

---

# 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

Astrophys. J. 681, 1419 (2008)

GRB070201: Short gamma ray burst (SGRB)

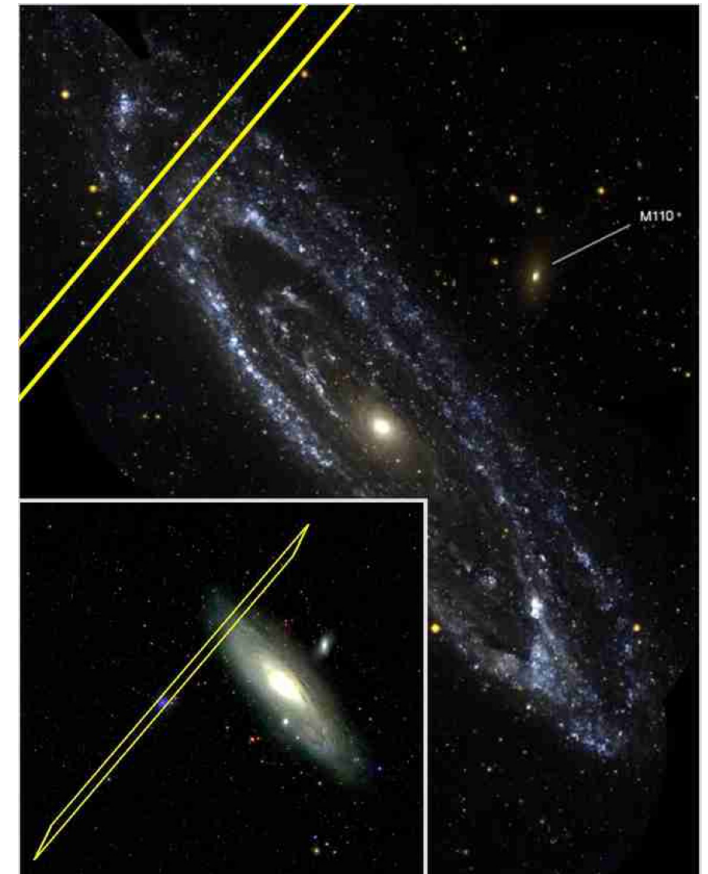
Direction: M31 (Andromeda nebula, 770kpc)

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

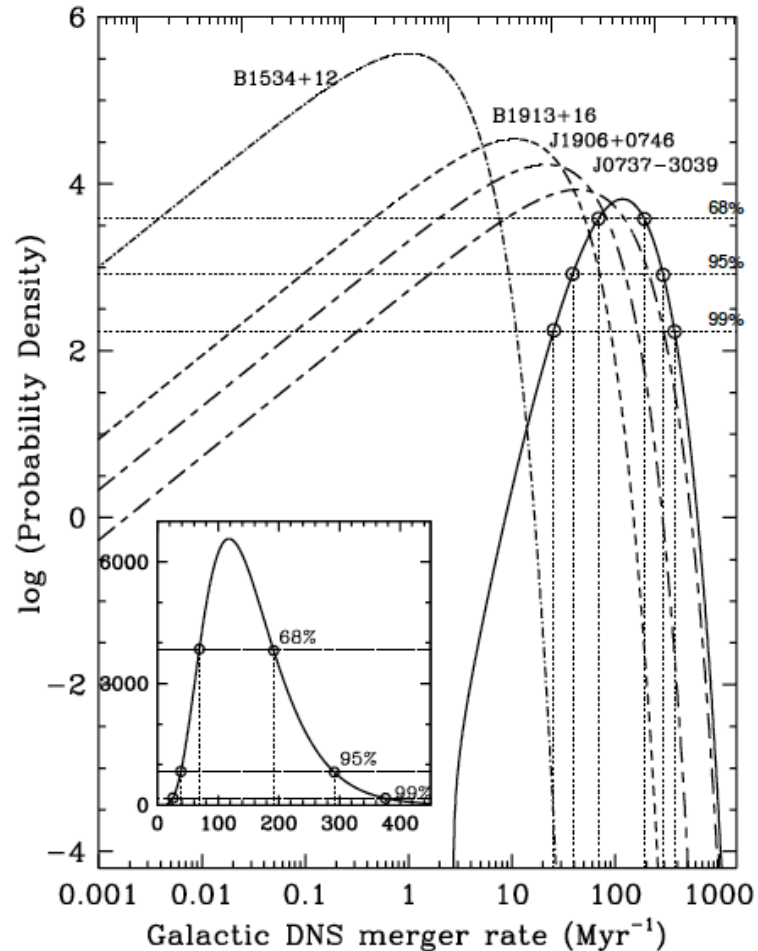
# NS-NS merger rate

There are about 10 known and likely neutron star binaries.

6 neutron star binaries have life time is shorter than the age of the universe

PSR name	$P_s$ (ms)	$P_b$ (hr)	e	$\tau_{\text{life}}$ (Gyr)	(Lorimer, LRR, 11, (2008), 8)
B1913+16 <sup>a</sup>	59.03	7.75	0.617	0.37	
B1534+12 <sup>a</sup>	37.90	10.10	0.274	2.93	
J0737-3039A <sup>a</sup>	22.70	2.45	0.088	0.23	Double pulsar
J1756-2251 <sup>a</sup>	28.46	7.67	0.181	2.03	
J1906+0746 <sup>b</sup>	144.14	3.98	0.085	0.082	Most recently discovered (2006)
J2127+11C <sup>bcd</sup>	32.76	8.047	0.681	0.32	

# NS-NS merger rate



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

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

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

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

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



# Parameter estimation accuracy

---

Parameter estimation accuracy is the 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

$$(\ln(r), \ln(M_c), \delta \text{ or } \ln(\eta), t_c f_0, \phi_c, \underbrace{\theta_s, \phi_s}_{\text{Direction to the source}}, \psi, \epsilon)$$

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

Direction  
to the source

Polarization  
angle  
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

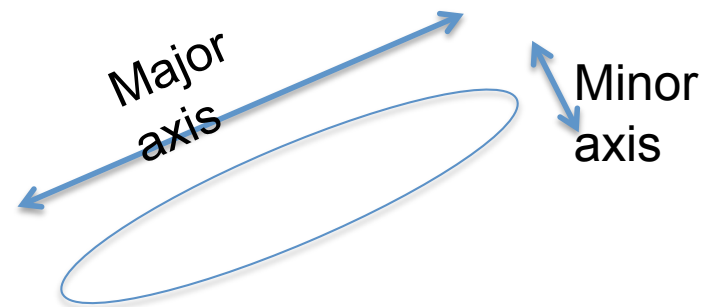
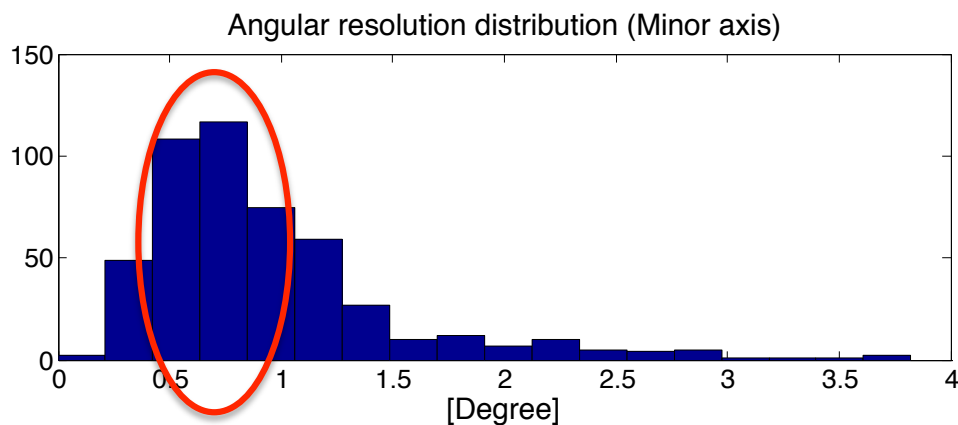
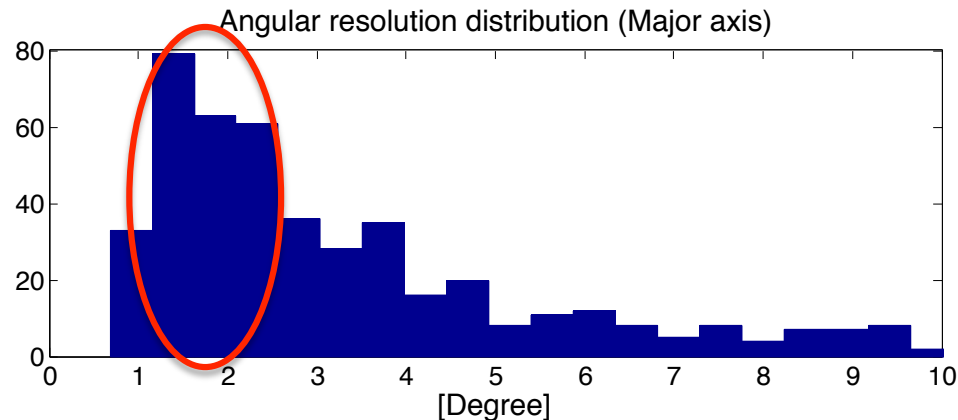
Advanced LIGO noise spectrum

LIGO-L1, VIRGO, LCGT (3 detectors)

Average S/N ( $\rho$ ) 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.



Error ellipse

Direction, inclination, polarization are given randomly

# 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[deg]	Omega [sr]	minor axis [min]	Major axis [min]
FWF	LHVK	0.49	$3.7 \times 10^{-5}$	0.34	0.17	35	80	$4.9 \times 10^{-4}$	23	160
	LVK	0.50	$4.4 \times 10^{-5}$	0.41	0.20	36	100	$6.4 \times 10^{-4}$	24	200

		ln(r)	ln(Mc)	ln(eta)	tc[msec]	theta [min]	phi[deg]	Omega [sr]	minor axis [min]	Major axis [min]
RWF	LHVK	0.46	$9.0 \times 10^{-5}$	$8.9 \times 10^{-3}$	0.35	33	75	$4.3 \times 10^{-4}$	22	150
	LVK	0.48	$1.1 \times 10^{-4}$	$1.1 \times 10^{-2}$	0.42	33	94	$5.6 \times 10^{-4}$	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 have to wait for more sensitive detectors like Einstein telescope 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.

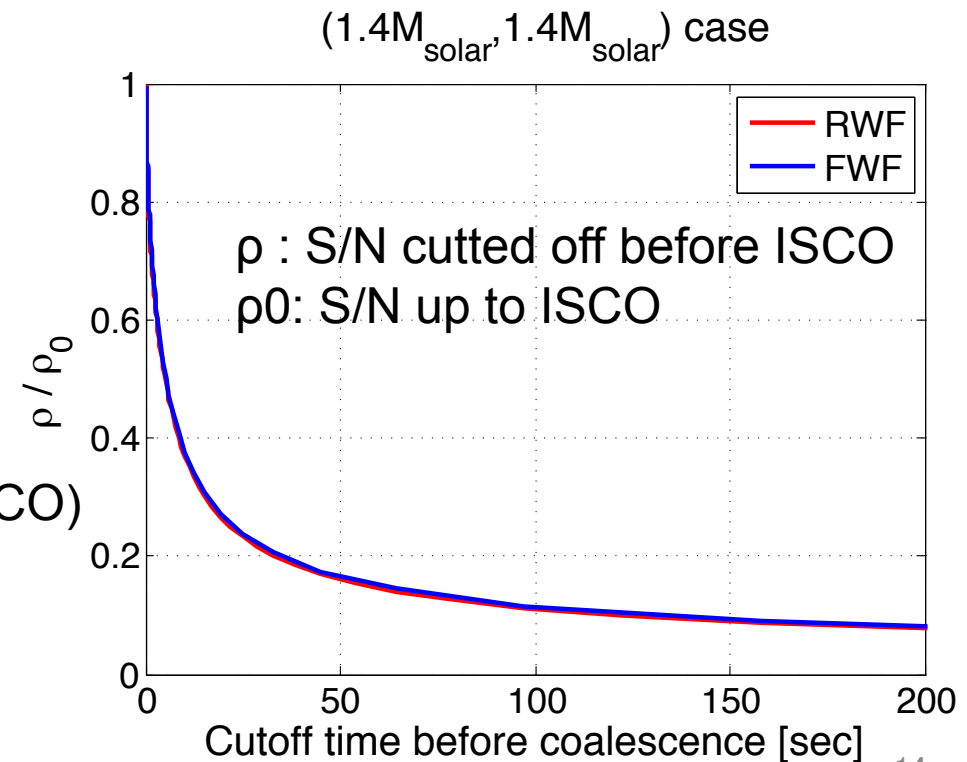
Parameter estimation accuracy become very bad.

(1.4, 1.4) Msolar, @200Mpc

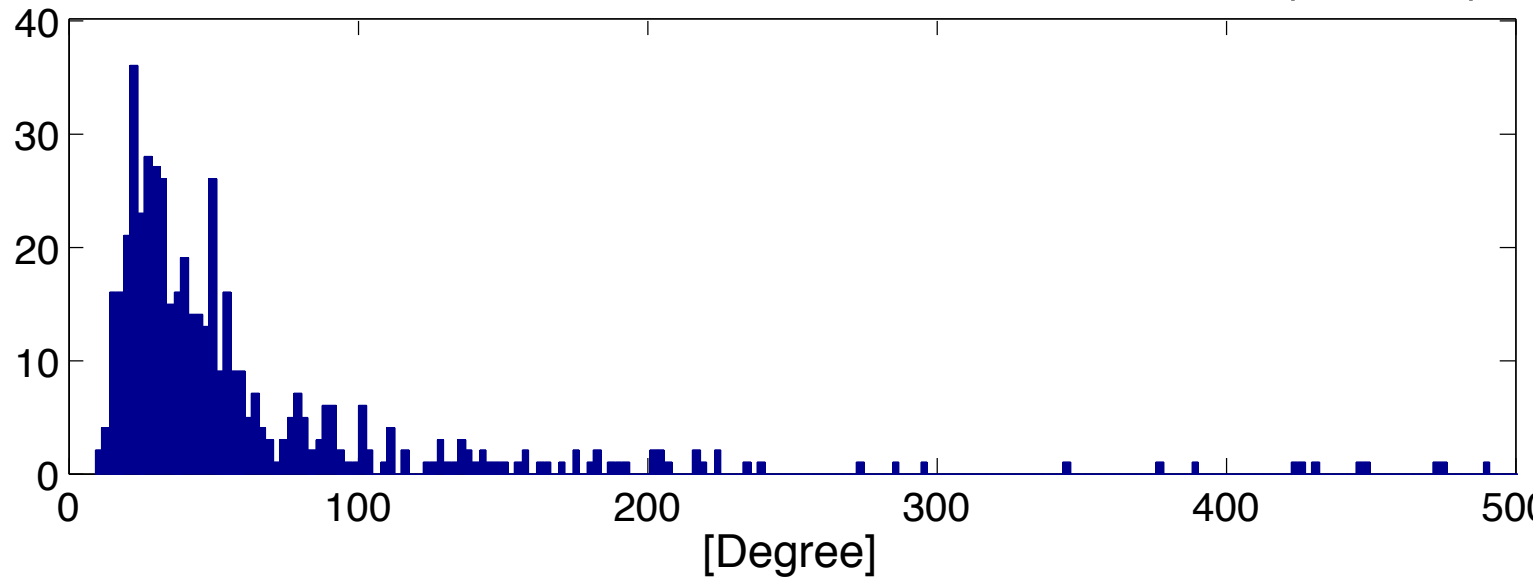
Cutoff frequency : 50Hz (13 sec before ISCO)



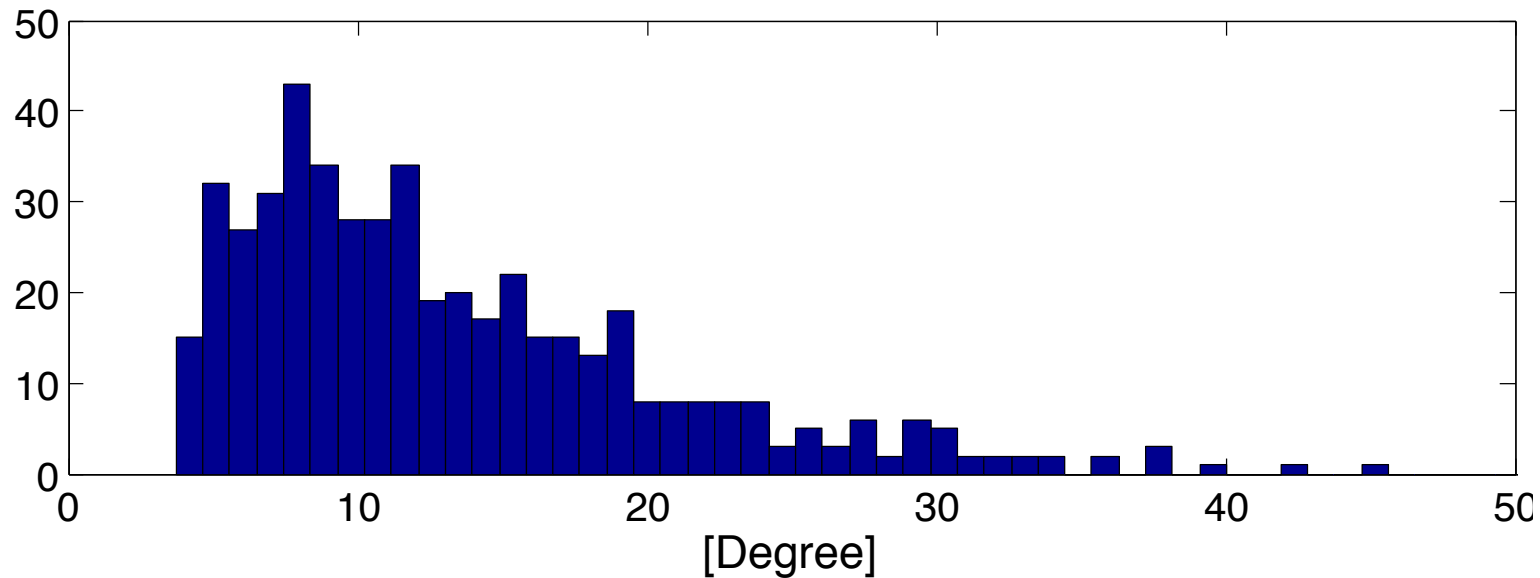
Angular resolution : several 10 degree.



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



Angular resolution distribution (Minor axis)

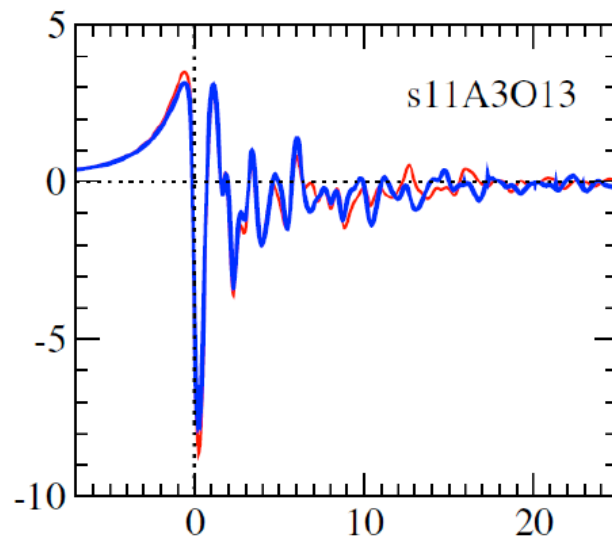


# Supernova (Gravitational Collapse)

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

Various possible gravitational wave emission mechanism.

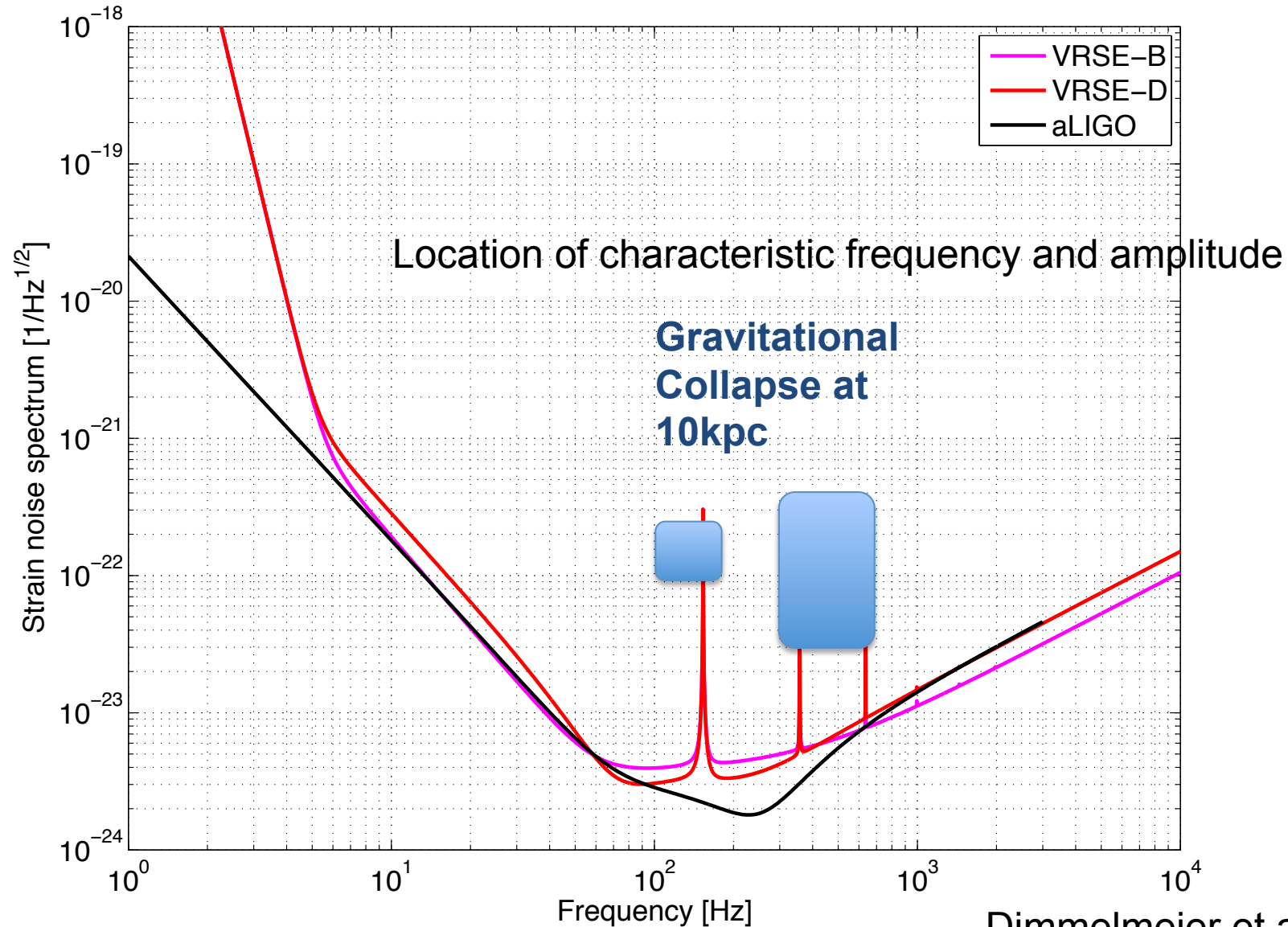
- Core collapse and bounce
  - Rotational non-axisymmetric instabilities of proto-neutron star
  - Post-bounce convection
  - Non-radial pulsations of proto-neutron star
  - Anisotropic neutrino emission
- etc.
- } Related to the explosion mechanism



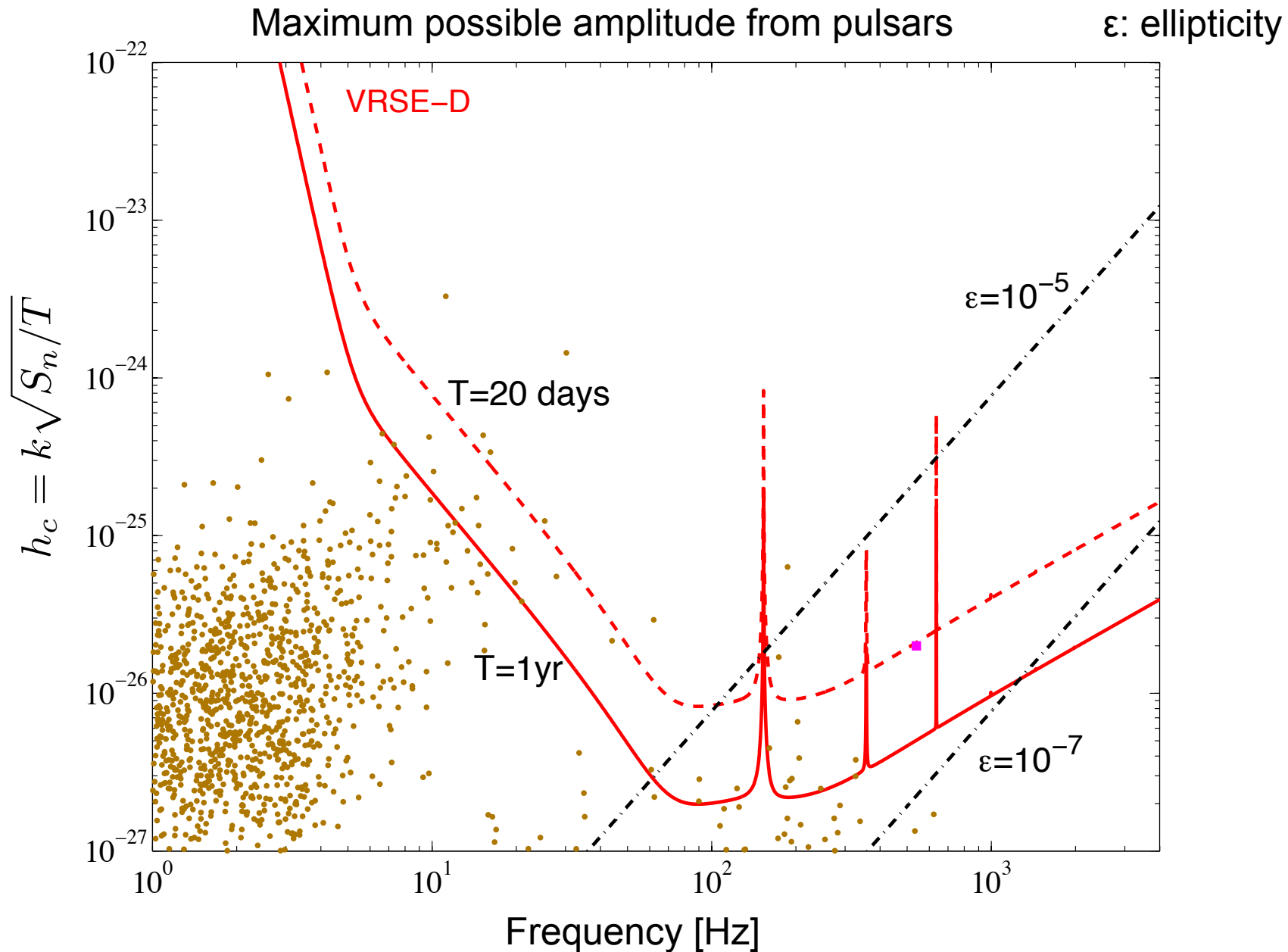
Collapse and bounce wave form from  
Dimmelmeier et al. 2008 [PRD 78, 064056]



# Gravitational Collapse



# Continuous wave (rotating NS)



# LIGO -Crab pulsar-

Neutron star in Crab nebula  
Borne in 1054 by supernova

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)

It was shown directly 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:

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

Crab nebula



Spin frequency 29.78Hz  
Distance 2kpc

# Magnetars

---

- Soft gamma repeaters, anomalous X-ray pulsars  
compact X-ray sources, occasional short burst ( $\sim 0.1\text{sec}$ )
- Neutron stars with strong magnetic field ( $\sim 10^{15}\text{G}$ )
- 20 such objects are known
- Possible GW source

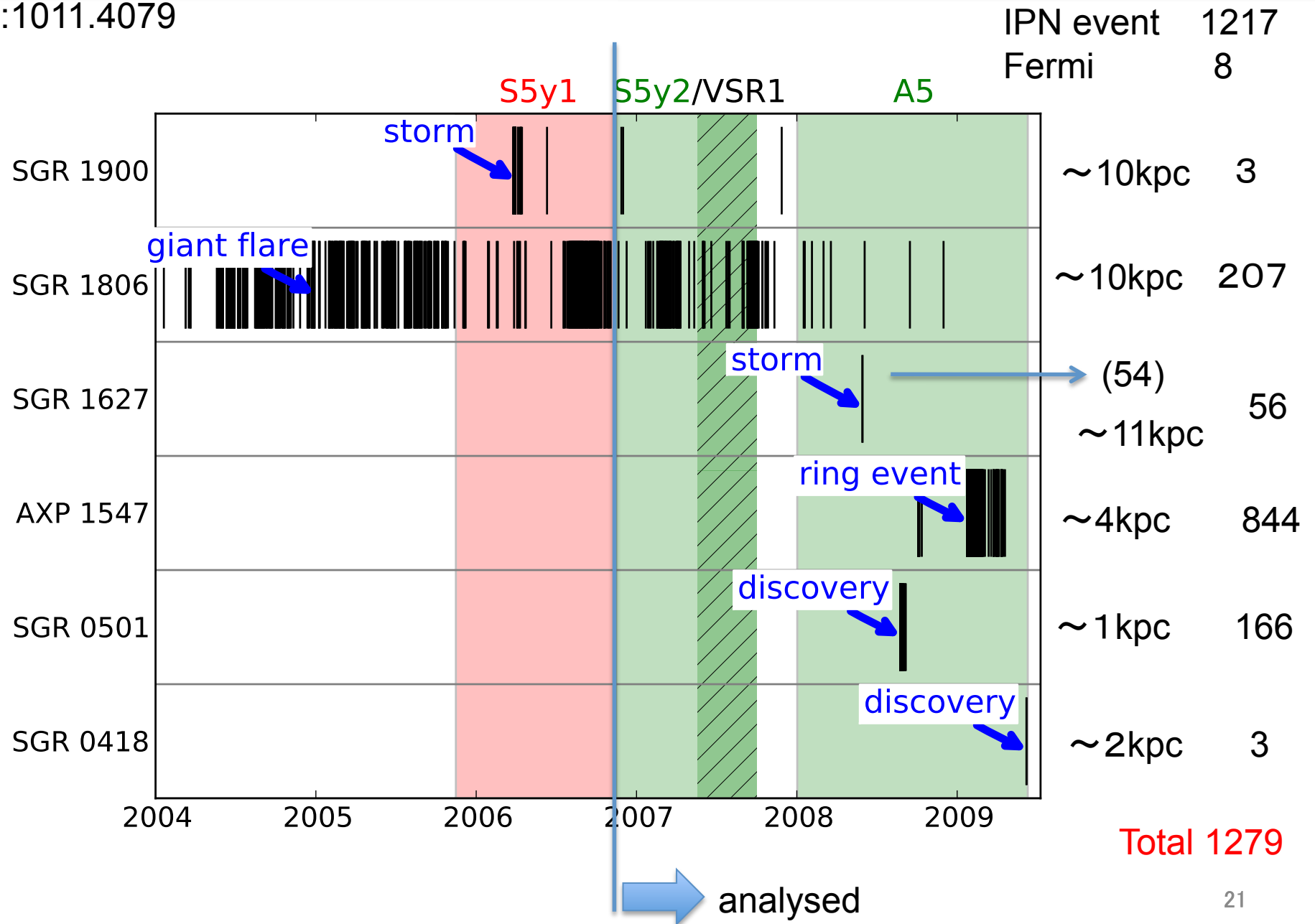
Non-radial pulsation modes may be excited.

Time and direction will be inferred from X- and  $\gamma$ -ray.

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

# LIGO analysis of magnetars

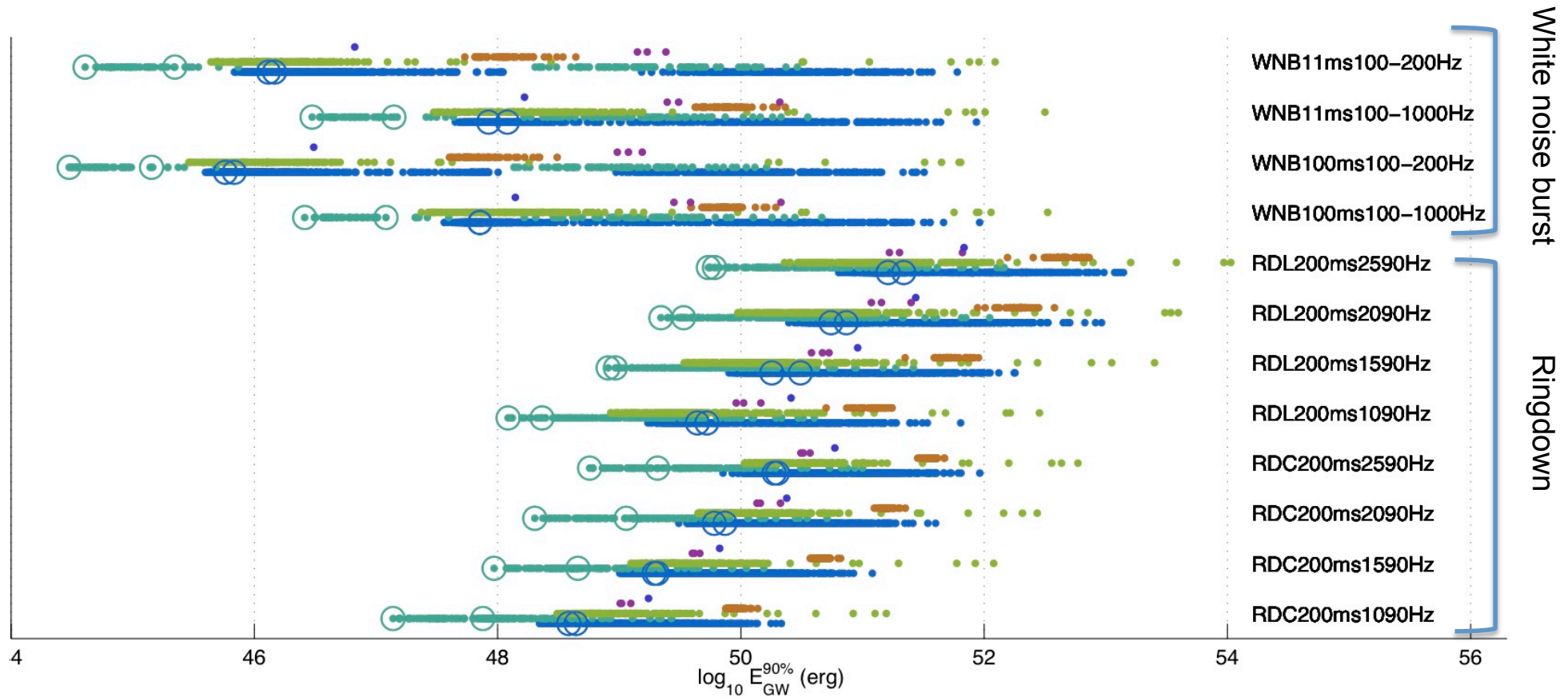
arXiv:1011.4079



# 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,  $\omega_{BD}$ , are already constrained experimentally

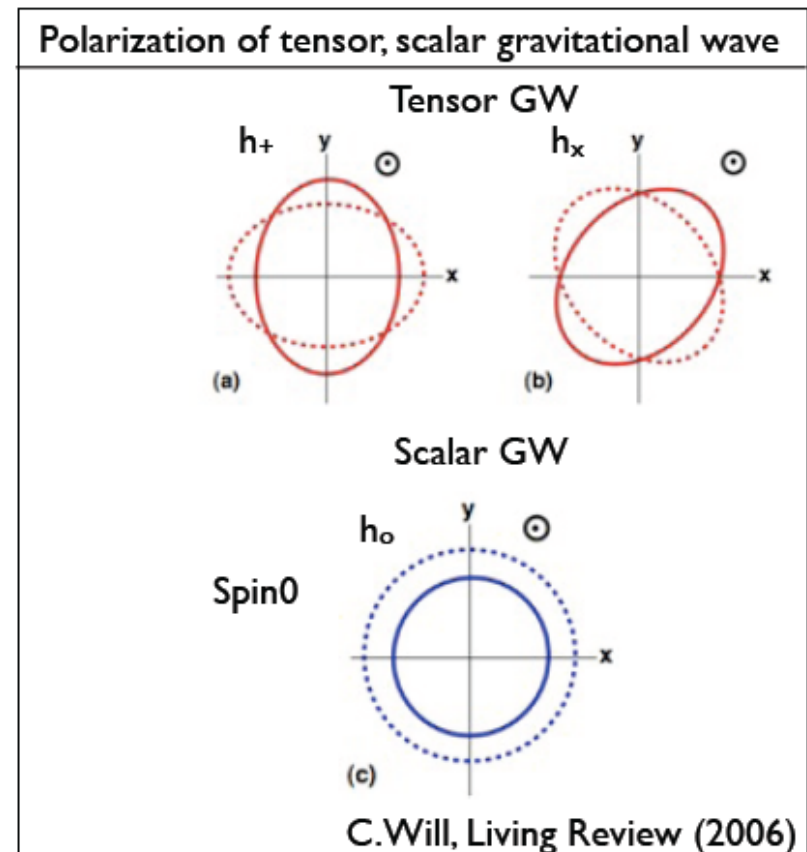
( $\omega_{BD} > 40000$ , Cassini satellite)

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

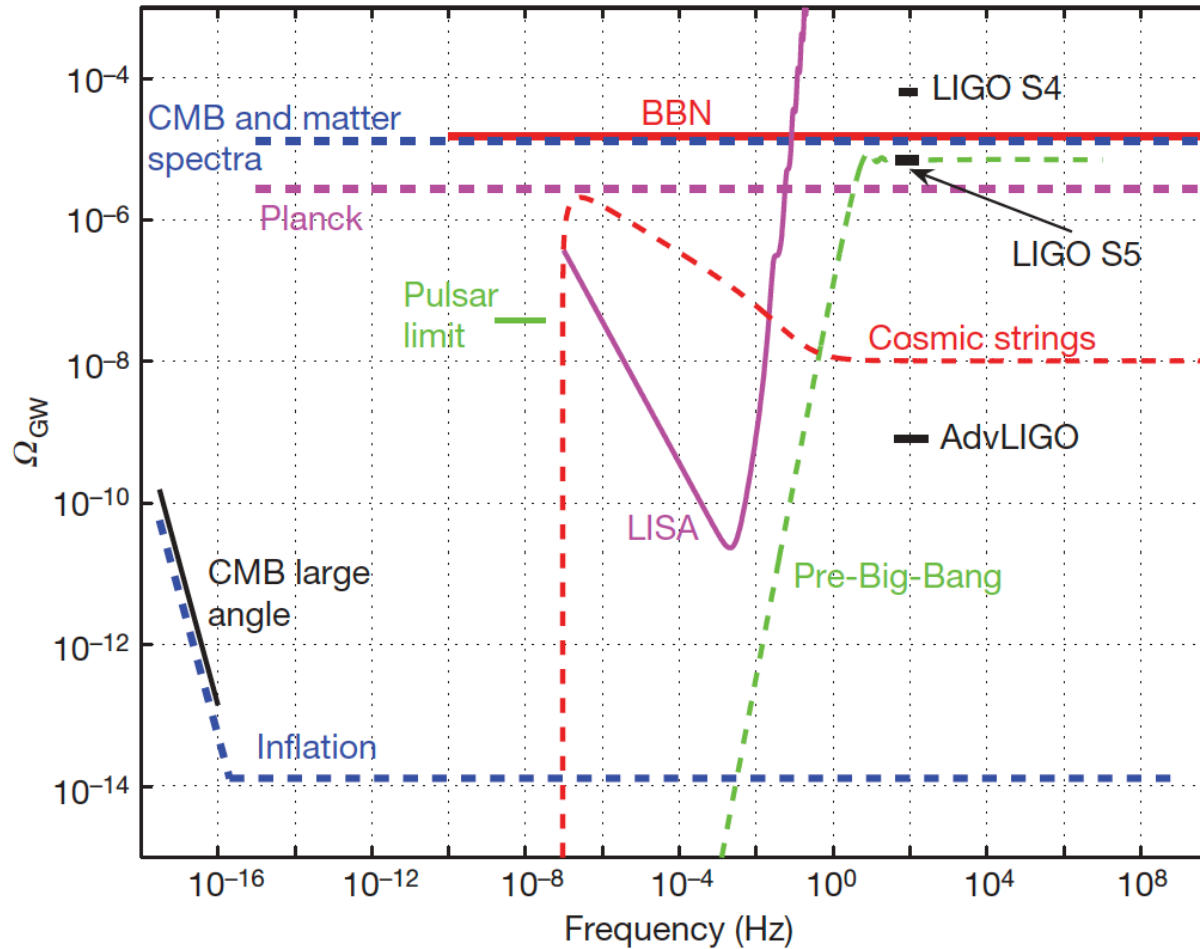
- Spherical core collapse of stars produce scalar GW even if it is spherical symmetric.

If  $\omega_{BD} = 160,000$ , we can detect scalar GW due to

Spherical core collapse occurred at 10kpc. (Hayama, talk at GWPAW(2011))



# 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 are given.

may not be determine the distance to the source accurately.

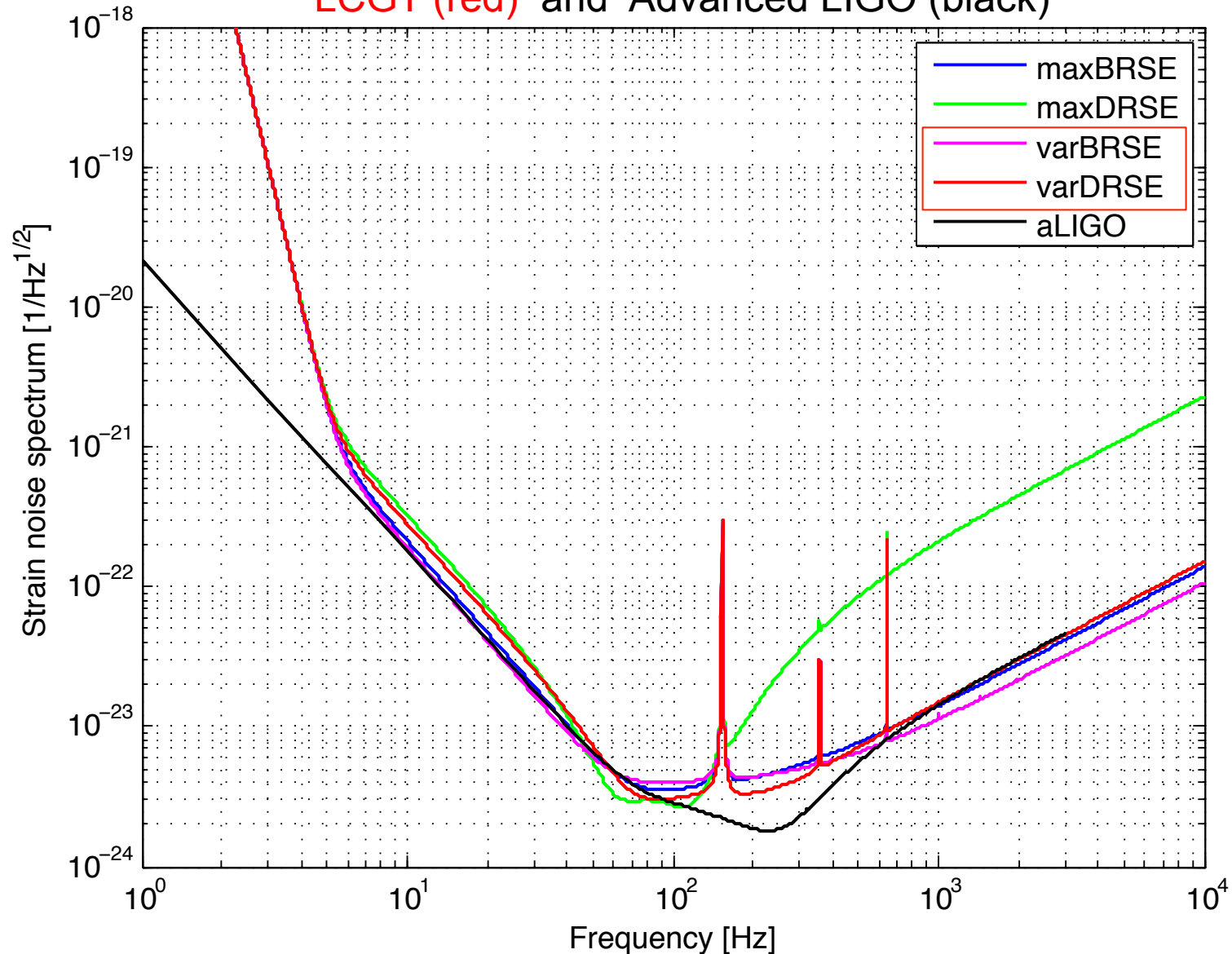
Multimessenger gravitational wave astronomy is essential part to perform science.  
(EM wave, neutrino, cosmic ray, ...)



# Detectors

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

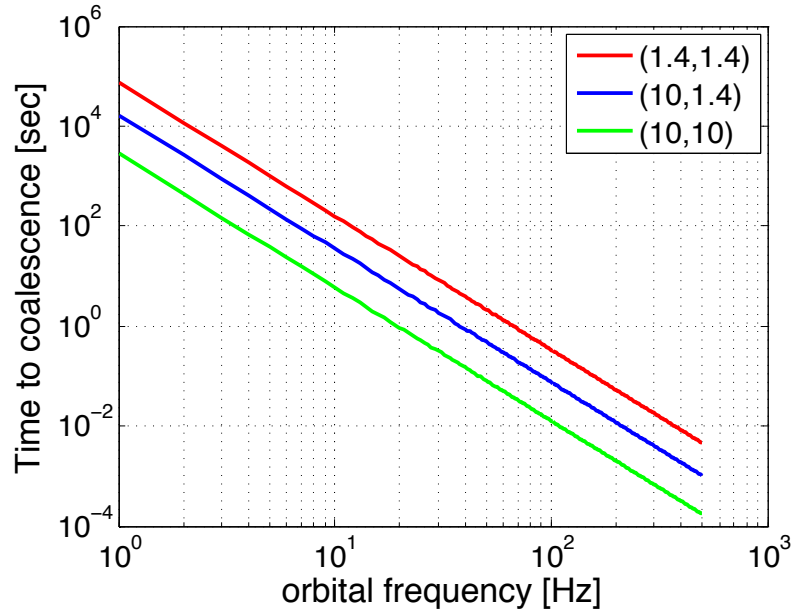
LCGT (red) and Advanced LIGO (black)



Today's results  
are obtained by  
Using aLIGO

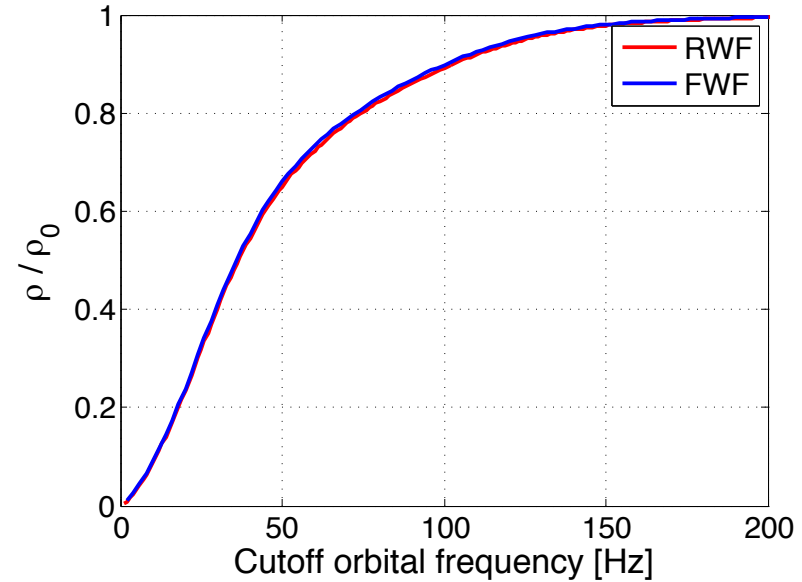
# 合体前でのカットオフとS/N減少率

軌道周波数と合体までの時間の関係



Cutoff周波数とS/Nの減少割合

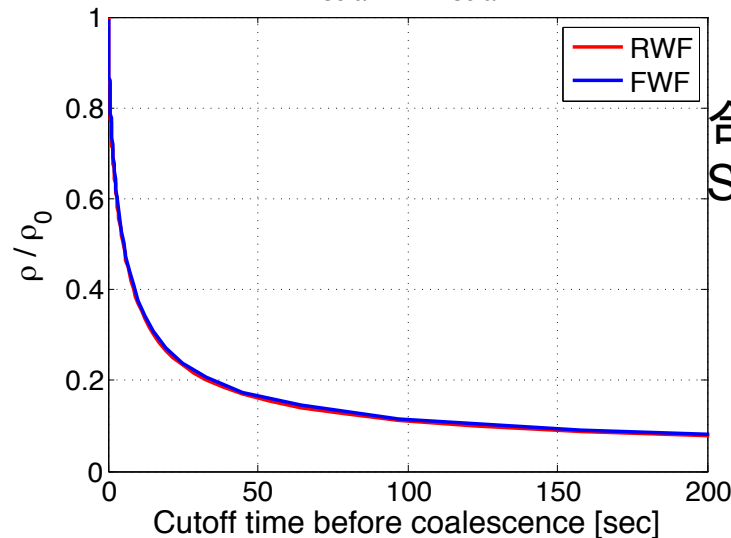
( $1.4M_{\text{solar}}, 1.4M_{\text{solar}}$ ) case



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

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

(1.4,1.4)Msolarの場合

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
$\rho/\rho_0$	0.15	0.21	0.37	0.50	0.76

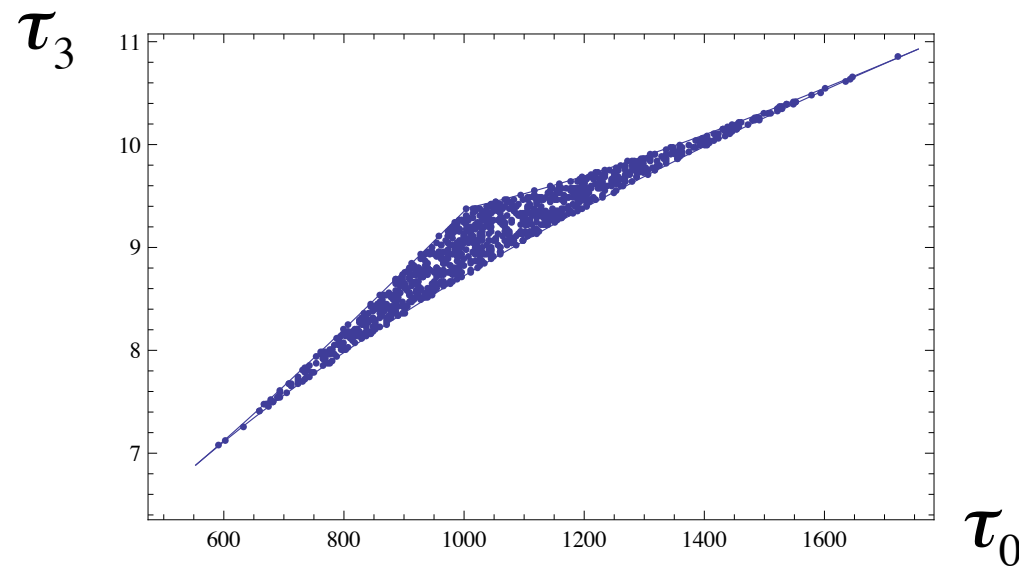
$\rho_0$ : ISCOまで積分する場合のS/N

ISCOでの周波数:  $\sim 1570\text{Hz}$

# 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	$1.1 \times 10^5$	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。

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

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

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

# 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	$2.9 \times 10^{-5}$	$5.7 \times 10^{-3}$	0.32	34	94	$5.6 \times 10^{-4}$	22	187
400Hz	0.53	0.50	$3.1 \times 10^{-5}$	$6.9 \times 10^{-3}$	0.44	37	103	$6.8 \times 10^{-4}$	25	207
200Hz	0.34	0.63	$3.5 \times 10^{-5}$	$1.0 \times 10^{-2}$	0.99	66	171	$1.9 \times 10^{-3}$	41	343
100Hz	2.15	1.1	$4.7 \times 10^{-5}$	$2.2 \times 10^{-2}$	3.9	187	437	$1.2 \times 10^{-2}$	102	877
50Hz	13.7	2.7	$7.6 \times 10^{-5}$	$6.5 \times 10^{-2}$	24.5	805	1623	$1.8 \times 10^{-1}$	6.9度	54度
30Hz	53	6.2	$1.3 \times 10^{-4}$	$2.0 \times 10^{-1}$	128	2841	4813	1.9	25度	161度
20Hz	157	12.3	$2.4 \times 10^{-4}$	$6.0 \times 10^{-1}$	575	124度	177度	12.3	72度	357度

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