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Particle acceleration in supernova remnants
X-ray, radio and optical

Test what happens precisely at the shock

- ❑ X-ray synchrotron emission
- ❑ Magnetic field inclination
- ❑ Search for a precursor ahead of the shock
- ❑ Optical constraints

Pending questions

- How **efficient** is cosmic-ray acceleration in SNRs? What is the energy density of accelerated particles?
- What is the **maximum energy** of accelerated particles?
- How **large** is the **magnetic field**? Is it amplified? Is it very **turbulent**? What is its **spectrum**?
- What is the **geometry** of acceleration with respect to the magnetic field?

Let us see what we can learn from observations

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- Age (historical SNRs)
- Distance (absorbing column, stars, angular vs actual velocity)
- Angular size (E/n_0, t_0)

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- Thermal X-ray emission (n_0)
- Synchrotron radio emission level (B_0, W_{CR} x K_{ep})
- π^0 GeV or TeV emission level (W_{CR}, n_0)
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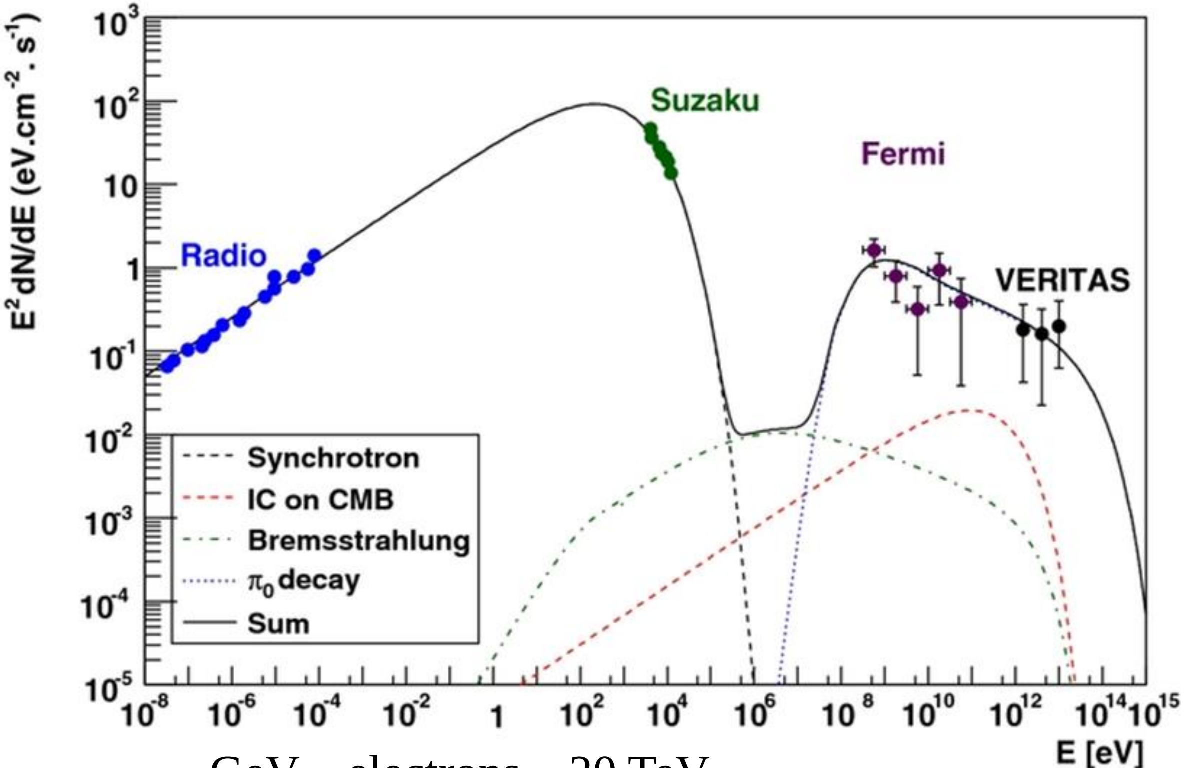
Morphological

- Expansion over time: shock velocity (E/n_0, t_0)
- X-ray synchrotron rim width (B_0)
- Width between ejecta and blast wave (W_{CR}, B_0)

Spectral information

Giordano et al 2012, ApJ **744**, L2, Tycho



GeV electrons 20 TeV

- π^0 following p-p collisions in GeV range (proportional to gas density)
- Inverse Compton on CMB (or local photons) in TeV range
- Synchrotron from radio to X-rays cutoff at **maximum electron energy**
- Fγ / Fsync ~ U_{CMB}/U_B = 1 for B = 3.27 μG
- Thermal (continuum + lines) in X-rays

$$dN/dE \propto E^{-p}\exp(-E/E_{\max})$$

$$F_\nu \propto \nu^{-\alpha}\exp\left(-\sqrt{\nu/\nu_{\max}}\right), \qquad \alpha = (p-1)/2$$

$$\nu_{\rm sync} = 1.82\times10^6\, B_{\rm mG} E_{\rm erg}^2\ \text{GHz}$$

Synchrotron spectrum in young SNRs

- ✓ **Normalization and slope** (α around 0.5) anchored in the **radio**
- ✓ **X-ray** slope always steeper (around 1.5), constrains $\boldsymbol{\nu_{max}}$
- ✓ Cannot work as such over full SNR (space-dependent due to cooling)
- ✓ Should be applied **precisely at the shock**
- ✓ Difficult to extract exactly the same area in the radio and X-rays
- ✓ Very difficult to extract slope over small regions in the radio
- ✓ Overall slope is often fitted to X/radio ratio
- ✓ Complications due to modified shocks (concavity) can exist
- ✓ Cutoff may not be exponential (cooling, diffusion not Bohm)

➔ Not so easy quantitatively !

Cut-off frequency shape

Miceli et al 2013, A&A 586, A80

XMM-Newton Large Program on SN 1006

Attempt at quantifying cooling effect

Curvature of X-ray spectrum should be able to tell, because **cooling predicts a steeper cutoff than escape**

Requires large energy range

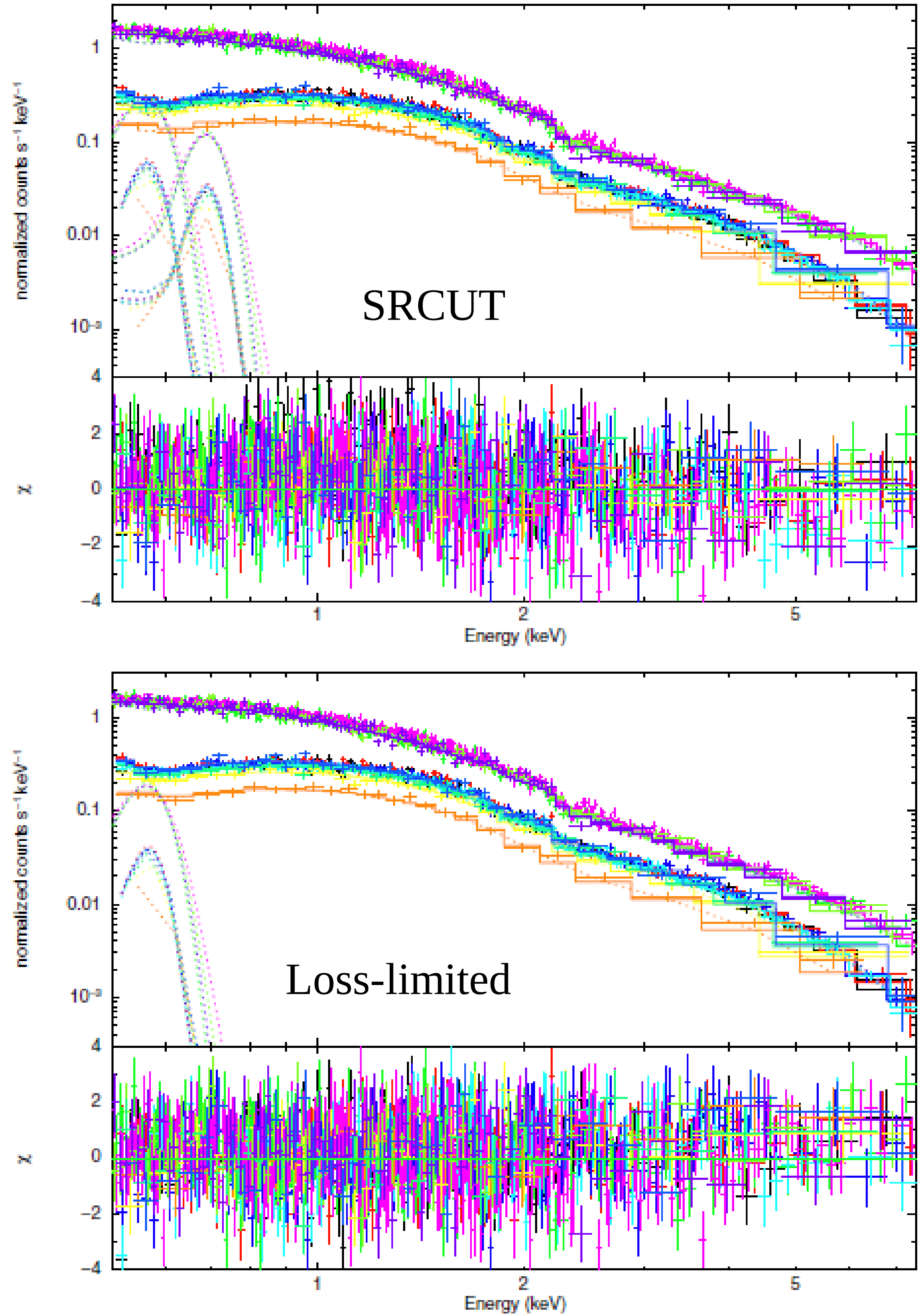
Comparison between SRCUT (escape) and Zirakashvili & Aharonian 2007 (cooling)

4 areas along SN 1006 bright limbs

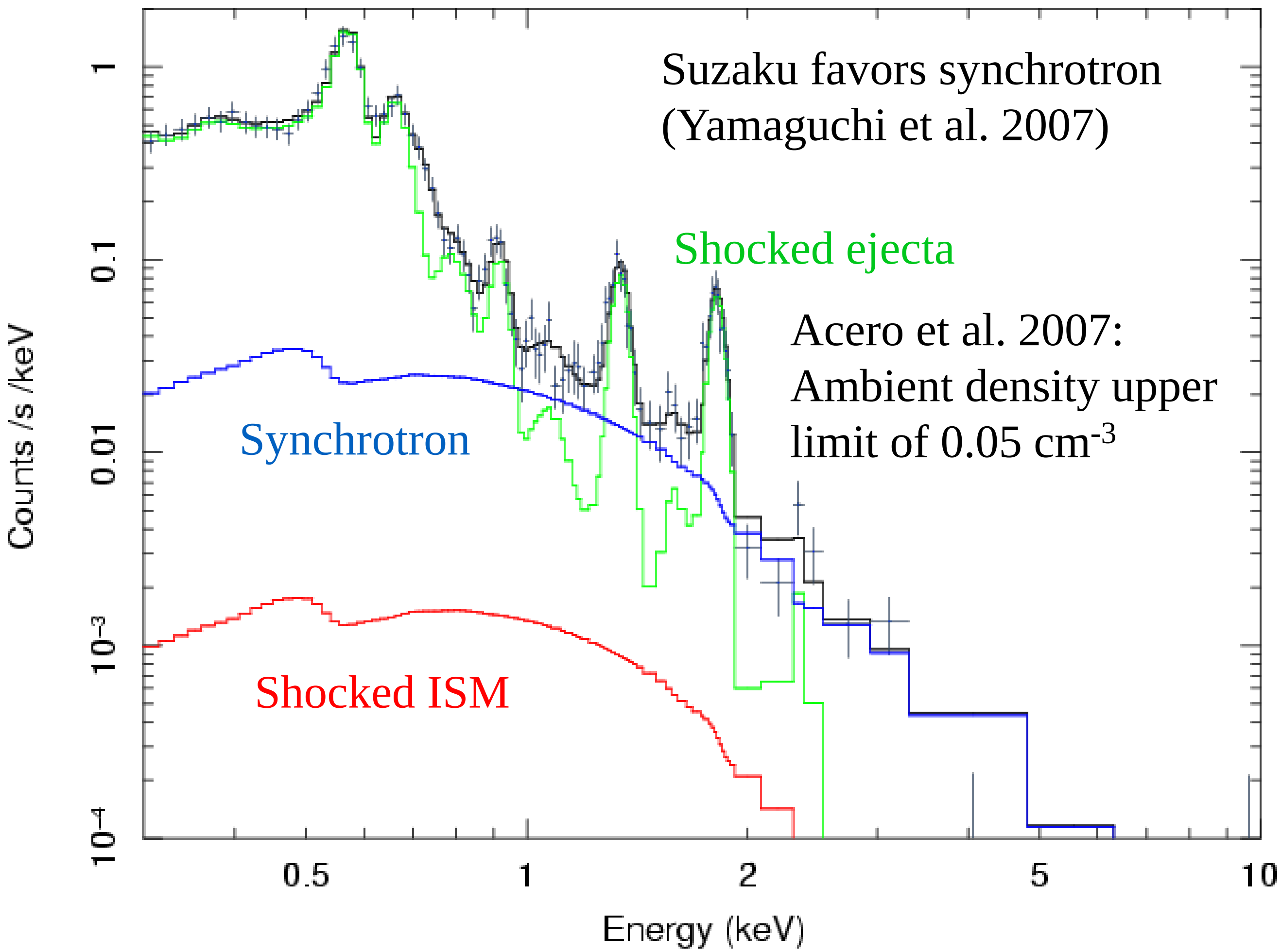
Rather **subtle effect**

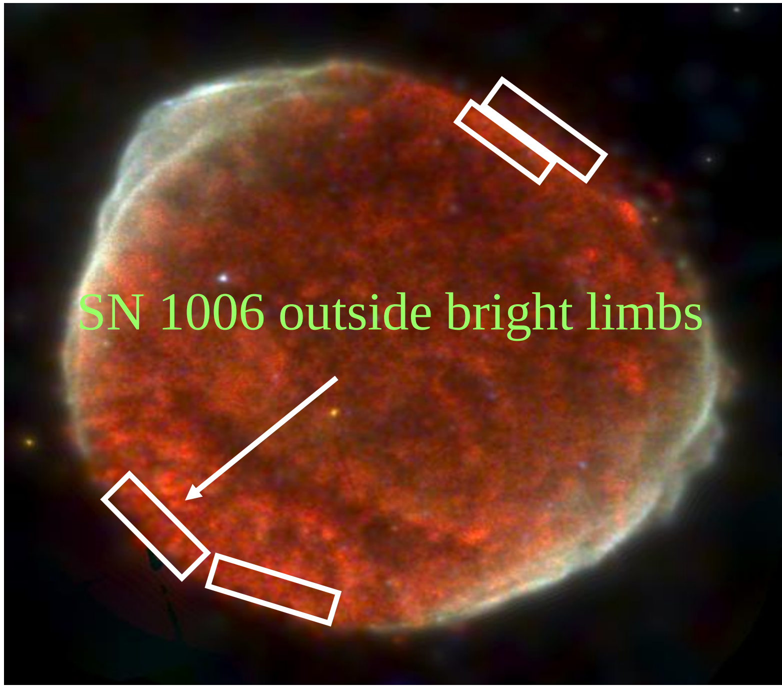
Radio point too low for SRCUT

Should be redone more carefully



Ambient density from thermal emission



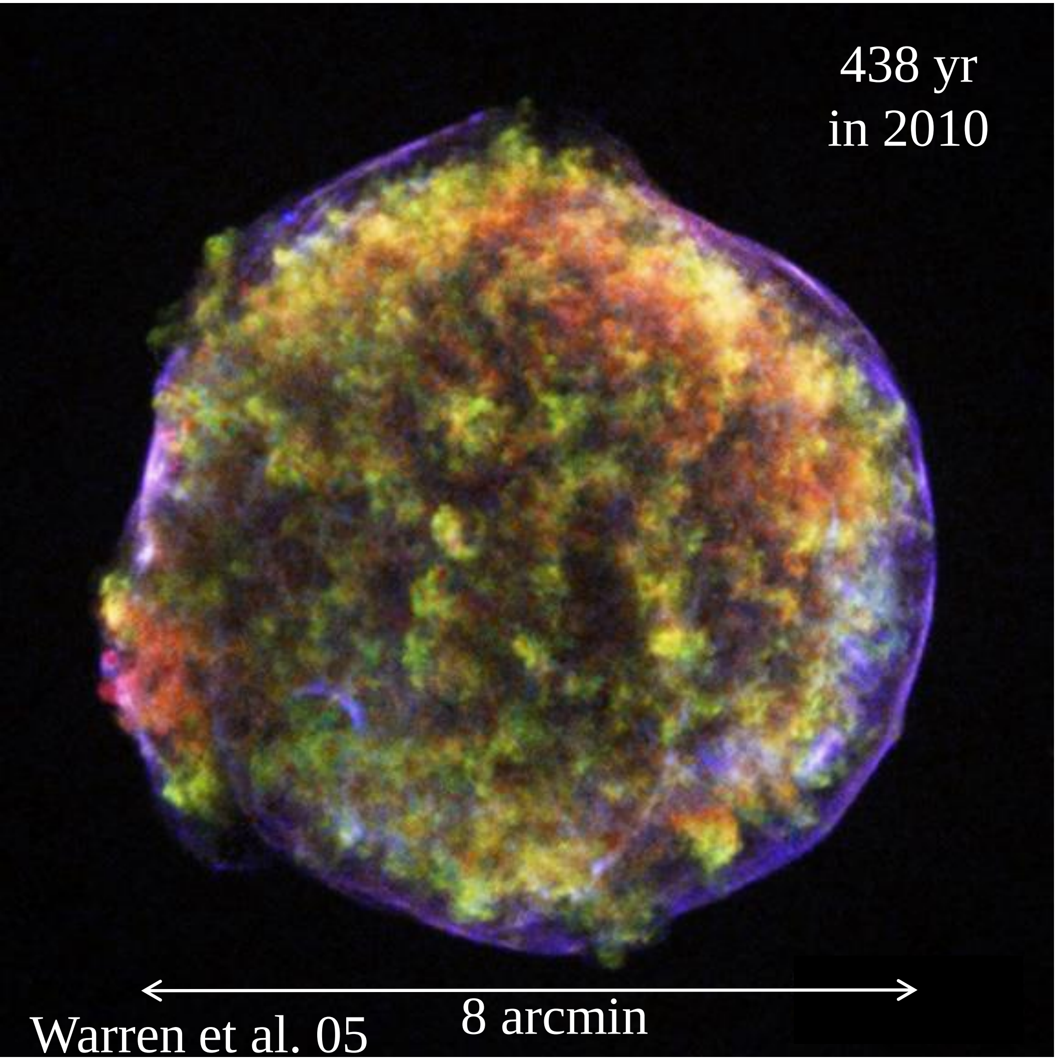


Surprisingly **difficult** to detect thermal emission of ambient medium.

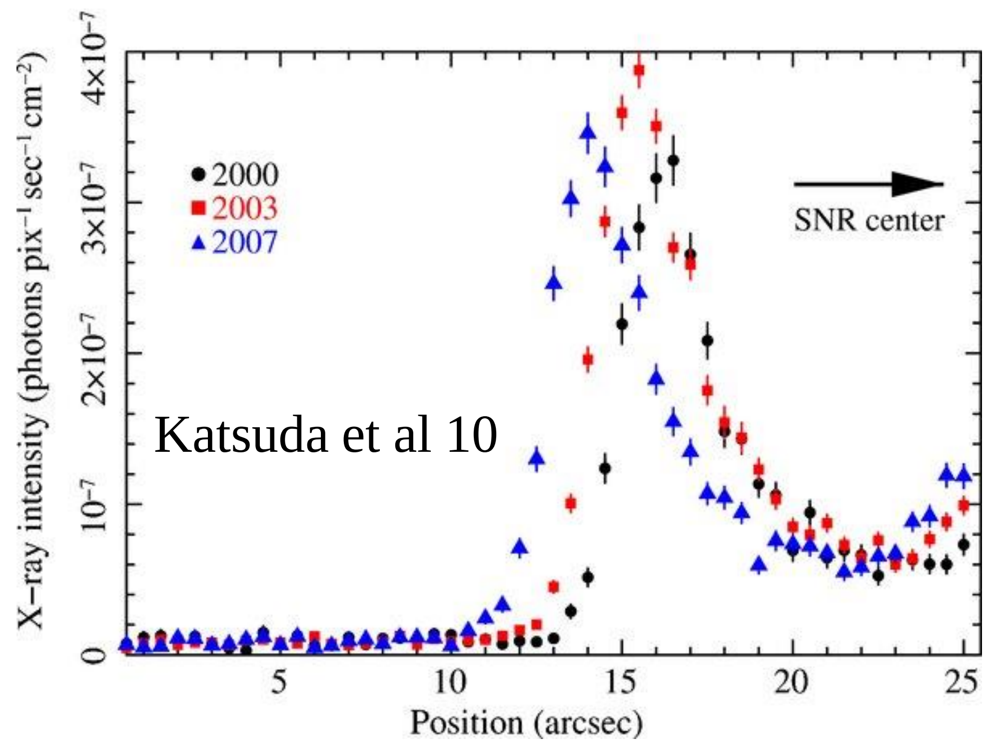
Implies **low density** in most young SNRs

Morphology: expansion

Tycho (SN 1572)
Type Ia



Sharp edge offers a very accurate way of measuring expansion of a few arcsec over 10 years in young SNRs. Has been done for many.



Particularly powerful if distance is known (gives **shock velocity**)

Morphology: sharp non-thermal X-ray rims

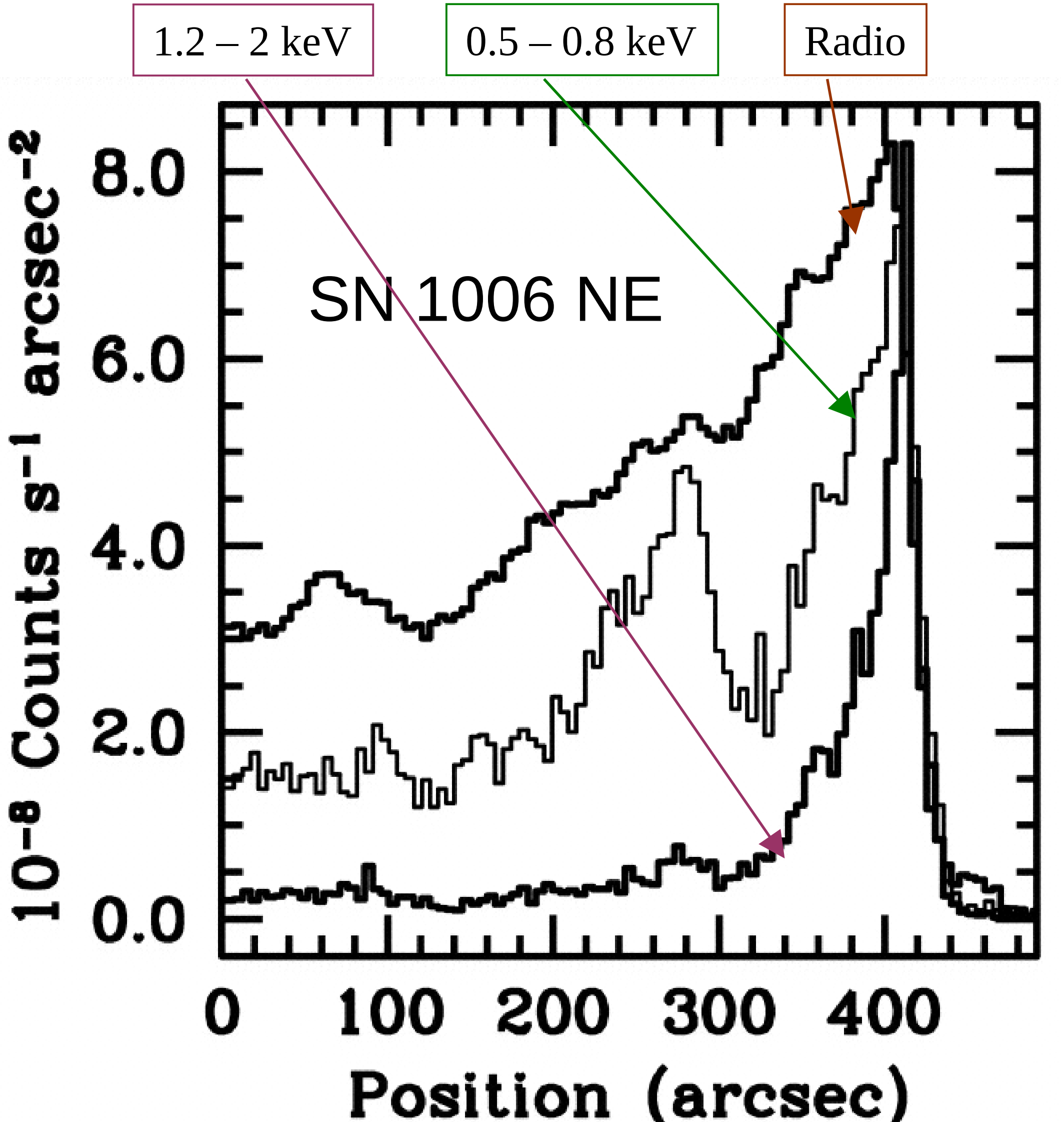
- ✓ **Synchrotron losses** ➔ emission shifted out of the X-ray range not far behind the shock
- ✓ Cooling time

$$t_{\rm cool} = 6.37 \times 10^{8} B_{\rm mG}^{-2} E_{\rm erg}^{-1} \quad {\rm s}$$

$$t_{\rm cool} = 5.5 \times 10^{7} B_{\rm mG}^{-3/2} \nu_{\rm keV}^{-1/2} \quad {\rm s}$$

$$l_{\rm dif} = \sqrt{\kappa_d t_{cool}} = 1.2\ B_{mG}^{-3/2}\ {\rm mpc}$$

Long et al. 2003, ApJ **586**, 1162
Bamba et al. 2003, ApJ **589**, 827



Requires magnetic field amplification
(Lucek and Bell 2000, MNRAS 314,65)

Can account for the observed geometry with **B ≈ 90 µG**

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Radio synchrotron not as sharp

Radio profile key observable to test whether turbulent ***B*** decays downstream (Pohl et al. 2005, ApJ 626, L101)

Better radio data would be very valuable

Requires magnetic field amplification (Lucek and Bell 2000, MNRAS 314,65)

Long et al. 2003, ApJ **586**, 1162
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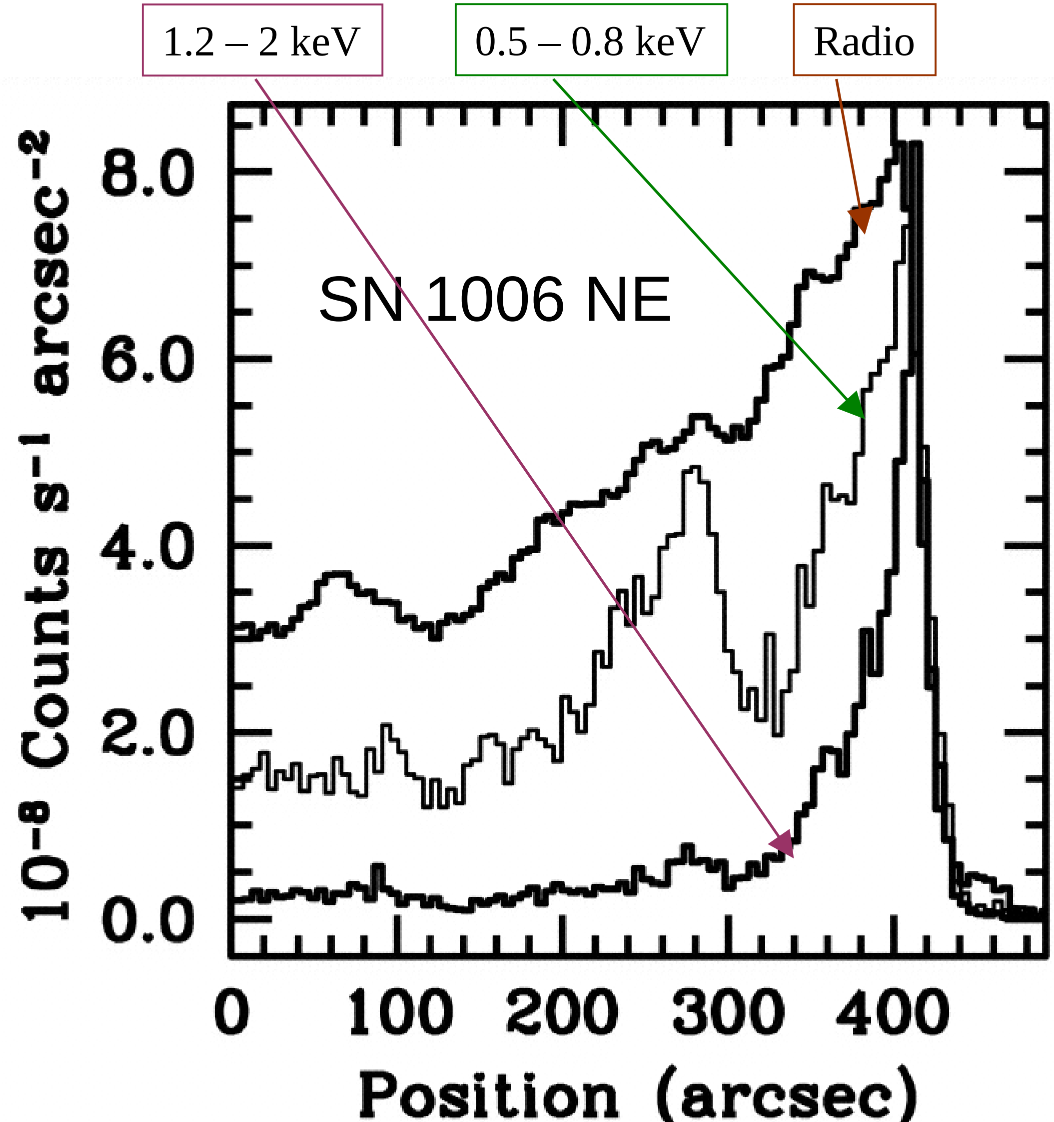


Can account for the observed geometry with **B ≈ 90 μG**

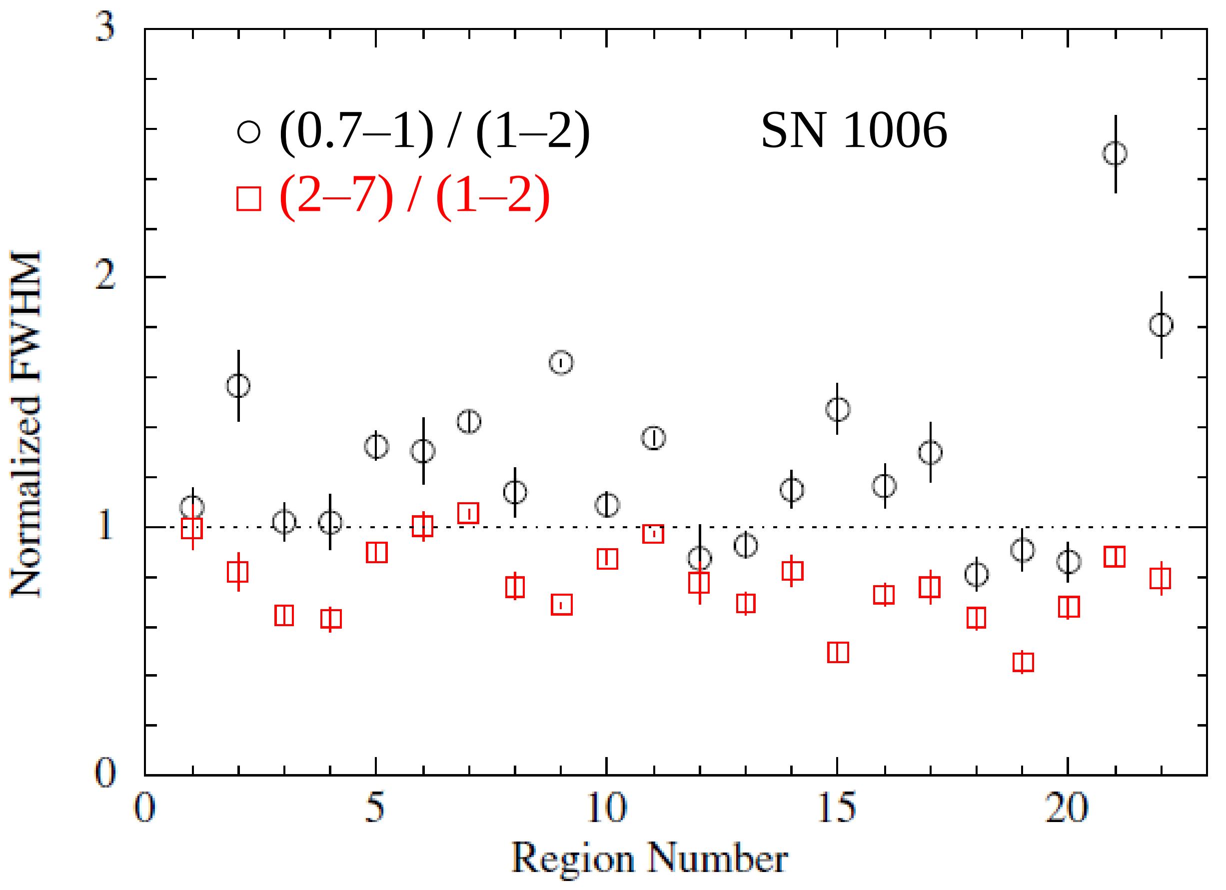
Constraints on diffusion as a function of energy

Extract rim width over 3 energy ranges: 0.7 – 1, 1 – 2, 2 – 7 keV

Should decrease in **advection**-dominated regime as $E^{-0.5}$, then switch to **diffusion**-dominated regime depending on turbulence index α

In nearly all cases, width is measurably less at higher energy

But at places goes down faster than $E^{-0.5}$!



Ressler et al. 2014, ApJ 790, 85

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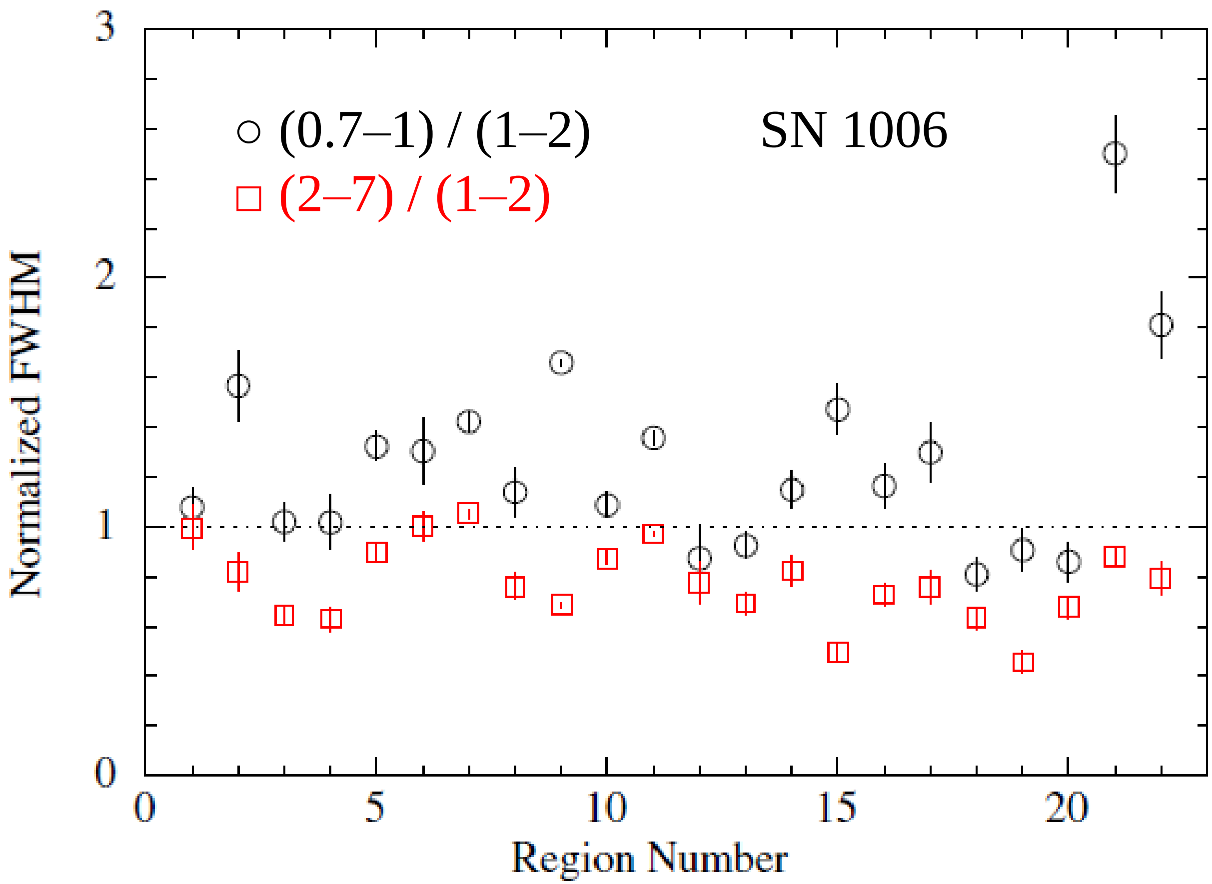


Probably not quite good enough to be a measure of the turbulence spectrum, but worth pursuing

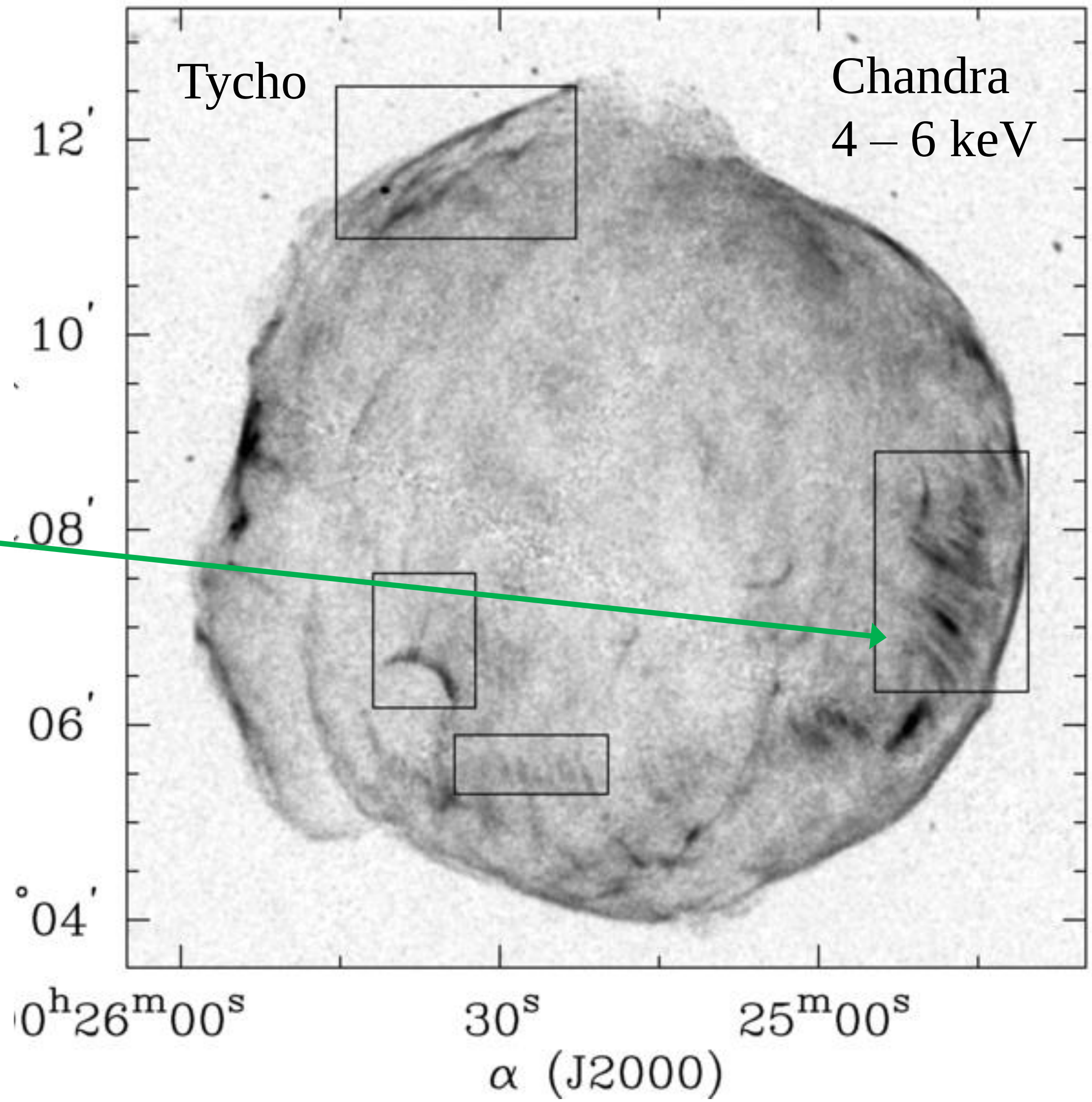
Going to higher energy would be excellent, but requires a very sensitive high-resolution instrument above 10 keV

Ressler et al. 2014, ApJ 790, 85

Radial structures

Eriksen et al 2011, ApJ 728, L28

- **Stripes** parallel to shock velocity
- Definitely non-thermal emission
- Azimuthal spacing (0.15 pc or so) corresponds to gyroradius at energy of 2 10^{15} eV for B = 30 μG (amplified upstream field from Cassam-Chenaï et al 2007)
- Looks like the filamentary instability reported in simulations by Caprioli and Spitkovsky 2013 (ApJ 765, L20)

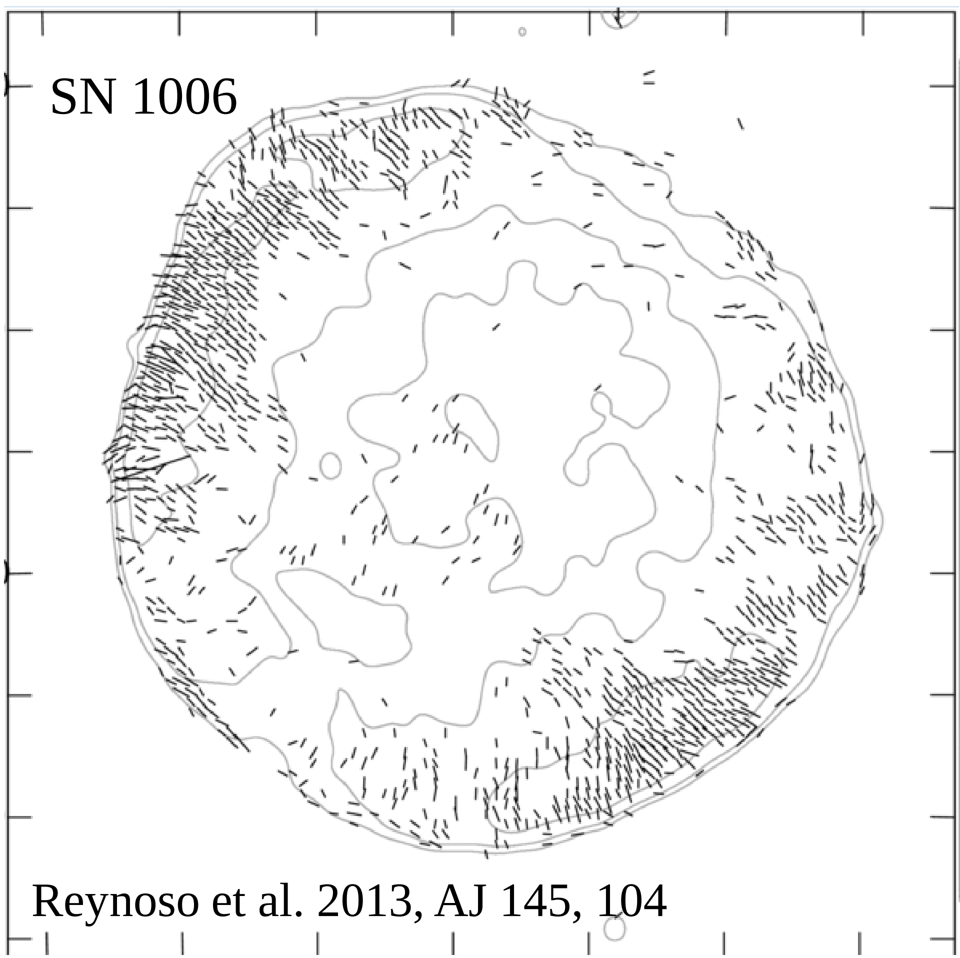


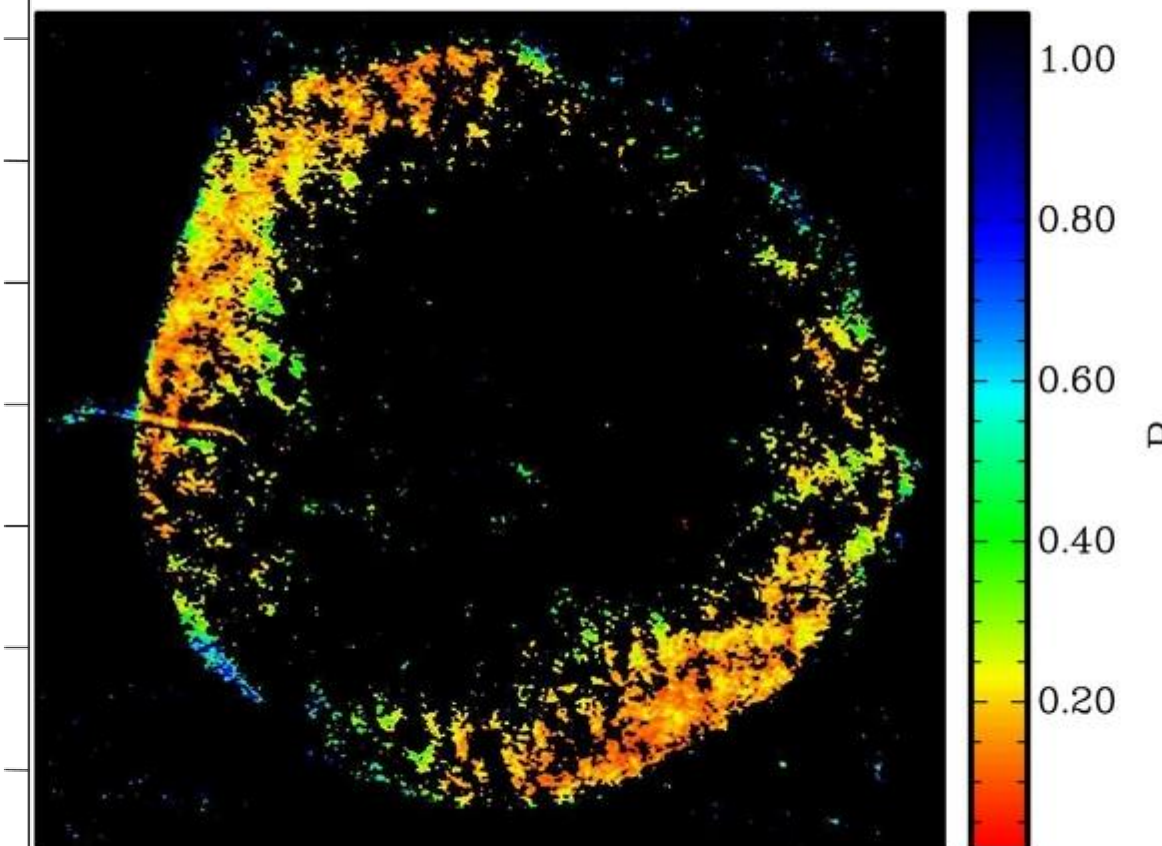
Magnetic orientation: radio polarization

Mostly radial in the limbs (NE and SW), tangential in SE

Much larger polarized fraction in SE (ordered field) than limbs (turbulent)

Simpler interpretation: external field is oriented NE - SW

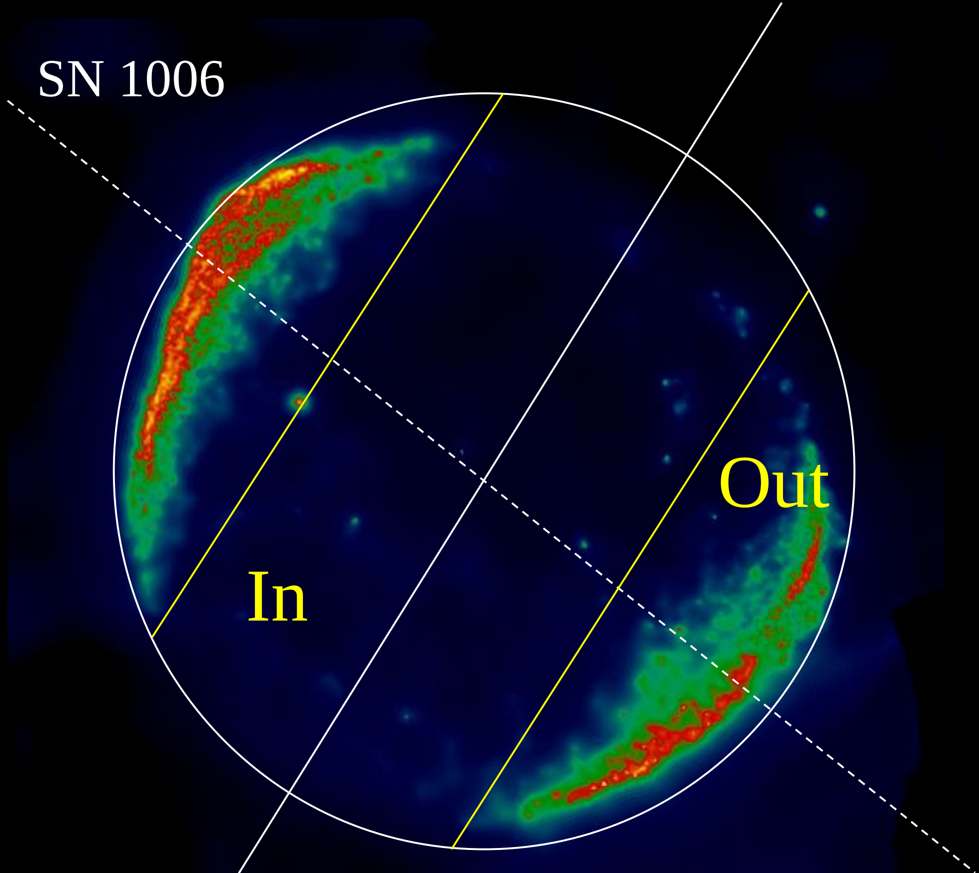




Fractional polarization

Magnetic orientation: X-rays

Rothenflug et al 2004, A&A 425, 121: if the bright limbs were an equatorial belt, non-thermal emission should also be seen in the interior



Observed $F_{in}/F_{out} < 0.5$ ➔ polar caps

- 0.8 – 2 keV: 0.300 ± 0.014
- 2 – 4.5 keV: 0.127 ± 0.074

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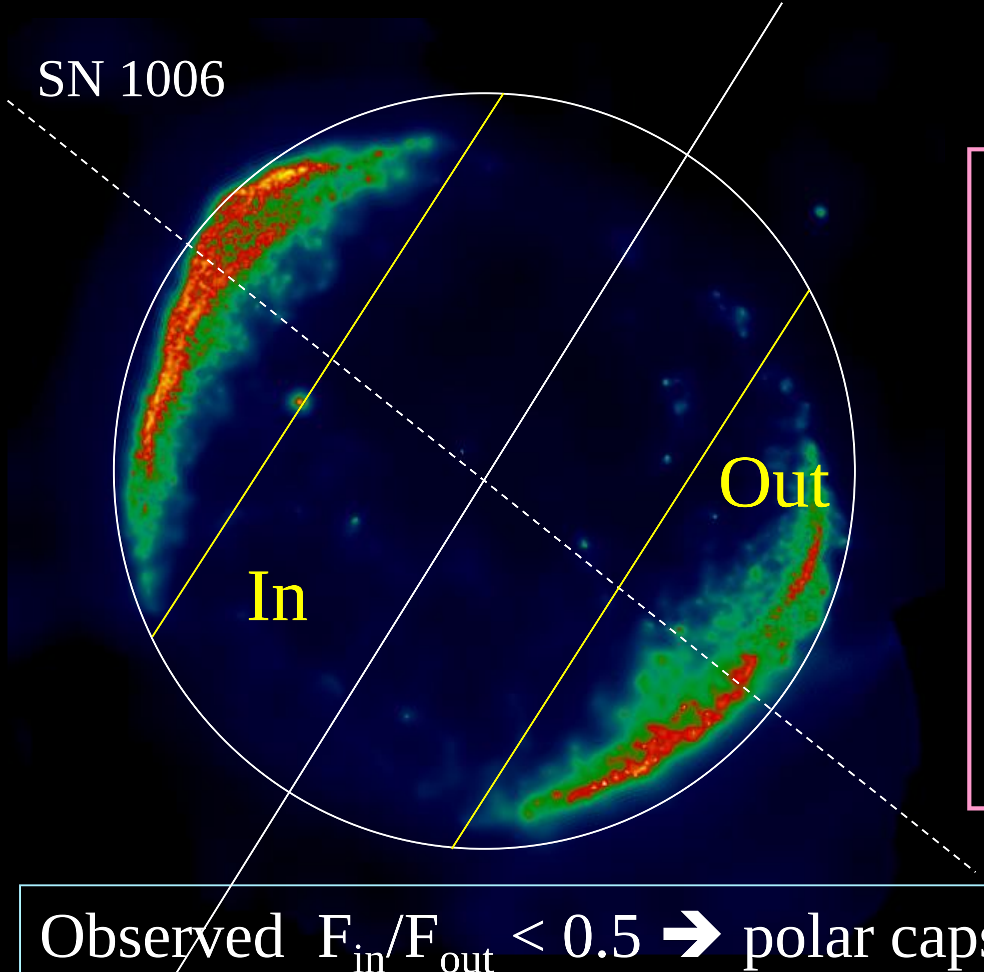

Assumes that B is more or less **random**

If **dominantly radial turbulence** up to the shock (not due only to RT) then **synchrotron** emission from the center is **suppressed** and equatorial geometry is possible (West et al 2017, ApJ 849, L22)

In **older SNRs** statistical arguments (Gaensler 1998, ApJ 493, 781) favor **equatorial** belts and magnetic compression ($\Delta B/B \ll 1$)

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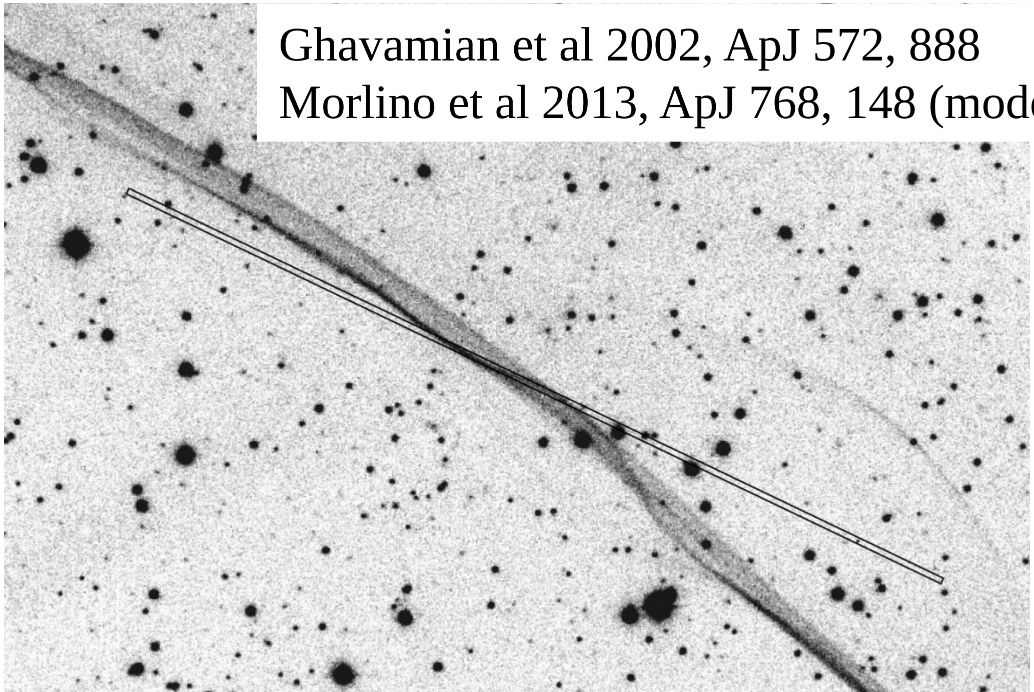
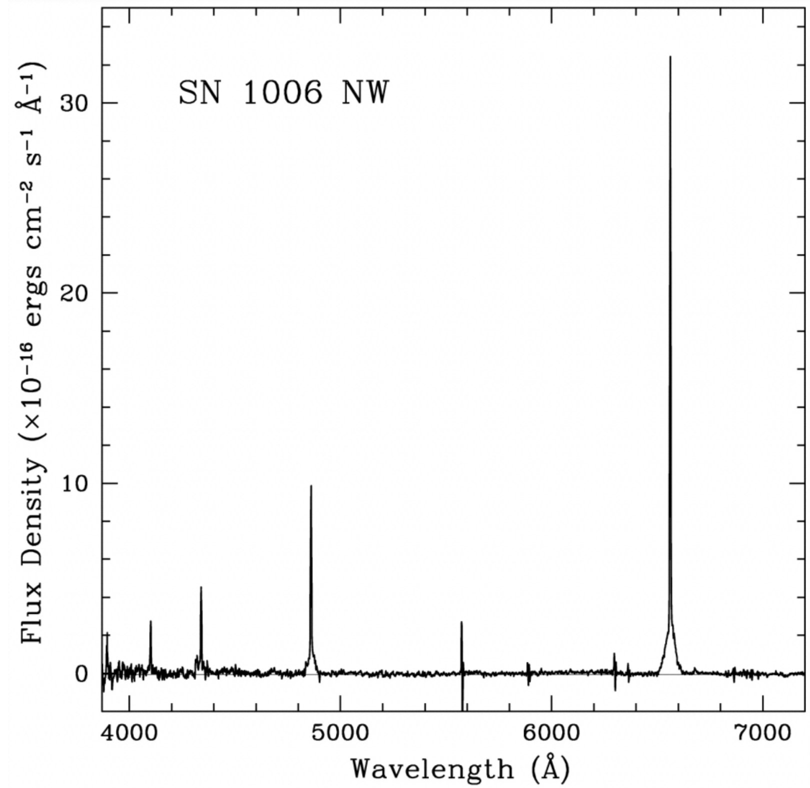
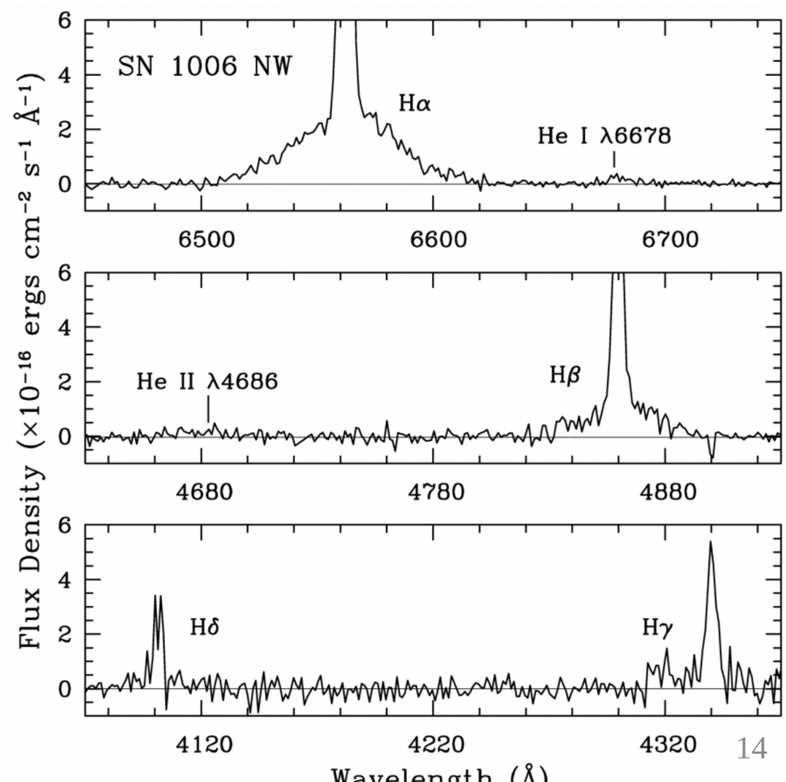
Optical Balmer lines



Ghavamian et al 2002, ApJ 572, 888
Morlino et al 2013, ApJ 768, 148 (models)





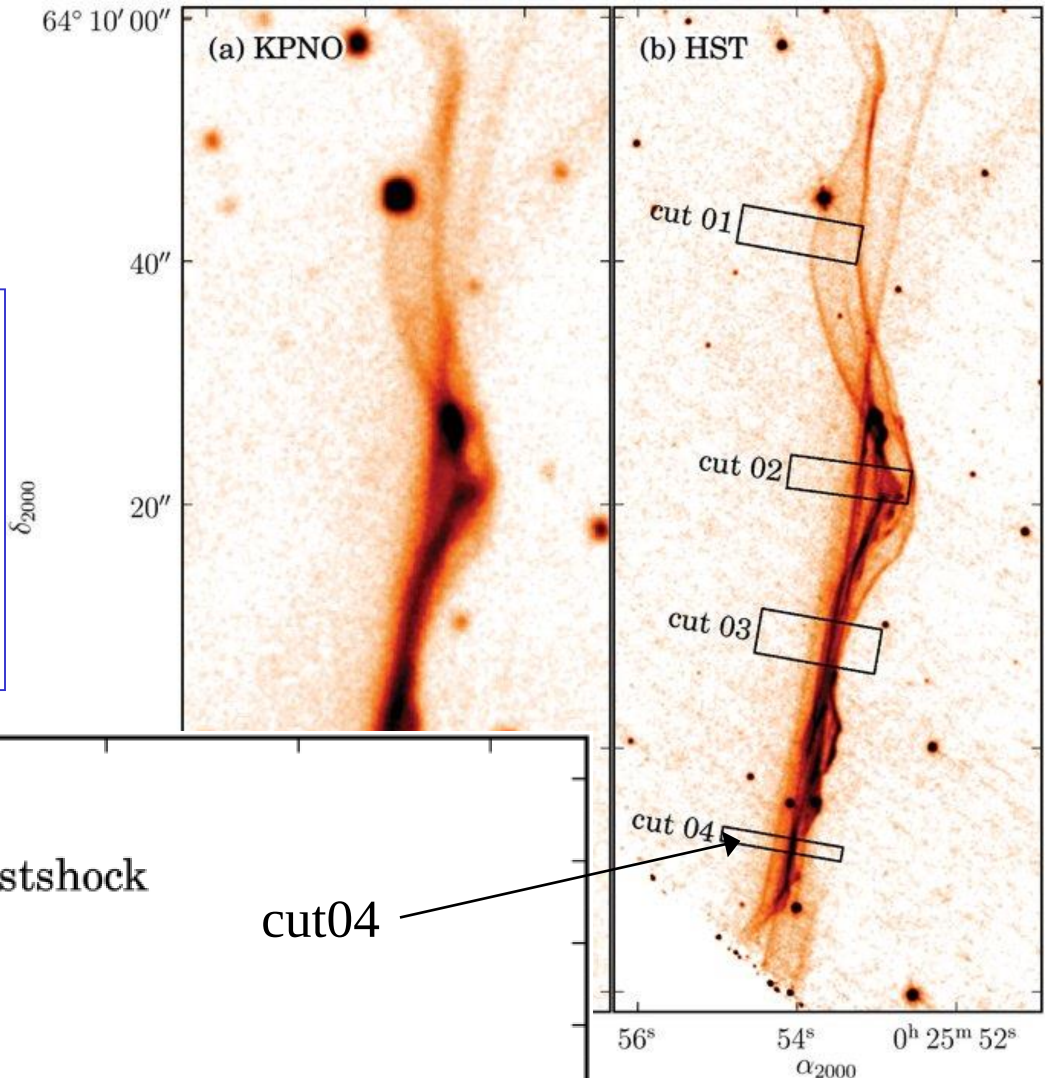
- ✓ Excitation and charge exchange vs ionization
- ✓ The width of the broad component gives the **proton temperature**. The ratio between the flux in the narrow and broad components depends on the **electron temperature**. In SN 1006, those observations give $T_p \sim 10$ keV and $T_e \sim 0.7$ keV.
- ✓ If **shock velocity** can be measured (proper motion + distance), can tell power lost to CR acceleration. No indication that it is large.
- ✓ Applicable only if **sizable neutral fraction**

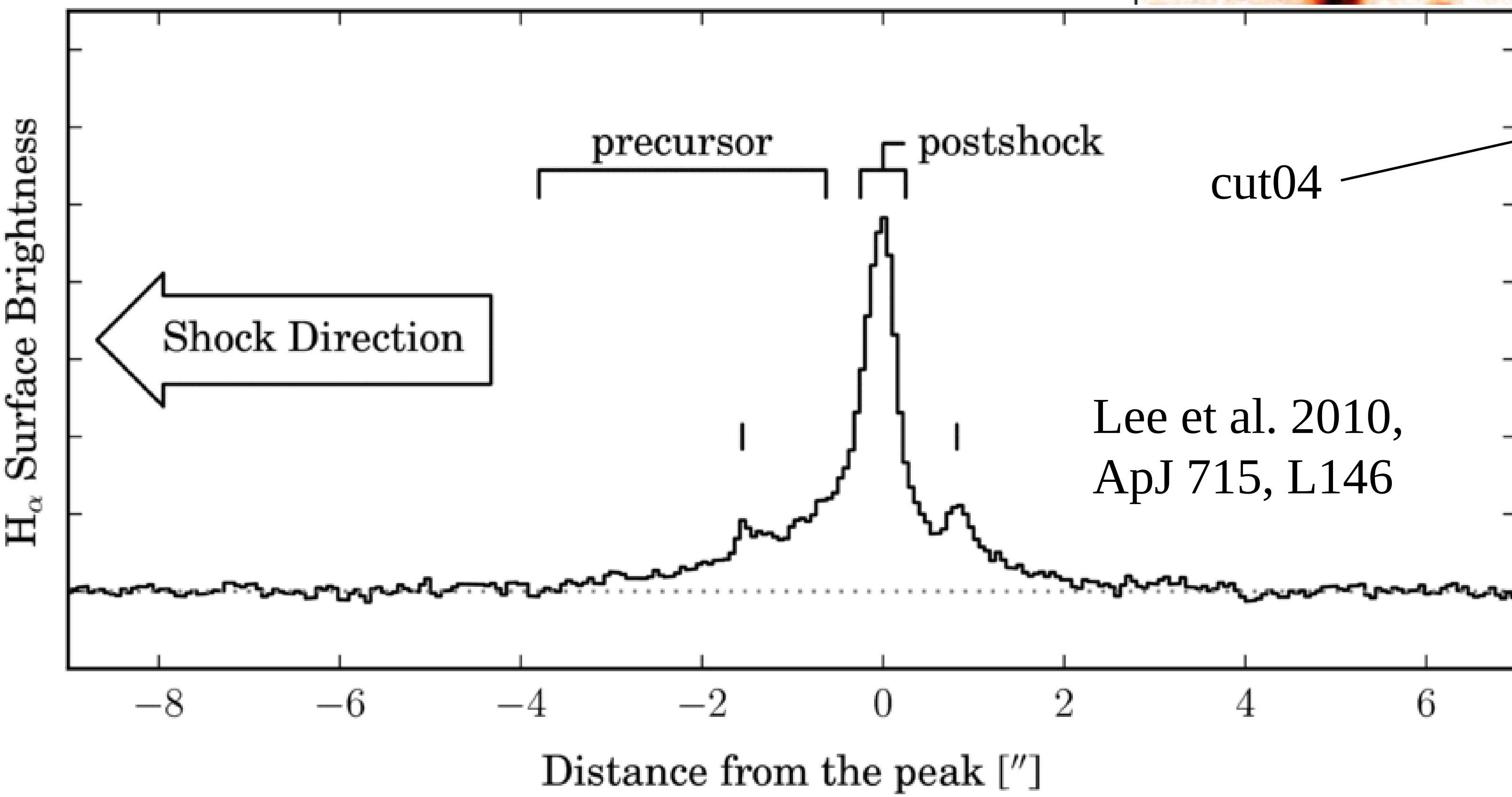
Balmer lines in Tycho: Precursor?

Narrow line broader than 10^4 K ➔ Pre-heating by proton CRs?

HST imaging ➔ precursor?

Implies 2-fluid effective D = 2 10^{24} cm^2/s
(Wagner et al 2009, ApJ 690, 1412)



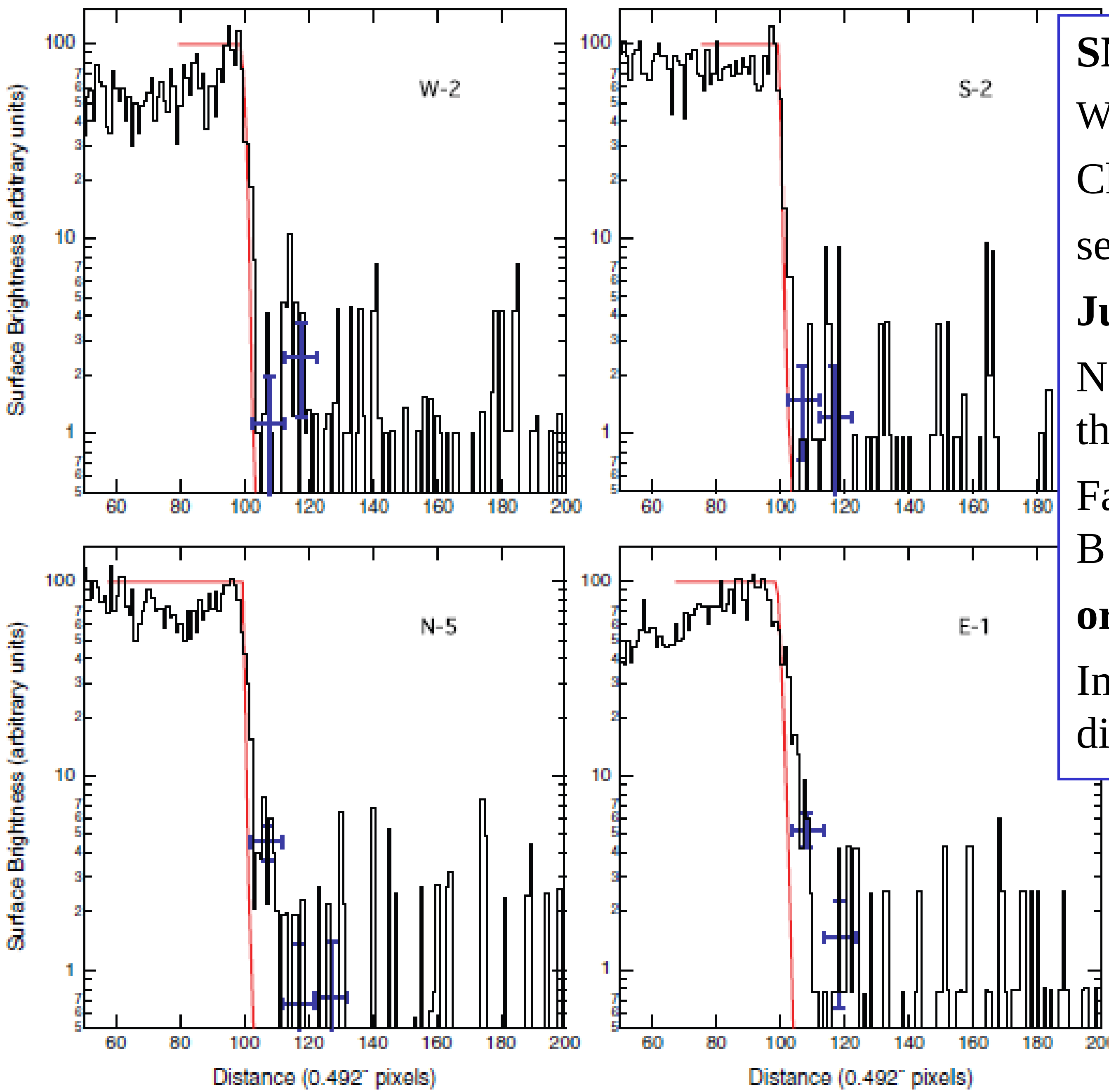


cut04

Lee et al. 2010, ApJ 715, L146

Shock precursor in X-rays

The Astrophysical Journal, 781:65 (18pp), 2014 February 1



SN 1006 in X-rays:

Winkler et al 2014, ApJ 781, 65

Chandra LP, covers whole SNR

see **no precursor**

Jump by factor > 20

No way to make jump sharper than it is with clever geometry

Factor 20 requires factor 3.3 on B compression

or width < 3" (0.03 pc)

Implies B_0 > 40 μG, for Bohm diffusive scale

Very close to what is expected

Observational summary

Large body of observations:

- **Historical SNRs** are the best opportunity for detailed modeling
- **X-rays**: rims (**total B field**), cutoff (**diffusion coefficient**), variability (both), azimuthal variations (dependence on **B inclination**)
- **Optical**: Balmer lines (proton temperature, **precursor**)
- **Radio**: **polarization**, **B decay** (comparison to X-rays). Probably **best prospects for improvement** in near future
- Also: SNe radio light curves and spectral hardening, LE CRs effect on chemistry and neutral Fe K line outside SNRs, distance between shock and ejecta (shock compression)

Backup

Cut-off frequency and cloud interaction

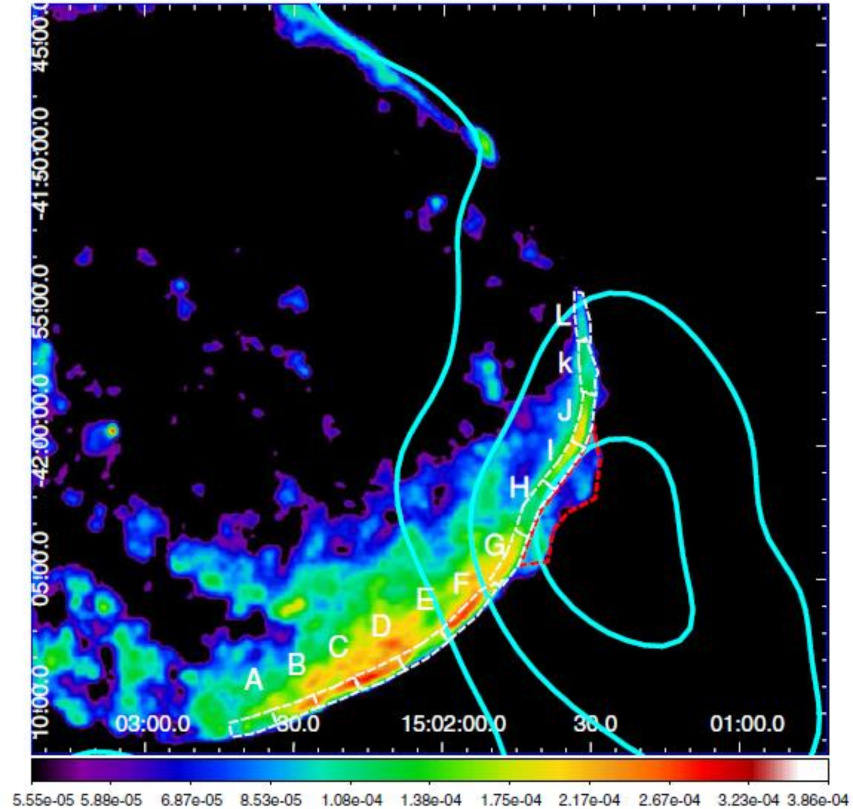
Miceli et al 2014, ApJ 782, L33

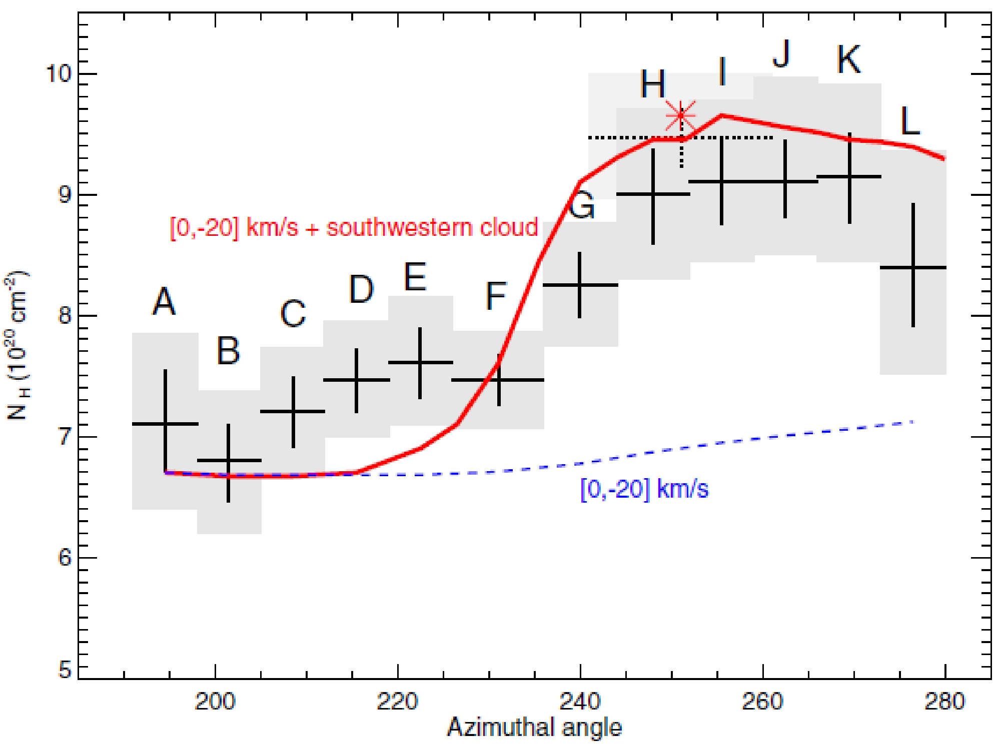
XMM-Newton Large Program on SN 1006

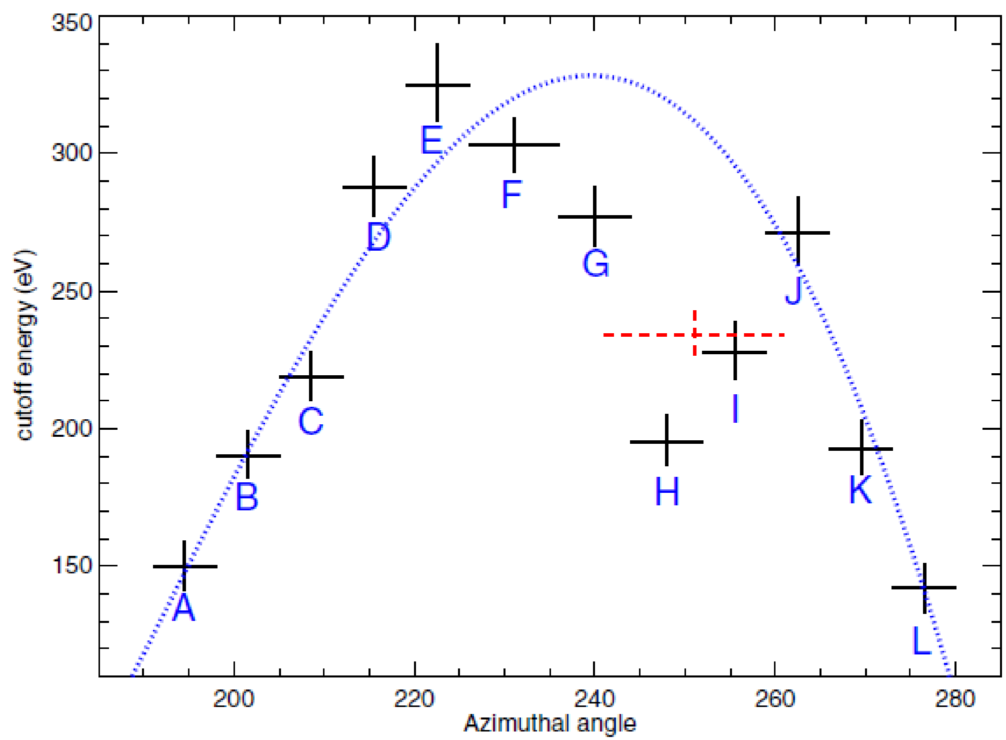
Interaction with a small cloud

Cutoff frequency decreases at interaction point

Consistent with ν_{cut} α V_{sh}^2 α 1/ρ in cooling-limited regime







Sharp rims at the forward shock. Known cases

Compression ratio fixed to 6 (rough estimate from non linear diffusive shock acceleration)

Equating 4.6 l_{dif} ($l_{adv} < l_{dif}$) and the projected FWHM gives B (downstream).

$$\varepsilon_B = \frac{B^2}{8\pi \rho V_{sh}^2}$$

	Dist. kpc	Speed km/s	Projected FWHM	Age yr	Density cm^{-3}	B μG	ε_B(%)
Cas A	3.4	5200	0.03 pc (2”) at 5 keV	320	1 ?	300	> 1.4
Kepler (SE)	4.8	5400	0.07 pc (3”) at 5 keV	400	0.10	180	> 2
Tycho	2.3	4600	0.05 pc (4”) at 5 keV	430	0.20	250	> 3
SN 1006	2.2	4900	0.20 pc (20”) at 2 keV	1000	0.05	90	1
RX J1713…	1.0	3500	0.19 pc (40”) at 2 keV	2000 ?	0.02	90	6 ?
RCW 86	2.5	2700 ?	1.20 pc (100”) at 2 keV	1800 ?	0.10	24	0.1 ?
Vela Junior	0.75	2000 ?	0.18 pc (50”) at 5 keV	3000 ?	0.05 ?	100	8 ?

Requires magnetic field amplification (Lucek and Bell 2000, MNRAS 314,65)
but not equipartition with the accelerated protons

Sharp rims at the forward shock. Radiative interpretation

Three effects combine to set the observed width of the emitting region behind the shock:

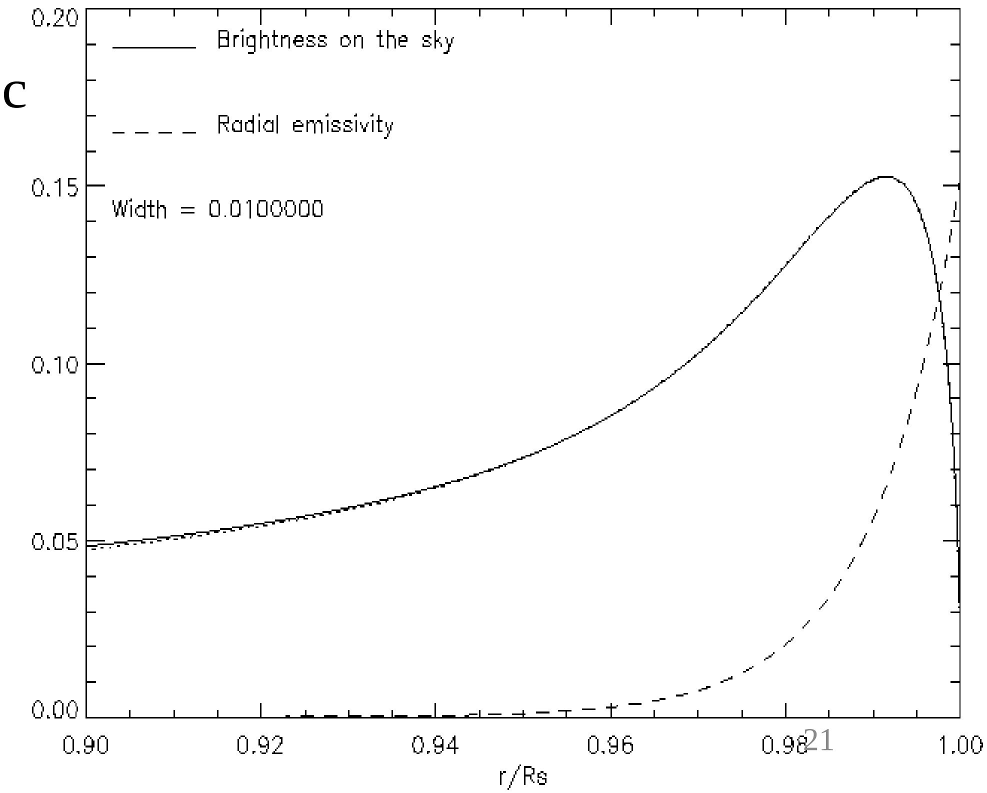
- ✓ Advection (Vink and Laming 2003, ApJ 584, 758; Bamba et al. 2003, ApJ **589**, 827) depends on the shock speed and the compression ratio
- ✓ Diffusion (Berezhko et al. 2003, A&A 412, L11; Yamazaki et al. 2004, A&A 416, 595) assuming Bohm limit
- ✓ Projection (Berezhko et al. 2004, A&A 419, L27)

$$l_{\mathrm{adv}} = t_{\mathrm{cool}} V_{\mathrm{sh}} / r = 1.8\times10^{-3}\, B_{\mathrm{mG}}^{-3/2}\, \nu_{\mathrm{keV}}^{-1/2}\, V_{1000} / r \quad \mathrm{pc}$$

$$l_{\mathrm{dif}} = \sqrt{\kappa_{\mathrm{d}} t_{\mathrm{cool}}} = 1.2\times10^{-3}\, B_{\mathrm{mG}}^{-3/2} \quad \mathrm{pc}$$

$$l_{\mathrm{adv}} / l_{\mathrm{dif}} = 1.5\, \nu_{\mathrm{keV}}^{-1/2}\, V_{1000} / r$$

Observed FWHM = 4.6 times scale height for exponential decrease (thin shell)



Shock precursor: radio

Accelerated particles should diffuse ahead of the shock, leading to non-thermal emission

$$l_{\rm diff} = \sqrt{2D\tau_{\rm acc}} \approx \sqrt{\frac{2r(r+1)}{3(r-1)}}\,\frac{cE}{eB_{\rm turb}V_{sh}} \qquad \nu_{\rm sync} = 1.82\times10^{18} B_{\rm tot}E^2 \quad \text{Hz}$$

$$l_{\rm diff} \approx \frac{9.75\times10^{10}\ \text{cm}}{B_{\rm turb}V_{sh}}\sqrt{\frac{\nu_{\rm sync}}{B_{\rm tot}}} \qquad < 0.1\ \text{pc}$$

Not seen in the radio (ν ~ GHz) => $B_{\rm turb} > 10^{-2}$ µG => stronger magnetic turbulence than in ISM (Achterberg et al. 1994, A&A 281, 220)

More stringent in X-rays ($\nu_{\rm sync}$ 10^8 times larger)

Optical Balmer lines

- IFU on VLT/VIMOS
- Unresolved (ie ionization occurs over a size smaller than 1 pixel)
- Very large **scatter** on ratio of broad to narrow fluxes
- Large number of points below (ie broad line not bright enough) what is expected for charge exchange and ionization behind the shock
- Argue that part of the narrow line comes from precursor
- Require closer distance than usual
- Interpret shock as coming from **only one side of the cloud**. Should come from both sides, and would change the analysis a lot

Nikolic et al 2013, Science 340, 45