The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA
International Atomic Energy Agency

SMR.1832- 9

SPRING SCHOOL ON SUPERSTRING THEORY AND RELATED TOPICS

22 - 30 March 2007

Brane Inflation
PART 3

H. TYE

Department of Physics
Cornell University
117 Clark Hall
Ithaca, NY 14853-501
U.S.A.

Brane Inflation :
III. Cosmic Strings

Henry Tye

Cornell University

ICTP, Trieste, 3/23/07

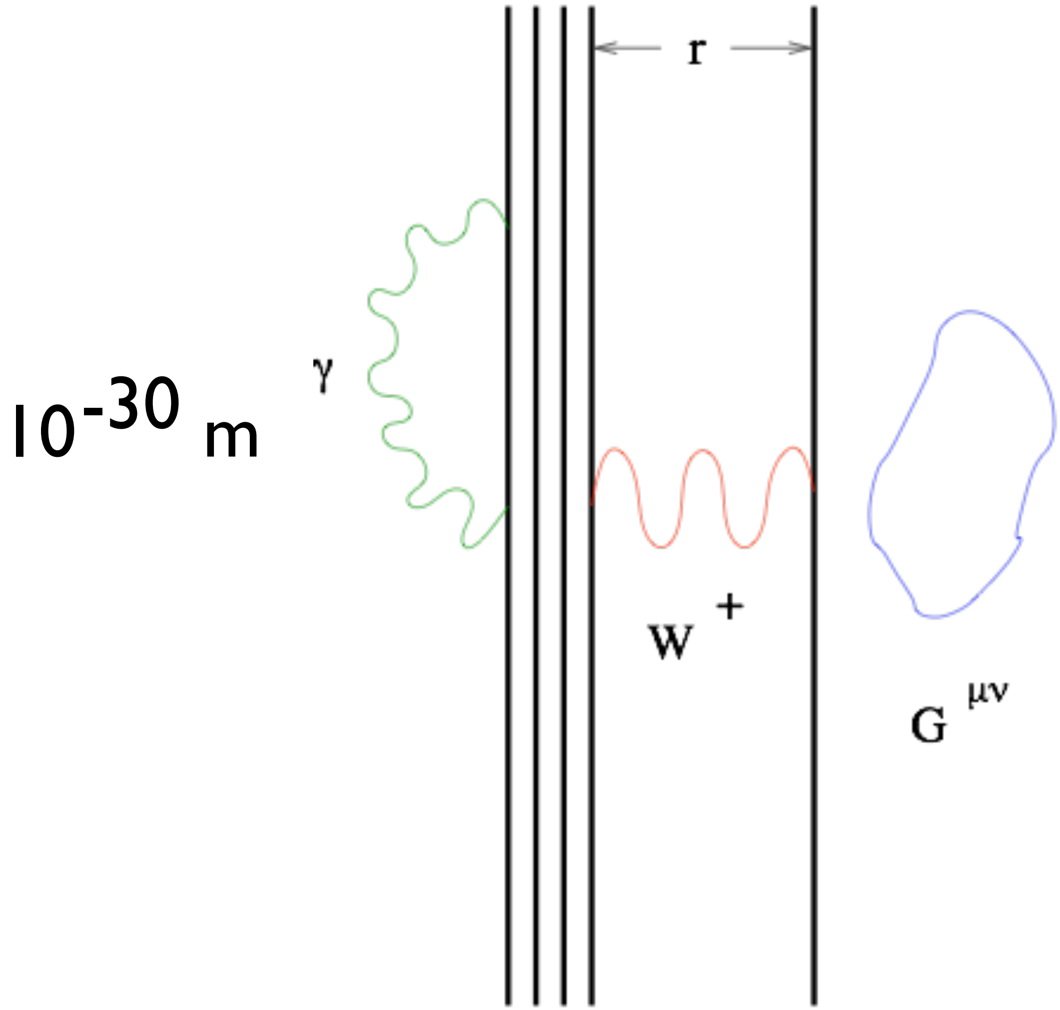
Superstring theory contains Dp-branes

A p-brane has p spatial dimensions:
a string is like a 1-brane;
a membrane is a 2-brane

We are living inside a D3-brane
(or a Dp-brane wrapping a p-3 cycle)

Outside our branes is the bulk,
which is compactified.

Brane world in Type IIB



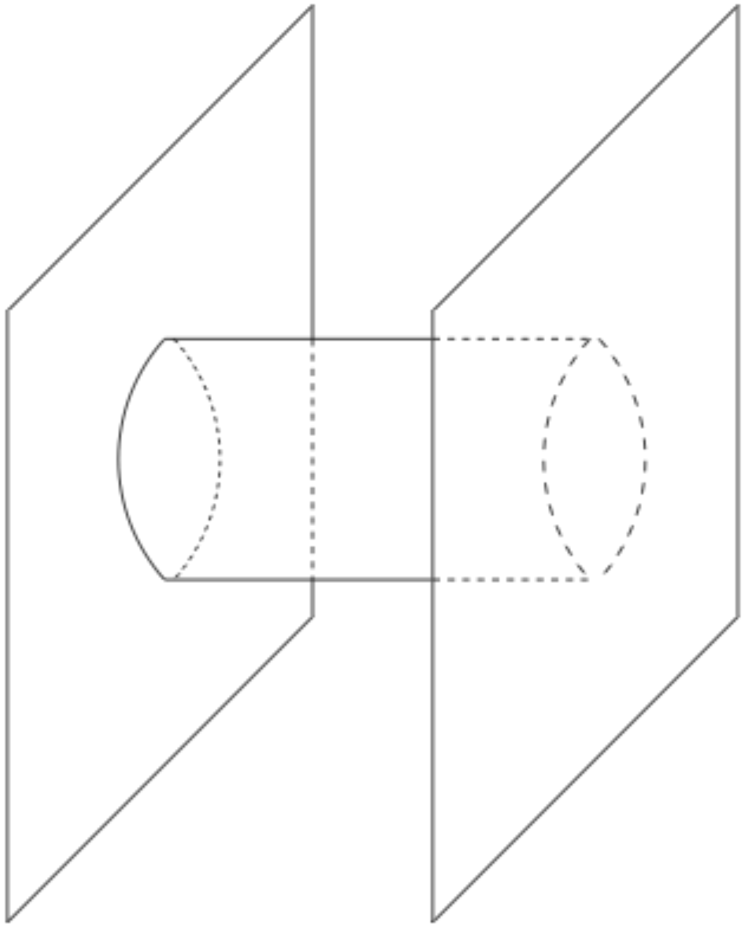
How is inflation realized in brane world ?

Brane inflation

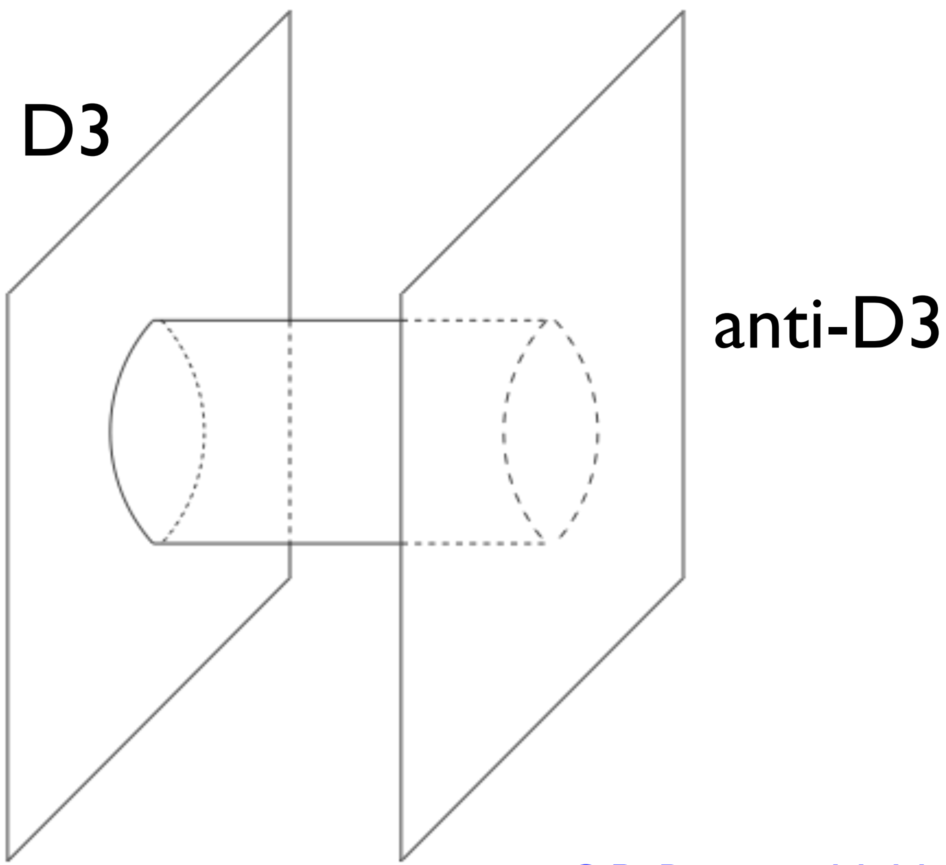
Dvali and H.T. hep-ph/9812483

Inflaton is an open string mode

Inflaton potential comes from the closed string exchange

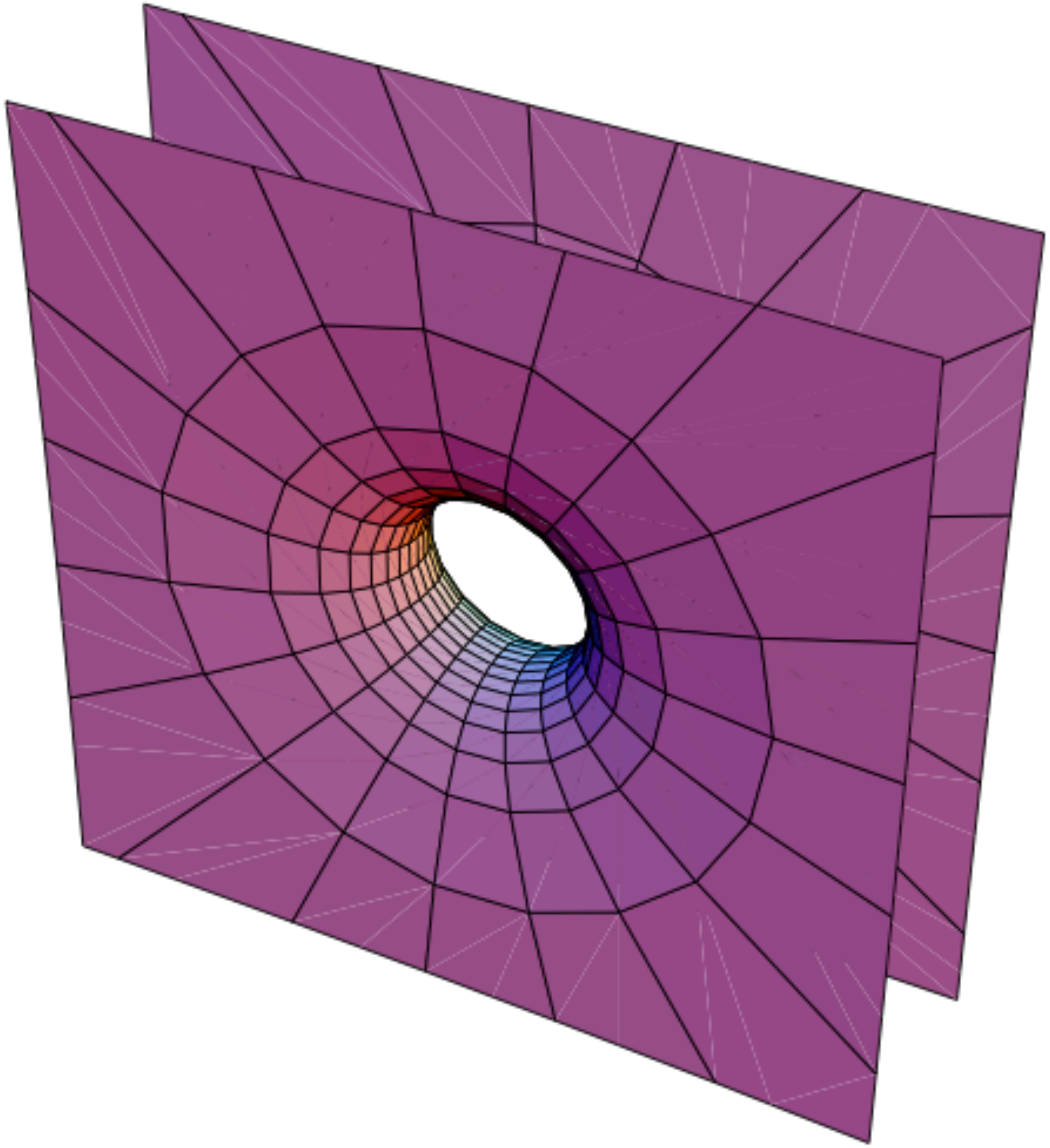


D3-anti-D3 brane inflation



C.P. Burgess, M. Majumdar, D. Nolte, F. Quevedo, G. Rajesh, R. Zhang, hep-th/0105204
G. Dvali, Q. Shafi and S. Solganik, hep-th/0105203

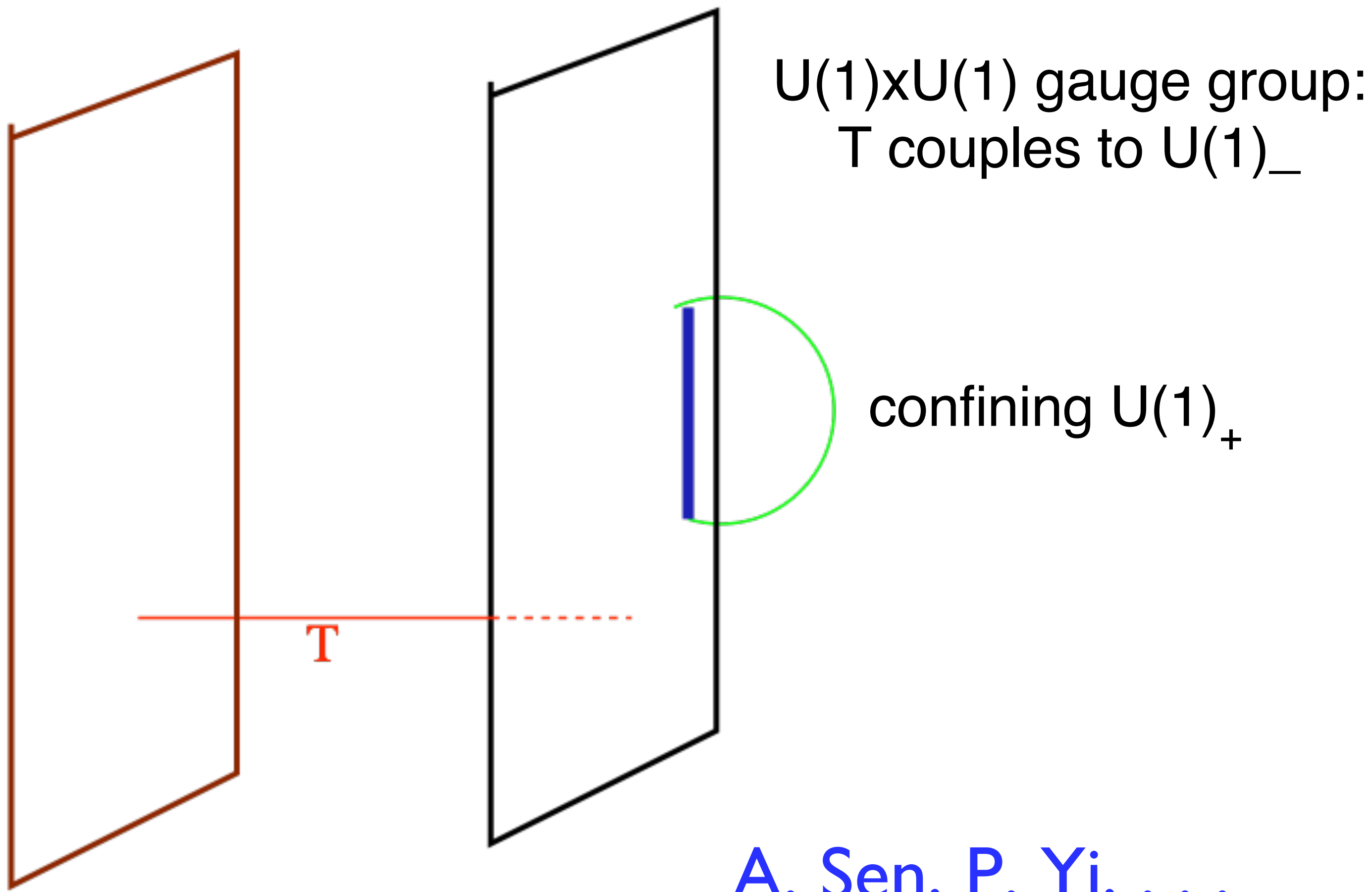
Brane-anti-brane Annihilation



Production of cosmic strings

towards the end of brane inflation

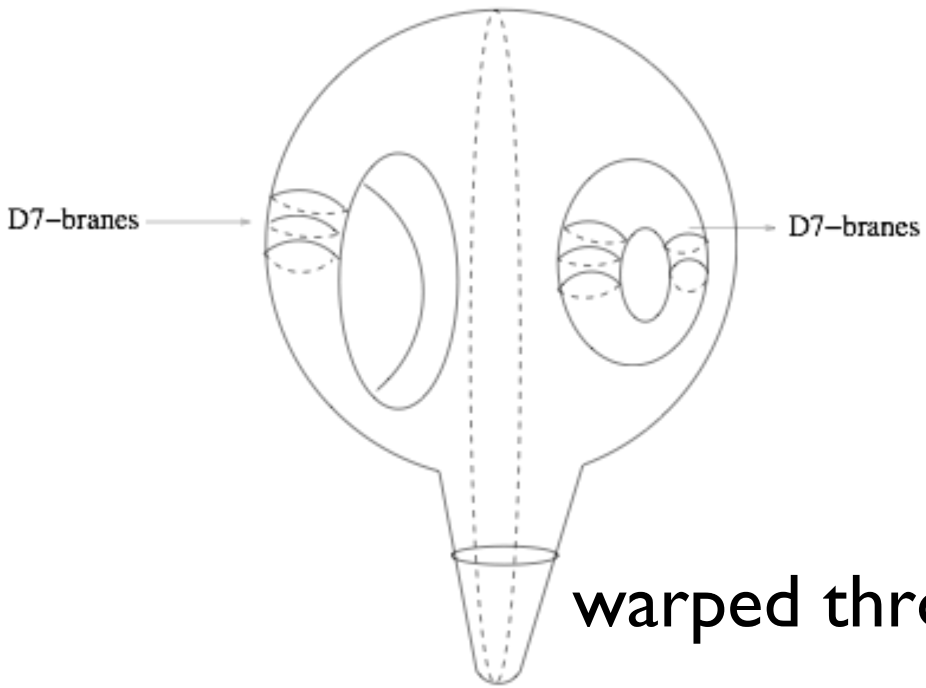
from the D3-anti-D3 annihilation



A. Sen, P. Yi, . . .

Flux compactification

where all moduli of the 6-dim. manifold are stabilized



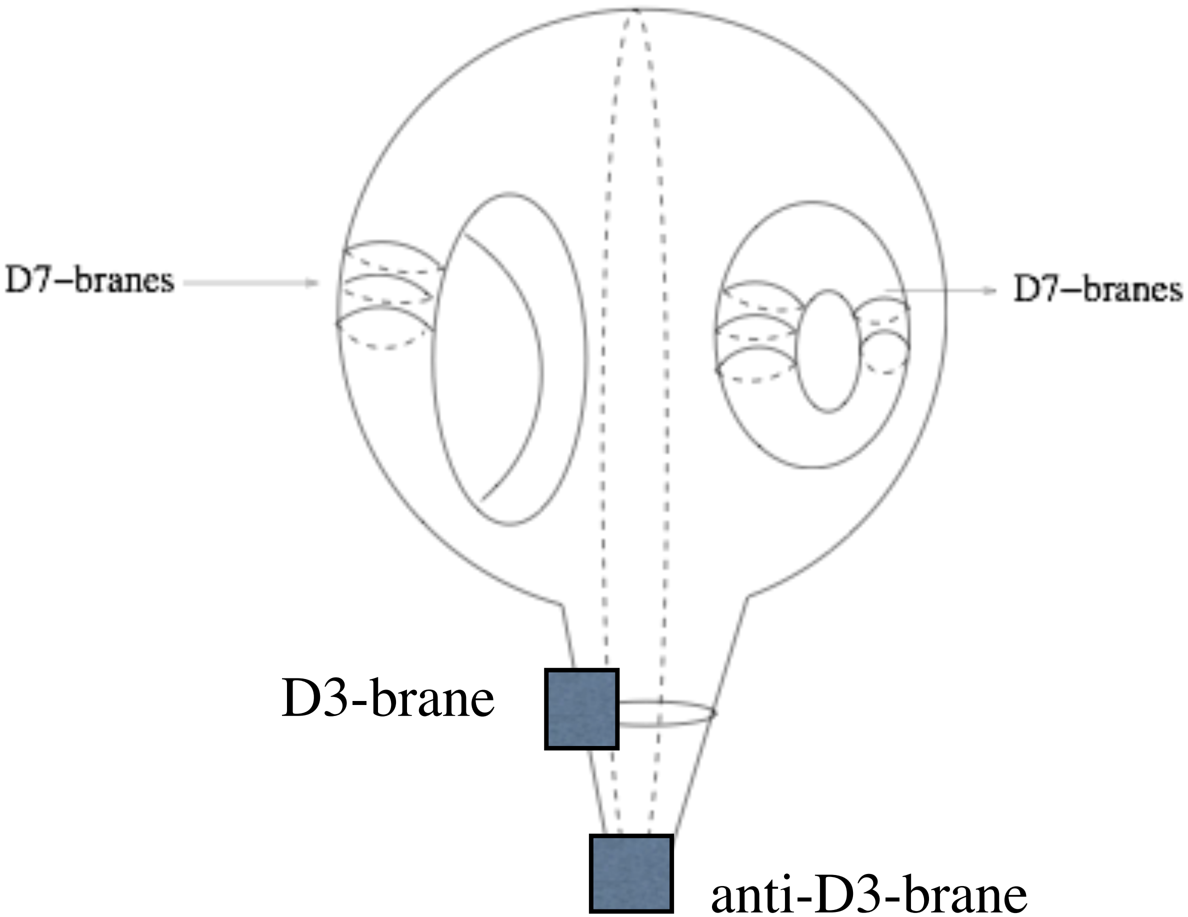
warped throat

Giddings, Kachru, Polchinski
Kachru, Kallosh, Linde, Trivedi

and many others

KKLT vacuum

The KKLMMT scenario



Kachru, Kallosh, Linde, Maldacena, MacAllister, Trivedi,
hep-th/0308055

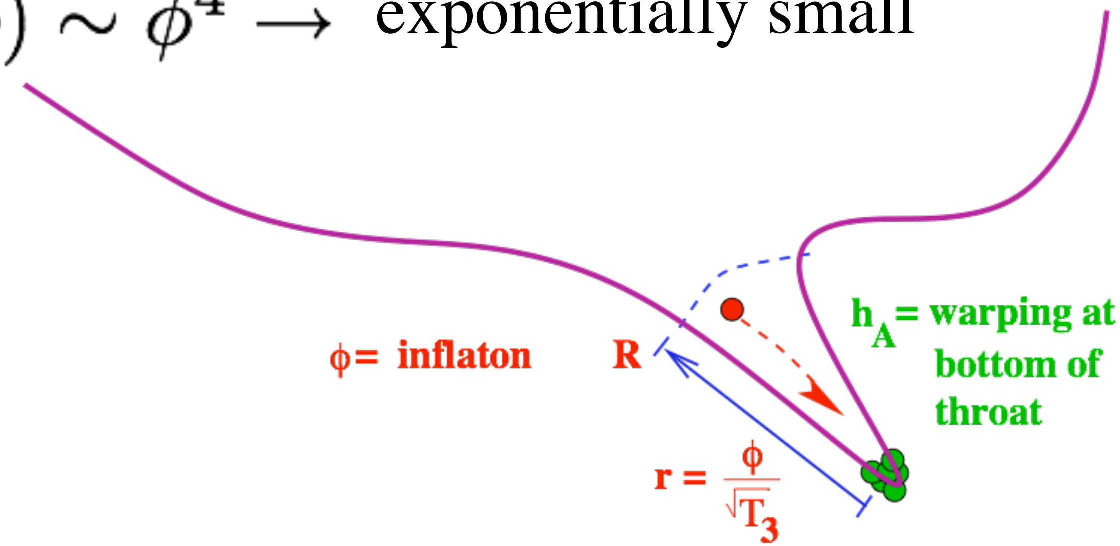
Why brane inflation is so robust ?

$$S = -\int d^4x\, a^3(t) \left[T\sqrt{1-\dot{\phi}^2/T} + V(\phi) - T \right]$$

Dirac-Born-Infeld action yields Lorentz factor :

$$\gamma = \frac{1}{\sqrt{1-\dot{\phi}^2/T}} \quad \rightarrow \quad \dot{\phi}^2 < T(\phi)$$

$$T(\phi) \sim \phi^4 \rightarrow \text{exponentially small}$$



E. Silverstein and D. Tong, hep-th/0310221

Well-known cosmological properties

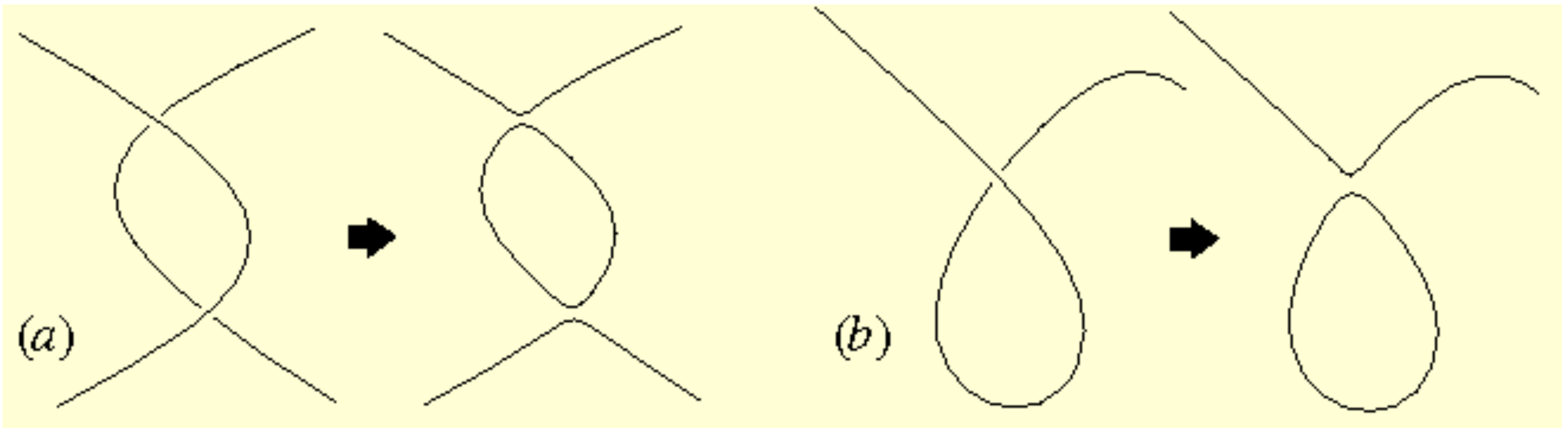
- Monopoles : density ~ a^{-3} Disastrous
- Domain walls : density ~ 1/a Dangerous
- cosmic strings : density ~ a^{-2}
  interaction cuts it down to a^{-4} during radiation
  Safe

$$10^{-11} < G\mu < 10^{-6}$$

N. Jones, H. Stoica, H.T., hep-th/0203163
S. Sarangi , H.T., hep-th/0204074

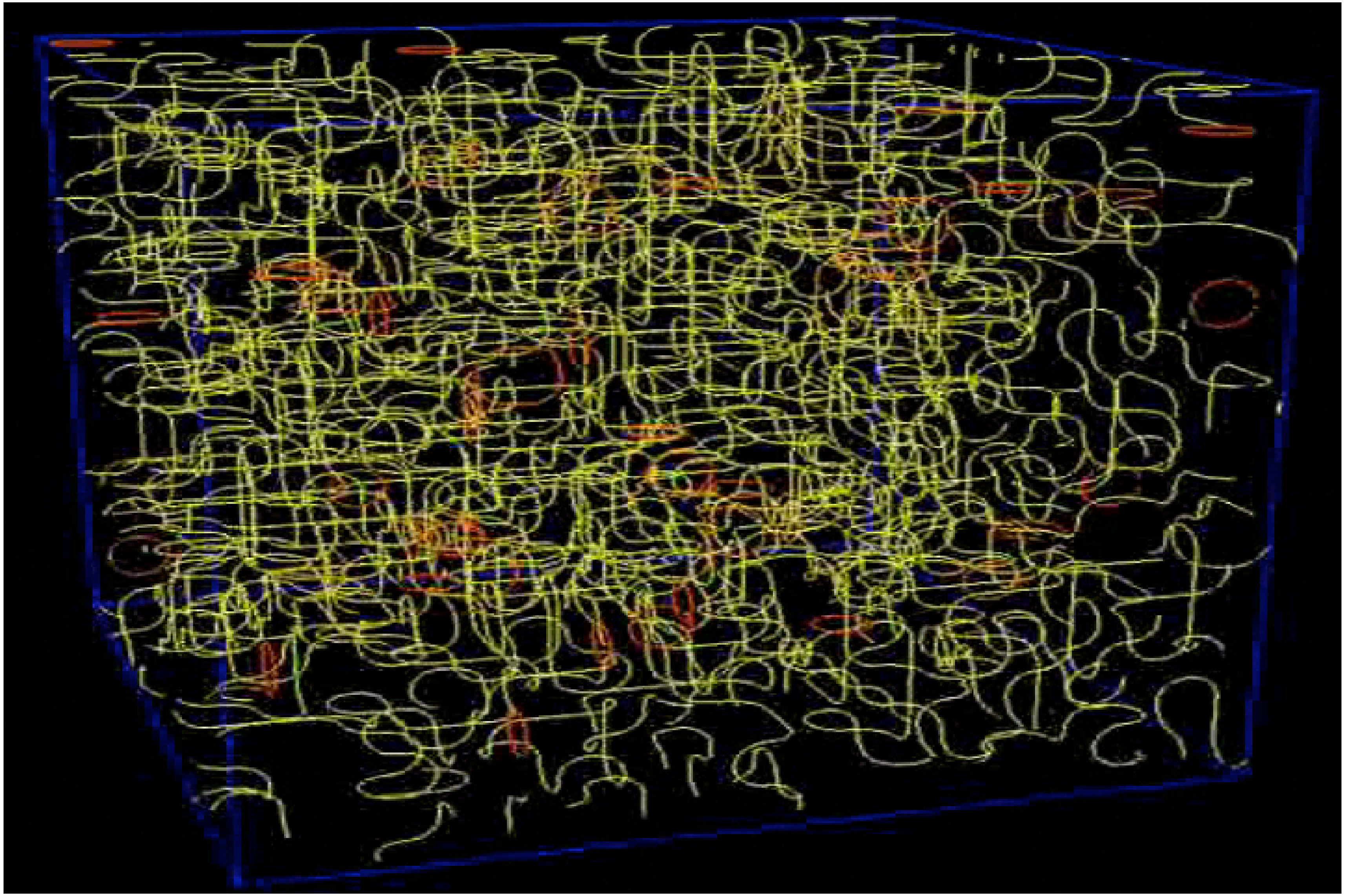
Cosmic strings

- Cosmic string interactions



Cosmic String Network Evolution

Allen, Martins & Shellard



A simple way to see why cosmic string network scales

$$\rho \simeq \frac{E}{L^3} \simeq \frac{\mu L}{L^3} \simeq \frac{\mu}{L^2}$$

$$\dot{\rho} = -2\frac{\dot{a}}{a}\rho - \lambda\frac{\rho}{L}$$

$$\lambda = 0)$$

$$L\left(t\right) = \gamma\left(t\right)t$$

$$\gamma \sim \sqrt{t}$$

$$\dot{\gamma} = -\frac{1}{2t}\left(\gamma - \lambda\right)$$

This equation has a stable fixed point at $\gamma(t) = \lambda$.

$$\rho = \frac{\mu}{\lambda^2 t^2} \sim \begin{cases} \mu/\left(\lambda^2 a^4\right) & \text{radiation dominated era} \\ \mu/\left(\lambda^2 a^3\right) & \text{matter dominated era} \end{cases}$$

History of cosmic strings

- Early 1980s : proposed to generate density perturbation as seed for structure formation; as an alternative to inflation; Kibble, Zeldovich, Vilenkin, Turok, Shellard, . . . $G\mu > 10^{-6}$
- 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 the stability issue.
- In early 1990s, COBE data disfavors cosmic strings.
- By late 1990s, CMB data supports inflation and ruled out cosmic string as an explanation to the density perturbation.
- In 1995, Polchinski and others pointed out the presence of D-branes in string theory. This led to the brane world/brane inflation scenarios, which led to a revival of cosmic strings,
- These cosmic strings have a much lower tension, were produced cosmologically, and can be quite stable.

Production of cosmic strings not guaranteed

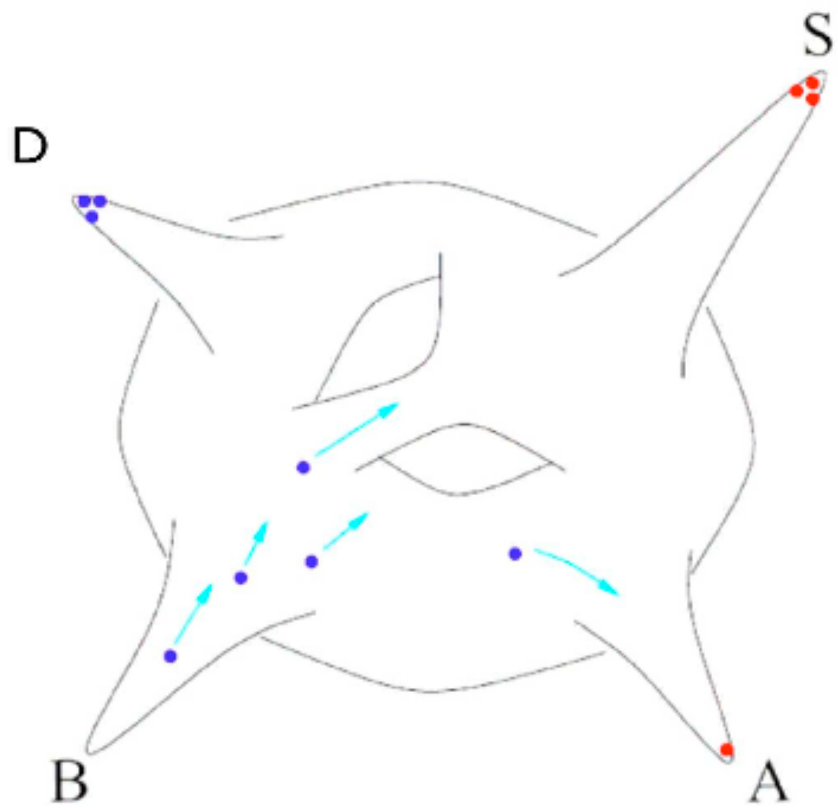
- there are scenarios where probably no cosmic strings are produced
- or strings produced are not stable while (meta-)stable strings are not produced

However,

- parametric resonance production of pairs of closed strings (Gubser) is possible

$$\rho_{loop} > \mu/l^2$$

Scenarios :

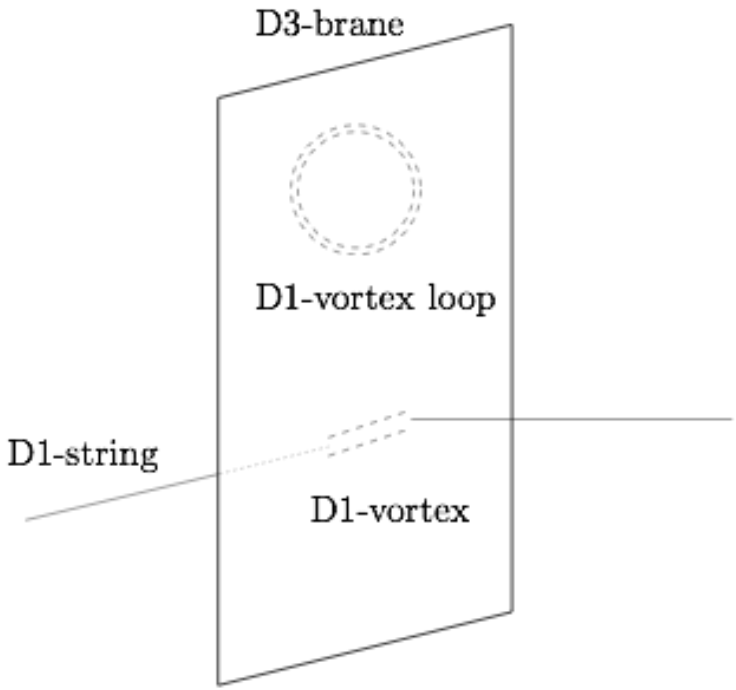


Reheating is fine

D1-string inside D3-brane

$$S = -\int_{M_4} \frac{1}{2}|G_2|^2 + \frac{1}{2}|dC_2|^2 + \xi C_2 \wedge G_2 + 2\pi n a \delta^2(x_\perp) \wedge C_2$$

$$a = \sqrt{2}\tau_1 \kappa_4$$



L. Leblond and HT
hep-th/0402072

Uncertainties in the amount of sub-horizon loops

$$\Omega_{cs} = \Omega_\infty + \Omega_{loop} = 50G\mu + \chi\sqrt{\alpha}\sqrt{G\mu}$$

$$\chi \sim 100$$

The typical size of the loops is parameterized as αt

$$\alpha \sim 0.25, 0.1, 10^{-4}, 50G\mu, (50G\mu)^{5/2}$$

$$\alpha \sim 10^{-20}$$

V. Vanchurin, K. Olum and A. Vilenkin, gr-qc/0501040, 0511159

C. Ringeval, M. Sakellariadou and F. Bouchet, astro-ph/0511646

C. Martin and E.P. Shellard, astro-ph/0511792

J. Polchinski and J. Rocha, hep-ph/0606205

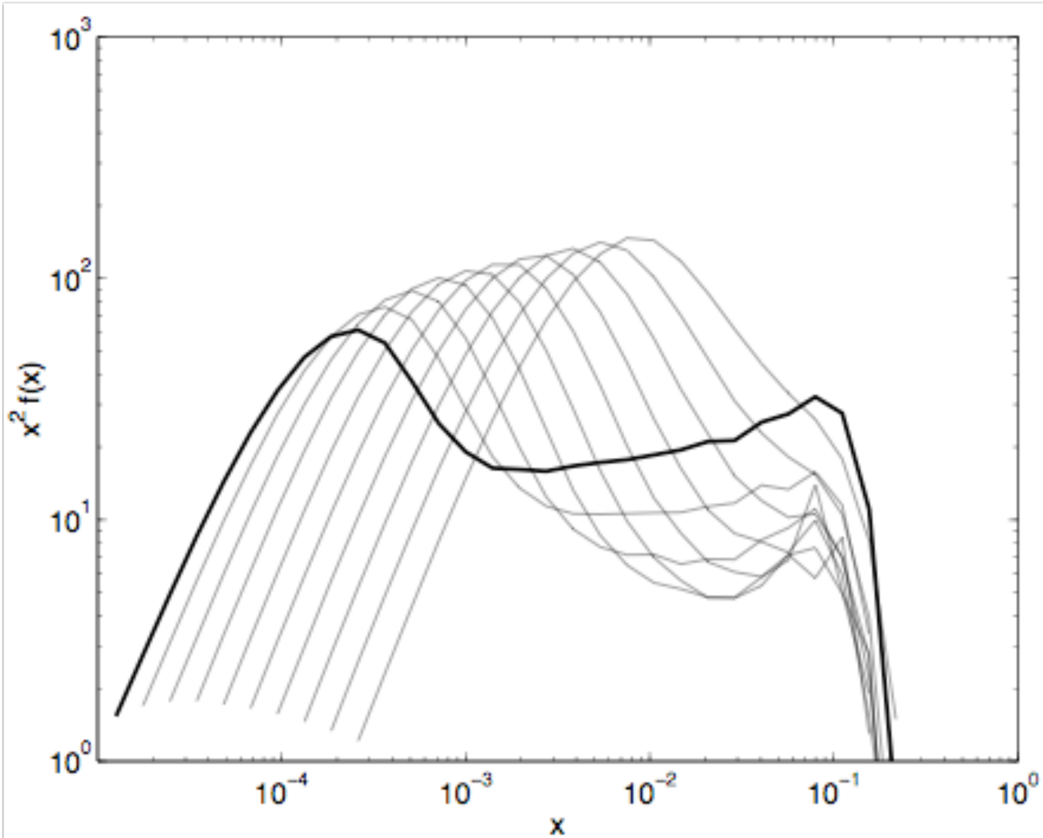
Uncertainties

$$\Omega_{cs} = \Omega_{\infty} + \Omega_{loop} = 50G\mu + \chi\sqrt{\alpha}\sqrt{G\mu}$$

$$G\mu \sim 10^{-11} \quad to \quad 10^{-7}$$

$loops\ production$

$f(x)\ peaks\ at\ x = \alpha$



V. Vanchurin, K. Olum and A. Vilenkin

Which peak is real ?

Vanchurin, Olum and Vilenkin : $\alpha \simeq 0.1$

2006

C. Ringeval, M. Sakellariadou and F. Bouchet
C. Martin and E.P. Shellard
J. Polchinski and J. Rocha

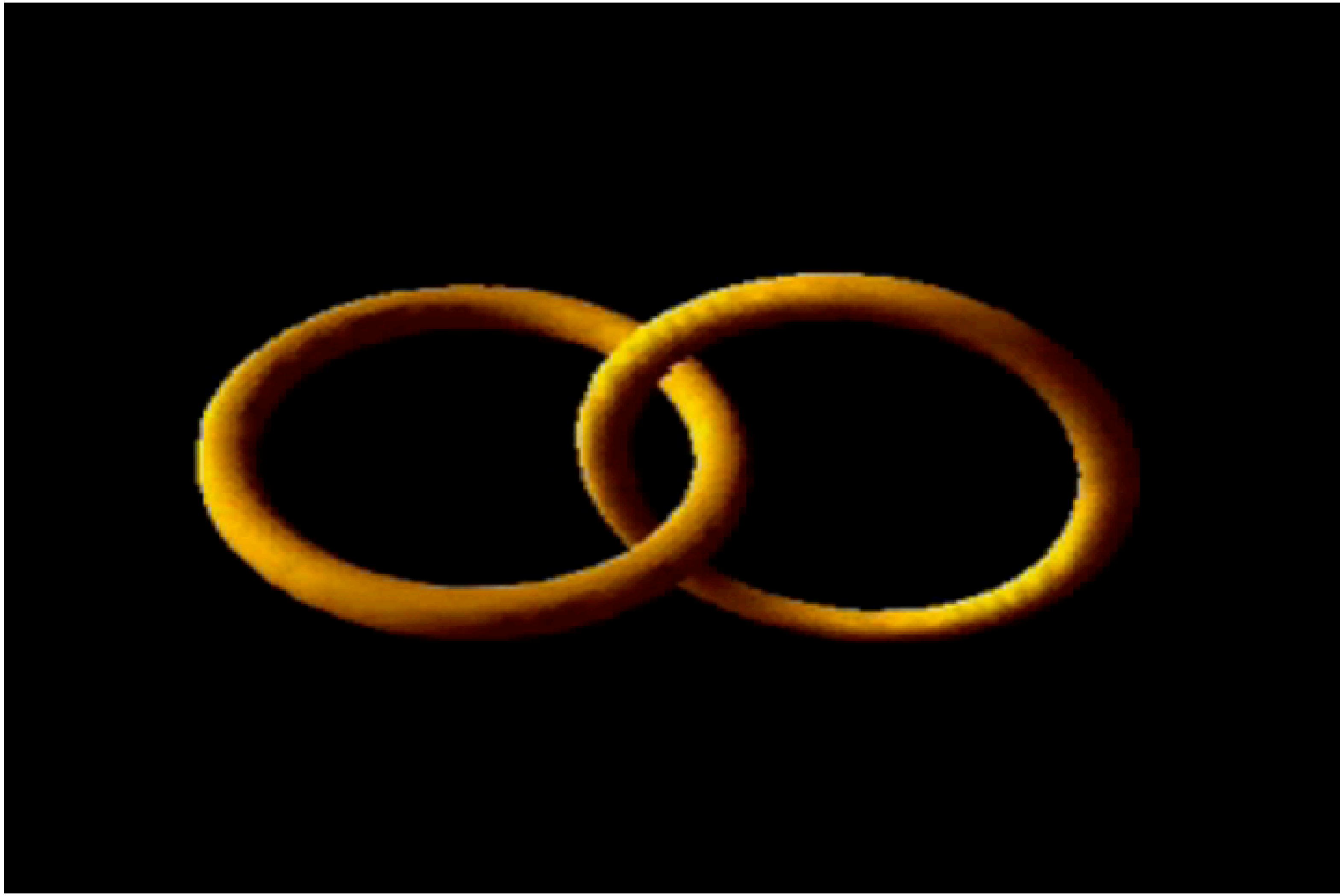
$\alpha \simeq 10^{-4}$

Both are real.

J. Polchinski and J. Rocha, gr-qc/0702055
F. Dubath and J. Rocha, gr-qc/0703109

There are lots of small loops.

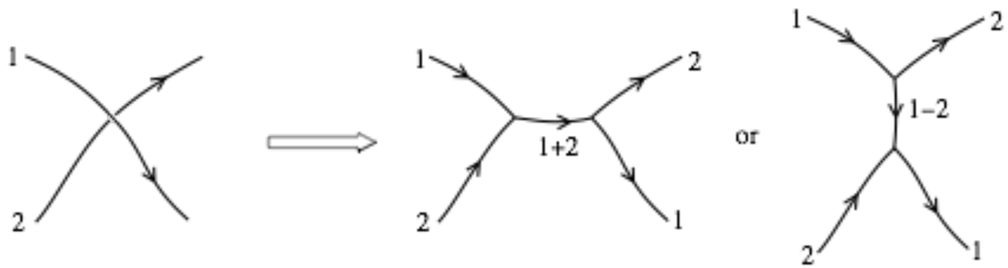
small loops joining to bigger loops



Cambridge U.

(p,q) Superstrings

- In contrast to vortices in Abelian Higgs model, cosmic strings from brane inflation should have a spectrum in tension.
- 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 particular brane inflationary scenario.



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

They have non-trivial interactions.

E. Copeland, R. Myers and J. Polchinski, hep-th/0312067
G. Dvali and A. Vilenkin, hep-th/0312004

Strings and axions

- A point particle can be charged under a gauge field, a one-form field.
- A string is charged under a two-form field.
- In 4-dim., a two-form field (NS-NS or RR) is dual to an axion.
- In a typical realistic stringy vacuum, there are a number of axions.
- So we expect a variety of cosmic string types.

Scaling of the cosmic string network

Velocity-dependent one-scale model

$$v = HL\left(\frac{1+3\omega}{2c}\right)$$

$$\frac{dn}{dt} + 2Hn = -\frac{cnv}{L} - Pn^2vL$$

$$\Omega_{cs} \sim 8\pi G\mu(10)$$

$$v \sim 0.65$$

Kibble, Martins, Shellard etc.

Evolution of the (p,q) Cosmic Superstring Network

$$\frac{dn_\alpha}{dt} + 2Hn_\alpha \quad (1)$$

$$= -\frac{cn_\alpha v}{L} - Pn_\alpha^2 vL + FvL\left(\frac{1}{2}\sum_{\beta,\gamma} P_{\alpha\beta\gamma} n_\beta n_\gamma - \sum_{\beta,\gamma} P_{\beta\gamma\alpha} n_\gamma n_\alpha\right) \quad (1)$$

$$\alpha = (p, q)$$

$$\dot{v} = (1 - v^2)\left(-2Hv + \frac{c_2}{L}\right) \qquad \dot{L} = HL + c_1 v$$

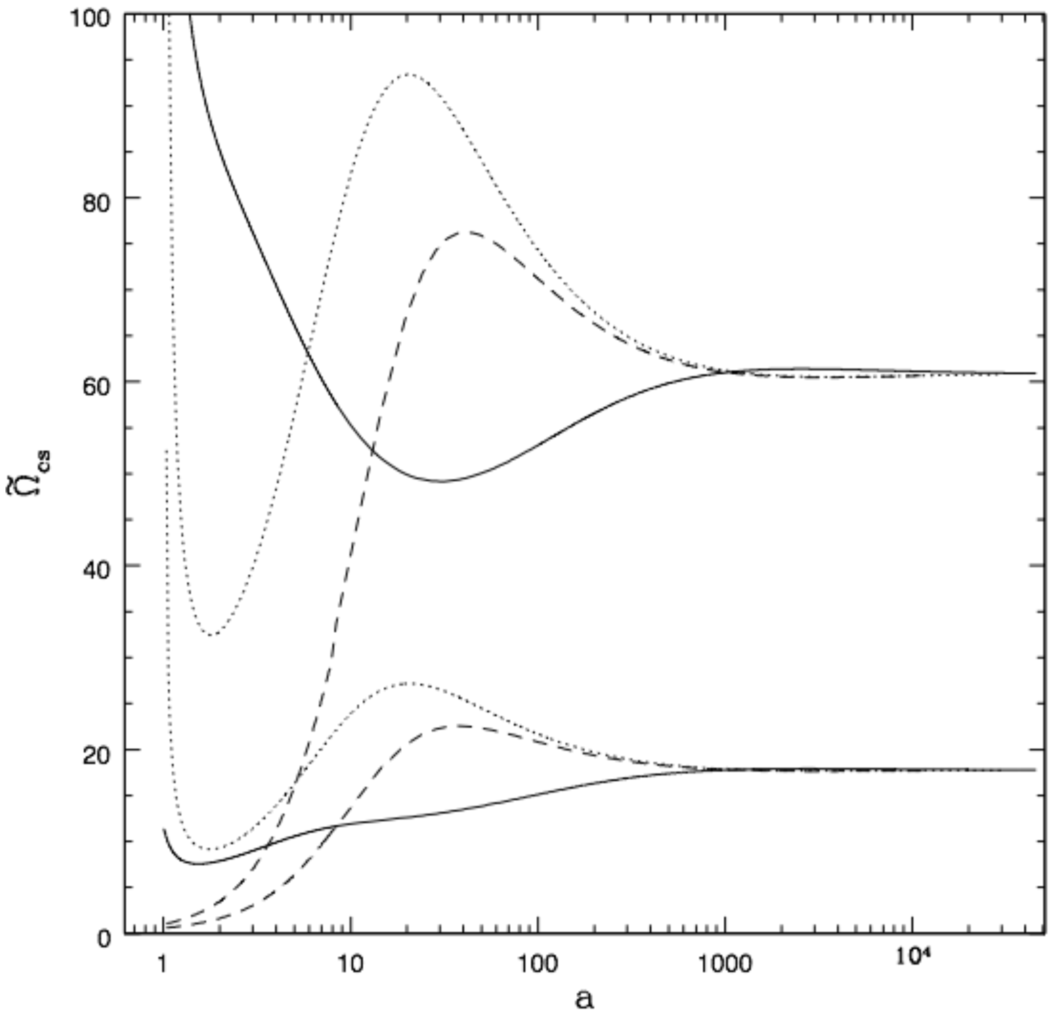
$$c_1 = 0.21 \quad c_2 = 0.18 \quad v = 0.655 \quad HL = 0.137$$

Scaling of the Cosmic Superstring Network

independent of initial conditions

Insensitive to the details of the interactions

$$\Omega_{cs} = \frac{10\Gamma G\mu}{g_s^2}$$

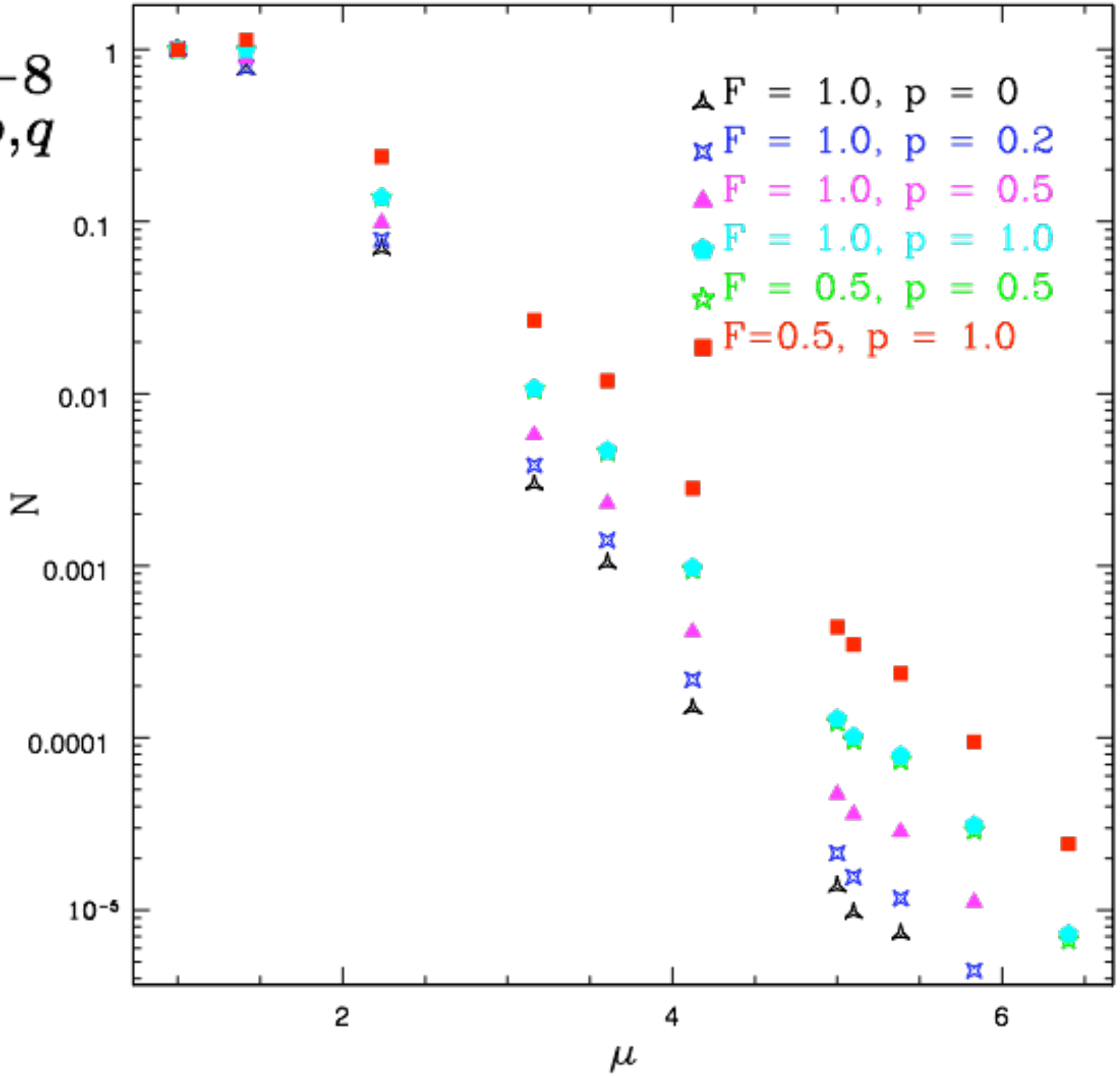


M. Jackson, N. Jones and J. Polchinski, hep-th/0405229

H.T., I. Wasserman, M. Wyman, astro-ph/0503506

Relative density of (p,q) strings

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



Cosmic string tension in a warped deformed conifold

One may view the fundamental strings in a dual picture as D3-branes wrapping a 2-cycle inside the S3 at the bottom of the throat.

$$pT_1 \to T_1 \frac{g_s M}{\pi} \sin\left(\frac{p\pi}{g_s M}\right)$$

Klebanov, Strassler, Gubser, Herzog,...

Cosmic string tension spectrum in a warped deformed conifold
(Klebanov-Strassler)

One may view the strings as D3-branes wrapping a 2-cycle inside the S^3 at the bottom of the throat.

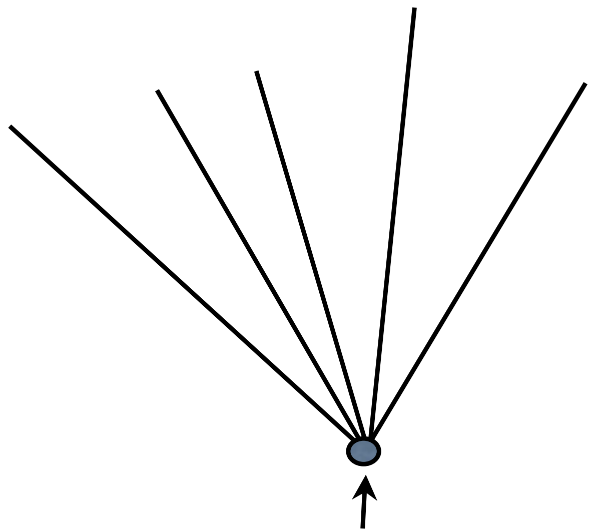
$$T_{p,q} \simeq \frac{h_A^2}{2\pi\alpha'}\sqrt{\frac{q^2}{g_s^2}+(\frac{bM}{\pi})^2\sin^2(\frac{\pi p}{M})},$$

$$b = 0.93266$$

M is the RR flux wrapping S^3.

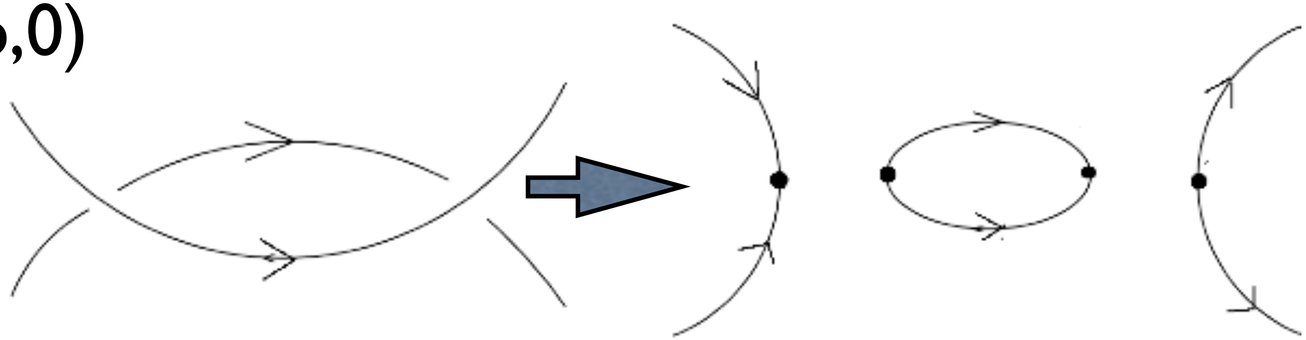
S. Gubser, C. Herzog, I. Klebanov, hep-th/0405282,
H. Firouzjahi, L. Leblond, H.T., hep-th/0603161.

Example :
M=5



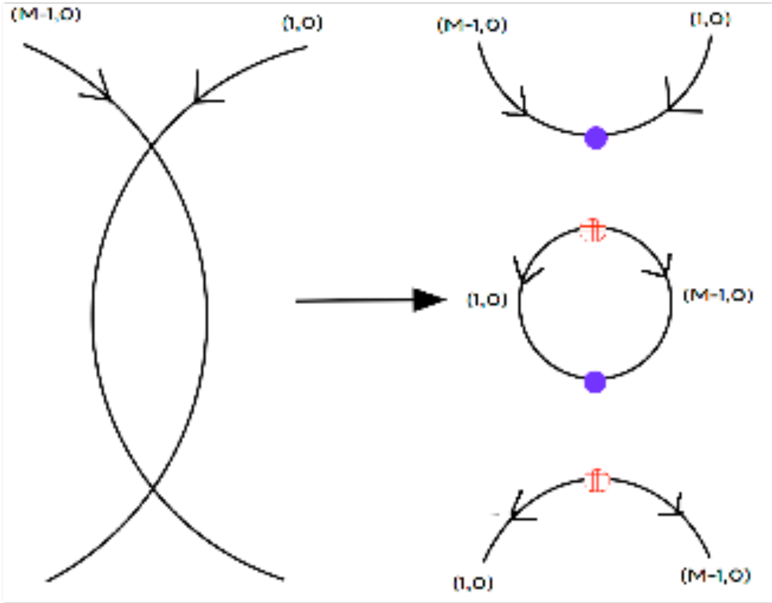
A baryon with mass $\sim M^{3/2} h_A / \sqrt{\alpha'}$

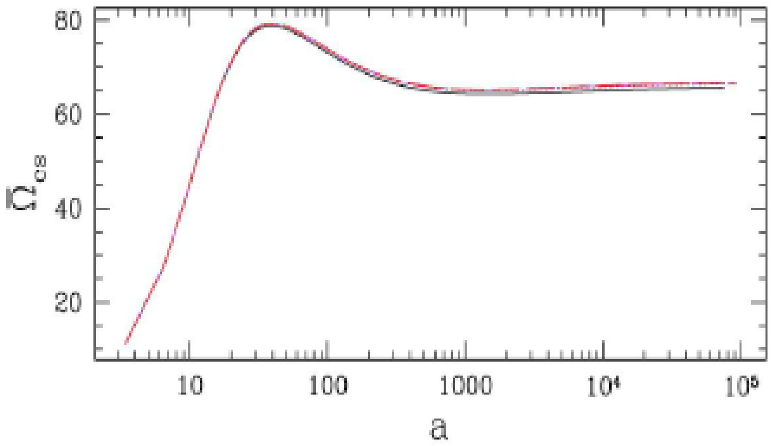
(M-p,0)

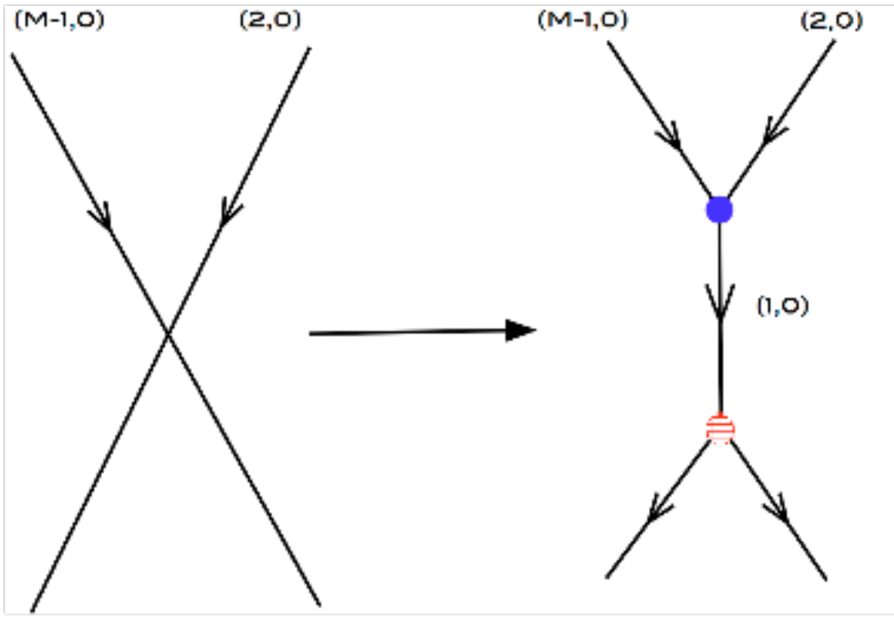


(p,0)

X. Siemens, X. Martin and K. Olum, astro-ph/0005411,
T. Matsuda, hep-th/0509061, ...





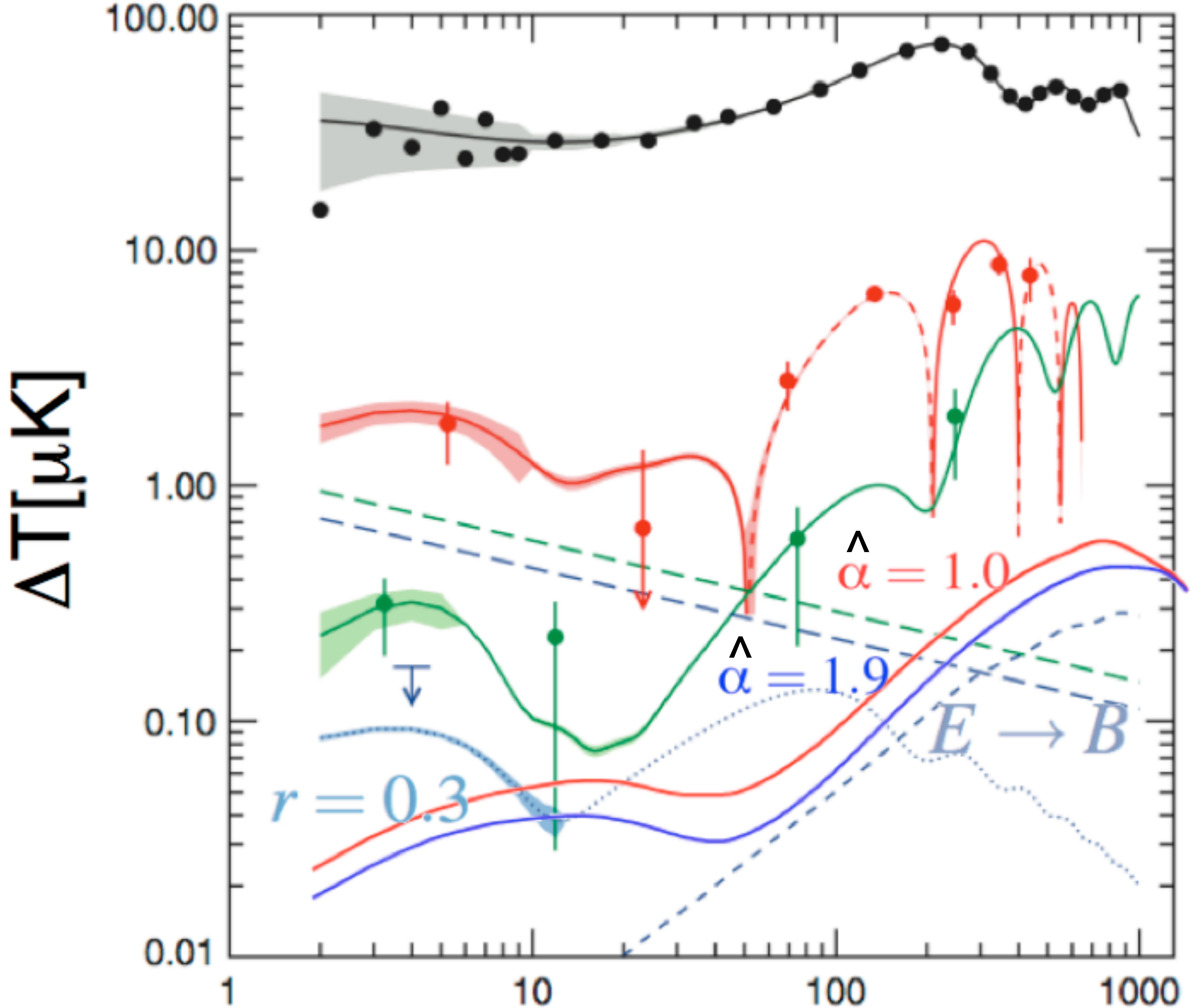


L. Leblond and M. Wyman
astro-ph/0701427

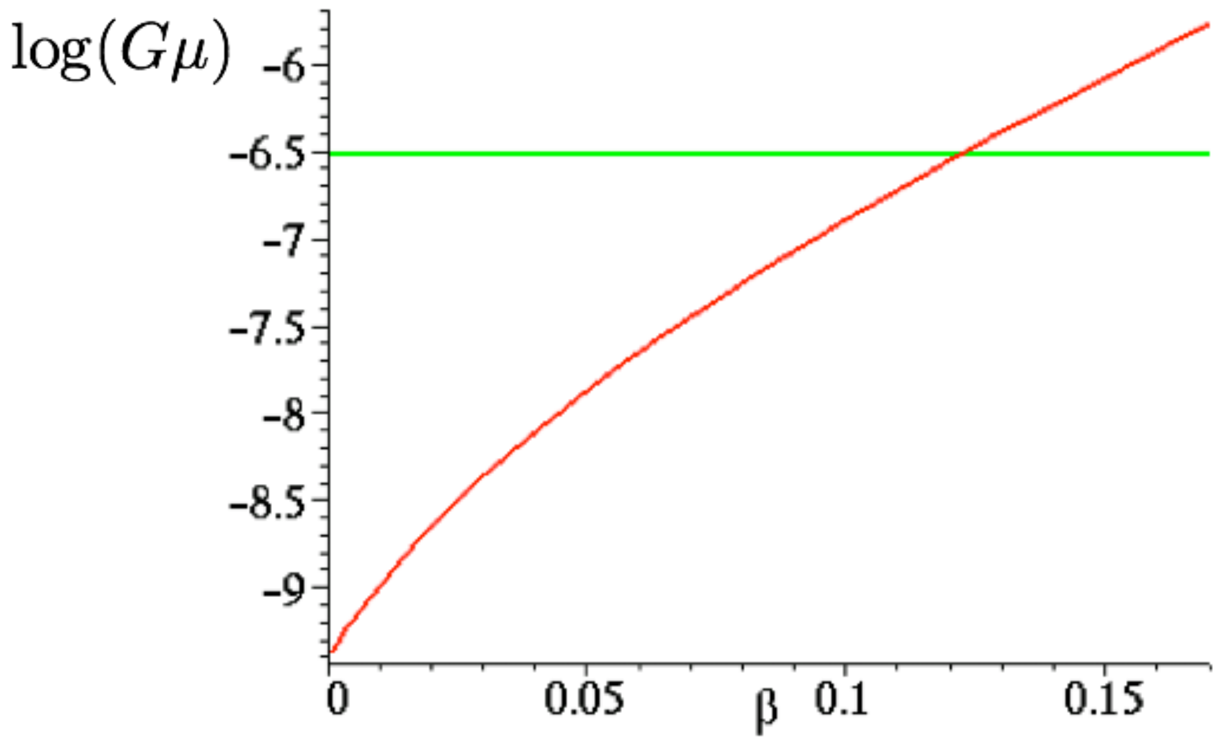
Search for Cosmic Strings

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

Possible CMB B-mode detection



Cosmic string tension in the KKLMMT scenario



$$5 \times 10^{-7} > G\mu \geq 4 \times 10^{-10}$$

H. Firouzjahi, H.T.

Observational bound from WMAP :

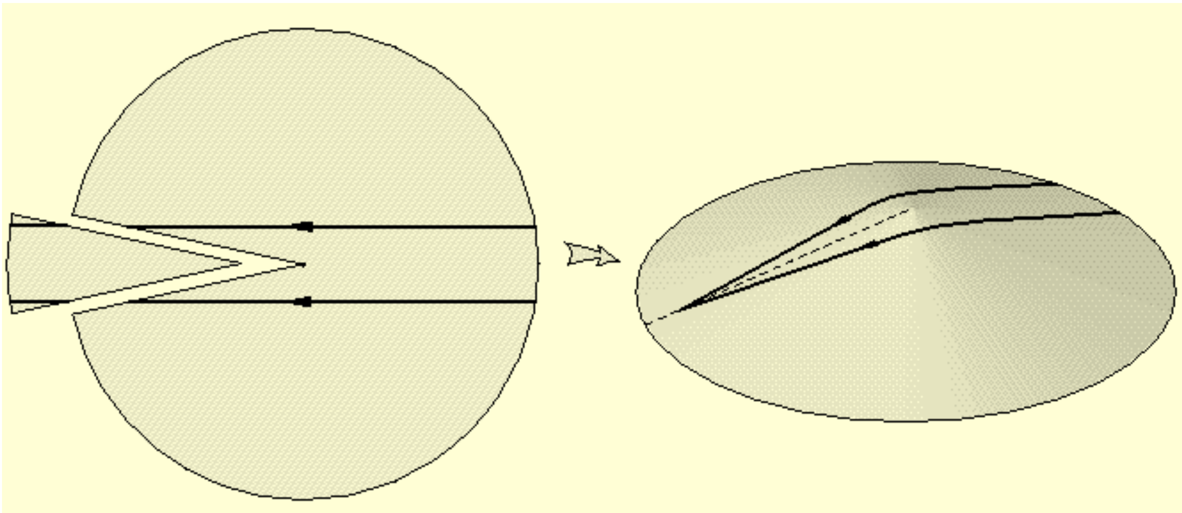
$$5 \times 10^{-7} > G\mu$$

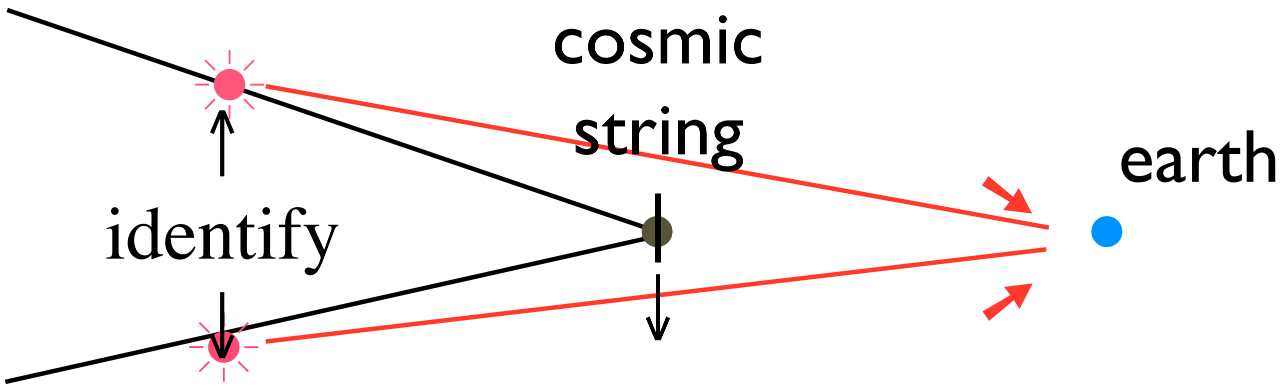
L. Pogosian, I. Wasserman, M. Wyman

Jeong, Smoot

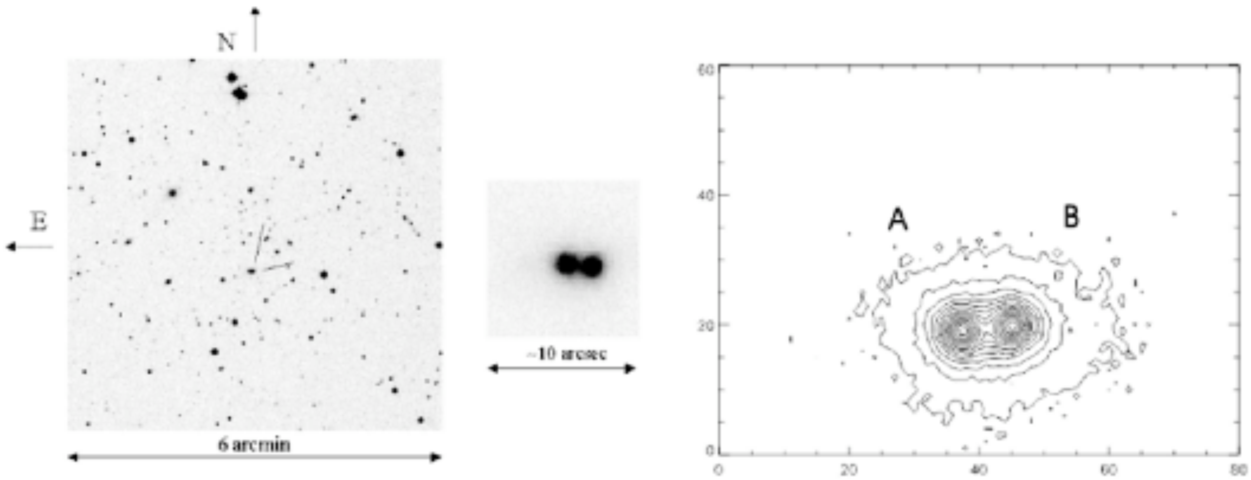
cosmic string lensing

cosmic string introduces a deficit angle



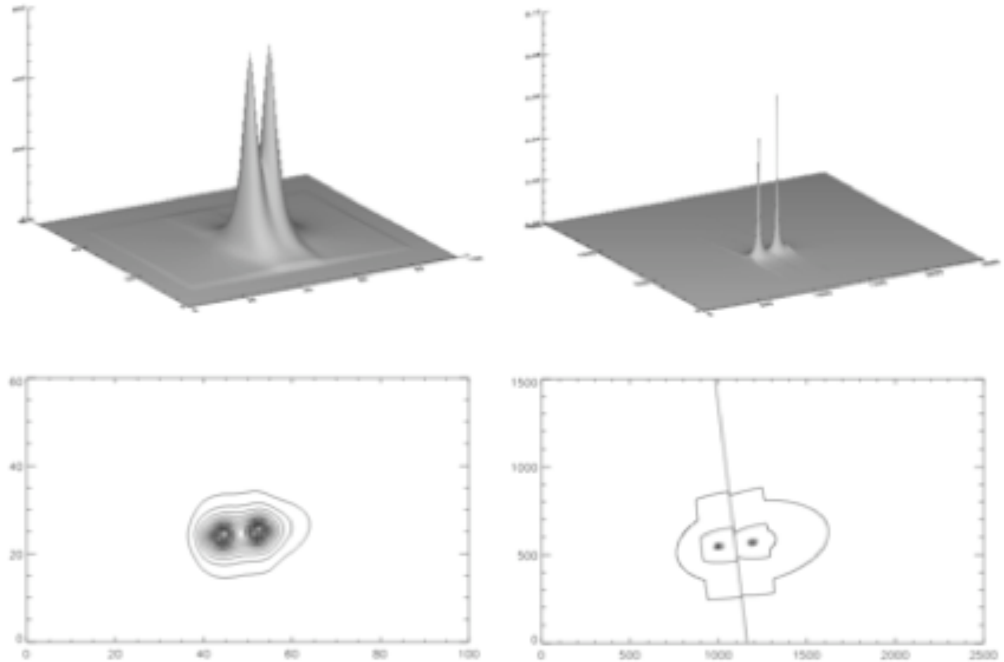


CSL-1 Sazhin etc. astro-ph/0302547



$z=0.46 \pm 0.008$

identical spectra with confidence level above 99.9%

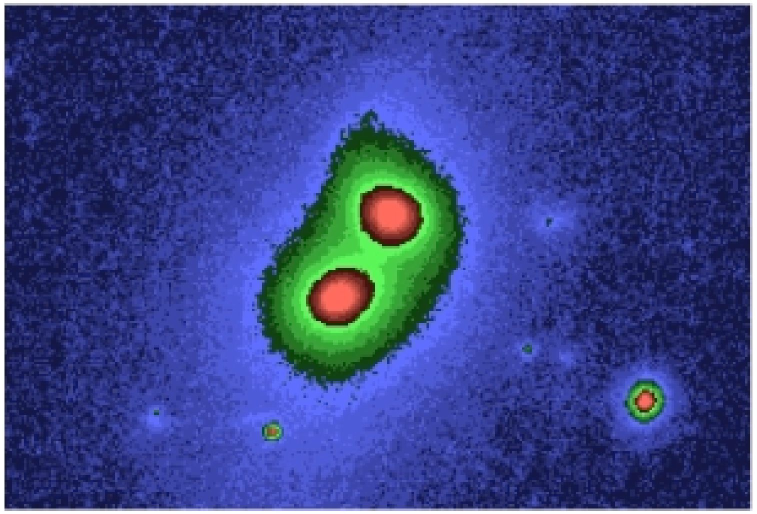


1.9 arc sec

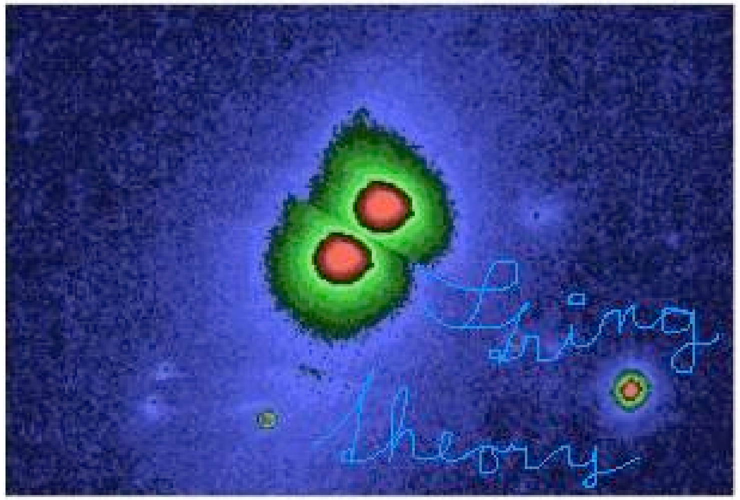
$\Downarrow$

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

Unfortunately not (higher resolution Hubble pictures):



January 2006

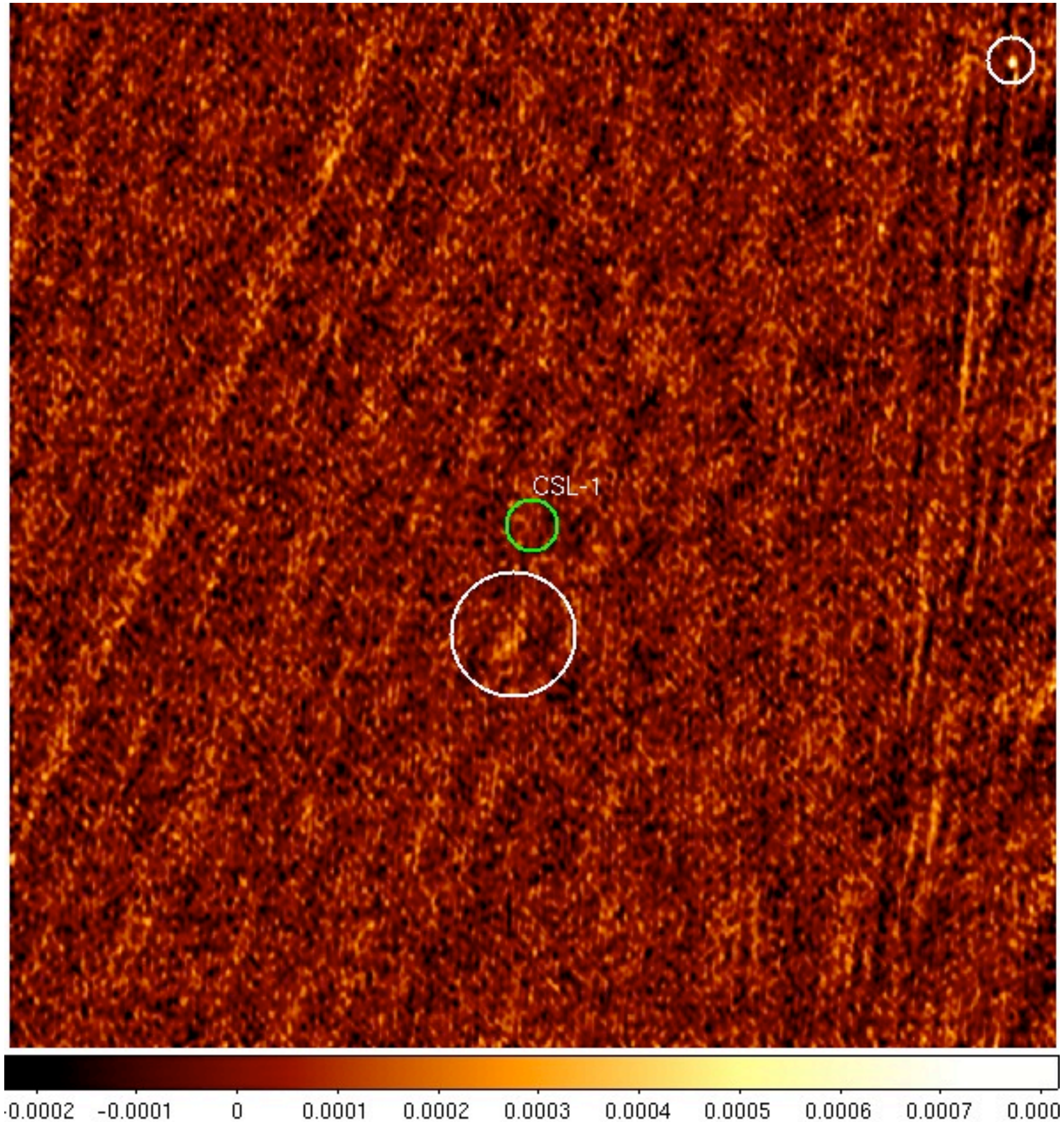


If it is cosmic string lensing

Radio telescope ?

Recall Cowen and Hu.

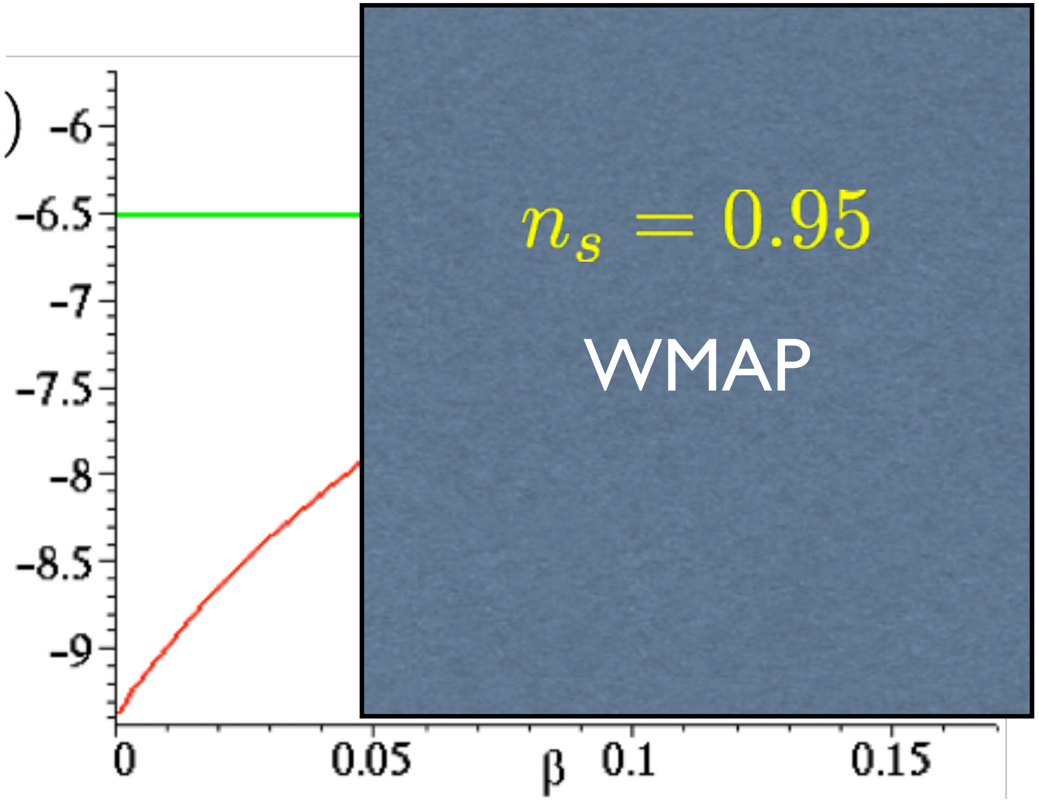
National Radio Astronomy
Observatory



Shami Chatterjee, Jim Cordes, H.T., Ira Wasserman

Bound on cosmic string tension

U. Seljak and A. Slosar, astro-ph/0604143



$$0 \leq \beta \leq 0.05$$

$$n_s \sim 0.98 + \beta \rightarrow n_s \leq 1.03$$

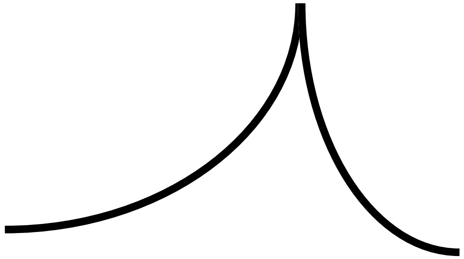
$$\log r \sim -8.8 + 60\beta$$

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

$$\log G\mu \sim -9.4 + 30\beta$$

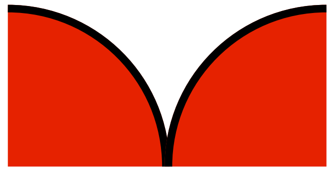
S. Shandera and H.T., 0601099

cusps and kinks
are quite common in string evolution

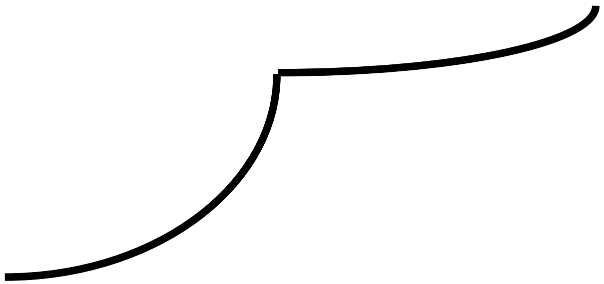


CUSP

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



wave form of gravitational wave bursts

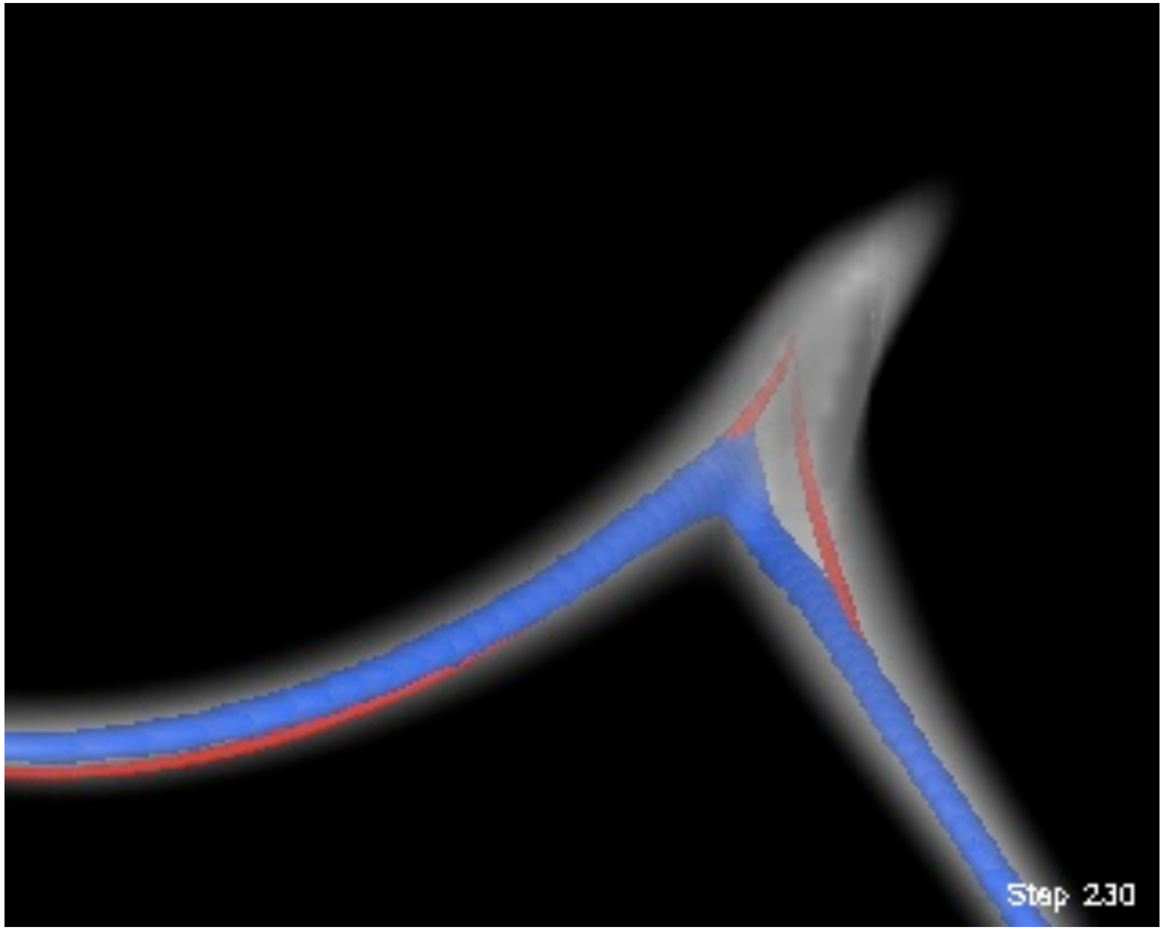


KINK

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

Damour and Vilenkin

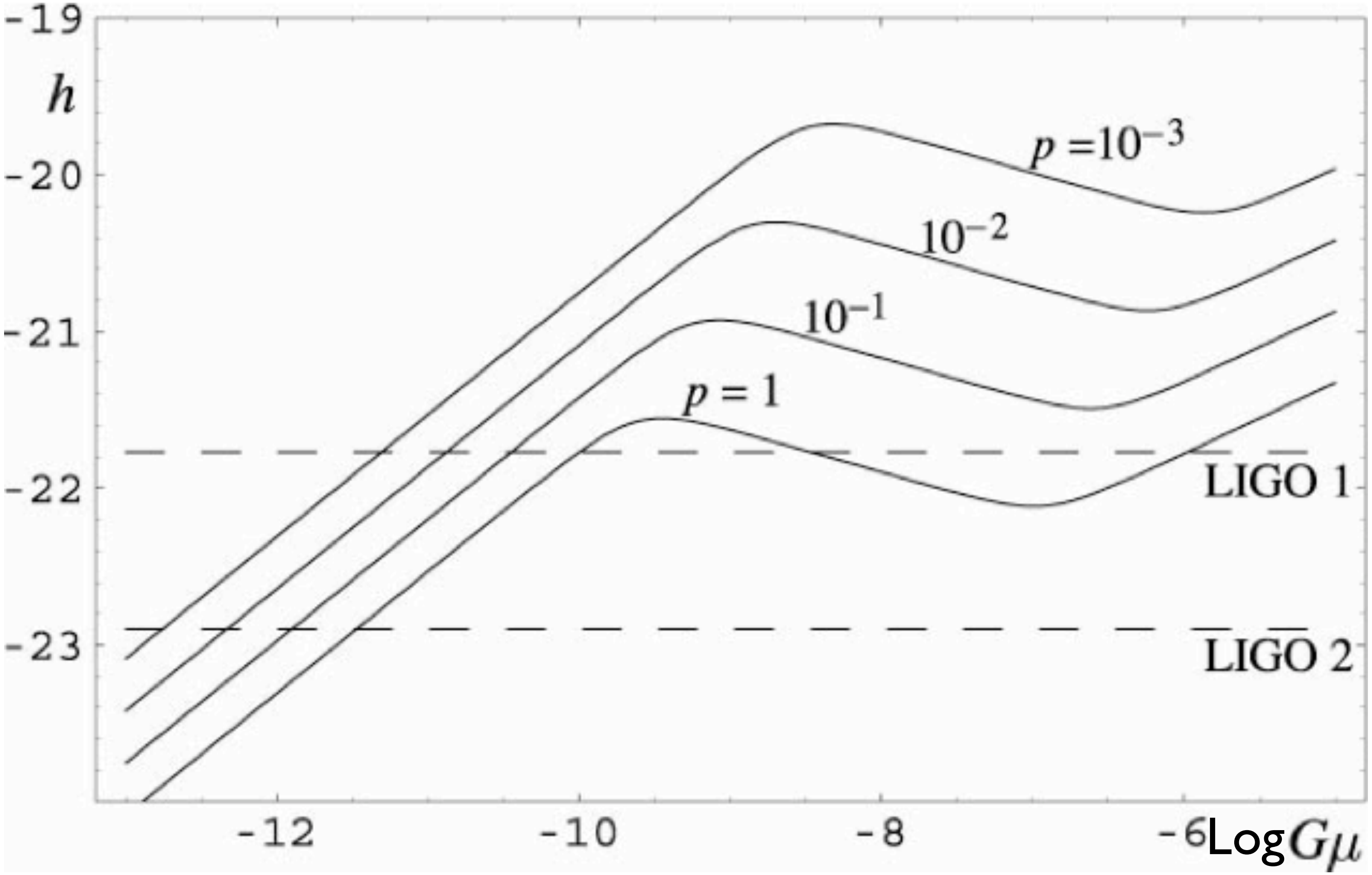
A cusp



Blanco-Padillo and Olum

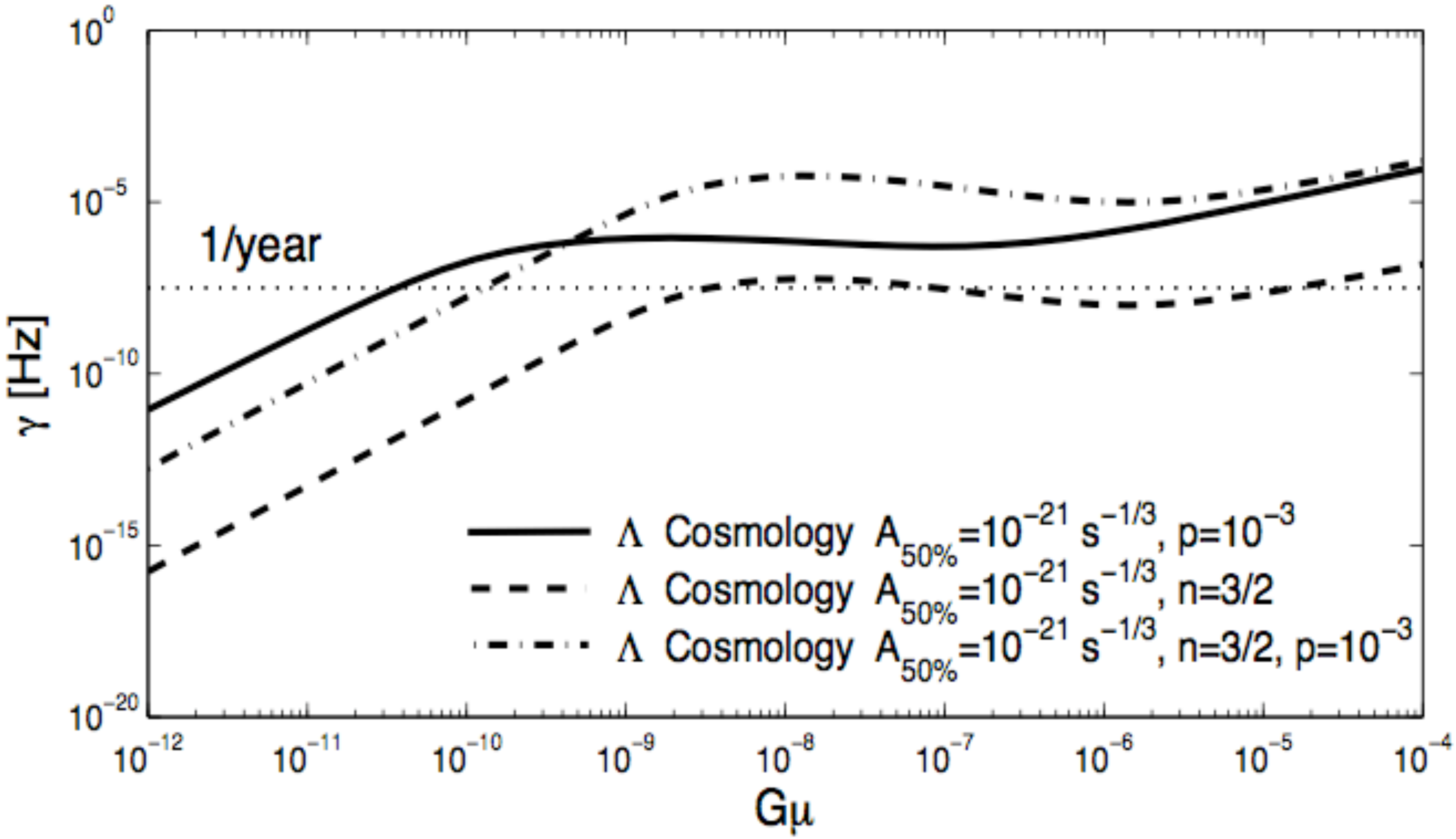
gravitational wave radiation from cusps

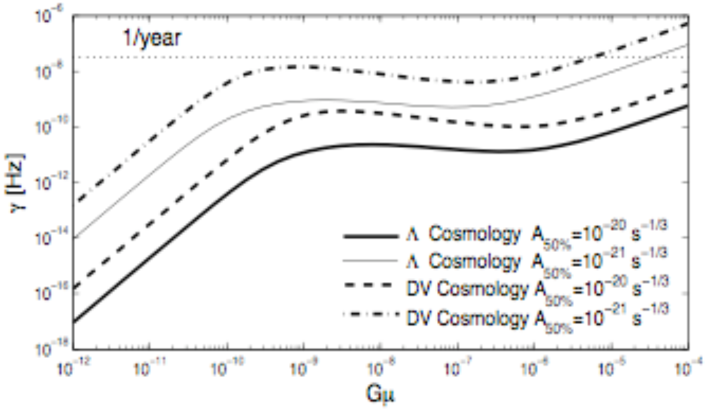
Damour and Vilenkin



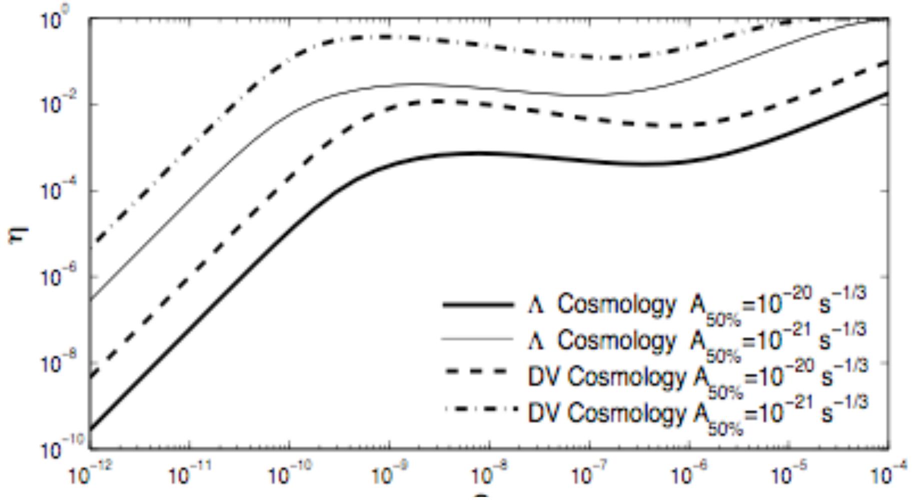
prediction

More recent analysis

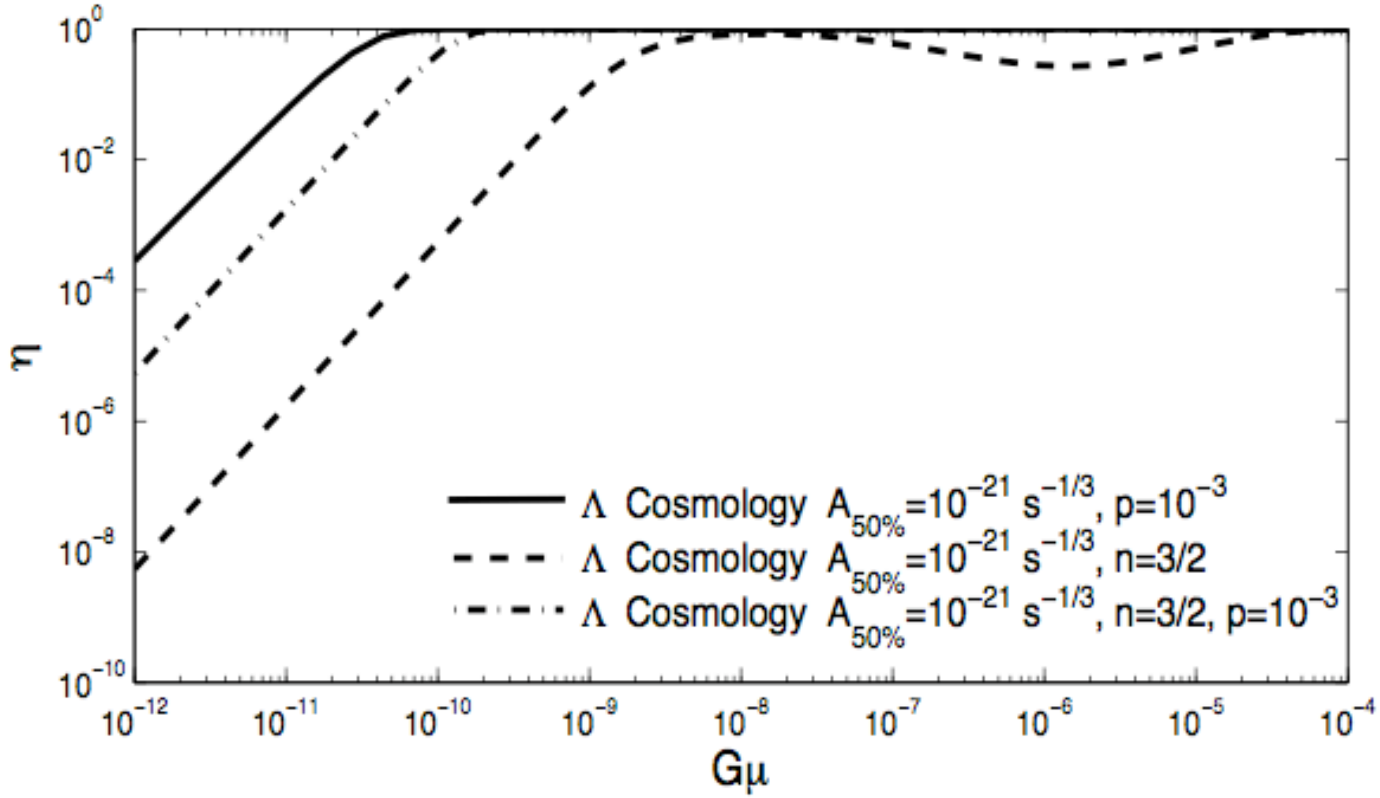




X. Siemens, J. Creighton, I. Maor, S. Majumder, K. Cannon and J. Reed, gr-qc/0603115



More recent analysis

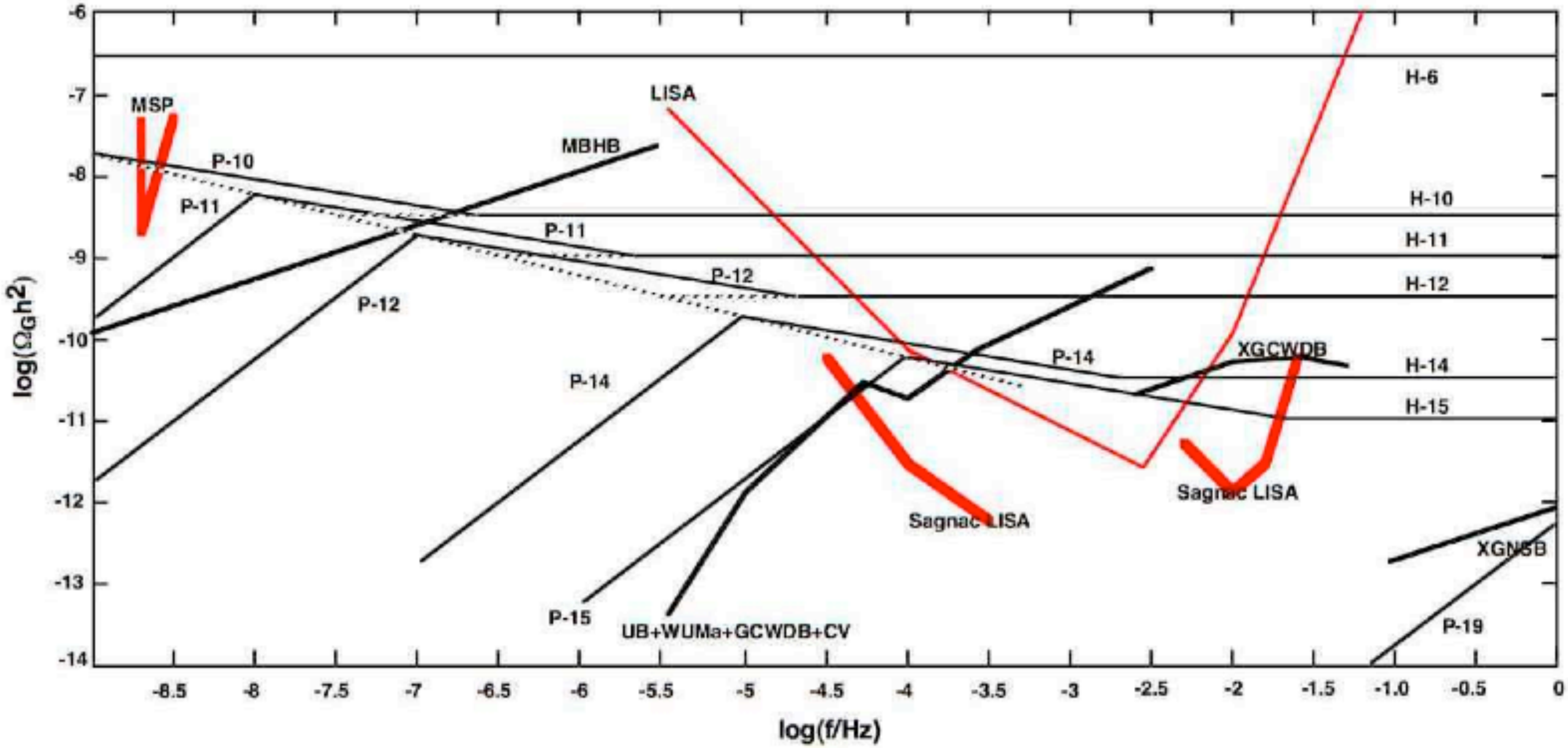


X. Siemens, J. Creighton, I. Maor, S. Majumder, K. Cannon and J. Reed, gr-qc/0603115

Number of gravitational wave bursts per year Advanced LIGO will see

- 10 (Damour and Vilenkin, 2001)
- 100 or more for cosmic superstrings (2004)
- down by a factor of 100 (2006)
- (p,q) string spectrum raises this by a factor of about 5
- lots of loops raises it more
- tension is getting smaller ?
- effect of beads ?

C. J. Hogan, astro-ph/0605567



R. Caldwell and B. Allen, PRD45, 3447 (1992)

Search for Cosmic Strings with low tension

- Lensing
- Cosmic Microwave Background Radiation
- Gravitational Wave Burst
- $\Delta T/T$ (Doppler effect)
- Pulsar Timing
- Stochastic Gravitation Radiation Background
- Micro-lensing
- Cusp Doppler effect

Micro-lensing

$$\Theta_E = 8\pi G\mu$$
$$= 1.04 \times 10^{-3} \left(\frac{G\mu}{2 \times 10^{-10}}\right)$$

$$\frac{\Theta_\odot}{\Theta_E} = 4.6 \times 10^{-5} \left(\frac{2 \times 10^{-10}}{G\mu}\right) \left(\frac{100\text{kpc}}{R}\right)$$

$$l_g = \Gamma_R G\mu t_{today} = 40\text{pc} \left(\frac{\Gamma_R G\mu}{10^{-8}}\right) \left(\frac{t_{today}}{13.5\text{Gyr}}\right)$$

$$t_{osc} \sim \frac{l_g}{c} \sim 135\text{yrs} \left(\frac{\Gamma_R G\mu}{10^{-8}}\right)$$

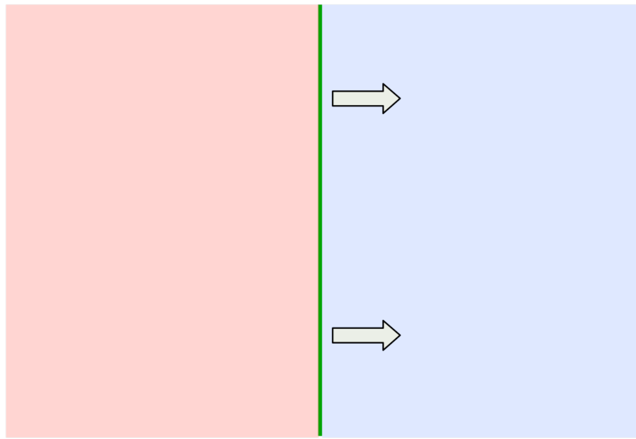
$$\delta t = 6.3 \times 10^3\text{sec} \left(\frac{R}{100\text{kpc}}\right) \left(\frac{G\mu}{2 \times 10^{-10}}\right)$$

GAIA : $N_L \sim 0.03$

Hogan and Narayan, 1984

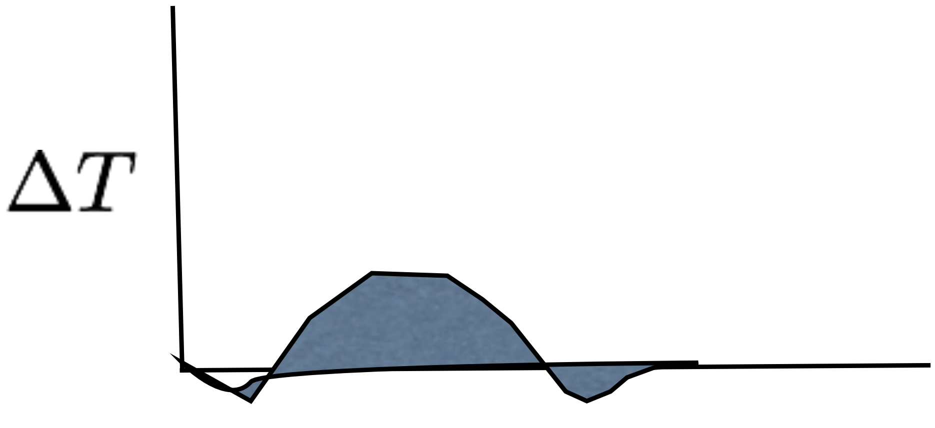
David Chernoff, to appear

Lensing+Doppler by a cusp



A moving string produces a differential redshift
~$8\pi G\mu\, v/(c^2-v^2)^{1/2}$ (lensing+Doppler)

ΔT in 10^{-3} °K or better ?



Vachaspati, ...

Superstring theory may be tested

- Instead of searching for tiny particles or signatures in accelerators, such superstrings may stretch across the universe.
- The string tensions have the right values so these cosmic superstrings are compatible with all present day observational bounds and yet can be detected in the near future.
- Their (p,q) properties give them quite distinct signatures.
- More work is needed on this and other brane inflationary and cosmic string scenarios.