Science by LCGT

Hideyuki Tagoshi
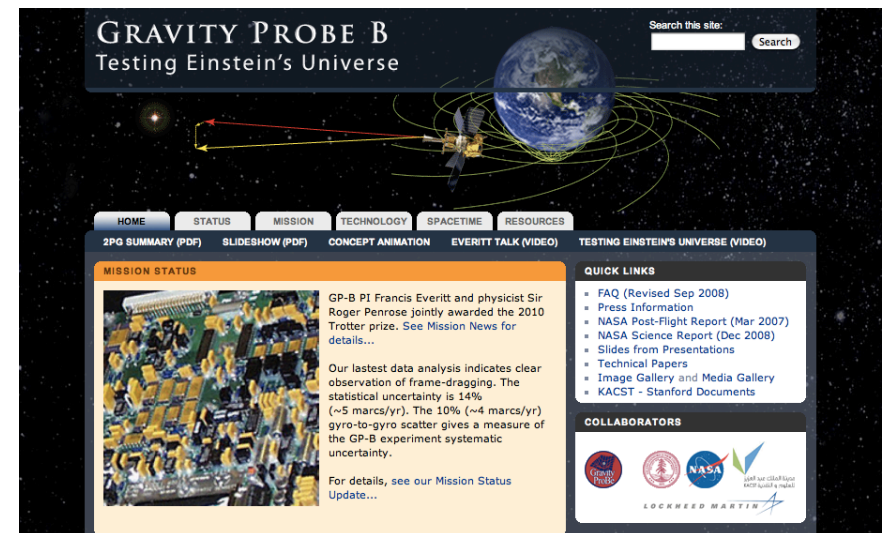
(Osaka University)

Contents

- Compact binary Coalescence (CBC)
  NS-NS Merger rate, event rate
  Parameter estimation accuracy

- Gravitational Collapse

- Pulsar

- Stochastic background

Detection of GW

Many aspect of general relativity have not been
tested experimentally.
Gravity Probe B project (USA):
test of frame dragging effect
around a rotating body

Gravitational wave: tensor mode propagating with
speed of light

Multimessenger gravitational-wave astronomy

Coordinated observations using different kinds of radiation : electromagnetic, neutrino, cosmic ray, and gravitational wave.

Triggered search

Information of time and direction from other observation tools
is extremely advantageous for the gravitational-wave detection.
Gamma ray burst: stellar core collapse, compact binary merger
Neutrino: Supernova in/near our Galaxy
Wide field optical/IR telescope: watch CBC, GRB, SN

Follow-up search

Laser interferometer GW detector is wide field telescope by nature.
First detect GW candidate events, and use the information of the time and
direction in the electromagnetic observation.
Low latency data analysis pipeline is essential for this purpose.

LIGO analysis : GRB070201
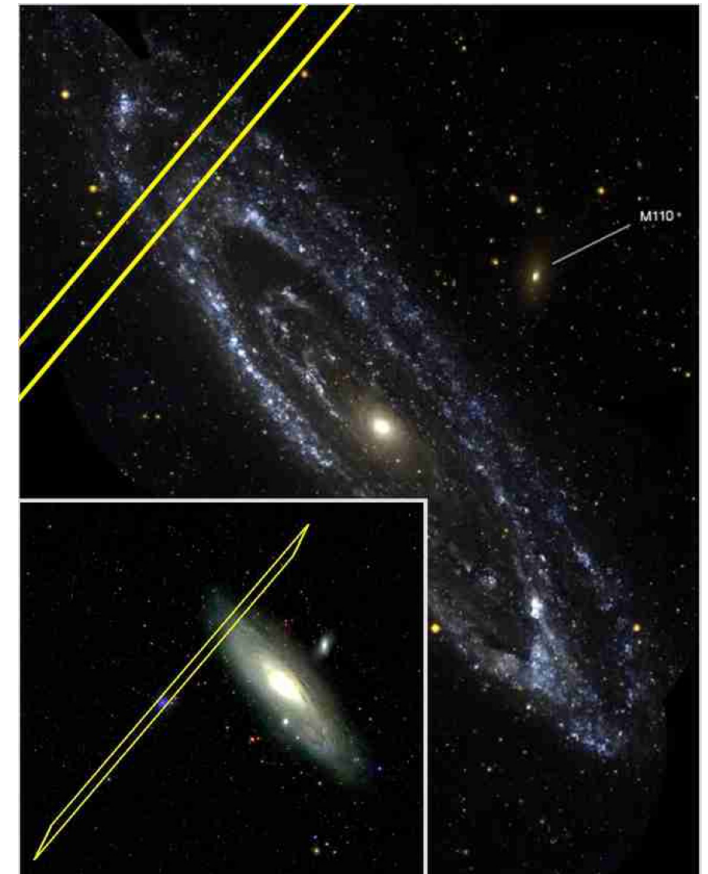
GRB070201: Short gamma ray burst (SGRB)
   Direction: M31(Andromeda nebula, 770kpc)

Progenitor candidate of SGRB:
coalescence of NS-NS or NS-BH

However, inspiral signals are
not detected around the GRB trigger time

Thus, it is not the binary merger event
occurred in M31 (at 99% C.L.)

Compact binary coalescence

NS-NS merger rate

There are about 10 known and likely neutron star binaries.
6 neutron star binaries have life time shorter than the age of the universe

PSR name	P_s (ms)	P_b (hr)	e	τ_{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

(Lorimer, LRR, 11, (2008), 8)

Double pulsar

Most recently discovered (2006)
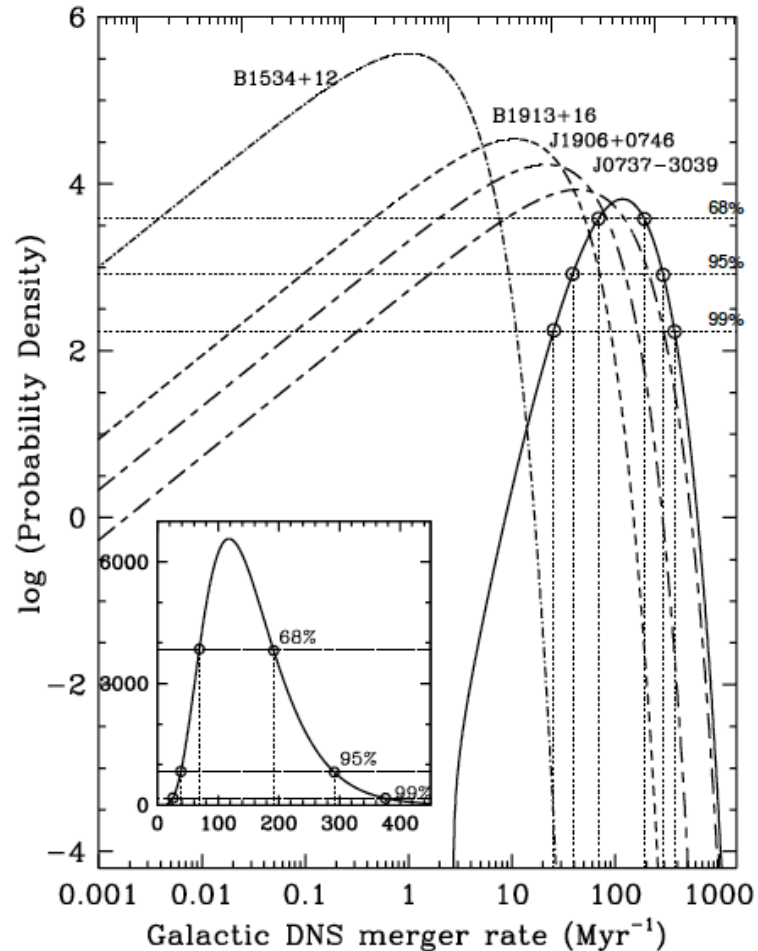
NS-NS merger rate

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

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

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 may be large.

Parameter estimation accuracy

Parameter estimation accuracy is a key factor toward the gravitational wave physics / astronomy

Especially, angular resolution is important for the multimessenger gravitational wave astronomy.

Can we identify the host galaxy of the source?

The answer is pessimistic.

Parameter estimation accuracy

Parameters of inspiral signals   9 parameters

Polarization angle

$$(\ln(r), \ln(M_c), \delta \text{ or } \ln(\eta), t_c f_0, \phi_c, \theta_s, \phi_s, \psi, \epsilon)$$

$$M_c = M\eta^{3/5}, \quad \delta = (m_1 - m_2)/M$$

Direction to the source

Inclination angle

Fisher matrix

Assume maximum likelihood detection strategy for multiple detectors (coherent detection) and evaluate by using the Fisher matrix

The effects included

• Detectors' orientation (Curvature of the Earth)
• The difference of the arrival time

Various value of $(\theta_s, \phi_s, \psi, \epsilon)$ are generated randomly, and the distribution of the standard deviation of parameters are drawn.

Angular resolution

(1.4,1.4)Msolar, @200Mpc

Advanced LIGO noise spectrum

LIGO-L1, VIRGO, LCGT (3 detectors)

Average S/N (ρ)   8.2-8.9 (at each detector)
Average resolution: major axis 7.6 deg., minor axis 0.99 deg.
Typical value: major axis 1-2 deg., minor axis 0.5-1 deg.

Angular resolution distribution (Major axis)

[Degree]

Angular resolution distribution (Minor axis)

[Degree]

Major axis

Minor axis
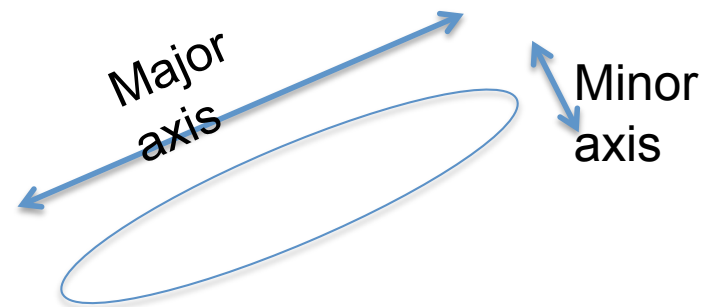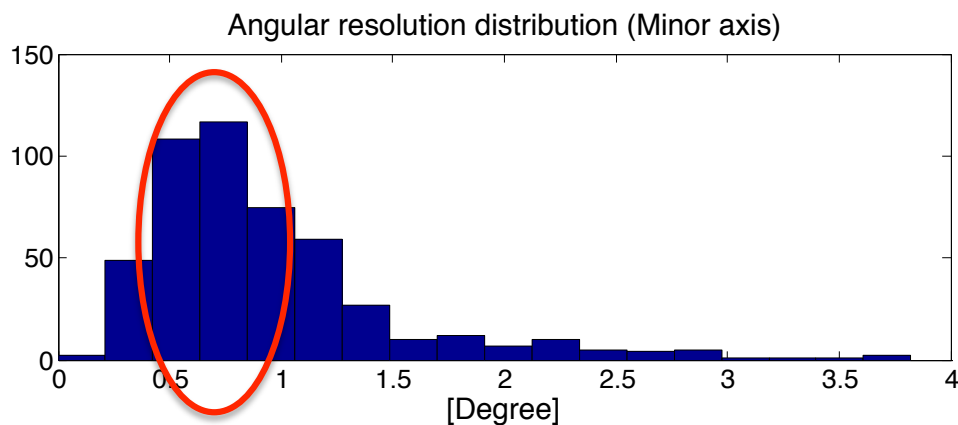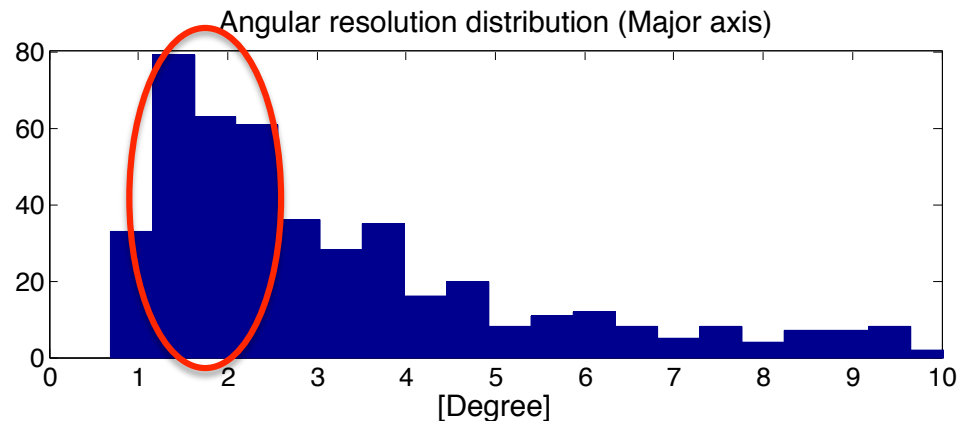
Error ellipse

Direction, inclination, polarization are given randomly

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Parameter estimation accuracy

Advanced LIGO noise spectrum

$(1.4, 1.4) M_{\text{solar}}$

Signal to noise ratio at each detector (up to ISCO)

	LIGO-L1	LIGO-H1	VIRGO-V1	LCGT-K1
RWF	6.6	8.3	6.4	8.1
FWF	6.4	8.0	6.2	7.9

$$\theta_s = \frac{\pi}{9}, \; \varphi_s = \frac{8}{9}\pi, \; \psi = \frac{\pi}{4}, \; \varepsilon = \frac{\pi}{3}$$

$$(m_1, m_2) = (1.4, 1.4) M_{\text{solar}}$$

$$r = 200 \text{ Mpc}$$

Parameter estimation errors (up to ISCO)

		ln(r)	ln(Mc)	delta	tc[msec]	theta [min]	phi[min]	Omega [sr]	minor axis [min]	Major axis [min]
FWF	LHVK	0.49	3.7×10^{-5}	0.34	0.17	35	80	4.9×10^{-4}	23	160
	LVK	0.50	4.4×10^{-5}	0.41	0.20	36	100	6.4×10^{-4}	24	200

		ln(r)	ln(Mc)	ln(eta)	tc[msec]	theta [min]	phi[min]	Omega [sr]	minor axis [min]	Major axis [min]
RWF	LHVK	0.46	9.0×10^{-5}	8.9×10^{-3}	0.35	33	75	4.3×10^{-4}	22	150
	LVK	0.48	1.1×10^{-4}	1.1×10^{-2}	0.42	33	94	5.6×10^{-4}	22	188

Parameter estimation accuracy

Angular resolution

- Angular resolution is not very good for sources at typical distance (@200Mpc).

- The direction of the source may not be determined by GW alone.

Detection of the electromagnetic and neutrino counterpart is necessary to identify the host galaxy.

Distance

- Chirp signal is often called "the standard siren".

- However, distance can not be determined very accurately due to the pure accuracy of polarization and inclination angle. We will have to wait for more sensitive detectors like Einstein telescope and LISA, DECIGO/BBO to study cosmology by chirp signals.

Low latency search for CBC

We want to analyze data as fast as possible.

Naive question: Is it possible to predict (or forecast) of the compact star merger before the merger time by using inspiral signal?

Inspiral signal continues for a few seconds.
However, if we cut off the integration of the matched filter before the ISCO time,
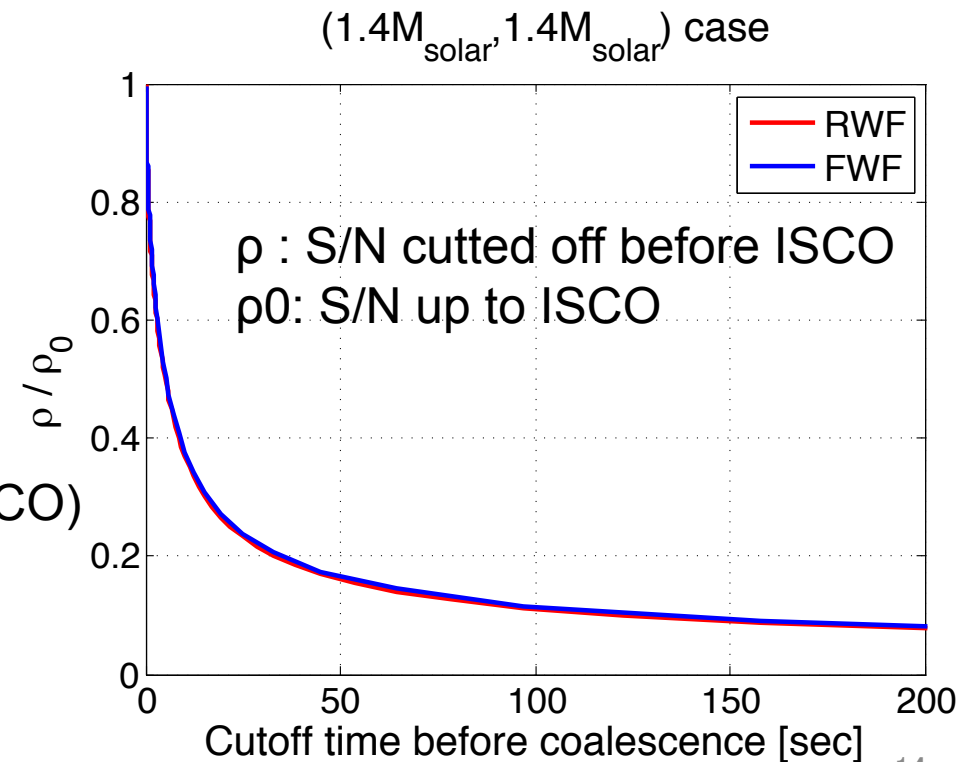
S/N ratio decreases rapidly.

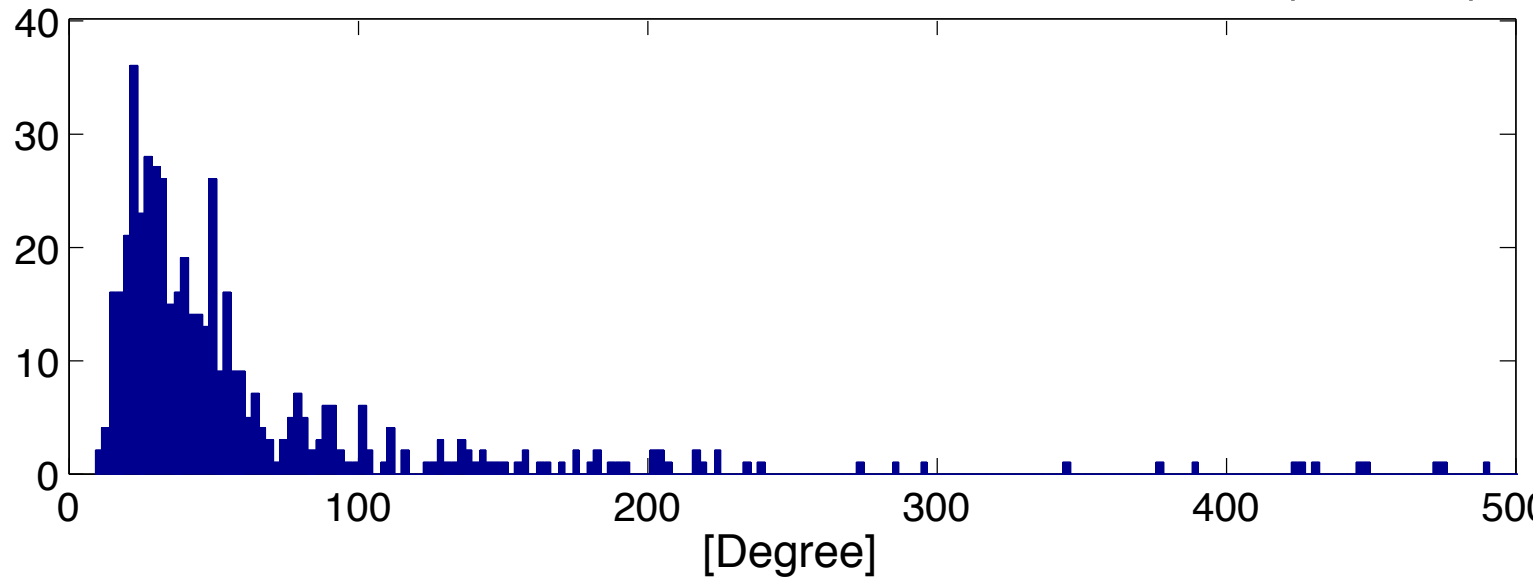Parameter estimation accuracy become very bad.

(1.4,1.4)Msolar, @200Mpc

Cutoff frequency : 50Hz (13 sec before ISCO)

⬇

Angular resolution : several 10 degree.

$(1.4M_{solar}, 1.4M_{solar})$ case

ρ : S/N cutted off before ISCO
$\rho 0$: S/N up to ISCO

Legend:
— RWF
— FWF

y-axis: ρ / ρ_0
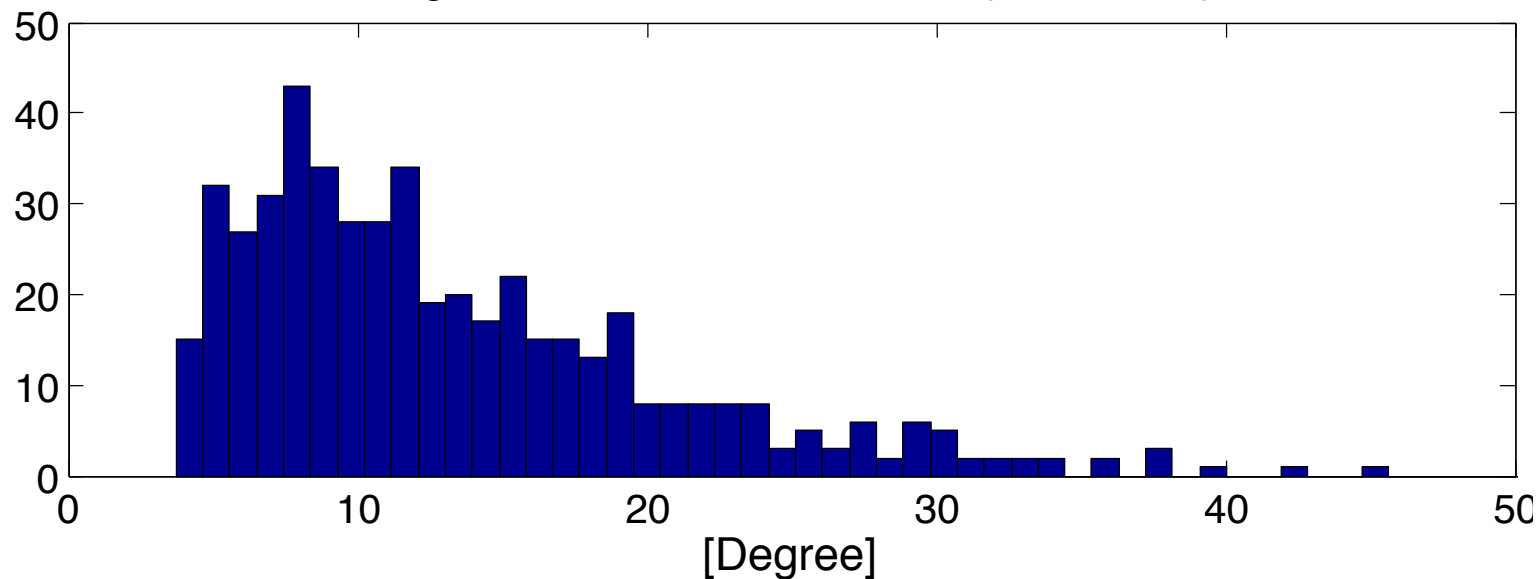
x-axis: Cutoff time before coalescence [sec]

Angular resolution distribution (Major axis)   (1.4,1.4)Msolar, @200Mpc

Cutoff at 50Hz (13 sec. before ISCO)

Angular resolution distribution (Minor axis)

Supernova (Gravitational Collapse)

Ref. Ott, CQG, 26, 063001 (2009), Fryer and New, LRR, 14, 1 (2011)

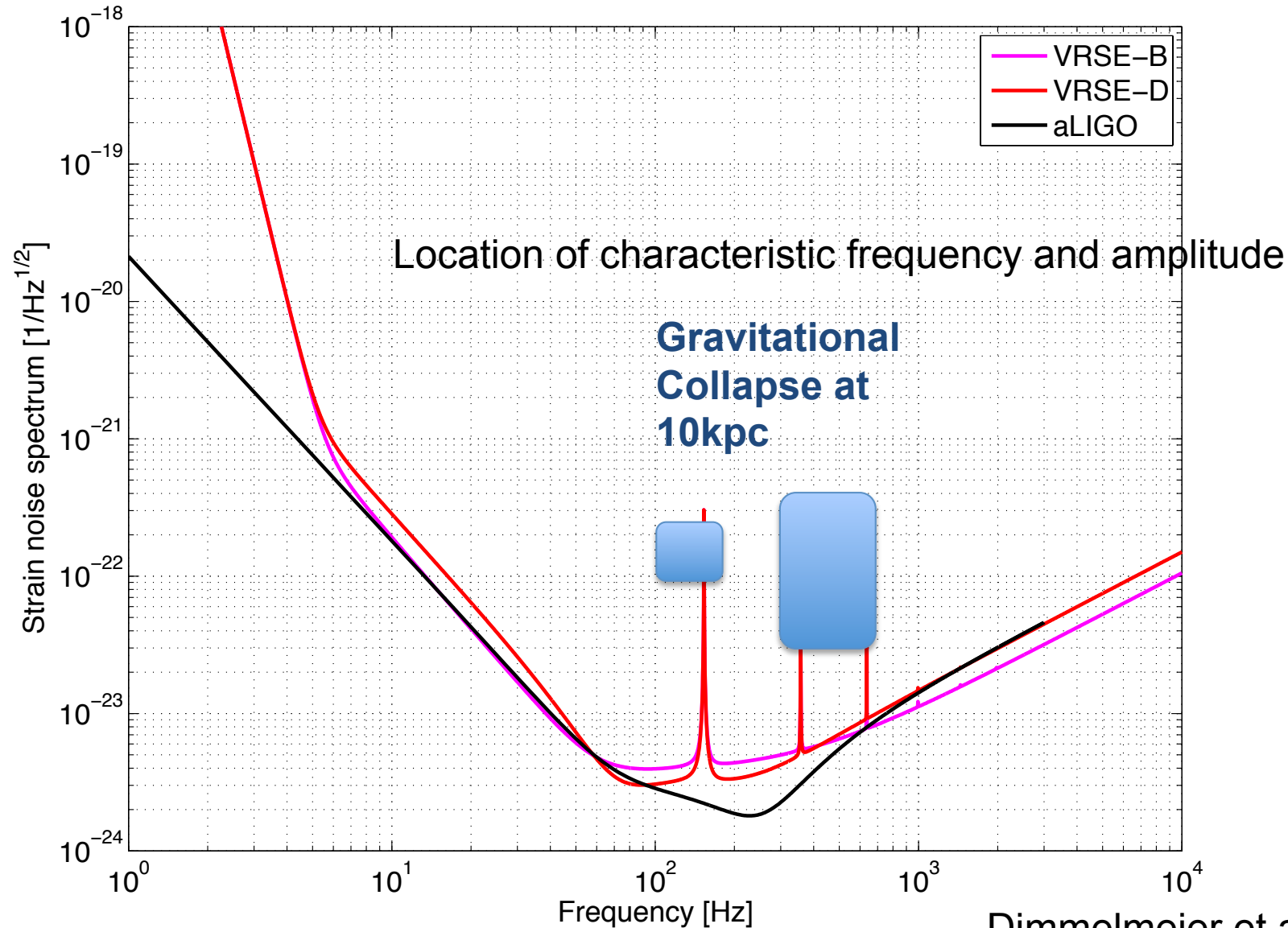Various possible gravitational wave emission mechanism.

- Core collapse and bounce
- Rotational non-axisymmetric instabilities of proto-neutron star
- Post-bounce convection
- Non-radial pulsations of proto-neutron star

Related to the explosion mechanism

- Anisotropic neutrino emission
  etc.
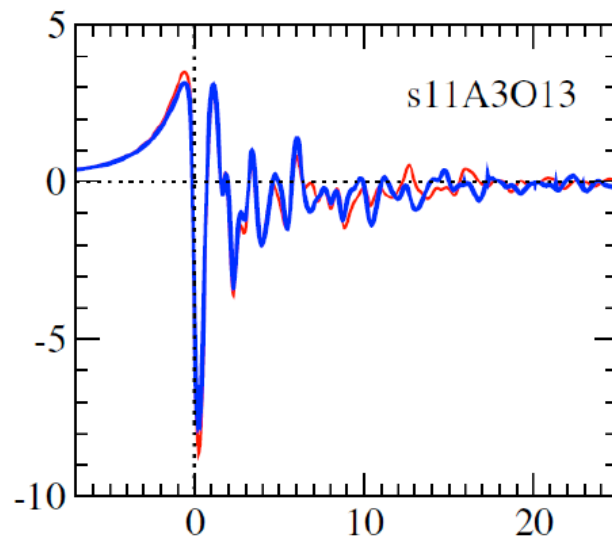
Collapse and bounce wave form from
Dimmelmeier et al. 2008 [PRD 78, 064056]

Gravitational Collapse

Location of characteristic frequency and amplitude

Gravitational Collapse at 10kpc

Legend: VRSE-B, VRSE-D, aLIGO

Y-axis: Strain noise spectrum [1/Hz$^{1/2}$]

X-axis: Frequency [Hz]

Dimmelmeier et al. ('08)
PRD 78, 064056

Continuous wave (rotating NS)

Maximum possible amplitude from pulsars   ε: ellipticity

VRSE–D

$h_c = k\sqrt{S_n/T}$

$\varepsilon = 10^{-5}$

characteristic amplitude at 10kpc

T=20 days

T=1yr

$\varepsilon = 10^{-7}$

Frequency [Hz]
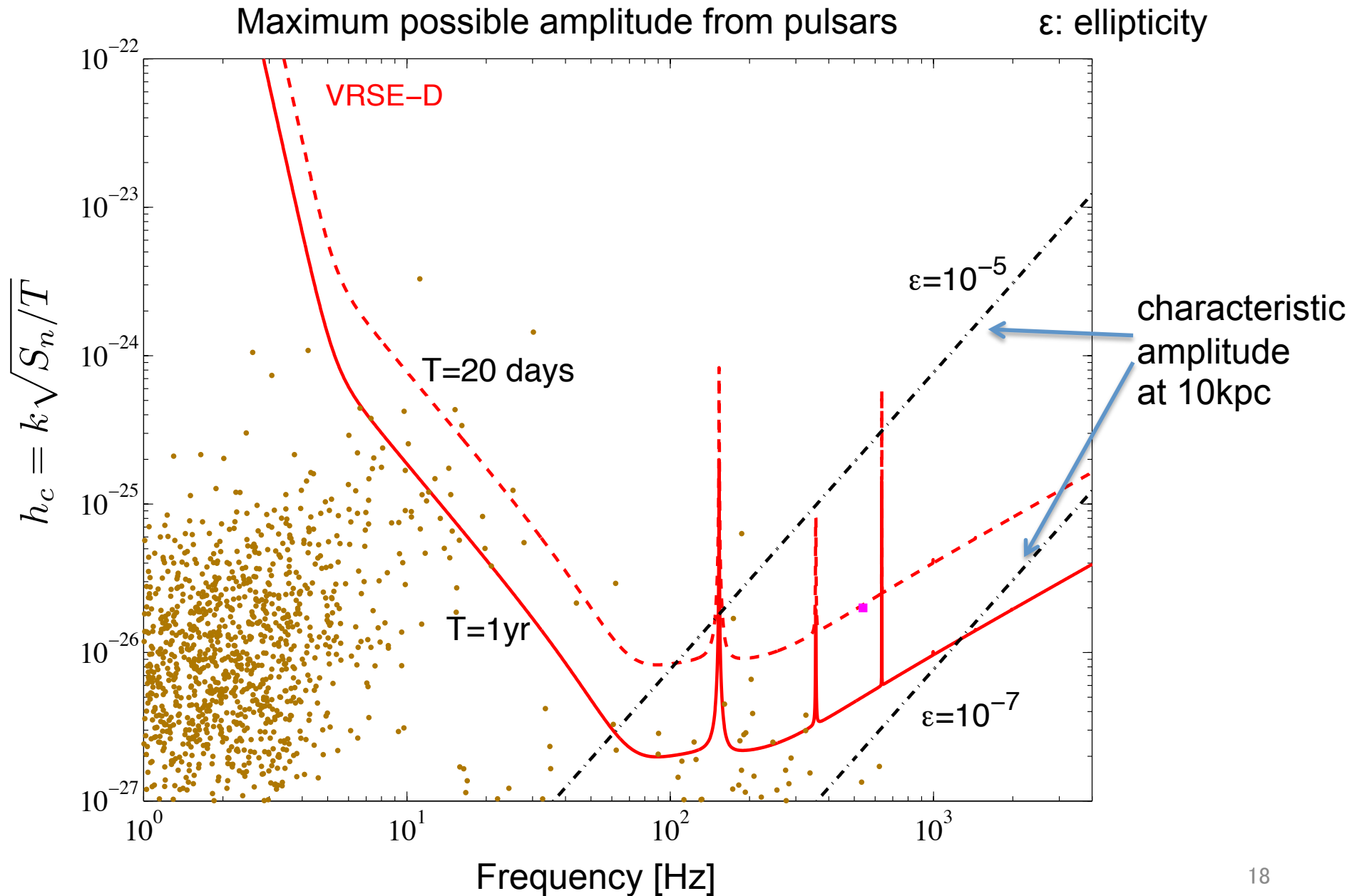
LIGO -Crab pulsar-

Neutron star in Crab nebula
Borne in 1054 by supernova

Crab nebula

Upper limit of gravitational amplitude derived from
the spin down rate of pulsar:

$$h \sim 1.4 \times 10^{-24}$$

LIGO 9 months data from 2005-2006:

$$h < 2.7 \times 10^{-25}$$

Astrophys. J. Lett. 683, L45 (2008)

Spin frequency 29.78Hz
Distance 2kpc

It was shown directory for the first time that
the gravitational radiation is not the major source of the spin down.

Most recent LIGO 2yrs data from 2005-2007:

$$h < 2 \times 10^{-25}$$ Astrophys. J. 713, 671 (2010)

Magnetars

- Soft gamma repeaters, anomalous X-ray pulsars
  compact X-ray sources, occasional short burst (～ 0.1sec)

- Neutron stars with strong magnetic field(～10^{15}G)

- 20 such objects are known

- Possible GW source

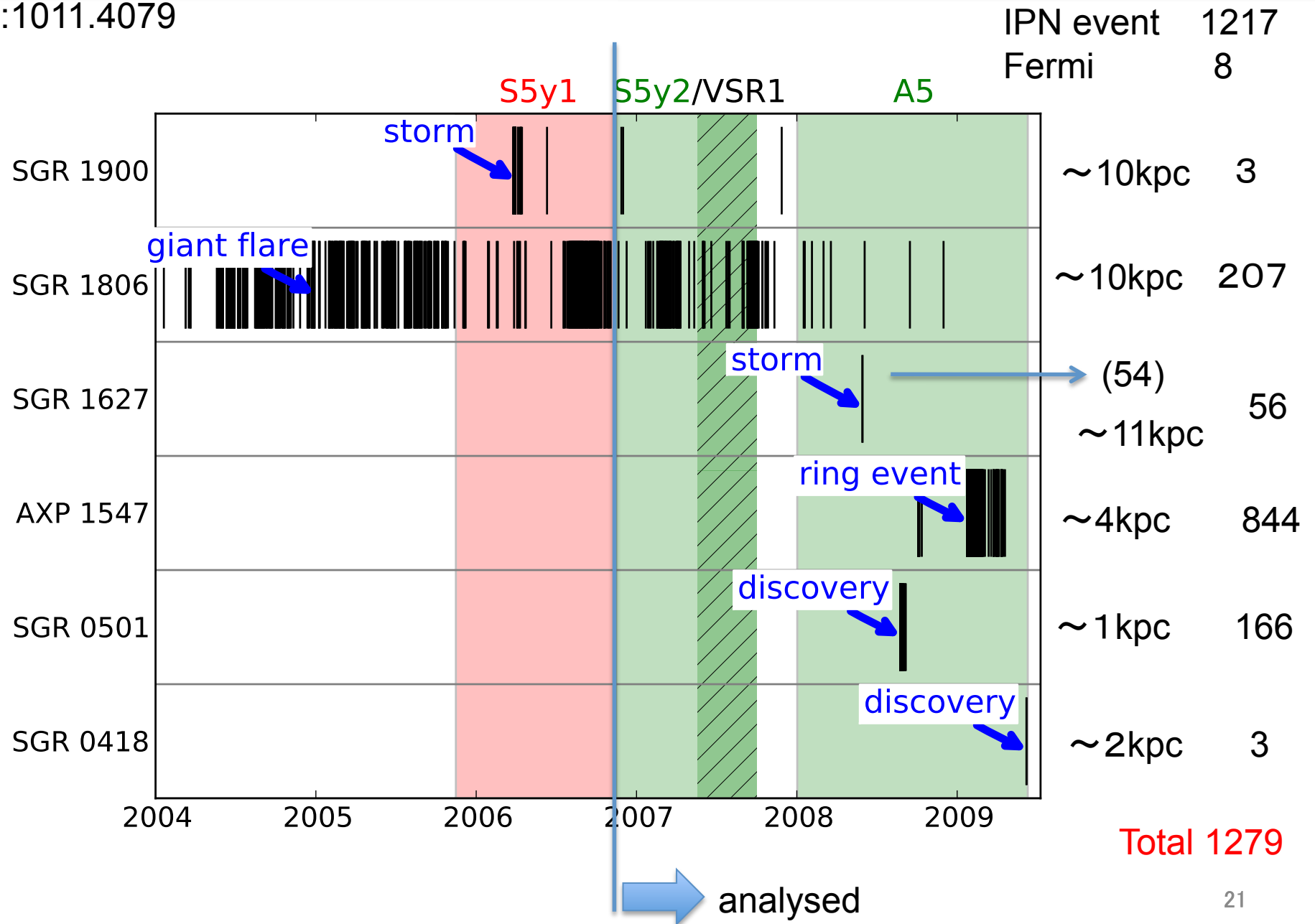Non-radial pulsation modes may be exited.

Time and direction will be inferred from X- and γ-ray.

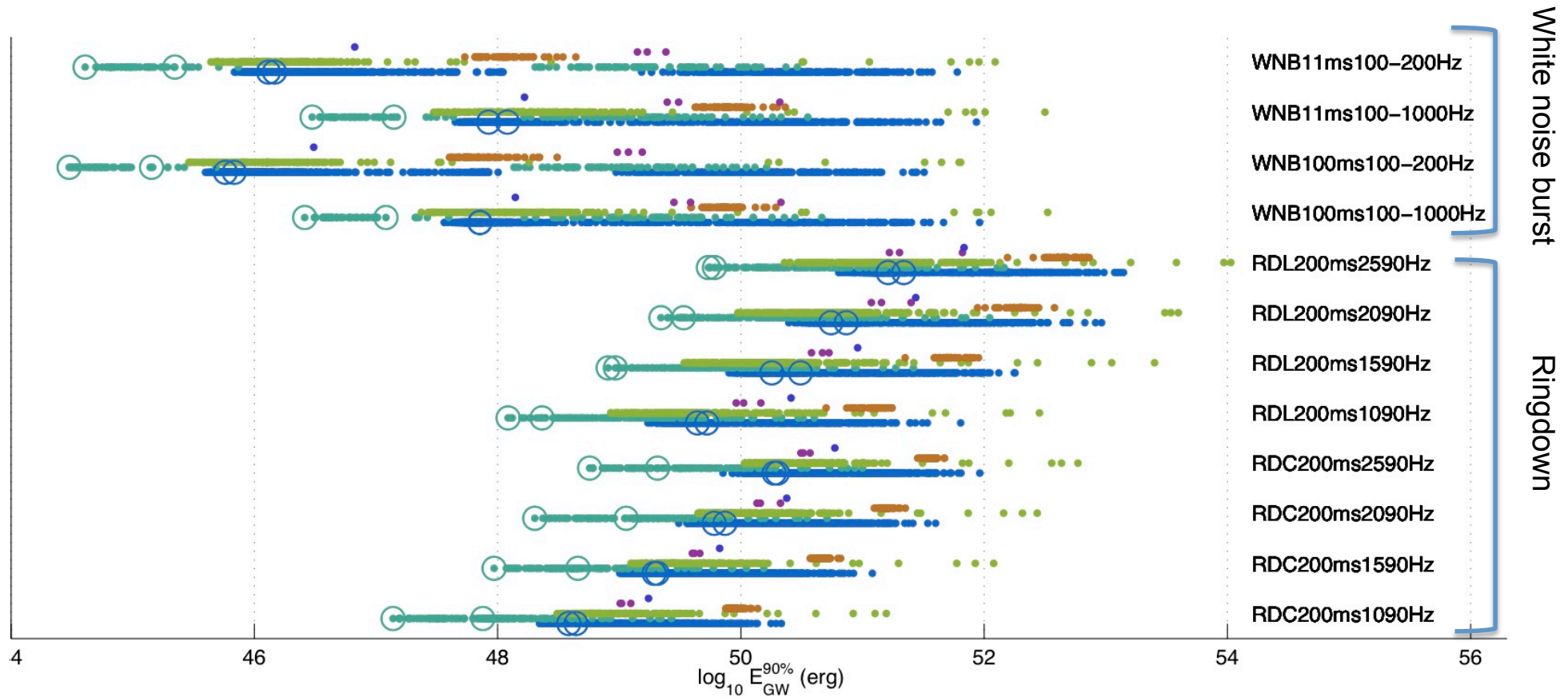They exist in our Galaxy. Much closer than CBC or SNs

LIGO analysis of magnetars

arXiv:1011.4079

IPN event 1217
Fermi 8

Total 1279

21

LIGO analysis of magnetars

arXiv:1011.4079

Upper limit to the energy radiated in GW

Each color represent a magnetar

Gravitation theory

Scalar tensor theory of gravity (including Brans-Dicke theory)

Scalar gravitational wave

• Binary NS-BH emit scalar gravitational waves.
(In NS-NS case, scalar wave emission is
suppressed due to symmetry)
However, in Brans-Dicke type theory,
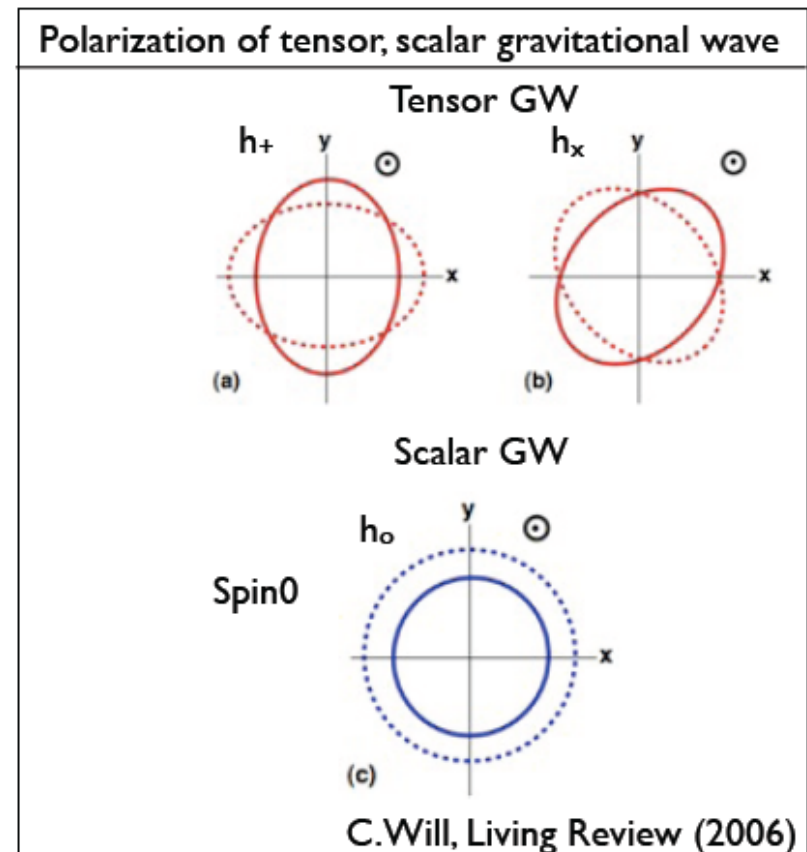the Brans-Dicke parameter, ω_{BD} , are already
constrained experimentally
(ω_{BD} >40000, Cassini satellite)

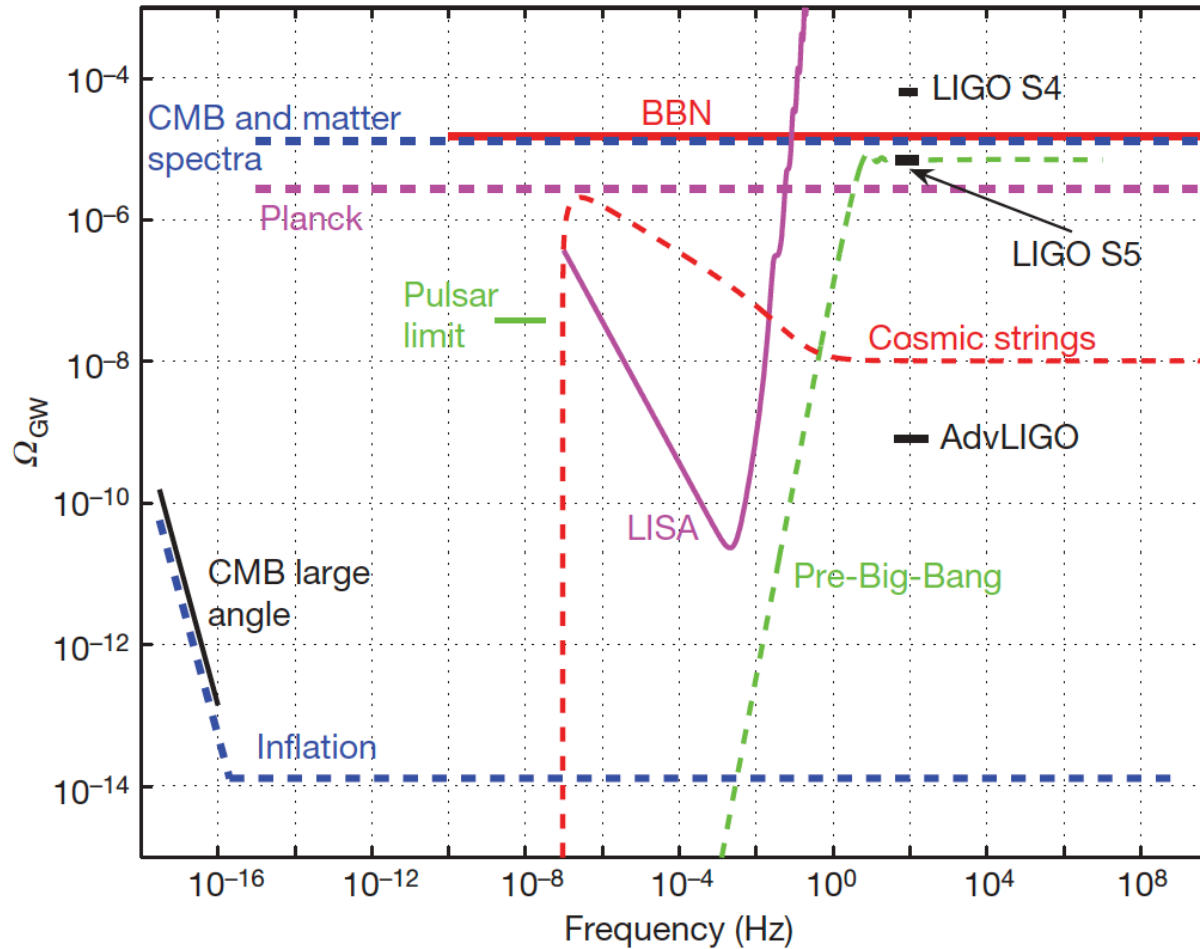It is difficult to defeat this bound by using
inspiral signal.

• Spherical core collapse of stars produce
scalar GW even if it is spherical symmetric.
Even if ω_{BD} =160,000 , we can detect scalar GW due to
Spherical core collapse occurred at 10kpc.   (Hayama, talk at GWPAW(2011))

Polarization of tensor, scalar gravitational wave

Tensor GW

h_+ $h_\times$

(a)   (b)

Scalar GW

h_o

Spin0

(c)

C.Will, Living Review (2006)

Stochastic background

LSC&Virgo, Nature 460, 990 (2009)

Summary

LCGT and advanced LIGO, advanced Virgo

will observe GW from
- CBC (NS-NS, possibly NS-BH, BH-BH) => GRB progenitor
- Stellar core collapse within several 100 kpc.

might observe GW from (at least give strong constraint to)
- continuous waves from rotating NS
- burst waves from magnetars (SGR, AXP)

may not observe stochastic background (from inflation)
but some constraint will be given.

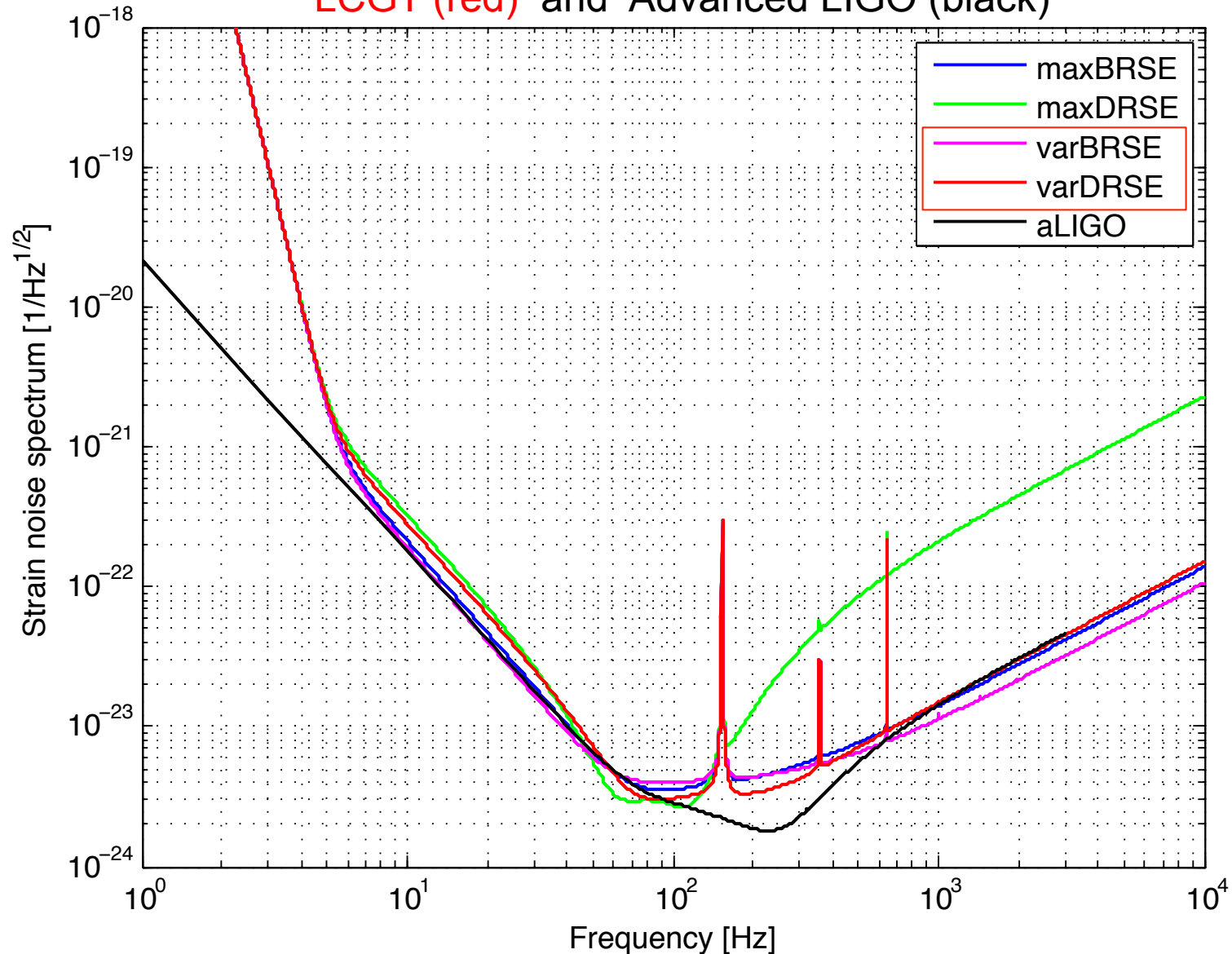may not determine the distance to the source accurately.

Multimessenger gravitational wave astronomy is essential part to perform science.
(EM wave, neutrino, cosmic ray, …)

Detectors

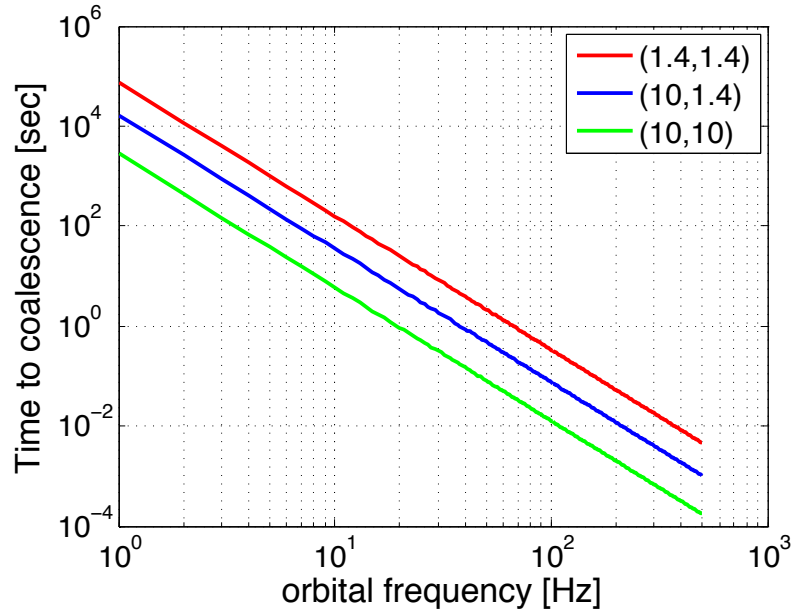Noise power spectrum・・・ assume all detectors have the same spectrum

LCGT (red) and Advanced LIGO (black)
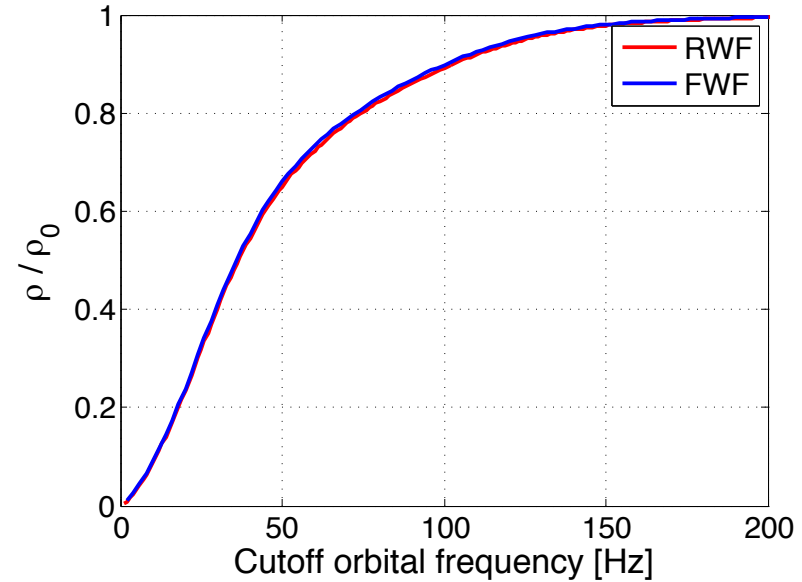

Today's results
are obtained by
Using aLIGO

合体前でのカットオフとS/N減少率

軌道周波数と合体までの時間の関係

合体までの時間と軌道周波数
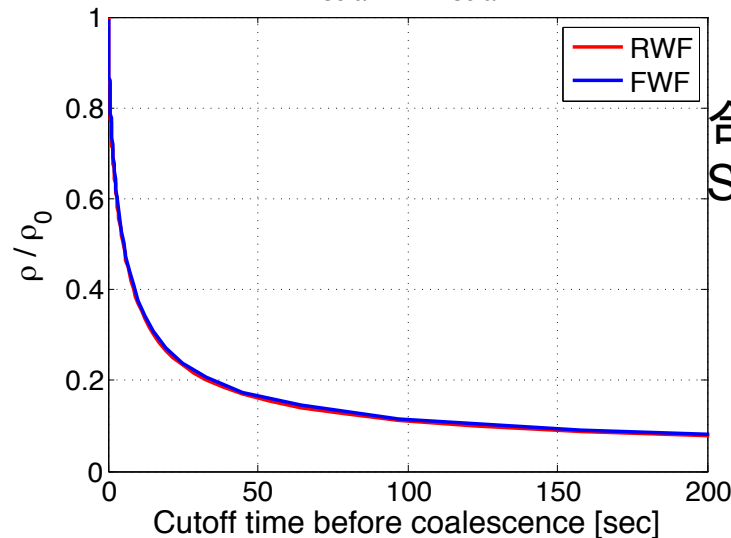
合体前	(1.4,1.4)	(10,1.4)	(10,10)
60秒	14.3Hz	8.2Hz	4.2Hz
10秒	28Hz	16Hz	8.2Hz

Cutoff周波数とS/Nの減少割合

$(1.4M_{solar}, 1.4M_{solar})$ case

$(1.4M_{solar}, 1.4M_{solar})$ case

合体前打ち切り時間と
S/Nの減少率

合体前でのカットオフとS/N減少率

合体までの時間と軌道周波数，S/N減少率の関係

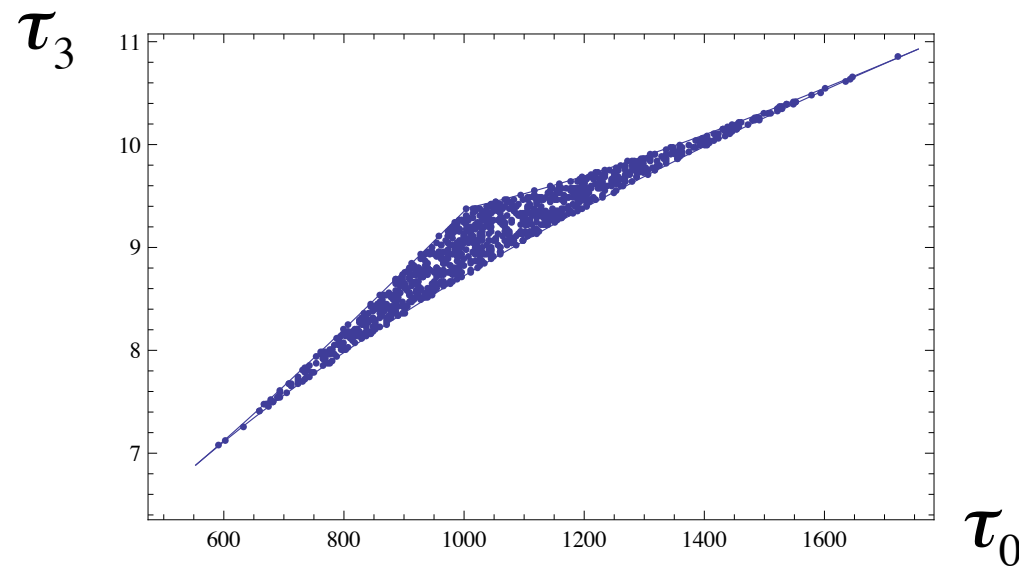| 合体前	60秒	30秒	10秒	5秒	1秒
軌道周波数	14.4Hz	18.6Hz	28.1Hz	36.5Hz	66.7Hz
ρ/ρ_0	0.15	0.21	0.37	0.50	0.76

ρ_0: ISCOまで積分する場合のS/N

ISCOでの周波数: ～1570Hz

テンプレート数、CPUパワー

aLIGO ノイズスペクトラム

m$_1$, m$_2$	1-40Msolar	1-2Msolar	1.3-1.5Msolar
テンプレート数	1.1×10^5	4800	36
CPU power	28Gflops	1.2Gflops	8.8Mflops

パラメータ推定誤差

Maximum likelihood 法による重力波信号検出を想定する.
それによるパラメータ推定誤差をフィッシャー行列により評価する.
複数の検出器のときは、検出器間のノイズに相関がなければ、
検出器ネットワークのFisher行列は、各検出器のFisher行列の和になる.

$$\Gamma_{ij} = \sum_{I=1}^{N} \Gamma_{ij}^{(I)} \qquad \Gamma_{ij}^{(I)} = 2\int_0^\infty \frac{\partial_i \tilde{h}^I(f)\partial_j \tilde{h}^{I*}(f)}{S_h(f)} df$$

誤差 $\quad \delta\mu^i = \hat{\mu}^i - \mu_{\text{true}}^i \quad$ の分布

$$p(\delta\mu^i) = Ne^{-\frac{1}{2}\Gamma_{ij}\delta\mu^i\delta\mu^j}$$

パラメータ推定誤差

Parameter estimation errors (LVK 3 detectors' case, RWF)

fcutoff	Time to coalesce [sec]	ln(r)	ln(Mc)	ln(eta)	tc[msec]	theta [min]	phi[min]	Omega [sr]	minor axis [min]	Major axis [min]
ISCO	---	0.48	2.9×10^{-5}	5.7×10^{-3}	0.32	34	94	5.6×10^{-4}	22	187
400Hz	0.53	0.50	3.1×10^{-5}	6.9×10^{-3}	0.44	37	103	6.8×10^{-4}	25	207
200Hz	0.34	0.63	3.5×10^{-5}	1.0×10^{-2}	0.99	66	171	1.9×10^{-3}	41	343
100Hz	2.15	1.1	4.7×10^{-5}	2.2×10^{-2}	3.9	187	437	1.2×10^{-2}	102	877
50Hz	13.7	2.7	7.6×10^{-5}	6.5×10^{-2}	24.5	805	1623	1.8×10^{-1}	6.9度	54度
30Hz	53	6.2	1.3×10^{-4}	2.0×10^{-1}	128	2841	4813	1.9	25度	161度
20Hz	157	12.3	2.4×10^{-4}	6.0×10^{-1}	575	124度	177度	12.3	72度	357度

$$= 2 f_{orbit}^{cut}$$