ULTRA-HIGH ENERGY COSMIC RAYS FROM RADIO GALAXIES

James Matthews

Tony Bell, Katherine Blundell, Anabella Araudo

UHECR 2018, Paris

Image credits

Fornax A: NRAO/AUI and J. M. Uson

Cen A: Feain+ 2011, Morganti+ 1999

Pictor A: X-ray: NASA/CXC/Univ of Hertfordshire/M.Hardcastle et al., Radio: CSIRO/ATNF/ATCA

PART 1: PHYSICAL REQUIREMENTS

See Tony Bell's talk!

- Requirements for acceleration to high energy:
  - Non-relativistic shock

$$u < c$$

  - Hillas condition

$$uBL \sim R$$

- Minimum power requirement

$$Q \gtrsim 10^{43}\ erg/s \left(\frac{u}{0.1c}\right)^{-1}\left(\frac{R}{10EV}\right)^{2}$$

<u>Can shocks in radio galaxies meet these criteria?</u>

Throughout talk, R = E/Z

Can shocks in radio galaxies meet these criteria?

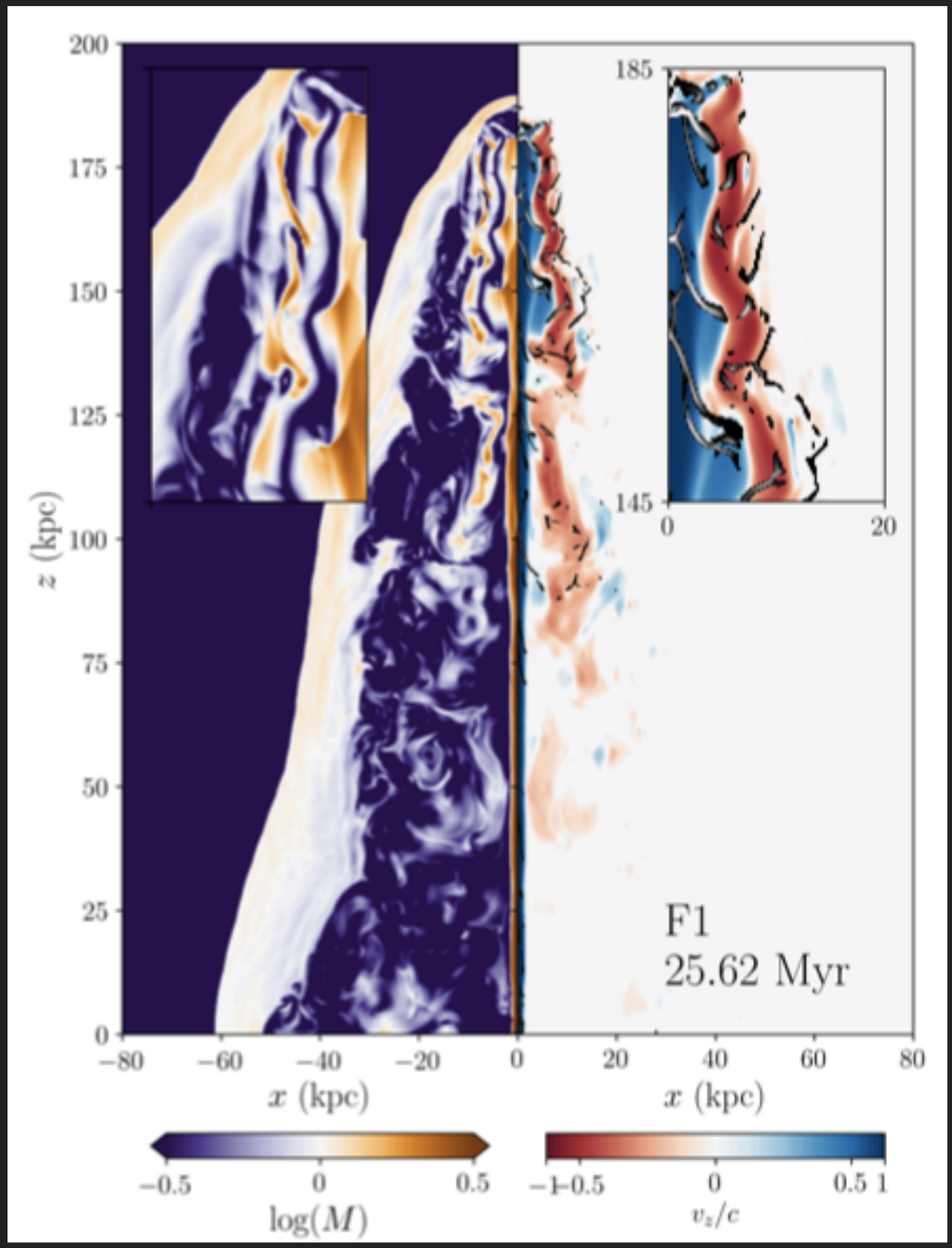
To investigate, we use hydrodynamic simulations of jets

Throughout talk, R = E/Z

JET SIMULATIONS: V, M, COMPRESSION

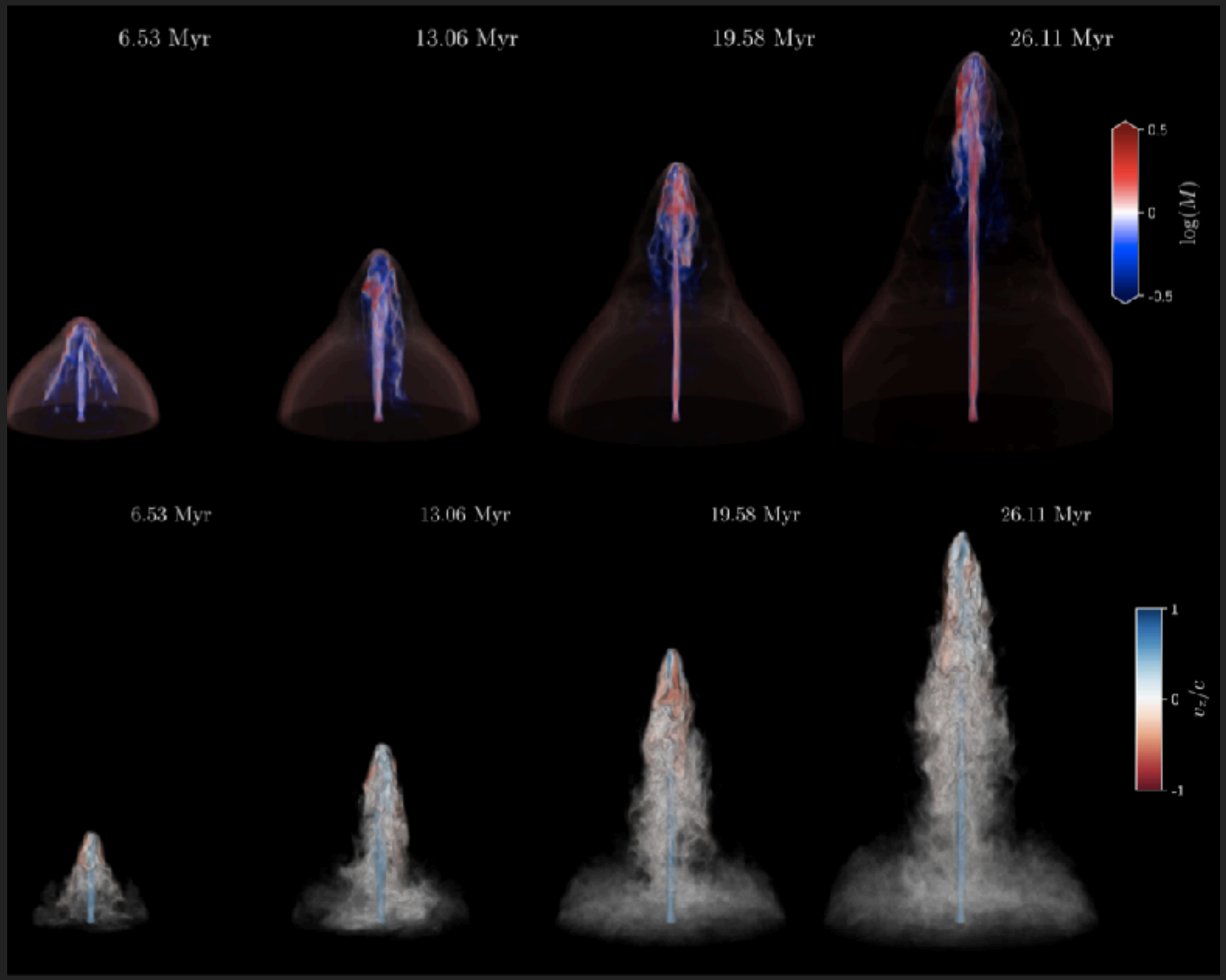
Matthews+ 2018b

- We have conducted relativistic hydro sims of light jets in a realistic cluster
  - 2D and 3D, using PLUTO, a shock capturing Godunov code
- Jets produce strong backflow
- Backflow can be supersonic -> shocks
- We clearly observe compression structures and pressure jumps
- Observed in other simulations (e.g. Saxton+ 2002)



JET SIMULATIONS: 3D

Matthews+ 2018b

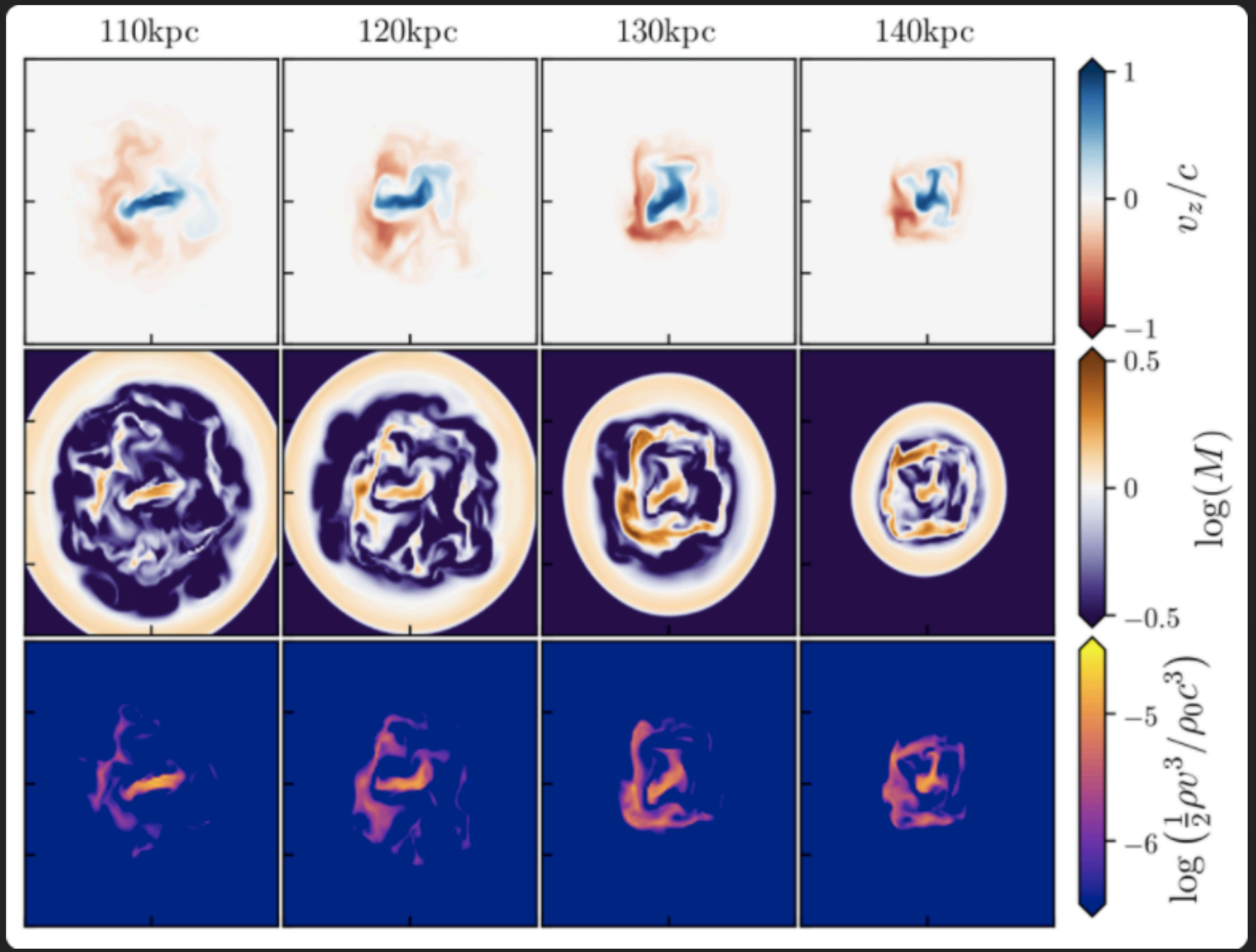


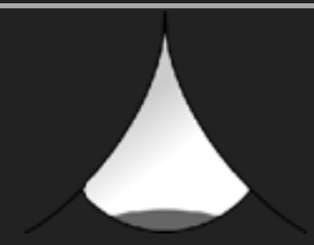
Mach number

Vertical velocity

JET SIMULATIONS: 3D

Matthews+ 2018b

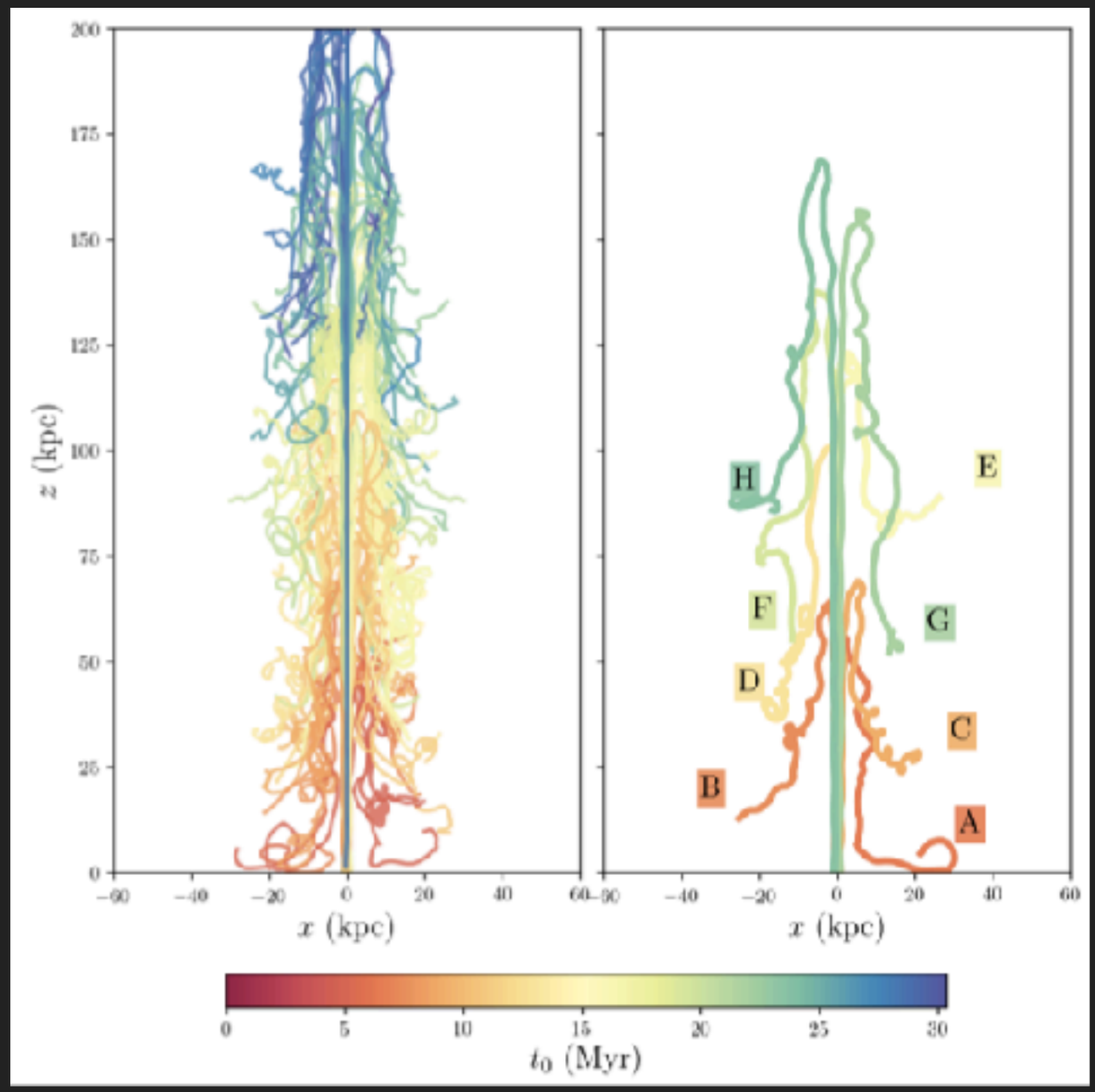




SHOCK DIAGNOSTICS

Matthews+ 2018b

- Lagrangian tracer particles track shock crossings
- Simulations post-processed to calculate shock-sizes, velocities, Mach numbers and internal energy
- Characteristic B field estimated
  - Could do MHD, but can't resolve scales that matter (r_g) for UHECR acceleration

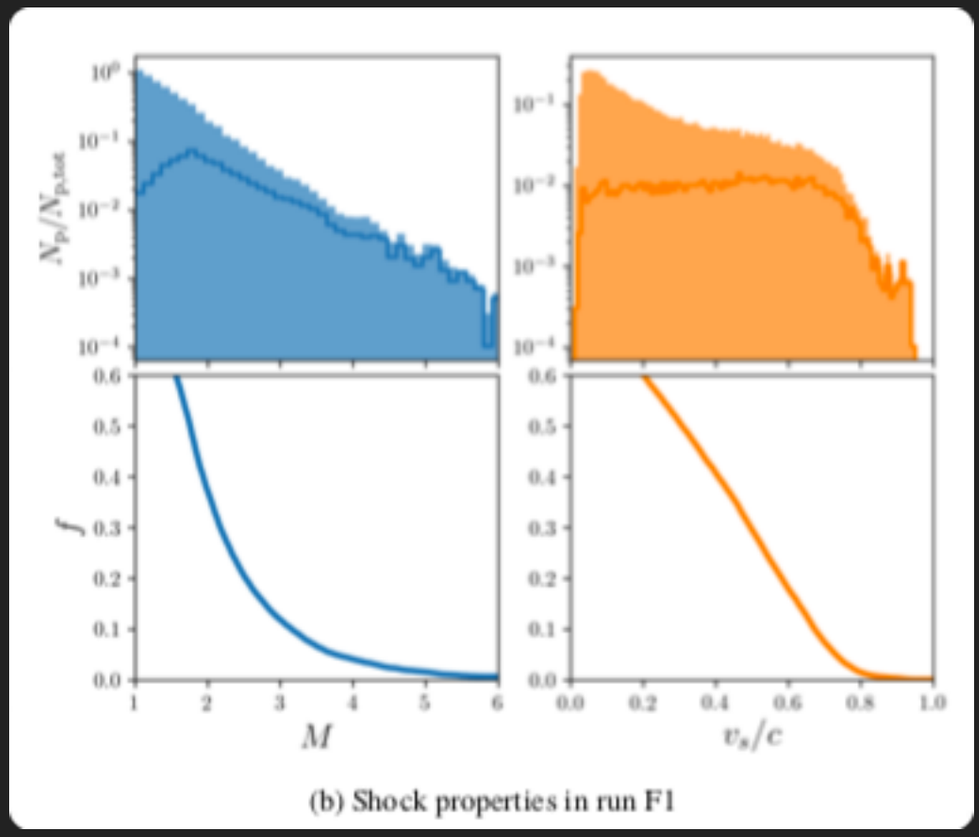


(i) show compression, $\nabla \cdot \boldsymbol{v} < 0$;
(ii) show a pressure jump, $\Delta P/P > \epsilon_p$;

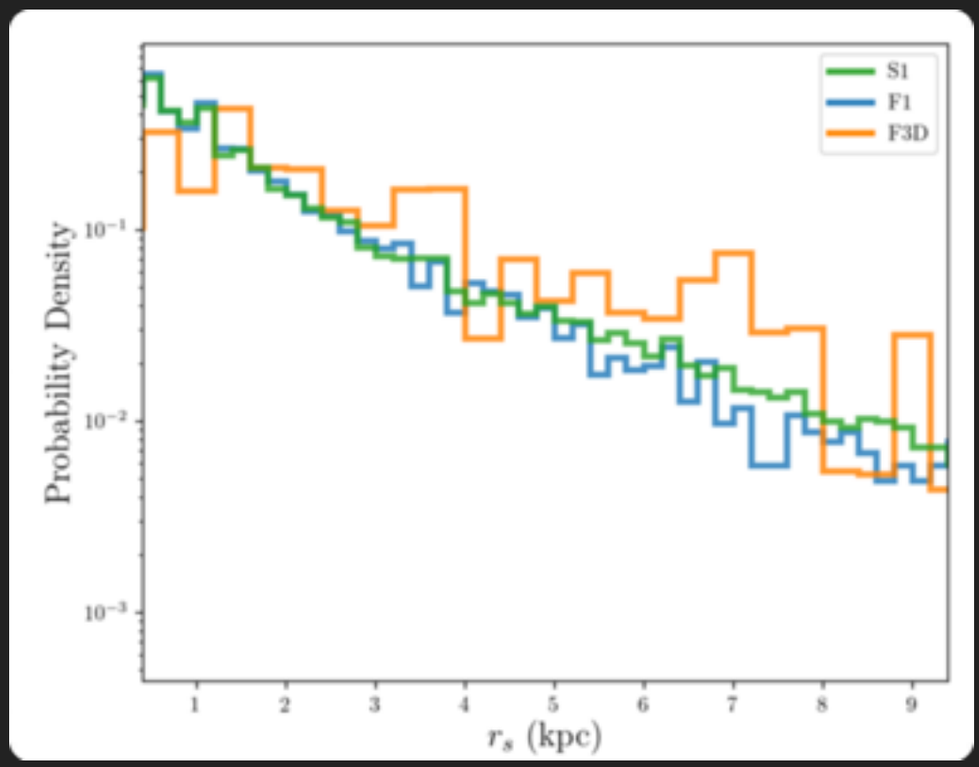
SHOCK DIAGNOSTICS

Matthews+ 2018b

- We find:
  - About 10% of particles pass through a shock of M>3
  - Shock velocities have range of values (Take 0.2c as typical)
  - ~2 kpc typical shock size
  - 5% of particles pass through multiple strong shocks
- Hillas estimate taking 140 microG:
  - **<u>Maximum rigidity R=E/Z~50 EV</u>**



(b) Shock properties in run F1



PHYSICAL REQUIREMENTS RECAP

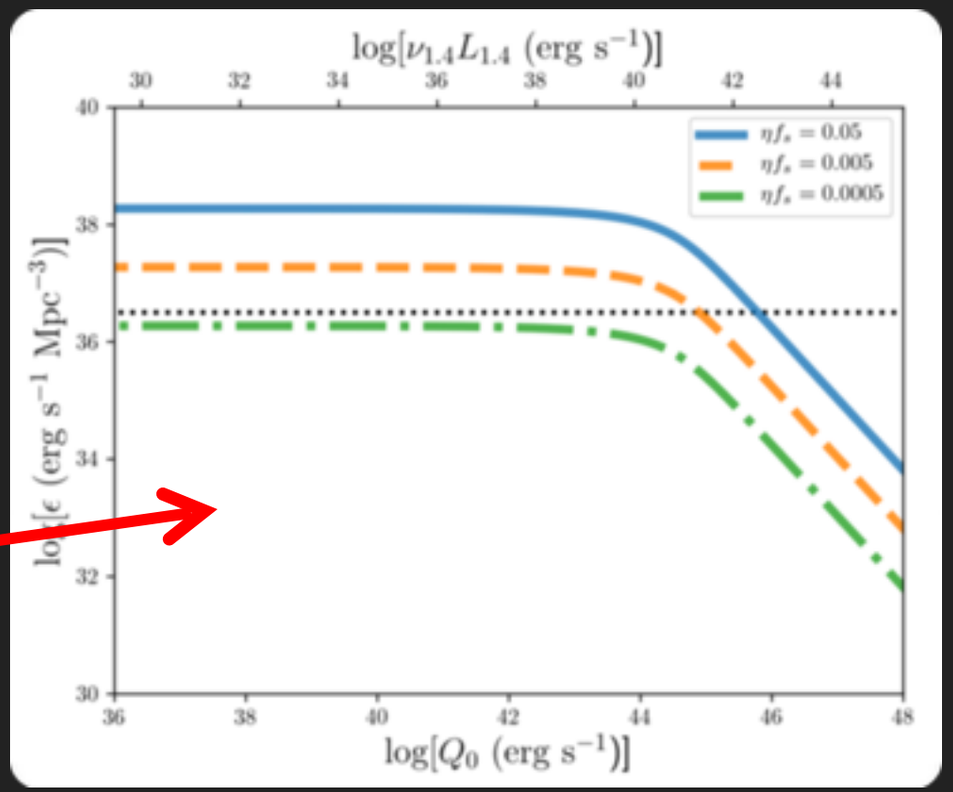
- Requirements for acceleration to high energy:
  - Non-relativistic shock ✓ $u < c$
  - Hillas condition ✓ $uBL \sim R$
- Minimum power requirement? $Q \gtrsim 10^{43}\ erg/s \left(\frac{u}{0.1c}\right)^{-1}\left(\frac{R}{10EV}\right)^{2}$

We also need to reproduce the right number of UHECRs at Earth?

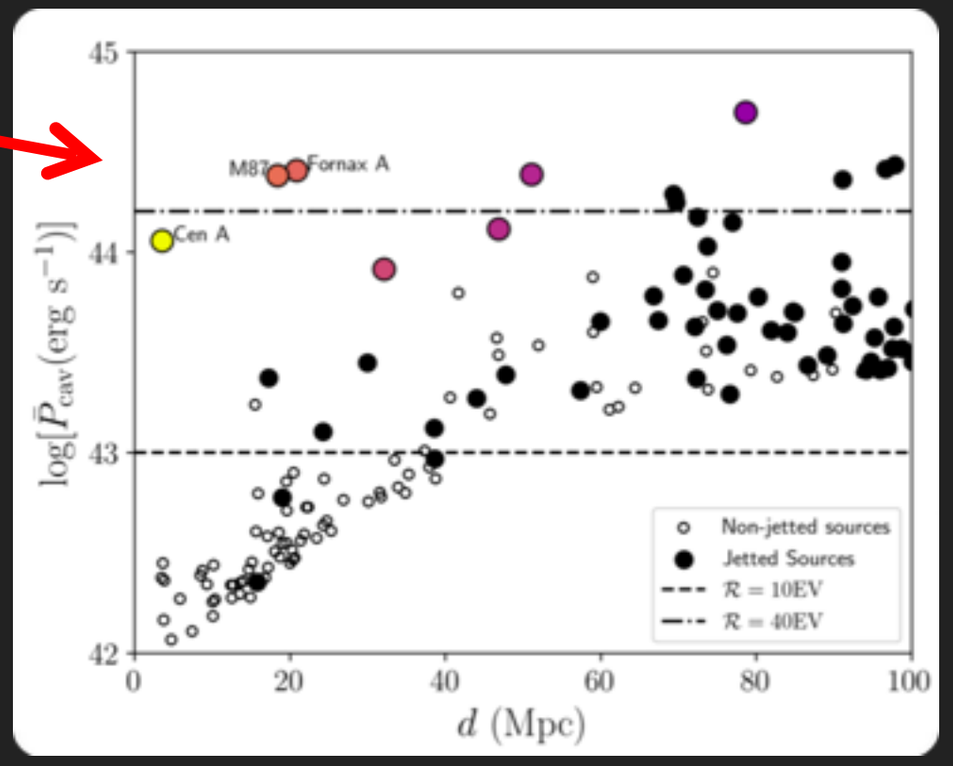
ARE THERE ENOUGH POWERFUL SOURCES?

Matthews+ 2018b

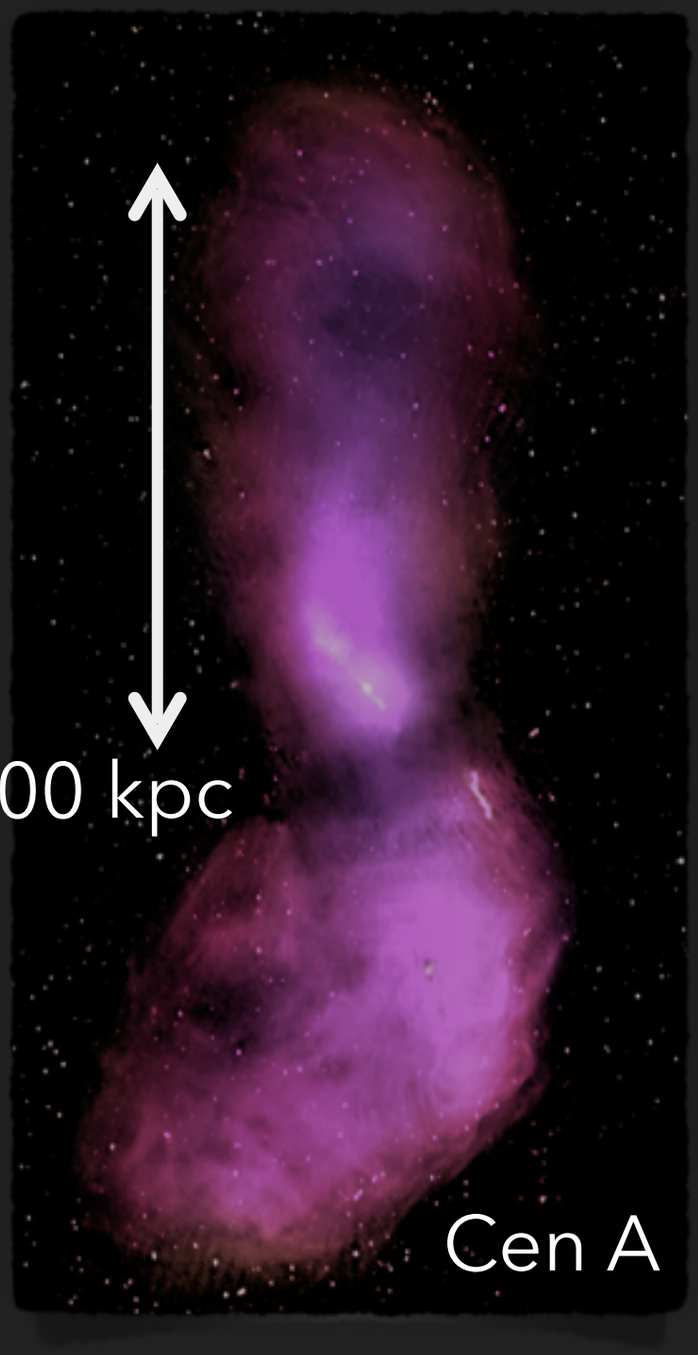
- These two requirements can be expressed as an integral over radio galaxy luminosity function above power threshold
- Powerful RGs are on average common and energetic enough to produce UHECR flux



- But, barely any currently active sources within GZK horizon satisfy power constraint!
  - *Starburst winds are slow and can't satisfy power constraint - much worse for UHECR.*
- Are the sources variable / intermittent?

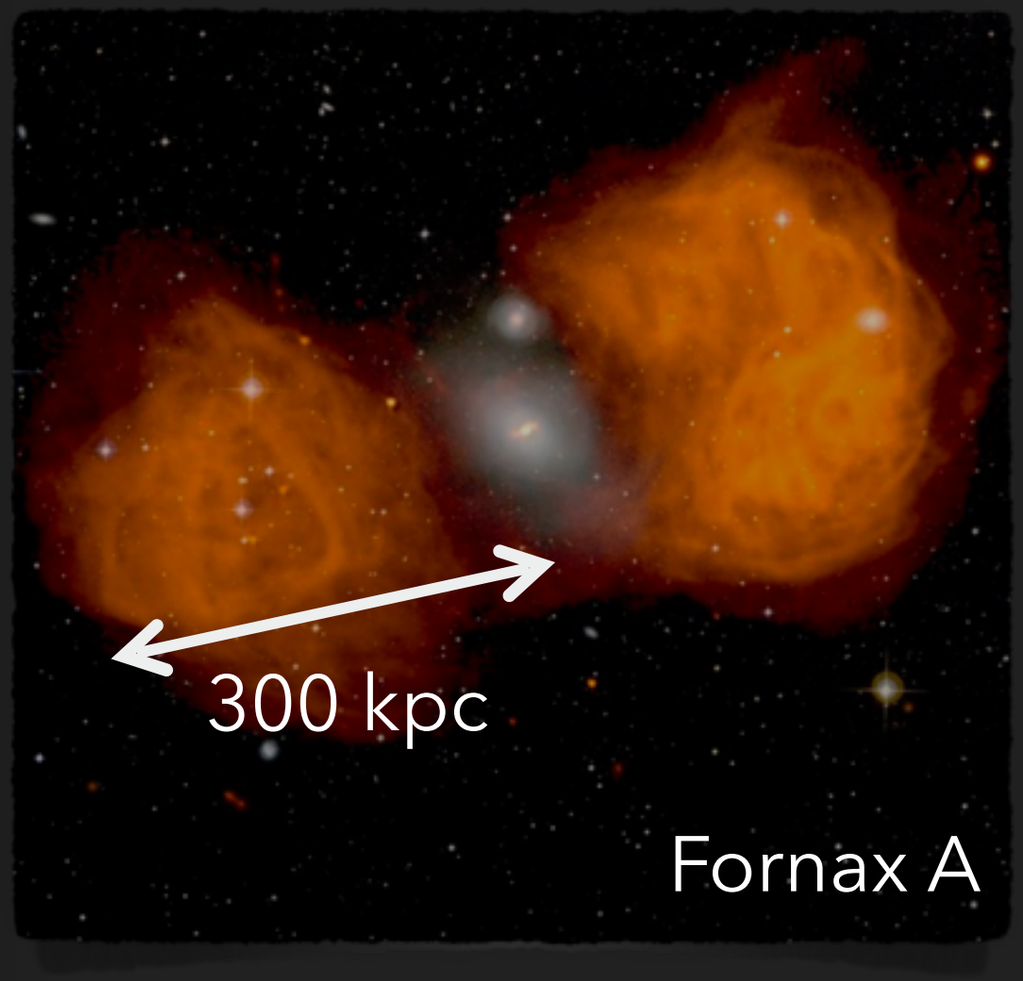


DORMANT RADIO SOURCES AS UHECR RESERVOIRS



Low-power jets

Large lobes, energy content $>10^{58}$ erg



- Declining AGN activity in Fornax A
- Recent merger activity in both sources
- “Dormant” radio galaxies? More active in the past?

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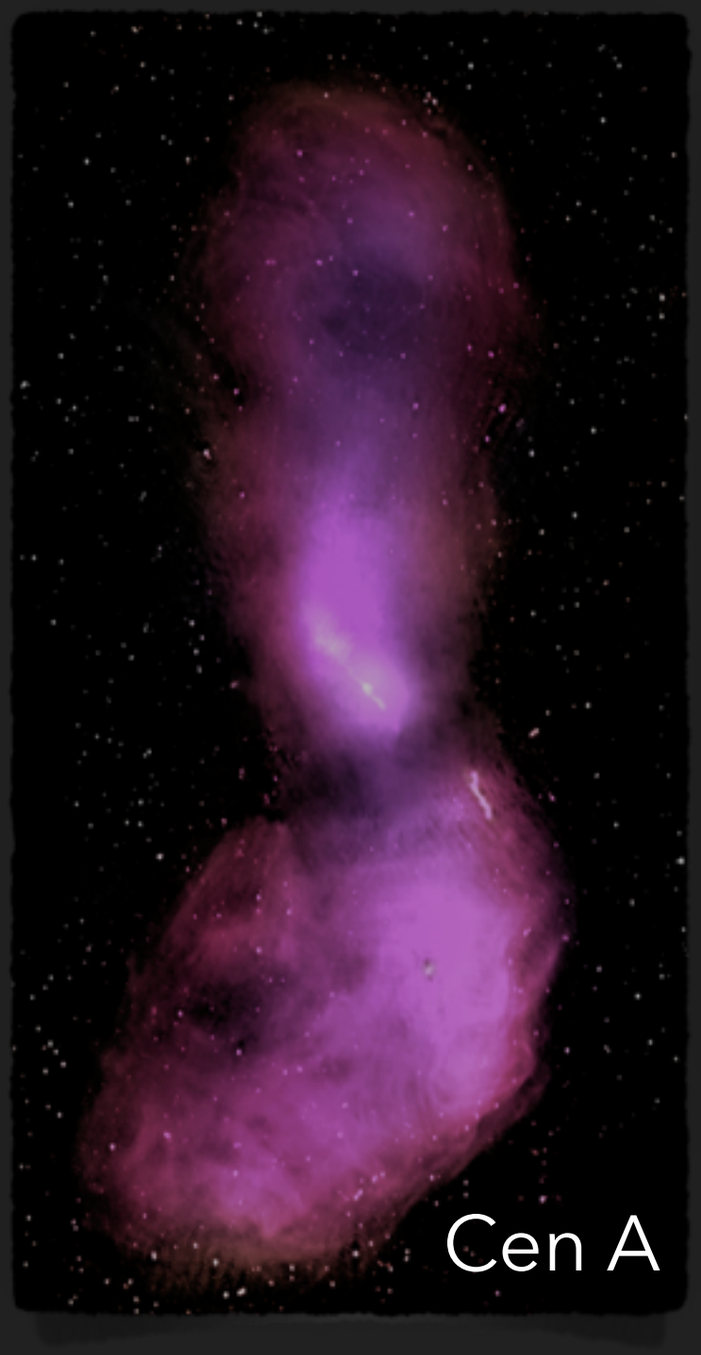

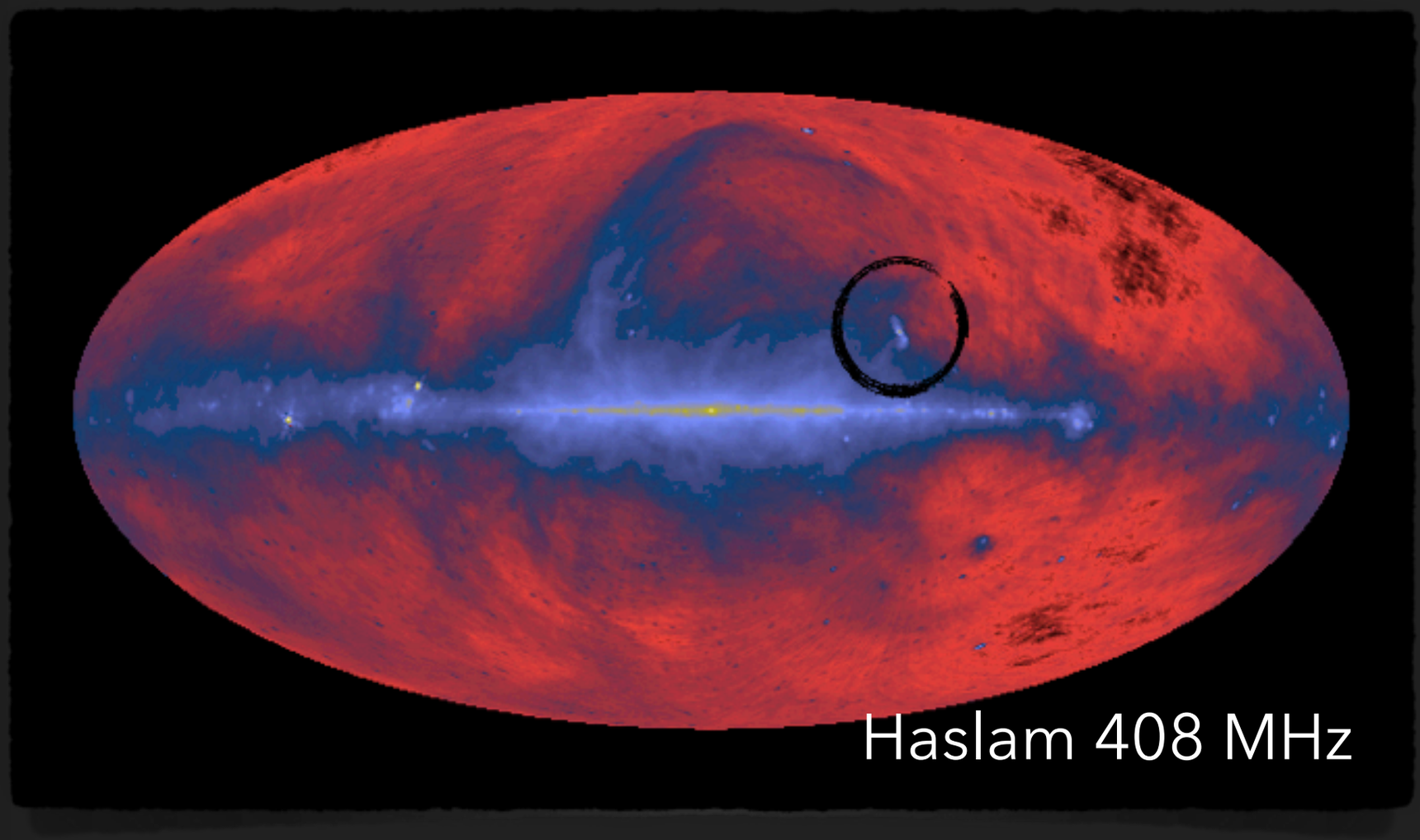

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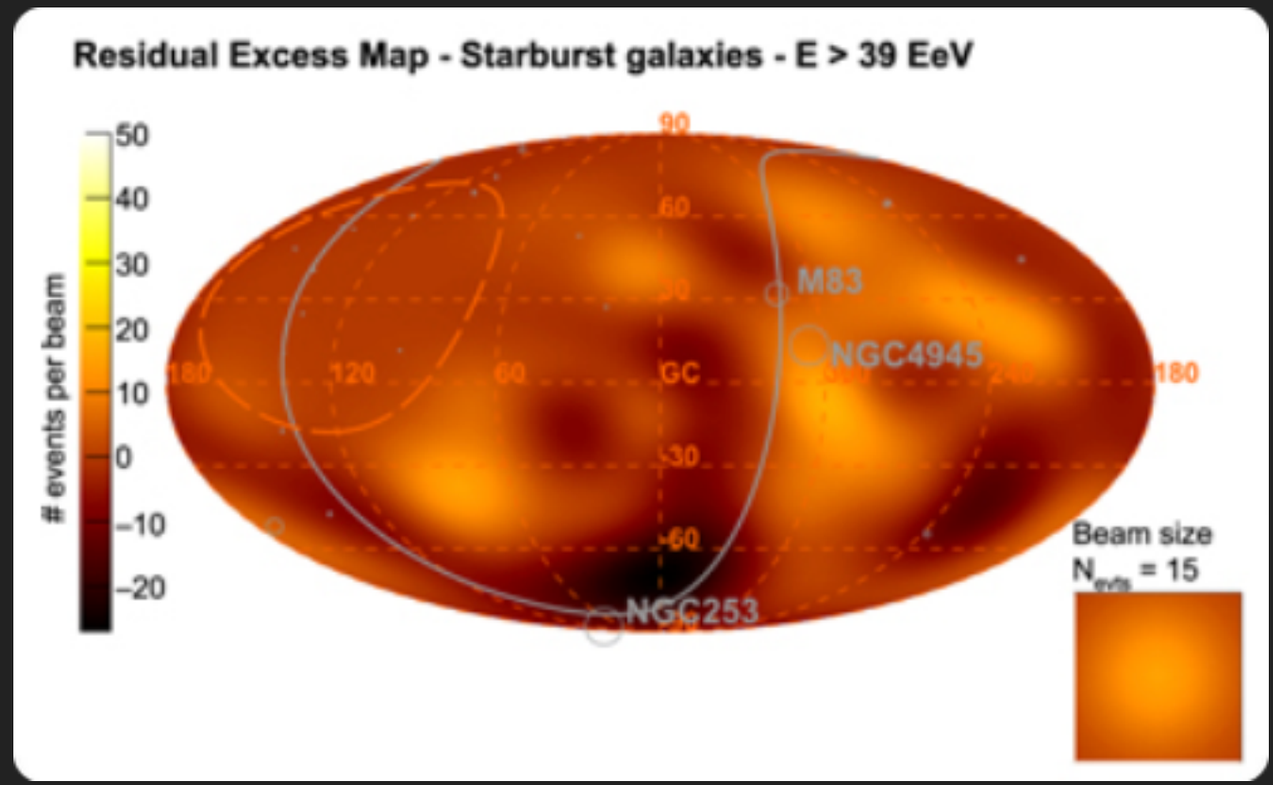
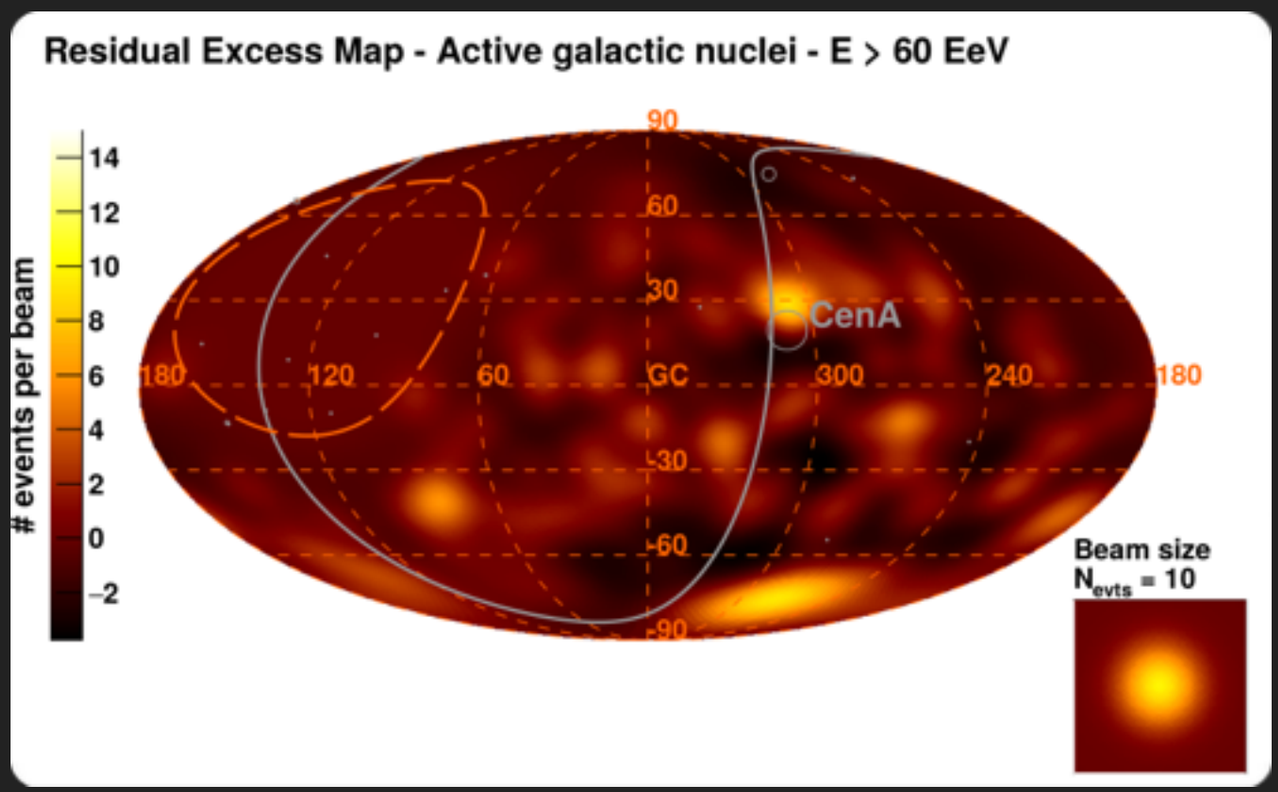
PART 2: ARRIVAL DIRECTIONS

Aab+ 2018

- Aab et al. 2018 (A18) show PAO anisotropies correlated with AGN and SBGs
- 2 Main residuals in AGN fit near Cen A and southern galactic pole
- Scenario A uses quite a short attenuation length, spectral index of 1
  - based on “data-driven” model assuming homogeneity
- ***Used 2FHL catalog - no Fornax A, and Cen A flux lower than in 3FHL***

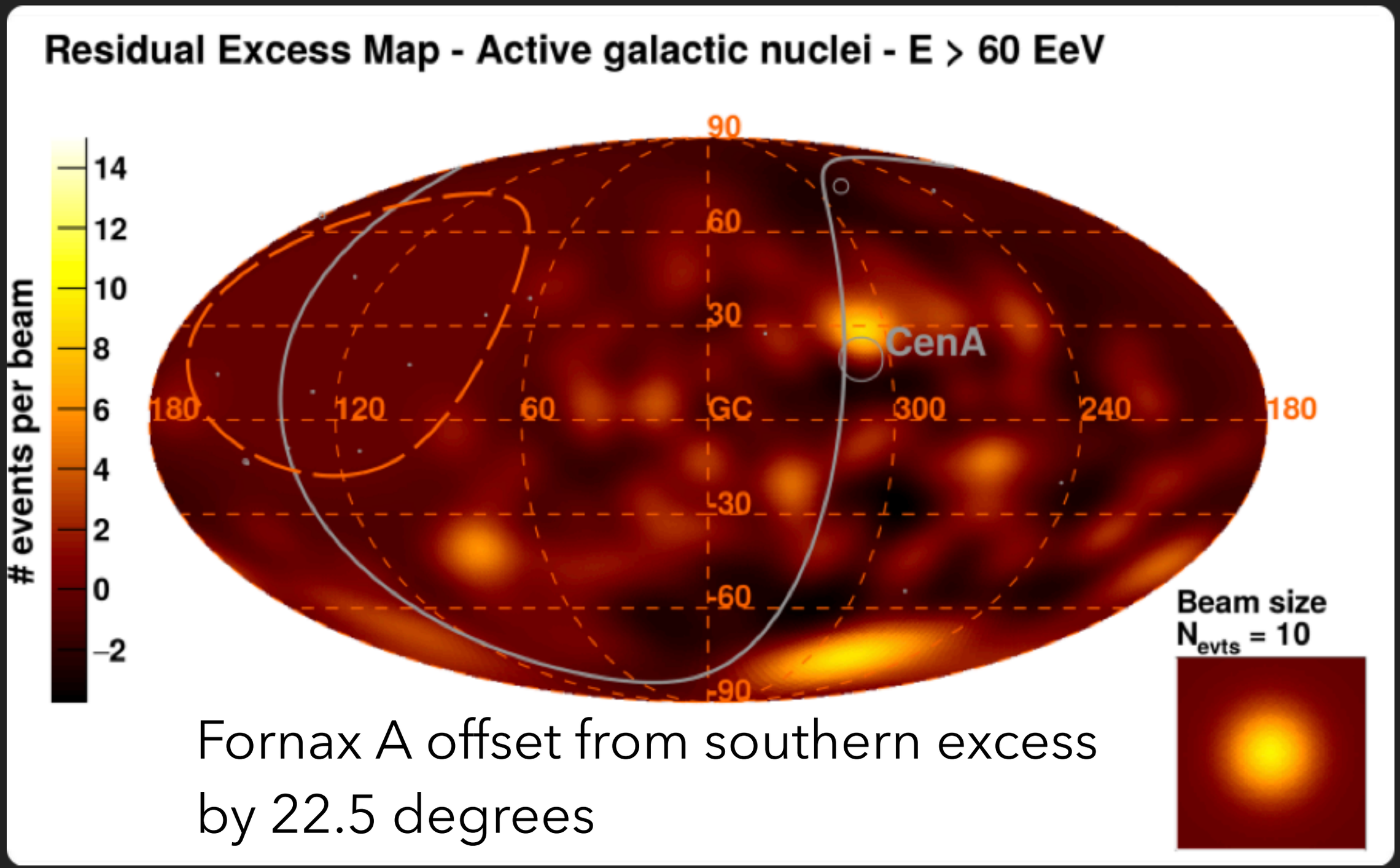




ARRIVAL DIRECTIONS

Matthews+ 2018a

- The same sources I discussed are also compellingly close to Auger excesses!



Fornax A offset from southern excess by 22.5 degrees

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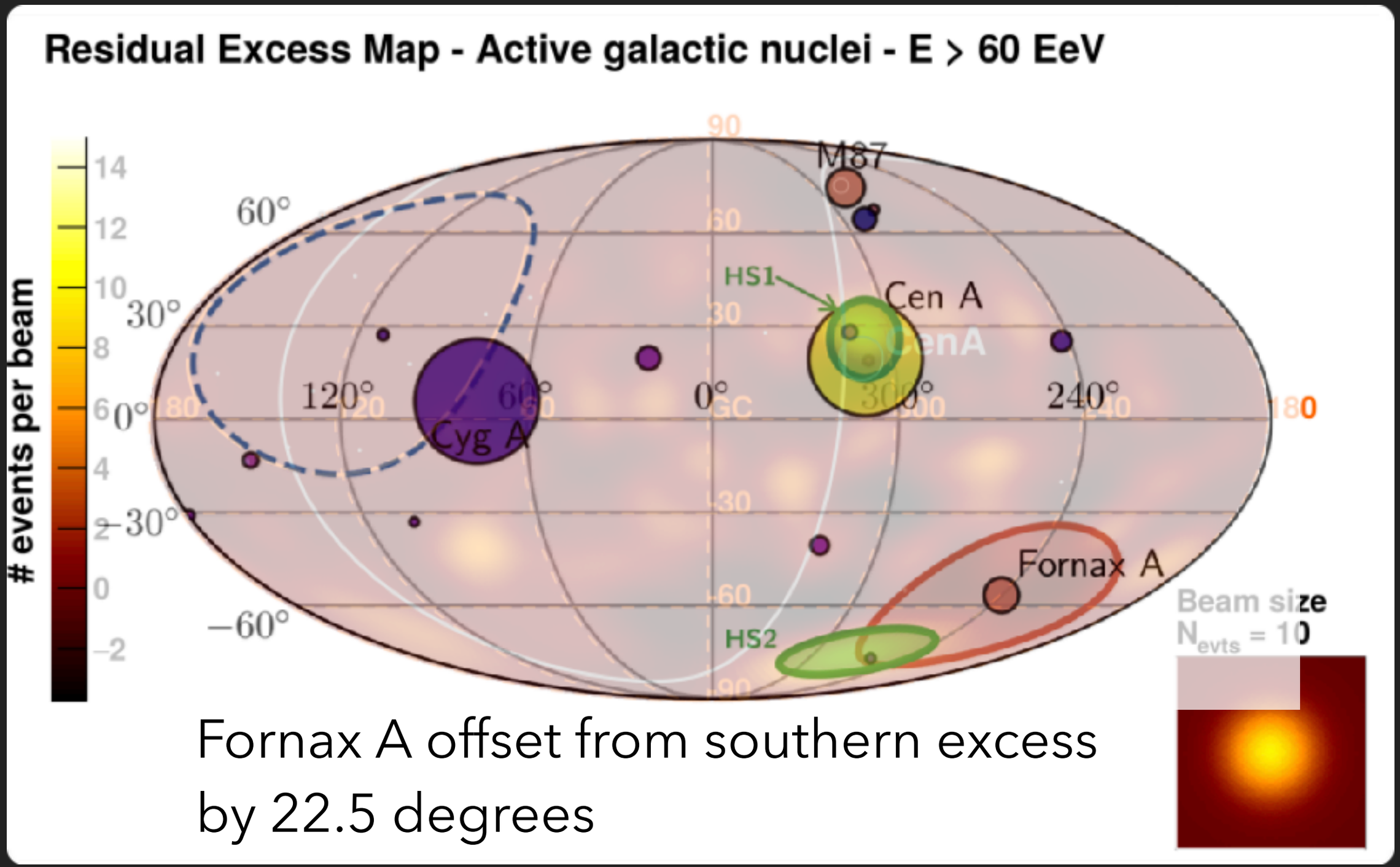

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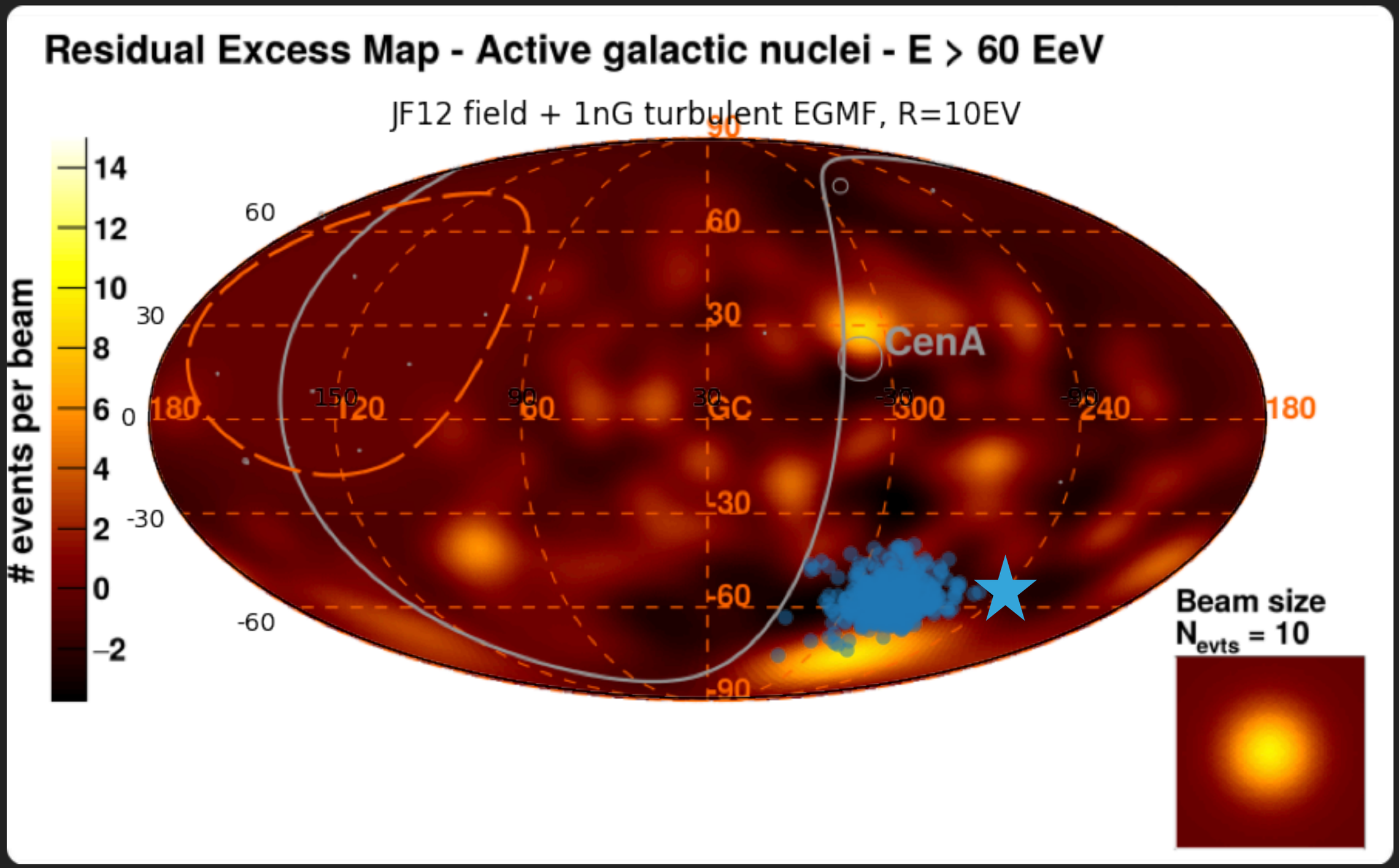
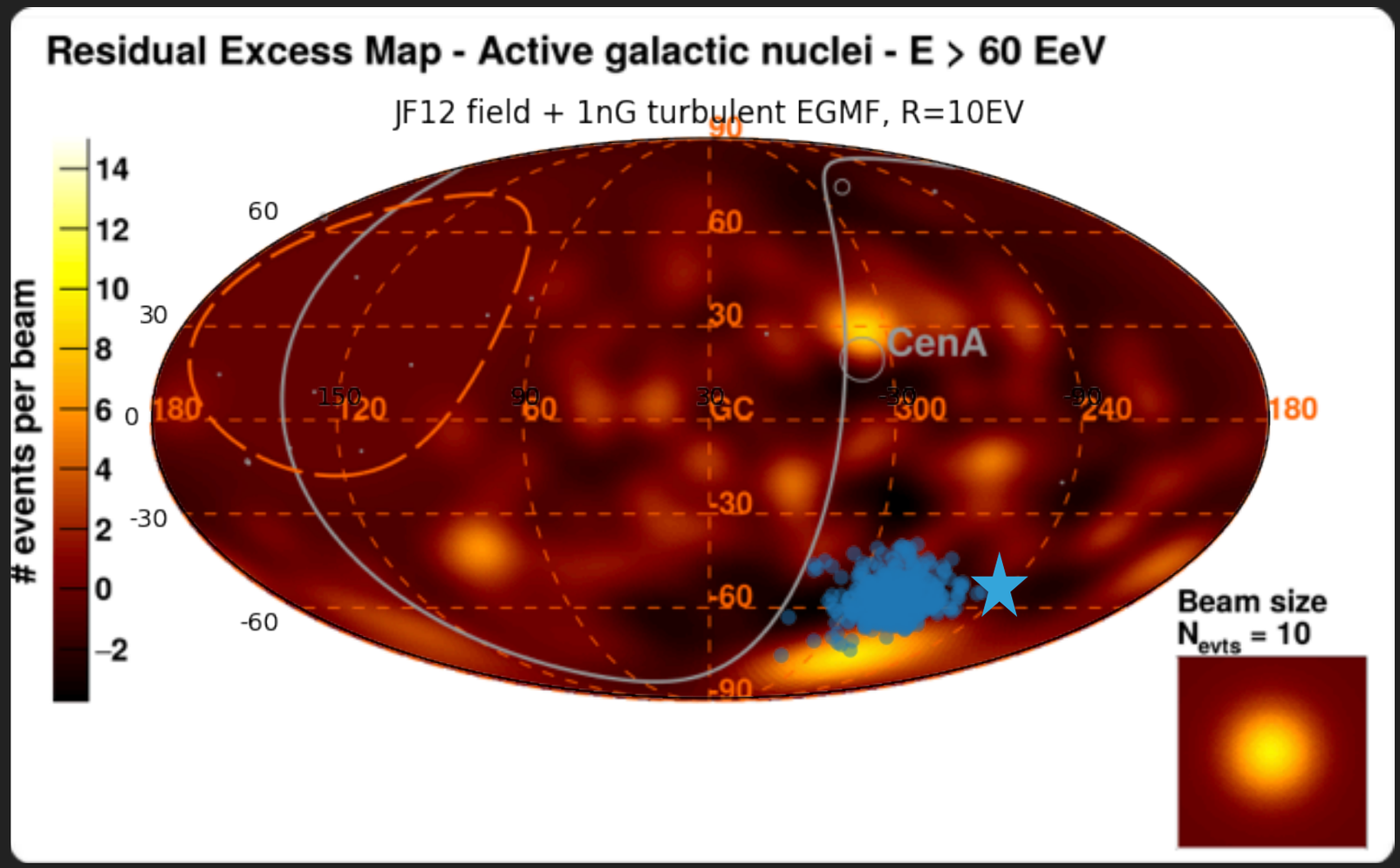


ARRIVAL DIRECTIONS

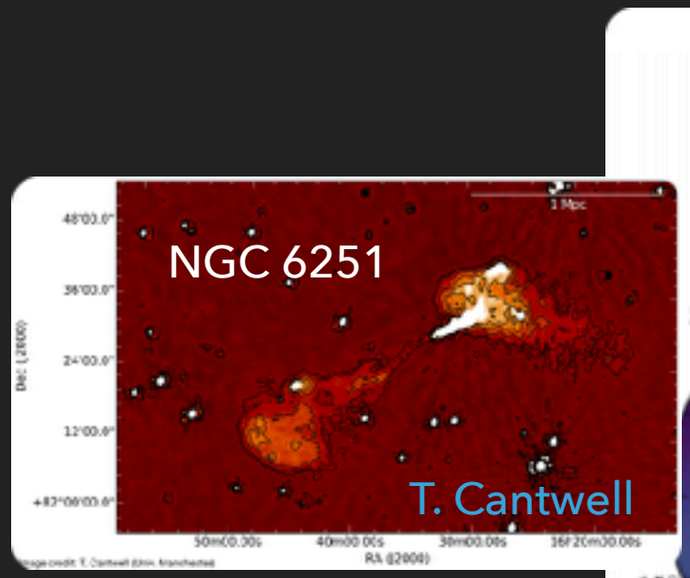
- Deflection of R=10EV UHECR goes roughly the right way, using CRPROPA3 (Alves-Batista+ 2016) with “Full” Jansson & Farrah 2012 lens
- Scatter in particles EGMF and JF12 turbulent component comparable to angular separation from source
- Affected by large uncertainty in EGMF, GMF and Composition

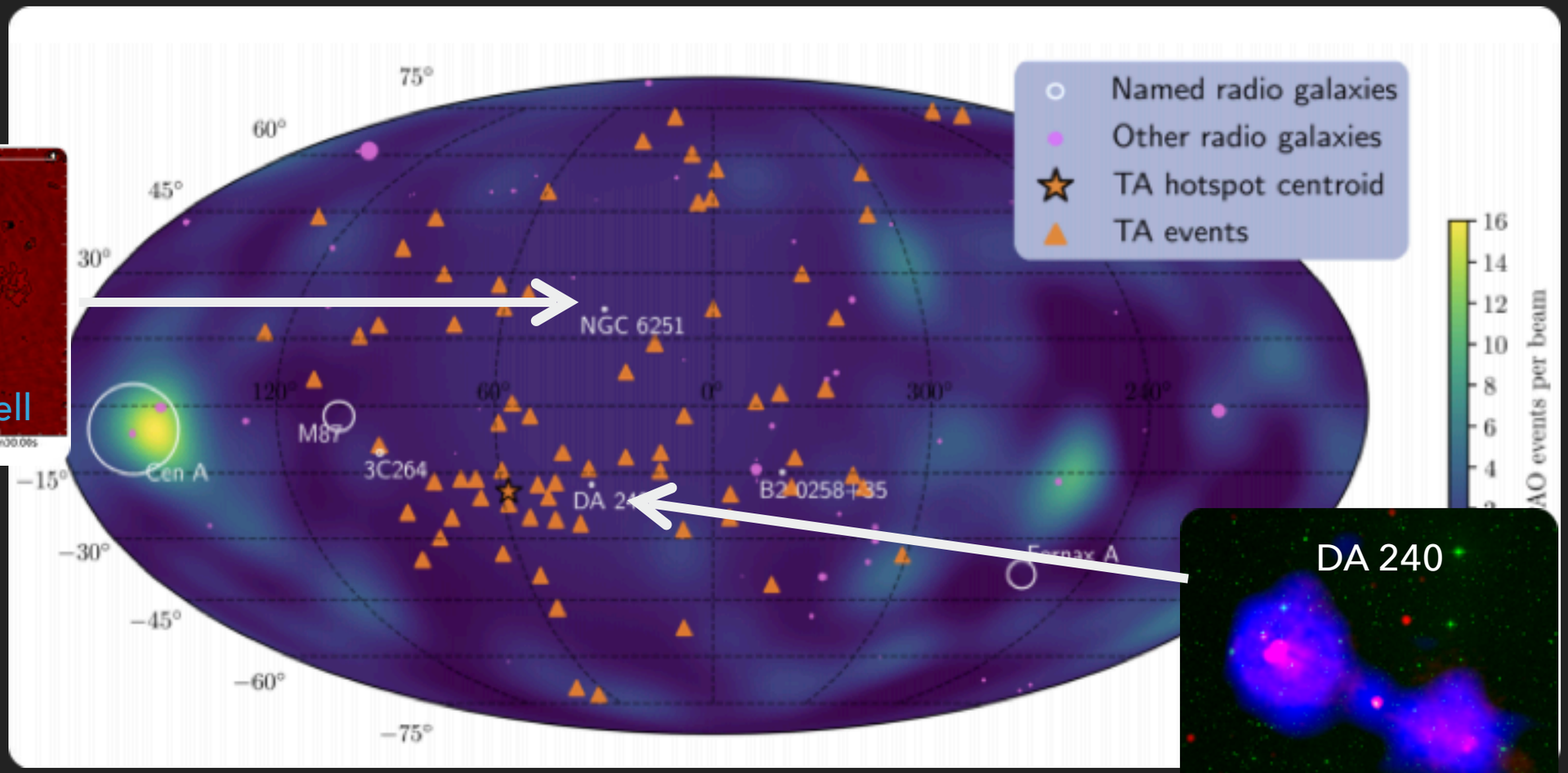


WHAT ABOUT TA?

Matthews+ 2018a,b

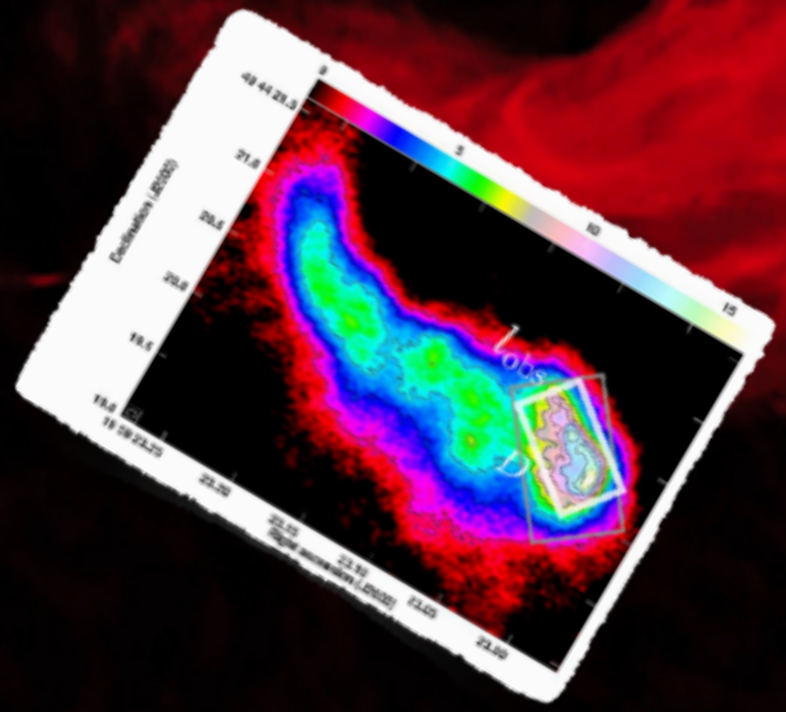
- Southern hemisphere: UHECR escaping from reservoirs in close-by Fornax A and Cen A?
- Northern hemisphere: Diffuse component just below supergalactic plane?
  - Also, giant radio galaxies like NGC 6251 and DA 240 interesting
  - Question for TA: Instead of a declination dependence, what is the optimum coordinate system that maximises difference in spectra?





Supergalactic coordinates!

See **Anabella Araudo's poster**, for observational evidence that maximum energies are low in relativistic shocks!



On the maximum energy of non-thermal particles in the primary hotspot of Cygnus A

Anabella T. Araudo ✉, Anthony R. Bell, Katherine M. Blundell, James H. Matthews

Monthly Notices of the Royal Astronomical Society, Volume 473, Issue 3, 21 January 2018, Pages 3500–3506, https://doi.org/10.1093/mnras/stx2552

Published: 24 October 2017 **Article history** ▾

SUMMARY

CONCLUSIONS

- UHECR can be accelerated in “secondary” shocks in the lobes of radio galaxies
  - e.g. those formed in supersonic backflows
- Fornax A and Cen A show evidence of enhanced activity in the past; this helps with power requirement
- PAO Arrival directions suggest Fornax A and Cen A – Fornax not in 3FHL

QUESTIONS

- Can the radio lobes contain the UHECRs for a reasonable time?
- What’s the composition? crucial for attenuation length and deflection angle
- What is the appropriate attenuation length, injection index and UHECR luminosity proxy?
  - Knowledge of source physics critical

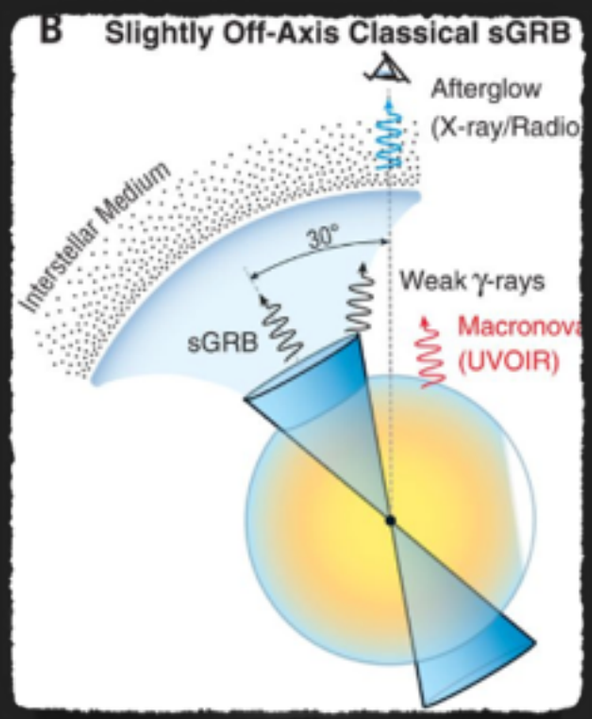
PAPERS

Matthews, Bell, Blundell, Araudo, 2018a, MNRAS, 479, 76, arXiv:1805.01902
Matthews, Bell, Blundell, Araudo, 2018b, MNRAS resubmitted, arXiv: imminent!

Additional slides

OTHER SOURCES

- Starburst winds can't meet power requirement - maximum energy ~$10^{17\text{-}18}$ eV (e.g. Romero et al. 2018
  - No correlation from TA (Abbasi+ 2018)
- Gamma-ray bursts definitely meet power requirements. Issues with
  - Rate
    - Is the rate high enough? Waxman 2001 estimates v. high efficiency needed
    - What about off-axis / weak sGRBs?
    - Note relevance of GW170817!
- Relativistic shocks
  - Can similar backflow models apply?
    - c.f. "Internal shocks" model of E. Waxman



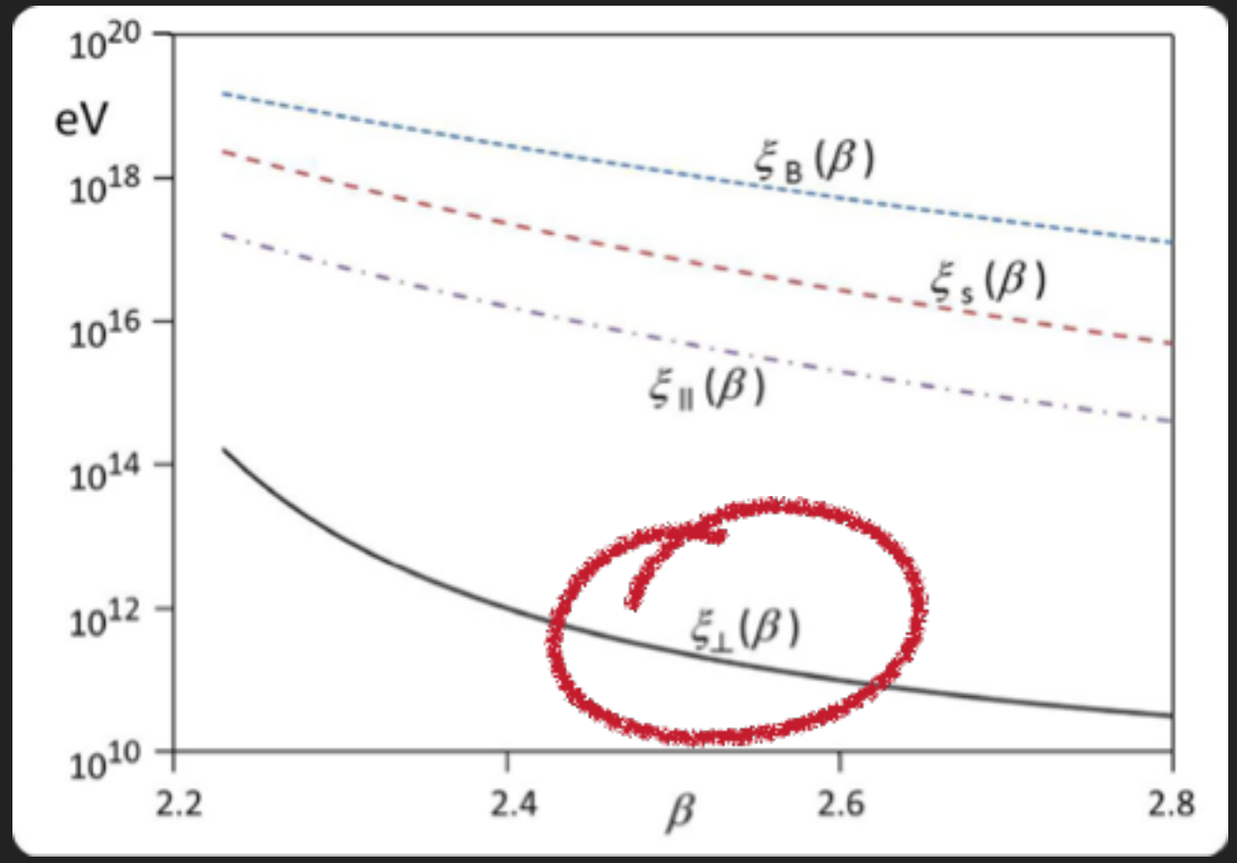
Kasliwal+ 2017

RELATIVISTIC SHOCKS

- Naively, relativistic shocks are natural candidates for UHECRs (v is max)
- However, other considerations actually make it tricky (Lemoine & Pelletier 14, Bell+ 18)
  - Relativistic shocks have steep spectra (Kirk+ 00, Sironi+ 13)
  - Relativistic shocks are quasi-perpendicular

Shock and B-field physics

- These effects work in tandem
  - Difficult to amplify the field quickly enough
  - Difficult to scatter the CRs within one Larmor radius
  - Difficult to create turbulence on large enough scales



Steeper energy spectra

WHAT ABOUT NON- OR MILDLY RELATIVISTIC SHOCKS?

Cosmic-ray acceleration by relativistic shocks: limits and estimates

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ABSTRACT

We examine limits to the energy to which cosmic rays can be accelerated by relativistic shocks, showing that acceleration of light ions as high as 100 EeV is unlikely. The implication of our estimates is that if ultrahigh energy cosmic rays are accelerated by shocks, then those shocks are probably not relativistic.

- Options include:
  - Disc winds / UFOs
  - FRI sources / lower velocity jets
  - Intermittent / precessing jets
  - Do powerful jets also produce slower shocks?

> Consequently, it appears that if shocks are to accelerate UHE-CRs, they probably must have velocities less than c by a factor of a few, but not by a factor very much larger than this. An important

"Goldilocks shocks?"