Searching for Cosmic Superstrings

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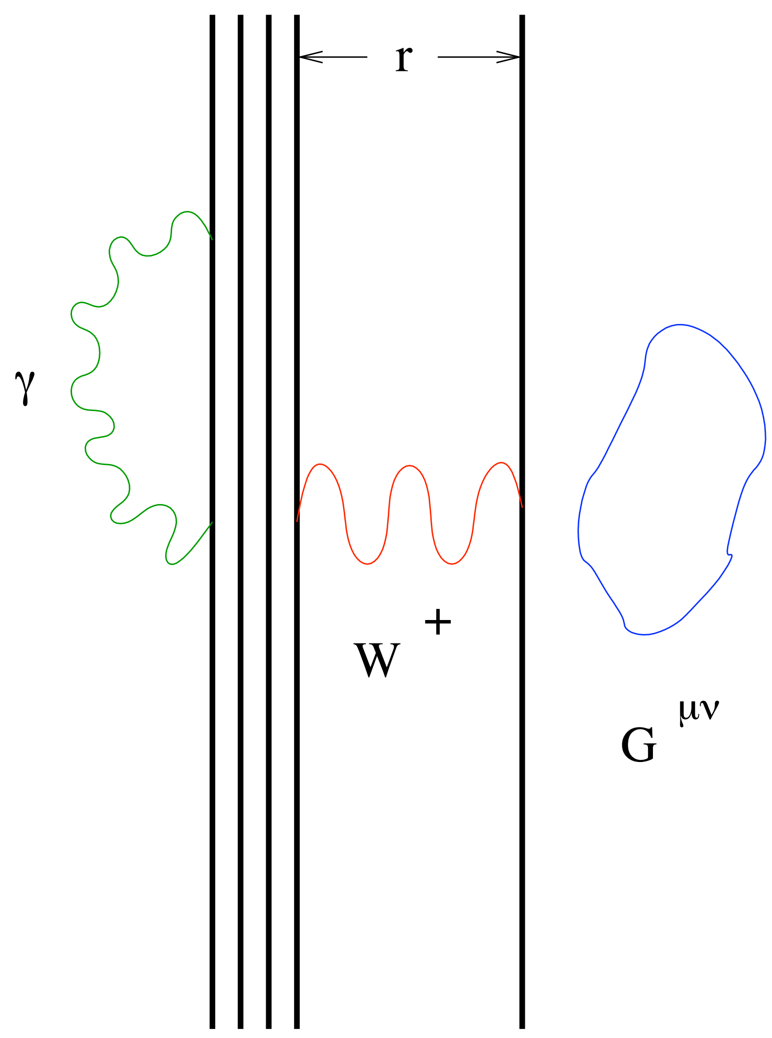
Many solutions in Flux Compactification

- Flux compactification into a Calabi-Yau like manifold yields a stabilized 6-dim. internal space;
- So far, we have not yet found a solution that may be identified with nature
- We do not know whether we are close to identifying the solution or we are still way off
- Calculation is getting harder
- What observational evidence do we have that string theory is correct ?

- Distinctive signatures of string theory is strings and branes, so it will be nice if we can detect them directly.
- Early universe acts as a microscope that "magnifies" tiny strings to cosmological sizes so they may be detected.
- In Type IIB, there are D3-branes that span our uncompactified 3-dimensional space; they appear as points in the internal space;
- We may live in a stack of these D3-branes, or a stack of D7-branes wrapping 4-cycles in the internal space.

Brane World

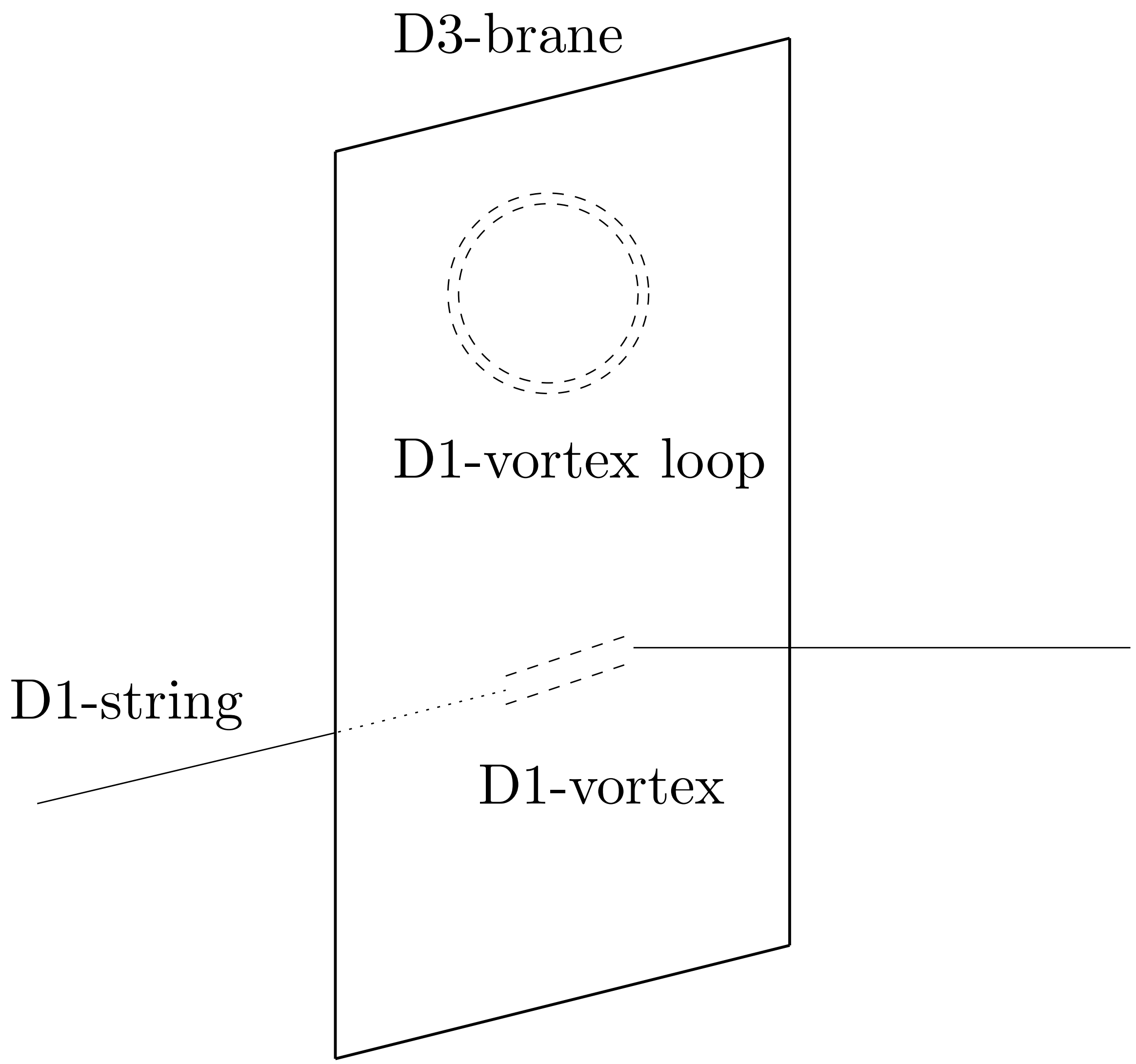
Standard model particles are open string modes
inside D3-branes



Graviton is a
closed string mode

Besides fundamental strings,
there are also D1-branes,
or D1-strings

D1 and F1 strings

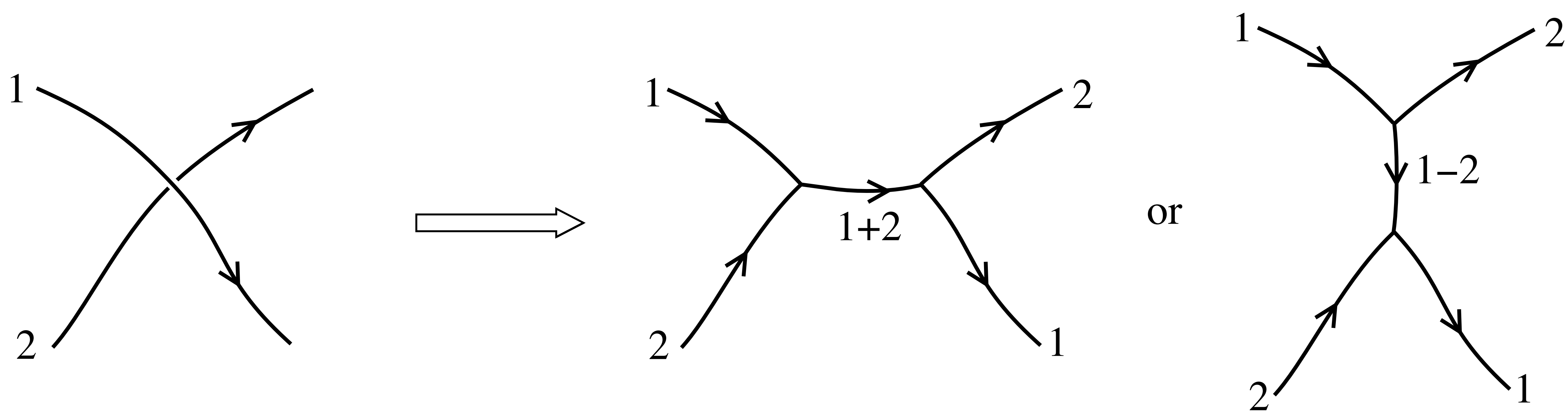


F1 strings break up into pieces inside D3-branes

D1-strings become (metastable) vortices

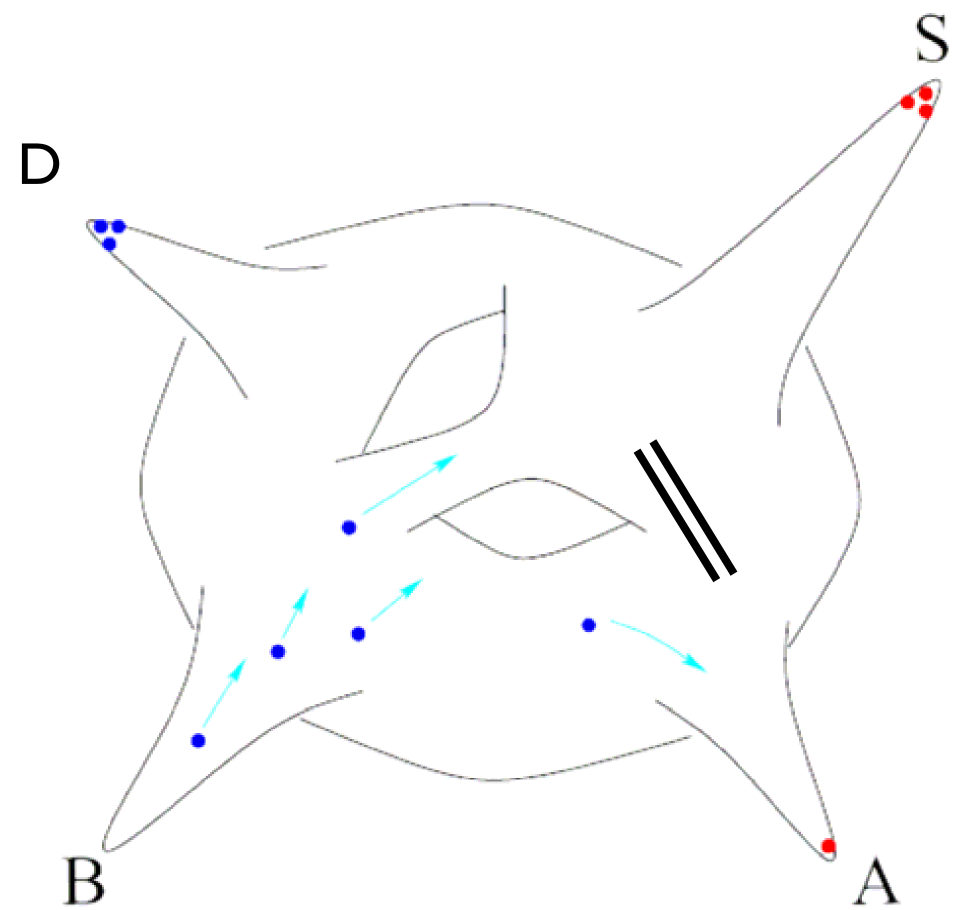
Size of vortex $r \sim \dfrac{\sqrt{\alpha'}}{h\sqrt{g_s}}$

- In contrast to vortices in Abelian Higgs model, cosmic strings are the strings in string theory.
- This is the (p,q) strings, where p and q are coprime. (1,0) strings are fundamental strings while (0,1) strings are D1-strings.
- The spectrum depends on the details.



$$G\mu_{p,q} = \sqrt{p^2 g_s^2 + q^2}\, G\mu$$

Manifold with warped throats and D3-branes



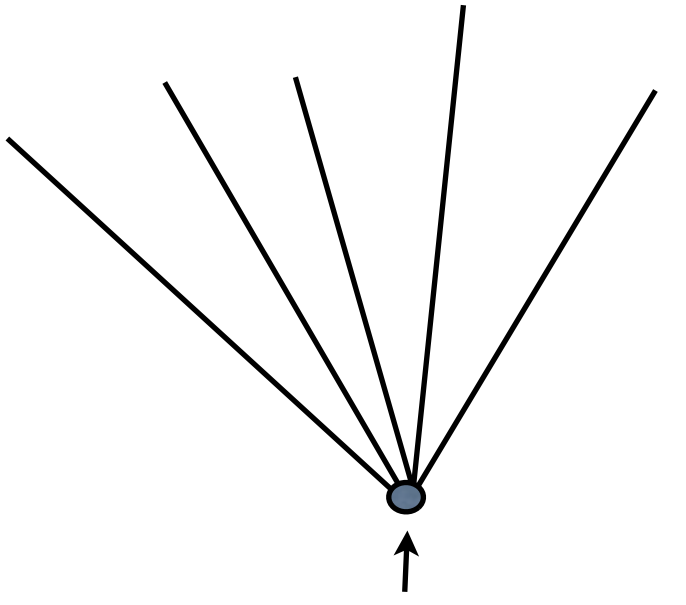
Each warped throat has its own warped factor h.

Energetically, D3-branes, D1-strings and F1 strings like to move to the bottom of the warped throats

String tension spectrum in a warped deformed throat

E.g. Klebanov-Strassler Throat :

A baryon with mass $\sim M^{3/2} h_A / \sqrt{\alpha'}$



$$T_{p,q} \simeq \frac{h_A^2}{2\pi\alpha'} \sqrt{\frac{q^2}{g_s^2} + (\frac{bM}{\pi})^2 \sin^2(\frac{\pi p}{M})}, \qquad b = 0.93266$$

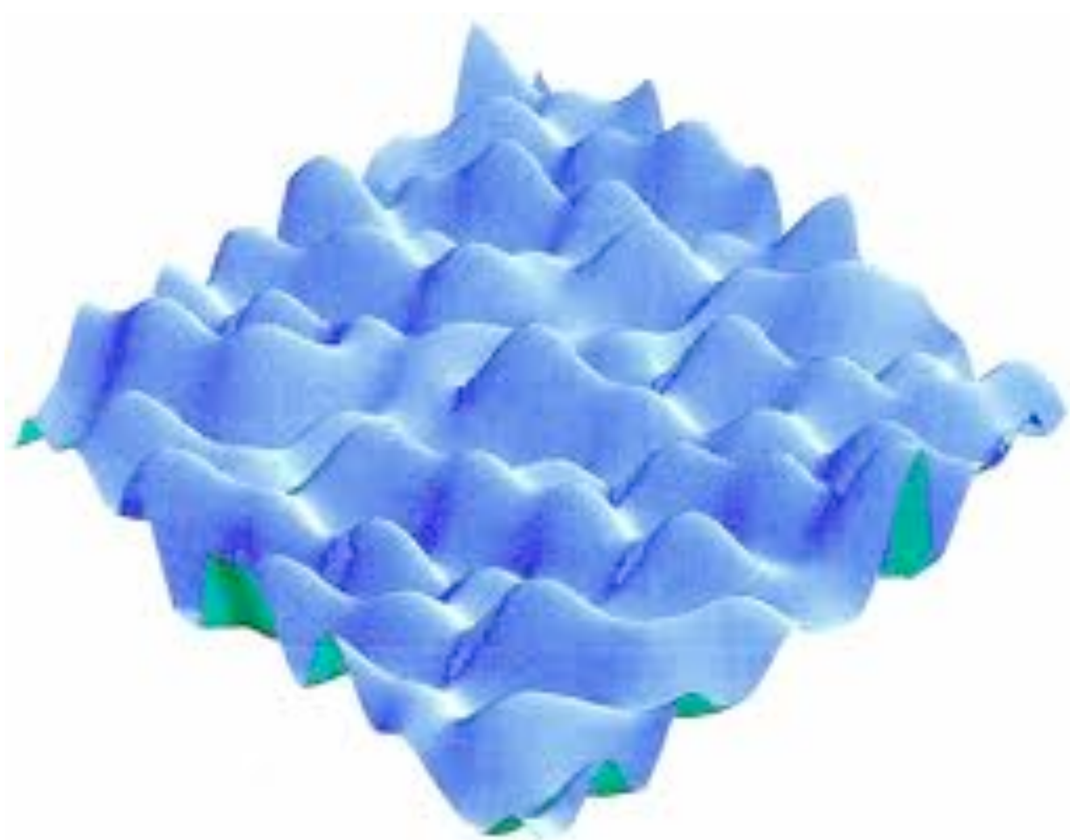
b=0 in the presence of branes

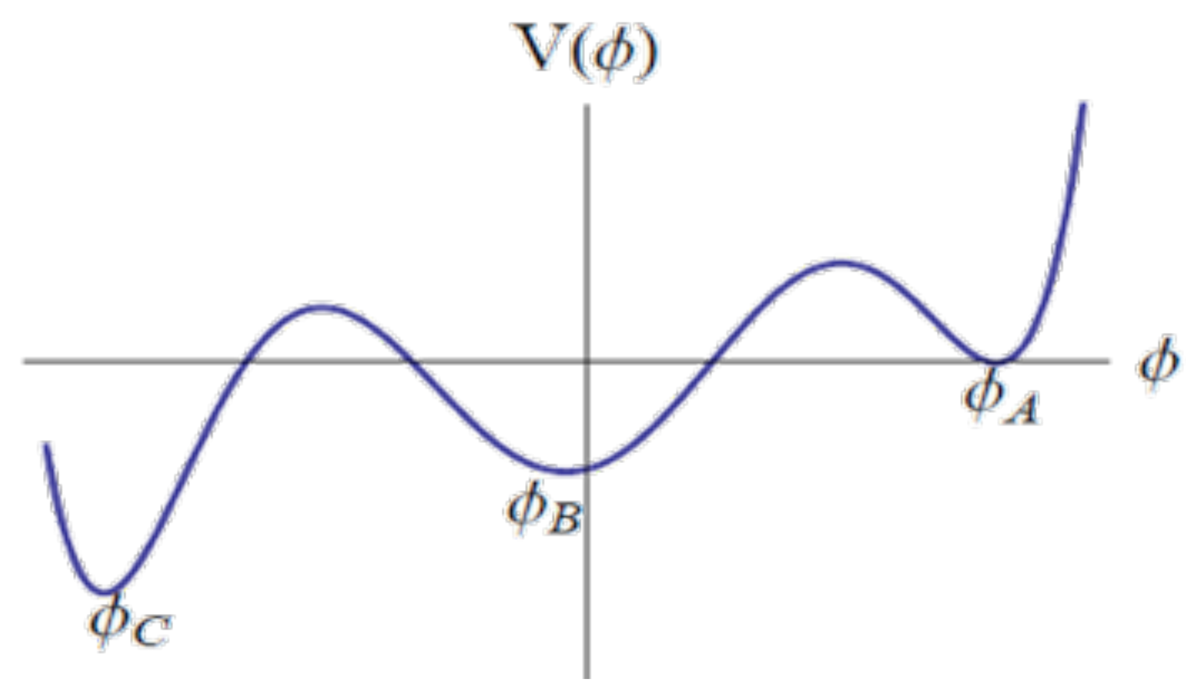
Very large M in bulk

Leblond, Firouzjahi, HT, hep-th/0603161
Herzog, Klebanov, hep-th/0111078

3 properties to consider

- If a throat has no branes, the beads and junctions can slow down the strings.
- If a throat has D-3 branes, or D7-branes are around, the thickness of the D1-vortex $r \sim \dfrac{\sqrt{\alpha'}}{h\sqrt{g_s}}$
- Many throats





A typical flux compactification in Type IIB

$$\chi(M) = 2(h^{1,1} - h^{2,1})$$

Manifold	$h^{1,1}$	$h^{2,1}$	χ
$\mathcal{P}^4_{[1,1,1,6,9]}$	2	272	-540
$\mathcal{F}_{11}$	3	111	-216
$\mathcal{F}_{18}$	5	89	-168
$\mathcal{CP}^4_{[1,1,1,1,1]}$	1	$\mathcal{O}(100)$	$\mathcal{O}(-200)$

A manifold has $h^{1,1}$ number of Kähler moduli and $h^{2,1}$ number of complex structure moduli.

A typical flux compactification has hundreds of warped throats, each described by a complex structure modulus.

Cosmic strings produced towards the end of Inflation

- They are fundamental strings or D1-strings or vortices stretched to cosmological sizes.
- They may be produced via the annihilation of brane-anti-brane. These have tensions around or below the inflation scale.
- They may be produced thermally after inflation when the universe heats up to start the hot big bang. These have tensions below the temperature scale.

$$\phi_j = \rho_j e^{-ia_j/f_j} \qquad \partial_\mu a = \epsilon_{\mu\nu\lambda\kappa}\partial^\nu B^{\lambda\kappa}$$

Possibilities

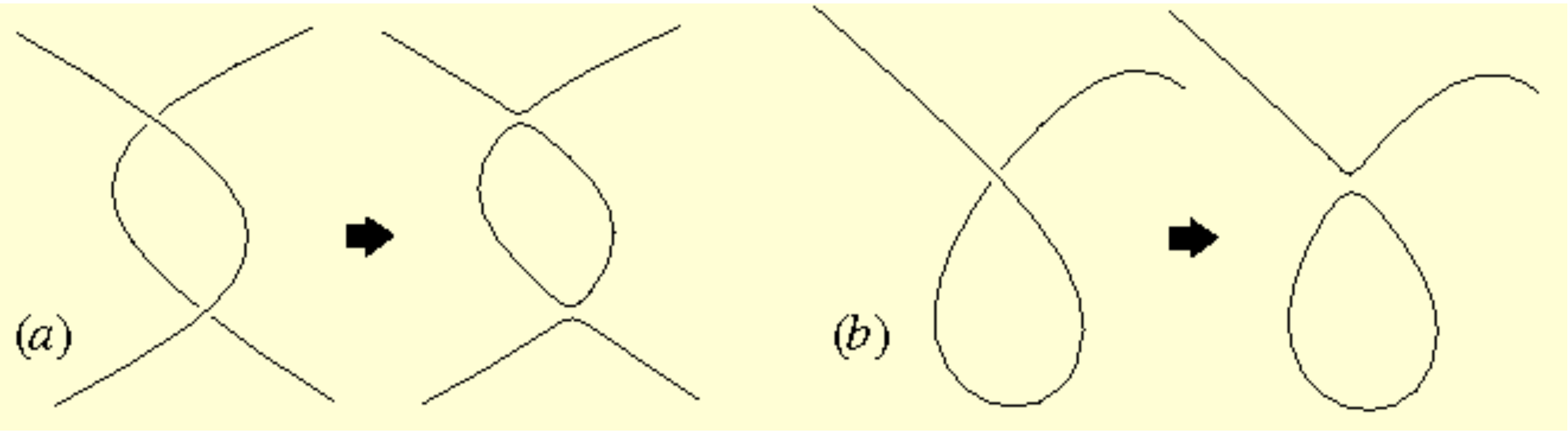
- Cosmic strings may fall into the throats. Each warped throat (with no D3-branes in its bottom) has its own (p,q) spectrum.
- A throat with D3-branes at its bottom will only have D1 vortices.
- Presumably most if not all the throats have their own cosmic string networks. Each throat has its own tension scale, typically some orders of magnitude below the string scale.
- This results in high cosmic string density (i.e., sum of cosmic string networks).

Cosmic string network

- Monopoles : density ~ a^{-3} Disastrous
- Domain walls : density ~ 1/a Disastrous
- cosmic strings : density ~ a^{-2}
  interaction cuts it down to a^{-4} during radiation

$$\Omega_{cs} = \Gamma G\mu$$

Cosmic string interactions



p = Probability of intercommutation

p=1 in abelian Higgs model

$1 > p > 10^{-3}$ in string theory

Jones, Jackson, Polchinski

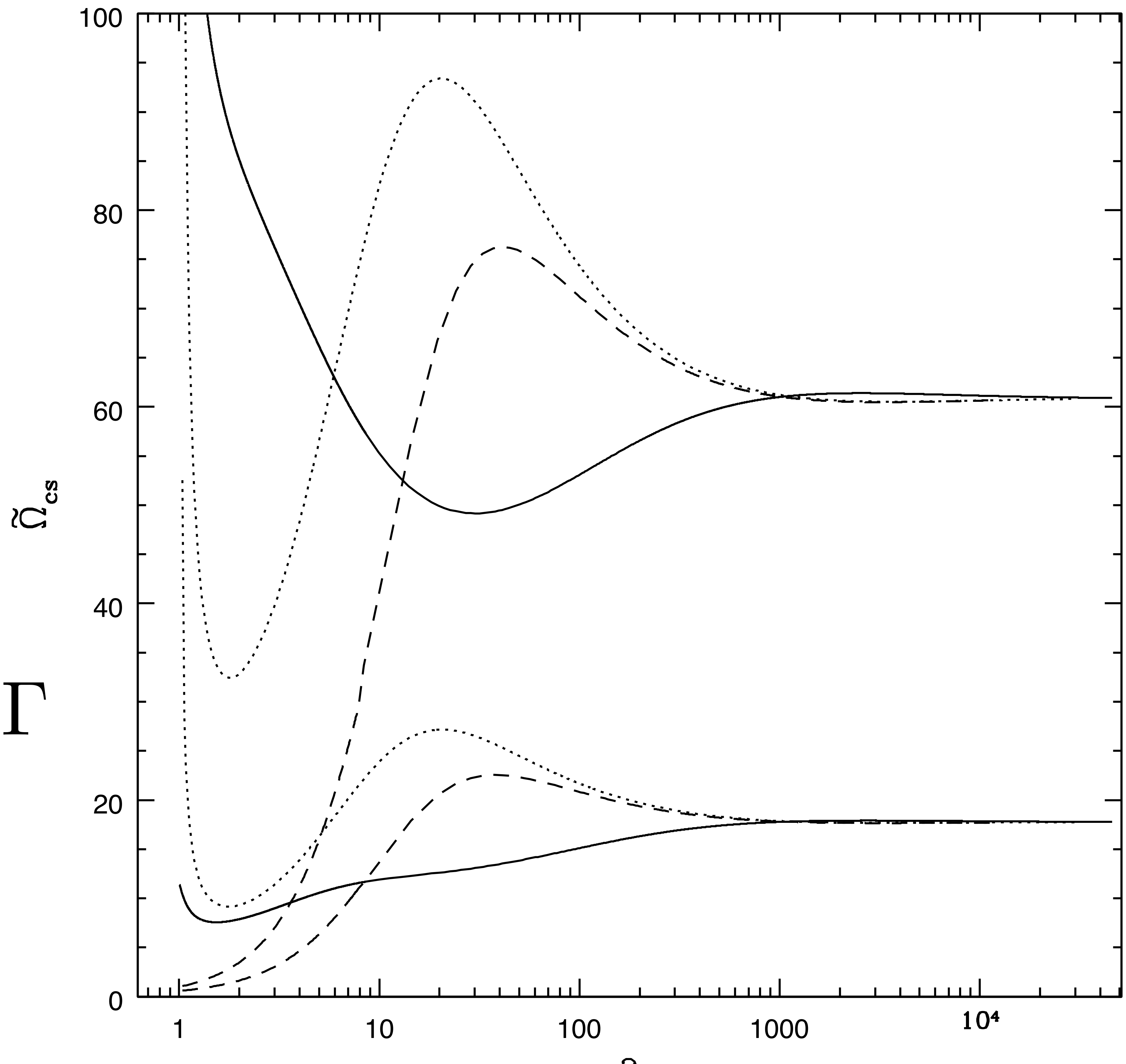
Scaling of the Cosmic Superstring Network

independent of initial conditions

Insensitive to the details of the interactions

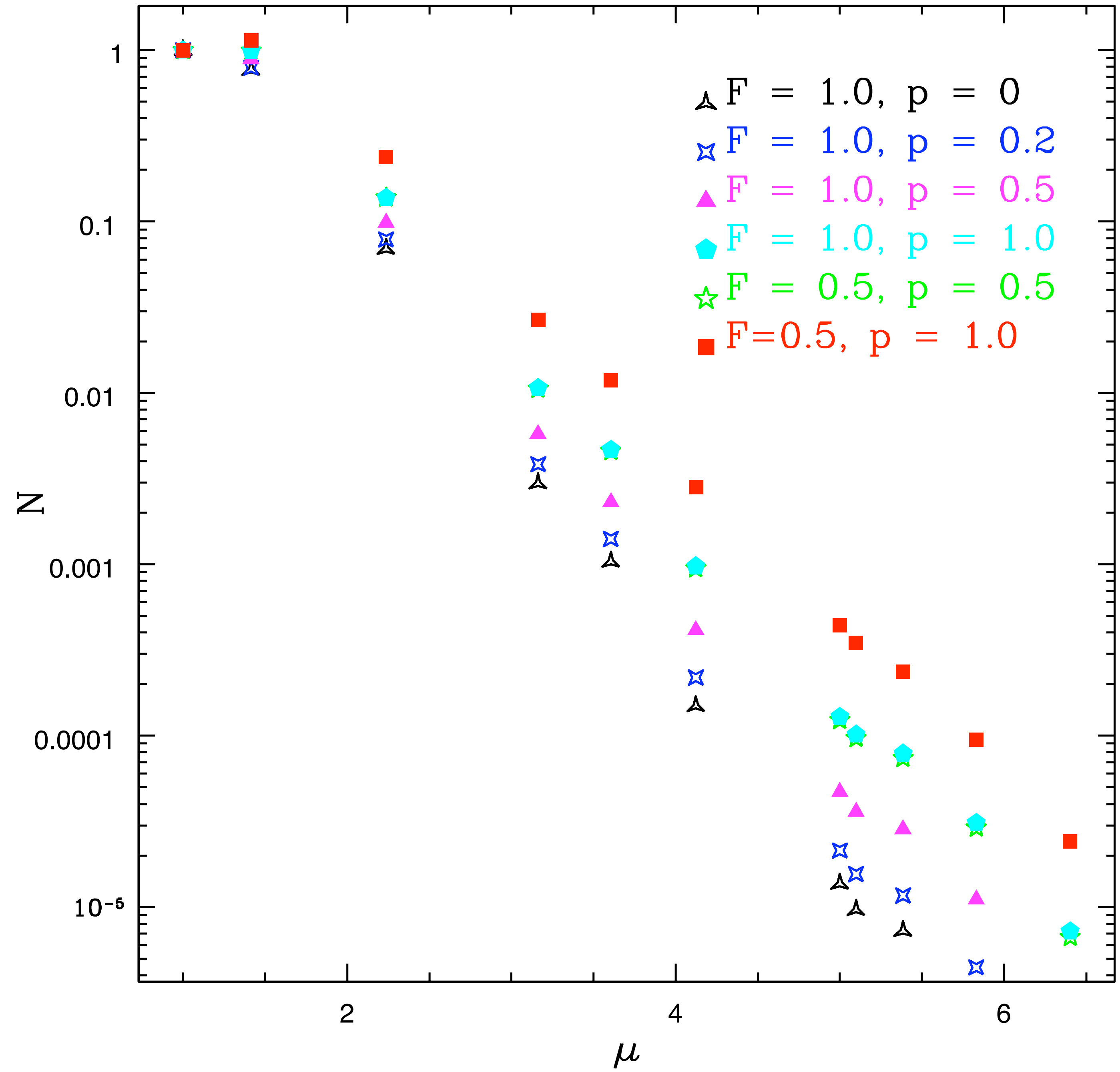
$$\Omega_{cs} = 8\pi G\mu\Gamma$$

$$\Gamma \sim 10$$



Relative density of (p,q) strings

$$n_{p,q} \sim \mu_{p,q}^{-8}$$



$$\Omega_{cs} = 8\pi G \sum_i \Gamma_i \mu_i / p_i \to$$

$$\sim 8\pi Z G\mu, \qquad Z \sim 100$$

History of Cosmic Strings

Early 1980s : Proposed to generate density perturbation as seed for structure formation; as an alternative to inflation; $G\mu \sim 10^{-6}$
Kibble, Zeldovich, Vilenkin, Turok, Shellard, Vachaspati, ...

- In 1985, Witten attempted to identify the cosmic strings as fundamental strings in superstring (heterotic) theory. He pointed out a number of problems with this picture: tension too big, no production and stability.

- By late 1990s, Cosmic Microwave Background Radiation data supports inflation and ruled out cosmic string as an explanation to the density perturbation.

- Polchinski and others pointed out the presence of D-branes and so D1-strings in IIB string theory.

- Flux compactification suggests that a variety of cosmic superstrings with low tensions are produced after inflation.

The cosmic superstring density can be much higher than expected, because of a collection of cosmic superstring network with low p.

$$\Omega_{cs} = \Gamma G \mu$$

$$\Omega_{cs} = 8\pi G \sum_i \Gamma_i \mu_i / p_i$$

In general, one should detect different string tensions.

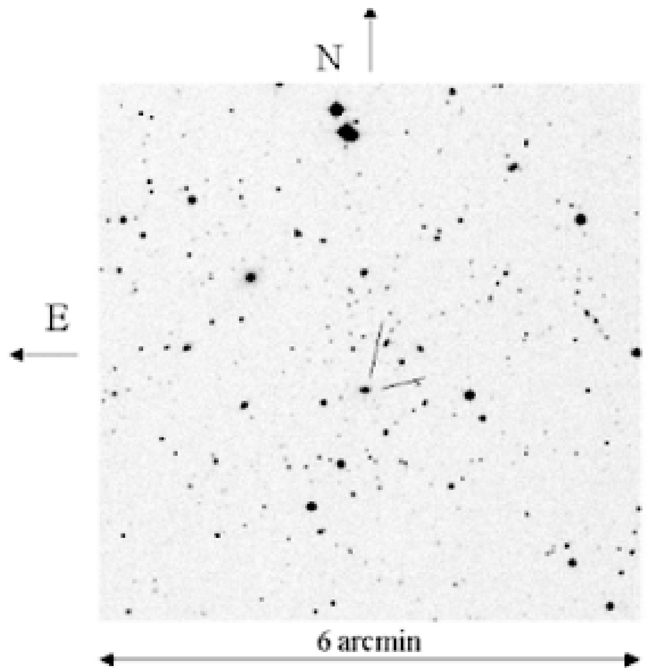
- Cosmic strings may oscillate in the internal space because the damping into a throat is too weak.

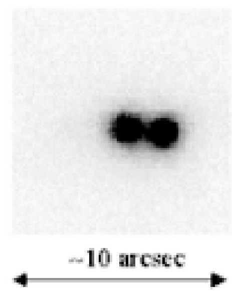
Search for Cosmic Strings

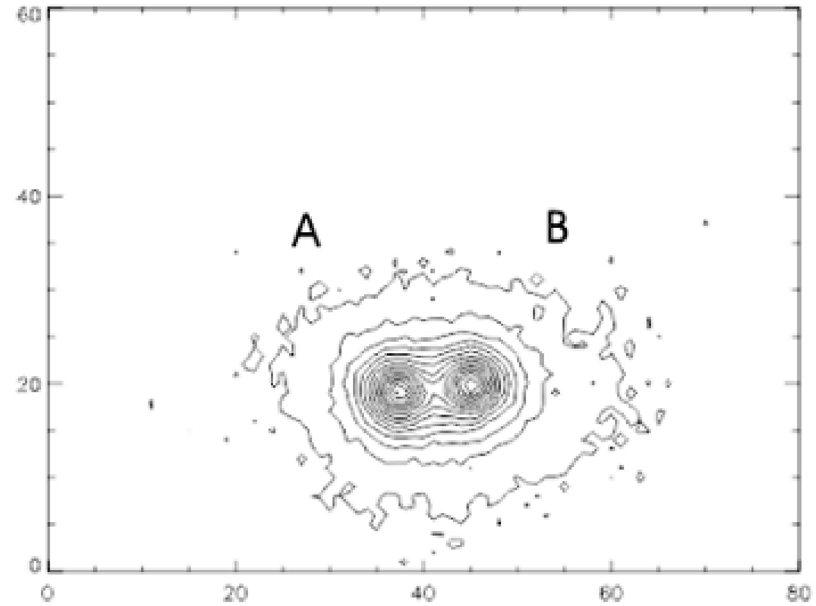
- Lensing
- Cosmic Microwave Background Radiation
- Gravitational Wave Burst
- $\Delta T/T$
- Pulsar Timing
- Stochastic Gravitation Radiation Background

Micro-lensing of Stars

Lensing CSL-1





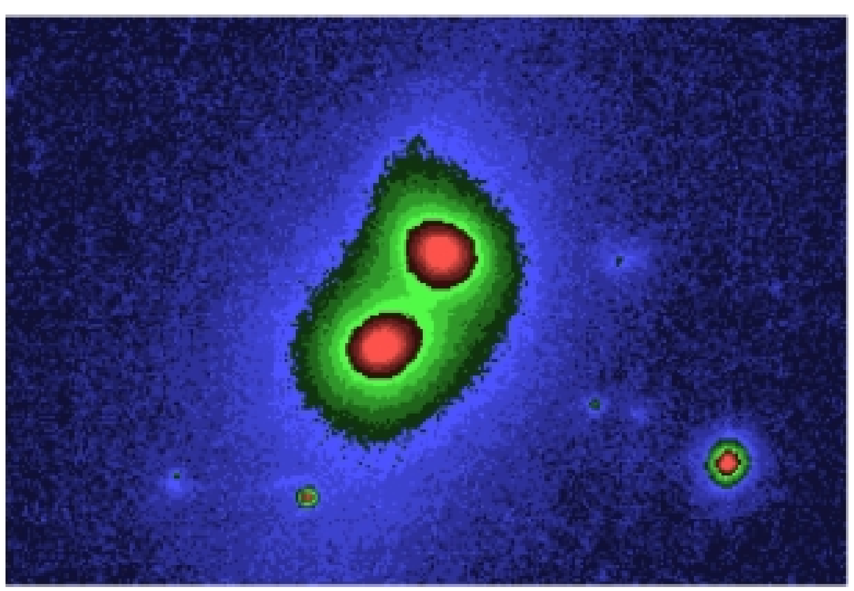


1.9 arc sec

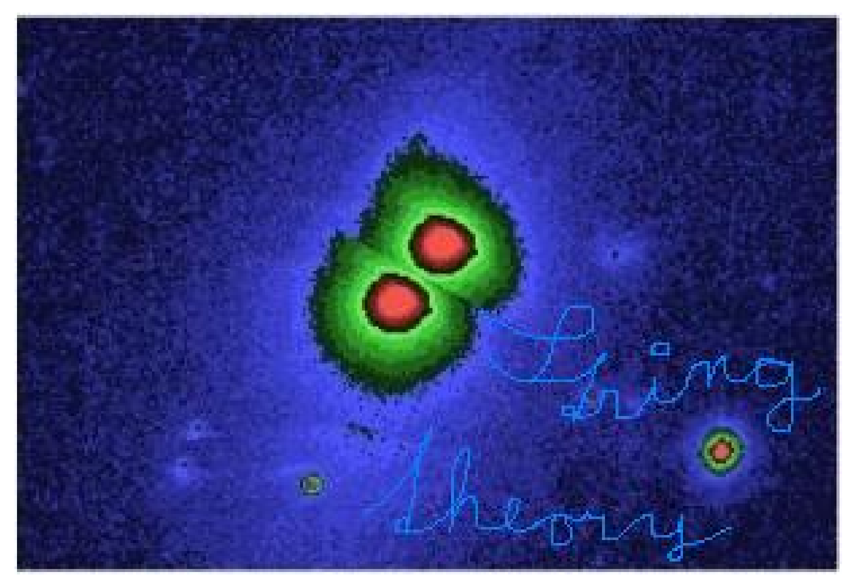
$\Downarrow$

$G\mu \sim 4 \times 10^{-7}$

Unfortunately not (higher resolution Hubble pictures):

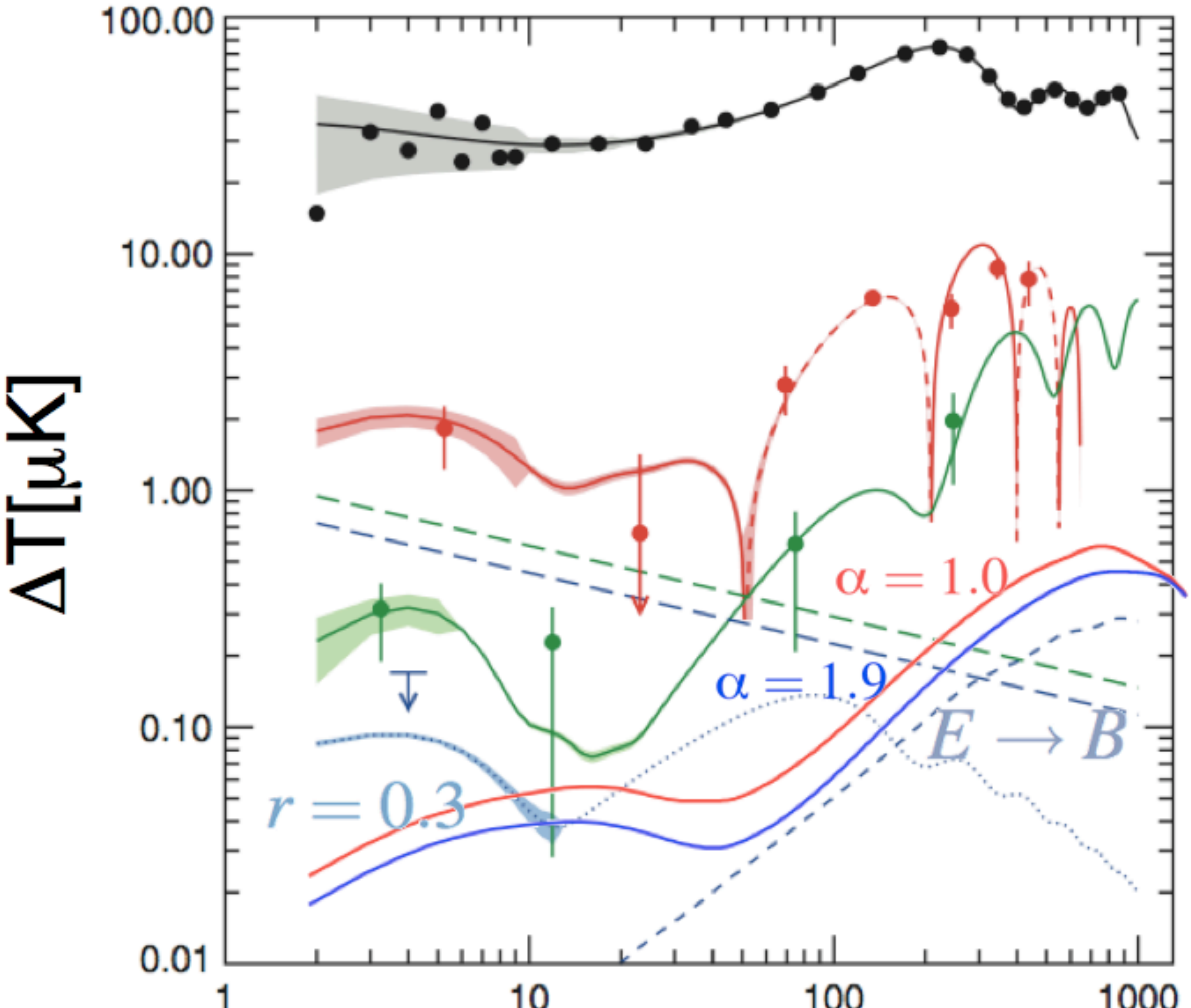


January 2006

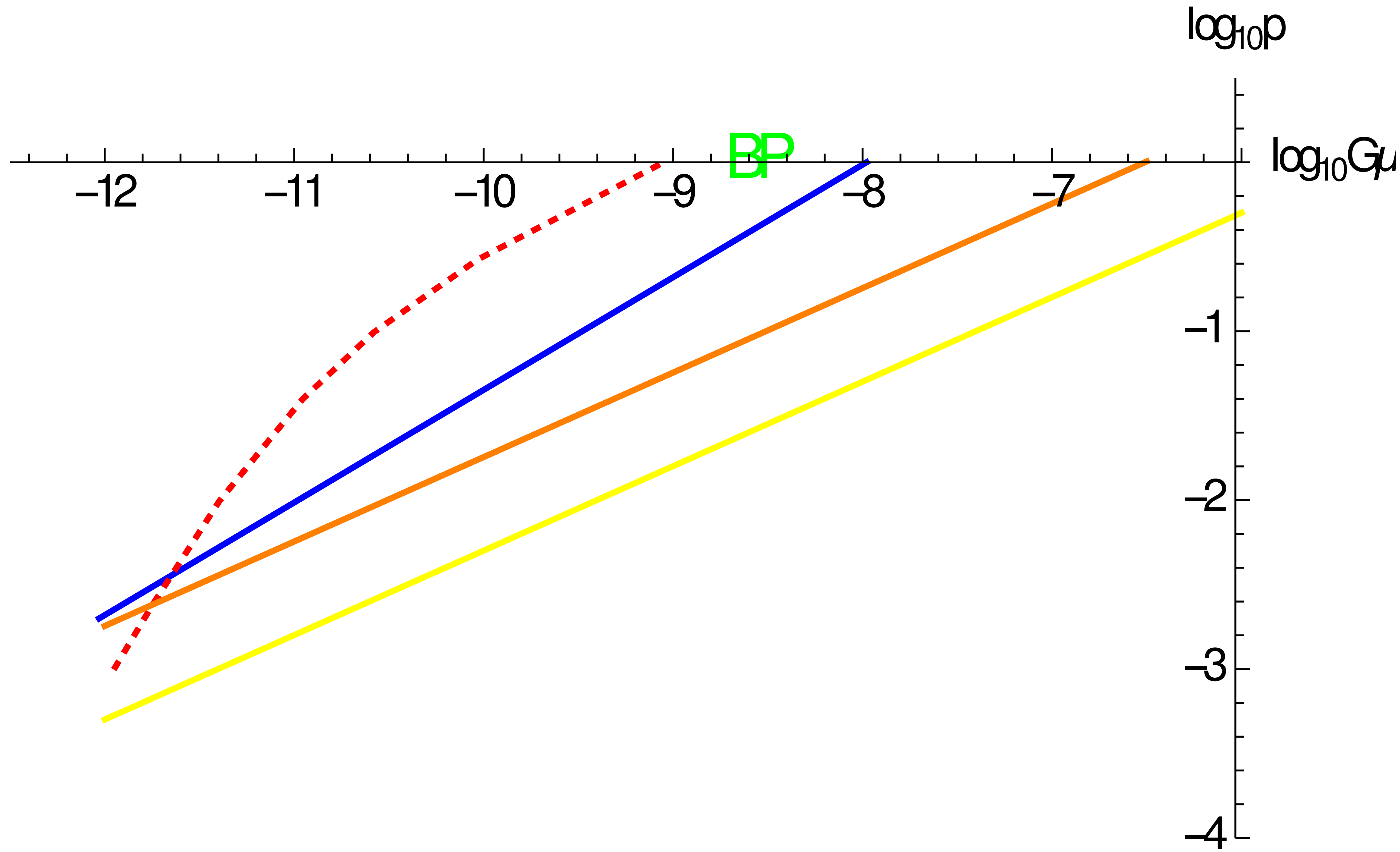


If it is cosmic string lensing

Possible CMB B-mode detection



Bounds on cosmic string tension

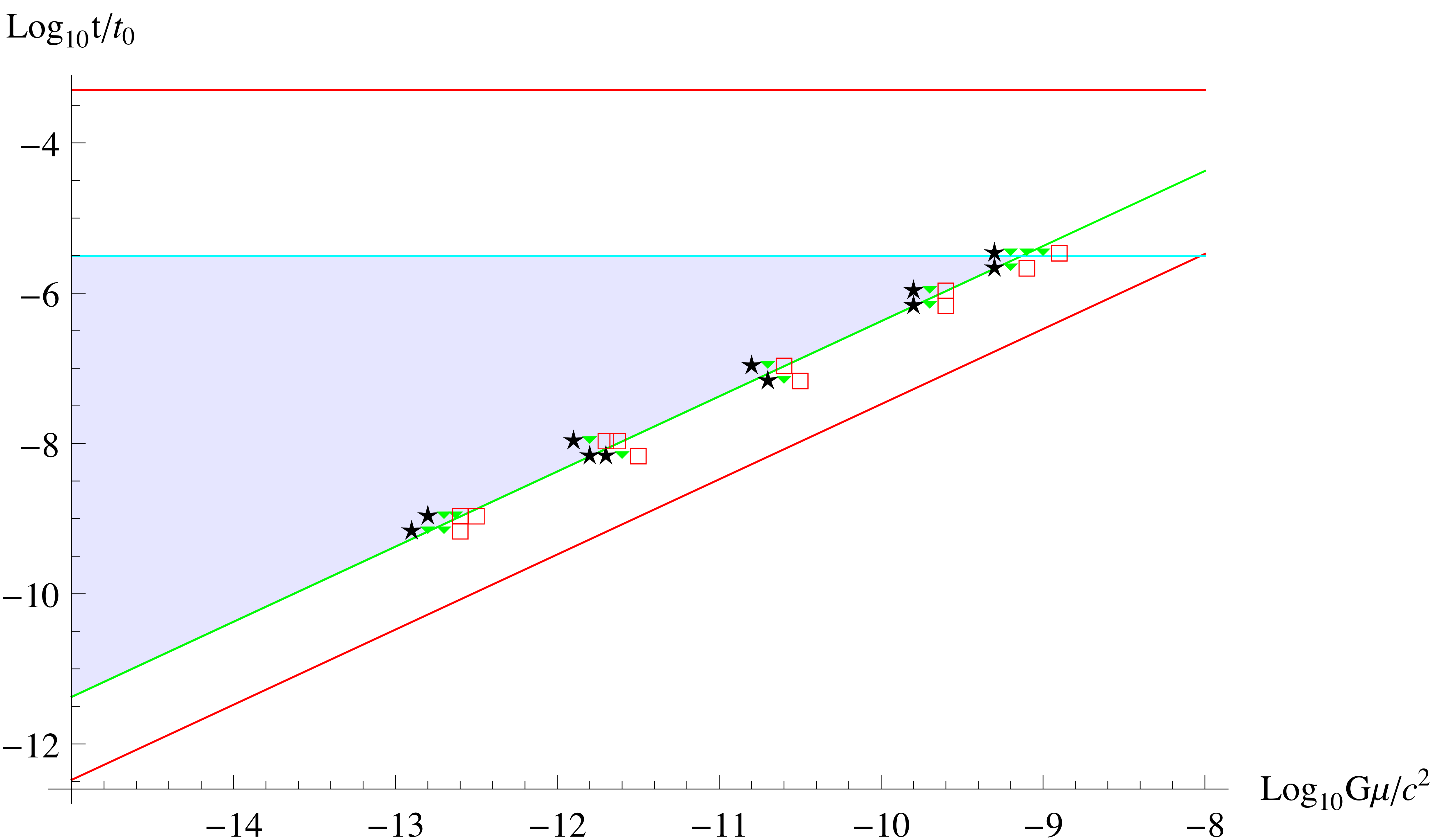


Big Bang Nucleosynthesis (orange line) and CMB (yellow line) from the gravitational wave spectra, the Parkes Pulsar Timing Array (blue line) and NANOGrav (red dotted line)

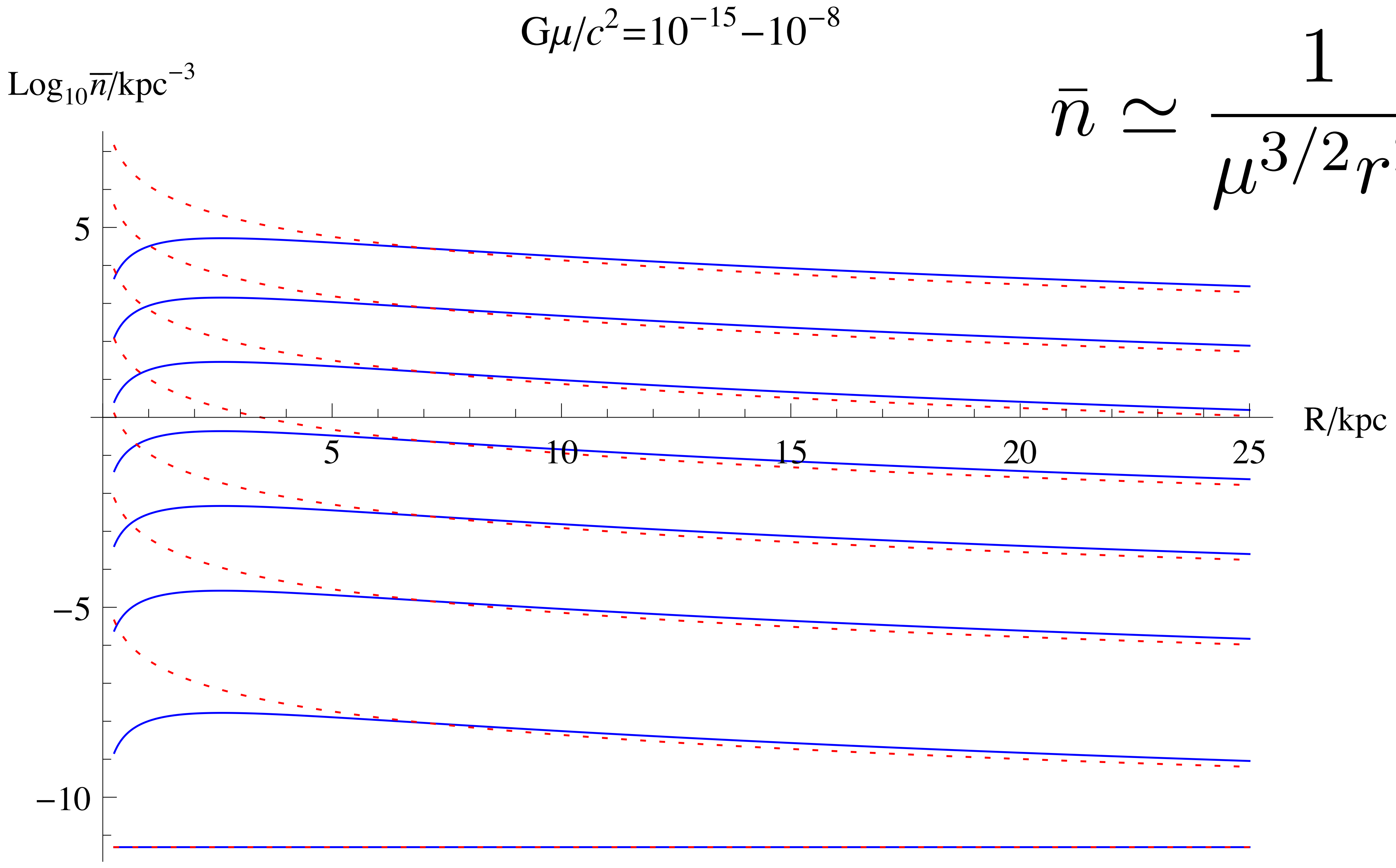
$$G\mu < 10^{-8} - 10^{-9}$$

Clustering like dark matter

$10^{5.5}$



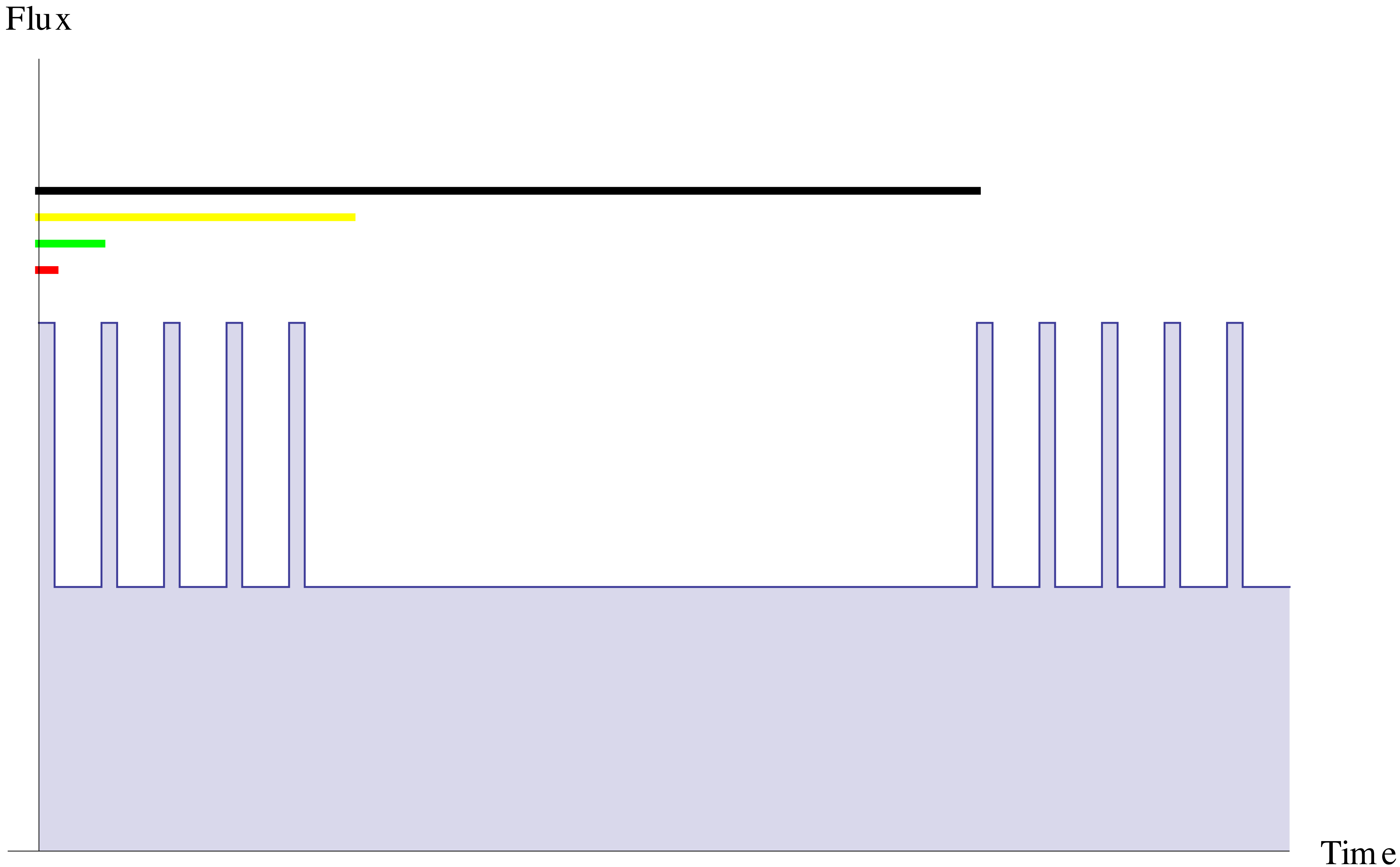
Energy density of small cosmic string loops

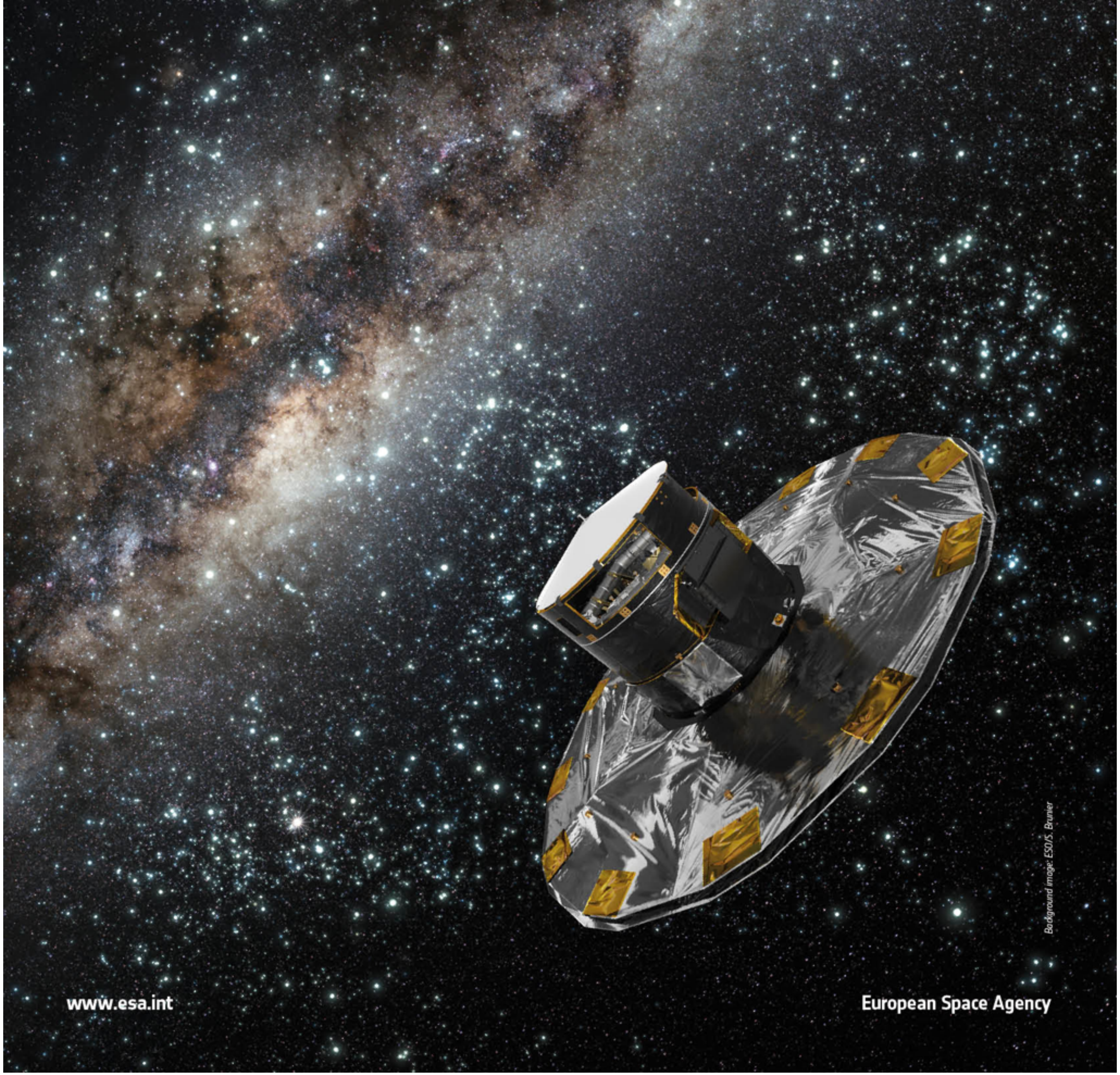


$$\bar{n} \simeq \frac{1}{\mu^{3/2} r^2}$$

Our sun is 8-8.5 kpc from the center of galaxy

A typical microlensing signal of a star by a moving cosmic string



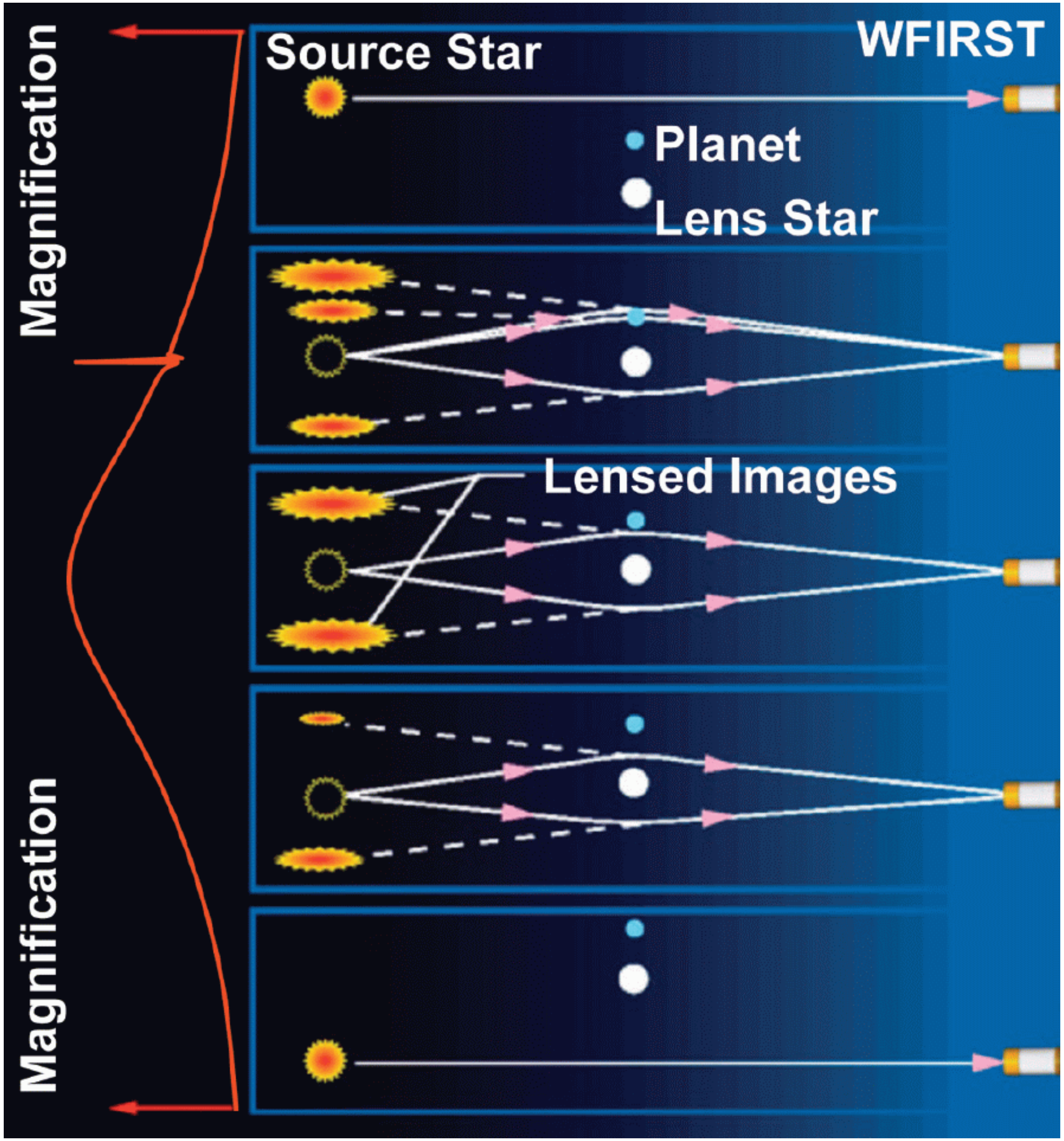


GAIA is the primal Greek Goddess of the Earth

Search

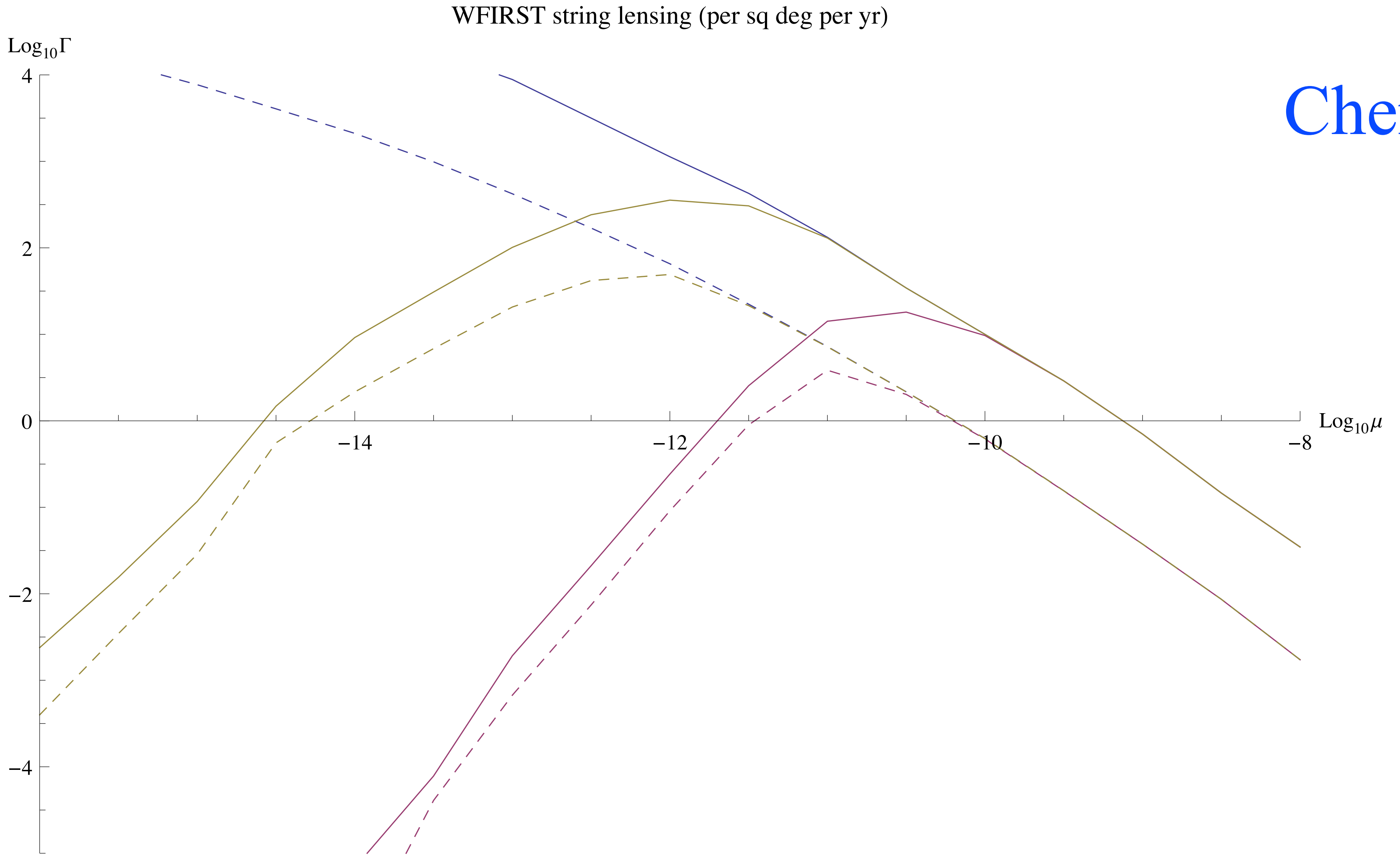
- GAIA (ESA) was launched December 2013, will look at a billion stars (1% of Milky Way). It will look at each of its target 70 times in 5 years.
- LSST (Large Synoptic Survey Telescope) will photograph the entire observable sky every few days, starting in 2022.
- WFIRST (Wide Field Infrared Survey Telescope) to be launched 2024. It is selected to be the top priority for the next decade in astronomy, to study dark energy, gravitational lensing and exoplanets. (From National Reconnaissance Office, 94 in (diameter) is twice the original design size.)

WFIRST gravitational microlensing



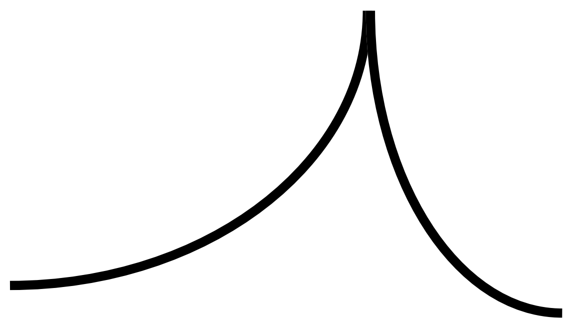
Rate for WFIRST

Chernoff et al.



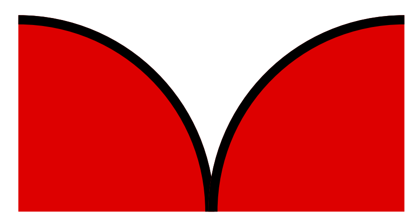
WFIRST will carry out a microlensing survey program for exo-planet detection in the direction of the galactic bulge by observing a total of 2.8 square degrees for 1.2 years.

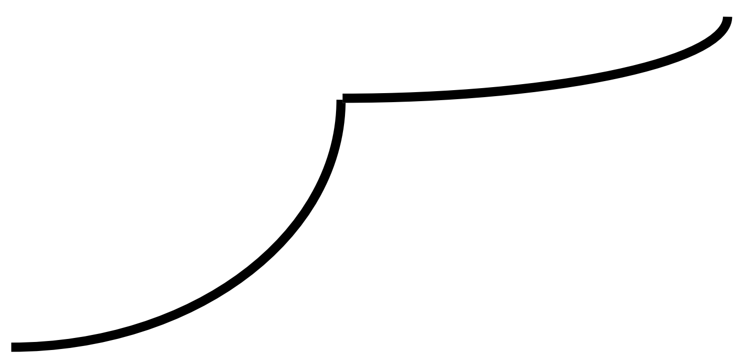
cusps and kinks
are quite common in string evolution



CUSP

$h(t) \sim |t|^{1/3}$





wave form of
gravitational wave bursts

KINK

$h(t) \sim |t|^{2/3}$

Damour and Vilenkin

Summary

Cosmic strings with tension

$G\mu > 10^{-9}$ to be detected via pulsar timing.

$10^{-9} \geq G\mu \geq 10^{-14}$ to be detected via microlensing.

Cosmic strings with different tensions or even junctions will provide distinct signatures.

The coming decade can be exciting.