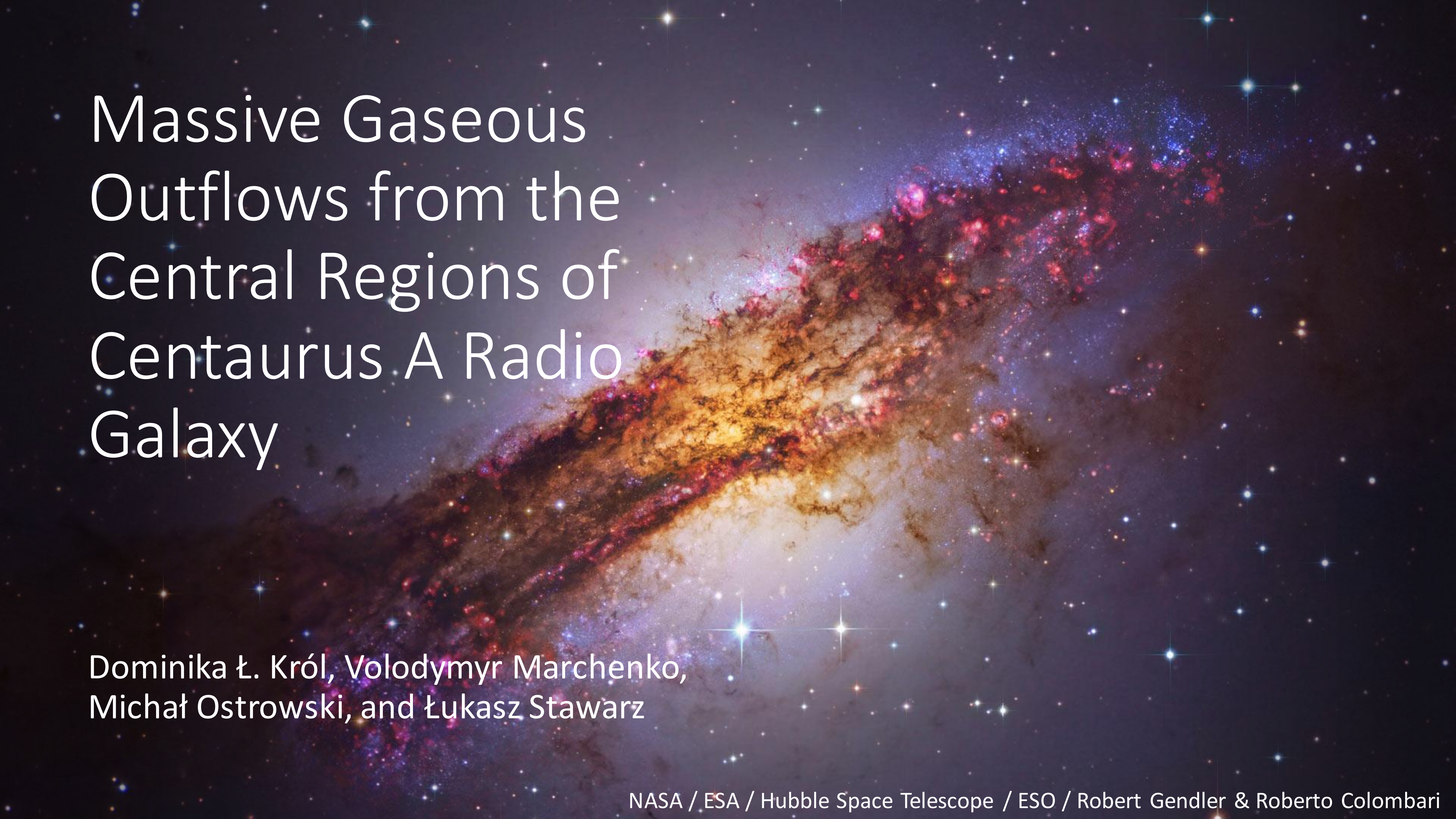
Massive Gaseous Outflows from the Central Regions of Centaurus A Radio Galaxy

Dominika Ł. Król, Volodymyr Marchenko, Michał Ostrowski, and Łukasz Stawarz



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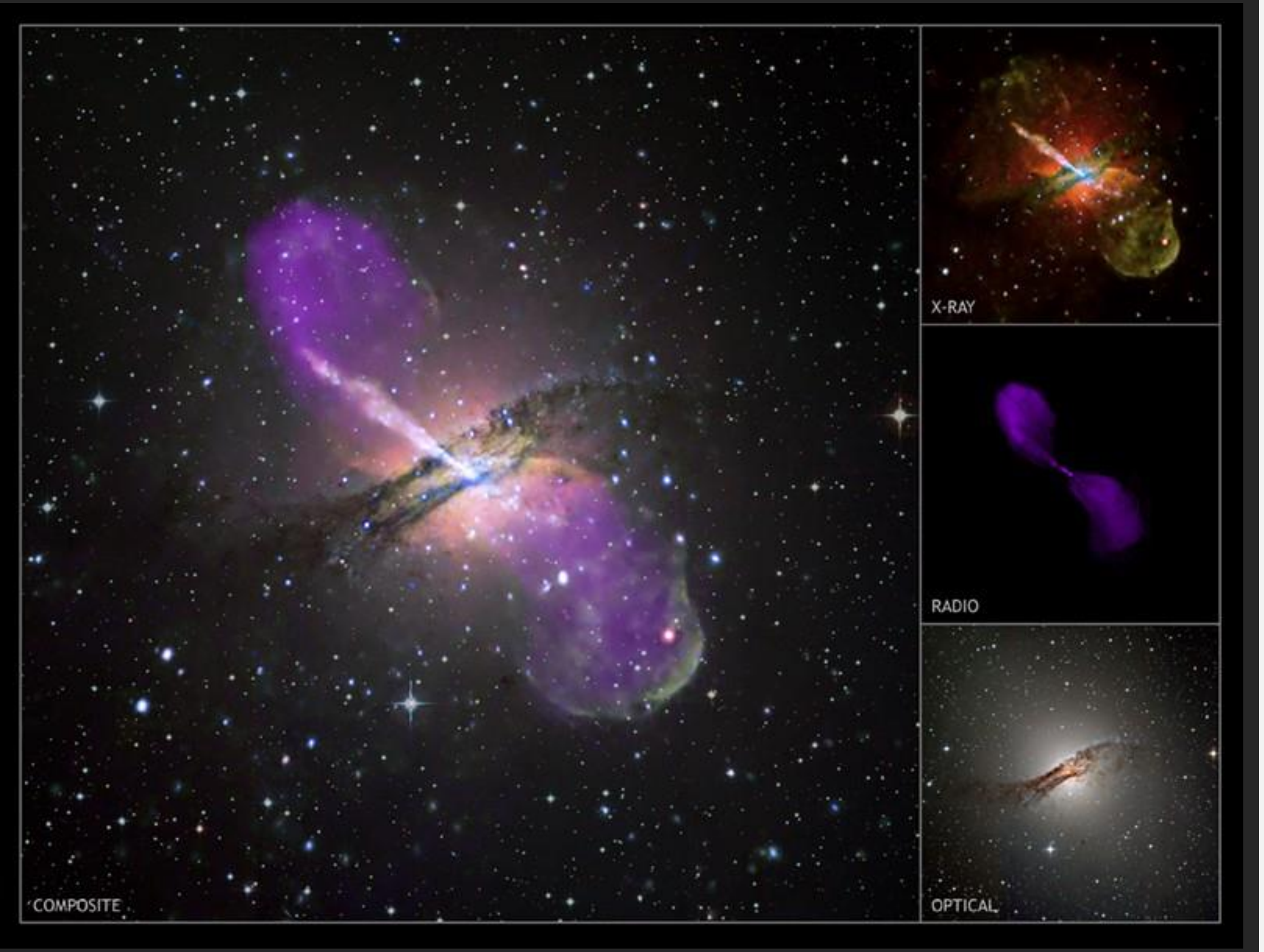
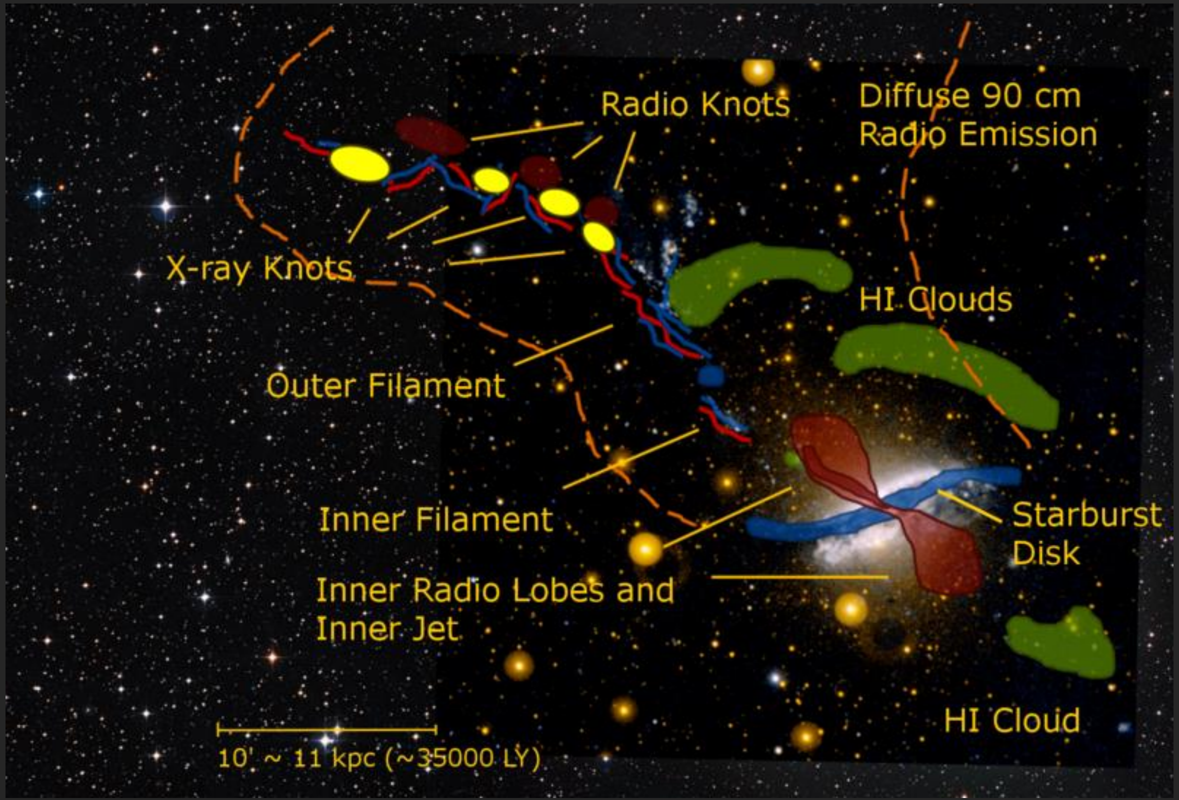
Centaurus A



APOD: X-ray - NASA, CXC, R.Kraft (CfA), et al.;
Radio - NSF, VLA, M.Hardcastle et al.; Optical - M.Rejkuba (ESO-Garching) et al.

- AGN hosted by a NGC 5128
- Located at the distance of 3.85+- 0.35 Mpc
- NGC 5128 is an elliptical galaxy with a dust lane and other distinct morphological features indicating multiple mergers about 200-700 Myrs ago (Israel 1998; Morganti 2010).
- Complex radio morphology consisting of giant radio lobes and inner young radio structure, indicative of a recurrent jet activity

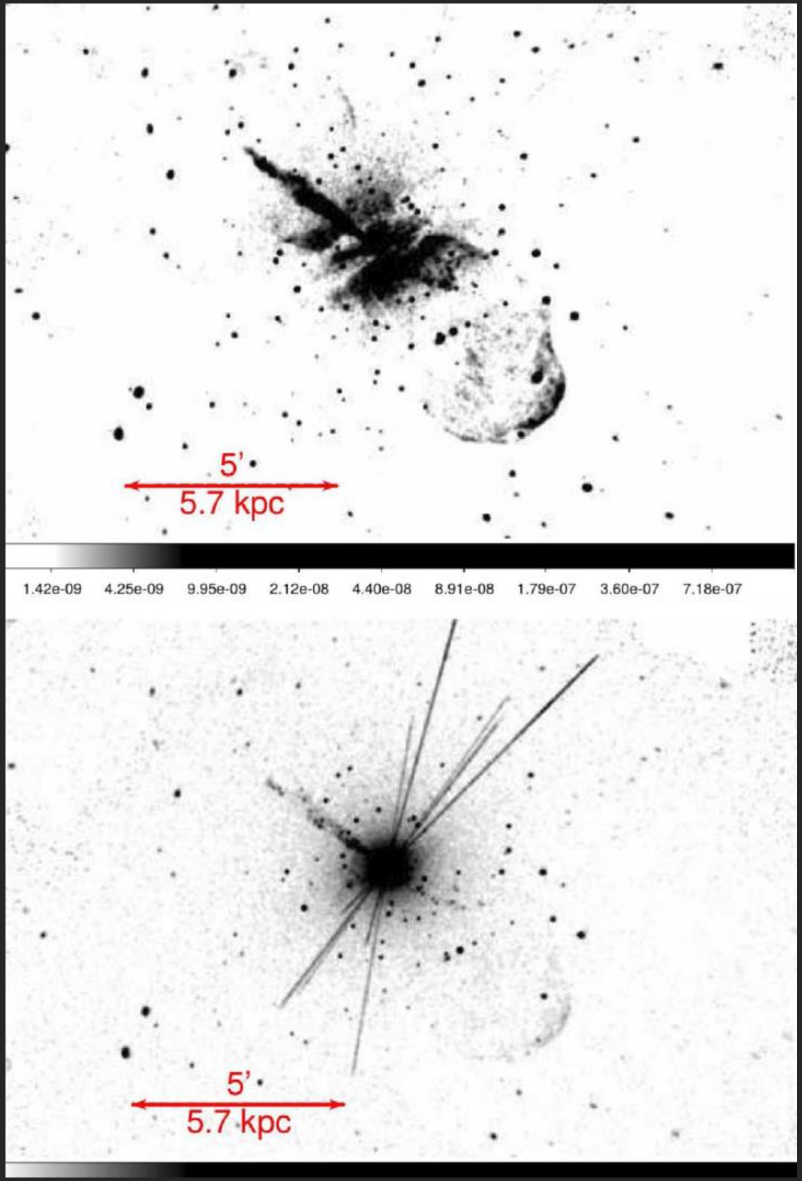
Motivation



https://commons.wikimedia.org/wiki/File:StuctureCenA-EN.png

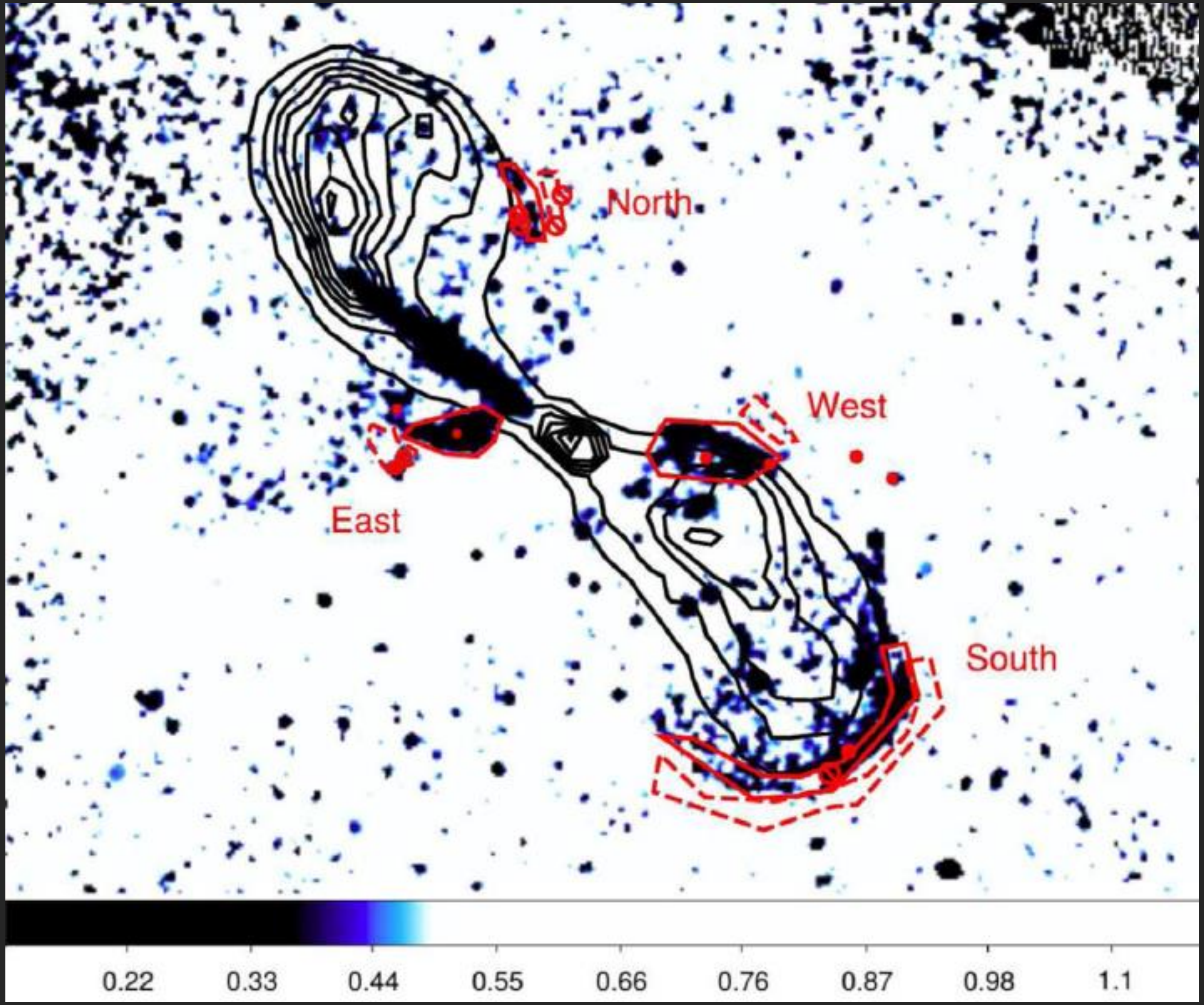
- Cen A is known for a displaying various signatures of an interaction of "northern middle lobe" (tens to several kpc to the North from the nucleus) with ISM e.g.: complex net of op-tical filaments of ionized gas, clouds of atomic gas with anomalous velocities, young stars, and large-scale X-ray filaments composed of discrete knots (Morganti et al. 1999; Oosterloo & Morganti2005; Kraft et al. 2009; Crockett et al. 2012; Neff et al.2015; Salom´e et al. 2016)
- Our goal is to examine occurrence of similar interactions on the smaller scales (namely kpcs distance form the nucleus) driven by a small-scale radio structure and young inner jet.

Analysed data



- Data merged from 6 archival observations made by Chandra (ObsIDs: 316, 962, 2978, 3965, 8489, and 8490).
- Upper panel shows 0.4-2.5 keV energy range.
  - Soft X-ray emission from kpcs central region with the "hourglass" appearance and jet.
  - Bow-shock structure at the edges of a radio lobes.
- Lower panel shows 2.7-8.0 keV energy range.
  - Jet and nucleus are prominent.
  - Southern bow-shock structure.

Regions chosen for spectral analysis



Smoothed hardness ratio map with imposed radio contours at 21 cm (Condon et al.) with ragions of spectra extraction

For spectral analysis we chosen regions which are characterized by an excess of soft emission.

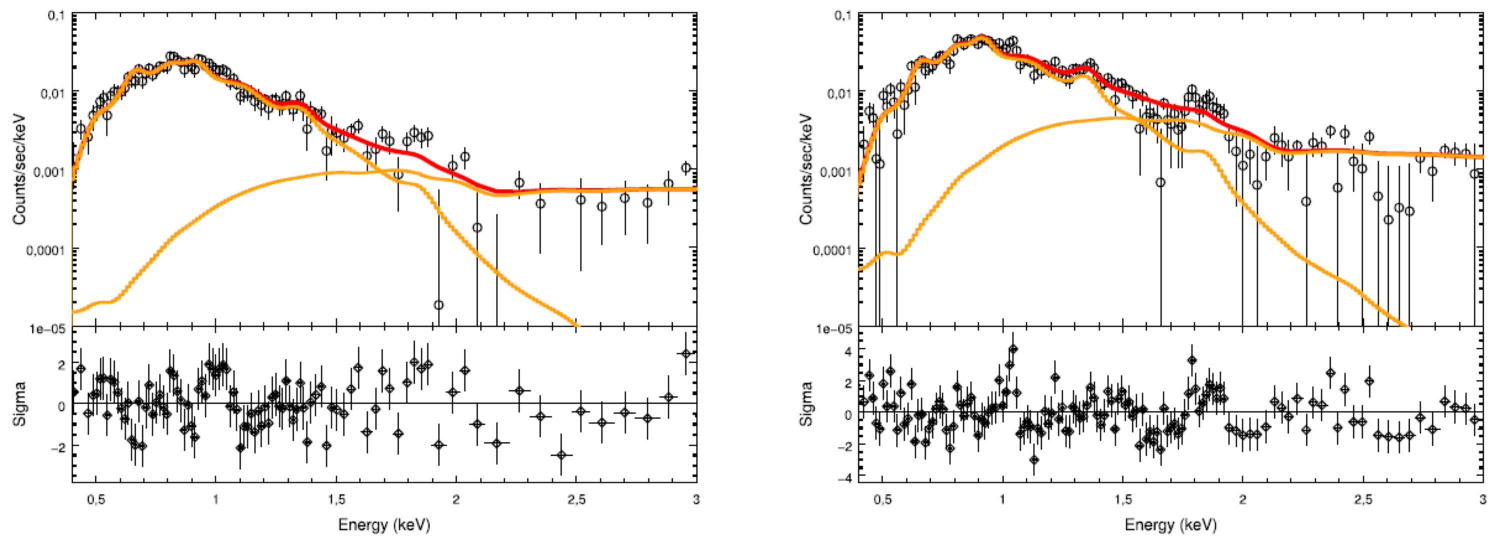
- East and West – symmetrical cone-like structures inclined at 35 deg with respect to the jet
- North arc which is on the edge of a radio lobe
- Sothern arc which is on the edge of a radio lobe

South region was previously analyzed by Croston et al., also part of the West structure was analyzed by Kraft et al.

Best fit parameters

East and West

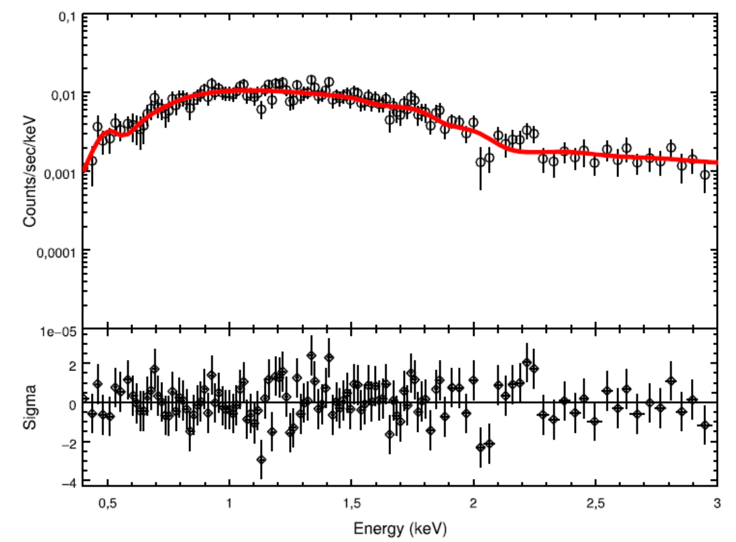
Region/Model	Parameter	Value	1σ Errors	Units
East	kT	0.23	0.01	keV
xsphabs*(xsapec+xspowerlaw)	norm	0.4	0.1	10^{-2} × apec
	Abundanc	0.09	0.03	…
	Γ	0.24	0.66	…
	ampl	2.5	1.5	$10^{-6} \times$ ph keV^{-1} cm^{-2} at 1 keV
	N_H	0.40	0.04	10^{22} cm^{-2}
	Final fit statistic	125.33		
	Degrees of freedom	92		
West	kT	0.19	0.01	keV
xsphabs*(xsapec+xspowerlaw)	norm	1.9	0.7	10^{-2} × apec
	Abundanc	0.20	0.09	…
	Γ	1.75	0.28	…
	ampl	32.1	7.1	$10^{-6} \times$ ph keV^{-1} cm^{-2} at 1 keV
	N_H	0.65	0.03	10^{22} cm^{-2}
	Final fit statistic	208.34		
	Degrees of freedom	128		

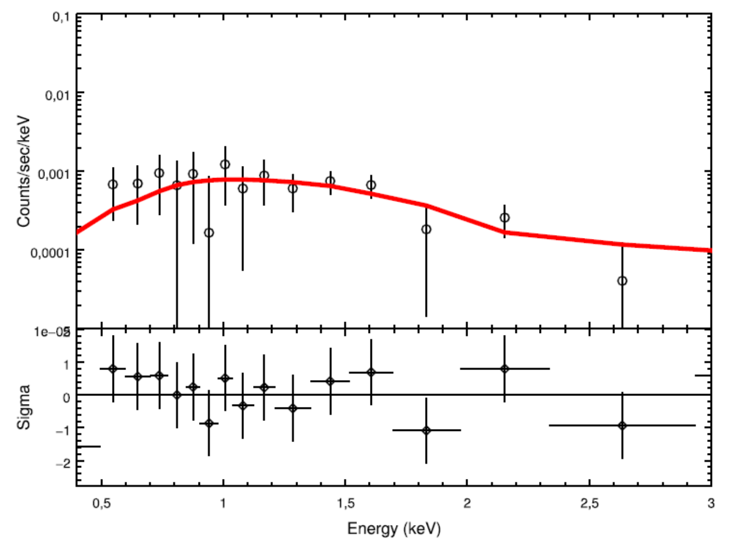


Best fit parameters

South and North

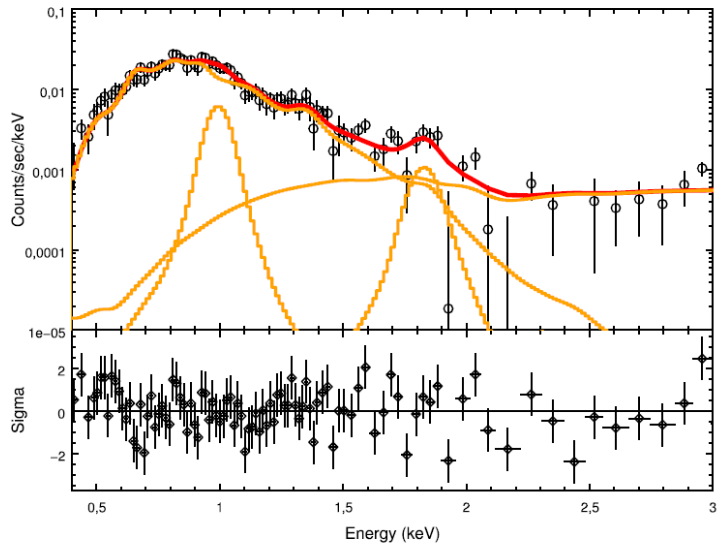
Region/Model	Parameter	Value	1σ Errors	Units
South	Γ	2.14	0.13	…
xsphabs*xspowerlaw	ampl	46.4	4.2	$10^{-6} \times$ ph keV^{-1} cm^{-2} at 1 keV
	N_{H}	0.026	$^{+0.030}_{-}$	10^{22} cm^{-2}
	Final fit statistic	104.49		
	Degrees of freedom	121		
North	Γ	2.02	0.43	…
xspowerlaw	ampl	3.0	0.65	$10^{-6} \times$ ph keV^{-1} cm^{-2} at 1 keV
	Final fit statistic	8.82		
	Degrees of freedom	15		

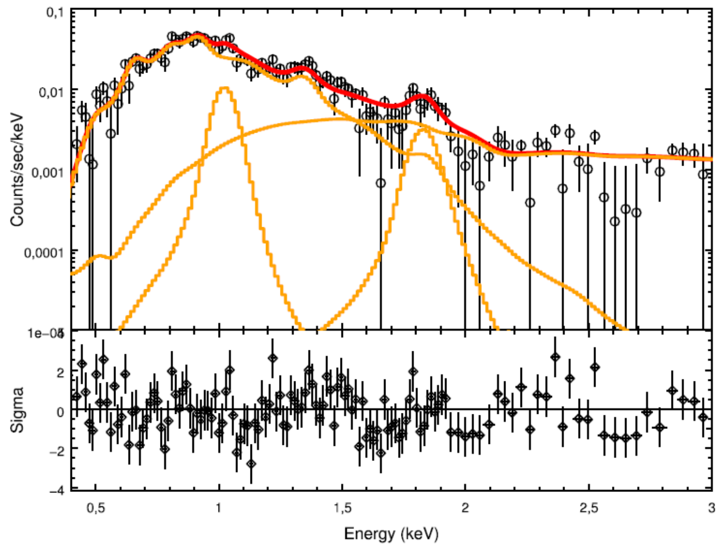




Best fit parameters

Region/Model	Parameter	Value	1σ Errors	Units
East	kT	0.22	0.01	keV
xsphabs*(xsapec+xspowerlaw	norm	0.4	0.2	$10^{-2} \times$ apec
+ xsgaussian1+ xsgaussian2)	Γ	0.25	0.74	...
	ampl	2.4	1.65	$10^{-6} \times$ ph keV^{-1} cm^{-2} at 1 keV
	Line 1 position	1.0	...	keV
	Line 1 normalization	7.6	1.6	$10^{-6} \times$ ph cm^{-2} s^{-1}
	Line 2 position	1.83	0.03	keV
	Line 2 normalization	0.42	0.21	$10^{-6} \times$ ph cm^{-2} s^{-1}
	N_H	0.42	0.03	10^{22} cm^{-2}
	Final fit statistic	99.55		
	Degrees of freedom	89		
West	kT	0.19	0.01	keV
xsphabs*(xsapec+xspowerlaw	norm	0.4	0.2	$10^{-2} \times$ apec
+ xsgaussian1+ xsgaussian2)	Γ	1.75	0.32	...
	ampl	30.2	7.7	$10^{-6} \times$ ph keV^{-1} cm^{-2} at 1 keV
	Line 1 position	1.02	...	keV
	Line 1 normalization	17.1	3.4	$10^{-6} \times$ ph cm^{-2} s^{-1}
	Line 2 position	1.83	0.02	keV
	Line 2 normalization	1.2	0.3	$10^{-6} \times$ ph cm^{-2} s^{-1}
	N_H	0.42	0.03	10^{22} cm^{-2}
	Final fit statistic	99.55		
	Degrees of freedom	89		





East and West

Goodness of the fit can be improved by adding two lines to the model.

Fitted lines positions reflect following elements:

- At ~1keV hydrogen-like Ne Lyα line, or the iron L-shell blend
- At ~1.85 keV Si XIII blend

Fitted lines are the same for East and West regions.

Summary of the fit parameters

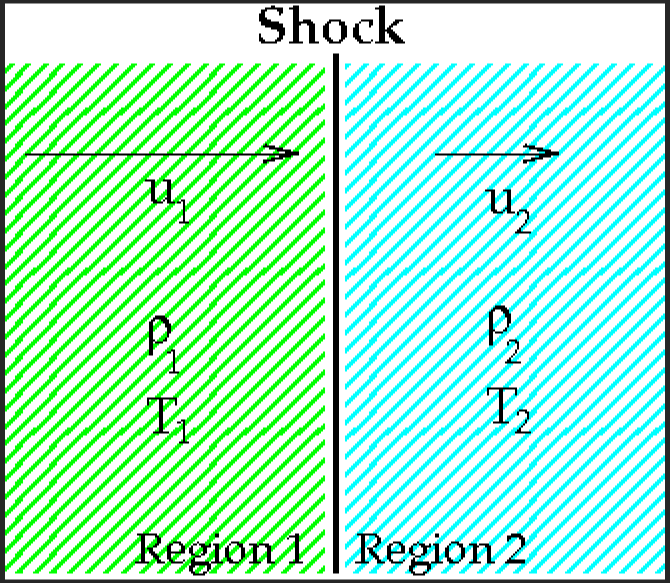
Model		Parameter	Region 1	Region 2	Region 3
Model IV:	power law	Γ	$2.20^{+0.02}_{-0.02}$	$2.01^{+0.04}_{-0.03}$	$2.54^{+0.05}_{-0.05}$
		χ^2 (d.o.f.)	931 (744)	333 (309)	445 (98)

Corresponding to the South region

Croston et al. 2009

- East region which not coincide with radio lobe is fitted with a plasma of kT~0.2 keV and abundance ~0.1 and very flat not well-constrained power-law of a low amplitude which can be connected to energy-dependant PSF wings from heavily piled-up core (Mingo et al. (2011) and Hardcastle et al. (2016)).
- In West region which is within the radio lobe we see plasma of the same abundance and temperature and the power-law emission with steep slope ~1.75(28) and high amplitude
- South region is characterized by a power-law emission with 2.14(13) index
- North region best fit model is power-law with a index 2.02(43).
- South, North and West power-law indexes imply that the efficiency of the electron acceleration at the termination shock front does not vary dramatically over the inner lobes extension

East and West structures origin



$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} \approx \frac{\gamma+1}{\gamma-1} = 4$$

$$T_2 \approx \frac{3}{16}\frac{m}{k}u_1^2$$

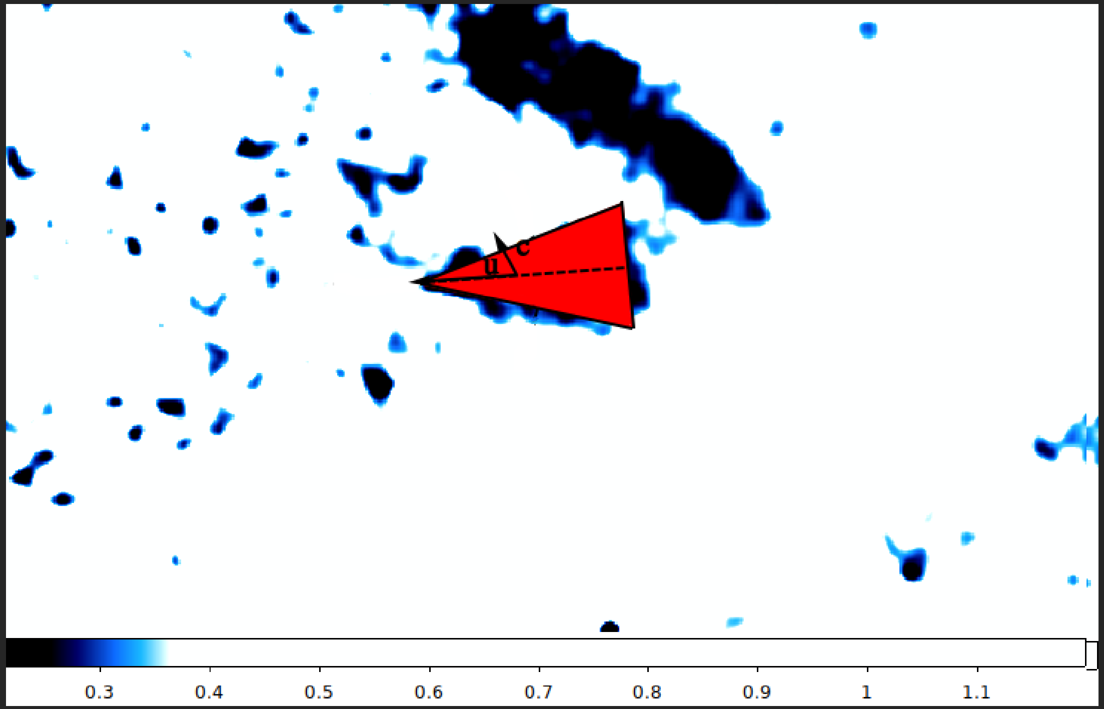
Shock scenarios

Physical parameters of the gas in the West and East structures are following: $n \sim 0.3 cm^{-3}$, $kT \sim 0.2$ keV

ISM at corresponding distances from the nucleus: $n \sim 0.01 cm^{-3}$, $kT \sim 0.35$keV(Kraft et al. 2003)

- "Clasical" strong shock can be ruled out due to the density of the gas in the structure which is ~30 times higher than in the ISM. Moreover, temperature is almost the same
- Isothermal radiative shock:
    - When the gas cooling in the downstream is sufficiently fast narrow relaxation layer can be formed and density contrast can be than arbitrary high.
    - BUT in our case the cooling immediately behind the shock to the f-f and line emission is not sufficiently fast

East and West structures origin



Ejections of dense plasmoids

- Matter which is an ejected dense plasmoid with super-sonic velocity
  - Such a ejection derive pressure waves which merge at the Mach cone into a sonic boom propagating within ISM – what is aligned with morphologies of the structures
  - Measuring roughly the opening angles of the cones we obtained Mach number ~3-5, which gives ejection velocities around 600-1000 km/s.
  - Timescale given by the ejection velocity is similar to the timescale of the formation of inner jet and lobes at Cen A and is smaller than calculated cooling time

Thank You for Your attention!

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