X-ray Synchrotron Polarization from Turbulent Plasmas in Supernova Remnants

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Outline of Talk

- Bon anniversaire a SN1987a!
- Supernova remnant shells – enhanced fields with strong synchrotron cooling in X-rays;
- Theoretical paradigm of turbulent field amplification due to cosmic ray currents;
- X-ray polarimetry is ideal probe of turbulence on the largest diffusion scales;
  - Prospects are soon –IXPE, XIPE, eXTP;
- Modeling synchrotron polarization in turbulent fields yields probes of turbulence character.

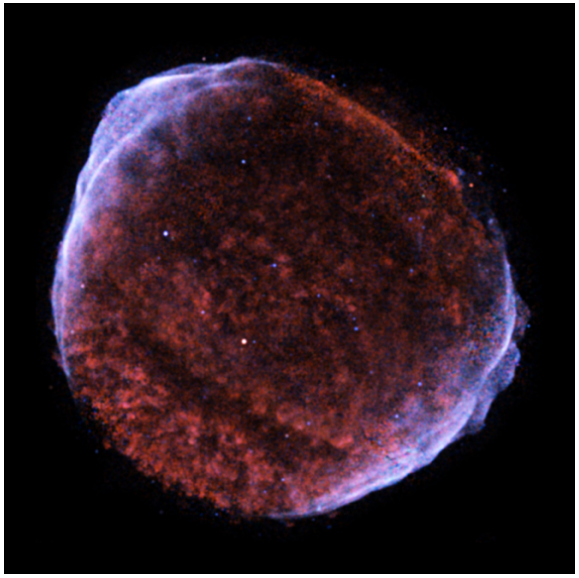
X-ray + TeV Supernova Remnants

- Emerging class of young SNRs emitting synchrotron X-rays
  - e.g., SN 1006, G347.3-0.5, Vela Jr., G330.2+1.0, RCW 86
  - direct evidence of electron acceleration up to ~50-100 TeV

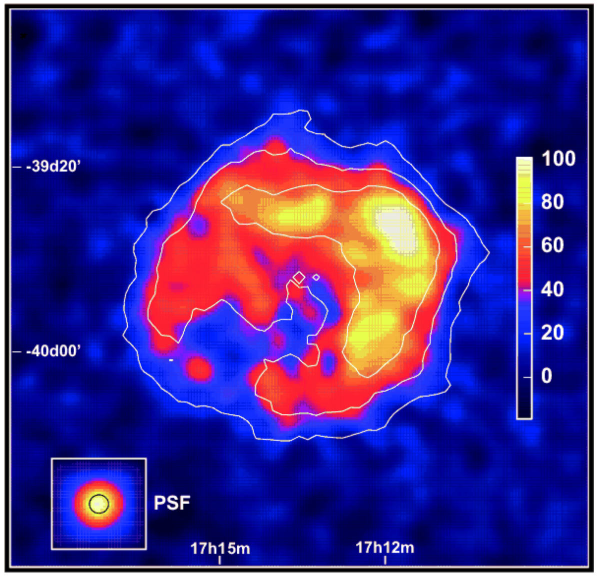
  (e.g. Koyama et al. 1995, 1997; Slane et al. 1999, 2001; Vink et al. 2006)

- G347.3-0.5 & Vela Jr.: now seen at E > 100 GeV

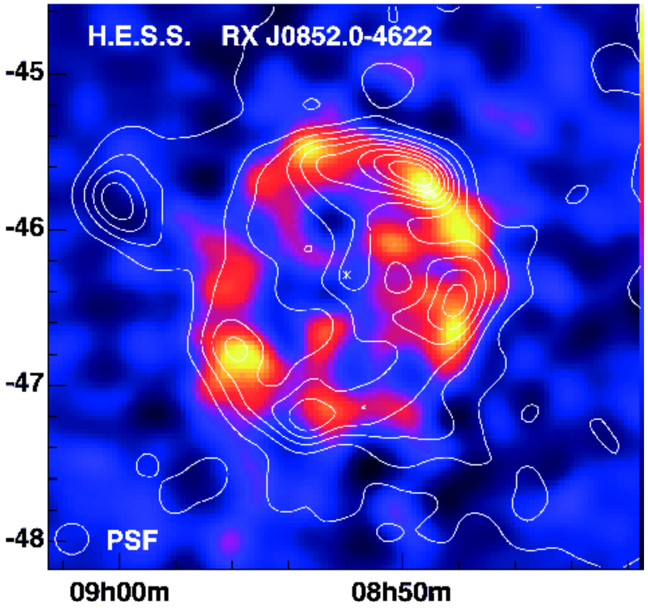
  (Muraishi et al. 2000; Aharonian et al. 2004, 2005; Katagiri et al. 2005)



SN 1006 (X-rays; Chandra CXC /Rutgers, Hughes et al.)



G347.3-0.5/RXJ1713.7-3946 (TeV; Aharonian et al. 2006)

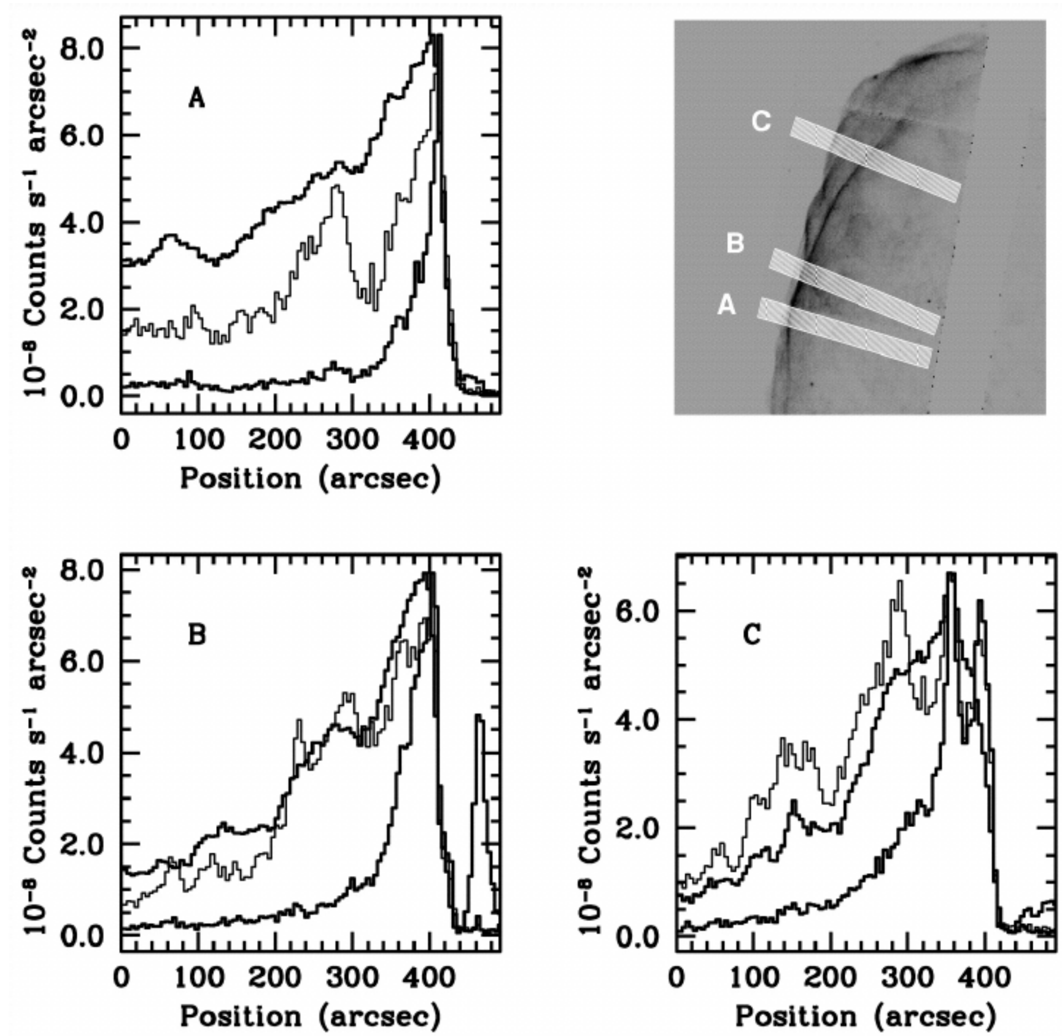


Vela Jr. (TeV; Aharonian et al. 2005)

Chandra Spatial Brightness Profiles in SN1006

Long et al. 2003

- Surface brightness profiles are much broader for thermal X-rays and radio synchrotron than for non-thermal X-rays;
- Narrowness of profiles along scans argues for shocks ⊥ to sky, i.e. no projectional smearing;
- Flux contrast ratio (< 1.5%) for upstream to downstream 1.2-2.0 keV suggests $\mathbf{B}_d/\mathbf{B}_u>>4$, i.e. *greater than standard MHD compression in high M_S shocks* (Cas A offers similar picture: Vink & Laming 2003);
- Non-thermal X-ray width suggests a connection between cosmic rays and **B**-field amplification.



Thin black line: 0.5-0.8 keV; Black line: 1.2-2.0 keV; Grey line: 1.4 GHz radio.

Non-Linear Field Amplification by Cosmic Ray Streaming

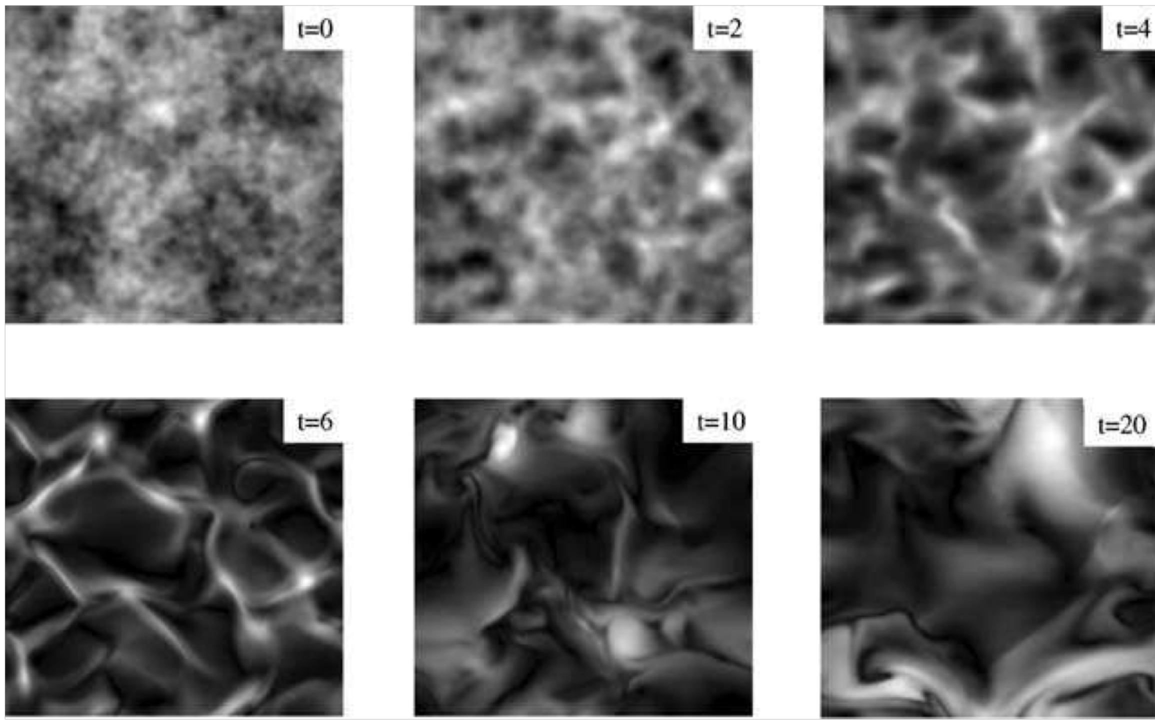


Figure 4. Magnitude of the magnetic field in the (x, y) plane; slices at $z = 0$. The grey-scale minima (black) and maxima (white) at each time as bracketed pairs (minimum, maximum) are: (0.81, 1.22) at $t = 0$, (0.69, 1.35) at $t = 2$, (0.40, 2.30) at $t = 4$, (0.20, 12.01) at $t = 6$, (0.09, 39.88) at $t = 10$, (0.24, 79.72) at $t = 20$.

See also Morlino, Niemiec talks

$\delta B/B_0 > 1$

- Lucek & Bell (2000) proposed that high energy cosmic rays (CRs) in strong shocks could amplify B when streaming upstream (Fig.: Bell 2005);
- Work done on Alfven turbulence scales as the CR pressure gradient: $dU_A/dt = v_A\, dP_{CR}/dx$. Amplification should then scale as $(\delta B/B)^2 \sim M_A\, P_{CR}/\rho u^2$.

First polarization measurement of Crab Nebula

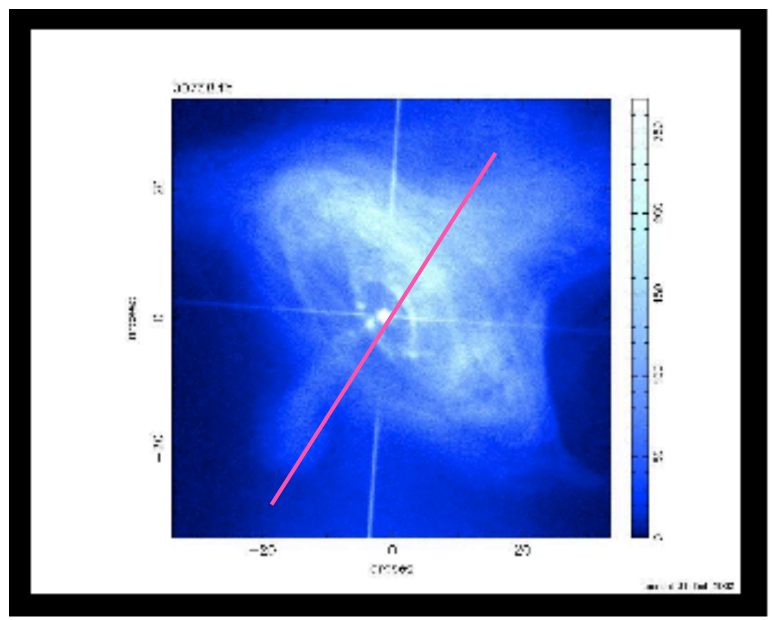
OSO-8 satellite experiment 1975 (Weisskopf et al. 1976)

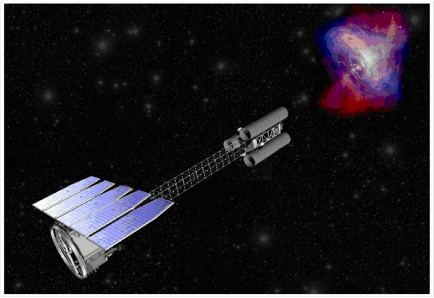
Precision measurement at 2.6 keV

Position angle: $f = 156^0 + 2^0$ (from North, counterclockwise on sky)

Polarization degree: $P = 19\% + 1\%$

- **Upper limit on pulsed emission from pulsar**





IXPE: Prime SNR Targets

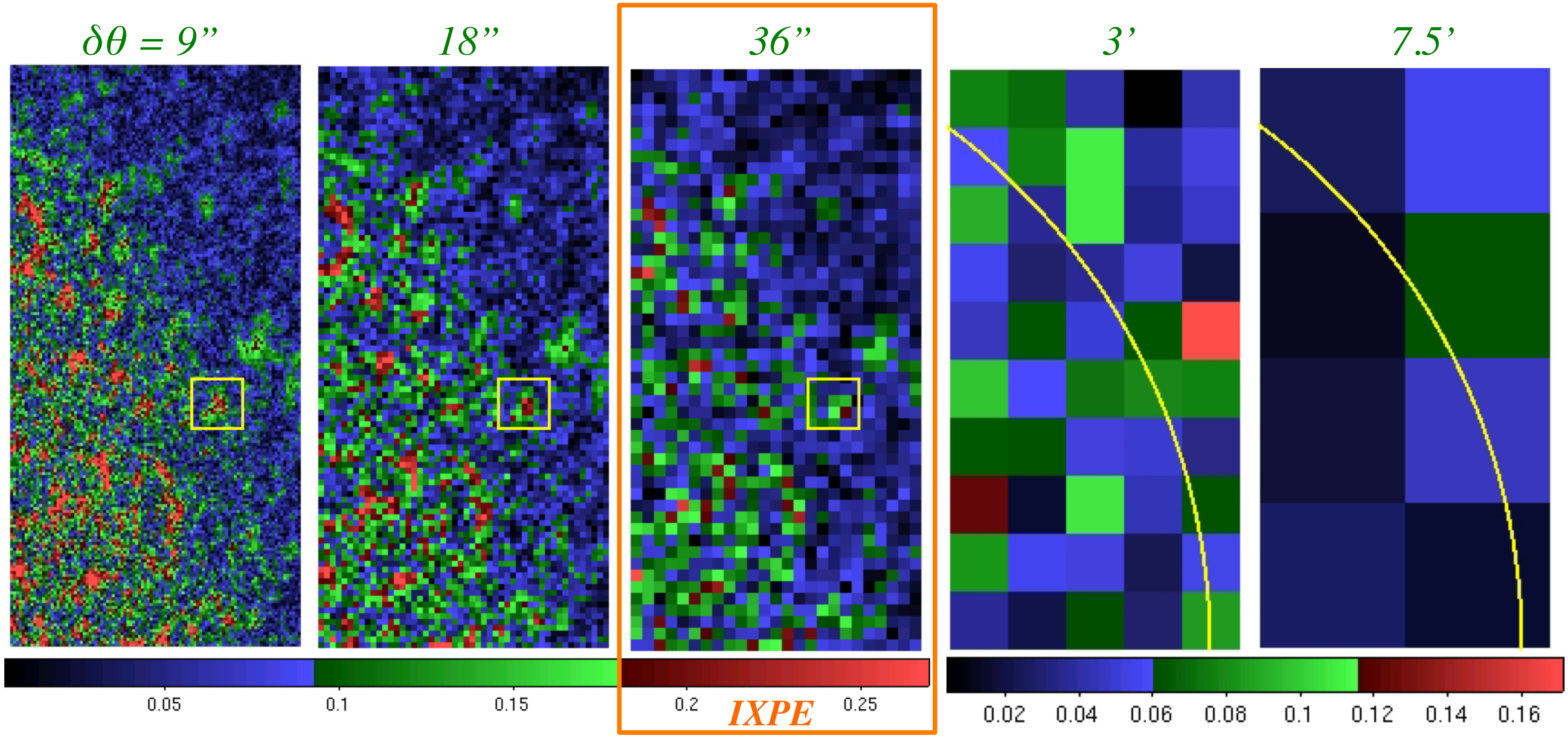
Weisskopf et al. (2013)

Table 5. MDP (99%) for selected supernova remnants[57,59,60] with 10^5 s of observation (or a single observation of 10^6 s but in each of ten regions of the extended source).

Name	**Flux** (5 keV, ph/s/keV/cm^2)	**MDP** (4-6 keV)	Angular size (Approx.[59])
Cas A	1.3 10^{-2}	2.75%	4'
Kepler	5.3 10^{-4}	13.5%	4'
Kes 73	5.5 10^{-4}	13.3%	2.5'
W49 B	5.6 10^{-4}	13.3%	3'
W66	1.5 10^{-4}	25.7%	15'
Tycho	3.3 10^{-3}	5.5%	8'
MSH 11-54	1.1 10^{-3}	9.39%	8'
RCW 103	5.2 10^{-4}	13.7%	15'

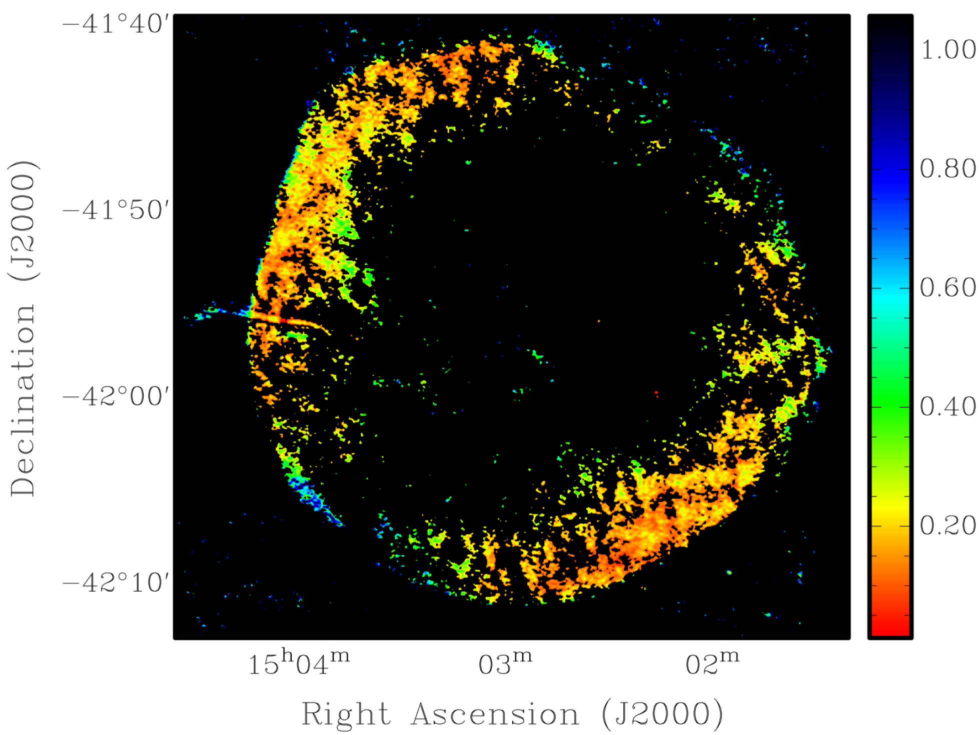
- IXPE's nominal 30" angular resolution can probe diffusive scales of the most energetic electrons emitting synchrotron X-rays in SNRs.
- Should be able to explore polarization position angles and degrees at different parts of rims and interiors.

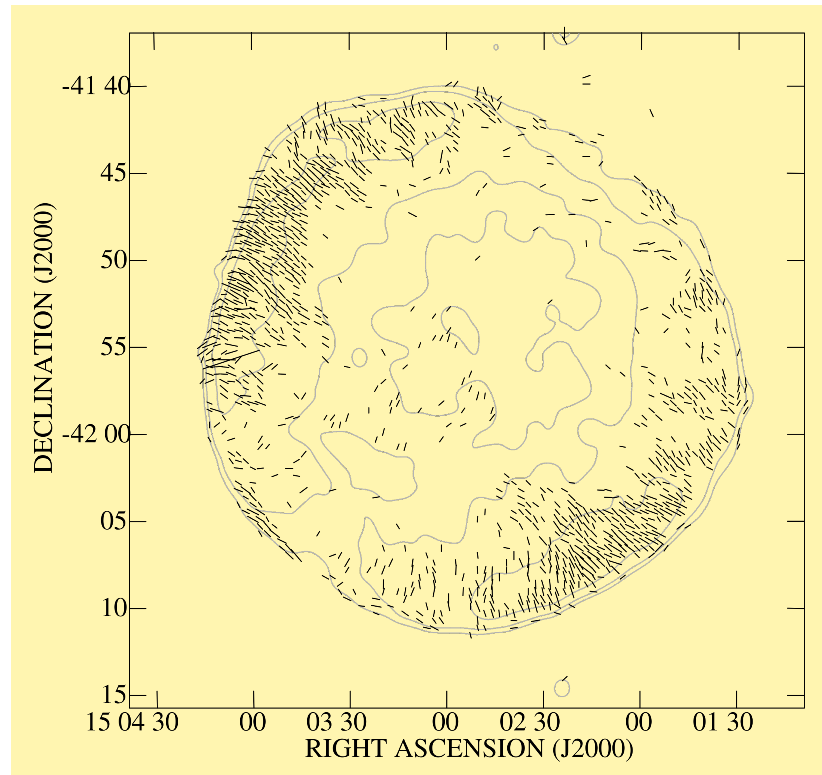
Synchrotron Polarization from Turbulent SNR shells



- Polarization degrees (fractional colour scale) in 20 keV synchrotron emission from power-law turbulence spectra (δ=2). Angular resolution is blurred increasingly from left to right.
- From Bykov et al. (2009) MNRAS 399, 1119.

Radio Polarimetry of SN 1006





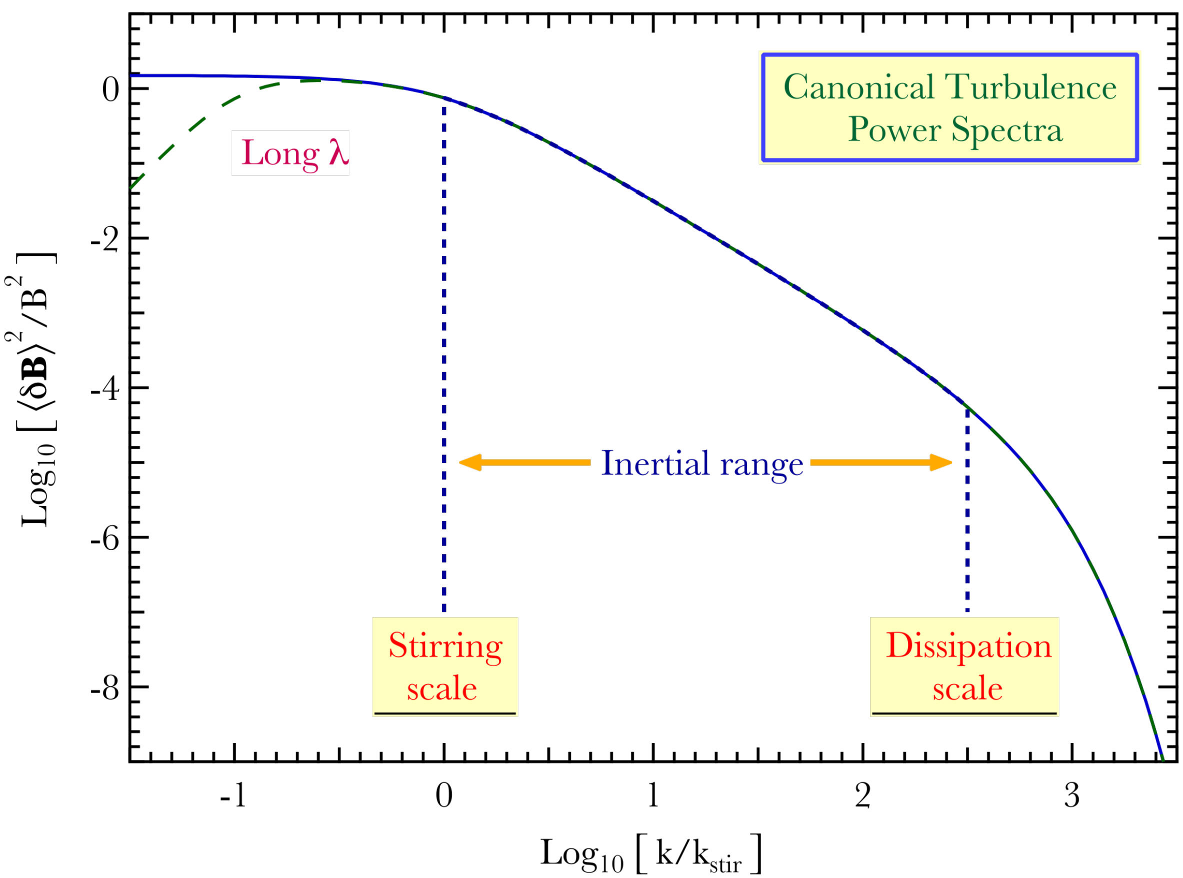
- *Left panel*: 1.4 GHz VLA/ATCA map of polarization degree. Resolution is 10".
- *Right panel*: sky-projected **B** field vectors derived from Stokes' parameters. Corrected for line-of-sight Faraday rotation. Vector length scales with flux.
- From Reynoso, Hughes & Moffett, Astron J. 145:104 (2013).

Path to Turbulence Probes

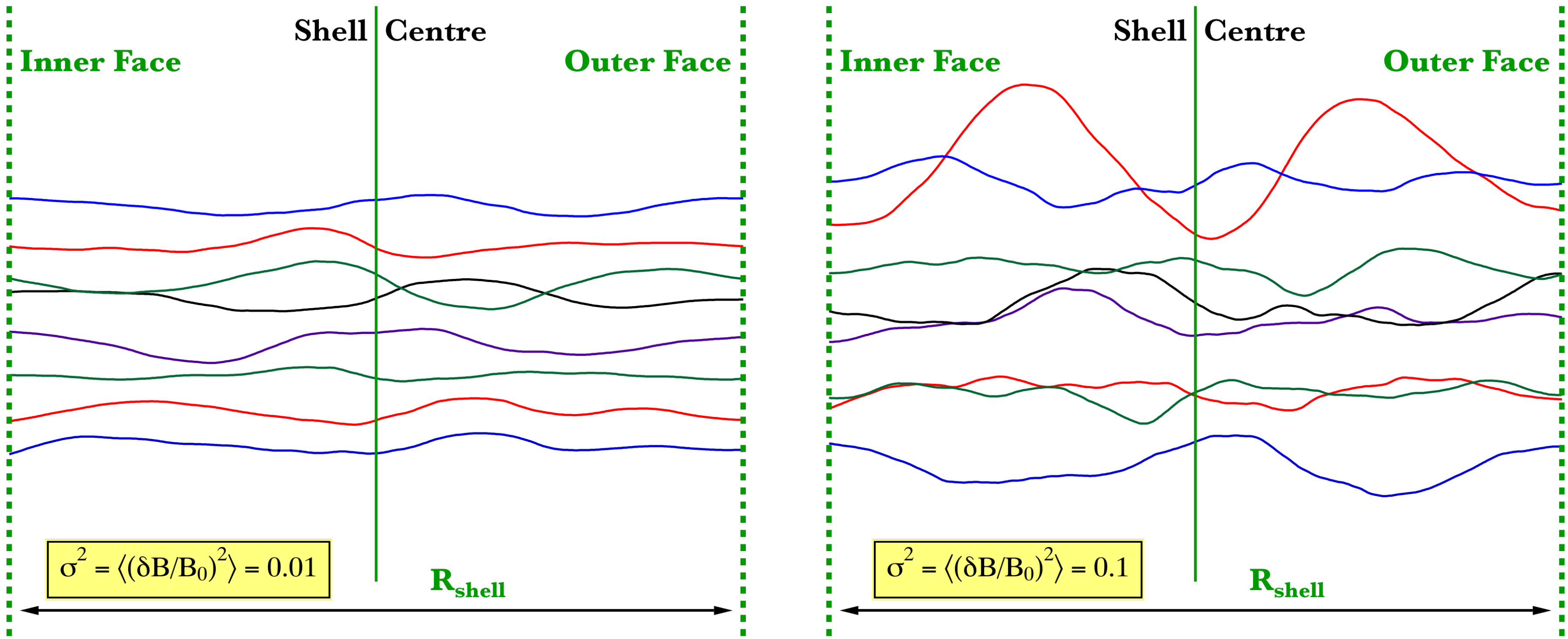
- Propagate electrons in prescribed magnetostatic turbulence - Kolmogorov for now, slab geometries.
- Inject steep power law e^- distributions ($p \sim 3$) to match spectra in X-ray band. Gyroradius smaller than cell & pixel size.
- Add up synchrotron emissivities and polarization parameters (Q, U, I, V) from small cells as part of bigger pixel grid.
- Spatial fluctuations in Stokes parameters emerge, coupling to strength $\sigma^2 = \langle (\delta B / B_0)^2 \rangle$ of turbulence.
- End goal: to identify signatures and correlations that will enable X-ray polarimetry to diagnose nature of turbulence.

Canonical Turbulence Power Spectrum

- Inertial range can span 1-5 orders of magnitude.
- Doppler gyro-resonance condition $\omega=\Omega/\gamma$ may not be satisfied by charges with large gyroradii;
- => increase of diffusive mean free path parameter $\eta=\lambda/r_g$ at large momenta.
- Expect $\lambda \propto p^2$ at long wavelengths, below stirring scale (QLT).



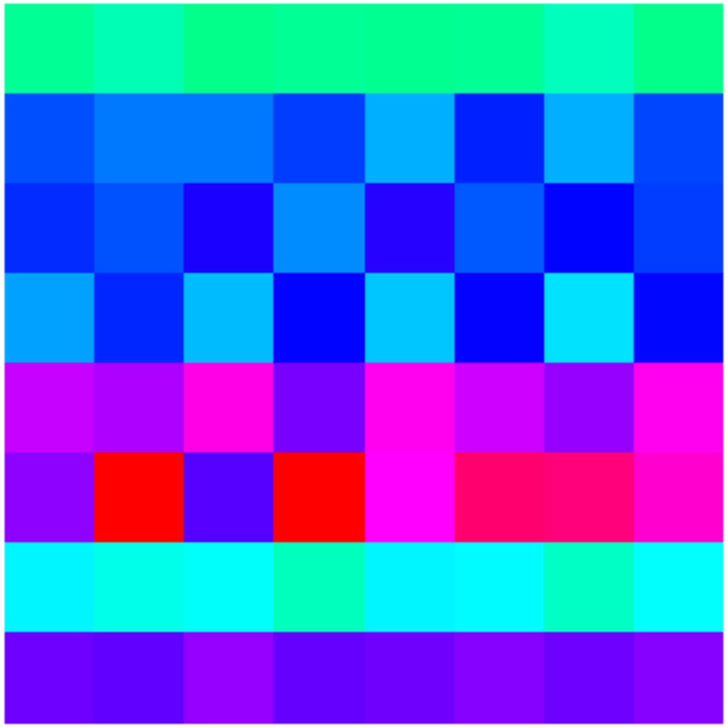
Turbulent Field Lines



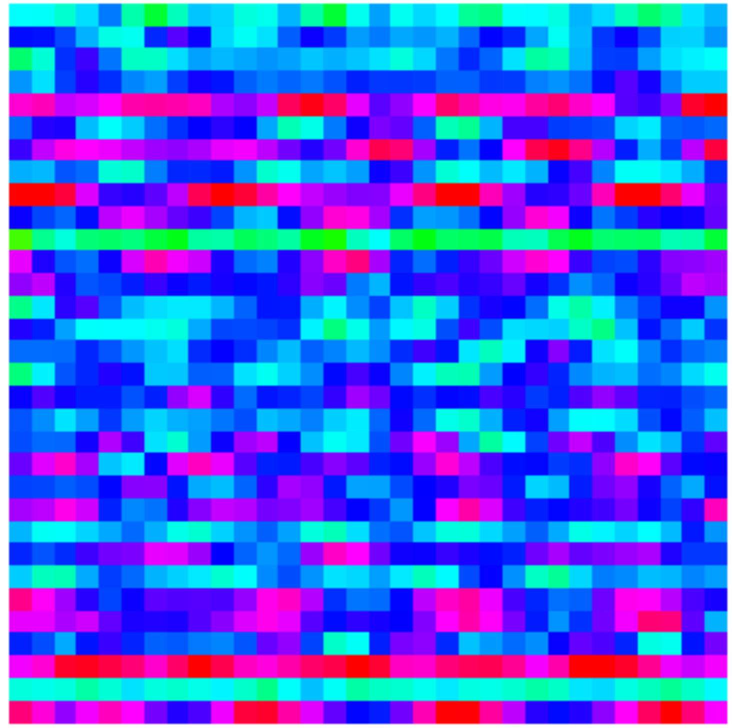
- *Sky plane projection* of magnetostatic Kolmogorov ($k^{-5/3}$) turbulence superposed on a uniform **B** in a model of a SNR shell.
- Moderately strong turbulence $\sigma\sim0.1$ on left, and extremely strong turbulence $\sigma\sim0.3$ on right. Stirring scale is $\sim R_{shell}/3$.

Synchrotron Intensity Pixelization

Low resolution

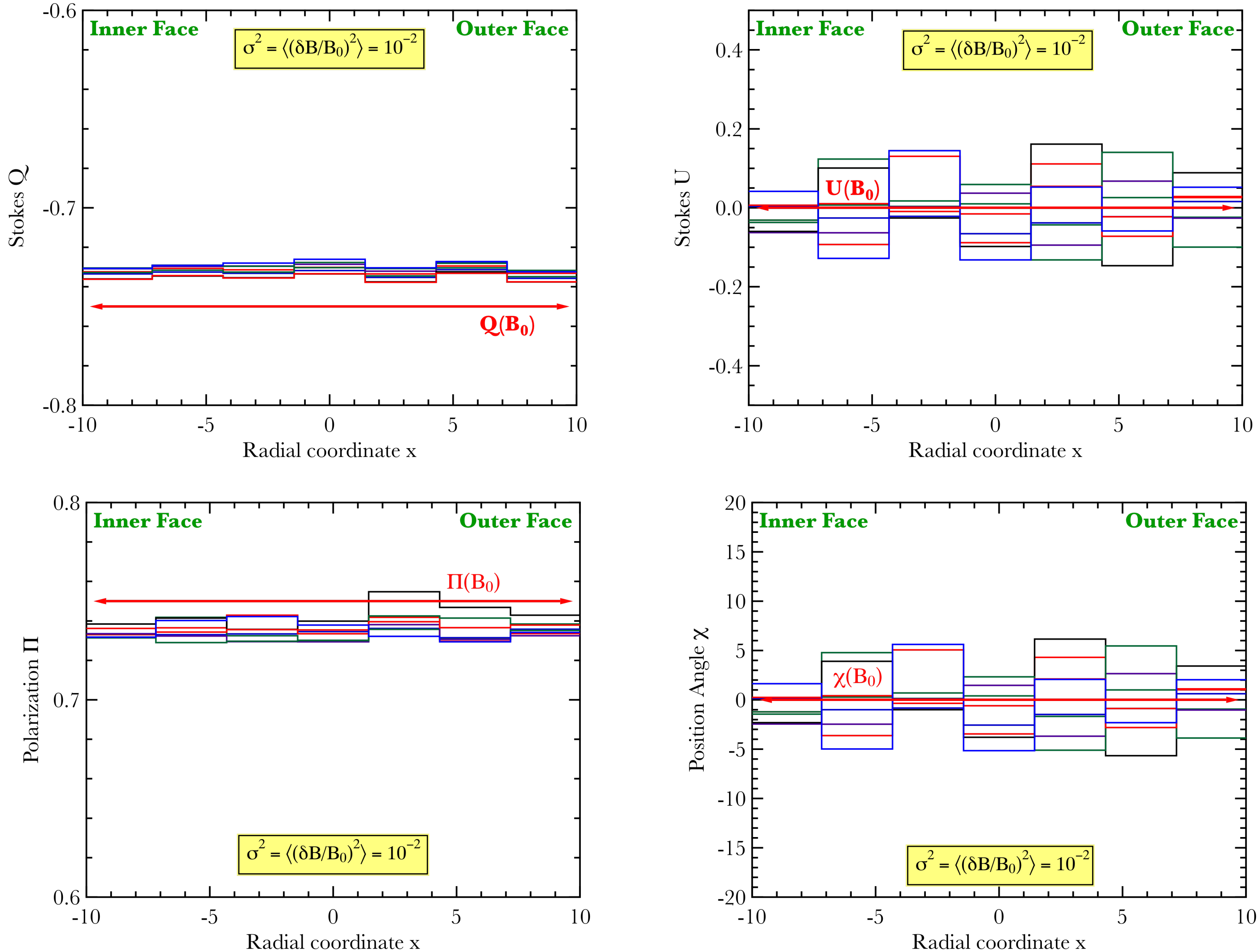


High resolution

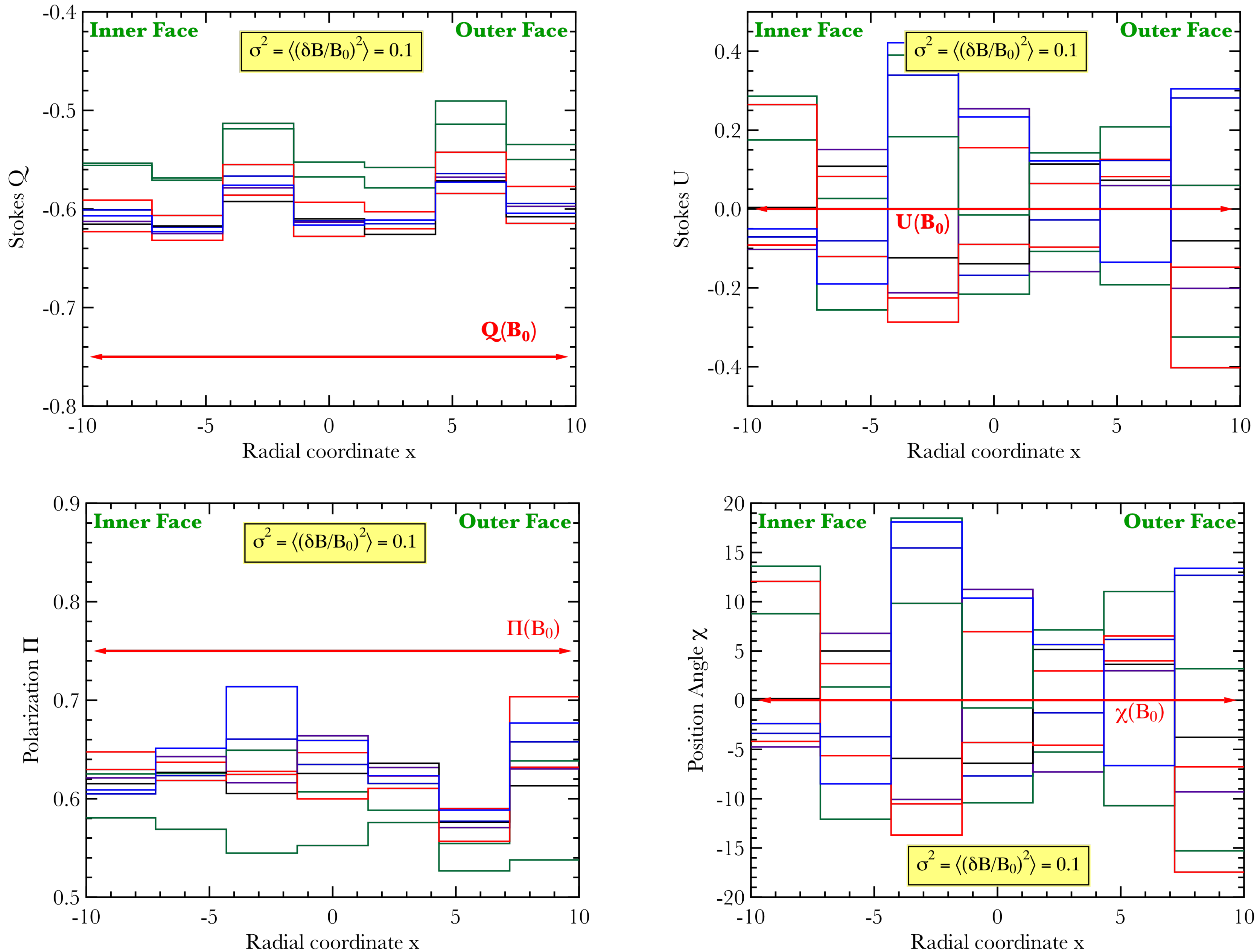


- Synchrotron intensity fluctuations (5% scale) in a sky map grid for Kolmogorov turbulence power σ=0.316; due to localized field enhancements. Red represents 1sigma positive enhancement over mean and green roughly 1 sigma negative decrement.

Polarization on the Grid: σ^2=0.01



Polarization on the Grid: σ^2=0.1



Conclusions

- Turbulence in the X-ray synchrotron emitting shells of SNRs is a prediction that is yet to be proved.
- Radio synchrotron polarization degree of ~20% suggests moderate turbulence but $\sigma^2 = \langle(\delta B/B_0)^2\rangle$ no more than 1.
- Stokes U and position angle behavior is most powerful diagnostic on turbulence level and power spectrum index.
  - Hope is that spatial distribution of turbulence (radial and latitudinal) will be discernible in larger remnants.
  - Mean field obliquity at shock may be identifiable.
- Work to do: introduce self-consistent cooling of electrons - it introduces spatial Q,U,V gradients in given turbulence.
- Work to do: define most useful assemblies of Stokes information for measuring turbulence parameters.
- What if IXPE measures $\Pi > 30\%$?....theorists will have to rethink the turbulence paradigm!