Cosmic rays and galactic dust: maverick-style

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SubirFest2023, Oxford
13 September 2023

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Where it all started

October 2007

PAMELA

In August 2008, a man took a photograph somewhere in Stockholm . . .

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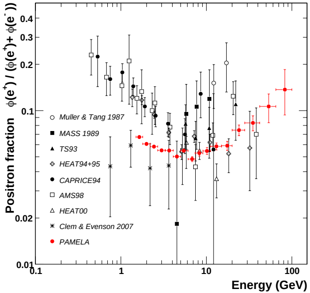

PAMELA

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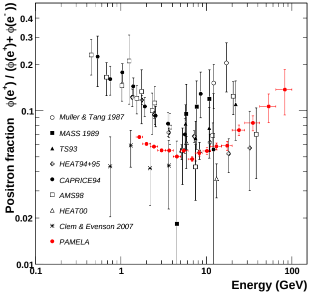

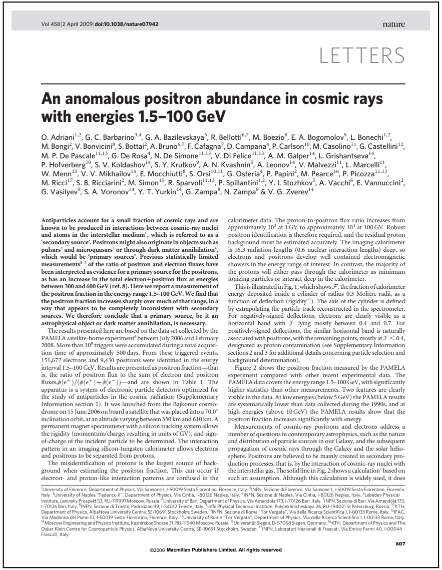

Vol 458 | 2 April 2009 | doi:10.1038/nature07942 nature

LETTERS

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

O. Adriani[1,2], G. C. Barbarino[3,4], G. A. Bazilevskaya[5], R. Bellotti[6,7], M. Boezio[8], E. A. Bogomolov[9], L. Bonechi[1,2], M. Bongi[2], V. Bonvicini[8], S. Bottai[2], A. Bruno[6,7], F. Cafagna[7], D. Campana[4], P. Carlson[10], M. Casolino[11], G. Castellini[12], M. P. De Pascale[11,13], G. De Rosa[4], N. De Simone[11,13], V. Di Felice[11,13], A. M. Galper[14], L. Grishantseva[14], P. Hofverberg[10], S. V. Koldashov[14], S. Y. Krutkov[9], A. N. Kvashnin[5], A. Leonov[14], V. Malvezzi[11], L. Marcelli[11], W. Menn[15], V. V. Mikhailov[14], E. Mocchiutti[8], S. Orsi[10,11], G. Osteria[4], P. Papini[2], M. Pearce[16], P. Picozza[11,13], M. Ricci[17], S. B. Ricciarini[2], M. Simon[15], R. Sparvoli[11,13], P. Spillantini[1,2], Y. I. Stozhkov[5], A. Vacchi[8], E. Vannuccini[2], G. Vasilyev[9], S. A. Voronov[14], Y. T. Yurkin[14], G. Zampa[8], N. Zampa[8] & V. G. Zverev[14]

Antiparticles account for a small fraction of cosmic rays and are known to be produced in interactions between cosmic-ray nuclei and atoms in the interstellar medium[1], which is referred to as a 'secondary source'. Positrons might also originate in objects such as pulsars[2] and microquasars[3] or through dark matter annihilation[4], which would be 'primary sources'. Previous statistically limited measurements[5–7] of the ratio of positron and electron fluxes have been interpreted as evidence for a primary source for the positrons, as has an increase in the total electron+positron flux at energies between 300 and 600 GeV (ref. 8). Here we report a measurement of the positron fraction in the energy range 1.5–100 GeV. We find that the positron fraction increases sharply over much of that range, in a way that appears to be completely inconsistent with secondary sources. We therefore conclude that a primary source, be it an astrophysical object or dark matter annihilation, is necessary.

The results presented here are based on the data set collected by the PAMELA satellite-borne experiment[9] between July 2006 and February 2008. More than 10^9 triggers were accumulated during a total acquisition time of approximately 500 days. From these triggered events, 151,672 electrons and 9,430 positrons were identified in the energy interval 1.5–100 GeV. Results are presented as positron fraction—that is, the ratio of positron flux to the sum of electron and positron fluxes, $\phi(e^+)/(\phi(e^+)+\phi(e^-))$—and are shown in Table 1. The apparatus is a system of electronic particle detectors optimized for the study of antiparticles in the cosmic radiation (Supplementary Information section 1). It was launched from the Bajkonur cosmodrome on 15 June 2006 on board a satellite that was placed into a 70.0° inclination orbit, at an altitude varying between 350 km and 610 km. A permanent magnet spectrometer with a silicon tracking system allows the rigidity (momentum/charge, resulting in units of GV), and sign-of-charge of the incident particle to be determined. The interaction pattern in an imaging silicon-tungsten calorimeter allows electrons and positrons to be separated from protons.

The misidentification of protons is the largest source of background when estimating the positron fraction. This can occur if electron- and proton-like interaction patterns are confused in the calorimeter data. The proton-to-positron flux ratio increases from approximately 10^3 at 1 GV to approximately 10^4 at 100 GV. Robust positron identification is therefore required, and the residual proton background must be estimated accurately. The imaging calorimeter is 16.3 radiation lengths (0.6 nuclear interaction lengths) deep, so electrons and positrons develop well contained electromagnetic showers in the energy range of interest. In contrast, the majority of the protons will either pass through the calorimeter as minimum ionizing particles or interact deep in the calorimeter.

This is illustrated in Fig. 1, which shows $\mathcal{F}$, the fraction of calorimeter energy deposited inside a cylinder of radius 0.3 Molière radii, as a function of deflection (rigidity^{-1}). The axis of the cylinder is defined by extrapolating the particle track reconstructed in the spectrometer. For negatively-signed deflections, electrons are clearly visible as a horizontal band with $\mathcal{F}$ lying mostly between 0.4 and 0.7. For positively-signed deflections, the similar horizontal band is naturally associated with positrons, with the remaining points, mostly at $\mathcal{F} < 0.4$, designated as proton contamination (see Supplementary Information sections 2 and 3 for additional details concerning particle selection and background determination).

Figure 2 shows the positron fraction measured by the PAMELA experiment compared with other recent experimental data. The PAMELA data covers the energy range 1.5–100 GeV, with significantly higher statistics than other measurements. Two features are clearly visible in the data. At low energies (below 5 GeV) the PAMELA results are systematically lower than data collected during the 1990s, and at high energies (above 10 GeV) the PAMELA results show that the positron fraction increases significantly with energy.

Measurements of cosmic-ray positrons and electrons address a number of questions in contemporary astrophysics, such as the nature and distribution of particle sources in our Galaxy, and the subsequent propagation of cosmic rays through the Galaxy and the solar heliosphere. Positrons are believed to be mainly created in secondary production processes, that is, by the interaction of cosmic-ray nuclei with the interstellar gas. The solid line in Fig. 2 shows a calculation[1] based on such an assumption. Although this calculation is widely used, it does

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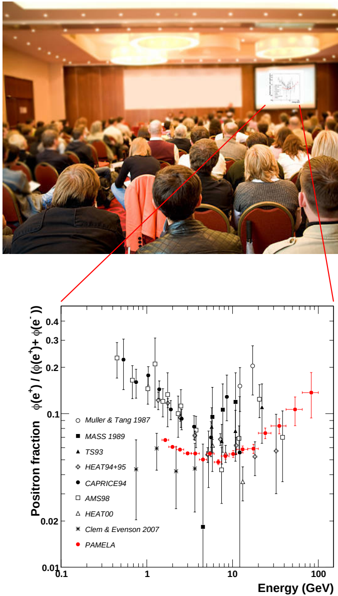
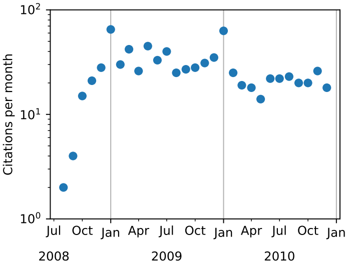
PAMELA

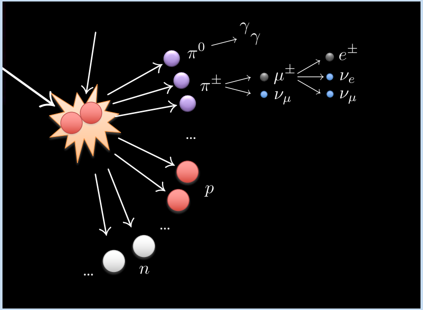
In August 2008, a man took a photograph somewhere in Stockholm . . .





Positron excess

Secondary



- e^+ from spallation of cosmic ray nuclei on gas
- Energy losses make $\mathrm{e}^\pm$ spectrum softer

$\rightarrow$ Positron fraction $\mathrm{e}^+/(\mathrm{e}^+ + \mathrm{e}^-)$ should decrease with energy

Positron excess

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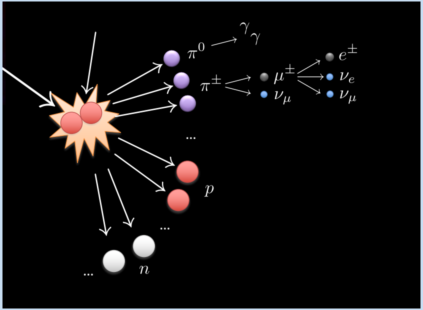

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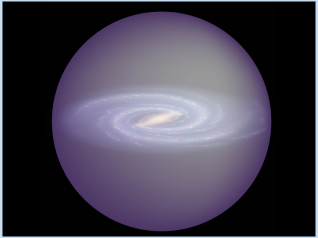
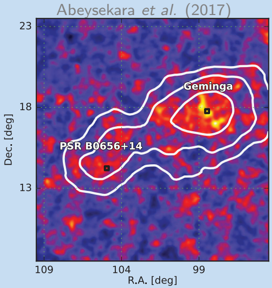
Dark matter



Now strongly constrained by γ-rays, $\bar{p}$, CMB!

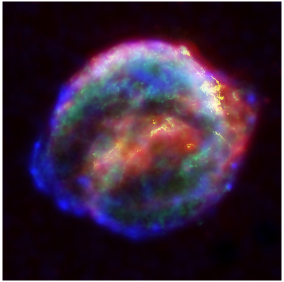
Pulsars/PWNe



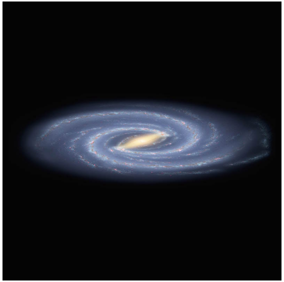
Must be contributing at some level?!

Secondaries from the source?

Common belief: secondaries from propagation dominate
since the grammage in the ISM is larger than in the source



$$\langle \tau_{\mathrm{src}} \rangle \lesssim \tau_{\mathrm{SNR}} \approx 10^{4\ldots5}\,\mathrm{yr}$$
$$n_{\mathrm{src}} \lesssim 10\,\mathrm{cm}^{-3}$$
$$\Rightarrow X_{\mathrm{src}} \approx 0.2\,\mathrm{g\,cm}^{-2}$$



$$\langle \tau_{\mathrm{ISM}} \rangle \sim \tau_{\mathrm{esc}} \approx 10^{7}\,\mathrm{yr}$$
$$n_{\mathrm{ISM}} \approx 0.1\,\mathrm{cm}^{-3}$$
$$\Rightarrow X_{\mathrm{ISM}} \approx \mathrm{few}\,\mathrm{g\,cm}^{-2}$$

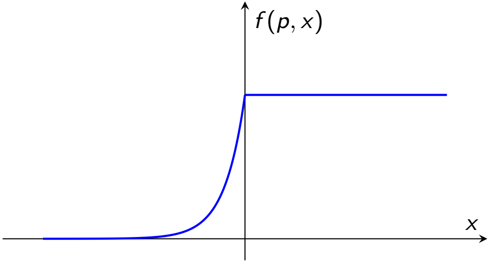
However, secondaries from source can have a harder spectrum!

Diffusive shock acceleration with secondaries

Blasi (2009); Blasi & Serpico (2009); Mertsch & Sarkar (2009); Ahlers *et al.* (2010); Tomassetti & Donato (2012); Cholis & Hooper (2012); Mertsch & Sarkar (2014); Cholis *et al.* (2017); Mertsch, Vittino, Sarkar (2021); Kawanaka & Lee (2021)

Spatial distribution

Primaries



Spectral distribution

$$f(x=0, p) \propto p^{-\gamma} \quad \text{with } \gamma = \frac{3U_1}{U_1 - U_2}$$

$\Rightarrow E^{-2}$ spectrum

Diffusive shock acceleration with secondaries

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Spatial distribution

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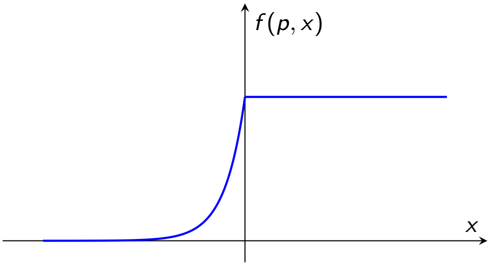
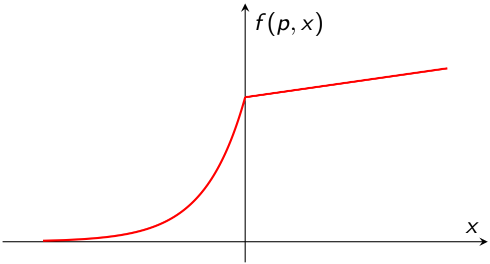


Secondaries



Spectral distribution

$$f(x=0,p) \propto p^{-\gamma} \quad \text{with } \gamma = \frac{3U_1}{U_1 - U_2}$$

$\Rightarrow E^{-2}$ spectrum

$$f(x=0,p) \propto p^{-\gamma+1}$$

$\Rightarrow$ Harder secondary spectrum

Secondary nuclei as a check

Mertsch & Sarkar, PRL 103 (2009) 081104

`On 17.03.09 14:47, Subir Sarkar wrote:`

> *However one can then ask why other secondary/primary ratios e.g. Li,Be,B/C,N,O in fact decrease with energy [. . .] So my question would be: if the same SNRs are also accelerating cosmic ray nuclei then is the expected secondary/primary ratio (according to Blasi's calculation) consistent with the observations?*

PRL **103,** 081104 (2009) PHYSICAL REVIEW LETTERS week ending 21 AUGUST 2009

Testing Astrophysical Models for the PAMELA Positron Excess with Cosmic Ray Nuclei

Philipp Mertsch and Subir Sarkar

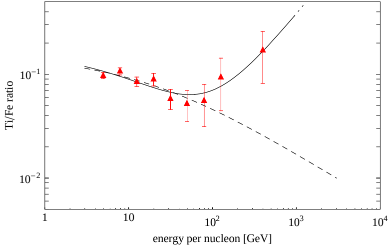
Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford OX1 3NP, United Kingdom

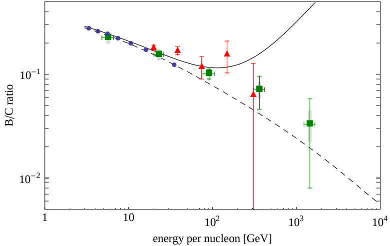
(Received 21 May 2009; revised manuscript received 9 July 2009; published 21 August 2009)

The excess in the positron fraction measured by PAMELA has been interpreted as due to annihilation or decay of dark matter in the Galaxy. More prosaically it has been ascribed to direct production of positrons by nearby pulsars or due to pion production during diffusive shock acceleration of hadronic cosmic rays in nearby sources. We point out that measurements of secondary cosmic ray nuclei can discriminate between these possibilities. New data on the titanium-to-iron ratio support the hadronic source model above and enable a prediction for the boron-to-carbon ratio at energies above 100 GeV.

DOI: 10.1103/PhysRevLett.103.081104 PACS numbers: 98.70.Sa, 96.50.sb, 98.58.Mj

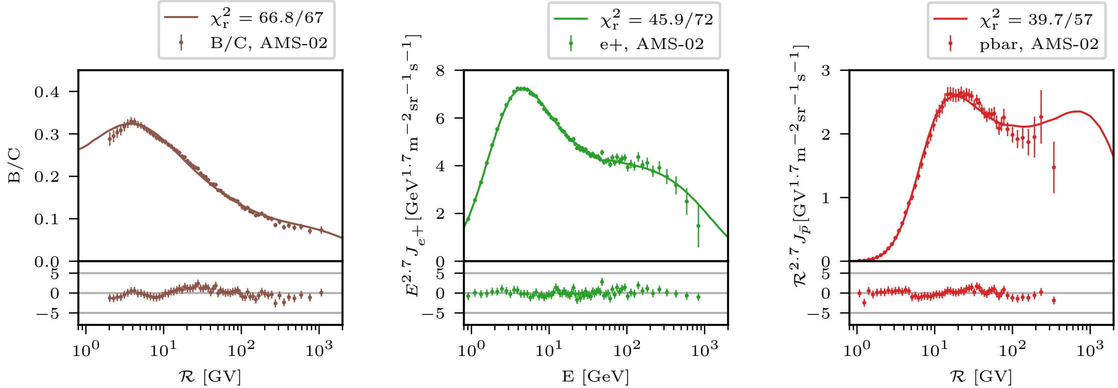
Tuned to ATIC data:





A recent update

Mertsch, Vittino, Sarkar, PRD 104 (2021) 103029



Further improvements

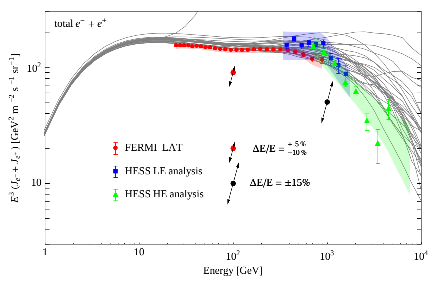
Ahlers, Mertsch, Sarkar (2009)

Stochasticity

- $e^{\pm}$ suffer severe energy losses

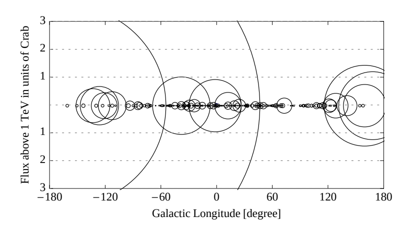
$\rightarrow$ Sensitivity to nearby sources

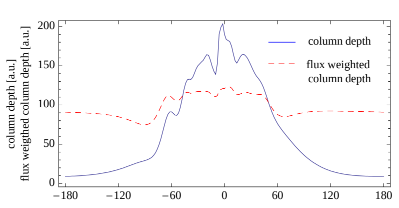
$\rightarrow$ Predictions are probabilistic



Gamma-rays

- If CR + gas $\rightarrow e^{\pm} + \ldots$, then also CR + gas $\rightarrow \gamma + \gamma$



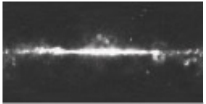


Exposure

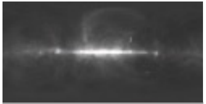



WMAP haze

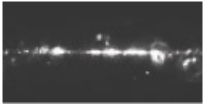
Claim by Finkbeiner (2004)



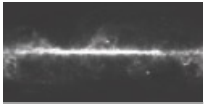
CMB-subtracted
WMAP K-band



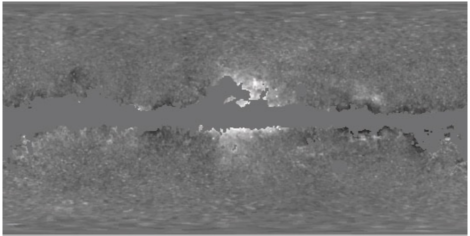
synchrotron



free-free



dust



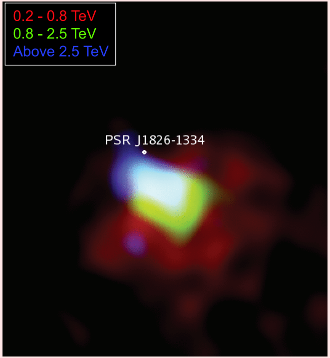
Dobler & Finkbeiner, ApJ **680** (2008) 1222

1. morphology: roughly spherical
2. power: few kJy sr^{-1}
3. spectrum: harder than usual synchrotron

Is the WMAP haze real?

Template subtraction assumes
that morphology
is energy-independent

Counter example



Funk *et al.*, ICRC proceedings (2007)

Is the WMAP haze real?

Template subtraction assumes
that morphology
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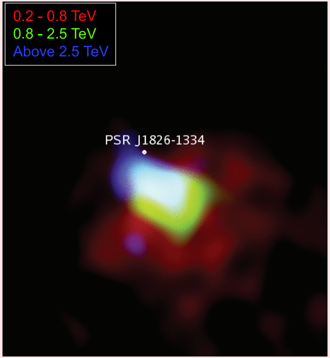
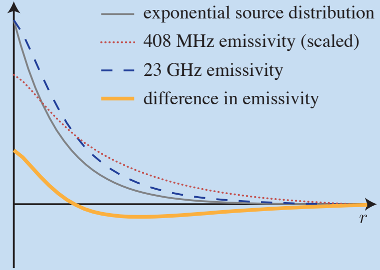
Counter example



Funk *et al.*, ICRC proceedings (2007)

Radial distribution of emissivity



Agrees with WMAP haze in ...

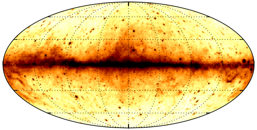
- Morphology
- Normalisation
- Spectrum

Mertsch & Sarkar, JCAP 10 (2010) 019

The Fermi bubbles

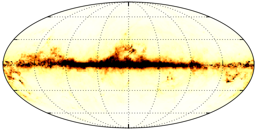
Su *et al.* (2010); Ackermann *et al.* (2013)

Fermi-LAT data



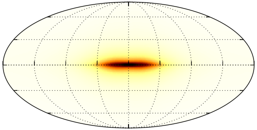
gas-correlated emission

-



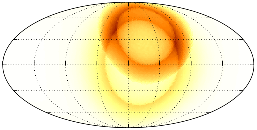
Inverse Compton model

-



some other stuff

-



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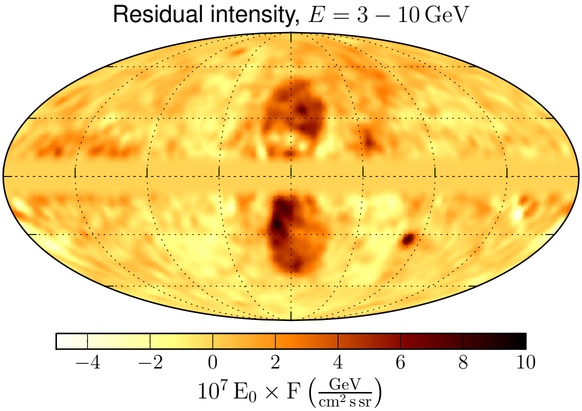
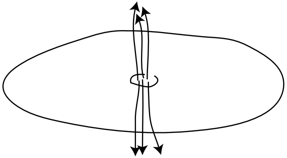


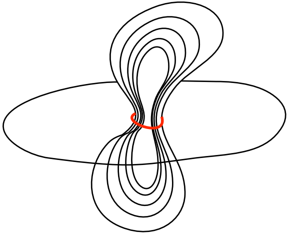
- Hard spectrum
- Sharp edges
- No spectral variation

Fermi bubbles

Star formation activity

Crocker & Aharonian (2011)





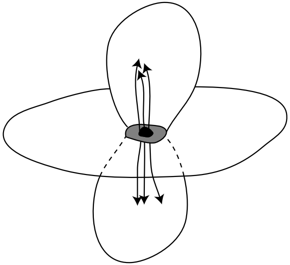
Tidal disruption events

Cheng *et al.* (2011)

Previous AGN phase

Guo & Mathews, ApJ 756 (2012) 181;

Yang et al., ApJ 761 (2012) 185



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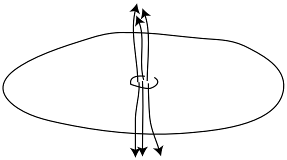

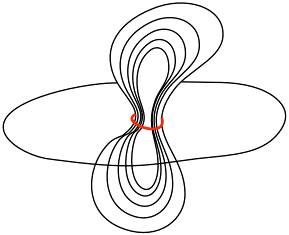

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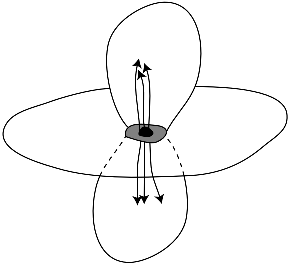

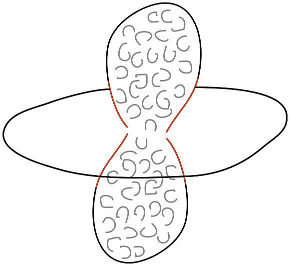

Large-scale turbulence

Mertsch & Sarkar (2011)

2nd order Fermi acceleration

Mon. Not. R. astr. Soc. (1984) **207**, 745–775

The evolution of supernova remnants as radio sources

Ramanath Cowsik and Subir Sarkar* *Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400005, India*

Received 1983 August 10; in original form 1982 July 9

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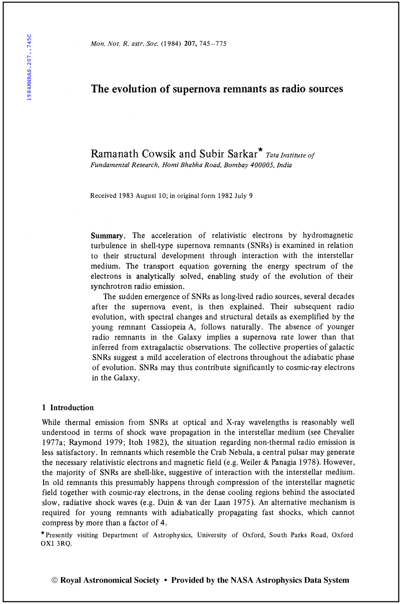
*Presently visiting Department of Astrophysics, University of Oxford, South Parks Road, Oxford OX1 3RQ.

2nd order Fermi acceleration



Mon. Not. R. astr. Soc. (1984) **207,** 745–775

The evolution of supernova remnants as radio sources

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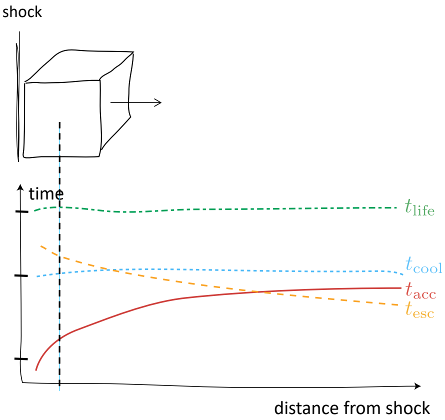

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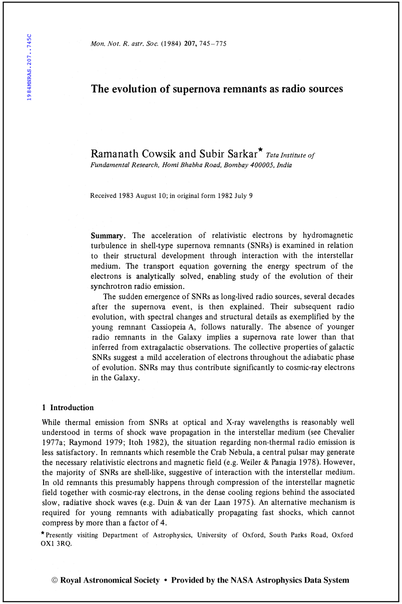

1984MNRAS.207..745C

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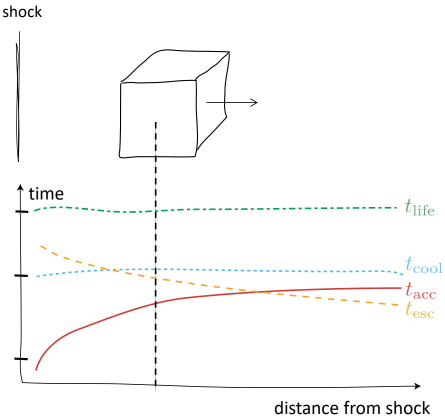

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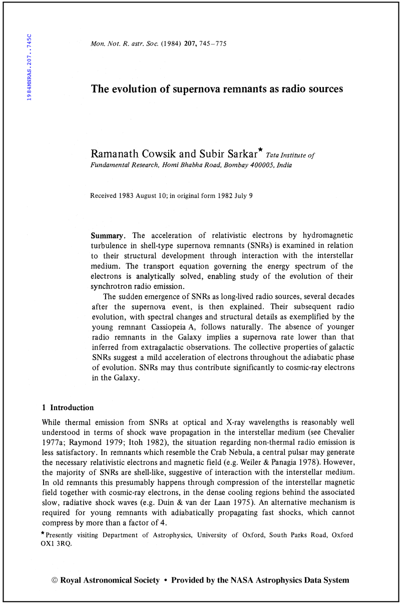

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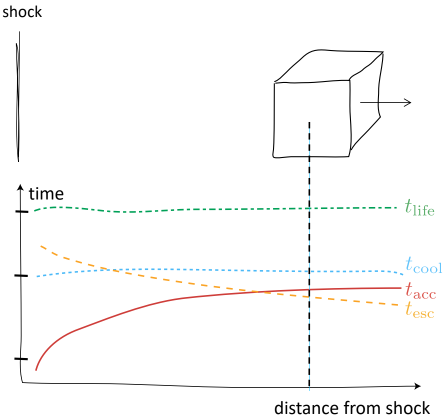
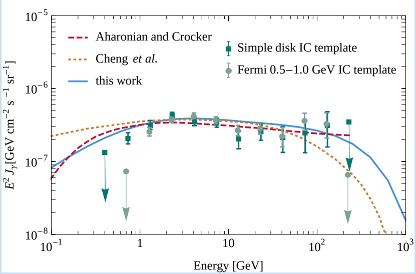


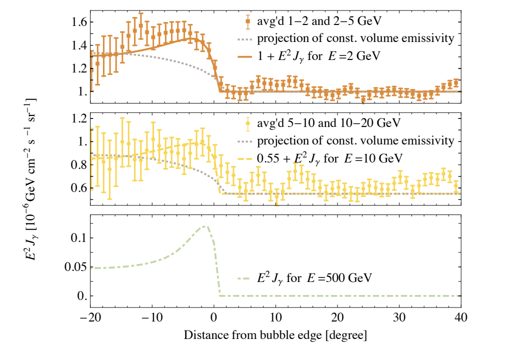
Fermi bubbles

Mertsch & Sarkar (2011)

Spectrum

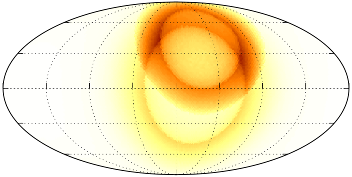


Profile



The elephant in the room

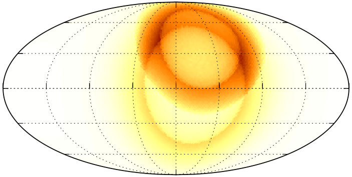
Banksy



The elephant in the room

Banksy

some other stuff



1982MNRAS.199...97S

Mon. Not. R. astr. Soc. (1982) 199, 97–108

Does the galactic synchrotron radio background originate in old supernova remnants?

Subir Sarkar *Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400005, India*

Received 1981 August 3; in original form 1981 May 7

Summary. Observations of the galactic synchrotron radio background indicate that the emission arises in localized regions of high emissivity. Various lines of evidence suggest that these are the radiative shells of old supernova remnants in which the synchrotron emissivity is enhanced due to compression of the interstellar magnetic field along with the correlated increase in the energy density of cosmic ray electrons. This possibility is consistent with recent observations of the interstellar medium that imply the presence of a large amount of hot, low density gas in the galaxy. In such a medium supernova remnants would expand to large radii before becoming radiative.

The intensity of the background can then be understood without needing to evoke higher magnetic fields or cosmic ray electron fluxes than are obtained from other observations. In this picture, the fluctuating component of the galactic magnetic field arises from the distortion of the regular field by the shells.

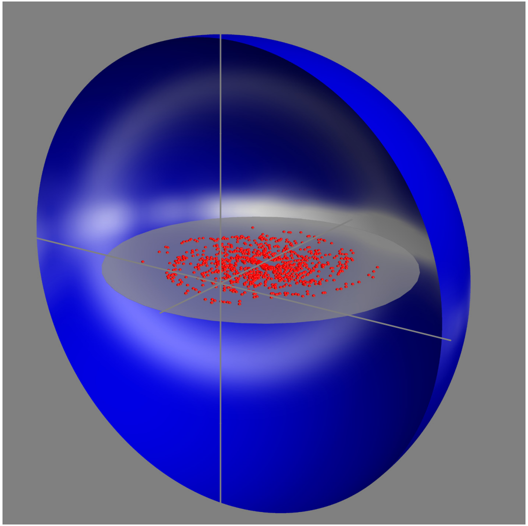
Other explanations for the origin of the background are briefly discussed. This result casts doubt on the existence of large-scale cosmic ray gradients inferred from galactic gamma ray observations.

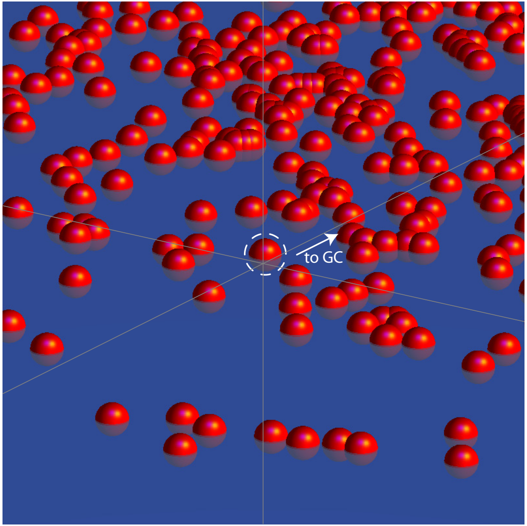
1 Introduction

The 'standard' interpretation of the diffuse galactic synchrotron radio background as due to cosmic ray electrons radiating uniformly throughout the Galaxy leads to the well-known discrepancy between the observed and calculated strength of the emission (*cf.* Daniel & Stephens 1975). To reconcile them it appears necessary to postulate either much higher electron fluxes elsewhere in the Galaxy than observed locally (Setti & Woltjer 1971) or much higher magnetic fields than are obtained from other observations (e.g. Badhwar, Daniel & Stephens 1977). As a conceptual way out of this difficulty, Cowsik & Mitteldorf (1974) have suggested that if fluctuations in the galactic magnetic field arise from compressions of the average fields by motions of the interstellar gas, then betatron processes induce a correlated increase of the relativistic electron energy density in the high field regions. The enhanced synchrotron emission from such regions then raises the average interstellar emissivity to match the observations.

4

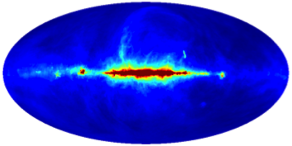
Where is Loop I?

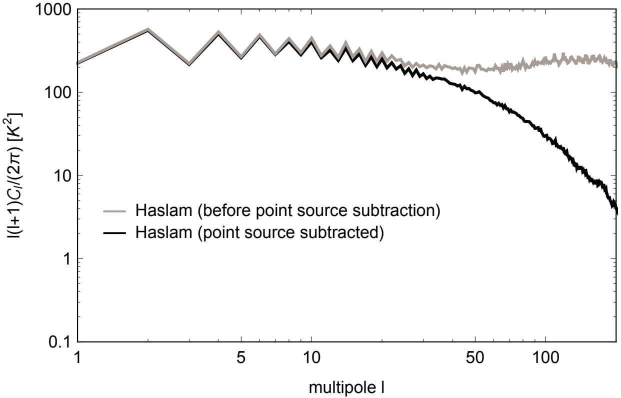




Are the $\mathcal{O}(1000)$ other old supernova remnants visible?

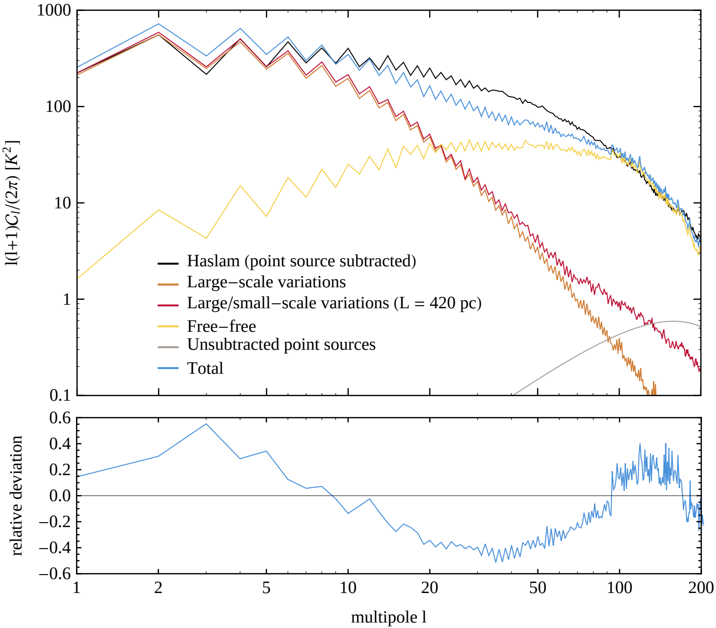
Haslam 408 MHz survey

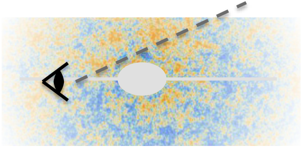




1. Even/odd structure ⇔ symmetry of Galactic disk
2. On large scales: less fluctuations
3. On large scales: power-law behaviour

GALPROP + turbulence + free-free + pt. sources

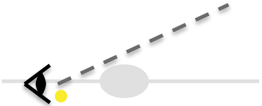




- Synchrotron from turbulent **B**-field
- Free-free: thermal bremsstrahlung
- Unsubtracted point sources: shot noise

Deficit in angular power spectrum

Modelling shells in harmonic space



Assumption: flux from one shell factorises into angular part and frequency part,

$$J_{\text{shell},i}(\nu, \ell, b) = \varepsilon_i(\nu) g_i(\ell, b)$$

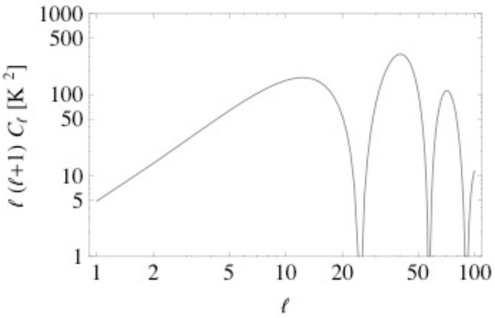
Frequency part $\varepsilon_i(\nu)$:

- Magnetic field compressed in SNR shell
- Electrons get betatron accelerated
- Emissivity increased with respect to ISM

Angular part $g_i(\ell, b)$:

Assume constant emissivity in thin shell:

$$a_{\ell m}^{(i)\prime} \sim \varepsilon_i(\nu) \int_{-1}^{1} \mathrm{d}z' \, \mathrm{P}_\ell(z') g_i(z')$$



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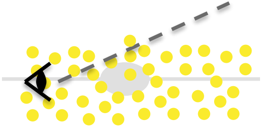

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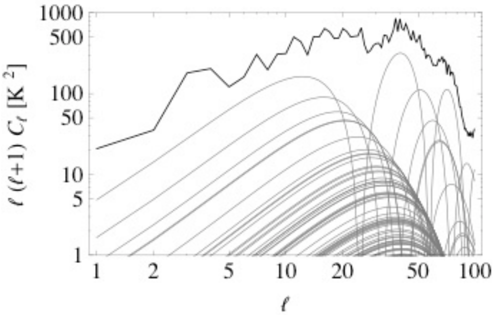
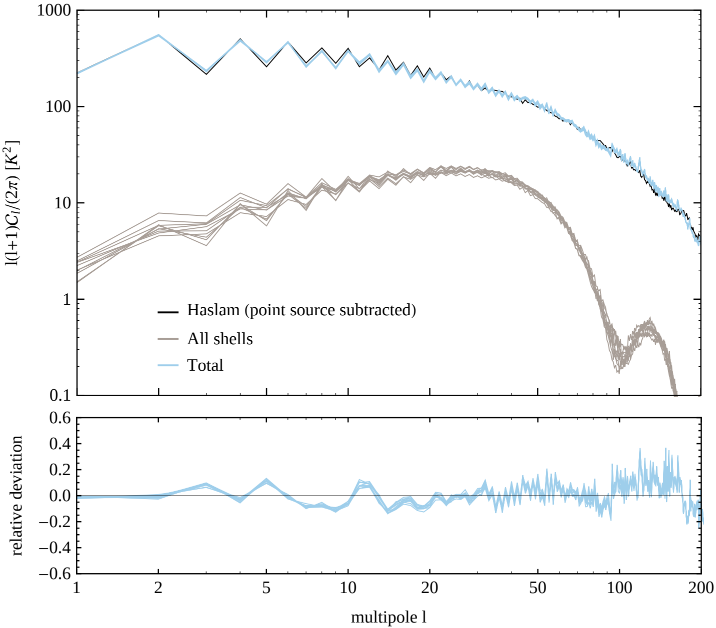
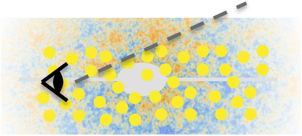


GALPROP + turbulence + free-free + pt. sources + shells

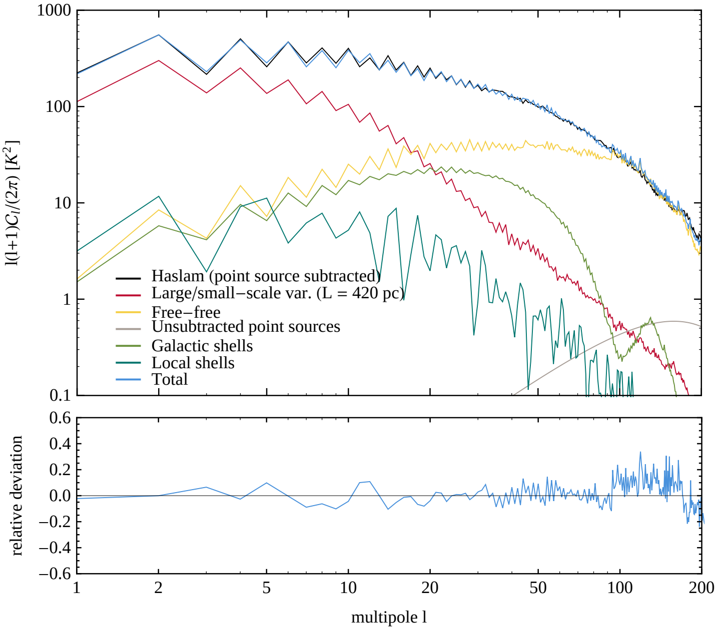


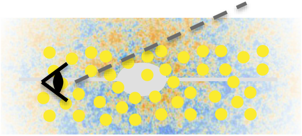


- Synchrotron from turbulent **B**-field
- Free-free: thermal bremsstrahlung
- Unsubtracted point sources: shot noise
- $\mathcal{O}(1000)$ shells of old supernova remnants

Contribute on exactly the right angular scales

GALPROP + turbulence + free-free + pt. sources + shells





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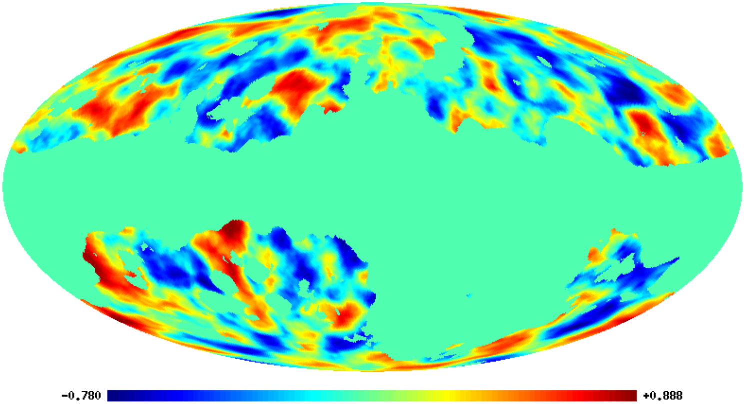
Contribute on exactly the right angular scales

CMB contamination at high latitudes?

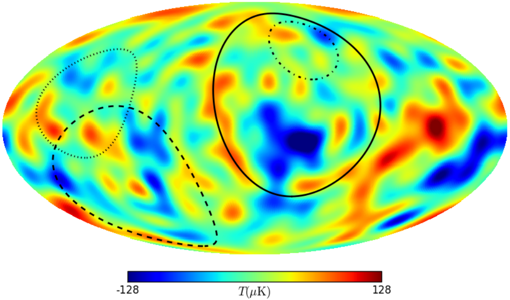


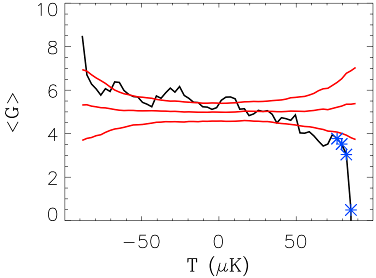
- Correlation between Faraday depth and WMAP7 ILC
- MC simulations: standard deviation of correlation anomalous with p-value $< 5 \times 10^{-4}$

Hansen *et al.*, MNRAS 426 (2012) 57; Dineen & Coles, MNRAS 347 (2004) 52

Anomalies in ILC9 ($\ell \leq 20$)

Liu, Mertsch & Sarkar, ApJL 789 (2014) 29





- Black: Loops I-IV Berkhuijsen, Salter (1971)
- Avergae temperature and skewness: p-values at 10^{-2} level

- Distance of clusters from ring: p-value 10^{-4}

BICEP2

In early March 2014, a man knocked on a door somewhere in Silicon Valley . . .

BICEP2

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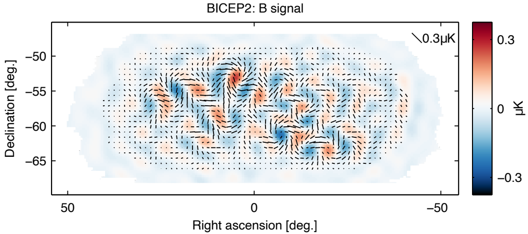
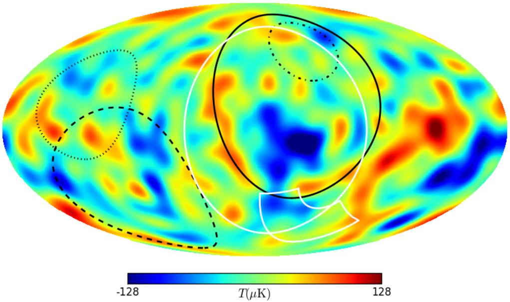


Ade *et al.*, PRL 112 (2014) 241101

- Observation of B-mode polarisation of the CMB, $r = 0.2$ at $\gtrsim 5\sigma$ significance
- Evidence for cosmological inflation
- Foreground contamination excluded

Anomalies in ILC9 ($\ell \leq 20$)

Liu, Mertsch & Sarkar, ApJL 789 (2014) 29



- Black: Loops I-IV Berkhuijsen, Salter (1971)
- White: S1 Wolleben (2007) and BICEP2 field

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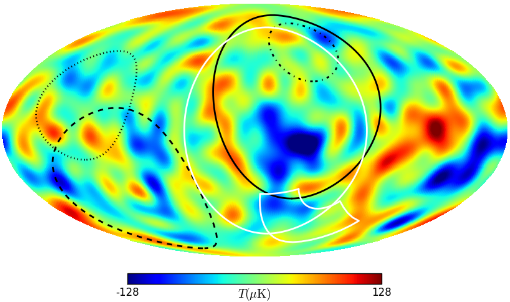


- Black: Loops I-IV Berkhuijsen, Salter (1971)
- White: S1 Wolleben (2007) and BICEP2 field

Added an innocent comment to last paragraph:

- Wolleben loop S1 goes through BICEP field
- Radio loops usually not modelled
- This can affect the significance

10 minutes in the (cosmo) spot light

- Some coverage by the Washington Post, New Scientist, Physics World, Die Zeit
- From the facebook thread "Live Discussion of BICEP Press Conference":

Scott Dodelson
Admin · 8 April 2014 ·

Any thoughts about http://arxiv.org/abs/1404.1899?

ARXIV.ORG
[1404.1899] Fingerprints of Galactic Loop I on the Cosmic Microwave Background

27 38 comments

Like Comment Send

. . .

[redacted]
These guys need to analyze the foreground cleaned Planck CMB maps, not just the WMAP ILC map. The spurs are known to have steeper spectral indices than the average synchrotron, and the ILC method cannot account for this. However, other methods do, so it's critical to check that this isn't just an ILC issue. Quite surprised they didn't already present those results, actually...

Like 9 y 3

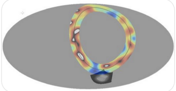
[redacted]
I strongly dislike papers that throw out a line at the end like: "this is a potential systematic for observation X or experiment Y" with zero quantitative backing to that statement.

Oh, and the 150x100 correlation in the bicep2 paper is with bicep1 data; the correlation with keck is all at 150.

Like 9 y 5

. . .

[redacted]
Things you do when you're in an all-day meeting: I grabbed Fig. 24, bottom left panel, from the BICEP2 instrument paper, reprojected it from Cartesian projection to Healpix pixelization, and overlaid it on Fig. 2 from 1404.1899. The full BICEP2 region just barely touches the loop, and the main, high-N_obs region is never less than 10 degrees away. Put more simply, Loop 1 extends to galactic latitude of about -40, while the important BICEP2 region is never higher than -50.



Like 9 y 20

. . .

Arman Shflu
Philipp Mertsch

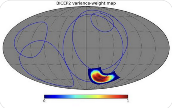
Like 9 y

Philipp Mertsch
Sorry, just catching up with this now:

Hans Kristian, we have studied the Planck SMICA map, also the map by Starck et al. (arXiv:1401.6016 [astro-ph.CO]), but this part of the analysis didn't make it into the final paper. I'm confident that whoever repeats our analysis with those maps will find largely the same results.

Tom, please note that we did not claim a systematic in the BICEP2 measurement, but instead pointed out that the foreground models they refer to lack an ingredient that we know must be there: radio loops. If it turns out it's negligible: fine, but don't you think it's worth checking?

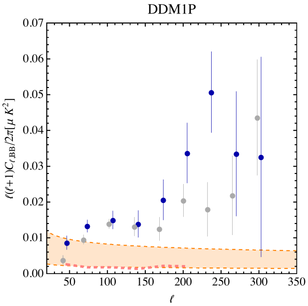
Finally, thanks, Dave and Colin, for emphasising that in our conclusion we were mainly referring to Wolleben's "New Loop". It is shown together with Loops I-IV (as defined by Berkhuijsen et al. in the early 70ies) and the variance-weighted BICEP2 field in this figure. The upper large loop roughly around the Galactic centre is Loop I, the lower one (cutting right through the BICEP2 field) is Wolleben's "New Loop".



Like 9 y 4

How this got resolved

- BICEP2 used some preliminary Planck polarisation fractions for foreground model
- Some ambiguity as to zero-levels and cosmic infrared background (CIB)
- Likely some underestimate of foregrounds



R. Flauger, "Simplicity" workshop (2014)

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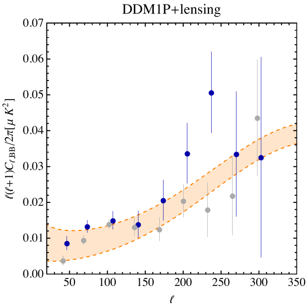

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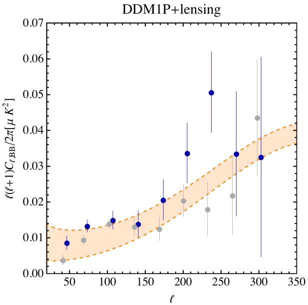
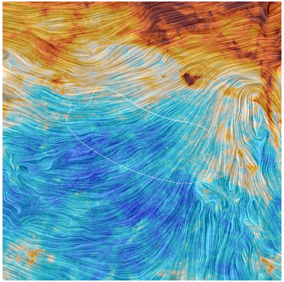
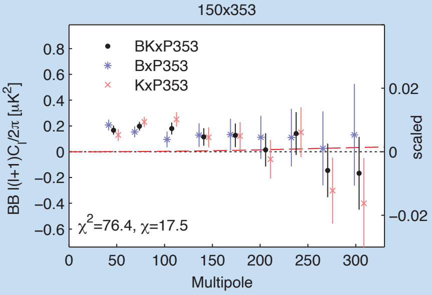


R. Flauger, "Simplicity" workshop (2014)

Planck view of BICEP2 field:



Joint Planck-BICEP2 analysis



"$r < 0.12$ at 95 % confidence"

Thank you, Subir,

- for giving me the freedom to choose my own projects,
- for giving me exposure with the community,
- for instilling critical thinking in me!

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