Is the Universe held together with cosmic string?

Mark Hindmarsh

Dept. of Physics & Astronomy
Sussex University

`m.b.hindmarsh@sussex.ac.uk`

Collaborators:

N. Bevis, M. Kunz, J. Urrestilla [astro-ph/0605018,astro-ph/0702223,0704.3800]

+ A. Liddle [0711.1842]

S. Borsanyi [0712.0300], P. Saffin [hep-th/0605014], P. Salmi [0712.0614]

G. Vincent & N.Antunes, [hep-ph/9708427]

G. Vincent & M. Sakellariadou [astro-ph/9612135]

University of Sussex

Cosmic strings observed in background radiation

11:46 21 January 2008
NewScientist.com news service
David Shiga

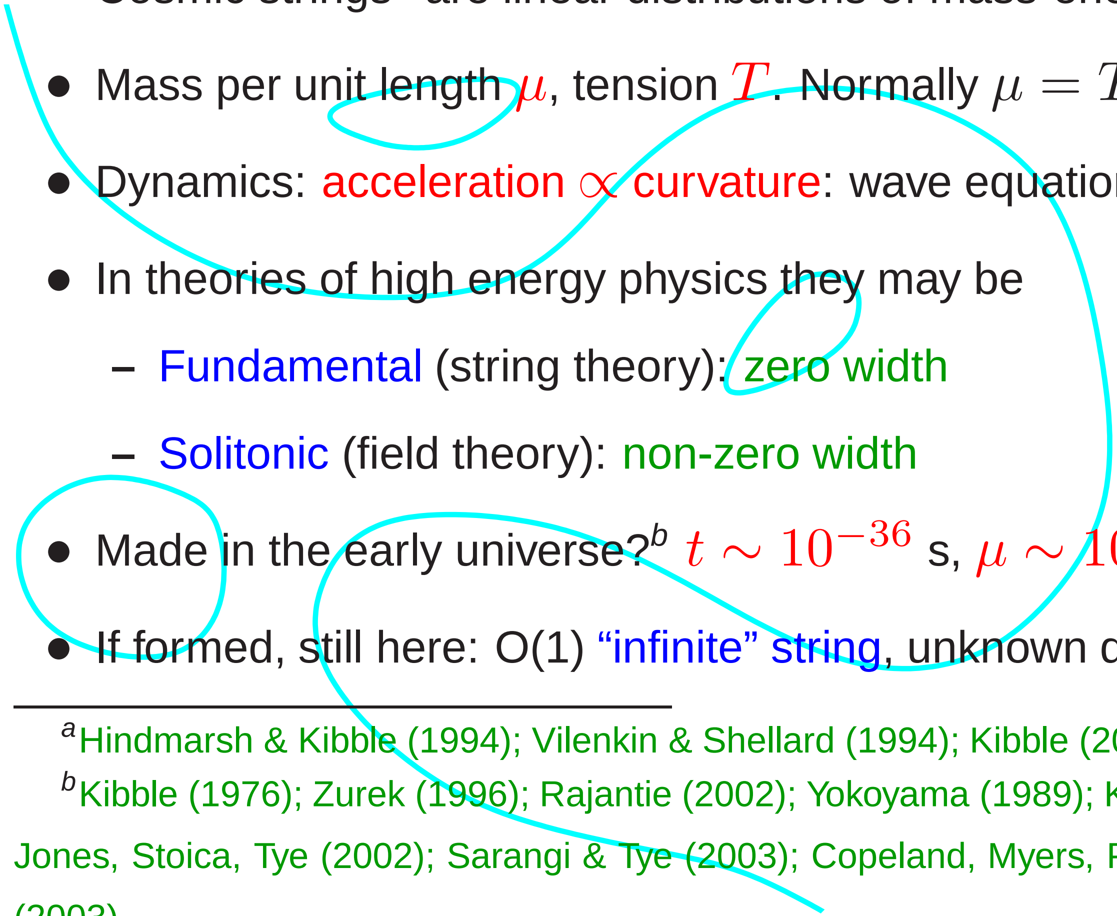
Traces of vast cosmic strings have been found in radiation from the early universe, a controversial new study says. If confirmed to exist, cosmic strings could offer an unprecedented window into the extreme physics of the infant universe.

Were cosmic strings seen in big bang afterglow?

11:46 21 January 2008
NewScientist.com news service
David Shiga

Traces of vast cosmic strings have been found in radiation from the early universe, a controversial new study says. If confirmed to exist, cosmic strings could offer an unprecedented window into the extreme physics of the infant universe.

Introduction



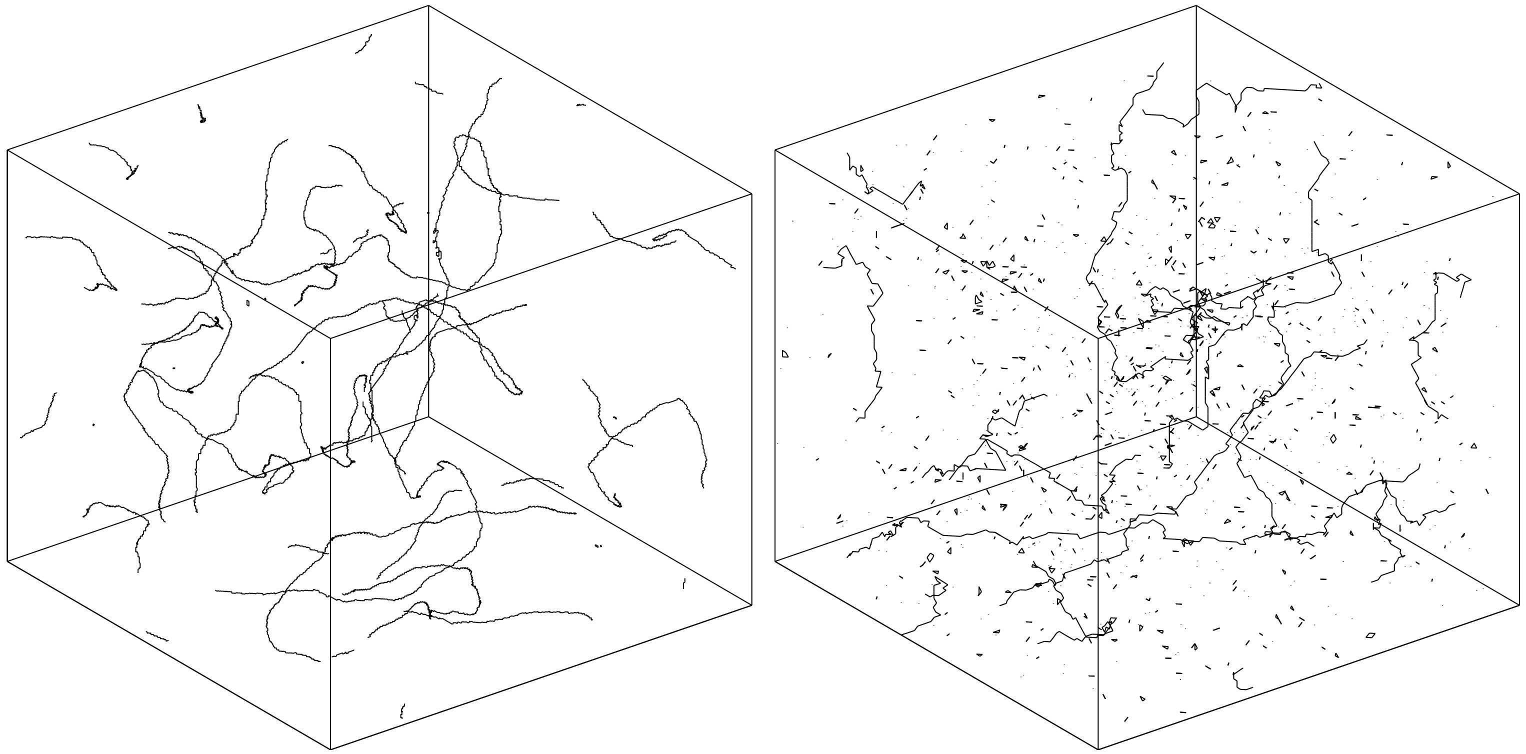
- Cosmic strings[a] are linear distributions of mass-energy in the universe.
- Mass per unit length μ, tension T. Normally $\mu = Tc^2$
- Dynamics: acceleration $\propto$ curvature: wave equation,
- In theories of high energy physics they may be
  - Fundamental (string theory): zero width
  - Solitonic (field theory): non-zero width
- Made in the early universe?[b] $t \sim 10^{-36}$ s, $\mu \sim 10^{20}$ kg/m, $w \sim 10^{-30}$ m
- If formed, still here: O(1) “infinite” string, unknown distribution of closed loops

---

[a] Hindmarsh & Kibble (1994); Vilenkin & Shellard (1994); Kibble (2004)

[b] Kibble (1976); Zurek (1996); Rajantie (2002); Yokoyama (1989); Kofman, Linde, Starobinski (1996); Jones, Stoica, Tye (2002); Sarangi & Tye (2003); Copeland, Myers, Polchinski (2003); Dvali & Vilenkin (2003)

Two models of a universe filled with string



Small-scale string dynamics not understood: Significant uncertainty in predictions

Observational signals from strings

Small theoretical disagreement (factor 10)

- Cosmic Microwave Background, density perturbations [a]

Large theoretical disagreement (factor 10^{lots})

- Gravitational radiation[b]
- Cosmic rays[c]
- Gravitational lensing[d]

---

[a] Zel'dovich (1980); Vilenkin (1981); Kaiser & Stebbins (1984); Landriau & Shellard (2004); Wyman et al (2005); Bevis et al (2006,2007)

[b] Vachaspati & Vilenkin (1985); Hindmarsh (1990); Damour & Vilenkin (2000,2001,2005)

[c] Bhattarcharjee (1990); Sigl (1996); Protheroe (1996); Berezhinksi (1997); Vincent, M.H., Sakellariadou (1998); Wichowski, MacGibbon, Brandenberger (1998)

[d] Vilenkin (1984); Hindmarsh (1989); de Laix & Vachaspati (1996,1997)

Danger! Natural Units

$$\hbar = c = k_B = 1$$

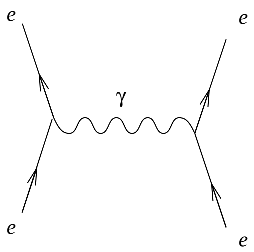
[Mass]	GeV	10^{-27} kg	proton mass
[Length]	GeV^{-1}	10^{-15} m	proton size
[Time]	GeV^{-1}	10^{-24} s	proton light crossing time
[Temperature]	GeV	10^{13} K	proton pair creation temperature

Planck mass:	$M_{\rm P} = 1/\sqrt{G}$	$\sim 10^{19}$ GeV
Reduced Planck mass:	$m_{\rm P} = 1/\sqrt{8\pi G}$	$\sim 2 \times 10^{18}$ GeV
Grand Unification (GUT) scale :	$M_{\rm GUT}$	$\sim 10^{16}$ GeV
Large Hadron Collider (LHC) energy :	$E_{\rm LHC}$	$\sim 10^{4}$ GeV

Quantum Field Theory in a Nutshell

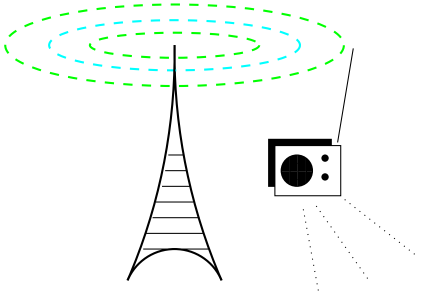
Quantum fields can behave either like particles or classical waves.

E.g. electromagnetic field can behave either as a photon or a radio wave:



Quantum

Low occupation number



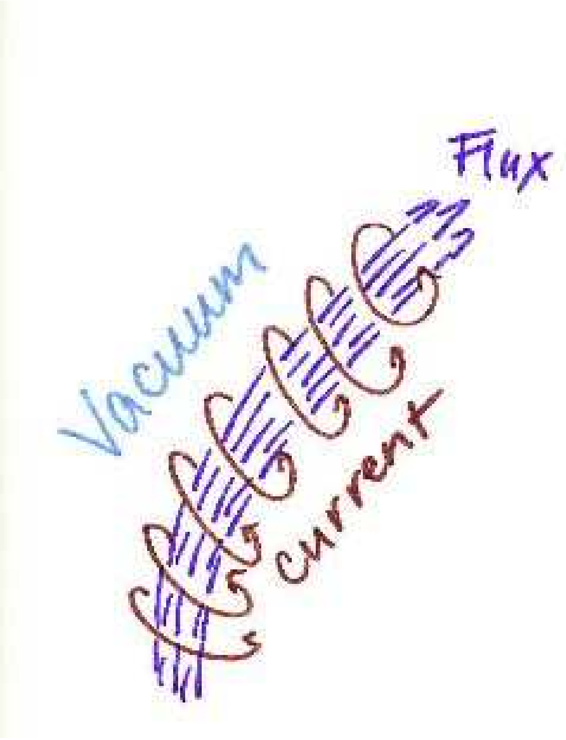
Classical

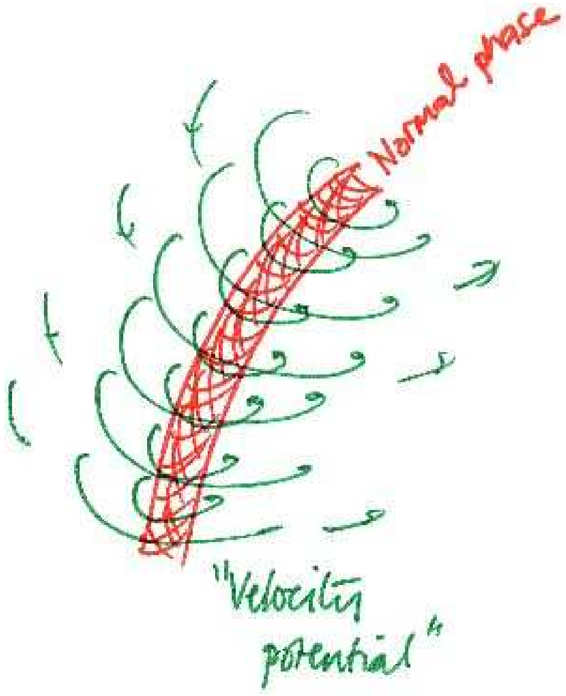
High occupation number

Classical behaviour possible only for bosons (spin 0, 1, 2 ...).

- Spin 0: scalar field ϕ (e.g. Higgs field)
- Spin 1: gauge field A_μ (e.g. electromagnetic field)
- Spin 2: gravitational field $g_{\mu\nu}$

Cosmic string zoo: field theory





Gauge/local string

Nearest living relative:

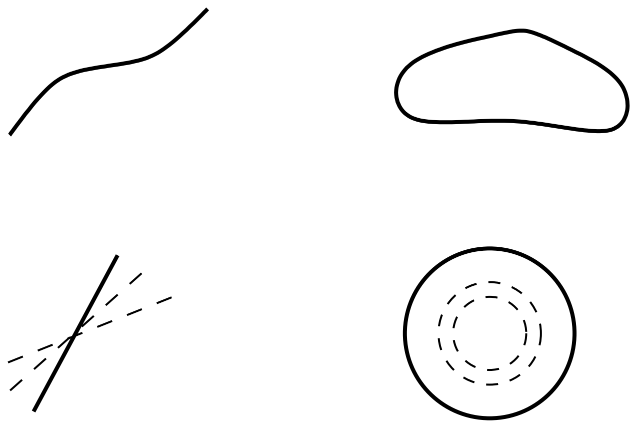
Type II superconductor flux tube

Global string

Nearest living relative:

superfluid vortex

String theory in a nutshell



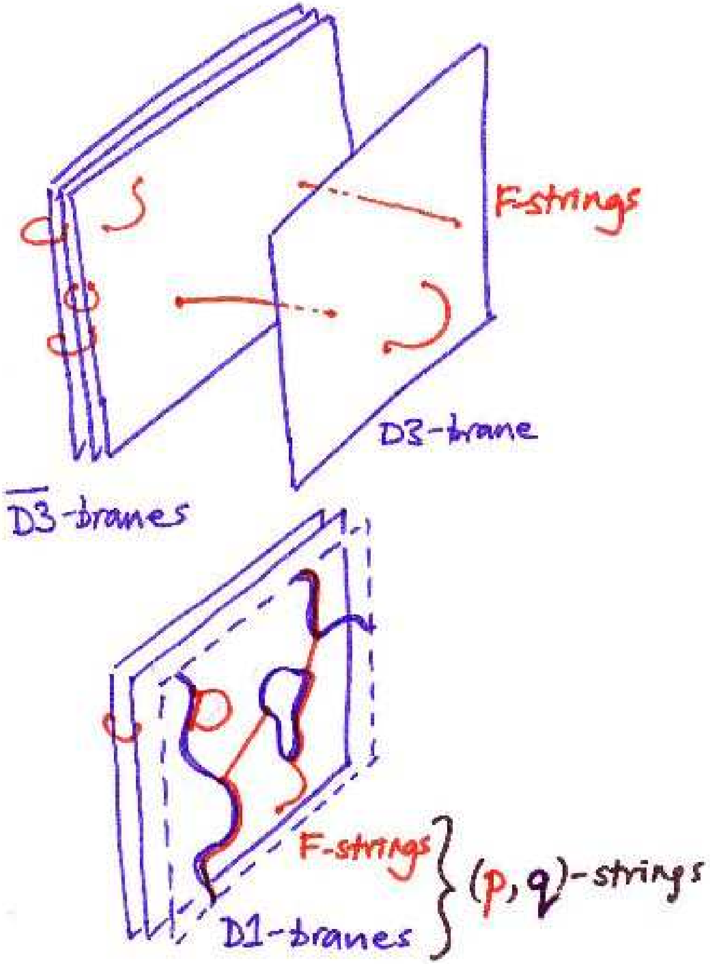
- Fundamental object is a string.
- Strings may be open or closed.
- “Particles” are tiny strings.
- Different particles - different vibration modes.
- Strings may also be macroscopic.
- Superstrings have supersymmetry:

  fermions ↔ bosons.
- Superstrings live in 10 spacetime dimensions.

(Loading ...)

Cosmic string zoo: string theory

- Fundamental strings F-strings
- Extended objects D-branes
- IIA (IIB): 2, 4, 6, 8 (1, 3, 5, 7, 9) dimensions
- F-strings end on D-branes, (D1 = D-string)
- Bound states, junctions: (p, q)-strings & more[a]
- Formation: D3-$\overline{\text{D3}}$, tachyon field theory[b]
- Evolution: analytic & numerical modelling[c]



---

[a] Copeland, Myers, Polchinski (2004); Firouzjahi, Leblond, Tye (2006); Dasgupta, Firouzjahi, Gwyn (2007); Leblond, Wyman (2007)

[b] Sarangi & Tye (2002); Dvali & Vilenkin (2004); Barnaby, Berndsen, Cline, Stoica (2005)

[c] Tye, Wasserman, Wyman (2005); Copeland & Saffin (2006); Hindmarsh & Saffin (2006)

Formation of strings (Kibble-Zurek) (2+1)D model

Real scalar field $\phi(\mathbf{x},t)$, symmetry $\phi \to -\phi$. Lagrangian density:

$$\mathcal{L} = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}(\nabla\phi)^2 - V(\phi), \qquad V(\phi) = V_0 - \frac{1}{2}\mu^2(T)\phi^2 + \frac{1}{4!}\lambda\phi^4.$$

$T(t)$ is a control parameter

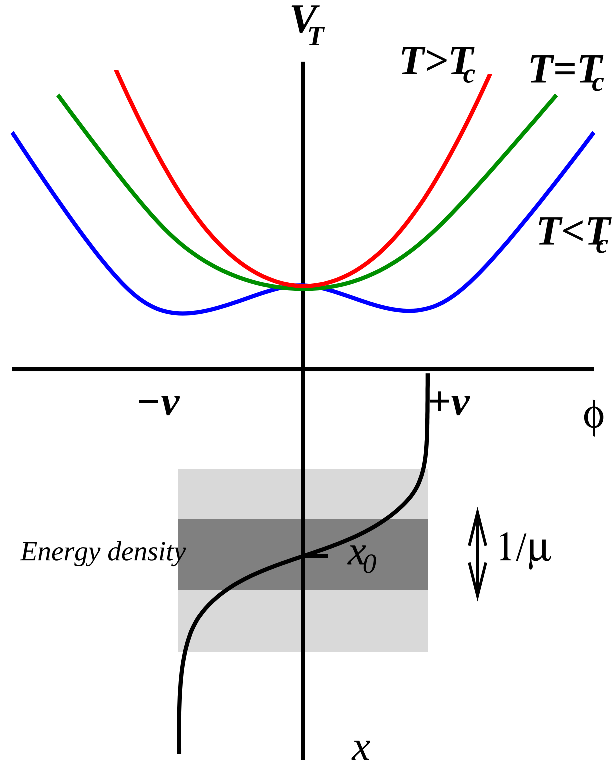
(e.g. temperature, inflaton)

$\mu^2(T > T_c) < 0$, $\mu^2(T < T_c) > 0$

Phase transition at $T = T_c$.

Field eqn. (Minkowski space)

$$\frac{\partial^2\phi}{\partial t^2} - \nabla^2\phi - \mu^2(T)\phi + \frac{1}{3!}\lambda\phi^3 = 0$$



"String" solutions $\phi = v\tanh(\mu x)$

Formation of strings in 2D: numerical simulation

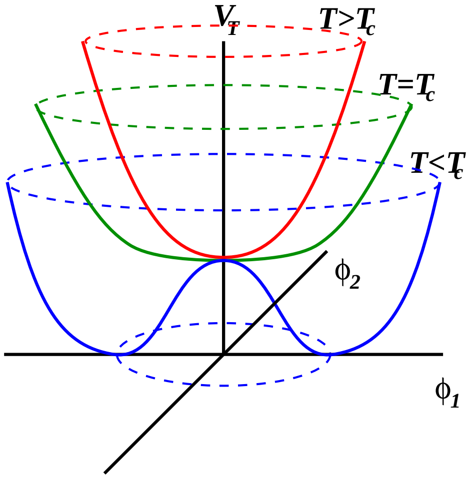
$$\ddot{\phi} + \eta(t)\dot{\phi} - \nabla^2\phi + (\phi^2 - \mu^2(t))\phi = 0$$

Initial conditions: $\phi(\mathbf{x})$ Gaussian random variable on each lattice site

(Loading ...)

Gauge field theories: Abelian Higgs model

$$S = -\int d^4x \left(D_\mu \phi^* D^\mu \phi + V(\phi) + \frac{1}{4e^2} F_{\mu\nu} F^{\mu\nu} \right)$$



Complex scalar field $\phi(\mathbf{x}, t)$, vector field $A_\mu(\mathbf{x}, t)$

Covariant derivative $D_\mu = \partial_\mu + iA_\mu$.

Potential $V(\phi) = \frac{1}{2}\lambda(|\phi|^2 - v^2)^2$.

“Relativistic Ginzburg-Landau”

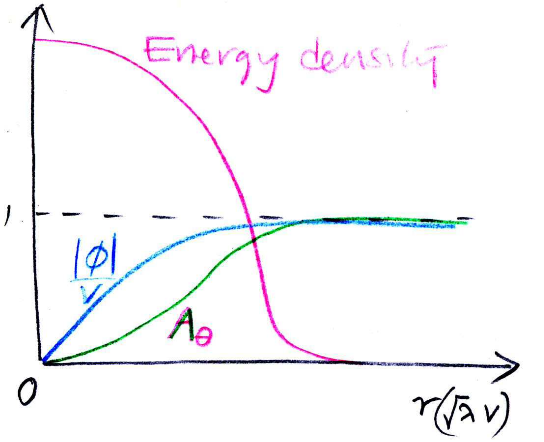
Temporal gauge ($A_0 = 0$) field equations

$$\begin{aligned} \ddot{\phi} - D_i^2 \phi + \lambda(|\phi|^2 - v^2)\phi &= 0, \\ \frac{\partial}{\partial t} E_i + \epsilon_{ijk} \partial_j B_k - ie(\phi^* D_i \phi - D_i \phi^* \phi) &= 0, \end{aligned}$$

Vortex solutions in the Abelian Higgs model

Static finite energy (2D) cylindrically symmetric:

$$\phi = v f(\rho) e^{i\theta}, \quad A_\theta = a(\rho)$$



Energy density:

$$\rho = |D_i\phi|^2 + V + \frac{1}{2}B^2$$

Magnetic field:

$$B = a'(\rho)$$

Visualising Abelian Higgs string simulations

(Loading ...)

Isosurfaces of constant energy density. Size: 256^3, lattice spacing $0.5m^{-1}$

Computing 1976 to 2008

Kibble, J. Phys A (1976): Topology of cosmic domains and strings

Best 1976: Cray 1 120 MHz 64-bit vector processor, 250 MFlops, 8 MB RAM

58^3 requires 7.8 MB

Our simulations on Cosmos 152 1.6GHz Itanium2, 790 GFlops, 456GB RAM

1024^3 requires 40 GB

Best 2008: Blue Gene/L 106,496 700MHz PowerPC, 478 TFlops, 74TB RAM

8192^3 requires 20 TB

COSMOS

UK National Cosmology Computer 148 1.6Ghz Itanium II 444 Gb

Visualisation COSMOS SAN XFS server

Parallel simulations of field theories: LATfield

- Public C++ library of objects for parallel classical lattice fields[a]
- Rewrite of MDP/FermiQCD[b]
- Objects:

  Lattice: Takes care of boundary conditions and domain decomposition

  Field: Template - can have real, complex, user-defined object.

  Site: Accesses elements of field
- Parallelisation by compiler switch

---

[a] Bevis & Hindmarsh http://www.latfield.org/

[b] Massimo di Pierro et al., http://www.fermiqcd.net/

Abelian Higgs model simulations: string length scale

Scaling: $L/V \propto \tau^{-2}$

Network scale: $\xi = \sqrt{(V/L)}$

Hence $\xi \propto \tau$

Lattice spacing: $\Delta x = 0.5$

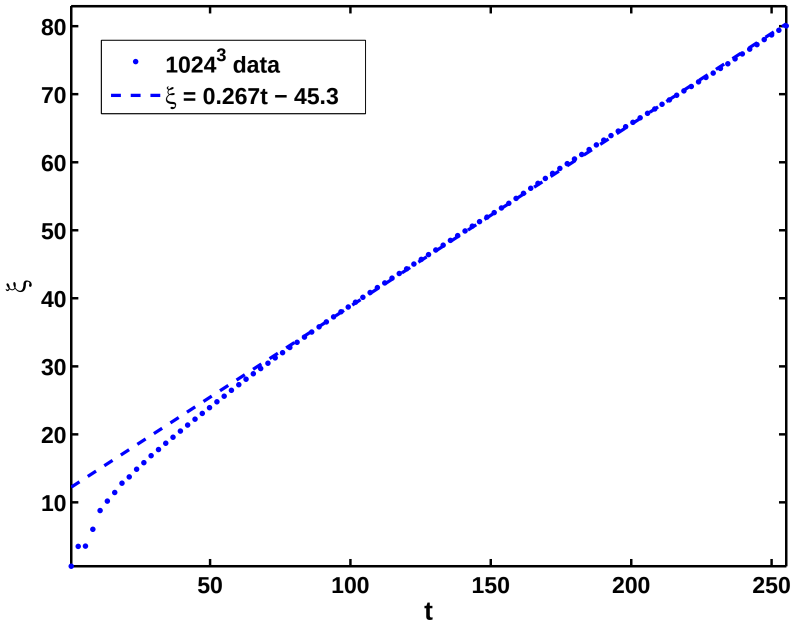
Time step: $\Delta t = 0.1$

Volume: 1024^3

Couplings: $\lambda = 2, e = 1$

Masses: $m_s = m_v$

Matter era



String network scaling hypothesis

- String network characteristic scale ξ ($= \sqrt{V/L}$, i.e. average curvature radius)
- Network scaling hypothesis: $\boxed{\xi = x_* t}$ (x_* constant O(1))
- String energy density: $\rho_s \simeq \mu/\xi^2$
- Total energy density: $\rho_t \sim 1/Gt^2$:
- String density fraction: $\boxed{\Omega_s \sim G\mu/x_*^2}$
- Grand Unification: $G\mu \sim 10^{-6}$

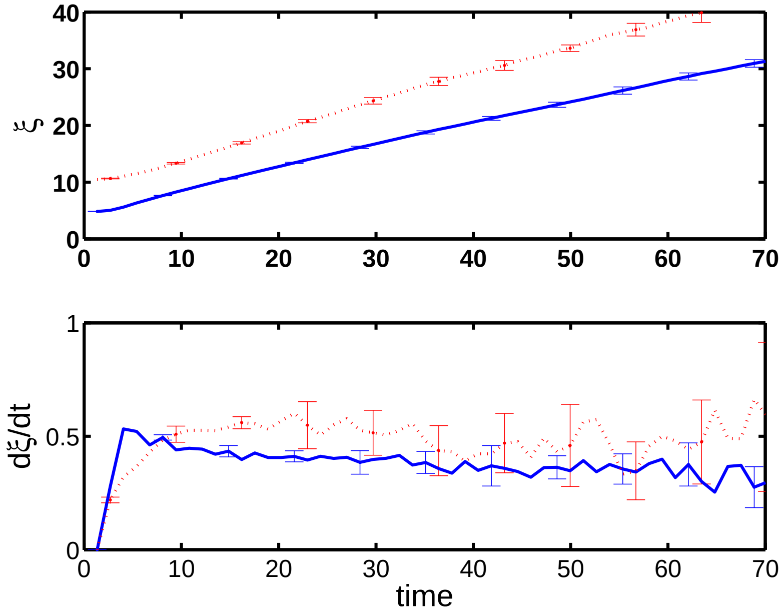
Scaling: extrapolate from $t_i \sim 10^{-36}$ s to $t_0 \sim 3 \times 10^{17}$ s today

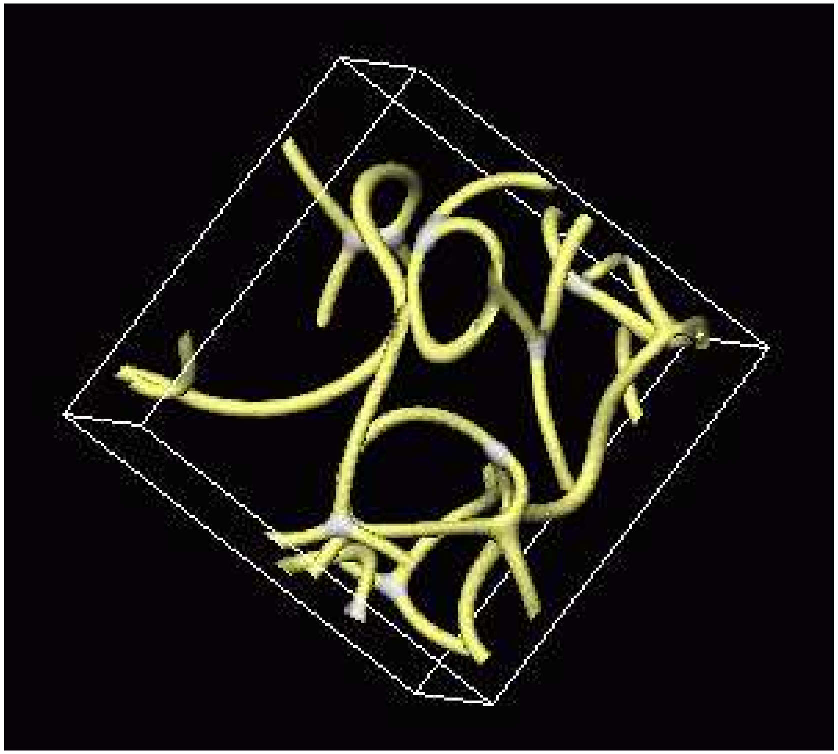
Modelling cosmic superstrings

Field theory model with junctions[a]

$SU(2) \rightarrow U(1) \rightarrow Z_3$

(global symmetry)

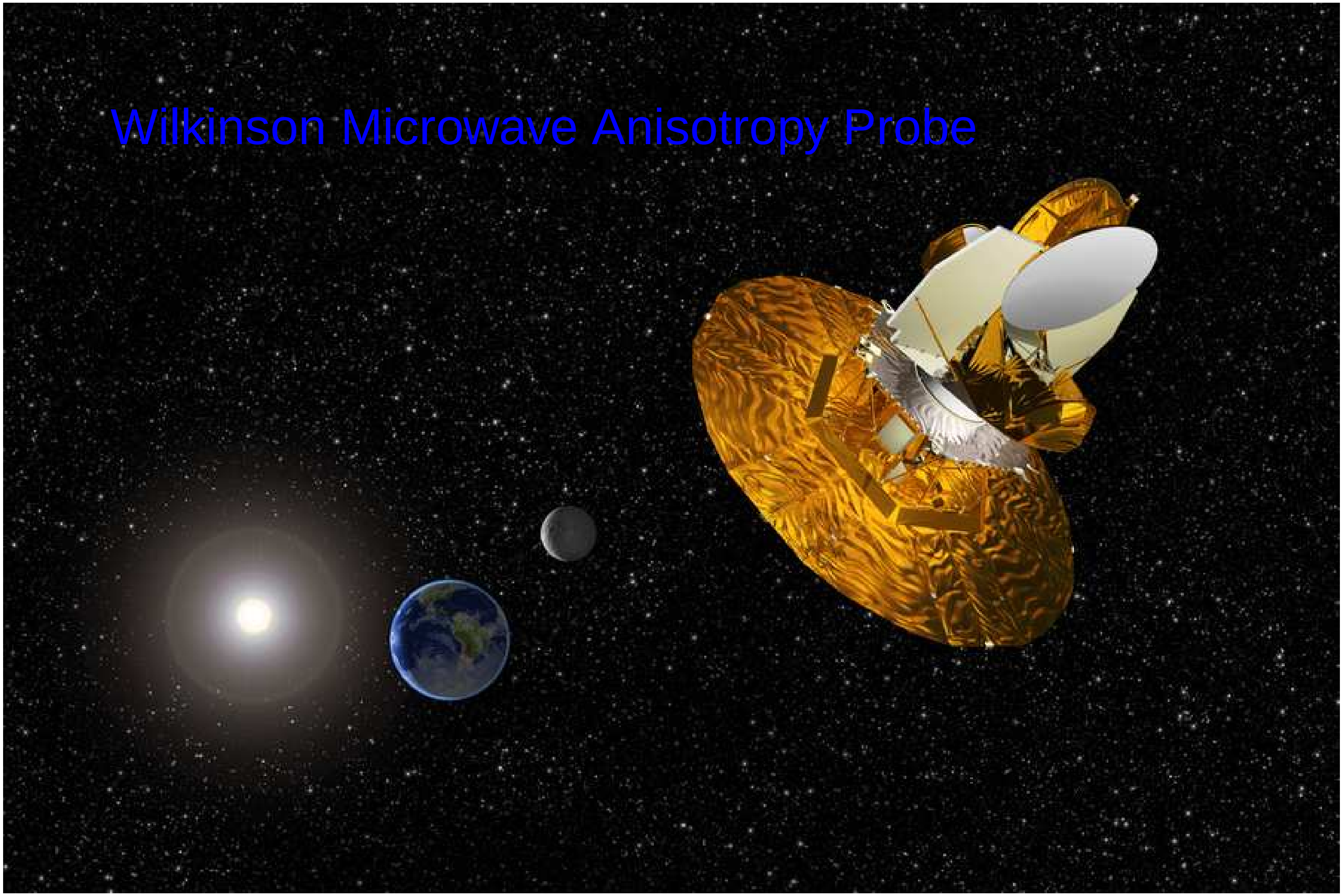




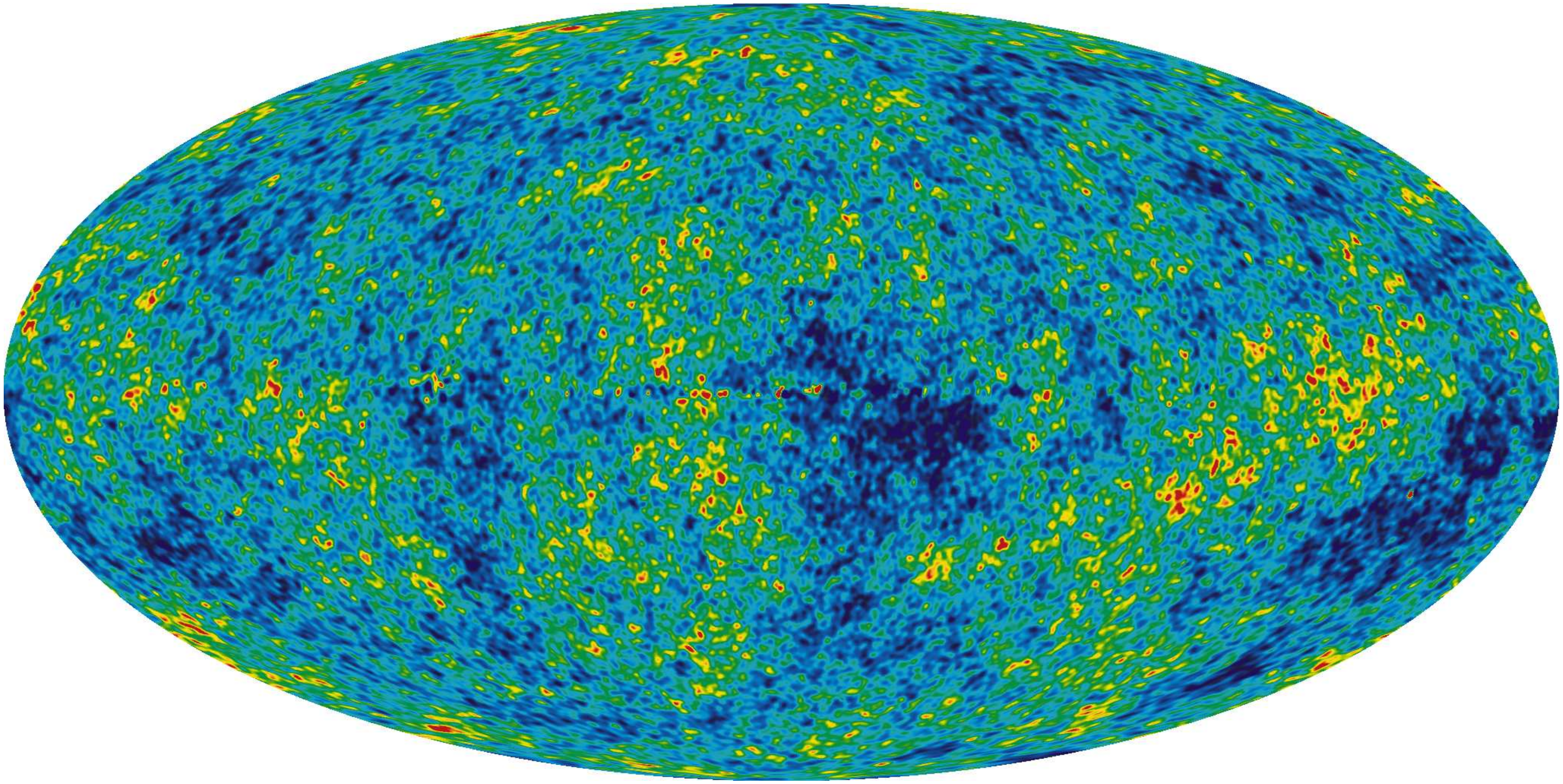
---

[a] Hindmarsh & Saffin (2006)

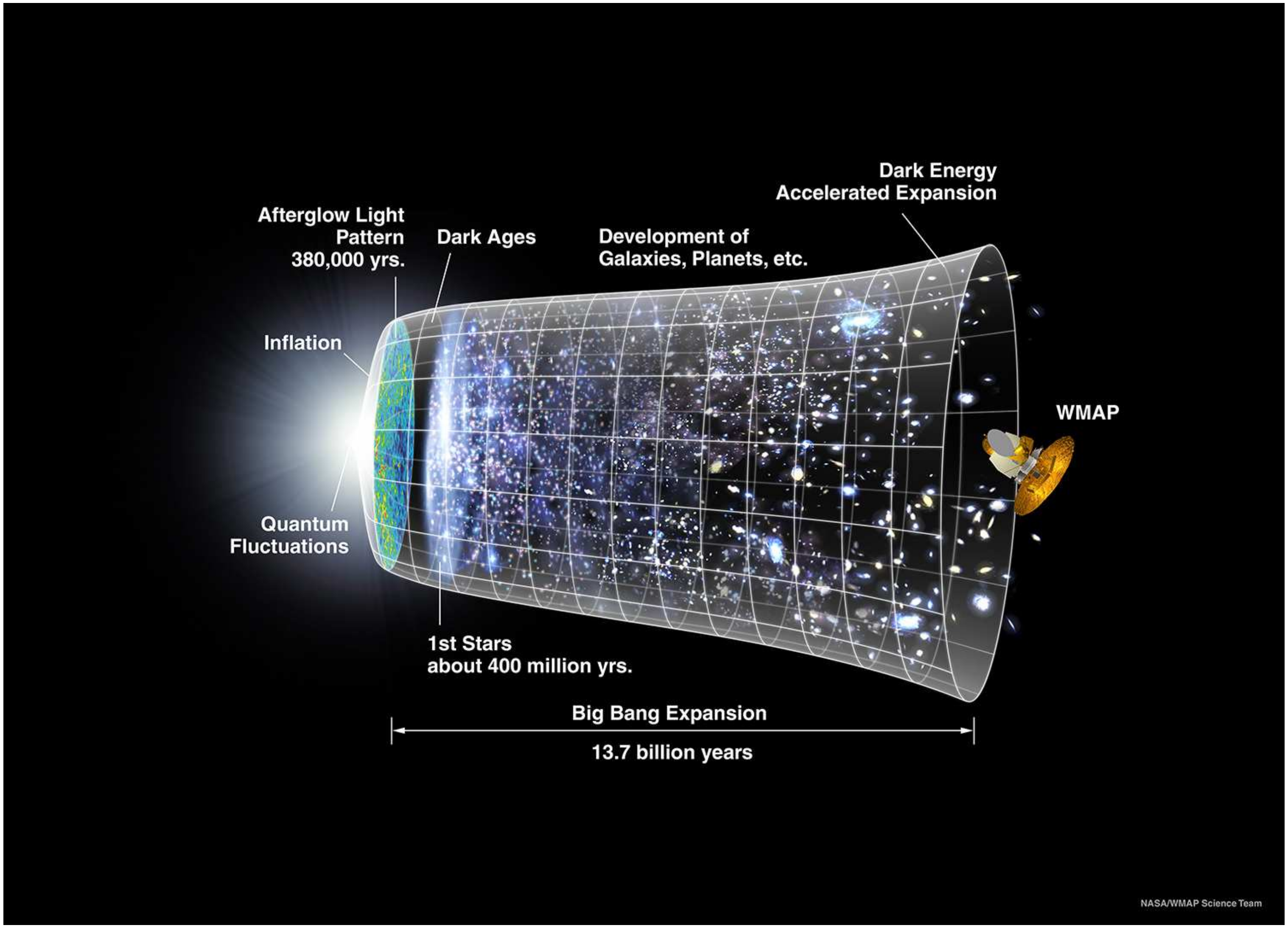
Wilkinson Microwave Anisotropy Probe



Strings and the Cosmic Microwave Background

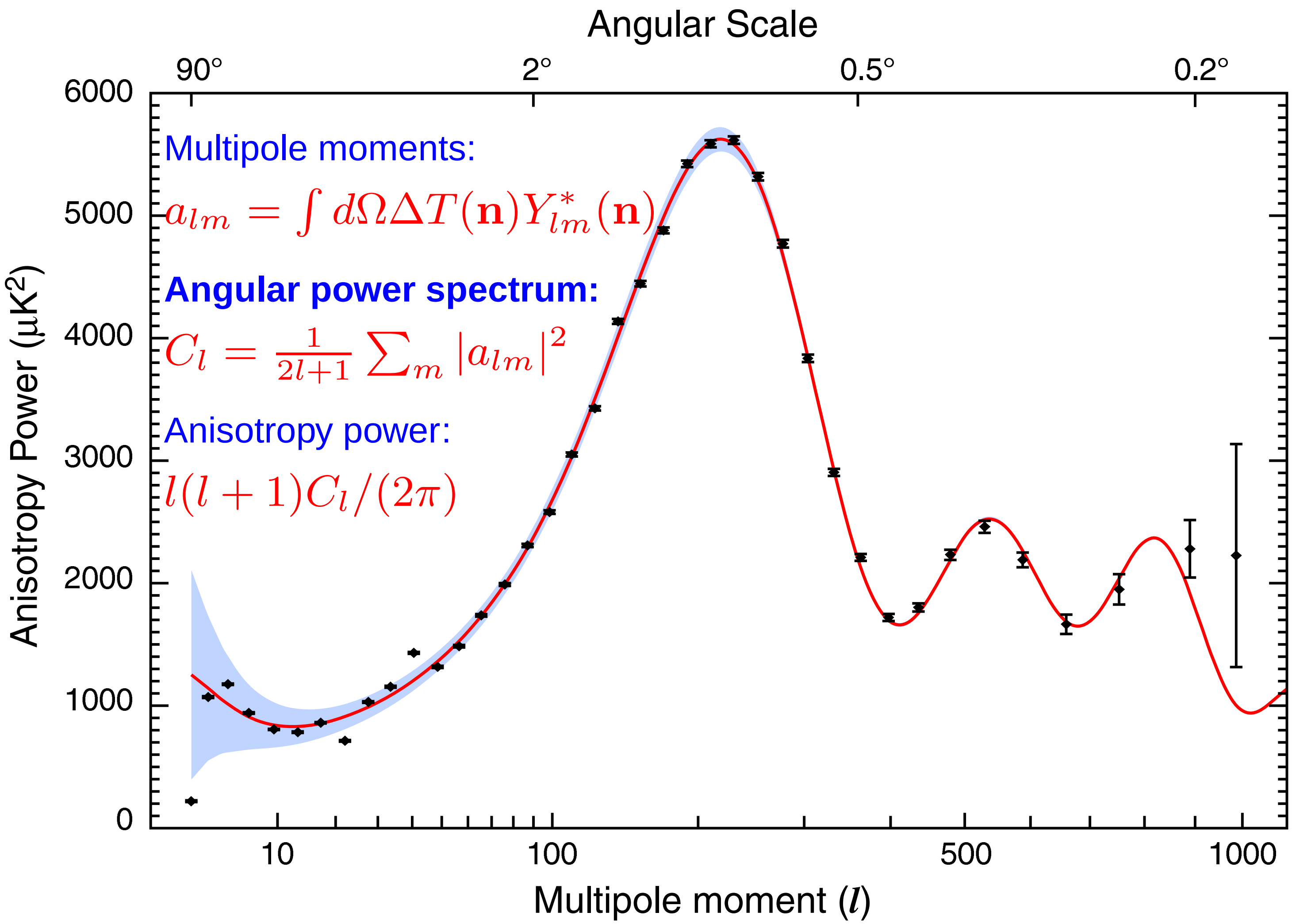


$-200 < \Delta T < 200\ \mu\text{K}$



NASA/WMAP Science Team

Angular power spectrum C_ℓ



Multipole moments:

$$a_{lm} = \int d\Omega \Delta T(\mathbf{n}) Y^*_{lm}(\mathbf{n})$$

Angular power spectrum:

$$C_l = \frac{1}{2l+1} \sum_m |a_{lm}|^2$$

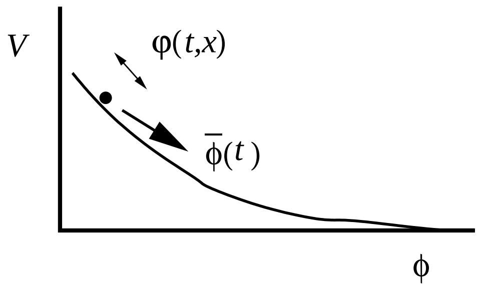
Anisotropy power:

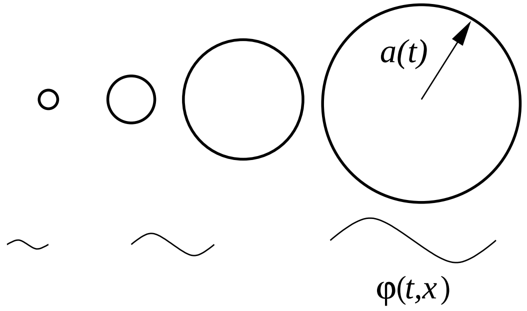
$$l(l+1)C_l/(2\pi)$$

Explanation - Inflation

Energy density of Universe dominated by homogeneous scalar field $\bar{\phi}(t)$

- Scalar field equation: $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$
- Friedmann equation: $H^2 = \frac{8\pi G}{3}\left(V(\phi) + \frac{1}{2}\dot{\phi}^2\right)$
- “Slow roll” $|\ddot{\phi}| \ll |\dot{\phi}|$: overdamped evolution
- Accelerated expansion: $a(t) \sim t^{\text{huge}}$,
- Quantum fluctuations in field:
  $\phi(x) = \bar{\phi}(t) + \varphi(t, \mathbf{x})$
- Quantum fluctuations in energy density:
  $\delta\rho_\phi(t, \mathbf{x}) = V'(\bar{\phi})\varphi(t, \mathbf{x})$





Inflation (Power-law ΛCDM): just 6 numbers

CMB angular power spectrum $C_\ell = C_\ell^{\rm inf}(H_0, \Omega_b, \Omega_m, \tau, A_s, n_s)$

	Parameter		ΛCDM
1	Hubble parameter	H_0(km/s/MPc)	74 ± 3
2	“Baryon” density fraction	$100\Omega_b$	4.2 ± 0.2
3	Total matter density fraction	$100\Omega_m$	24.0 ± 1.7
4	Optical depth to last scattering	τ	0.093 ± 0.029
5	Perturbation amplitude	$10^{10}A_{\rm s}^2$	22 ± 2
6	Perturbation tilt	$n_{\rm s}$	0.961 ± 0.017

NB Inflation gives $\Omega_\Lambda = 1 - \Omega_m$ **NB** Matter perturbations $\langle \delta\rho^2 \rangle\big|_{d_h} = A_s^2 (d_h/d_{h0})^{1-n_s}$, d_h = Horizon distance

Inflation + strings: just 7 (or 6) numbers

$$C_\ell = C_\ell^{\rm inf}(H_0, \Omega_b, \Omega_m, \tau, A_s, n_s) + C_\ell^{\rm string}(G\mu)$$

Parameter	ΛCDM	+strings	HZ+strings
H_0(km/s/MPc)	73	82	82
$100\Omega_b$	4.2	3.7	3.7
Ω_m	24.0	17.9	17.9
τ	0.092	0.11	0.11
$10^{10}A_{\rm s}^2$	22	20	20
$n_{\rm s}$	0.958	1.00	1
f_{10}	–	0.099	0.099
$\Delta\chi^2$	0	-3.9	-3.9
Evidence	1	1.2 ± 0.1	7.3 ± 1.2

NB HZ = Harrizon-Zel'dovich model of scale-free perturbations $n_{\rm s} = 1$

NB $f_{10} \propto (G\mu)^2$, amplitude-squared of string-induced perturbations

Abelian Higgs string C_ℓs vs. WMAP3 and BOOMERanG

Multipole moments:

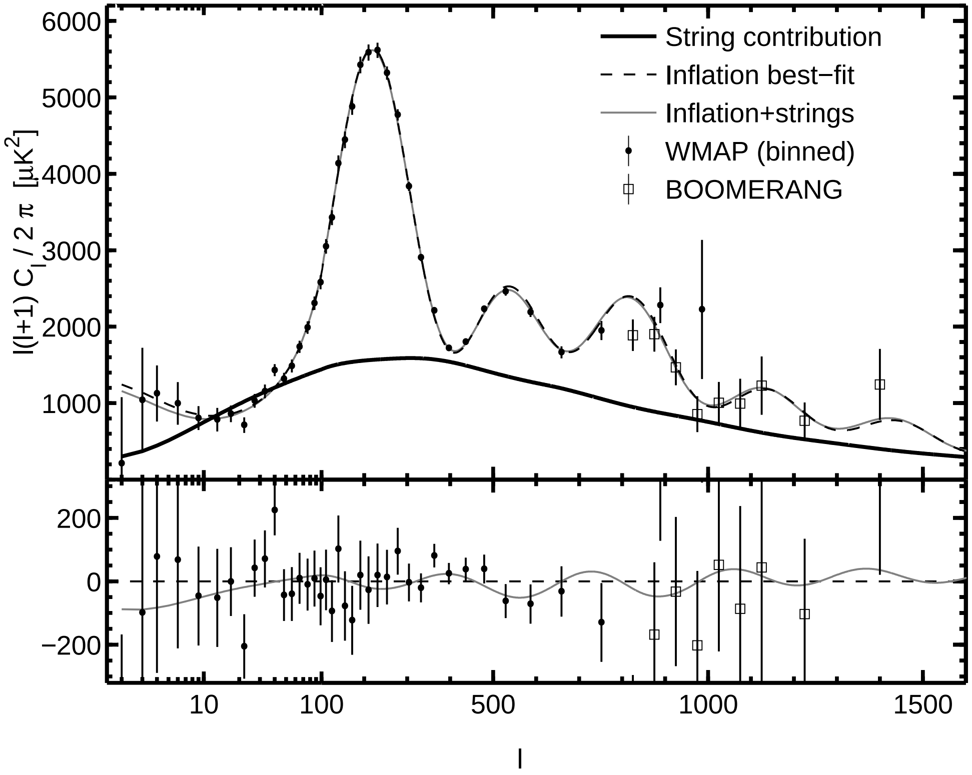
$$a_{lm} = \int d\Omega \Delta T(\mathbf{n}) Y^*_{lm}(\mathbf{n})$$

Angular power spectrum:

$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

Anisotropy power:

$$l(l+1)C_l/(2\pi)$$



Top: Strings normalised to WMAP3 ($\ell = 10$)[a]

Bottom: Differences from best-fit ΛCDM

---

[a] Bevis, Hindmarsh, Kunz, Urrestilla (2006)

Results slide for string-o-philes

Fit to CMB data (WMAP3, Boomerang, CBI, ACBAR, VSA)[a]

$$G\mu = (0.65 \pm 0.10) \times 10^{-6}$$

Ingredients for a stringy universe:

- Hubble parameter $H_0 = 82$ km s^{-1} Mpc^{-1}
- Baryon fraction $\Omega_b = 3.7 \times 10^{-2}$
- Scale-invariant (Harrison-Zel'dovich) power spectrum $n_s = 1$

---

[a] Classical Abelian Higgs model

Results slide for string-o-phobes

Fit to CMB (7 parameters)[a]

- + Hubble Key Project ($H_0 = 72 \pm 8$ km s^{-1} Mpc^{-1})
- + D abundance & Big Bang Nucleosynthesis ($\Omega_{\mathrm{b}} h^2 = 2.14 \pm 0.20 \times 10^{-2}$)

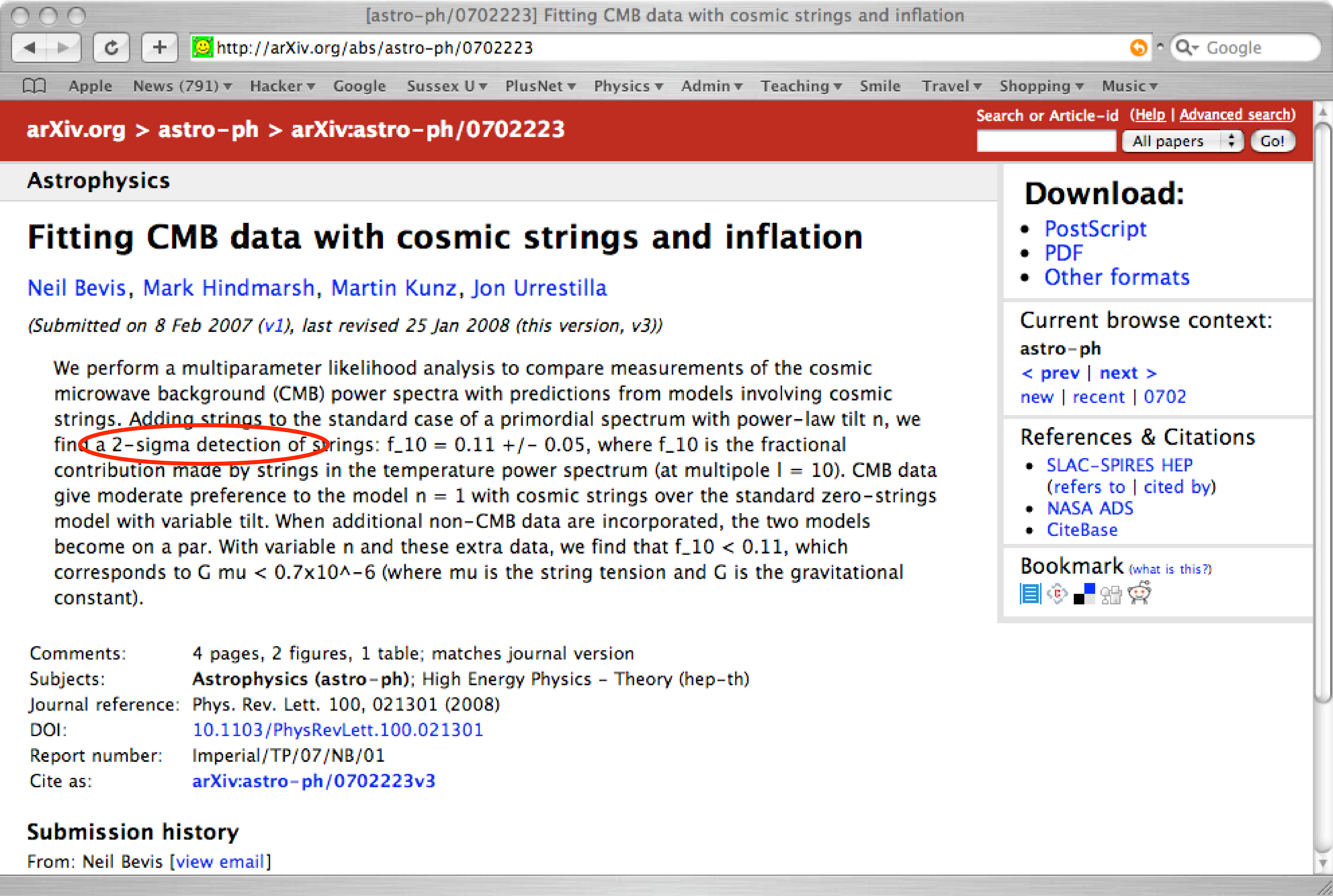
$$G\mu < 0.7 \times 10^{-6} \text{ (95\%)}$$

---

[a] Classical Abelian Higgs model

Conclusions

- Strings are common in high energy physics theories
- If strings were every formed, they would still be here.
- Field theory calculations of string Cosmic Microwave Background signal
- Results:
  - (CMB only fit) $G\mu = 0.65 \pm 0.10 \times 10^{-6}$ ($n_{\rm s} = 1$, high $\Omega_{\rm b}h^2$, h)
  - (CMB + Hubble + BBN) $G\mu \lesssim 0.7 \times 10^{-6}$ (95% C.L.)
  - Strings improve CMB in range $300 < \ell < 700$:
- Technology spin-off: parallel N-dimensional field theory simulations: LATfield
- Future: WMAP 5-year data, Planck CMB space mission launch 2008.
- Future: distinguishing between superstrings and field theory strings?



Astrophysics

Fitting CMB data with cosmic strings and inflation

Neil Bevis, Mark Hindmarsh, Martin Kunz, Jon Urrestilla

(Submitted on 8 Feb 2007 (v1), last revised 25 Jan 2008 (this version, v3))

We perform a multiparameter likelihood analysis to compare measurements of the cosmic microwave background (CMB) power spectra with predictions from models involving cosmic strings. Adding strings to the standard case of a primordial spectrum with power-law tilt n, we find a 2-sigma detection of strings: f_10 = 0.11 +/- 0.05, where f_10 is the fractional contribution made by strings in the temperature power spectrum (at multipole l = 10). CMB data give moderate preference to the model n = 1 with cosmic strings over the standard zero-strings model with variable tilt. When additional non-CMB data are incorporated, the two models become on a par. With variable n and these extra data, we find that f_10 < 0.11, which corresponds to G mu < 0.7x10^-6 (where mu is the string tension and G is the gravitational constant).

Comments:	4 pages, 2 figures, 1 table; matches journal version
Subjects:	**Astrophysics (astro-ph)**; High Energy Physics - Theory (hep-th)
Journal reference:	Phys. Rev. Lett. 100, 021301 (2008)
DOI:	10.1103/PhysRevLett.100.021301
Report number:	Imperial/TP/07/NB/01
Cite as:	**arXiv:astro-ph/0702223v3**

Submission history

From: Neil Bevis [view email]