Strings, Texture and the CMB

Björn Garbrecht

Department of Physics
University of Wisconsin–Madison

Cosmo 08, Madison, August 25th 2008

R. A. Battye, B. Garbrecht, A. Moss, JCAP **0609**, 007 (2006) [arxiv:astro-ph/0607339]
R. A. Battye, B. Garbrecht, A. Moss, H. Stoica JCAP **0801**, 020 (2008) [arxiv:0710.1541 [astro-ph]]
R. A. Battye, B. Garbrecht, A. Pilaftsis, arxiv:0807.1729 [hep-ph], to appear in JCAP

Outline

1. Adiabatic and String Perturbations in the Cosmic Microwave Background (CMB)
2. Bounds on Strings from the Temperature-Temperature (*TT*) Perturbation of the CMB
3. Hybrid Inflation, Strings & Texture

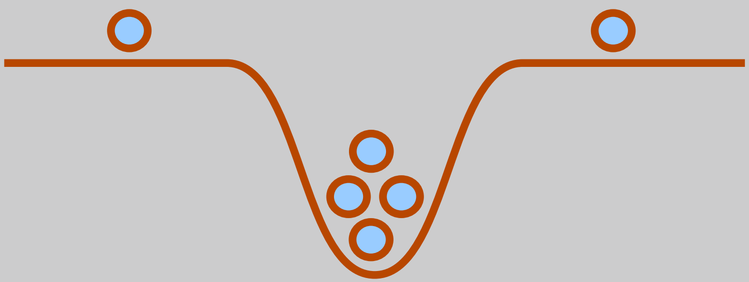
1

Adiabatic and String Perturbations in the Cosmic Microwave Background (CMB)

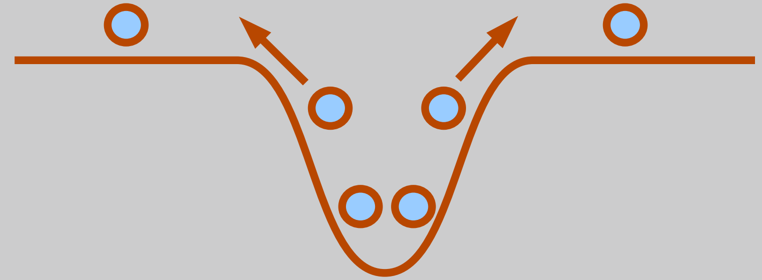
Acoustic Oscillations

[Peebles, Yu (1970); Sunyaev, Zel'dovich(1970)]

The baryon-photon fluid oscillates within the gravitational dark-matter potential:



1. fluid compressed inside potential well



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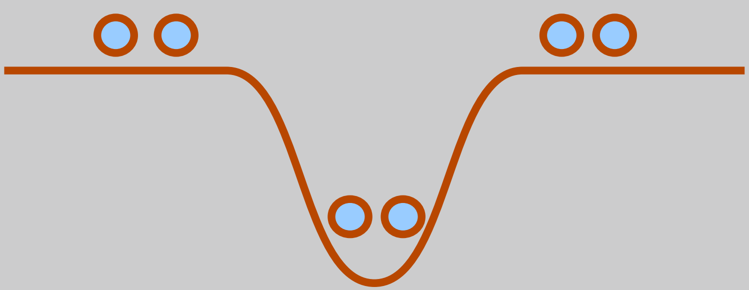

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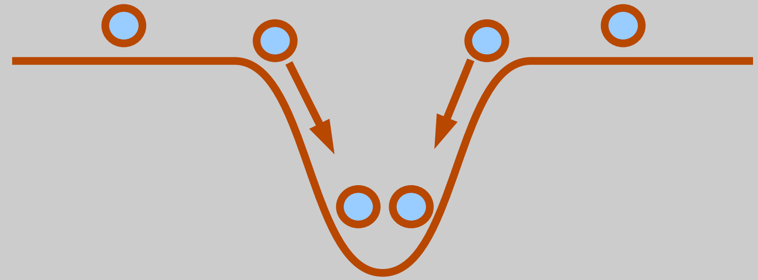
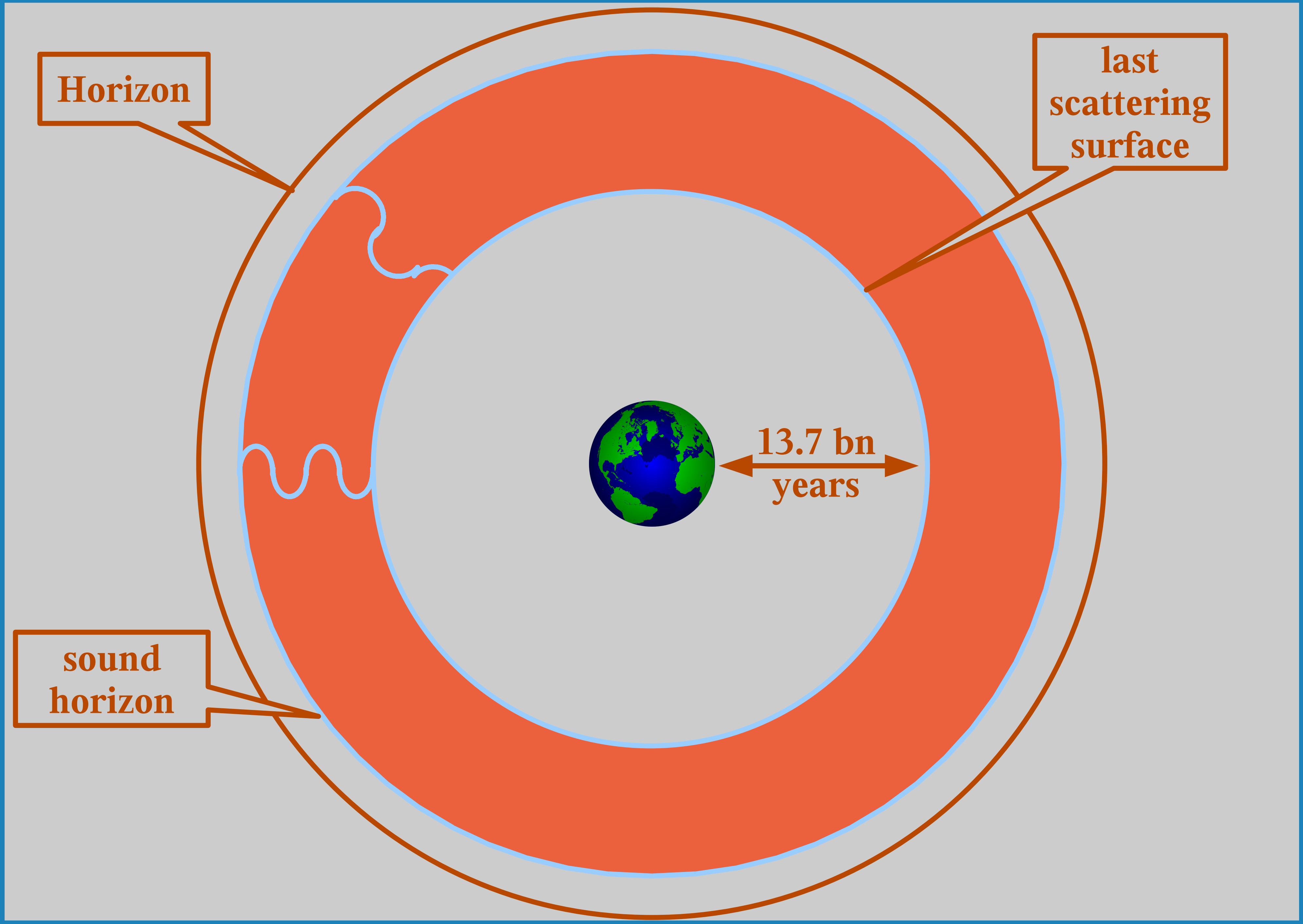


4. fluid compresses due to gravitation


Horizon
last scattering surface
13.7 bn years
sound horizon

Oscillating Baryon-Photon Fluid

$$\Theta := \frac{\Delta T_{\text{intrinsic}}}{T_{\text{intrinsic}}}$$

$$\ddot{\Theta} + (v_s k)^2 \Theta = -\frac{k^2}{3}\Psi$$

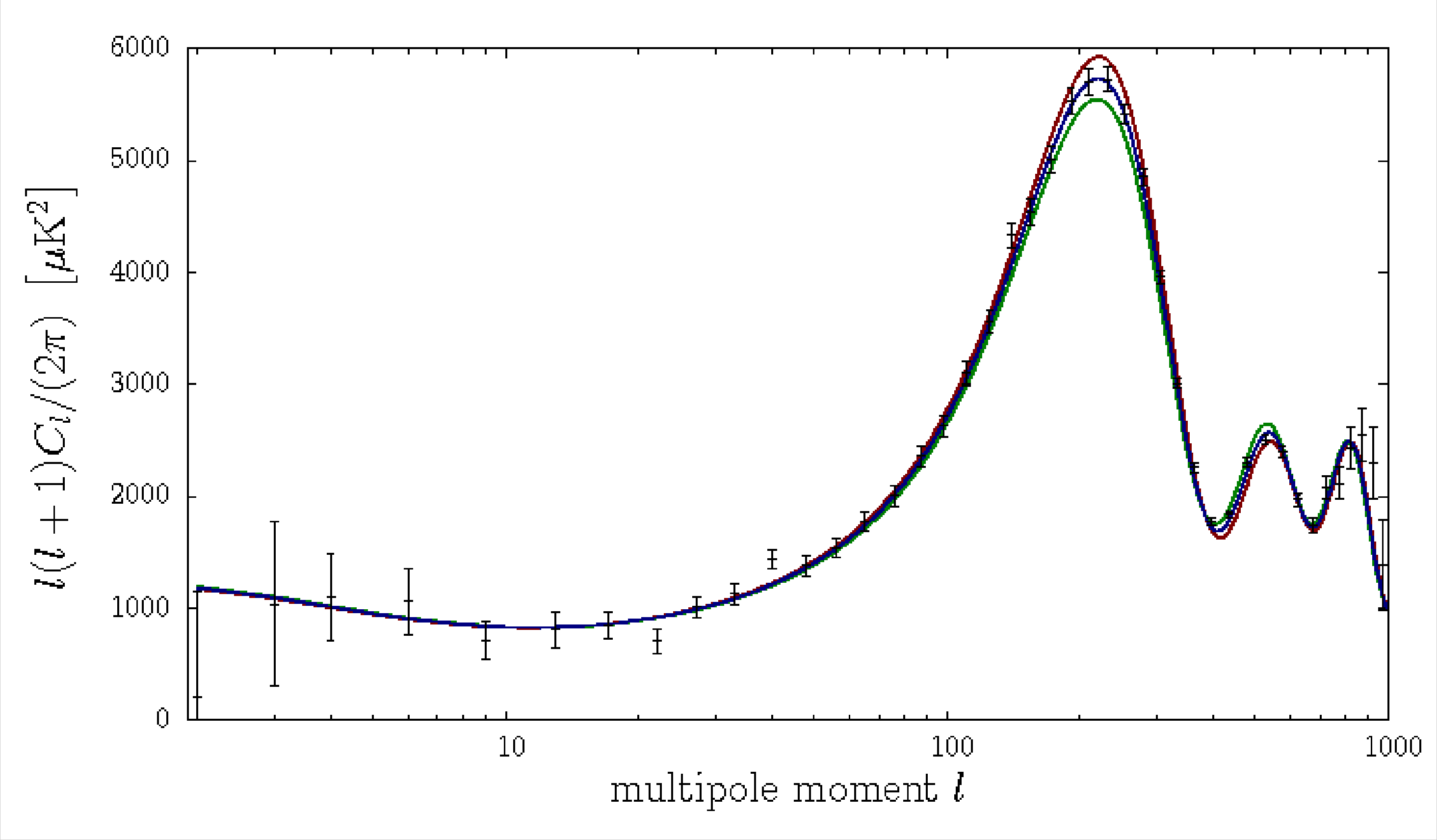
simplification of a network of Boltzmann equations

$\Psi:$ Newtonian potential sourced by dark matter

$k:$ wavenumber

sound speed: $v_s = \sqrt{\frac{p}{\varrho}} \lesssim 1/\sqrt{3}$ for relativistic fluid, $\rho_B \ll \rho_\gamma$

BAU and Acoustic Peaks



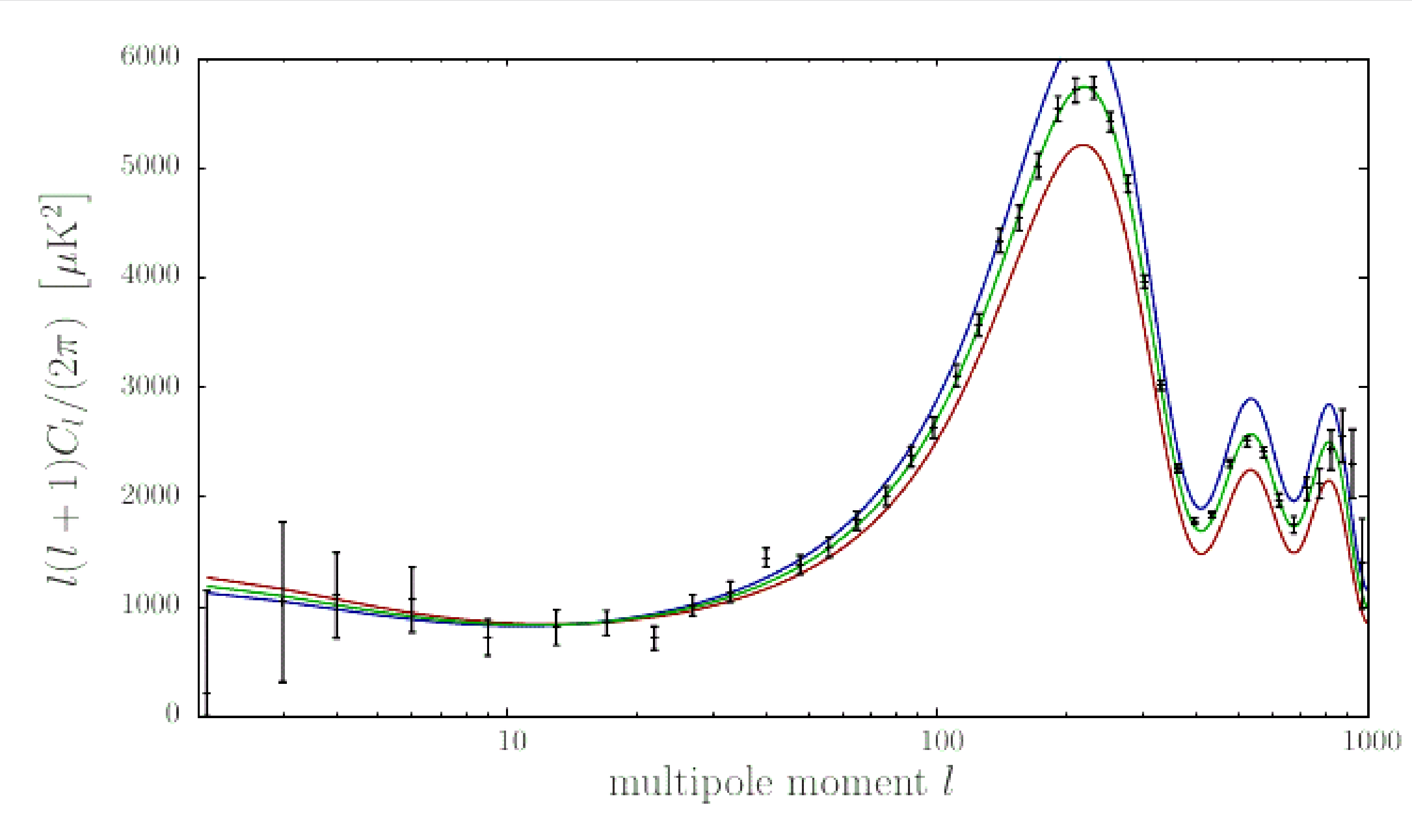
observed BAU

110% obs. BAU

90% obs. BAU

[CMBFAST (1996), Seljak & Zaldarriaga; CAMB (2000), Lewis, Challinor & Lasenby]

$n_{\rm S}$ and Acoustic Peaks



$n_{\rm s} = 1.000$

$n_{\rm s} = 0.963$

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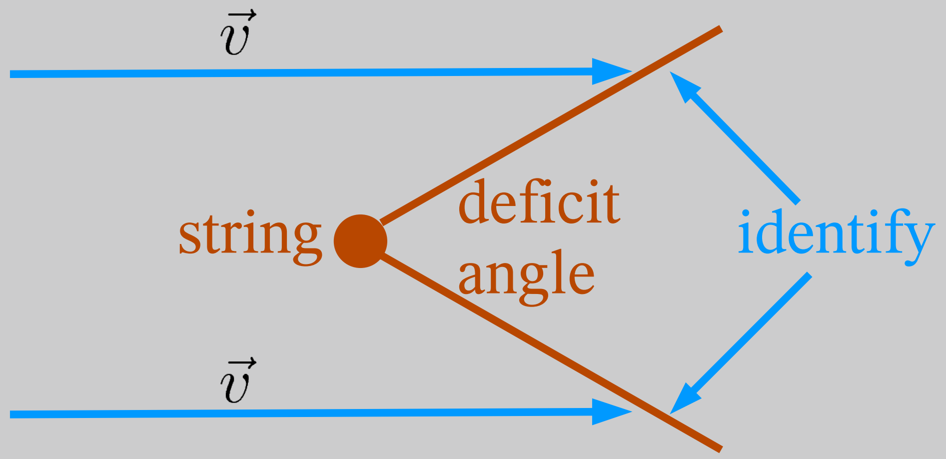
String Perturbations

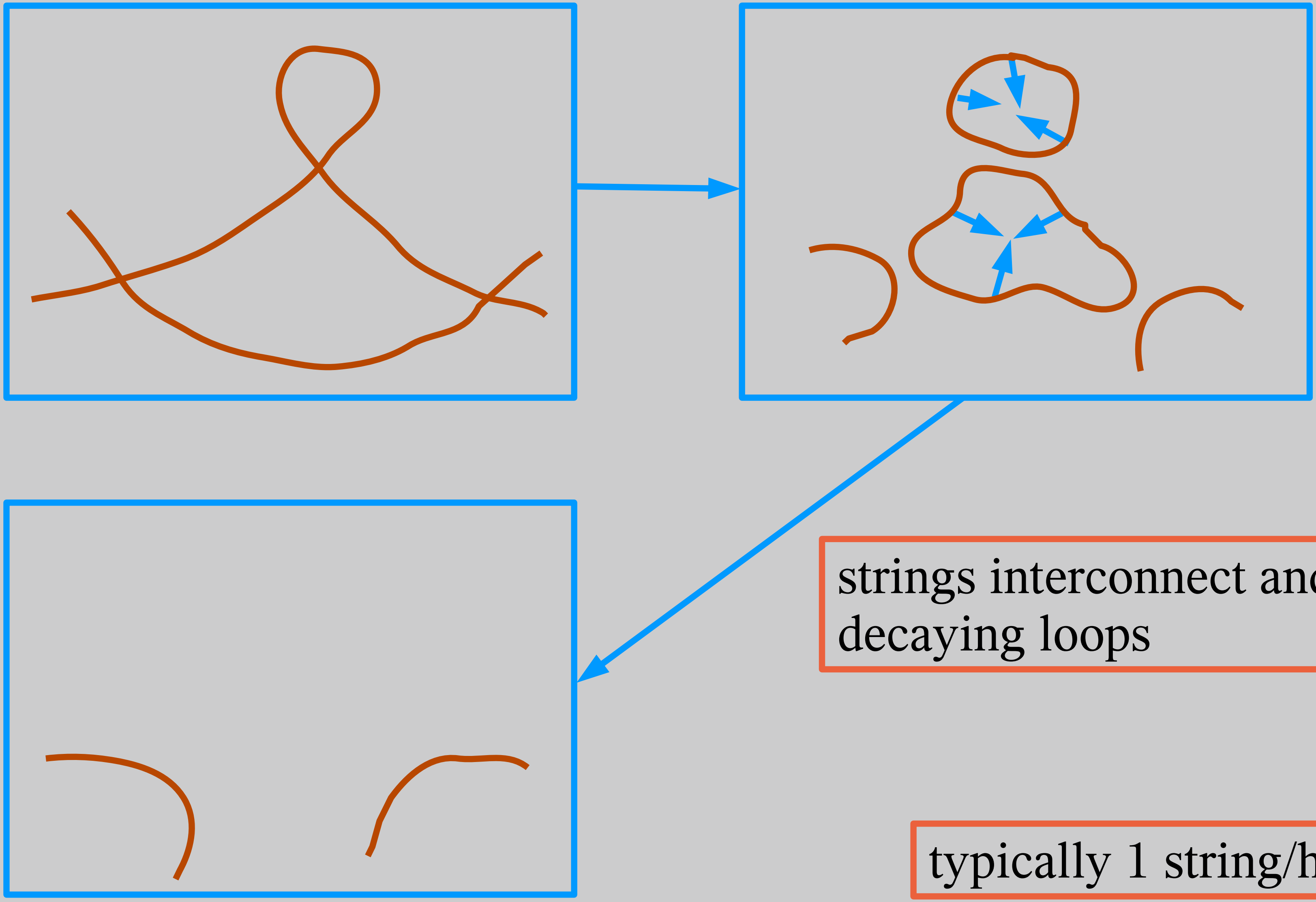
red- and blue-shift cancel for string at rest

however: Kaiser-Stebbins effect [Kaiser & Stebbins (1984)]



particles move towards each other after string has moved by ↔ **net red-shift for photons**

Scaling



strings interconnect and form decaying loops

typically 1 string/horizon

Impact on CMB

$$\ddot{\Theta} + (v_s k)^2 \Theta = -\frac{k^2}{3} \left(\Psi + \Psi_{\text{string}}(t) \right)$$

time dependence (incoherent) due to scaling

strings do not give rise to coherent acoustic oscillations → cannot be the primary source of CMB perturbations

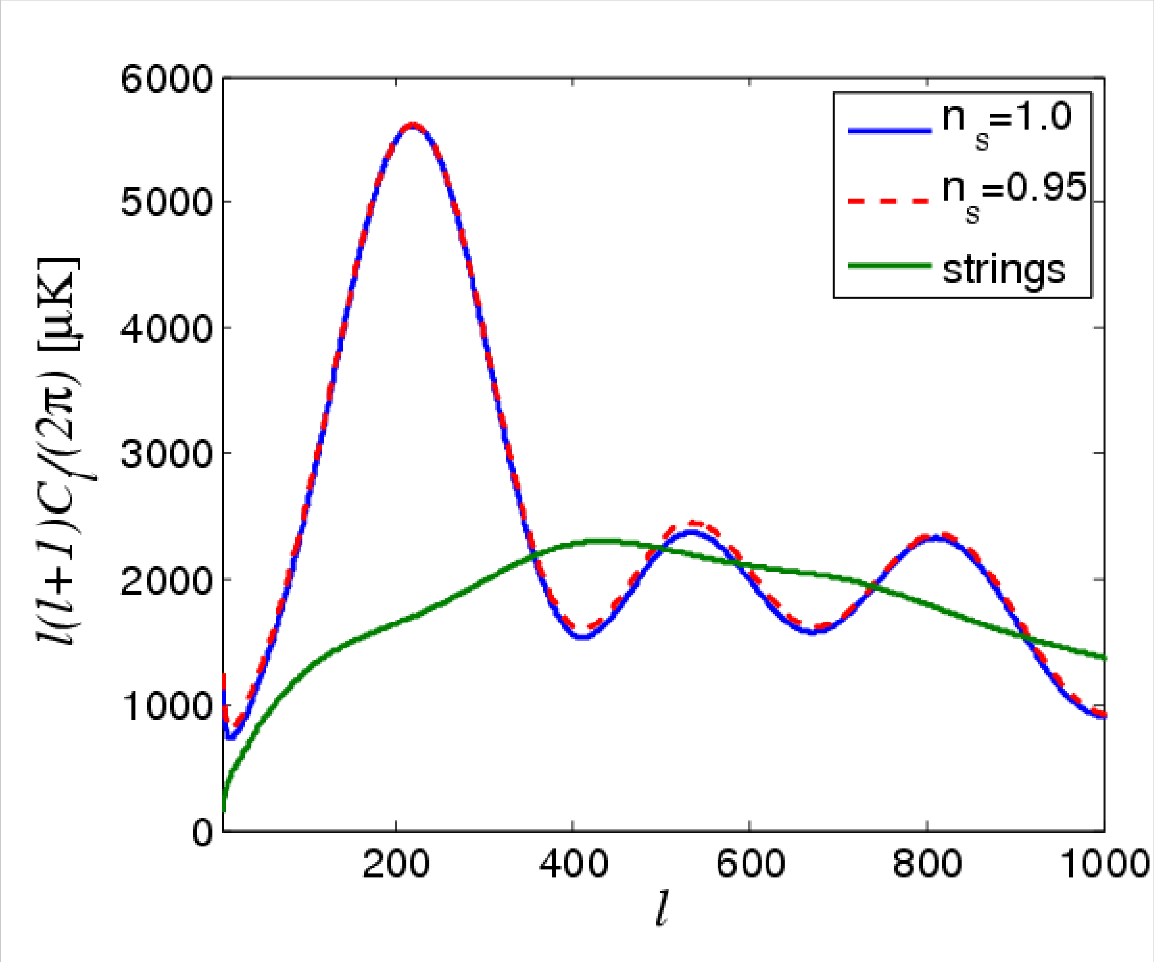
There may however be a subdominant ($\sim 10\%$) contribution to the perturbations.
[Battye, Weller (1998), Hindmarsh, Contaldi, Magueijo (1998)].

String contribution proportional to tension μ (mass per unit length). Dimensionless parameter: $G\mu$

Determine spectrum from computer simulation. [Pogosian, Vachaspati (1999)]

String-Induced Temperature Spectrum

String contribution magnified.



Blue model fits the data when subdominant string contribution added.
NB: Also other parameters (in particular larger Ω_B) are different.

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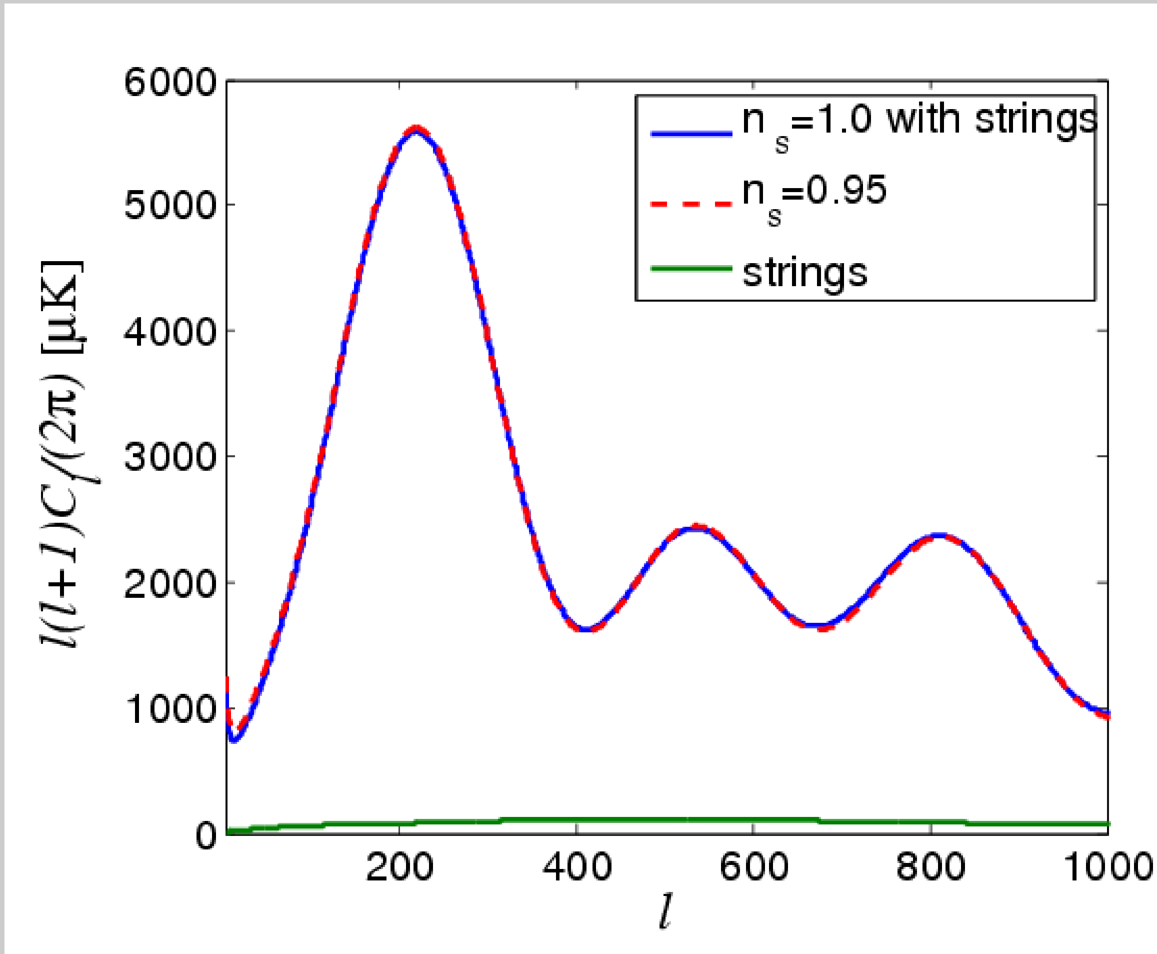
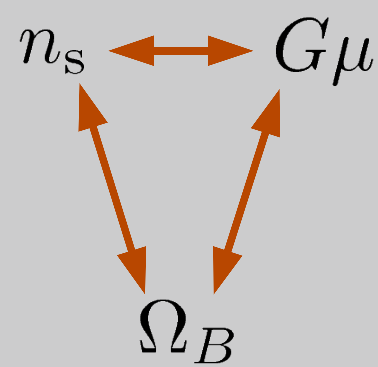




Scale-Invariant model can fit the data due to degeneracy $\{G\mu, n_{\rm s}, \Omega_B\}$.

2

Bounds on Strings from the Temperature-Temperature (*TT*) Perturbation of the CMB

MCMC Analysis

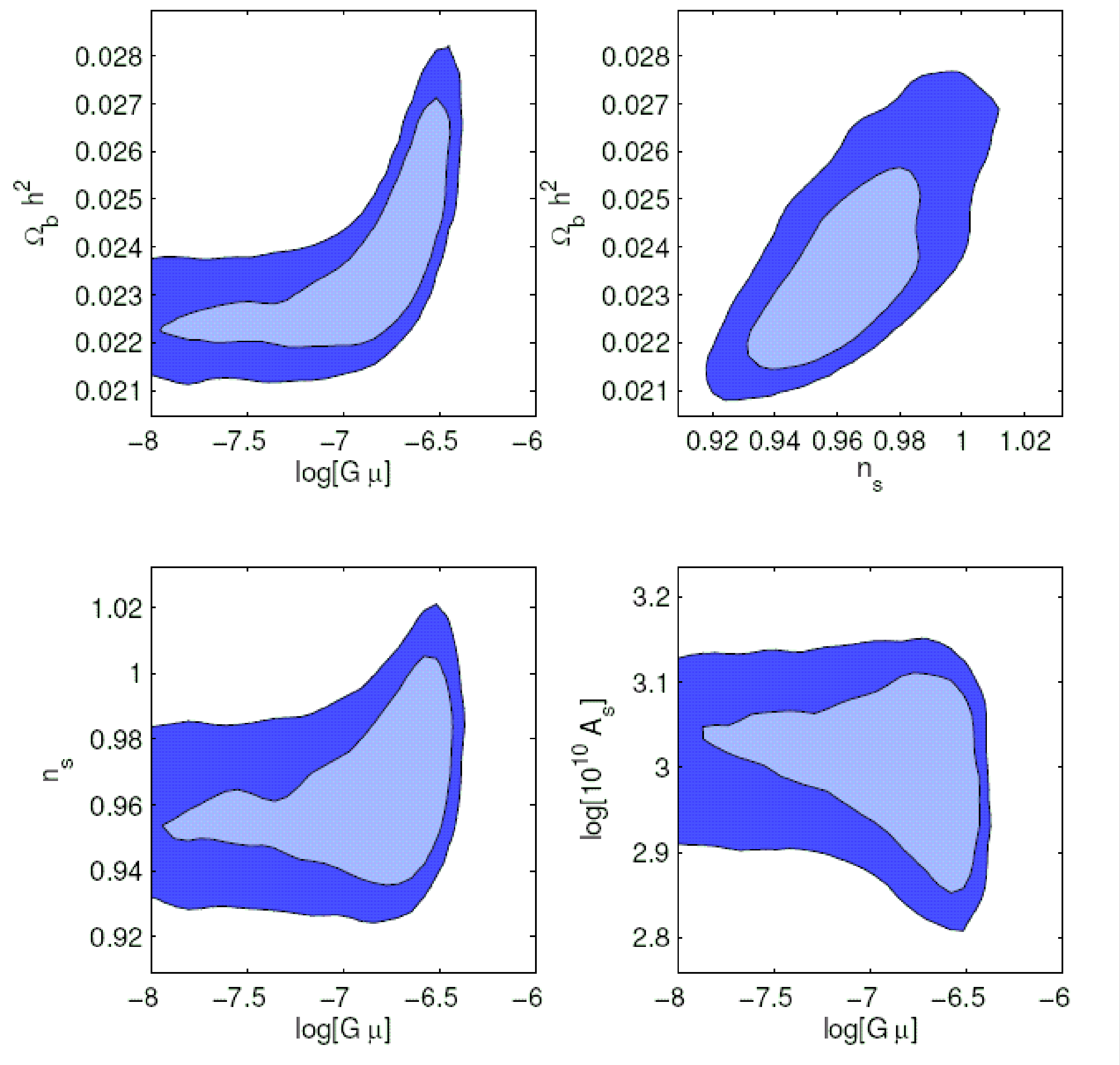
$$\Big\{ \underbrace{P_{\mathcal{R}}, n_{\rm s}, \Omega_{\rm B}, \Omega_{\rm DM}, \Omega_{\Lambda}, \tau}, \underbrace{G\mu} \Big\}$$

Standard 6 cosmological parameters.

String tension – vary this to change the amplitude of the string spectrum, which is proportional.

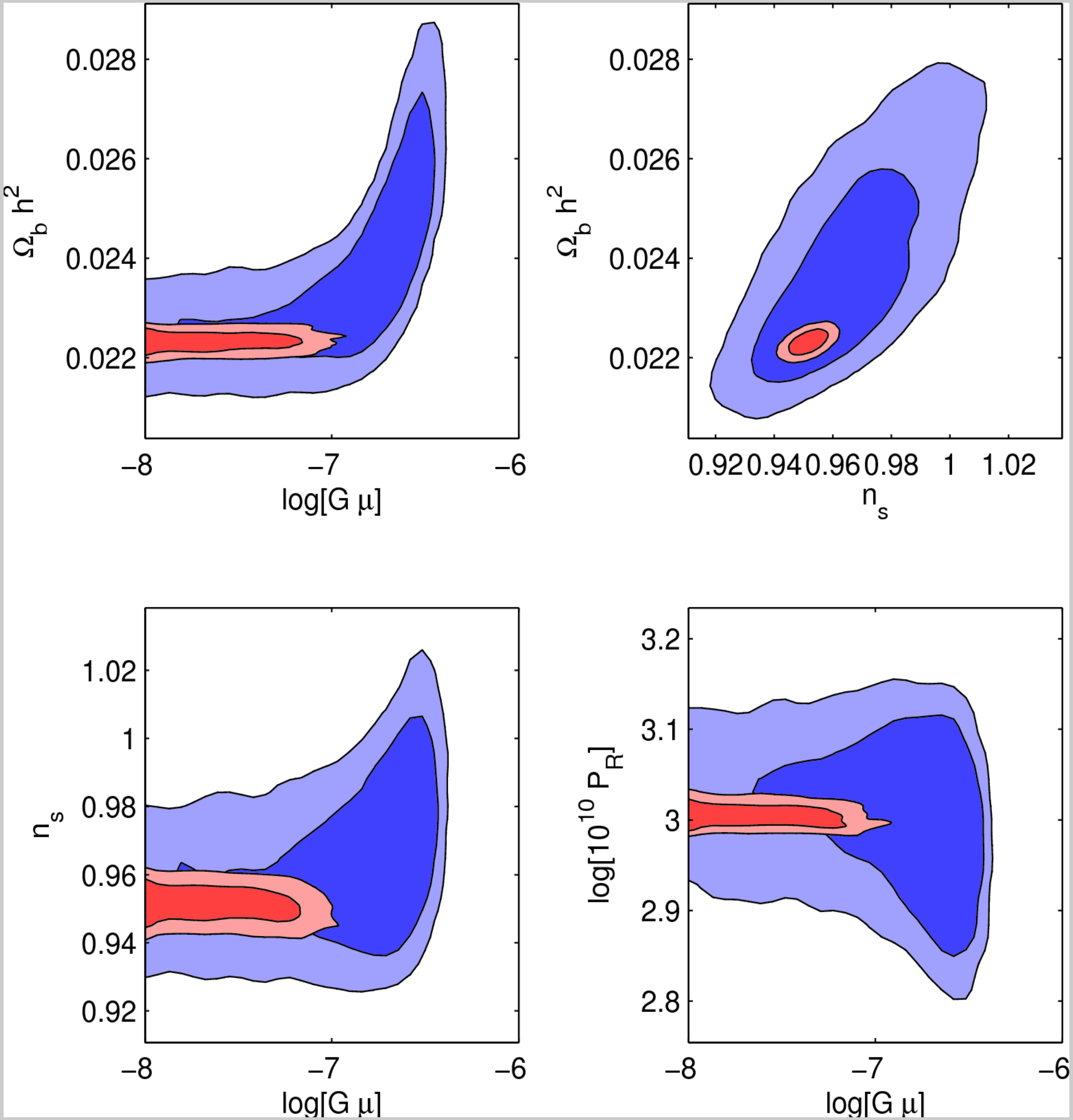
Use modified version of COSMOMC. [Lewis, Bridle (2002)]

Strings allow for Blue Spectrum



[Battye, BG, Moss (2006)]

Anticipated Planck Bounds



Blue: WMAP3 data.
Red: simulated Planck data.

[Battye, BG, Moss, Stoica (2008)]

Tighter bounds from improved small scale data.

[*cf.* also Pogosian, Tye, Wasserman, Wyman (2008)]

Bound on String Contribution

Upper bound on string tension: $G\mu = 3 \times 10^{-7}$ at 68% c.l.

$$\mu = (6.6 \times 10^{15}\mathrm{GeV})^2 = 3.9 \times 10^{20}\,\frac{\mathrm{kg}}{\mathrm{m}} = 2.6 \times 10^{20}\,\frac{\mathrm{lb}}{\mathrm{ft}}$$

$$m_{\mathrm{Earth}} = 6.0 \times 10^{24}\mathrm{kg}$$

3

Hybrid Inflation, Strings & Texture

F-Term Hybrid Inflation

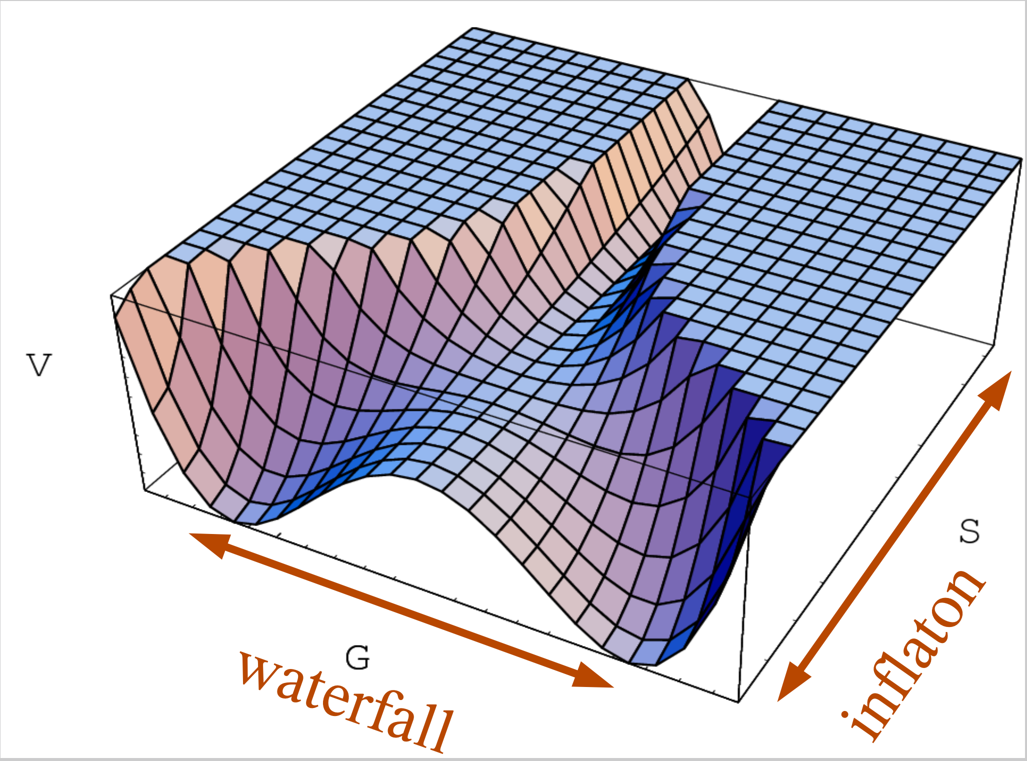
Superpotential:

$$W = \kappa \widehat{S}(\widehat{\overline{G}}\widehat{G} - M^2)$$

U(1) -fields

Tree-level potential:

$$V_0 = \kappa^2 \Big[\big|\overline{G}G - M^2\big|^2 + \big|S\overline{G}\big|^2 + \big|SG\big|^2 \Big]$$



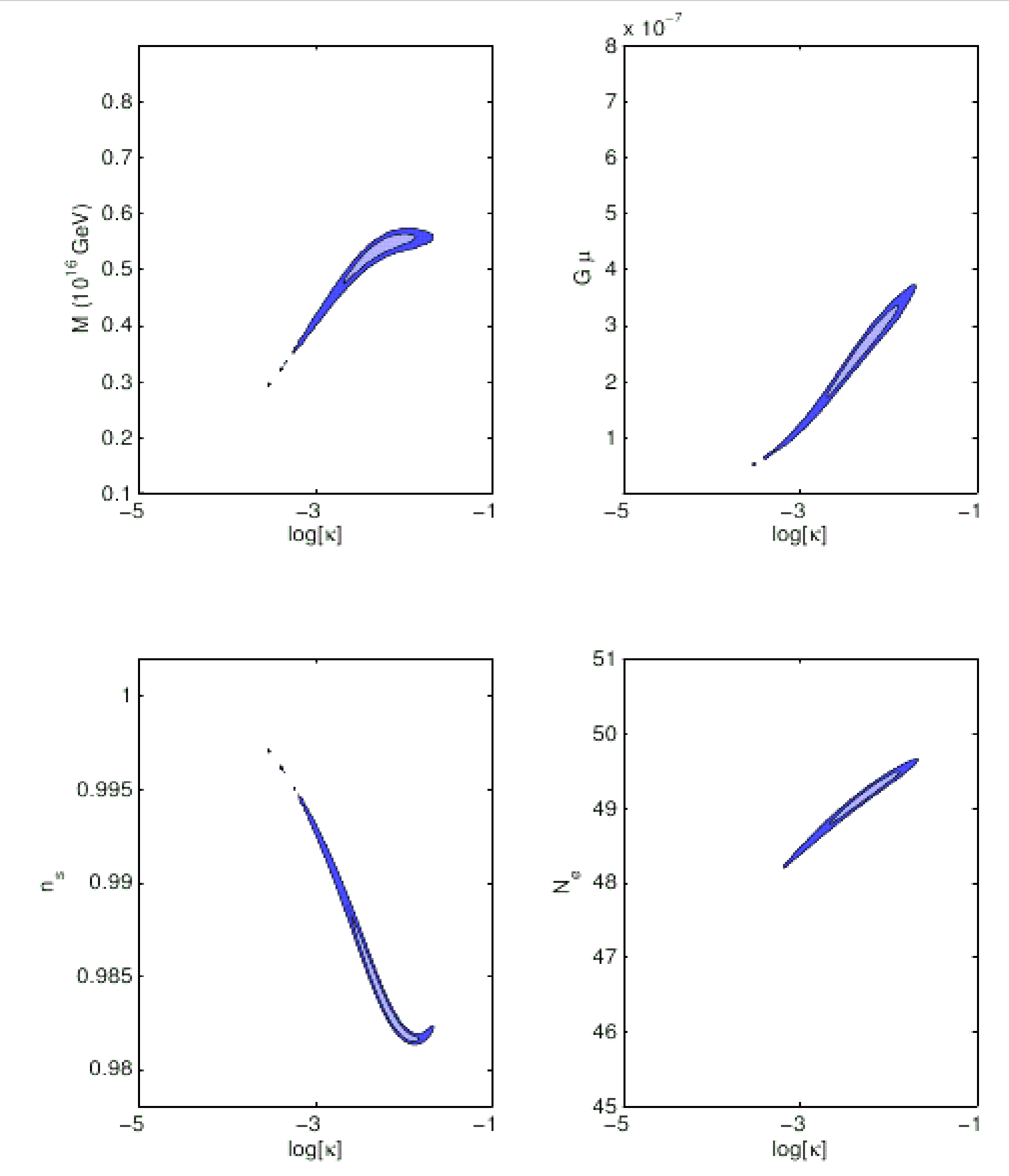
Radiative correction:

$$V_{\rm CW} = \frac{\kappa^4}{32\pi^2}\Big\{(S^2+M^2)^2 \ln\left(1+\frac{M^2}{S^2}\right) + (S^2-M^2)^2 \ln\left(1-\frac{M^2}{S^2}\right) + 2M^4 \ln\frac{\kappa^2 S^2}{Q^2}\Big\}$$

Furthermore, SUGRA corrections from canonical Kähler potential.

Only two parameters: $\{\kappa,\ M\}$ ⟷ trade for ⟷ $\left\{\sqrt{P_\mathcal{R}}, n_{\rm s}.G\mu\right\}$

F-Term Inflation 6 Parameter Fit



$$\log_{10}\kappa = -2.34 \pm 0.38$$

$$M = (0.518 \pm 0.059) \times 10^{16}\text{GeV}$$

χ^2-goodness of fit:

$$-2\log_{10}\mathcal{L} = 11303.3$$

cf. standard 6 parameter fit

$$-2\log_{10}\mathcal{L} = 11305.5$$

D-Term Inflation

[Binetruy, Dvali; Halyo (1996)]

Superpotential: $W = \kappa \widehat{S}\widehat{\overline{G}}\widehat{G}$

D-Term: $D = \frac{g}{2}\left(|G|^2 - |\overline{G}|^2 + m_{\mathrm{FI}}^2\right)$

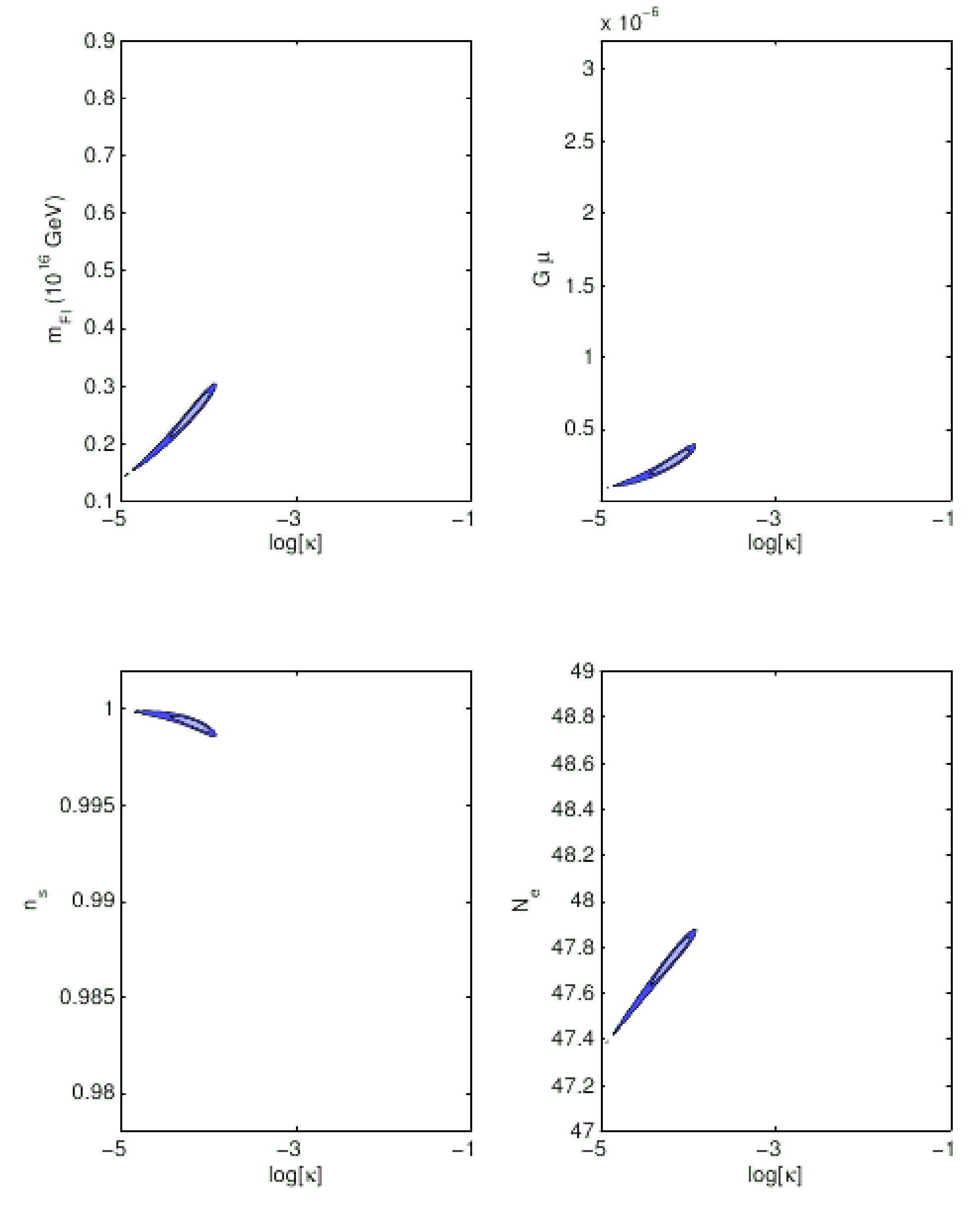
Tree-level potential: $V_0 = \kappa^2\left[|\overline{G}G|^2 + |S\overline{G}|^2 + |SG|^2\right] + \frac{1}{2}D^2$

Radiative correction:

$$\begin{aligned} V_{\mathrm{CW}} = & \frac{1}{32\pi^2}\left\{(\kappa^2 s^2 + \tfrac{g^2}{4}m_{\mathrm{FI}}^2)^2 \ln\left(1 + \tfrac{g^2}{4\kappa^2}\tfrac{m_{\mathrm{FI}}^2}{s^2}\right)\right. \\ & \left. +(\kappa^2 s^2 - \tfrac{g^2}{4}m_{\mathrm{FI}}^2)^2 \ln\left(1 - \tfrac{g^2}{4\kappa^2}\tfrac{m_{\mathrm{FI}}^2}{s^2}\right) + \tfrac{g^4}{8}m_{\mathrm{FI}}^4 \ln\tfrac{\kappa^2 s^2}{Q^2}\right\} \end{aligned}$$

- **No sizable SUGRA correction.**
- **Naturally induces cosmic strings.**
- **Can arise as an effective theory of brane inflation.**
  [Haack, Kallosh, Krause, Linde, Lüst, Zagermann (2008)]

D-Term Inflation 6-Parameter Fit



$$\log \kappa = -4.24 \pm 0.19$$

$$m_{\rm FI} = (0.24 \pm 0.03) \times 10^{16}{\rm GeV}$$

χ^2-goodness of fit:

$$-2 \log_{10} \mathcal{L} = 11303.0$$

cf. standard 6 parameter fit

$$-2 \log_{10} \mathcal{L} = 11305.5$$

Model fits slightly better, even though adiabatic contribution is scale-invariant.

F-Term Inflation with Texture

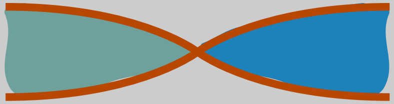
[Battye, Garbrecht, Pilaftsis (2008)]

waterfall field *globally* SU(2)-symmetric

vacuum manifold is isomorphic to S^3

global textures [Turok (1989)]

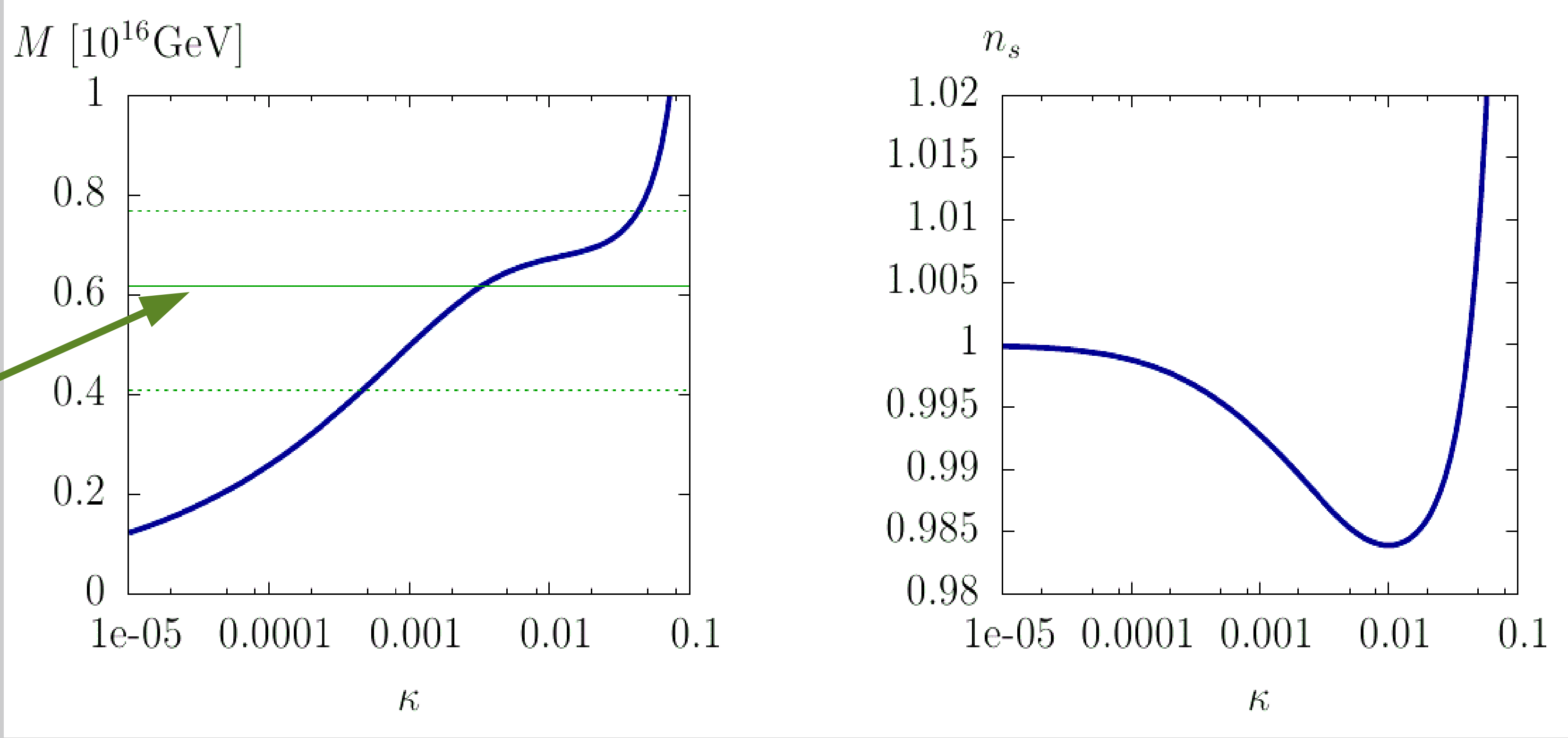
one-dimensional analogue:
Ribbon (symmetry U(1), vacuum manifold S^1)



global defects have long-range interactions (no Meißner effect)

can interact on subhorizon scales and create non-gaussian cold and hot spots, besides spectrum similar to the case of local strings

Hybrid Inflation, Texture & the Cold Spot



scale of candidate spot identified by Cruz, Turok, Vielva, Martinez-Gonzalez, Hobson (2007)

- scale of hybrid inflation coincides with symmetry breaking scale from cold-spot hint
- have discussed a cosmological (reheating) scenario taking account of the Goldstone modes associated with the broken global symmetries

Conclusions

- **Strings can contribute subdominantly to the CMB perturbation.**
- **If the strings contribute at a few percent level, the scalar spectral index may be as large as *one*.**
- **If the strings contribute at a few percent level, the fit to the data is slightly, but not significantly better. This holds even when the spectrum is scale invariant.**
- **The symmetry breaking scale associated with a percent-level string contribution coincides with the energy scale of SUSY hybrid inflation.**
- **Global defects, for example texture, can in addition explain the presence of the cold spot.**

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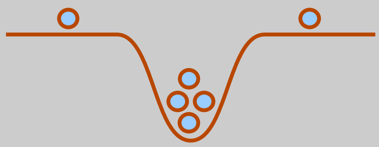

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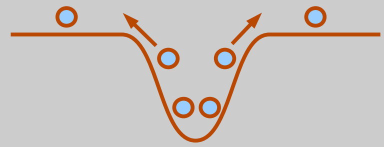

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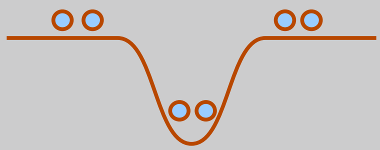

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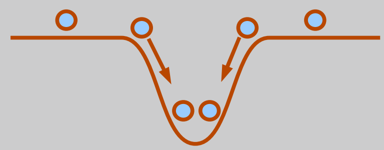

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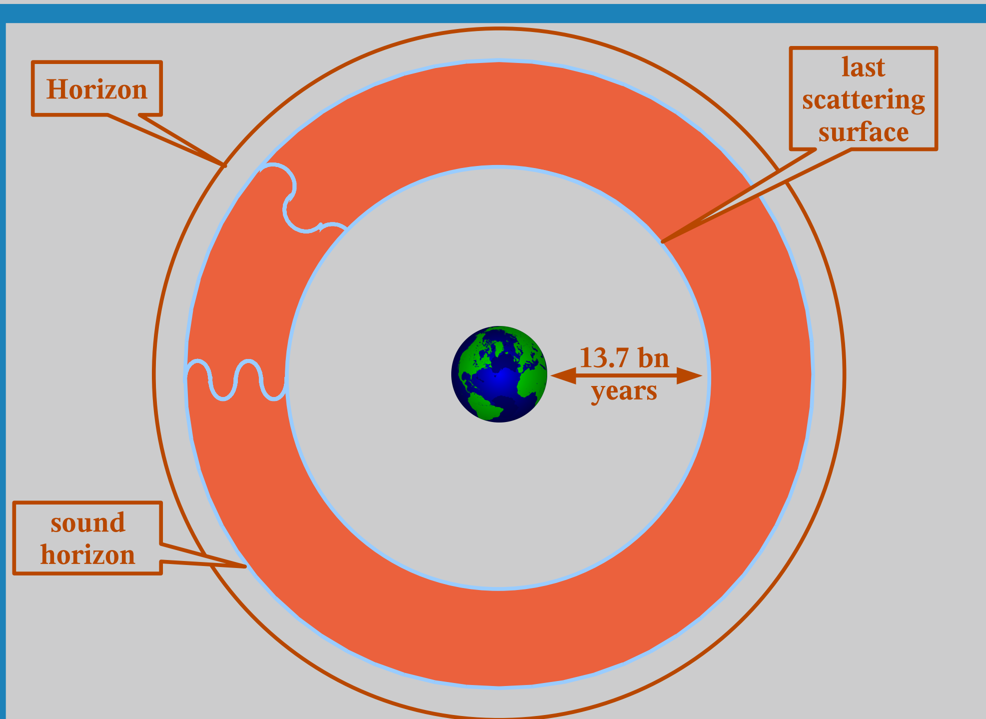
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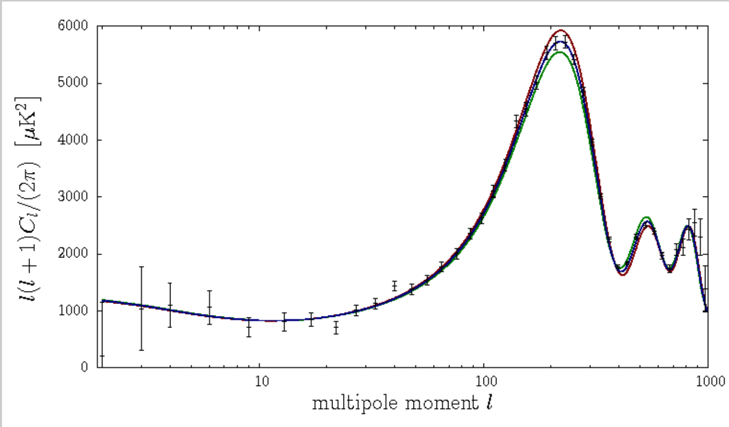

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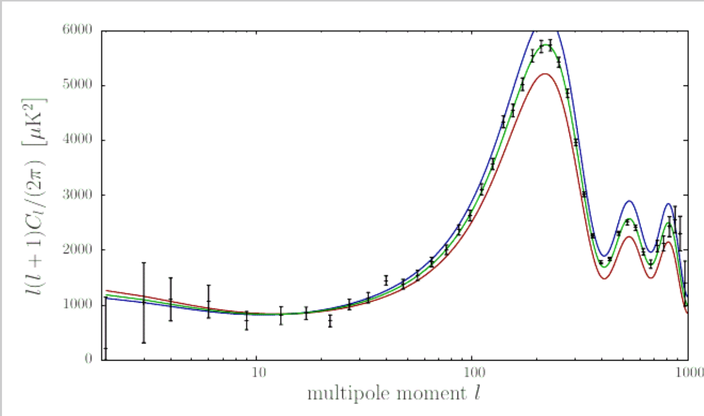
n_S and Acoustic Peaks



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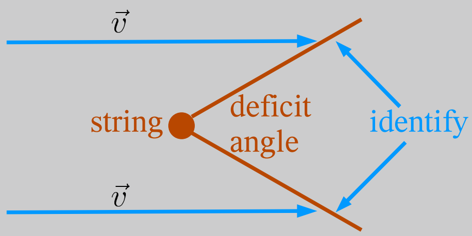
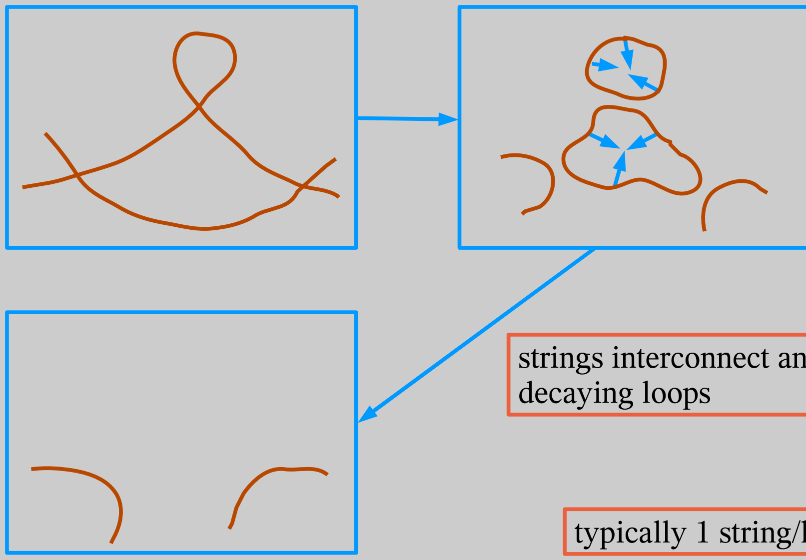
however: Kaiser-Stebbins effect [Kaiser & Stebbins (1984)]



particles move towards each other after string has moved by ↔ **net red-shift for photons**

Scaling



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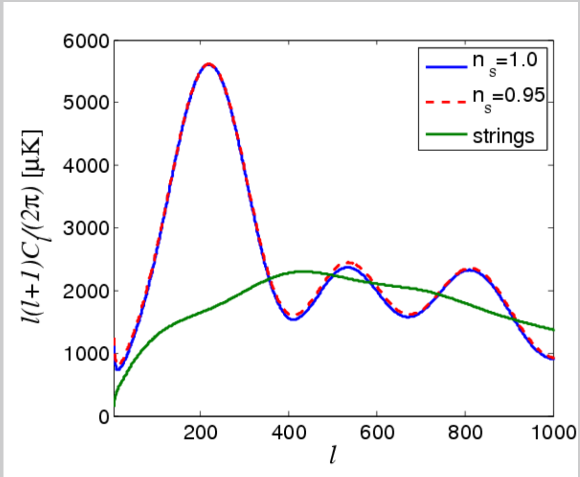
Determine spectrum from computer simulation. [Pogosian, Vachaspati (1999)]

String-Induced Temperature Spectrum

String contribution magnified.



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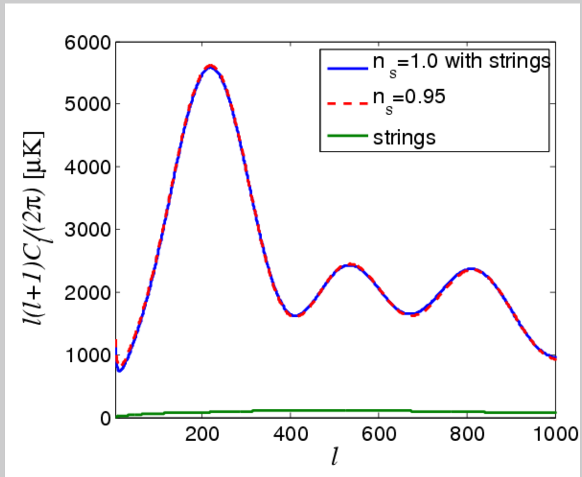

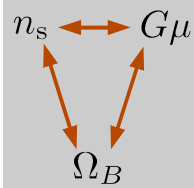

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MCMC Analysis

$$\Big\{\underbrace{P_{\mathcal{R}}, n_{\mathrm{s}}, \Omega_{\mathrm{B}}, \Omega_{\mathrm{DM}}, \Omega_{\Lambda}, \tau,}\ \underbrace{G\mu}\Big\}$$

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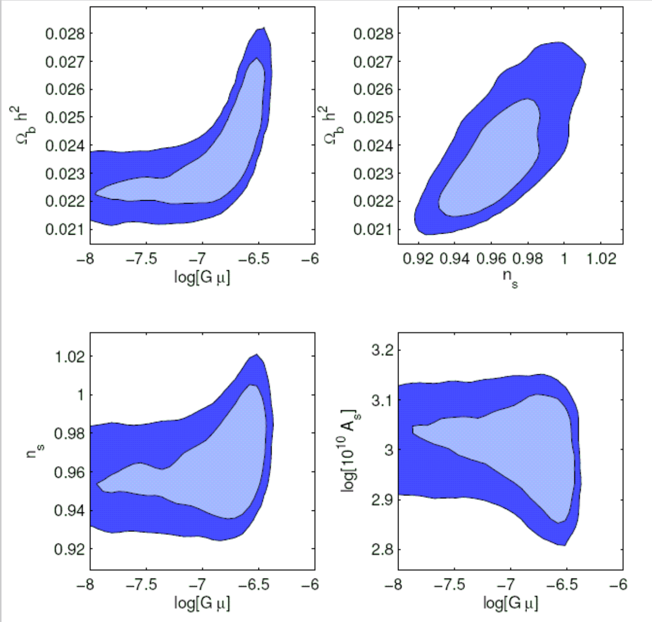
String tension
– vary this to change the amplitude of the string spectrum, which is proportional.

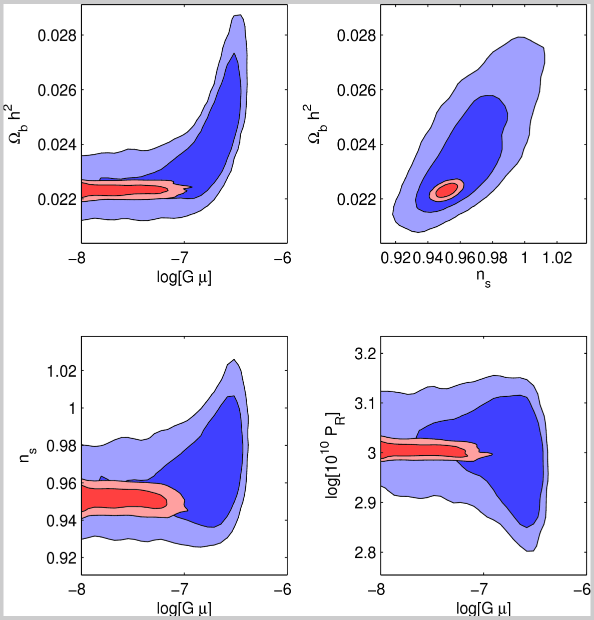
Use modified version of COSMOMC. [Lewis, Bridle (2002)]

Strings allow for Blue Spectrum



[Battye, BG, Moss (2006)]

Anticipated Planck Bounds



Blue: WMAP3 data.
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Bound on String Contribution

Upper bound on string tension: $G\mu = 3 \times 10^{-7}$ at 68% c.l.

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Hybrid Inflation, Strings & Texture

F-Term Hybrid Inflation

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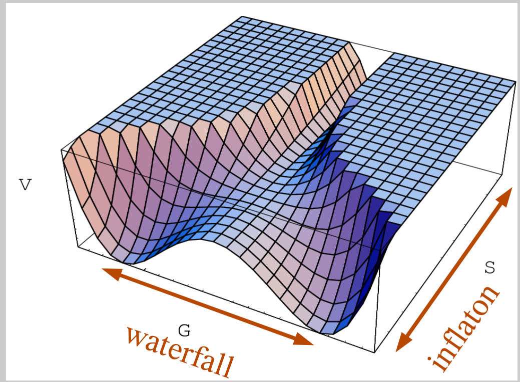

Tree-level potential:

$$V_0 = \kappa^2 \Big[\left|\overline{G}G - M^2\right|^2 + \left|S\overline{G}\right|^2 + \left|SG\right|^2 \Big]$$

Radiative correction:

$$V_{\rm CW} = \frac{\kappa^4}{32\pi^2}\Big\{(S^2+M^2)^2 \ln\left(1+\frac{M^2}{S^2}\right) + (S^2-M^2)^2 \ln\left(1-\frac{M^2}{S^2}\right) + 2M^4 \ln\frac{\kappa^2 S^2}{Q^2}\Big\}$$

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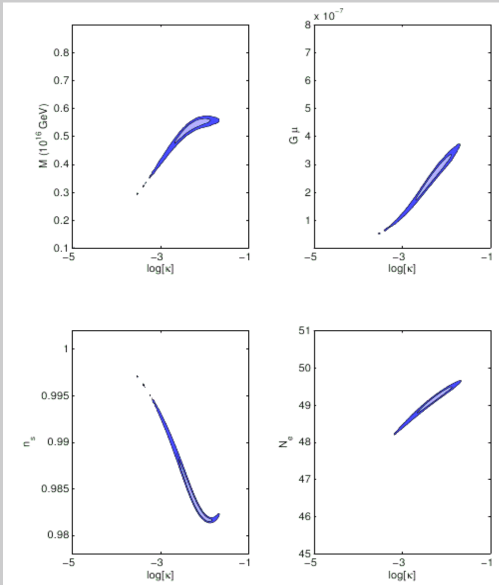
F-Term Inflation 6 Parameter Fit



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cf. standard 6 parameter fit

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D-Term Inflation

Superpotential: $W = \kappa \widehat{S}\widehat{\overline{G}}\widehat{G}$ [Binetruy, Dvali; Halyo (1996)]

D-Term: $D = \frac{g}{2}\left(|G|^2 - |\overline{G}|^2 + m_{\rm FI}^2\right)$

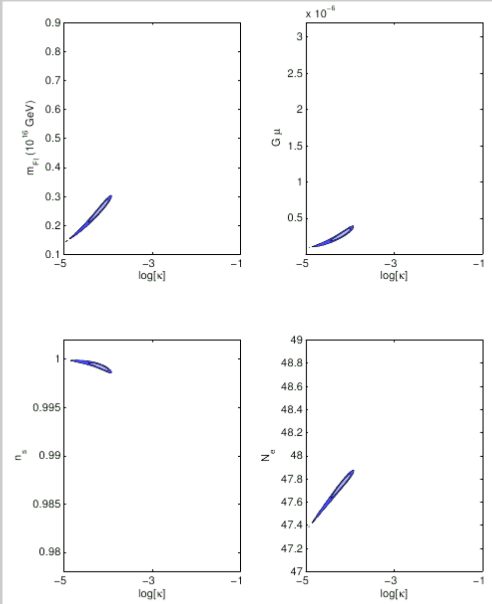
Tree-level potential: $V_0 = \kappa^2\left[|\overline{G}G|^2 + |S\overline{G}|^2 + |SG|^2\right] + \frac{1}{2}D^2$

Radiative correction:

$$\begin{aligned} V_{\rm CW} \;=\; & \tfrac{1}{32\pi^2}\Big\{(\kappa^2 s^2 + \tfrac{g^2}{4}m_{\rm FI}^2)^2 \ln\left(1 + \tfrac{g^2}{4\kappa^2}\tfrac{m_{\rm FI}^2}{s^2}\right) \\ & +(\kappa^2 s^2 - \tfrac{g^2}{4}m_{\rm FI}^2)^2 \ln\left(1 - \tfrac{g^2}{4\kappa^2}\tfrac{m_{\rm FI}^2}{s^2}\right) + \tfrac{g^4}{8}m_{\rm FI}^4 \ln \tfrac{\kappa^2 s^2}{Q^2}\Big\} \end{aligned}$$

- **No sizable SUGRA correction.**
- **Naturally induces cosmic strings.**
- **Can arise as an effective theory of brane inflation.**
  [Haack, Kallosh, Krause, Linde, Lüst, Zagermann (2008)]

D-Term Inflation 6-Parameter Fit



$$\log \kappa = -4.24 \pm 0.19$$

$$m_{\rm FI} = (0.24 \pm 0.03) \times 10^{16} \text{GeV}$$

χ^2-goodness of fit:

$$-2 \log_{10} \mathcal{L} = 11303.0$$

cf. standard 6 parameter fit

$$-2 \log_{10} \mathcal{L} = 11305.5$$

Model fits slightly better, even though adiabatic contribution is scale-invariant.

F-Term Inflation with Texture

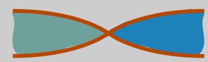
[Battye, Garbrecht, Pilaftsis (2008)]

waterfall field *globally* SU(2)-symmetric

vacuum manifold is isomorphic to S^3

global textures [Turok (1989)]

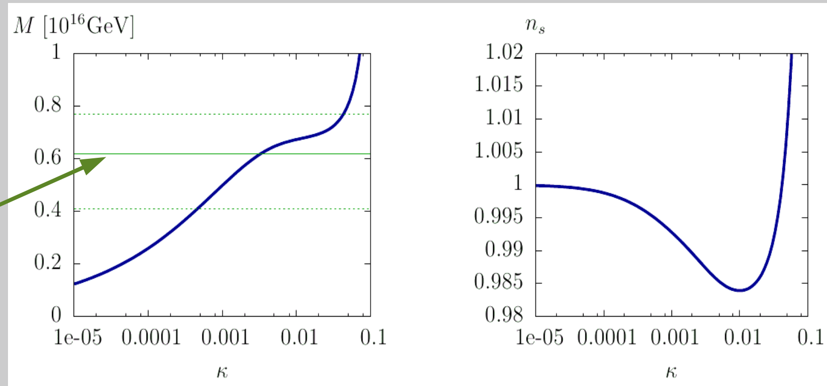
one-dimensional analogue:
Ribbon (symmetry U(1), vacuum manifold S^1)



global defects have long-range interactions (no Meißner effect)

can interact on subhorizon scales and create non-gaussian cold and hot spots, besides spectrum similar to the case of local strings

Hybrid Inflation, Texture & the Cold Spot



scale of candidate spot identified by Cruz, Turok, Vielva, Martinez-Gonzalez, Hobson (2007)

- scale of hybrid inflation coincides with symmetry breaking scale from cold-spot hint
- have discussed a cosmological (reheating) scenario taking account of the Goldstone modes associated with the broken global symmetries

Conclusions

- **Strings can contribute subdominantly to the CMB perturbation.**
- **If the strings contribute at a few percent level, the scalar spectral index may be as large as *one*.**
- **If the strings contribute at a few percent level, the fit to the data is slightly, but not significantly better. This holds even when the spectrum is scale invariant.**
- **The symmetry breaking scale associated with a percent-level string contribution coincides with the energy scale of SUSY hybrid inflation.**
- **Global defects, for example texture, can in addition explain the presence of the cold spot.**