# Search for Black Hole Ringdowns Using TAMA300 Data

Method, Event Selections,
Rate, and Upper Limit

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**for the TAMA Collaboration**

GWDAW-9 2004, Dec 15-18, Annecy, France

# Ringdown GWs


Waveform: Damped sinusoid (Quasi-normal modes)

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

central frequency $f_c = \dfrac{3.2\times10^4[\mathrm{Hz}]}{M/M_\odot}\left[1-(1-a)^{0.3}\right]$ Echeverria (1989)

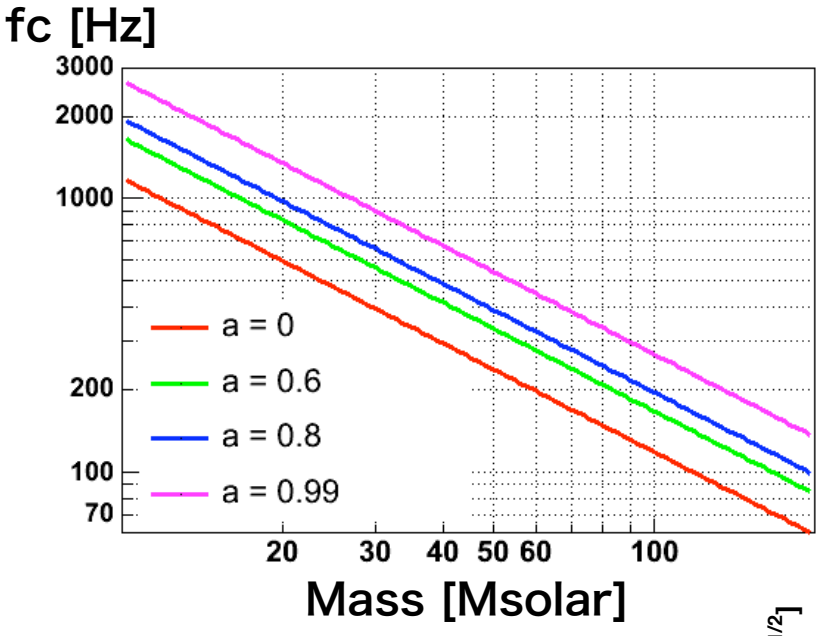
Quality factor $Q = 2.0(1-a)^{-0.45}$

M: Mass

a: Spin

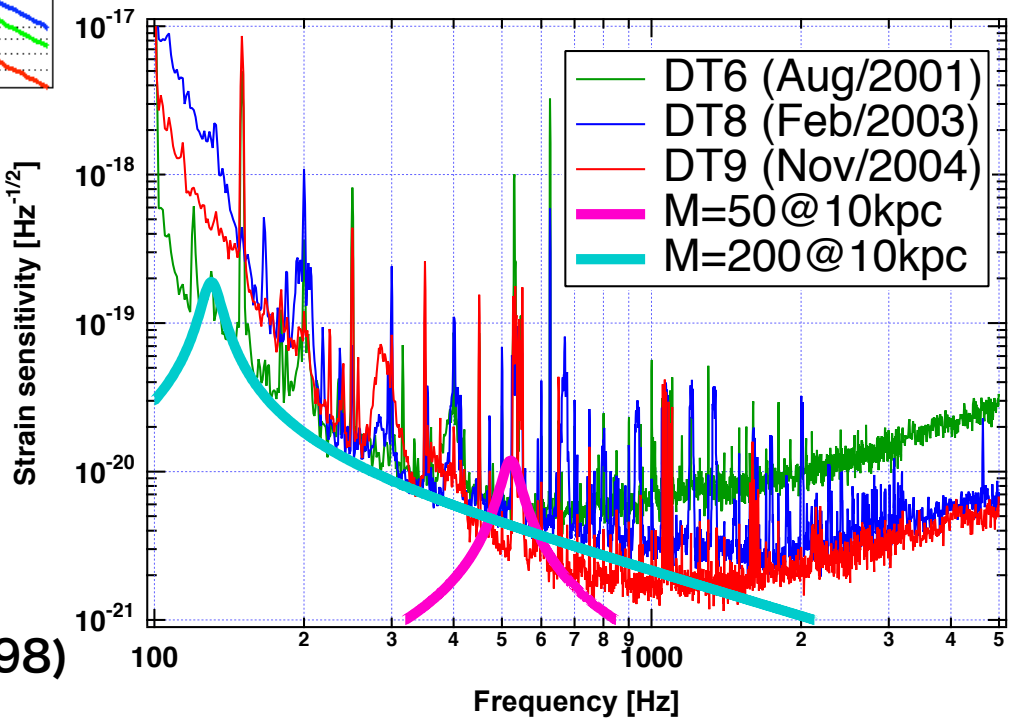
* Probe for BH direct observation
* BH physics in inspiral-merger, core collapses, ...
* Good SNR expected, ~ 100@10kpc (TAMA sensitivity)

# Ringdown GWs




## Mass-frequency relation

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




GW luminosity ~3%
(Hughes&Flanagan 1998)

# Matched Filter

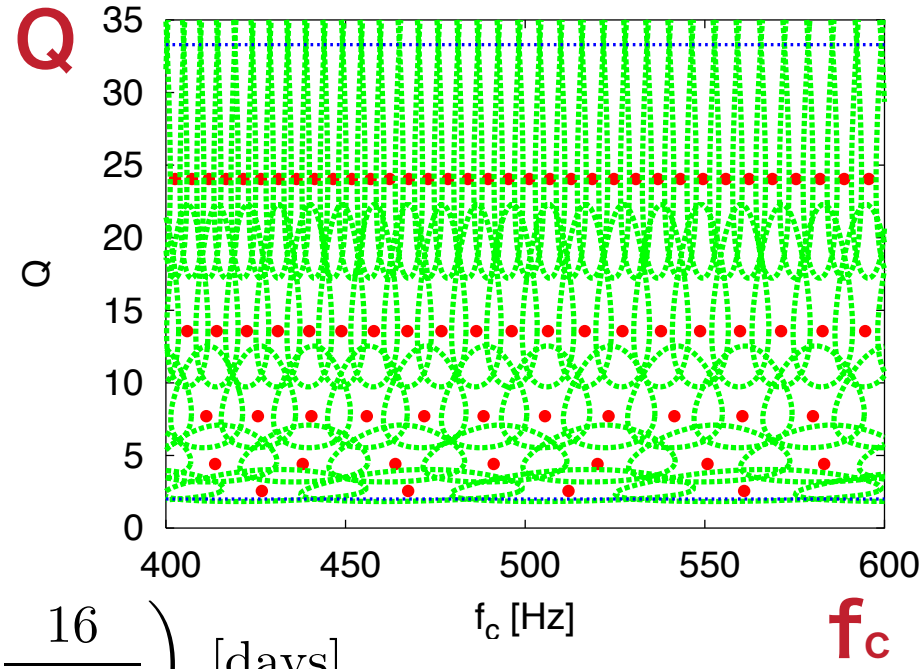
$$\rho = \int \frac{s(f)h^*(f; f_c, Q)}{S_n(f)} \mathrm{d}f$$

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

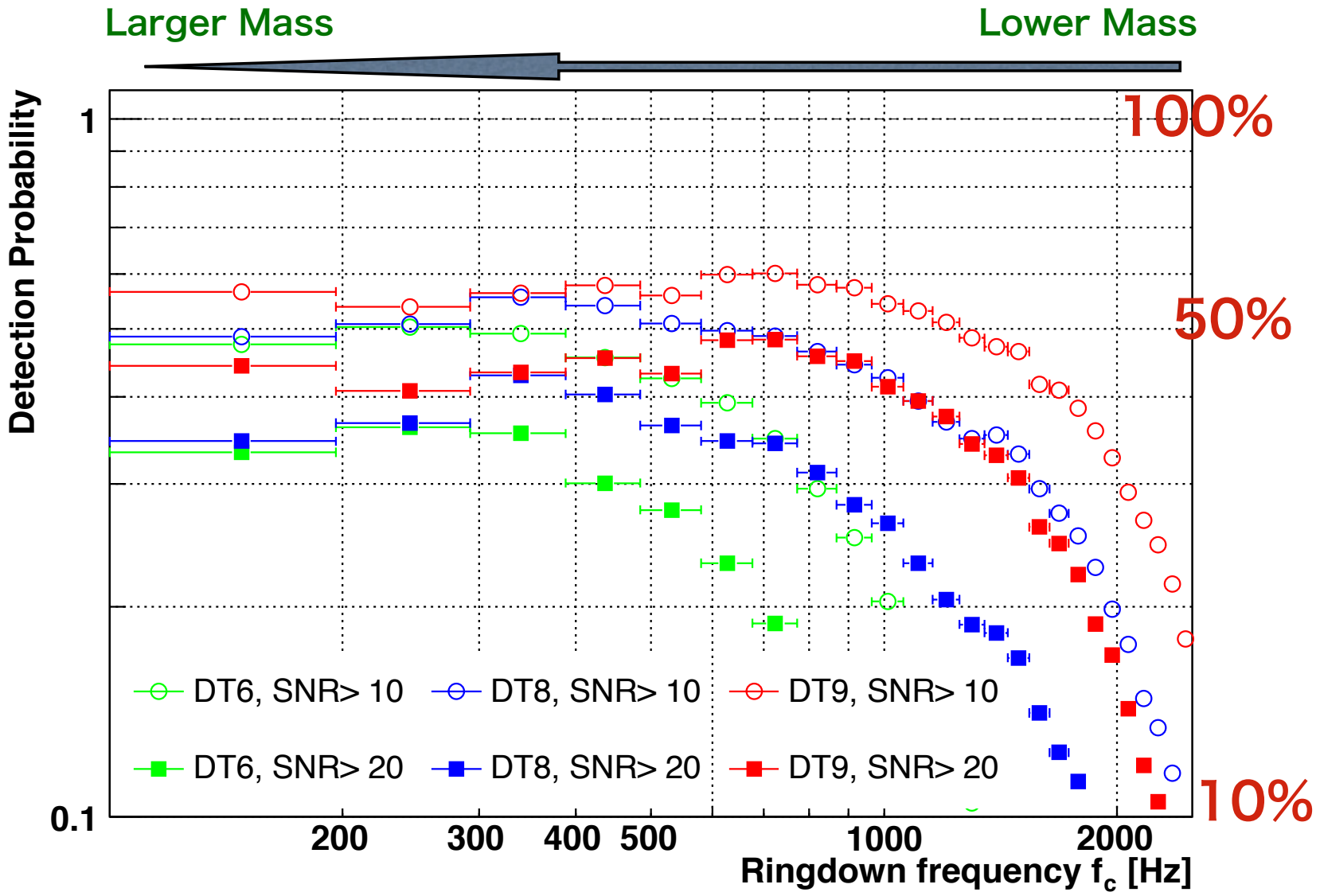
Intel
PenIV 2.5GHz $T_{1000\mathrm{h}} = 6.5 \left( \frac{N_{\mathrm{tmplt}}}{682} \right) \left( \frac{16}{N_{\mathrm{CPU}}} \right)$ [days]

# TAMA Observations

| | Year<br>Month | Lock Time [H] | Eff. Time [H] |
|---|---|---|---|
| **DT6** | 2001<br>Aug-Sep | 1042 | 959 |
| **DT8** | 2003<br>Feb-Apr | 1166 | 1086 |
| **DT9** | 2003/4<br>Dec-Jan | 472 | 430 |

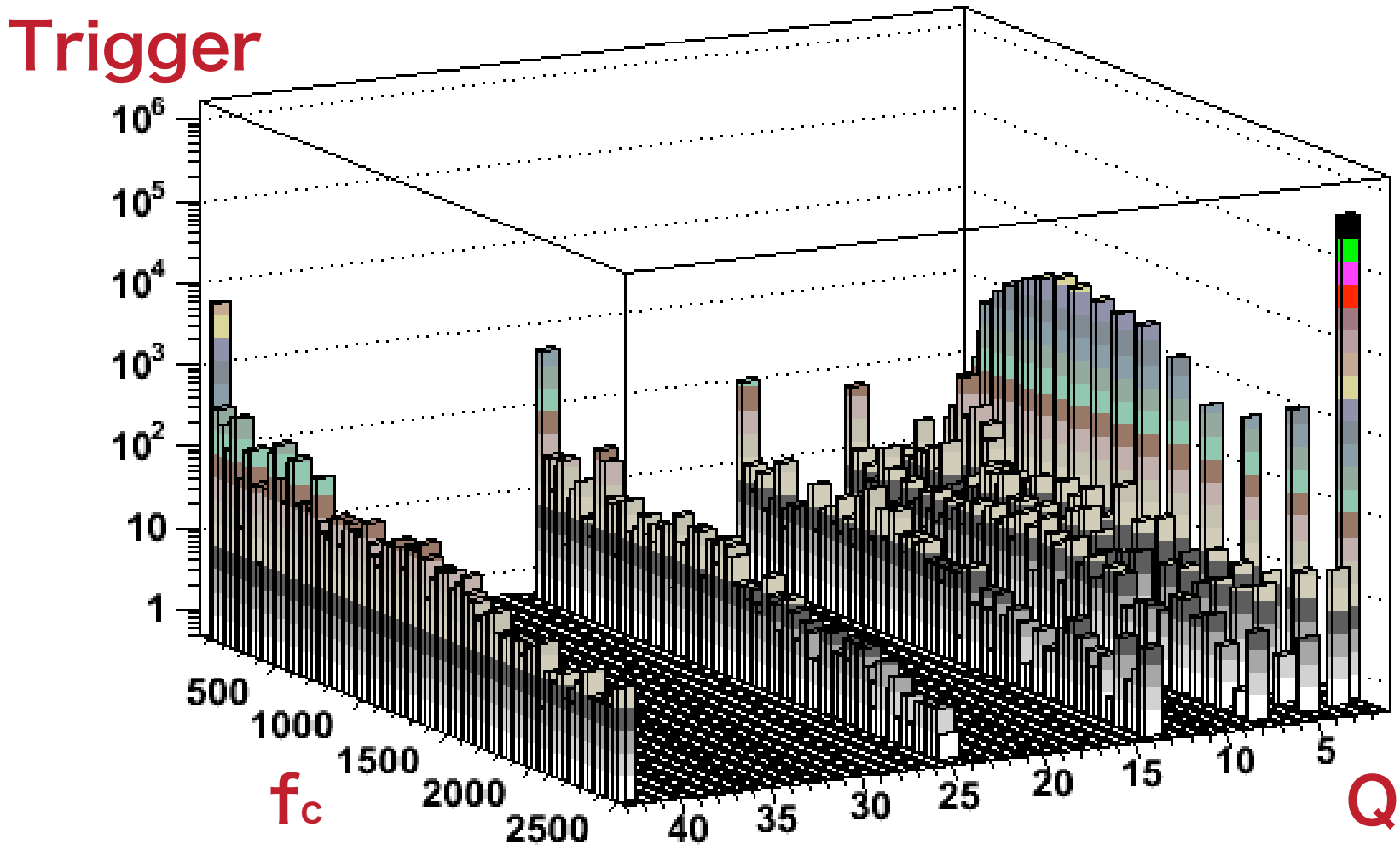
Eff. Time = (Lock Time) - [4min * 2 * (number of locked segments)]

# Detection Probability for Galactic events

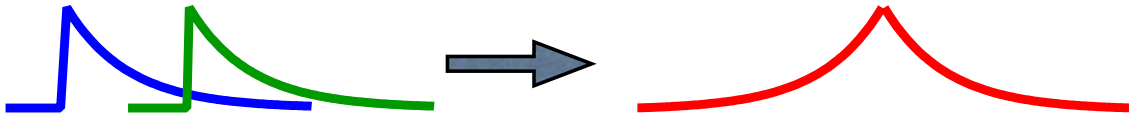


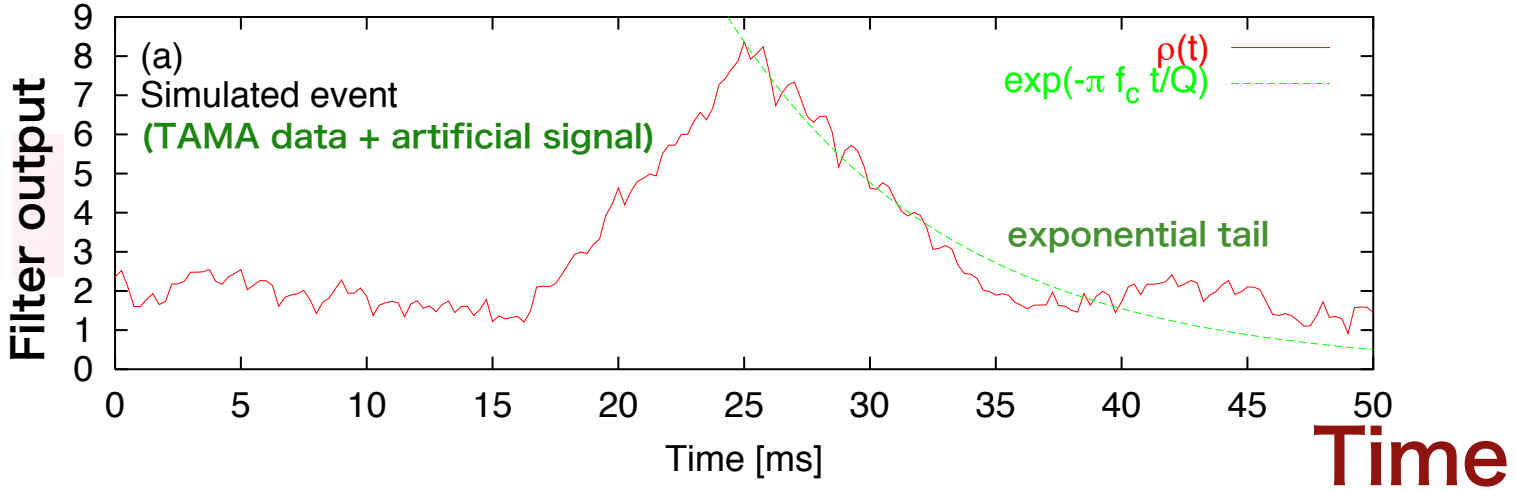
# Matched Filter Triggers

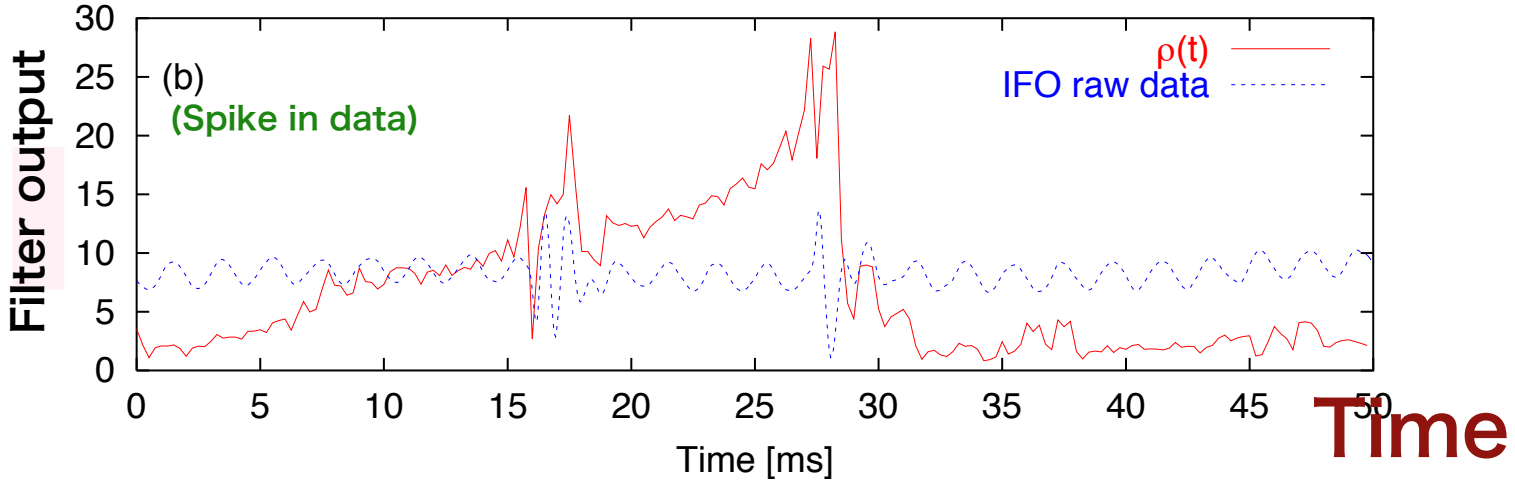
Trigger rate ~ 1/min (!)



# Filter Output Examples:



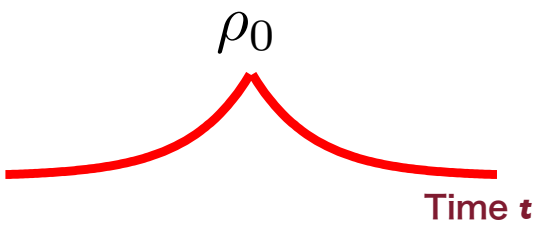


# Event Selection

**True signal** :

* exponential tail $\tau = Q/\pi f_c$
* symmetric around the local maximum $\rho_0$

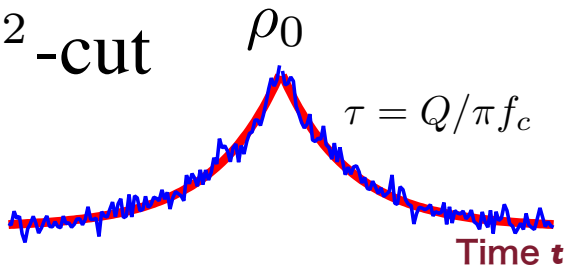



**Fake triggers** :

* exp rising, no tail

## Time Domain Cuts:

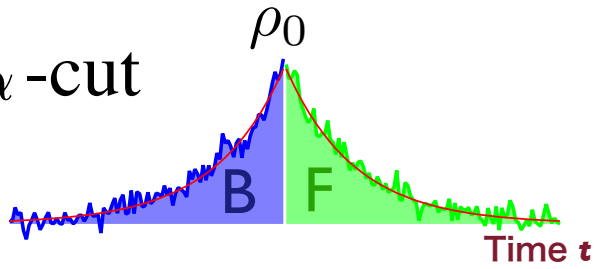
$\xi^2$-cut




filter output  expected tail

$$\xi^2 \equiv \frac{1}{\rho_0^2} \sum [\rho(t) - \rho_0 \exp(-t/\tau)]^2$$

$\alpha$-cut

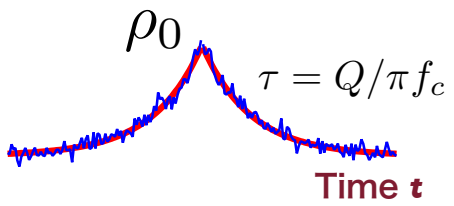



$$\alpha \equiv \frac{F - B}{F + B}$$

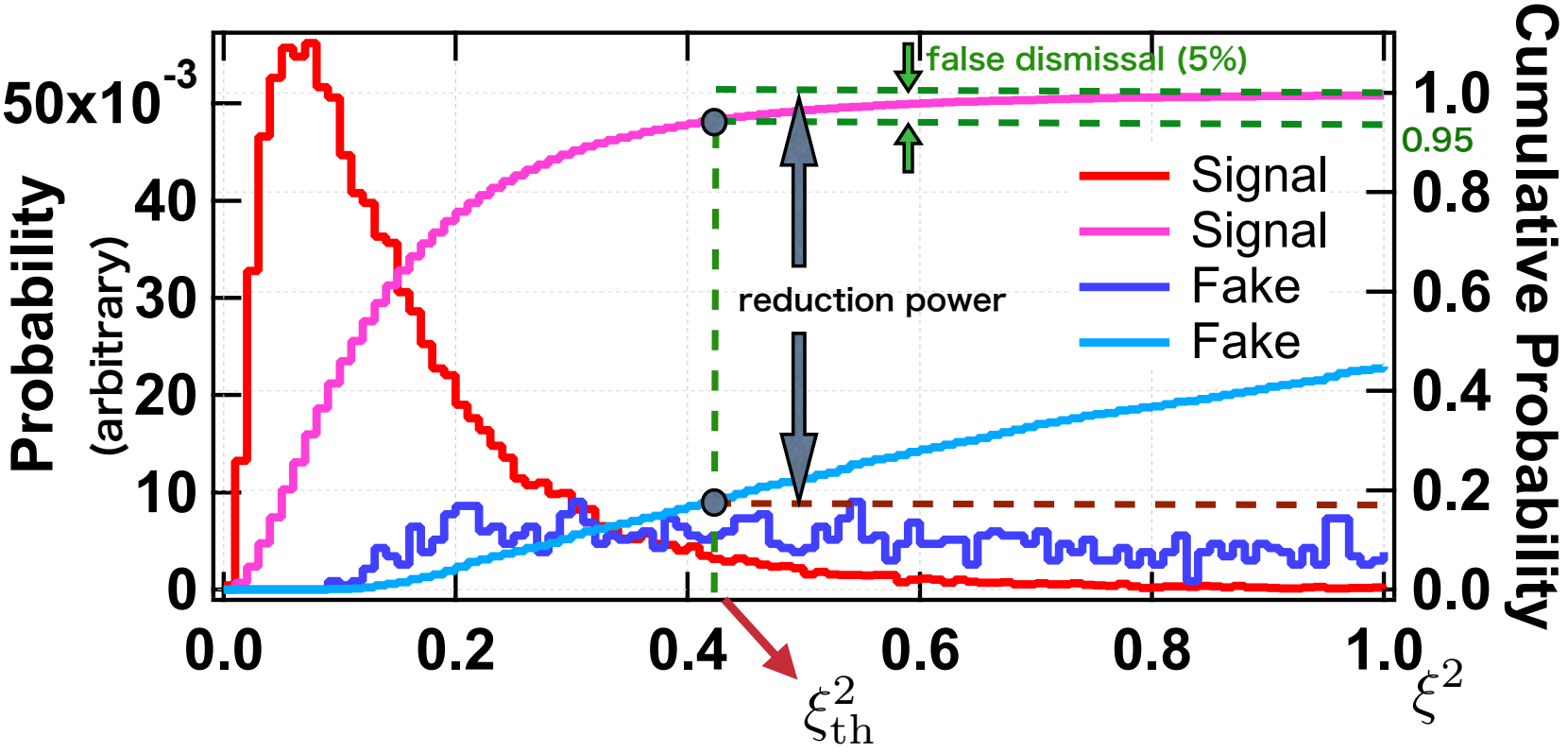
True signal

---> smaller $\xi^2$ $\alpha$

# Event Selection parameter cut

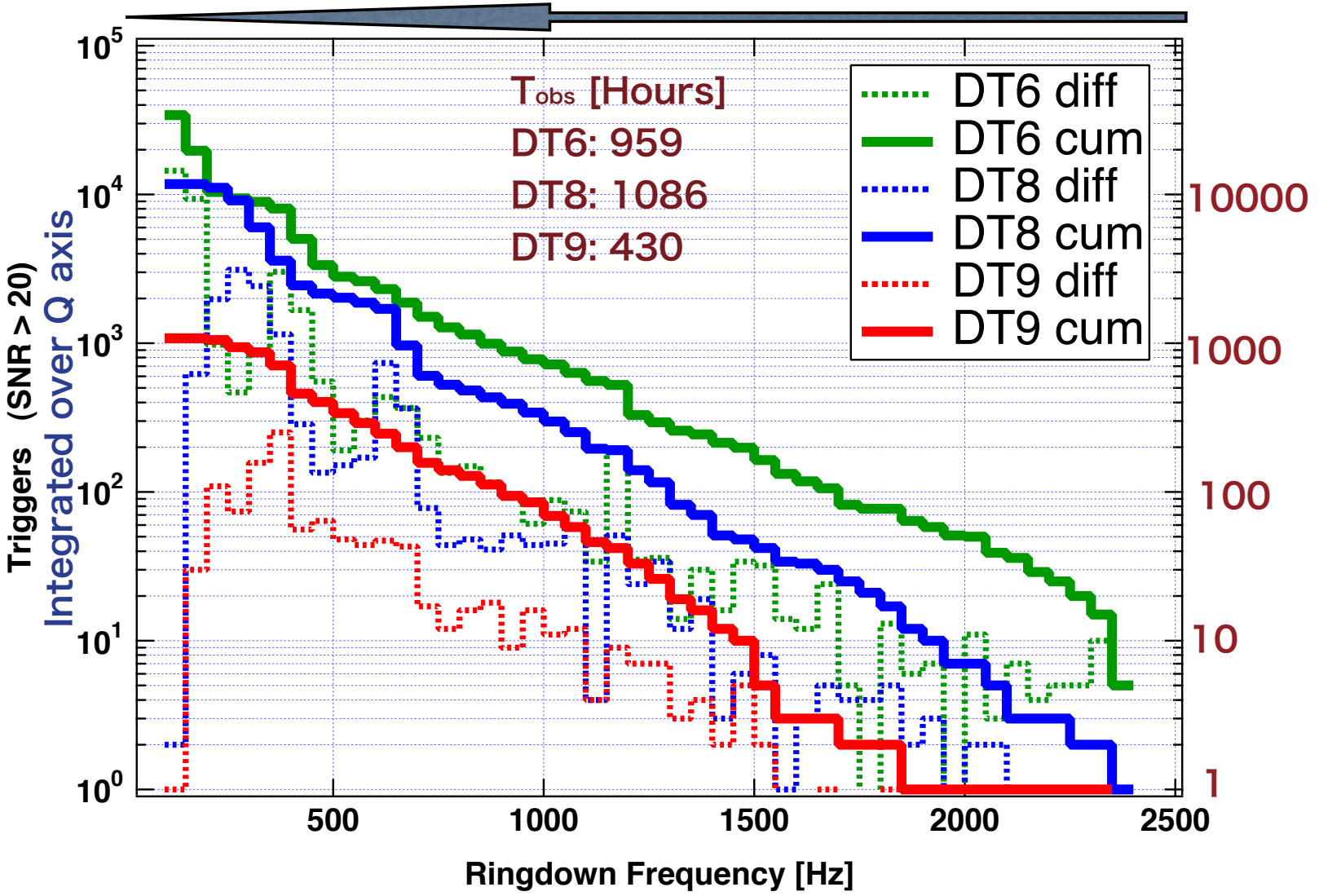



$$\xi^2 \equiv \frac{1}{\rho_0^2} \sum \left[\rho(t) - \rho_0 \exp(-t/\tau)\right]^2$$



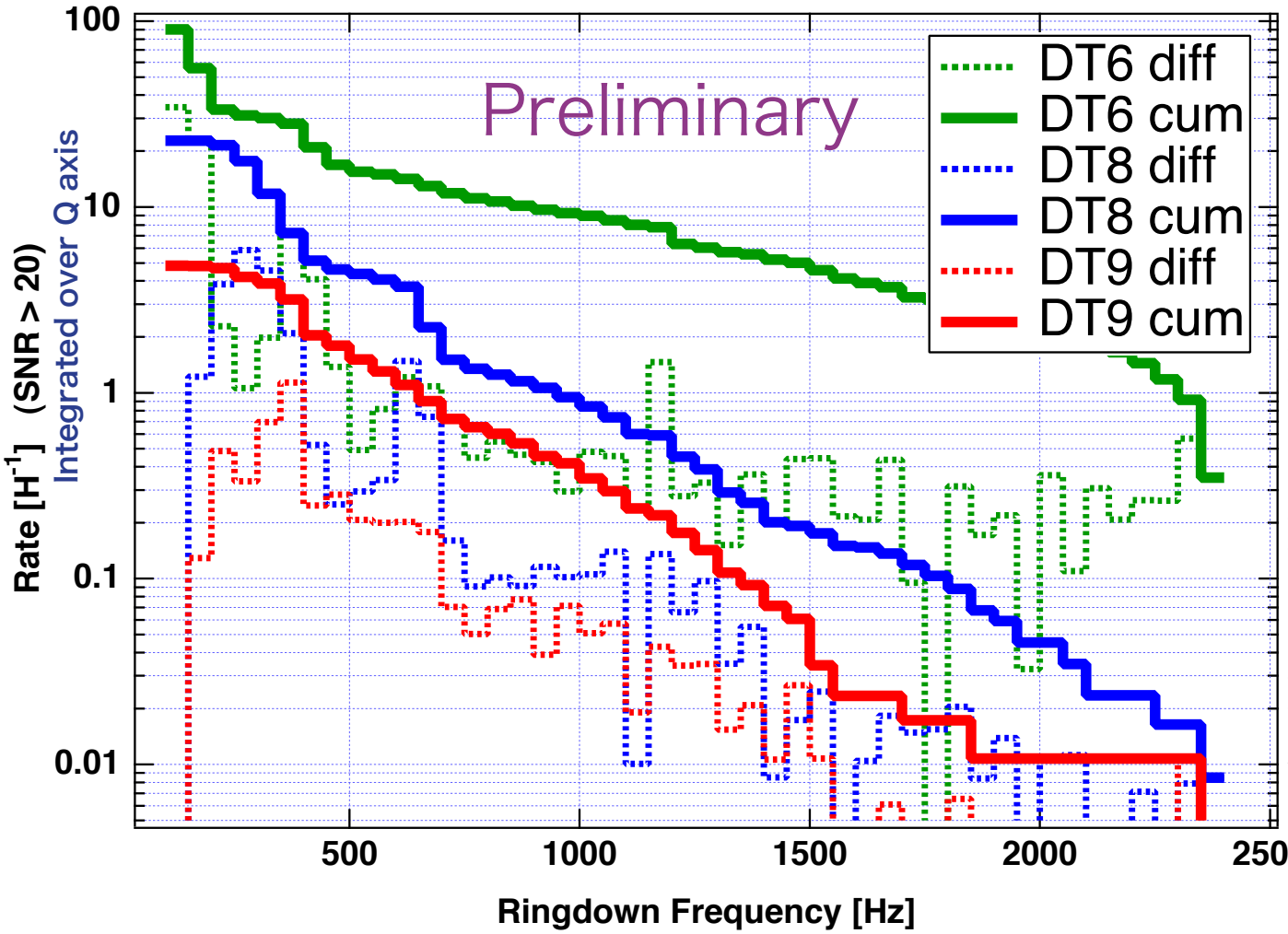
# Triggers

## after selections



# Galactic Event Rate

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




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

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

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

DT9:
$R < 3.4 \times 10^{-2}\,[\mathrm{H}^{-1}]$

(SNR > 20)

# Summary

* BH ringdown is promising GW source

* Matched filtering code developed

* TAMA has good sensitivity to detect Galactic events, detection probability > 10%

* Galactic event rate < 1 event/day

    * DT9
    * SNR > 20
    * 1500Hz < fc < 2500Hz (10 < M < 20)

# Galactic Event Simulation

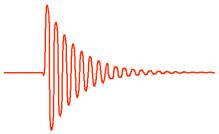
(software injection)

## Event Generator

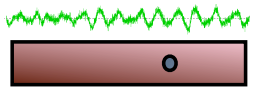
Position ($R$, $z$, $\varphi$)

Waveform ($f_c$, $Q$)

phase $\phi$, spin axis/rad.pattern



Source info.

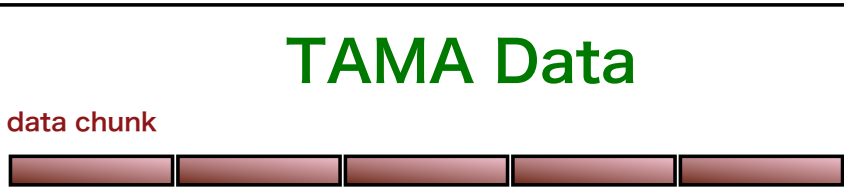


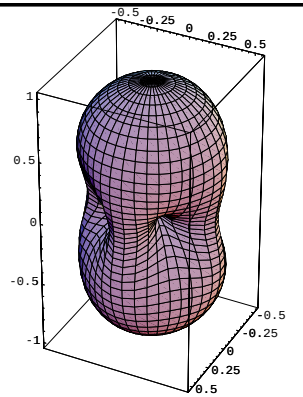
injection point

Time info.

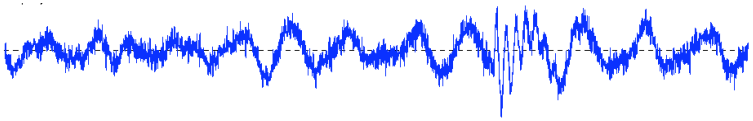
## TAMA Data

data chunk



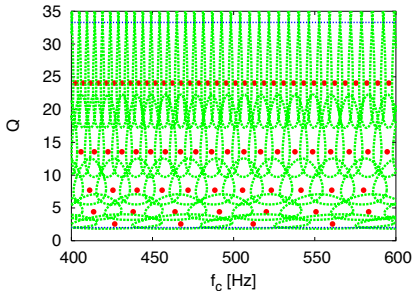



Injection

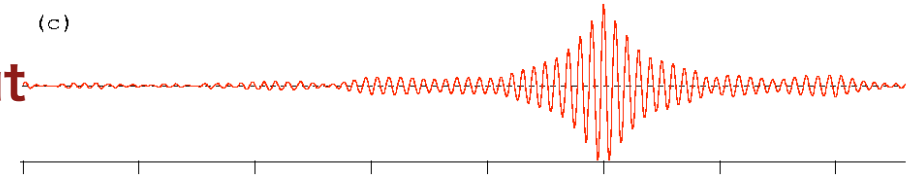


Matched filter

Template bank




Filter output




- SNR
- Detection prob.
- Waveform param acc.
- How signals look like?