Concluding discussion

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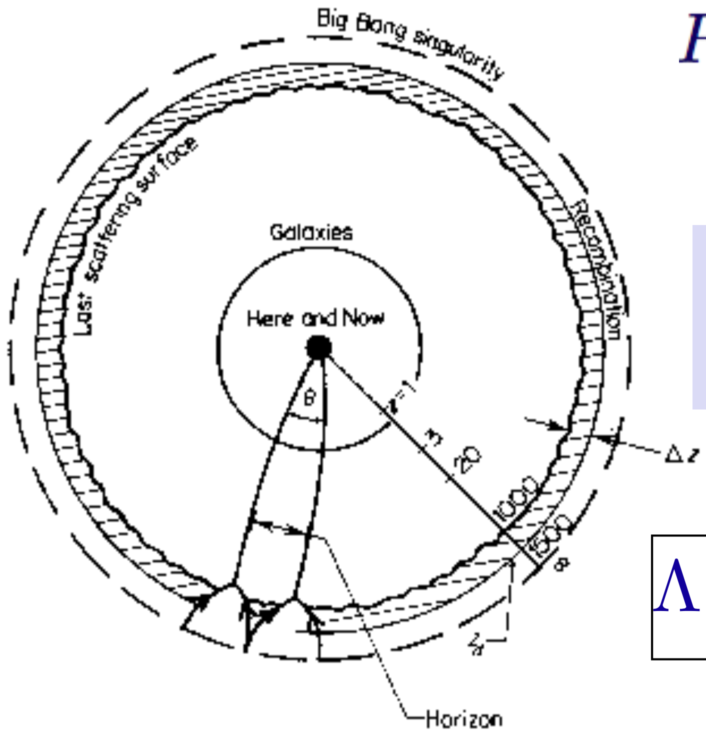
25 talks
3 discussion sessions
42 participants

2nd NBIA-APCTP Workshop on Cosmology & Astroparticle Physics
18-22 August 2014, Niels Bohr Institute, Copenhagen

The **standard cosmological model** is based on several key assumptions:
maximally symmetric space-time + general relativity + *ideal fluids*

$$ds^2 \equiv g_{\mu\nu} dx^\mu dx^\nu$$
$$= a^2(\eta)\left[d\eta^2 - d\bar{x}^2\right]$$
$$d\eta^2 \equiv dt^2/a^2(t)$$

Space-time metric
Robertson-Walker



$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu}$$
$$= 8\pi G_{\rm N} T_{\mu\nu}$$

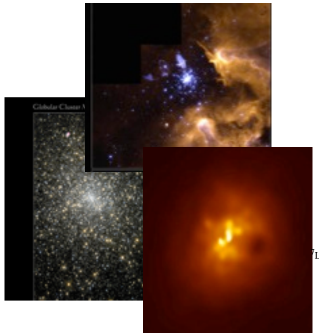
Geometrodynamics
Einstein

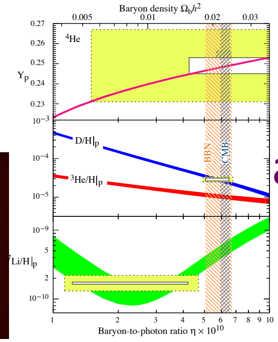
$$\Lambda \equiv \lambda_{\rm metric} + \frac{\langle\rho\rangle_{\rm fields}}{M_{\rm P}^2}$$

$$\Rightarrow H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_{\rm N}\rho_{\rm m}}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$
$$\equiv {H_0}^2\left[\Omega_{\rm m}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right]$$

where $: z \equiv \frac{a_0}{a} - 1, \Omega_{\rm m} \equiv \frac{\rho_{\rm m}}{3H_0^2/8\pi G_{\rm N}}, \Omega_k \equiv \frac{k}{a_0^2 H_0^2}, \Omega_\Lambda \equiv \frac{\Lambda}{3H_0^2}$

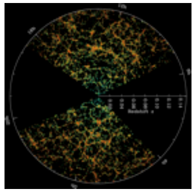
The world is indeed a strange place!

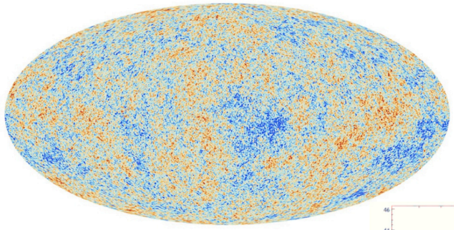


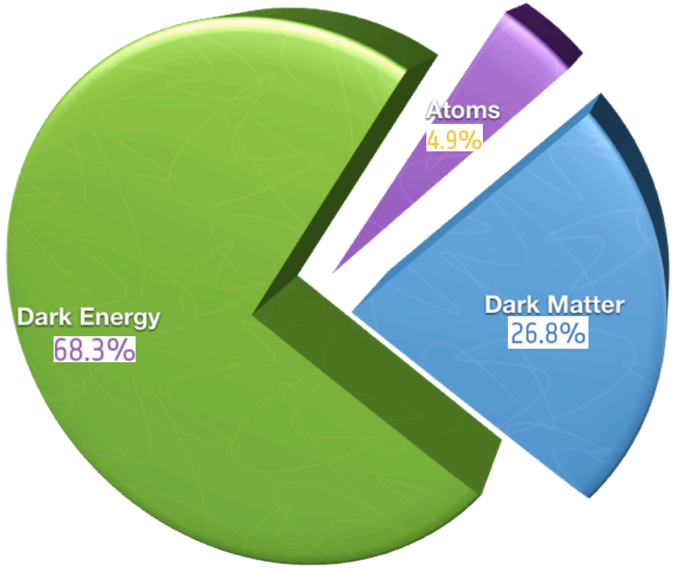


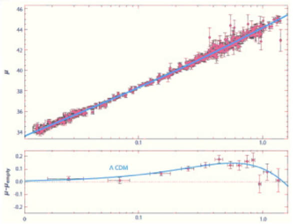
Baryons (*no* anti-baryons)

Mainly geometrical evidence:
Dark energy is *inferred* from the 'cosmic sum rule': $\Omega_m + \Omega_k + \Omega_\Lambda = 1$
$\Lambda \sim O(H_0^2)$, $H_0 \sim 10^{-42}$ GeV

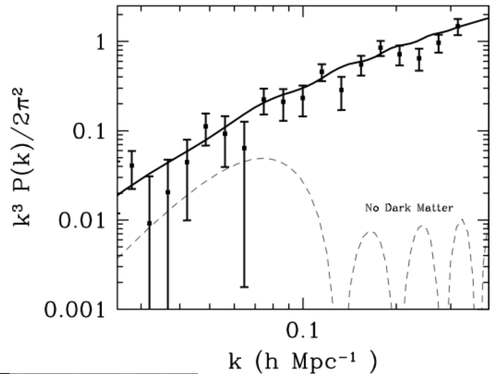






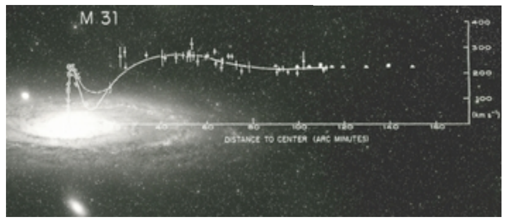


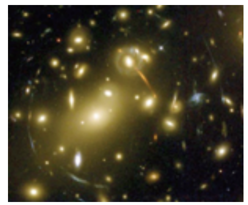
Both geometrical & dynamical evidence (assuming GR is valid)



Both the baryon asymmetry and dark matter require that there be *new* physics beyond the Standard $SU(3)_c \mathrm{x} SU(2)_L \mathrm{x} U(1)_Y$ Model

… dark energy is even more mysterious (but as yet lacks compelling *dynamical* evidence)





The Standard $SU(3)_c \times SU(2)_L \times U(1)_Y$ Model (viewed as an effective field theory up to a high energy cut-off scale ***M***) accurately describes *all* of microphysics …

$$+M^4 + M^2\Phi^2 \qquad m_H^2 \simeq \frac{h_t^2}{16\pi^2}\int_0^{M^2} \mathrm{d}k^2 = \frac{h_t^2}{16\pi^2}M^2$$

vacuum energy problem — hierarchy problem — **super-renormalisable**

$$\mathcal{L}_{\rm eff} = F^2 + \bar{\Psi}\not{D}\Psi + \bar{\Psi}\Psi\Phi + (D\Phi)^2 + V(\Phi)$$

renormalisable

$$+\frac{\bar{\Psi}\Psi\Phi\Phi}{M} + \frac{\bar{\Psi}\Psi\bar{\Psi}\Psi}{M^2} + \dots$$

non-renormalisable

neutrino mass — proton decay

New physics beyond the SM ⇒ **non-renormalisable operators** suppressed by M^n which 'decouple' as $M \to M_{\rm P}$ (… so **neutrino mass** is small, **proton decay** is slow *etc*)

But as *M* is raised, the effects of the **super-renormalisable operators** are *exacerbated*
One solution for Higgs mass divergence → 'softly broken' supersymmetry at $M \sim 1$ TeV

This provides a candidate for **dark matter** – the **lightest supersymmetric particle** (typically the neutralino χ) – as do other extensions beyond the Standard Model e.g. new dimensions at the TeV scale (the lightest Kaluza-Klein particle)

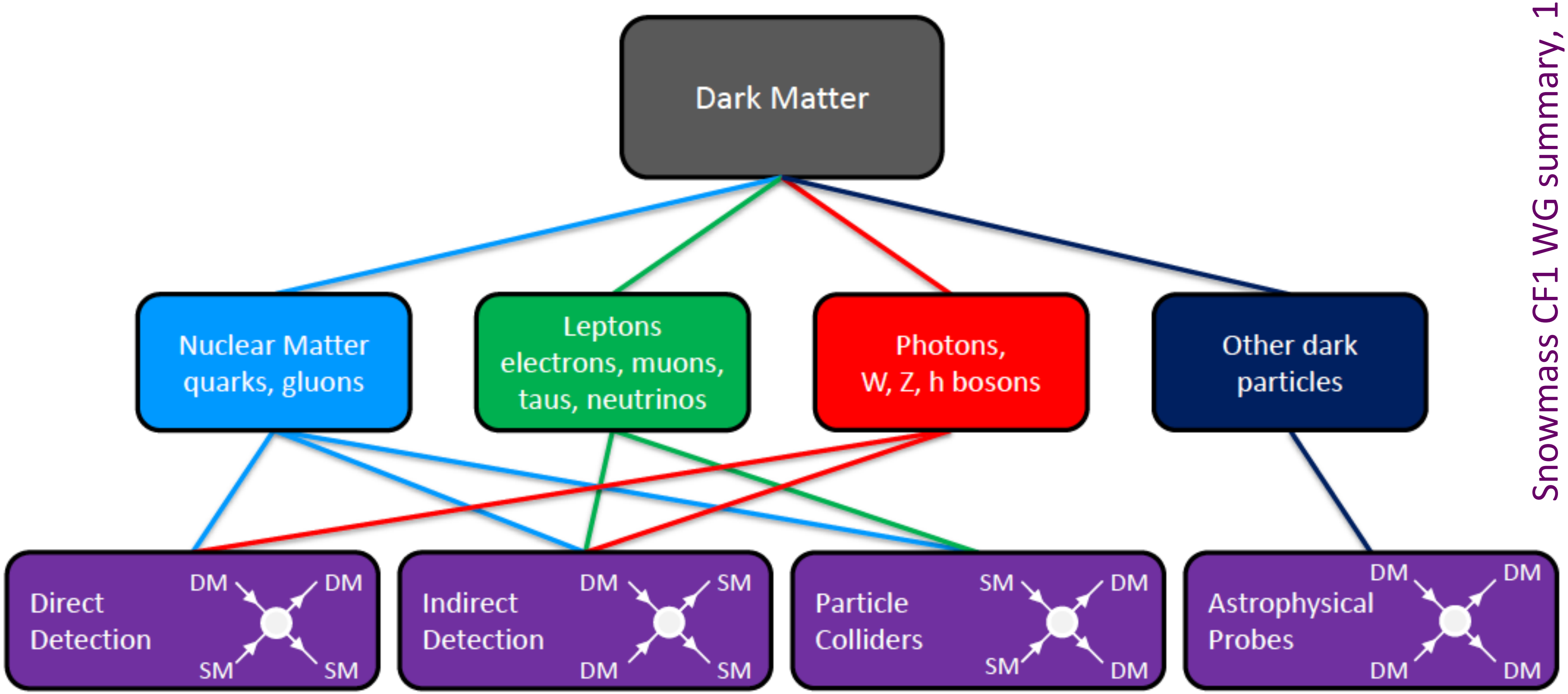
But the 'cosmological constant' is then ~10^{60} times higher than the maximum vacuum energy tolerable today … we do *not* understand how the SM couples to gravity!

What *should* the world be made of ?

Mass scale	Lightest stable particle	Symmetry/ Quantum #	Stability ensured?	Production	Abundance
Λ_{QCD}	**Nucleons**	Baryon number	$\tau > 10^{33}$ yr	~~'Freeze-out' from equilibrium~~ Asymmetric baryogenesis	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$
$\Lambda_{QCD'} \sim 5\Lambda_{QCD}$	Dark baryon?	$U(1)_{DB}$	plausible	Asymmetric (like *observed* baryons)	$\Omega_{DB} \sim 0.3$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	R-parity	violated?	'freeze-out' from equilibrium	$\Omega_{LSP} \sim 0.3$
	Technibaryon?	(walking) Techni-colour	$\tau \sim 10^{18}$ yr	Asymmetric (like observed baryons)	$\Omega_{TB} \sim 0.3$
$\Lambda_{hidden\ sector} \sim (\Lambda_F M_P)^{1/2}$	Crypton? hidden valley?	Discrete (very model-dependent)	$\tau \gtrsim 10^{18}$ yr	Varying gravitational field during inflation	$\Omega_X \sim 0.3$?
$\Lambda_{see\text{-}saw} \sim \Lambda_{Fermi}^2/\Lambda_{B\text{-}L}$	**Neutrinos**	Lepton number	Stable	Thermal (abundance ~ CMB photons)	$\Omega_\nu > 0.003$
M_{string}/M_{Planck}	Kaluza-Klein states? Axions	? Peccei-Quinn	? stable	? Field oscillations	? $\Omega_a \gg 1$!

No definite indication from theory
must decide by experiment!

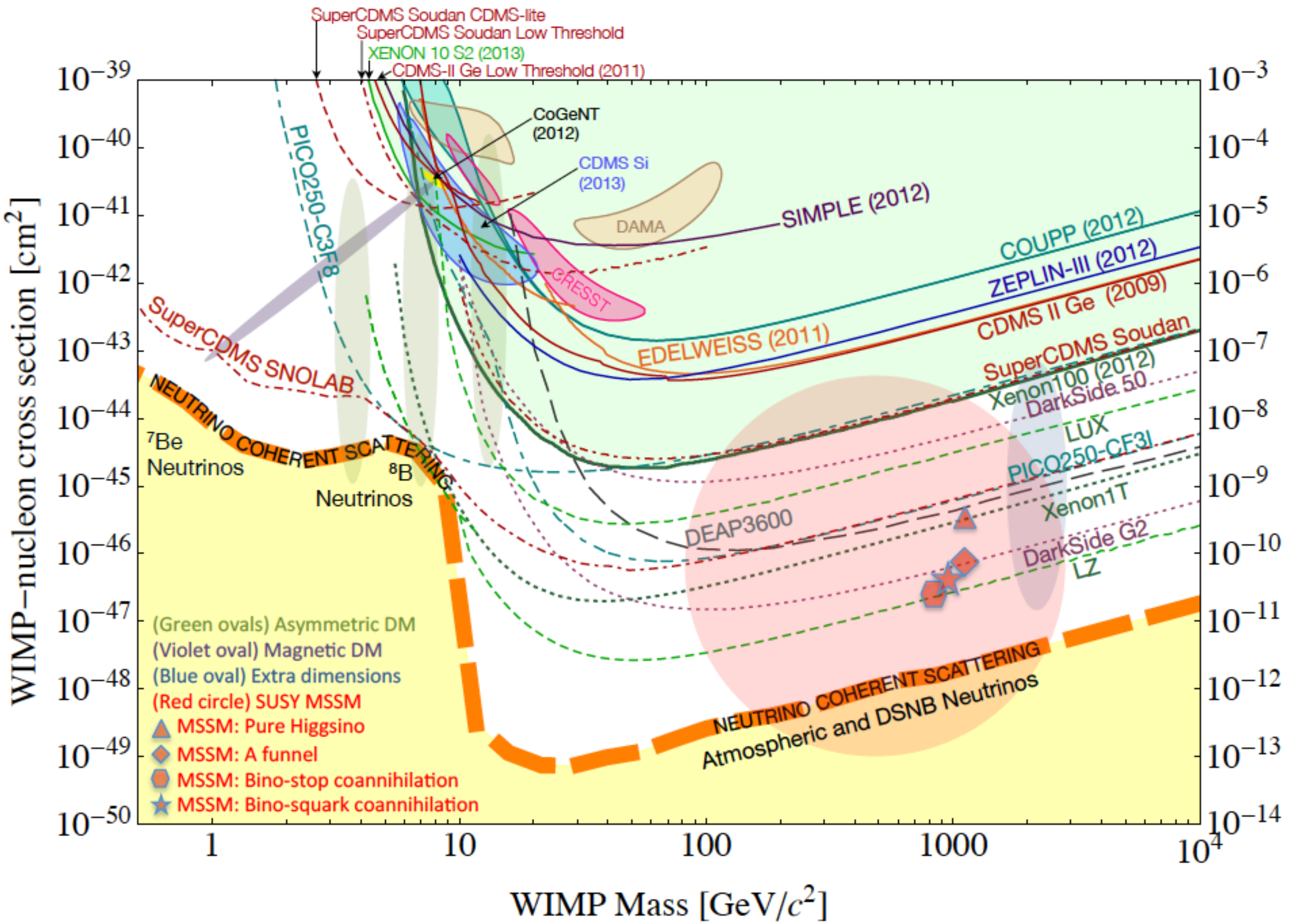
Detecting dark matter particles



Snowmass CF1 WG summary, 1310.8327

Rich experimental programme extending from low-background underground laboratories to balloon/space experiments to colliders …

Mainly *negative* results in 25 yr old world-wide race on to detect dark matter



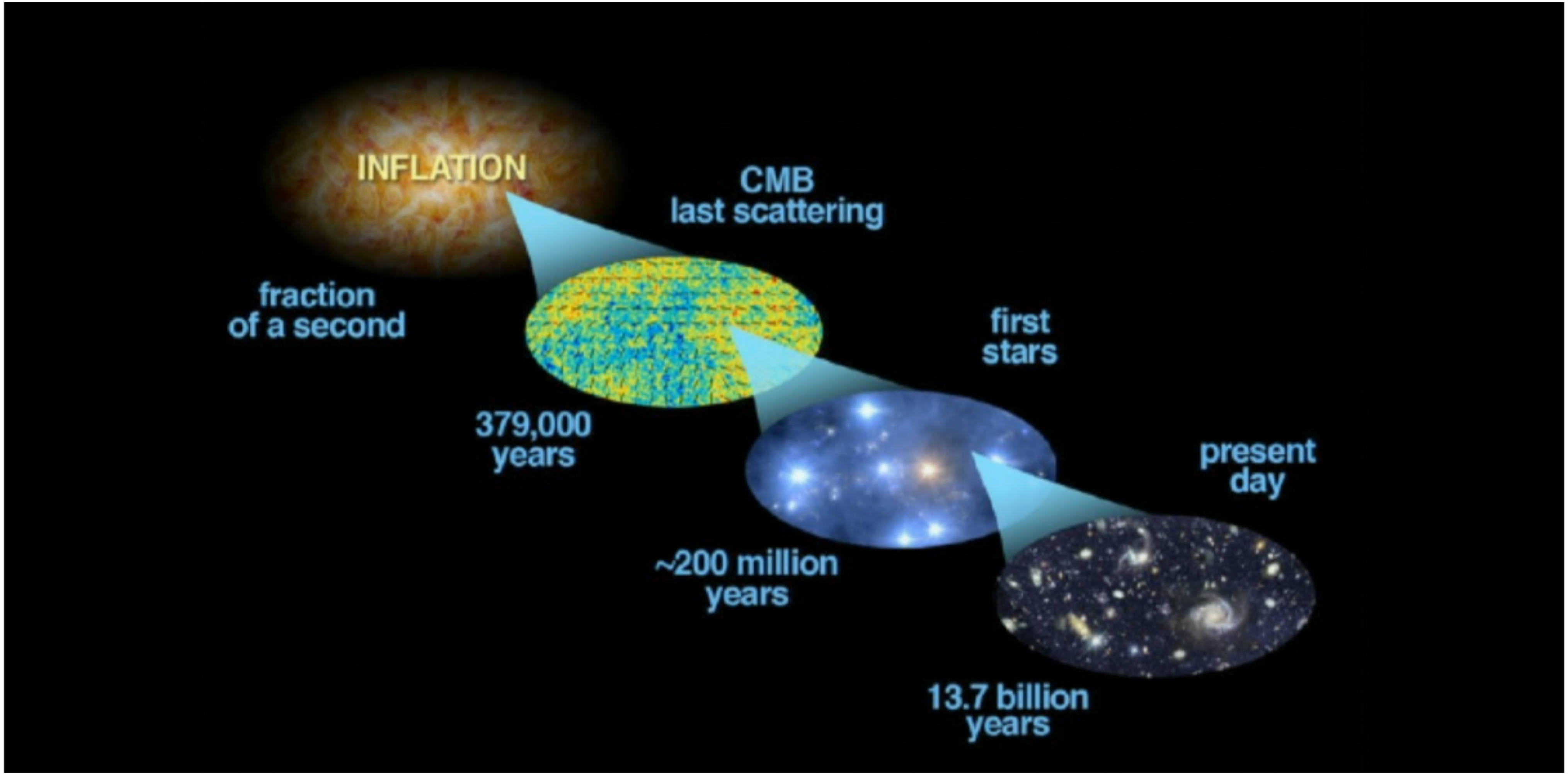
Snowmass CF1 WG summary, 1310.8327

Several claims for signals have been ruled out by more sensitive experiments … but are we making a fair comparison (e.g. isospin dependence, non-Maxwellian velocity distribution …)

No single experiment can either confirm or rule out dark matter

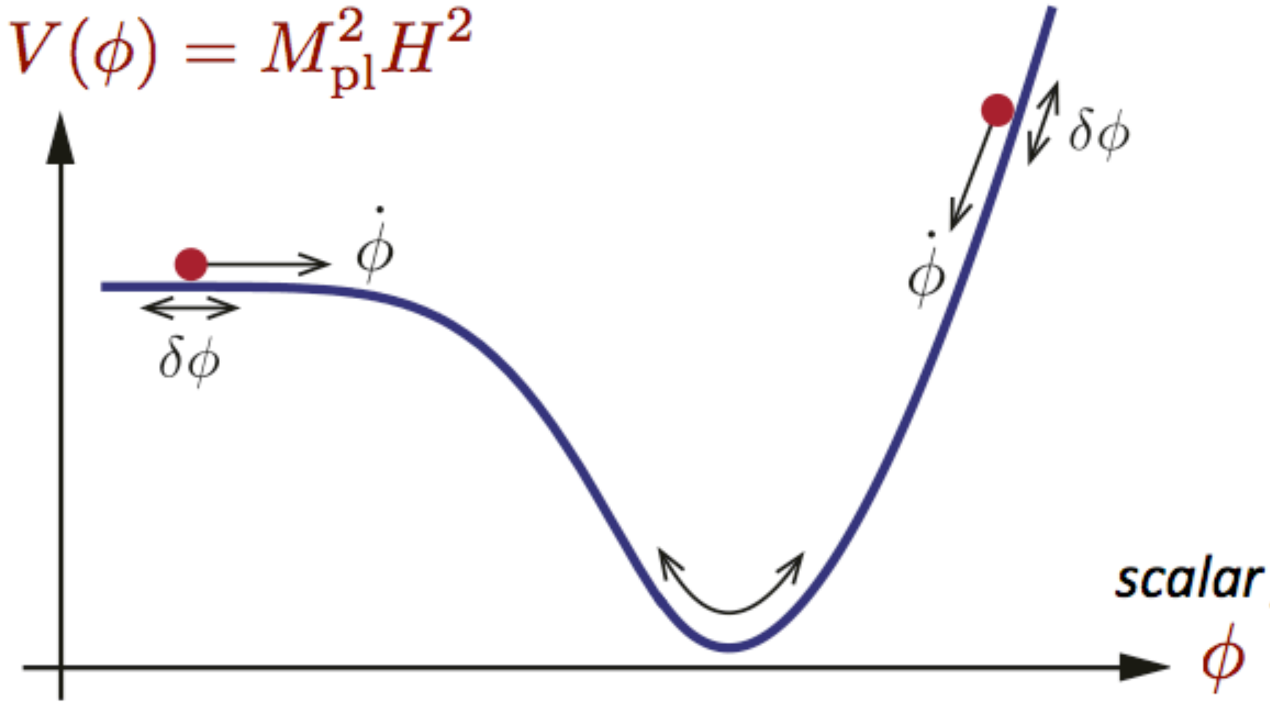
(… also not a good strategy to look just under the supersymmetric lamp post!)

Why this is so very exciting …



We have a nearly complete picture of the growth of **large-scale structure** through **gravitational instability** in a sea of **dark matter**, starting with **scalar density perturbations** which we have detected imprinted on the **cosmic microwave background** … if these were created by '**inflation**' then seeing the associated **tensor perturbations** would *prove* that inflation actually occurred!

Toy model of slow-roll inflation:



$$\varepsilon = \frac{M_{\rm pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

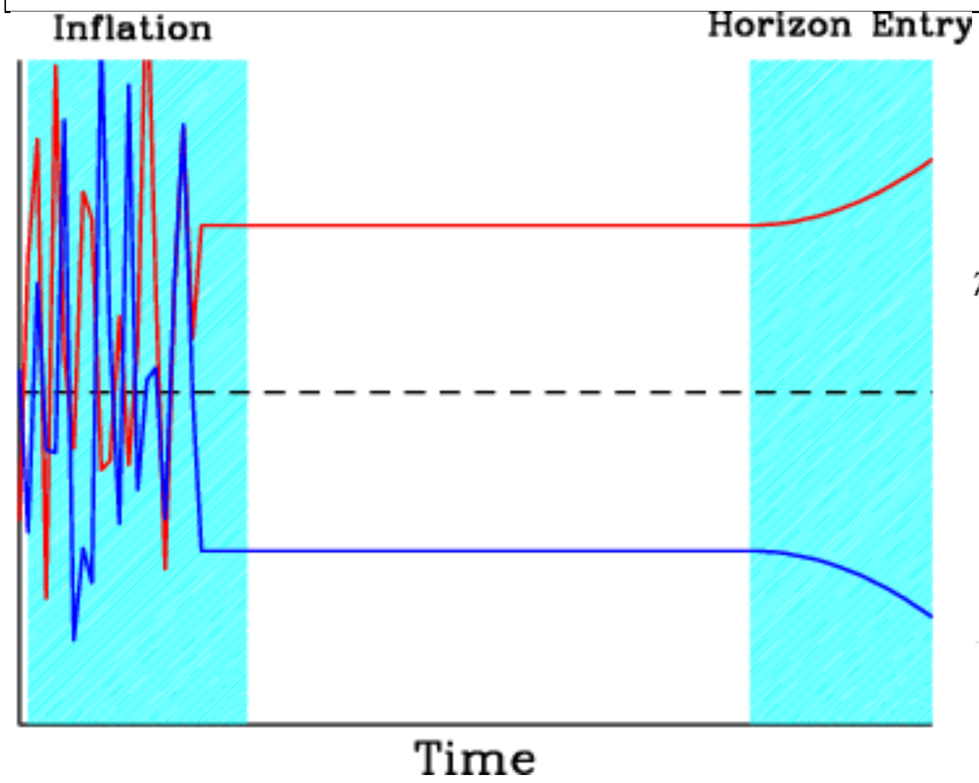
$$\eta = M_{\rm pl}^2 \frac{V''}{V} \ll 1$$

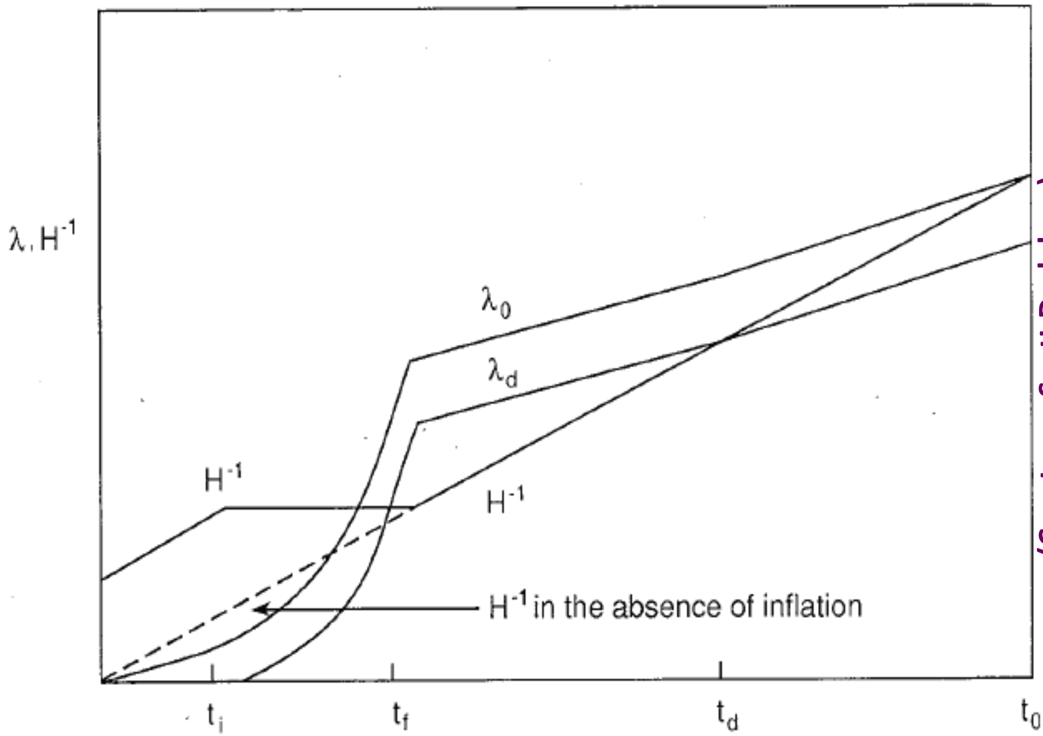
The slow evolution of a scalar field down a nearly flat part of its potential during which its vacuum energy is nearly constant so:

$$a \propto e^{H_{\rm infl} t}, \quad \text{with} \quad H_{\rm infl} = \sqrt{\frac{8\pi G_N}{3} V_0}$$

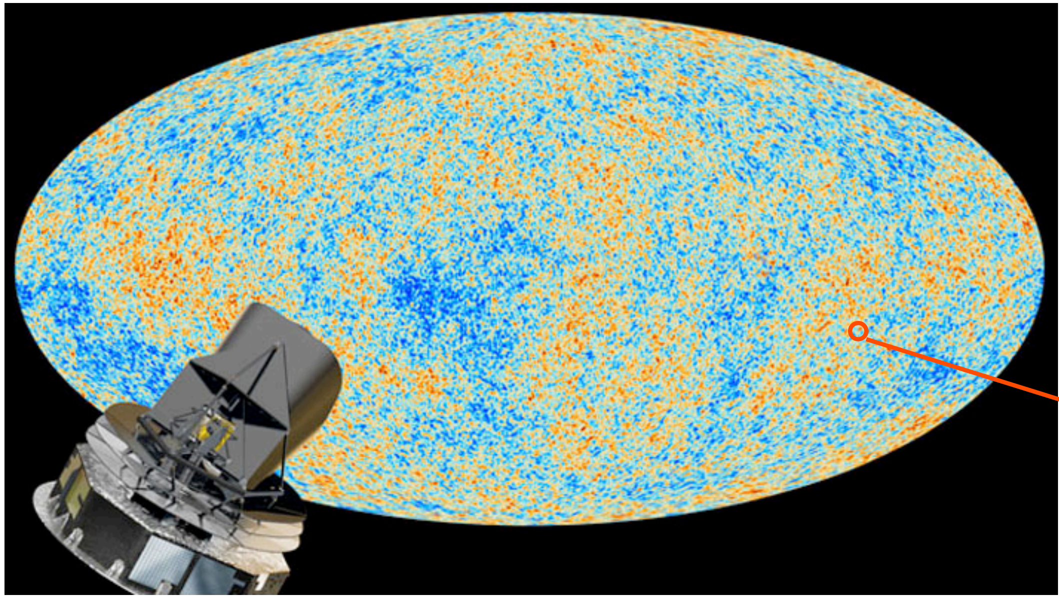
If the number of e-folds $N(\phi) = \int_{\phi_{\rm ini}}^{\phi_{\rm end}} \frac{H_{\rm infl}}{\dot\phi} {\rm d}\phi$ exceeds ~50-60, the region within the present Hubble radius would have been causally connected at the inflationary epoch, thus solving the 'horizon problem' (also the 'monopole problem')

- Quantum mechanical fluctuations: $<\Psi(\mathbf{k})\,\Psi(\mathbf{k'})> = (2\pi)^3\,\delta^3(\mathbf{k}-\mathbf{k'})\,P_\Psi(\mathbf{k})$
- Inflation *stretches* wavelength beyond horizon: $\Psi(\mathbf{k}, \mathbf{t})$ becomes constant (until horizon reentry after inflation ends – *first out, last in*)
- Infinite number of independent perturbations with independent amplitudes, but … inflation synchronizes all modes!





(Courtesey Scott Dodelson)



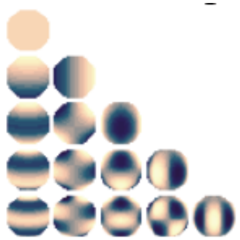
Coherent oscillations in a photon+baryon plasma excited by primordial perturbations on *super*-horizon length scales

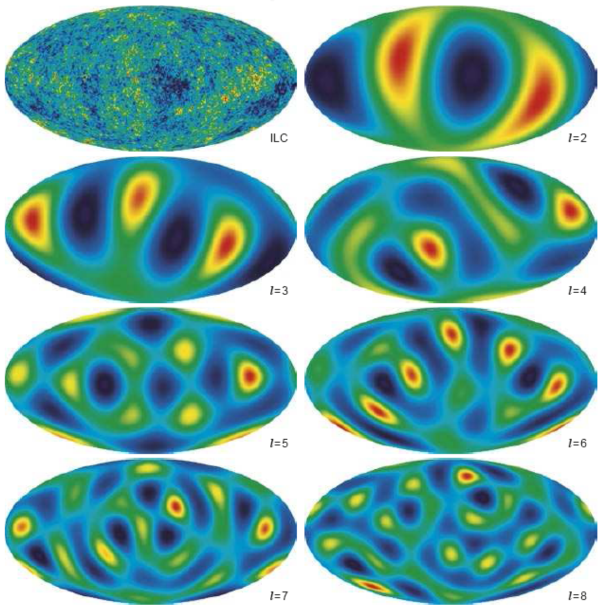
'Size' of the present universe at (re)combination epoch

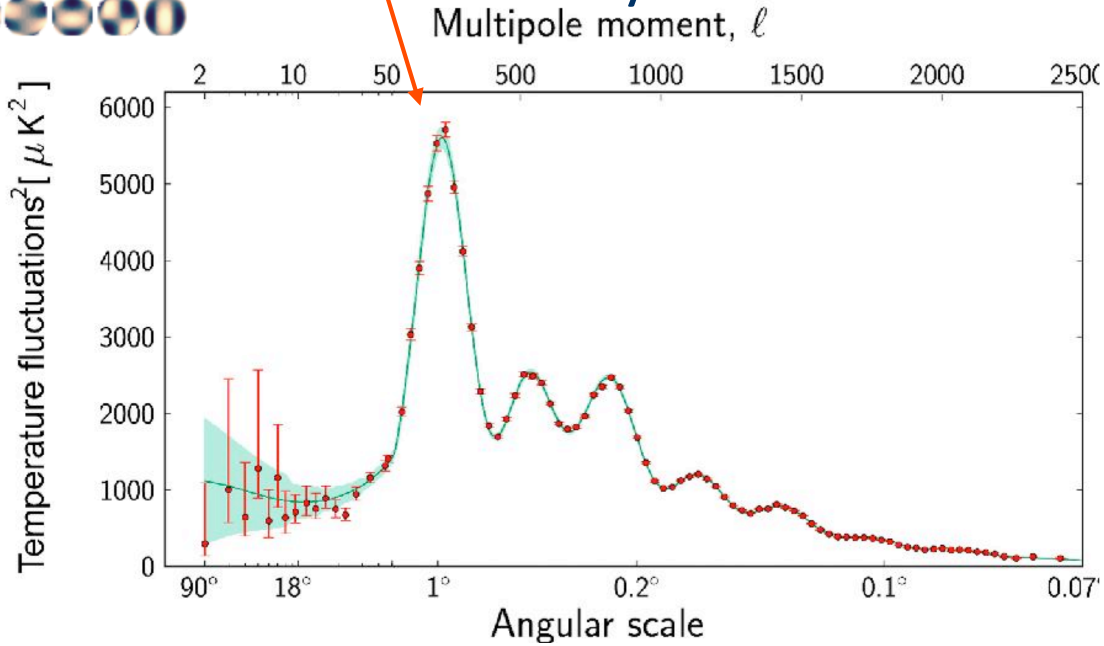
By analysing this pattern we can infer the values of the cosmological parameters *and* test the theory of inflation

$$\Delta T(\mathbf{n}) = \sum a_{lm} Y_{lm}(\mathbf{n})$$

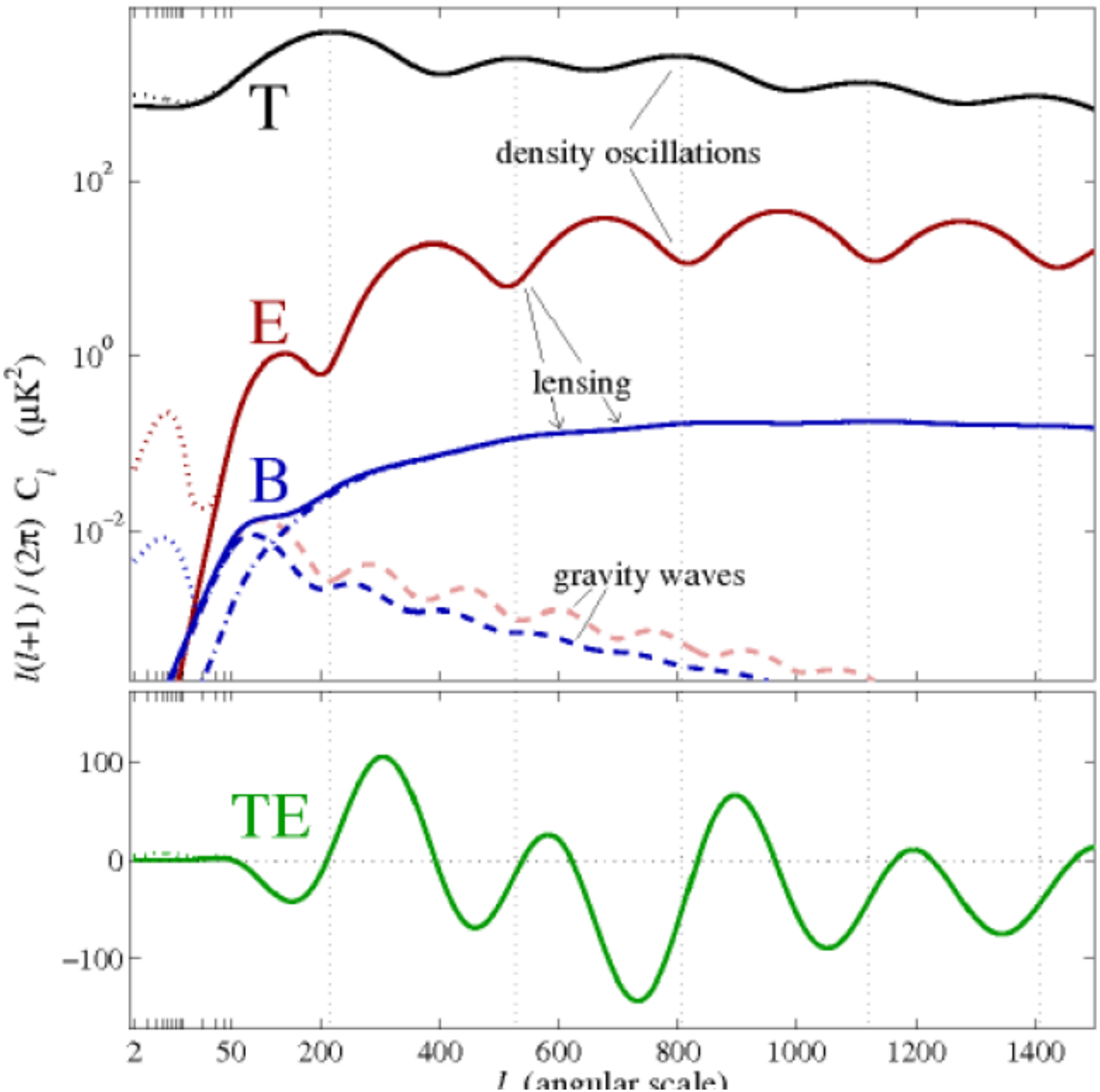
$$C_l \equiv \frac{1}{2l+1} \sum |a_{lm}|^2$$





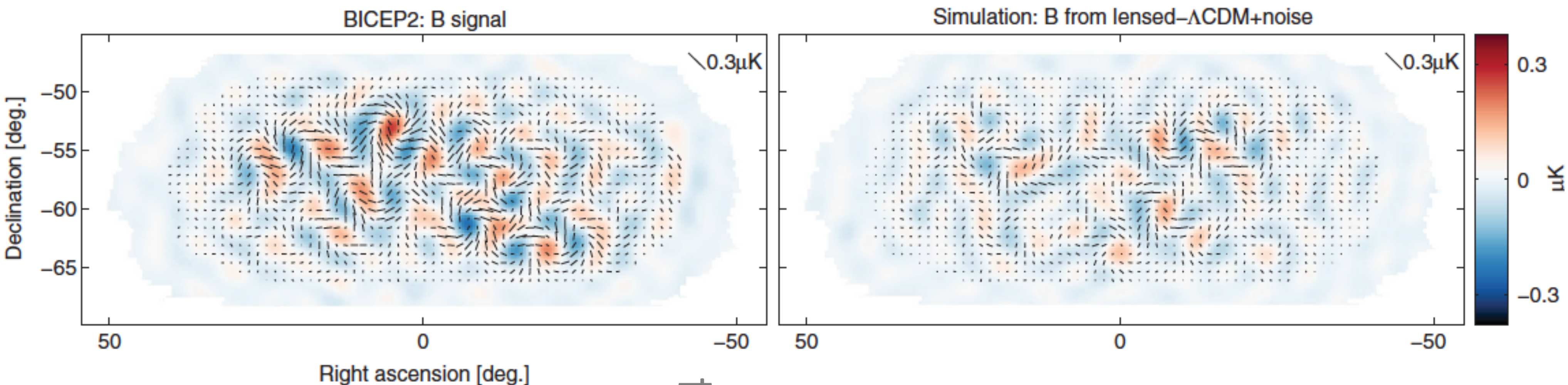


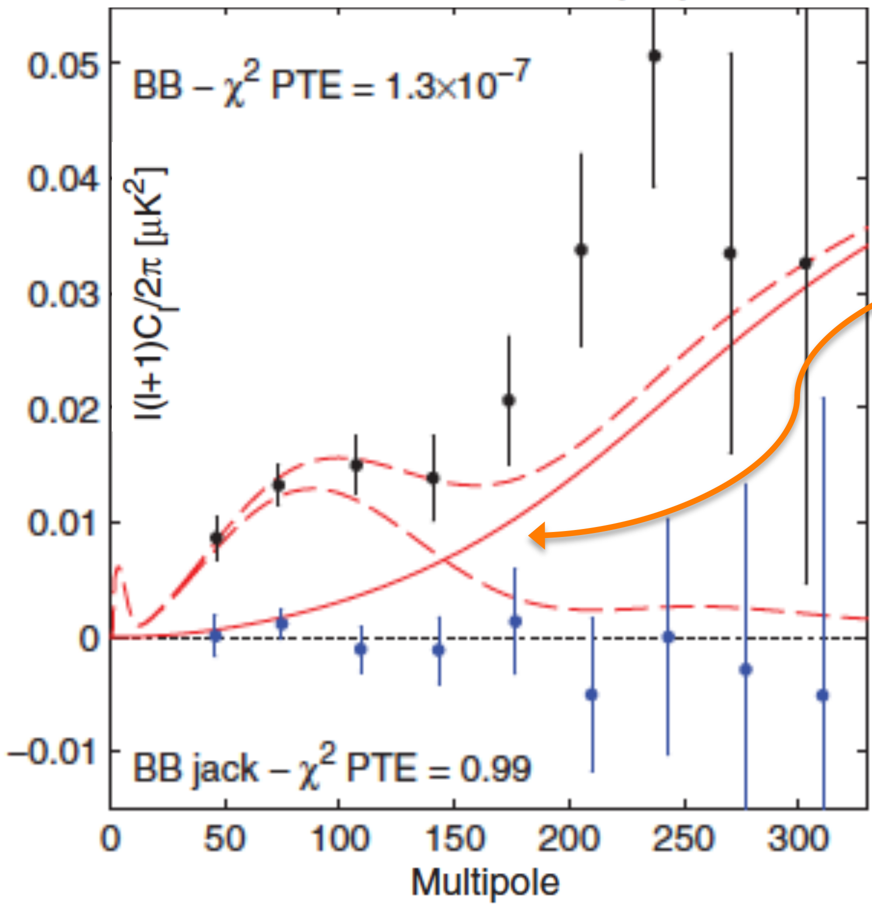
Intensity and Polarization E and B modes



(Courtesey: Phil Lubin)

BICEP2 claims to have detected the B-mode signal from inflation!





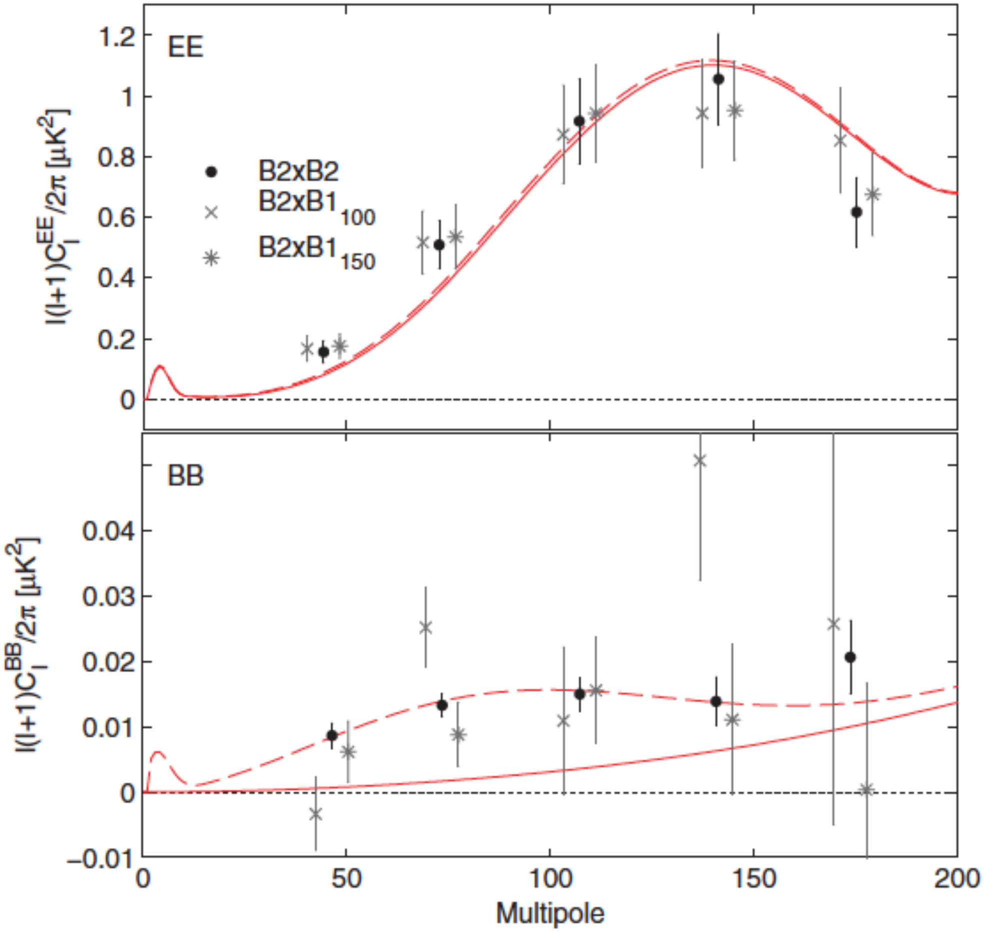
Ade *et al*, PRL 112:241101,2014

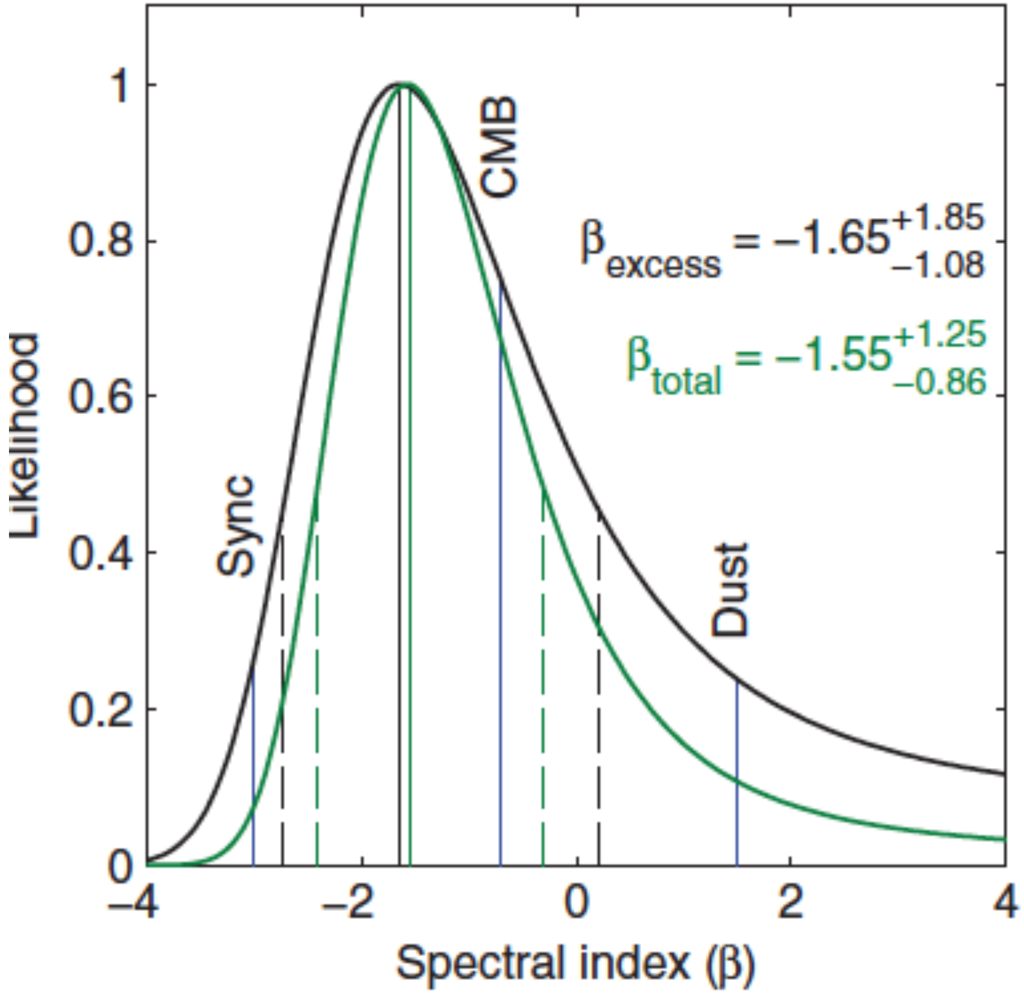
The probability of the B-mode signal to be a chance fluctuation of the lensed E-mode signal is small (5.2σ)

But what is the probability that it is some polarized *Galactic* foreground?

NB: Both synchrotron radiation and (some types of) dust emission are polarized and can mimic the B-mode pattern (depending on magnetic field)

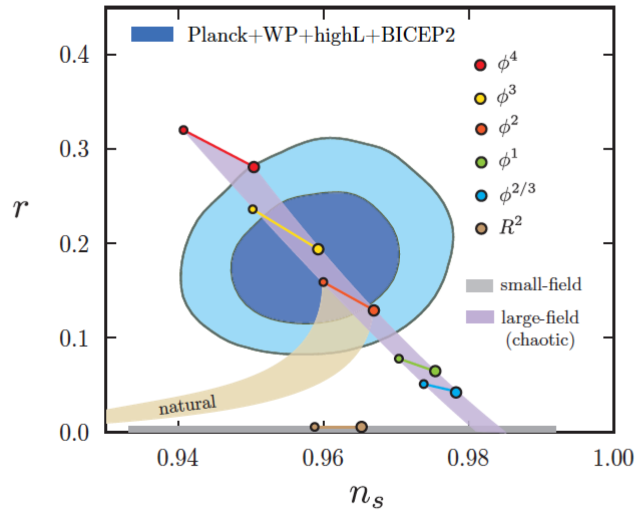
"We can use the BICEP2 auto and BICEP2xBICEP1$_{100}$ spectra to constrain the frequency dependence of the nominal signal, If the signal at 150 GHz were due to synchrotron we would expect the frequency cross spectrum to be much larger in amplitude than the BICEP2 auto spectrum. Conversely if the 150 GHz power were due to polarized dust emission we would not expect to see a significant correlation with the 100 GHz sky pattern." (PRL 112:241101,2014)





… so the significance with which the observed signal is likely to be CMB (β ~ −0.7) rather than either synchrotron (β ~ −3) or dust (β ~ 1.5) emission is in fact 1.6/1.7σ

If this is all true *then* ...



1. gravity is quantized

2. the energy scale of inflation is

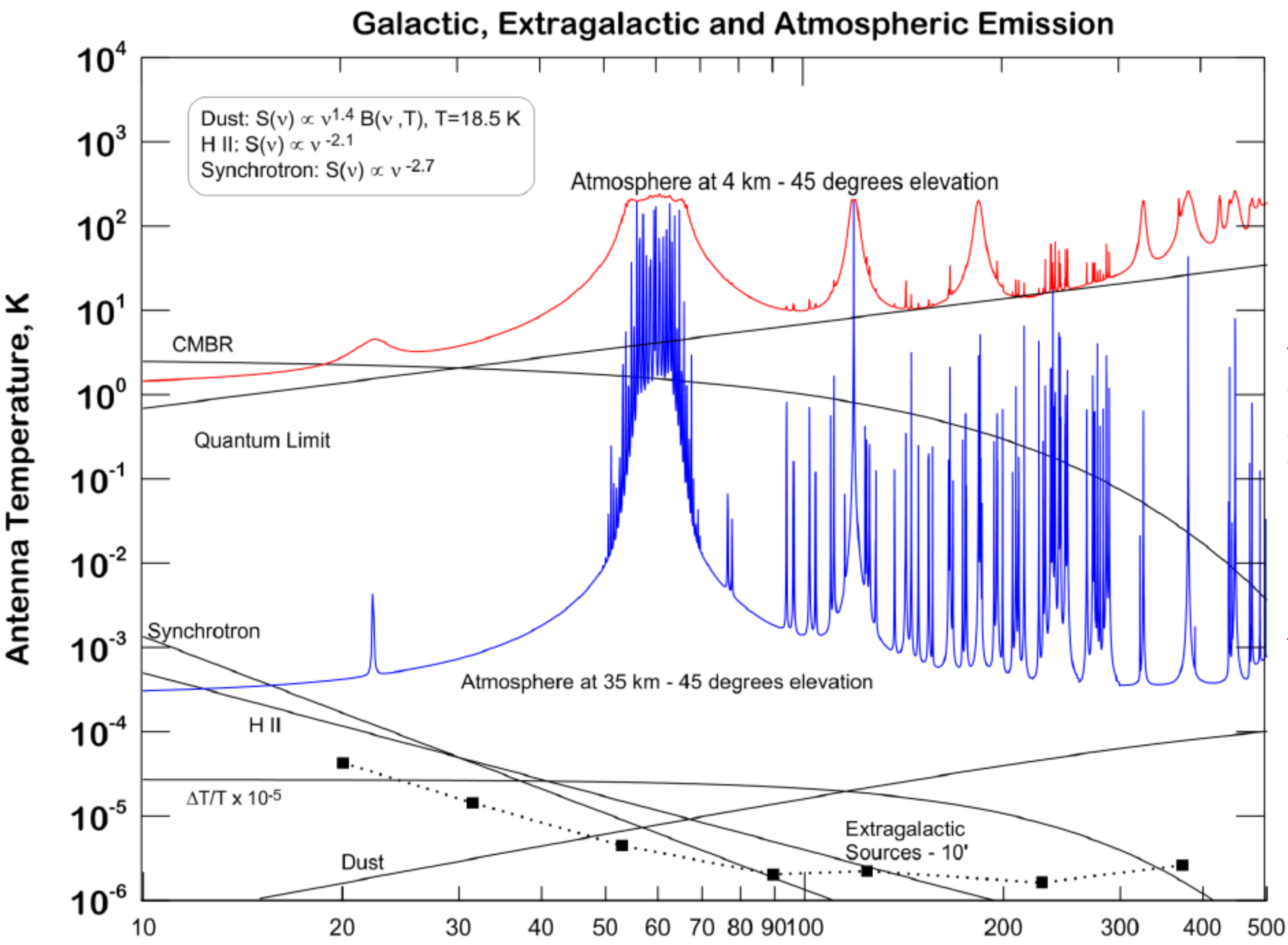
$$V^{1/4} = 1.8 \times 10^{16}\text{GeV} \times \left(\frac{r}{0.1}\right)^{1/4} \sim 10^{-2}\, M_{\rm pl}$$

3. the field excursion was super-Planckian:

$$\frac{\Delta\phi}{M_{\rm pl}} \gtrsim 3 \times \left(\frac{r}{0.1}\right)^{1/2}$$

4. But must cancel vacuum energy to 1 part in 10^{112} at the end of inflation!

So we must be *very* cautious about interpreting the observational result given its momentous implications ... e.g. could it just be some astrophysical foreground?



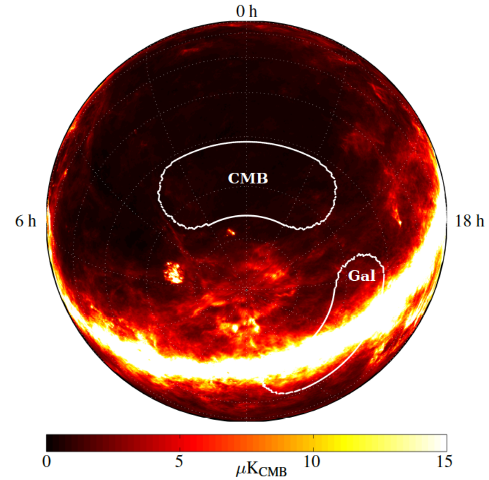
(Courtesey: Phil Lubin)

The most important "foreground" (i.e. astrophysical) sources of emission at CMB frequencies are

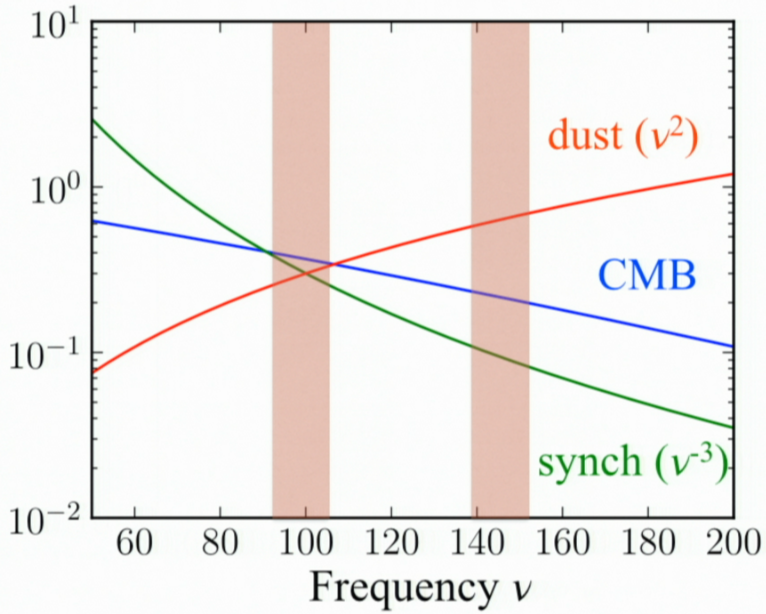
Synchrotron radiation from high-energy electrons accelerating in the magnetic field of our galaxy (polarized perpendicular to magnetic field)

Thermal dust emission, weakly polarized perpendicular to B due to tendency for shortest axis of dust grains to line up with magnetic field

BICEP2 observes in a small (~1%) patch of sky chosen to minimize these foregrounds



Foregrounds/CMB can be separated by making observations at multiple frequencies

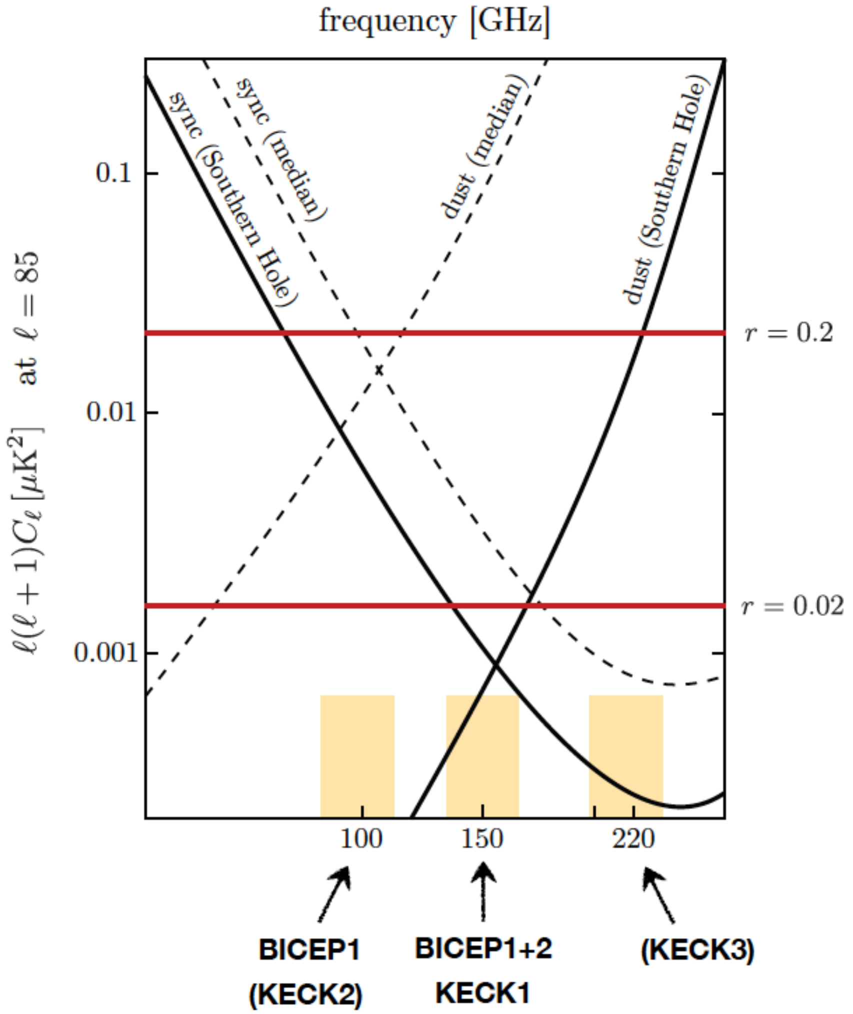


BICEP1
100+150 GHz

BICEP2
150 GHz only

WMAP
23-94 GHz

Planck
30-353 GHz
(polarization)

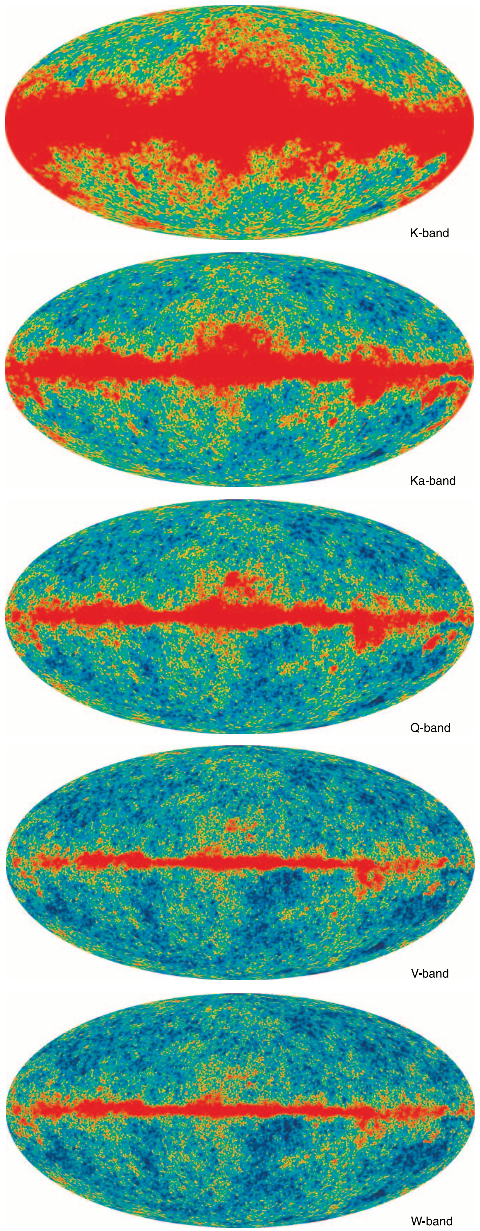


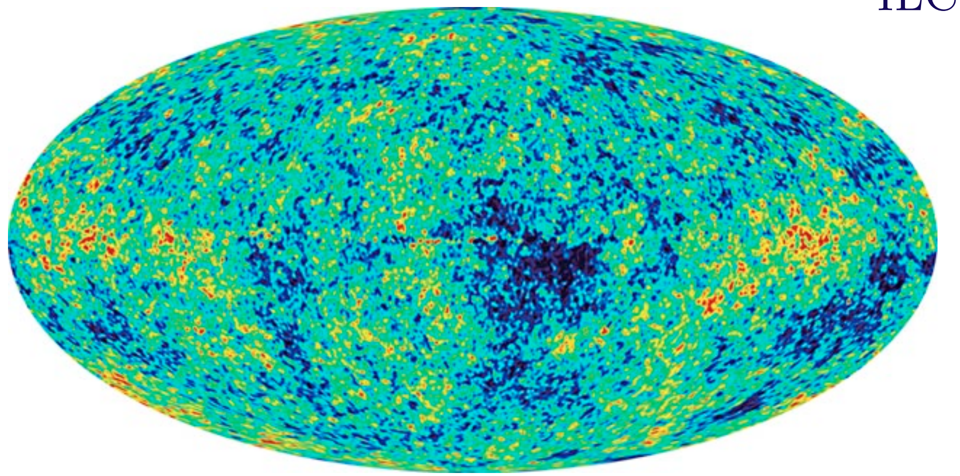
CMB foreground removal: Internal Linear Combination (ILC)

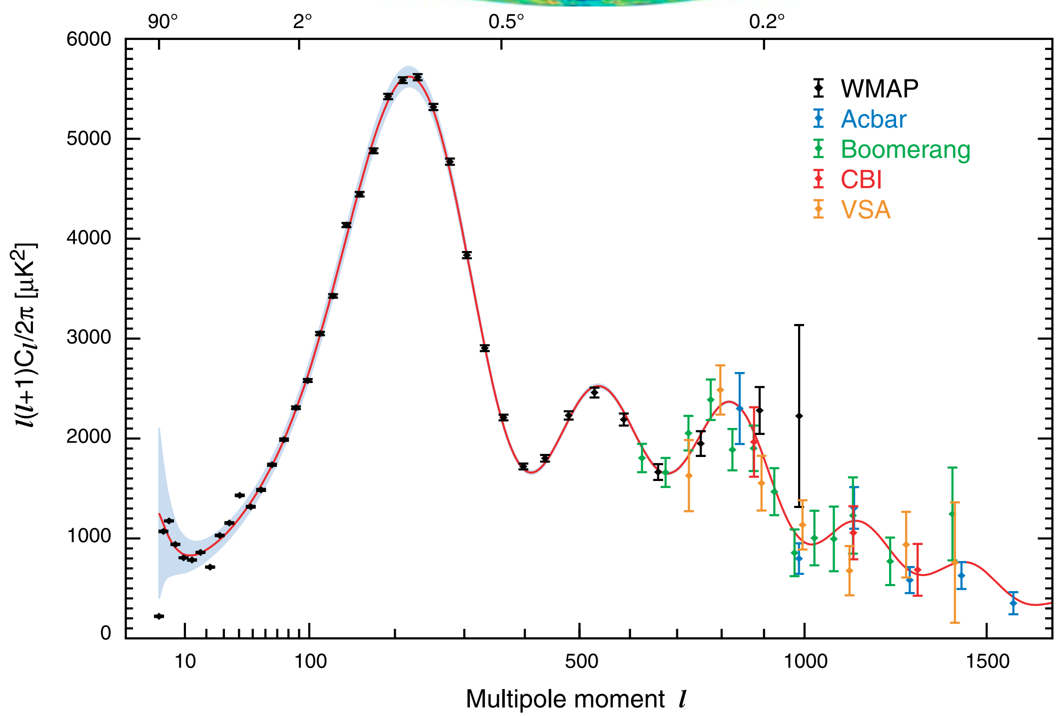
$$T_{\rm ILC} = \sum_i \zeta_i T_i = \sum_i \left(T_{\rm CMB} + S_i T_{\rm foreground}\right)$$

… and minimise the variance $\sigma^2_{\rm ILC}$

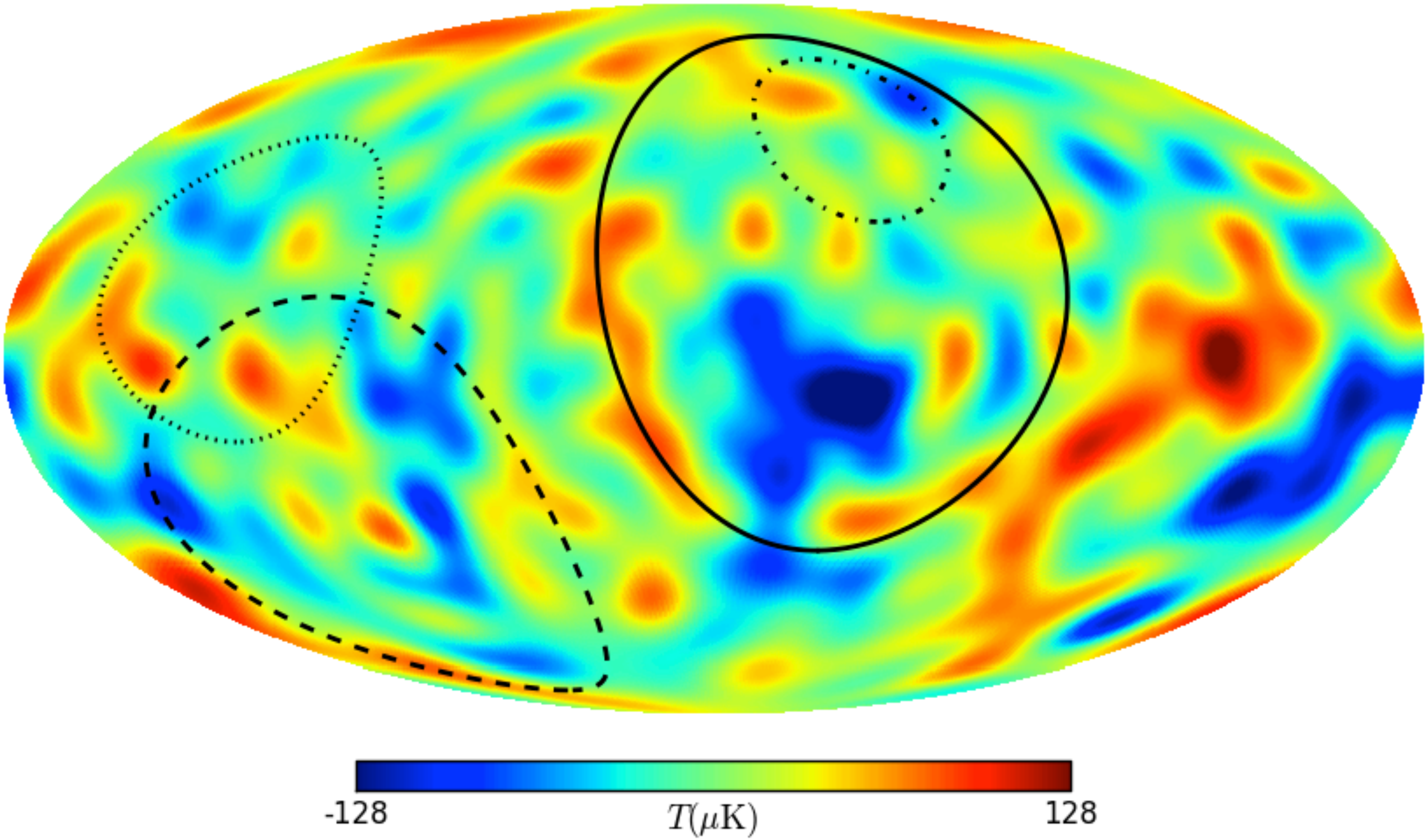
Hinshaw *et al*, ApJS 170:288,2007







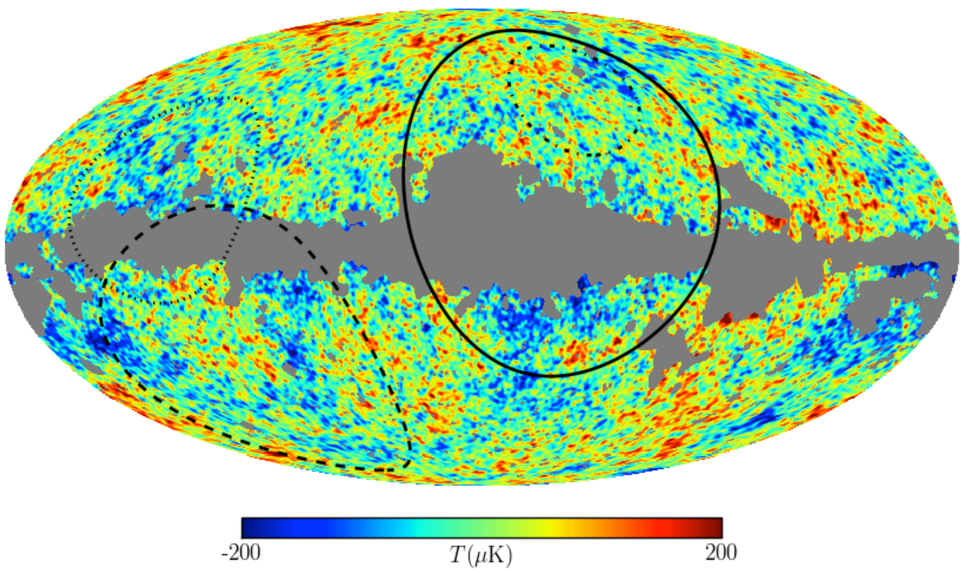
Anomalies in WMAP-9 Internal Linear Combination map ($\ell \leq 20$)



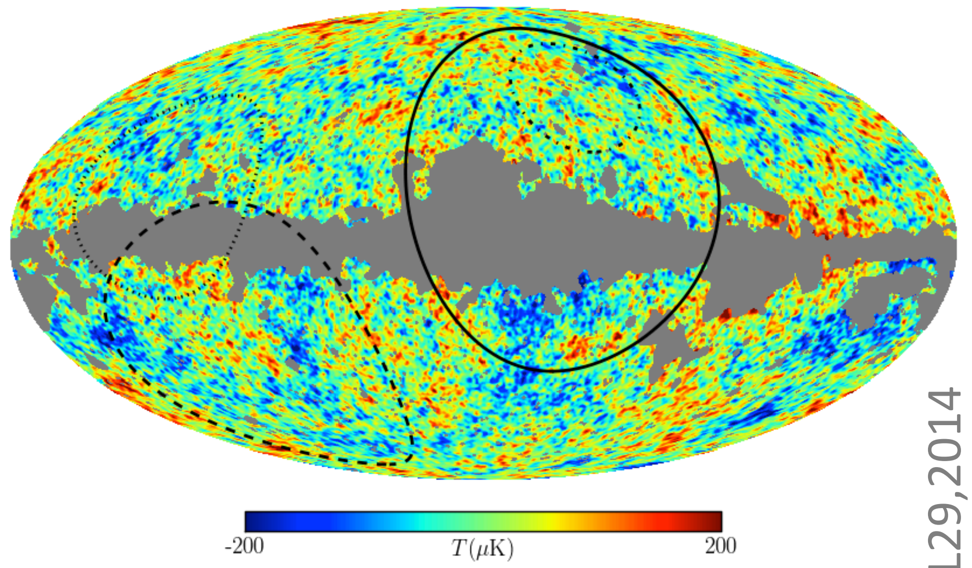
Bennett et *al*, ApJS **208**:20,2013

Are the radio loops visible (even in microwaves)?

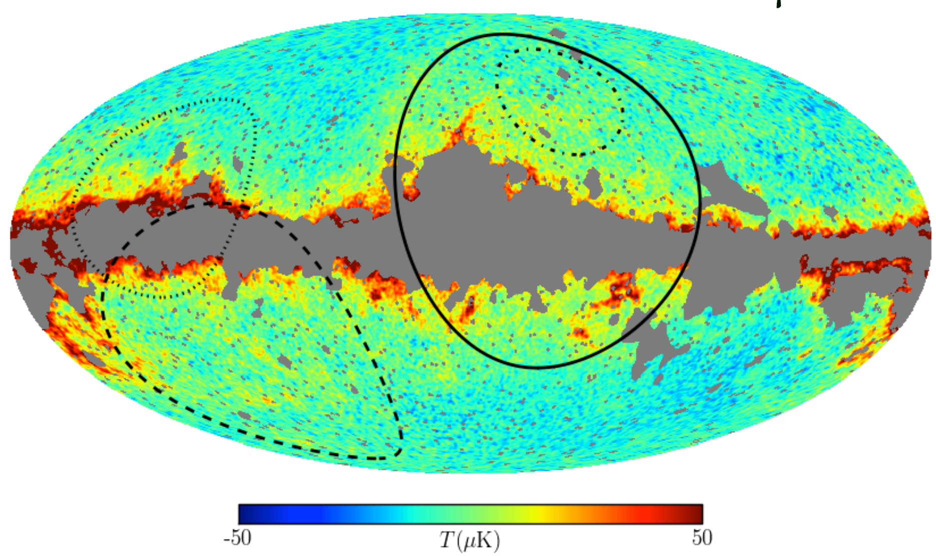
ILC coefficients from Loop I region



ILC coefficients from rest of sky



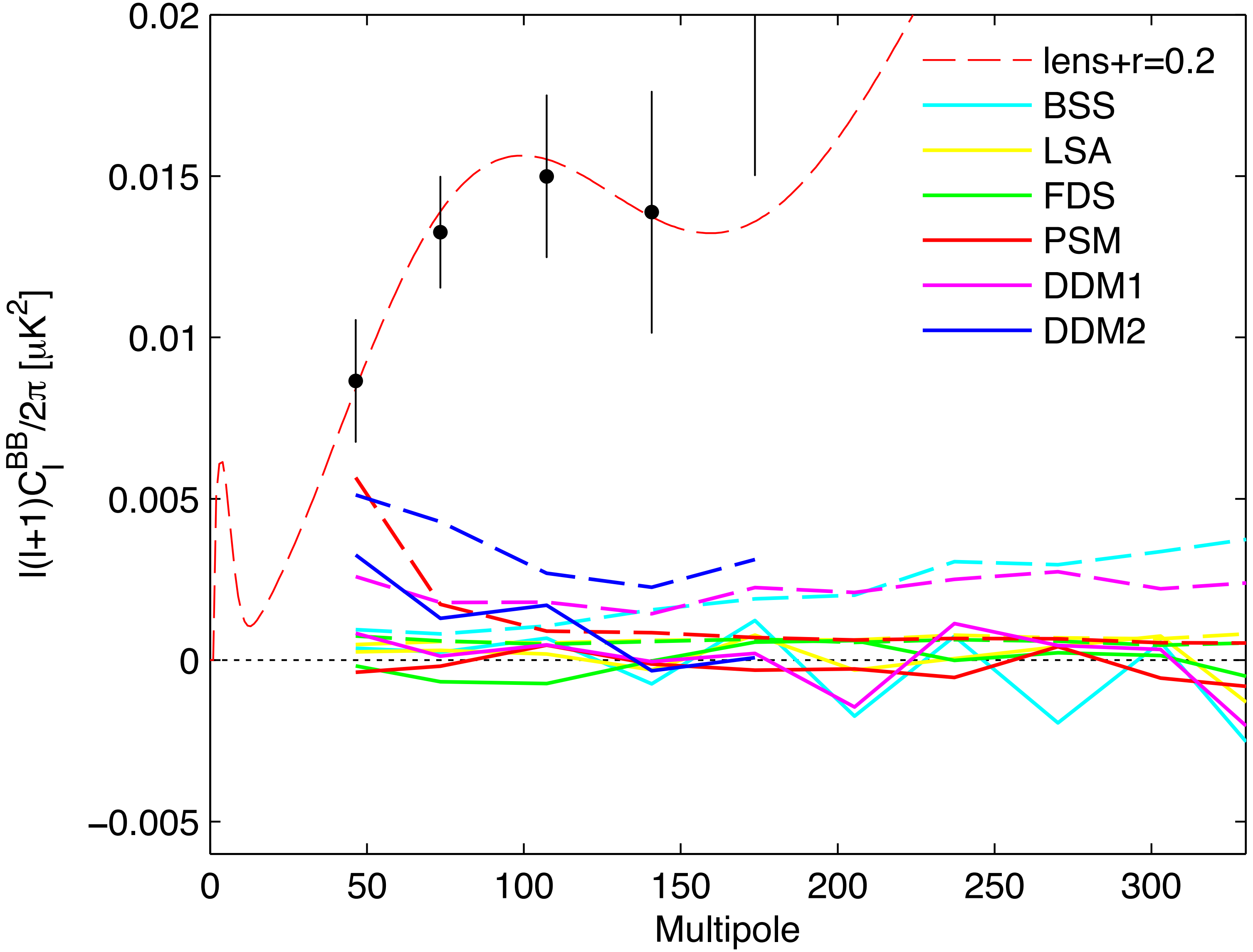
Difference $ILC_{rest} - ILC_{Loop\ I}$



Liu, Mertsch & Sarkar, ApJL 789:L29,2014

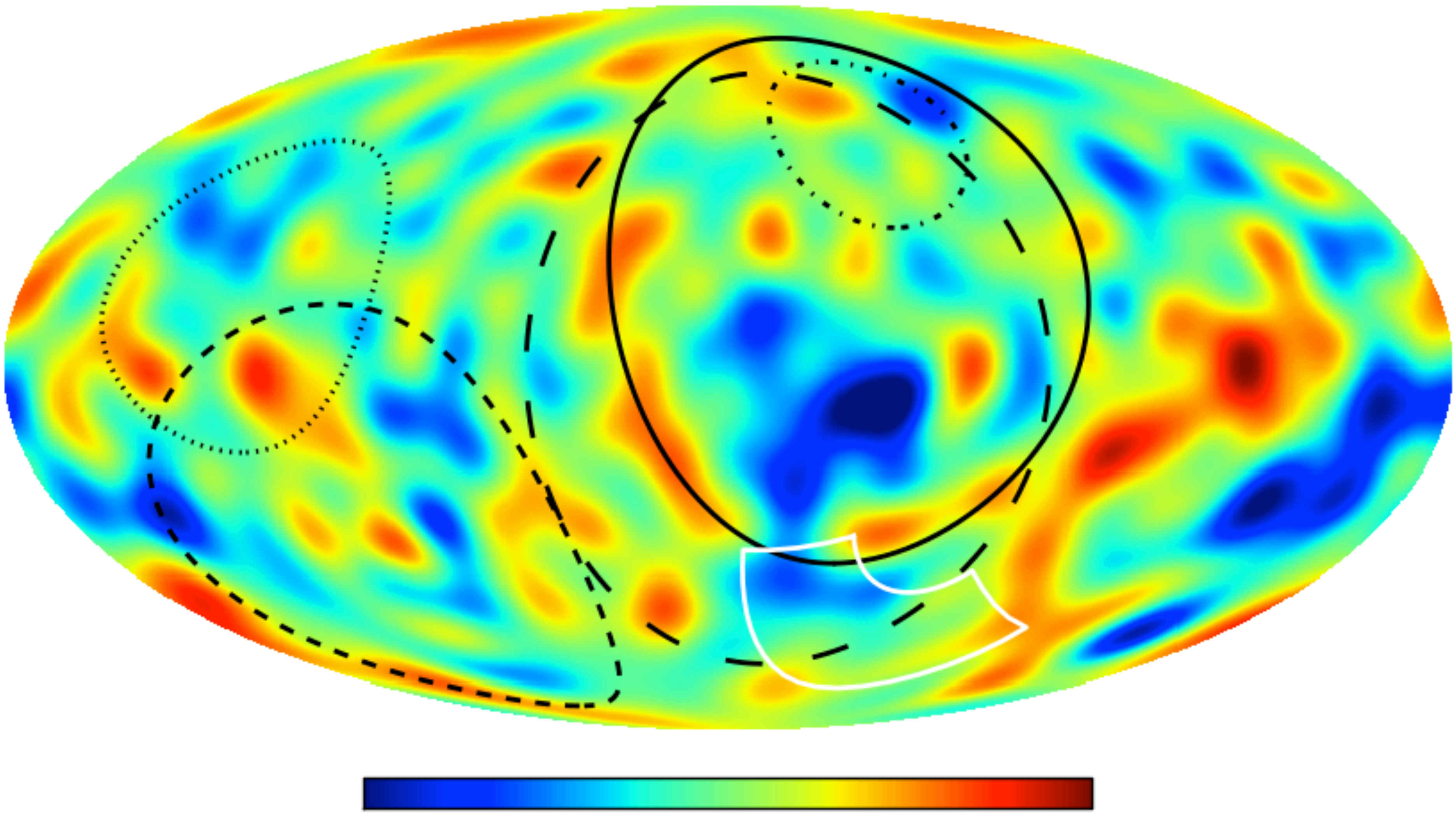
This demonstrates the presence of the radio loops in the ILC map which has supposedly been cleaned of all foreground emissions and shows just the CMB!

BICEP2 signal is said not to correlate with 'known foregrounds'



However the new foreground we have identified is *not* included in any of the models…

Wollebenʼs 'new loop S1' goes through the BICEP2 region!



Of which they say: "*... such ultra clean regions are very special – at least an order of magnitude cleaner than the average b >50⁰ level* [PRL 112:241101,2014]

Conclusions

BICEP2 has detected a ~0.3 μK B-mode signal in a patch of sky believed to be free of foreground Galactic emissions … this is claimed *not* to correlate with (extrapolated) 'known foregrounds' so is evidence for gravitational waves from GUT-scale inflation

However this sky patch is crossed by a 'radio loop' – remnant of a nearby ancient supernova – which also contains dust … these have a spectrum that *evades* standard foreground cleaning methods so they have lurked undetected in maps of the CMB

Forthcoming maps of *polarized* dust emission (e.g. *Planck*) will show if this can indeed account for the B-mode signal observed by BICEP2

Concerning dark matter, the experimental situation is reminiscent of searches in the '80s for temperature fluctuations in the CMB … there were clear theoretical predictions but only upper limits on detection (causing near crisis for theory)

Finally breakthrough in 1992 that transformed cosmology!

Theoretical expectations for dark matter are not as clear but there are *complementary* experimental approaches and impressive recent progress

There are bound to be false alarms but it is a reasonable expectation that the nature of dark matter will soon be determined experimentally