Search for Black Hole Ringdown Gravitational Waves in TAMA300 Data

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TAMA Collaboration

Outline

- **Black hole *ringdowns***
  - Motivation
  - BH quasi-normal oscillation
  - (M, a) and (f_c, Q) of ringing
- **Search for ringdowns in TAMA300 data**
  - TAMA sensitivity, SNR
  - Matched-filter analysis
    - ✔ Template construction
    - ✔ Galactic event simulation
    - ✔ Veto techniques
- **Conclusions**

Ringdown GWs

■ *Ringdown GW*

Binary SN expl. --Insp-merger / Core clps--> BH formation → QNM **Rindown** → Kerr BH

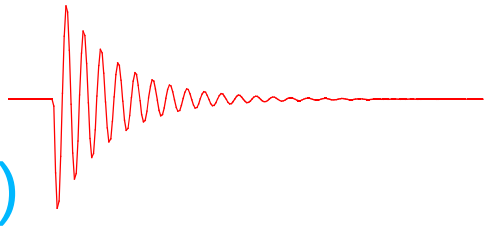
- BH direct observation
- Another mass window to binary observation → **BH probe**

(*M=10*M_{sol}: ~ *100*Hz for chirp, ~kHz for ringdown)

■ Ringdown Waveform:

- **Quasi-normal oscillation with (f_c , Q)**

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



- f_c: Central frequency $$f_c \approx \frac{3.2\times10^4}{M}\left[1-0.63\left(1-a\right)^{0.3}\right]$$ [Hz]
- Q: Quality factor $$Q \approx 2.0\left(1-a\right)^{-0.45}$$ for least damped modes, Echeverria(1989)

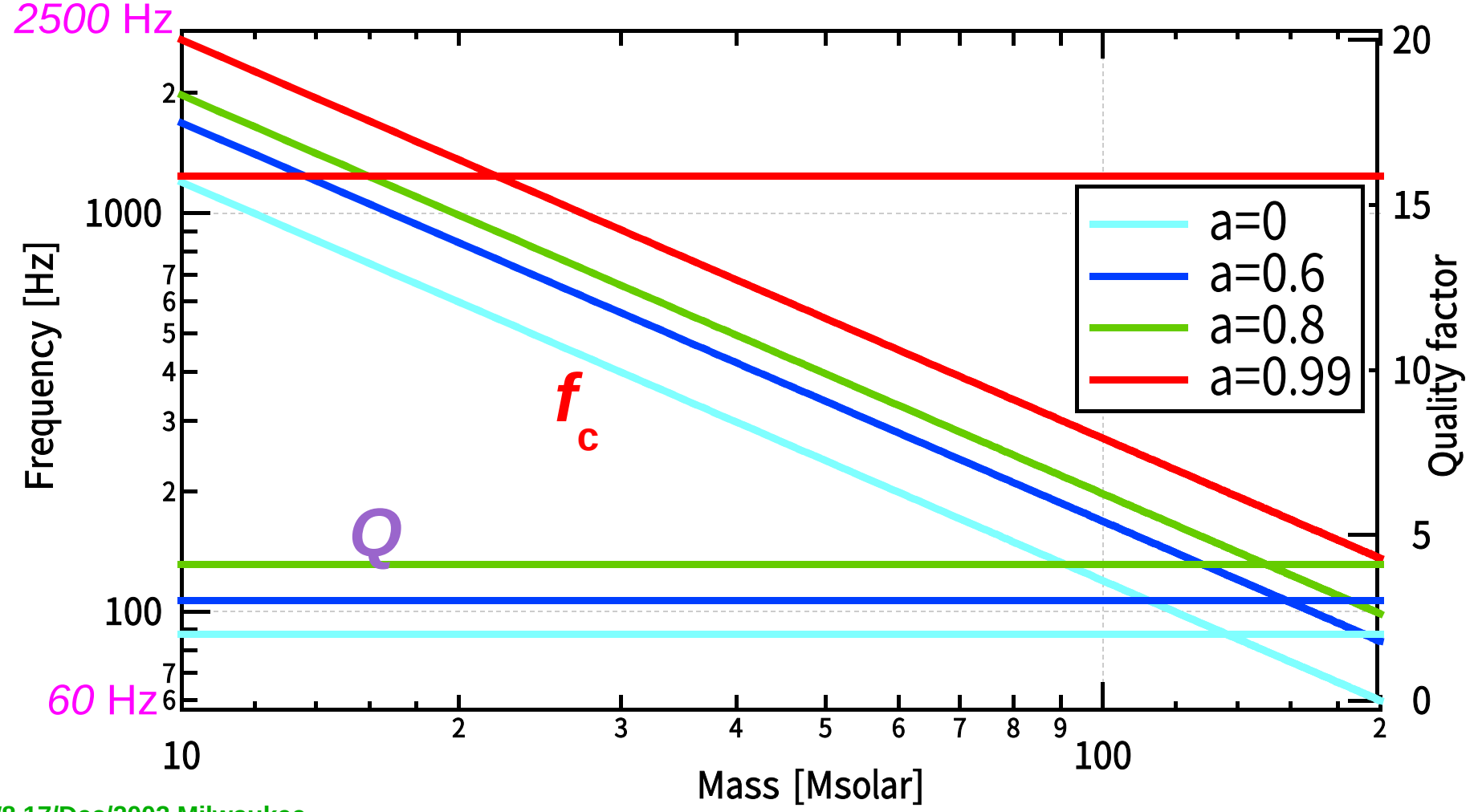
- M: BH mass
- a: Angular momentum [0, 1)

$(f_c, Q) - (M, a)$ Echeverria formulae

$$f_c \approx \frac{3.2\times10^4\,[Hz]}{M}\left[1-0.63(1-a)^{0.3}\right],$$

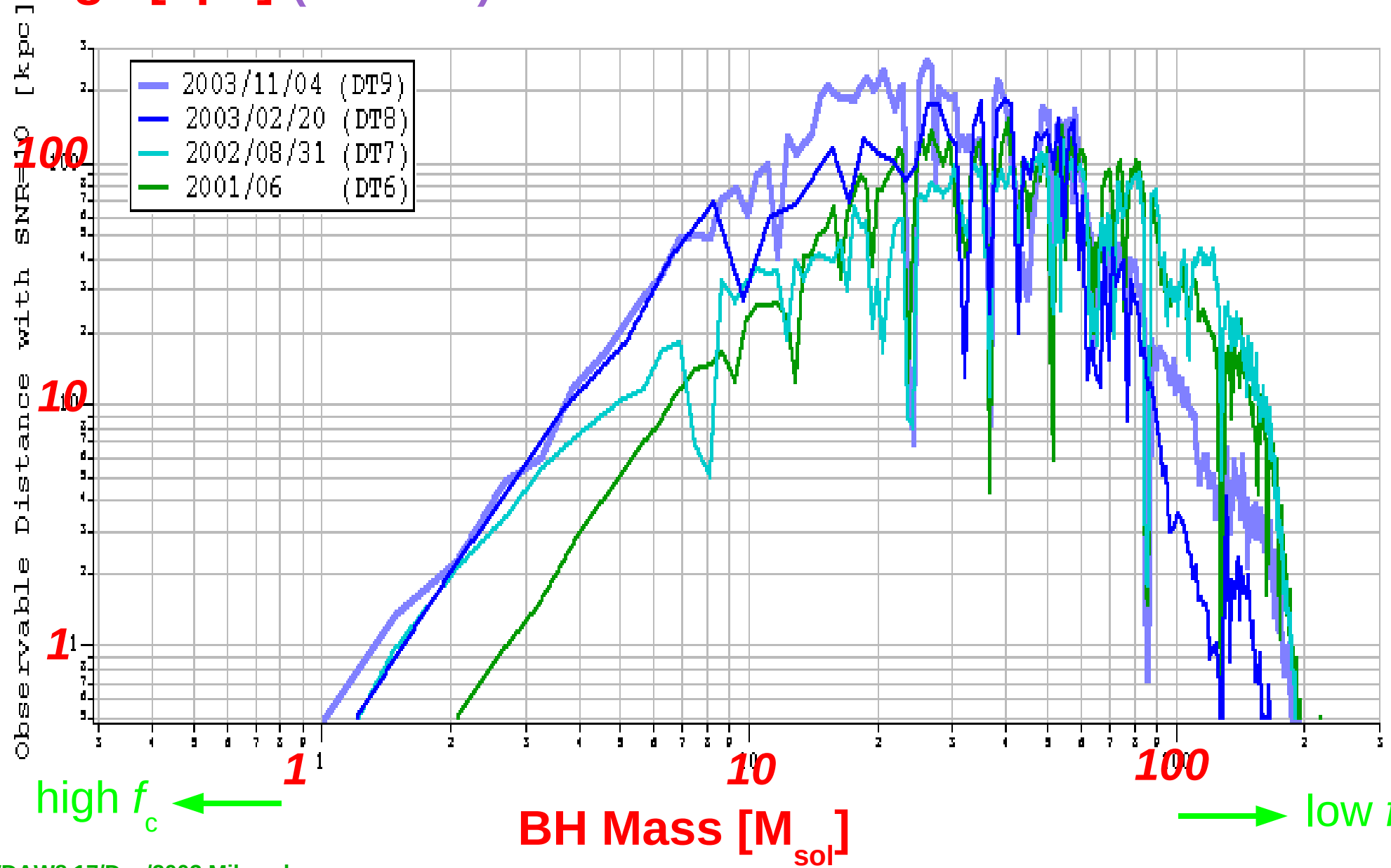
$$Q \approx 2.0(1-a)^{-0.45}$$

Typical time scale: $\tau = Q/\pi f_c \sim 10$ [ms]



TAMA Sensitivities to Ringdowns

Range [kpc] (SNR=*10*)



Template Construction

- **Nakano's formalism for template placement**

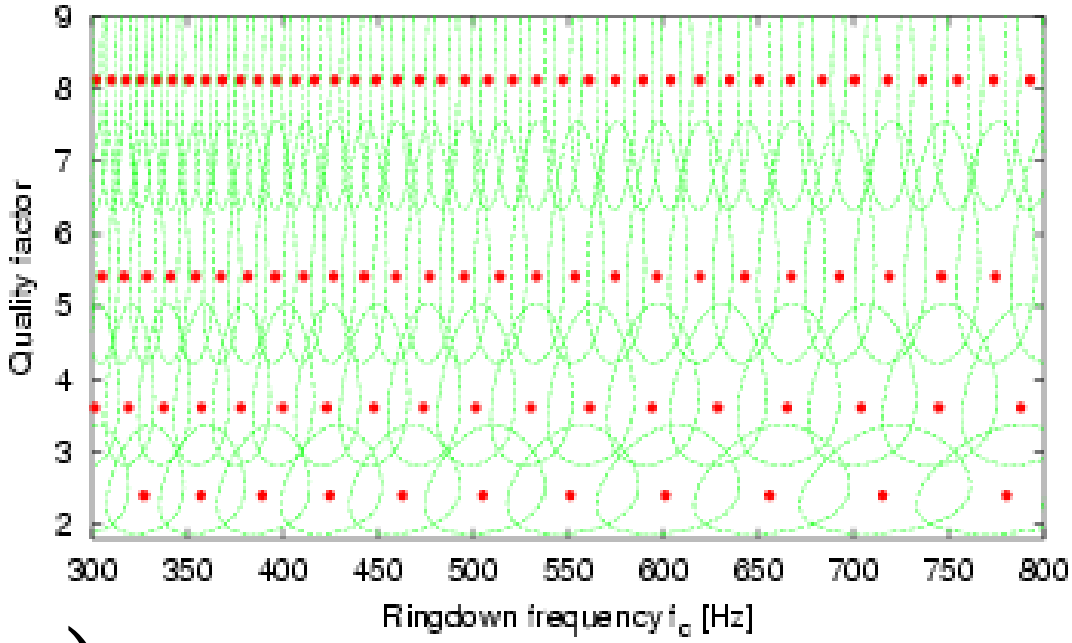
(published in *PRD* Nov 2003, see poster by Nakano !)

$$\rho = \int \frac{s(f)h^*(f)}{S_n(f)} df$$

h(*f*) = *h*(*f* ; f_c, *Q*)

- f_c = *100 – 2500* [Hz]
- *Q = 2 – 22* *(a = 0 – 0.995)*
- SNR loss < *2%* *(MM = 0.98)*

→ **800 templates**



- **Computation Time:**

Intel Pen-IV 2.5GHz Linux2.4

$$T^{1}_{50s} = 3\left(\frac{N_{tmplt}}{800}\right) \quad \text{[min]}$$

50sec data chunk

$$T_{1kh} = 10\left(\frac{N_{tmplt}}{800}\right)\left(\frac{16}{N_{node}}\right) \quad \text{[day]}$$

1000h data

Galactic Event Simulation

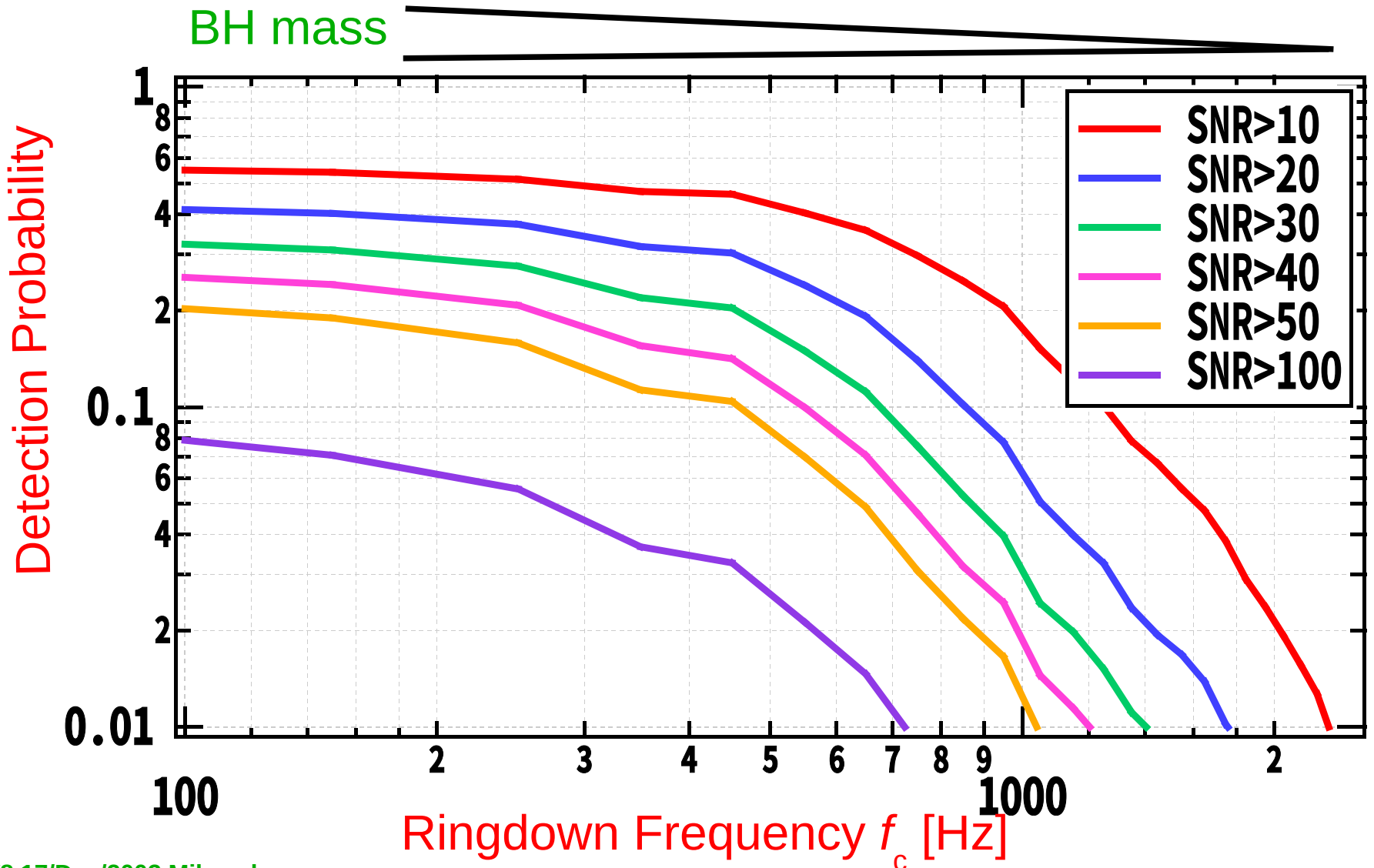
- **Signal (software) injection into TAMA data,**
- **matched filter with the template bank**
  - Detection probability
  - SNR loss due to template distance, noise ⟷ template design
  - How "true" ringdown signals look like in data stream?

◆ Source parameters

- **Random, uniform in (f_c, Q) plane** and initial phase
- **Distance:** (R_0 = *4.8* kpc, h_z = *1* kpc)
  - ✔ Galactic distribution $dN = \exp(-R^2/2R_0^2)\exp(-z/h_z)\,R\,dR\,dz$
- **Incident direction, Sensitivity correction**
  - ✔ (l, b) and injection time ---> TAMA antenna pattern
  - ✔ ${}_{-2}S_{22}(\cos\theta, a)$: BH Radiation pattern
- $\eta=0.03$:
  - ✔ fractional BH mass energy radiated as GWs (*Flanagan&Hughes, 1998)*

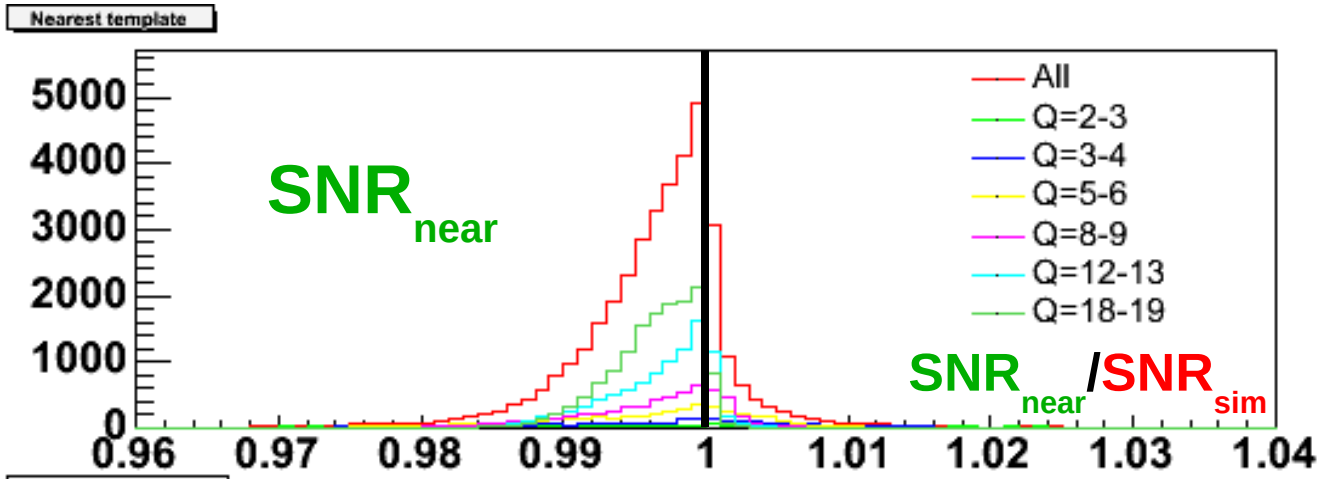
Detection Probability

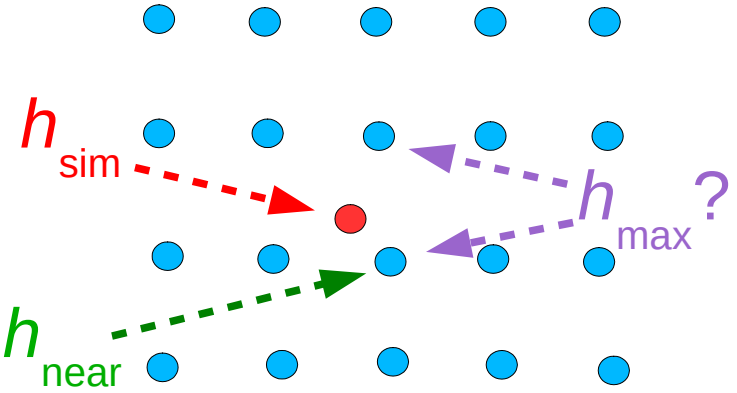
- ~ 50% Galactic events can be detected (SNR > 10, DT6 sensitivity)



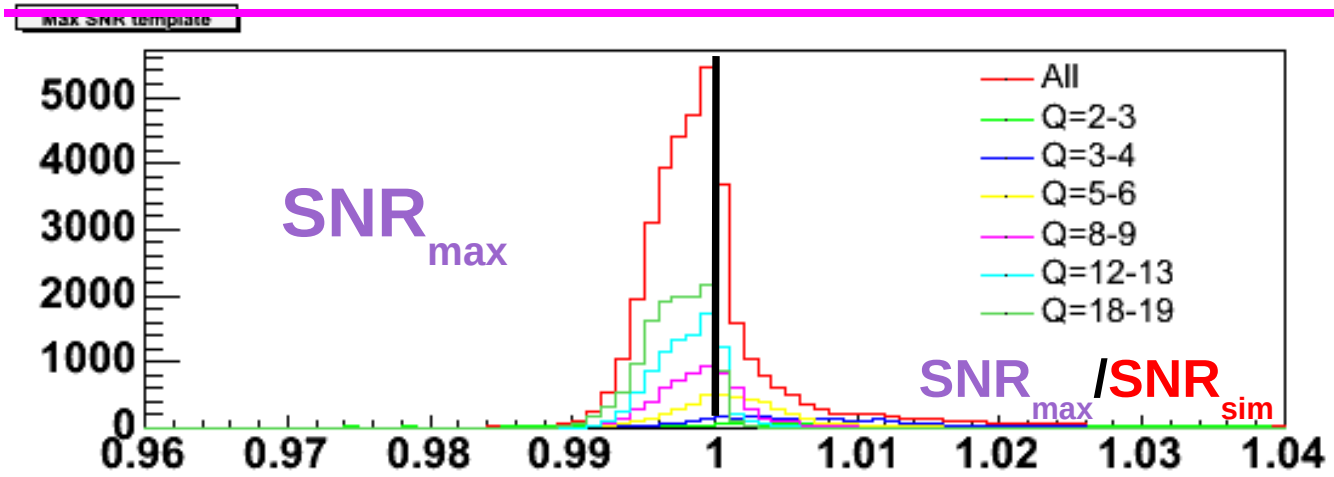
Template Effectiveness

- SNR_{sim} : (h_{sim}, h_{sim})
- SNR_{near} : (h_{sim}, h_{near})





$$\frac{N_{error>2\%}}{N_{sim}} = 0.3\ \%$$



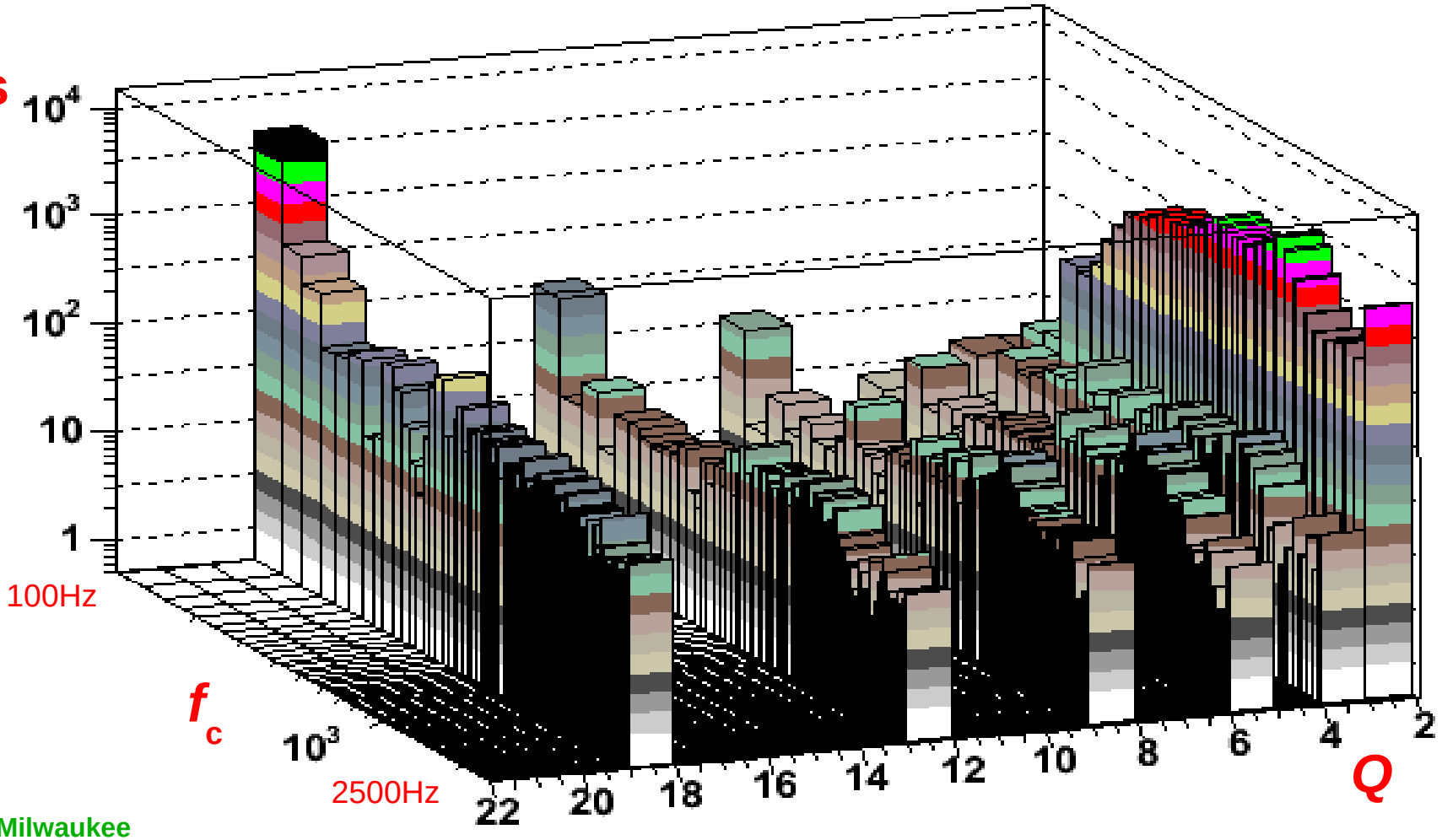
- SNR_{sim}
- SNR_{max} : (h_{sim}, h_{max})

$$\frac{N_{max=near}}{N_{sim}} = 67\ \%$$

$$\sqrt{\langle \Delta f_c^2 / f_c \rangle} = 1.4\ \%$$

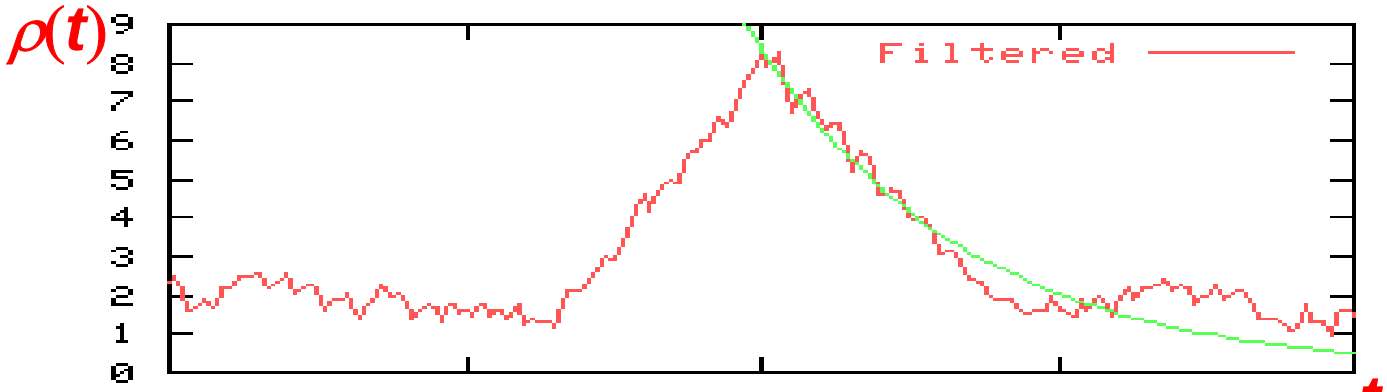
DT6 Event Search

- **TAMA DT6 Run111** (17/Sep/2001 – 20/Sep/2001)
  - **Observation time** : *243000* [sec] ~ *67* [h]
  - **Triggered event** (800 filters, SNR > *10*) : *56400*
  - **Trigger rate** : ~ *0.23* [Hz] (!) ~ 840 [h^{-1}] (SNR > 10)

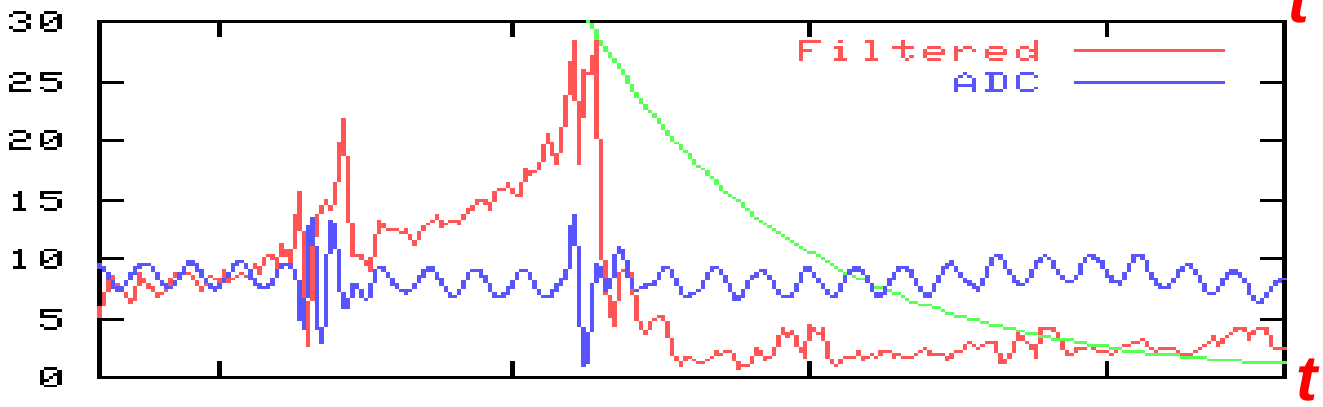


Event Examples

“ *True*” signal
(simulated event)



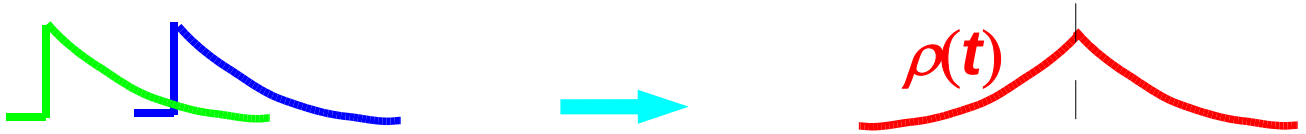
Spurious events
(impulse in ADC)



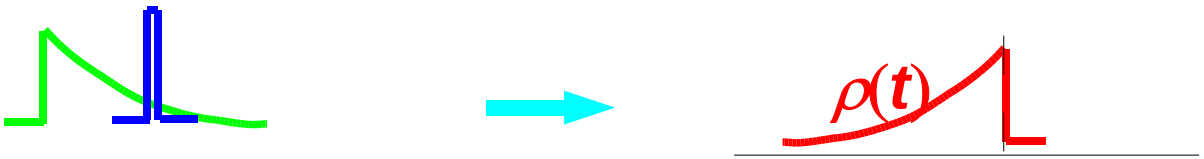
$\rho(t)$
IFO data
$\exp(-\pi f_c t / Q)$

Template X strain data → cross-correlation → Filter output $\rho(t)$

“ *True*” signal



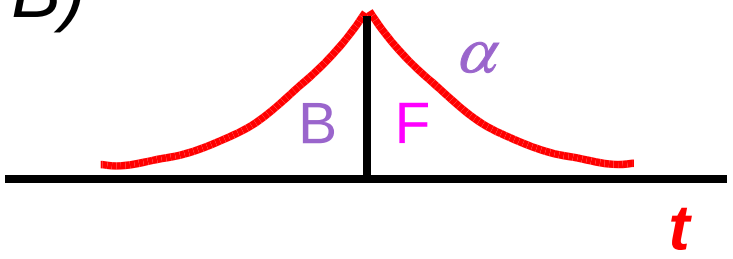
Impulse



Veto Techniques

- Parameters for event selection

  - **Asymmetry** $\alpha = (F - B) / (F + B)$

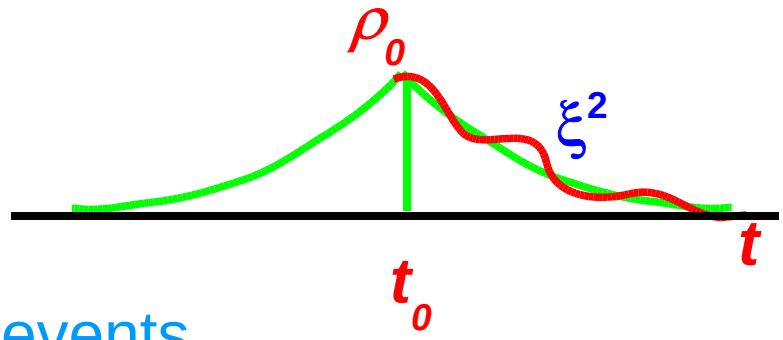


  - **Fit to the exponential tail**

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

template tail

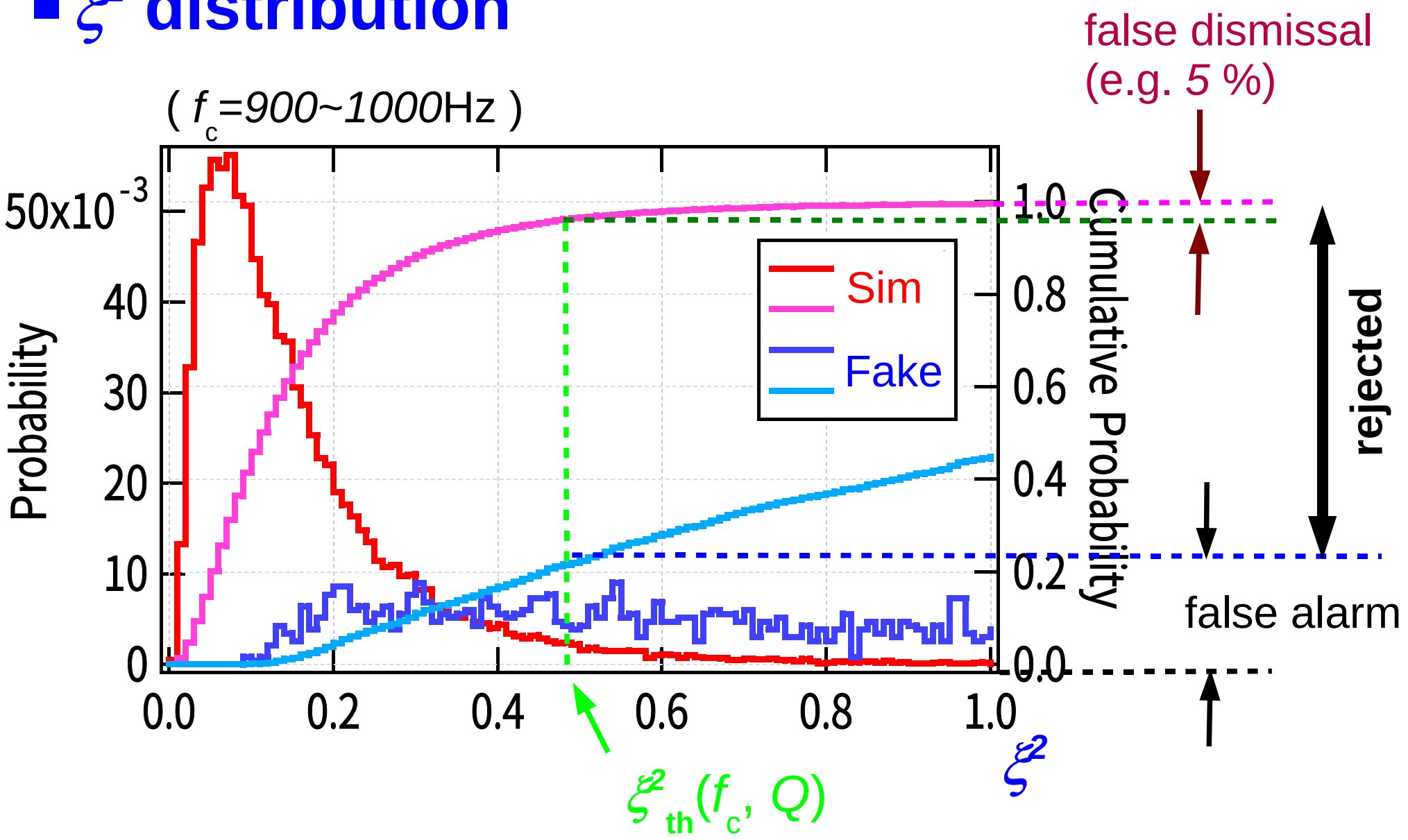
Filter output



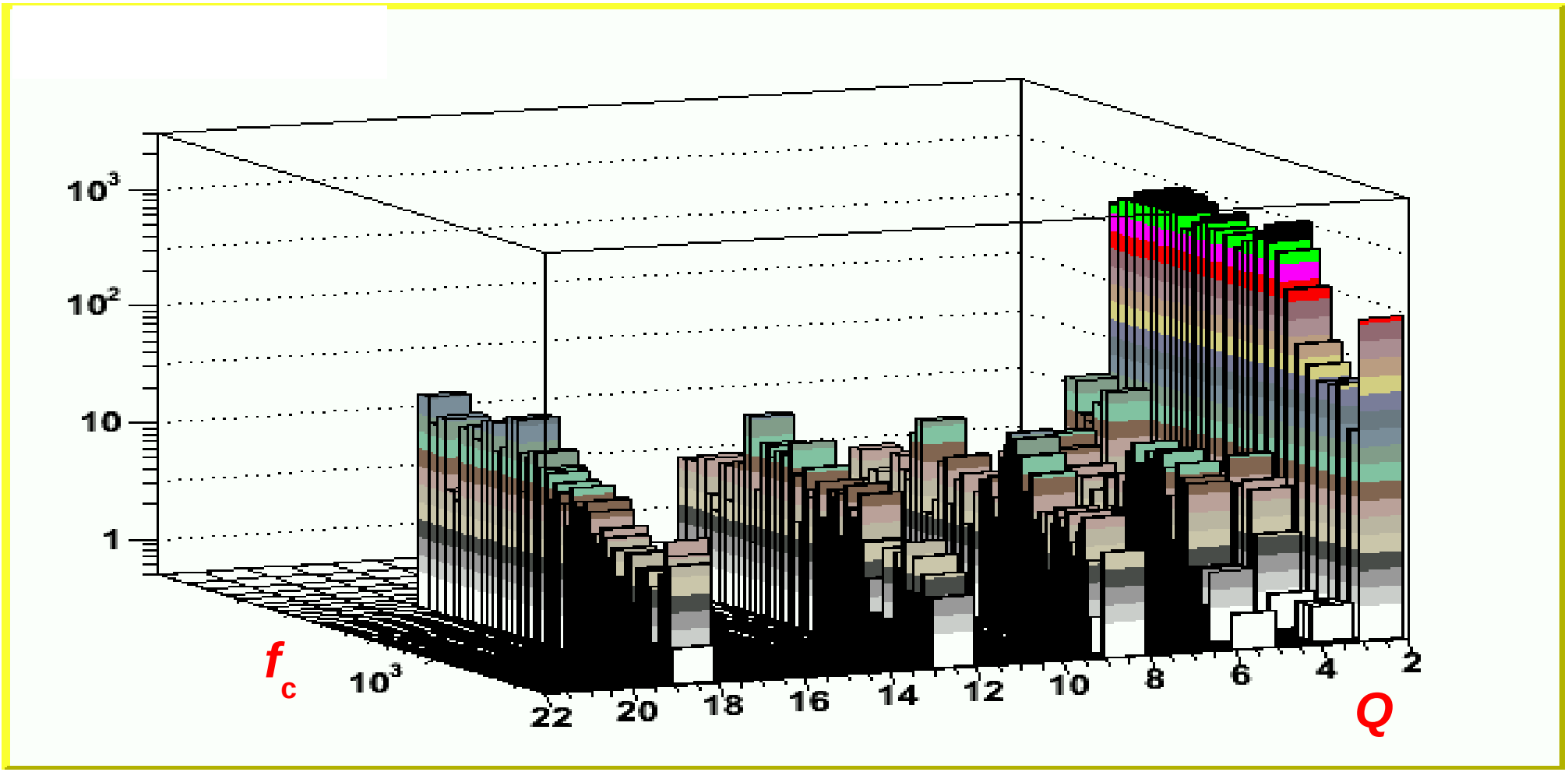
- True signal → small α, small ξ^2
- Fake events → large α, large ξ^2

Veto Techniques

- ξ^2 distribution



Event Distribution after α, ξ^2 veto



***300 < f_c < 2500* [Hz], *3 < Q < 22* (*~M < 100* [M_{sol}])**

9799 events ---> *2044* events (*20*%)

(SNR > *10*, false dismissal < *1-0.95*^{2} = *10*%)

Conclusions

- **TAMA BH ringdown search**
  - ➔ **Matched-filter analysis**
    - ➢ Nakano method for template construction works well.
  - ➔ **Galactic event simulation**, injection into TAMA data
    - ➢ Detection probability ~ *50%* of Galactic events (DT6 sensitivity, SNR>*10* , ~*30 %* SNR>*20*)
  - ➔ **DT6 data analysis**
    - ➢ R111, 17/Sep/2001 – 20/Sep/2001
    - ➢ Trigger rate *0.23* [Hz] (~*840* [h^{-1}], SNR > *10*)
      - Low *Q*, low f_c events dominated
    - ➢ Event selection with α, ξ^2 parameters
    - ➢ for $300 < f_c < 2500$ [Hz], $3 < Q < 22$ (~ $M < 100$ M_{sol})
      - *30.2* [h^{-1}] (SNR > *10*, false dismissal < *10 %*)
      - *3.65* [h^{-1}] (SNR > *20*)