Lecture 4 on String Cosmology: Brane Inflation and Cosmic Superstrings

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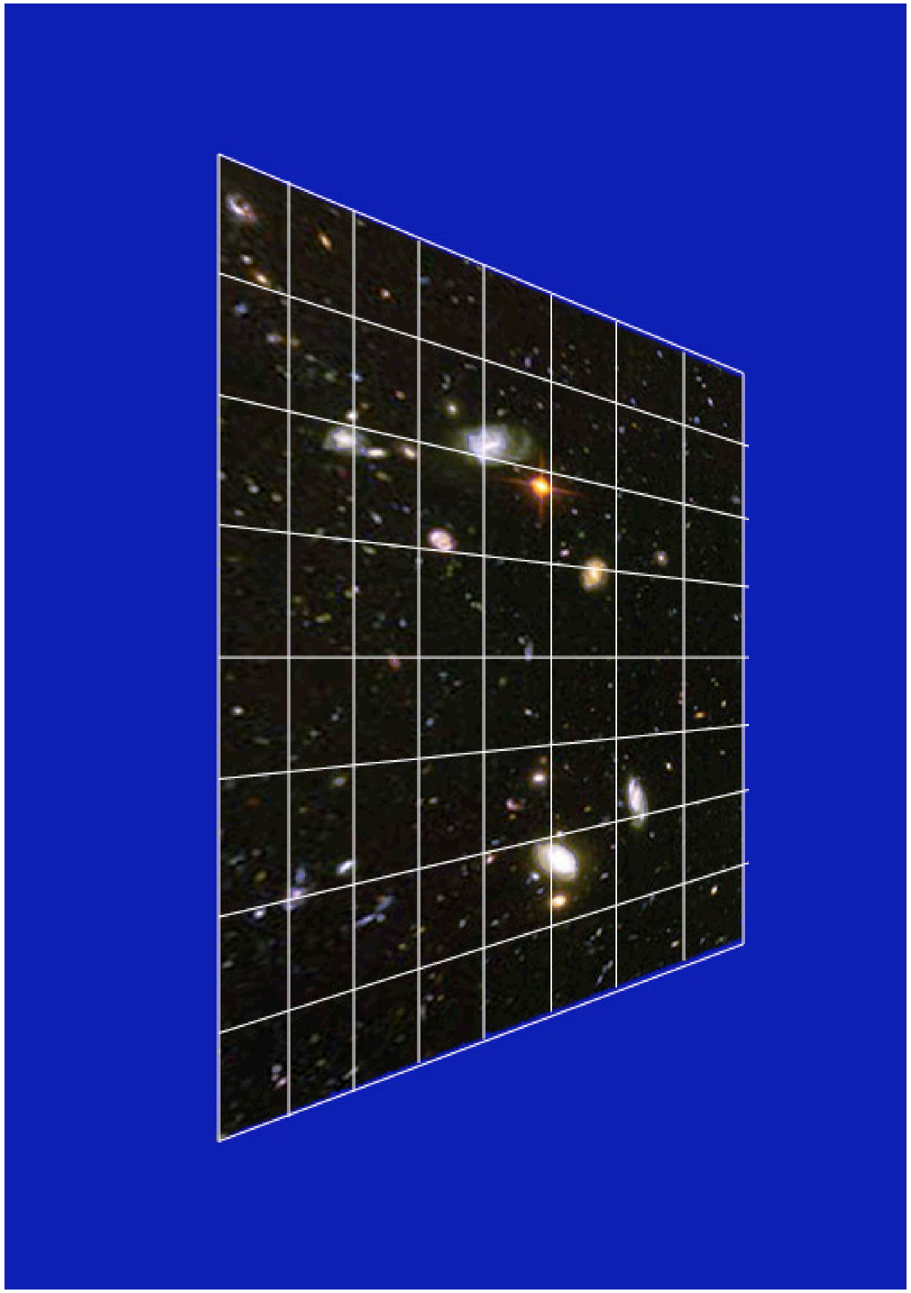
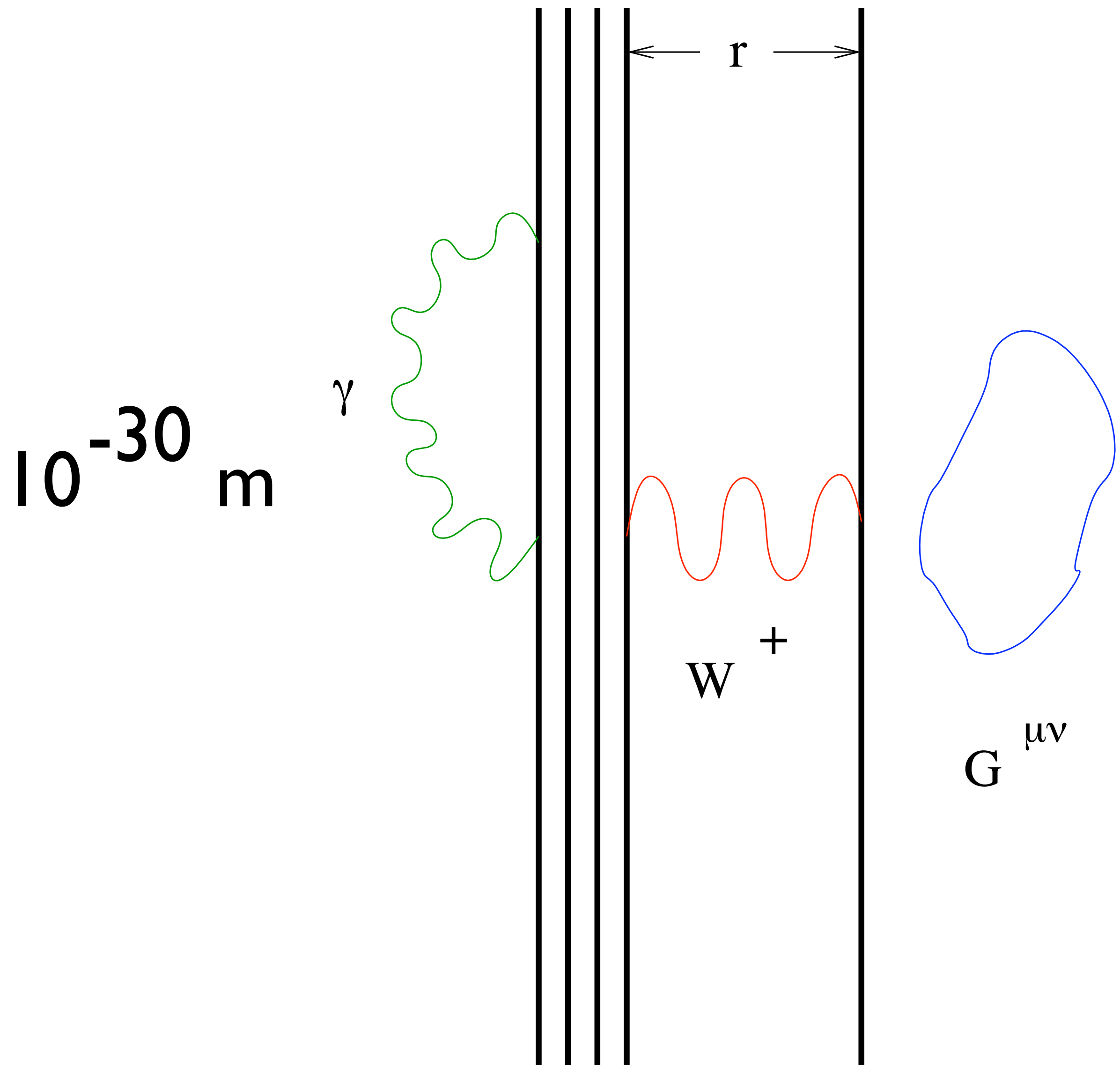
Cornell University
and HKUST

Asian Winter School,
Japan, January 2012

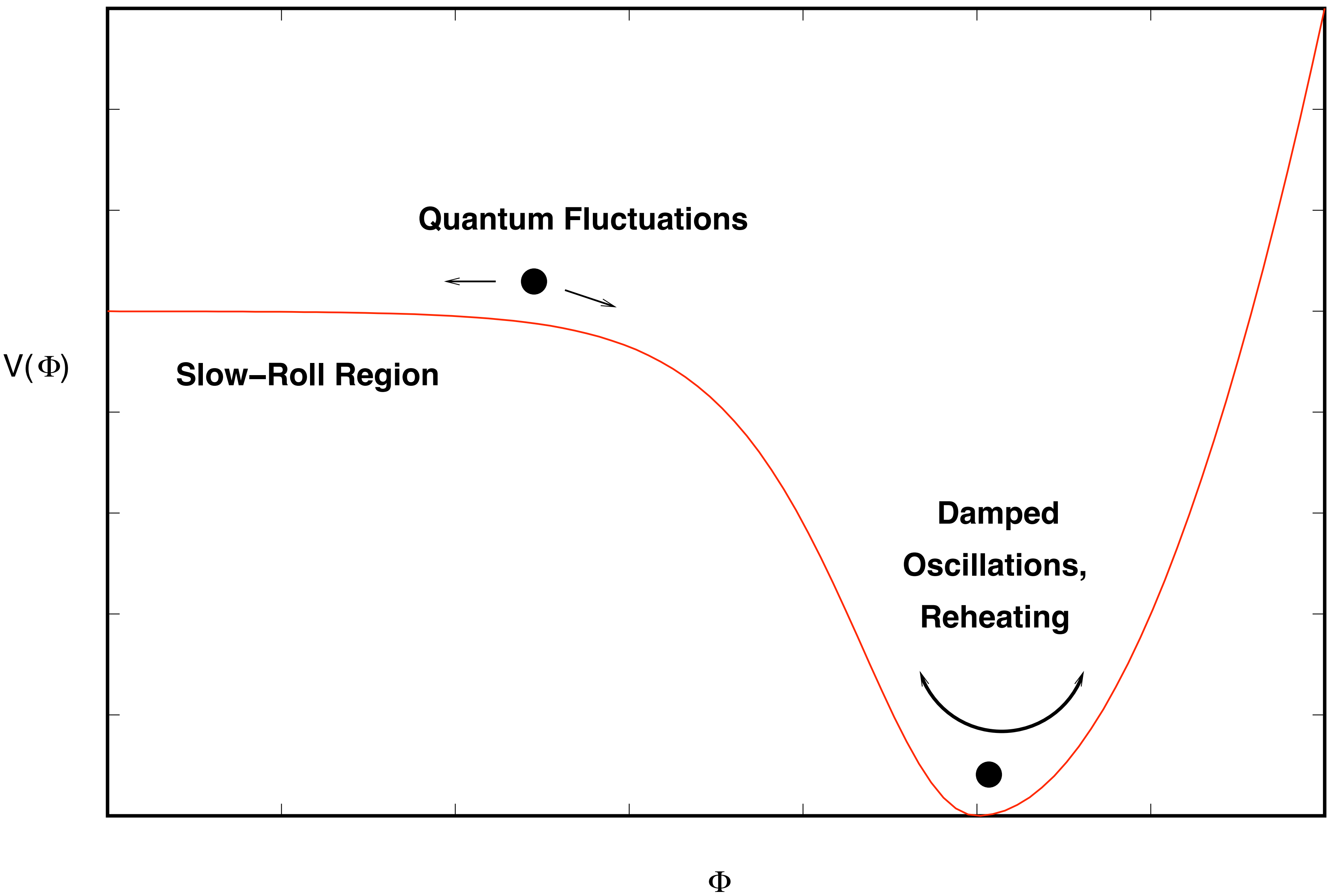
Brane world



Brane world in Type IIB



Inflationary Scenario

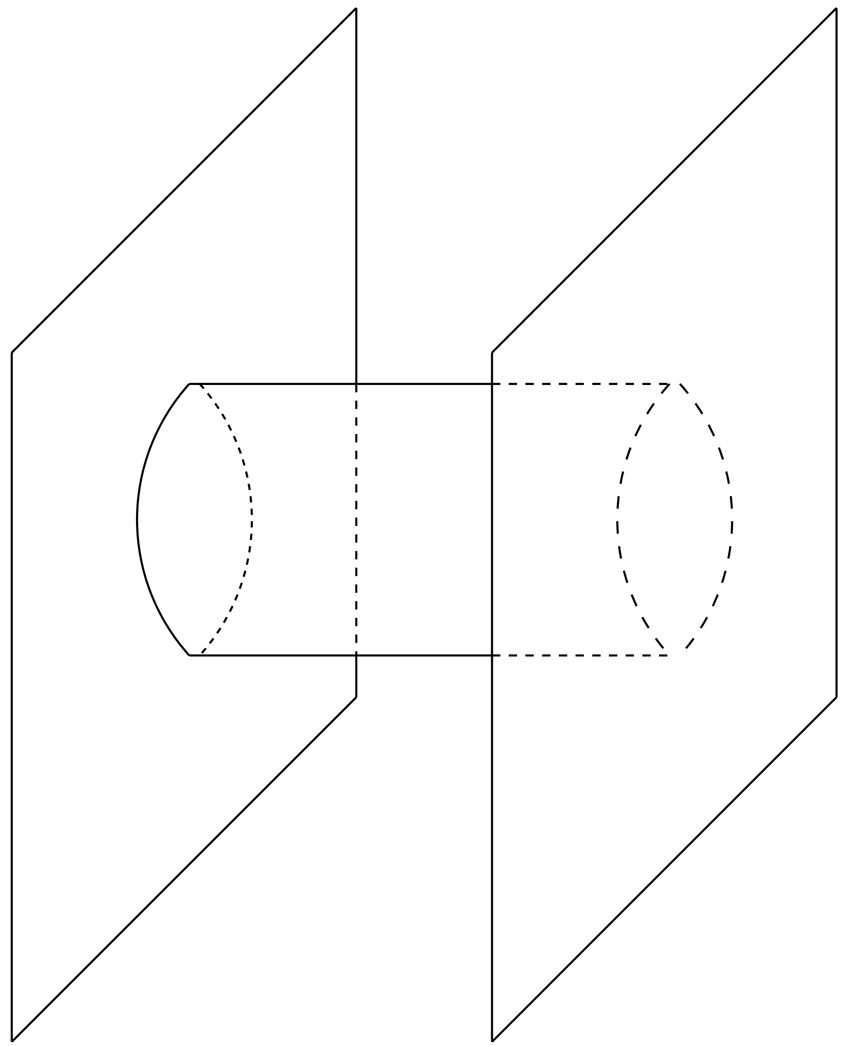


How is inflation realized in brane world ?

Brane inflation

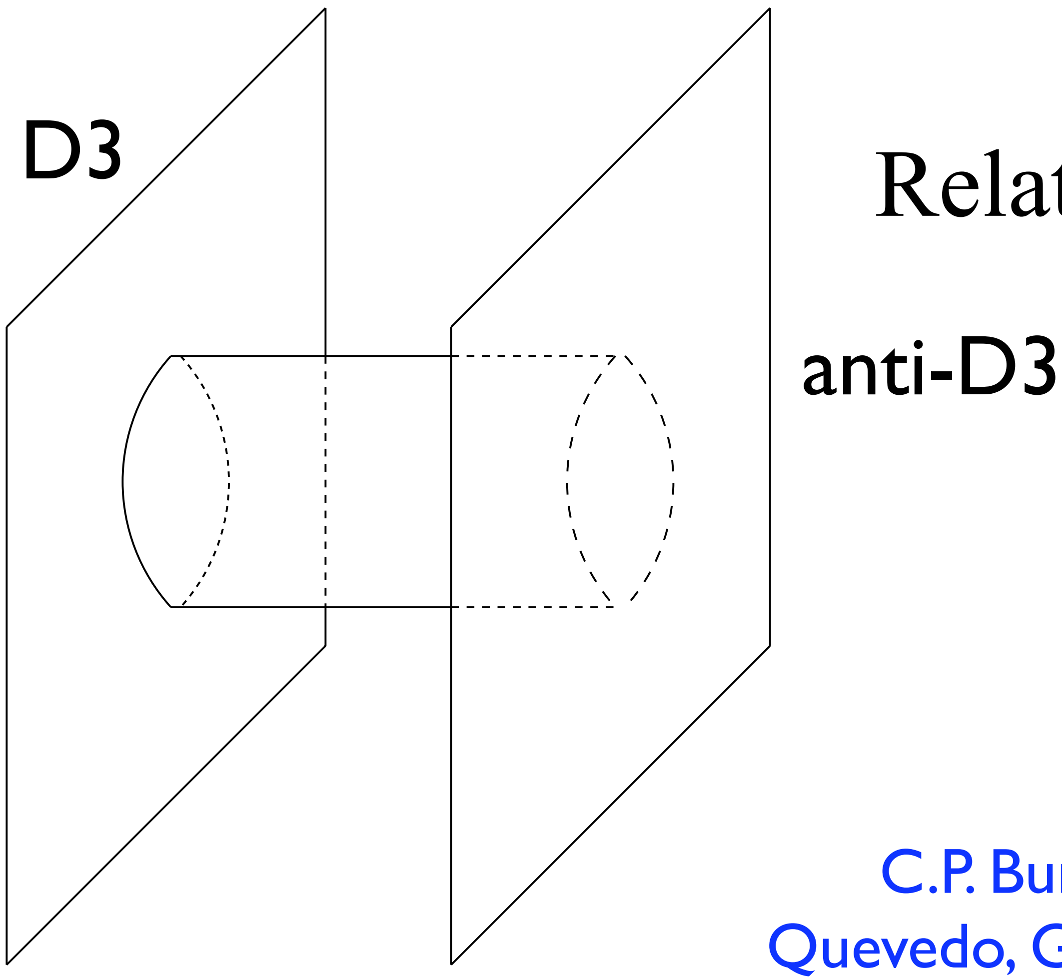
Dvali and H.T. hep-ph/9812483

Inflaton is an open string mode



Inflaton potential comes from the closed string exchange

D3-anti-D3 brane inflation

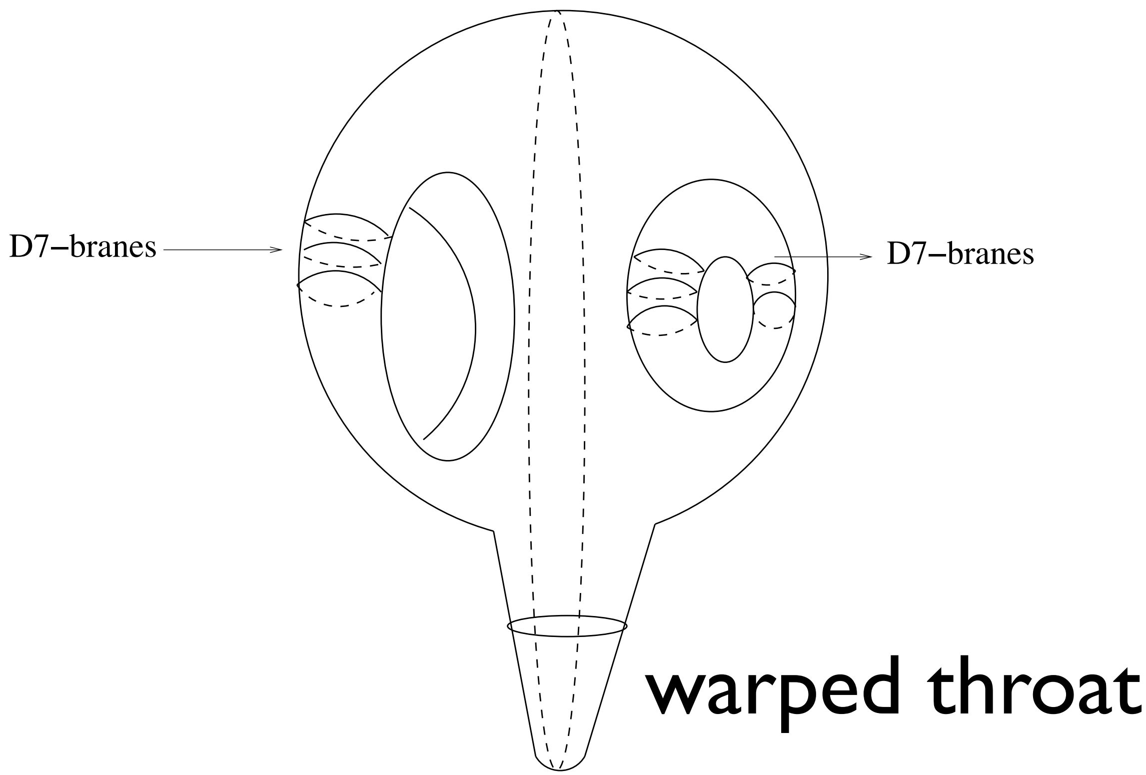


Relatively flat potential ?

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

Flux compactification

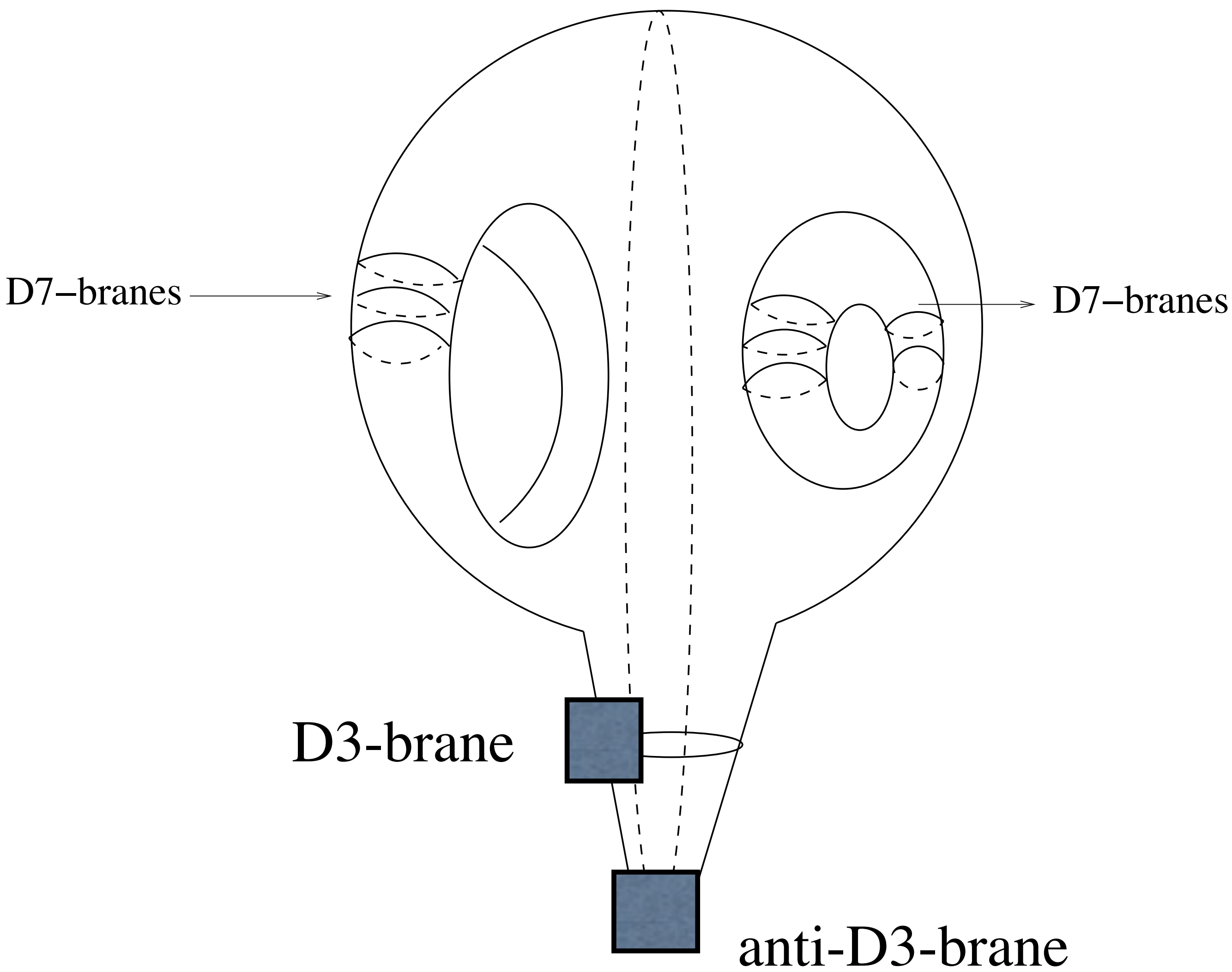
where all moduli of the 6-dim. manifold are stabilized



Giddings, Kachru, Polchinski
Kachru, Kallosh, Linde, Trivedi
and many others

KKLT vacuum

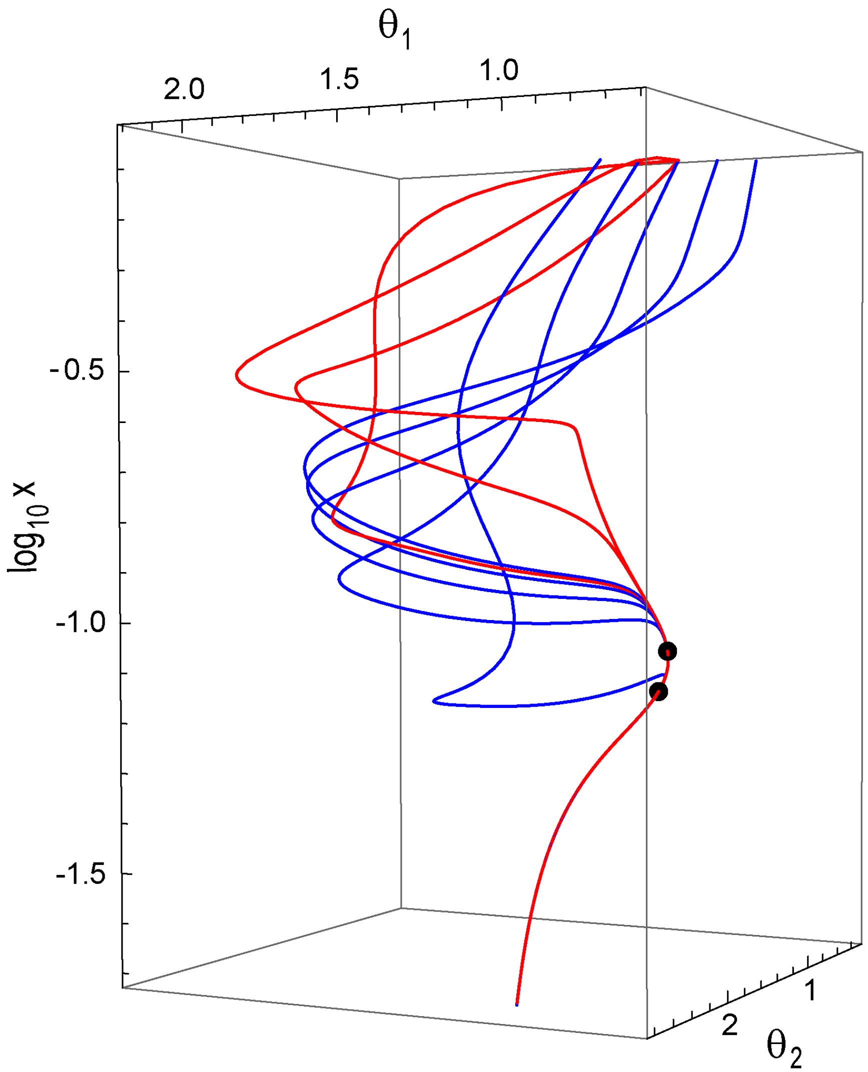
The KKLMMT scenario

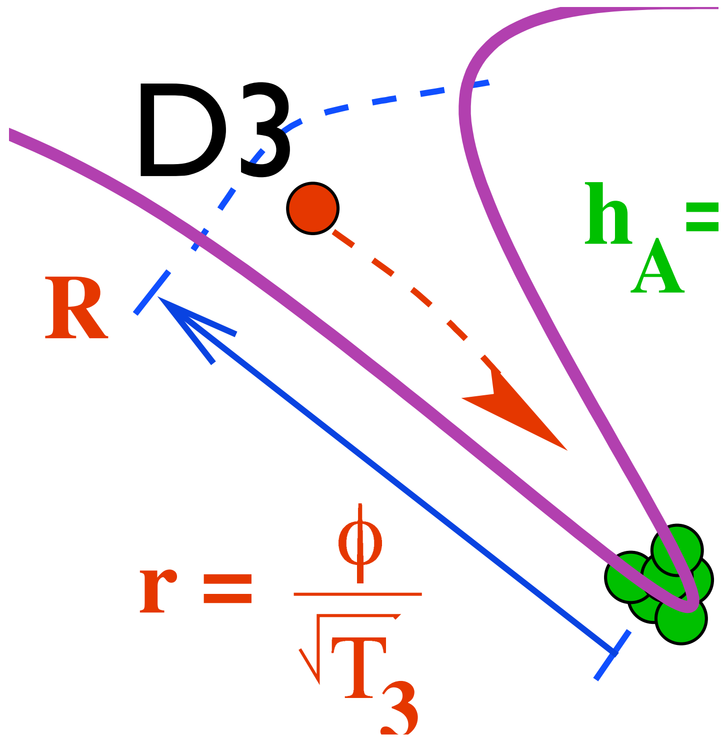


Kachru, Kallosh, Linde, Maldacena, MacAllister, Trivedi,
hep-th/0308055

Probability with N e-folds:

$$P(N_e) \sim N_e^{-3}$$

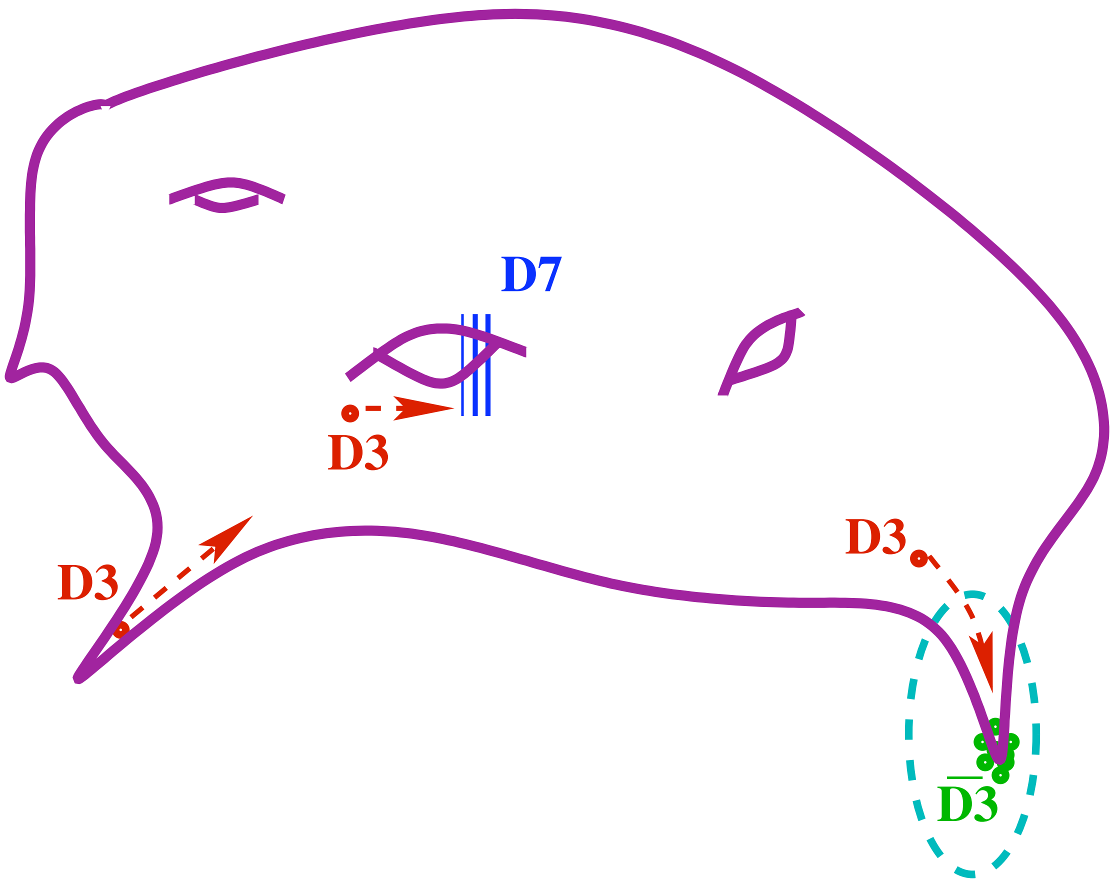




N. Agarwal, R. Bean, L. McAllister, G. Xu, 1103.2775

Other Possibilities

Some simple scenarios



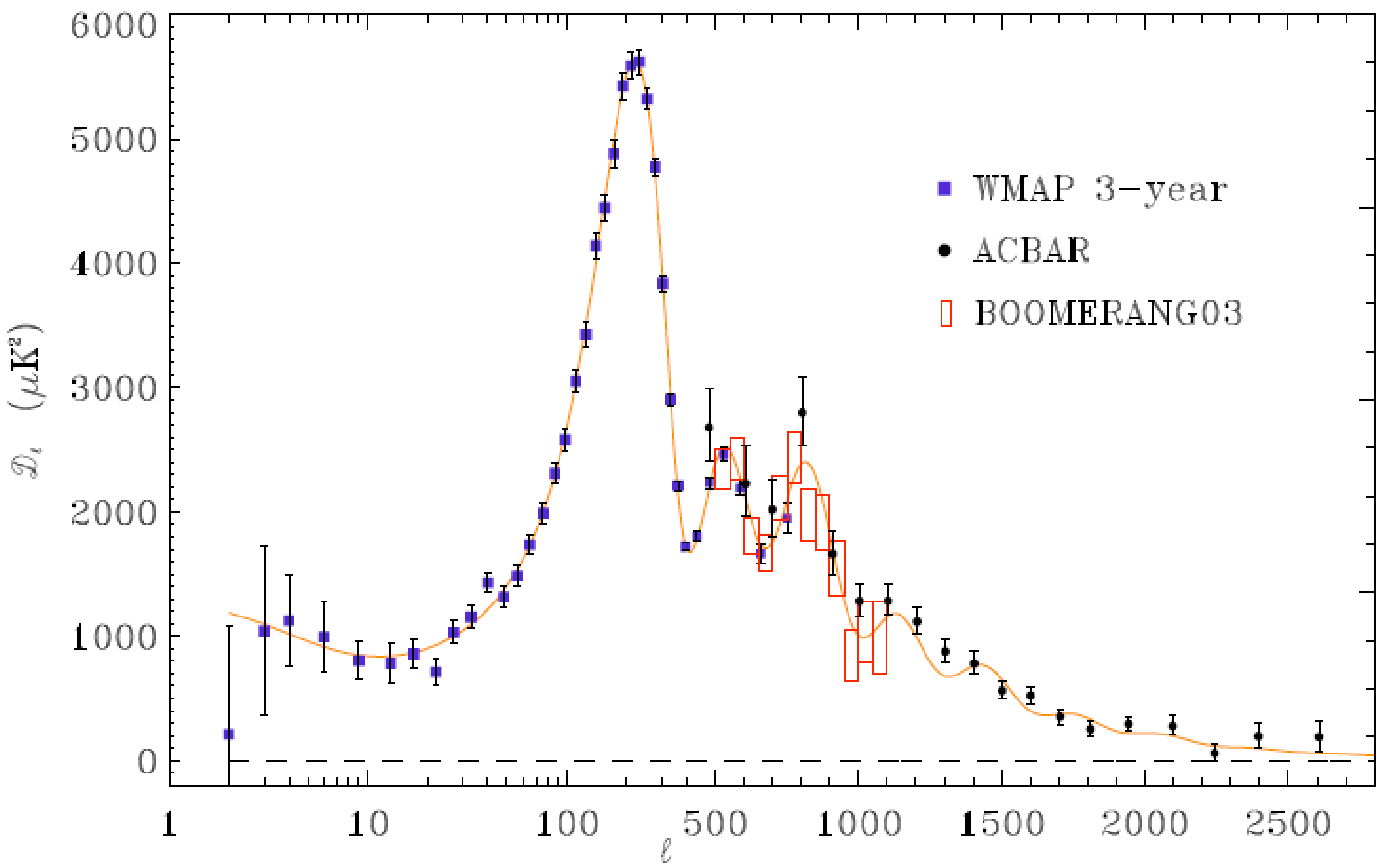
Features:

- Mobile D3s
- warped throats
- anti-D3s in throats
- Wrapped D7s
- DBI

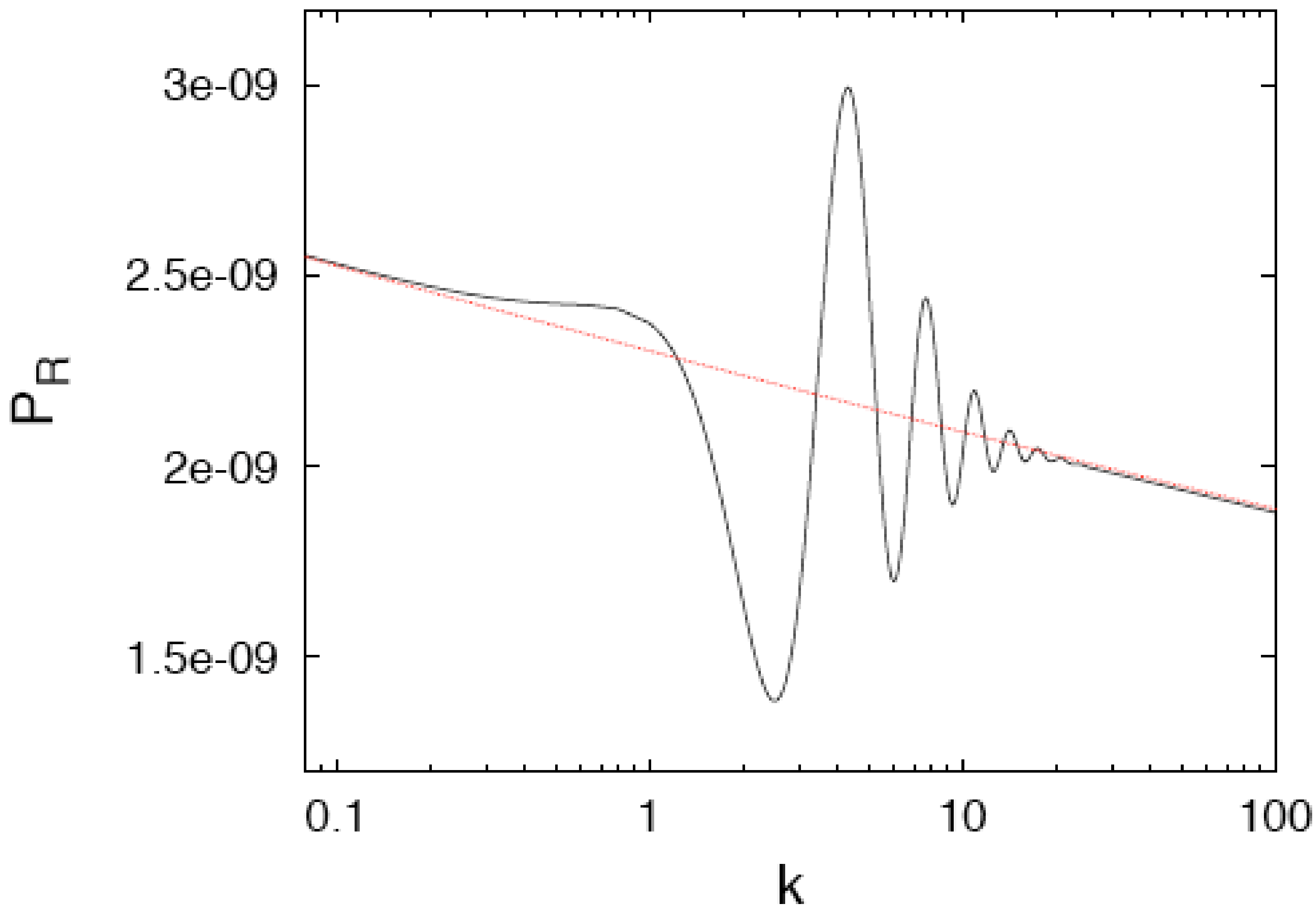
Testing Brane Inflation

- Compare power spectrum and its running
- Tensor mode (B mode polarization)
- Non-Gaussianity
- Steps (from Gauge-gravity duality)

A blip in CMB power spectrum



A small step in the potential can generate such a blip



Adam, Cresswell, Easther, astro-ph/0102236

As the D3 brane moves down the throat: Cascade

Klebanov-Strassler throat

$$SU((K+1)M) \times SU(KM)$$

$r = r_0$

$l = 1$

$$\downarrow$$

$$SU((K-1)M) \times SU(KM)$$

$r = r_1$

$l = 2$

$$\downarrow$$

$$SU((K-1)M) \times SU((K-2)M)$$

$r = r_2$

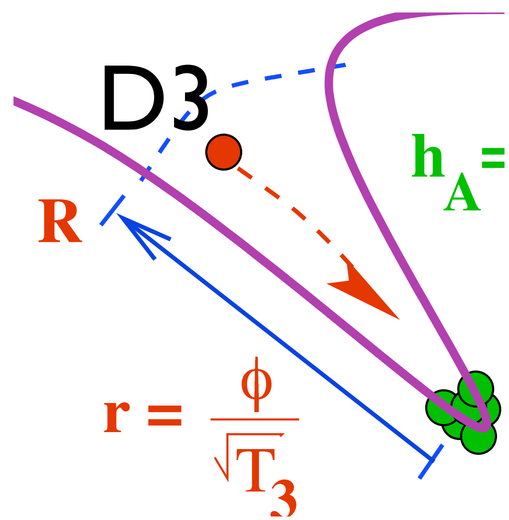
$$\downarrow$$

....

....

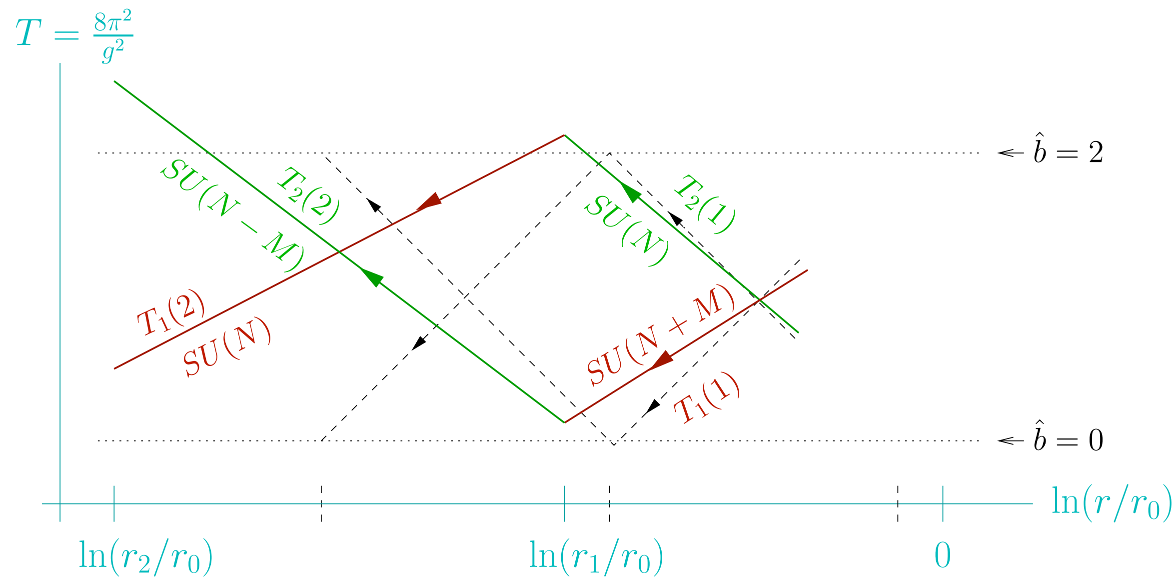
$$\downarrow$$

$$SU(2M) \times SU(M)$$



RG Flow and Seiberg Duality

Cascade



- The anomalous mass dimension has a correction that depends on which step the RG flow is at. This means that the coupling flows depend on which step the flow is at.
- Using gauge/gravity duality, we see that the dilaton runs and it has a kink at the position where Seiberg duality transition takes place.
- this leads to steps in the warp factor, which then leads to steps in the inflaton potential.

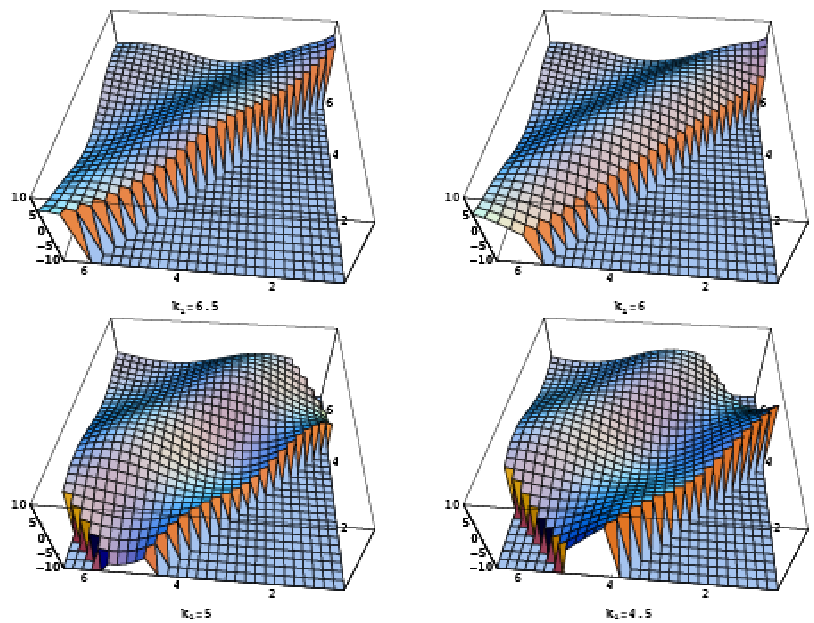
Predictions

- After fitting the feature at l ~ 20 in WMAP data,

p	l	$\Delta T/T$	Δl_p
2	~ 2	~ 0.7	~ 1
3	~ 20	0.2	~ 5
4	~ 170	~ 0.08	~ 40
5	~ 1300	~ 0.04	~ 260

- it predicts additional steps : their positions, their heights and their widths.

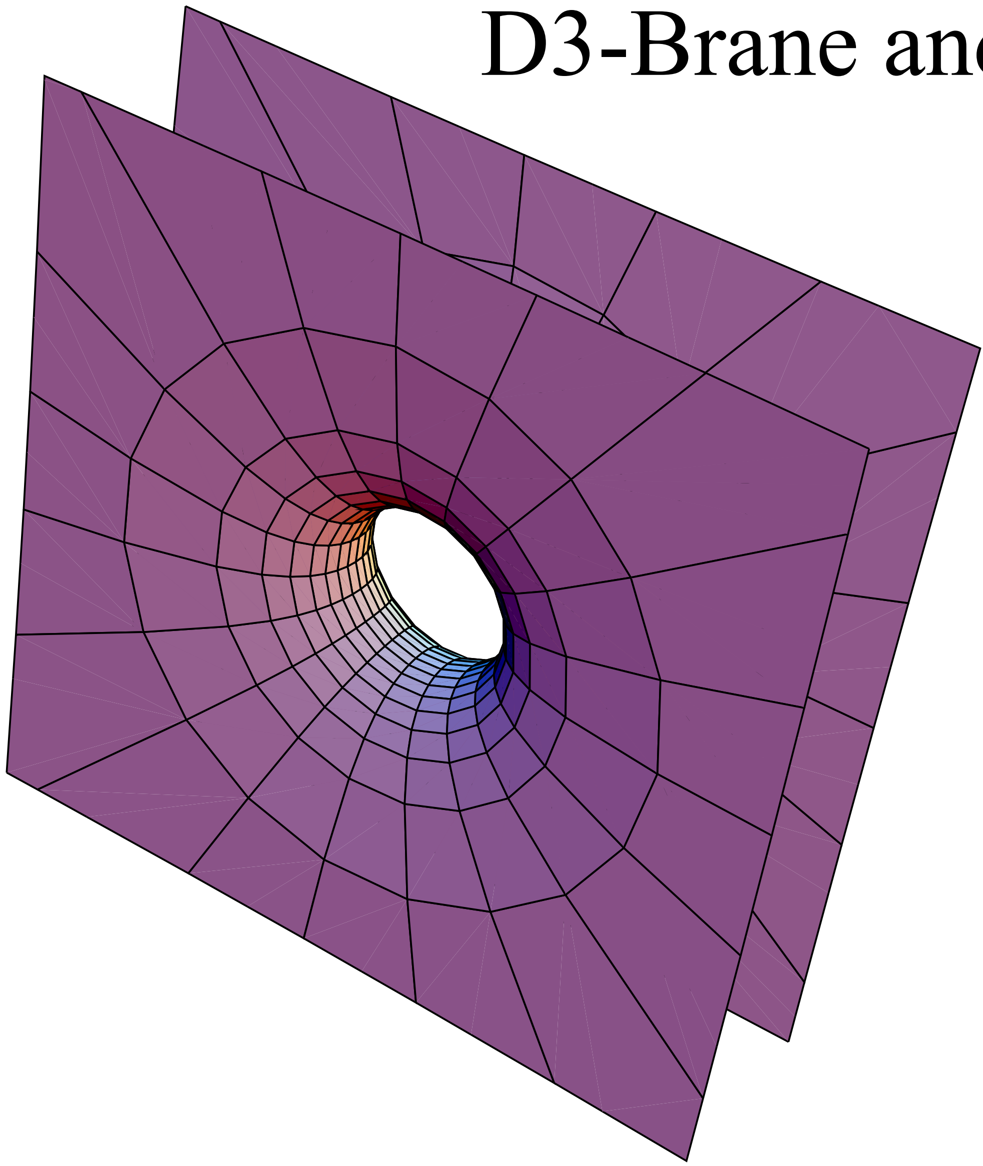
- it also predicts non-Gaussianity features due to the steps.



X. Chen, R. Easther, E. Lim, astro-ph/0611645

Girma Hailu and HT, Hep-th/0611353
R. Bean, X. Chen, G. Hailu, HT and J. Xu, 0802.0491

At the end of brane inflation:



D3-Brane and anti-D3-brane annihilate:

All energy released
goes to strings:

fundamental strings
and D1-branes

Well-known important cosmological properties:

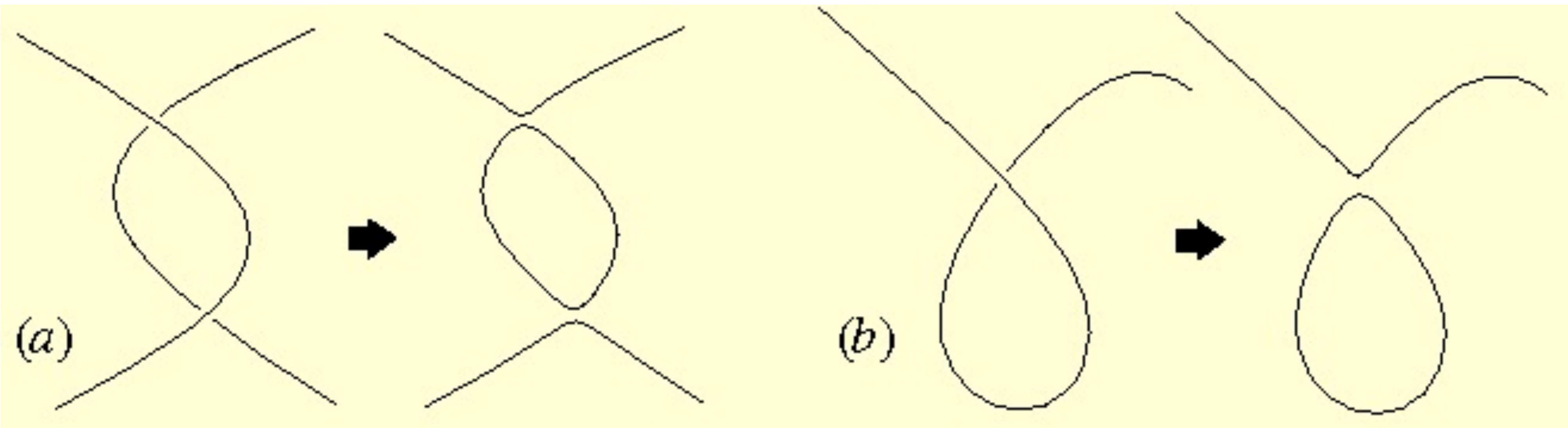
- Monopoles : density ~ a^{-3} Disastrous
- Domain walls : density ~ 1/a Dangerous
- cosmic strings : density ~ a^{-2}
  interaction cuts it down to a^{-4} during radiation
  Safe

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

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

Cosmic strings

- Cosmic string interactions produce a scaling cosmic string network.



History of cosmic strings

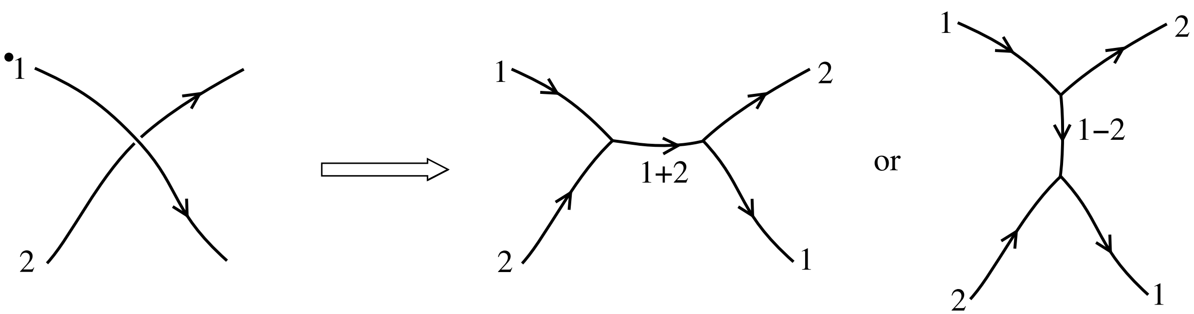
- Early 1980s : proposed to generate density perturbation as seed for structure formation; as an alternative to inflation; $G\mu > 10^{-6}$ Kibble, Zeldovich, Vilenkin, Turok, Shellard, ...
- In 1985, Witten attempted to identify the cosmic strings as fundamental strings in superstring (heterotic) theory. 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, which can have much lower tensions and can be quite stable.
- These cosmic strings were produced cosmologically.

(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.



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

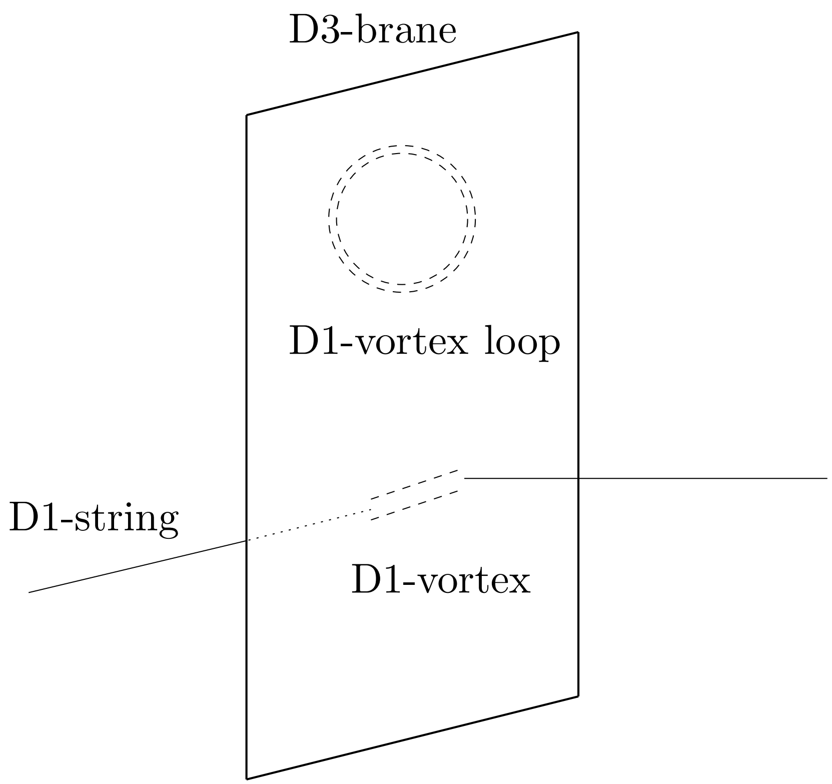
They have non-trivial interactions.

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

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

Strings and axions

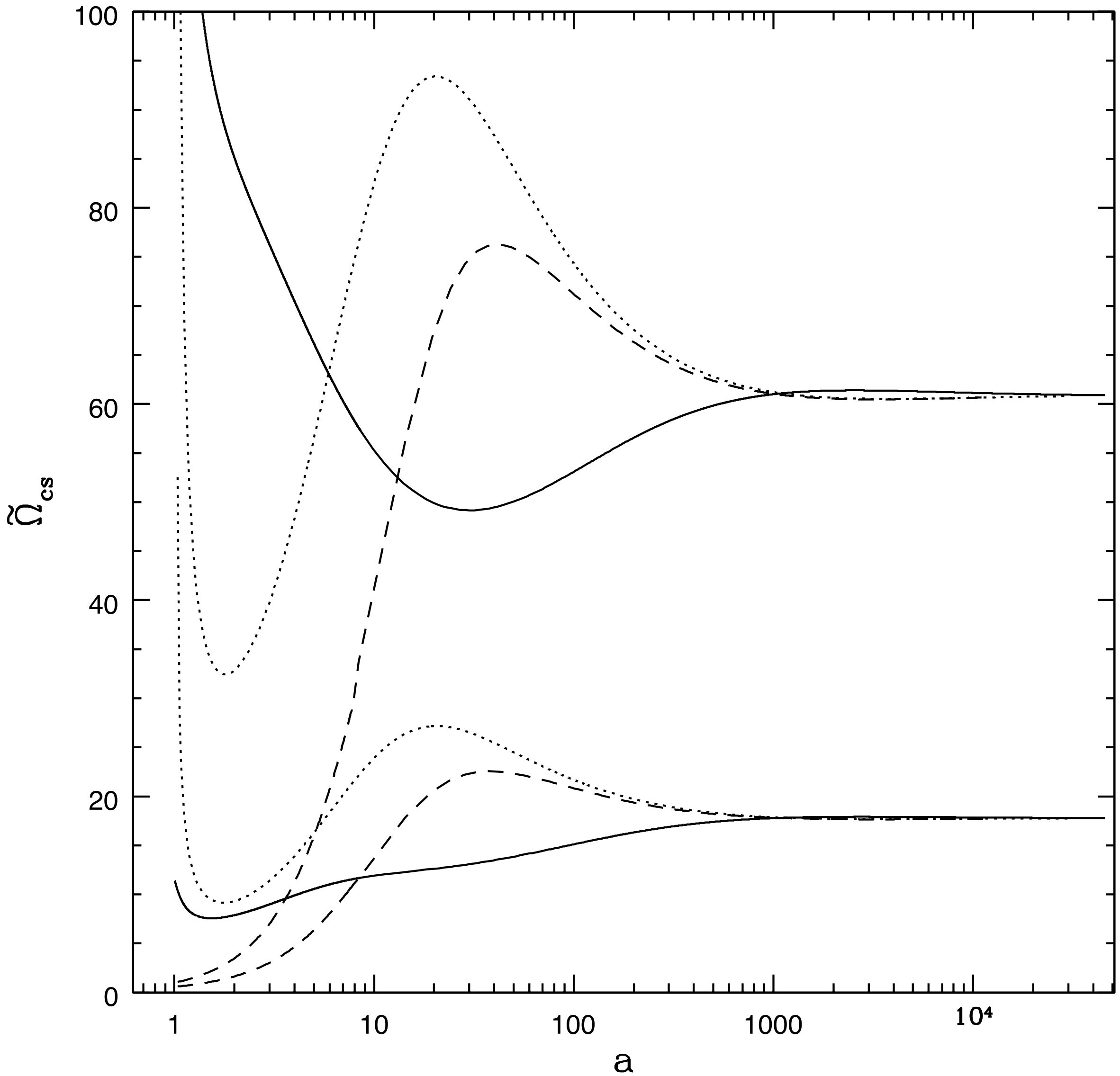
- A point particle can be charged under a gauge field, a one-form field.
- A string is charged under a two-form field.
- In 4-dim., a two-form field (NS-NS or RR) is dual to an axion.
- In a typical realistic stringy vacuum, there are a number of axions.
- So we expect a variety of cosmic string types.

Scaling of the Cosmic Superstring Network

independent of initial conditions

Insensitive to the details of the interactions

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

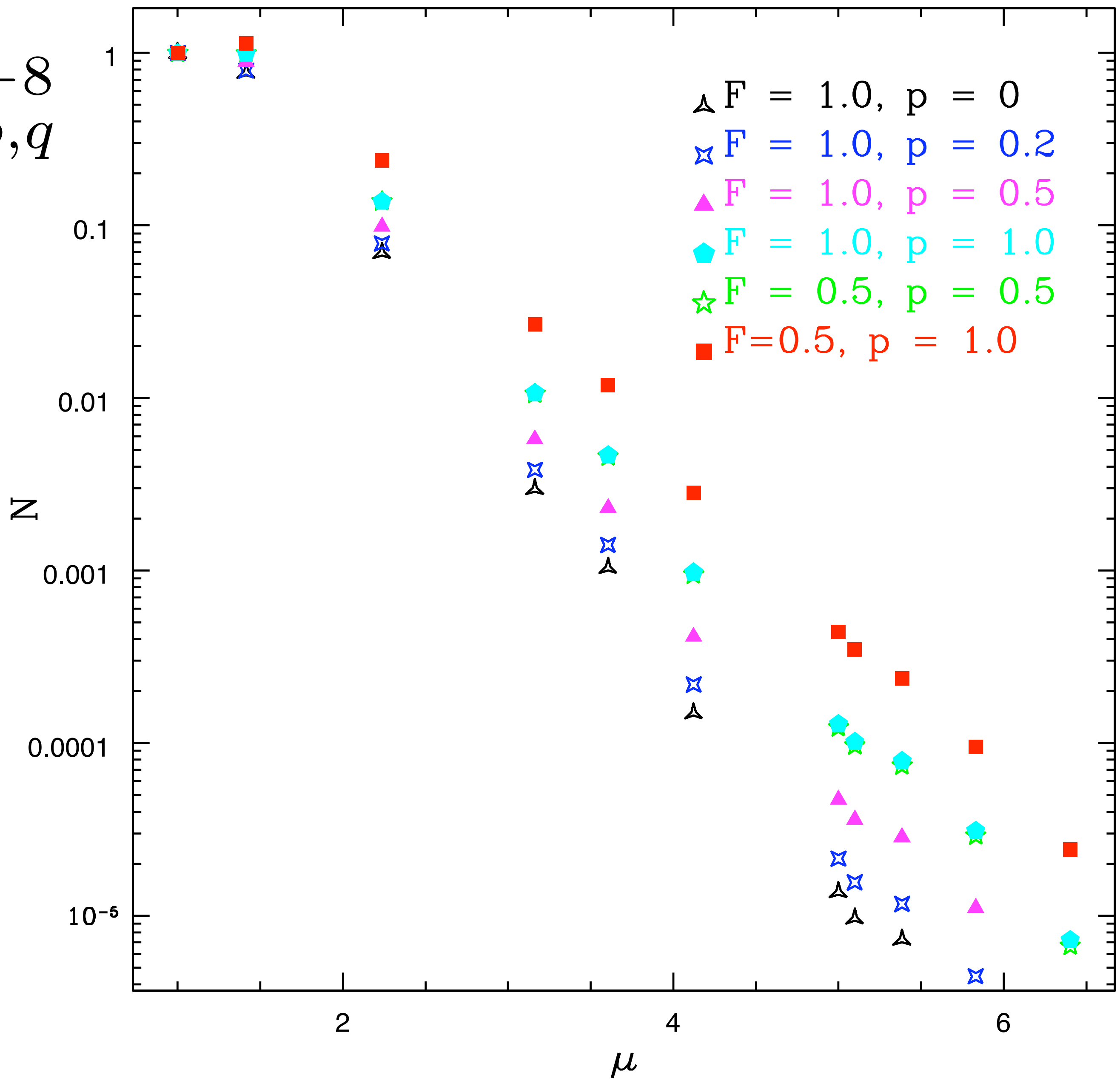


M. Jackson, N. Jones and J. Polchinski, hep-th/0405229

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 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.

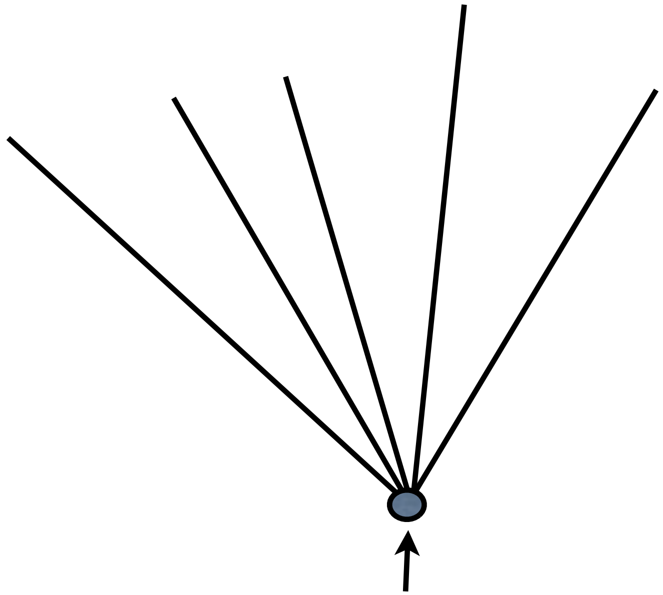
$$T_{p,q} \simeq \frac{h_A^2}{2\pi\alpha'}\sqrt{\frac{q^2}{g_s^2}+(\frac{bM}{\pi})^2\sin^2(\frac{\pi p}{M})},$$

$$b = 0.93266$$

M is the RR flux wrapping S^3.

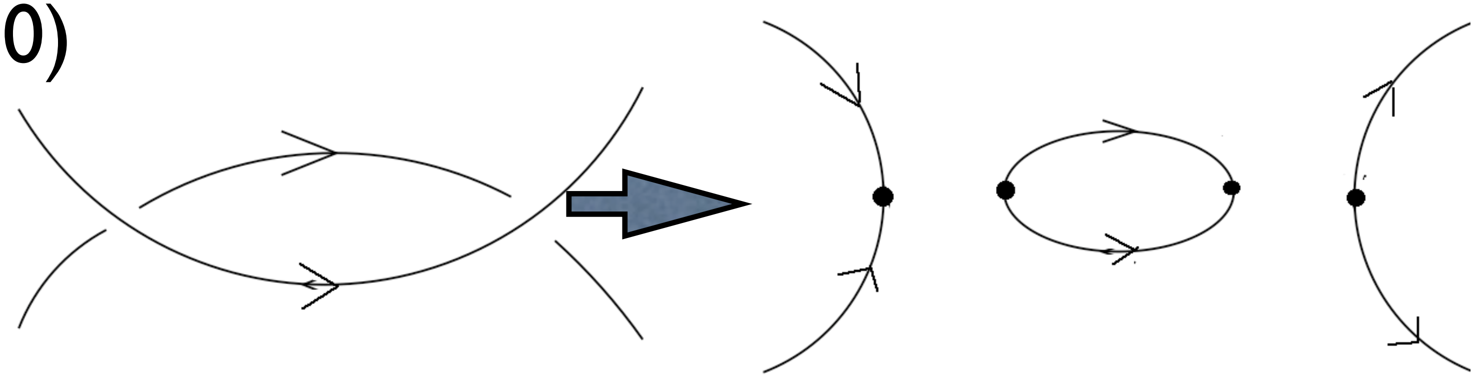
S. Gubser, C. Herzog, I. Klebanov, hep-th/0405282,
H. Firouzjahi, L. Leblond, H.T., hep-th/0603161.

Example :
M=5



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

(M-p,0)



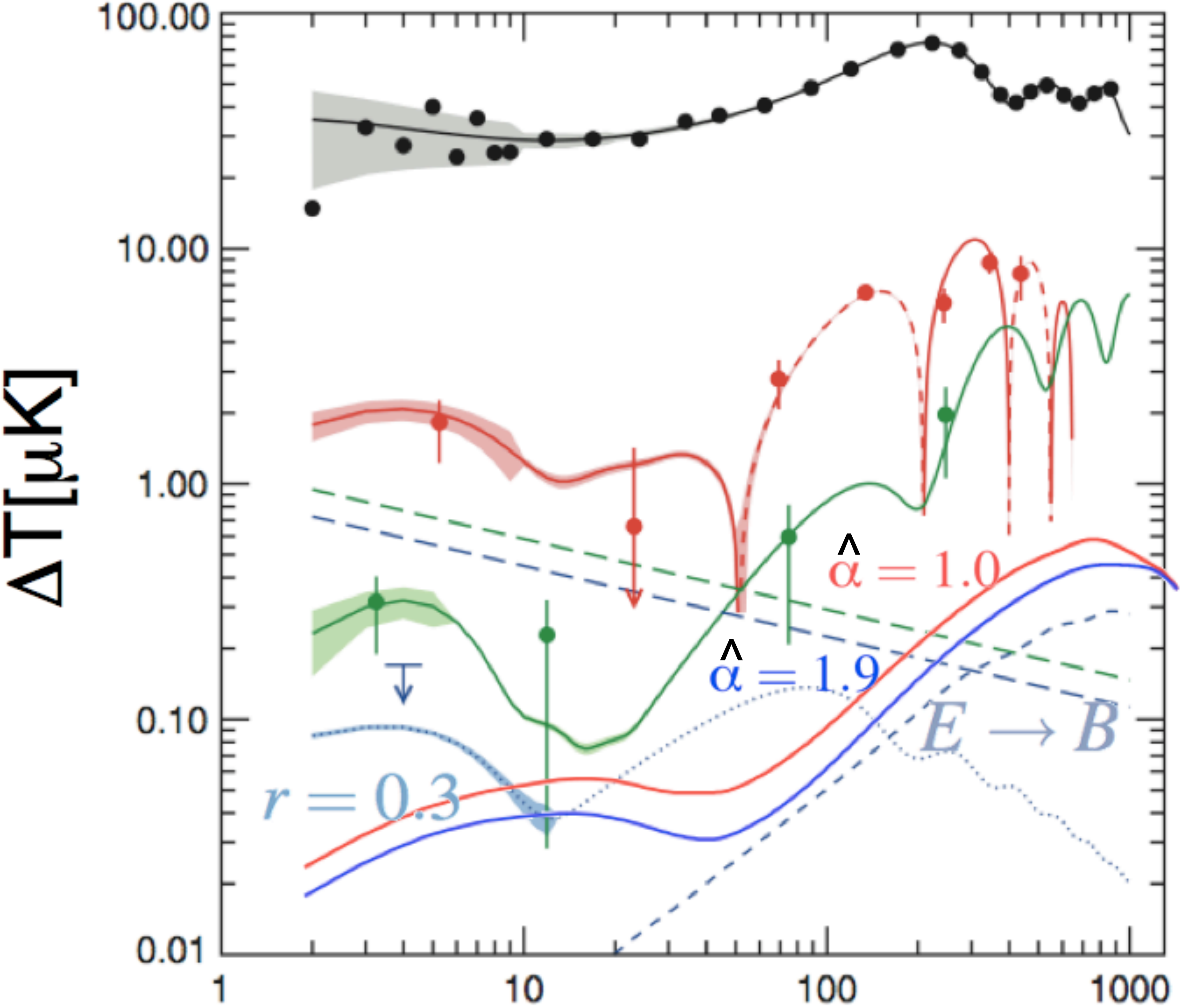
(p,0)

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

Search for Cosmic Strings

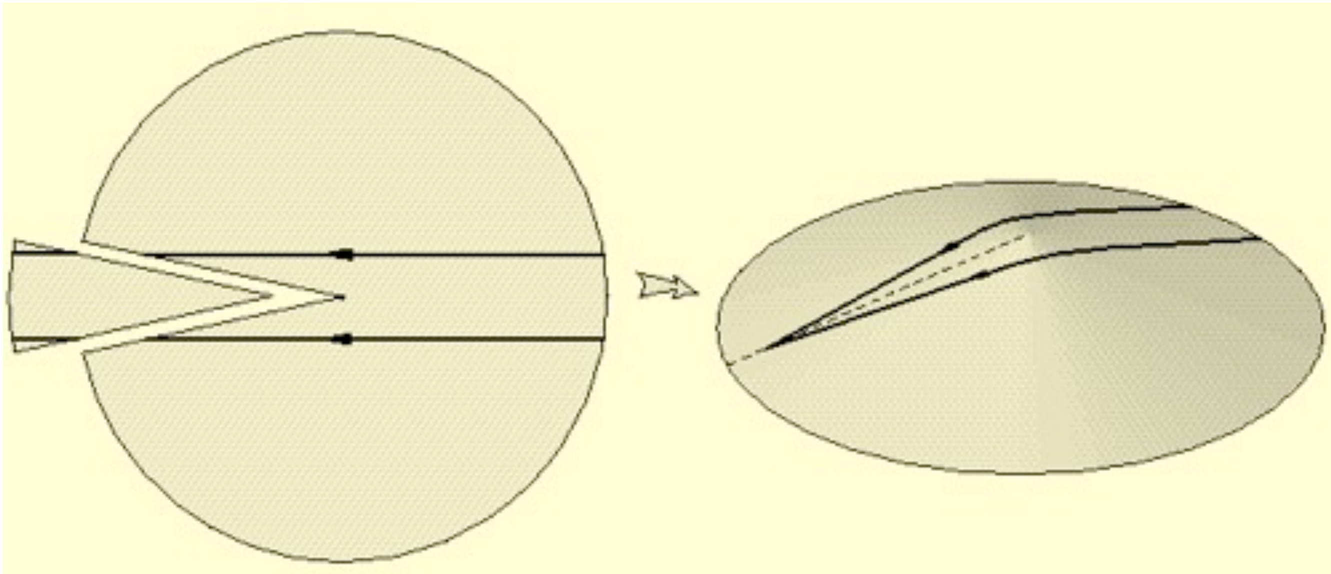
- Lensing
- Cosmic Microwave Background Radiation
- Gravitational Wave Burst
- $\Delta T/T$ (Doppler effect)
- Pulsar Timing
- Stochastic Gravitation Radiation Background

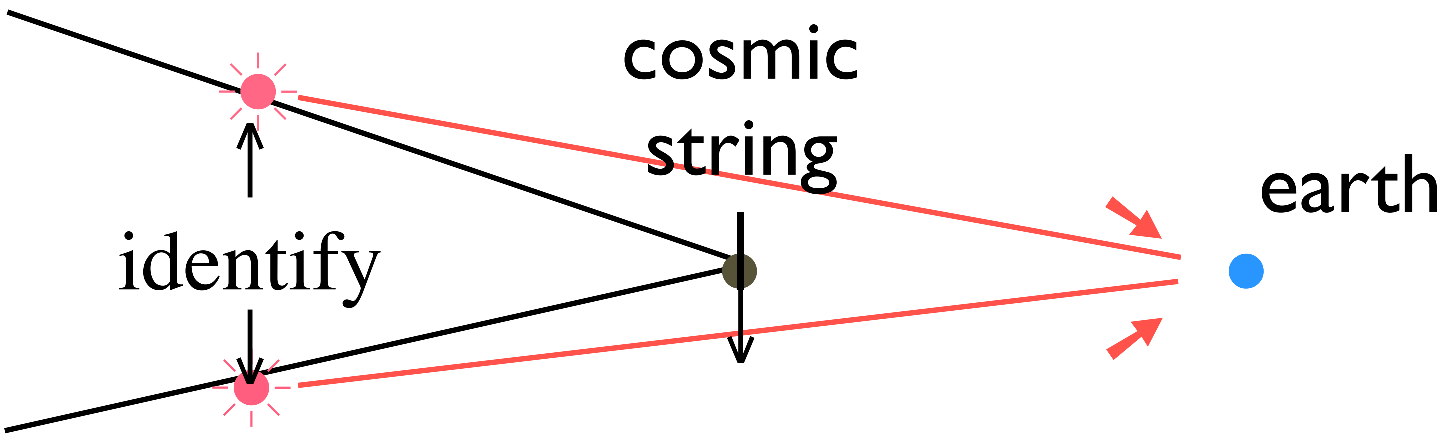
Possible CMB B-mode detection



cosmic string lensing

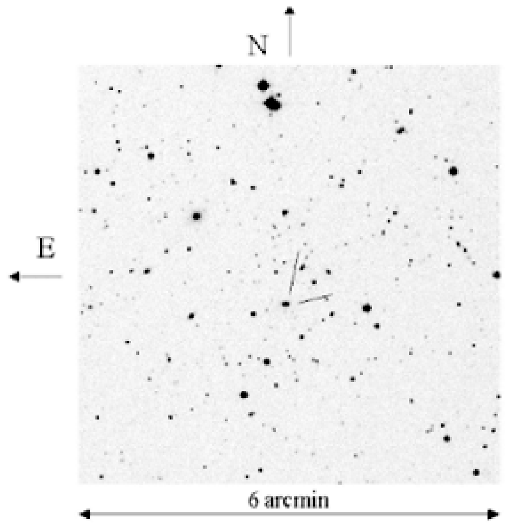
cosmic string introduces a deficit angle

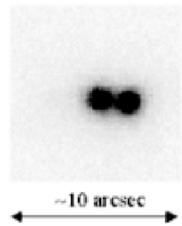


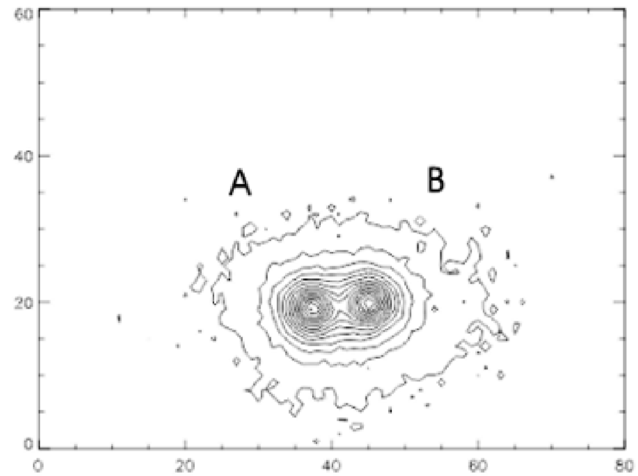


CSL-1

Sazhin etc. astro-ph/0302547

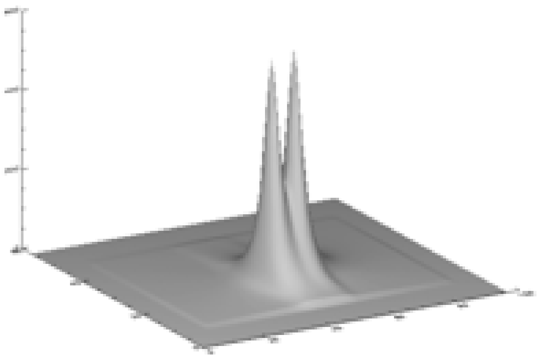


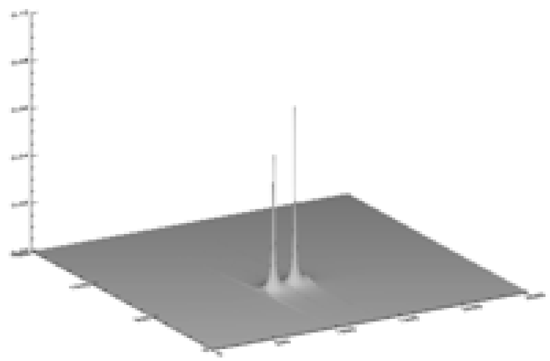


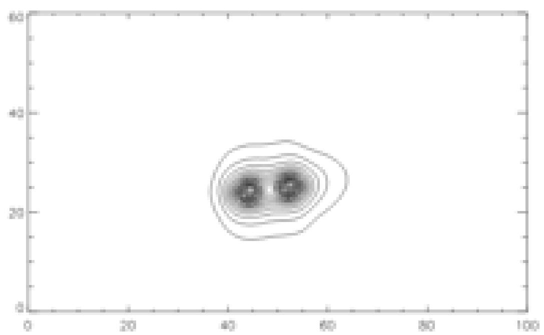


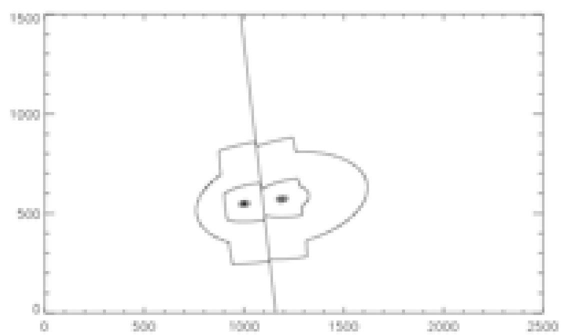
z=0.46 ± 0.008

identical spectra with confidence level above 99.9%









1.9 arc sec

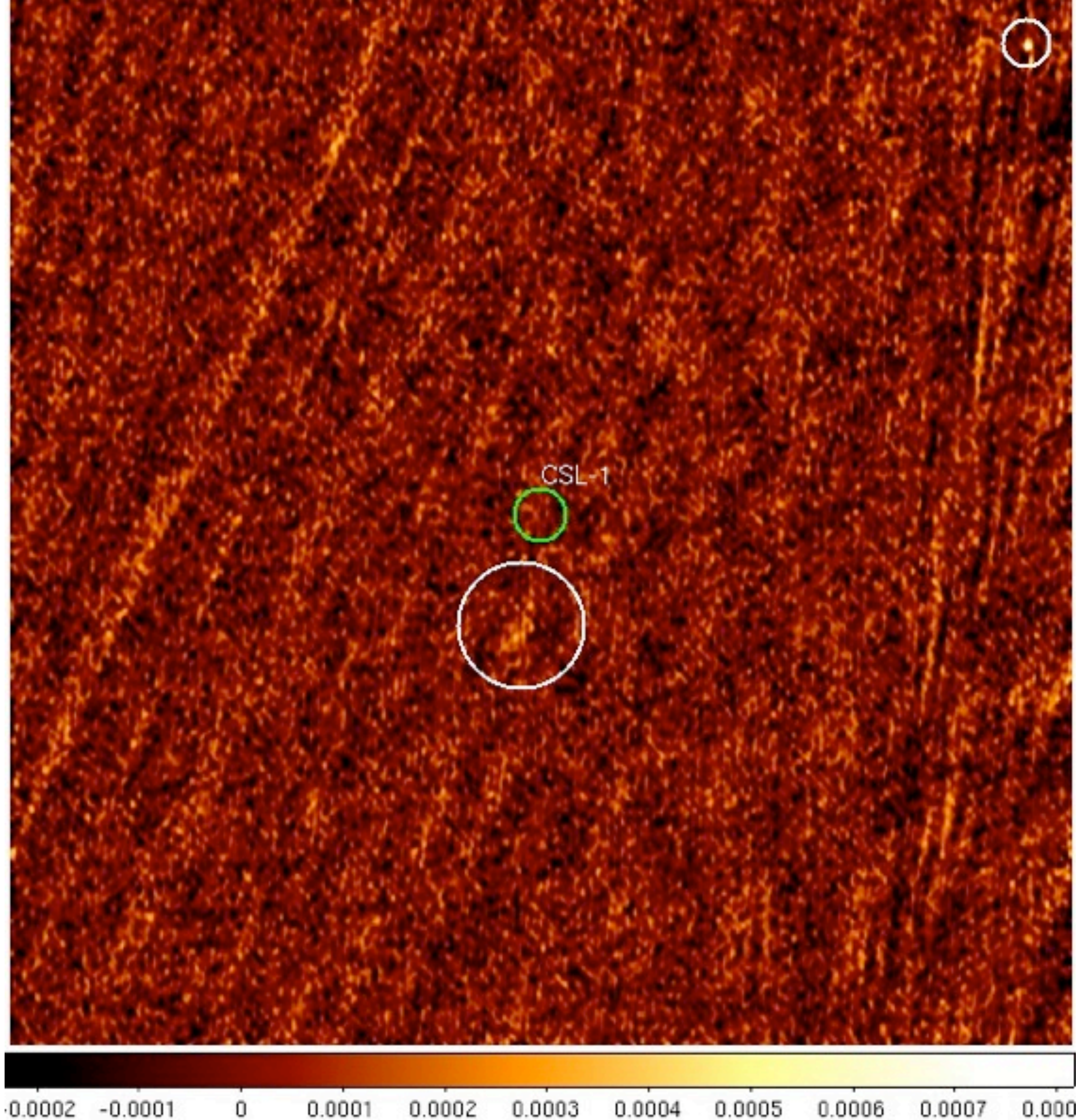
$\Downarrow$

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

Radio telescope ?

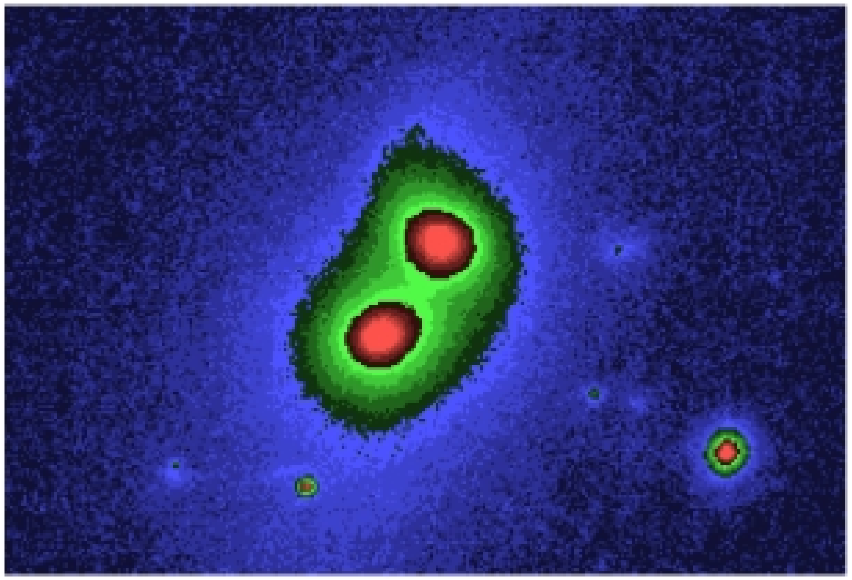
Recall Cowen and Hu.

National Radio
Astronomy Observatory

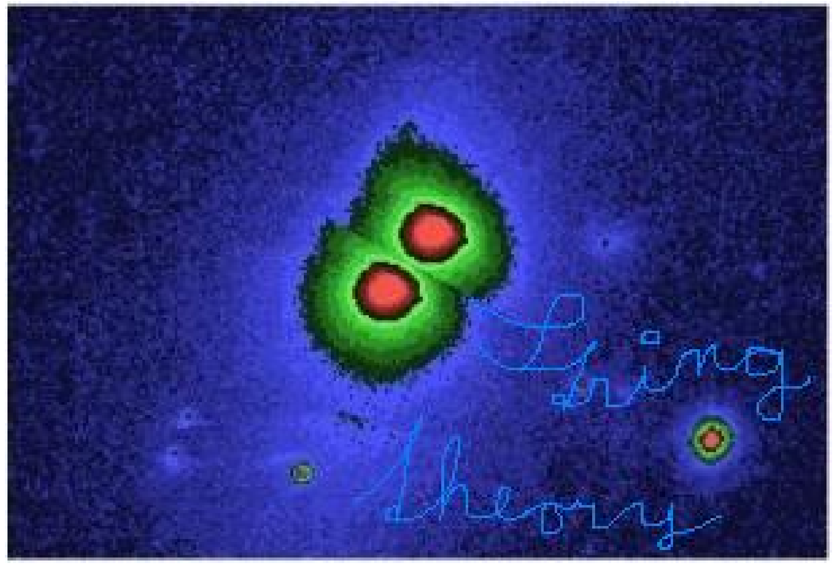


Shami Chatterjee, Jim Cordes, H.T., Ira Wasserman

Unfortunately not (higher resolution Hubble pictures):

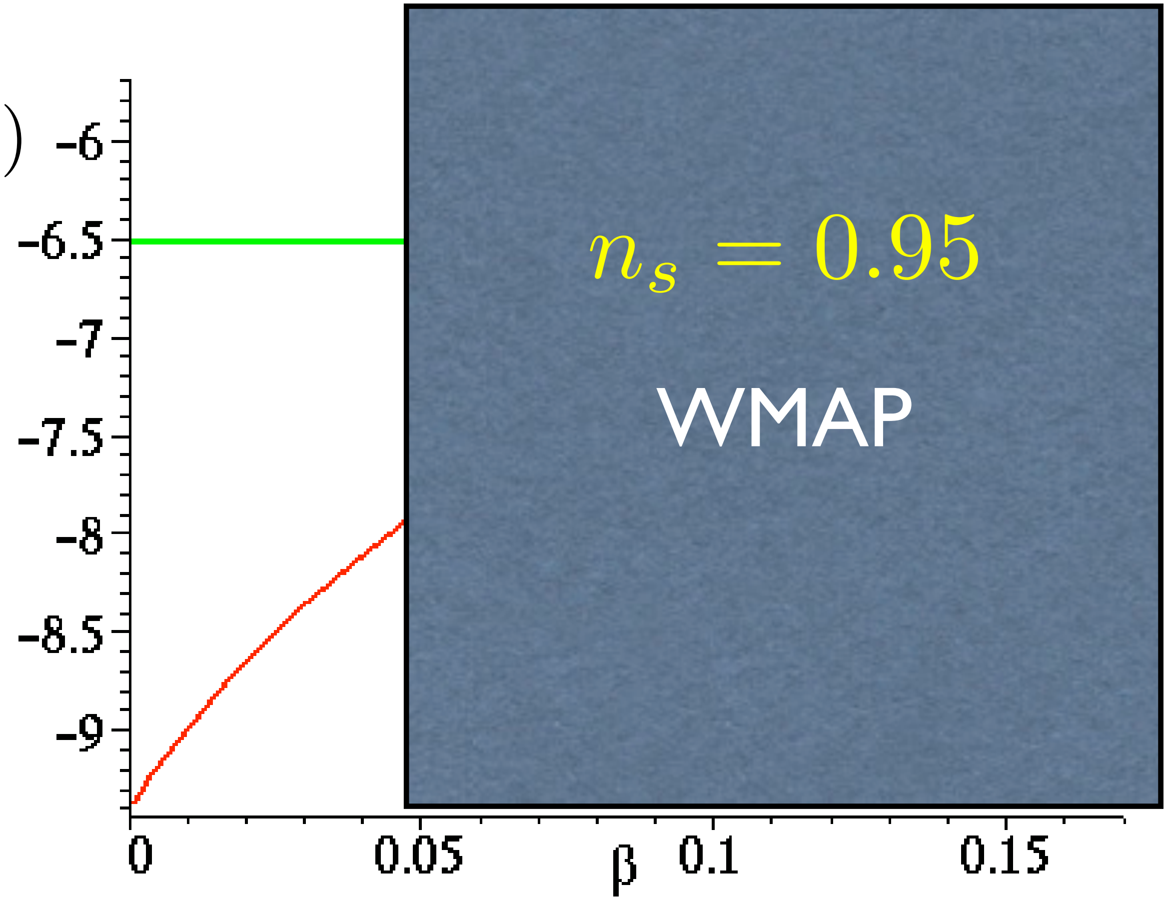


January 2006



If it is cosmic string lensing

Bound on cosmic string tension



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

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

$$n_s \sim 0.98 + \beta \quad \longrightarrow n_s \leq 1.03$$

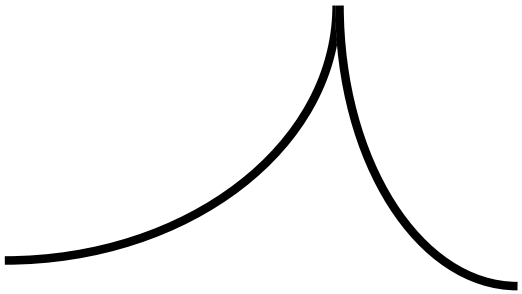
$$\log r \sim -8.8 + 60\beta$$

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

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

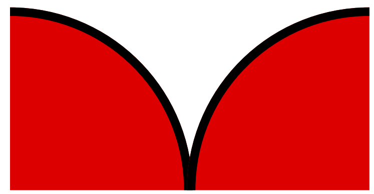
S. Shandera and H.T., 0601099

cusps and kinks are quite common in string evolution

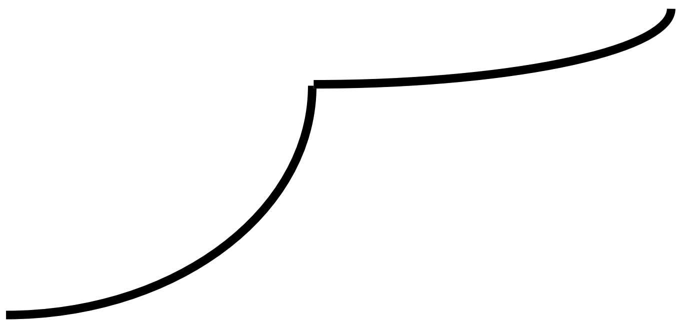


CUSP

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



wave form of gravitational wave bursts

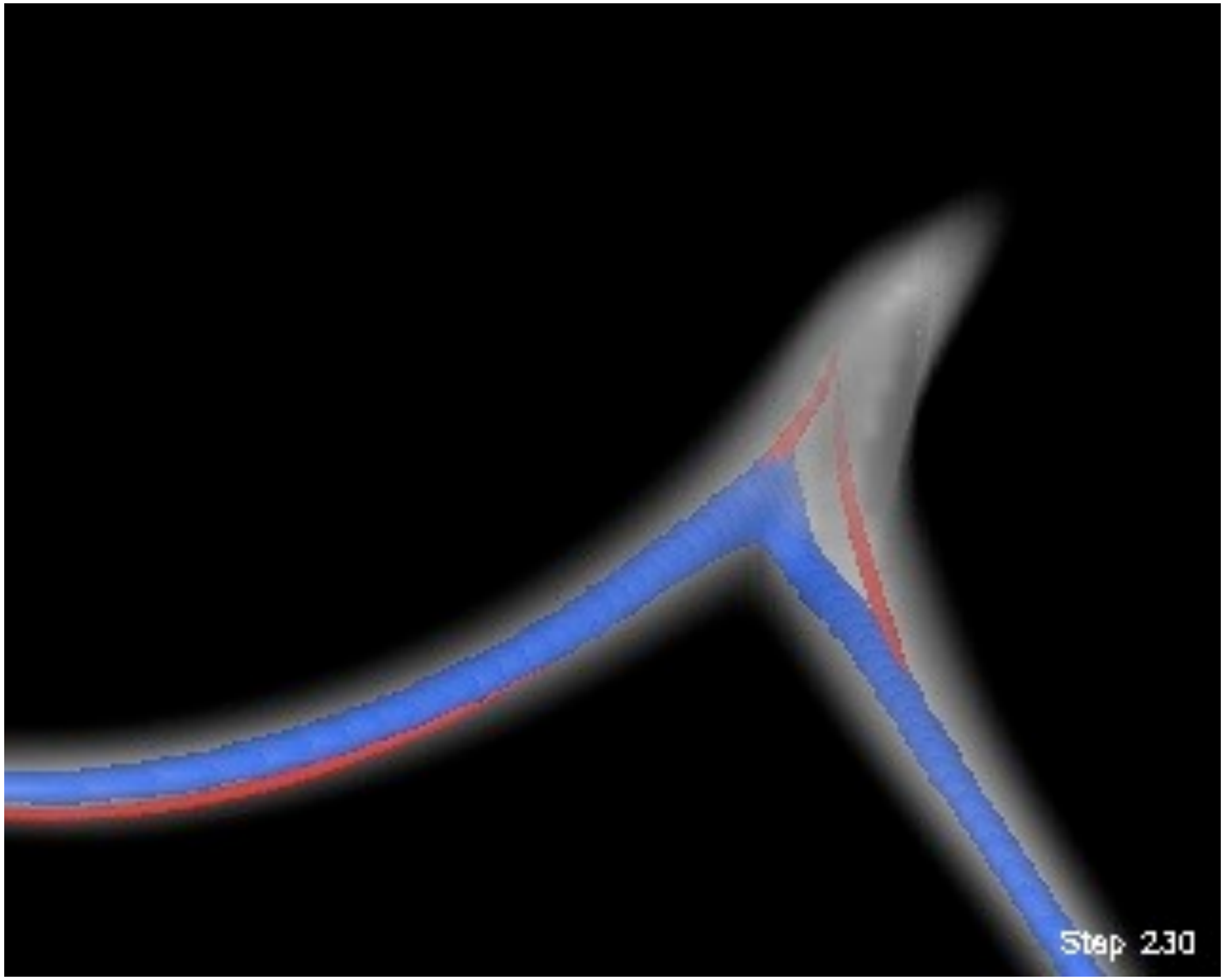


KINK

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

Damour and Vilenkin

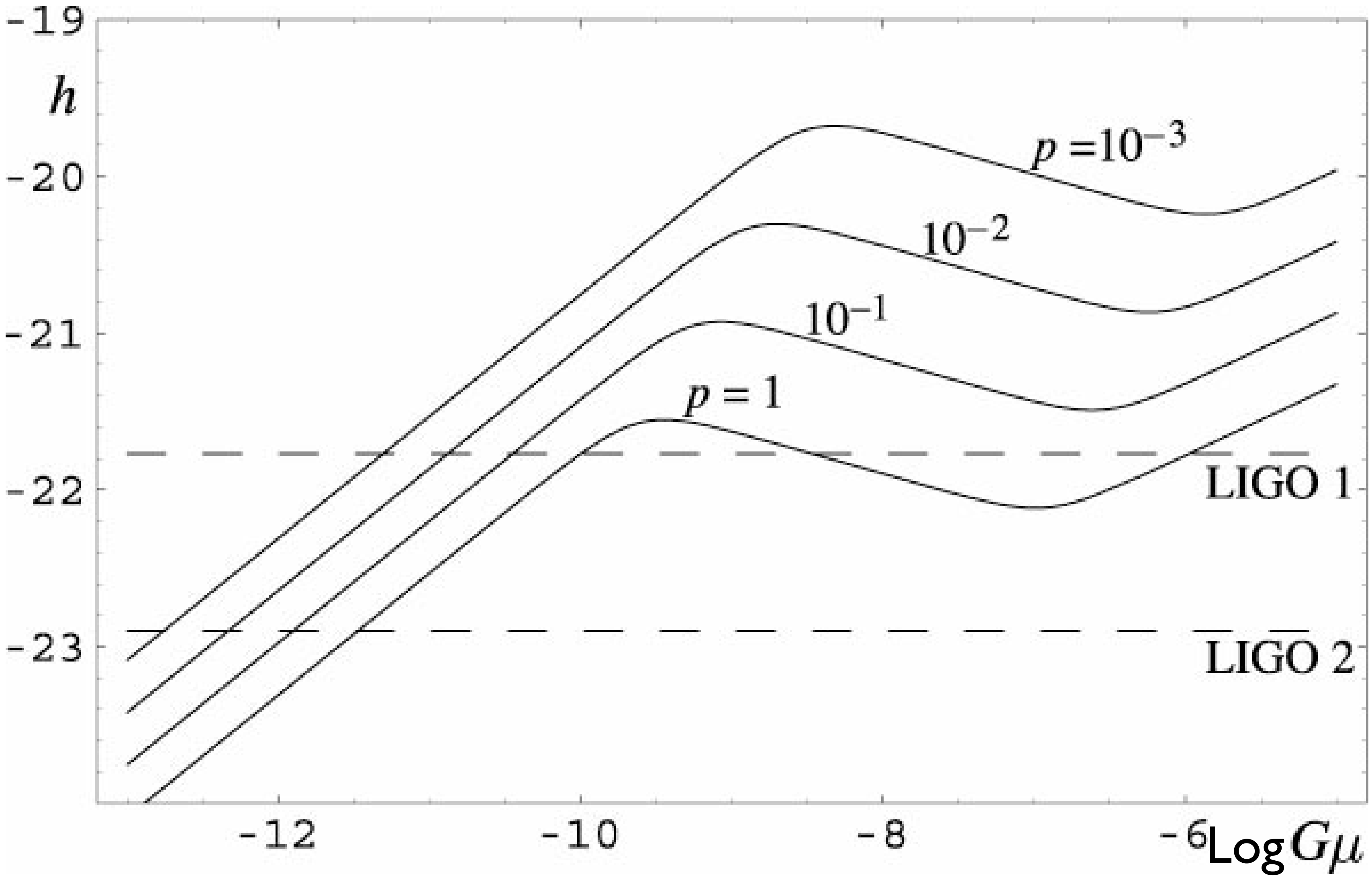
A cusp



Blanco-Padillo and Olum

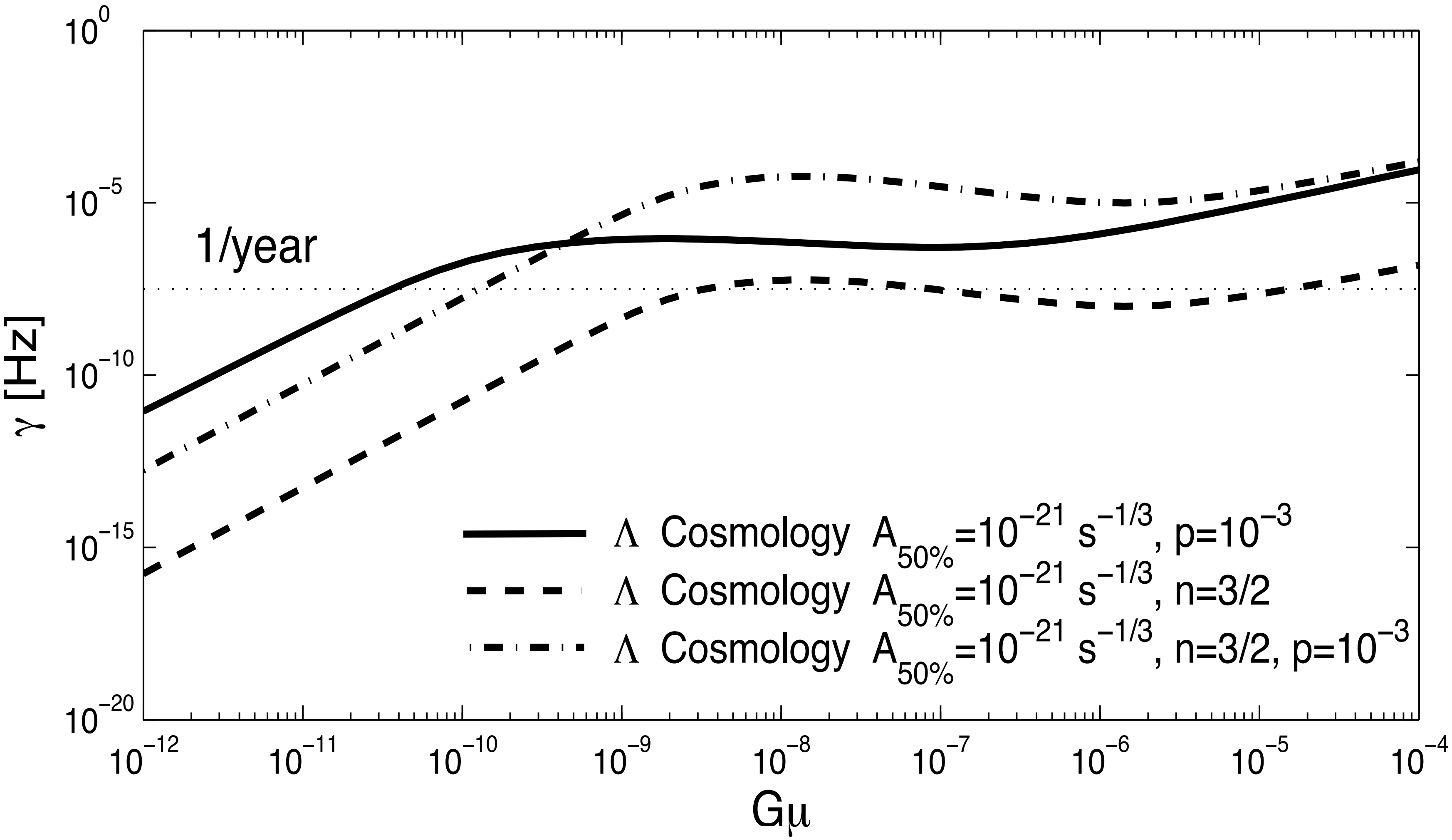
Gravitational wave radiation from cusps

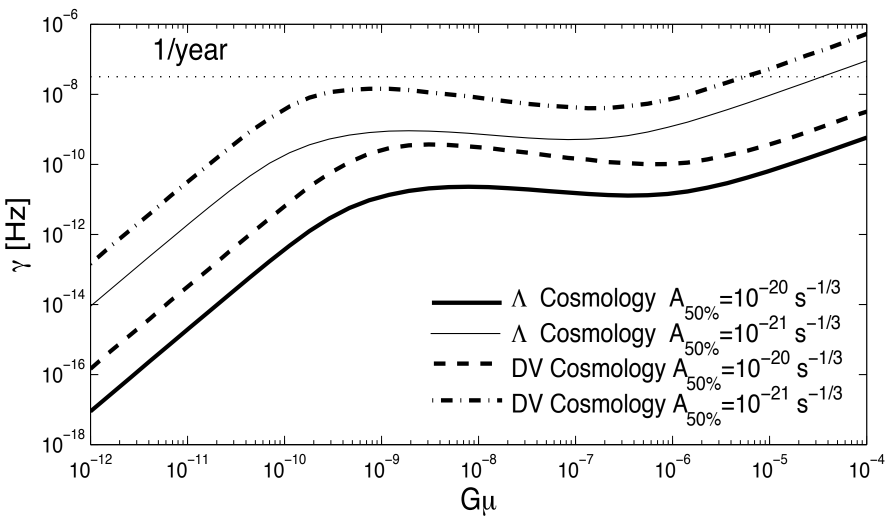
Damour and Vilenkin



prediction

More recent analysis



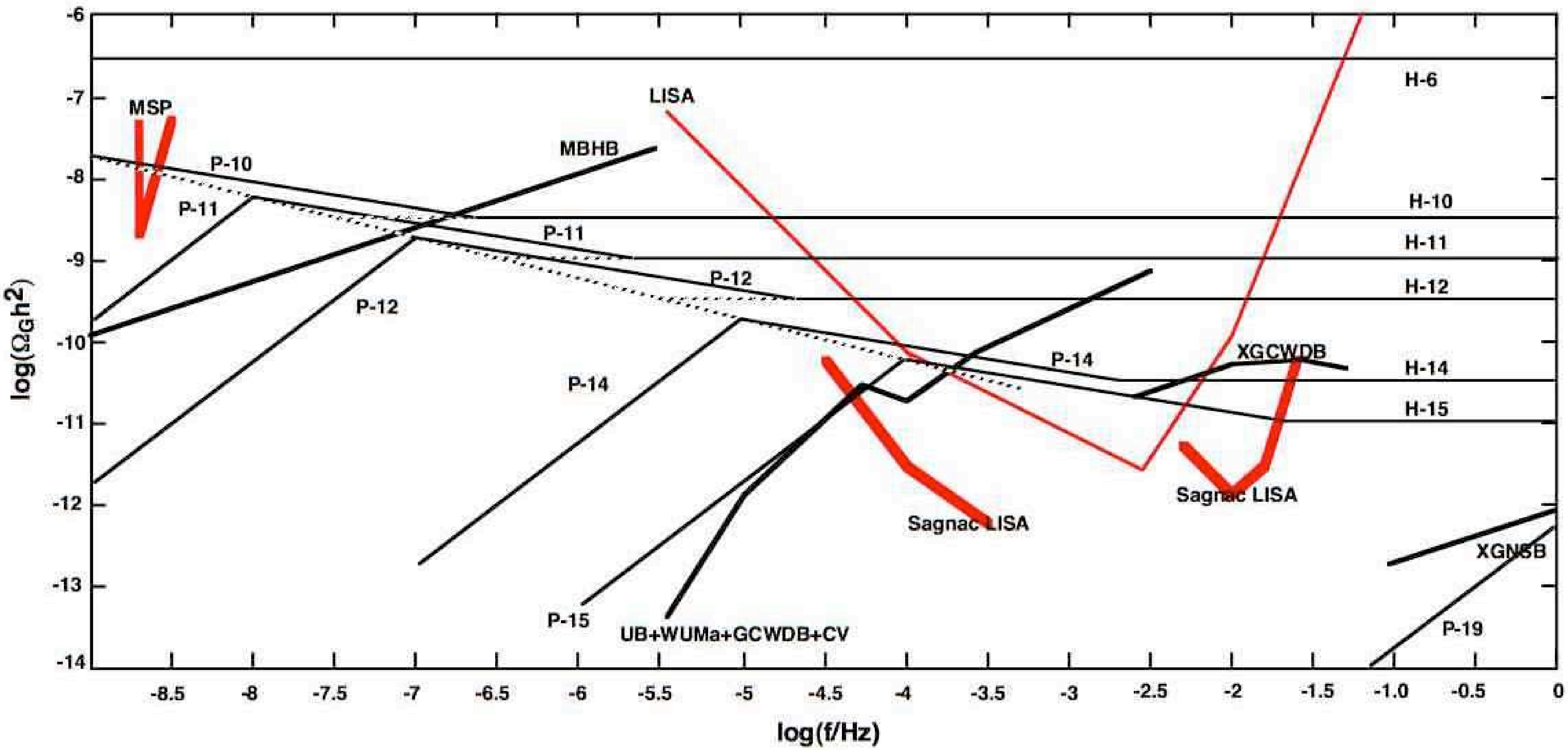


X. Siemens, J. Creighton, I. Maor, S. Majumder, K. Cannon and J. Reed, gr-qc/0603115

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 ?

Low tension strings

$$10^{-8} > G\mu > 10^{-14}$$

- Warped geometry can provide very low tension cosmic strings.
- They radiate gravitational waves much slower, so they live much longer, in particular the small loops.
- The small loops can cluster like dark matter; thus their local density is 5 orders of magnitude larger than that from the scaling cosmic string network.

David Chernoff and HT, 0708.4282
Chernoff 0908.4077

Micro-lensing

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

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

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

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

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

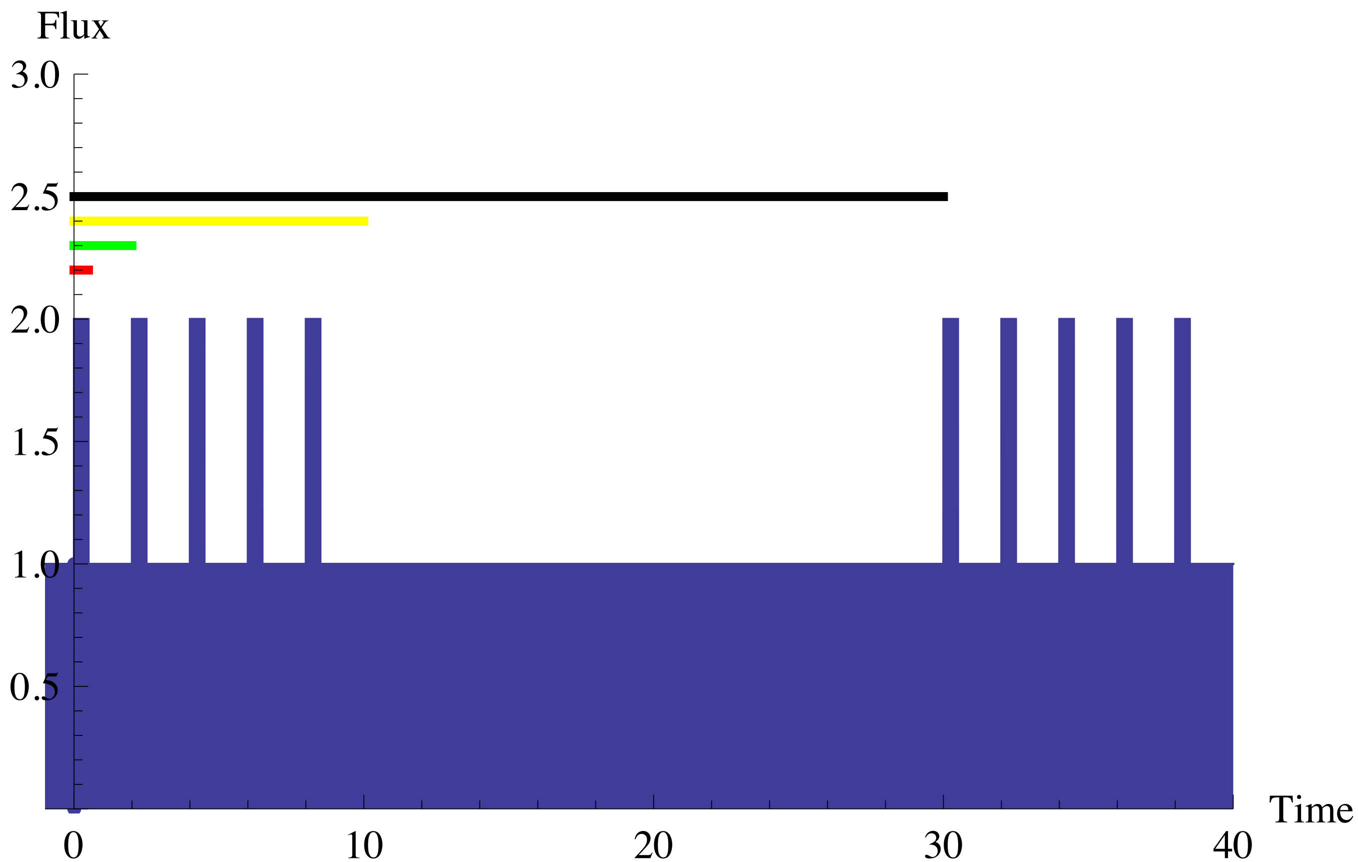
GAIA : $N_L \sim 0.03$

Hogan and Narayan, 1984

David Chernoff

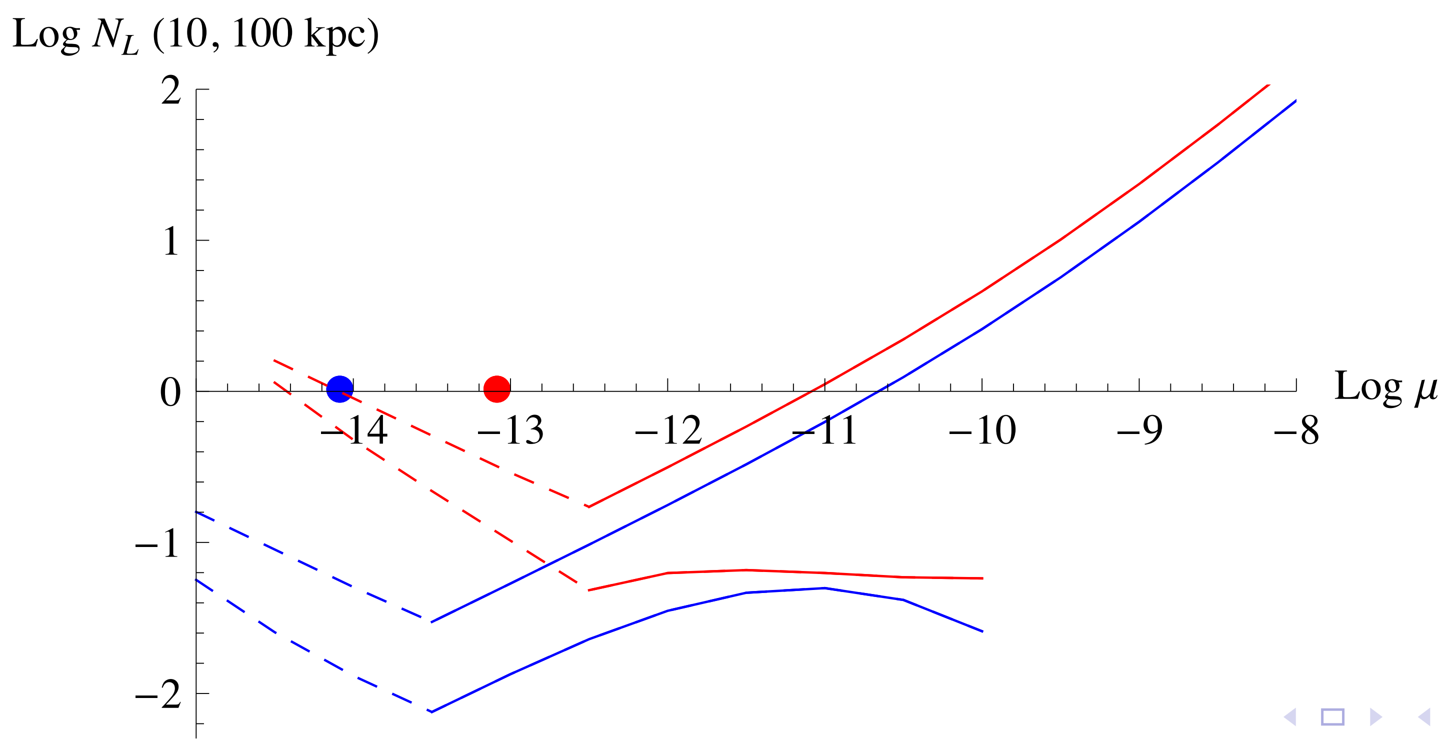
Typical scenario

$\delta t \sim 300s(R/10 \text{ kpc })(G\mu/10^{-10})$ and $t_{osc} \sim 70$ yr $(G\mu/10^{-10})$.
Repetition : $\sim 10^3$



Rate for LSST (Large Synoptic Survey Telescope)... similar to European GAIA

- LSST : 4×10^8 stars observed 10^3 times each with a 15 s exposure over a 10 year period. Red for 10 kpc and blue for 100 kpc.
- Figure with $\mathcal{G} = 1$; expect $\mathcal{G} \sim 10^3$.



Superstring theory may be tested

- Instead of searching for tiny particles or signatures in accelerators, we can search for distinctive features suggested by string theory.
- Steps in the CMB power spectrum suggested by gauge-gravity duality in a warped throat.
- Production of cosmic superstrings that 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.
- Micro-lensing detection offers the best hope to reach to very low tensions and provide very distinctive signatures.

Thank you !