty d\ln f\, \frac{h^2_{\rm char}}{h^2_{\rm rms}}}$$

$$h_{\rm rms} = \sqrt{f S(f)}$$

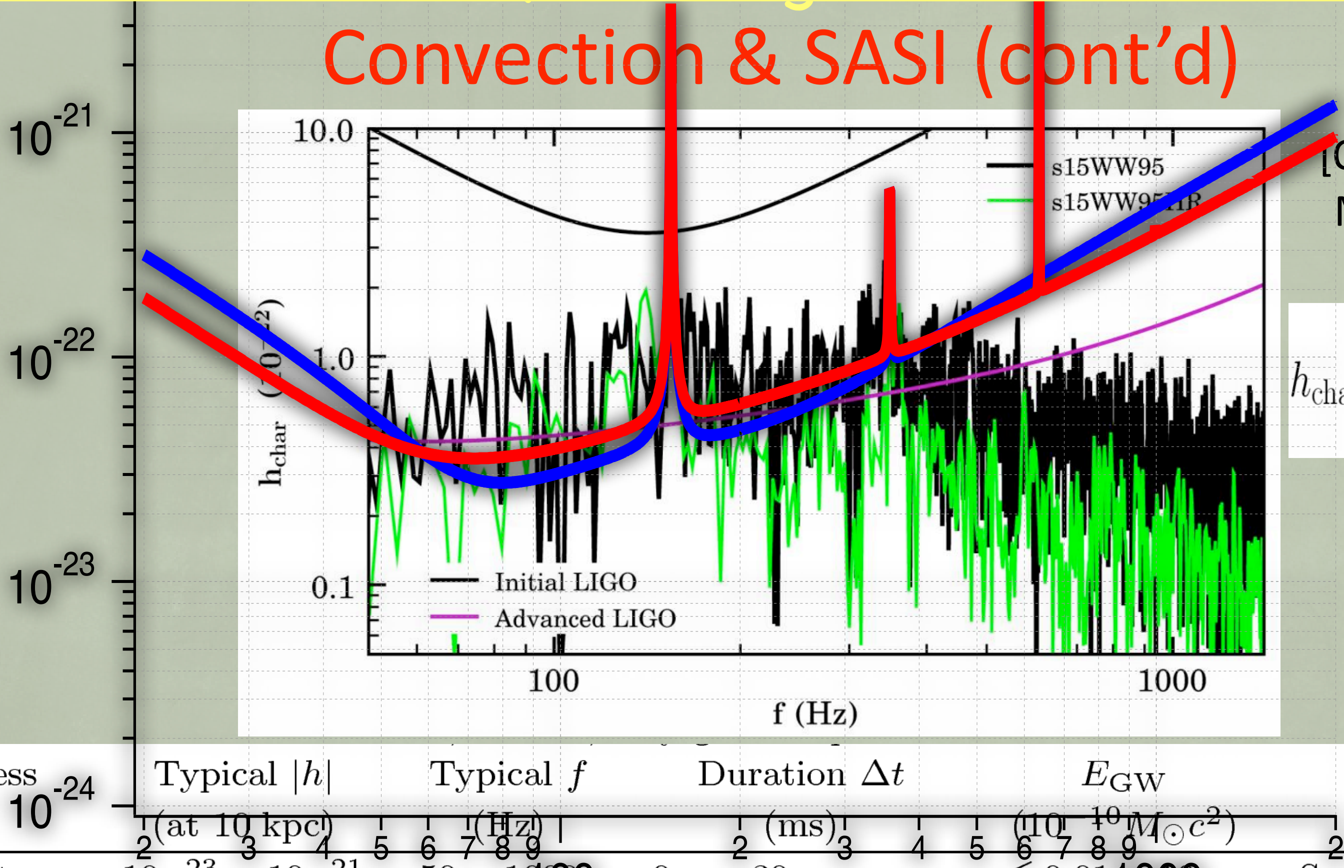


- 3D component: lower in amplitude than core-bounce GW spike, but greater in energy! Emission in narrow frequency band around 900—930 Hz (~2 x pattern speed of the unstable mode!) models.

viewgraph by C.D.Ott

Convection and SASI (standing-accretion-shock instability)

Convection & SASI (cont'd)



[Ott 2008, see also Marek et al. 2008]

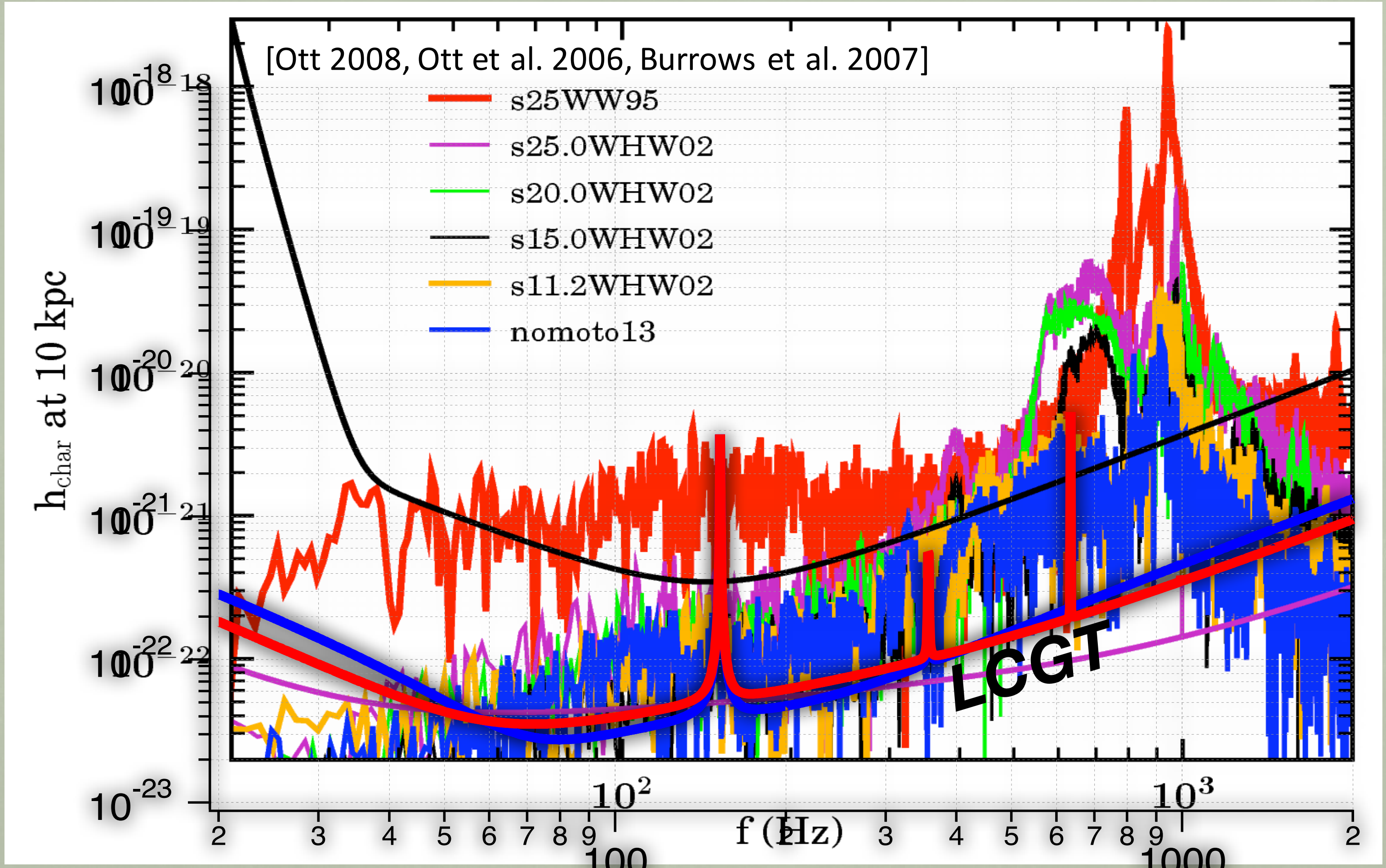
$$h_{\rm char} = \sqrt{\frac{2}{\pi^2}\frac{1}{D^2}\frac{G}{c^3}\frac{dE_{\rm GW}}{df}}$$

Process	Typical $\lvert h \rvert$ (at 10 kpc)	Typical f (Hz)	Duration Δt (ms)	$E_{\rm GW}$ $(10^{-10} M_\odot c^2)$	Limiting Factors or Processes
Prompt Convection	$10^{-23} - 10^{-21}$ (Emission characteristics depend on seed perturbations.)	$50 - 1000$	$0 - \sim 30$	$\lesssim 0.01$	Seed perturbations, entropy/lepton gradient, rotation
PNS Convection	$2 - 5 \times 10^{-23}$	$300 - 1500$	$500 -$ several 1000	$\lesssim 1.3(\frac{\Delta t}{1s})$	rotation, BH formation, strong PNS g-modes
Neutrino-driven Convection and SASI	$10^{-23} - 10^{-22}$ (peaks up to 10^{-21})	$100 - 800$	$100 - \gtrsim 1000$	$\gtrsim 0.01(\frac{\Delta t}{100ms})$ $\lesssim 15(\frac{\Delta t}{100ms})$	rotation, explosion, BH formation

viewgraph by C.D.Ott

PNS core g-mode

GW Spectra and LIGO Sensitivity



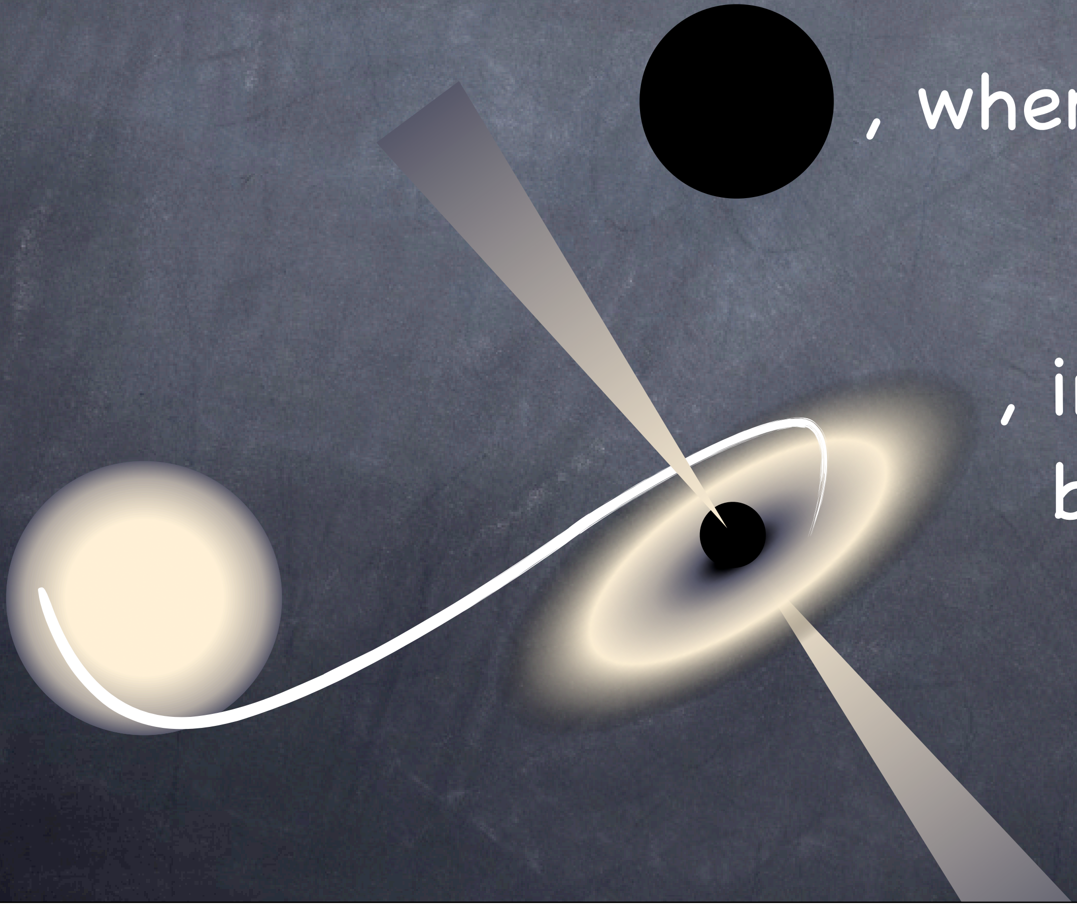
[Ott 2008, Ott et al. 2006, Burrows et al. 2007]

- $E_{GW} \sim 10^{-8} - 10^{-6}\ M_{SUN}c^2$, one model $8 \times 10^{-5}\ M_{SUN}c^2$.
- Progenitor mass (= accretion rate) dependence.

viewgraph by C.D.Ott

Black holes

It illustrated in juvenile scientific magazine as …



, when I was a child.

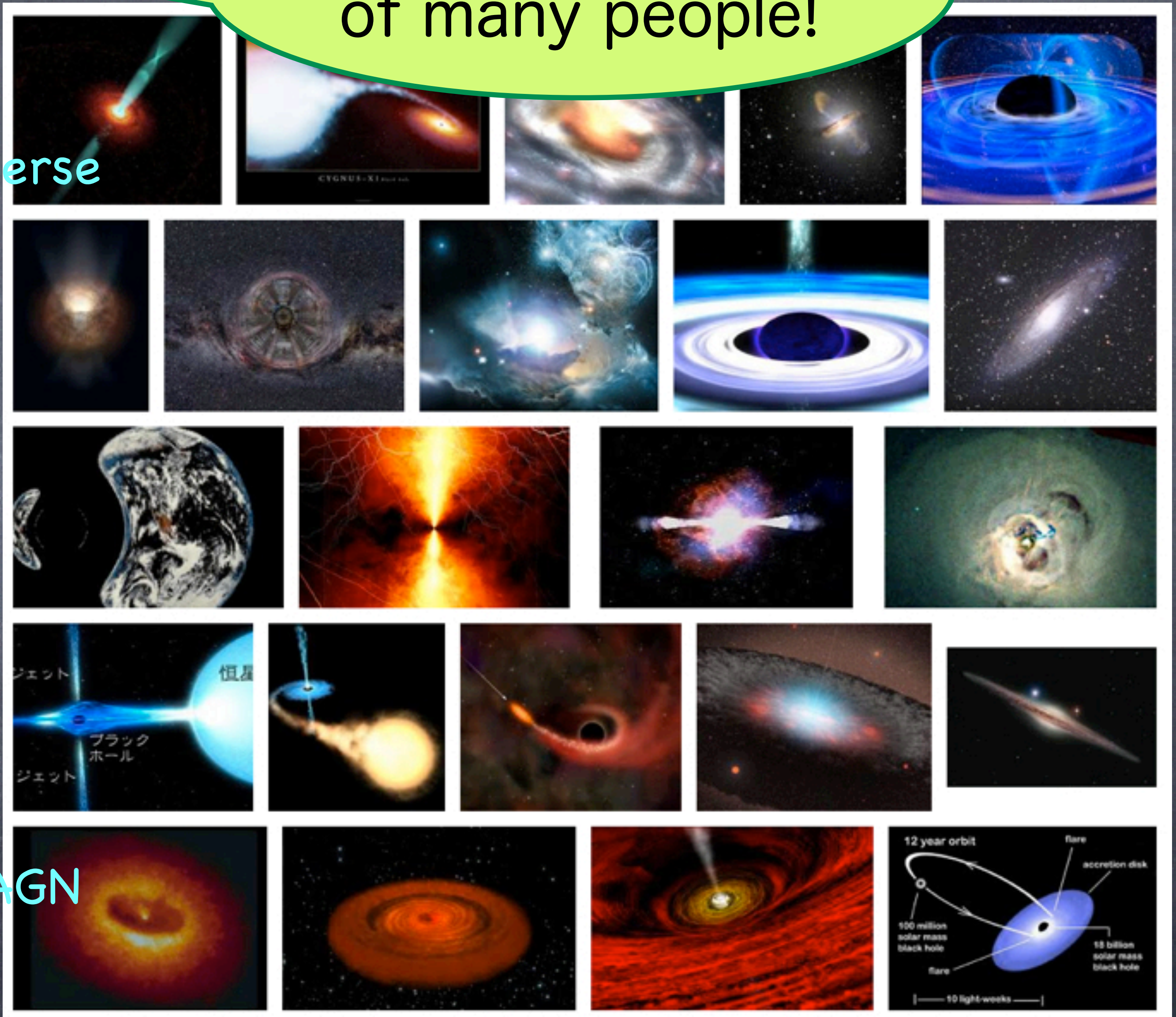
, in my children's book recently …amazing!!

Black holes

favorite
of many people!

rch results)

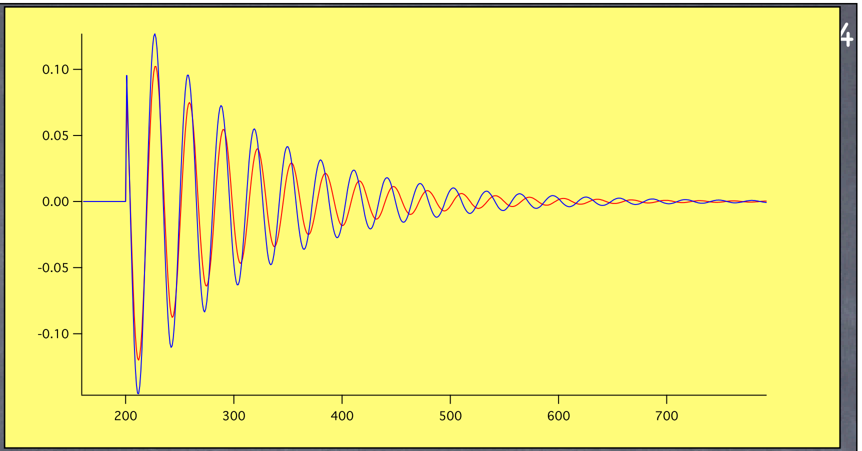
- **Primordial BH**
  Formed at eary universe
  ~0.5 Msolar
- **Stellar mass BH**
  (also final state
  of NS-NS merger)
- **IMBH**
  intermediate mass
  10^3 ~ 10^5 Msolar ?
- **SMBH**
  super-massive BH@AGN
  ~ 10^6 Msolar



BHs have a hierarchy of mass.

GW is come from BH itself.

Ringdown GW from BH Quasi-Normal Mode



Binary, SN expl.

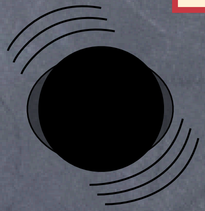
inspiral-merger → core collapse

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

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

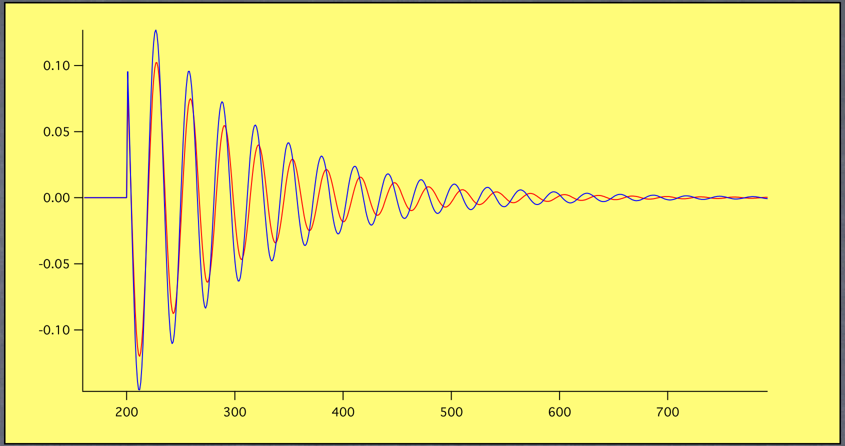
M: Mass

a: Spin

* Probe for BH direct observation

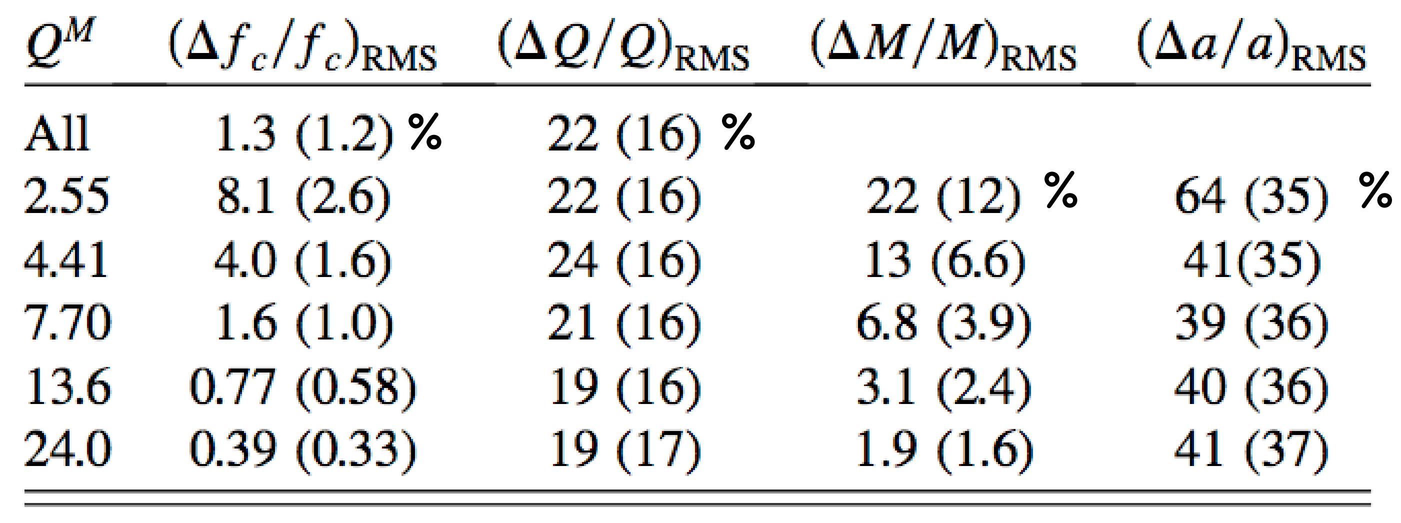
* BH physics in inspiral-merger, core collapses, ...

BH Mass Spectroscopy ...



Q = Kerr parameter

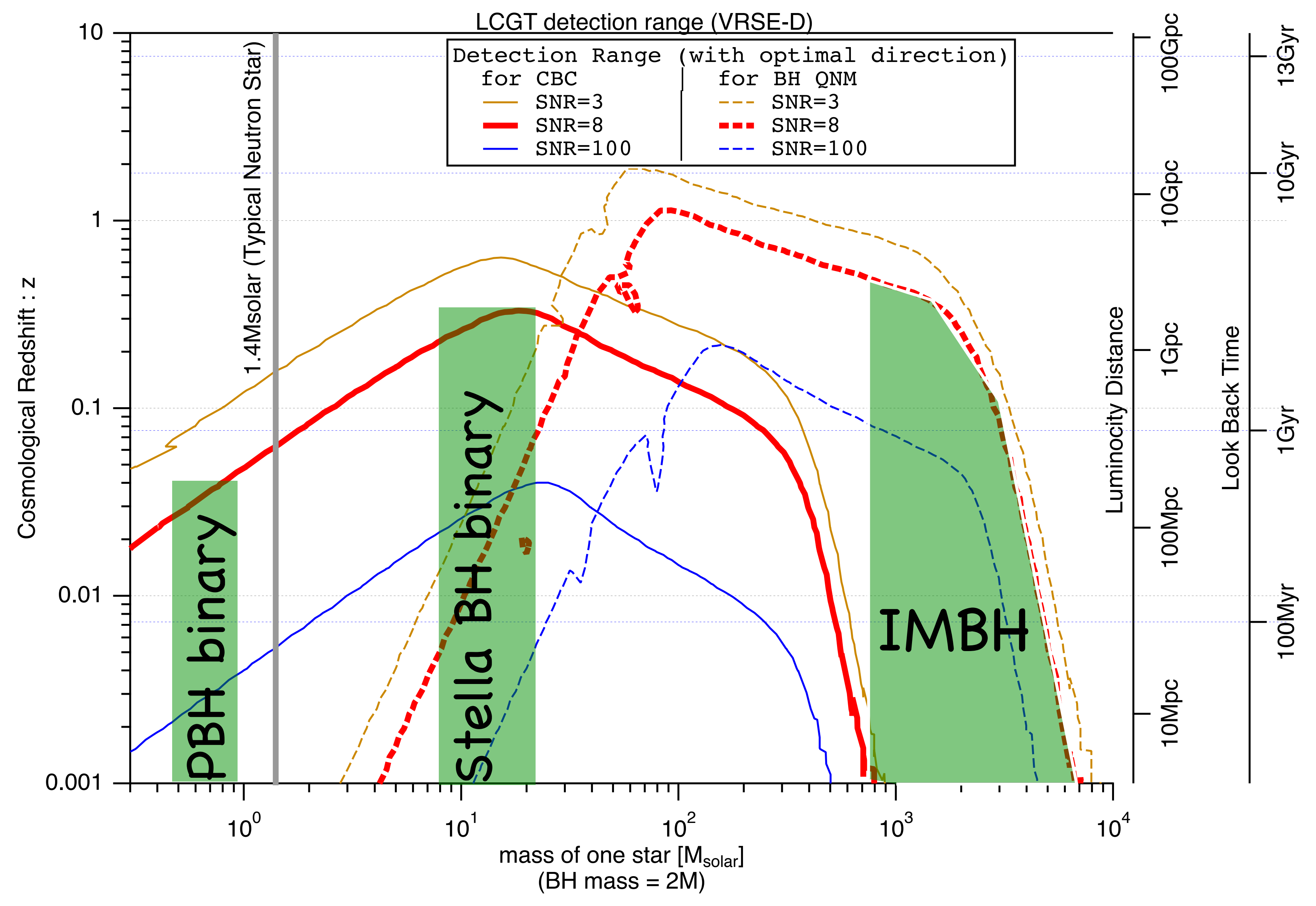
fc = Mass of BH



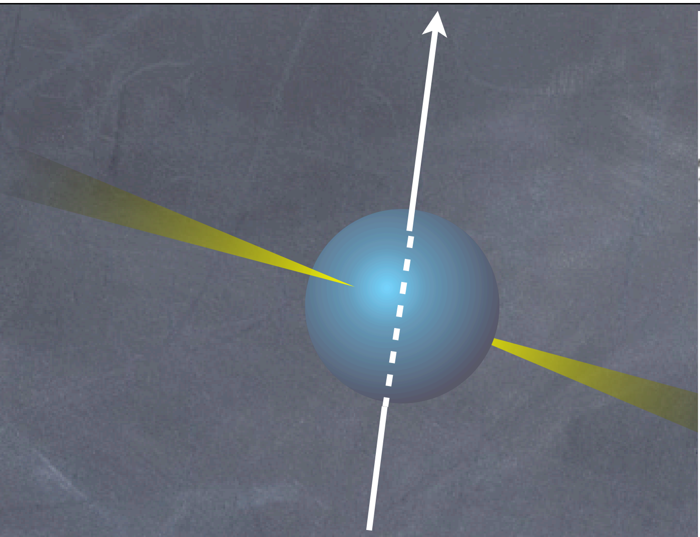
Q^M	$(\Delta f_c/f_c)_{\rm RMS}$	$(\Delta Q/Q)_{\rm RMS}$	$(\Delta M/M)_{\rm RMS}$	$(\Delta a/a)_{\rm RMS}$
All	1.3 (1.2) %	22 (16) %		
2.55	8.1 (2.6)	22 (16)	22 (12) %	64 (35) %
4.41	4.0 (1.6)	24 (16)	13 (6.6)	41(35)
7.70	1.6 (1.0)	21 (16)	6.8 (3.9)	39 (36)
13.6	0.77 (0.58)	19 (16)	3.1 (2.4)	40 (36)
24.0	0.39 (0.33)	19 (17)	1.9 (1.6)	41 (37)

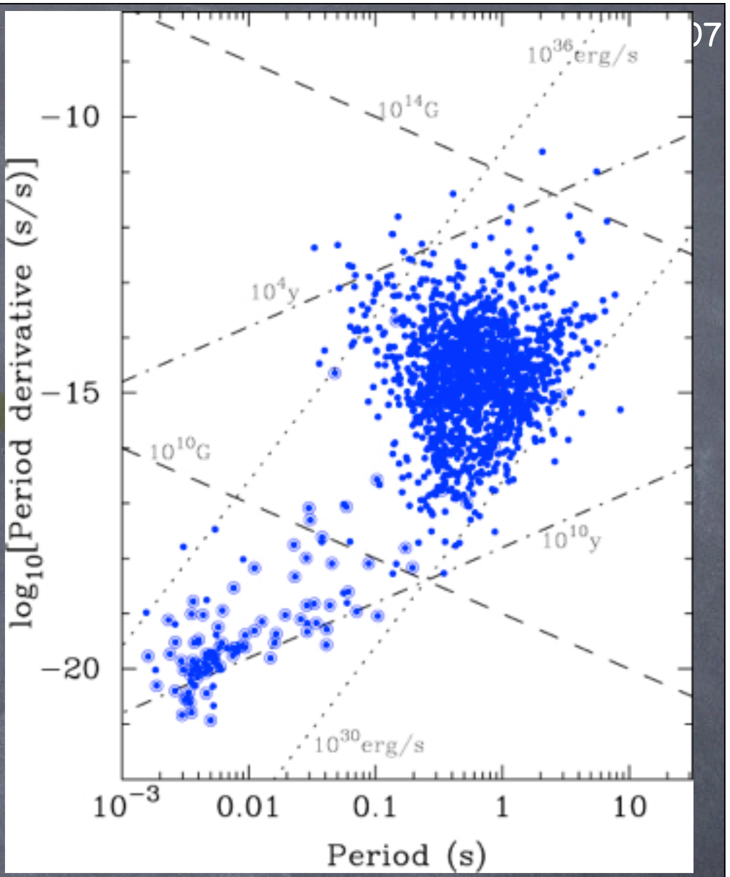
Tsunesada, Kanda et al. Phys.Rev.D 71, 103005 (2005)

LCGT's detection range for Black hole quasi-normal mode oscillation



Pulsars





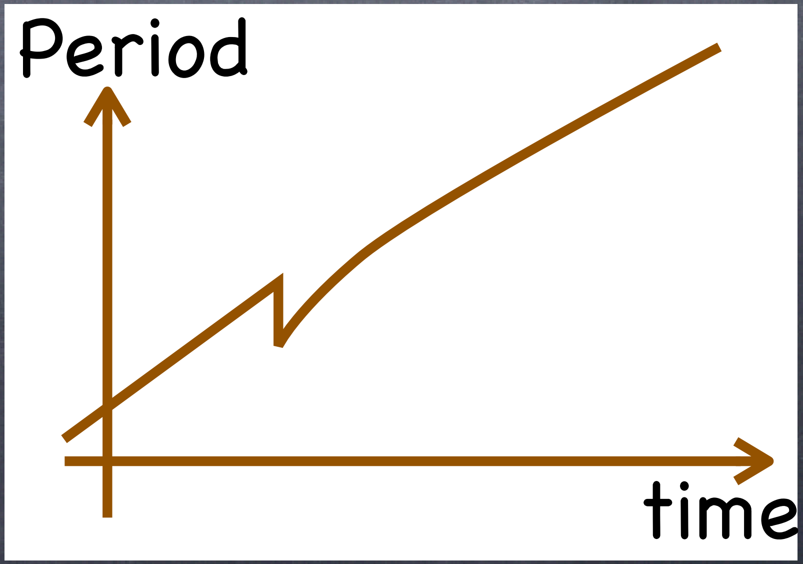
- **Continuous GW**

  non-axisymetric --> GW radiation

  GW radiation may cause spin down.

- **Burst like GW**

  Glitches



Structure of Neutron star

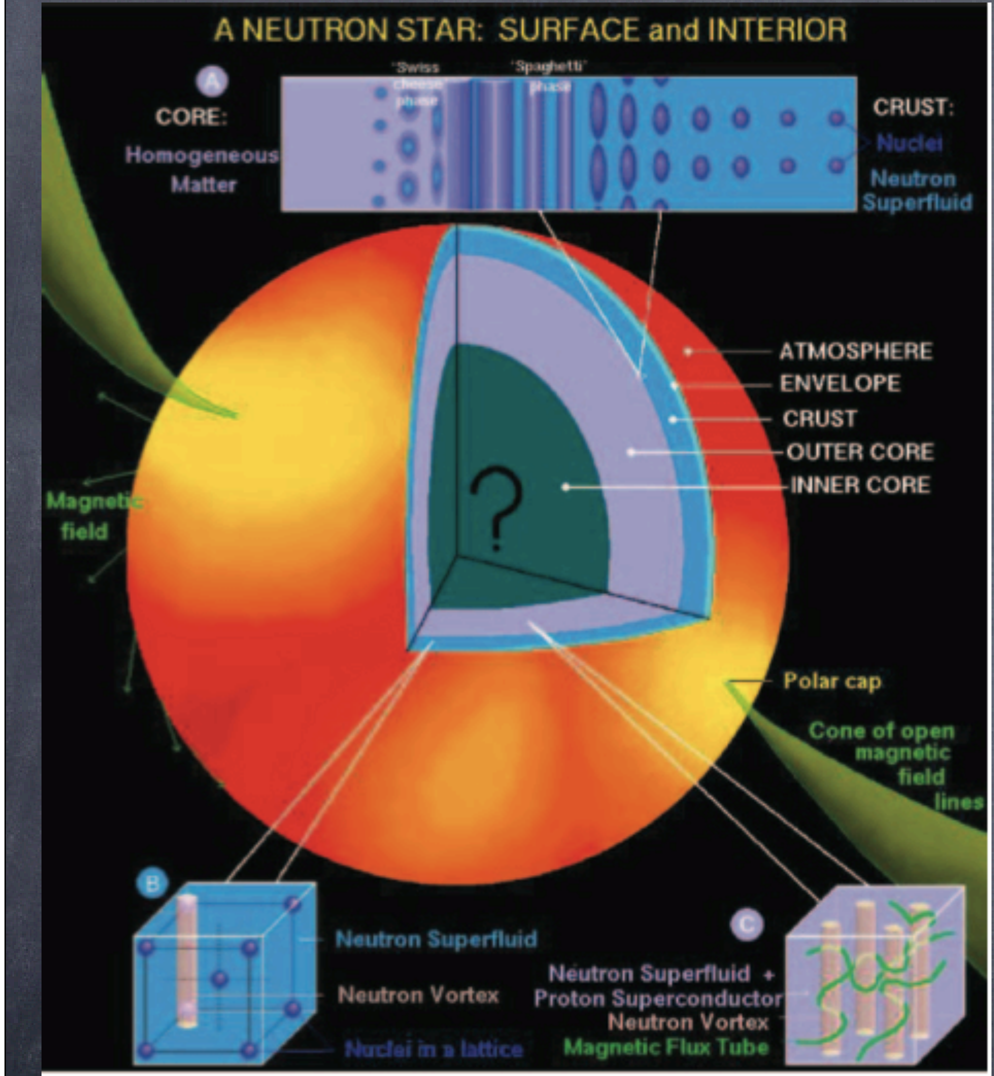
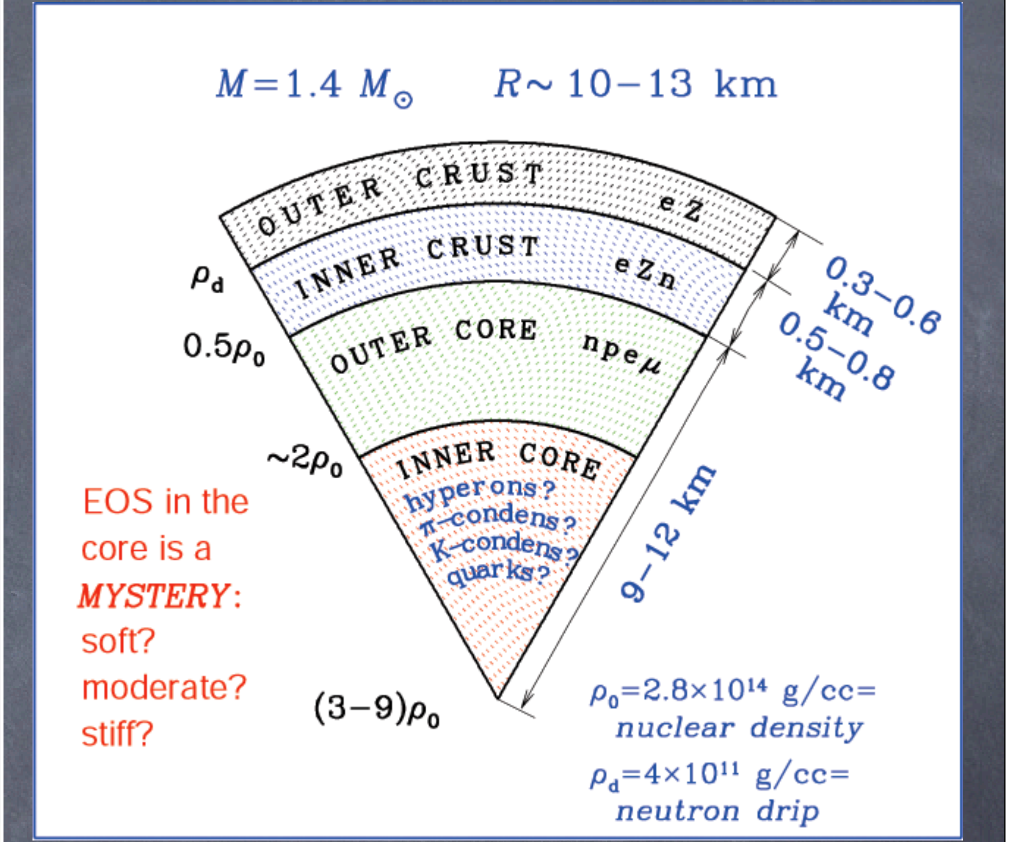


Fig. 3. The major regions and possible composition inside a normal-matter neutron star. The top bar illustrates expected geometric transitions from homogeneous matter at high densities in the core to nuclei at low densities in the crust. Superfluid aspects of the crust and outer core are shown in the insets. [Figure courtesy D. Page]

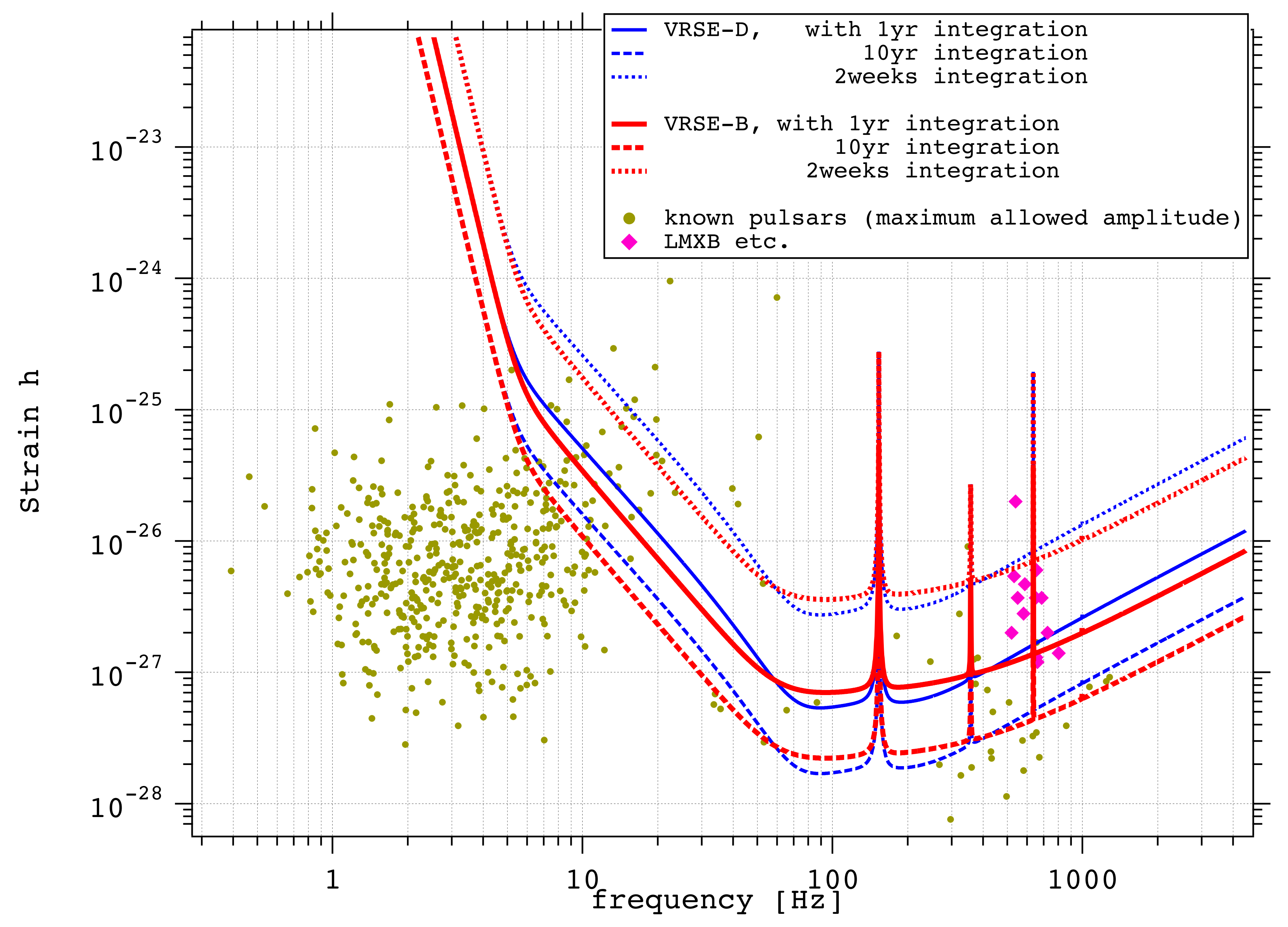
Lattimer, et al. Science 304, 536(2004)



EOS in the core is a *MYSTERY*: soft? moderate? stiff?

Yakovlev 2005

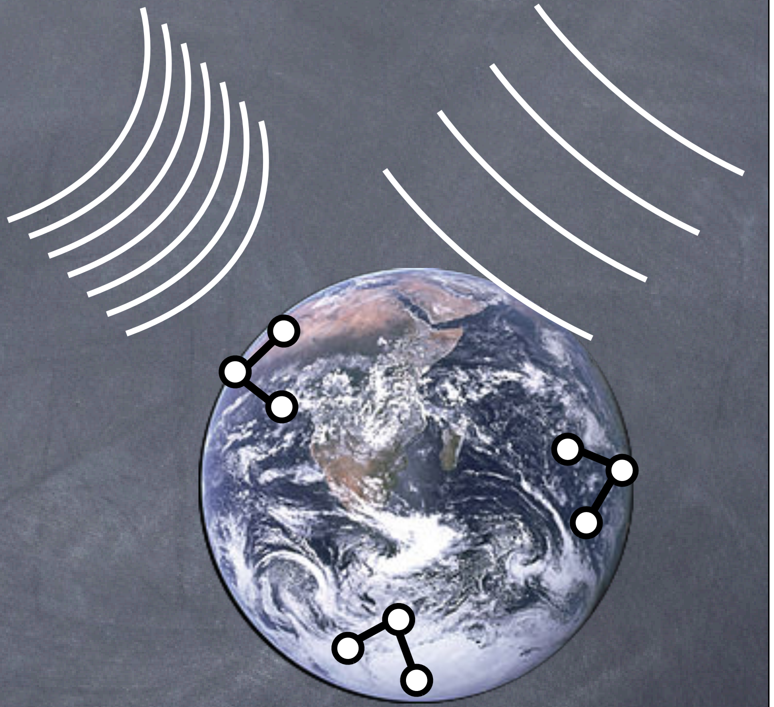
Expected Upper bound for known pulsars' GW

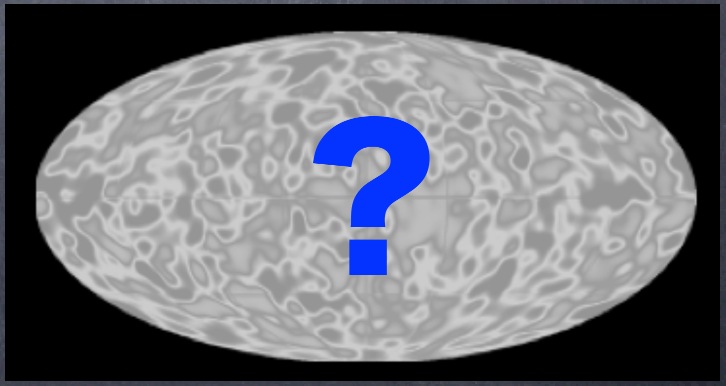


Stochastic background GW

- **Like as cosmic microwave background, GW from ...**
  - Inflation
  - Phase transition in early universe
  - String cosmology predicts...
  - Cosmic string

  - Huge num. of astronomical objects (unresolved) overlap
- **Search using two or more detectors**





Stochastic background GW

$$\Omega_{gw}(f) = \frac{1}{\rho_c}\frac{d\rho_{gw}}{d\log f}$$

critical density : $\rho_c = \frac{3H_0^2}{8\pi G_N}$

GW energy density : ρ_{gw}

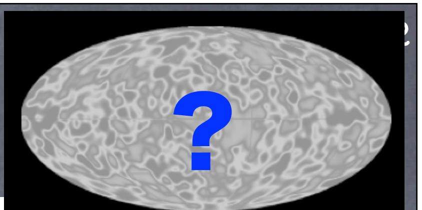
GW spectral density : $S_h(f)$

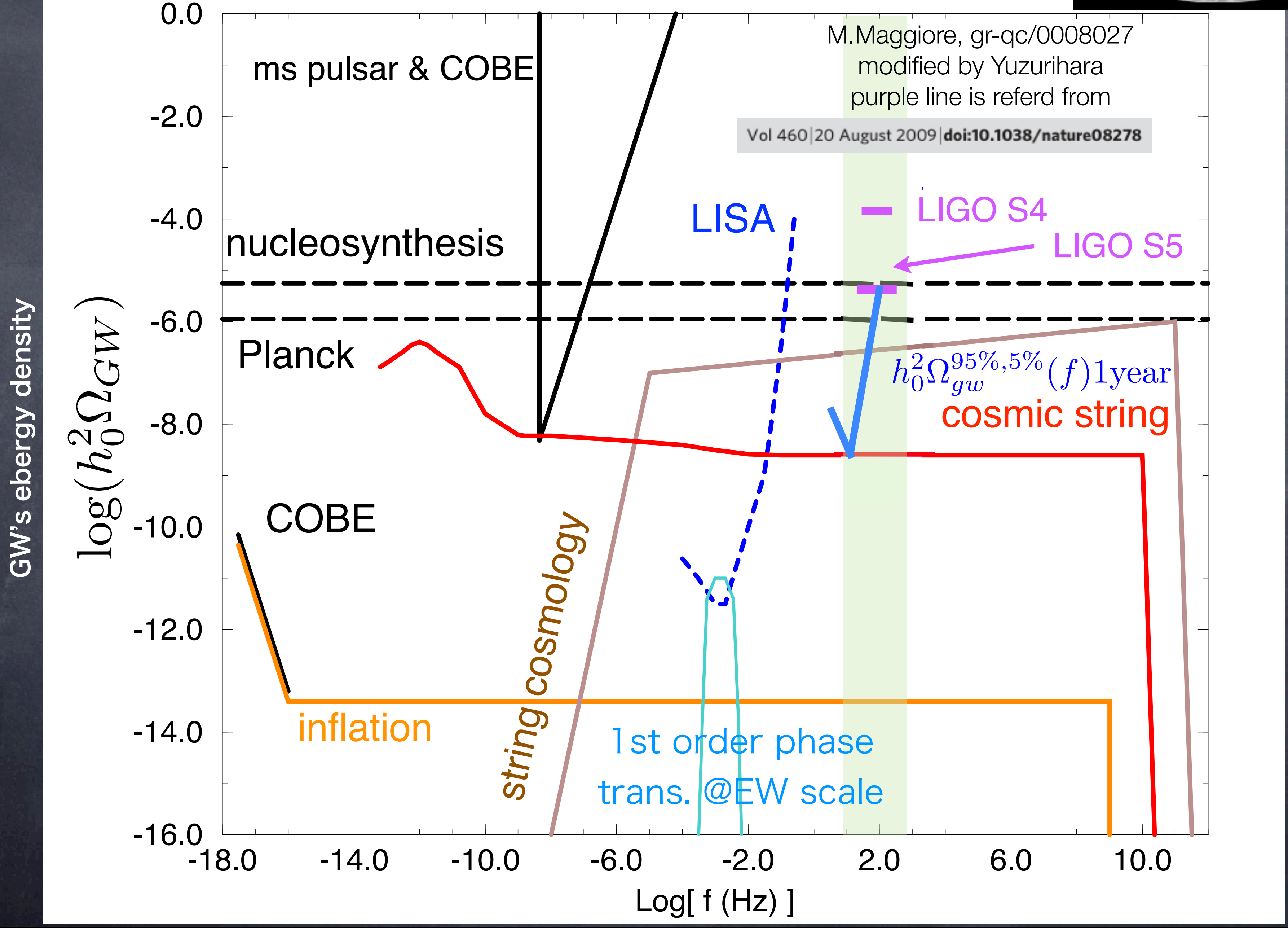
$$\Omega_{gw}(f) = \frac{4\pi^2}{3H_0^2} f^3 S_h(f)$$

Hubble Const. : $H_0 = h_0 \times 100[\mathrm{km}/(\mathrm{s}\cdot\mathrm{Mpc})]$

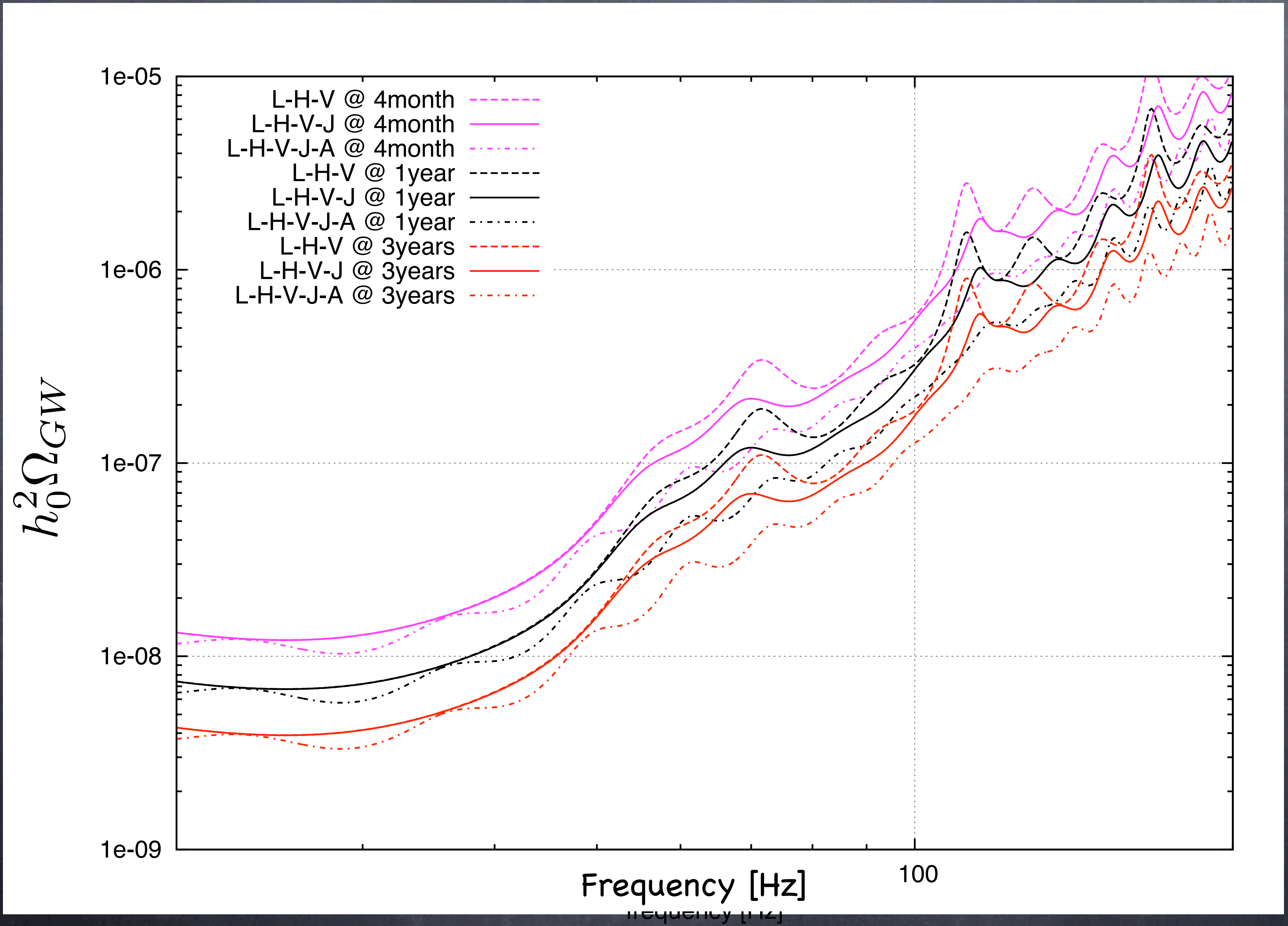
$$h_0^2\Omega_{gw}(f)$$

Stochastic background GW : observational limit





Stochastic background GW : for ground-based detectors

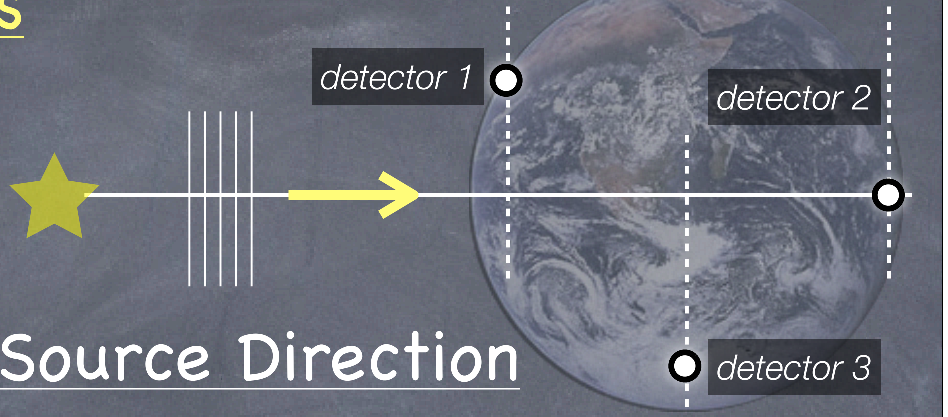


Global Network of GW Detectors

- **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.

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.

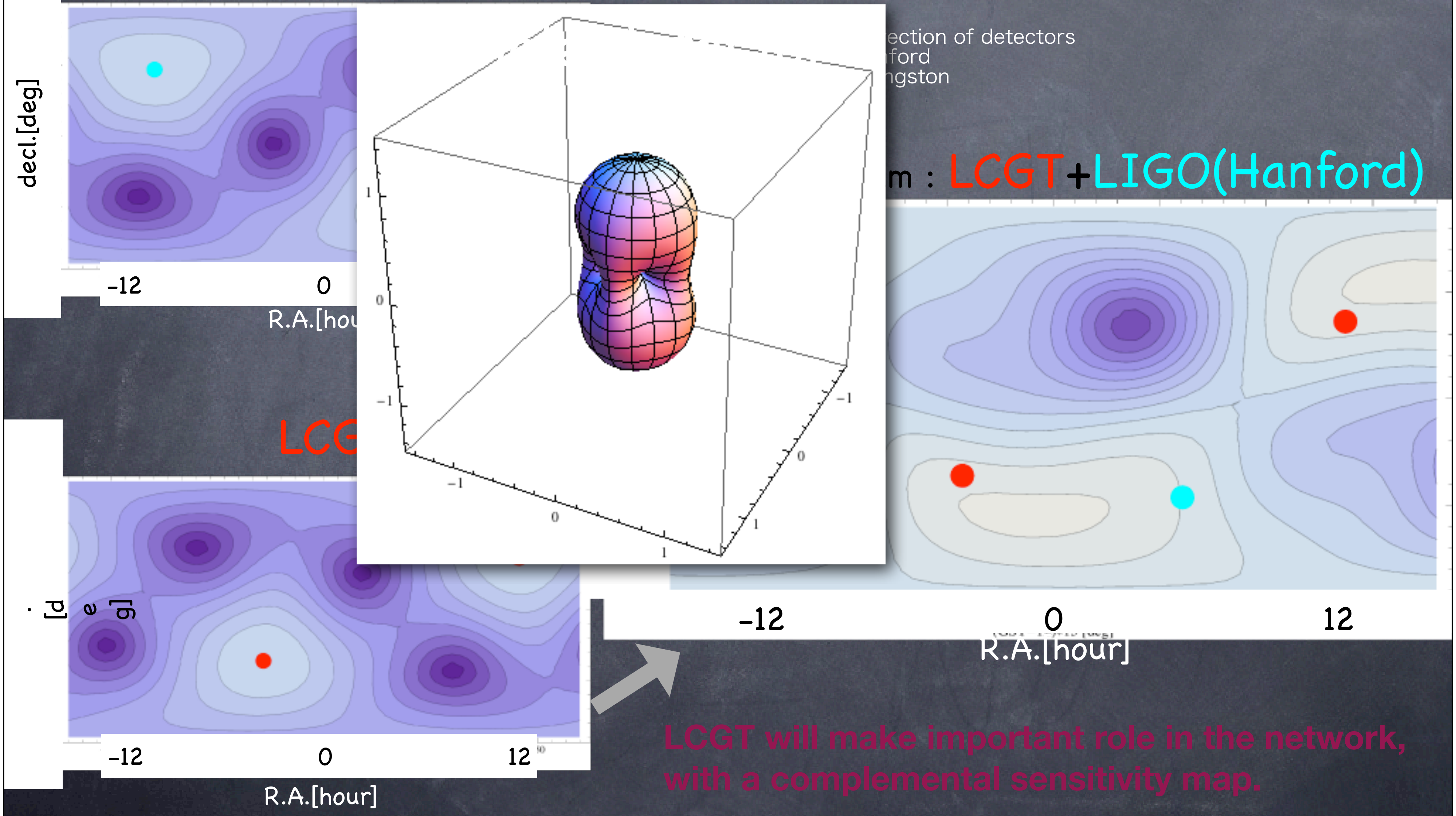
  to be the "Standard Siren"!

- **Sky coverage**
- **Duty Time of Observation**

  More GW events

  Chance for follow-up observations

Sky coverage by detector network



LIGO (Hanford)

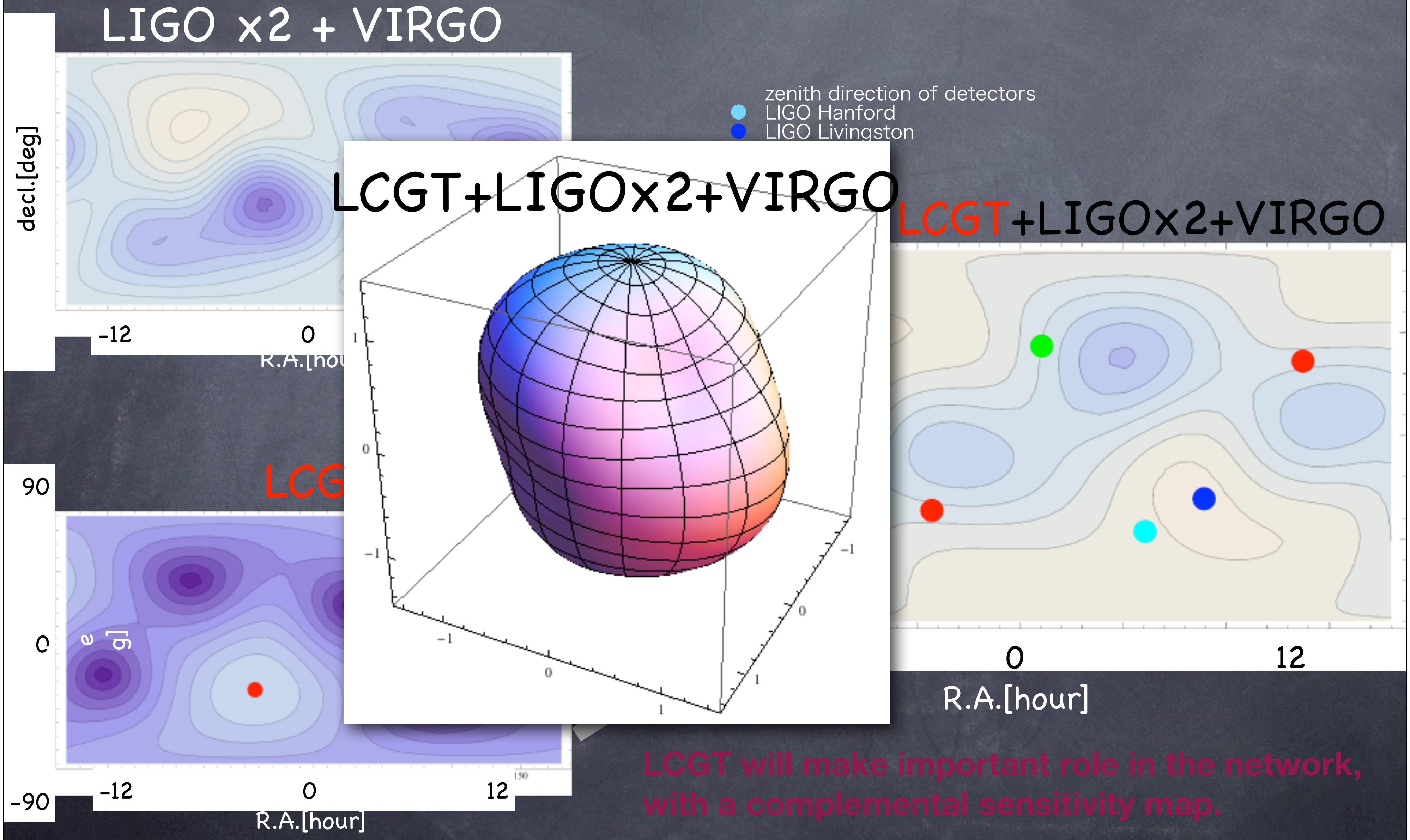
LCG

ection of detectors
ford
ngston

m : LCGT+LIGO(Hanford)

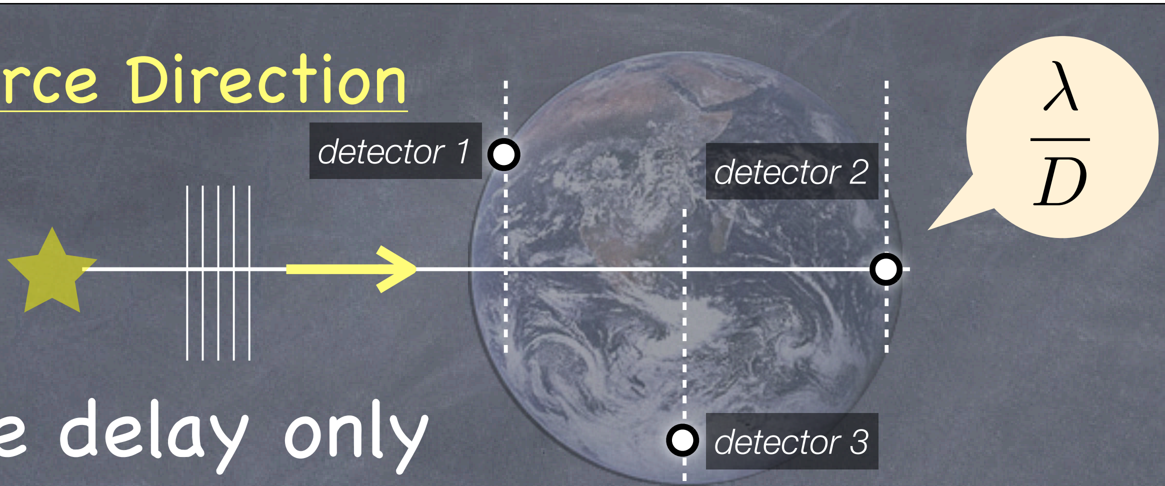
LCGT will make important role in the network, with a complemental sensitivity map.

Sky coverage by detector network

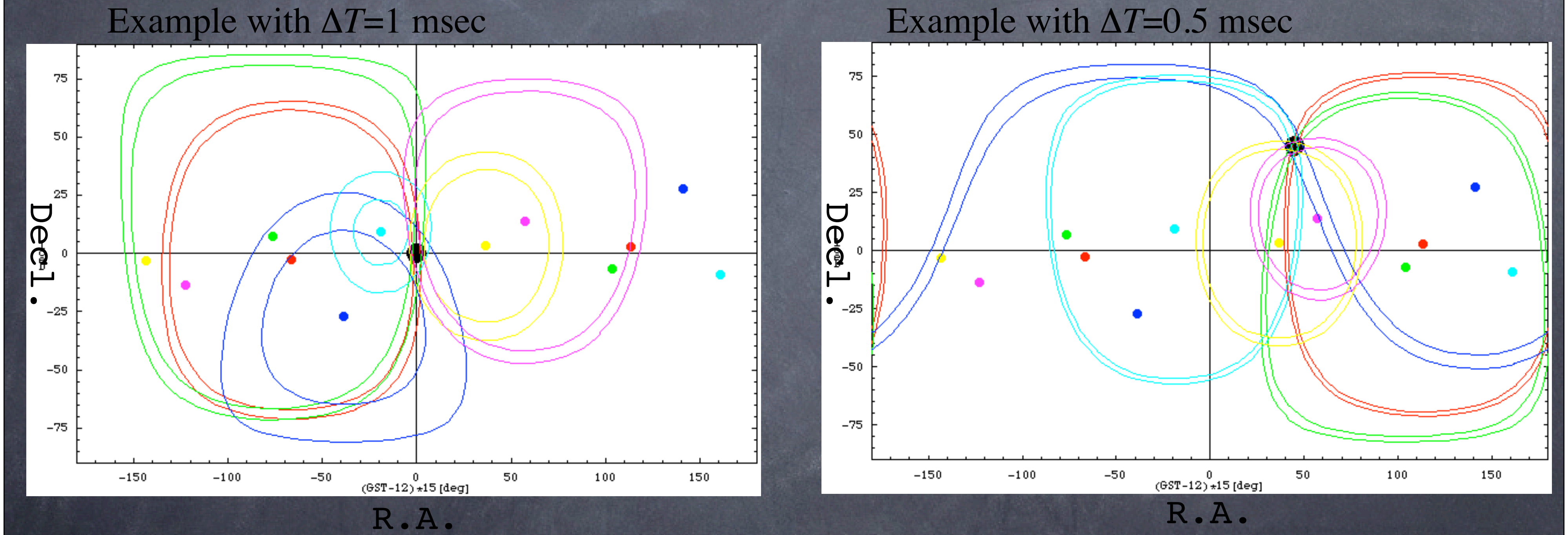


LCGT will make important role in the network, with a complemental sensitivity map.

Determination of Source Direction

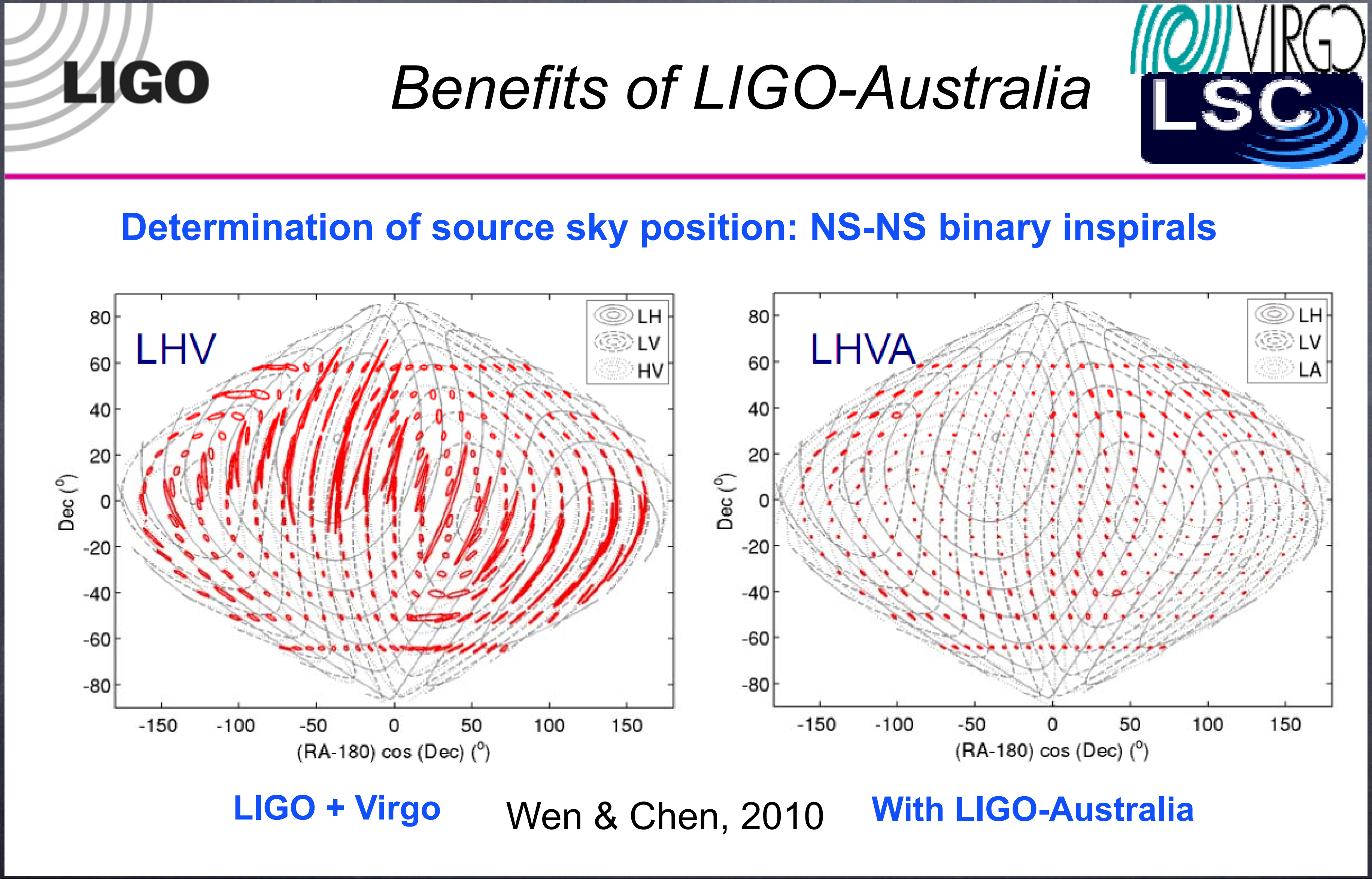


example with time delay only



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

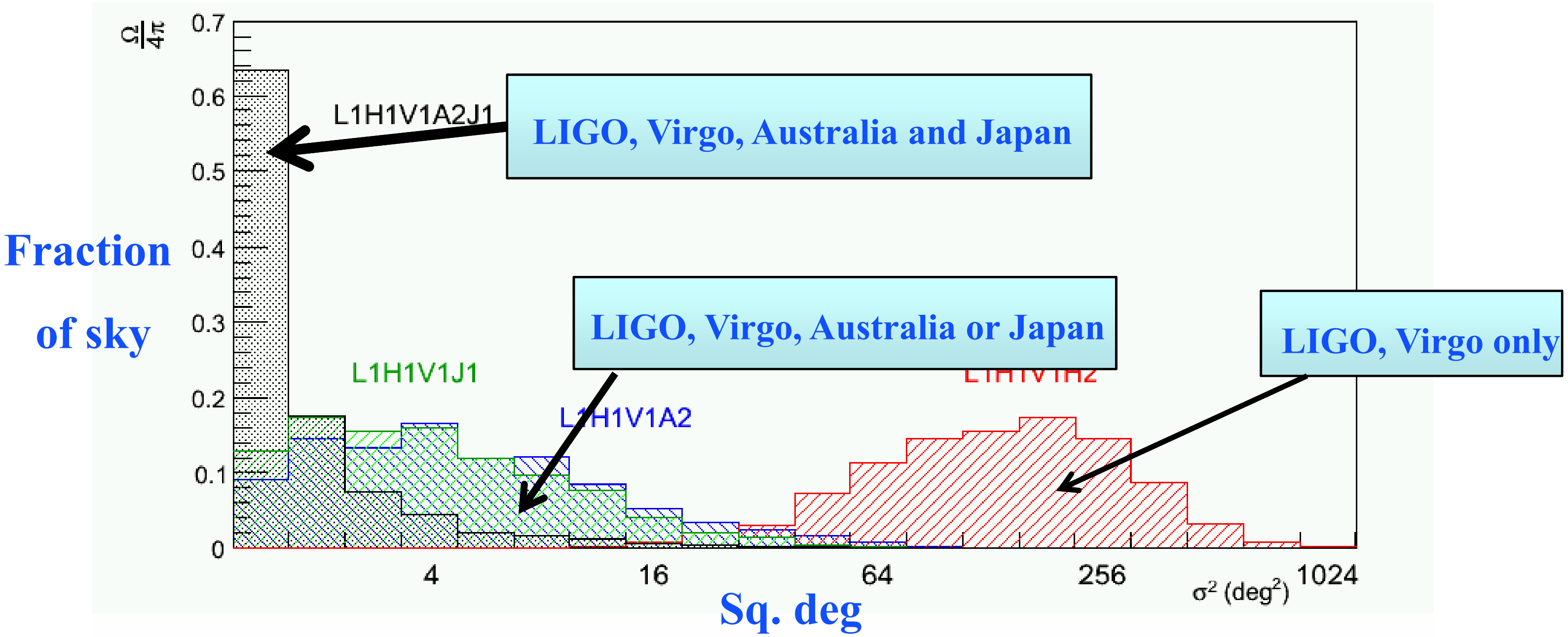
Determination of source sky position: NS-NS binary inspirals

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

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



LIGO, Virgo, Australia and Japan

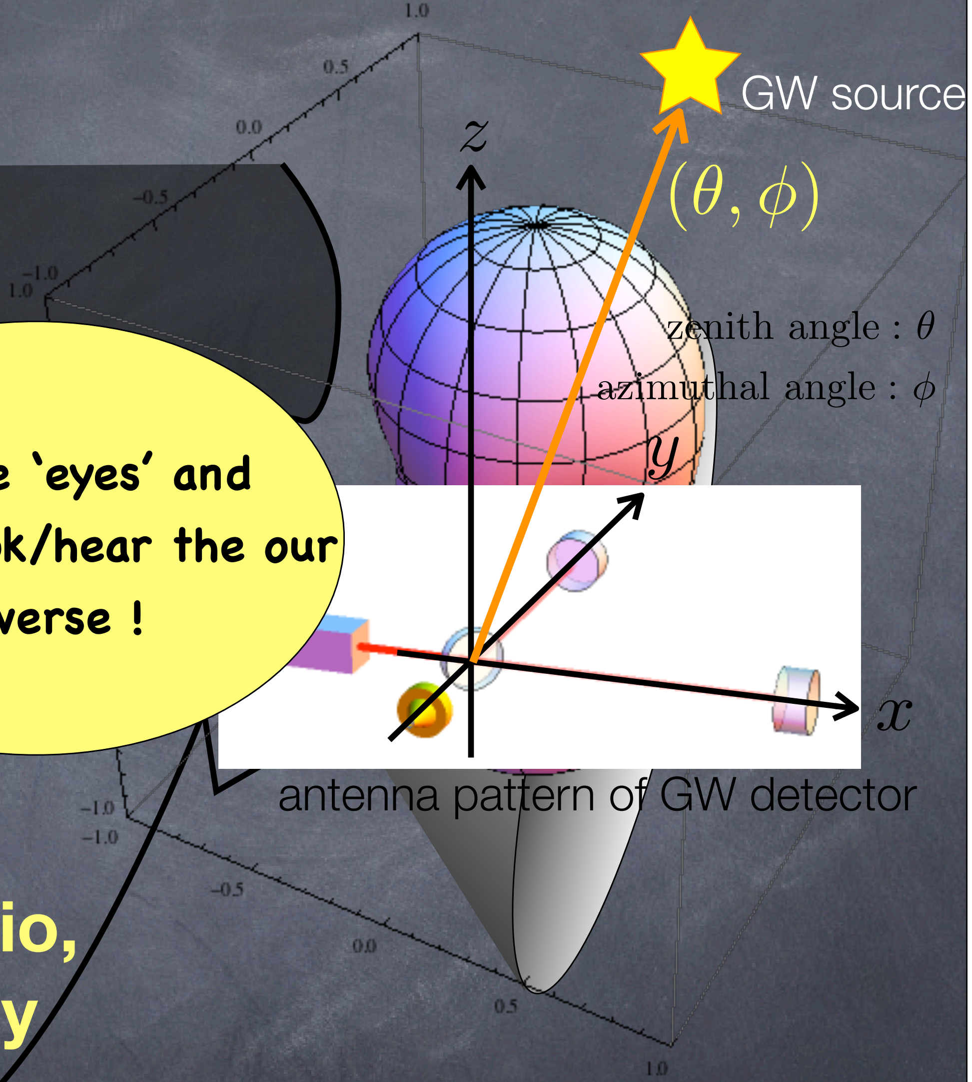
LIGO, Virgo, Australia or Japan

LIGO, Virgo only

viewgraph by Alan Weinstein

Eye and Ear

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



antenna pattern of GW detector

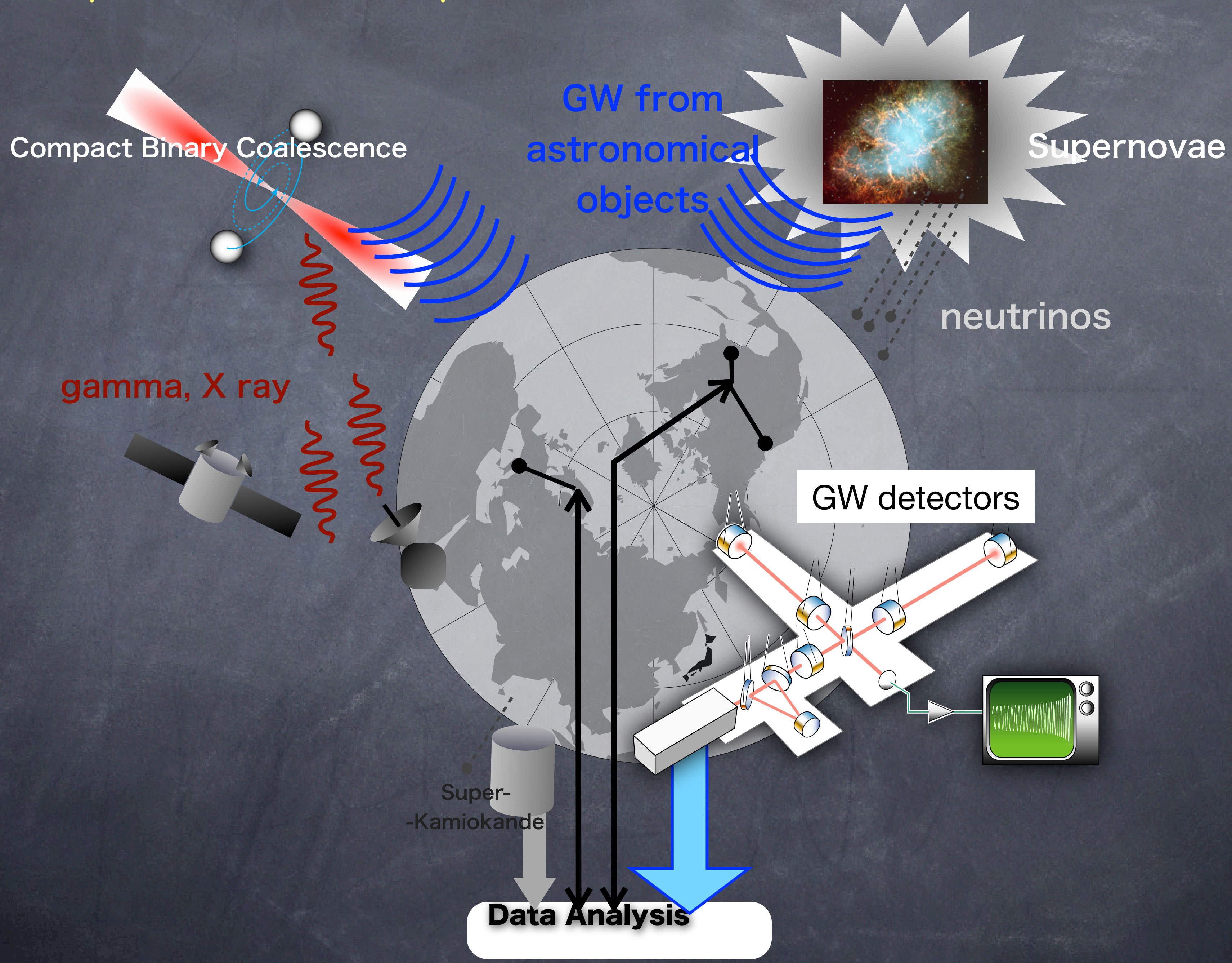
Optical (visible - infrared), Radio, X-ray, Gamma-ray, Cosmic-Ray

Eye and Ear complete the information from outside.

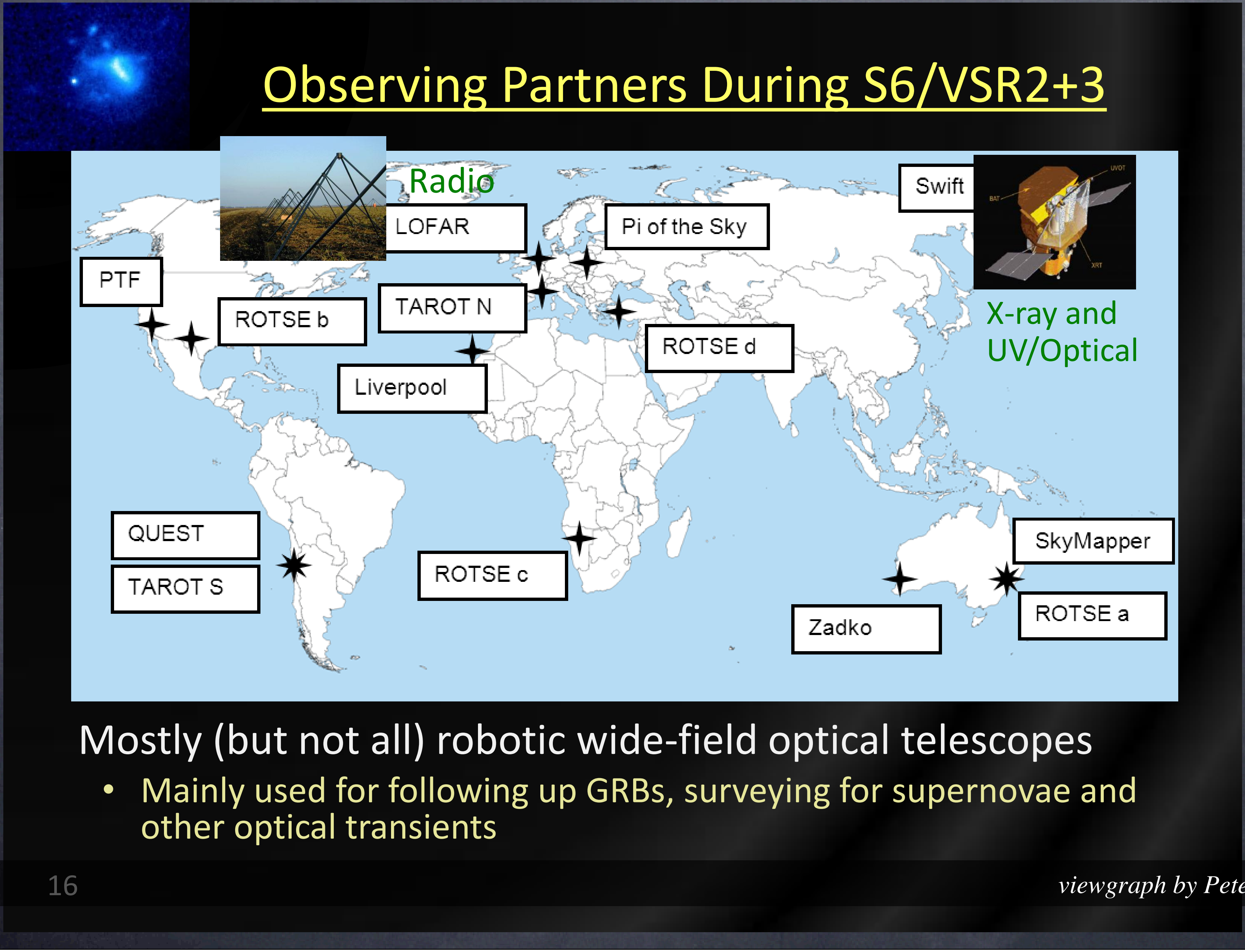
Eye : fine spatial resolution, good to see the surface of object, hard to see the hidden inside...

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

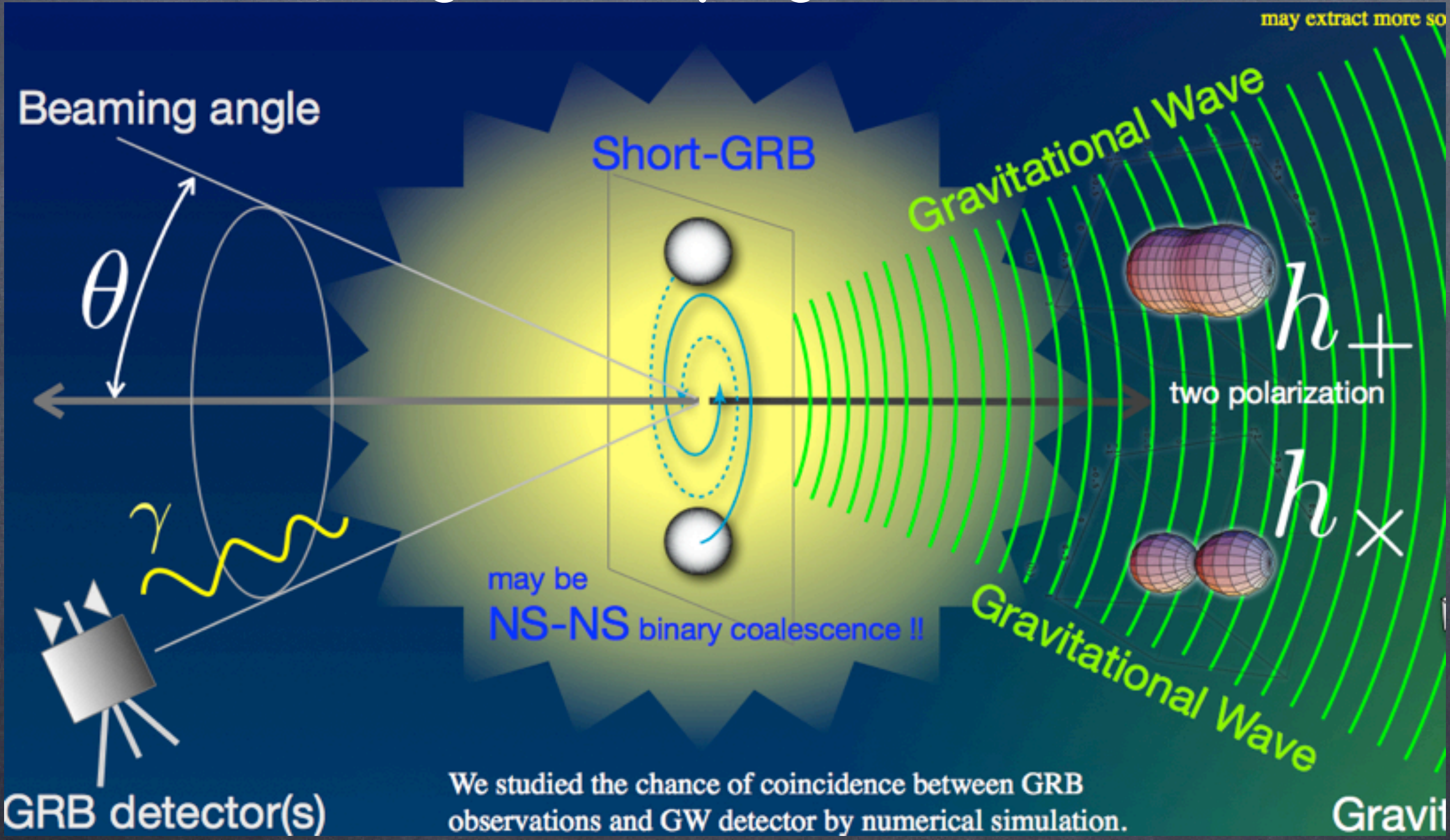
Mostly (but not all) robotic wide-field optical telescopes

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

viewgraph by Peter Shawhan

Compact Binary Coalescences

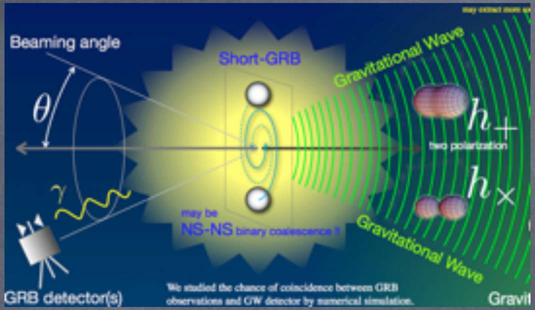
- NS-NS binary might be a progenitor of Short-GRB.



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

Followup by
X, Gamma, Optical

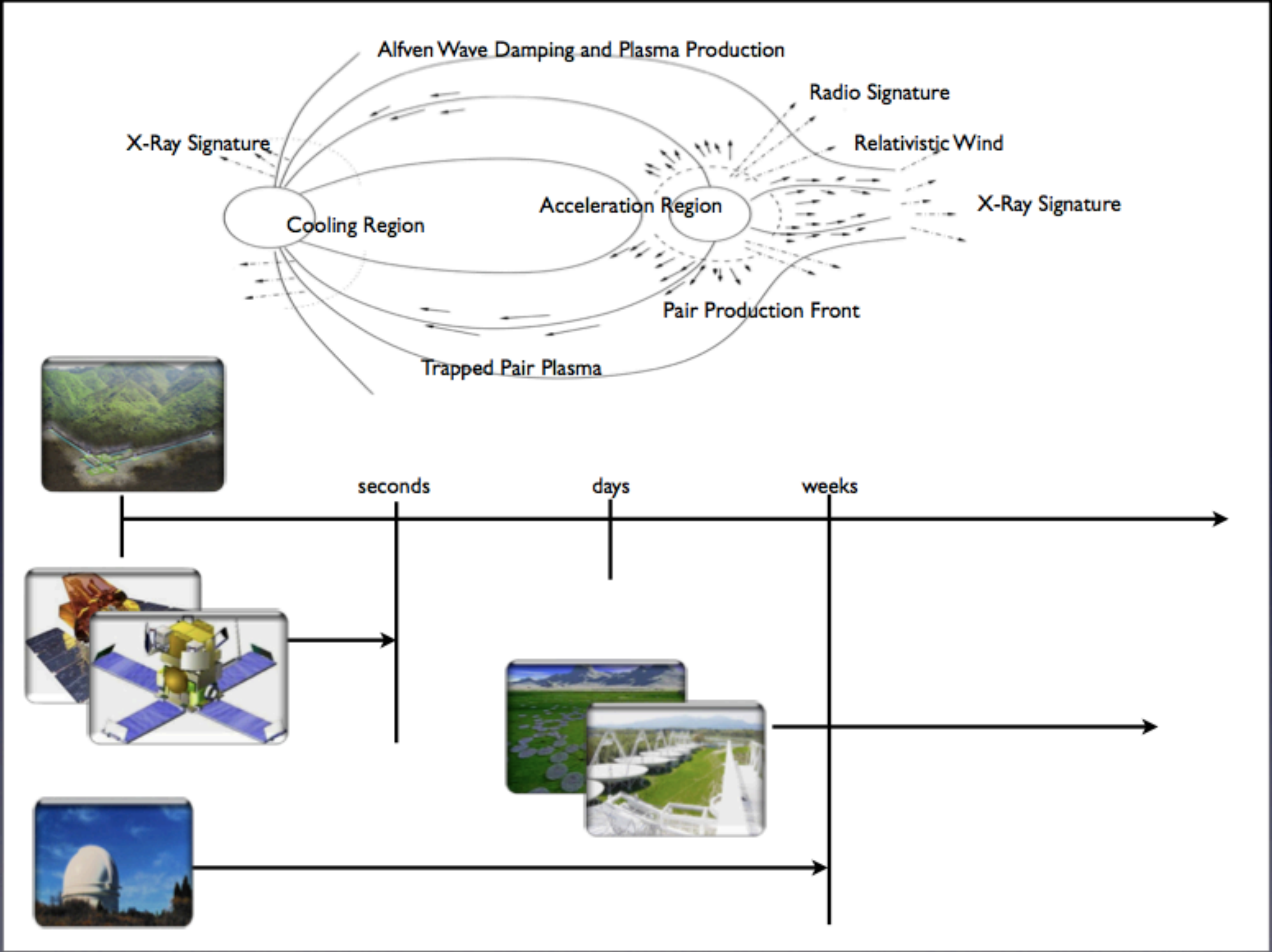
[Aux trigger]
Date, direction, ...

Delayed precise
analysis

Confirmation of
Afterglow

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

CBC

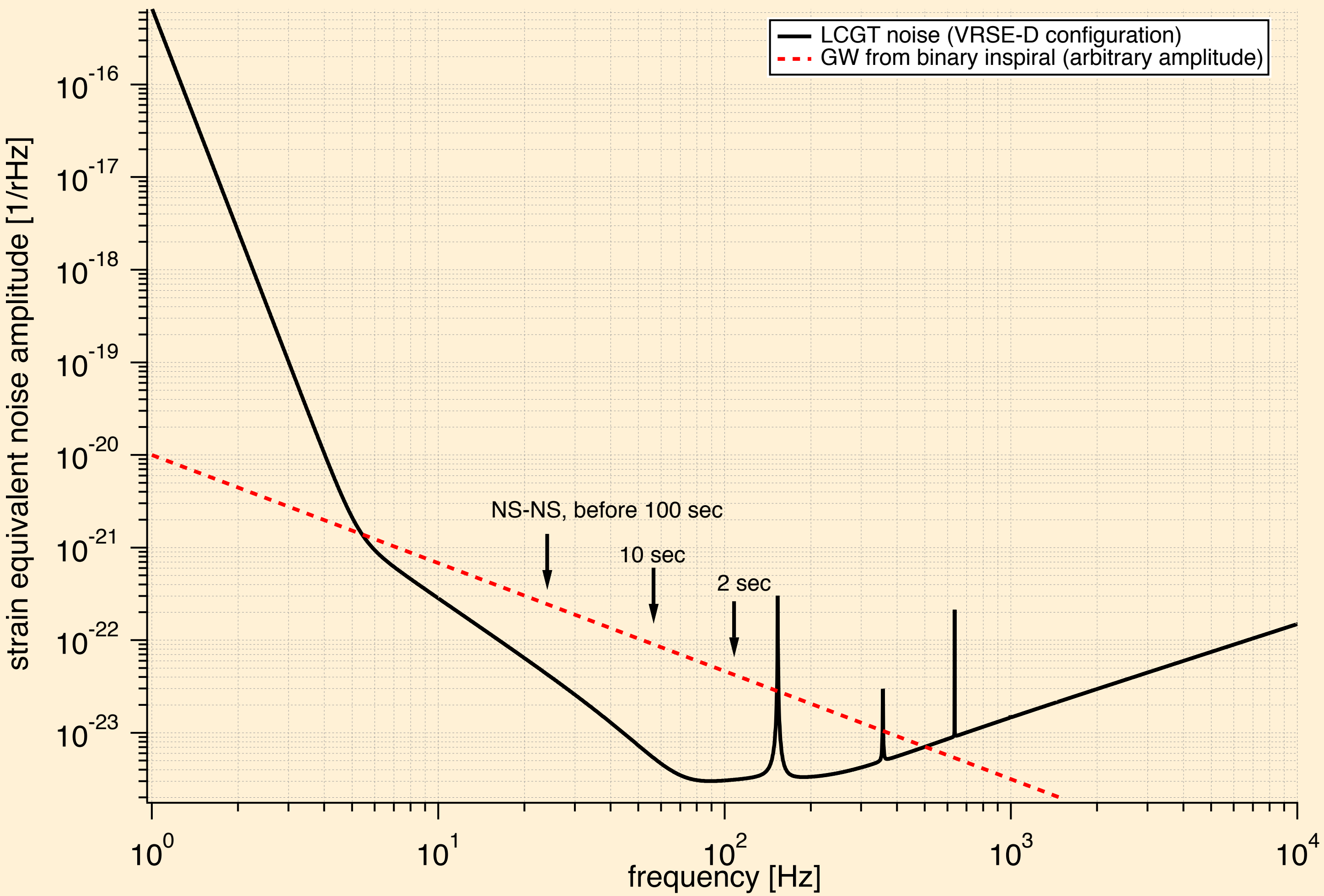


2010年8月11日水曜日

arranged by K.Hayama

Forecast !?

- GW are emitted continuously before coalescence.



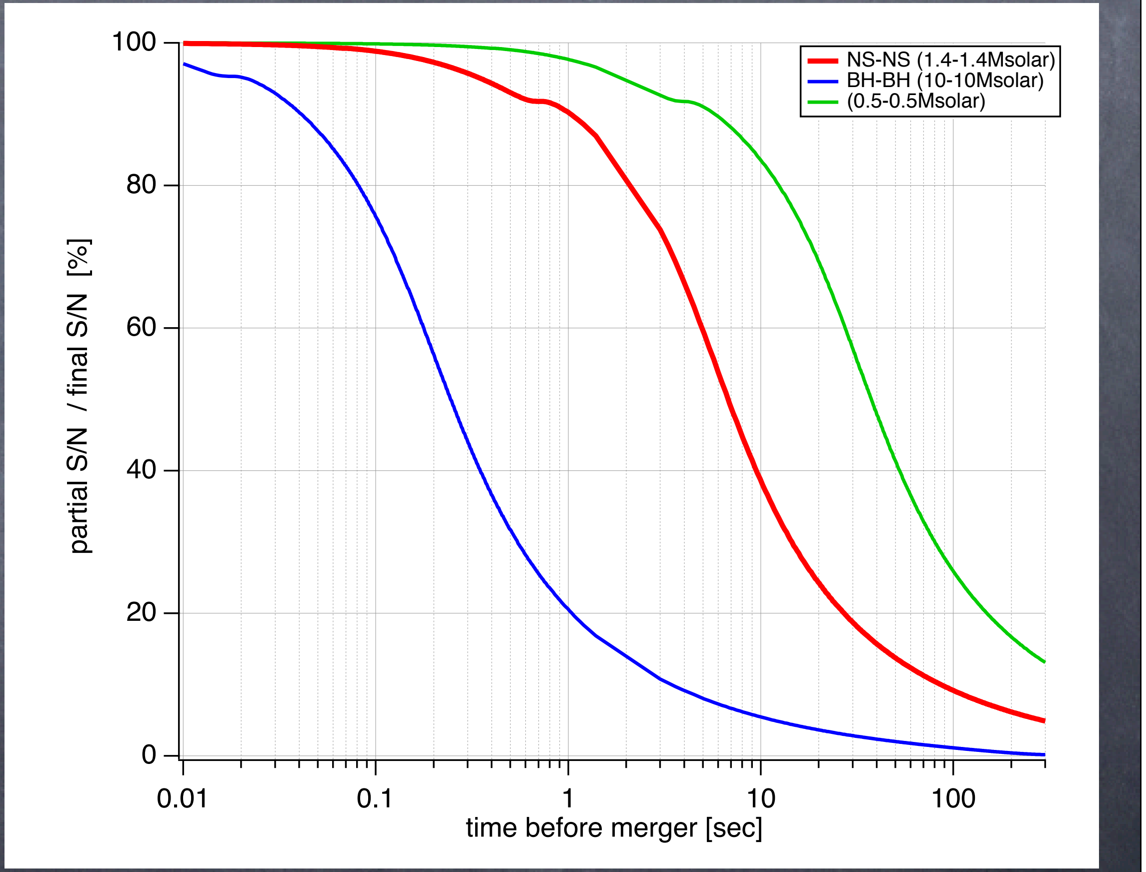
Example of Practical Issue : NS-NS forecast

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

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

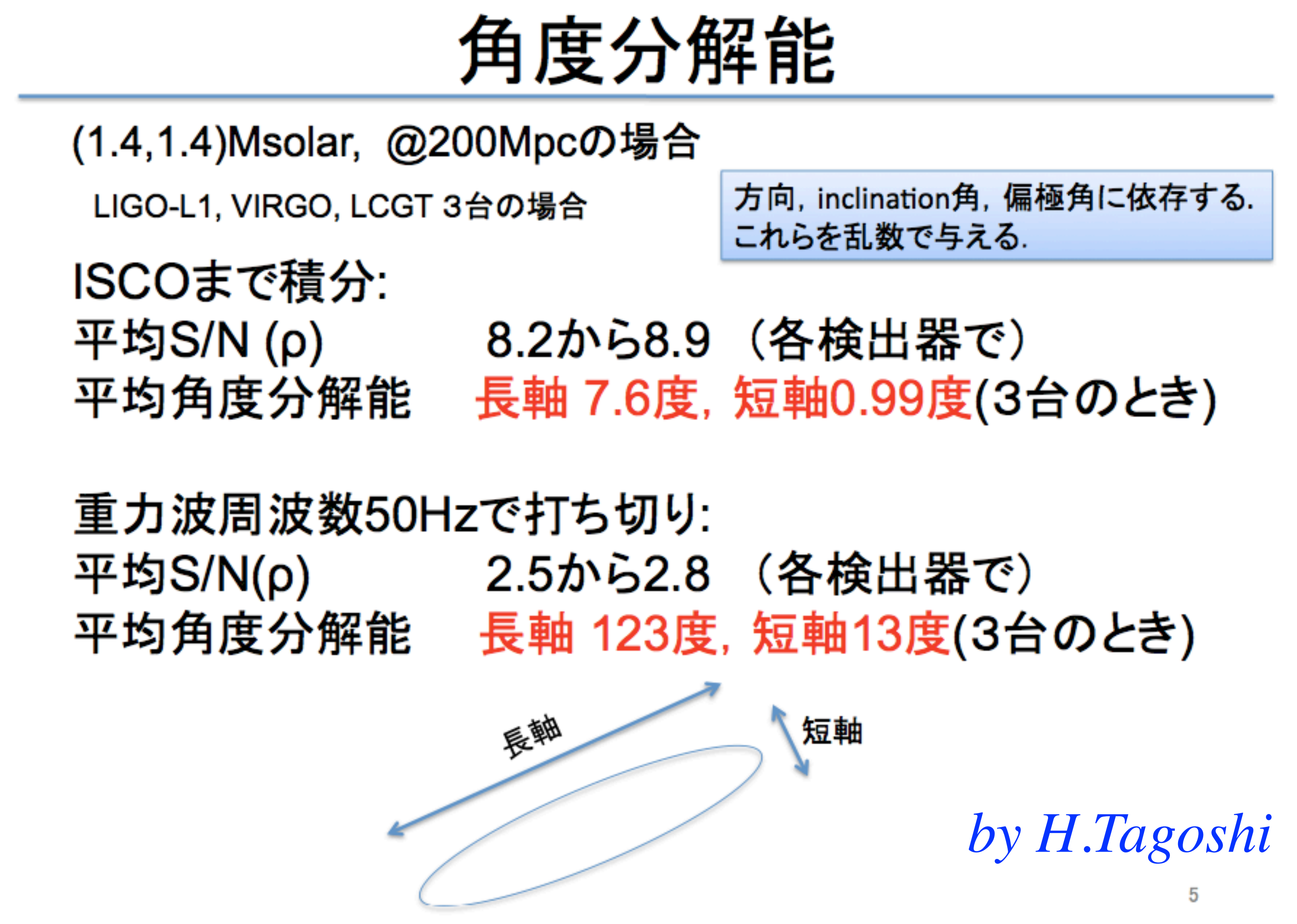
Forecast by GW is not easy, however it is not impossible in principle.

Even it is not a forecast,
faster alert is useful for observe the transient behavior.



Direction of Sources

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



角度分解能

(1.4,1.4)Msolar, @200Mpcの場合

LIGO-L1, VIRGO, LCGT 3台の場合

方向，inclination角，偏極角に依存する．
これらを乱数で与える．

ISCOまで積分:
平均S/N (ρ)　8.2から8.9（各検出器で）
平均角度分解能　長軸 7.6度，短軸0.99度(3台のとき)

重力波周波数50Hzで打ち切り:
平均S/N(ρ)　2.5から2.8（各検出器で）
平均角度分解能　長軸 123度，短軸13度(3台のとき)

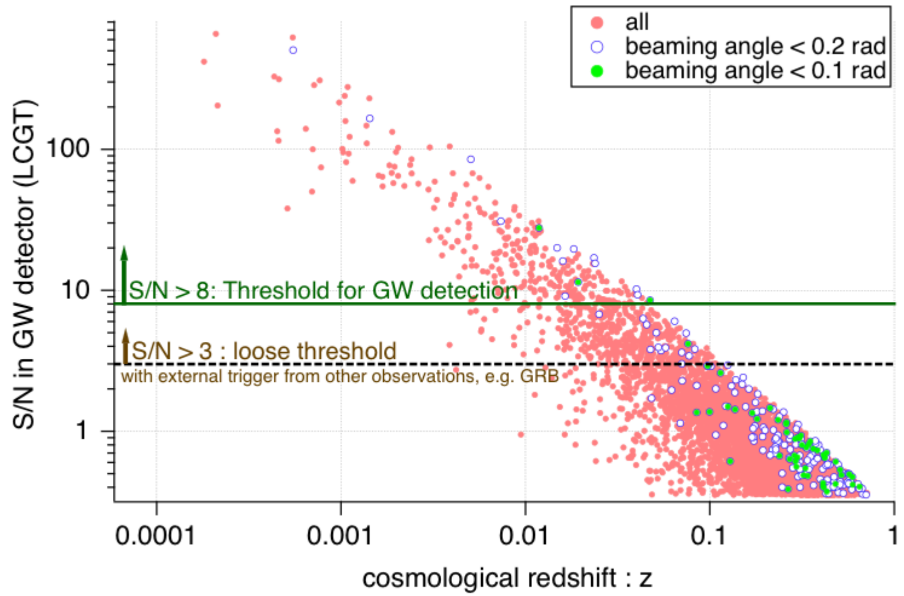
by H.Tagoshi

Coincidence chance between GW and GRB

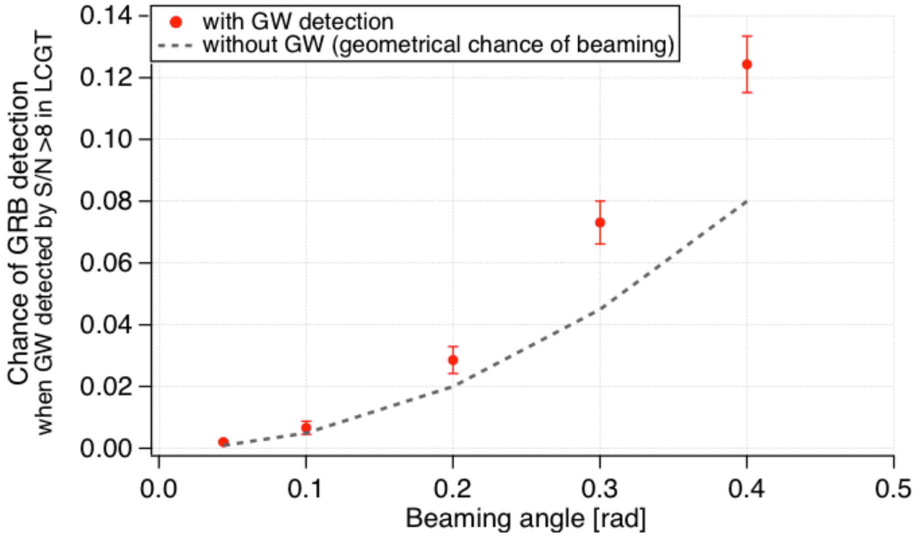
z distribution	Beaming of GRB	Chance of GRB found
pre-Swift	0.2 rad	2.9%
Swift	2.5 deg	0.2%
	0.1 rad	0.7%
	0.2 rad	2.9%
	0.3 rad	7.3%
	0.4 rad	12.4%

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

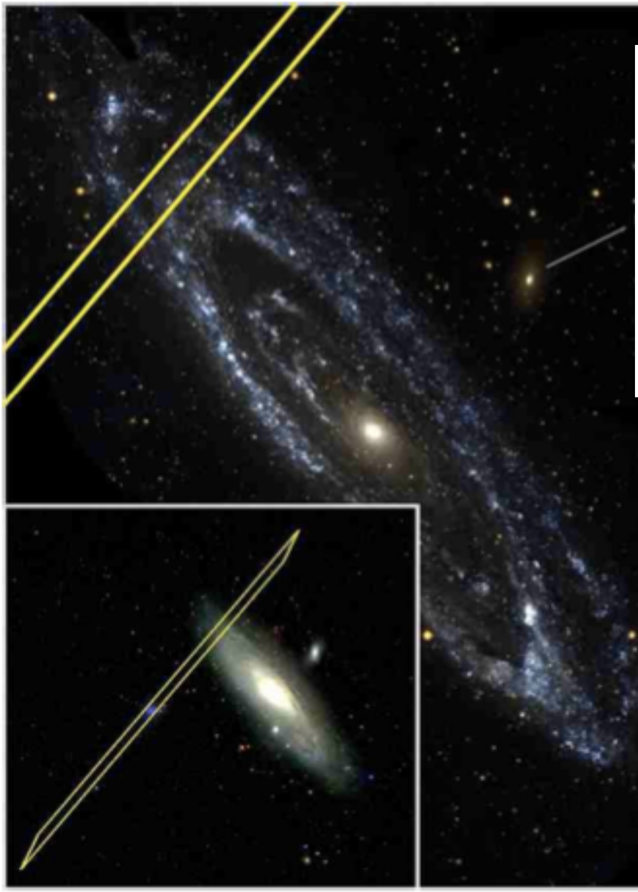
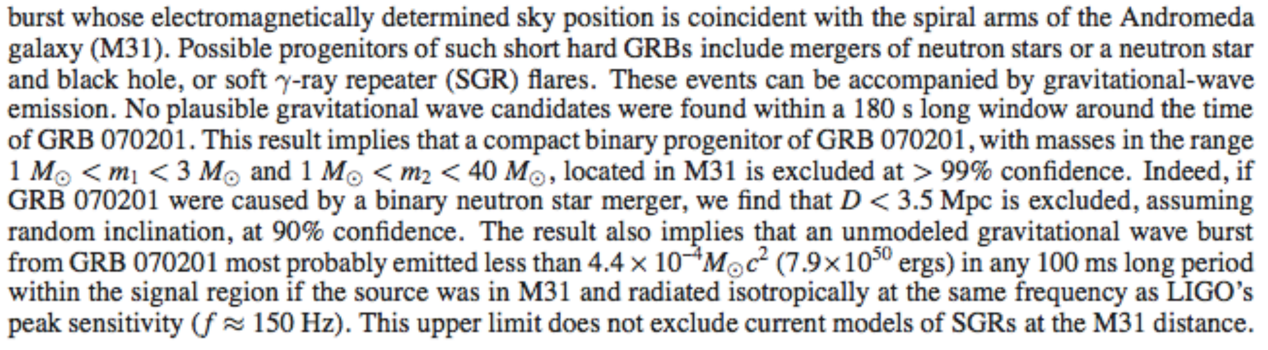


FIG. 1.— The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (Adelman-McCarthy et al. 2006; SDSS 2007) image of M31. The main figure shows the overlap of the error box and the spiral arms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

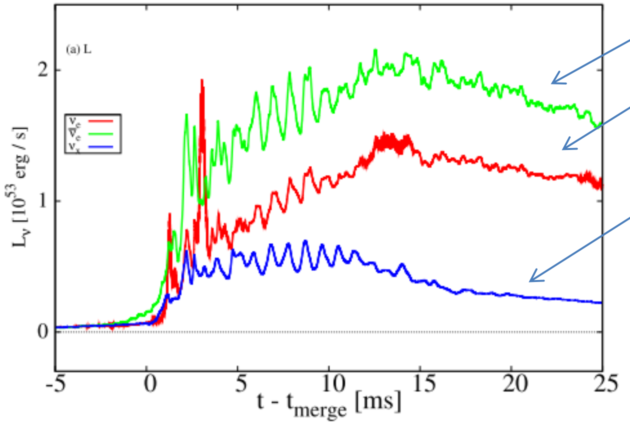
It was NOT CBC. (excluded 99%)

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
(2.7 $M_\odot$)

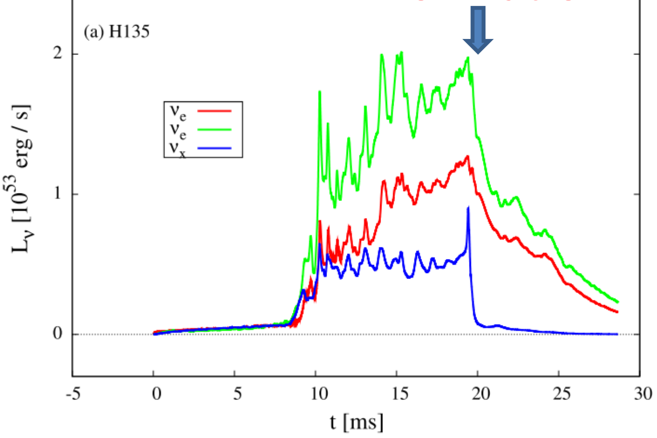


Anti electron neutrino

Electron neutrino

μ, τ neutrino

Shen+
Hyperon
(2.7 $M_\odot$)



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

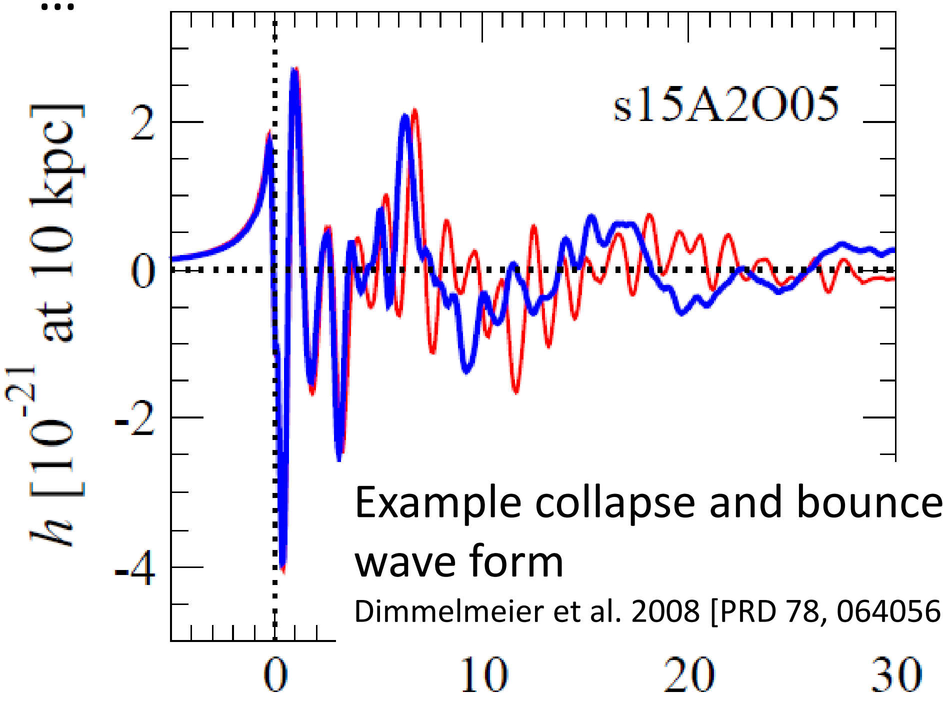
viewgraph by Kenta Kiuchi

Supernova : Neutrino and GW

may be more promising source for both neutrino and GW.

Various possible gravitational wave emission mechanism:

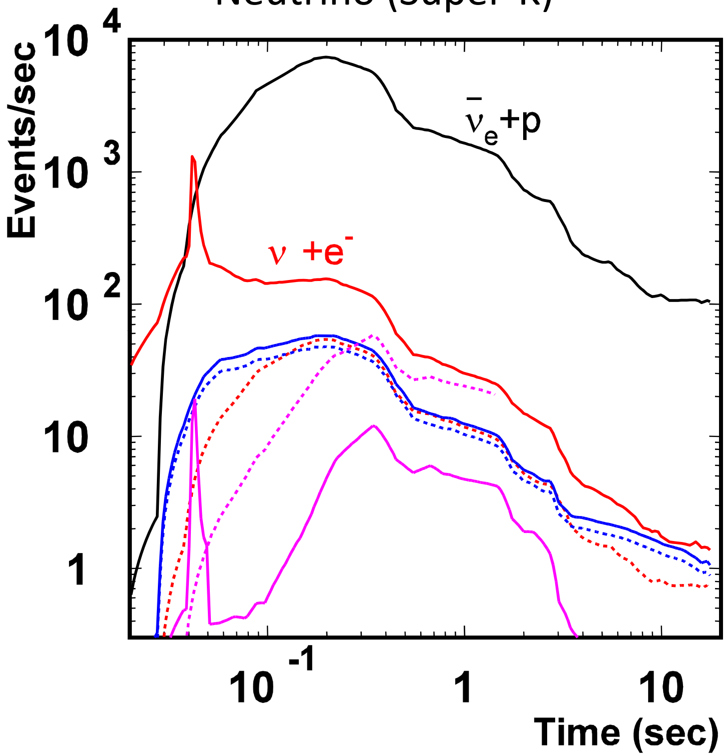
- Core collapse and bounce
- Rotational non-axisymmetric instabilities of proto-neutron star
- Post-bounce convection
- …



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

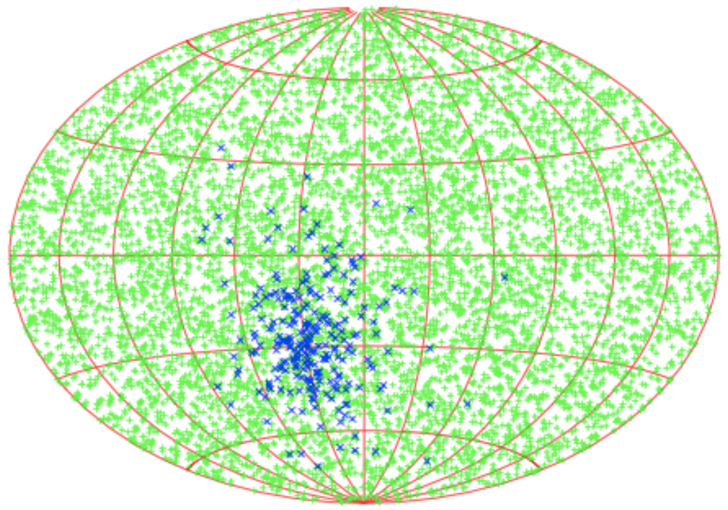


FIG. 4: Angular distribution of $\bar{\nu}_e p \to n e^+$ events (green) and elastic scattering events $\nu e^- \to \nu e^-$ (blue) of one simulated SN.

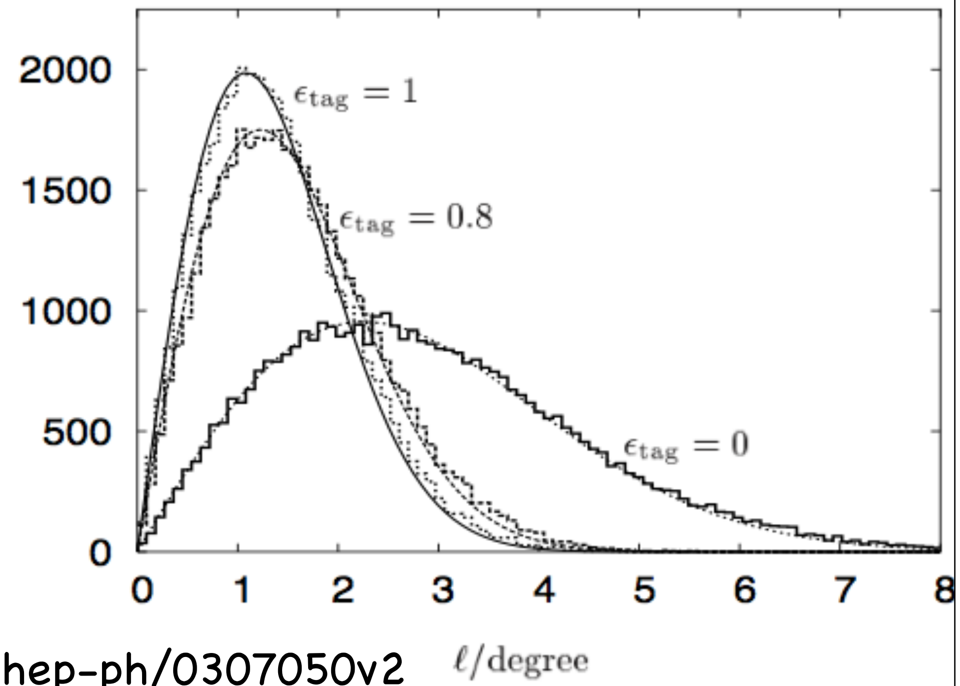
- **Neutrino (Super-Kamiokande)**

  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



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Summary & Future

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

  has been funded partially, and its **construction started !**

  (First run will be 2014.)

- **2nd Generation Detectors (LCGT, aLIGO, aVirgo...)**

  will start netwoek observation at late 2016 or early 2017.

  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'.

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TAMA Project Office http://tamago.mtk.nao.ac.jp/spacetime/index.html

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