# *Short gravitational wave signal searches in TAMA300 data : stellar core collapse and black hole*

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TAMA collaboration

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*Special Thanks to
M.Ando, T.Akutsu, R.Honda and Y.Tsunesada*

# *TAMA's searches for Short GW*

- 1. Stelar-core collapse (SN) : Burst GW
  - 1-1 Excess Power Filter
  - 1-2 ALF
  - 1-3 TF-Cluster
- 2. Black-hole quasi-normal mode : Ringdown GW
  - Matched filter
- 3. Keyword for short signal searches

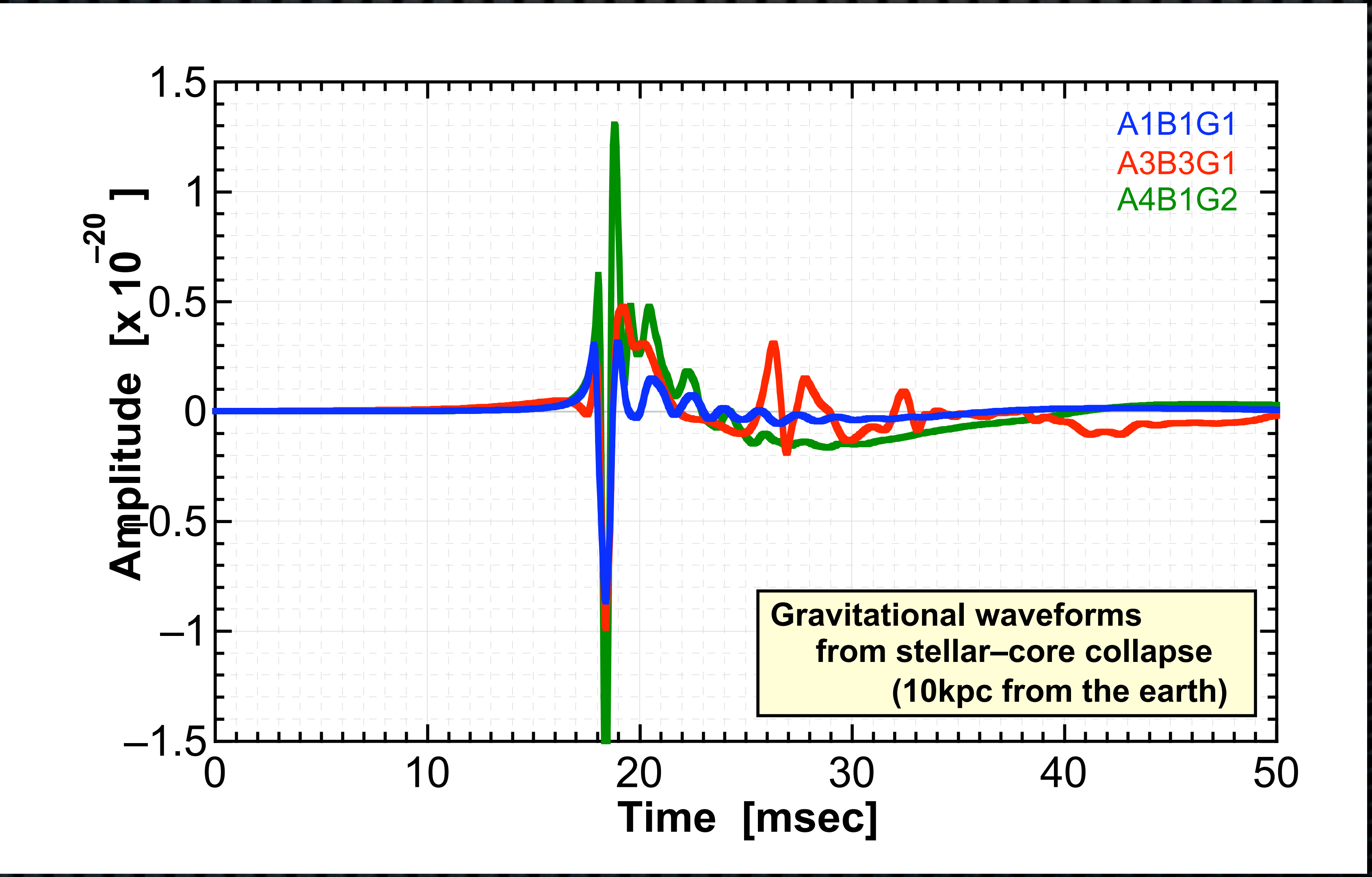
# *Observational runs and data*

| Data Taking | period | actual data amount | remarks |
|---|---|---|---|
| DT1 | 8/6 - 7/1999 | ~3 + ~7 hours continuous lock | first whole system test |
| DT2 | 9/17 - 20/1999 | 31 hours | first Physics run |
| DT3 | 4/20 - 23/2000 | 13 hours | |
| -- | 8/14/2000 | World best sensitivity | h ~ $5 \times 10^{-21}$ [1/√Hz] |
| DT4 | 8/21 - 9/3/2000 | 167 hours | stable long run |
| DT5 | 3/1 - 3/8/2001 | 111 hours | |
| Test Run 1 | 6/4 - 6/6/2001 | Longest stretch of continuous lock is 24:50 | keep running all day |
| DT6 | 8/1 - 9/20/2001 | **1038 hours**<br>duty cycle 86% | full-dressed run |
| DT7 | 8/31 - 9/2/2002 | 24 hours with duty cycle 76.7% | Recycling,<br>h ~ $3 \times 10^{-21}$ [1/√Hz],<br>Simultaneous obs with LIGO & GEO |
| DT8 | 2/14 – 4/14/2003 | **1168 hours,**<br>duty cycle 81.1% | coincidence obs with LIGO S2 |
| DT9 | 10/31(Actually 11/28)/2003<br>– 1/5/2003 | **558 hours,**<br>(weekday: night time,<br>weekend: full time) | partial coincidence run with LIGO S3<br>'crewless' operation |

# *1. Burst Gravitational Waves from Stellar-core collapse*

- Numerical Simulation Predicts GW Waveform.

Komatsu et al. (1989)
Zwerger & Müler (1997)
Dimmelmeier et.al., (2001,2002)



# *TAMA300 Sensitivity : Range of Detection for Burst GW from Stellar-Core Collapse*

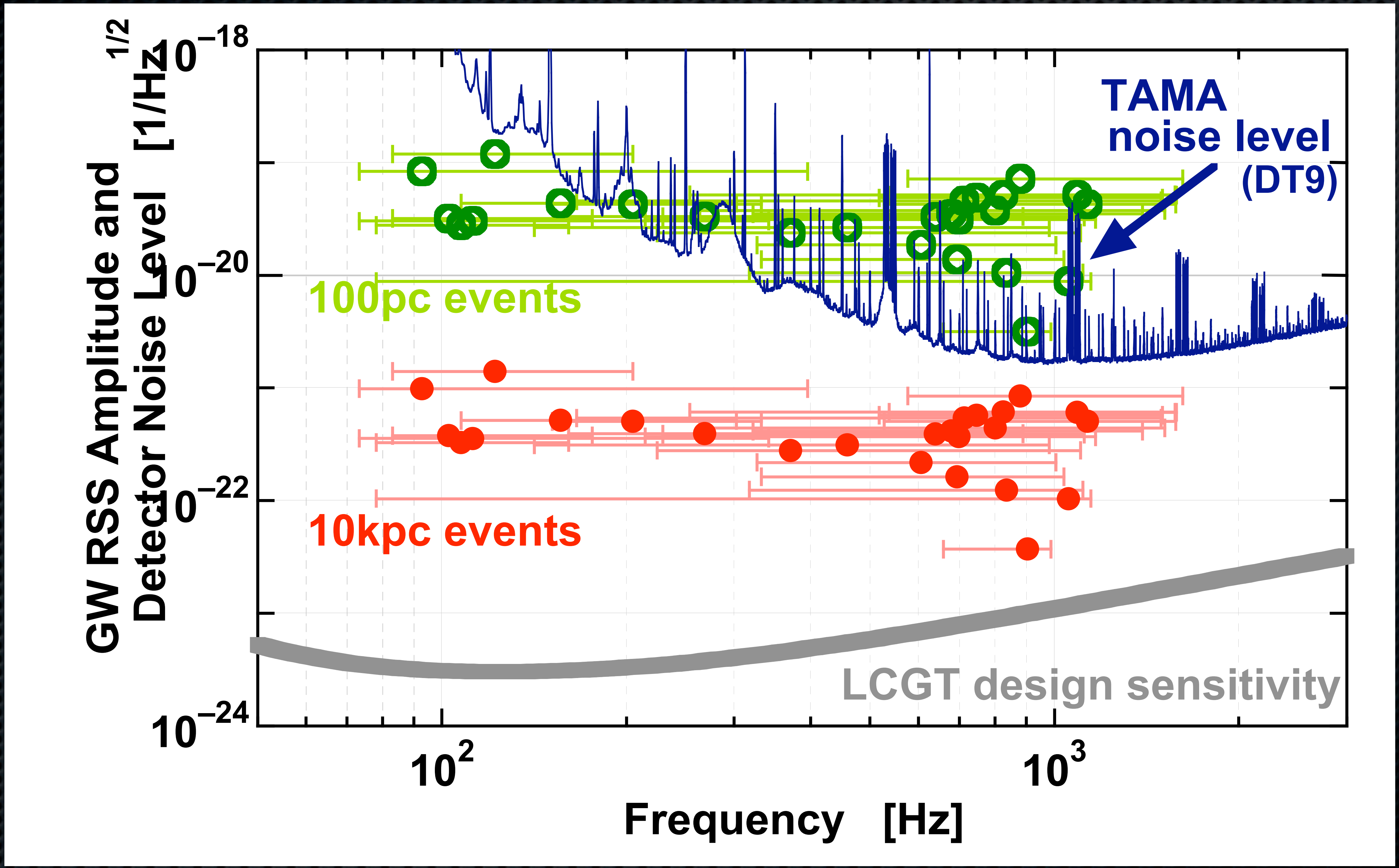
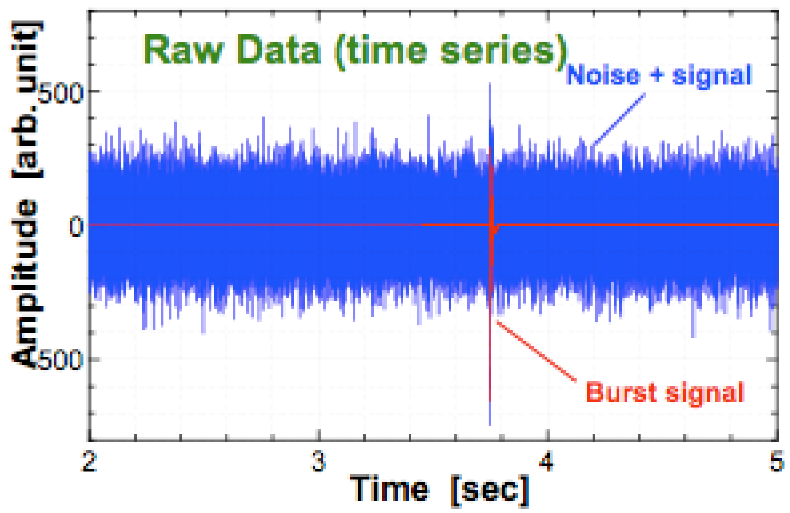


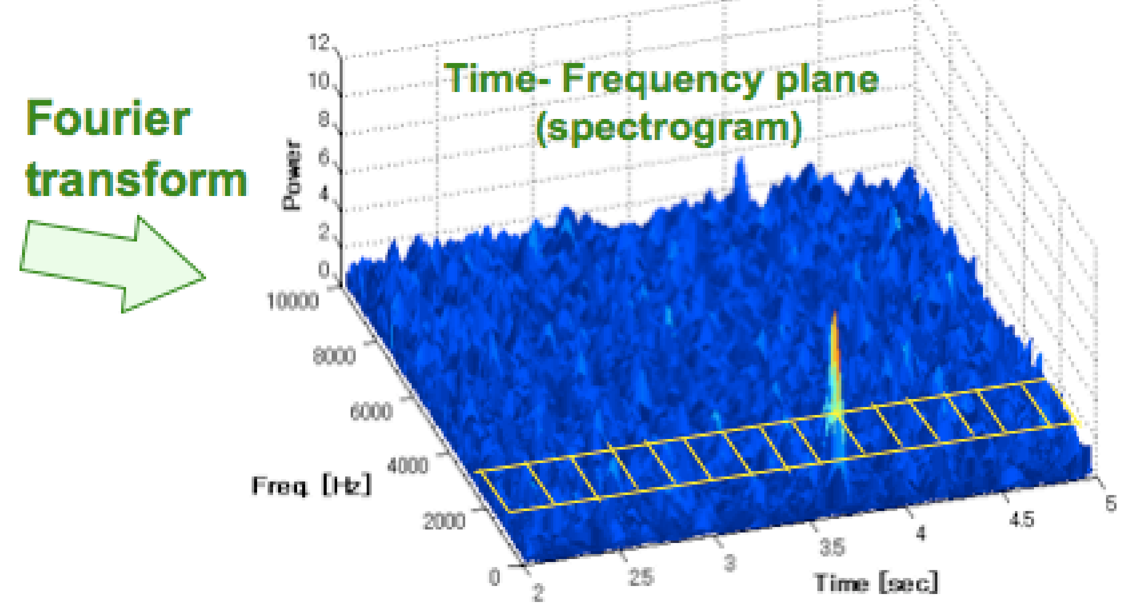

Figure by M.Ando,
GW signals by Dimmelmeier, et al. (2002)

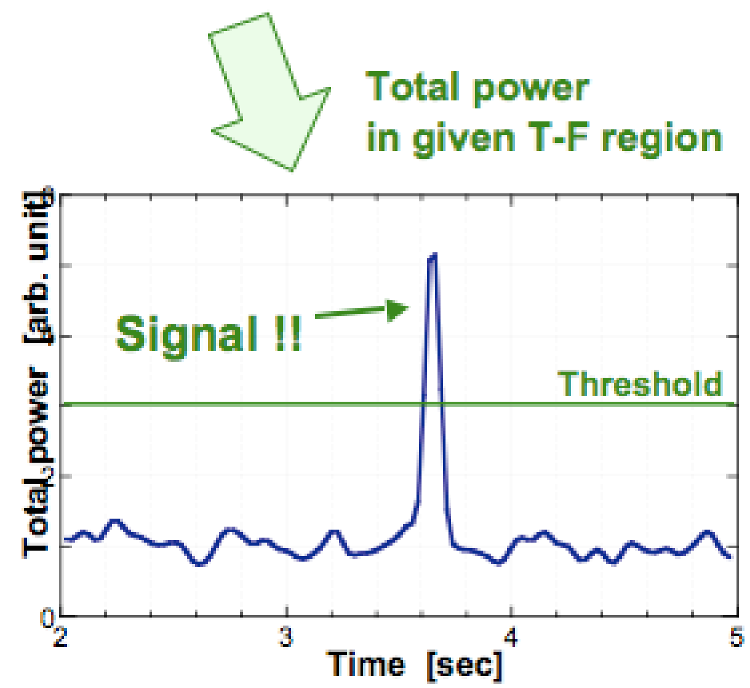
# 1-1. Excess Power Filter

**Burst filter: Excess-power filter**

**Evaluate signal power in given time-freqency regions**




**Few assumptions for signal …**

**time-frequency bands**

**Robust for waveform uncertainties**

**Selected parameter:**

$\Delta t$ = 12.8 [msec]

$\Delta f$ = 2300 [Hz]

*by M.Ando (Tokyo Univ.)*

# Upper-limit results

- **Event candidates**

  **Event-selection threshold : SNR>2.9**

  ⇨ **Detection efficiency : $1\times10^{-5}$**
  **Observation result : $7\times10^{-2}$ events/sec**

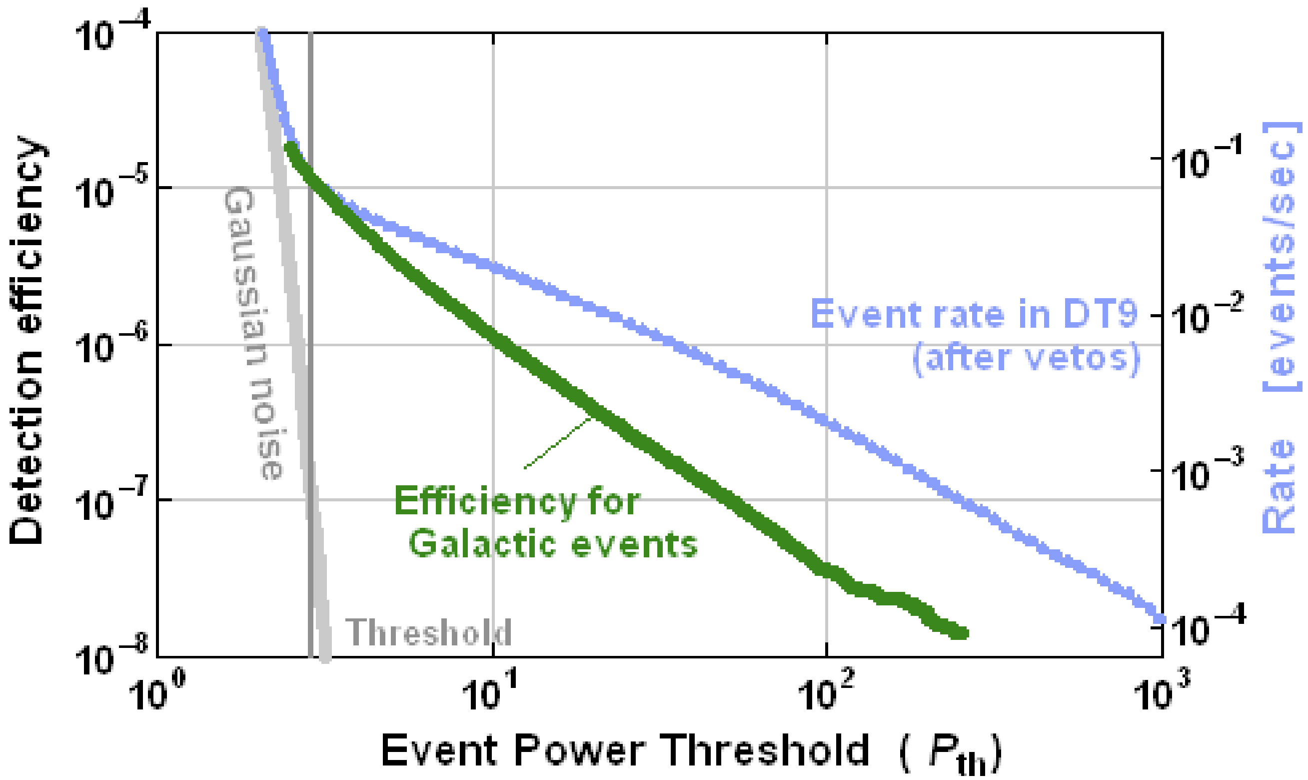
- **Upper limit**

  **Assume a Poisson distribution for the observed event number**

  $N_{obs} \rightarrow N_{ul}$

$$R_{\rm ul} = \frac{N_{\rm ul}}{\epsilon_{\rm gal} \cdot T_{\rm obs}}$$

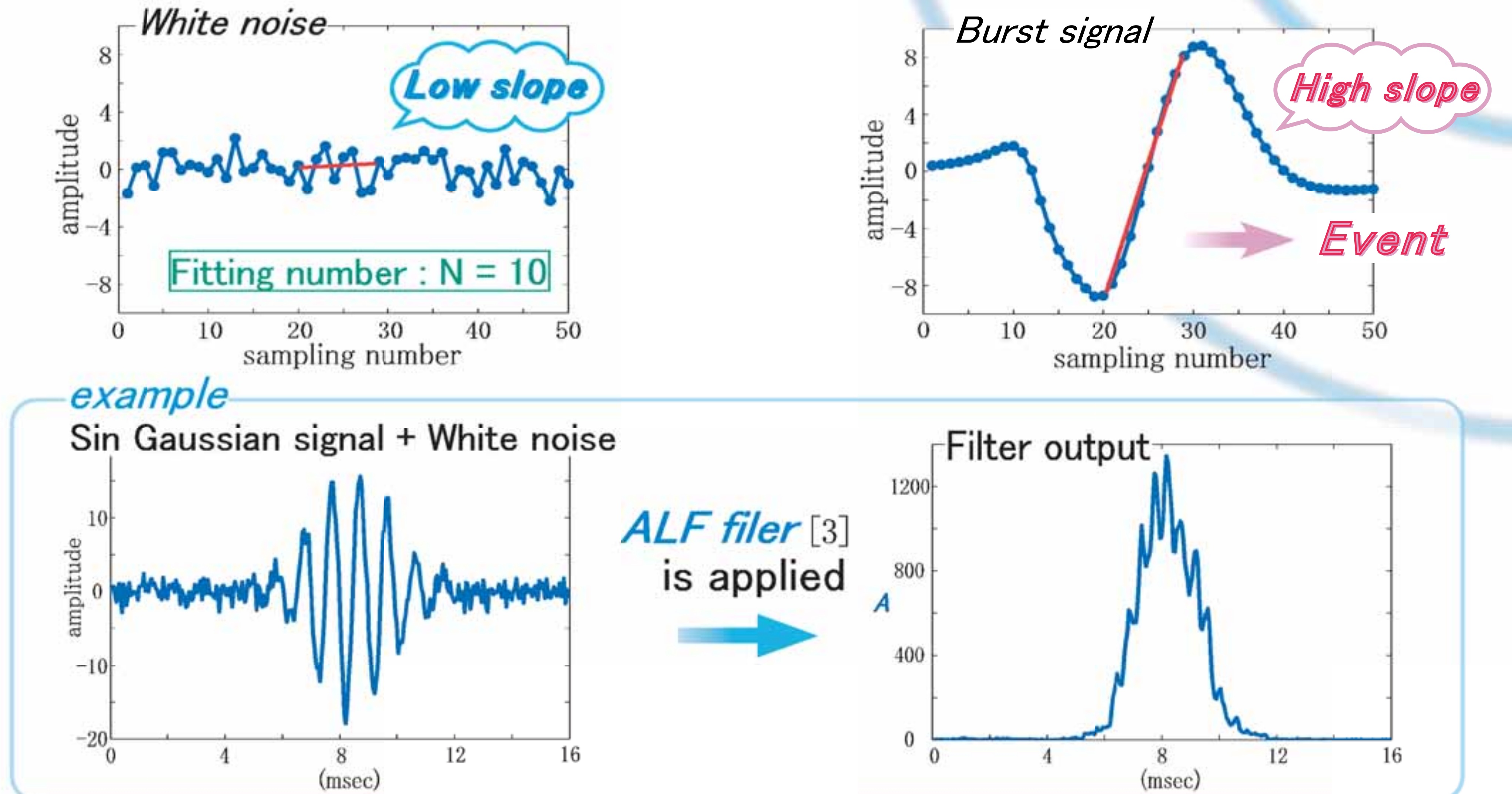
**Galactic event rate**
**$5 \times 10^3$ events/sec**
**GW energy rate**
**$4 \times 10^{-4}$ $M_{\odot} c^2$/sec**
**(90% C.L.)**




by M.Ando
Phy. Rev. D71, 082002 (2005)

# 1-2. ALF (Alternative Linear Filter)

A slope value of a raw of data (N samples) is used to trigger an event.
When there is a white noise, a slope value is low. If there is a burst signal, a slope value will be high.




by Tomomi Akutsu (ICRR, Tokyo Univ. / Osaka City Univ.),

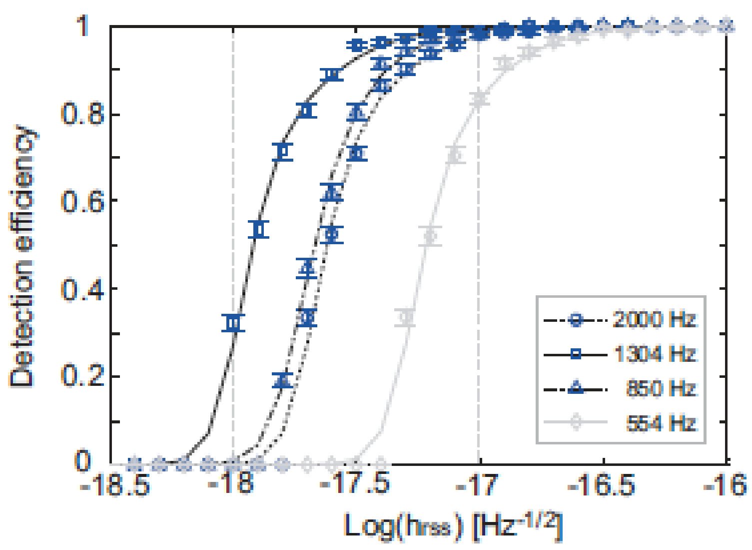



**Figure 4.** Detection efficiency for sine-Gaussiaon signals.

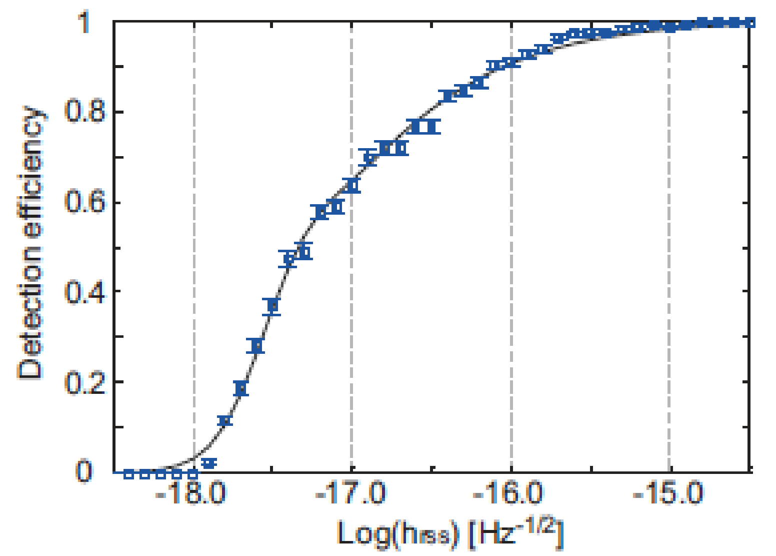



**Figure 5.** Detection efficiency for the DFM catalogue signals.

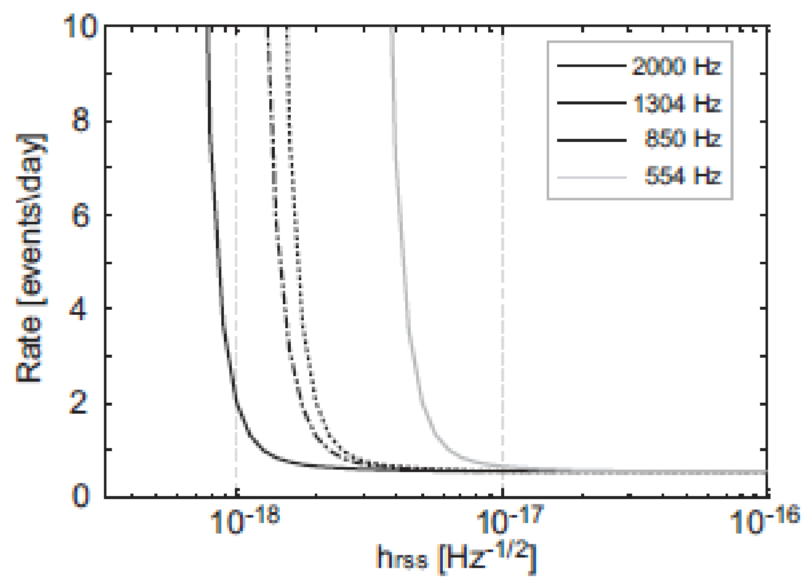


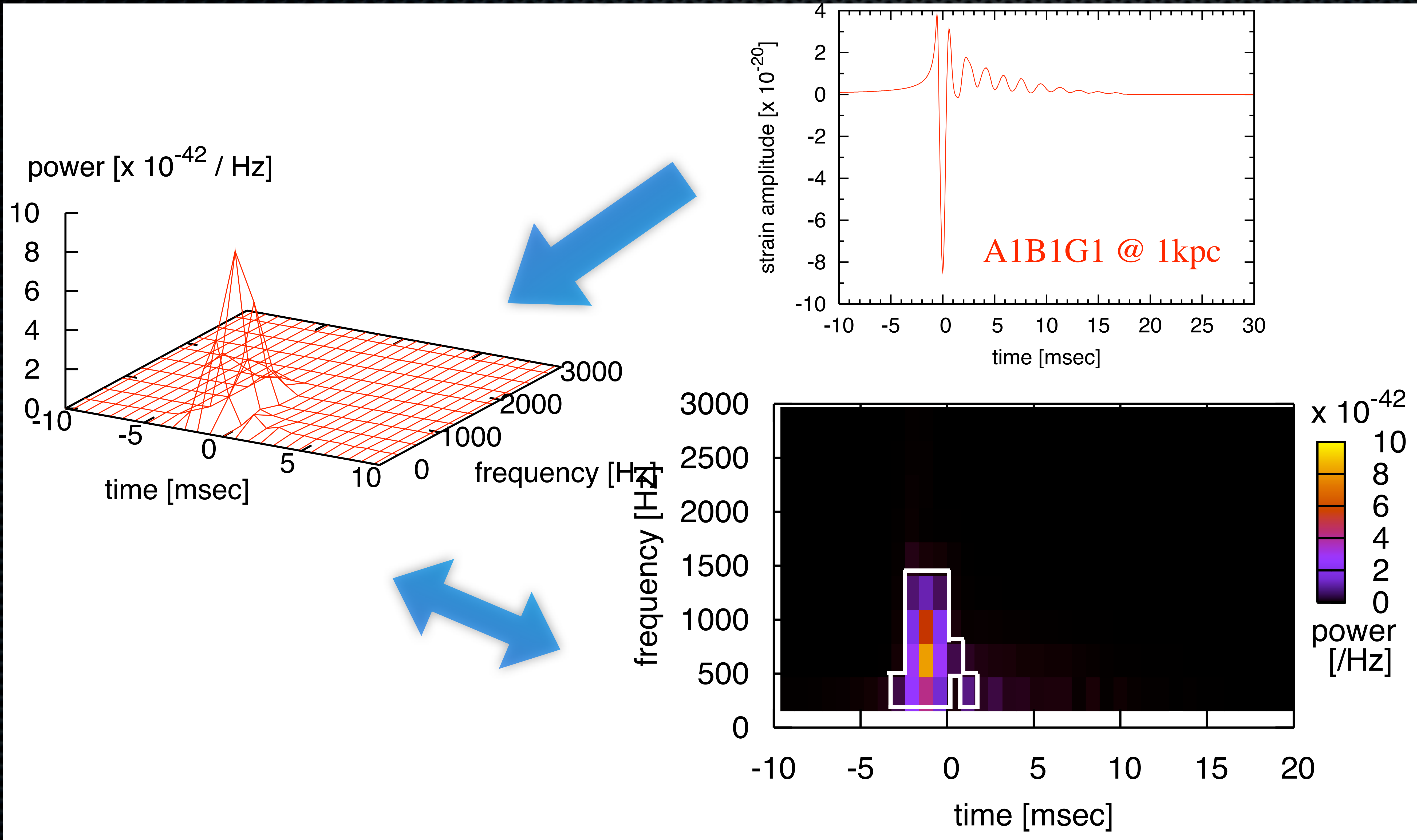

**Figure 6.** Rate limit for GW amplitude $h_{\rm rss}$. A vertical axis and a horizontal axis are a rate limit [events/day] with a confidence level 90 % and $h_{\rm rss}$ amplitude, respectively. At the level of $h_{\rm rss} = 10^{-17}$, we obtained 0.55 events/day of upper rate limit with 90 %confidence level.

*U.L. for $h_{rss}>10^{-17}$*

0.55 [events/day] , C.L.90%

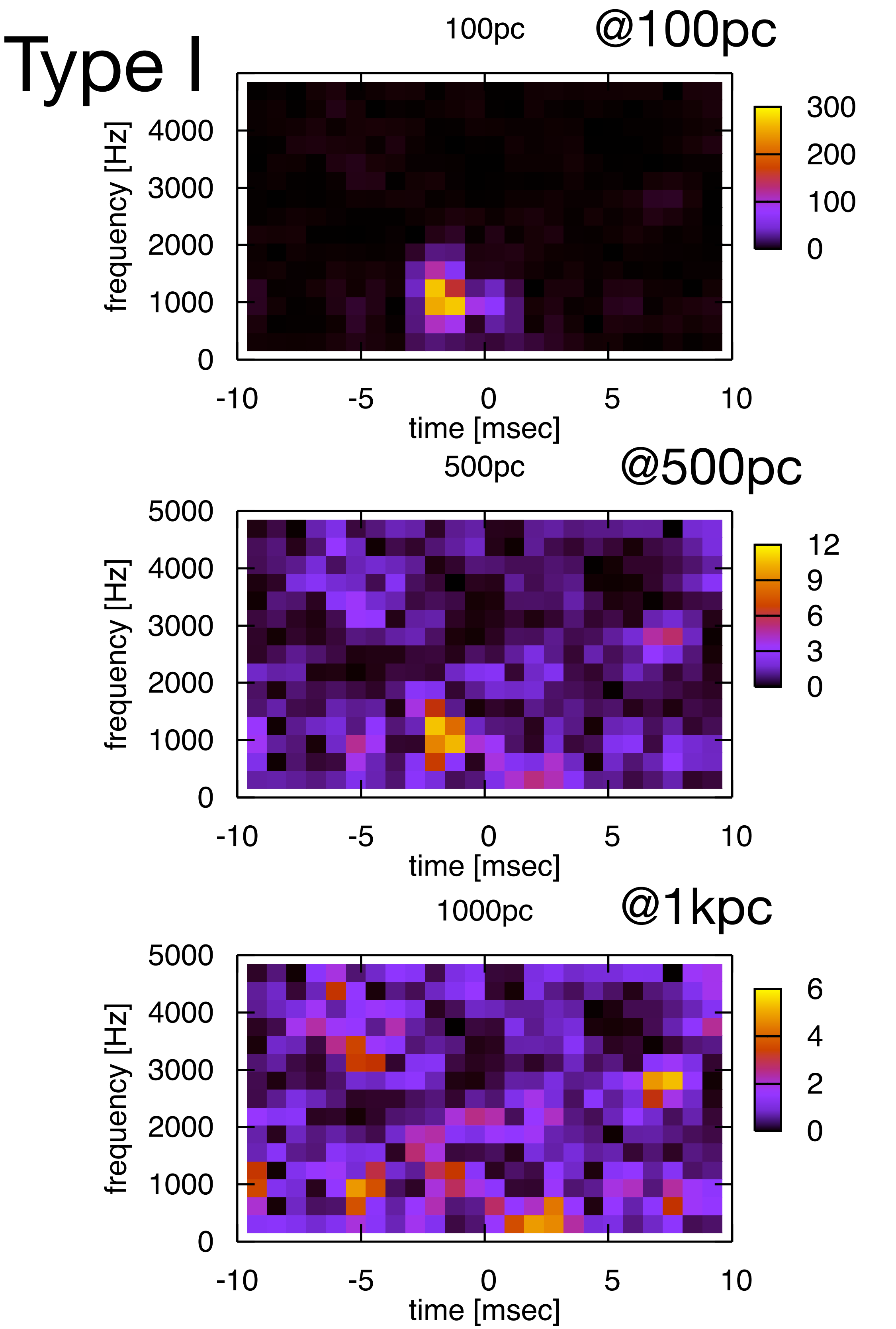
by Tomomi Akutsu , et al.
Class. Quantum Grav. 23 (2006) S715

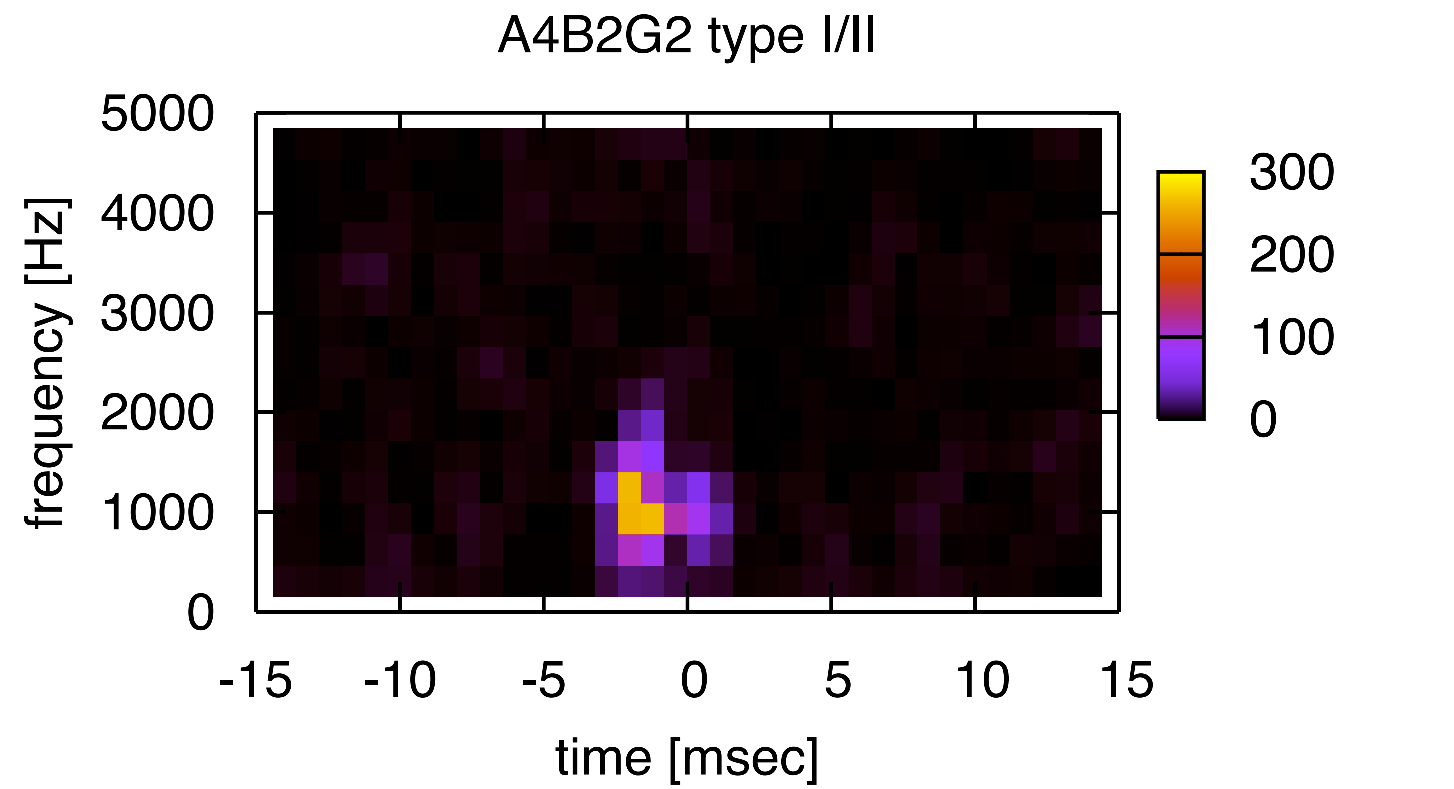
# 1-3 TF (Time-Frequency) - cluster

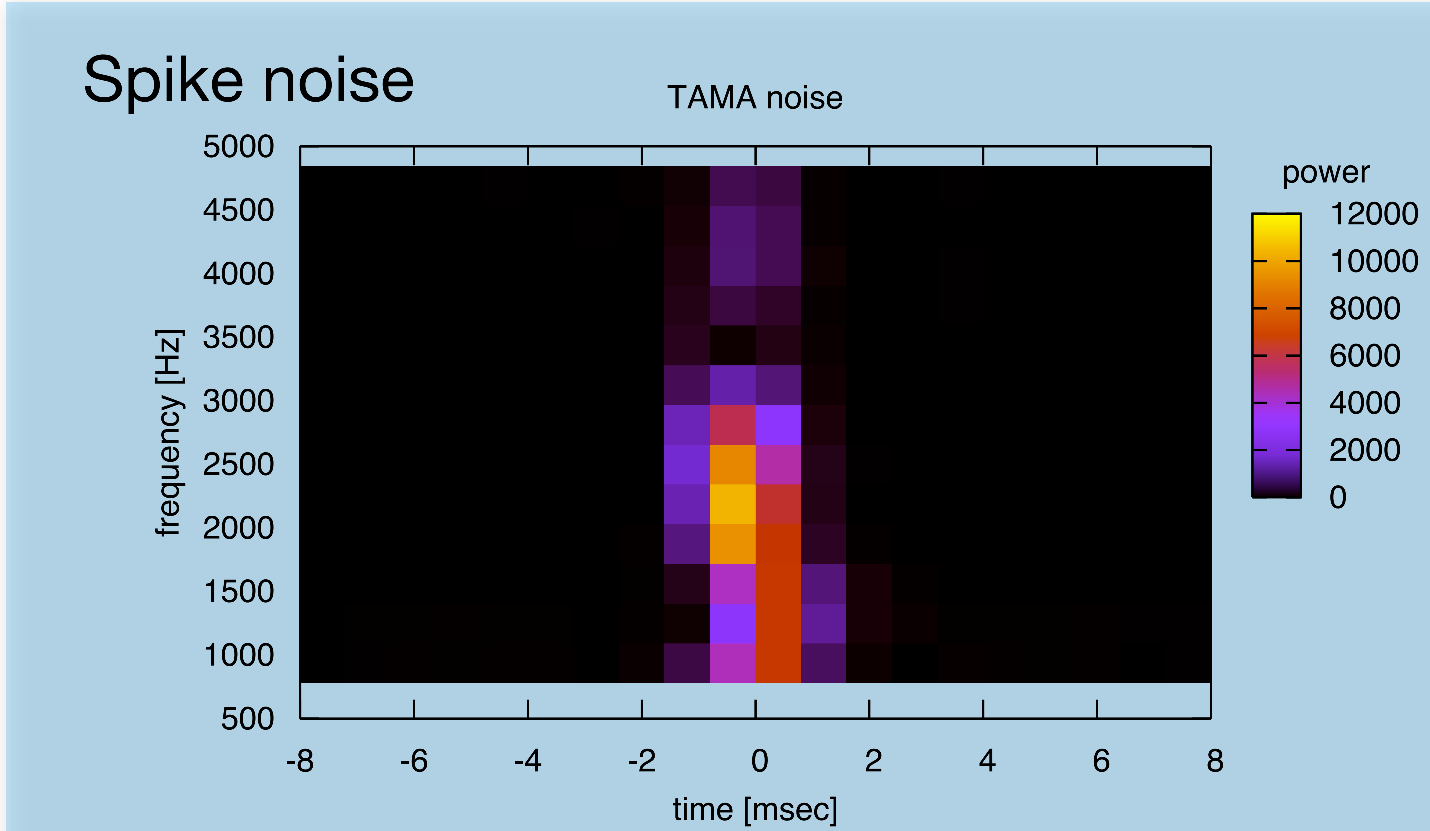



by R.Honda (Osaka City Univ.)

# Example



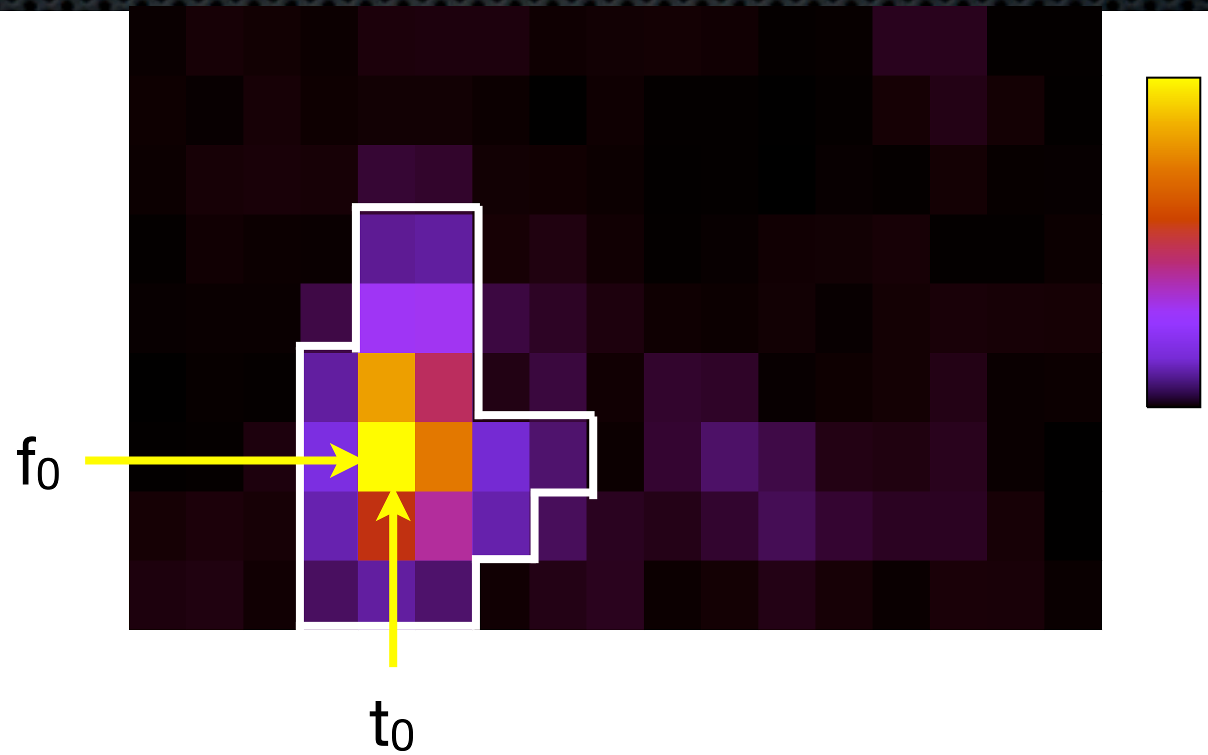




by R.Honda (Osaka City Univ.)

# *Clustering (recognization of connected region)*

peak hight : $P(t_0,f_0)$
cluster threshold : $P(t_0,f_0)^{1/2}$




cluster characteristics parameters :

$$S = \sum_{t,f} 1$$

$$V = \sum_{t,f} P(t,f)$$

$$\mathrm{t1s} = \frac{\sum t}{S} \qquad \mathrm{t1v} = \frac{\sum tP(t,f)}{V}$$

$$\mathrm{t2s} = \frac{\sum (t-\mathrm{t1s})^2}{S} \qquad \mathrm{t2v} = \frac{\sum (t-\mathrm{t1v})^2 P(t,f)}{V}$$

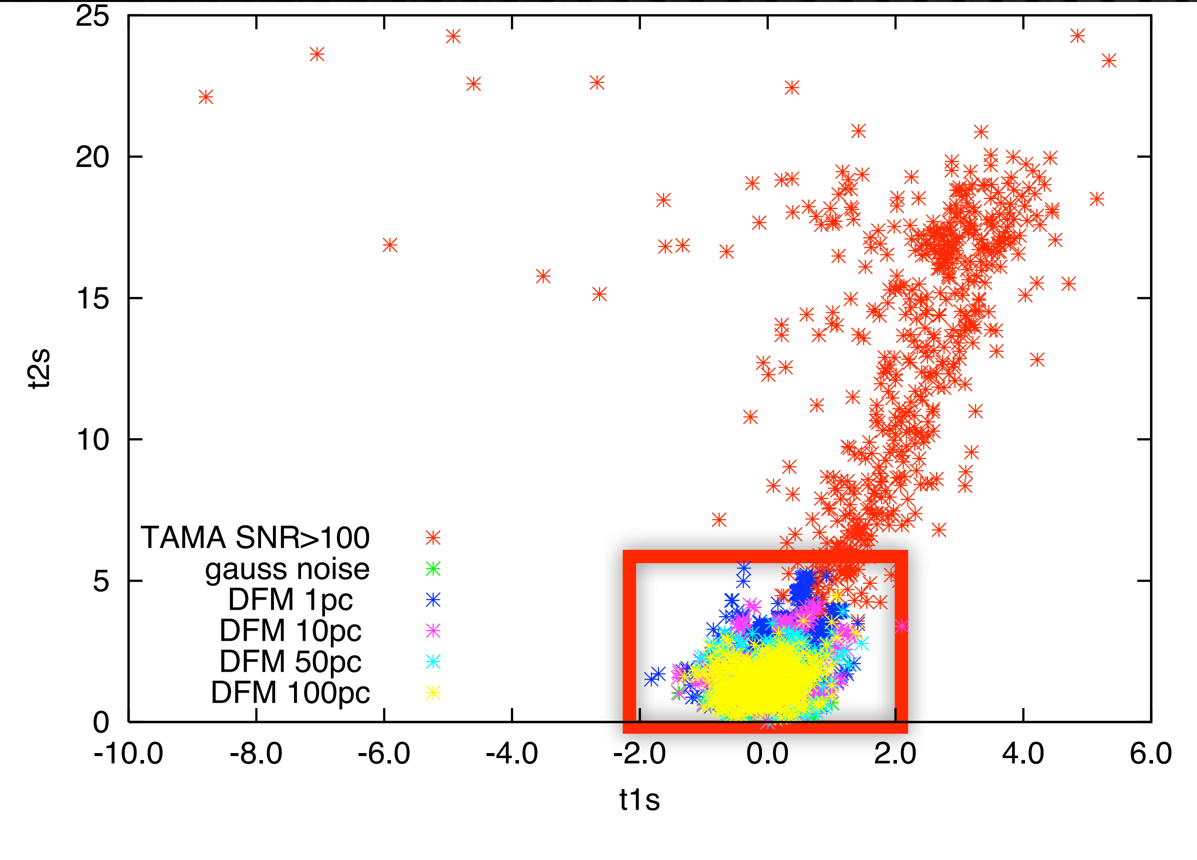
$$\mathrm{t3s} = \frac{\sum (t-\mathrm{t1s})^3}{S(\mathrm{t2s})^{3/2}} \qquad \mathrm{t3v} = \frac{\sum (t-\mathrm{t1v})^3 P(t,f)}{V(\mathrm{t2v})^{3/2}}$$

$$\mathrm{t4s} = \frac{\sum (t-\mathrm{t1s})^4}{S(\mathrm{t2s})^{4/2}} \qquad \mathrm{t4v} = \frac{\sum (t-\mathrm{t1v})^4 P(t,f)}{V(\mathrm{t2v})^{4/2}}$$

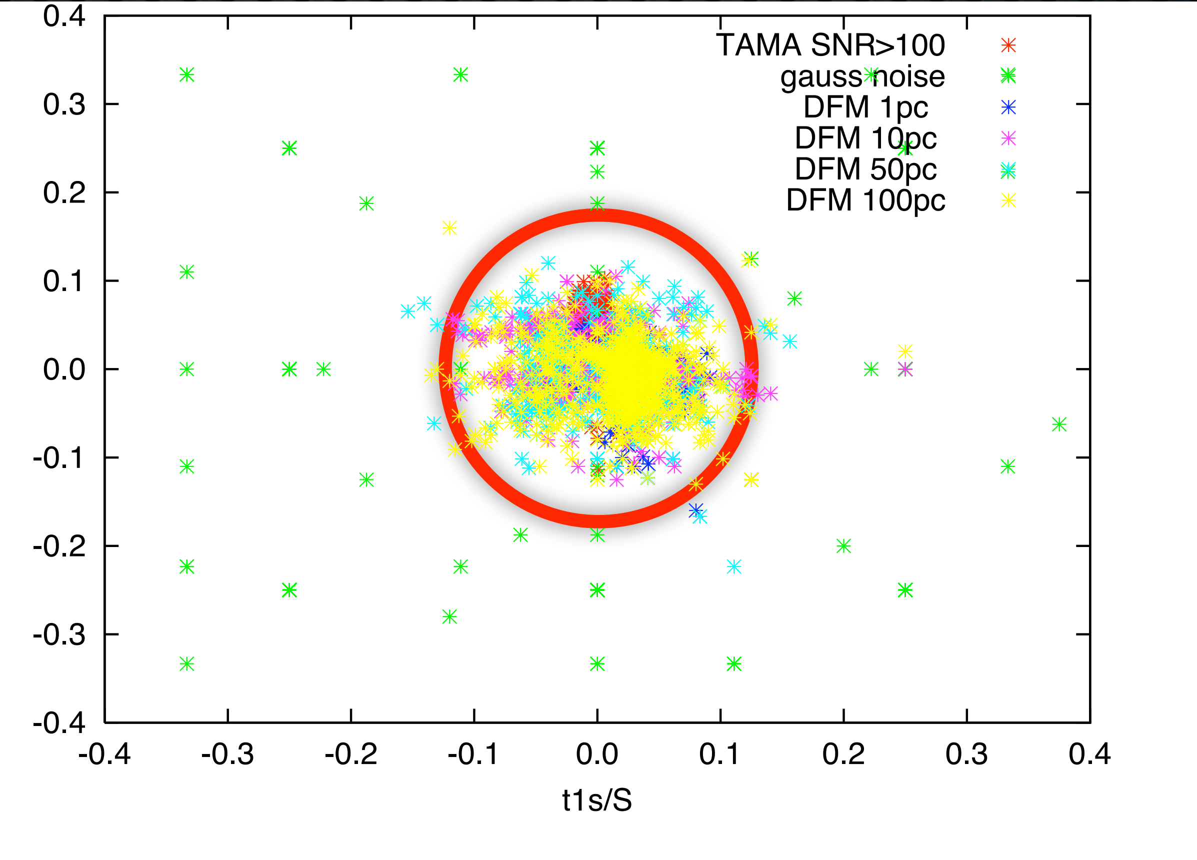
by R.Honda (Osaka City Univ.)

# *TF-cluster : Event Selection*

exclude TAMA noises
f1s vs f2s




exclude Gauss noise
t1s/S vs f1s/S




$-2.0 \leq f1s \leq 2.0$

$f2s \leq 5.0$

$(t1s^2+f1s^2)^{1/2}/S \leq 0.15$

$S \geq 4$

$F \leq 4$

(1250Hz)

$-1.5 \leq t1v \leq 1.5$

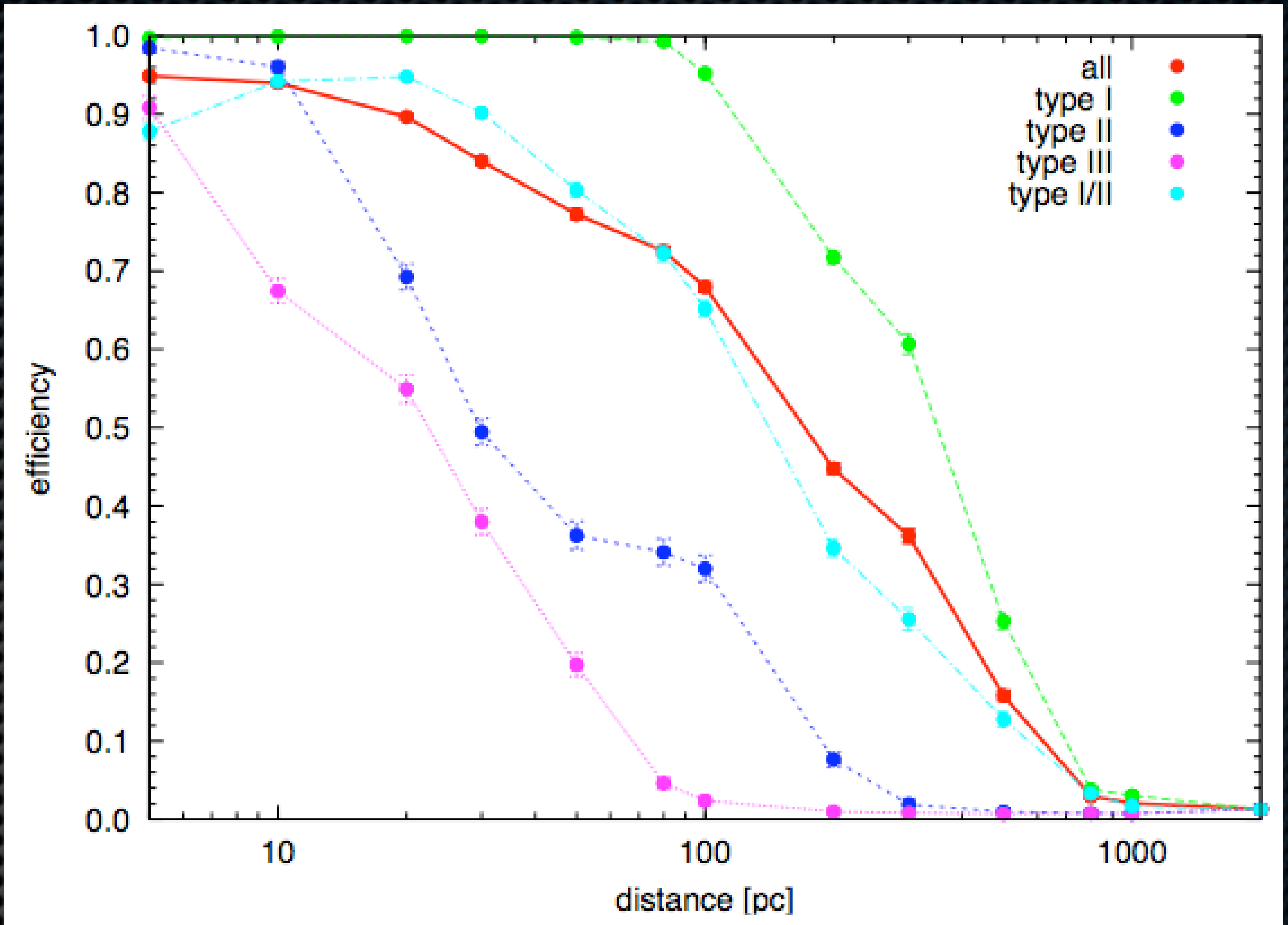
$t2v \leq 3.0$

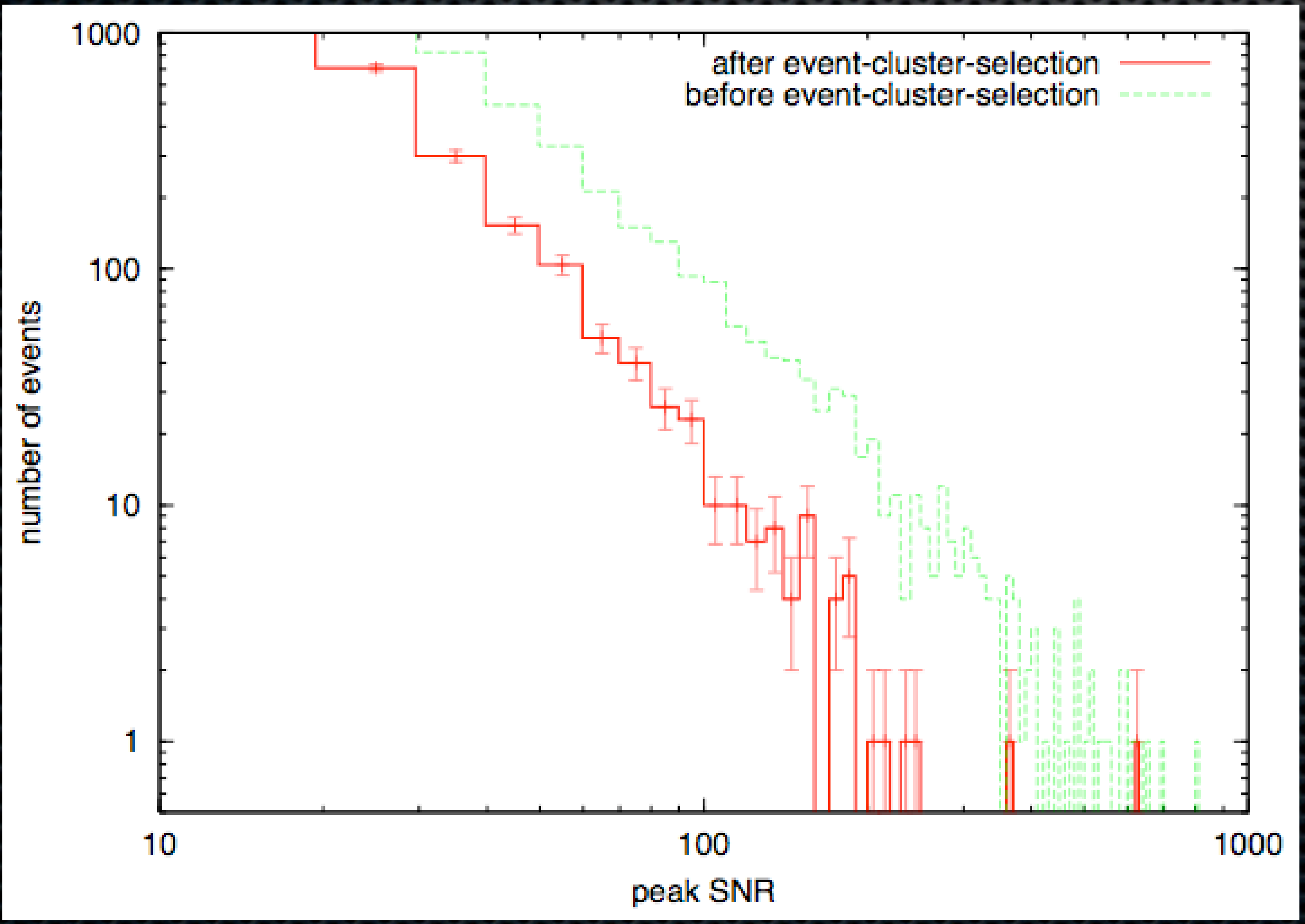
$f4v \leq 6.0$

$t2v^{1/2}/S \geq 0.04$

by R.Honda (Osaka City Univ.)

# *Efficiency and Selected Events*




efficiency = 86 % within 10pc (SNR > 70)

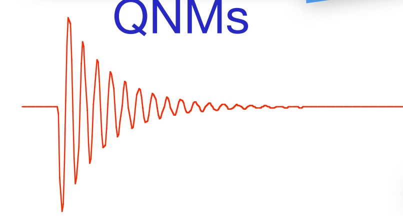
N = 152 event for 1.26 x $10^5$ sec data

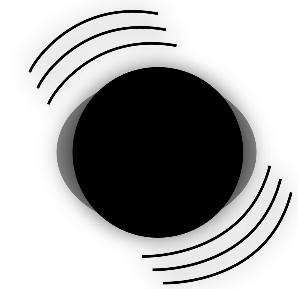
Rate = N / (T x efficiency)
= **1.4 x $10^{-3}$ events/sec**
= 4.9 events/hour

by R.Honda (Osaka City Univ.), Master Thesis, Feb. 2007

# 2. Ringdown GW
# from black-hole quasi-normal mode

Binary, SN expl. — inspiral-merger / core collapse → BH formation (perturbed BH) — Ringdown (QNMs) → Kerr BH





Waveform: Damped sinusoid (Quasi-normal modes)

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

**central frequency**

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

**Quality factor**

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

M: Mass
a: Spin

**Echeverria (1989)**

* Probe for BH direct observation
* BH physics in inspiral-merger, core collapses, ...
* Good SNR expected, ~ 100@10kpc (TAMA sensitivity)

by Y.Tsunesada (NAO, Tokyo Institute of Technology)

# Matched Filter Design for BH Ringdown

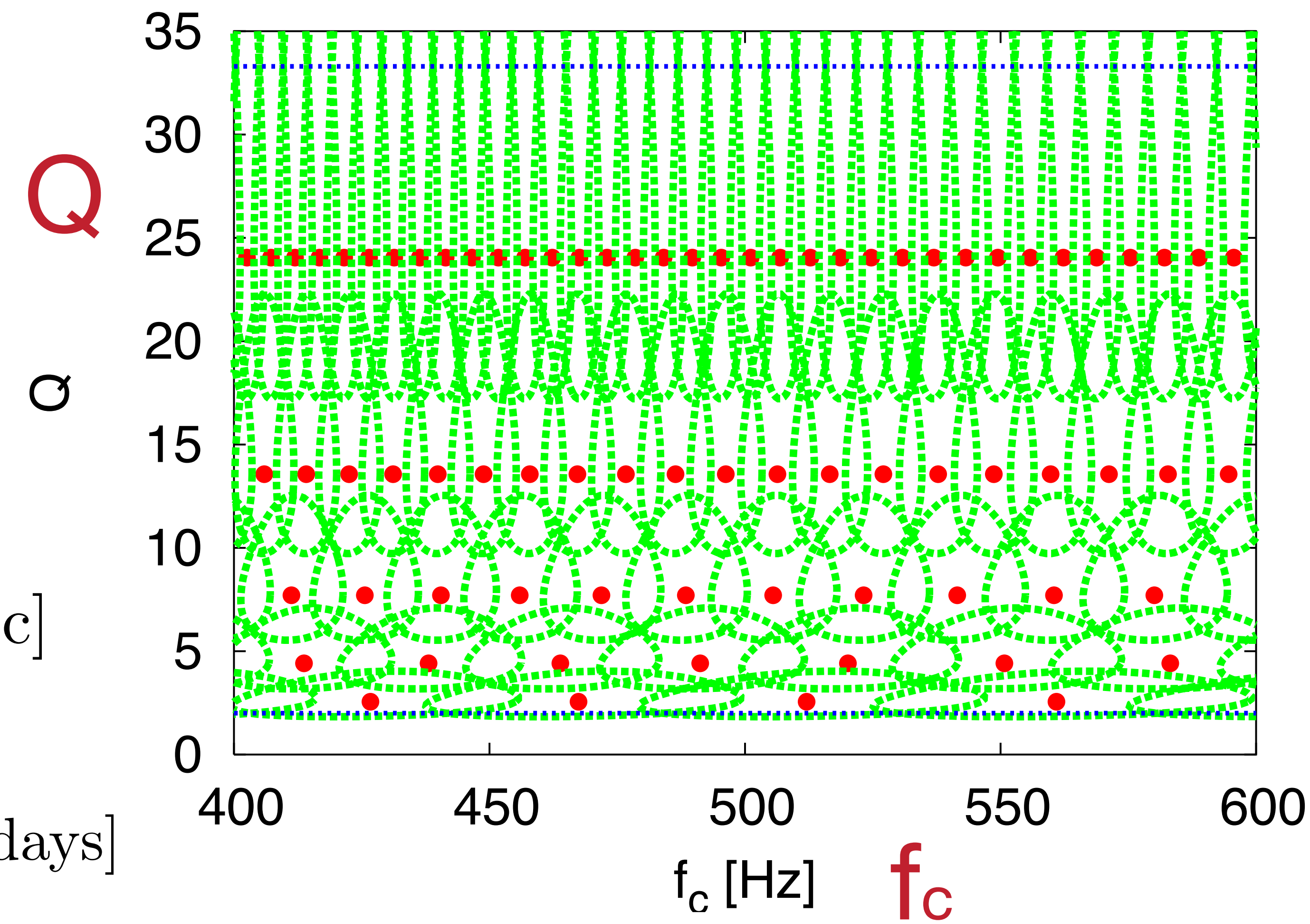
$$\rho = \int \frac{s(f) h^*(f; f_c, Q)}{S_n(f)} \mathrm{d}f$$

s(f): signal + noise
h(f): template
Sn(f): Weight (noise power)

Template construction in (fc, Q) plane
(Nakano, Takahashi, Tagoshi, Sasaki, PRD 2003)

fc = 100 ~ 2500 [Hz]
Q = 2 ~ 33.3 (a = 0 ~ 0.998)

682 templates (SNR loss < 2%)




CPU Time

Intel
PenIV 2.5GHz

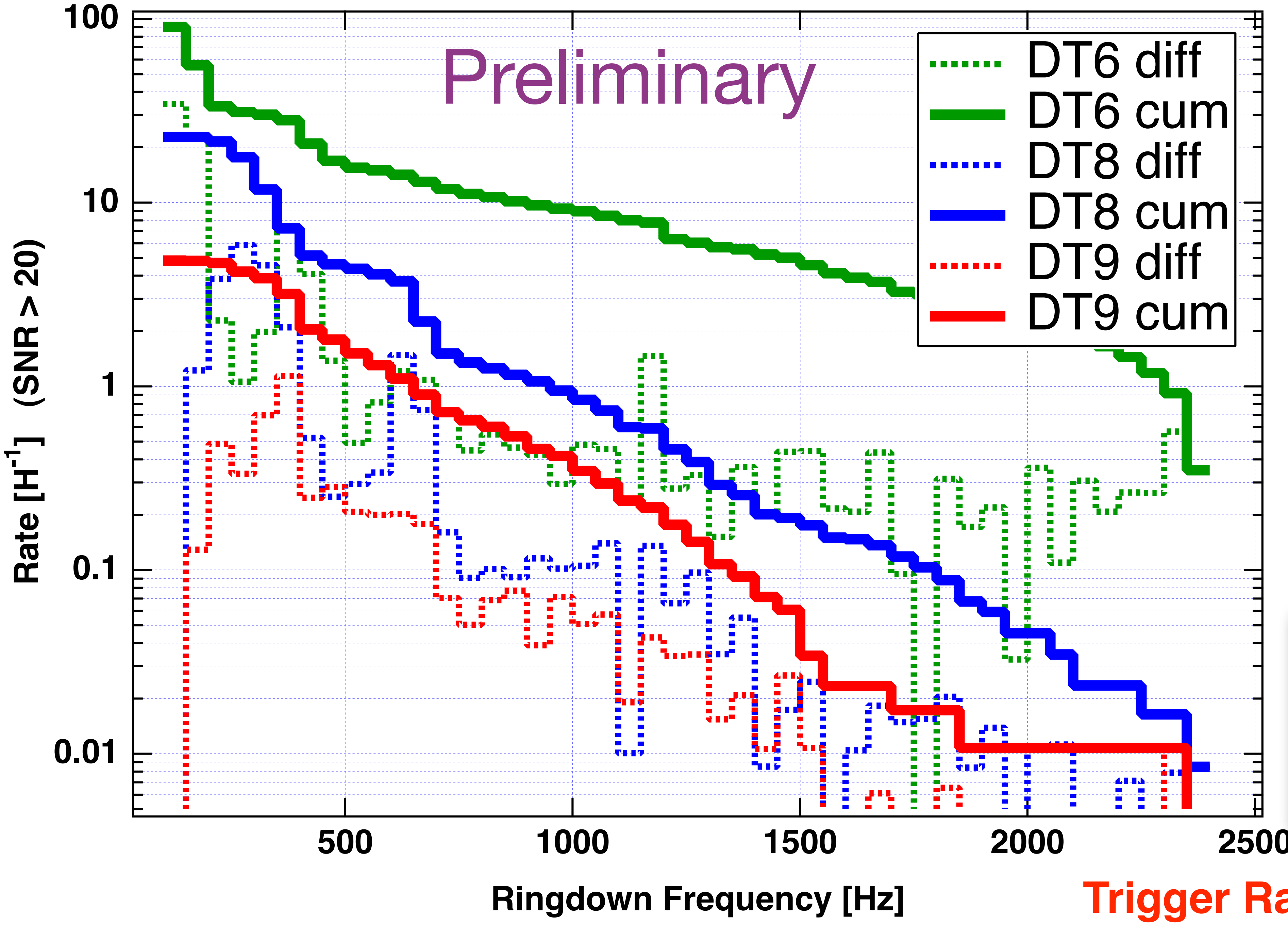
$$T^1_{50\mathrm{s}} = 130 \left( \frac{N_{\mathrm{tmplt}}}{682} \right) [\mathrm{sec}]$$

$$T_{1000\mathrm{h}} = 6.5 \left( \frac{N_{\mathrm{tmplt}}}{682} \right) \left( \frac{16}{N_{\mathrm{CPU}}} \right) [\mathrm{days}]$$

by Y.Tsunesada

# *Trigger Rate of the Ringdown Search*

$$R(f_c) = \frac{N_{\rm trg}(f_c)}{T_{\rm obs}} \frac{1}{\epsilon(f_c)} \frac{1}{1 - ({\rm false\ dismissal})}$$




$f_c$ > 1500Hz:
($M < 20M_{solar}$)

DT6:
$$R < 4.6\,[{\rm H}^{-1}]$$

DT8:
$$R < 1.8 \times 10^{-1}\,[{\rm H}^{-1}]$$

DT9:
$$R < 3.4 \times 10^{-2}\,[{\rm H}^{-1}]$$
(SNR > 20)

**Trigger Rate (DT9) < 1ev/day**

*by Y.Tsunesada*

# *BH Mass Spectroscopy ...*

- Ringdown GW detection can measure;
  - Q = Kerr parameter
  - fc = Mass of BH

| $Q^M$ | $(\Delta f_c/f_c)_{RMS}$ | $(\Delta Q/Q)_{RMS}$ | $(\Delta M/M)_{RMS}$ | $(\Delta a/a)_{RMS}$ |
|---|---|---|---|---|
| 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)

## *3. Keyword for short signal searches*

- Different types of ‘waveforms’ and search methods
  - Burst : only numerical predicted, power filter
  - Ringdown : anlytical prediction, matched filter
- Even so, there are same noise sources !
  - Spike, Glitch, Steps...
  - Non-Gaussianity
  - Instabilit
    - Short GW search requires ‘silent detector’.

# *Summary*

- TAMA searched for short GW signals, and derive upper limits:
  - Burst GW
    - Excess power filter, ALF, TF cluster
  - BH ringdown GW
    - Matched Filter
- The data analysis evaluated a kind of TAMA detector noise characteristics.