# ULTRA-HIGH ENERGY COSMIC RAYS FROM RADIO GALAXIES

James Matthews

Tony Bell, Katherine Blundell, Anabella Araudo

Hillas Symposium, Dec 2018

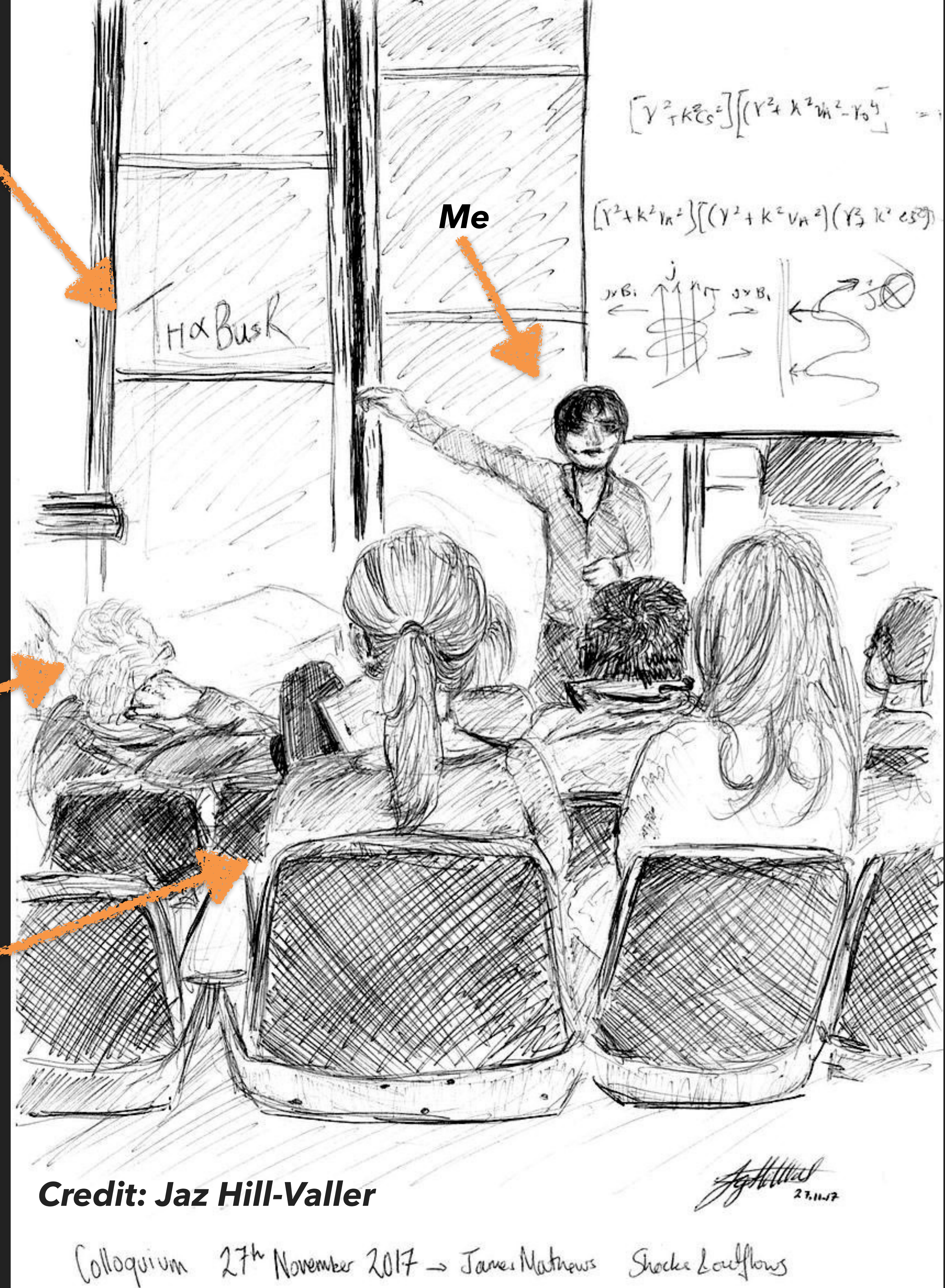
**Image credits**

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

## *A tribute:*




**Credit: Jaz Hill-Valler**

# PROBLEM AND PUNCHLINE

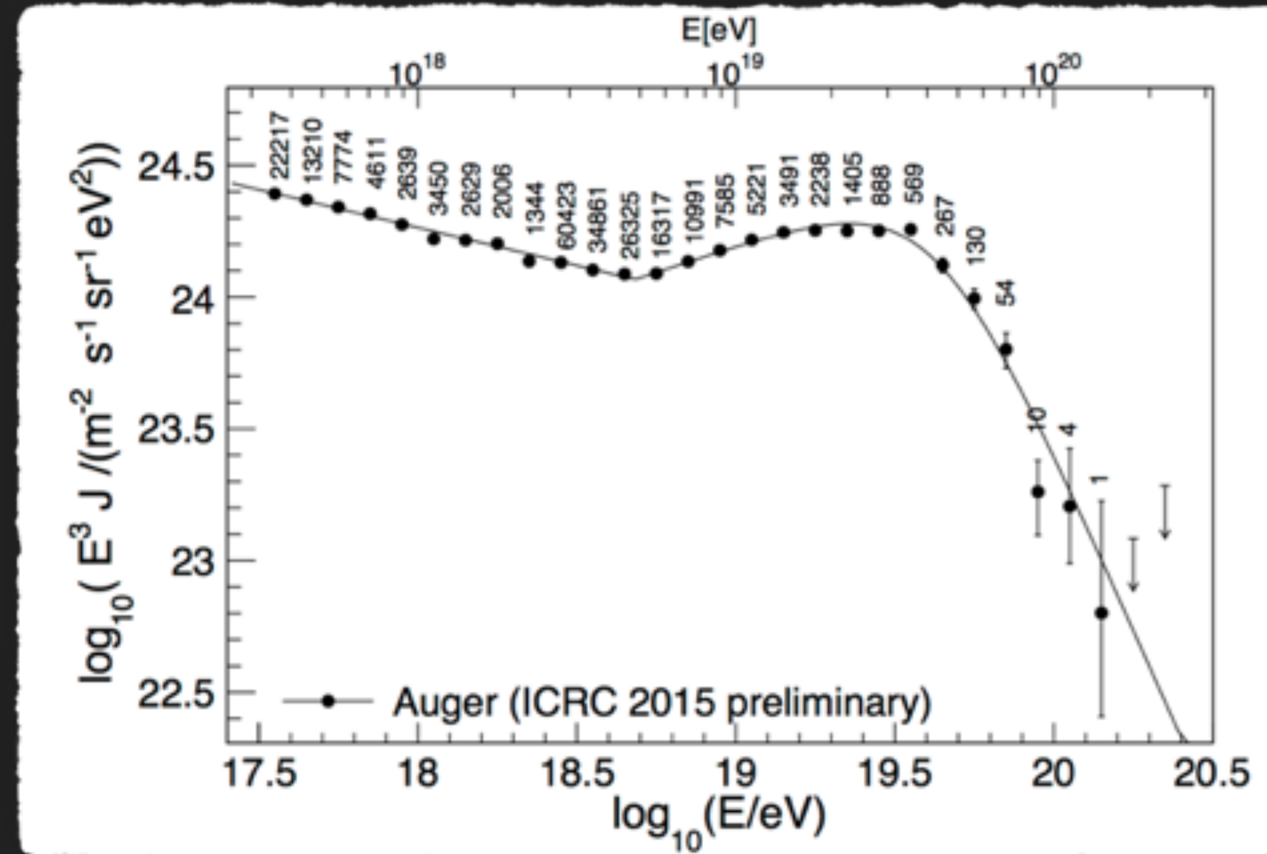
Matthews+ 2018b

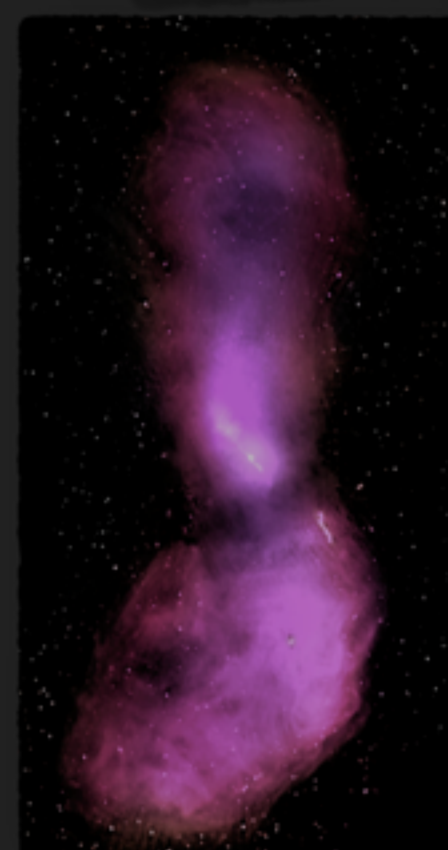
***Problem:***
Origin of CRs with energies up to 3e20 eV a decades-old mystery.

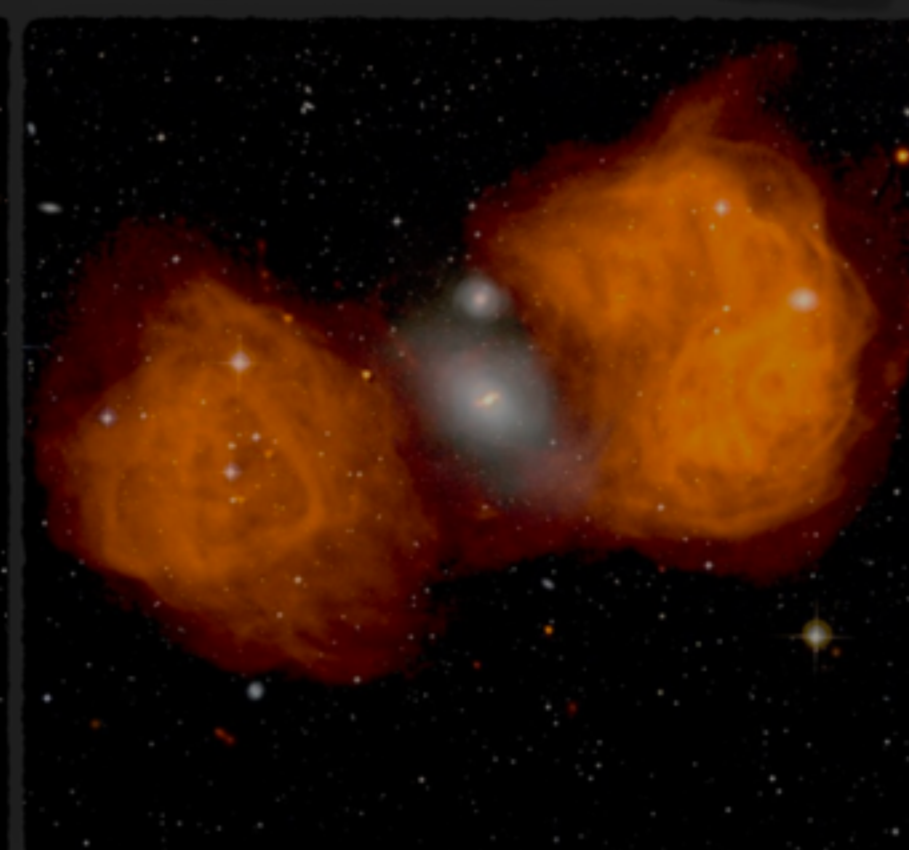
Need to get protons to (at least) 1e19 eV.

**Punchline:**
Shocks in the backflows of radio galaxies can accelerate UHECRs.

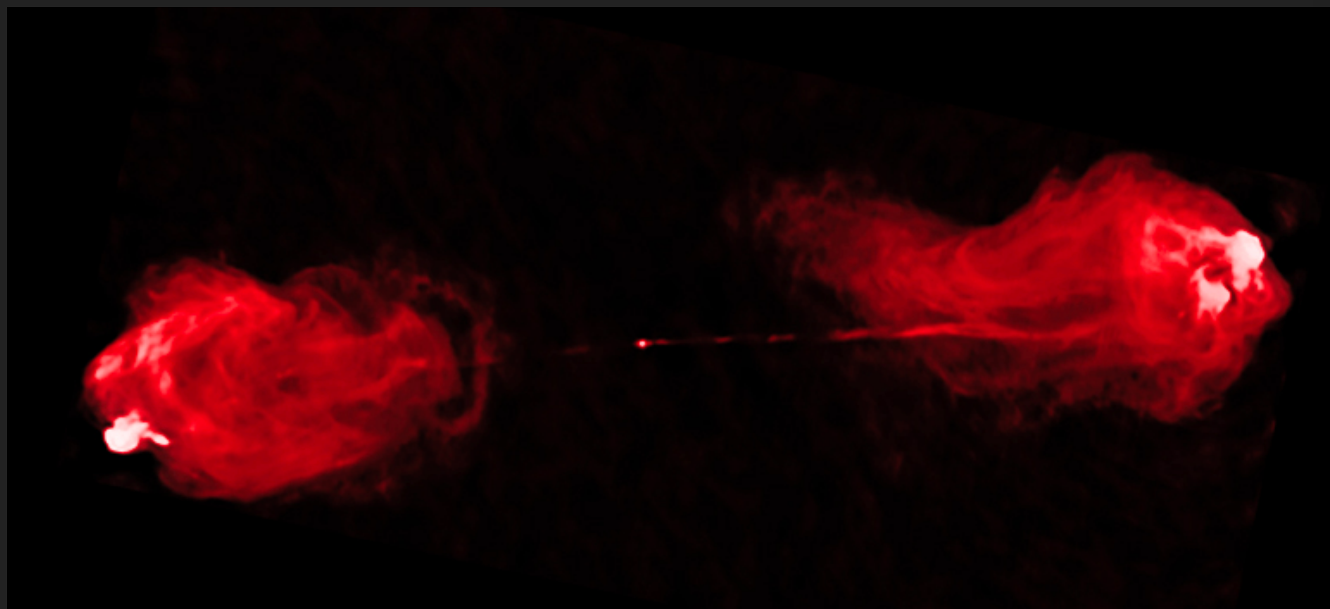
Radio galaxies are compelling candidates for explaining the data from the Pierre Auger Observatory.

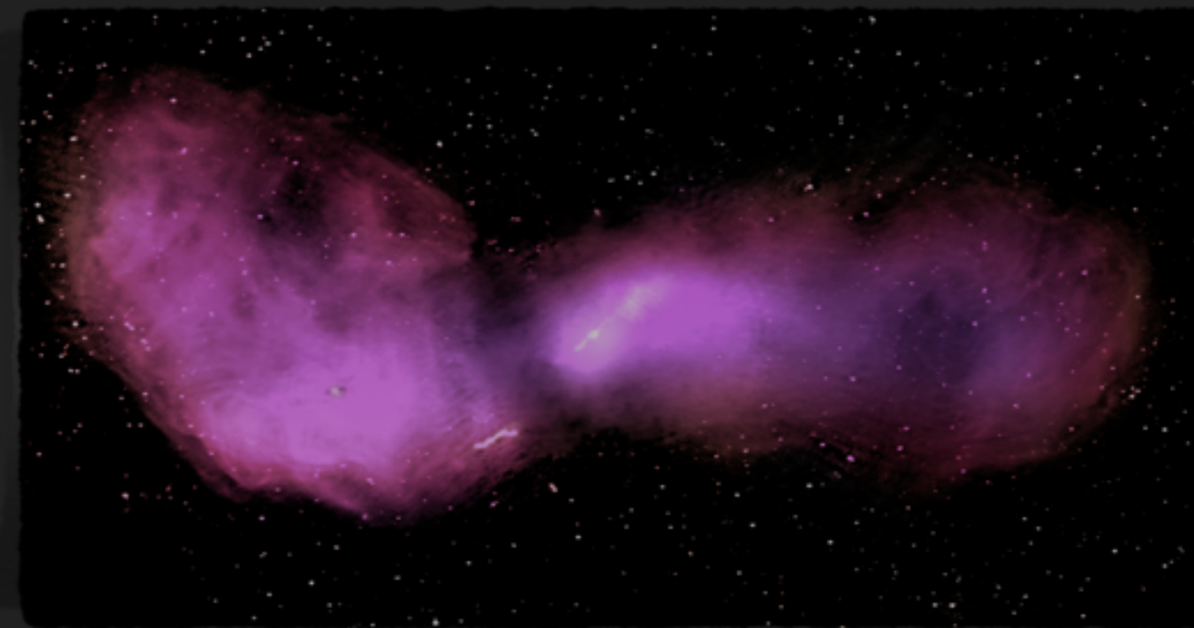




# RADIO GALAXIES





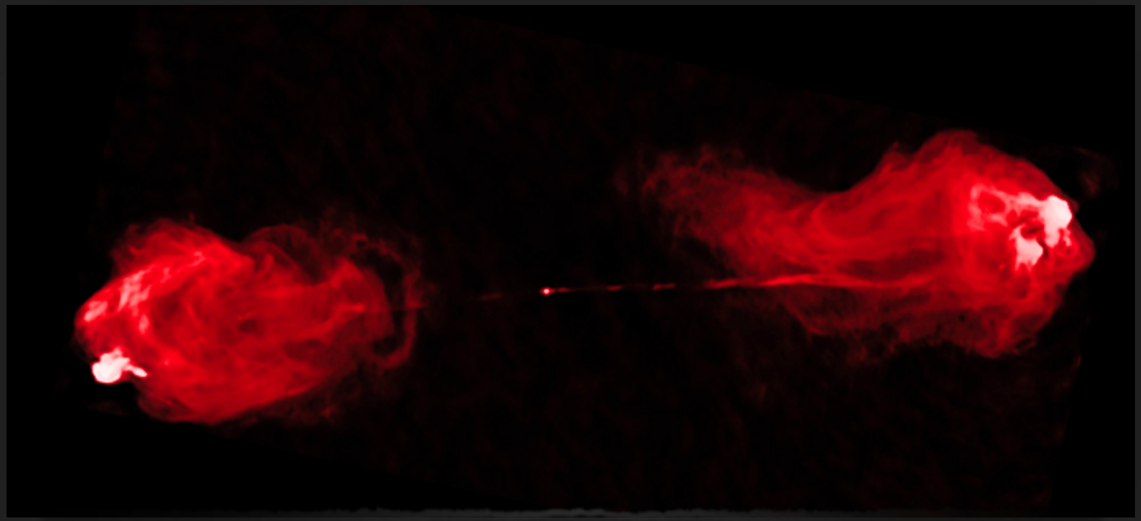
- Giant (kpc to Mpc) jets from AGN that produce lobes or cocoons of radio emitting plasma
  - Clear parallels with supernova remnants and stellar mass jetted systems
- Two main morphologies – high power (FRII, left), low power (FRI, right)
- Obvious UHECR candidates, since they are **big** and **fast** and we know they accelerate electrons (from radio and X-ray) - See e.g. Hillas 1984, Norman+ 1995, Hardcastle 2010, but also many, many others!

Hillas energy: $E_H = ZuBR$

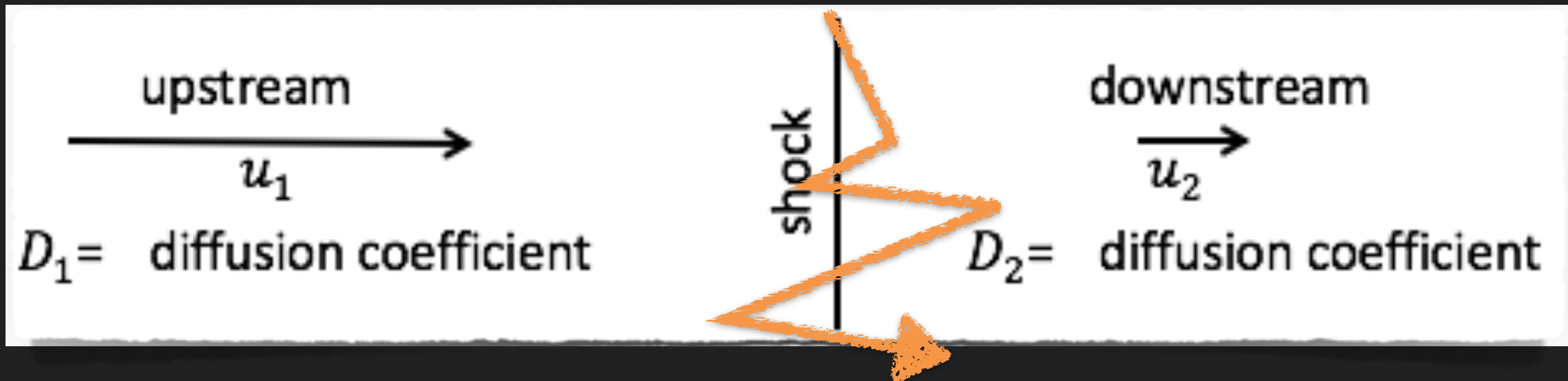
**<u>All CR energies in eV!</u>**

# HILLAS ENERGY IN SHOCKS

- Diffusive shock acceleration (DSA) one of the the best candidate mechanisms for UHECRs
  - u in Hillas energy becomes shock velocity
- Hillas energy can be understood in terms of moving a distance R through a **-u x B** electric field
- Note extra factor of (u/c) compared to confinement condition



$$E_H = ZuBR$$

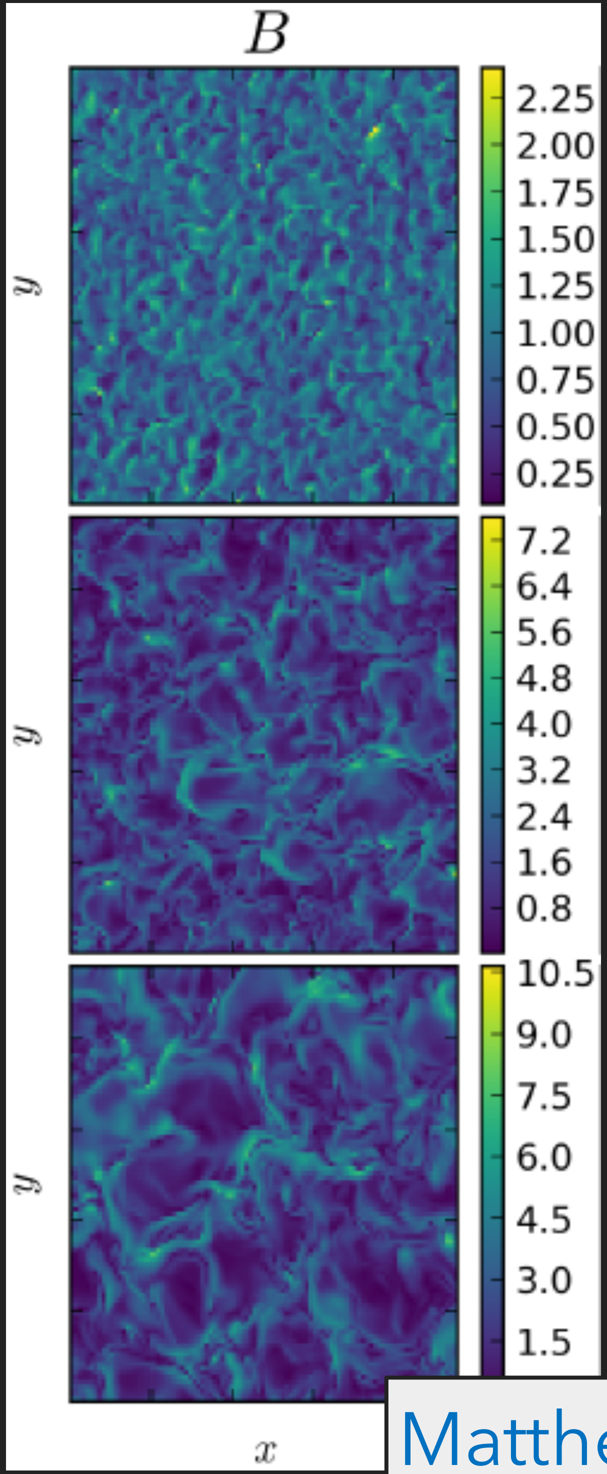


# HILLAS ENERGY IN SHOCKS

- From Hillas, can derive a minimum power requirement (Blandford/ Waxman/Lovelace)

$$Q_k > 10^{43}\ Z^{-2} \left(\frac{E}{10^{19}\mathrm{eV}}\right)^2 \left(\frac{u}{c}\right)^{-1} \mathrm{erg\ s^{-1}}$$

- **Hillas is necessary, but not sufficient**
- Need turbulence on scale of Larmor radius
  - Bell instability provides one mechanism (Bell 2004,2005) – also amplifies field
  - Still need enough time to stretch and grow the field
    - Parallels with SN remnants e.g. Lagage & Cesarsky, Bell+ 2013



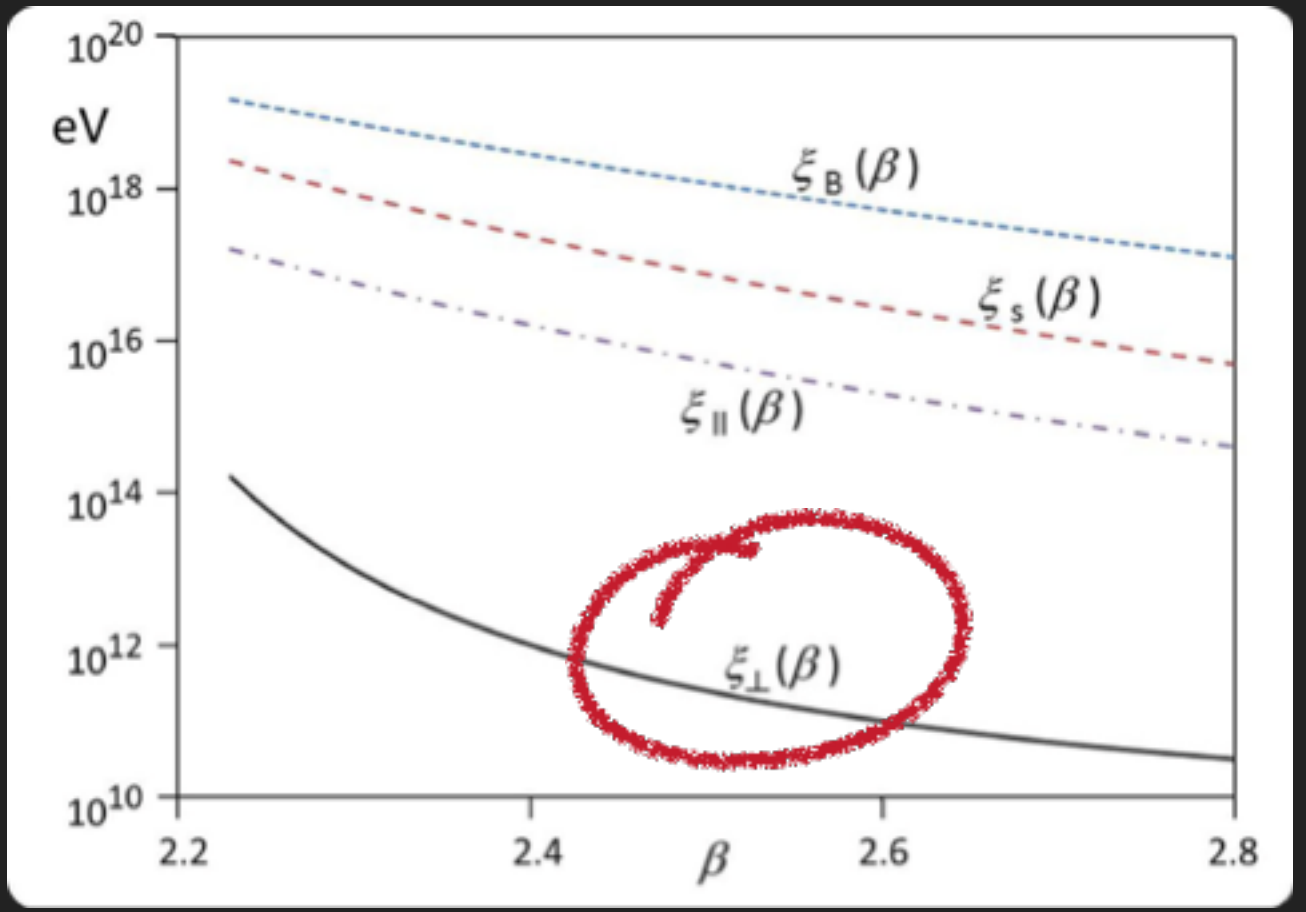

Matthews+ 2017

# RELATIVISTIC SHOCKS ARE PROBLEMATIC

- Naively, relativistic shocks are natural candidates for UHECRs (v is max)
- However, actually rather tricky (Lemoine & Pelletier 10, Reville & Bell 14, Bell+ 18)

Shock and B-field physics

- Can't amplify the field quickly enough
- Can't scatter the CRs within one Larmor radius
- Can't generate turbulence on large enough scales

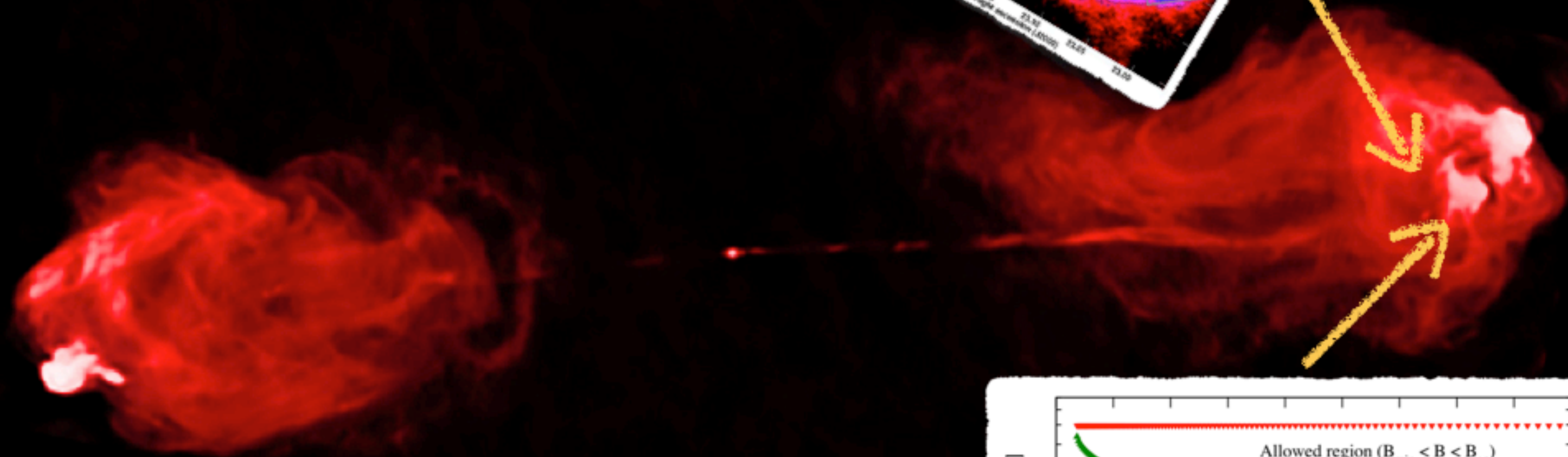


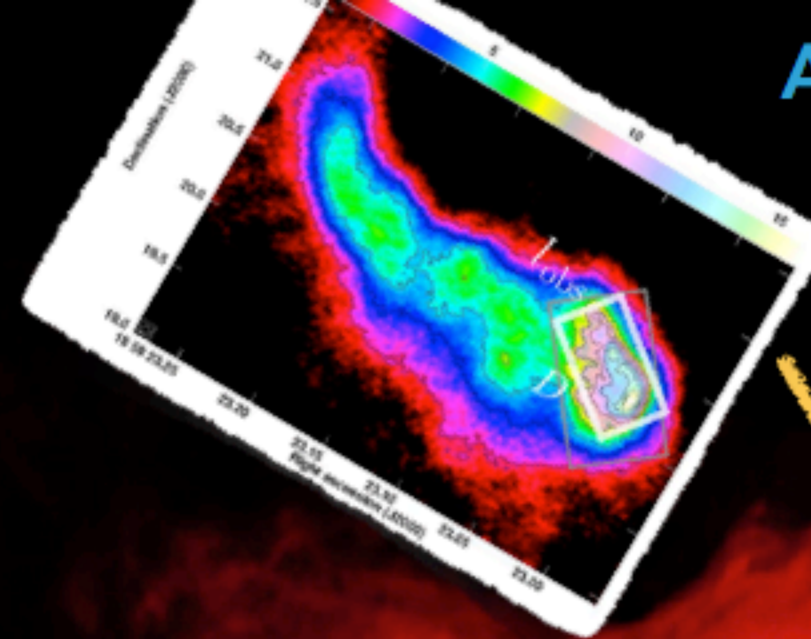

*Caveat: pre-existing turbulence changes this!*

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

$$\frac{E_{\rm e,max}}{\rm TeV} \sim 0.8 \left(\frac{\nu_{\rm c}}{5\times 10^{14}\,{\rm Hz}}\right)^{\frac{1}{2}} \left(\frac{B}{100\,\mu{\rm G}}\right)^{-\frac{1}{2}}$$

Araudo+ 2018





- In Cyg A, need B ~50-400μG to explain synchrotron flux
- Maximum energy of electrons and protons not determined by synchrotron cooling
- Limit of ~1 TeV also applies to CR protons/nuclei

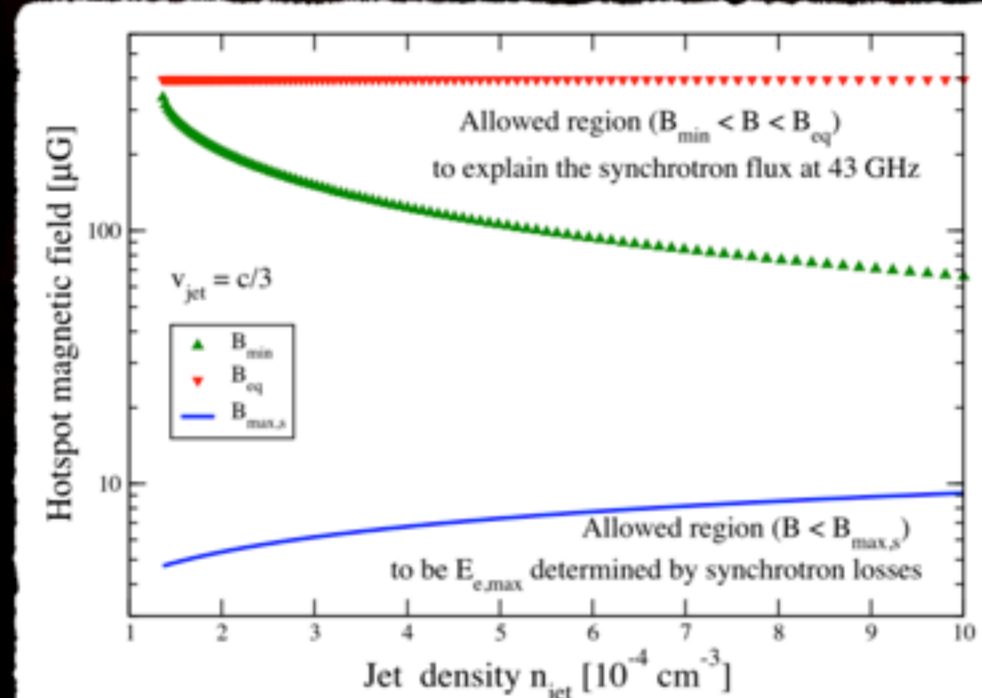



**Figure 4.** Comparison between the magnetic field required to explain the synchrotron flux at 43 GHz ($B_{\rm min} \le B \le B_{\rm eq}$) and the magnetic field required to satisfy the condition $s \le c/\omega_{\rm pi}$ ($B \le B_{\rm max,s}$). We can see that $B_{\rm max,s} < B_{\rm min}$ and therefore the condition $B \le B_{\rm max,s}$ is not satisfied.

# PHYSICAL REQUIREMENTS

See Tony Bell's talk!

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

$$u < f_{\mathrm{crit}}\ c$$

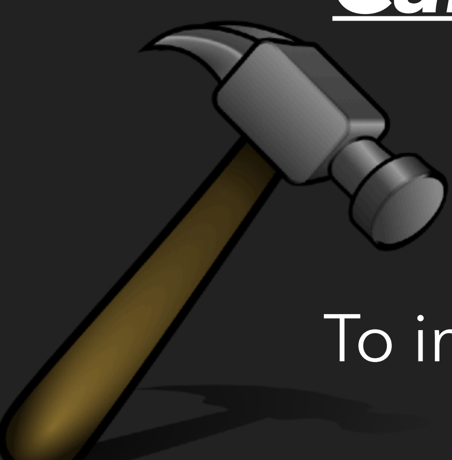
  - Hillas condition

$$E_H = ZuBR$$

  - Minimum power requirement

$$Q_k > 10^{43}\ Z^{-2} \left(\frac{E}{10^{19}\mathrm{eV}}\right)^2 \left(\frac{u}{c}\right)^{-1} \mathrm{erg\ s^{-1}}$$

***Can shocks in radio galaxies meet these criteria?***

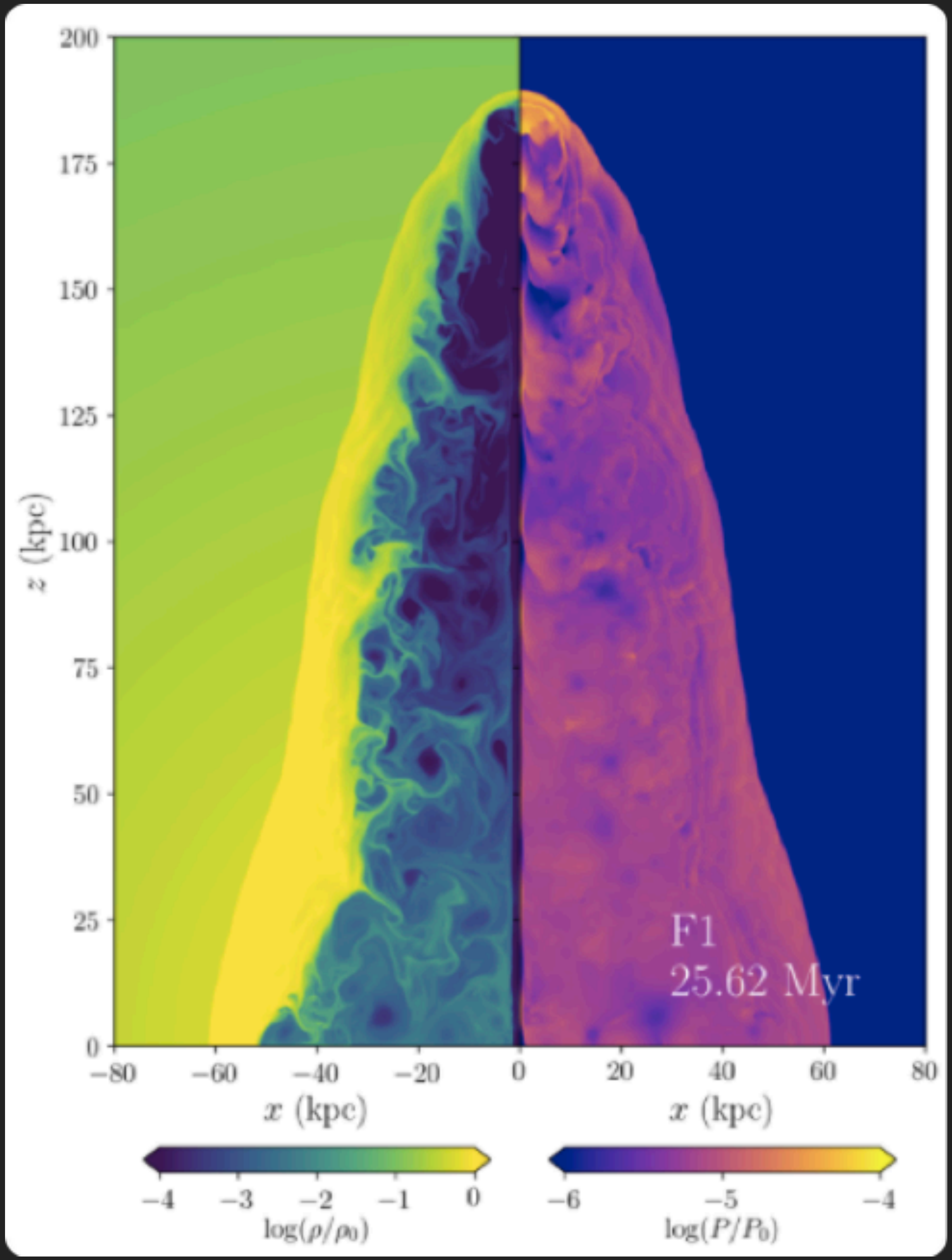


To investigate, we use hydrodynamic simulations of jets

# 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)



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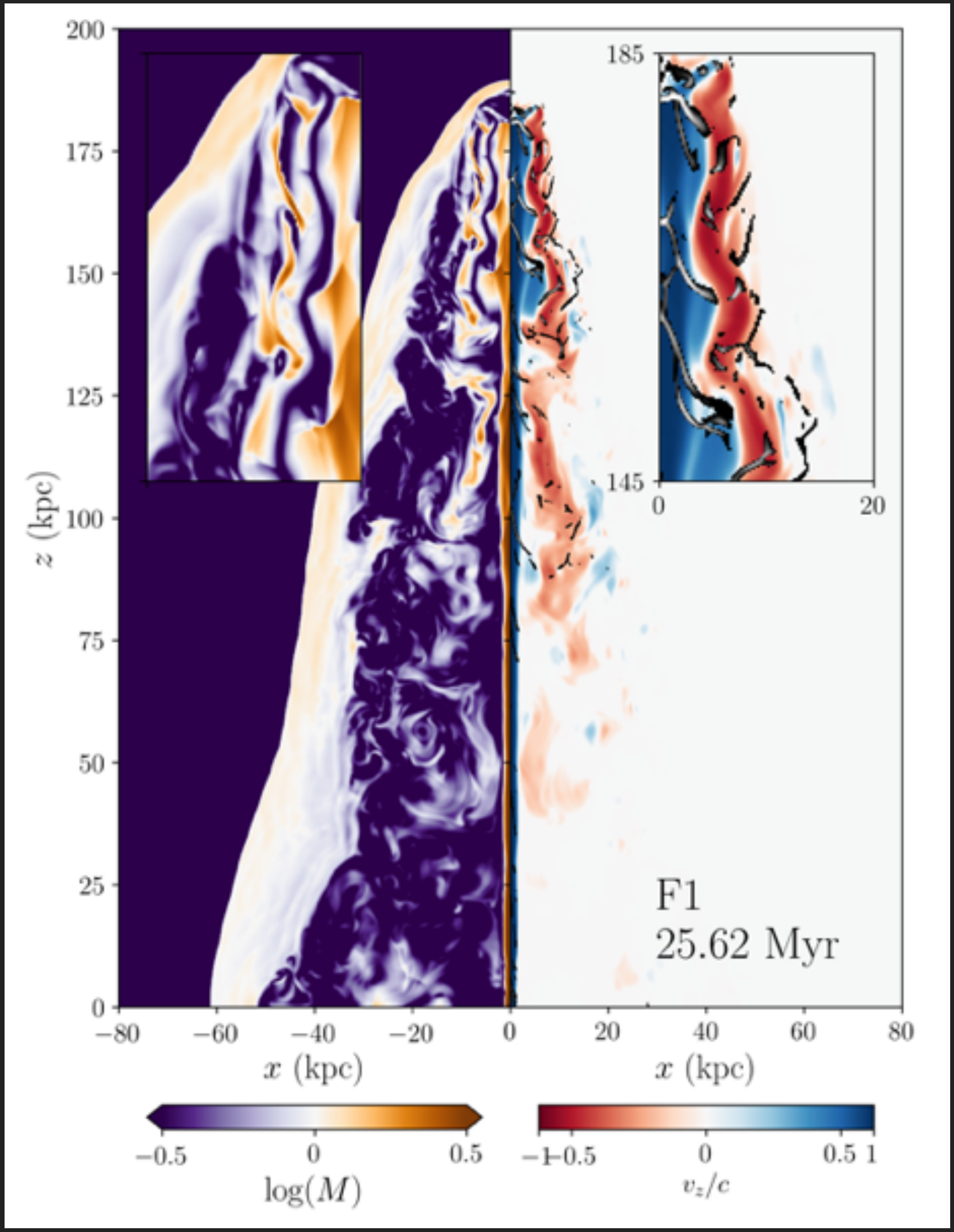
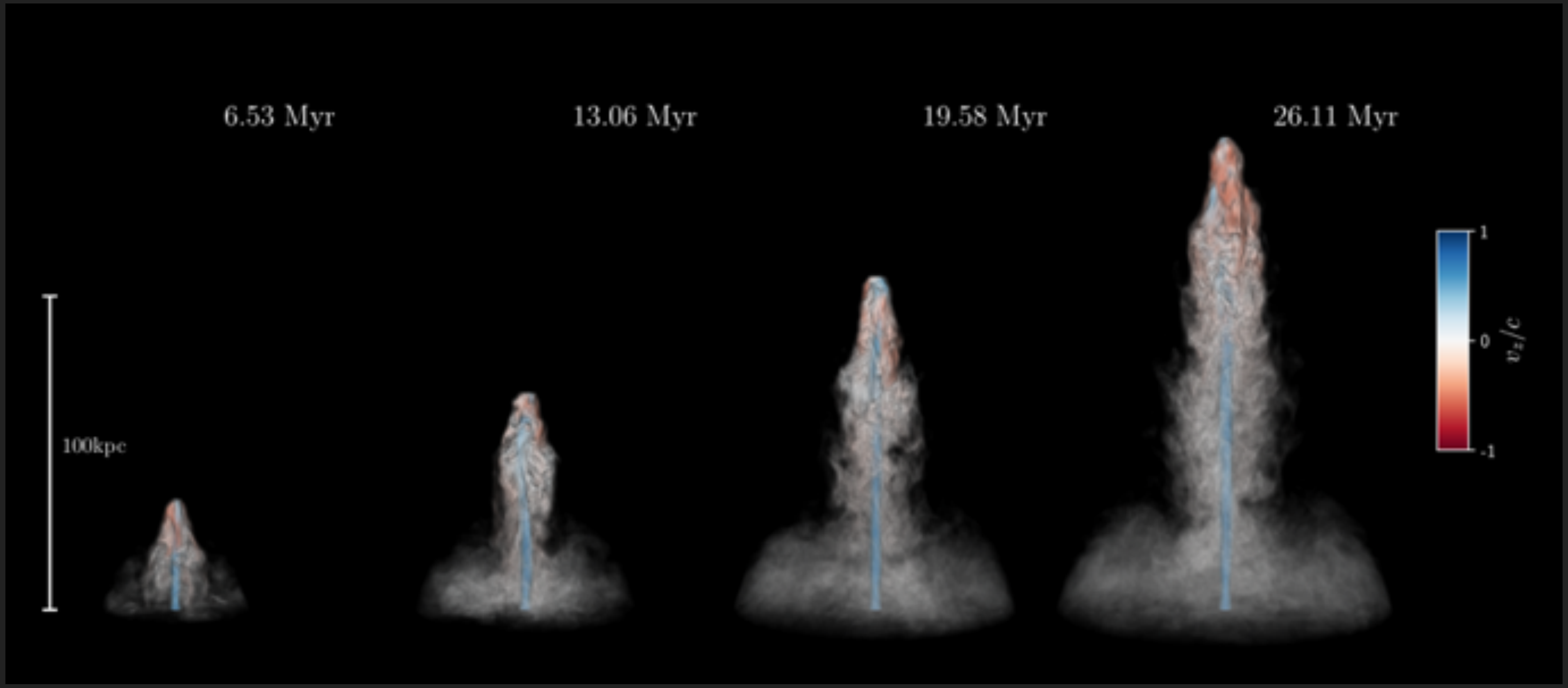
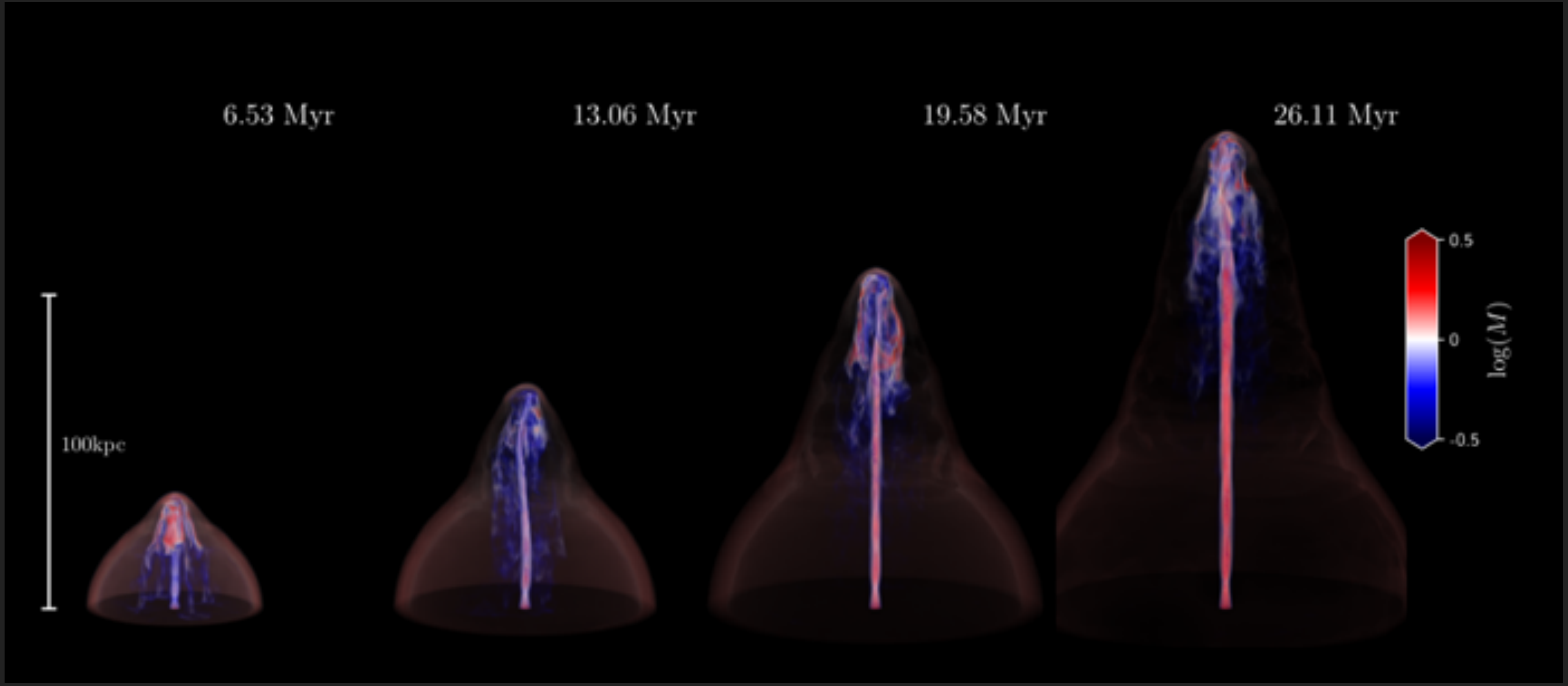


# JET SIMULATIONS: 3D

Matthews+ 2018b



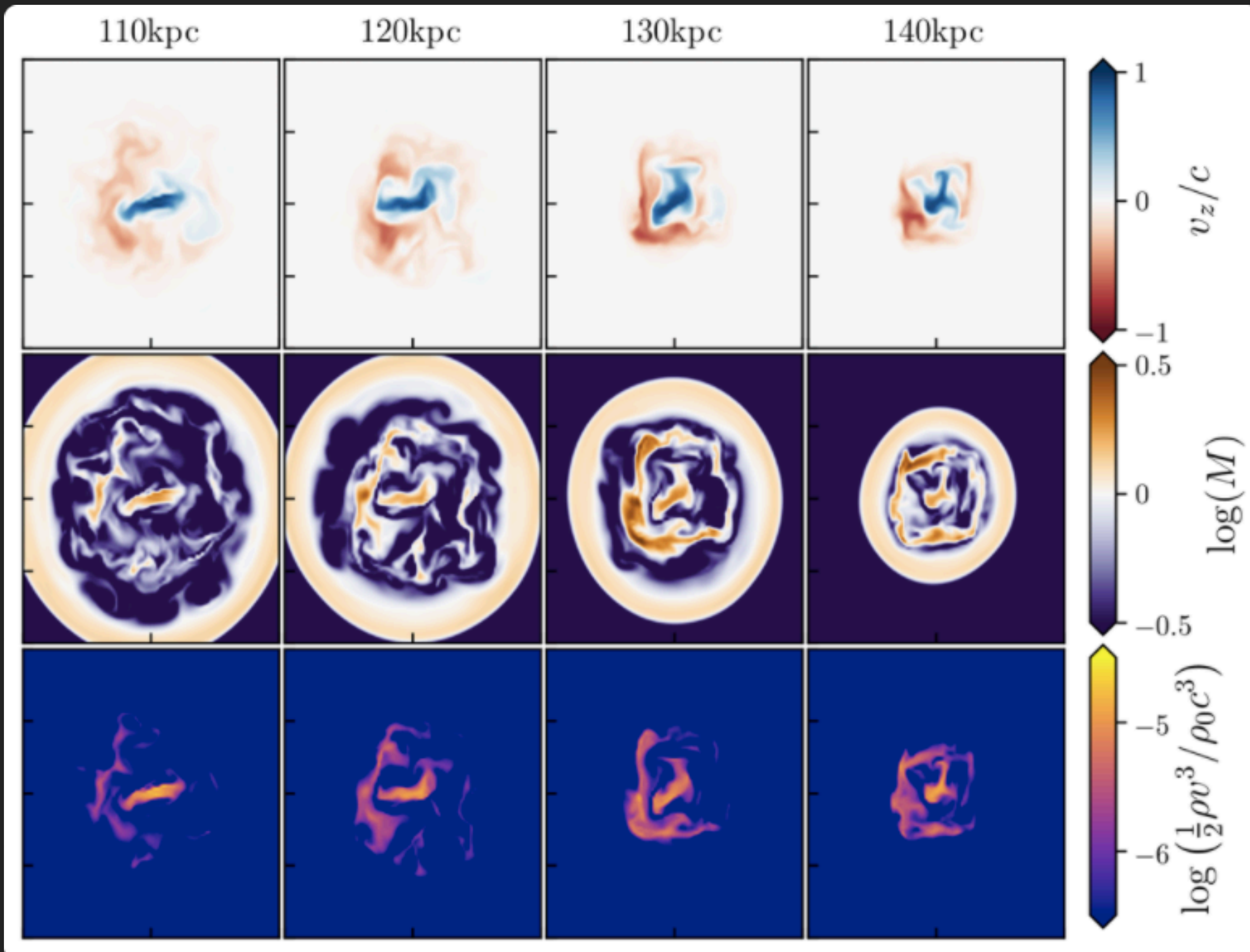

Vertical velocity

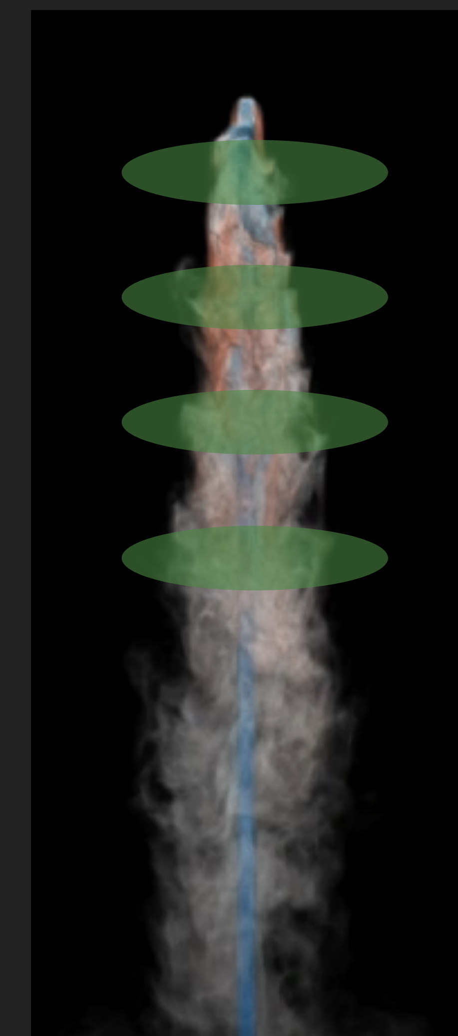



Mach number

# JET SIMULATIONS: 3D

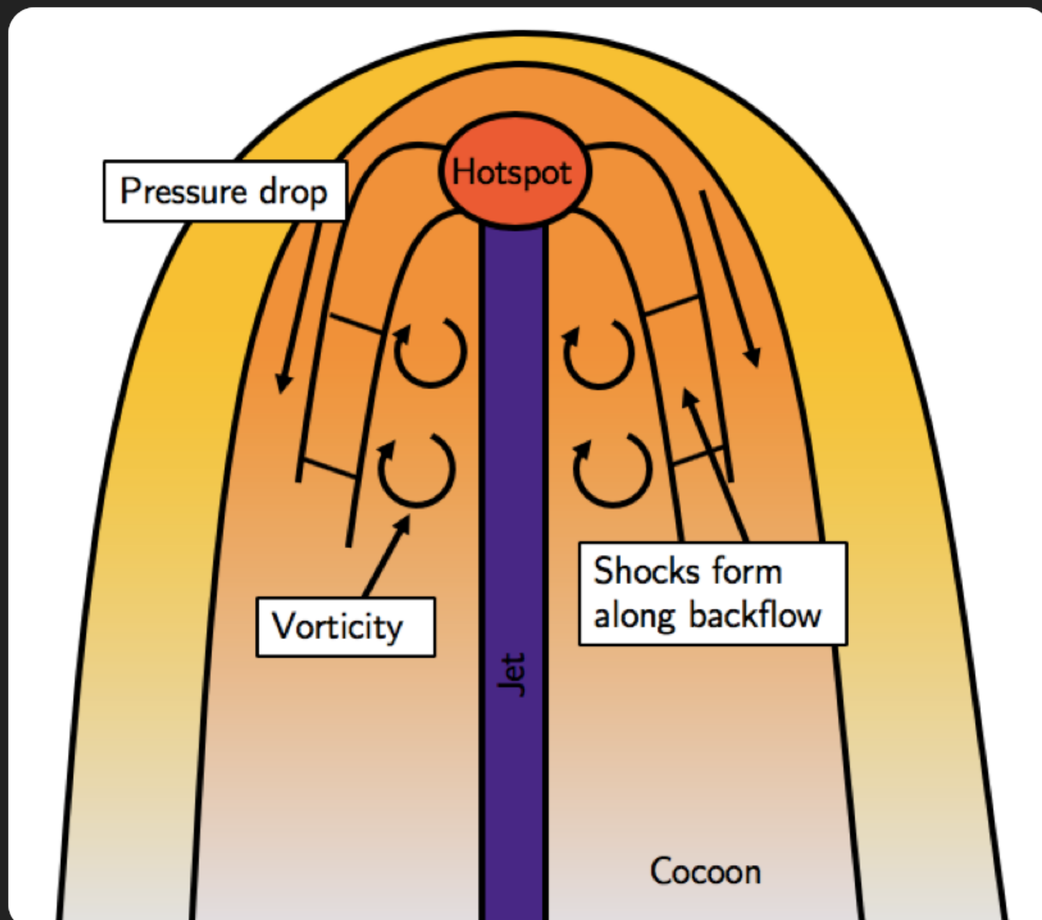
Matthews+ 2018b

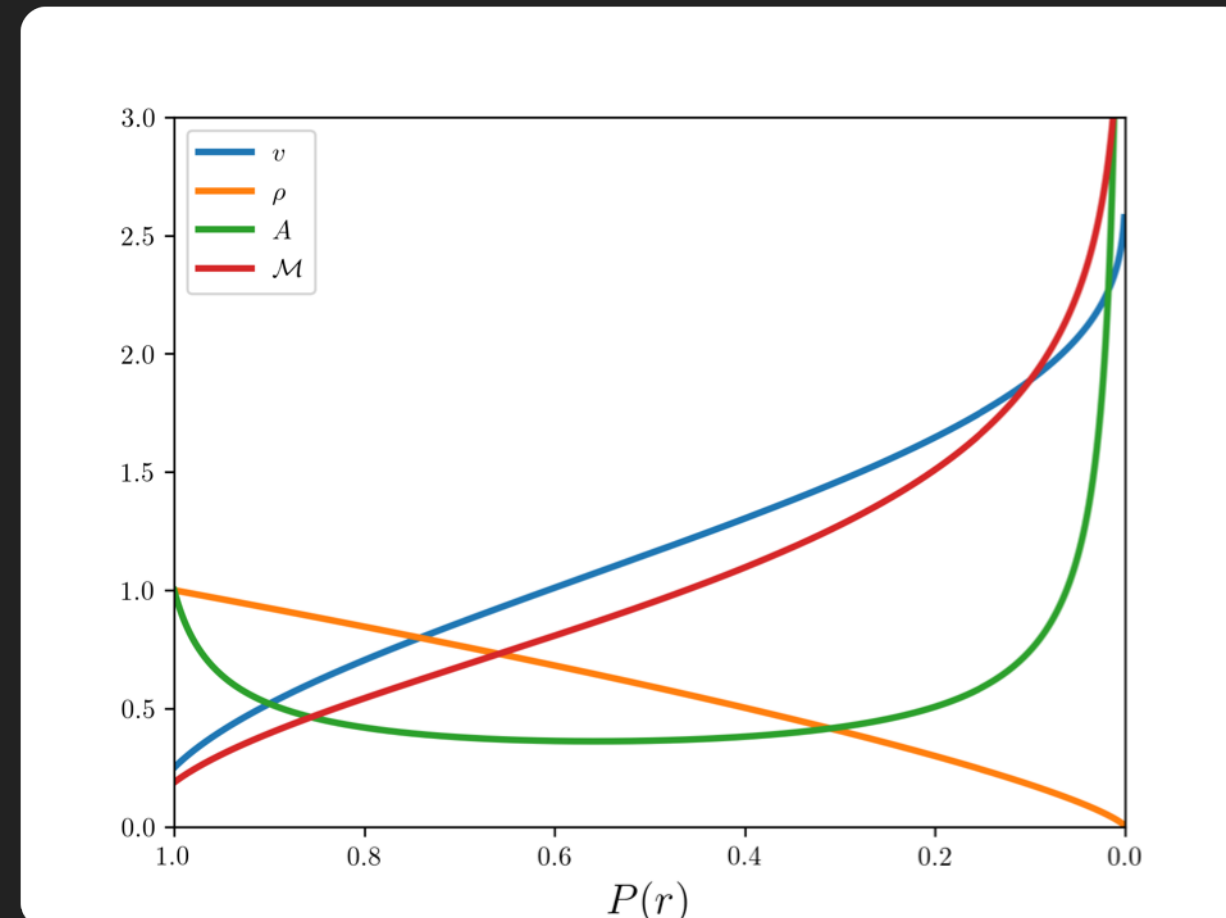


# WHY BACKFLOW?

Matthews+ 2018b




- Bernoulli flux tube!
- Flow goes supersonic as surrounding pressure drops

$$\chi = \frac{v^2}{2} + \frac{\gamma}{\gamma - 1}\frac{P}{\rho} = \text{constant.}$$

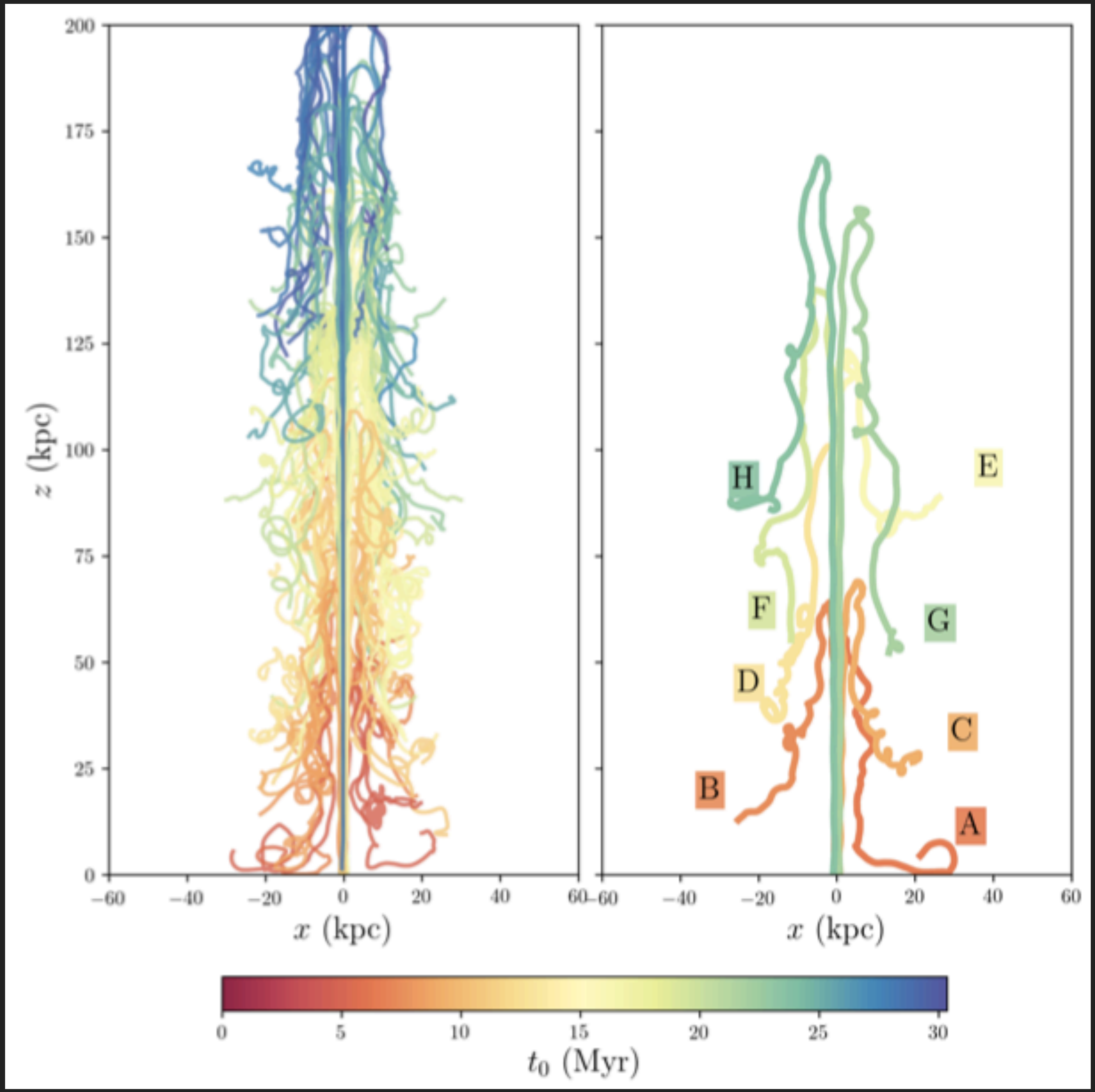
$$P\rho^{-\gamma} = \text{constant}$$

$$\rho u A = \text{constant}$$

# 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

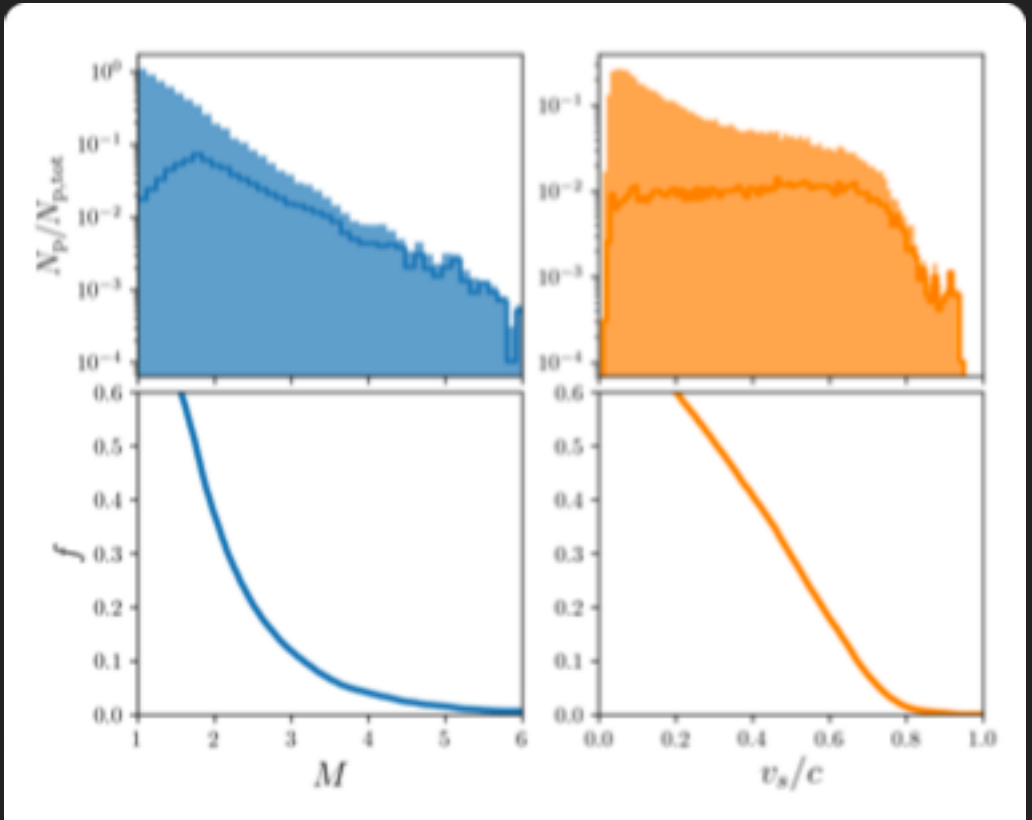



(i) show compression, $\nabla \cdot \boldsymbol{v} < 0$;
(ii) show a pressure jump, $\Delta P/P > \epsilon_p$;

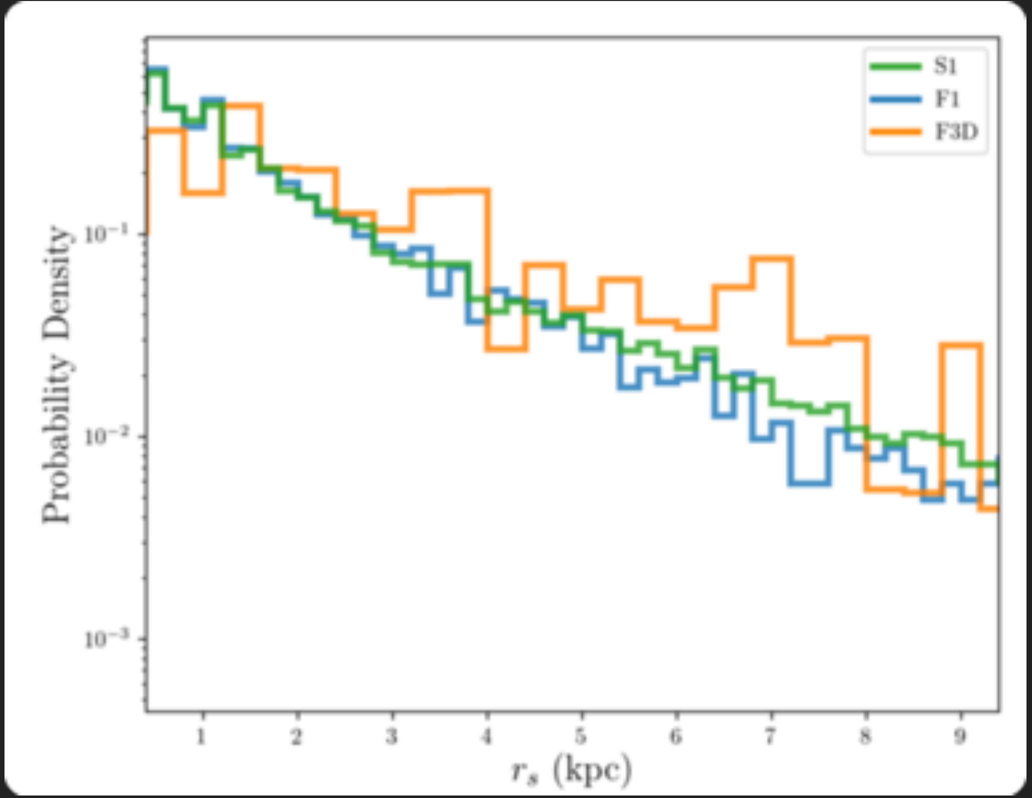
# SHOCK DIAGNOSTICS

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:
  - **Maximum rigidity R=E/Z~50 EV**



(b) Shock properties in run F1



# PHYSICAL REQUIREMENTS RECAP

- Requirements for acceleration to high energy:
  - Non-relativistic shock ✓
  - Hillas condition ✓
  - Minimum power requirement ?

$$u < f_{\rm crit}\, c$$

$$E_H = ZuBR$$

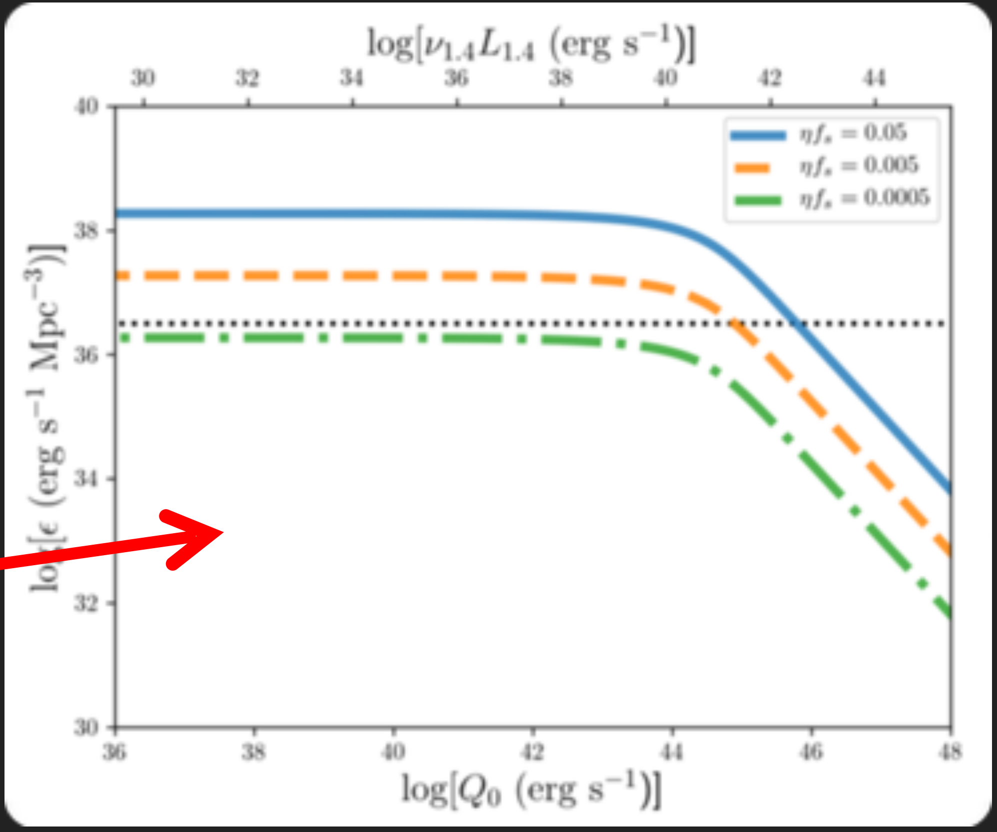
$$Q_k > 10^{43}\, Z^{-2} \left(\frac{E}{10^{19}\mathrm{eV}}\right)^2 \left(\frac{u}{c}\right)^{-1} \mathrm{erg\ s^{-1}}$$

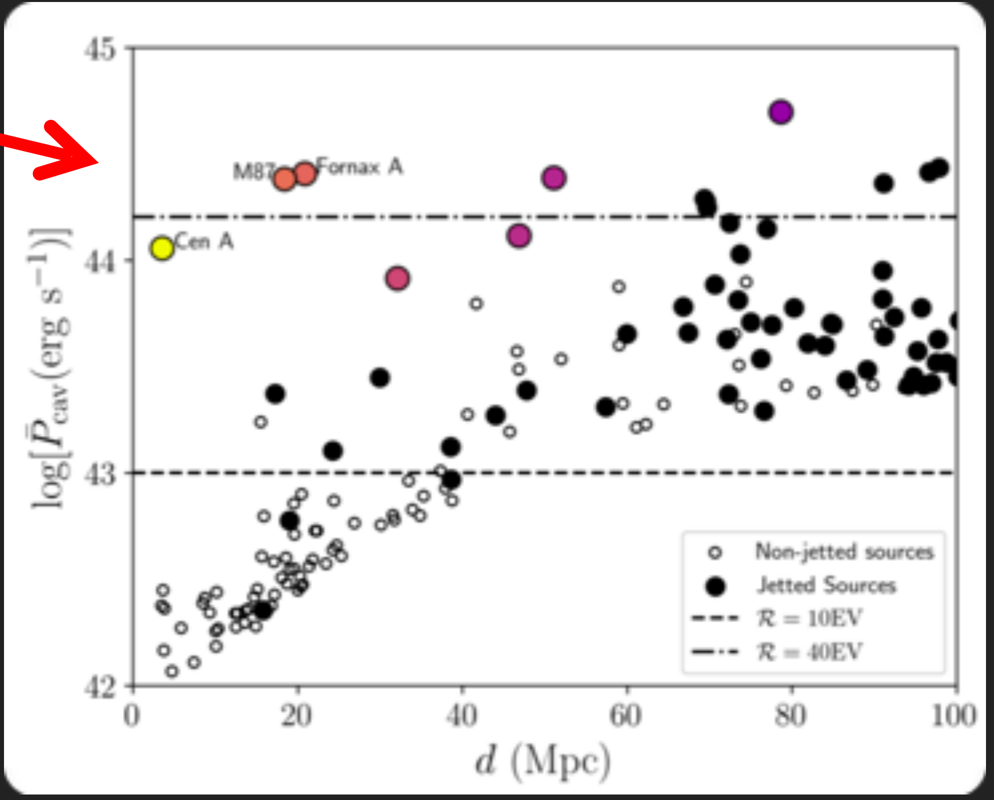
We also need to reproduce the right number of UHECRs at Earth ?

# ARE THERE ENOUGH POWERFUL SOURCES?

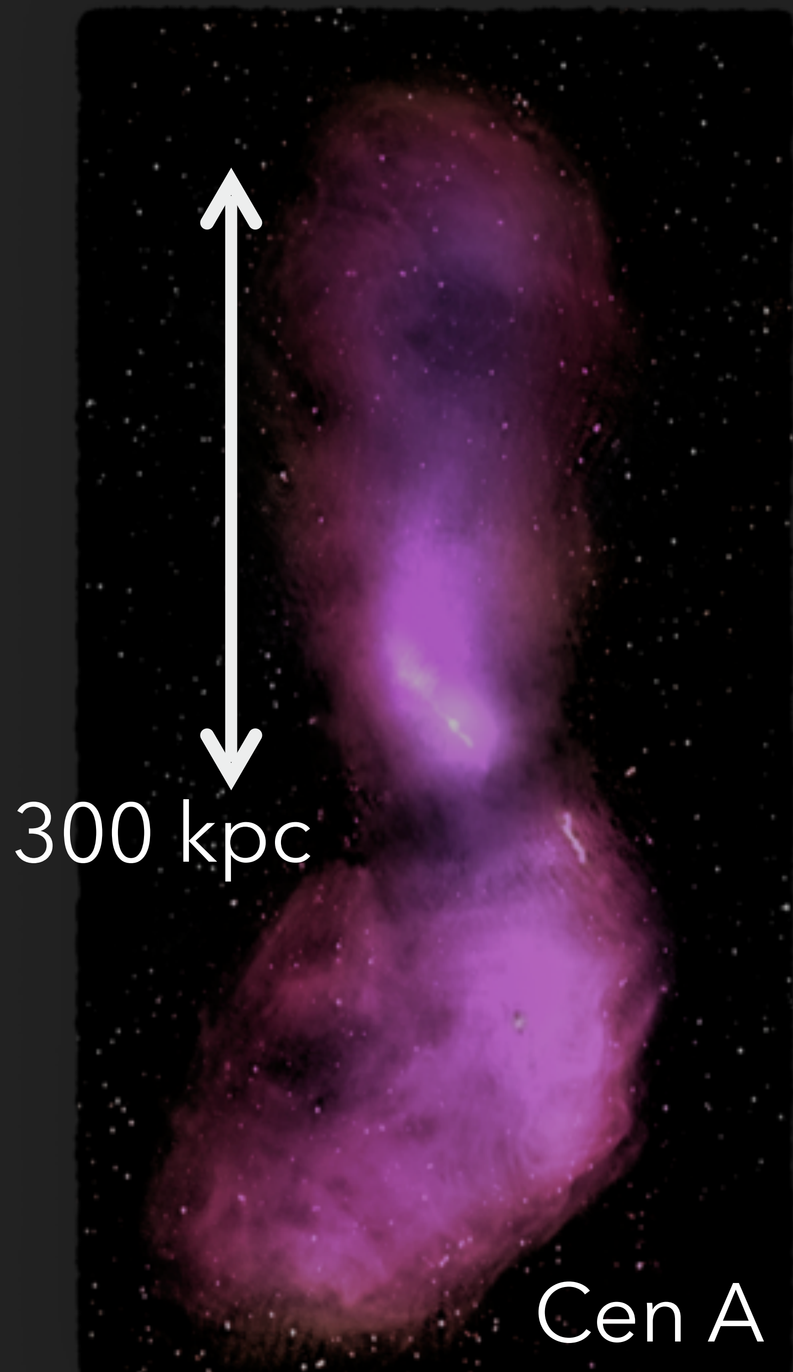
Matthews+ 2018b

- 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?

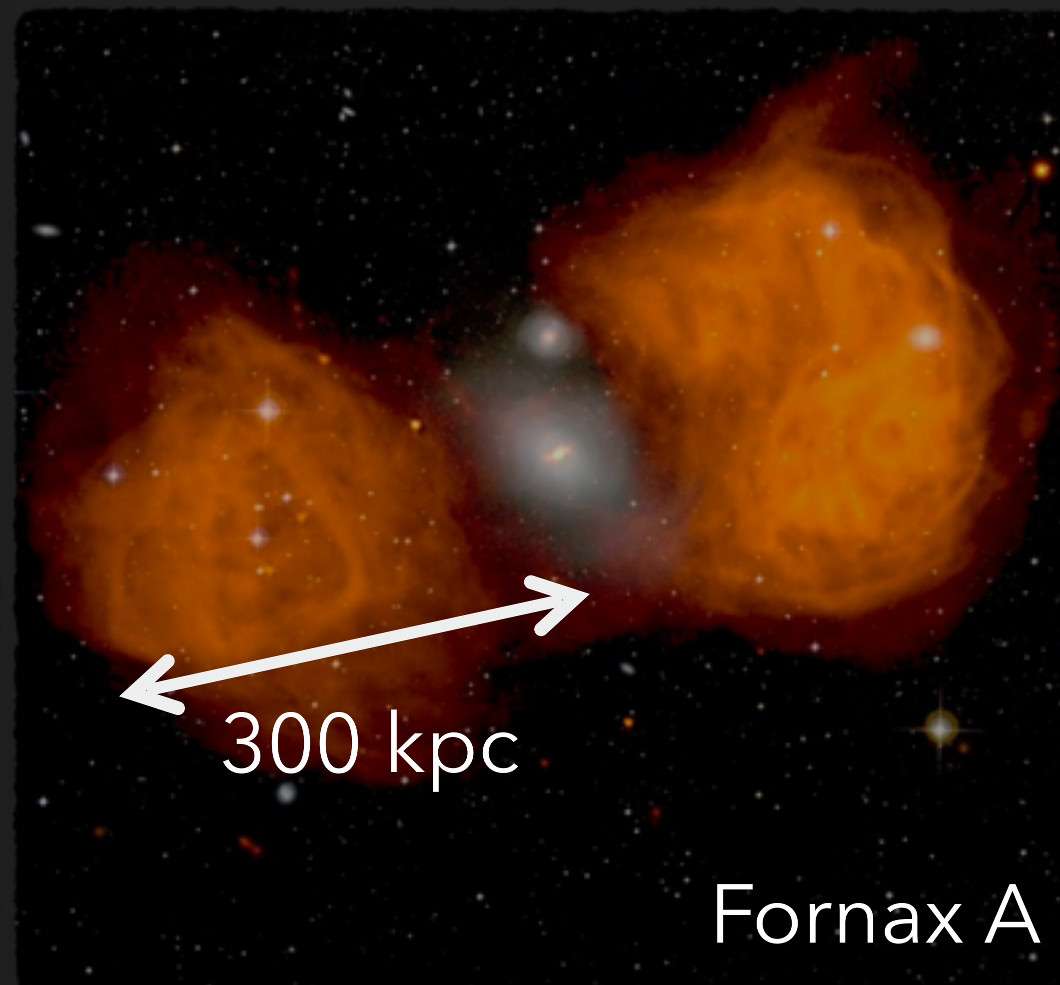


# DORMANT RADIO SOURCES AS UHECR RESERVOIRS



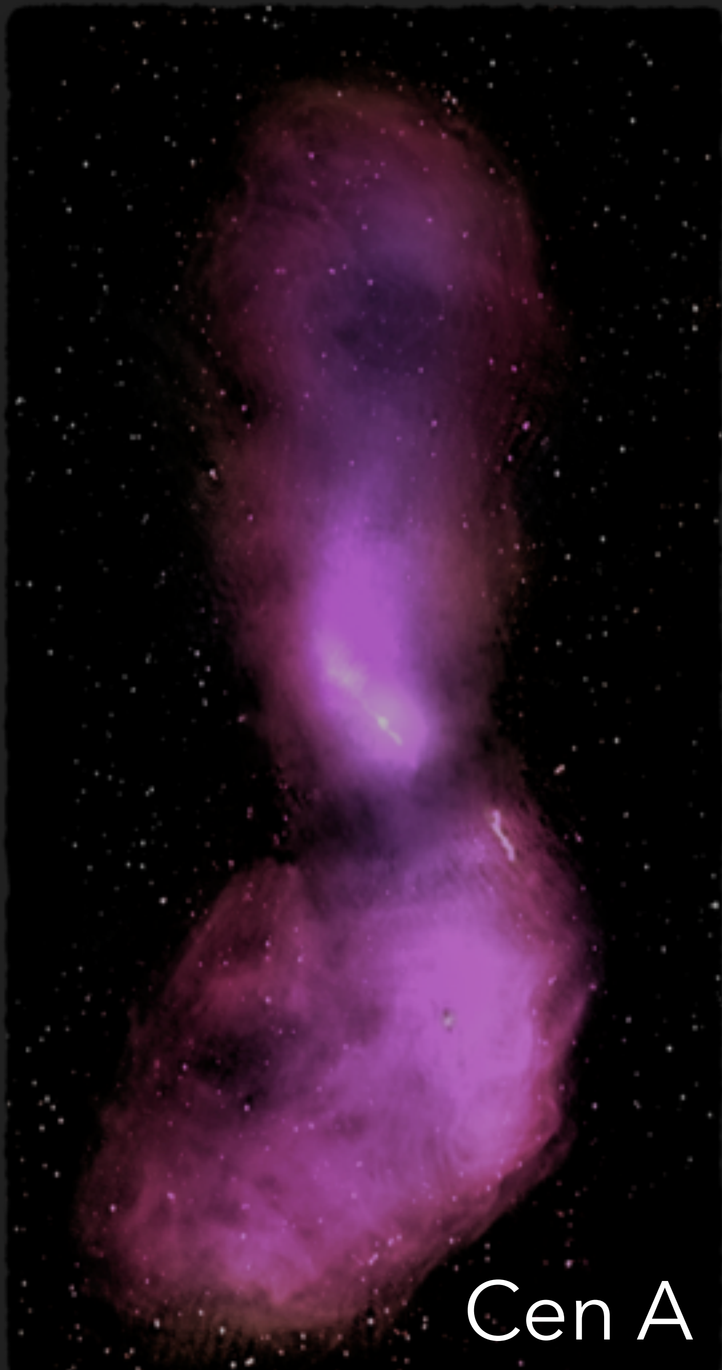

Large lobes, energy content $>10^{58}$ erg

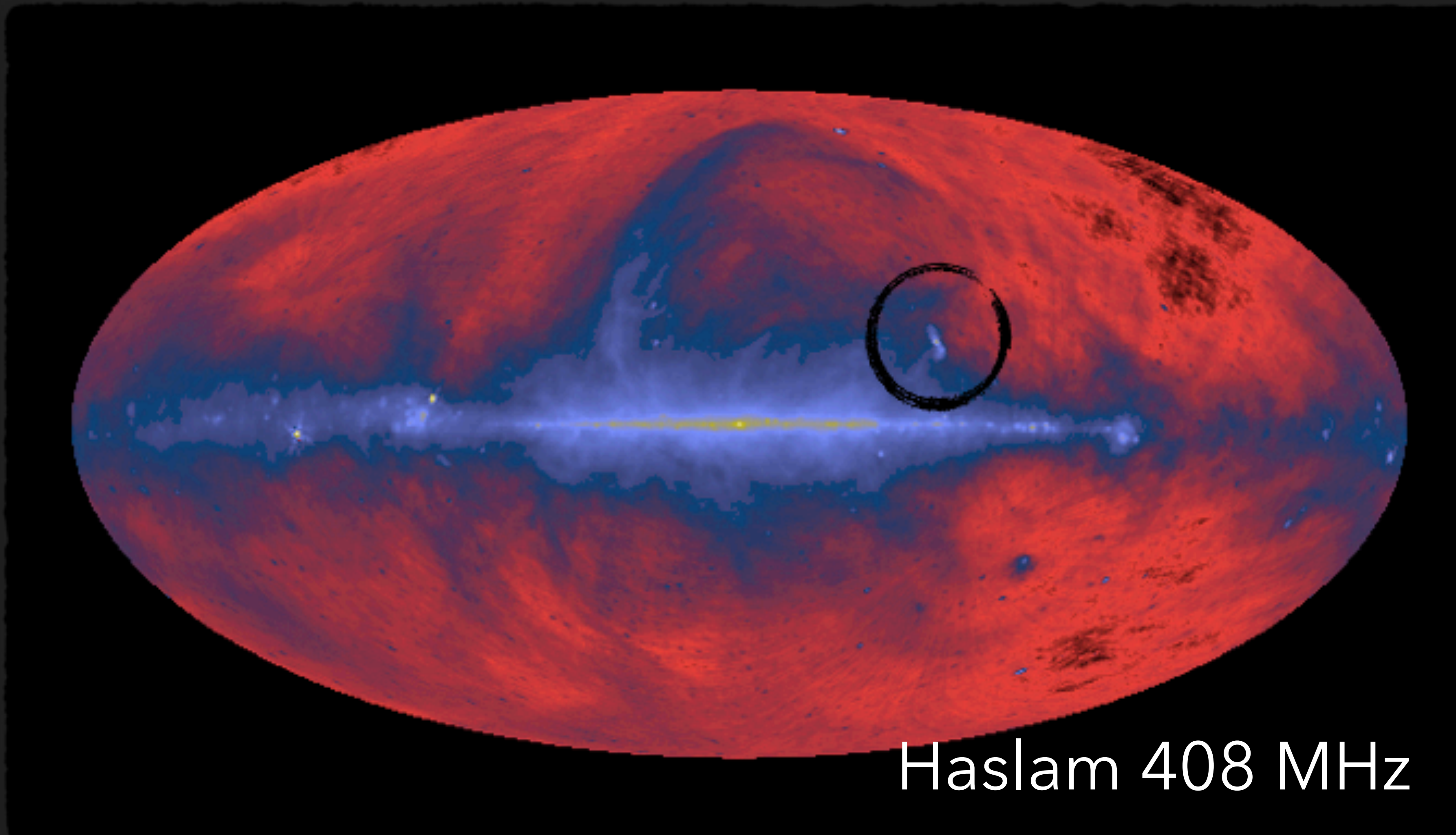



- Declining AGN activity in Fornax A
- Recent merger activity in both sources
- "Dormant" radio galaxies? More active in the past?

Low-power jets

# DORMANT RADIO SOURCES AS UHECR RESERVOIRS

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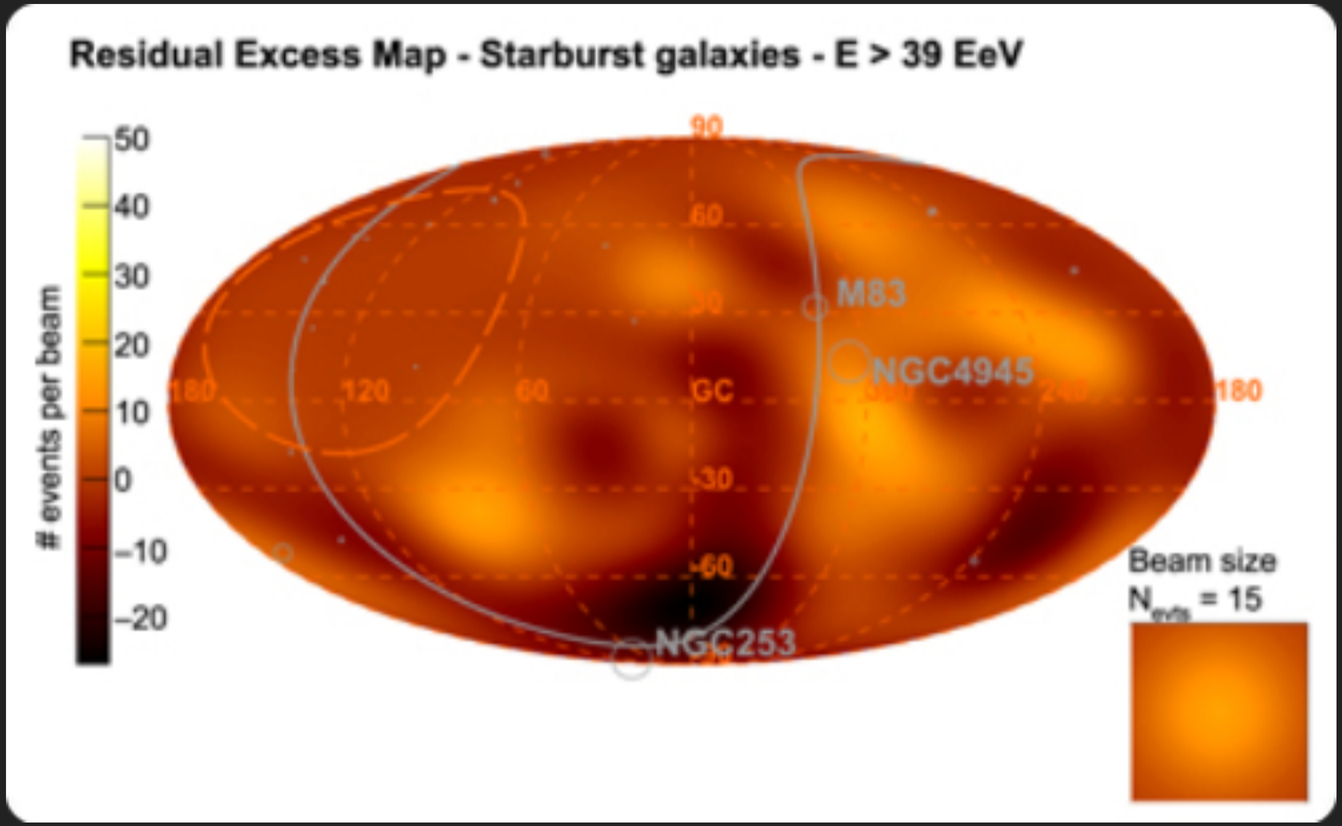
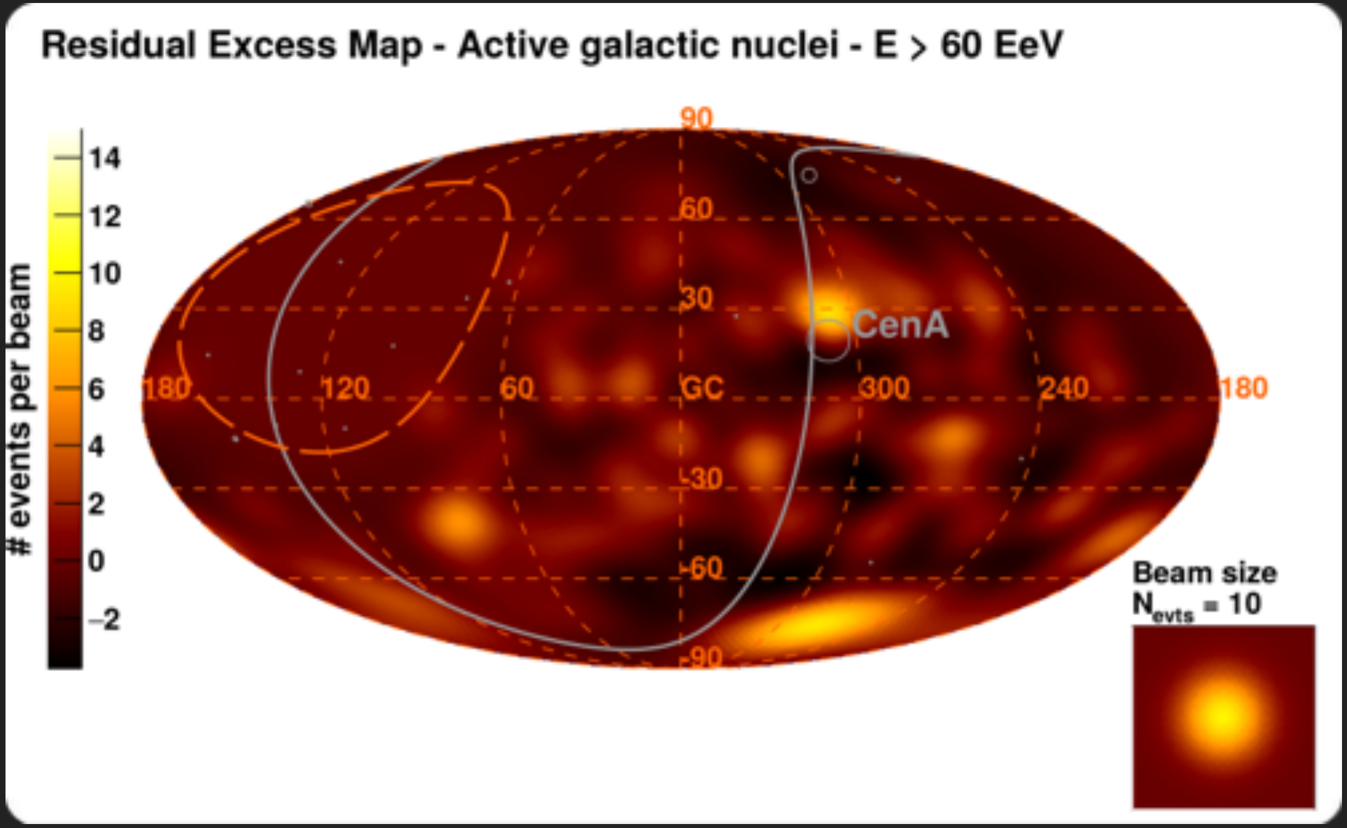
# ARRIVAL DIRECTIONS

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
- ***<u>Used 2FHL catalog - no Fornax A, and Cen A flux lower than in 3FHL</u>***

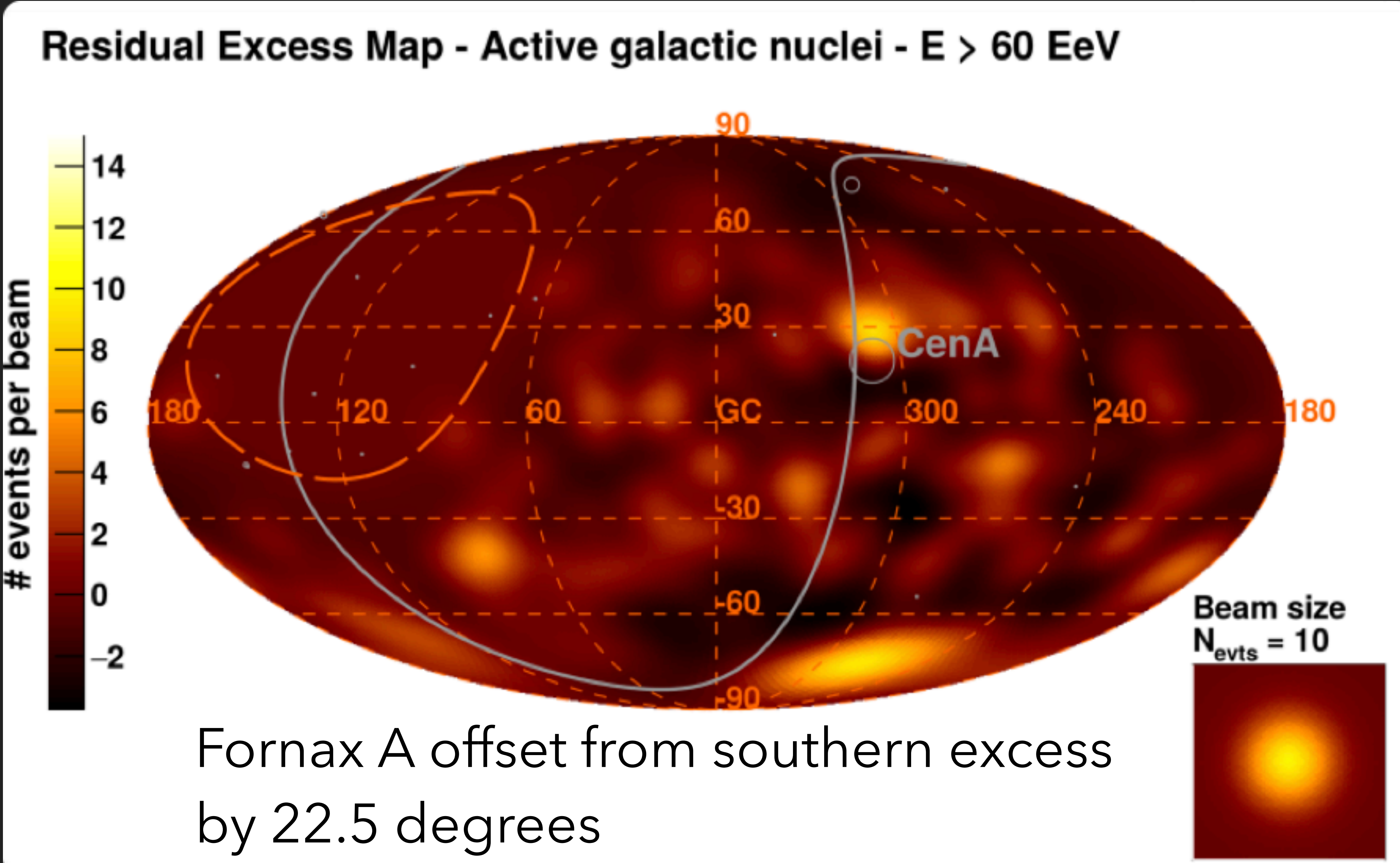


# ARRIVAL DIRECTIONS

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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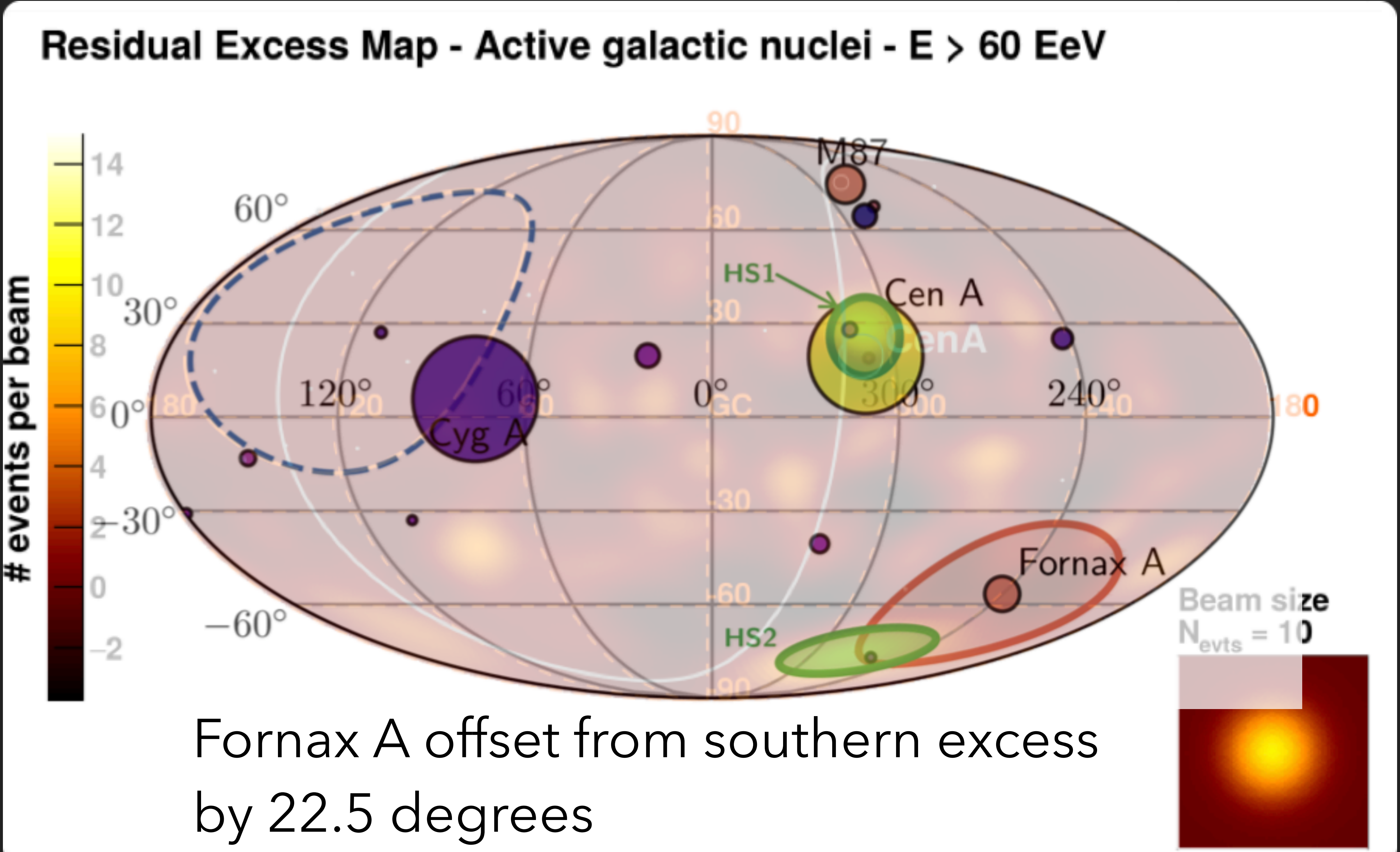


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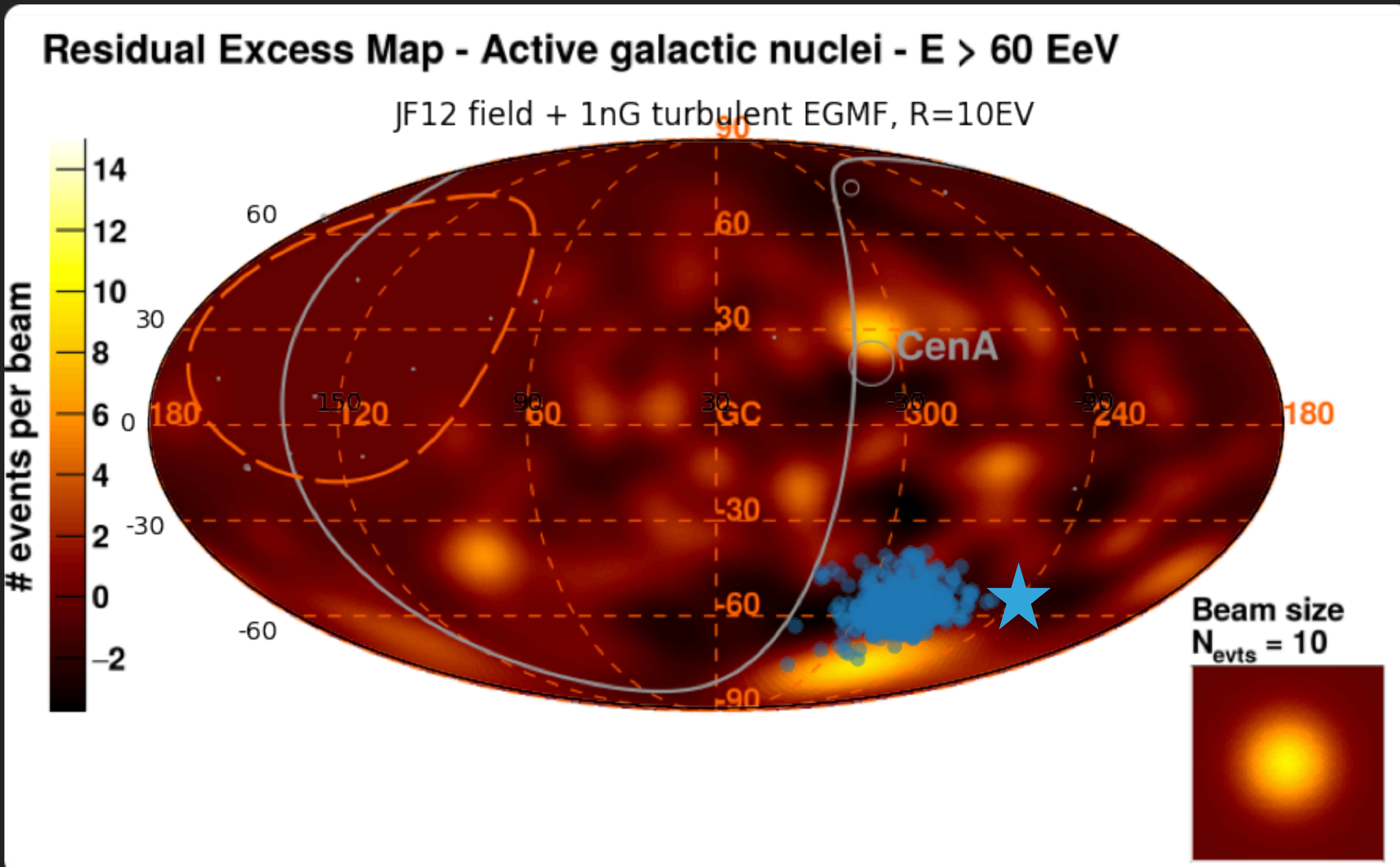
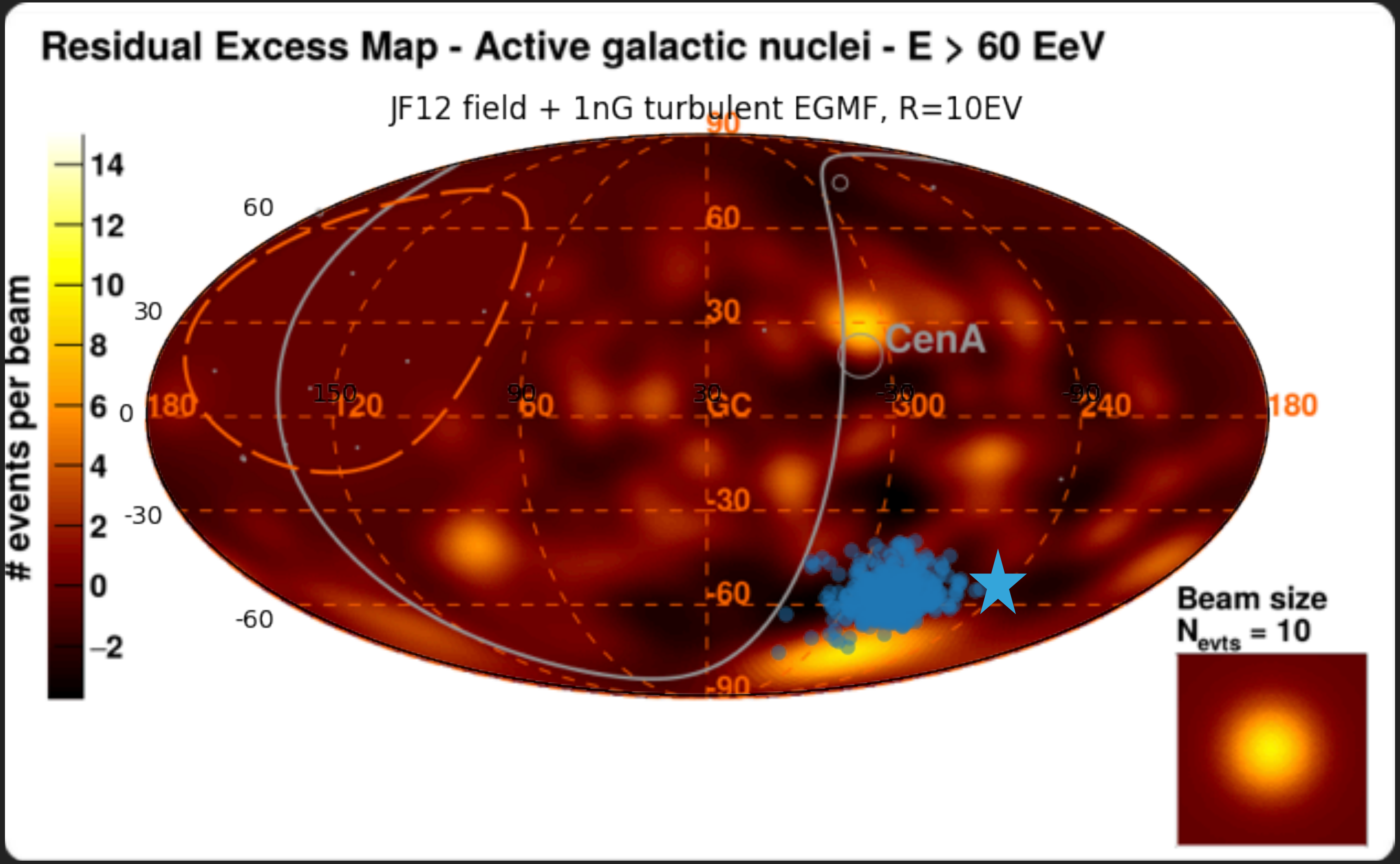


# ARRIVAL DIRECTIONS

- 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



# 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
- Auger arrival directions suggest Fornax A and Cen A – Fornax not in 3FHL

QUESTIONS

- Can the radio lobes confine the UHECRs for a reasonable (>Myr) time?
- How are UHECRs transported through magnetic fields in clusters, filaments and the galaxy?
- Is there a way around the relativistic shocks issue? Can we learn from smaller systems?
- What is the appropriate attenuation length, injection index and UHECR luminosity proxy?

PAPERS

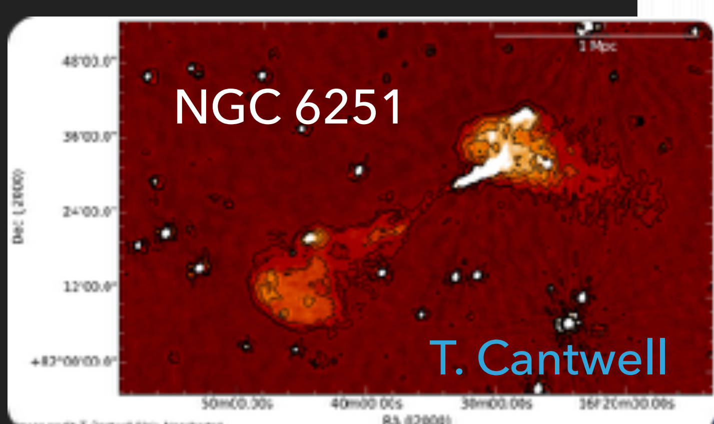

Matthews, Bell, Blundell, Araudo, 2017, MNRAS, 469,1849, arXiv:1704.02985
Araudo, Bell, Blundell, Matthews, 2018, MNRAS, 473, 3500, arXiv:1709.09231
Bell, Araudo, Matthews, Blundell, 2018, MNRAS, 473, 2364, arXiv:1709.07793
Matthews, Bell, Blundell, Araudo, 2018a, MNRAS, 479, 76, arXiv:1805.01902
Matthews, Bell, Blundell, Araudo, 2018b, MNRAS in press, arXiv:1810.12350

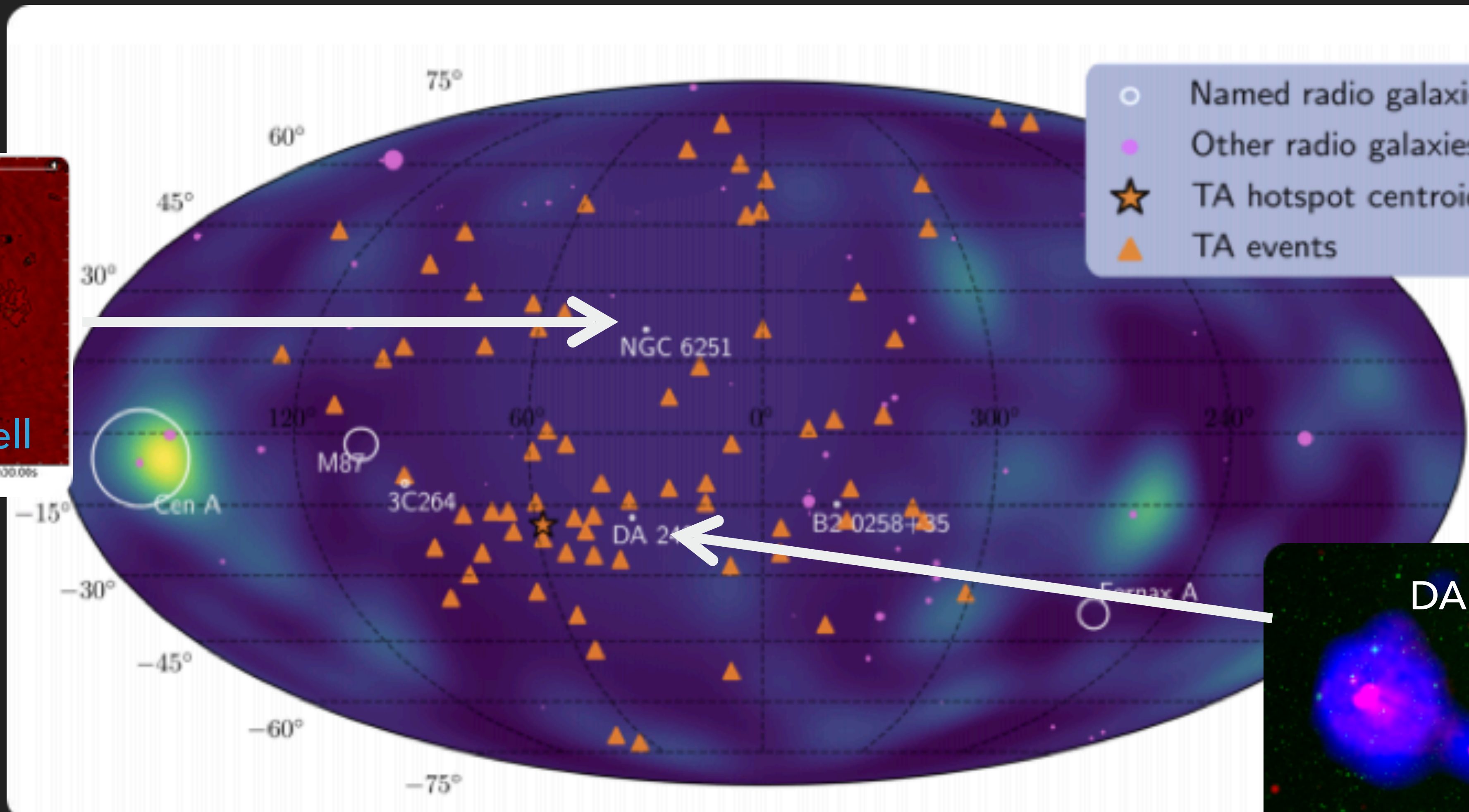
# Additional slides

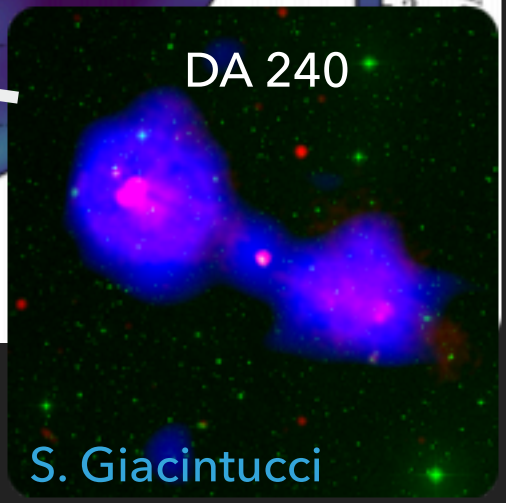
# WHAT ABOUT TA?

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?

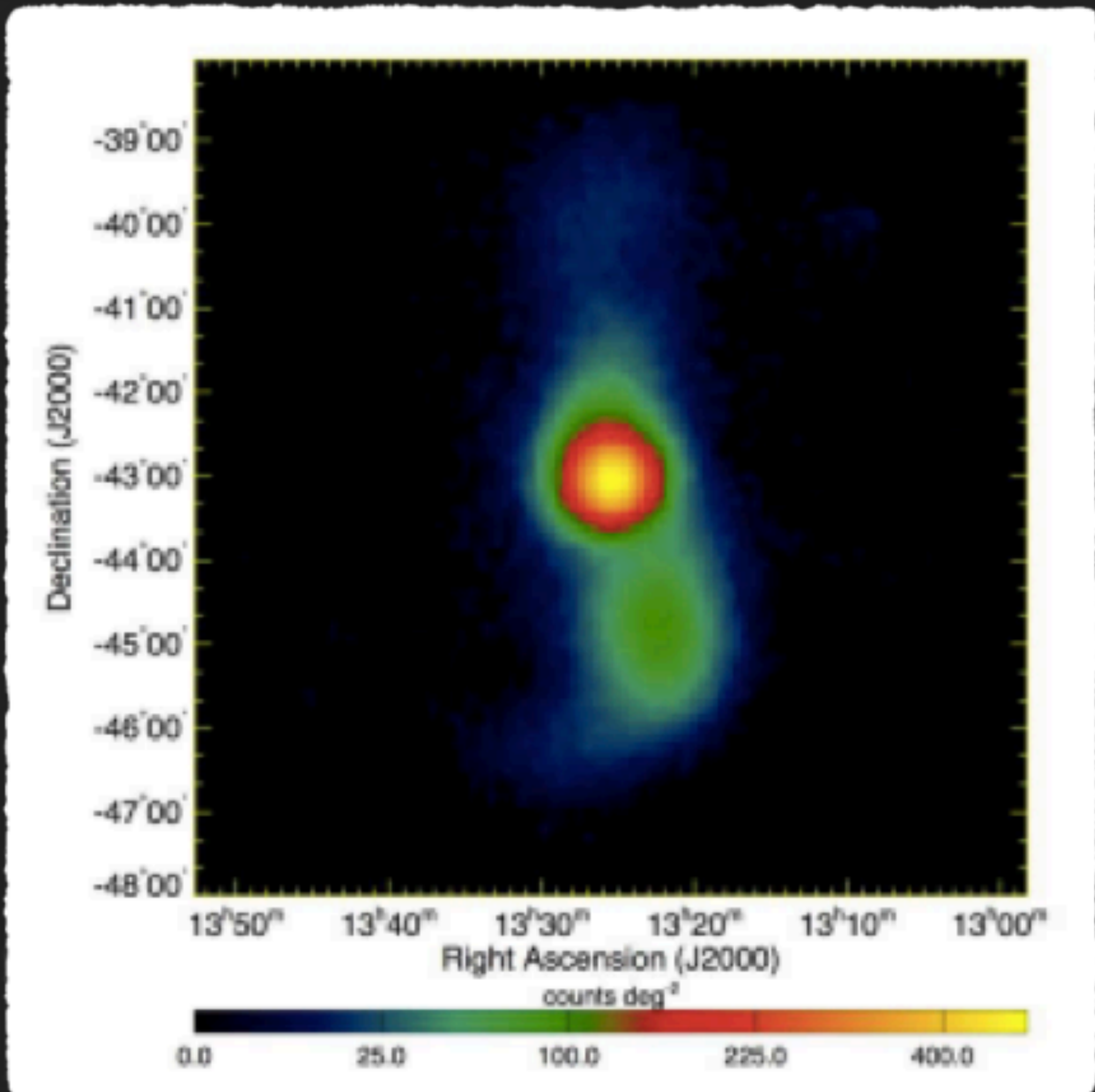


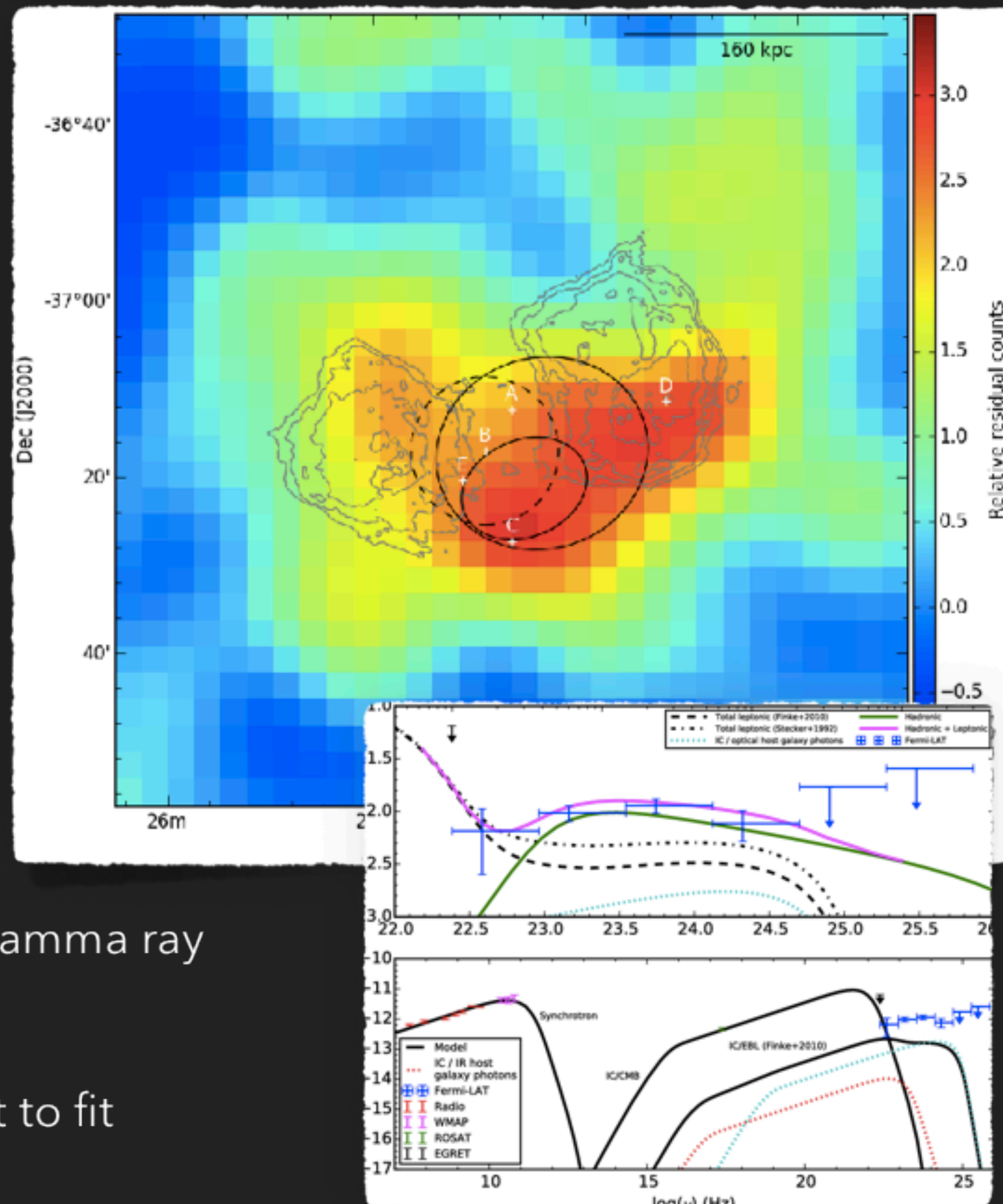




Supergalactic coordinates!

# GAMMA RAYS




Ackermann et al. 2010

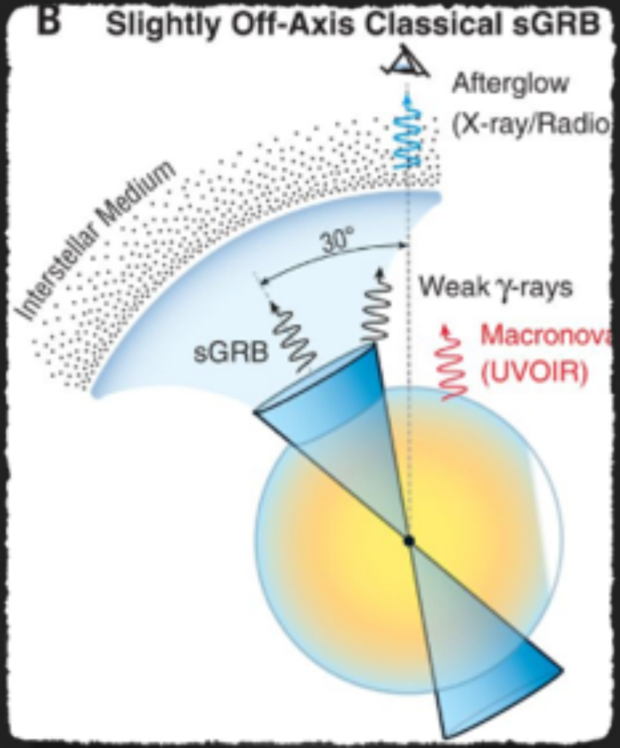



Ackermann et al. 2016

- Both sources show very extended gamma ray emission in Fermi (~200 MeV)
- Fermi requires hadronic component to fit Fornax spectrum (p-p and p-γ)

# 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

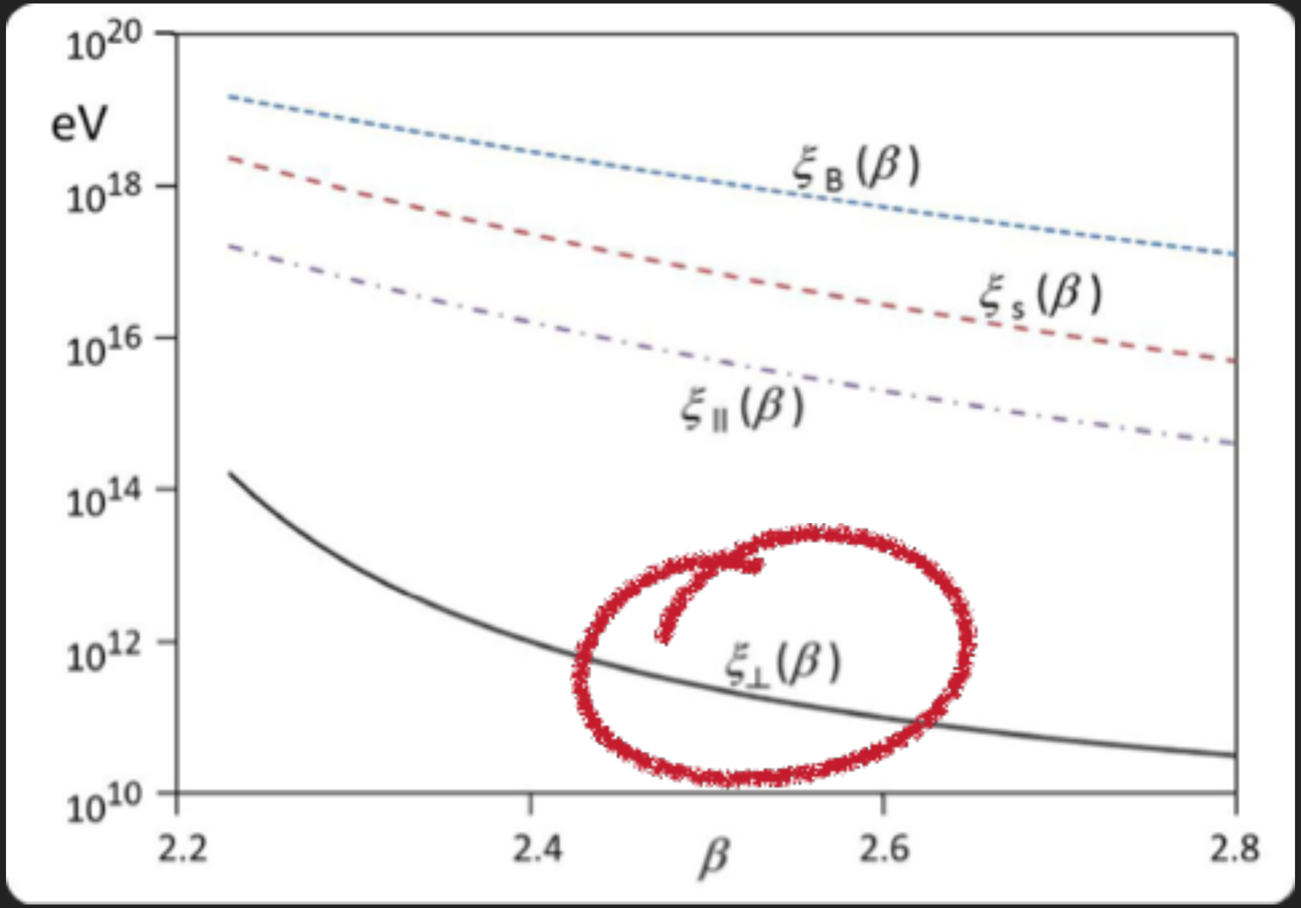




Kasliwal+ 2017

# 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
- 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

Shock and B-field physics




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?"*

# COSMIC RAYS DRIVE TURBULENCE: THE BELL INSTABILITY

- Cosmic rays produce a return current in a plasma that drives MHD turbulence
- Also amplifies magnetic field
- A natural way to grow turbulence to Larmor radius scales and reach the Hillas energy

$$r_g = \frac{E}{cB}$$