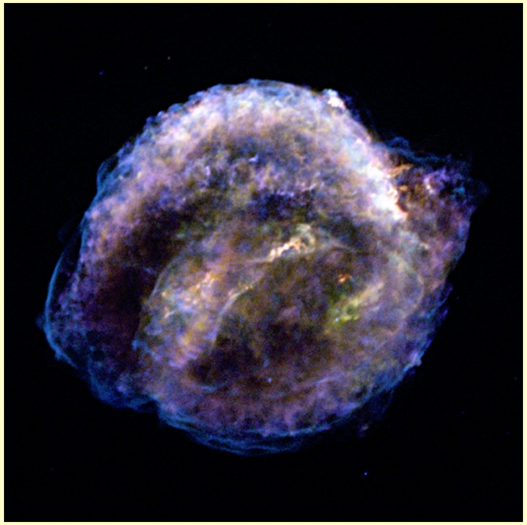
Magnetic Fields in Supernova Remnants and Pulsar-Wind Nebulae: Deductions from X-ray (and gamma-ray) Observations

Stephen Reynolds (NC State U)



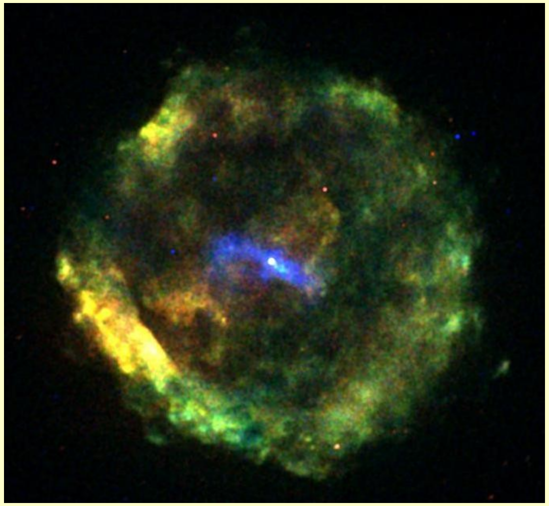
Kepler's SNR (Chandra; Reynolds et al. 2007)

1. Introduction

2. Determining *B* in SNRs
   SED modeling
   Thin rims
   Time variability

3. Determining *B* in PWNe

4. Summary



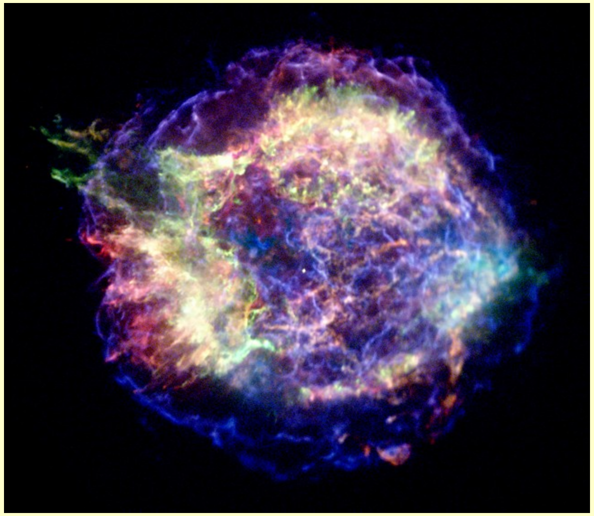
G11.2-0.3 (Chandra; Borkowski et al. 2016)

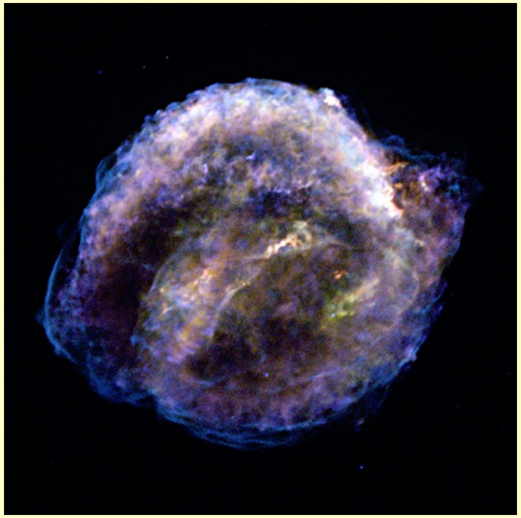
Importance of *B* in (shell) SNRs

1. It's not dynamical! (e.g., Cas A, $R \sim 2.5$ pc: $U_B \sim 2 \times 10^{49}\,(B/1\ \mathrm{mG})^2$ erg;
   Kepler, $R \sim 2$ pc: $U_B \sim 4 \times 10^{47}\,(B/200\ \mu\mathrm{G})^2$ erg)

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

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





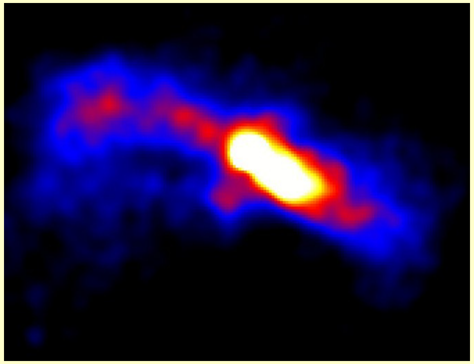
NASA/CXC

B in pulsar-wind nebulae

1. PWNe are primarily nonthermal emitters (unlike shell SNRs): B is crucial to both dynamics, emission.

2. Particle transport in PWNe may also be diffusive: depends on both strength and geometry of B

3. Pulsar energy loss is expected to be largely magnetic-dipole radiation: somehow $U_B \rightarrow U_e$ beyond light cylinder or at wind termination shock ("σ problem")



PWN in G11.2-0.3: Borkowski et al. 2016

Estimating magnetic-field strengths in SNRs

Recall for $N(E) = KE^{-s}$, synchrotron flux $\propto KB^{(s+1)/2} \simeq u_e u_B$ for $2 < s < 3$.

1. Equipartition (from radio data typically). But include ions or not? Why should Nature produce this? (Both u_e and u_B are small compared to total SN energy)
2. SED modeling: Compare synchrotron with GeV/TeV emission when seen.
3. Masers (but very local, unusual conditions)

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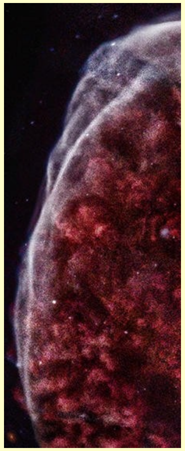
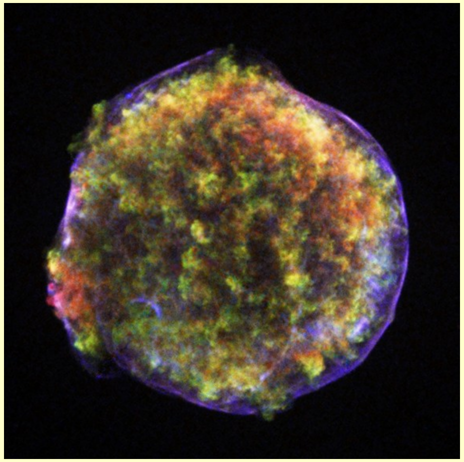
For remnants showing X-ray synchrotron emission (younger than a few thousand years old):

4. "Thin rims:" If rim widths are limited by synchrotron losses as particles advect downstream, can estimate B
5. Time variability of X-ray synchrotron emission: either brightening (acceleration timescale) or fading (loss timescale) (unless B varies on similar timescales)

SN 1006
Winkler et al. 2014





Tycho
NASA/CXC

X-ray synchrotron radiation in SNRs

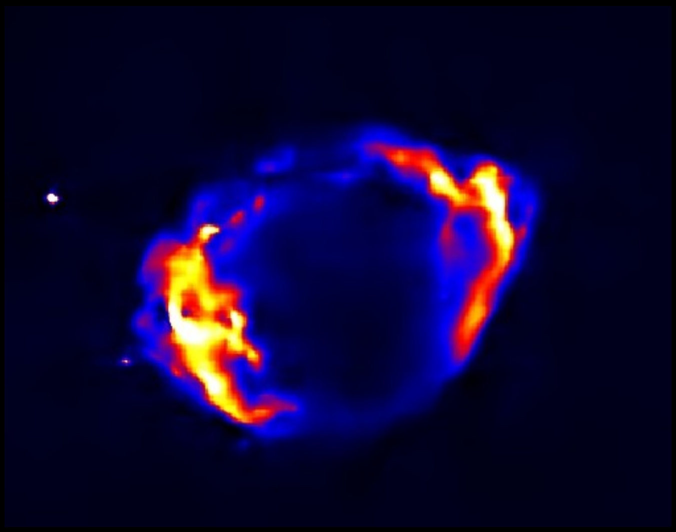
1. X-ray spectra dominated by synchrotron emission:
   SN 1006: archetype
   G347.3–0.5 (RX J1713.7–3946)
   G266.2–1.2 ("Vela Jr.")
   G1.9+0.3
   G330.2+1.0

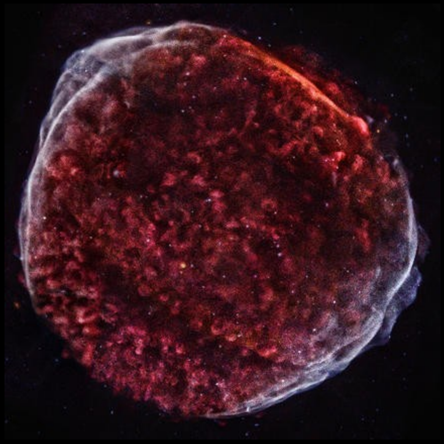
2. Synchrotron components: "thin rims" usually
   Historical shells Kepler, Tycho, RCW 86 (SN 185)
   Young shells Cas A, G11.2–0.3
   Less clear possible cases: G28.6-0.1, CTB 37B,
   HESS 1731-347, G32.45+0, G156.2+5.7

3. GeV/TeV detections of SNRs with X-ray synchrotron
   SN 1006, Tycho, RCW 86
   G347.3–0.5, Vela Jr.
   Cas A

The Big Four: synchrotron X-ray dominated

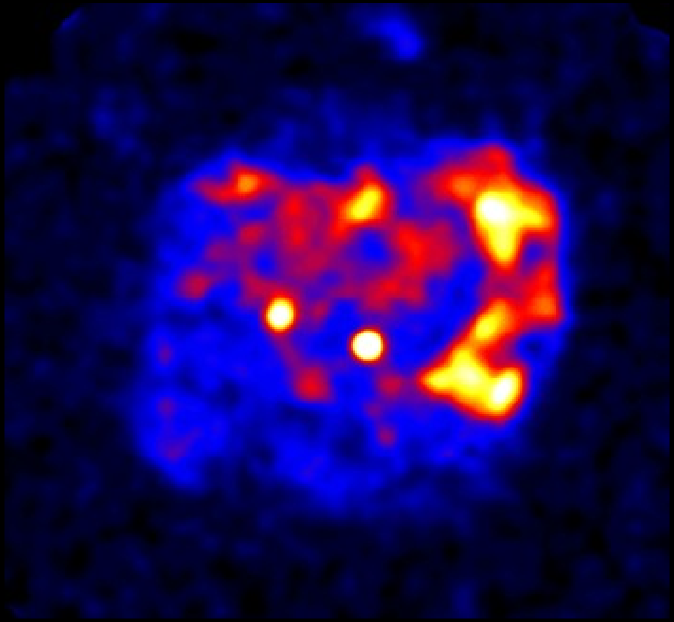
G1.9+0.3: youngest SNR! (Chandra; Reynolds et al. 2008)

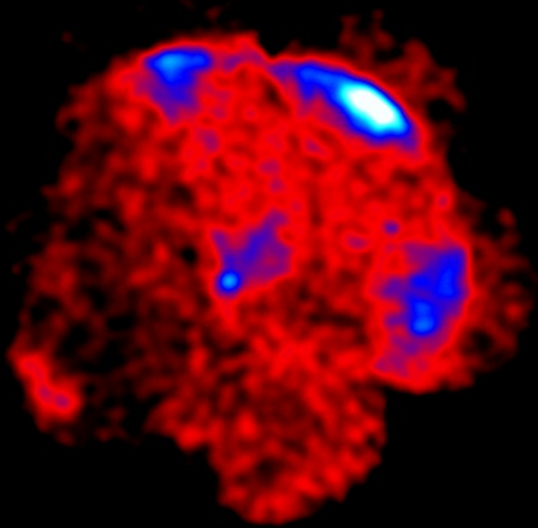




SN 1006 (Winkler et al. 2014)

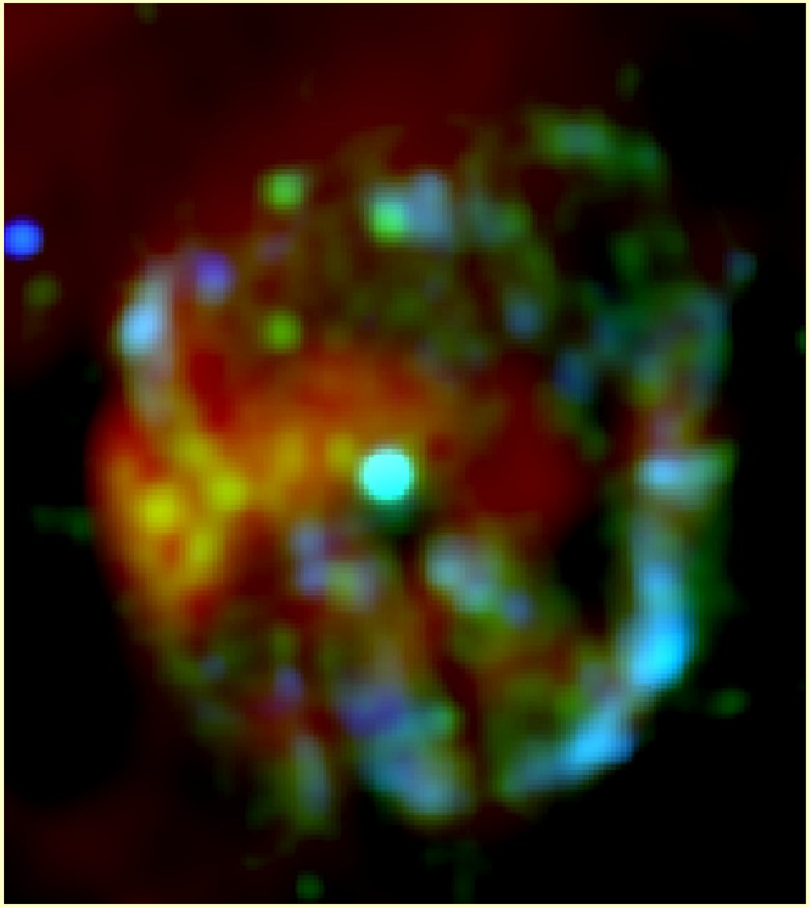
G347.3-0.5 (RX J1713.7-3946) (ROSAT; Slane et al. 1999)



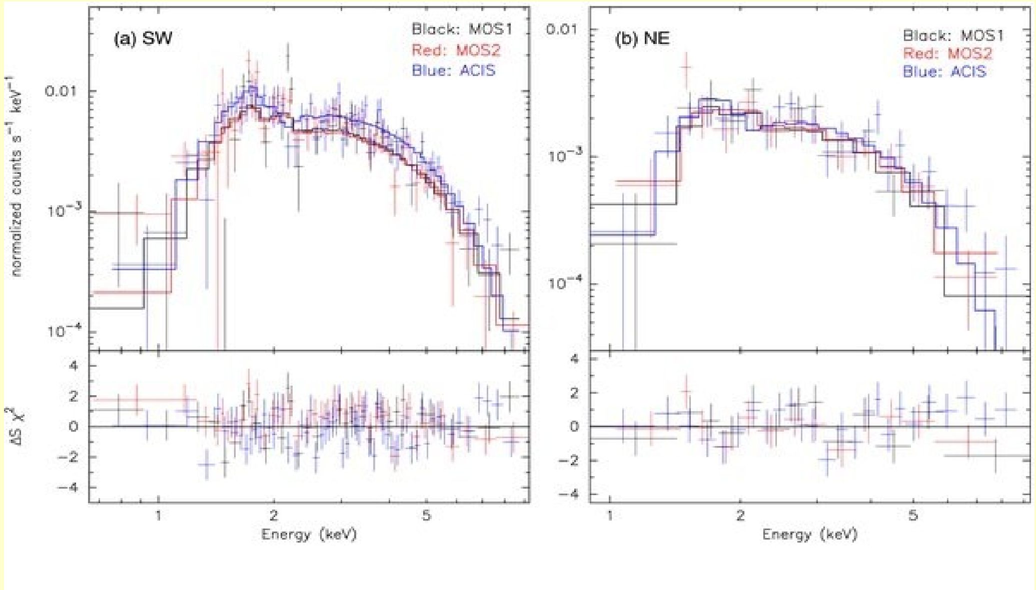


G266.2-1.2 (“Vela Jr.”) (ASCA; Slane et al. 2001)

...and one more: G330.2+1.0



Red: radio (Whiteoak & Green 1996); green, 1.2 – 2 keV; blue, 2 – 8 keV (XMM). Central object: a non-pulsing CCO (Park+2009)



Park+ 2009

Featureless X-ray spectra from brighter parts (faint thermal emission in one location)

Distance, age, shock speeds all poorly known

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*, *u*(shock). Cutoffs:

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

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

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

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

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

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 $E_{\rm max}$

Measuring or constraining $h\nu_{roll}$ alone may give little information on B

1. **If acceleration is loss-limited, no *B*-dependence.** (Other $h\nu_{roll}$ values must be larger, but this gives only a weak lower limit on B)

2. Most SNRs show no evidence for X-ray synchrotron. In fact: **For no known SNR (galactic or extragalactic) is X-ray flux on or above the extrapolation from radio.**

   So rolloff must occur between radio and X-ray bands:
   $h\nu_{roll}$ must be well below 0.1 keV in most cases.
   (Note: a synchrotron component could be detected even if $h\nu_{roll}$ is < 1 keV, if thermal emission is not strong. So not impossible to see X-ray synchrotron emission if $u_{sh} < 2{,}000$ km/s.)

   Strong u_{sh} -dependence means upper limits on $h\nu_{roll}$ provide little information about B.

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

One hadronic process: cosmic-ray p + thermal p $\rightarrow$ 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.

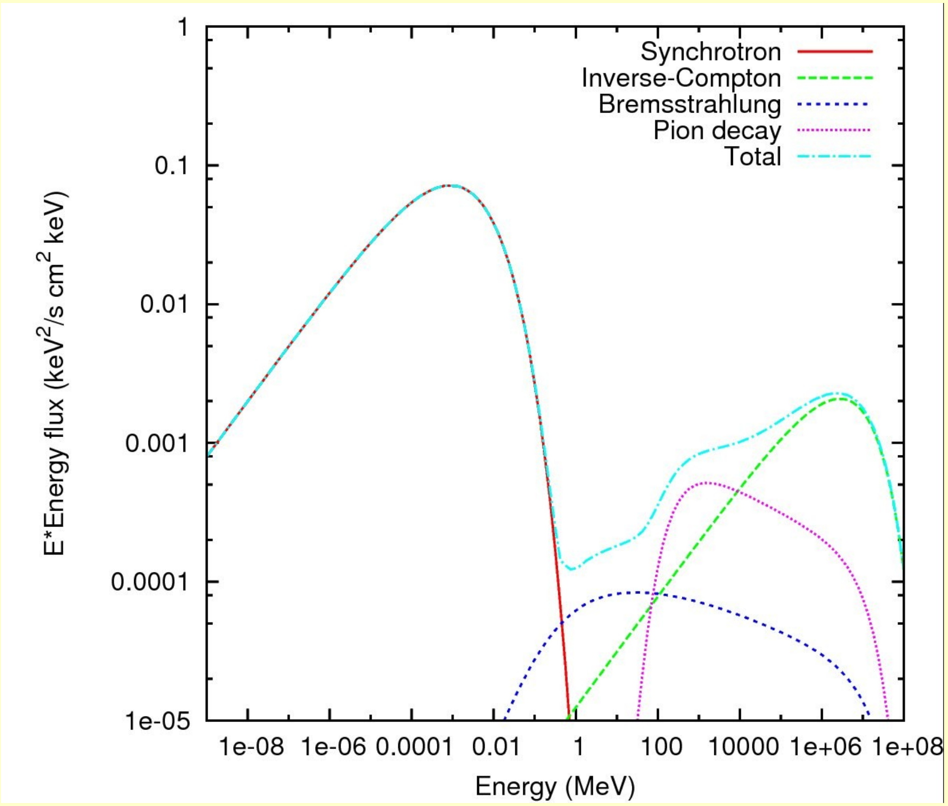
Synchrotron radiation: Important from radio to soft X-rays. Flux fixes only combination of magnetic field, electron energy density

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.

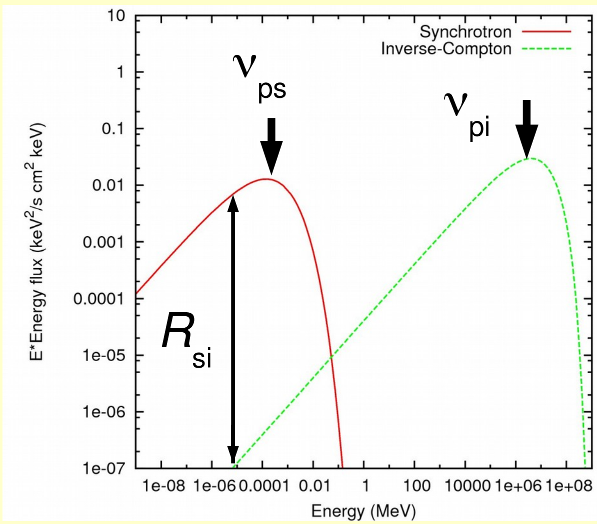
All of these may contribute to high-energy photon emission from SNRs

Typical spectral calculation: homogeneous source ("one-zone" model)

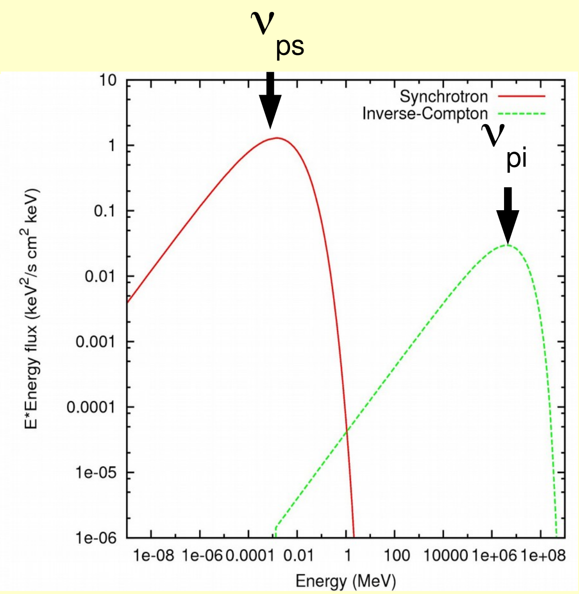


Simplistic particle spectra: single power-laws with exponential cutoffs.
Main parameters: B, particle acceleration efficiencies, maximum energies

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



$B = 1\ \mu$G



$B = 10\ \mu$G

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

Ratio of peaks (in νF_ν space) gives B:

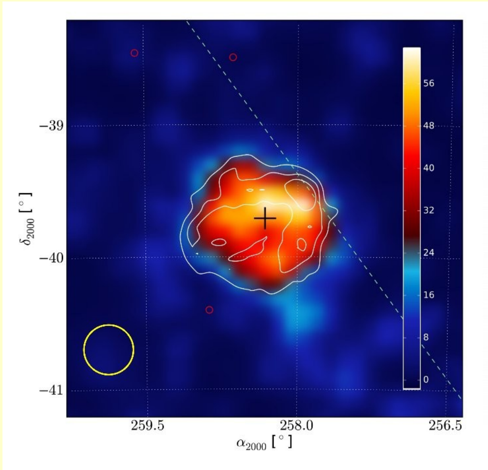
$B \sim 9 \times 10^4 (\nu_{ps}/\nu_{pi})$

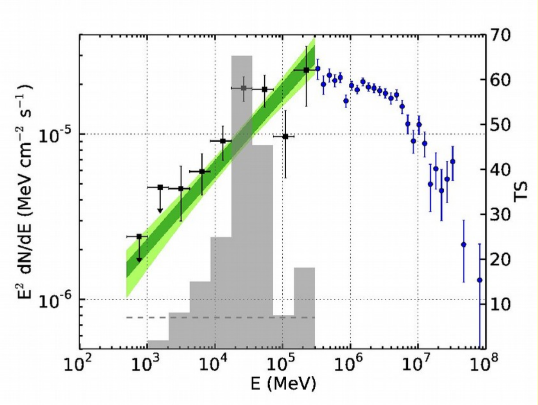
Ratio of fluxes at a frequency depends on B -- and its filling factor f_B:

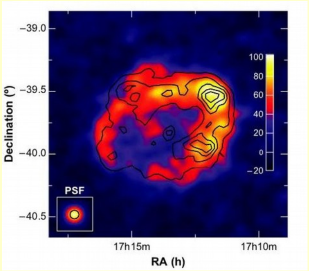
F(SR)/F(IC) $\equiv R_{si}$ $\sim 5 \times 10^{13} f_B B^{1.5}$ (for E^{-2} electron spectrum)

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

Federici+ 2015



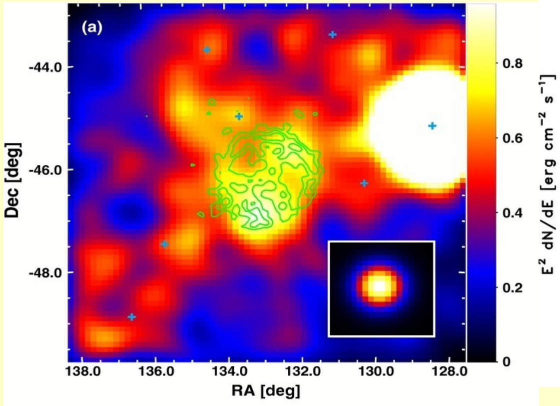


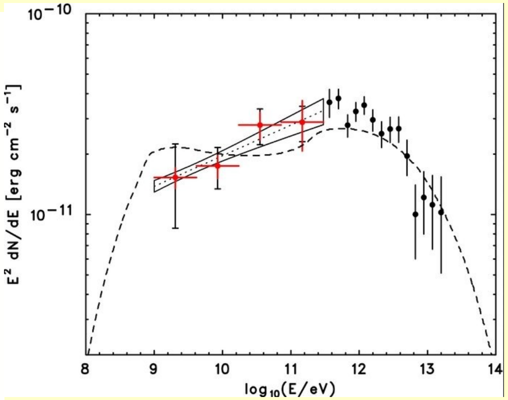


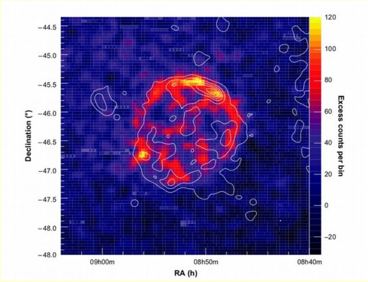
Aharonian+ (H.E.S.S. collab.) 2007

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

Tanaka+ 2011





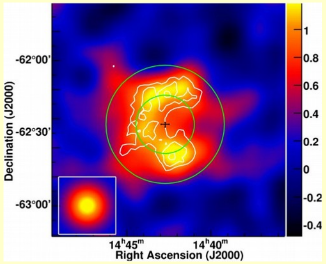


Aharonian+ (H.E.S.S. collab.) 2007

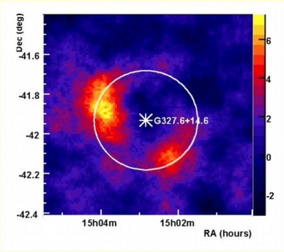
Vela Jr.

VERITAS images

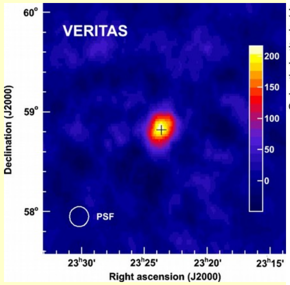
H.E.S.S. images



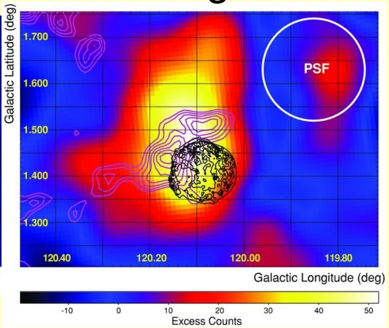
RCW 86
Aharonian+ 2009



SN 1006
Acero+ 2010

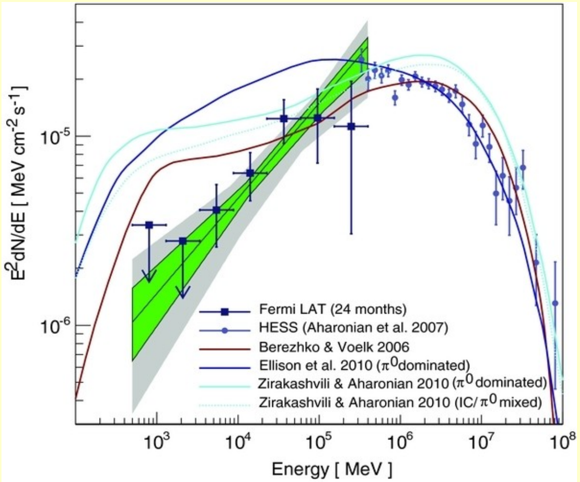


Cas A
Acciari+ 2010

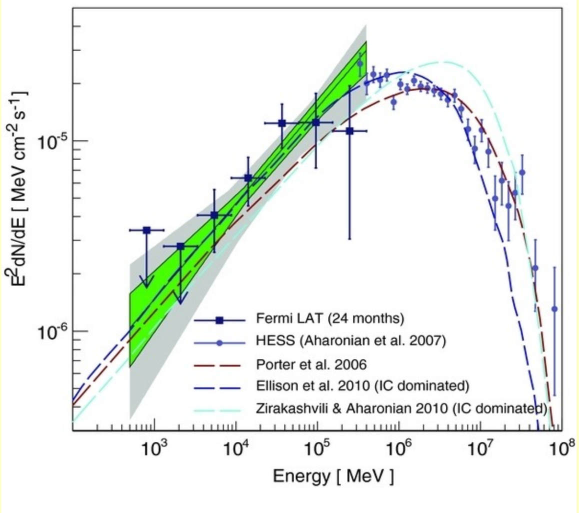


Tycho: Acciari+ 2011

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

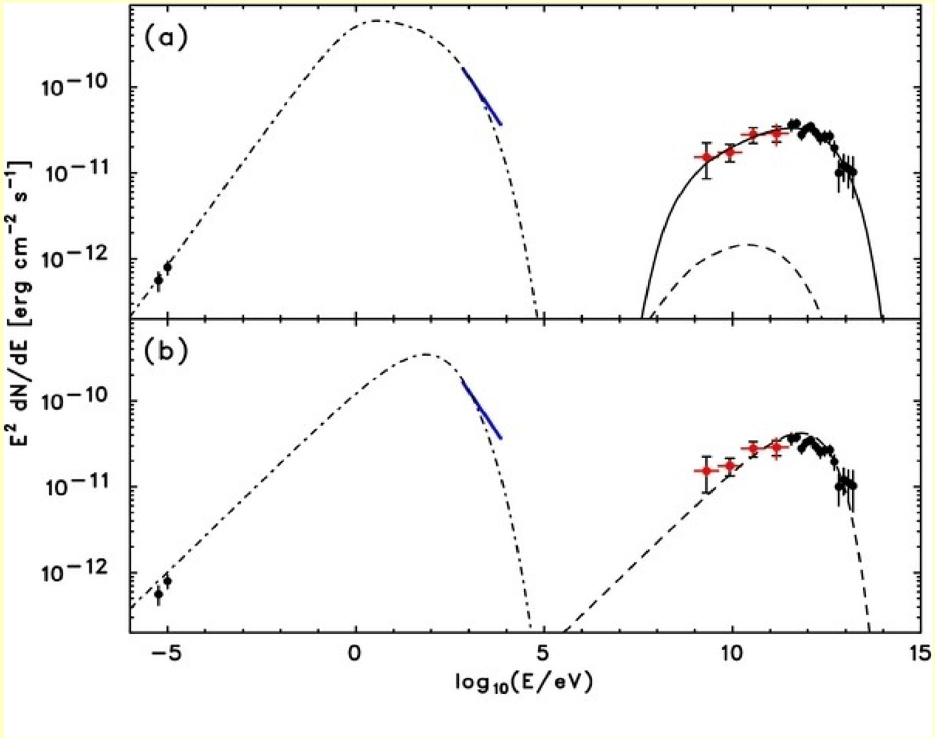


Hadronic model



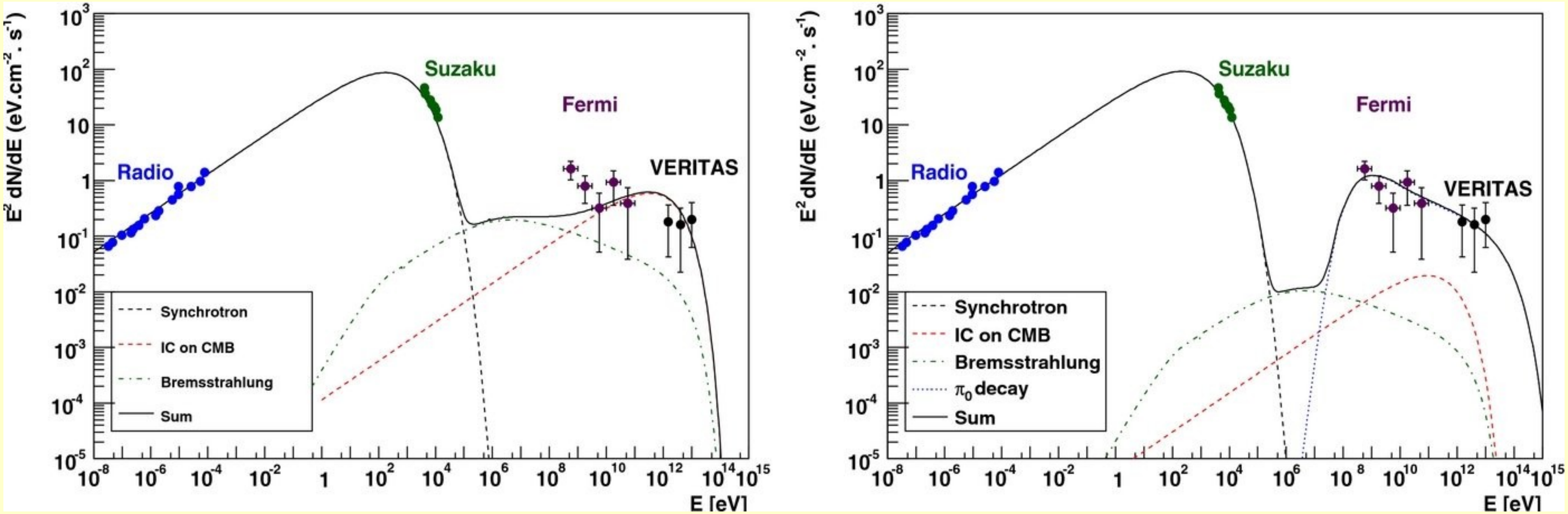
Leptonic model

RX J1713.7-6946 (G347.3-0.5):
A. A. Abdo et al. 2011 ApJ 734.
Get ***B* ~ 10 μG** for leptonic model

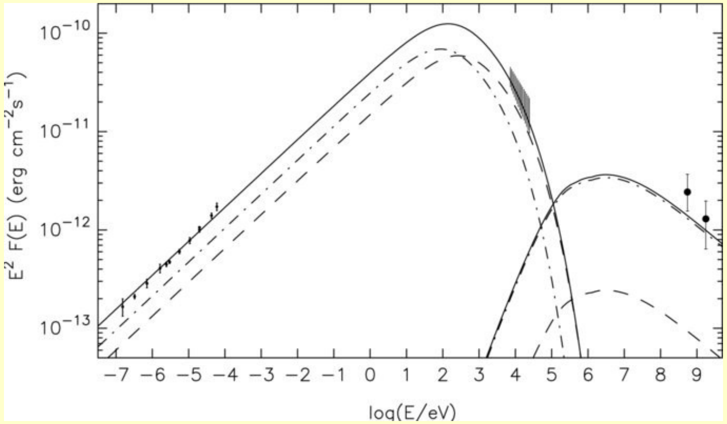


Vela Jr: (Tanaka et al. 2011 ApJ 740 L51).
Top: **Hadronic model, *B* > 50 μG**.
Bottom: **Leptonic model, *B* ~ 12 μG**

Tycho (Giordano et al. 2012)



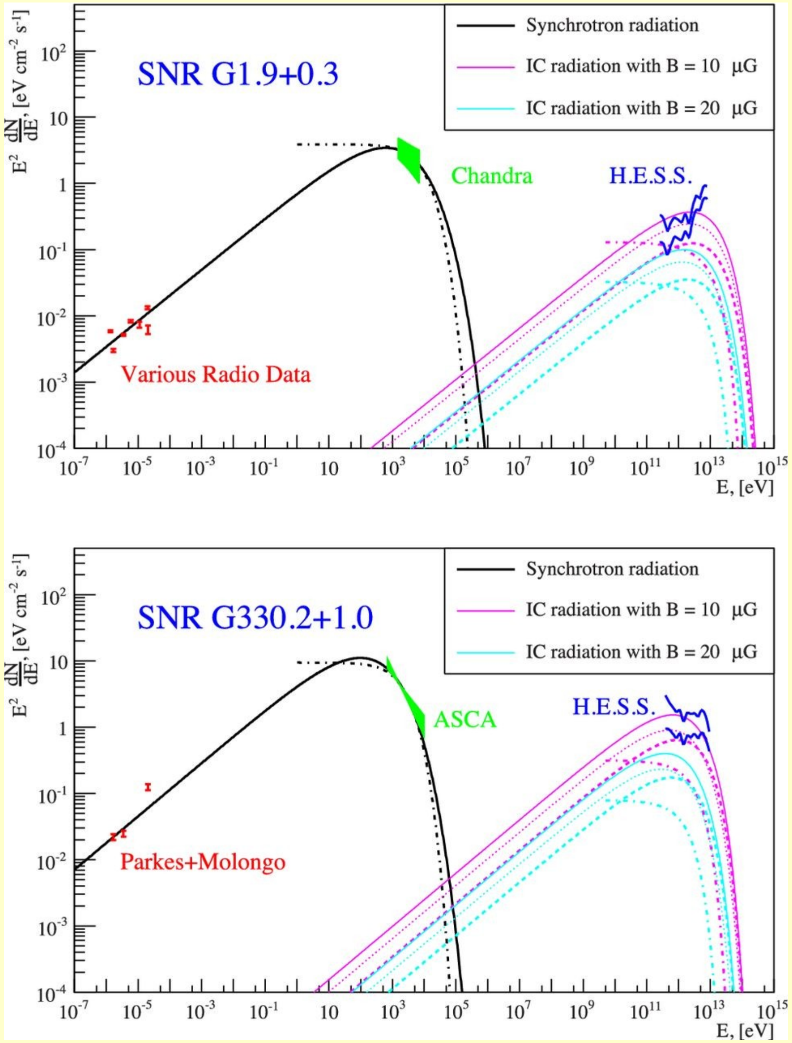
One-zone hadronic model takes ***B*** **= 215 μG**



...but **two-zone leptonic** model can work too (Atoyan & Dermer 2012):
get ***B*** **= 100 μG in one region, 34 in the other**

...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

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 $\kappa(E)$, 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]).**

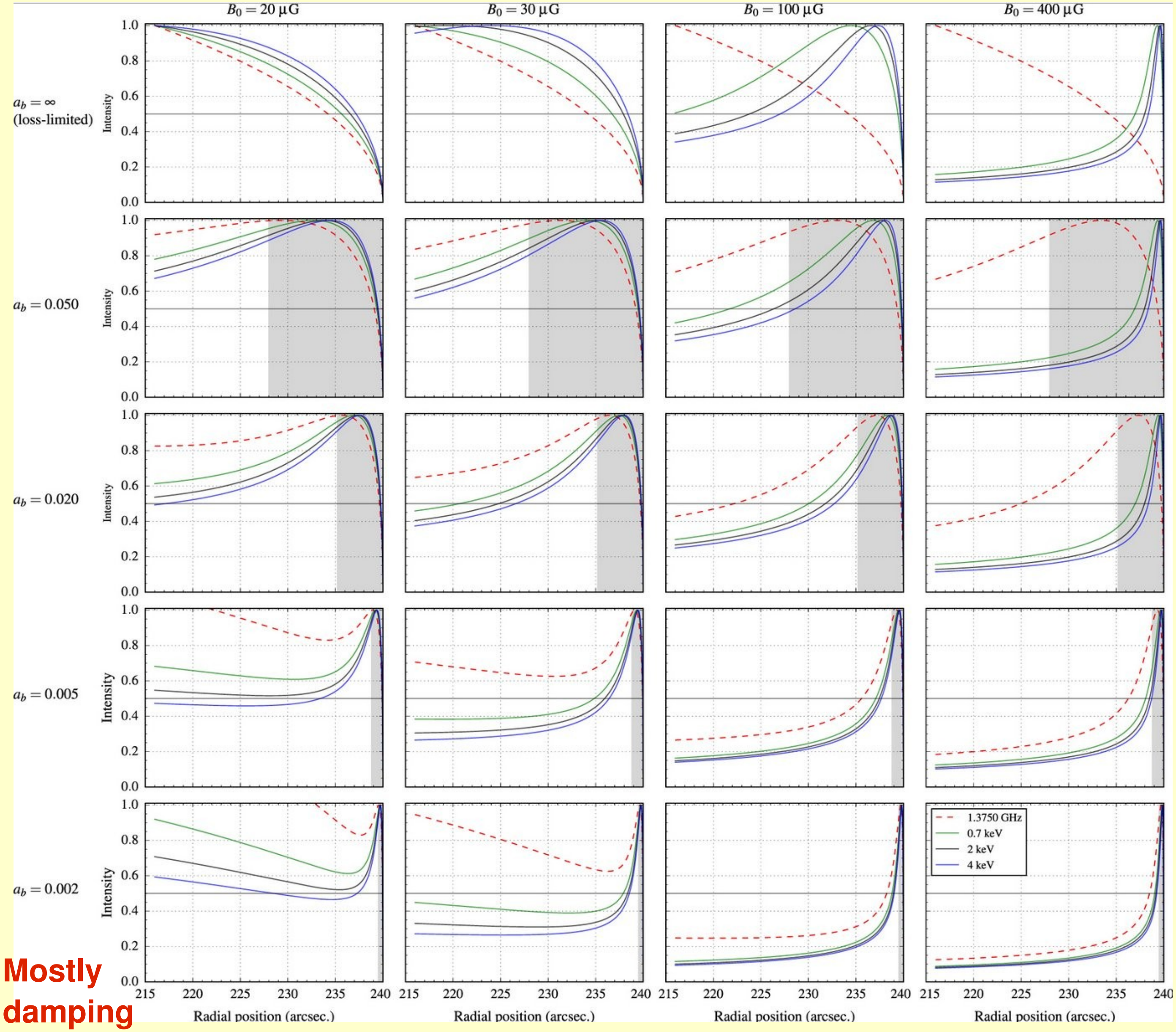
Actual situation: More complicated

Damping length

long

short

Mostly loss-limited



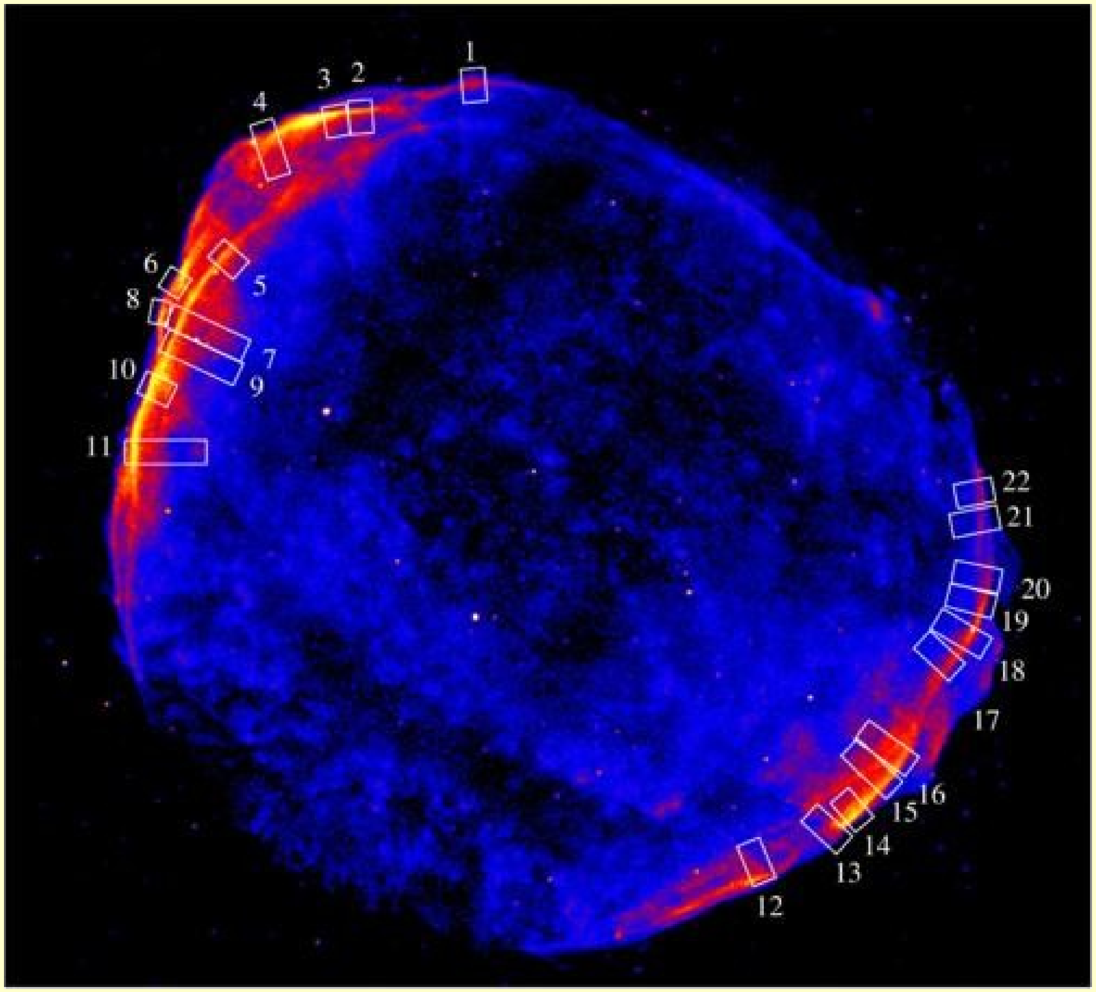
Tran et al. 2015

Mostly damping limited

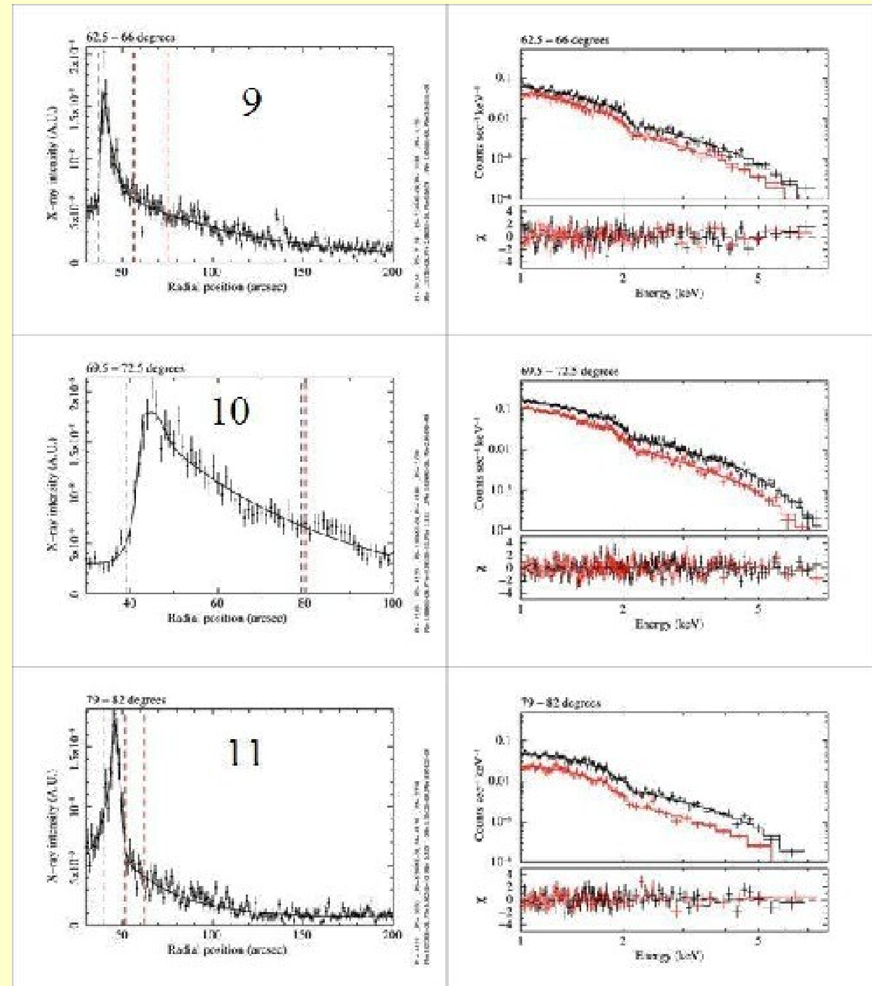
Magnetic field 20 μG 30 μG 100 μG 400 μG

Radio 0.7 keV 2 keV 4 keV

SN 1006 observations: rims at 3 photon energies

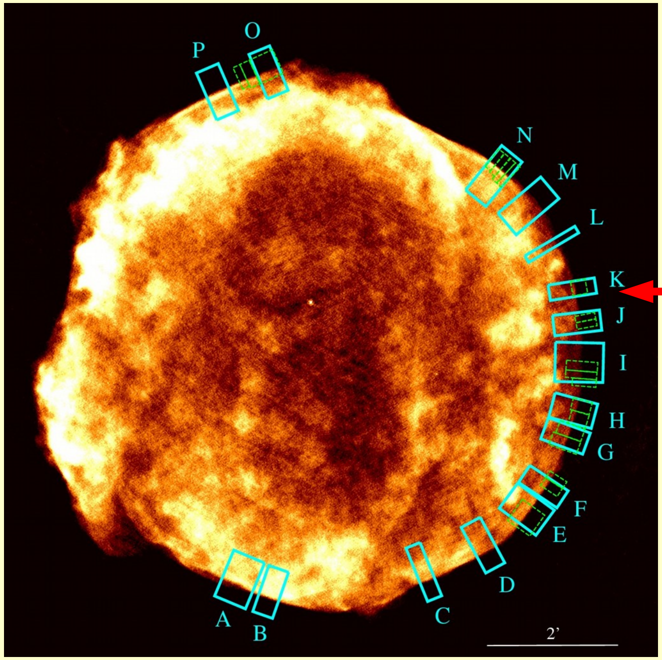


Regions measured. Adjacent measurements on same filament were averaged. (Ressler et al. 2014)



Example profiles for regions 9, 10, 11, with spectra of rim peak region (black) and several FWHMs downstream (red)

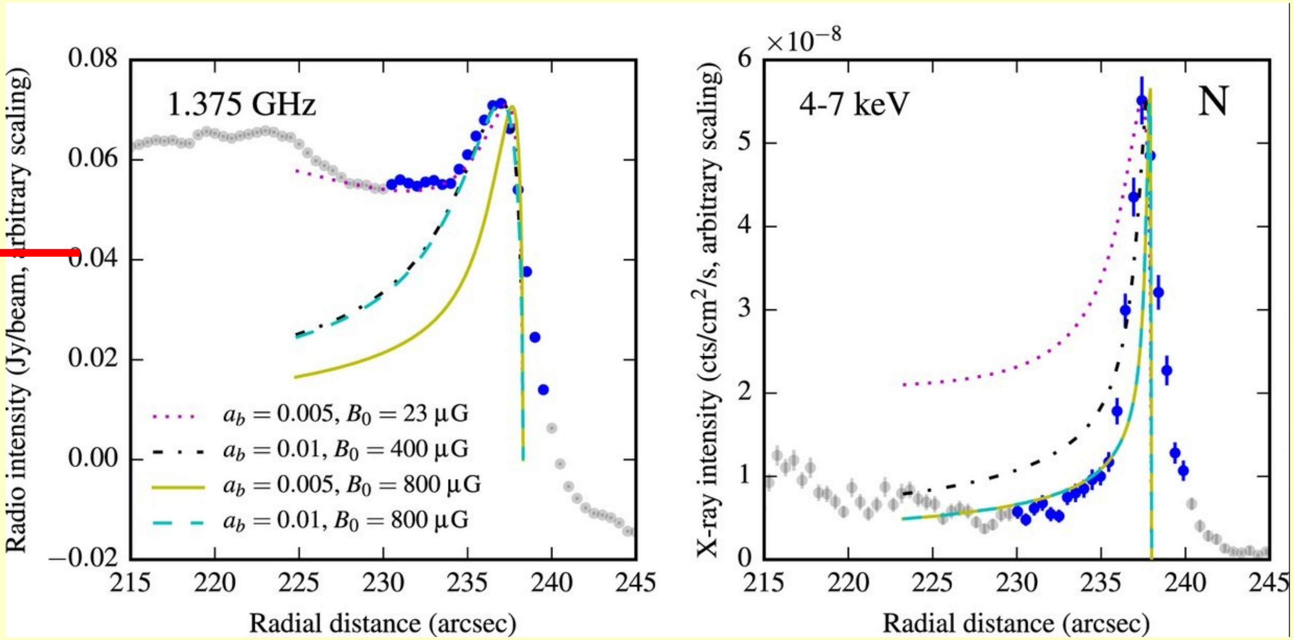
Tycho: Rims also shrink with X-ray energy. But some rims are thin in radio as well.



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

radio (1.4 GHz)

X-ray (4 – 7 keV)



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

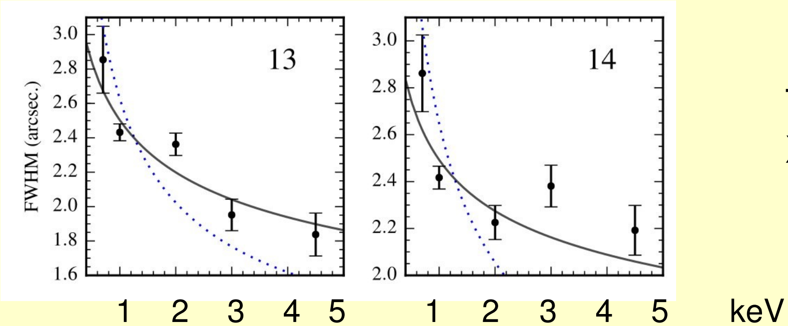
Results: Find strong energy-dependence of rim widths

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:** $B > 20\ \mu$G. 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

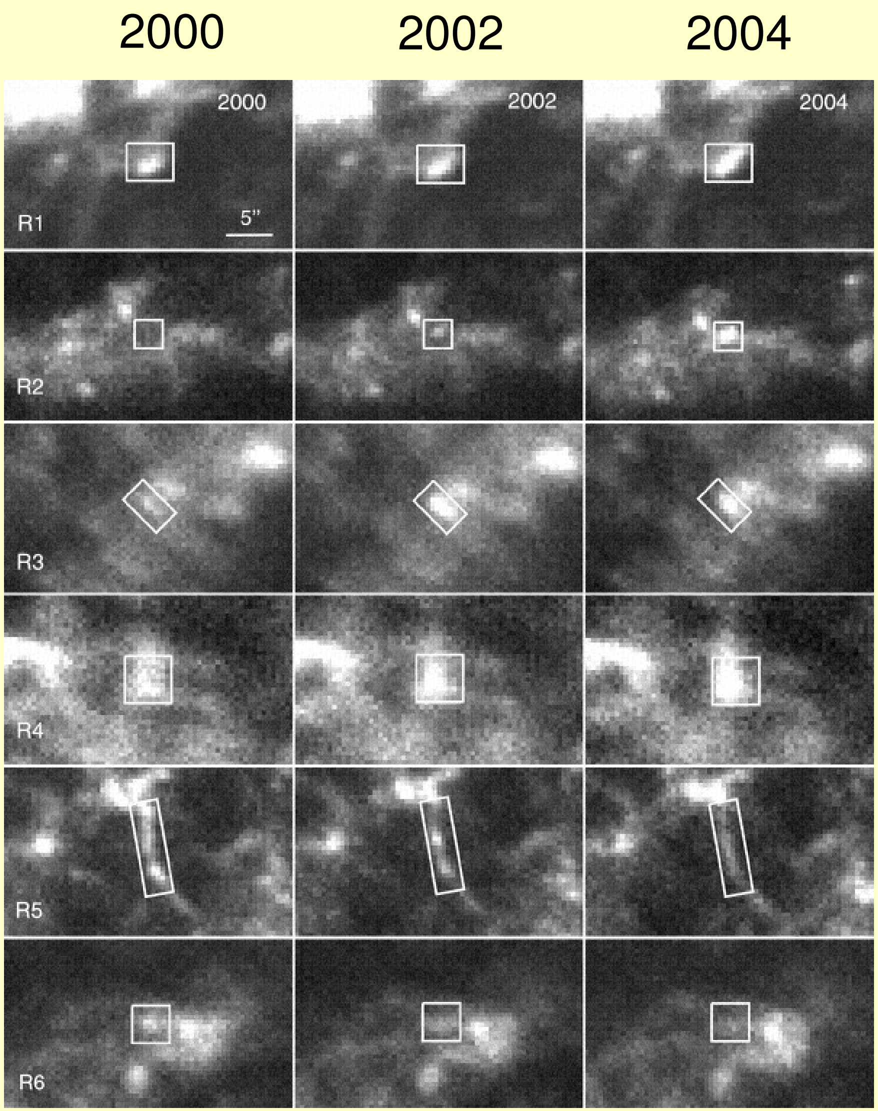
Rim-width analyses differ in detail

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



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 (or RX J1713) (Uchiyama et al. 2007)

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

$$\tau_{accel} \propto \kappa/(u_{shock})^2$$

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 very high *B* (Bykov et al. 2008, 2009)

Summary: Magnetic field strengths in shell SNRs

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.

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.

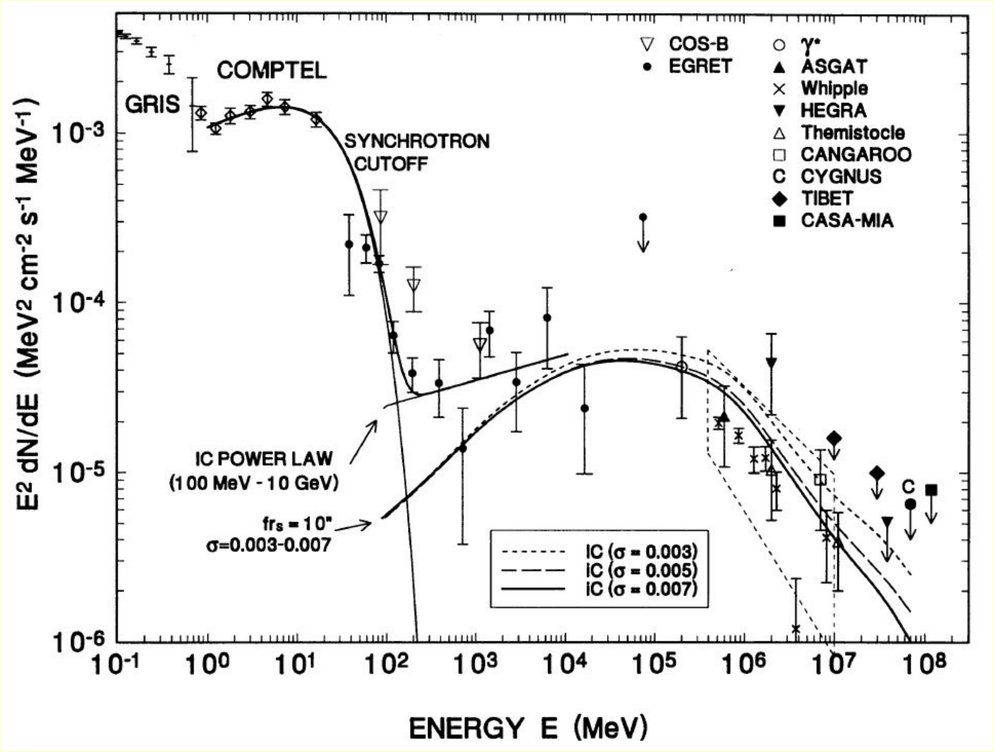
5. SNRs are inhomogeneous! Conditions can vary substantially with location! **Need to move beyond one-zone modeling.**

Magnetic fields in pulsar-wind nebulae: inferences of *B* are model-dependent

0. Since pulsar initial energy loss is primarily in *B* but nebulae are not *B*-dominated, **all PWNe must involve magnetic dissipation and/or reconnection in a fundamental way.** So *B* varies in space and time.

1. Energy input from pulsar + magnetization σ (Poynting flux/particle flux) (from, e.g., expansion velocity of PWN) gives *B* at wind termination shock.
2. One-zone evolutionary models can give nebular average $\langle B \rangle$.
3. If GeV/TeV seen (along with radio or X-rays): IC/SR gives $\langle B \rangle$
4. Particle transport can constrain $\langle B \rangle$. Models predict spatial profiles of brightness or spectral index

Early Crab SED modeling



de Jager et al. 1996: get ***B* = (130 ± 10) μG**
averaged over radio nebula, excluding equipartition value ~ 300 μG

Advective and diffusive transport

1. **Advection** (Kennel & Coroniti 1984; Reynolds 2009): B(r) with $B_0 \equiv B(r_0)$ probably much larger than $\langle B \rangle$.
2. **Diffusion** (Wilson 1972, Gratton 1972, Tang & Chevalier 2012)
3. **Combination** (Tang & Chevalier 2012, Porth et al. 2016)

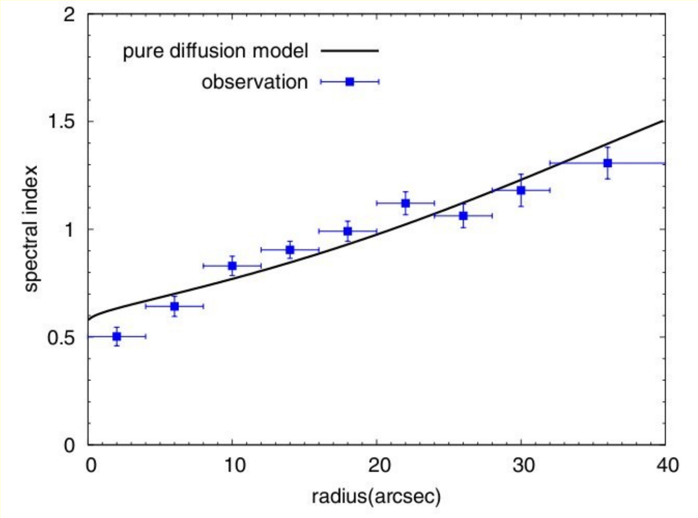
Models: Fit spatial profiles of brightness or photon index Γ.

Average fields $\langle B \rangle$ in μG

Object	KC84	P+16	TC12
G21.5−0.9	160	43	180
Vela	30	6	
3C 58	63	46	80

KC84: Kennel & Coroniti 1984, ApJ, 283, 694
P+16: Porth et al. 2016, arXiv:1604:03352
TC12: Tang & Chevalier 2012, ApJ, 752:83

Moral: Mean fields in PWNe are difficult to estimate, and different techniques give different answers.



One model for spectral index for G21.5-0.9 (Tang & Chevalier 2012)

Summary, and future prospects

1. What do we know for sure?

Shell SNRs: "Thin rims" require field amplification beyond compression, but amount is model-dependent.
SED modeling: Hadronic models need larger fields to suppress ICCMB. Leptonic models may need small magnetic-field filling factors (but rims are thin...)
Variability: Continue to monitor (but applies only to small regions)

PWNe: SR/SSC (synchrotron self-Compton) does a good job; typically get $\langle B \rangle$ near but below equipartition strengths.

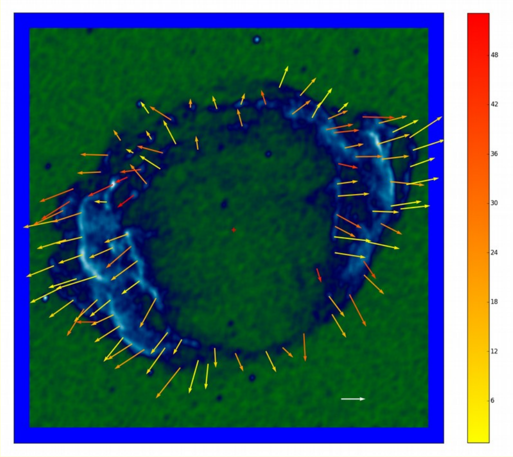
Summary, and future prospects

2. Where do we go from here?

Models are still very simple! One-zone models can give very different results from inhomogeneous models. Better spatial resolution (e.g., with CTA) may be necessary. For thin rims: Get widths at a range of X-ray energies; use best models.

Radio emission is underutilized. Polarization in particular can help constrain models.

Careful study of a few well-constrained cases may be worth more than fitting simple models to many objects.



G1.9+0.3 proper motions (see poster S10.16)