Gravitational waves from Cosmic strings

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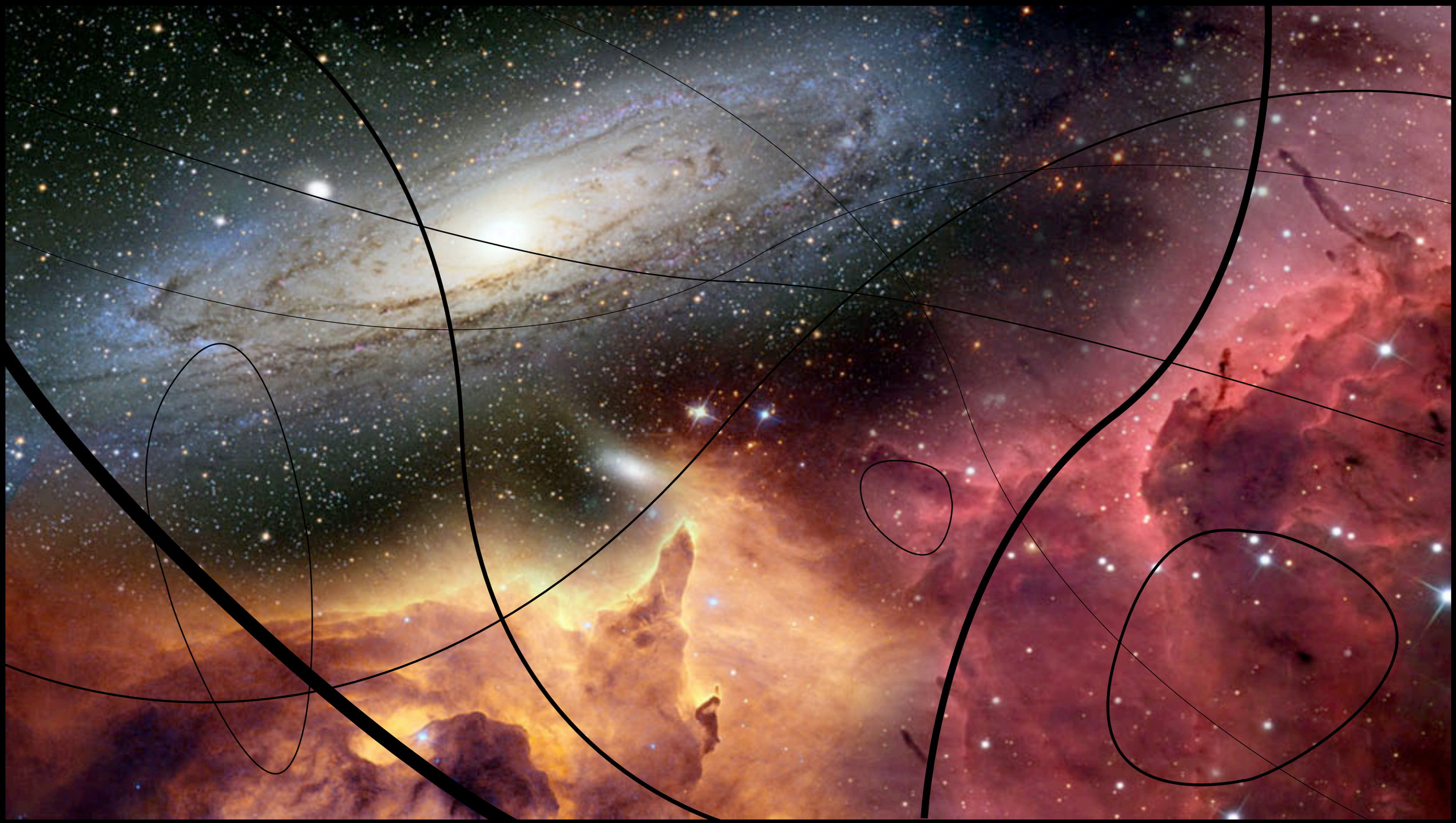
References

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

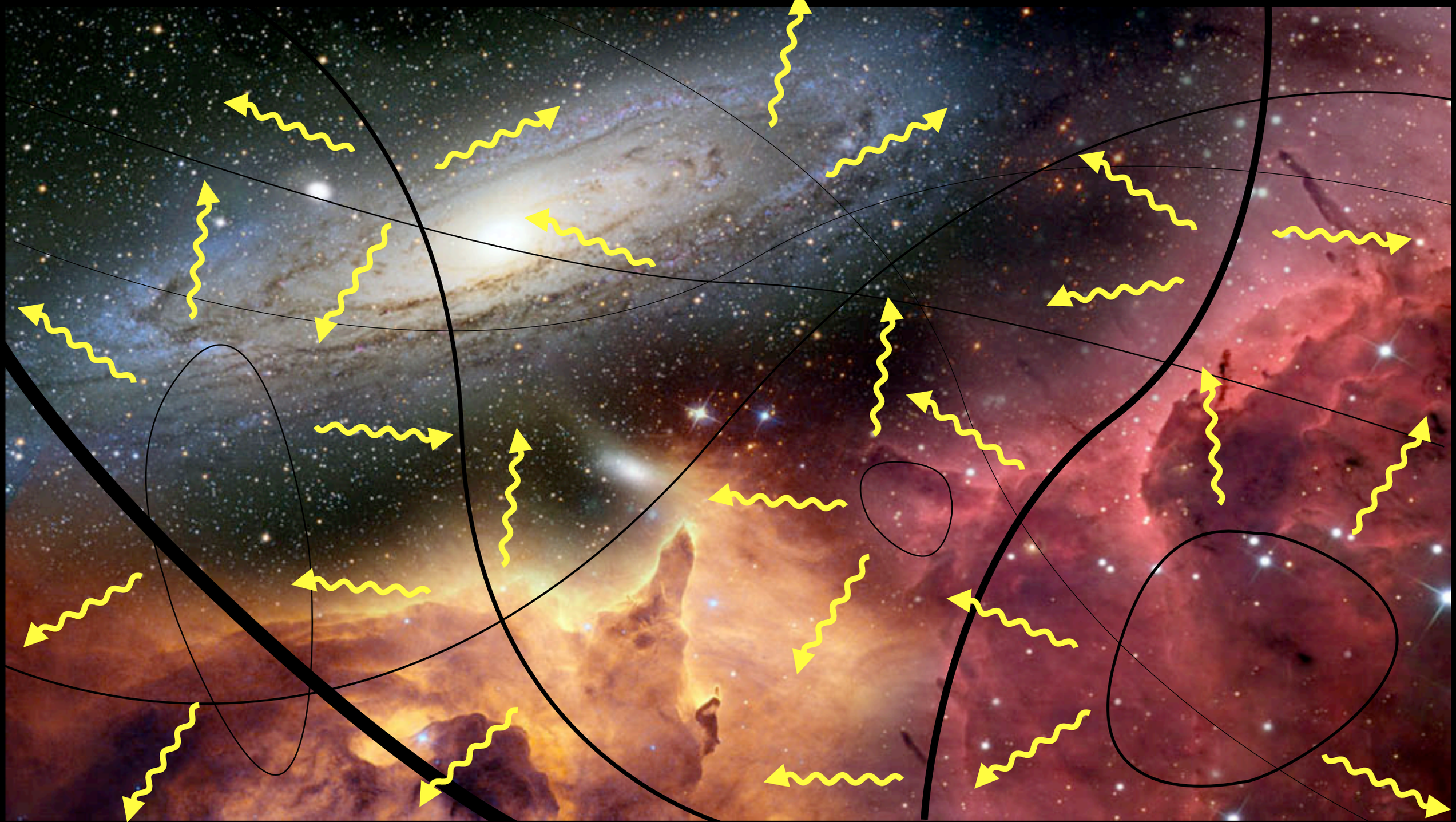
Cosmic string ?

HEAVY, LONG and FAST strings floating in the Universe



Cosmic string ?

emits gravitational waves!



Generation mechanism

1. Phase transition in the early Universe

→ Grand unification theory

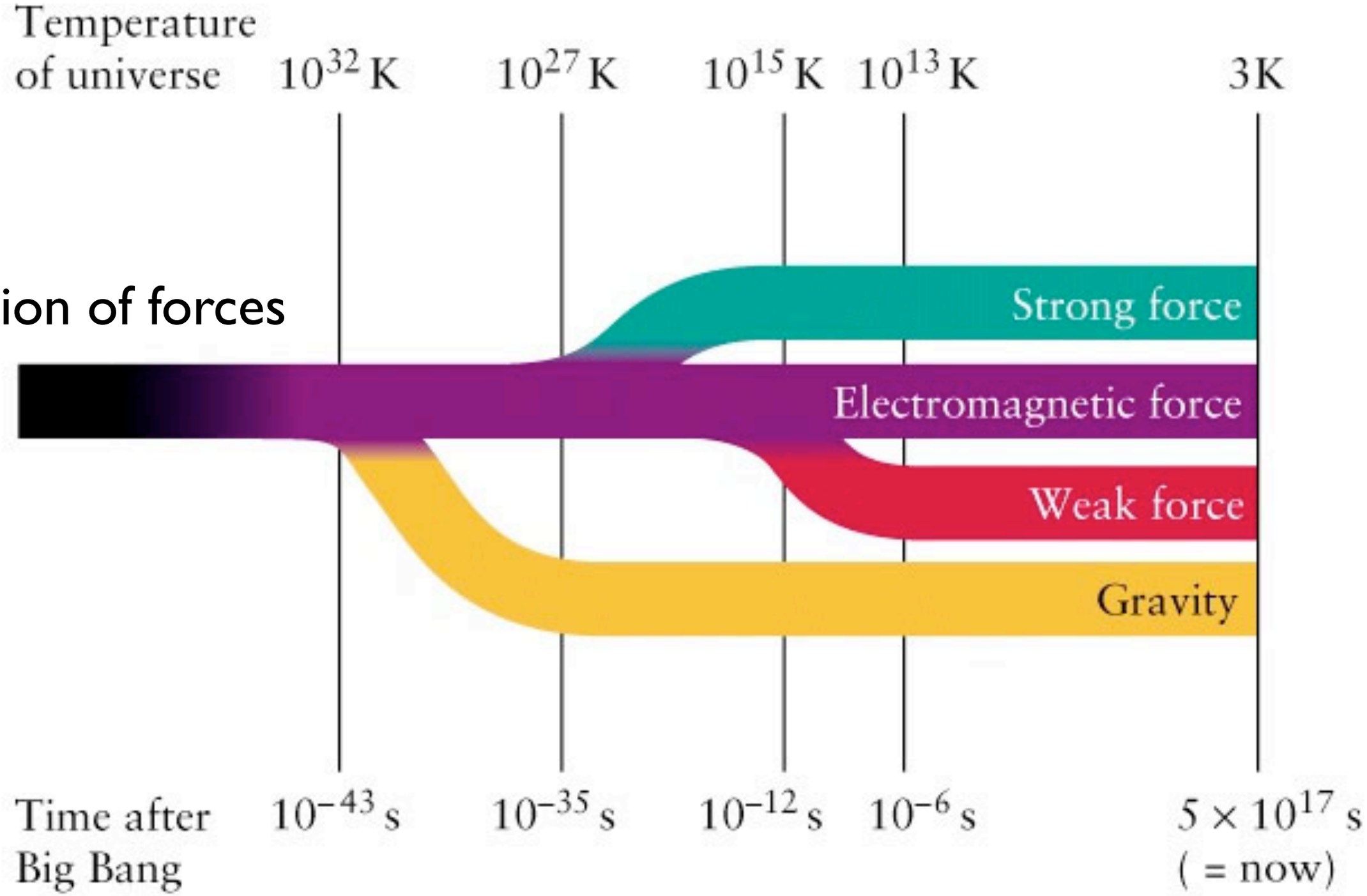
2. Cosmic superstrings

→ Superstring theory

Cosmic strings provides insight into fundamental physics

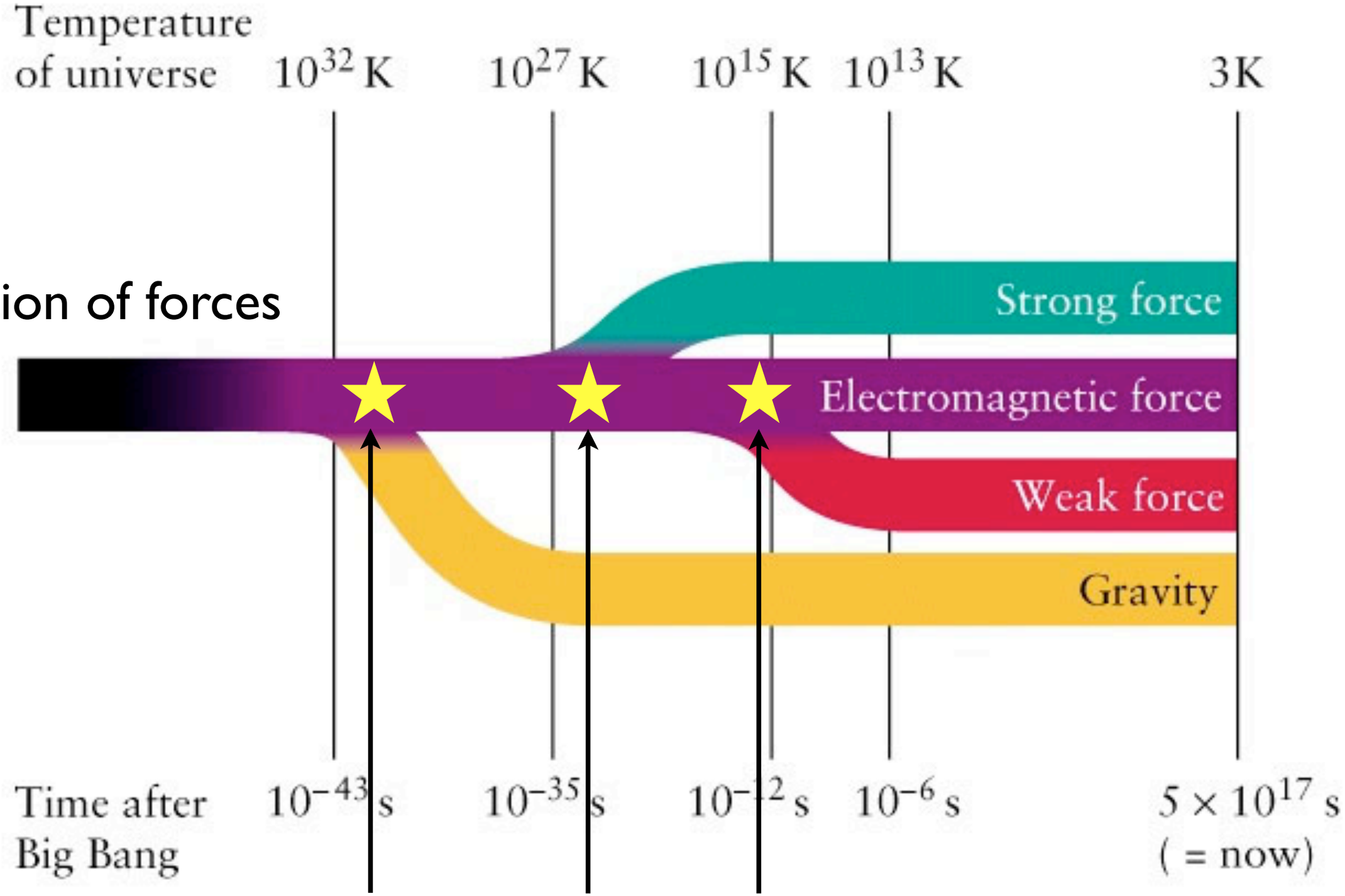
Grand unification theory

Unification of forces



Grand unification theory

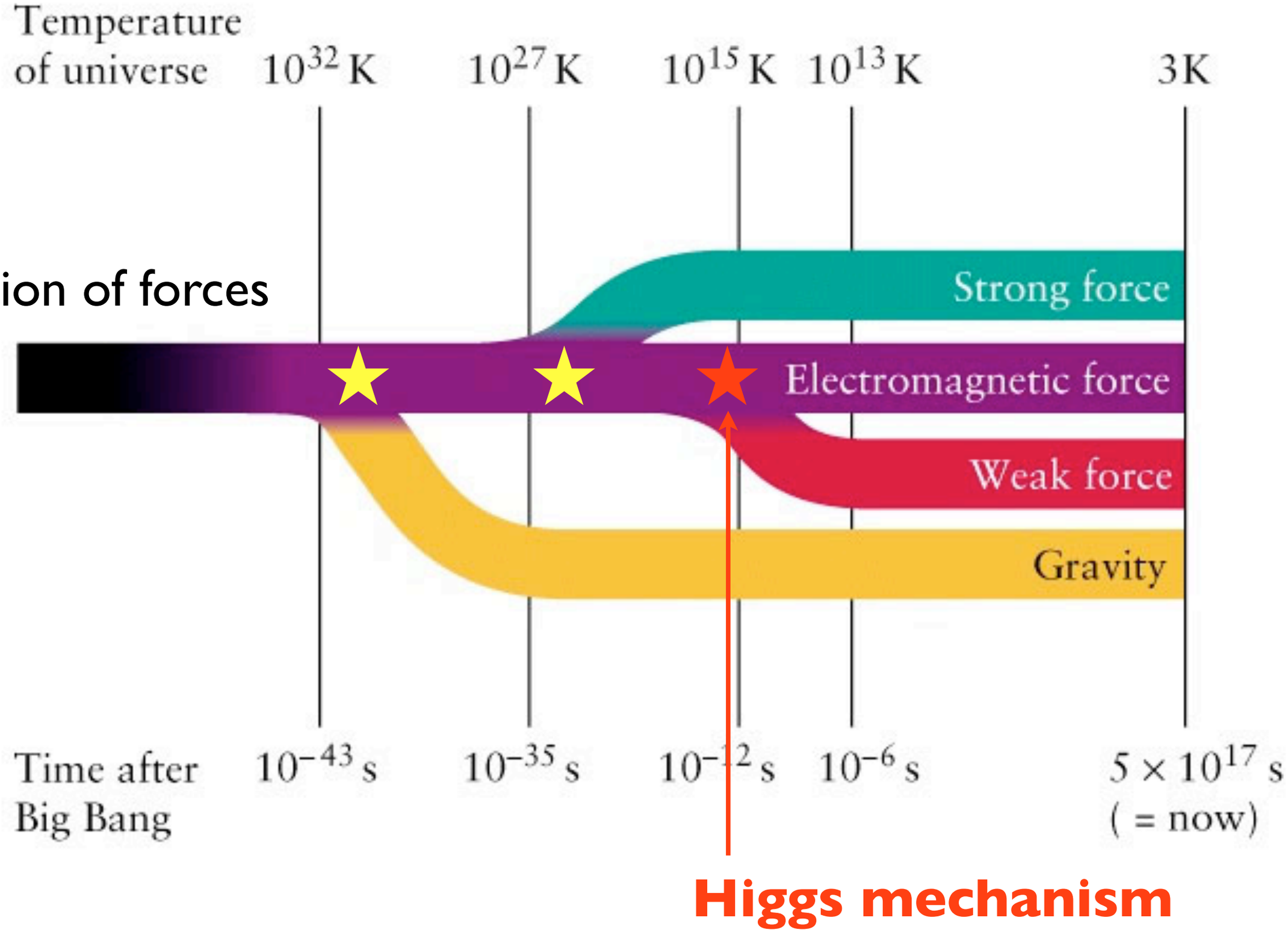
Unification of forces



The Universe has experienced phase transitions!

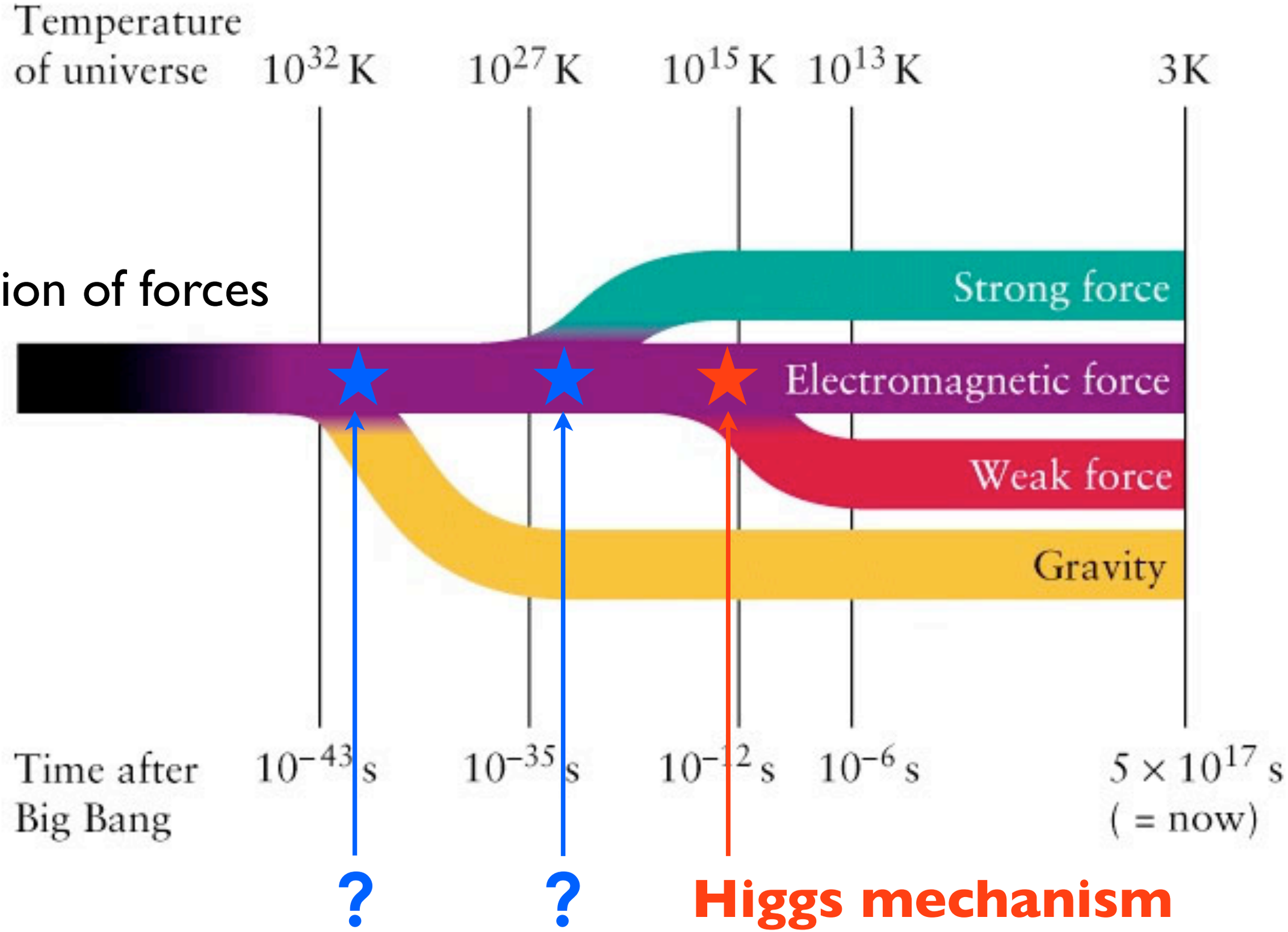
Grand unification theory

Unification of forces



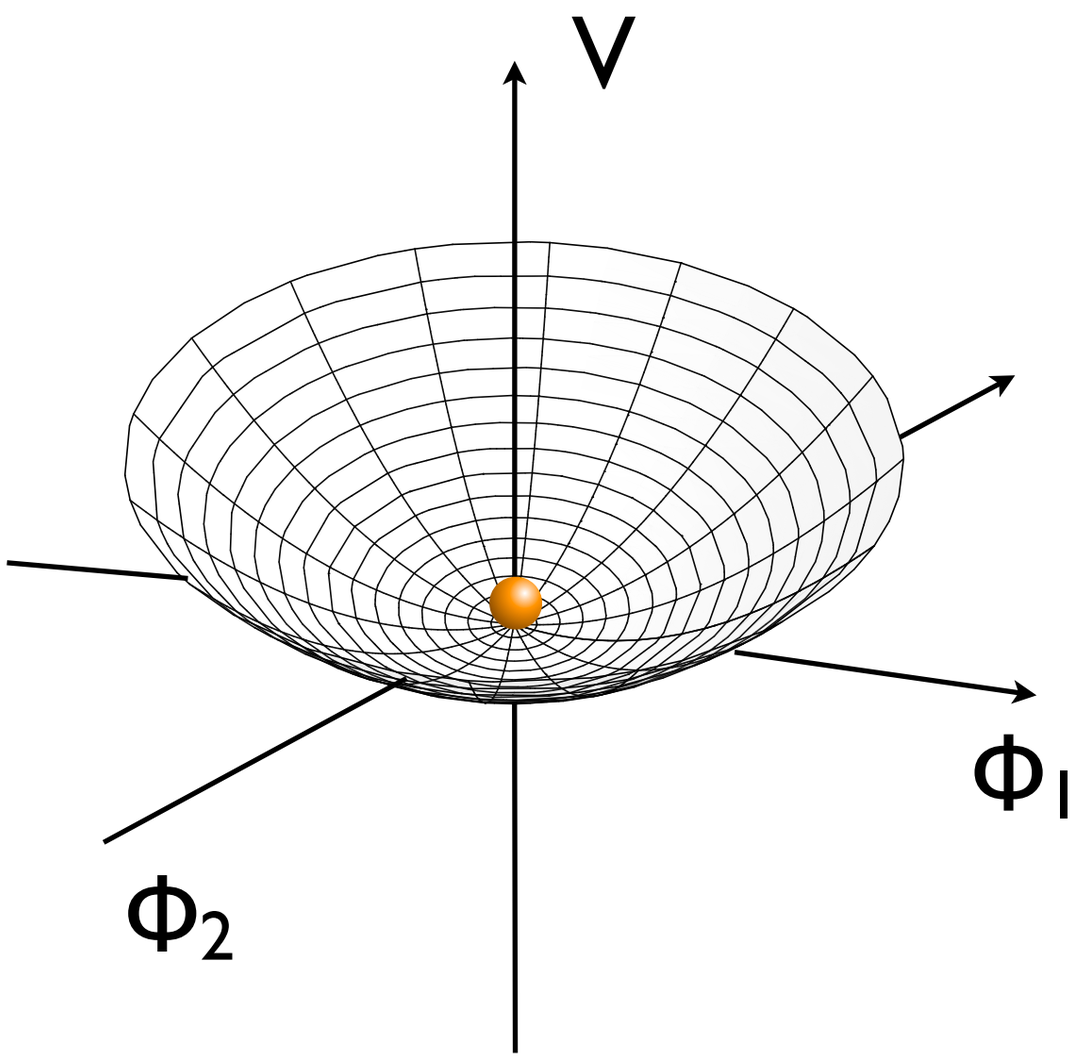
Grand unification theory

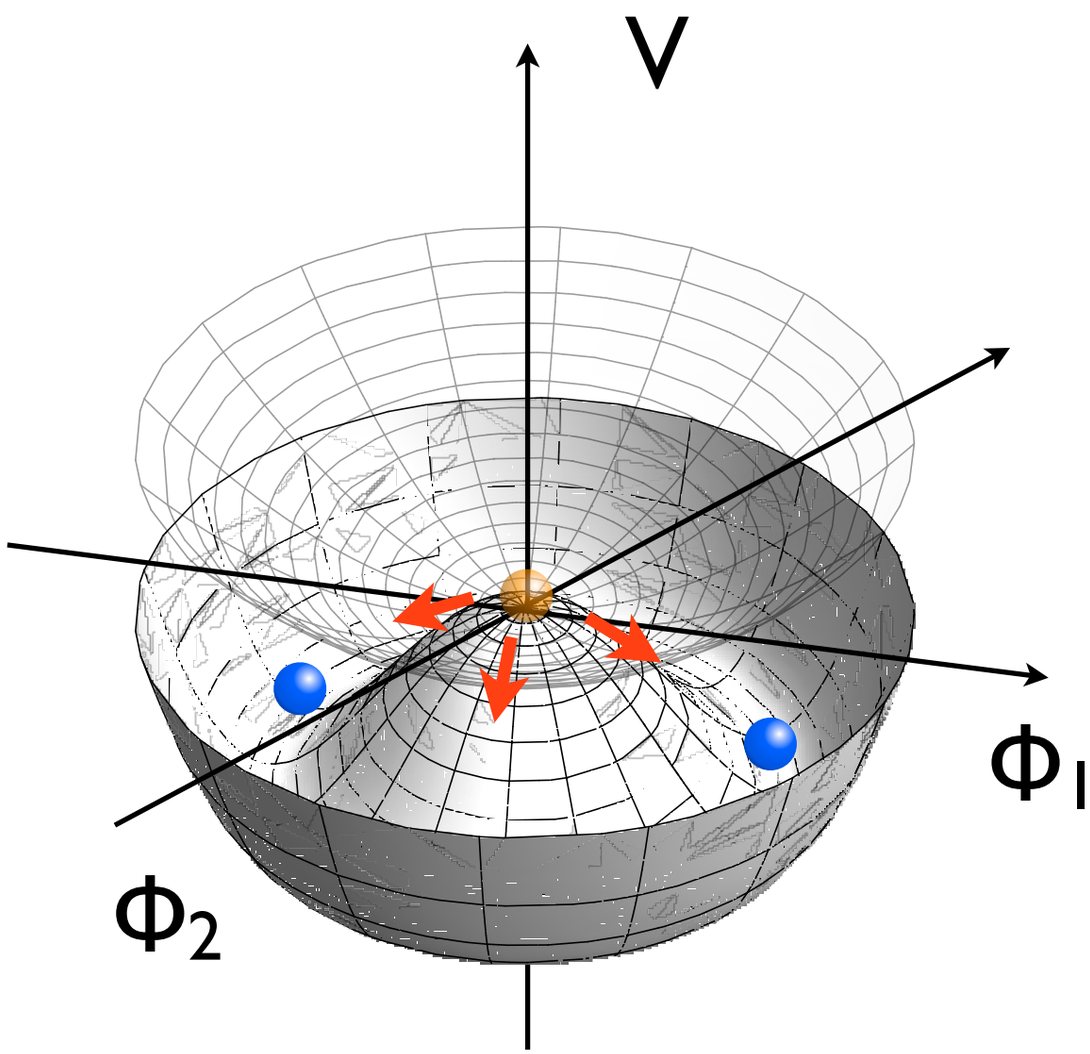
Unification of forces



Phase transition in the early Universe

Symmetry breaking phase transition

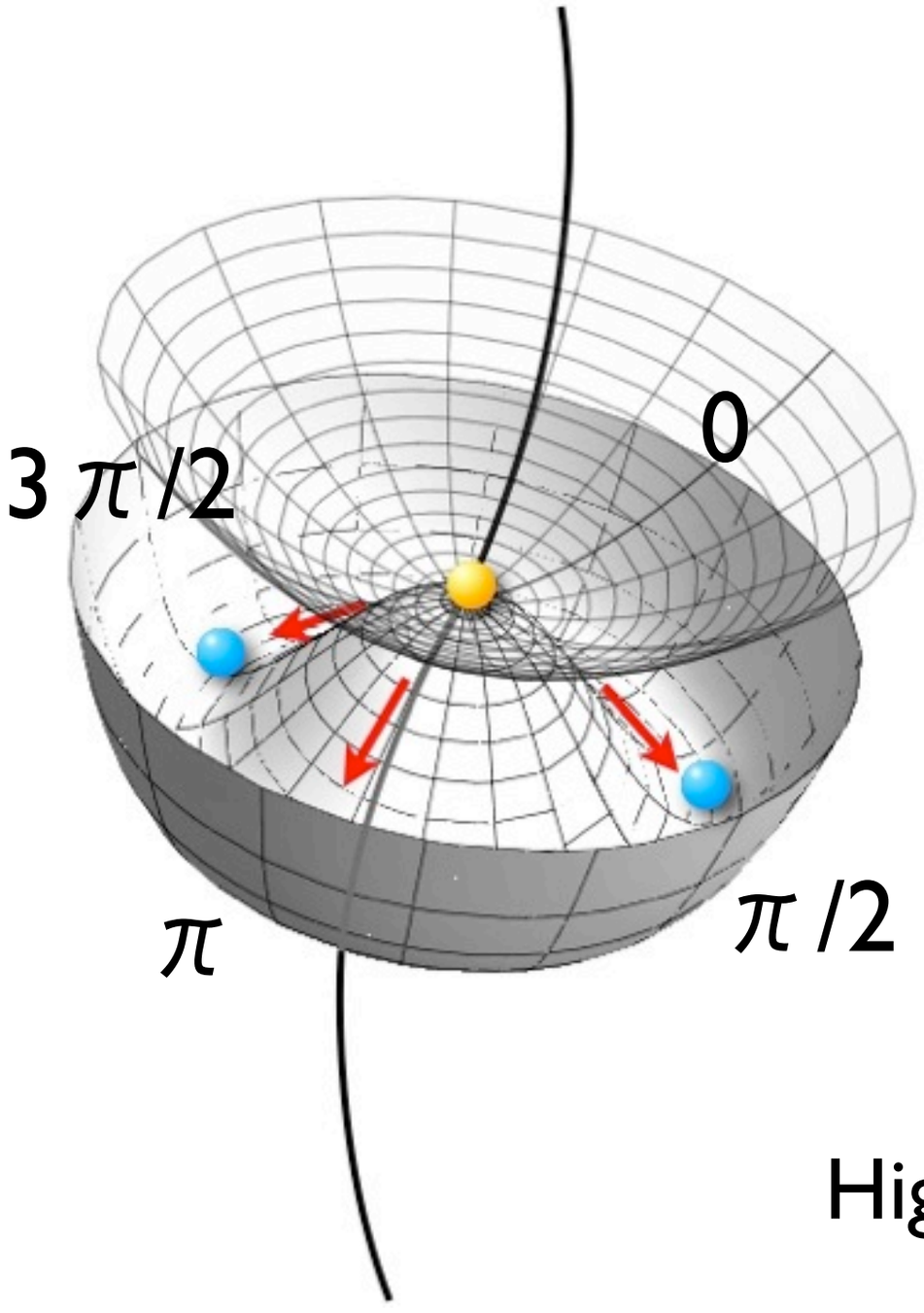


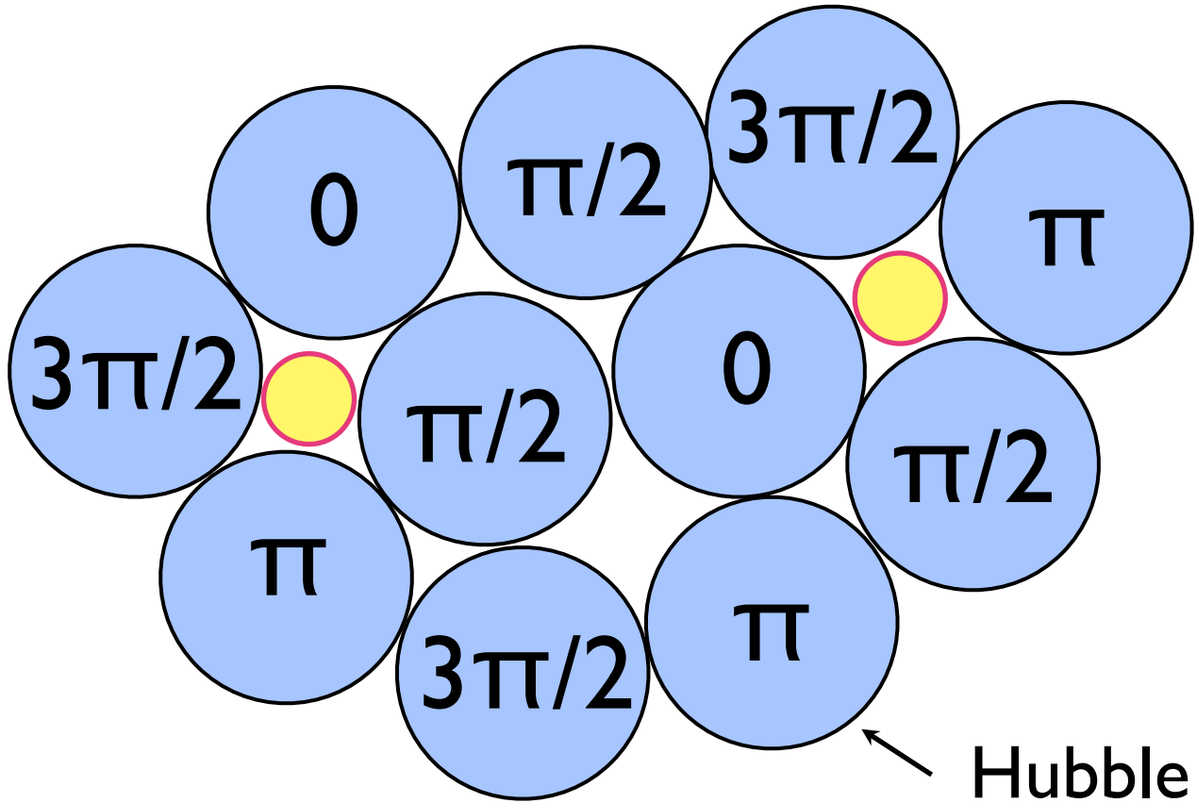


Vacuum energy: high

Vacuum energy: low

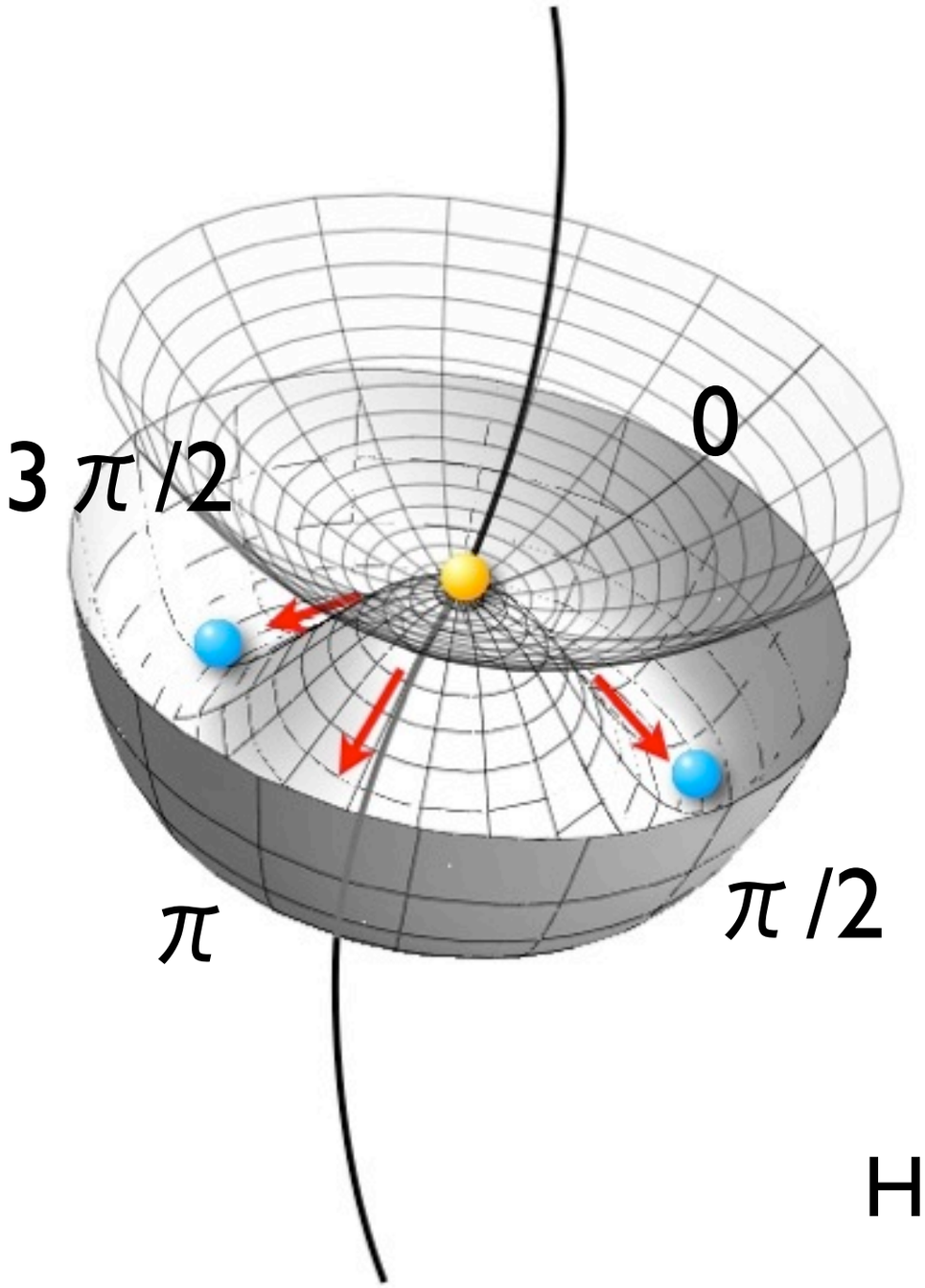
Generation mechanism 1: phase transition

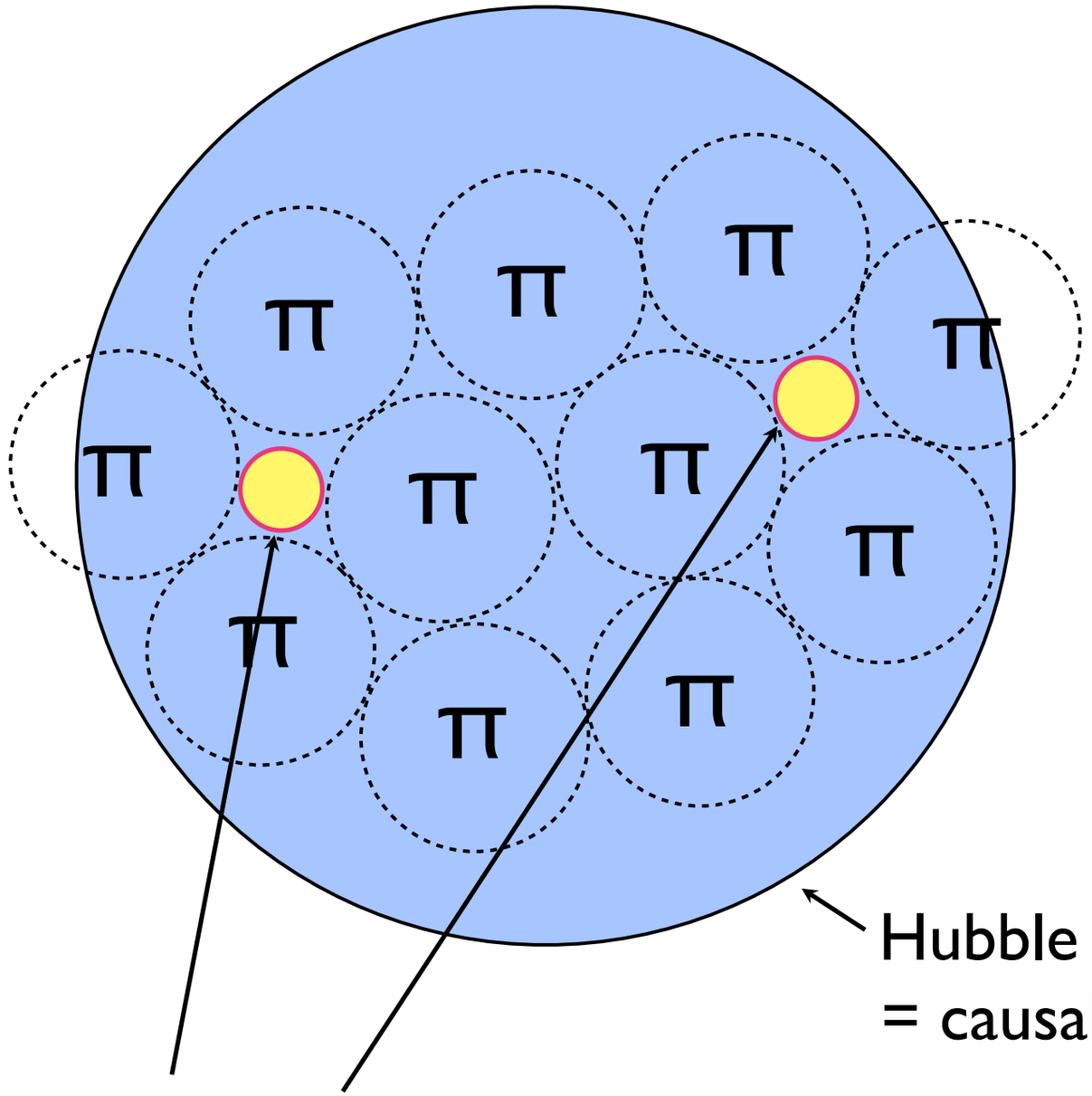




High energy vacuum remains at the center!

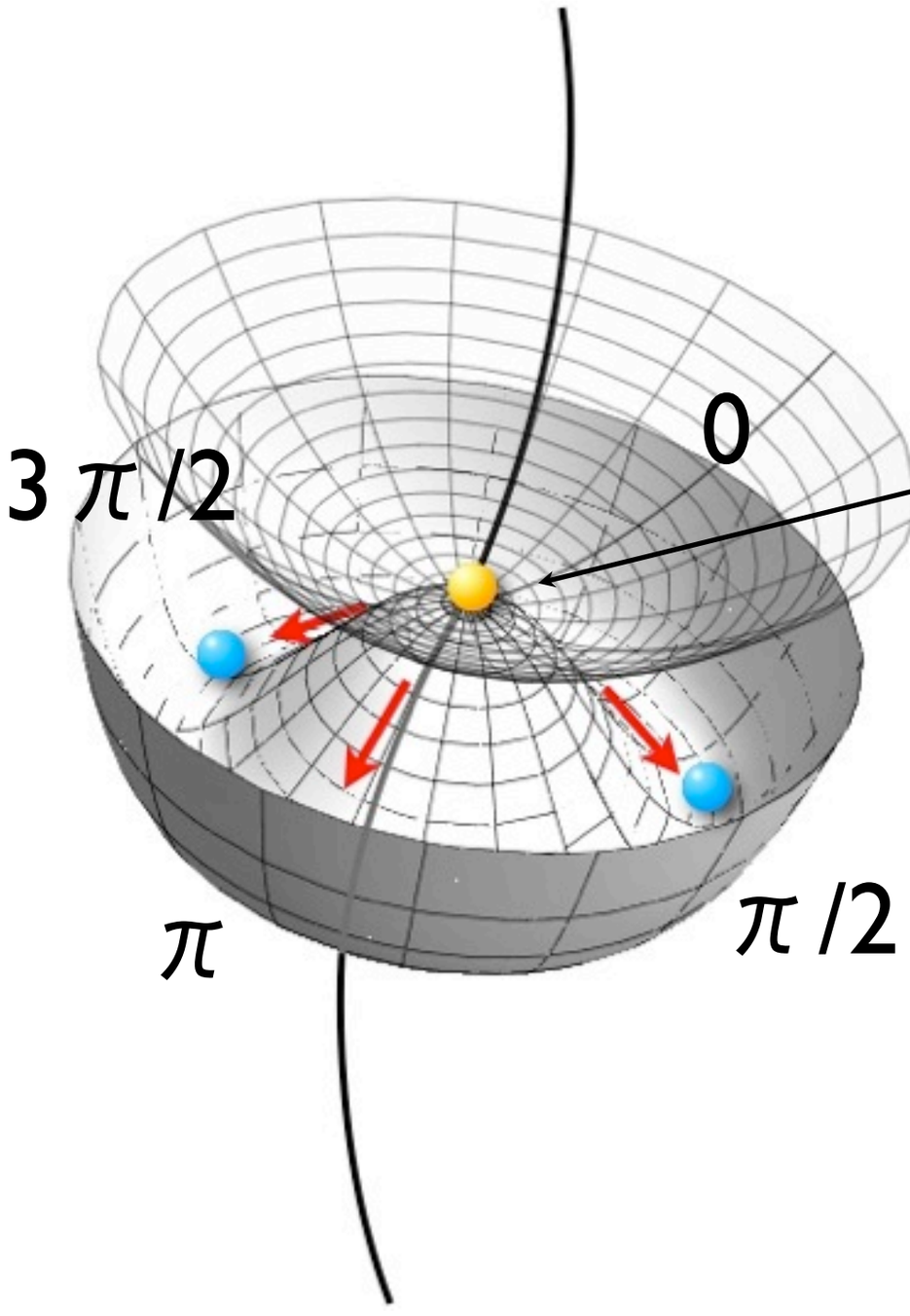
Generation mechanism 1: phase transition





High energy vacuum = cosmic string

Generation mechanism 1: phase transition



μ : tension = line density

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

$G\mu$ ~ the potential energy of the high-energy vacuum

~ the energy scale of the phase transition

Example:

GUT phase transition (~10^{16}GeV)

→ $G\mu \sim 10^{-6}$

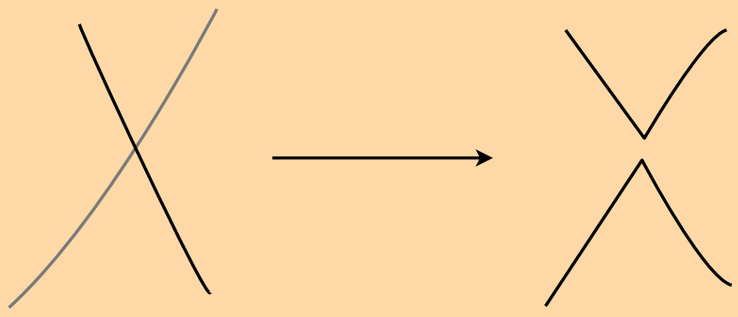
→ 10 km length of string weighs as much as the earth

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>

p : recconection probability



Phase transition origin: p=1

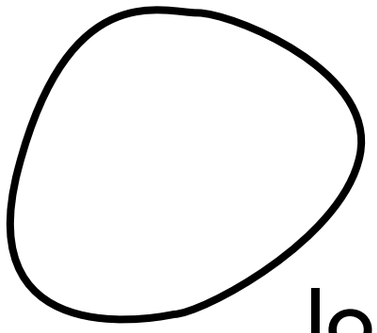
D-string: p=0.1-1

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

effect of extra dimension

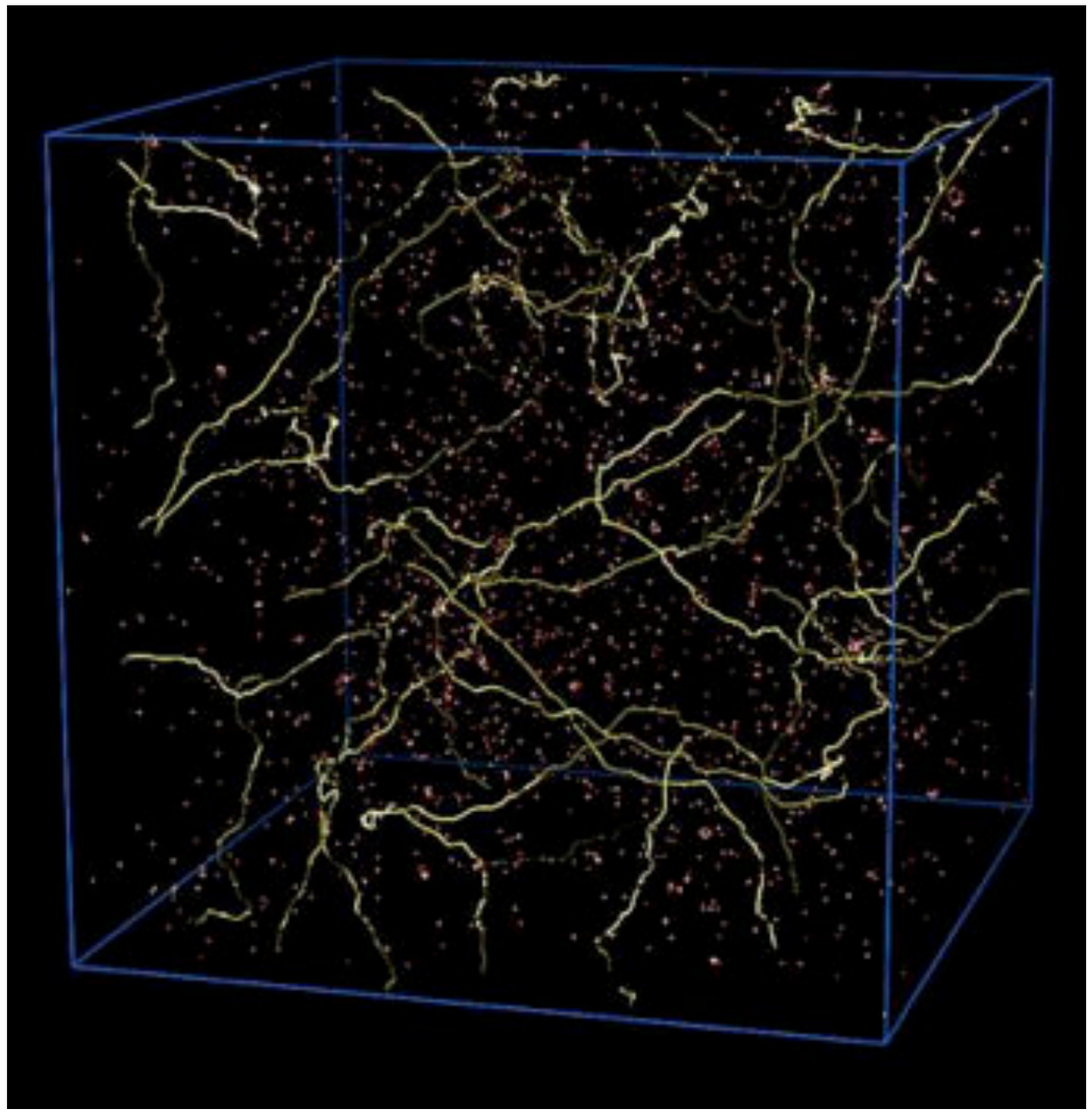
Cosmic string network

Mixture of infinite strings and loops



loop

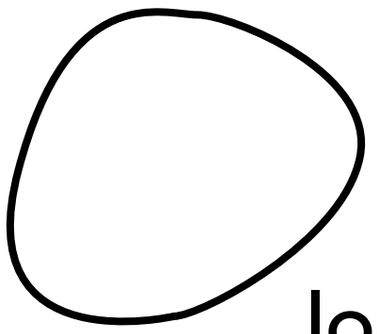
infinite
string



Many simulation works going on...

Cosmic string network

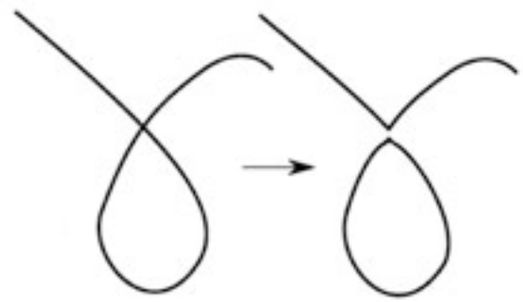
Mixture of infinite strings and loops

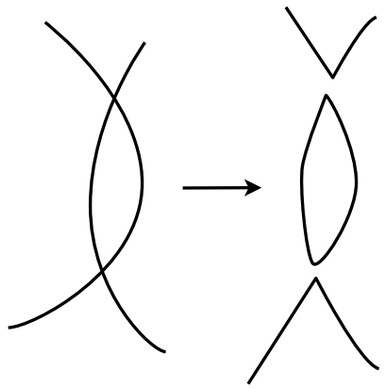


loop

infinite string

Cosmic strings become loops via reconnection



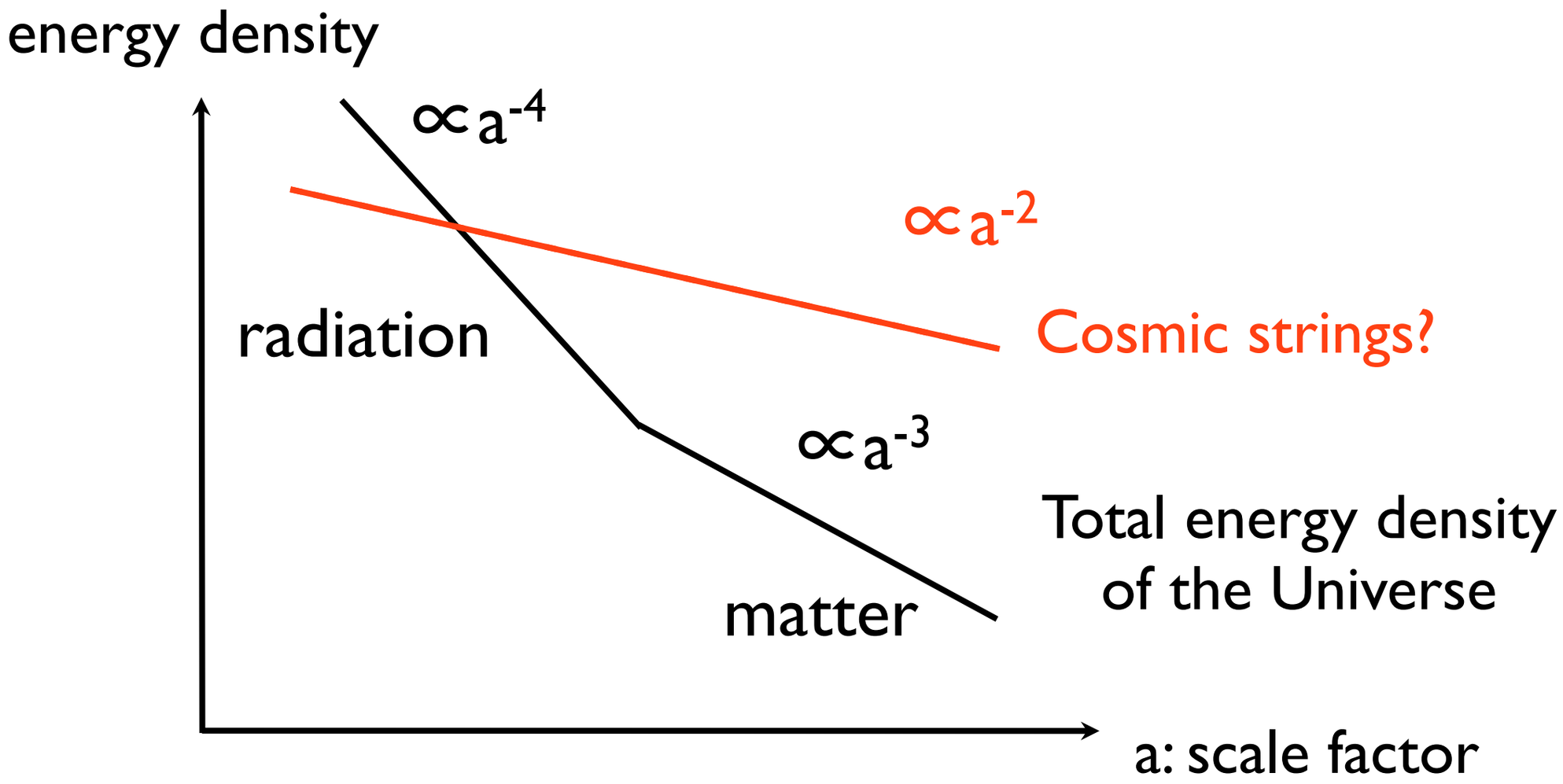


α ： initial loop size $L \sim \alpha H^{-1}$

H^{-1}: Hubble horizon size (size of causal region)

recent trend of simulations $\alpha \sim 0.1$

Evolution of cosmic strings



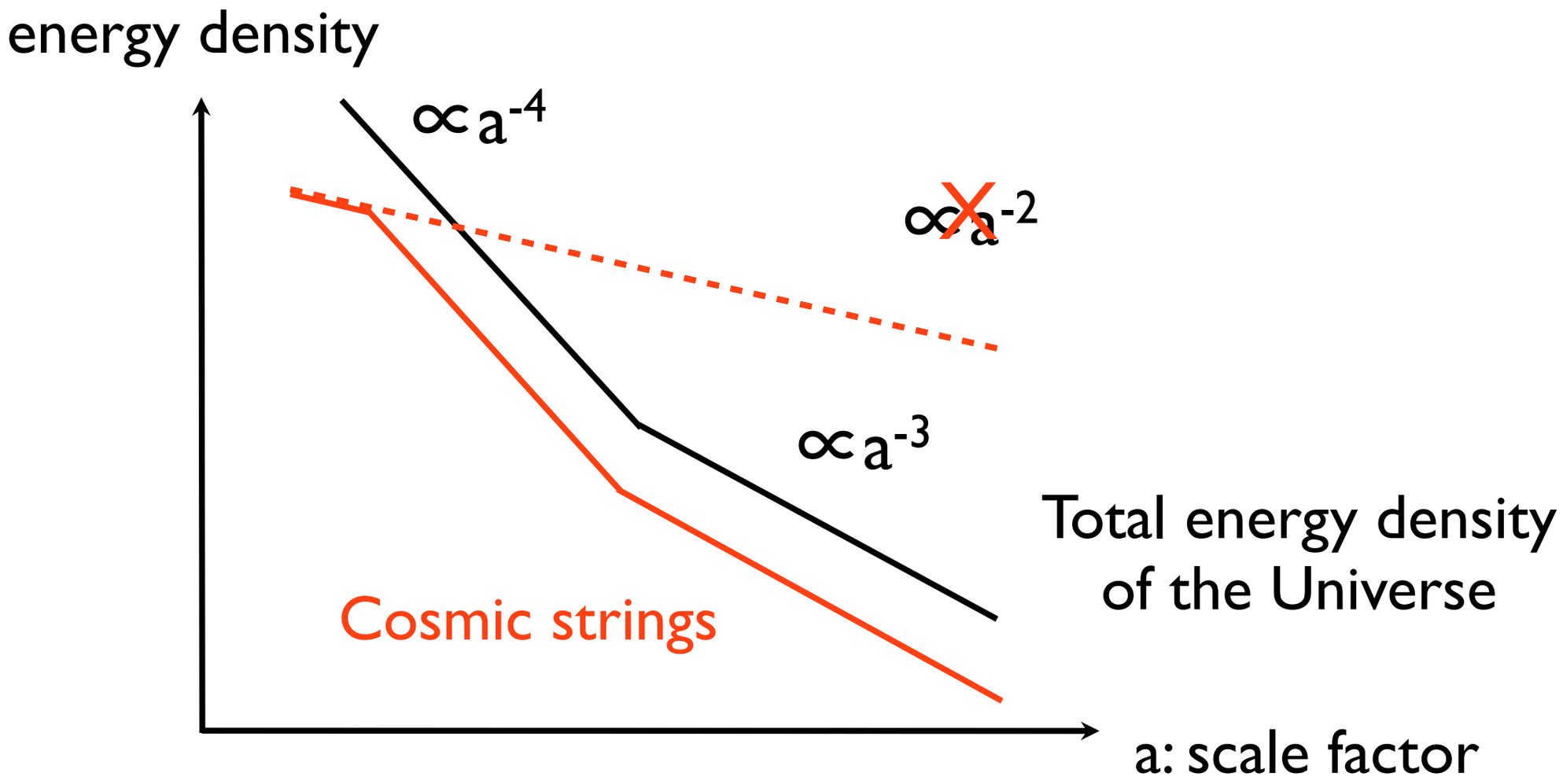
energy density of cosmic strings

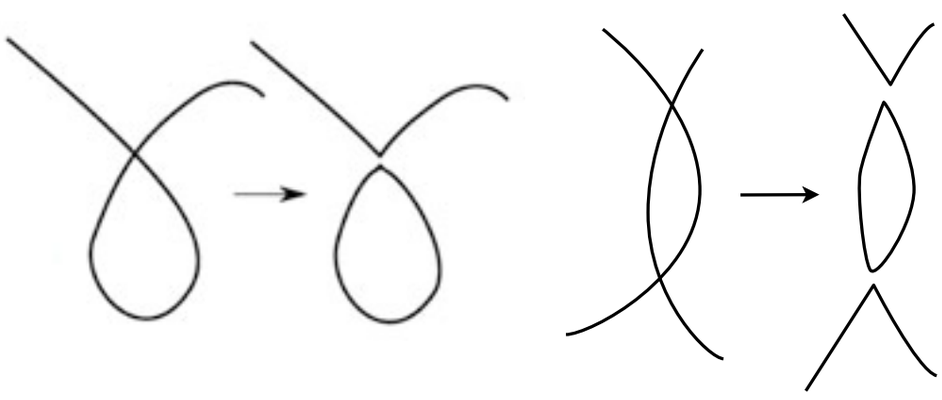
$\sim$ (line density $\times$ length)/volume $\propto a^{-2}$

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

$\rightarrow$ easily dominates the energy density of the Universe

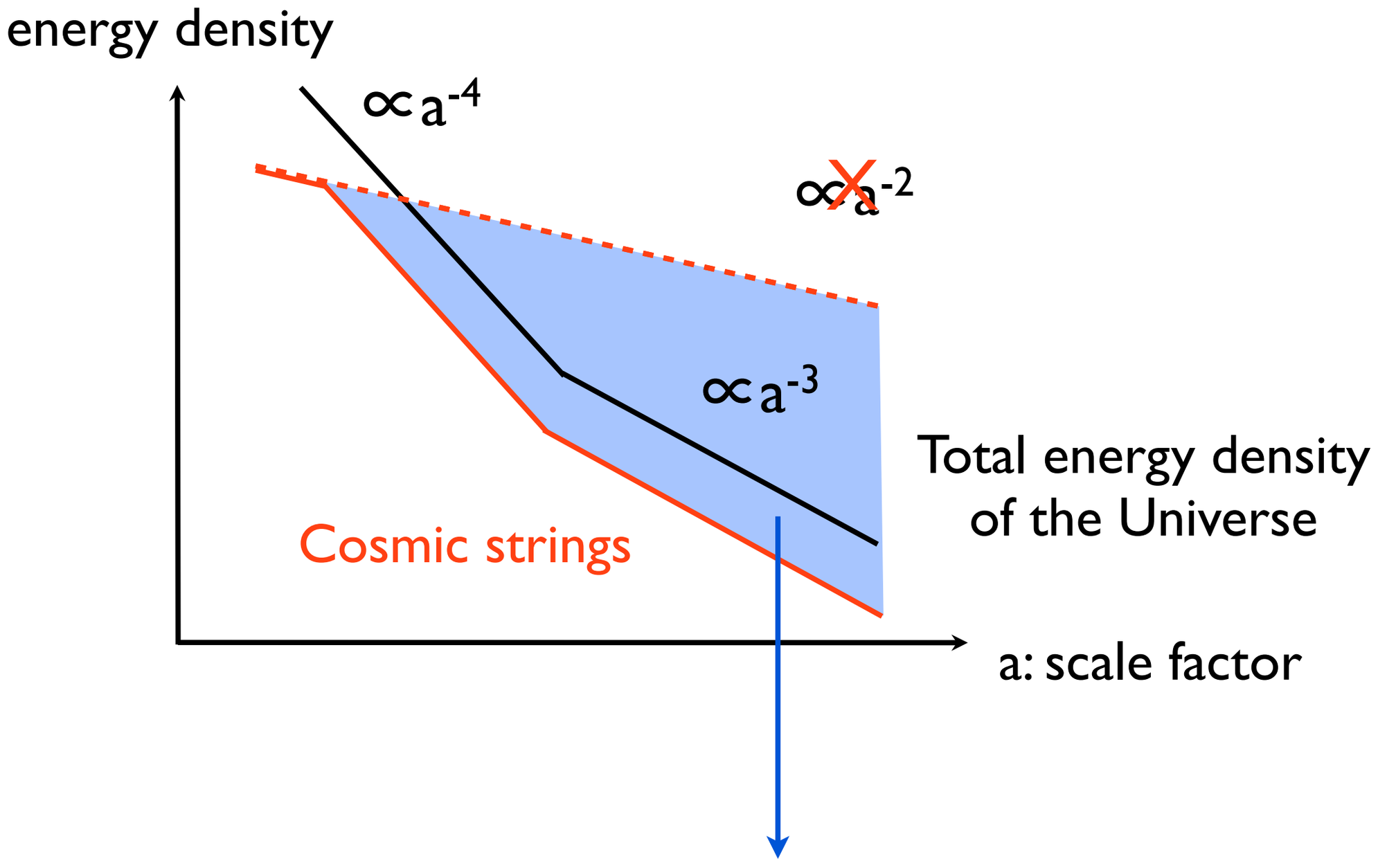
Evolution of cosmic strings





Loops lose energy by emitting gravitational waves

Evolution of cosmic strings

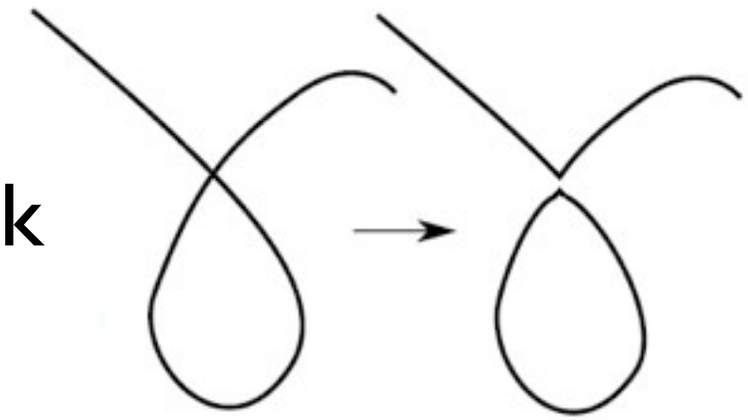


String energy goes to gravitational waves

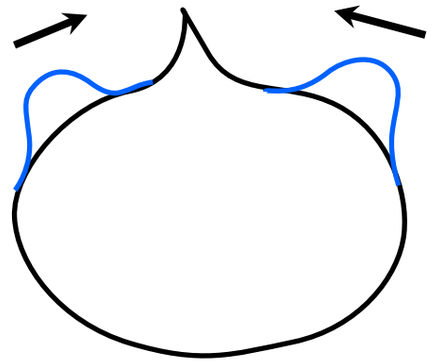
Gravitational waves from cosmic strings

Strong GW emittion from singular points
called kinks and cusps

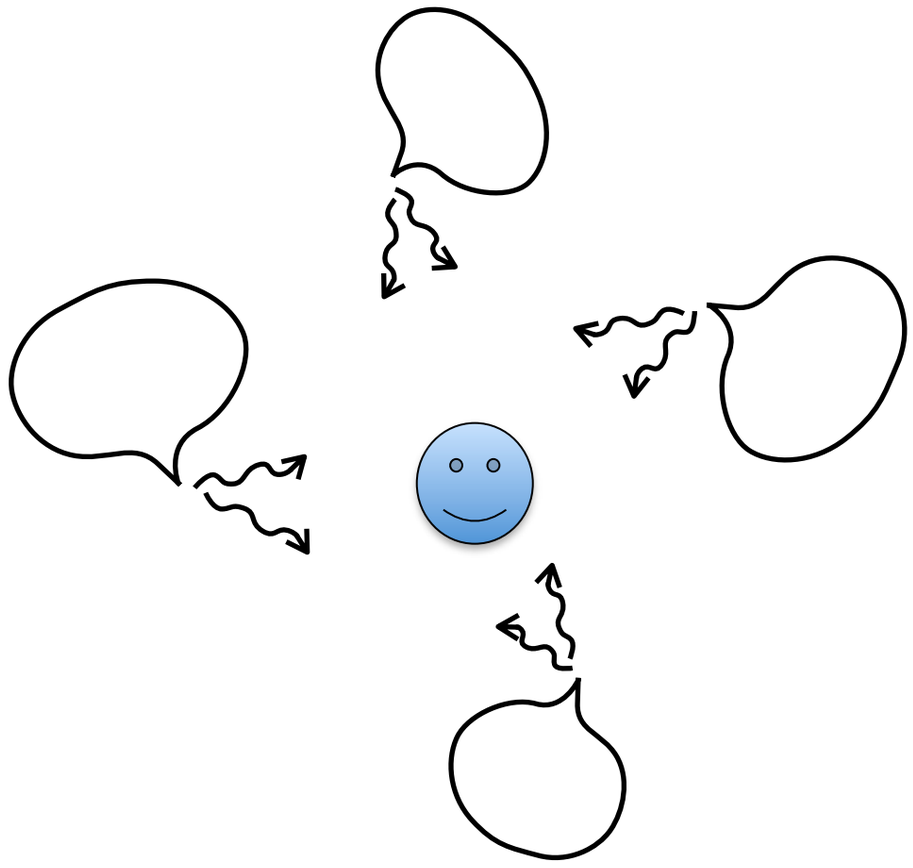
kink



cusp



gives dominant contributions



Rare Burst: GWs with large amplitude coming from close loops

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

Estimation of the GW burst rate

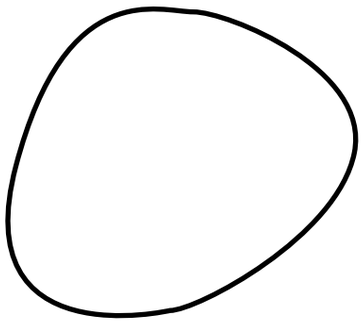
GW burst rate = $\int$ dt (GW emission per 1 loop
× Number density of loops)

Initial number density of loops $= (p\alpha)^{-1}$

(naive estimation)

Not to dominate the Universe...
infinite strings
should lose O(1) Hubble length per 1 Hubble time
= should reconnect O(1) times per Hubble time → more loops for small α
→ for small p, string density should increase to reconnect O(1) times

Evolution of a loop



Initial loop length $= \alpha t_i$

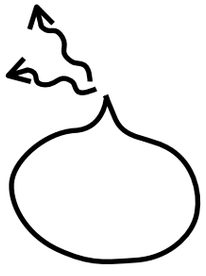
t_i : time when the loop formed

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

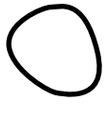
From the energy conservation law

(energy of loop at time t =μl)

= (initial energy of the loop =μαt_i) − (enegry released to GWs =PΔt)



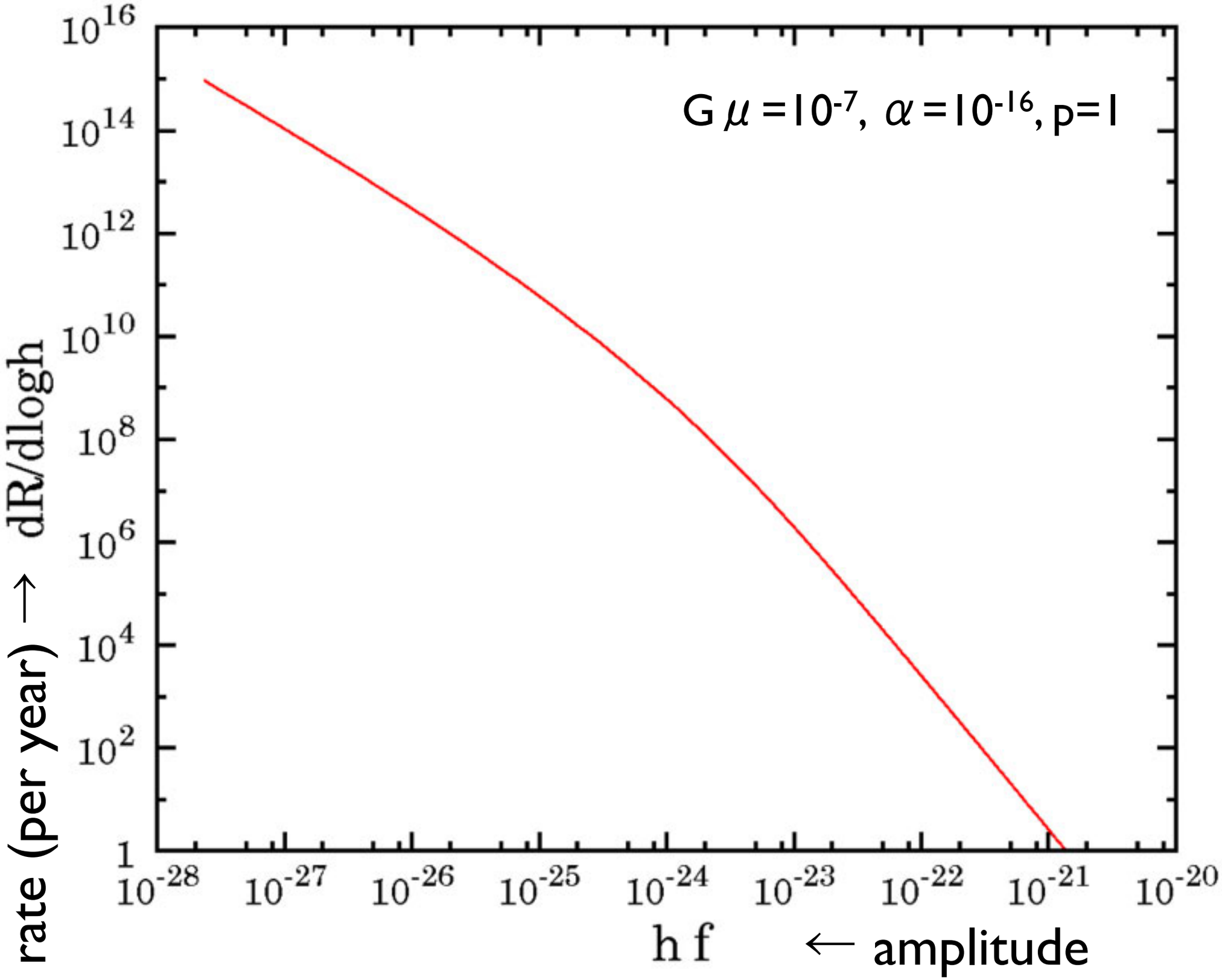
Loop length at time t $l(t, t_i) = \alpha t_i - \Gamma G \mu (t - t_i)$



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

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

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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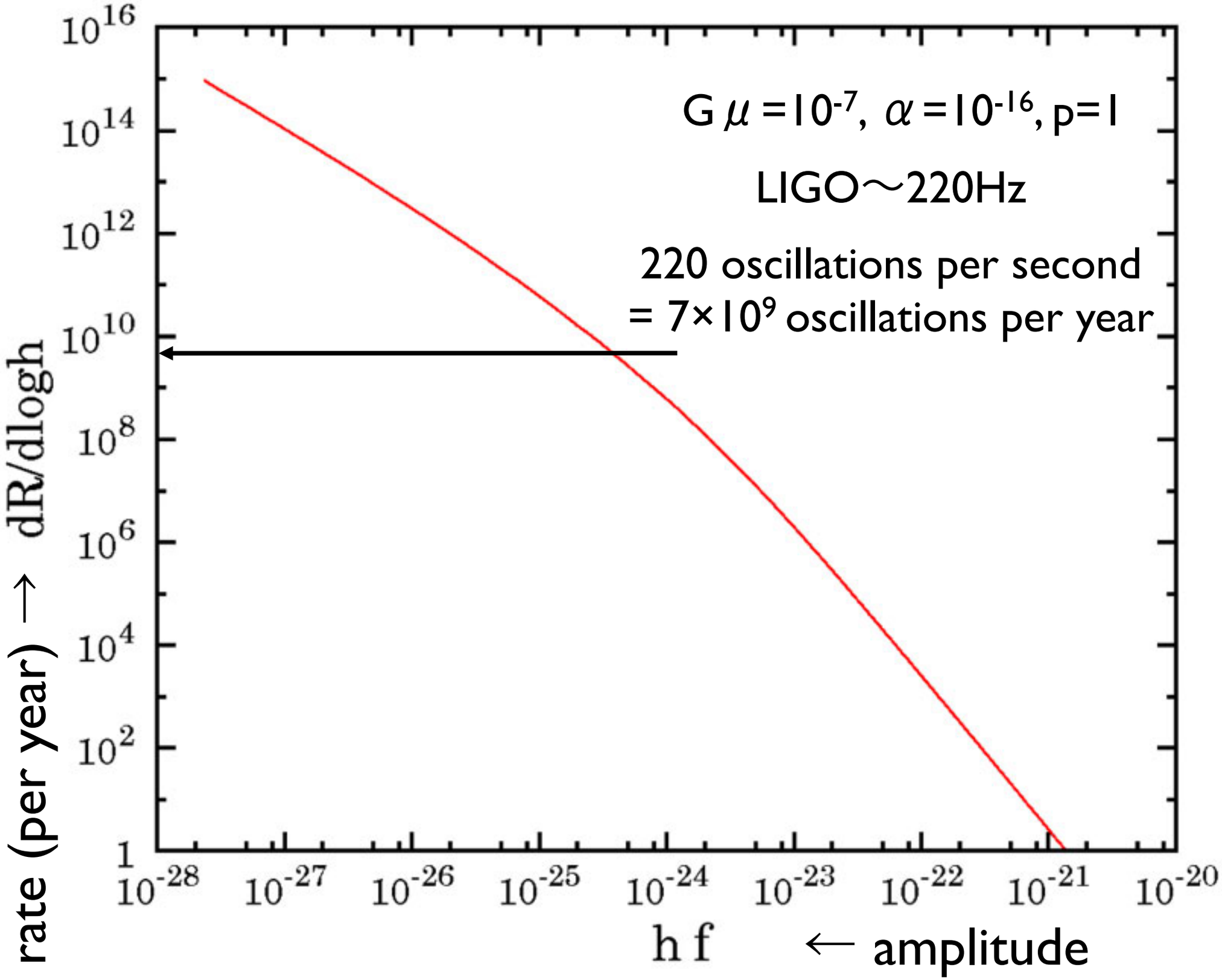

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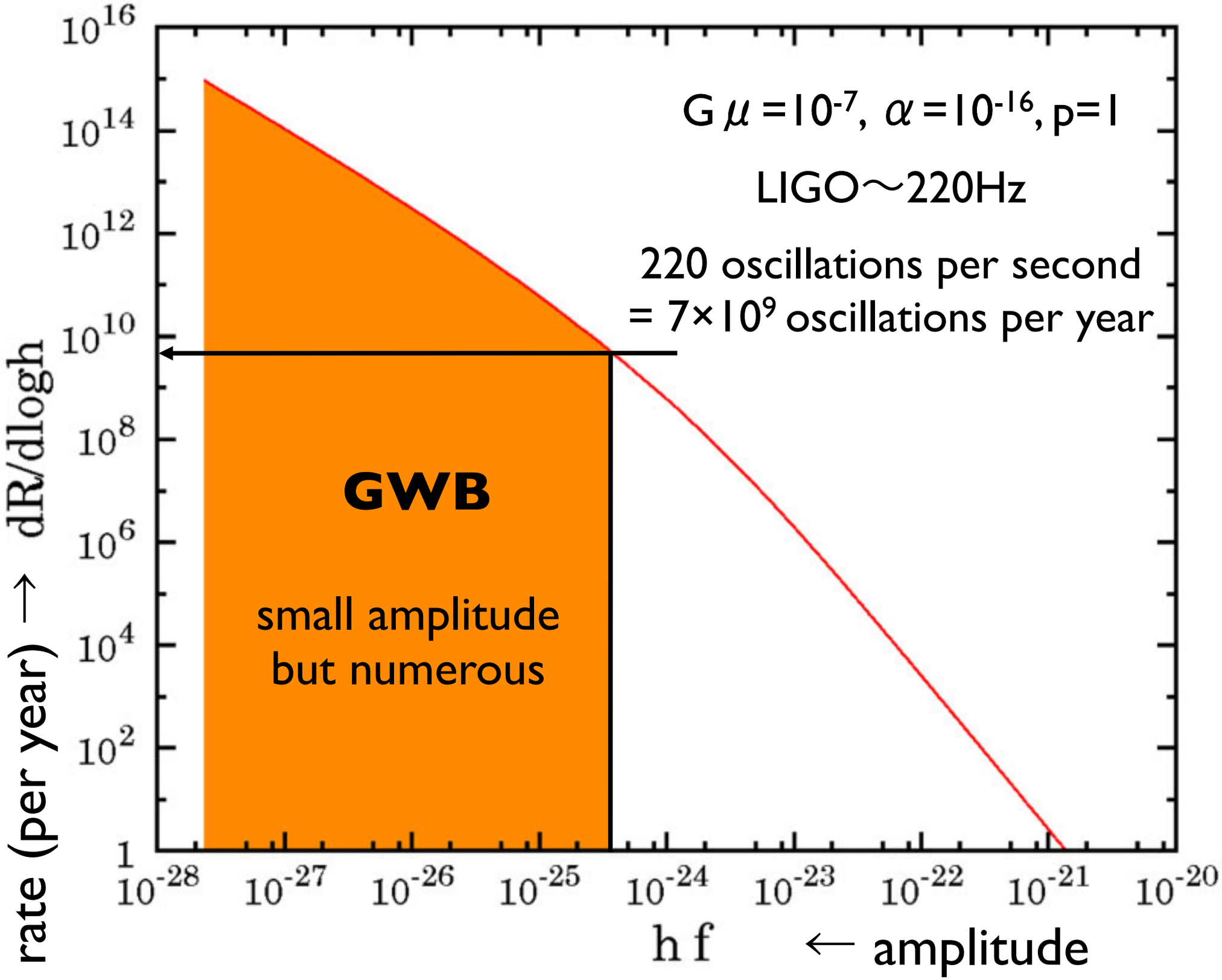

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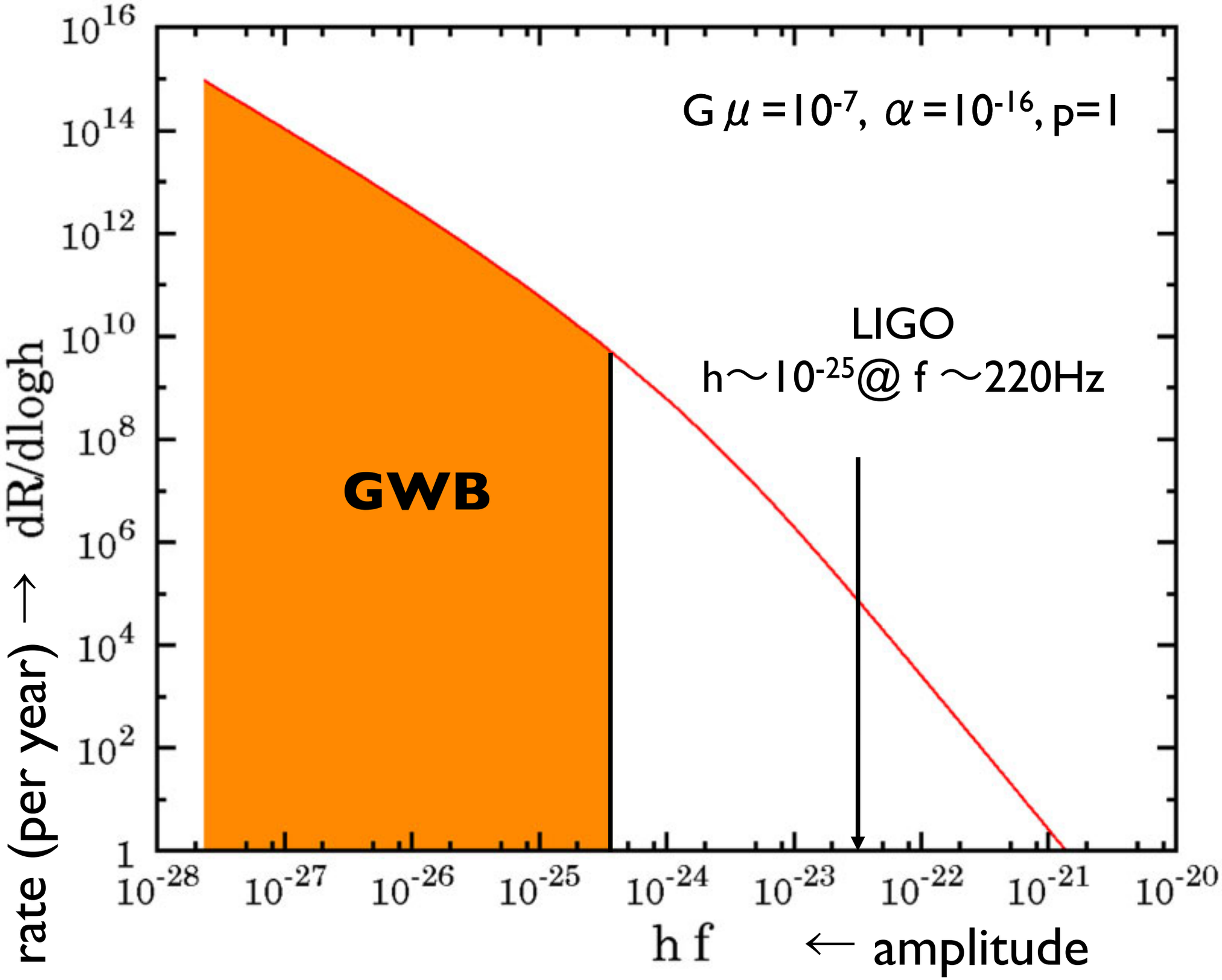

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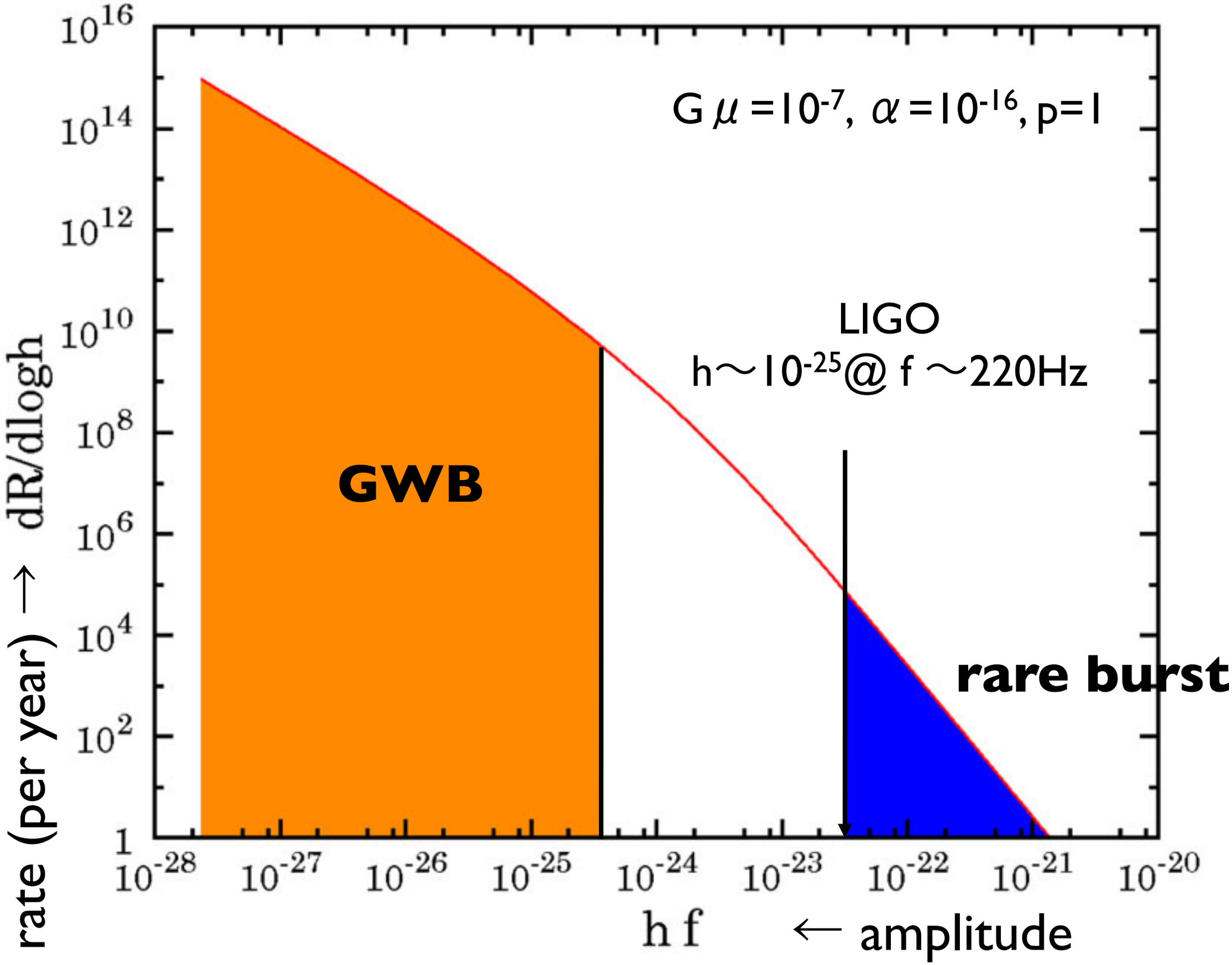

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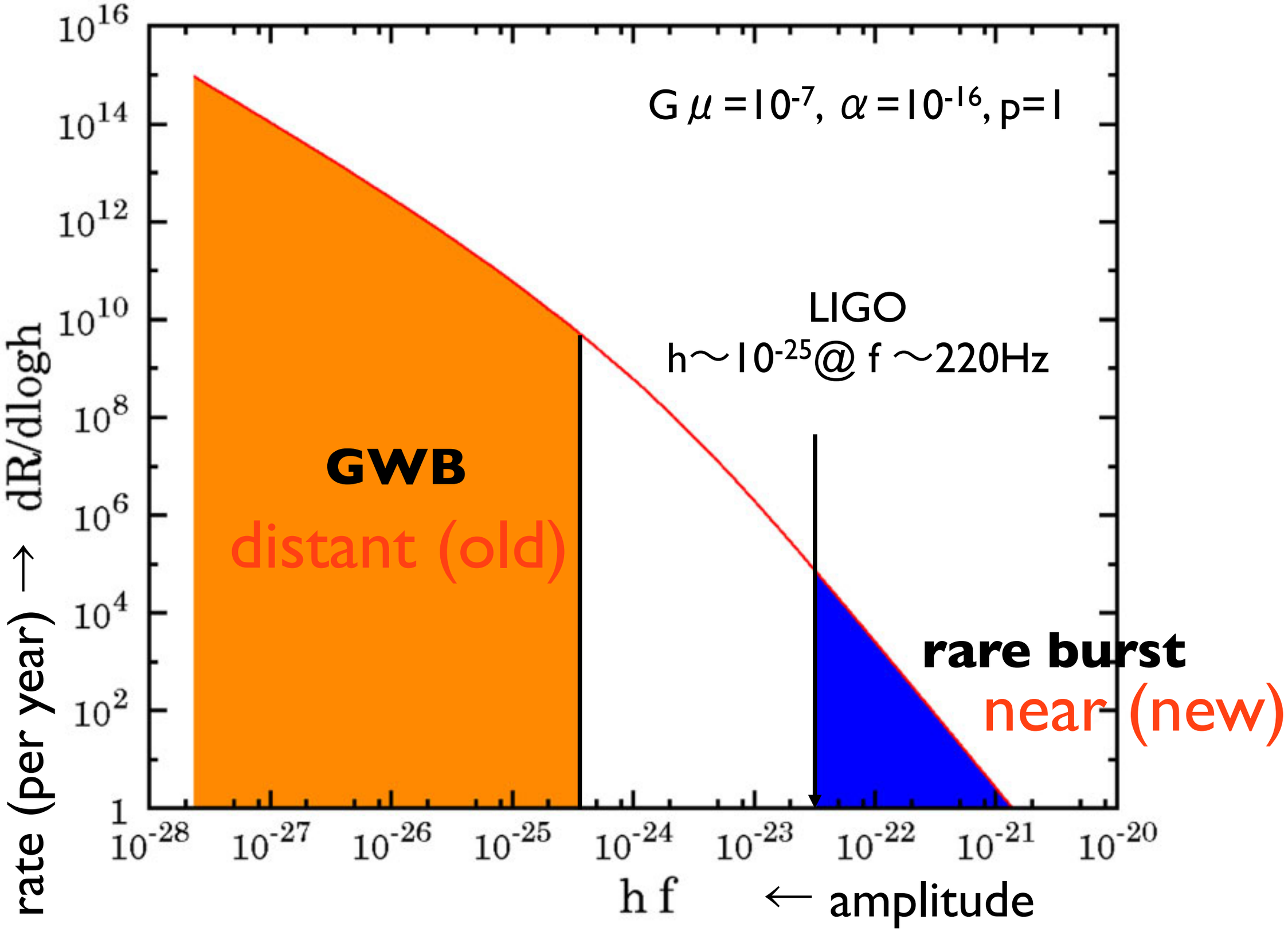
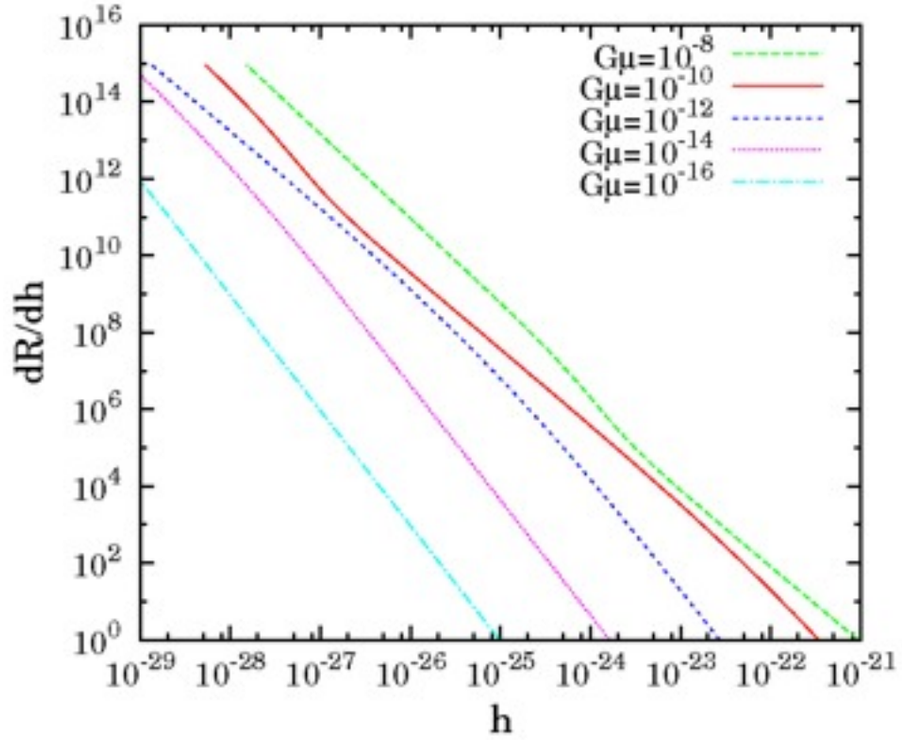
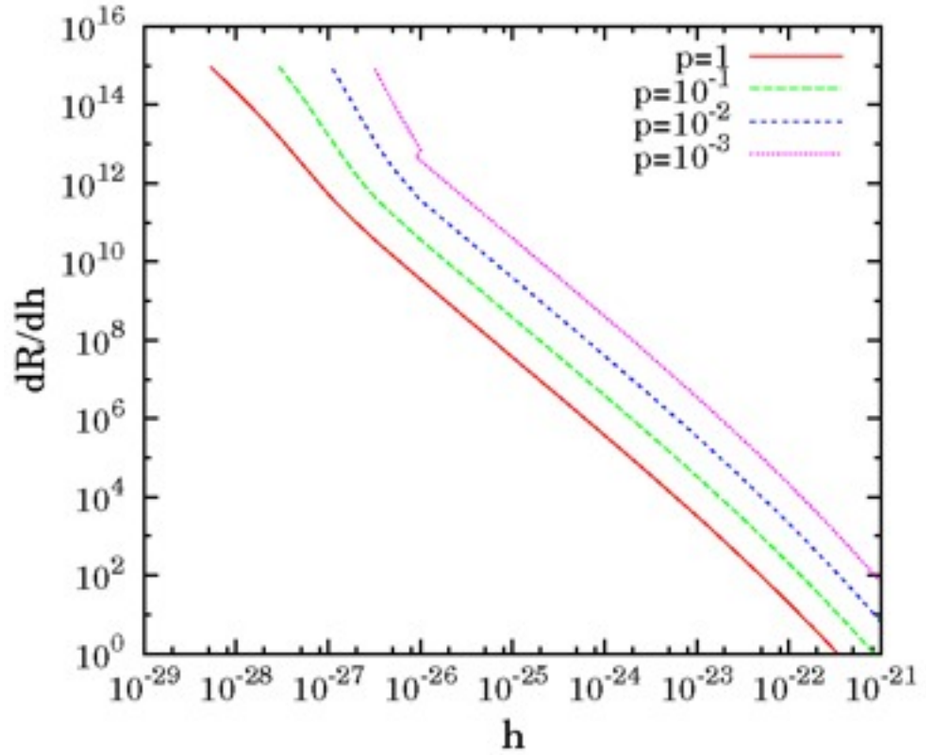


Parameter dependences of the rate

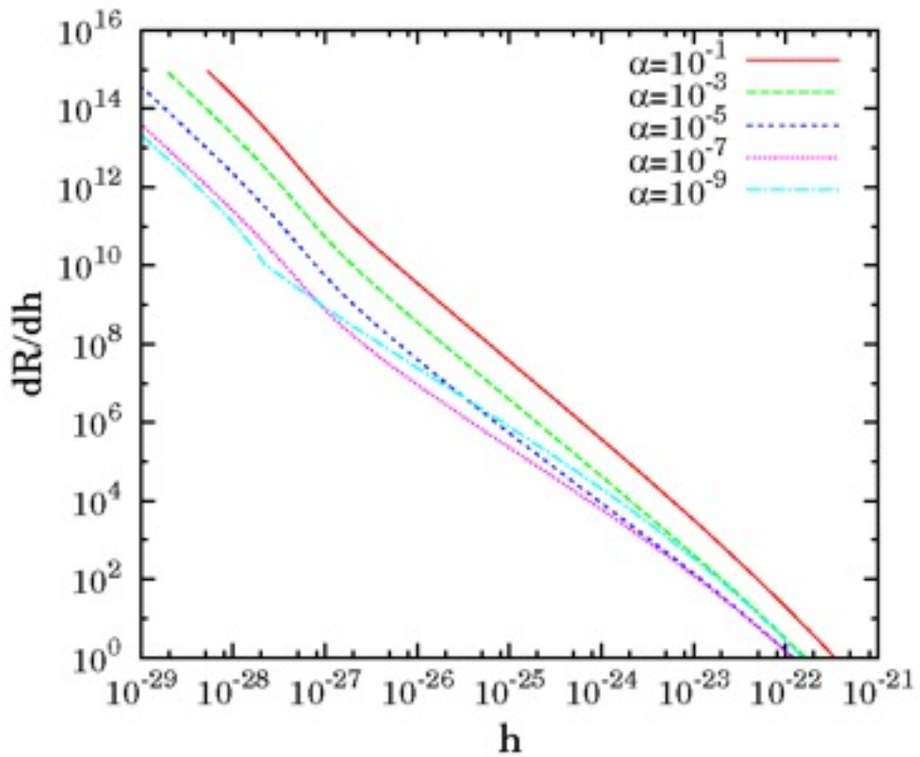
G μ



p



α



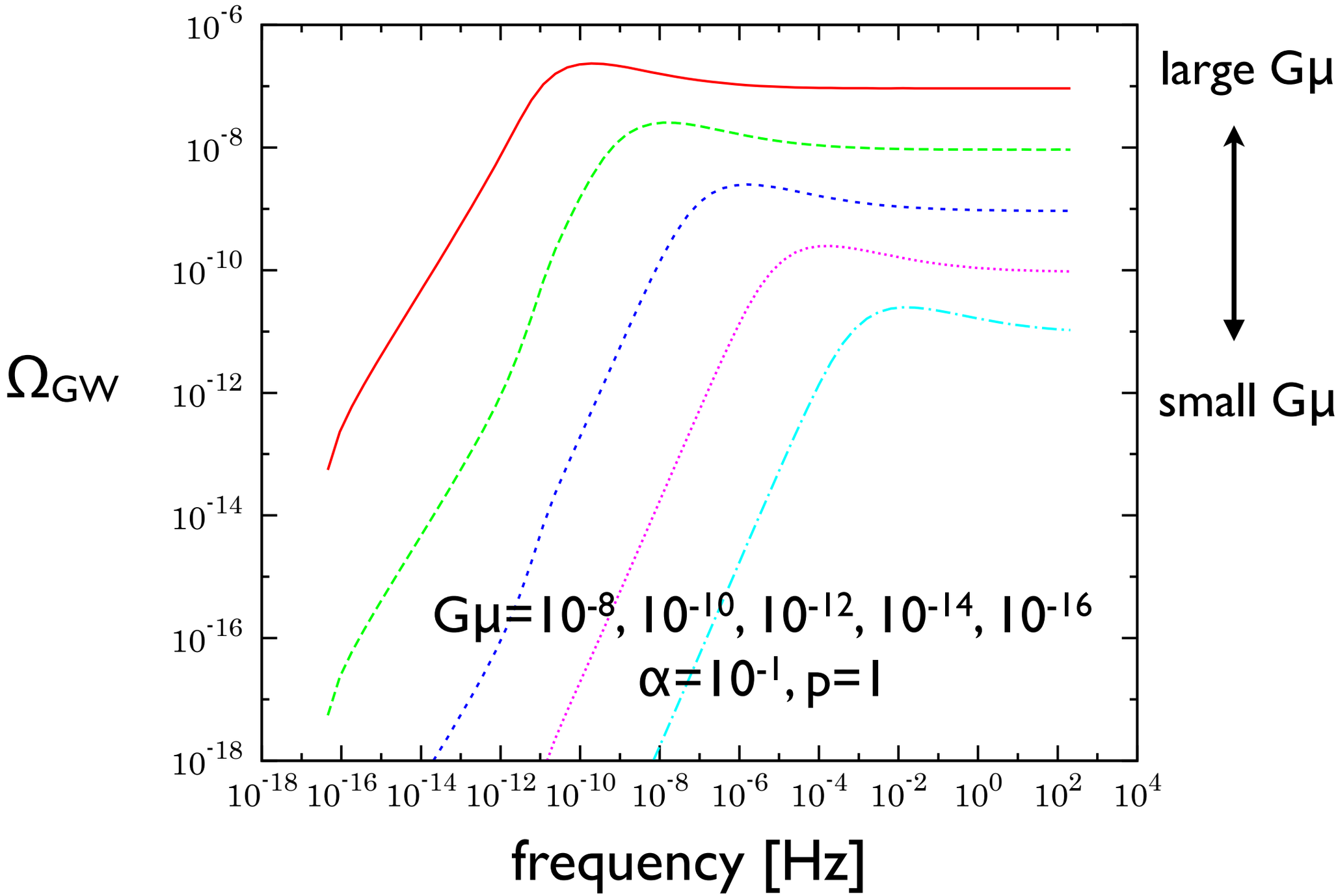
The parameter dependences of the large burst (rare burst) and small burst (GWB) are different because they are looking at different epoch of the Universe

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

Spectrum of the GWB

dependence on Gμ

GW power increases for large Gμ

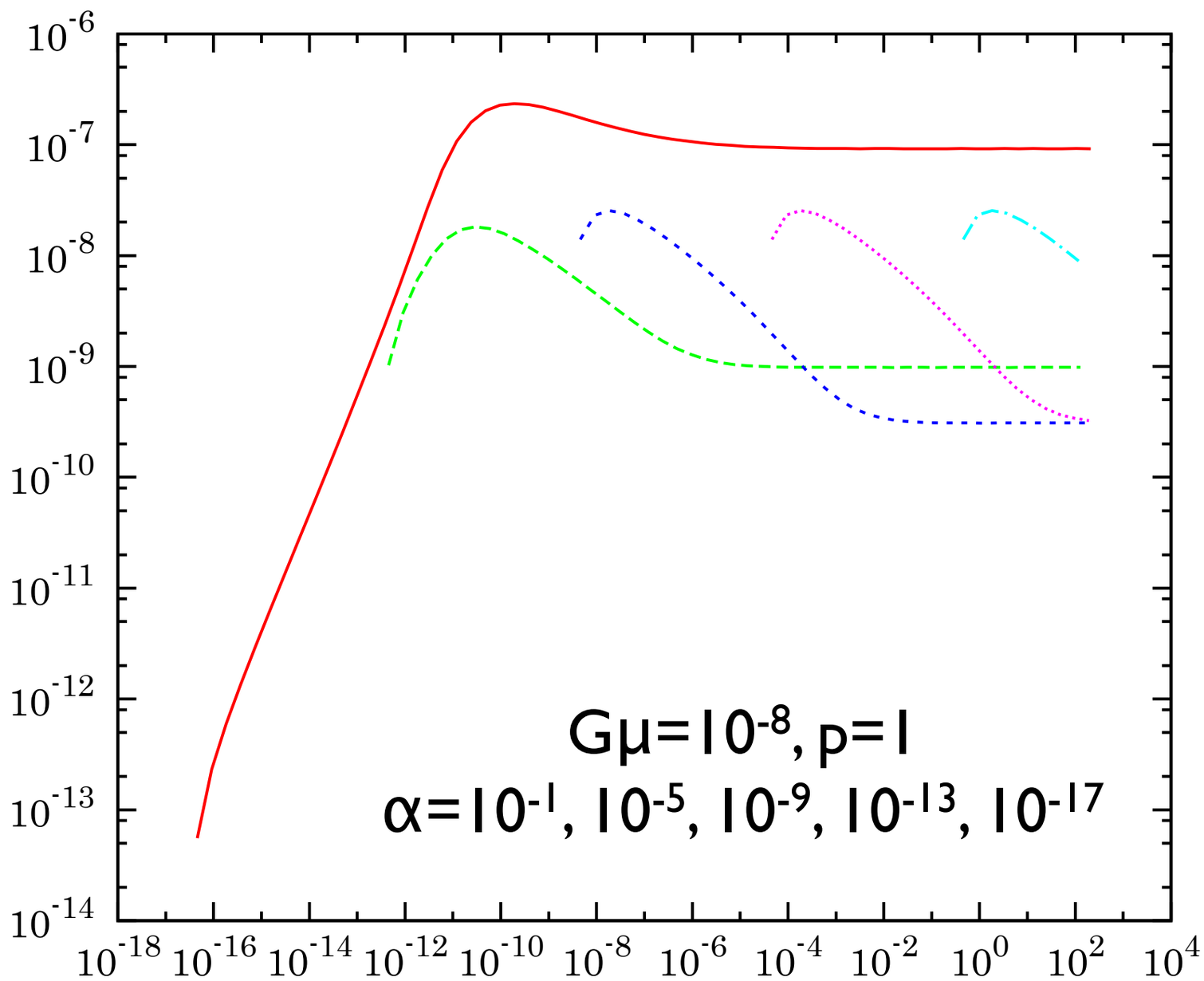


Spectrum of the GWB

dependence on α

loop size directly corresponds to the frequency of the GW

small α



Ω_{GW}

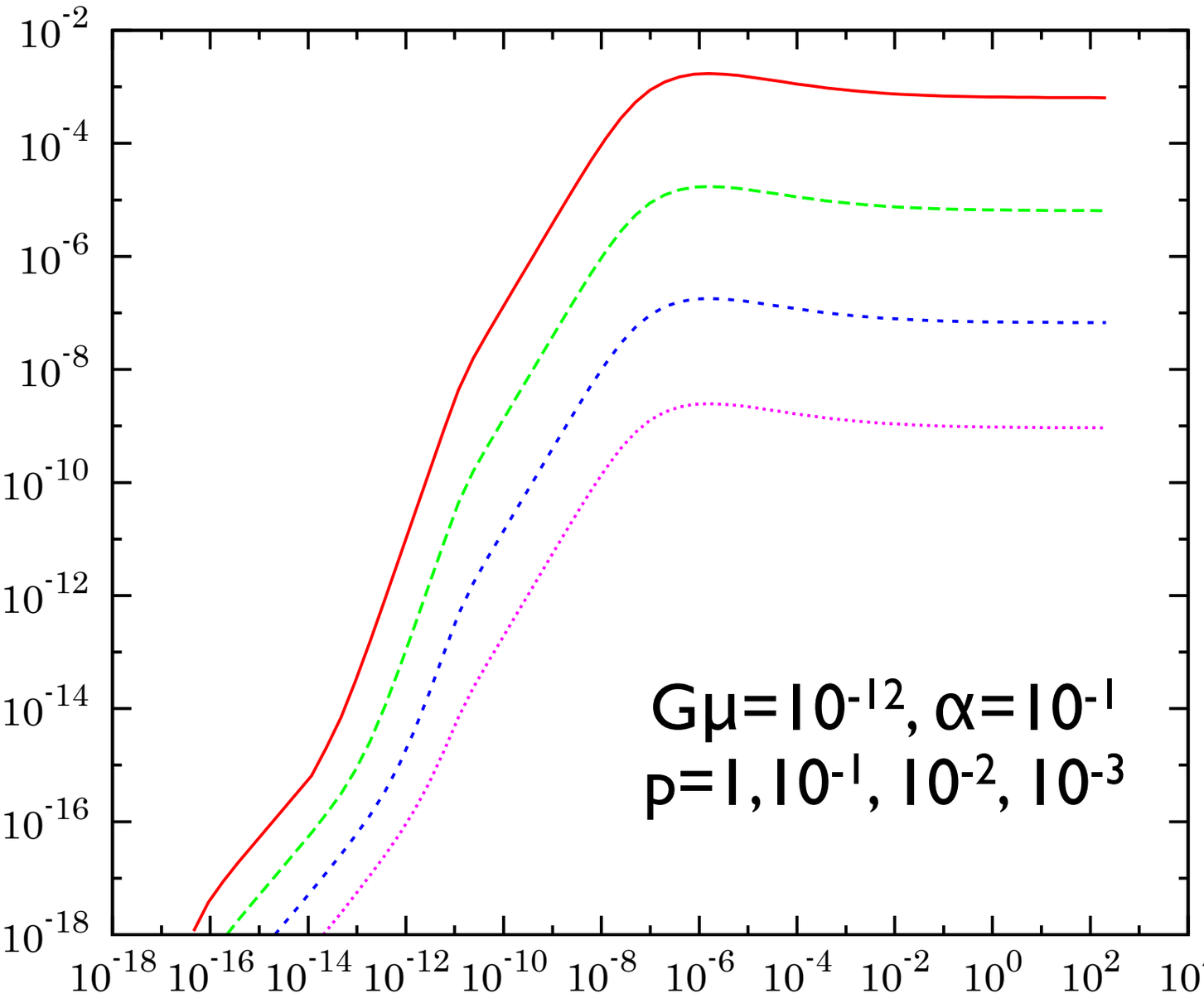
frequency [Hz]

Spectrum of the GWB

dependence on p

small p increases the number density of loops

small p



large p

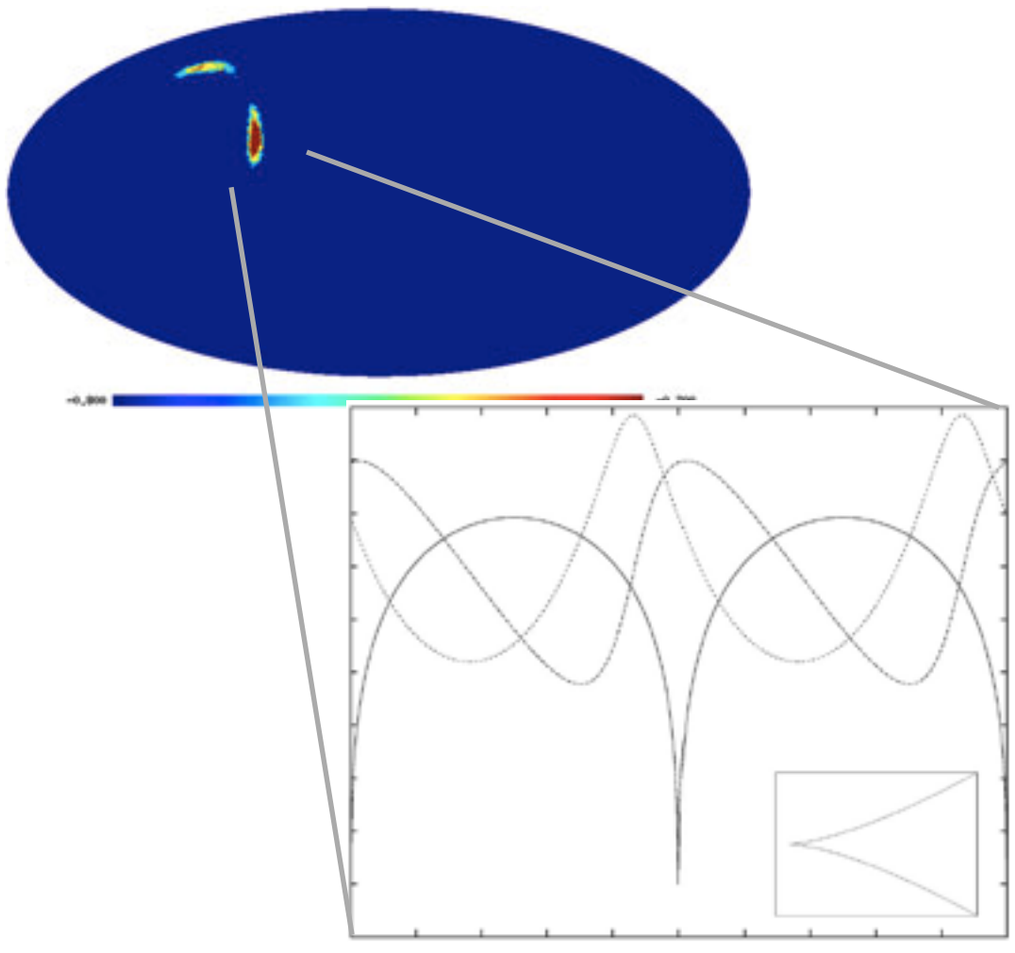
Ω_{GW}

frequency [Hz]

Observations of GWs

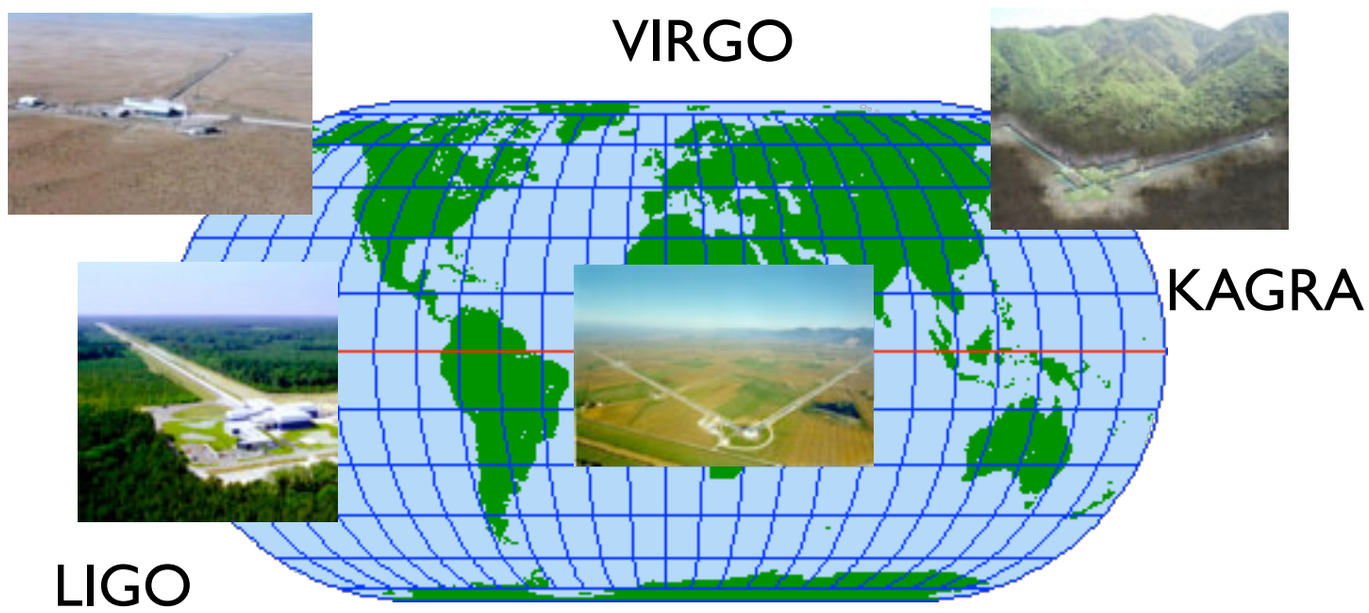
GWs with large amplitude

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

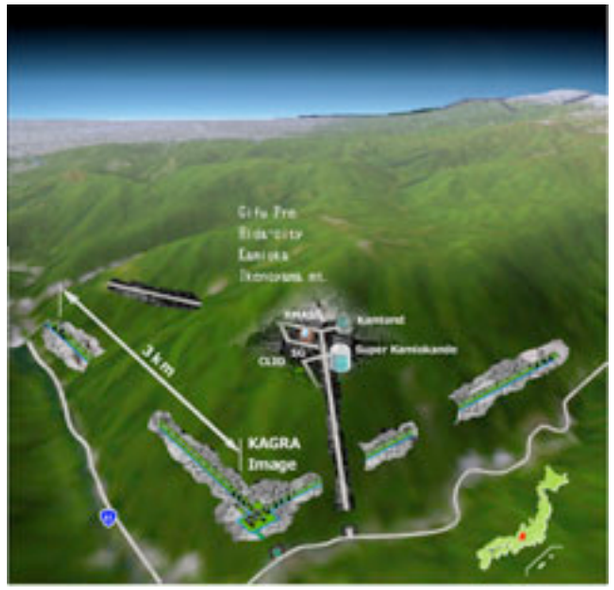
  Ground：**Advanced-LIGO、KAGRA、**

  Virgo、IndIGO

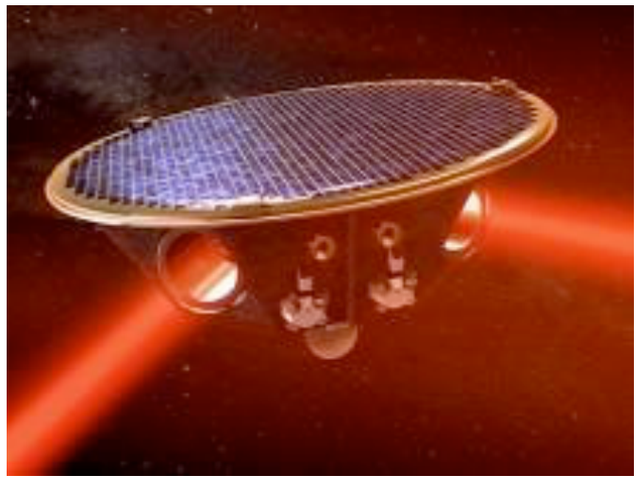
  Space：**eLISA/NGO、DECIGO**

- Pulsar timing: **SKA**

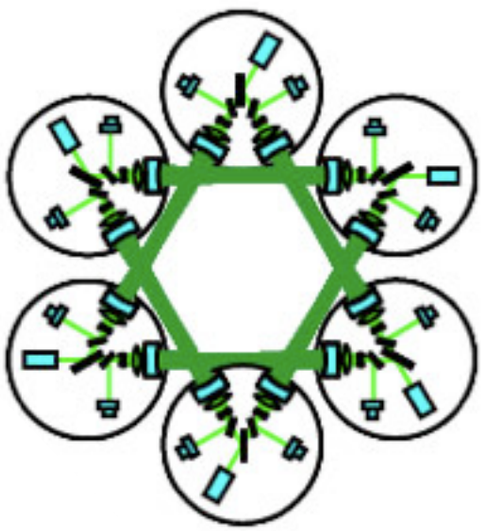
- CMB B-mode polarization: **Planck, CMBpol**



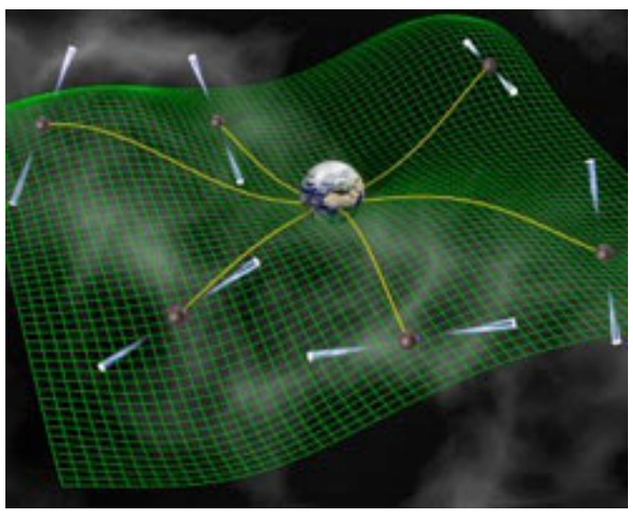
KAGRA image (http://gwcenter.icrr.u-tokyo.ac.jp/)



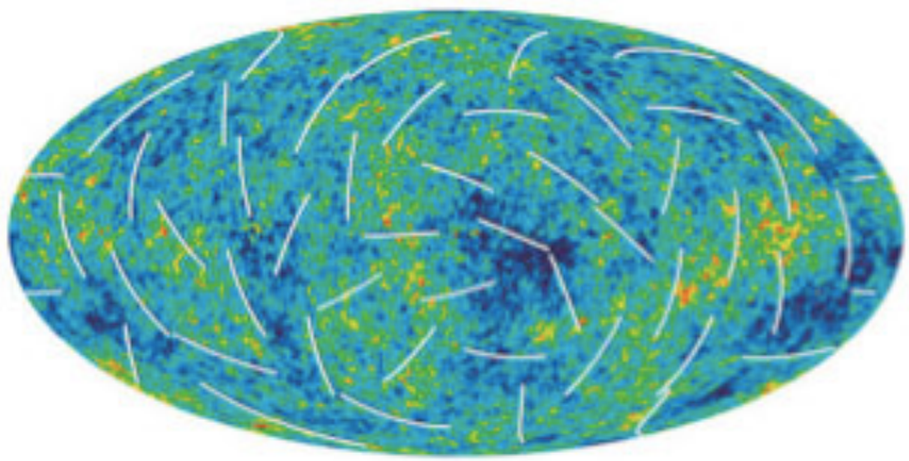
eLISA image (http://elisa-ngo.org/)



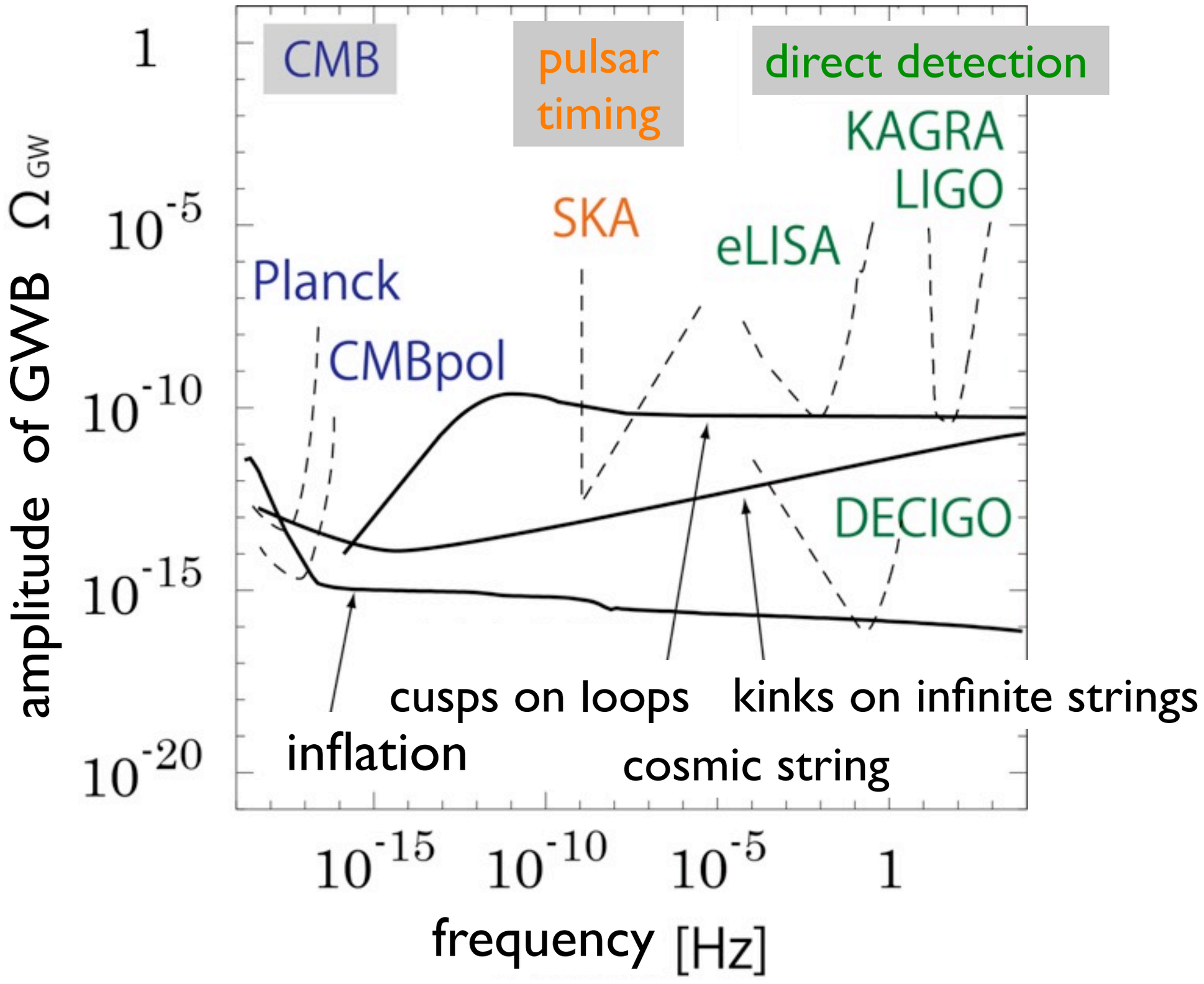
DECIGO image, S. Kawamura et al,
J. Phys.: Conf. Ser. 122, 012006 (2006)



PTA image (NRAO)



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

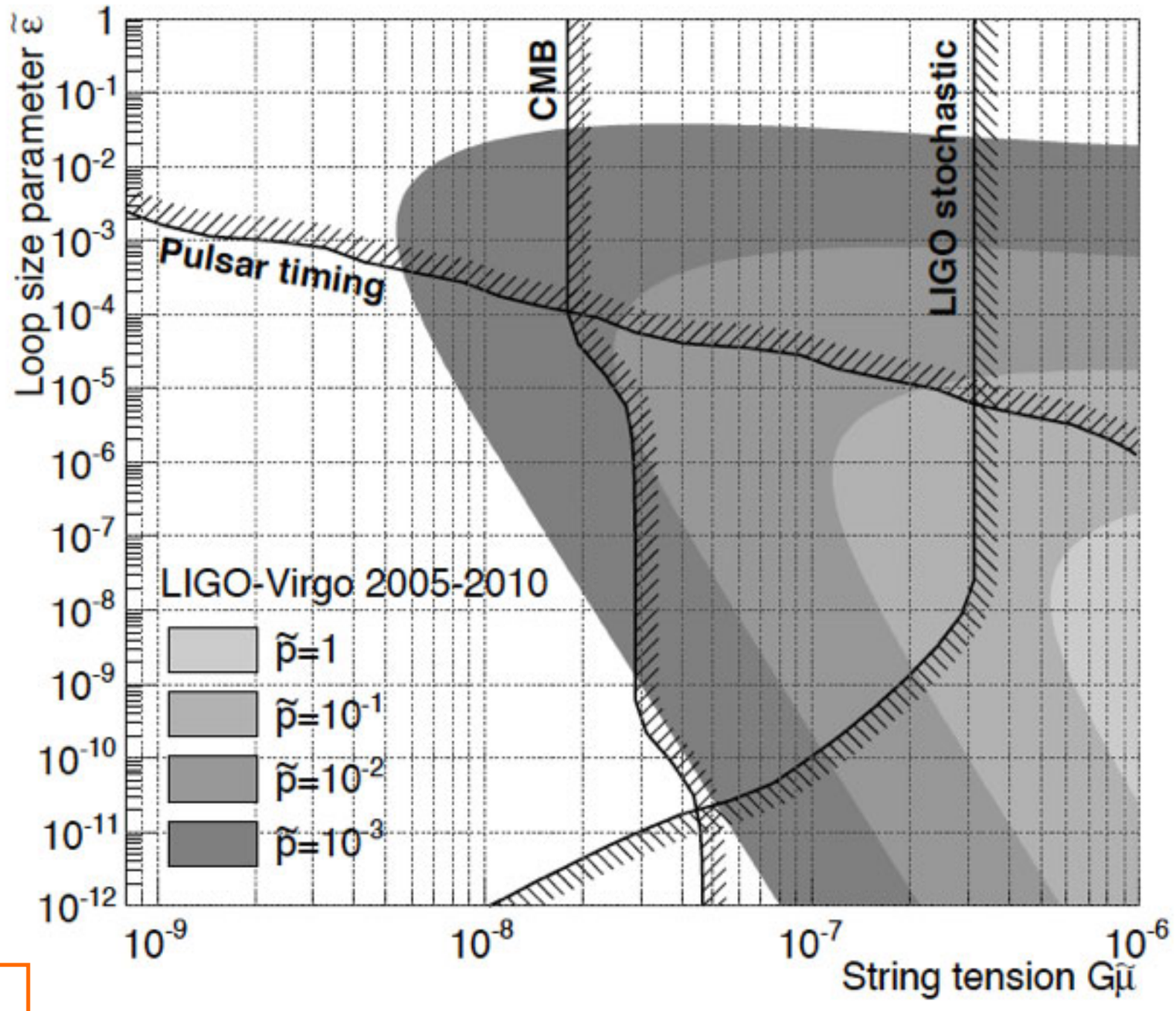


→ **also provide different information on cosmic strings**

Current constraints on cosmic string parameters

LIGO-Virgo collaboration
arXiv:1310.2384 [gr-qc]

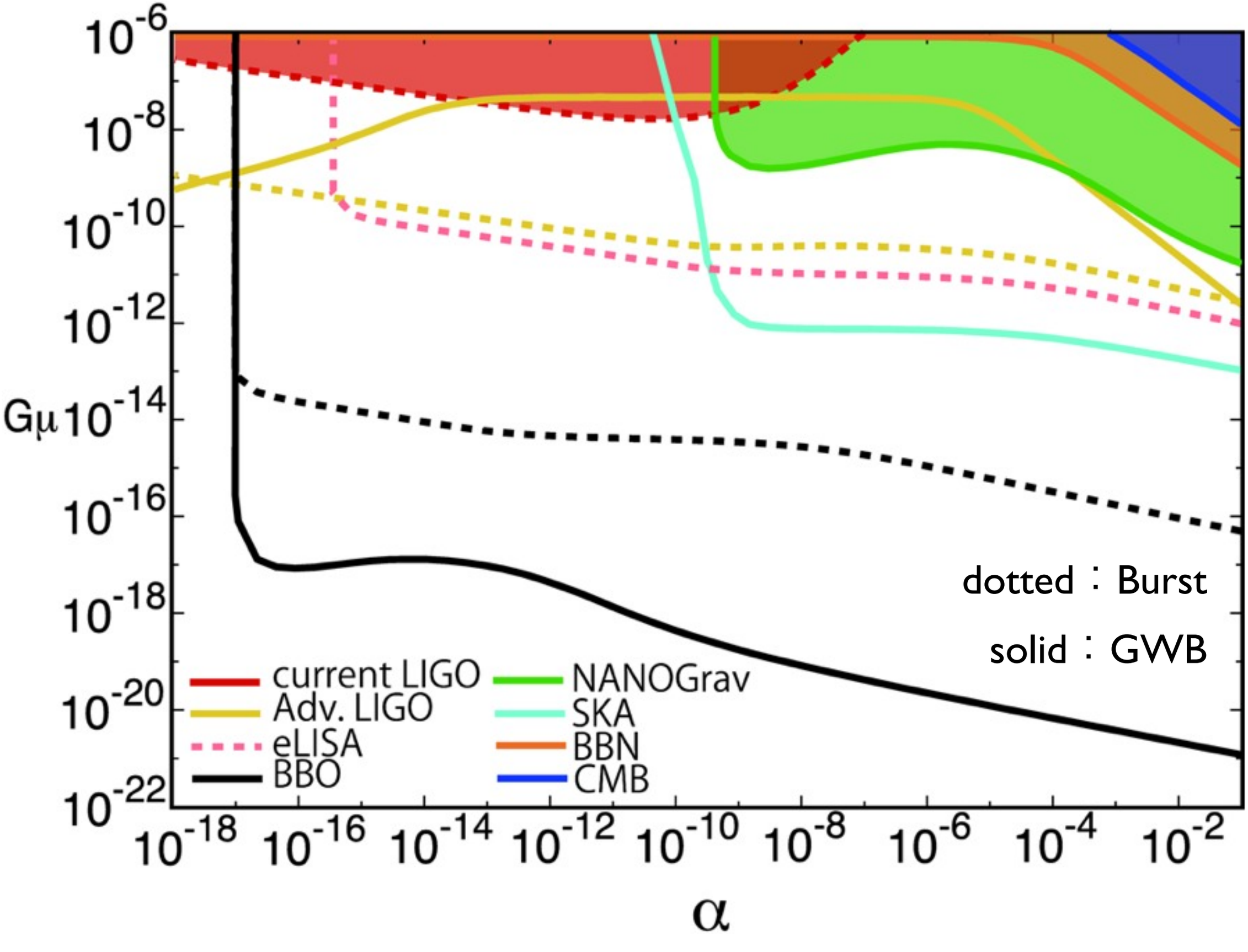
LIGO S5, S6 + VIRGO
625-day burst search



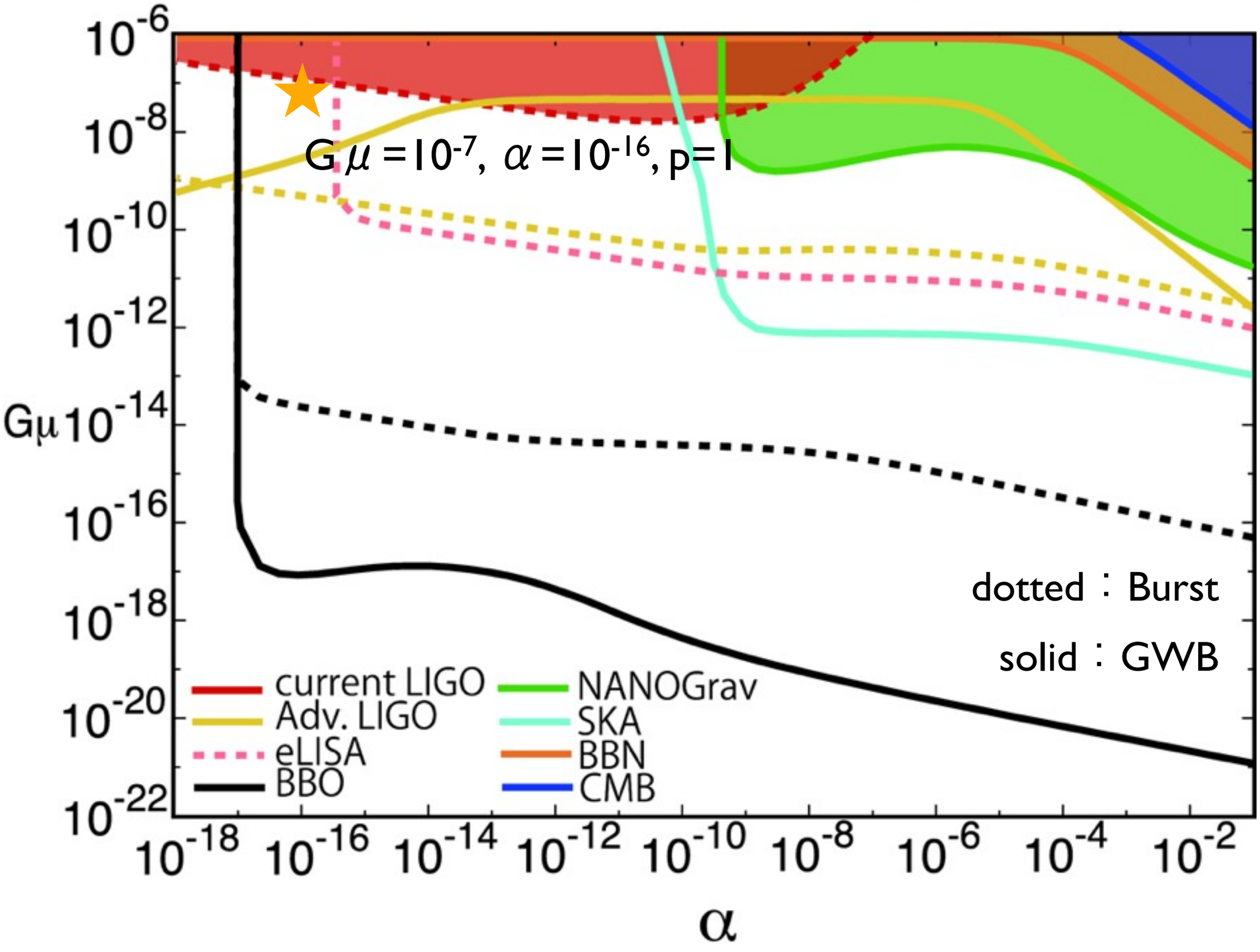
- $G\mu$: tension (line density)
- α : initial loop size $L \sim \alpha H^{-1}$
- p : reconnection probability

3 parameters to
characterize cosmic string

Future accessible parameter region (for p=1)



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

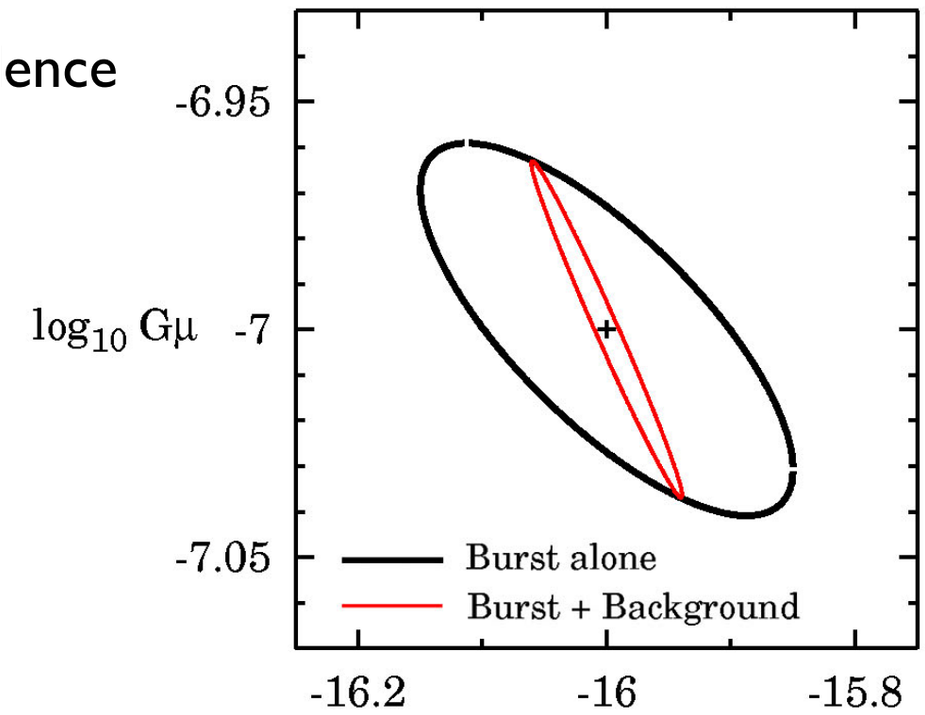


Predicted constraint on parameters

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

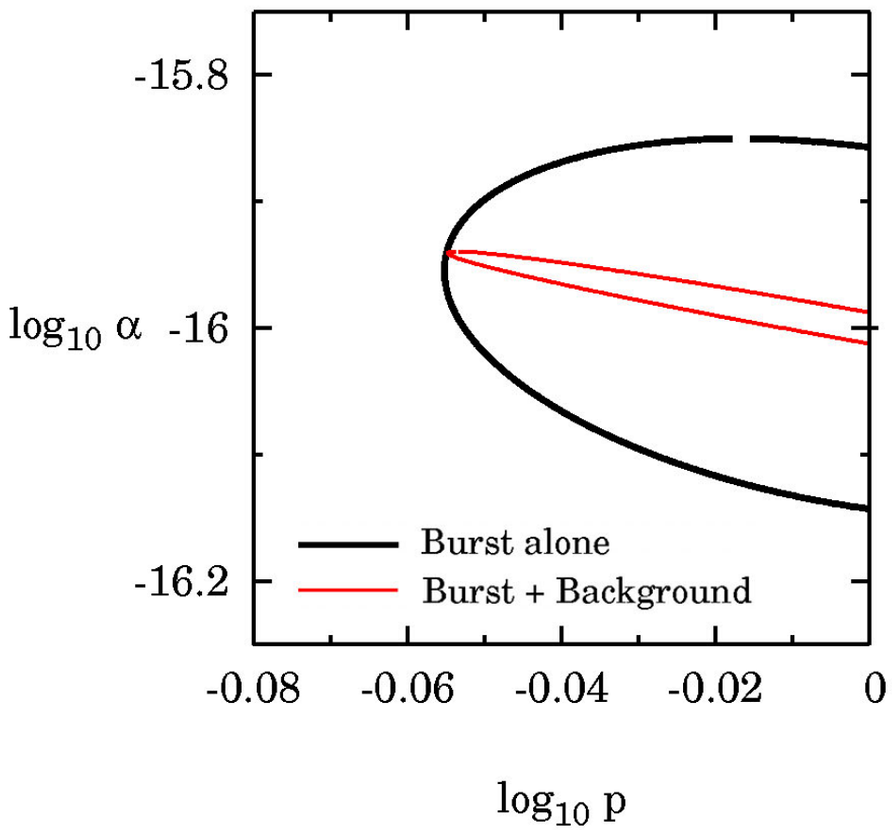
Kuroyanagi et. al. PRD 86, 023503 (2012)

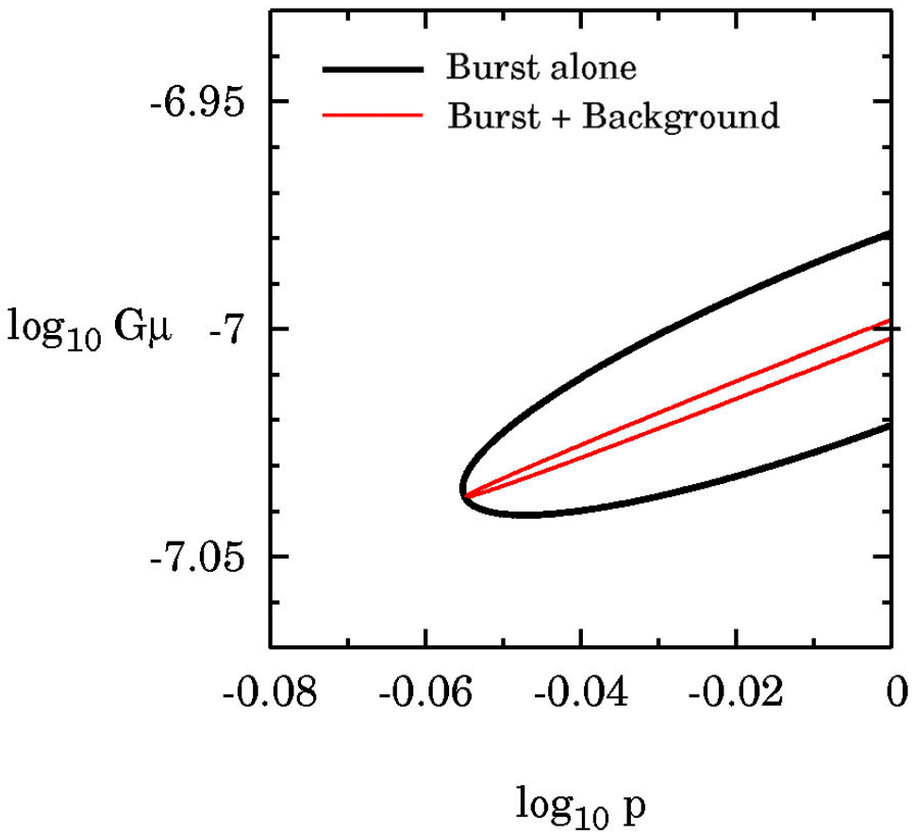
different parameter dependence
= different constraints on
parameters



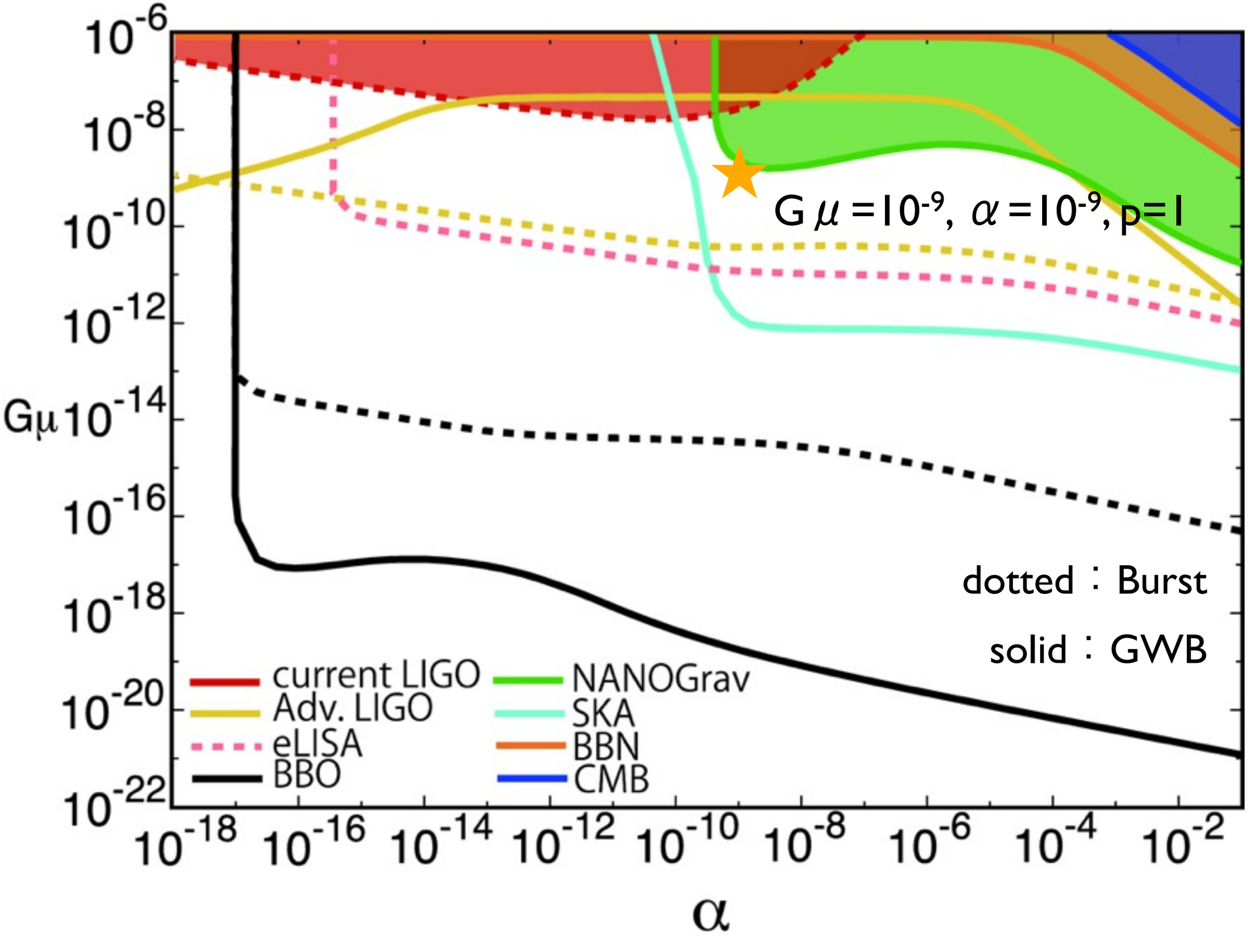
black ： Burst only

red ： Burst + GWB





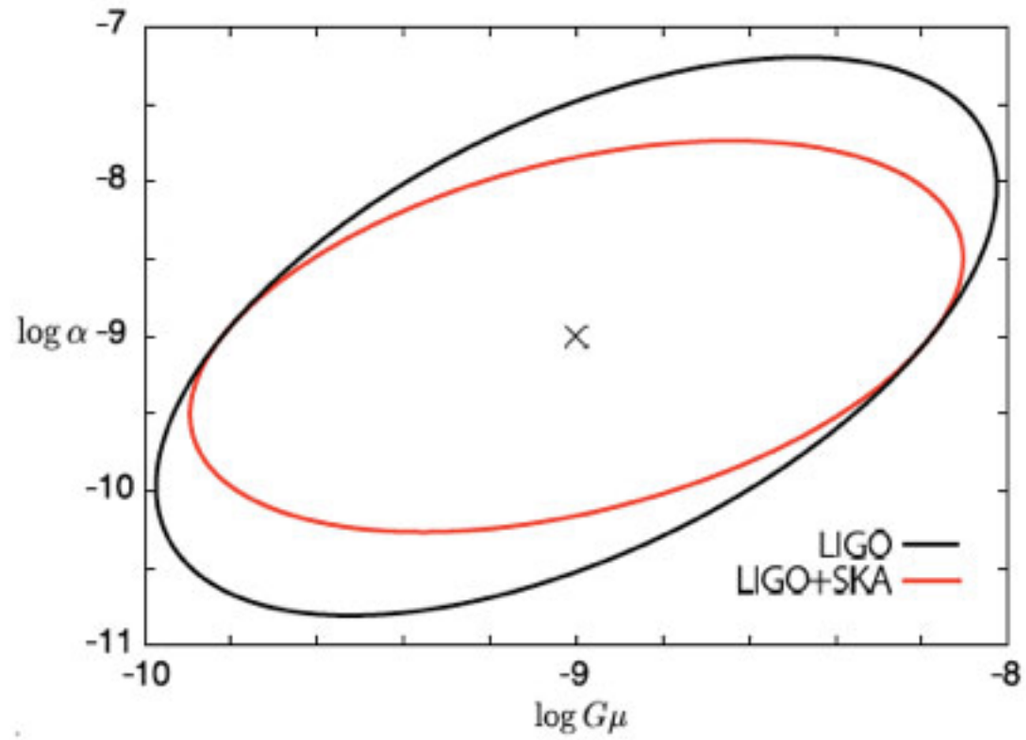
Pulsar timing (SKA) + Advanced-LIGO burst search

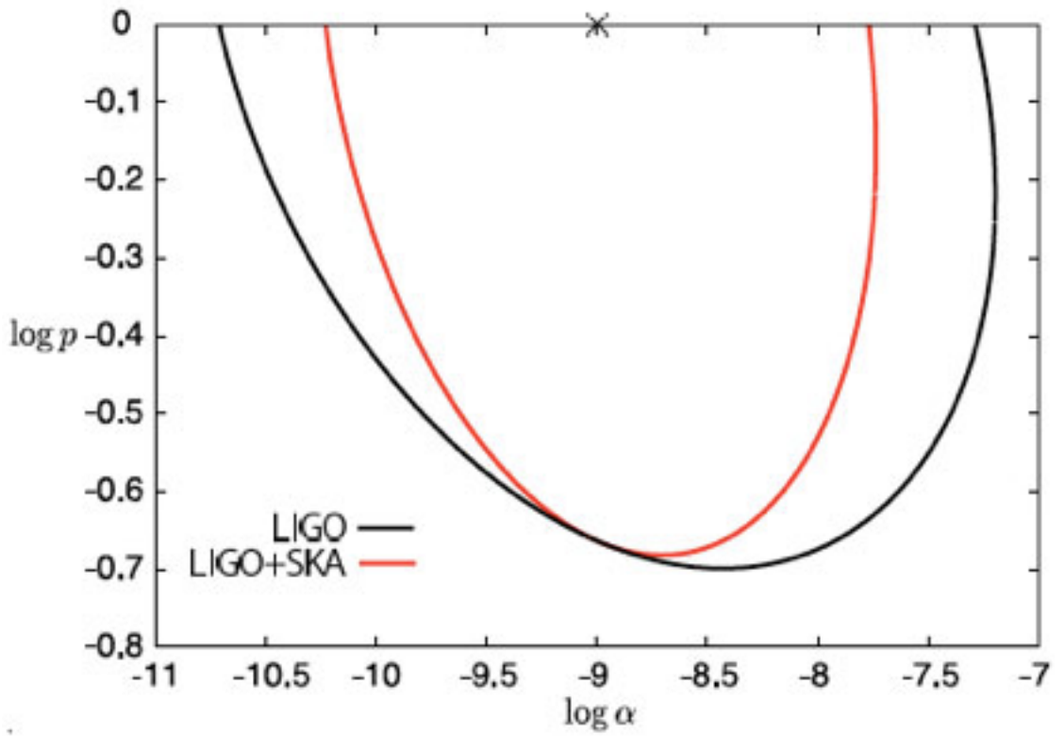


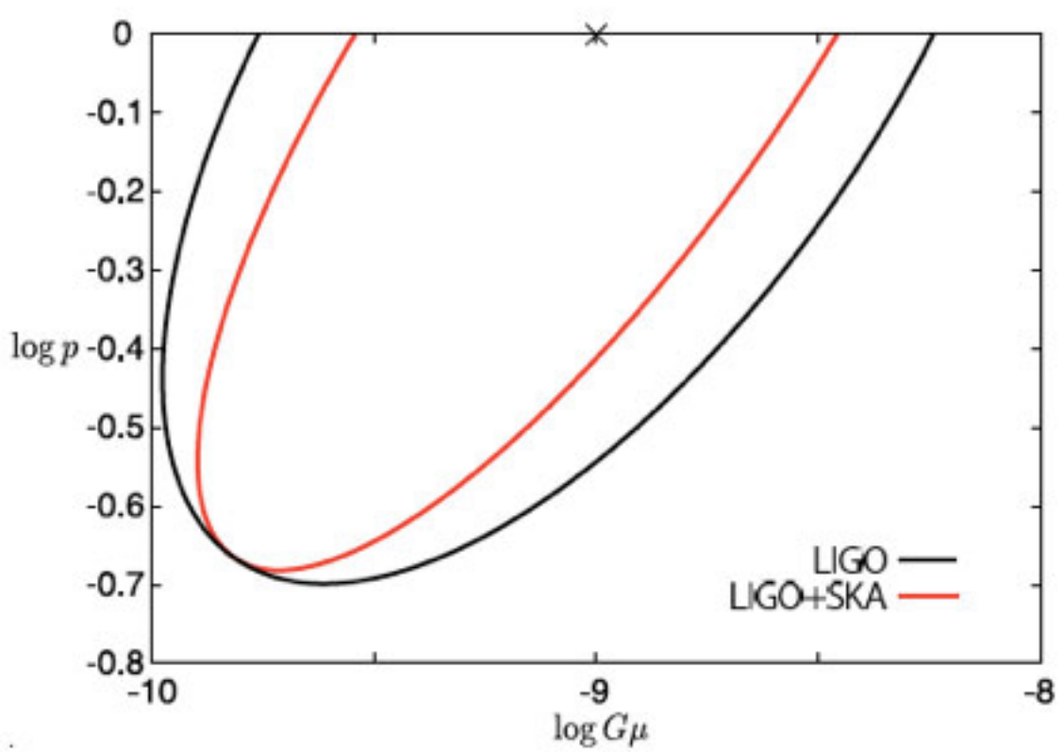
Direct detection + Pulsar timing

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

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



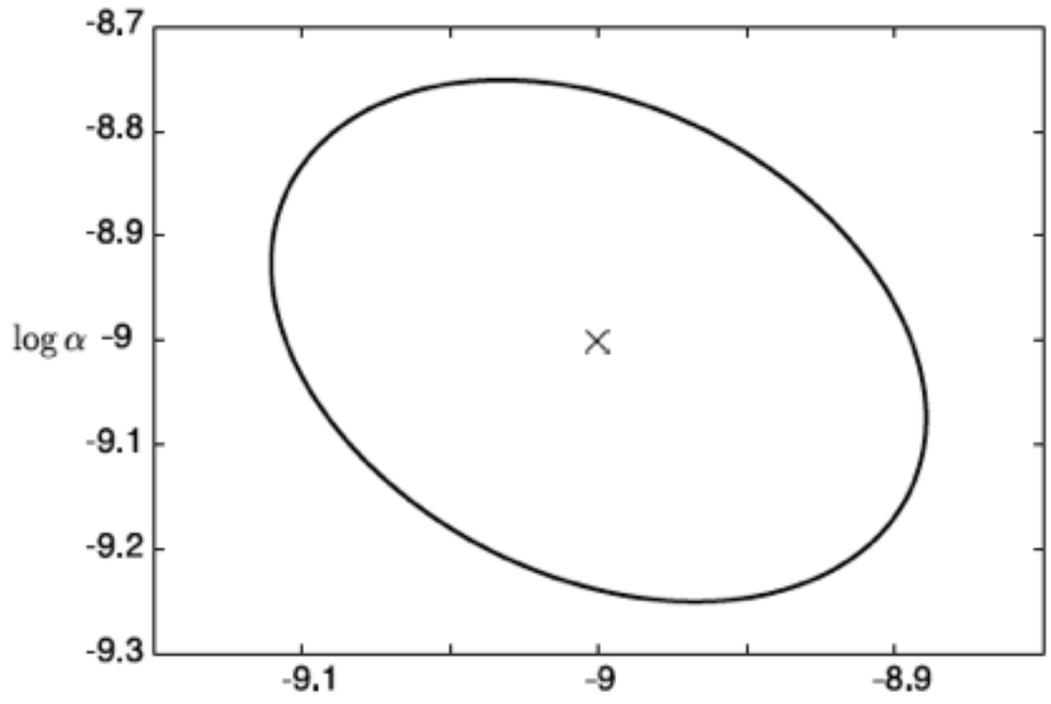


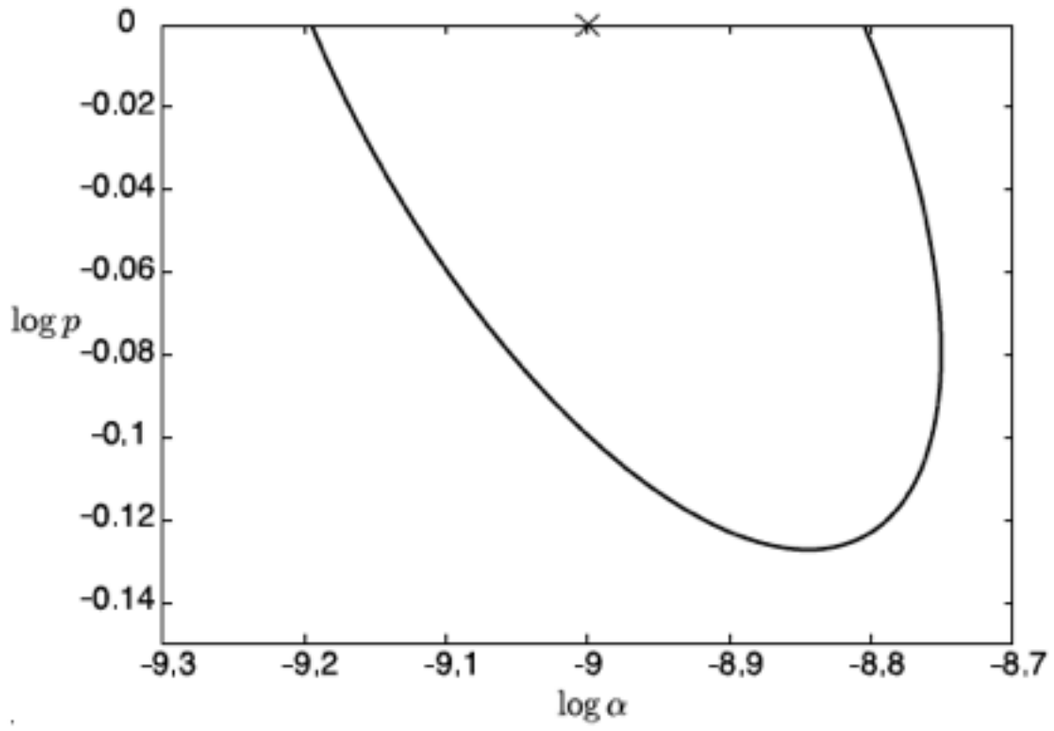


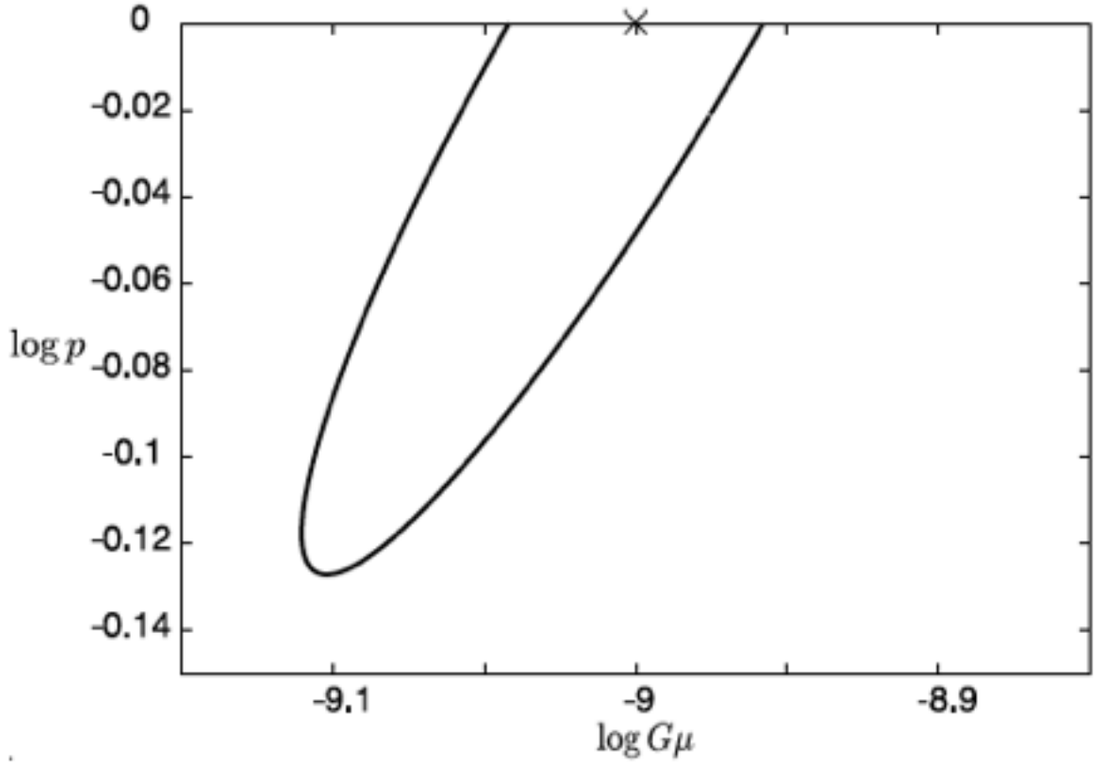
Parameter constraint by eLISA

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

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







Summary

Future GW experiments will be a powerful tool to probe cosmic strings

- It is important to obtain hints on fundamental physics such as particle physics and superstring theory.

- Two different GW observables (rare burst and GWB) provide different information on cosmic string parameters.

- Combination with CMB or Pulser timing also helps to get stronger constraints, depending on the value of the parameters.

- Space GW missions are extremely powerful to probe cosmic strings!