Science by LCGT

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2011/02/04 LCGT f2f meeting

Contents

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

- Gravitational Collapse

- Pulsar

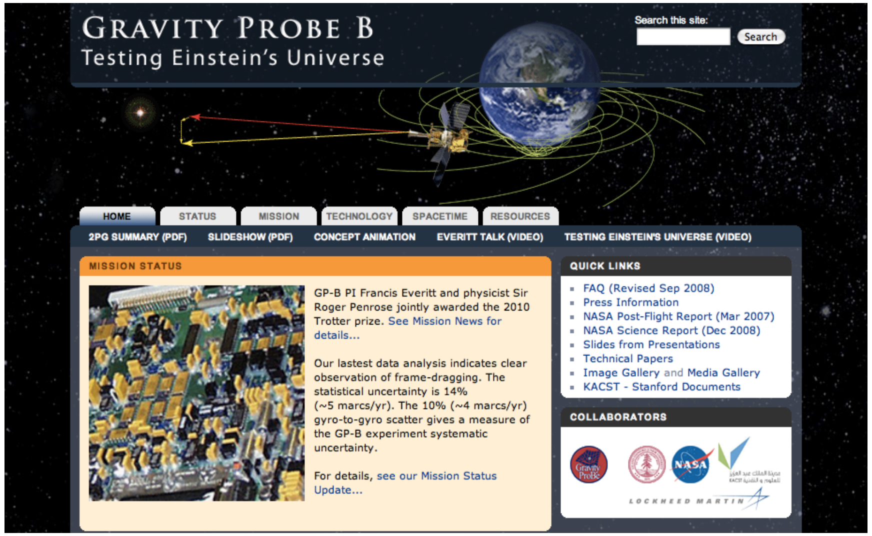
- Stochastic background

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



GP-B PI Francis Everitt and physicist Sir Roger Penrose jointly awarded the 2010 Trotter prize. See Mission News for details...

Our lastest data analysis indicates clear observation of frame-dragging. The statistical uncertainty is 14% (~5 marcs/yr). The 10% (~4 marcs/yr) gyro-to-gyro scatter gives a measure of the GP-B experiment systematic uncertainty.

For details, see our Mission Status Update...

- FAQ (Revised Sep 2008)
- Press Information
- NASA Post-Flight Report (Mar 2007)
- NASA Science Report (Dec 2008)
- Slides from Presentations
- Technical Papers
- Image Gallery and Media Gallery
- KACST - Stanford Documents

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

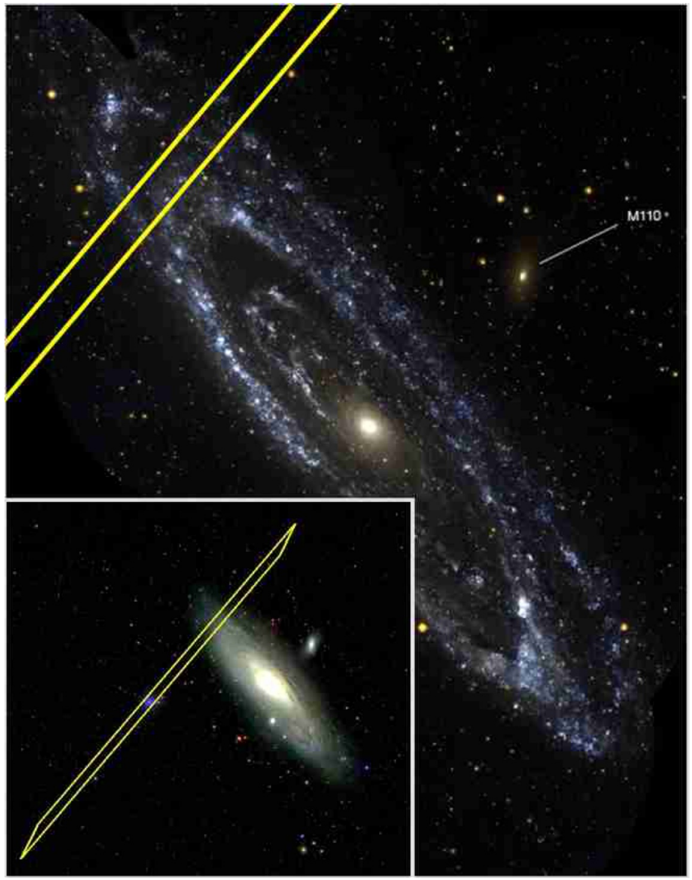
Astrophys. J. 681, 1419 (2008)

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

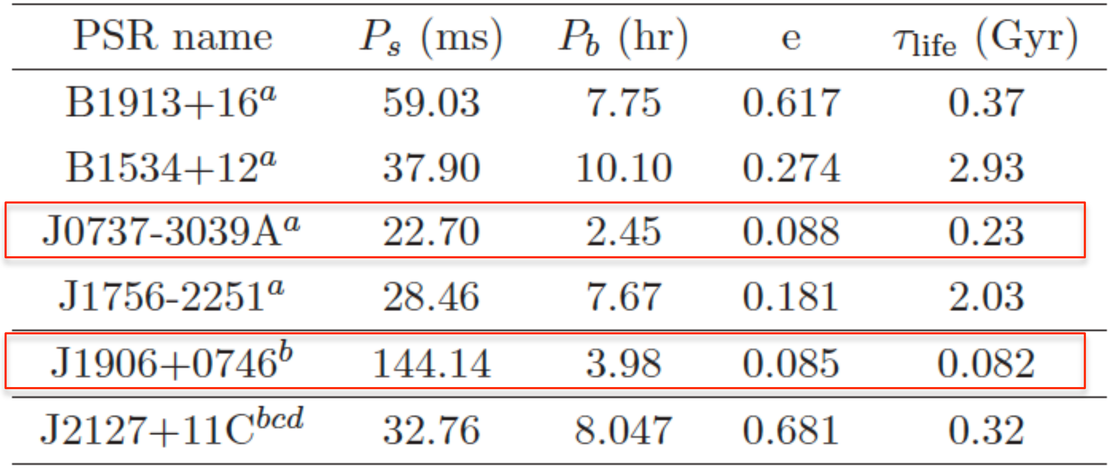
Thus, it is not the binary merger event
occurred in M31 (at 99% C.L.)



Compact binary coalescence

NS-NS merger rate

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



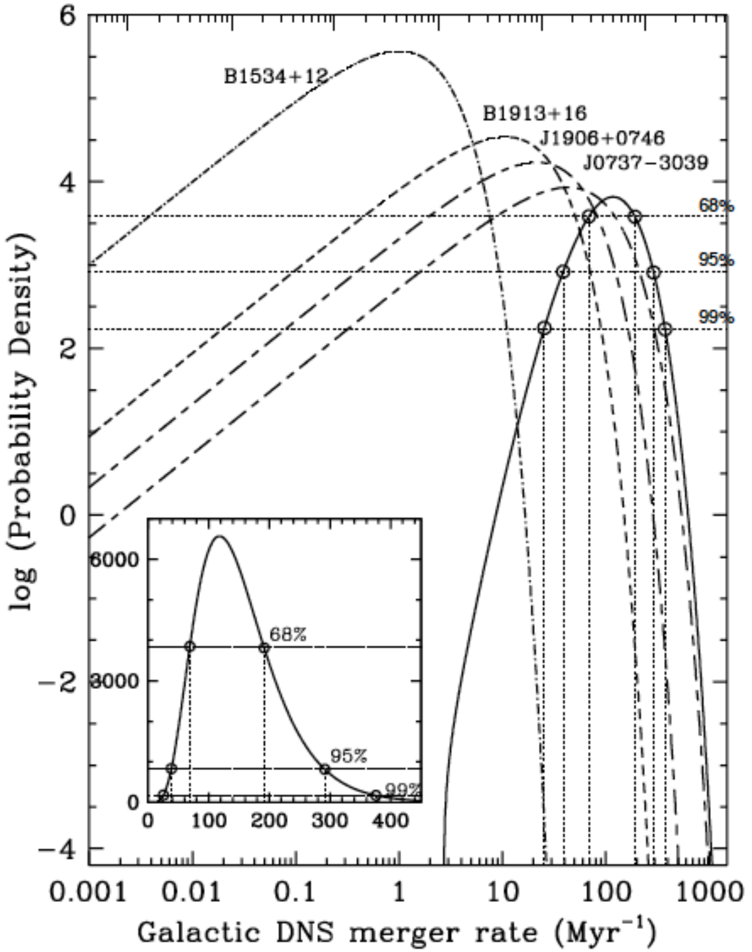
PSR name	P_s (ms)	P_b (hr)	e	$\tau_{\rm life}$ (Gyr)
B1913+16[a]	59.03	7.75	0.617	0.37
B1534+12[a]	37.90	10.10	0.274	2.93
J0737-3039A[a]	22.70	2.45	0.088	0.23
J1756-2251[a]	28.46	7.67	0.181	2.03
J1906+0746[b]	144.14	3.98	0.085	0.082
J2127+11C[bcd]	32.76	8.047	0.681	0.32

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

Double pulsar

Most recently discovered (2006)

NS-NS merger rate



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

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

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

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

However, systematic errors which are not included in this evaluation 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

$$\left(\ln(r), \ln(M_c), \delta \text{ or } \ln(\eta), t_c f_0, \phi_c, \underbrace{\theta_s, \phi_s}_{\text{Direction to the source}}, \overset{\text{Polarization angle}}{\psi}, \underset{\text{Inclination angle}}{\epsilon}\right)$$

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

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

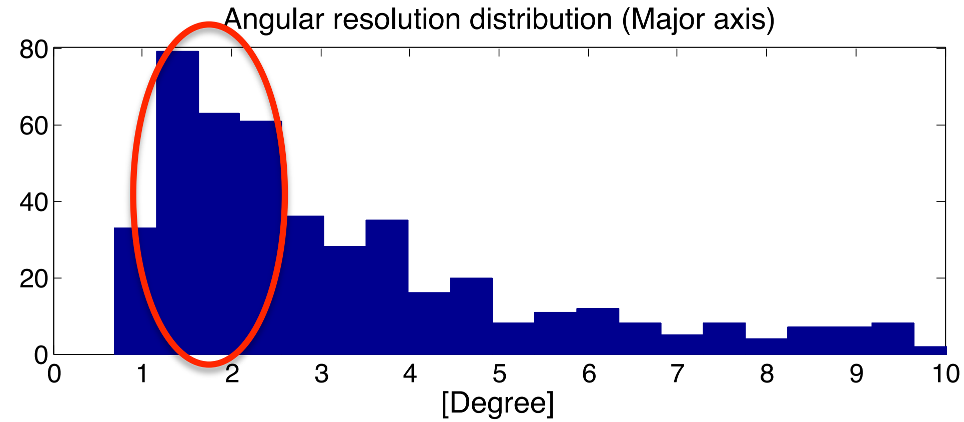
Advanced LIGO noise spectrum

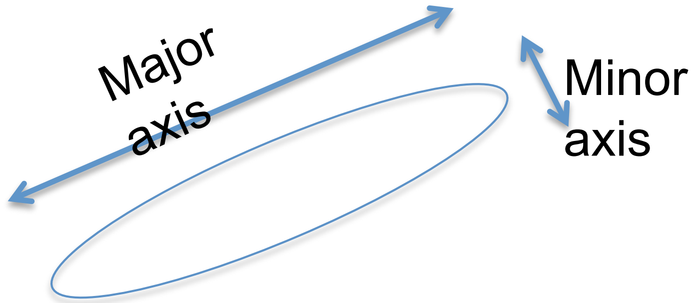
LIGO-L1, VIRGO, LCGT (3 detectors)

Average S/N (ρ) 8.2-8.9 (at each detector)

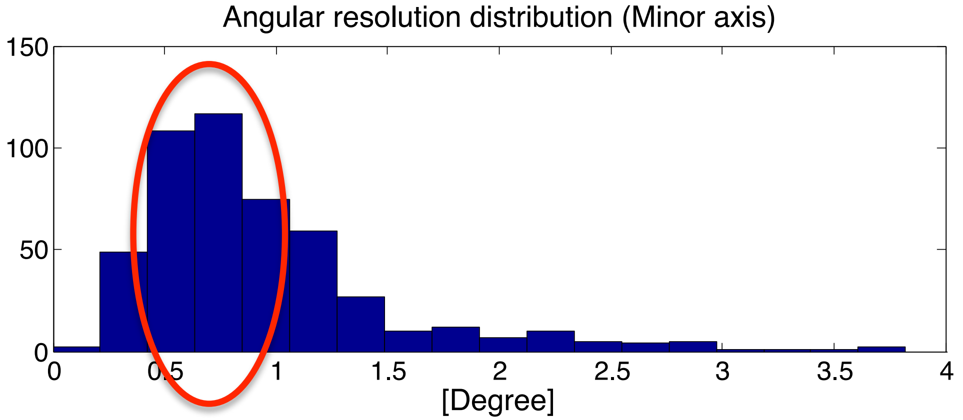
Average resolution: major axis 7.6 deg., minor axis 0.99 deg.

Typical value: major axis 1-2 deg., minor axis 0.5-1 deg.


Angular resolution distribution (Major axis)



Error ellipse


Angular resolution distribution (Minor axis)

Direction, inclination, polarization are given randomly

Parameter estimation accuracy

Advanced LIGO noise spectrum

$(1.4,1.4)\mathrm{M}_{\mathrm{solar}}$

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

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

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

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

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.

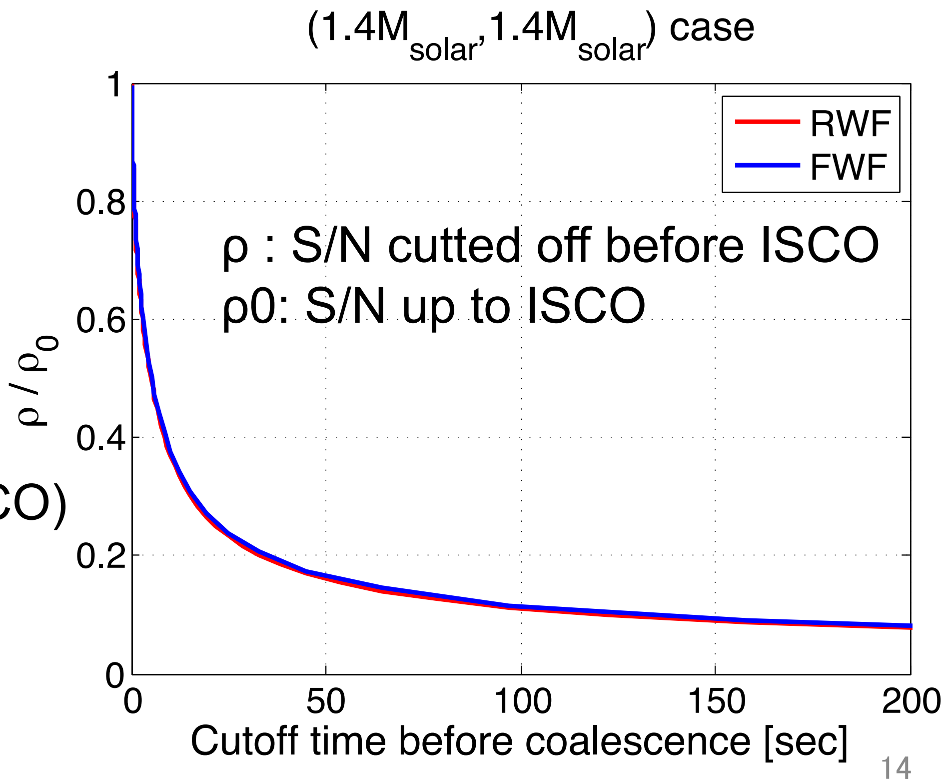
Parameter estimation accuracy become very bad.

(1.4,1.4)Msolar, @200Mpc

Cutoff frequency : 50Hz (13 sec before ISCO)

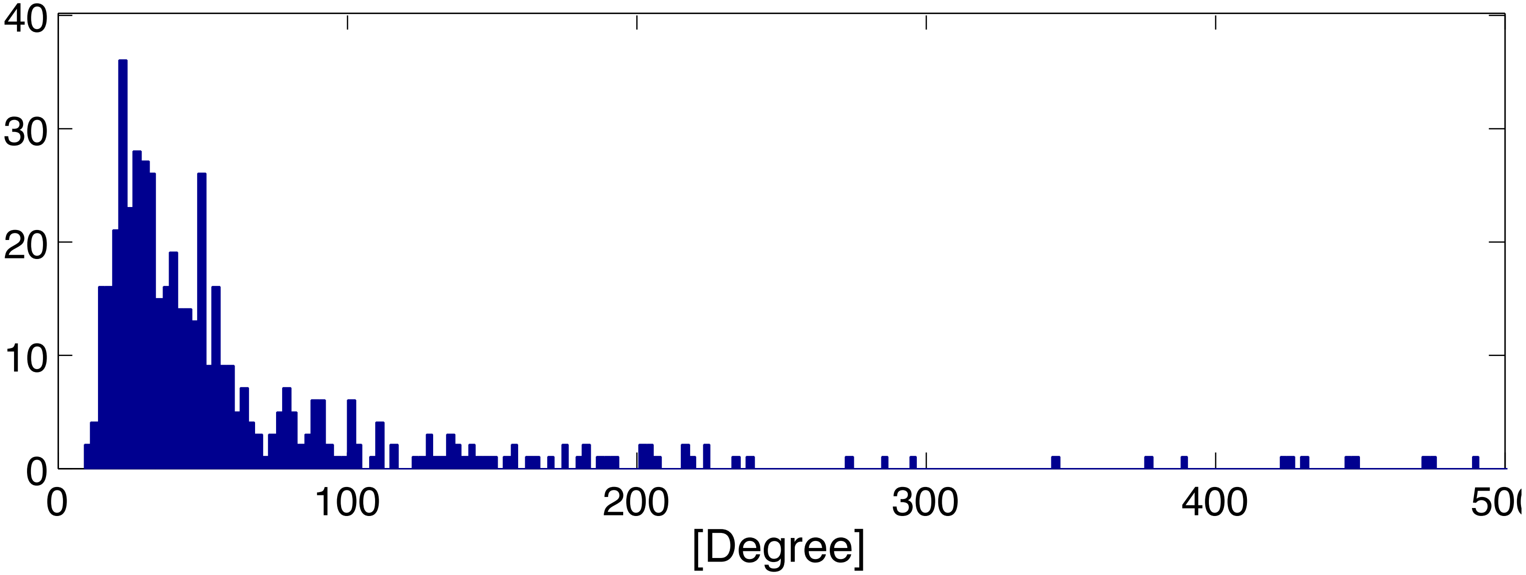
↓

Angular resolution : several 10 degree.



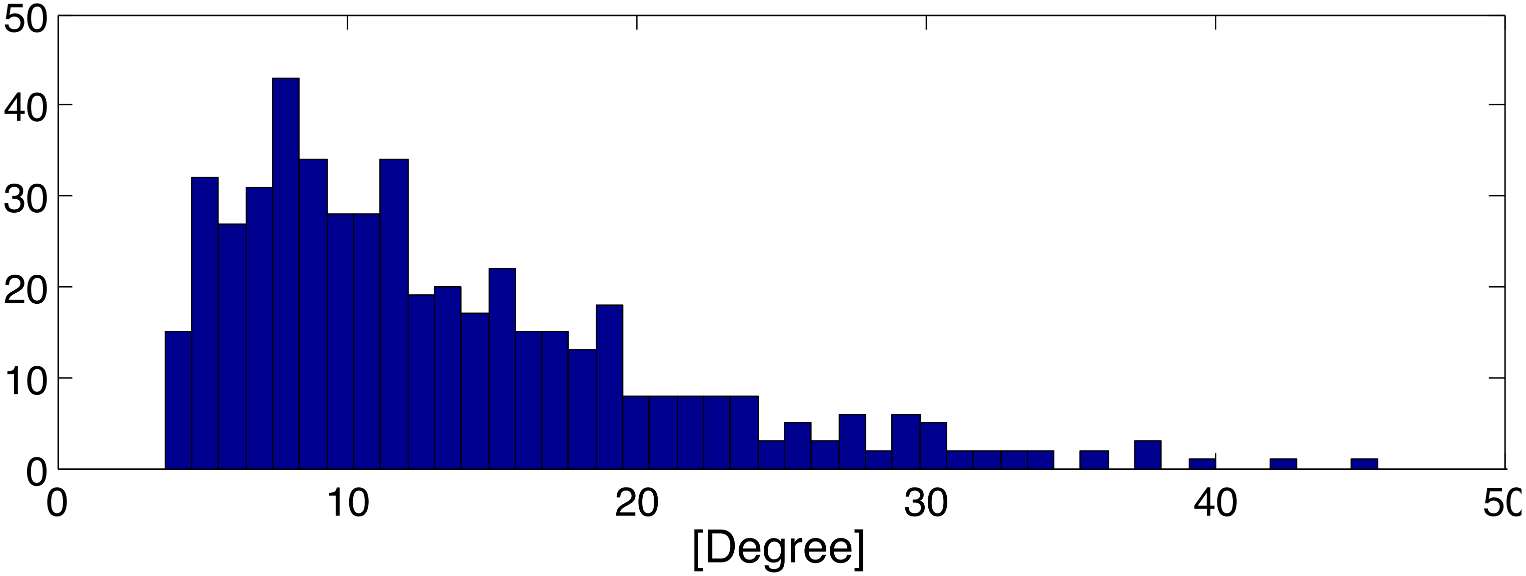
(1.4,1.4)Msolar, @200Mpc

Angular resolution distribution (Major axis)



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)

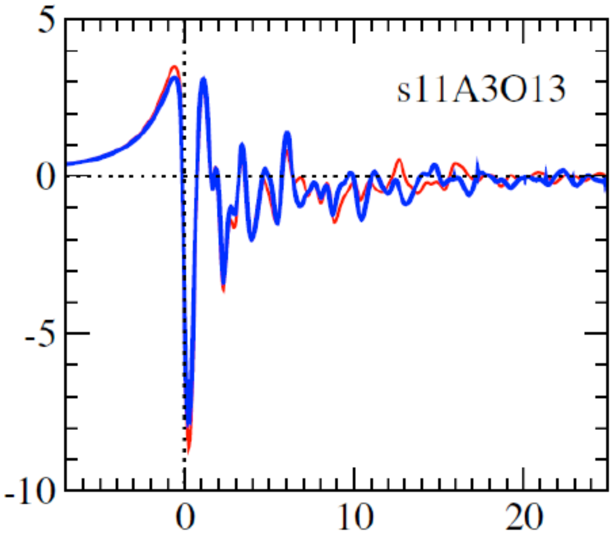
Various possible gravitational wave emission mechanism.

- 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

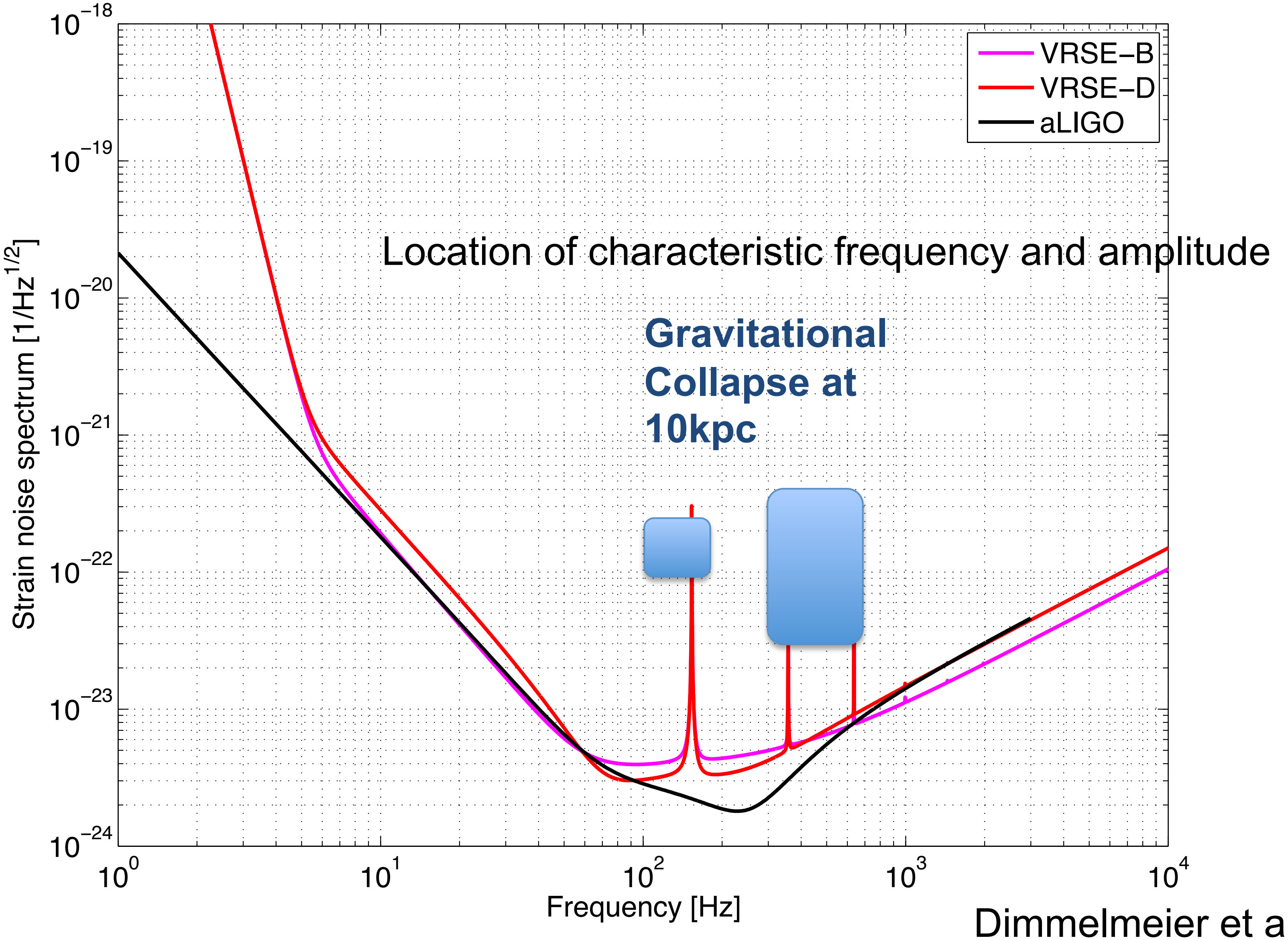
- Anisotropic neutrino emission

etc.



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

Gravitational Collapse

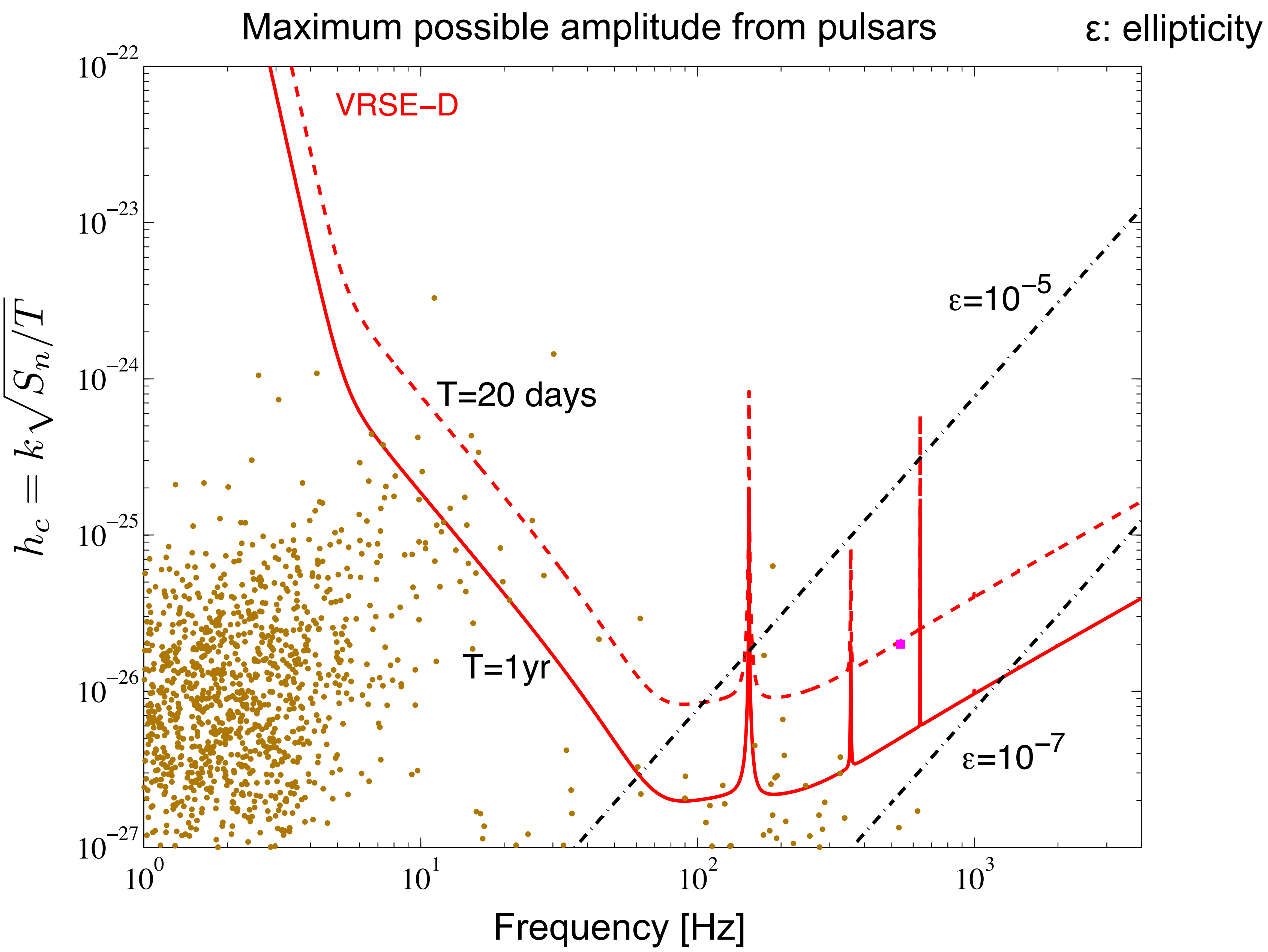


Location of characteristic frequency and amplitude

Gravitational Collapse at 10kpc

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

Continuous wave (rotating NS)



LIGO -Crab pulsar-

Neutron star in Crab nebula
Borne in 1054 by supernova

Crab nebula

Spin frequency 29.78Hz
Distance 2kpc

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 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.

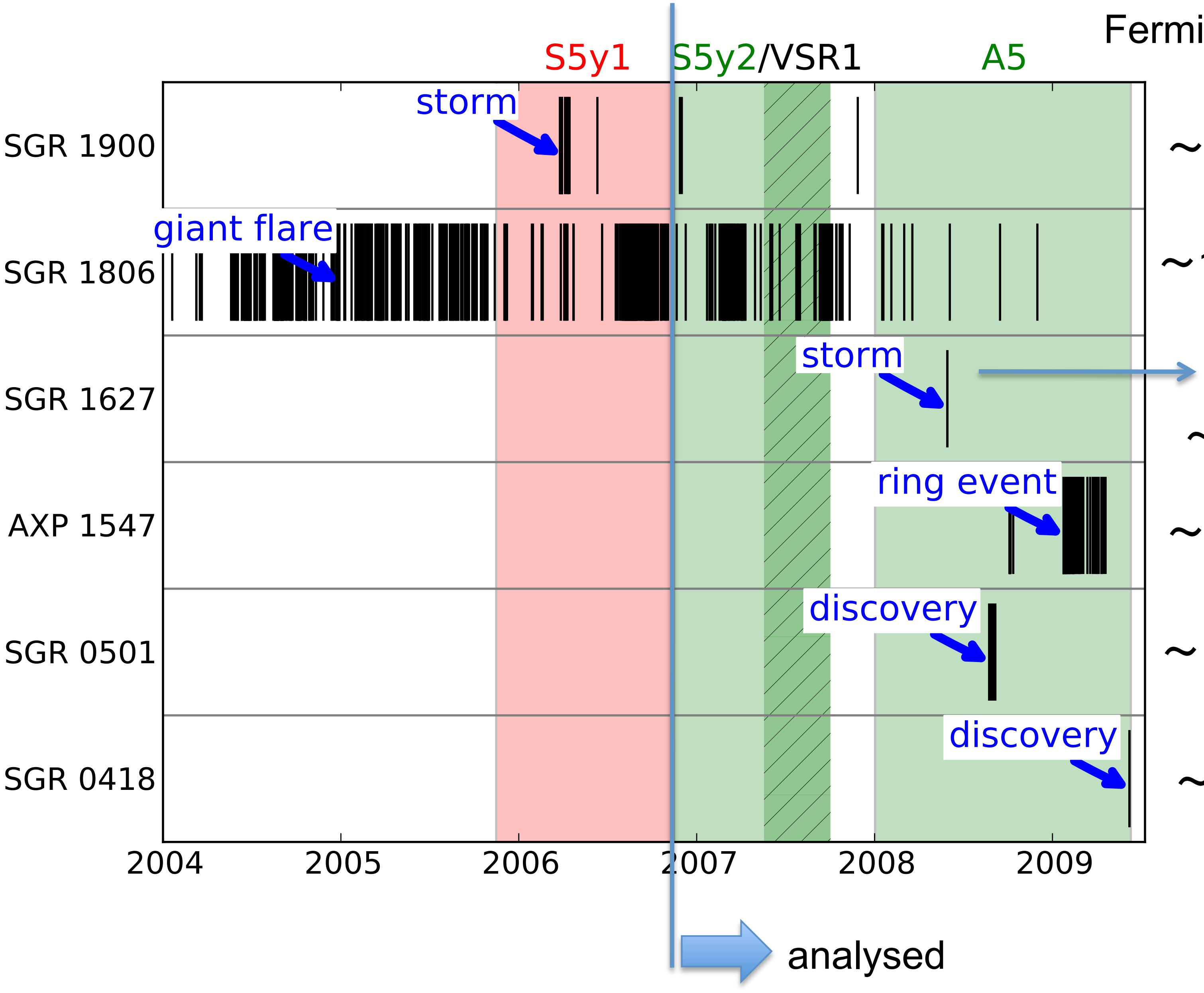
  Time and direction will be inferred from X- and γ-ray.

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

LIGO analysis of magnetars

arXiv:1011.4079

IPN event	1217
Fermi	8



∼10kpc 3

∼10kpc 207

(54)

56

∼11kpc

∼4kpc 844

∼1kpc 166

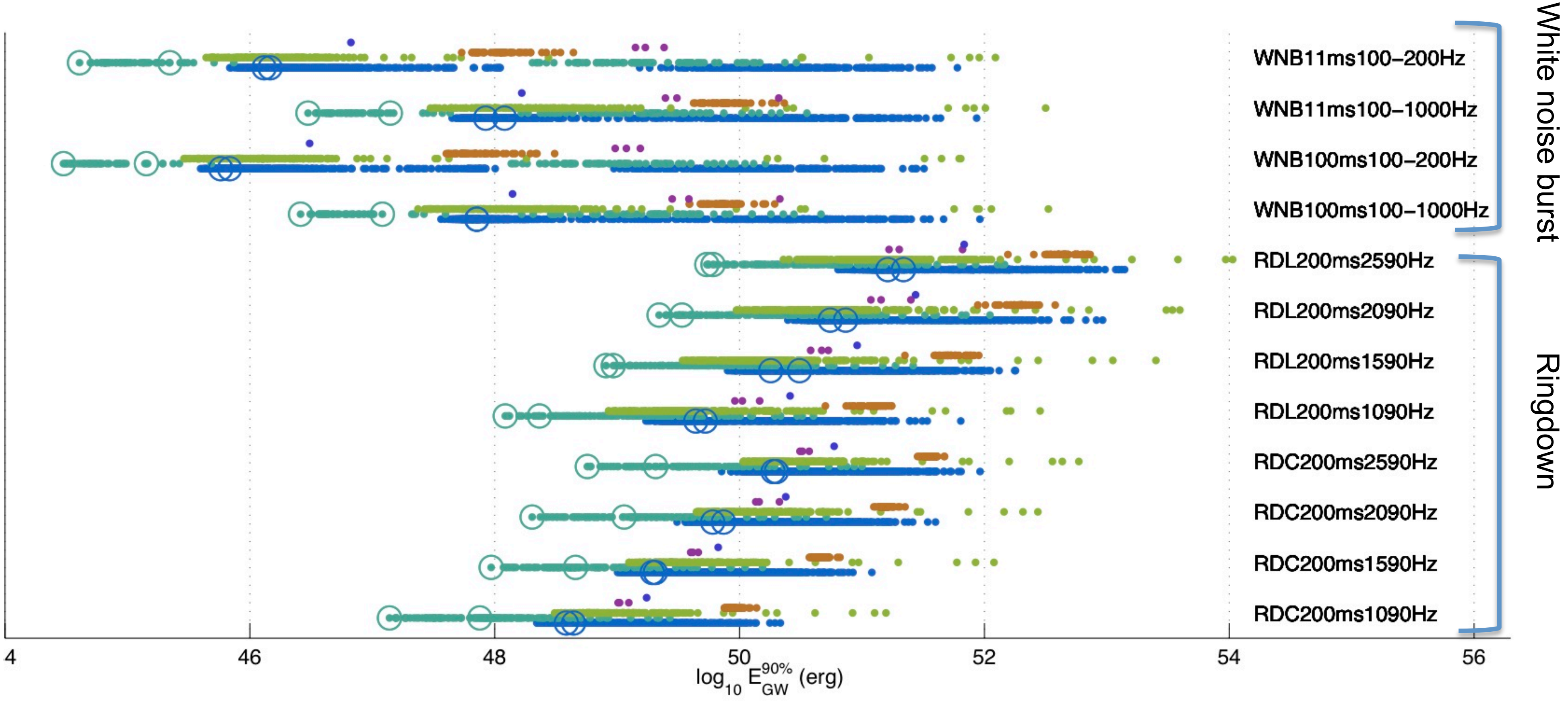
∼2kpc 3

Total 1279

LIGO analysis of magnetars

arXiv:1011.4079

Upper limit to the energy radiated in GW

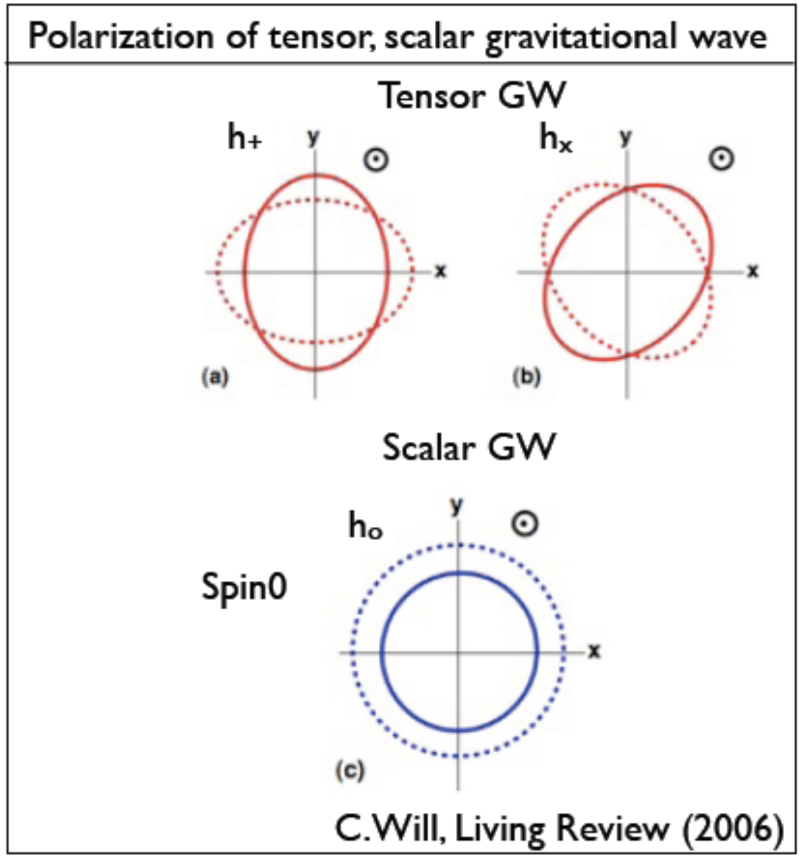


Each color represent a magnetar

Gravitation theory

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

Scalar gravitational wave


Polarization of tensor, scalar gravitational wave

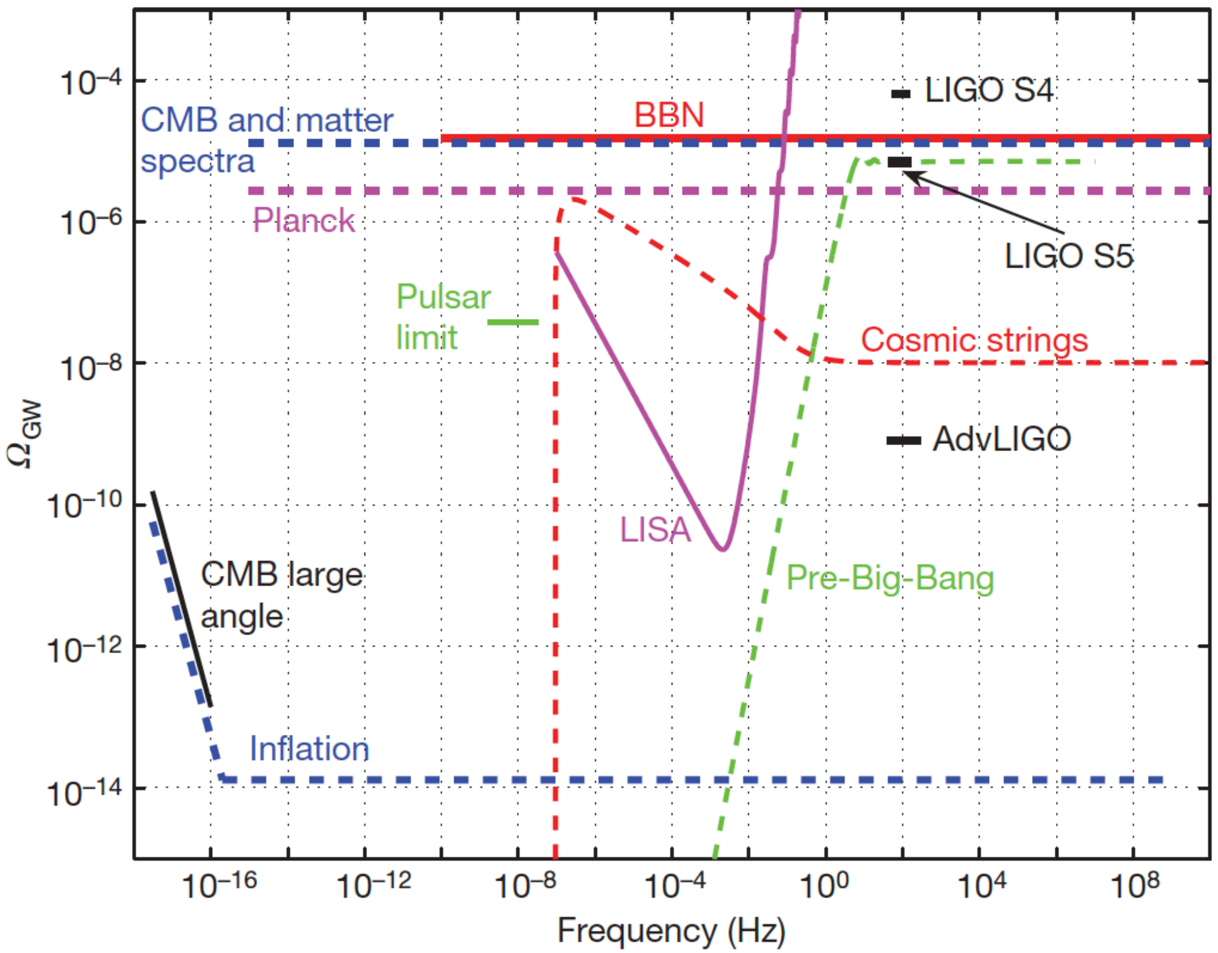
C.Will, Living Review (2006)

•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))

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.

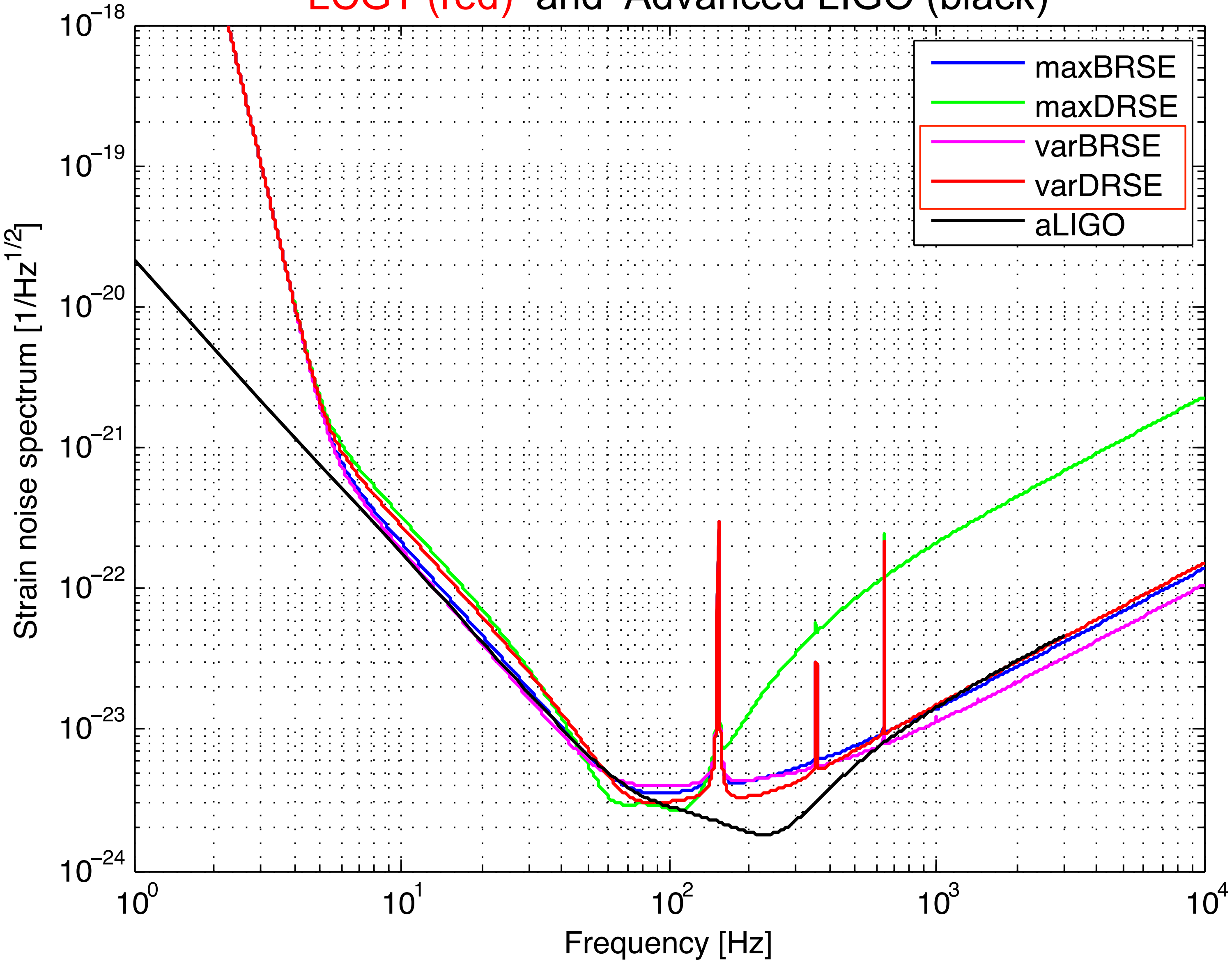
may not determine the distance to the source accurately.

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

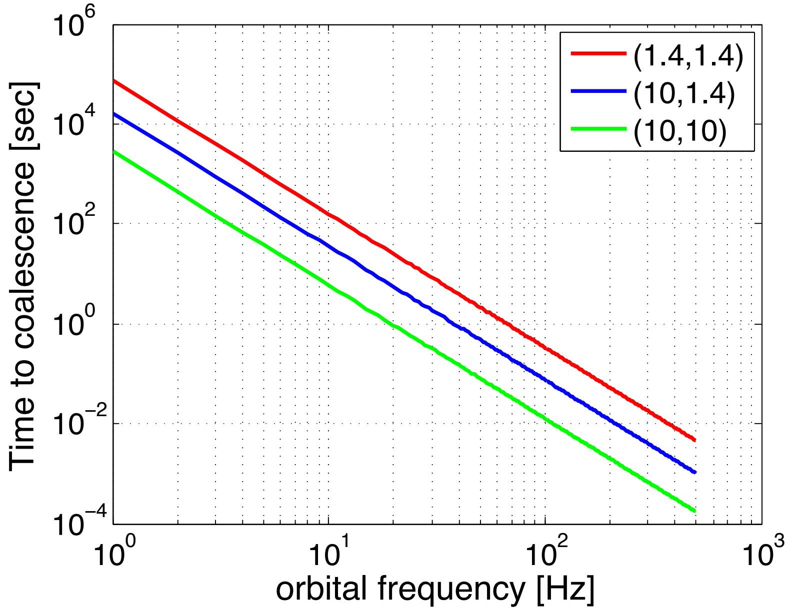
LCGT (red) and Advanced LIGO (black)



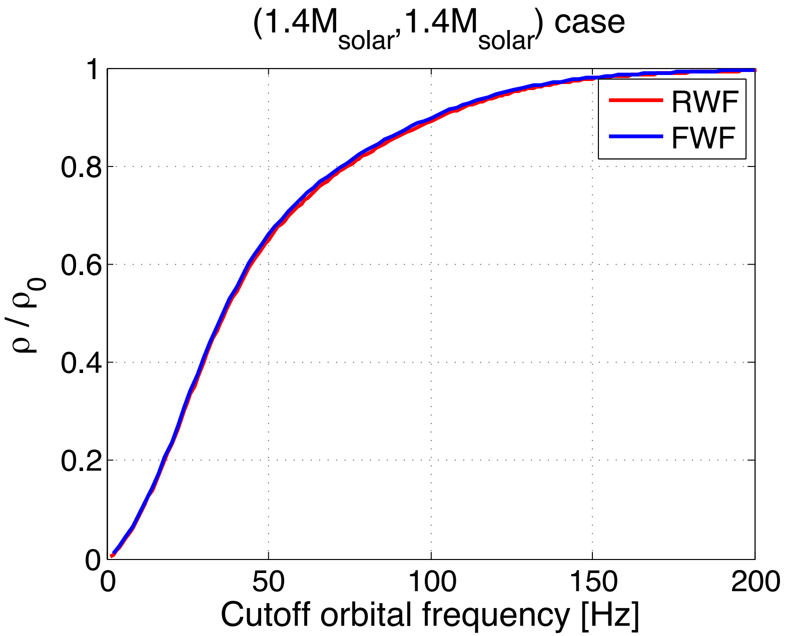
Today's results are obtained by Using aLIGO

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

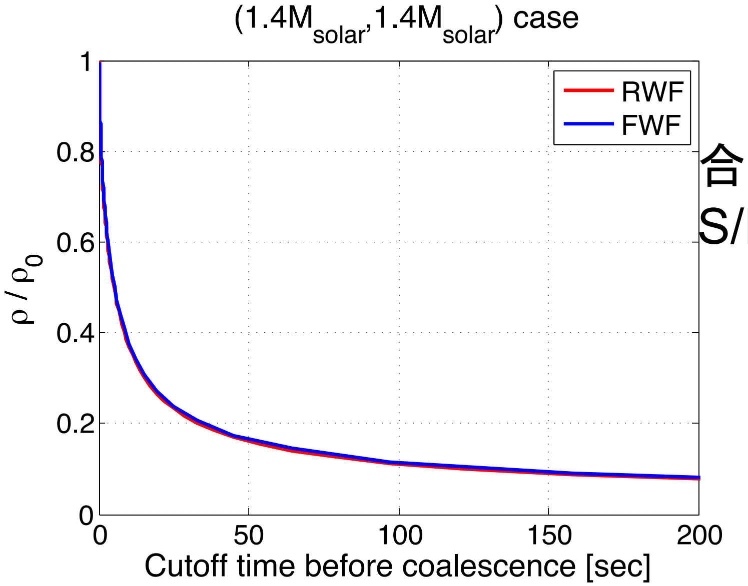


Cutoff周波数とS/Nの減少割合



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



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
ρ/ρ_0	0.15	0.21	0.37	0.50	0.76

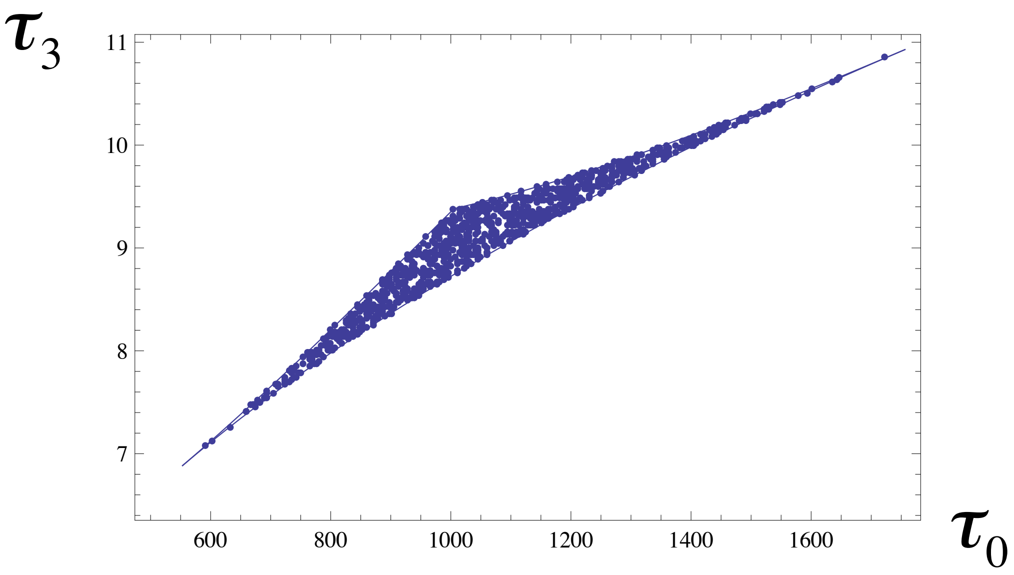
ρ_0: ISCOまで積分する場合のS/N

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

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