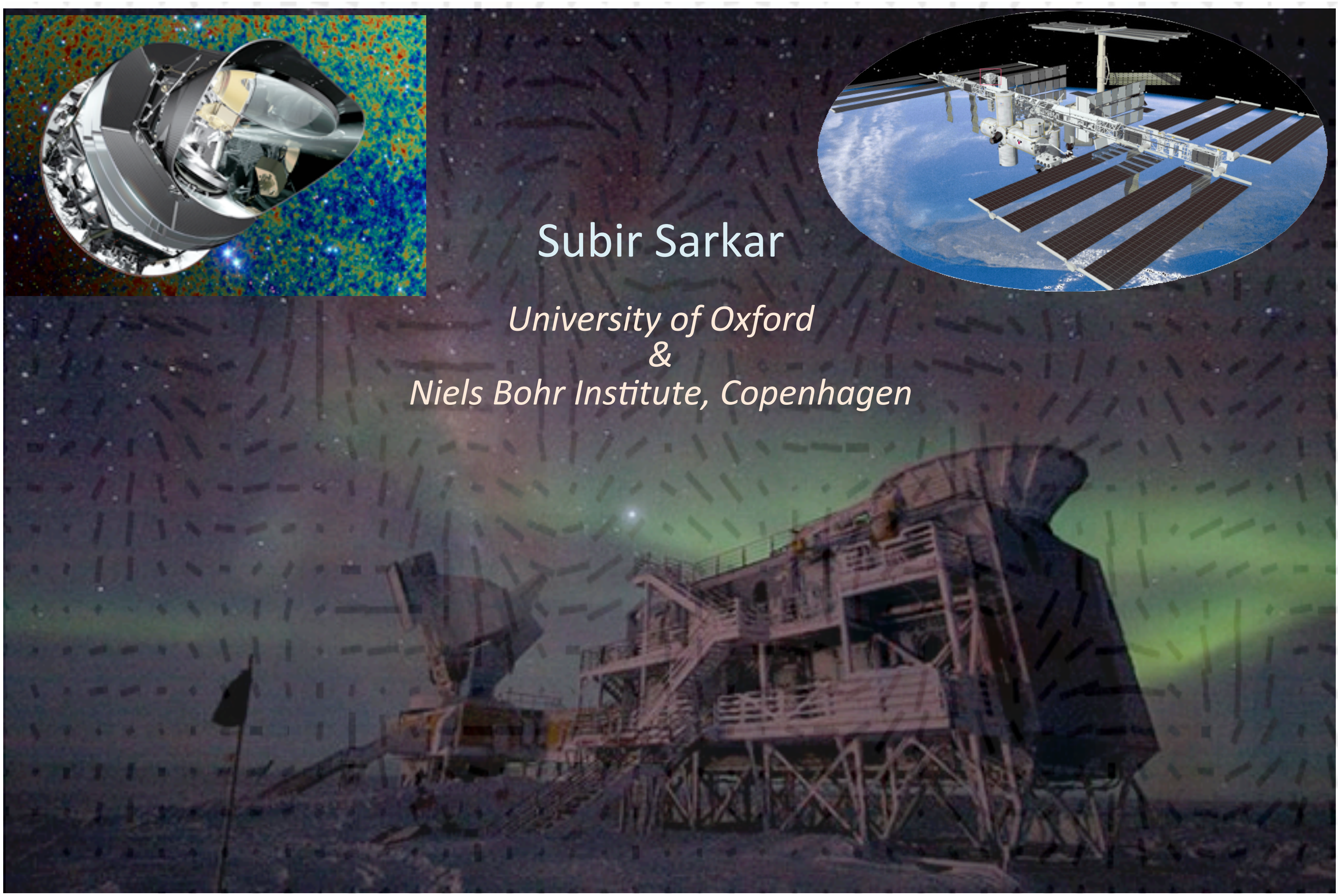
News from the universe

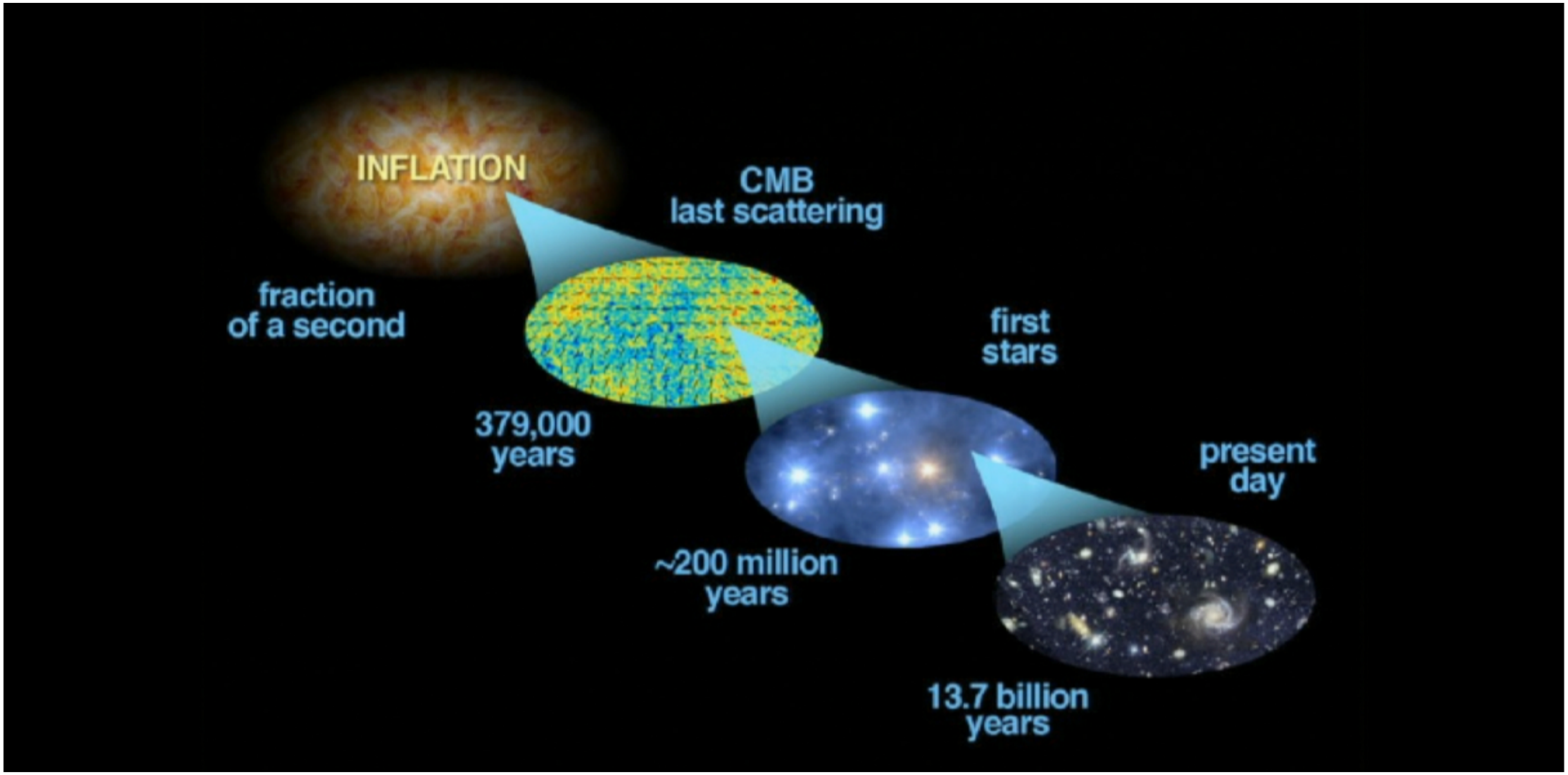


Subir Sarkar

University of Oxford
&
Niels Bohr Institute, Copenhagen

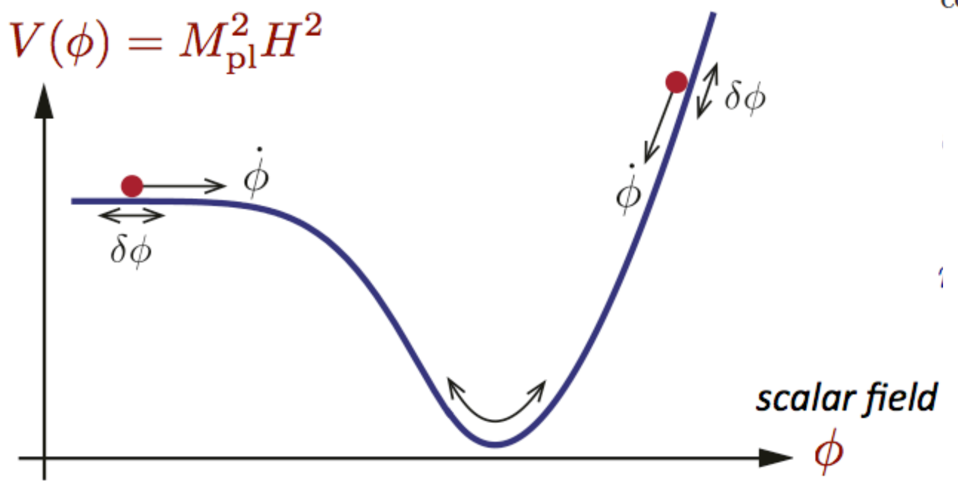
DISCRETE 2014, King's College, London, 2-6 December 2014

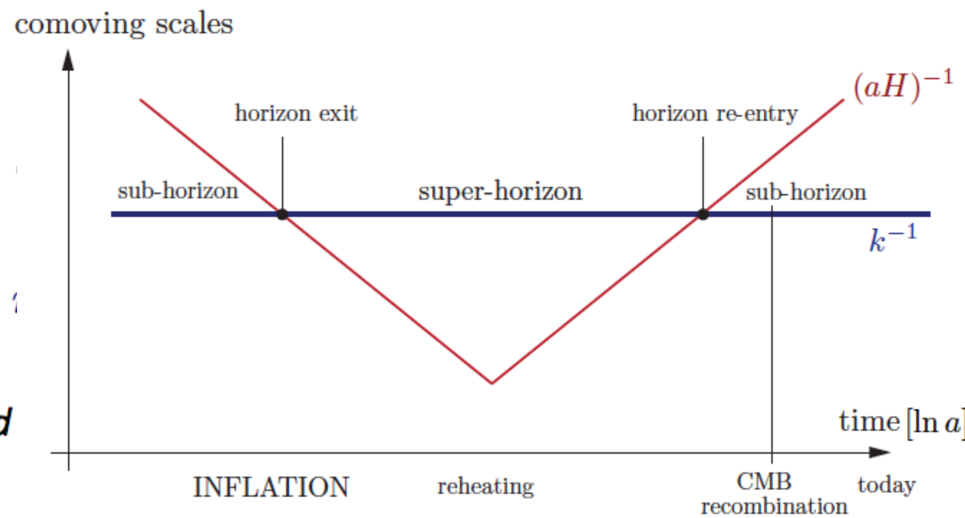
Why is the BICEP2 claim so very exciting …



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!

Inflation: If at some early time the universe undergoes a period of exponentially fast expansion due to the energy density being briefly dominated by the **vacuum energy** of a scalar field while it evolves towards the minimum of its potential, it would solve the horizon/flatness problems of the Standard Cosmology and also generate the ~scale-invariant **density fluctuations** necessary for the formation of large-scale structure



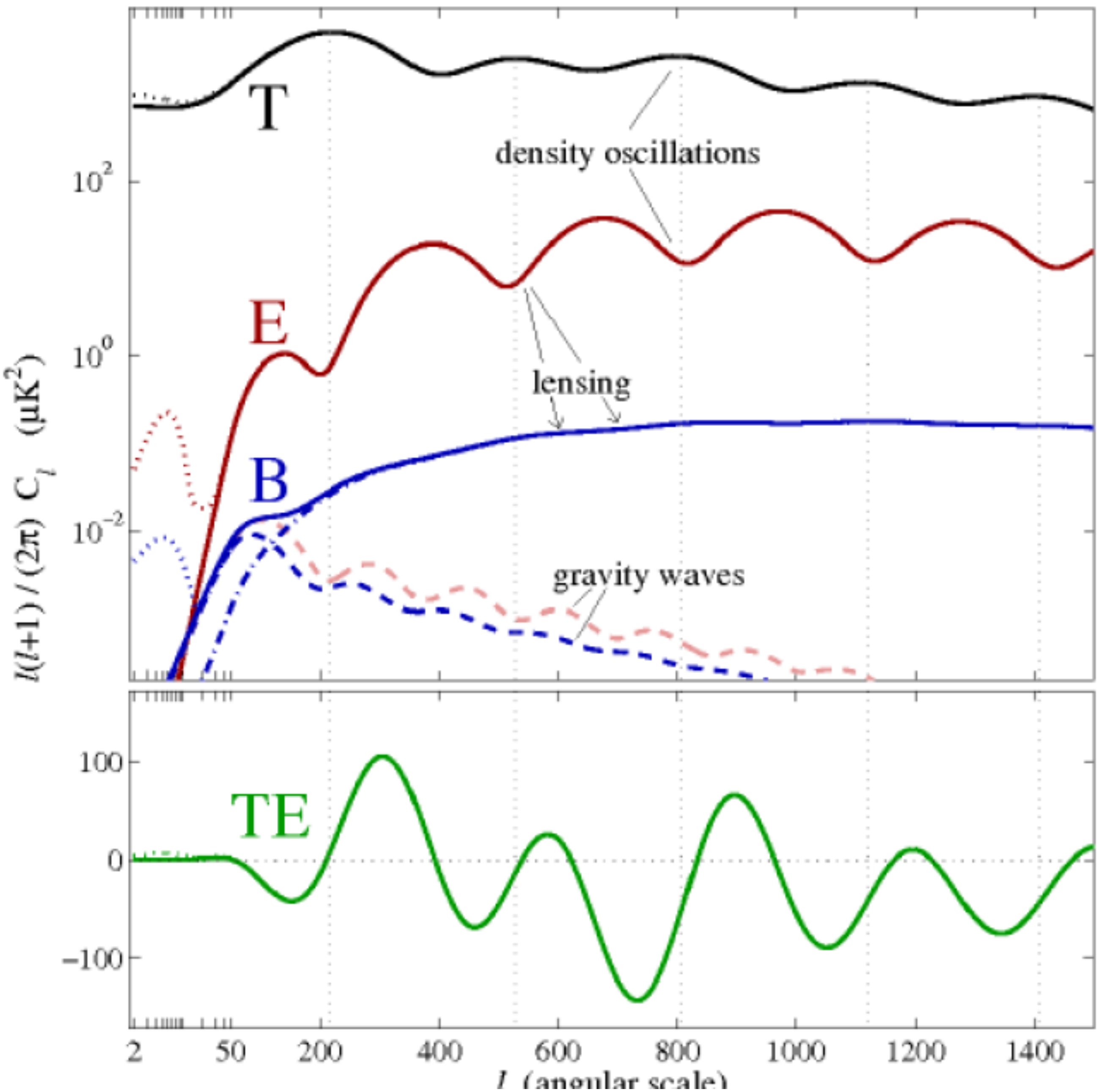


The spectrum of **scalar density perturbations** is $\Delta_s^2 \equiv \left(\frac{H^2}{2\pi\dot{\phi}}\right)^2$, and **gravitational waves** (tensor perturbations) are also generated with spectrum: $\Delta_t^2 \equiv \frac{2}{\pi^2}\frac{H^2}{M_{\rm Pl}^2}$

The ratio of tensor to scalar perturbations is: $r \equiv \frac{\Delta_t^2}{\Delta_s^2} = \frac{8}{M_{\rm pl}^2}\left(\frac{\dot{\phi}}{H}\right)^2$

Having reached its minimum the scalar field oscillates, transferring its energy into radiation, thus 'reheating' the universe and starting off the hot 'Big Bang' Cosmology

Inflationary predictions for (adiabatic) CMB fluctuations



✔ COBE '92

✔ DASI '02

✔ PolarBear '12

? BICEP2 '14

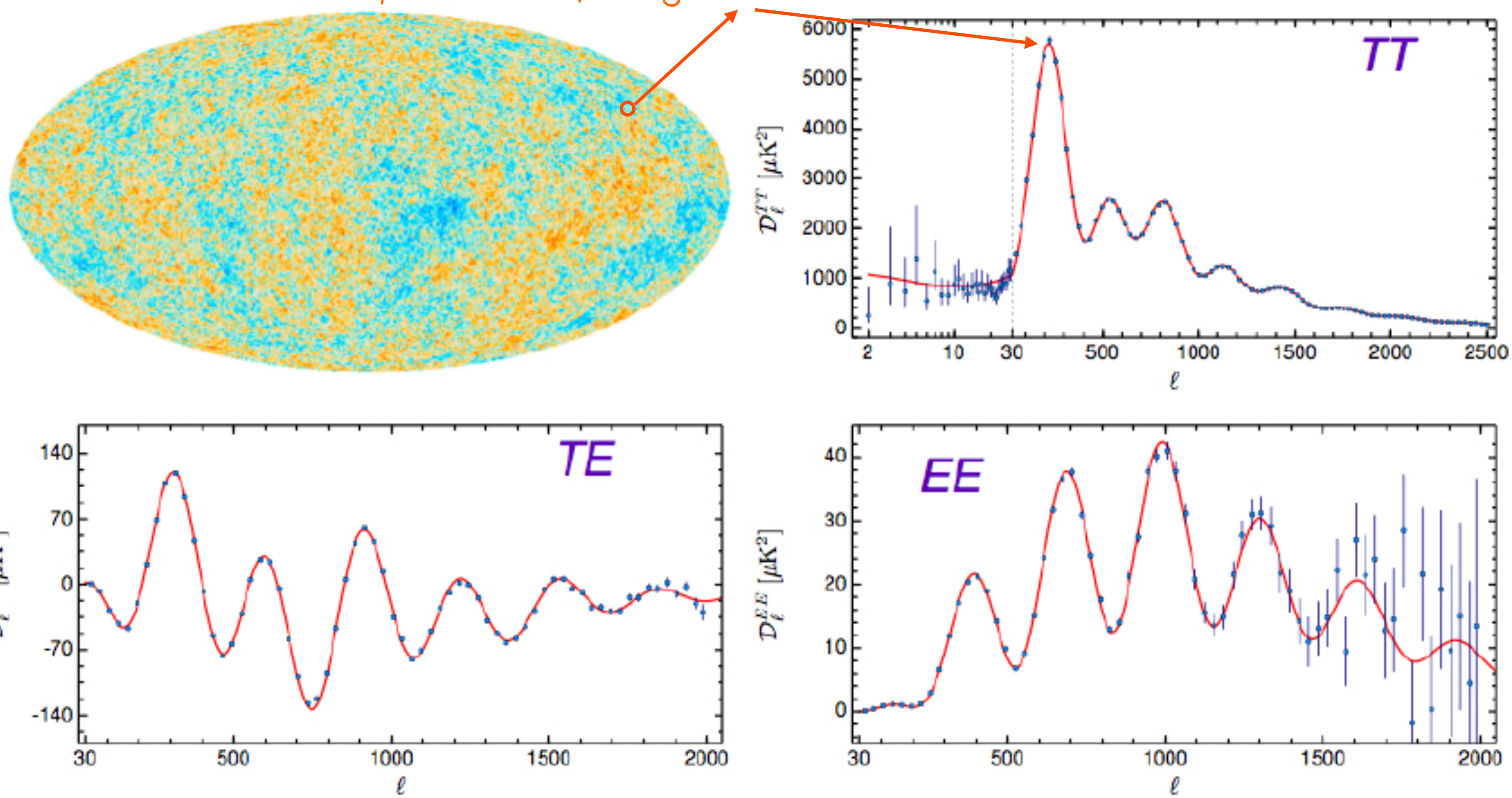
✔ WMAP '02

(Courtesey: Phil Lubin)

Planck data release II – 1st December 2014

$$\Delta T(\mathbf{n}) = \sum a_{lm} Y_{lm}(\mathbf{n}) \qquad C_l \equiv \frac{1}{2l+1} \sum |a_{lm}|^2$$

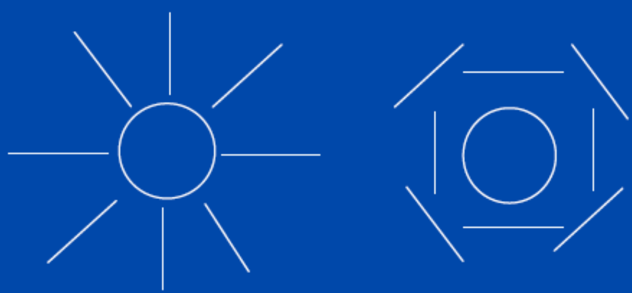
spatial scale of today's universe at (re)combination

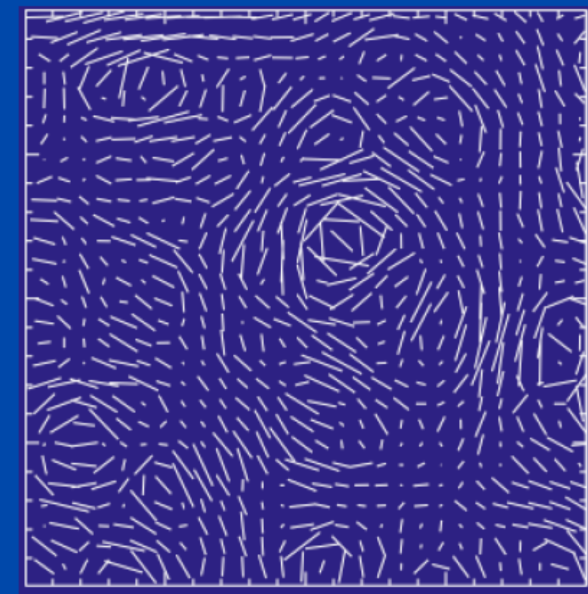


Coherent oscillations in a photon+baryon plasma excited by primordial scalar density perturbations on *super*-horizon length scales

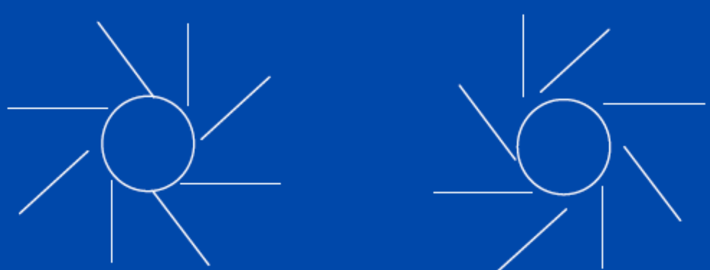
E and B modes polarization (similar to gradient/curl decomposition of vector field)

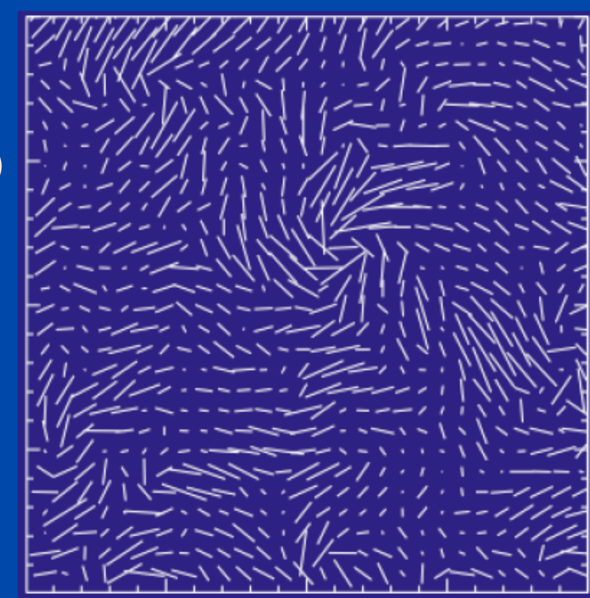
E polarization
from scalar, vector and tensor modes





B polarization only from (vector)
tensor modes (*and* gravitational lensing of E polarization)





Kamionkowski, Kosowsky, Stebbings 1997, Zaldarriga & Seljak 1997

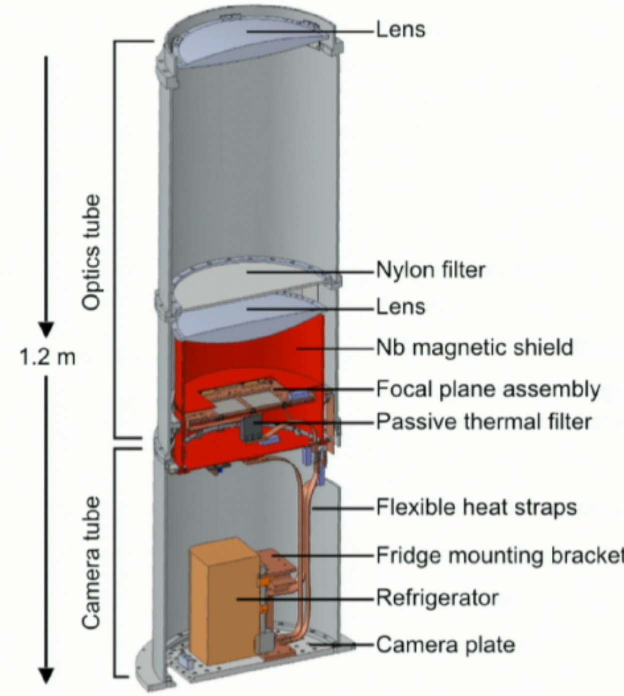
The BICEP2 Telescope

Telescope as compact as possible while still having the angular resolution to observe degree-scale features.

On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation.

Liquid helium cools the optical elements to 4.2 K.

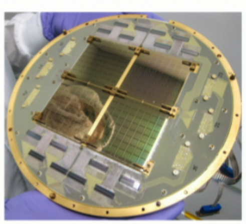
A 3-stage helium sorption refrigerator further cools the detectors to 0.27 K.

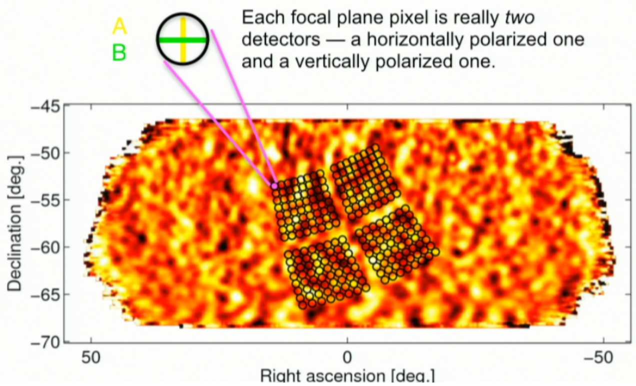


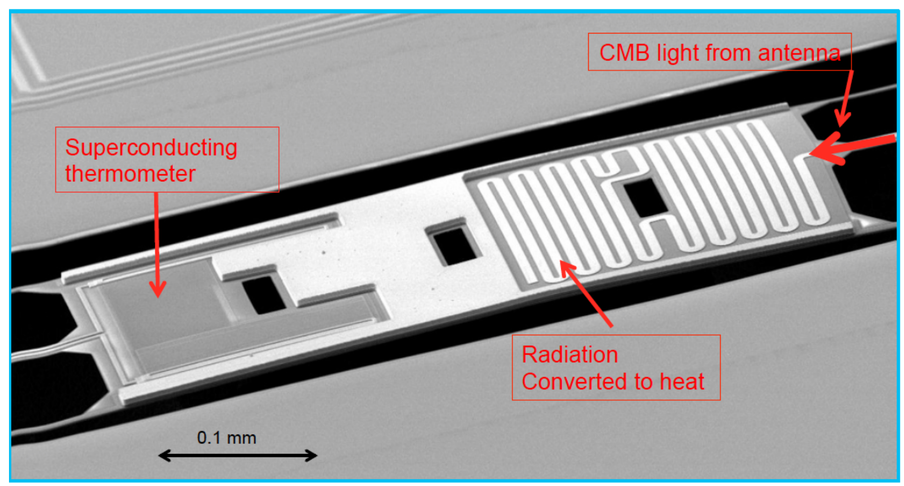
Scan the telescope back and forth on the sky.

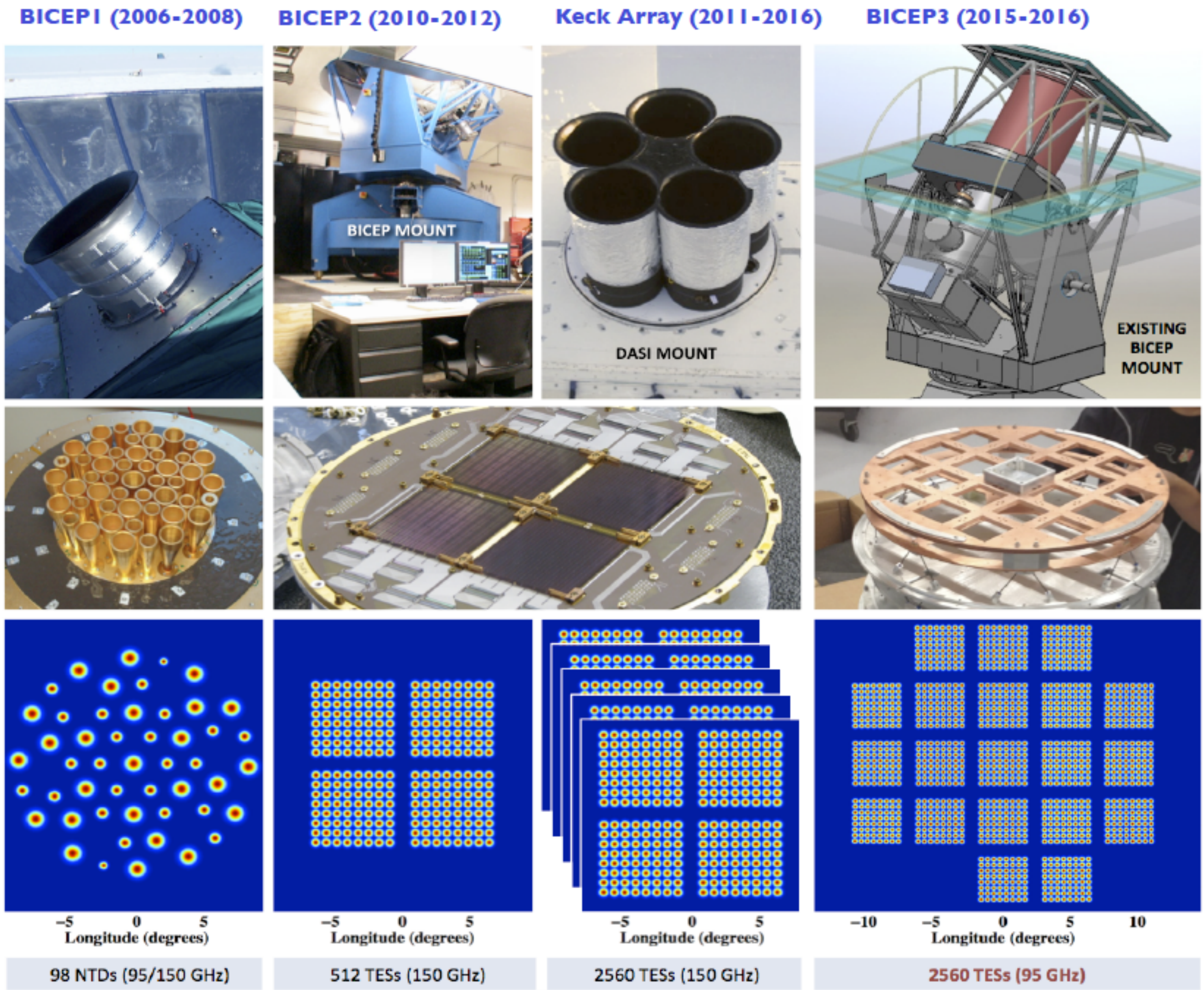
Measure CMB T by summing the signal from orthogonally polarized detector pairs.

Measure CMB polarization by differencing the signal.









BICEP1 (2006-2008)
BICEP2 (2010-2012)
Keck Array (2011-2016)
BICEP3 (2015-2016)
BICEP MOUNT
DASI MOUNT
EXISTING BICEP MOUNT
−5 0 5
Longitude (degrees)
−10 −5 0 5 10
98 NTDs (95/150 GHz)
512 TESs (150 GHz)
2560 TESs (150 GHz)
2560 TESs (95 GHz)

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

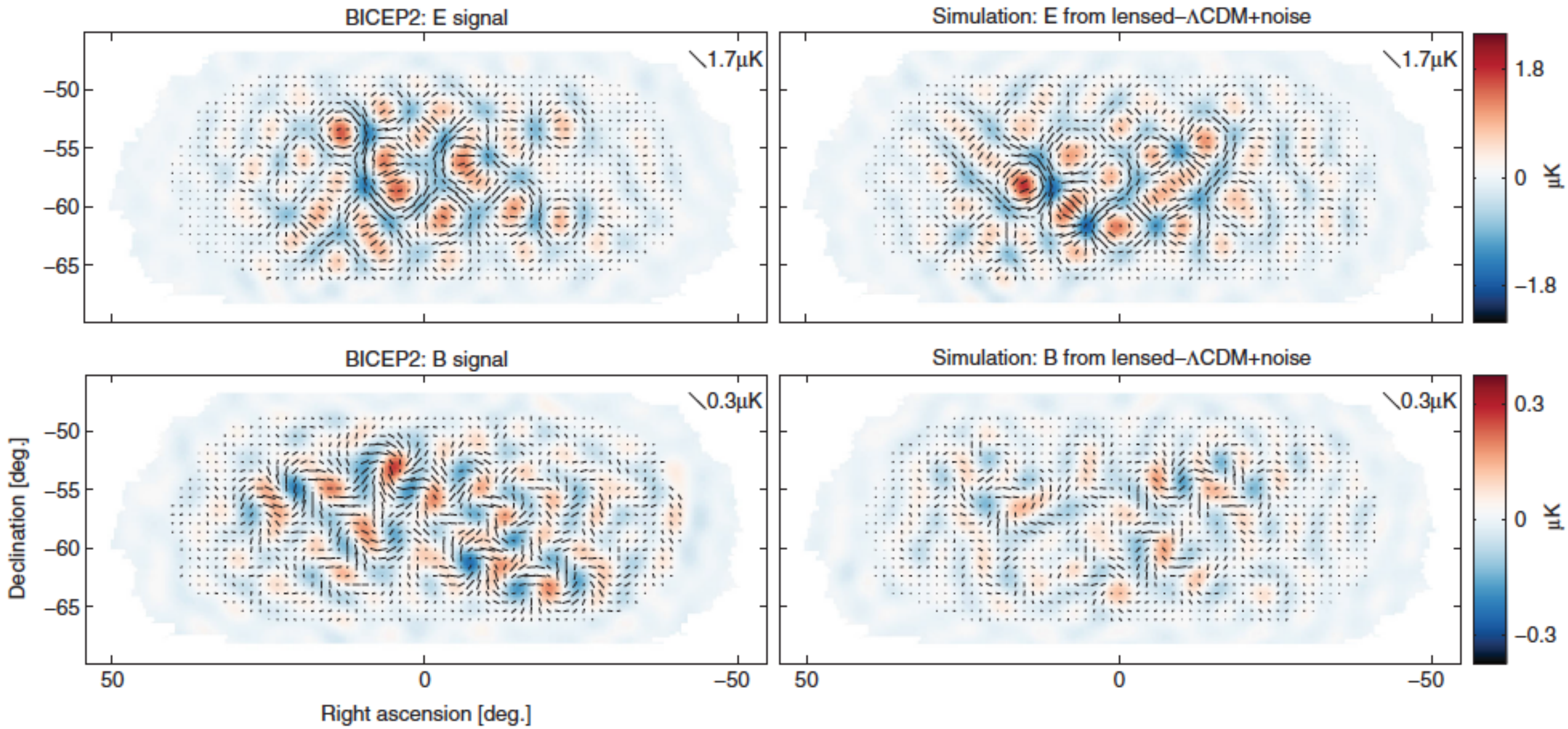
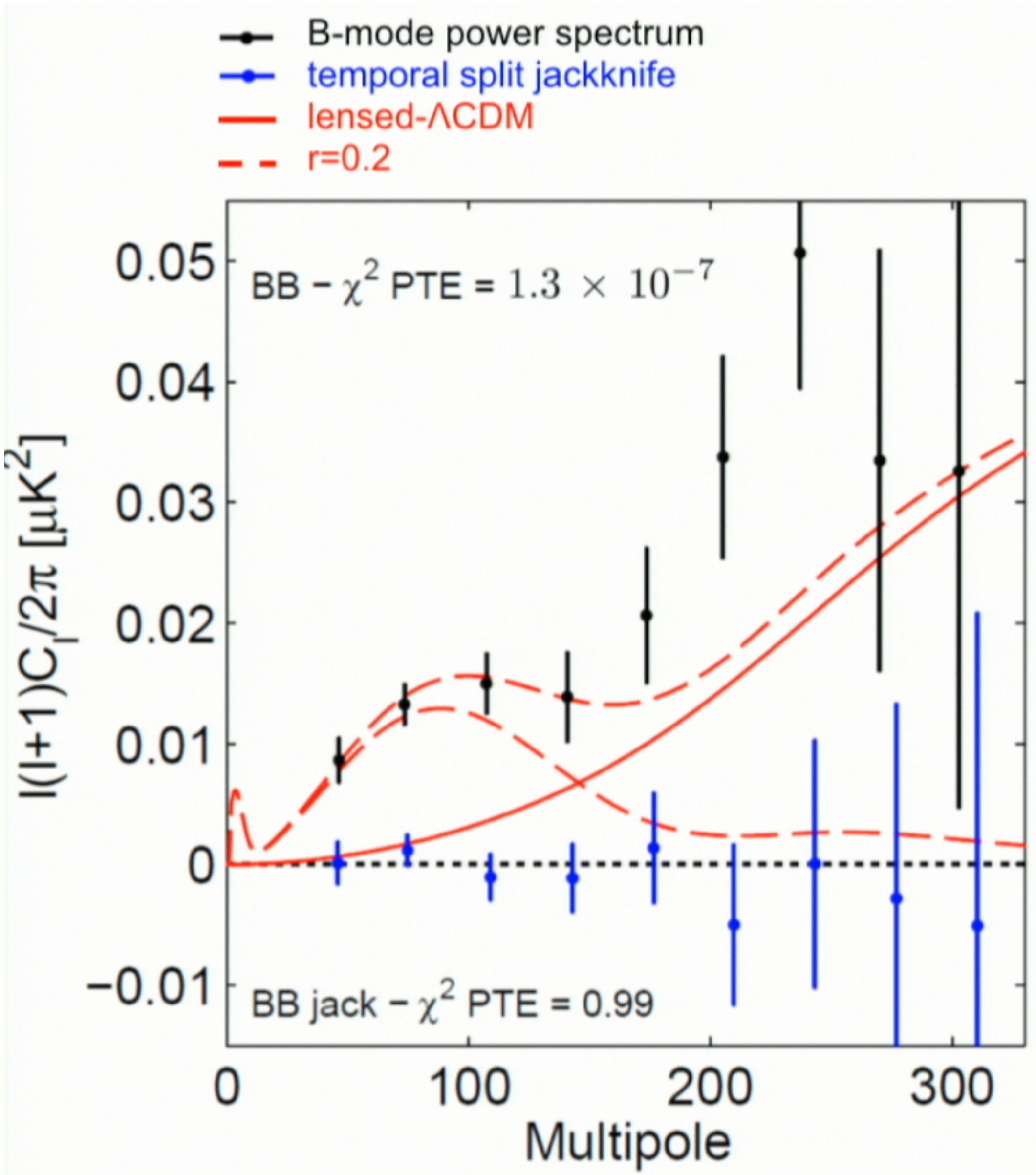


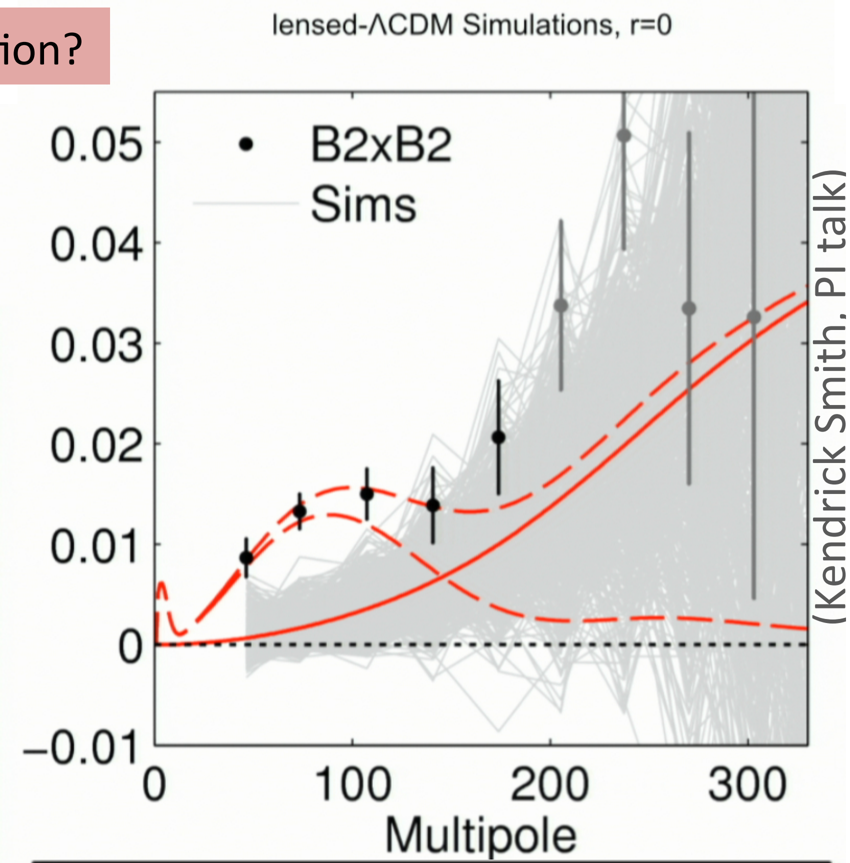
FIG. 3 (color). Left: BICEP2 apodized E-mode and B-mode maps filtered to $50 < \ell < 120$. Right: The equivalent maps for the first of the lensed-ΛCDM + noise simulations. The color scale displays the E-mode scalar and B-mode pseudoscalar patterns while the lines display the equivalent magnitude and orientation of linear polarization. Note that excess B mode is detected over lensing+noise with high signal-to-noise ratio in the map ($s/n > 2$ per map mode at $\ell \approx 70$). (Also note that the E-mode and B-mode maps use different color and length scales.)

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

What is the actual significance of the B-mode detection?



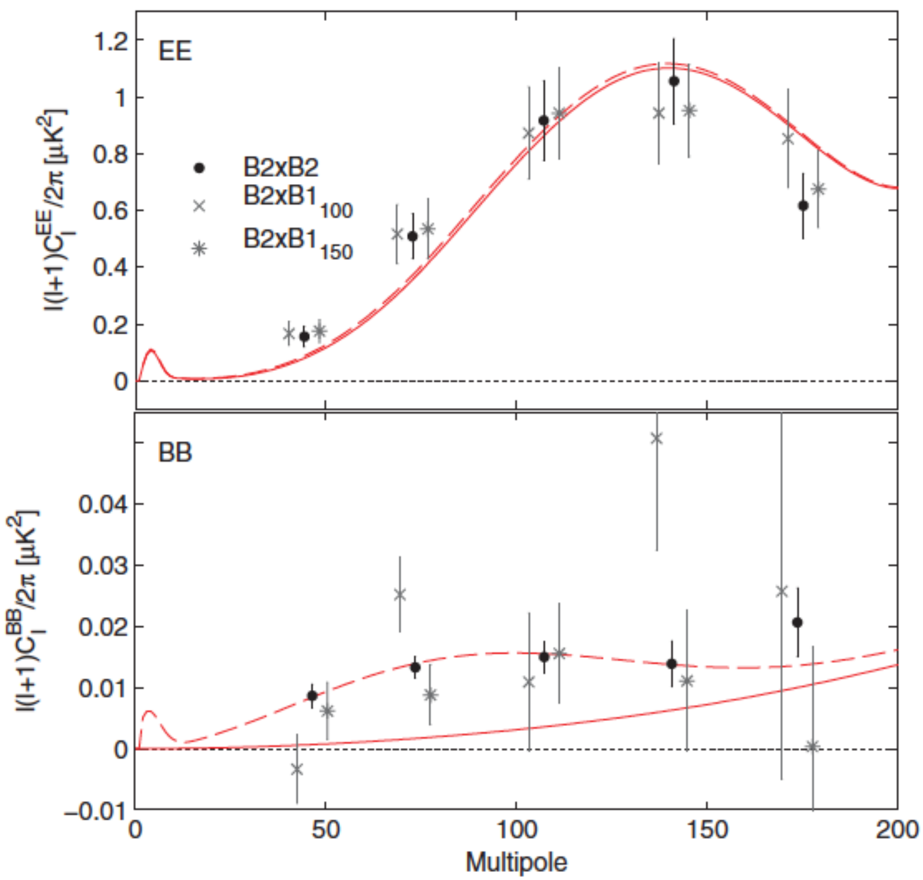
Ade *et al*, PRL 112:241101,2014

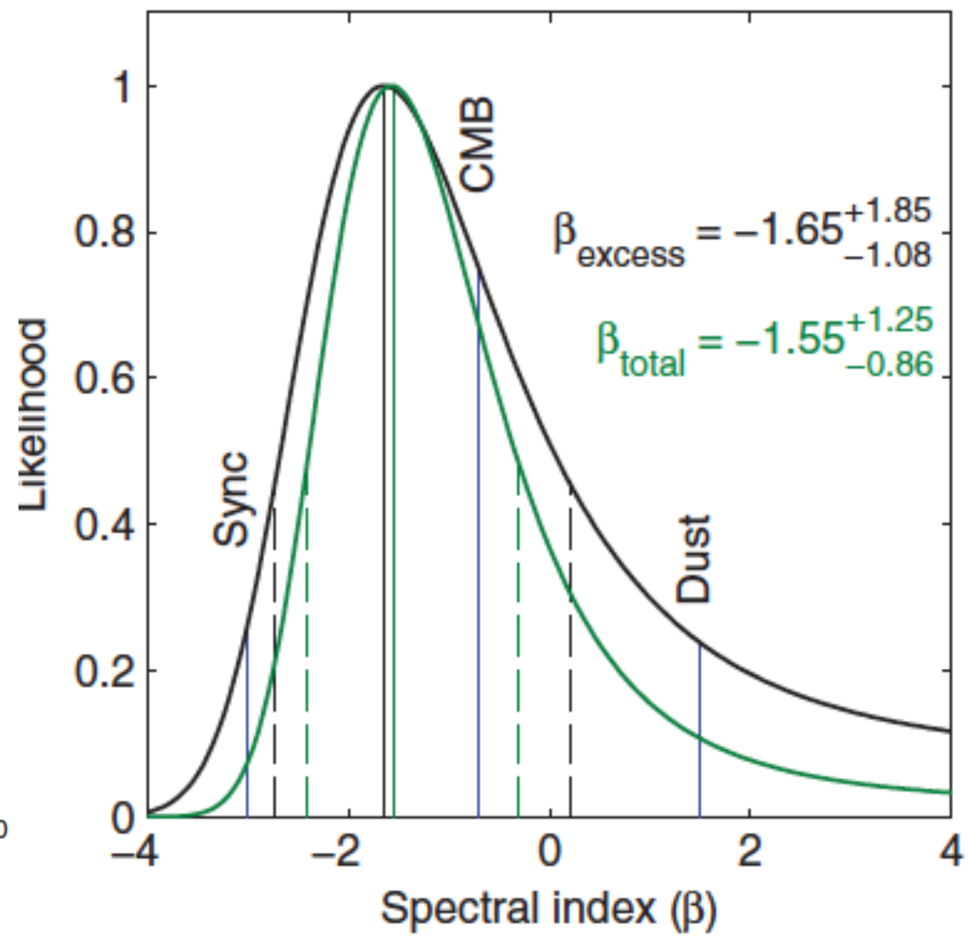


χ^2 PTE	1.3×10^{-7}
significance	$5.2\,\sigma$

This is just the chance probability of the observed B-mode signal to arise as a fluctuation of the lensed E-mode signal …
it is *not* a '>5σ detection' of a CMB signal

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

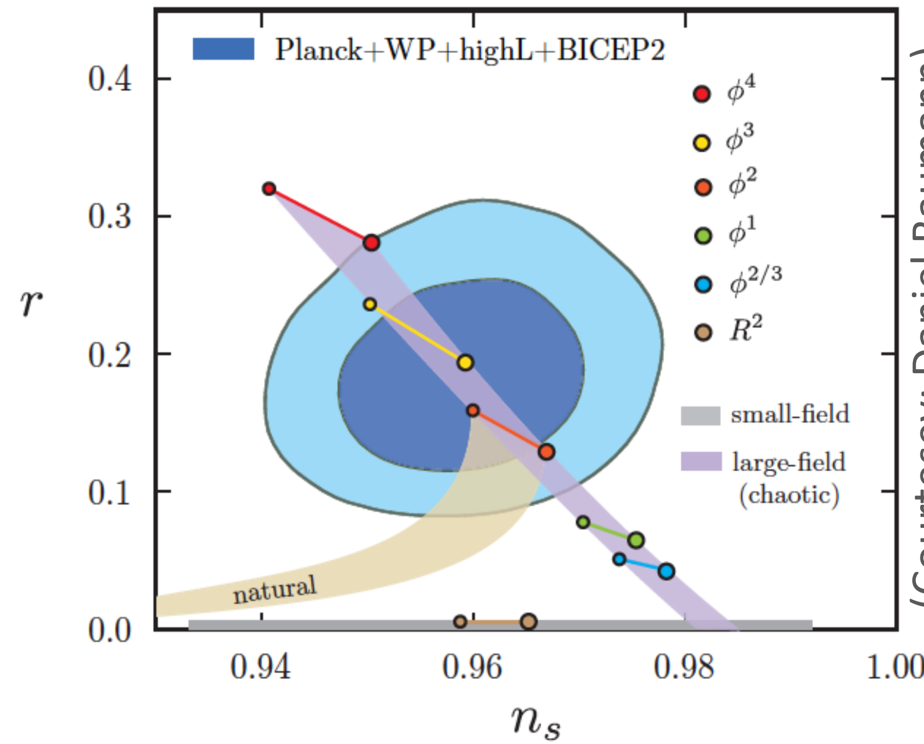




… so the significance with which the observed signal is likely to be **CMB** ($\beta \sim -0.7$) rather than either **synchrotron** ($\beta \sim -3$) or **dust** ($\beta \sim 1.5$) emission is *only* 1.6 or 1.7σ

If the BICEP2 interpretation were correct *then* …

- The energy scale of inflation is: $V^{1/4} \approx 2.1\text{x}10^{16}$ GeV $(r/0.2)^{1/4} \sim M_{GUT}$
- The field excursion was super-Planckian: $\Delta\phi \approx 4\ M_{Pl}\ (r/0.2)^{1/2}$



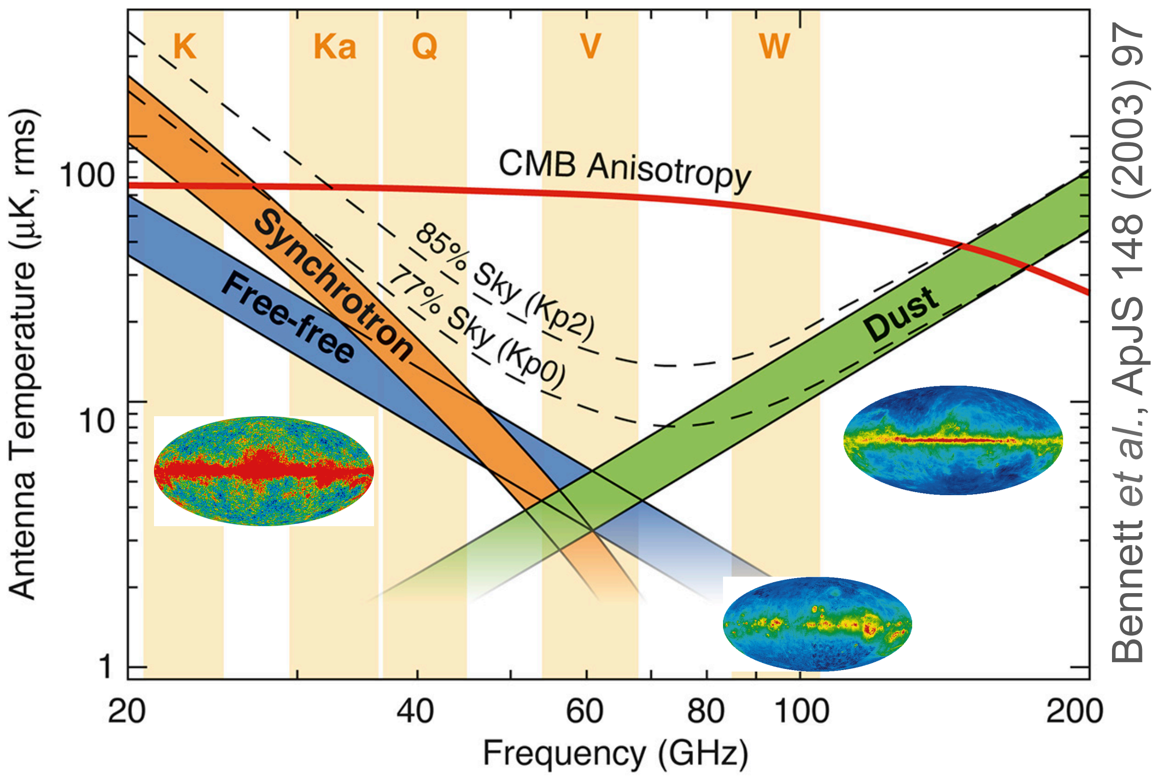
(Courtesey: Daniel Baumann)

- **The vacuum energy was cancelled to 1 part in 10^{112} after inflation!**

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

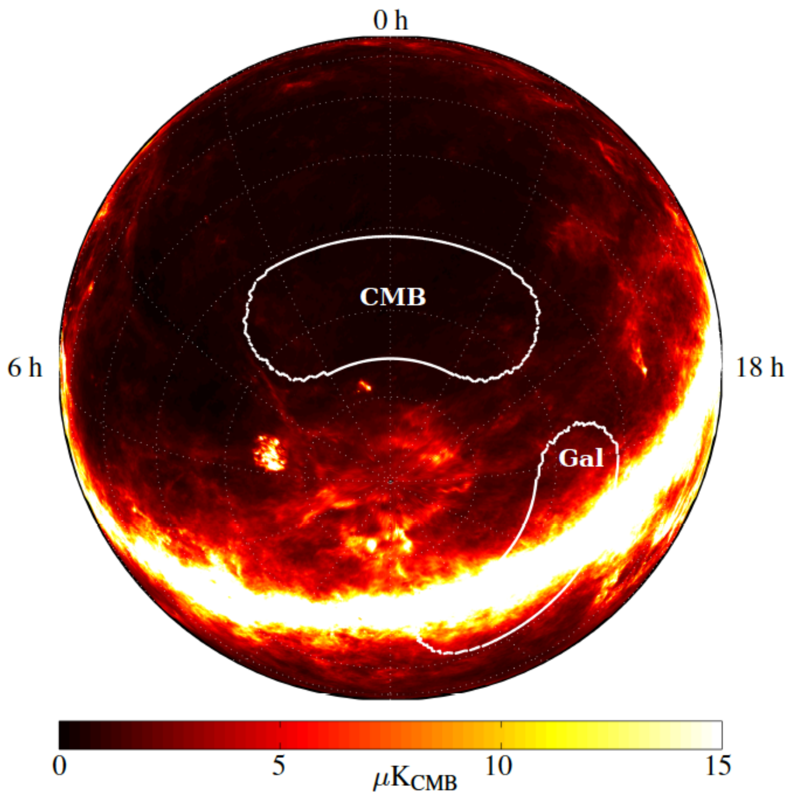
At CMB frequencies the most important sources of foregrounds are:

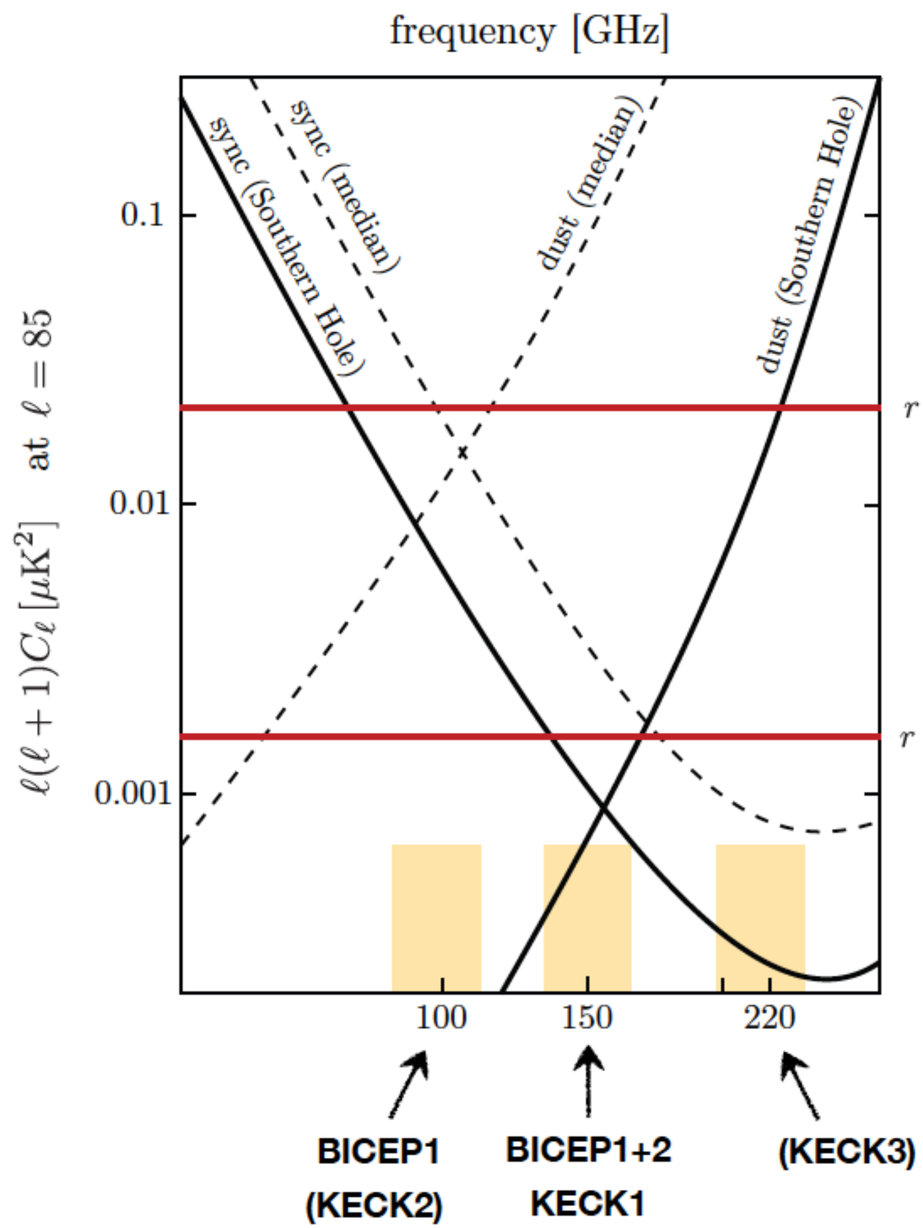
- Synchrotron radiation by cosmic ray electrons in the (ordered + turbulent) Galactic magnetic field (strongly polarised)
- Free-free emission from ionised hydrogen (unpolarised)
- Thermal dust emission (weakly polarised) + 'spinning dust' (unpolarised) + ?



To subtract out the foregrounds, observe at multiple frequencies and isolate the CMB by its blackbody spectrum … and/or look at high galactic latitude away from Milky Way

BICEP2 observes a small patch of high-latitude sky chosen to minimise these foregrounds … but the levels are estimates *(not observations)*

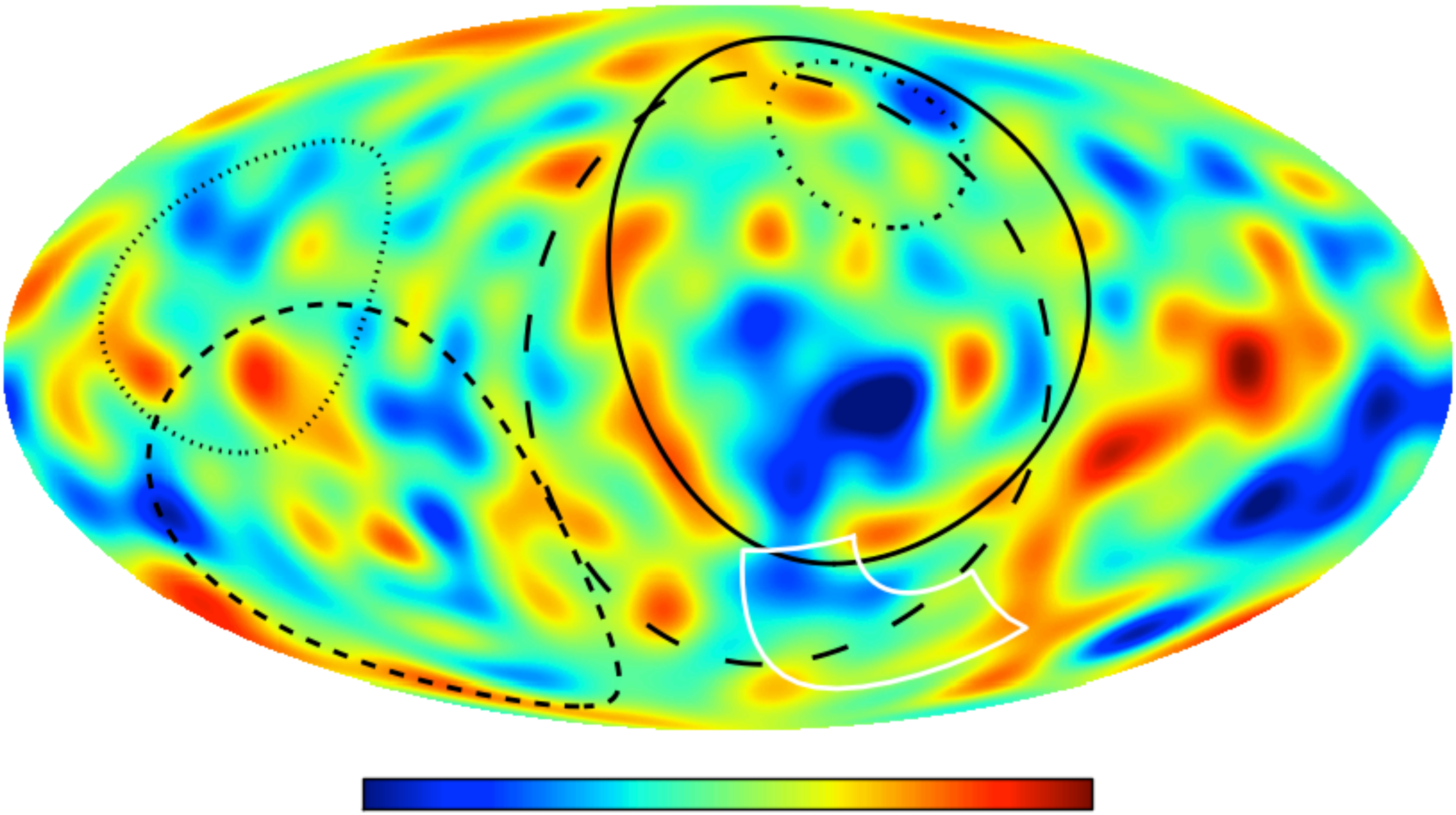




(Kendrick Smith, PI talk)

This particular patch of sky was chosen to be observed because:

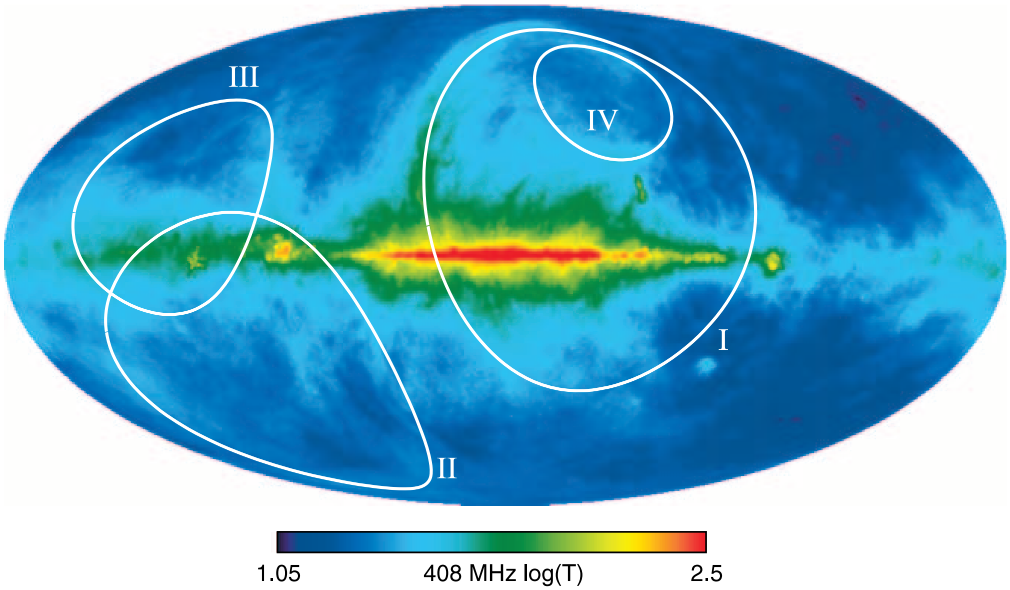
"… such ultra clean regions are very special – at least an order of magnitude cleaner than the average b >50^0 level" Ade *et al*, PRL 112:241101,2014



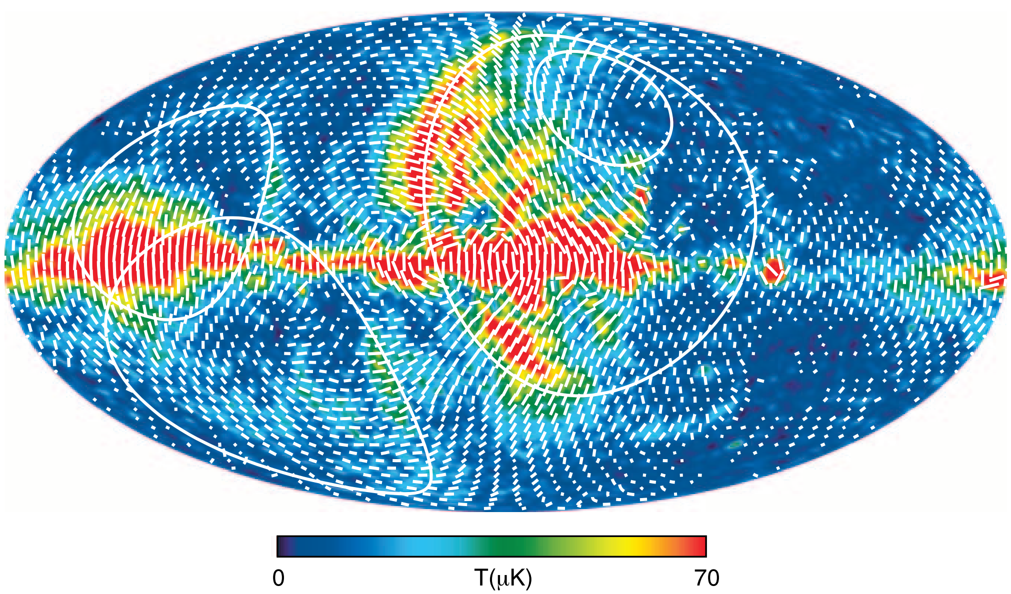
However it is in fact crossed by a galactic 'radio loop'!

What are the 'radio loops'?

Haslam *et al*, A&AS **47**:1,1982



Page *et al*, ApJS **170**:335,2007

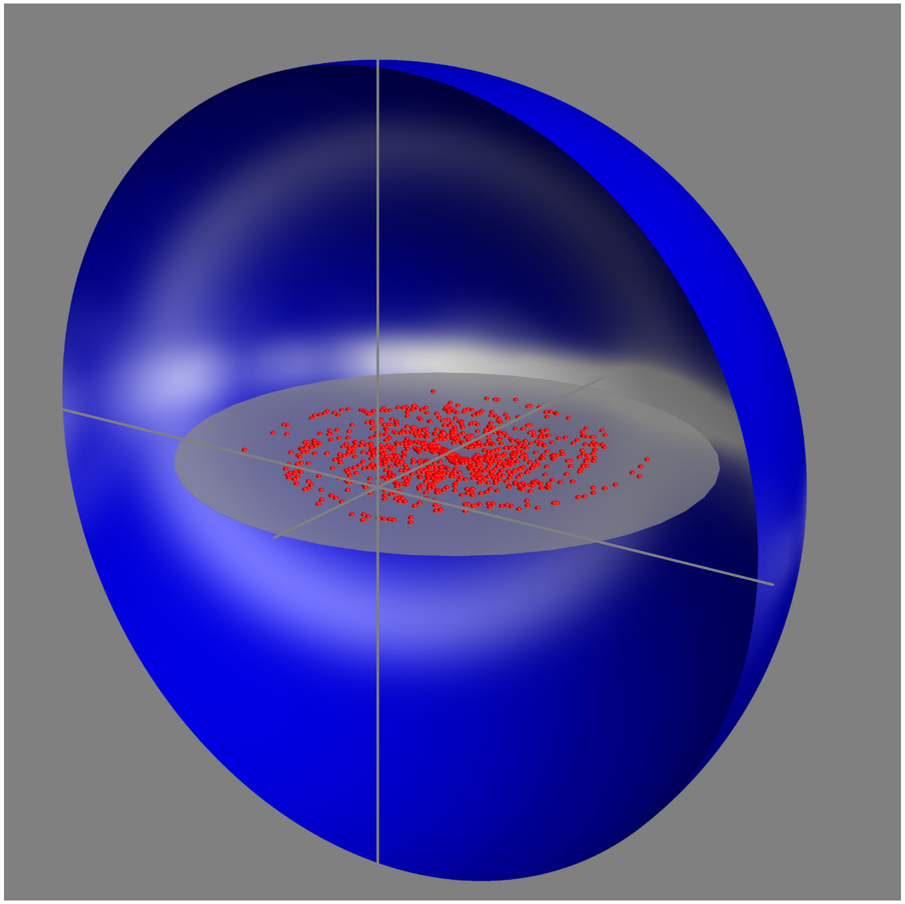


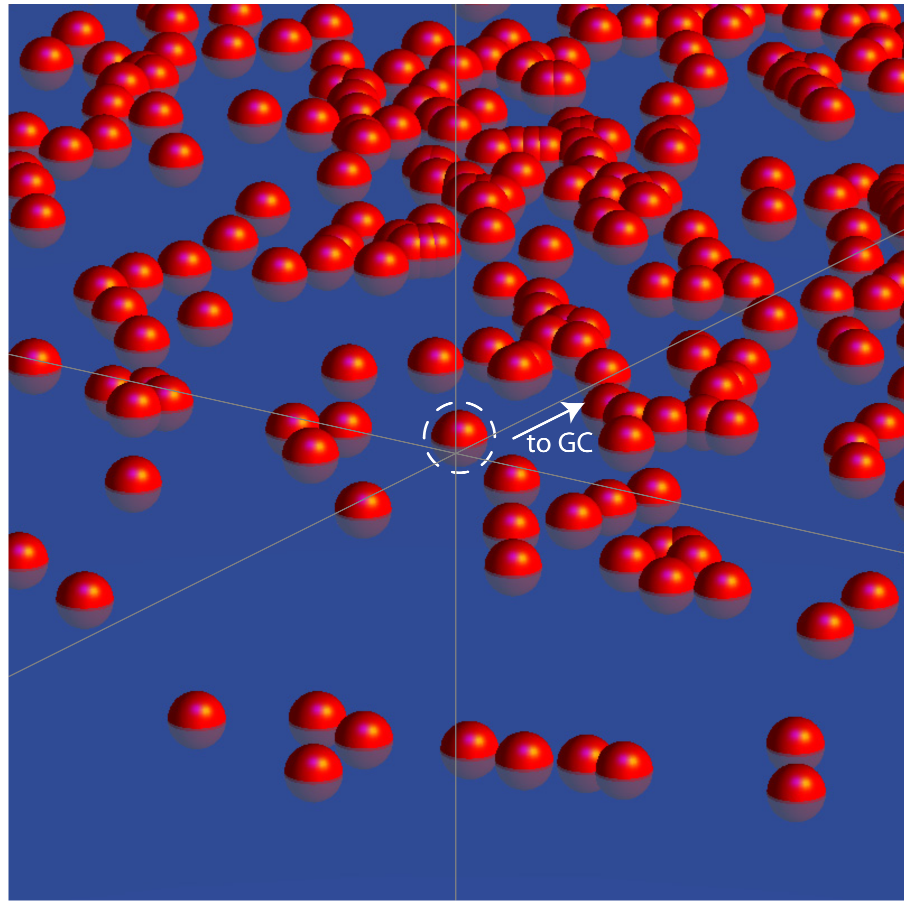
- ✧ Probably the radiative shells of very old nearby supernova remnants
- ✧ Can only see 4-5 of these in the 408 MHz radio sky

  Berkhuijsen *et al*, A&A **14**:252,1971
- ✧ However there must be *several thousand* loops in the Galaxy which cannot be resolved against the 'diffuse' galactic radio background … indeed they probably constitute most of the background

  Sarkar, MNRAS **199**:97,1982

Simulating the galactic distribution of old SNRs





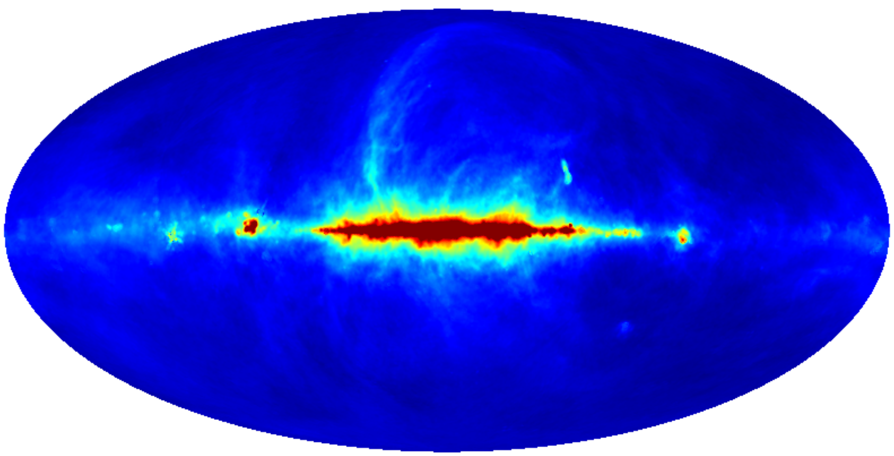
With ~3 SN/century, there must be *several thousand* old SNRs in the radiative phase of evolution … their shells will compress the interstellar magnetic field – and the *coupled* cosmic ray electrons – to high values, significantly boosting the synchrotron emissivity

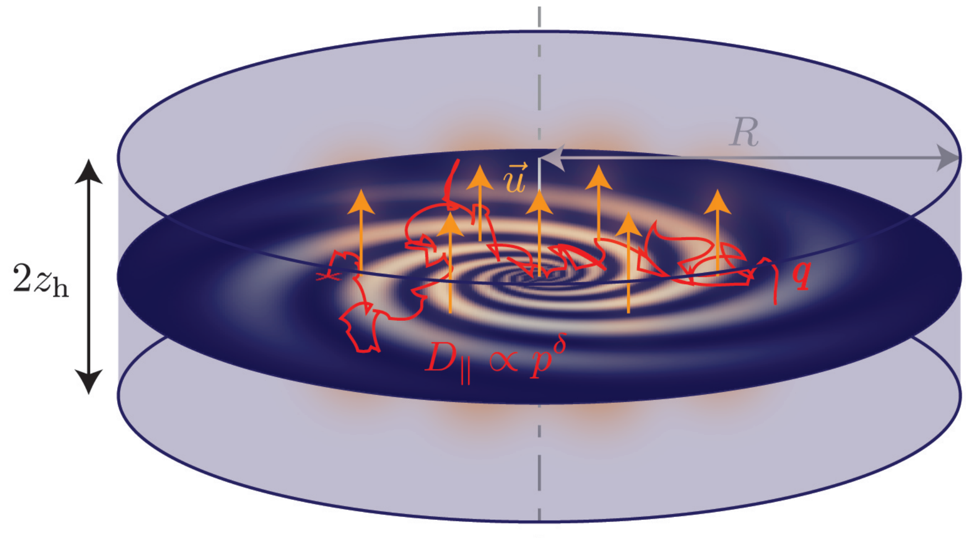
The galactic radio background

Synchrotron radiation by **relativistic cosmic ray electrons** spiralling in the **galactic magnetic field** (regular spiral + turbulent component):

$$P(\mathbf{r};\nu) = \int \mathrm{d}E\, n_e(\mathbf{r};E)\, \frac{\sqrt{3}e^3 B_\perp(\mathbf{r})}{8\pi^2 \varepsilon_0 c\, m_e} F\left(\frac{\nu}{\nu_c}\right)$$

where $\nu_c = \frac{3}{2}\left(\frac{E}{m_e}\right)^2 \frac{B_\perp(\mathbf{r})}{B(\mathbf{r})}$, $\quad F(x) = x \int_x^\infty \mathrm{d}x' K_{5/3}(x')$

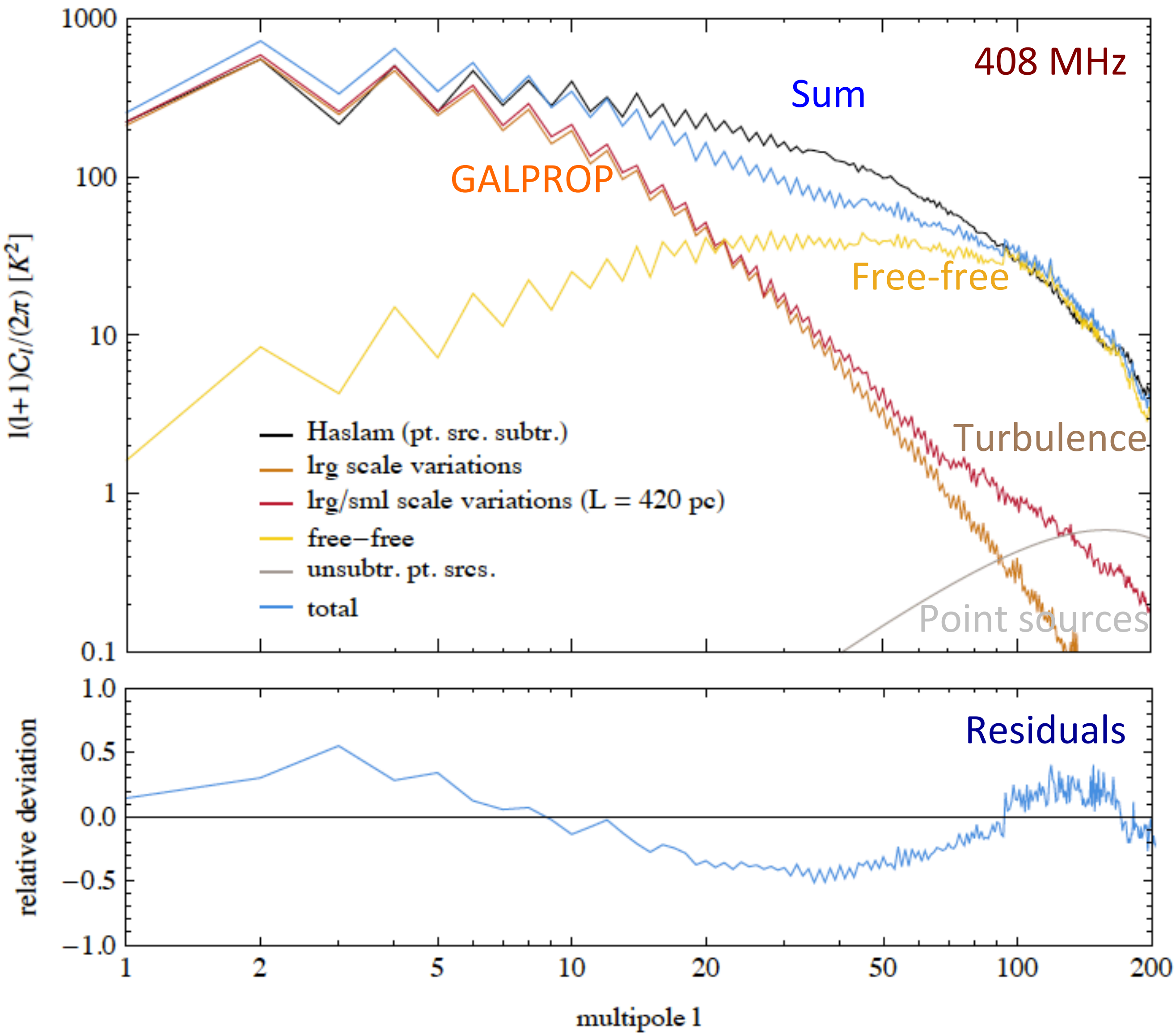




Can model using GALPROP code which solves for the diffusion of cosmic rays in the Galaxy (assumed to be a cylindrical slab + extended 'halo')

+ add emissivity on small-scales from MHD turbulence (with Kolgomorov spectrum)

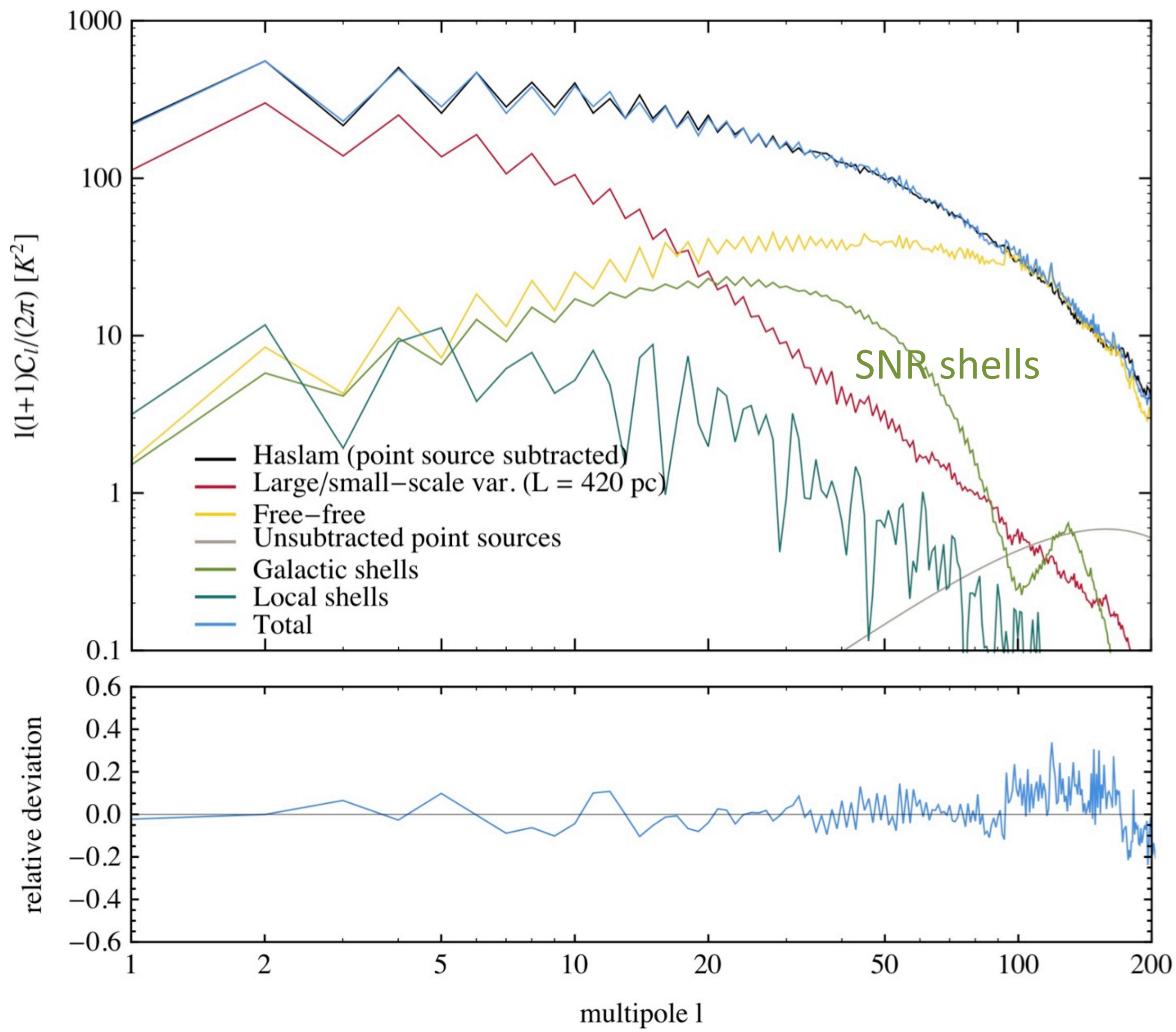
The uniform galaxy model does *not* provide a match to the angular power spectrum of the radio background

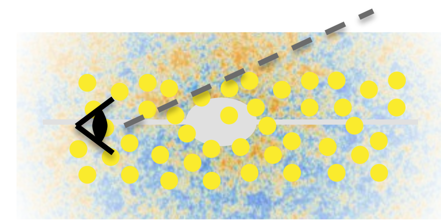


Mertsch & Sarkar, JCAP **06**:041,2013

… but adding a population of old SNRs does!

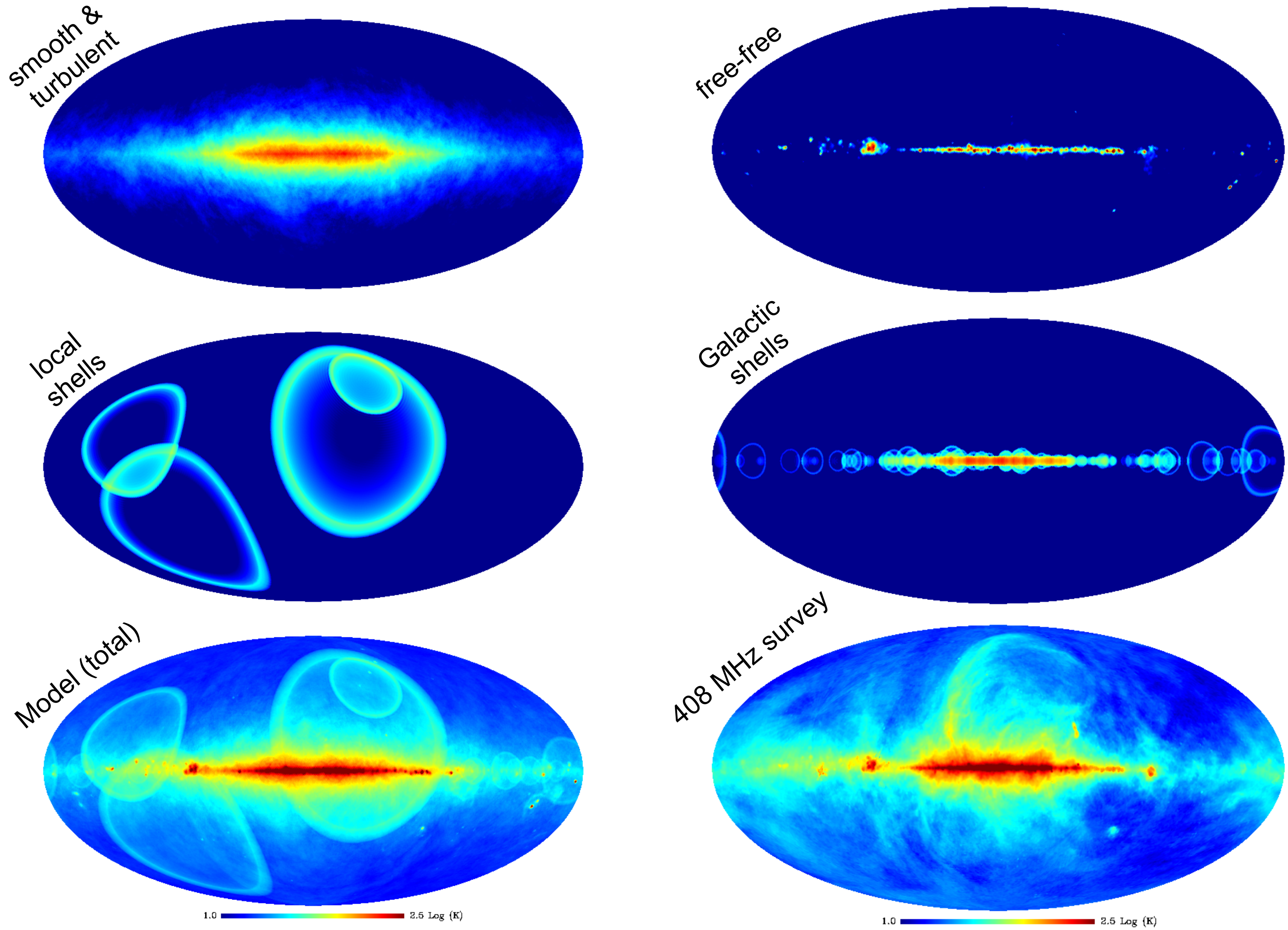
Mertsch & Sarkar, JCAP **06**:041,2013





- Several thousand shells of old SNRs in Galaxy
- We know 4 local shells (Loop I-IV) but others are modeled in MC approach
- They contribute in *just* the required multipole range

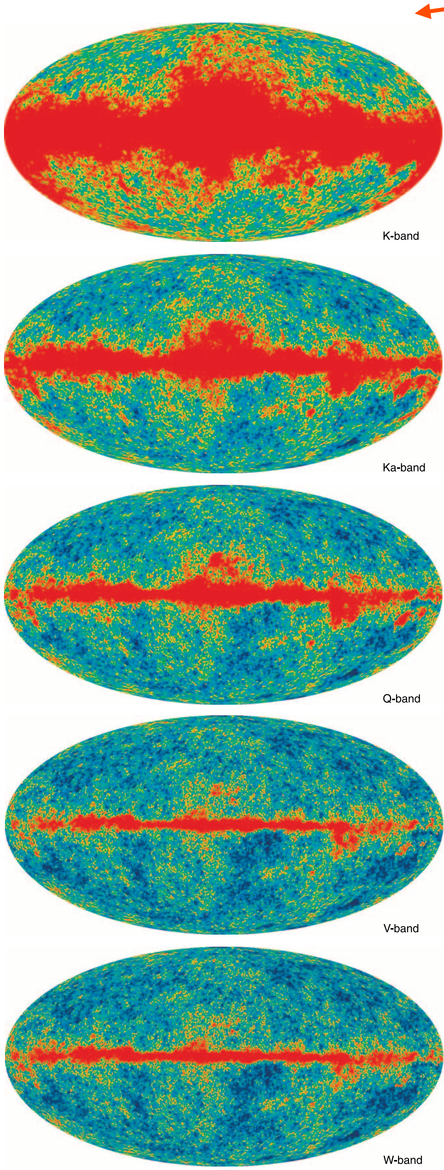
This model has structure at high latitude (like the *real* radio sky)

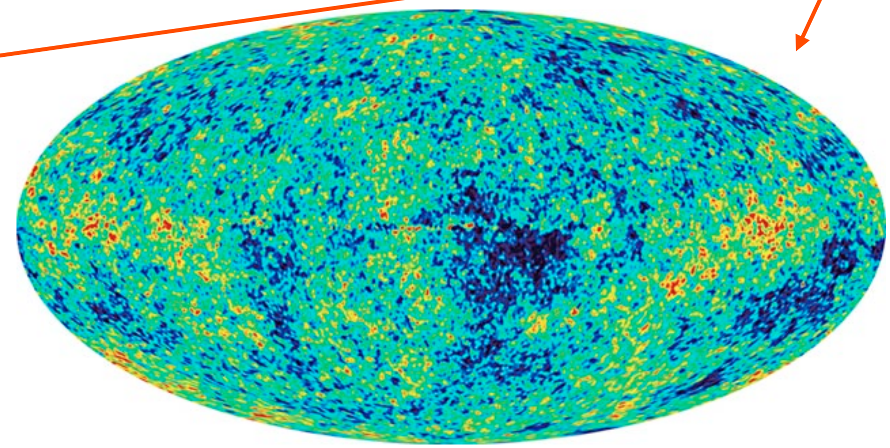


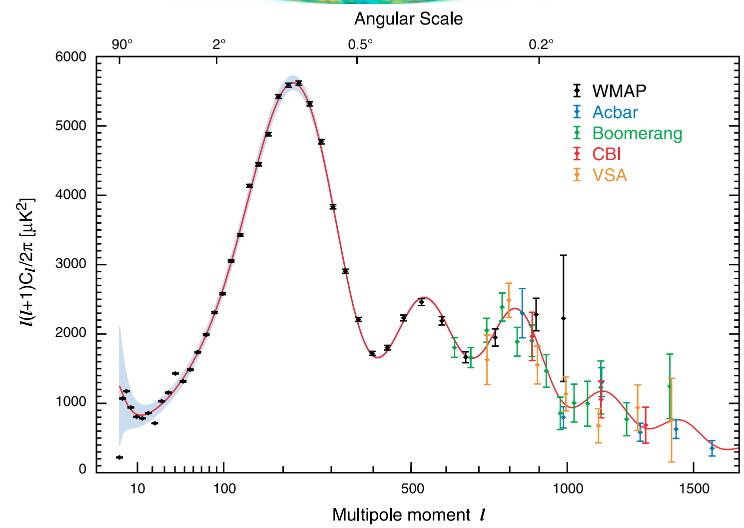
Mertsch & Sarkar, JCAP 06:041,2013

CMB foreground removal: How do we get from this to this?

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







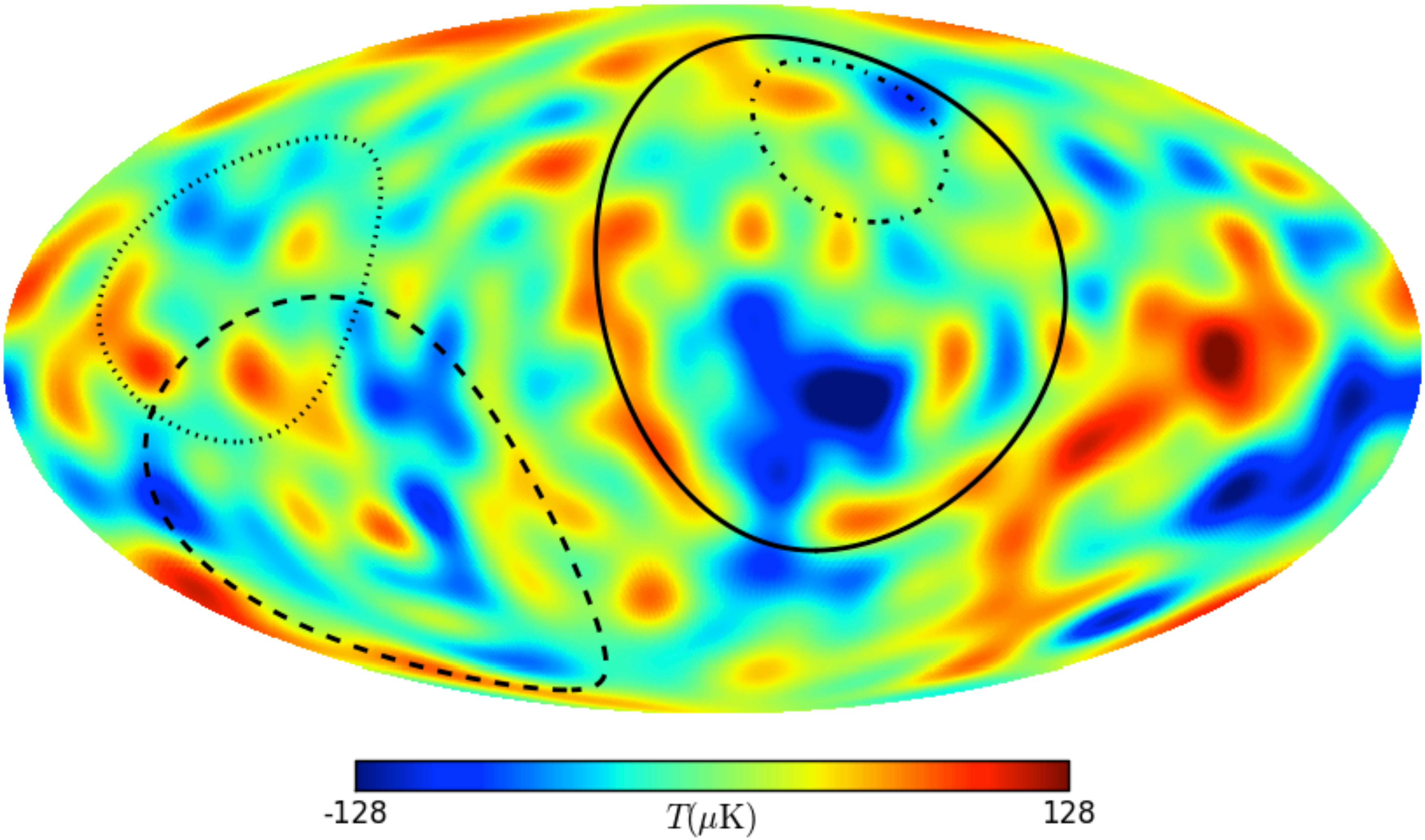
<u>Answer</u>: ILC – Internal Linear Combination (SMICA for Planck)

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

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

But this technique may fail *locally* in regions where there is *both* synchrotron and dust emission - e.g. in old supernova remnant shells (nearby … so at high latitude)

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



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

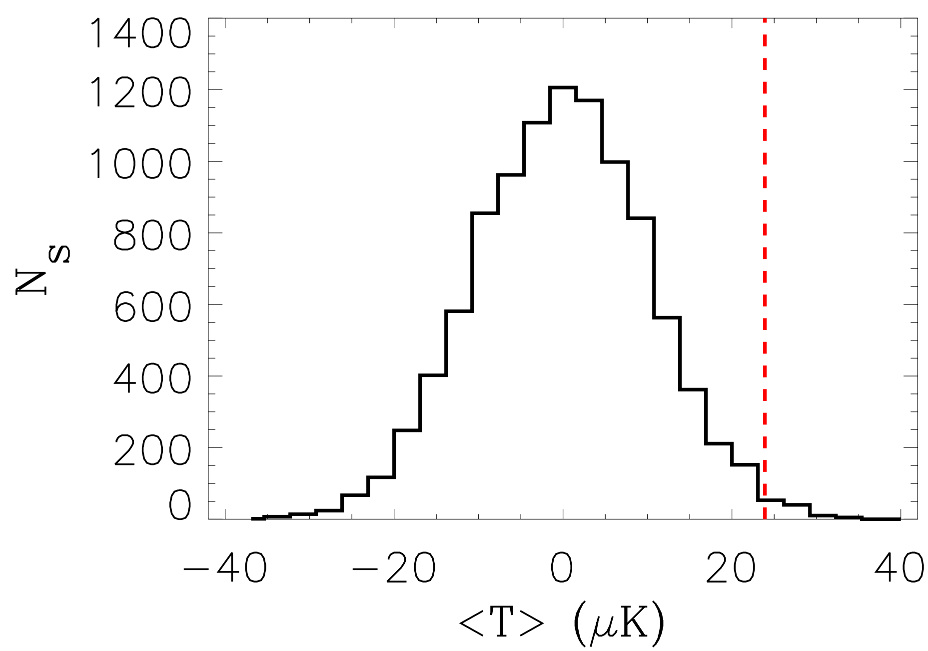
Are the radio loops visible (even in microwaves)?

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

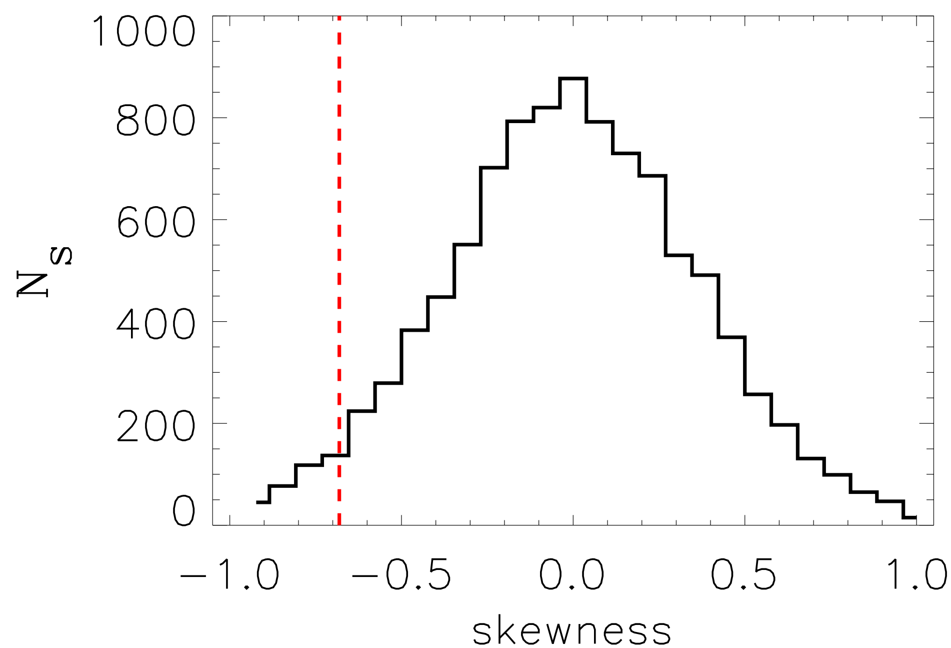
There is a 22 μK excess temperature in ring around Loop I

(NB: This is ~1/4 of the total TT signal in the 'cleaned' CMB map)

Temperature



Skewness

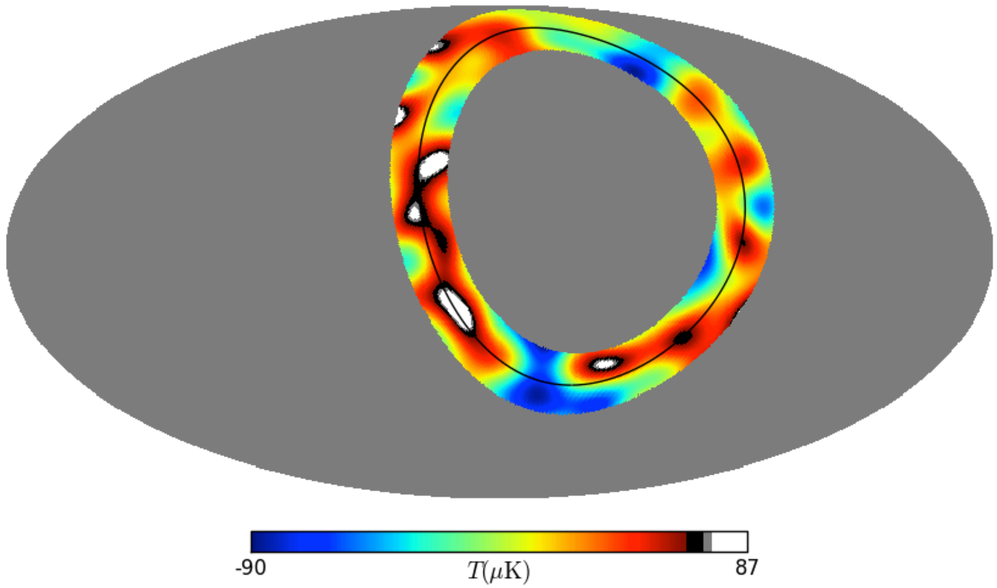


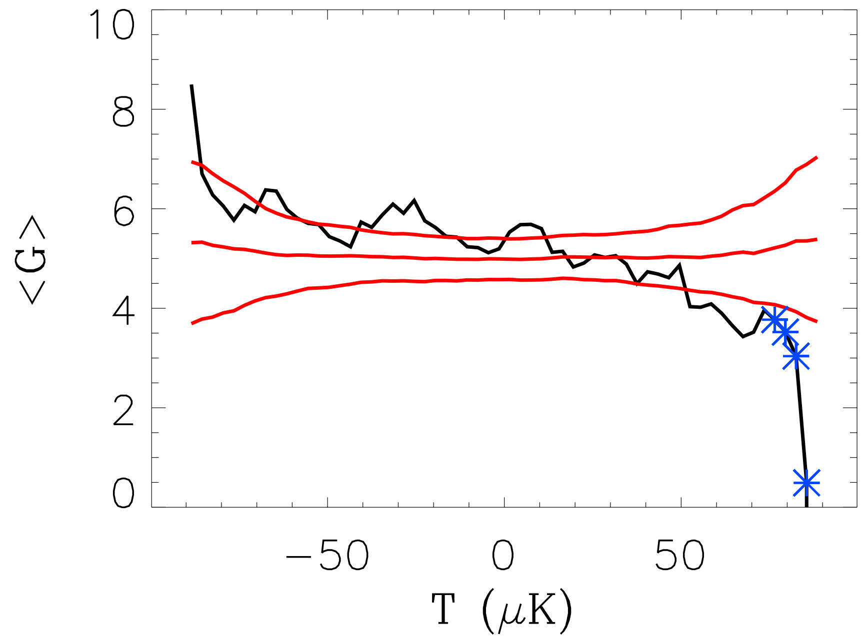
Compare with MC $\Rightarrow$ p-values of $\mathcal{O}(10^{-2})$

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

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

Cluster analysis (Naselsky & Novikov, ApJ **444**:1,1995): Compute for each pixel the angular distance G from Loop I along great circles crossing both the pixel and the loop center and compare with random realisation of best-fit ΛCDM model

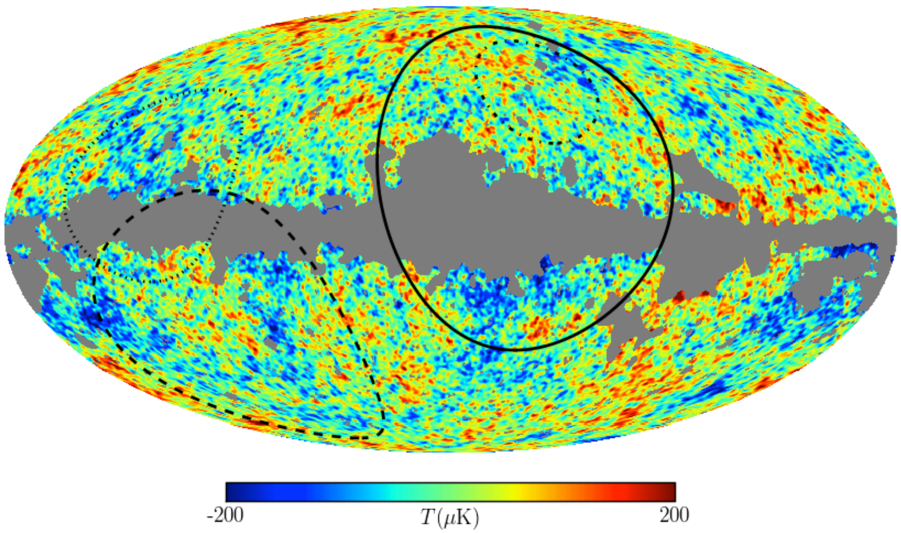




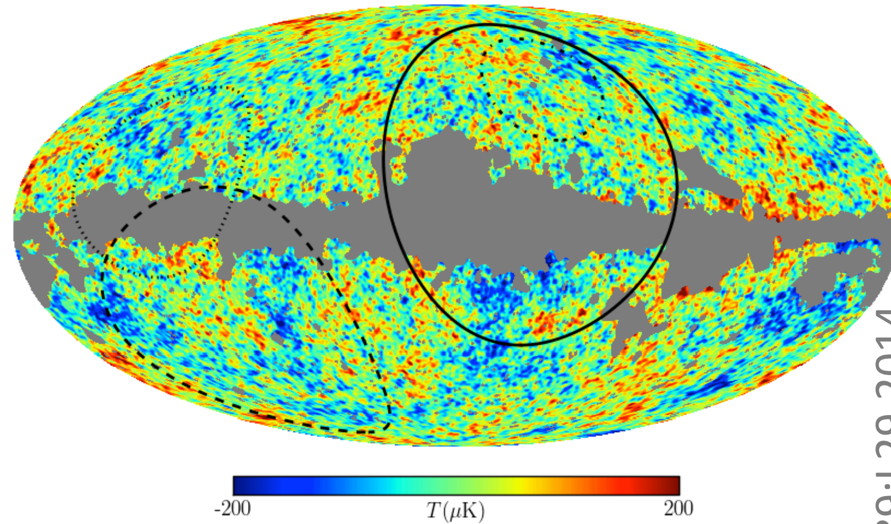
From 100,000 MC runs: probability for *smaller* $\langle G \rangle$ in last 4 bins $\sim 10^{-4}$

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

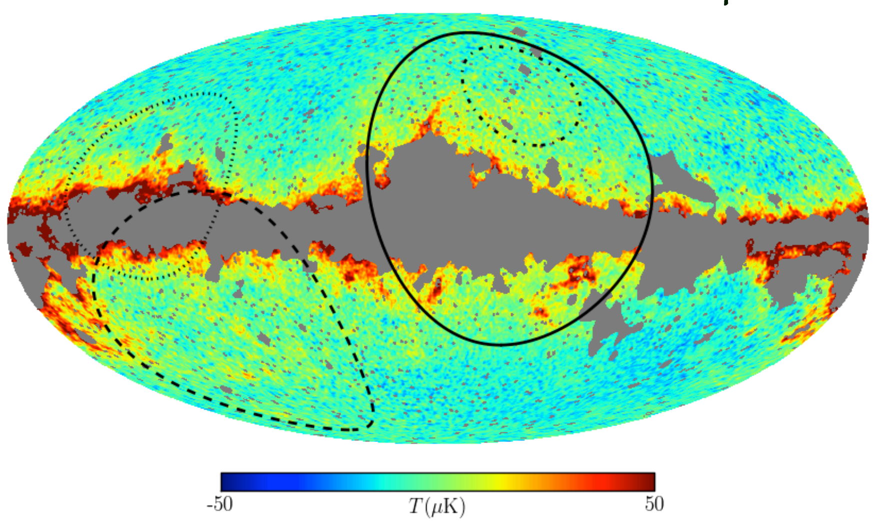
ILC coefficients from Loop I region



ILC coefficients from rest of sky



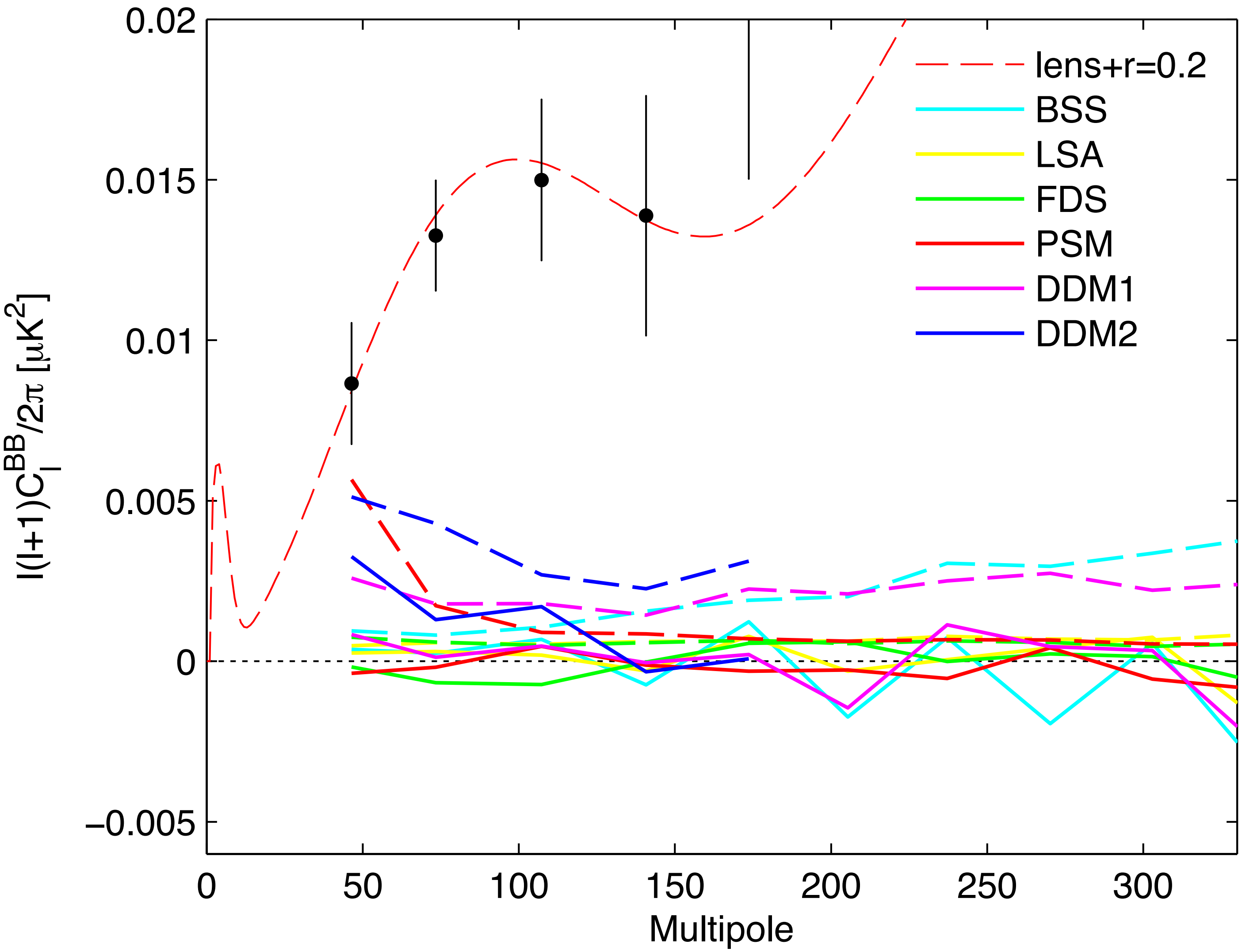
Difference $ILC_{rest} - ILC_{Loop\ I}$



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

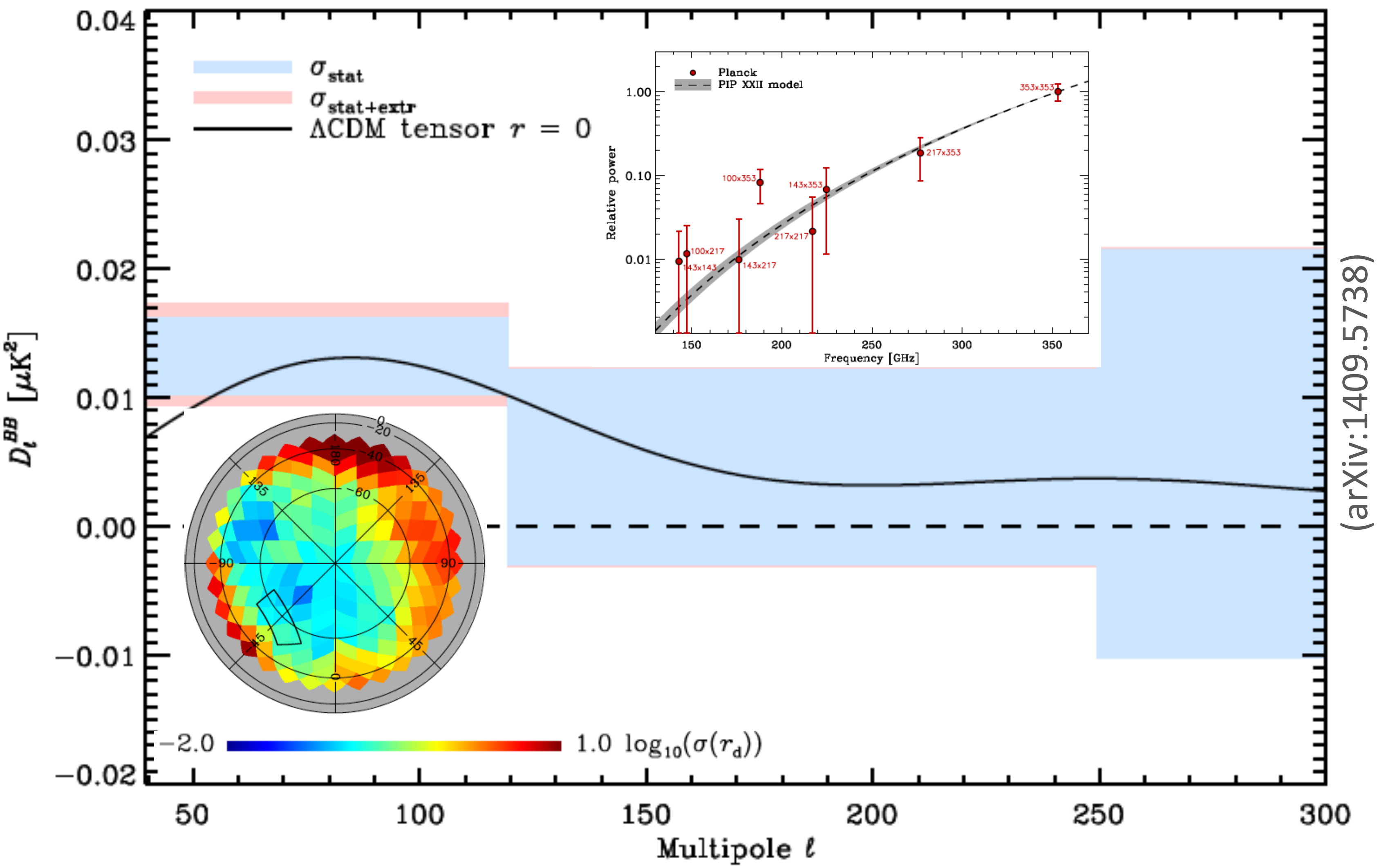
This confirms there is an imprint of the radio loops in the 'internal linear combination' map of the CMB which has supposedly been cleaned of all foreground emissions!

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…

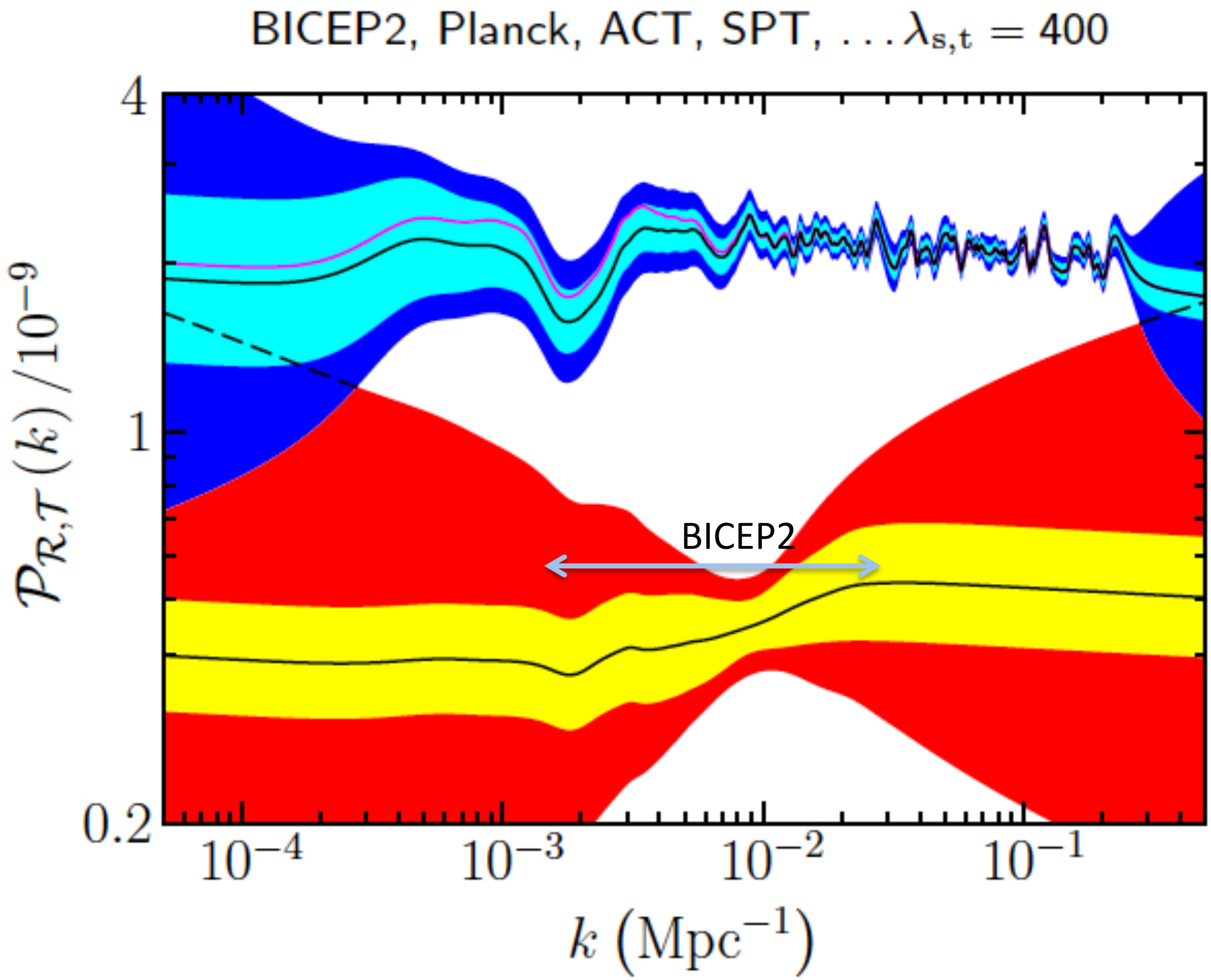
The 353 GHz polarised dust emission map from *Planck* shows high latitude emission from dust with a high polarisation fraction of ~20% - extrapolated to 150 GHz, this is comparable to the BICEP2 'signal'!



(arXiv:1409.5738)

Still waiting for cross-correlation between BICEP2 and Planck to settle the issue …

Moreover it is difficult to reconcile the BICEP2 claim with TT data … because the spectral slope of the 'tensor signal' is of *opposite* sign to the inflationary expectation!



Hunt & Sarkar, JCAP **01**:025,2014 + to appear

$\mathcal{P}_{\mathcal{R}}(k)$ & $\mathcal{P}_{\mathcal{T}}(k)$ recovered with prior of $n_s = 0.969$ & $n_t = -0.025$.

Yet another exciting 'discovery'

- CERN DG Rolf Heuer [CERN Press Release, 18 September 2014]

So what's all the excitement about?

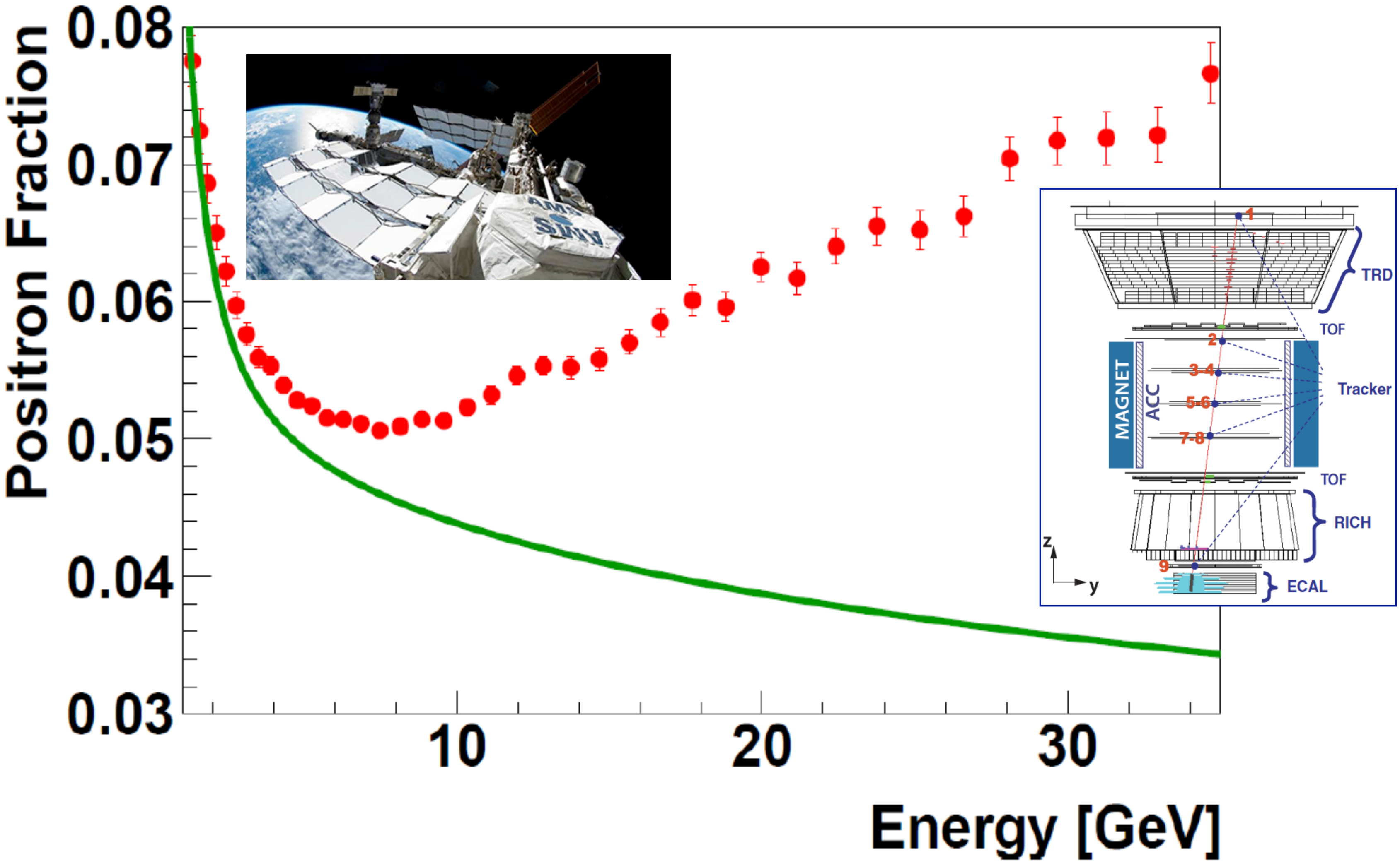
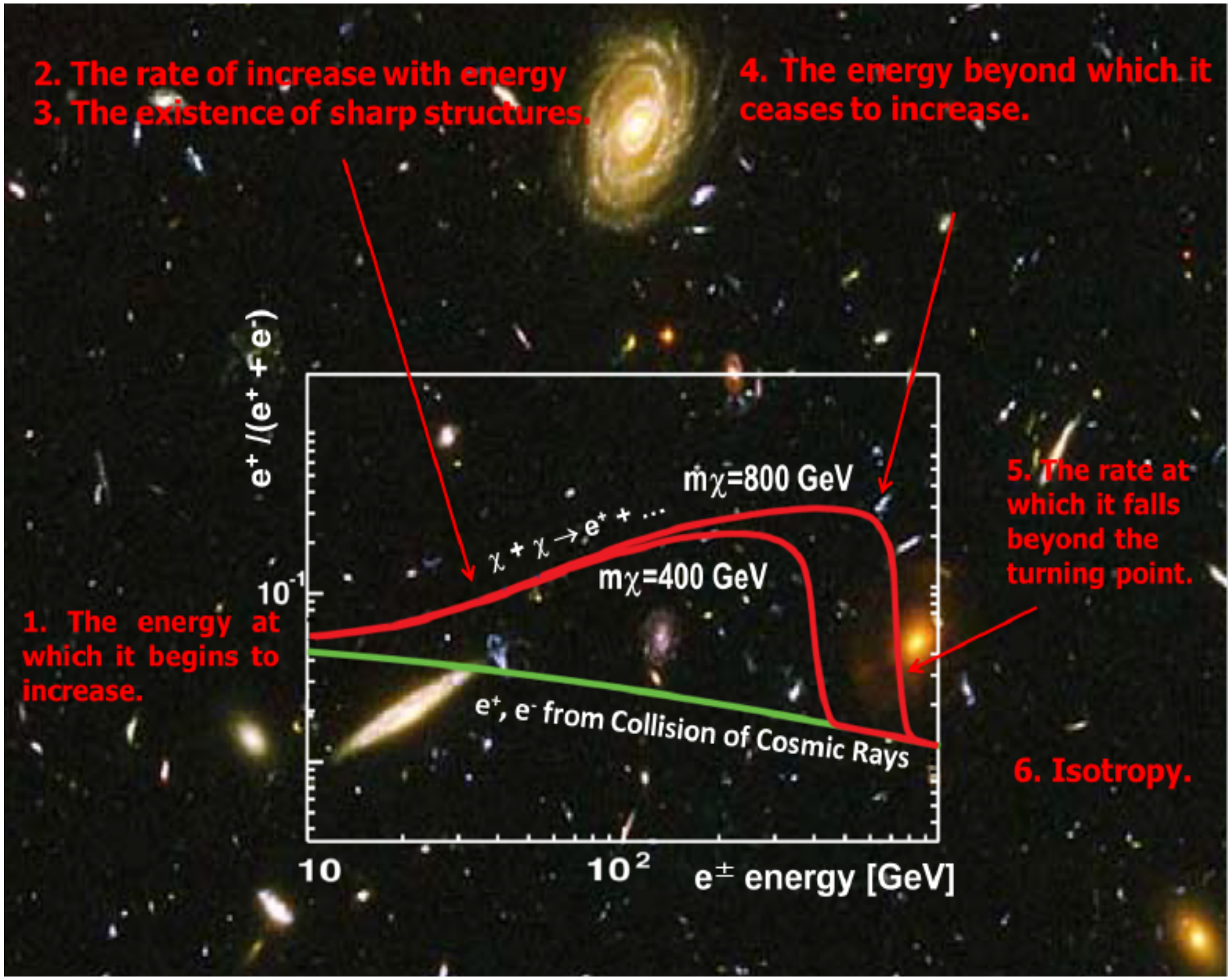


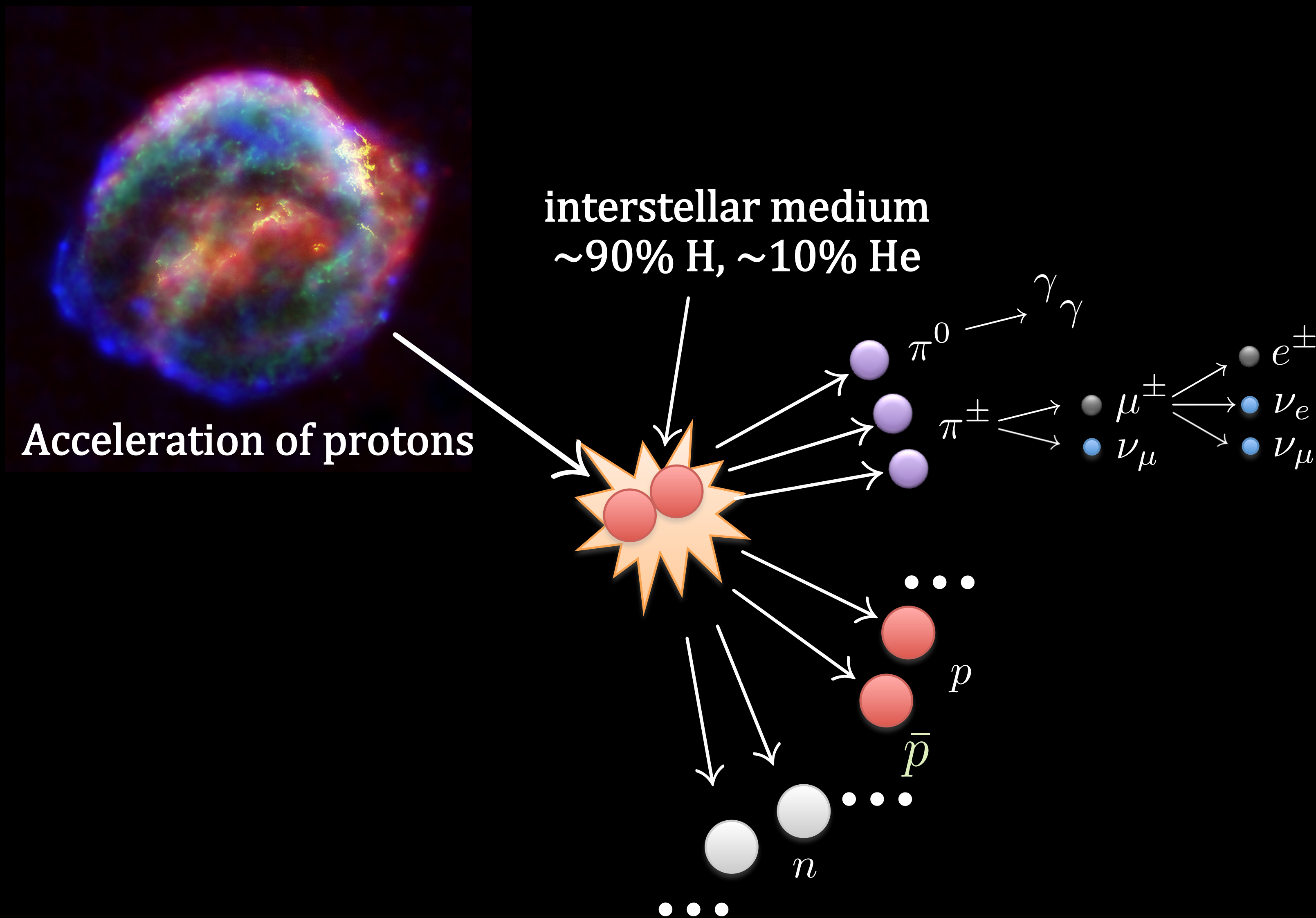
Figure 1. The positron fraction measured by AMS (red circles) compared with the expectation from the collision of ordinary cosmic rays showing that above 8 billion electron volts (8 GeV) the positron fraction begins to quickly increase. This increase indicates the existence new sources of positrons.

… and this is the bold claim!

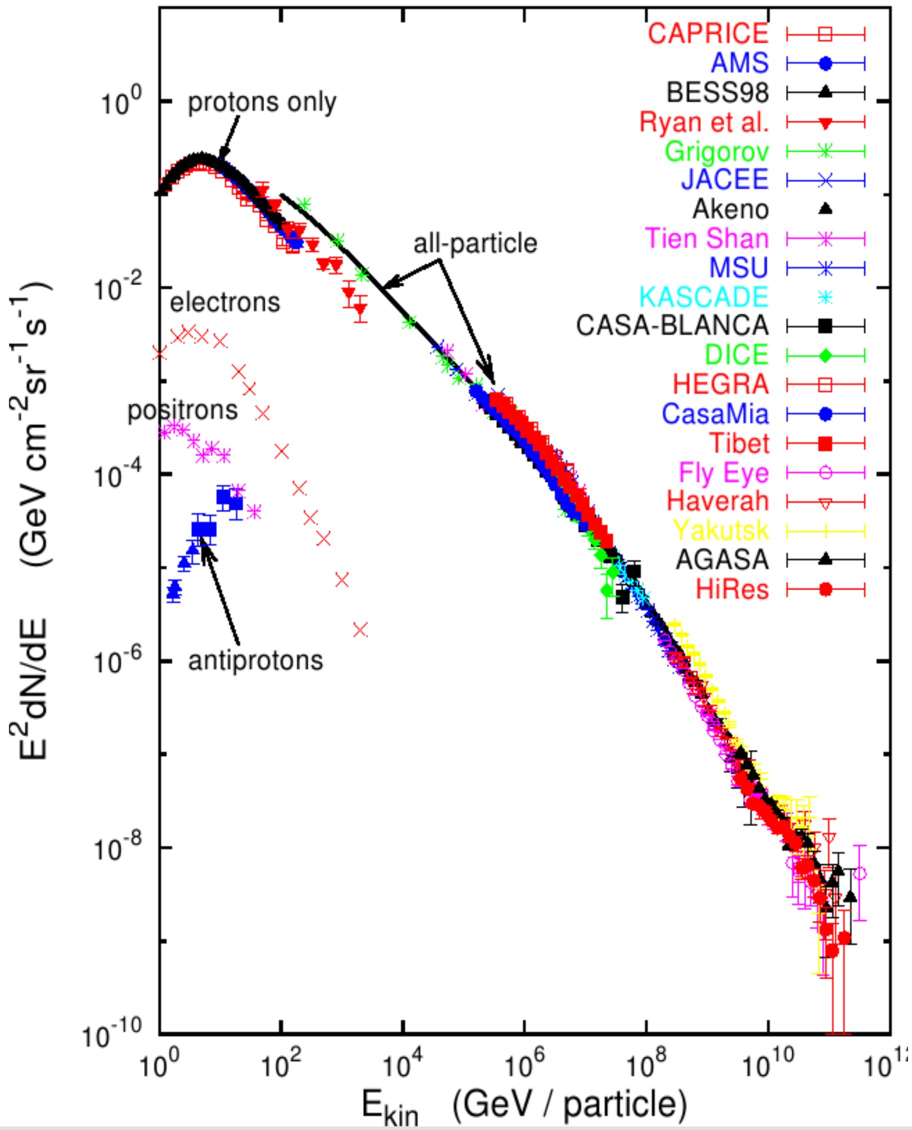


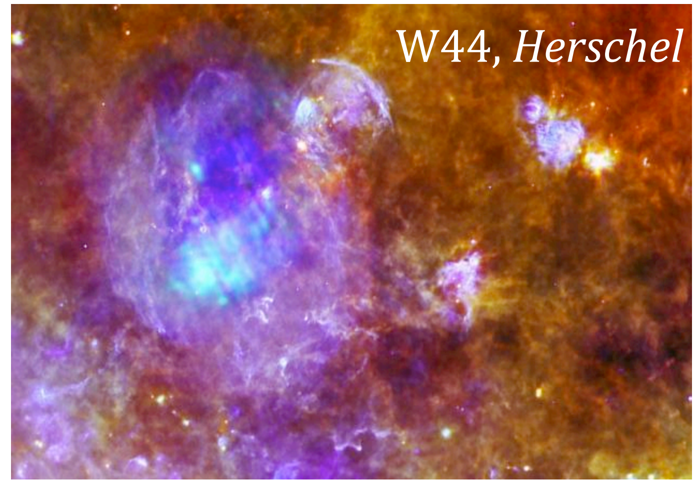
The new results from AMS on the positron fraction published in *Physical Review Letters* show that items (1)-(4) highlighted in Figure 3 have been unambiguously resolved, yielding observations of a new phenomenon. They are consistent with a dark-matter particle (neutralino) of mass on the order of 1 TeV. To determine if the observed new phenomenon is from dark matter or from astrophysical sources such as pulsars, AMS is now making measurements to determine the rate of decrease of the positron fraction beyond the turning point (item 5), as well as to determine the antiproton fraction ...

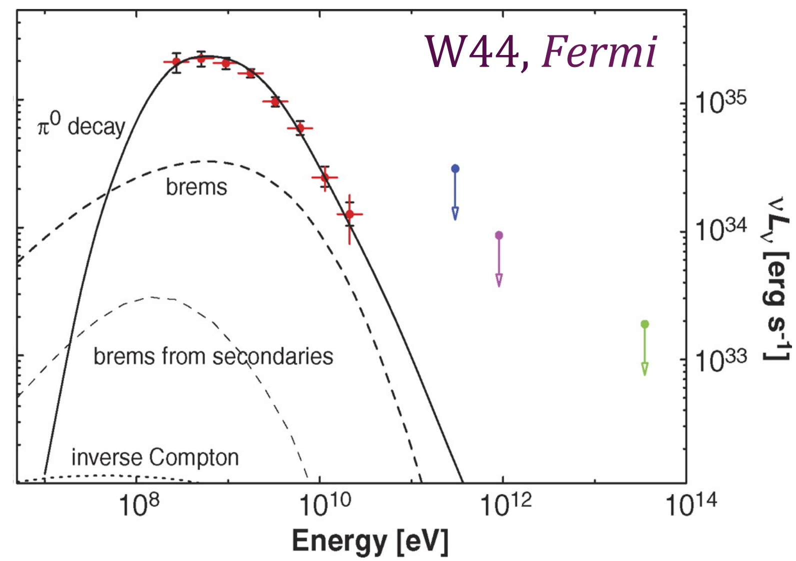
The ‘background’ is the production of secondary $e^{\pm}$ during diffusion of nuclear cosmic rays in the Galaxy



The sources of galactic cosmic rays are believed to be **supernova remnants** … responsible for accelerating particles up to ~10^3 TeV (the 'knee')

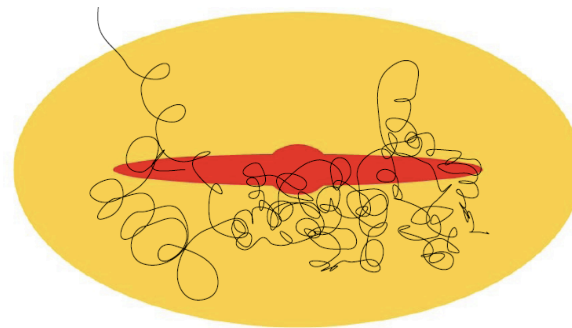






If O(10%) of the shock K.E. of ~10^{51} erg can be converted into hadronic cosmic rays, then the observed ~3 SN/century can maintain the energy density of ~0.3 eV/cm^3 in galactic cosmic rays

The diffusion model



Transport equation:

$$\frac{\mathrm{d}n(\vec{r},t)}{\mathrm{d}t} = \underbrace{\nabla(D\nabla n(\vec{r},t))}_{\text{diffusion}} - \underbrace{\frac{\partial}{\partial E}(b(E)n(r,t))}_{\text{energy losses}} + \underbrace{q(\vec{r},t)}_{\text{injection}}$$

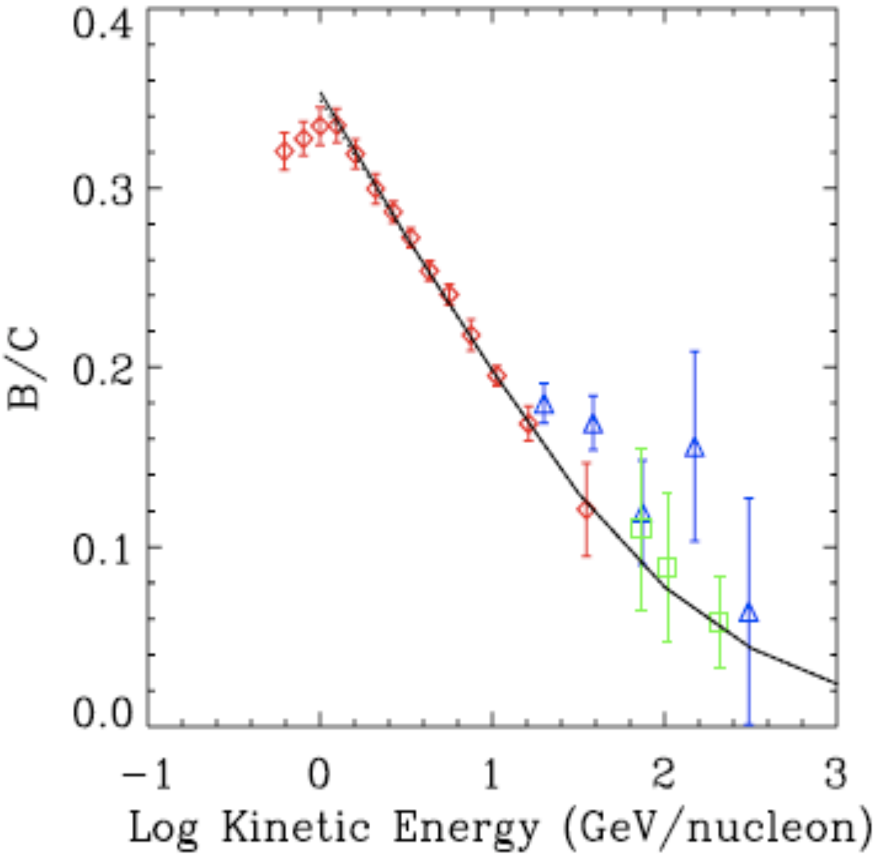
Averaging over extended cosmic ray halo ⇒ steady state solution ('leaky box'):

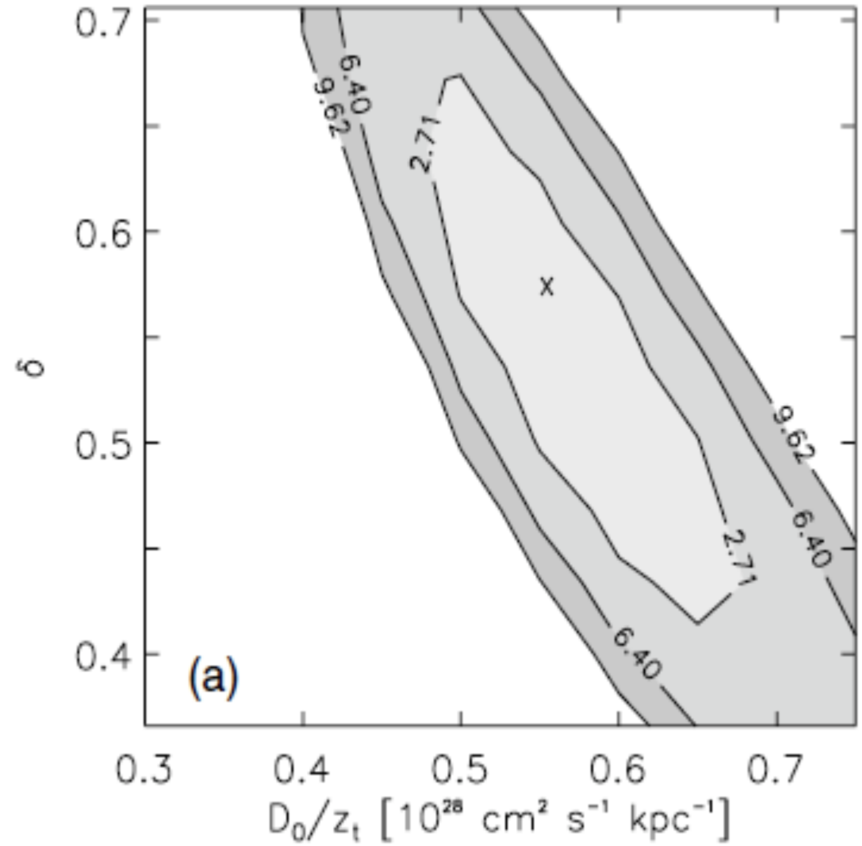
$$0 = -\frac{n}{\tau_{\mathrm{esc}}} - \frac{n}{\tau_{\mathrm{cool}}} + q$$

Diffusive escape: $\tau_{esc} \sim E^{-\delta}$ (δ ~ -0.6 from secondary/primary ratios)

Energy loss through synchrotron radiation/IC scattering: $\tau_{cool} \sim E^{-1}$

Secondary-to-primary ratios (using DRAGON code)





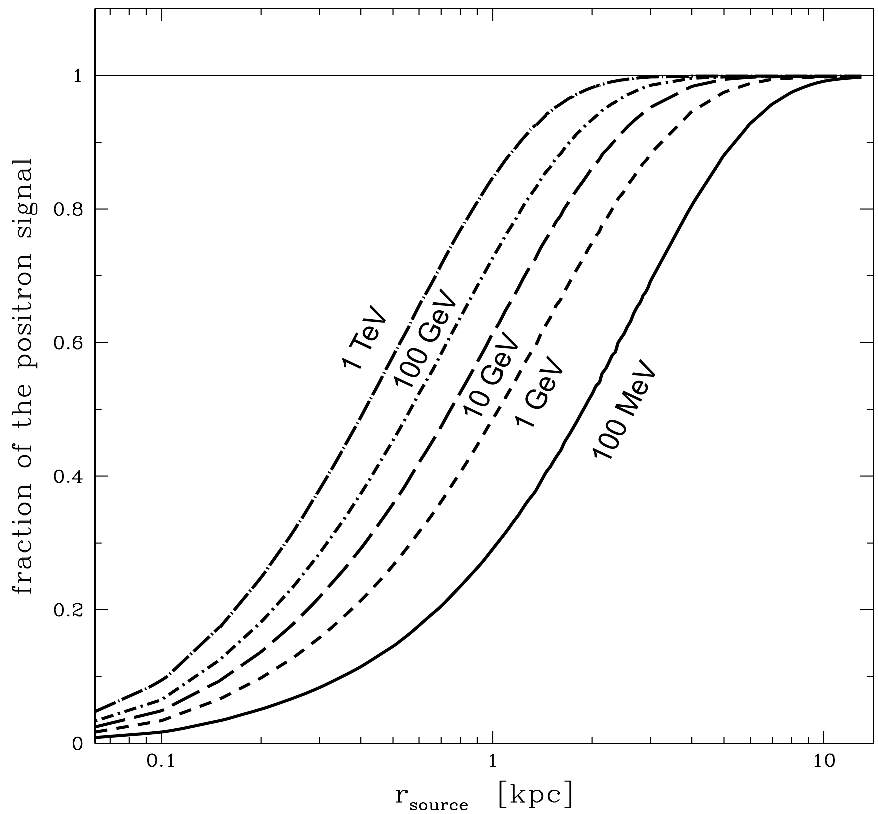
Evoli, Gaggero, Grasso & Maccione, JCAP 10:018,2008

All measured ratios consistent with diffusion model with
$\tau_{esc} \sim E^{-\delta}$, $\delta \sim 0.6$

NB: Kolmogorov spectrum for interstellar magnetic field turbulence would imply $\delta = 1/3$, while Kraichnan spectrum yields $\delta = 1/2$

However e$^{\pm}$ lose energy readily during propagation, so only nearby sources dominate at such high energies … the usual background calculation is then *irrelevant*

$$\tau \simeq 5 \times 10^5 \mathrm{yr} \left(\frac{1\mathrm{TeV}}{E} \right)$$



Delhaye *et al*, A&A 501:821,2009

Might there be *primary* sources of e^+ (with a hard spectrum) in our Galactic neighbourhood?

In fact the rising positron fraction had been seen earlier … the *PAMELA* 'anomaly' (and confirmed by *Fermi-LAT*)

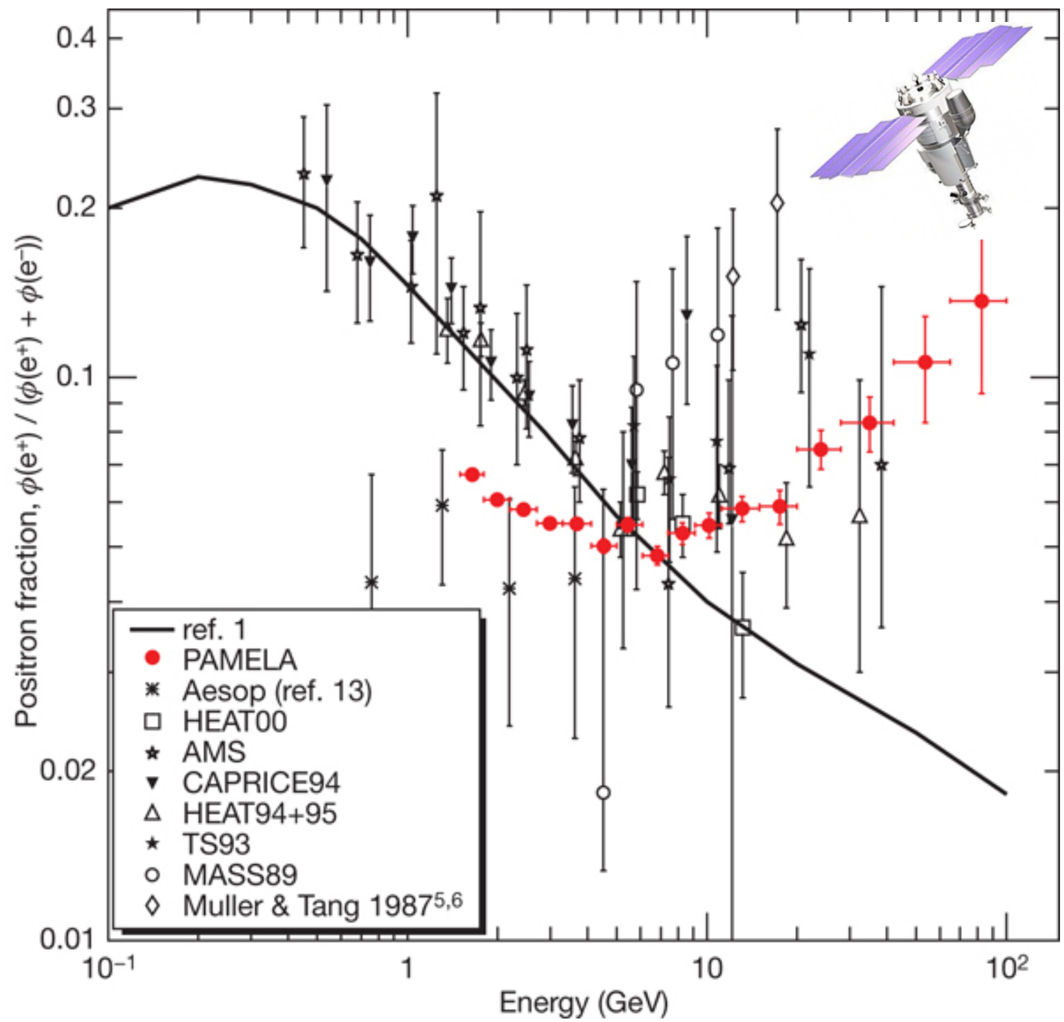
Source of anomaly:

- Dark matter?

(500+ papers!)

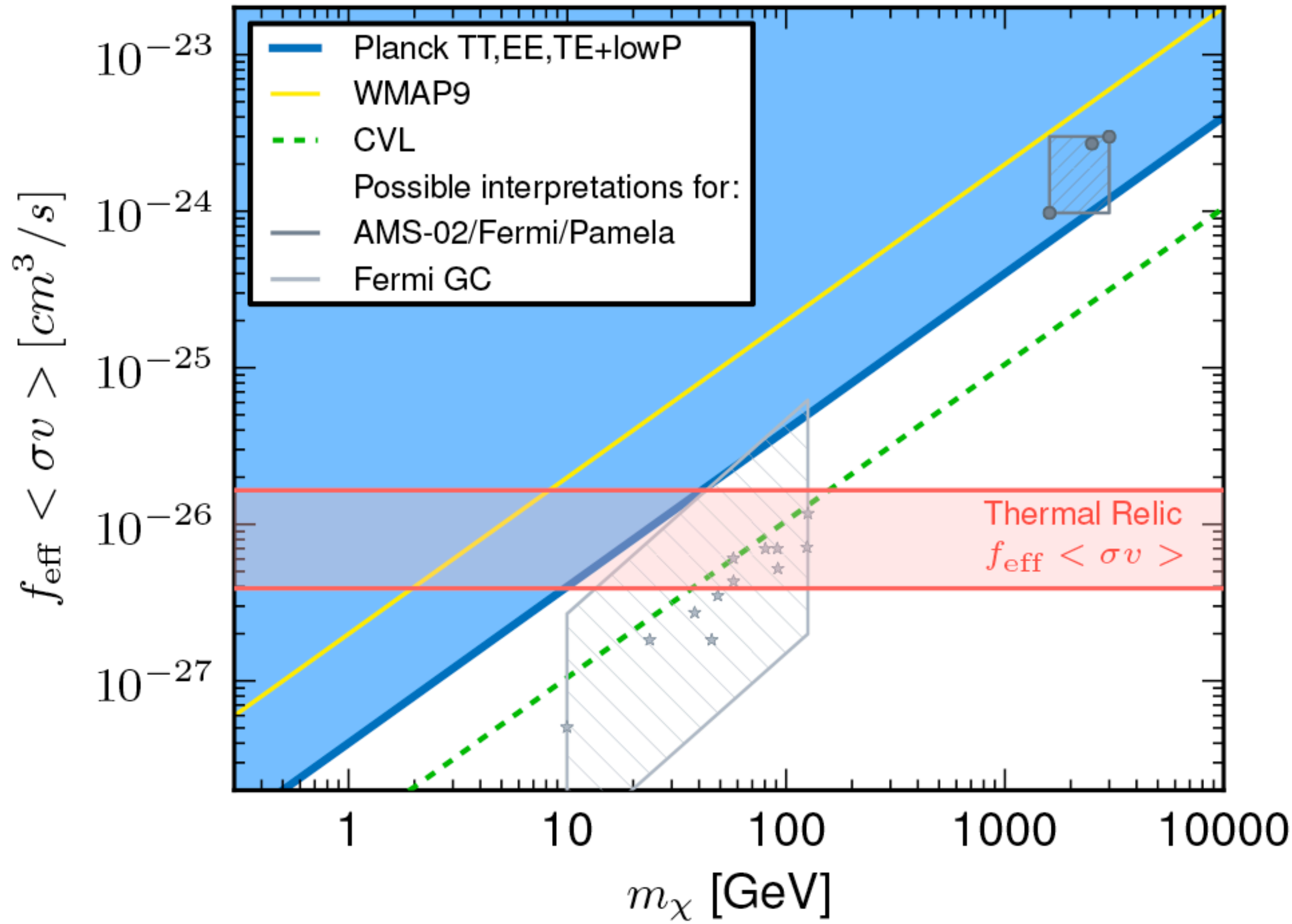
- Nearby pulsars?

- Nearby supernova remnants?



Adriani *et al*, Nature 458:607,2009

DM annihilation energy release would also increase the ionisation fraction of the intergalactic medium and broaden the 'last scattering surface' of the CMB



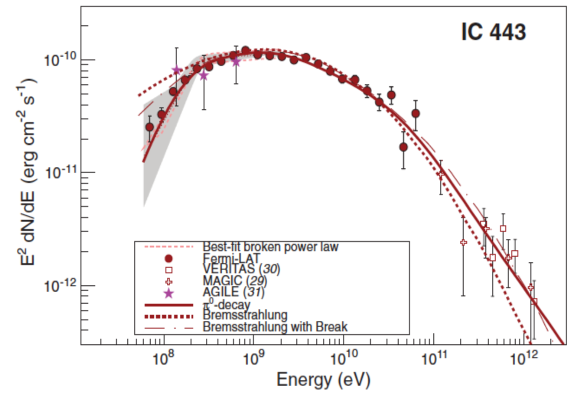
This affects the CMB temperature and polarisation spectra … Planck has just set new limits on this, *disfavouring* DM interpretations of the PAMELA/AMS-02 anomaly

A nearby cosmic ray accelerator?

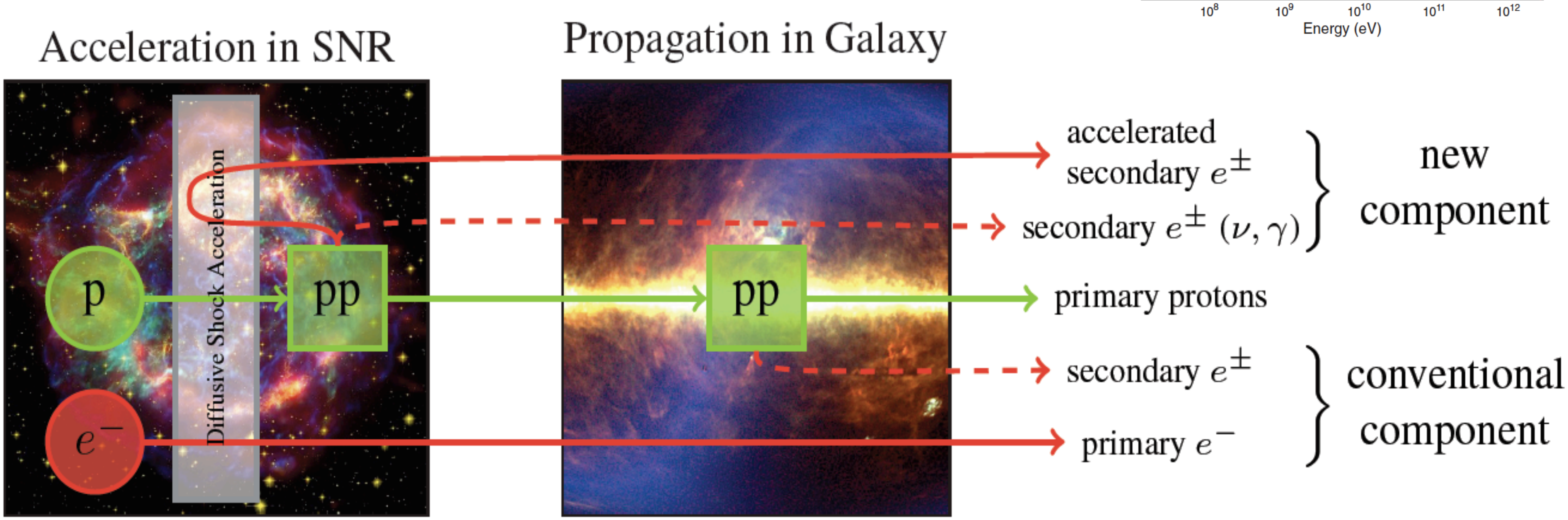
Rise in e^+ fraction could be due to secondaries produced *during* acceleration … which are then accelerated along with the primaries (Blasi 2009)

… generic feature of a *stochastic* acceleration process, if

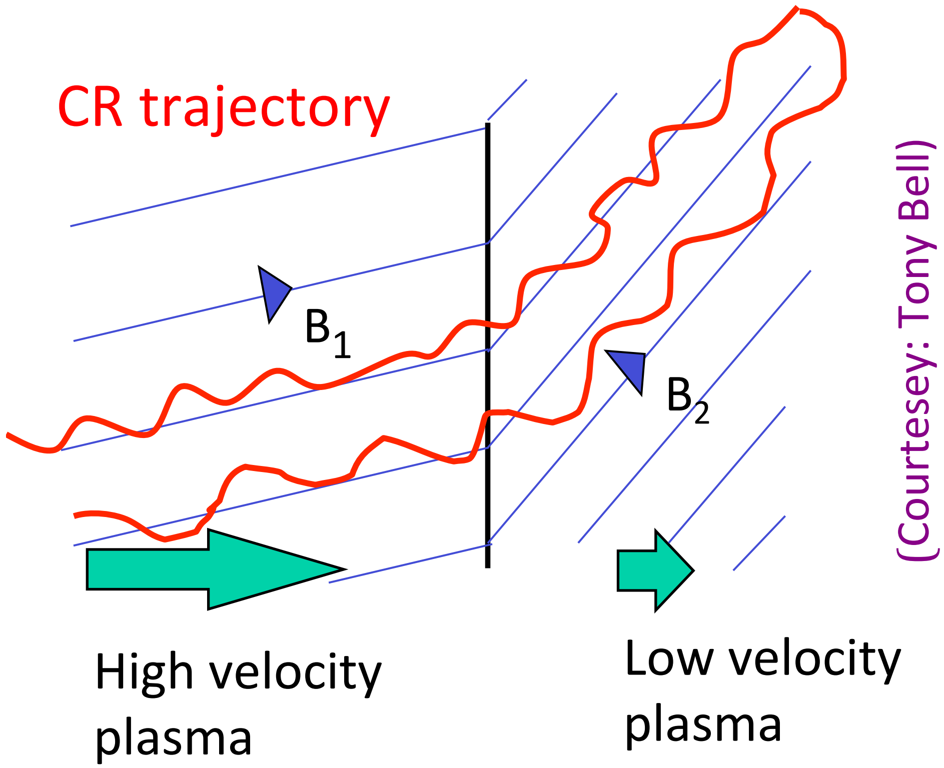
$\tau_{1\to2} < \tau_{acc}$ (Cowsik 1979, Eichler 1979)



This component has a harder spectrum so *naturally* fits the PAMELA/AMS-02 excess!



(1st-order Fermi) diffusive shock acceleration



Shock velocity v_s: $\beta = v_s/c$

Simple diffusion theory: prob. of CR crossing shock > *m* times is: $(1\text{-}\beta)^m$

Average fractional energy gained at each crossing: $\Delta\varepsilon/\varepsilon = \beta$

$\Rightarrow$ differential spectrum: $\propto \varepsilon^{-2}$

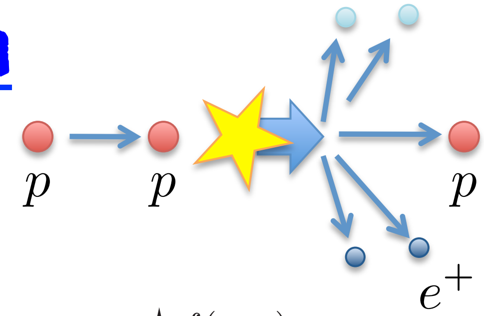
Due to scattering on magnetic field irregularities, cosmic ray crosses shock many times, gaining energy each time, so *can* yield the required 10% conversion of the shock wave K.E. into relativistic particles

If cosmic rays diffuse out of Galaxy on a time-scale decreasing $\propto 1/\varepsilon^{0.6}$, then the observed spectrum $\propto \varepsilon^{-2.6}$ can be matched

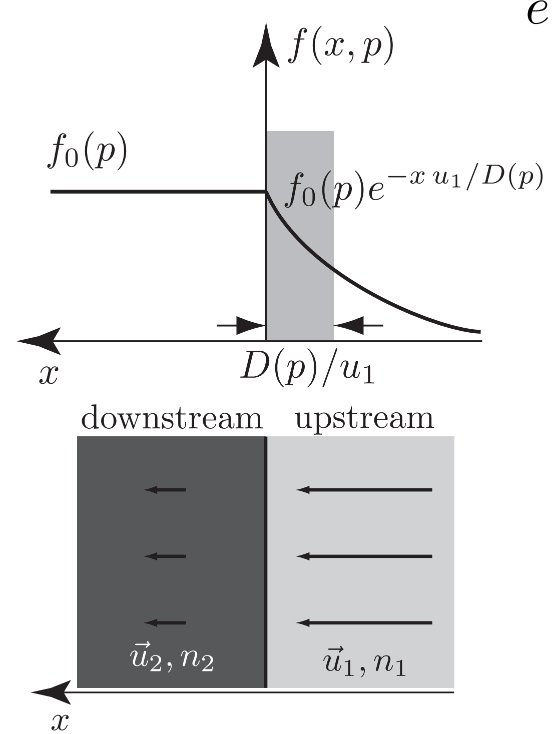
DSA with secondary production

- Secondaries have *same* spectrum as primaries (Feynman):

$$q_{e^\pm} \propto f_{\rm CR} \propto p^{-\gamma}, \quad \gamma = \frac{3r}{r-1} \qquad r = \frac{u_1}{u_2} = \frac{n_2}{n_1}$$



- Only particles with $|x| \lesssim D(p)/u$ are accelerated

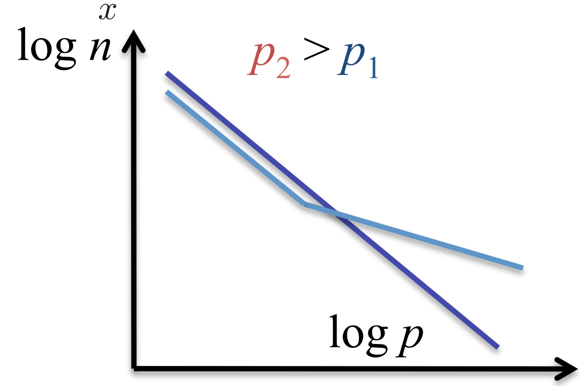


- Bohm diffusion: $D(p) \propto p$

⇒ Fraction of accelerated secondaries is $\propto p$

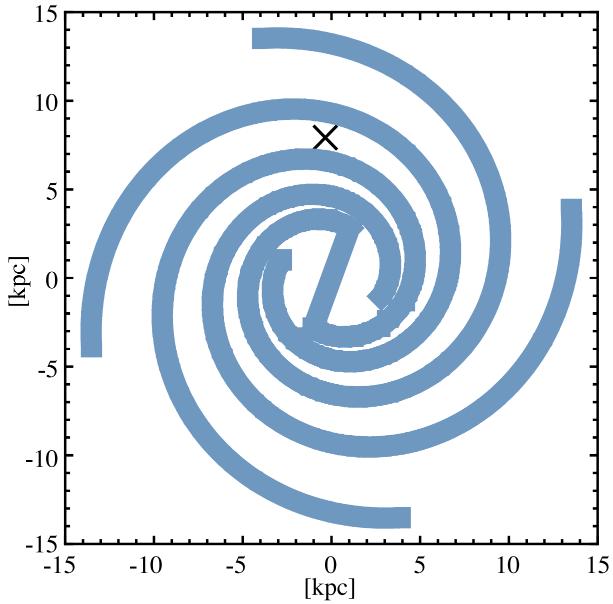
i.e. steady state spectrum is:

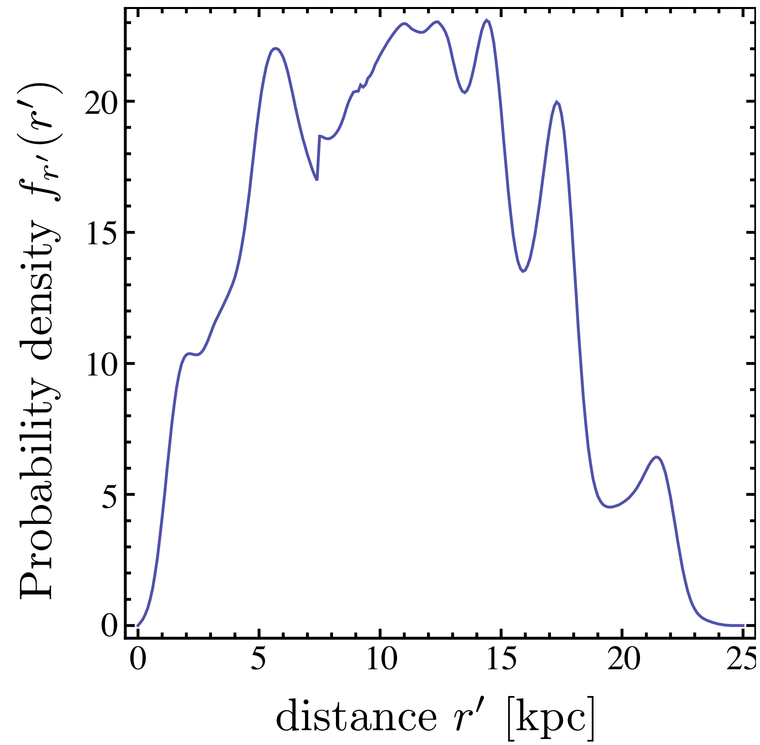
$$n_{e^\pm} \propto q_{e^\pm}\left(1 + \frac{p}{p_0}\right) \propto p^{-\gamma} + p^{-\gamma+1}$$



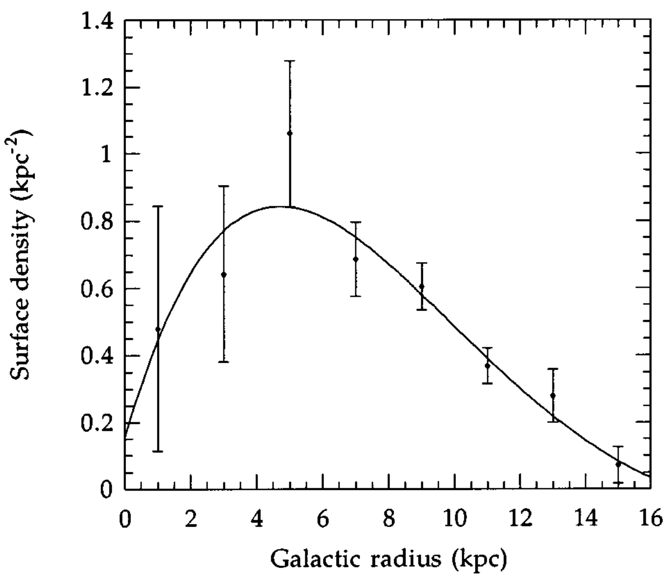
... thus yielding a *rising* positron fraction

Statistical distribution of SNRs in our neighbourhood





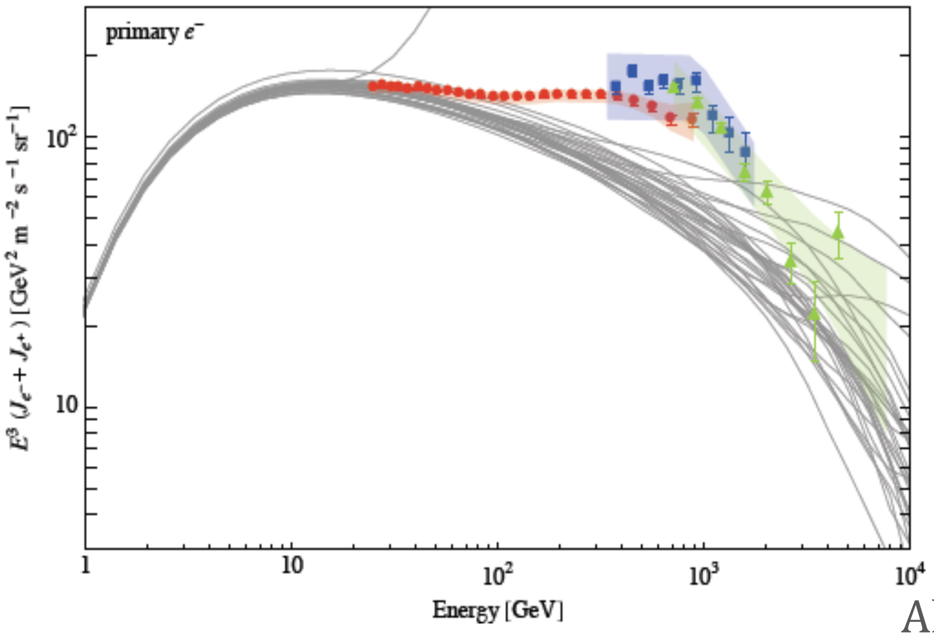
Ahlers, Mertsch, Sarkar,PRD80:123017,2009



(Case & Bhattacharya, ApJ 504:761,1998)

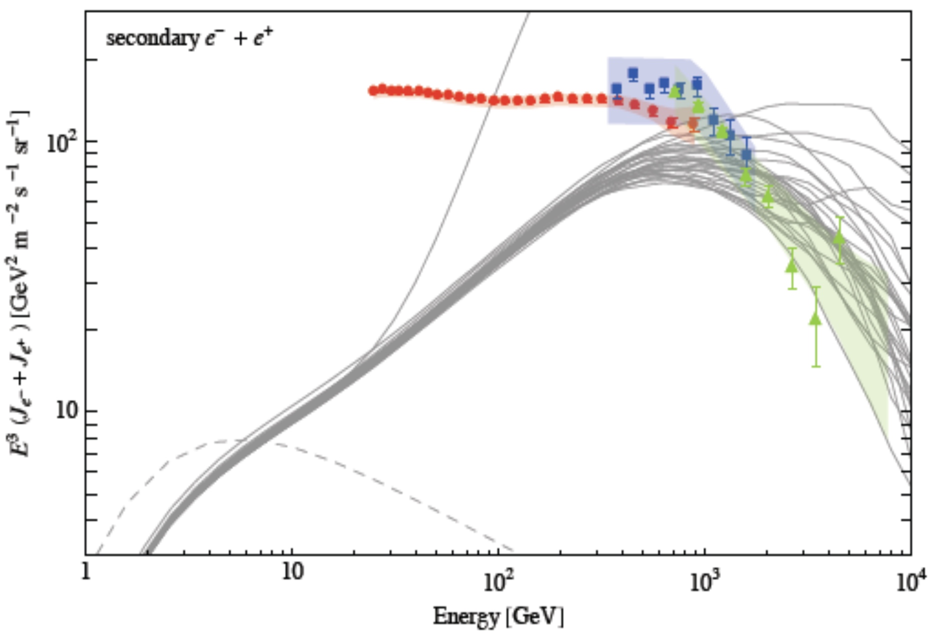
- Draw source positions from this distribution
- Inject e^- & e^+ normalized to observables
- Propagate to Earth accounting for synchrotron and inverse-Compton scattering energy losses
- Confront total e^-+e^+ flux at Earth with data
- The *best fit* to data is closest to real distribution

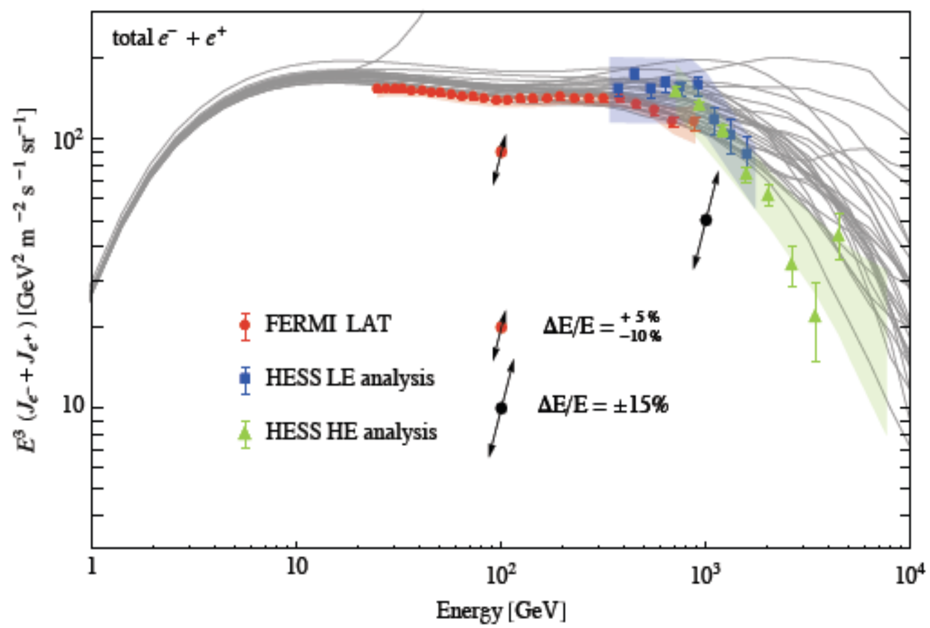
Fitting the $e^+ + e^-$ flux



The propagated primary e^- spectrum is much too *steep* to match the data ... but the *accelerated* secondary $e^+ + e^-$ component has a harder spectrum so does fit the 'bump'!

Ahlers, Mertsch & Sarkar, PRD80:123017,2009

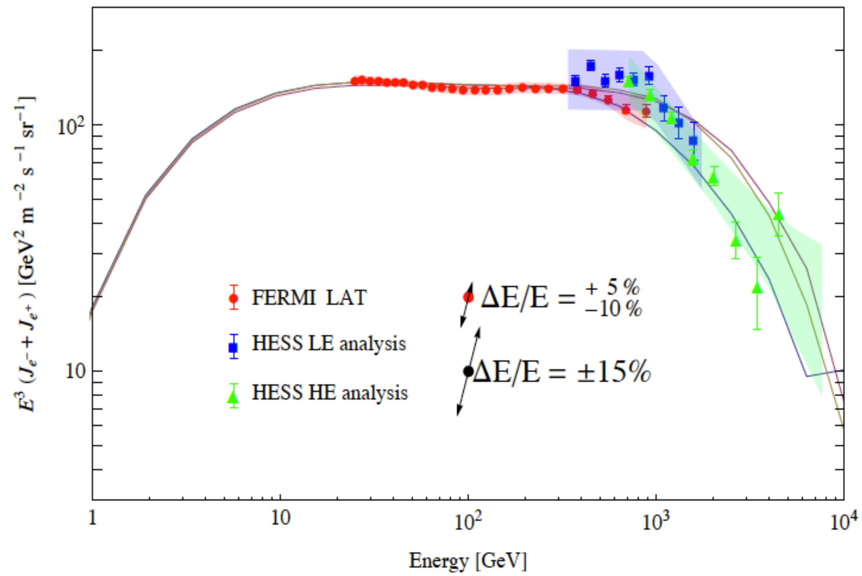


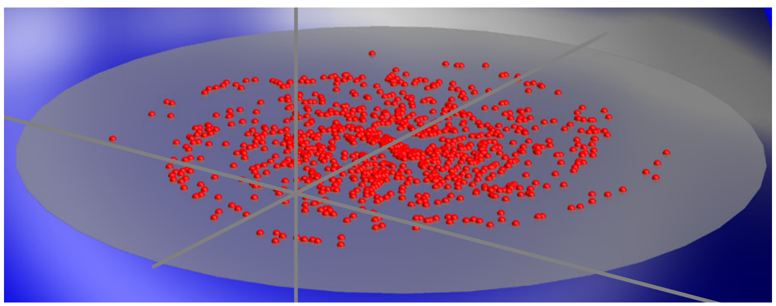


The '*postdicted*' positron fraction

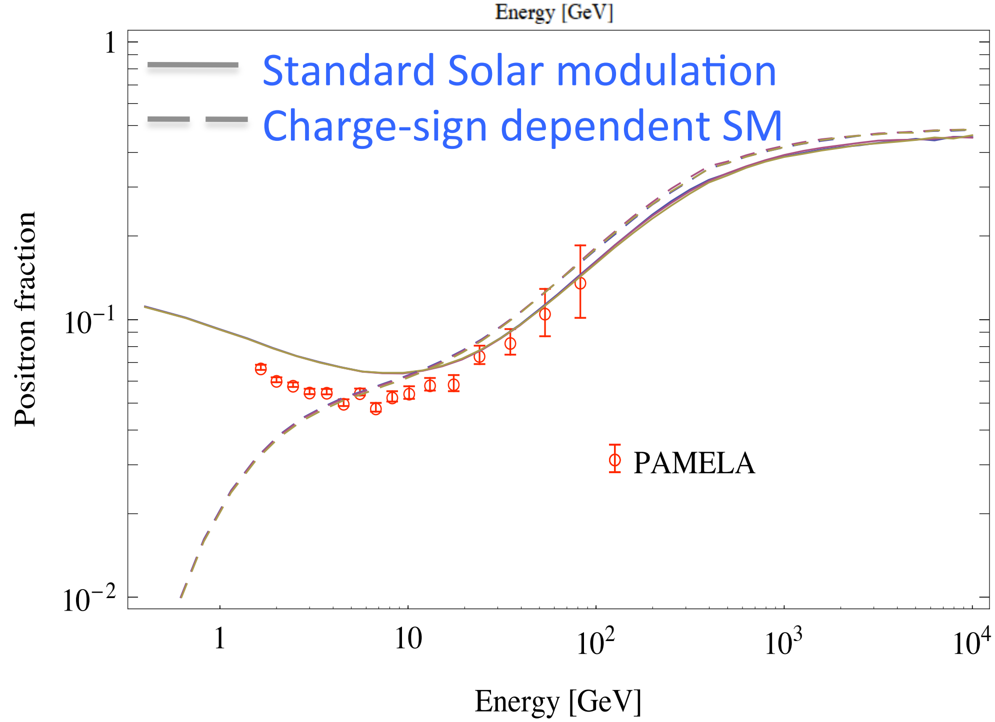
This also allows us to identify just which configurations of supernova remnants in our simulations corresponds to the *real* Galaxy

(Only 6 out of 10,000 runs give good fit to observed $e^{-}+e^{+}$ spectrum)





... and we can read off the positron fraction for these configurations, finding it to be rising with energy as observed!



Ahlers, Mertsch, Sarkar, PRD80:123017,2009

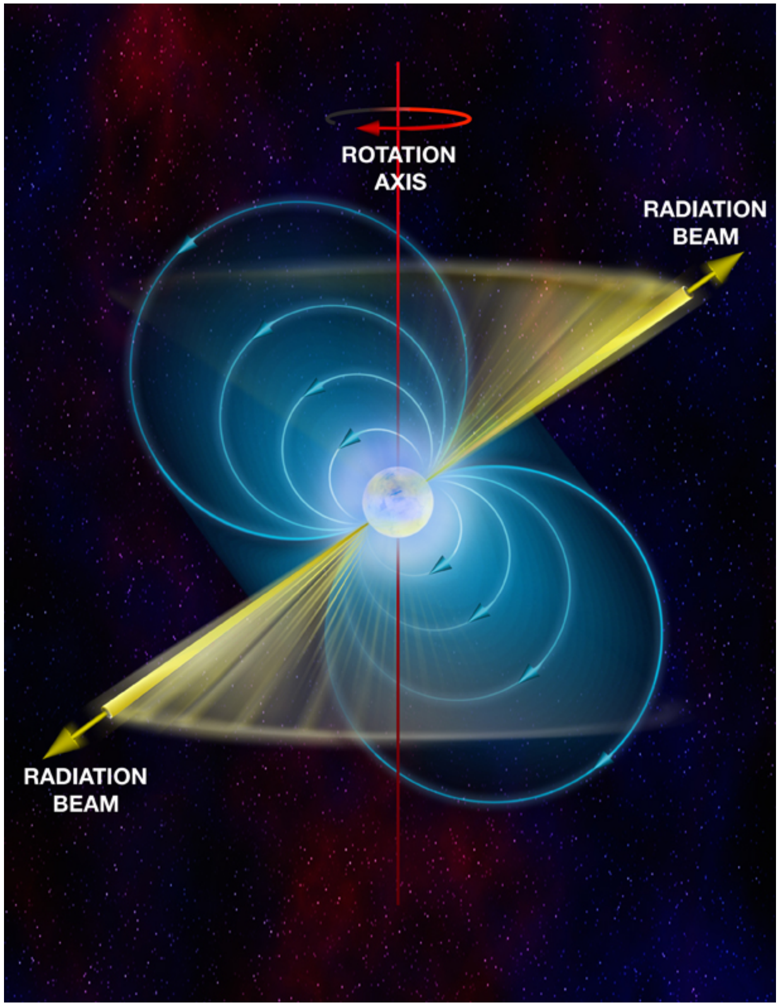
Nearby pulsars can also be source of $e^{\pm}$

- Highly magnetized, fast spinning neutron stars

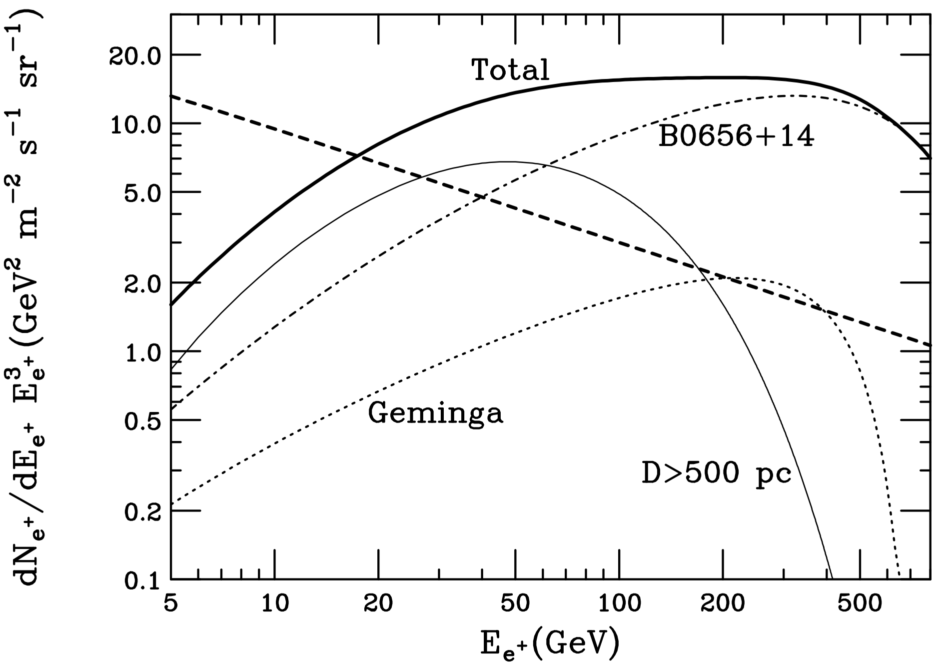
- γ -rays and electron/positron pairs produced along the magnetic axis

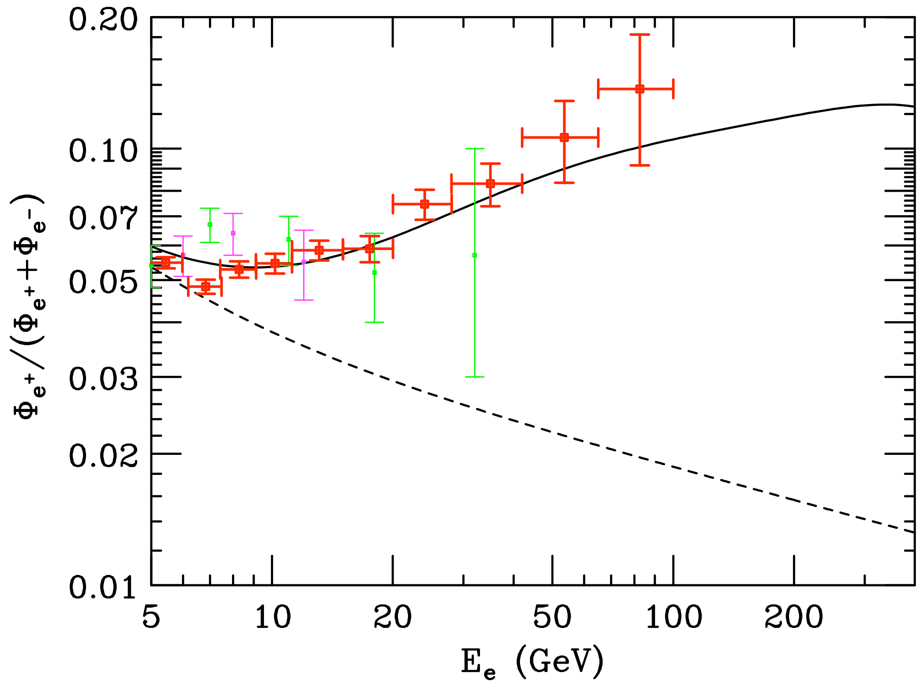
- Spectrum is *hypothesised* to be harder than background from propagation:

$$N \propto E_e^{\pm\,-1.6} e^{-E_e^{\pm}/100\,\mathrm{GeV}}$$



Combination of Galactic contribution and two nearby pulsars, **Geminga** (157 pc) and **B0656+14** (290 pc), *can* ideed fit the *PAMELA/AMS-02* excess





Hooper, Blasi & Serpico, JCAP 0901:025,2009

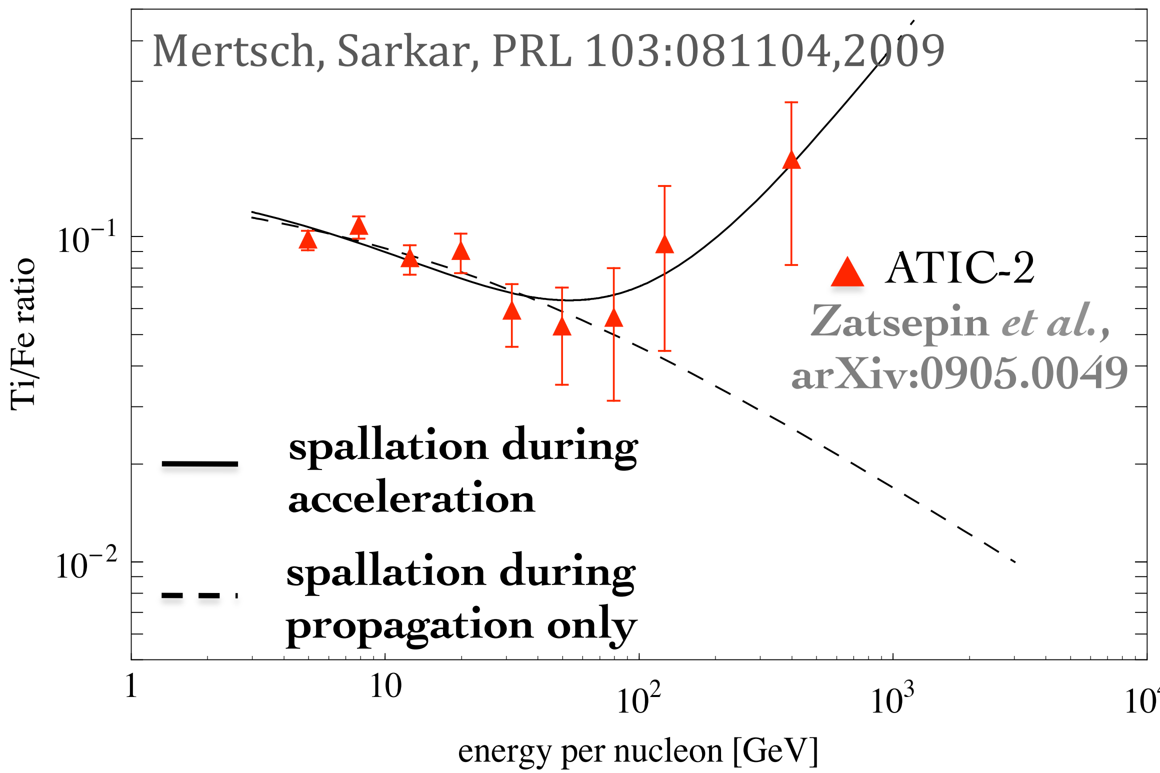
However ~40% of rotational energy must be released as energetic e^+ ... is this plausible?

Nuclear secondary-to-primary Ratios

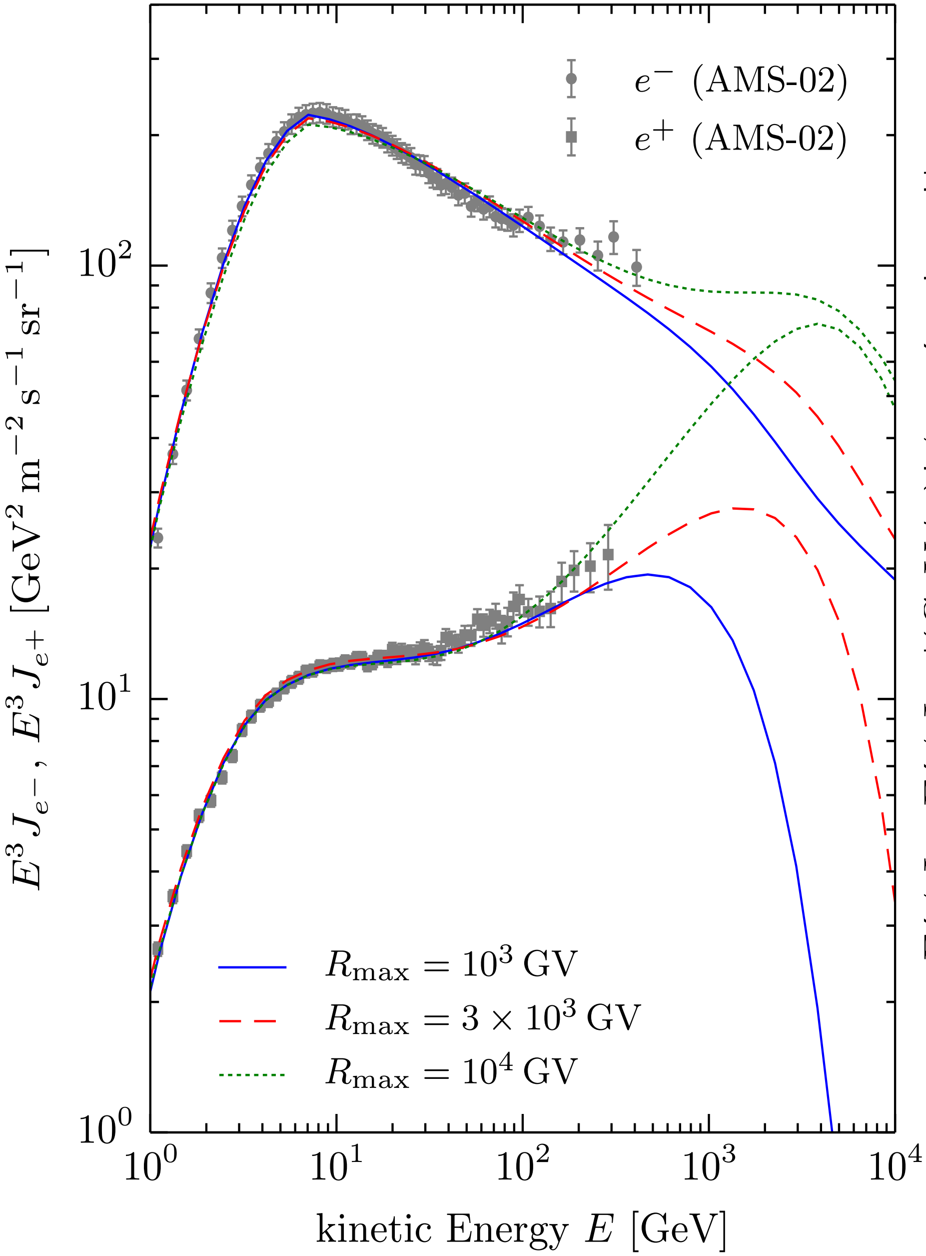
Dark matter	✗
Pulsars	✗
Acceleration of secondaries (TBD)	✓

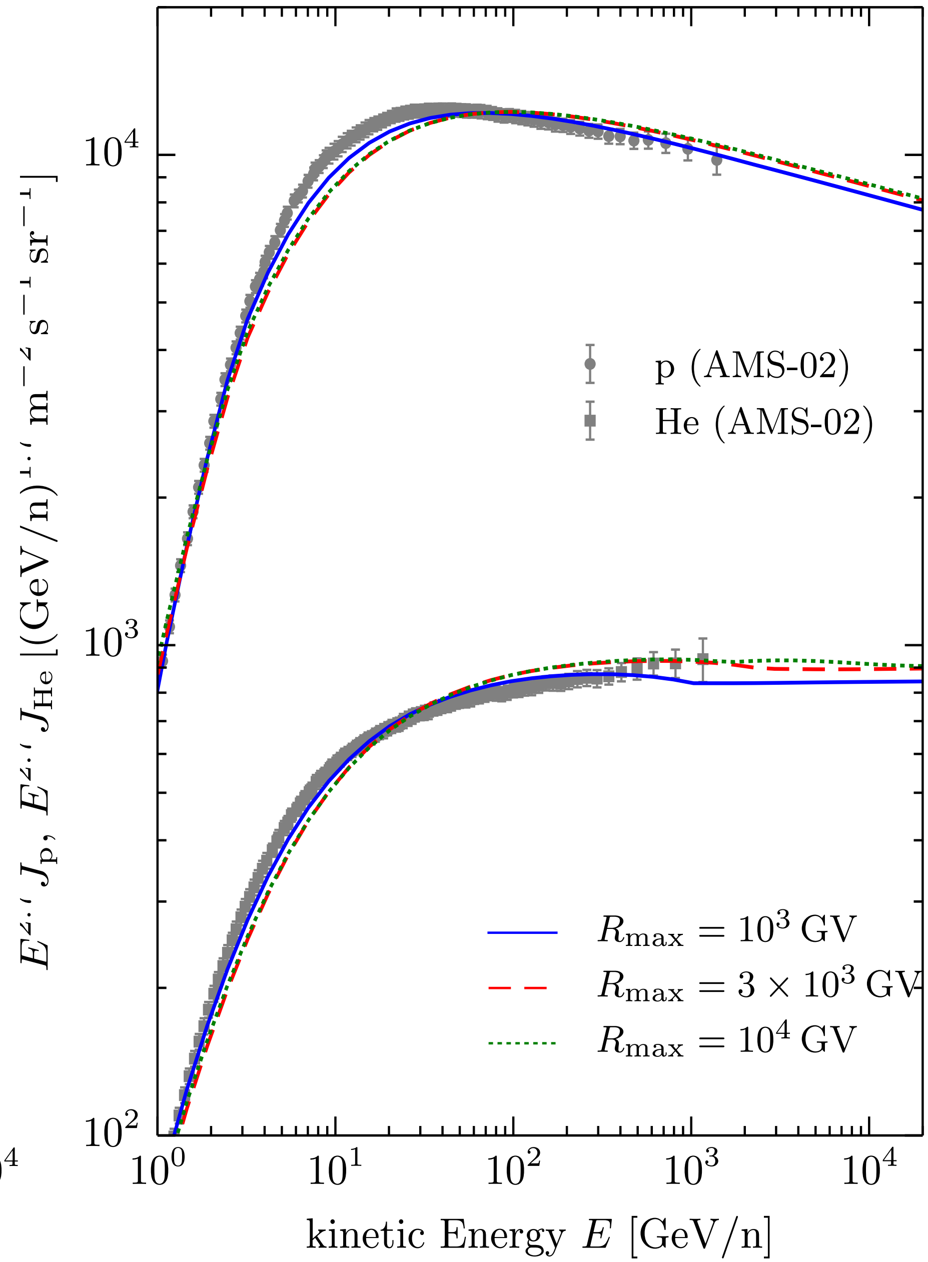
Since nuclei are accelerated in the *same* sources, the ratio of secondaries (e.g. Li, Be, B) to primaries (C, N, O) must also *rise* with energy beyond ~100 GeV

If this is confirmed, pulsar origin models would be ruled out along with dark matter!

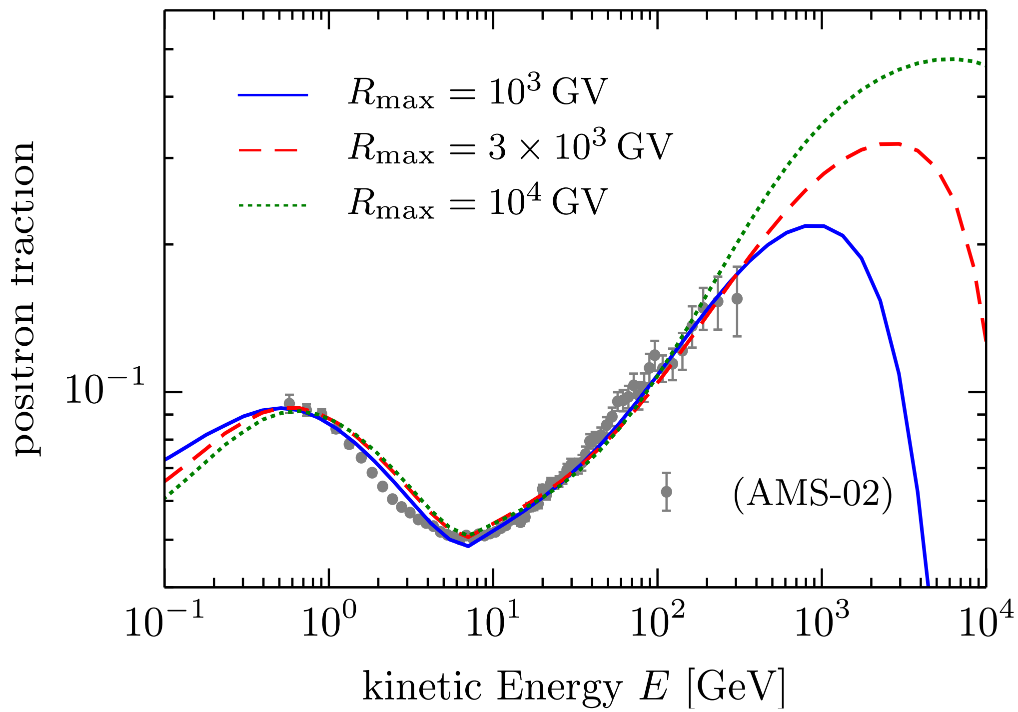


The AMS-02 *p*, *He* fluxes fix the spectral indices and normalisation, and the *e*⁻ flux must be fitted in accordance with radio data



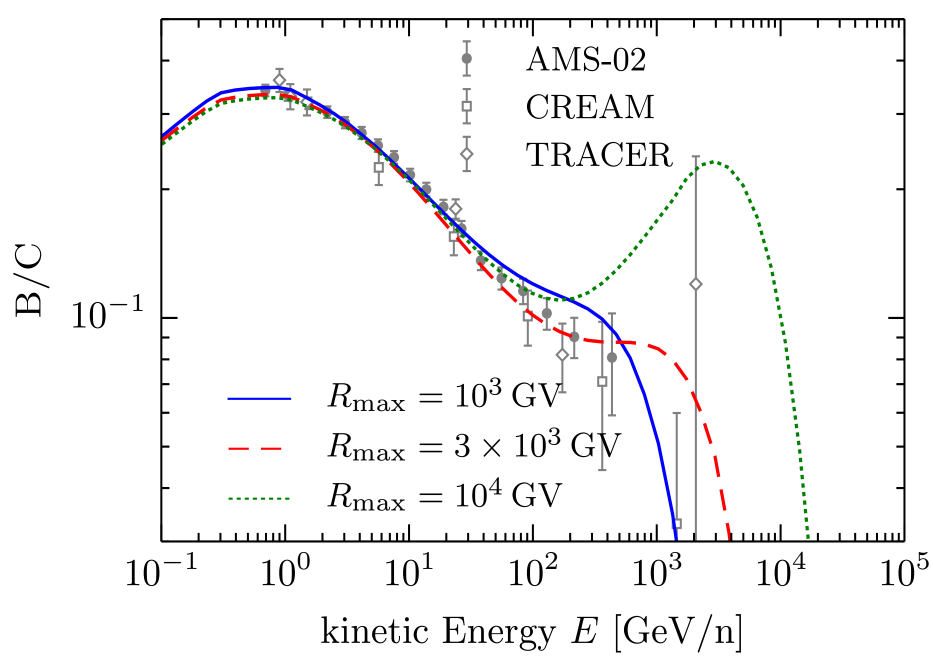


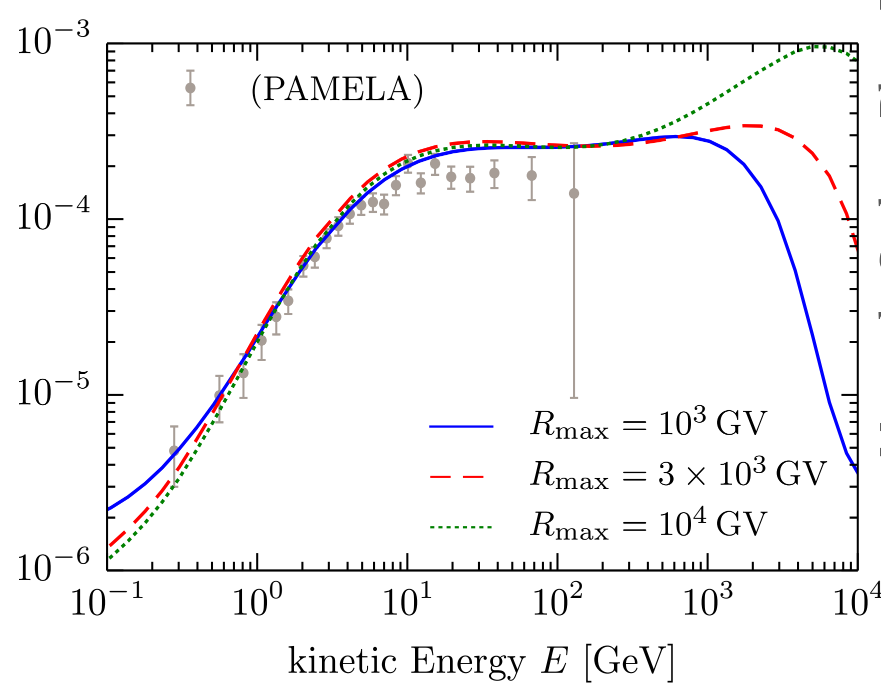
Mertsch, Sarkar, Phys.Rev.D90, 061301(R),2014



We can then fit as before, secondary/primary ratios e.g. the rising positron fraction *without* needing to invoke dark matter annihilations

B/C and the antiproton fraction are currently being measured to higher energies
… this will test the model





Mertsch, Sarkar, Phys.Rev.D90, 061301(R),2014

Summary

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

AMS-02 has confirmed the rising positron fraction in cosmic rays (first observed by PAMELA) … and this has been interpreted as due to the annihilation of ~TeV mass dark matter particles in the Galaxy

In both cases, the claims are seriously undermined by uncertainties in the modelling of the astrophysical foreground/background

These uncertainties must be quantified through a better understanding of the *conventional* physics before claims for new physics are made (just as establishing new phenomena in the lab depends on precise knowledge of SM processes)

… this becomes increasingly important as we come to rely on astroparticle arguments to motivate BSM physics in the absence of signals at the LHC