Gravitational waves from Cosmic strings

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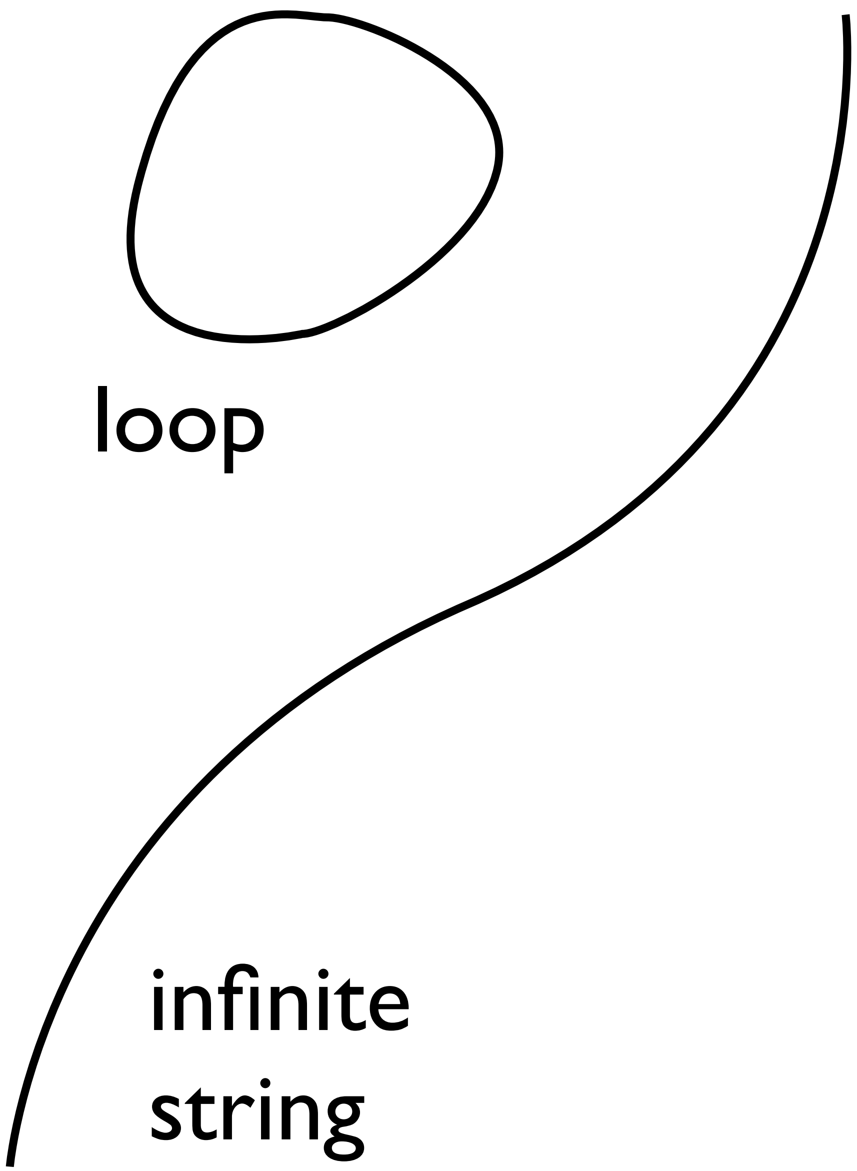
2013/12/3 関西合同セミナー

Based on
S. Kuroyanagi, K. Miyamoto, T. Sekiguchi, K. Takahashi, J. Silk,
PRD 86, 023503 (2012) and PRD 87, 023522 (2013)

Cosmic string ?

One dimensional topological defects
generated in the early universe



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

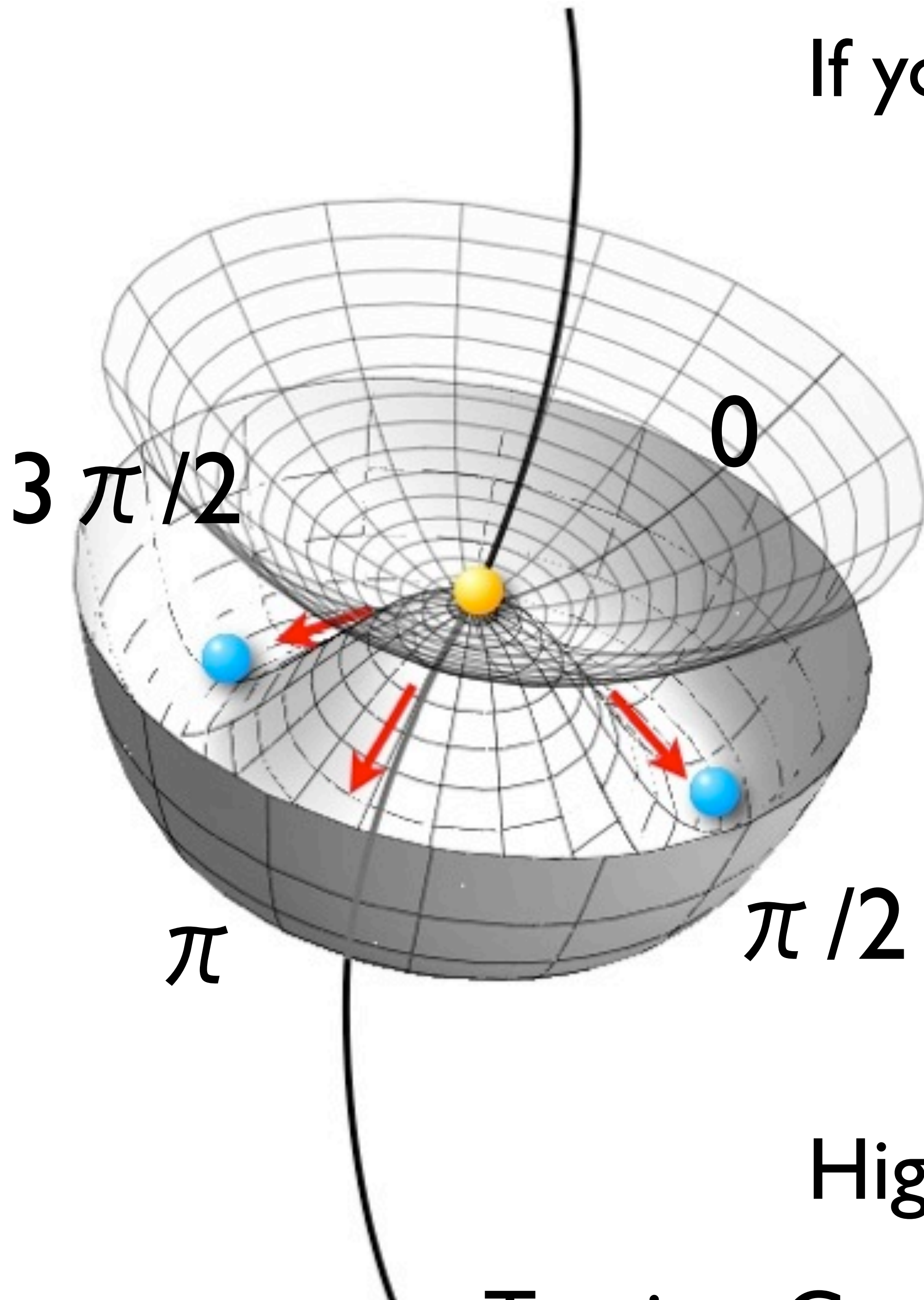
- emits gravitational waves

μ : tension (line density)

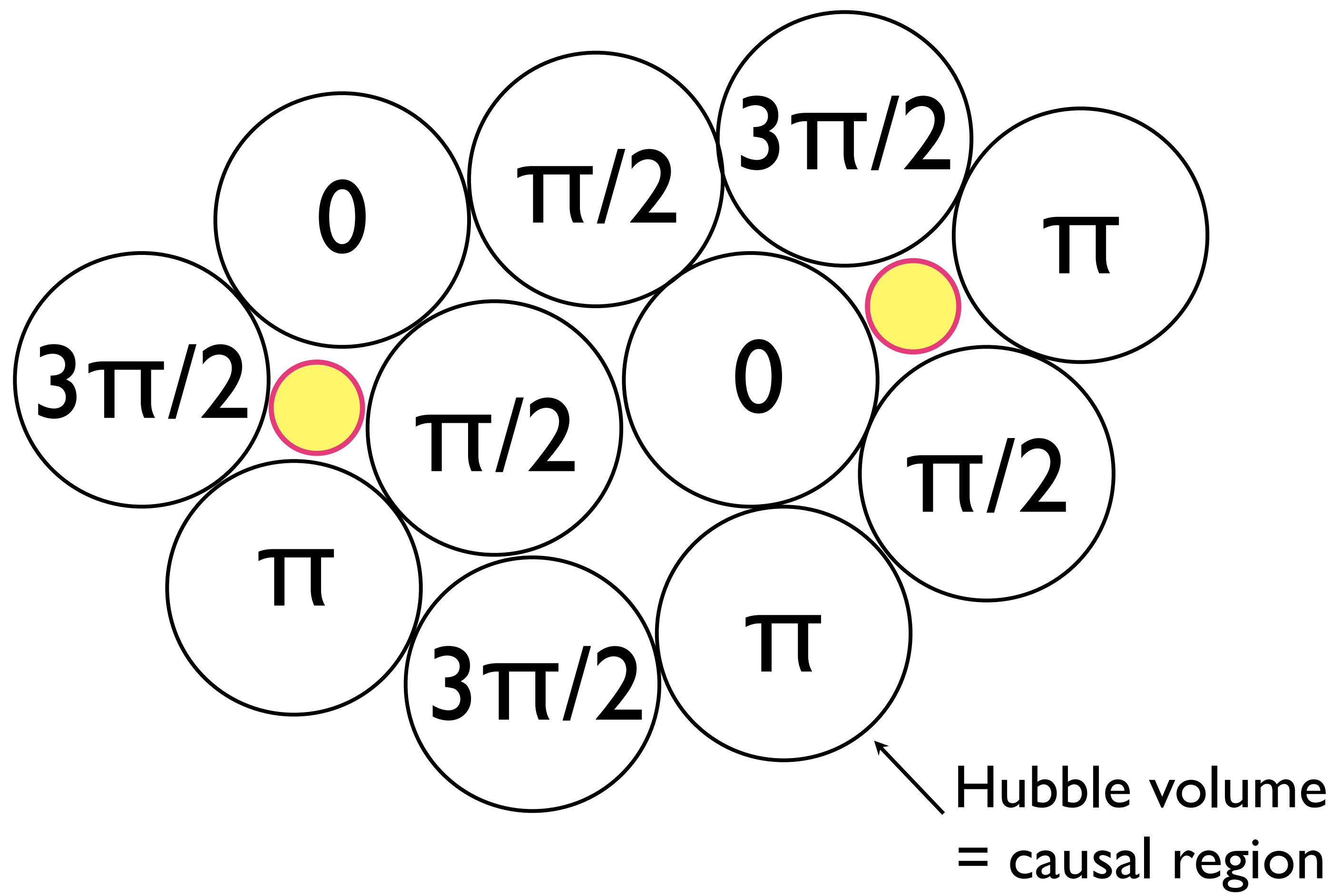
$G\mu = \mu / m_{pl}^2$

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

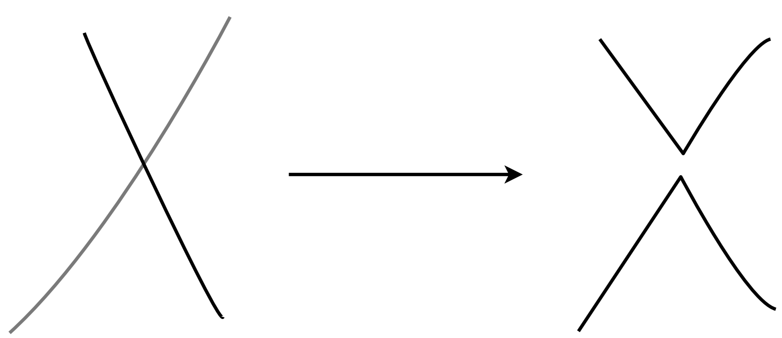
Tension $G\mu$ ~ the energy scale of the phase transition

Generation mechanism 2: Cosmic superstrings

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

<u>Difference from phase transition origin</u>

- reconnection probability: p



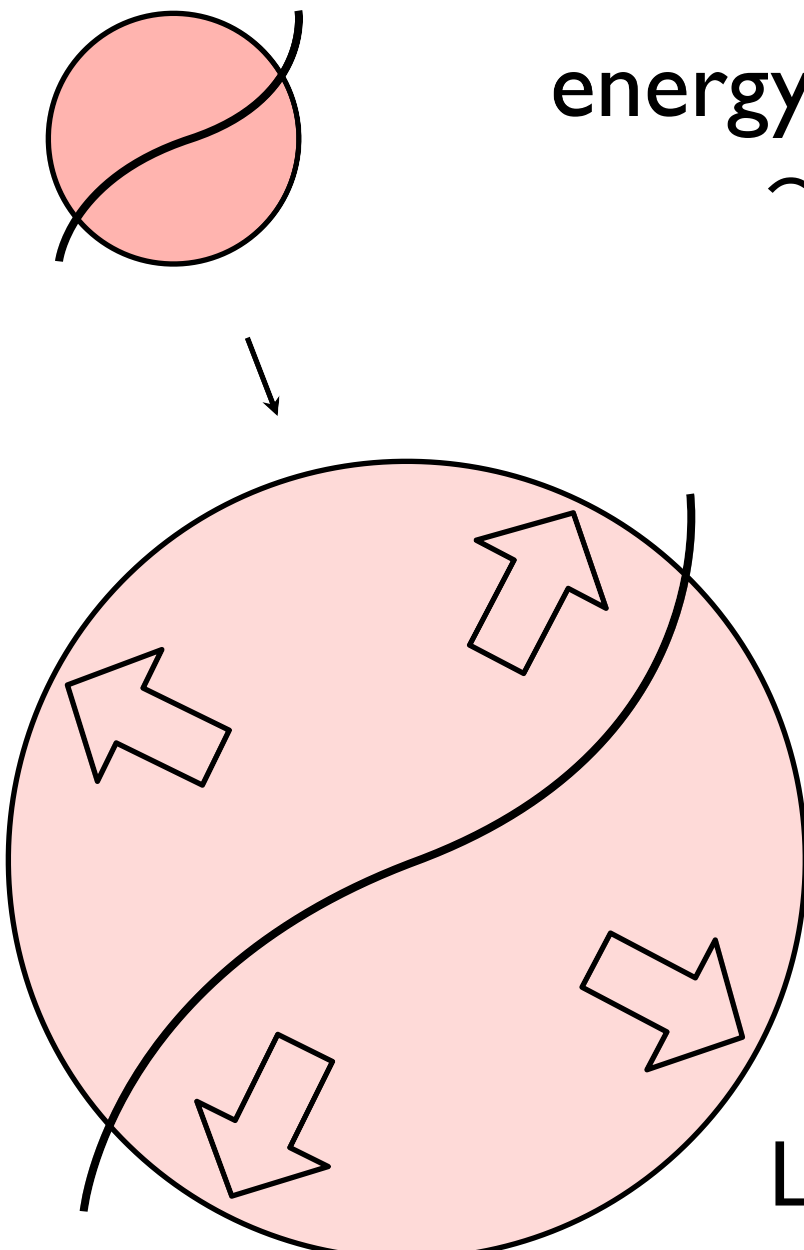
Phase transition origin: p=1

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

- can have broad values of Gμ
- have Y junction
- mixed network of different Gμ

→ Cosmic strings provides insight into fundamental physics

Evolution of cosmic strings



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

$\sim$ (line density × length)/volume

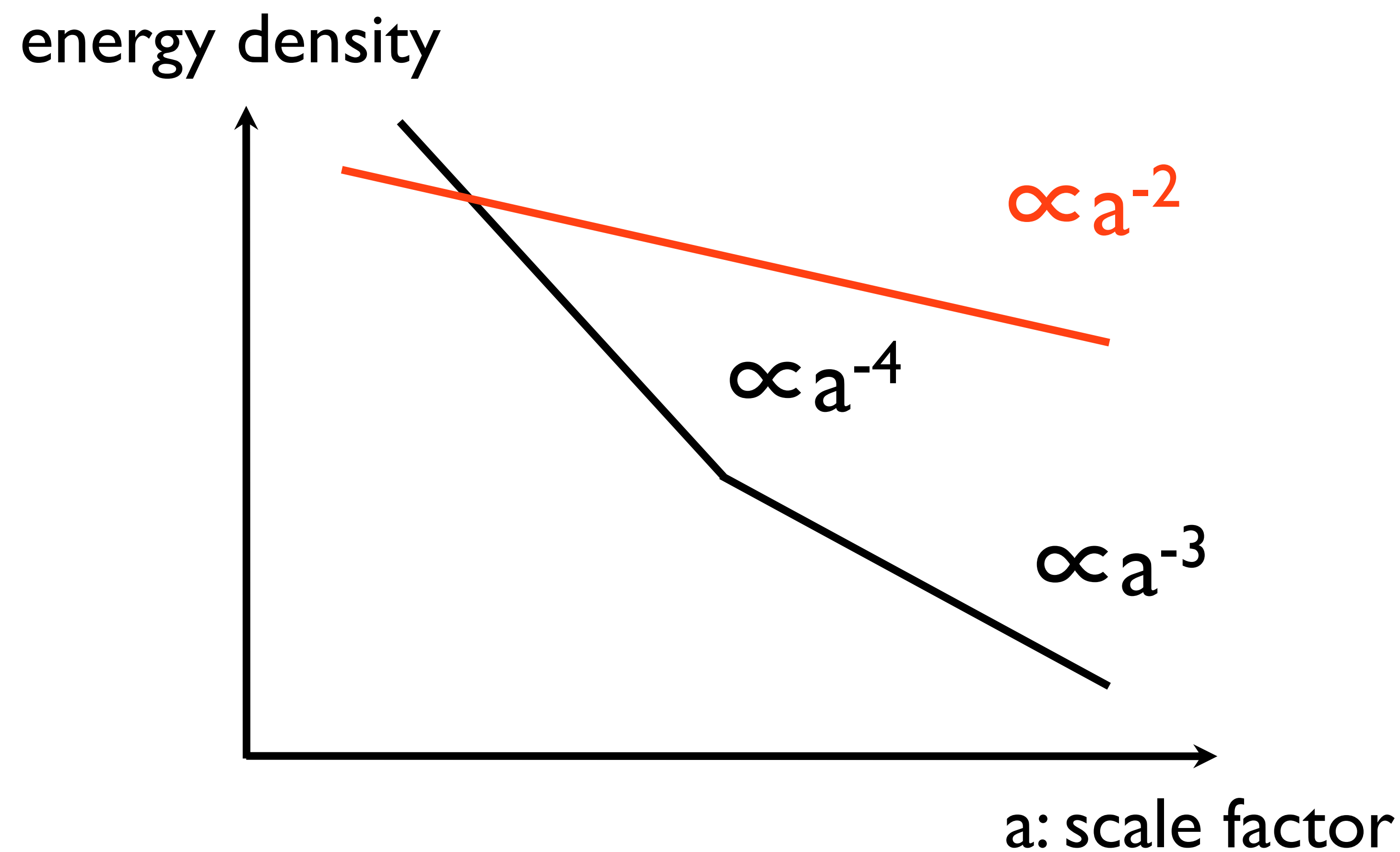
constant $\quad \propto a^{1} \quad \propto a^{-3}$

radiation $\propto a^{-4}$

matter $\propto a^{-3}$

$L \propto a^{1}$

$V \propto a^{3}$



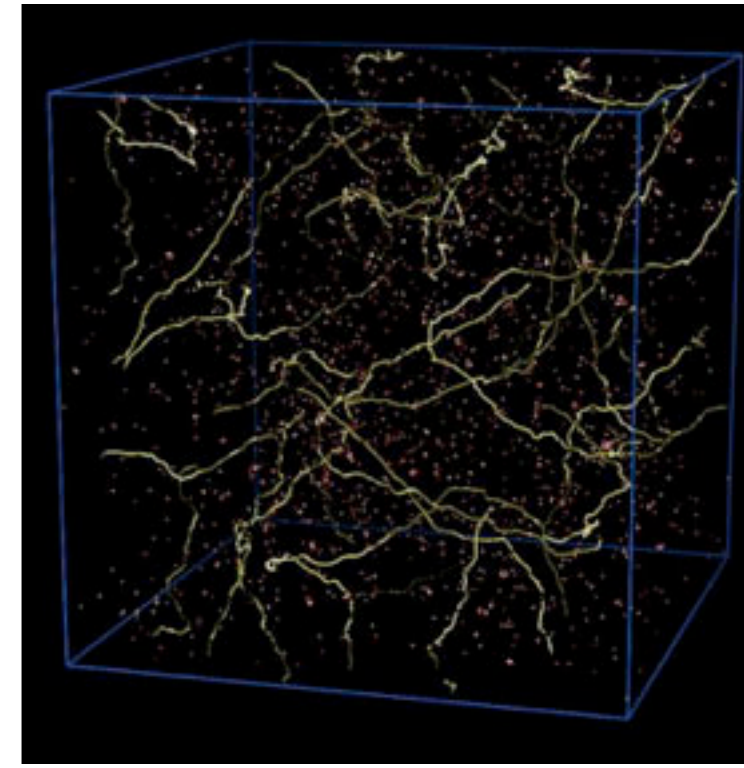
→ easily dominates the energy density of the Universe.

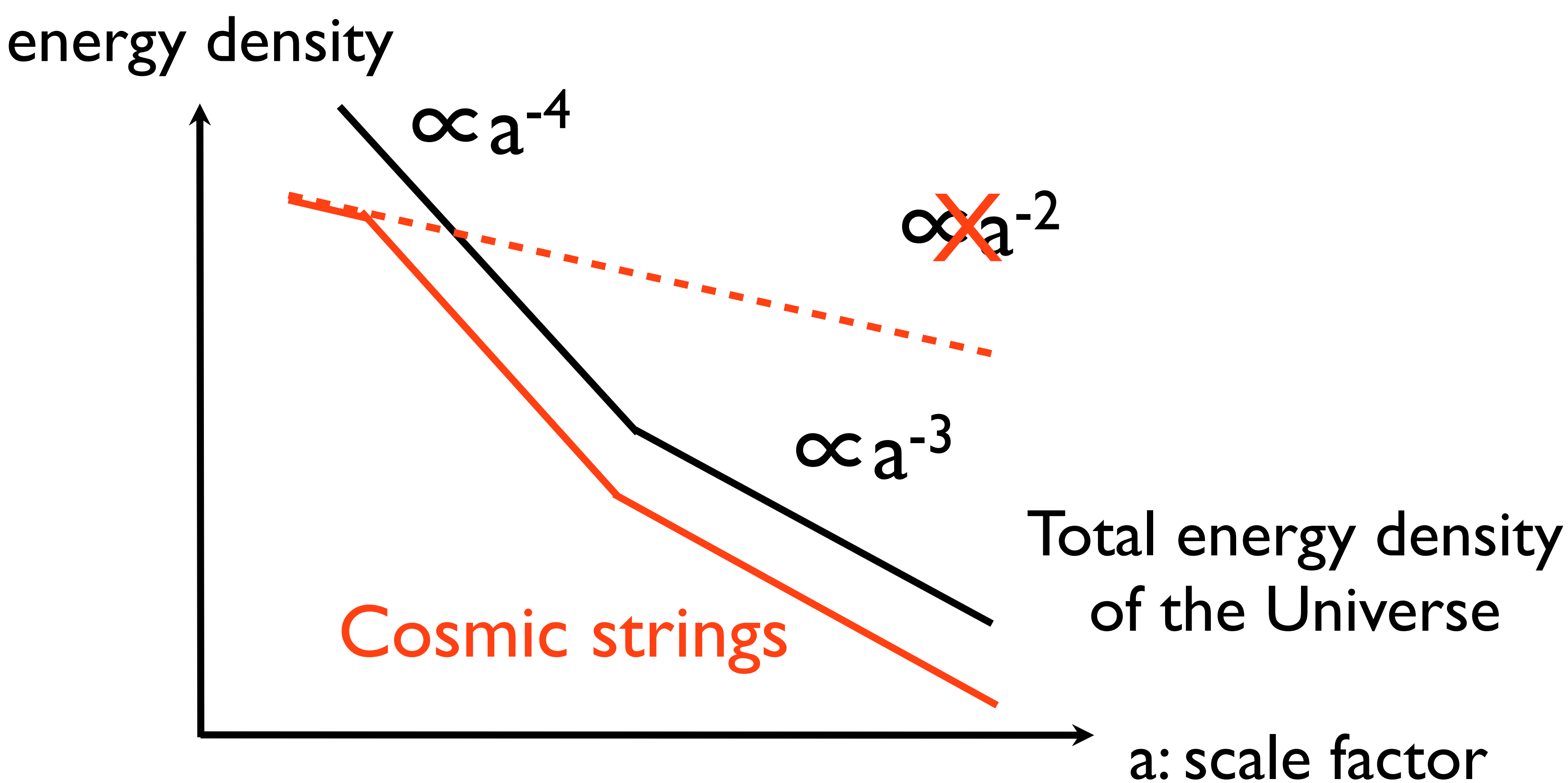
not allowed by observation?

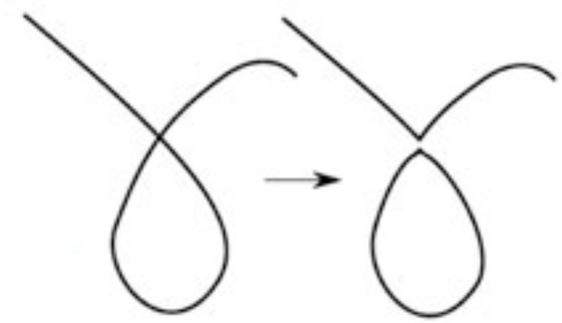
Evolution of cosmic strings

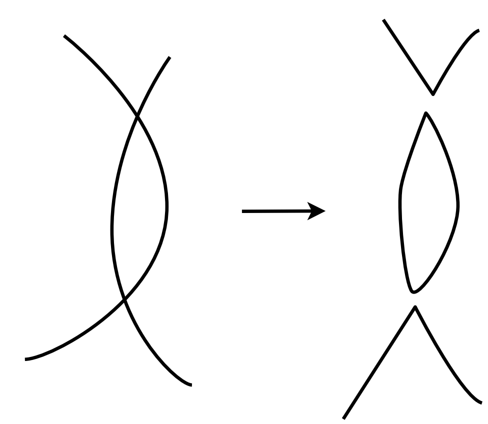
Scaling law

O(1) infinite strings in the Hubble horizon









Cosmic strings become loops via reconnection.

Loops lose energy by emitting gravitational waves.

Evolution of cosmic strings

Scaling law

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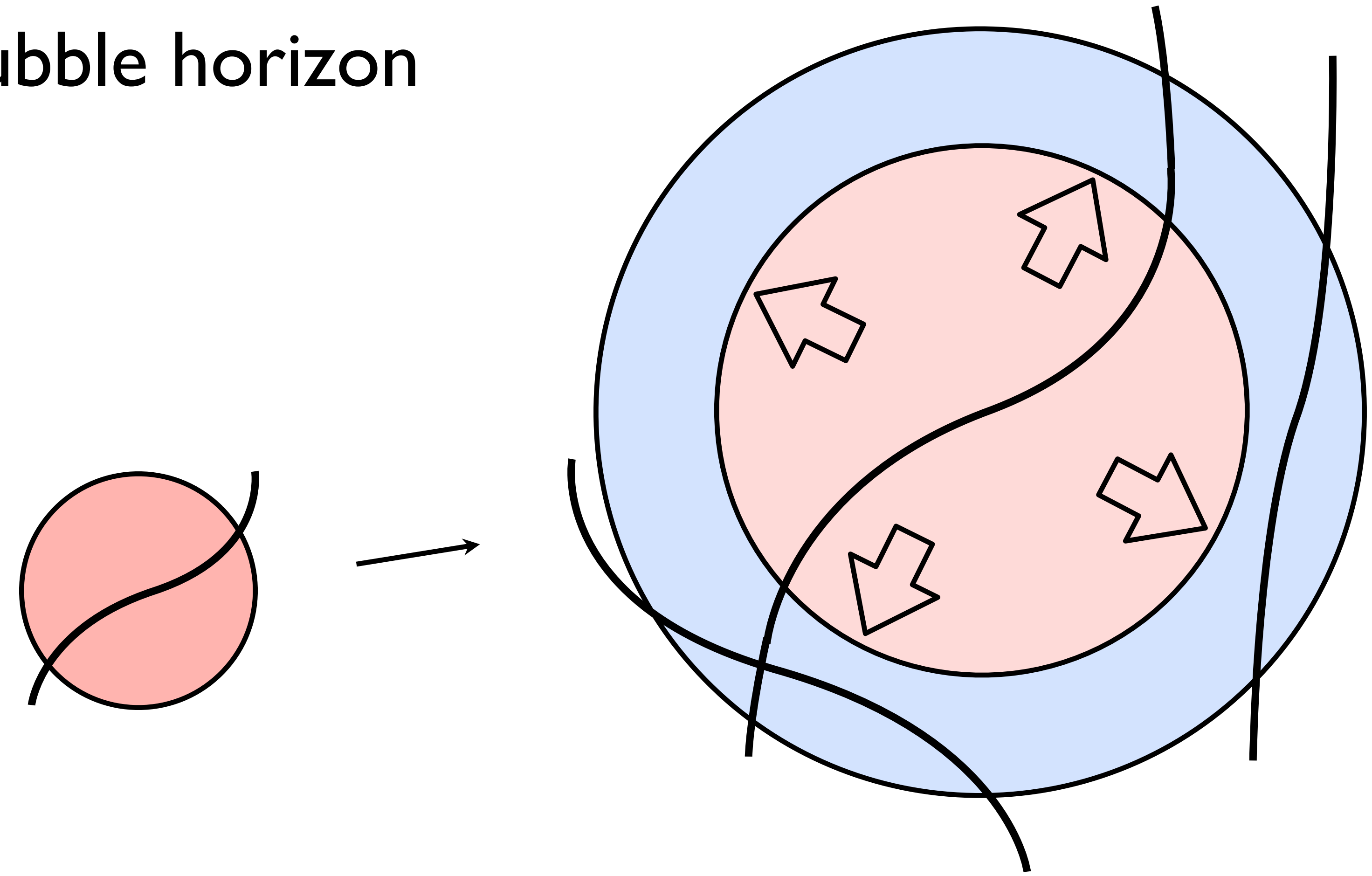


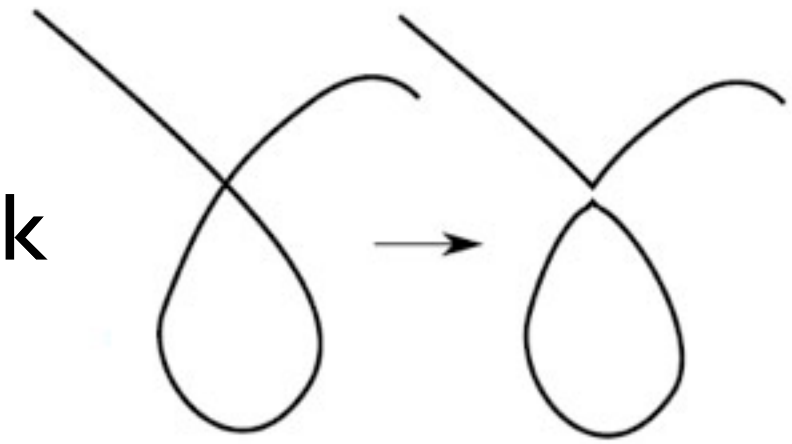
Increase of infinite string length by the horizon growth ⇔ Loss of infinite string length by generation of loops

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

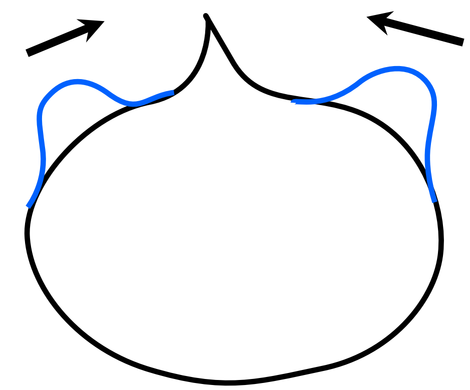
Gravitational waves from cosmic strings

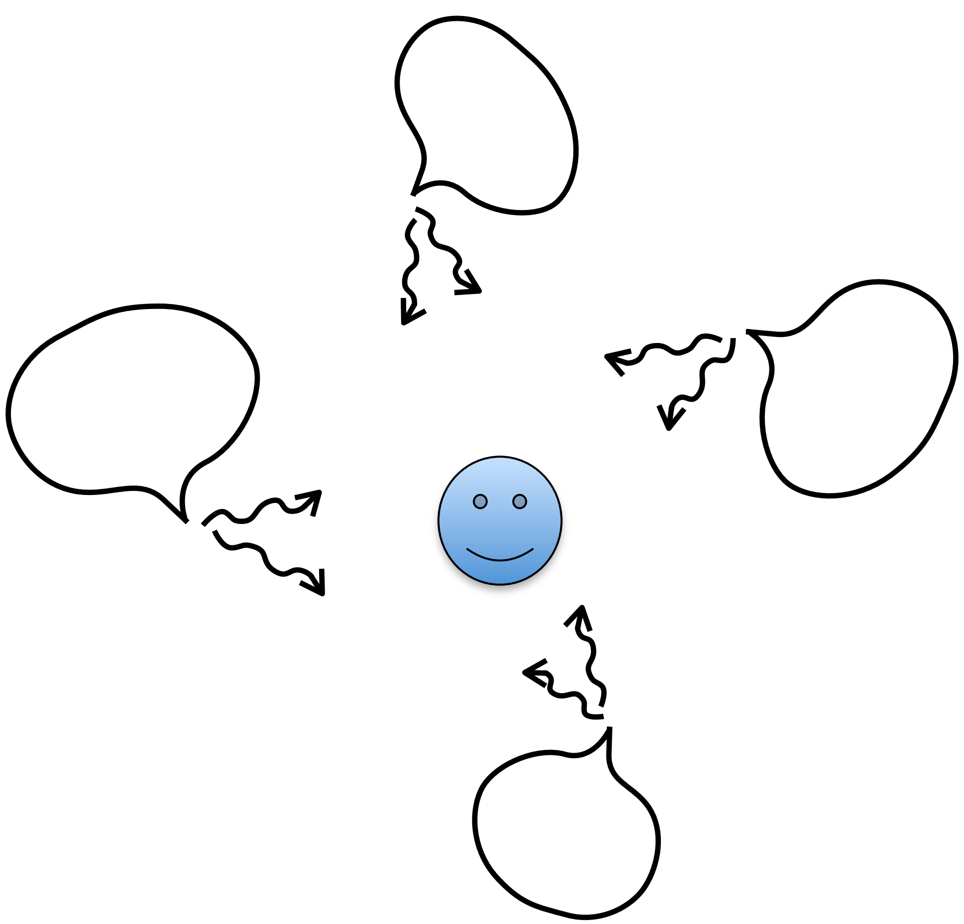
Strong GW emittion from singular points
called kinks and cusps

kink



cusp





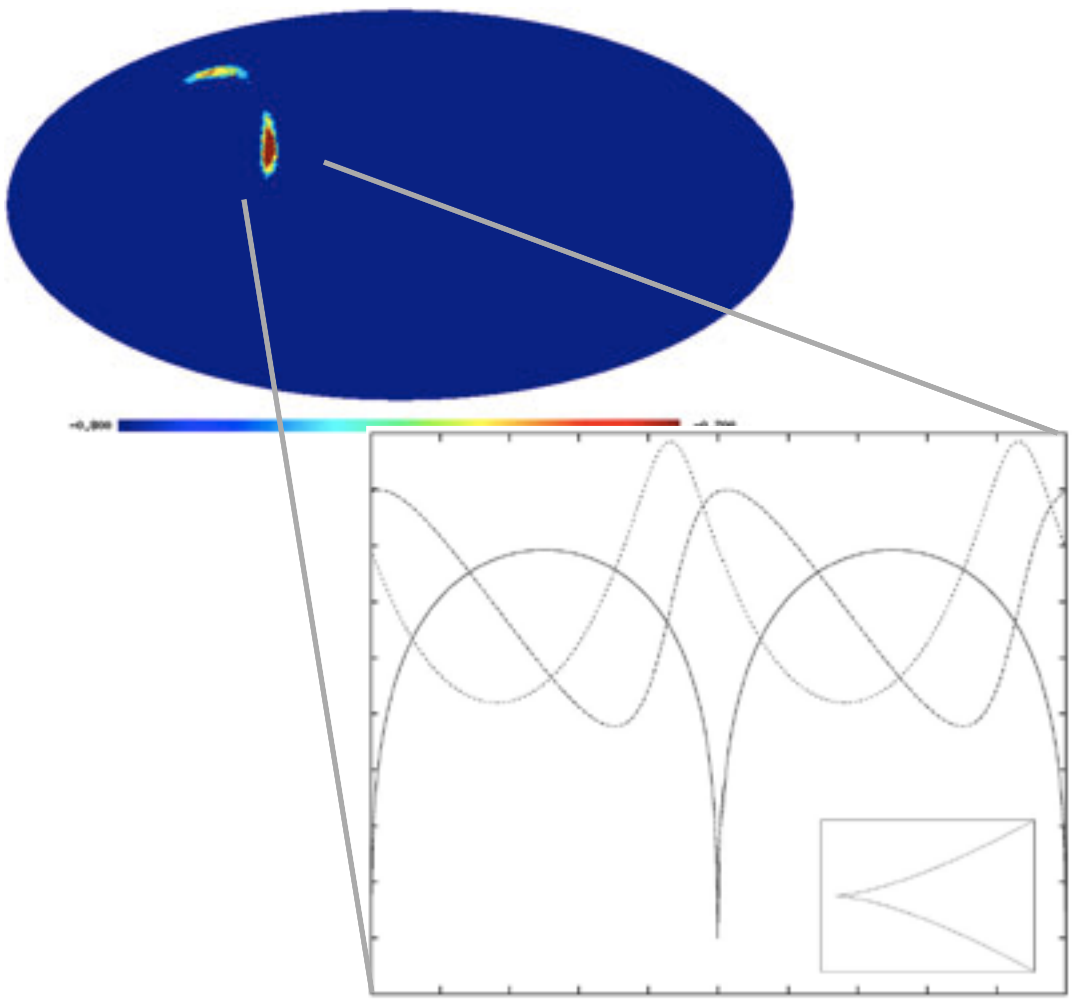
Rare Burst: GWs with large amplitude coming from close loops

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

Observations of GWs

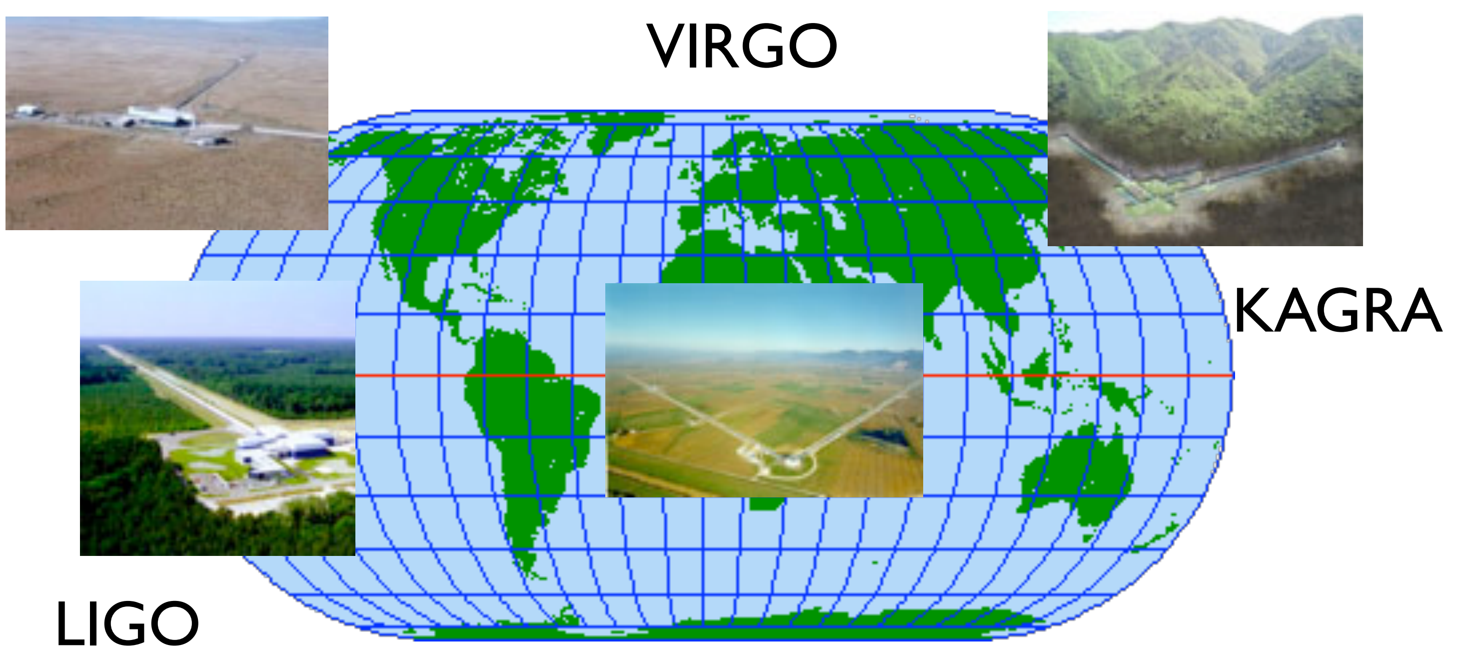
GWs with large amplitude

Burst



GWs with small amplitude
but numerous

GWB



Cross correlation analysis

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

→ provide different information on cosmic strings

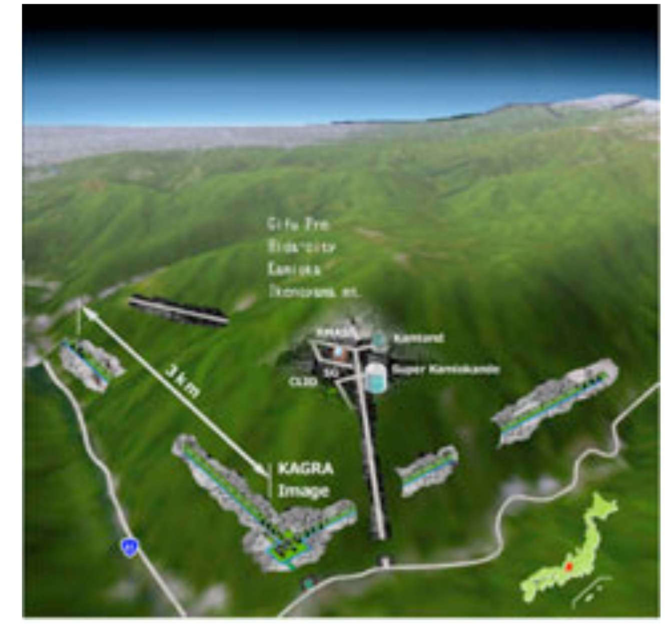
Gravitational wave experiments

- Direct detection

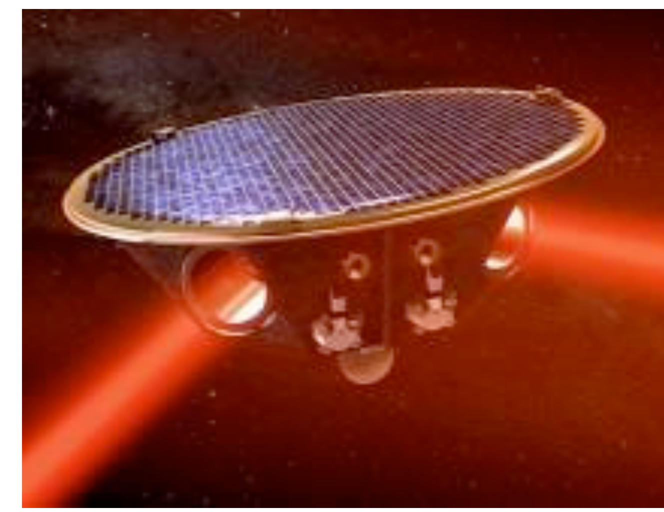
  Ground：**Advanced-LIGO、KAGRA、Virgo、IndIGO**

  Space：**eLISA/NGO、DECIGO**

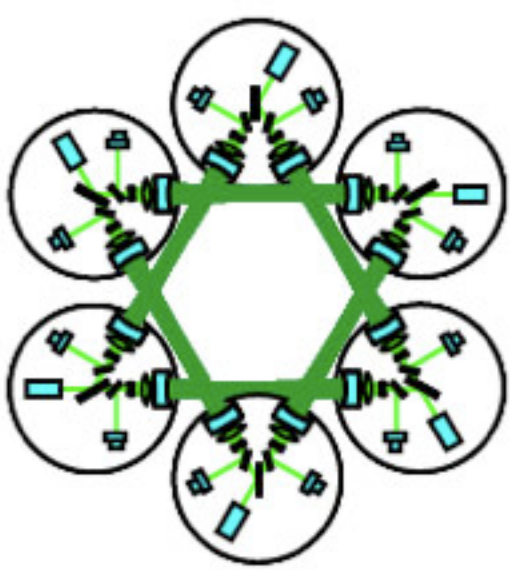
- Pulsar timing: **SKA**
- CMB B-mode polarization: **Planck, CMBpol**



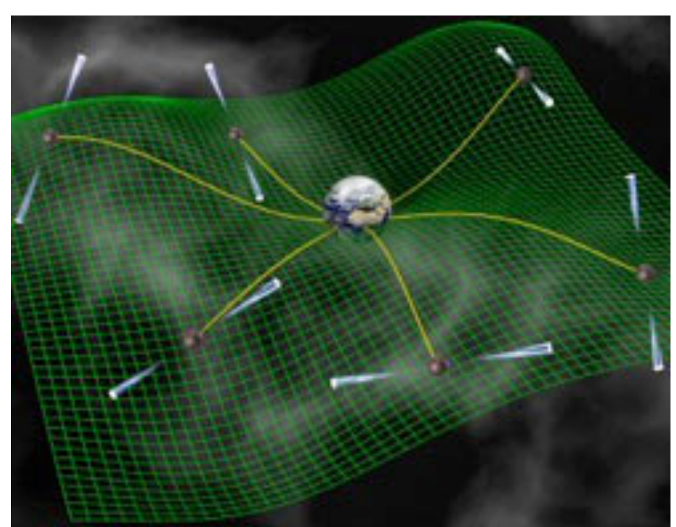
KAGRA image (http://gwcenter.icrr.u-tokyo.ac.jp/)



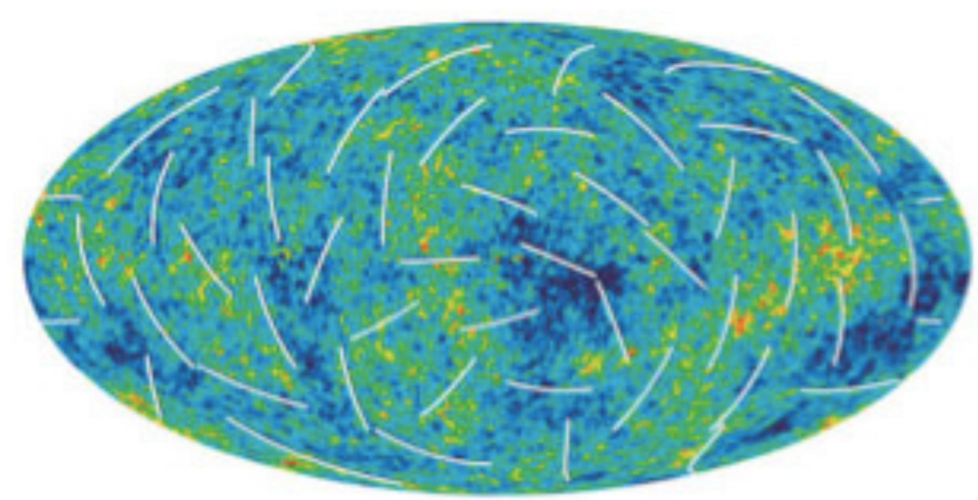
eLISA image (http://elisa-ngo.org/)



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: $G\mu <\sim 10^{-7}$
- Gravitational lensing: $G\mu <\sim 10^{-6}$

for infinite strings

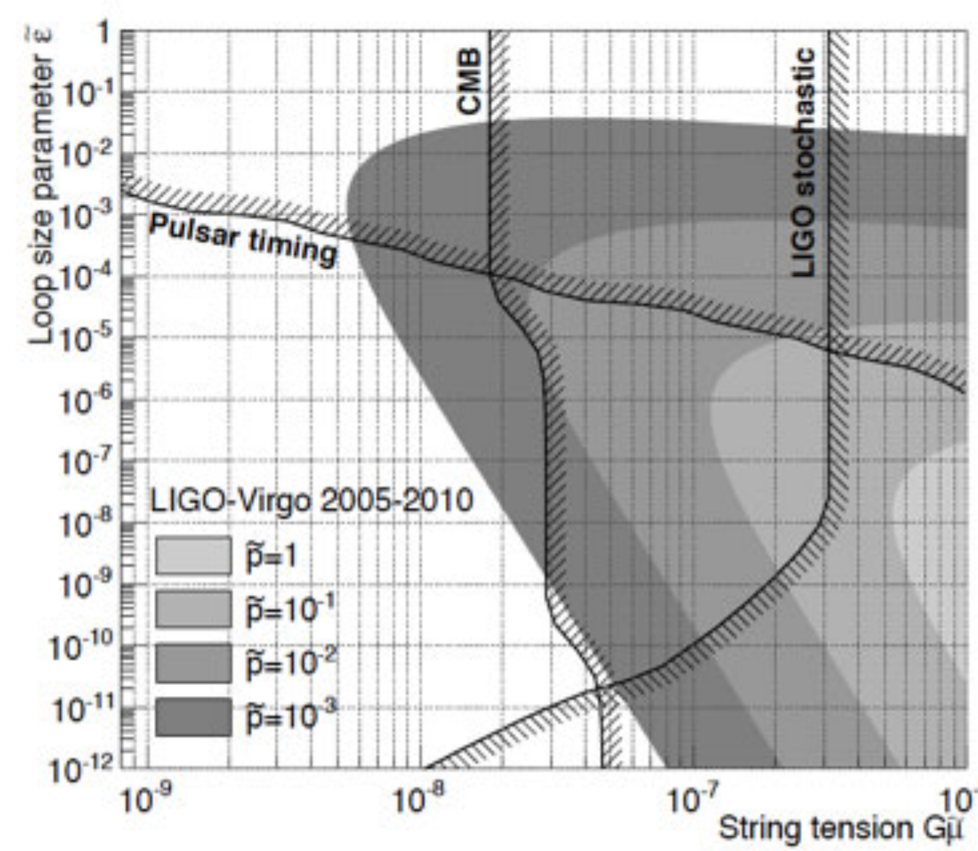
- **Gravitational waves**

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

for loops $\alpha = 0.1$, p=1

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

What about future constraints？

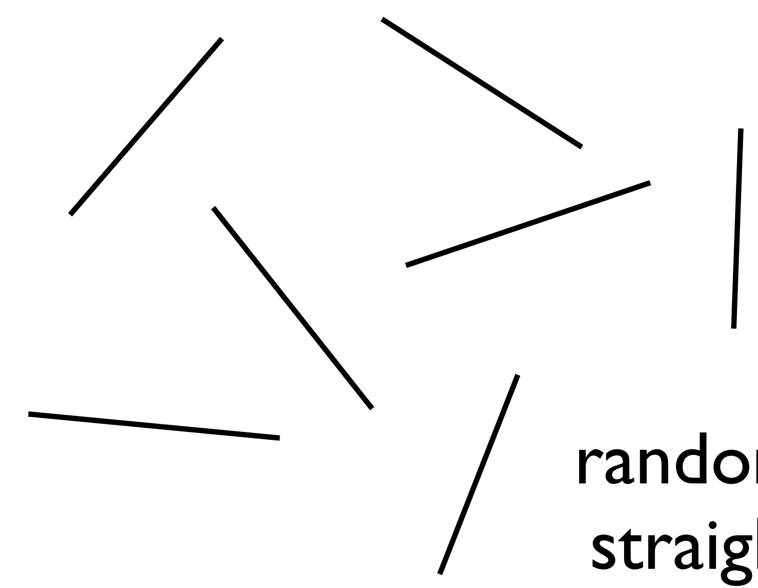


Estimation of the GW burst rate

Initial number density of loops

depends on α and p

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



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 goes to loops

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

for small p: c → cp

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

acceleration due to the curvature of the strings

damping due to the expansion

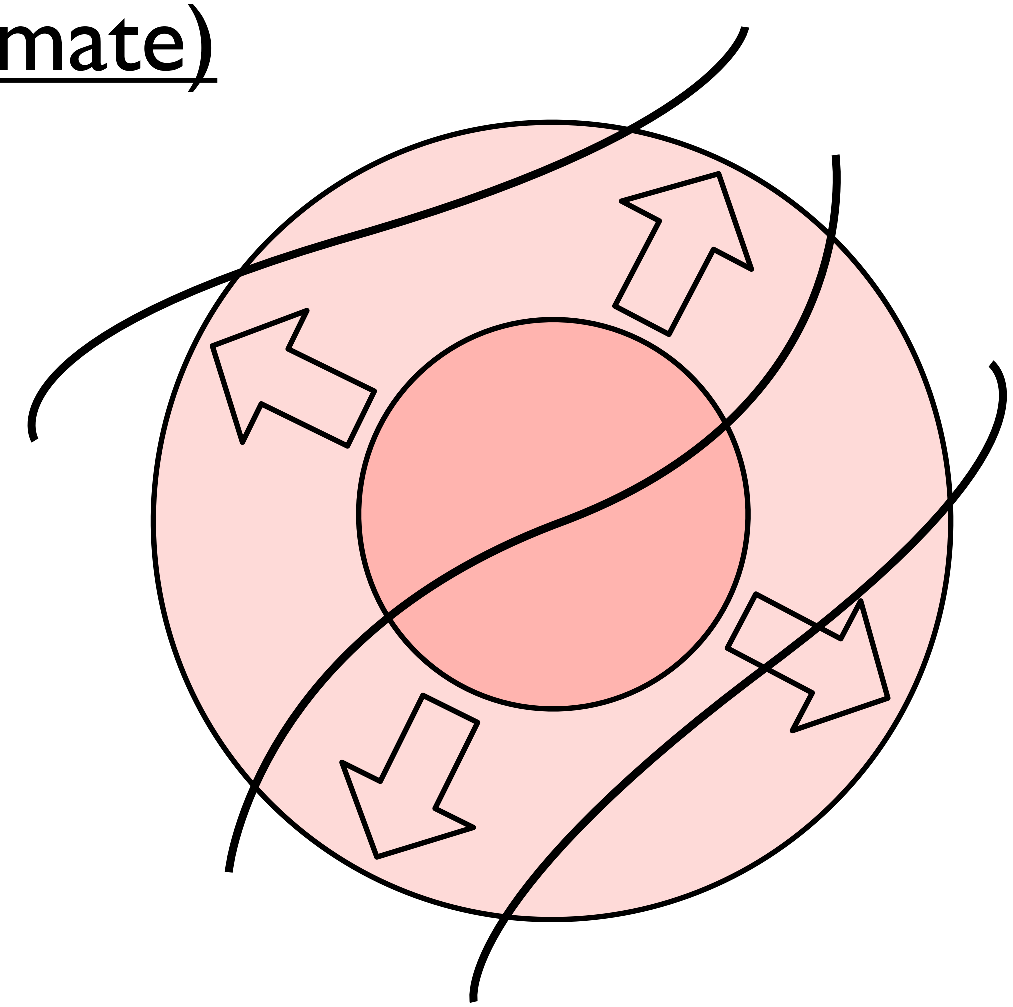
momentum parameter: $k = \frac{2\sqrt{2}}{\pi}\left(\frac{1-8v^6}{1+8v^6}\right)$

Estimation of the GW burst rate

Initial number density of loops (naive estimate)

$$\textbf{Number of loops} = \frac{\text{(length to lose)}}{\text{(initial length of loops)}}$$

$$= \frac{p^{-1}t}{\alpha t} = \frac{1}{p\alpha}$$



Scaling law

O(1) infinite strings in the Hubble horizon

To satisfy the scaling law...
infinite strings
should lose O(1) Hubble length per 1 Hubble time → more loops for small α
= should reconnect O(1) times per Hubble time
→ for small p, string density should increase to reconnect O(1) times

Estimation of the GW burst rate

<u>loop evolution</u>   depends on Gμ 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

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

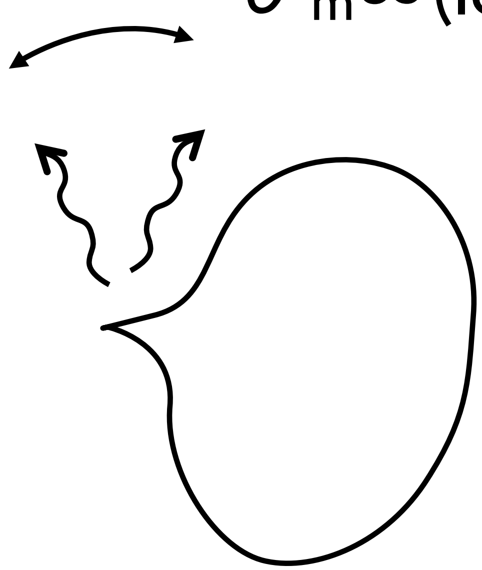
Beaming

Time interval of GW emission

Loop number

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

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

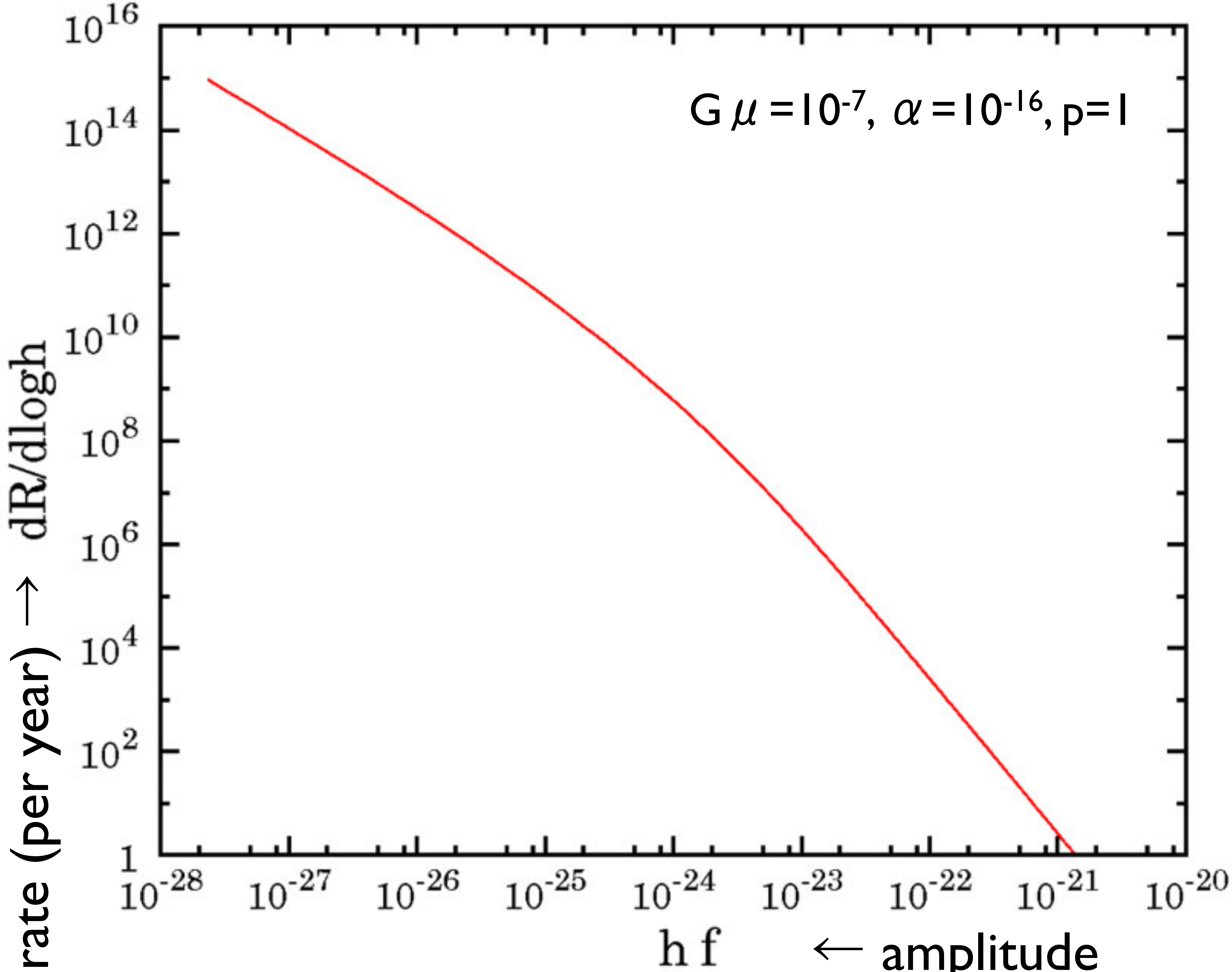


$$l(t,t_i) = \alpha t_i - \Gamma G\mu(t-t_i)$$

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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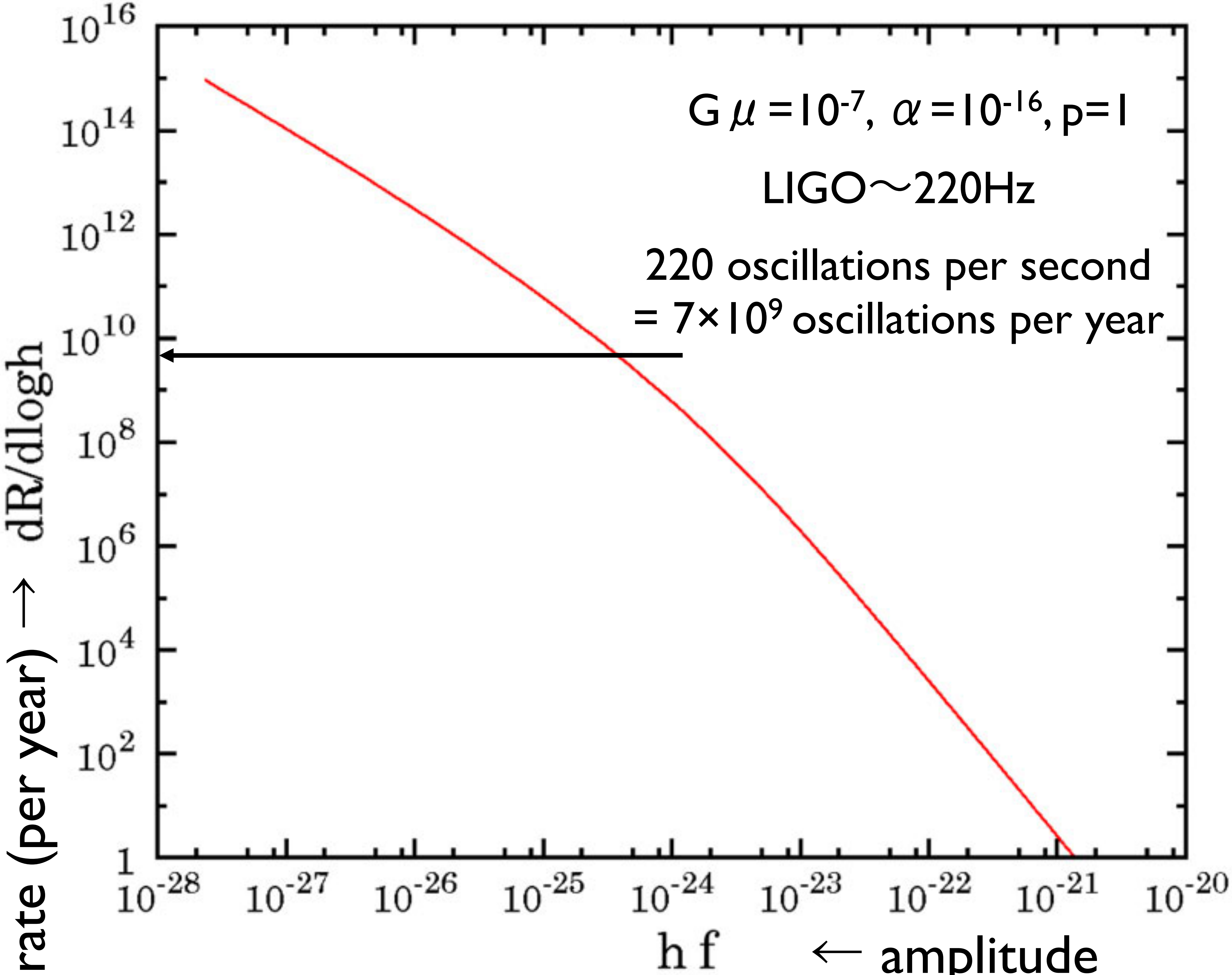

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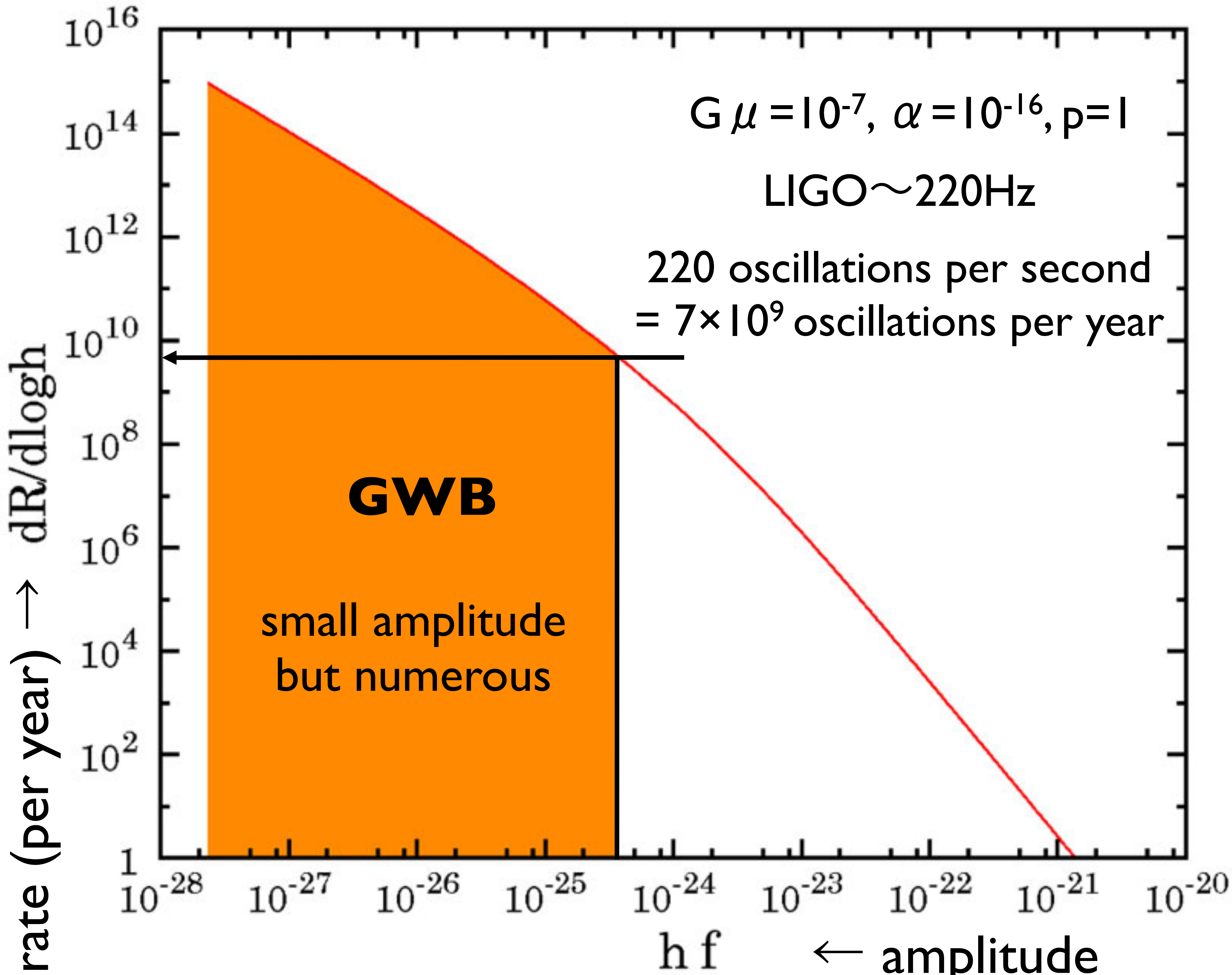

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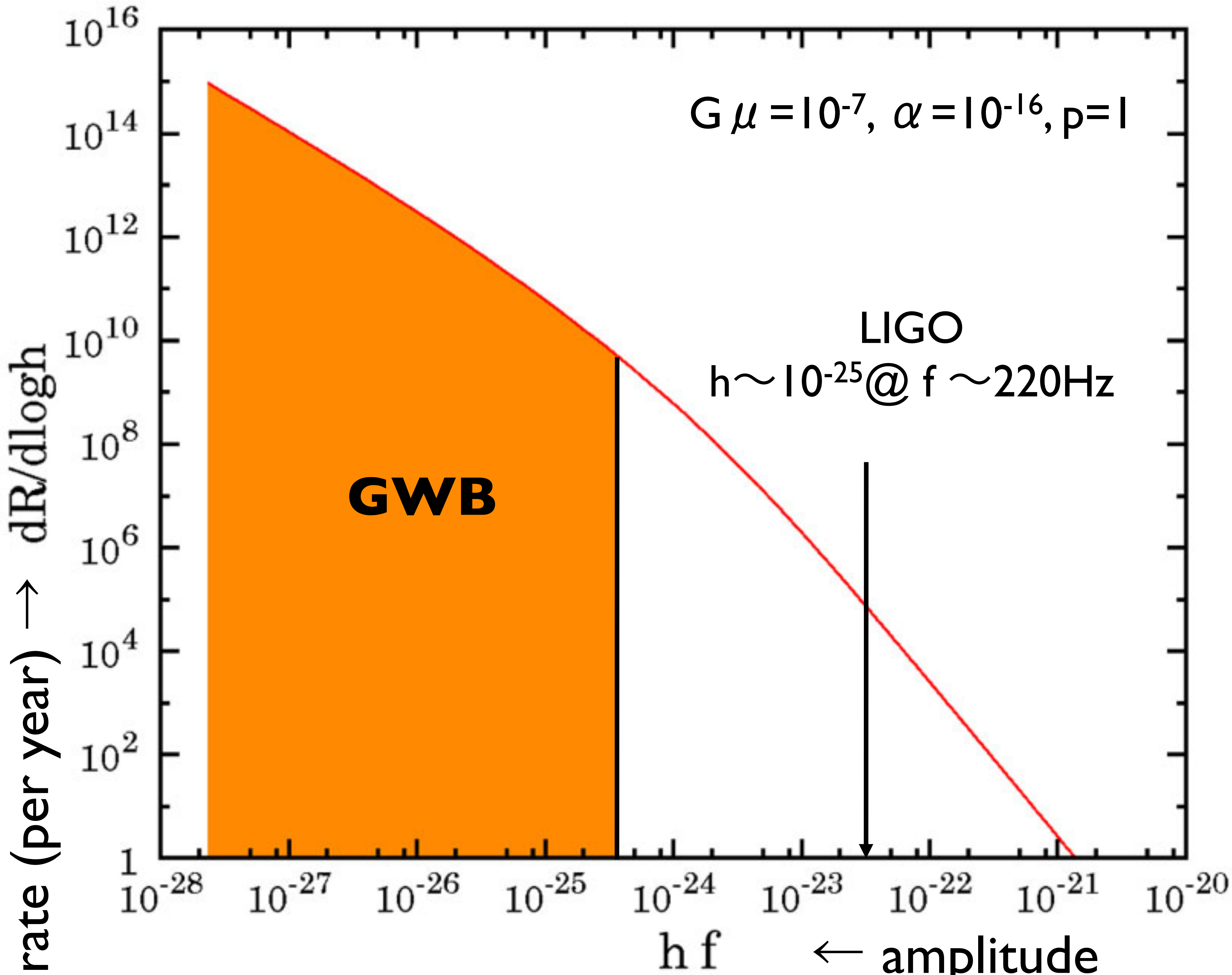

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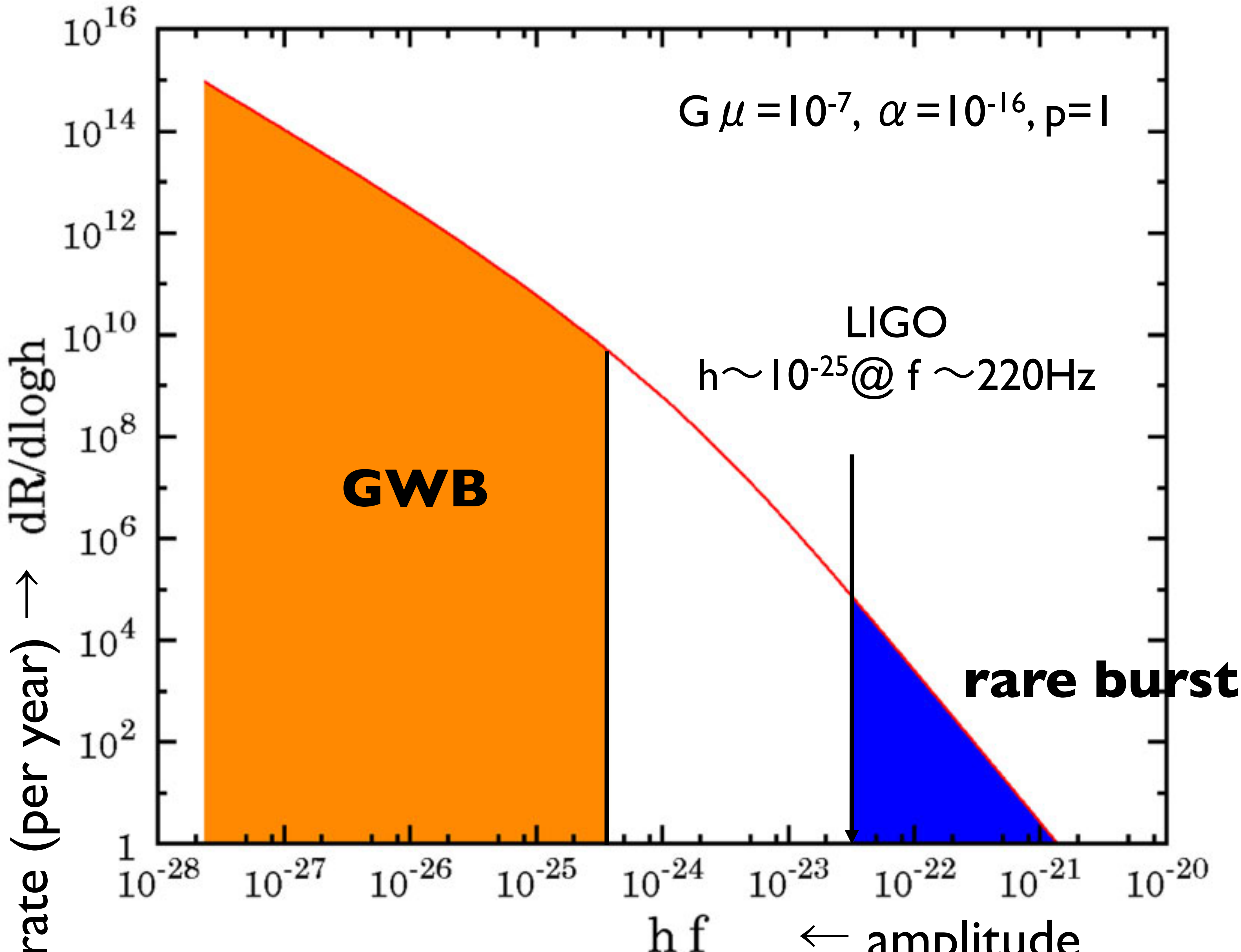

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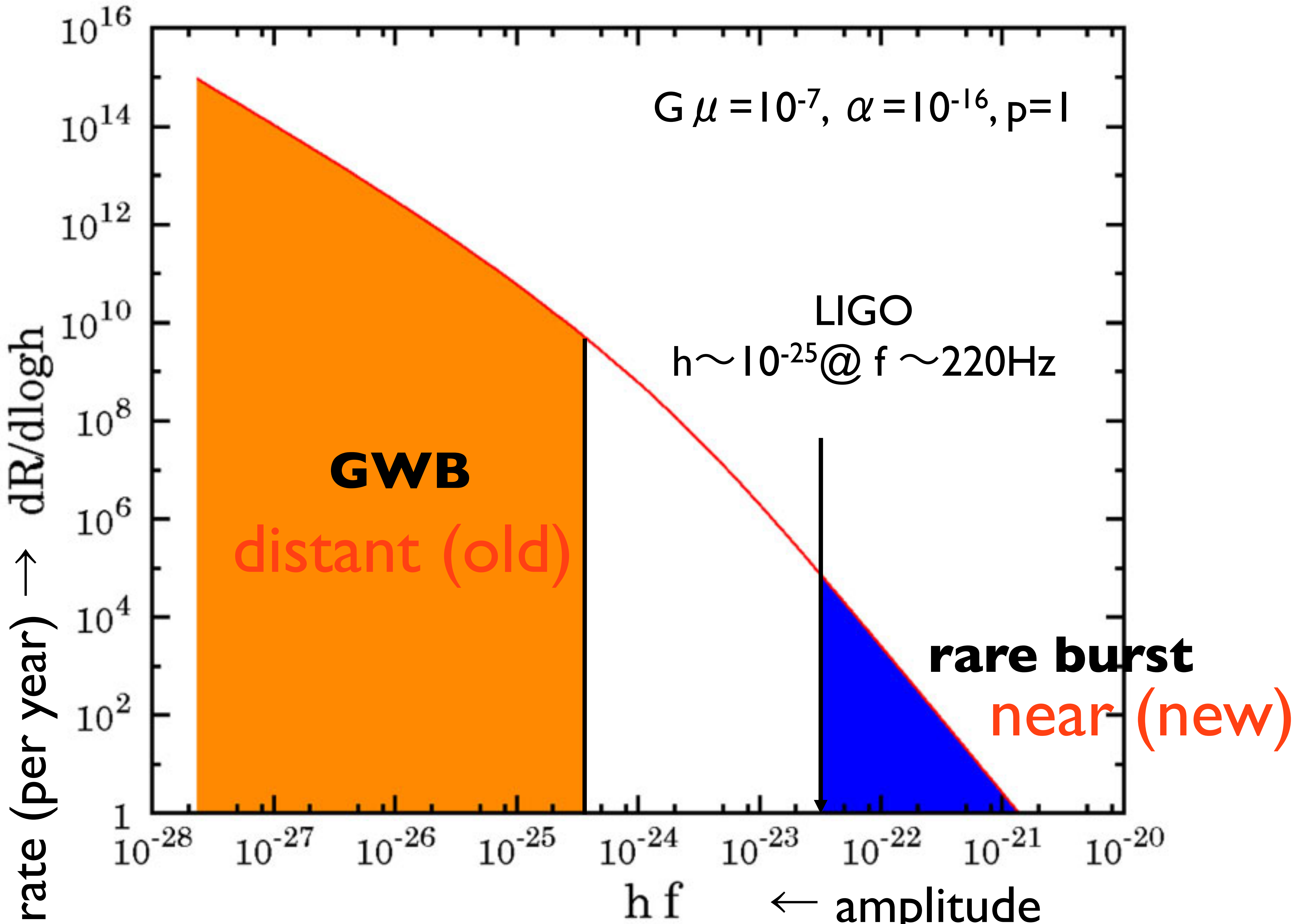
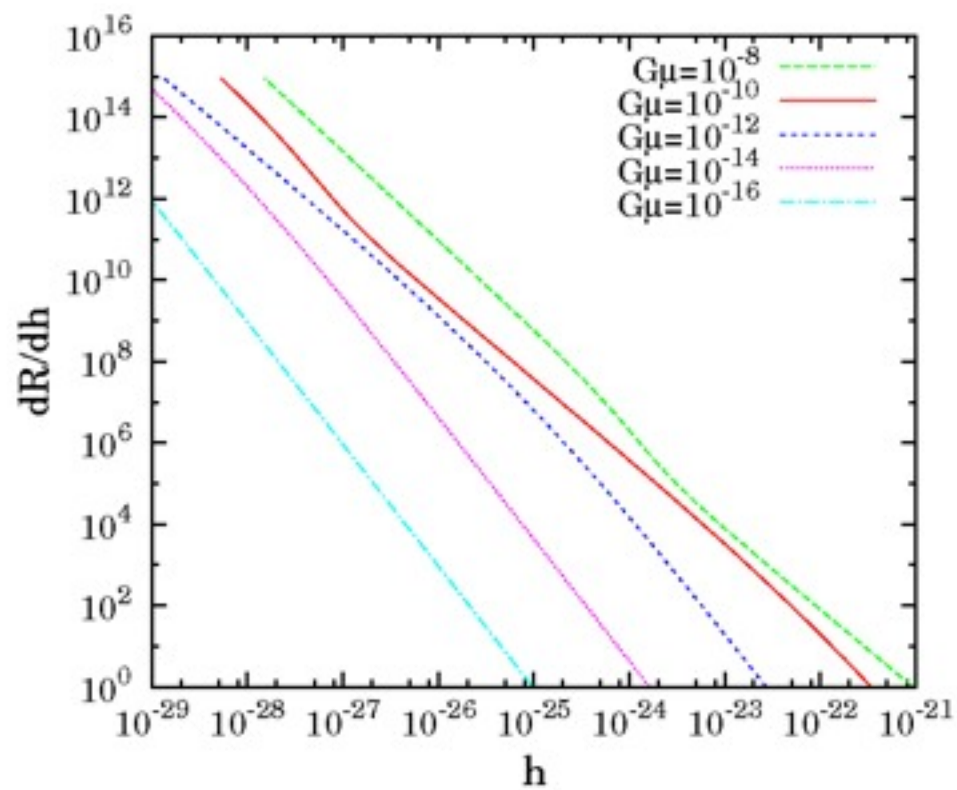
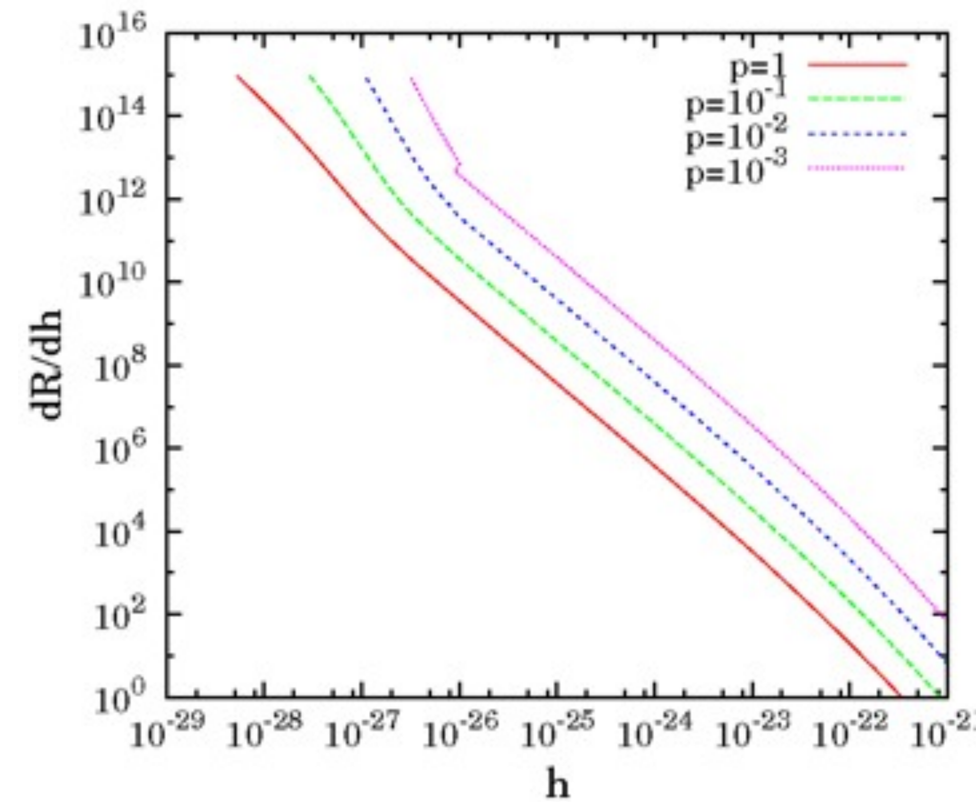


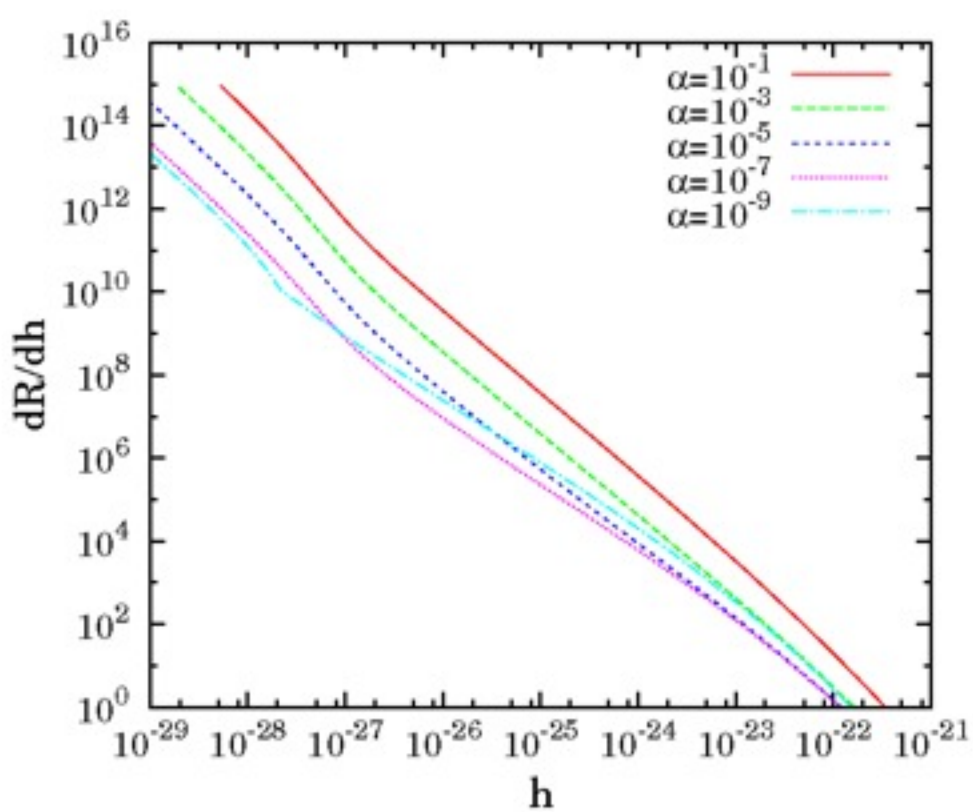
Parameter dependences of the rate

$G\mu$



p





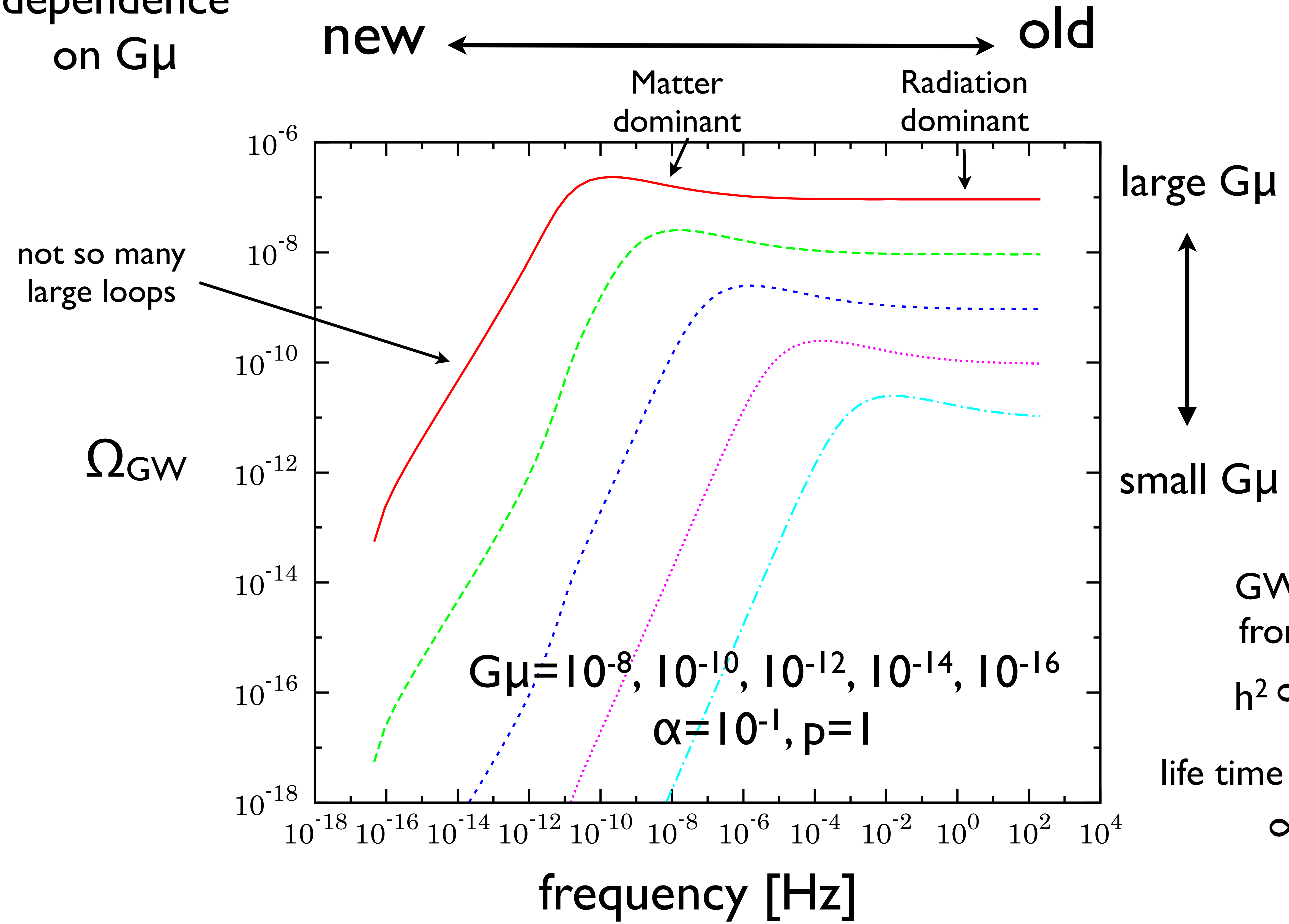
α

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



GW power from cusps

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

life time of loops

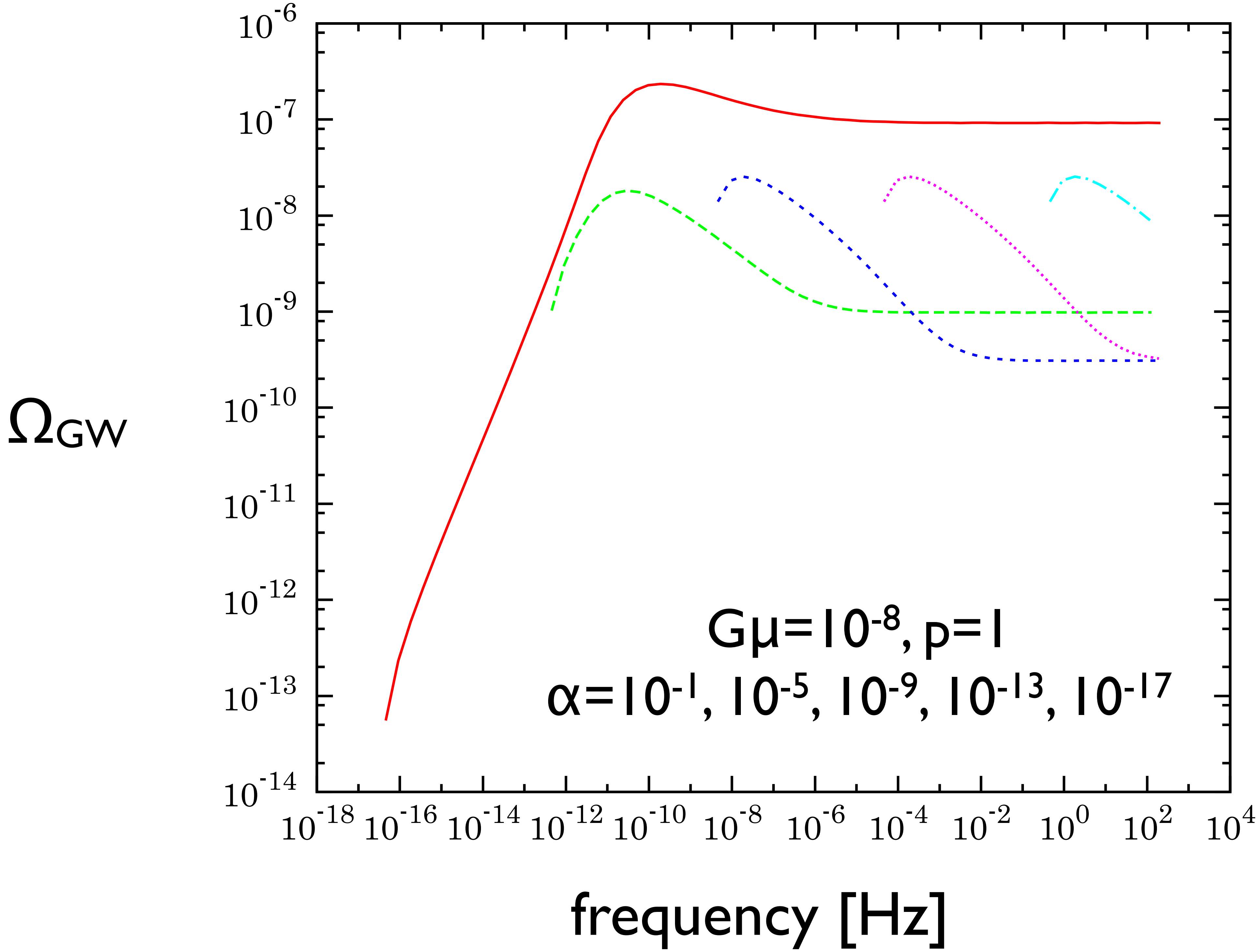
$\propto (G\mu)^{-1}$

Spectrum of the GWB

dependence on α

loop size directly corresponds to the frequency of the GW

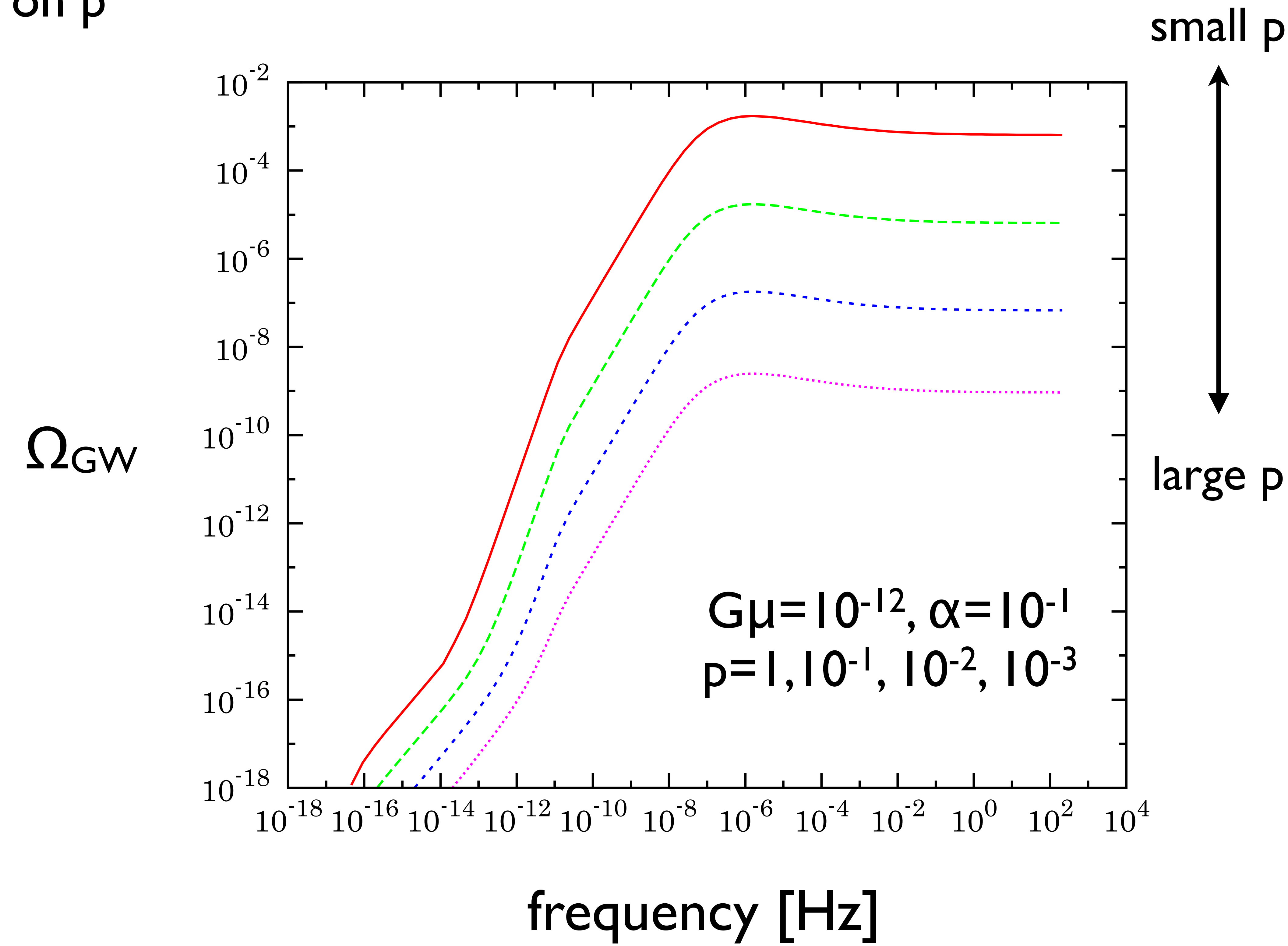
→ small α



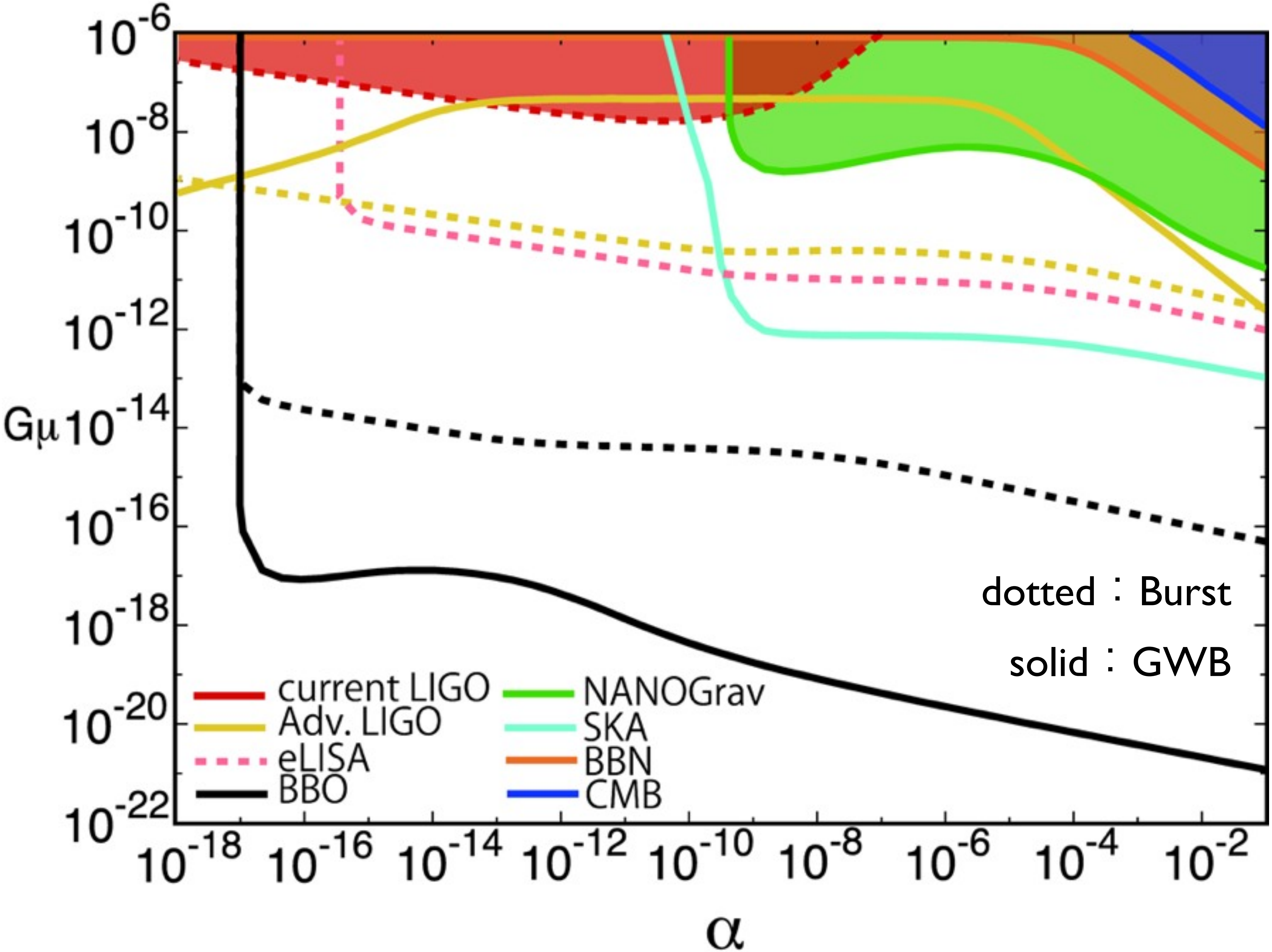
Spectrum of the GWB

dependence on p

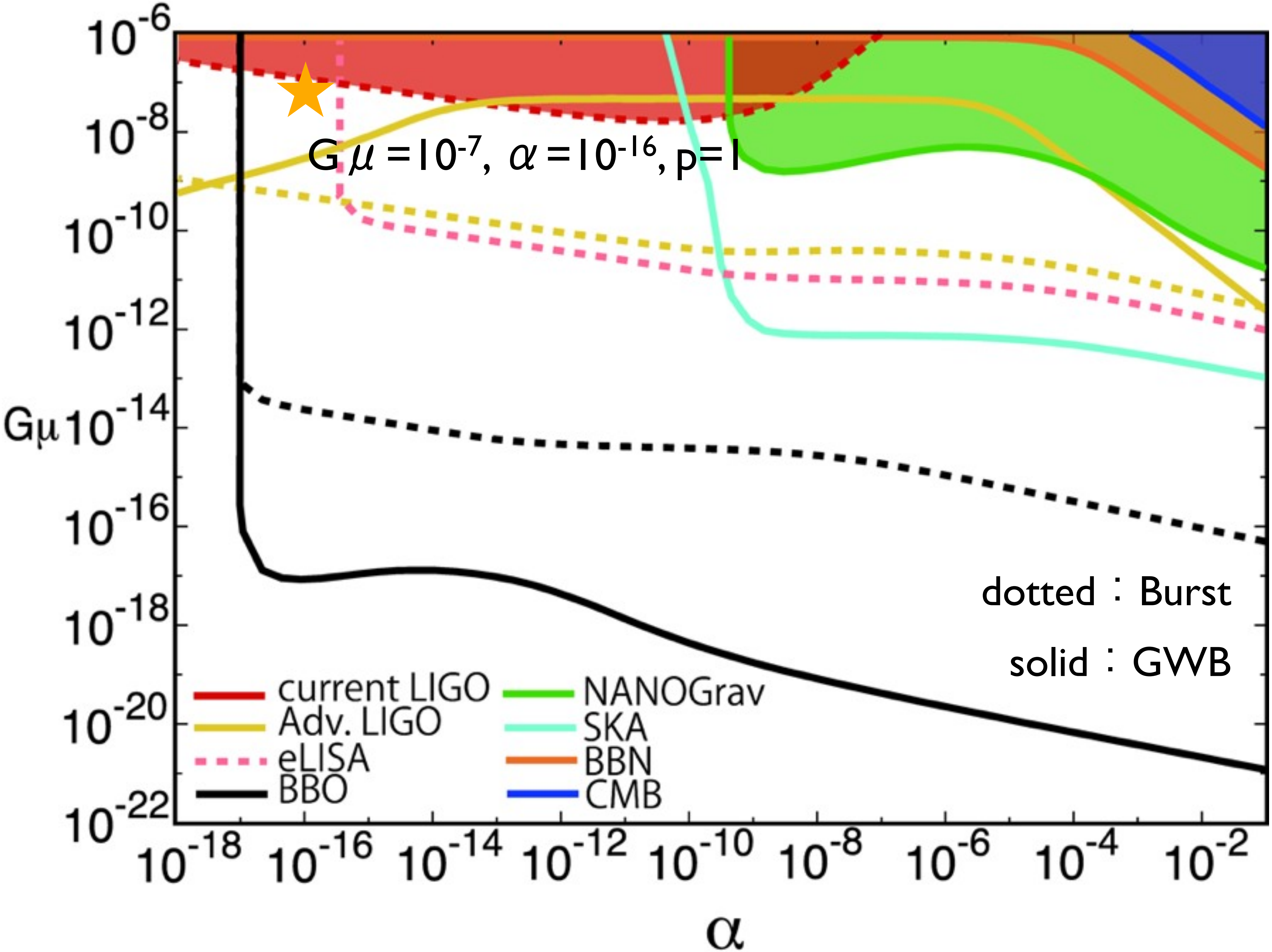
small p increases the number density of loops



Accessible parameter region (for p=1)



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

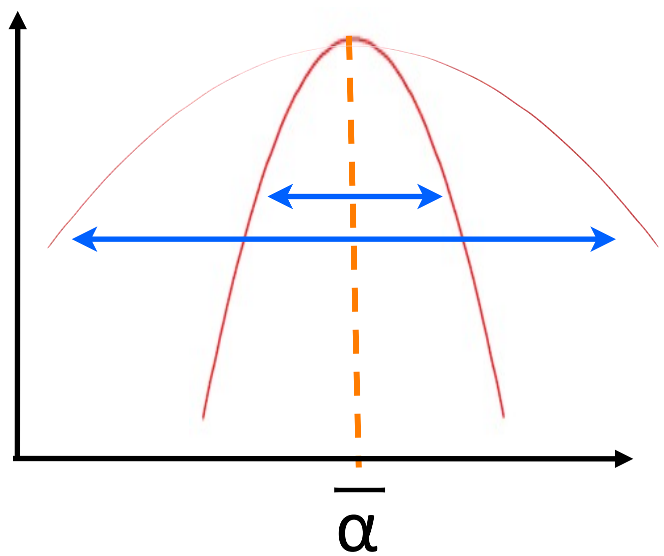


Constraint on parameters

Fisher information matrix

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

log(Likelihood)



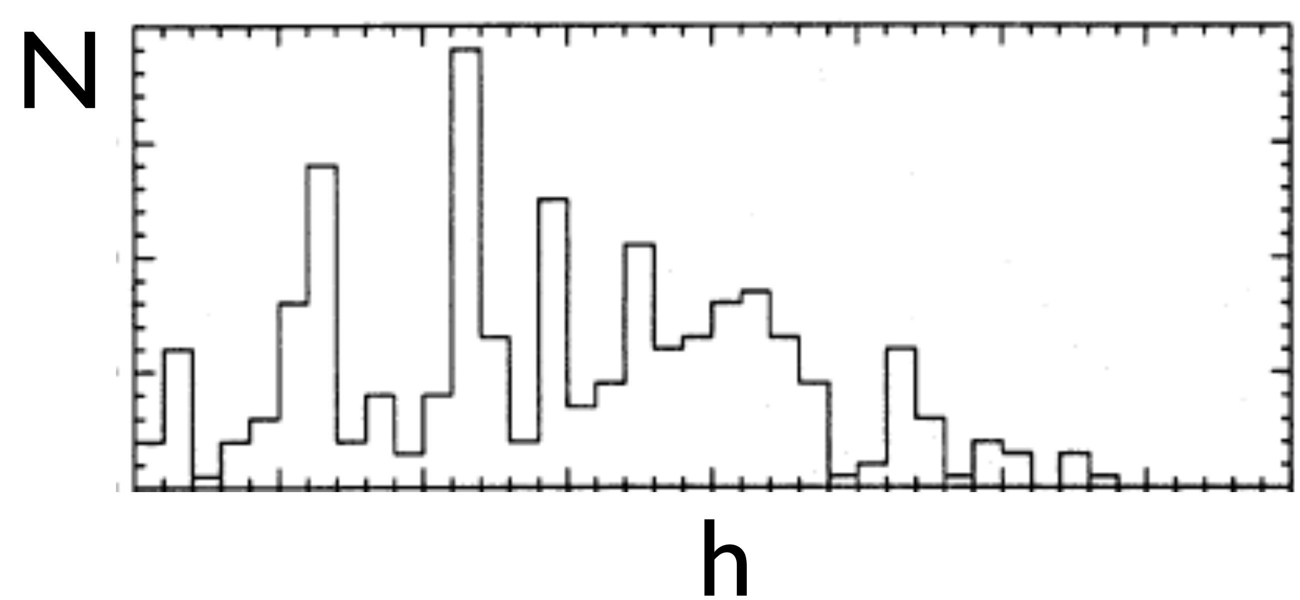
If the likelihood shape is sensitive to the parameter
= easy to estimate the parameter

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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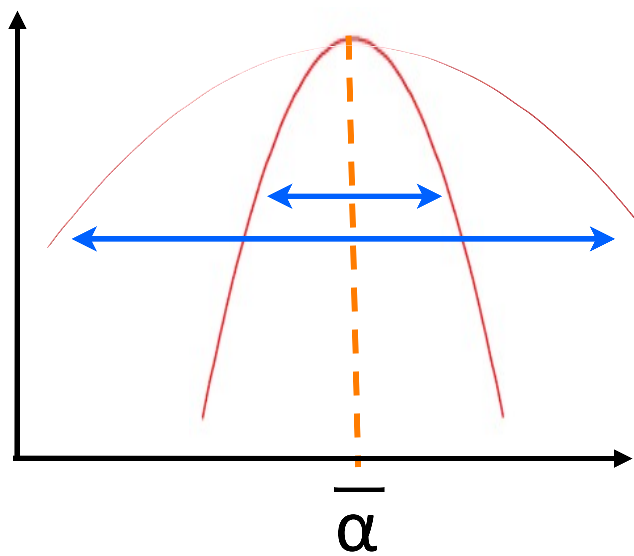
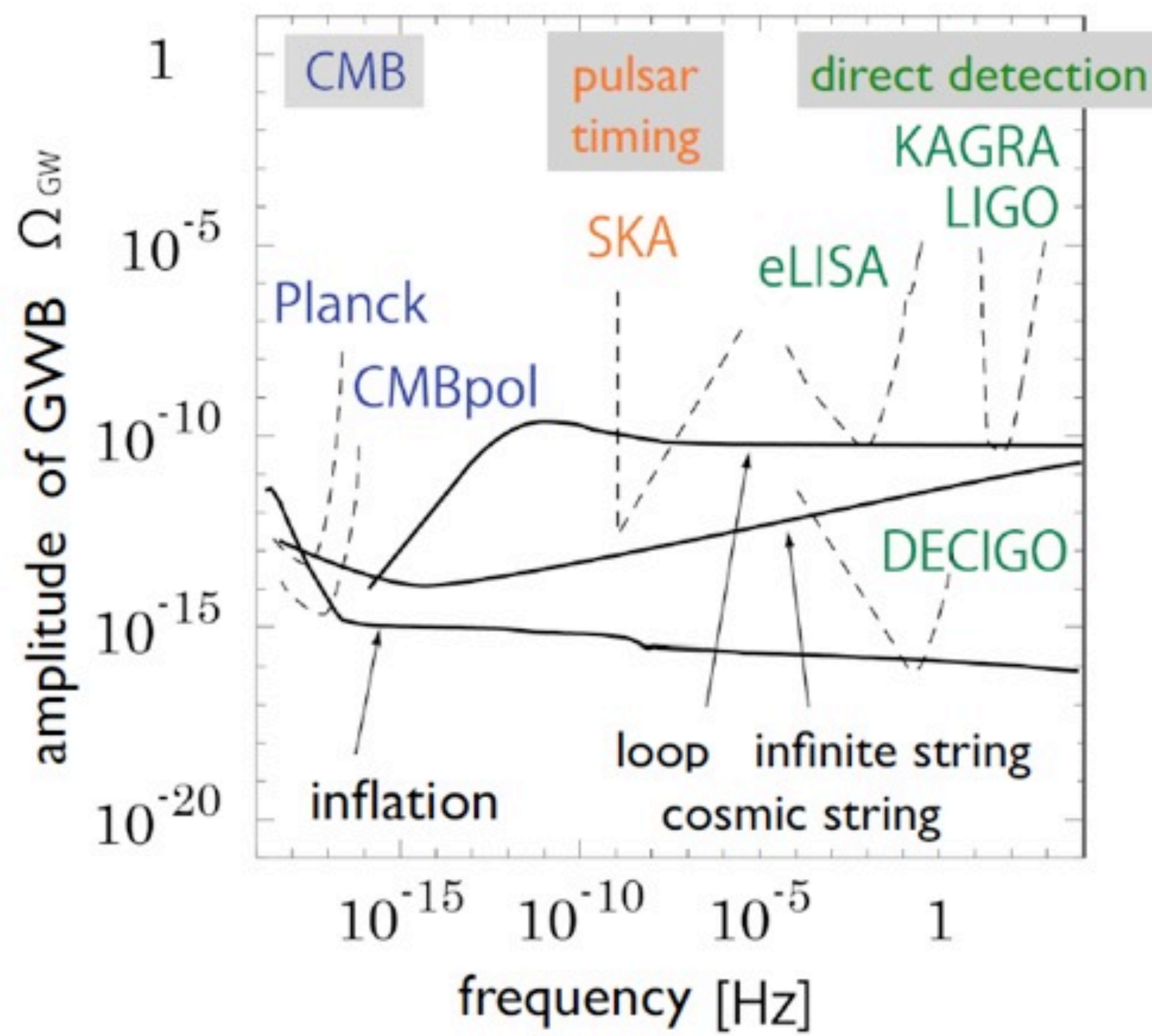


If the likelihood shape is sensitive to the parameter
= easy to estimate the parameter

GWB Observable : Ω_{GW}

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



Predicted constraint on parameters

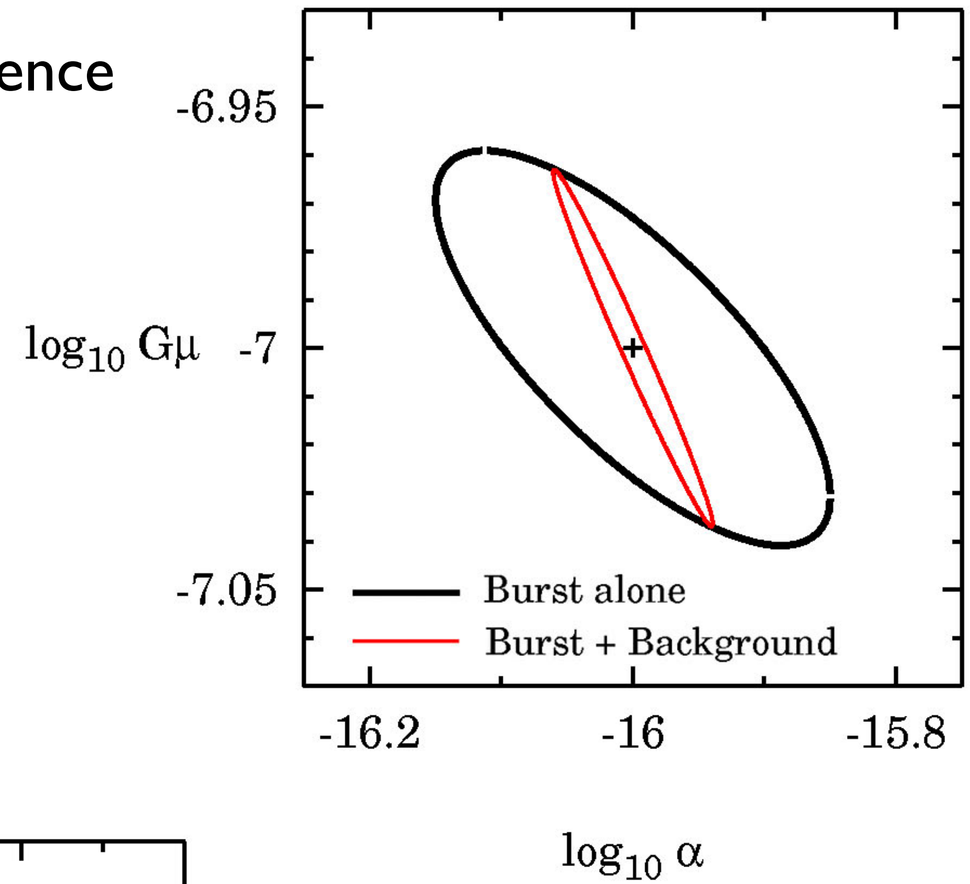
$G\mu = 10^{-7}$, $\alpha = 10^{-16}$, p=1
LIGO 3year

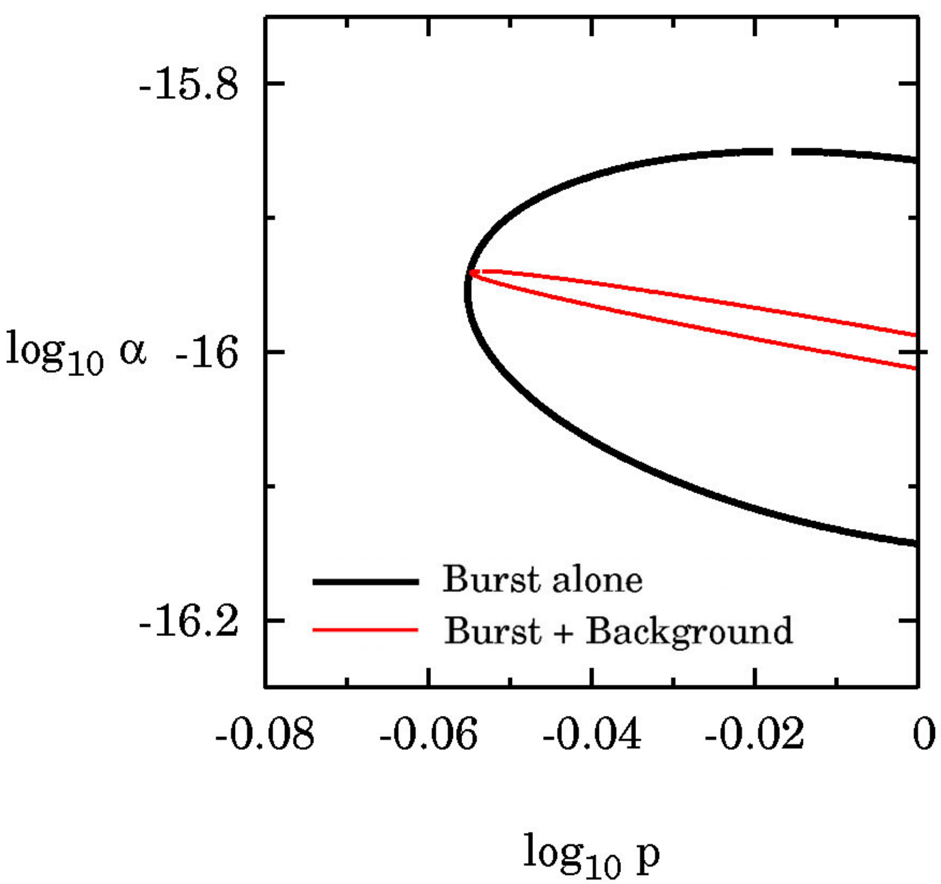
Kuroyanagi et. al. PRD 86, 023503 (2012)

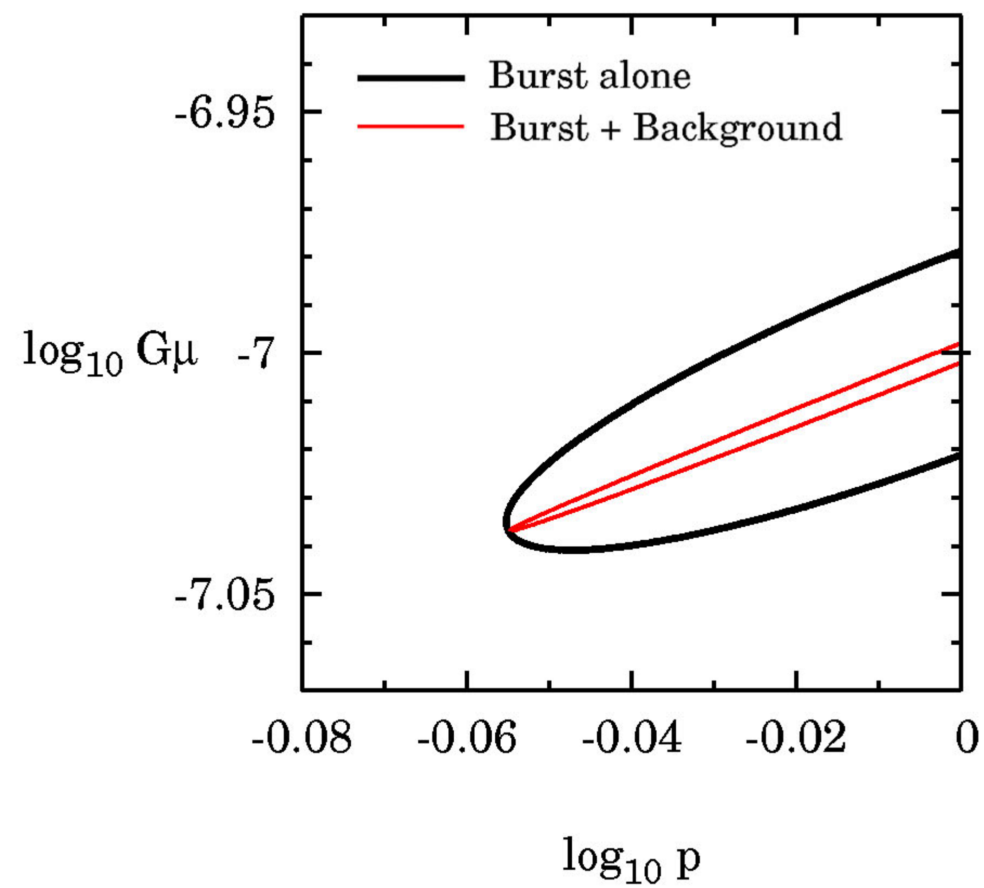
different parameter dependence
= different constraints on
parameters

black : Burst only

red : Burst + GWB







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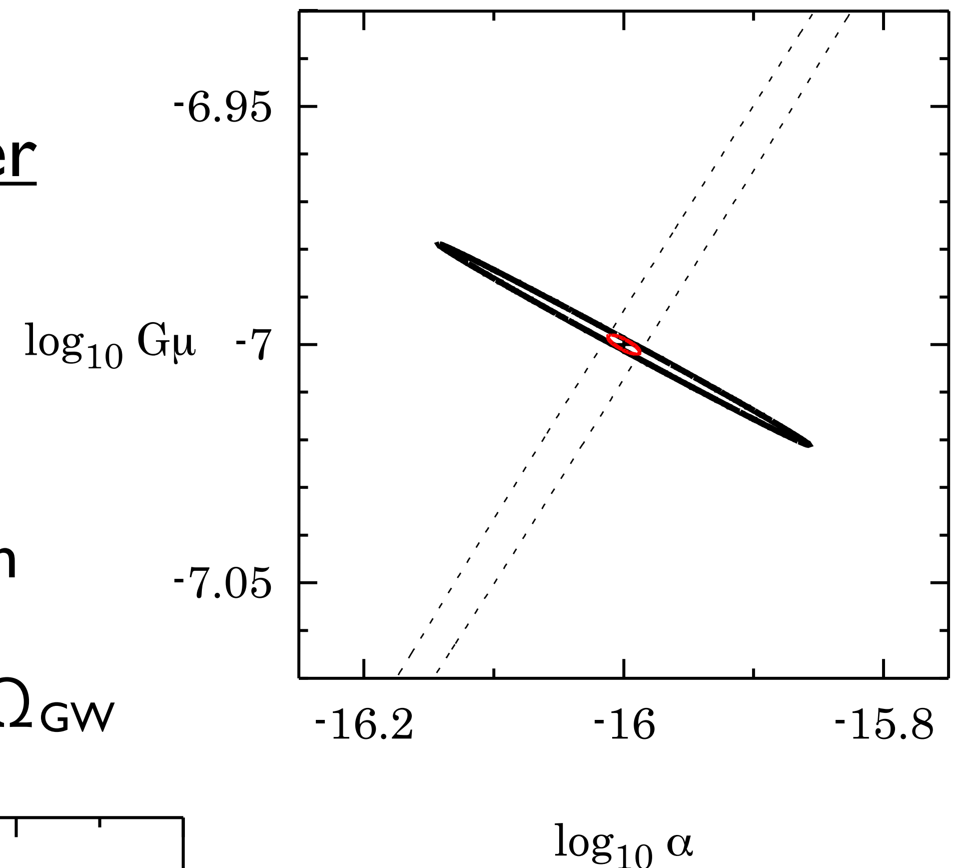
black ：Burst only

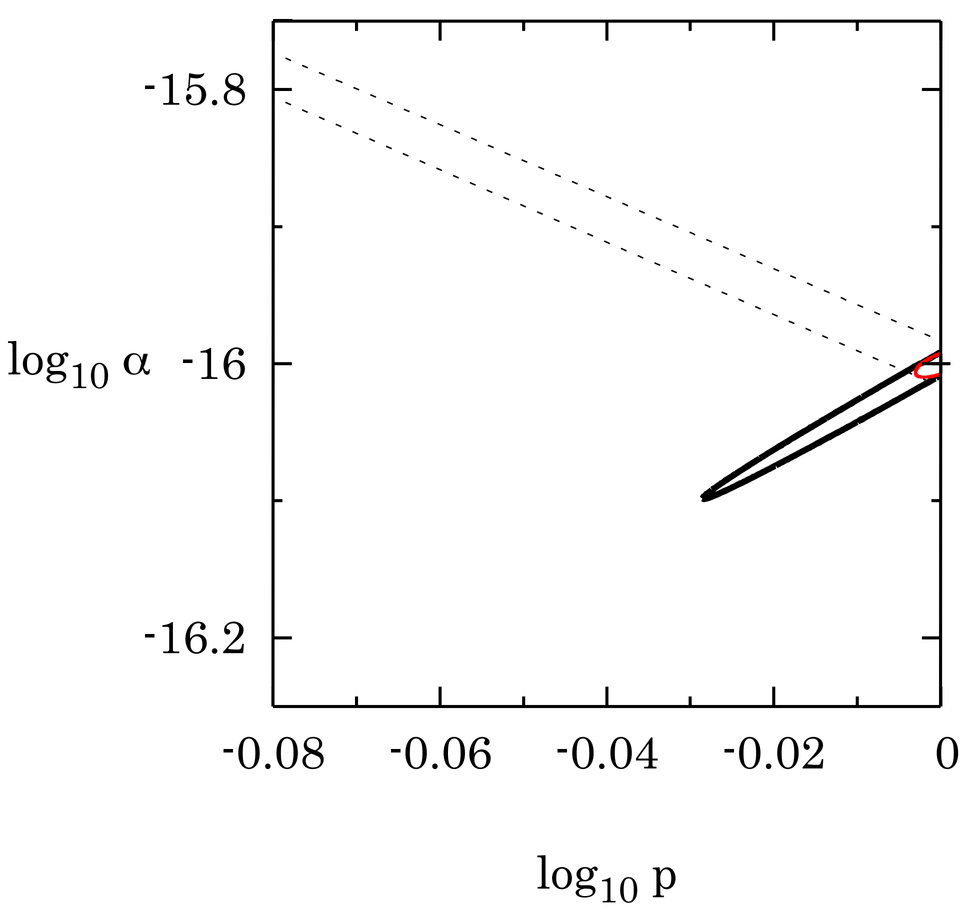
dotted: GWB only

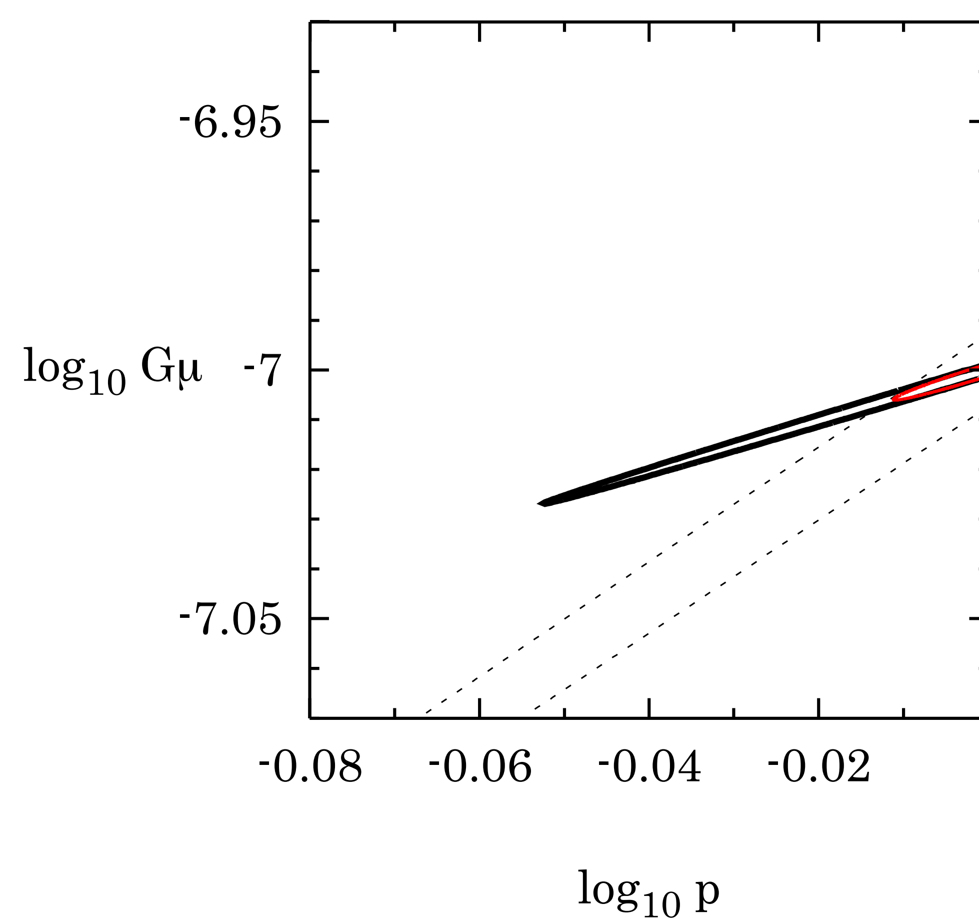
red：Burst + GWB

<u>Before marginalized over</u>

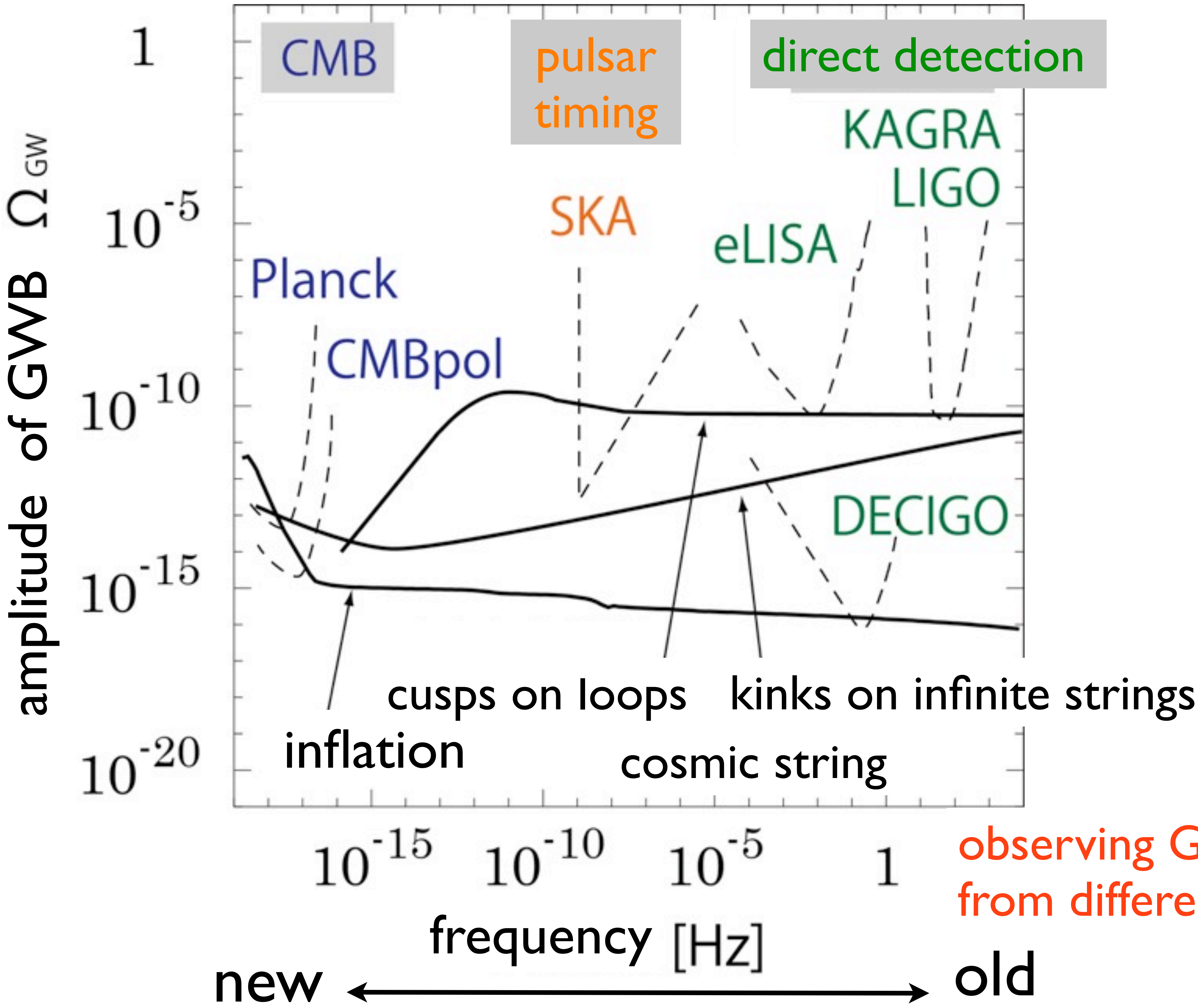


Strong degeneracy seen in constraint from GWB since the observable is only Ω_{GW}





Constraints from other experiments?



observing GWs
from different epochs

CMB signals

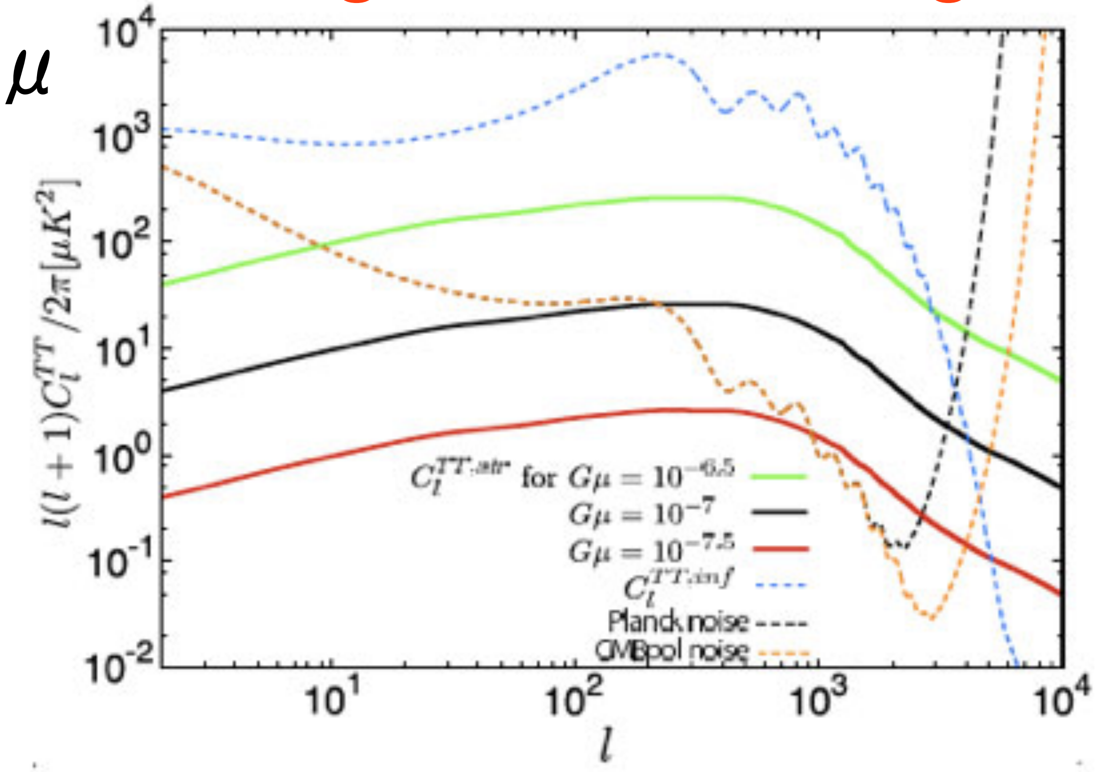
Temperature

string motion ＋ lensing

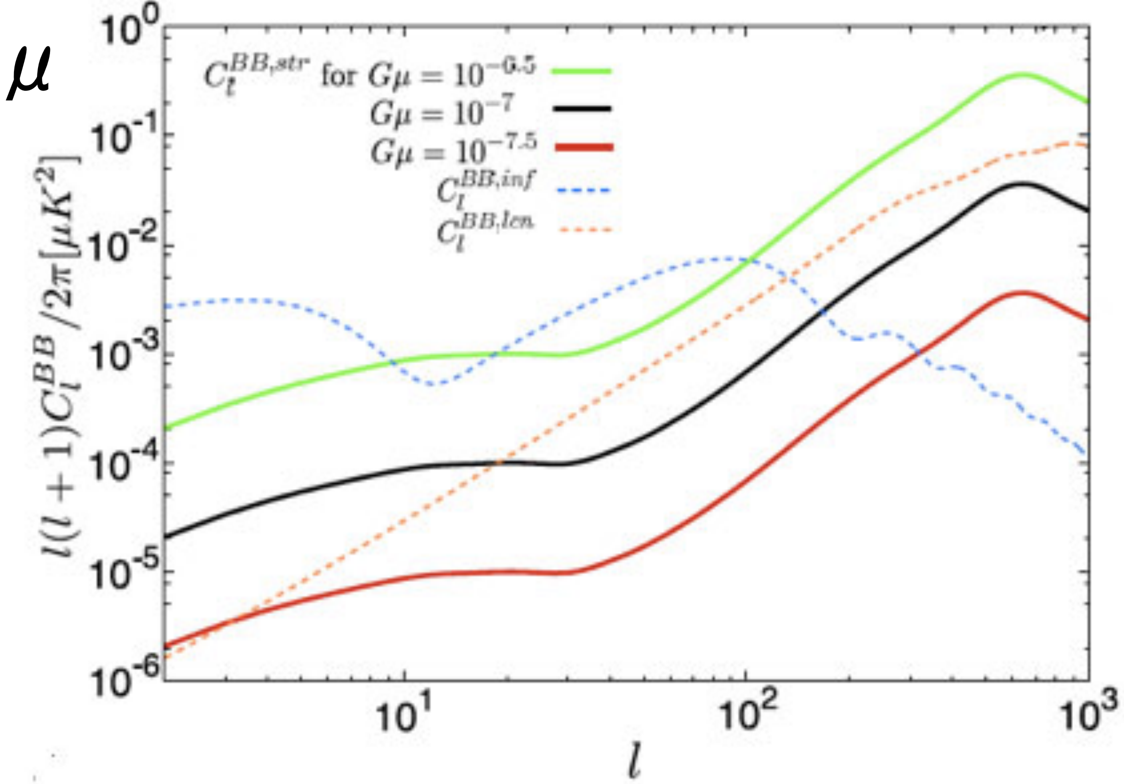
B-mode

Note: lensing>GW

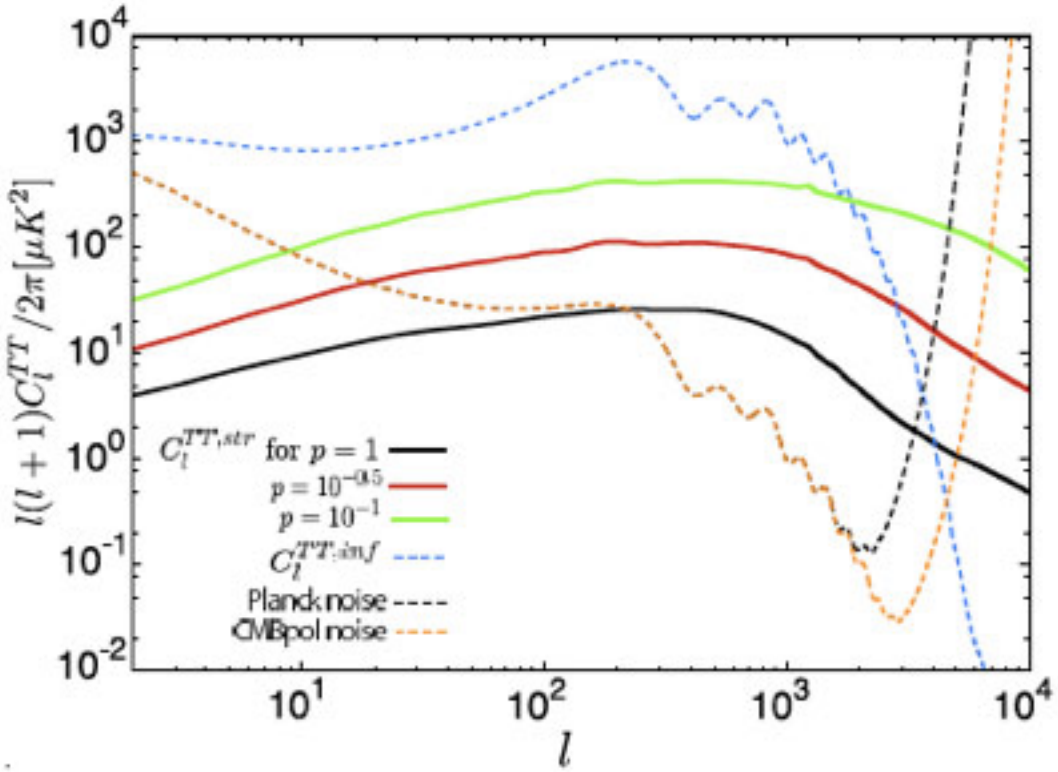
G μ



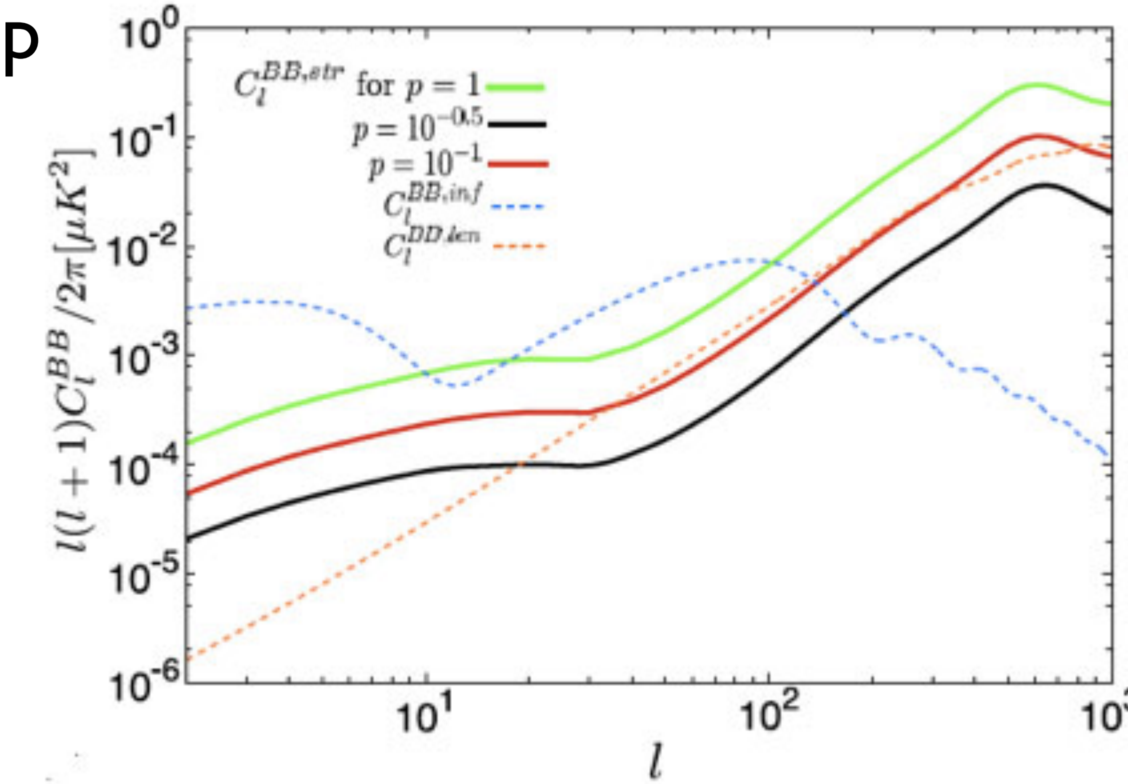
G μ



P



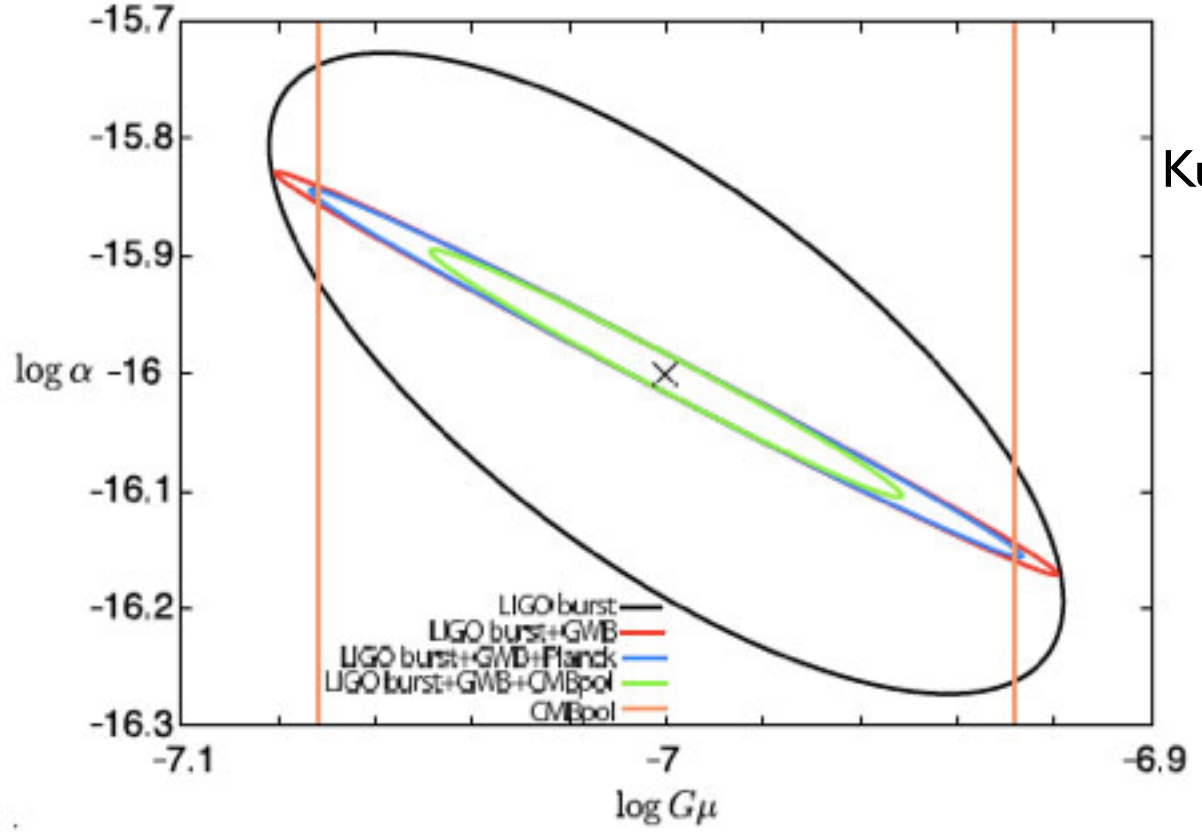
P



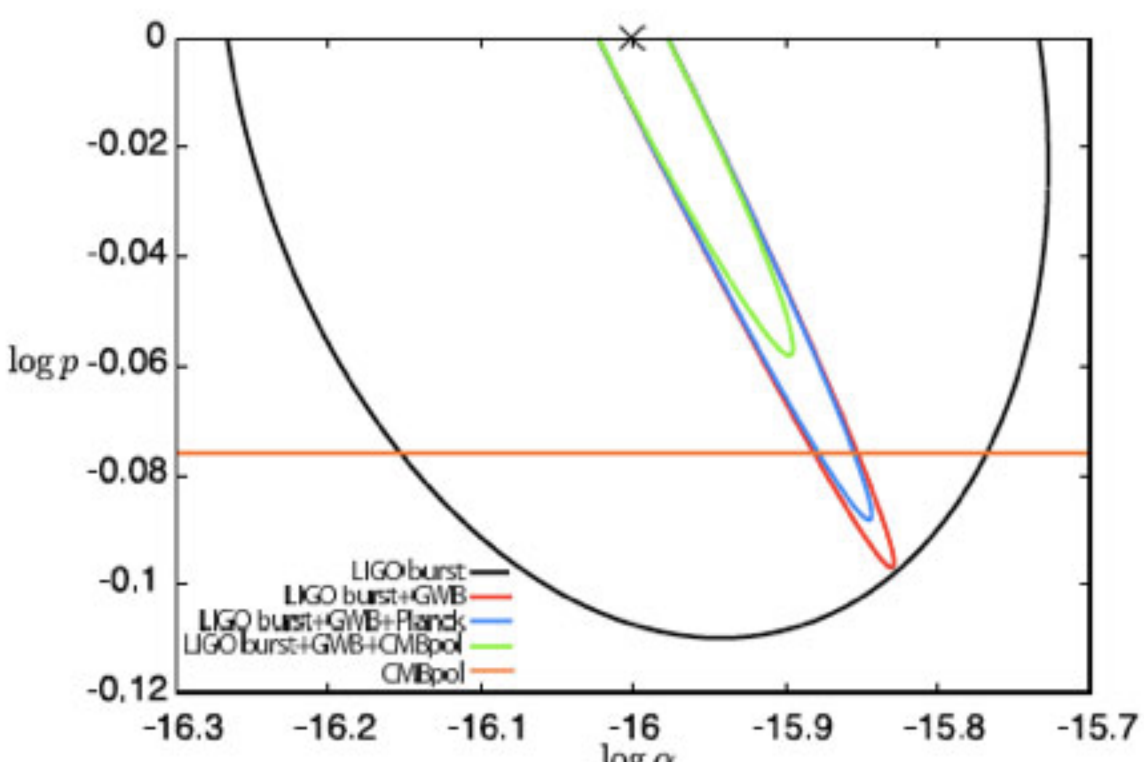
If we combine CMB constraints...

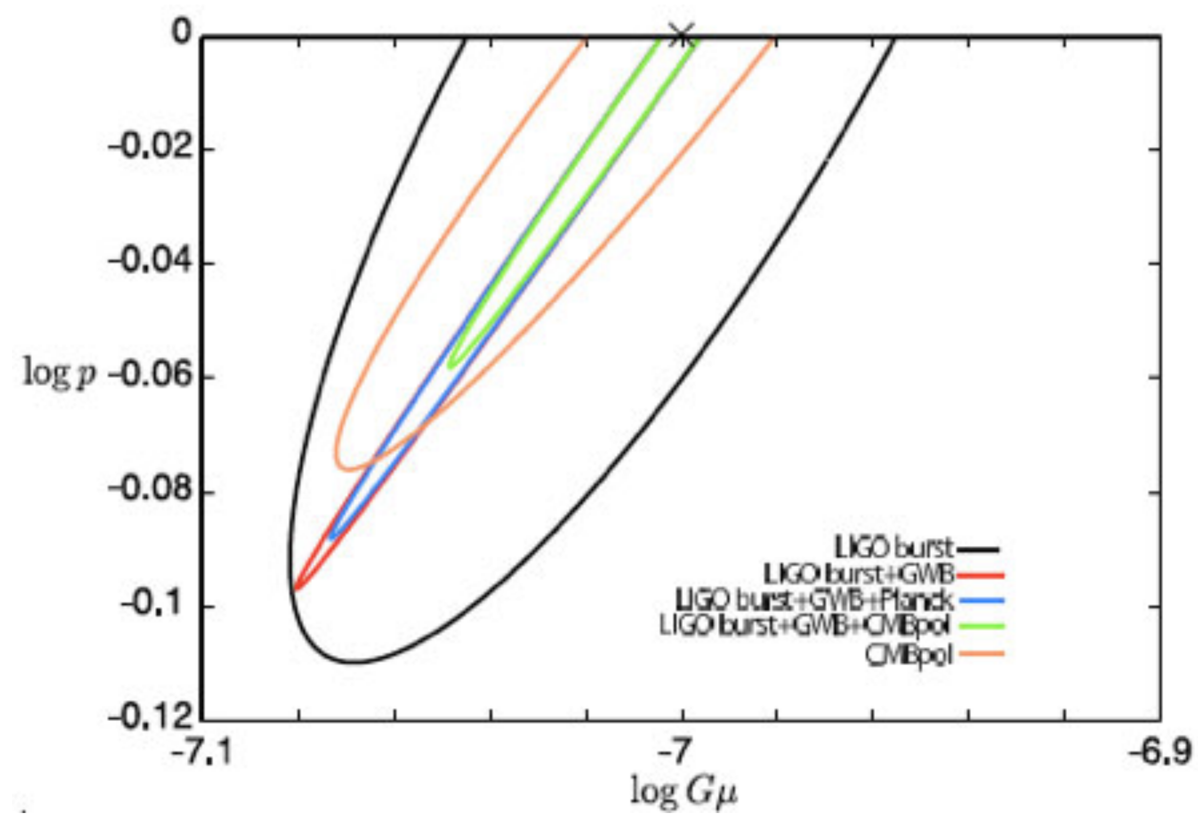
$G\mu = 10^{-7}$, $\alpha = 10^{-16}$, p=1
LIGO 3year
+ CMB B-mode

Kuroyanagi et. al. PRD 87, 023522 (2013)

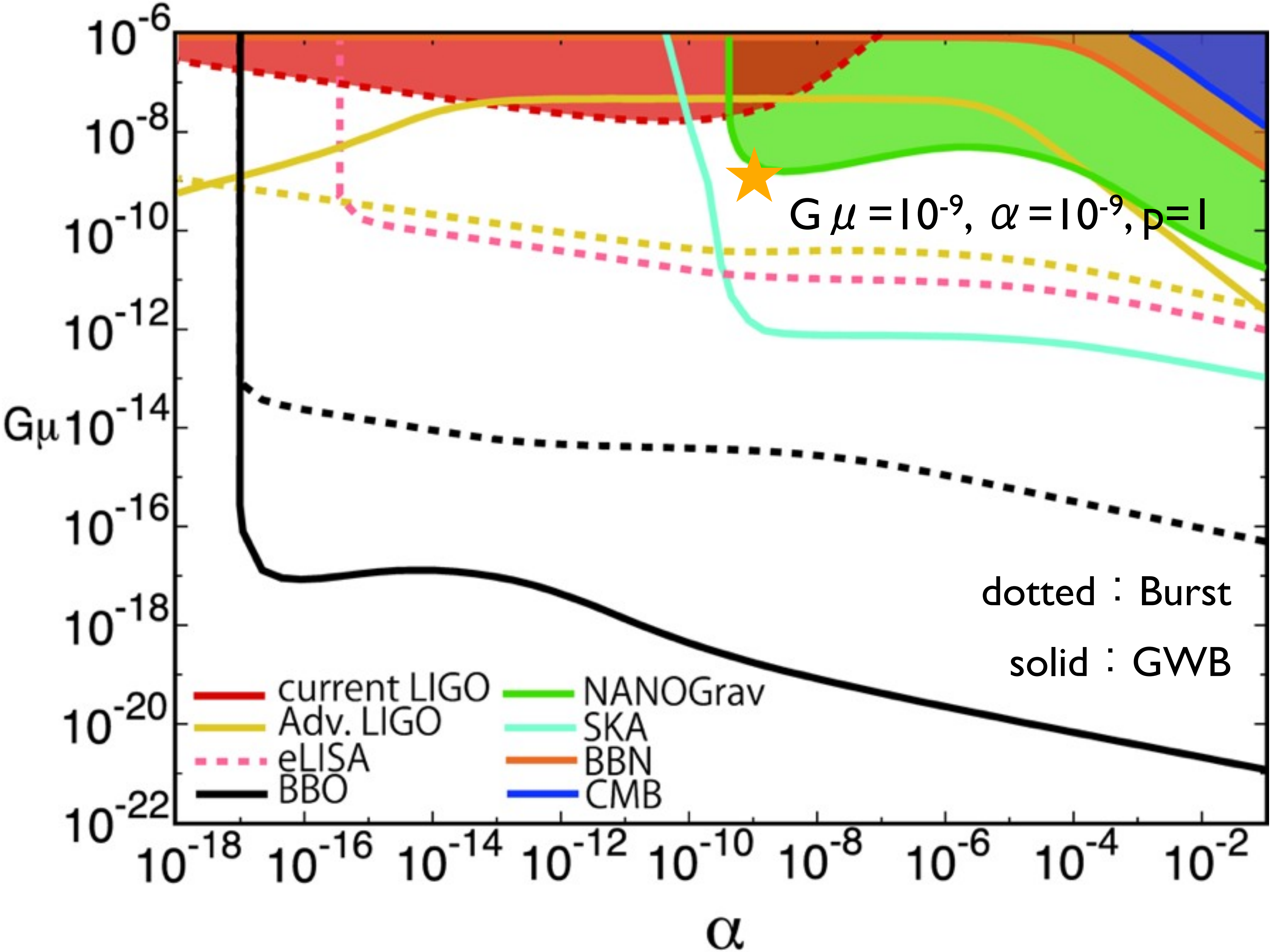


black : LIGO Burst only
red : LIGO Burst + GWB
blue: LIGO +Planck
green: LIGO+CMBpol
orange: CMB pol only





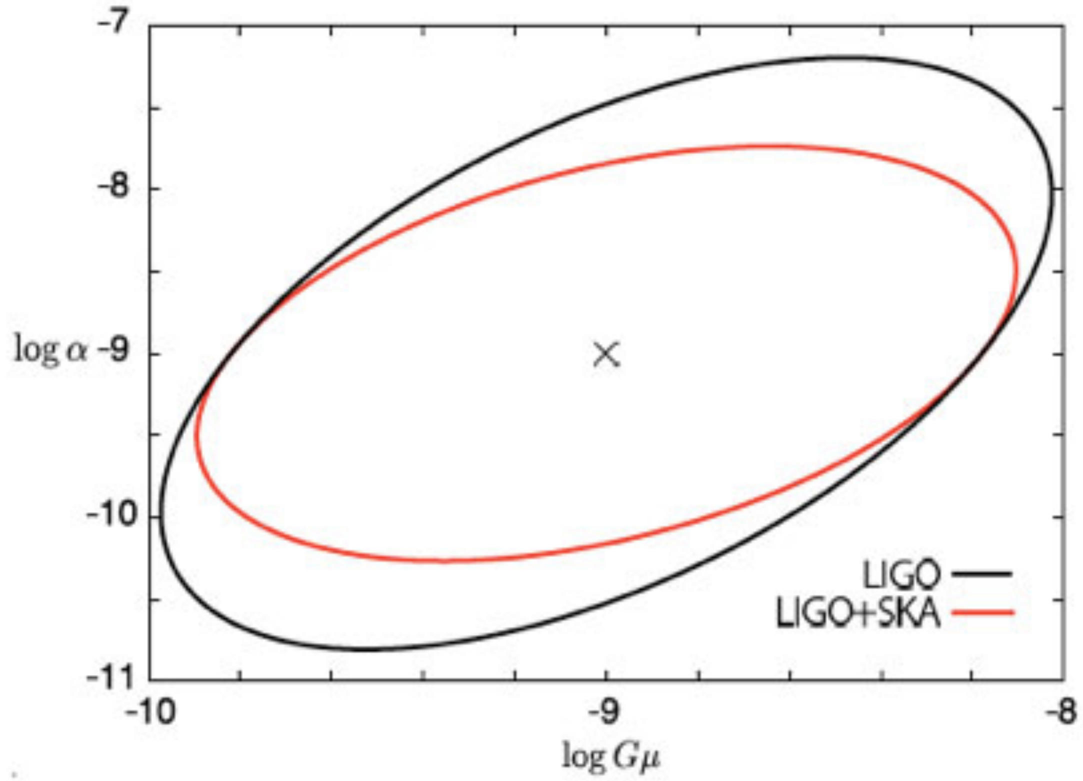
Pulsar timing (SKA) + Advanced-LIGO burst search

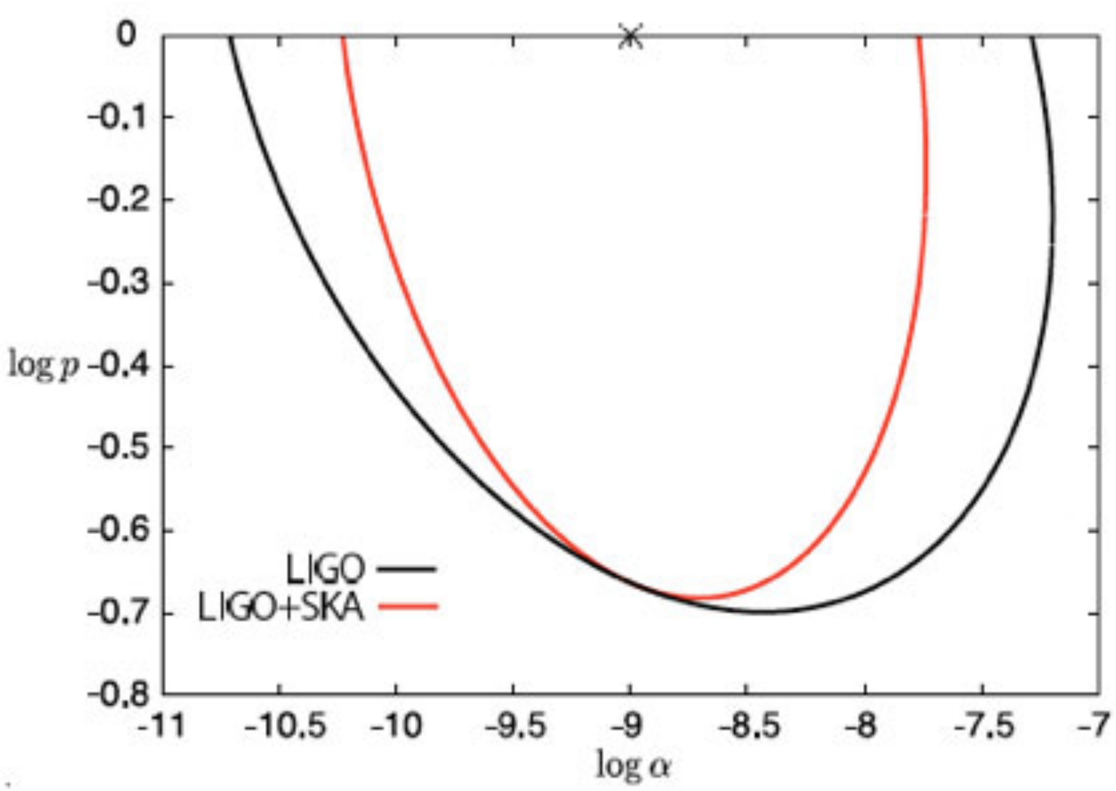


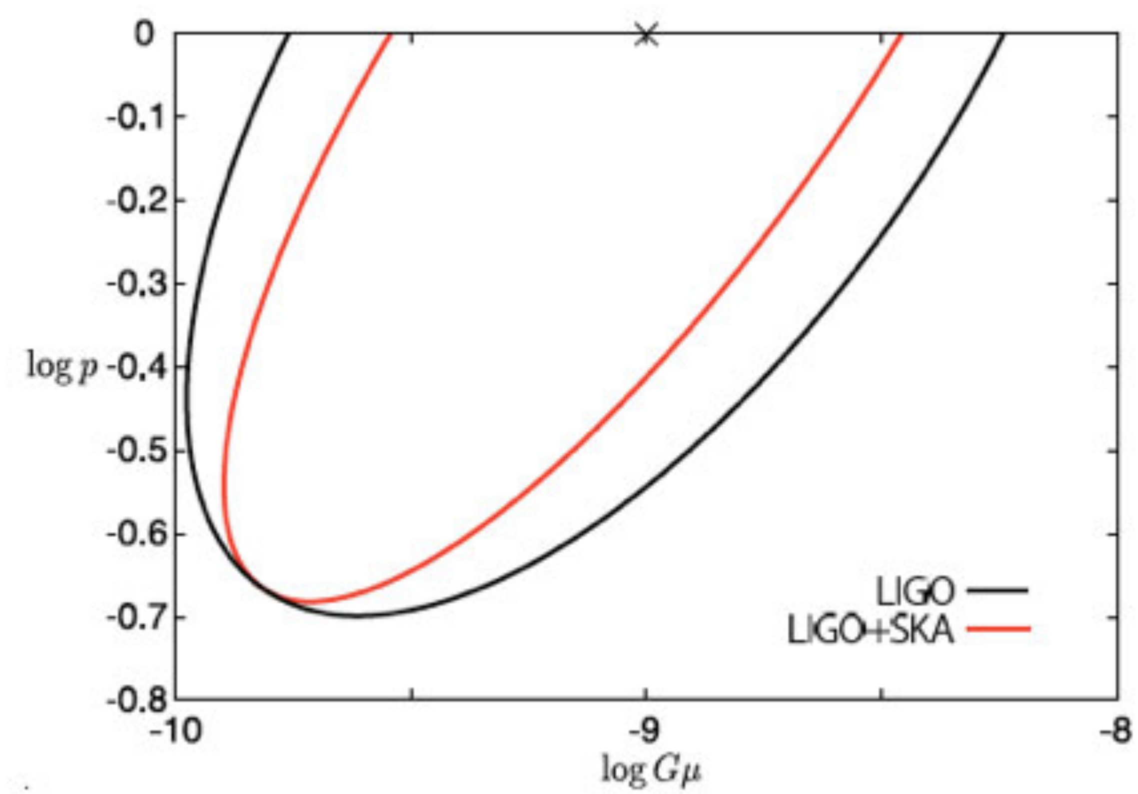
Direct detection + Pulsar timing

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

Kuroyanagi et. al. PRD 87, 023522 (2013)



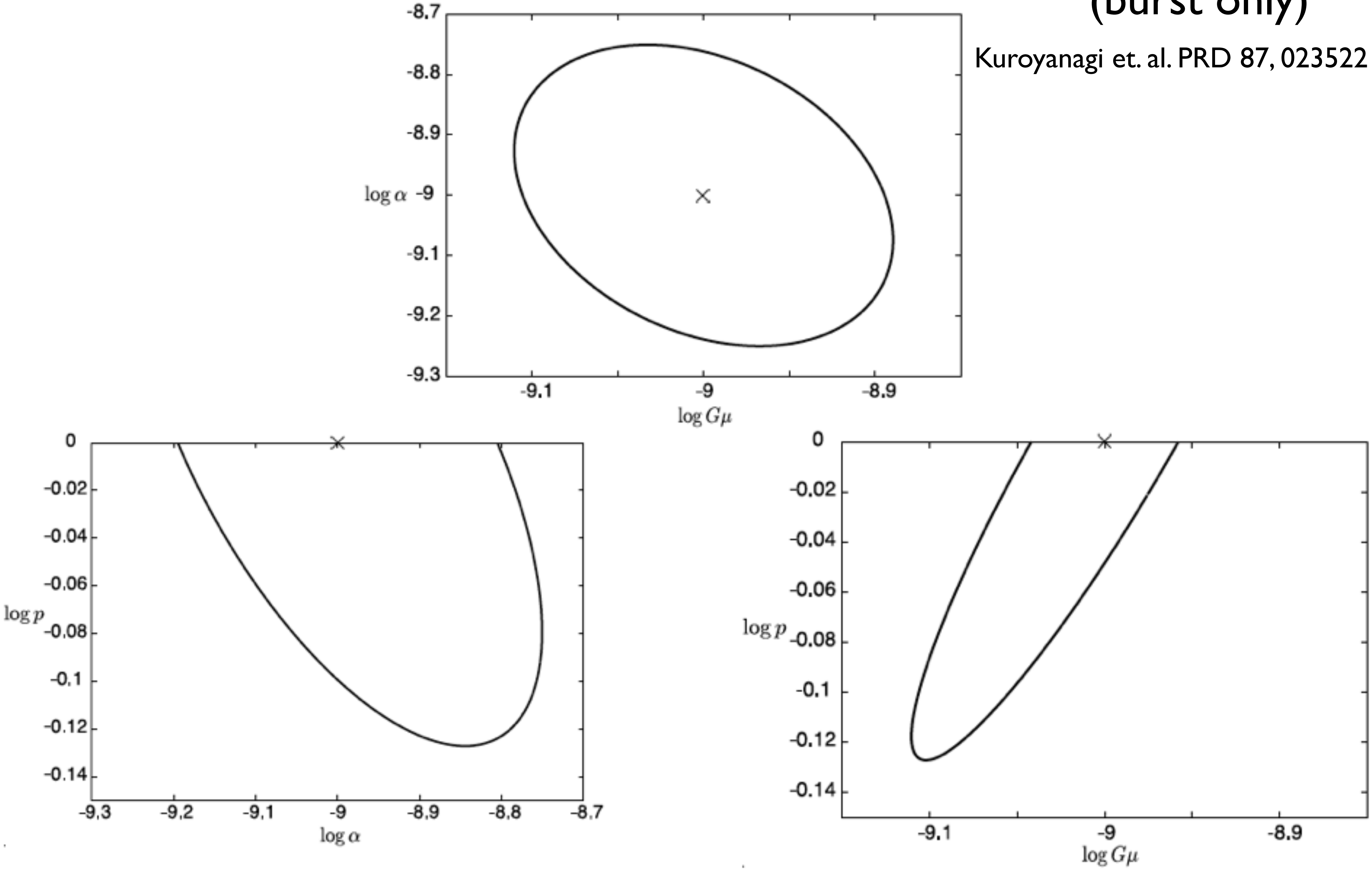




Parameter constraint by eLISA

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

Kuroyanagi et. al. PRD 87, 023522 (2013)



Summary

- Future GW experiments can be a powerful tool to probe 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 probe cosmic strings.