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Synchrotron Surveys and their Astrophysical Interpretation

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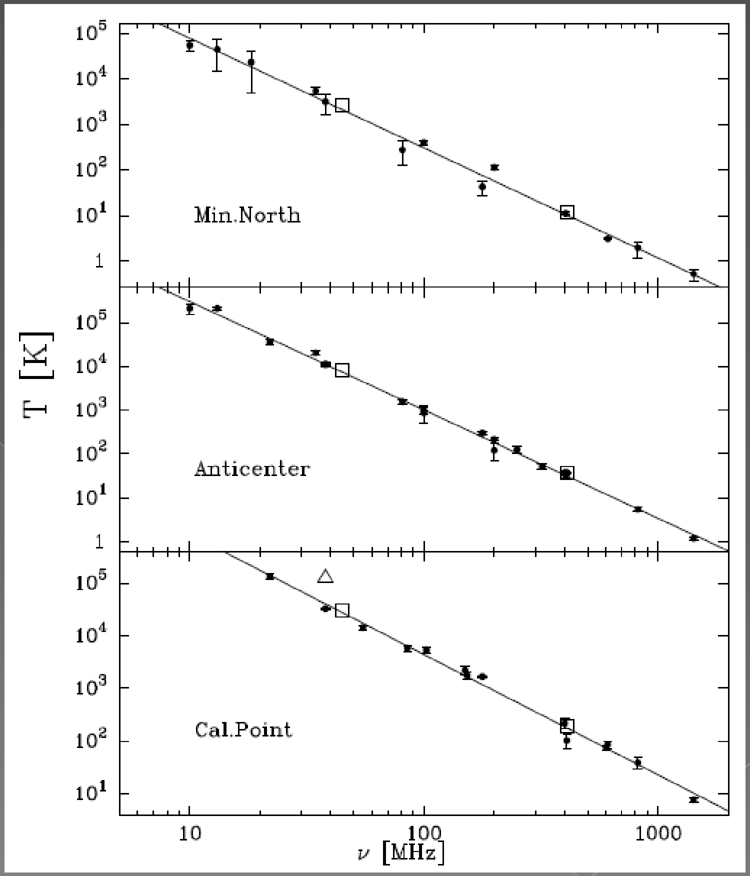
Picture: GALFACTS Collaboration

What we talk about when we talk about Synchrotron Radiation

- Cosmic ray leptons (electrons, mostly)
  - Origin
  - Propagation
  - Distribution
- Magnetic Fields (at source)
  - Structure
    - Coherent/Ordered/Random
  - Intensity
- Propagation effects
  - Faraday Rotation
  - Free-free absorption

50 First surveys

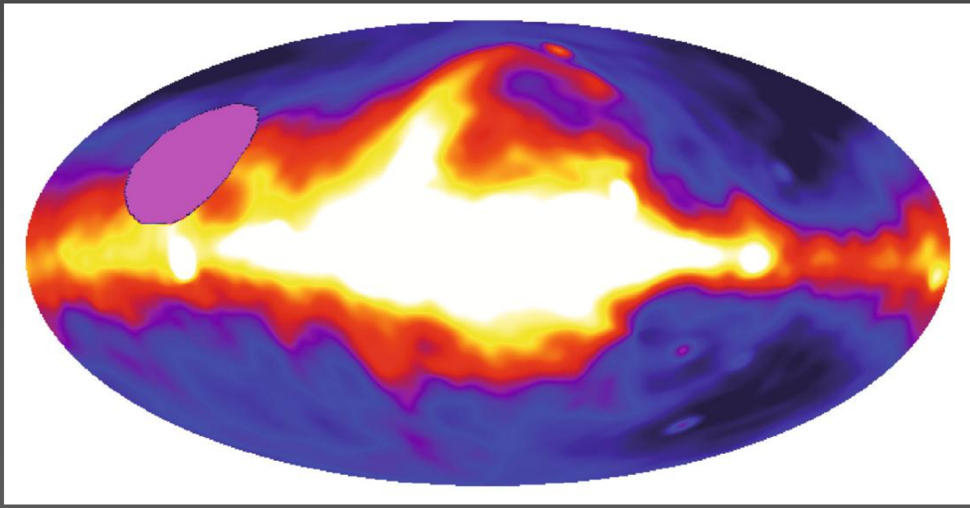
- Many surveys exist but quality uneven
  - Strong et al (2011) for an up-to-date list
- Complications:
  - Below 300 MHz: free-free absorption, especially in the plane
  - Above 1 GHz: free-free emission
  - Below 5 GHz Faraday rotation
  - Above 10 GHz: AME

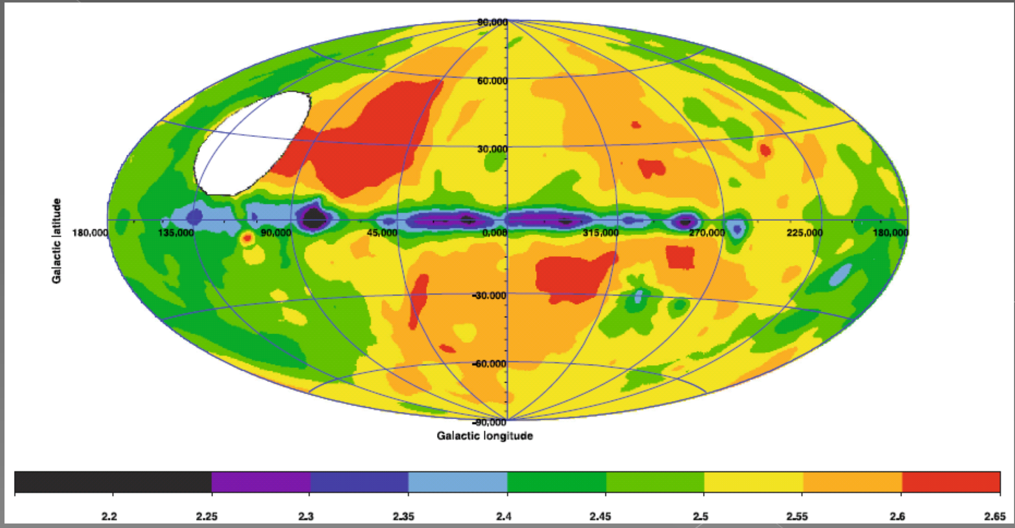


Guzmán et al 2011

45 MHz Survey

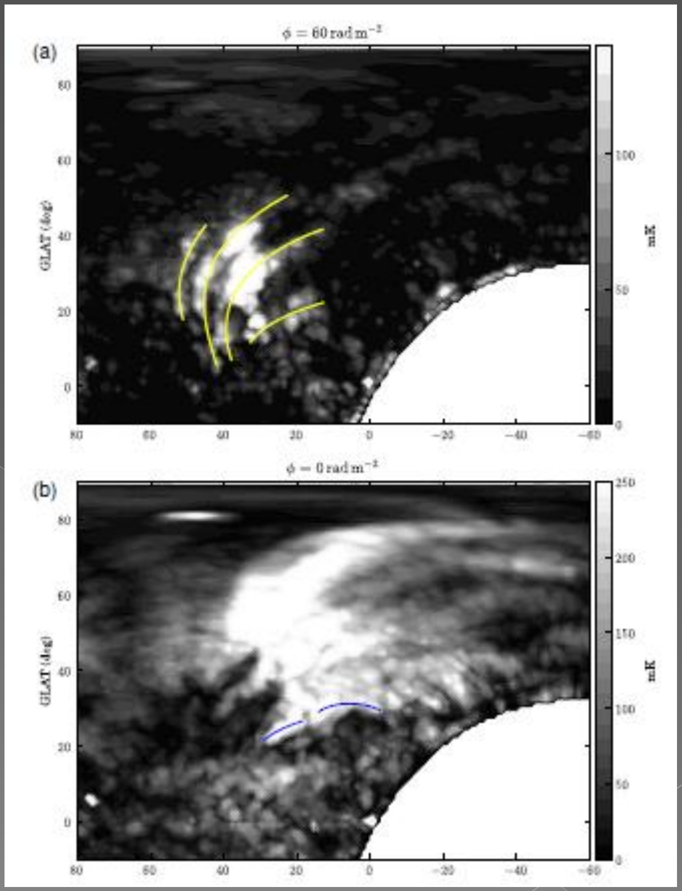
- Dipole arrays
  - Japan (Maeda et al 1999)
  - Chile (Alvarez et al 1997)
- Merged map Guzmán et al (2011)
- Spectral index vs 408 MHz





GMIMS/STAPS: IQU at 21 cm

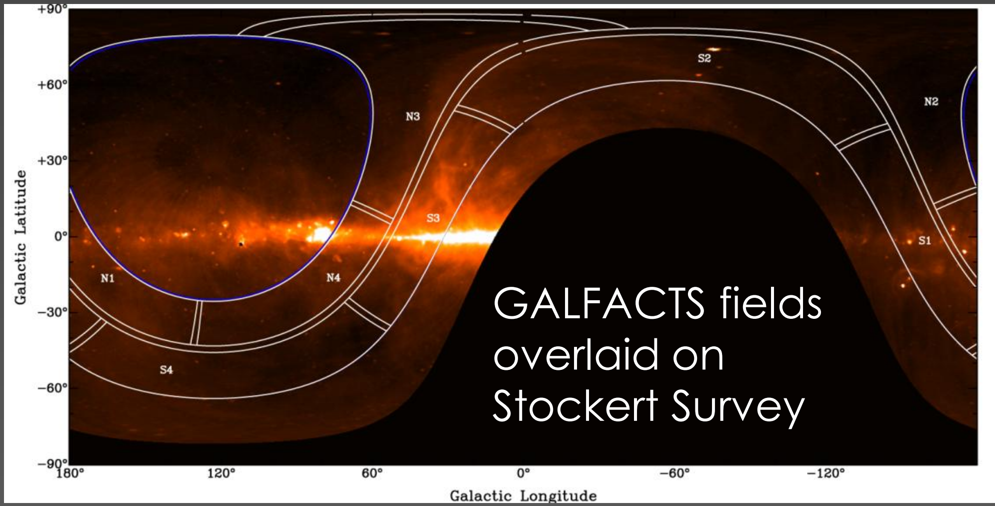
- Replacement for DRAO/Villa Elisa 21 cm survey
- Fully sampled
- 1.3 -1.8 GHz
- 2048 channels
  - for RM Synthesis
- I as well as Q U
- South from Parkes
  - STAPS (PI Haverkorn)
- Also 'low' band: 300 - 900 MHz.



Wolleben et al (2010, ApJL)

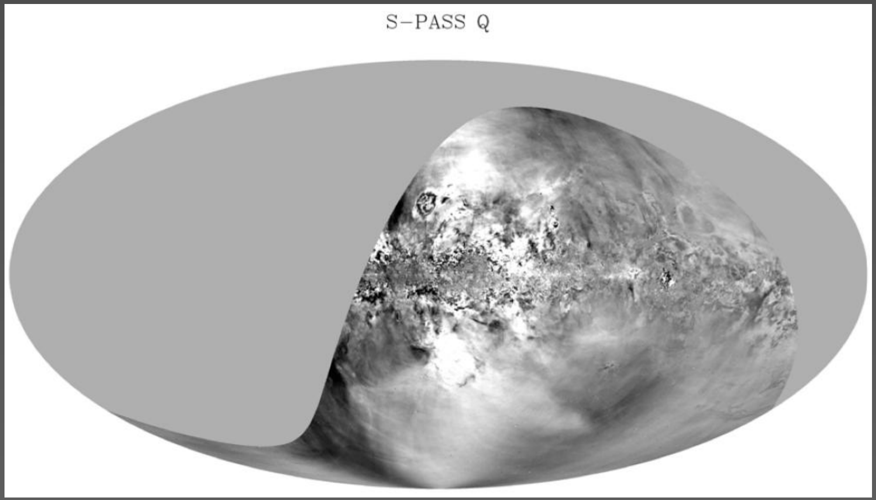
GALFACTS

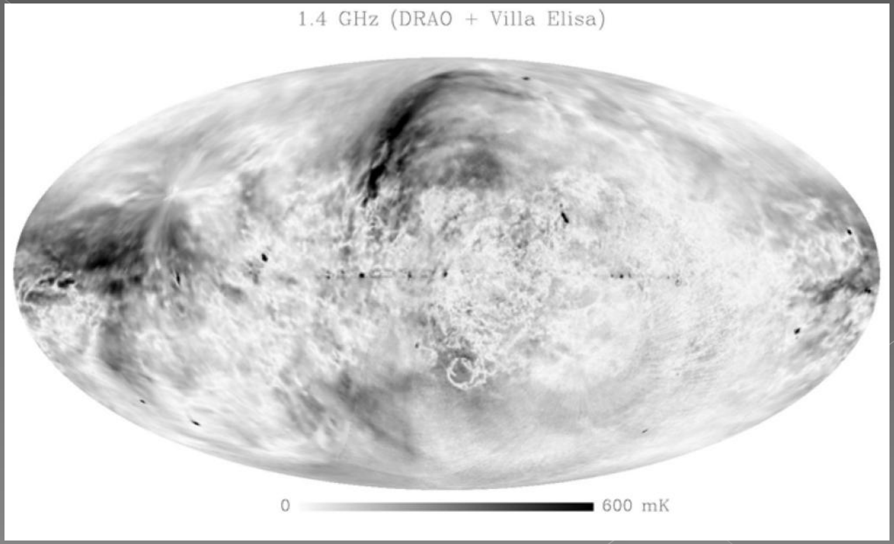
- Continuum Transit Survey with Arecibo L-Band Feed Array
  - 32% of sky
- 3 arcmin beam
- 300 MHz
- 2048 channels
- Final maps will use GMIMS to recover large-scale structure



S-PASS

- 2.3 GHz Southern-sky polarization survey with Parkes
- 9′ beam
- Data collected, processing under way
- Much less depolarized than 21 cm.
- Figs from Carretti (2011)
  - ATNF Newsletter



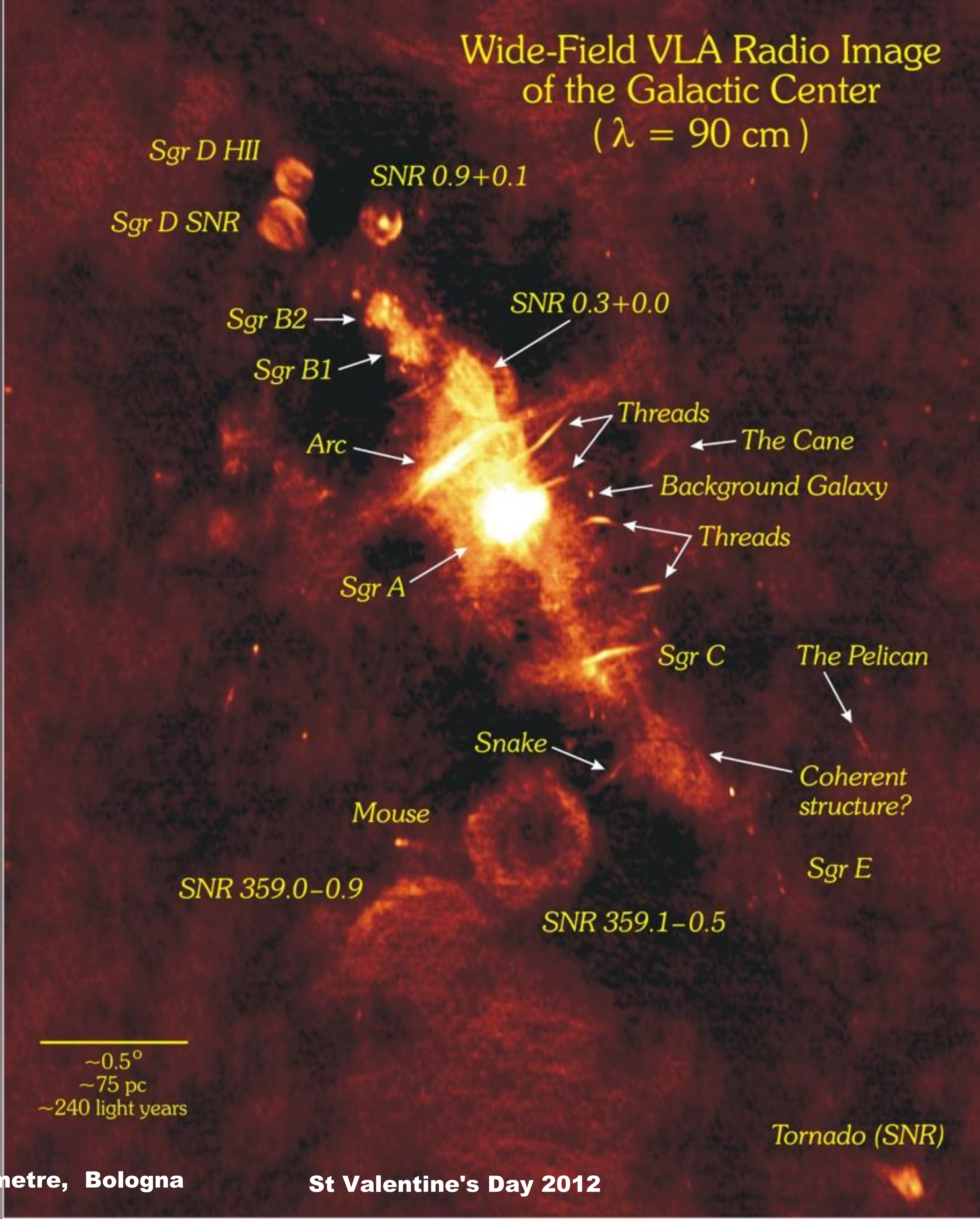


C-BASS

- 5 GHz all-sky survey
- Talk by A. Taylor
- Poster by M. Irfan

Origin of CR

- Supernova remnants prominent in Galactic synchrotron emission
- Strong shocks
- Pulsar winds

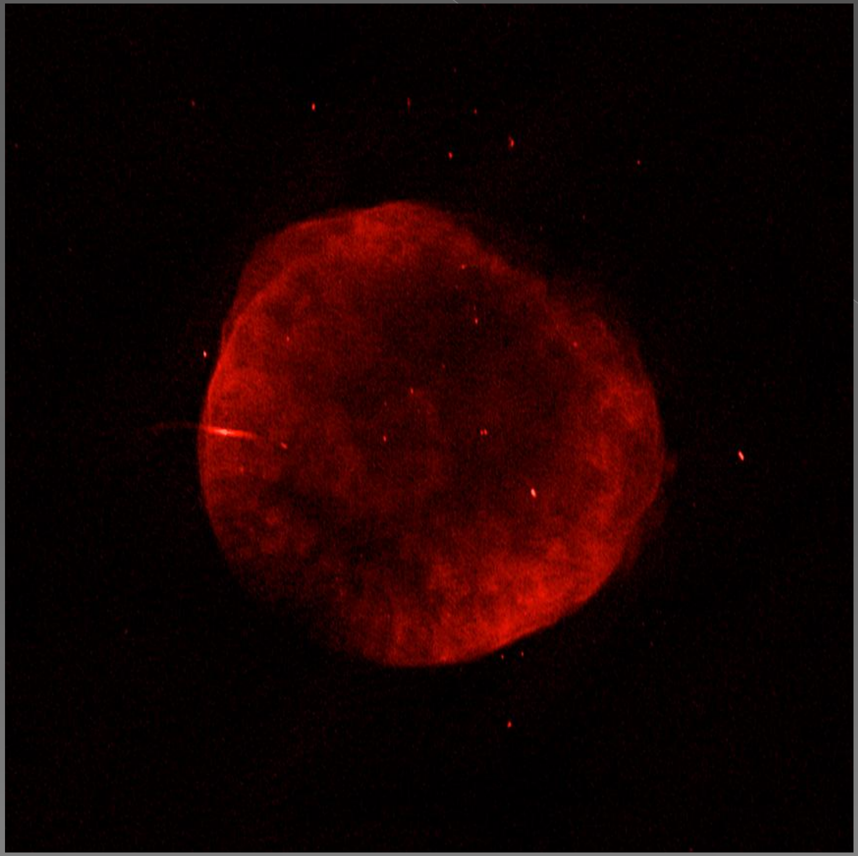


Shock acceleration

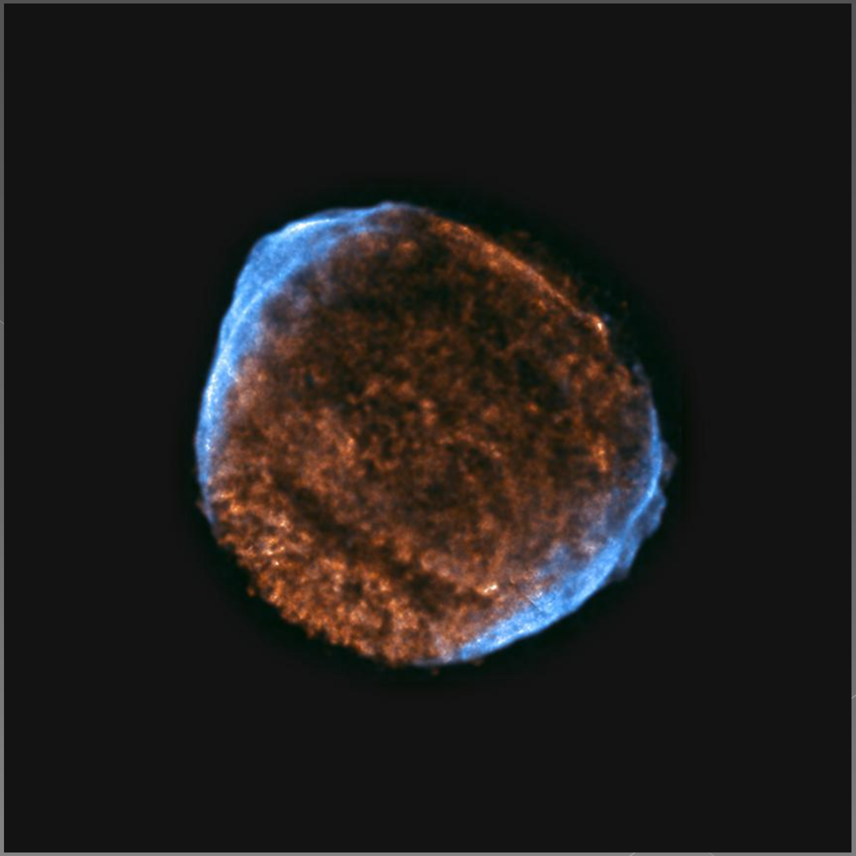
- First-order Fermi (e.g. Bell 1978):
  - $N(E) \propto E^{-s}$, $I \propto \nu^{-\alpha}$, $s = 2\alpha+1$
  - $s = (r+2)/(r-1)$
  - $r = 4$ for strong adiabatic shock: $s = 2$, $\alpha = 0.5$
  - $r < 4$ weak shock: $s > 2$, $\alpha > 0.5$
  - $r = 7$ relativistic shock
    - $s = 4/3$, $\alpha = 0.167$ (Test particle)
    - Complicated (CR-dominated)
  - $r >> 4$ cooling shock
    - but fast particles don't see this compression ratio

SN 1006

VLA (Dyer et al 2009)

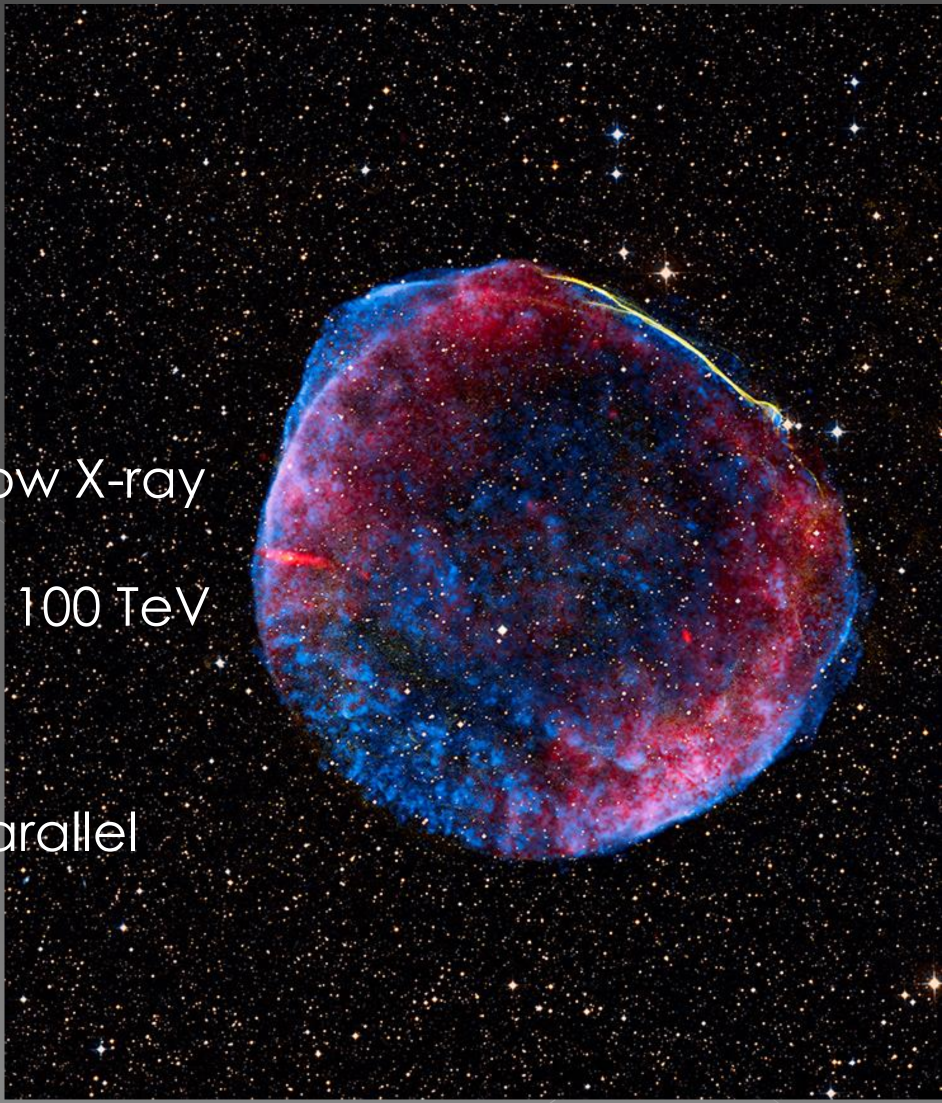


Chandra (NASA/CXC)



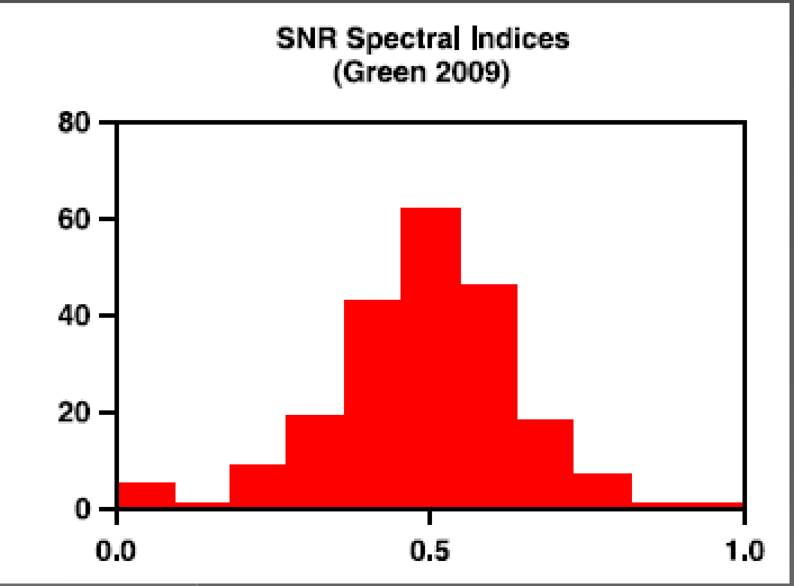
SN 1006

- Shock front Radio-X-ray:
  - $\alpha = 0.50 \pm 0.02$
  - Decourchelle et al (2011)
- X-ray synchrotron $\alpha = 1.5$
  - Cutoff in spectrum just below X-ray band
  - Highest-energy electrons ~ 100 TeV
- Thin shock suggests $r > 4$
- Barrel shape:
  - Efficient acceleration at parallel shocks?
    - Contrary to Bell model!
    - SN1006 has radial B-field



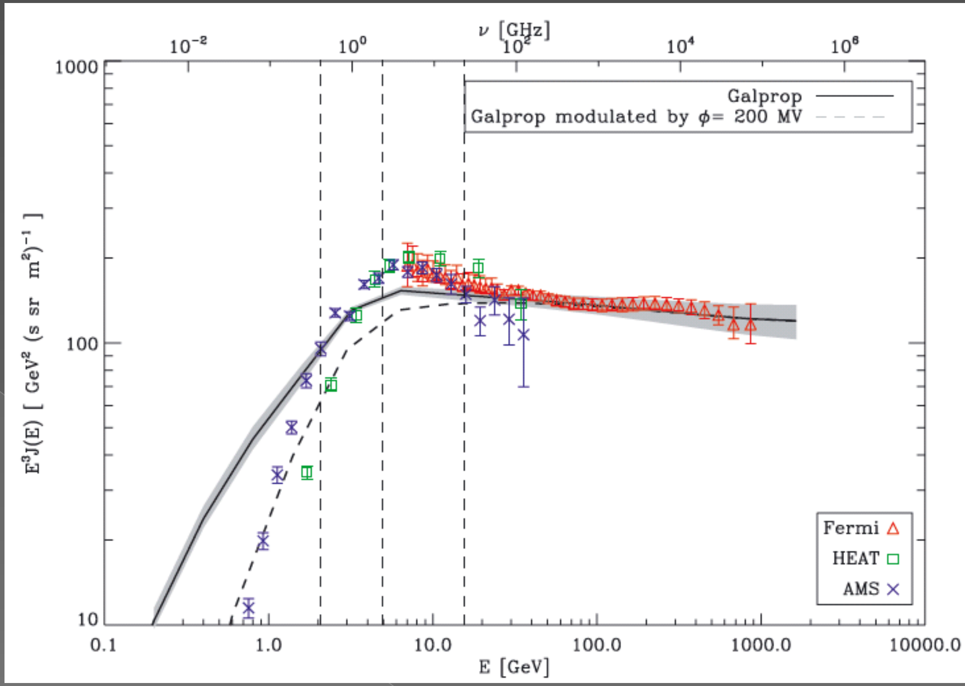
Complexities

- Significant variation in SNR spectral indices
- Pulsar Wind nebulae flatter, e.g. Crab $\alpha = 0.3$
- Balance between steepening spectrum of old material and injection of new material:
  - Young SNR (+radio SN) have steeper spectra.



Propagation effects

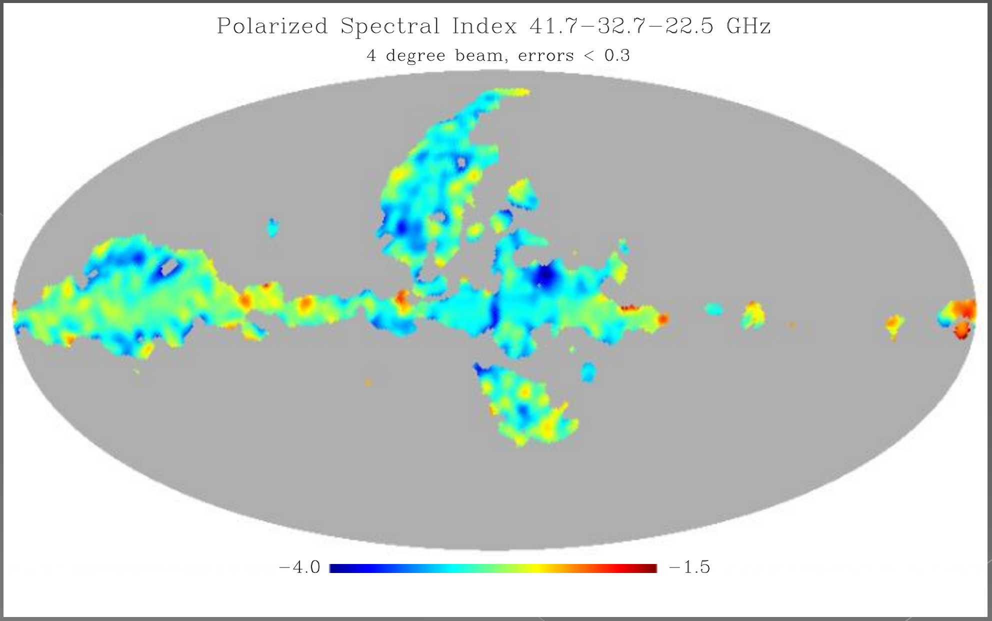
- Ambient spectrum of CRs in ISM is steady state between injection & loss
  - radiative, diffusive, convective
- Direct measurement in good agreement with inferred spectrum from synchrotron emission (B ~ 6 μG)
- Detailed modelling suggests injection spectrum with several breaks, very hard at low frequency (s ~ 1.6)
- → talk by Orlando.



- Jaffe et al 2011: E^3 scaling
- GALPROP prediction fitted to synchrotron data vs local e^- spectrum.

Spectral Index: 13:7 mm

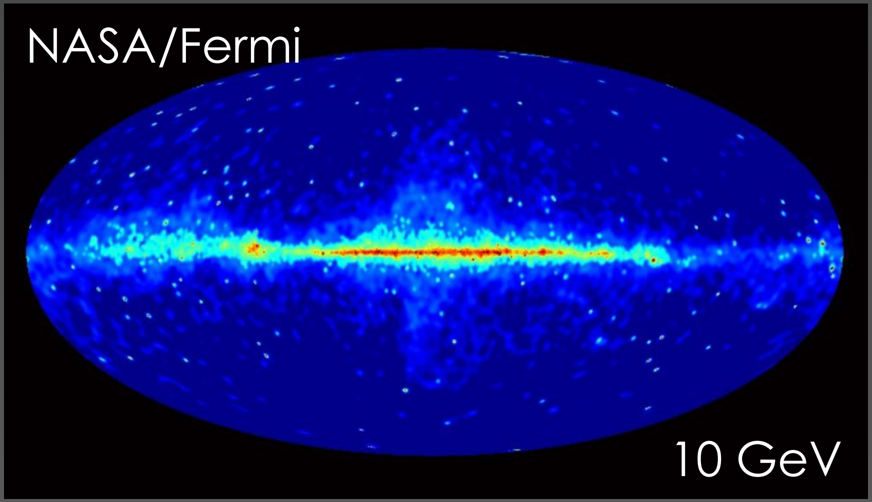
- Low sensitivity in WMAP data at $\lambda < 1.3$ cm gives limited sky coverage
- Note flat spectrum for Crab nebula
- Mean $\beta_P \approx -3.0$
  - Slightly flatter than at lower frequencies. (−3.1 in same regions)
- Kogut et al (2007) claim detection of flattening from $\beta_P \approx -3.2$ to -3.0 from WMAP data alone…
  - Use smoothing from 7° to 18°
  - No allowance for pol. bias at 23 GHz: artifact?

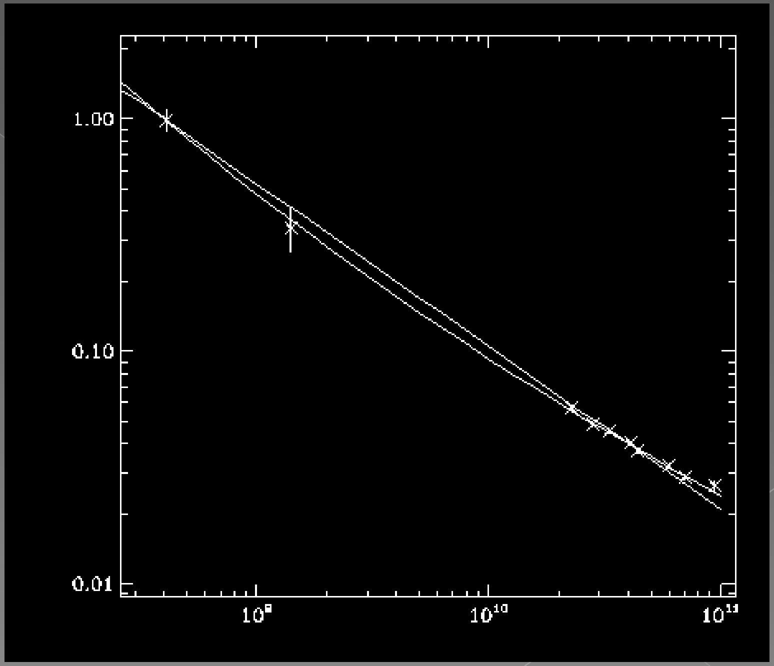


(3-year WMAP data)

Hazy thoughts

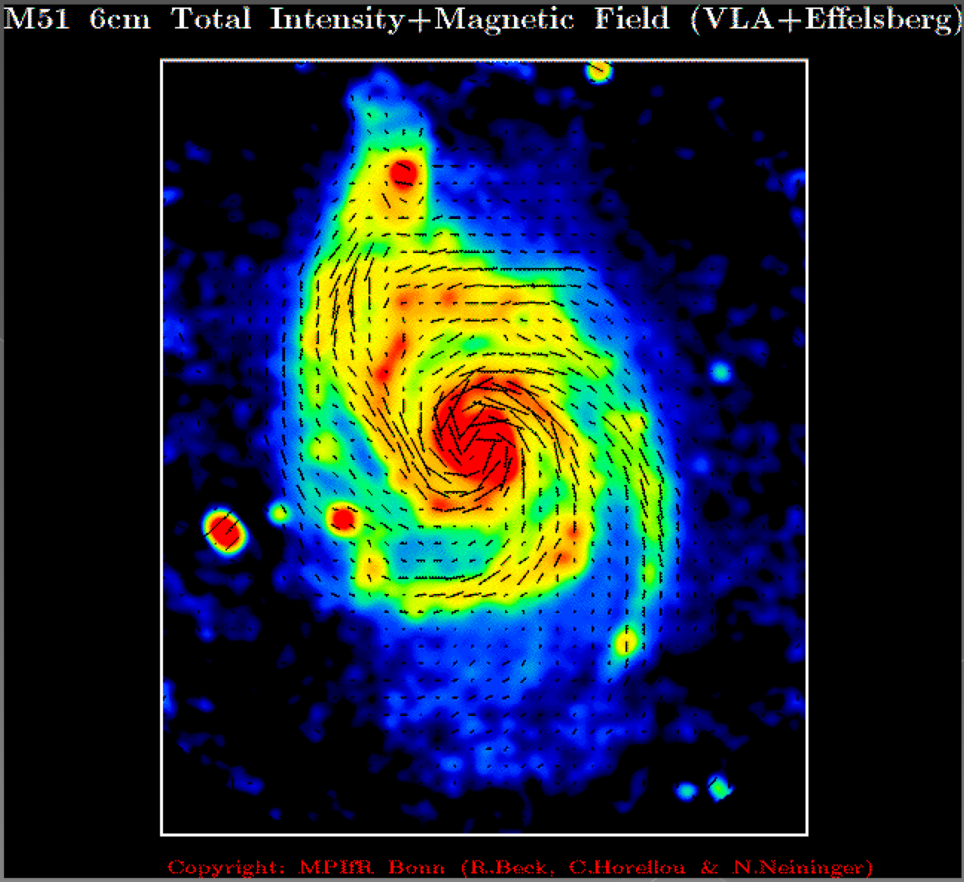
- Existence of "haze" conclusively demonstrated
  - Gorski talk
- Interpretation:
  - Two components, α = 0.5 and α = 1
    - Implicit in template method
  - Region with single unusual α = 0.7
  - Very hard to distinguish without ultra-precise measurements
  - Illustration assumes 2% errors for WMAP/Planck, except at > 50 GHz
  - Actual errors dominated by residuals from other foregrounds



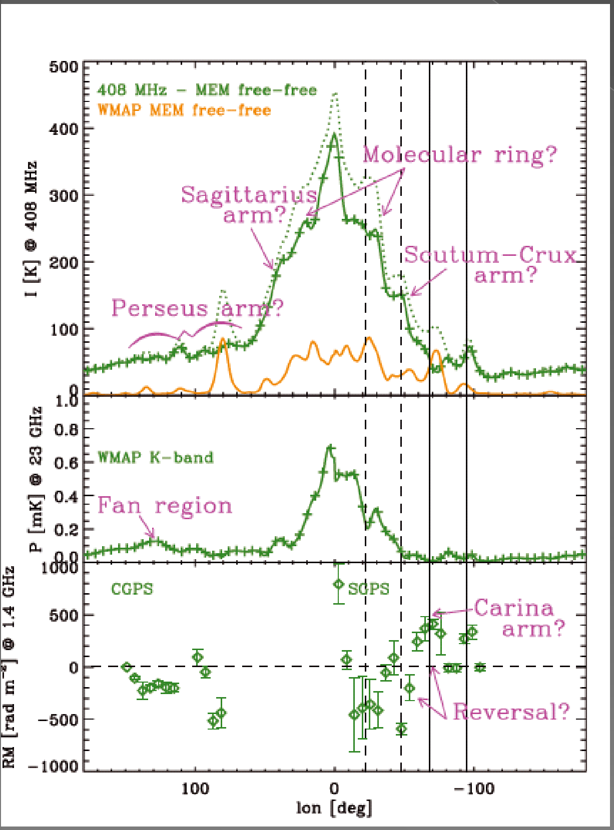


Spatial distribution of Synchrotron

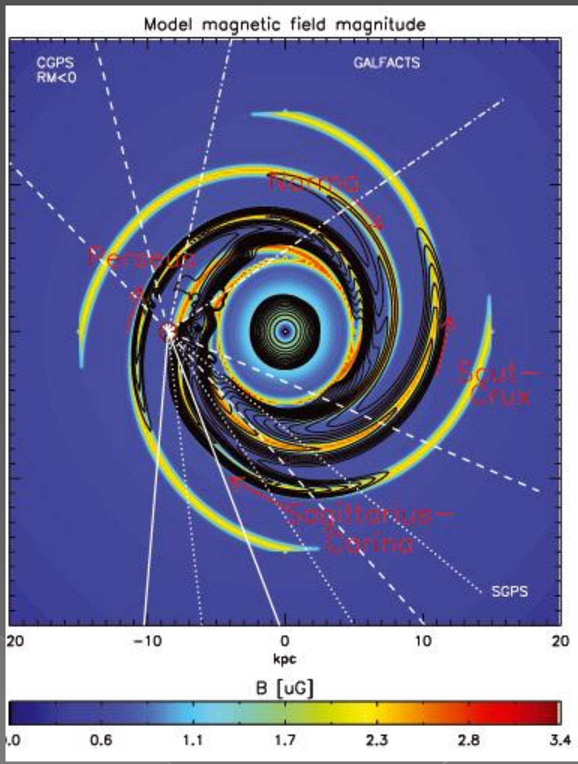
- External galaxies show SR most intense in spiral arms
- (M51 extreme case)
- Highest fractional polarization in interarms
  - Field more ordered



3D Emission models



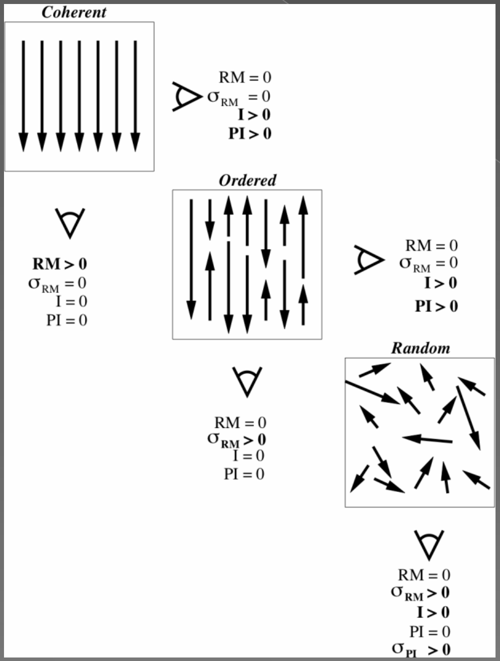
- Milky Way also has distinct radio spiral arms
- Consistent with arms in NE2001 model.
- Cosmic ray analysis suggests CRs very smoothly distributed
  - e.g. *Fermi:* outer galaxy ≈ constant density
- Major variation in B-field
- Hammurabi code
  - Waelkens, Jaffe et al.
  - Sun et al (2008)
  - Jaffe et al (2010)
- Fit:
  - 408 MHz I
  - 23 GHz p



NE2001 electron density contours

Tangled up in *B*

- Hammurabi model:



- B: 2 3 7 μG
  - Jaffe et al (2010,2011)

- Yet another wrinkle:

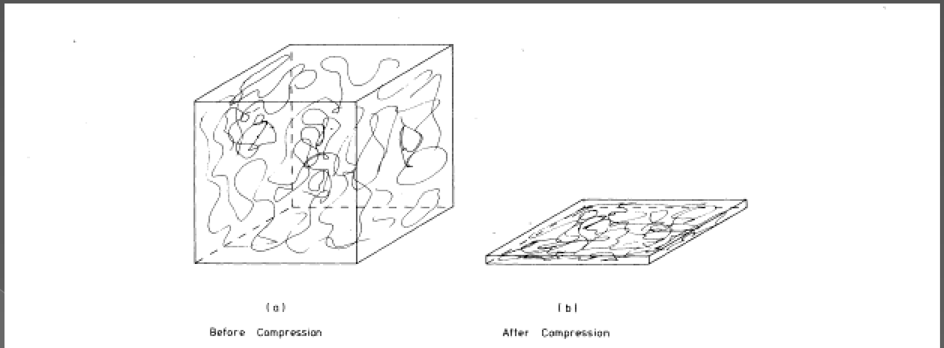
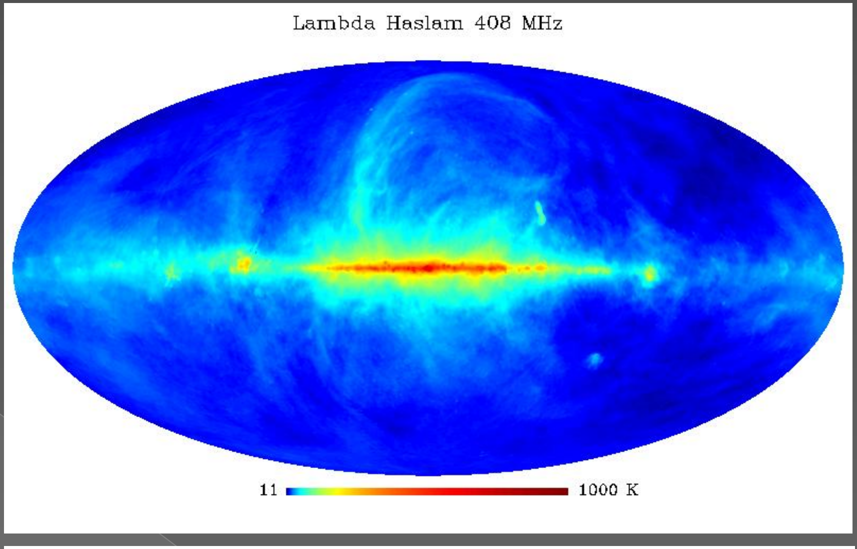


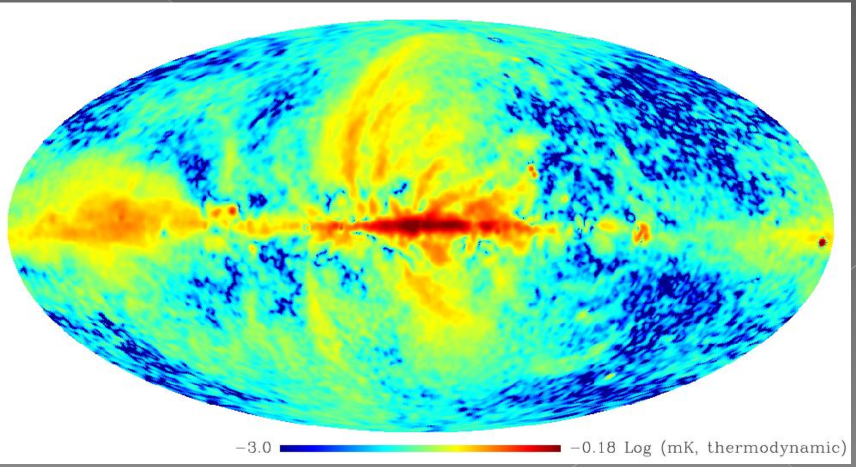
Figure 1. The compression of a cube containing an initially random magnetic field.

  - Laing (1980)
  - Not included in Hammurabi model
    - too poorly constrained

Synchrotron Radiation is all around

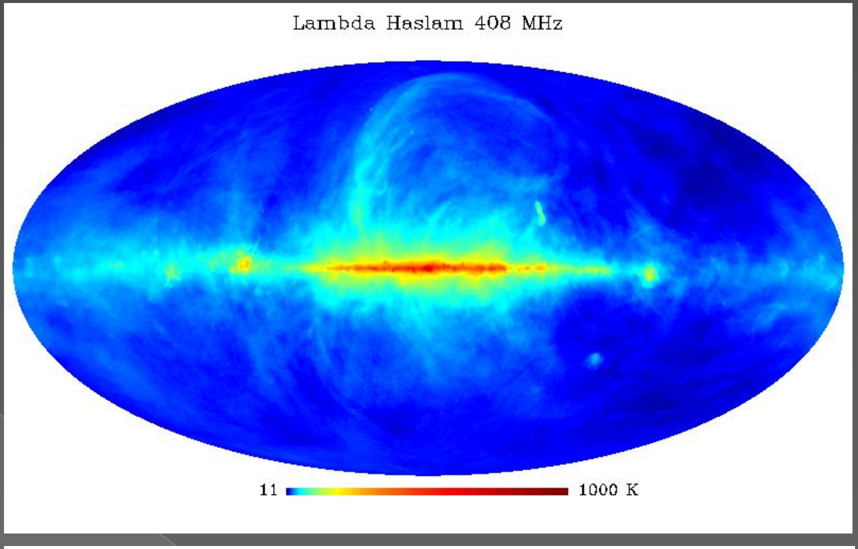
- 408 MHz I + 23 GHz P
- Minimum intensity at mid latitudes
- Synchrotron monopole:
  - Cosec |b| fit to Haslam map: zero level = 9.8 K (N), 10.1 K (S)
  - But already zeroed to ±3 K
  - Would give negative intensity at faintest points
  - cf ARCADE2
- Isotropic component!
  - Local bubble or halo?

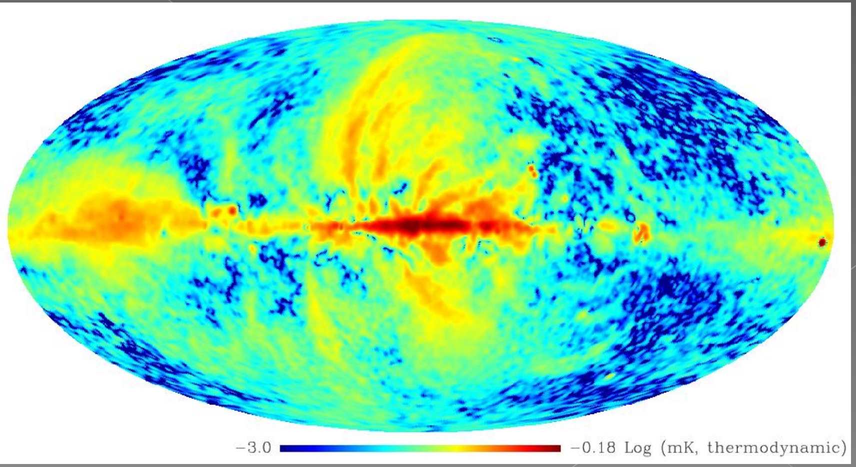




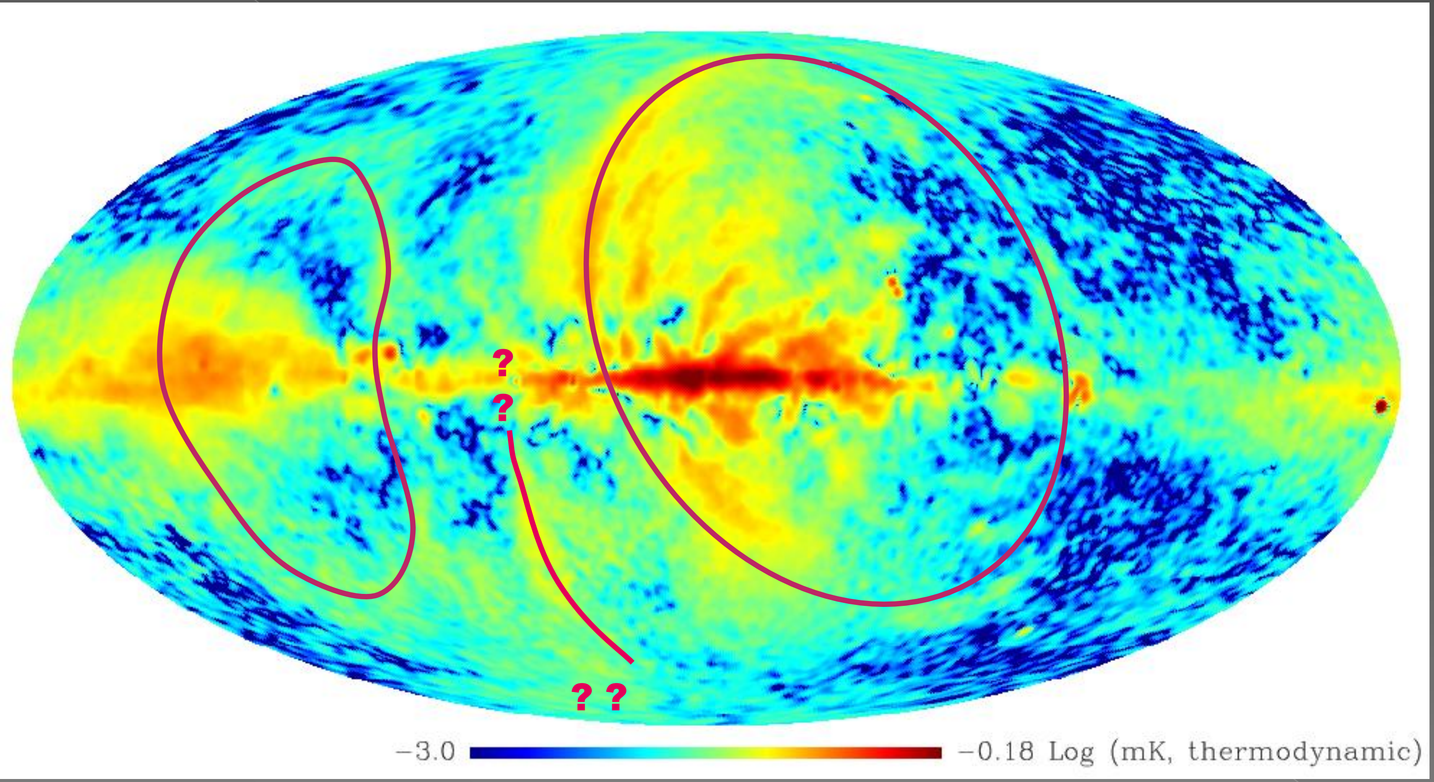
The Synchrotron Sky

- On large scale mostly dominated by coherent structures
  - Loops (local)
  - Fan (c. 1 kpc)
  - SNRs
- Not a lot of scope for meaningful statistical analysis
  - higher resolution needed!





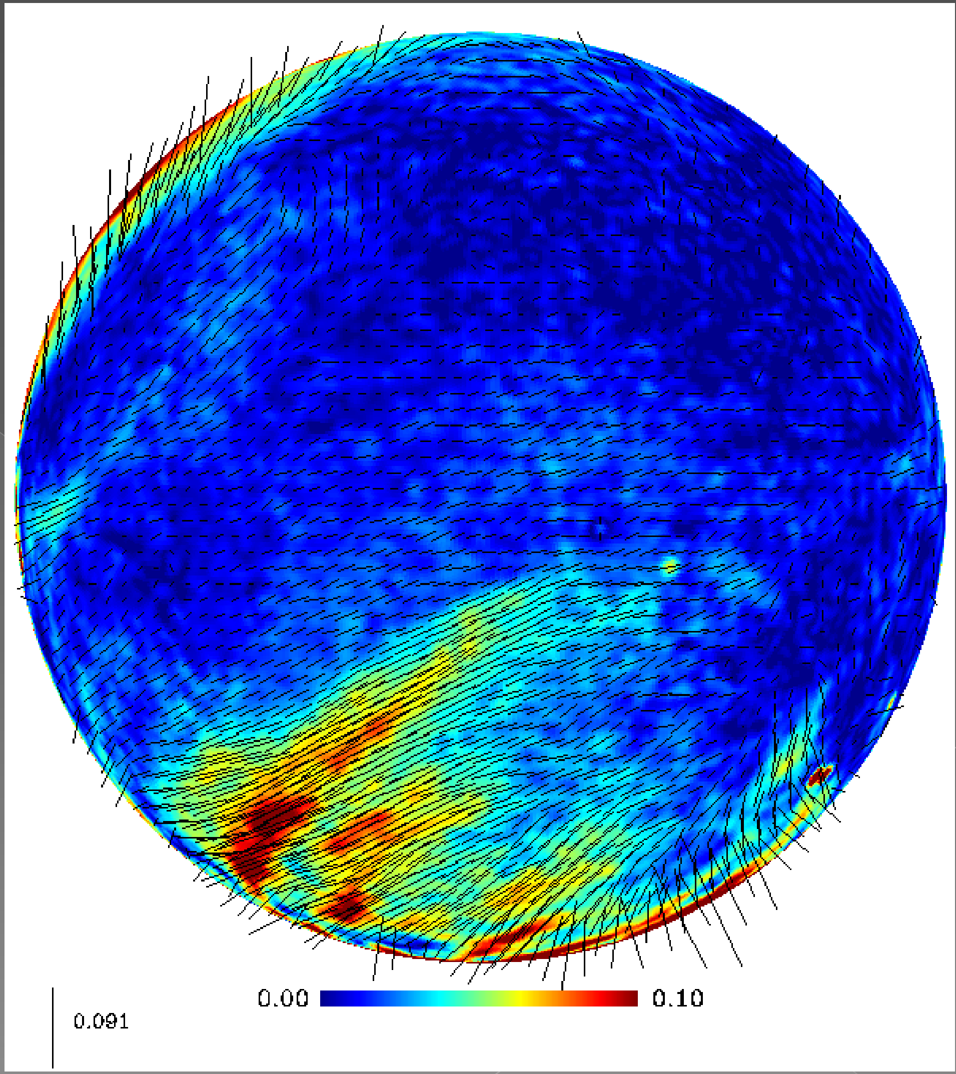
Loops



- Only Loop I and top half of Loop III clear

NGP Polarization

- Polarization well organized across NGP
- Fractional polarization low outside Spur: ~ 10%
  - Complex structure along LOS
- Field in Spur follows outside field
  - Bright rim effect?



Outlook

- Planck data will be complemented with new, high-precision surveys dramatically improving observational situation 1-20 GHz
  - Much cleaner synch/free-free/AME separation
- New Faraday surveys @ ~ 1 GHz will dramatically improve Faraday modelling
  - Still a lot of work to do on ‘ordered’ field
- Major puzzle understanding CR electron injection spectrum
  - Look to observations of other galaxies with new low-frequency arrays