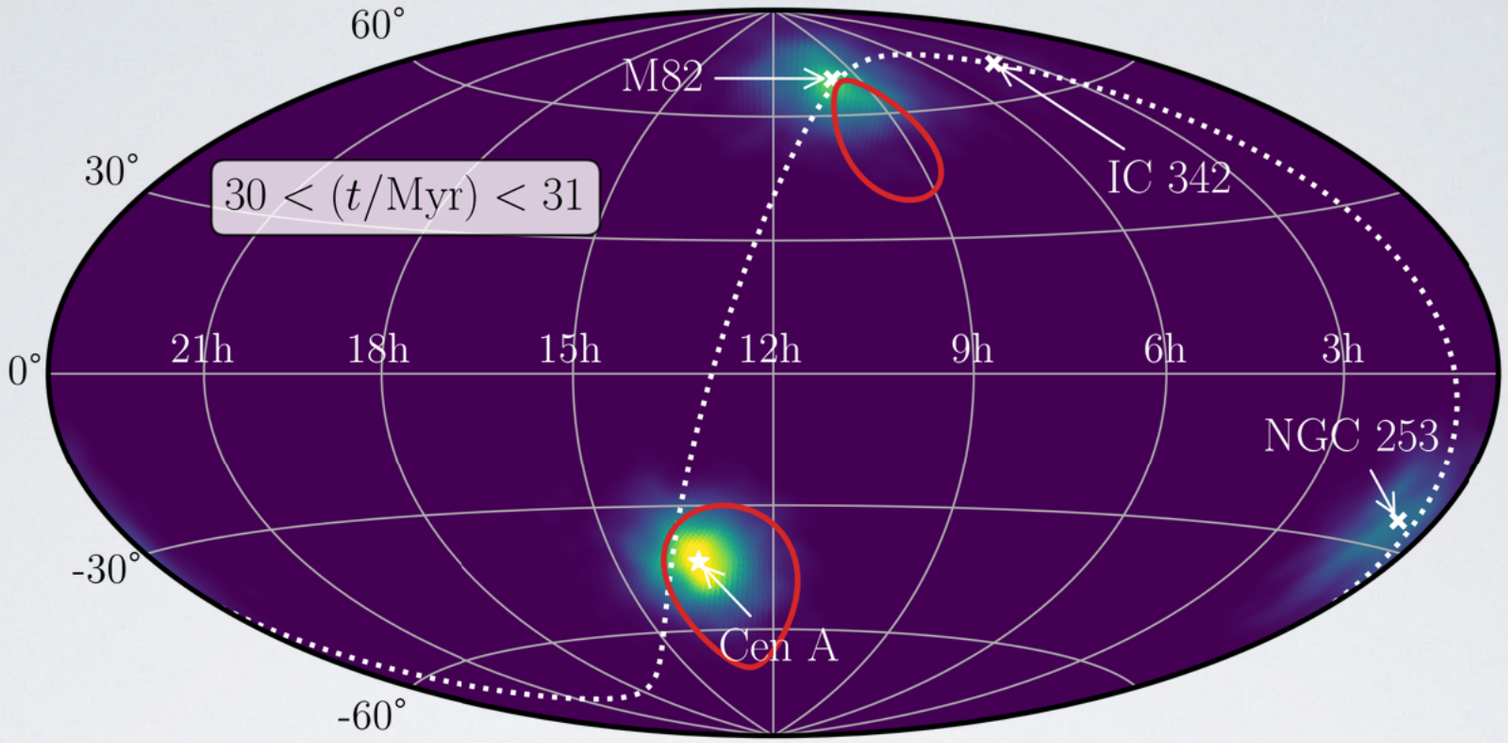

How, where and *when* do cosmic rays reach ultrahigh energies?

James Matthews (IoA, Cambridge)

Tony Bell, Katherine Blundell (Oxford), Andrew Taylor (DESY Zeuthen), Anabella Araudo (Czech Academy of Sciences)

European Cosmic Ray Symposium, Nijmegen, 2022

UNIVERSITY OF CAMBRIDGE
Herchel Smith Fund

ioa

Talk Structure

Intro / Primer

1 ***How?*** Physics of UHECRs

2 ***Where?*** Sources of UHECRs

A Biased Review

3 ***When?*** UHECR Echoes

Some Recent Ideas

Talk Structure

Intro / Primer

1 ***How?*** Physics of UHECRs

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A Biased Review

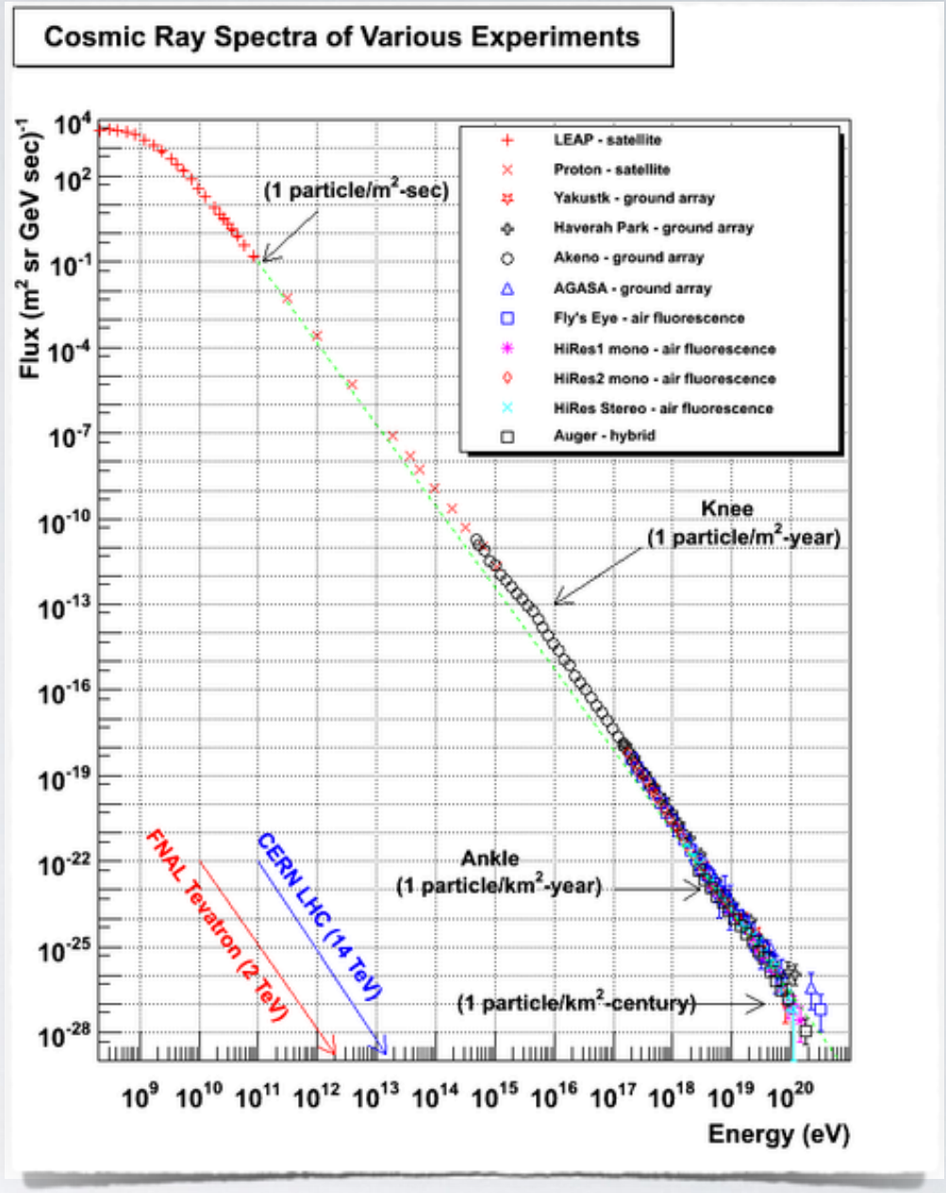
Some Recent Ideas

For recent UHECR+ reviews see:

- Alves-Batista+ 2019, *Open Questions in Cosmic-Ray Research at Ultrahigh Energies*, arXiv:1903.06714
- EuCAPT White Paper, *Opportunities and Challenges for Theoretical Astroparticle Physics in the Next Decade* (chapters 5 & 7), arXiv: 2110.10074

The CR Spectrum

- The Cosmic Ray spectrum: The best power law in nature? (see Fujita talk)
- 11 OOM in particle energy and 32 OOM in flux!
- n(E) ~ $E^{-2.7}$, sometimes steeper (3) or shallower (2.6)
  - Intrinsic galactic CRs have $E^{-2.3}$ (Hillas 2006)
- Similar to non-thermal electrons in SNR, AGN, XRBs etc.
- Huge range of Larmor radius scales!



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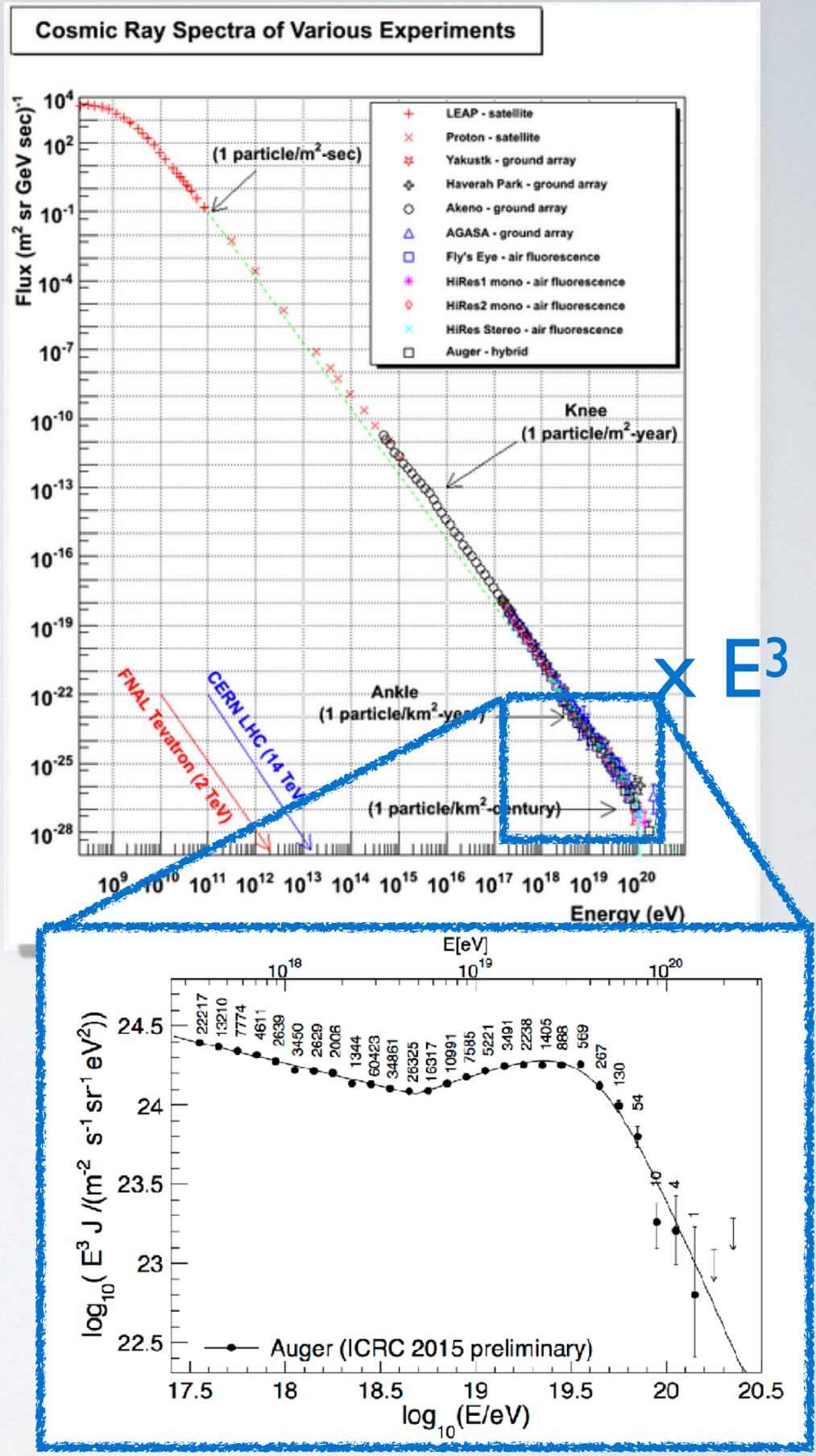


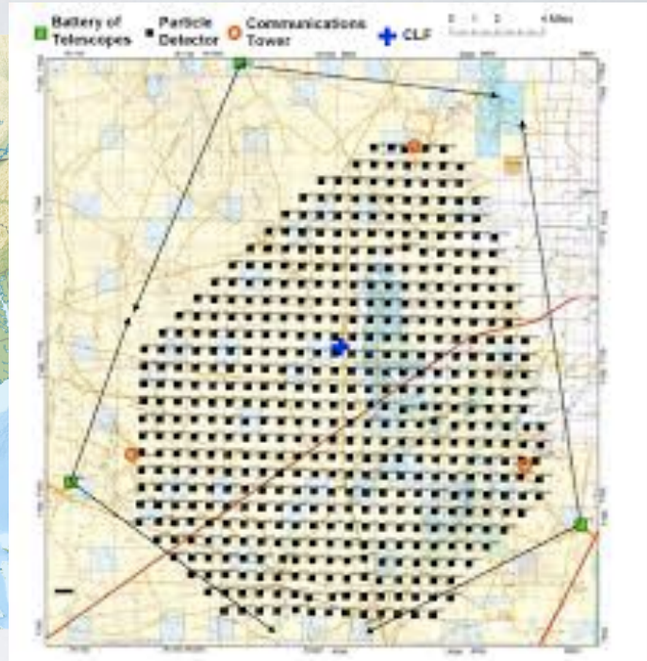
UHECR Fundamentals

- First discovery of a 10^{20} eV particle made by Linsley & Scarsi in 1963
  - see Watson 2019 for a history
- UHECR definition used here: $E \gtrsim 10^{18}$ eV
- UHECRs in practice always protons or nuclei
- Rigidity (volts) is a useful quantity - both deflection in a B-field and acceleration in an E-field depend on rigidity and not energy
- I will ignore fundamental charge: energies and rigidities in eV

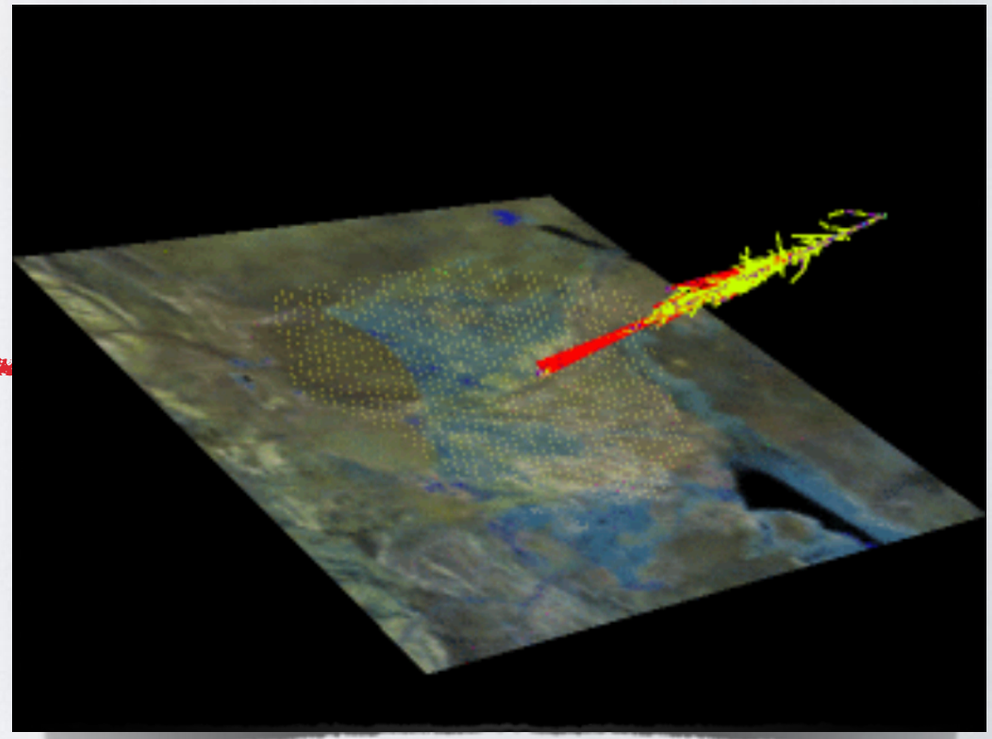
$$\mathscr{R} = \frac{E}{Z}$$

UHECR Observatories

- Telescope Array
- effective area ~700 sq km
- 507 surface detectors with plastic scintillators
- 3 atmospheric Fluorescence Detector telescopes



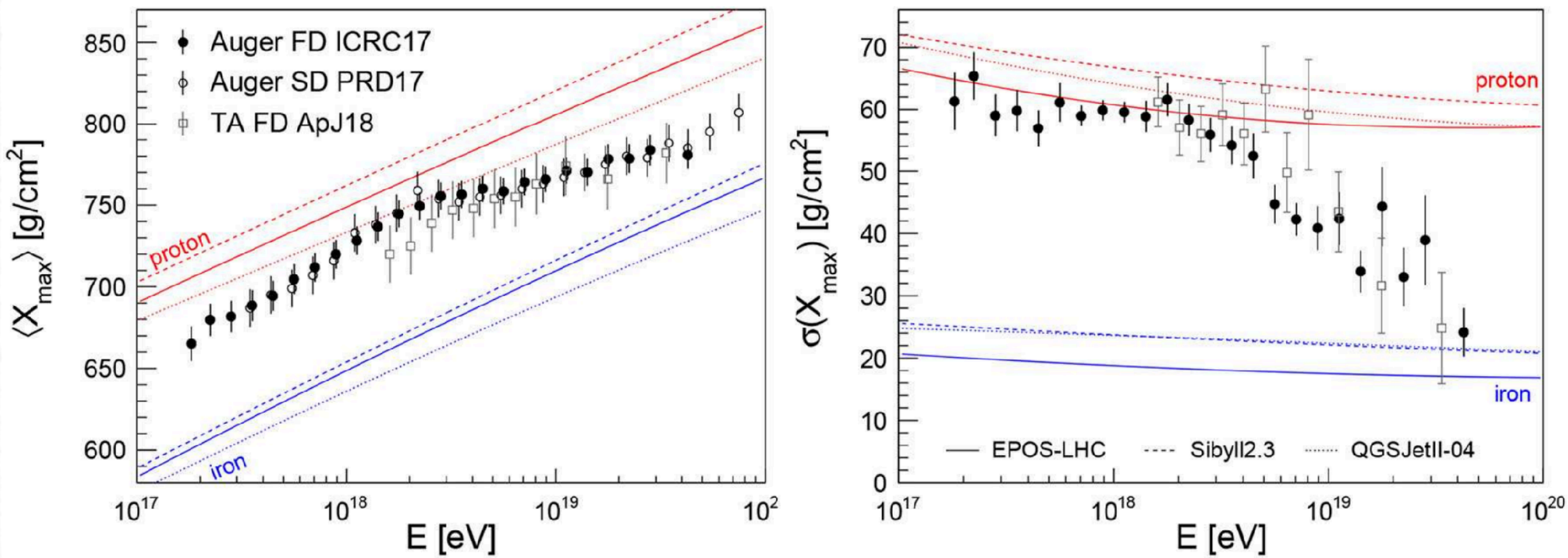
- Pierre Auger observatory
- effective area ~3000 sq km
- 1600 water Cherenkov Detectors
- 24 atmospheric Fluorescence Detector telescopes



Both also measure ***directions*** and ***composition*** of UHECRs

Composition and Max Rigidity

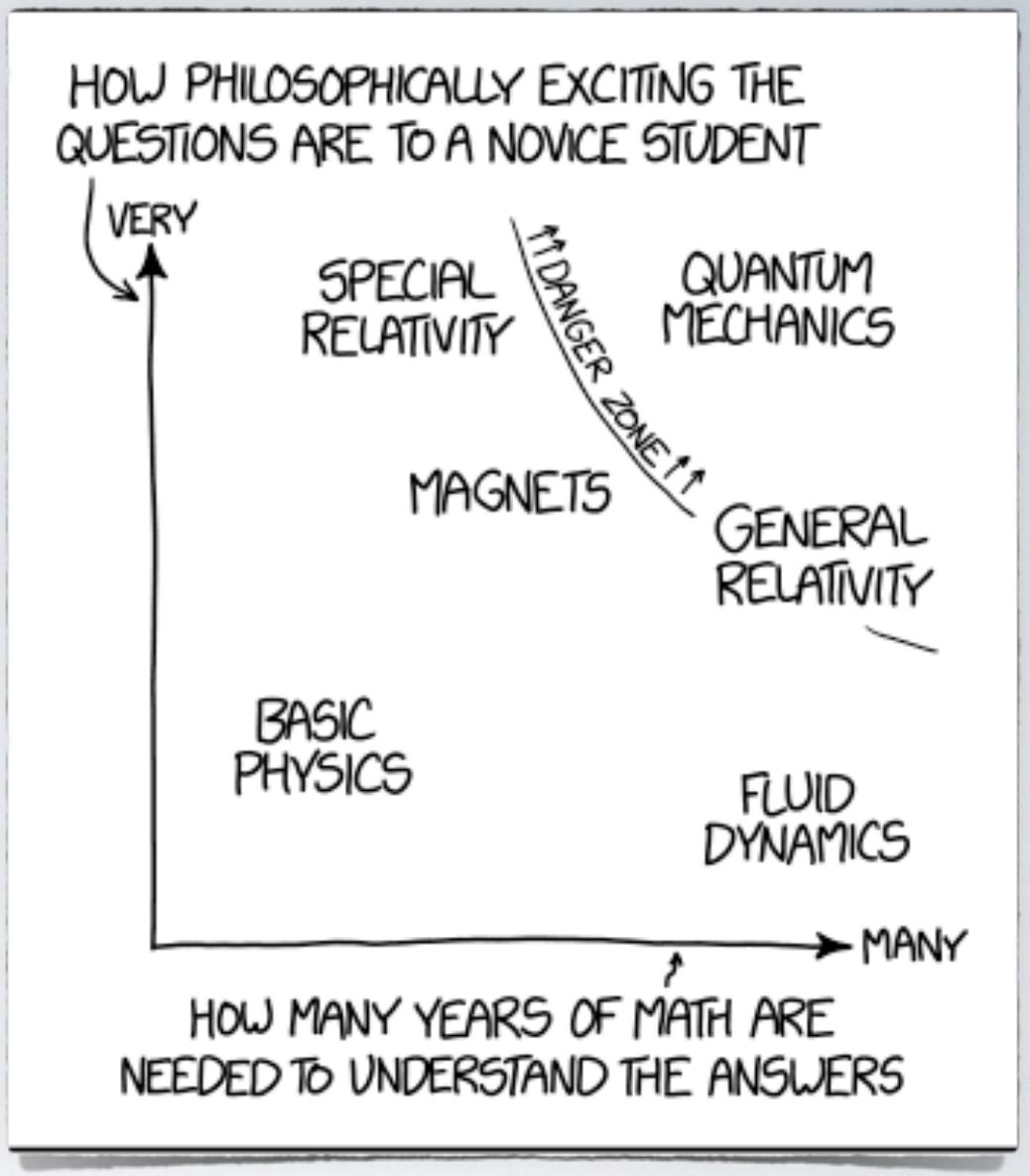
M. Unger



- General picture emerging from Xmax data that composition becomes heavier around 5 EeV

- In this talk I will assume we need to get protons to 10 EeV, which implies

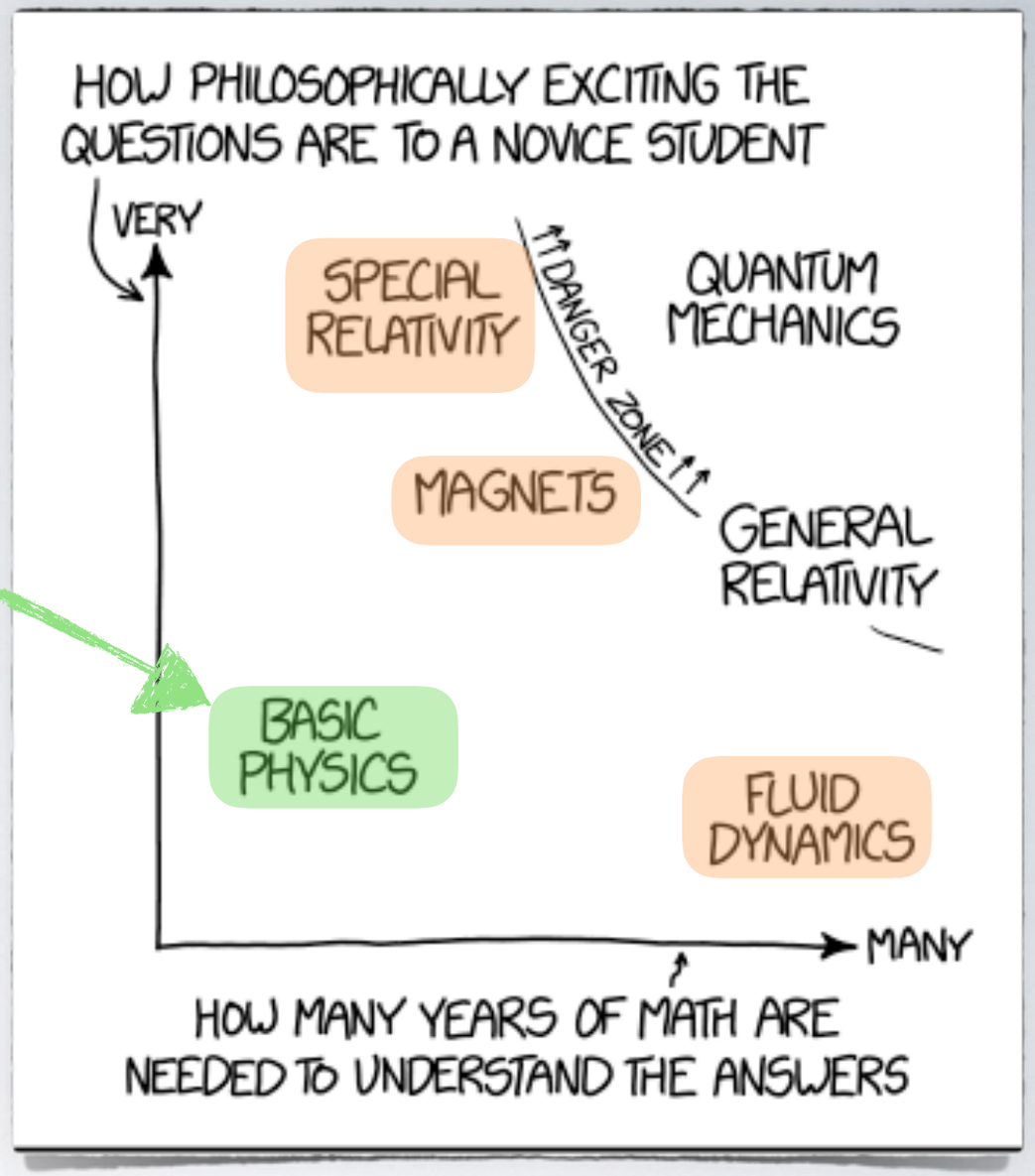
$$\mathscr{R}_{\max} = E/Z \sim 10^{19}\ \mathrm{eV}$$



Credit: xkcd (Randall Munroe)

I *How?* Physics of UHECRs

My comfort zone

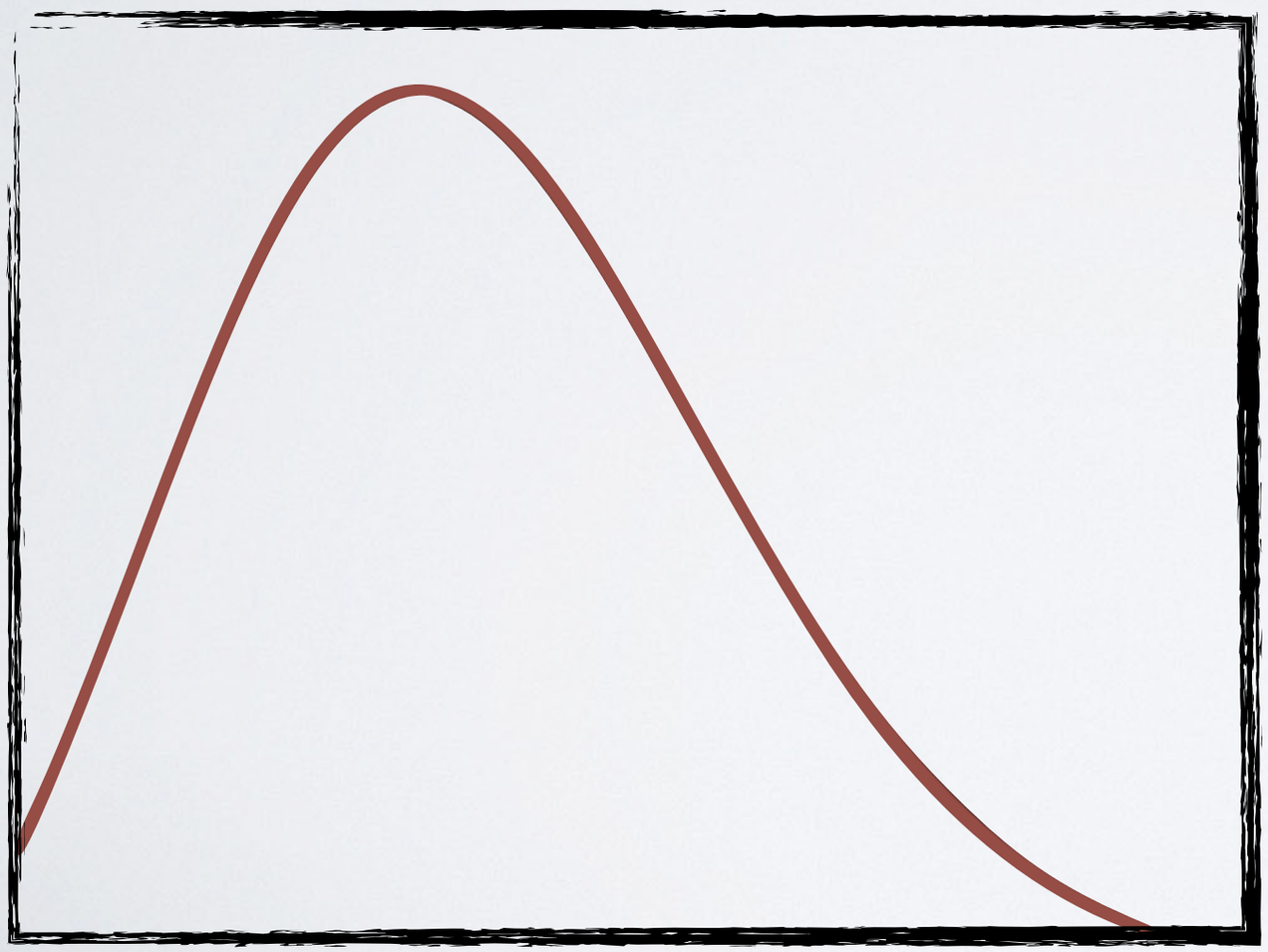


Credit: xkcd (Randall Munroe)

I *How?* Physics of UHECRs

How to accelerate a particle

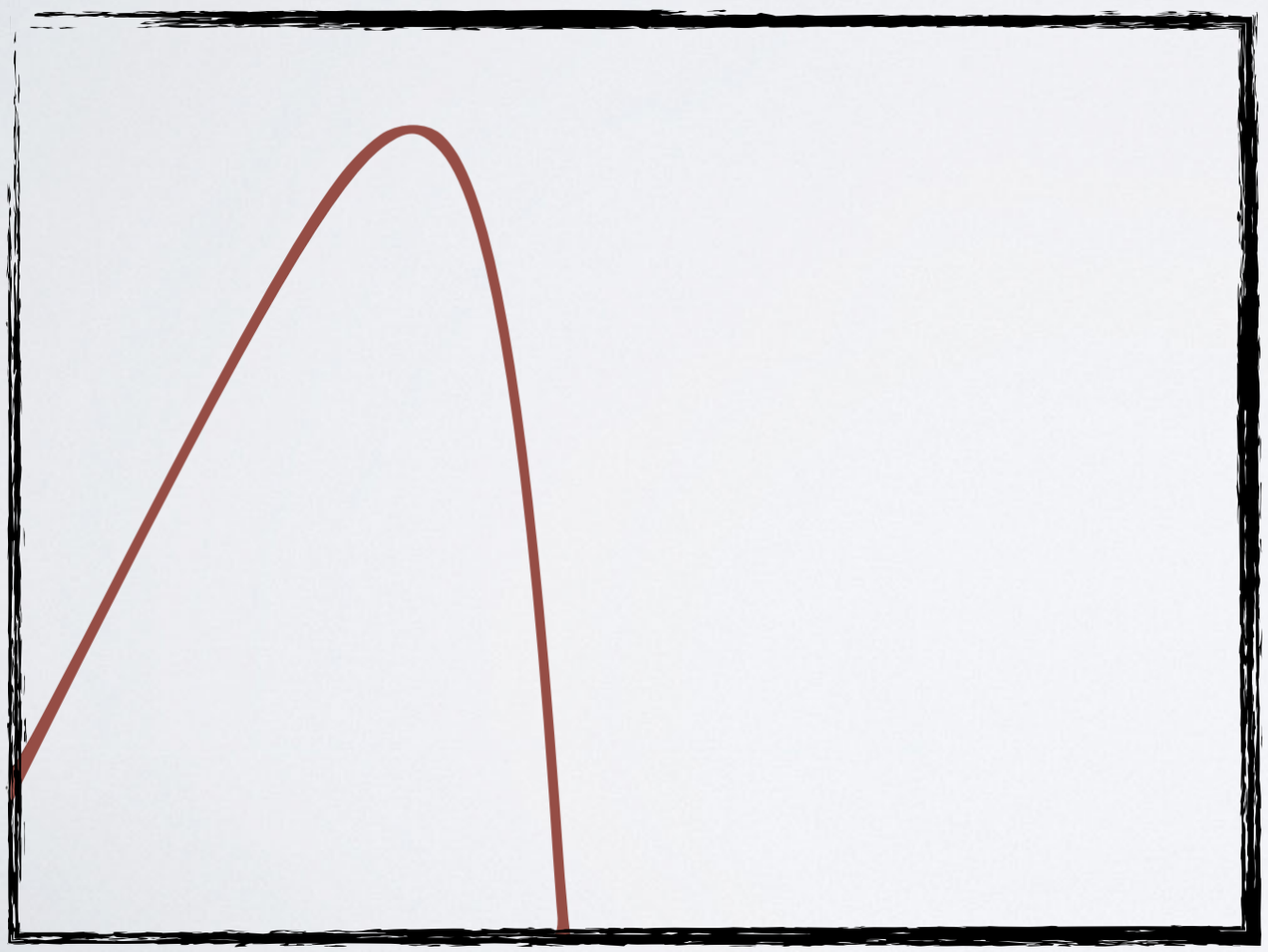
Maxwellian



How to accelerate a particle

Maxwellian

Log-scaled and shifted



How to accelerate a particle

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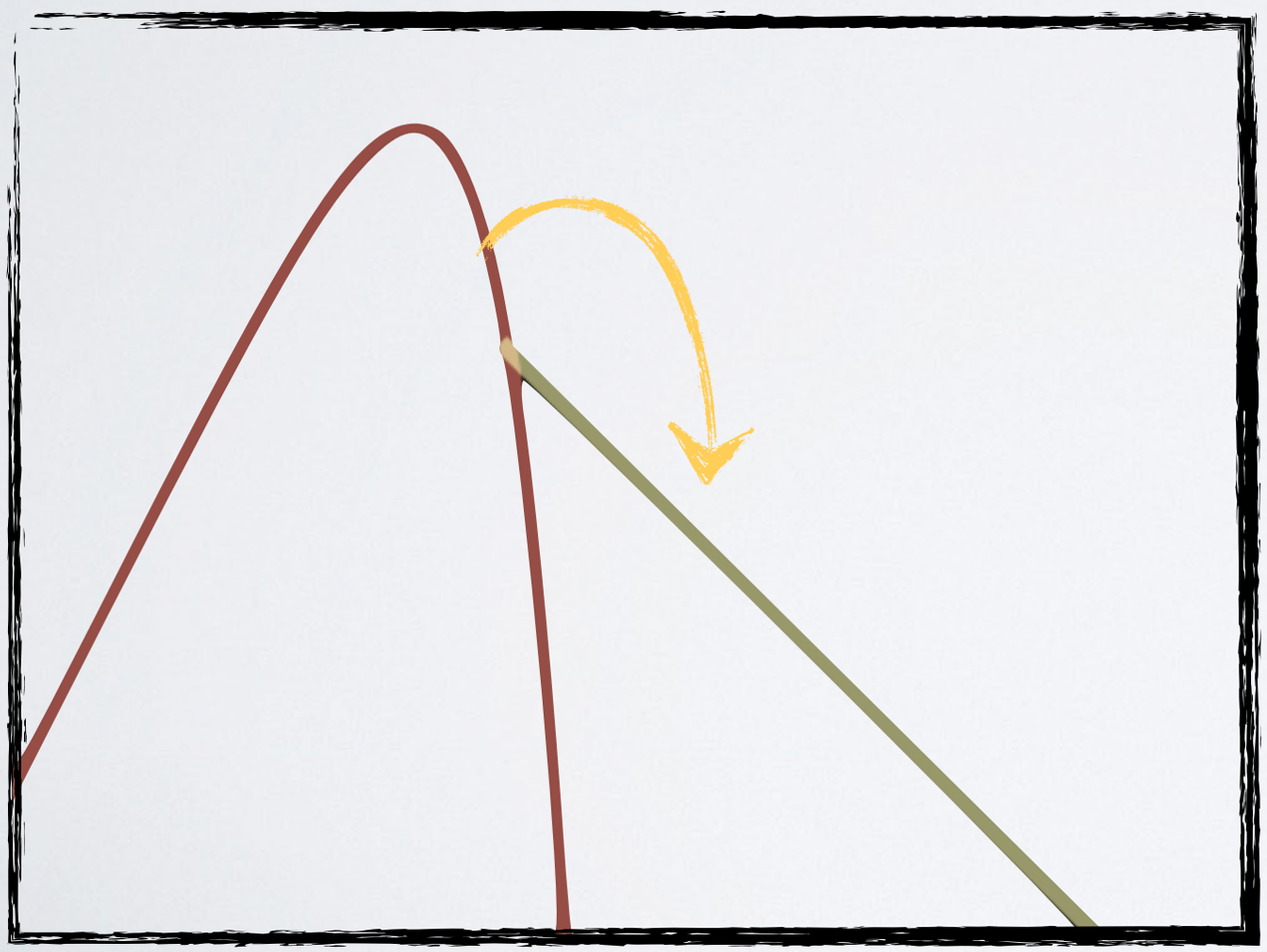
With a non-thermal tail



Particle acceleration is the process of "lifting" particles from thermal population onto non-thermal tail

How to accelerate a particle

Maxwellian

Log-scaled and shifted

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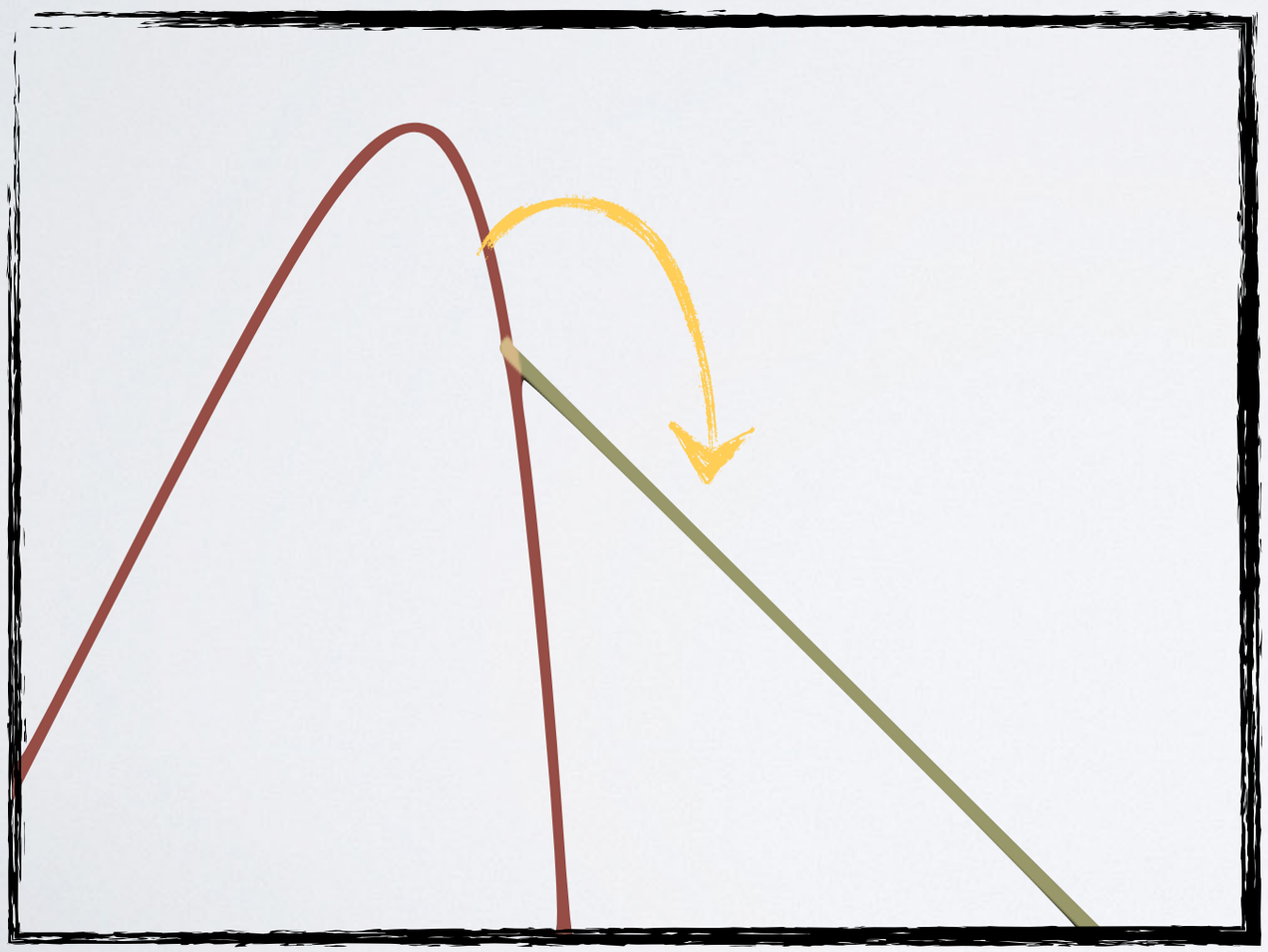
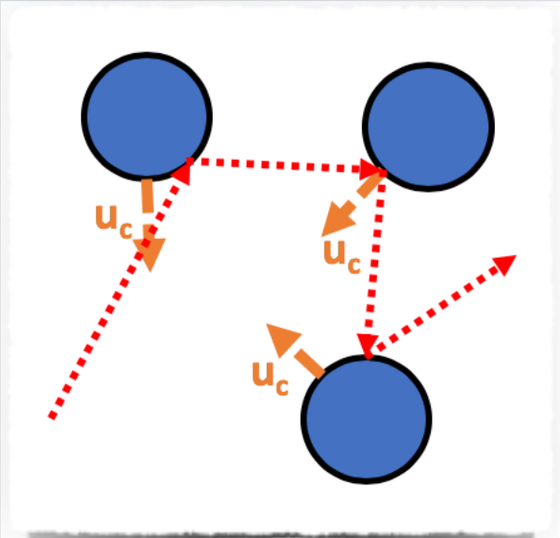


Particle acceleration is the process of "lifting" particles from thermal population onto non-thermal tail

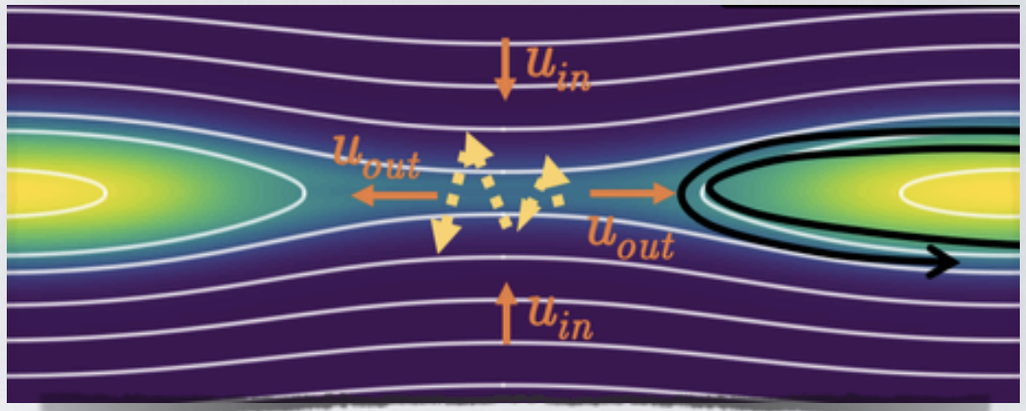
How do we form a power-law?

What sets the maximum energy?

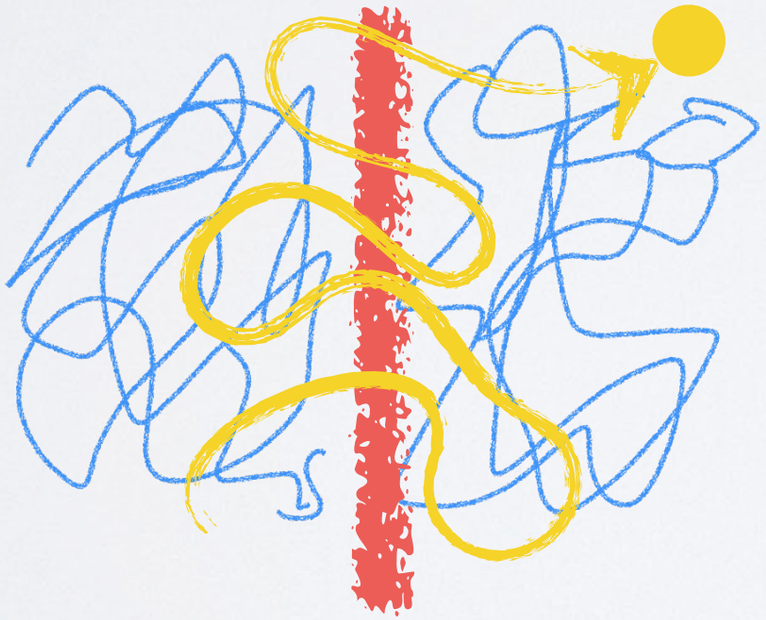
Particles are accelerated in sites of energy dissipation



Turbulence/Fermi II



Reconnection



Shocks

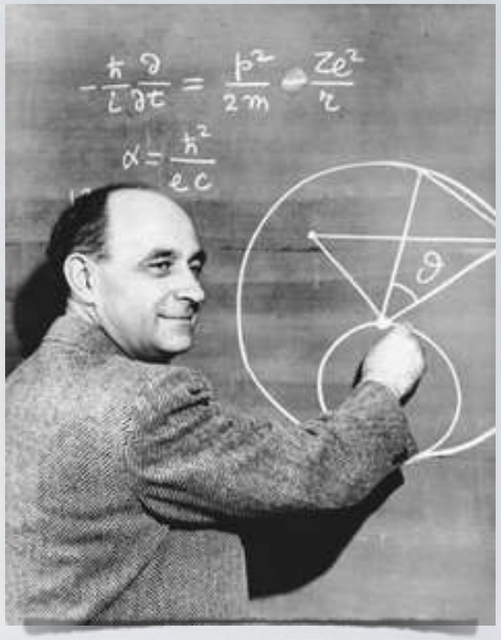
Also:

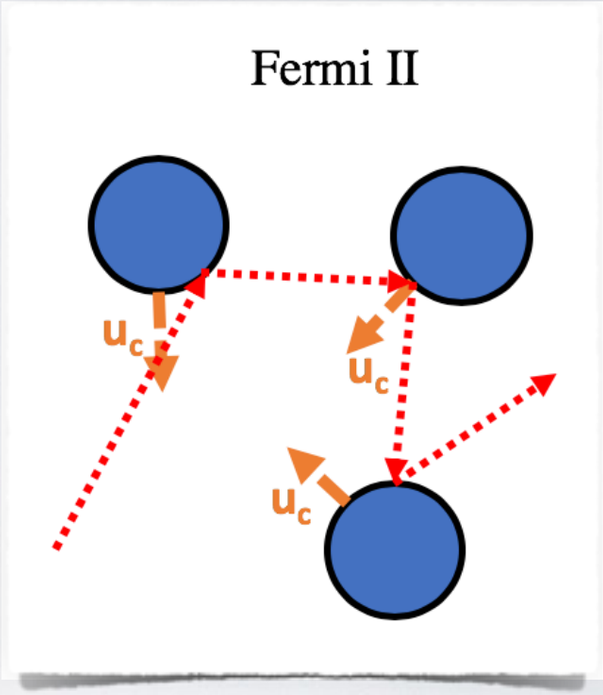
- Shear acceleration (e.g. Rieger & Duffy 2019; Rieger 2019)
- "One-shot / Espresso" mechanisms (e.g. Caprioli 2016; Kimura+ 2018)
- Direct E-fields / spark gaps
- Kink instabilities (e.g. Alves+ 2018)

Fermi II

- Second-order Fermi acceleration was proposed in 1949 by Fermi
- Particles scatter off cloud/turbulence that acts as magnetic mirrors, particle gains or loses u/c on each collision, but head on collisions more likely
- Requires fine tuning to get a power-law, more fine-tuning for specific index
- Energy gain is second-order, so a slow process unless u is high

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{8}{3}\left(\frac{u_c}{c}\right)^2$$

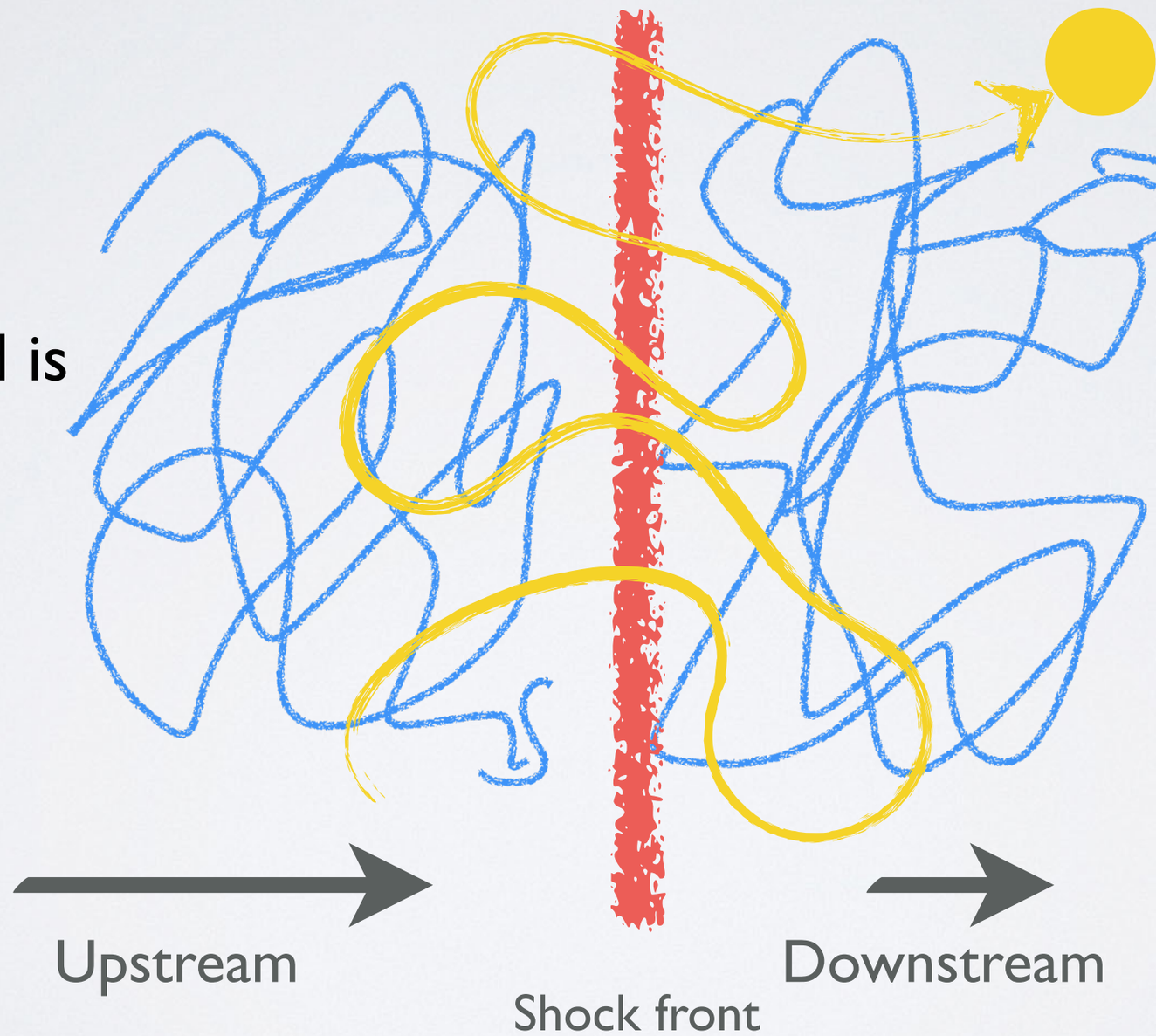




Shock acceleration

- Basic theory of shock acceleration developed in the late 70s (Bell 1978; Blandford & Ostriker 1978)

Turbulent B field is crucial!

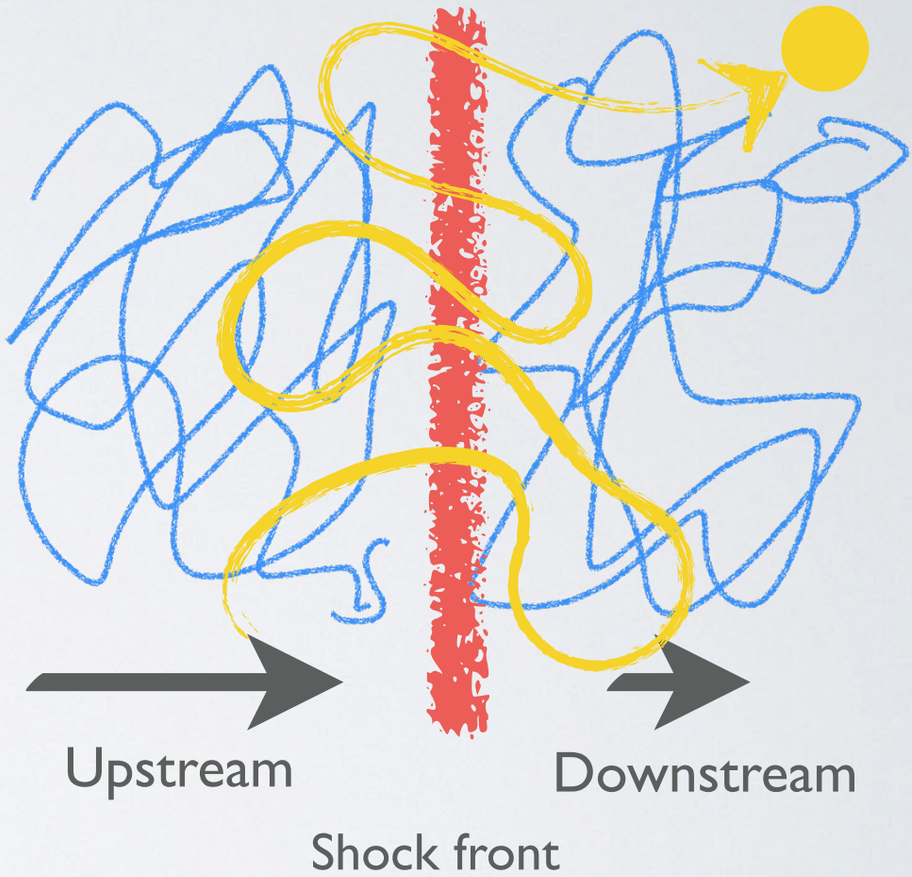


$$\frac{\Delta E}{E} \sim \frac{v_s}{c}$$

(e.g. jet termination shock, SN blast wave)

Shock acceleration

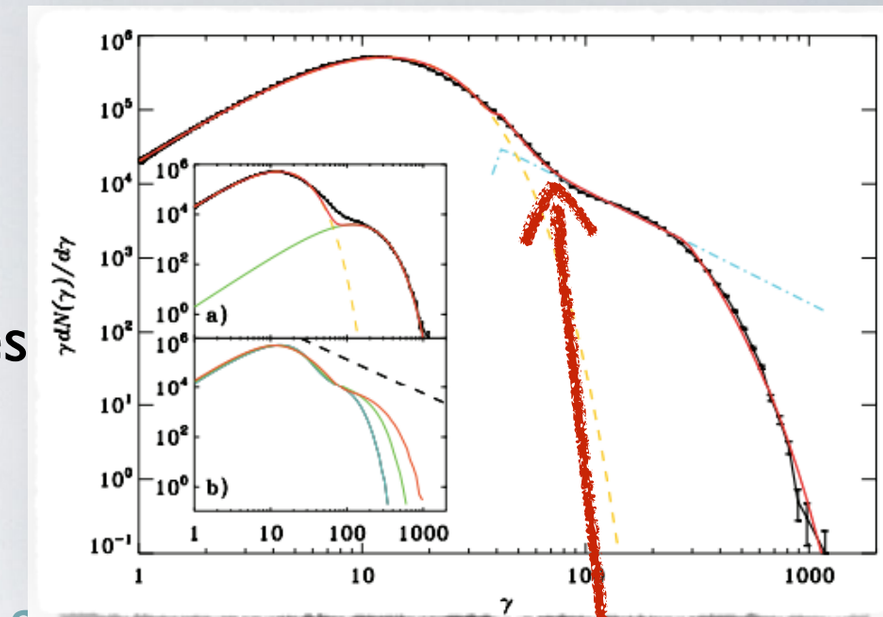
- Crucial aspect of shock acceleration:
  - <u>escape prob (P) and energy gain (β) are hard-wired by shock jump conditions</u>
- Good reason for a power-law to be produced!
- Well-motivated spectral index of ~2 or a bit steeper
- Other flavours: shock drift acceleration, shock surfing acceleration - similar principle.
- Reviews: Drury 1981, Blandford & Eichler 1987, Bell 2014, Marcowith+ 2018, JM+ 2020.



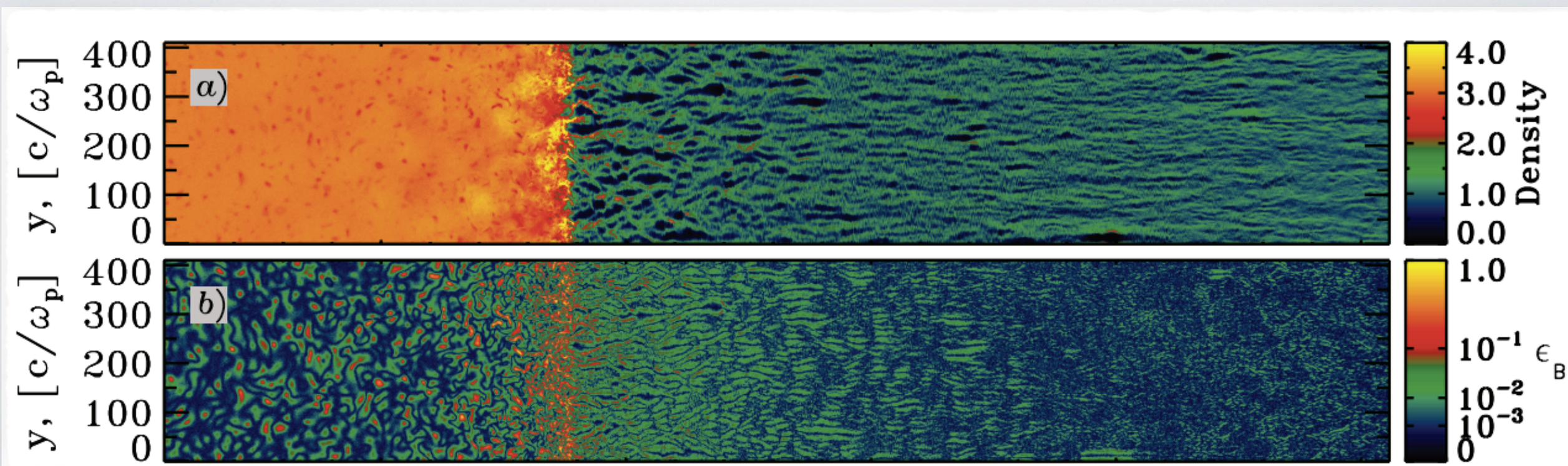
$$\frac{dN}{dE} \propto E^{(\ln P/\ln \beta_e - 1)}$$

Shocks with PIC

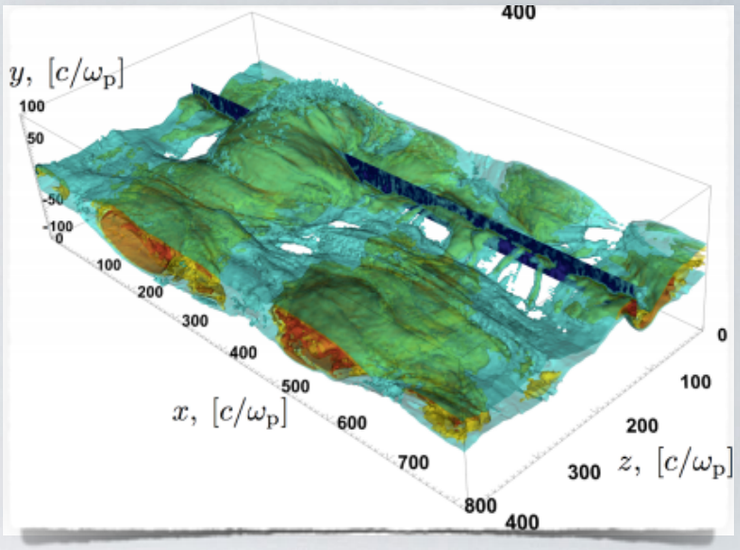
- Relatively simple theory where particle escape balances energy gain = power-law spectrum
- Verified by complex particle-in-cell (PIC) simulation (e.g. Spitkovsky 2008)
- Self-consistent generation of instabilities and power-law super thermal tail in momentum distribution



"Injection"

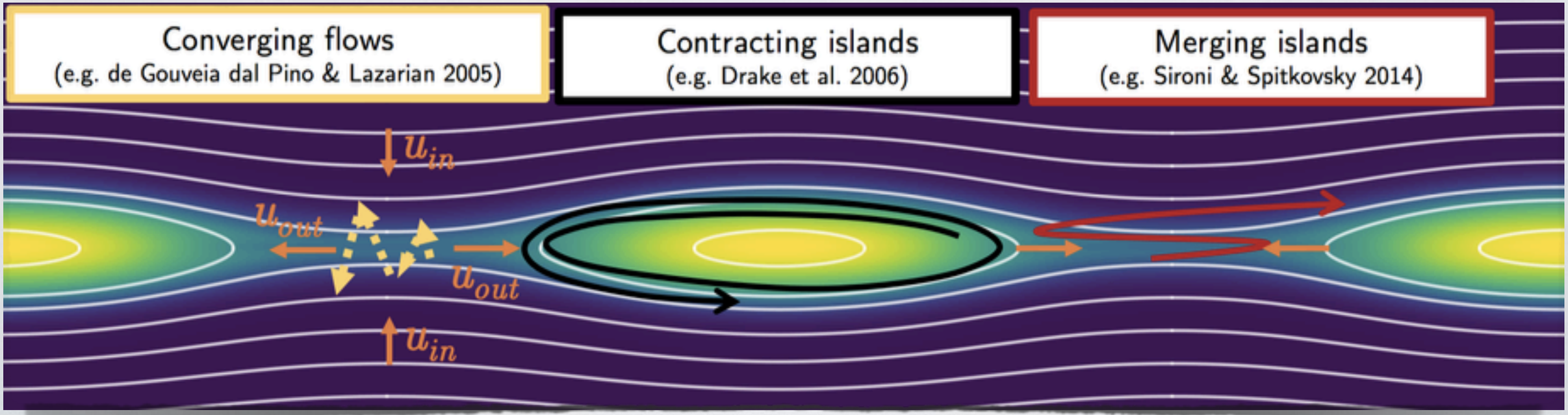


Magnetic Reconnection



Sironi & Spitkovsky 2014

- Regions of opposite magnetic polarity approach each other at Alfven speed, ~0.1c (if relativistic reconnection)
- Dissipates magnetic energy - important in astrophysical jets
- Direct acceleration in X-point electric field
- Particles undergo various forms of Fermi acceleration by scattering off and within "magnetic islands"



Hillas Energy

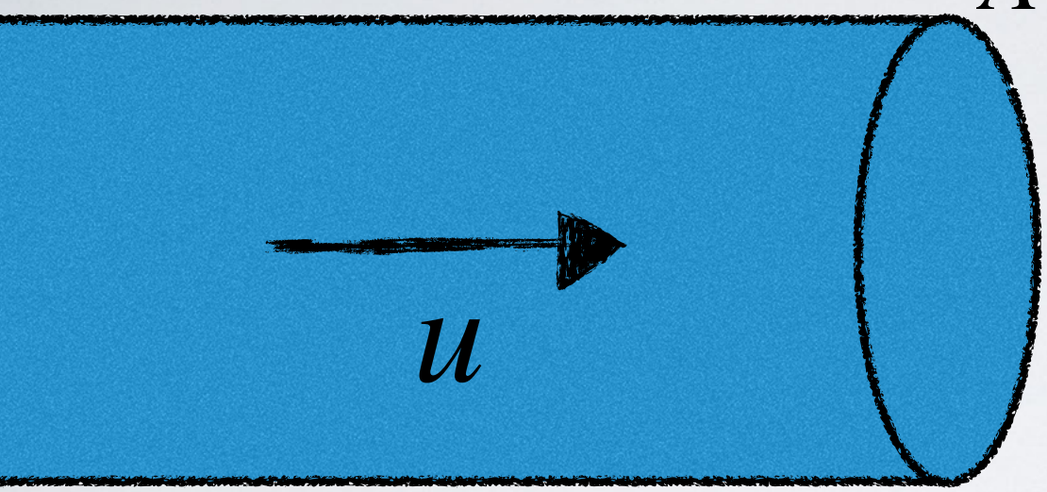
Michael Hillas

- Hillas energy: R bigger than R_g by factor (c/u)

$$E_H = ZuBR$$

- Can be understood in various ways, e.g.:
  - Moving particle a distance R through u x B electric field
  - Taking time derivative of magnetic flux BR^2 to give potential drop uBR

Power Requirement (Hillas-Lovelace limit)



$A = \pi R^2$

$$Q_B \sim \frac{B^2}{\mu_0} u \pi R^2$$

Power Requirement (Hillas-Lovelace limit)

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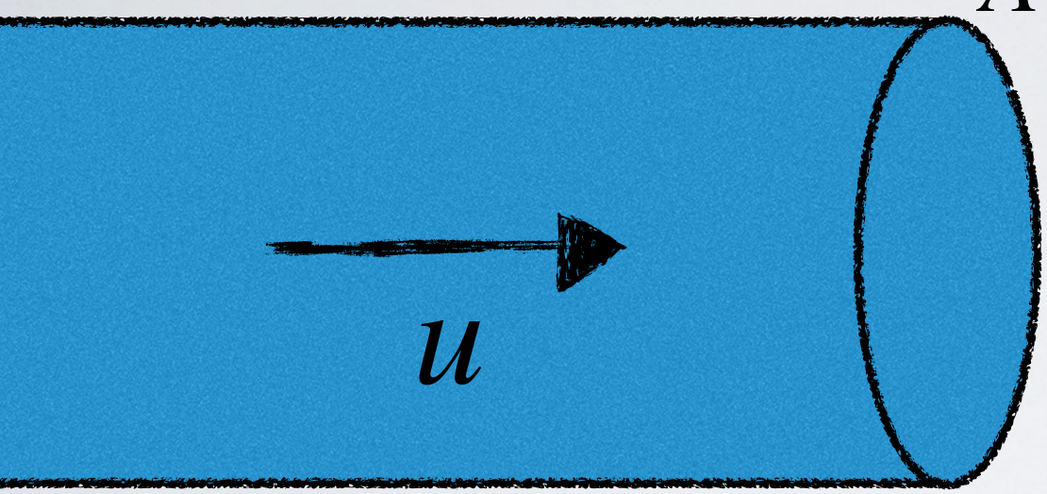

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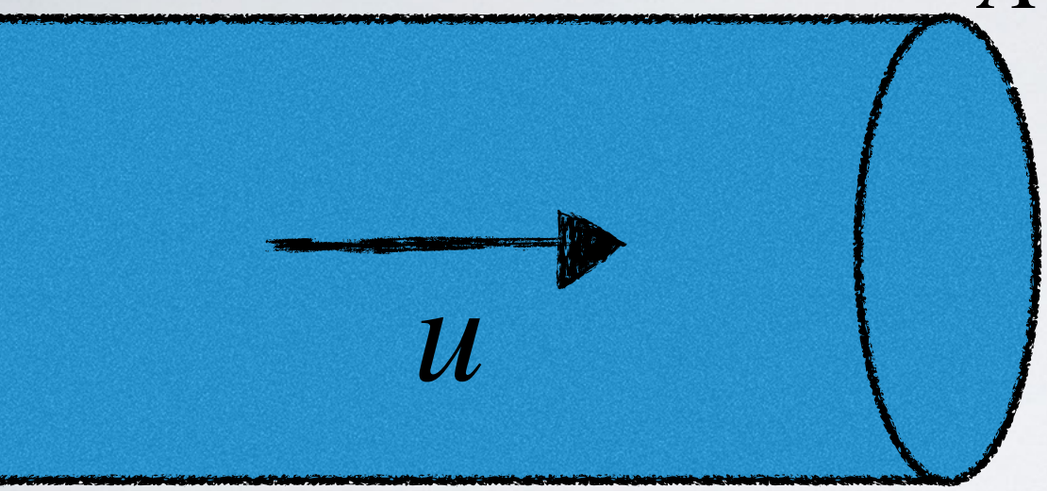


$$A = \pi R^2$$

$$Q_B \sim \frac{B^2}{\mu_0} u \pi R^2$$

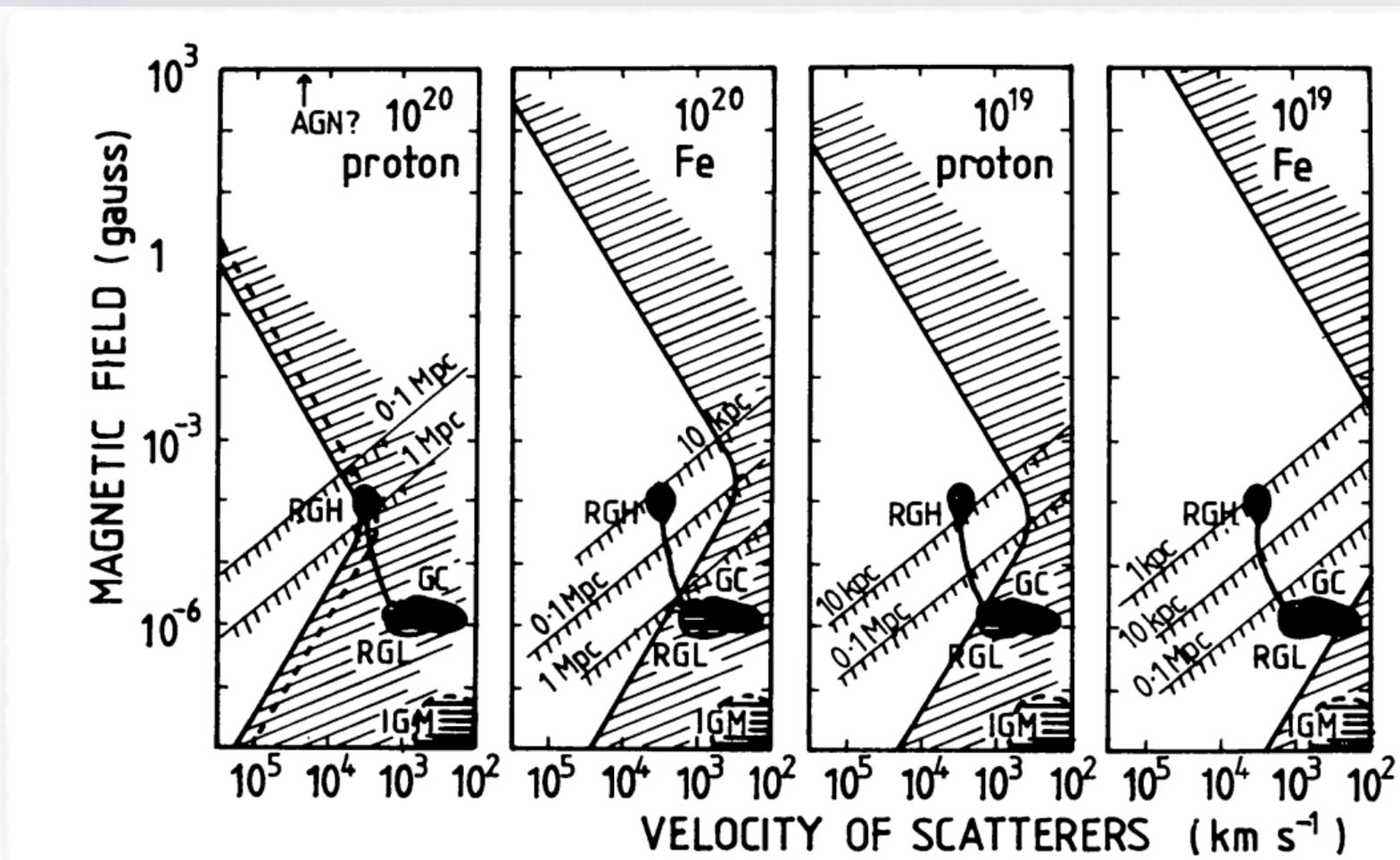
$$E_H = ZuBR$$

$$Q_B \sim \frac{\pi}{\mu_0} \frac{1}{uZ^2} E_H^2$$

Power Requirement (Hillas-Lovelace limit)

- Assume kinetic power higher than magnetic power $Q_B \sim \epsilon Q_k$

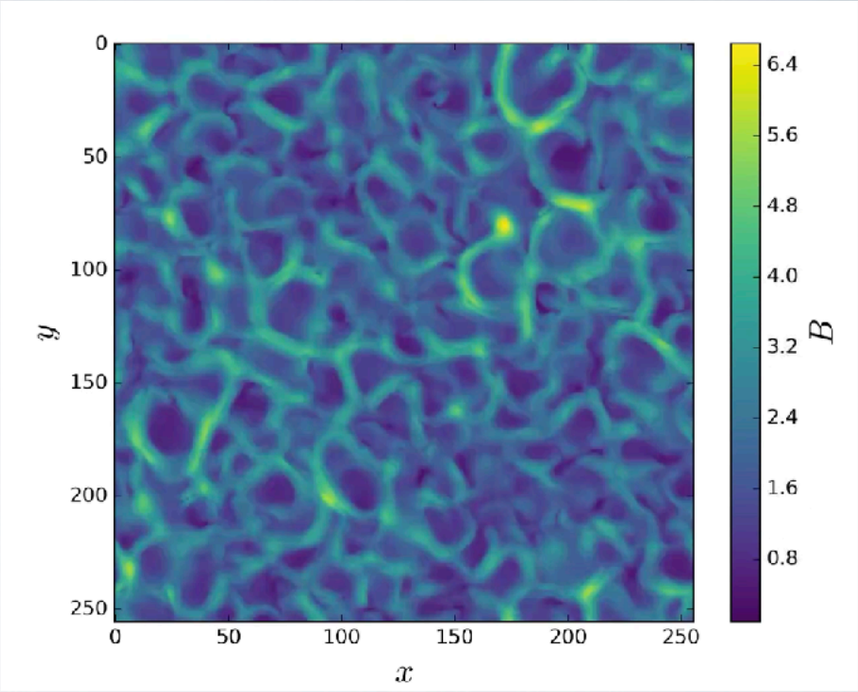
$$Q_k \gtrsim 10^{43}\ \epsilon^{-1} \left(\frac{E/Z}{10^{19}\mathrm{eV}} \right)^2 \left(\frac{u}{c} \right)^{-1} \quad \mathrm{erg\ s^{-1}}$$



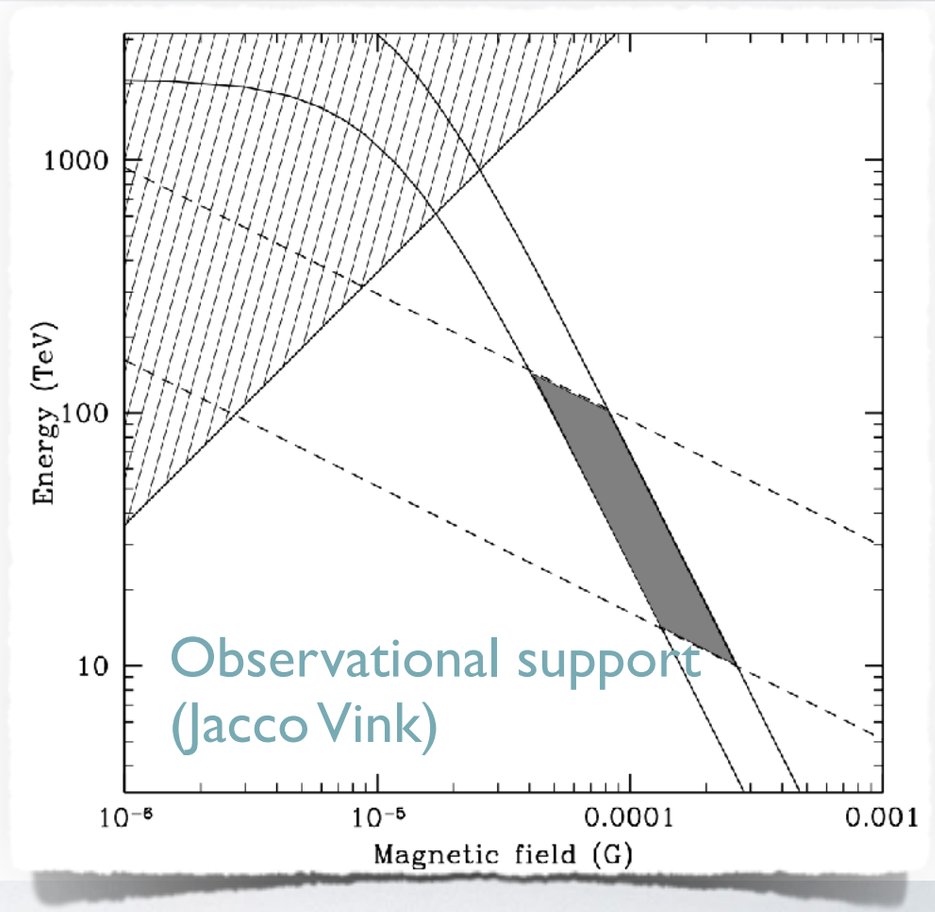
Hillas (1984) fig. 6: the more important Hillas diagram?

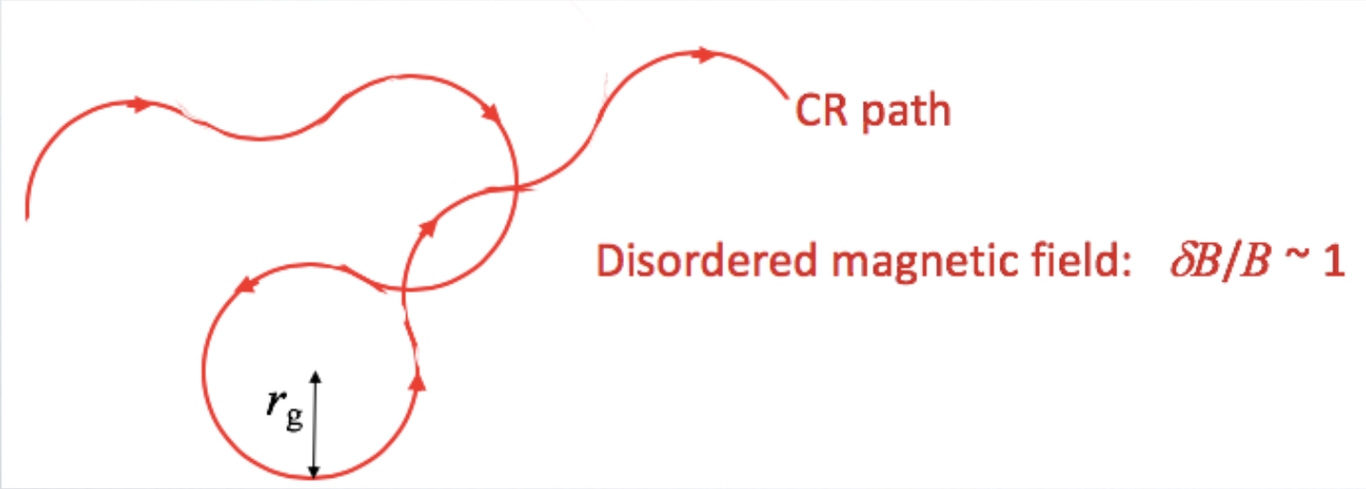
CR-Driven Instabilities

- Hillas condition is *necessary but not sufficient*
- Need to be in "Bohm diffusion" regime where mean free path is equal to Larmor radius ($\lambda \sim r_g$)
- CRs produce a return current in a plasma that drives MHD turbulence - the non-resonant or Bell instability* (e.g. Bell 2004, Zirakashvili+ 2008)
- A natural way to grow turbulence to Larmor radius scales and amplify magnetic field.



Matthews+ 2017



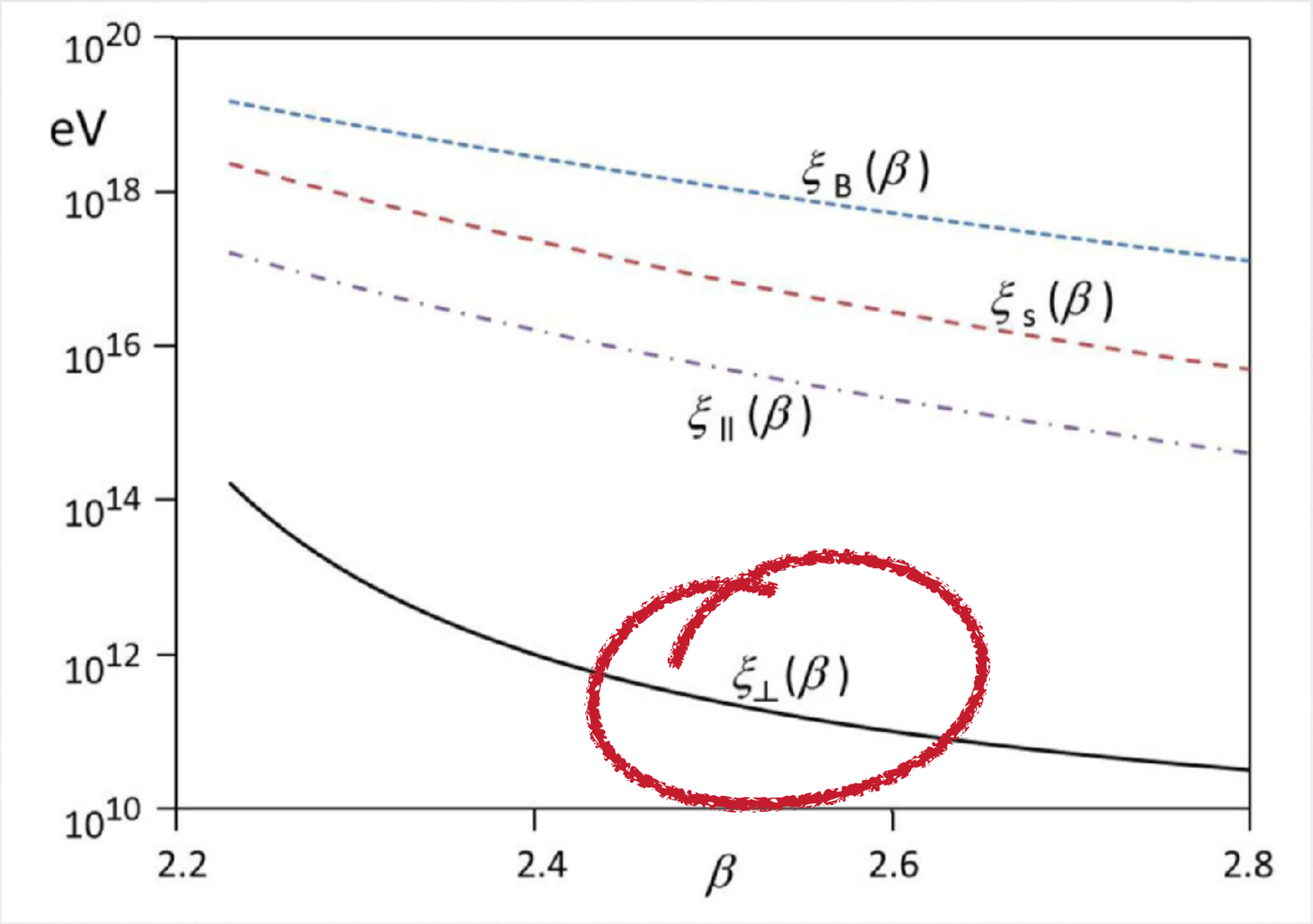


* Other instabilities are available

Relativistic Shocks Are Problematic

- Not enough time to grow turbulent B field to UHECR Larmor radii scales (Lemoine & Pelletier 2010; Reville & Bell 2014; Bell+ 2018)

Shock and B-field physics



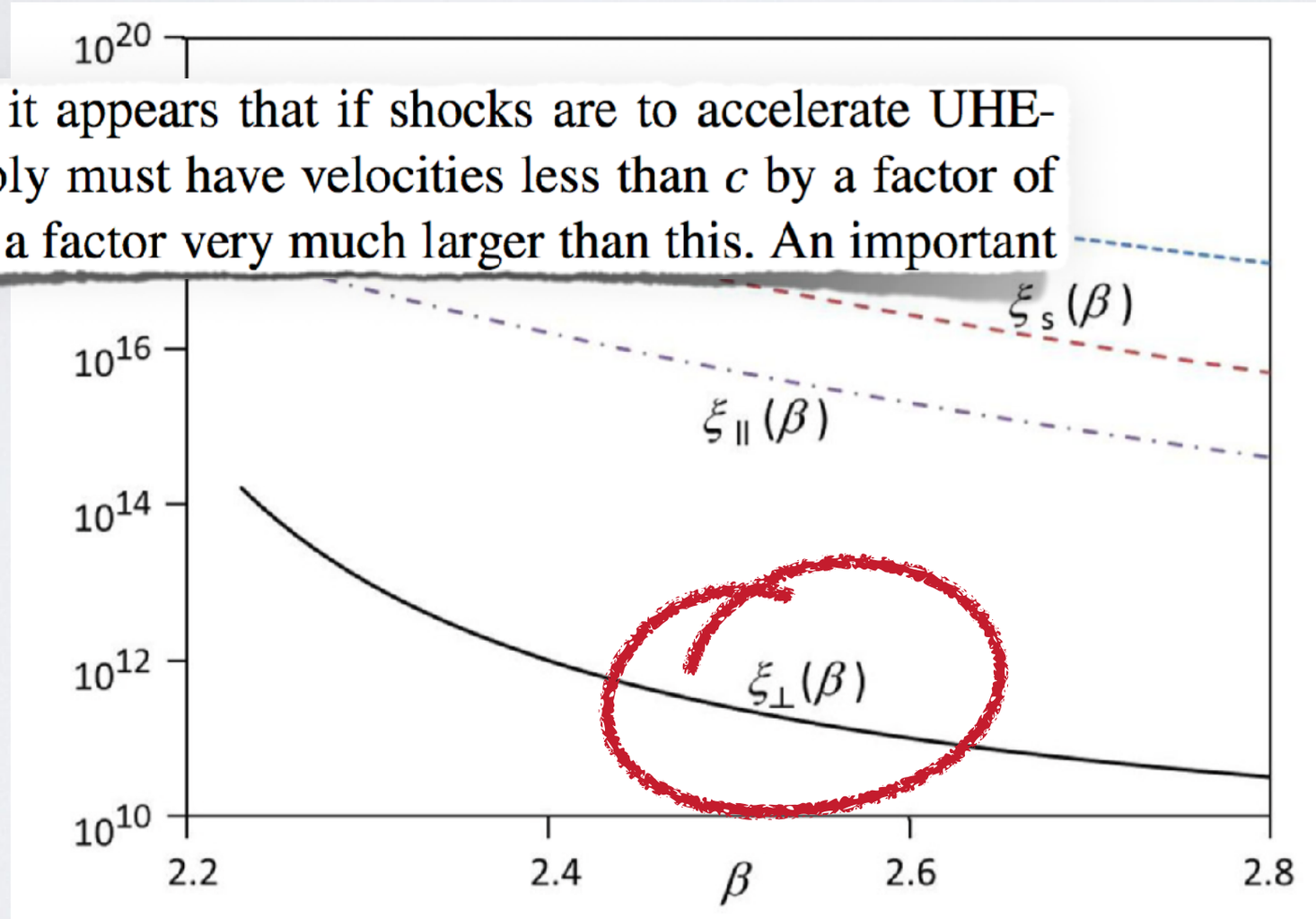
Steeper energy spectra

Relativistic Shocks Are Problematic

- Not enough time to grow turbulent B field to UHECR Larmor radii scales (Lemoine & Pelletier 2010; Reville & Bell 2014; Bell+ 2018)

Shock and B-field physics

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



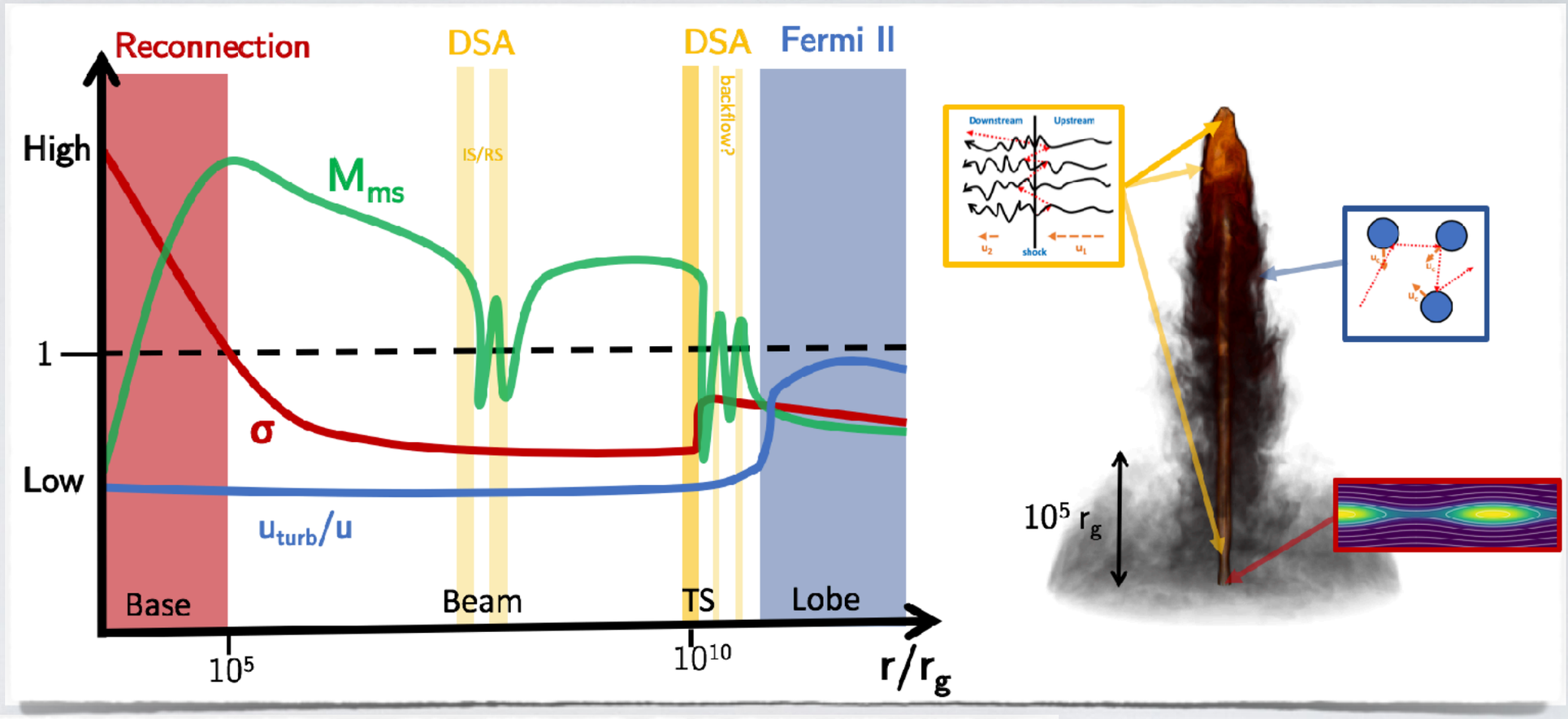
"Goldilocks shocks?"

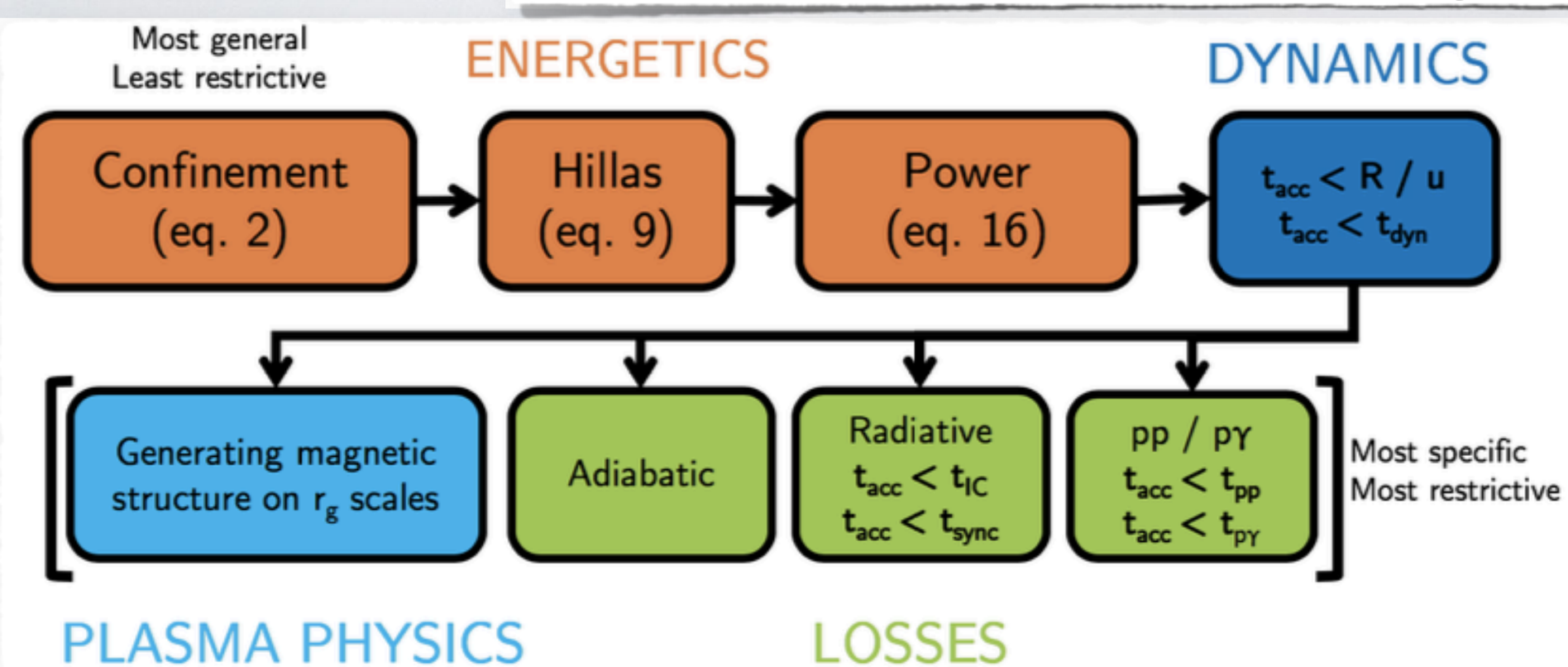
Steeper energy spectra

‘Schematic Physics’

“100 years of jets” anthology, Eds: Wijers, Fender.

In jets, which mechanisms operate where?





What sets the maximum particle energy?

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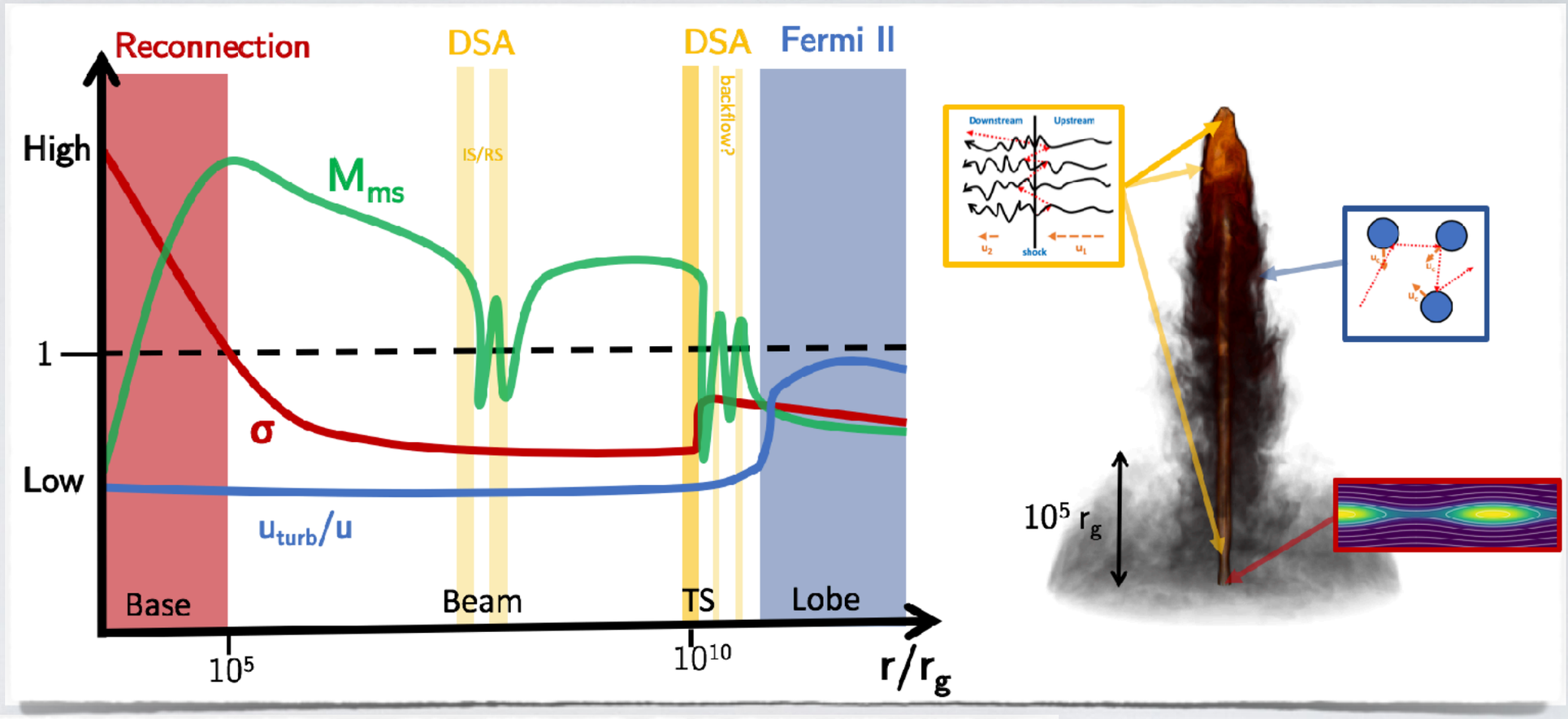


New Astronomy Reviews
Volume 89, September 2020, 101543
ELSEVIER
Particle acceleration in astrophysical jets
James H. Matthews [a], Anthony R. Bell [b], Katherine M. Blundell [c]

What sets the maximum particle energy?

2

Where?

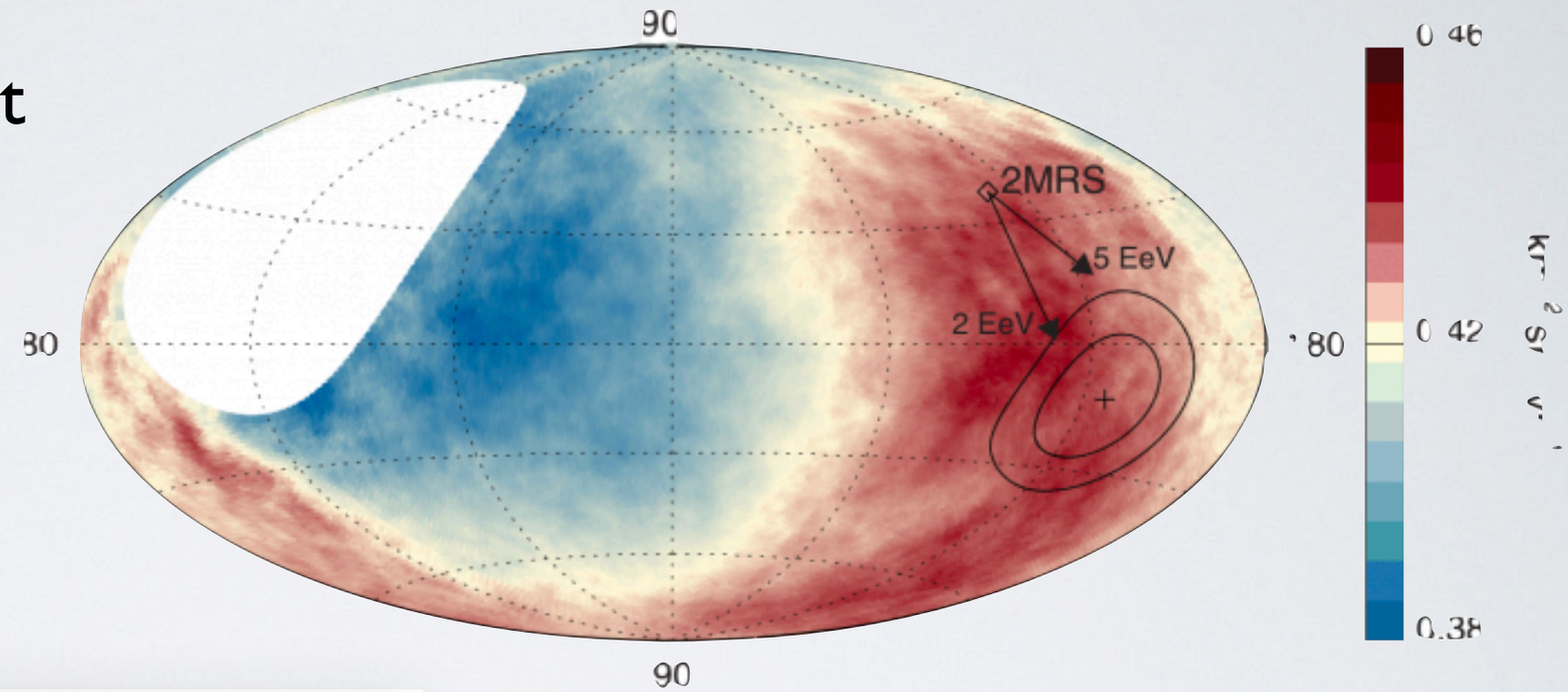
Sources of UHECRs

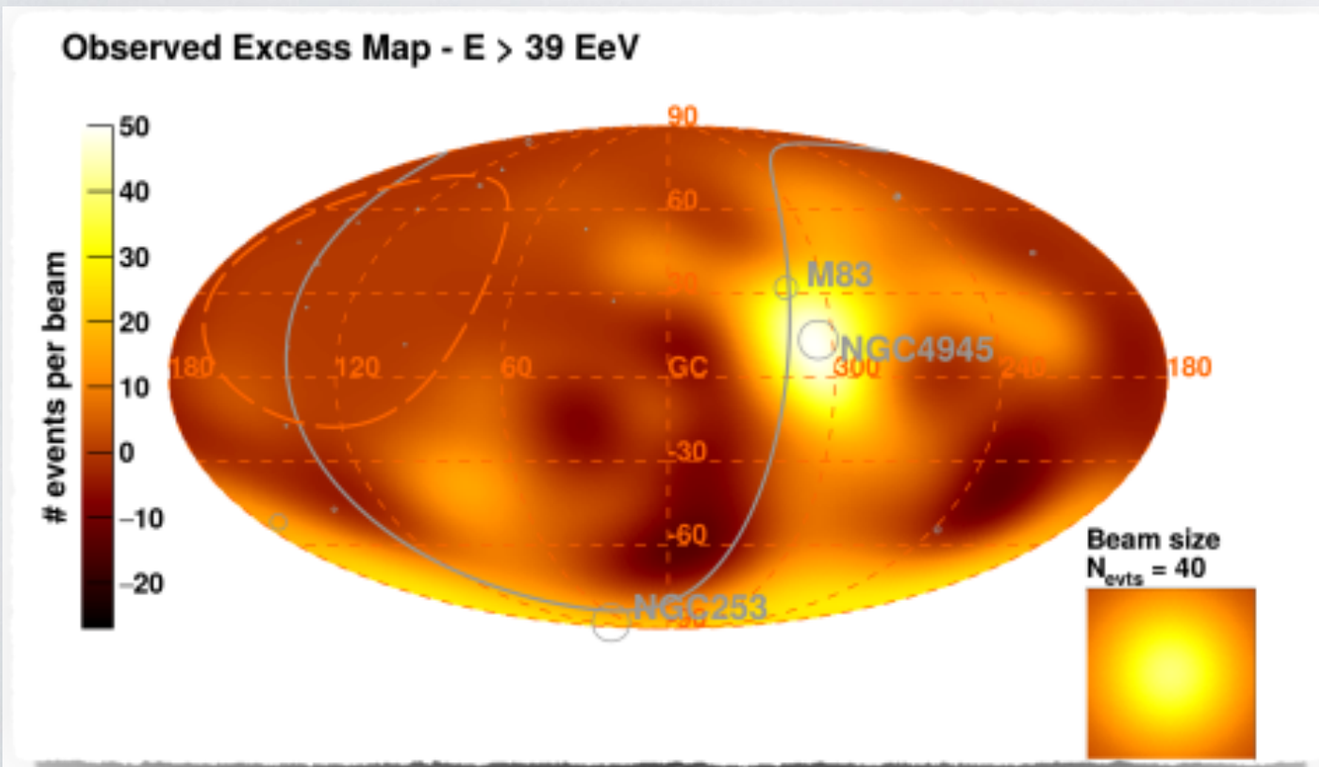
UHECR Anisotropies (PAO)

Dipole in Auger data at >8 EeV (PAO 2017)

5.2σ Significance

Spectacular!





Galactic Coordinates

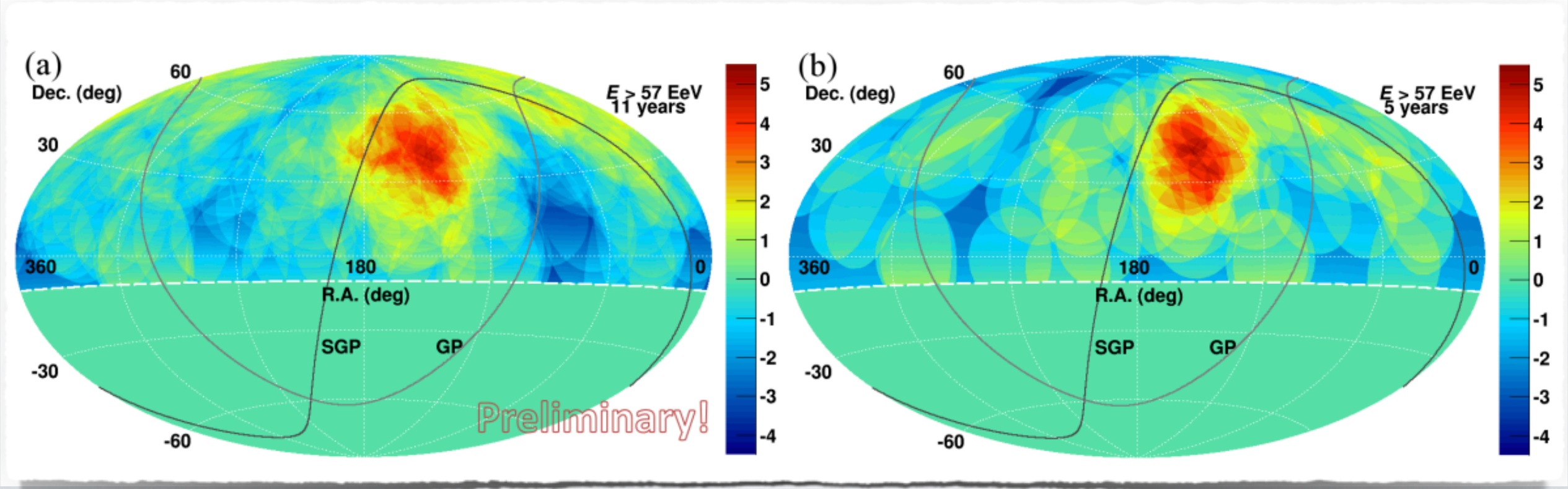
Indications of anisotropy at >40 EeV (PAO 2018, ApJL)

Significance: ~3σ (AGN), ~4σ (SBGs)

More model-dependent than dipole

UHECR Anisotropies (TA)

- TA "hotspot": excess in northern sky close to supergalactic plane (e.g. Kawata+ ICRC 2019)
- Possible correlation with M81/M82? …or?
- Another new excess associated with Perseus-Pisces supercluster? (TA 2021)



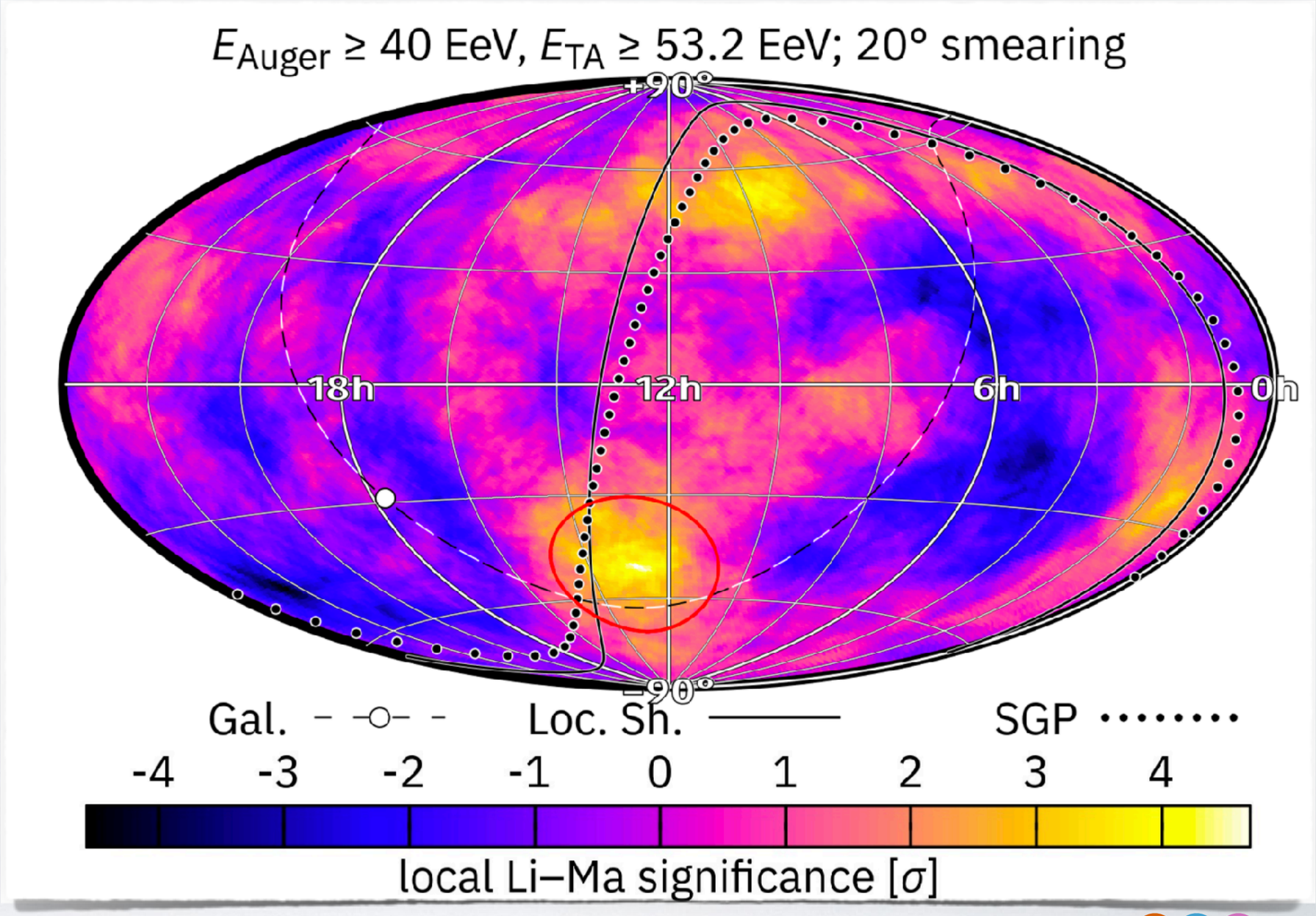
Kawata+ ICRC 2019

UHECR Anisotropies (All-Sky)

Suggestive of an all-sky correlation with supergalactic plane or local sheet? …I'll come back to this

Di Matteo+, ICRC 2021

Unambiguous source IDs still not possible…



Equatorial Coordinates

UHECR Candidates

$$E_{\max} \sim Z\eta^{-1}\left(\frac{B}{\mu G}\right)\left(\frac{R}{10\ \mathrm{kpc}}\right)\left(\frac{u}{c}\right)\ 10^{19}\ \mathrm{eV}$$

UHECR Candidates

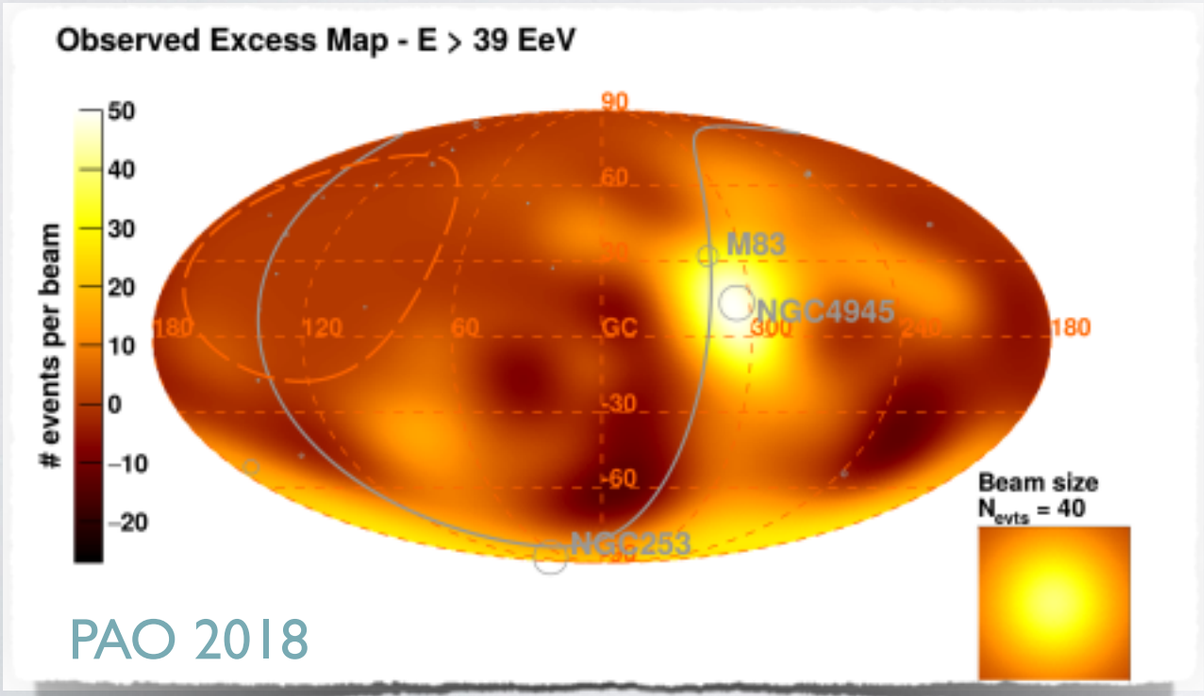
$$E_{\max} \sim Z\eta^{-1}\left(\frac{B}{\mu G}\right)\left(\frac{R}{10\ \mathrm{kpc}}\right)\left(\frac{u}{c}\right)\ 10^{19}\ \mathrm{eV}$$

Starburst Winds

- Starbursts can produce dramatic, galactic-scale outflows driven by combined power from stellar mass-loss and supernova blast waves (e.g. M82)

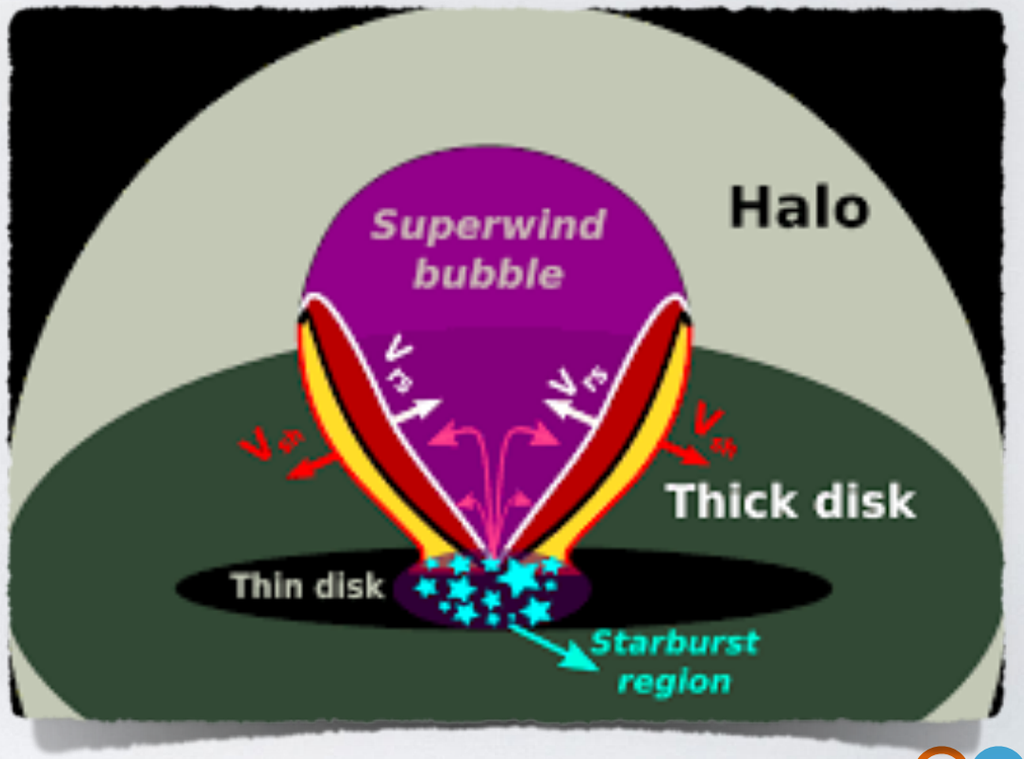
- Tantalising indications of UHECR anisotropies in directions of Starbust galaxies (PAO 2018)

- Acceleration in the termination shock of the starburst "superwind" proposed (e.g. Anchordoqui 2018; see e.g. Marinelli, van Vliet talks)



PAO 2018

Romero+ 2018



Can Starburst Winds do it?

- …I don't think so.

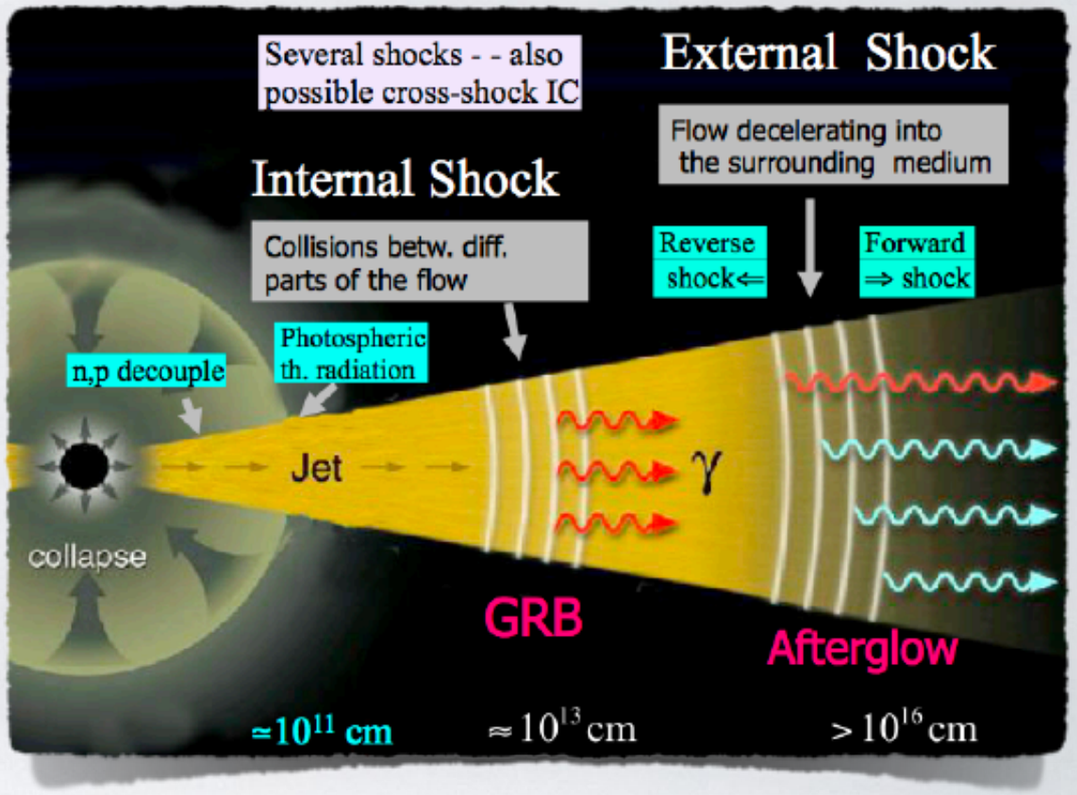
- Even assuming high efficiencies, superwinds in starburst galaxies like M82 have powers of ~10^{42} erg/s ande shock velocities of ~1000 km/s (Heckman+ 1990; Strickland & Stevens 2000; Romero+ 2018)

$$\frac{E}{Z} \sim 10^{17}\ \mathrm{eV} \left[\epsilon \left(\frac{Q_k}{10^{42}\ \mathrm{erg\ s^{-1}}} \right) \left(\frac{u}{3000\ \mathrm{km\ s^{-1}}} \right) \right]^{1/2}$$

- Doesn't rule out something else another UHECR source in starburst galaxies associated with high SFRs

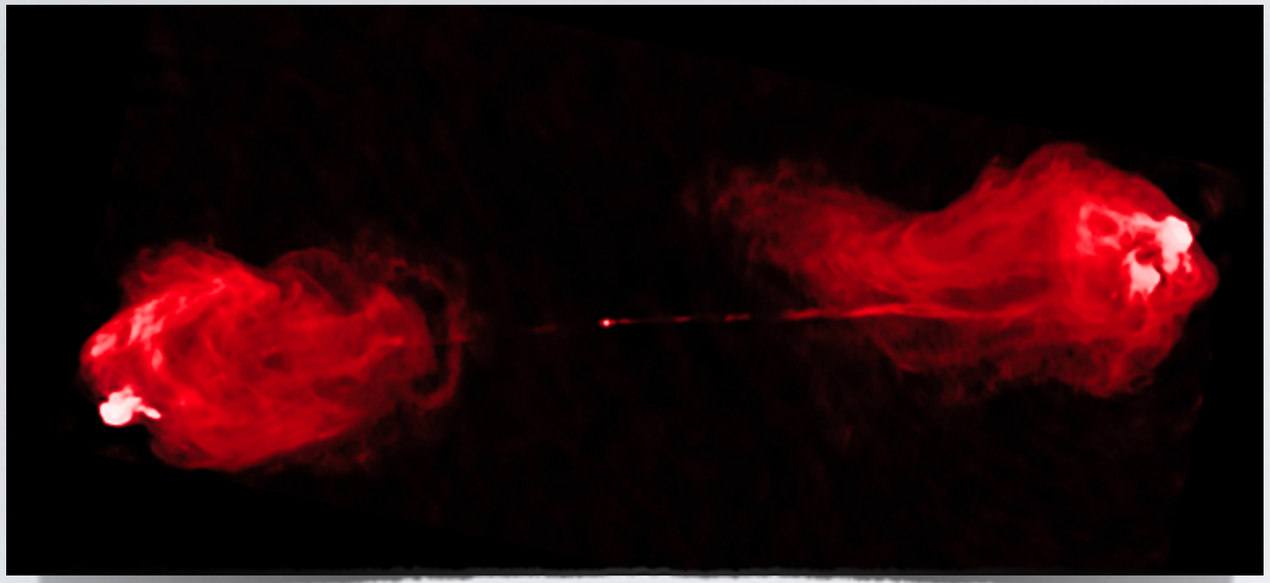
Gamma-Ray Bursts

- Loads of power!!!
- Pioneering work by Waxman (1995) suggests GRB internal shocks as accelerators
- Need high baryon loading and high efficiencies to explain observed UHECR flux (e.g. Baerwald+ 2014, Globus+ 2015)
- Shocks are highly relativistic which prohibits UHECR acceleration (e.g. Reville & Bell 2014, Bell+ 2018)

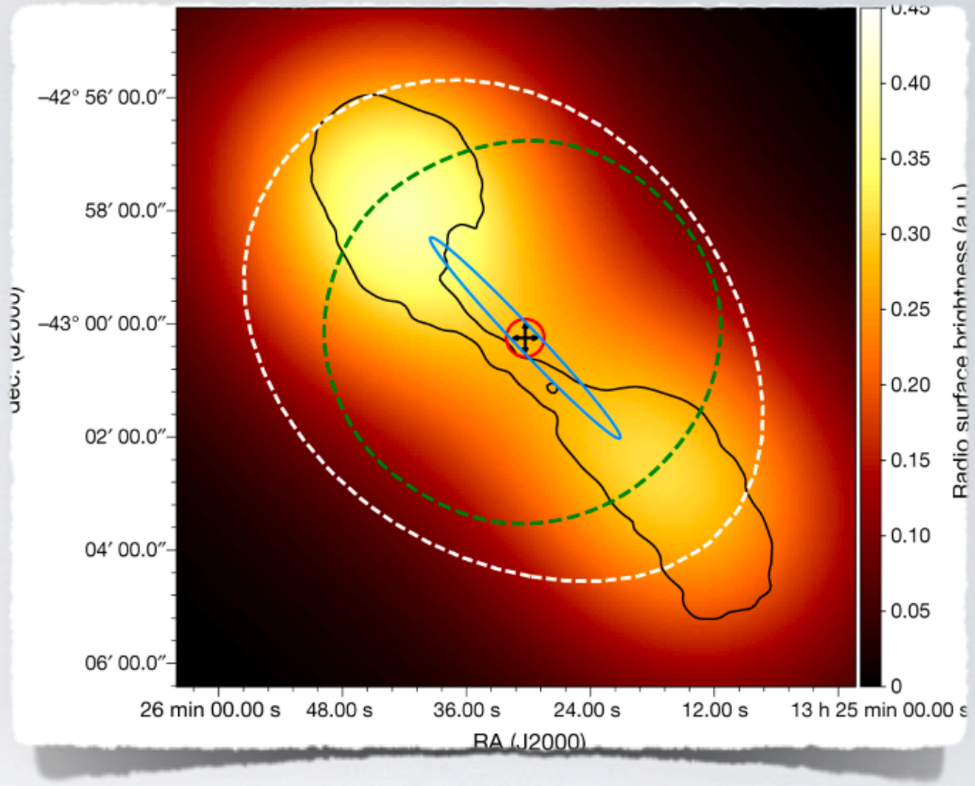


Radio Galaxies

Cen A, H.E.S.S. collaboration



Cygnus A, VLA image

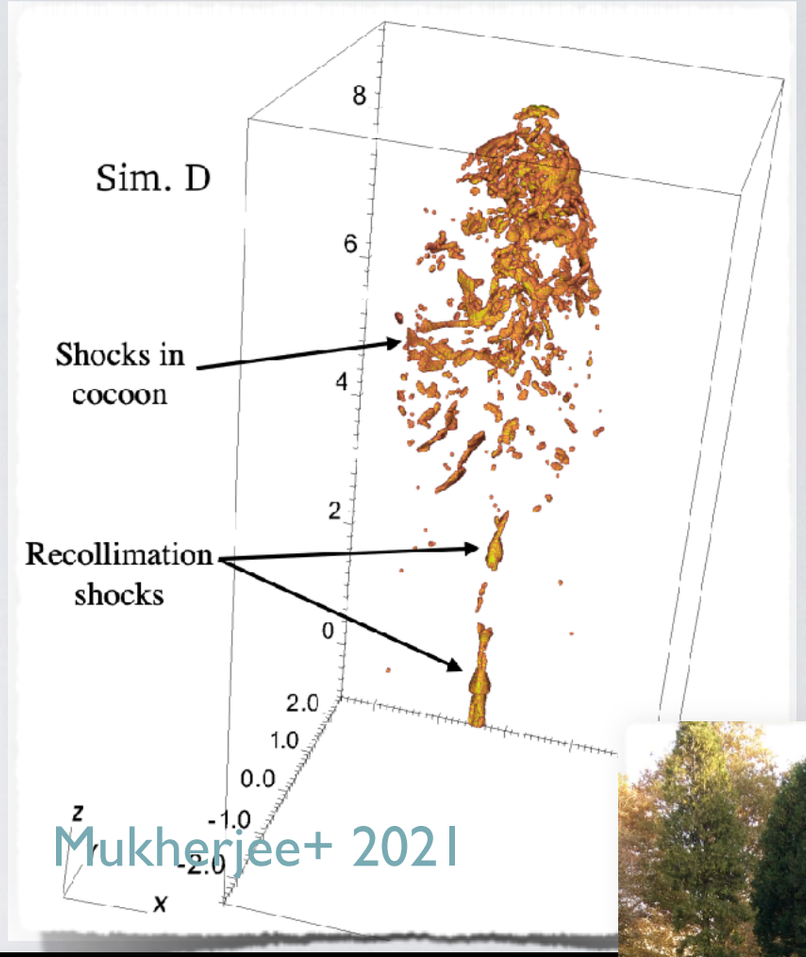


- Giant (kpc to Mpc) jets from AGN that produce lobes or cocoons of radio and gamma-ray emitting plasma
- Obvious UHECR candidates, since they are **big** and **fast**- See e.g. Hillas 1984, Norman+ 1995, Hardcastle 2010, but also many, many others!
- However - relativistic hotspots don't appear to reach high enough energies (Araudo+ 2015, 2016, 2018)
- Search for non-relativistic shocks that have high enough Hillas energy!

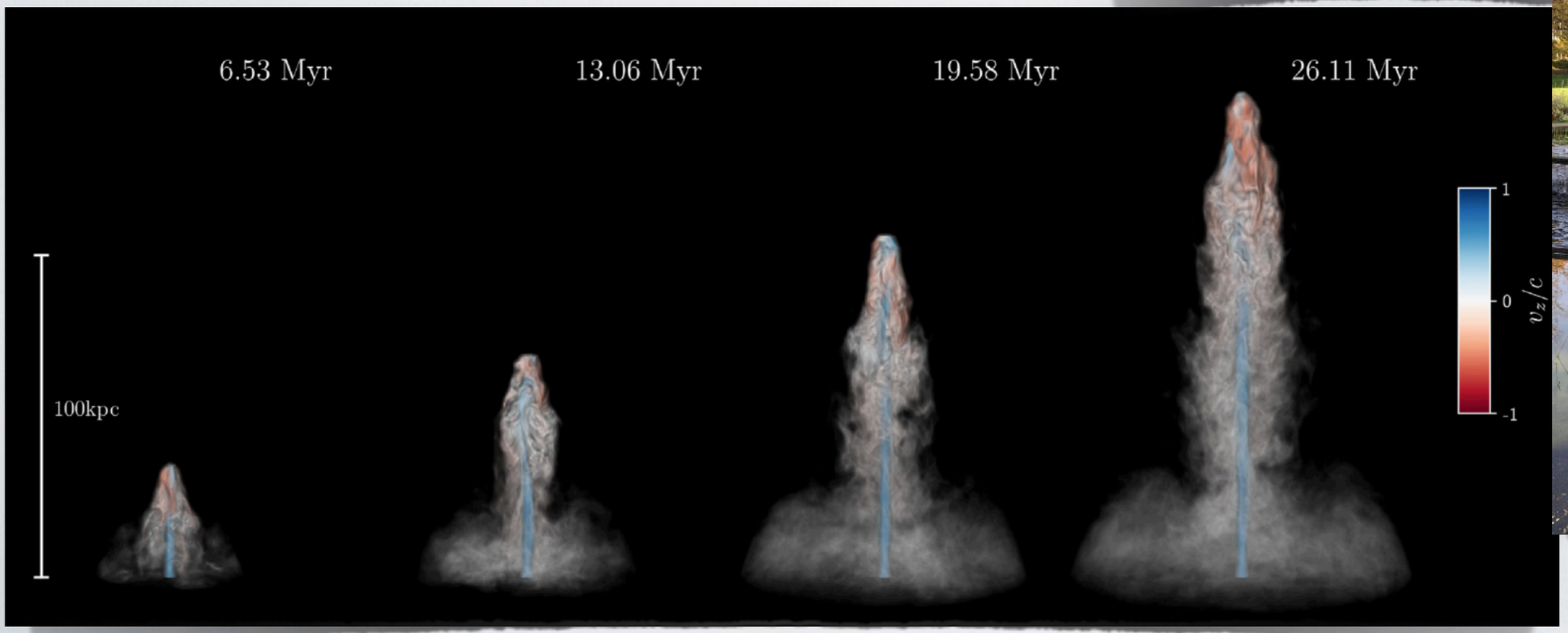
Matthews+ 2019a,b
http://jhmatthews.github.io/uhecr-movies

UHECRs from jet backflows?

- Jets produce strong backflow, which can be supersonic, v~0.1-0.5c
- Shocks produced in the cocoon from backflow
  - See also Reynolds+ 2003, Mukherjee+ 2021
- Estimate of maximum proton energy: 5e19 eV …..UHECRs!

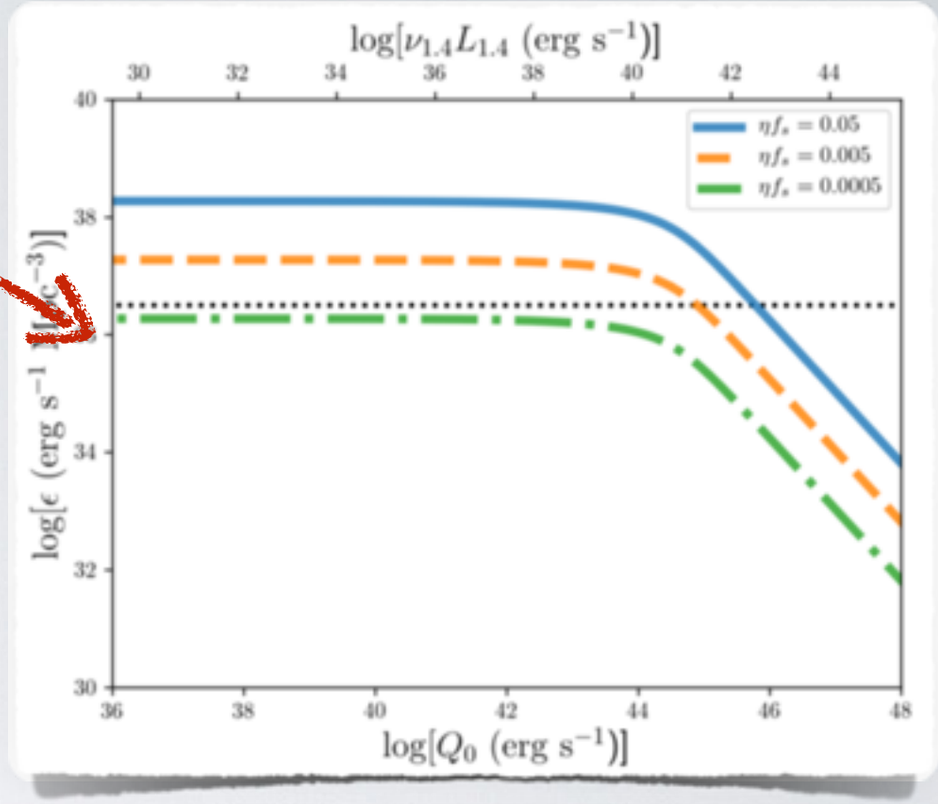


Mukherjee+ 2021



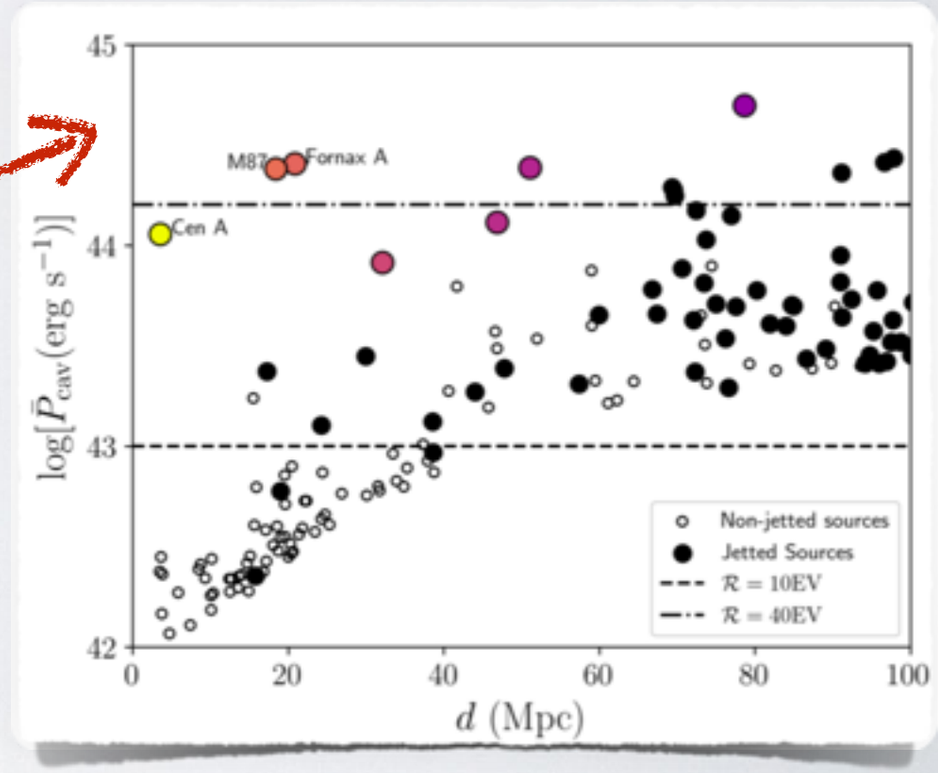
Are there enough powerful sources?

- Powerful RGs are *on average* common and energetic enough to produce the UHECR flux



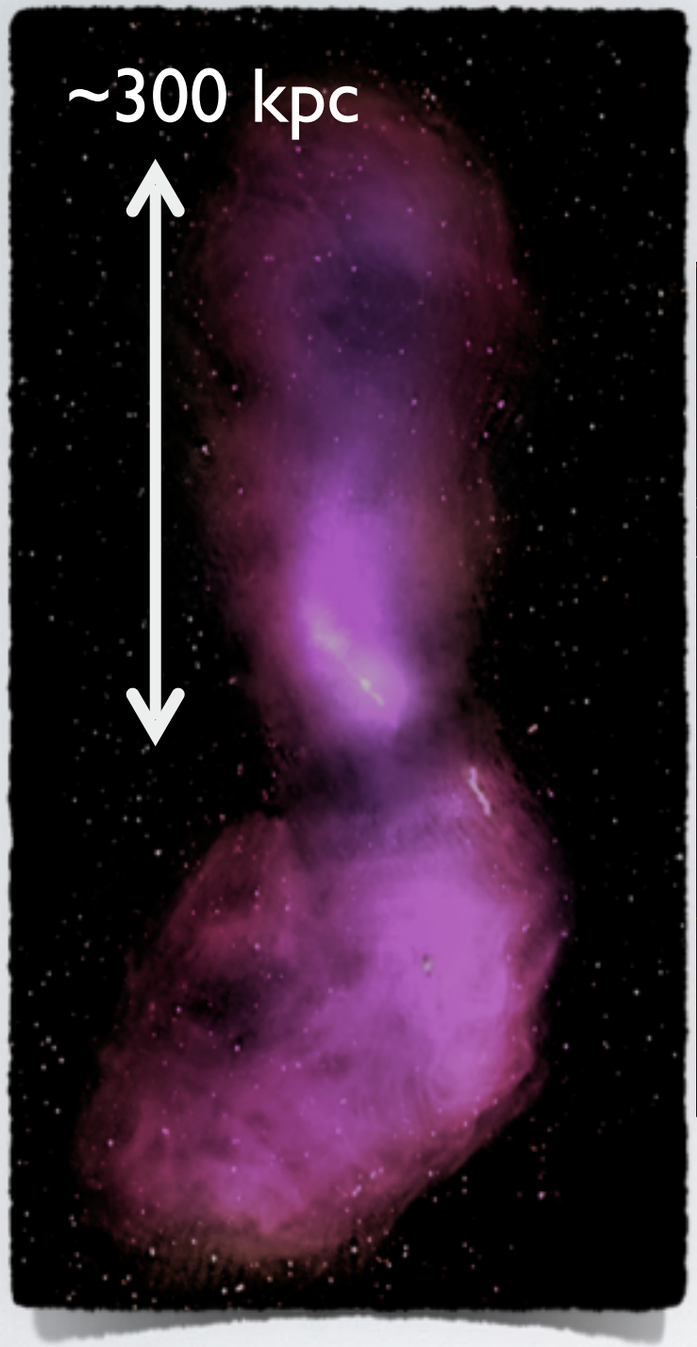
- But UHECRs have a "GZK" horizon due to photopion, pair-production and photodistintegration w/ CMB+EBL. L~100Mpc

- ….barely any currently active sources within this GZK horizon powerful enough

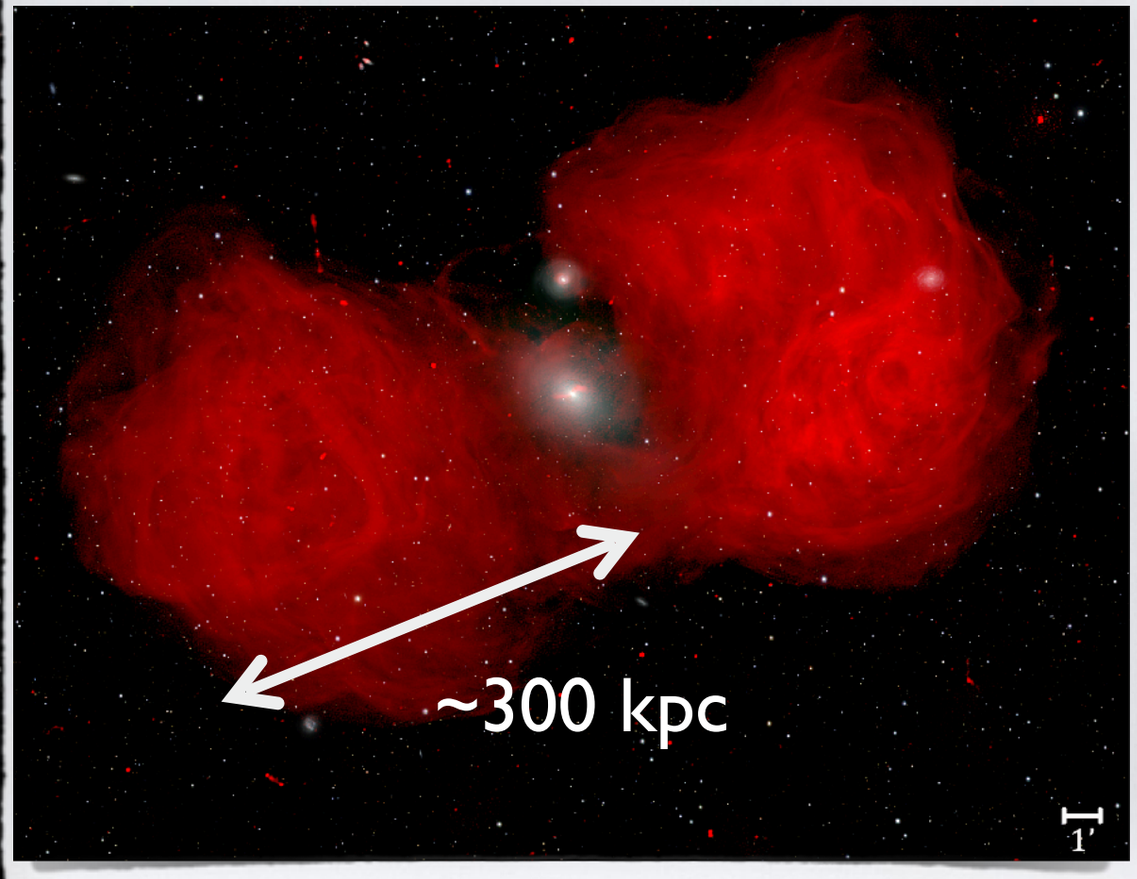


- Are the sources variable / intermittent?

Dormant radio galaxies?



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



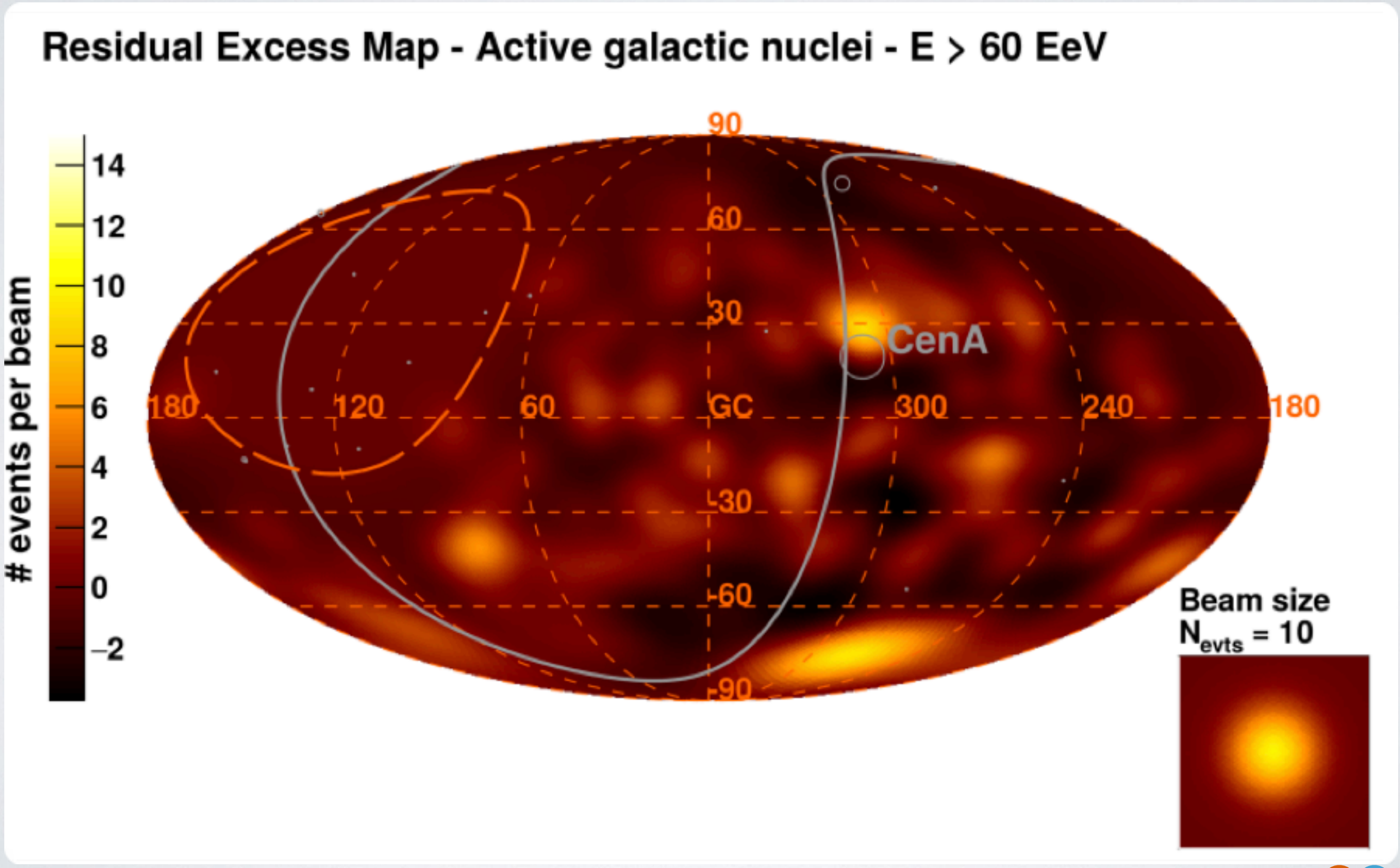
Low-power jets

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

Arrival Directions

Matthews+ 2018

- Fornax A and Cen A are also compellingly close to UHECR excesses!



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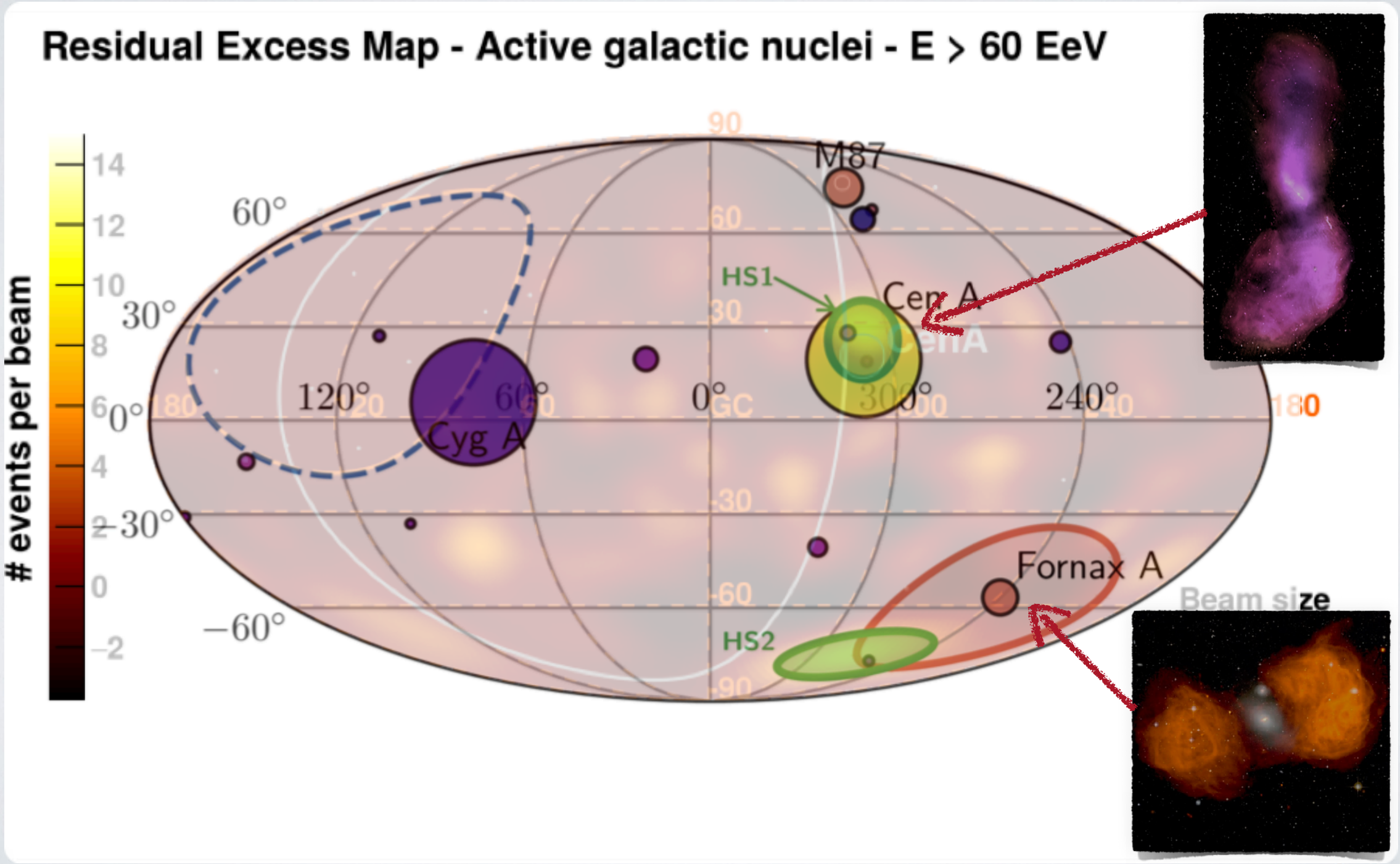
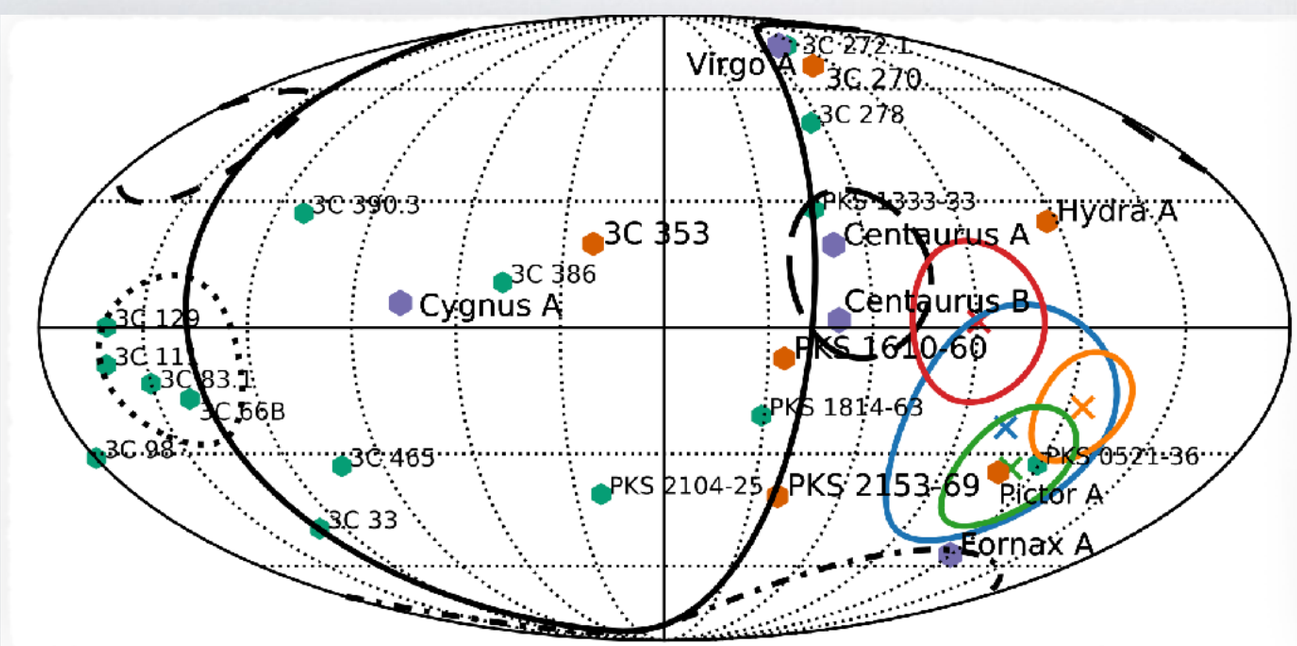
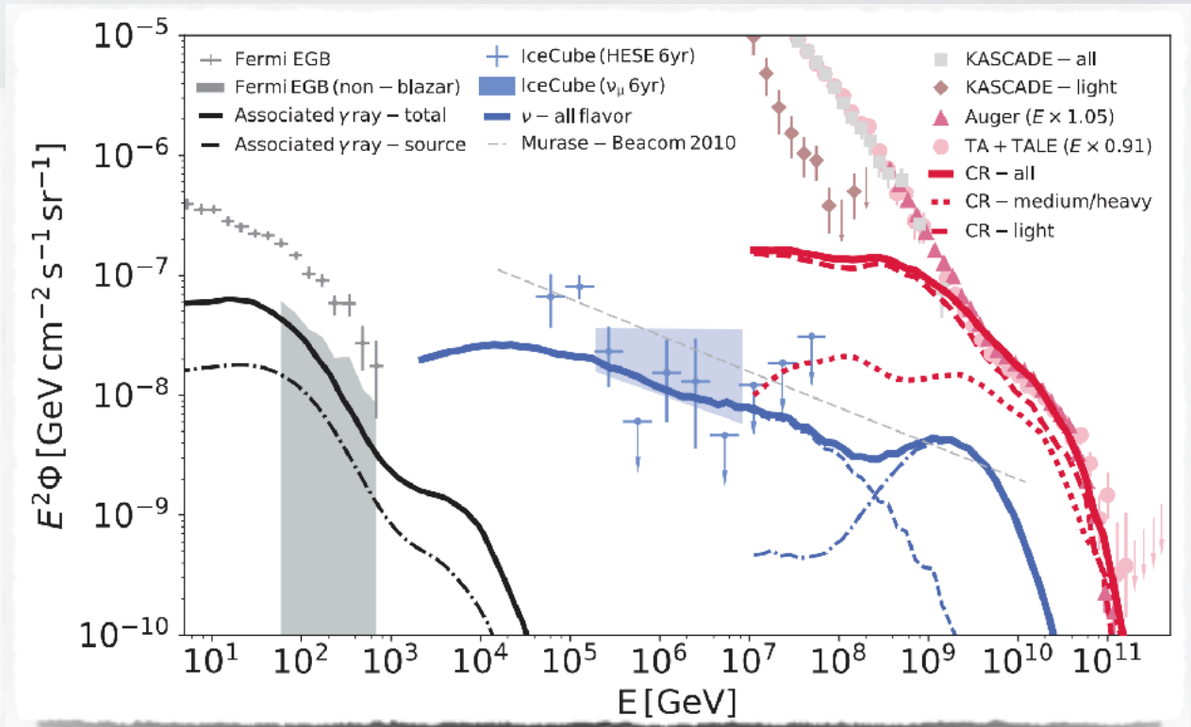


Other Radio Galaxy Models

- Rich literature on UHECRs from radio galaxies
  - Alfvenic / turbulent acceleration in Cen A lobes (Hardcastle+ 2009, Wykes+ 2013)
  - Series of papers from Bjorn Eichmann and collaborators on UHECR acceleration and propagation from radio galaxy population (Eichmann+ 2018, 2019, 2022)
  - Fang & Murase 2018 link UHECRs from AGN jets to MM signals



Eichmann+ 2022



Fang & Murase 2018

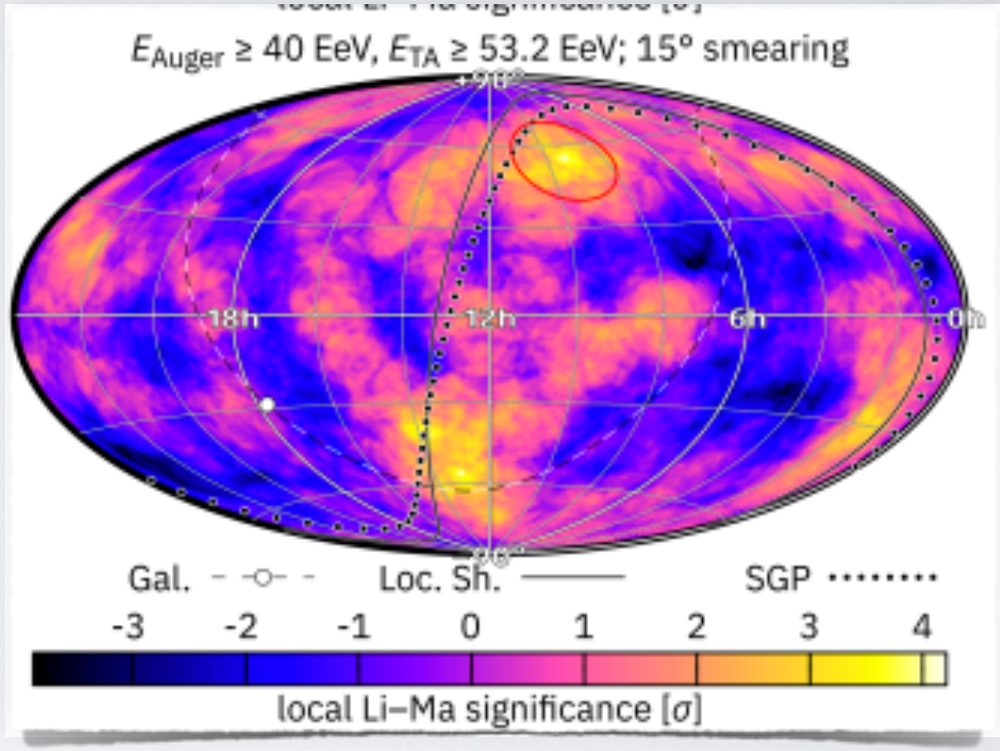
3

When?

UHECR Echoes

Motives for local UHECR sources

UHECR anisotropies appear to line up with local structure (supergalactic plane, "local sheet")



The Curious Case of Near-Identical Cosmic-Ray Accelerators

D. Ehlert,[1,*] F. Oikonomou,[1] and M. Unger[2,1]

"Unless exotic mechanisms limit the maximum rigidities of accelerators to the same value, the inferred small source variance could be an indicator that the observed flux of UHECRs is dominated by a single local source."

arXiv:2207.10691

Revisiting the distance to the nearest UHECR source: Effects of extra-galactic magnetic fields

Rodrigo Guedes Lang* and Vitor de Souza
Instituto de Física de São Carlos, Universidade de São Paulo, Av. Trabalhador São-Carlense, 400, São Carlos, SP, Brazil

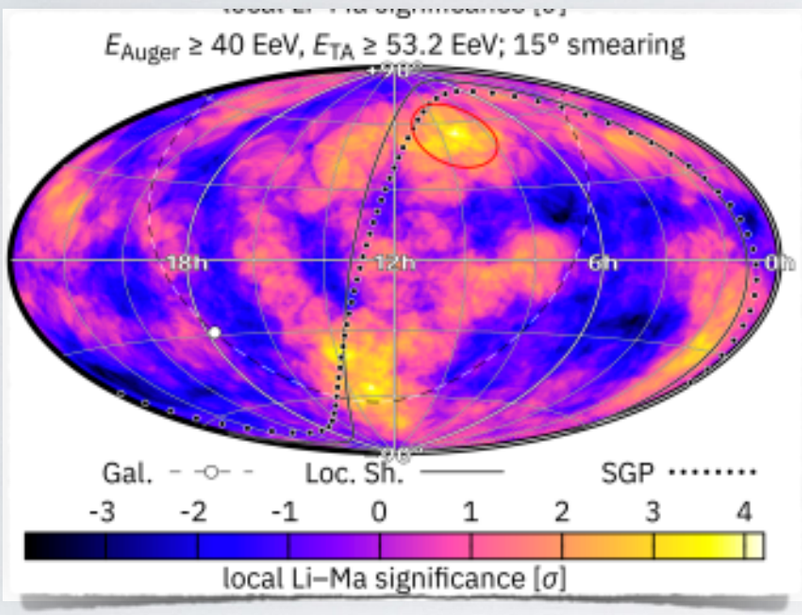
"…we reaffirm the previous results that sources at D < 25 − 100 Mpc are imperative to describe the experimental data from the Pierre Auger Observatory"

arXiv:2005.14275

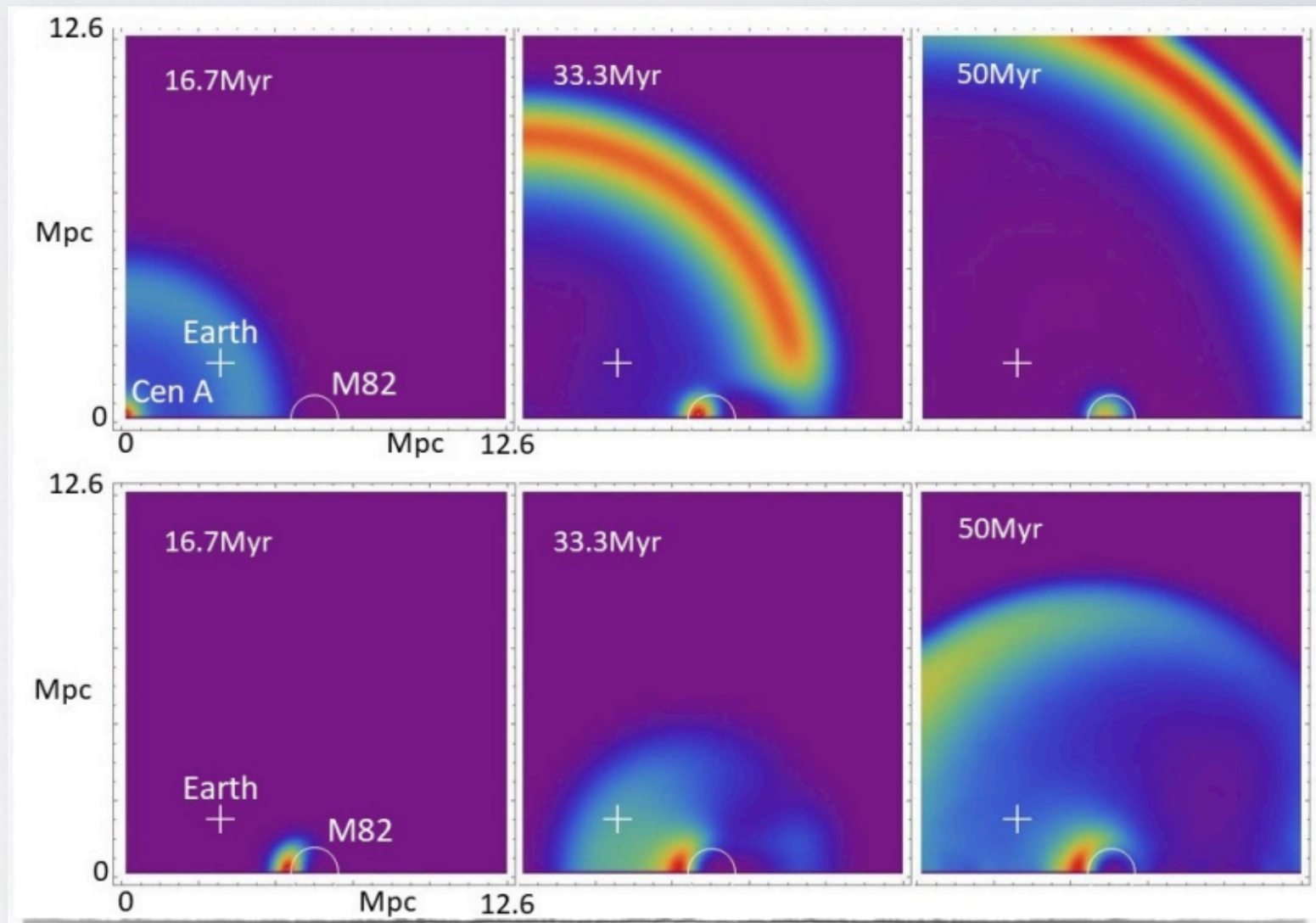
UHECR "Echoes of the past"

Bell & Matthews 2022
arXiv:2108.08879

- New idea: Cen A was 100x more luminous than it is now and these UHECRs are scattering towards us off magnetic structures like starburst galaxy haloes
- UHECR map may be "echo" of past activity from nearby structure



Observed excesses,
Di Matteo+ 2019



Equatorial Coordinates

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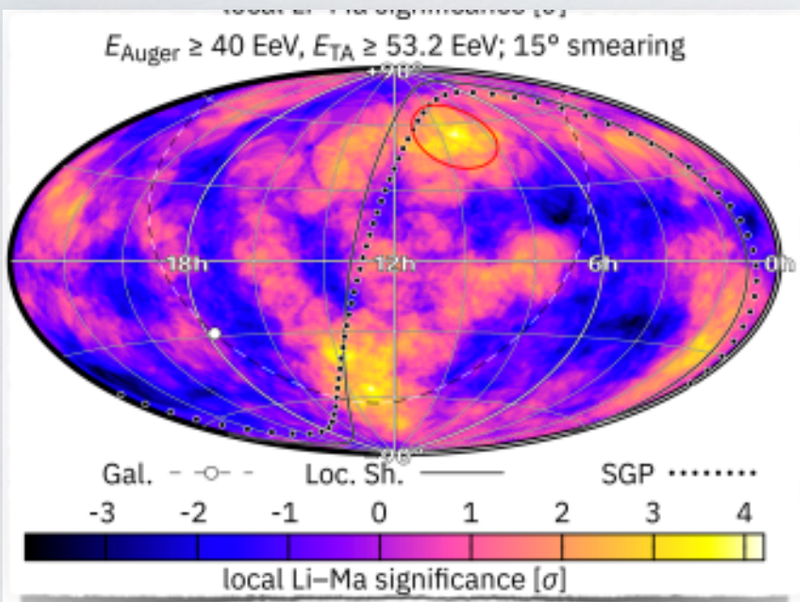

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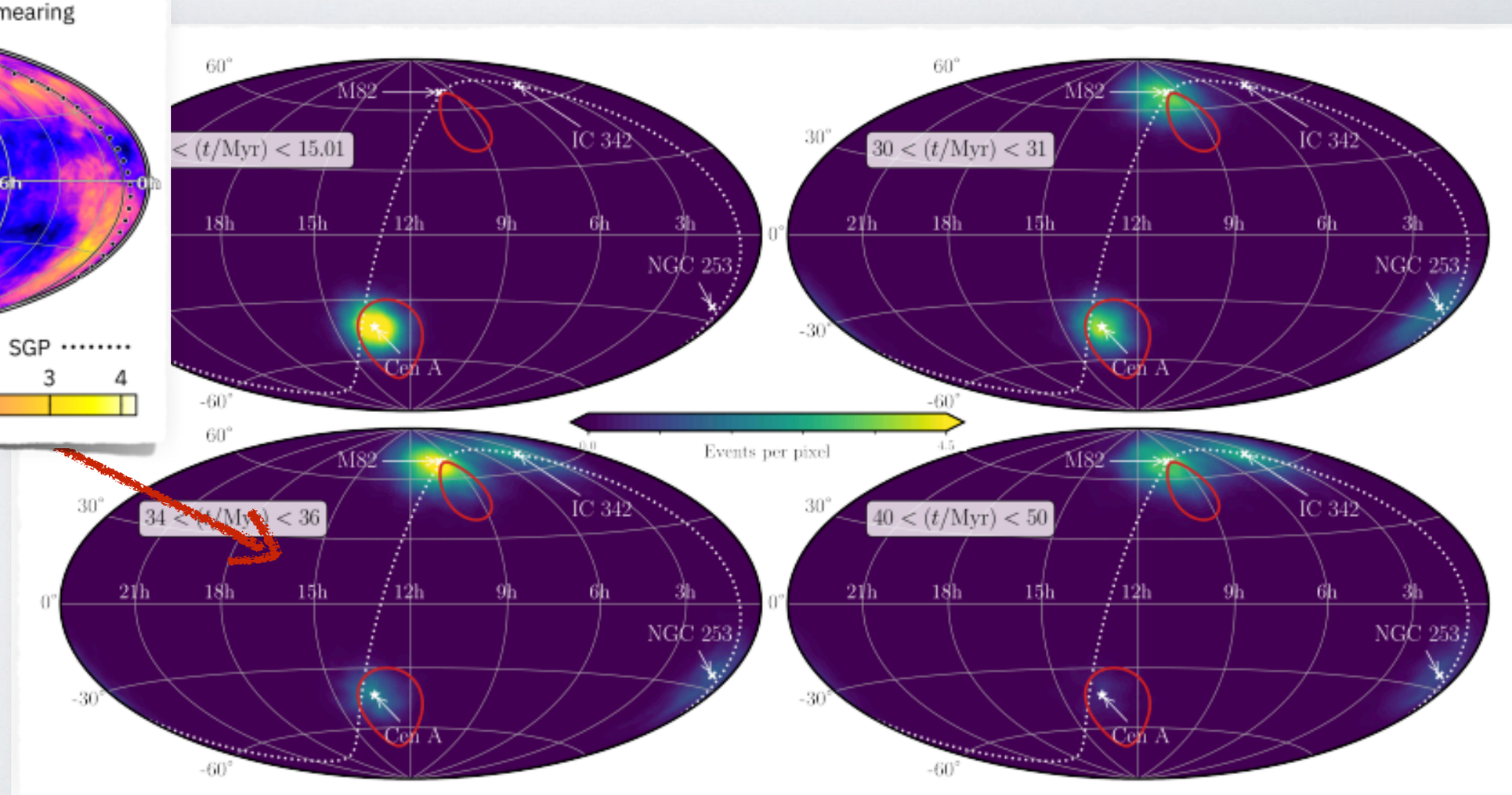
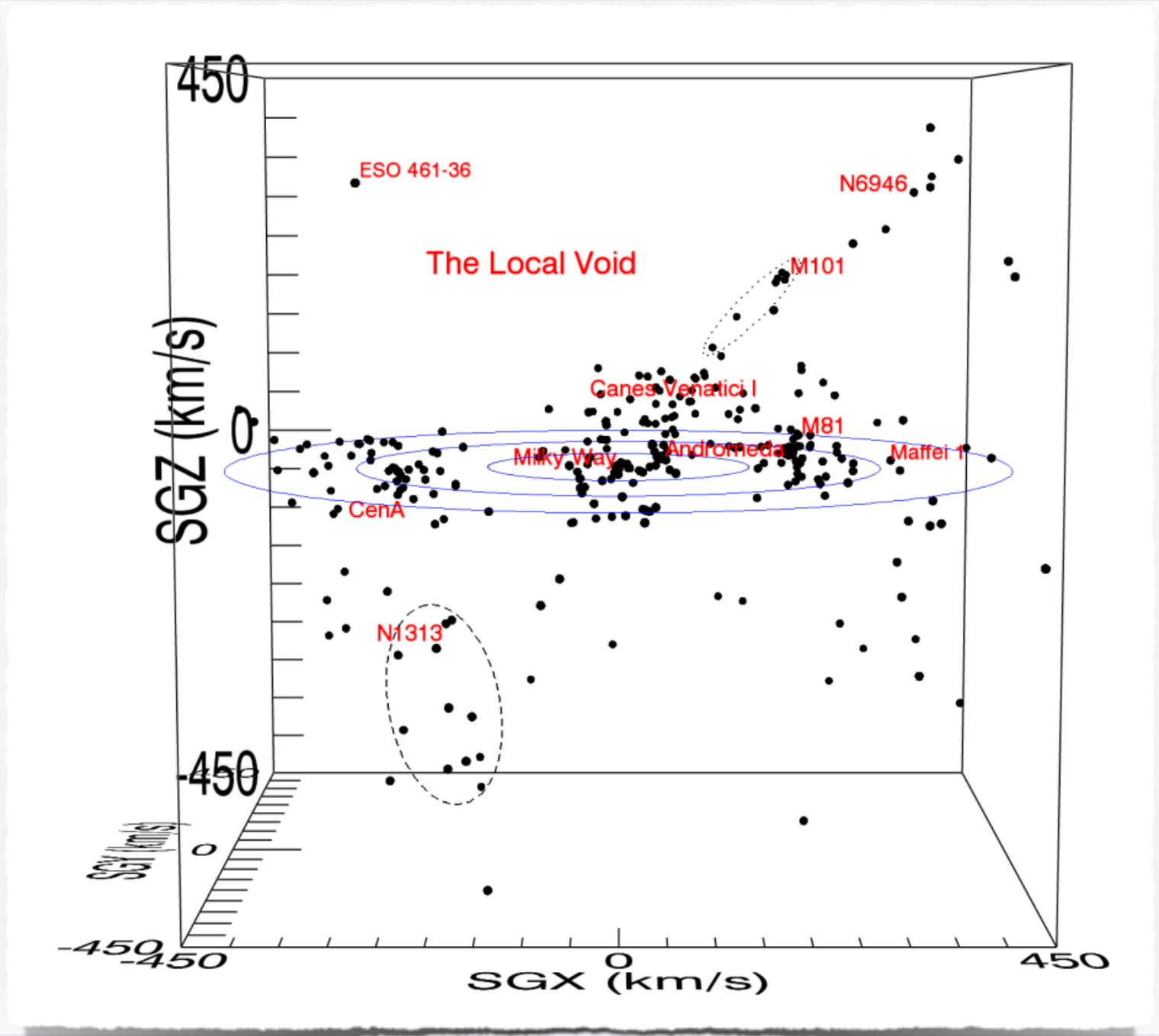


Equatorial Coordinates

Local sheet / Council of giants

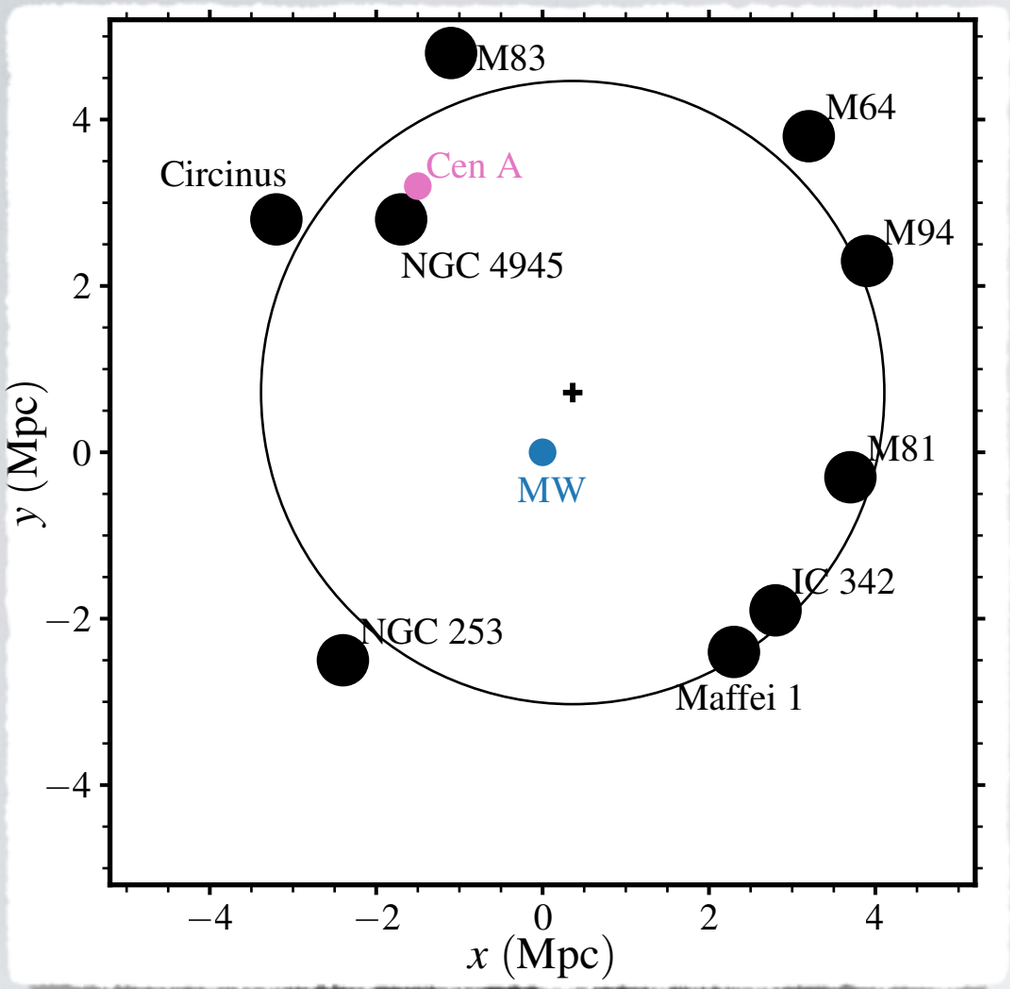


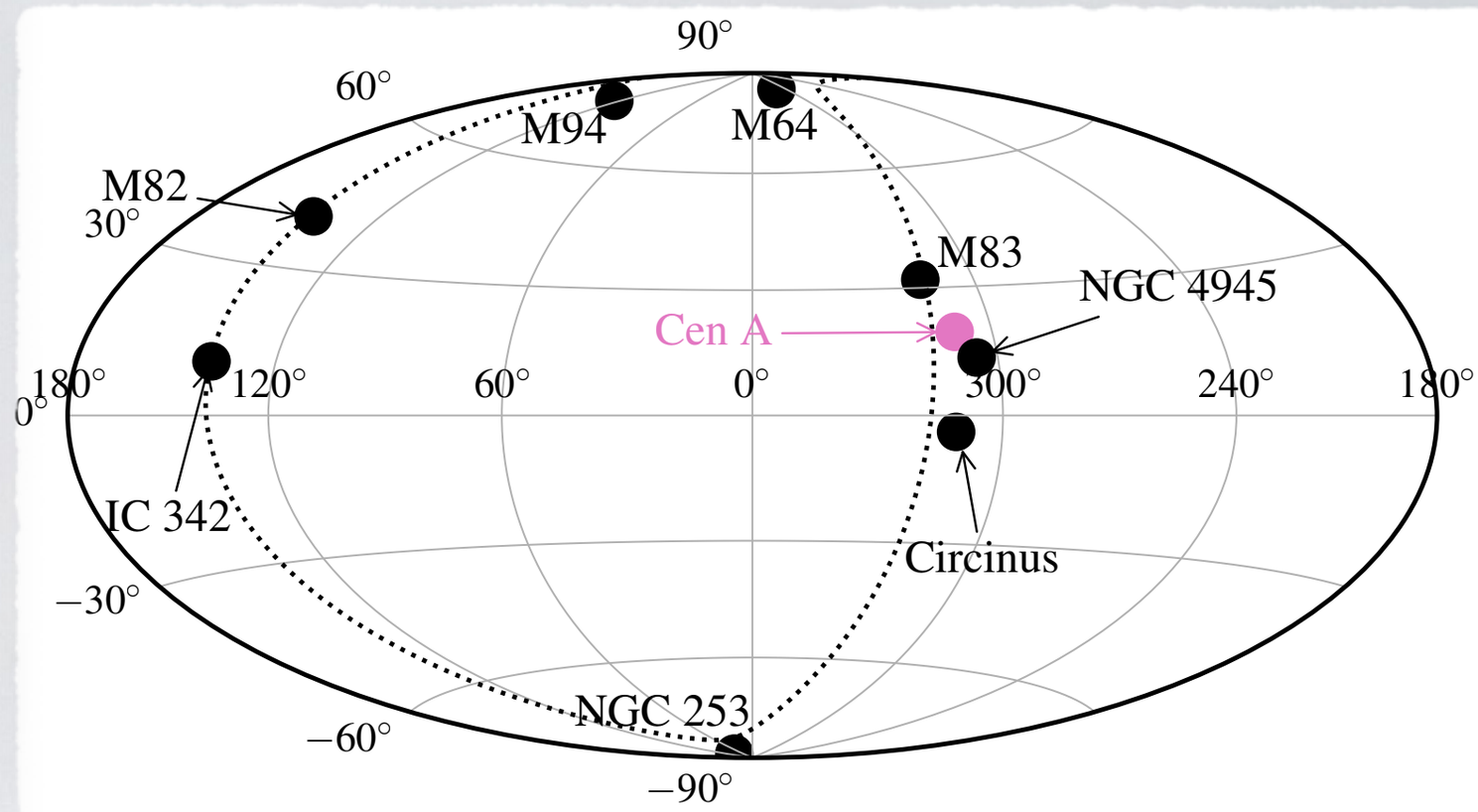
Courtois+ 2013, arXiv:1306.0091, see also McCall 2014

Local sheet / Council of giants

Taylor+, in prep

PRELIMINARY





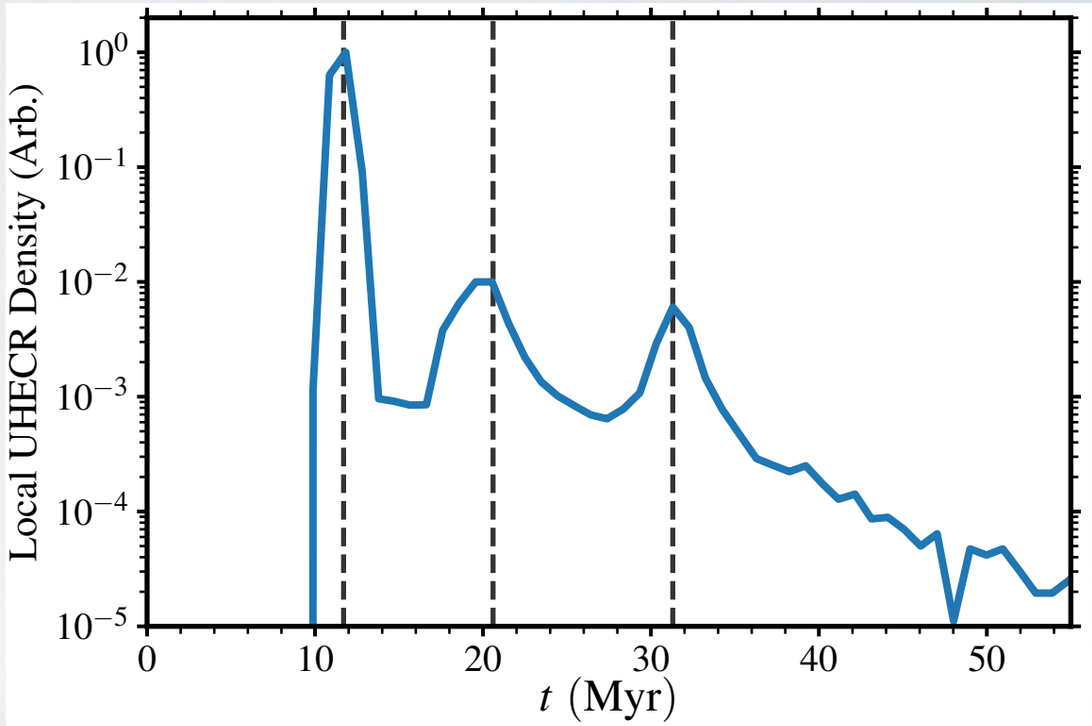
Galactic Coordinates

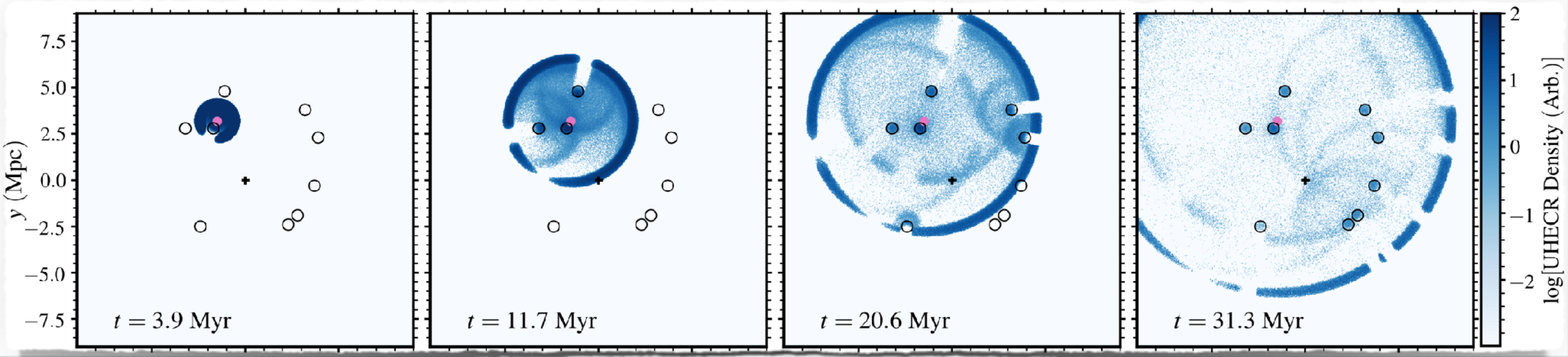
UHECR "Echoes of the past"

Taylor+, in prep

PRELIMINARY

- Simple Monte Carlo "scattering" code (no B field model)
- Now with losses, multi-species and energy spectrum
- Interesting "focusing effects" at two critical times
- w/ Andrew Taylor, Tony Bell



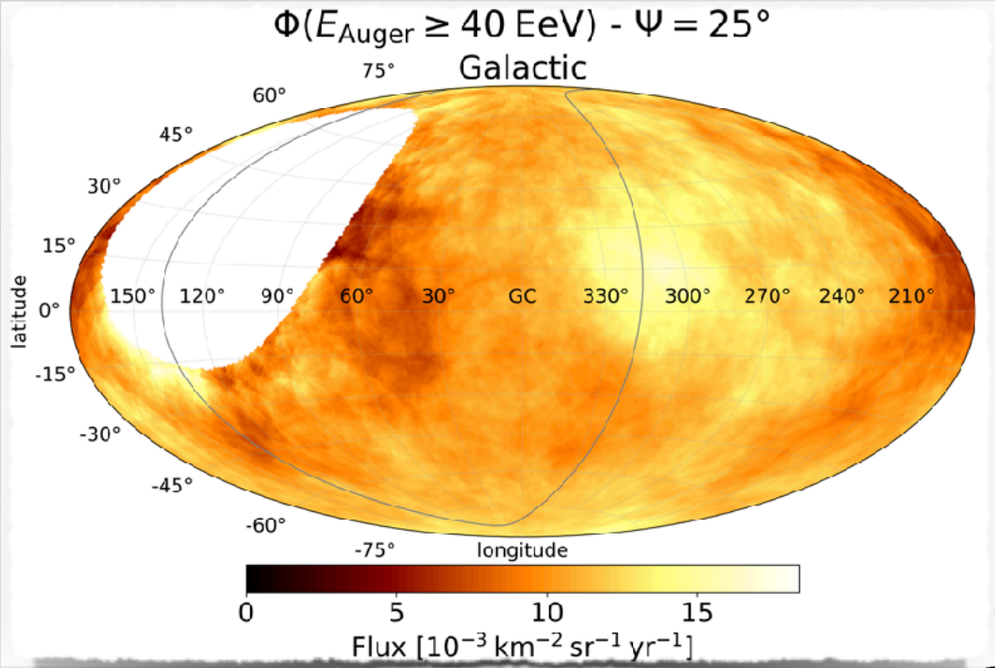


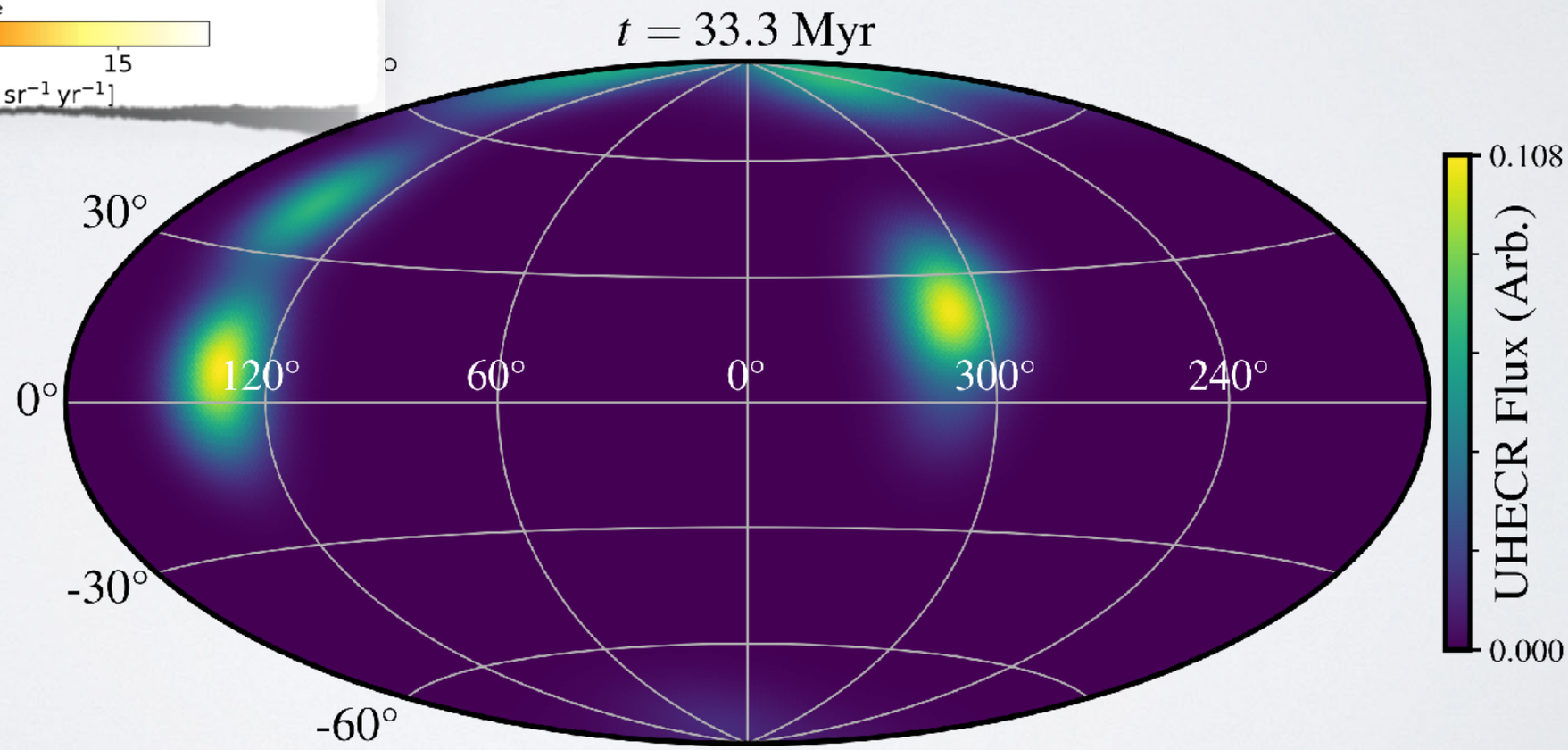
UHECR "Echoes of the past"

Taylor+, in prep

PRELIMINARY

PAO 2022, arXiv:2206.13492





Galactic Coordinates

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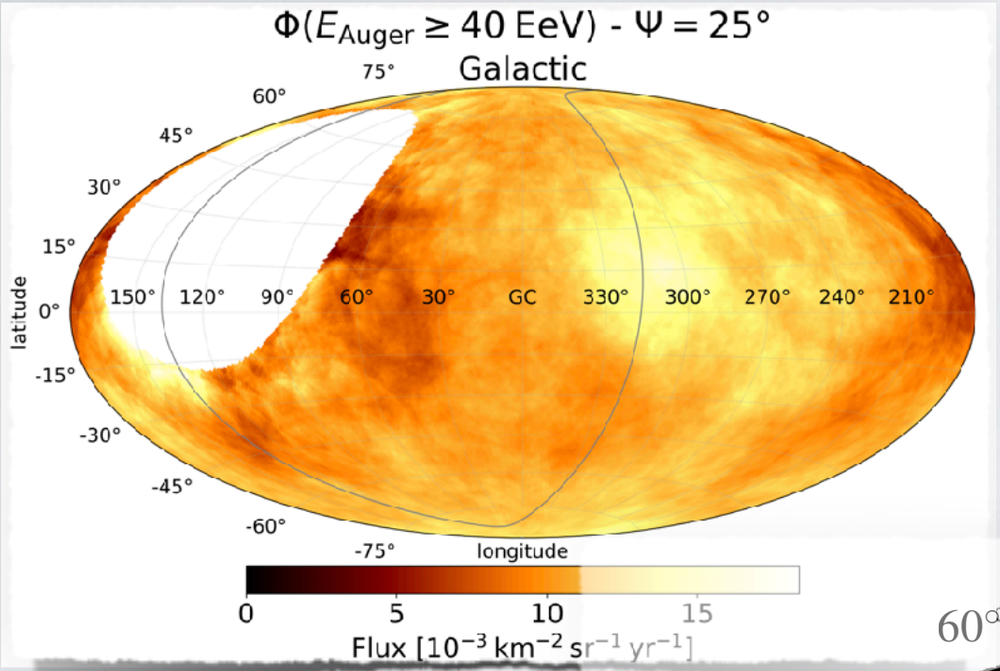
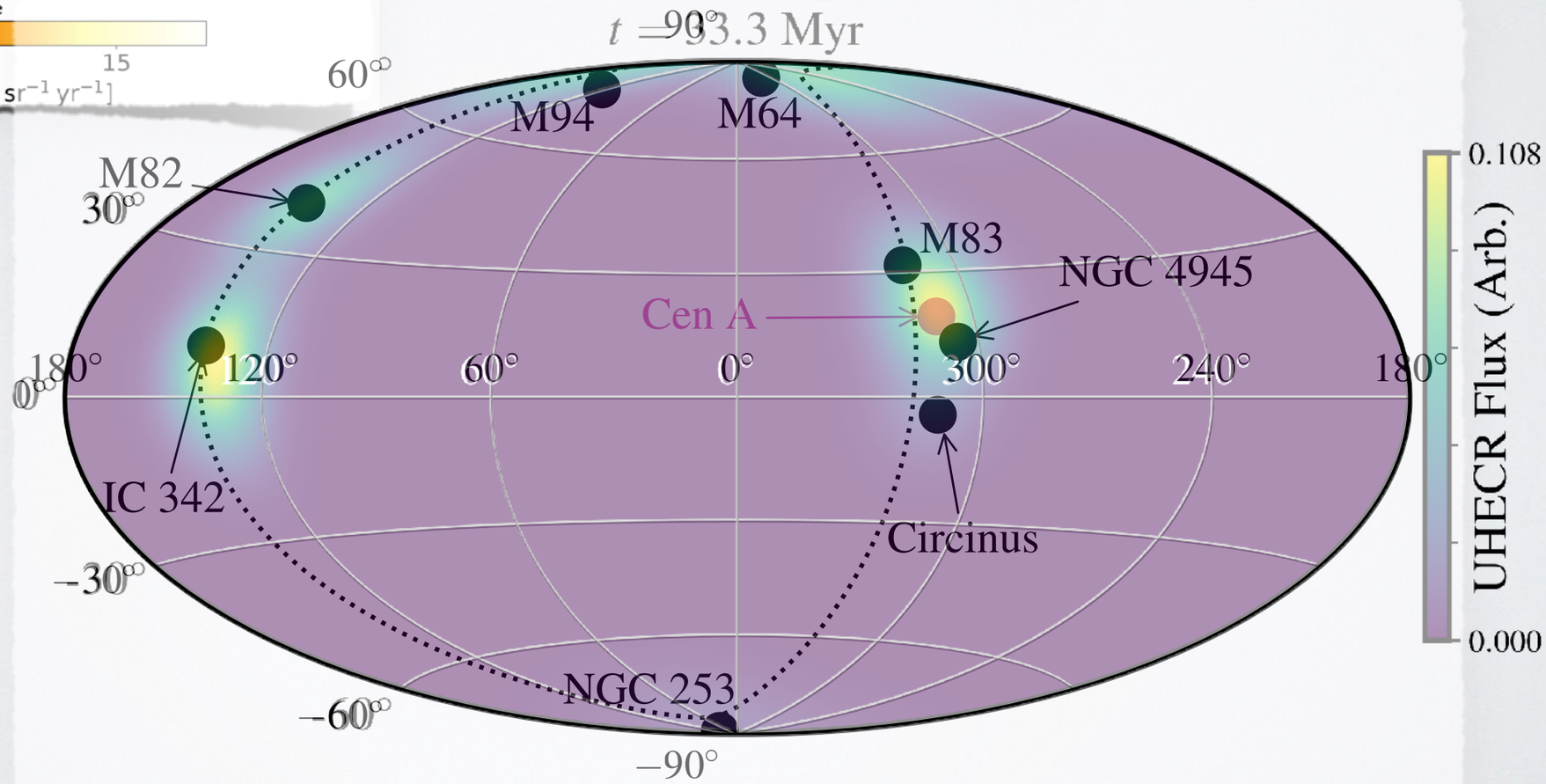
Taylor+, in prep

PRELIMINARY

PAO 2022, arXiv:2206.13492

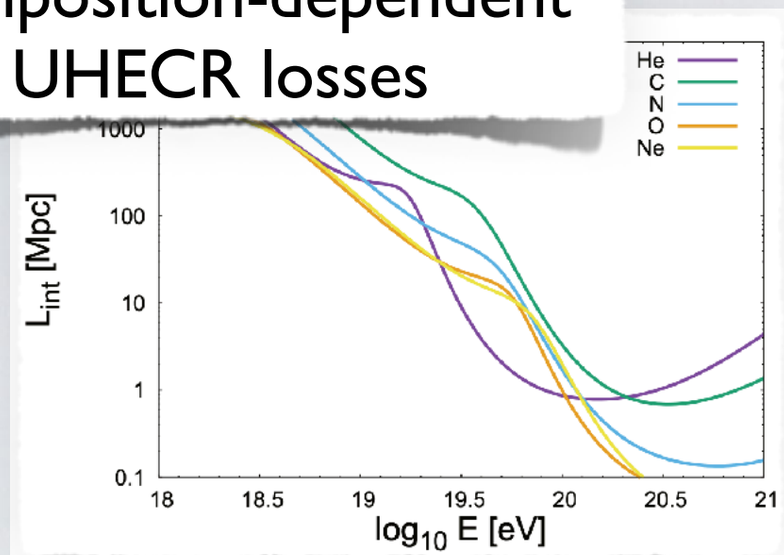




Galactic Coordinates

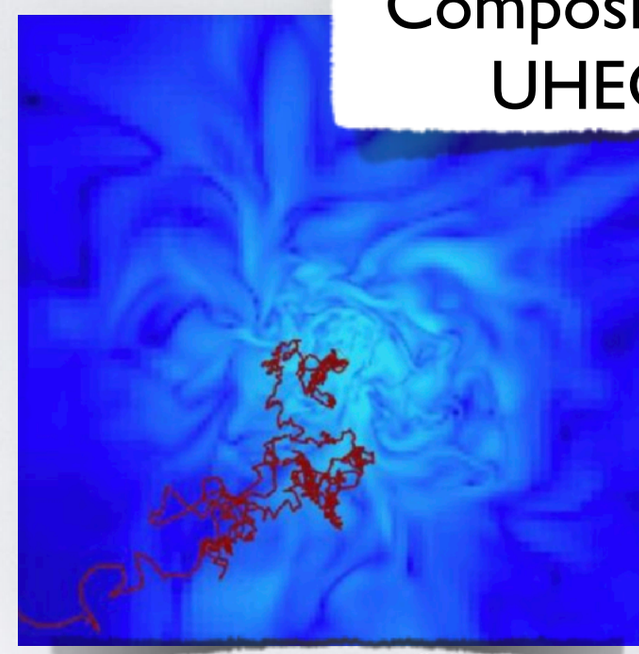
UHECR Composition Clocks

Composition-dependent UHECR losses

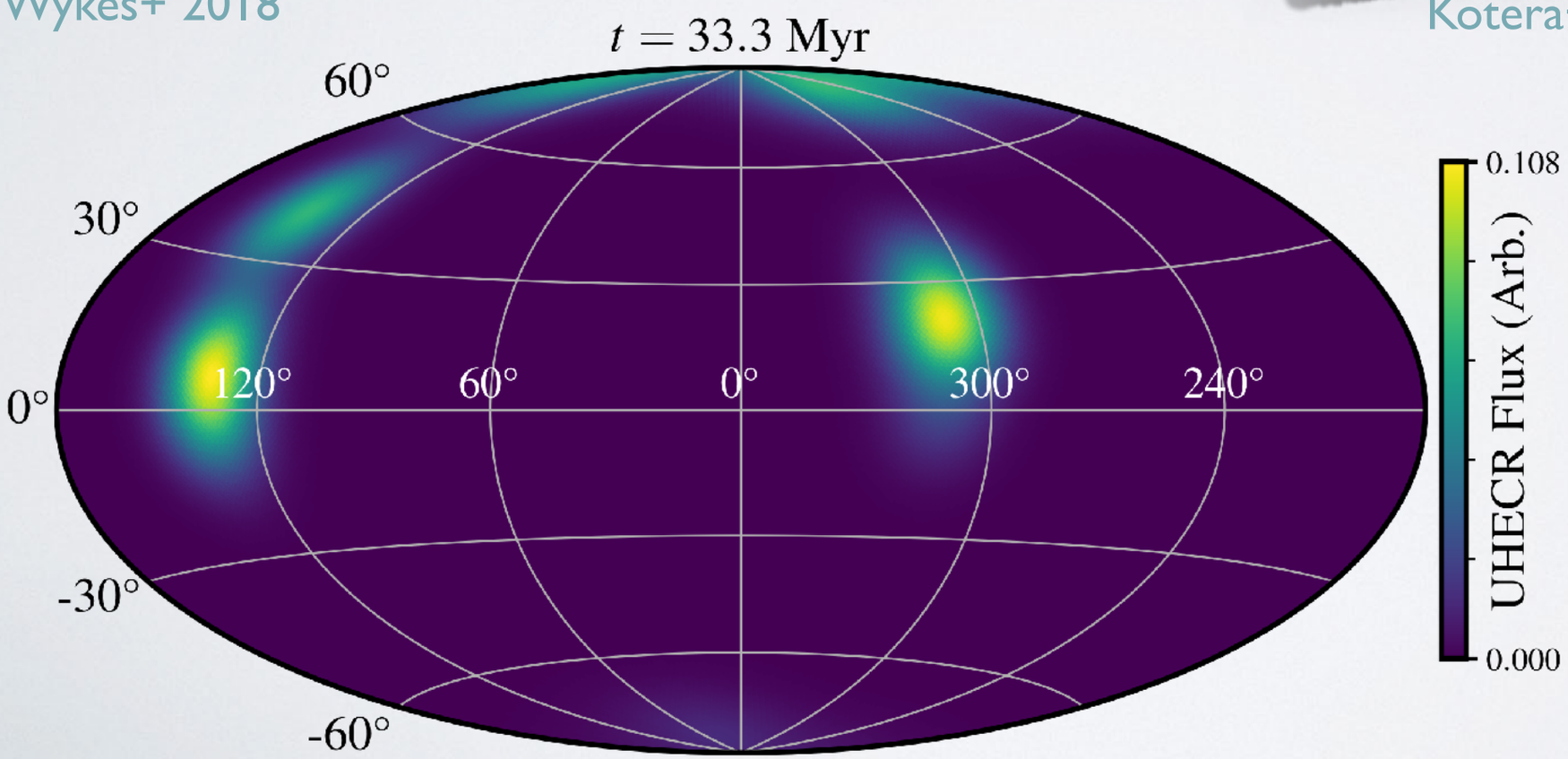


Wykes+ 2018

Composition-dependent UHECR diffusion



Kotera+ 2009



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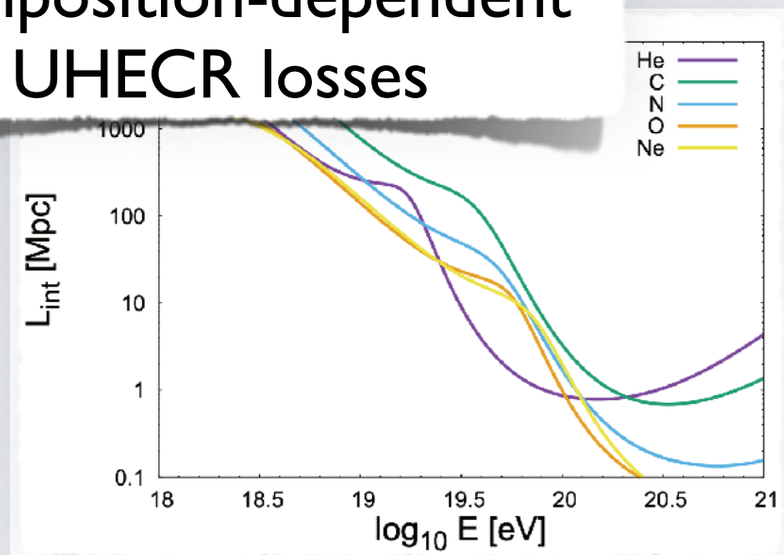

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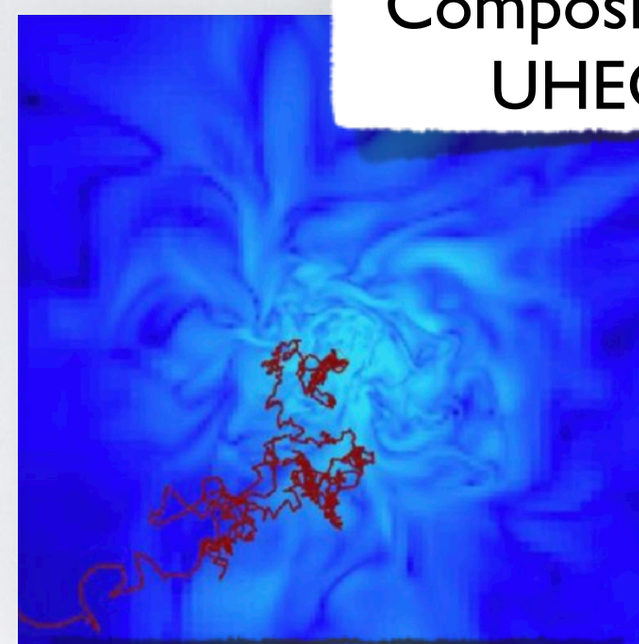

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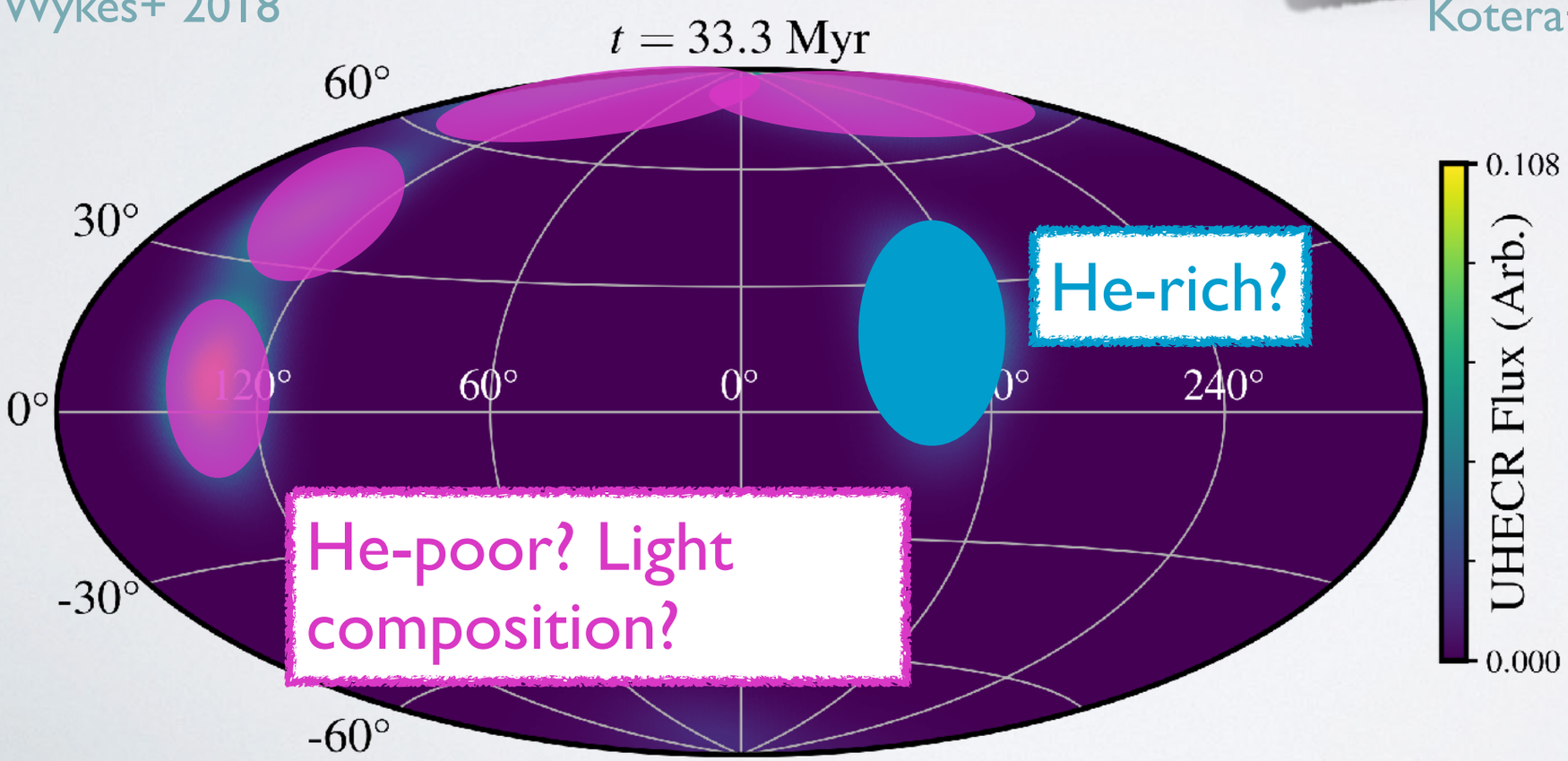
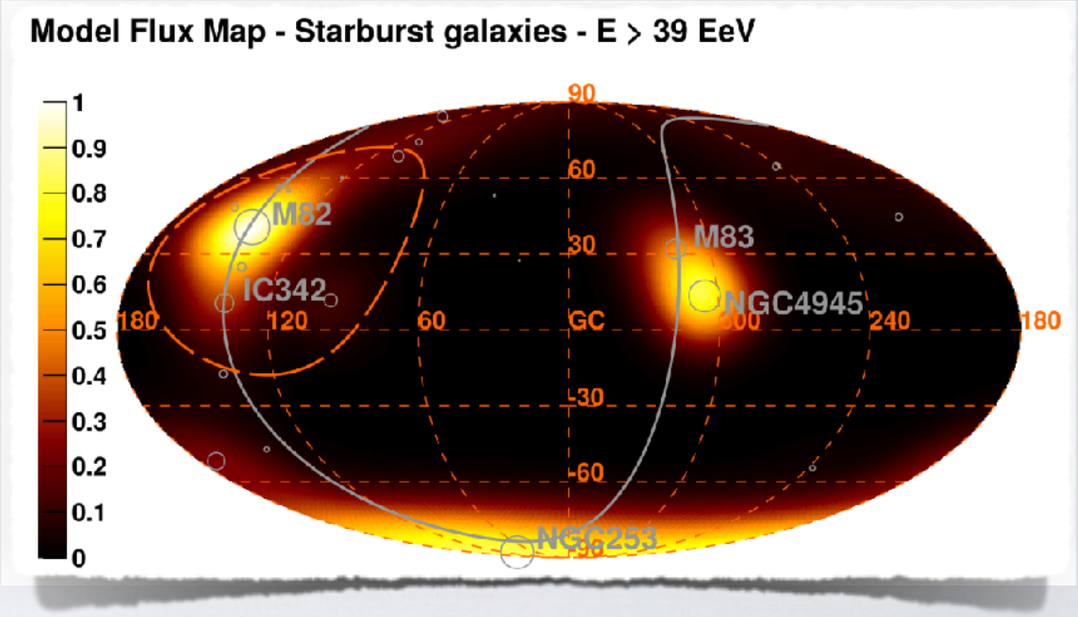


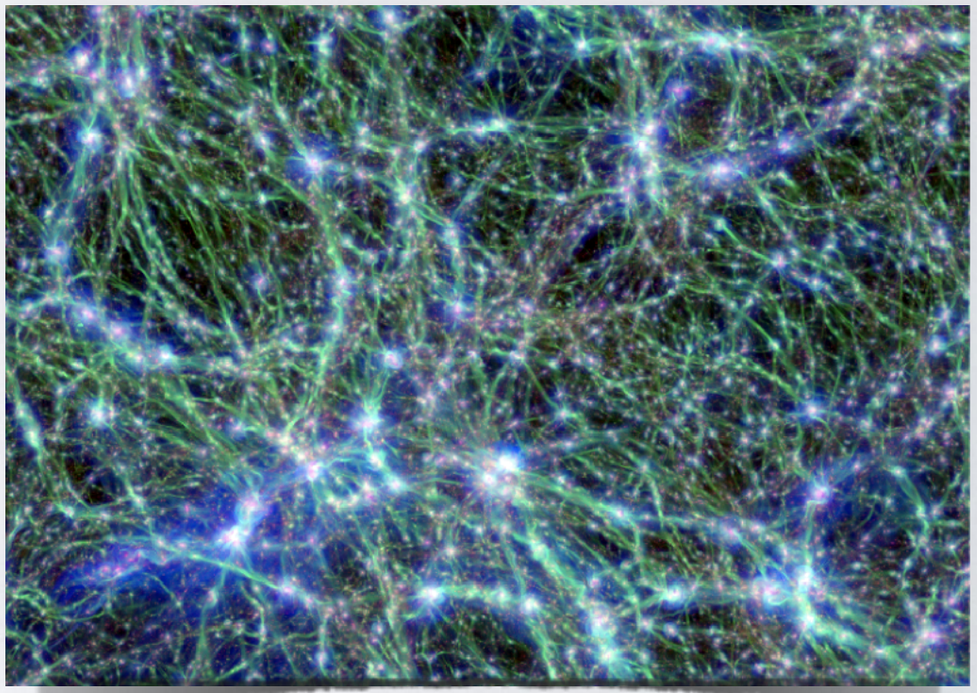
Predictions for Auger Prime and TA x4 possible. Watch this space!

Astrophysics matters for UHECR searches

- At this stage, a purely "data-driven" study is hard at the highest energies
- Pesky astrophysics creates systematics, e.g.:
  - UHECR "proxies" (gamma-rays? Radio? Mass? Something else?)
  - Milky Way and extragalactic B field
  - Intrinsic spectral index depends on nonlinear acceleration physics
- Holistic, multimessenger approach is needed

PAO 2018





Vazza+ 2018

The Phenomenological Bridge

Cambridge

The Phenomenological Bridge

Data

Spectrum $\phi(E)$

Anisotropy $\phi(\theta, \phi, E)$

Composition $\mu(X_{\max}), \sigma(X_{\max})$

Sims: PIC, MHD, Propagation

Physics/Theory

Hillas

Power

Magnetic Fields

Cambridge

The Phenomenological Bridge

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UHECR Phenom.

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Nijmegen

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Nijmegen

Summary

- Simple back of envelope calculations can be used to identify potential UHECR sources
- Shocks and reconnection can both transfer energy to nonthermal particles and create power law particle distributions
- The maximum CR energy is limited by a variety of factors - self-regulating acceleration process must be carefully considered
- Tantalising correlations emerging, but problems with starbursts as UHECR sources: jetted AGN energetically favourable?
  - UHECR "echoes" may be responsible for what we see today
- ***Understanding the physics and origin of UHECRs is a perennial challenge***
  - A phenemenological, multimessenger approach is needed!

Thank you to Jorg and the organising and advisory committees!