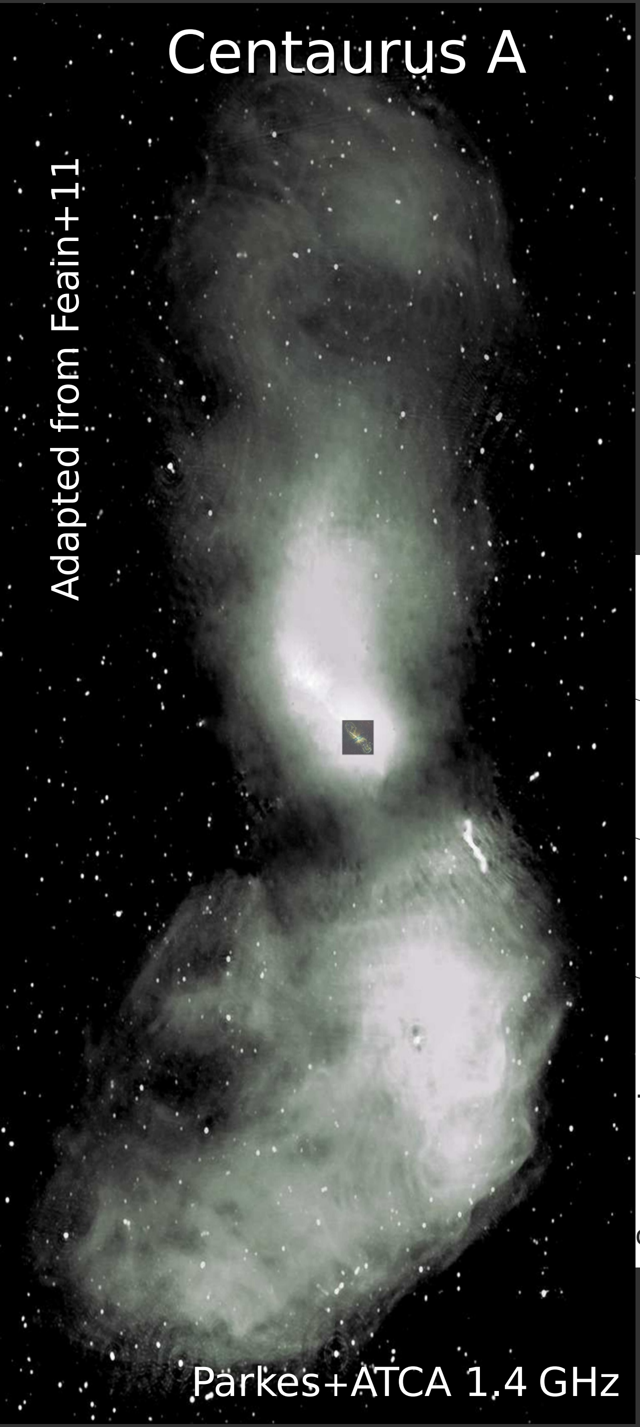
UHECR propagation from Centaurus A

Sarka Wykes
University of Manitoba

Andrew Taylor, Martin Hardcastle, Michael Hillas

in preparation

San Vito di Cadore, 23 September 2016


Centaurus A

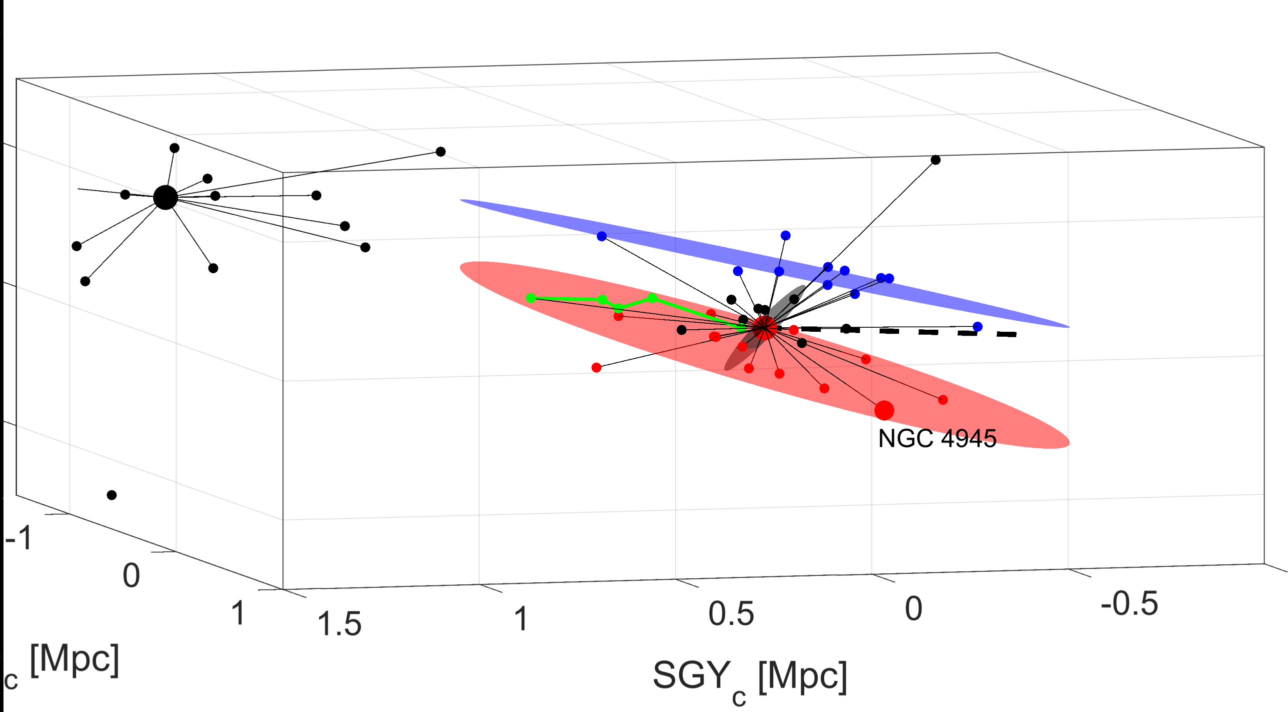
Adapted from Feain+11

Parkes+ATCA 1.4 GHz

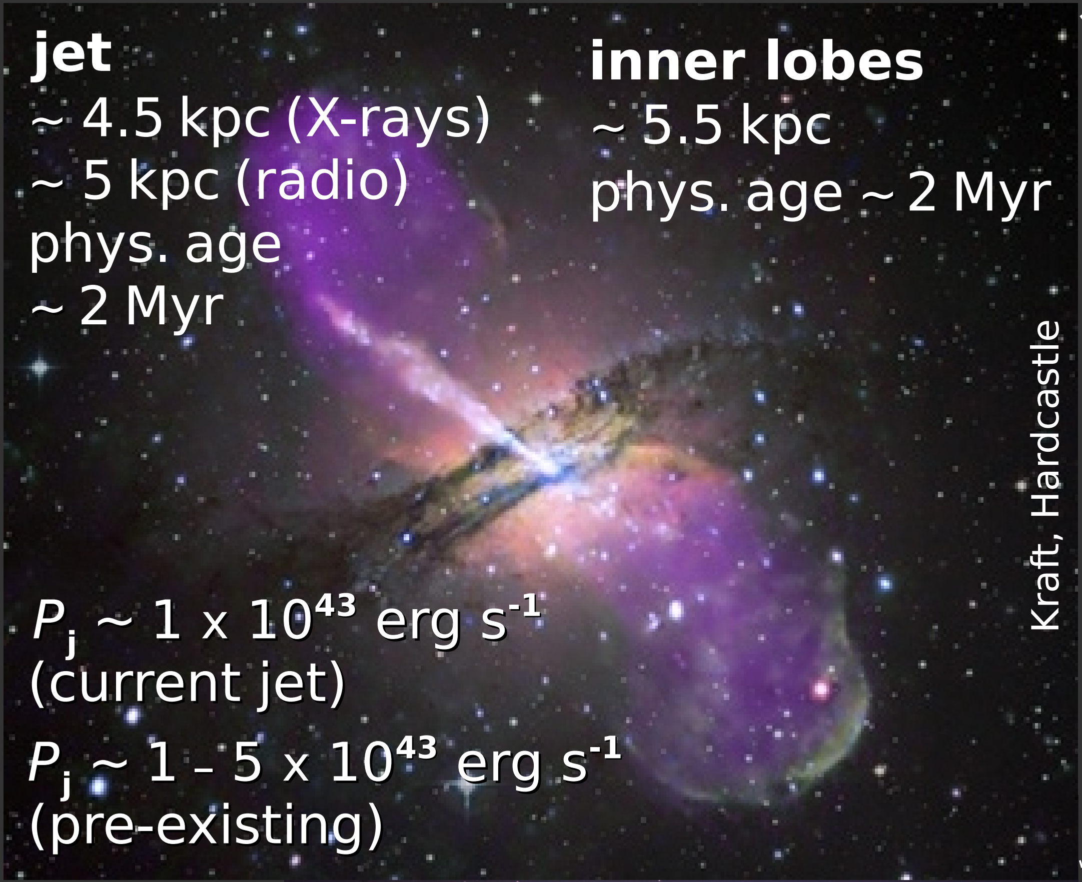
Closest (3.8 ± 0.1 Mpc) radio galaxy, FR I class, hosted by massive elliptical NGC 5128, group member

Centaurus group: ~ 100 dwarf galaxies (confirmed and candidates)

Dwarf galaxies in general useful to trace matter (cosmological filaments)



3D structure (Crnojević+16; Müller+16)



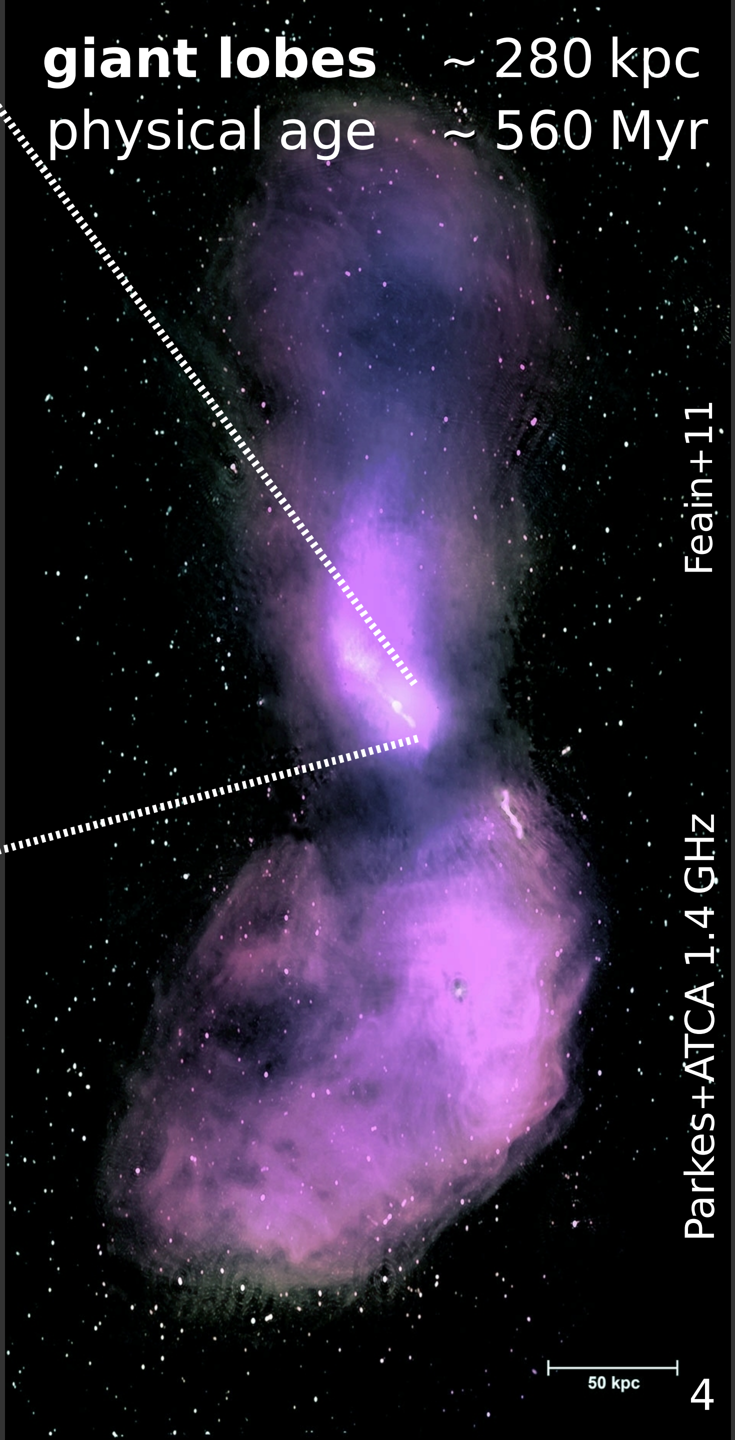
jet
~ 4.5 kpc (X-rays)
~ 5 kpc (radio)
phys. age
~ 2 Myr

inner lobes
~ 5.5 kpc
phys. age ~ 2 Myr

$P_\mathrm{j} \sim 1 \times 10^{43}$ erg s^{-1}
(current jet)

$P_\mathrm{j} \sim 1 - 5 \times 10^{43}$ erg s^{-1}
(pre-existing)

Kraft, Hardcastle



giant lobes ~ 280 kpc
physical age ~ 560 Myr

Feain+11

Parkes+ATCA 1.4 GHz

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

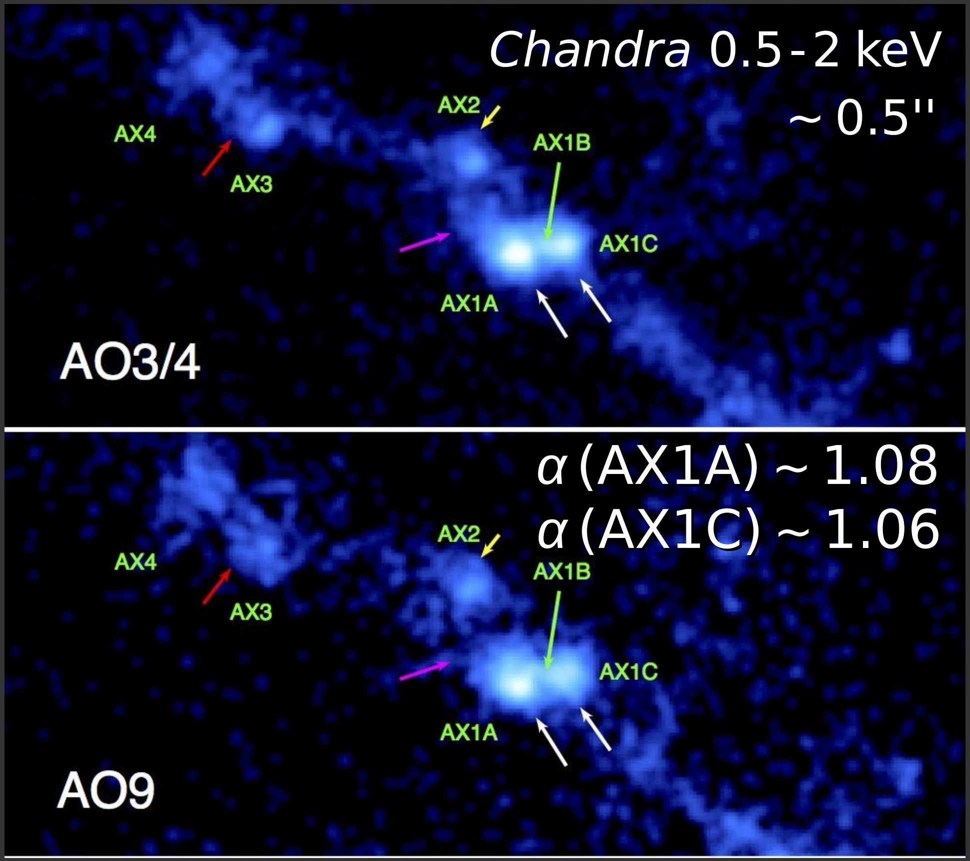
parent elliptical
~ 12 & 3 Gyr
stars

HST
R. Gendler, R. Colombari

Knotiness of X-ray jet

- Support for model with discrete interaction sites
- Possible obstacles in jet:
  - stars, planetary nebulae
  - gas/molecular clouds

- Alternative explanations of knots (in general):
  - variations in jet speed
  - recollimation shocks
  - plasma instabilities



Chandra 0.5 - 2 keV

~ 0.5''

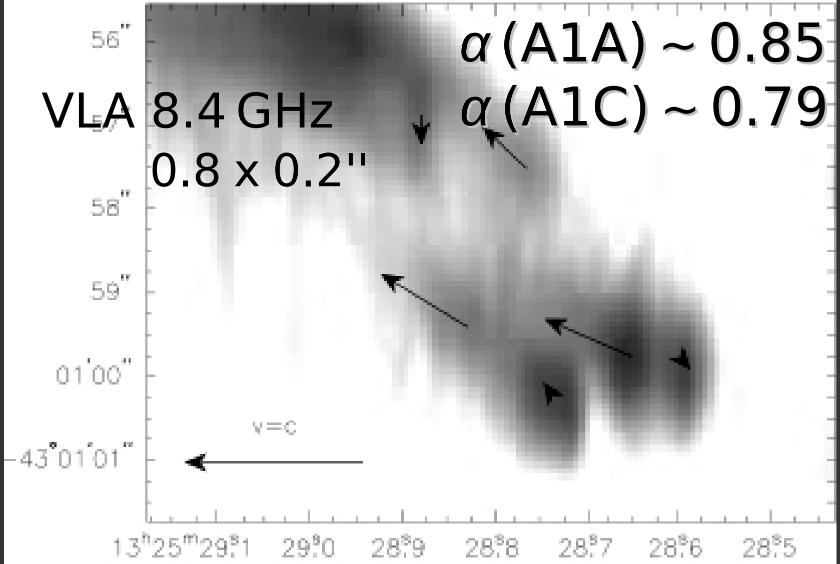
α (AX1A) ~ 1.08

α (AX1C) ~ 1.06

Kraft, Hardcastle

Radio view of the jet:

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



VLA 8.4 GHz

0.8 x 0.2''

α (A1A) ~ 0.85

α (A1C) ~ 0.79

Goodger+10

Jet–stellar wind interactions: basic model

- Stand-off distance:

  Distance from a star at which momentum fluxes from the stellar wind and surroundings match,

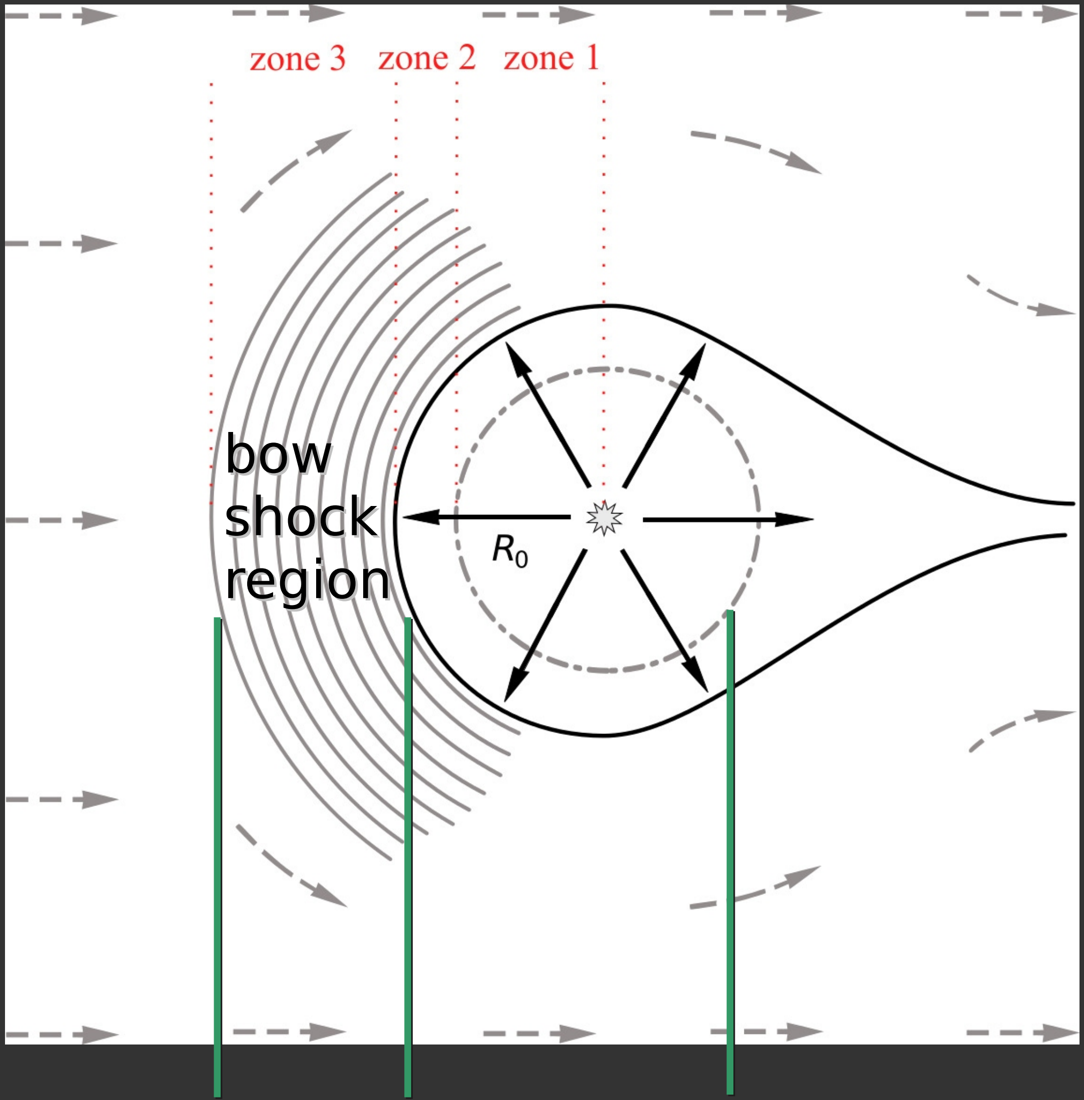
$$R_0 = \left(\frac{\dot{M} v_{\rm w}}{4\pi (U_{\rm j}/c^2)\, v_{\rm j}^2\, \Gamma_{\rm j}} \right)^{1/2}$$

- zone 3: very hot swept-up jet medium; subsonic

- termination shock: non-relativistic, weak, $\mathcal{M} = v_{\rm w} / c_{\rm s} \sim 1.3$

- bow shock: relativistic, weak, $\mathcal{M} = \sqrt{2}\, \beta_{\rm j}\, \Gamma_{\rm j} \sim 1.3$

spectral index not simple to predict; $E_{\rm max} = Z\, e\, B\, R\, \beta\, \Gamma_{\rm j}$ does roughly apply

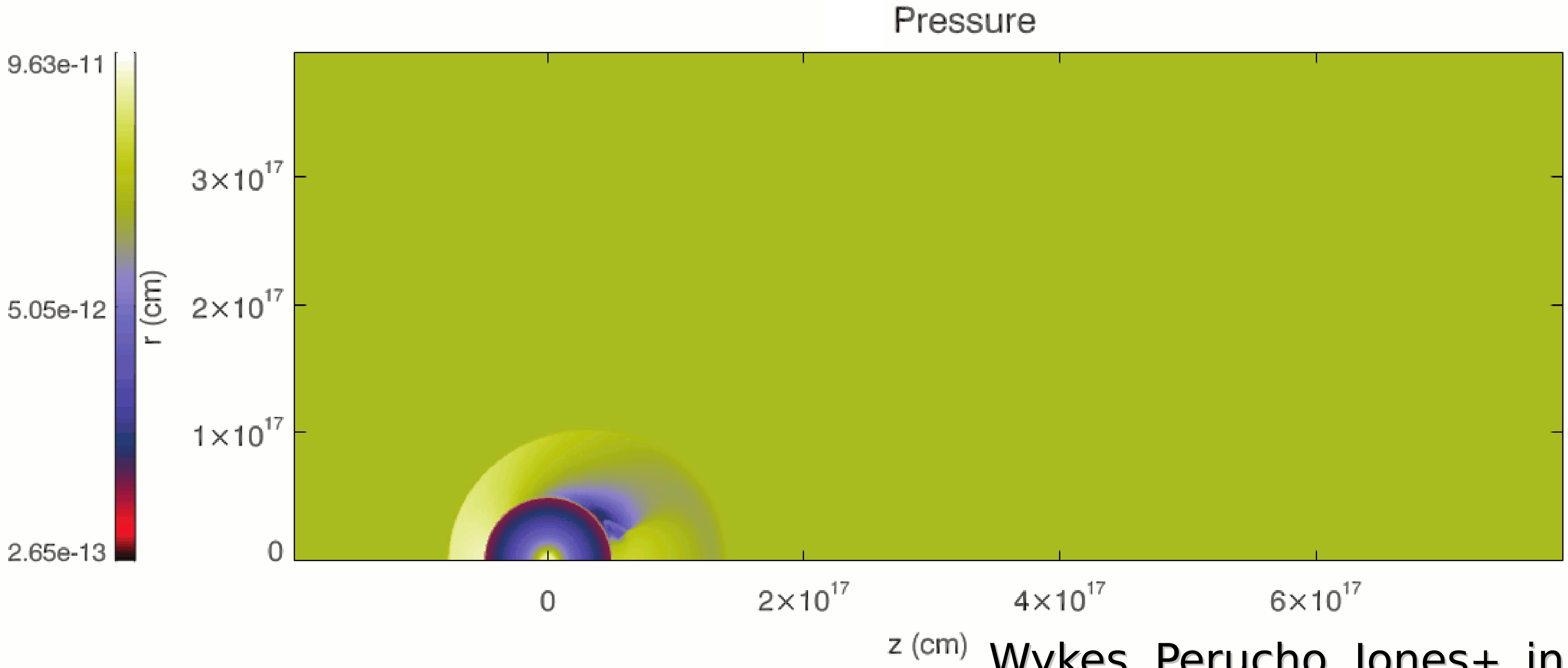


Bow shock development, 2D HD simulations

jet: electron-positron plasma moving at 2c/3

obstacle: 12 Gyr TRGB star ($\dot{M} = 4.3 \times 10^{-8}\ M_\odot$/yr; v_w = 10 km/s)

575 physical days into development



Wykes, Perucho, Jones+, in prep.

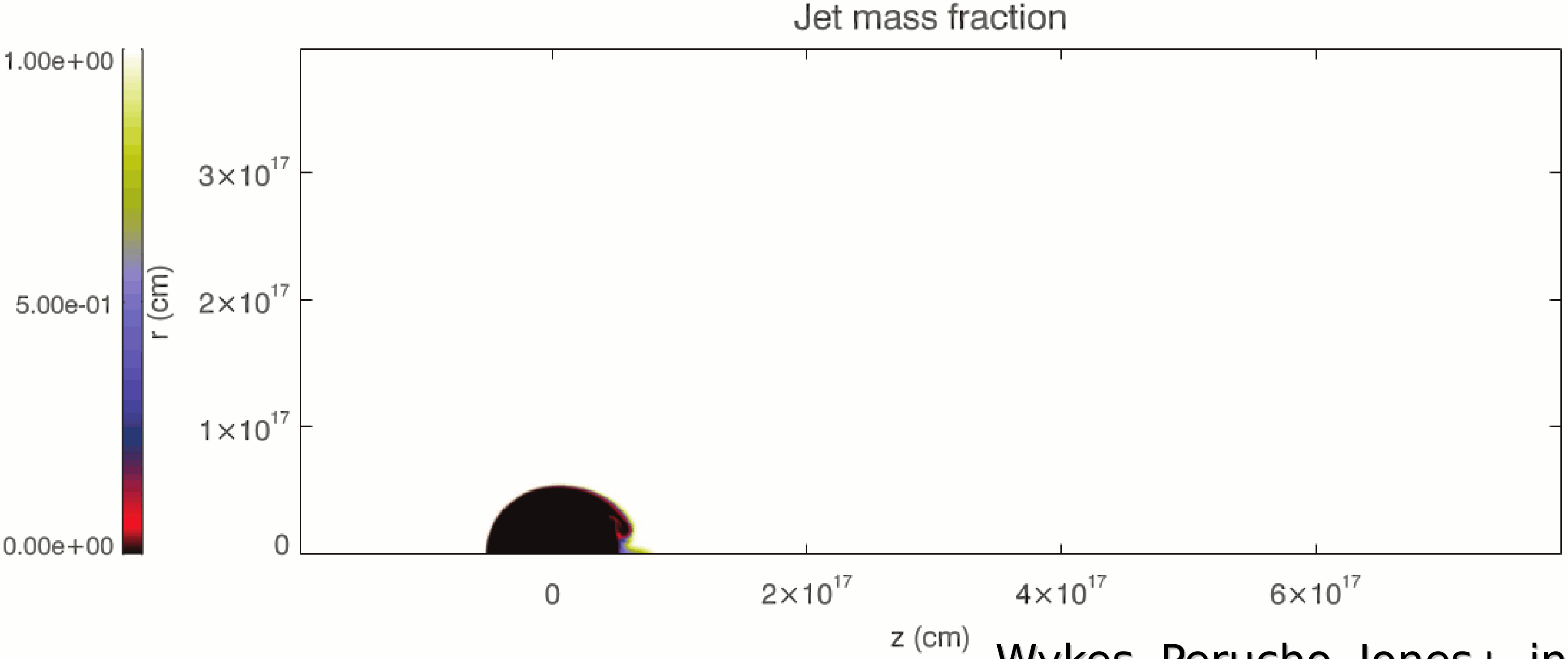
- Bow shock front: hyperbolic shape away from obstacle
- Thickness of bow shock region in steady state similar to stand-off distance

Jet mass fraction development, 2D HD

jet: electron-positron plasma moving at 2c/3

obstacle: 12 Gyr TRGB star ($\dot{M} = 4.3 \times 10^{-8}\ M_\odot/\mathrm{yr}$; $v_w = 10$ km/s)

575 physical days into development



Wykes, Perucho, Jones+, in prep.

- Stellar material lost to the jet
- Wake shows von Kármán-like vortices; break-up of vortices prohibited in 2D

Principal results from previous work on jet-sw interactions in Centaurus A (Wykes+13,15a)

- Jet-stellar wind interaction model for electron acceleration at bow shocks (Fermi I-type acceleration)
  - produces X-rays
  - can reproduce combined diffuse- and knot X-ray luminosity of the whole jet

- Derived internal entrainment rate (mass-loss from 8 x 10^{8} jet-contained stars) of ~ 2.3 x 10^{-3} $M_{\odot}$ yr^{-1} implies substantial jet deceleration

- External entrainment (via turbulent jet boundary) plausible: solely ~ 4.7 x 10^{-5} $M_{\odot}$ yr^{-1}

- Baryons in Centaurus A's jet essentially from mass loss by ~ 12 Gyr (Z ~ 0.004) and ~ 3 Gyr (Z ~ 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

Mass-loss rates in individual isotopes Based on codes calculating nucleosynthetic yields (e.g. Karakas 2010)

Isotope		Amount expelled (in $M_\odot$/yr) by AGB stars	
	Age	12 Gyr	3 Gyr
	Metallicity	0.004	0.008
	Initial stellar mass	0.9 $M_\odot$	1.4 $M_\odot$
		75%	25%
^{1}H		3.17×10^{-5}	8.80×10^{-5}
^{3}He		1.27×10^{-8}	4.16×10^{-8}
^{4}He		1.14×10^{-5}	3.37×10^{-5}
^{12}C		2.30×10^{-8}	1.34×10^{-7}
^{14}N		1.33×10^{-8}	1.10×10^{-7}
^{16}O		8.28×10^{-8}	4.70×10^{-7}
^{20}Ne		1.40×10^{-8}	7.96×10^{-8}
^{22}Ne		1.11×10^{-9}	7.22×10^{-9}
^{24}Mg		4.47×10^{-9}	2.53×10^{-8}
^{26}Mg		6.74×10^{-10}	3.82×10^{-9}
^{28}Si		5.67×10^{-9}	3.21×10^{-8}
^{32}S		8.10×10^{-9}	1.95×10^{-8}
^{56}Fe		1.02×10^{-8}	5.75×10^{-8}

Cosmic-ray energisation: jet

e.g. jet-stellar wind interaction model

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

- Shear acceleration (Fermi I-like process)

  kpc jet boundaries
  - Relatively fast
  - Particle spectra flatter than $p = 2$

- Magnetic reconnection (Fermi I-like process)

  small jet scales
  - Relatively fast
  - Particle spectra flatter than $p = 2$ (?)

- Stochastic acceleration (Alfvénic or magnetosonic turbulence)
  - Slow in general, relatively fast in the jet

  kpc jet
  - No fundamental particle slope (depends on physical conditions at the source)

Hybrid models perfectly possible!

Cosmic-ray energisation: giant lobes

- Amount of entrained material: seems large, but (volume, age lobes)! → density ~ 1×10^{-8} cm^{-3} → Alfvén speed $v_A \sim 0.08c$
- Resonant acceleration time for particle of energy γ:

$$\tau_{\mathrm{res}} \simeq \frac{\gamma mc}{ZeB} \frac{c^2}{\upsilon_{\mathrm{A}}^2} \frac{U_B}{U_{\mathrm{res}}}$$

- (Wykes+13) 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: $\tau_{\mathrm{res}} \sim 5.5$ Myr, ^{16}O: $\tau_{\mathrm{res}} \sim 4.1$ 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

Propagation model

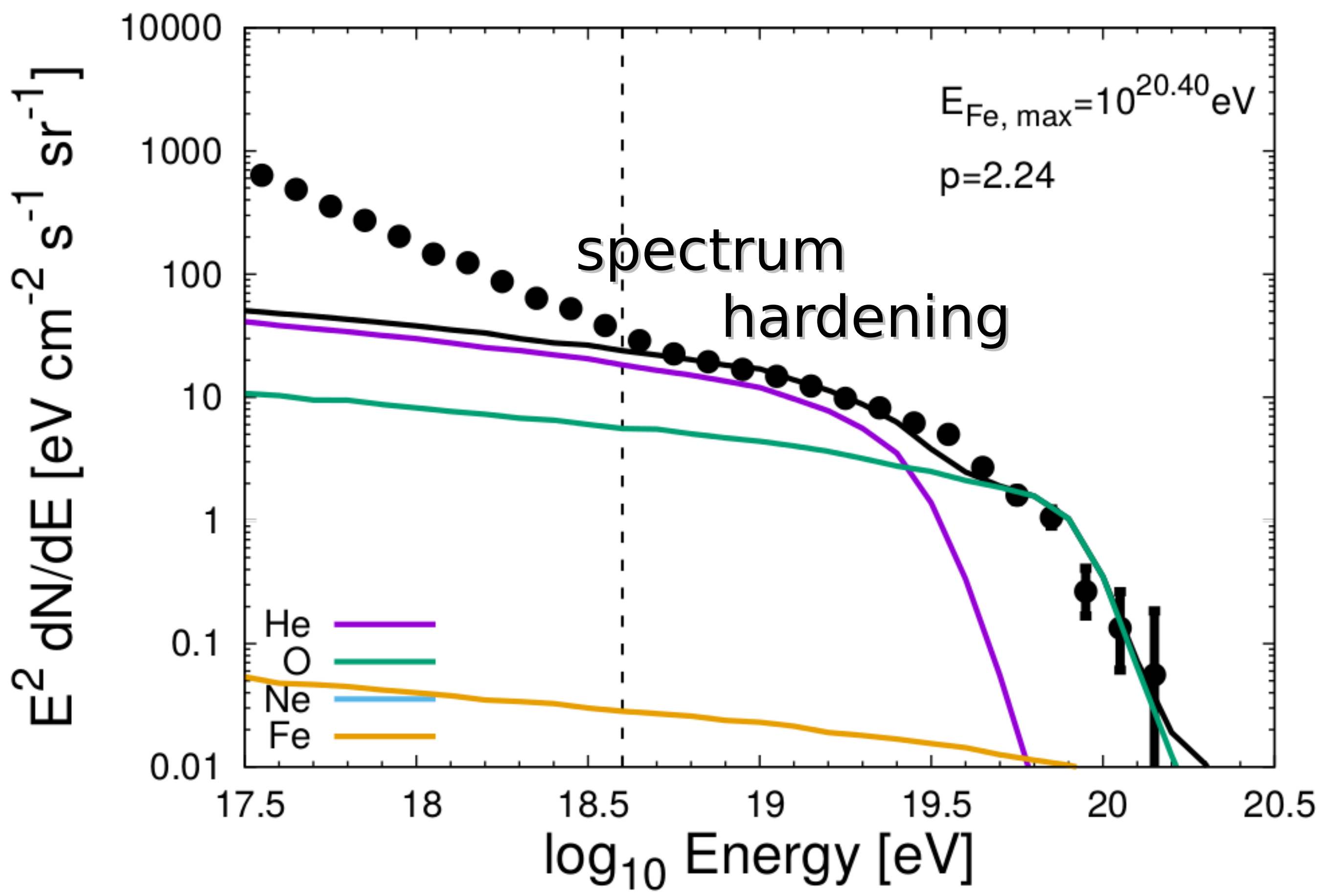
- Monte Carlo description of UHECR propagation (Taylor+15)
  - protons and nuclei propagated through CMB and CIB
  - energy losses via photodisintegration, pair production, photo-pion collisions, losses due to redshift
- Hadronic models QGSJET II-4, EPOS-LHC, Sybill 2.1
- Max ^{56}Fe energy at source 250 EeV (i.e. proton cutoff 9.6 EeV)
- Flux normalised to Auger data (so far)
- Effects of extragalactic magnetic fields (EGMFs)

  EGMF strength and coherence length are used to define scattering lengths. Particles then isotropically scattered each time they propagate a scattering length distance in the Monte Carlo simulation

  - fitting: B = 0 (simple ballistic model) and B = 1 nG
  - coherence length: 0.1 Mpc
  - turbulence slope: Kolmogorov
- Scanning over particle index

Propagation spectra: mixture of ^{4}He, ^{16}O, ^{20}Ne and ^{56}Fe

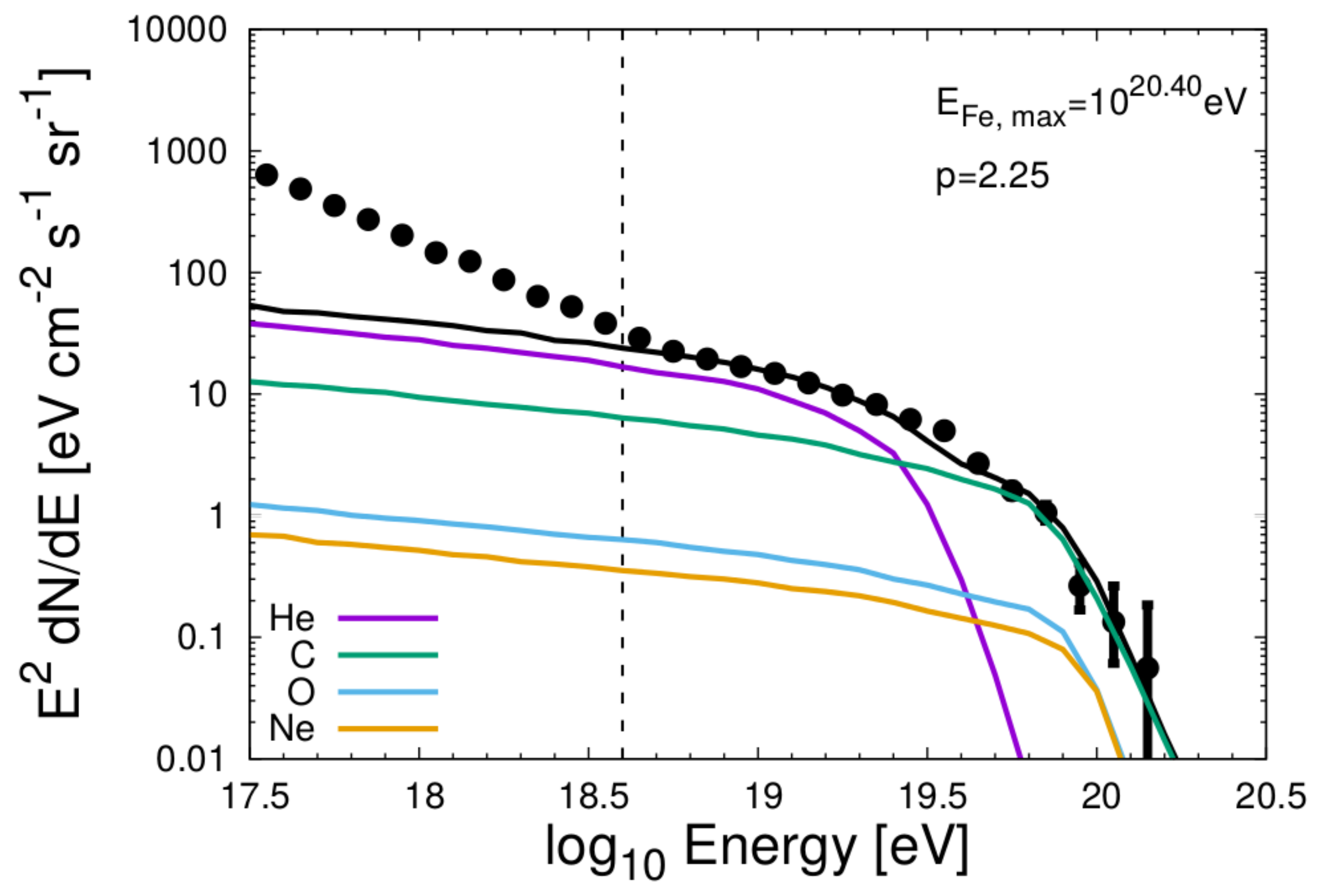
^{16}O best fit at UHE; ^{20}Ne and ^{56}Fe hardly required at all



Propagation spectra: mixture of ^{4}He, ^{12}C, ^{16}O and ^{20}Ne

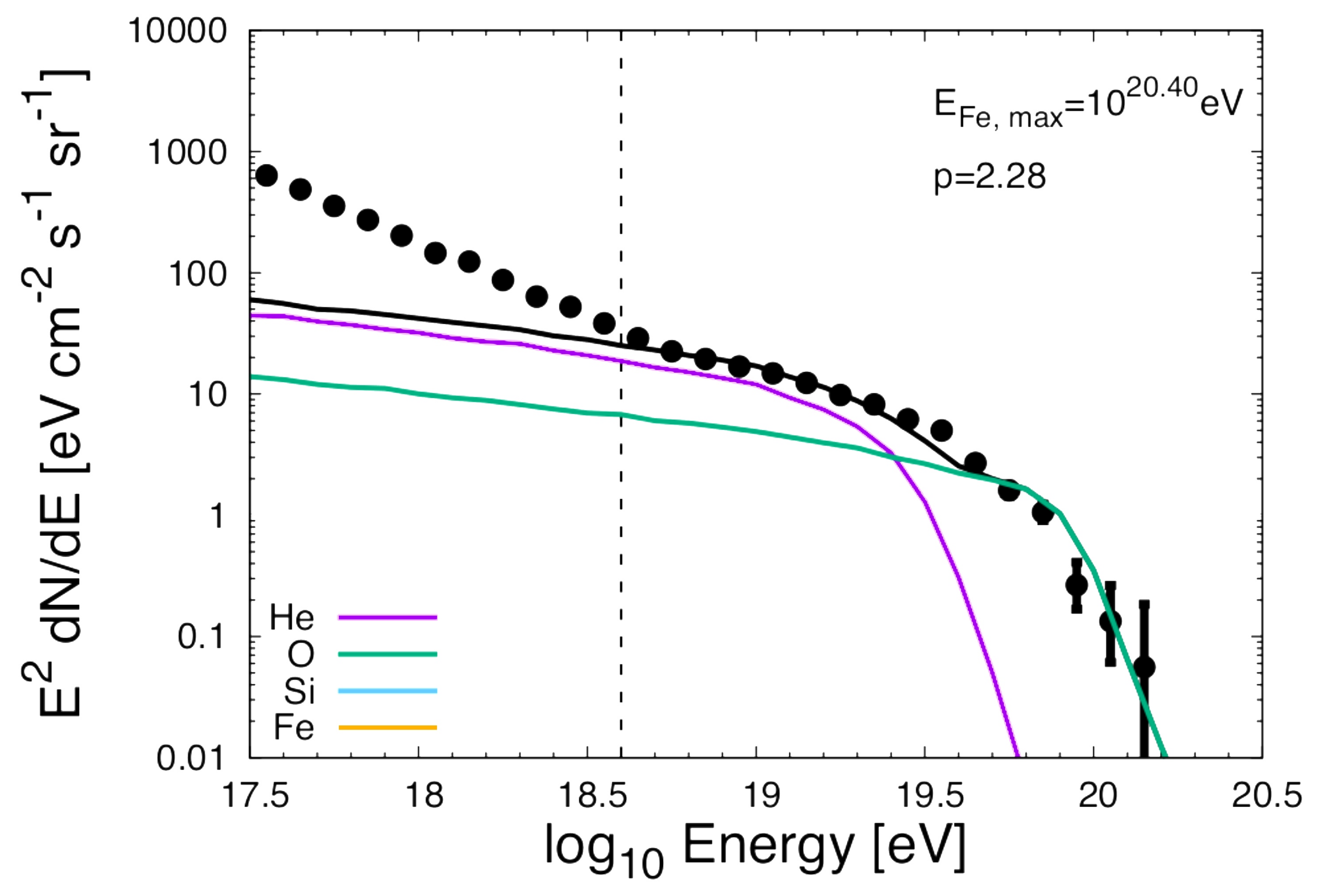
^{12}C best fit at UHE

^{12}C spectrum break earlier than ^{16}O (Lorentz factor effect) – makes larger fraction of ^{12}C preferable in the admixture



Propagation spectra: mixture of ^{4}He, ^{16}O, ^{28}Si and ^{56}Fe

^{16}O best fit at UHE; ^{28}Si and ^{56}Fe not required at all



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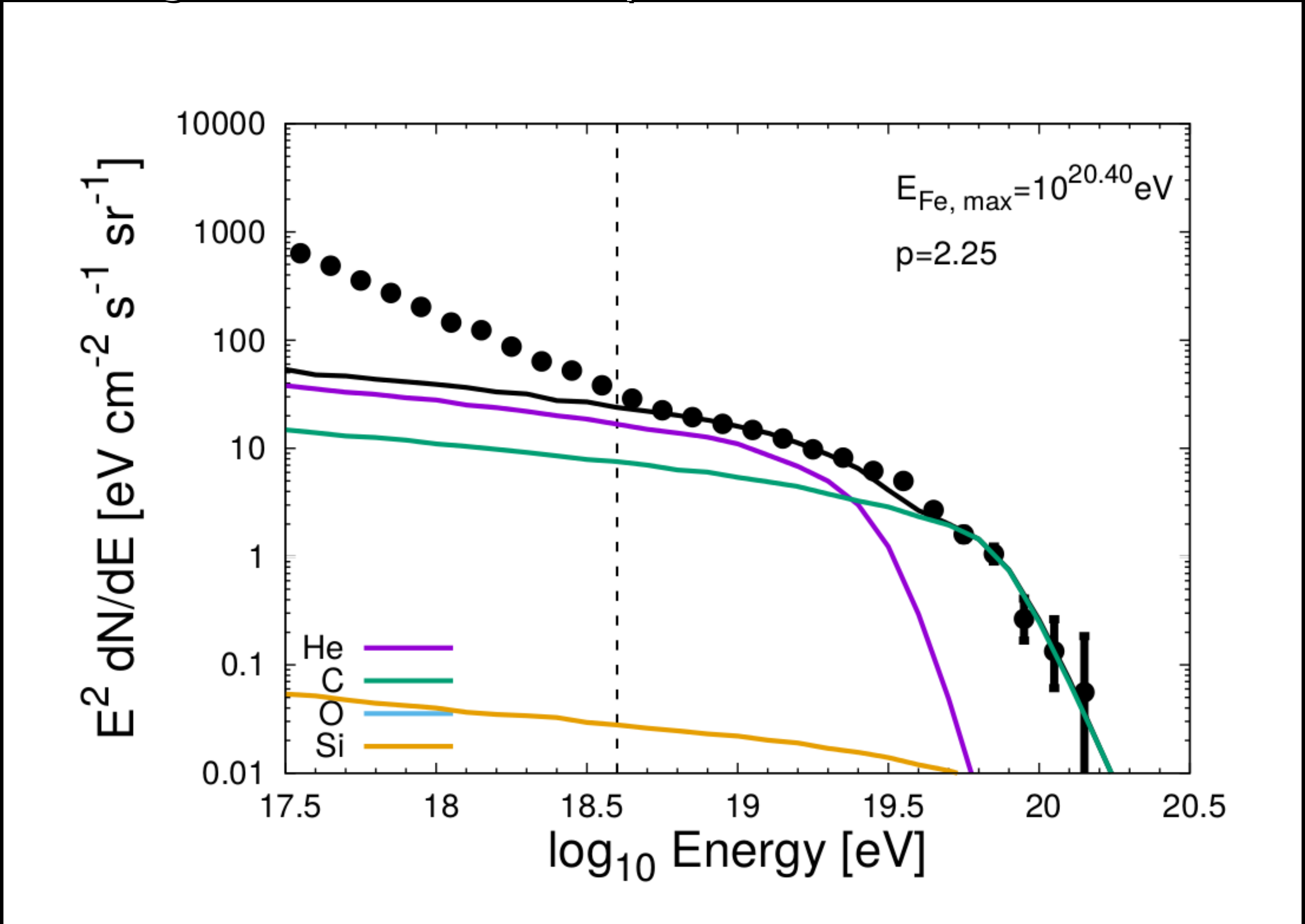
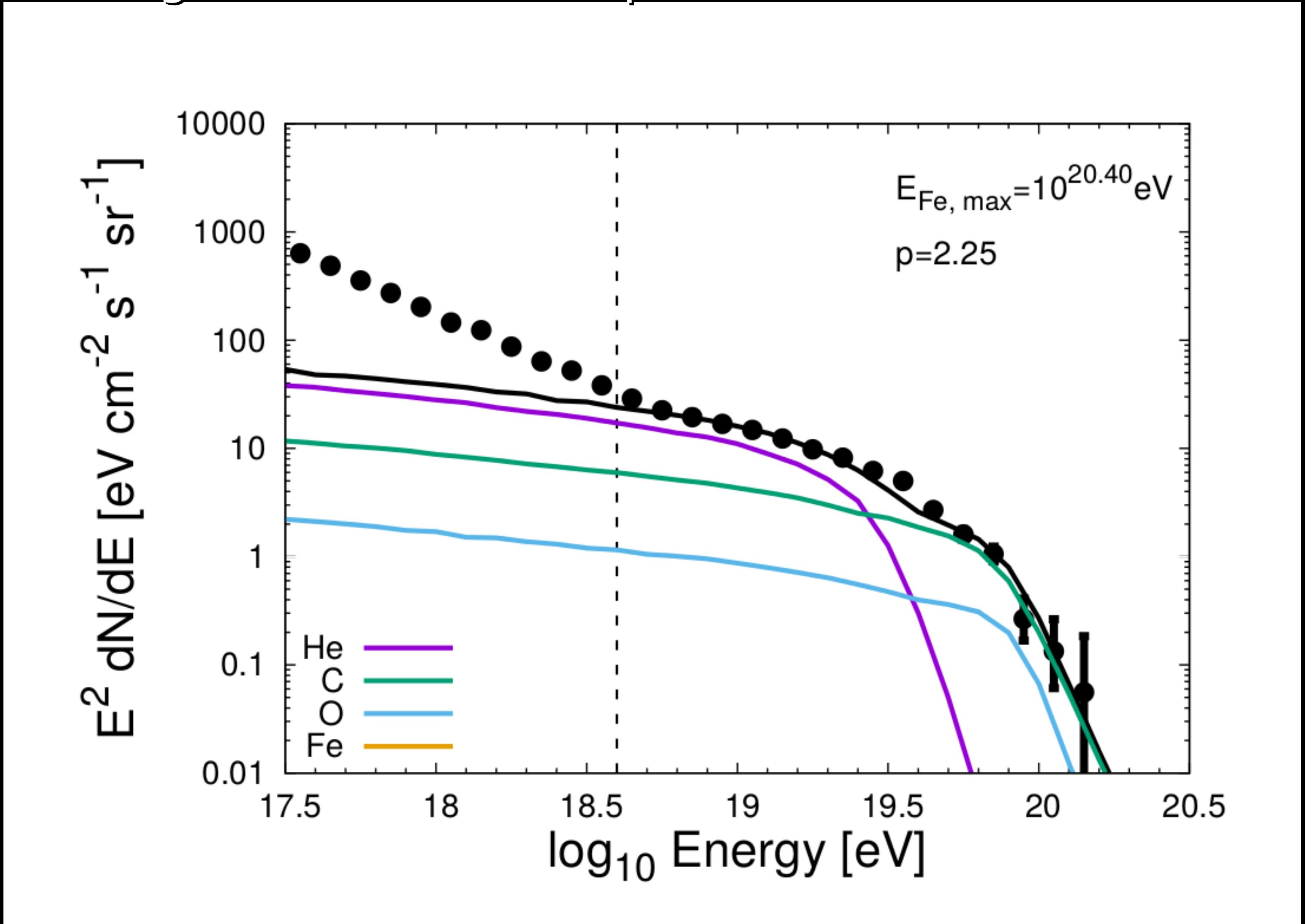


Propagation spectra: mixture of ^{4}He, ^{12}C, ^{16}O and ^{56}Fe

^{12}C best fit at UHE; ^{16}O some contribution

^{12}C spectrum break earlier than ^{16}O (Lorentz factor effect) – makes larger fraction of ^{12}C preferable in the admixture

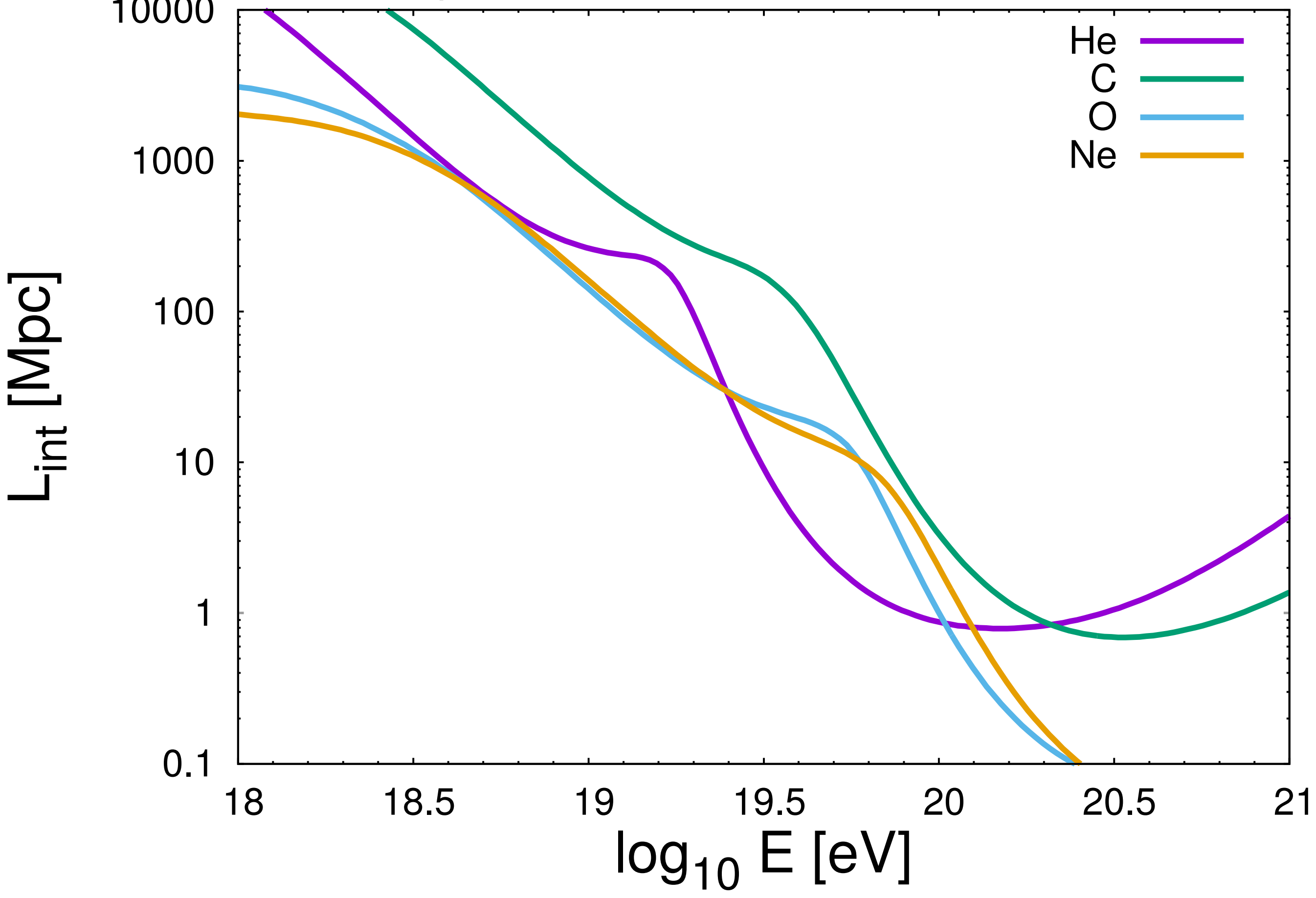


Interaction length (energy loss length)

^{12}C relatively robust; ^{16}O and ^{20}Ne relatively fragile at 100 EeV; robustness higher at lower energies

important decay channels feed into ^{12}C:

$^{16}\mathrm{O} \rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}$; $^{20}\mathrm{Ne} \rightarrow {}^{16}\mathrm{O} + {}^{4}\mathrm{He}$



First prediction of composition of an extragalactic jet on kpc scale:
Composition of Centaurus A's jet largely solar-like, originating from stellar mass-loss
→ seeds

Propagation: preliminary conclusions

- Centaurus A and/or other nearby sources well motivated as source of UHECRs by composition and spectral shape
- Best-fitting isotopes with maximum ^{56}Fe energy fixed at 250 EeV are ^{12}C to ^{16}O. Species too closely spaced in mass number for a clear preference for either ^{12}C or ^{16}O (or ^{14}N)
- Best-fitting particle spectral index in the range 2.2 – 2.3, compatible with plausible acceleration scenarios at the source
- Flux normalisation and diffusion yet to be fully addressed