UNIVERSITÉ DE GENÈVE

SPACEPART12

What does the Cosmic Microwave Background tell us about our origin?

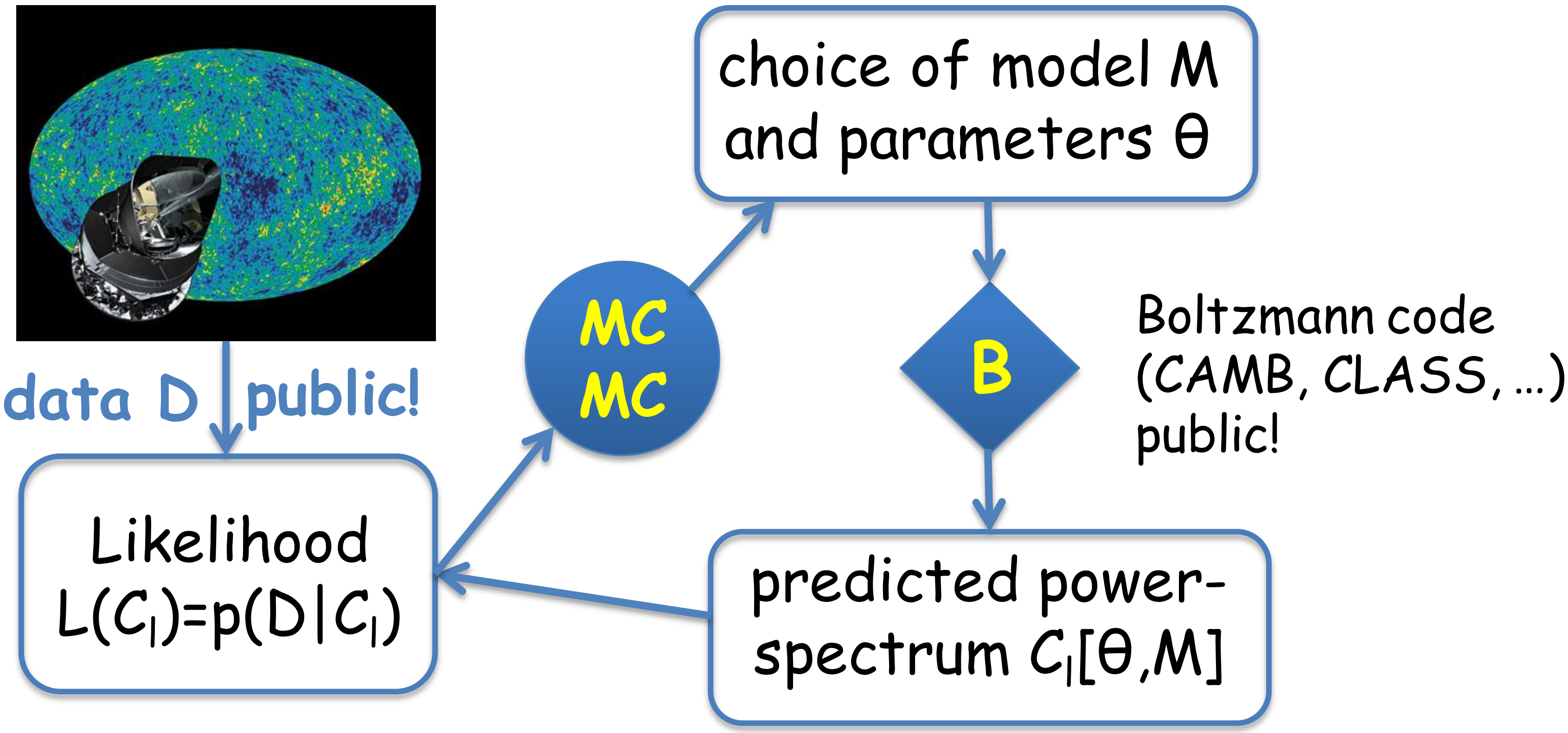
Martin Kunz

Université de Genève

overview

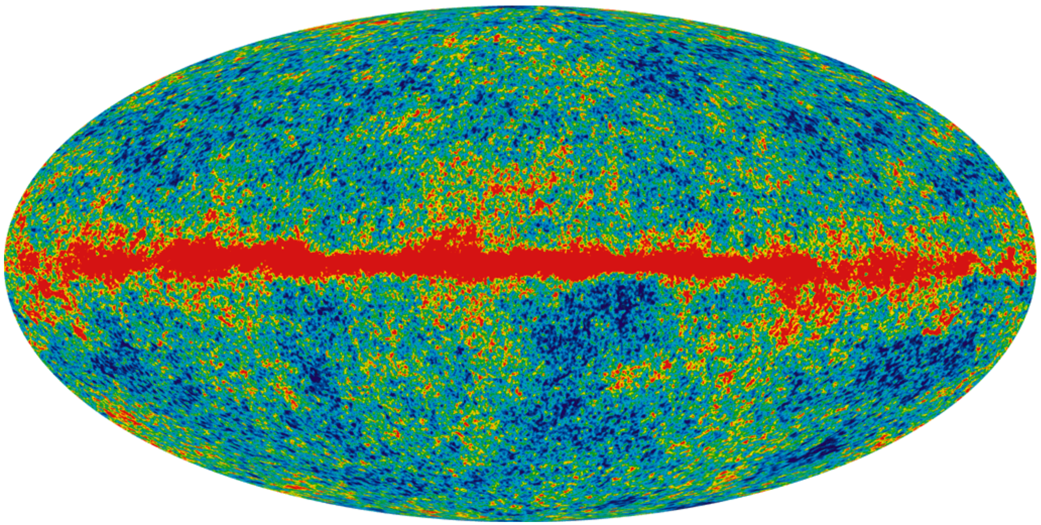
- cosmological data analysis
- what is the origin of the large-scale structure? (can we avoid ‘acausal’ physics to generate the initial perturbations?)
- our knowledge about inflation
  – from CMB temperature anisotropies
  – gravitational waves
  – non-Gaussianity
  – cosmic strings

analyzing cosmological data



- Experiment (WMAP, Planck, …) -> likelihood
- Boltzmann code: computes power spectrum of anisotropies
- MCMC: efficient exploration of $L(\theta) = L(C_l[\theta,M])$
- Bayesian statistics: $p(\theta,M|D) \sim p(D|\theta,M)\ p(\theta,M)$

CMB data

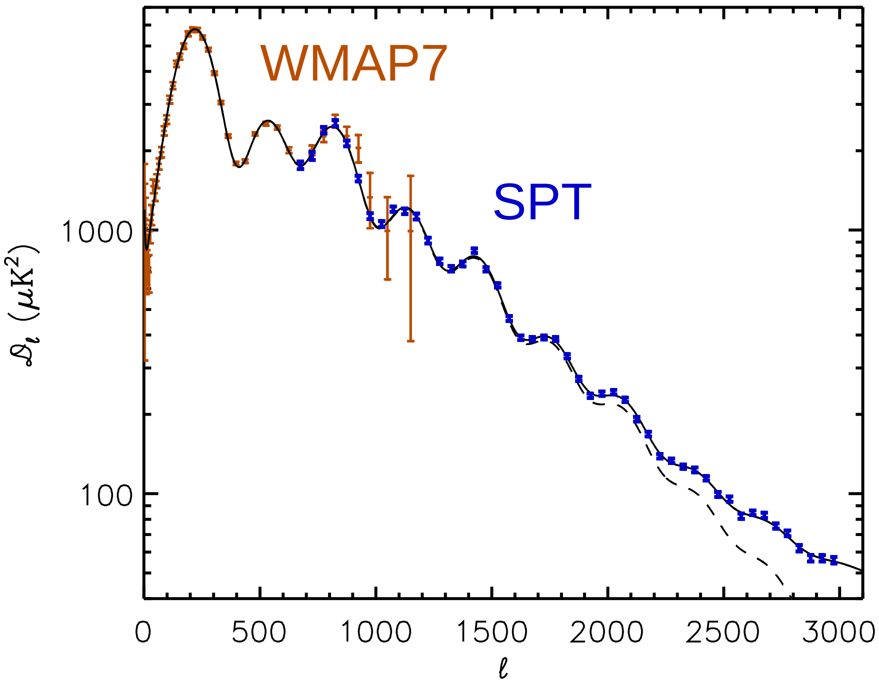


WMAP 7-year
co-added sky map
at 94 GHz

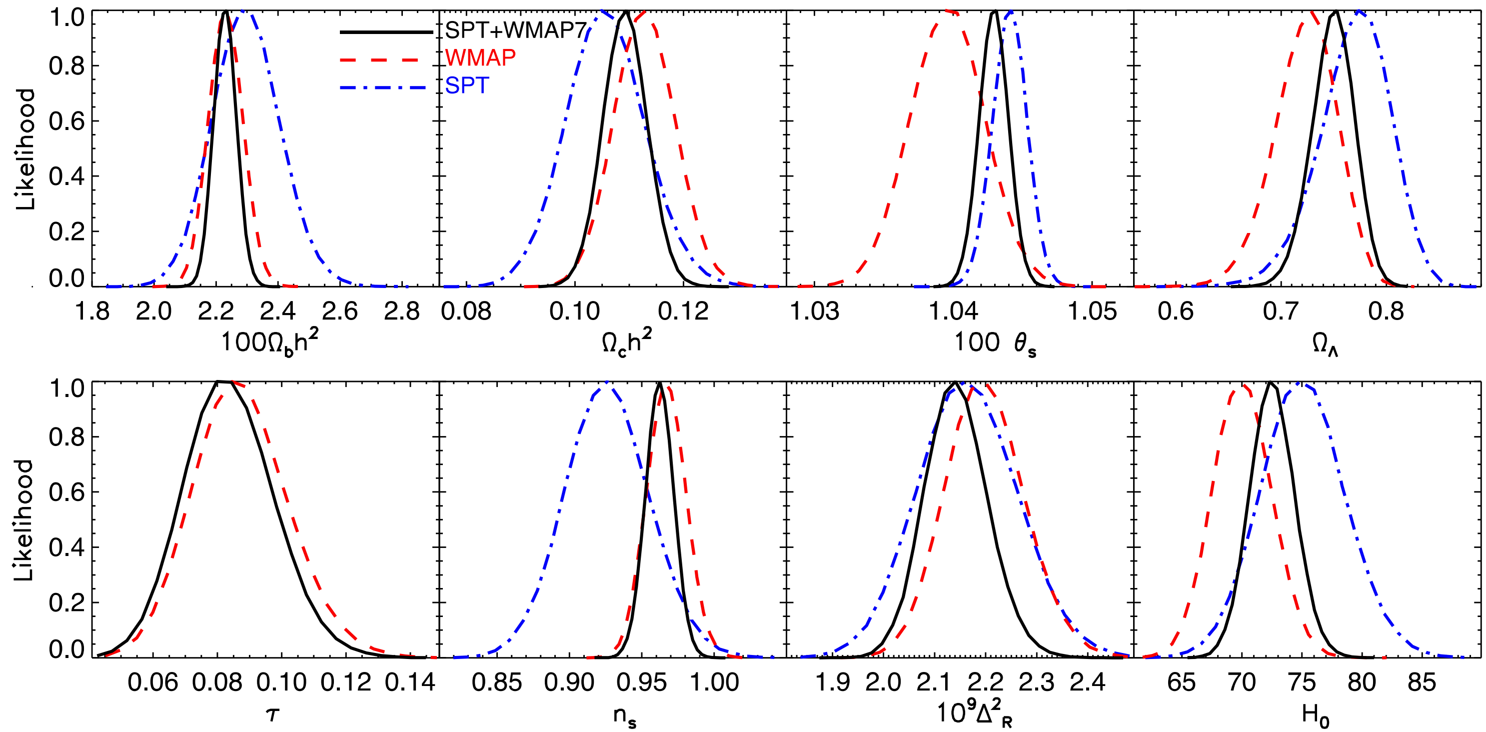
(source: WMAP science team)

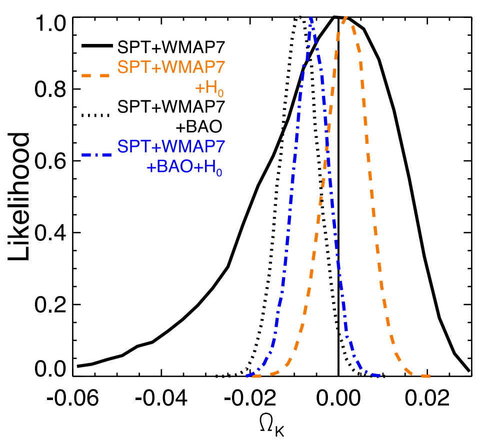
Angular power spectrum of temperature anisotropies from WMAP 7 year data (red) & South-Pole telescope (blue)

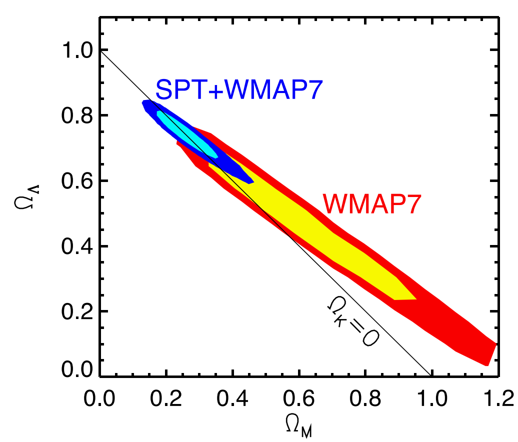
(source: Story et al, arXiv:1210.7231)



the power of the CMB



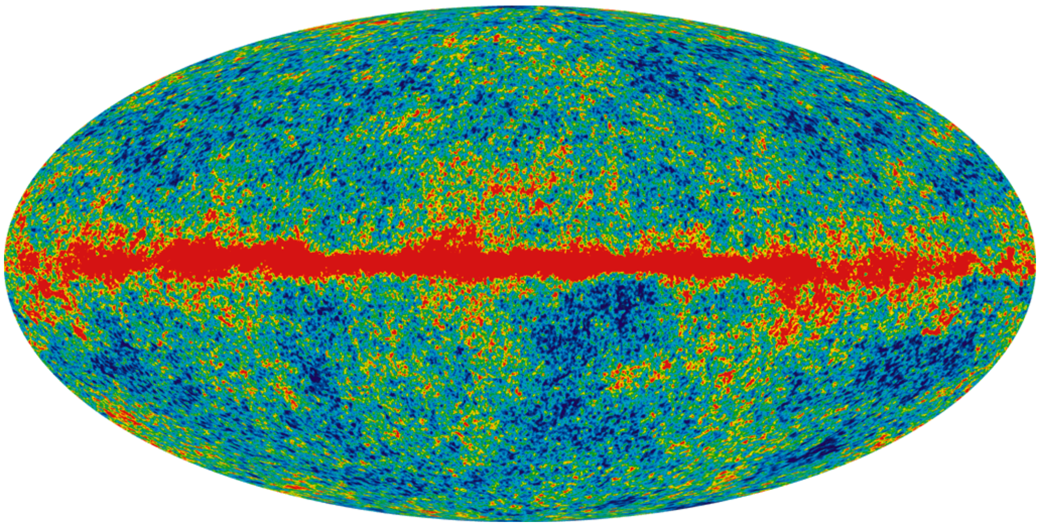




(figures: Story et al, arXiv:1210.7231)

- Amazing progress over the last two decades
- Waiting for Planck … mid-March 2013! ☺

CMB data



WMAP 7-year
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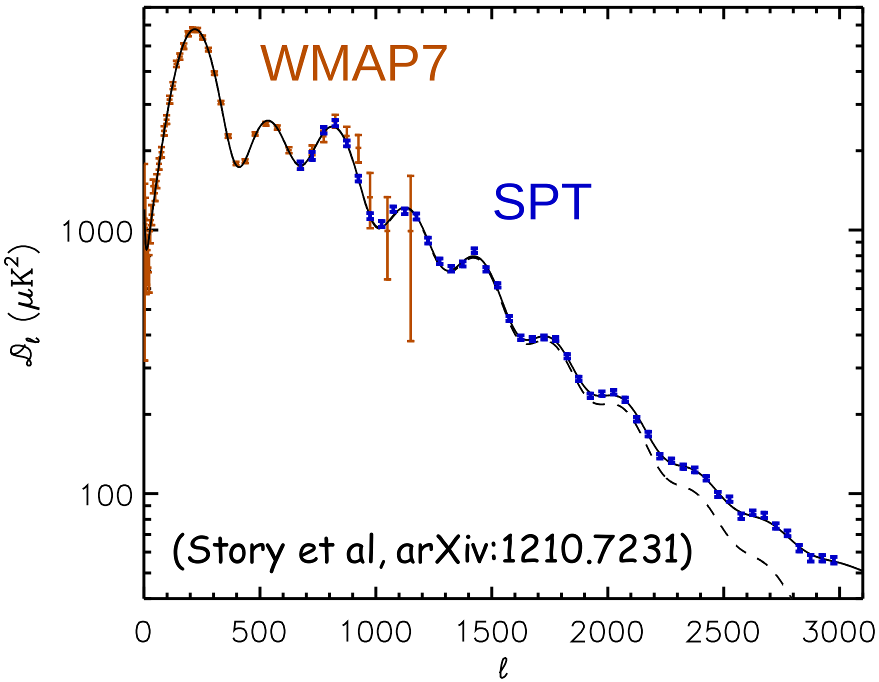
(source: WMAP science team)



Spectacular agreement of observations and theory for adiabatic and nearly scale invariant initial fluctuations…

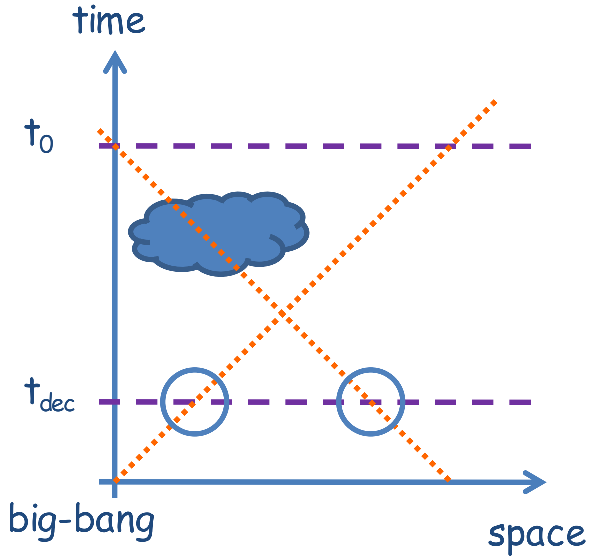
… but what created these fluctuations?!

Origin of the perturbations

COBE observed fluctuations correlated on scales much larger than the horizon at last scattering!

-> Horizon problem

-> is this not proof of "acausal" physics?



NO!

We can create them at late times with time-dependent gravitational potentials (ISW).

(a)causality constraints

(Scodeller, MK & Durrer, 2009)

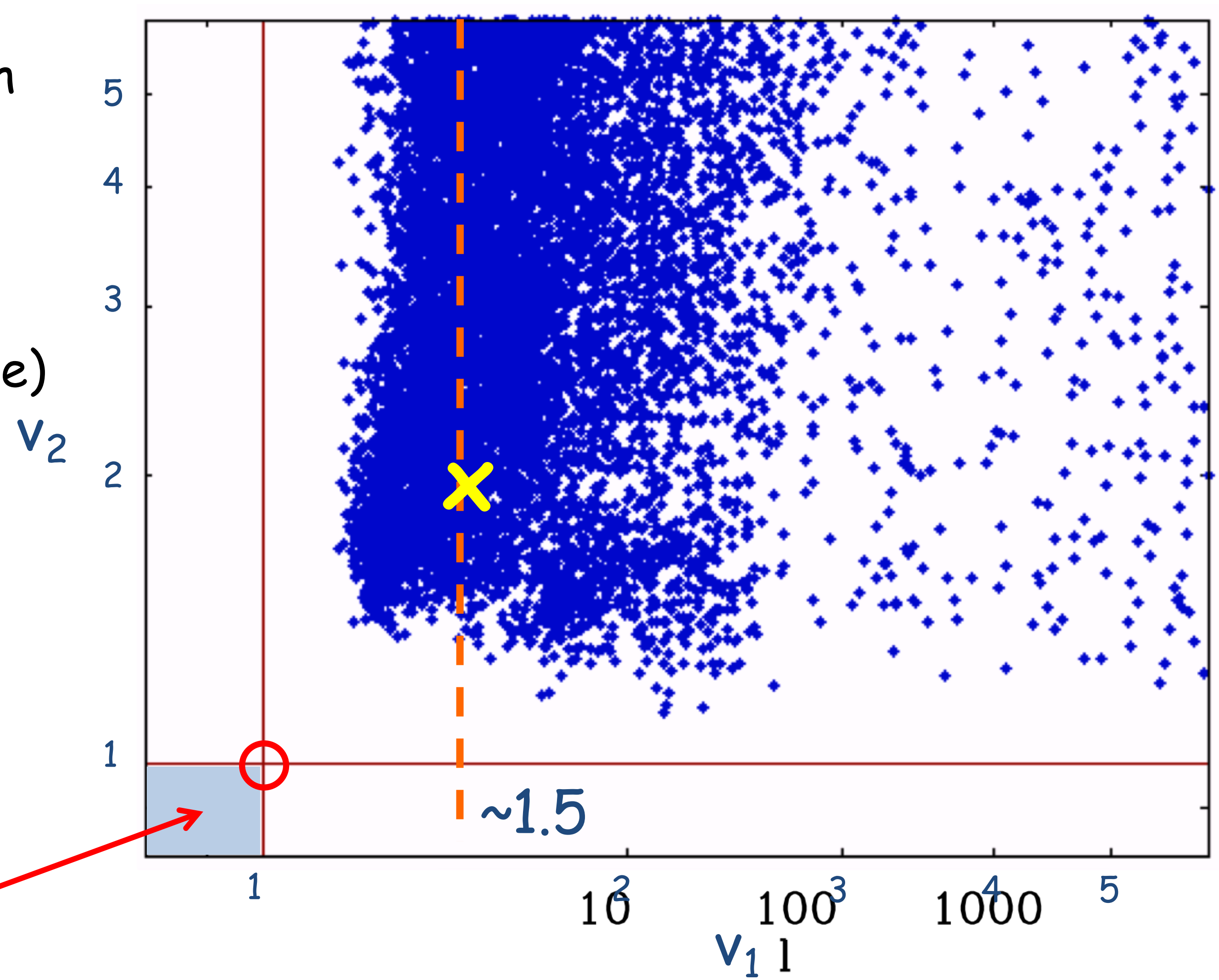
outgoing spherical shells of energy with velocity v

accepted points in MCMC chain
(sorry for ugly figure)

good fit requires:

- $v_1 > 1.2c$
- $v_2 > 1.3c$

other parameters roughly as always



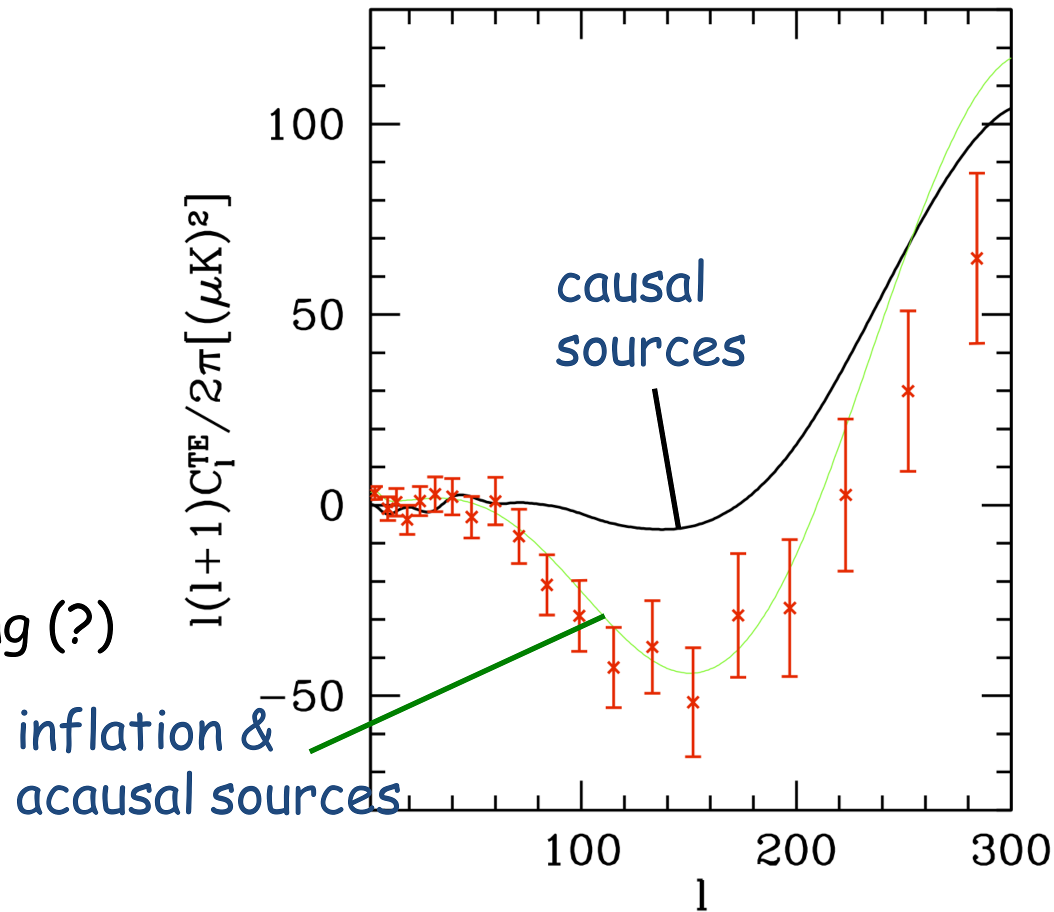
causal region

TE cross-polarisation

Polarisation induced at last scattering and reionisation
[Spergel & Zaldarriaga, 1997] -- TE shows a dip around l ~ 100 :
adiabatic density mode ~ $\cos(kc_s t_{dec})$
velocity mode: derivative ~ $\sin(kc_s t_{dec})$
} TE: $\sin(2kc_s t_{dec})$

peak: $kt_{dec} \approx 0.66$
horizon: $kt_{dec} \sim 1/v$
-> v ~ 1.5

possibilities:
- inflation
- other acausal physics
- huge reionisation finetuning (?)



what is “inflation”?

- We need physics acting on super-horizon scales!
  - very rapid expansion
  - collapsing universe (plus bounce)
- How can we probe the nature of the unknown physics and distinguish between different models? What can we learn from observations?

Can we see the dynamic nature of inflation?
(compare with dark energy: cosmological constant has constant $w = p/\rho = -1$)

What is the link with the usual parameters?

- initial power spectrum index n_s: $P(k) \propto \left(\frac{k}{k_0}\right)^{n_s}$
- tensor to scalar ratio r = T/S

the pressure of inflation

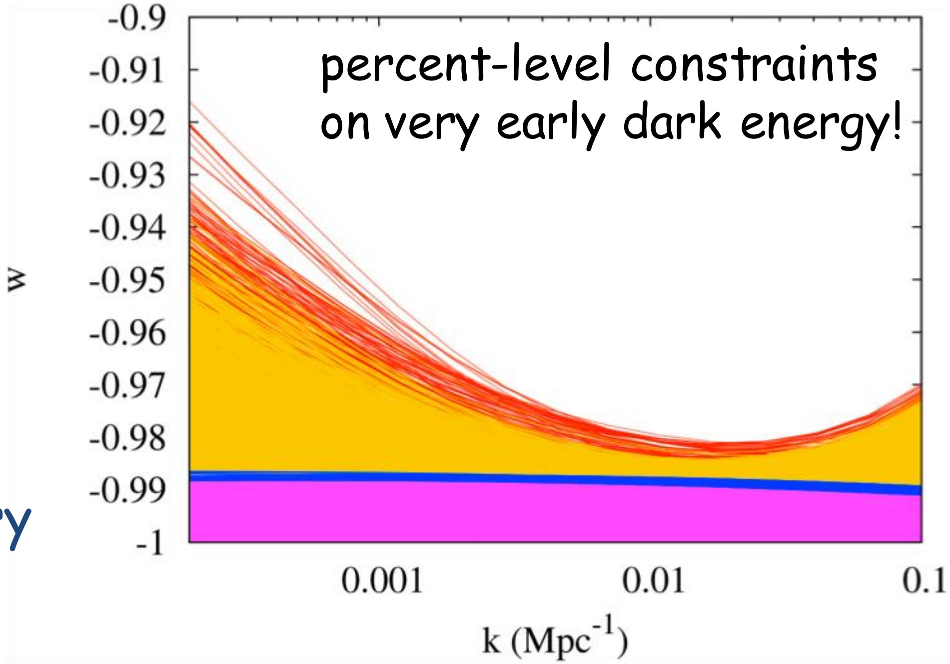
(Ilic, MK, Liddle & Frieman, 2010)

expansion rate: $$1 + w = -\frac{2}{3}\frac{\dot{H}}{H^2} = \frac{2}{3}\epsilon_H \approx \frac{r}{24}$$

link to w'=dw/da: $$\frac{d\ln(1+w)}{dN} = 2(\eta_H - \epsilon_H) = (n_s - 1) + 3(1+w)$$

$n_s \neq 1 \Rightarrow \varepsilon \neq 0$ or $\eta \neq 0$
$\Rightarrow w \neq -1$ and/or
w not constant!

WMAP 5yr constraints on w:
(1+w) < 0.02
No deviation from w=-1 necessary

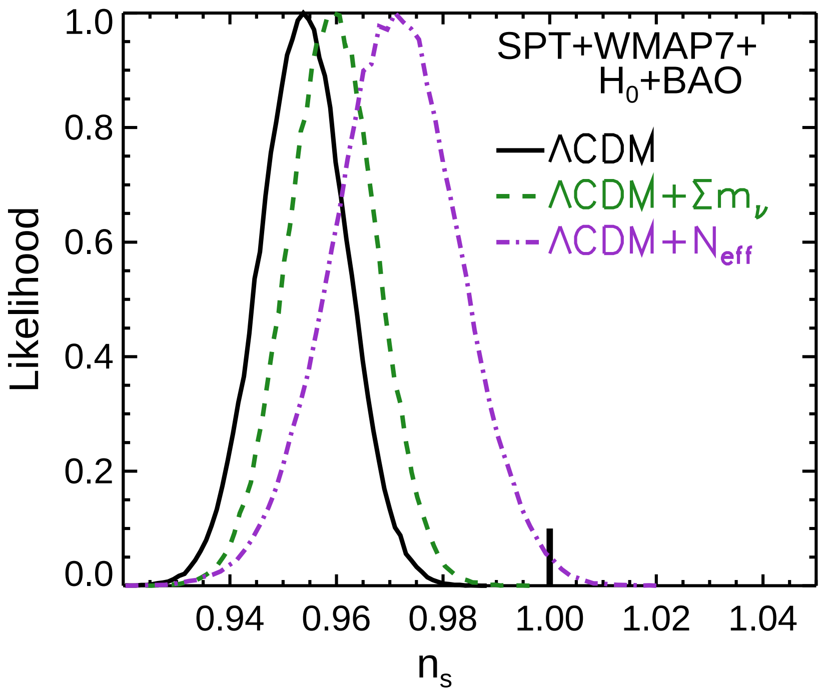


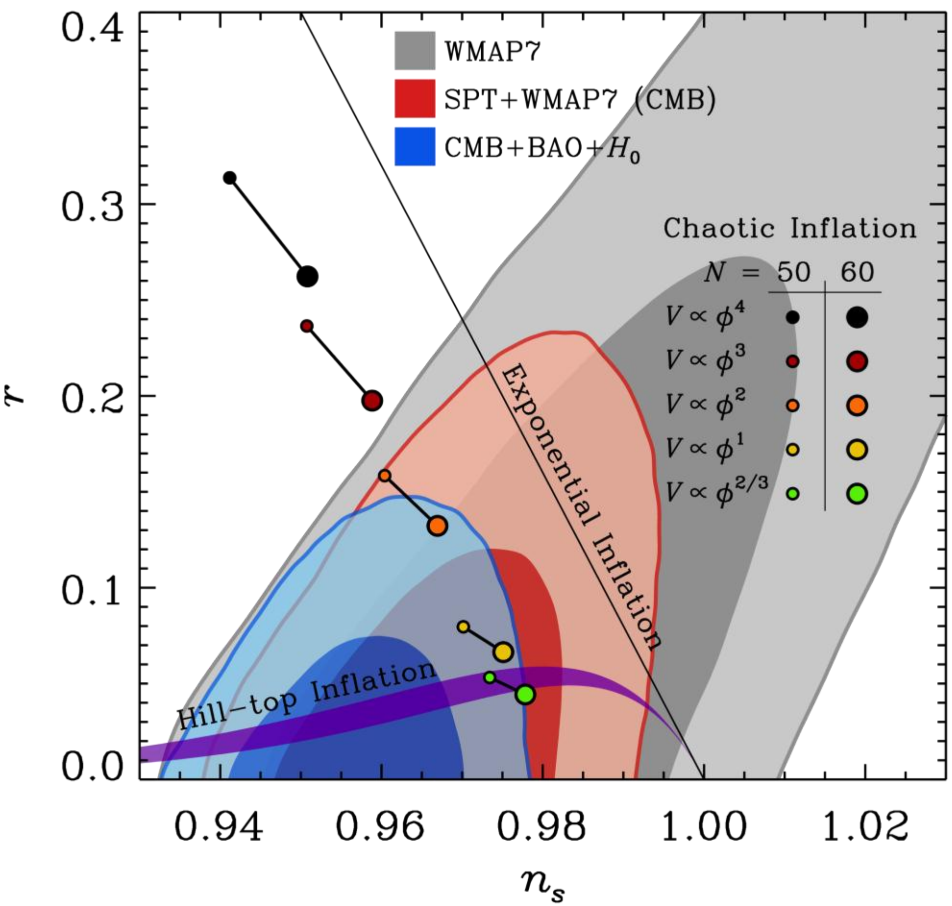
detection of $n_s \neq 1$ points towards dynamical mechanism!

CMB constraints on inflation

- CMB power spectrum starts to constrain inflation models
- $n_s < 1$ now at nearly 4σ (but beware model assumptions)
- Planck: $\sigma[n_s] \sim 0.005$!

(figures: Story et al, arXiv:1210.7231)





intermediate summary

- **what's the point so far?**
  - new physics needed to explain structure
  - dynamical nature very likely
- **what's missing? (literally…)**
  1. primordial gravitational waves
  2. deviations from Gaussianity
  3. phase-transition remnants

  (+ features in P(k)

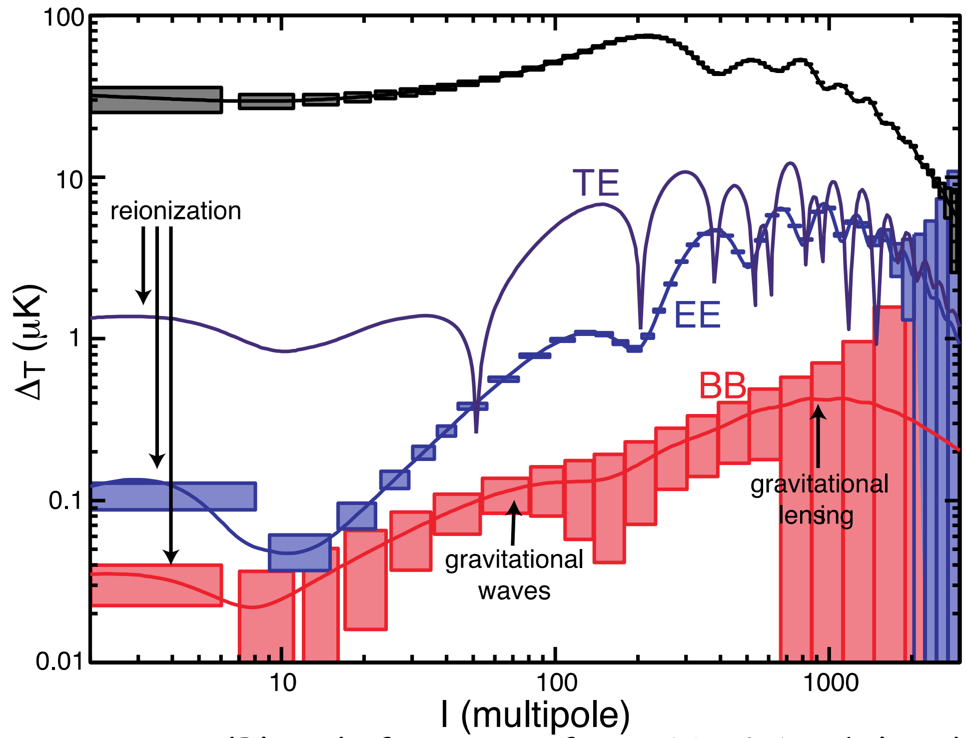
  \+ isocurvature perturbations)

  } No traces yet
- the absence of a signal starts to become a signal!

1. Gravitational waves

- gravitons are a light degree of freedom ***necessarily*** present during inflation
- we expect a background of gravitational waves, with amplitude related to energy scale of inflation
- very hard to detect

- space missions:
  - LISA : direct detection
  - Planck: $r > 0.05$
  - COrE: $r > 10^{-3}$
- 'trick': grav. waves lead to B-type polarization pattern of CMB



(Planck forecast from Hu & Dodelson)

2. non-Gaussianity

(Komatsu, Maldacena, Matarrese, Senatore, Creminelli, Zaldarriaga, … many others…)

- So far we have only looked at the power spectrum of perturbations
- If perturbations have a Gaussian probability distribution then this gives full description
- Needs to be tested … natural first test is 3-point function (bispectrum)

$$\langle \Phi(\mathbf{k_1})\Phi(\mathbf{k_2})\Phi(\mathbf{k_3})\rangle \sim B(k_1, k_2, k_3)\delta^{(3)}(\mathbf{k_1} + \mathbf{k_2} + \mathbf{k_3})$$

(vanishes for Gaussian distribution)

- (of course also 4-point function, etc, …!)
- usually written with amplitudes $\mathbf{f_{NL}}$ for certain shapes $f(k_1,k_2,k_3)$ → minimize $|^2$ as estimator

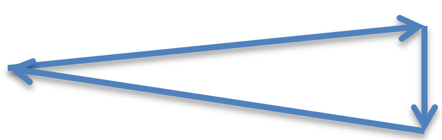
inflation and nG

- what are the predictions for inflation?

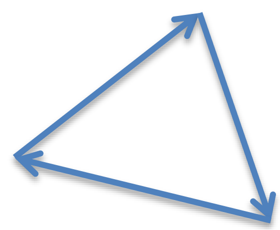
-> non-Gaussianity is small if we have (at least)

  - **single scalar field**
  - **canonical kinetic term**
  - **slow roll**

- can be linked to terms in EFT action of inflaton field
- typical shapes:



squeezed (local)
$k_1 \sim k_2 \gg k_3$
e.g. features in $V(\varphi)$



equilateral
$k_1 \sim k_2 \sim k_3$
non-standard kinetic term

+ shape 'orthogonal' to local and equilateral
e.g. Galileon inflation

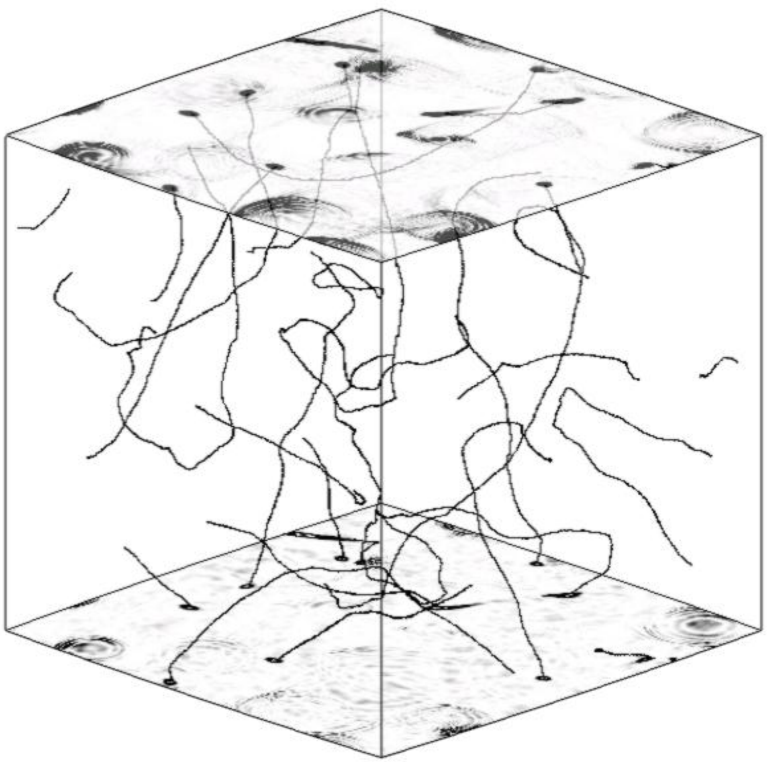
- often correlated w/ features in P(k) or isocurvature
- gravity will produce O(1) local f_{NL}

current knowledge

- WMAP 7 : (Komatsu et al)
  - f_{NL}[local] = 32 ± 21 [foregrounds f_{NL} ~ 10]
  - f_{NL}[equil] = 26 ± 140
  - f_{NL}[ortho] = -202 ± 104 [contamination?]
- Planck expectations:
  - 2013: σ[local] ~ 7, σ[equil] ~ 60, σ[ortho]~ 40
  - another factor of two in second release?
- large-scale structure also probes nG
- f_{NL} <~ 1 : supports slow-roll inflation
- f_{NL} >~ 1 : rules out SR, probes non-trivial interactions

3. phase-transition remnants

- Realistic inflation models embedded in particle physics models generically produce phase transition remnants.
- These topological defects create additional perturbations (+B modes +nG), visible in the CMB for GUT-scale models!
- Defects typical for hybrid inflation models with small r



sims w/ Bevis, Daverio, Hindmarsh, Urrestilla

(defects also emit gravitational waves and cosmic rays – really multi-messenger!)

that for e.g. $3_C\ 2_L\ 2_R\ 1_{B-L}$ stands for $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.

$$E_6 \xrightarrow{1} SO(10)\ 1_{V'} \left\{ \begin{array}{lcl} \xrightarrow{2} SO(10) & \longrightarrow & \text{Eq. (23)} \\ \xrightarrow{1} 5\ 1_V\ 1_{V'} & \longrightarrow & \text{Eq. (24)} \\ \xrightarrow{1} 5_F\ 1_V\ 1_{V'} & \longrightarrow & \text{Eq. (25)} \\ \xrightarrow{1} 5_E\ 1_V\ 1_{V'} & \xrightarrow{2',2} & G_{SM}\ Z_2 \\ \xrightarrow{2} 5\ 1_{V'}\ Z_2 & \longrightarrow & \text{Eq. (24a)} \\ \xrightarrow{1,2} 5\ 1_V & \longrightarrow & \text{Eq. (23a)} \\ \xrightarrow{1} 5_F\ 1_V & \xrightarrow{2',2} & G_{SM}\ Z_2 \\ \xrightarrow{1} G_{SM}\ 1_V & \xrightarrow{2} & G_{SM}\ Z_2 \\ \xrightarrow{1,2} G_{SM}\ 1_{V'}\ Z_2 & \xrightarrow{2} & G_{SM}\ Z_2 \\ \xrightarrow{1,2} 4_C\ 2_L\ 2_R\ 1_{V'} & \longrightarrow & \text{Eq. (26)} \\ \xrightarrow{1} 4_C\ 2_L\ 2_R & \longrightarrow & \text{Eq. (27)} \\ \xrightarrow{1} 3_C\ 2_L\ 2_R\ 1_{B-L}\ 1_{V'} & \longrightarrow & \text{Eq. (26c)} \\ \xrightarrow{1} 3_C\ 2_L\ 1_R\ 1_{B-L}\ 1_{V'} & \longrightarrow & \text{Eq. (26b)} \end{array} \right. \quad (22)$$

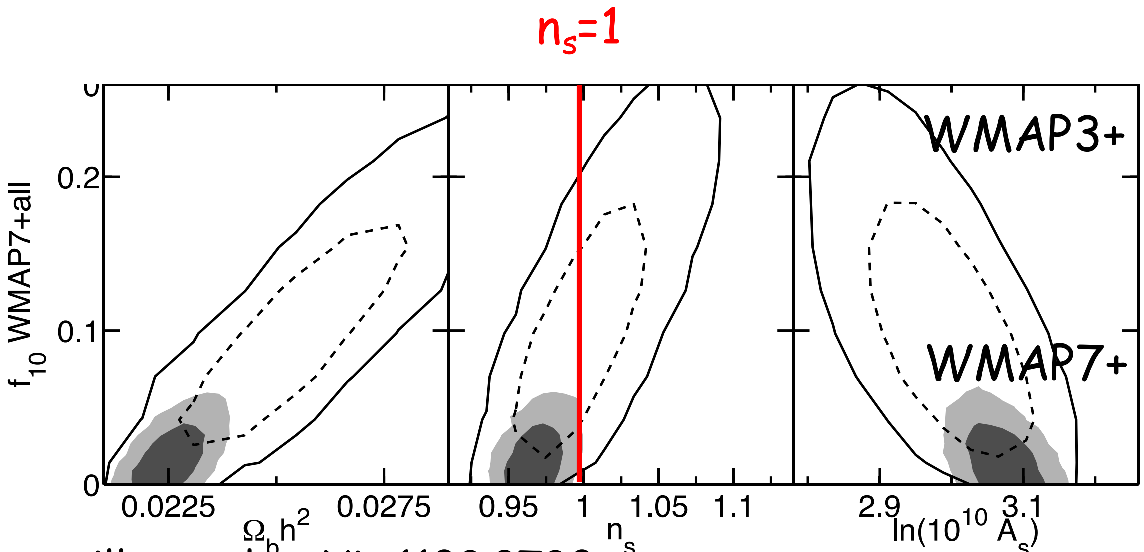
Sakellariadou, hep-th/0702003

cosmic string constraints

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	

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

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



Urrestilla et al, arXiv:1108.2730

Hybrid SUSY inflation predicts strings, wants n_s close to 1

Planck will get down to f_{10} ~ 1%, COrE to f_{10} ~ 0.1%

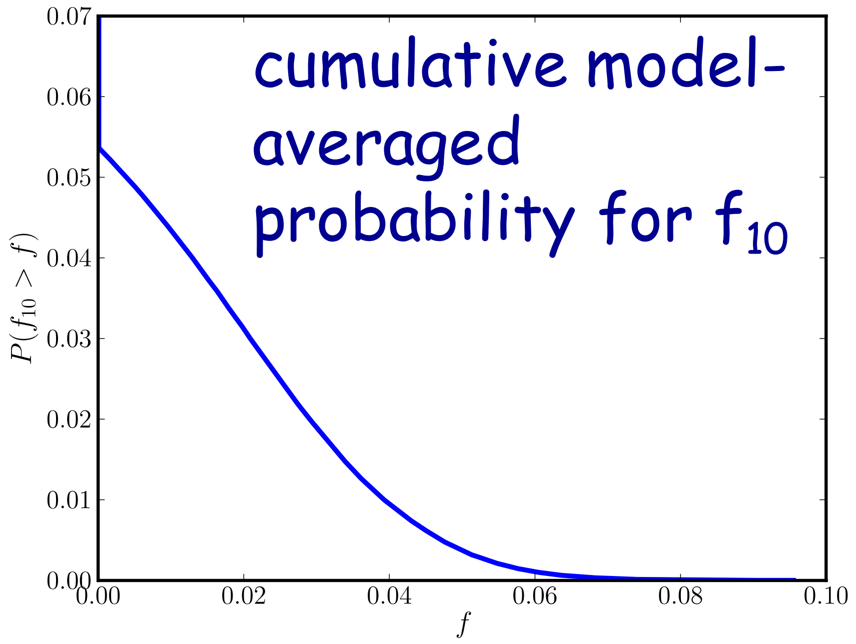
where are the defects?

Can we rule out GUT scale strings?

- 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 $0.75 < n_s < 1.25$; $0 < f_{10} < 1$
- assumption: GUT scale strings should lie in this range
- 4 models: 'PL', 'HZ', 'PL+AH', 'HZ+AH'

-> ln prob[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 GUT strings!

conclusions

Why are we here?

- Something *dynamic* generated *superhorizon* perturbations in the early universe
- The perturbations are nearly scale invariant, consistent with Gaussian distribution function

Where is the action (in the CMB)?

1. Rapid expansion should have generated gravitational wave background, depending on energy scale of inflation
2. Deviations from Gaussianity would probe e.g. higher-order interactions of effective field theory
3. Topological defects from phase transitions would probe symmetry breaking and structure of vacuum manifold

The CMB can probe fundamental physics at extremely high energy scales!