The radio-lobe shock of Cen A: particle acceleration & environmental impact

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The Many Faces of Centaurus A
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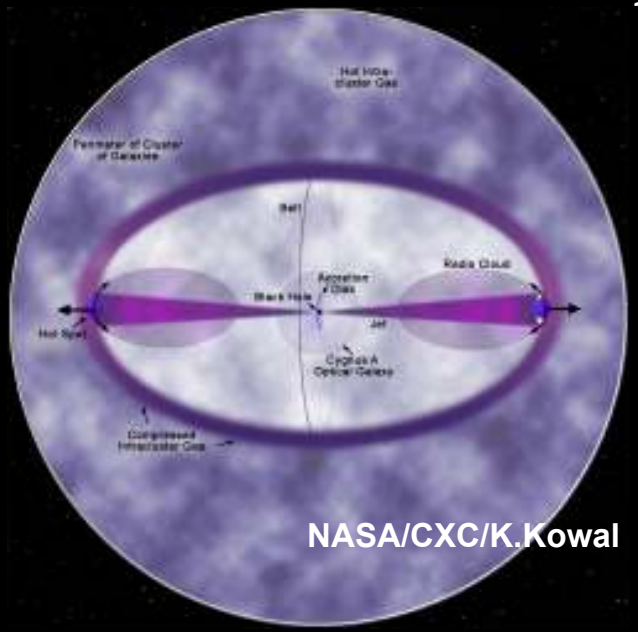
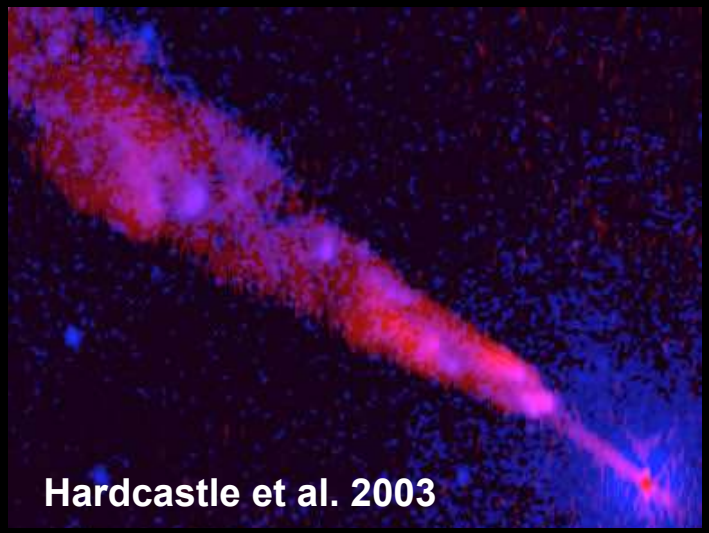
Outline

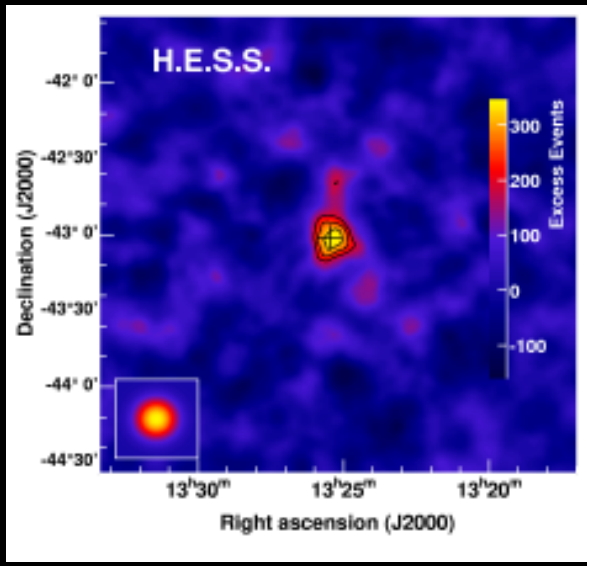
- Context: the first detected strong radio-lobe shock
- The non-thermal interpretation of the X-ray feature
- The X-ray structure of the shock region
- Constraints on particle acceleration and magnetic field properties at the shock front
- TeV emission from the shock
- Cosmic rays from the shock
- Implications for shocks and particle acceleration in other radio galaxies

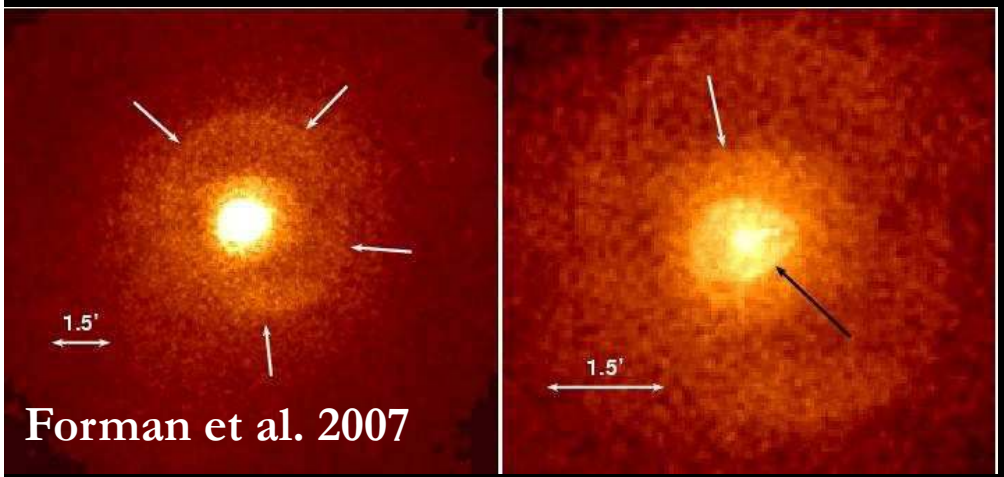
Some reasons for studying shocks in radio galaxies

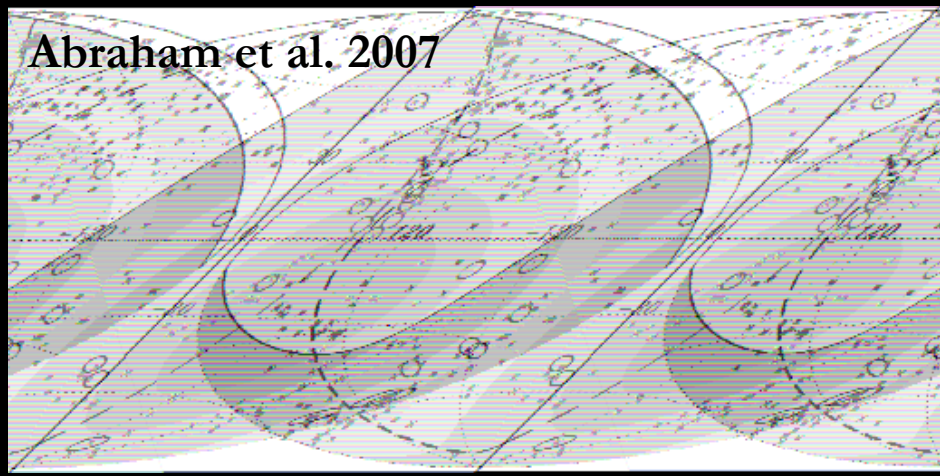




Aharonian et al. 2009







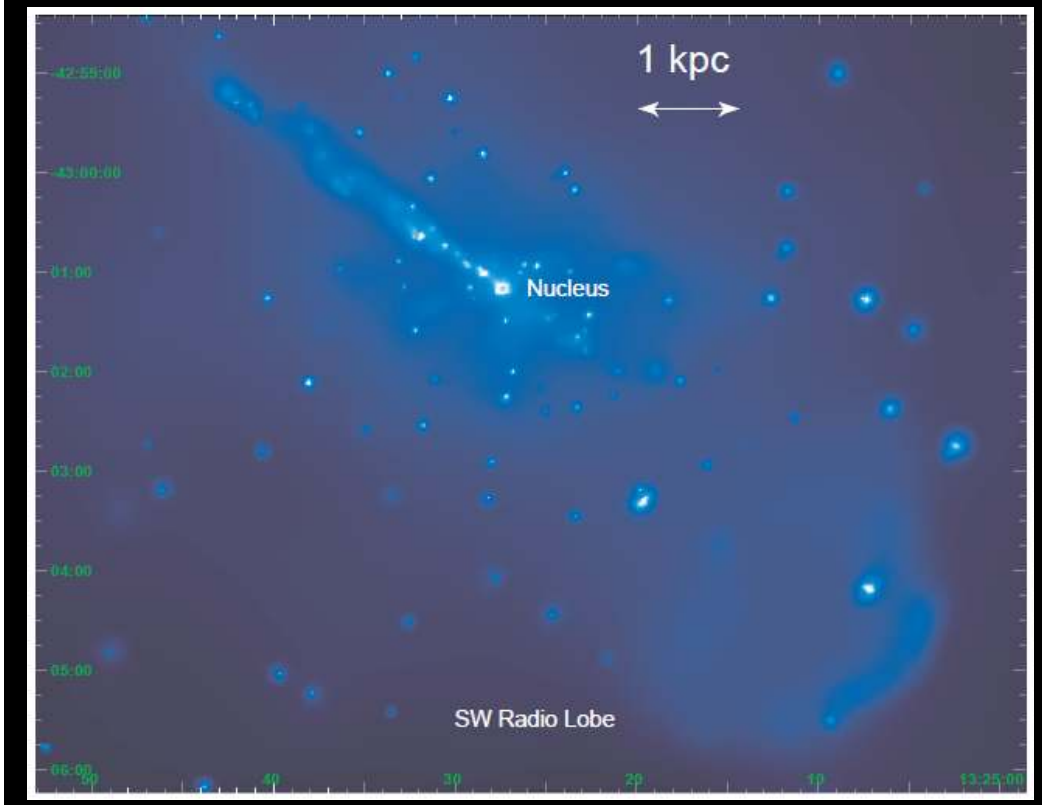
The radio-lobe shock in Cen A

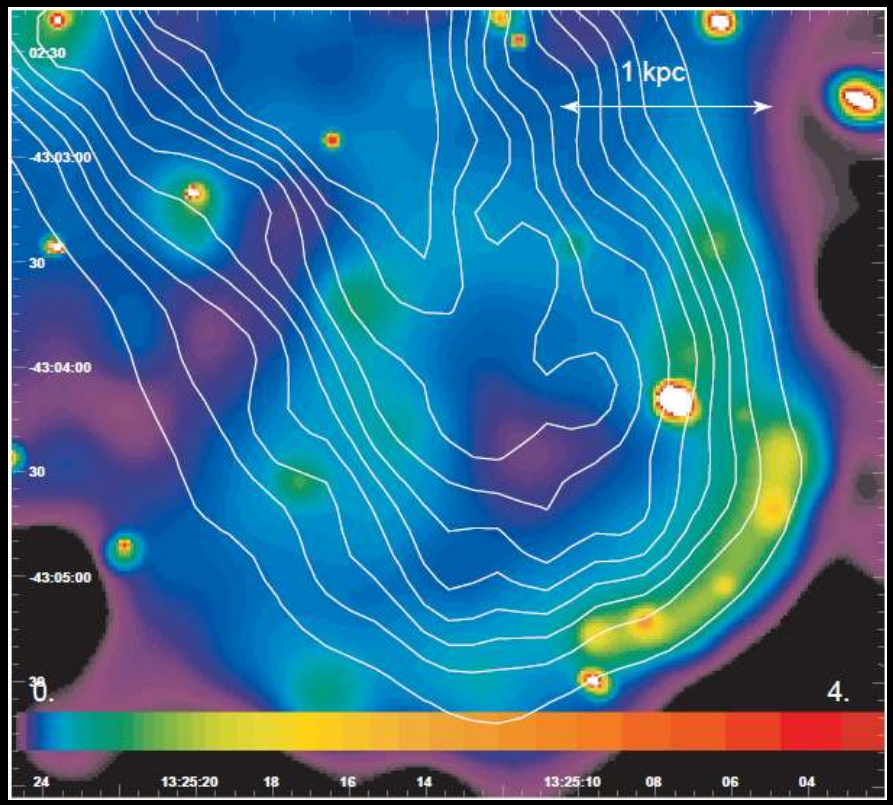
Detection of the X-ray shell

Dobereiner et al. 1999

- ROSAT detected an X-ray enhancement associated with SW lobe – inferred to be hot gas compressed by lobe expansion.

Chandra & XMM observations





Kraft et al. 2003

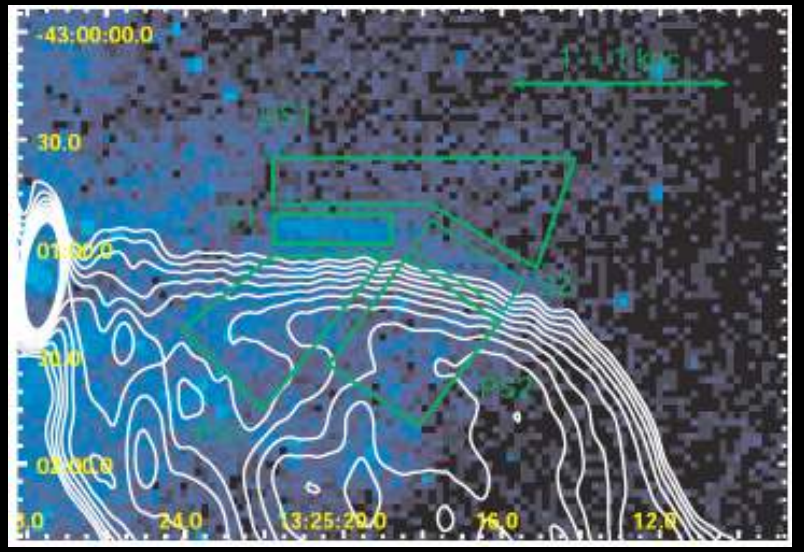
Initial results

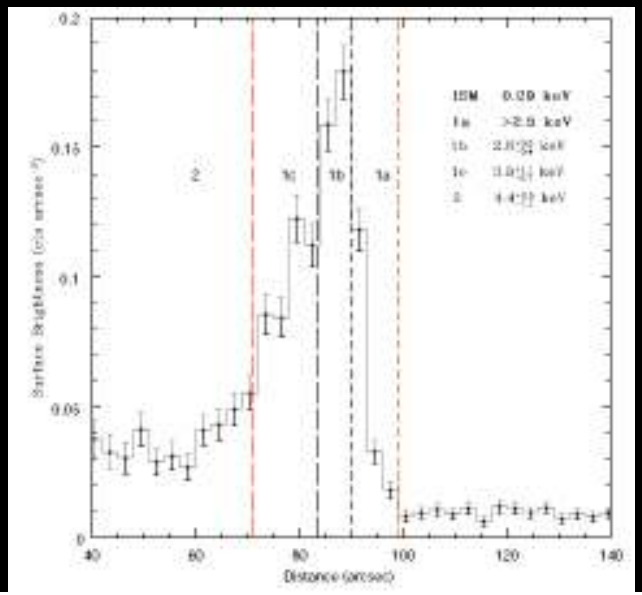
- X-ray shell interpreted as thermal emission from hot gas based on spectrum & lack of non-thermal emission at other wavelengths.
- Pressure-driven expansion of the (inner) radio lobes at Mach ~8 is shock heating the ISM of NGC 5128.
- FRIs can be expanding supersonically!
- $\sim 10^{56}$ ergs injected into the ISM
- Direct measure of jet power:
  $P \sim 10^{42}$ ergs/s

Temperature structure and transport processes

- Shell is cooler closer to the nucleus, as expected for an isobaric lobe expanding into a declining density gradient.
- Tight constraints on size of shocked gas region (between contact discontinuity at radio-lobe edge and shock front) = significantly smaller than scale for electron-ion equilibrium
- => measured T_e may underestimate shock strength considerably.

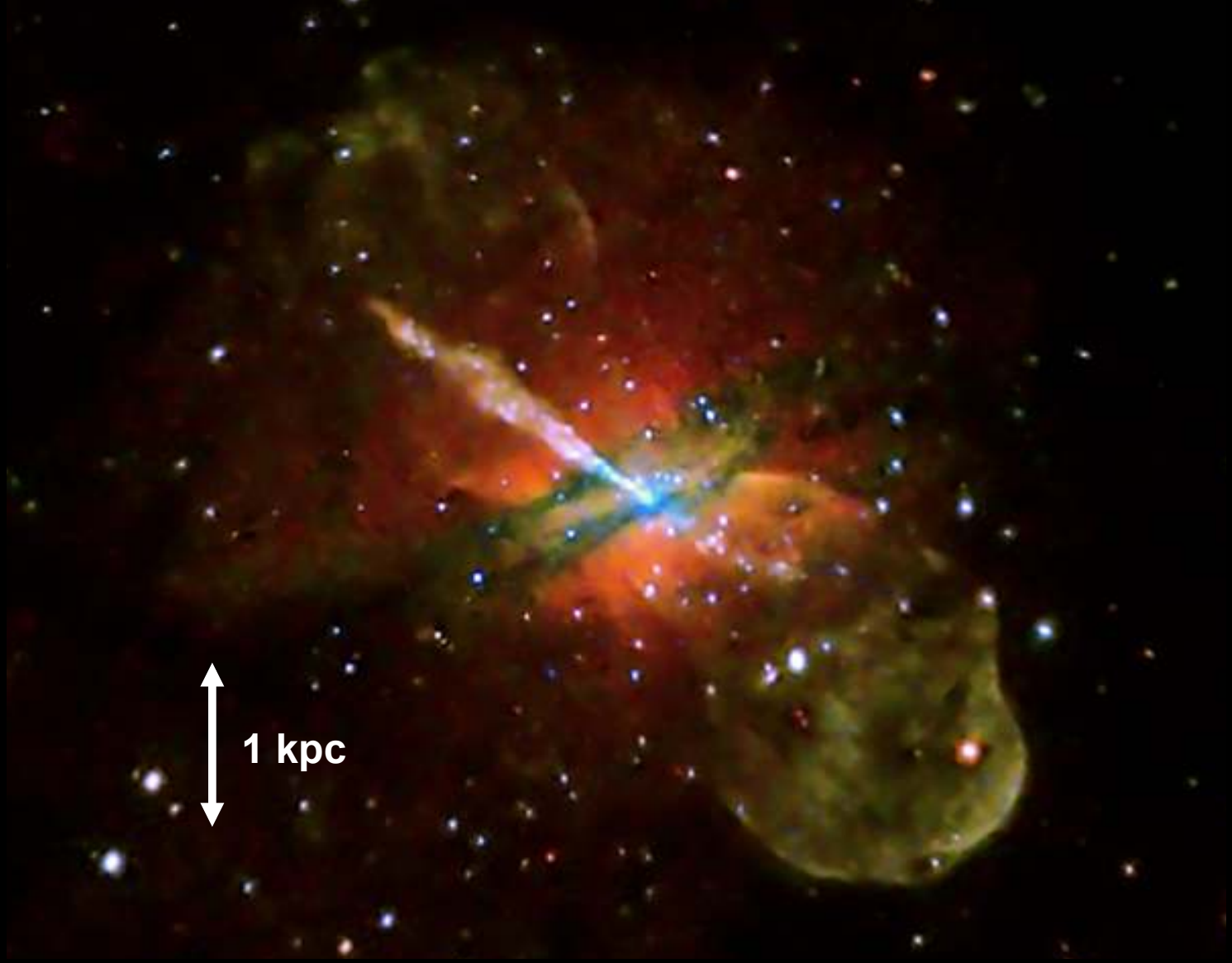
Kraft et al. 2007 (~150 ks of Chandra data)



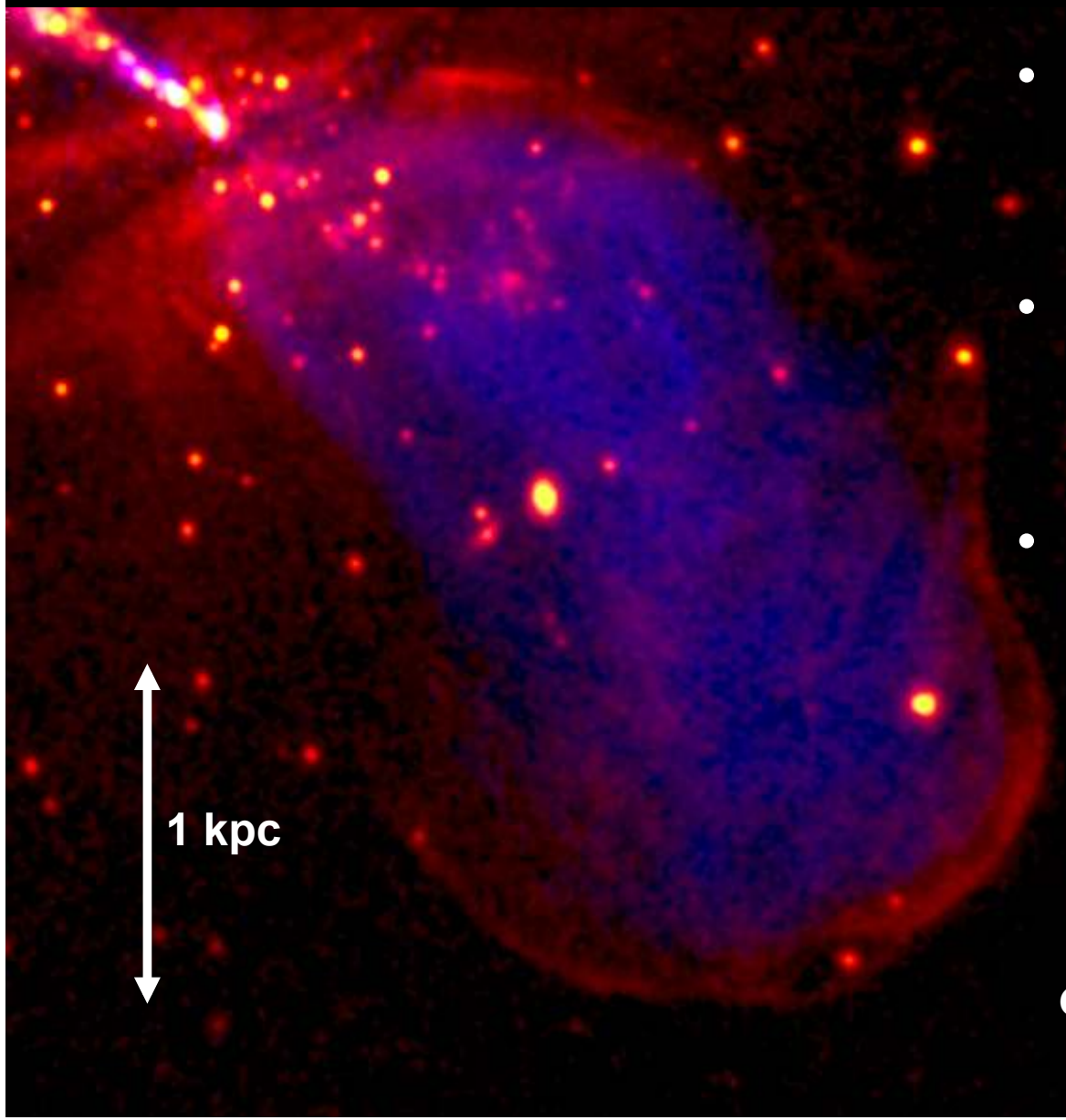


New results on the X-ray shell

The Chandra VLP data



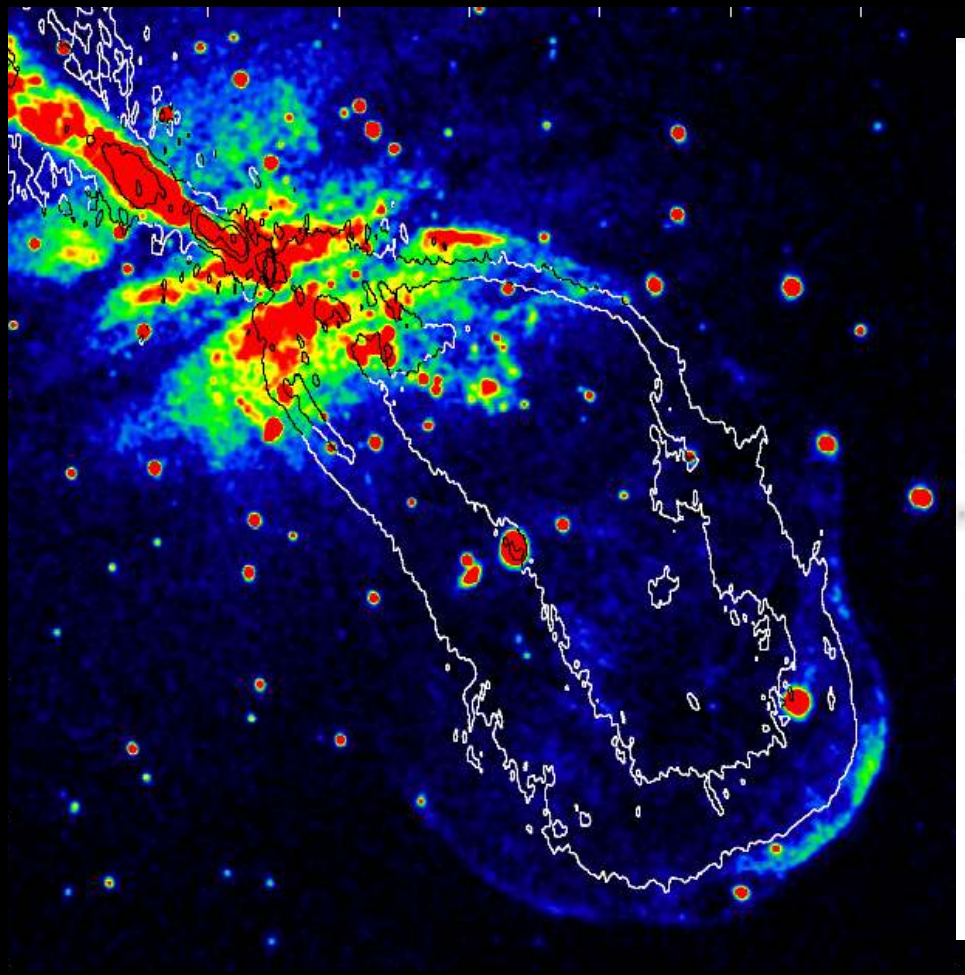
A new interpretation for the X-ray shell



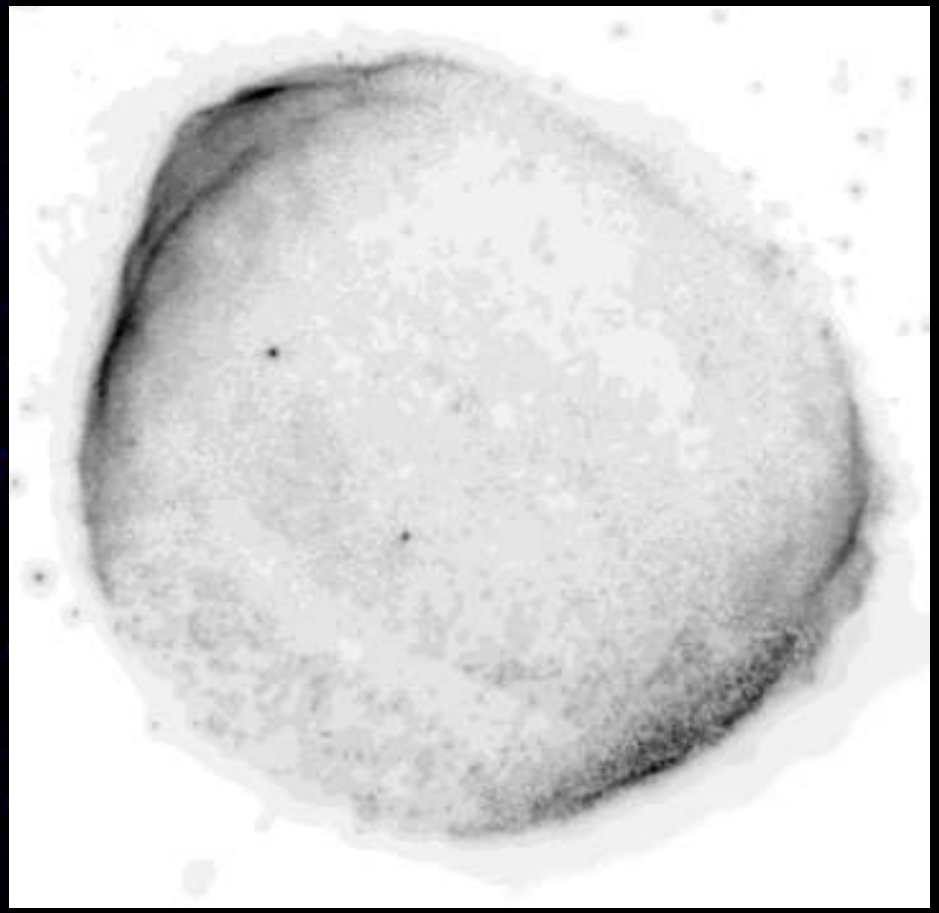
- The new, deeper data reveal most of the X-ray emission is **non-thermal**
- Thermal models for the outer shell can be ruled out at high significance.
- Spectrum well fitted by a power law with $\Gamma \sim 2.0$, consistent with an X-ray synchrotron interpretation.

Croston et al. 2009 MNRAS 395 1999

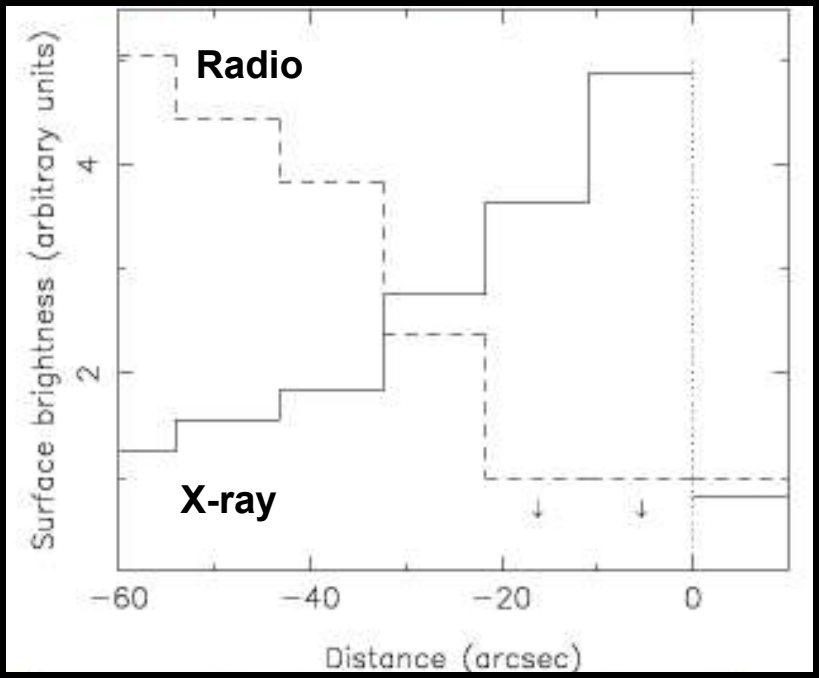
Particle acceleration at the shock front?



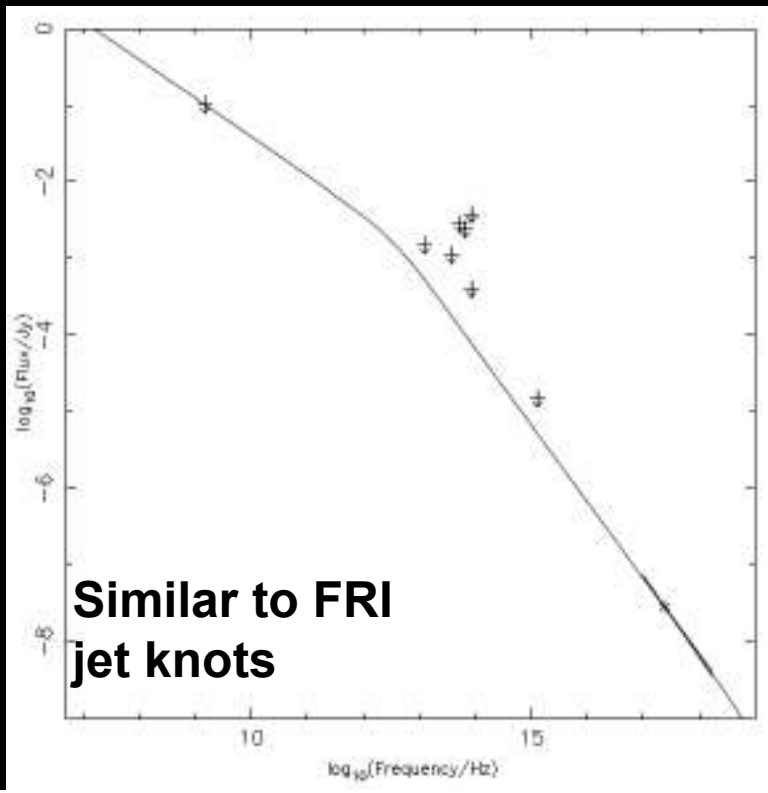
X-ray synchrotron emission
at the shock front in Cen A

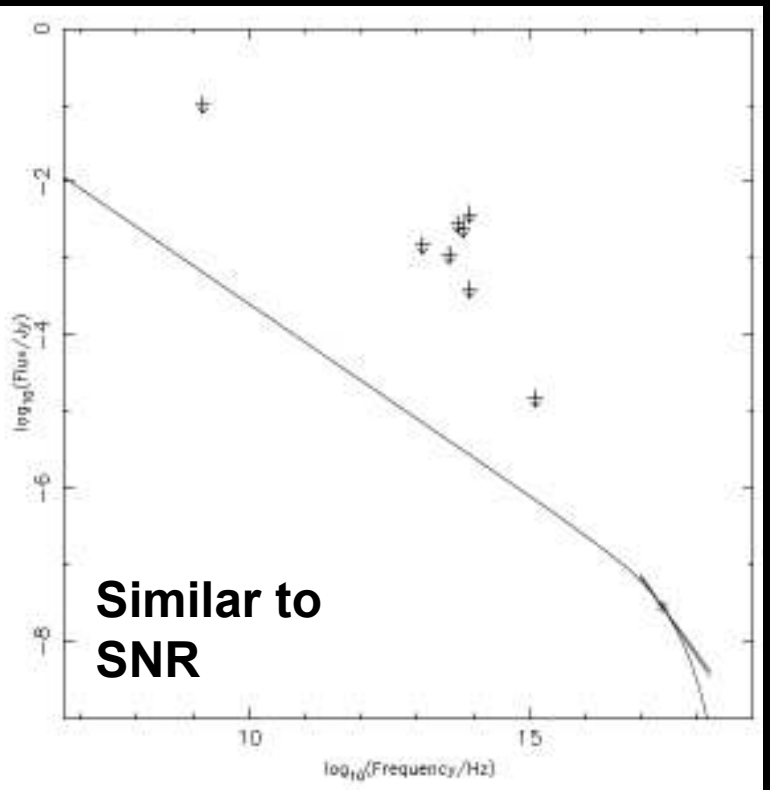


X-ray synchrotron emission
from SN1006 (Rothenflug et al. 2004)

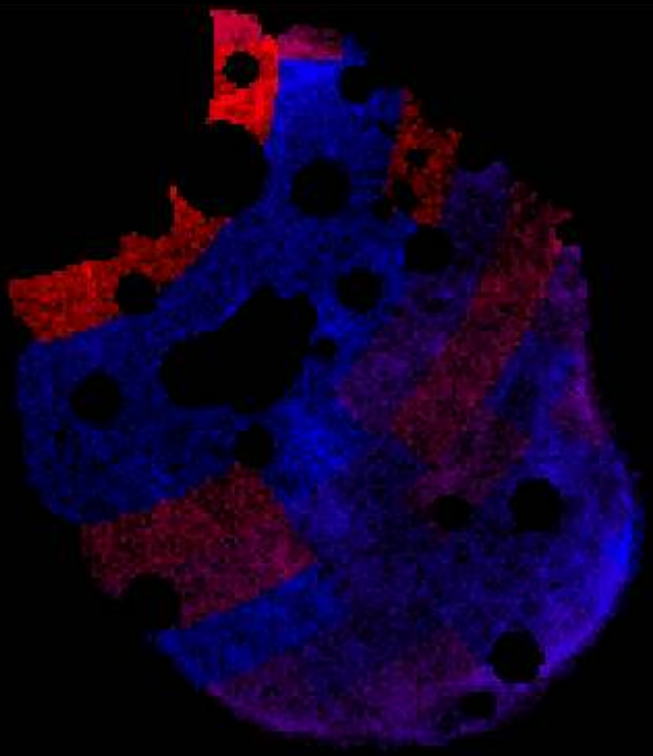


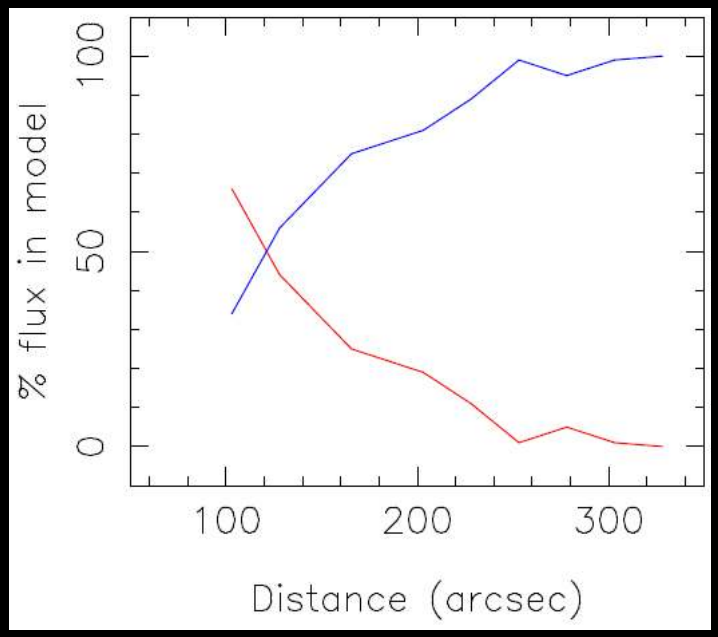
- The shock front region is not detected in the radio, IR (Spitzer) or UV (GALEX). Deeper Spitzer data coming.
- Limits at these wavelengths don't rule out plausible synchrotron spectra.

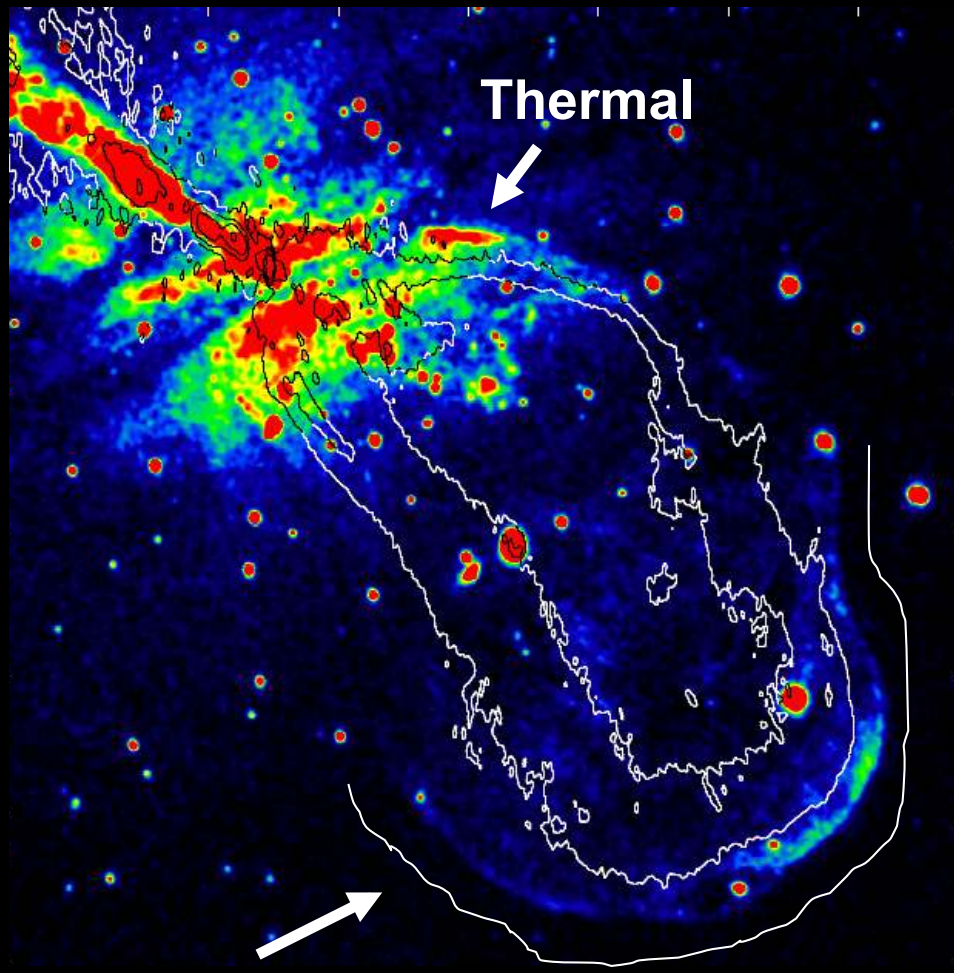




Spectral structure within the shell

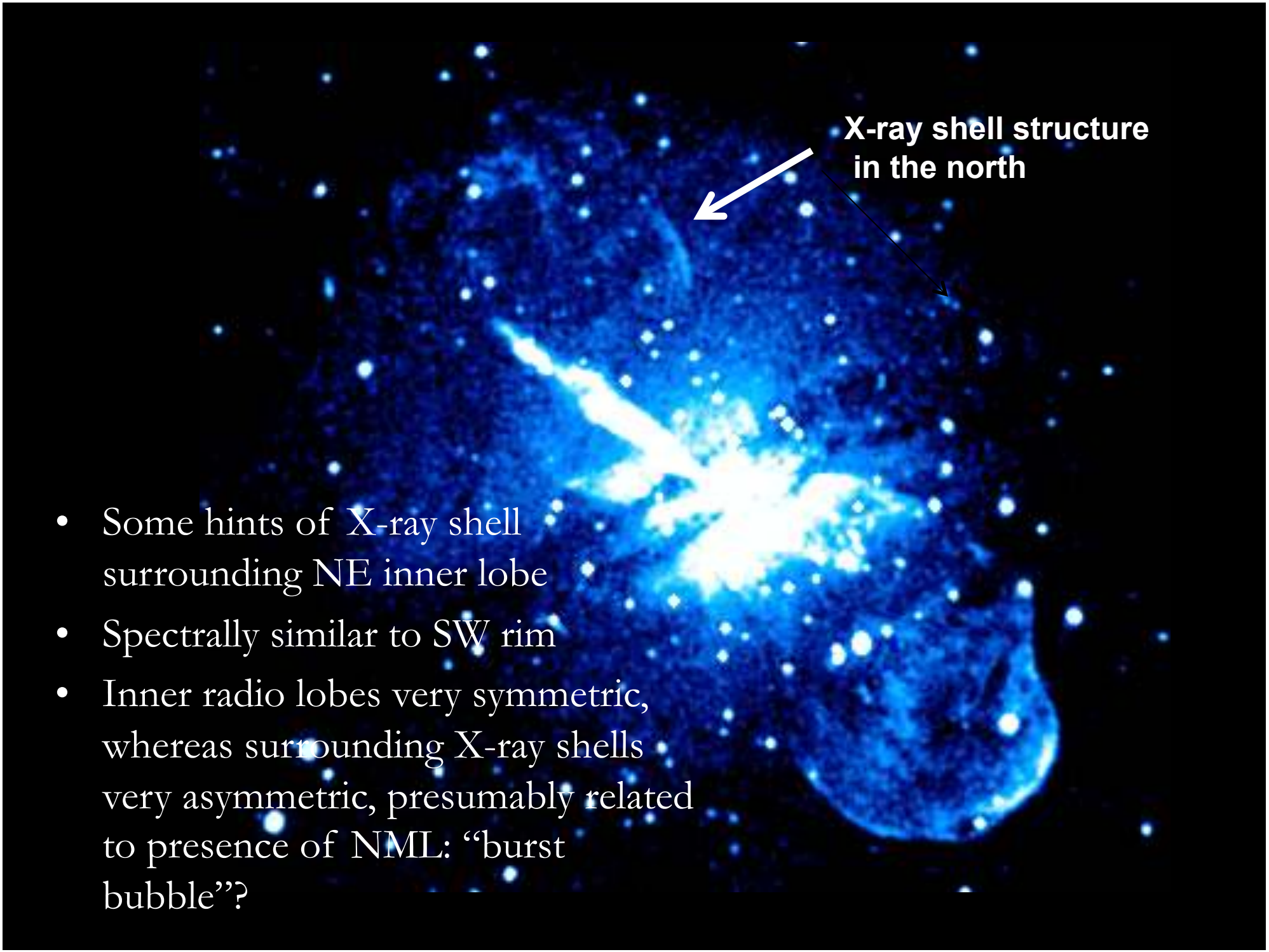






Shell and lobe dynamics

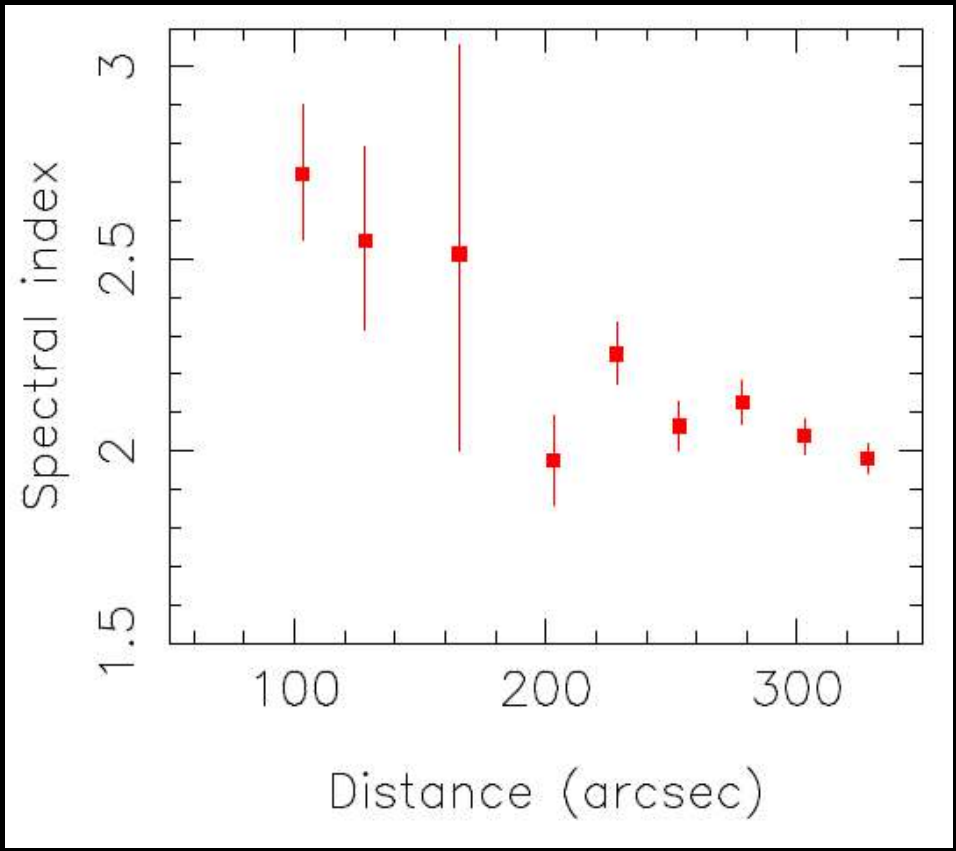
- Thermal part of the shell (inner region) can be used to investigate shock jump conditions.
- Pressure jump of ~10x implies Mach ~2.8 (v ~ 850 km/s) close to the nucleus
- Lobe assumed to be isobaric, so if $P_{lobe} = P_{shell}$, then can infer pressure jump for outer shell.
- $P_{outer}/P_{ism} \sim 87$, corresponding to Mach ~ 8.4 (v = 2600 km/s) => $t_{shock} \sim 10^6$ y
- Inferred expansion speed very similar to SNR with X-ray synchrotron emission (e.g. Vink et al. 2006, Warren et al. 2005, Rothenflug et al. 2004)



- Some hints of X-ray shell surrounding NE inner lobe
- Spectrally similar to SW rim
- Inner radio lobes very symmetric, whereas surrounding X-ray shells very asymmetric, presumably related to presence of NML: "burst bubble"?

Particle acceleration, magnetic fields & cosmic ray acceleration

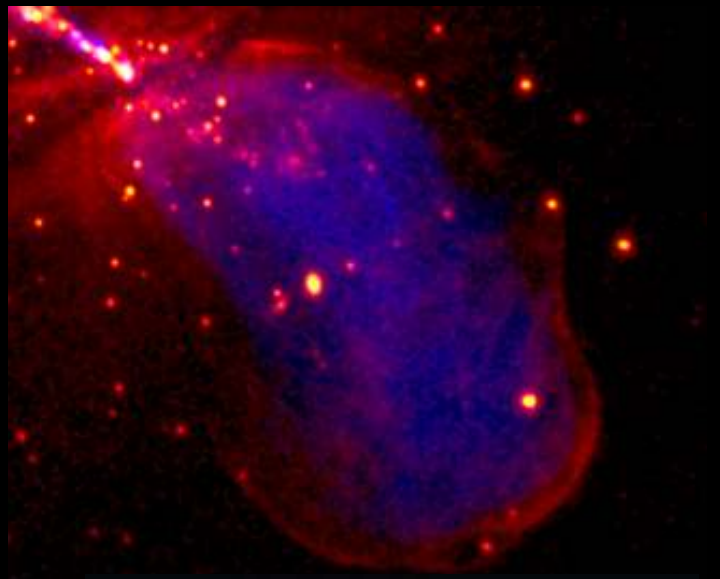
Particle acceleration constraints



- Flattening of spectral index in outer parts of the shell could be explained by increase in γ_{max} with shock speed.
- Requires γ_{max} between 10^7 and 10^9 over the shock region.
- γ_{max} depends mainly on B and v_{shock} (e.g. Lagage & Cesarsky 1983, Reynolds 1996): for equipartition B, we find $\gamma_{max} \sim 10^8$ at the outer edge, and 3×10^7 for the inner ($v \sim 850$ km/s) region.
- To fit a synchrotron model to the X-ray spectral index at the outer edge, we require $\gamma_{max} \sim (2 - 4) \times 10^8$.

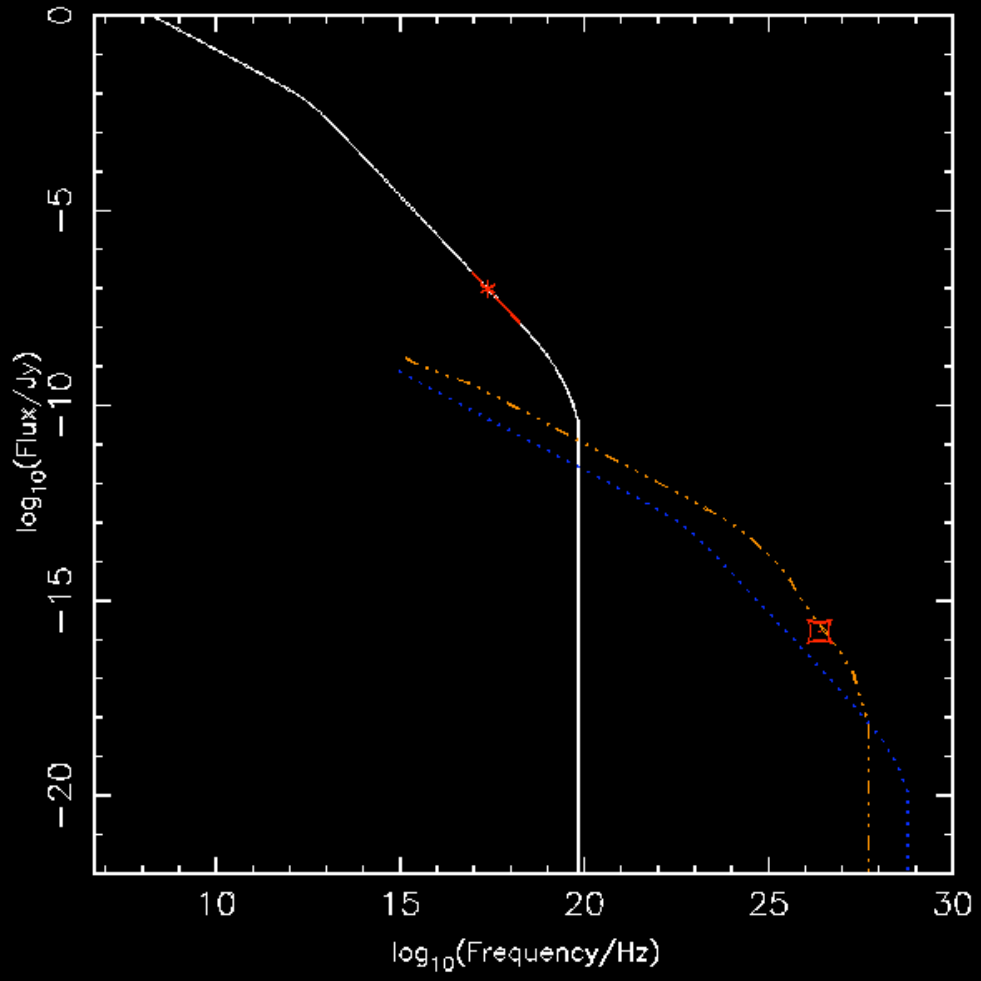
Particle acceleration & B fields: comparison with SNRs

- SNR shells are inferred to have *B* fields >> simple compression of the ISM (e.g. Ellison & Vladimirov 2008, Reynolds 2008) => non-linear DSA with *B* amplification (e.g. Bell & Lucek 2001).
- *B*-field amplification by factors of 10 – 100 plausible in Cen A (B_{eq} ~ 8 μG for κ=1 and ~30 μG for κ=100).
- Spectral indices somewhat steeper in SNRs (typically Γ ~ 2.5), consistent with lower E_{max} .



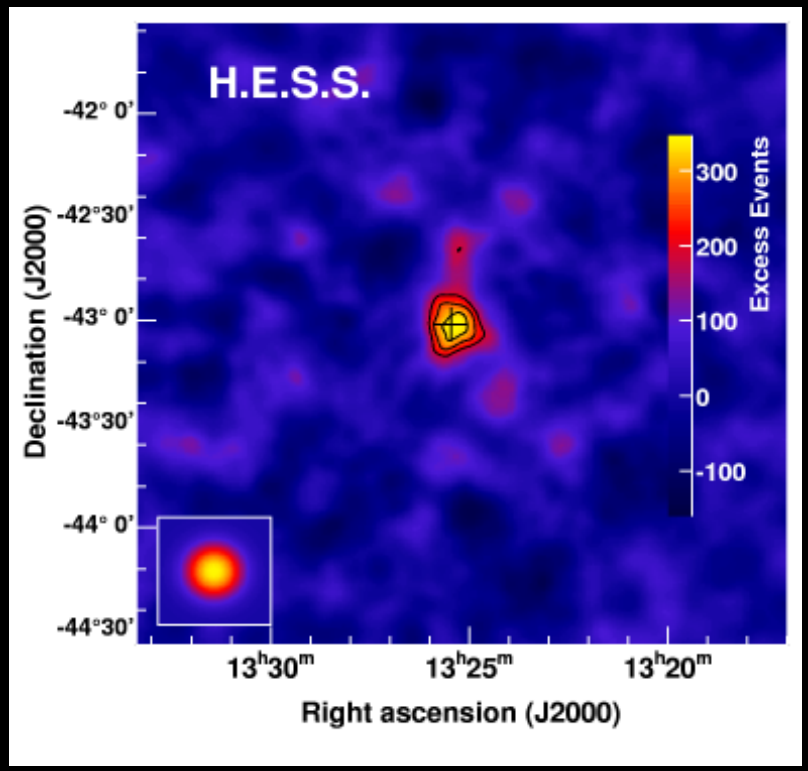
TeV emission from the shell?

- X-ray synchrotron from the shell implies electrons with TeV energies, hence IC emission in the TeV range might be expected.
- Scattering of galaxy starlight and CMB should result in TeV emission from the shell at detectable levels.
- Recent HESS detection (Aharonian et al. 2009) consistent with our prediction for $B \sim 7$ μG (Γ also in agreement), but more probable it's associated with inner regions.



Implications of HESS detection

- If the inner-lobe shock only responsible for small fraction of the HESS flux, then tight limits on *B* in shell.
- Implies $B >> 7\ \mu G$, consistent with equipartition fields if $\kappa \sim 100$.
- Consistent with shock behaviour similar to SNR including *B* amplification.
- Important implications for Cen A as a source of UHECRs...



Aharonian et al. 2009

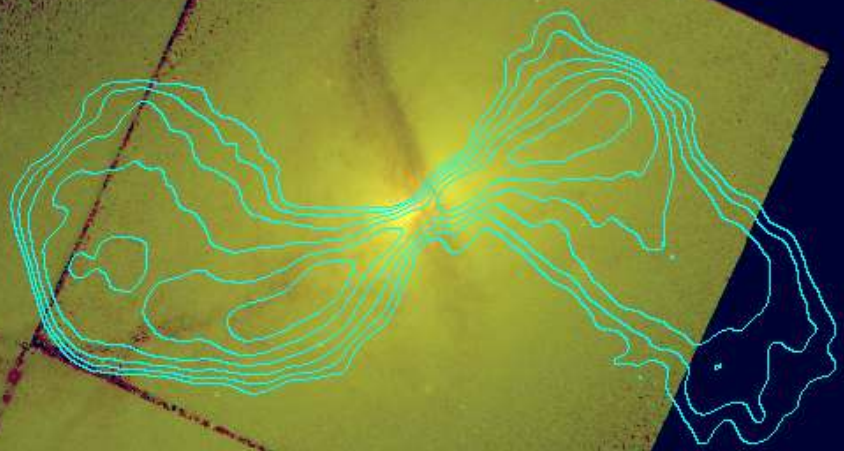
Cosmic rays from the radio-lobe shock?

- Recent results from the Pierre Auger observatory point to nearby AGN, and Cen A in particular, as a source of the highest energy cosmic rays (Abraham et al. 2007, Moskalenko et al. 2008)
- For an acceleration region of ~300pc, and $B \sim 8.5$ μG, typical particle energies won't exceed ~ 2×10^{18} eV
- Postshock B would need to be much higher than equipartition value for the shell to accelerate UHECRs (~350 μG or higher) .
- HESS detection would be consistent with such high B fields.
- If we are indeed observing γ_{max} in the X-ray region, then maximum electron energy is ~ 10^{14} eV; however, if γ_{max} is dominated by losses it could be significantly higher for protons.

Radio-lobe shocks in other galaxies

NGC 3801

- z = 0.0113
- disturbed, isolated elliptical

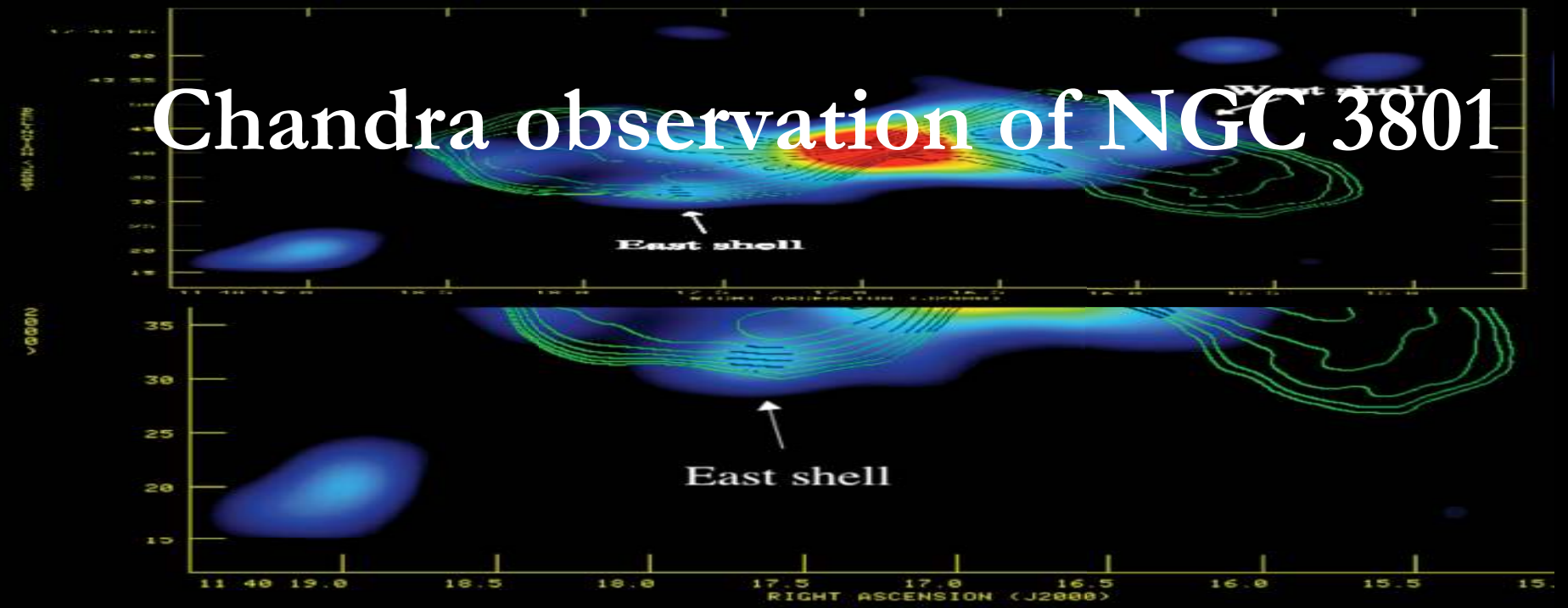


HST F814W (red) & F555W (green): VLA 1.5-GHz contours

- Radio source with very similar morphology to Cen A inner lobes, but no evidence for larger-scale radio structure

- **60-ks *Chandra* observation to look for shocks similar to Cen A**

Chandra observation of NGC 3801



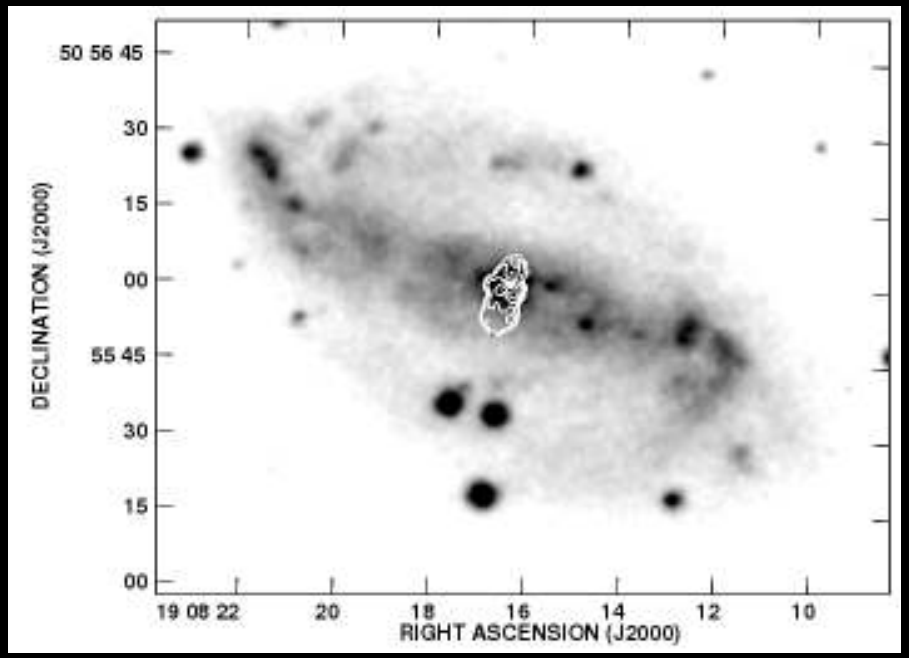
Croston et al. 2007 ApJ, 660, 191

Physical properties of the X-ray shells in NGC 3801

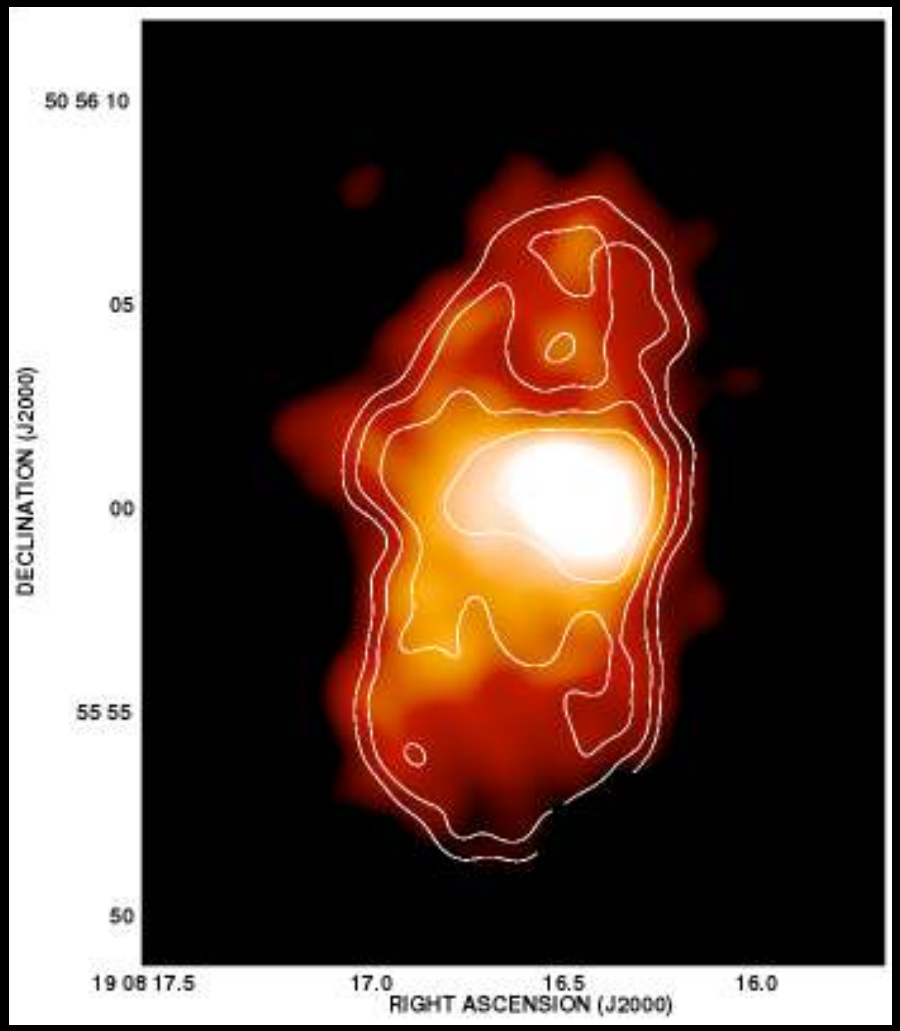
- *Non-thermal model ruled out* (strong Fe L complex).
- Shells have kT = 1.0 keV (W) & 0.7 keV (E); ISM has kT = 0.23 keV
- Density jump consistent with 4, as expected for strong shock.
- Using observed temperature jump, Rankine-Hugoniot conditions give $\mathcal{M}$ = 3.8±1.3 (W) and 3.2 ± 1.0 (E)
- Implies an expansion speed of 600-1200 km s^{-1} => comparable to inner region of Cen A where no particle acceleration observed.
- Total energy in shells, 1.7 x 10^{56} ergs, is equivalent to thermal energy of ISM within 11 kpc (or 25% of thermal energy within 30 kpc) – similar to Cen A energetics.
- A couple of other examples with less good X-ray data: e.g. NGC 1052, B2 0838+32A (Jetha et al. 2008 MNRAS 391 1052)

AGN shock-heating in spirals

- NGC 6764 is a Seyfert with kpc-scale radio synchrotron bubbles (one of ~25 known examples – e.g. Hota & Saikia 2006; Gallimore et al. 2006)
- New Chandra data reveal bubbles of ~ 0.8 keV gas closely matching the radio structure.

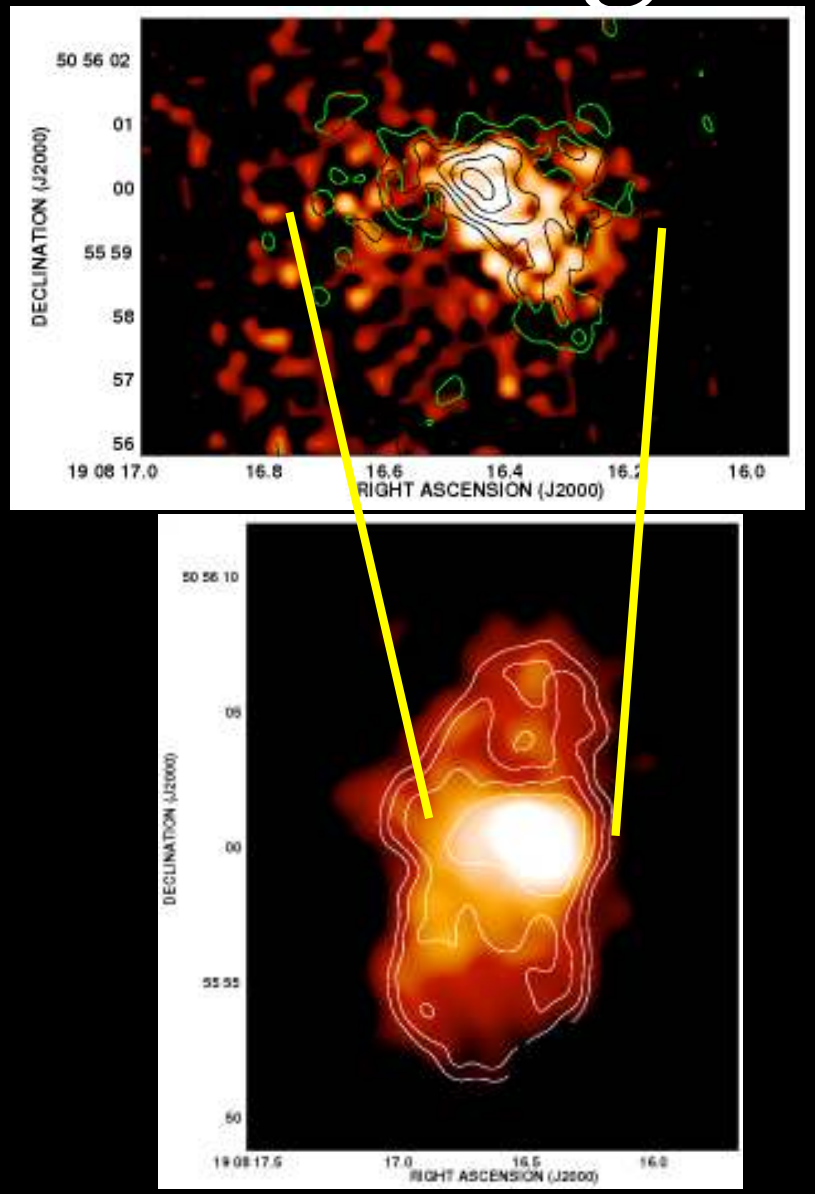


Croston et al. 2008 ApJ 688 190



AGN or starburst heating?

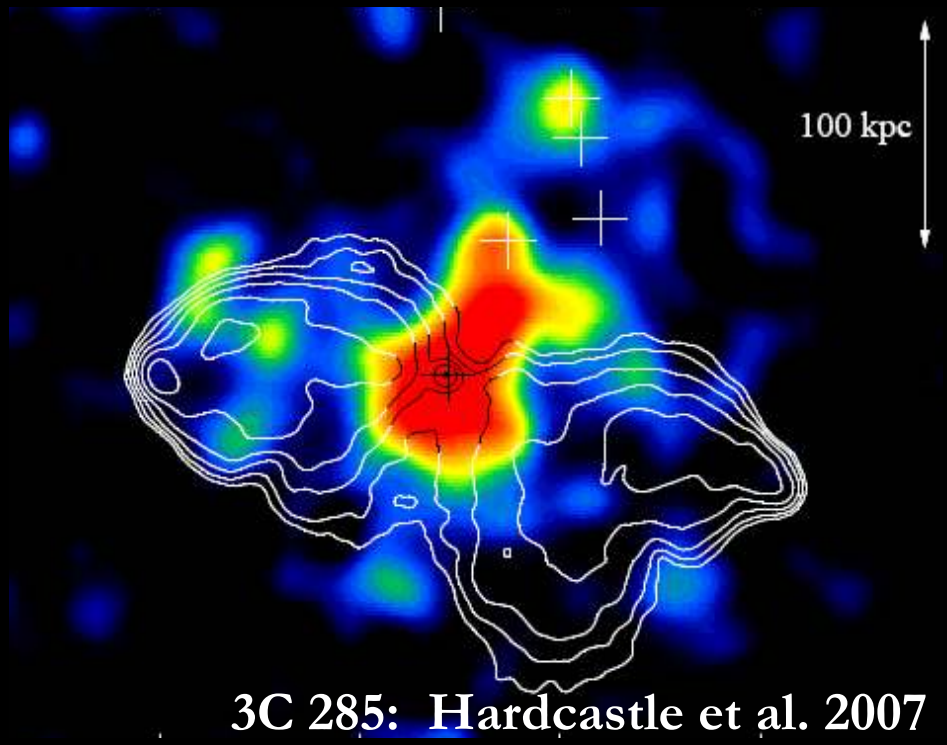
- X-ray bubbles are 2x more luminous than any known starburst wind, while estimated SFR is at least 3x lower.
- Sharp drop in X-ray surface brightness at bubble edges – inconsistent with freely expanding wind.
- E-W radio outflow from AGN associated with brighter X-ray emission from hotter gas.
- Model where disrupted inner jet entrains and shock-heats ISM gas into the kpc-scale bubbles is favoured.
- Some similar Seyferts: NGC 1068 (Young et al. 2001), M51 (Terashima & Wilson 2001), Circinus?
- Energy in bubbles similar to that in NGC 3801 and Cen A (~ 10^{55} erg)



Shocks & particle acceleration in FRIIs

- Self-similar models of FRII lobes (e.g. Kaiser & Alexander 1997) assume strong over-pressuring (Model A of Scheuer et al. 1974) => predict shocked cocoon (e.g. Heinz et al 1998)
- So far only weak shocks found (e.g. Cygnus A: Smith et al. 2002)
- Unlike Cyg A, many nearby FRIIs are in gas-poor environments (e.g. Croston et al. 2004, Kraft et al. 2005, 2007) so may be more highly supersonic.
- Evidence that some FRII lobes are close to pressure balance (Hardcastle et al. 2002, Croston et al. 2004, Belsole et al. 2004, 2007)

Cygnus A: Smith et al. 2002



3C 285: Hardcastle et al. 2007

Should we see X-ray synchrotron shells around FRII lobes?

- If FRIIs have similar shock conditions to Cen A, we might expect to detect X-ray synchrotron shells around them.
- Using nearby FRII 3C 33 as an example, it is plausible for its lobes to expand at similar speed to Cen A, so we assume similar particle acceleration efficiency and

  $n_{CR} \alpha n_{shocked} \alpha n_{ISM}$
- Expected X-ray synchrotron flux should scale as:

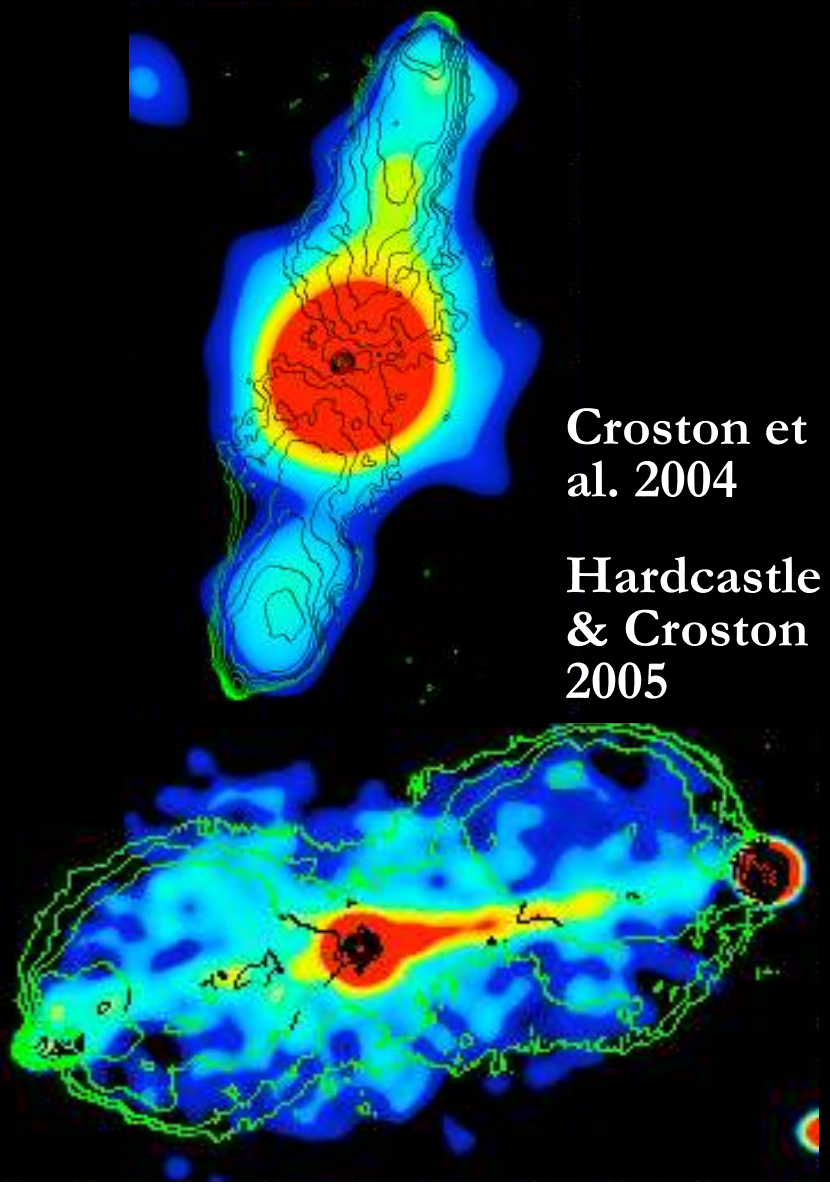
  $$S \propto n_{ism} V D_L^{-2}$$
- $V_{3C33}/V_{CenA} \sim 7500$; $n_{3C33}/n_{CenA} \sim 0.01$; $D_{3C33}/D_{CenA} \sim 72$,

  => predicts a shell flux a factor ~70 lower than Cen A,

  ~ 1 nJy

Should we see X-ray synchrotron shells around FRII lobes?

- Expected flux levels are a significant fraction of those from lobe IC/CMB (e.g. Croston et al. 2005 ApJ 626 733).
- No evidence for edge-brightening in FRIIs & spectral indices flatter than Cen A ($\Gamma = 1.5 - 1.7$) so lobe IC/CMB must dominate
- 3C 33 is relatively nearby – predicted X-ray synchrotron flux drops as distance squared, whereas lobe IC/CMB predictions don't, so will be difficult to constrain this process except in the nearest FRIIs.

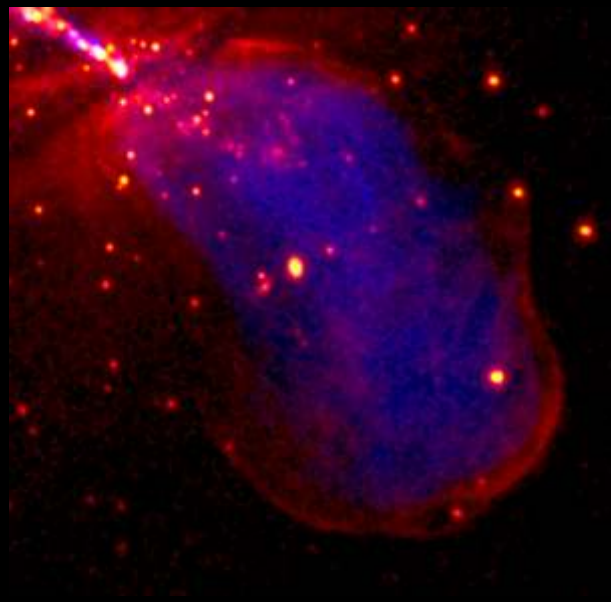


Croston et al. 2004

Hardcastle & Croston 2005

Summary

- The inner radio-lobe shock in Cen A is accelerating particles to X-ray emitting energies, with shock properties similar to SNR such as SN1006.
- Significant magnetic field amplification may be occurring.
- *B* appears too low for the shock to accelerate UHECRs: the outer lobes may be a more plausible origin for the PAO events.
- TeV emission from IC scattering by the shell electrons is predicted; level is consistent with recent HESS detection – if only a fraction of the HESS flux comes from the shell this places tight constraints on *B*.
- Radio-galaxy shocks, now seen in a few other galaxies (including spirals!) can inject the energy of ~1 million SNe, and will have a long-term impact on the host galaxy ISM – given their short lifetimes, such episodes could be common in massive galaxies.
- Particle acceleration at radio-lobe shocks could occur in powerful FRIIs, but X-ray synchrotron shells difficult to detect beyond modest redshifts.
- Details of Cen A shock results in Croston et al. 2009 MNRAS 395 1999



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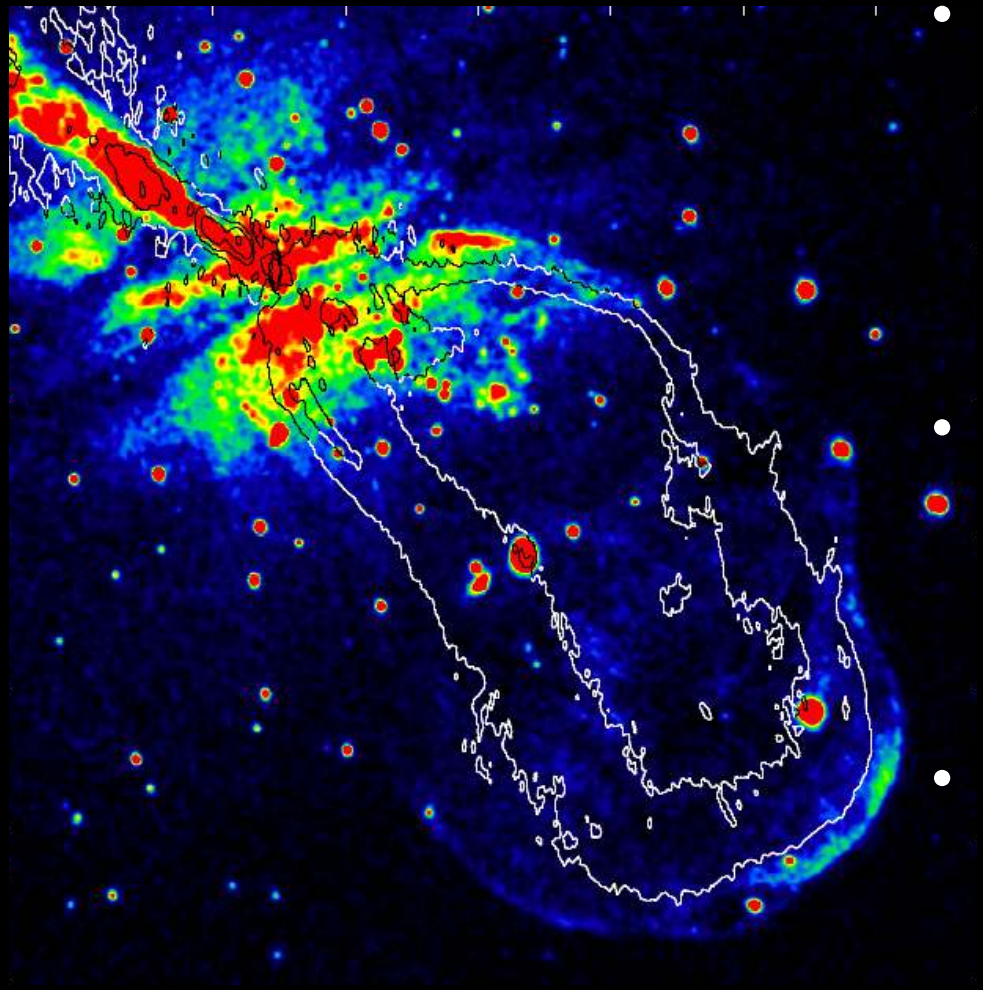
Dan Evans
Preeti Kharb
Ananda Hota
the Cen A ChandraVLP collaboration

Magnetic field strength constraints



- The shock front appears resolved in the Chandra data, so its width can be used to determine B, assuming synchrotron losses dominate
- Using method of Vink & Laming (2003), we find synchrotron lifetimes of $\sim 5 \times 10^4$ y => $B \sim 1$ μG.
- Consistent with equipartition calculations (B < 8.5 μG for κ=1) & consistent with expectation from compression of the ISM if $B_{ISM} \sim 0.1 - 1$μG.

Electron-proton equilibriation

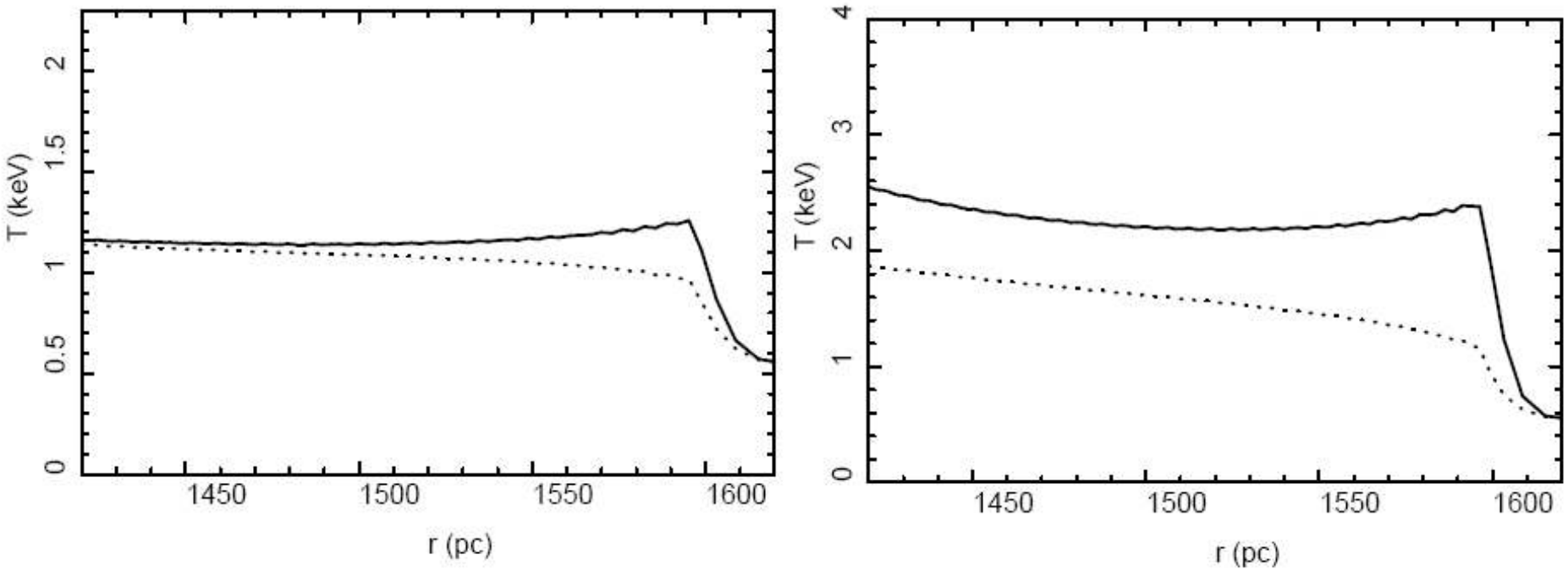
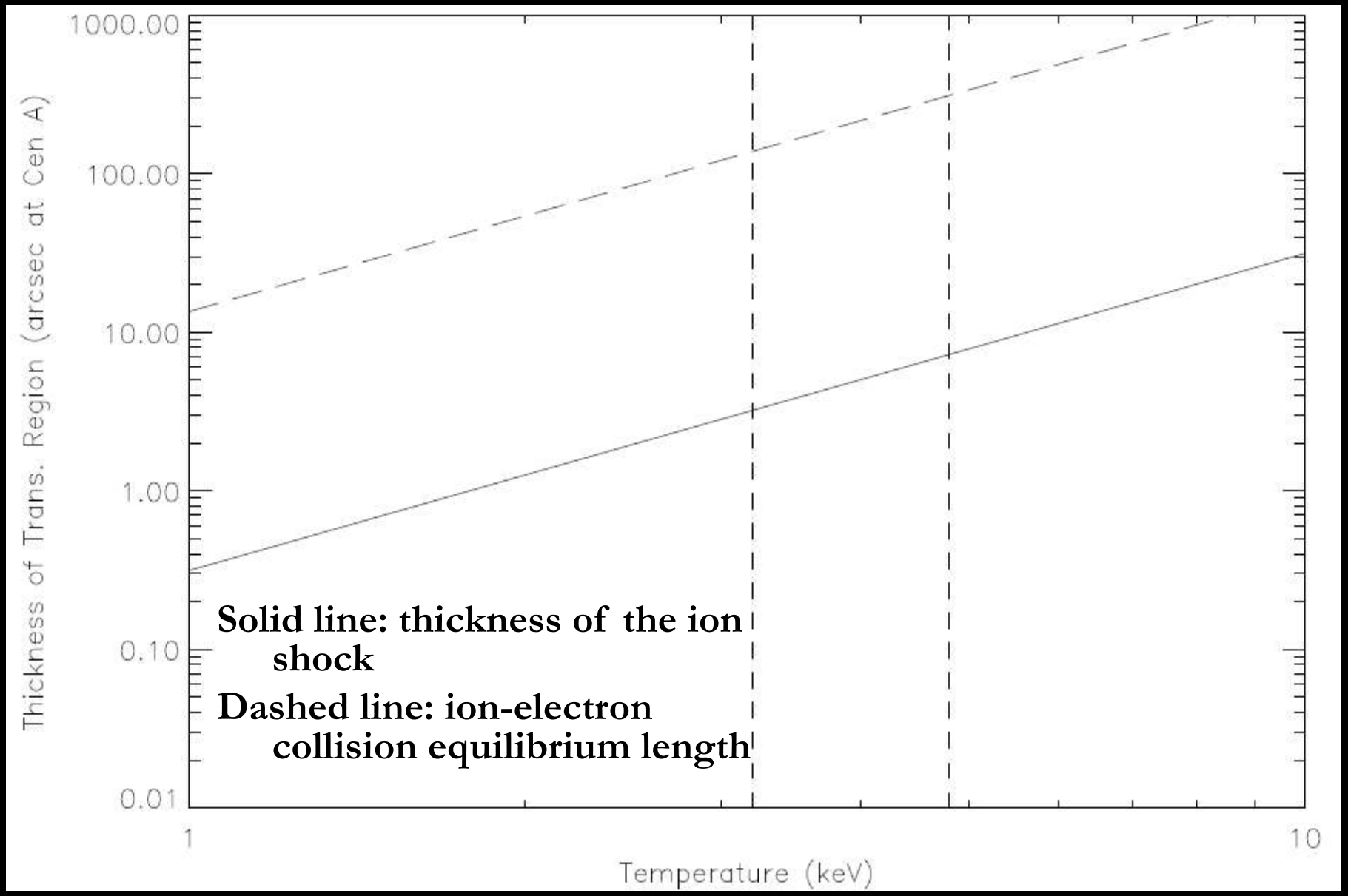


Fig. 7.— Post-shock proton temperature (solid line) and electron temperature (dotted line) profiles obtained from our two-fluid hydrodynamical modelling (§ 4.4) for $kT = 1$ keV (left) and $kT = 1.4$ keV (right).



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Spectra for the shell region

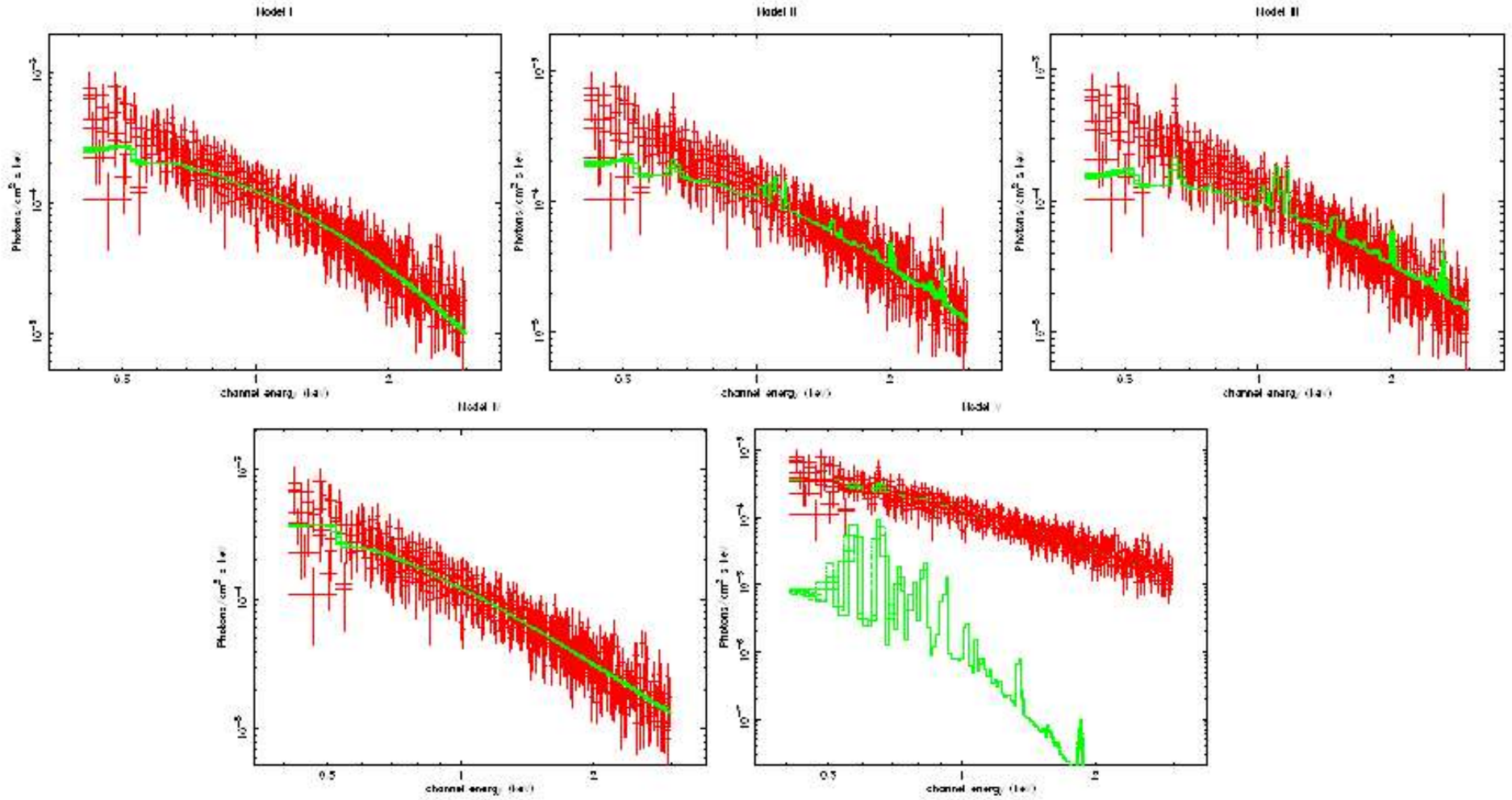

Fig. 4.— Spectral fits for Region 1. Clockwise from top left: Model I (free-abundance *apec*), Model II (*apec* with $Z = 0.15Z_{\odot}$), Model III (*apec* with $Z = 0.5Z_{\odot}$, Model V (power law + *apec*), and Model IV (power law).

Shell spectra (2)

Model		Parameter	Region 1	Region 2	Region 3
Model I:	*apec* (free abundance)	kT (keV)	$1.60^{+0.07}_{-0.06}$	$2.03^{+0.24}_{-0.14}$	$0.91^{+0.04}_{-0.04}$
		Z ($Z_\odot$)	< 0.007	< 0.05	$0.17^{+0.05}_{-0.04}$
		χ^2 (d.o.f.)	1010 (743)	344 (308)	137 (97)
Model II:	*apec* (fixed abundance)	kT (keV)	$2.22^{+0.08}_{-0.06}$	$2.59^{+0.13}_{-0.13}$	$0.90^{+0.03}_{-0.02}$
		Z ($Z_\odot$)	0.15	0.15	0.15
		χ^2 (d.o.f.)	1213 (744)	377 (309)	138 (98)
Model III:	*apec* (fixed abundance)	kT (keV)	$3.26^{+0.09}_{-0.09}$	$3.58^{+0.24}_{-0.19}$	$0.97^{+0.01}_{-0.02}$
		Z ($Z_\odot$)	0.5	0.5	0.5
		χ^2 (d.o.f.)	1478 (744)	437 (309)	177 (98)
Model IV:	*power law*	Γ	$2.20^{+0.02}_{-0.02}$	$2.01^{+0.04}_{-0.03}$	$2.54^{+0.05}_{-0.05}$
		χ^2 (d.o.f.)	931 (744)	333 (309)	445 (98)
Model V:	*apec* + *power law*	kT (keV)	$0.23^{+0.09}_{-0.08}$	0.93^{a}	$0.89^{+0.05}_{-0.06}$
		Z ($Z_\odot$)	0.5	0.5	0.5
		Γ	$2.15^{+0.06}_{-0.05}$	$2.00^{+0.15}_{-0.06}$	$2.13^{+0.30}_{-0.27}$
		χ^2 (d.o.f.)	928 (742)	332 (307)	141 (96)