27pSK10

重力波を用いた重力理論の検証

に向けたデータ解析パイプライン

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大阪市立大学, 16:00-16:15 (10+5分), 9月27日

Strategy

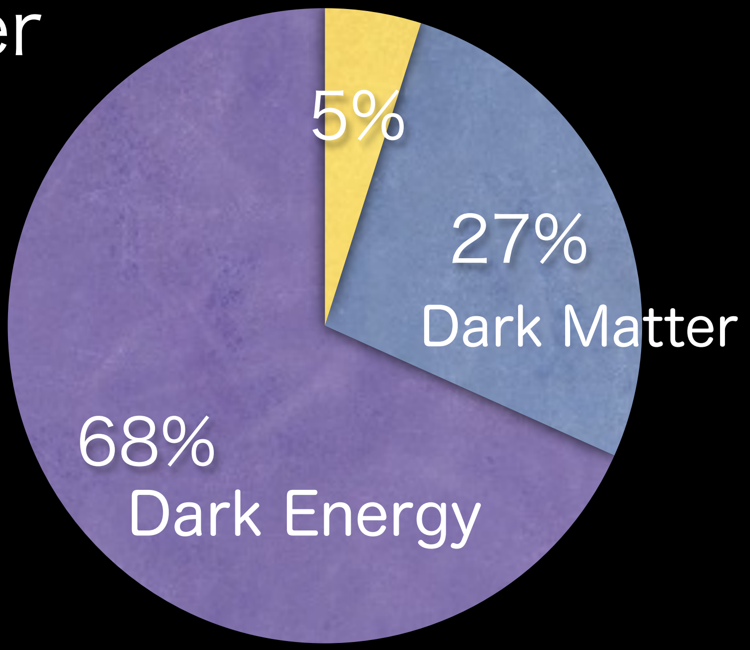
Parametrized post-Einsteinian Framework
Approximate Bayesian analysis
Detectable regions of ppE corrections to GR

Summary

We demonstrate that adv. GW detectors, including KAGRA, have tremendous potential for new bounds on deviations from GR.

Why considering Alternative Theories of Gravity?

- GR passes all tests with flying colors so far.
- Motivations for modified gravity theories
  - Black Hole singularity ← Unphysical!
  - Unification with other forces or Quantization of gravity
  - Alternative to Dark Energy and/or Dark Matter
  - Useful to contrast their predictions with GR
    → evaluate the correctness of GR



33rd SLAC Summer Institute on Particle Physics (SSI 2005), 25 July - 5 August 2005

Tests of Alternative Theories of Gravity

Gilles Esposito-Farèse

Useful lecture note (http://www.slac.stanford.edu/econf/C0507252/papers/T025.PDF)
slide (http://www-conf.slac.stanford.edu/ssi/2005/lec_notes/Esposito-Farese/default.htm)

Classifying tests defined by Yunes & Siemens LRR 2013

Top-down approach Direct Tests

One starts from a particular model, and then predicts certain observables that might or might not agree with experiment.

Brans-Dicke, Bigravity, Massive graviton,...

[Narikawa, et al. PRD 2015 is categorized in this.]

Bottom-up approach Model-independent Tests

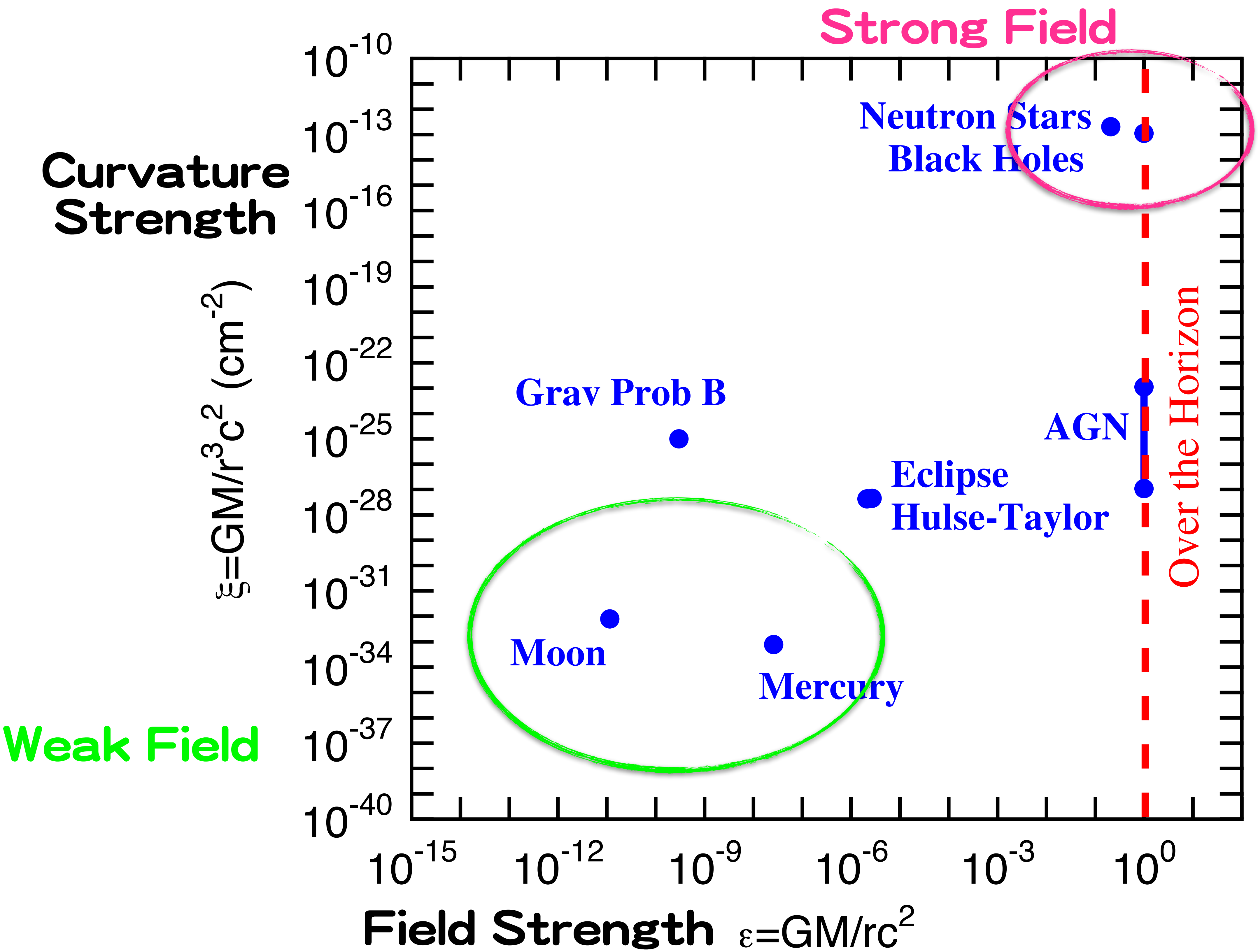
One considers Einstein's theory as a null hypothesis and searches for generic deviations.

[This work is categorized in this.]

Both approaches are complementary.

Why GR-by-GW Tests?

[Psaltis, LRR, 2008]



GWs from CBC can be powerful probe of the strong-field, dynamical regime of gravity.

Our Strategy

After usual CBC search with GR template, we perform parameter estimation and model selection against candidate events.

The simplest ppE models

A simple decision scheme based on Bayesian statistics

Detectable regions of ppE corrections to GR

→ Suggestion of interesting models with detectable prediction

Here, we focus on a 1.4M_{sun} BNS system, @200Mpc; aLIGO ZDHP the restricted inspiral, ignore spin for simplicity.

Parametrized post-Einsteinian Framework [Yunes & Pretorius, PRD 2009]

$$\boxed{\tilde{h}(f) = \mathcal{A}(f) e^{i\Phi(f)} \left(1 + \alpha_{\rm ppE} u^{a_{\rm ppE}}\right) \exp[i\beta_{\rm ppE} u^{b_{\rm ppE}}]}$$

A generic parametrization which characterizes the departures from GR through free parameters (a, α, b, β).

Restricted Inspiral Waveform in GR

$$\tilde{h}_{\rm GR}(f) = A_{\rm GR} e^{i\Psi_{\rm GR}(f)}$$

$$A_{\rm GR}(f) = \mathcal{A} u^{-7/2} \left[1 + \cdots\right]$$

$$\Psi_{\rm GR} = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128} u^{-5} \times \left\{1 + \sum_{k=2}^{7} \left[\psi_k + \psi_k^{\log} \log(u)\right] \eta^{-k/5} u^k\right\}$$

where the inspiral reduced frequency $u = (\pi \mathcal{M}_c f)^{1/3}$

The ppE framework reproduces most the models

$$\tilde{h}(f) = \mathcal{A}(f) e^{i\Phi(f)} \left(1 + \alpha_{\rm ppE} u^{a_{\rm ppE}}\right) \exp[i\beta_{\rm ppE} u^{b_{\rm ppE}}]$$

$u = (\pi \mathcal{M}_c f)^{1/3}$

Modified Gravity Zoo

Theory	$\alpha_{\rm ppE}$	$a_{\rm ppE}$	$\beta_{\rm ppE}$	$b_{\rm ppE}$
Jordan–Fierz–Brans–Dicke	$-\frac{5}{96}\frac{S^2}{\omega_{\rm BD}}\eta^{2/5}$	-2	$-\frac{5}{3584}\frac{S^2}{\omega_{\rm BD}}\eta^{2/5}$	-7
Dissipative Einstein-Dilaton-Gauss–Bonnet Gravity	0	$\cdot$	$-\frac{5}{7168}\zeta_3\eta^{-18/5}\delta_m^2$	-7
Massive Graviton	0	$\cdot$	$-\frac{\pi^2 D\mathcal{M}_c}{\lambda_g^2(1+z)}$	-3
Lorentz Violation	0	$\cdot$	$-\frac{\pi^{2-\gamma_{\rm LV}}}{(1-\gamma_{\rm LV})}\frac{D_{\gamma_{\rm LV}}}{\lambda_{\rm LV}^{2-\gamma_{\rm LV}}}\frac{\mathcal{M}_c^{1-\gamma_{\rm LV}}}{(1+z)^{1-\gamma_{\rm LV}}}$	$-3\gamma_{\rm LV}-3$
$G(t)$ Theory	$-\frac{5}{512}\dot{G}\mathcal{M}_c$	-8	$-\frac{25}{65536}\dot{G}_c\mathcal{M}_c$	-13
Extra Dimensions	$\cdot$	$\cdot$	$-\frac{75}{2554344}\frac{dM}{dt}\eta^{-4}(3-26\eta+24\eta^2)$	-13
Non-Dynamical Chern–Simons Gravity	$\alpha_{\rm PV}$	3	$\beta_{\rm PV}$	6
Dynamical Chern–Simons Gravity	0	$\cdot$	$\beta_{\rm dCS}$	-1

and may cover unknown models.

[Yunes & Siemens, LRR 2013]

A simple Bayesian decision scheme

Vallisneri's analysis

[Vallisneri, PRD 2012]

using the odds ratio as a detection statistic,

with approximation $O \propto SNR^2(1\text{-}FF)$,

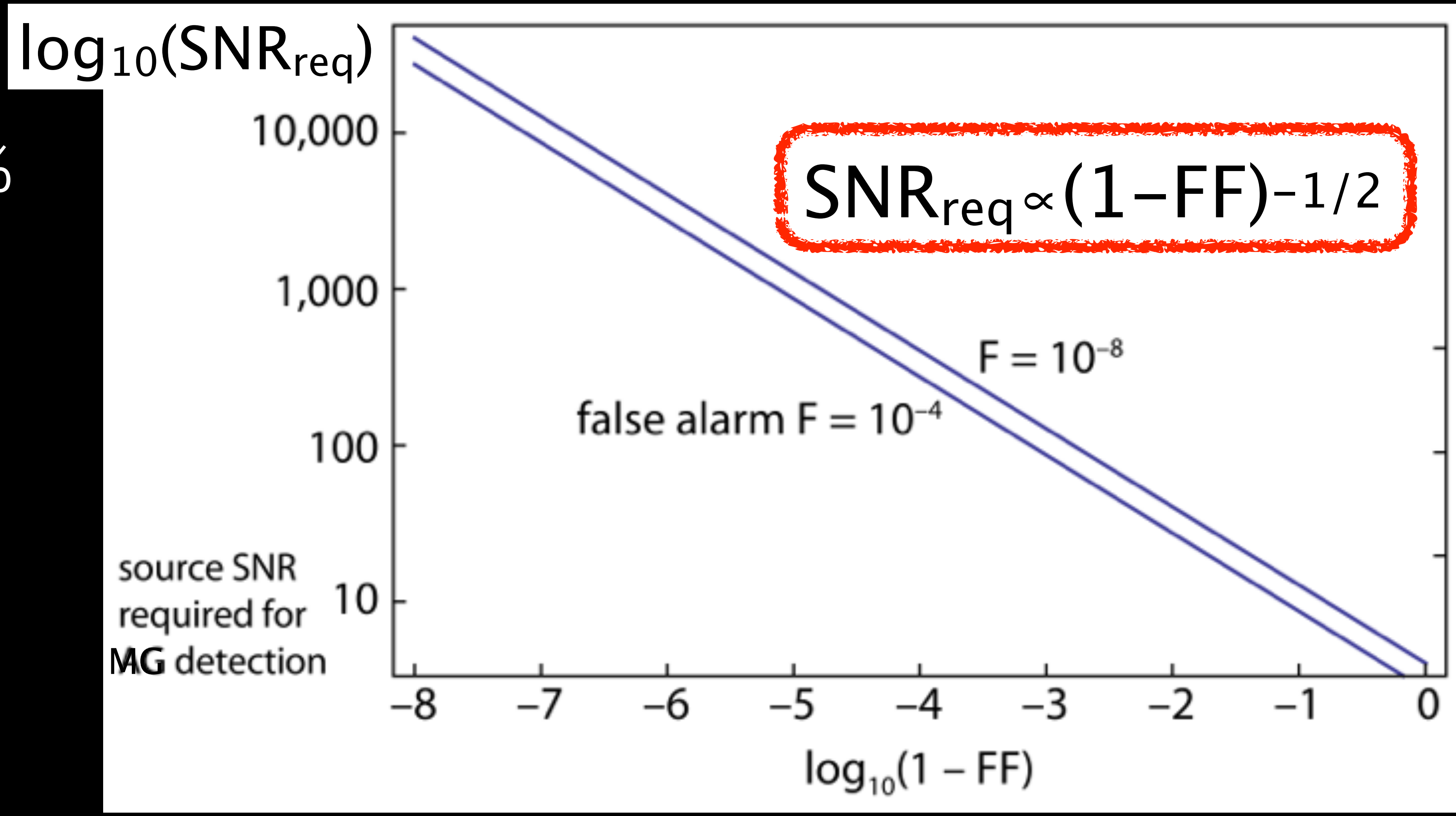
setting O_{thr} by requiring a given FAP:

$O_{MG,GR} > O_{thr}$ for a FAP → MG detection!!

Efficiency E=50%

FAP $F=10^{-4}$

FF	SNR_{req}
0.9	8.699
0.95	12.3
0.99	27.5



SNRreq : the value of the signal SNR required to detect a given deviation from GR waveform.

The simplest ppE models

$$\tilde{h}(f) = \mathcal{A}(f) e^{i\Phi(f)} \left(1 + \alpha_{\rm ppE} u^{a_{\rm ppE}}\right) \exp[i\beta_{\rm ppE} u^{b_{\rm ppE}}]$$

$u = (\pi \mathcal{M}_c f)^{1/3}$

Model 1. phase-modified model: $\alpha = 0$, $\{b, \beta\}$

$h_{\rm model1} = h_{\rm GR} \exp[i \beta u^b]$ $\quad SNR^{\rm ppE} = SNR^{\rm GR}$

Model 2. amplitude-modified model: $\beta = 0$, $\{a, \alpha\}$

$h_{\rm model2} = h_{\rm GR}(1 + \alpha u^a)$ $\quad SNR^{\rm ppE} \neq SNR^{\rm GR}$

Model 3. 1PN & 1.5PN phase: $\alpha = 0$, $\{\beta_{-3}, \beta_{-2}\}$

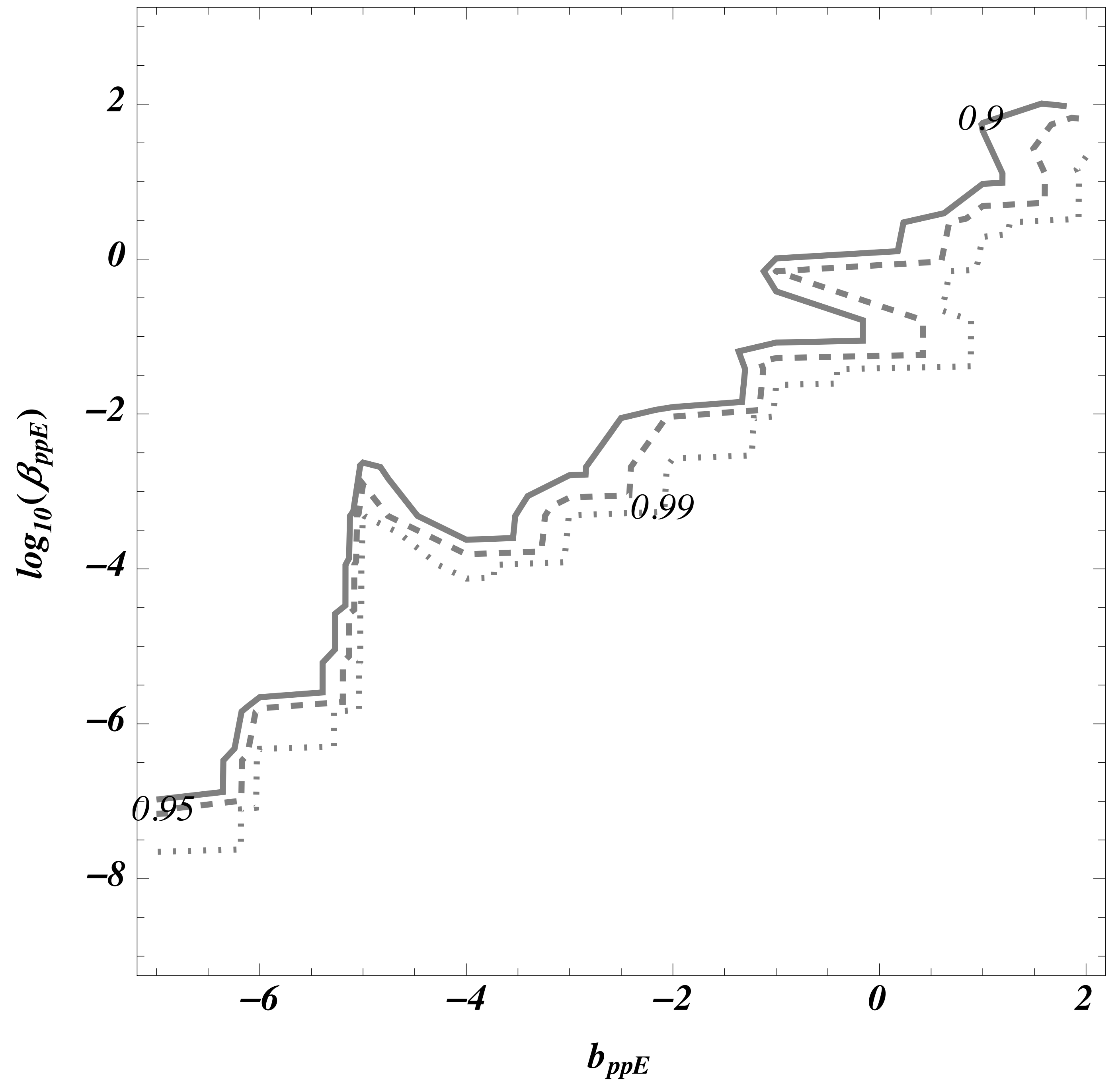
$h_{\rm model3} = h_{\rm GR} \exp[i(\beta_{-3} u^{-3} + \beta_{-2} u^{-2})]$ $\quad SNR^{\rm ppE} = SNR^{\rm GR}$

Model 4. 1PN phase & amplitude: $\{\beta_{-3}, \alpha_1\}$

$h_{\rm model4} = h_{\rm GR}(1 + \alpha_1 u^1) \exp[i \beta_{-3} u^{-3}]$ $\quad SNR^{\rm ppE} \neq SNR^{\rm GR}$

・Model A1. Parameters (β,b), b={-7,-6,...,-1,1,2}.

FF contour



b_{ppE}	-7	-5	-3	-1	1	2
PN order	-1	0	1	2	3	3.5

Source:
BNS
200Mpc

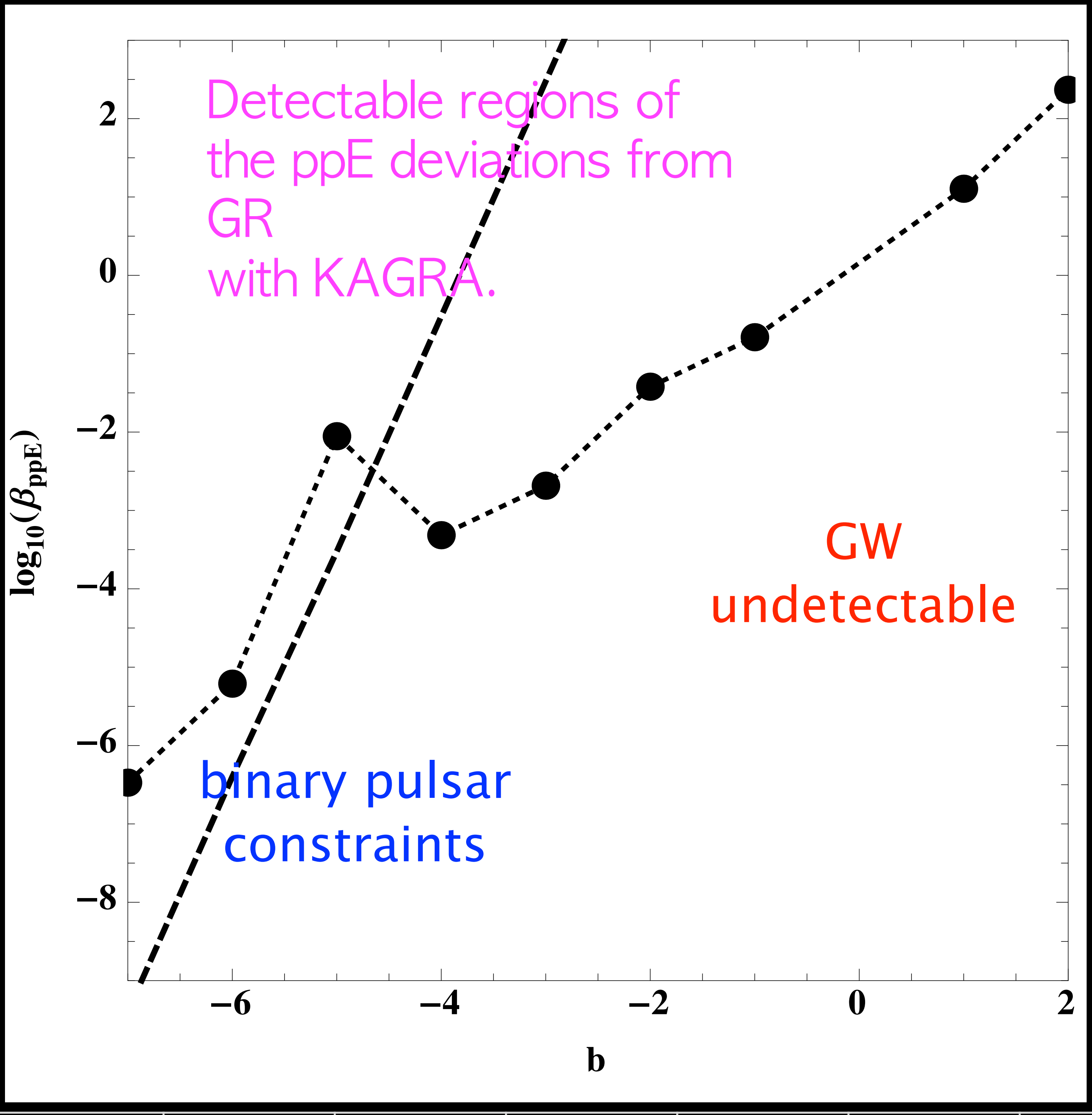
SNR is the same value as that of GR.
SNR=8.7 for BNS, at 200Mpc

We derive SNRreq from FF with Vallisneri's method.

[Vallisneri, PRD 2012]

Model A1. phase-modification: $\alpha=0$, $\{b, \beta\}$ $h_{model1}=h_{GR}\exp[i\beta u^b]$

Detectable Region ($SNR>SNR_{req}$)



The results demonstrate that KAGRA has potential to detect phase-deviations from GR.

This is consistent with Vallisneri & Yunes PRD 2013

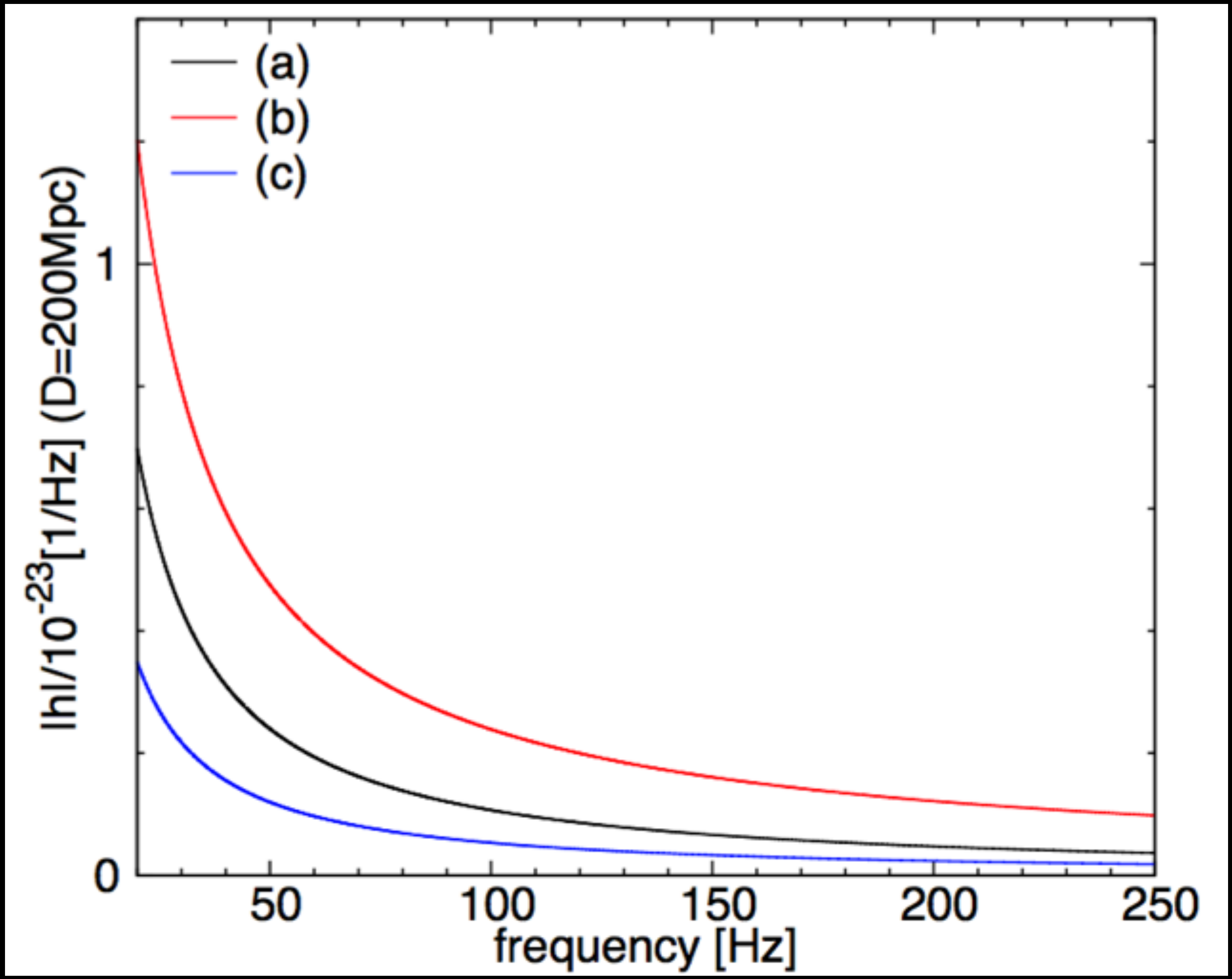
Efficiency E=50%

FAP $F=10^{-4}$

b_{ppE}	-7	-5	-3	-1	1	2
PN order	-1	0	1	2	3	3.5

Model 2. amplitude-modification: $\beta=0$, $\{a, \alpha\}$ $h_{model2}=h_{GR}(1+\alpha u^a)$

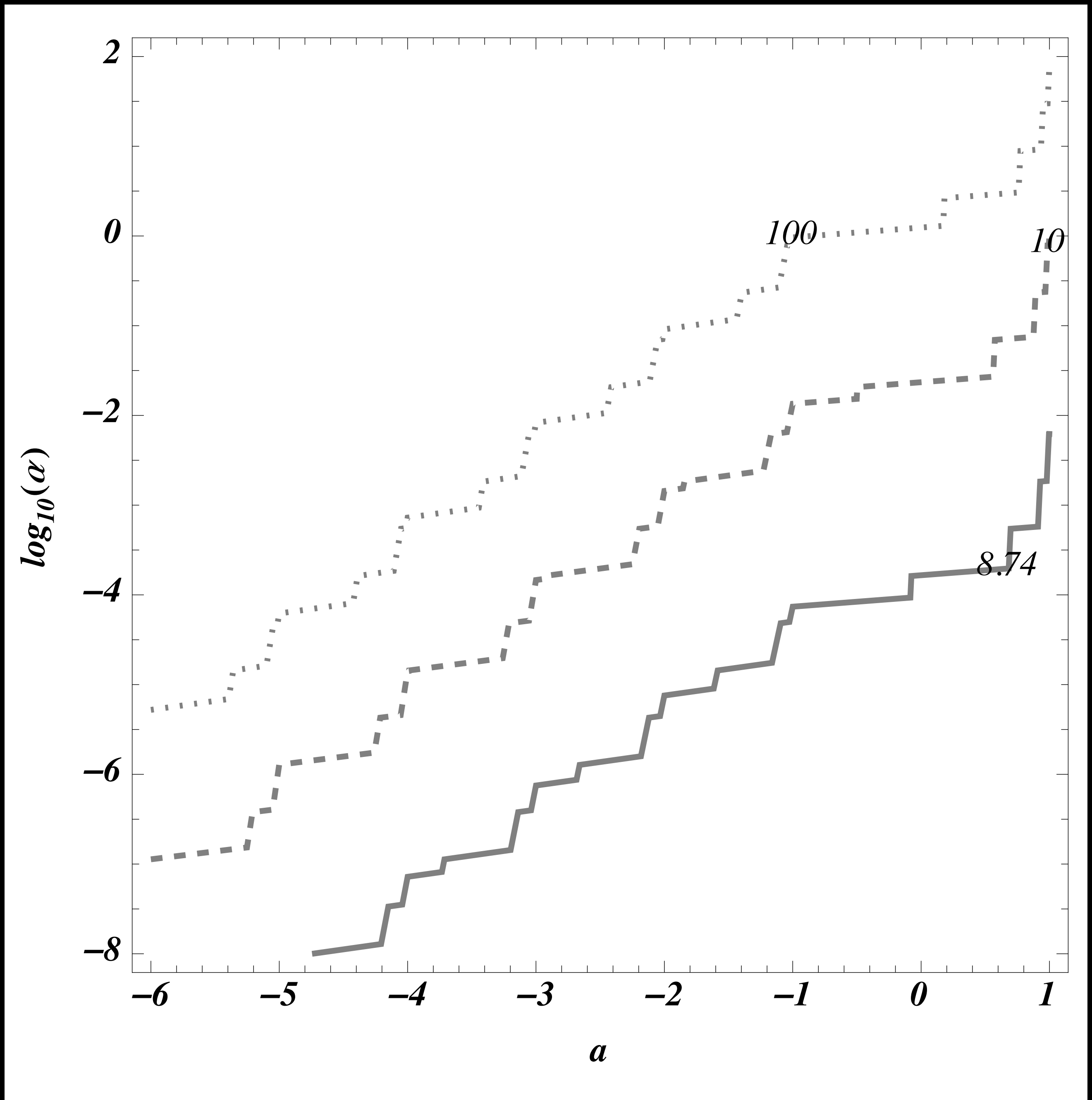
Waveform in FD



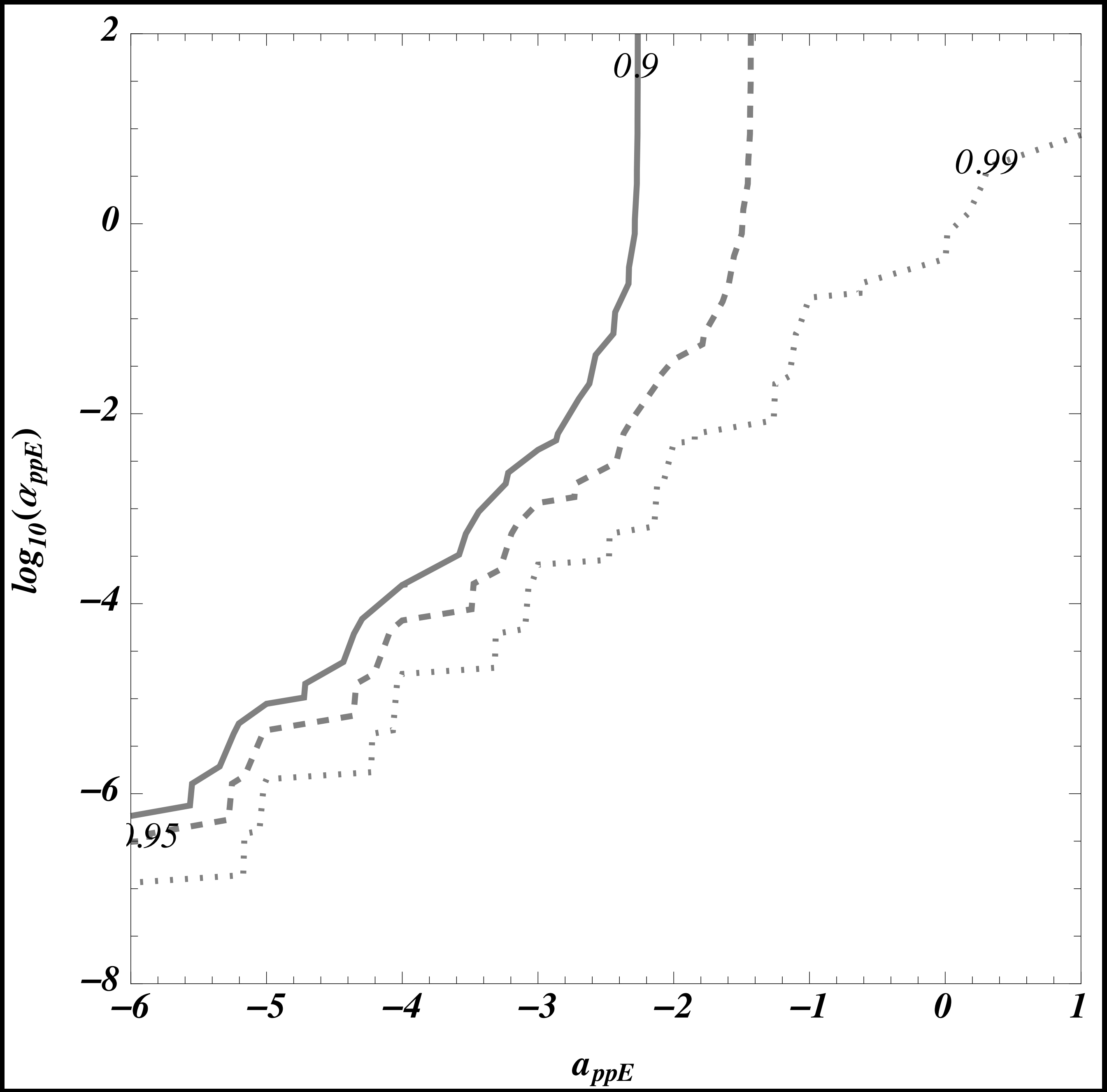
	SNR
GR---	8.73
Model2(α,a)=(10,1)---	18.9
=(-1.5,0)---	4.36

Model A2. amplitude-modification: $\beta=0$, {a, α} $h_{model2}=h_{GR}(1+\alpha u^a)$

SNR contour



FF contour

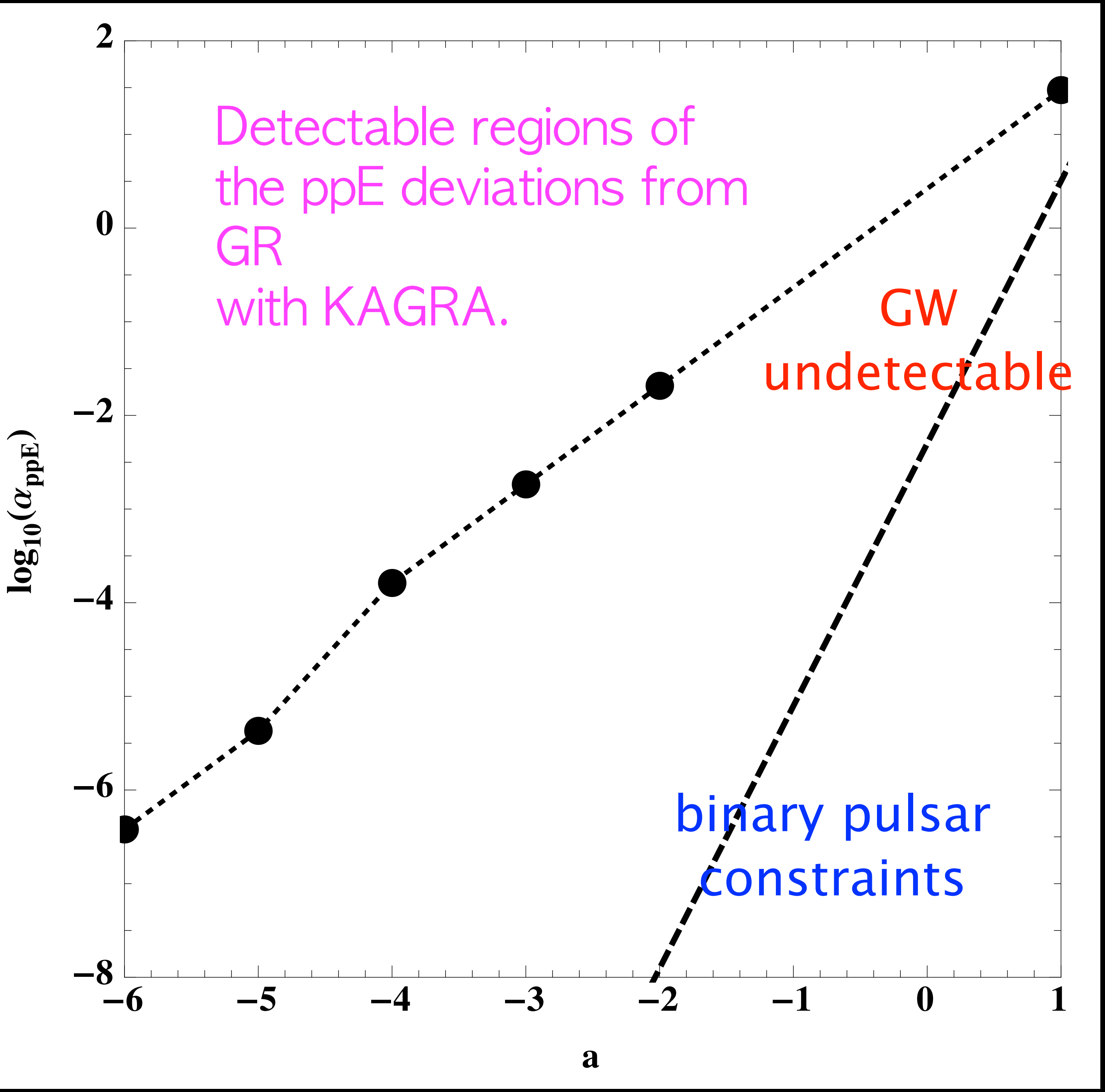


We derive SNRreq from FF with Vallisneri's method.

[Vallisneri, PRD 2012]

Model A2. amplitude-modification: $\beta=0$, $\{a, \alpha\}$ $h_{model2}=h_{GR}(1+\alpha u^{a})$

Detectable Region (SNR>SNR_{req})



Efficiency E=50%

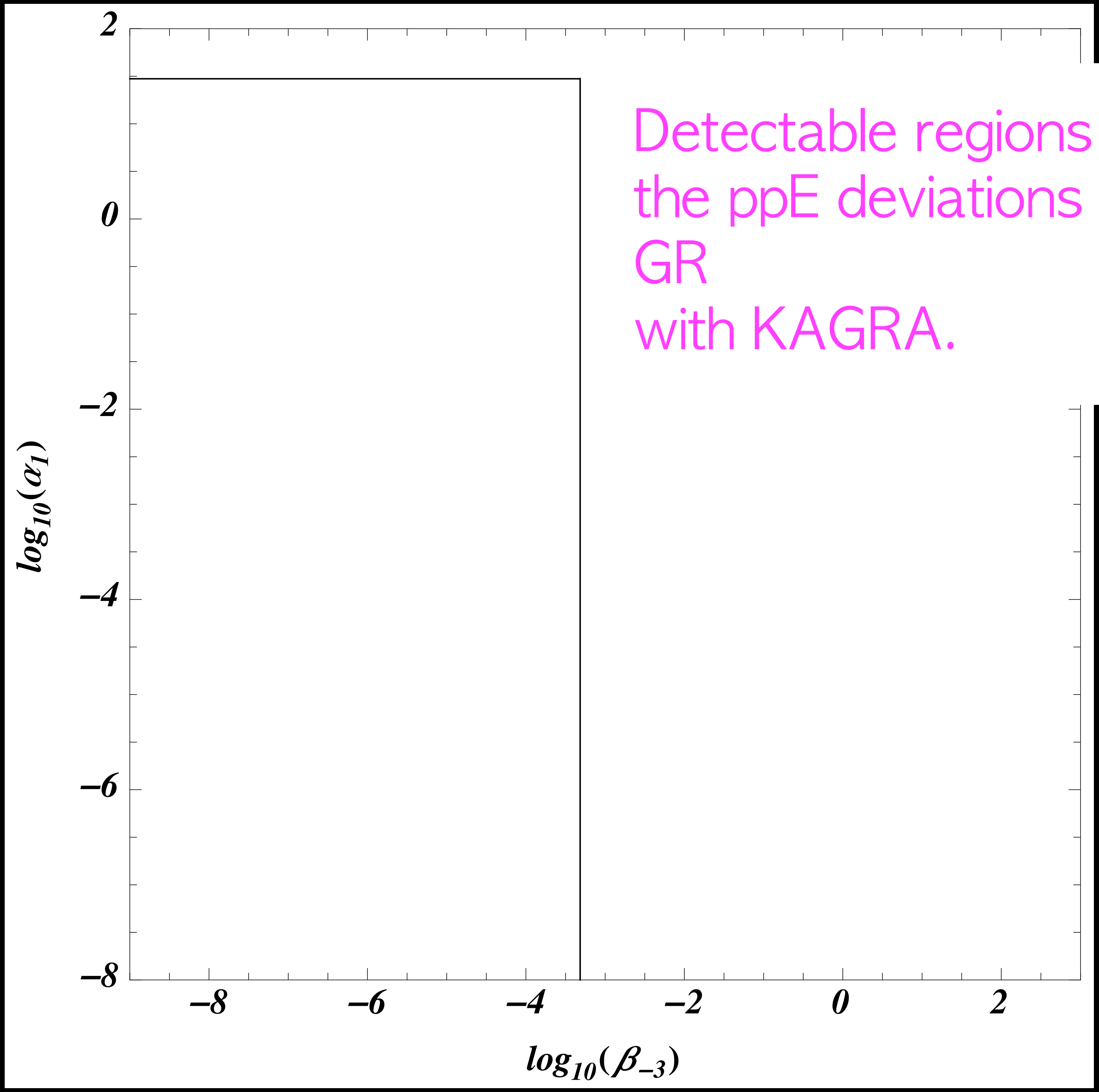
FAP F=10^{-4}

Binary pulsar observations can do a better constraint than GWs observations.

Model A4. β_{-3}, α_1 for a fixed b=-3, a=1

$h_{model4}=h_{GR}(1+\alpha_1 u^{1.5})\exp[i\beta_{-3}u^{-3}]$

Detectable Region (SNR>SNR_{req})



Detectable regions of the ppE deviations from GR
with KAGRA.

Efficiency E=50%
FAP F=10^{-4}

The constraints on the amplitude and phase ppE parameters are independent from each other.

Strategy

Parametrized post-Einsteinian Framework
Approximate Bayesian analysis
Detectable regions of ppE corrections to GR

Summary

We demonstrate that adv. GW detectors, including KAGRA, have tremendous potential for new bounds on deviations from GR.

Future

New constraints on Massive graviton and Chern-Simons.

We will calculate the Bayesian odds ratio for weaker signals with a full-scale MCMC in CBC-PE pipeline.

Thank you for your attention.