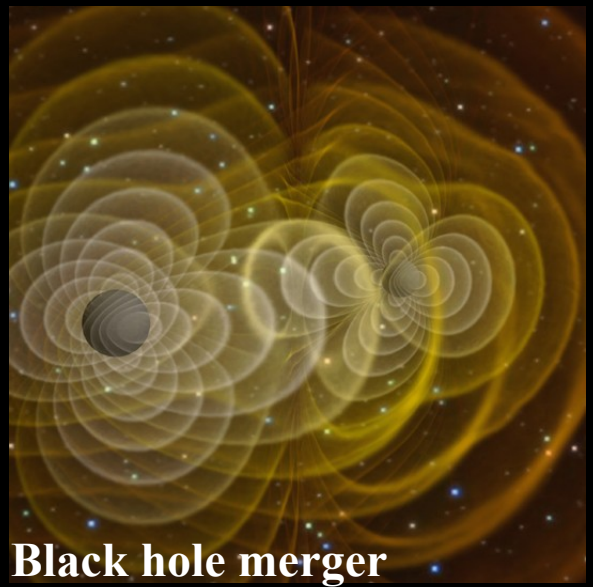
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

Gravitational Wave Bursts Produced by Cosmic Strings Cusps

Florent Robinet

VIRGO

Gravitational Waves


Black hole merger

Gravitational waves = "ripples" in space-time

Weak field approximation : $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad |h_{\mu\nu}| \ll 1$

Wave equation, speed *c*

Solution with 2 d.o.f. : polarizations h_+ and h_x

Dimensionless amplitude given by *h*

Production of gravitational waves

$$\mathscr{L} = \frac{c^5}{G}\epsilon^2\left(\frac{R_s}{R}\right)^2\left(\frac{v}{c}\right)^6$$

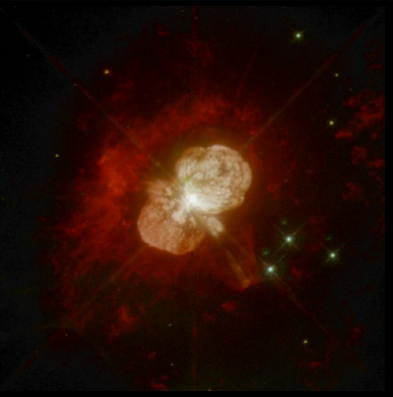
A good GW source :

- **is compact and massive**
- **is asymmetric**
- **has a relativistic speed**

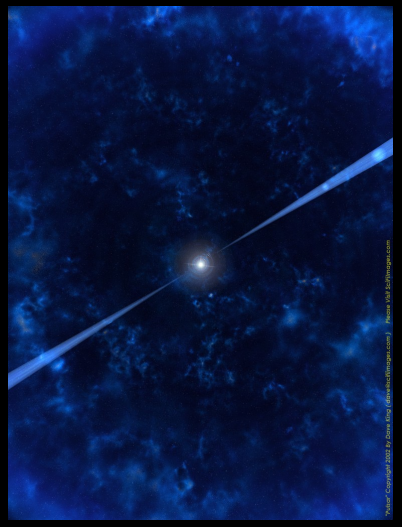
Lab production : $h \sim 10^{-39}$

Astrophysical sources : $h \sim 10^{-21}$

Gravitational Wave Sources

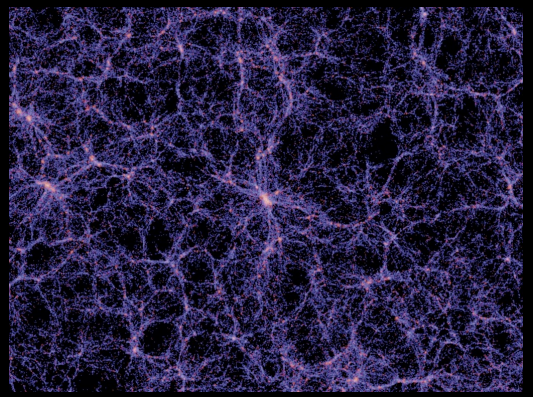


Supernovae
(asymmetric core
bounce)

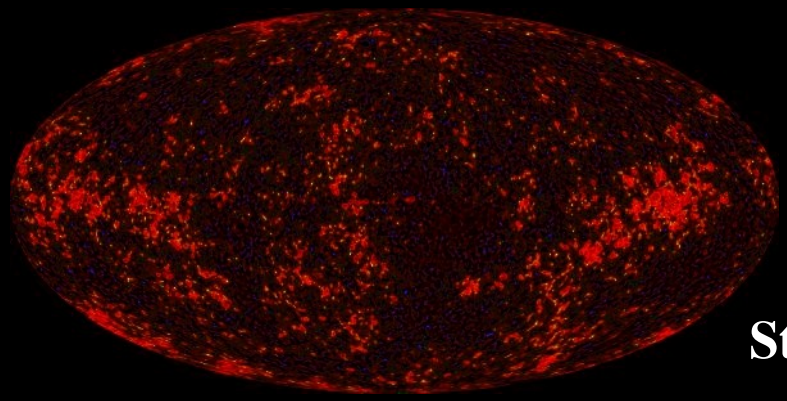


Pulsars
(asymmetric rotations,
instabilities)

Compact binary
coalescence of neutron
stars &/or black holes



Cosmic string cusps

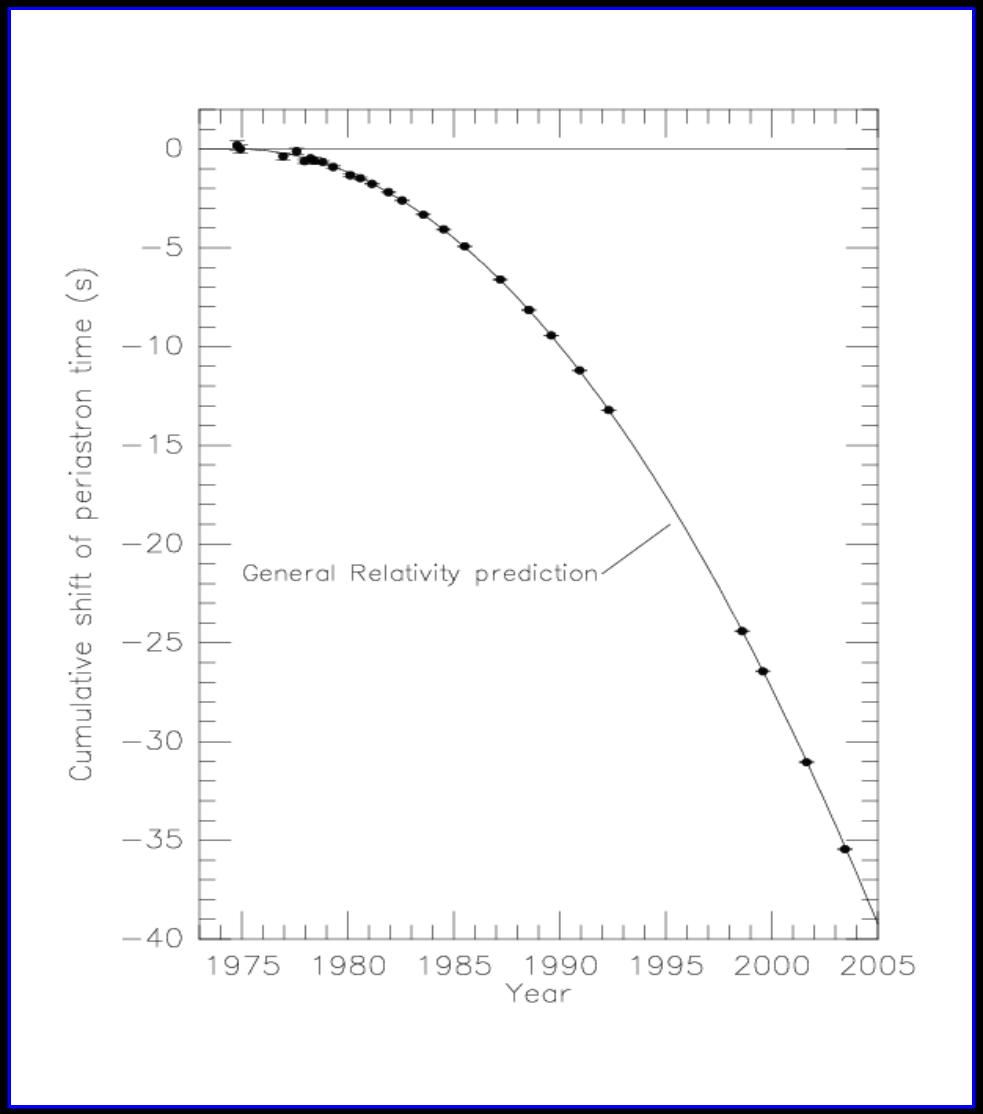


Stochastic background

The unexpected

?

They are real !



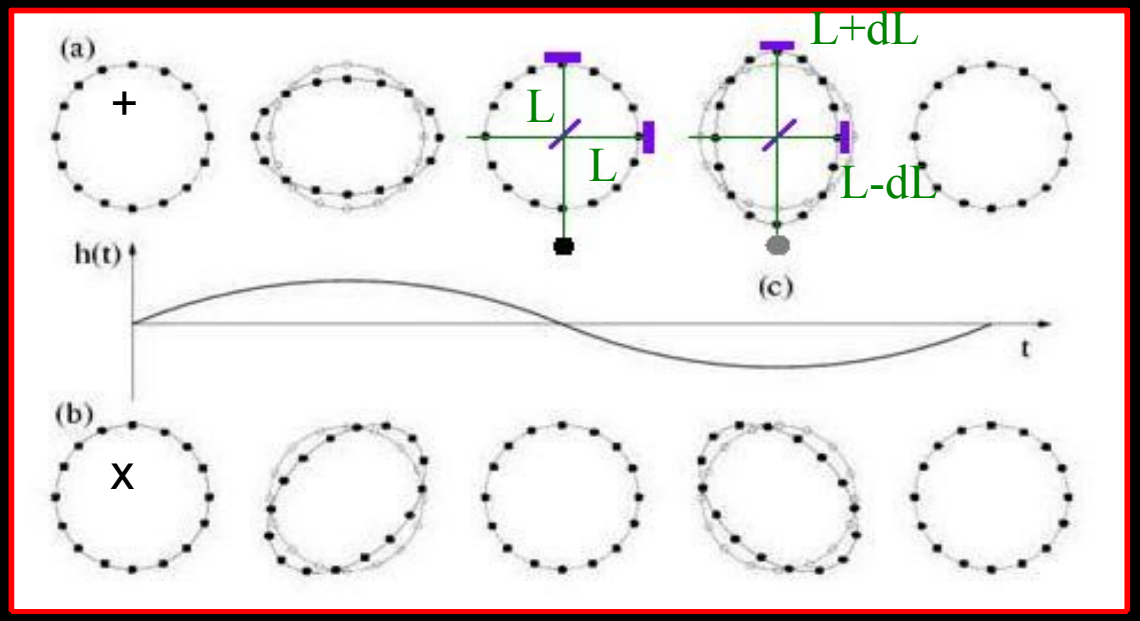
Binary pulsar PSR 1913+16

The decrease of the orbital period has been studied over more than 20 years

It can be fully explained by the energy loss due to the emission of gravitational waves

Nobel Prize 1993 Hulse-Taylor

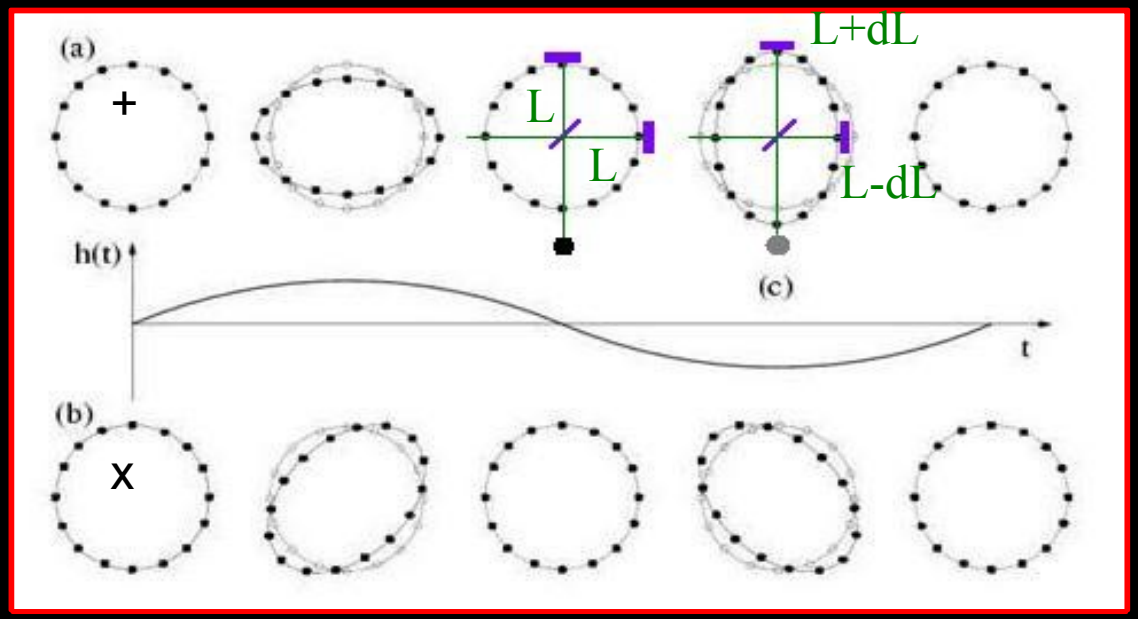
Detection of Gravitational Waves



The interferometry seems to be appropriate

Differential length variations can be measured with a Michelson interferometer

Detection of Gravitational Waves

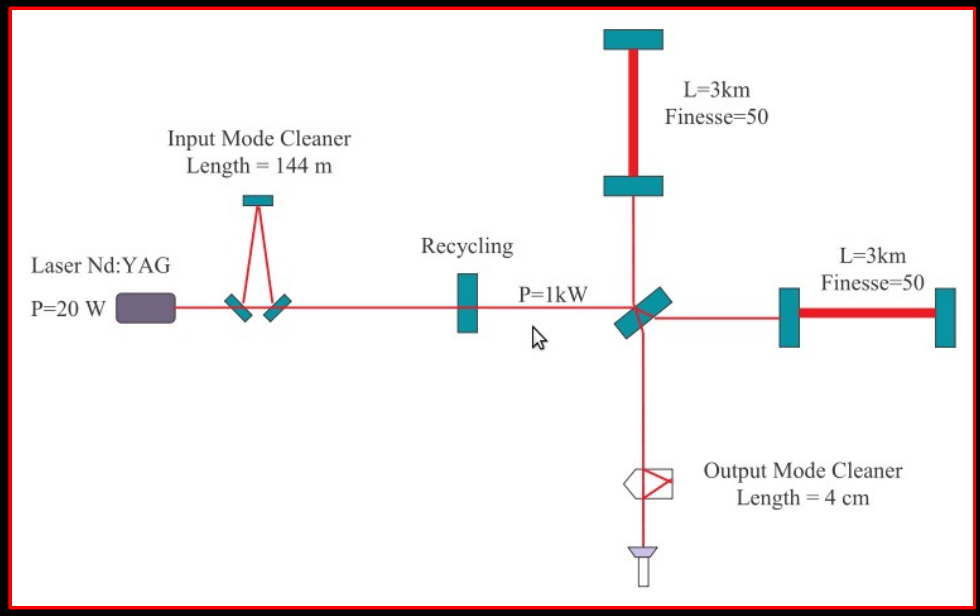


The interferometry seems to be appropriate

Differential length variations can be measured with a Michelson interferometer

To be able to detect gravitational waves with $h < 10^{-21}$ the basic concept of the Michelson needs to be improved :

- **Kilometric arms**
- **Fabry-Perot Cavities**
- **High power laser**
- **Power recycling**
- **Noise limitation**



The Virgo Interferometer

Pisa

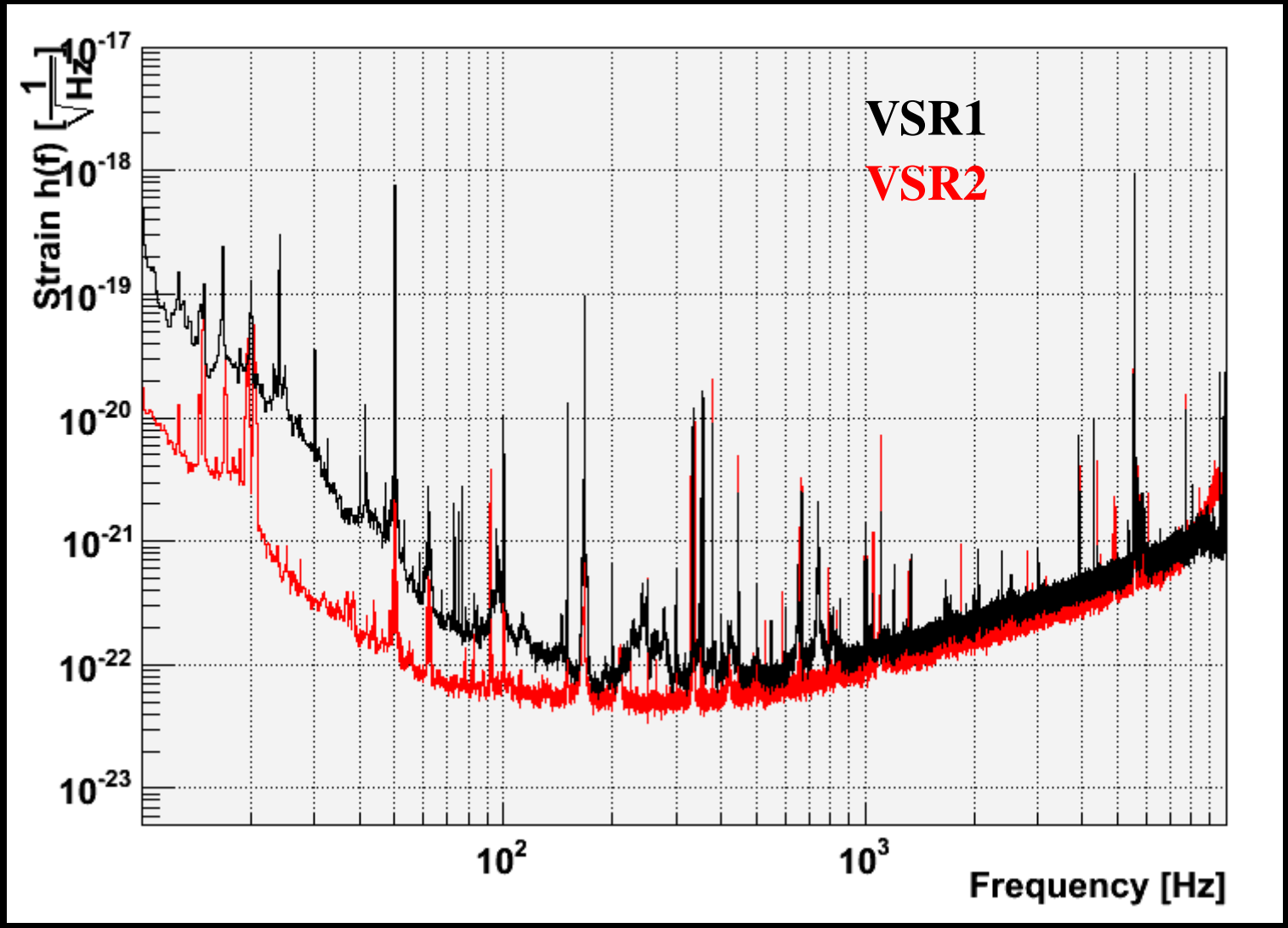
The Virgo Interferometer

1st Science Run : May → Oct 2007 : VSR1
Duty cycle = 81%
Long locks up to 94h
Range for a 1.4-1.4 M⊙ system : ~4Mpc

Commissioning
Higher laser power
Thermal compensation of the mirrors
New control of the interferometer
New electronics
Better scattered light mitigation

2nd Science Run
7th of July 2009 → Jan 2010 : VSR2
Duty cycle = 81 %
Long locks up to 150h (world record !)
Range for a 1.4-1.4 M⊙ system : ~9Mpc

Virgo Sensitivity



A Network of Detectors

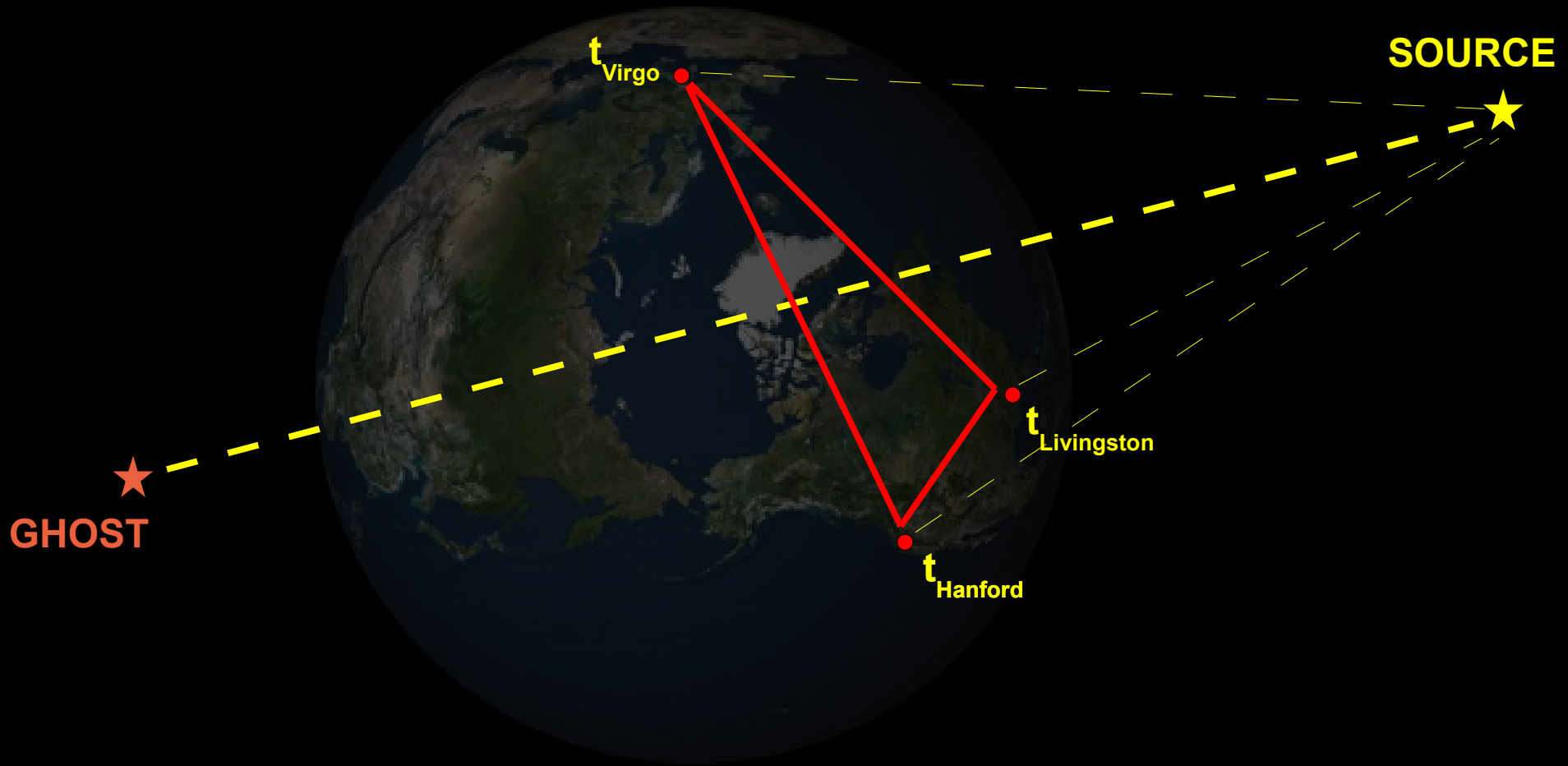
LSC – Virgo collaboration

- Full data sharing since May 2007
- Common analyses and papers
- Common tools

A Network of Detectors

SOURCE POINTING

- **Source location within a few degrees**
- **Serious candidates follow-up (EM, neutrinos...)**



Analysis Groups

Compact Binary Coalescence (CBC)

- Template searches of well-modeled signals
- Free parameters : mass, spin and orbits

Burst Signals

- Short-lived signal (< 1 s)
- Unknown or poorly known waveforms
- Minimal or no assumption about the waveforms
- Searches open to the unexpected

Continuous Waves

- Targeted search (pulsars)
- Integrated signal over time and/or over space
- Can provide information about the pulsar physics

Stochastic Background

- Early universe GW background
- Integrated signal
- Ω_w

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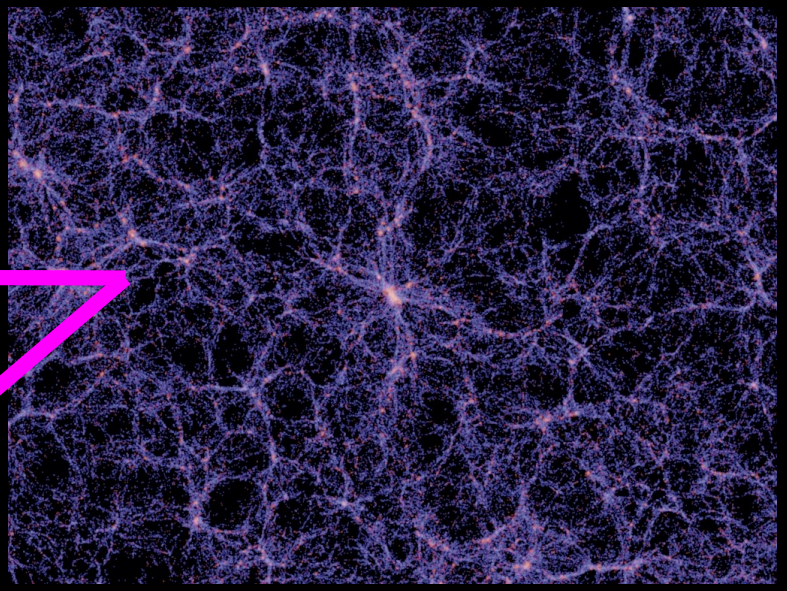


GW produced by cosmic string

Cosmic Strings : Sources of Gravitational Waves

Cosmic strings :

Linear topological defects formed at a symmetry breaking phase transition in the early universe

Since the early 80's, we know that oscillating loops can generate a potentially observable GW background (Zel'dovich, Vilenkin, Kibble...).

At the time of formation, the strings have the shape of Brownian trajectories

Tension in convoluted strings

Oscillations

Oscillations damped by : GW radiation

The strings gradually straighten out

The network of cosmic strings is usually parameterized by the string tension μ (or $G\mu$) and the reconnection probability p

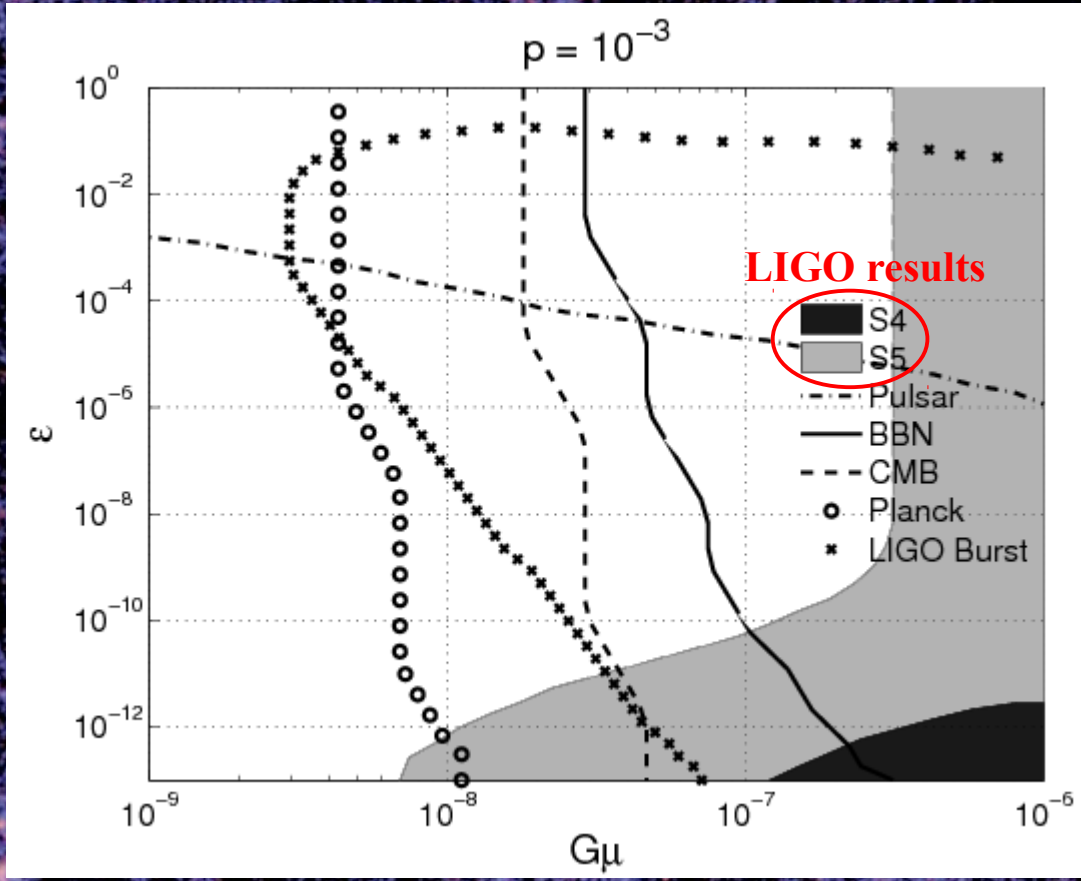
Cosmic Strings : Sources of Gravitational Waves

Mechanism : string loops which decay by radiating gravitationally.
Additional parameter ε : loop size parameter

Constraining the parameter space $(G\mu, \varepsilon, p)$ = Constraining the loop formation models

Results from the stochastic background analysis

(indirect bounds)

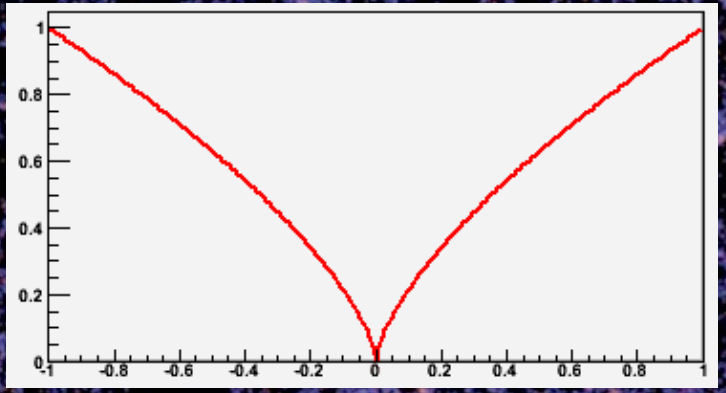


The LSC & the Virgo Collaboration, Nature 460, 990

Cosmic Strings Cusps

The GW background generated by cosmic strings has been assumed nearly gaussian for a long time
In 2000-2001 T. Damour and A. Vilenkin suggest that :

"The GW background from strings is strongly non gaussian and includes sharp GW bursts emanating from cosmic string cusps"



Cusp shape

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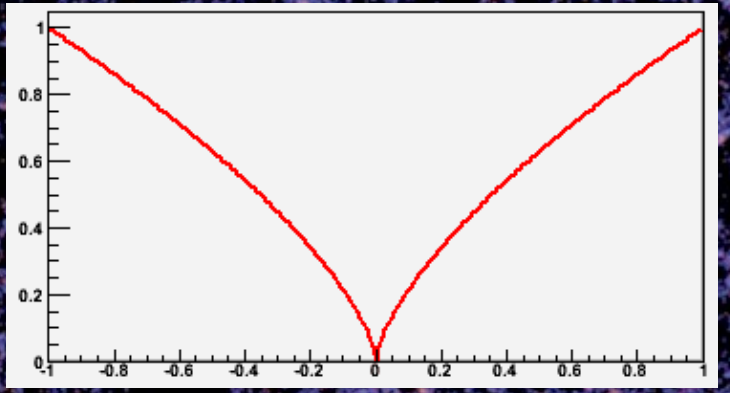

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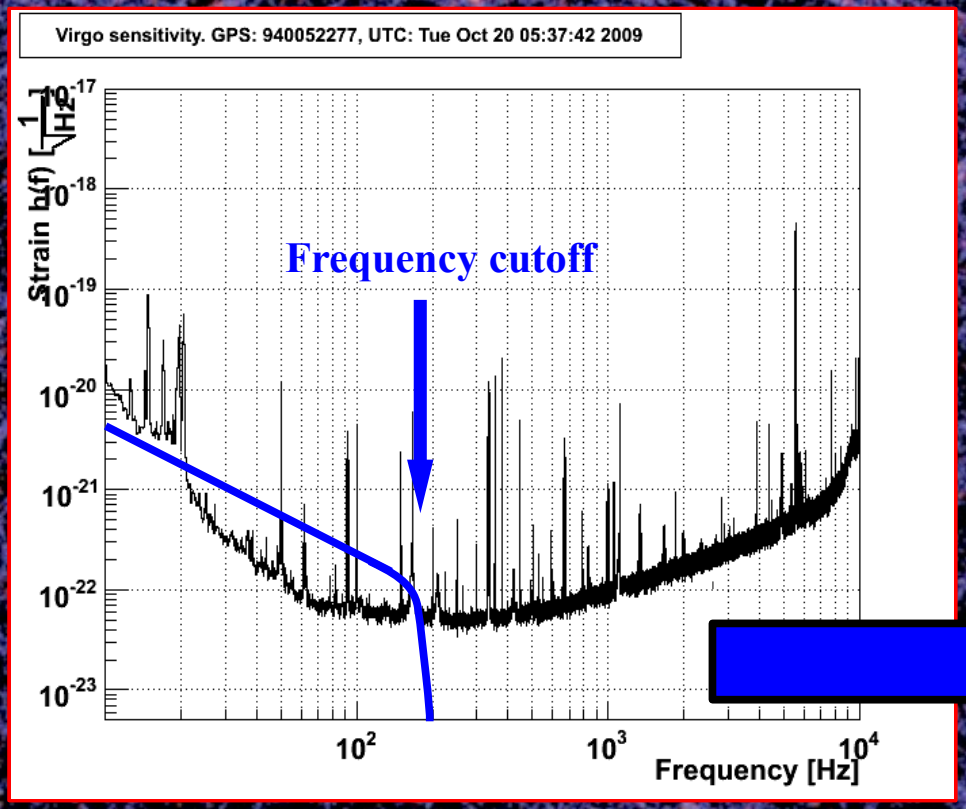
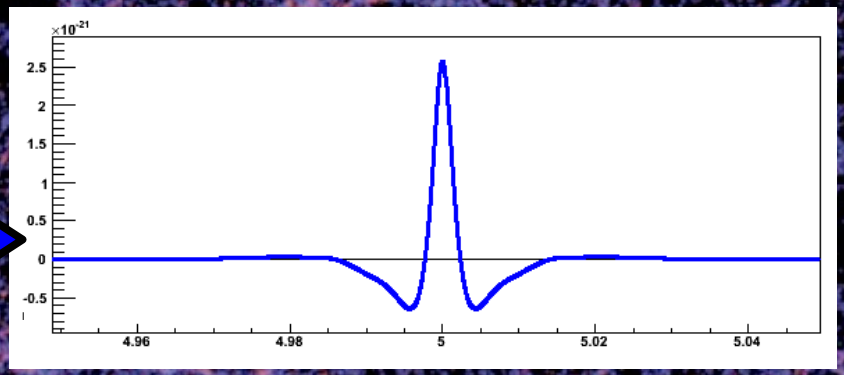


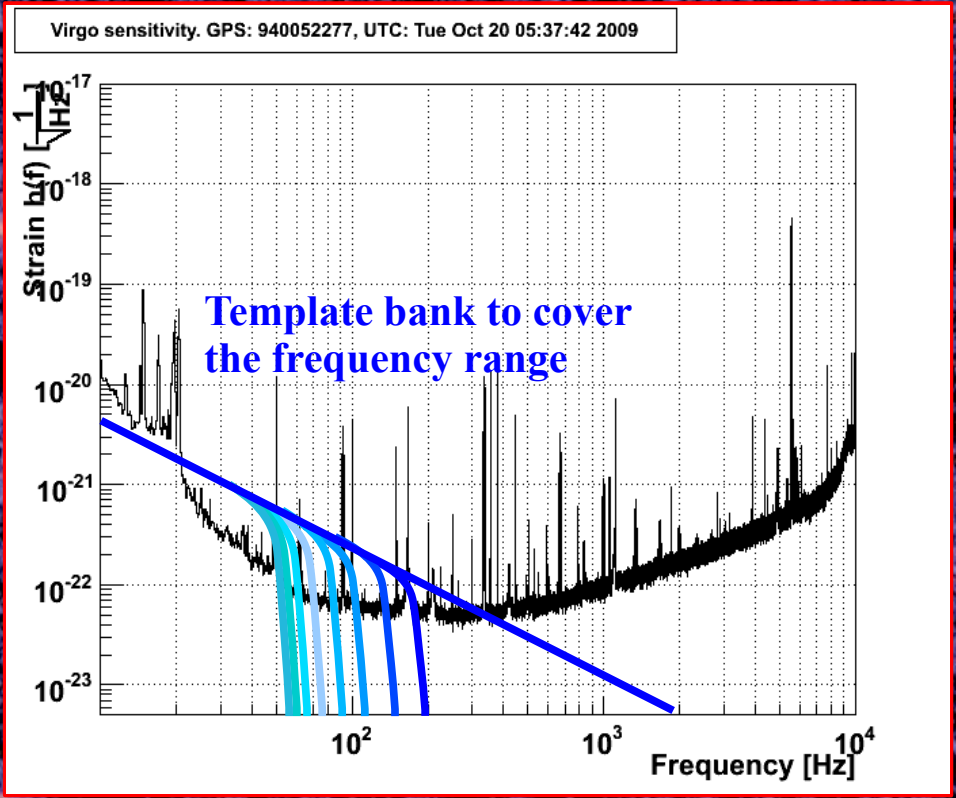
$$A = \frac{G \mu L^{2/3}}{r}$$ Scaled amplitude

$$f_{cutoff} = \frac{2}{\theta^3 L}$$ Free parameter of the search

Time Signal ~ 10 ms



Cosmic Strings : The Trigger Production



Match-filtered Search

~ 20 templates to cover the frequency range :
f_{cutoff} : 75 to 2048 Hz

LIGO S4 Analysis (2005 data) :

Triple coincidence between Hanford (H1&H2) and Livingston (L1)

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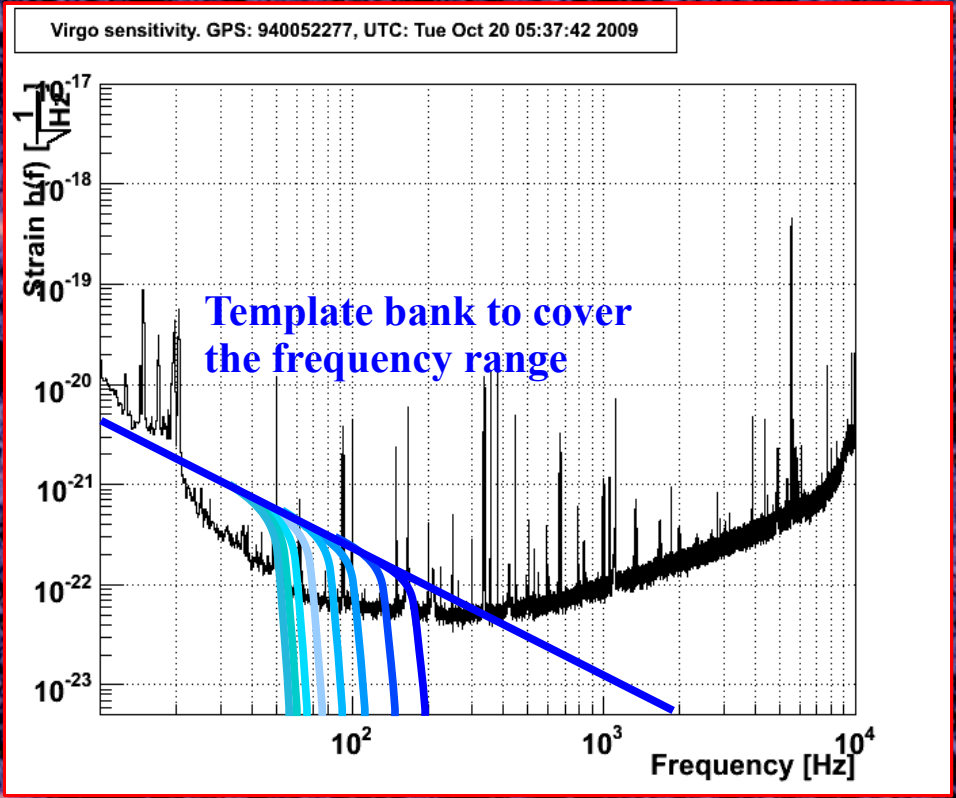

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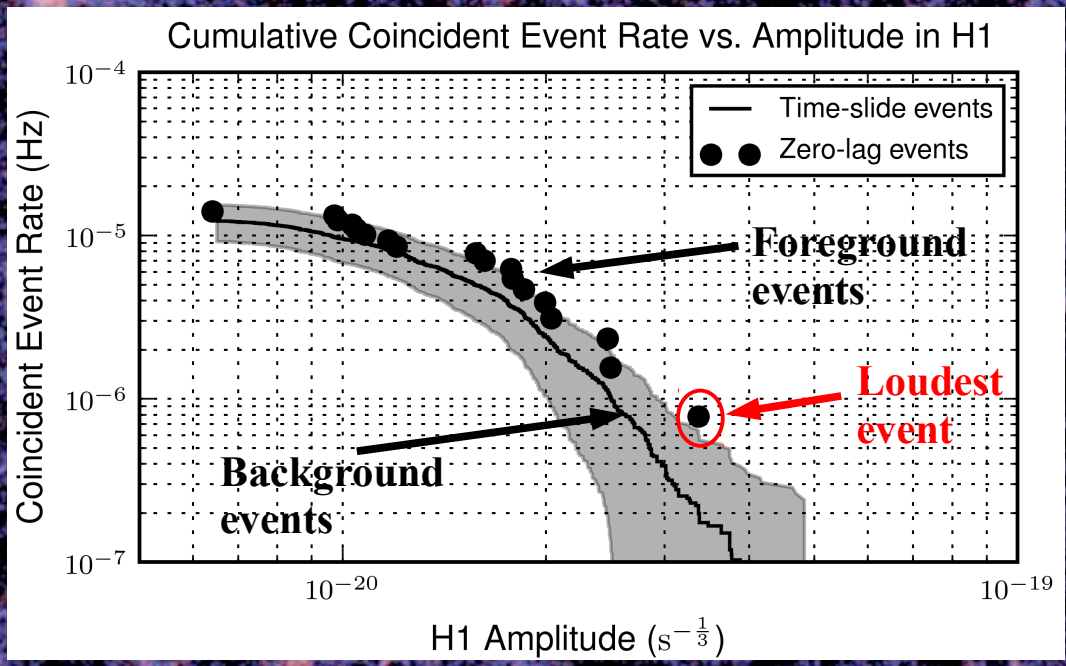
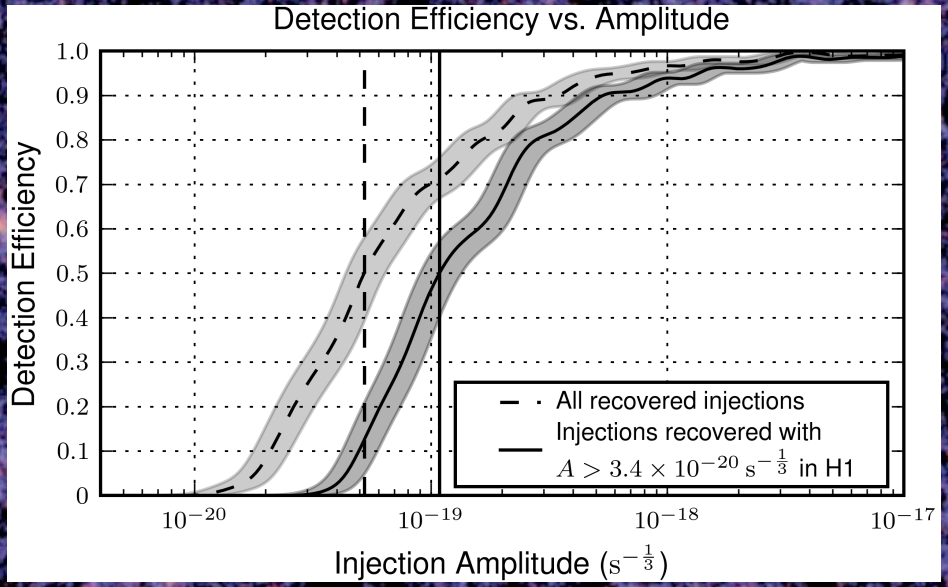


The LSC and F. Robinet, *First LIGO search for gravitational wave bursts from cosmic (super)strings*, Phys. Rev. D 80 (2009) 062002

Cosmic Strings : Efficiency and Upper Limits



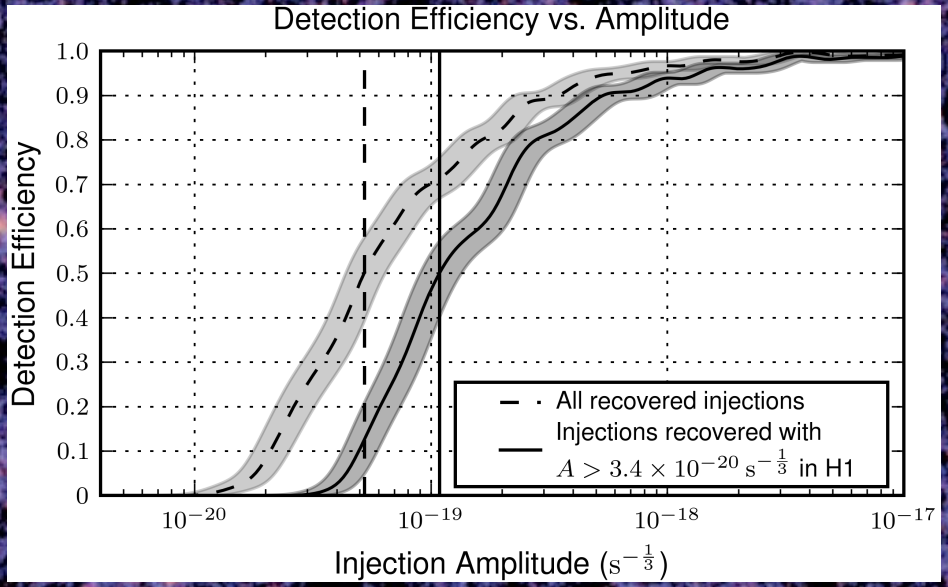
Efficiency determined with a set of ~7000 fake signal injections of random amplitudes, f_{cutoff} and sky positions

Effective rate :

$$\gamma(G\mu, \varepsilon, p) = \int_0^\infty \epsilon(A) \frac{dR(A; G\mu, \varepsilon, p)}{dA} dA$$

R : production rate

Cosmic Strings : Efficiency and Upper Limits



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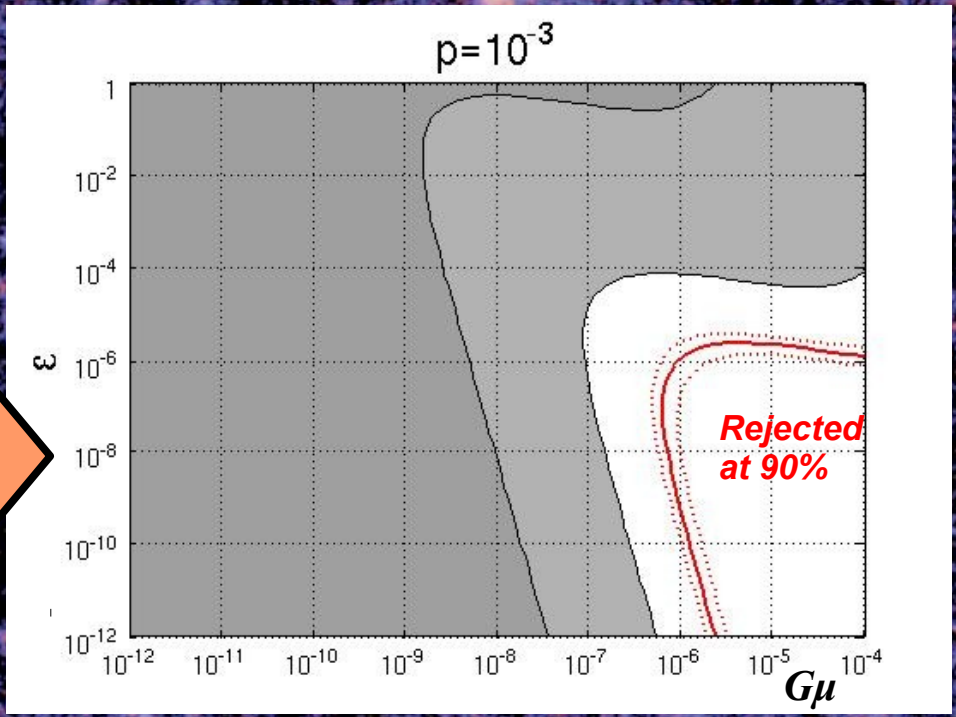
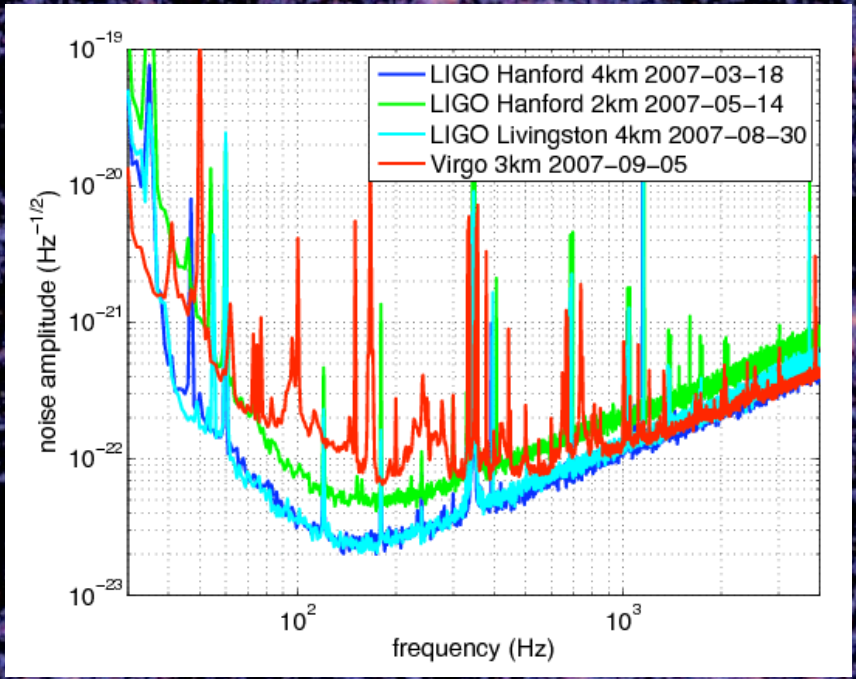


Cosmic Strings : The Upcoming Analysis

LIGO S5 data + Virgo VSR1 data (2007)

Main features :

1) **Better sensitivity** (~ factor 2)
2) **Longer live-time**
   – longer run
   – all combinations of detectors (double, triple, quadruple)
3) **More refined analysis**



Cosmic Strings : A Bayesian Approach

If an event is characterized by a set of variables $\vec{x}$ the following likelihood ratio can be used :

$$R(\vec{x}) = \frac{P(\vec{x}|T \in S)}{P(\vec{x}|T \in B)}$$

Can be used to rank the foreground events

S : is a population of fake signal injections
B : is a population of background events

Training samples

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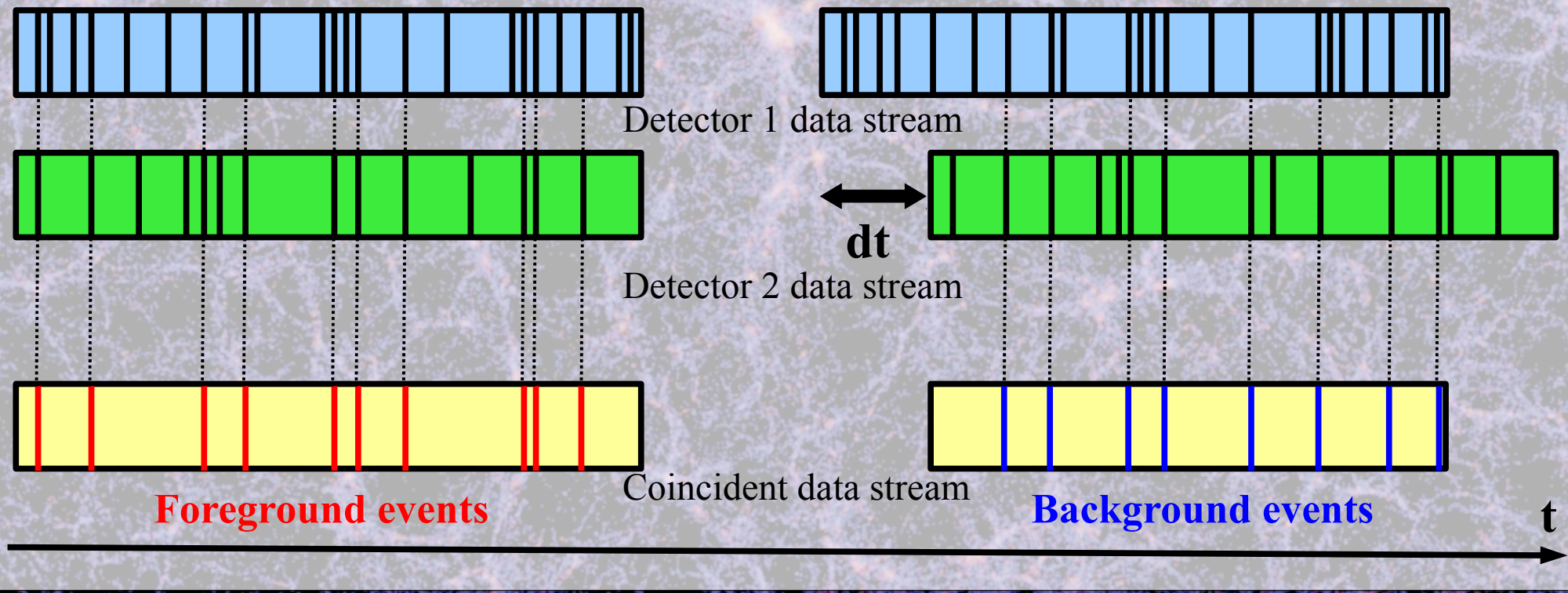
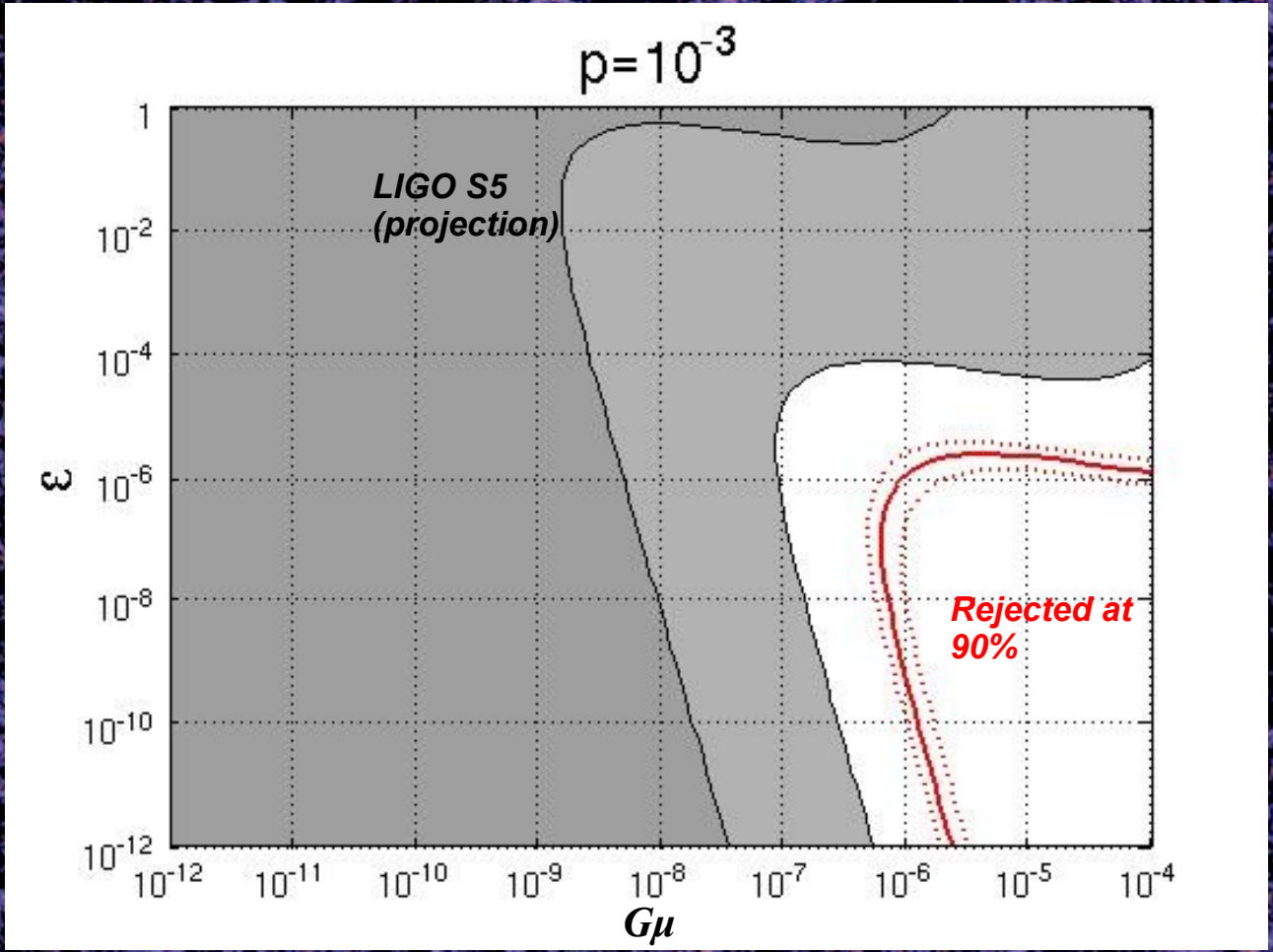


Cosmic Strings : Promising Upper Limits



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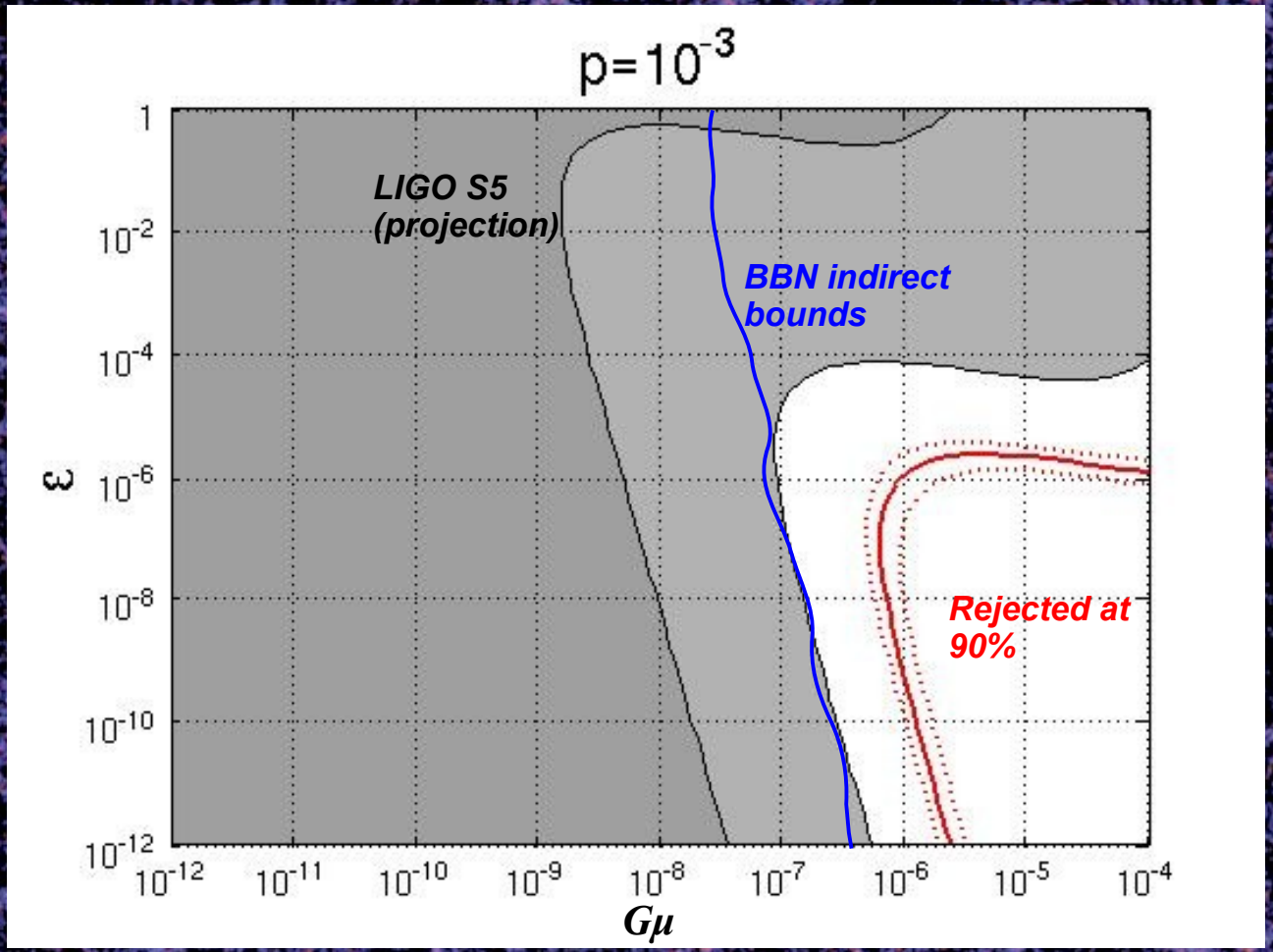

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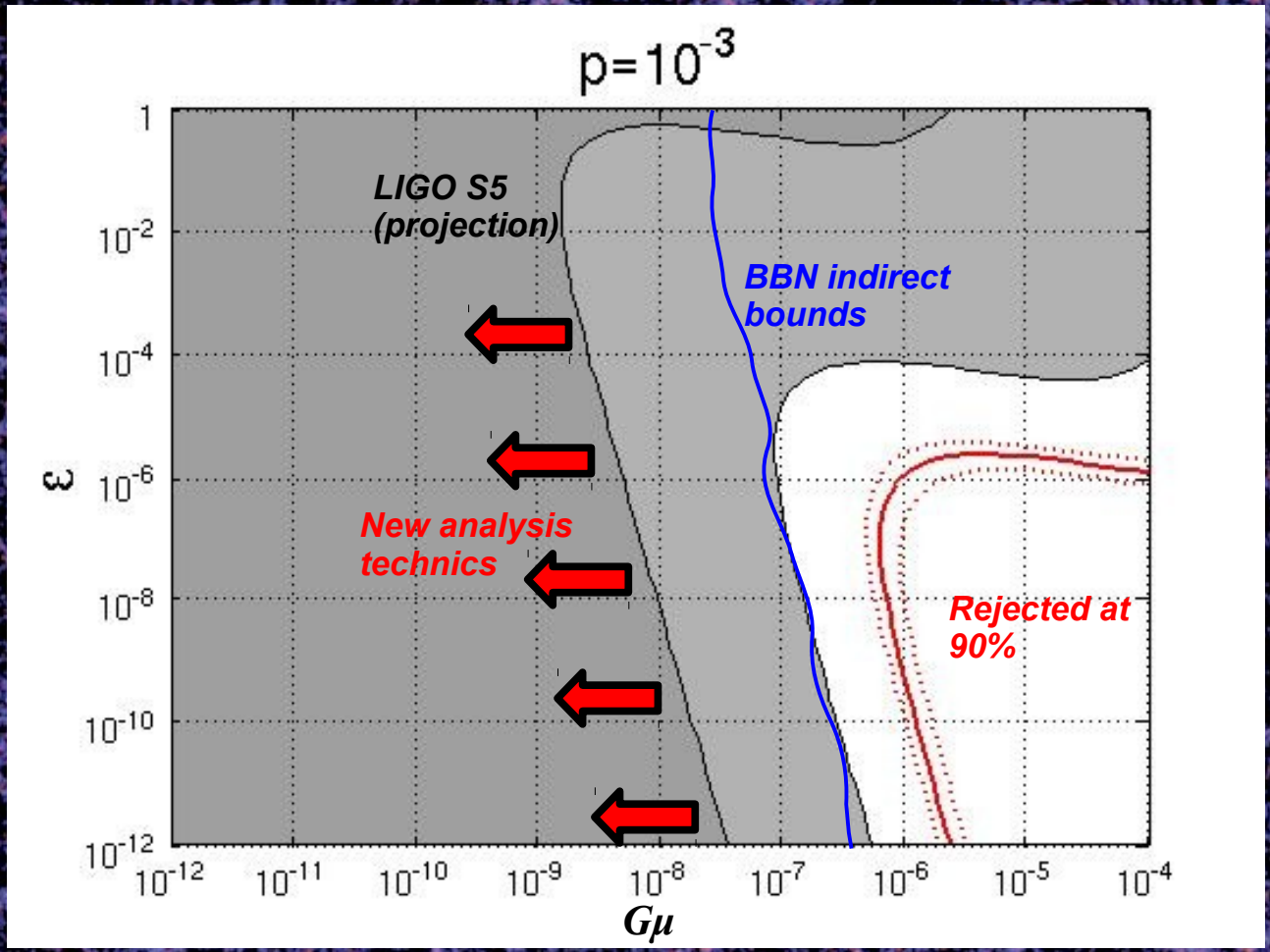

The upcoming analysis should put significant constraints on the cosmic string parameter space

Conclusions

• Many cosmological models can originate from the cosmic strings (the galaxy formation, the matter distribution in the universe...). So it is important to constrain the free parameters of the theory

• The search for gravitational waves produced by cosmic string cusps is an efficient way of directly constraining the string parameters

• The upcoming S5/VSR1 analysis should be able to give the most competitive limits

• The data of S6/VSR2 remain to be analyzed