CMB and B-modes

from cosmic strings

Levon Pogosian
Simon Fraser University

APC, Paris, 10 June, 2014

SFU from the air. Image kindly provided by Stefan Lorimer (UniverCity).

Workshop on Testing Gravity at SFU Harbour Centre

January 15-17, 2015

- Alternative theories of gravity
- Pulsars and other astrophysical tests
- Gravitational wave detectors
- Gravity at short distances
- Quantum gravity and black holes
- Cosmological tests - CMB, large scale structure

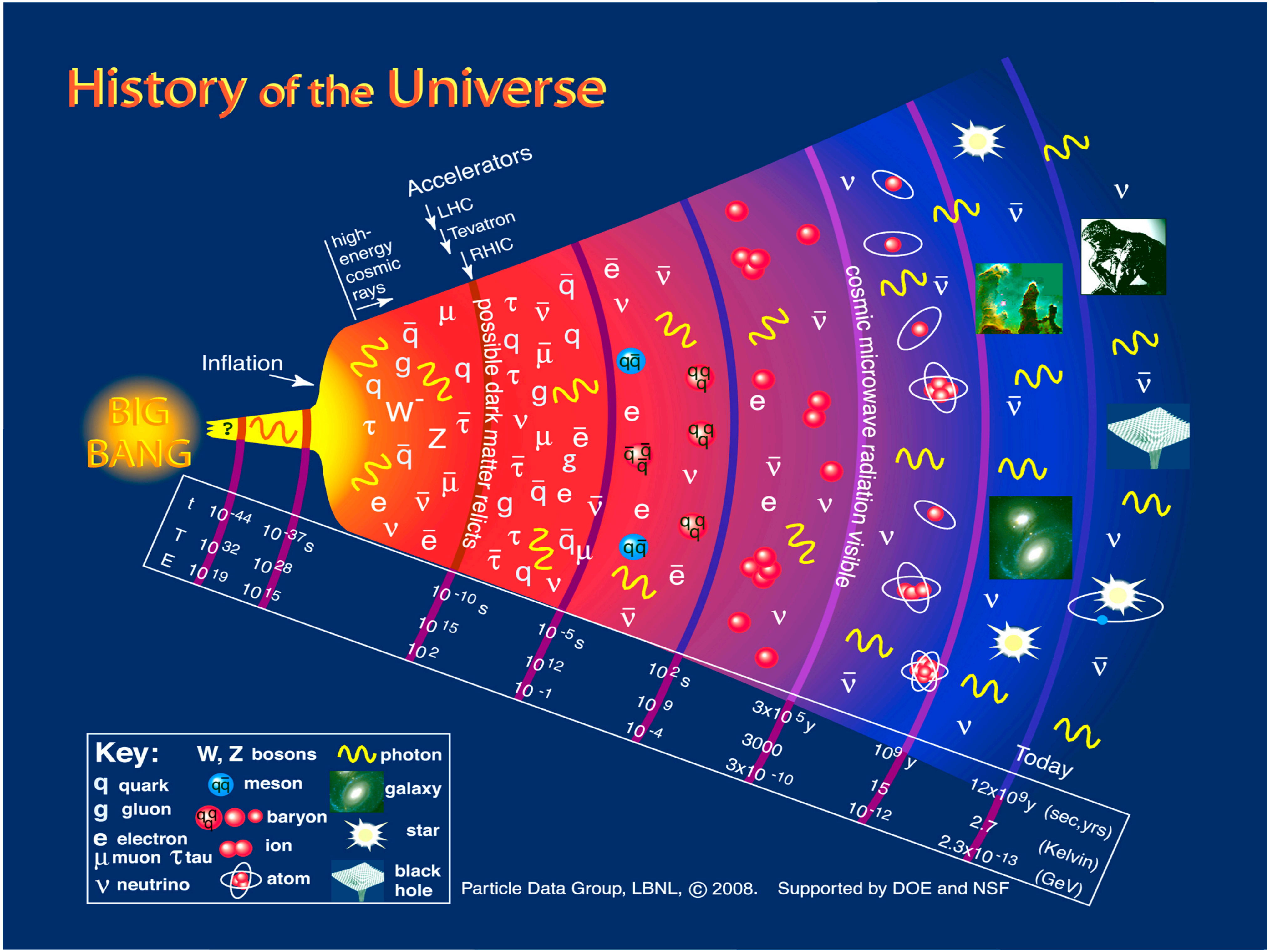
SFU TRIUMF …

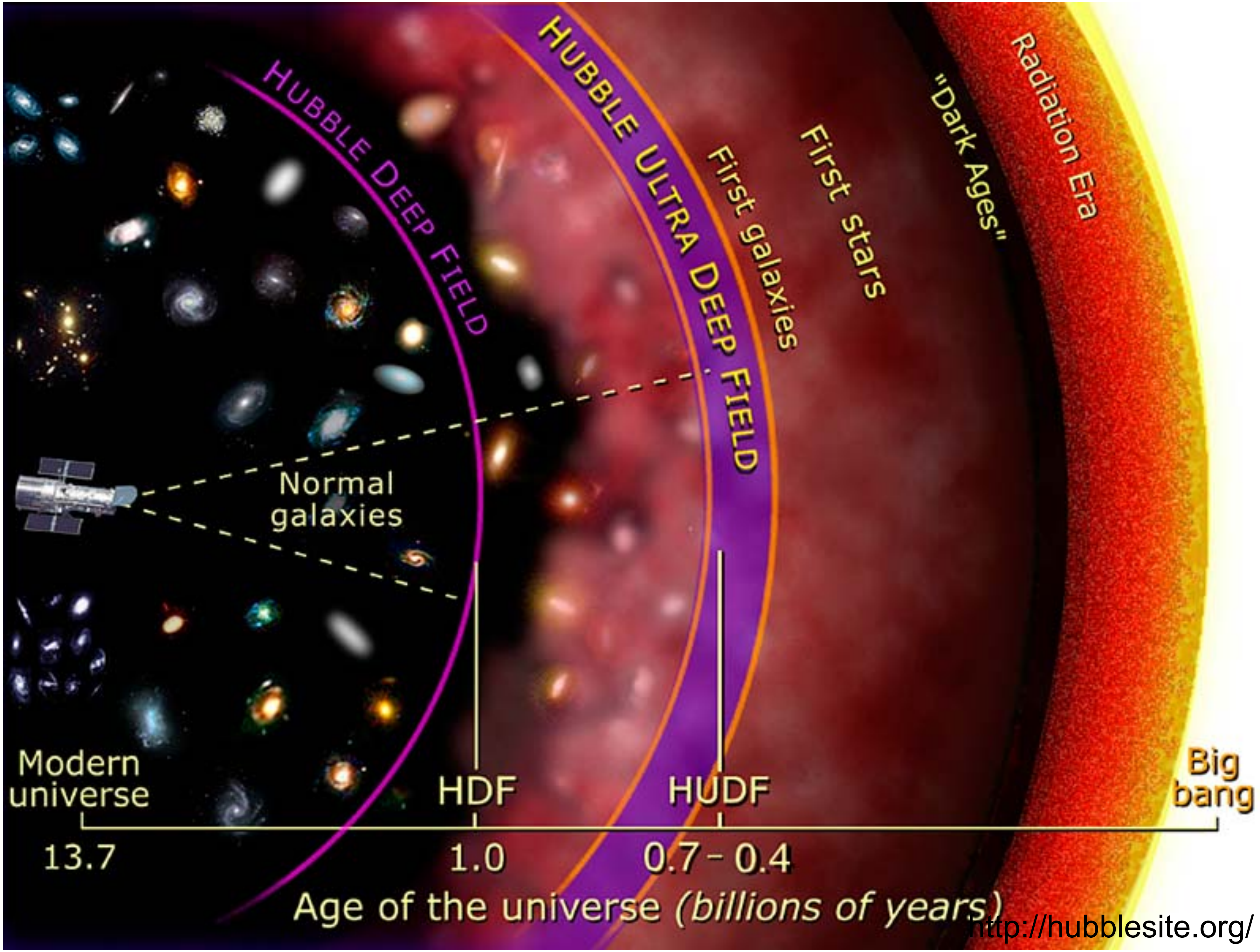
http://www.sfu.ca/physics/cosmology/TestingGravity2015

This talk

- Relevant CMB basics
- Cosmic strings and their CMB signatures
- B-modes from cosmic strings
- Outlook

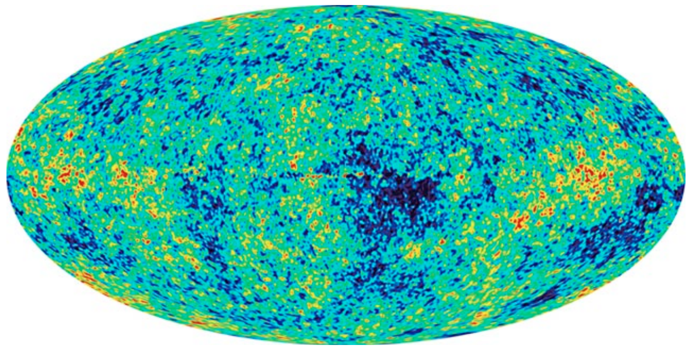
Based on work with Tasos Avgoustidis, Ed Copeland, Adam Moss, Alkistis Pourtsidou, Dani Steer, Henry Tye, Tanmay Vachaspati, Ira Wasserman, Mark Wyman

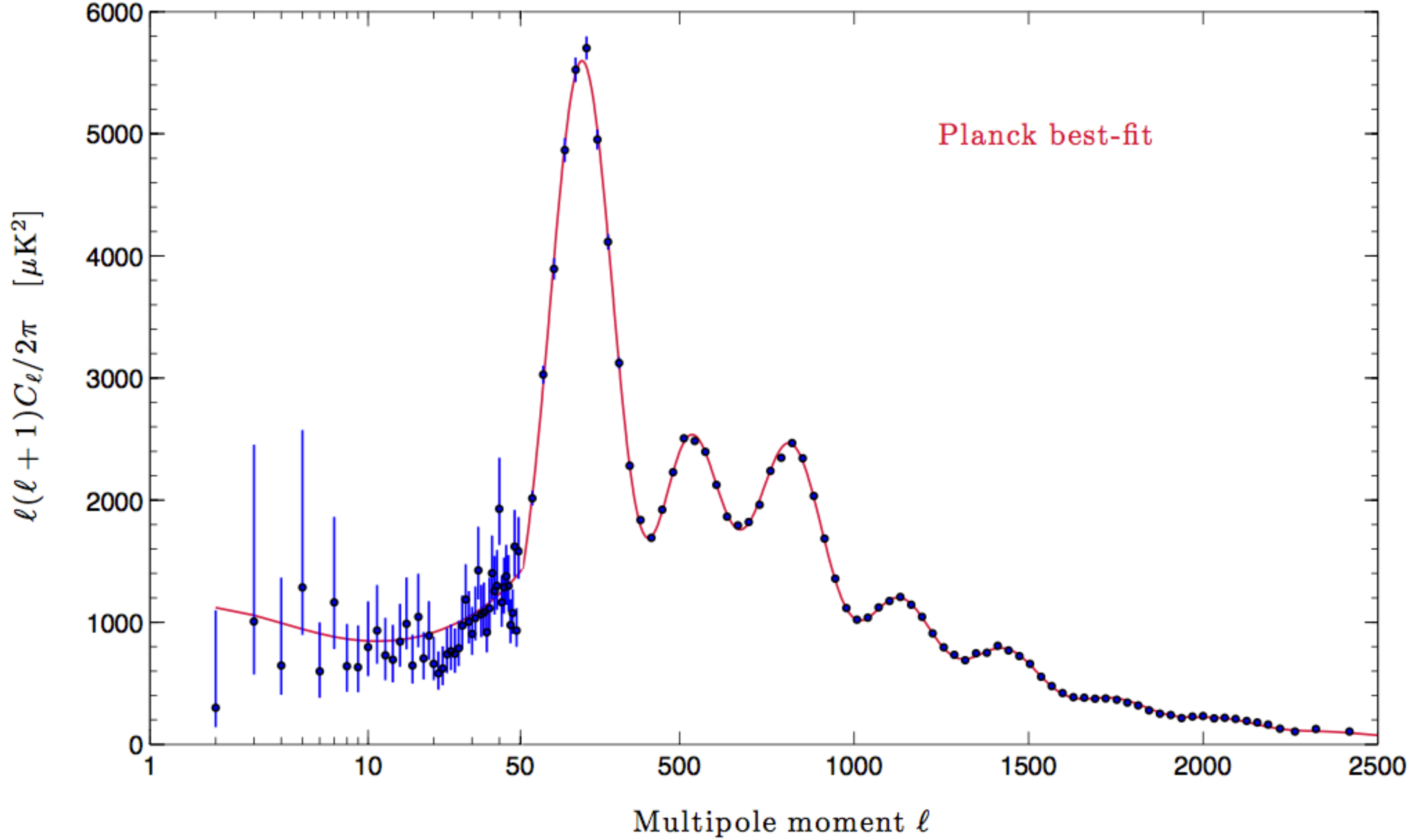

History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
t 10^-44 10^-37 s 10^-10 s 10^-5 s 10^2 s 3x10^5 y 10^9 y 12x10^9 y (sec,yrs)
T 10^32 10^28 10^15 10^12 10^9 3000 15 2.7 (Kelvin)
E 10^19 10^15 10^2 10^-1 10^-4 3x10^-10 10^-12 2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

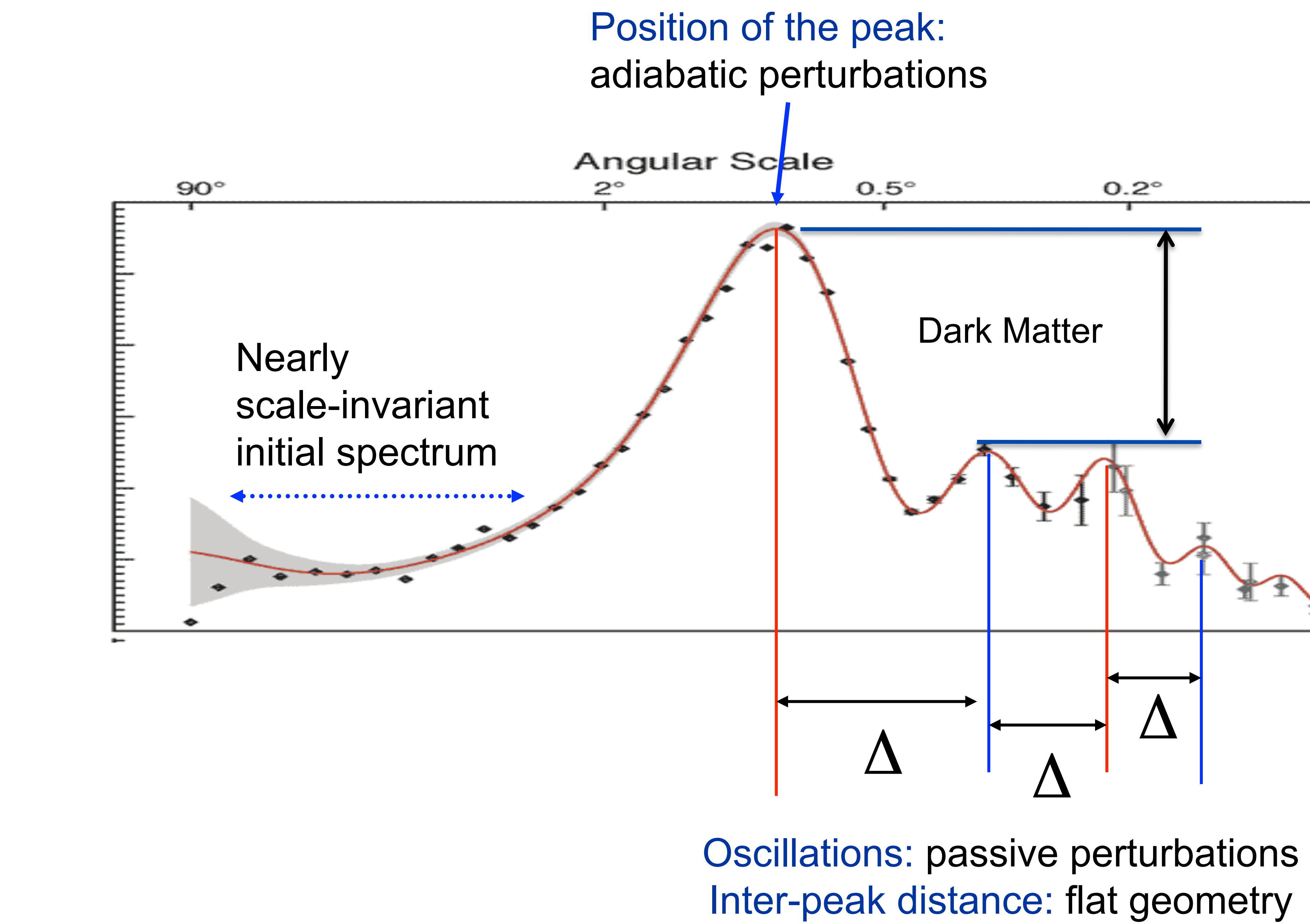


http://hubblesite.org/

The spectrum of CMB anisotropies

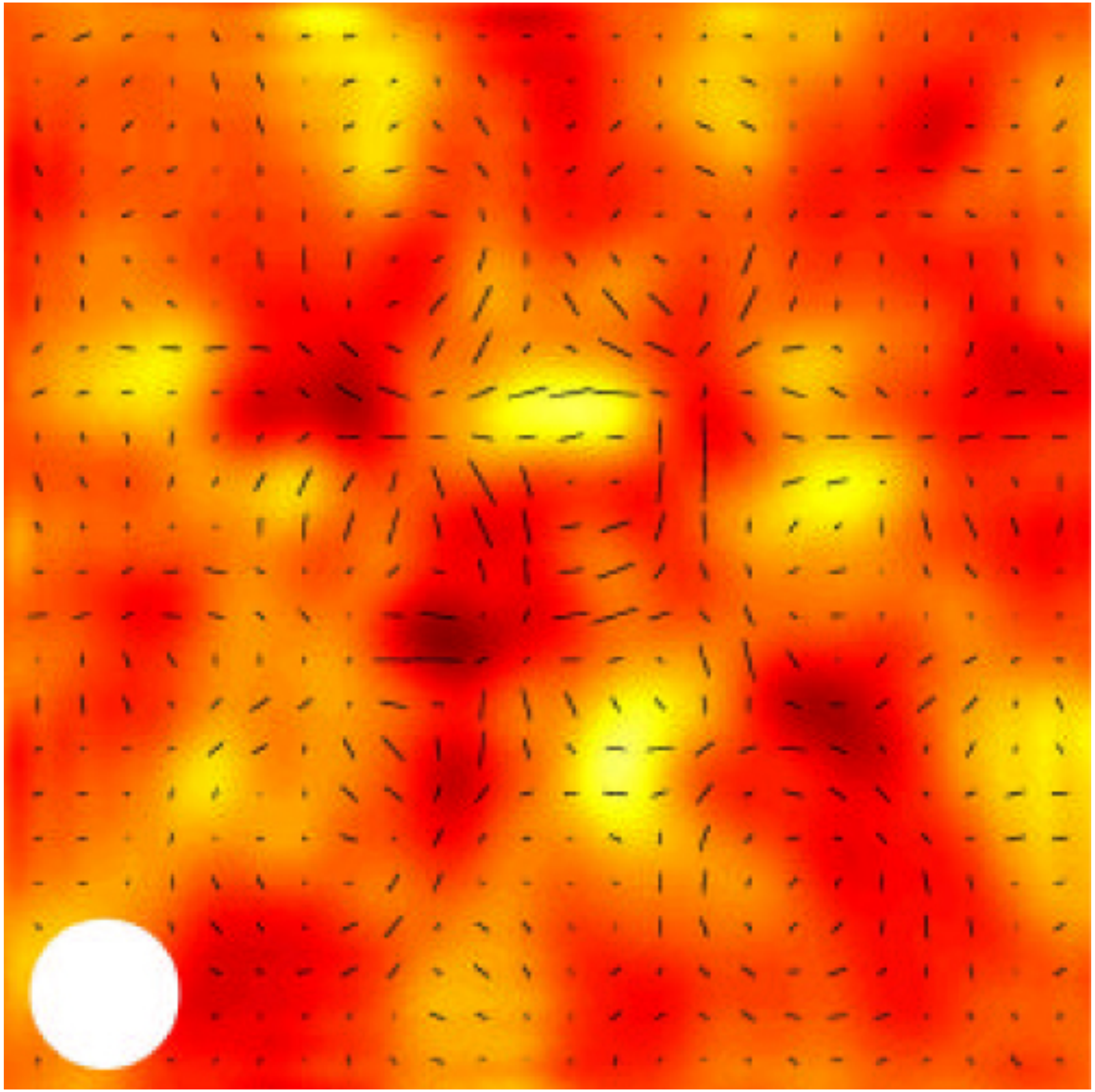





Position of the peak:
adiabatic perturbations
Angular Scale
90°
2°
0.5°
0.2°
Dark Matter
Nearly
scale-invariant
initial spectrum
Δ
Δ
Δ
Oscillations: passive perturbations
Inter-peak distance: flat geometry

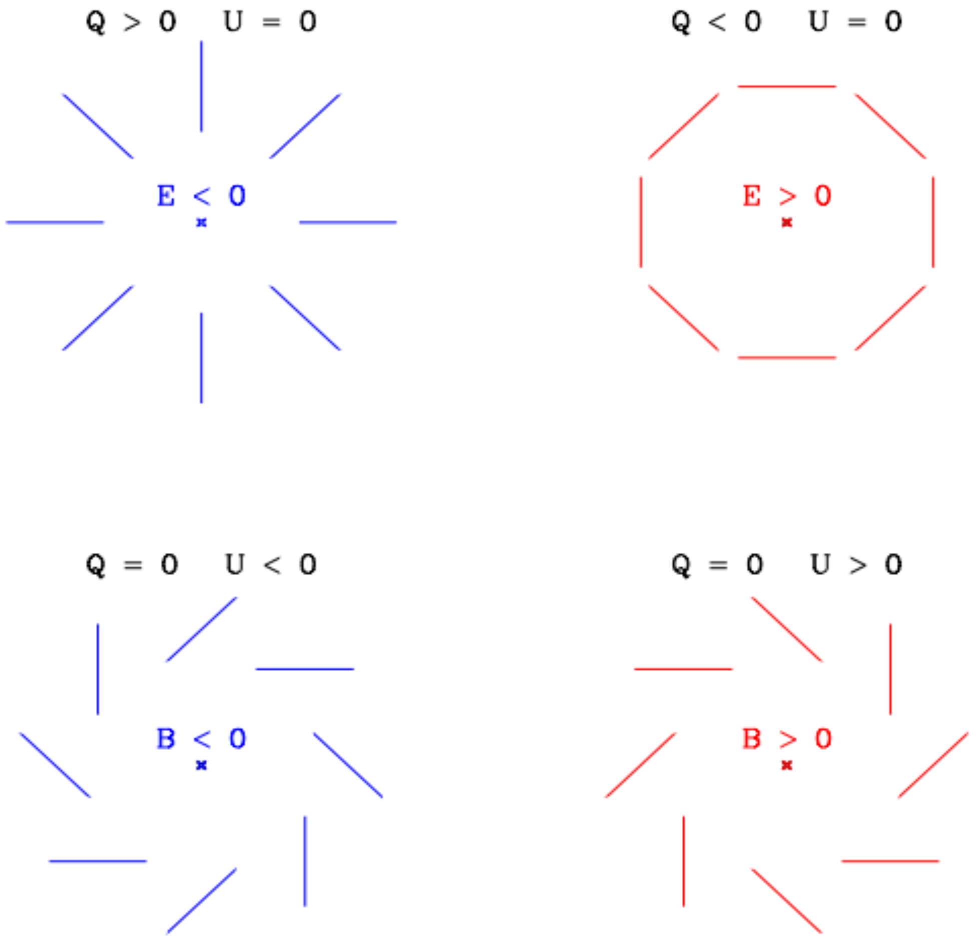
Facts from CMB TT and TE	**Generic prediction of simplest inflationary models**
Almost isotropic	Homogeneity
Almost flat	Flatness
Almost Gaussian statistics	Gaussianity
Adiabatic initial conditions	Adiabatic initial conditions
Almost scale-invariant spectrum	Almost scale-invariant spectrum
$r < 0.2$	Gravitational wave background

CMB Polarization



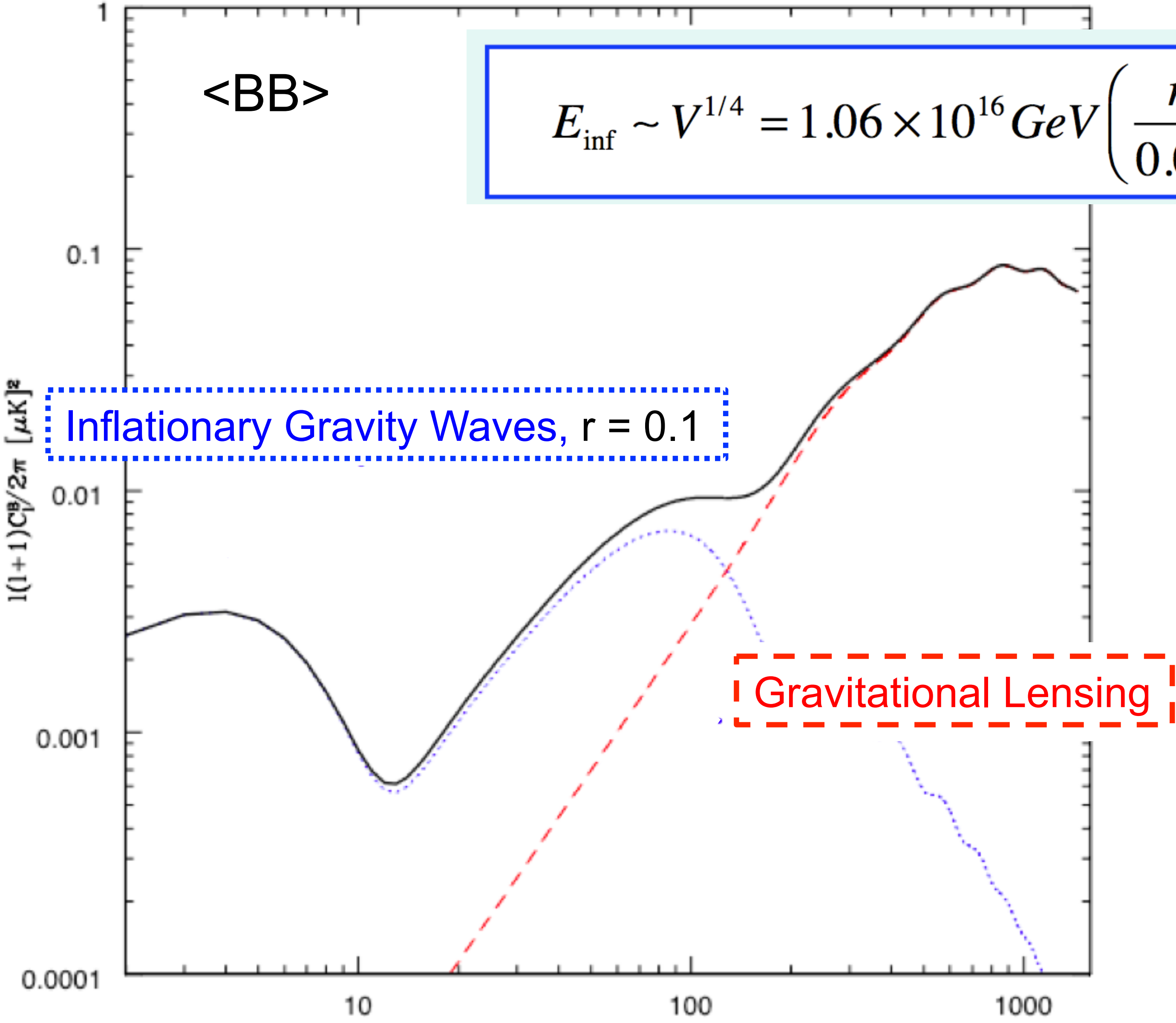
DASI
2002

E (parity-even) and B (parity-odd) modes



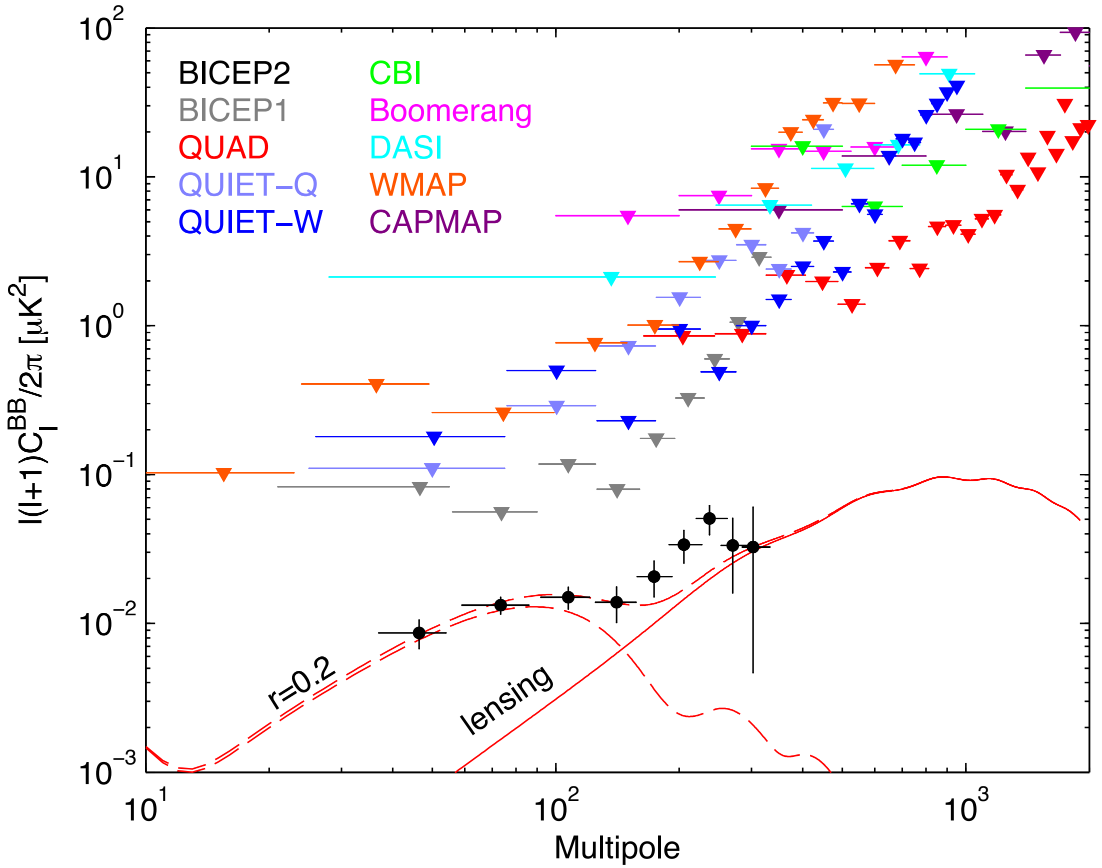
from M. Zaldarriaga, astro-ph/0305272

The smoking gun of Inflation



$$E_{\inf} \sim V^{1/4} = 1.06 \times 10^{16}\, GeV \left(\frac{r}{0.01} \right)^{1/4}$$

B-modes from BICEP2



Has the smoking gun been found?

- Whether or not they have seen the inflationary gravity waves, BICEP2 opened the era of precision B-mode science

- Other fundamental physics can be studied with B-modes, e.g. vector and tensor modes sourced by relics of the early universe:

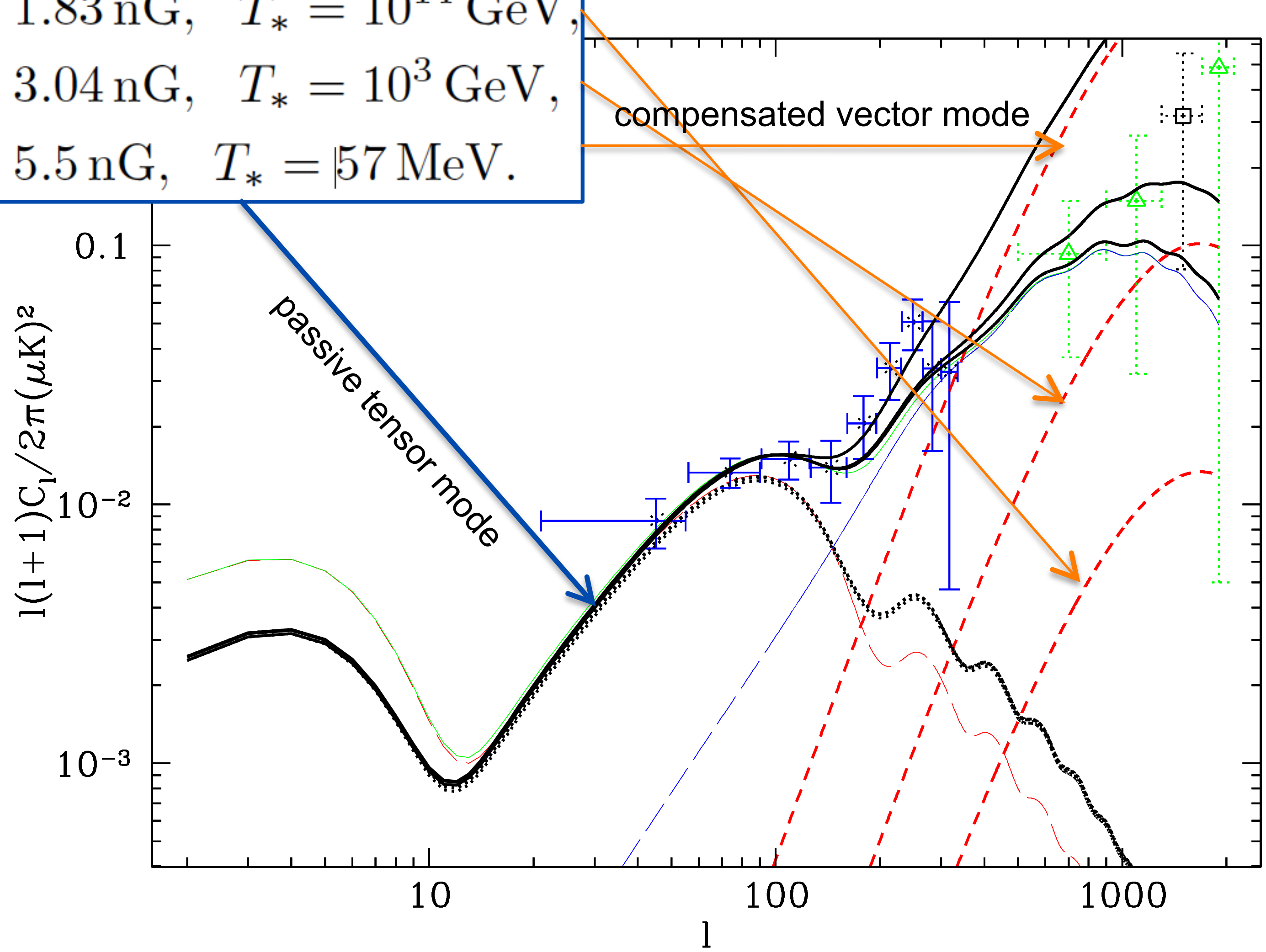
    - magnetic fields

    - cosmic defects

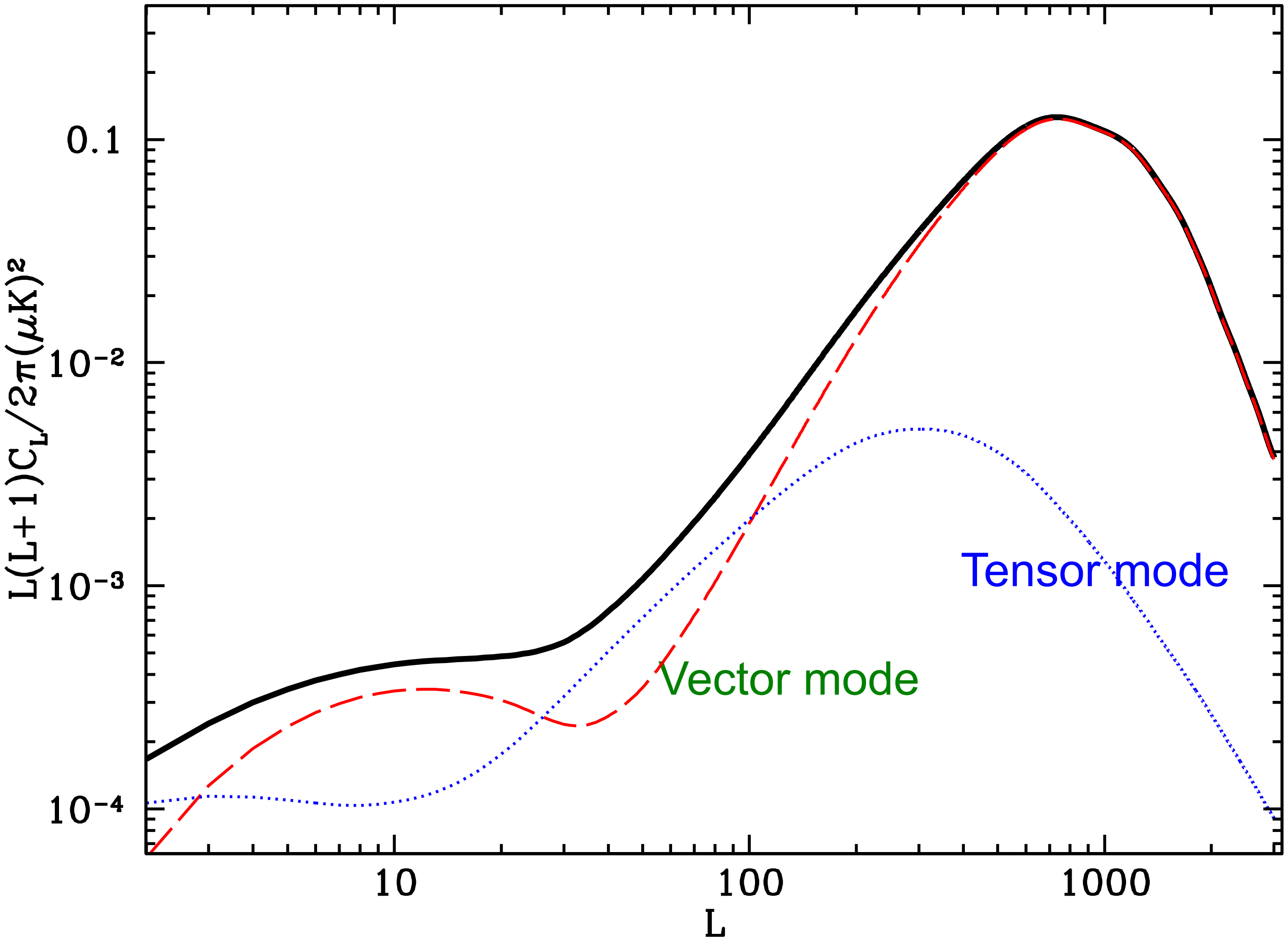
BB from a scale-invariant tangled primordial magnetic field

Bonvin, Durrer, Maartens, 1403.6768, PRL; Lewis, 2004; Shaw and Lews, 2010

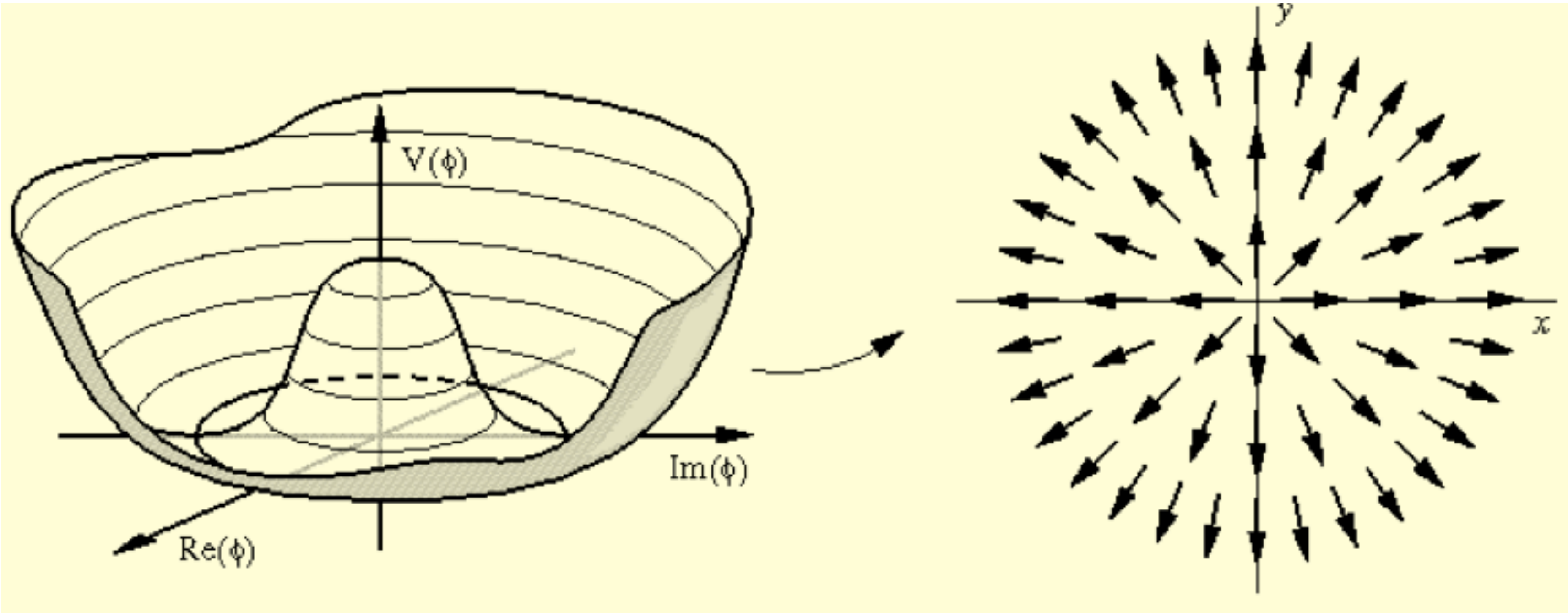
$$B_1 = 1.83\,\mathrm{nG}, \quad T_* = 10^{14}\,\mathrm{GeV},$$
$$B_1 = 3.04\,\mathrm{nG}, \quad T_* = 10^{3}\,\mathrm{GeV},$$
$$B_1 = 5.5\,\mathrm{nG}, \quad T_* = 57\,\mathrm{MeV}.$$



B-modes from cosmic strings

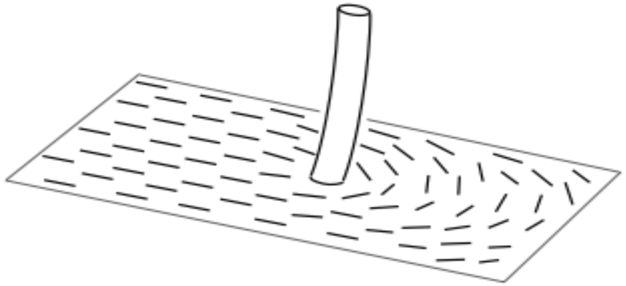


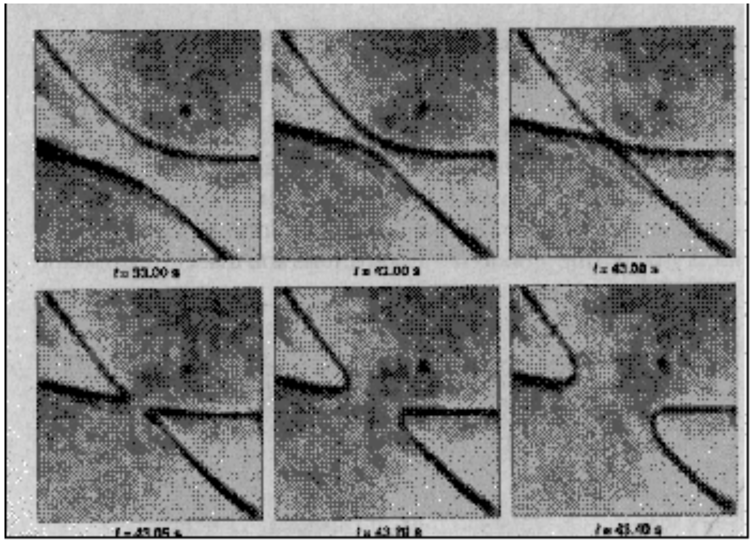
Strings form when an axial symmetry is spontaneously broken



Disclinations in Liquid Crystals

Linear regions of
trapped isotropic phase

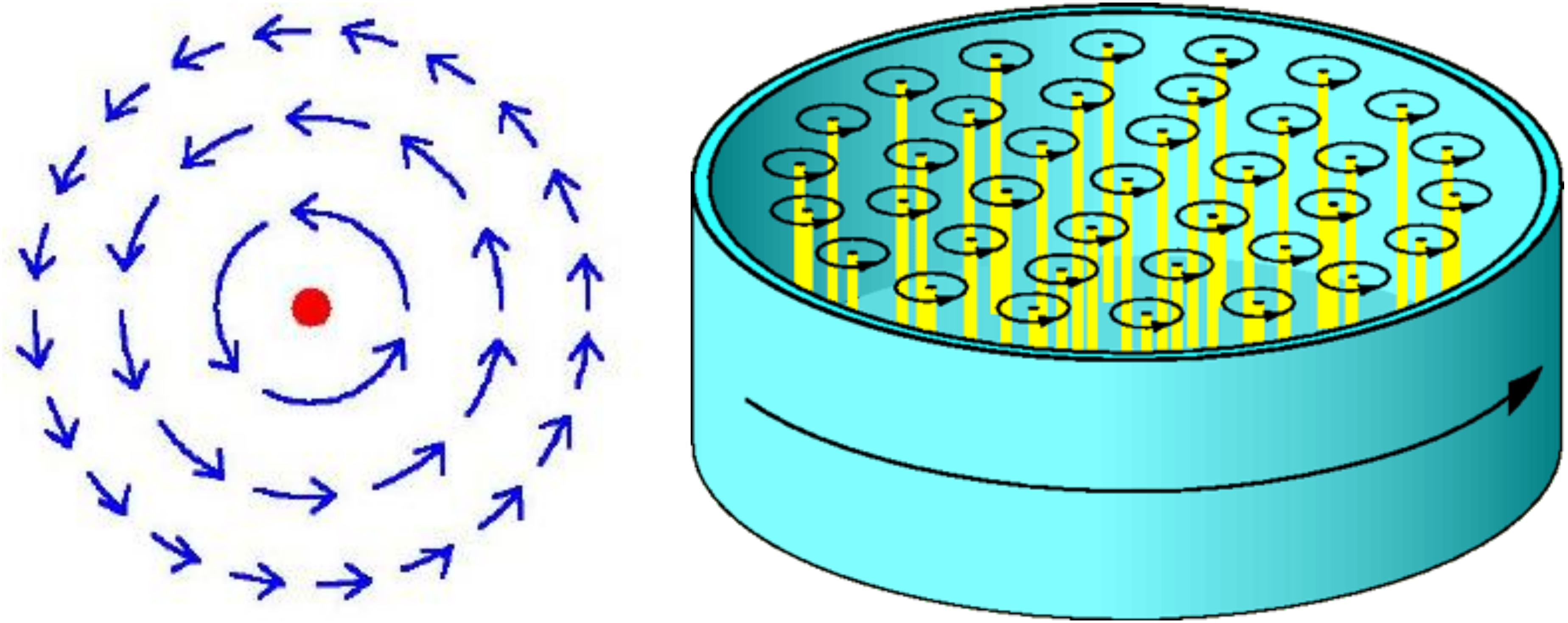




I.Chuang et. al., Science (1991)

M.Bowick et al, Science (1994)

Vortices in superfluids

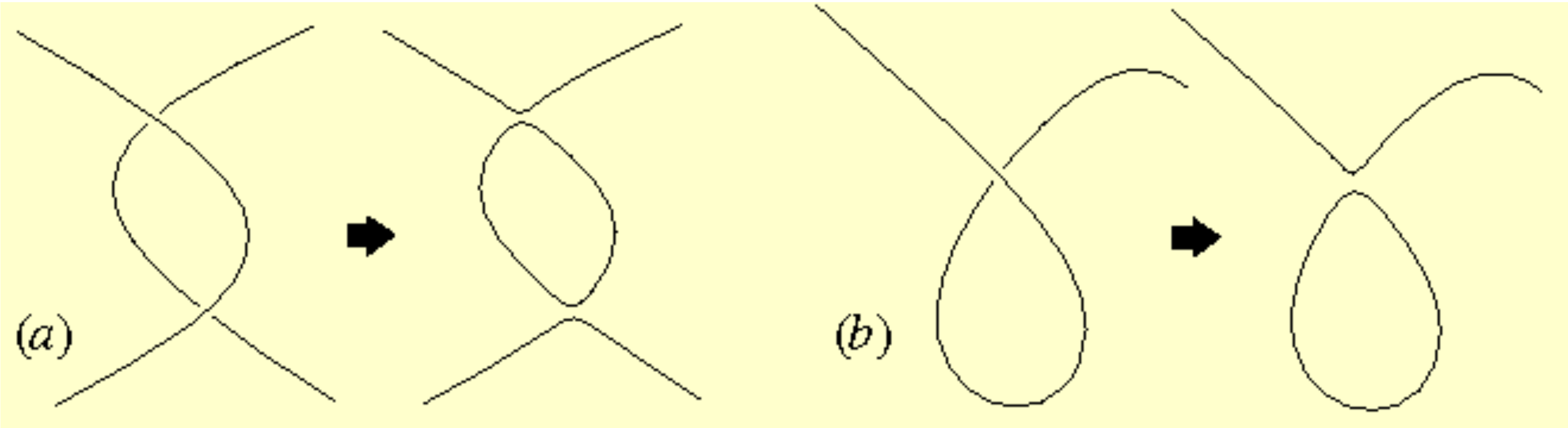


Linear regions of trapped normal fluid

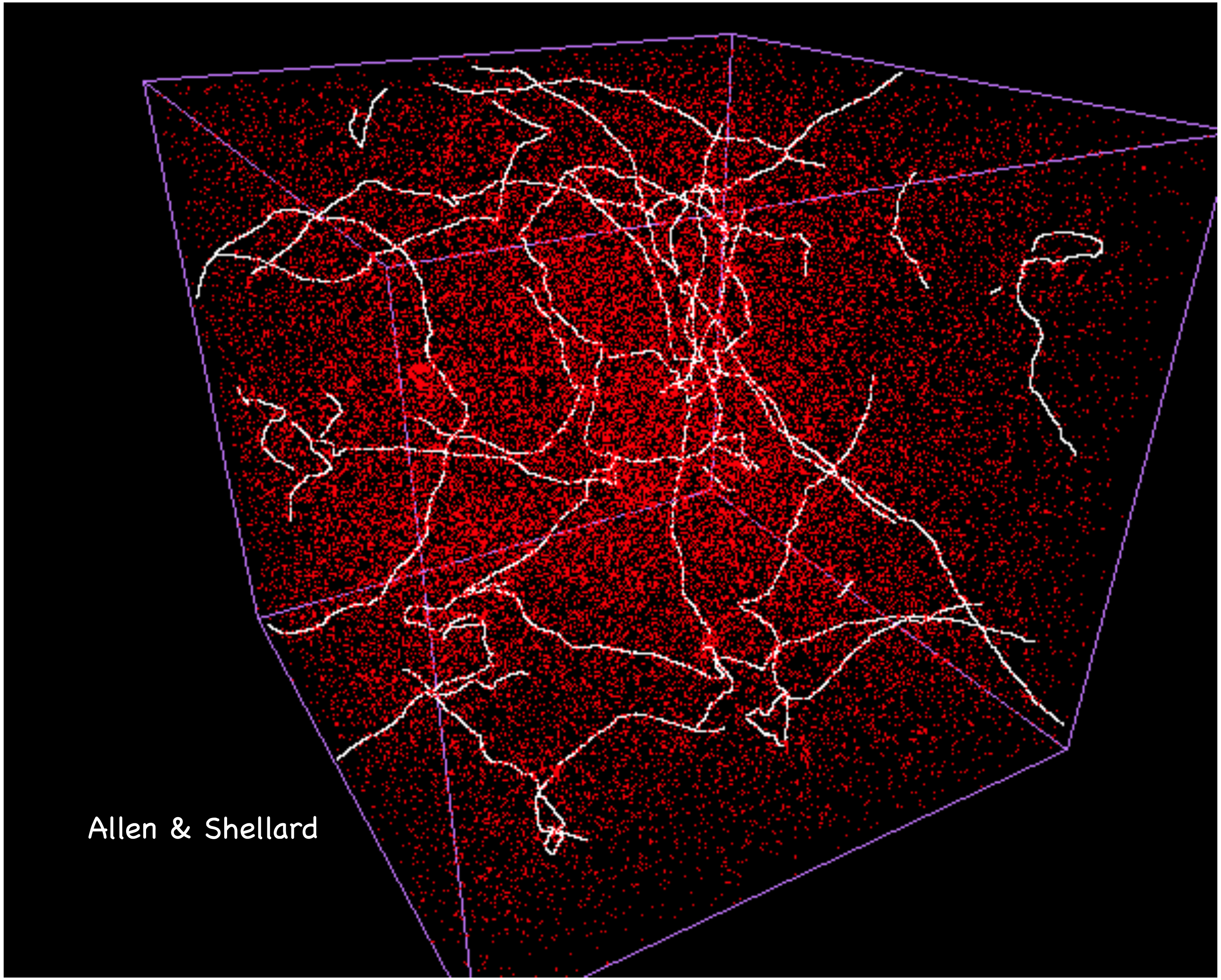
Ingredients for scaling

- Expansion of the universe increases the length of the infinite strings without making them thinner!

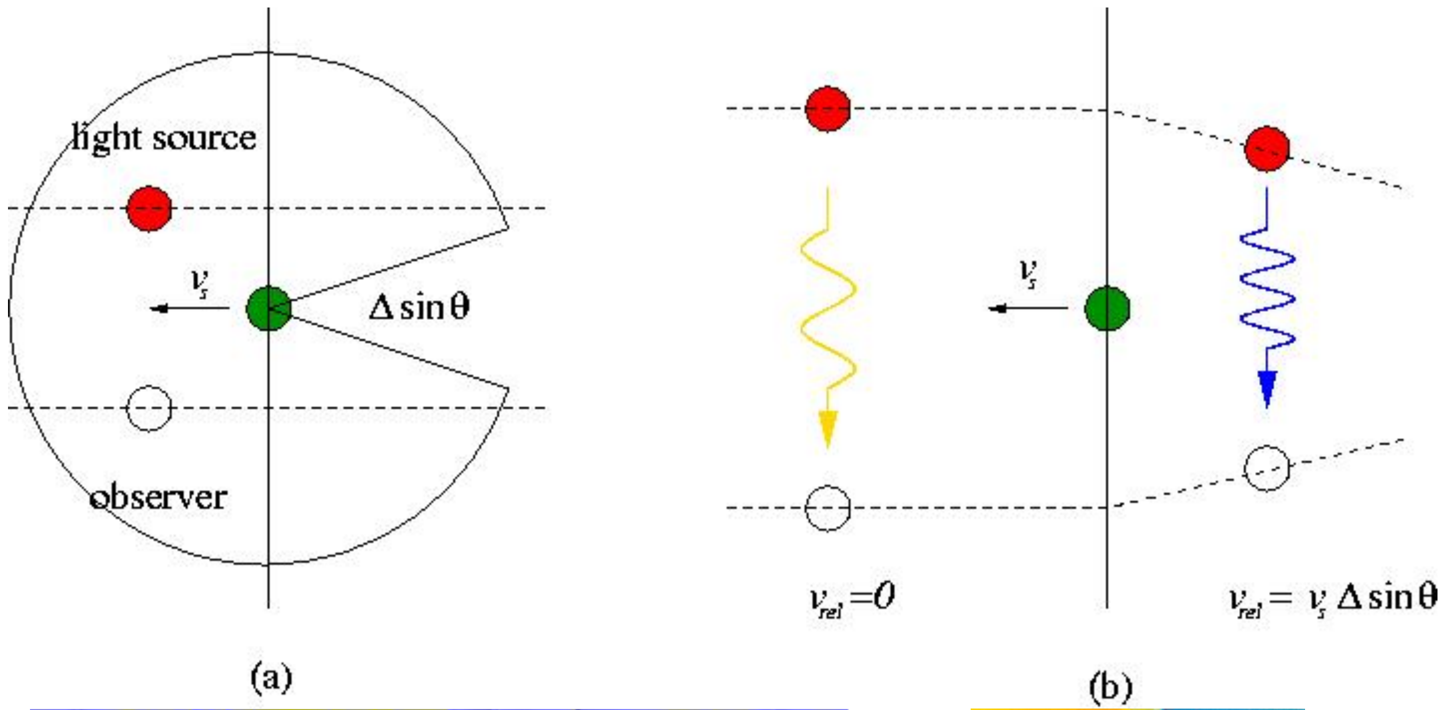
- When strings intersect, they can reconnect and chop off loops

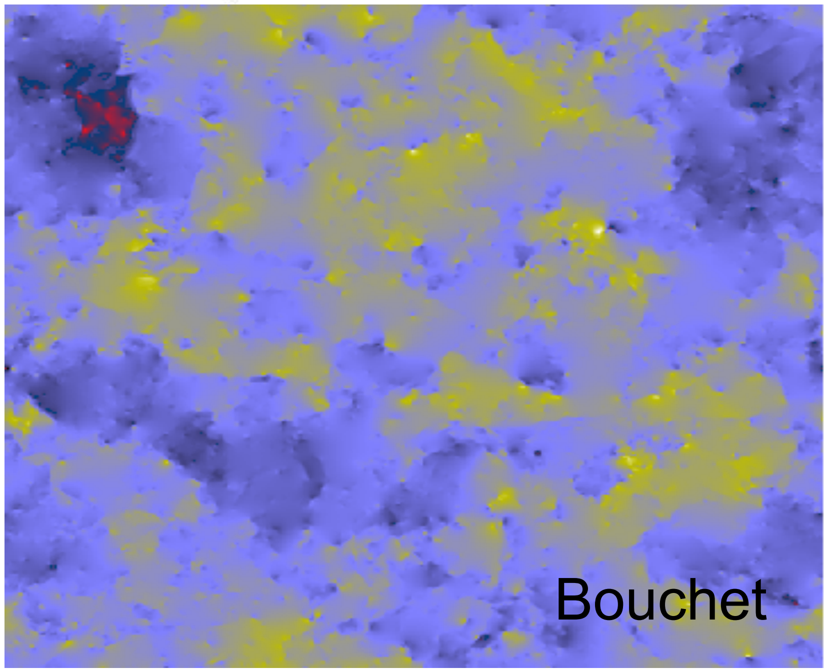


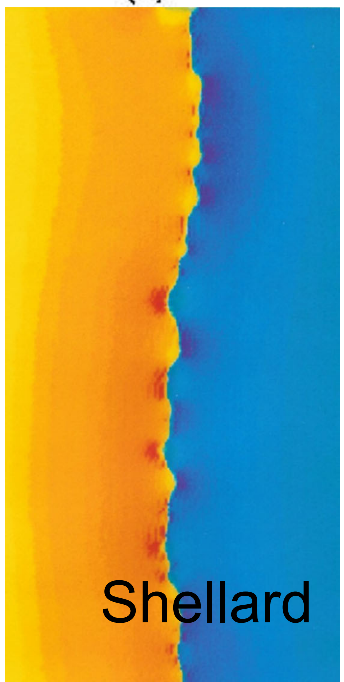
Scaling network of cosmic strings



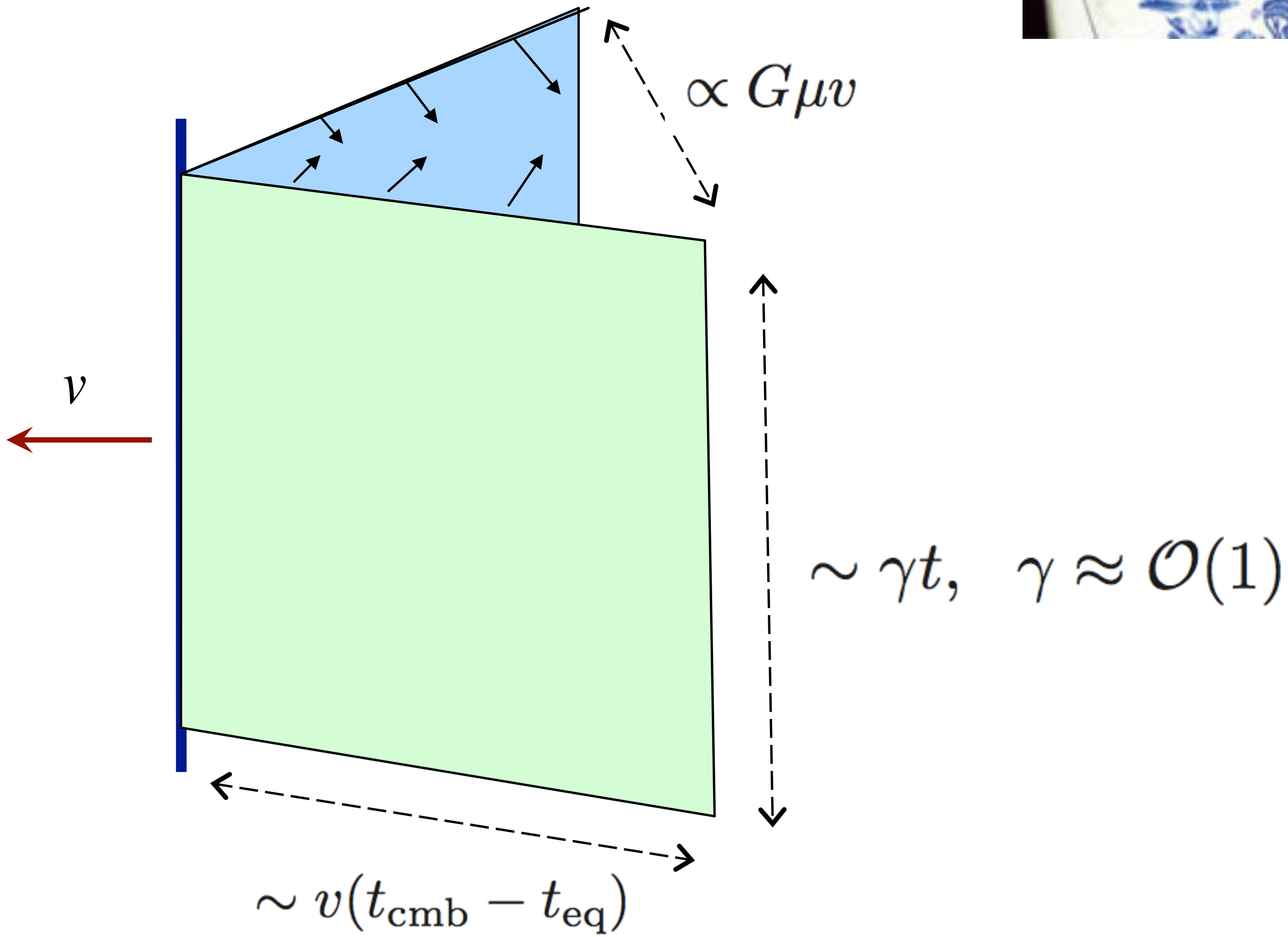
Stringy signatures in CMB



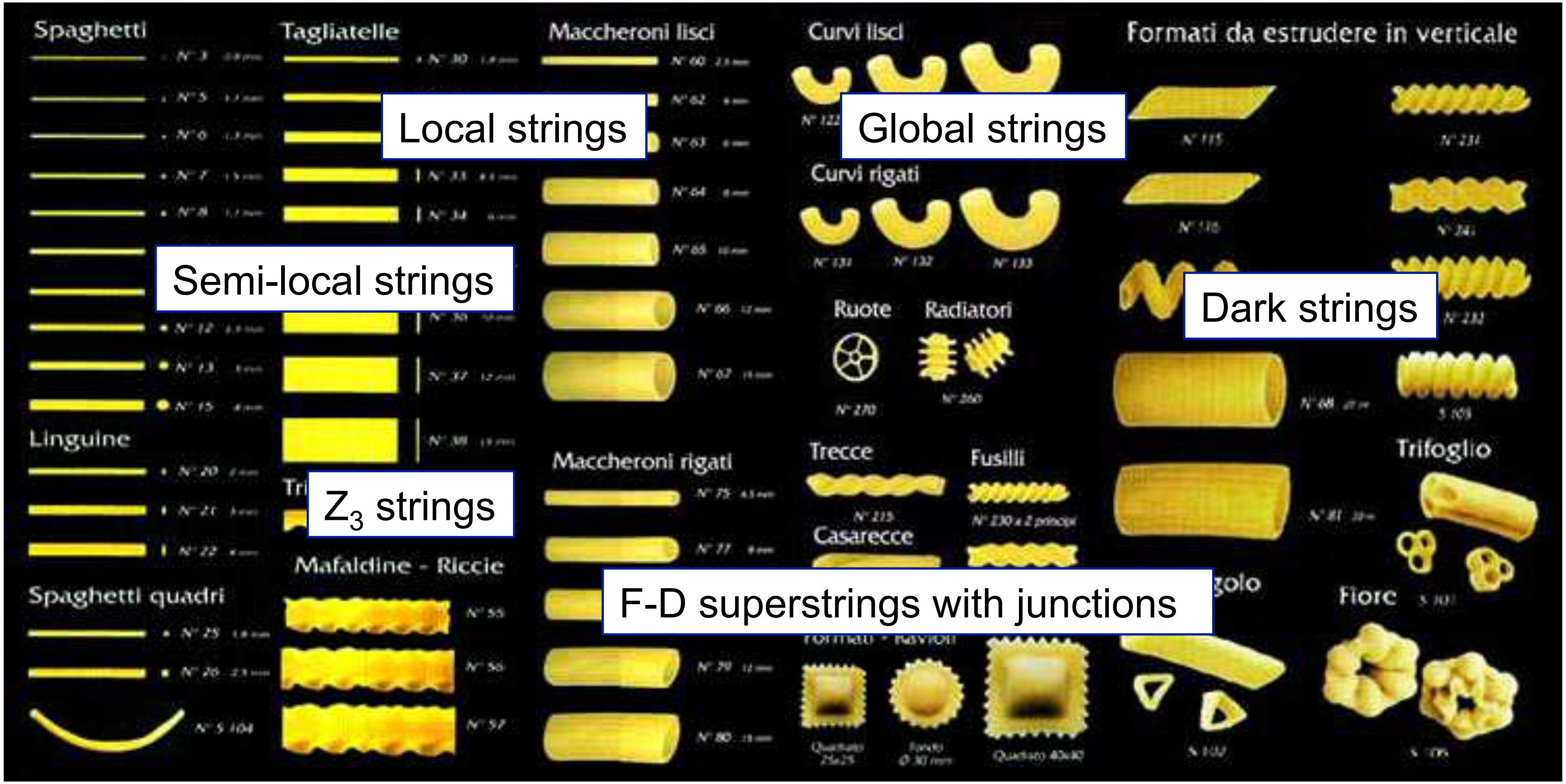




Wakes in matter



The string menu



Observational probes

- Gravitational waves
  - Pulsar timing
  - LIGO, LISA
- Cosmic rays
- Gravitational lensing of compact light sources
- Cosmic Microwave Background (and 21 cm)
  - Line discontinuities
  - Power Spectra*
  - Bispectrum, trispectrum, …

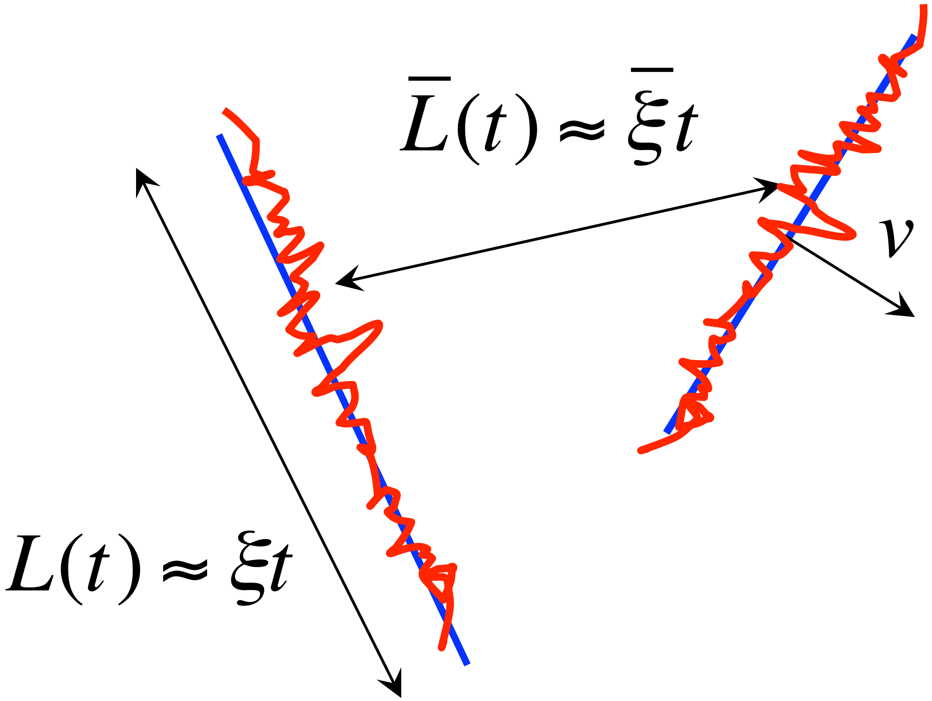
The Unconnected Segment Model

- Straight, randomly oriented, moving string segments

- Density, correlation length, and rms v

  determined from the one-scale model

- Segments can have wiggles



Vincent, Hindmarsh, Sakellariadou (1996)
Battye, Robinson, Albrecht (1997)
Pogosian & Vachaspati (1999): publicly available as CMBACT (CMB from ACTive sources)
Avgoustidis, Copeland, Moss & Skliros (2012): approximate analytical UETC's

The One-Scale Model

$$\rho = \frac{\mu}{L^2}$$

expansion

Formation of loops

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

Kibble, 1985

Loop chopping efficiency

$$\dot{\rho} = -2\frac{\dot{a}}{a}(1+v^2)\rho - \frac{\tilde{c}\,v\rho}{L}$$

Velocity-dependent one-scale model

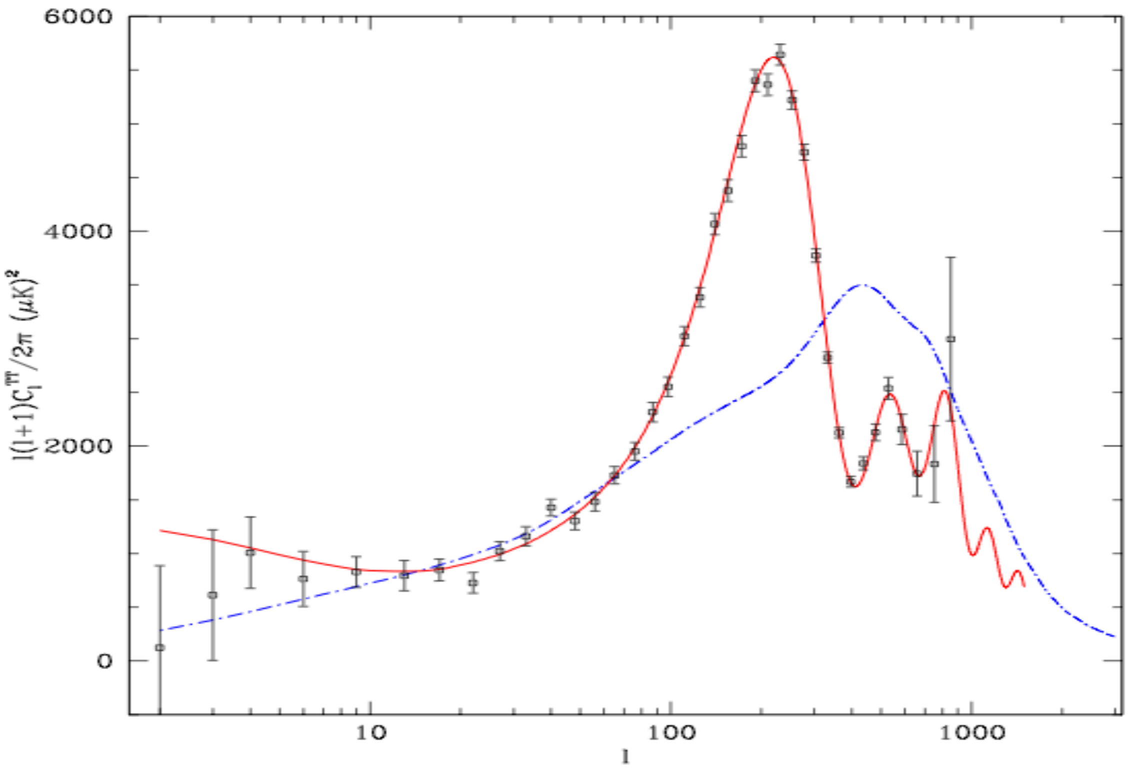
Martins & Shellard, 1996, 2002

"Momentum Parameter"

$$\dot{v} = (1-v^2)\left(\frac{k}{L} - 2\frac{\dot{a}}{a}v\right)$$

Inflation vs Strings

LP, T. Vachaspati, PRD60 (1999) 083504



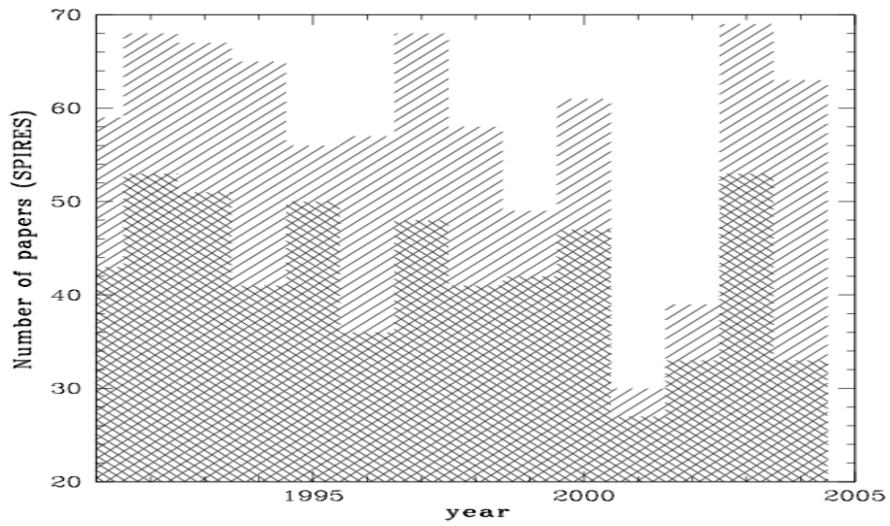
Cosmic Strings

Inflation

Planck can tolerate a 3% contribution from strings

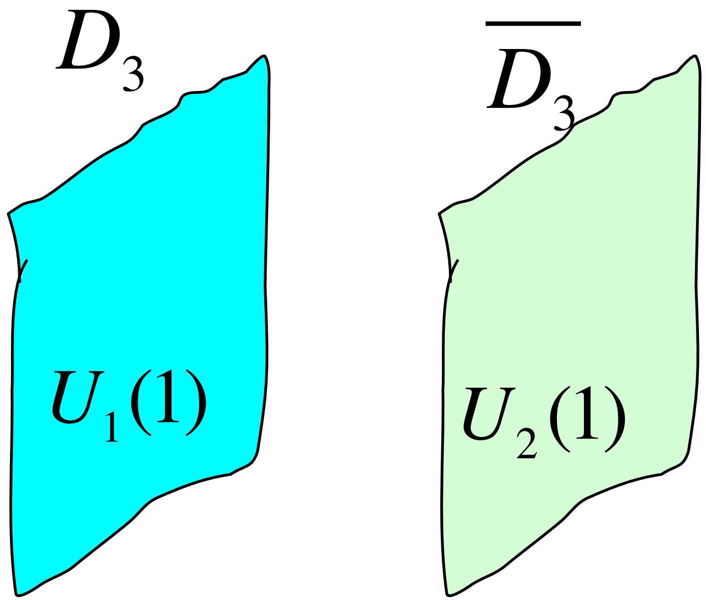
Why cosmic strings again?

- Topological defects persist
- Beyond simplest inflation
  - multi-field inflation models
- Superstrings can be cosmic
  - brane inflation
  - string theory in the sky…



Jones, Stoica and Tye, JHEP 07 (2002) 051
Sarangi and Tye, PLB 536 (2002) 185
Kachru, Kallosh, Linde, Maldacena, McAllister and Triverdi, JCAP 0310 (2003) 013
Dvali and Vilenkin, JCAP 0403 (2004) 010
Copeland, Myers and Polchinski, JHEP 06 (2004) 013
….

Strings from brane annihilation



$$U_-(1) \quad : \quad A_1 - A_2$$

$$U_+(1) \quad : \quad A_1 + A_2$$

Tachyon acquires VEV:

$$U_-(1) \to 1$$

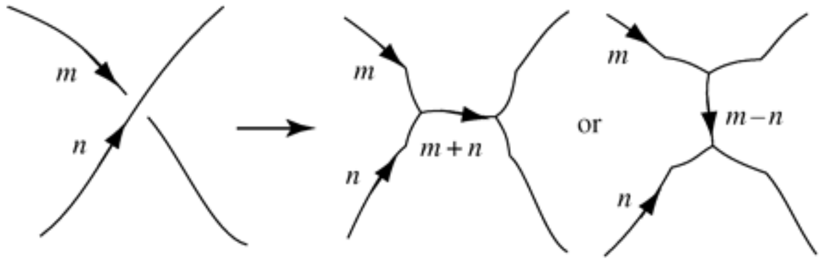
$$\pi_1(U(1)) = Z \neq I$$ → **Strings (D_1-branes)**

$U_+(1)$ confined to **flux tubes (F-strings)**

Dvali and Vilenkin, JCAP (2004) 010

F-D superstring networks with junctions

Copeland, Kibble, Steer PRL'06, PRD'07



A Multi-Tension String Network Model

- extend the VOS model of Martins & Shellard:

$$\rho_i = \frac{\mu_i}{L_i^2} \qquad \mu_i \equiv \mu_{(p_i,q_i)} = \frac{\mu_F}{g_s}\sqrt{p_i^2 g_s^2 + q_i^2}$$

$$\dot{\rho}_i = -2\frac{\dot{a}}{a}(1+v_i^2)\rho_i - \frac{c_i v_i \rho_i}{L_i} - \sum_{a,k} \frac{d_{ia}^k \bar{v}_{ia} \mu_i \ell_{ia}^k(t)}{L_a^2 L_i^2} + \sum_{b,\, a \le b} \frac{d_{ab}^i \bar{v}_{ab} \mu_i \ell_{ab}^i(t)}{L_a^2 L_b^2},$$

$$\dot{v}_i = (1-v_i^2)\left[\frac{k_i}{L_i} - 2\frac{\dot{a}}{a}v_i + \sum_{b,\, a \le b} b_{ab}^i \frac{\bar{v}_{ab}}{v_i} \frac{(\mu_a + \mu_b - \mu_i)}{\mu_i} \frac{\ell_{ab}^i(t) L_i^2}{L_a^2 L_b^2}\right].$$

Avgoustidis & Copeland, 2010

Scaling solutions at different g_s:

$$L_i(t) = \xi_i t$$

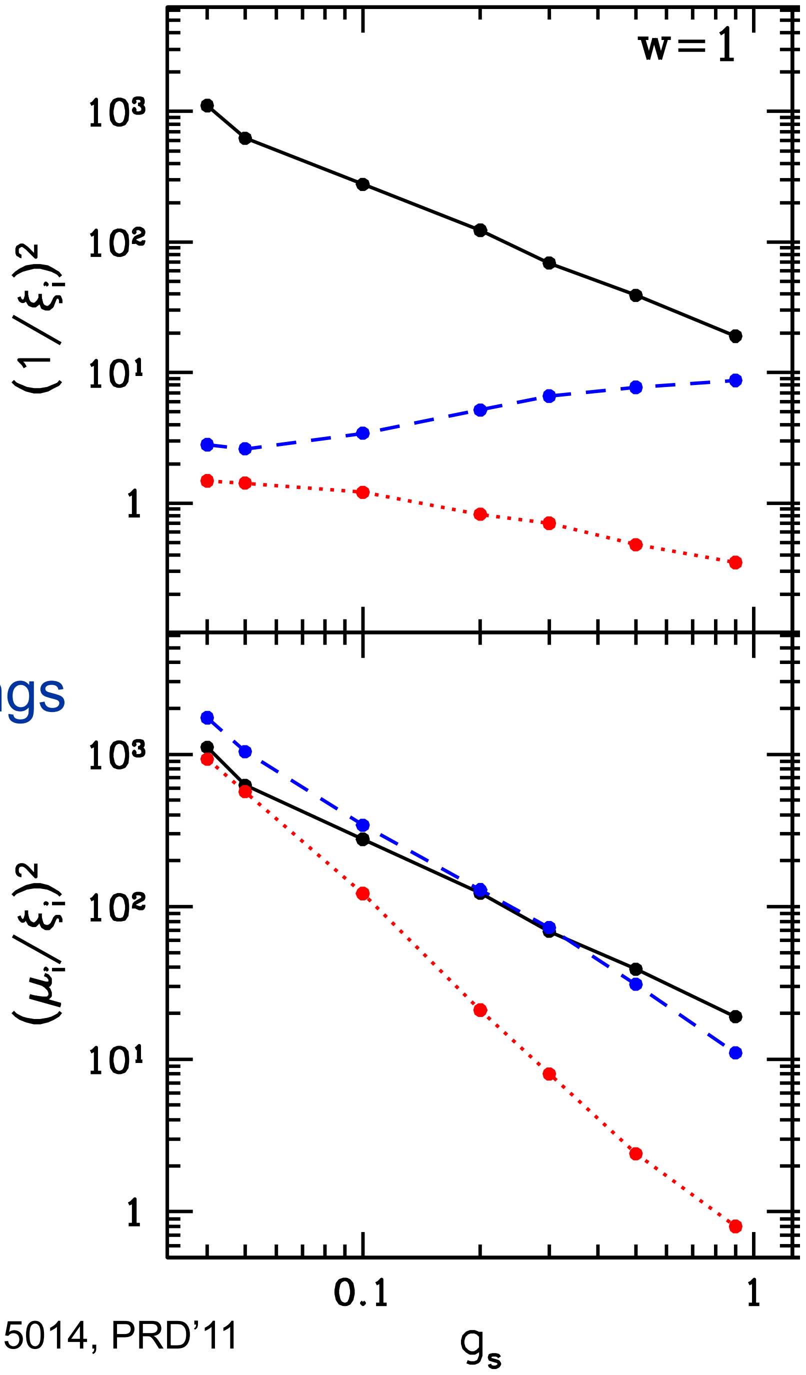
- The lightest (F) strings are always the most populous

$$N_i \propto \frac{1}{\gamma \xi_i^2}$$

- D strings become much heaver than F strings at small couplings. Heavy, rare D strings dominate the CMB spectra at small g_s

$$C_\ell^{(i)} \propto \frac{\mu_i^2 \gamma}{\xi_i^2}$$

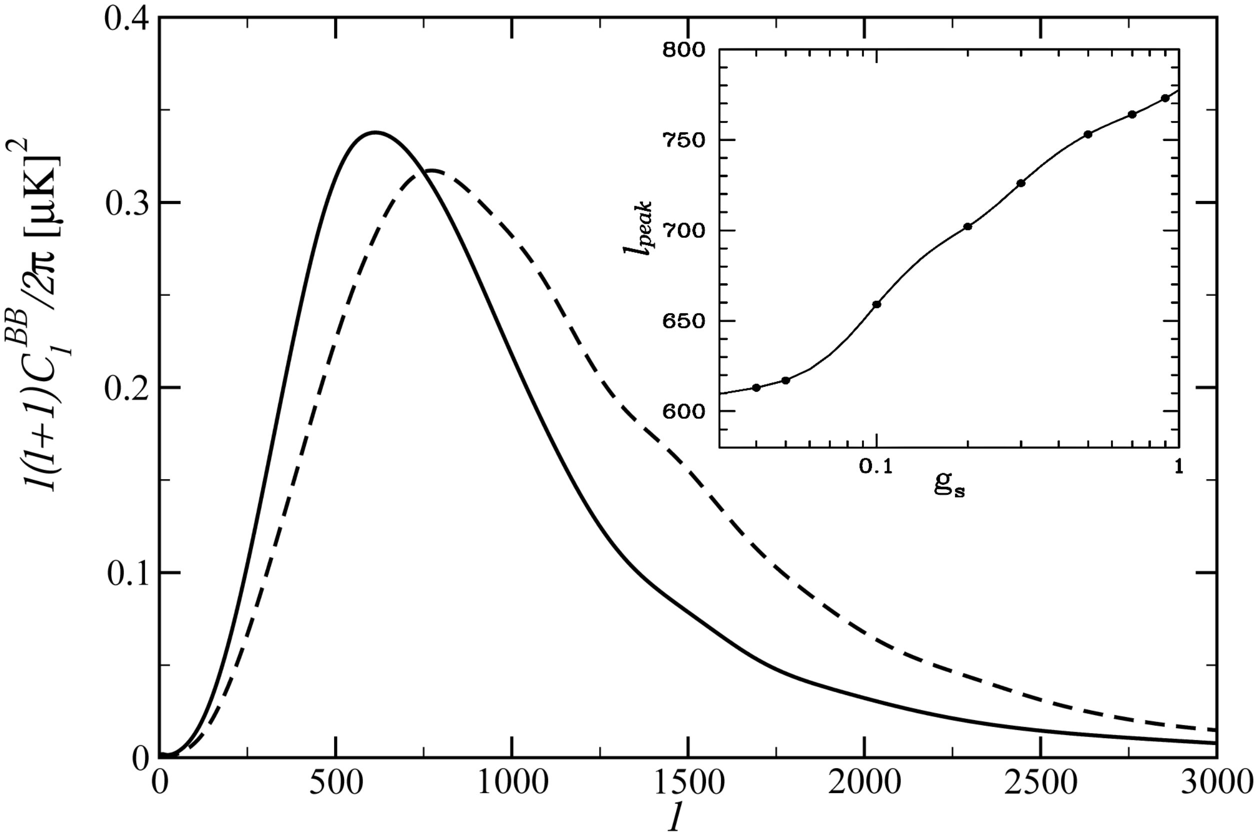
- F strings dominate the CMB power spectrum at large couplings



A. Pourtsidou, A. Avgoustidis, E.J. Copeland, LP, D.A. Steer, 1012.5014, PRD'11

Strings and future B-mode data

The peak of the B-mode spectrum at different fundamental string couplings

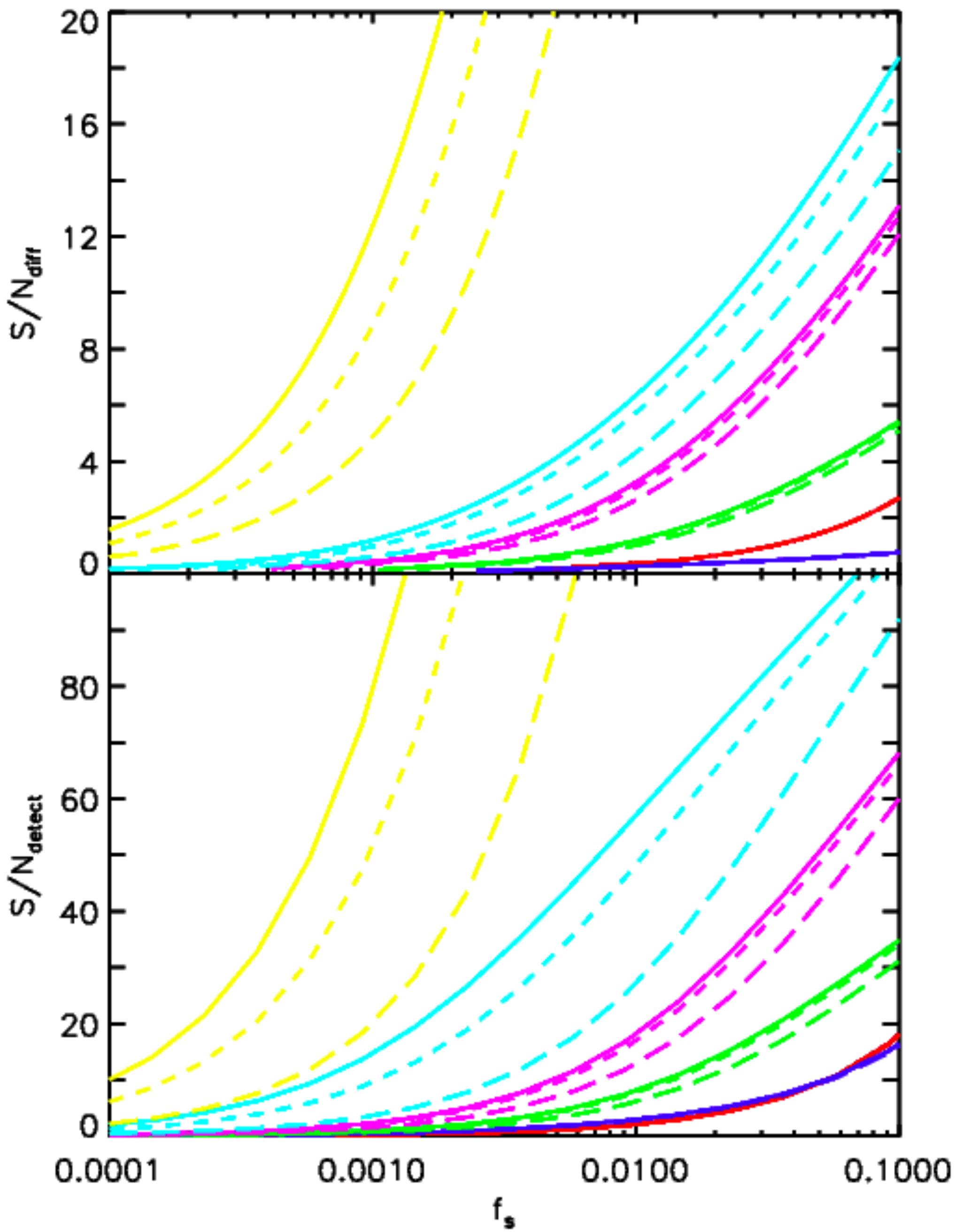


A. Pourtsidou, A. Avgoustidis, E.J. Copeland, LP, D.A. Steer, 1012.5014, PRD'11

Planck, SPIDER, EBEX, POLARBEAR, QUIET, COrE

- S/N in detecting the difference between large and small g_s

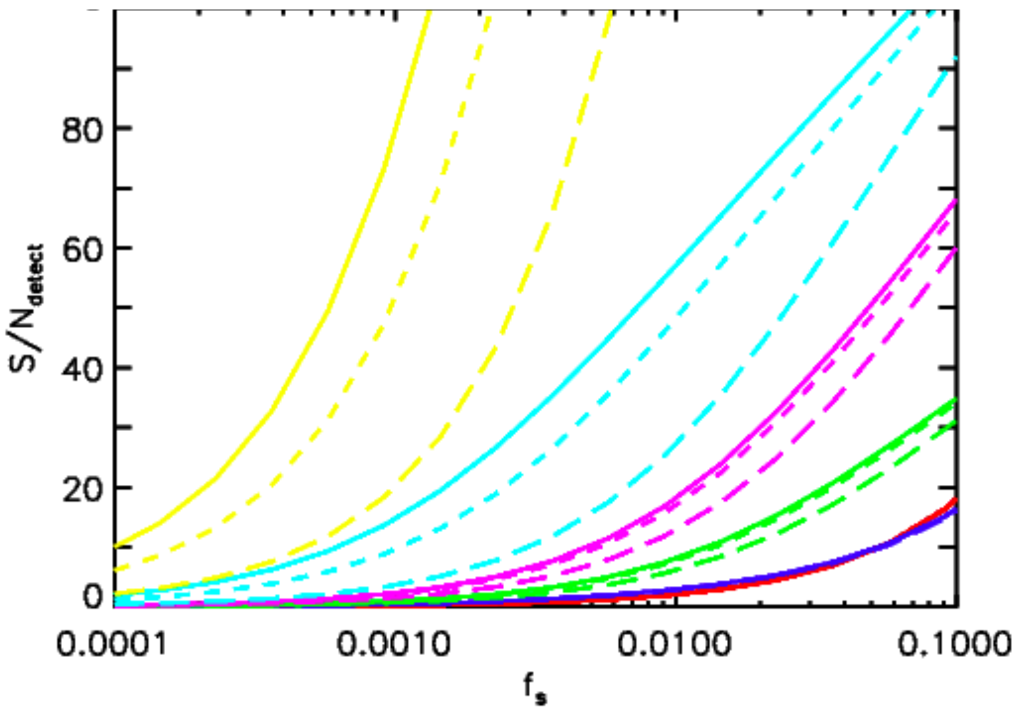
- S/N of overall detection



A. Avgoustidis, E.J. Copeland, A. Moss, LP, A. Pourtsidou, D.A. Steer, 1105.6198, PRL'11

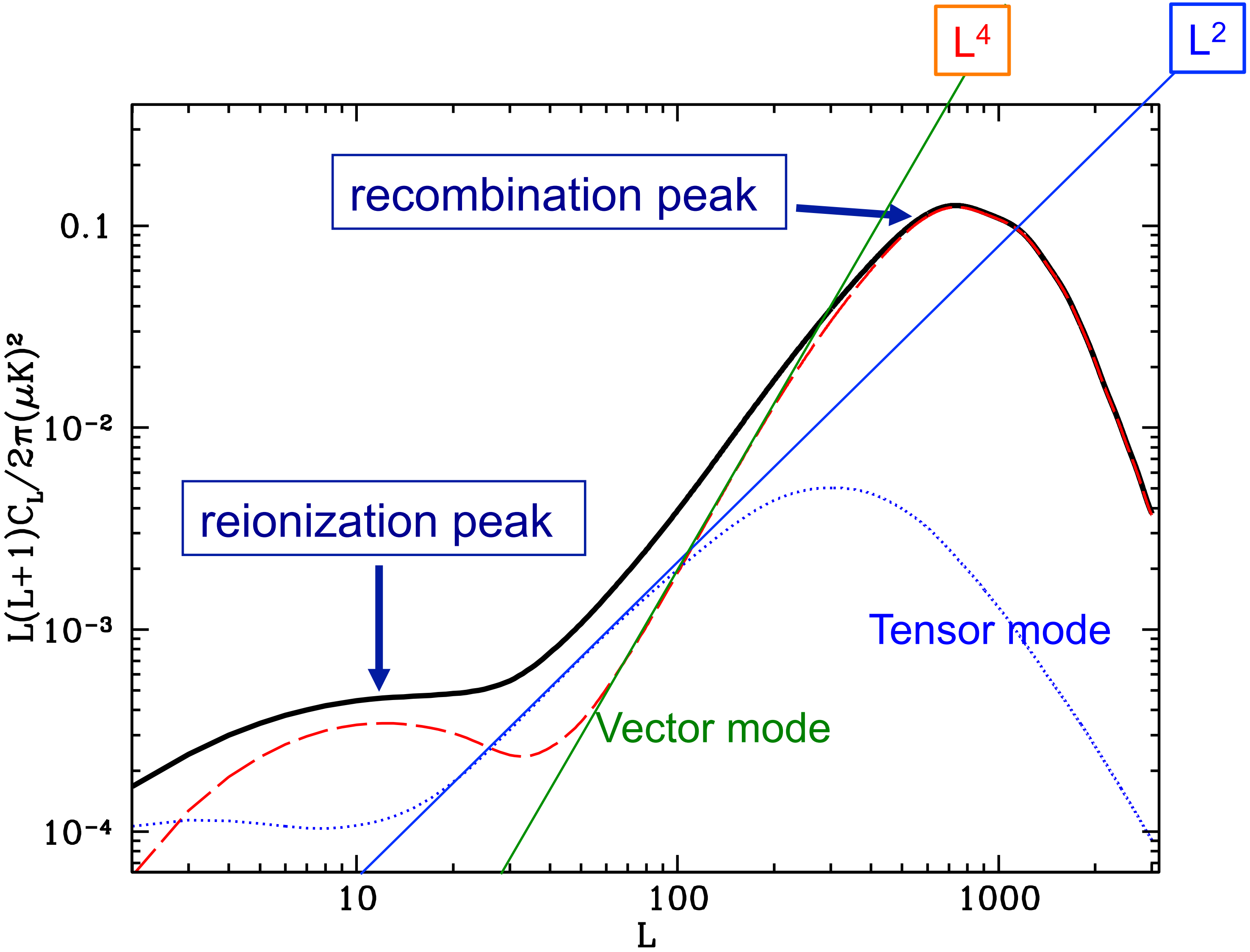
- Strings can source up to 3% of CMB TT power
- Even at 0.01%, they can source observable B-modes

Planck, SPIDER, EBEX, POLARBEAR, QUIET, COrE

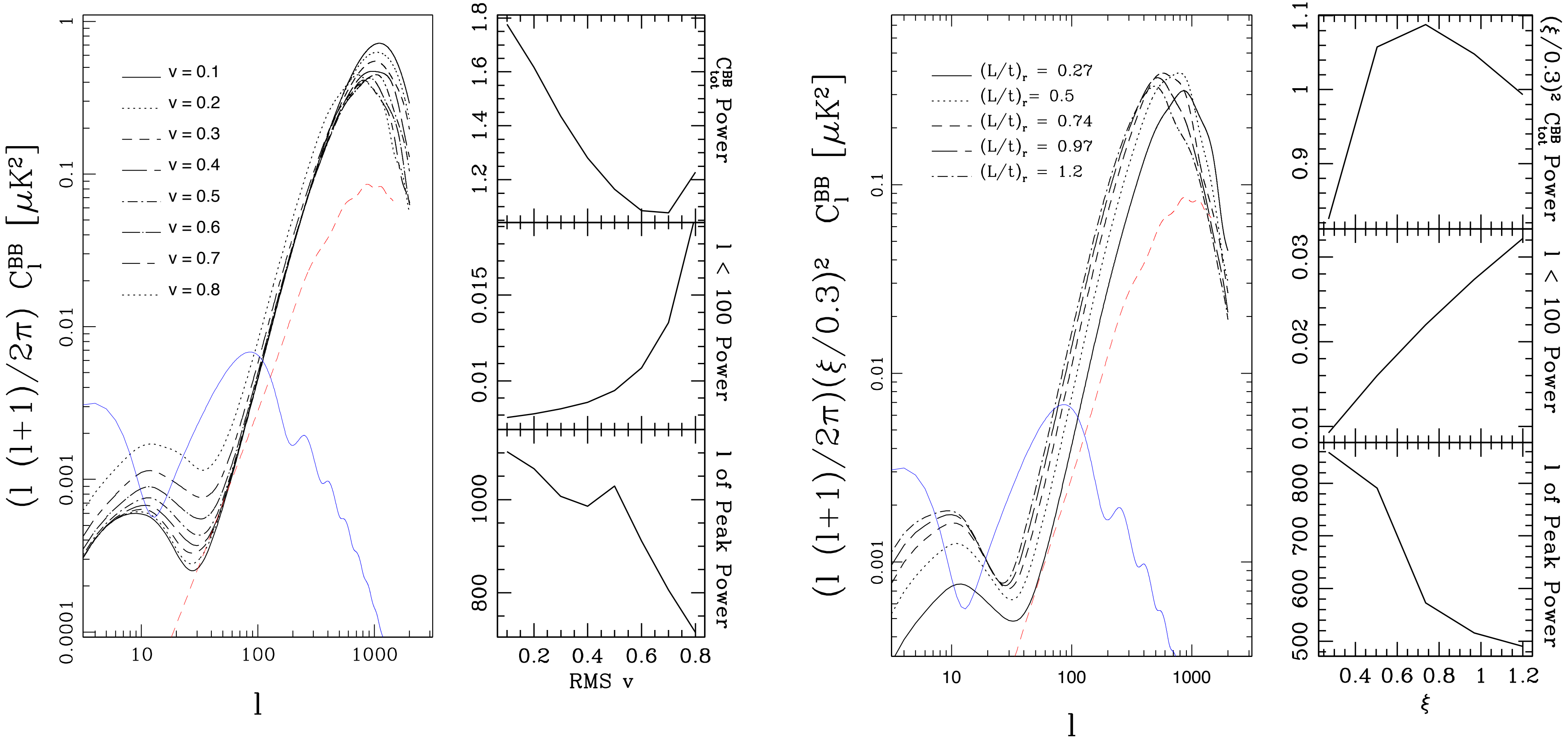


A.Avgoustidis, E.J.Copeland, A.Moss, LP, A.Pourtsidou, D.A.Steer, 1105.6198, PRL

B-modes from cosmic strings

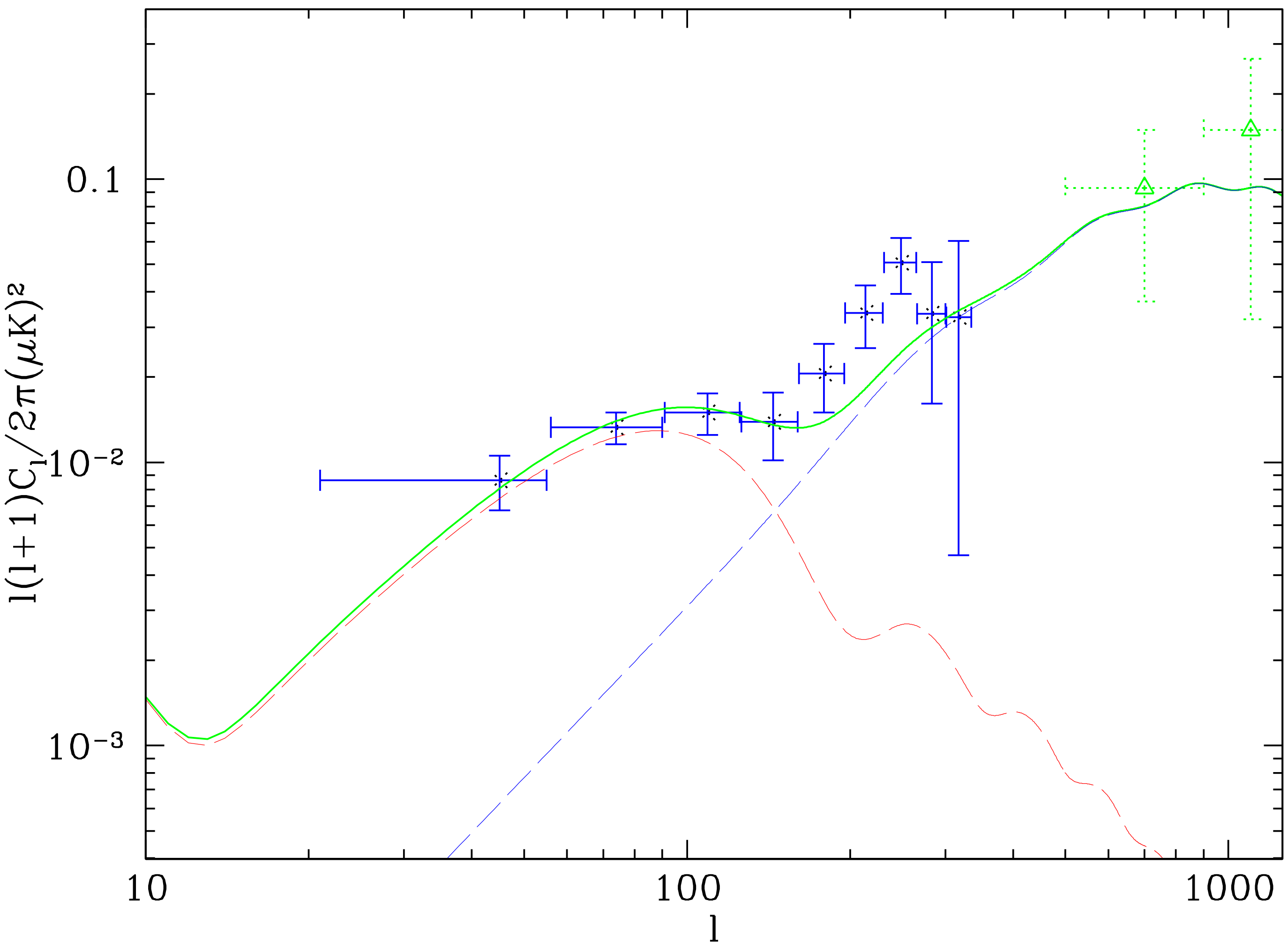


Dependence on ξ and v

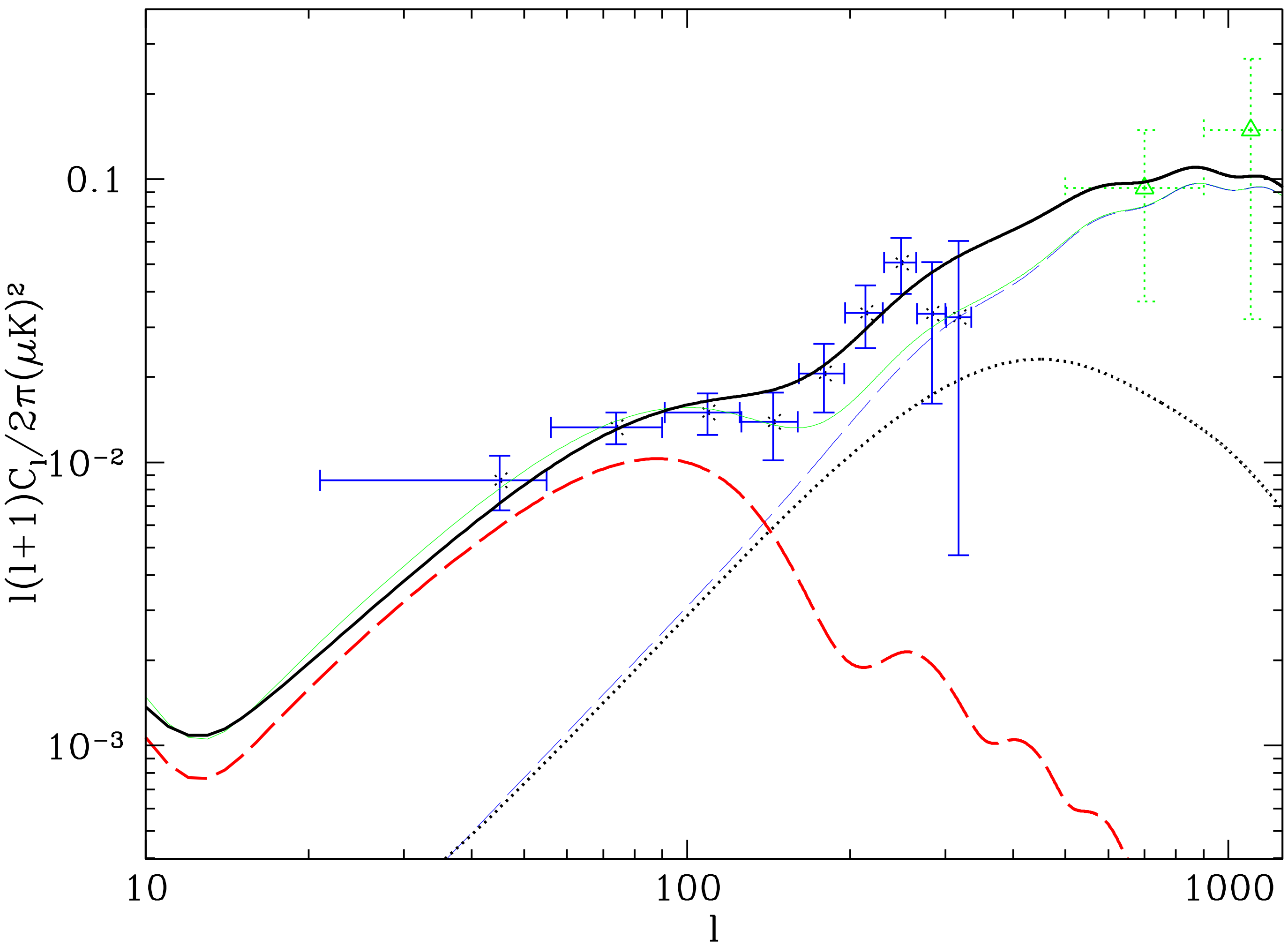


M. Wyman and LP, 0711.0747, PRD'08

No strings, r = 0.2

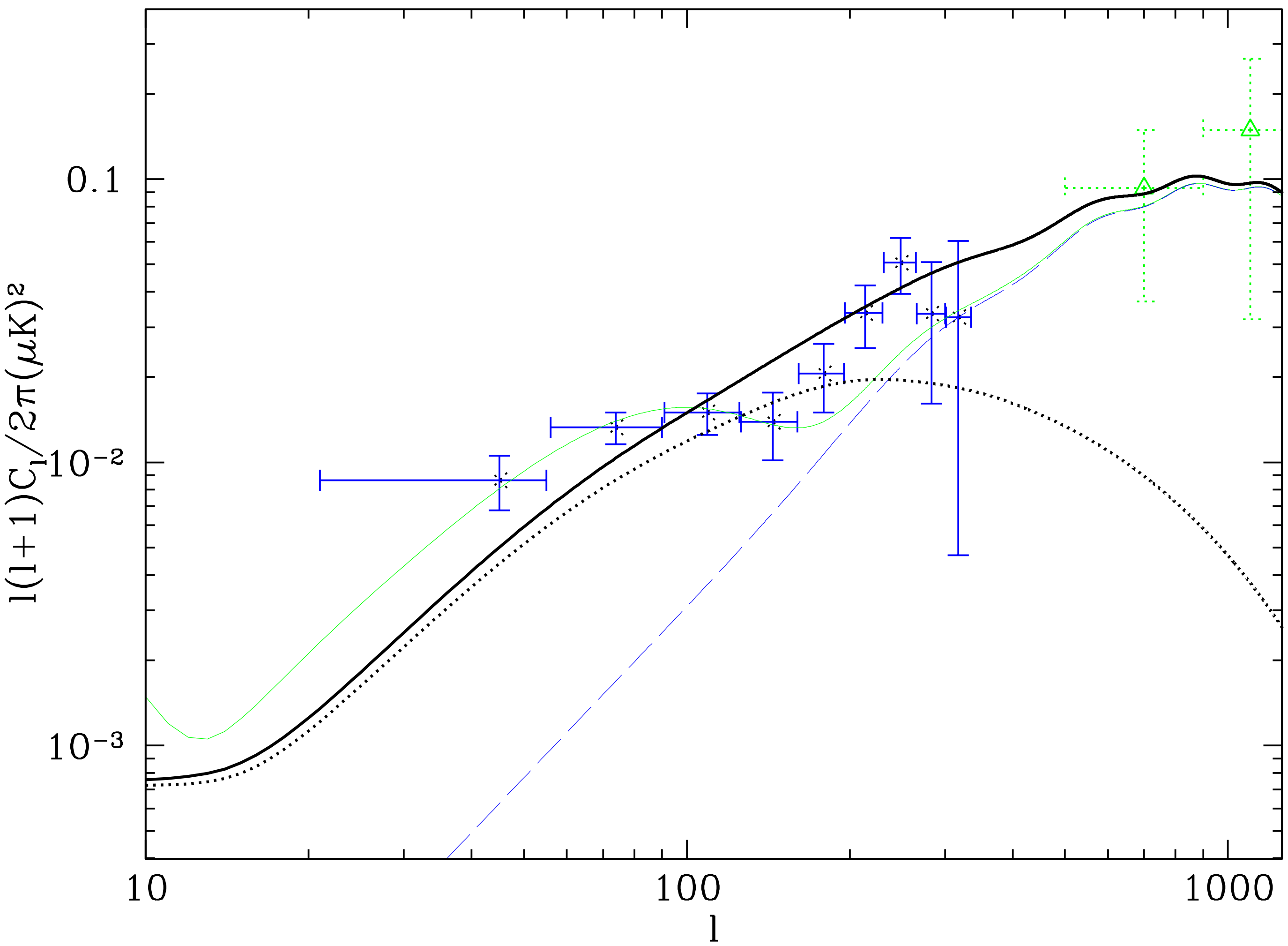


Strings & r = 0.15



A. Moss and LP, 1403.6105, PRL

Strings* & r = 0



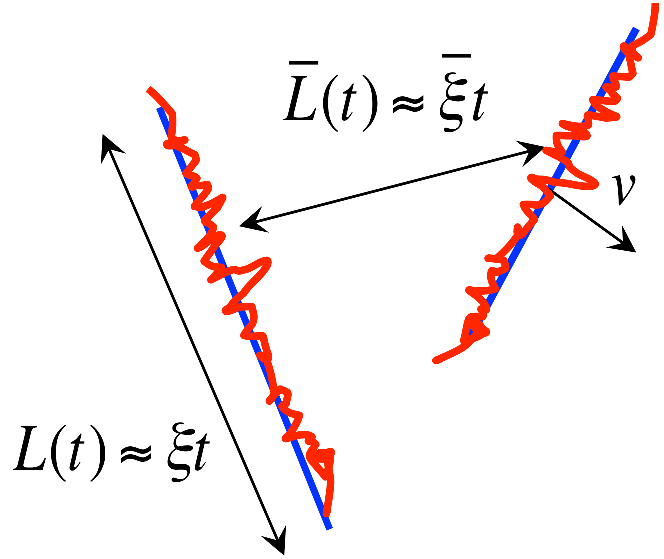
* with very large correlation lengths

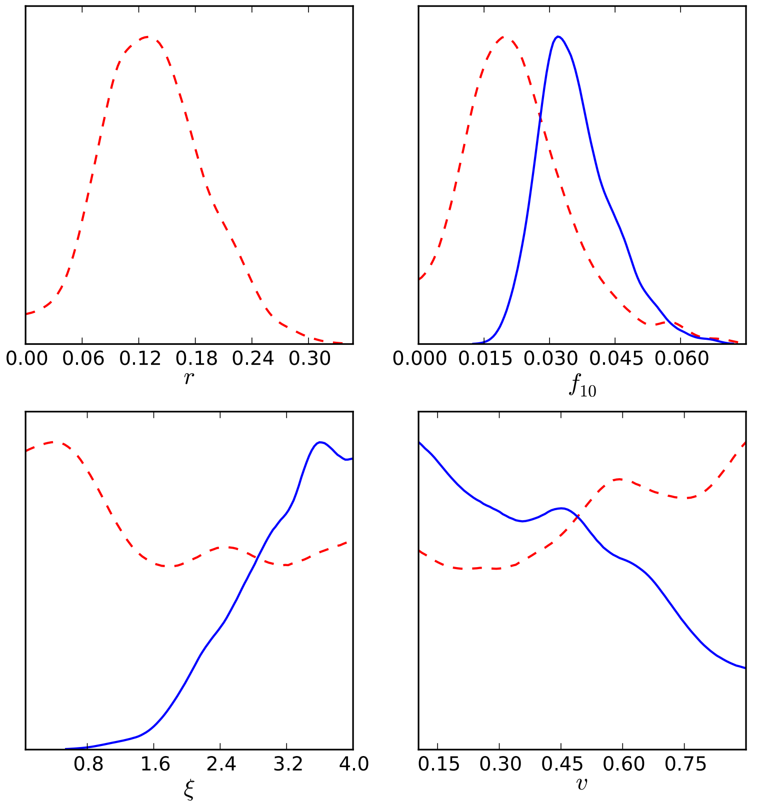
A. Moss and LP, 1403.6105, PRL

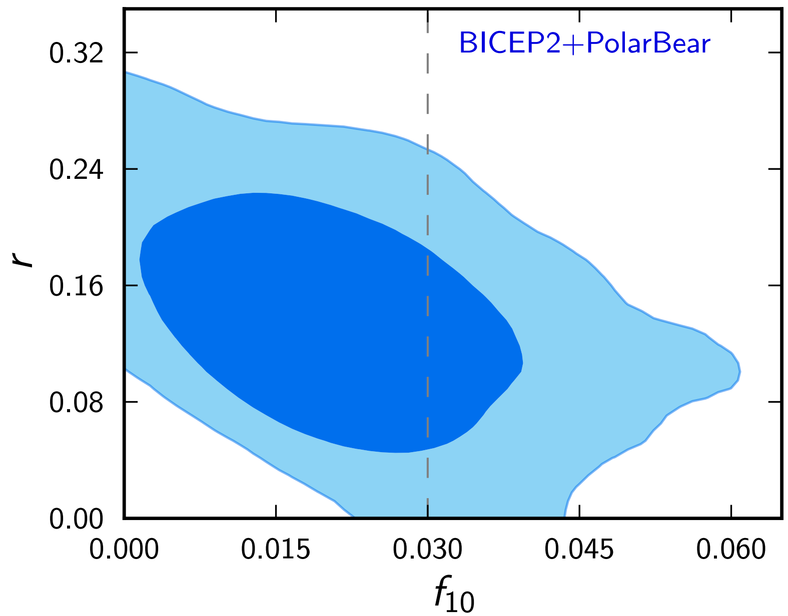
f_{10} : fraction of the string contribution to TT at L=10

ξ : inter-string distance

v : root-mean-square velocity







A. Moss and LP, 1403.6105, PRL

Cosmic microwave anisotropies from BPS semilocal strings

Jon Urrestilla,[1,*] Neil Bevis,[2,1,†] Mark Hindmarsh,[1,‡] Martin Kunz,[3,1,§] and Andrew R. Liddle[1,¶]

http://arxiv.org/abs/0711.1842

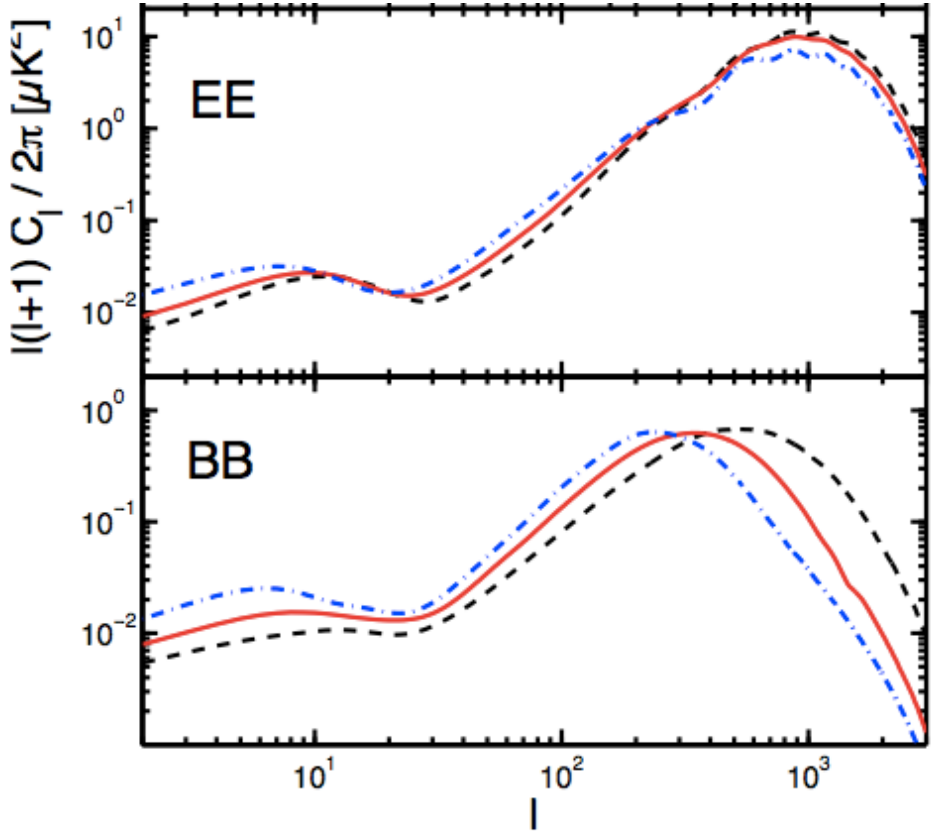


FIG. 9: Polarization power spectra for semilocal strings (solid red), compared to Abelian Higgs strings (dashed black) and textures (dot-dash blue). The top figure is the TE power

Implications of BICEP2 for strings*

- Local (Nambu-Goto-like) strings can improve the fit if added to the inflationary GW contribution, but cannot fit BICEP2 on their own
    - F-D superstrings need a non-zero r to fit BICEP2

- Global strings or textures may provide an acceptable fit

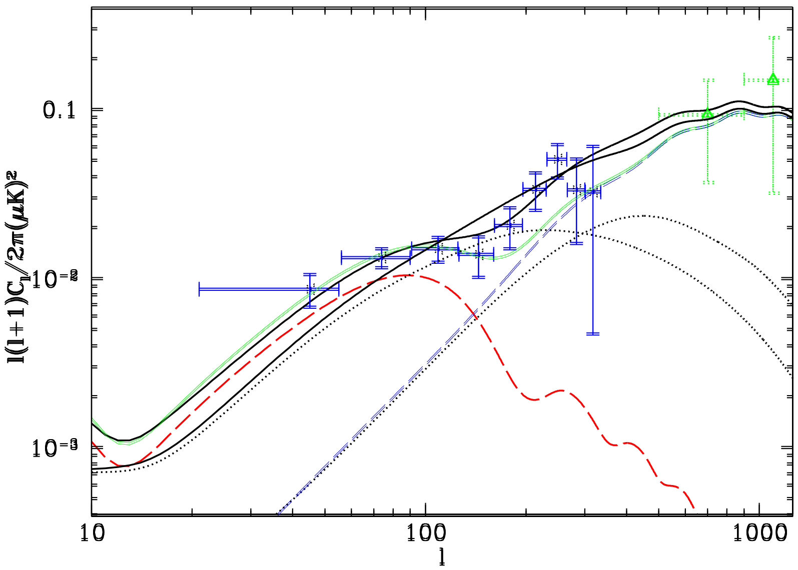
- Strings formed during (as opposed to after) Inflation?

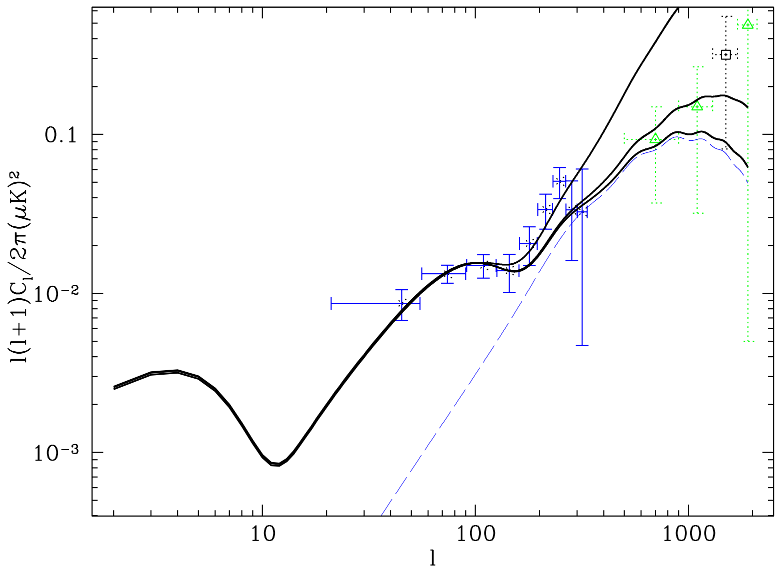
Lazarides and Shafi; Shafi and Vilenkin (1984)

* Pending a better understanding of foregrounds

Summary

Did BICEP2 find inflationary gravity waves, primordial magnetic fields or cosmic defects?





We have entered the era of precision B-mode science - a new frontier for testing fundamental physics with cosmology

Why to CMBACT?

- Performing high resolution simulations of string networks is costly

- Explore CMB spectra from different types of strings by scanning the effective parameter space

- Can tune CMBACT parameters to match UETCs from simulations
  The wiggliness parameter provides an additional lever
  Battye and Moss (2010)

- Can be extended to calculate bispectra
  Gangui, LP, Winitzki (2001)

- Can be extended to multi-tension networks
  Avgoustidis, Copeland, Moss, LP, Pourtsidou, Steer (2011, 2012)