Forecast constraints on cosmic string parameters from future gravitational wave experiments

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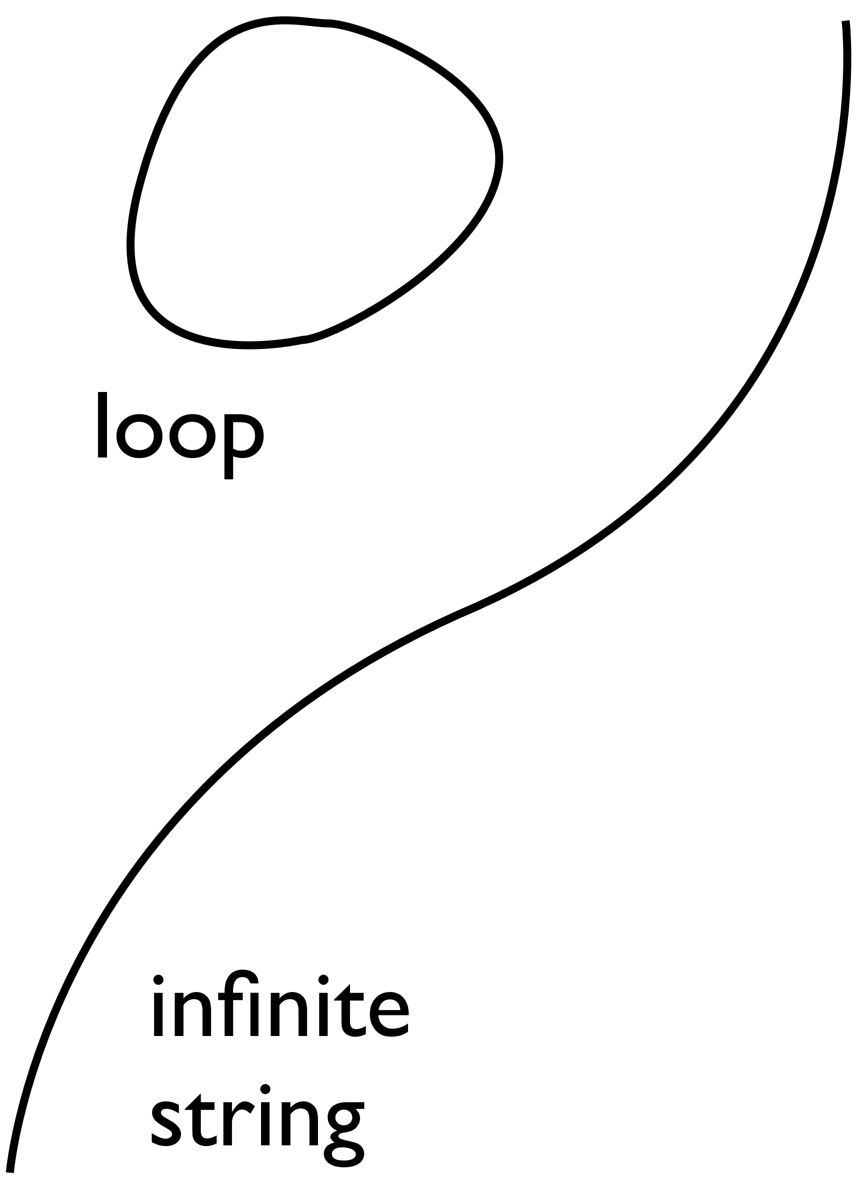
Based on
S. Kuroyanagi, K. Miyamoto, T. Sekiguchi, K. Takahashi, J. Silk,
PRD 86, 023503 (2012), arXiv:1202.3032 [astro-ph]

Cosmic string ?

One dimensional topological defects generated in the early universe



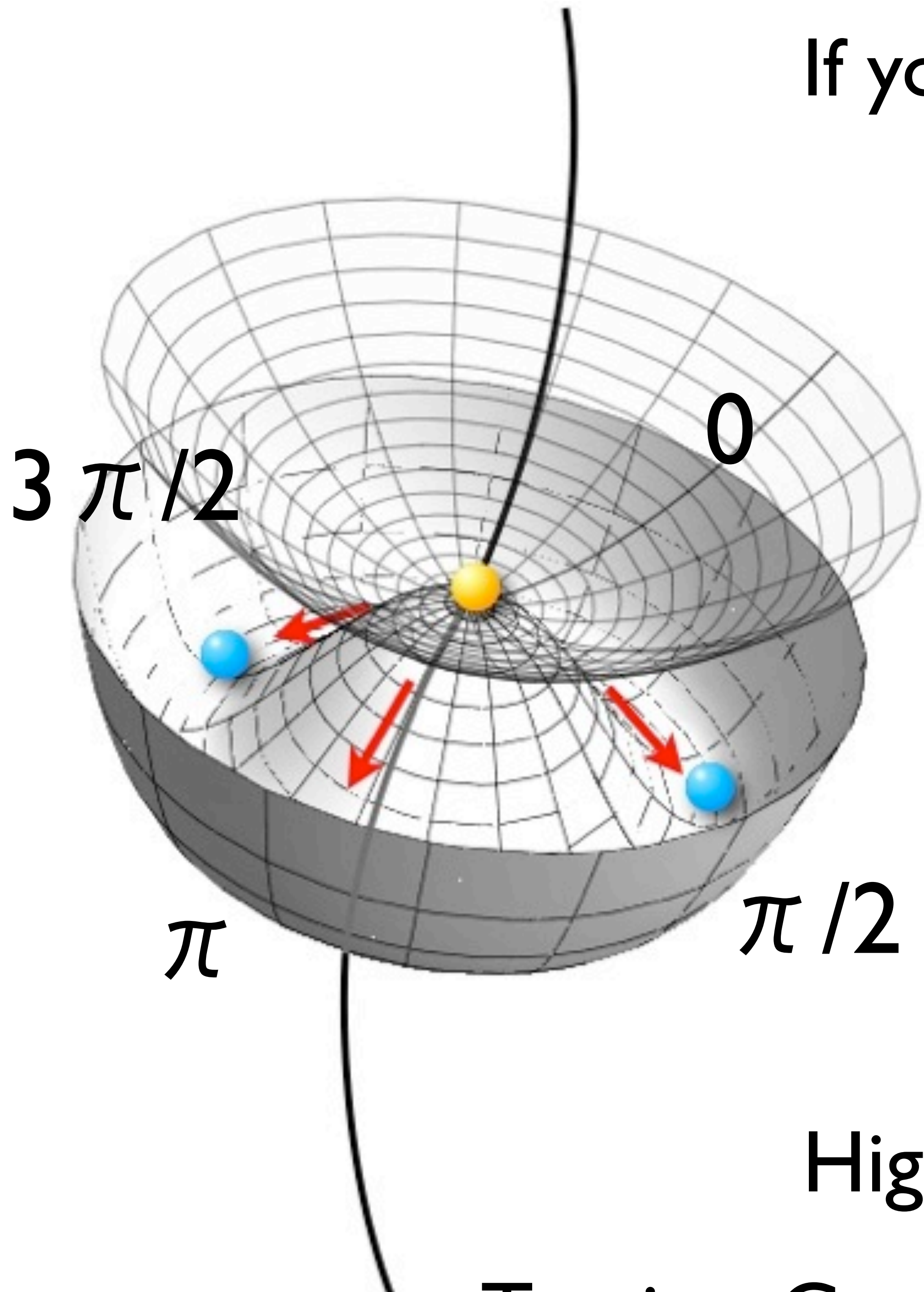
- have infinite length (= no end point)
- can be a form of loop
- affect only through gravitational force

- emits gravitational waves

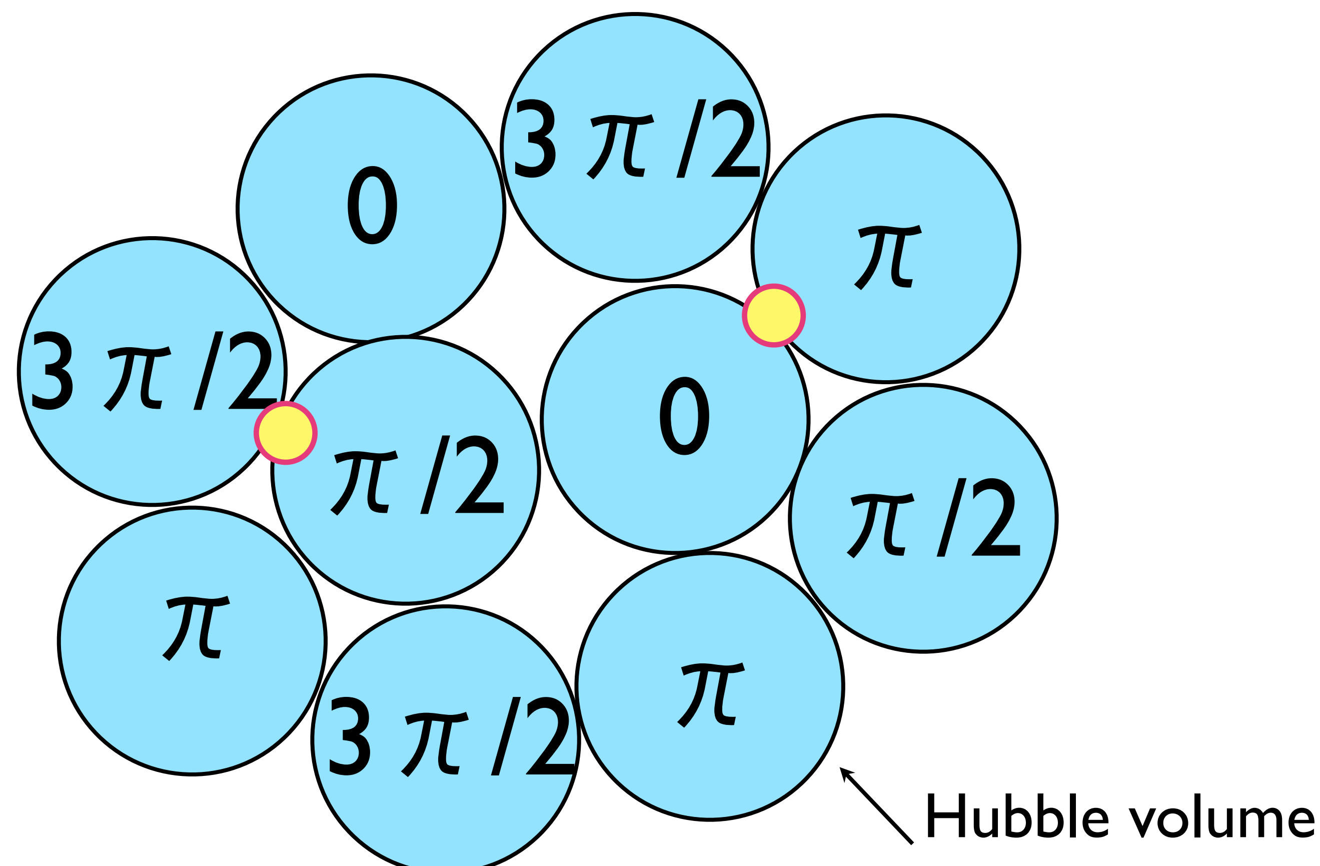
μ : tension (line density)
$G\mu = \mu / M_{pl}^2$

Generation mechanism 1: phase transition

The Universe has experienced symmetry breakings.



If you consider U(1) symmetry breaking...



High energy vacuum remains at the center

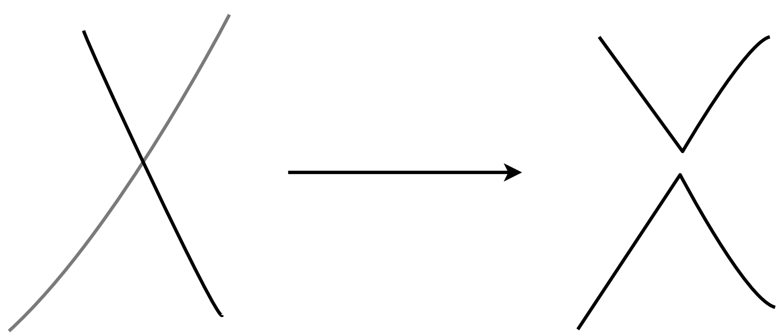
Tension $G\mu$ ~ the energy scale of the phase transition

Generation mechanism 2: Cosmic superstrings

Cosmological size D-strings or F-strings remains after inflation in superstring theory

Difference from phase transition origin

- reconnection probability: p



Phase transition origin: p=1

D-string: p=0.1-1
F-string: $p=10^{-3}$-1

- can have broad values of $G\mu$

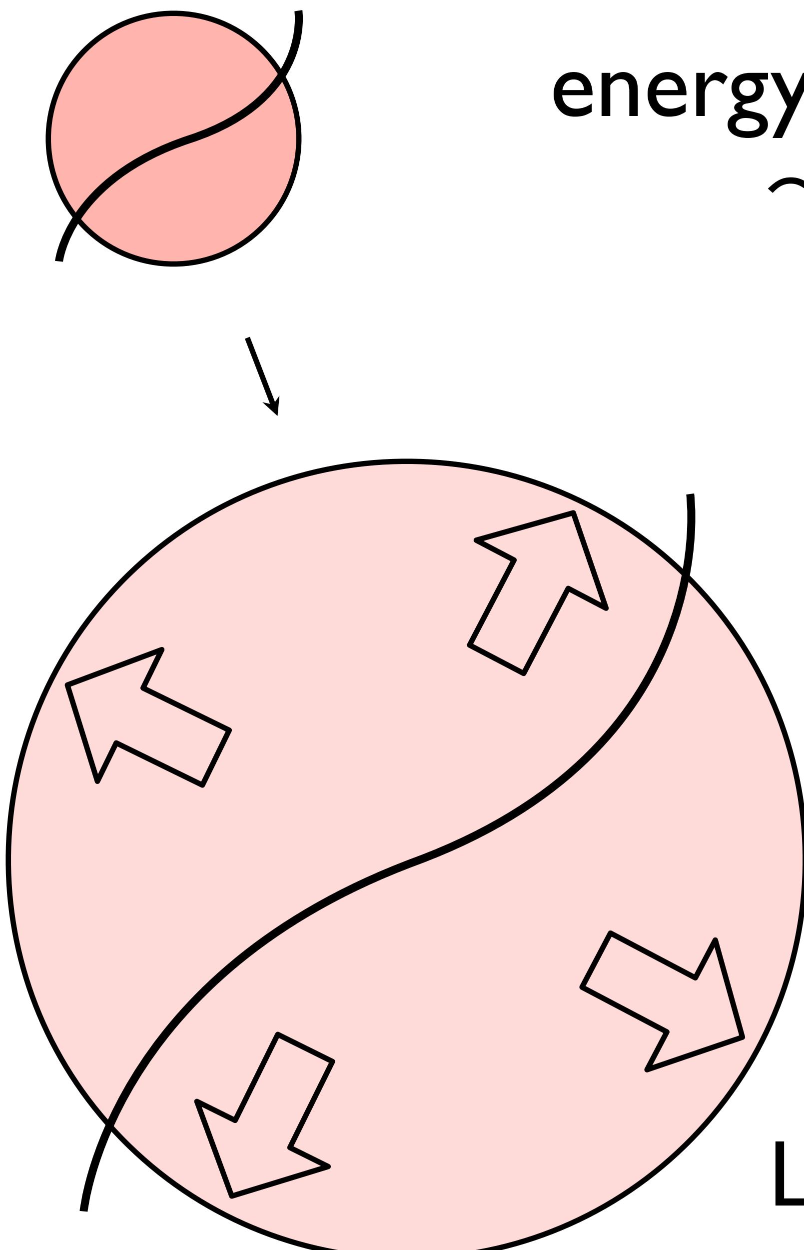
→ Cosmic strings could give some insight into fundamental physics

Evolution of cosmic strings

energy density of the cosmic strings $\propto a^{-2}$

$\sim$ (line density × length)/volume

constant $\propto a^{1}$ $\propto a^{-3}$

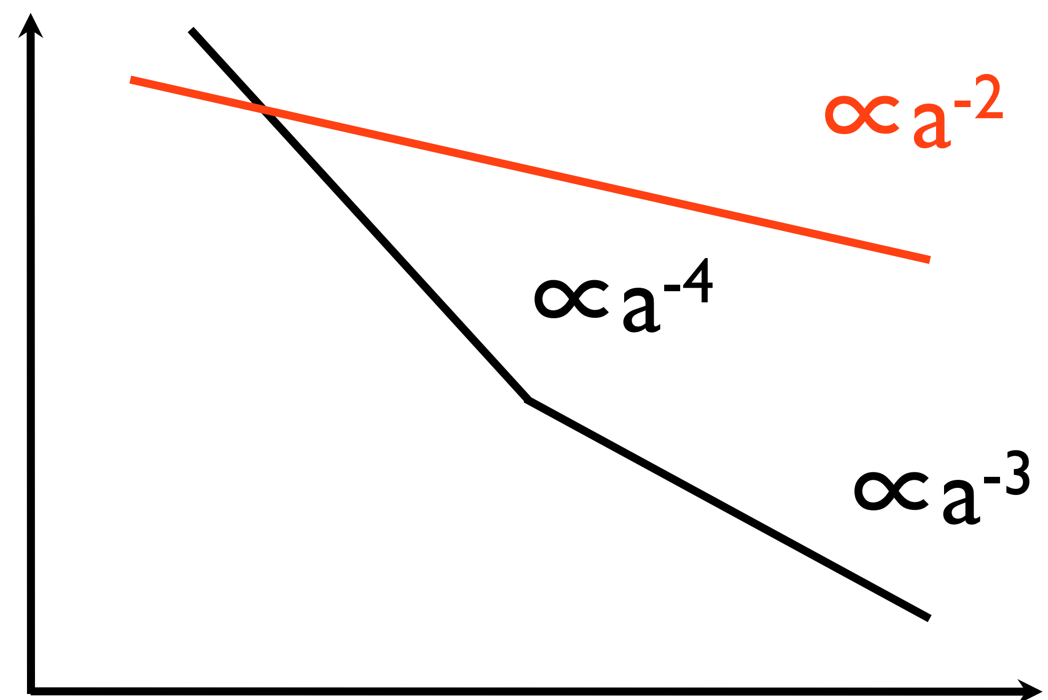


$L \propto a^{1}$
$V \propto a^{3}$

radiation $\propto a^{-4}$

matter $\propto a^{-3}$

energy density



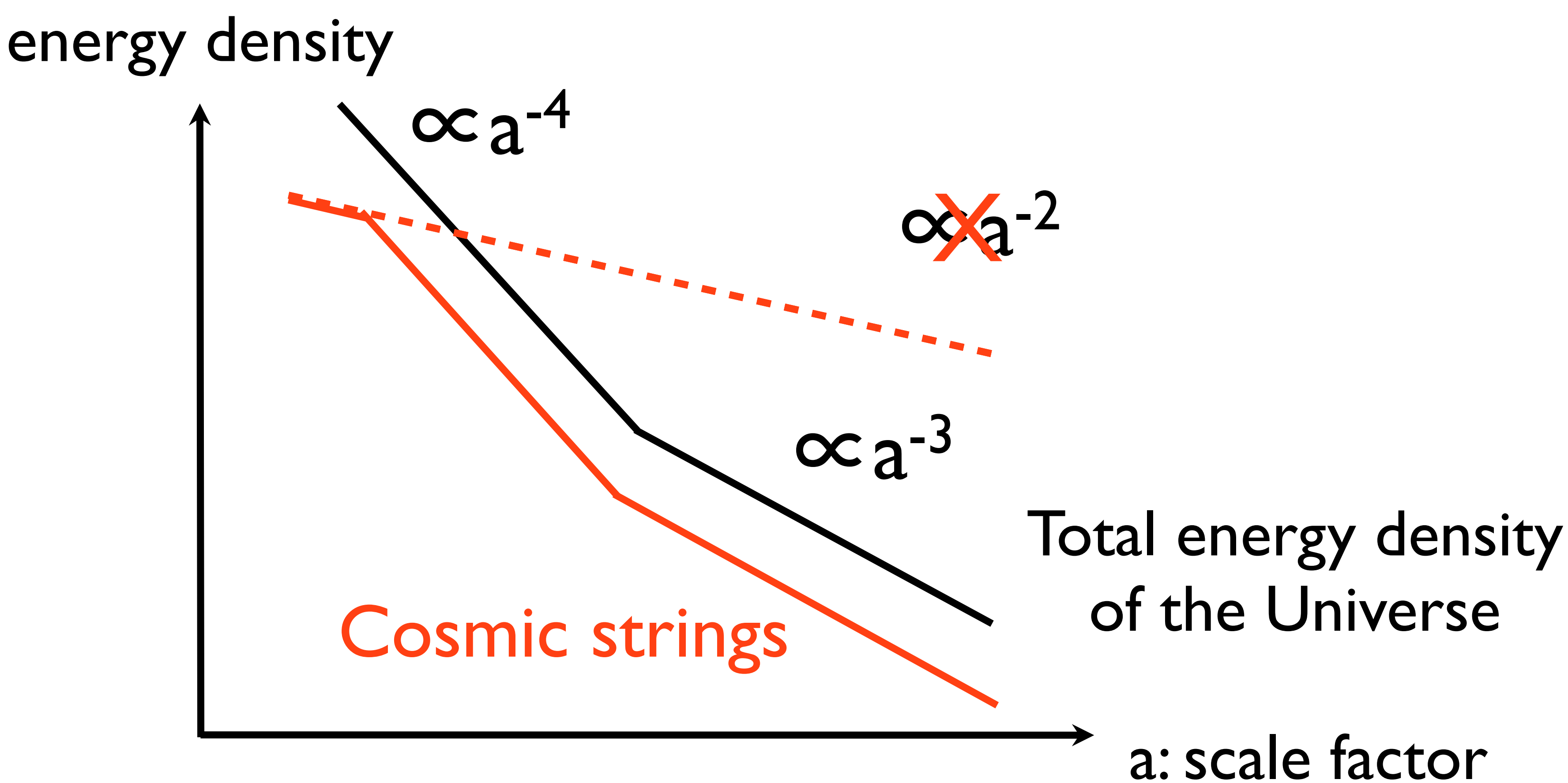
a: scale factor

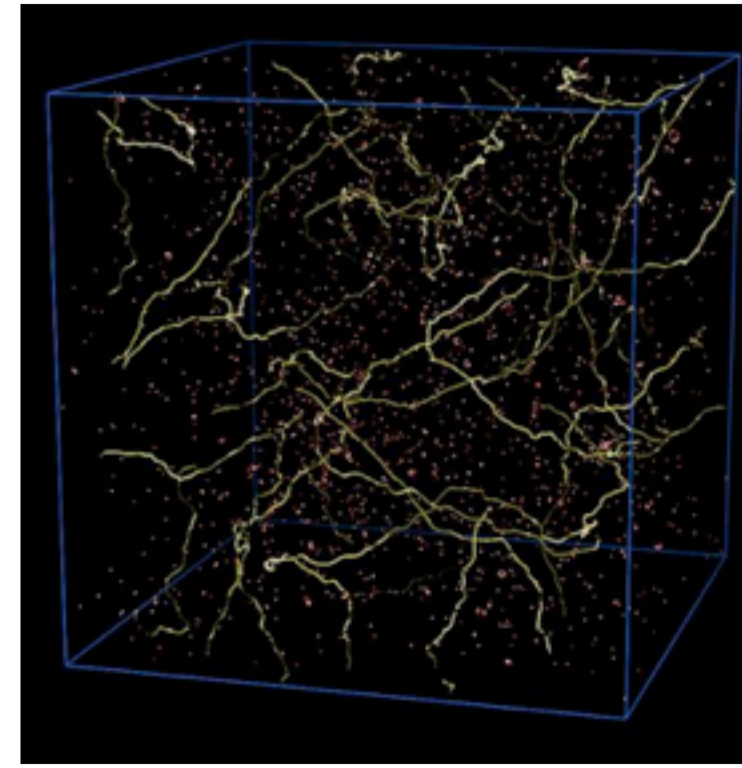
→ easily dominates the energy density of the Universe.
not allowed by the observational facts?

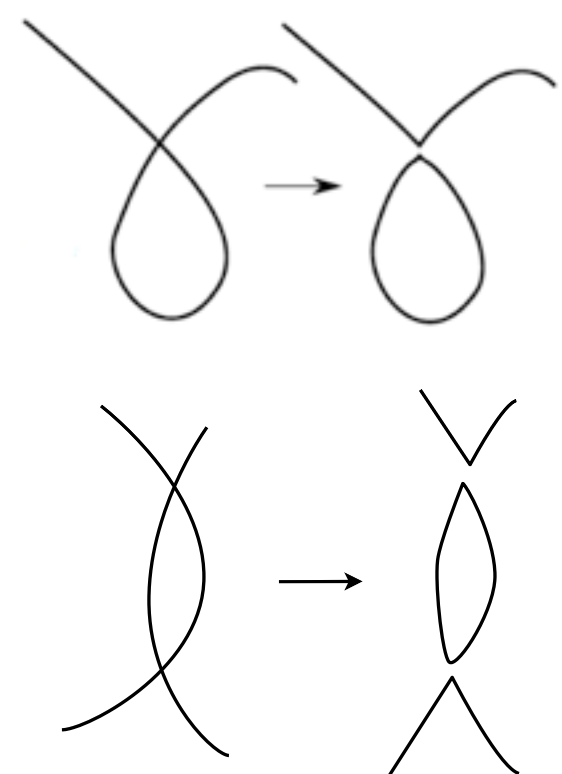
Evolution of cosmic strings

Scaling law

Cosmic String Networks approach a self-similar solution, which always looks same at the Hubble scale.







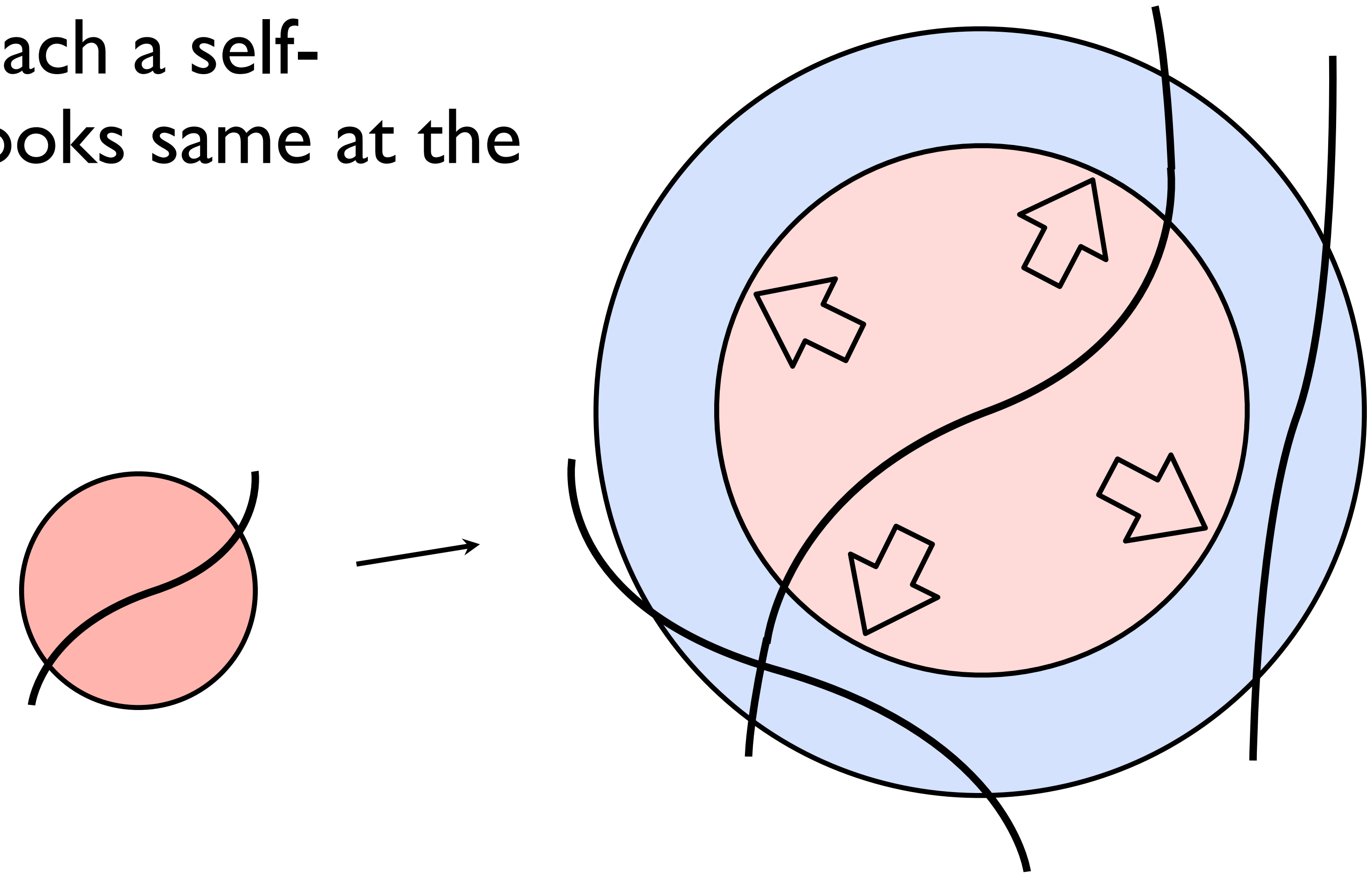
Cosmic strings become loops via reconnection.

Loops lose energy by emitting gravitational waves.

Evolution of cosmic strings

Scaling law

Cosmic String Networks approach a self-similar solution, which always looks same at the Hubble scale.



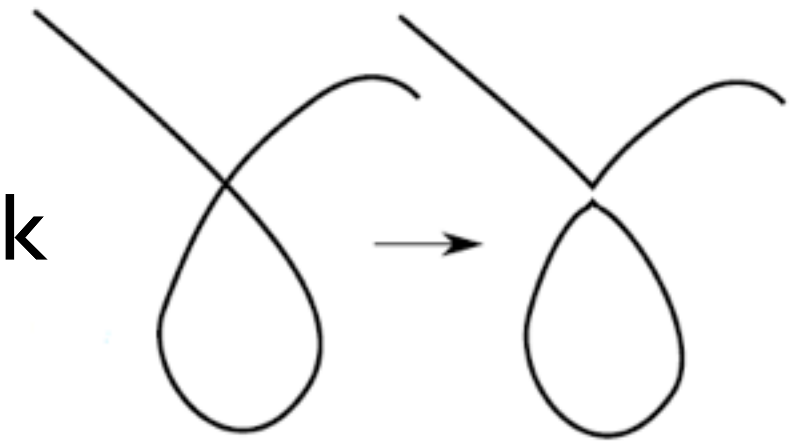
Increase of infinite string length by the Hubble expansion ⇔ Loss of infinite string length by generation of loops

Higher reconnection rate
more efficient generation of loops
more energy release by the emission of GWs

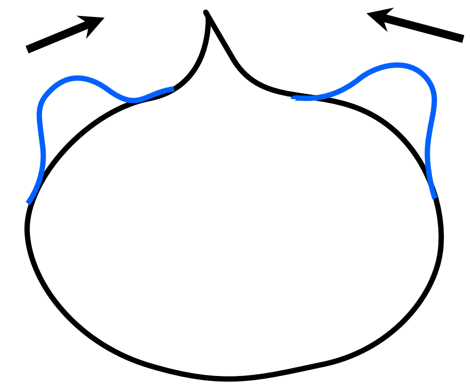
Gravitational waves from cosmic strings

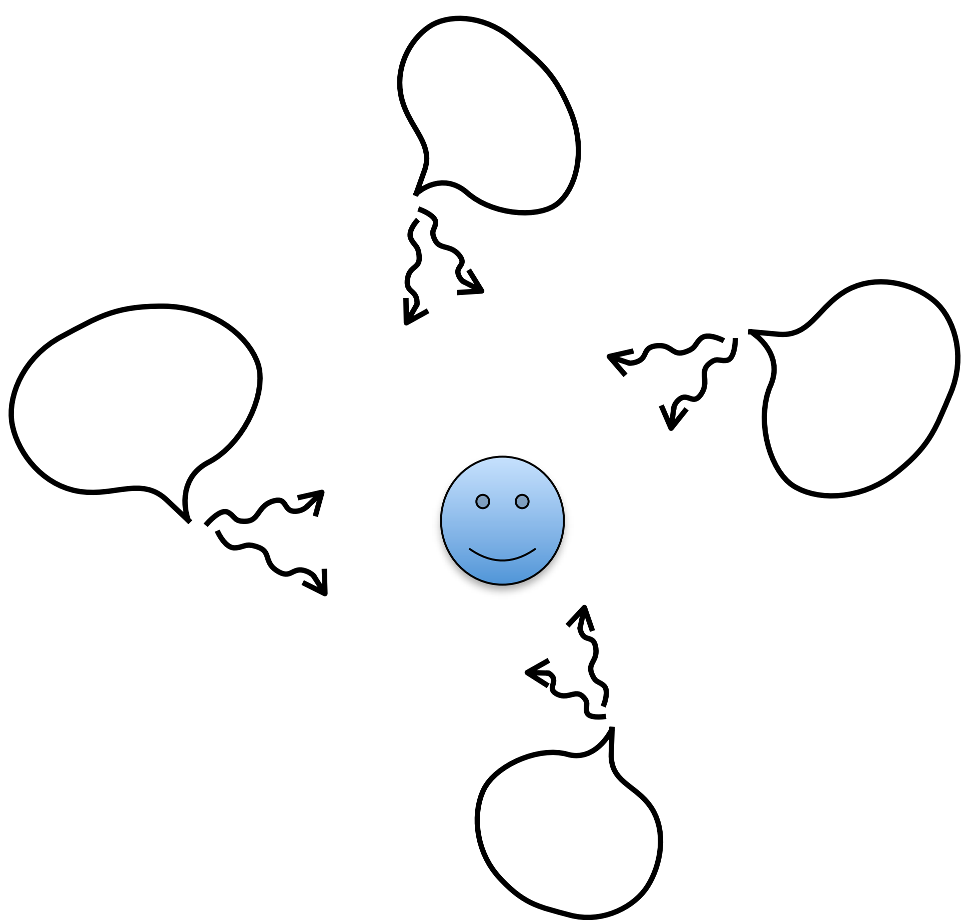
Strong GW emittion from singular points
called kinks and cusps

kink



cusp





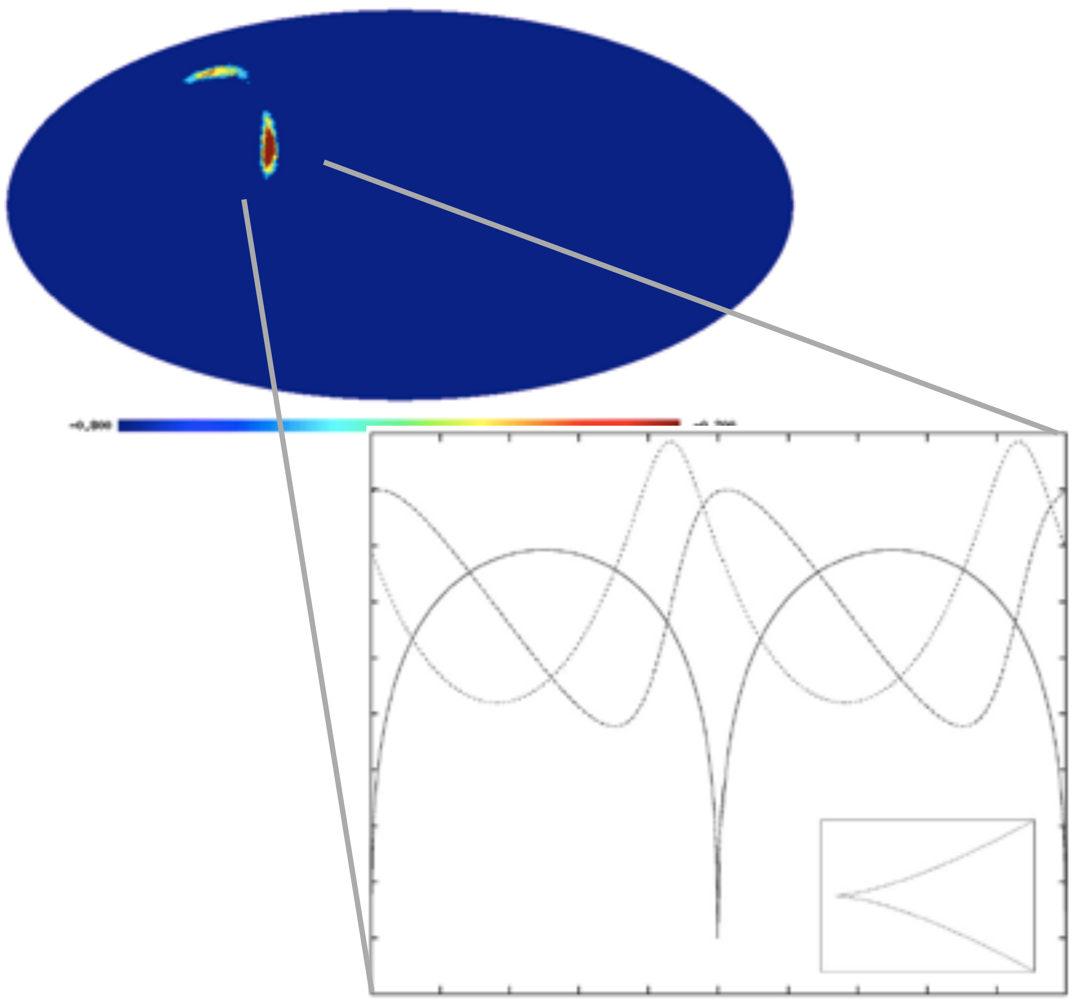
Rare Burst: GWs with large amplitude coming from close loops

Gravitational wave background (GWB): superposition of small GWs coming from the early epoch

Observations of GWs

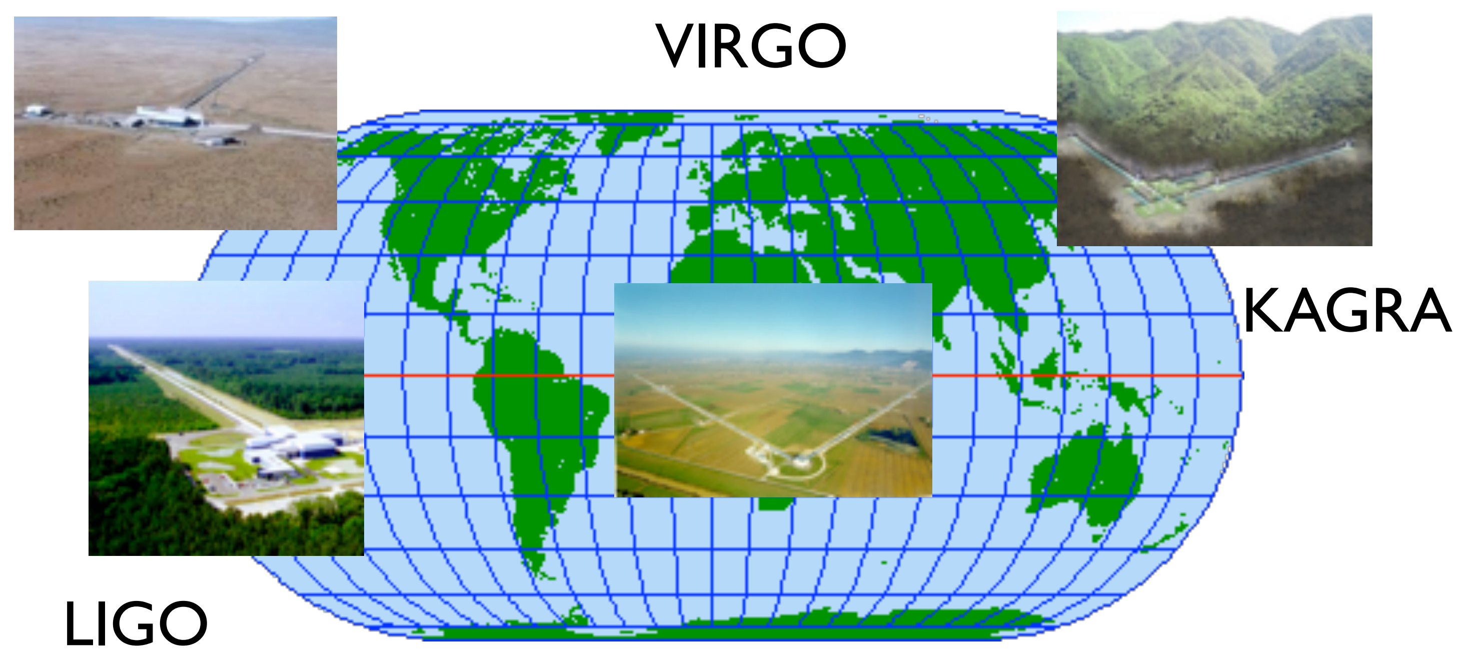
GWs with large amplitude

Burst



GWs with small amplitude
but numerous

GWB



<u>Cross correlation analysis</u>

Cross correlate the signals from two or more detector and extract stable GWs

Gravitational wave experiments

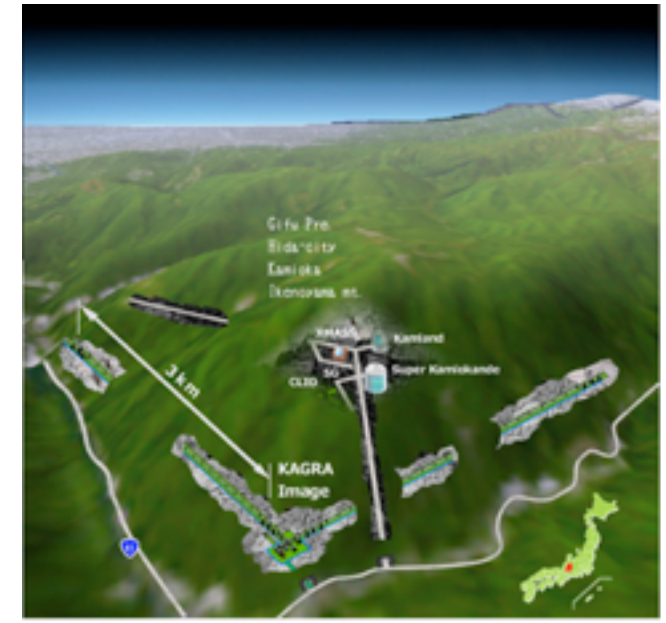
- Direct detection

  Ground：**Advanced-LIGO、KAGRA、**
  Virgo、IndIGO (2017-)

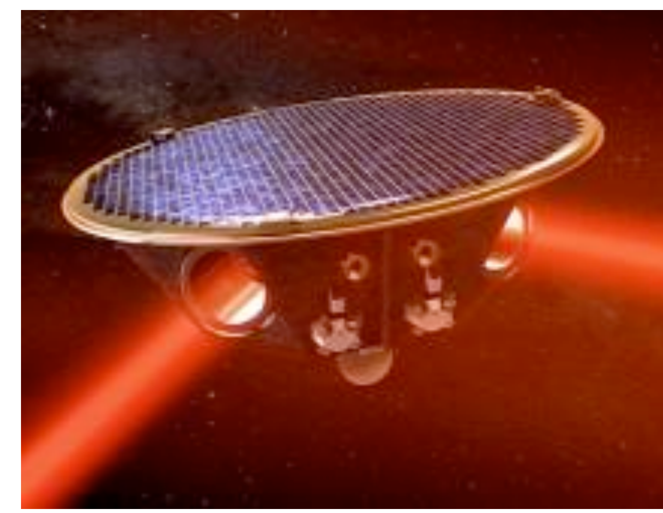
  Space：**eLISA/NGO (2022?)、DECIGO (2027)**

- Pulsar timing: **SKA (2020)**

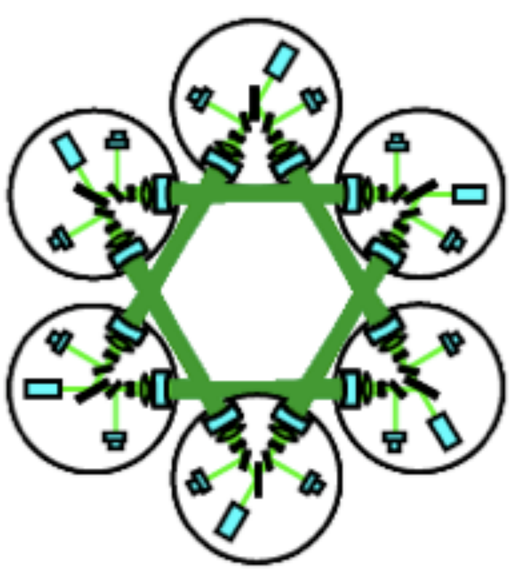
- CMB B-mode polarization: **Planck, CMBpol**



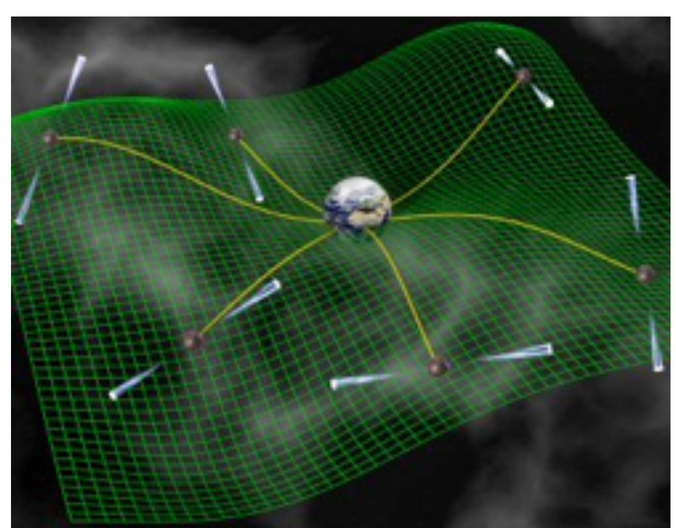
KAGRA image (http://gwcenter.icrr.u-tokyo.ac.jp/)



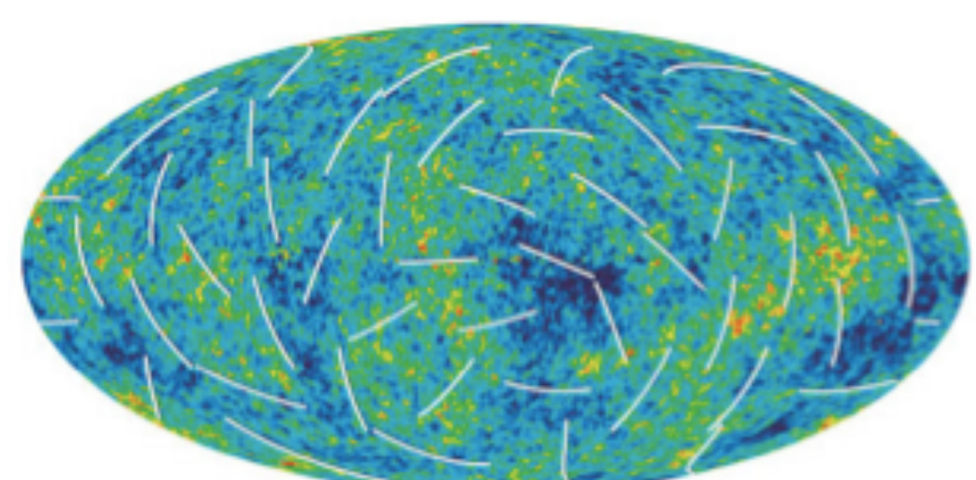
eLISA image (http://elisa-ngo.org/)



DECIGO image, S. Kawamura et al, J. Phys.: Conf. Ser. 122, 012006 (2006)



PTA image (NRAO)



WMAP Three Year Polarized CMB Sky (http://wmap.gsfc.nasa.gov/)

Current constraints on cosmic string parameters

3 parameters to characterize cosmic string

- ・$G\mu$ (= μ/M_{pl}^2) : tension (line density)
- ・α : initial loop size $L \sim \alpha H^{-1}$
- ・p : reconnection probability

・CMB temperature fluctuation: $G\mu$ <~10^{-7}
・Gravitational lensing: $G\mu$ <~10^{-6}

for infinite strings

• Gravitational waves

Pulsar timing: $G\mu$ <~10^{-9}

Direct detection (LIGO GWB): $G\mu$ <~10^{-6}

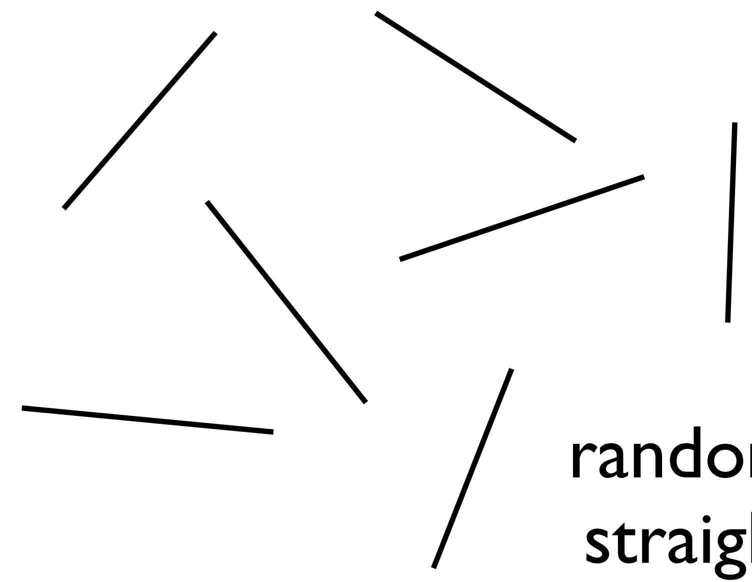
for loops α =0.1, p=1

What about future constraints from Advanced-LIGO？

Estimation of the GW burst rate

Initial number density of loops depends on α and p

$$= \frac{\text{(length of infinite string discarded to loops)}}{\text{(initial length of loops} = \alpha t_i\text{)}}$$



random walk of straight strings

length L, velocity v

Evolution of infinite strings

- velocity-dependent one-scale model

$$2\frac{dL}{dt} = 2HL(1+v^2) + cv$$

energy conservation

energy discarded to loops

$$\left.\frac{d\rho_{inf}}{dt}\right|_{loop} = cv\frac{\rho_{inf}}{L}$$

for small p: c → cp

$$\frac{dv}{dt} = (1-v^2)\left(\frac{k}{R} - 2Hv\right)$$

damping due to the expansion

acceleration due to the curvature of the strings

momentum parameter: $k = \frac{2\sqrt{2}}{\pi}\left(\frac{1-8v^6}{1+8v^6}\right)$

Estimation of the GW burst rate

<u>loop evolution</u> depends on $G\mu$ and α

Initial loop length $= \alpha t_i$

t_i : time when the loop formed

GW power $P = \Gamma G \mu^2$ Γ: numerical constant ～50-100

From the energy conservation law

(energy of loop at time t $= \mu l$)

$=$ (initial energy of the loop $= \mu\alpha t_i$) $-$ (enegry released to GWs $= P\Delta t$)

Loop length at time t $l(t, t_i) = \alpha t_i - \Gamma G \mu (t - t_i)$

Lifetime of the loop $= \dfrac{\text{(initial loop energy)}}{\text{(energy release rate per time)}}$

$$= \frac{\mu \alpha t_i}{\Gamma G \mu^2} = \frac{\alpha t_i}{\Gamma G \mu}$$

Estimation of the GW burst rate

GW burst rate emitted at t〜t+dt from loops formed at t_i〜t_i+dt_i

$$\frac{dR}{dtdt_i}dtdt_i = \underbrace{\frac{1}{4}\theta_m(f,z,l)^2}_{\text{Beaming}}\underbrace{\frac{2c}{(1+z)l(t,t_i)}}_{\text{Time interval of GW emission}}\underbrace{\frac{dn}{dt_i}(t,t_i)\frac{dV}{dt}dtdt_i}_{\text{Loop number}} \times \underbrace{\Theta(1-\theta_m(f,z,l))}_{\text{Beaming}}$$

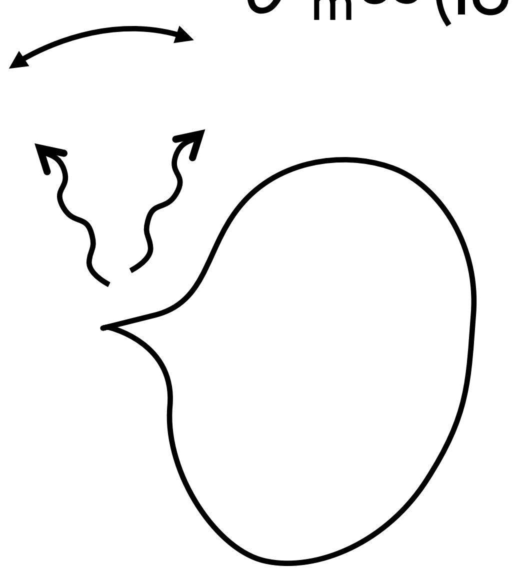
Beaming

Time interval of GW emission

Loop number

$\propto$ (loop length at t)$^{-1}$

$\theta_m \propto$ (loop length at t)$^{1/3}$

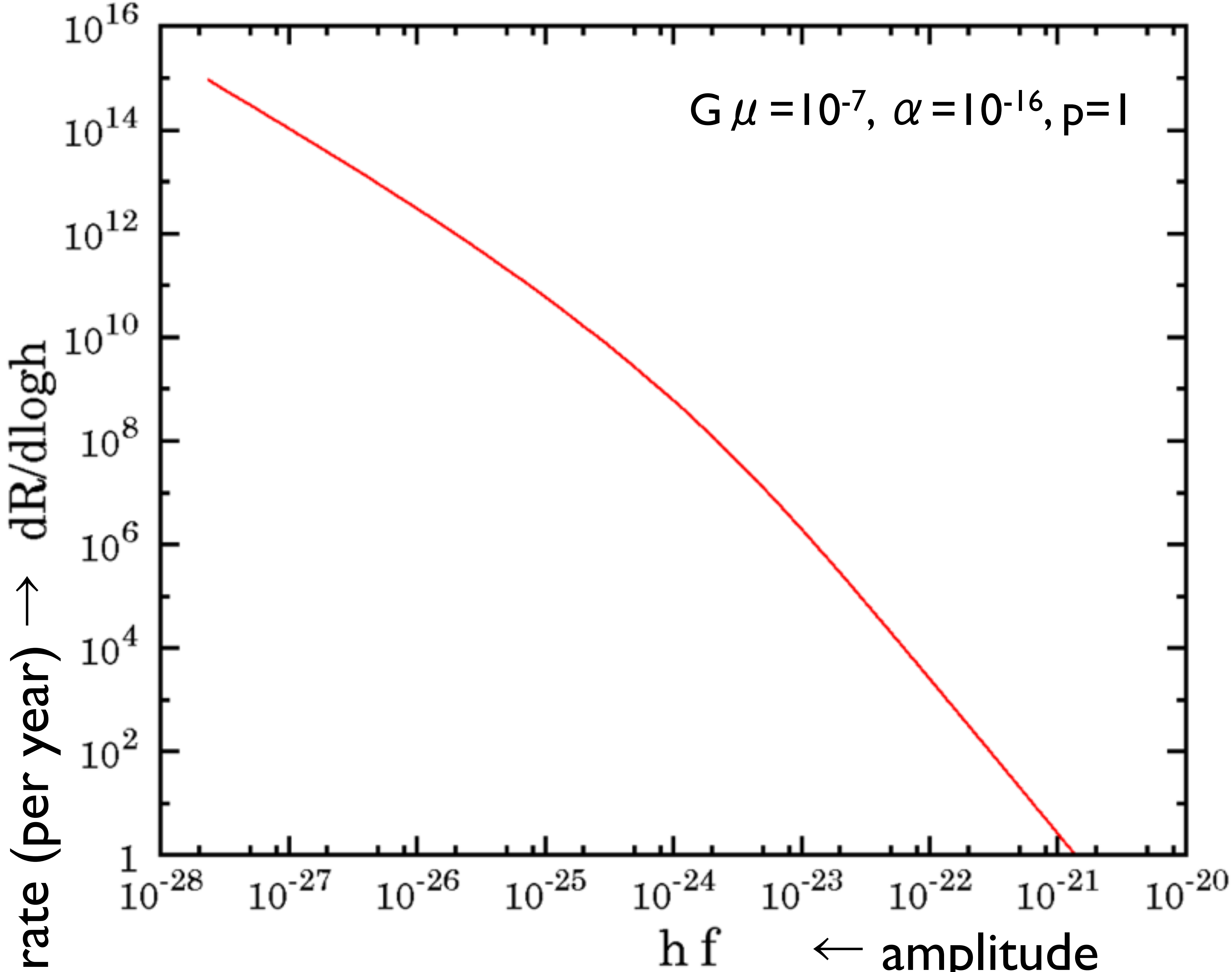


$$l(t,t_i) = \alpha t_i - \Gamma G\mu(t-t_i)$$

GW amplitude from loop of length l

$$h(f,z,l) \simeq 2.68\frac{G\mu l}{((1+z)fl)^{1/3}r(z)f}$$

How many cosmic string bursts are coming to the earth per year?
(plotted as a function of the amplitude for the fixed frequency @220Hz)



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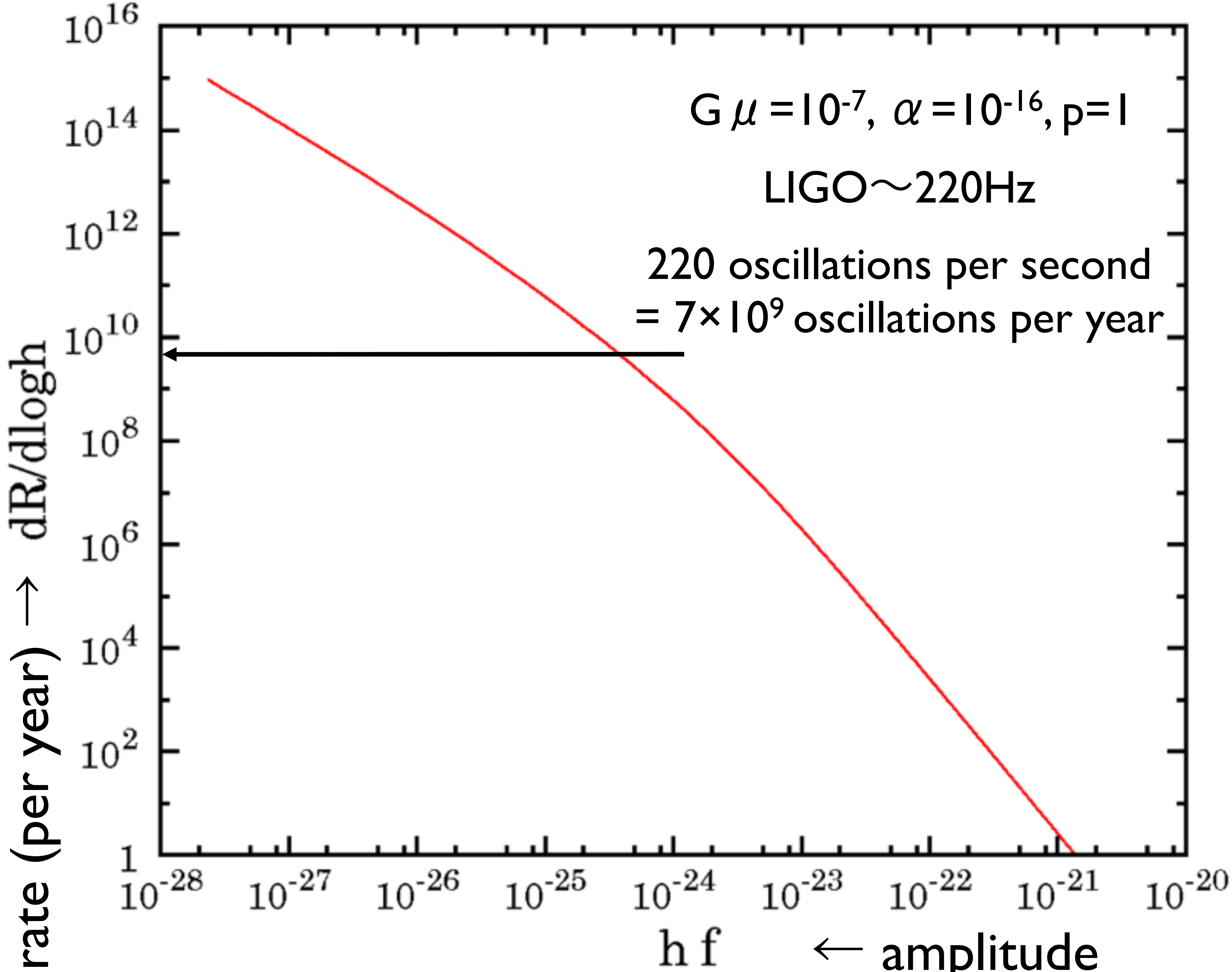

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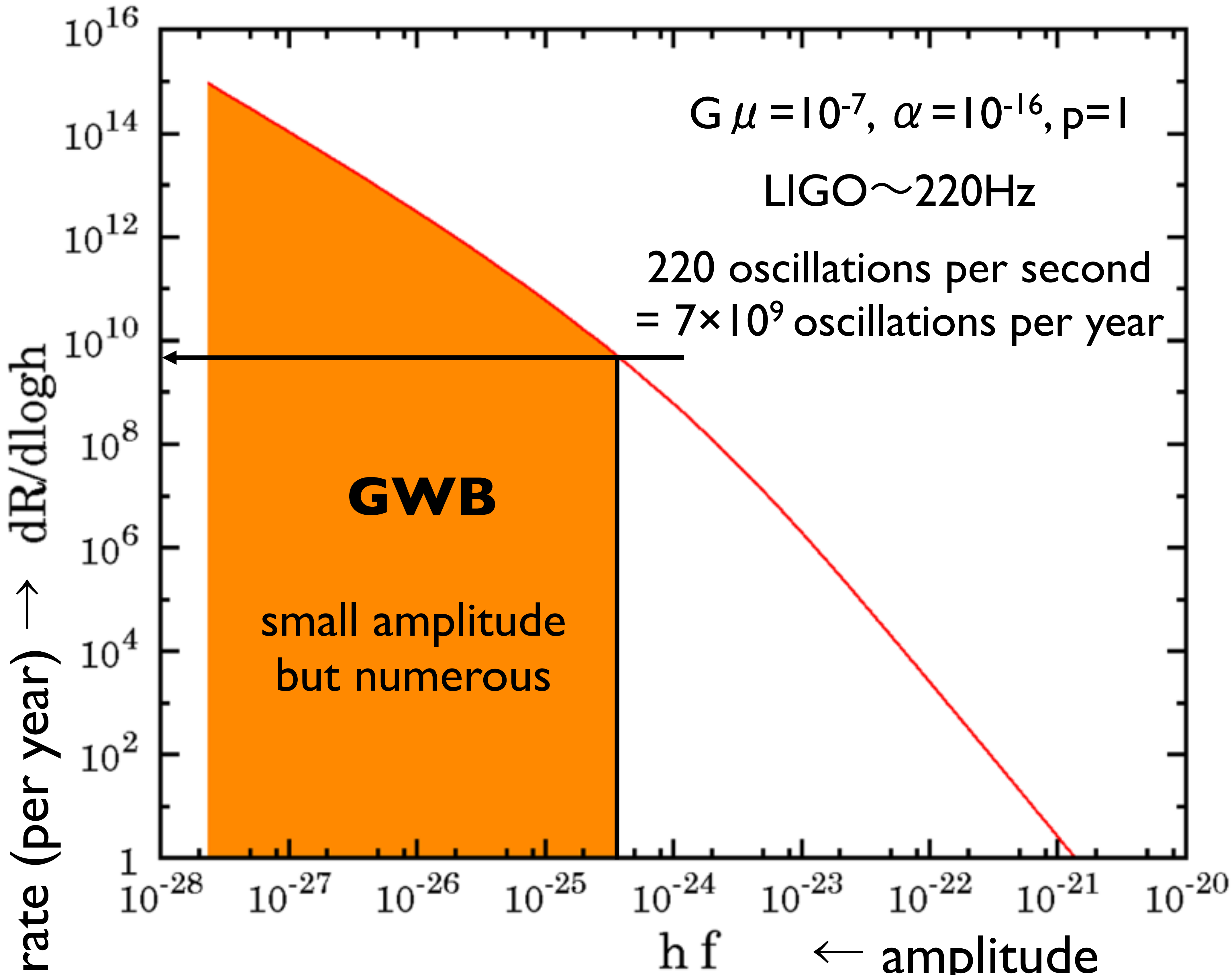

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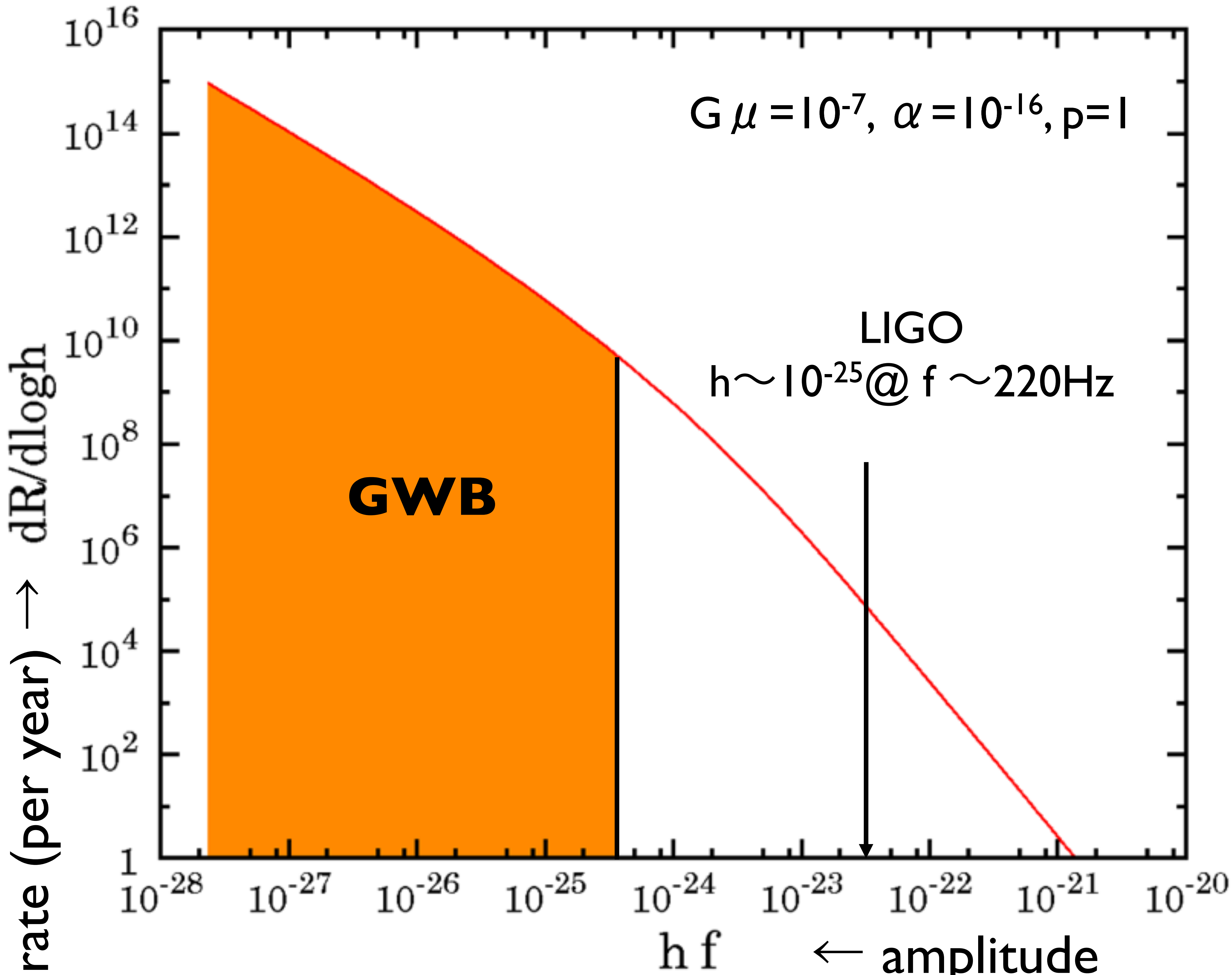

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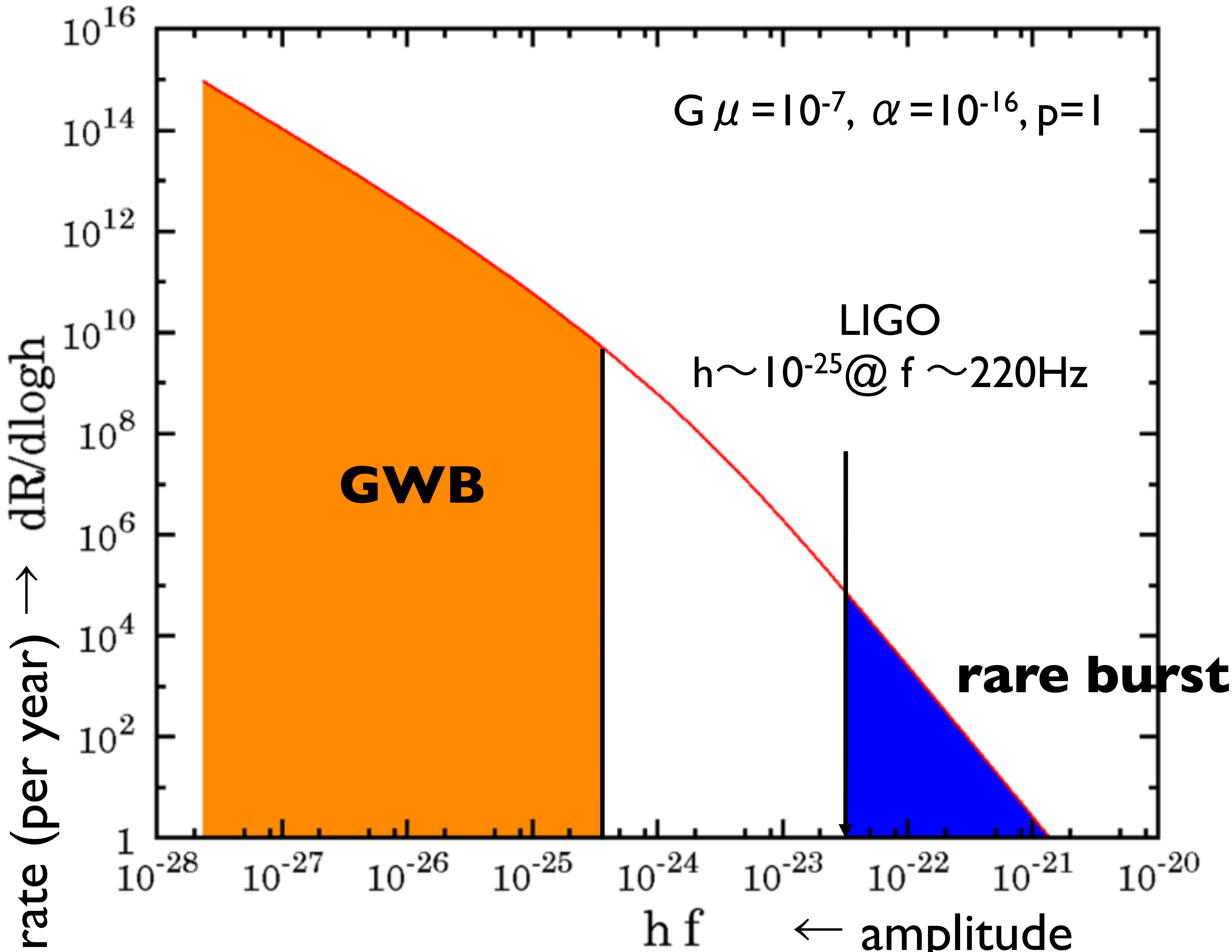

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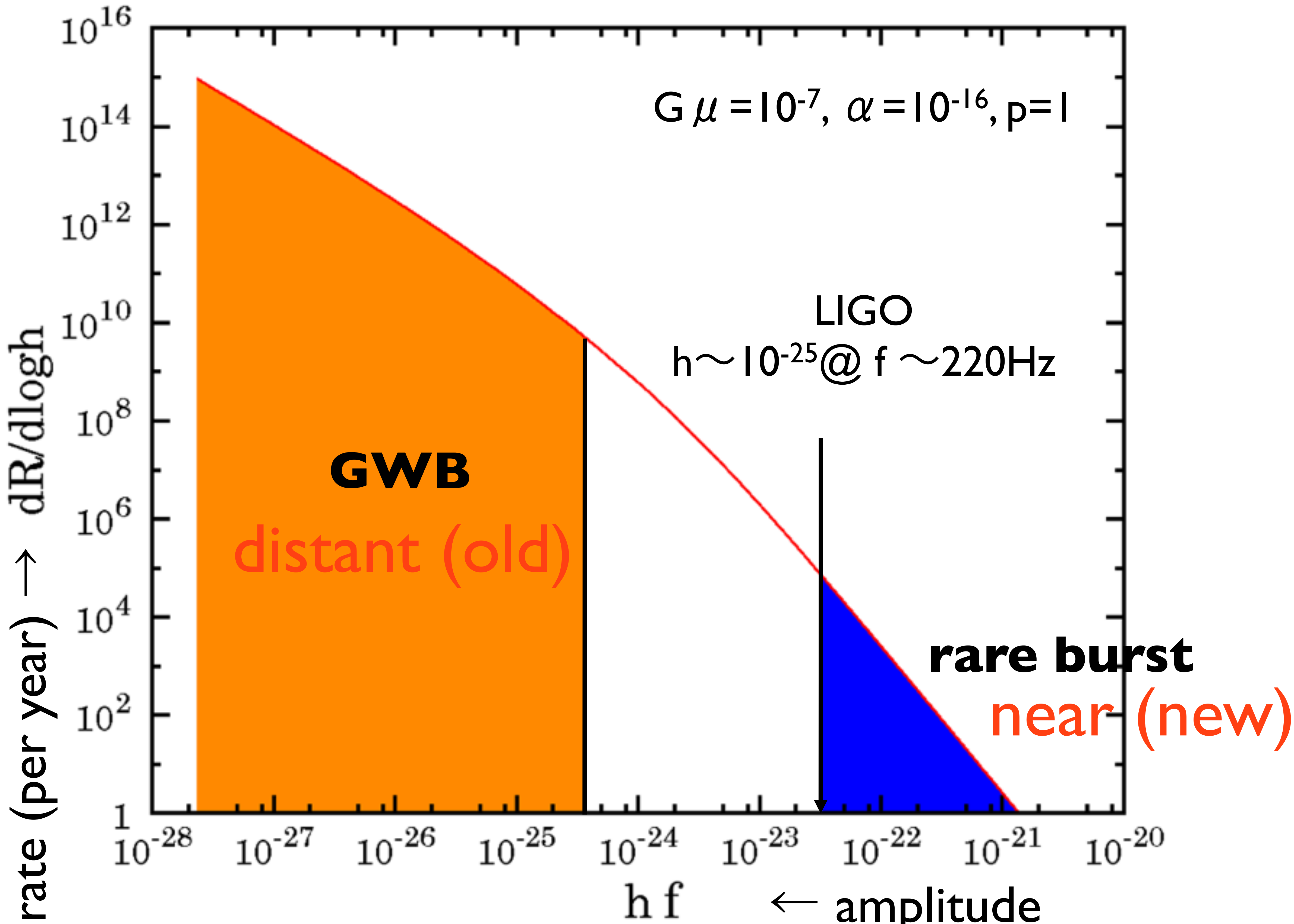
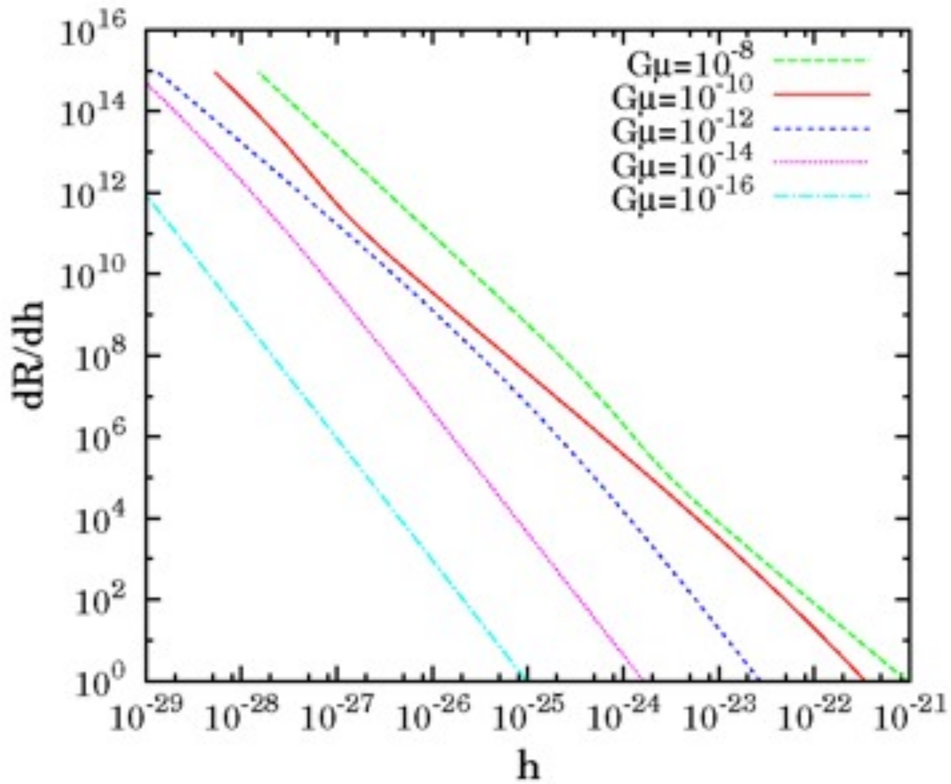
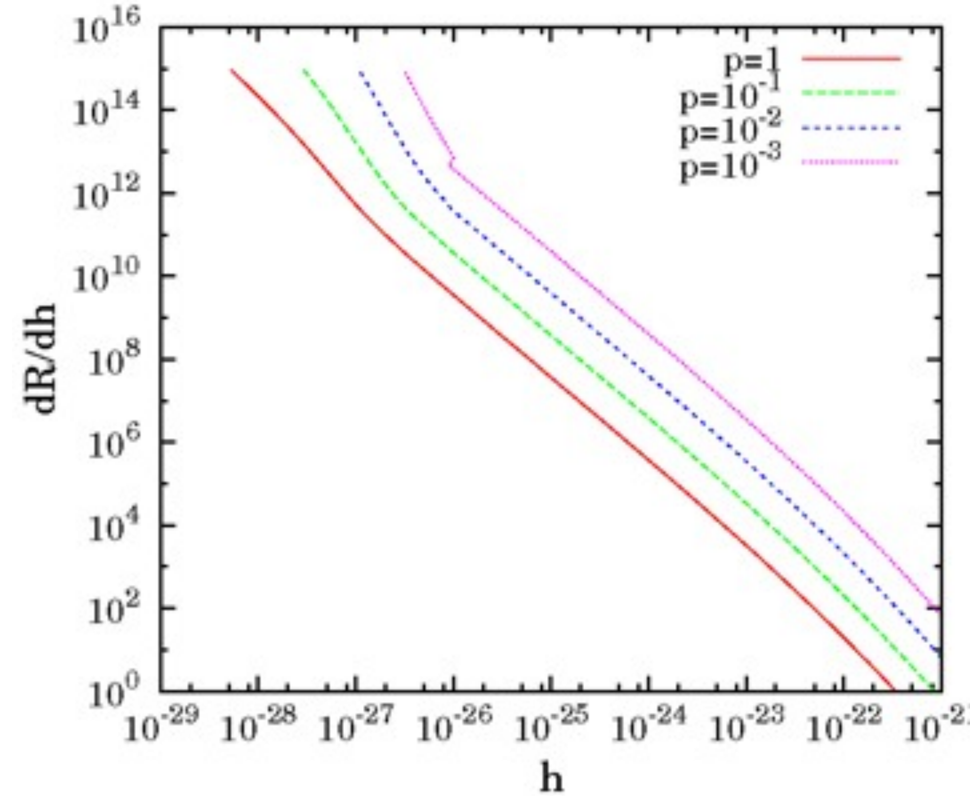


Parameter dependences of the rate

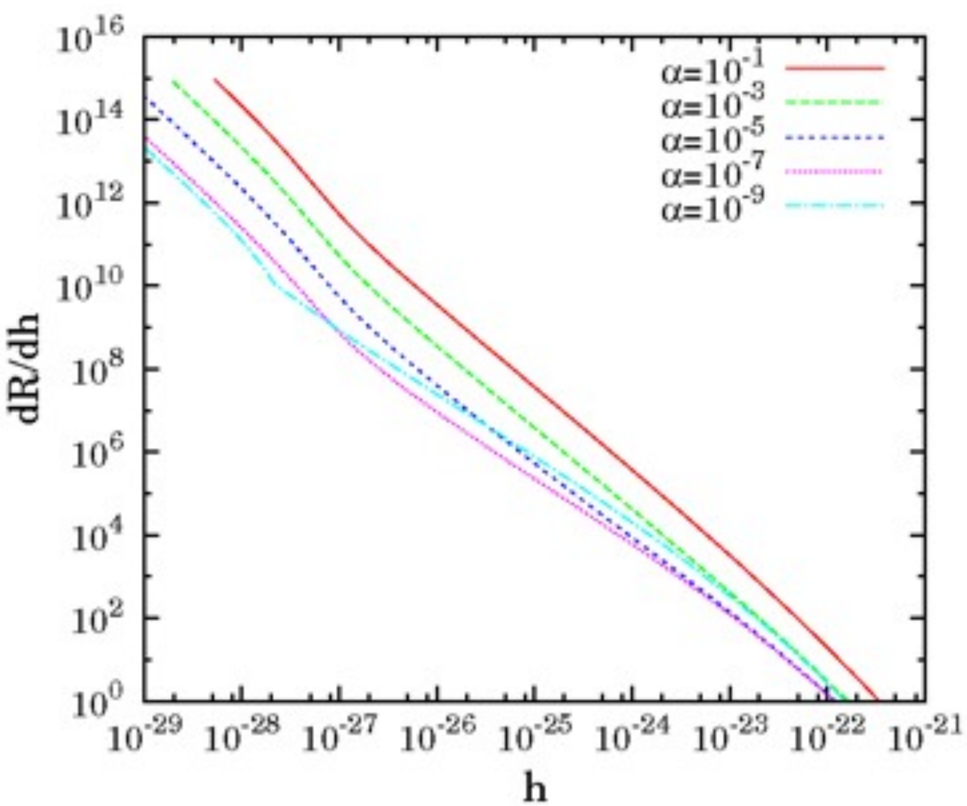
$G\mu$



p



α



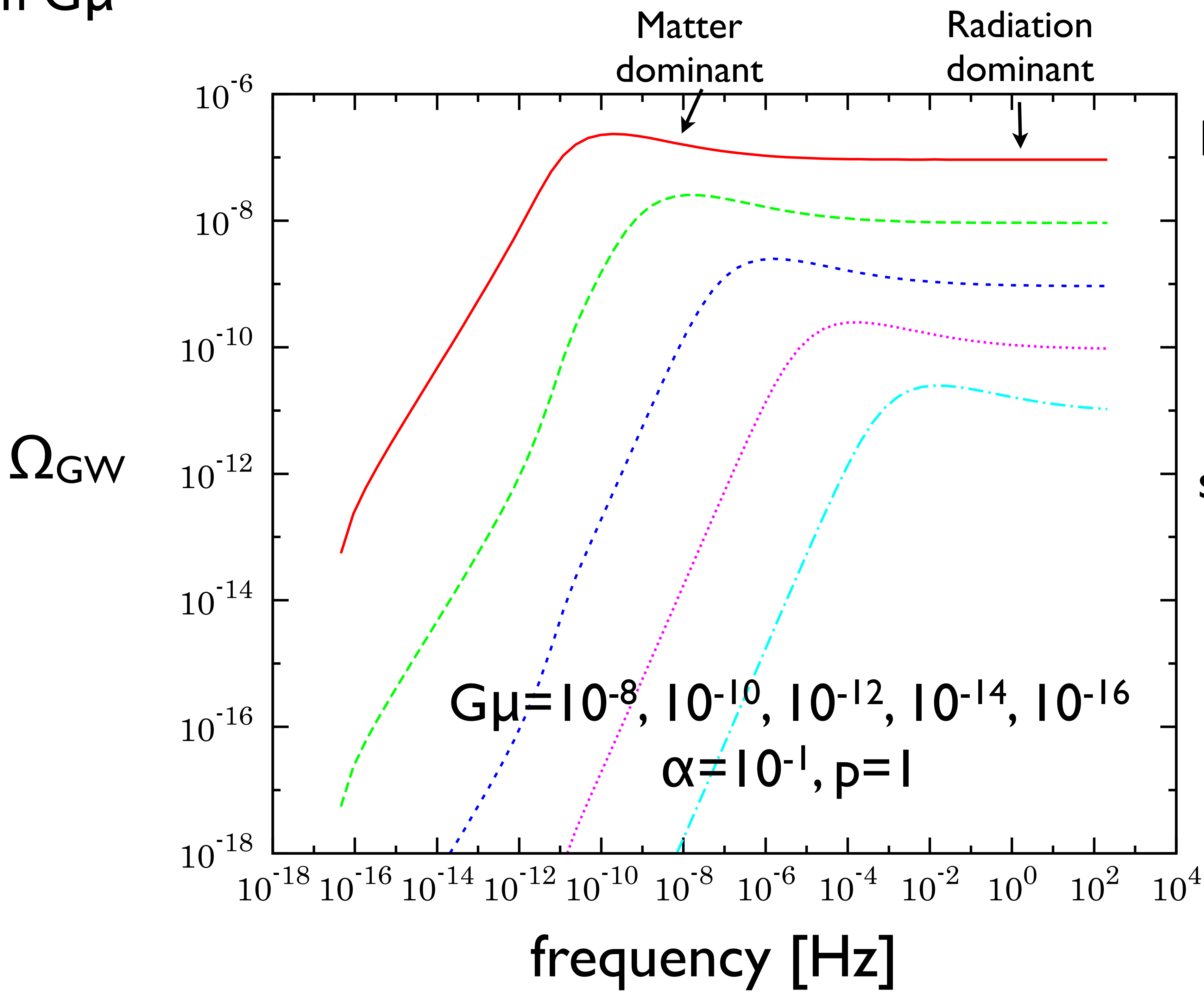
The parameter dependences of the large burst (rare burst) and small burst (GWB) are different because they are looking at different epoch of the Universe

→ **give different information on cosmic string parameters**

Spectrum of the GWB

dependence on Gμ

new ⟷ old



large Gμ

small Gμ

GW power from cusps

$h^2 \propto (G\mu)^2$

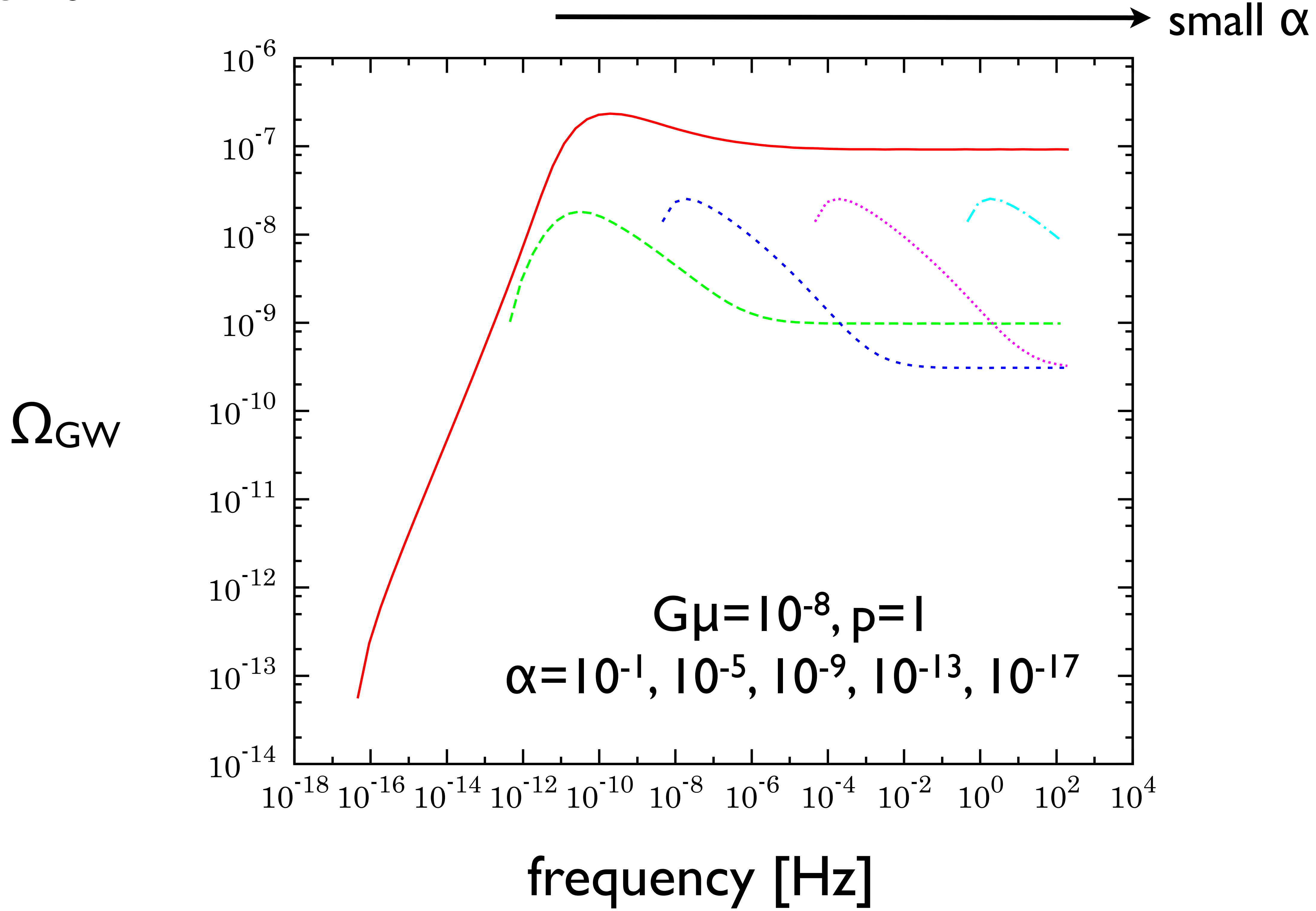
life time of loops

$\propto (G\mu)^{-1}$

Spectrum of the GWB

dependence on α

loop size directly corresponds to the frequency of the GW

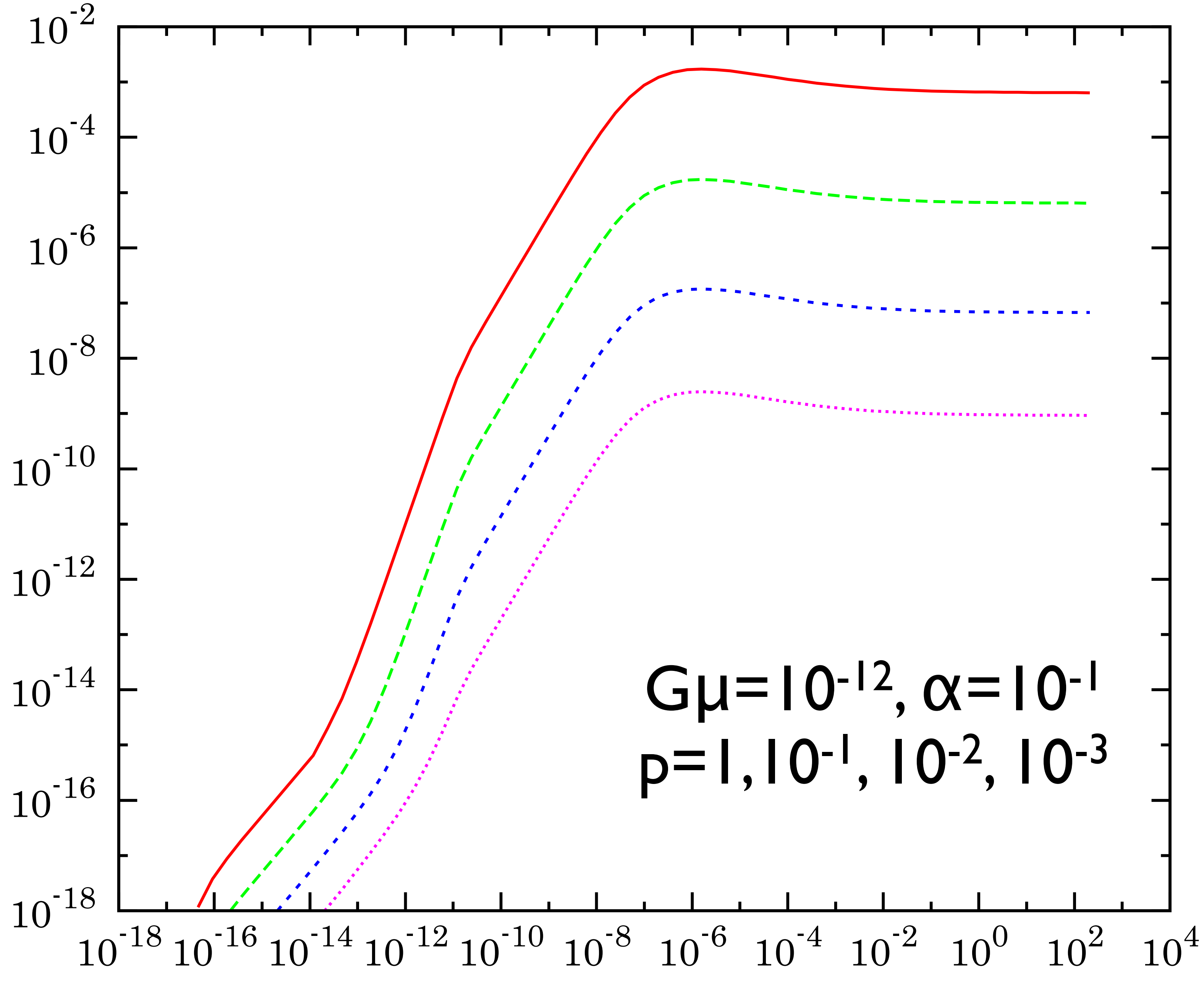


Spectrum of the GWB

dependence on p

small p increases the number density of loops

small p

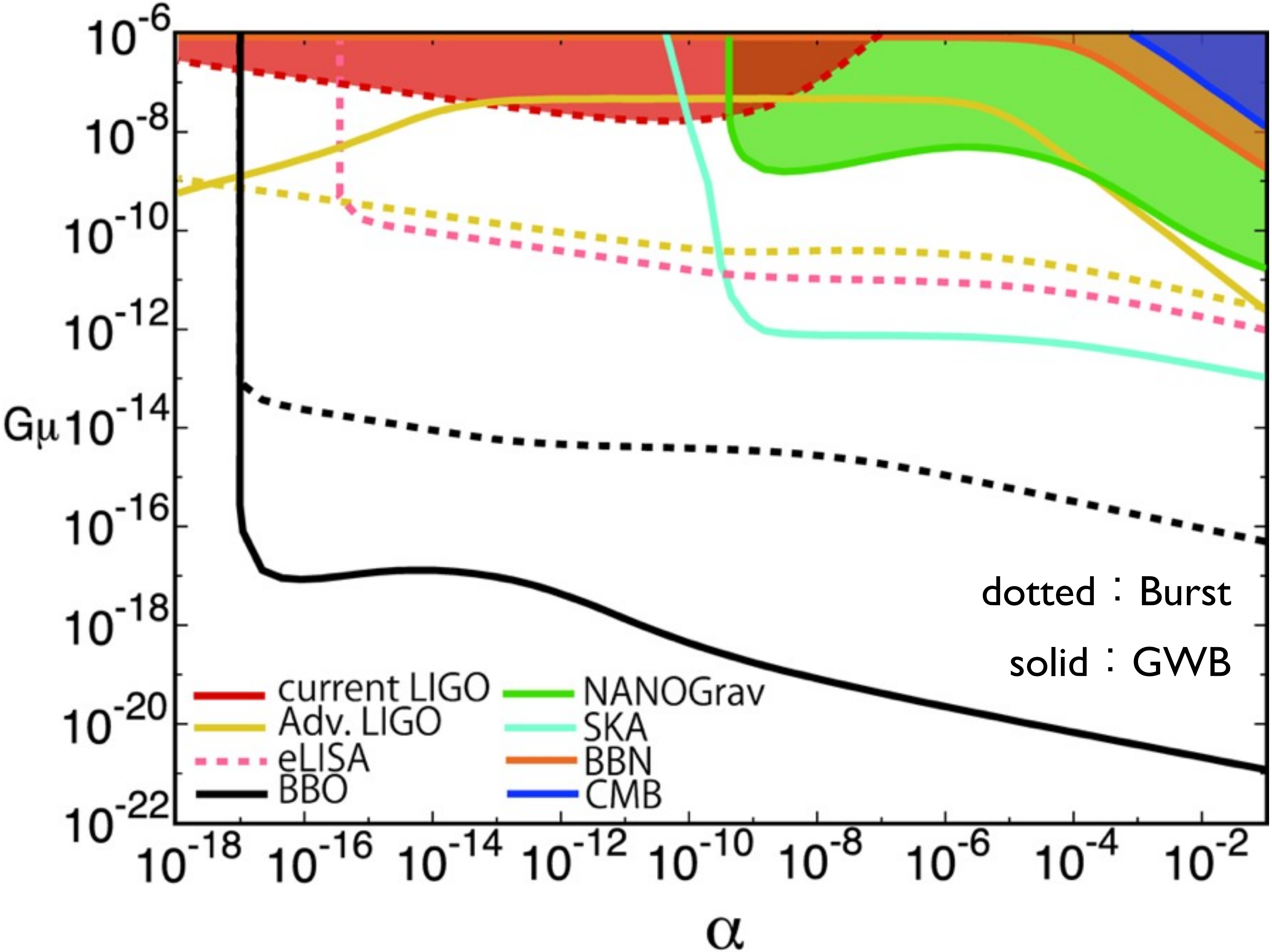


Ω_{GW}

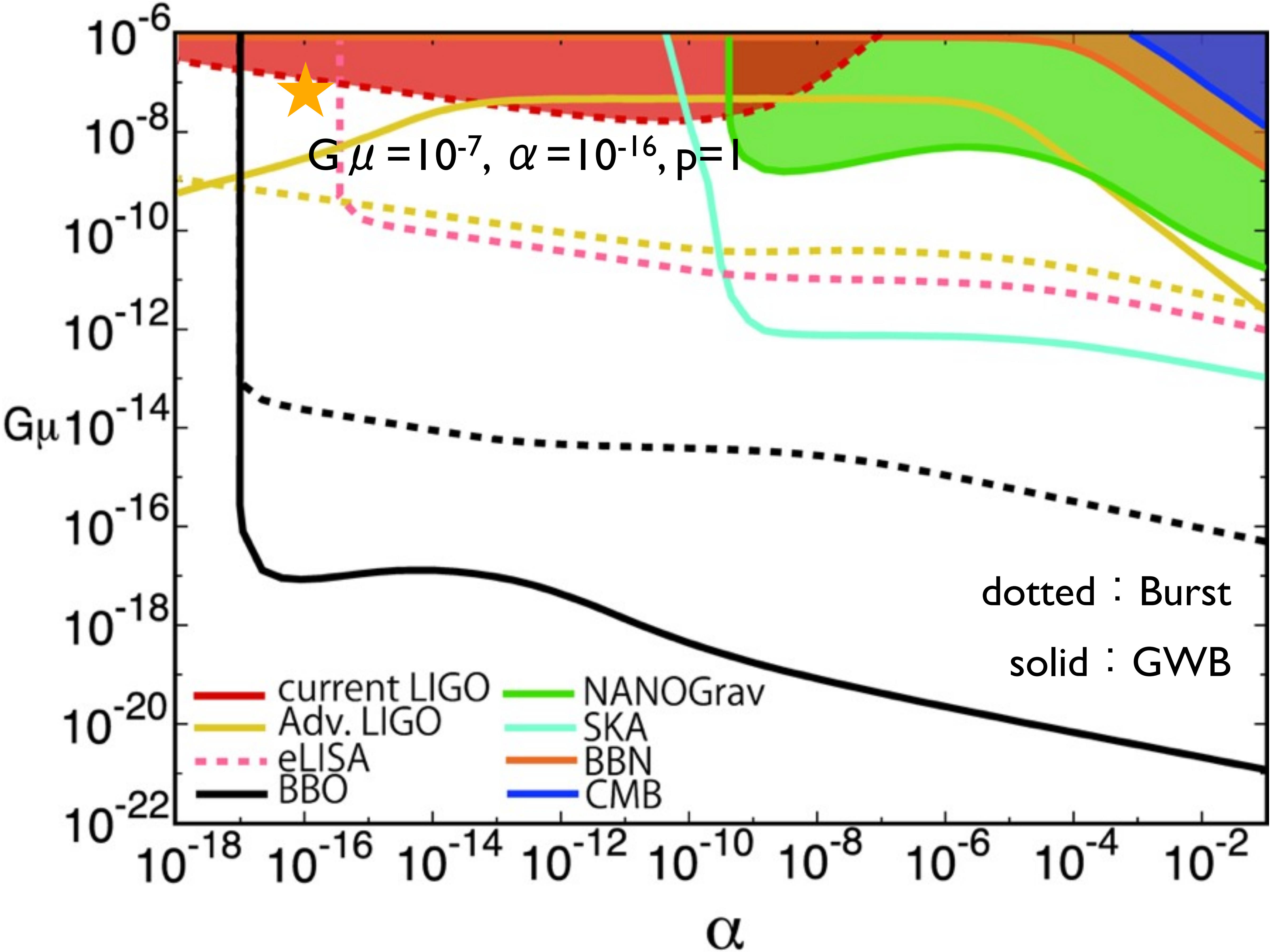
large p

frequency [Hz]

Accessible parameter region (for p=1)



What if both bursts and GWB are detected by Advanced-LIGO?

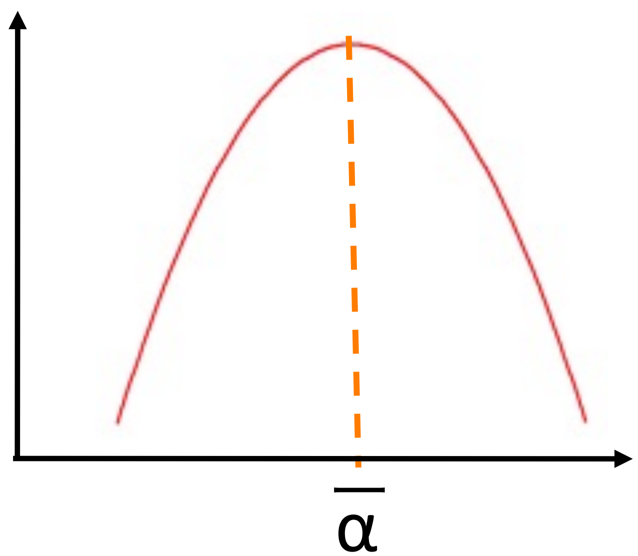


Constraint on parameters

Fisher information matrix

$$\mathcal{F}_{ij} = -\left\langle \frac{\partial^2 \ln \mathcal{L}}{\partial p_i \partial p_j} \right\rangle$$

log(Likelihood)



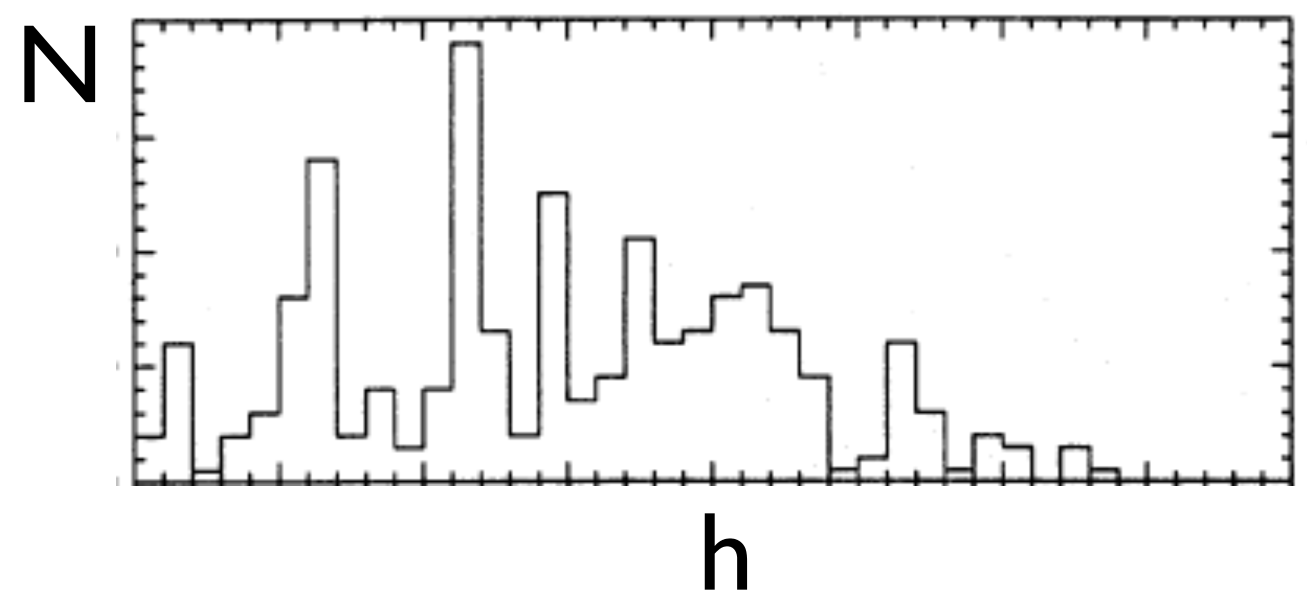
If the likelihood shape is sensitive to the parameter
= easy to estimate the parameter

Burst

Observable : amplitude vs number

N is predictable by the rate dR/dh

$$\mathcal{F}_{ij} \propto \frac{\partial(dR/dh)}{\partial p_i} \frac{\partial(dR/dh)}{\partial p_j}$$



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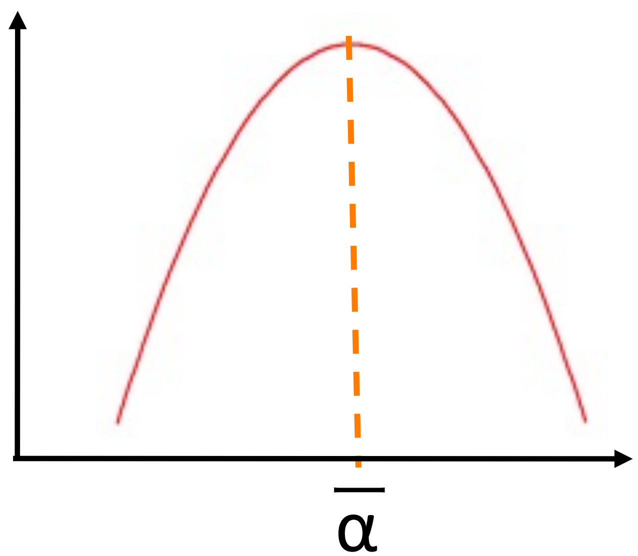
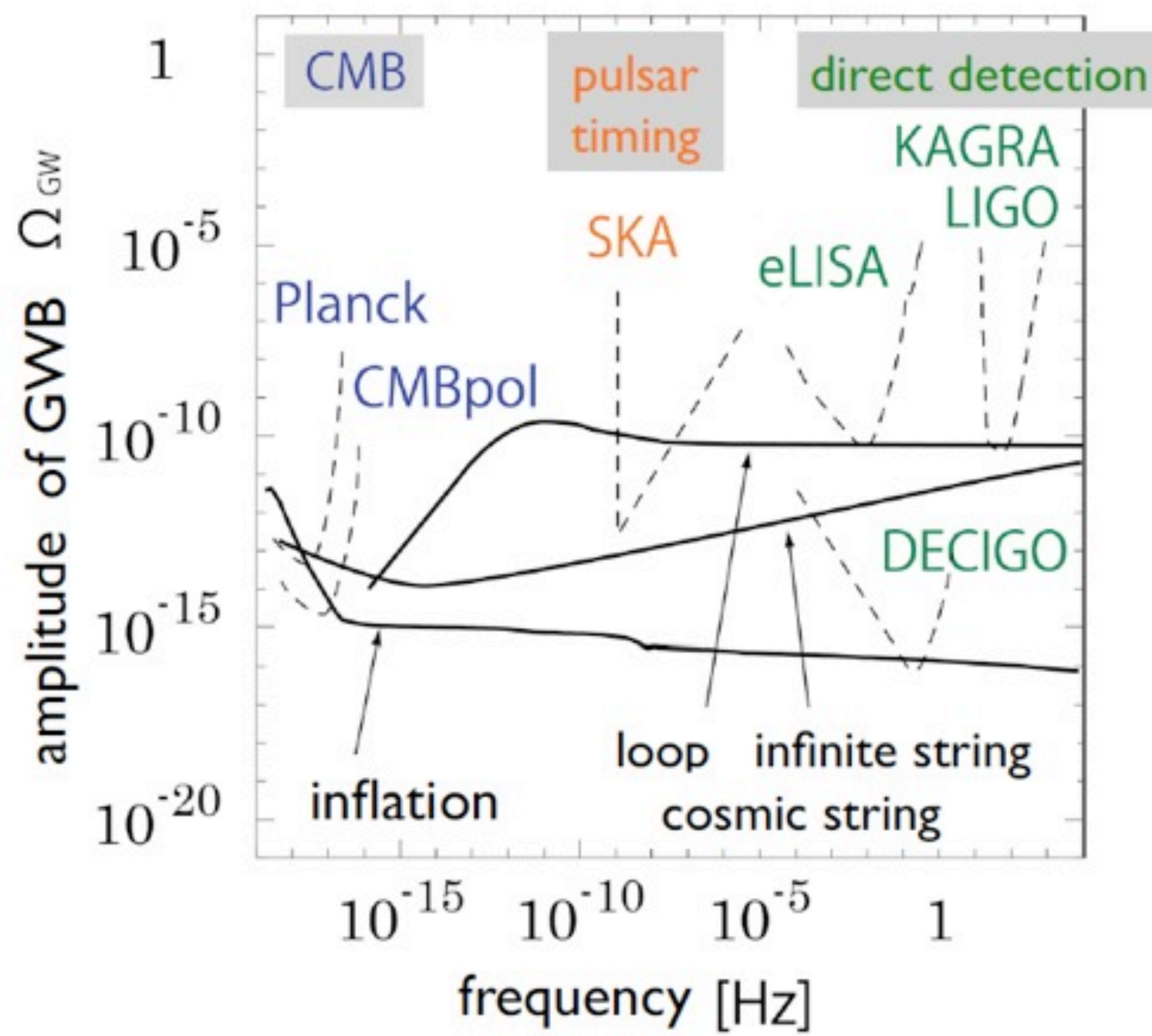


If the likelihood shape is sensitive to the parameter
= easy to estimate the parameter

GWB Observable : Ω_{GW}

$$\mathcal{F}_{ij} \propto \frac{\partial \Omega_{\rm GW}}{\partial p_i} \frac{\partial \Omega_{\rm GW}}{\partial p_j}$$



Predicted constraint on parameters

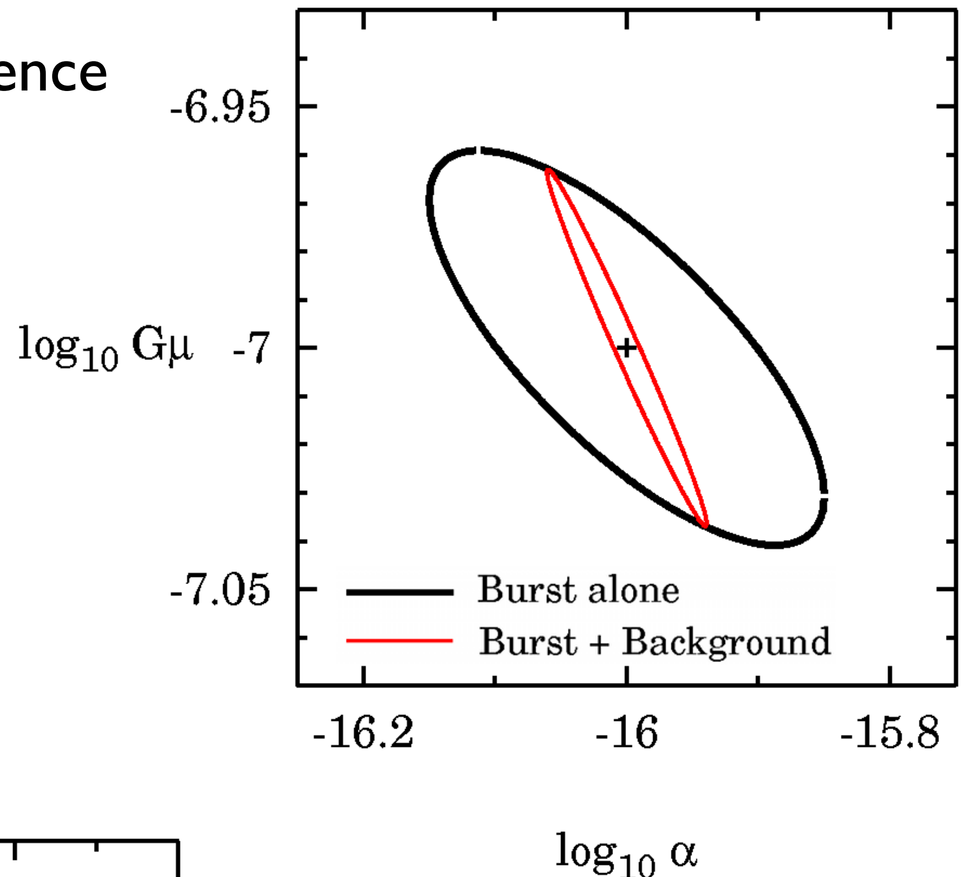
$G\mu = 10^{-7}$, $\alpha = 10^{-16}$, p=1
LIGO 3year

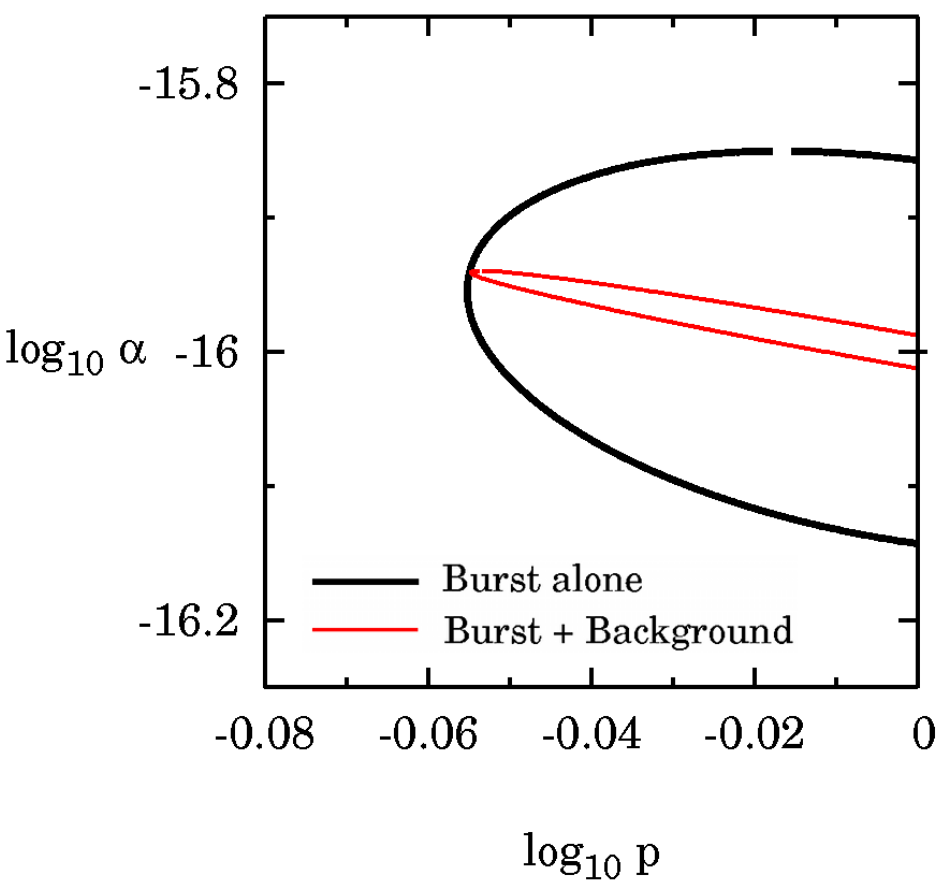
Kuroyanagi et. al. PRD 86, 023503 (2012)

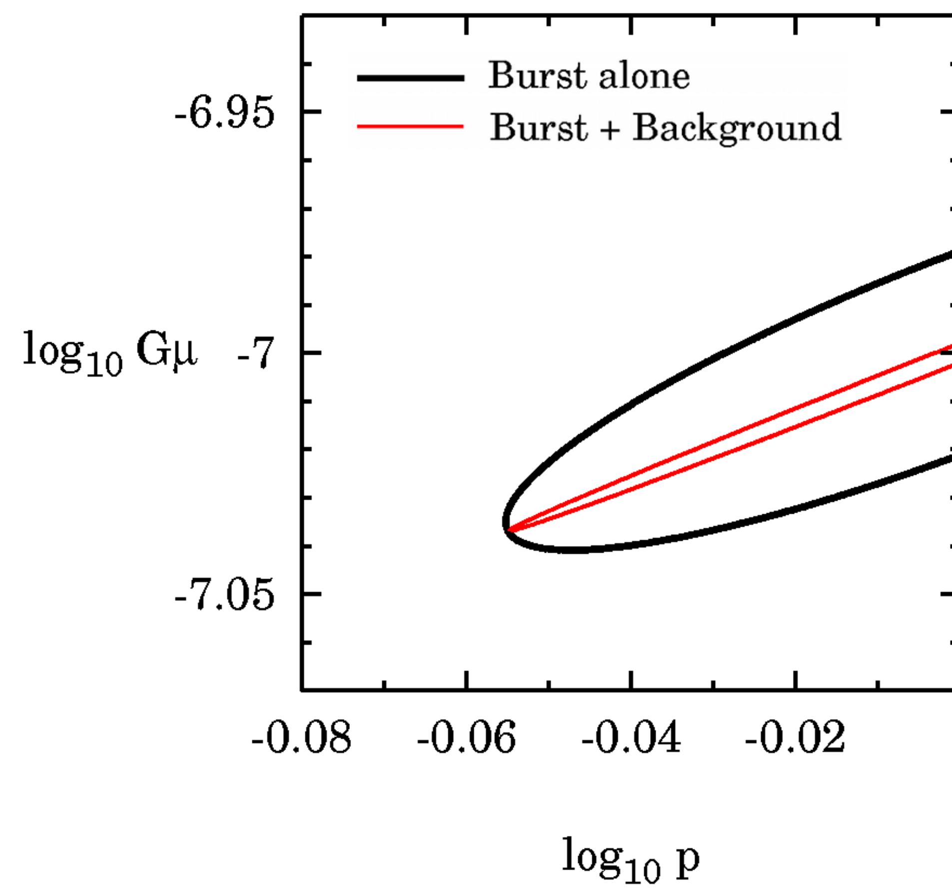
different parameter dependence
= different constraints on parameters

black : Burst only

red : Burst + GWB







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LIGO 3year

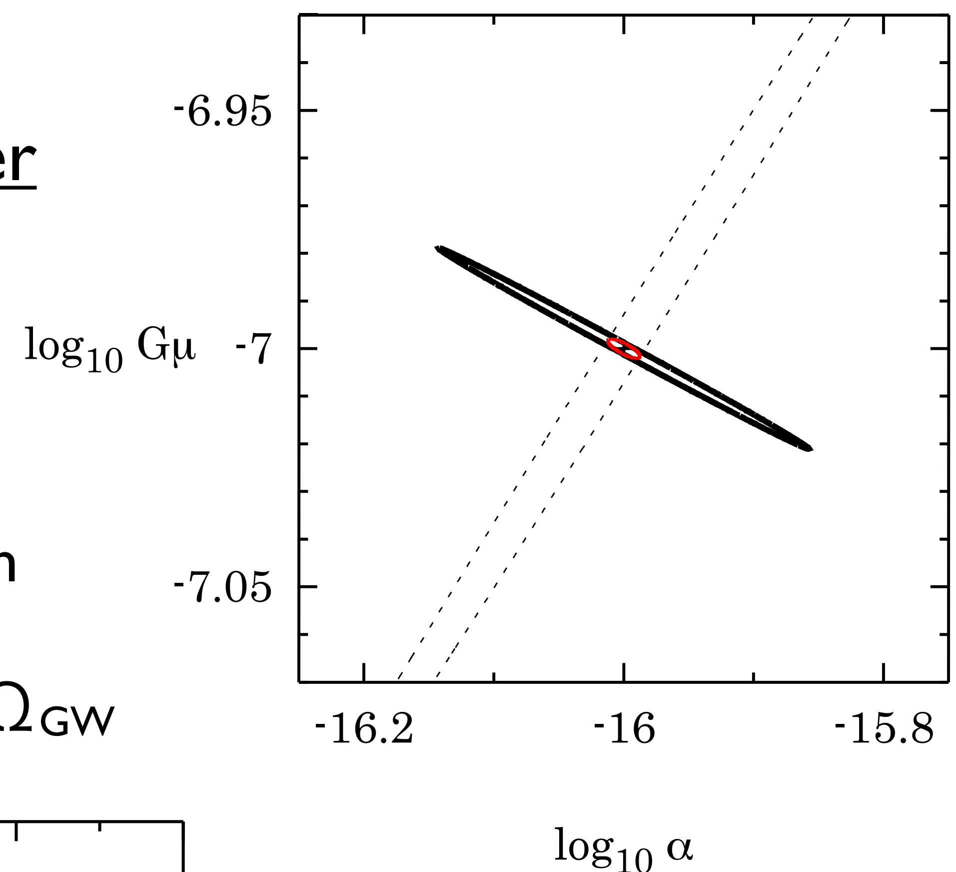
Kuroyanagi et. al. PRD 86, 023503 (2012)

black ：Burst only

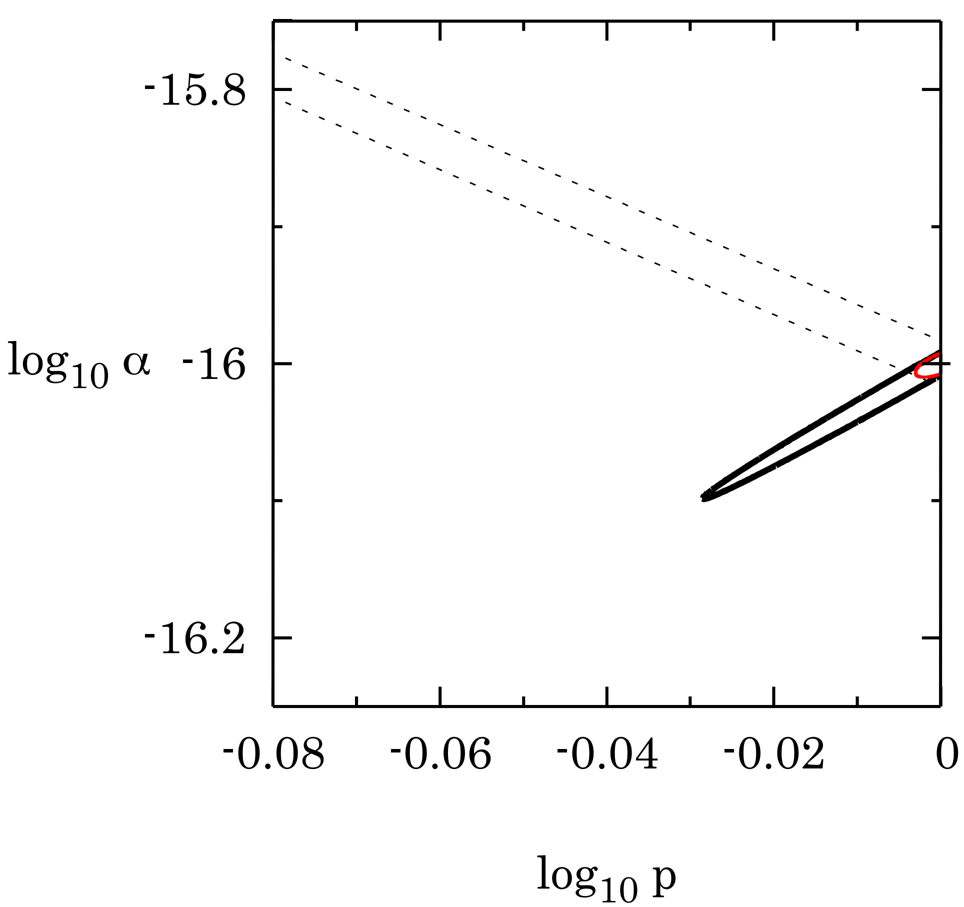
dotted: GWB only

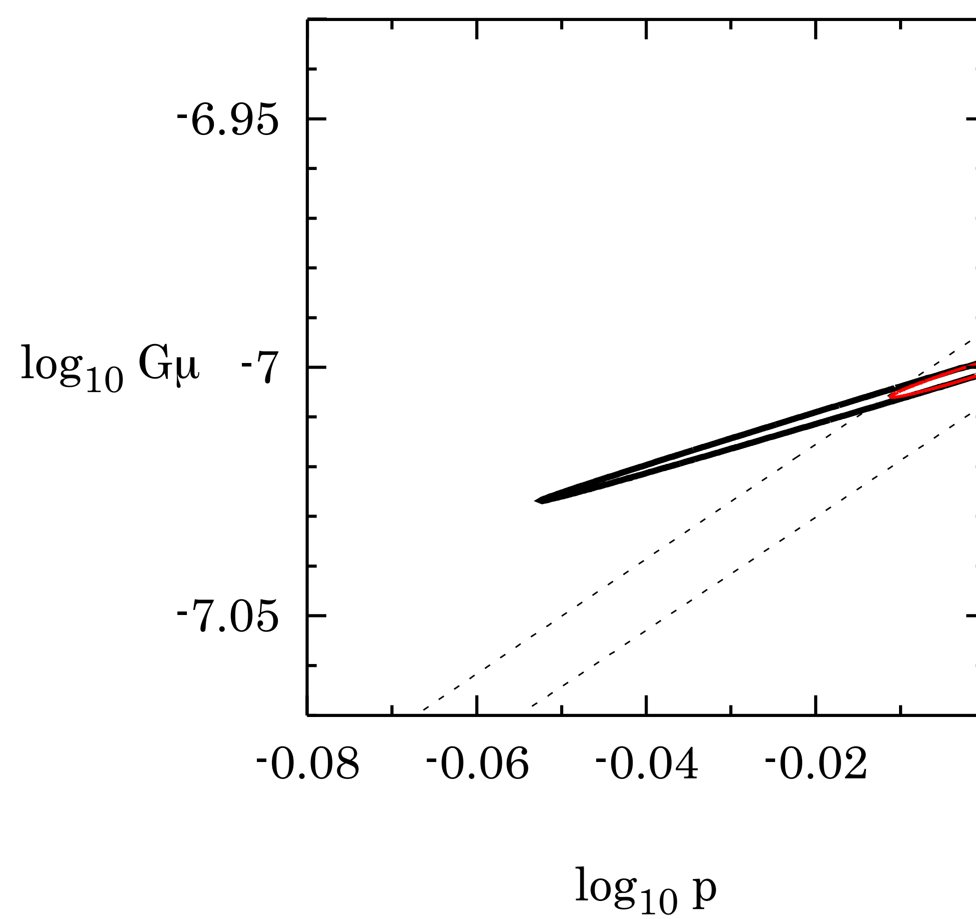
red ：Burst + GWB

Before marginalized over

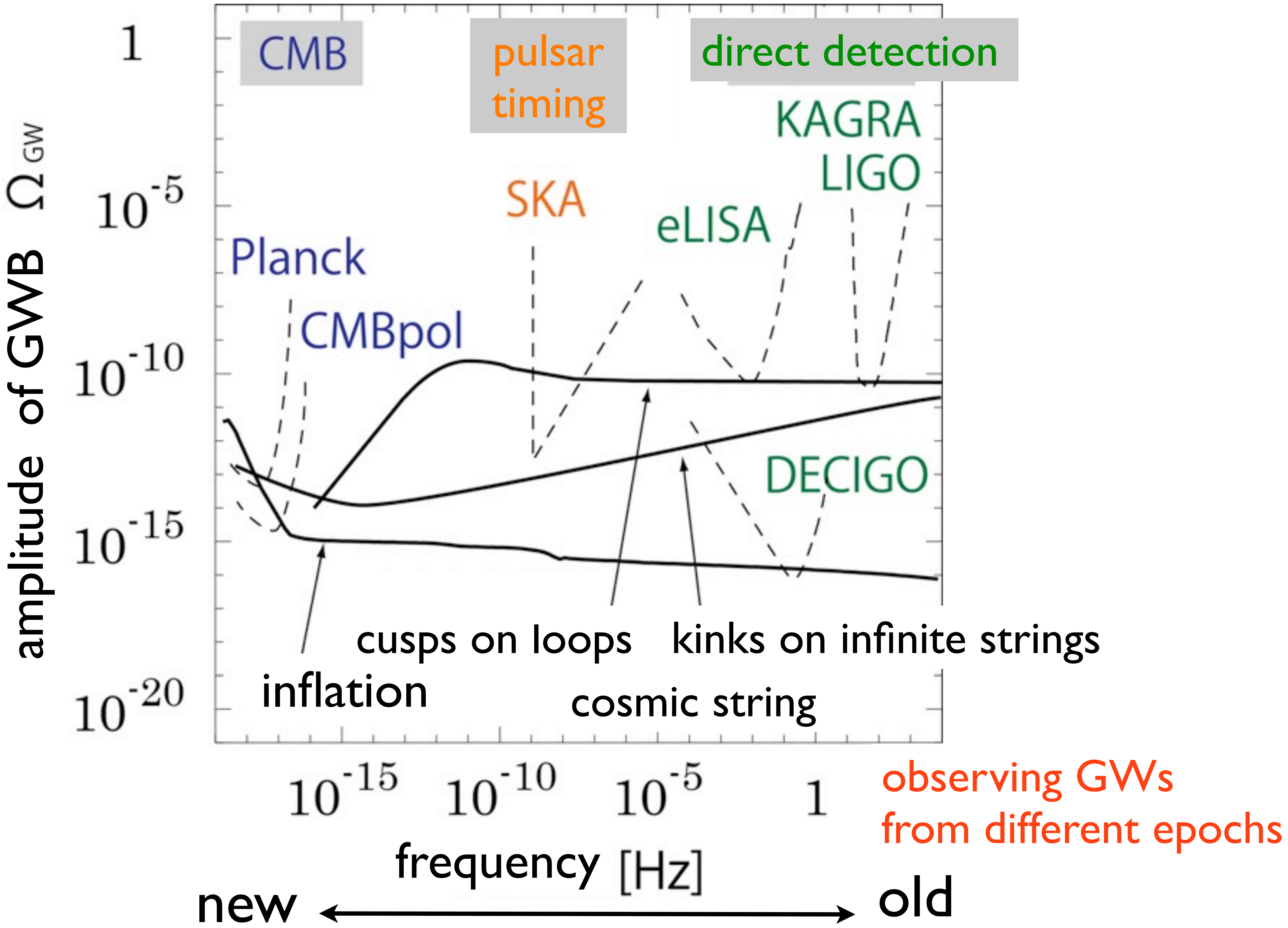


Strong degeneracy seen in constraint from GWB since the observable is only Ω_{GW}



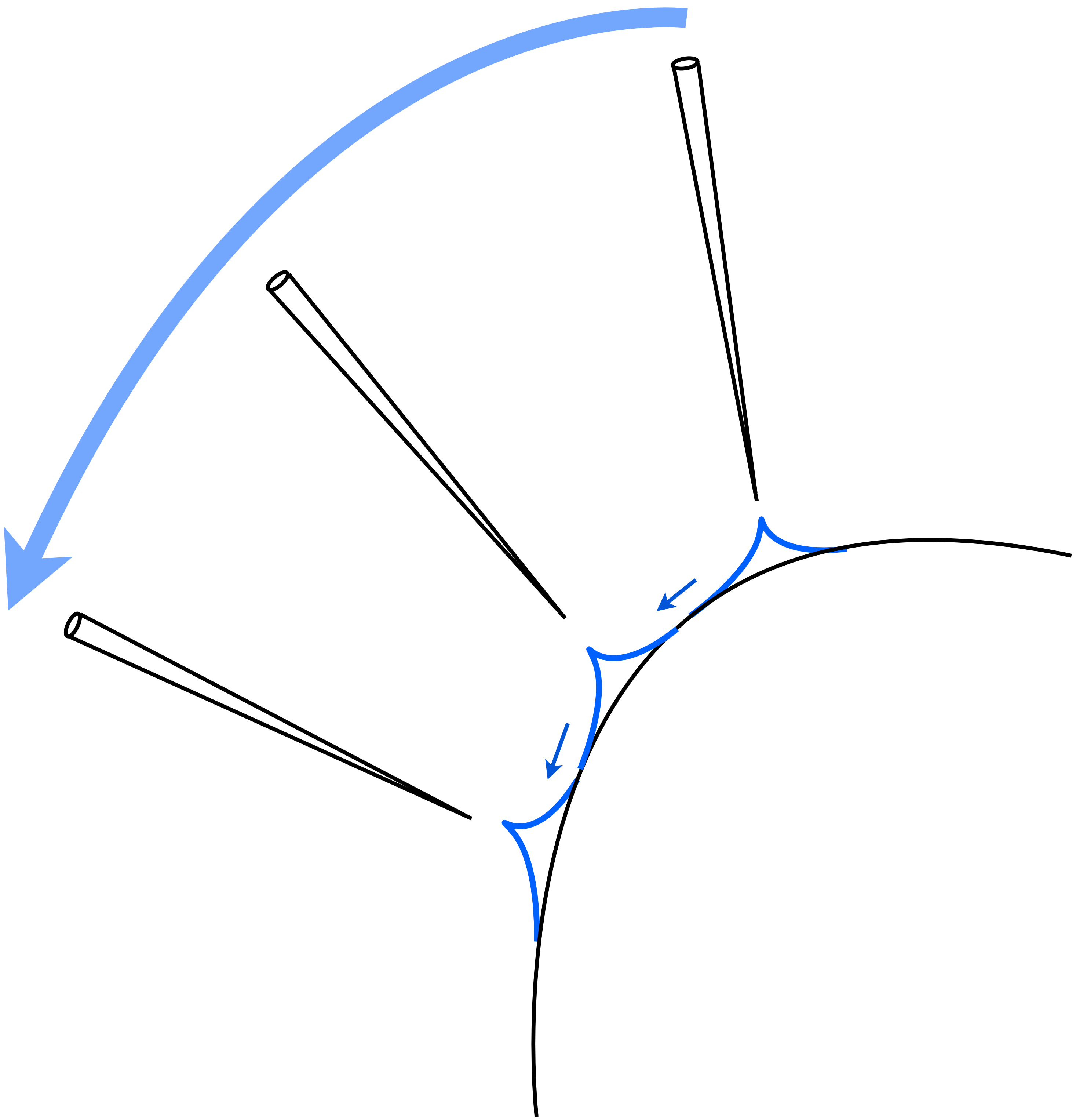


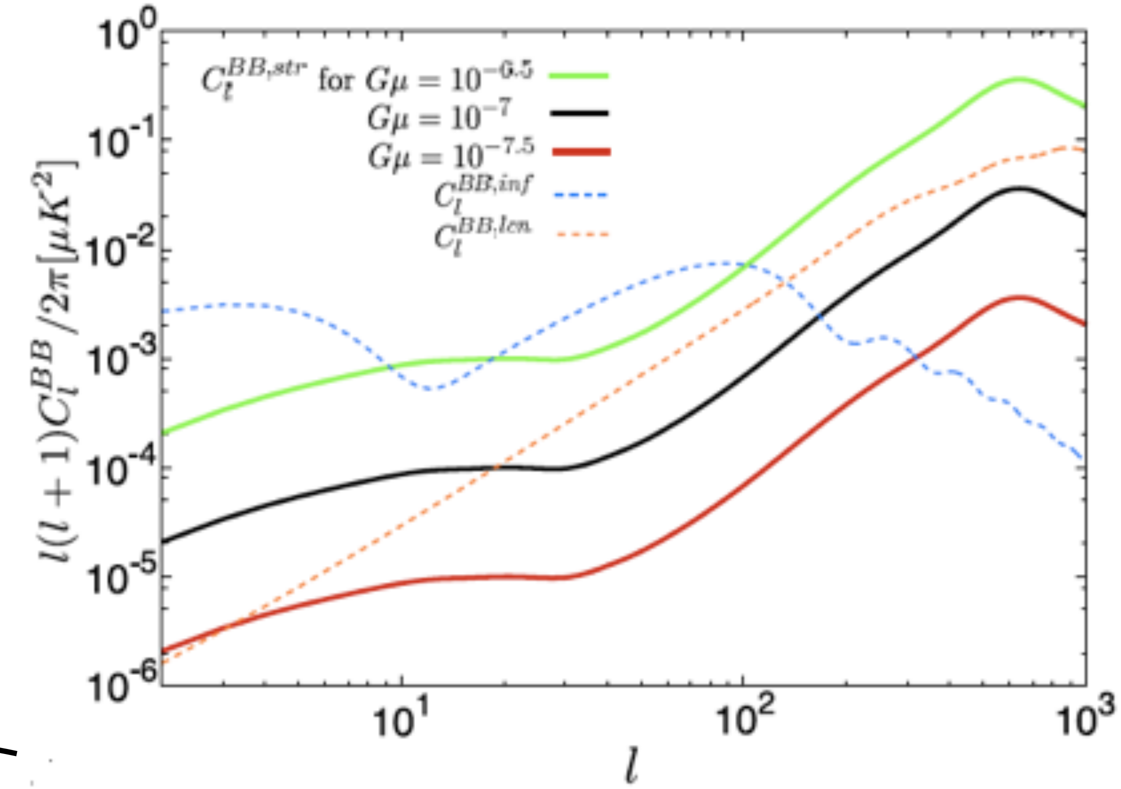
Constraints from other experiments?

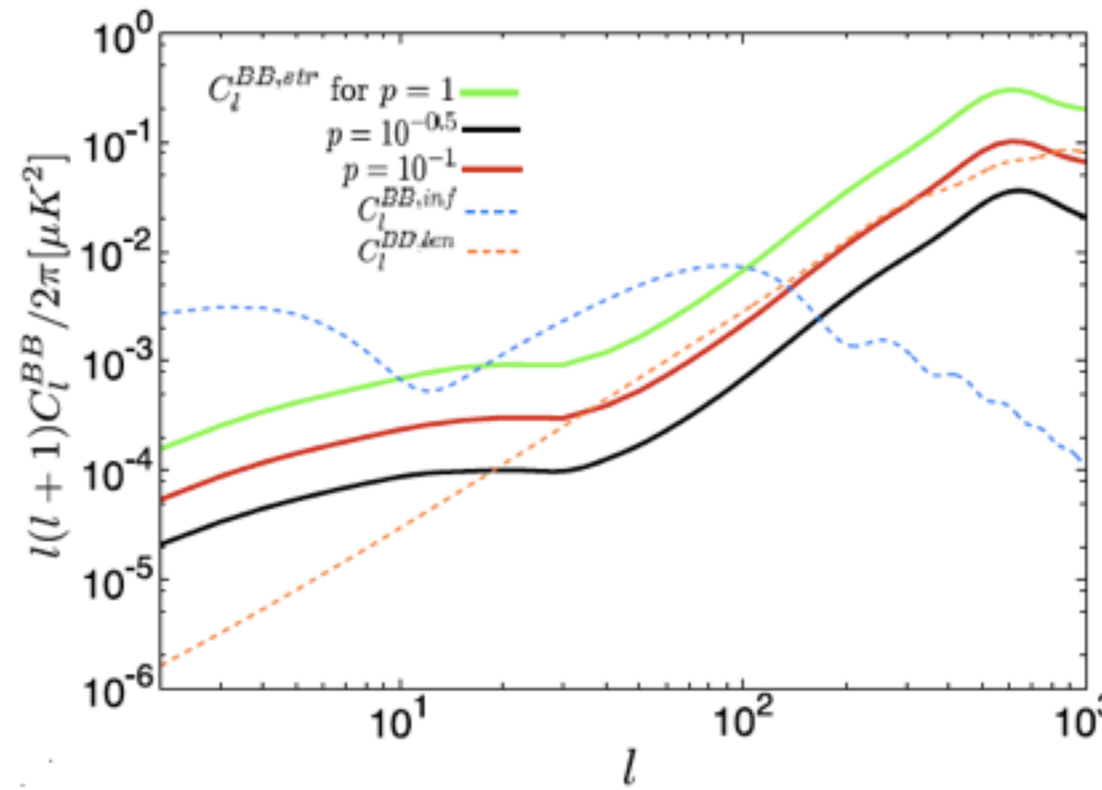


Signal in the CMB B-mode

kink on infinite string can generate large scale GWs



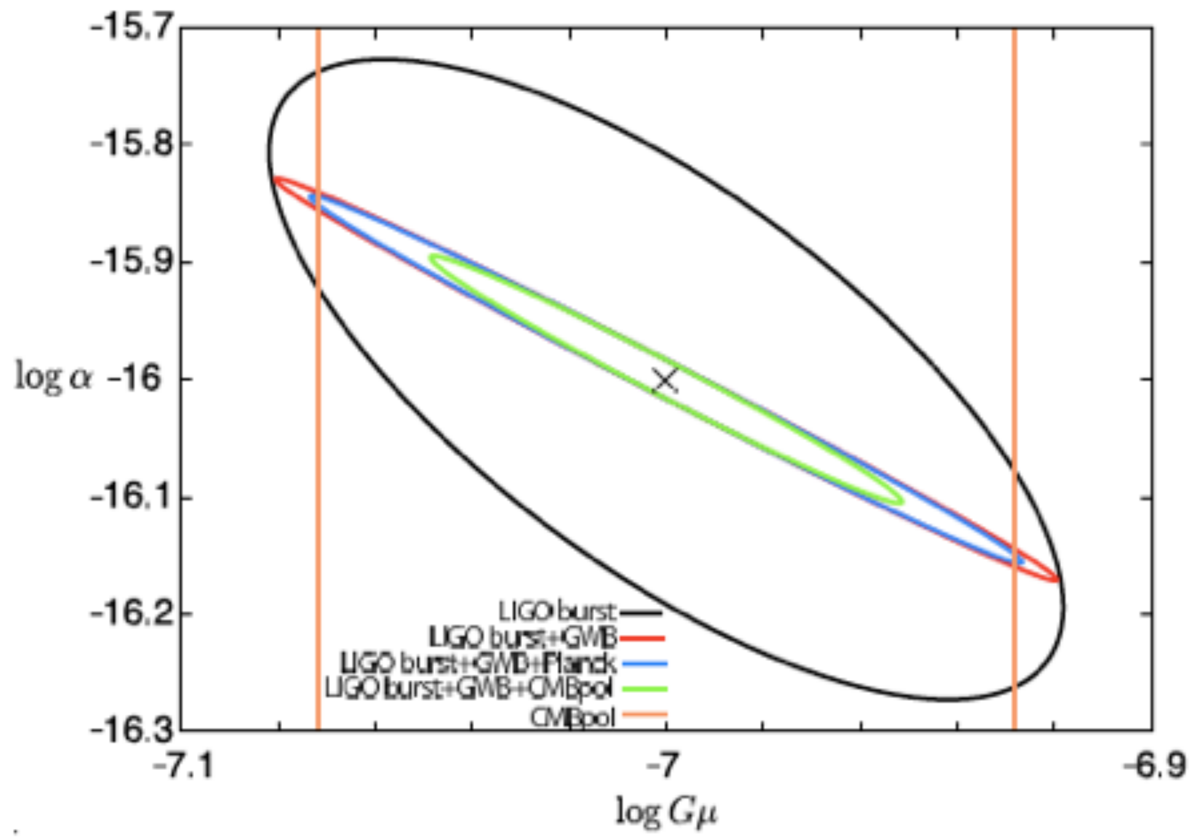




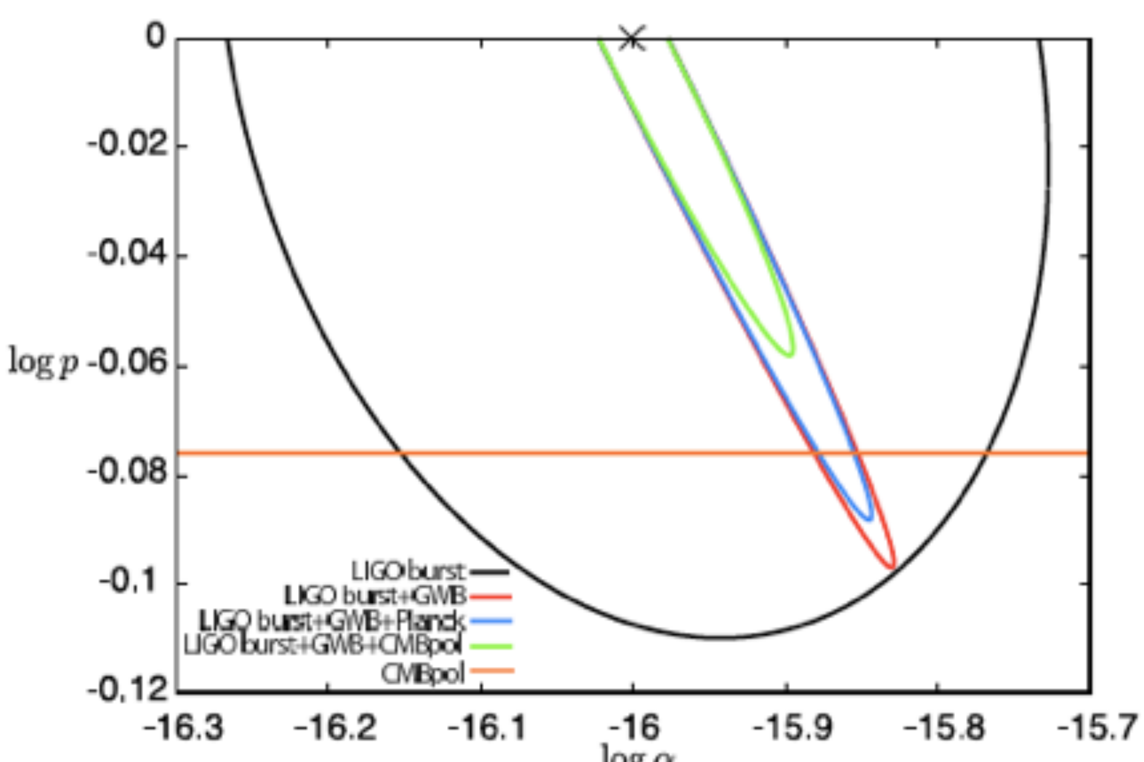
If we combine CMB constraints...

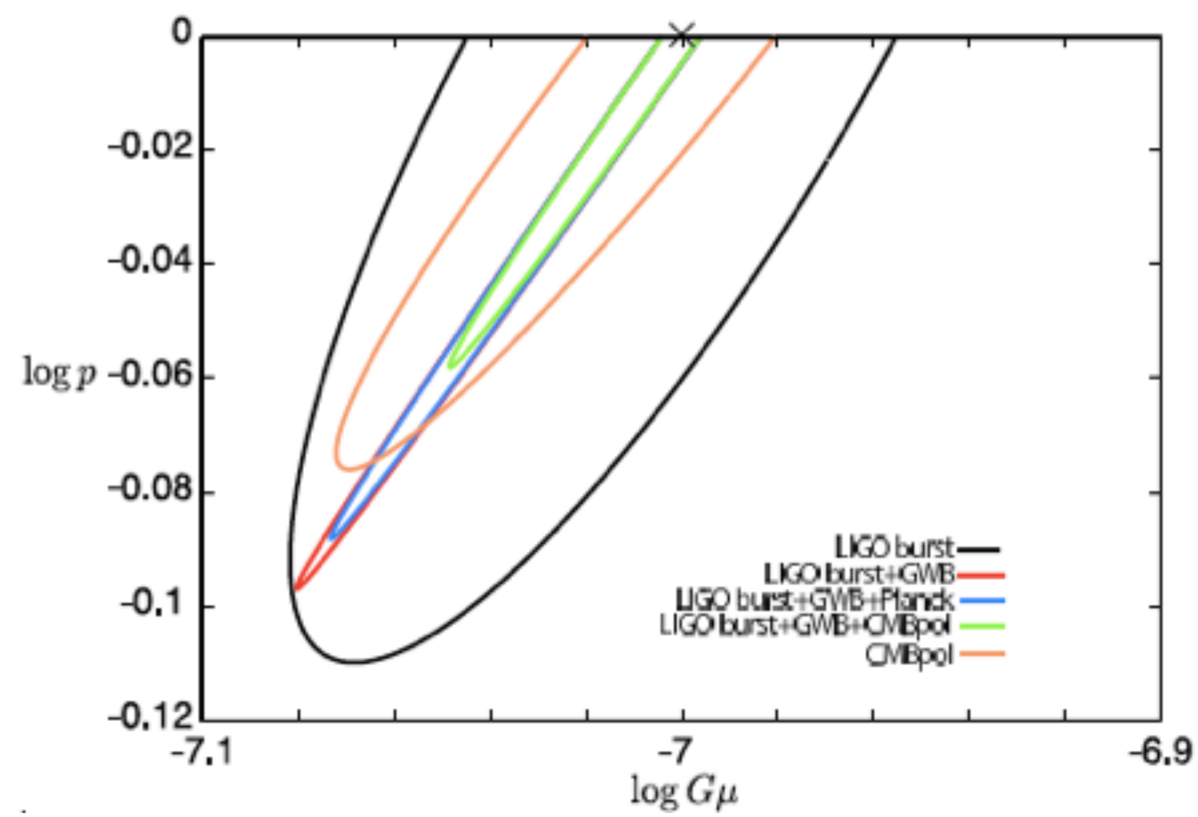
$G\mu = 10^{-7}$, $\alpha = 10^{-16}$, p=1
LIGO 3year
+ CMB B-mode

Kuroyanagi et. al. in preparation

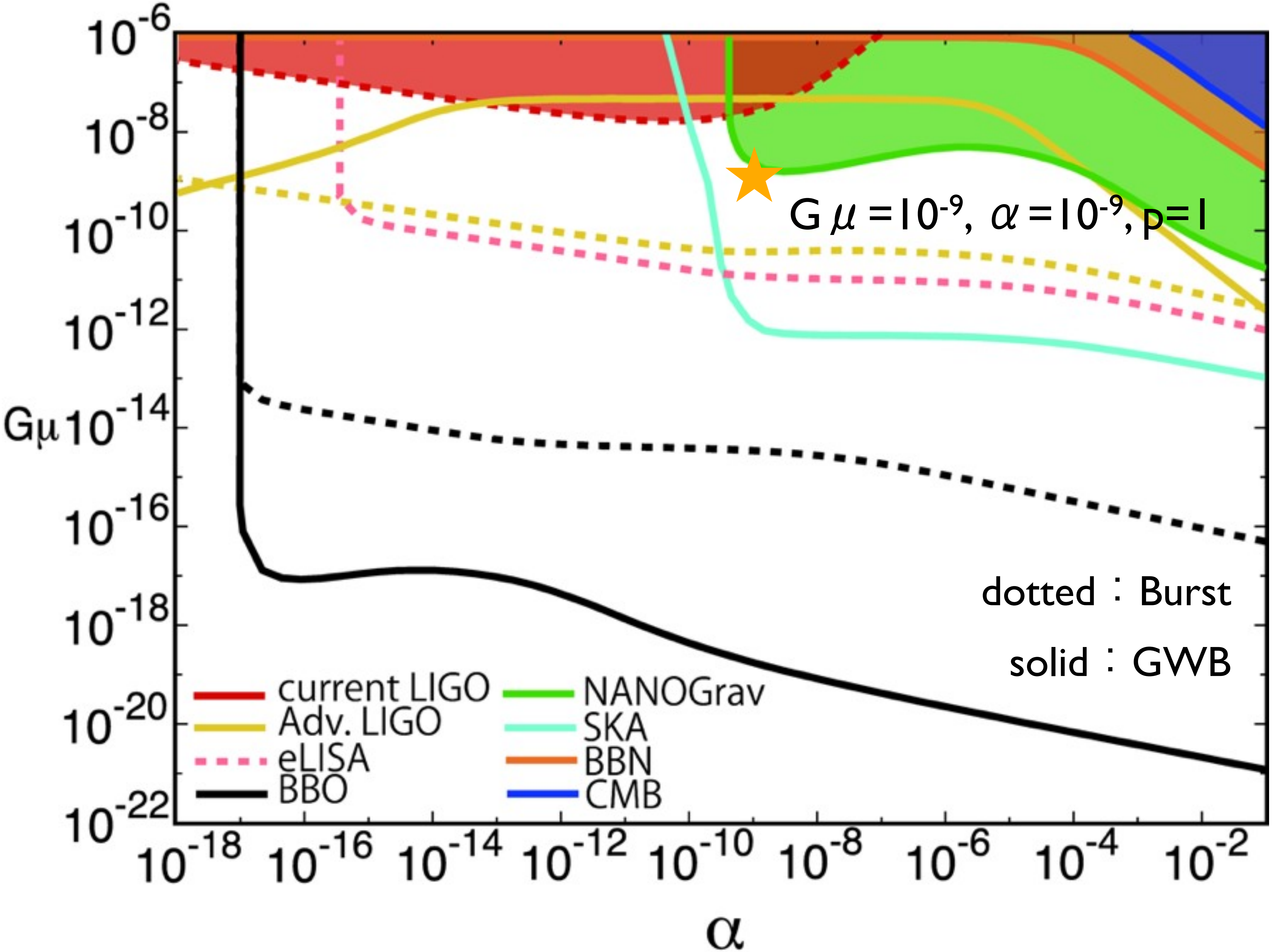


black : LIGO Burst only
red : LIGO Burst + GWB
blue: LIGO +Planck
green: LIGO+CMBpol
orange: CMB pol only





Pulsar timing (SKA) + Advanced-LIGO burst search



Direct detection + Pulsar timing

G μ =10^{-9}, α =10^{-9}, p=1
LIGO 3year (burst only)
+ SKA 10year

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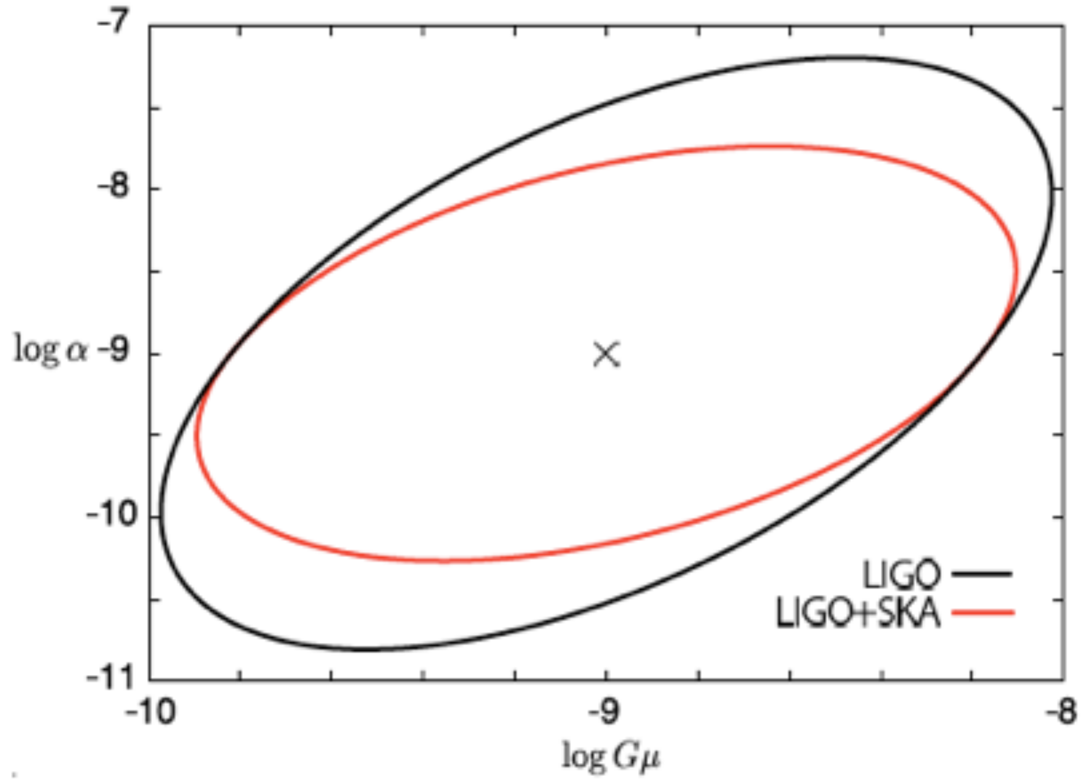

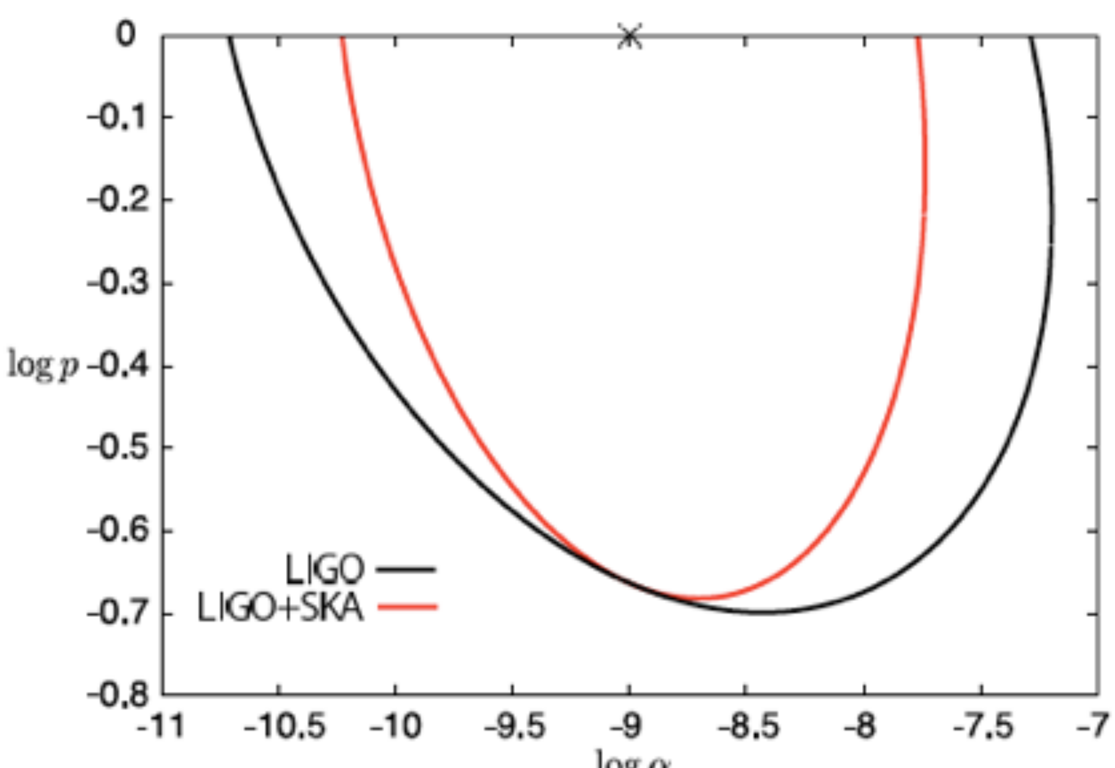

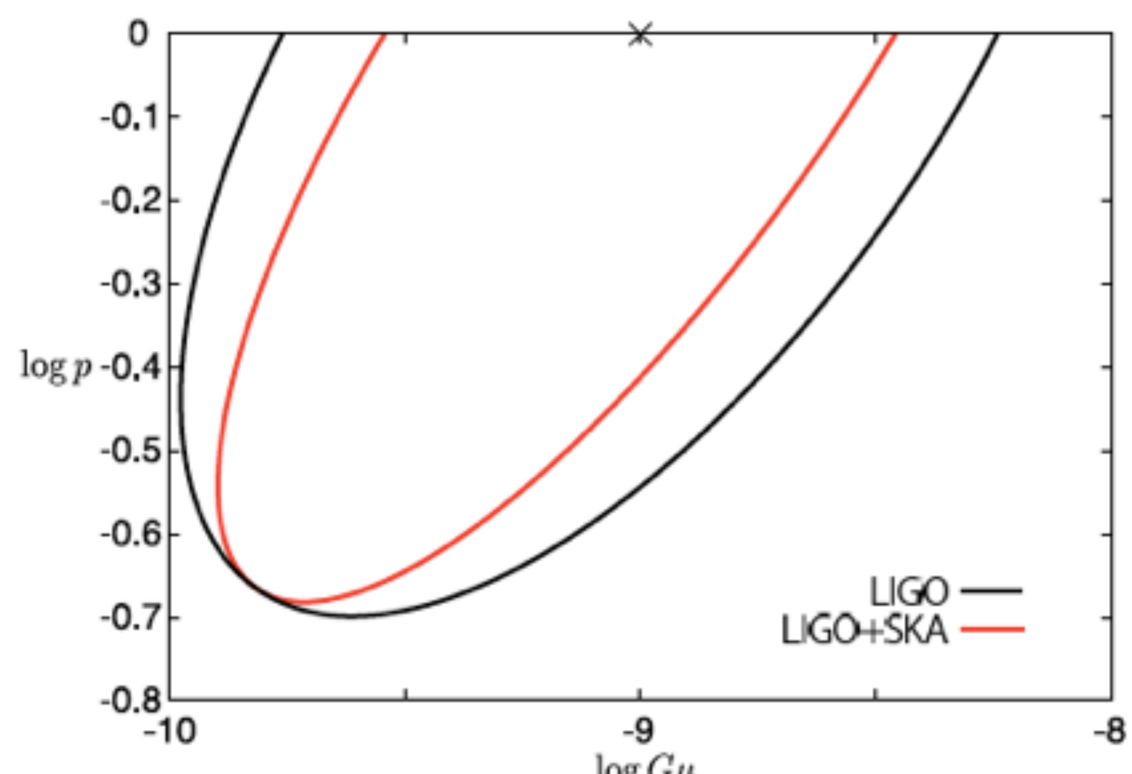

Parameter constraint by eLISA

$G\mu = 10^{-9}$, $\alpha = 10^{-9}$, p=1
eLISA 3year
(burst only)
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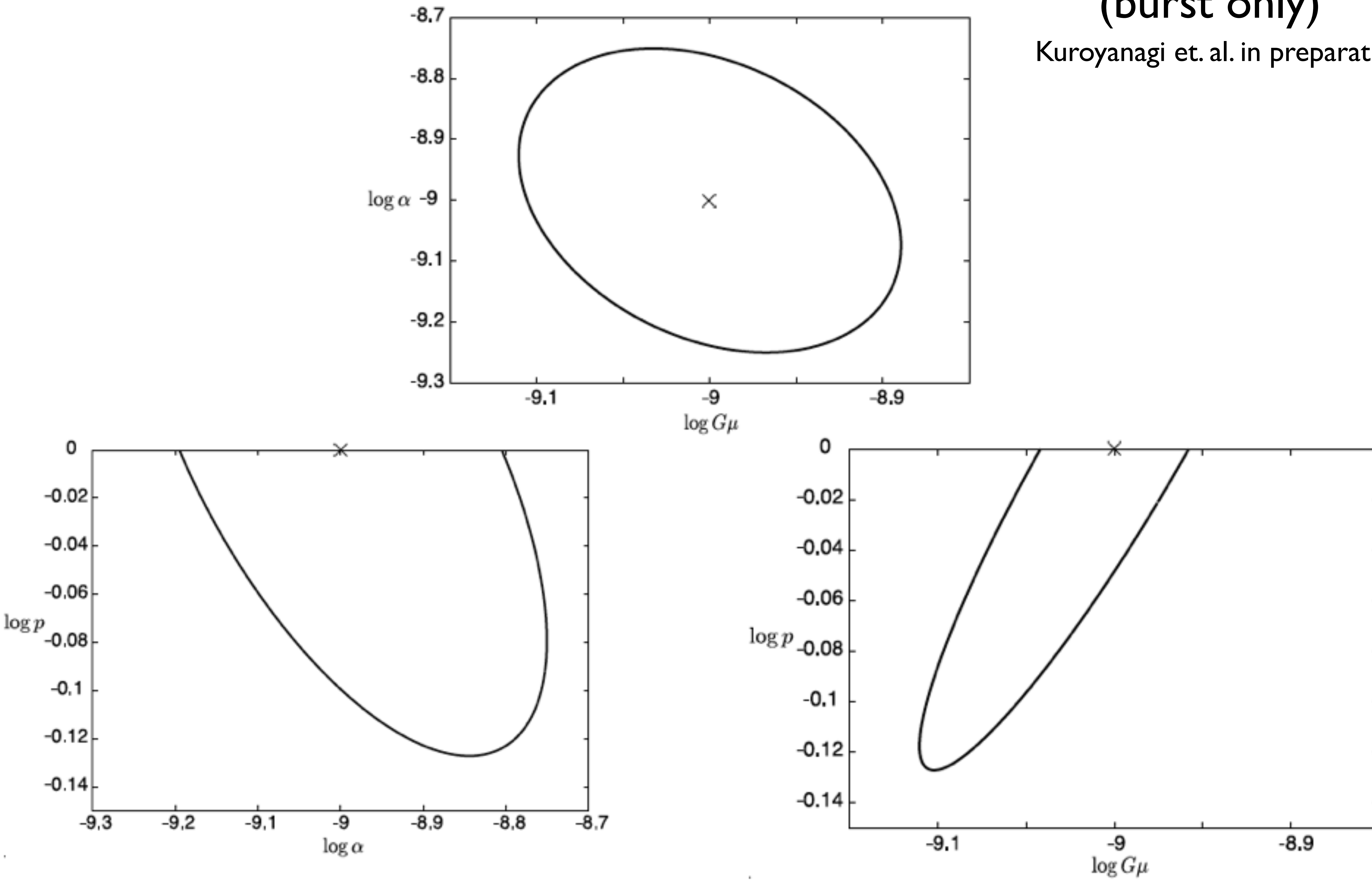

Summary

- Future GW experiments can be a powerful tool to prove cosmic strings.
- It could provide strong constraints on cosmic string parameters. If it is detected, it would determine cosmic string parameters, which can provide us with hints of fundamental physics such as particle physics or superstring theory.
- Two different kinds of GW observation (rare burst and GWB) provide different constraints on cosmic string parameters and lead to better accuracy in determining parameters.
- Combination with CMB or Pulser timing also helps to get stronger constraints, depending on the value of the parameters.
- Space GW missions are more powerful to prove cosmic strings.