Current cosmic string constraints based on the Sussex-Imperial-Geneva defect simulations

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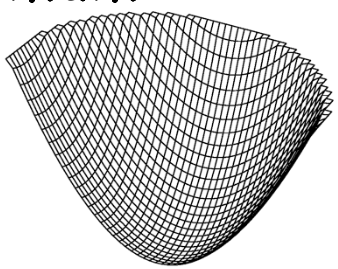
overview

- what are topological defects?
- why are they interesting?
- defect simulations
- from simulations to the CMB
- current power spectra results
- outlook: beyond the CMB
- conclusions

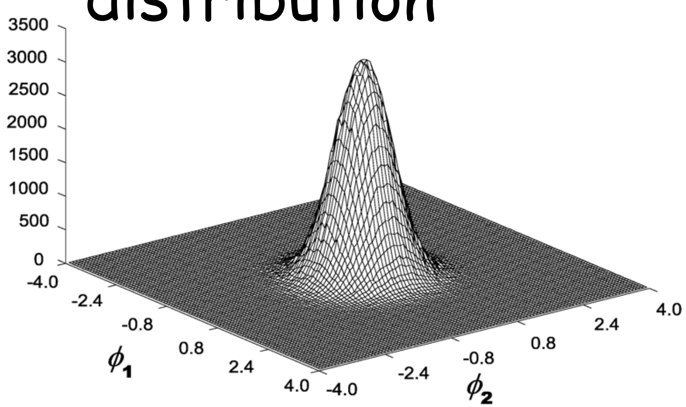
what are topological defects?

High temperature

- potential has single minimum

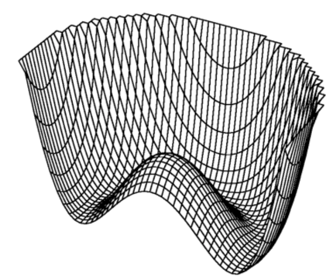


- symmetric field distribution

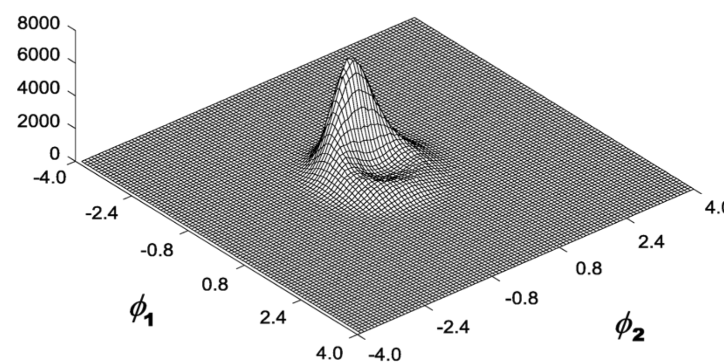


low temperature

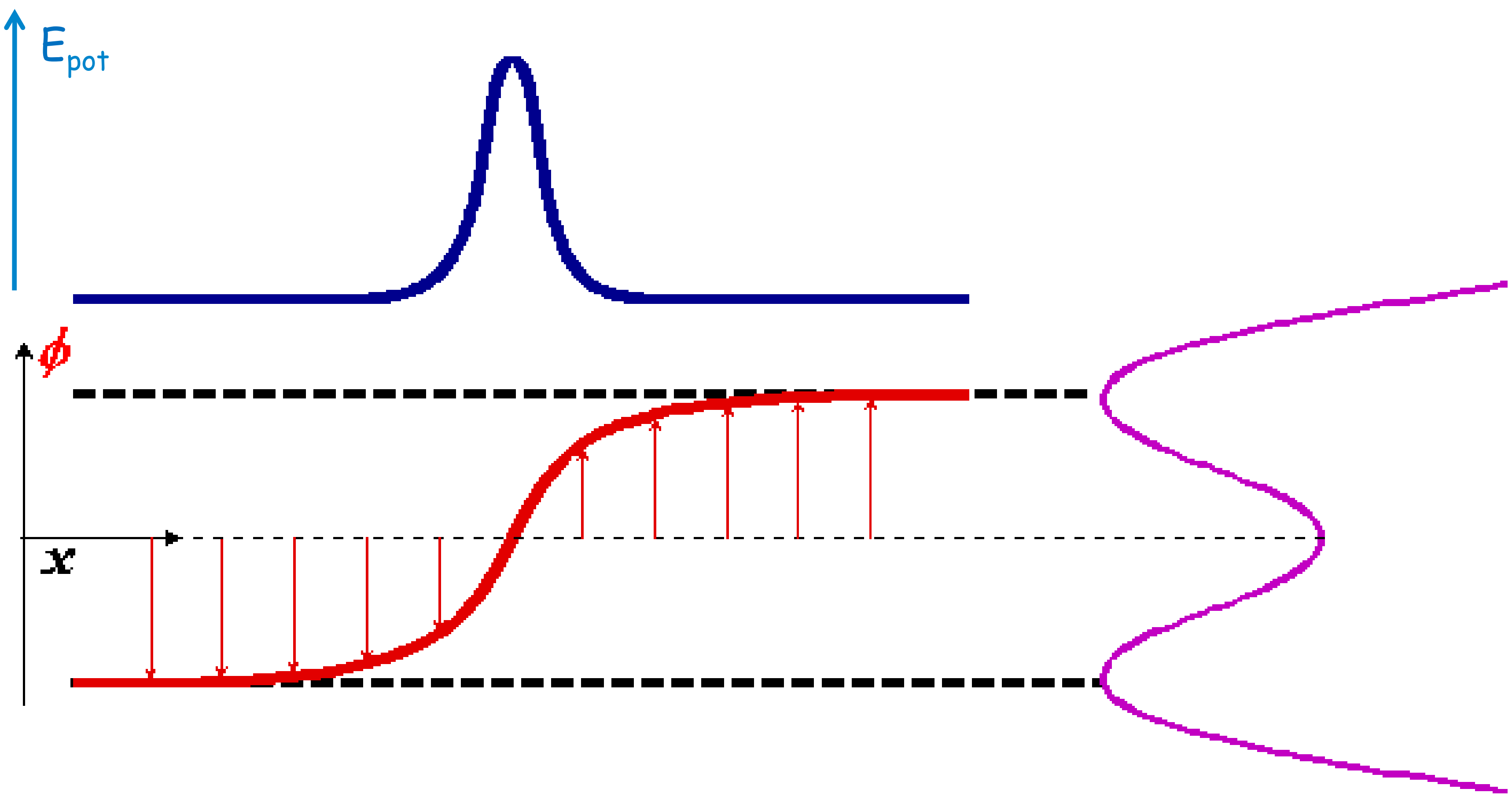
- potential has several minima



- asymmetric field distribution



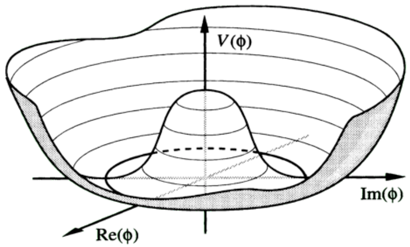
what are topological defects?



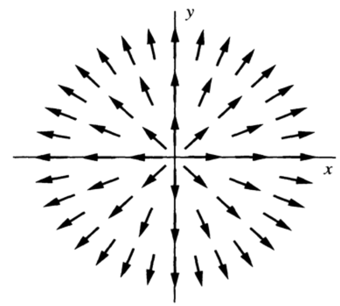
- crossing of ϕ=0 protected by topology of V_{min}
- field has to balance potential and gradient energy

zoology I

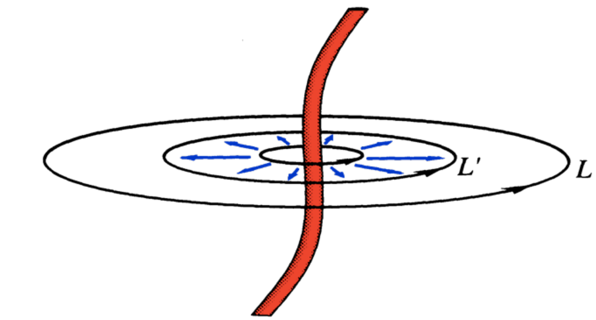
strings:



potential

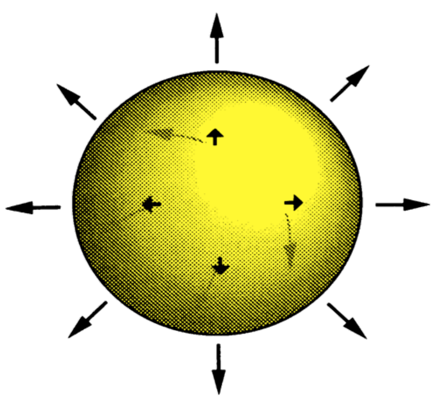


field configuration

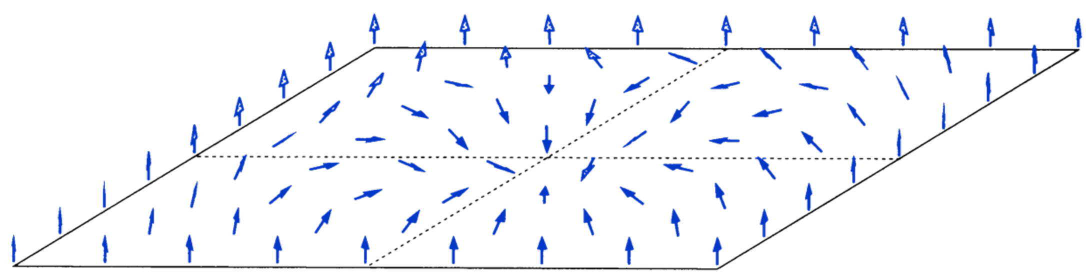


string in 3D

monopoles:



texture:



(illustrations from Vilenkin&Shellard)

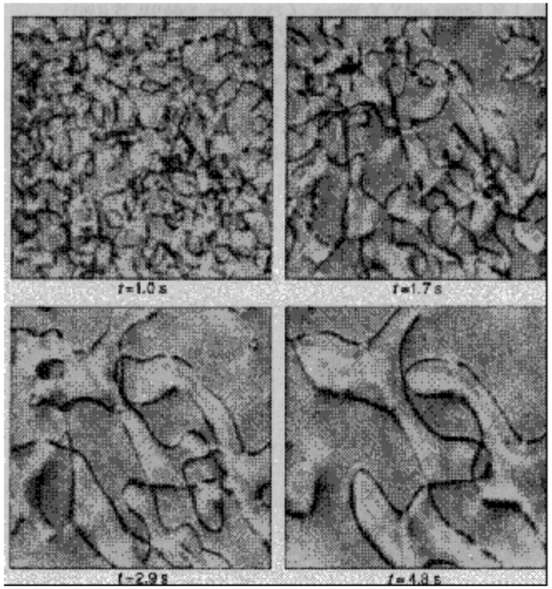
zoology II

- **global defects**
  - big, fat, fluffy things
  - just one (N-component) scalar field -> long range forces
  - gradient and potential energy balance
- **local defects**
  - scalar and gauge fields
  - gauge field can remove gradients, no long range force
  - small
  - only strings relevant (others disappear or dominate)
- **other strings**
  - semilocal strings: not topologically stable, can disappear
  - fundamental strings
  - (p,q) strings
  - many more possibilities! (eg strings ending on monopoles, etc)

do topological defects exist?

Yes! At least in "normal" physics:

- vortices in superfluid helium
- flux lines in superconductors
- polymers
- liquid crystals
- ...



defects in liquid crystals
(Chuang, Durrer, et al)

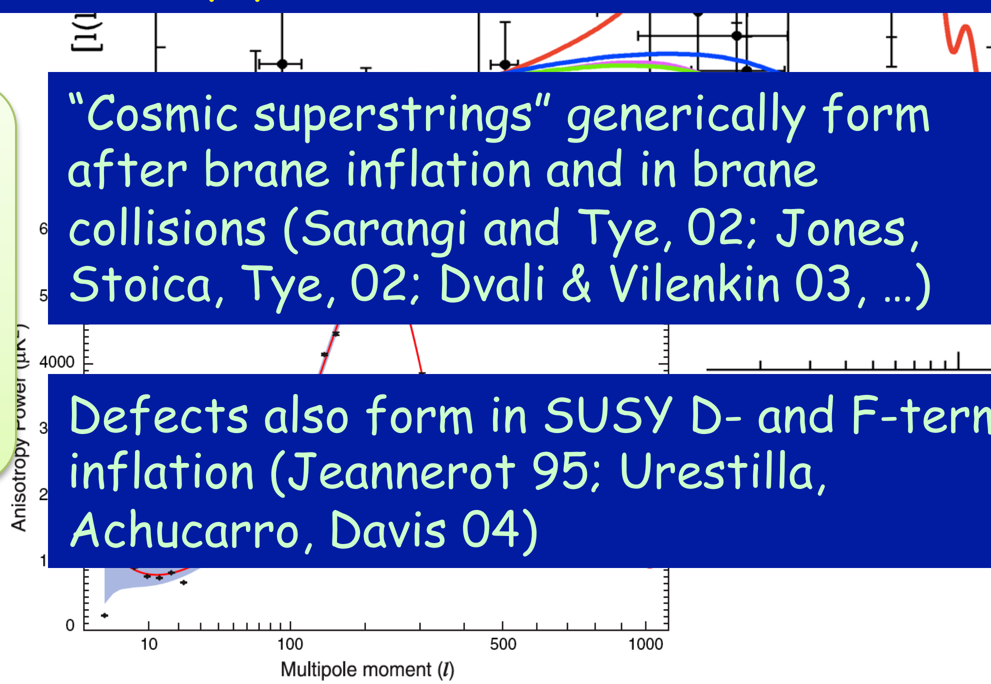
why think about defects?

- ***topological defects exist in nature***
- defects are created naturally in phase transitions
- phase transitions are natural in the universe
- cosmic defects would perturb the universe
- the universe shows perturbations at the level of 10^{-5} (e.g. in the CMB)
- the scale would be just right for a "GUT" (Grand Unified Theory)
- did the defects cause the initial perturbations?

defects *and* inflation

"We consider gauge groups having a rank between 4 and 8. We examine all possible spontaneous symmetry breaking patterns from the GUT down to the standard model gauge group. 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 lifetime measurements. We conclude that in all acceptable spontaneous symmetry breaking schemes, cosmic string formation is unavoidable."
(Jeannerot, Rocher & Sakellariadou, hep-ph/0308134)

BUT:
many "realistic" inflationary models create generically defects after inflation!



"Cosmic superstrings" generically form after brane inflation and in brane collisions (Sarangi and Tye, 02; Jones, Stoica, Tye, 02; Dvali & Vilenkin 03, ...)

Defects also form in SUSY D- and F-term inflation (Jeannerot 95; Urestilla, Achucarro, Davis 04)

how do we study defects?

- run defect simulation (field theory on a grid)
- record energy-momentum tensor
- defects are highly non-linear objects, so assume that they are stable against small perturbations

  -> they perturb the universe, but are not perturbed by it
- add their perturbation of the metric to the perturbations from everything else
- run CMBEasy (or CAMB, CLASS or cmbfast)

progress in computing

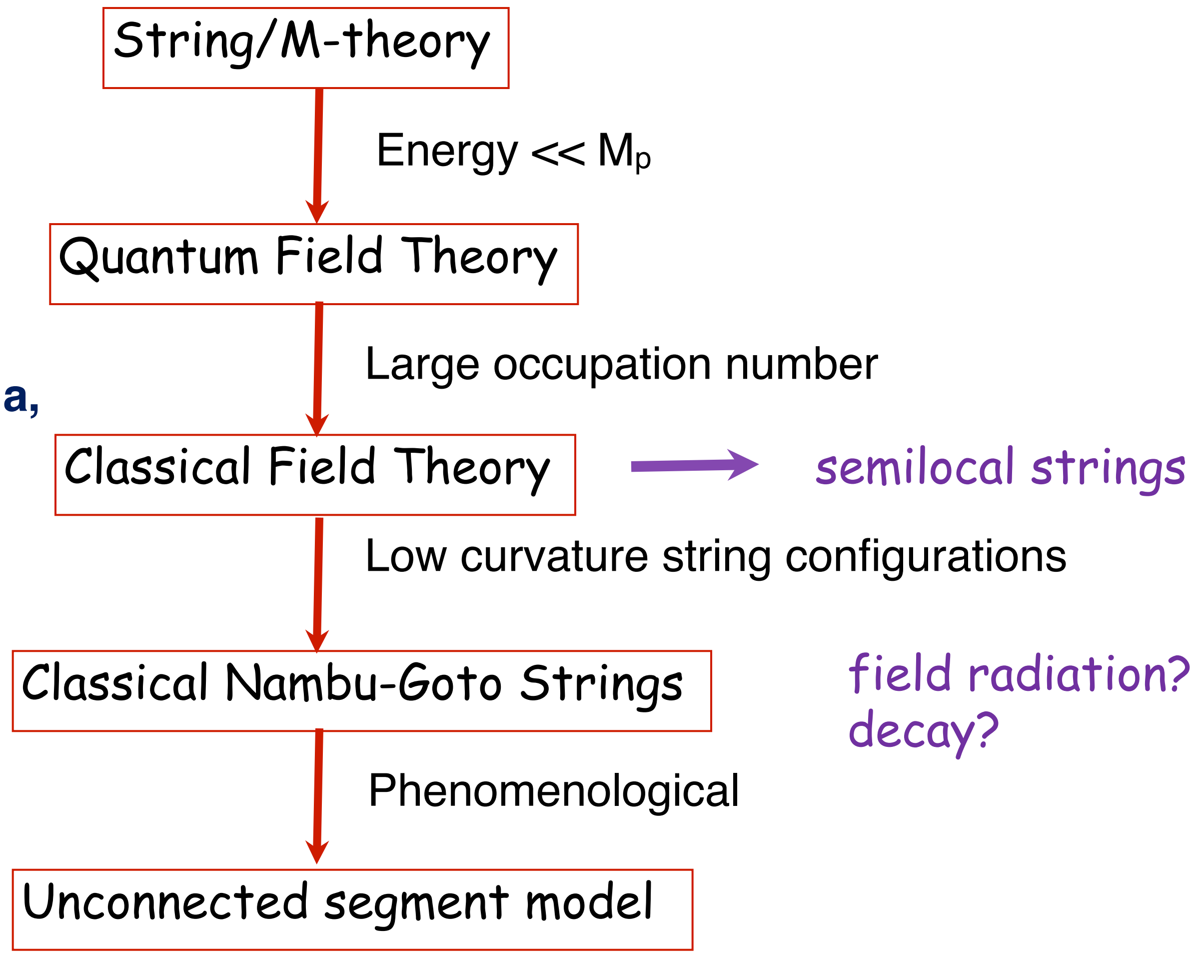
- ca 1998: global defects, 400^3 grid
  - single vector processor
- ca 2005: cosmic strings, 512^3 grid
  - MPI code w/ '1D' parallelisation (FFT issue)
- ca 2009: cosmic strings, 1024^3 grid
  - bigger computer (some other improvements)
- 2012: cosmic strings, 4096^3 grid
  - '2D' parellelisation (MPI), scales to $>10^5$ cores
  - 11 TB of field-data in memory…
  - improved parallel I/O -> David Daverio's talk

levels of approximations

Sussex String Simulations
Bevis, Hindmarsh, Urrestilla, MK et al, astro-ph:0605018 arXiv:0704.3800, arXiv: 1005.2663

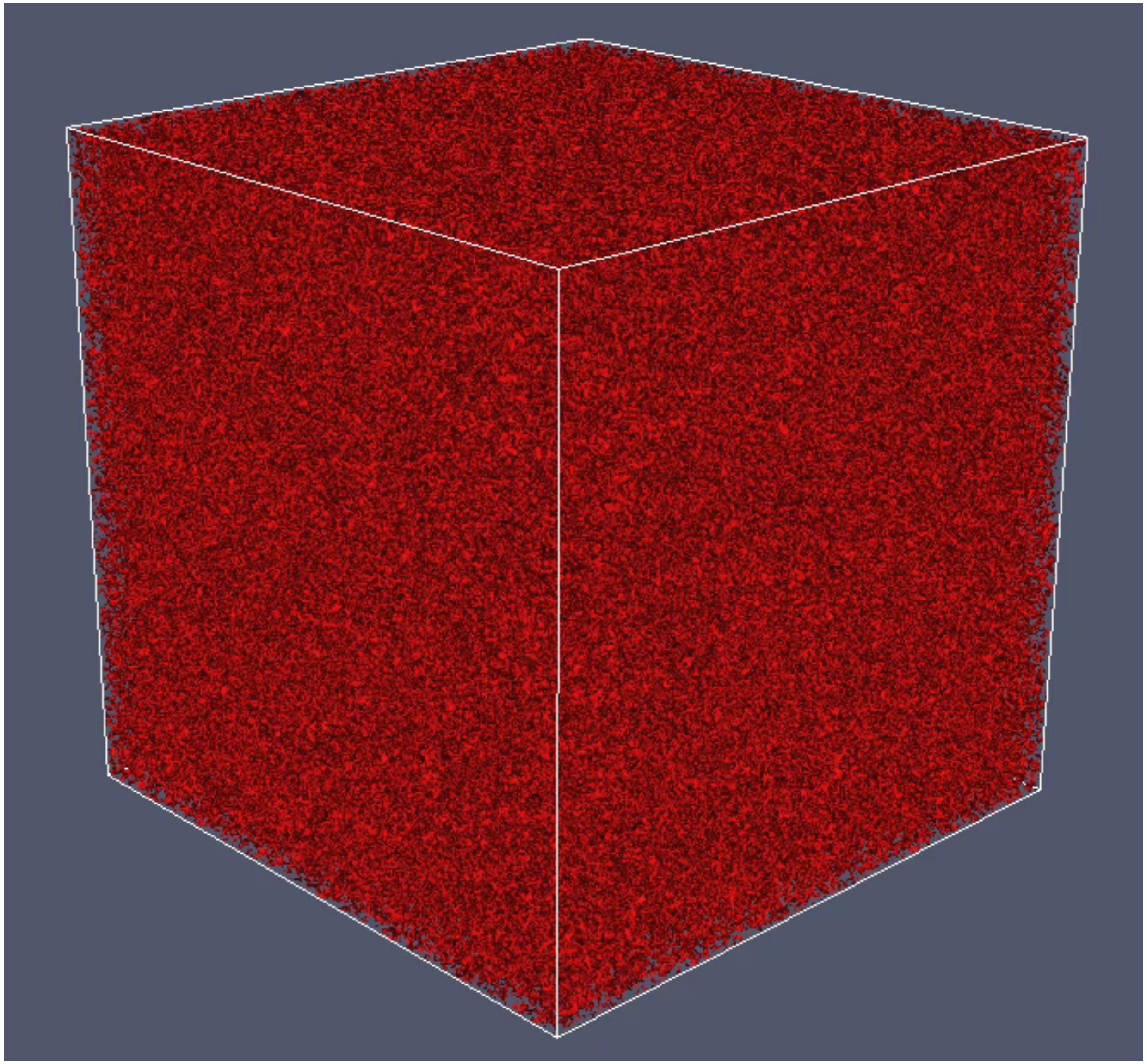
Allen (1997)
Contaldi et al (1998)
Landriau et al (2004)
Olum et al (2005)
Ringeval et al (2005)

Perivolaropoulos (1995)
Albrecht et al (1997)
Wyman et al (2005,2006)
Pogosian et al (1999, 2006)



"less modelling, more physics" : fully field-theoretic cosmic strings!

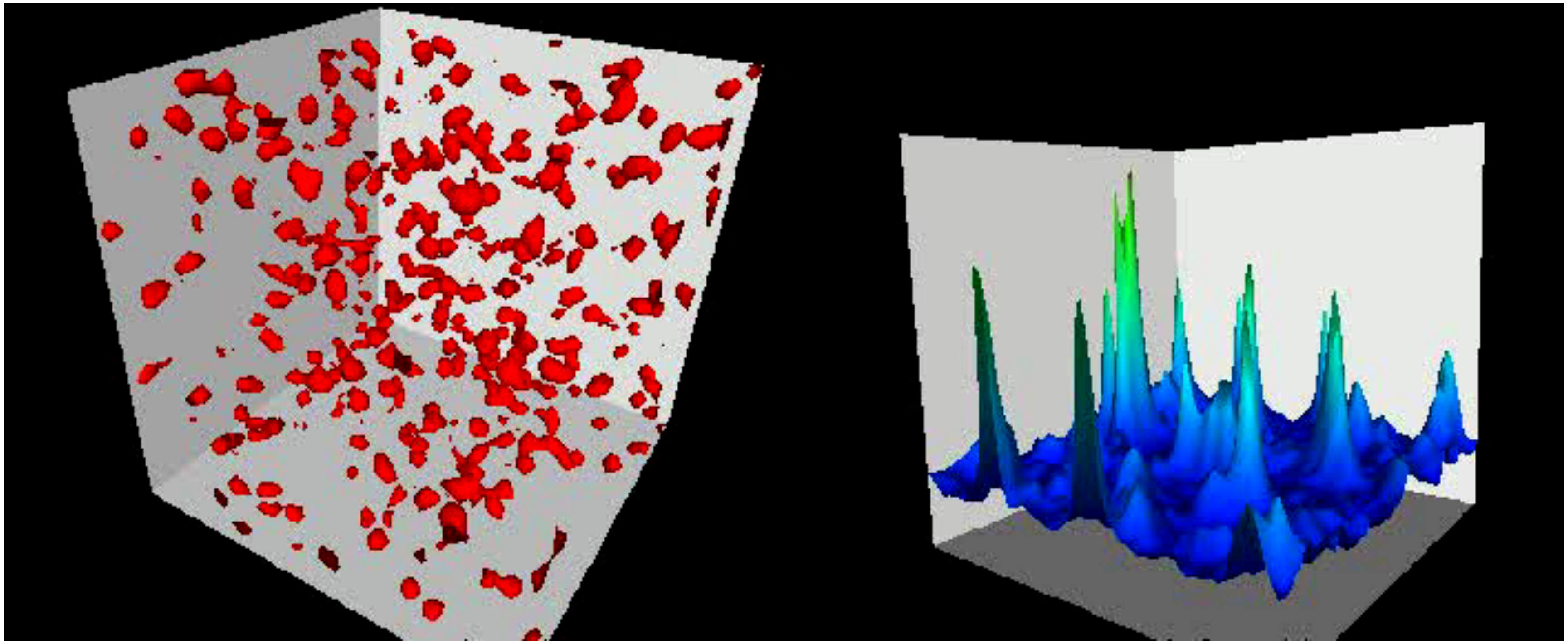
how do they look like?



animation by David Daverio

how do they look like?

global texture



$$\mathcal{L} = -\frac{1}{4e^2} F_{\mu\nu}F^{\mu\nu} + (D_\mu\phi)^*(D^\mu\phi) - \frac{\lambda}{4}\left(|\phi|^2 - \phi_0^2\right)^2$$

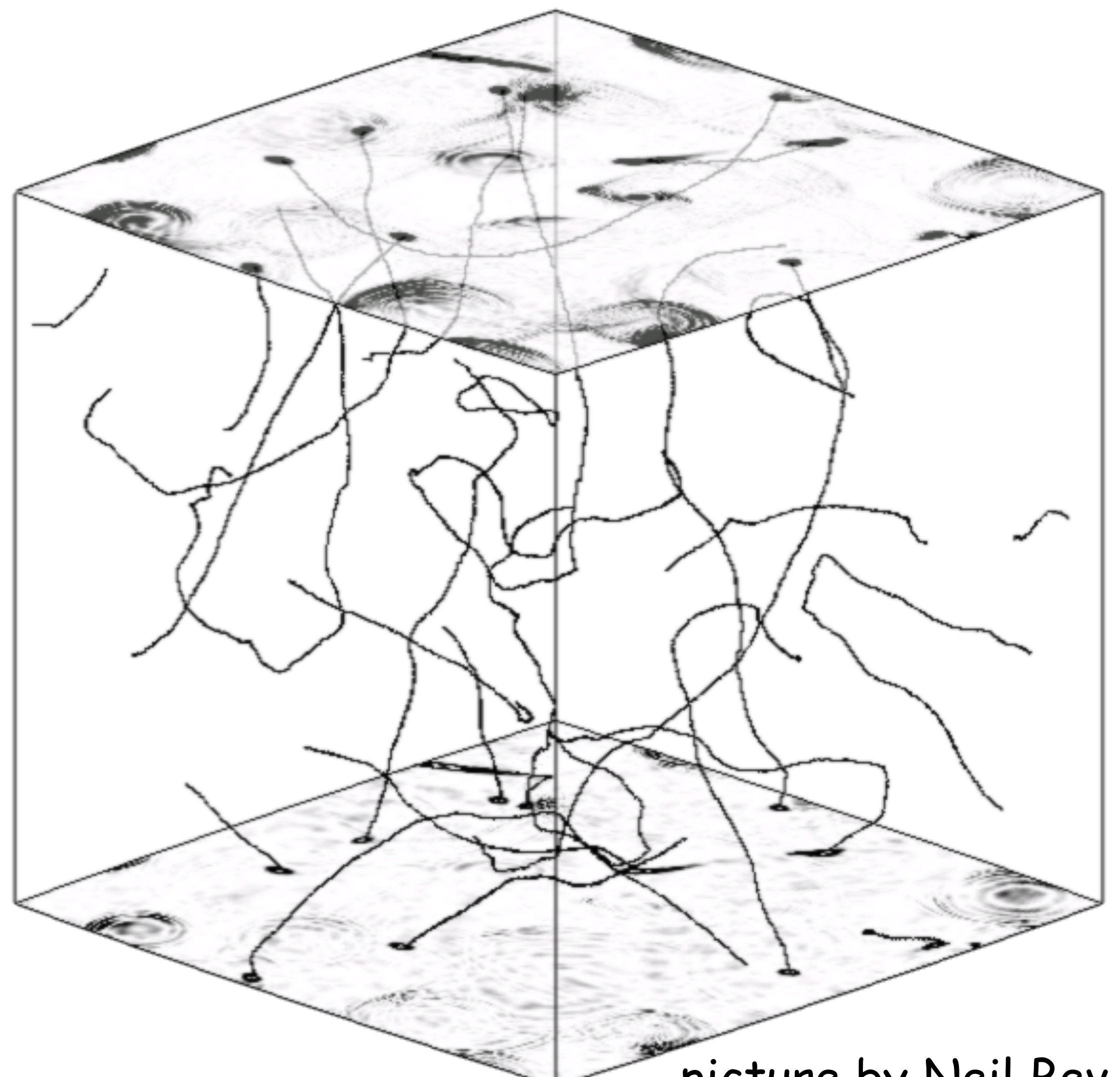
Abelian Higgs strings
(scalar + electromagnetic fields)

Horizon roughly fills box

lines: string centres (from winding of field)

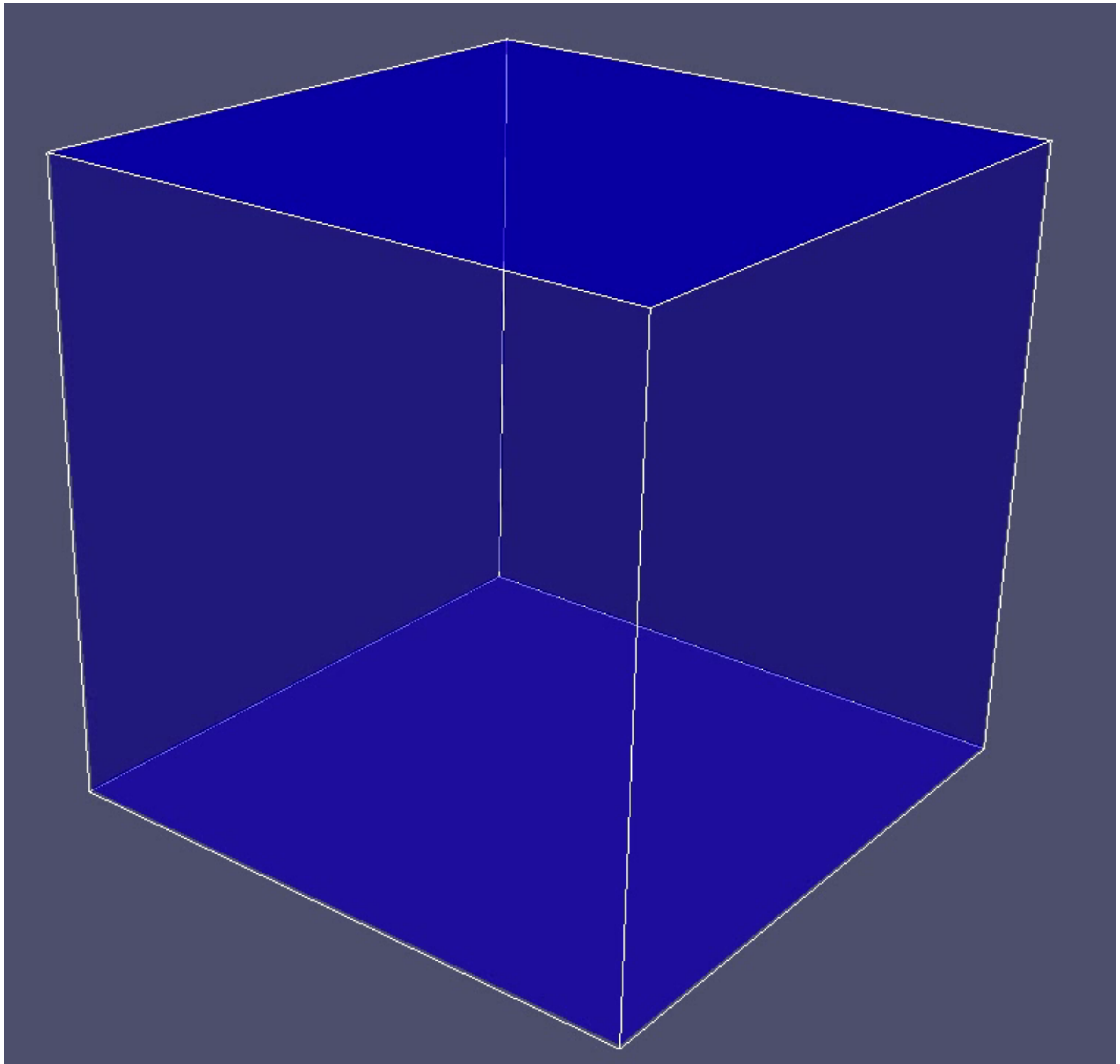
bottom: scalar field energy density

top: EM field energy density (curl around string cores from counteracting scalar field gradients)



picture by Neil Bevis

how do they look like?



animation by David Daverio

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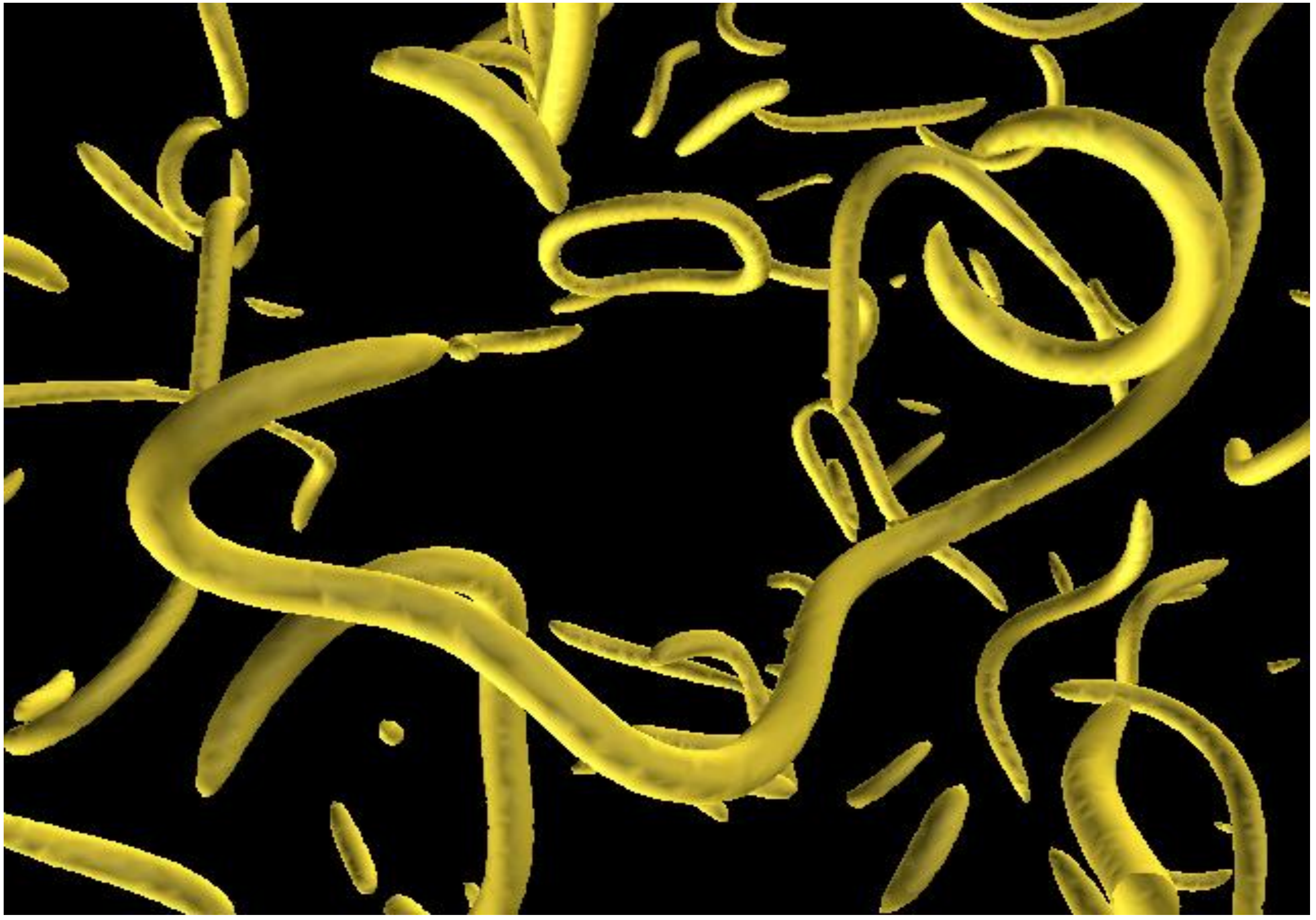


semilocal strings

need field theory simulations

Achucarro, Borrill, Liddle

slim strings, fat strings

- the universe is expanding!
- comoving coordinates expand with the universe
- no problem for big, fluffy global defects
- but cosmic strings shrink! width ~ 1/a
- very quickly they are no longer resolved
- limits dynamical range (already quite small)
- need to blow them up artificially
- check with different blow-up parameters (including no fattening), find little systematic effect

Press, Ryden, Spergel (1989); Moore, Shellard, Martins (2001)

UETC formalism

How can we get the defects into cmbfast/CAMB/CLASS/CMBEasy?

Typical structure of CMB code:

$$C_\ell \sim \left\langle \int dk \left| \int d\eta X(k,\eta) j_\ell(k(\eta_0-\eta)) \right|^2 \right\rangle$$

$$\sim \int dk d\eta d\eta' \langle X(k,\eta) X(k,\eta') \rangle j_\ell(k(\eta_0-\eta)) j_\ell(k(\eta_0-\eta'))$$

$X(k,\eta)$ are quantities like δ_γ, V_b, Φ, etc, which are solutions of a system of linear differential equations, sourced by the defects.

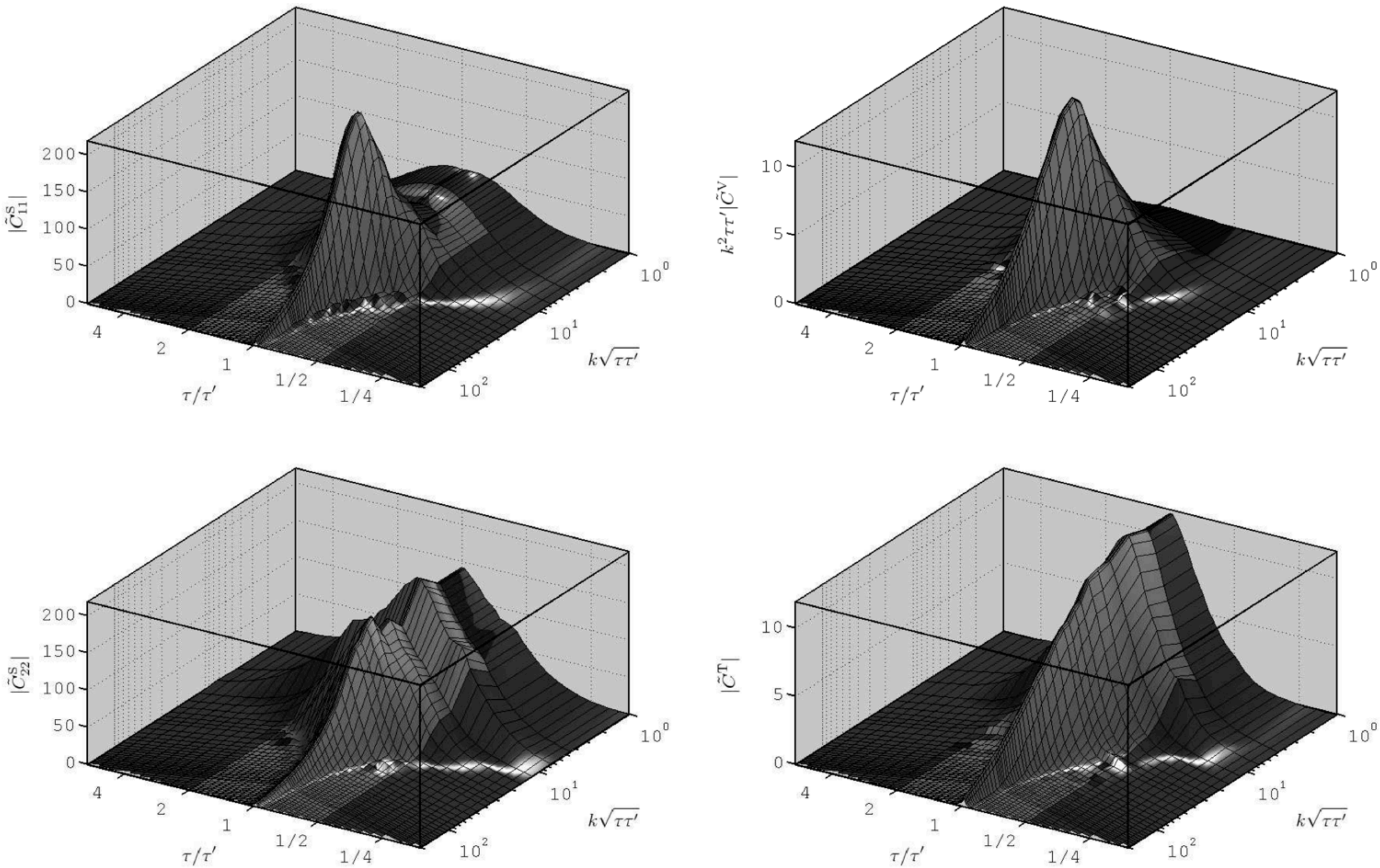
$$X(k,\eta) = \int d\eta' S(k,\eta') \mathcal{G}(k,\eta,\eta')$$

$$\langle X(k,\eta) X(k,\eta') \rangle = \int d\eta_1 d\eta_2 \underbrace{\langle S(k,\eta_1) S(k,\eta_2) \rangle}_{\text{UETC}} \mathcal{G}(\cdots) \mathcal{G}(\cdots)$$

UETC : $F(k,\eta_1,\eta_2) = F(k\eta_1,k\eta_2)$

Pen, Seljak, Turok 97; Durrer, Kunz, Melchiorri 98

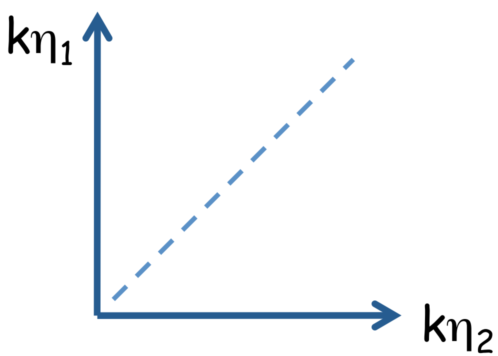
big universe, small computer

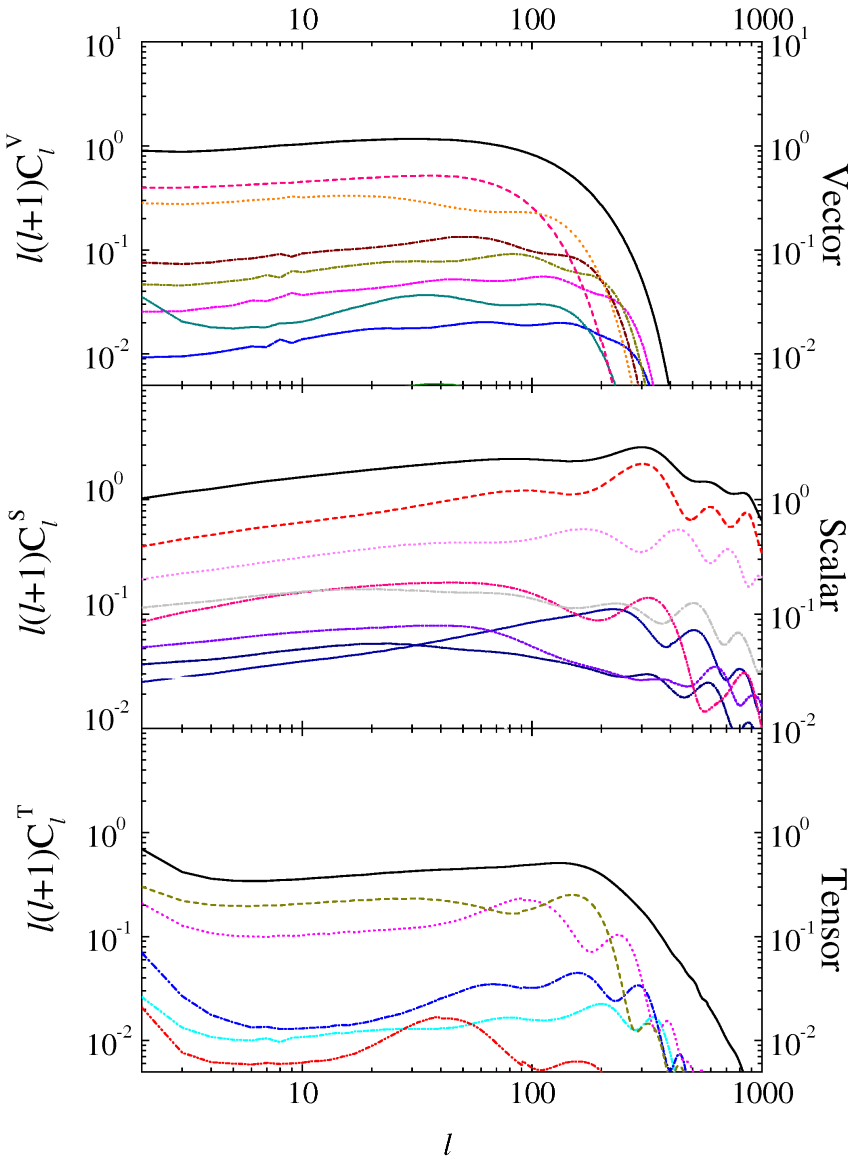


why there are no peaks

We can think of the two-point function $F(k\eta_1, k\eta_2)$ as a matrix that can be diagonalised. Each eigenvector $v_i(k, \eta_1)$ becomes a source.

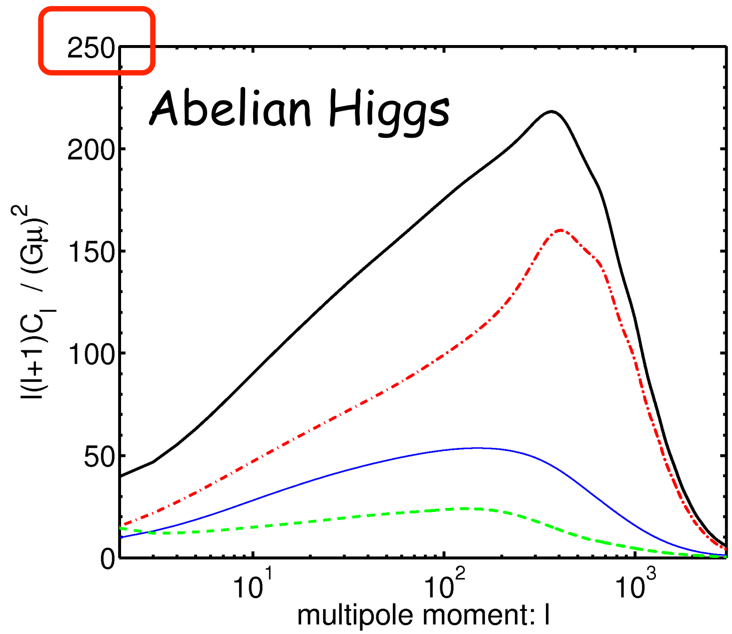
$$C_\ell \sim \sum_i \lambda_i \underbrace{\int dk \left| \int d\eta\, v_i(k,\eta) \mathscr{G}(\cdots) \right|^2}_{C_\ell^{(i)}}$$

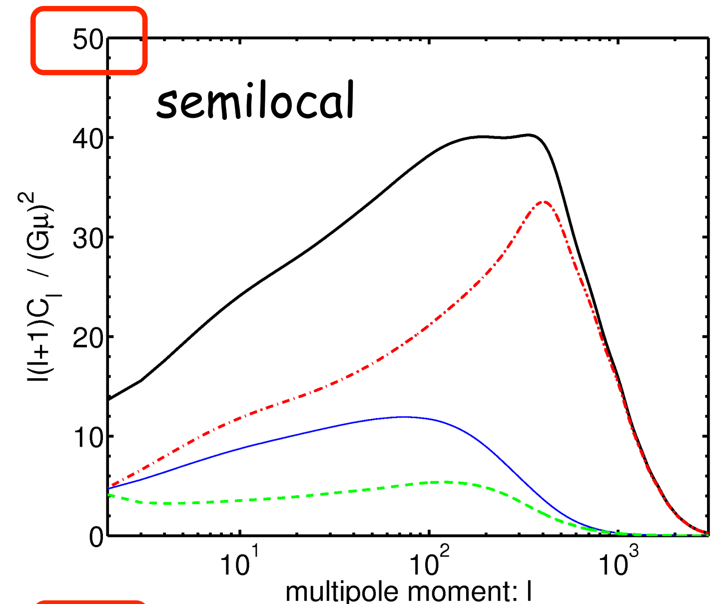


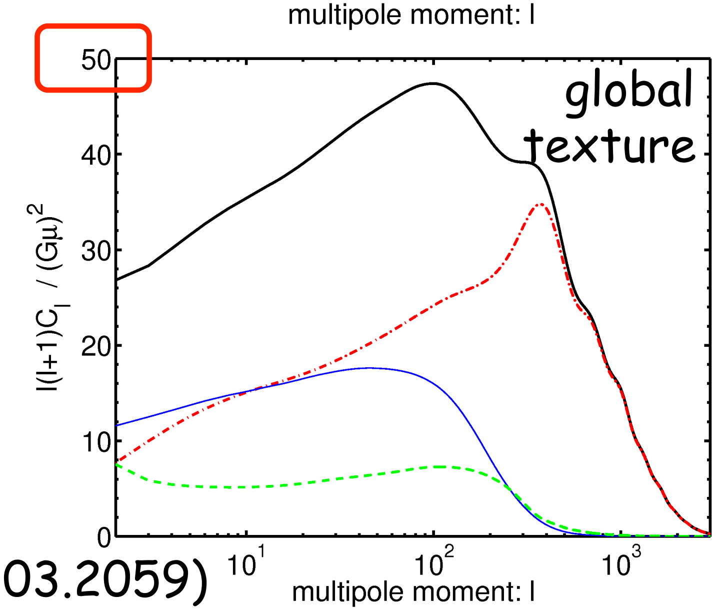


Each source has (small) oscillations, but they do not add coherently and the peaks get smeared out.

CMB 'TT' power spectra







total (sum)

scalar (~ density perturbations)

vector (~ vorticity)

tensor (gravitational waves)

(defects generically have all three contributions!)

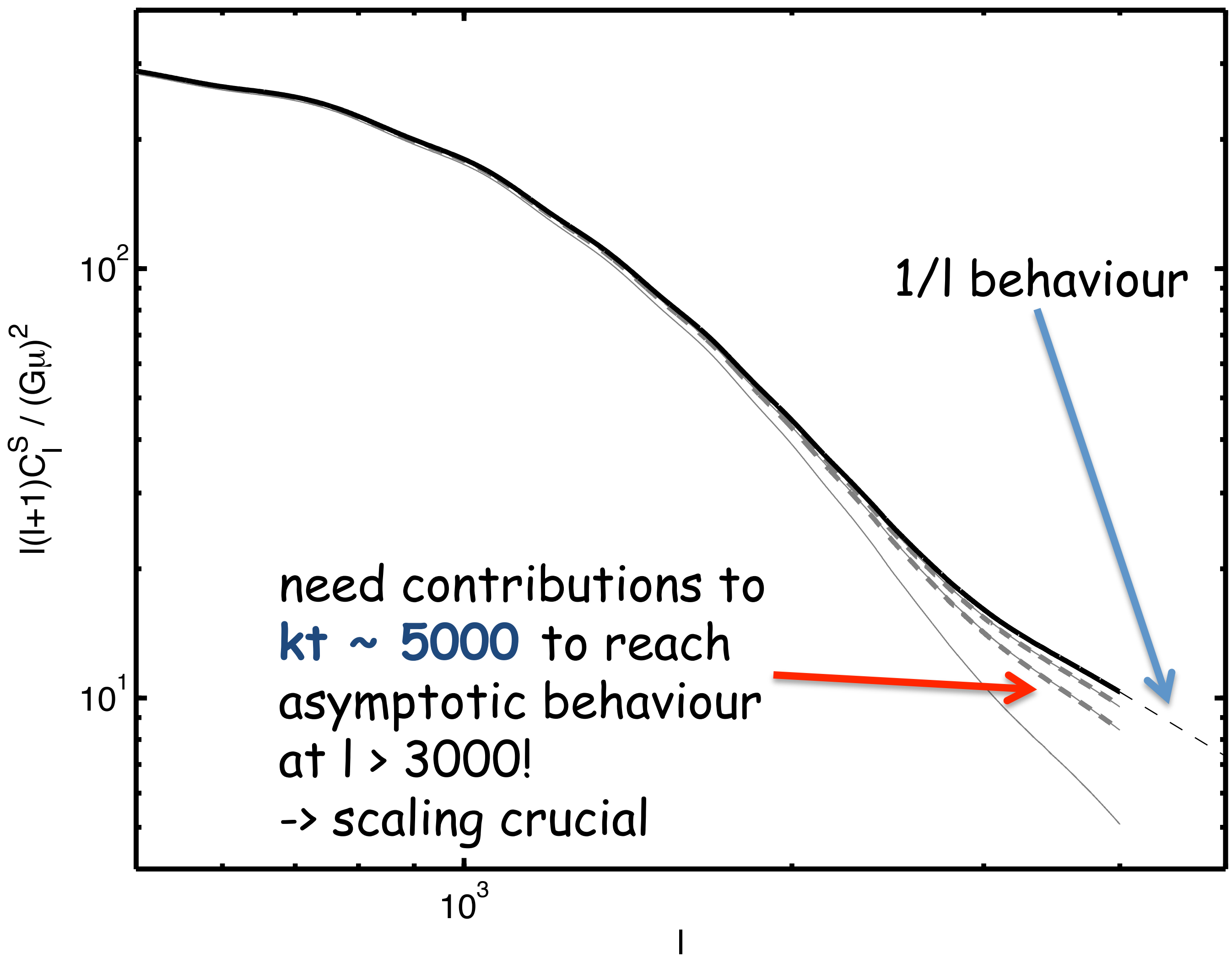
(Urrestilla et al, arXiv:0803.2059)

high-l behaviour

cosmic strings expected to scale like $l*(l+1)*C_l \sim 1/l$

primary CMB drops very fast at high l

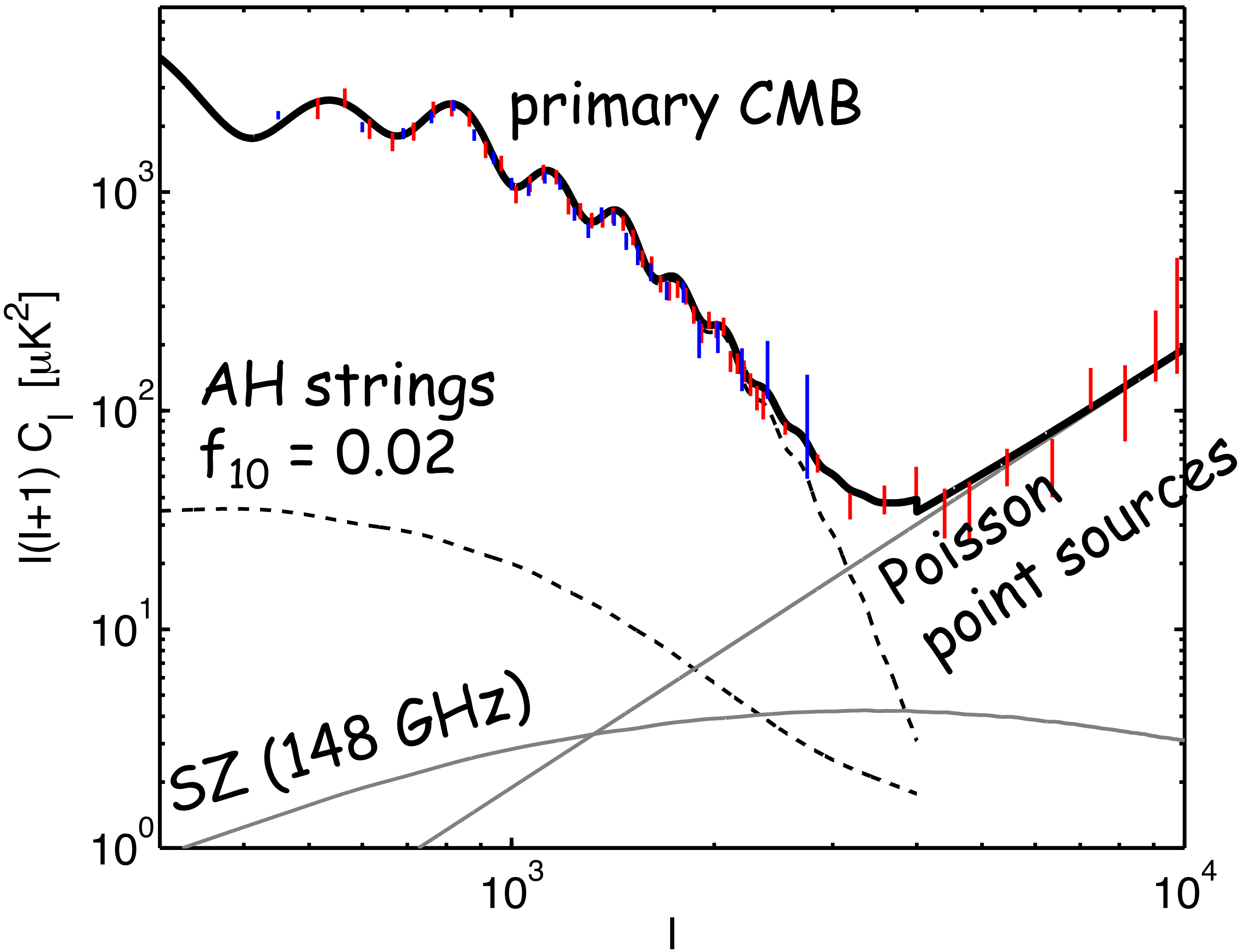
so maybe strings will dominated eventually?



high-l behaviour

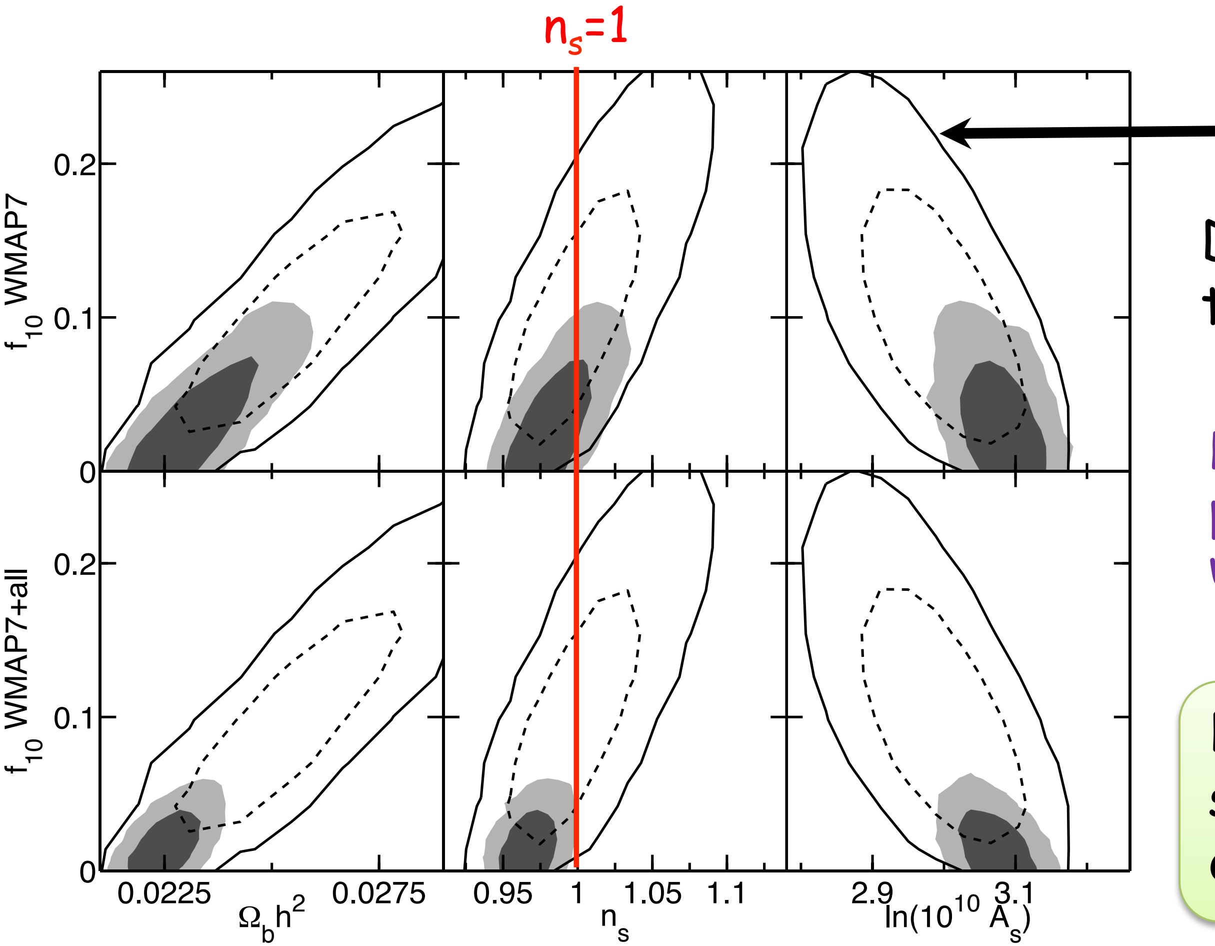
high-l region strongly dominated by point sources
completely buries string (and SZ) signal

data:
ACT
ACBAR



did WMAP measure a tilt?

MCMC with CMB (WMAP7, ACBAR+QUAD+ACT) for AH
Urrestilla et al, arXiv:1108.2730



Degeneracies start to be broken!

Hybrid SUSY inflation predicts strings, wants n_s close to 1

Data starts to put significant constraints on "defect models"

(n_s=1 & strings when varying e.g. N_{eff}, see Lizarraga, Sendra, Urrestilla 2012)

cosmic string constraints

$G\mu$: string scale (1 = Planck scale)

f_{10}: ratio of C_l from inflation and defects at l = 10

Model	Data set	$10^6\, G\mu$ (95%)	f_{10} (95%)
AH [25]	WMAP3+BOOMERANG+CBI+ACBAR+VSA	0.7	0.11
AH (this work)	WMAP7	0.57	0.095
AH (this work)	WMAP7 + ACBAR + QUAD + ACT	0.42	0.048
USM-AH [35]	WMAP5	0.68	0.11
USM-NG [35]	WMAP5	0.28	0.054
USM-NG [5]	WMAP7+ACT	0.16	

- slight preference for strings seen in WMAP3 has gone away
- notice model dependence: AH vs NG
  -> mostly due to higher string density in NG simulations (cannot model decay into massive radiation)

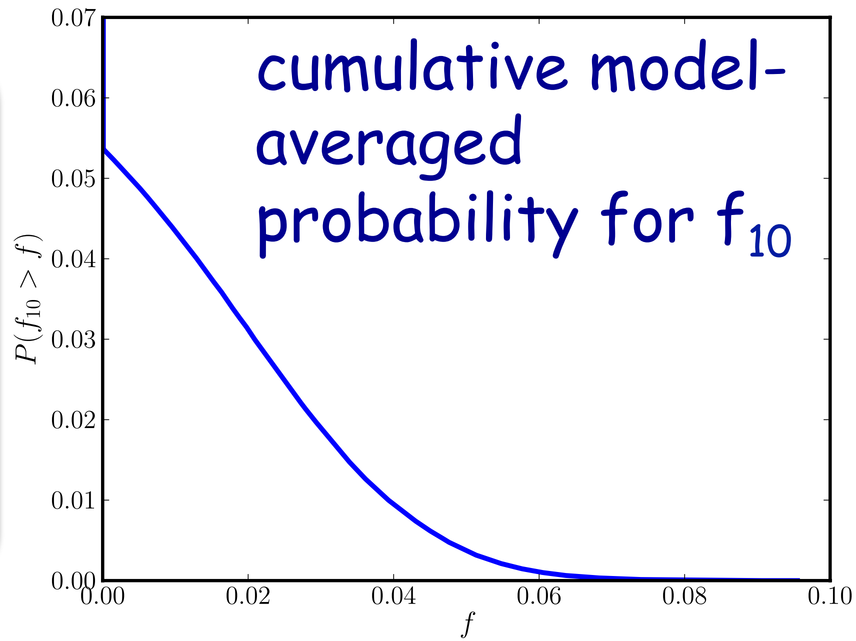
how about "defect models"?

Are "cosmic strings" in trouble?

- we can always only get an upper limit on Gμ
- but we can address the question with Bayesian model comparison
- depends on priors … we use flat priors $0.75 < n_s < 1.25$; $0 < f_{10} < 1$
- we compute the Bayes ratio B with the Savage-Dickey method
- 4 models: 'PL', 'HZ', 'PL+AH', 'HZ+AH'

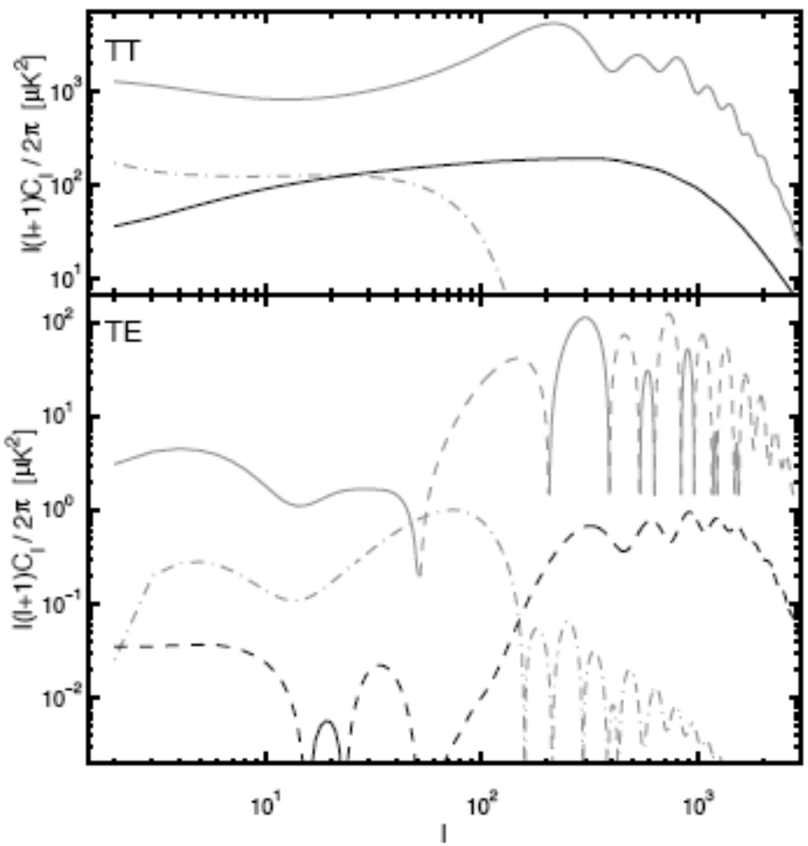
-> ln B [AH] ~ -3
-> presence of Abelian-Higgs strings moderately disfavoured!

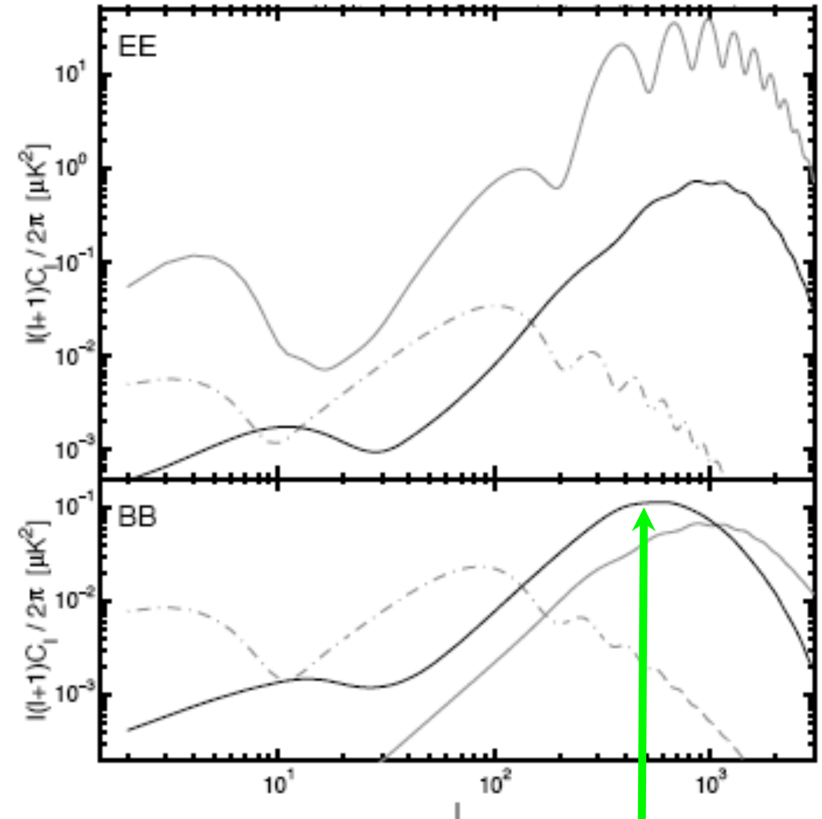
-> nearly 95% of probability is in 'no-strings' models



Current CMB data starts to put pressure on strings!

smoking gun: B-mode polarisation





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

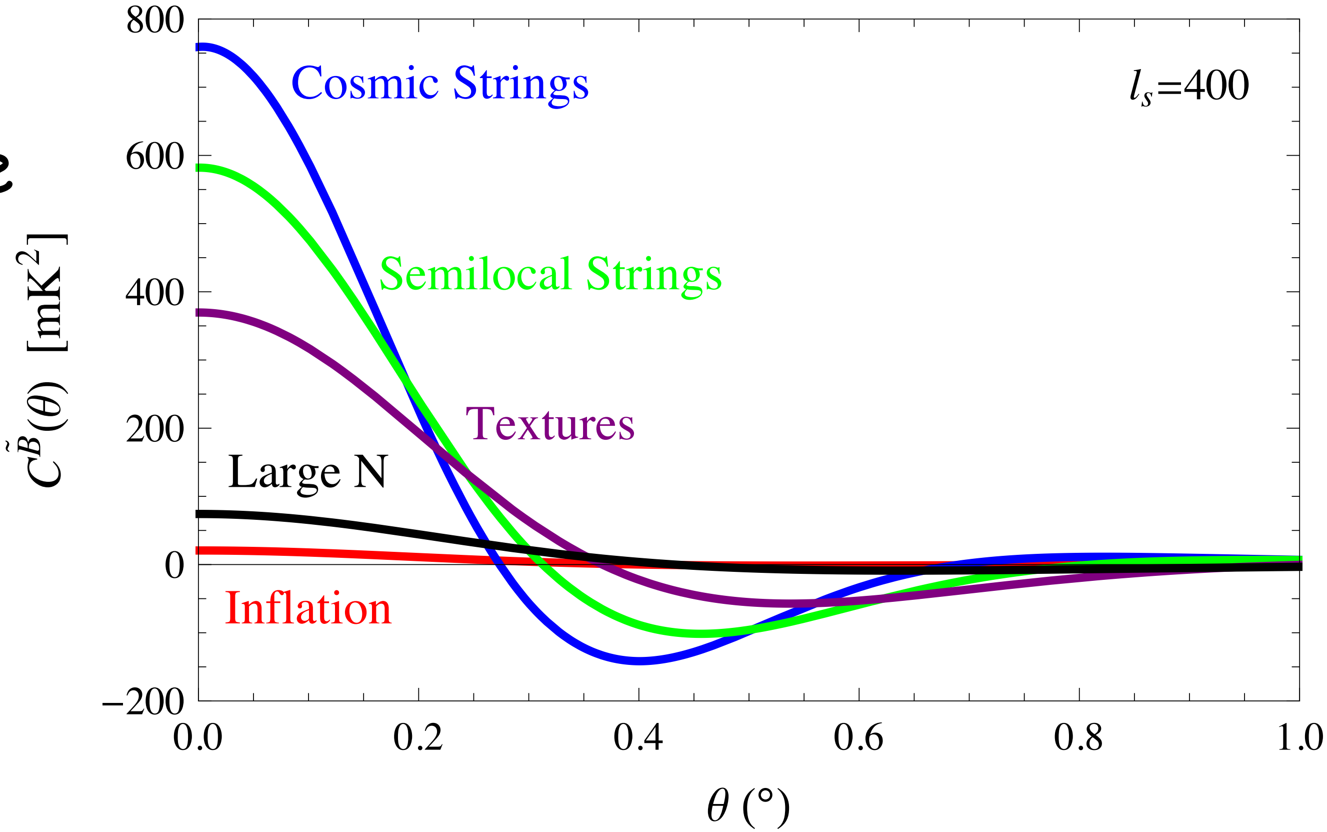
AH STRINGS!

topological defects can dominate in B-mode polarisation spectrum

angular correlation function

other way to look at B-mode polarisation: angular correlation function of local B-modes!

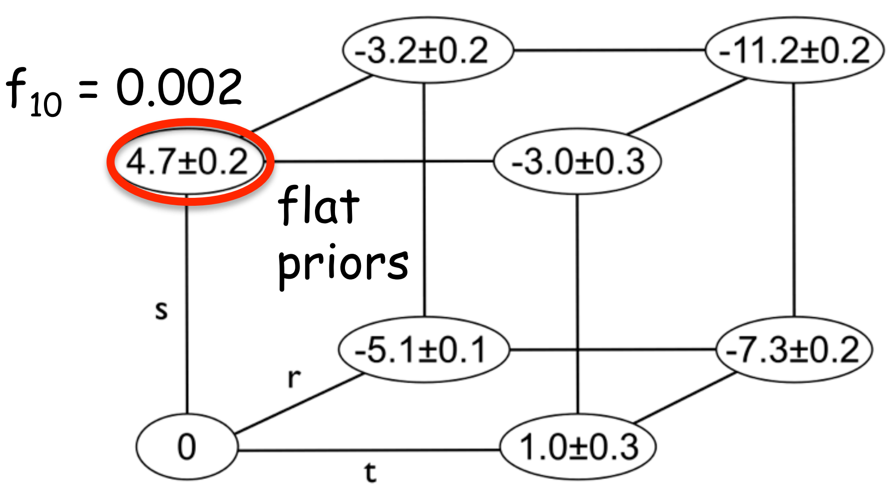
- $f_{10} = 0.1$
- defects have a huge peak in local B-mode correlation function!

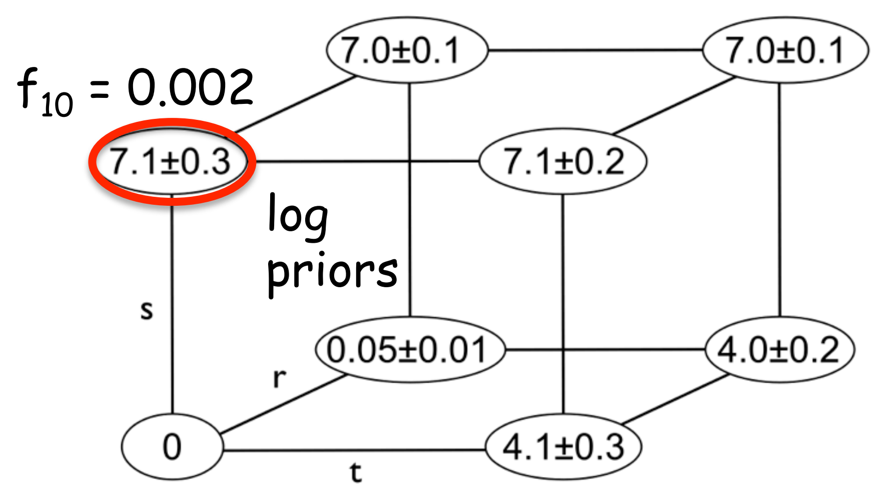


(Garcia-Bellido, Durrer, Fenu, Figueroa, MK, arXiv:1003.0299)

how about future CMB data?

- **Planck:** (Urrestilla et al, arXiv:0803.2059)
  - can distinguish between tensors and strings
  - should reach limit $f_{10} \sim 0.01$ at 95%
- **CMBPol / COrE:** (Mukherjee et al, arXiv:1010.5662)
  - can distinguish between different defects
  - could reach $f_{10} \sim 0.001$ at 95% ($G\mu < 6\times10^{-8}$)





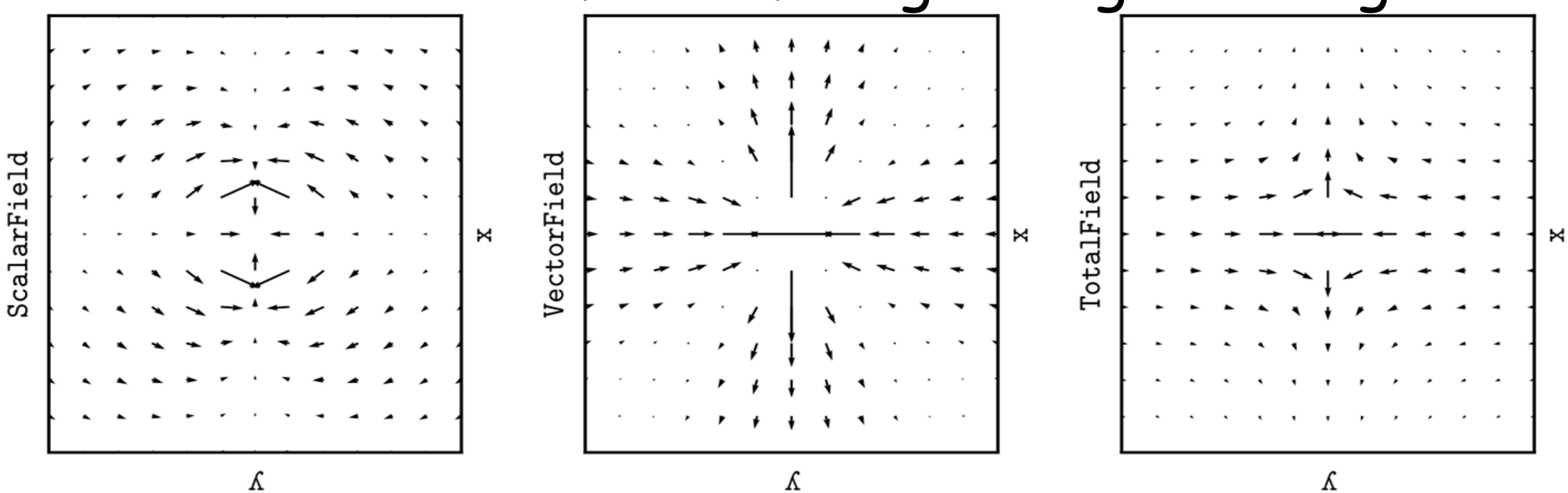
P(k) and N-body simulations

Do strings affect galaxy clustering?
-> important question if we want to use P(k)
-> we include strings in N-body simulations, using

$$\ddot{x}_i + 2\frac{\dot{a}}{a}\dot{x}_i = -\frac{1}{a^2}\partial_i\psi + \frac{1}{a}\Sigma_i + \frac{\dot{a}}{a^2}\Sigma_i$$

(Obradovic et al, arXiv:1106.5866)

ex: acceleration field of long straight string



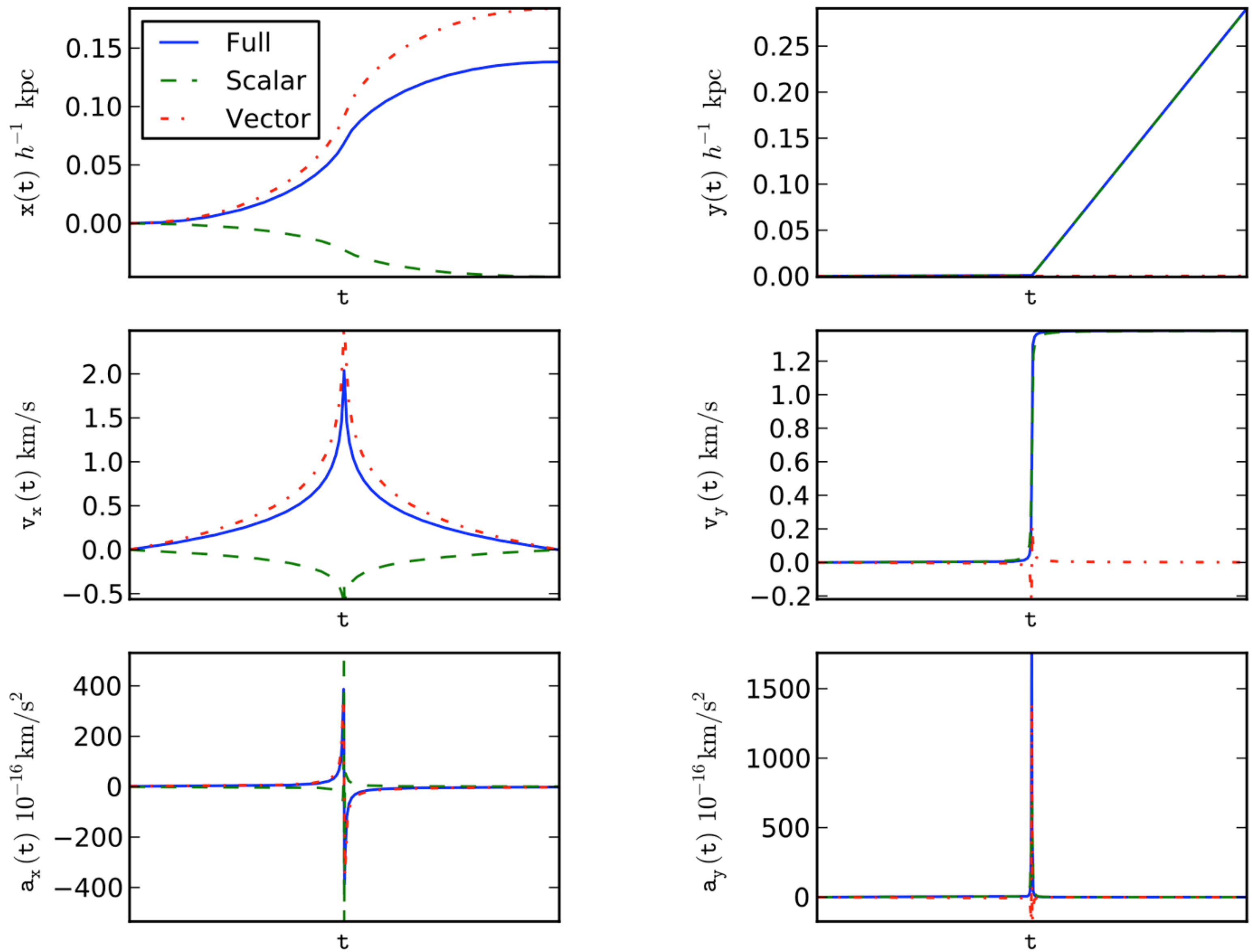
velocity kick of straight string

analytical solution: velocity kick

reproduced correctly by N-body simulation

working on including actual string simulation

-> watch this space! ☺



summary & outlook

- topological defects exist!
- at least in the lab...
- ... but also in many (most? all?) realistic inflation models
- data starts to constrain defect models non-trivially
  -> impact on inflation models?
- (AH: $f_{10} < 0.05$, $G\mu < 0.4\times10^{-6}$ @ 95%)
- defects generically have vector and tensor perturbations
  -> B-mode polarisation (and non-Gaussianity) in the CMB
- Planck should improve limits by a factor of 5-10 in f_{10}
  -> waiting for spring 2013 ... ☺
- large-scale structure may provide an additional window
  -> work in progress