Title: Gravitational Waves from a Decaying Network of Cosmic Strings

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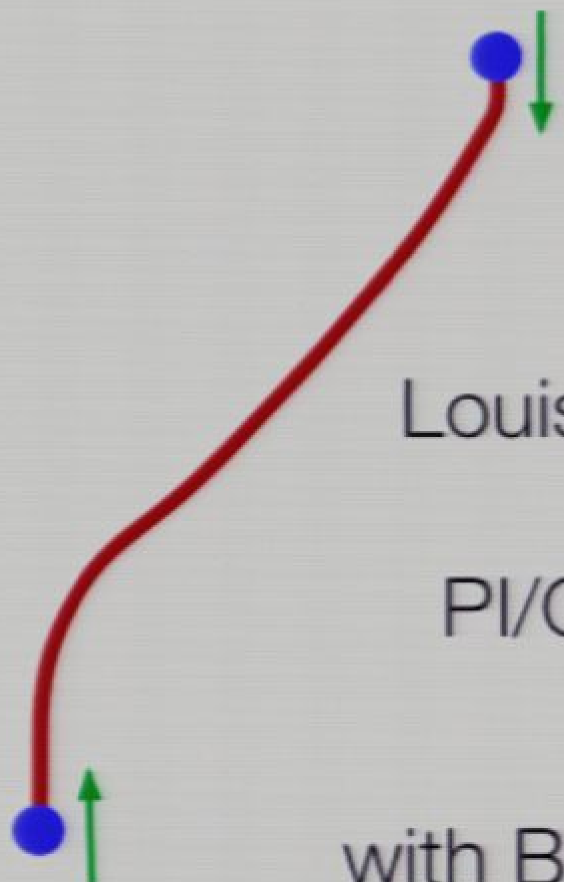
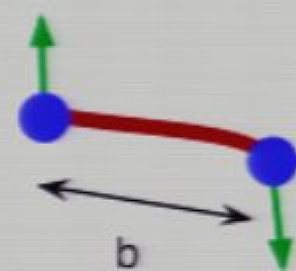
Abstract:

Gravitational Waves from a Decaying Network of Cosmic Strings



Louis Leblond



PI/CITA day

with Ben Shlaer and Xavier Siemens
0903.4686

with Wyman: astro-ph/0701427
with Tye hep-th/0402072

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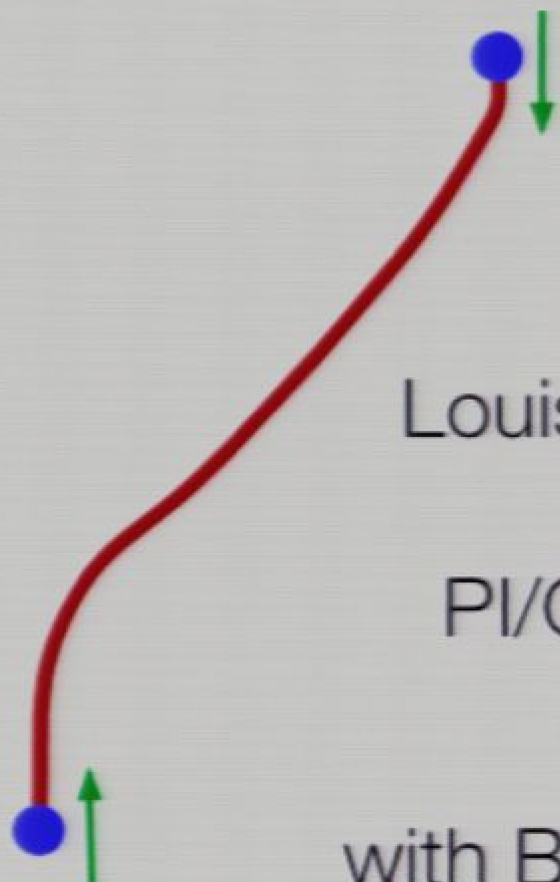

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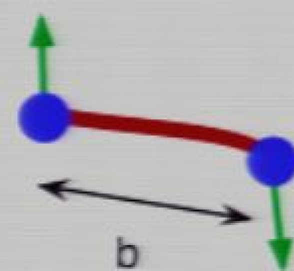

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Motivation and Basic Idea

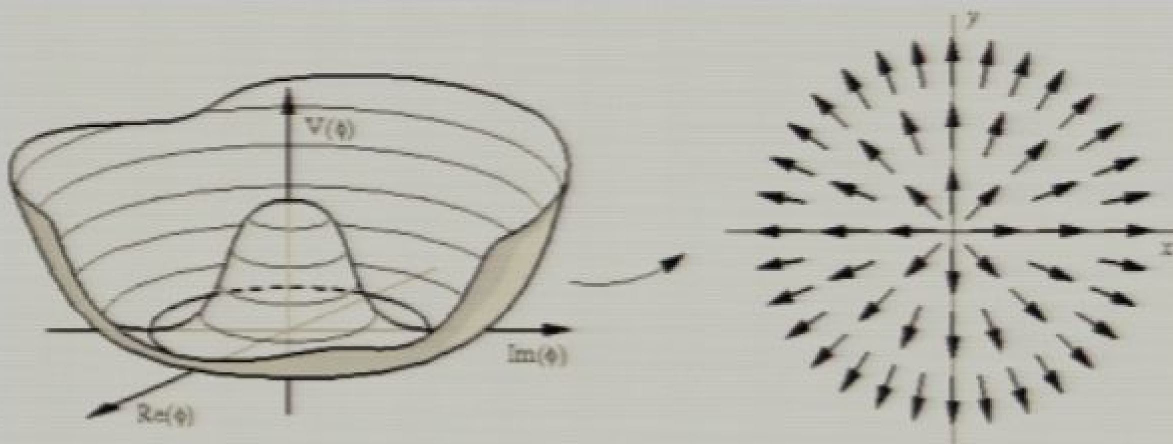
- Cosmic strings can be produced in phase transitions in the early universe
- Their density scale to the dominant fluid in the universe
- Many observational probes and they have a rich phenomenology!
- generically produced but in many models, particularly in string theory, they are often unstable ---> different possibilities, here we will look at breakage.

Q. Can we observe today the remnants of a decay of an unstable network of strings?

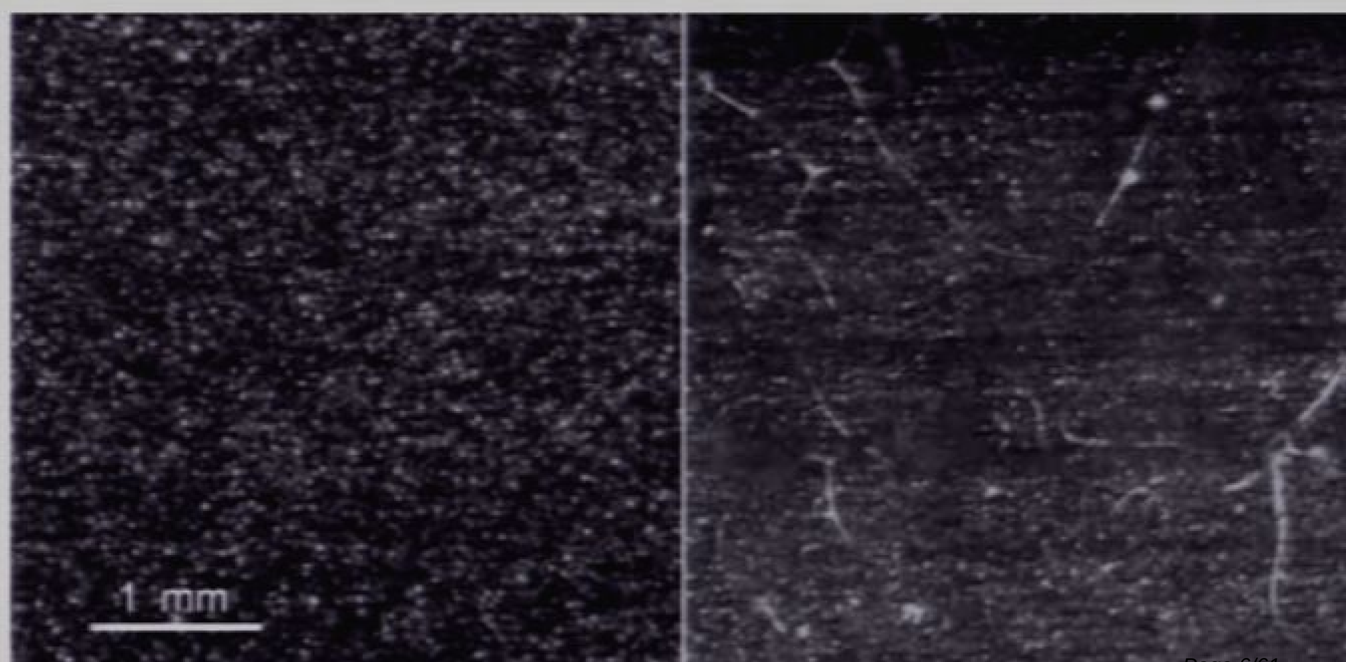
Outline

- Production and Stability of Cosmic Strings
- Gravitational Radiation from a Uniformly Accelerated Mass
- Cosmology of the Decaying Network
- Observational Possibilities with pulsar timing, LIGO, Advanced LIGO and LISA

Typical example: Break a U(1) symmetry -> vortices (cosmic strings)



Vortices in superfluid

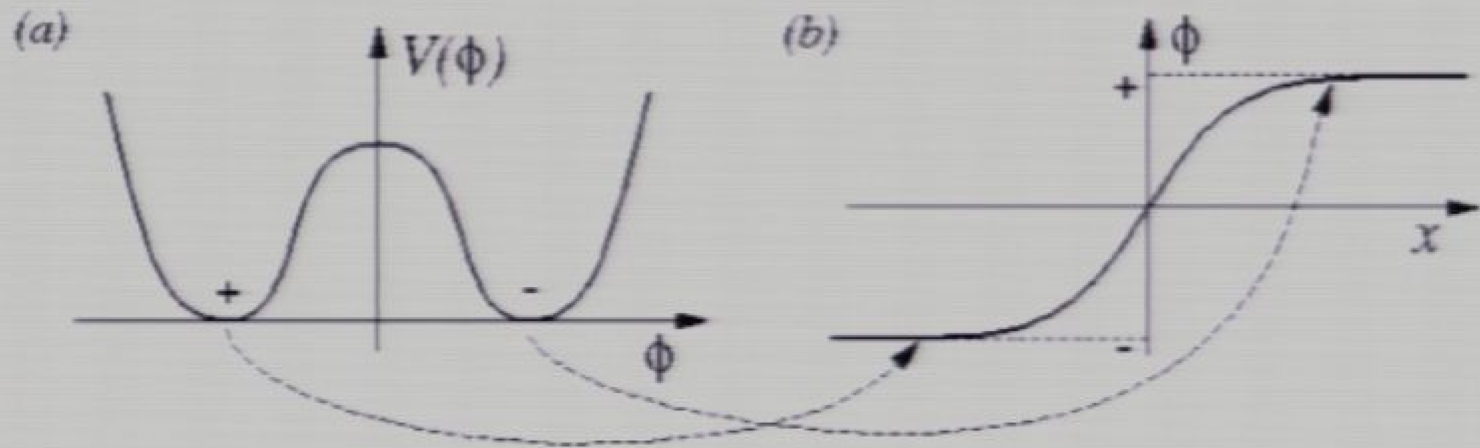


Bewley et al

Other defects are possibles

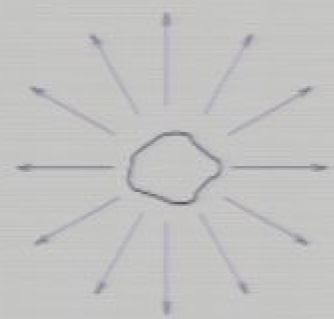
Monopoles (occur when you break a non-Abelian gauge group)

Domain walls
Break to a discrete subgroup

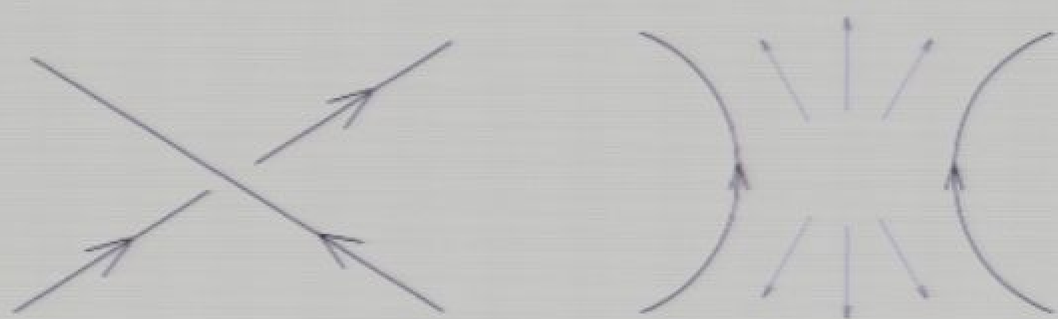


These are usually a cosmological problem b/c their energy density come to fluctuate... infamous monopole problems

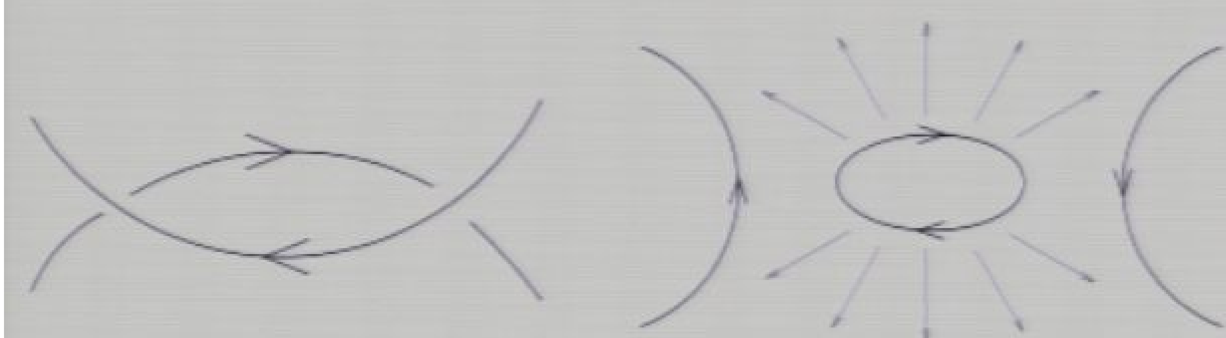
Cosmic strings are cosmologically safe because they can self-destruct



Naively $\rho_{cs} \sim \dfrac{1}{a^2}$



But interaction makes the network track the dominant energy density



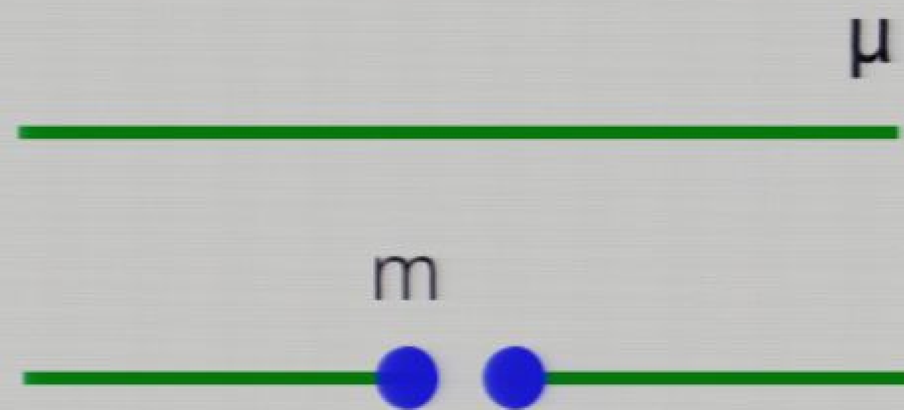
$$\rho_{cs}^{scaling} \sim \frac{1}{a^3} \mathrm{or} \frac{1}{\mathrm{a}^4}$$

Instability to breakage

Local U(1) string

no long range axion force,
no detectable charge at infinity

The string can break on monopoles

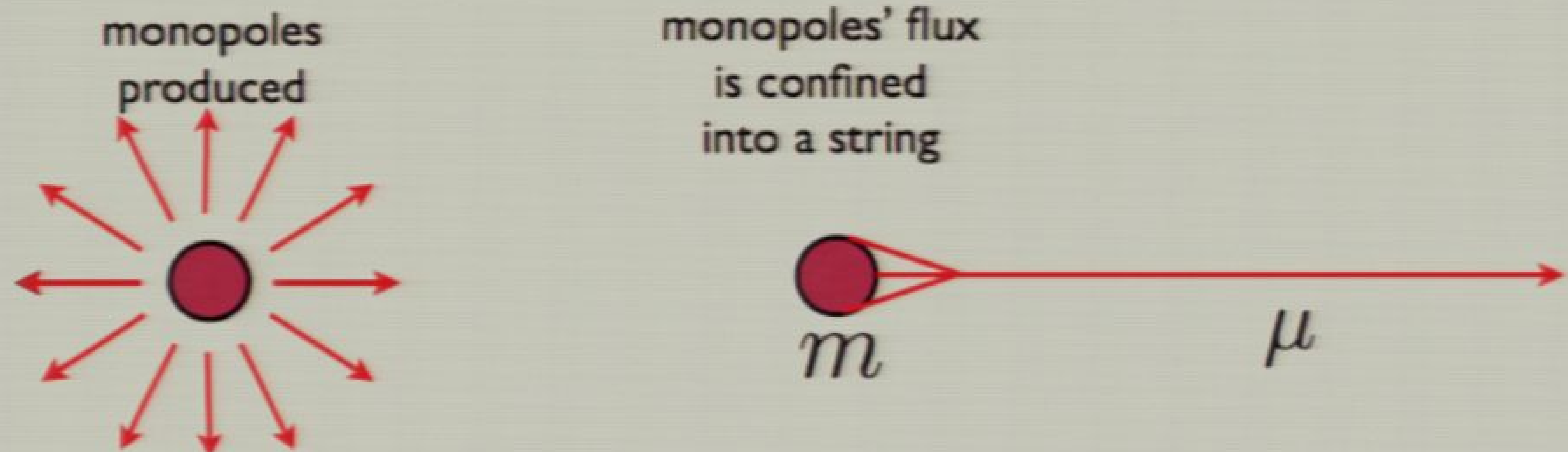


Breakage is a tunneling event

$$\Gamma = \frac{\mu}{2\pi} \exp\left(-\pi m^2/\mu\right)$$

Standard GUT Scenario/Hybrid defects

$$G \to H \times U(1) \to H$$



So we can break on monopoles if U(1) is embedded in a bigger gauge group in the UV completed theory

Langacker & Pi

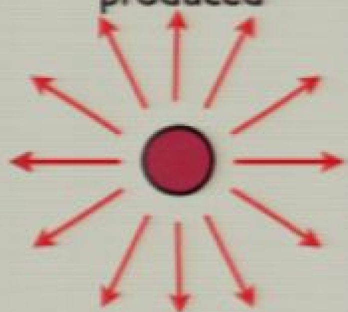
Inflationary Scenario, long lived network

- If inflation occurs below the GUT scale then monopoles are diluted away

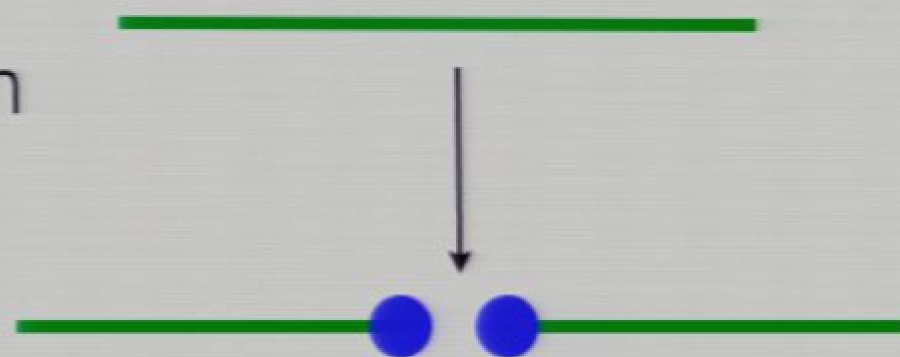
$$G \to H \times U(1) \to H$$

monopoles produced

monopoles' flux



Inflation



$$\kappa \equiv \frac{m^2}{\mu} \qquad t_* \sim \frac{1}{\sqrt{\Gamma}}$$

For a network with $G\mu \sim 10^{-7}$, we need, $\kappa > 84$ for $t_* > t_0$.

So $m = 10\mu^{1/2}$ is a metastable network

Gravitational Waves

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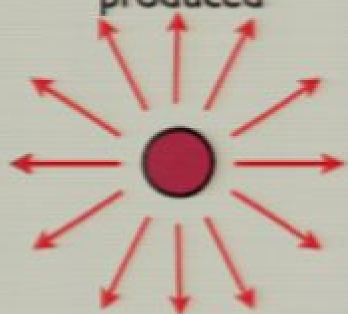

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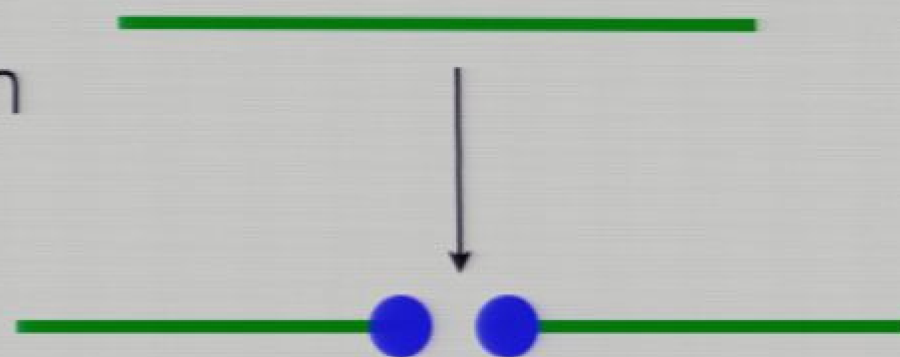

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Gravitational Waves

Cosmic Strings are a potent source of GW. (stochastic and bursts)

strain $h(f)$

GW bursts

Stochastic Background

Sharp step in time domain, mean long tail in frequency domain

unresolved bursts

advanced LIGO

$f_{LIGO} \sim 100Hz$

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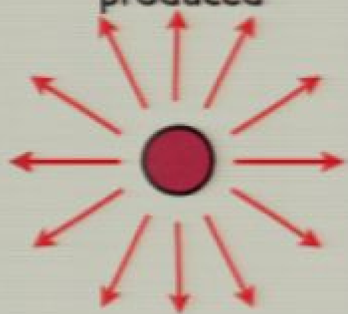

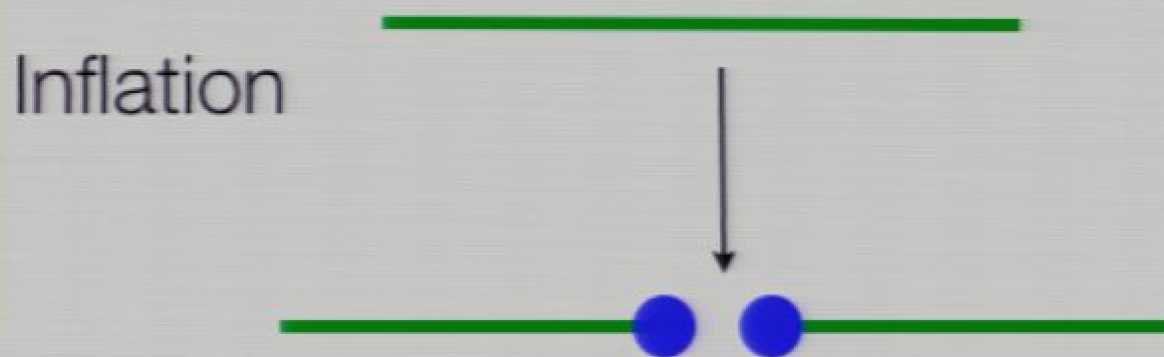

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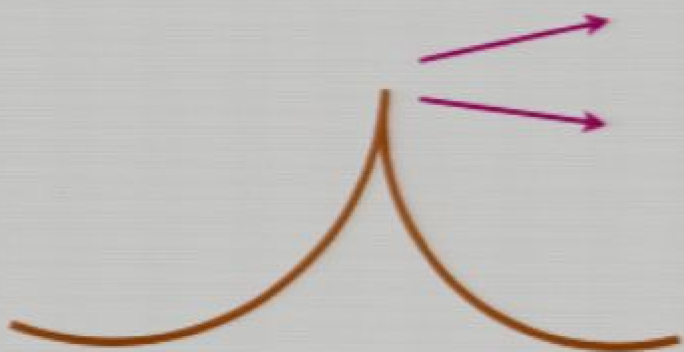
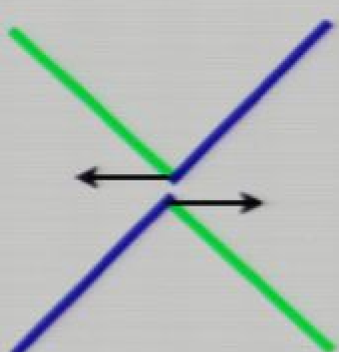
Cusps and Kinks

- Cusps occur when the derivative is infinite at a point on the string. Periodically occur when a cosmic string loop oscillates

- Kinks occur when the derivative is discontinuous.

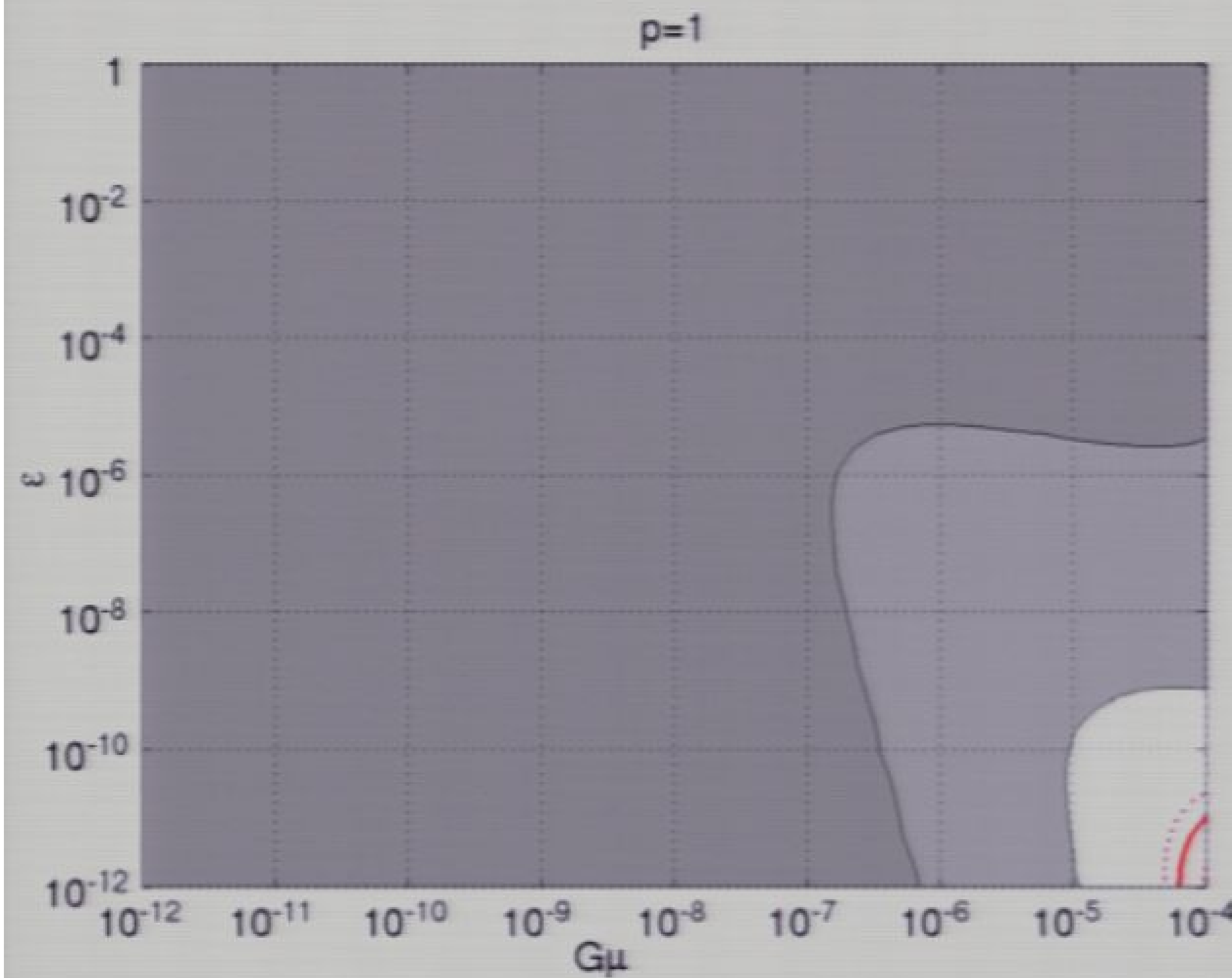


$$h(f) = \frac{A}{f^{4/3}}$$



$$h(f) = \frac{A}{f^{5/3}}$$

Damour & Vilenkin



Cusps

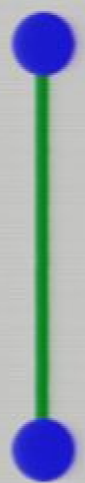
Ligo S4

Matched filters with template $f^{-4/3}$

loop size at formation time

$$l = 50\epsilon G\mu t$$

LIGO collaboration
0904.4718



Start with the idealize situation, straight oscillating segment

Martin & Vilenkin

Approximation, length of string much bigger than its thickness and we use Nambu-Goto action, (neglecting spacetime expansion)

$$T^{03}(t,\mathbf{x}) = m(\gamma_0 v_0 - a|t|)[\delta(\mathbf{x} - x_1(t)\hat{z}) - \delta(\mathbf{x} + x_1(t)\hat{z})],$$

$$x_i(t) = (-1)^i \frac{sgn(t)}{a}(\gamma_0 - \sqrt{1 + (\gamma_0 v_0 - a|t|)^2})$$

period $T = \dfrac{2\gamma_0 v_0}{a}$ acceleration is constant $a = \mu/m$

The monopoles are ultra-relativistic!!

Gravitational Waveforms for a periodic source

Solution of Einstein equation in the Wavezone

$$h_{\mu\nu}(\mathbf{x},t) = \sum_{n=-\infty}^{\infty} \epsilon_{\mu\nu}^{(n)}(\mathbf{x},\omega_n)e^{-ik_n\cdot x},$$

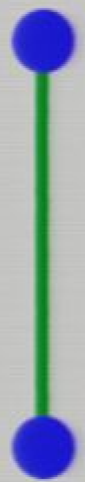
Polarization tensor

$$\epsilon_{\mu\nu}^{(n)}(\mathbf{x},\omega_n) = \frac{4G}{r}(T_{\mu\nu}(k_n) - \frac{1}{2}\eta_{\mu\nu}T_{\lambda}^{\lambda}(k_n))$$

$$T^{03}(\omega_n,\mathbf{k}) = m\gamma_0 v_0 I_n(u)$$

$$I_n(u) = \int_0^1 \xi d\xi[\cos(n\pi(1-\xi-\frac{u}{v_0}+u\sqrt{\xi^2+1/(\gamma_0 v_0)^2}))$$

$$-\cos(n\pi(1-\xi+\frac{u}{v_0}-u\sqrt{\xi^2+1/(\gamma_0 v_0)^2}))]$$



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$$u = \cos\theta$$

$$n = fl$$

- Linearly polarized (plus polarization)
- large frequency n>> γ_0^2, the waveform α $1/n^2$
- in this range of frequency, we have a burst

$$\frac{1}{l} < f < \frac{\gamma_0^2}{l}$$

$$h(f,r) \approx C\frac{G\mu}{r}\frac{l}{f}$$

focused in a beaming angle

$$\theta_f \approx \frac{\mathcal{O}(1)}{\sqrt{fl}}$$

Power Radiated--- Flat Spectrum

$$P_n = 2n^2\pi^2 G\mu^2 \int_0^1 du\,(1/u - u)^2\,|I_n(u)|^2$$

In frequency range $\frac{1}{l} < f < \frac{\gamma_0^2}{l}$

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Power per log interval (nP_n) is quasi constant flat spectrum!

$$P = \sum_n P_n \sim 8G\mu^2 \ln \gamma_0$$

nearly independent of mass

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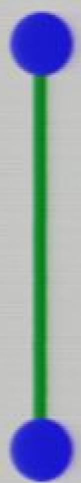

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Rate of Bursts

Let n(l,t)dl be the number density of segment of length l at time t. (length is max length = E/μ)

There is one burst per oscillation, T~l

$$\nu(l,t)dl \sim \frac{1}{l} n(l,t)dl$$

Beaming fraction

$$\Delta(l,f,z) \sim \frac{1}{4(1+z)fl}\Theta(\gamma_0 - 1)\Theta\left((1+z)fl - 1\right)$$

$$\frac{dR}{dzdl} \sim H_0^{-3}(1+z)^{-1}\varphi_V(z)\nu(l,z)\Delta(l,f,z)$$

↑ cosmological function

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↑ cosmological function

Amplitude, we look at a template

$$h(f) = A/f \qquad h(f,r) \approx C\frac{G\mu}{r}\frac{l}{f}$$

We can relate the length of a string to the amplitude of the burst emitted

$$l(A,z) \sim \frac{A\varphi_r(z)}{G\mu H_0}$$

include cosmological function

Given a experiment sensitivity to this template we can calculate the minimum detectable amplitude A_m

$$R_{>A_{\min}} = \int_{A_{\min}}^{\infty} dA \int_0^{\infty} dz \frac{dR}{dz dA}$$

$$A_m^{LIGO} \approx 10^{-21}$$
$$A_m^{ADV} \approx 10^{-22}$$

Stochastic Background

Even simpler to calculate, just sum all the bursts power per frequency interval

$$\Omega_{\rm gw}(f) = \frac{4\pi^2}{3H_0^2} f^3 \int dz \int dl\, h^2(f,z,l) \frac{dR}{dz\,dl},$$

Scale invariant

$$\Omega_{\rm gw} = \Omega_{\rm gw}(f) \ln \frac{f_{max}}{f_{min}}$$

Summary of properties of the gravitational radiation

- The power radiated is approximately independent of the length of the segment
- The power radiated is approximately independent of the mass of the bead
- The radiation is scale invariant for $1 < fl < \gamma_0^2$
- strong 1/f burst

Cosmology

$$n(l, t) = ??$$

- Basic idea. We form the network with some initial density of cosmic strings, it reaches the scaling solution quickly. Segment starts decaying right away but their average length is greater than Hubble horizon.

- At t=t*, the typical segment length becomes sub-horizon, the strings start oscillating, emits GW, no more scaling.

- At t=t**, the network is gone into radiation.

Let n(l,t)dl be the number density of segment of length l at time t. (length is max length = E/μ)

$$\int_0^\infty n(l,t)\mu l\,dl = \rho_{cs}$$

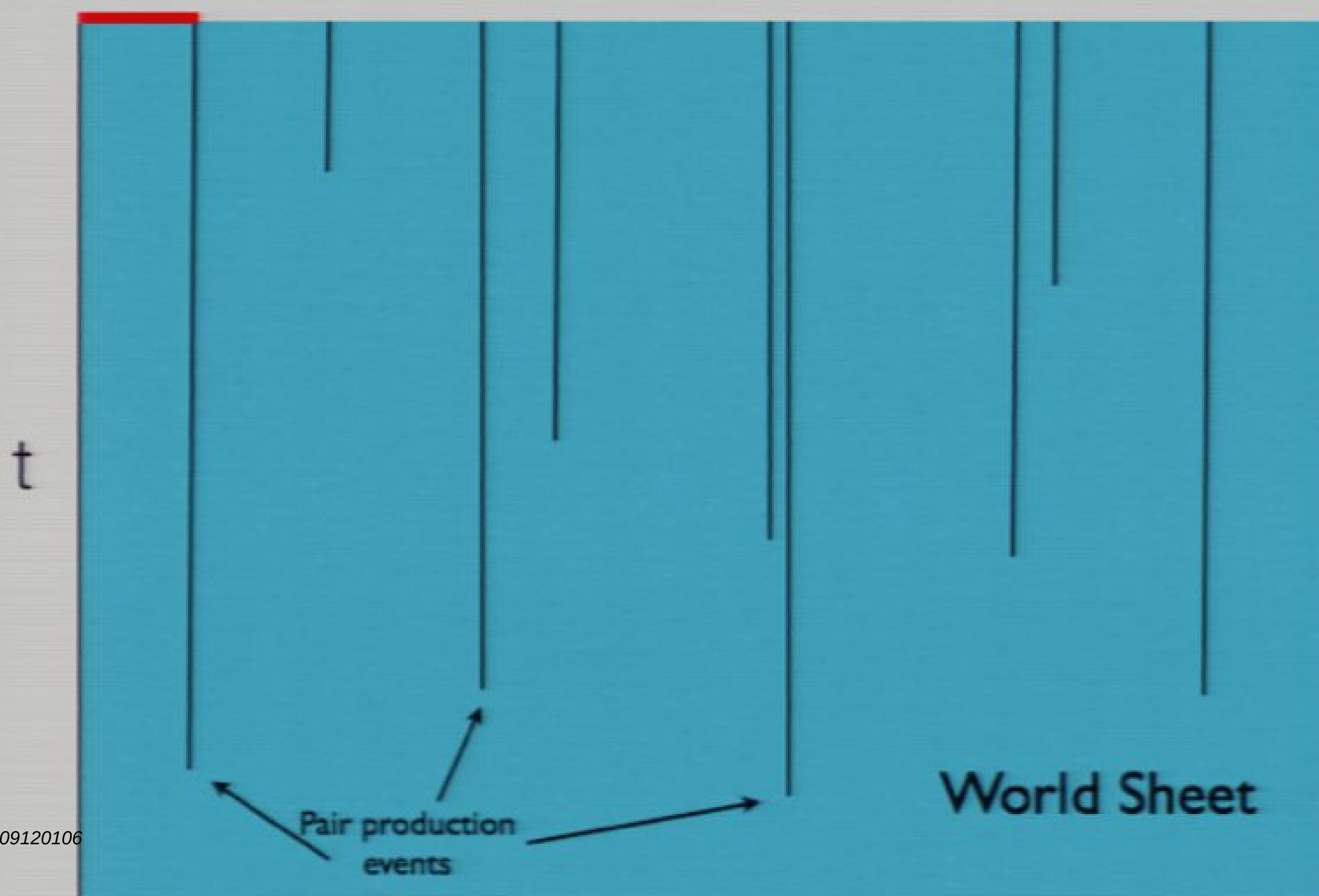
Simplistic derivation

$$P(l,t)dl = \Gamma_2 t \exp(-\Gamma_2 l t) dl$$

$$n(l,t)dl = P(l,t)dl \frac{\rho_{cs}(t)}{\int_0^\infty P(l',t)\mu l' dl'}$$

$$P_k(A) = \frac{(A\Gamma_2)^k e^{-A\Gamma_2}}{k!}$$

$$n(l,t)dl = \Gamma_2^2 \exp\left(-lt\Gamma_2\right) dl$$



$$\rho_{cs}(t) \sim \frac{\mu}{t^2}$$

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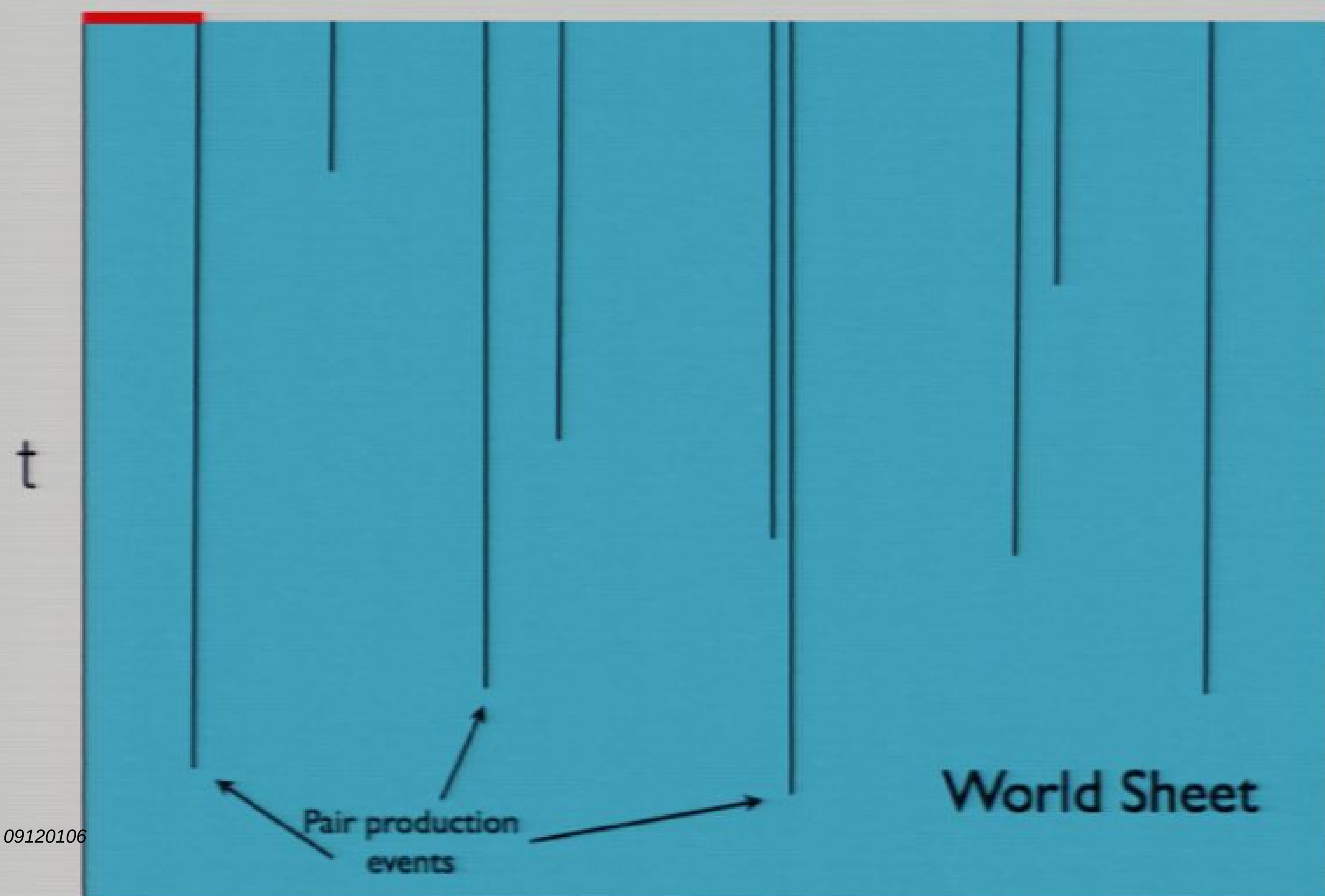
$$n(l,t)dl = P(l,t)dl \frac{\rho_{cs}(t)}{\int_0^\infty P(l',t)\mu l' dl'}$$

$$n(l,t)dl = \Gamma_2^2 \exp\left(-lt\Gamma_2\right) dl$$



$$\rho_{cs}(t) \sim \frac{\mu}{t^2}$$

The real thing, solving the Boltzmann Equation

$$\frac{\partial n(l,t)}{\partial t} = -\frac{\partial}{\partial l}\left(\dot{l}\, n(l,t)\right) - 3\frac{\dot{a}}{a} n(l,t) + g$$

loss/gain of length of an individual segment

production/annihilation of new string

We can characterize explicit terms within g as being one of three types: loop producing, segment intercommutation, and segment breaking.

$$g = g_{\mathtt{loop}} + g_{\mathtt{ic}} + g_{\mathtt{break}}$$

if g=0, $\rho \sim 1/a^2$ and strings dominate

if $g_{break} = 0$, we should reach scaling

So we can infer the effects of loops and intercommutation by requiring scaling

$$\begin{aligned} \dot{l} &= \dot{l}_H + \dot{l}_{\mathtt{loop}} \\ &= 3Hl - \frac{2l}{t} \qquad \text{(scaling solution)} \end{aligned}$$

$$g_{\mathtt{break}} dl \;=\; \Gamma_2 \left(2 \int_l^\infty n(l',t)dl' \; - l n(l,t) \right) dl$$

The breakage rate of strings of length l is Γ_2 l, which explains the last term. The first term can be understood by considering the process by which n(l,t)dl increases.This is entirely due to longer strings, those of length l' > l. The rate at which longer strings break to produce those of length between l and l + dl is given by the number of longer strings present (hence the integral), and the measure of string where a break yields a shorter string of length between l and l + dl, i.e. 2dl.

So we obtain an integro-differential equation

$$\frac{\partial n(l,t)}{\partial t} = -\frac{\partial}{\partial l}\left[\left(3Hl - \frac{2l}{t}\right) n(l,t)\right] - 3Hn(l,t) + g_{\mathtt{break}}$$

final answer for $t < t_*$
in rad era

- When the strings become sub-Hubble (t*), they start oscillating.

- Is loop production still strong enough to ensure scaling?? We will assume not but this should be checked (the answer does not change much). As the strings get shorter they actually start behaving like matter (which increase their density in the rad era)

- They start radiating bursts and losing energy to GW

$$P \approx 8\ln(\gamma_0)G\mu^2 \qquad\qquad \dot{l}_{\rm gw} \approx -8\ln(\gamma_0)G\mu$$

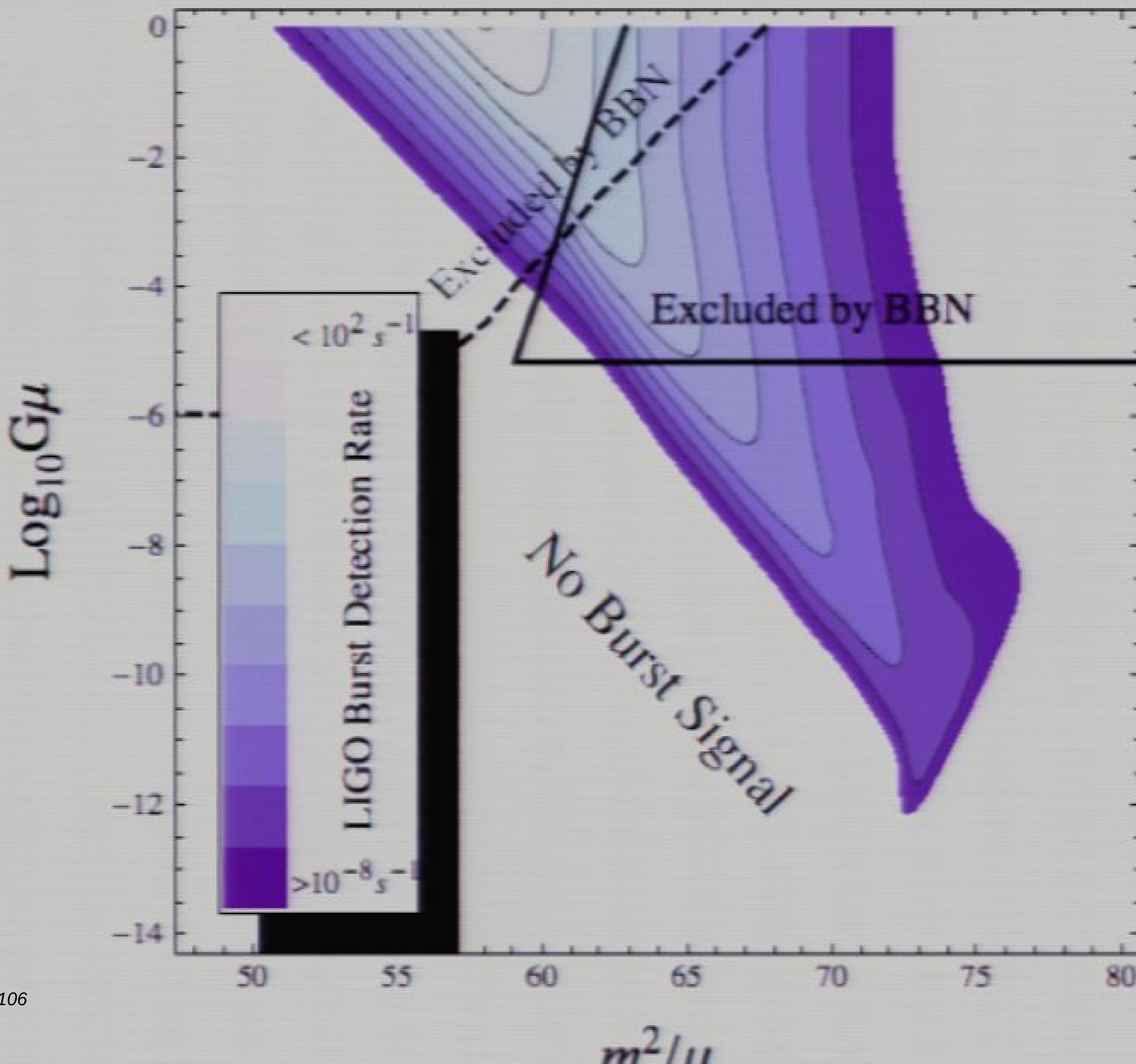
The string oscillate until some t** where the whole network is gone to GW radiation

$$t_{**} \;=\; t_*/\sqrt{8\ln\gamma_0 G\mu} \;=\; 1/\sqrt{8\ln\gamma_0\Gamma_2 G\mu}$$

note that lighter string will oscillate longer and produce a lot more bursts!!

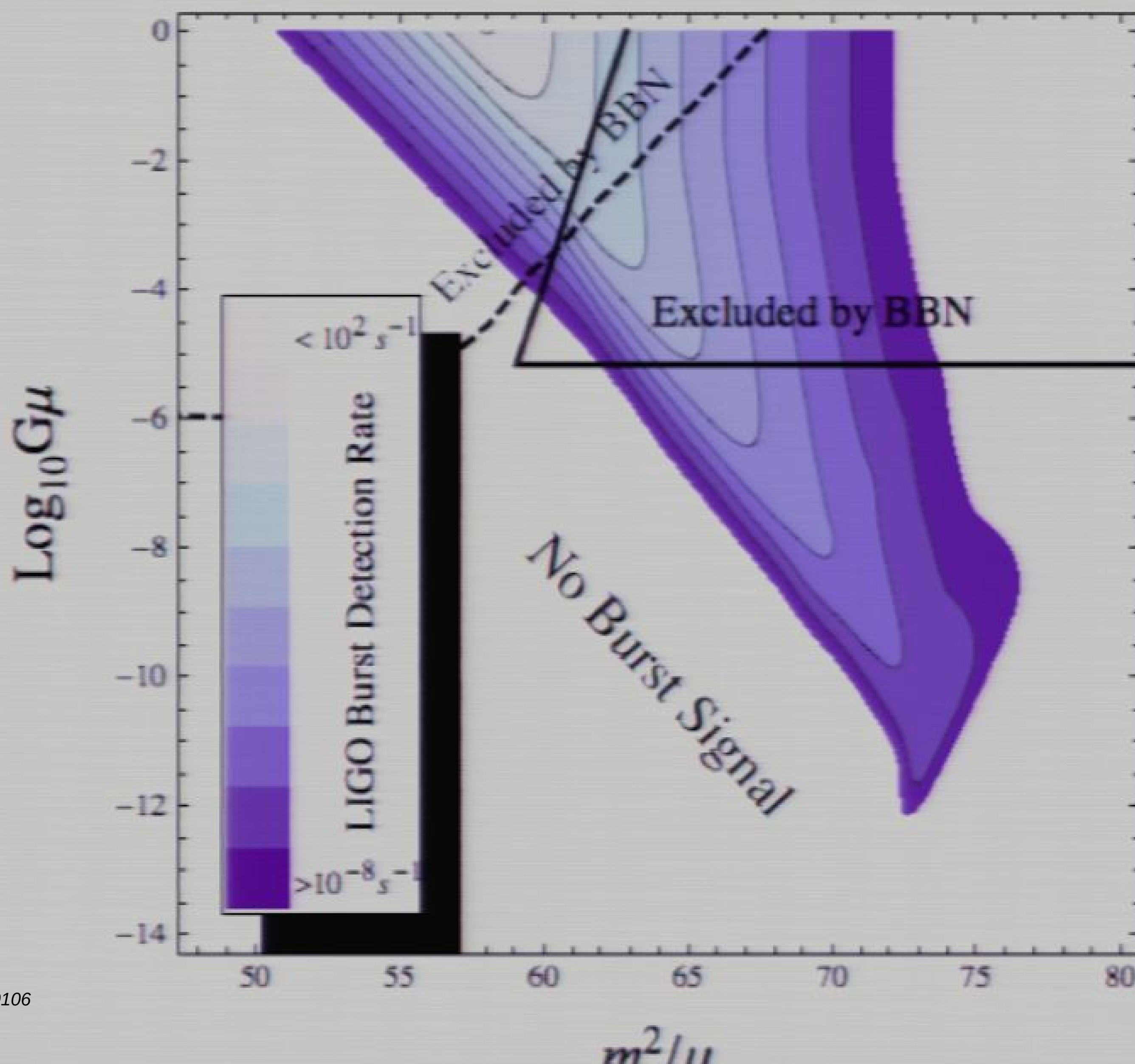
$$n(l,t) = \Gamma_2^2\exp(-\Gamma_2 l t)\sqrt{\frac{t}{t_*}}\exp(-\tfrac{1}{2}t^2/t_{**}^2) \qquad t_* < t < t_{**}$$

Bursts LIGO



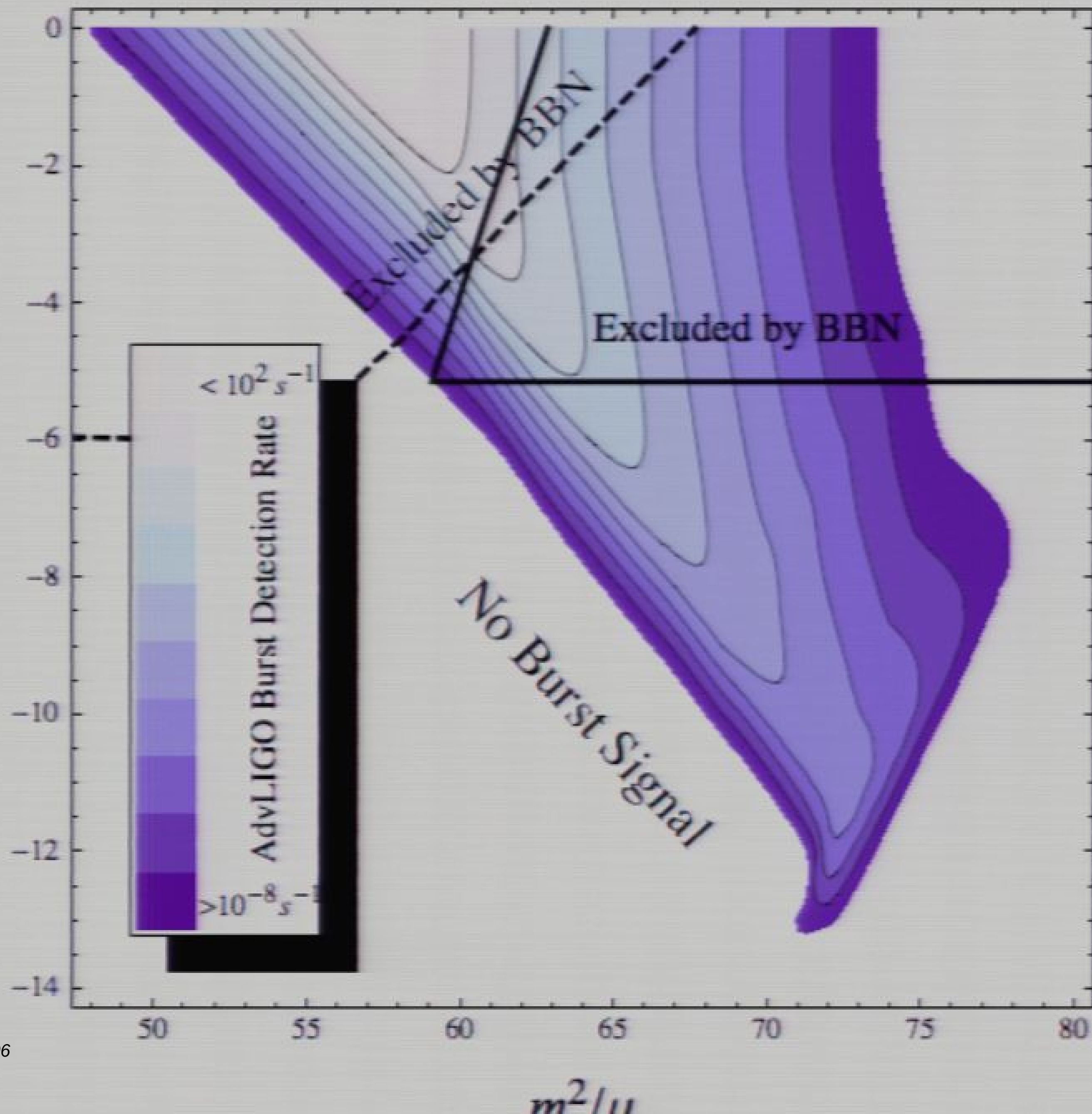
Most of the signal comes from z**

Bursts LIGO

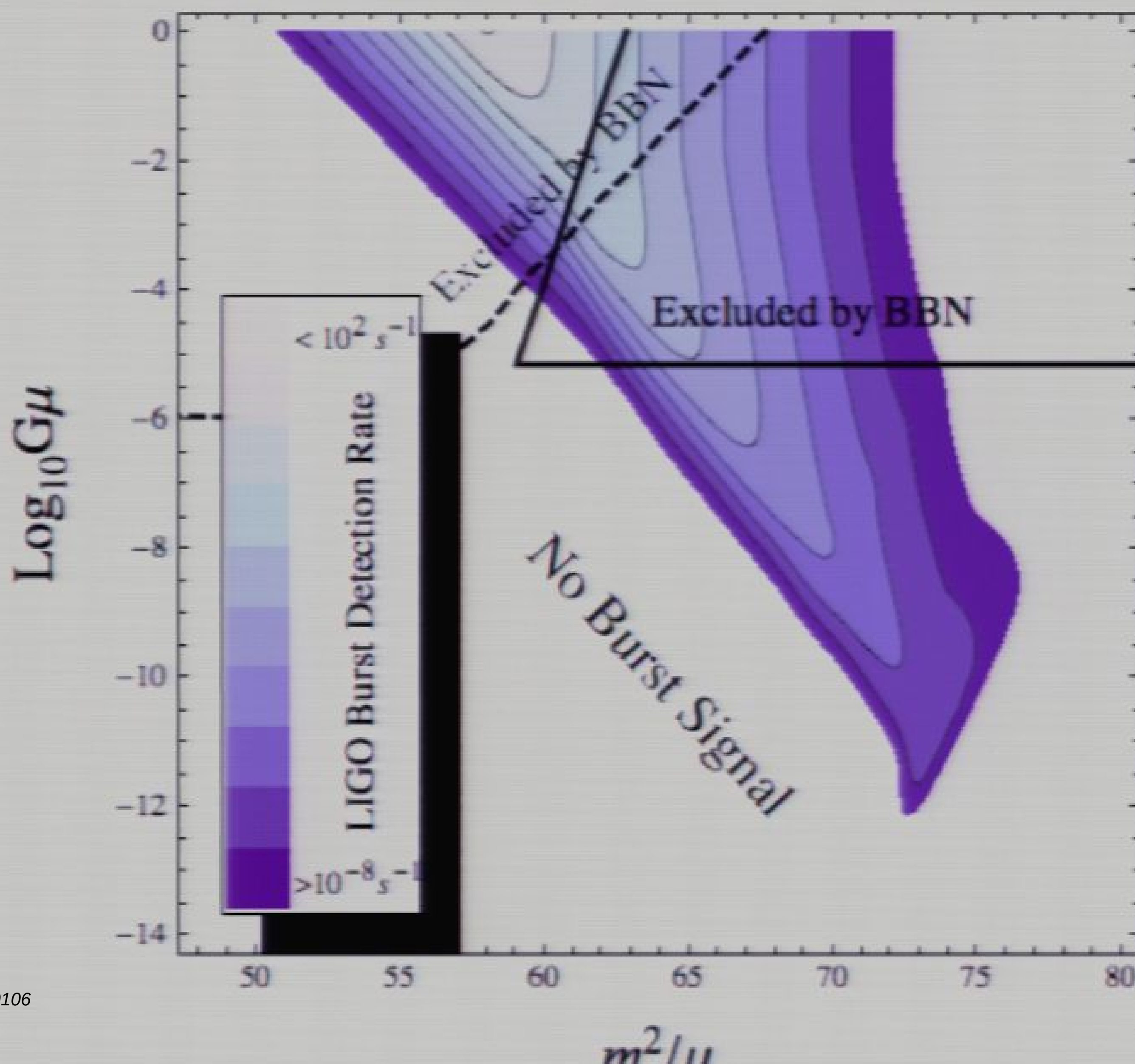


Most of the signal comes from z**

Advanced LIGO

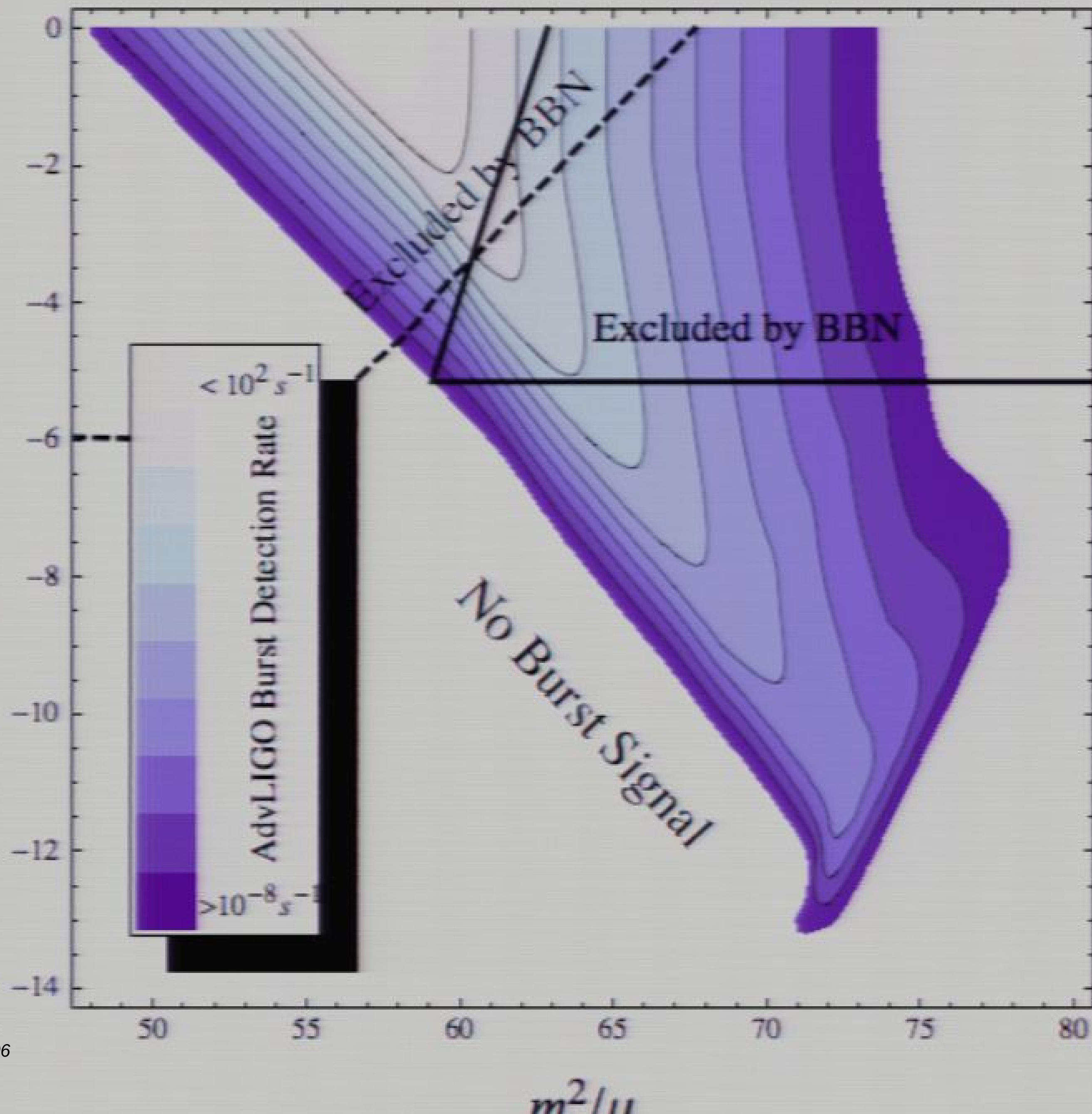


Bursts LIGO

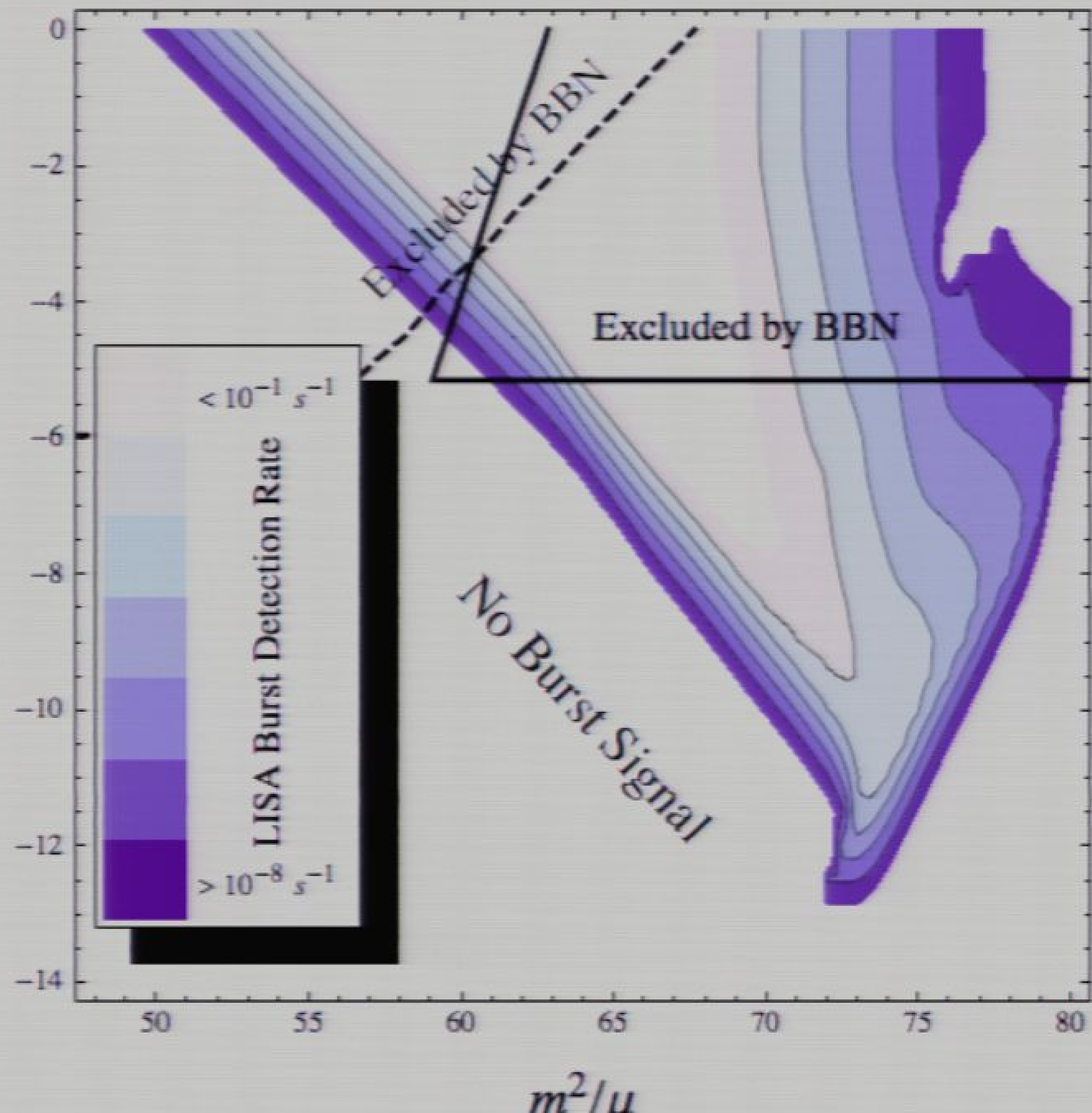


Most of the signal comes from z**

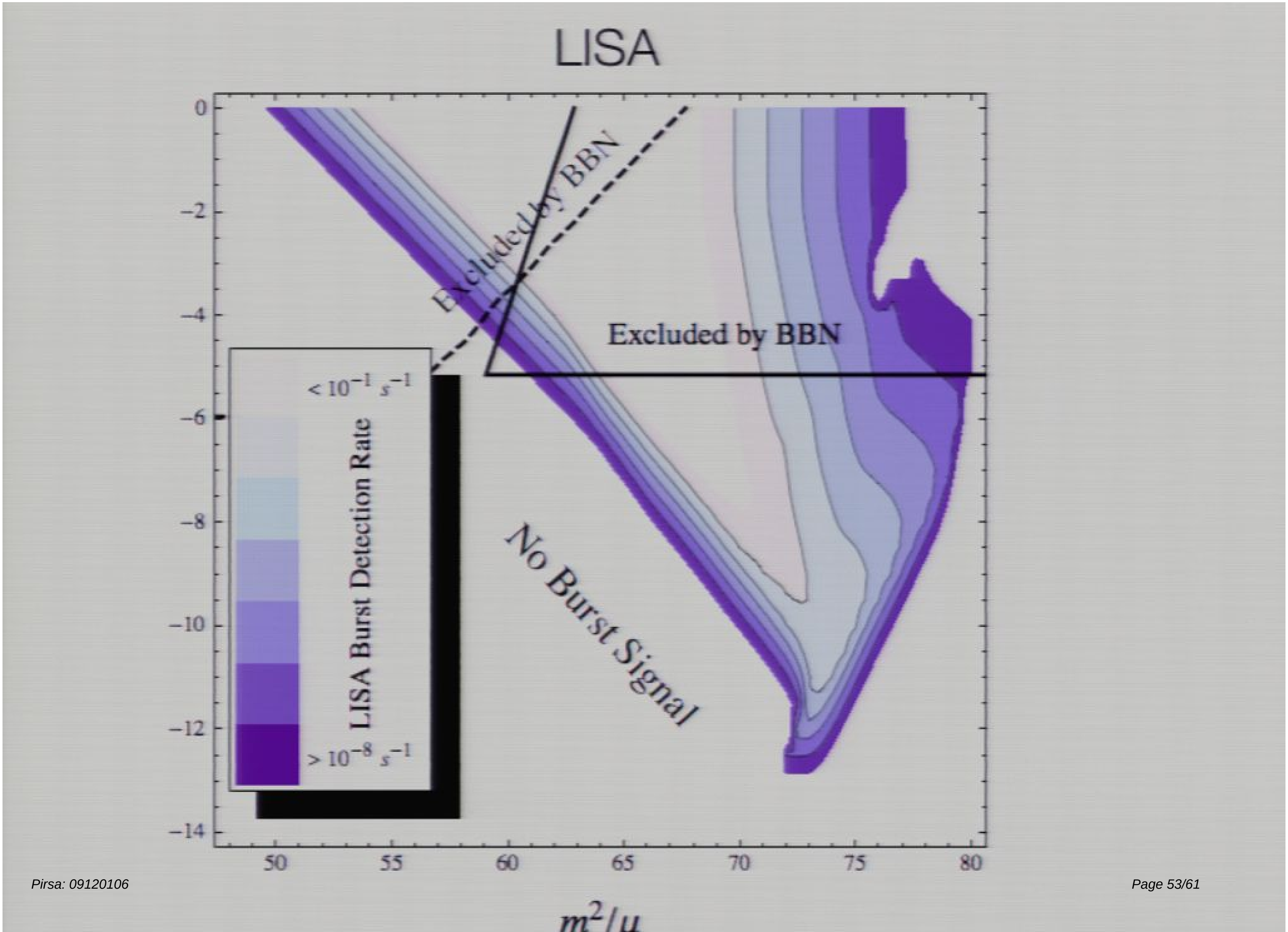
Advanced LIGO



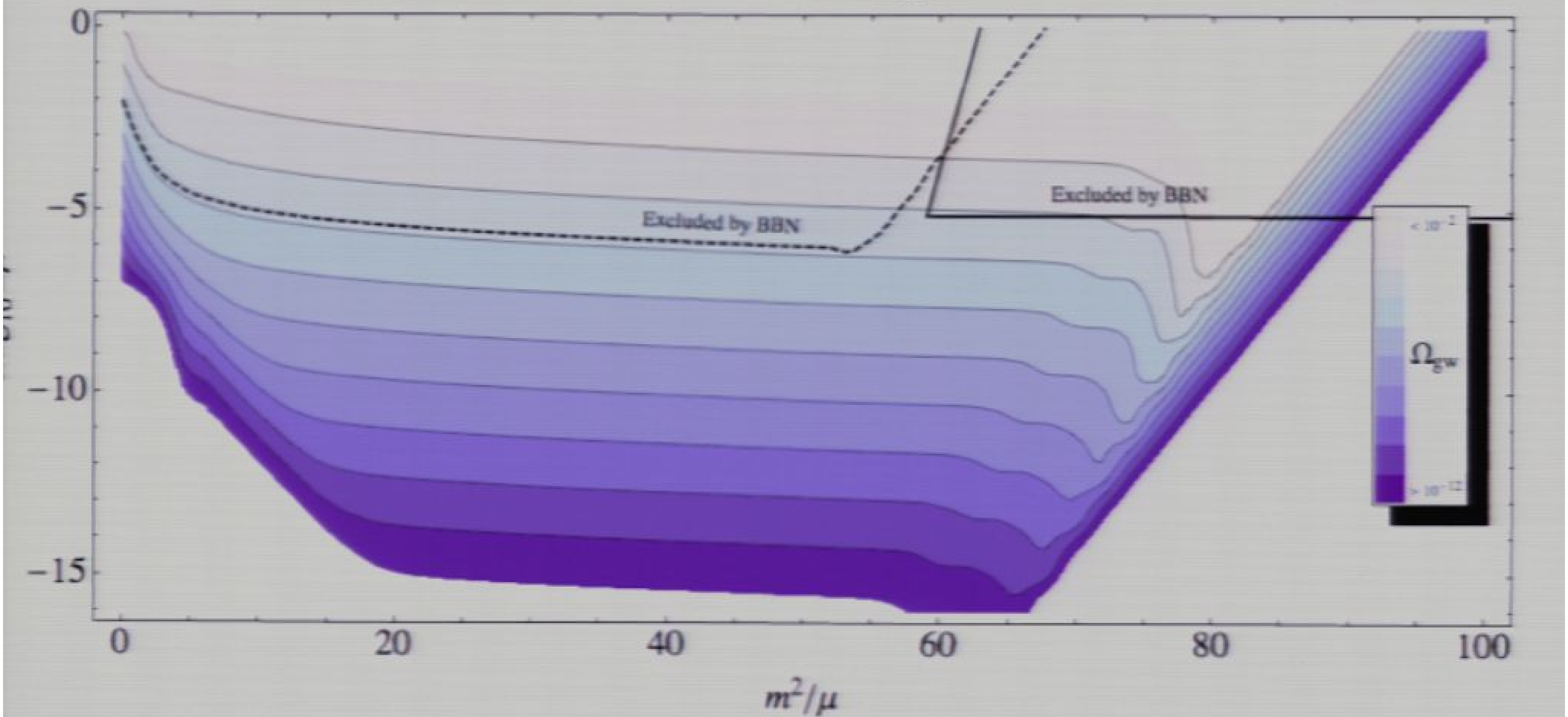
LISA



Excluded by BBN
Excluded by BBN
No Burst Signal
LISA Burst Detection Rate
$< 10^{-1}\ s^{-1}$
$> 10^{-8}\ s^{-1}$
m^2/μ


LISA
Excluded by BBN
Excluded by BBN
< 10^-1 s^-1
LISA Burst Detection Rate
> 10^-8 s^-1
No Burst Signal
0
−2
−4
−6
−8
−10
−12
−14
50
55
60
65
70
75
80
m²/μ

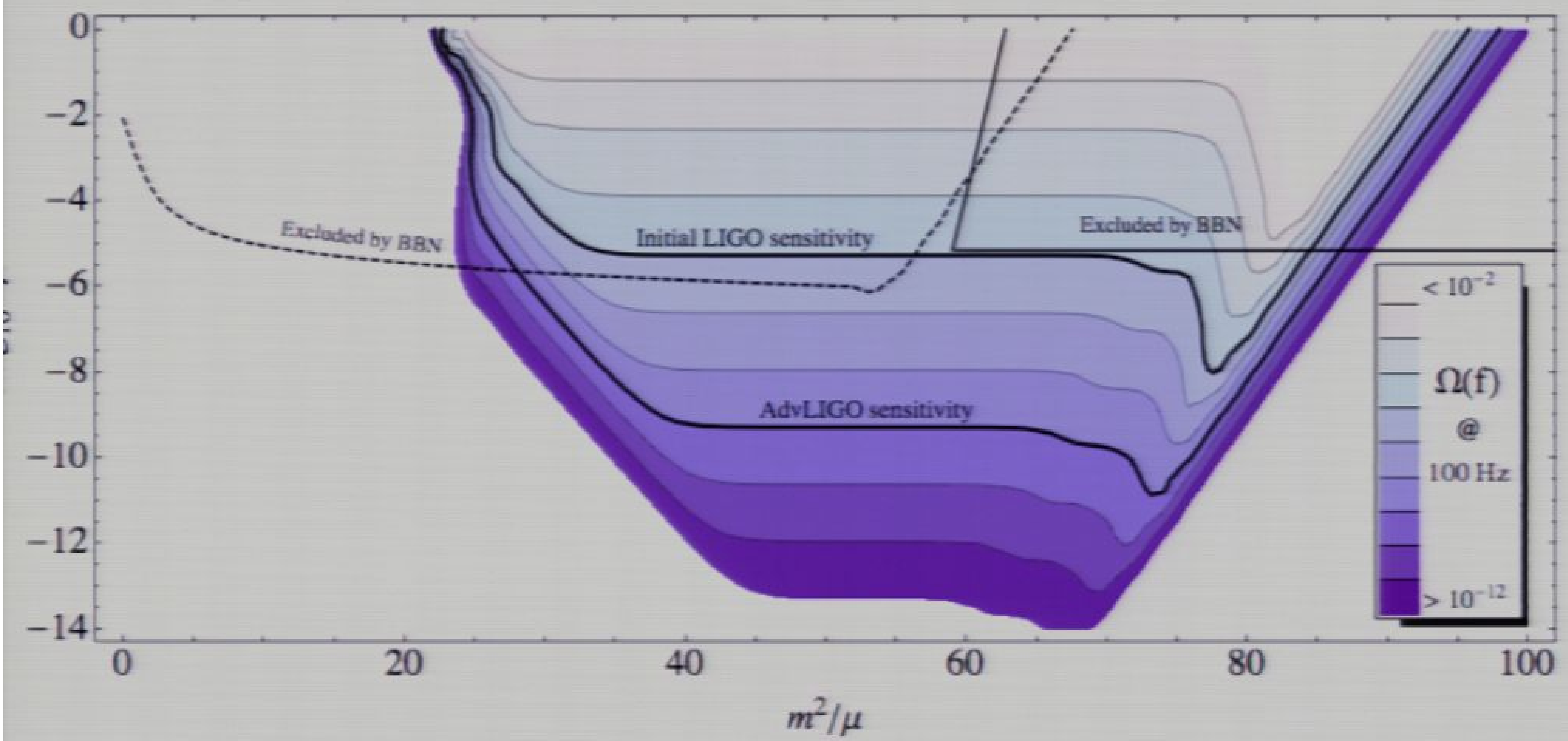
Stochastic Background



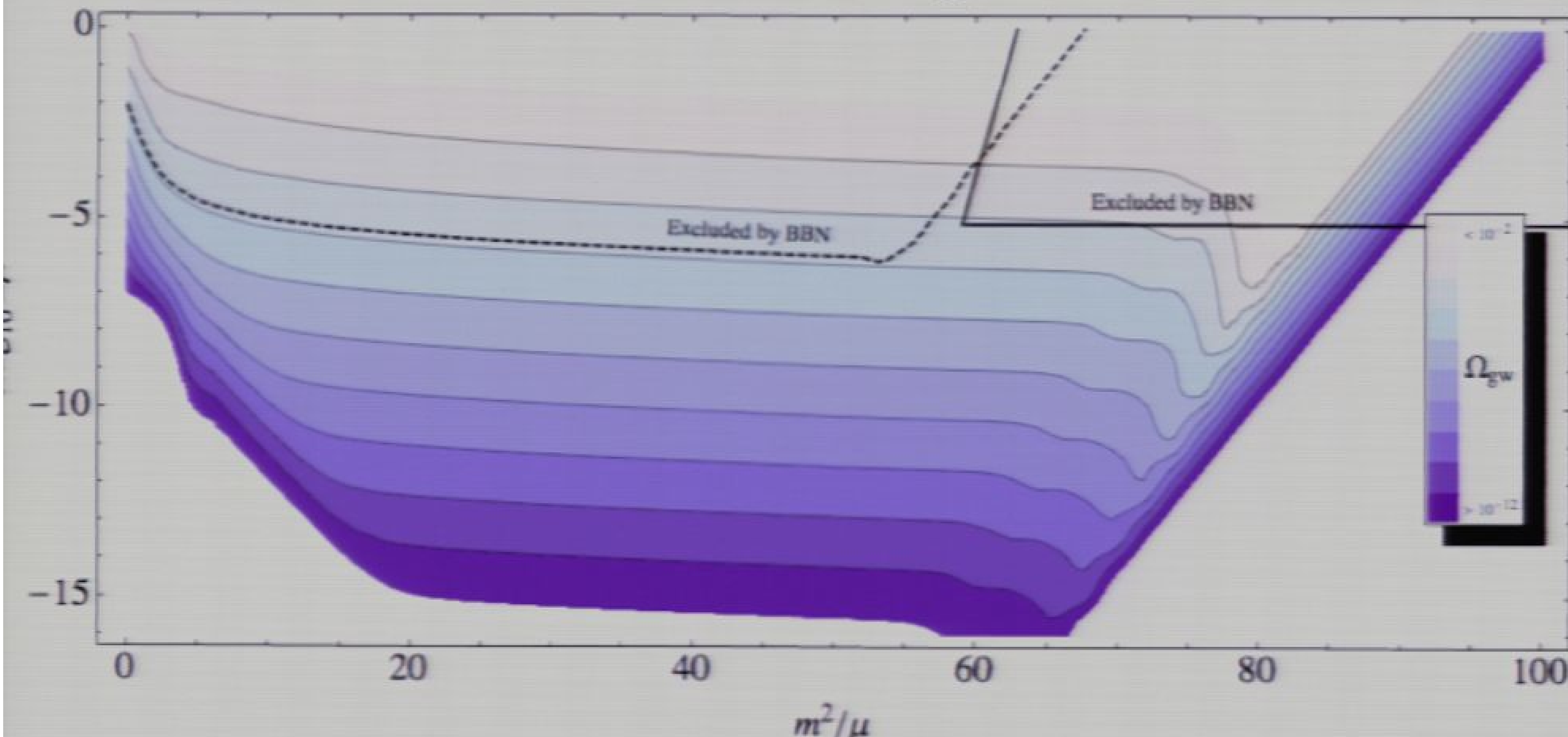
$$\Omega_{\rm gw} \propto (G\mu)^{3/4}$$

Because of the non-scaling between t* and t** get more radiation

Spectrum at LIGO frequency



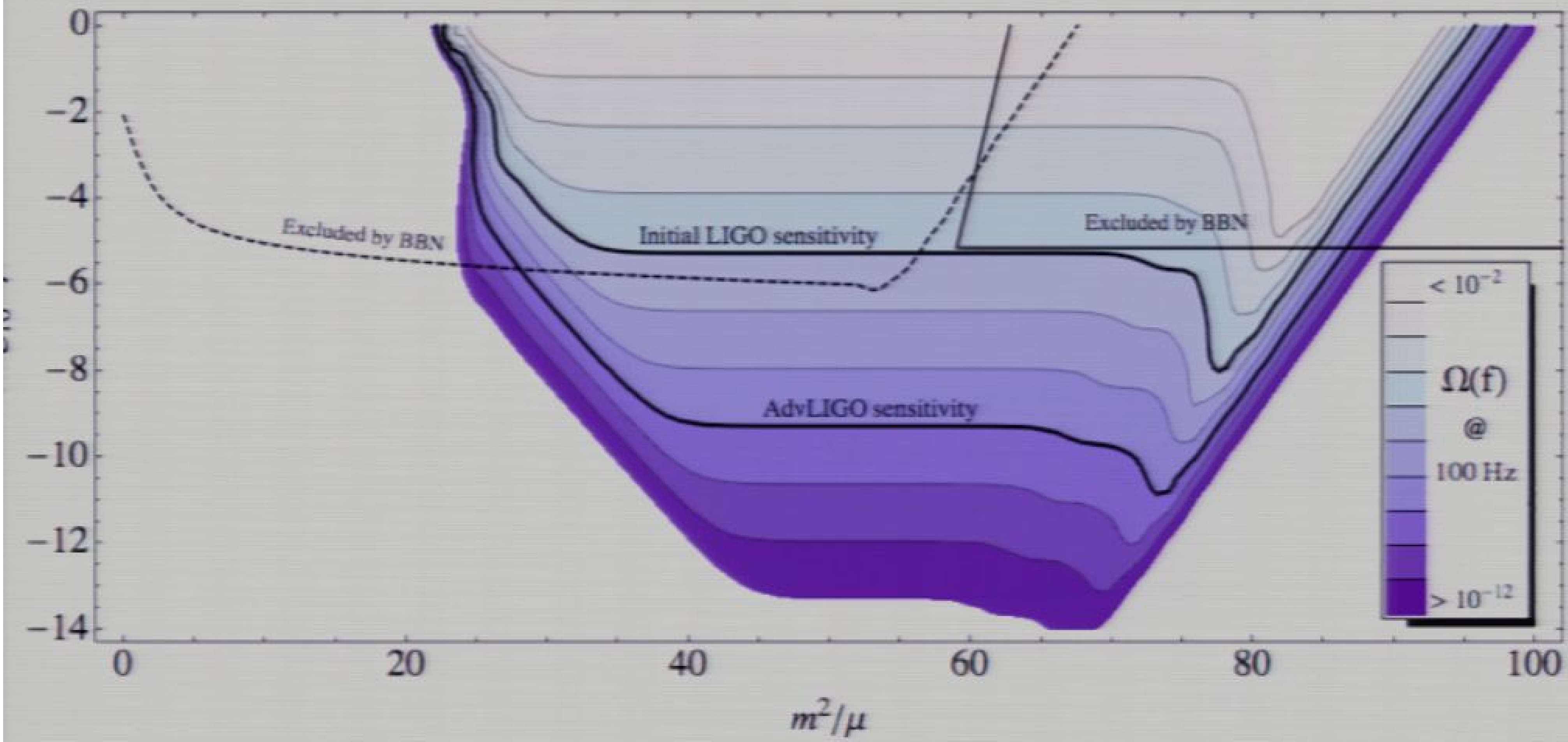
Stochastic Background



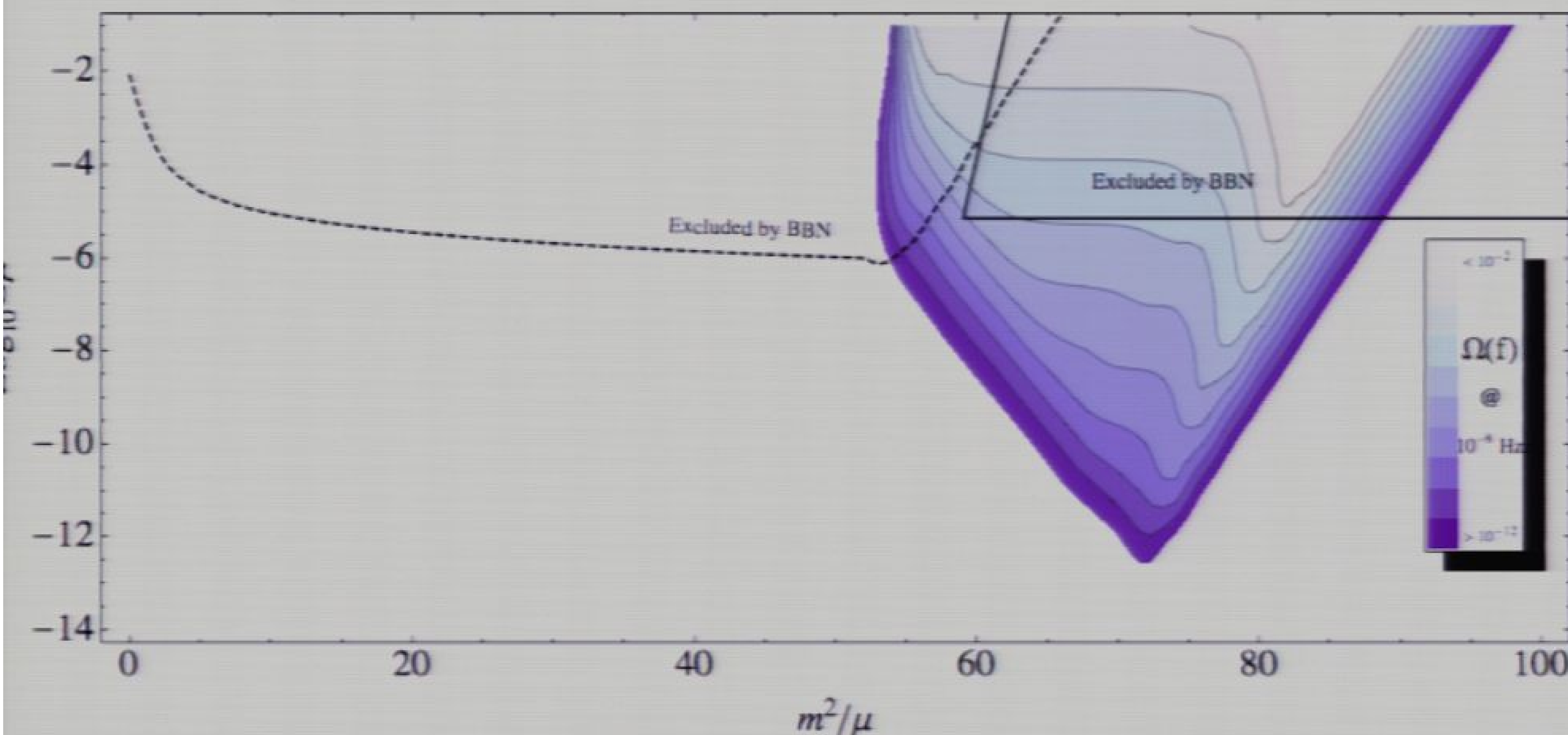
$$\Omega_{\rm gw} \propto (G\mu)^{3/4}$$

Because of the non-scaling between t* and t** get more radiation

Spectrum at LIGO frequency



Spectrum at Pulsar Timing frequency



Conclusion

- BBN constraints give a model independent constraint on cosmic strings, whether meta-stable or stable (for any bead mass)

$$G\mu \lesssim 10^{-5}$$

- The remaining observables depend upon the degree to which cosmic strings are stable. Theories of cosmic strings can only rarely claim the strings to be absolutely stable.We find interesting phenomenology for meta-stable strings with bead mass within the range

$$1 \lesssim \frac{m^2}{\mu} \lesssim 100 \; .$$

For bead mass range

$$40 \lesssim m^2/\mu \lesssim 80$$

a stochastic background is detectable by Advanced LIGO for tensions

$$G\mu \gtrsim 10^{-11}$$

a burst signal detectable by Advanced LIGO

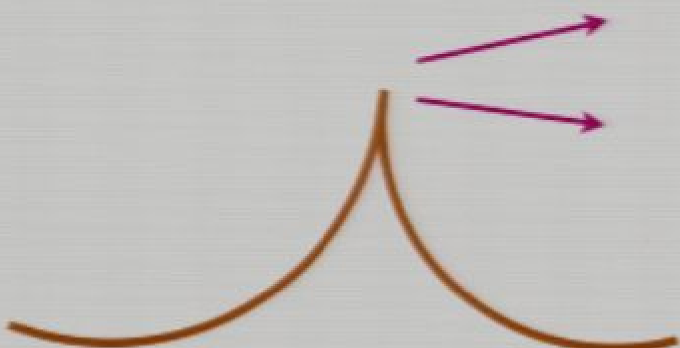
$$70 \lesssim m^2/\mu \lesssim 80$$

$$G\mu \gtrsim 10^{-12}$$

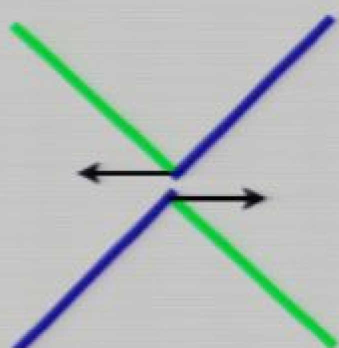
Thing to do

- High Frequencies. dilaton? KK modes emission?
- study of domain wall/string network (the other instability)
- Analyze the data to search for a 1/f burst.

Cusps and Kinks



$$h(f) = \frac{A}{f^{4/3}}$$



$$h(f) = \frac{A}{f^{5/3}}$$