

Search for Gravitational Waves from Black Hole Ringdowns

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and the TAMA Collaboration**

Outline



- **Black holes (BHs), quasi-normal modes (QNMs) and ringdowns**
- **TAMA300 sensitivity, signal-to-noise ratios (SNRs)**
- **Matched-filtering, template construction**
- **Detection probability of Galactic ringdown events with TAMA300**
- **Vetoing techniques**
- **Summary**

BHs, QNMs and Gravitational Waves



- **Black hole perturbations**

BH formation

Cmpct. Binary → Inspiral → Merger → Ringdown

SN explosion → Core collapse - - - → Ringdown



Damped oscillation with QNMs,
“*Ringdown*”

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

- **Central frequency**

$$f_c \approx \frac{3.2 \times 10^4}{M} [1 - 0.63(1 - a)^{0.3}] [\text{Hz}]$$

- **Quality factor**

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

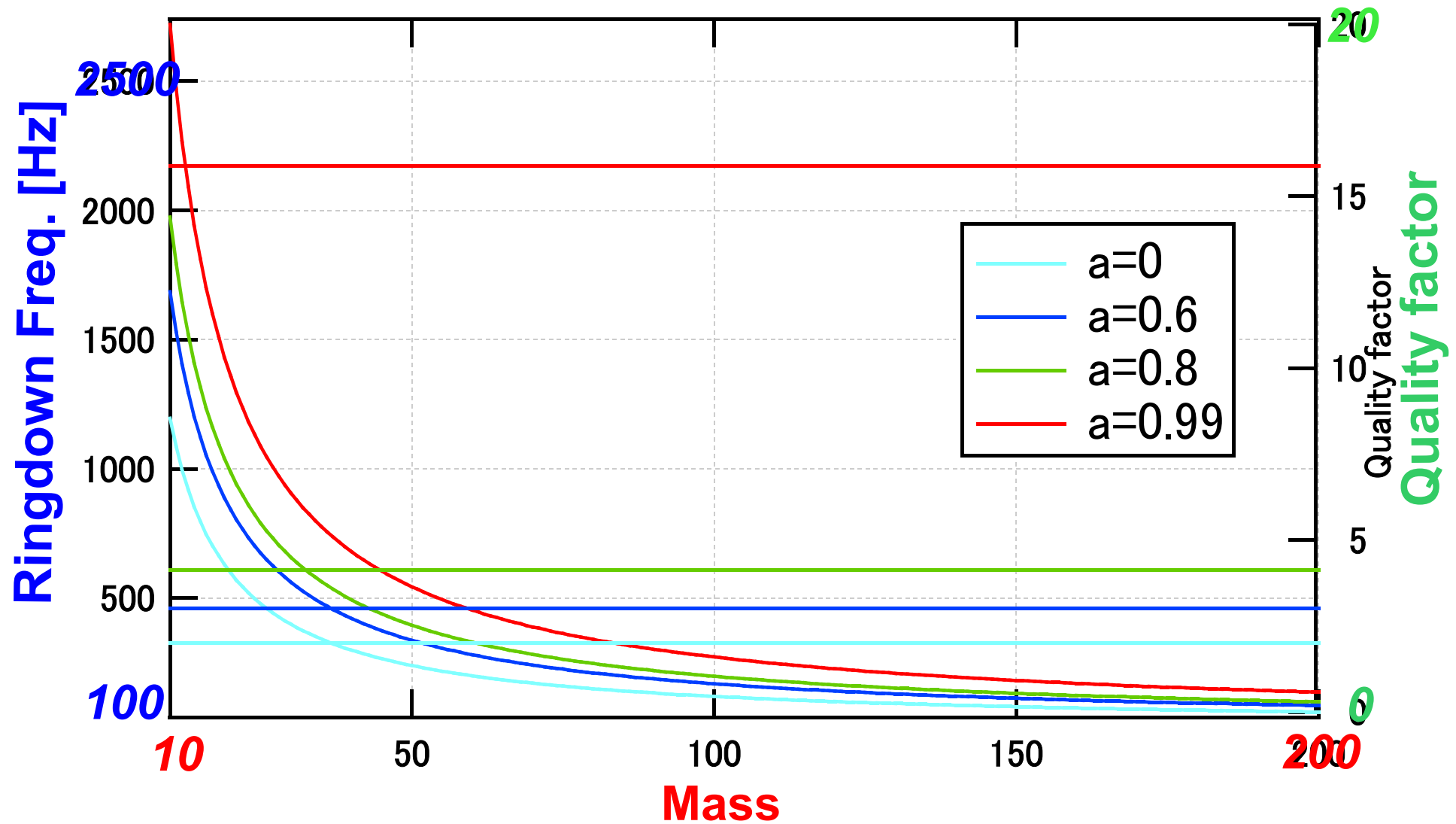
Echeverria, (1989)

M : BH mass (in solar mass unit)

a : Spin angular momentum, (0 - 1)

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

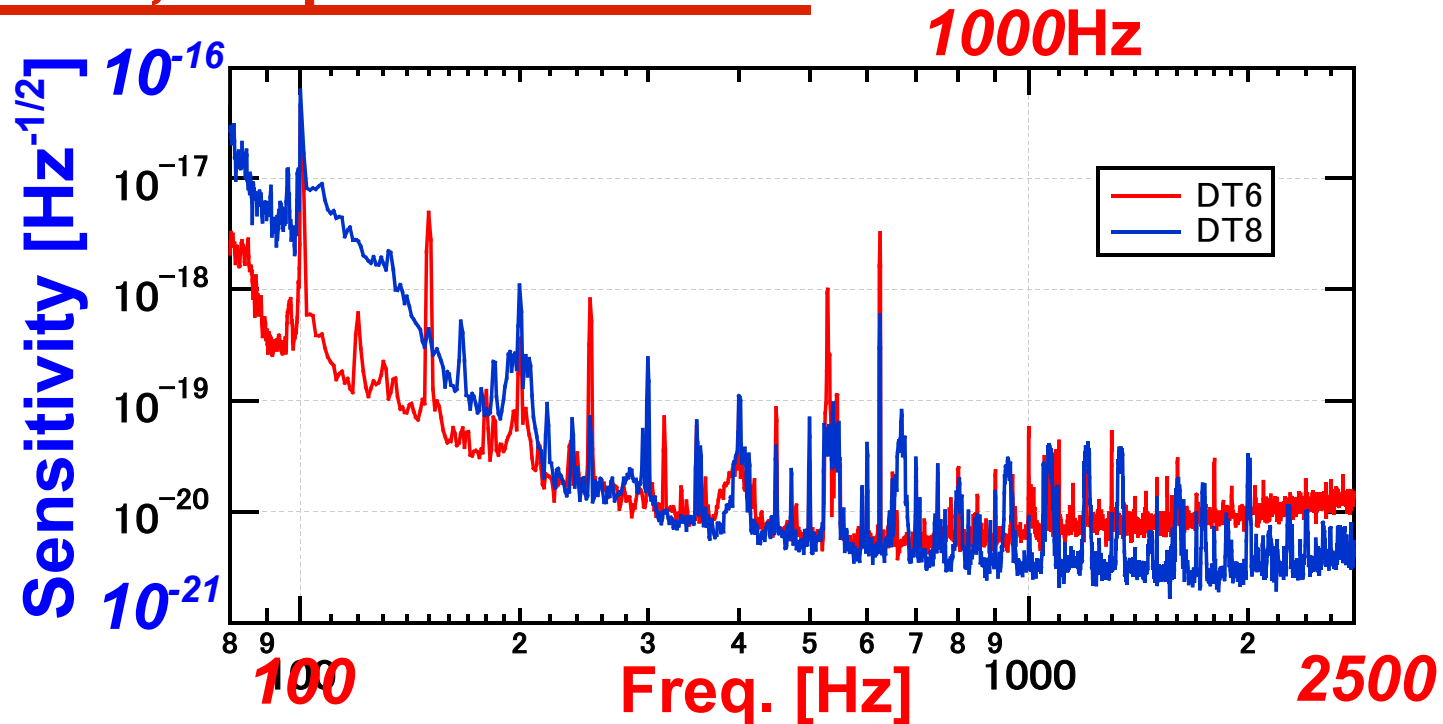
$$f_c \approx \frac{3.2 \times 10^4 [\text{Hz}]}{M} [1 - 0.63(1-a)^{0.3}], \quad Q \approx 2.0(1-a)^{-0.45}$$



TAMA sensitivities, Expected SNRs

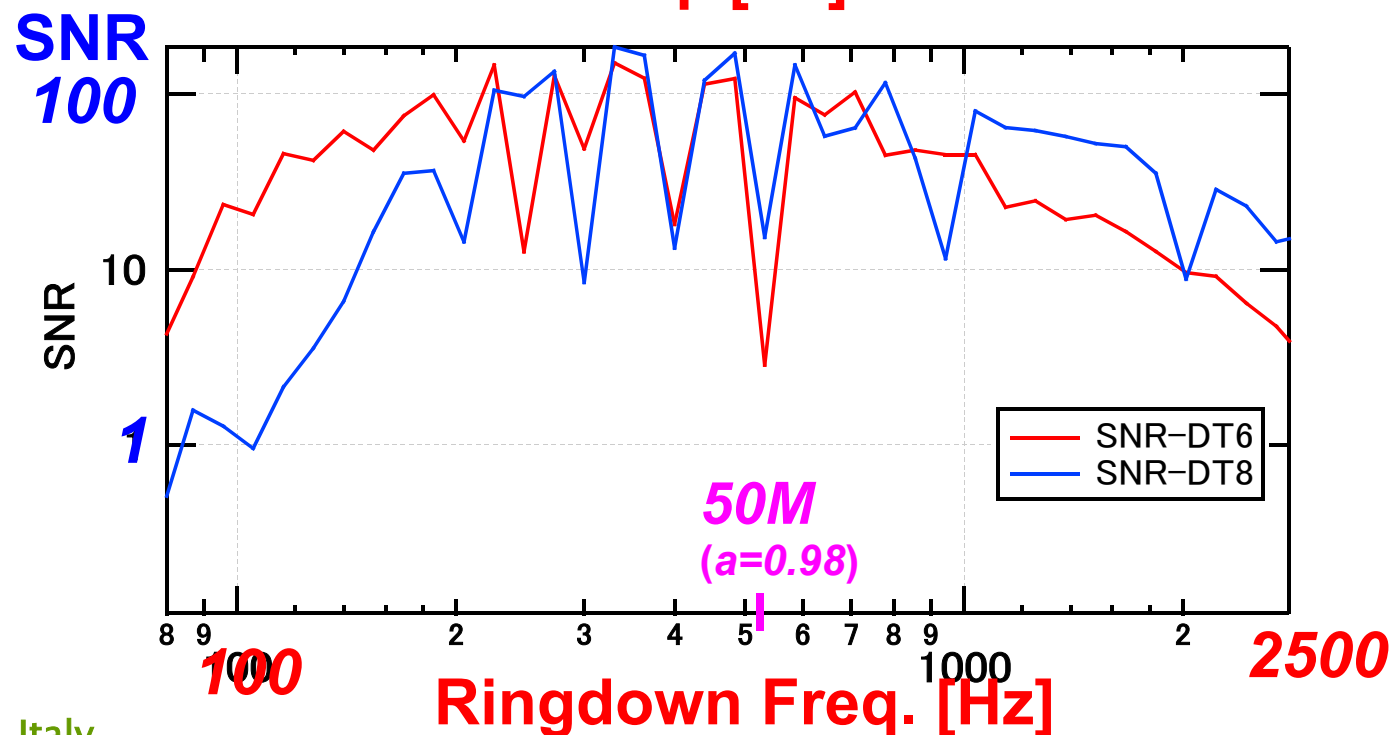


TAMA300
sensitivities
2001 (DT6)
2003 (DT8)



Signal-to-Noise
ratios

$a = 0.98,$
 $D = 10$ [kpc]



Matched-filtering

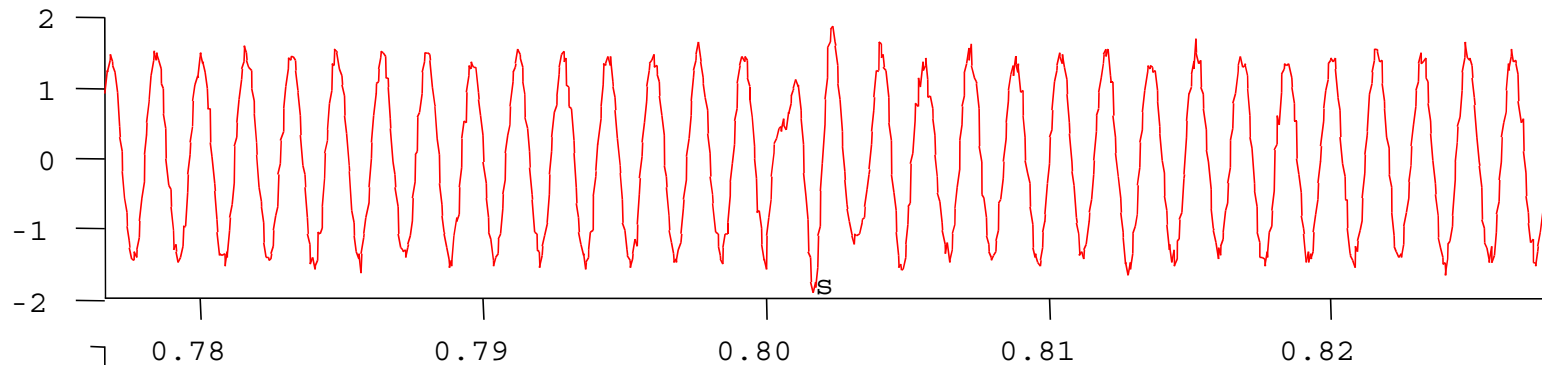
$$\rho = \int \frac{s(f) h^*(f)}{S_n(f)} df$$

$s(f)$: Strain data

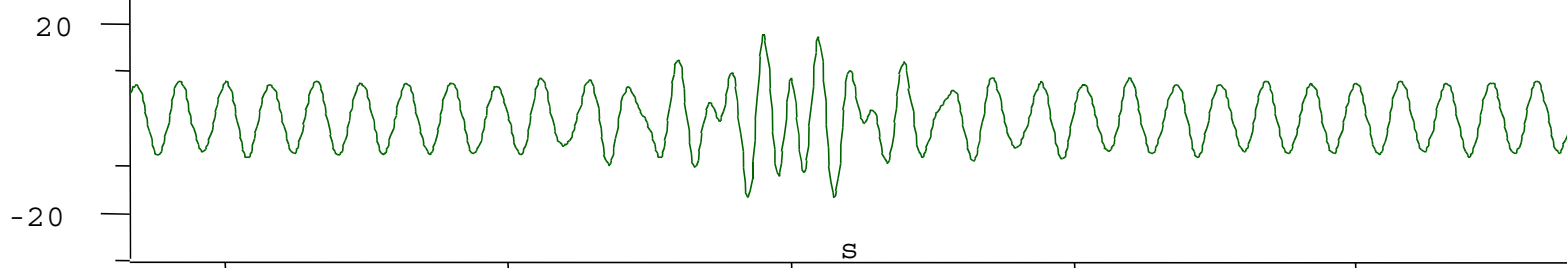
$h(f)$: Template

$S_n(f)$: Noise power

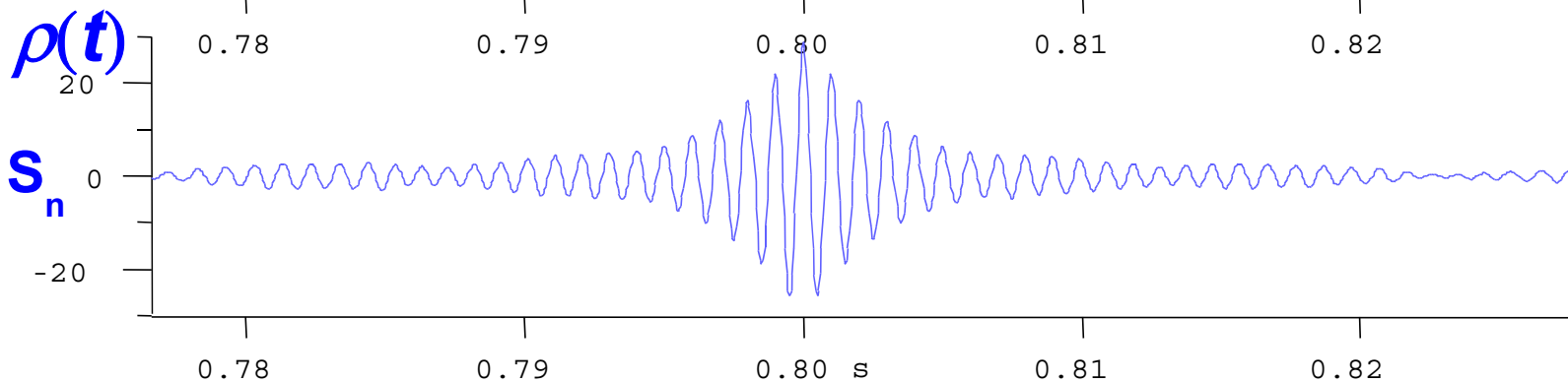
$s(t)$
strain data



$s(t)+h(t)$
(test signal)



Filter output
weighted by **S_n**



Template construction

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

- Search range:

$$f_c = 100 \sim 2500 \text{ [Hz]}$$

$$Q = 2 \sim 20$$

- Number of templates:

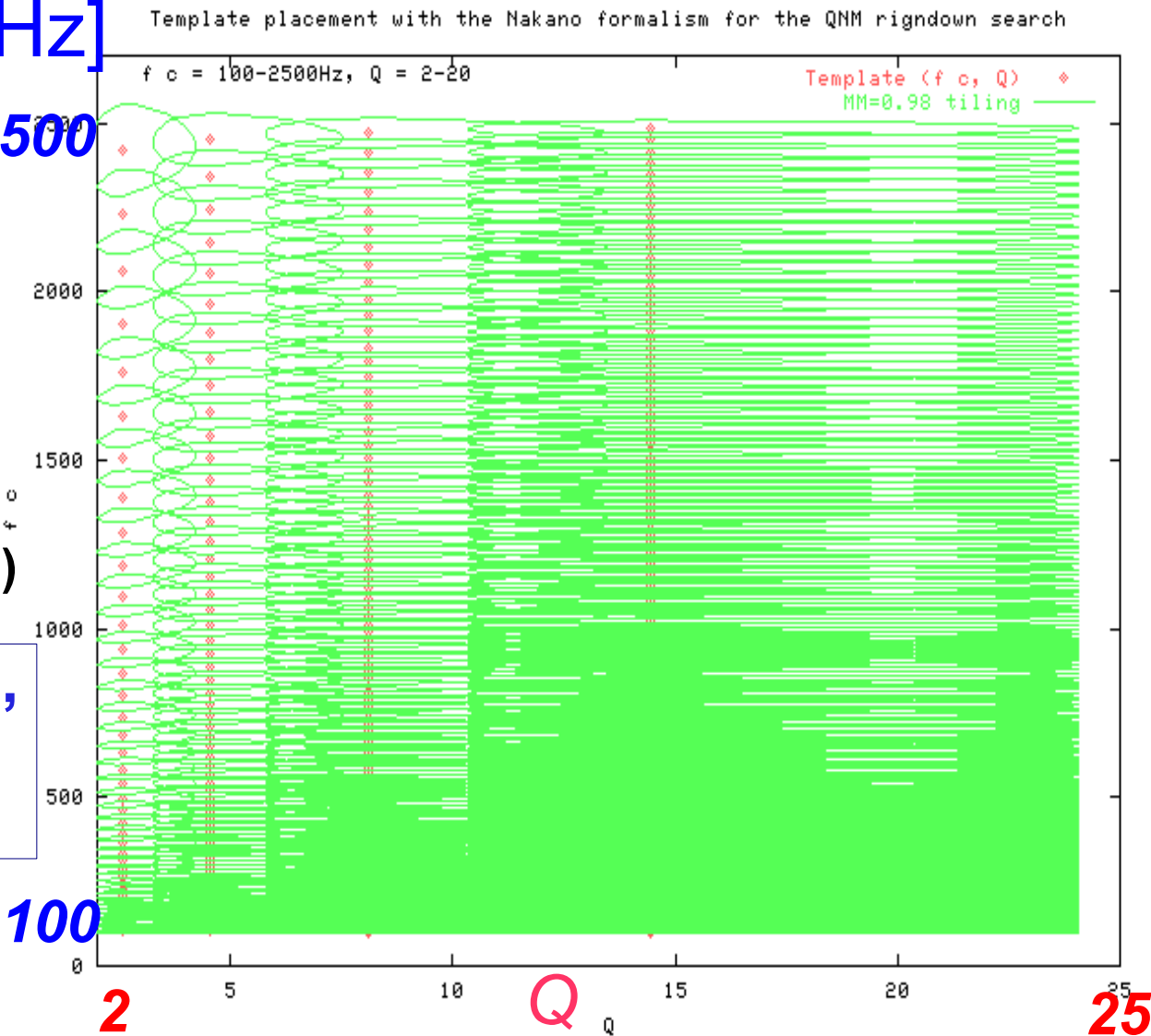
~ 800

for max SNR loss = 2 %
(Minimal match $MM = 0.98$)

Nakano, Takahashi *et al.*,
gr-qc/0306082
(submitted to PRD)

f_c [Hz]

2500



100

2

5

10

Q

15

20

25

Detection efficiency for Galactic Ringdowns



- **MC simulation** (Signal injection into the TAMA data)

- **Source distribution** $dN = \exp(-R^2/2R_0^2) \exp(-z/h_z) R dR dz$

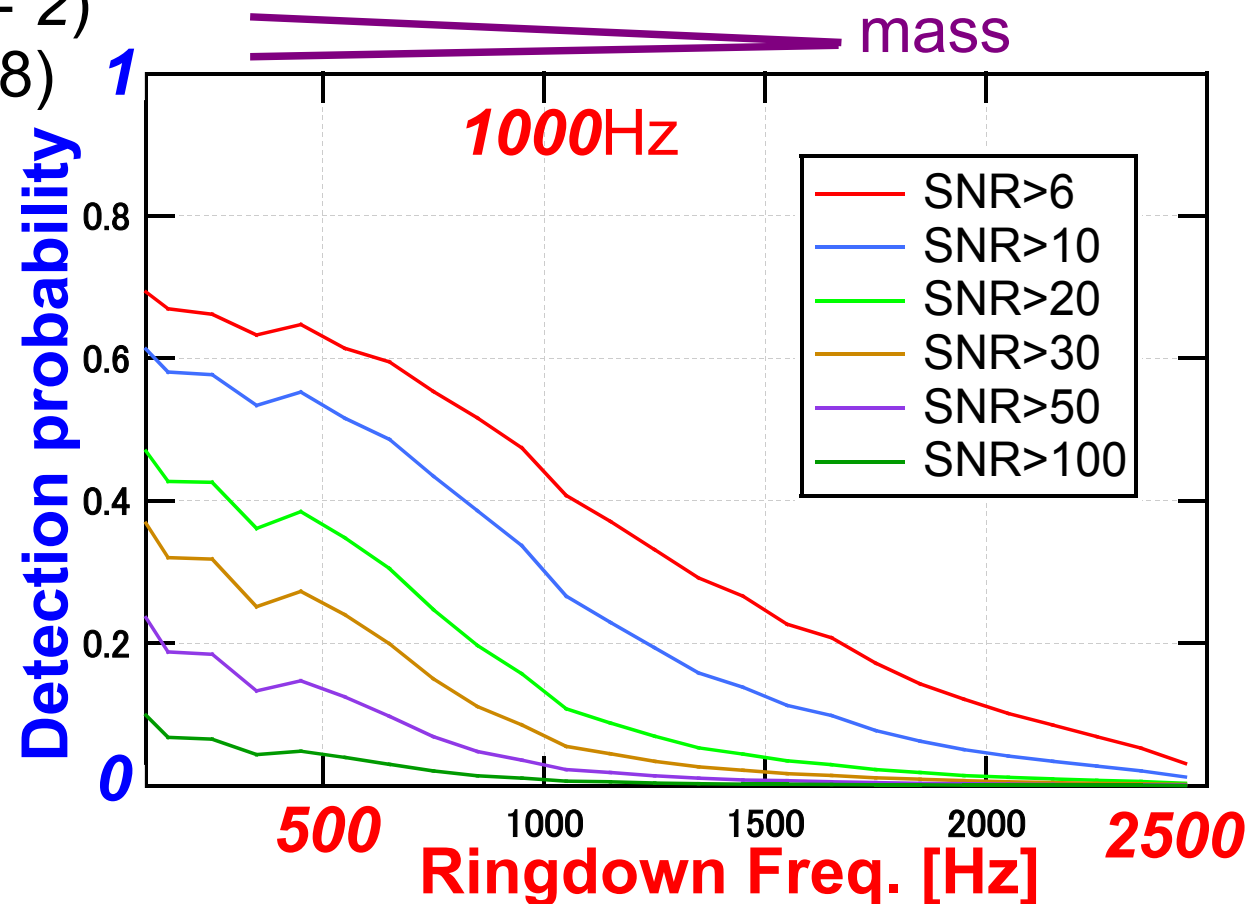
$$R_0 = 4.8 \text{ [kpc]}, h_z = 1 \text{ [kpc]}$$

- $\eta = 0.03$ for fractional mass energy radiated as GWs ($l = m = 2$) (Flanagan & Hughes, 1998)

- **Radiation pattern** (random inclination angle)

- **Observation period, antenna pattern**

- **SNR losses due to template spacing**

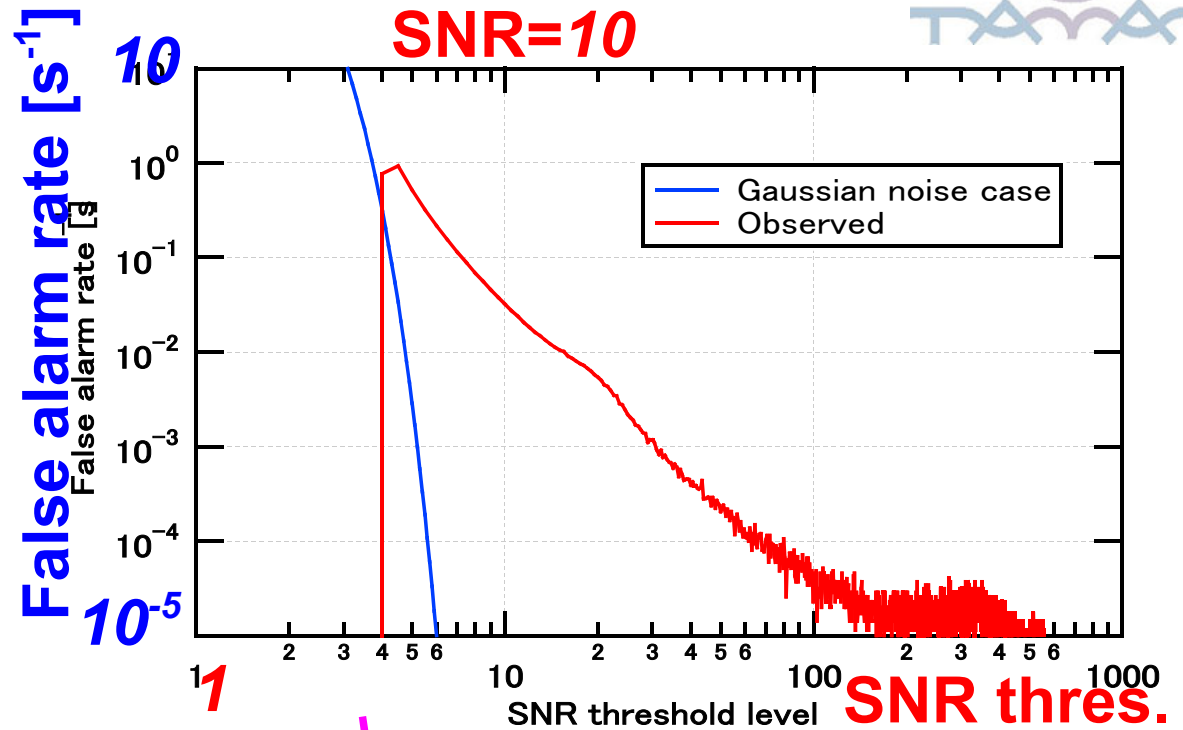


Filter outputs

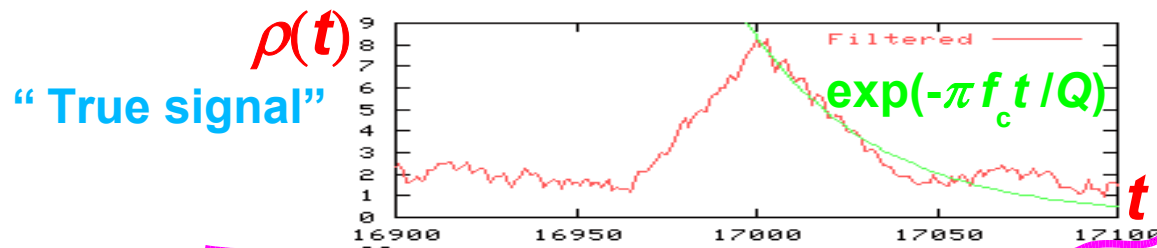
- False alarm rate
(SNR > 10)

$\sim 0.03 \text{ [s}^{-1}\text{]}$ (!)

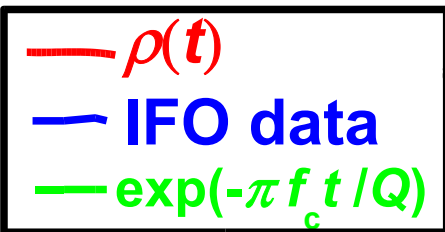
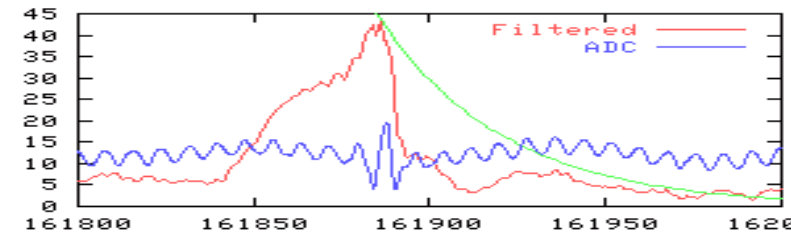
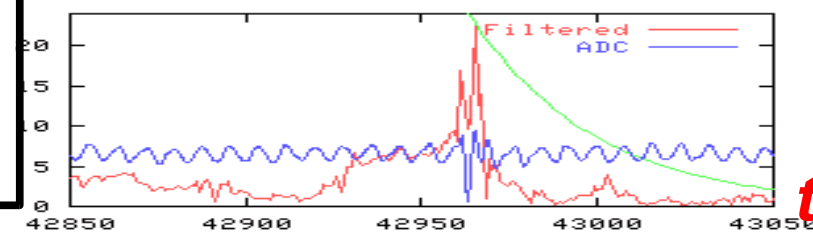
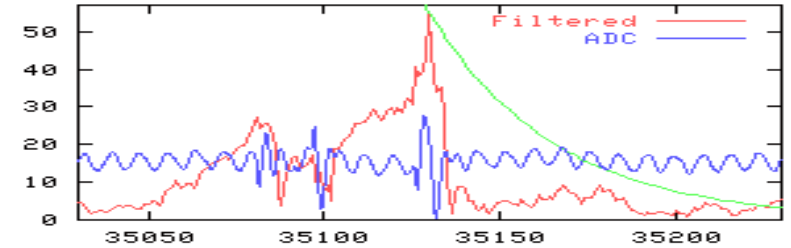
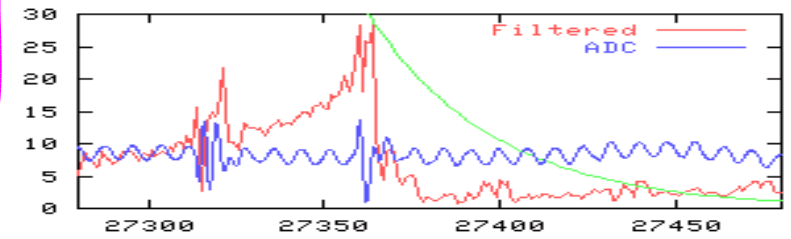
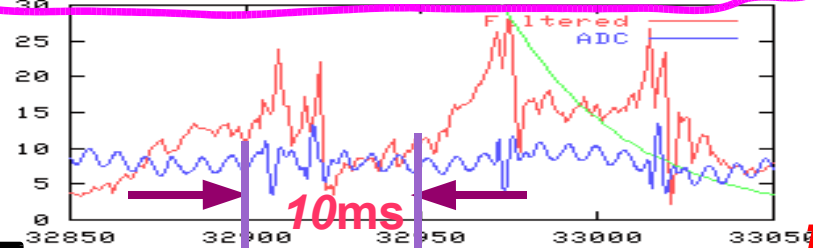
(cf. $\sim 10^{-19} \text{ [s}^{-1}\text{]}$
for Gaussian noises)



- Event appearance

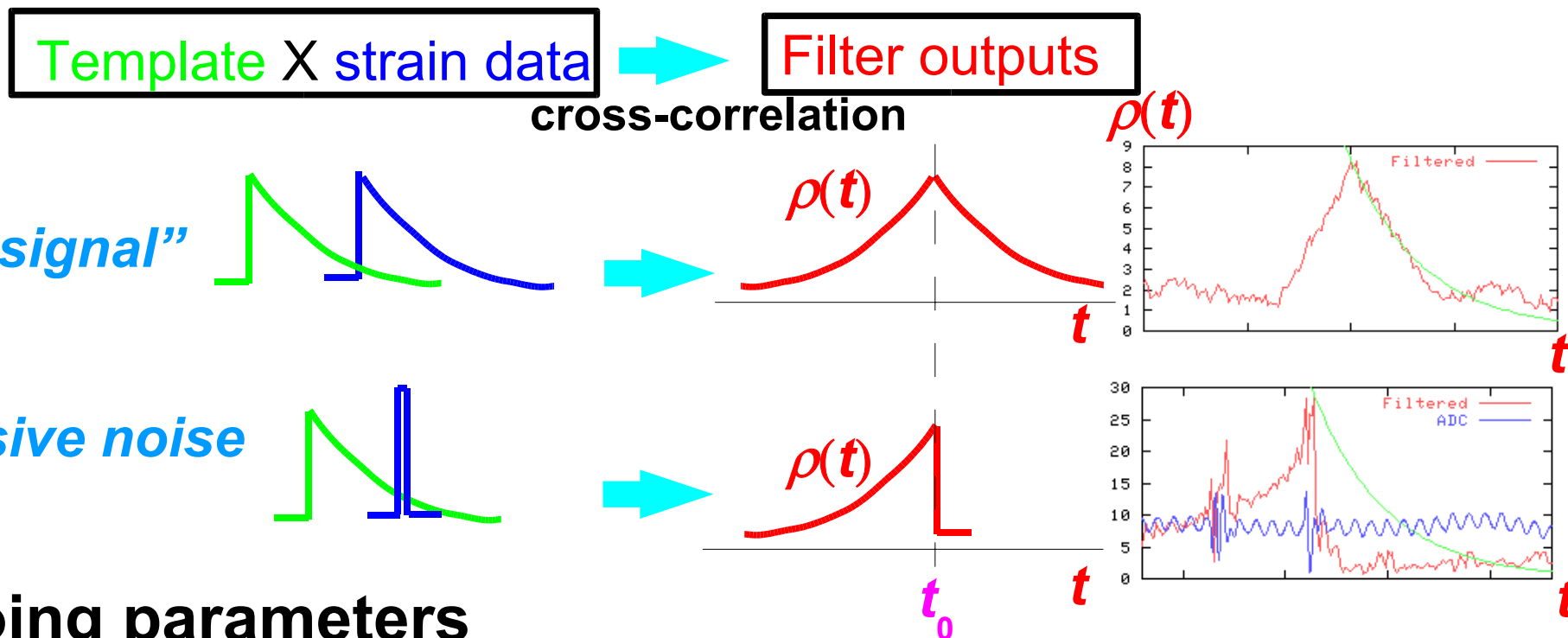


Spurious events



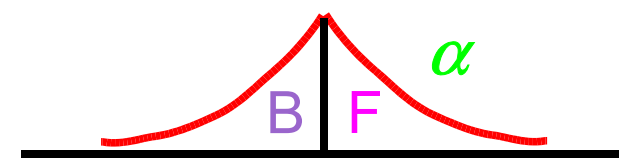
Vetoing techniques

- Characterizing spurious events



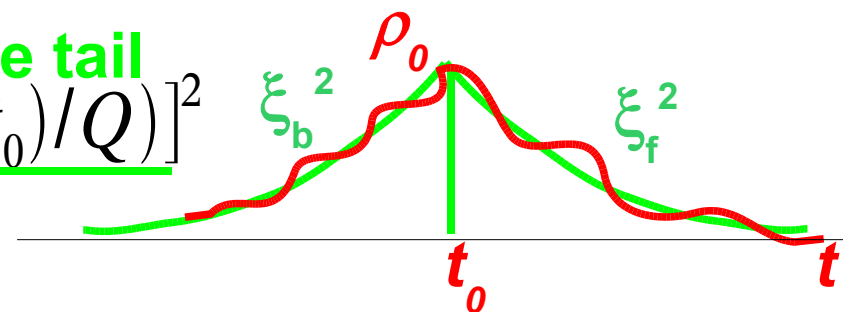
• Vetoing parameters

- asymmetry, $\alpha = (F - B) / (F + B)$
- Fit to the exponential tail



$$\xi^2 \equiv \frac{1}{\rho_0} \sum [\rho(t) - \rho_0 \exp(-\pi f_c (t-t_0)/Q)]^2$$

template tail
Filter output



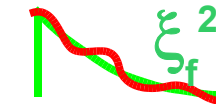
Vetoing techniques



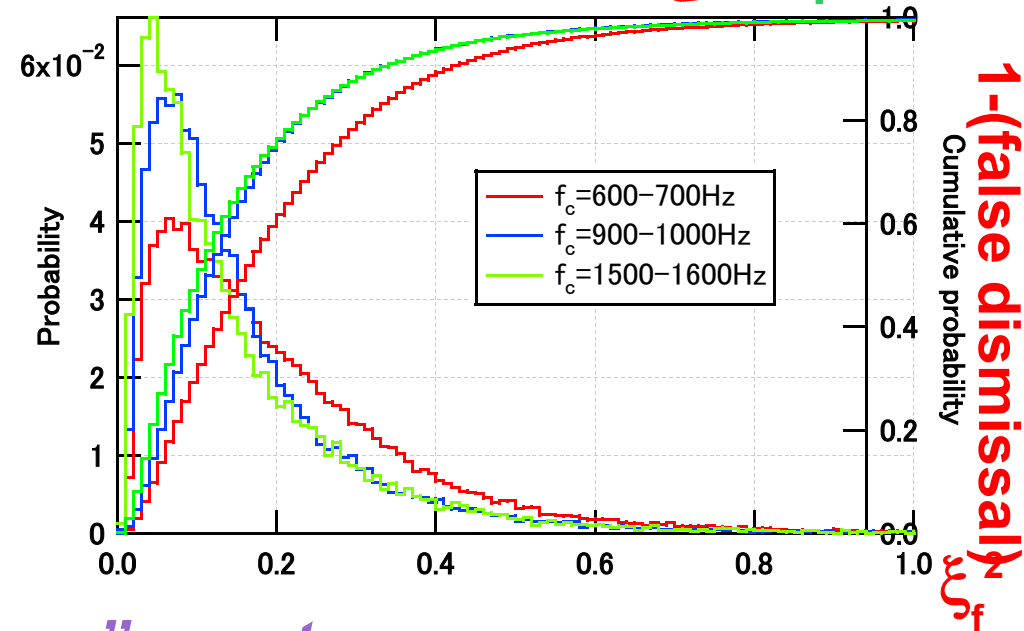
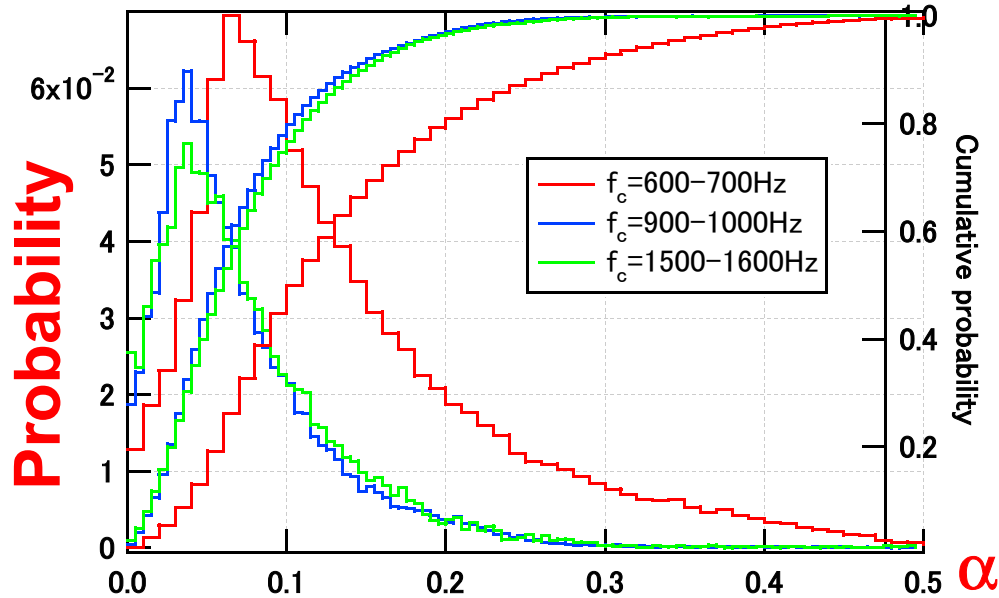
asymmetry



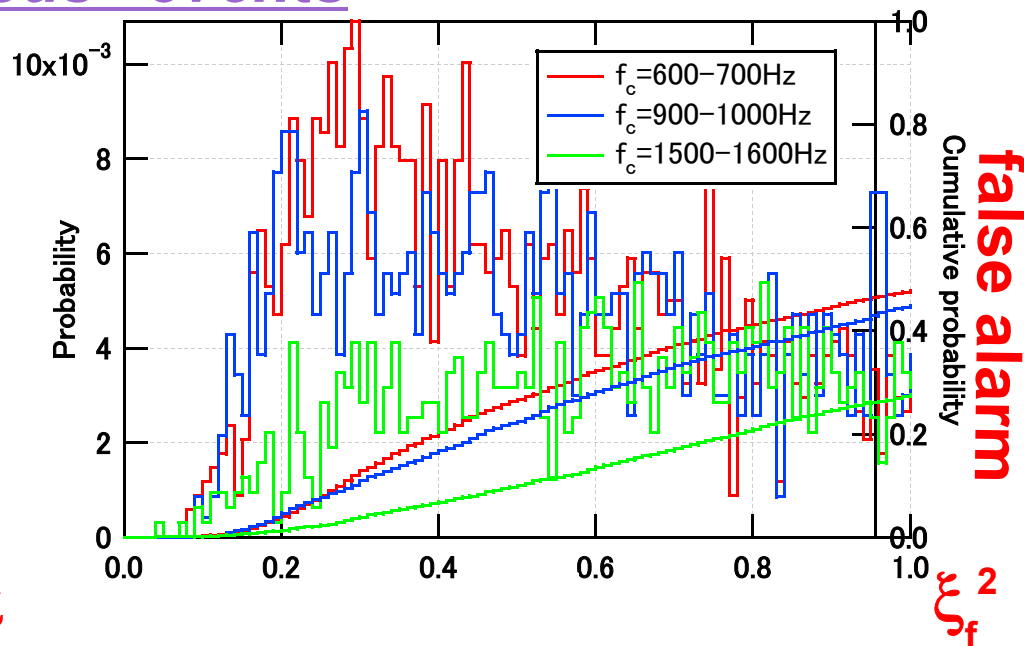
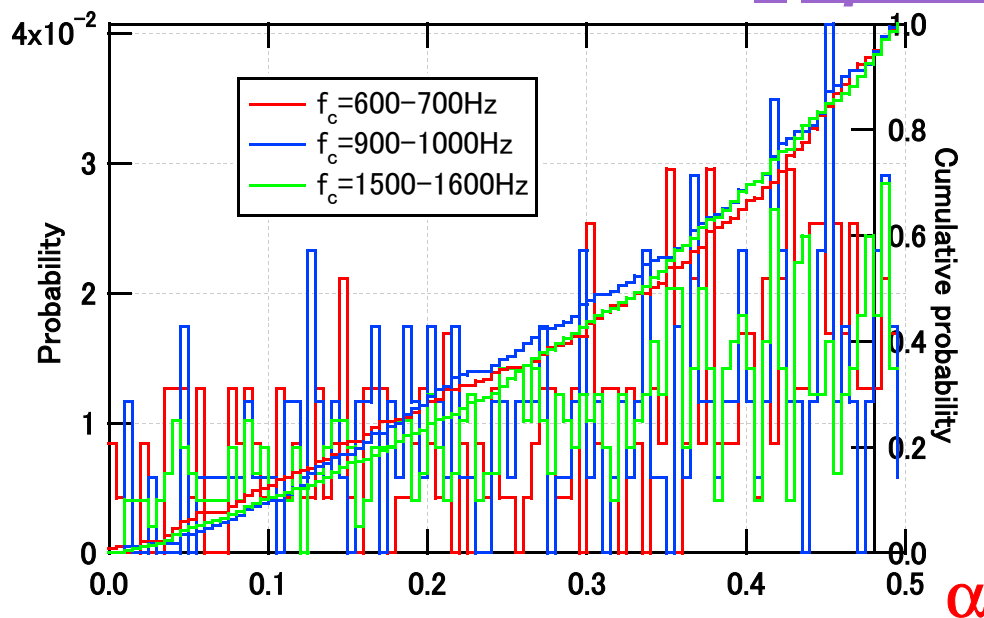
“True” (injected) signal



Fit to the exp tail



“Spurious” events

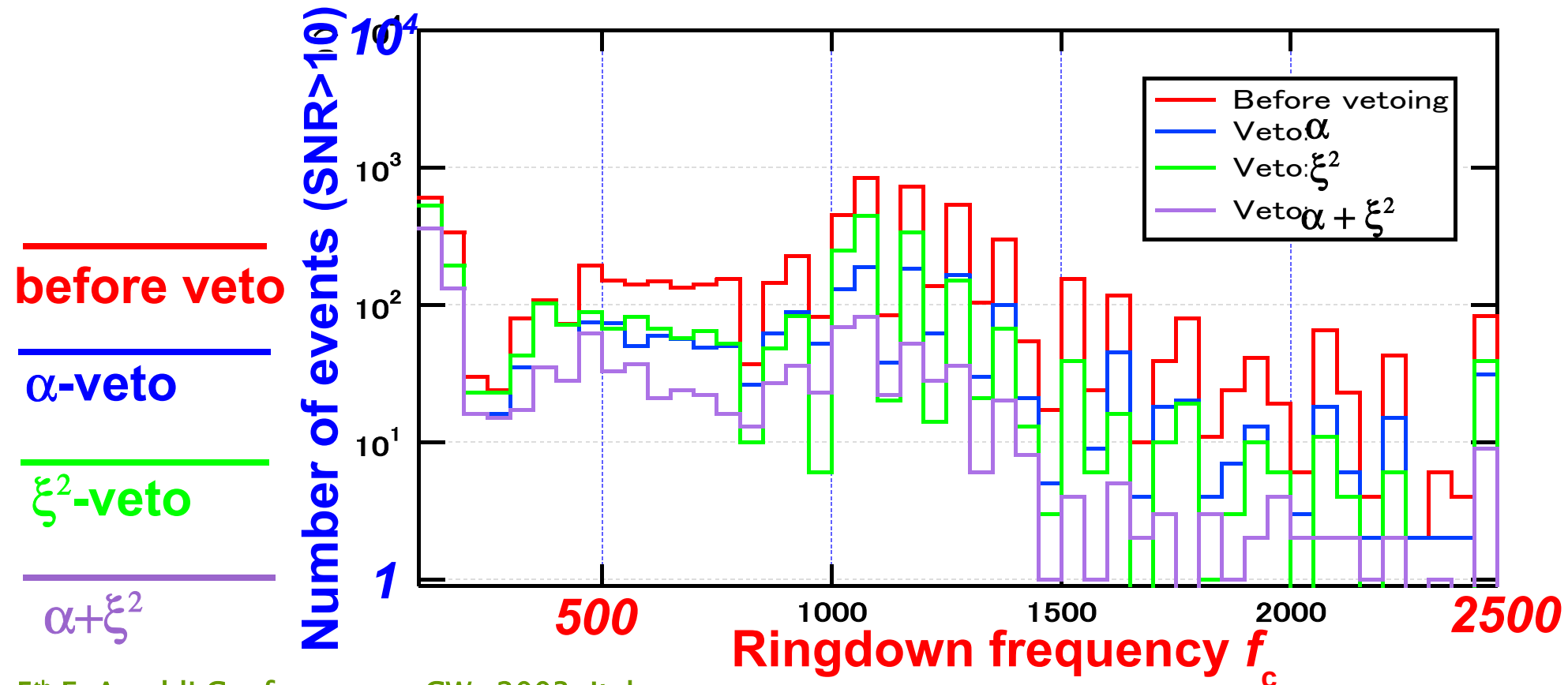


Veto: Example

- TAMA DT6/R101, ~1 day data

- **Criteria:**

- **SNR > 10**
- **α -veto, ξ_f^2 -veto:** cut so as to be false dismissal 5 %
(determined from the simulation results)



Summary



- **BH ringdown GW search with the matched-filtering analysis** DT6 analysis completed, DT8 under progress
- **An efficient template construction method implemented** (Nakano, Takahashi et al. 2003)
- **Ringdown parameters: $(f_c, Q) = (100 - 2500\text{Hz}, 2 - 20)$,
 $N_{\text{tmplt}} = 800$**
- **Detection efficiency 50 ~ 60% for Galactic ringdown events** (SNR > 10, assuming GW luminosity ~ 3 %)
- **Vetoing by examining asymmetries and exp tails of filter outputs $\rho(t)$**
- **Rejection power ~ 90% with a false dismissal 5%**
- **... Still a number of fakes, more careful investigation required for the event selection**