Magnetic Fields in Supernova Remnants: Observational Inferences

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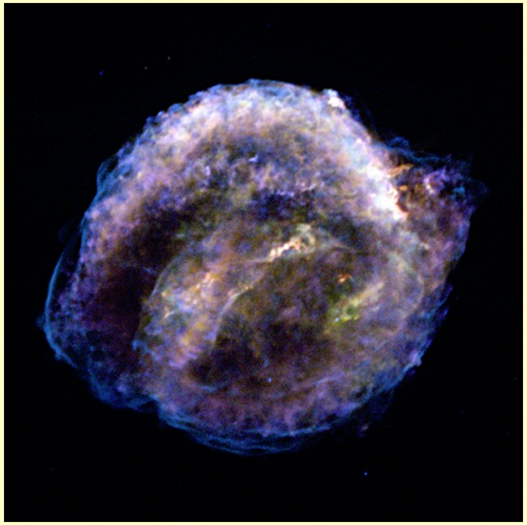


Kepler's SNR (Chandra; Reynolds et al. 2007)

1. Importance of *B* in SNRs

2. Determining *B* in SNRs
   - Radio observations
   - Thin X-ray rims
   - Time variability
   - Broadband SED modeling

3. Summary and future prospects

G11.2-0.3 (Chandra; Borkowski et al. 2016)

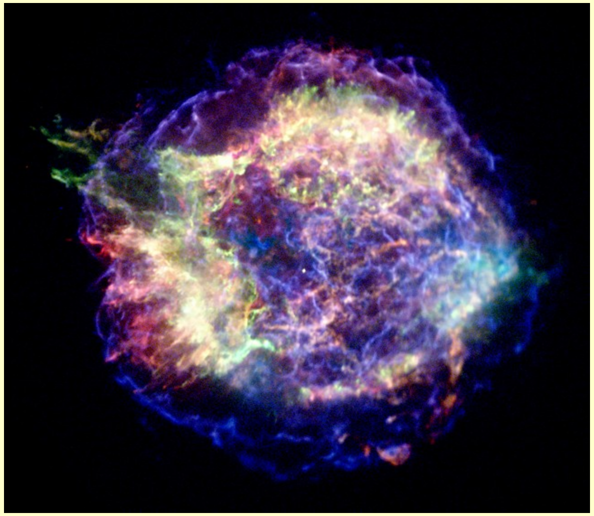
Importance of *B* in (shell) SNRs

I. Young remnants (adiabatic stages: ejecta-driven and Sedov):

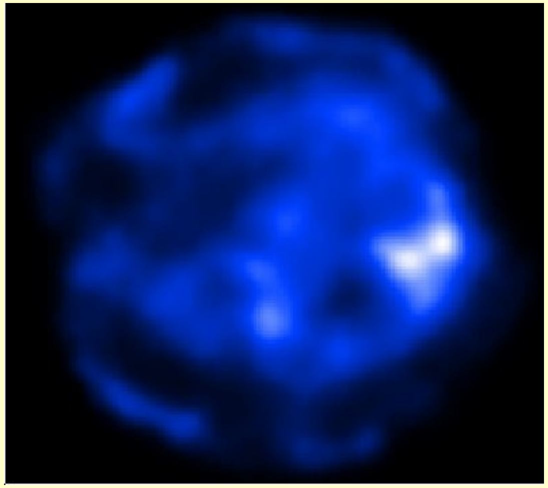
A. *B* isn't dynamically important!
Cas A, $R \sim 2.5$ pc: $U_B \sim 2 \times 10^{49} (B/1 \text{ mG})^2$ erg;
Kepler, $R \sim 2$ pc: $U_B \sim 4 \times 10^{47} (B/200\ \mu\text{G})^2$ erg)

B. Particle acceleration: Diffusive shock acceleration (DSA) predicts higher *B* gives faster acceleration, higher maximum particle energies

C. Observe strong-shock physics: magnetic-field amplification, evolution. Applications wherever strong shocks are found.



Chandra, 0.7 – 7 keV; NASA/CXC

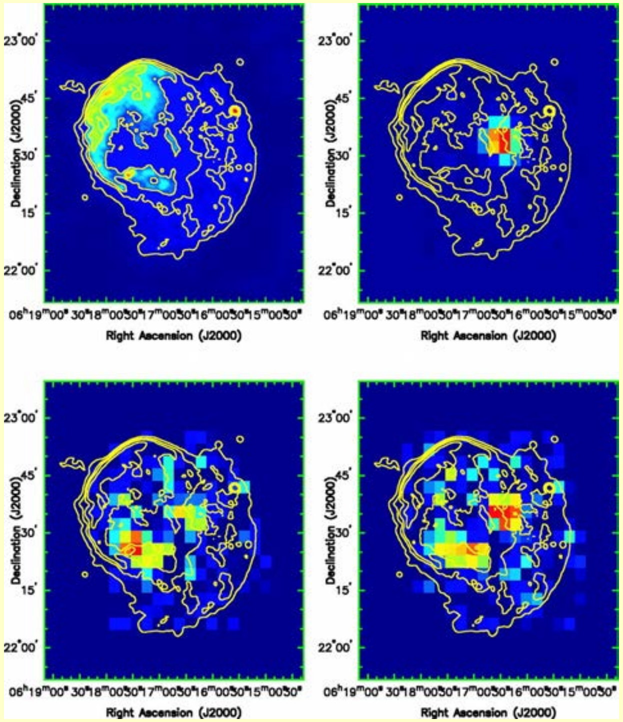


NuSTAR, 10 – 15 keV; Grefenstette et al. 2015

II. Older (radiative phase) remnants:

A. Much larger shock compressions: post-shock gas may be magnetically supported (Chevalier 1999).

Masers: Zeeman splitting ⇒ B ~ 0.1 – 1 mG ⇒ much higher pressure than thermal.



IC 443: radio continuum (upper left) not coincident with maser spots (dense clumps, magnetically supported)(Hewitt+ 2006).

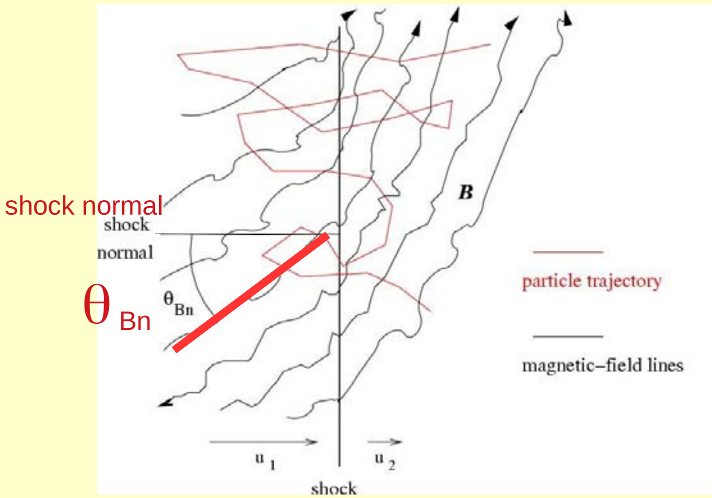
Tang & Chevalier 2014: model with B ~ 2 mG in clumps, B ~ 5 μG in interclump medium

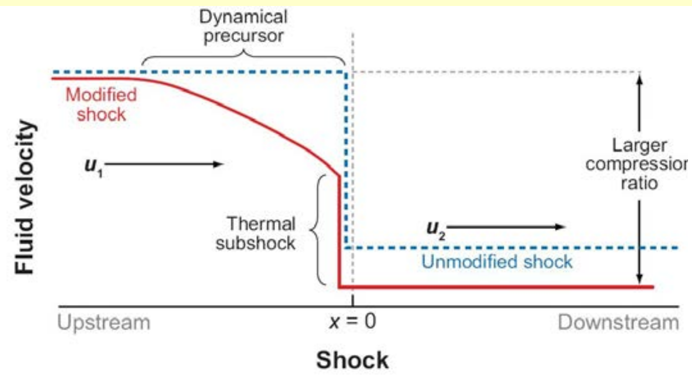
B. Turbulent re-acceleration of cosmic rays may be important in older remnants (e.g., Pohl+ 2015), requiring strong magnetic turbulence

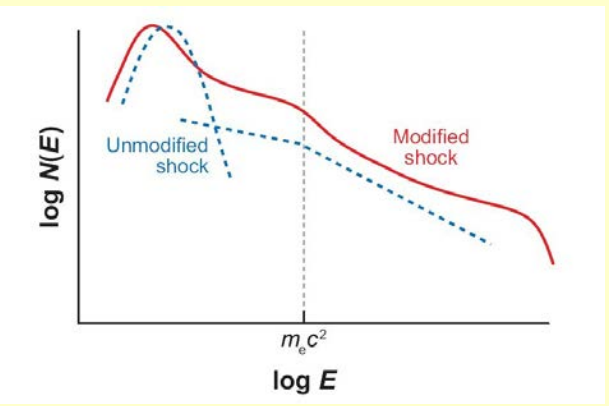
Outstanding problems involving magnetic fields in SNRs

I. Particle acceleration in shocks

A. Dependence on magnetic obliquity angle θ_{Bn}? (efficiency, rate)
B. Maximum energies attainable by electrons? Ions?
C. *B* amplification and nonlinear shock physics







II. Degree of order in *B*

A. Young SNRs: low polarization degree, but why radial excess?
B. How ordered do we expect *B* to be in X-ray "thin rim" regions?

Radio inferences: Strength and orientation

1. Strength.

Equipartition of energy between magnetic fields and electrons (with or without ions): Gives minimum energy for fixed synchrotron flux, spectrum.

$$B_{eq} \sim 20\,[(1+k)\,S_9\,D_{kpc}^2/(\varphi R_{pc}^3)]^{2/7}\ \mu\text{G} \qquad \text{(for spectral index } \alpha = -0.5\text{)}$$
$$\sim 20\,[(1+k)\,(R_{pc}\,\varphi)^{-1}\,\Sigma_9]^{2/7}\ \mu\text{G}$$

S_9: 1 GHz radio flux (Jy)

Σ_9: 1 GHz mean surface brightness S/θ^2 (Jy/sr)

φ: volume filling factor

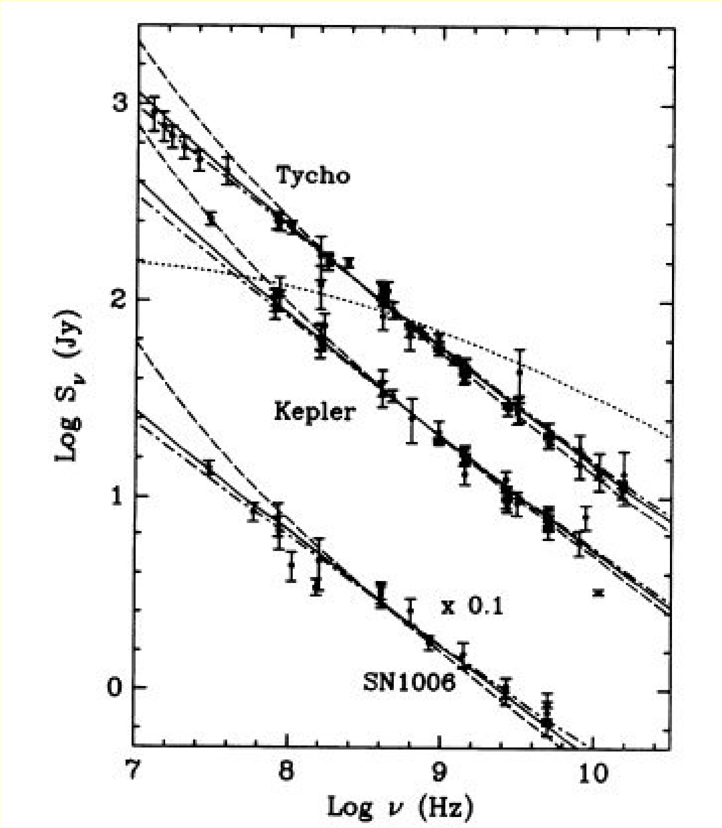
k: ratio of energy in electrons to that in ions.

Relatively weak dependence on all parameters! Basically just a measure of mean surface brightness.

For $k = 0$ (electrons only) and $\varphi = 0.2$,

$$B_{eq} \sim 5\,[\Sigma_9/(10^{-19}\ \text{W m}^{-2}\ \text{Hz}^{-1}\ \text{sr}^{-1})]^{2/7}\,(R/5\ \text{pc})^{-2/7}\ \mu\text{G}\ .$$

Integrated radio spectral indices may contain information on *B*



Tycho, Kepler, SN 1006 (every published flux up to 1992; Reynolds & Ellison 1992)

Nonlinear shock acceleration models predict concave curvature (Eichler 1979)

For specific model (Monte Carlo) can deduce *B*. Here, α (< 1 GHz) is larger (steeper) than α (> 1 GHz) by ~ 2 – 3 σ; models give $B \sim 10^{-4}$ G (Reynolds & Ellison 1992).

Mean spectral index is also steeper than prediction of test-particle diffusive shock acceleration (DSA).

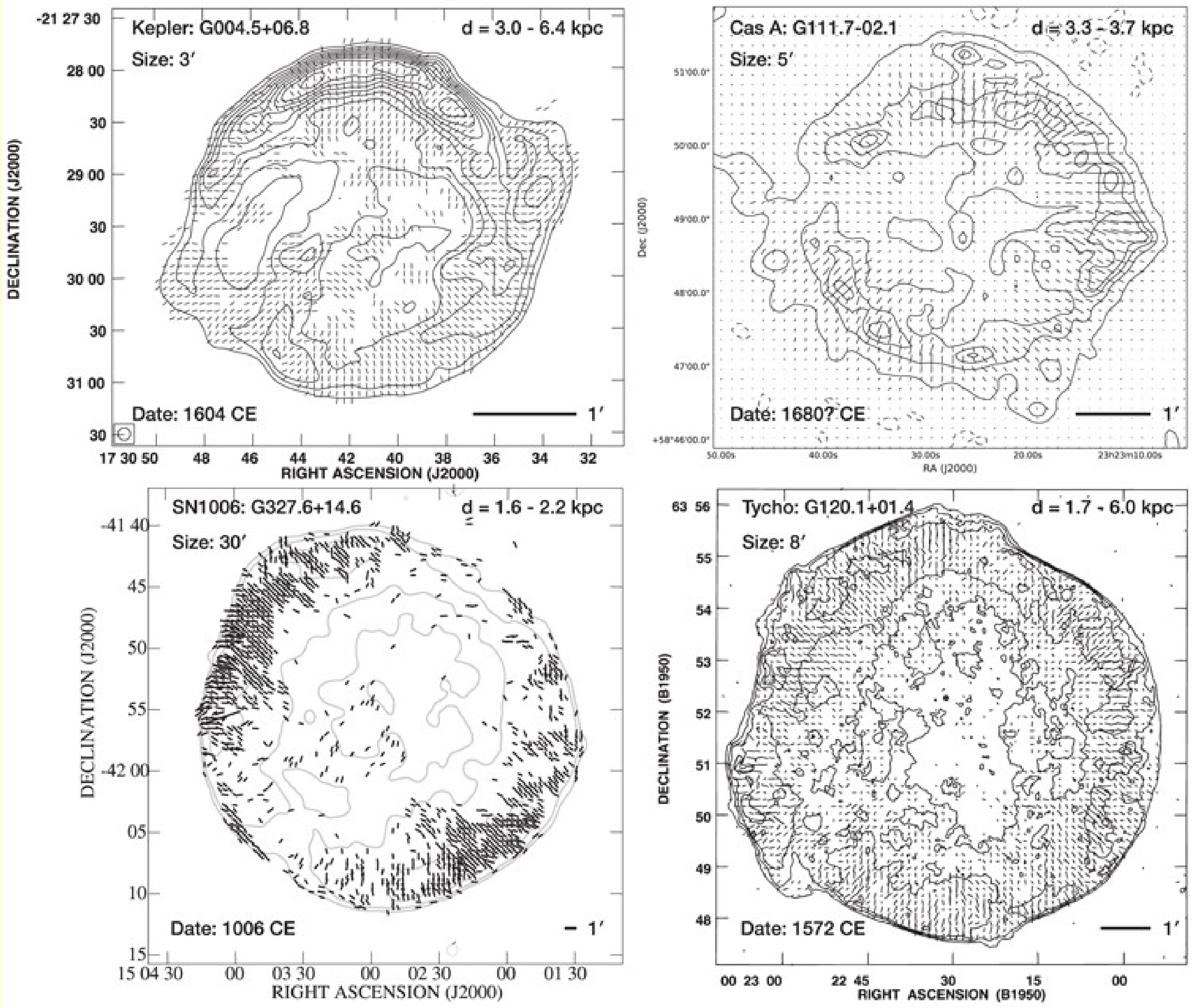
Still a lot of science in integrated radio spectral indices!

2. Orientation (and degree of order)

Polarimetry: Synchrotron radiation. For electron distribution $N(E) = KE^{-s}$, degree of polarization $\Pi = (s + 1)/(s + 7/3)$ ~ 70% for s ~ 2.

DeLaney+2002 (5 GHz; VLA)

Rudnick (VLA, 5 GHz)



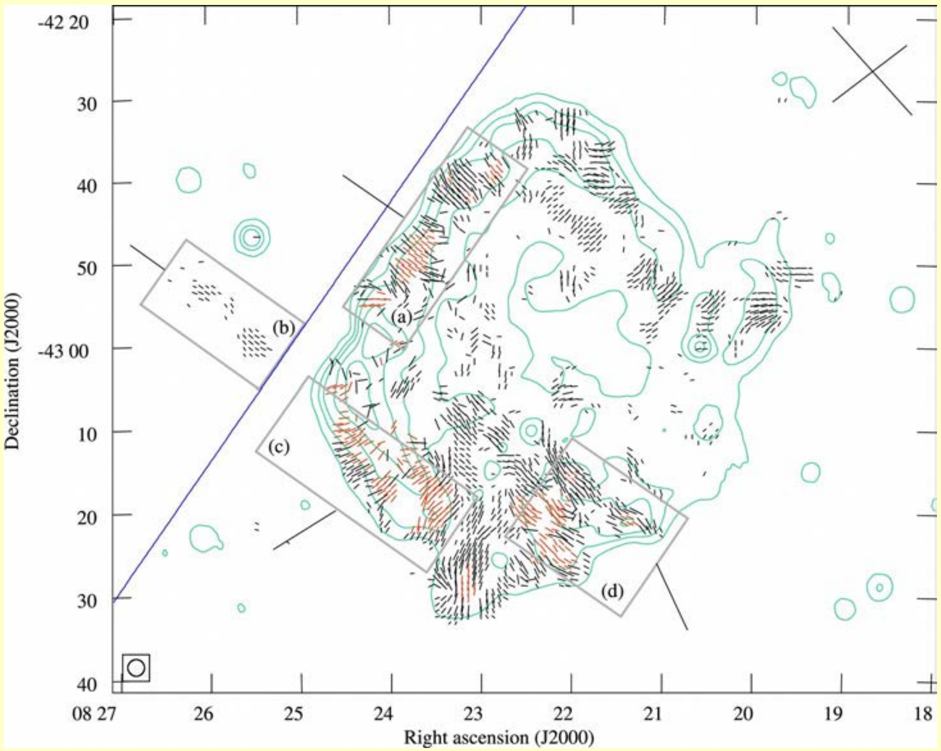
Reynoso+ 2013 (1.4 GHz, VLA + ATCA)

Reynoso+1997 (VLA, 1.4 GHz)

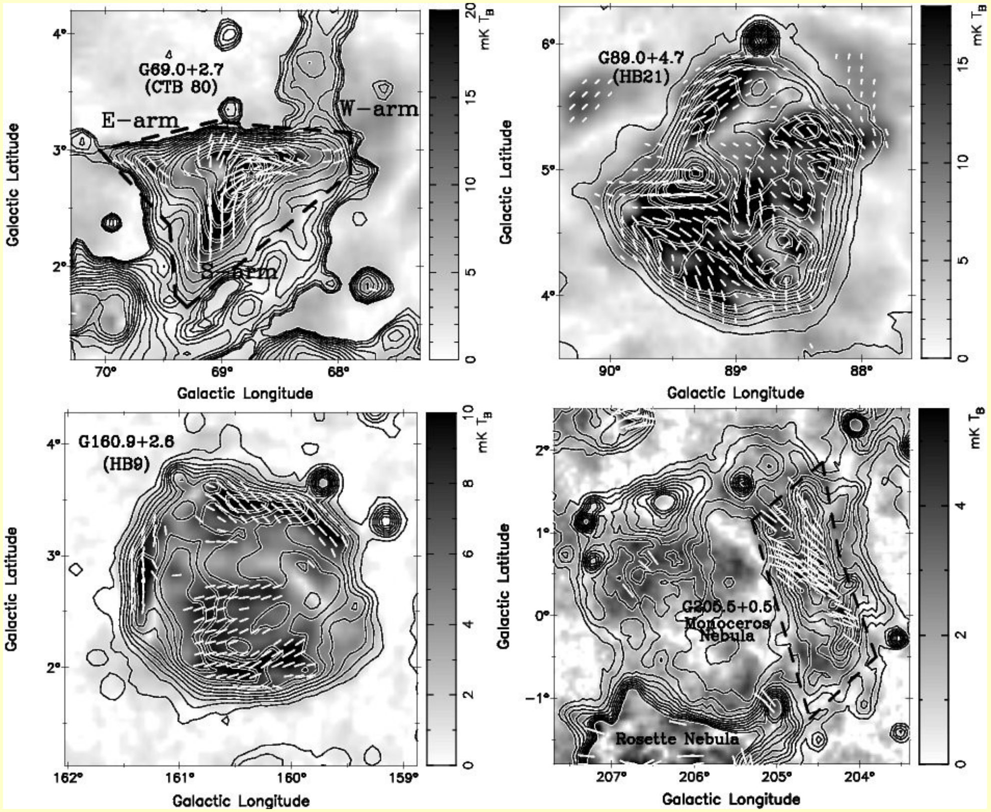
Young SNRs: Π = ~ 10% -- 15%; orientation mostly radial (but SN 1006: uniform?)
Low fractional polarization: **Field is primarily disordered** on lengthscales ~ 0.1 pc

Older (partially radiative) SNRs

Complex patterns, no clear order. Polarized fractions up to 50% in places. Often tangential (compression)



Pup A: Reynoso+ 2018



Four older SNRs (Gao+ 2011) at 6 cm. Greyscale: polarized intensity. Vectors: direction of *B* (no Faraday rotation correction, but should be small at 6 cm)

Higher frequency nonthermal radiation:
X-ray, GeV (Fermi+), TeV (HESS+)

1. **Synchrotron X-rays.**

   Spectral fitting for maximum electron energy

   Morphology (“thin rims”)

   Rapid time variability

2. **Gamma rays:** fitting broadband spectral-energy distribution (SED)

X-ray synchrotron radiation in SNRs

1. X-ray spectra dominated by synchrotron emission (XSSNRs):

G1.9+0.3 (youngest Galactic SNR)	G310.6-1.6
G330.2+1.0	G347.3−0.5 (RX J1713.7−3946)
SN 1006 (prototype)	G353.6-0.7 (HESS J1731-347)
G266.2−1.2 (“Vela Jr.”)	G32.4+0.1

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2. Synchrotron components: “thin rims” usually. In addition to several of the above:

   Historical shells Kepler, Tycho, RCW 86 (SN 185?)
   G11.2–0.3, Cas A

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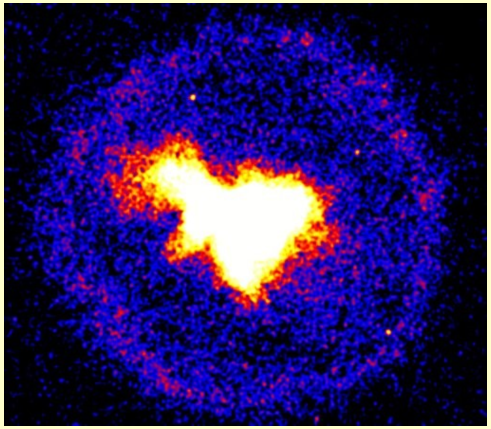
3. TeV detections of SNRs with X-ray synchrotron emission:

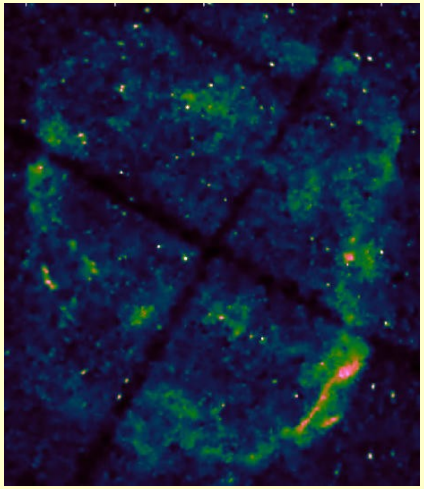
   SN 1006, G347.3−0.5, Vela Jr., G353.6-0.7 (XSSNRs)
   Cas A, RCW 86 (X-ray synchrotron components)

Eight X-ray Synchrotron-Dominated Supernova Remnants (XSSNRs)
(in order of increasing diameter)

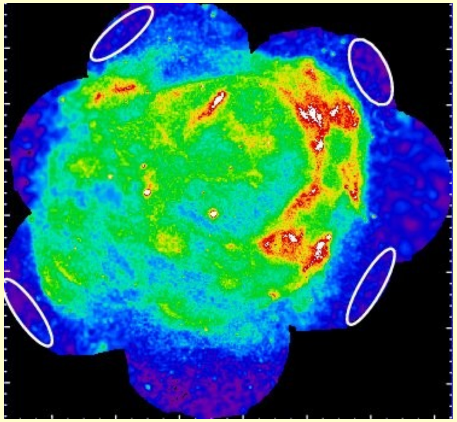
G1.9+0.3 (Borkowski+ 2013)



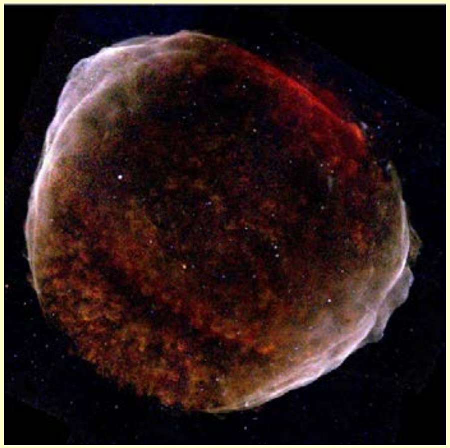
G310.6-1.6 (Borkowski+ in prep)



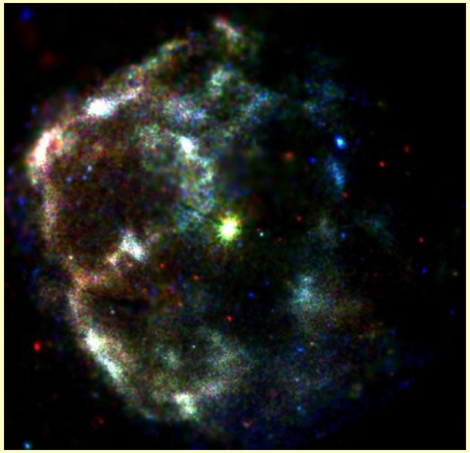
G330.2+1.0 (Borkowski+ 2018)



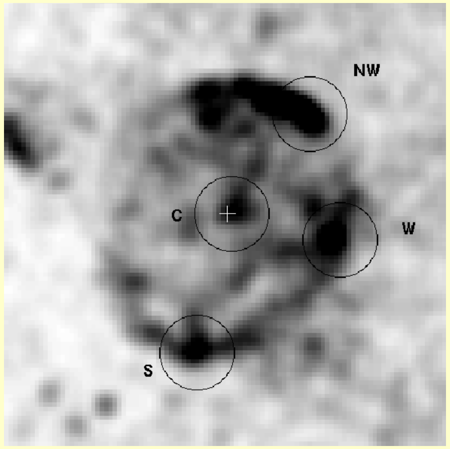
G347.3-0.5 (RX J1713.7-3946)
(XMM-*Newton*; Acero+ 2009)



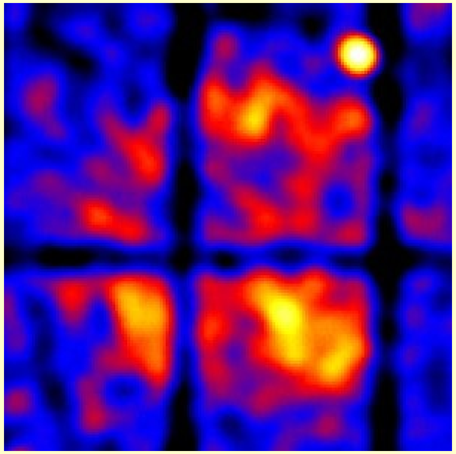
SN 1006 (Winkler+ 2014)



G353.6-0.7 (HESS J1731-347)
(XMM-*Newton*; Doroshenko+ 2017)



G266.2-1.2 (Vela Jr.)
(ROSAT; Iyudin+ 2005)



G32.4+0.1 (XMM-*Newton* archive)

Maximum energies from diffusive shock acceleration

Diffusion: $\kappa \propto$ mfp = $\eta\, r_g$ commonly assumed, so $\kappa \propto 1/B$
Rapid acceleration for high B, shock speed u_{sh}. Cutoffs:

1. **age (or size)** of remnant: $E_{max} \propto t\, u_{sh}^2\, B\, \eta^{-1}$
2. **lack of scattering** above some λ(MHD): $E_{max} \propto \lambda B$
3. **radiative losses** (electrons only): $E_{max} \propto u_{sh}\, \eta^{-1/2}\, B^{-1/2}$

In all cases, easily reach 10 – 100 TeV.

Spectrum should gradually roll off near $\nu_{roll} \propto E_{max}^2 B$.
So observing this frequency gives information on remnant properties.

Rolloff frequencies

Peak frequency emitted by an electron with energy E:
$\nu_m = 1.82 \times 10^{18} E^2 B$ Hz

$h\nu_{\rm roll}({\rm age}) \sim 0.4 \left(\frac{u_{\rm sh}}{3000\ {\rm km\ s^{-1}}}\right)^4 \left(\frac{t}{1000\ {\rm yr}}\right)^2 \left(\frac{B}{10\ \mu{\rm G}}\right)^3 (\eta f_\theta)^{-2}$ keV

$h\nu_{\rm roll}({\rm loss}) \sim 2 \left(\frac{u_{\rm sh}}{3000\ {\rm km\ s^{-1}}}\right)^2 (\eta f_\theta)^{-1}$ keV   *independent* of B!

$h\nu_{\rm roll}({\rm esc}) \sim 2 \left(\frac{B}{10\ \mu{\rm G}}\right)^3 \lambda_{17}^2$ keV

Here $f_\theta(\theta_{\rm Bn}, \eta, r) \equiv \tau_{\rm acc}(\theta_{\rm Bn})/\tau_{\rm acc}(\theta_{\rm Bn} = 0^\circ)$: obliquity-dependence of acceleration

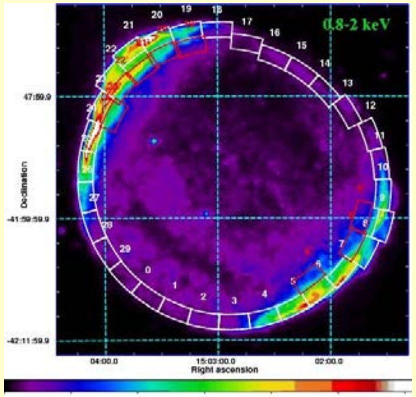
Operative value from loss mechanism giving lowest $E_{\rm max}$

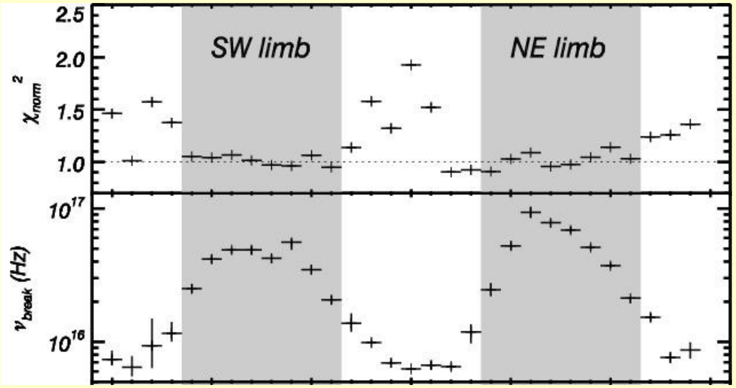
Which mechanism limits electron energies?

If *loss-limited*: **no** information on *B*

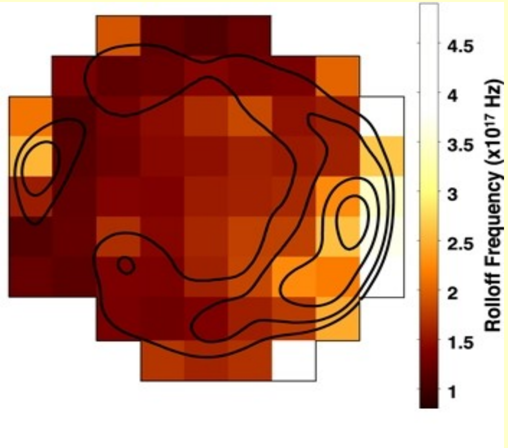
If *age-limited:* have limit on *B* (no independent knowledge of gyrofactor η).
Lower *B* favors age-limited.

Spatially resolved spectral fitting: get $h\nu_{roll}$ at different positions in one SNR.
Result: large variations! If loss-limited, not due to *B* variation. Obliquity effect?





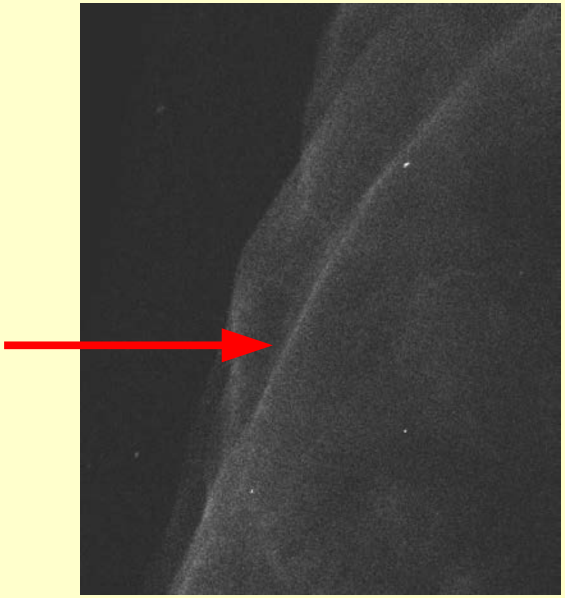
SN 1006: Miceli et al. 2009 A&A, 501, 239 (*XMM-Newton* data)



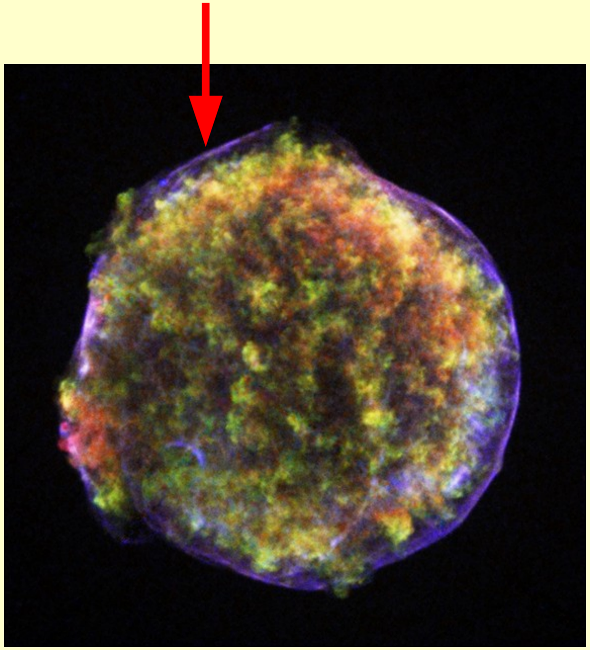
Tycho: Lopez et al. 2015 Chandra+NuSTAR data

Known SNR age: For electron acceleration in Tycho to be age-limited rather than loss-limited ($E_{age} < E_{loss}$), need B < 29 μG (Lopez+ 2015)

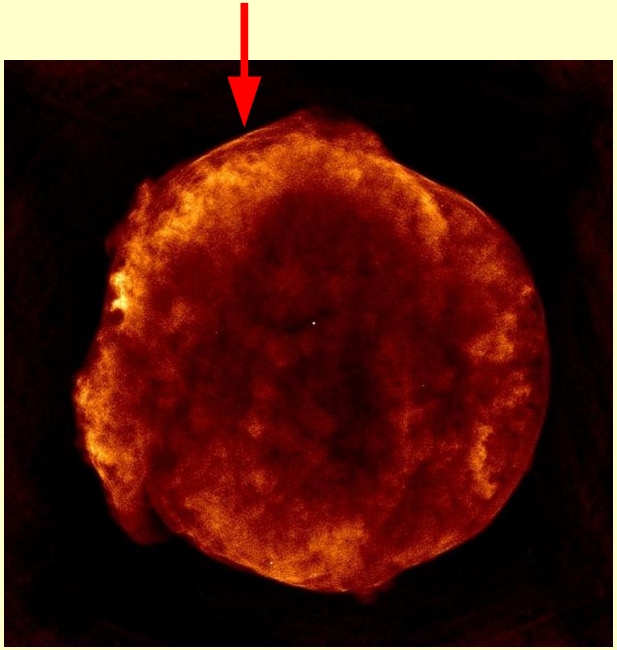
Thin X-ray rims: magnetic-field amplification



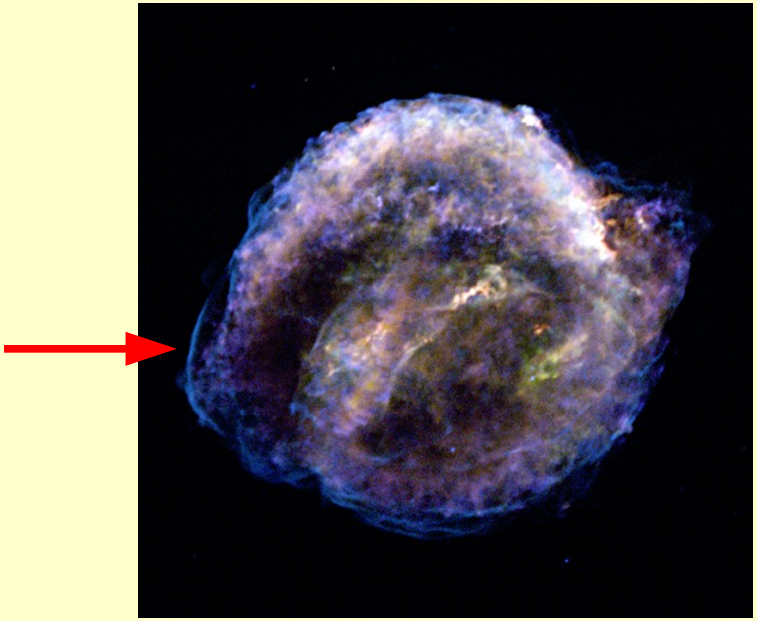
SN 1006 (Chandra)



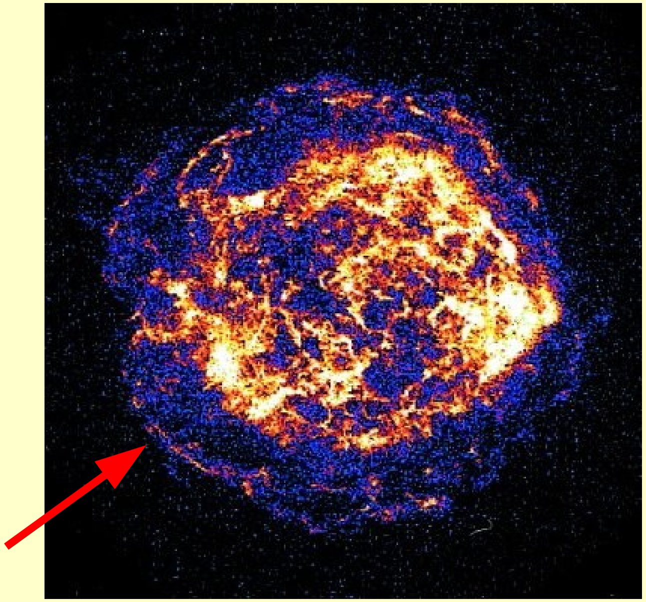
Tycho (Chandra)



Tycho (radio; VLA)



Kepler (Chandra)



Cas A (Chandra; Gotthelf+ 2001)

Thin X-ray synchrotron rims

Shock accelerates electrons, amplifies B: **sudden turnon of synchrotron emission.**
Thin rims: emission **turns off again** only ~ 10" – 100" downstream! Only two options:

1. **Eliminate electrons** by radiative losses. (**"Loss-limited;"** Bamba et al. 2003, Vink & Laming 2003, Parizot et al. 2006)
2. **Eliminate *B*** (if in wave form) by some kind of damping (**"Magnetically damped;"** Pohl et al. 2005; Rettig & Pohl 2012)

Detailed comparison, extension to arbitrary power-law κ(E), application to SN 1006: Ressler et al. 2014. Application to Tycho: Tran et al. 2015 ApJ

Basic physics: If B damps on a length scale a_b , both processes compete.
Particles move downstream by the **larger** of advection or diffusion distance L.

At a given photon energy $h\nu \propto E^2 B$, $L_{ad} \propto \nu^{-1/2} B^{-3/2}$ and $L_{diff} \propto B^{-3/2}$ independent of photon energy.

So **rim widths should first shrink with rising photon energy, then remain constant with width (min[a_b , L]).**

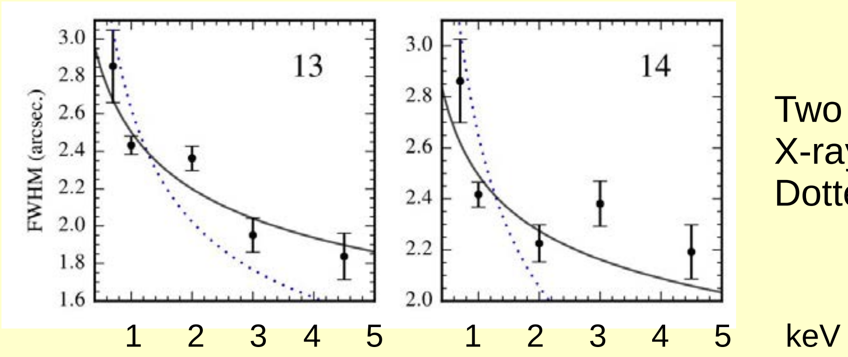
Results: Find strong energy-dependence of rim widths

1. Division into loss-limited and damped models is too simple: separation is photon energy-dependent.

2. Rim shrinkage in both Tycho and SN 1006 indicates that **in soft X-ray region, rim widths are affected by electron energy losses,** though mixed loss/damped models can reproduce observations. **Thin radio rims require some magnetic damping.**

3. **In all fits, *B* must be amplified beyond simple compression:** *B* > 20 μG. Quantitative fits give ***B* ~ 40 – 200 μG (SN 1006)** and ***B* ~ 50 – 400 μG (Tycho).** confirming, with most detailed calculations to date, strong amplification.

4. Longer observations of SN 1006 rims would allow widths to be measured at higher photon energies to test these conclusions.



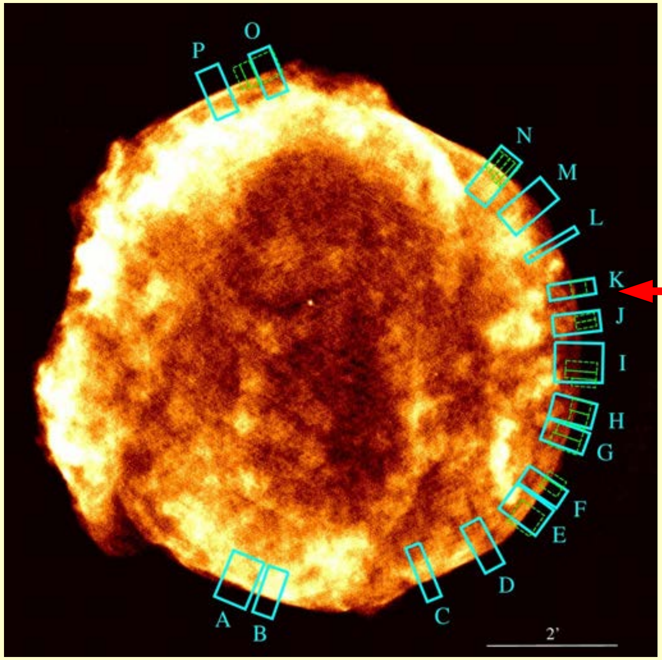
Two regions in Tycho: widths measured at 5 X-ray energies. Solid lines: loss-limited. Dotted: damped. (Tran et al. 2015)

Ressler et al. 2014, ApJ, 790:85; Tran et al. 2015, ApJ, 812:101

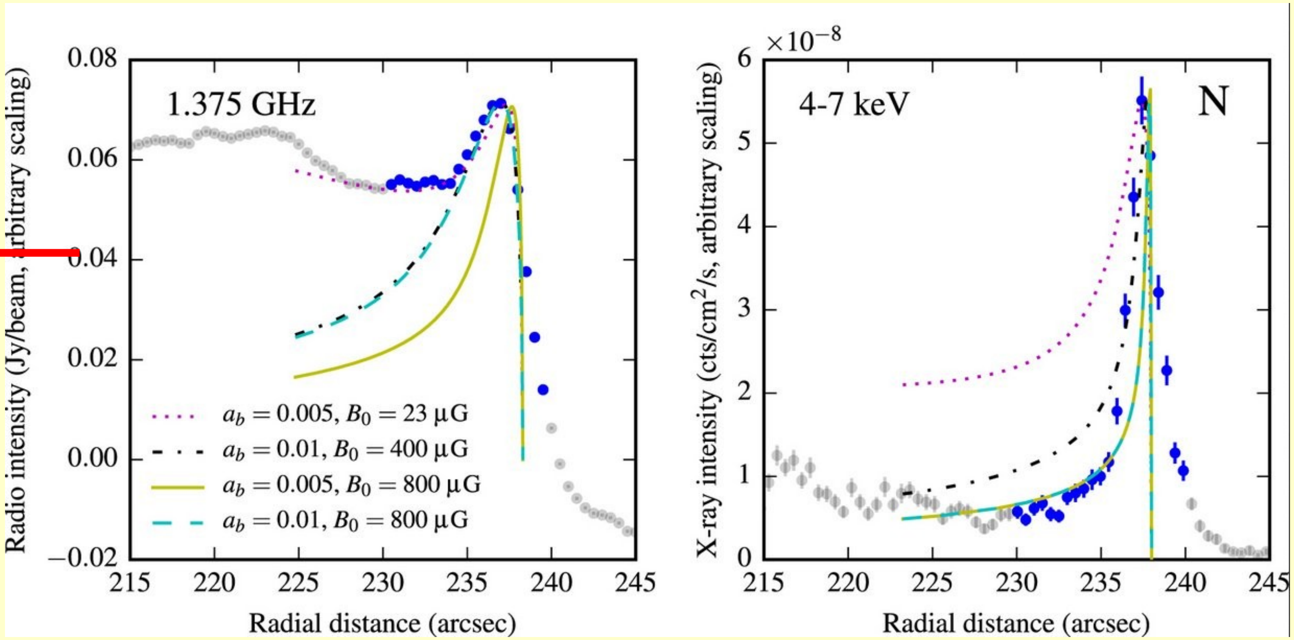
Tycho: Rims also shrink with X-ray energy.
But some rims are thin in radio as well.

radio (1.4 GHz)

X-ray (4 – 7 keV)



Tycho at 1.4 GHz (VLA; Reynoso et al. 1997)



Thin radio rims require some magnetic damping -- but still need strong *B* (~ 50 µG) (Tran+ 2015)

Rim-width analyses differ in detail

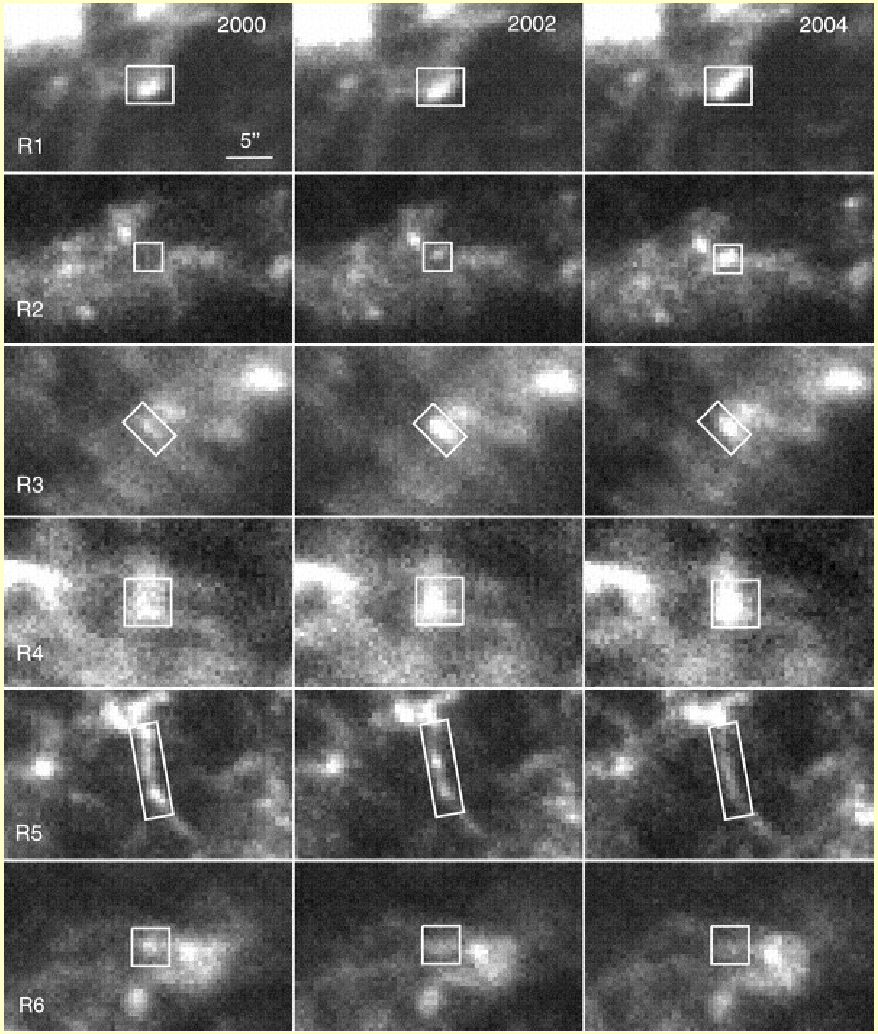
Object	P+06	VBK05	RP12 Loss	RP12 Damp	T+15
Cas A	210-230	500	520	115-260	
Kepler	170-180	200	250	80-135	
Tycho	200-230	300	310	85-150	50-400
SN 1006	57-90	140	130	64-65	40-200
RCW 86		100			
G347.3−0.5	61-77	60-300			

P+06, Parizot et al. 2006, A&A, 453, 387
VBK05, Völk et al. 2005, A&A, 433, 229
RP12, Rettig & Pohl 2012 A&A 545, 47
T+15, Tran et al. 2015 ApJ 812:101

Magnetic fields in μG. Some ranges are due to fitting rims at different locations. T+15: rims can be fit with different models.

Rapid X-ray variability

2000 2002 2004



Chandra observations of Cas A (Patnaude & Fesen 2007)

Small features seen to brighten or fade in ~ 1 yr in Cas A (Patnaude & Fesen 2007), G347.3−0.5 (RX J1713)(Uchiyama et al. 2007)

If this is timescale of particle acceleration,need high *B*:

$$\tau_{accel} \propto \kappa/u_{sh}^2$$

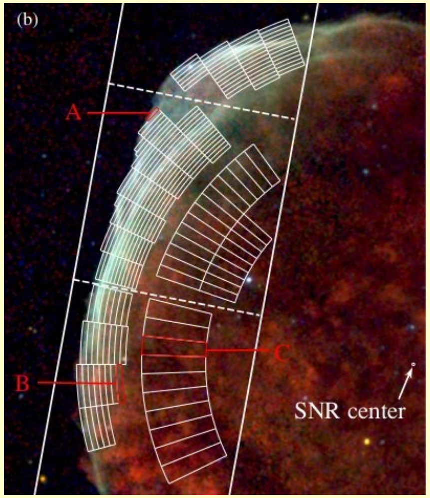
where κ is diffusion coefficient, $\kappa \propto 1/B$

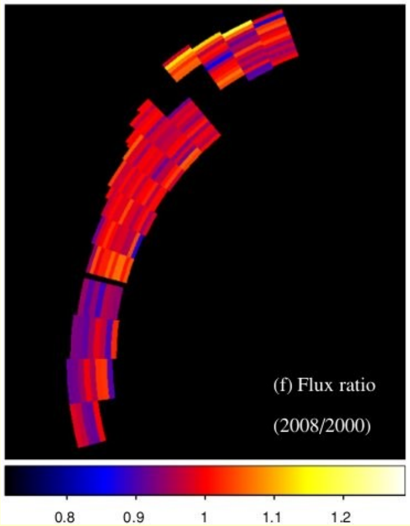
Get *B* ~ 1 mG (Uchiyama et al. 2007)

If fading is due to synchrotron losses, similar result.

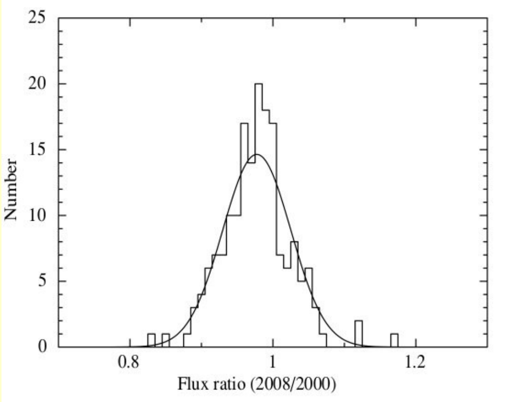
But *B* may be turbulent; see “twinkling” of temporary regions of high *B* (Bykov et al. 2008, 2009). In cutoff part of spectrum, smaller changes in electron distribution can cause larger variations in flux (i.e., $\tau_{var} < \tau_{accel}$) so smaller *B* suffices.

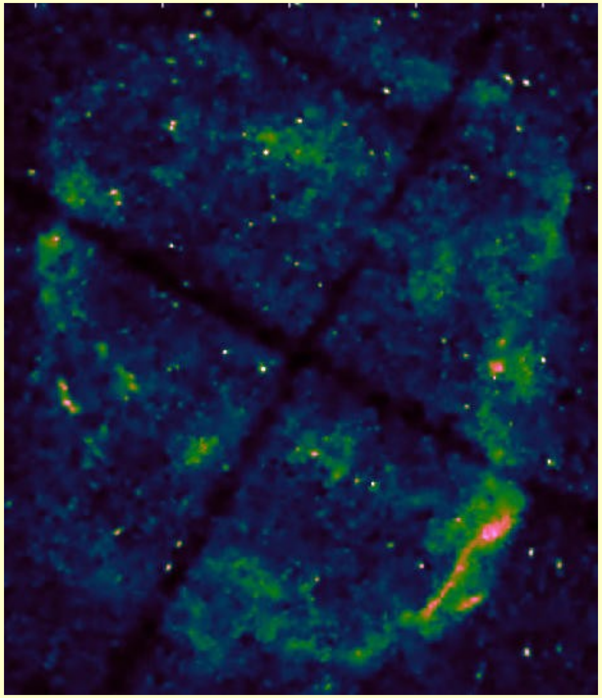
Variability in other SNRs?

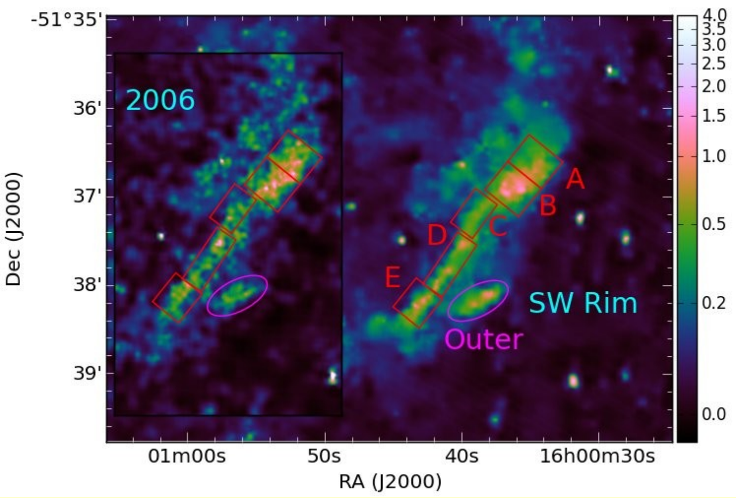




SN1006: **No significant small-scale changes** between 2000 – 2008 (Katsuda+ 2010). Mean is constant to within calibration uncertainties.







G330.2+1.0: changes between 2006 and 2017.
Region A: faded by (23 ± 7)%; B, faded by (12 ± 6)%.
Outer rim: brightened by (19 ± 7)% (Borkowski+ 2018)

Look higher: Radiative processes from X-ray to γ-ray

One hadronic process: cosmic-ray p + thermal p → pions; π^0's decay to γ-rays. Only potential direct evidence for cosmic-ray ions in SNRs. Distinguishing feature: 70 MeV "bump."

Three leptonic processes.

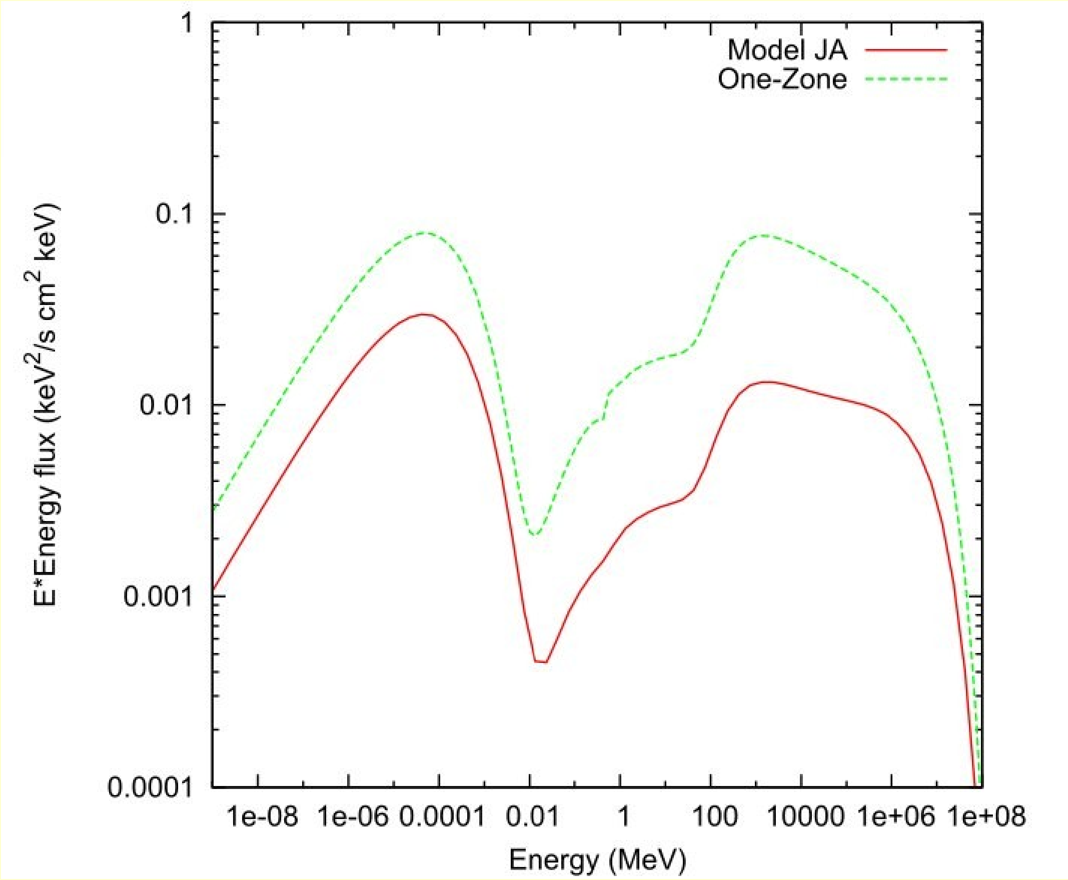
Synchrotron radiation: Important from radio to soft X-rays. Flux fixes only combination of magnetic field, electron energy density

Bremsstrahlung: Can be important from soft X-ray to TeV. Constrained above 100 MeV where same electrons produce radio synchrotron

Inverse-Compton: Present wherever relativistic electrons are present through ICCMB. Detection gives electron energy directly, allows inference of B from synchrotron fluxes.

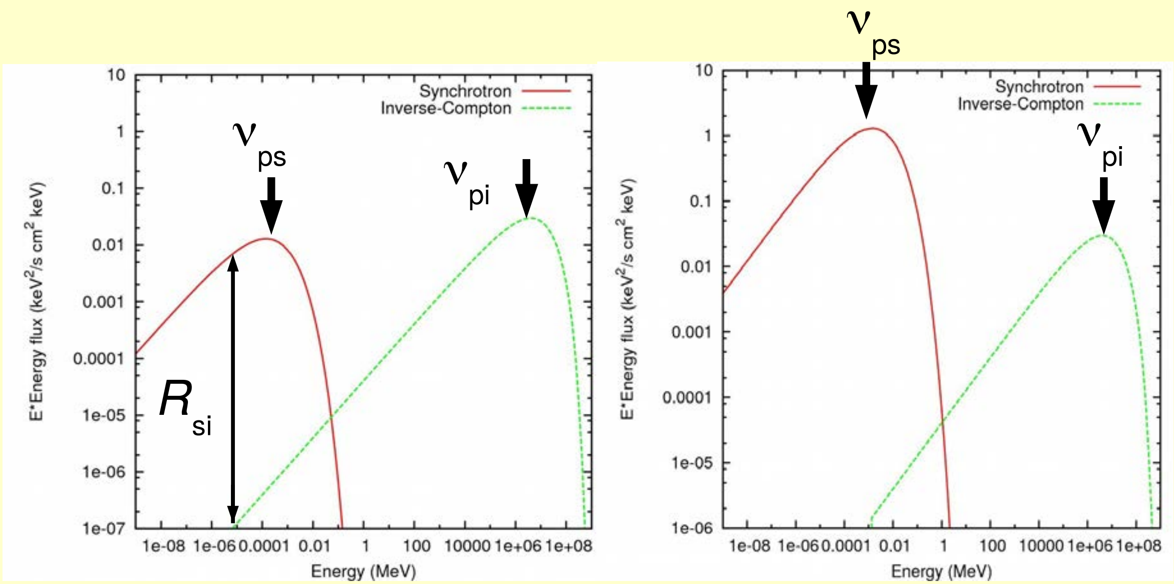
All of these may contribute to high-energy photon emission from SNRs

Cautionary tale: comparison of homogeneous source ("one-zone" model) with 1-D hydro model



Simplistic particle spectra: single power-laws with exponential cutoffs.
Main parameters: *B*, particle acceleration efficiencies, maximum energies.
Red: Cavity SNR shortly after collision with dense shell.
Green: homogeneous (one-zone) model with parameters of current blast wave (Tang+ 2016)

The same electrons that produce X-ray synchrotron emission produce TeV gamma rays from IC upscattering of CMB photons



B = 1 μG

B = 10 μG

Homogeneous source, input power-law electron spectrum $N(E) = KE^{-2}$ electrons/erg/cm^{-3}.

Ratio of peaks (in νF_ν space) gives B:

$B \sim 9 \times 10^4 \, (\nu_{ps}/\nu_{pi})$

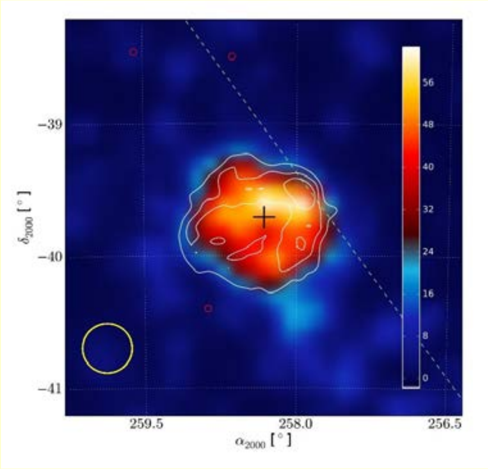
Ratio of fluxes at a frequency depends on B -- and its filling factor f_B:

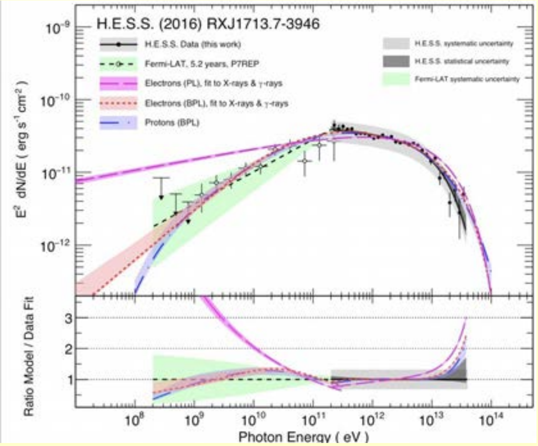
$F(SR)/F(IC) \equiv R_{si} \sim 5 \times 10^{13} f_B B^{1.5}$

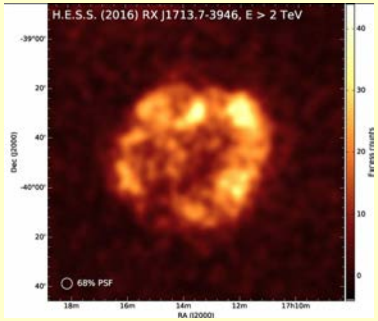
(for E^{-2} electron spectrum)

GeV (Fermi) and TeV (air-Čerenkov) observations

Federici+ 2015



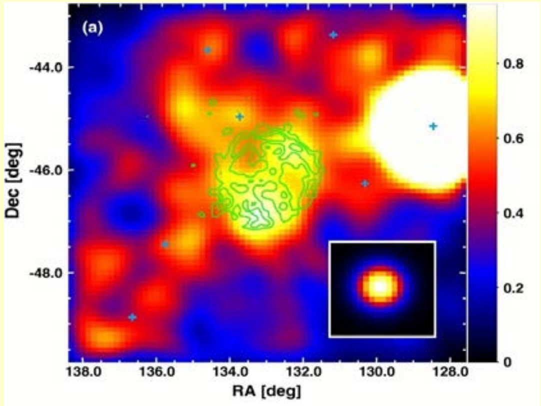


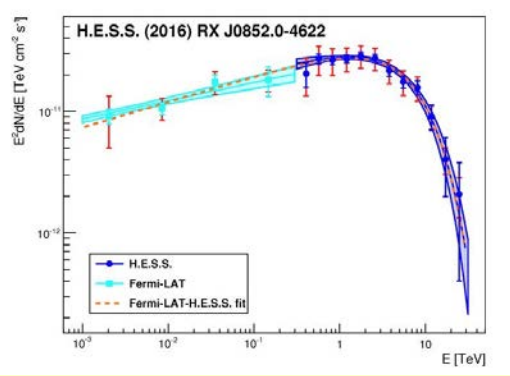


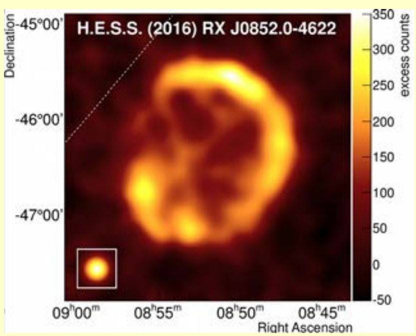
Abdalla+ (H.E.S.S. collab.) 2018a (E > 2 TeV)

G347.3-0.5 (RX J1713.7-3946)

Tanaka+ 2011





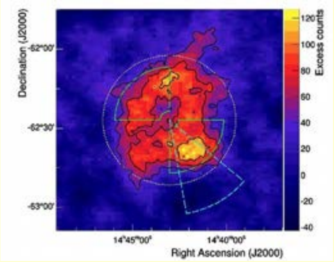


Abdalla+ (H.E.S.S. collab.) 2018b

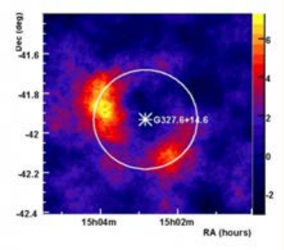
Vela Jr.

VERITAS images

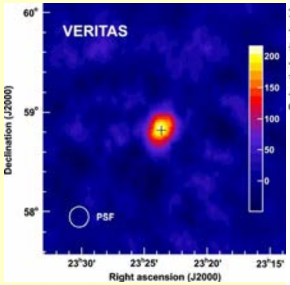
H.E.S.S. images



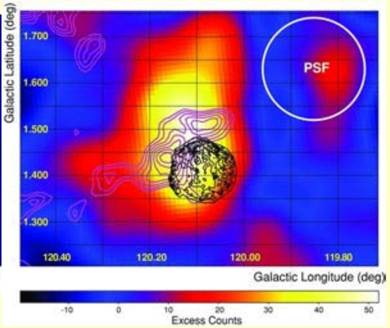
RCW 86
H.E.S.S. 2018c



SN 1006
Acero+ 2010

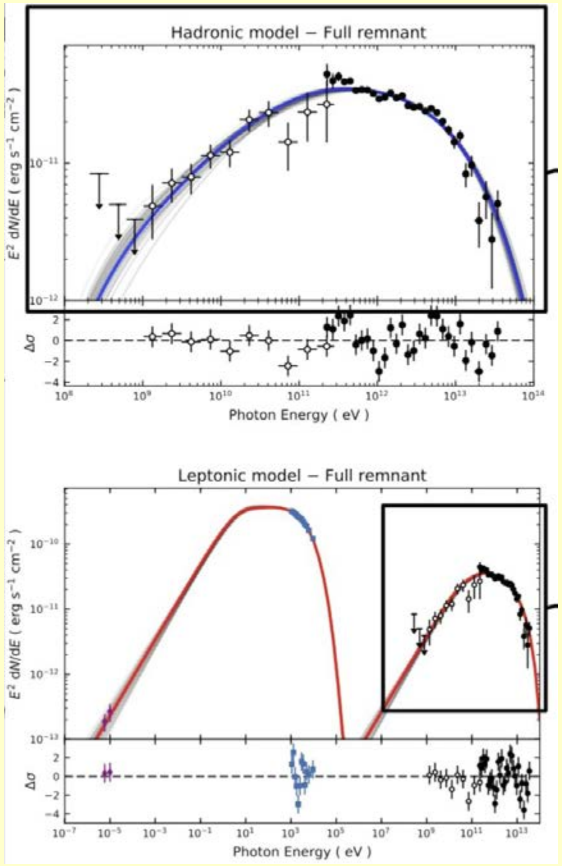


Cas A
Acciari+ 2010



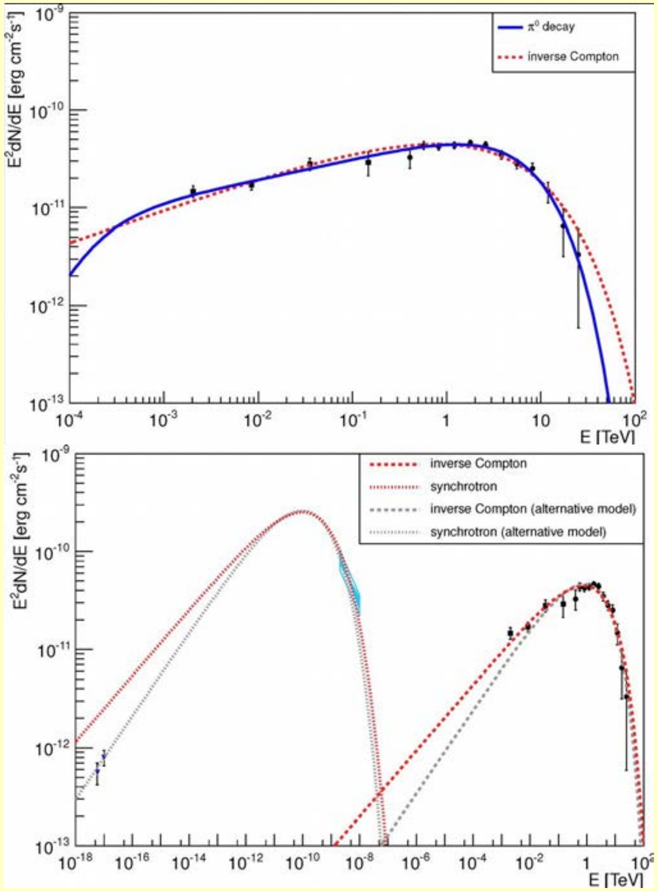
Tycho: Acciari+ 2011

Leptonic model for GeV/TeV gives *B*; hadronic, only lower limit



Hadronic model
(γ-ray only)

Leptonic model
(radio – TeV)

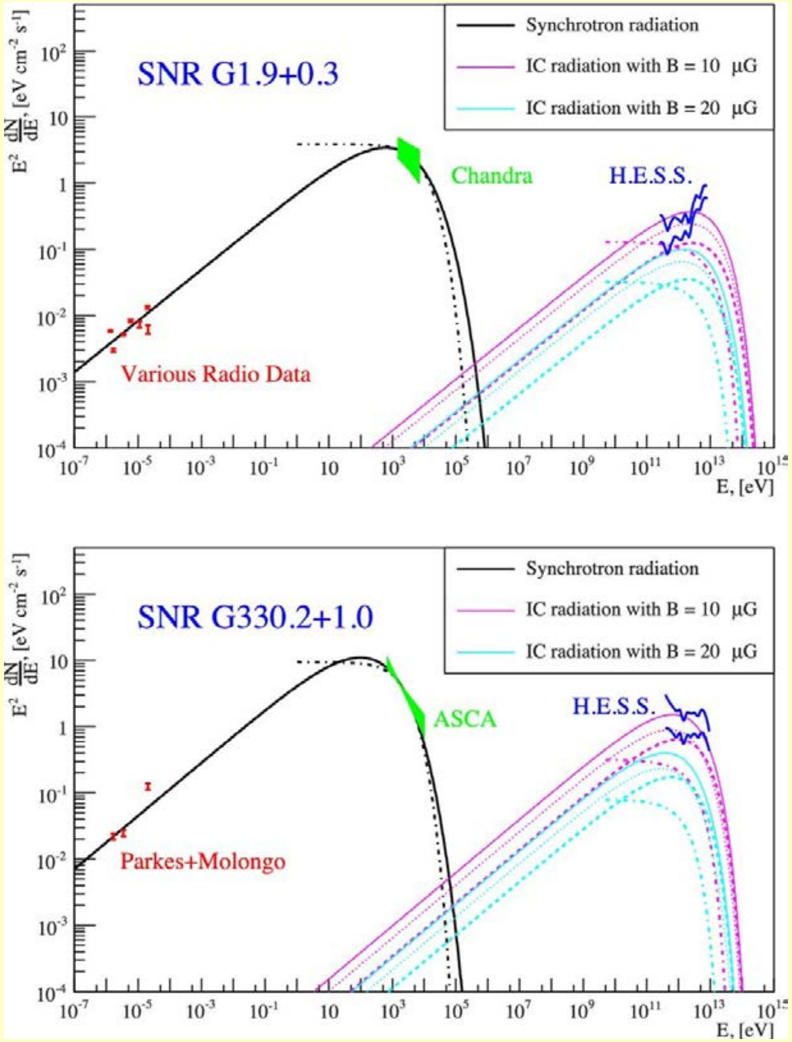


RX J1713.7-6946 (G347.3-0.5):
H.E.S.S. Collab. 2018a
Get ***B* ~ 14 μG** for leptonic model

Vela Jr: (H.E.S.S. Collab. 2018b).
Hadronic and leptonic models for gamma rays.
Bottom: **Leptonic model, *B* ~ 7 μG** (red lines: fit to gamma-rays only; grey, adding radio)

...but some are not detected

SEDs of G1.9+0.3 (top) and G330.2+1.0 (bottom) in a leptonic scenario



H.E.S.S. Collaboration et al. MNRAS 2014;441:790-799

Simple homogeneous (one-zone) leptonic (ICCMB) model gives lower limits on *B*:
12 μG for G1.9+0.3,
8 μG for G330.2+1.0

Limits from hadronic models are not constraining

Summary: Magnetic fields in shell SNRs

Radio

1. Strength

Dynamically important only in small regions of radiative (older) SNRs
No reason for minimum-energy constraint, so equipartition values not useful
Nonlinear shock models require curved radio spectra: extract (model-dependent) *B*
Thin rims require magnetic-field decay

2. Orientation and order

Young SNRs: *B* largely disordered; ordered component is often radial (but SN 1006?)
Old SNRs: Often tangential; sometimes highly ordered (well described by compression in radiative shocks)

In general, radio information is underutilized!

Summary: Magnetic fields in shell SNRs

X-ray and gamma-ray

1. Thin-rim analyses are complex in detail! A few thin radio rims require magnetic-field damping, but both damping and loss-limited models for SN 1006 and Tycho require *B* > 40 μG, i.e., **amplification above simple compression.**

2. Rim models for other young SNRs require *B* > 100 μG typically, but inferred values depend on analysis details (by factors of several).

3. One-zone SED models can give *B*, but results from more realistic models differ. Leptonic models for GeV/TeV emission require lower *B* than hadronic. Any detection or limit gives a lower limit on *B*.

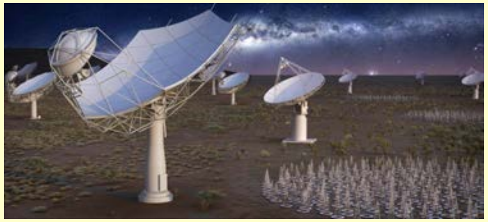
4. Amplified *B* probably fills only small volumes; filling factors f_B should be introduced in SED modeling.

5. SNRs are inhomogeneous! Conditions can vary substantially with location! **Need to move beyond one-zone modeling.**

Future prospects

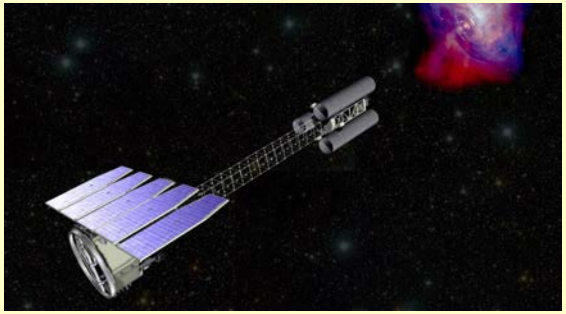
New observational opportunities in the next decade!

1. Radio. LOFAR, SKA: Lower frequency coverage: better integrated spectral indices. More collecting area: better surface-brightness sensitivity.



SKA (2024 – 2030)

2. X-ray: Polarimetry at last! IXPE: imaging polarimetry. Degree of order in B in region where nonthermal X-rays are produced.



IXPE (2020)

3. TeV gamma-rays: Cerenkov Telescope Array (CTA). Spatially resolved spectroscopy.

CTA (2022 – 2025)