CMB predictions from (semilocal) cosmic strings

Jon Urrestilla

University of Sussex
(Marie Curie Intra-European Fellow)

In collaboration with: N. Bevis, M. Hindmarsh, M. Kunz, A. Liddle

Cosmo 07

Brighton, 24-08-07

Defects vs. Inflation
for seeds of structure formation

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Nice link to High Energy Physics (Kibble mechanism)

Solved many more problems (horizon, flatness...)

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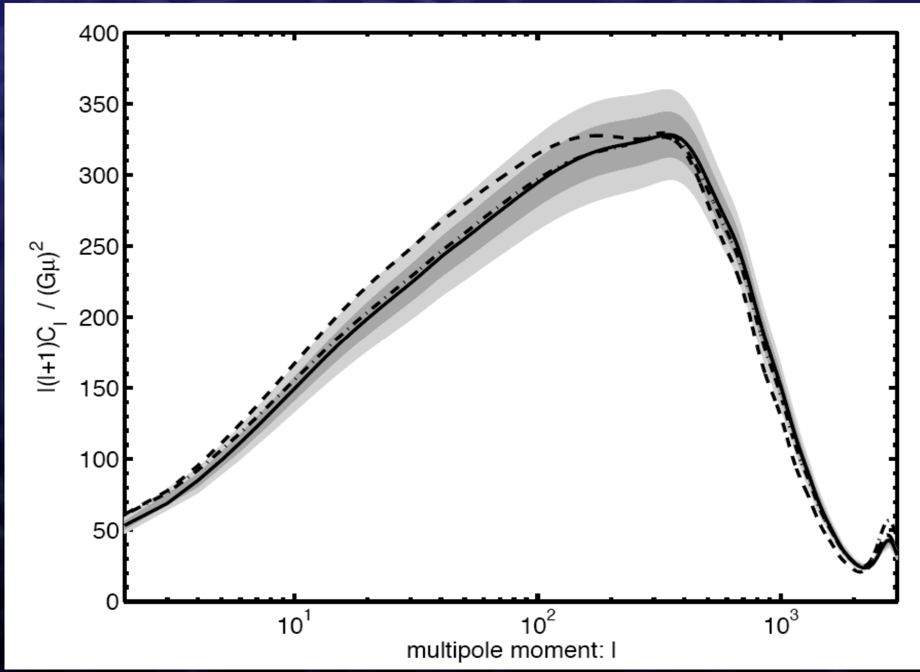

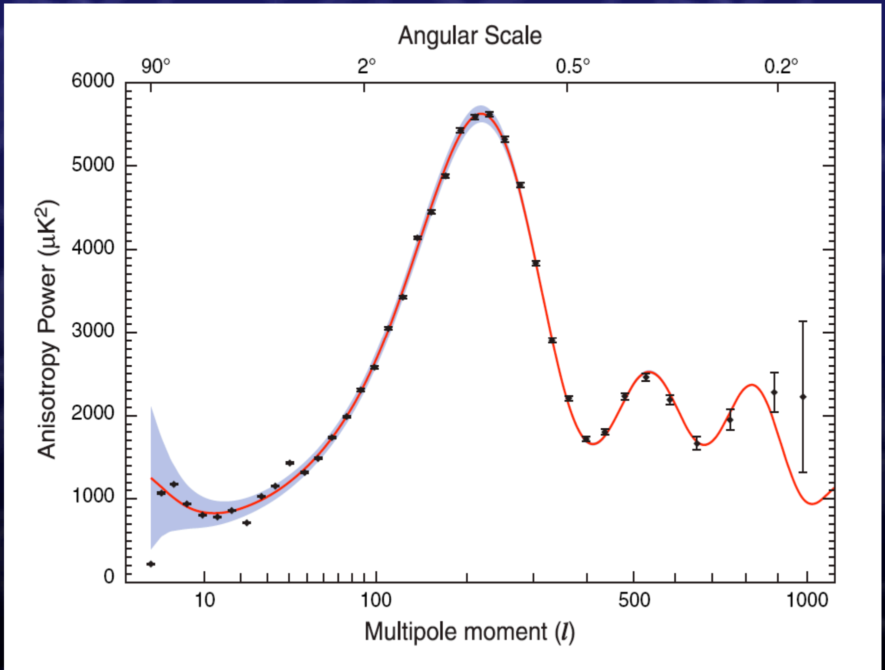

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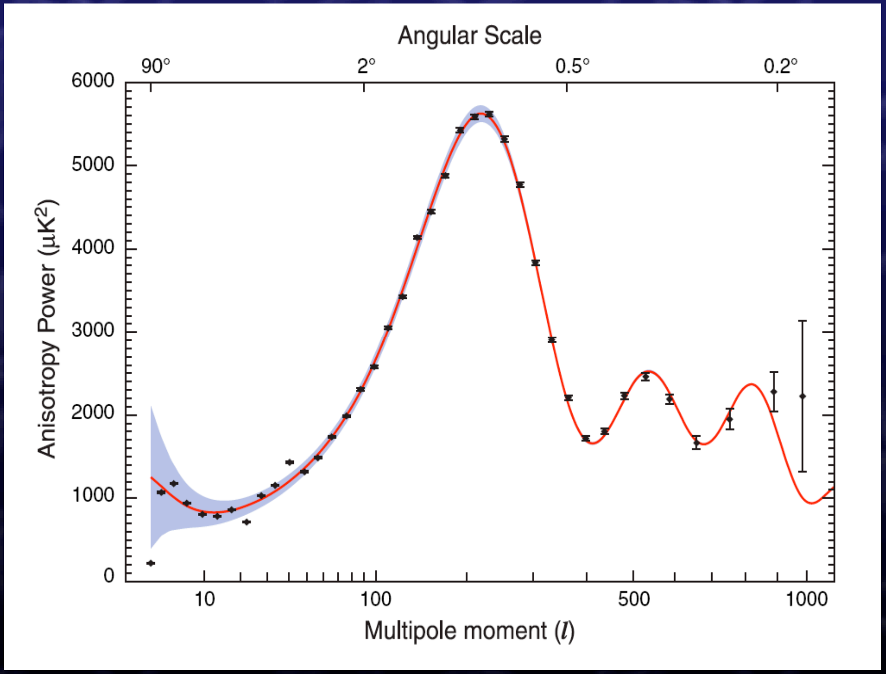


Particle Physics models of inflation?

“ Defects are generic in SUSY GUT models “

R.Jeannerot, J.Rocher, M. Sakellariadou PRD68 (2003)

Assuming standard hybrid inflation, we select all the models which can solve the GUT monopole problem, lead to baryogenesis after inflation and are consistent with proton life time measurements.

e.g.:

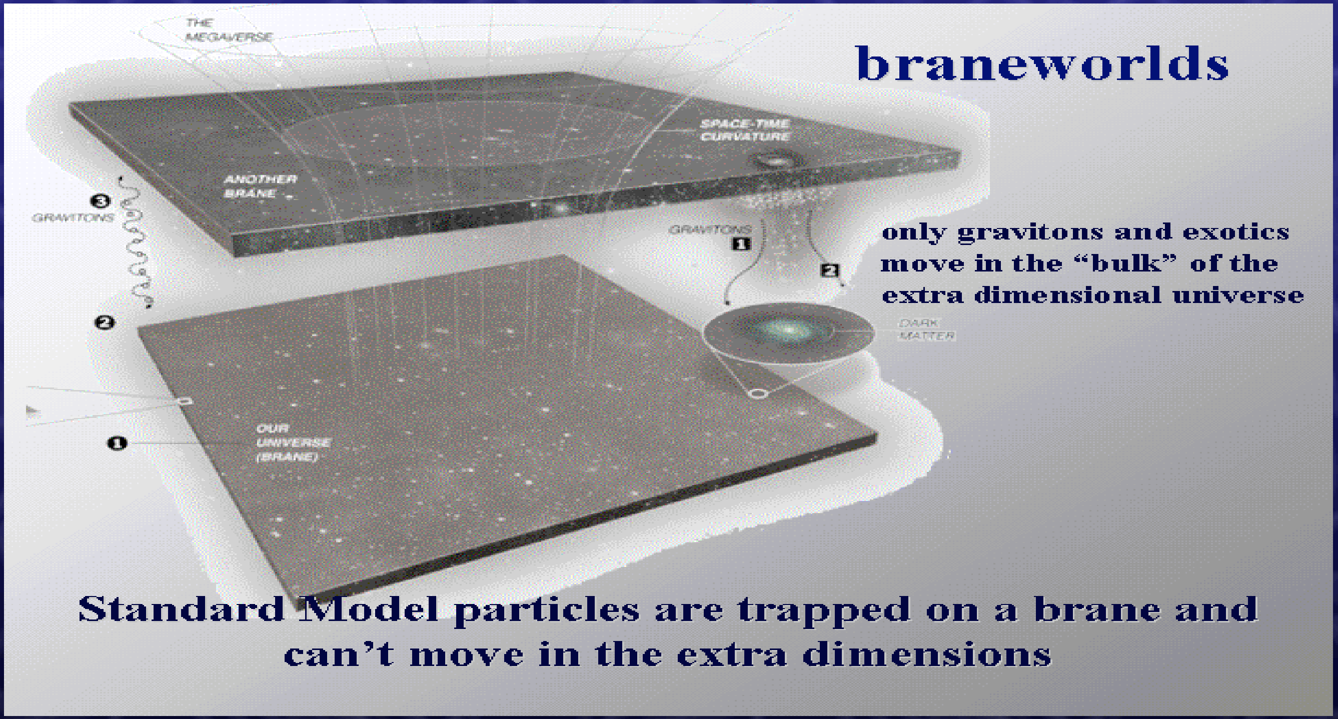
$$\mathrm{SO(10)} \supset \mathrm{SU(5)} \times \mathrm{U(1)_V} \supset \mathrm{SU(3)_C} \times \mathrm{SU(2)_L} \times \mathrm{U(1)_Z} \times \mathrm{U(1)_V}$$

$$\mathrm{SO(10)} \left\{ \begin{array}{l} \xrightarrow{1} \; 5\,1_V \left\{ \begin{array}{llll} \xrightarrow{2\;(2)} & 5\;(Z_2) & \xrightarrow{1} & G_{SM}\;(Z_2) \\ \xrightarrow{1} & 3_C\;2_L\;1_Z\;1_V & \xrightarrow{2\;(2)} & G_{SM}\;(Z_2) \\ \xrightarrow{1,2\;(1,2)} & G_{SM}\;(Z_2) & & \end{array} \right. \\ \xrightarrow{1} \; 5_F\;1_V \; \xrightarrow{2'\;(2)} \; G_{SM}\;(Z_2) \\ \xrightarrow{0\;(2)} \; 5\;(Z_2) \; \xrightarrow{1} \; G_{SM}\;(Z_2) \end{array} \right.$$

Among the SSB schemes which are compatible with high energy physics and cosmology, we did not find any without strings after inflation.

Particle Physics models of inflation?

Cosmic superstrings (generically) form at the end of brane inflation!



“Towards the end of the brane inflationary epoch in the brane world, cosmic strings are copiously produced during brane collision.”

Sarangi and Tye; PLB536 (2002)

Defects vs Inflation

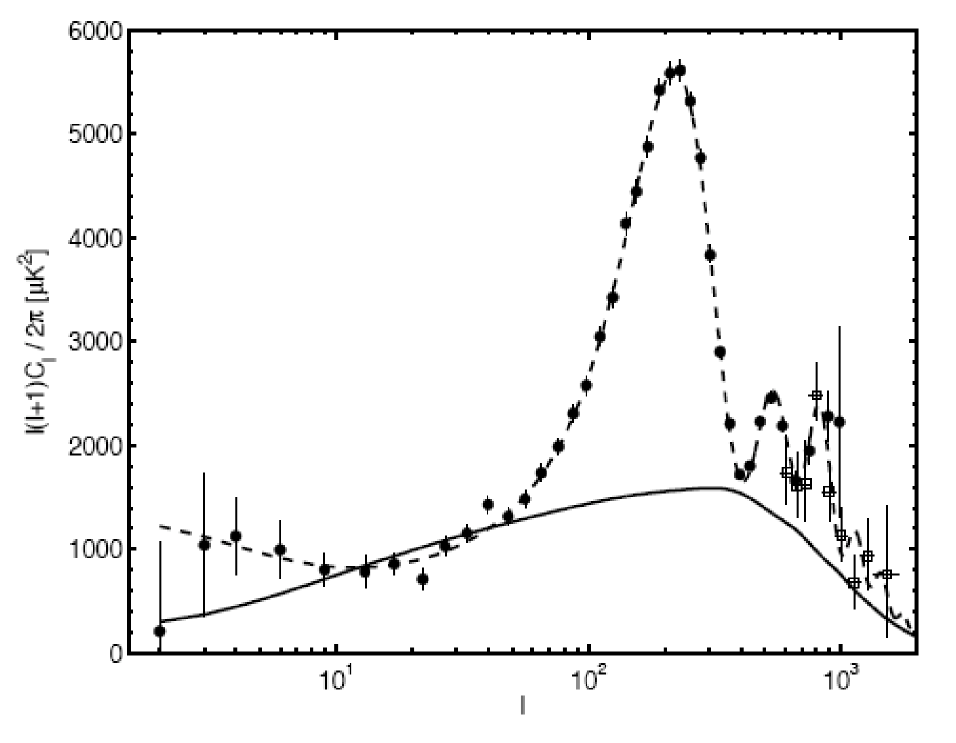
Defects AND Inflation

- Simplest model of the early Universe: inflation[a]
- String defects[b] may be formed at end inflation[c]:
  - Defects are generic in SUSY GUT models[d]
  - Strings from D + anti D-brane collisions[e]
- Also at later thermal phase transitions[f]
- Strings very important in SUSY F- & D-term inflation[g]

a) Starobinsky (1980); Sato (1981); Guth (1981); Hawking & Moss (1982); Linde (1982); Albrecht & Steinhardt (1982)
b) Hindmarsh & Kibble (1994); Vilenkin & Shellard(1994); Kibble (2004)
c) Yokoyama (1989); Kofman,Linde,Starobinski (1996)
d) Jeannerot, Rocher, Sakellariadou (2003)
e) Jones, Stoica, Tye (2002); Dvali & Vilenkin (2003); Copeland, Myers, Polchinski (2003)
f) Kibble (1976); Zurek (1996); Rajantie (2002)
g) Jeannerot (1995); JU, Achucarro, Davis (2004); Battye, Garbrecht, Pilaftsis (2006)

Defects AND Inflation

- Inflation explains CMB
- strong theoretical motivations for cosmic strings (defects)
- Are strings hidden in the CMB?



Dashed: best-fit power-law ΛCDM.
Solid: strings normalised at $l = 10$ [a]

a

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

Calculation difficulties: Approximations

String/M-theory

↓ Energy << M_p

Quantum Field Theory

↓ Large occupation number

Classical Field Theory

↓ Low curvature string configurations

Classical Nambu-Goto Strings

↓ Phenomenological

Unconnected segment model

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This talk → Classical Field Theory

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Classical Nambu-Goto Strings

Allen (1997)
Contaldi et al (1998)
Landriau et al (2004)

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Unconnected segment model

Perivolaropoulos (1995)
Albrecht et al (1997)
Wyman et al (2005,2006)

Calculation difficulties: Approximations

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This talk → Classical Field Theory → Semilocal strings

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Classical Nambu-Goto Strings

Small scale? Decay?

Phenomenological

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Unconnected segment model

Small scale? Decay?
Velocity correlations?

Semilocal Model [a]

$$\mathcal{L} = |D_\mu \phi_1|^2 + |D_\mu \phi_2|^2 - \frac{1}{4e^2} F_{\mu\nu} F^{\mu\nu} - \frac{\lambda}{4}\left(|\phi_1|^2 + |\phi_2|^2 - \eta^2\right)^2$$

2 complex scalar fields ϕ_1 ϕ_2

1 vector field A_μ

Covariant derivative $D_\mu = \partial_\mu - iA_\mu$

Metric $g_{\mu\nu} = a^2(\tau)\eta_{\mu\nu}$

(Talk by Achucarro)

Appear in D-term inflation [b] , D branes [c]...

[a] Vachaspati, Achucarro (1991)
[b] JU, Achucarro, Davis (2004)
[c] Dasgupta, Hsu, Kallosh, Linde, Zagermann (2004)

Semilocal Model [a]

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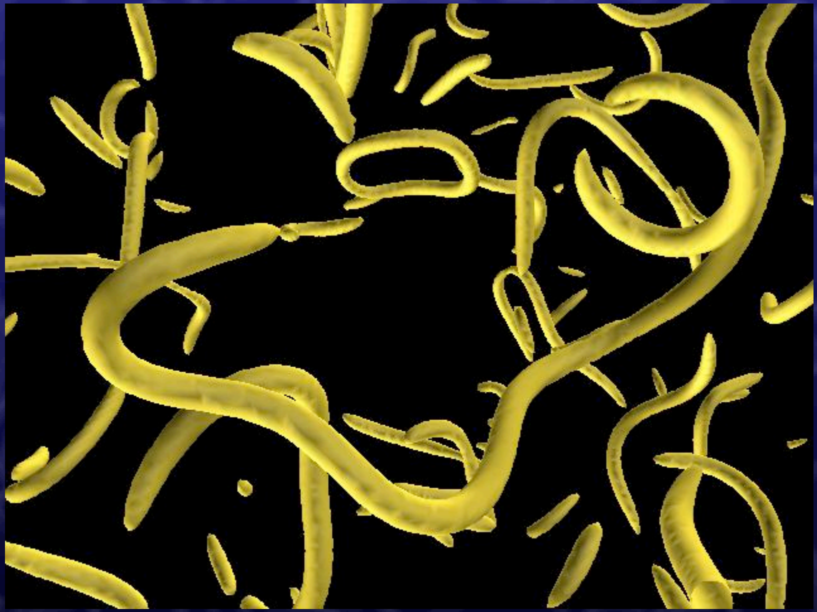

Achucarro, Borrill, Liddle

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Semilocal Model $\longrightarrow$ Abelian Higgs

$$\mathcal{L} = |D_\mu \phi_1|^2 + |D_\mu \phi_2|^2 - \frac{1}{4e^2} F_{\mu\nu} F^{\mu\nu} - \frac{\lambda}{4}\left(|\phi_1|^2 + |\phi_2|^2 - \eta^2\right)^2$$

Semilocal Model ⟶ Abelian Higgs

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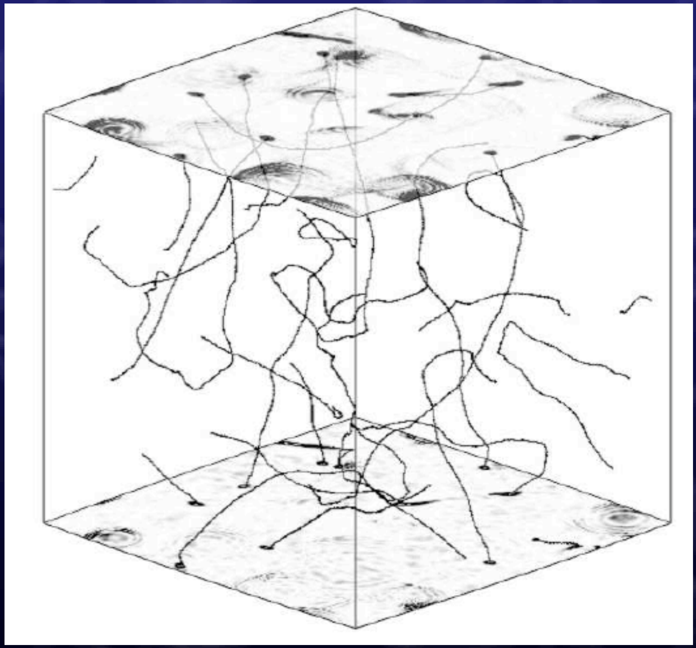
"Abelian Higgs" type much better studied:

Nambu-Goto, unconnected segments...

Our previous work using field theory:

PRD75 (2007): CMB power spectrum
astroph/0702223: Fitting to CMB data
0704.3800: Polarization



Semilocal Model ⟶ Textures

$$\mathcal{L} = |D_\mu \phi_1|^2 + |D_\mu \phi_2|^2 - \frac{1}{4e^2} F_{\mu\nu} F^{\mu\nu} - \frac{\lambda}{4} \left(|\phi_1|^2 + |\phi_2|^2 - \eta^2 \right)^2$$

Semilocal Model $\longrightarrow$ Textures

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Semilocal Model $\longrightarrow$ Textures

$$\mathcal{L} = |\cancel{D}_\mu \phi_1|^2 + |\cancel{D}_\mu \phi_2|^2 \cancel{- \frac{1}{4e^2} F_{\mu\nu} F^{\mu\nu}} - \frac{\lambda}{4}\left(|\phi_1|^2 + |\phi_2|^2 - \eta^2\right)^2$$

$$\mathcal{L} = (\partial_\mu \psi_1)^2 + (\partial_\mu \psi_2)^2 + (\partial_\mu \psi_3)^2 + (\partial_\mu \psi_4)^2 - \frac{\lambda}{4}(\psi_1^2 + \psi_2^2 + \psi_3^2 + \psi_4^2 - \eta^2)^2$$

4 real scalar fields ψ_i

No Gauge fields

Also much better studied:

Non-linear σ model

Semilocal string simulations

Abelian Higgs strings ⟵ Semilocal strings ⟶ Textures

CMB predicitions:
Textures less "dangerous" than Abelian Higgs
Semilocal strings? (In this work BPS semilocal strings)

Numerical simulations*
N=512^3
Matter & Radiation eras

Compare to Abelian Higgs strings
(and textures)

*Very nice C++ library of objects for classical lattice simulations in parallel:
LATfield: Bevis & Hindmarsh, http://www.latfield.org/

*Simulations in the UK-CCC facility COSMOS, sponsored by PPARC and SGI/Intel

Shrinking String - Fat strings

comoving string shrinks as a^{-1} → strings slip through lattice points

$$\ddot{\phi} + 2\frac{\dot{a}}{a}\dot{\phi} - D^2\phi + \lambda a^2(|\phi|^2 - v^2)\phi = 0,$$

$$\partial^\mu\left(\frac{1}{e^2}F_{\mu\nu}\right) - ia^2(\phi^* D_\nu\phi - D_\nu\phi^*\phi) = 0,$$

$(A_0 = 0)$

Shrinking String - Fat strings

comoving string shrinks as a^{-1} $\longrightarrow$ strings slip through lattice points

$$\begin{aligned} \ddot{\phi} + 2\frac{\dot{a}}{a}\dot{\phi} - D^2\phi + \lambda a^{2s}(|\phi|^2 - v^2)\phi &= 0, \\ \partial^\mu \left(\frac{a^{2(1-s)}}{e^2} F_{\mu\nu} \right) - ia^2(\phi^* D_\nu \phi - D_\nu \phi^* \phi) &= 0, \end{aligned}$$

$(A_0 = 0)$

"Real value" $\longrightarrow$ s=1

For s<1 $\longrightarrow$ string "fattens"

Preserves Gauss's Law,
but violates EM conservation

Production runs s=0.3
Check robustness with s!

Check scaling!

Press, Ryden, Spergel (1989); Moore, Shellard, Martins (2001); Bevis, Hindmarsh, Kunz, JU (2006)

UETC method for power spectrum (summary)

Time dependent diff operator

Source (Energy momentum)

$$\mathcal{D}_{\alpha\beta}(\tau,k)h_\beta(\tau,k) = S_\alpha(\tau.k)$$

Linear perturbations

Power spectrum [a]

$$\langle |h_\alpha(\tau_0,k)|^2\rangle = \int\int \mathcal{D}^{-1}\mathcal{D}^{-1}\,\langle S_\alpha(\tau,k)S^*_\alpha(\tau',k)\rangle$$

Need unequal-time correlators (UETCs) of energy-momentum tensor

$$C_{\mu\nu\rho\lambda}(k,\tau,\tau') = \langle T_{\mu\nu}(k,\tau)T^*_{\rho\lambda}(k,\tau')\rangle$$

[a] Pen, Seljak, Turok (1997); Durrer, Kunz, Melchiorri (1998, 2002)

UETC method for power spectrum (summary)

Calculate UETCs from defect simulations

↓

Diagonalise UETCs

↓

Solve perturbation equations with eigenfunctions as sources

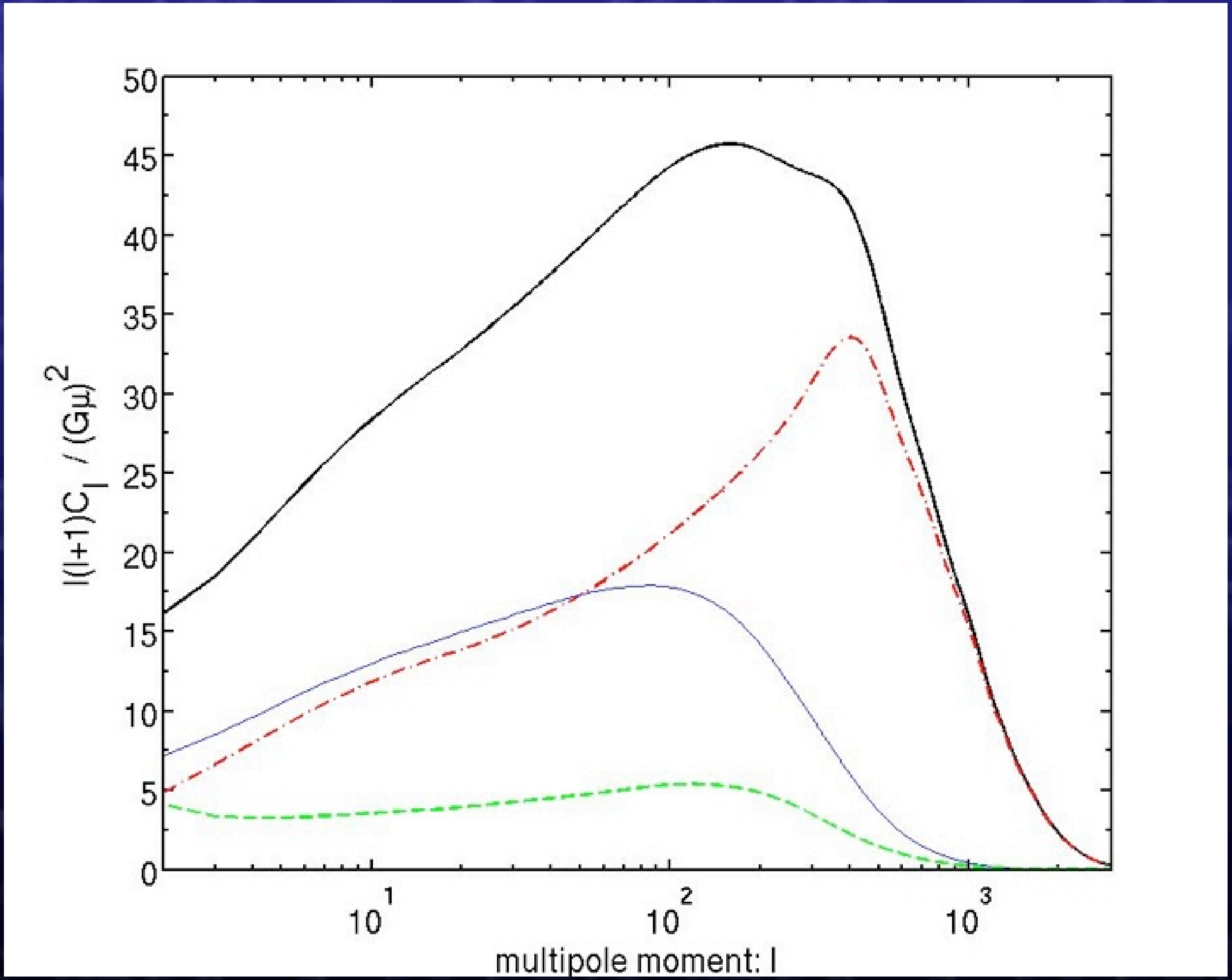
↓

Square $\Delta T^{(S,V,T)}$ and sum

Temperature power spectrum

scalar-vector-tensor

SEMILOCAL



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scalar-vector-tensor

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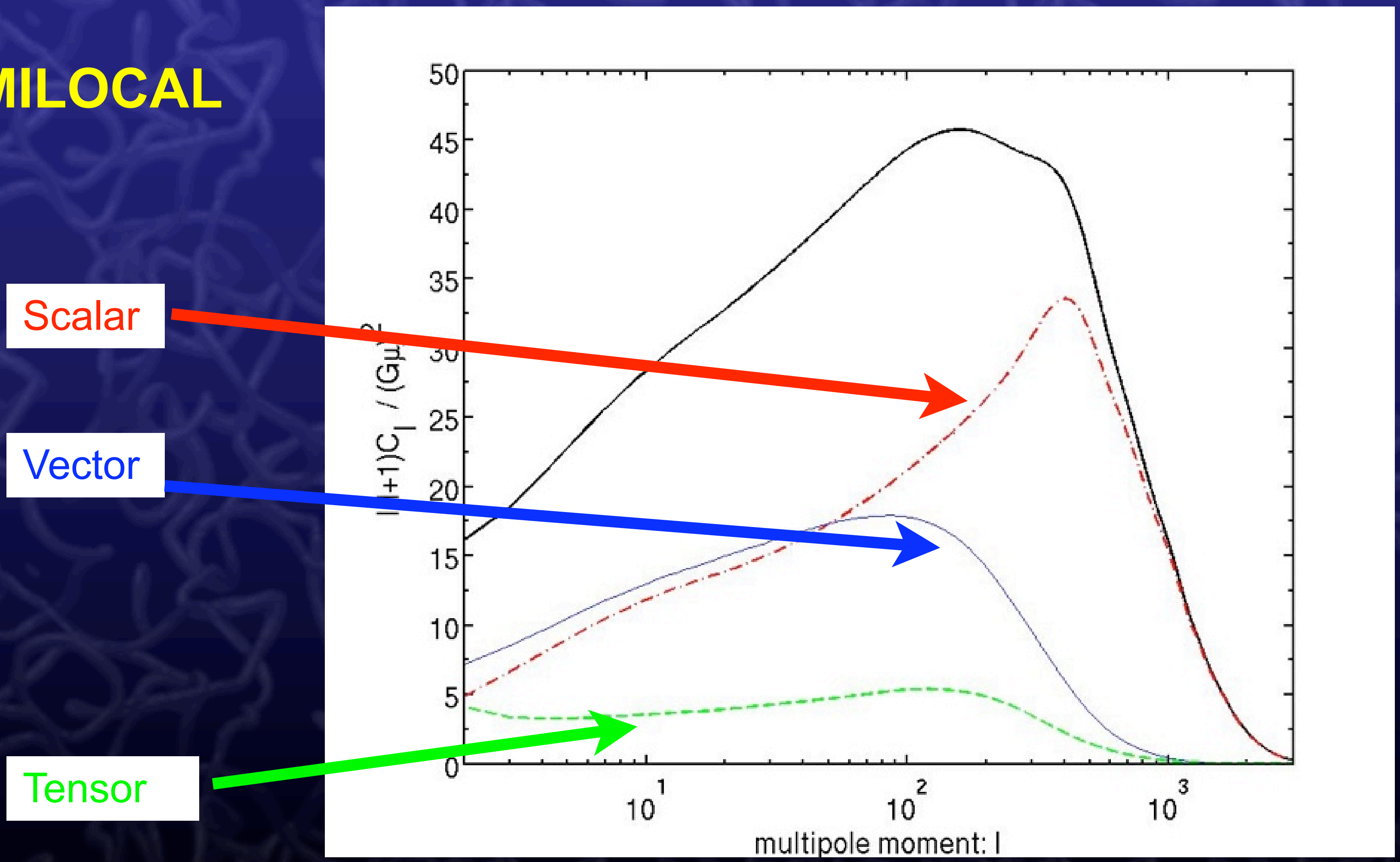
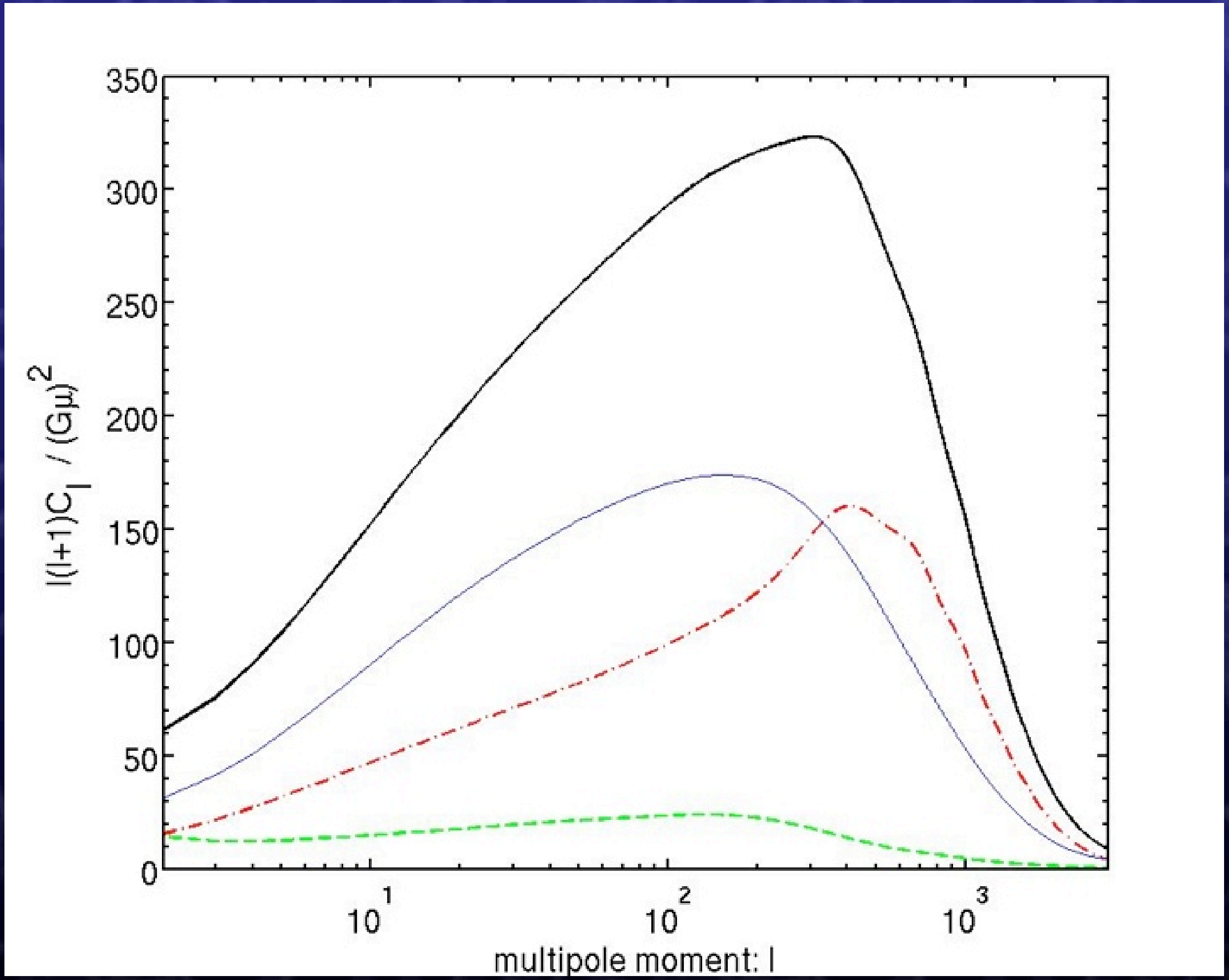


Temperature power spectrum

scalar-vector-tensor

ABELIAN HIGGS



Temperature power spectrum

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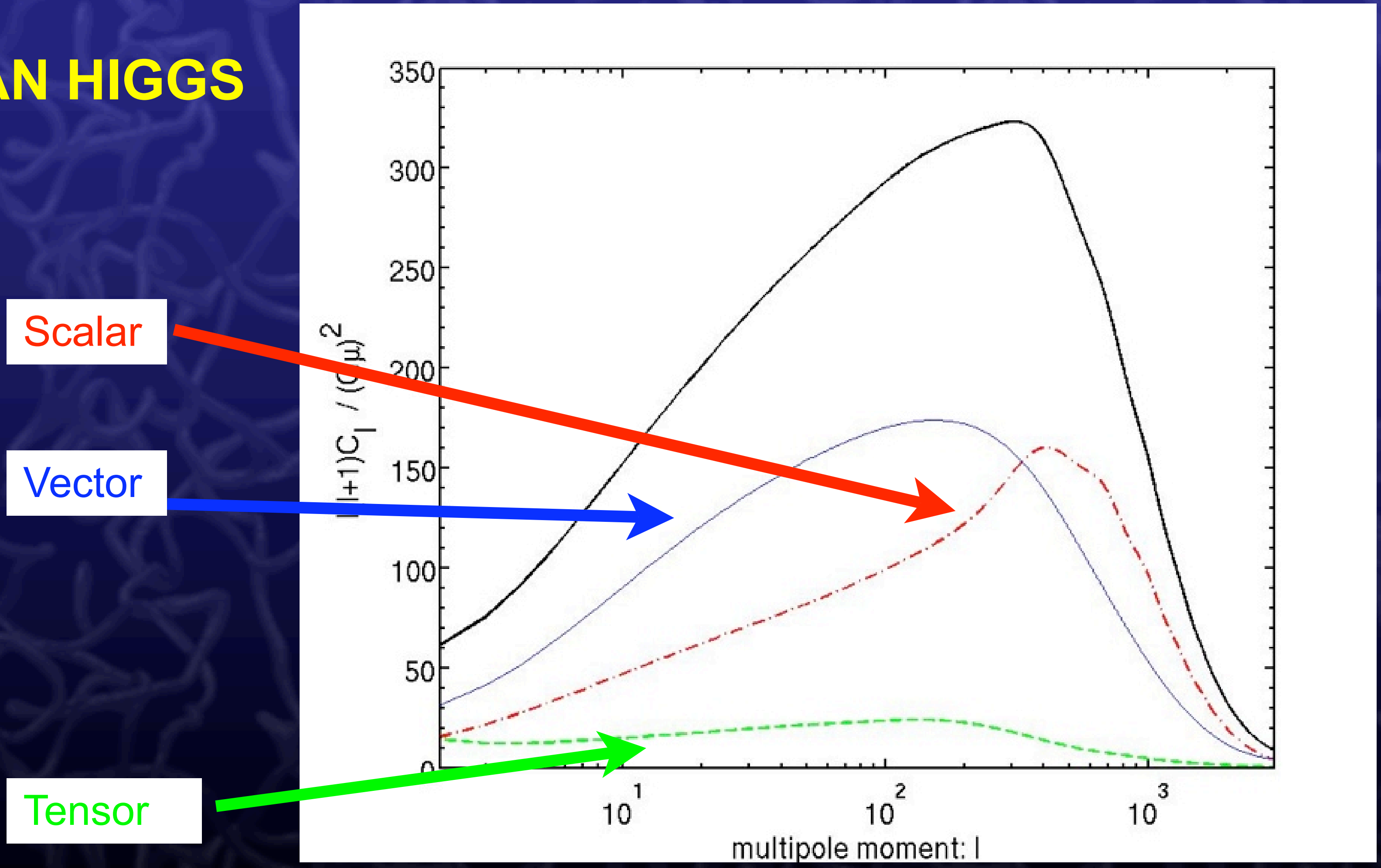
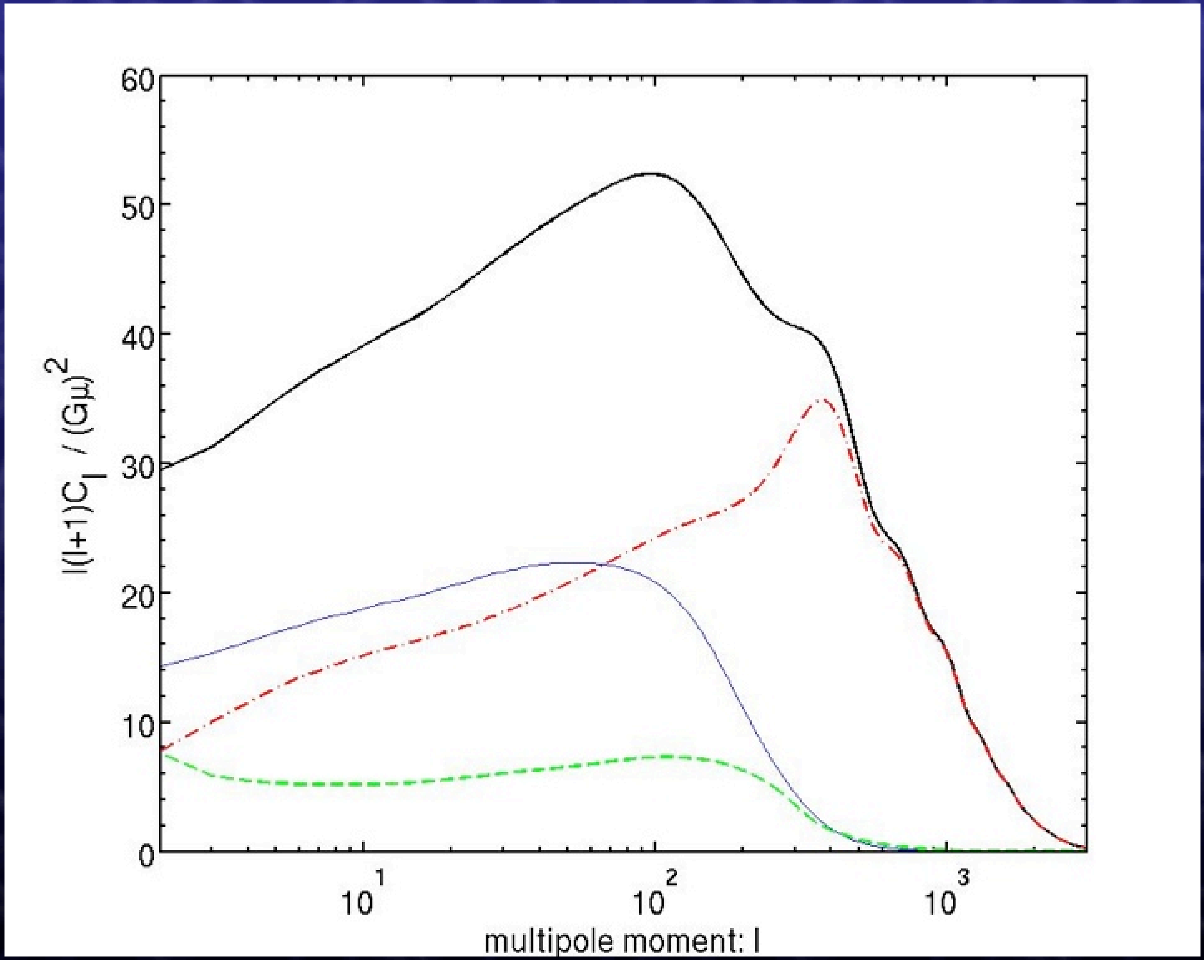


Temperature power spectrum

scalar-vector-tensor

TEXTURES



Temperature power spectrum

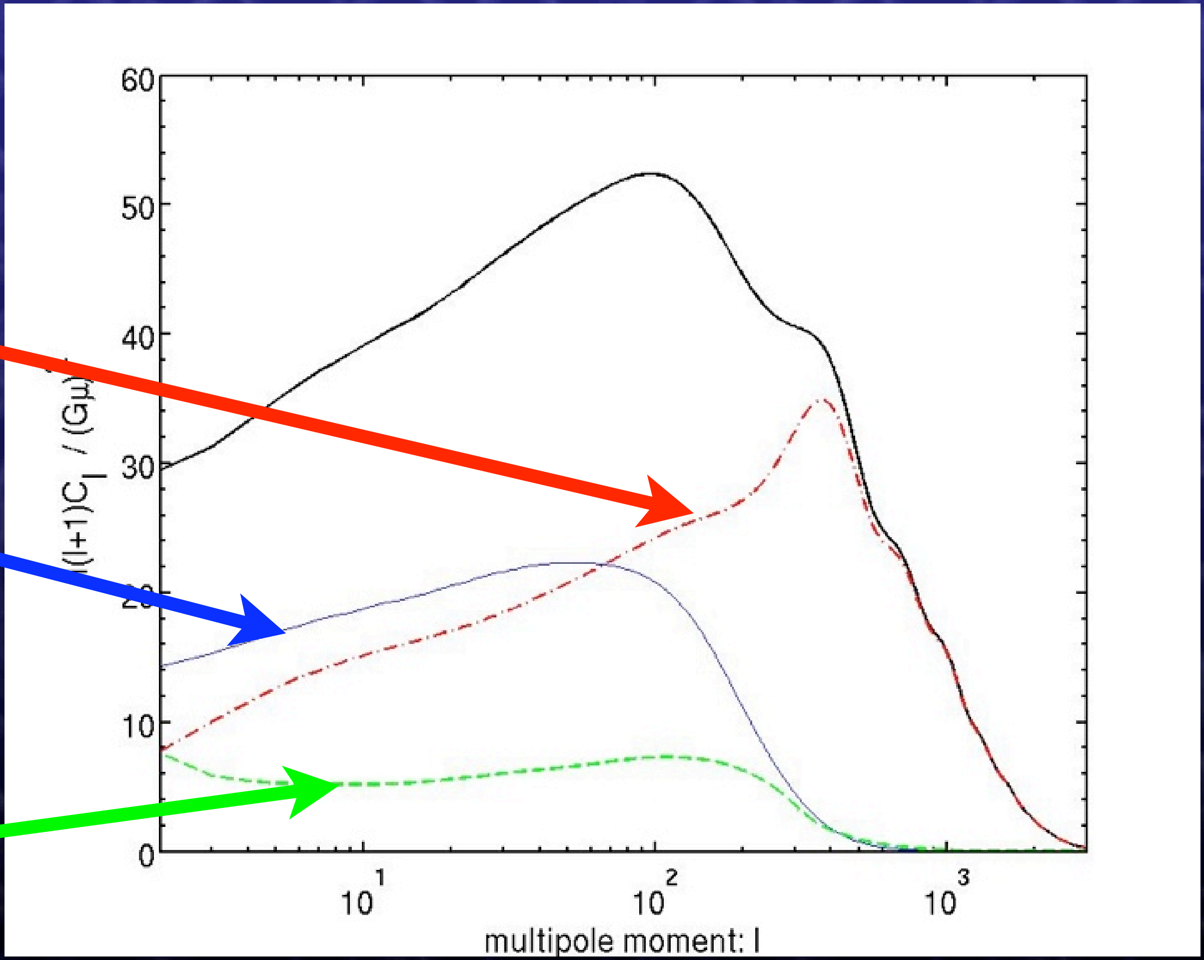
scalar-vector-tensor

TEXTURES

Scalar

Vector

Tensor



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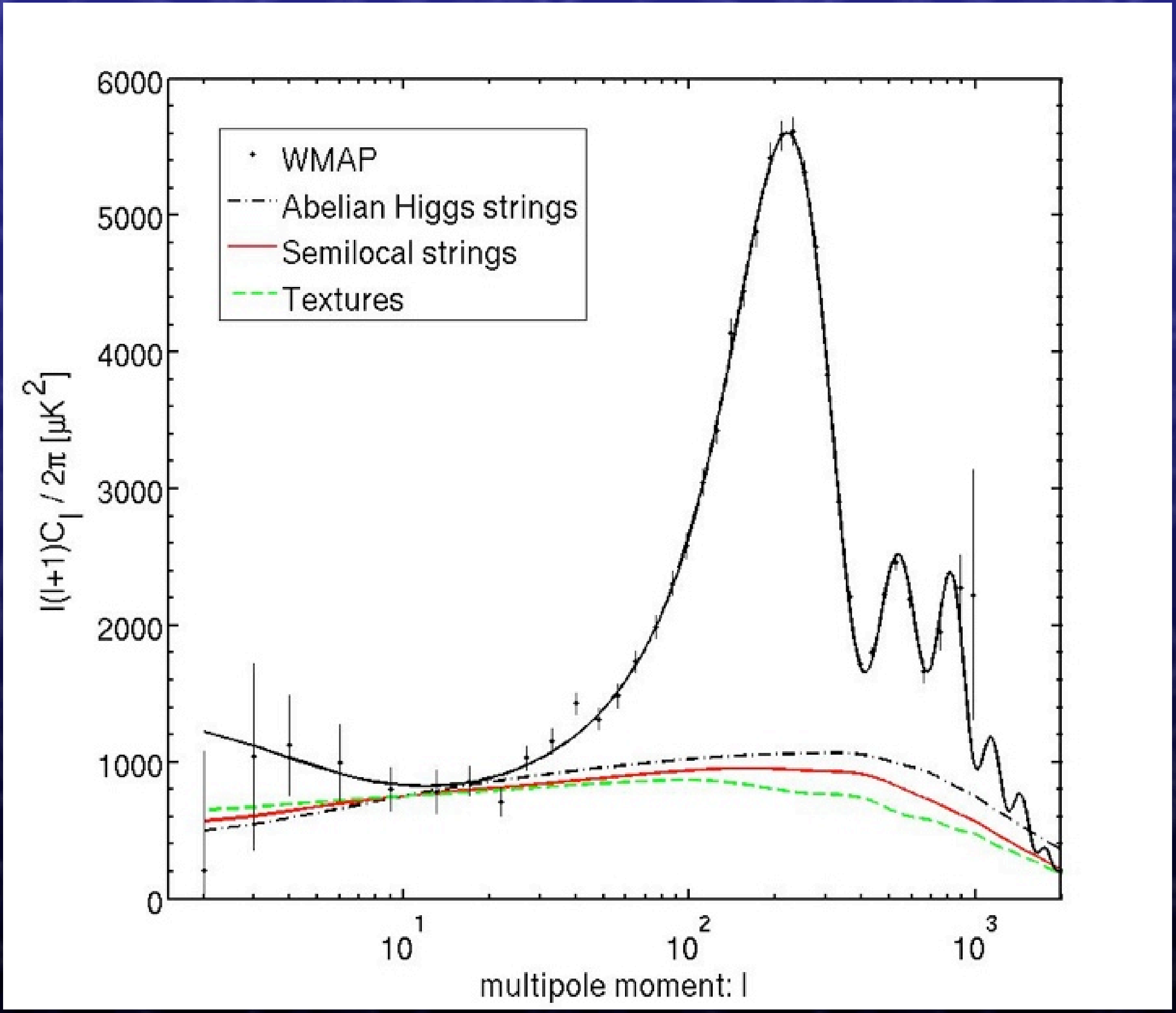


$G\mu_{10}=2.0 \times 10^{-6}$

$G\mu_{10}=4.9 \times 10^{-6}$

$G\mu_{10}=8.5 \times 10^{-6}$

Fitting CMB with inflation + strings

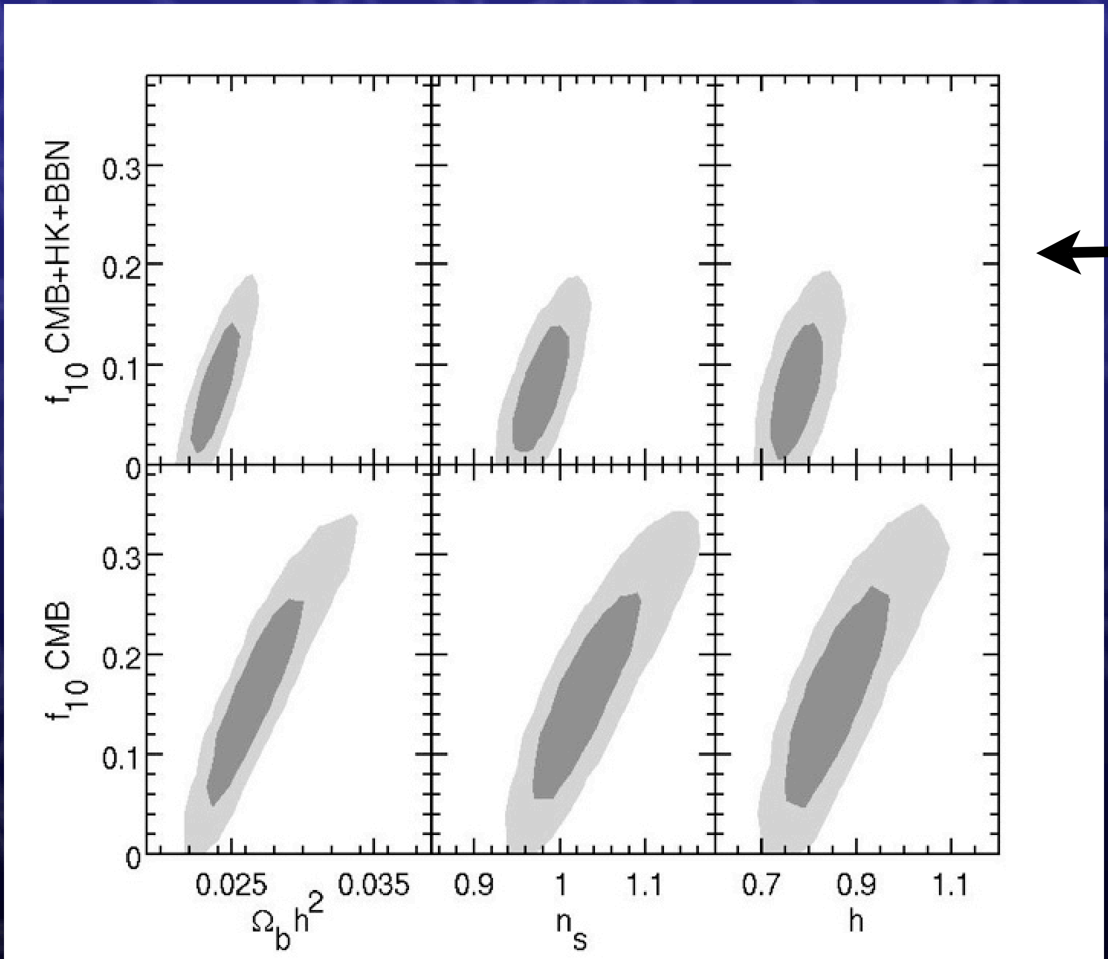
- Two sources of perturbations: incoherent, add in quadrature
- Cosmological model with 1 more parameter: $G\mu$, A_{cs} or f_{10}
- $f_{10} = [\ C^{string} / C^{total}\ ]_{10}$. Proportional to $(G\mu)^2$
- Modify cosmoMC and perform MCMCs
- Include polarization

Cosmological Parameters:

1. Hubble parameter h
2. physical baryon density $\Omega_b h^2$
3. physical matter density $\Omega_m h^2$
4. optical depth to last scattering τ
5. amplitude of scalar adiabatic perturbations A_s^2
6. tilt of scalar adiabatic perturbations n_s-1
7. string contribution to power spectra f_{10}

Fitting CMB with inflation + strings

MCMC with CMB (WMAP3, Boomerang, CBI, ACBAR, VSA)



Degeneracies!

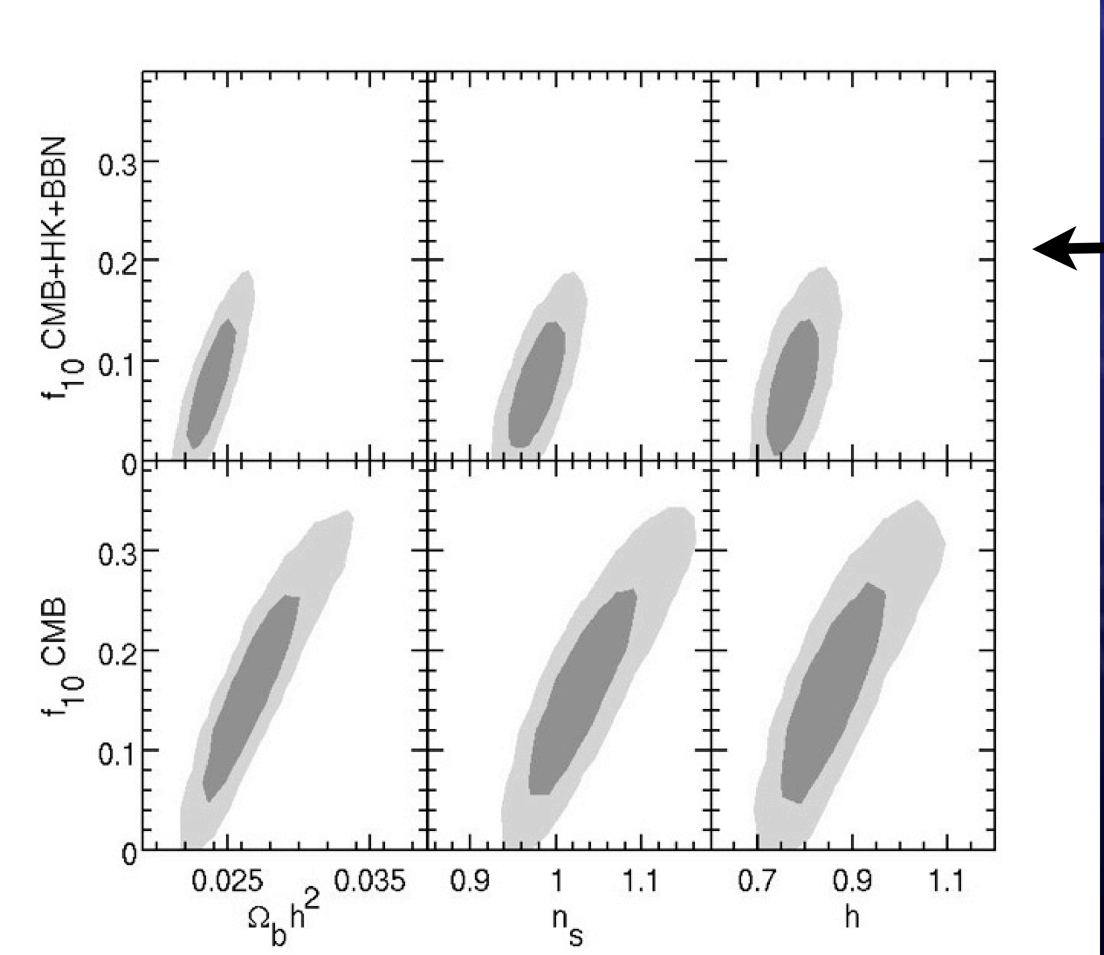
$n_s \to 1$[a]

Hybrid SUSY inflation predicts strings wants n_s close to 1

[a] Battye, Garbrecht, Moss (2006)

Fitting CMB with inflation + strings

MCMC with CMB (WMAP3, Boomerang, CBI, ACBAR, VSA)



Hubble key project
Big Bang Nucleosynthesis

Degeneracies!

$n_s \rightarrow 1$[a]

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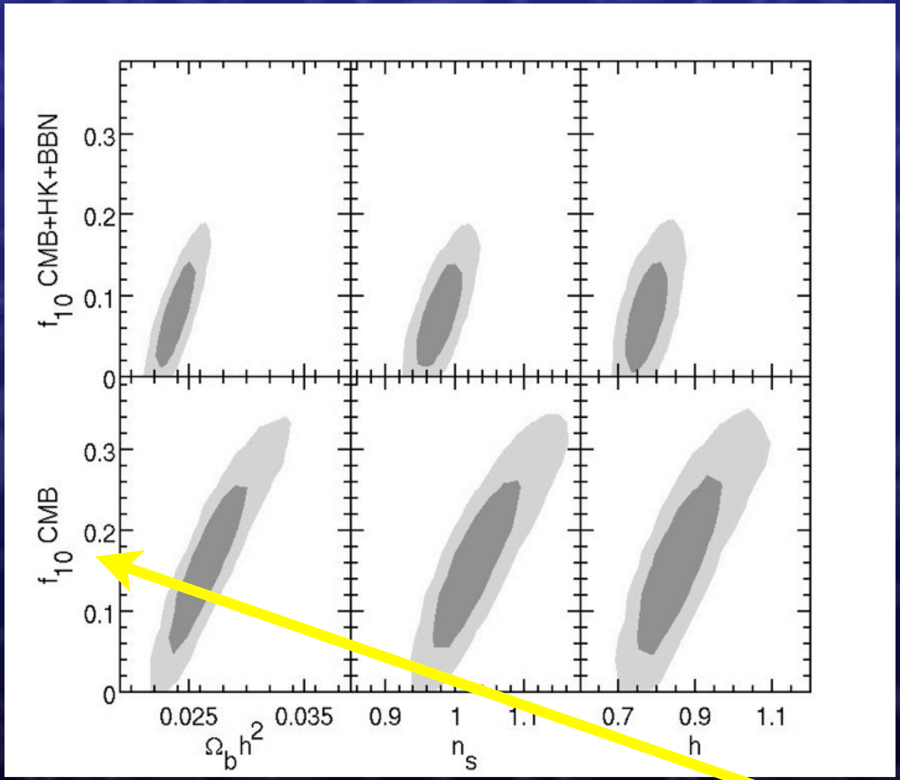
Fitting CMB with inflation + strings



Best fit:

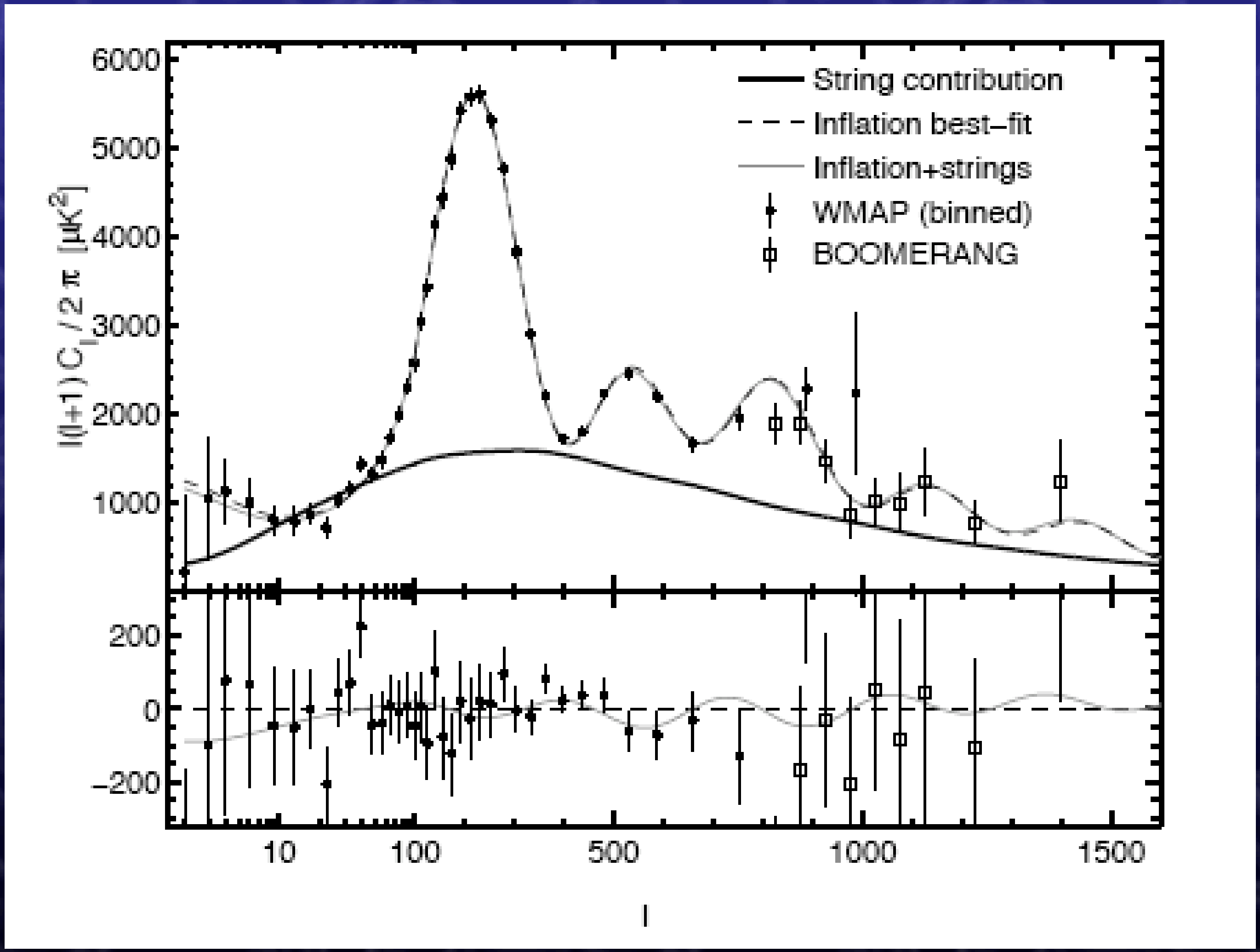
Semilocal:

f_{10}= 0.17 ± 0.08 Gμ= [1.9 ± 0.4]x10^{-6}

Abelian Higgs:

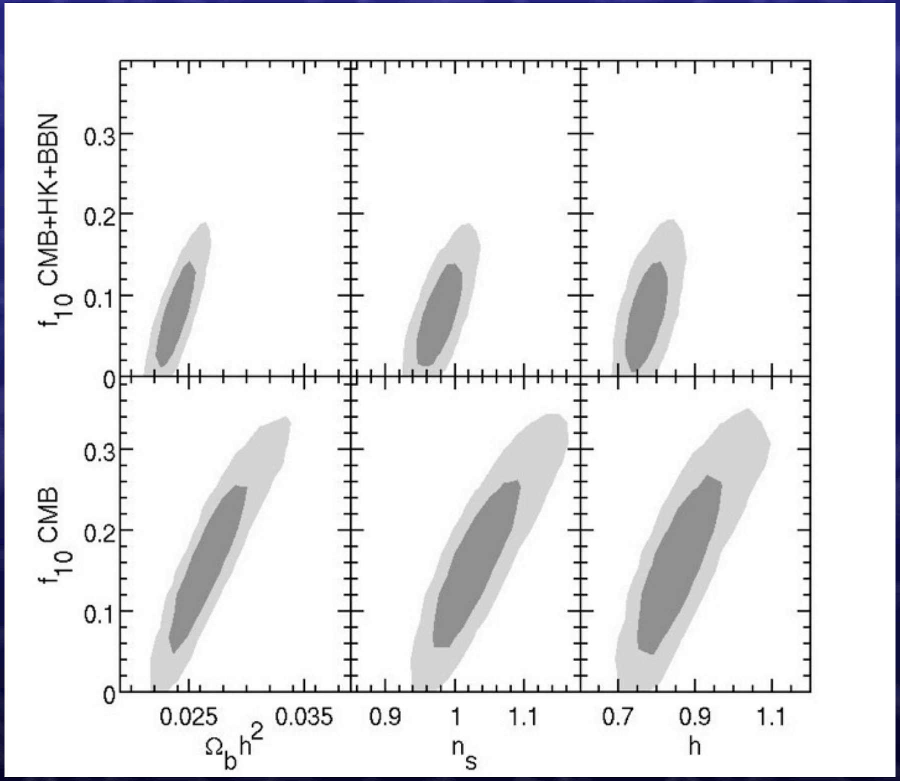
f_{10}=0.1 ± 0.03 Gμ=[0.65 ± 0.10]x10^{-6}

CMB prefers to have strings

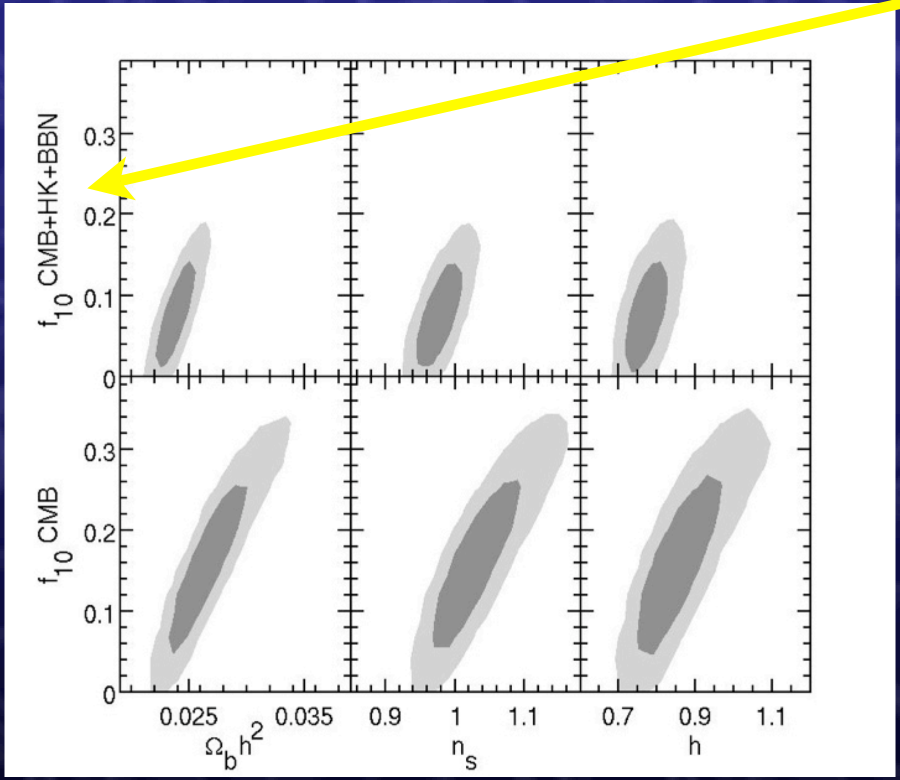


Difference from best fit ΛCDM

Fitting CMB with inflation + strings



Fitting CMB with inflation + strings

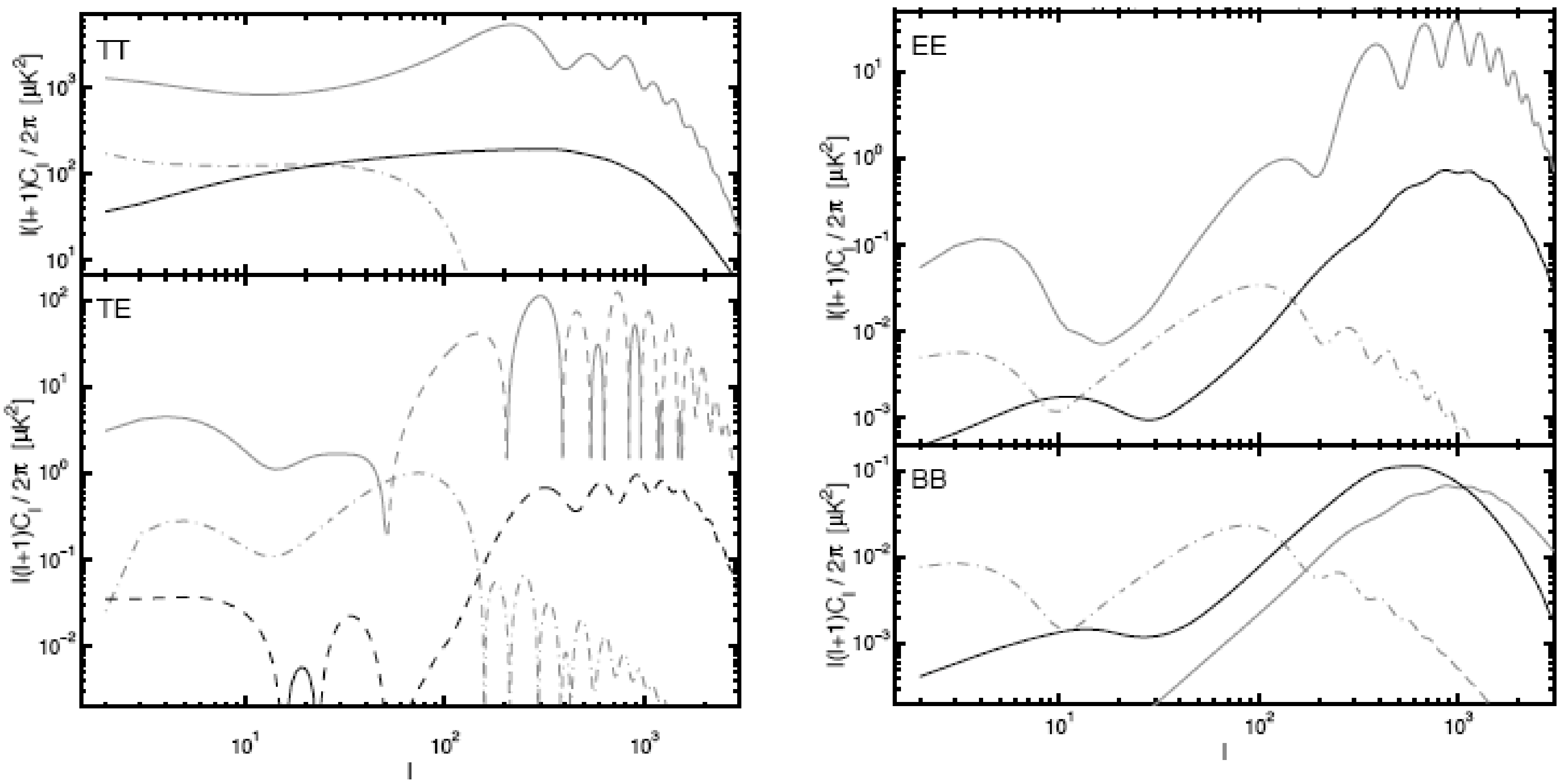


95% confidence level upper limit:

Semilocal:
$f_{10} < 0.17$ $G\mu < 1.9 \times 10^{-6}$

Abelian Higgs:
$f_{10} < 0.11$ $G\mu < 0.7 \times 10^{-6}$

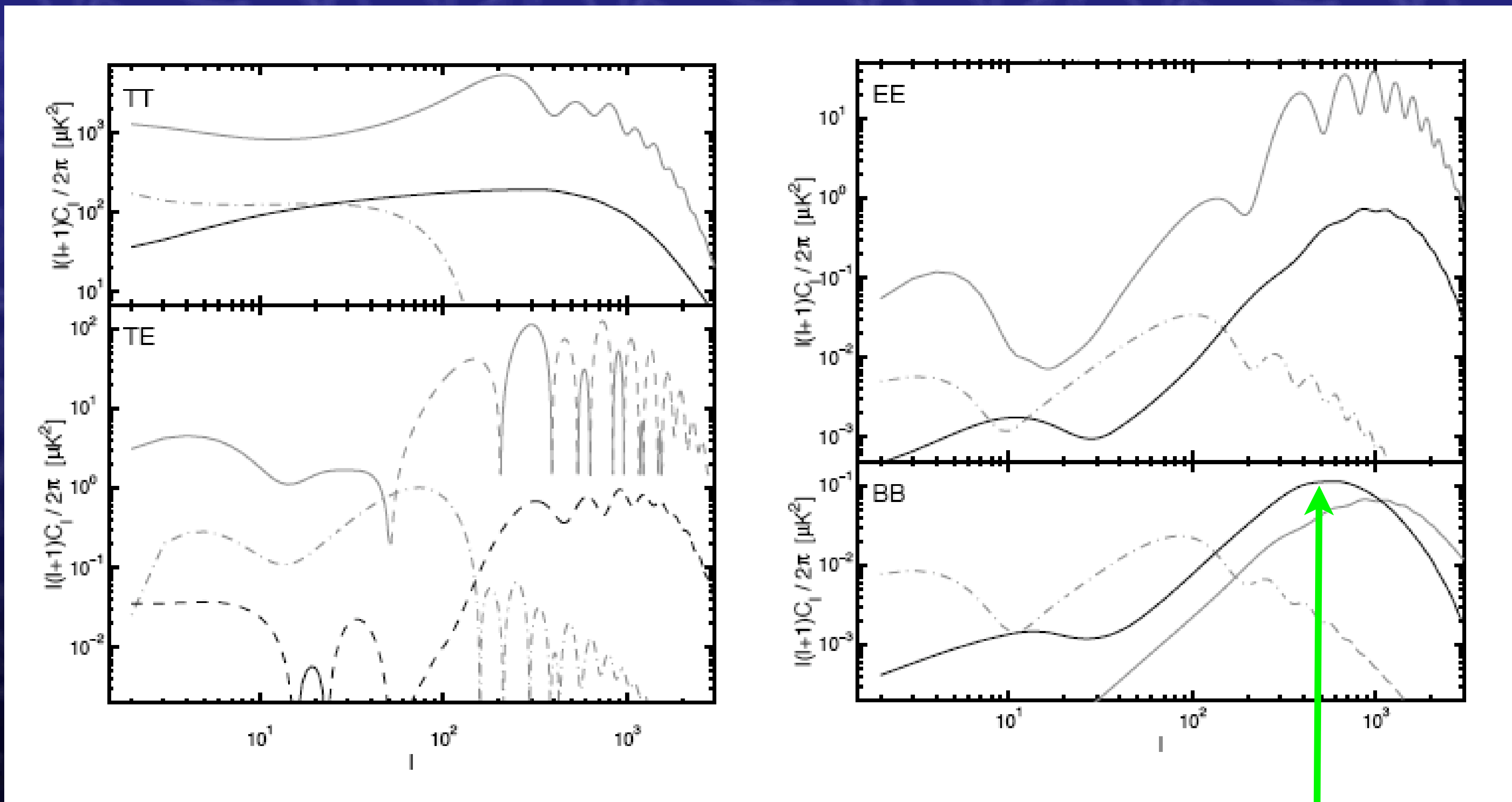
Temperature and Polarization CMB Power Spectra



Inflation r=0.4 and strings f_{10}=0.1

(Pogosian's talk)

Temperature and Polarization CMB Power Spectra

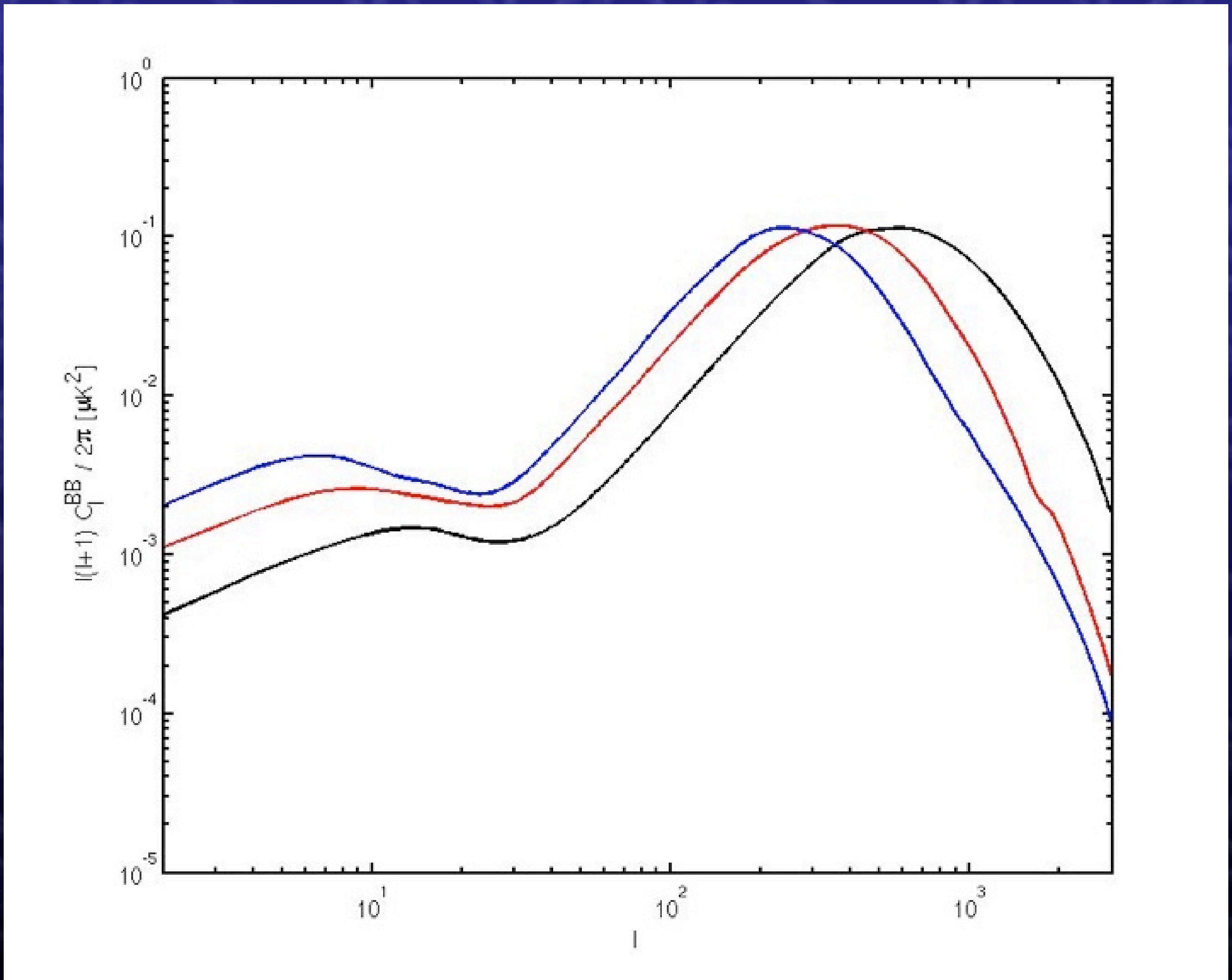


Inflation r=0.4 and strings f_{10}=0.1

AH STRINGS!

(Pogosian's talk)

Temperature and Polarization B mode Spectra



Abelian Higgs
Semilocal
Textures

Normalized at
best fit parameters

Likelihood and Evidence

model ID	no. param.	CMB only		CMB+HKP+BBN	
		$\Delta\chi^2_{\rm eff}$	evidence	$\Delta\chi^2_{\rm eff}$	evidence
HZ	5	$+7.7$	0.35 ± 0.03	$+10$	0.133 ± 0.005
PL	6	0	1	0	1
HZ+S	6	-3.9	7.3 ± 1.2	$+0.9$	0.76 ± 0.13
PL+S	7	-3.9	1.2 ± 0.1	-1.6	0.19 ± 0.01

Evidence numbers for semilocals underway; fairly similar

Bayesian Evidence using Savage + Dickey ratio
Flat priors: $0.75 < n_s < 1.25$; $0 < f_{10} < 1$

Strings are a viable component of inflationary cosmology!

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PL	6	0	1	0	1
HZ+S	6	-3.9	7.3 ± 1.2	$+0.9$	0.76 ± 0.13
PL+S	7	-3.9	1.2 ± 0.1	-1.6	0.19 ± 0.01

Evidence numbers for semilocals underway; fairly similar

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Conclusions

• First calculations of semilocal string CMB power spectra

• Temperature Power Spectrum:
- CMB only fit: $G\mu = [1.9 \pm 0.4\,] \times 10^{-6}$ ($n_s = 1$, high h, $\Omega_b h^2$) $\longrightarrow$ 17%
- CMB + Hubble + BBN: $G\mu < 1.9 \times 10^{-6}$ (95% C.L.) $\longrightarrow$ < 17%

• Semilocal string constraints less stringent than Abelian Higgs [$G\mu < 0.7 \times 10^{-6}$ (95% C.L.)], but not zero! Somewhere between Abelian Higgs and textures

• Polarisation Power Spectra, similar to Abelian Higgs:
-BB signal from semilocal strings (also) large

• Strings are a viable component of inflationary cosmology

To do list & questions

- LSS constraints?
- Cosmic/semilocal strings at low β (F-term inflation)
- Will it be possible to distinguish between different defect type?
- Cosmic super-string (p-q string) predictions?
- .....

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