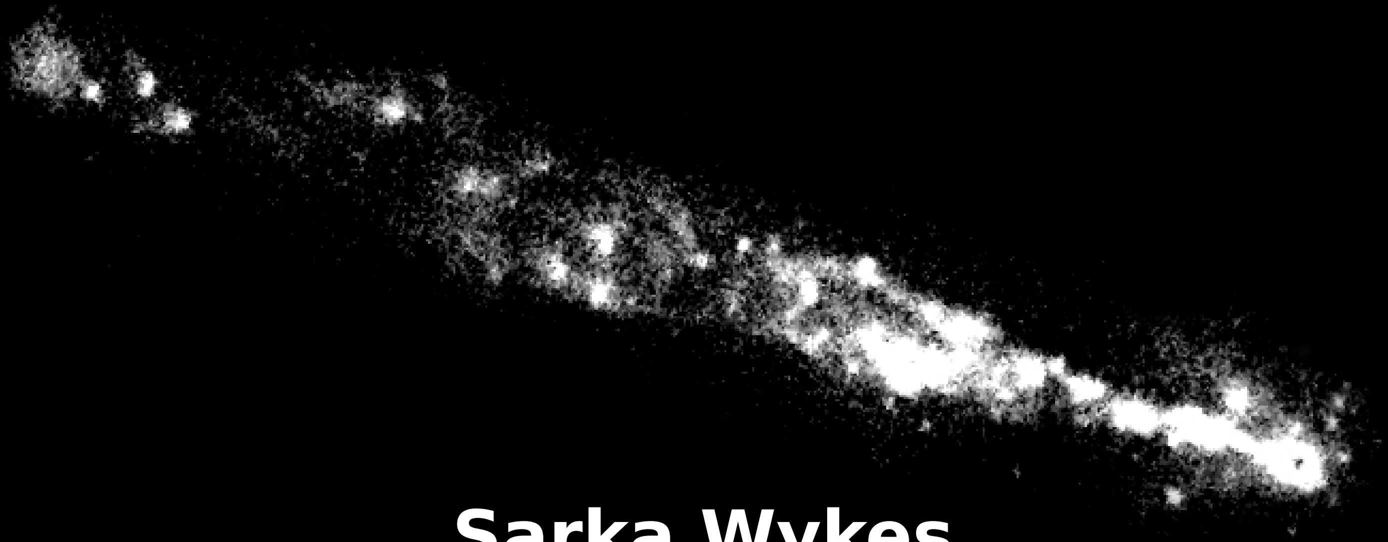
Probing jet composition in Centaurus A



Sarka Wykes
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Bangalore, 16th October 2015

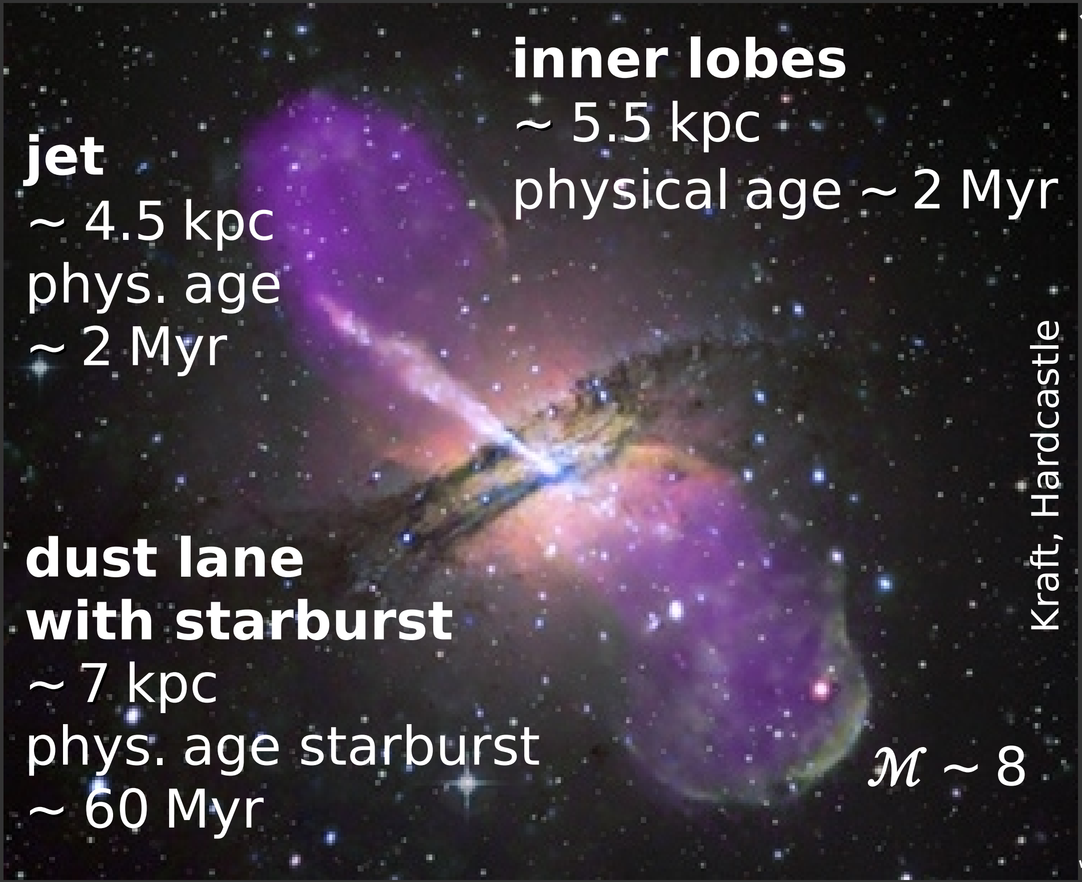
Motivation

Matter content of extragalactic jets poorly known

- Inferring composition at kiloparsec scales:
  - power carried by the jets and their impact on surrounding intracluster/intragroup gas
  - isotopes available for particle acceleration in jets/lobes
- Inferring composition at subparsec scales:
  - jet-launching mechanism

Relevant publications

- Wykes et al., 2013, A&A, 558, A19
- Wykes et al., 2015a, MNRAS, 447, 1005
- Wykes et al., 2015c,d, in preparation



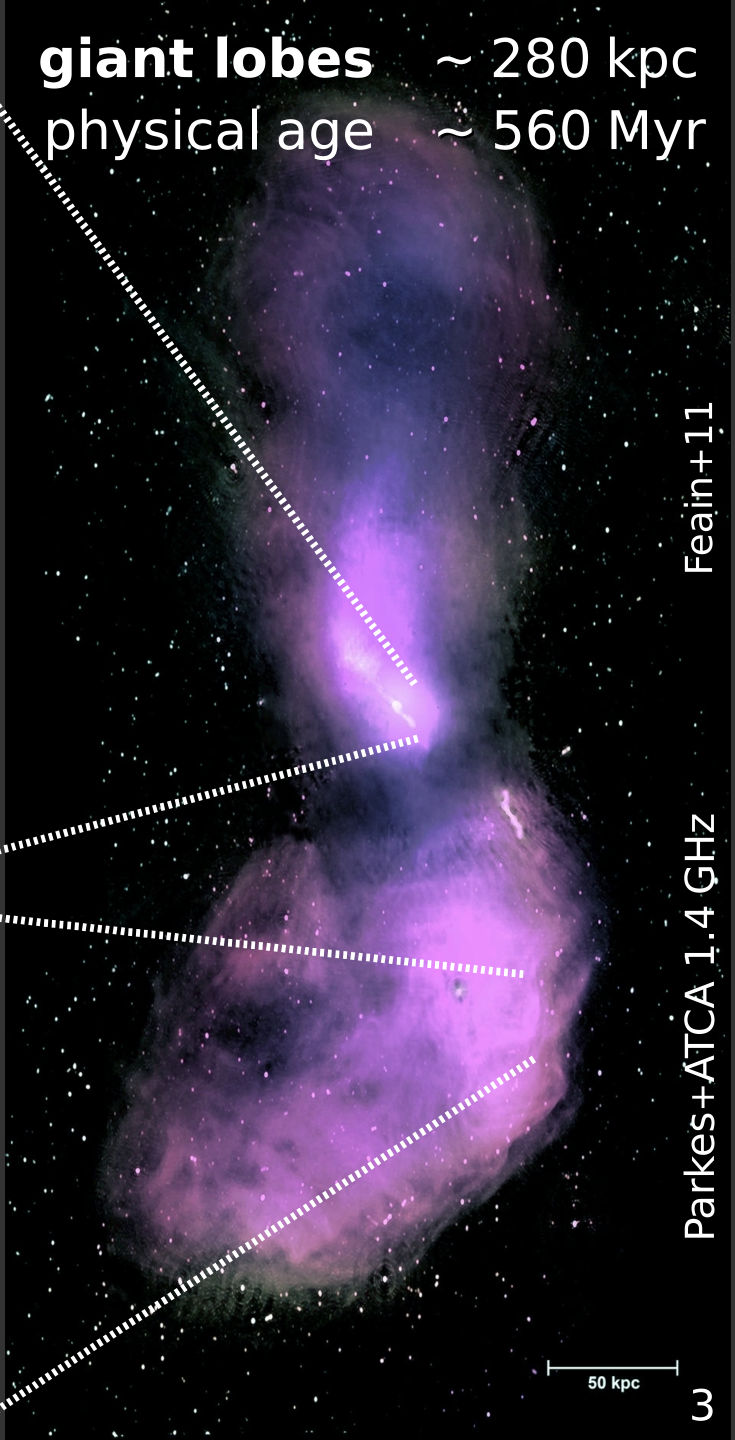
jet
~ 4.5 kpc
phys. age
~ 2 Myr

inner lobes
~ 5.5 kpc
physical age ~ 2 Myr

dust lane
with starburst
~ 7 kpc
phys. age starburst
~ 60 Myr

$\mathcal{M} \sim 8$

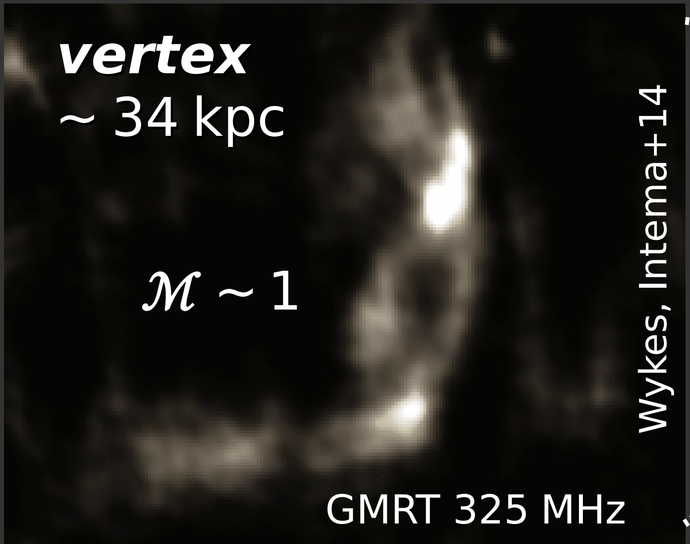
Kraft, Hardcastle



giant lobes ~ 280 kpc
physical age ~ 560 Myr

Feain+11

Parkes+ATCA 1.4 GHz



vertex
~ 34 kpc

$\mathcal{M} \sim 1$

Wykes, Intema+14

GMRT 325 MHz

- Jet embedded in inner lobes, or 'naked'?
- Inner lobes embedded in giant lobes?

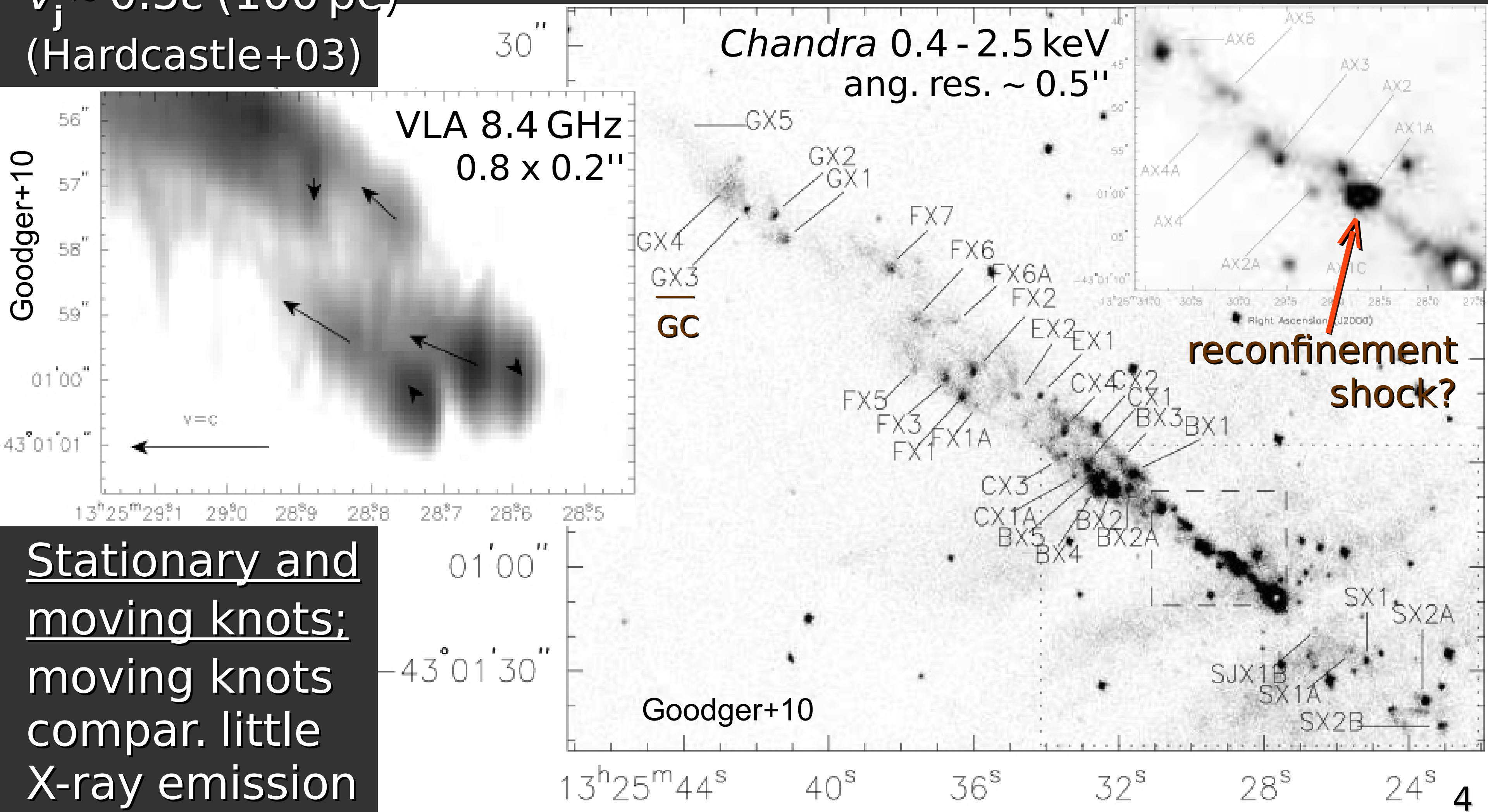
Kpc jet in radio and X-ray

$P_j \sim 1 \times 10^{43}$ erg s^{-1} (current jet)
$P_j \sim 1 - 5 \times 10^{43}$ erg s^{-1} (pre-existing)
(Wykes+13; Neff+15)

Centaurus A: strong case of dominant X-ray synchrotron

L_X (diffuse+knot emission) $\sim 1.1 \times 10^{39}$ erg s^{-1}

$v_j \sim 0.5c$ (100 pc)
(Hardcastle+03)

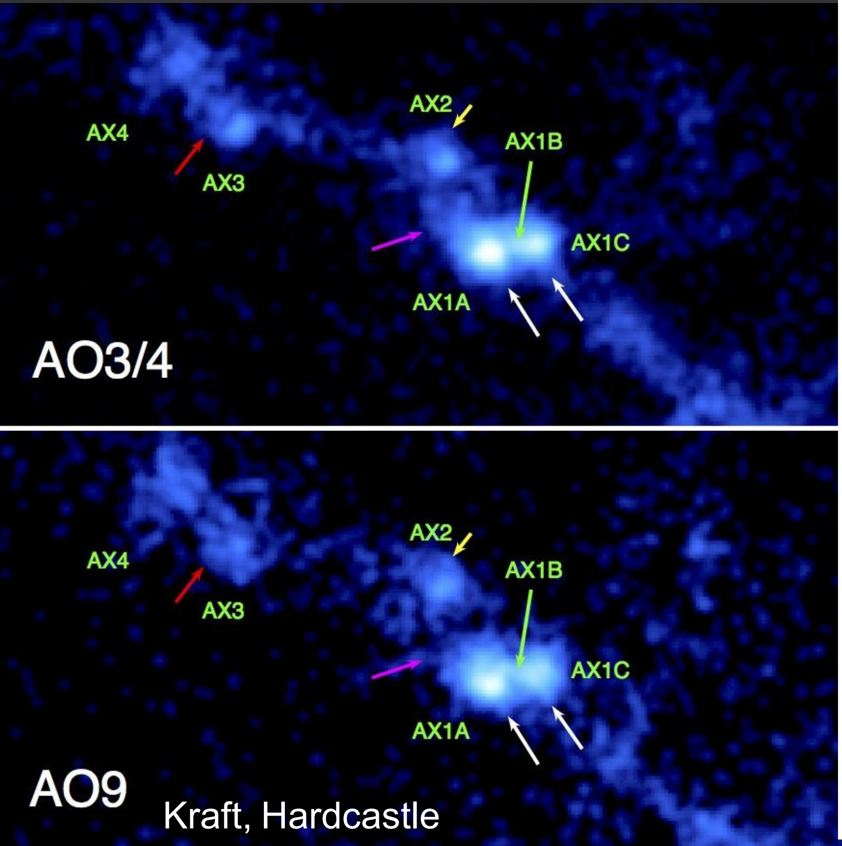


reconfinement shock?

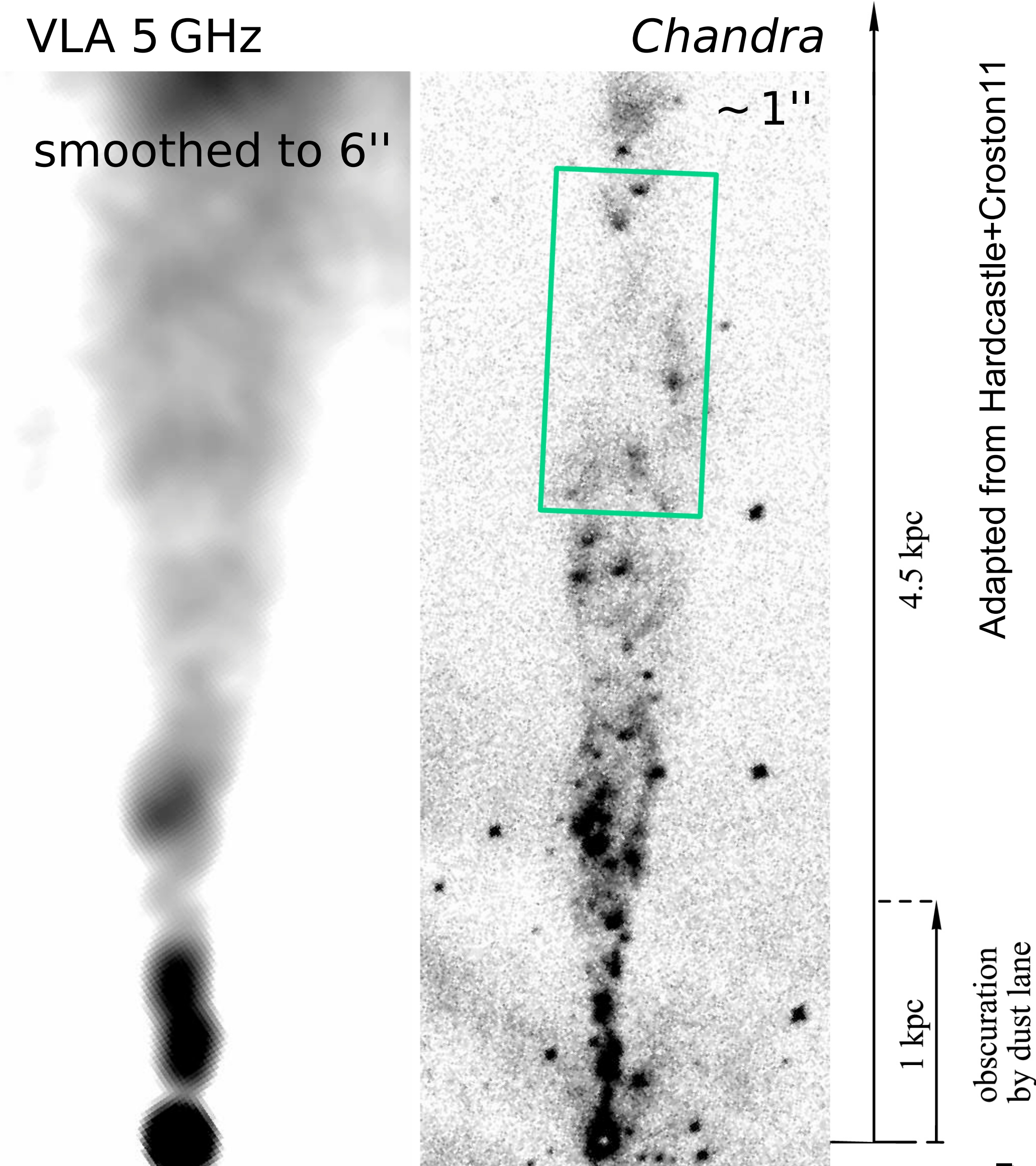
Stationary and moving knots;
moving knots compar. little X-ray emission

Kpc jet in radio and X-ray

- Knottiness of X-ray jet: support for model with discrete interaction sites
- Possible obstacles in jet:
  - stars, planetary nebulae
  - gas/molecular clouds



Kraft, Hardcastle



Adapted from Hardcastle+Croston11

Subparsec jet in radio

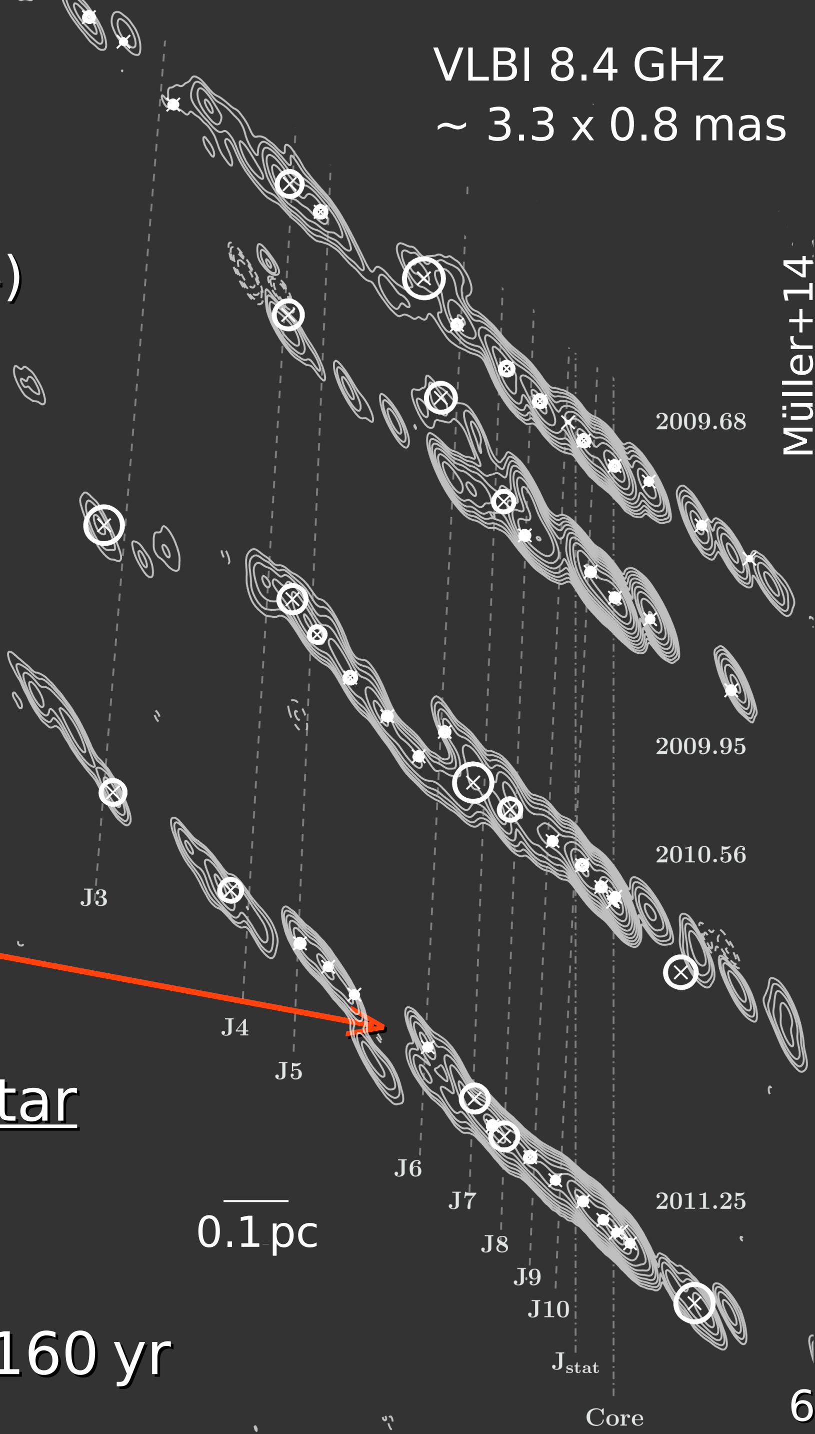
- Jet speed at subparsec scales
  $v_j \sim 0.1 - 0.3c$ (Tingay+01; Müller+14)
  - jet acceleration downstream
    or
  - sampling disparate jet layers

- Dip in surface brightness at 0.46 pc projected is stationary (2007 - 2011)

  Local jet morphology indicates circumfluent behaviour
  → standing discontinuity
  (Müller+14): likely distortion by a star

  Orbital speed ($M_{BH} \sim 5.5 \times 10^7 M_\odot$)
  ~ 600 km/s →
  crossing time ($r_j = 0.1$ pc) of star ~ 160 yr

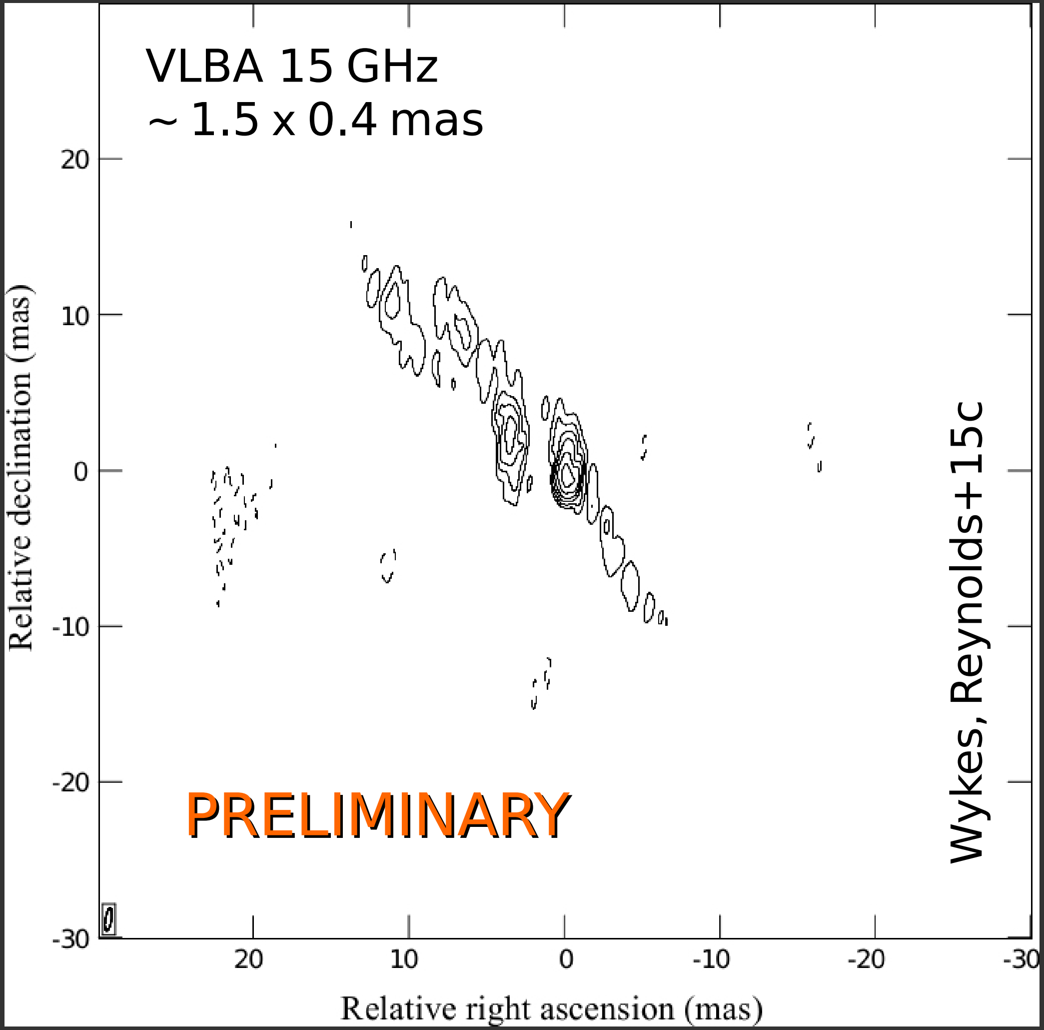
VLBI 8.4 GHz
~ 3.3 x 0.8 mas



Müller+14

Subparsec jet in radio

observations April 2014



- Feature ‘hanging’ to the south of jet at ~ 7 mas (phys. distance 0.182 pc from core): feature from intruder?

Internal entrainment

- Stars in ellipticals:

  - old population (K- and M-type stars)

  - young component in some sources (starburst)

- Central stellar densities

  $\lesssim 10^{10}$ $M_{\odot}$ kpc^{-3}, but fall off rapidly with distance from nucleus
  → stars in path of the jet

- Jet-stellar wind interactions

  most prominent for high-mass-loss stars:

  - Asymptotic Giant Branch (AGB) stars:

    $$M_{\mathbf{init}} = 0.8 - 8.0\ M_{\odot},\ \dot{M} = 1 \times 10^{-8} - 1 \times 10^{-4}\ M_{\odot}\,\mathrm{yr}^{-1}$$

  - Luminous Blue Variable (LBV) stars:

    $$M_{\mathbf{init}} \gtrsim 30\ M_{\odot},\ \dot{M} = 1 \times 10^{-4} - 1 \times 10^{-2}\ M_{\odot}\,\mathrm{yr}^{-1}$$

  - Wolf-Rayet (WR) stars:

    $$M_{\mathbf{init}} \gtrsim 20\ M_{\odot},\ \dot{M} = 1 \times 10^{-5} - 1 \times 10^{-4}\ M_{\odot}\,\mathrm{yr}^{-1}$$

Jet–stellar wind interactions: Basic model

- Stand-off distance:

  Distance from star at which balance between momentum flux from the star and of the surrounding medium

$$R_0 = \left(\frac{\dot{M} v_{\rm w}}{4\pi \rho\, v_*^2}\right)^{1/2}$$

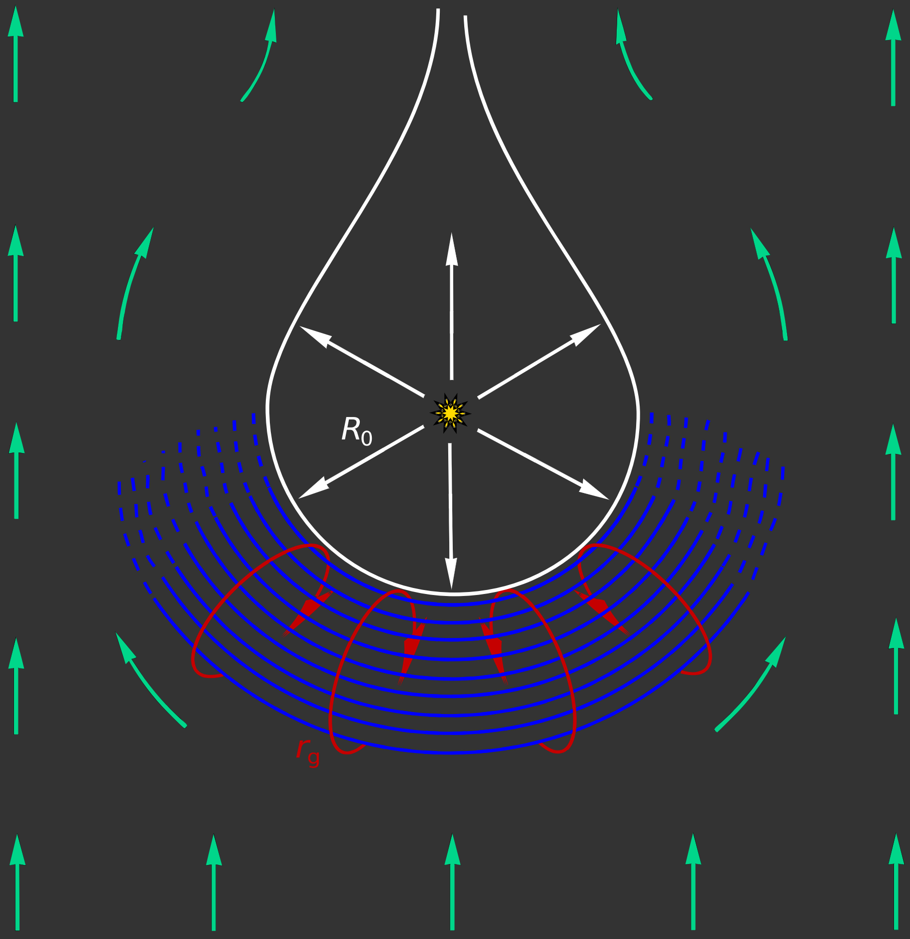
$v_{\rm w}$ velocity of isotropic stellar wind

ρ mass density of surroundings

v_* relative velocity star wrt surroundings

- For stars in jet fluid:

$$R_0 = \left(\frac{\dot{M} v_{\rm w}}{4\pi (U_{\rm j}/c^2)\, v_{\rm j}^2\, \Gamma_{\rm j}}\right)^{1/2}$$



At local R_0: acceleration of electrons of the jet plasma

Local wind material ablated, entrained for encounters downstream

Jet–stellar wind interactions: Basic model

- Suppose R_0 scales with thickness of the shocked region upstream of R_0:

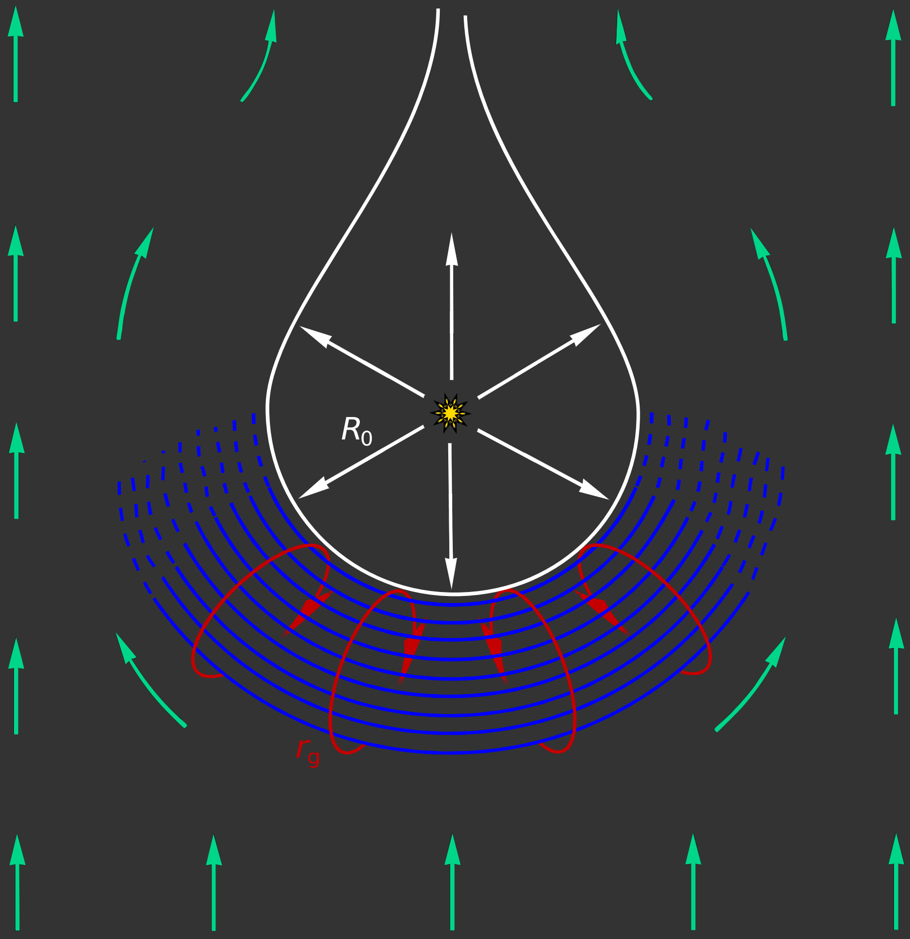
$$E_{\mathrm{e,max}} \simeq R_0\, e\, B$$

Jet mean B-field (66 µG) used (> star's B-field at R_0)

- Amount of jet <u>energy intercepted by each star</u>:

$$E_{\mathrm{intercept}} \simeq \pi R_0^2\, U_{\mathrm{j}}\, v_{\mathrm{j}}\, \Gamma_{\mathrm{j}}$$

- Spectrum: include cooling



Modelling designed for a mean population of stars at any given time in the jet

Distribution, ages, metallicities:

'Old' stars

- (Rejkuba+11) Two old populations throughout NGC 5128:
  70 - 80%: ages 12 ± 1 Gyr, range of Z
  20 - 30%: ages 2 - 4 Gyr, range of Z

($Z_\odot = 0.0198$)

- We adopt 'average' ages and metallicities:
  75% of stars of 12 Gyr, $Z = 0.004$ (AGB stars $R_0 \sim 0.1$ pc in jet)
  25% of stars of 3 Gyr, $Z = 0.008$ (AGB stars $R_0 \sim 0.8$ pc in jet)

'Young' stars

HST, NASA/ESA

- Dust lane with starburst:
  majority of the young stars here
  Ongoing star formation; VLT, *HST*:
  WR-type emission ($R_0 \sim 16$ pc in jet)
  Star ages 0 - 60 Myr, $Z \sim 0.02$
- Star-forming regions not coincident with dust lane:
  Star ages 1 - 15 Myr, $Z \sim 0.02$ (no AGB among these)

N_{real}: how many stars are in the jet?

- Observed luminosity from *R*-band photometry and population *N* stars synthesised using stellar evolution code → <u>number of stars in the jet</u> (physical length 5.9 kpc) <u>~ 8 x 10^8</u>
- Fraction young stars unknown; starburst lasting 60 Myr with SFR ~ 1.6 $M_\odot$ yr^{-1} → around 1% young stars

  Jet (viewing angle ~ 50°) traversing the starburst at all?
  Viability of model as plausible fraction (0 - 2%) of young stars

Framework

- Existing stellar evolution- and wind codes:

  SSE (Hurley+00): prediction for $\dot{M}$ for phases with high $\dot{M}$
  BOREAS (Cranmer & Saar 11): $\dot{M}$ for cool MS and evolved giants
  Mass-loss prescription (Vink+99,00,01): $\dot{M}$ for high-mass stars

- Additional codes to extract L and $\dot{M}$ for stellar populations with our adopted age and metallicity constraints, and compute $E_{\mathrm{e,max}}$, $E_{\mathrm{intercept,all}}$, $E_{\mathrm{intercept,X}}$, $N_{\mathrm{stars}} > 10^{16.5}$ Hz, L_{tot}, $\dot{M}_{\mathrm{tot}}$

Modelling: Output

f_{*}, young (per cent)	$E_{\mathrm{intercept,X}}$ (erg s^{-1})	N_{X}	$E_{\mathrm{intercept,all}}$ (erg s^{-1})	Ψ ($\mathrm{M}_{\odot}$ yr^{-1})
0	9.7×10^{39}	1.73×10^{4}	1.8×10^{40}	2.3×10^{-3}
0.1	6.2×10^{40}	1.84×10^{4}	7.1×10^{40}	2.9×10^{-3}
0.2	4.9×10^{40}	2.0×10^{4}	5.8×10^{40}	3.0×10^{-3}
0.3	3.5×10^{40}	2.16×10^{4}	4.4×10^{40}	4.4×10^{-3}
0.5	1.0×10^{41}	2.47×10^{4}	1.0×10^{41}	4.0×10^{-3}
1	3.7×10^{41}	3.40×10^{4}	3.8×10^{41}	7.4×10^{-3}
2	5.1×10^{41}	5.04×10^{4}	5.2×10^{41}	1.5×10^{-2}

- Model energetically capable of producing observed X-ray emission (~ 1.1×10^{39} erg s^{-1}), even without young stars
- There must be at least ~ 1×10^{4} AGB stars in the jet
- Entrainment rate Ψ consistent with our earlier rough estimate (Wykes+13) using different approach

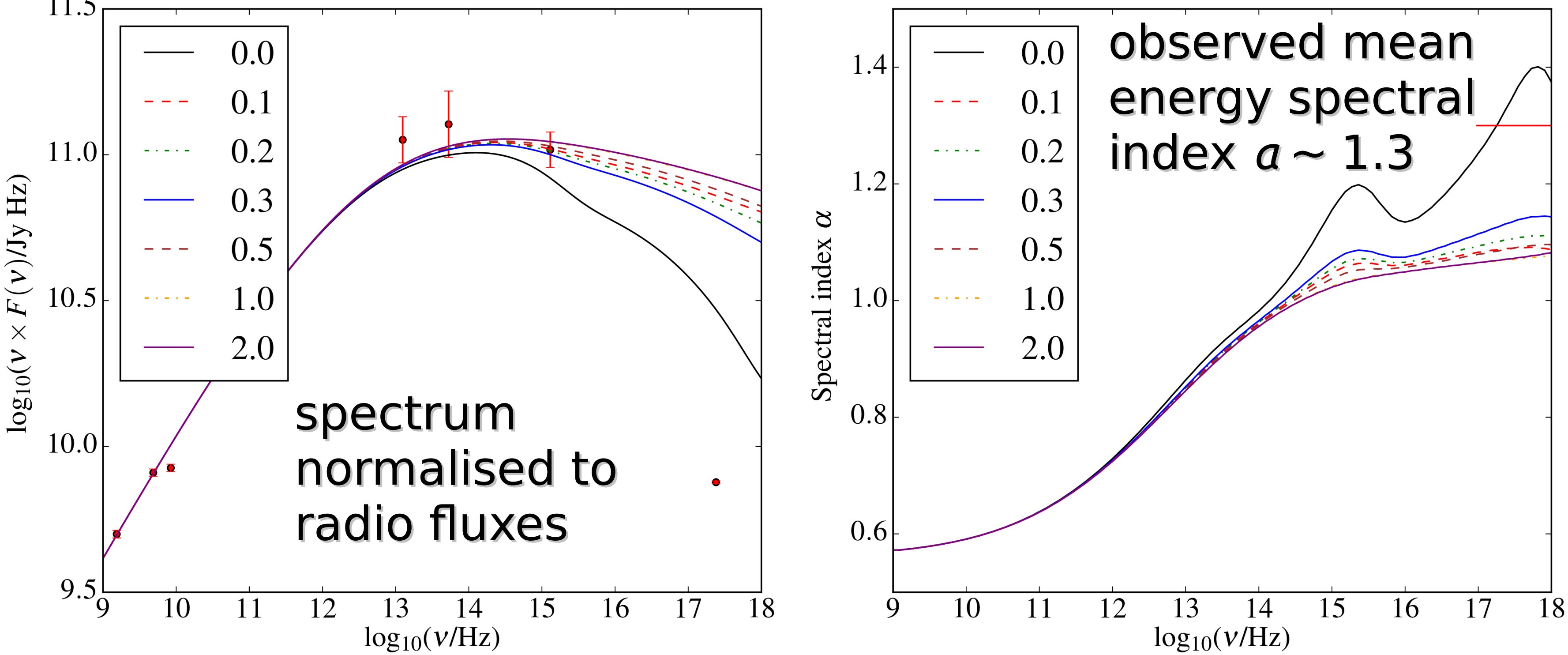
Broad-band spectrum of kpc jet

Old and young (0 - 2%) stellar components

$N_{\mathrm{real}} = 8 \times 10^8$

$N_{\mathrm{simulated}} = 1 \times 10^8$

observational data points are for 'inner region' (2.4 – 3.6 kpc)



spectrum normalised to radio fluxes

observed mean energy spectral index $\alpha \sim 1.3$

- Broad-band spectrum reproduced up to optical
- Mean energy index α reproduced for sensible fraction of young stars

Entrainment rate, jet deceleration

- Adding mass-loss rates for our stellar populations
  → total internal entrainment rate from runs:
  $\Psi = 2.3 \times 10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$ (for 0% young stars)
  → mass loading from internal entrainment of
  $4.6 \times 10^{3}\ M_\odot$ during lifetime of current jet
  $1.3 \times 10^{6}\ M_\odot$ over lifetime of giant lobes

  Amount of entrained material:
  (volume, age giant lobes) → density lobes ~ $1 \times 10^{-8}\ \mathrm{cm}^{-3}$

- What speed does the current jet have if initially baryon-free with $v_\mathrm{j} \sim 0.5c$, and momentum is conserved
  Relativistic leptonic jet fluid behaves as having density U_j/c^2. If relativistic momentum flux is $\dot{M}\, v\, \Gamma$:

$$\pi\, r_\mathrm{j}^2\, \frac{U_\mathrm{j}}{c^2}\, v_{\mathrm{j},1}^2\, \Gamma_{\mathrm{j},1} = \dot{M} v_{\mathrm{j},2}\, \Gamma_{\mathrm{j},2}$$

  Solving for $v_{\mathrm{j,2}}\, \Gamma_{\mathrm{j,2}}$ gives $0.04c$ → significant slow-down

Mass-loss rates in individual isotopes

Based on codes calculating nucleosynthetic yields (e.g. Karakas 2010)

Isotope	Amount expelled (in $M_\odot$ yr^{-1}) by AGB stars		
	age = 12 Gyr	age = 3 Gyr	age = 60 Myr
	$Z = 0.004$	$Z = 0.008$	$Z = 0.02$
M_{init} =	0.9 $M_\odot$ stars	1.4 $M_\odot$ stars	6 $M_\odot$ stars
	75%	25%	0 – 0.5%
^{1}H	3.17×10^{-5}	8.80×10^{-5}	$0 - 1.29 \times 10^{-4}$
^{3}He	1.27×10^{-8}	4.16×10^{-8}	$0 - 1.76 \times 10^{-10}$
^{4}He	1.14×10^{-5}	3.37×10^{-5}	$0 - 7.46 \times 10^{-5}$
^{12}C	2.30×10^{-8}	1.34×10^{-7}	$0 - 2.27 \times 10^{-7}$
^{14}N	1.33×10^{-8}	1.10×10^{-7}	$0 - 1.72 \times 10^{-6}$
^{16}O	8.28×10^{-8}	4.70×10^{-7}	$0 - 1.67 \times 10^{-6}$
^{20}Ne	1.40×10^{-8}	7.96×10^{-8}	$0 - 3.37 \times 10^{-7}$
^{22}Ne	1.11×10^{-9}	7.22×10^{-9}	$0 - 6.40 \times 10^{-8}$
^{24}Mg	4.47×10^{-9}	2.53×10^{-8}	$0 - 1.05 \times 10^{-7}$
^{26}Mg	6.74×10^{-10}	3.82×10^{-9}	$0 - 2.63 \times 10^{-8}$
^{28}Si	5.67×10^{-9}	3.21×10^{-8}	$0 - 1.37 \times 10^{-7}$
^{32}S	8.10×10^{-9}	1.95×10^{-8}	$0 - 8.23 \times 10^{-8}$
^{56}Fe	1.02×10^{-8}	5.75×10^{-8}	$0 - 2.42 \times 10^{-7}$

Isotope ratios overall solar-like

Approximate amount of mass (in $M_\odot$) in individual isotopes released to jet by AGB + main-sequence phases:

Isotope	Amount expelled	
	current jet 2 Myr	pre-existing jet 560 Myr
^{1}H	2.6×10^{2}	7.4×10^{4}
^{3}He	1.1×10^{-1}	3.1×10^{1}
^{4}He	9.8×10^{1}	2.7×10^{4}
^{12}C	3.4×10^{-1}	9.5×10^{1}
^{14}N	2.6×10^{-1}	7.2×10^{1}
^{16}O	1.2	3.3×10^{2}
^{20}Ne	2.0×10^{-1}	5.5×10^{1}
^{22}Ne	1.8×10^{-2}	5.0
^{24}Mg	6.4×10^{-2}	1.8×10^{1}
^{26}Mg	9.6×10^{-3}	2.7
^{28}Si	8.1×10^{-2}	2.3×10^{1}
^{32}S	5.8×10^{-2}	1.6×10^{1}
^{56}Fe	1.5×10^{-1}	4.1×10^{1}

External (lateral) entrainment from hot gas

- Centaurus A's jet: not significantly over/underpressured wrt surroundings → allows Kelvin-Helmholtz instability to develop at the jet-ISM interface

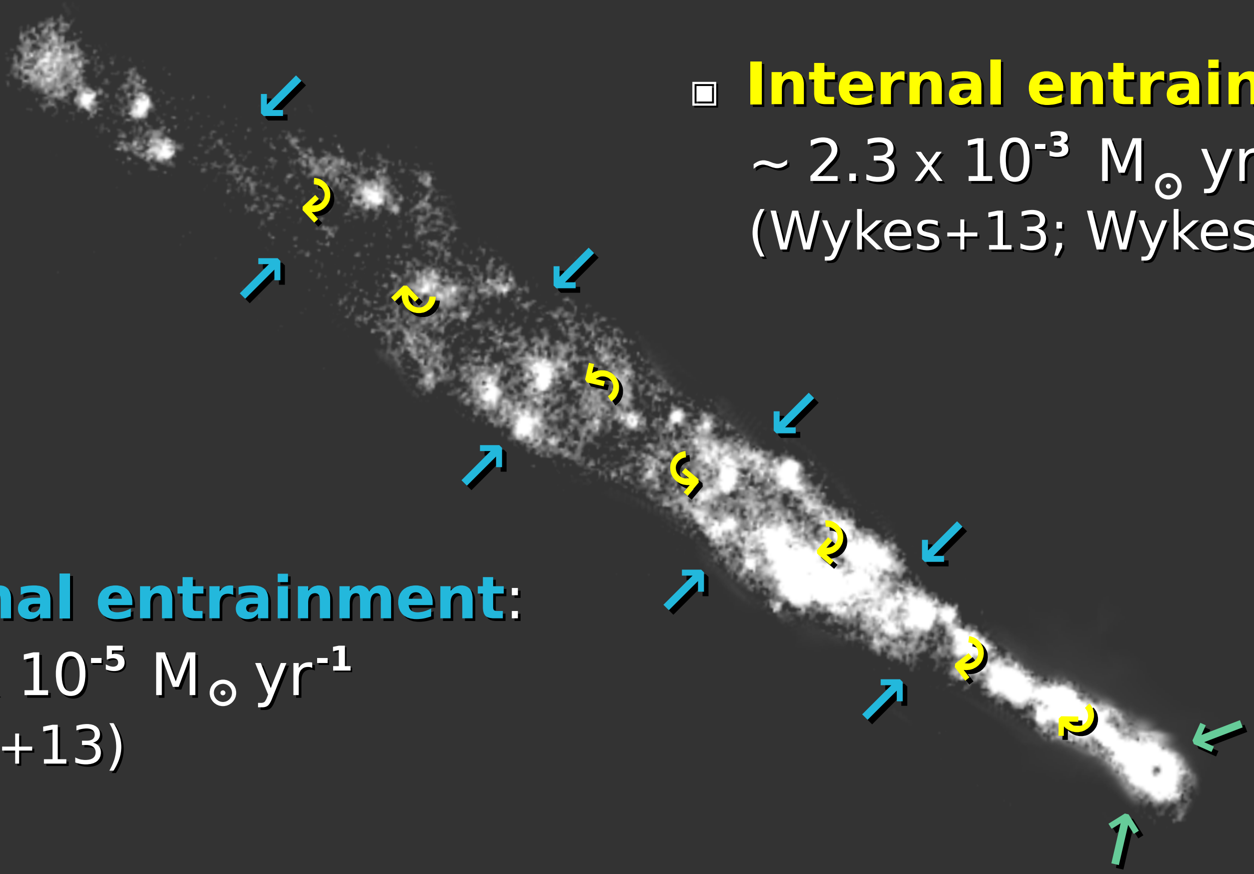
- Bulk entrainment: no differentiation between particle charges during jet boundary crossing → composition representative of surrounding galaxy ISM

- Simple scaling relations with position along the jet; results of Laing & Bridle 02 for FR I radio galaxy 3C 31 to characterise regions and normalise entrainment rate profile

- Integrated entrainment rate (0 - 3 kpc) implies total external entrainment rate

$\sim 4.7 \times 10^{-5}\ M_{\odot}\ yr^{-1}$ << total internal entrainment contribution

Centaurus A's jet:
Mass loading on kpc & pc scales



- **Internal entrainment**:
  ~ 2.3 x 10^{-3} $M_{\odot}$ yr^{-1}
  (Wykes+13; Wykes+15)

- **External entrainment**:
  ~ 4.7 x 10^{-5} $M_{\odot}$ yr^{-1}
  (Wykes+13)

- **Mass from accretion disc?**

Circular polarisation (CP)

- Intrinsically from synchrotron emission (likely pe$^-$ jet)
- Faraday conversion of linear polarisation to circular (e$^+$e$^-$ or pe$^-$; jet not dominated by non-relativistic pe$^-$ plasma)

Observations: VLBA's southern antennas; 8, 15, 22 GHz

Upper limits (3σ) at 8 GHz: LP: ~ 0.46 %, CP: ~ 0.92 %
at 15 GHz: LP: ~ 0.16 %, CP: ~ 0.16 %

↳ Shortfall of significant LP at 8 + 15 GHz most readily explained by strong Faraday screen (RM ~ 8 x 10^5 rad/m^2)

↳ However, external depolarisation not expected to affect CP. Lack of CP due to insufficient synchrotron self-absorption in jet?

Even clear signal suggesting pe$^-$ composition on smallest scales will not detract from total amount of baryon mass incorporated into jet

Summary

- Jet-stellar wind interaction model
  - produces X-rays (even for zero fraction young stars)
  - can reproduce combined diffuse- and knot X-ray luminosity of the whole jet, and the broad-band spectrum up to optical
  - mean X-ray spectral index recovered

- Derived internal entrainment rate of ~ $2.3 \times 10^{-3}\ M_\odot\ yr^{-1}$ implies substantial jet deceleration

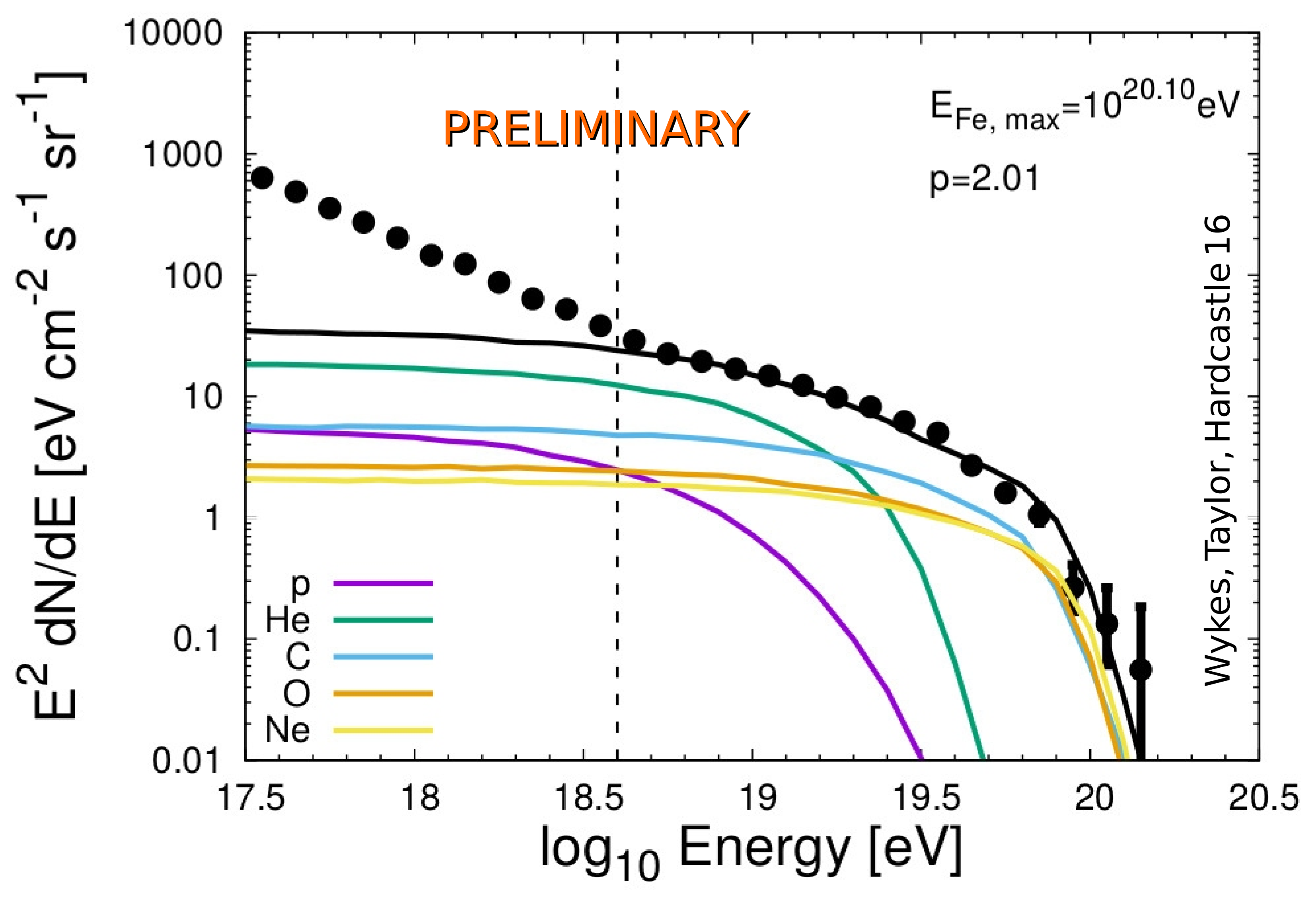
- External entrainment plausible: solely ~ $4.7 \times 10^{-5}\ M_\odot\ yr^{-1}$

- Mass loading from disc unconstrained thus far: if present, low

- Baryons in Centaurus A's jet essentially from mass loss by ~ 12 Gyr ($Z \sim 0.004$) and ~ 3 Gyr ($Z \sim 0.008$) AGB stars

- Composition of jet on kpc-scales largely solar-like with ^{4}He, ^{16}O, ^{12}C, ^{14}N and ^{20}Ne the key isotopes

Centaurus A: propagation spectrum



Wykes, Taylor, Hardcastle 16

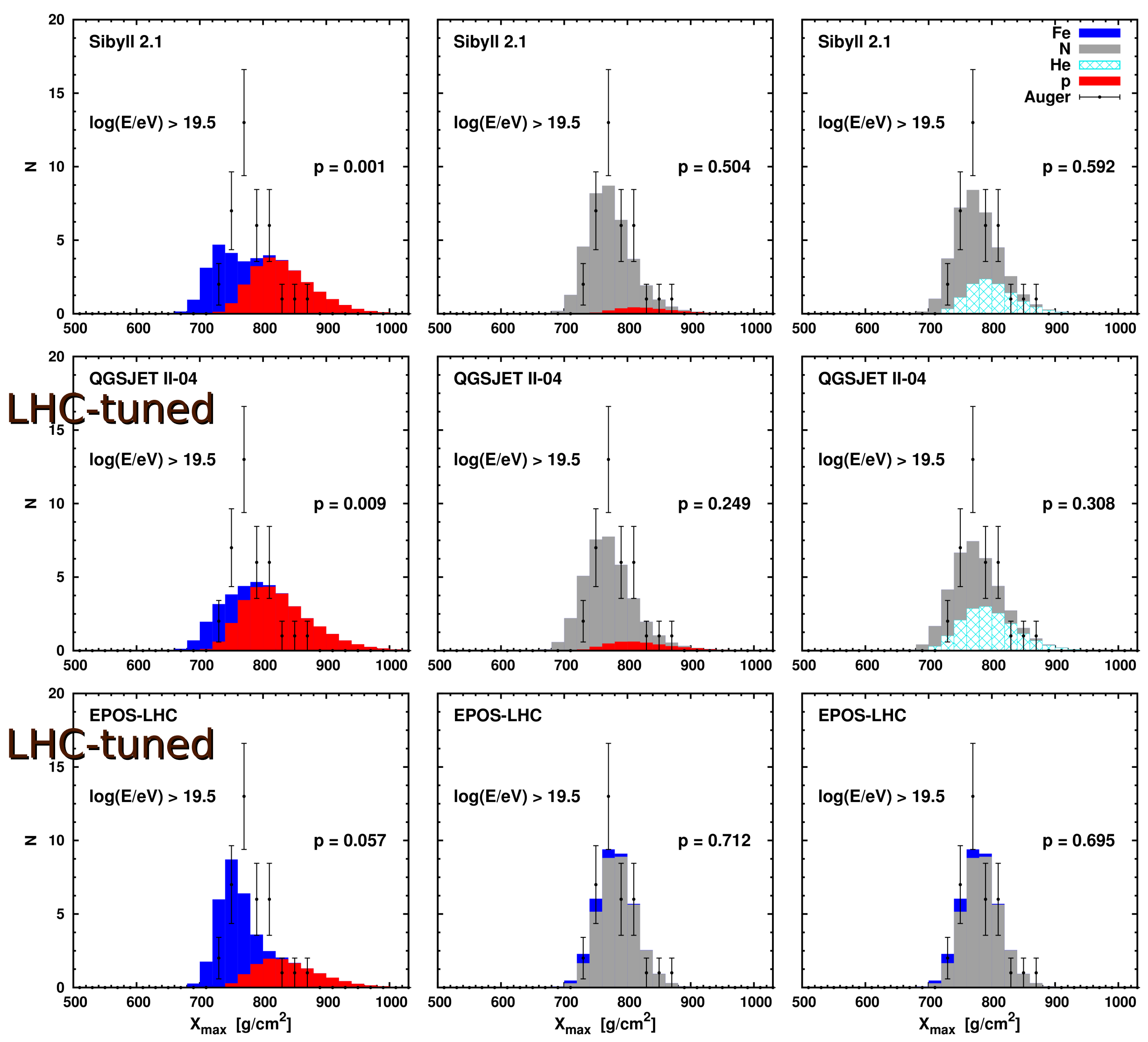
Good fits are possible

Pierre Auger Observatory: UHECR composition implications (arXiv: 1409.5083)

Shape of distribution of $X_{\mathbf{max}}$ data

- Inconsistent with composition dominated by protons
- Inconsistent with iron dominance
- Introducing <u>intermediate-mass nuclei greatly improves the fits</u>

Original source composition from nearby source/sources or photodisintegration products from distant one/ones, or both?



LHC-tuned

LHC-tuned

Cosmic-ray energisation: jet

- Diffusive shock acceleration ('Fermi I')
  - Relatively fast
  - Particle spectra around $p = 2$ at single, non-relativistic, strong, q-parallel shocks; flatter from ensemble of shocks

e.g. jet-stellar wind interaction model

- Shear acceleration (Fermi I-like process)
  - Relatively fast
  - Particle spectra flatter than $p = 2$

kpc jet boundaries

- Magnetic reconnection (Fermi I-like process)
  - Relatively fast
  - Particle spectra flatter than $p = 2$ (?)

small jet scales

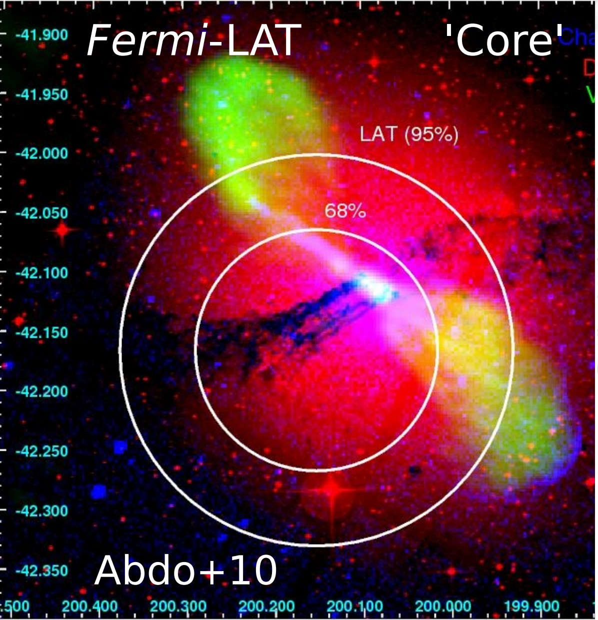
- Stochastic acceleration ('Fermi II' used inconsistently in lit., sometimes only referring to magnetosonic turbulence)
  - Slow in general, relatively fast in the jet
  - No fundamental particle slope (depends on physical conditions at the source)

Hybrid models perfectly possible!

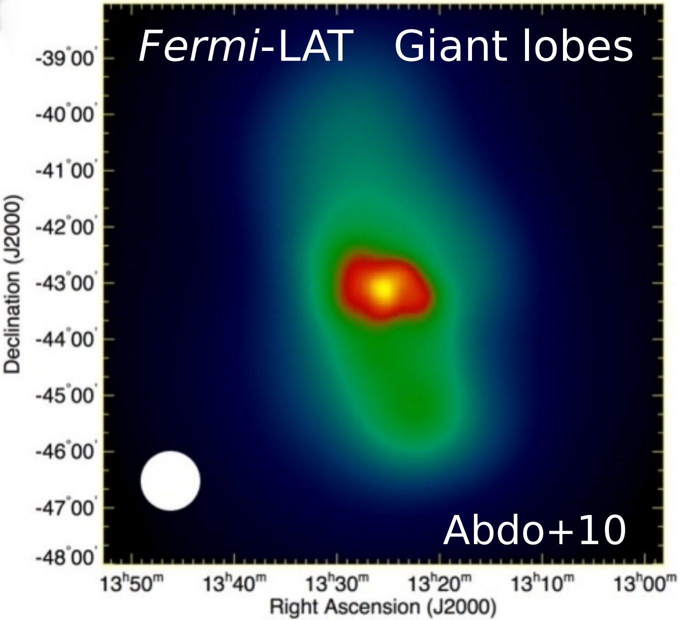
Fermi GeV source & HESS TeV source

MeV - GeV
ang. res. ≤ 1°

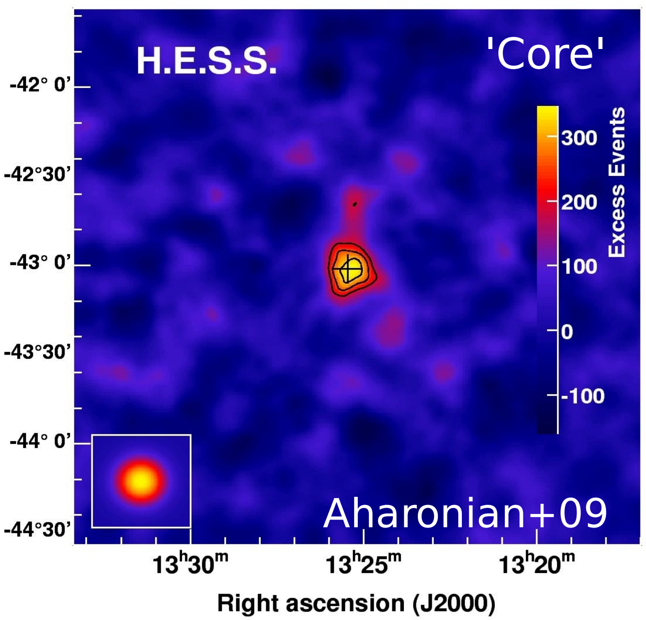
GeV - TeV
ang. res. ≤ 0.1°



Abdo+10



Abdo+10



Aharonian+09

L_γ (0.1 - 4 GeV)
~ 1.1 x 10^{41} erg s^{-1}

L_γ (> 250 GeV)
~ 2.6 x 10^{39} erg s^{-1}

---

no variability

no variability

no variability

---

leptonic/hadronic?

leptonic

leptonic/hadronic?

Internal entrainment – earlier approach

- Estimate total mass loss rate for the stellar population of Centaurus A, determining fraction of this mass loss to occur within jet boundaries

- Mass loss in ellipticals dominated by old-population stars with luminosity-to-mass-loss-rate ratio 7.88×10^{-12} $(L_B/L_{B\odot})$ $M_\odot$ yr^{-1}

- Apparent magnitude m_B of Centaurus A = 7.48

  → $L_B \sim 2.43 \times 10^{10}$ $L_{B\odot}$ → mass loss rate ~ 0.19 $M_\odot$ yr^{-1}

- Adopting spherically symmetric distribution, the fraction of stars in the jet determined by jet's solid angle. Opening angle 15° → 0.054 sterrad → entrainment rate ~ 5.2×10^{22} g s^{-1}

- Young stars: assumption: Centaurus A's FIR luminosity arises from dust heated by O stars & 50% of the output into heating the dust. Entrainment ~ 1.6×10^{22} g s^{-1}

  Total internal entrainment ~ 6.8×10^{22} g s^{-1} (1.1×10^{-3} $M_\odot$ yr^{-1})

External entrainment from hot gas – detailed

- Assumption: mass entrained per unit time for a section of jet of length $\Delta\, l$ scales according to the external gas density, jet velocity and surface area of the jet segment:

$$\dot{M} = \Psi_0\ \rho_{\mathrm{ext}}\,(l)\ v_{\mathrm{j}}\,(l)\ r_{\mathrm{j}}\,(l)\ \Delta\, l$$

- Then entrainment rate per unit length:

$$\Psi\ (l) = \Psi_0\, \rho_{\mathrm{ext}}\,(l)\ v_{\mathrm{j}}\,(l)\ r_{\mathrm{j}}\,(l)$$

- Assumption: external thermal number density described by a beta model:

$$n_{\mathrm{th}} = n_0\ (1 + (l\,/\,a)^2\,)^{(-3\,\beta\,/\,2)}$$

- Beta model parameters for Centaurus A (Kraft+2003): $\beta = 0.39$, $a = 0.5$ kpc, $n_{\mathrm{p,0}} = 0.037\ \mathrm{cm}^{-3}$

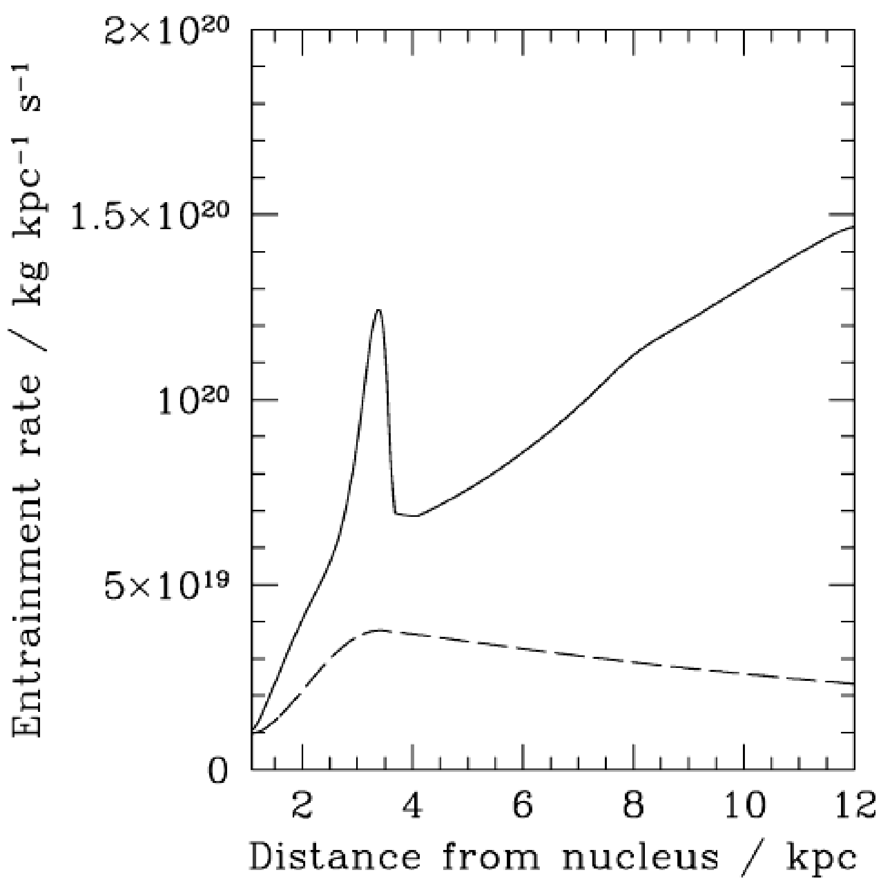
External entrainment from hot gas – detailed

- Assumptions: v_j ~ constant over inner 3 kpc, r_j proportional to distance l
  → separate out the entrainment rate:

  $\Psi\,(l) = \Psi_{\mathrm{norm}}\; l\,(1 + (l\,/\,a)^2\,)^{(-3\,\beta\,/\,2)}$

- Normalisation from Laing & Bridle (2002) by taking an estimate of the entrainment rate in the middle of the flaring region in 3C 31;

  the equivalent point in Centaurus A's jet is at ~ 0.7 kpc



- For 3C 31:

  $\Psi\,(2\ \mathrm{kpc}) = 4 \times 10^{22}\ \mathrm{g\ s^{-1}\ kpc^{-1}}$

External entrainment from hot gas – detailed

- Scaling entrainment rate at 2 kpc for 3C 31 based on the ratio of external density, jet velocity and jet radius at these equivalent points:

$$\rho_{\mathrm{Cen\,A}}/\rho_{\mathrm{3C\,31}} = 0.33, \quad v_{\mathrm{Cen\,A}}/v_{\mathrm{3C\,31}} = 1, \quad r_{\mathrm{Cen\,A}}/r_{\mathrm{3C\,31}} = 0.08$$

→ estimated entrainment rate for Centaurus A:

$$\Psi\,(0.7\ \mathrm{kpc}) \sim 1.1 \times 10^{21}\ \mathrm{g\ s^{-1}\ kpc^{-1}}$$

→ normalisation for the entrainment rate profile:

$$\Psi_{\mathrm{norm}} \sim 2.8 \times 10^{21}\ \mathrm{g\ s^{-1}\ kpc^{-2}}$$

- Integrating the entrainment rate (0 - 3 kpc) implies total entrainment rate

$$\sim 3.0 \times 10^{21}\ \mathrm{g\ s^{-1}} \quad (\sim 4.7 \times 10^{-5}\ M_{\odot}\ \mathrm{yr^{-1}})$$

Cosmic-ray energisation: giant lobes

- Amount of entrained material: seems large, but (volume, age lobes)! → density ~ 1 x 10^{-8} cm^{-3} → Alfvén speed $v_A \sim 0.08c$

- Resonant acceleration time for particle of energy γ:

$$\tau_{\rm res} \simeq \frac{\gamma mc}{ZeB}\frac{c^2}{v_A^2}\frac{U_B}{U_{\rm res}}$$

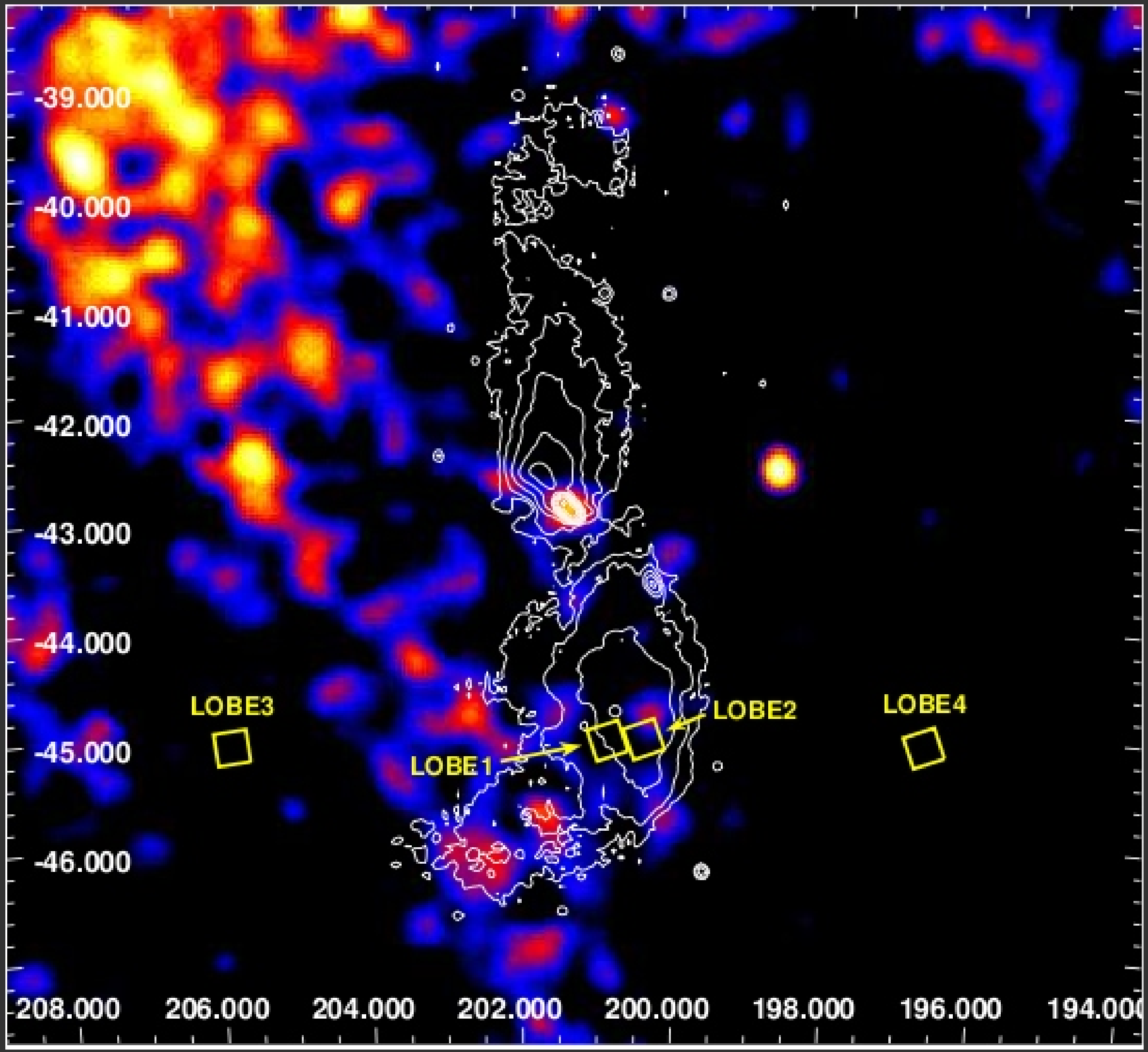
B-field giant lobes ~ 0.9 μG

- Interested in highest energies that can resonate: i.e. disregard U_B/U_{res}, estimate τ_{res} only for particles with gyroradius ~ turbulent driving scale (30 - 100 kpc): 55 EeV: ^{12}C: $\tau_{res} \sim$ 5.5 Myr, ^{16}O: $\tau_{res} \sim$ 4.1 Myr

- Requirement for a relatively flat power law, as generally assumed for UHECRs: acceleration time ≲ diffusion time

- Constraints on turbulent scale, acceleration time, escape time and physical age of the giant lobes: only ^{9}Be and heavier nuclei accelerated to ≥ 55 EeV regime

- Some of the X-ray synchrotron emission detected with *Suzaku* (Stawarz+13) may be associated with parts of *vertex* filament
- However, their X-ray thermal detection most likely Galactic foreground emission



Assumption to determine number density *n*:
all emission thermal bremsstrahlung;
emissivity to thermal bremsstrahlung goes as n^2

ROSAT count map

Parkes 4.75 GHz (Junkes+93)

Suzaku pointings