Title: Cosmic superstrings: observable relics of brane inflation

Date: Jan 20, 2006 02:30 PM

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Abstract: Cosmic strings are a generic by-product of string theory models of the inflationary epoch. These new cosmic "superstrings," as they are called, are distinct from the grand unified strings once thought to generate large scale structure. I will discuss what limits the WMAP and SDSS data have already placed on the properties of networks of cosmic strings, as well as avenues for their direct detection. I will also introduce cosmic superstrings' distinctive properties: they can bind into a possibly infinite number of higher-tension states, leading to the possibility of network frustration and for a high- string-tension UV-catastrophe. An analytical model constructed by myself and others has shown that superstring networks can evade these catastrophes under certain assumptions for the dynamics of string binding. I will describe ongoing work to verify numerically these binding dynamics. Finally, I will characterize several observational signatures that I and collaborators have identified that could allow us to discriminate between cosmic superstrings and other kinds of cosmic strings.

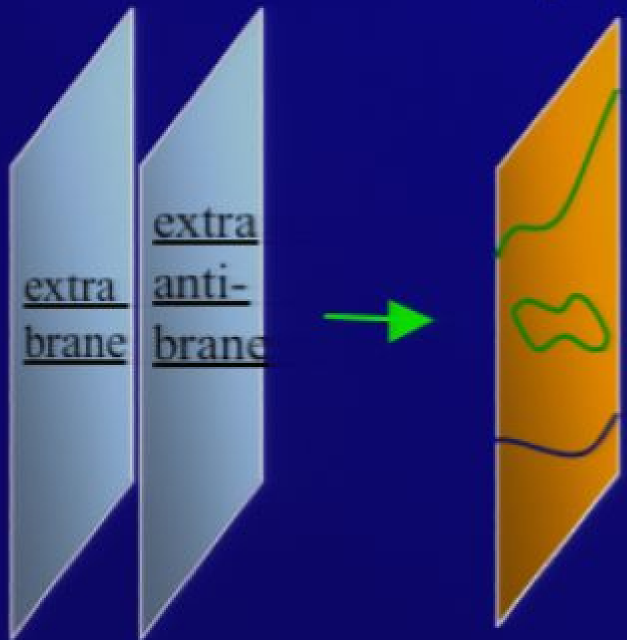
Outline

- Background and current observational limits on cosmic strings

- Cosmic superstring network modeling and observational signatures

Brane Inflation: New Source for Cosmic Strings?

(Tye and Sarangi 2002, Jones, Stoica, and Tye 2002, Copeland, Myers, and Polchinski 2004)



- Annihilation of inflating branes can produce strings (actual 1-D objects *or* "wrapped" higher-D objects)
- Predicts: few x $10^{-7} > G\mu > 10^{-11}$
- caveat: possible stability problems
- Not ruled out; potentially detectable

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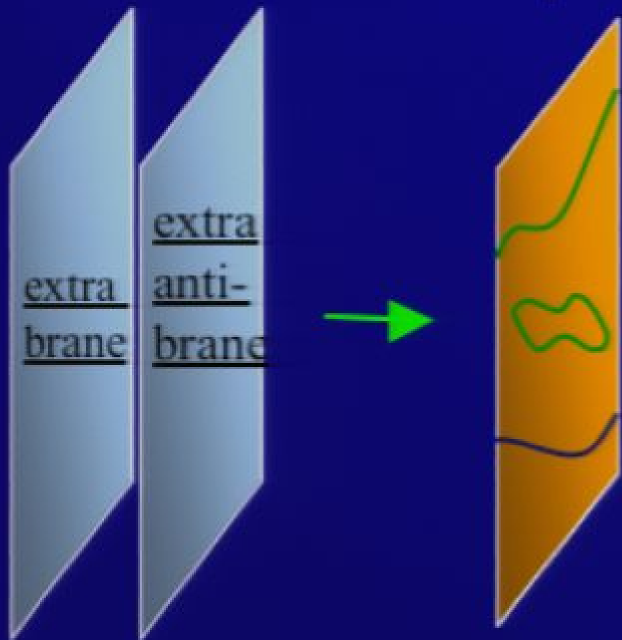

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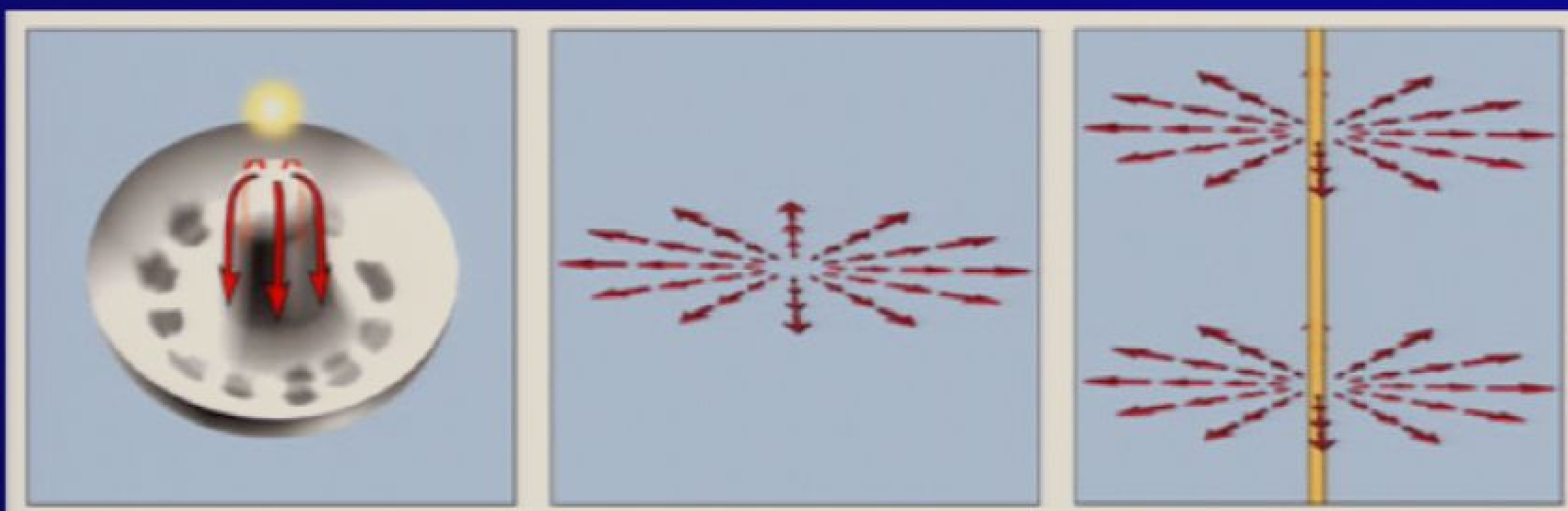
Cosmic Strings: What Are They?

Kibble Mechanism for defect formation:

Regions larger than H^{-1} are out of causal contact!



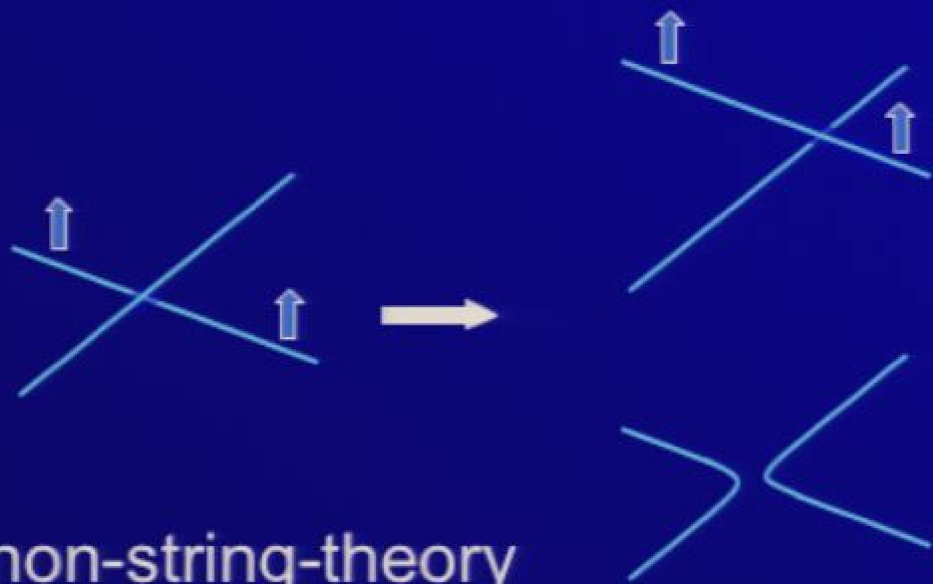
Cosmic string defect for U(1) symmetry

Cosmic Strings

$G\mu$: Key Dimensionless Parameter

G = Newton's constant $(\hbar = c = 1)$
μ = string tension
$G\mu$ ~ string tension in Planck units
~ gravitational coupling of string = size of metric perturbation.
~ 10^{-6} for μ at GUT scale

How do Strings Interact?



nothing:
probability $1-P$

reconnection:
probability P

$P = 1$ for non-string-theory cosmic strings

String Network Evolution: Scaling

Simplest one-scale model: energy lost in loops (Kibble)

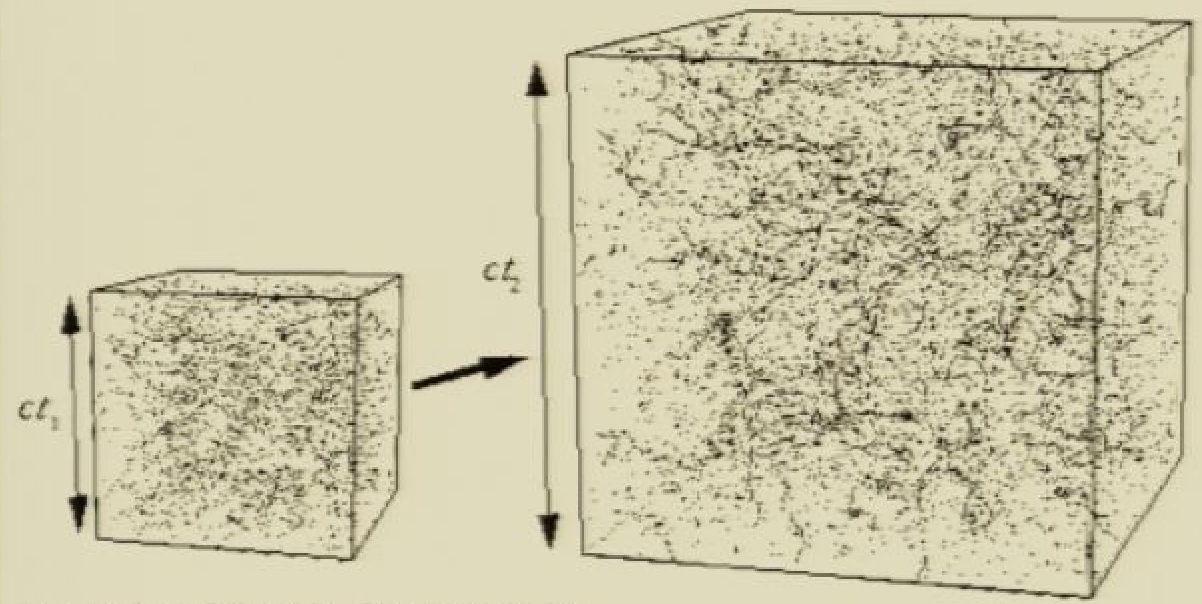


Image from Vilenkin, Shellard 1990

Naively, $\Omega_{\mathrm{strings}} \sim \frac{G\mu}{a^2}$

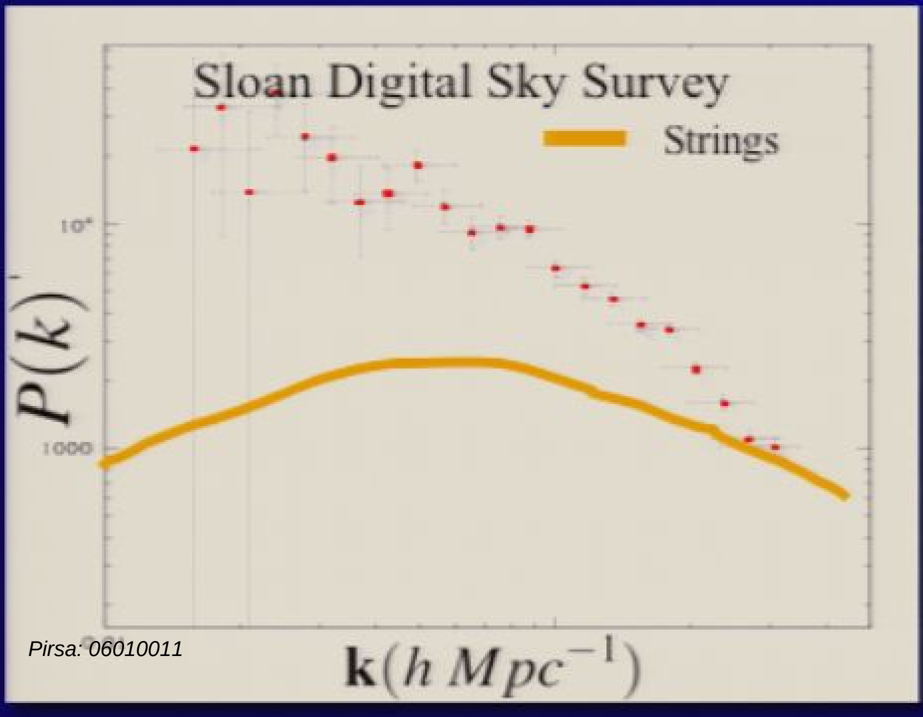
Simulations find $\Omega_{\mathrm{strings}} \sim \frac{G\mu}{P}$

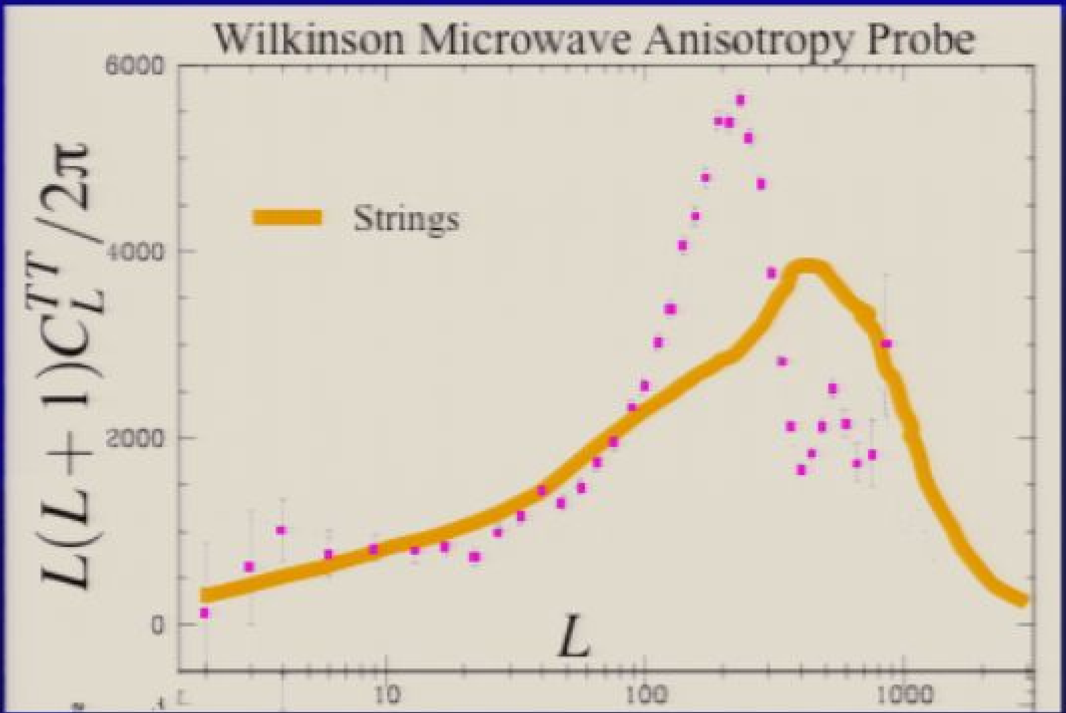
in Matter ***and*** Radiation Eras

Strings vs. Data: Review

Alone: Strings *FAIL*

(Albrect, Battye, & Robinson, PRL 79 (1997) 4736)





Strings ARE allowed at a subdominant level:

(Bouchet, Peter, Riazuelo, Sakellariadou, PRD 65 (2002) 021301)

Question: how much?

Our Modeling Parameters

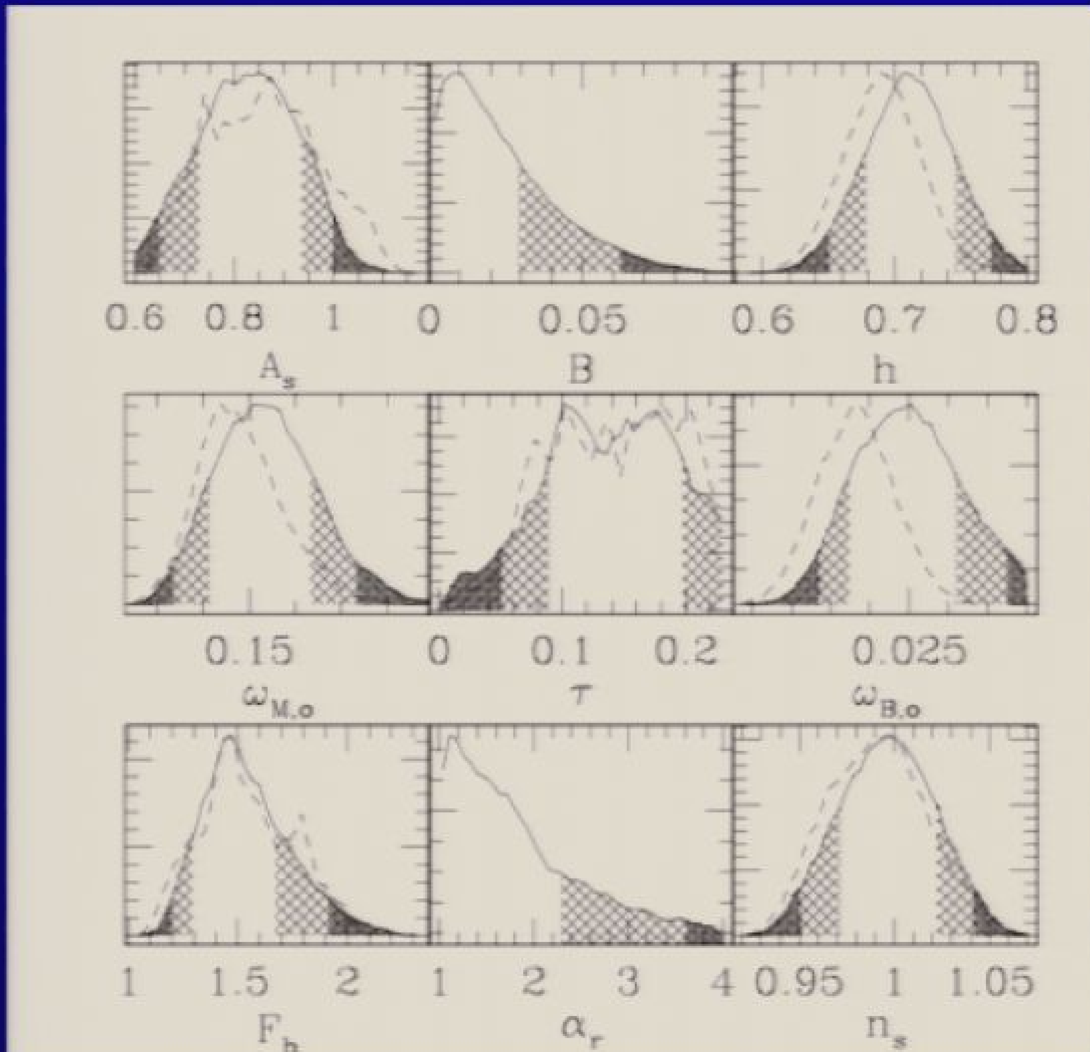
- Standard Cosmological Parameters: A_s, n_s, h, $\Omega_B h^2$, $\Omega_M h^2$, τ
- Cosmic String Model "Weight" $$B \equiv \left(\frac{\mu}{\mu_0}\right)^2$$ $$G\mu_o = 2 \times 10^{-6}$$
- Incoherently add String and Adiabatic Power Spectra:

$$C_l = C_l^{adiabatic} + C_l^{strings}$$
$$P(k)^{linear} = P(k)^{adiabatic} + P(k)^{strings}$$

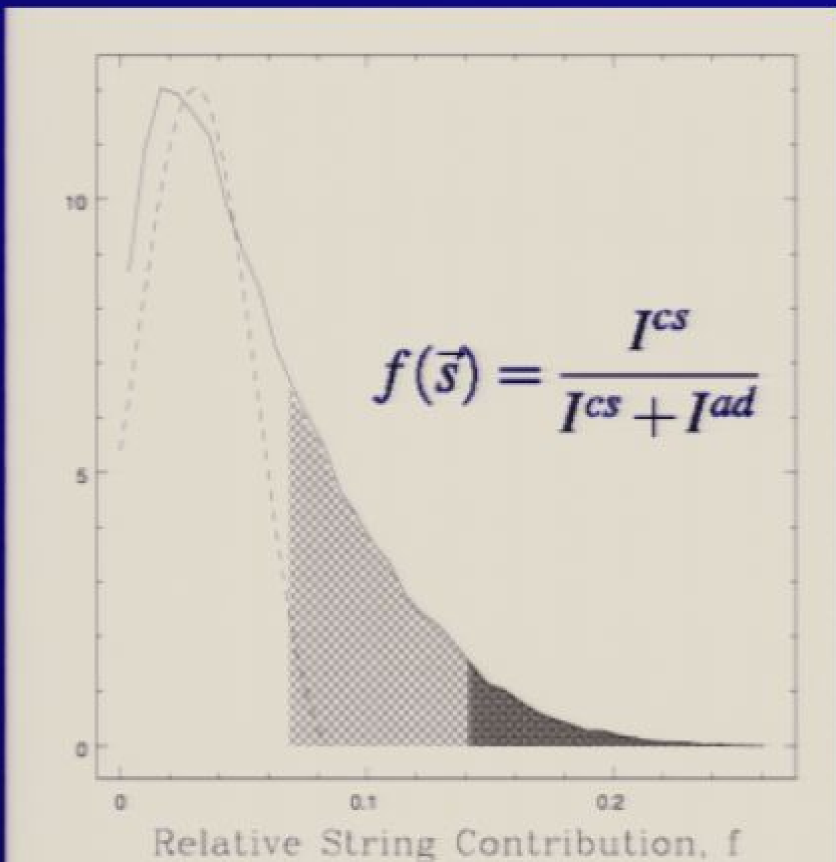
- Vary 7 Parameters using Markov Chain Monte Carlo (+ overall P(k) normalization and "string wiggliness", α)
  - Use SDSS and WMAP Likelihood Functions to construct a multi-dimensional posterior distribution function (pdf)

SDSS: Tegmark et al, PR D69 (2004) 103501 (astro-ph/0310723)
WMAP: Verde et al, ApJ Supp. 148 (2003) 135 (astro-ph/0302217

WMAP and SDSS Bounds: Summary of our Work



WMAP and SDSS Bounds: String power less than 14%



- CS fractional power $f < 0.14$ (95% c.l.)
- also: "test" of adiabatic model

$$I^{cs} = \sum_l \frac{(2l+1)}{4\pi} C_l^{cs}(\vec{s}) \qquad I^{ad} = \sum_l \frac{(2l+1)}{4\pi} C_l^{ad}(\vec{s})$$

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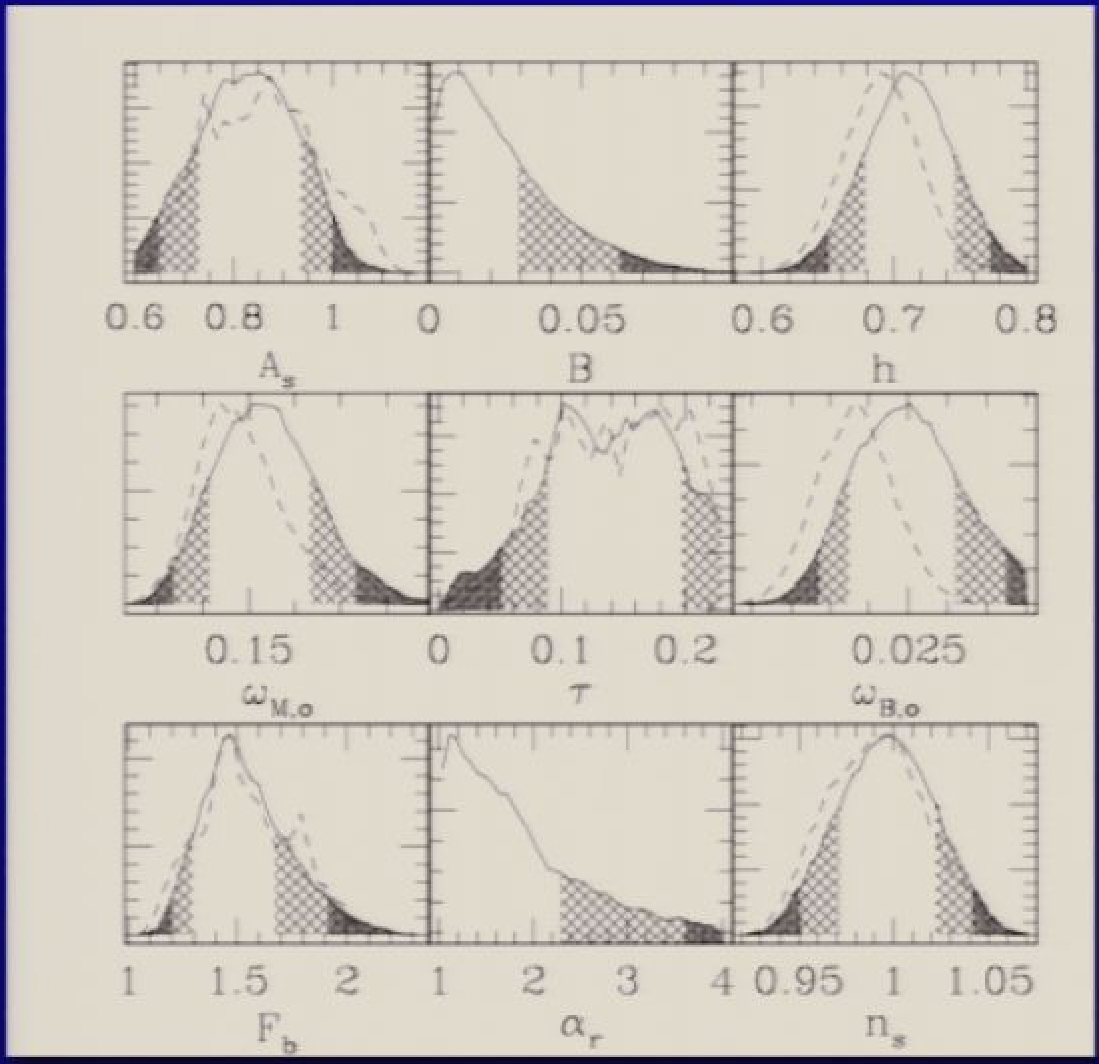

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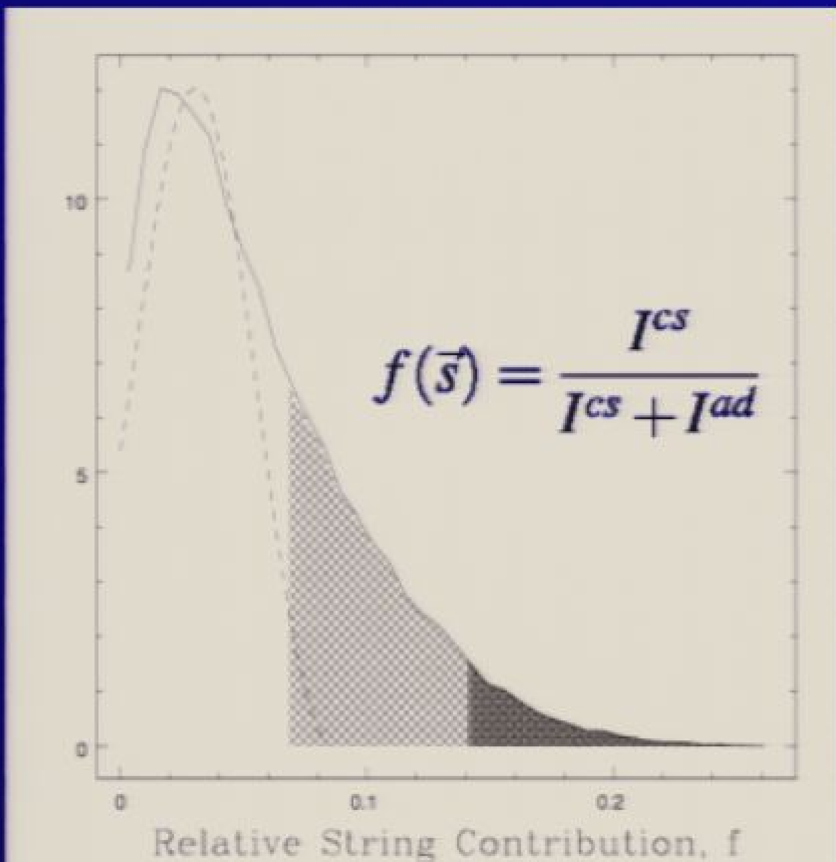

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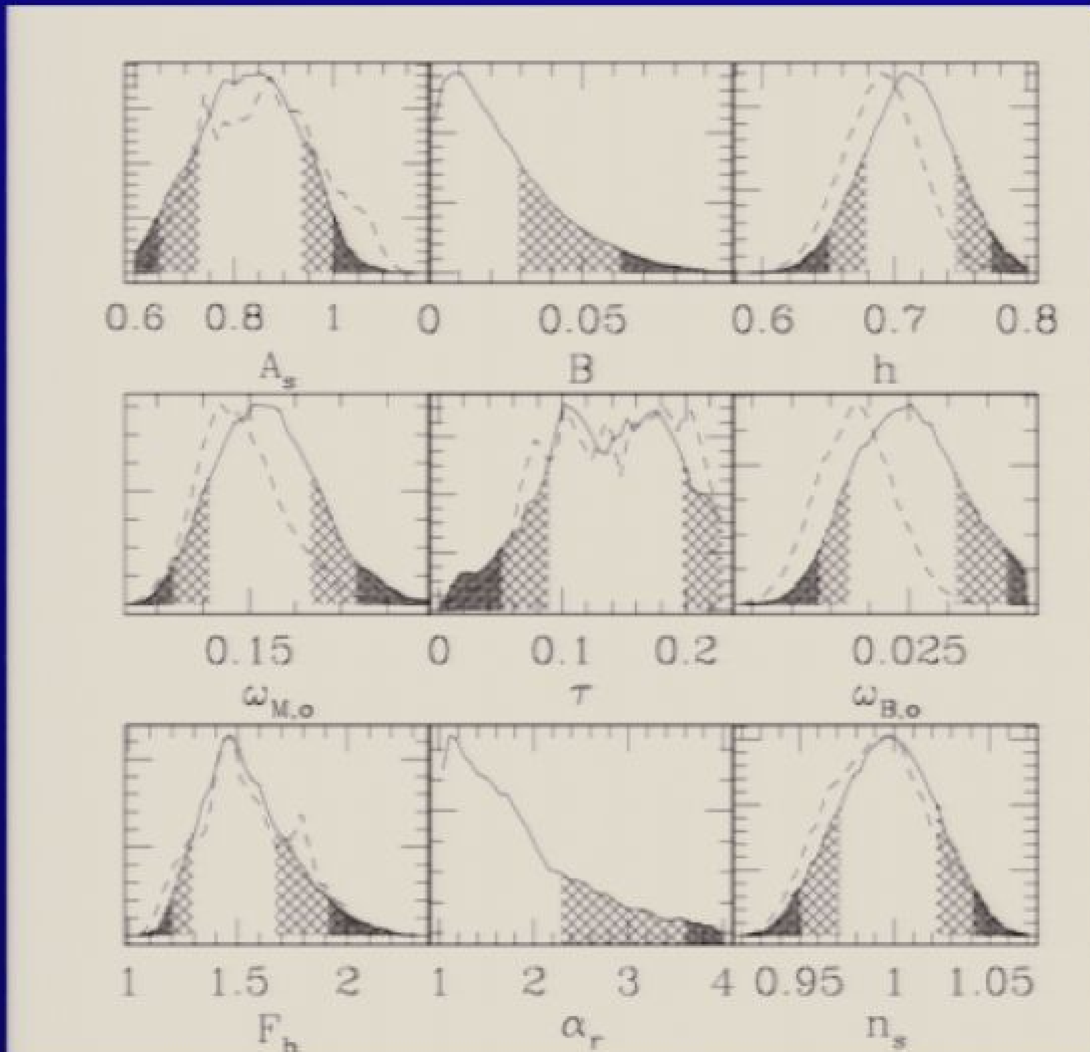

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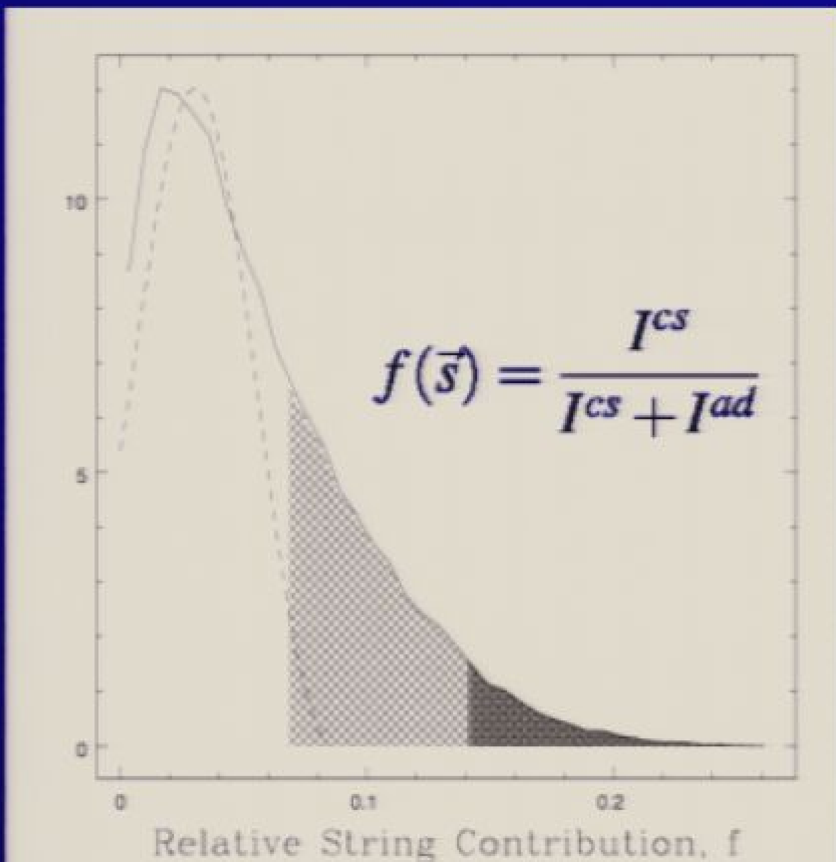

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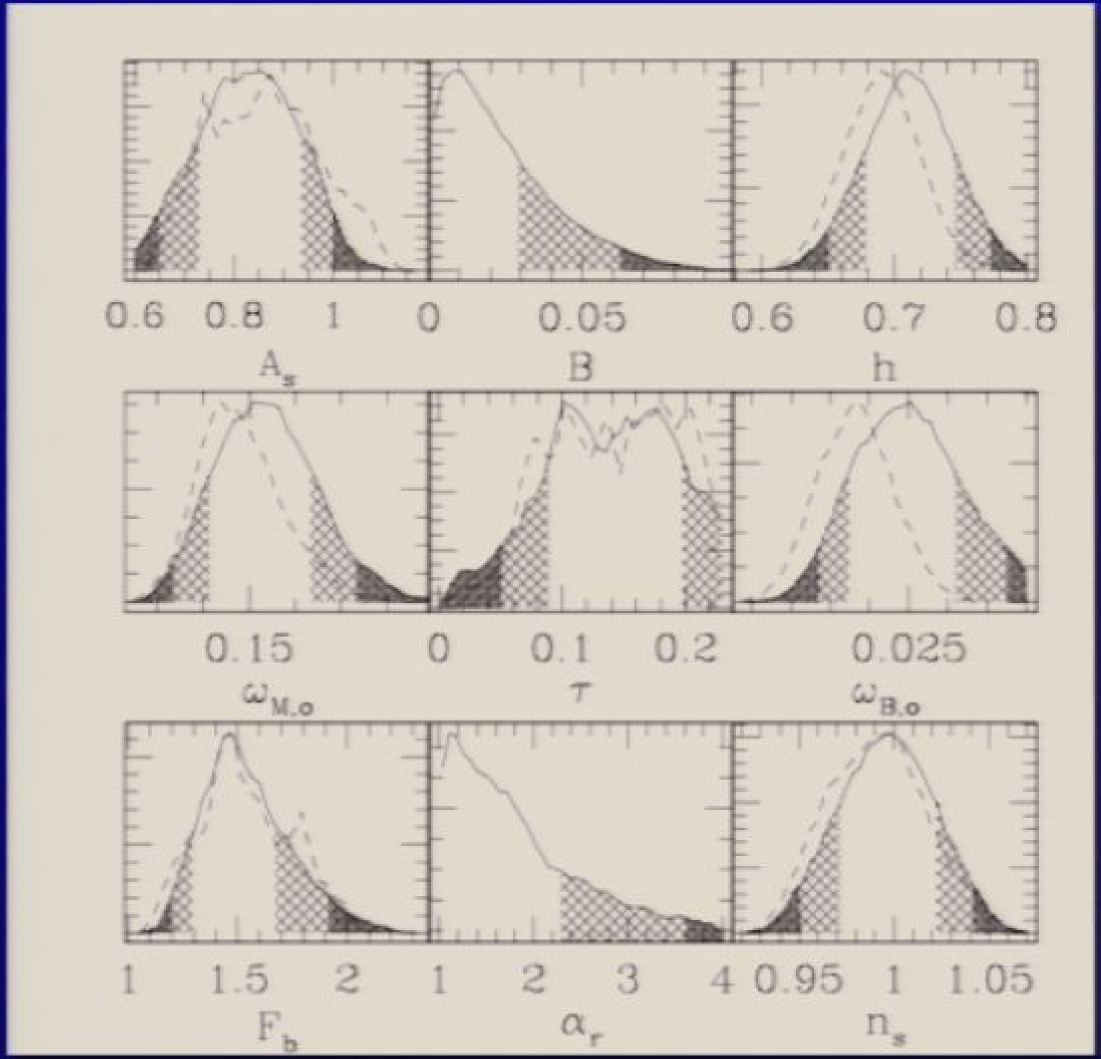

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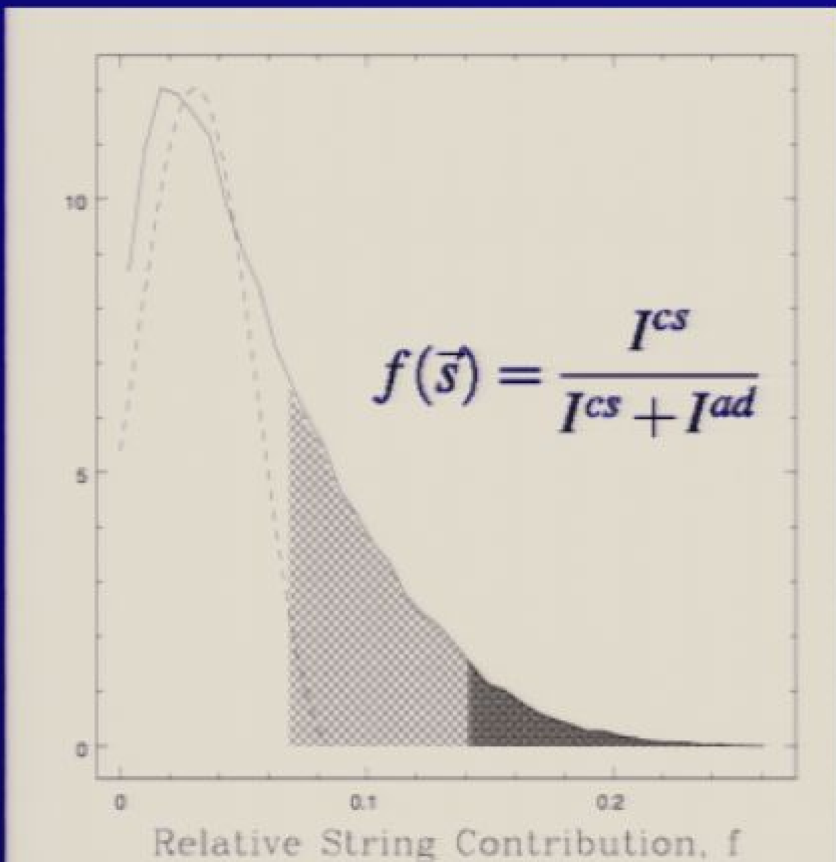

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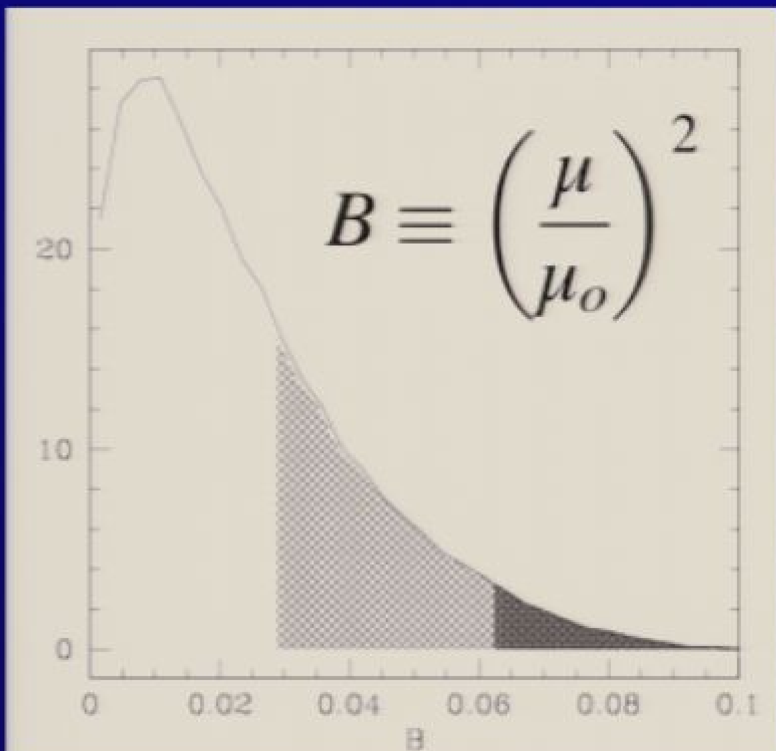
WMAP and SDSS Bounds: Direct limits on string tension



- Fix parameters at WMAP values
- *Define*

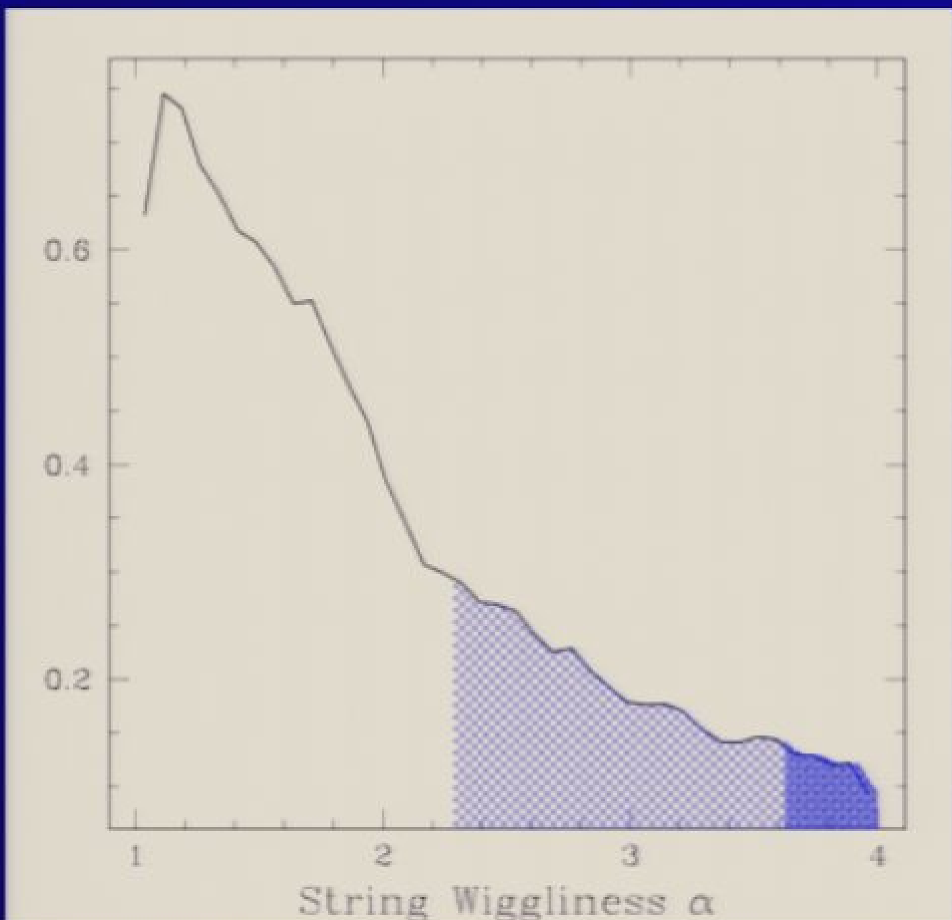
$$B \equiv \left(\frac{\mu}{\mu_0}\right)^2$$

$$I^{CS}(\mu_o, \vec{s}_{WMAP}) \equiv I^{AD}(\vec{s}_{WMAP})$$

$$\rightarrow G\mu_o = 2 \times 10^{-6}$$

$$G\mu < 3.4(5.0) \times 10^{-7}$$

String Wiggliness



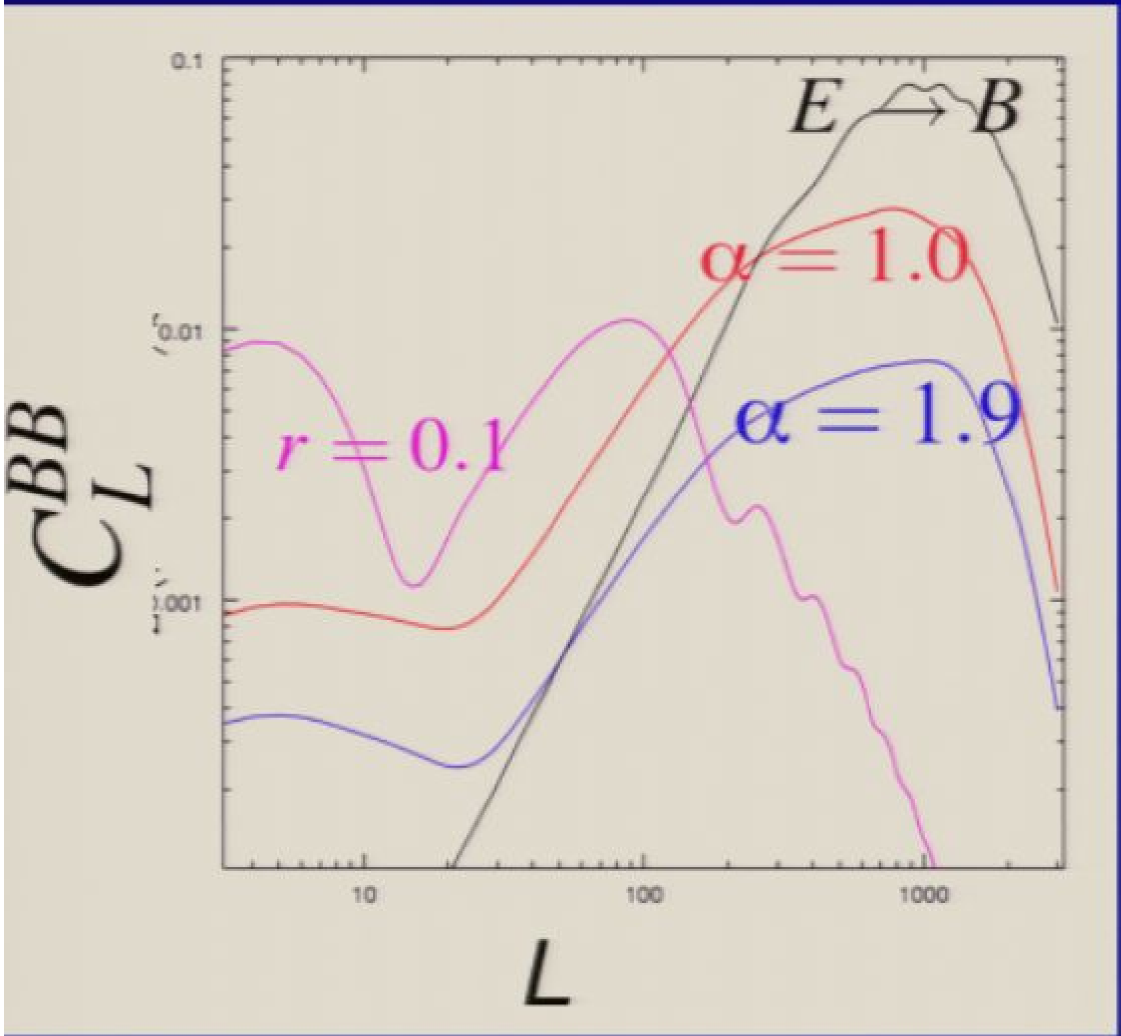
- String gravity:

$$ds^2 = (1 + 2\phi) ds_f^2 + (1 - 2\phi) dz^2$$
$$ds_f^2 = -dt^2 + dr^2 + (1 - 8G\tilde{\mu}) d\theta^2$$
$$\phi = 2G(\tilde{\mu} - \tilde{T}) \ln(r/r_o)$$
$$\tilde{\mu}\tilde{T} = \mu^2 \qquad \tilde{\mu} \equiv \alpha\mu$$

- *Weak Upper Bound*

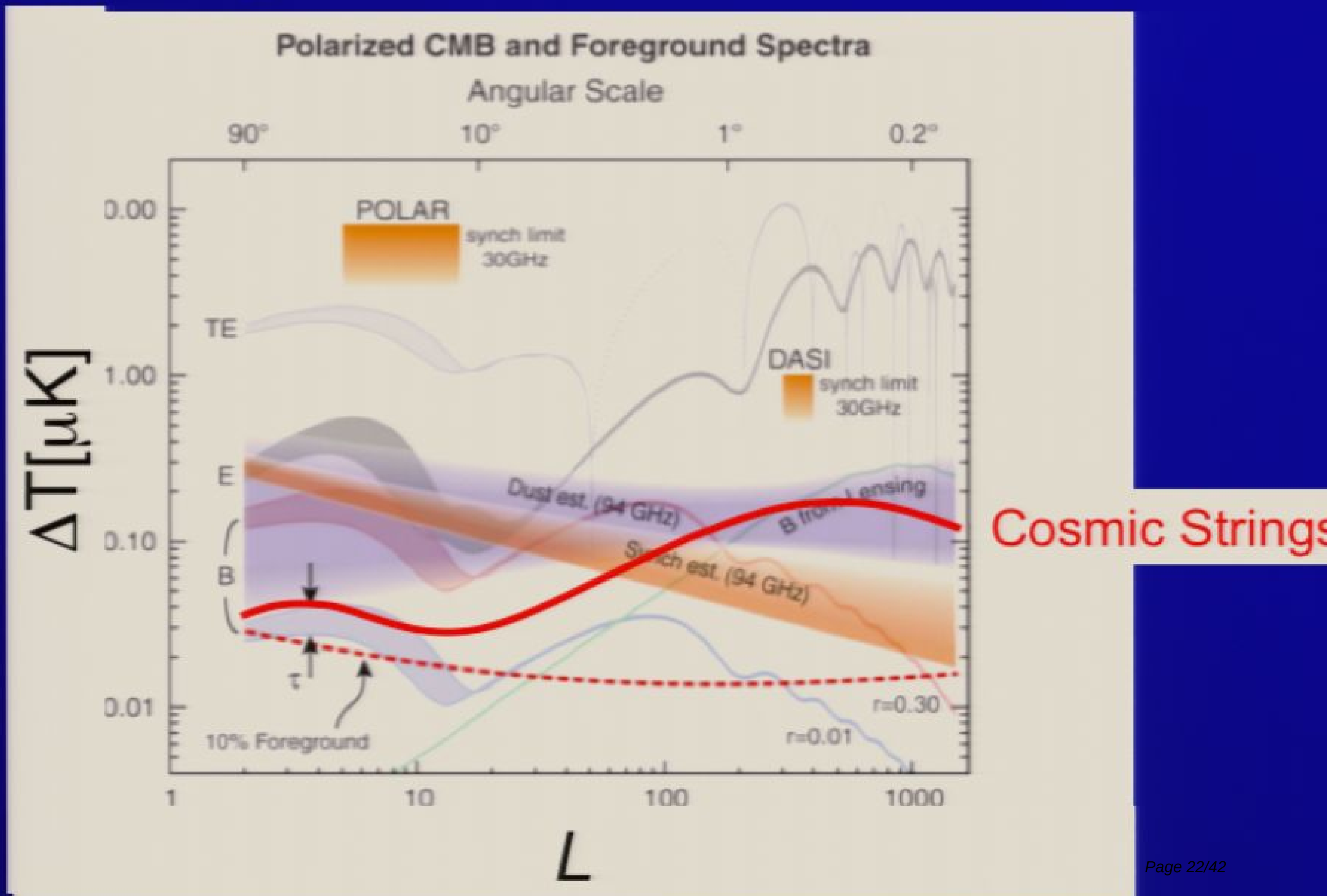
α string wiggliness

B-Mode Polarization in the CMB



- Odd parity
- Adiabatic: Tensor mode fraction, r = 0.1 in graph
- Strings: f = 0.1 in graph; 2 different alpha values

String B-Mode in Context



Outline

- Background and current observational limits on cosmic strings

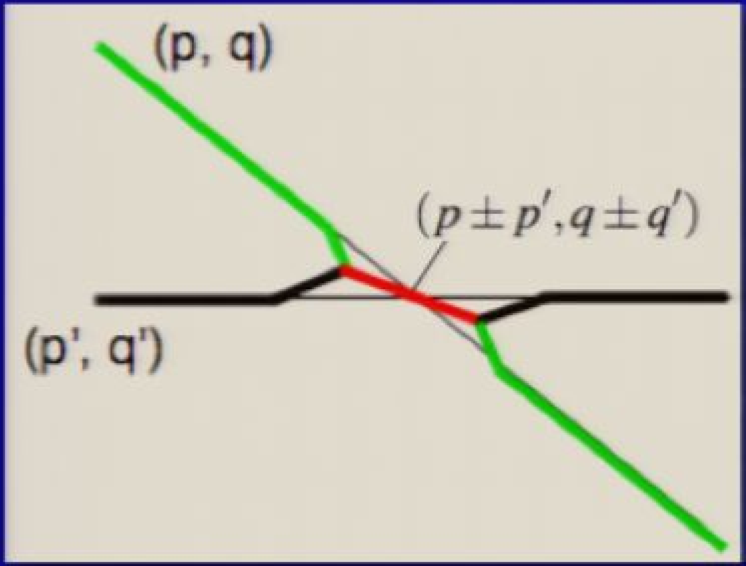
- **Cosmic Superstring network modeling and observational signatures**

Cosmic Superstrings: How Are They Different?

- Multi-μ networks: F, D, (p,q) bound states
- p F-strings + q D-strings = (p,q) string

$$G\mu_F \sim 10^{-12} - 10^{-6} \quad \mu_D = g_s\mu_F$$

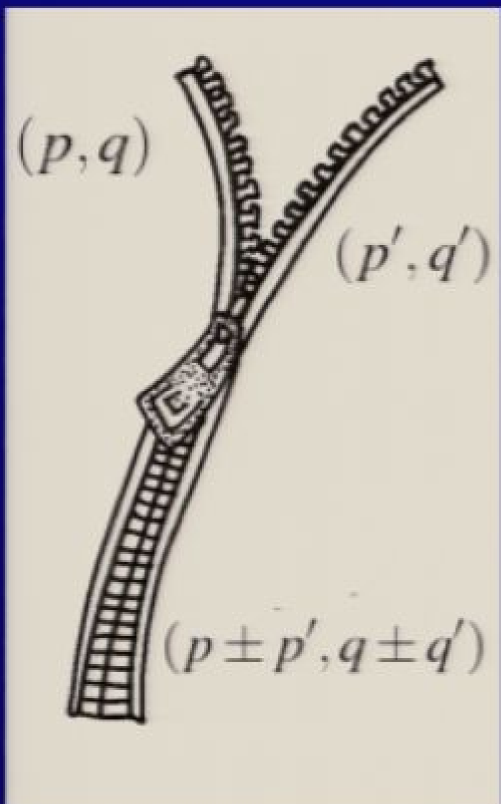
$$\mu_{(p,q)} = \mu_F\sqrt{(p - Cq)^2 + q^2/g_s^2}$$



(Copeland, Myers, and Polchinski, 2004)

- Scaling? Tension Distribution??

New Interaction Physics



$$\frac{dN_\alpha}{d\eta} = FL \sum_{\beta\gamma} \left[\frac{1}{2} P_{\beta+\gamma\to\alpha} N_\beta N_\gamma - P_{\alpha+\gamma\to\beta} N_\alpha N_\gamma \right]$$

(Note: hide dynamics / cosmology
in conformal time, η)

$$N_\alpha \eta^2 \to \text{Constant?}$$

Interaction Rules:

- p and q must be coprime to be stable
- (k,0) and (0,k) strings decay instantly
  Become k (1,0) or (0,1) strings
- All interactions **lose energy**

N+1 Length Scales, One Velocity

- Multiple tensions: $\mu_{(p,q)} = \mu_F \sqrt{p^2 + q^2/g_s^2}$
- L, v evolution similar to Martins / Shellard VOS Model

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

- Densities $n_{(p,q)}$ evolve via …
  - Dilution (2H) and straightening $(-c_2 v/L)$
  - Self-interaction $(-P n_{(p,q)}^2 v L)$
  - Reactions and breakup as in previous slide

  - P: self-interaction parameter;
    F: inter-string-interaction parameter (massive simplification of collision physics)

Possible Catastrophes

- Low P + reactions: leads to frustration (over-density, string domination)
- Low F: many tensions go to scaling …

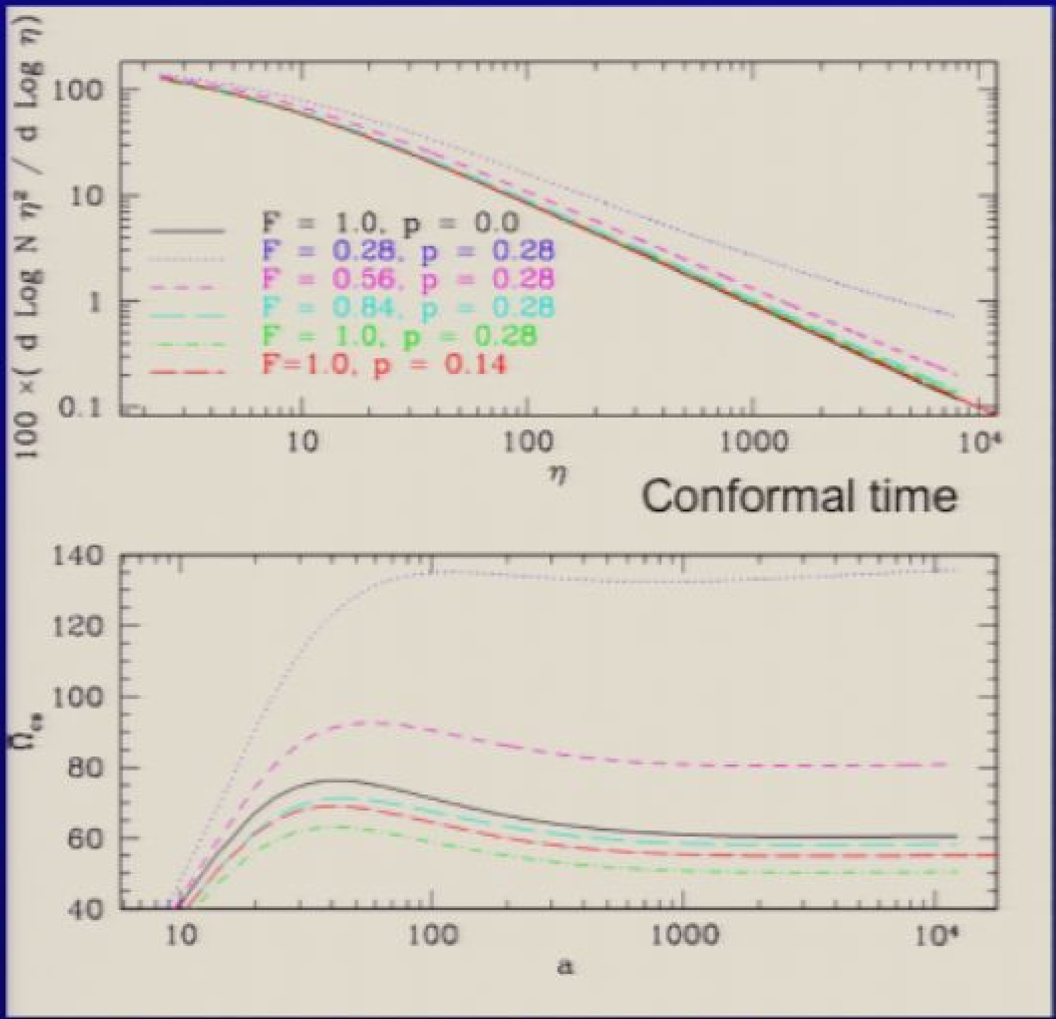
A Multi-Tension UV Catastrophe:

$$\left(\frac{\Omega_a^{strings}}{\mu_a}\right) \rightarrow \text{constant independent of } \mu_a!$$

Networks Go To Scaling

convergence test

$$\frac{3\Omega_{cs}}{8\pi G\mu_{(0,1)}}$$



Cosmological scale factor, a

Networks Go To Scaling

convergence test

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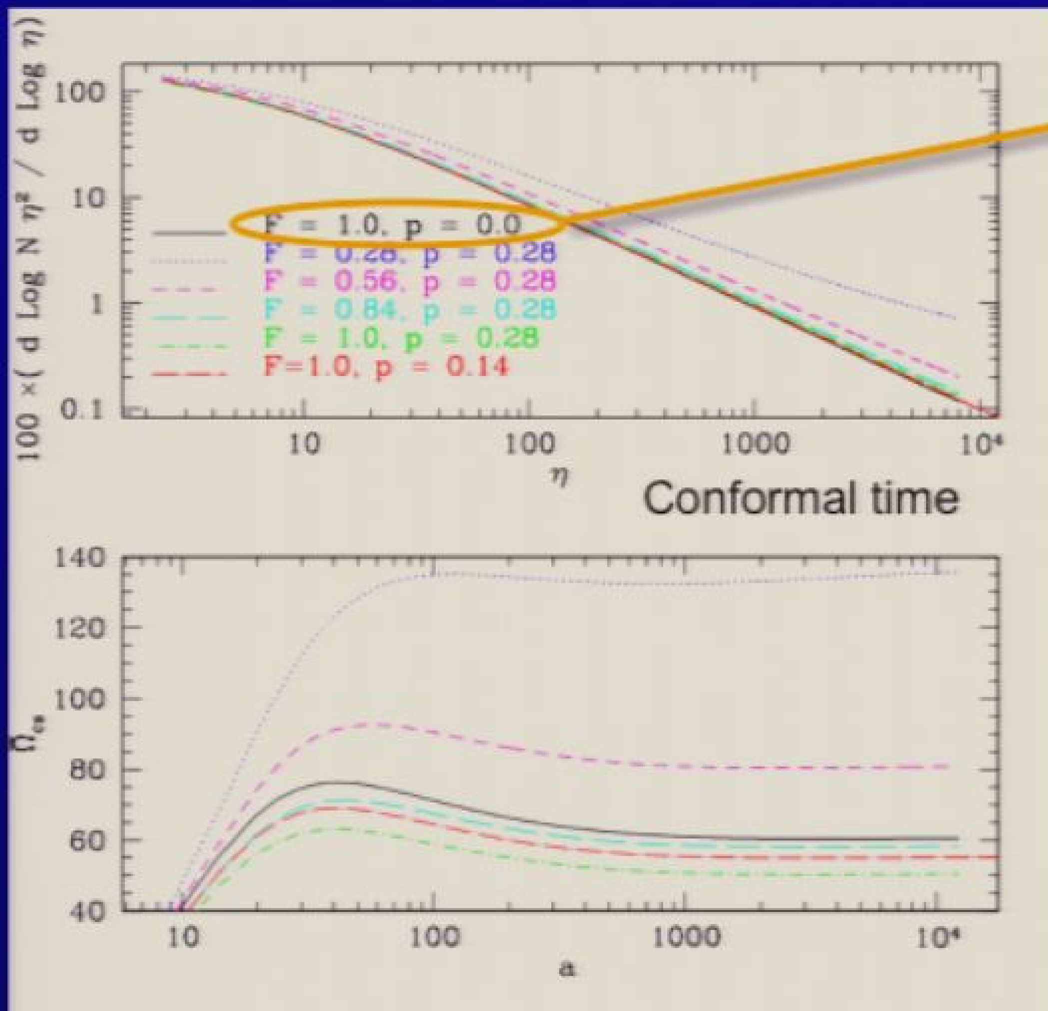
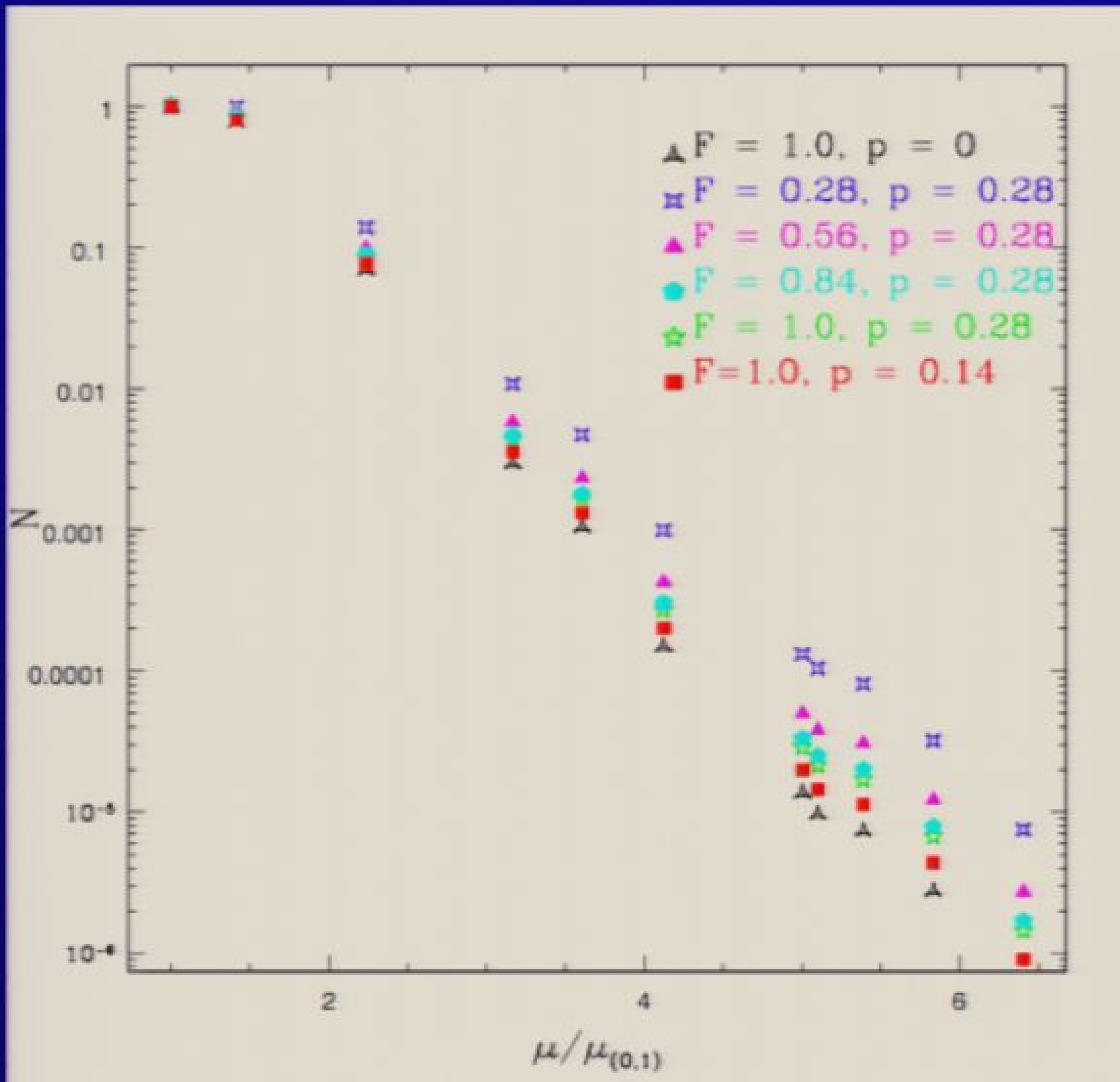


Scaling without Loop Formation!

Cosmological scale factor, a

Few Tensions are Populated

N(μ)



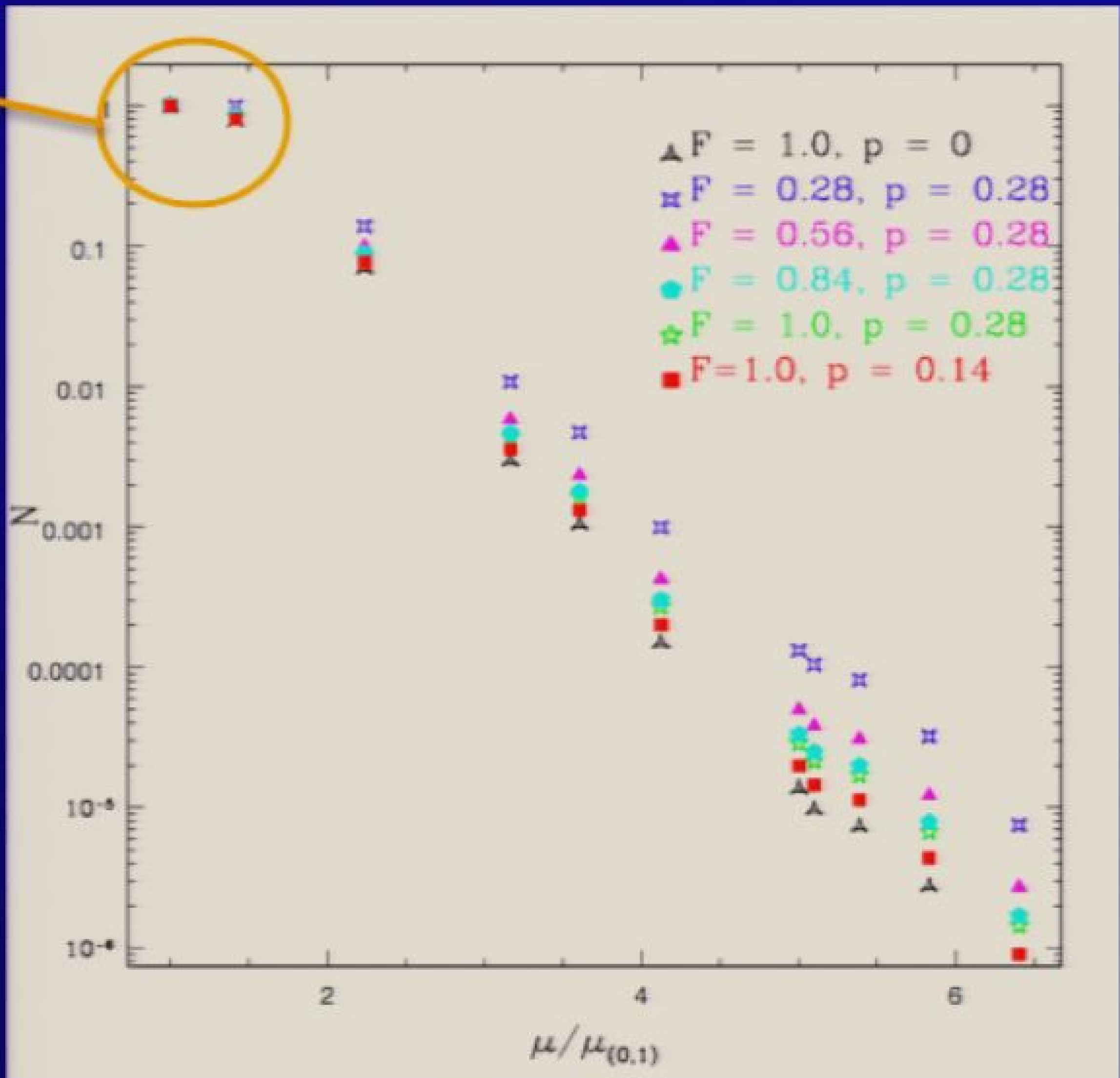
$(g_s=1.0)$

Tension

Few Tensions are Populated

(0,1) (1,0) (1,1)

N(μ)



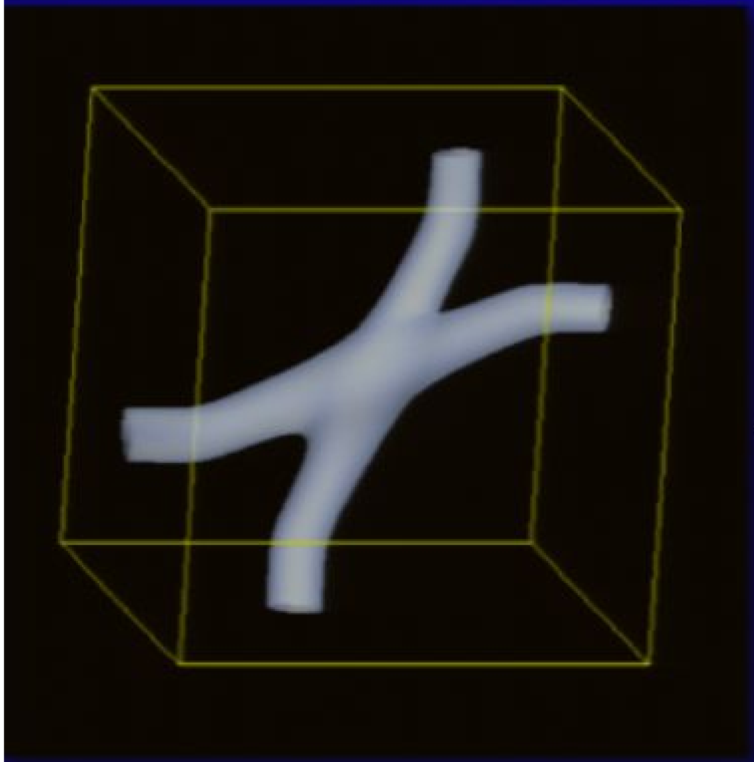
(g_s=1.0)

Tension

Current Work:

Interaction Dynamics

Modeling binding with a U(1)xU(1) gauge theory

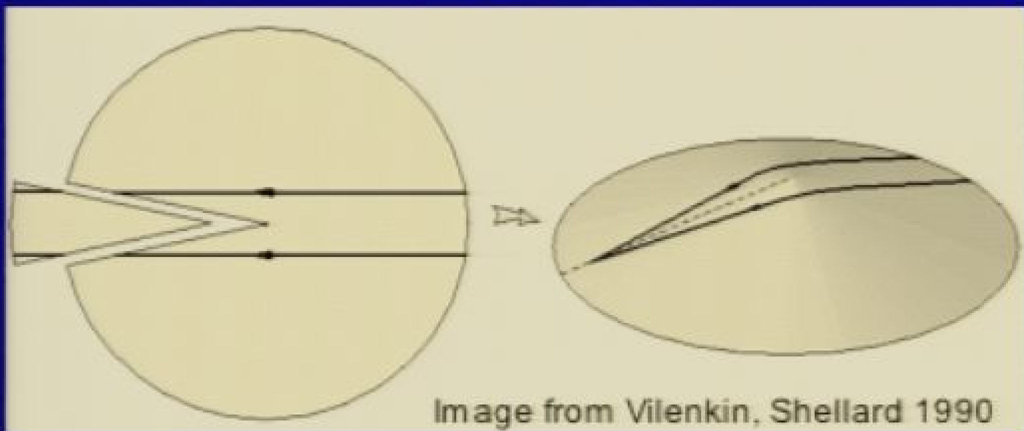


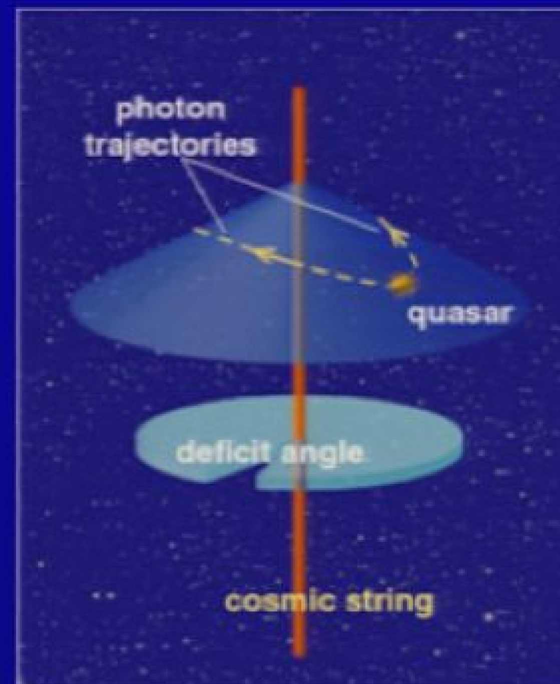
To test our analytic model's quick zip approximation

$$V(|\phi|,|\psi|)=\frac{\lambda_1}{4}(\bar{\phi}\phi-\eta^2)^2+\frac{\lambda_2}{4}(\bar{\psi}\psi-\nu^2)^2 -\kappa(\bar{\phi}\phi-\eta^2)(\bar{\psi}\psi-\nu^2)$$

(Model suggested by Carroll and Trodden (1997), Saffin (2005); code adapted from Moriarty et al, 1989)

String Gravitational Lensing





Conical spacetime:

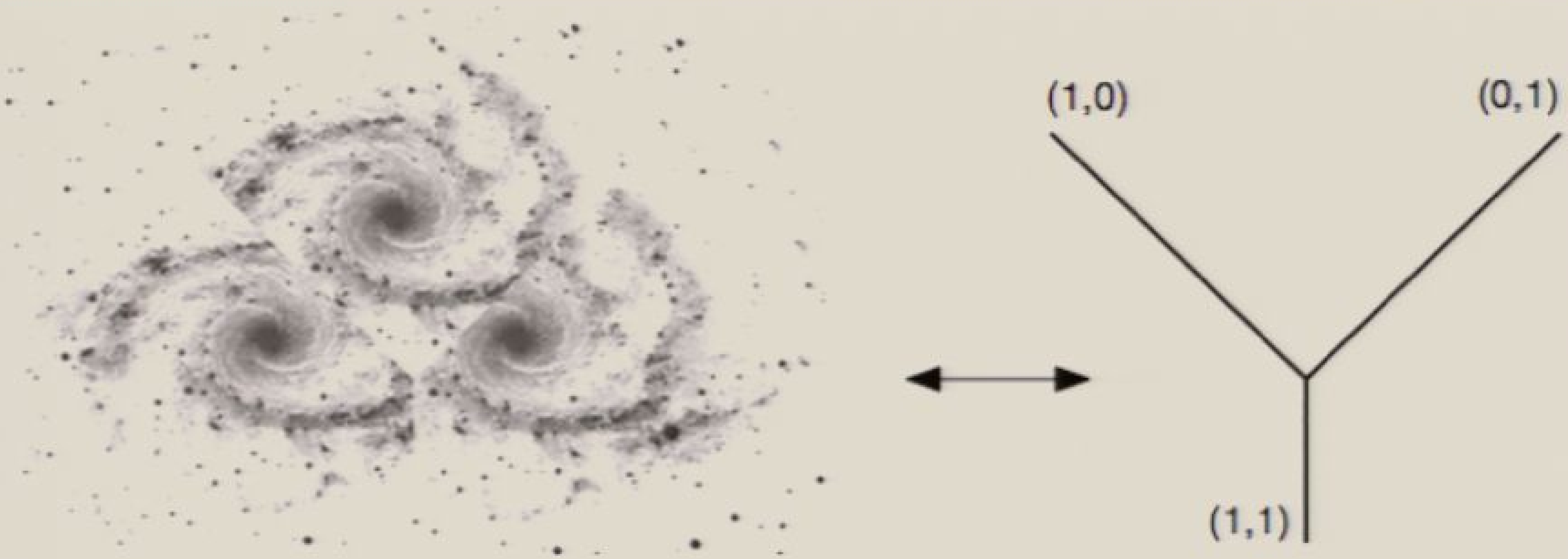
deficit angle ~ $8\pi G\mu$

$$\delta\phi = 1.0'' \leftrightarrow G\mu = 4 \times 10^{-7}$$ (~ State of the art)

Full formula (Shlaer and MW, 2005):

$$|\vec{\delta\varphi}| = 8\pi G\mu\sqrt{\gamma^2(1+\hat{n}\cdot v)^2 - \cos^2\theta}\,\frac{D_{s,cs}}{D_{\dots}}$$

Lensing at a Binding Vertex



Simulated image

Distinctive, but probably *very* rare

with B. Shlaer, PRD 72 (2005) 123504, hep-th/0509177

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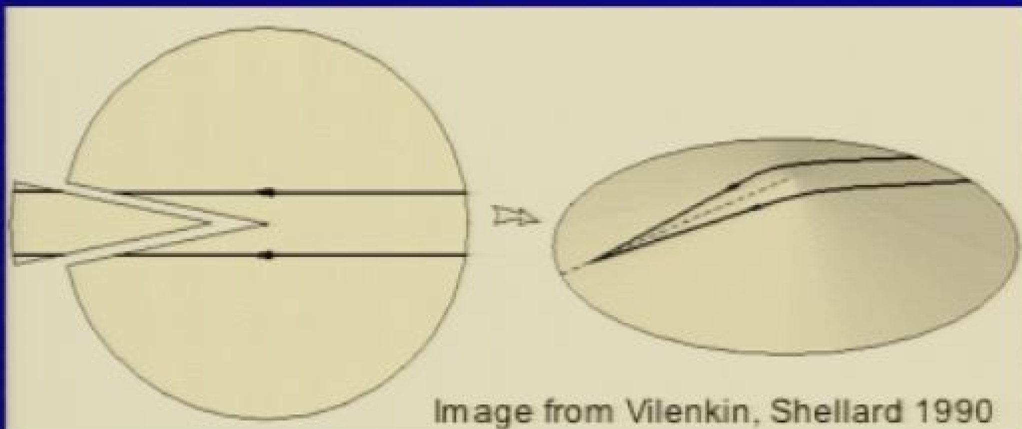
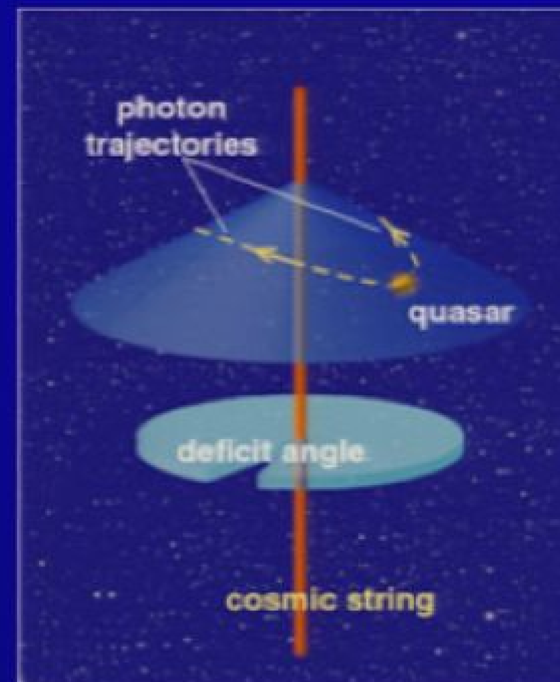


Image from Vilenkin, Shellard 1990



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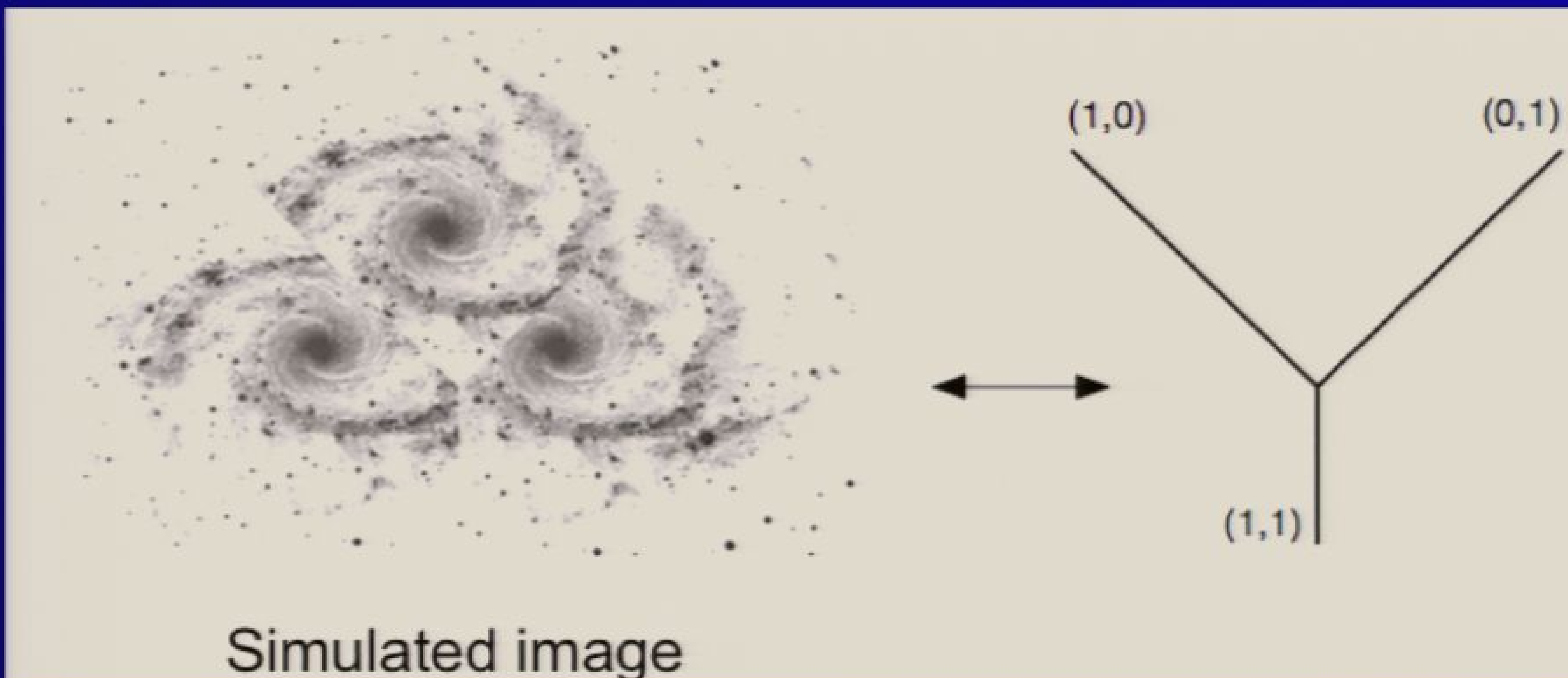

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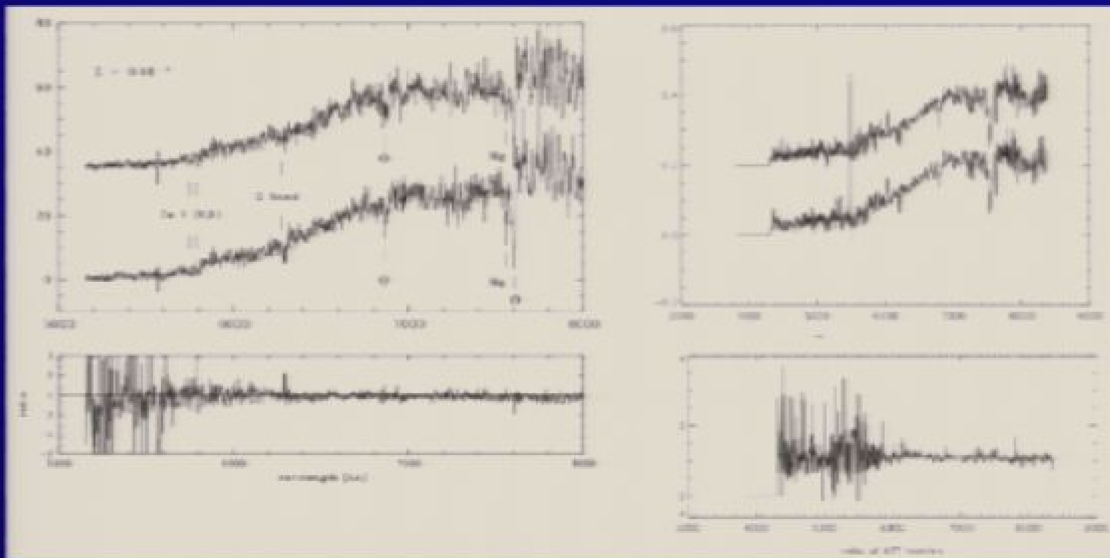
A cautionary tale:

CSL-1: A Detection?

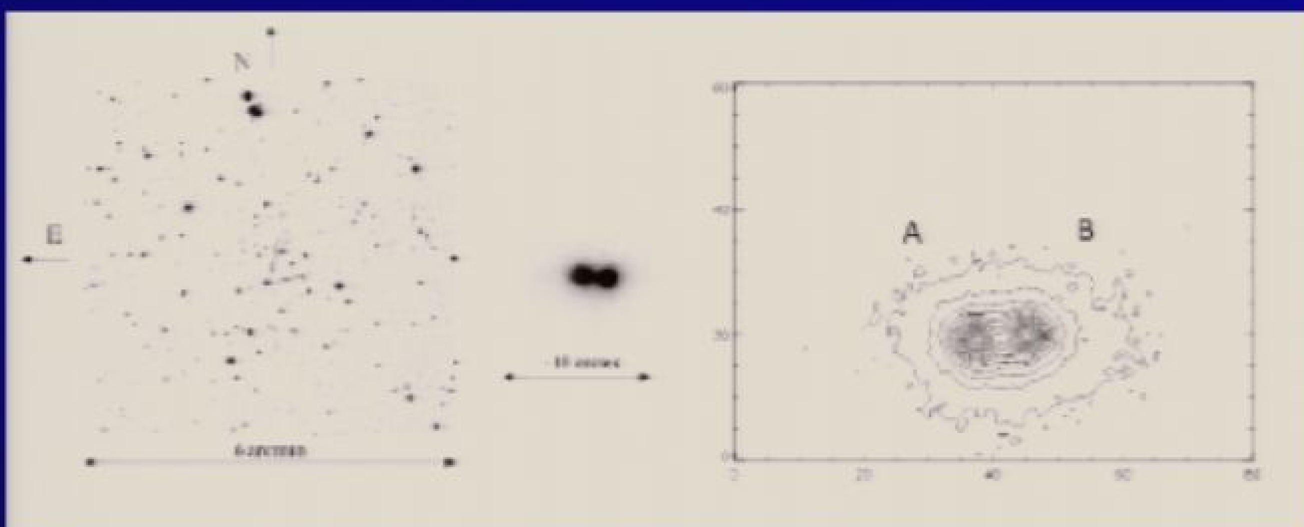
(Sazhin et al, 2002)



z = 0.46

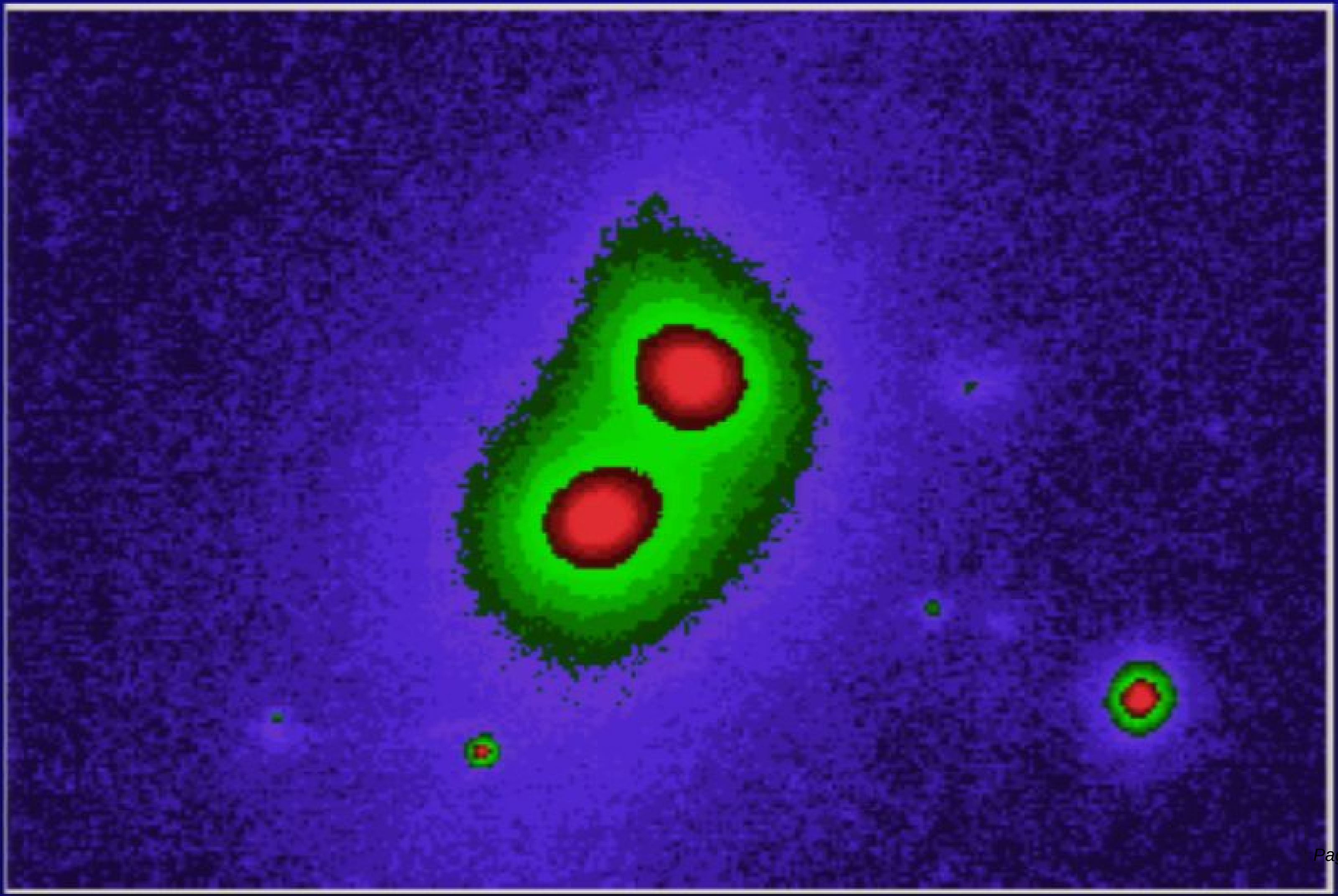
Separation ~ 20 Kpc
~ 1.9 "

--> $G\mu$ ~ few x 10^{-7}



Hot from the satellite (Jan. 12 2006) …

What the HST Saw



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  Tension limit: $G\mu < (\text{few}) \times 10^{-7}$
  - Possible source for B-mode polarization in CMB
- (p,q) network interpretation:
  - Few string tensions populated; successful scaling
  - Distinctive signatures
- Direct observational windows: lensing, gravity waves

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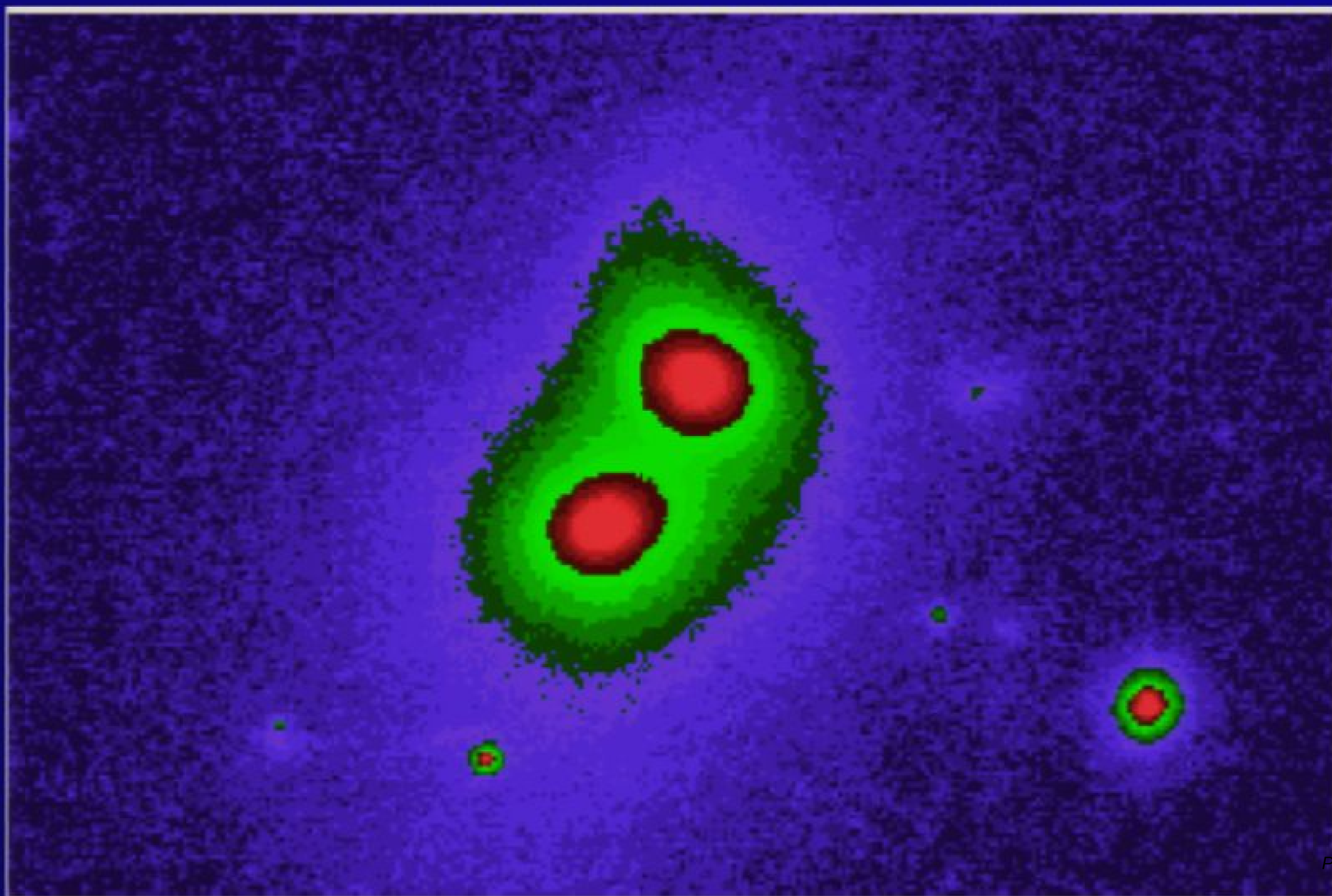

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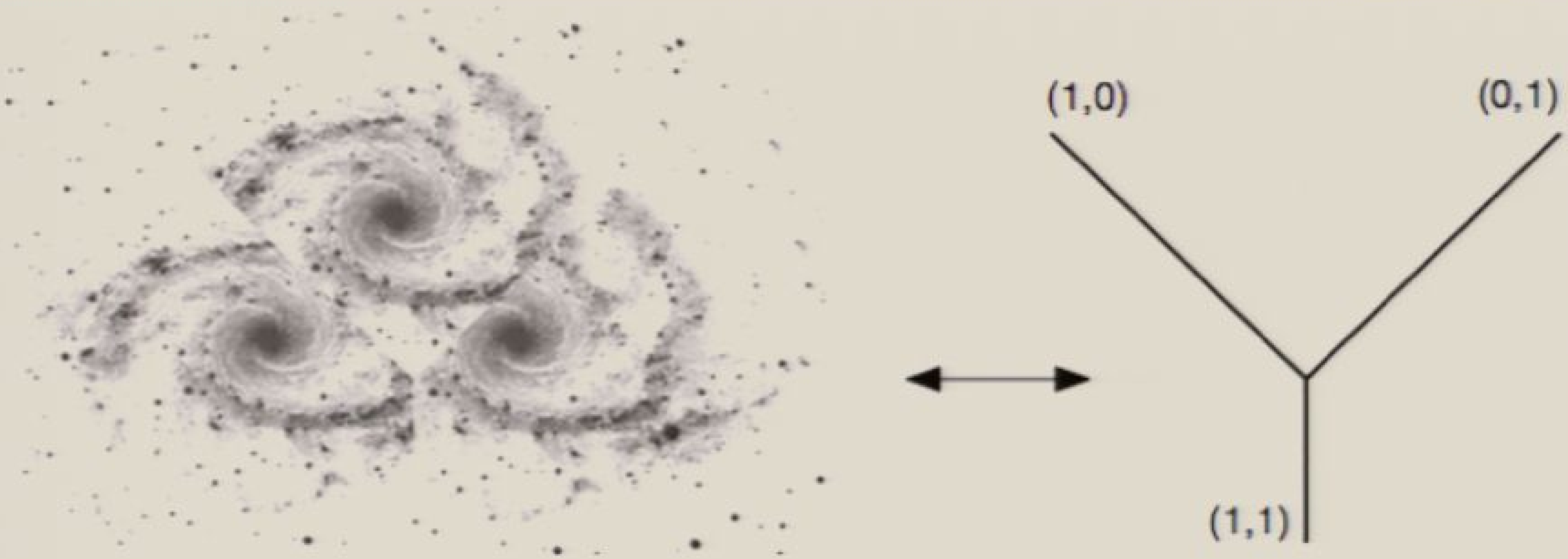

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