UNIVERSITY OF CAMBRIDGE
Herchel Smith Fund

How and where can cosmic rays reach ultrahigh energies?

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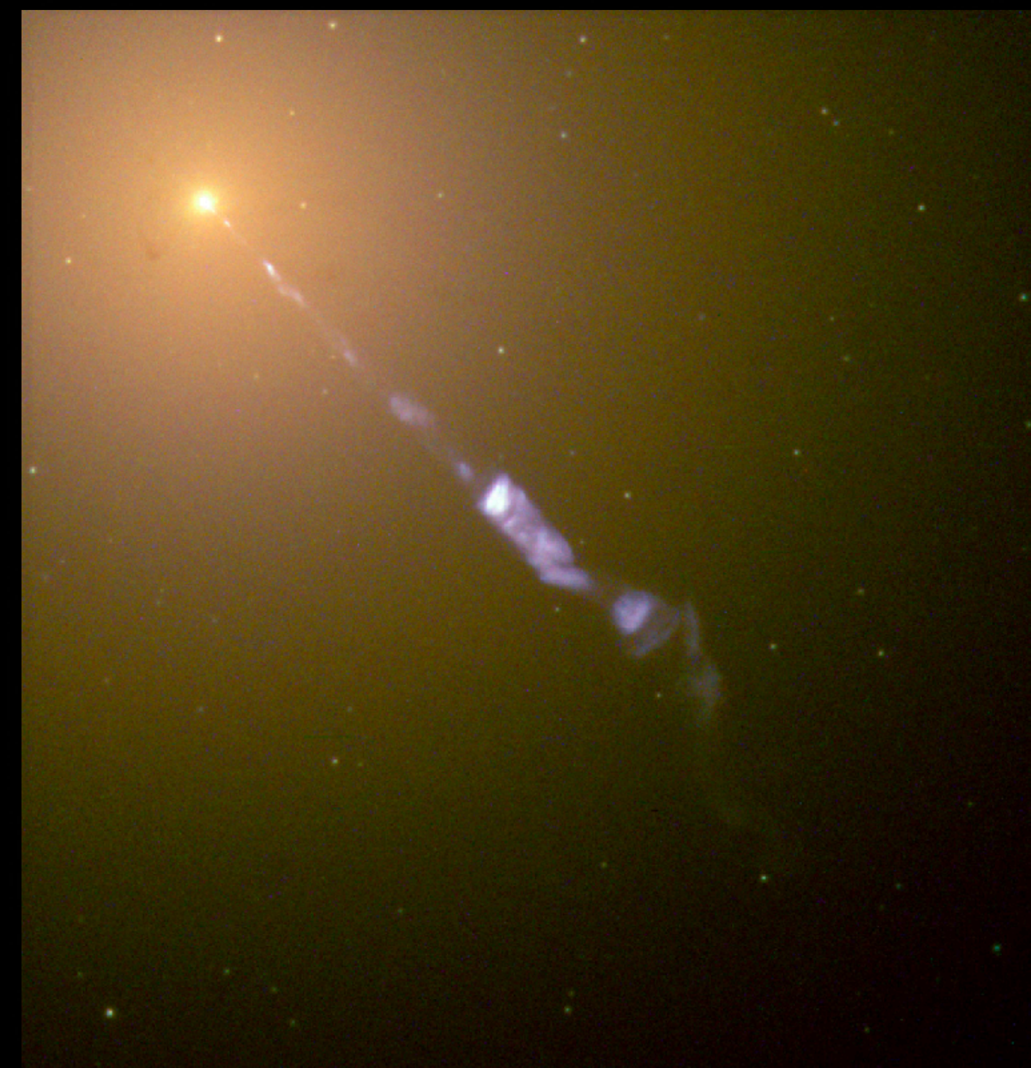
Thanks to:
Tony Bell, Katherine Blundell (Oxford),
Andrew Taylor (DESY Zeuthen)
Anabella Araudo (Czech Academy of Sciences)

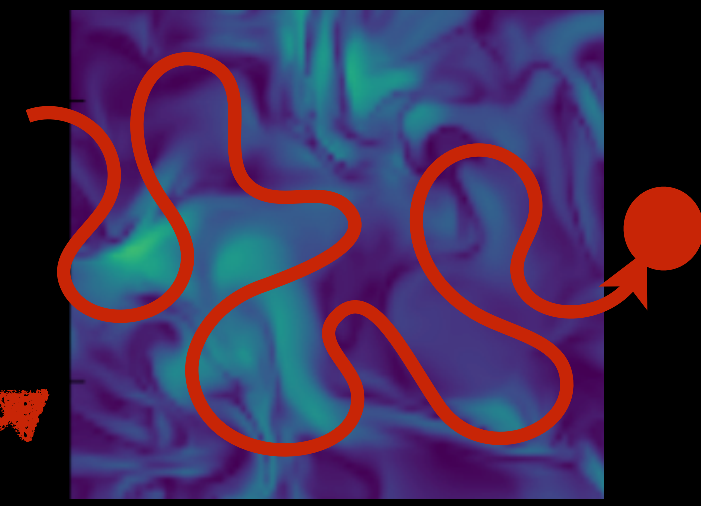
Two 100-year old physics problems…

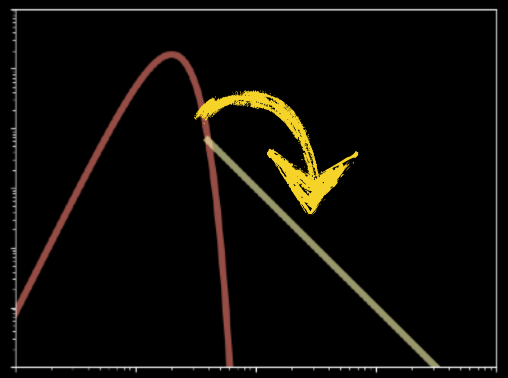
"The results of the observations seem most likely to be explained by the assumption that radiation of very high penetrating power enters from above into our atmosphere."



"A curious straight ray lies in a gap in the nebulosity, apparently connected with the nucleus by a thin line of matter."

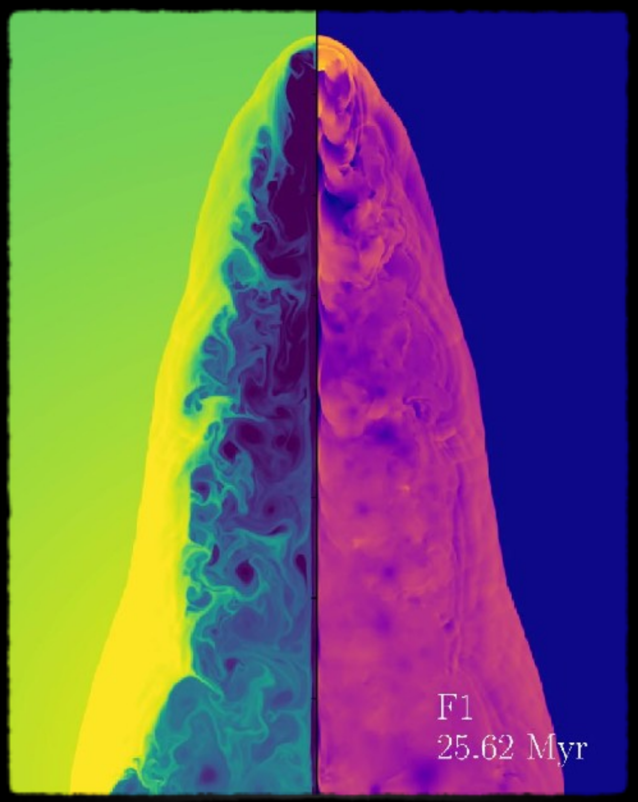
Structure



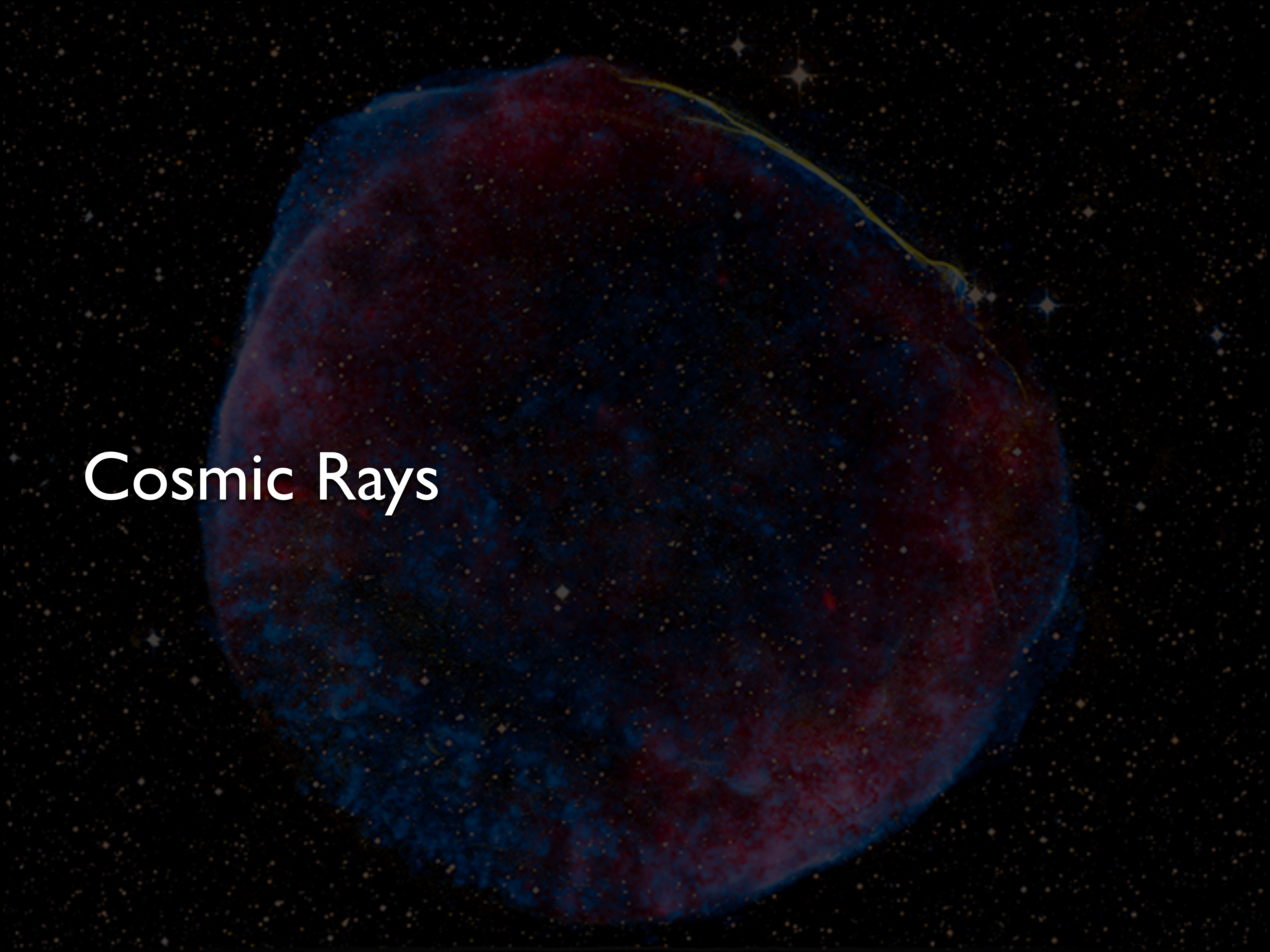


- Cosmic Ray Intro
- How to accelerate a particle
- The Hillas energy and the maximum energy
- UHECR sources

$$E_H = ZuBR$$



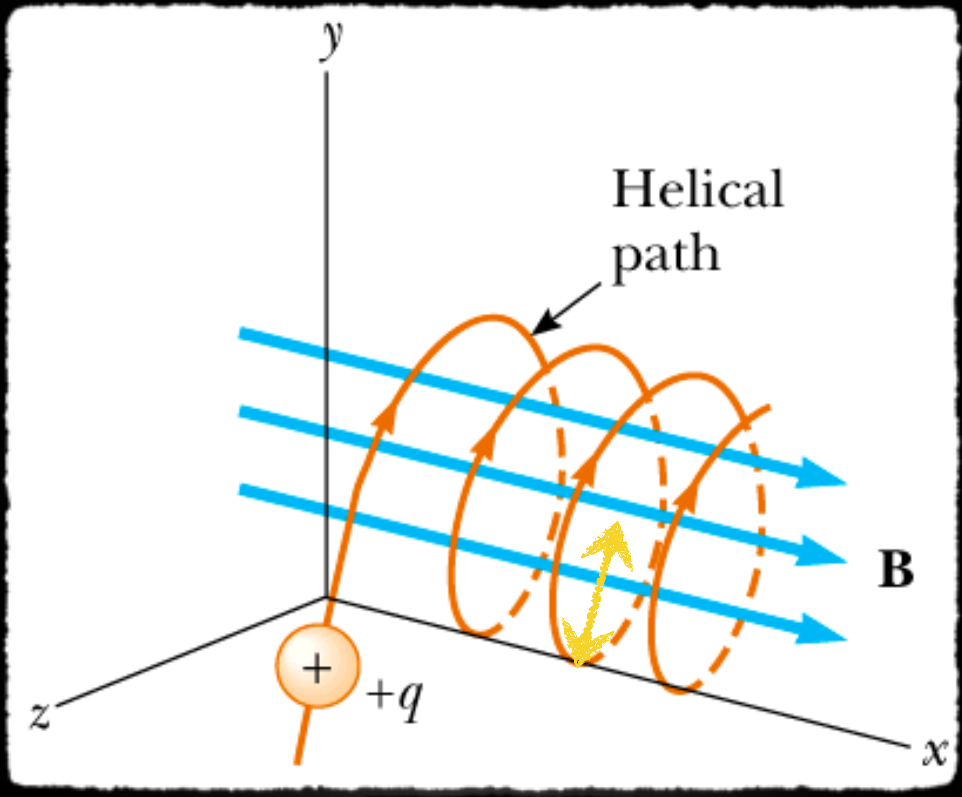
Cosmic Rays



Fundamentals: The Larmor radius or gyroradius

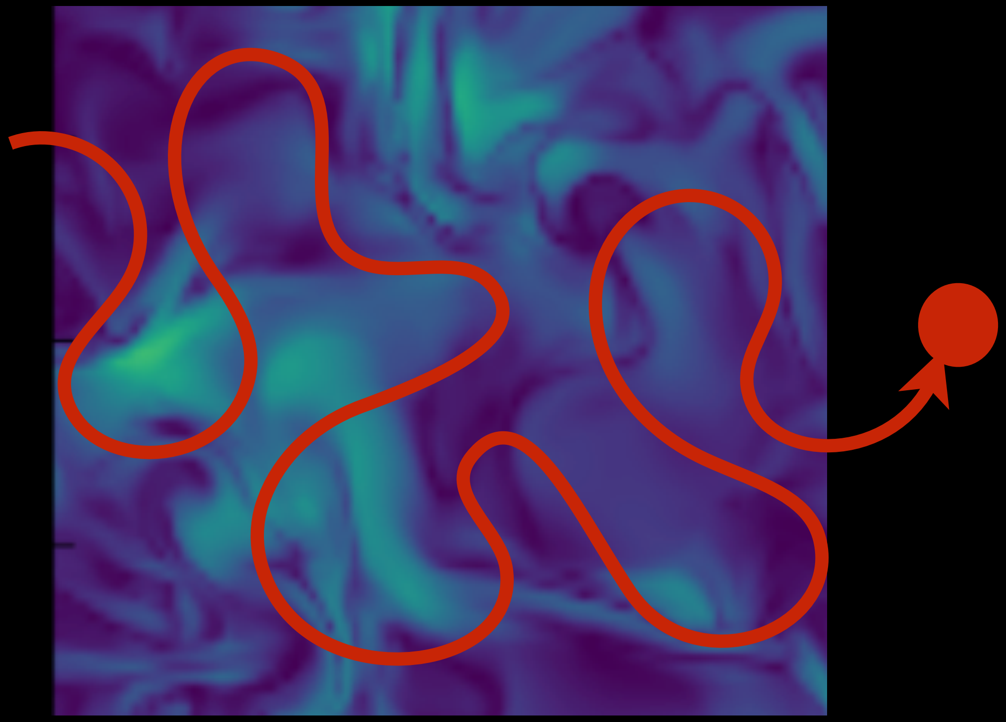
$$R_g = \frac{p_\perp}{ZeB}$$

$$R_g = \frac{E}{ZcB}$$ (if relativistic, eV energies)



…so energetic particles gyrate in bigger cycles

I'm going to talk about "scattering" and "diffusion" - what really happens:



$$\frac{dn}{dt} = \nabla \cdot (D \nabla n)$$

Victor Franz Hess (1912) - Nobel prize in 1936 for “his discovery of cosmic radiation”

Discovered ionisation rate increasing with altitude. We now know high energy particles (CRs) bombarding atmosphere.

Jargon etc:

UHECR = ultrahigh energy cosmic ray (~10^{18}eV or higher, ion or proton)

Throughout this talk: energies in eV (no elementary charge needed)

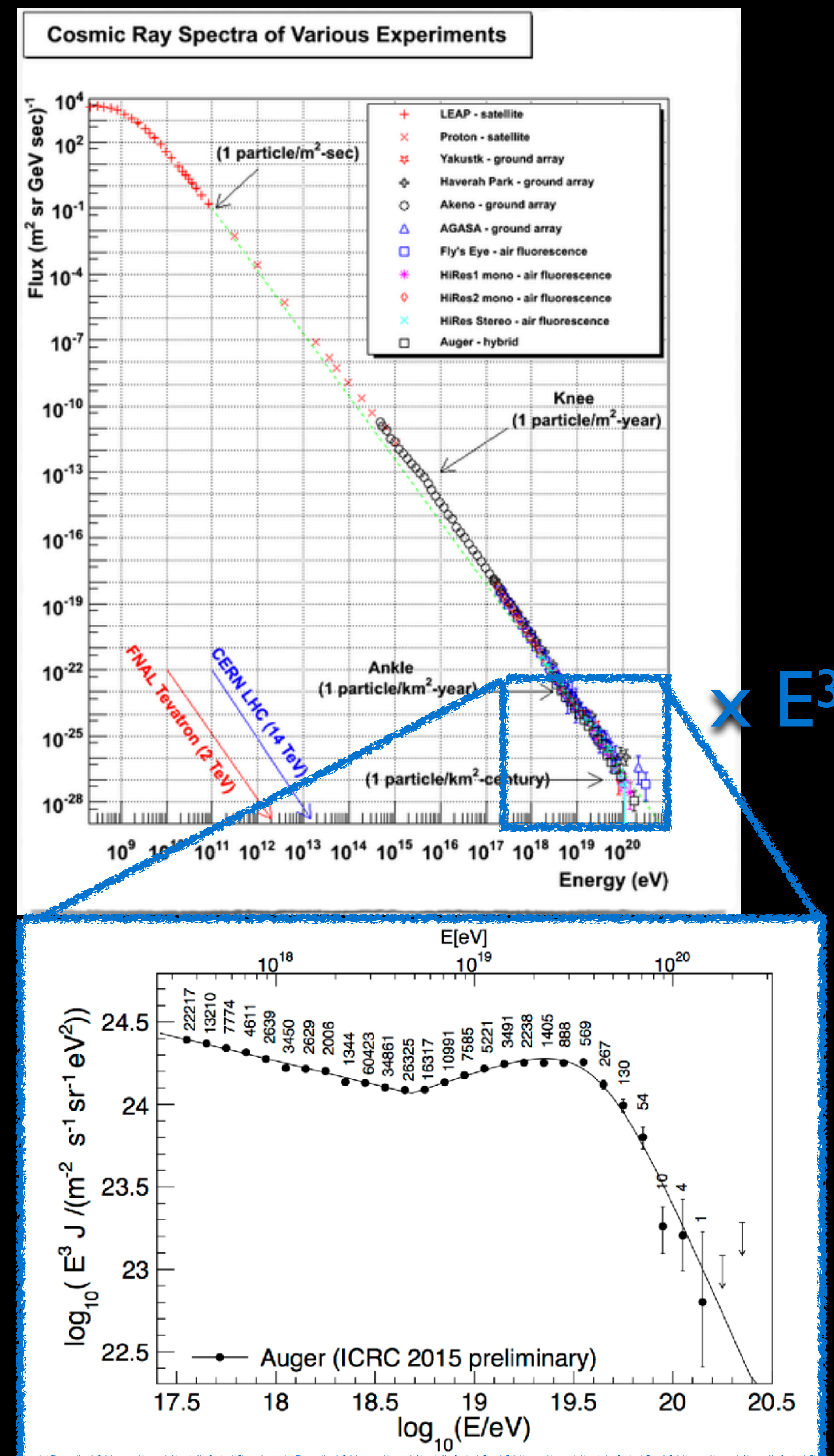
Cosmic rays

List of unsolved problems in physics

From Wikipedia, the free encyclopedia

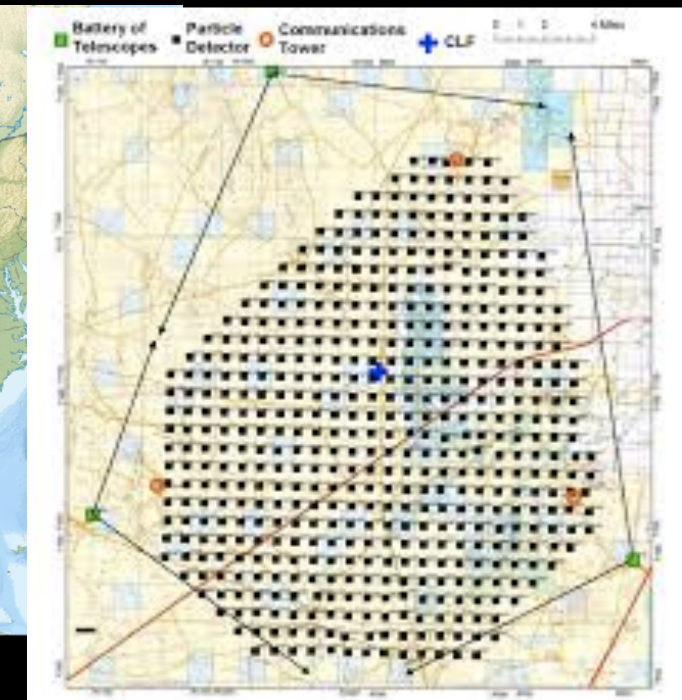
The CR power-law

- The Cosmic Ray spectrum: The best power law in nature?
- *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.
- Maximum energy of protons probably around10 EeV (10^{19} eV)

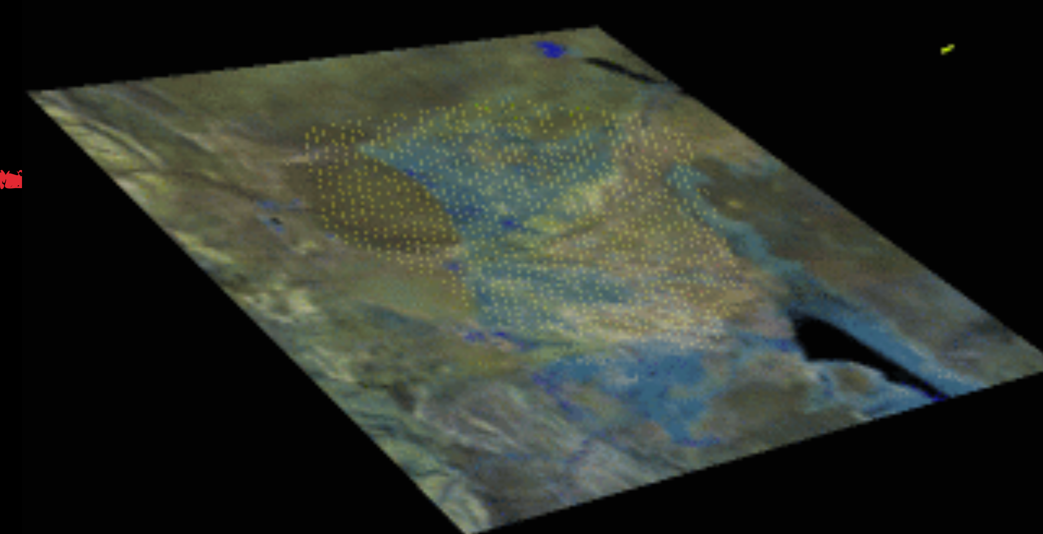


UHECR observatories

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



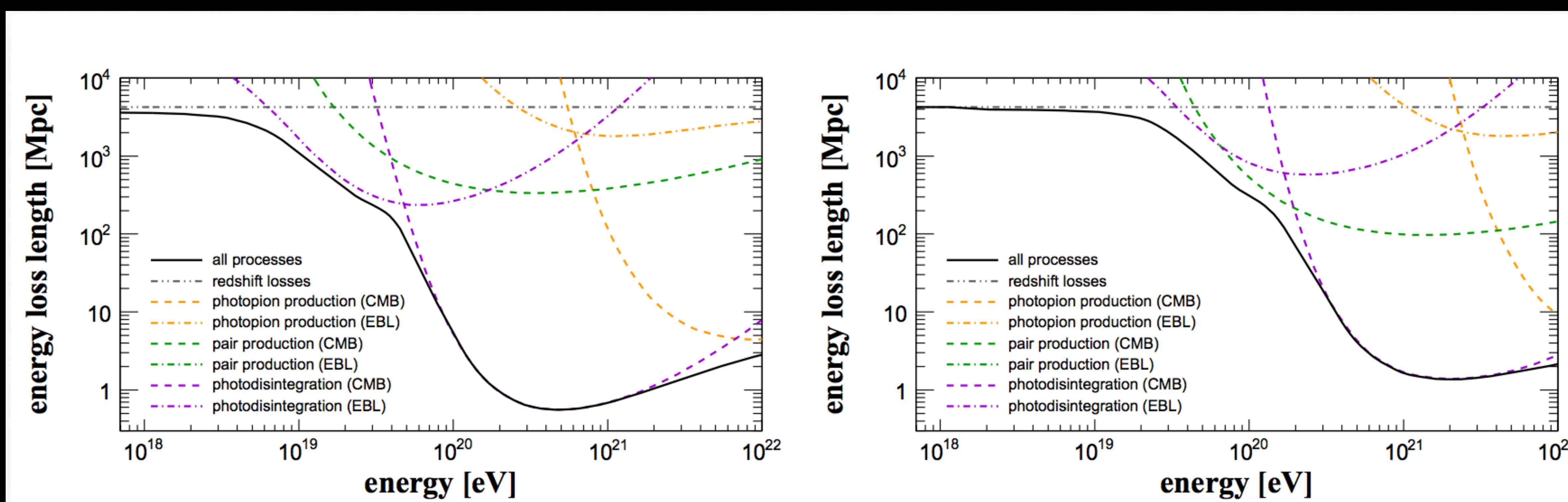
- Pierre Auger observatory
- effective area ~3000 sq km
- 1600 water Cherenkov Detectors
- 24 atmospheric Fluorescence Detector telescopes



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

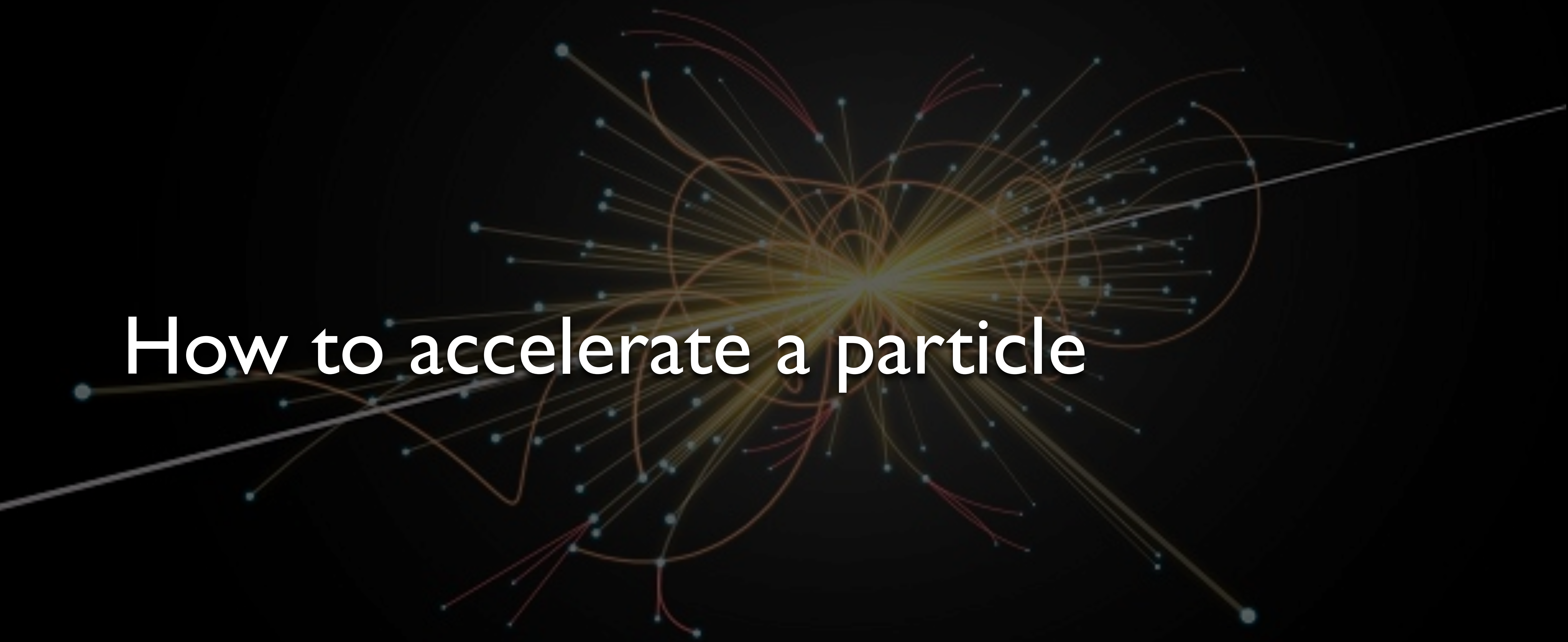
A Horizon for UHECRs

- UHECRs are "attenuated" by radiation fields (CMB and extragalactic background light):
  - Photopion or GZK effect: $$p + \gamma \rightarrow \Delta^{+} \rightarrow p + \pi$$
  - Pair production: $$p + \gamma \rightarrow e^{+} + e^{-} + p$$
  - Photodisintegration: $$A + \gamma \rightarrow (A - nN) + nN$$
- Horizon length is very composition dependent, ~100 Mpc for 60 EeV



Alves-Batista+ 2015

How to accelerate a particle

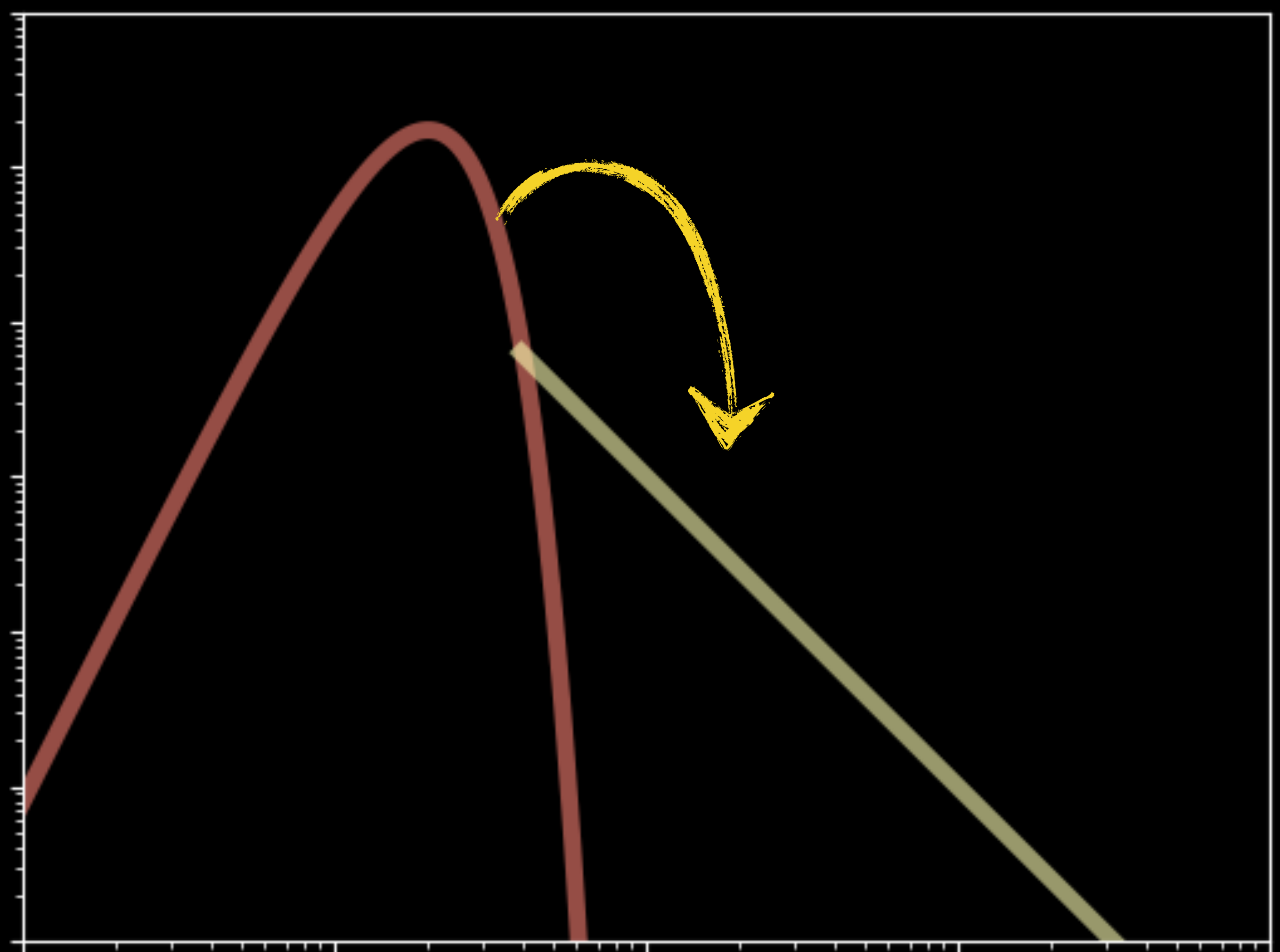


How to accelerate a particle

Maxwellian

Log-scaled and shifted

With a non-thermal tail



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

How do we form a power-law?

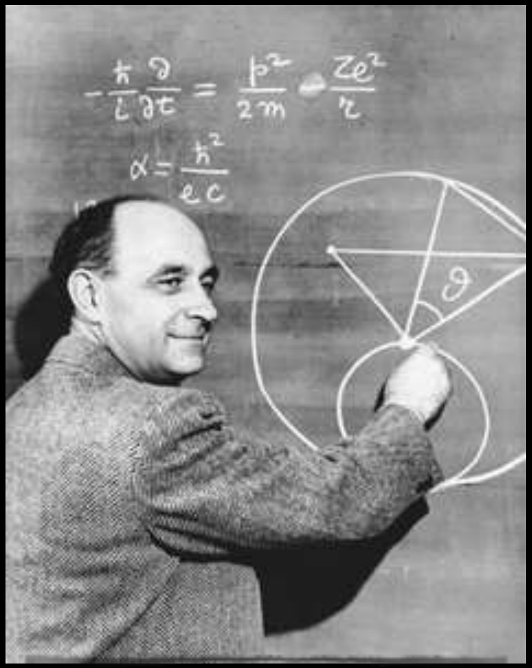
Particle Acceleration

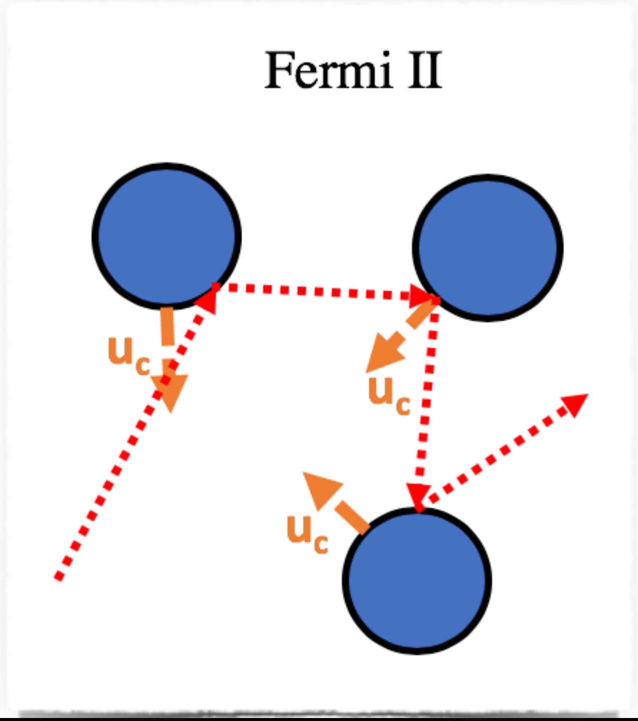
- Assume you undergo a series of "scattering" events
- Allow particles to gain a fractional increase of energy β in each scattering event
- Particles have a probability P of remaining in the interaction region after each scatter
- Produces a power-law as required for CR and observed nonthermal synchrotron spectra!

$$n(E)\, dE \propto E^{(\ln P/\ln\beta)-1}\, dE$$

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





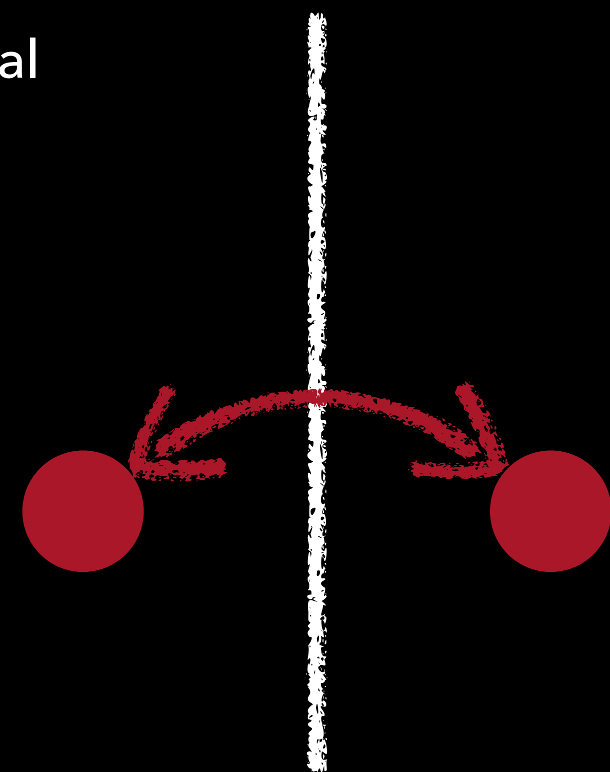
$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{8}{3}\left(\frac{u_c}{c}\right)^2$$

Shock Acceleration

(Krymskii 1977; Axford+ 1977; Bell 1978; Blandford & Ostriker 1978)

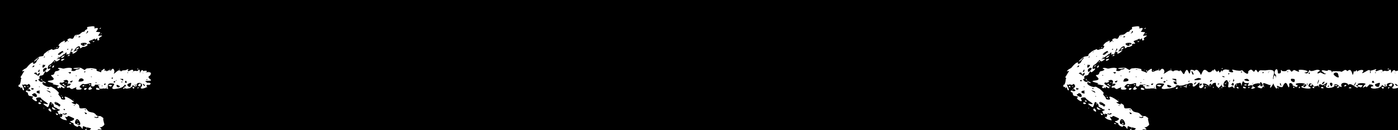
Shocked material

Unshocked ISM



- Transforming from U to D always results in head-on "collision"
- Fraction of CRs lost ~ $-u_s/c$
- Fractional energy gain per crossing ~ u_s/c
- Balance between them gives power law n(E) with slope -2

Shock frame



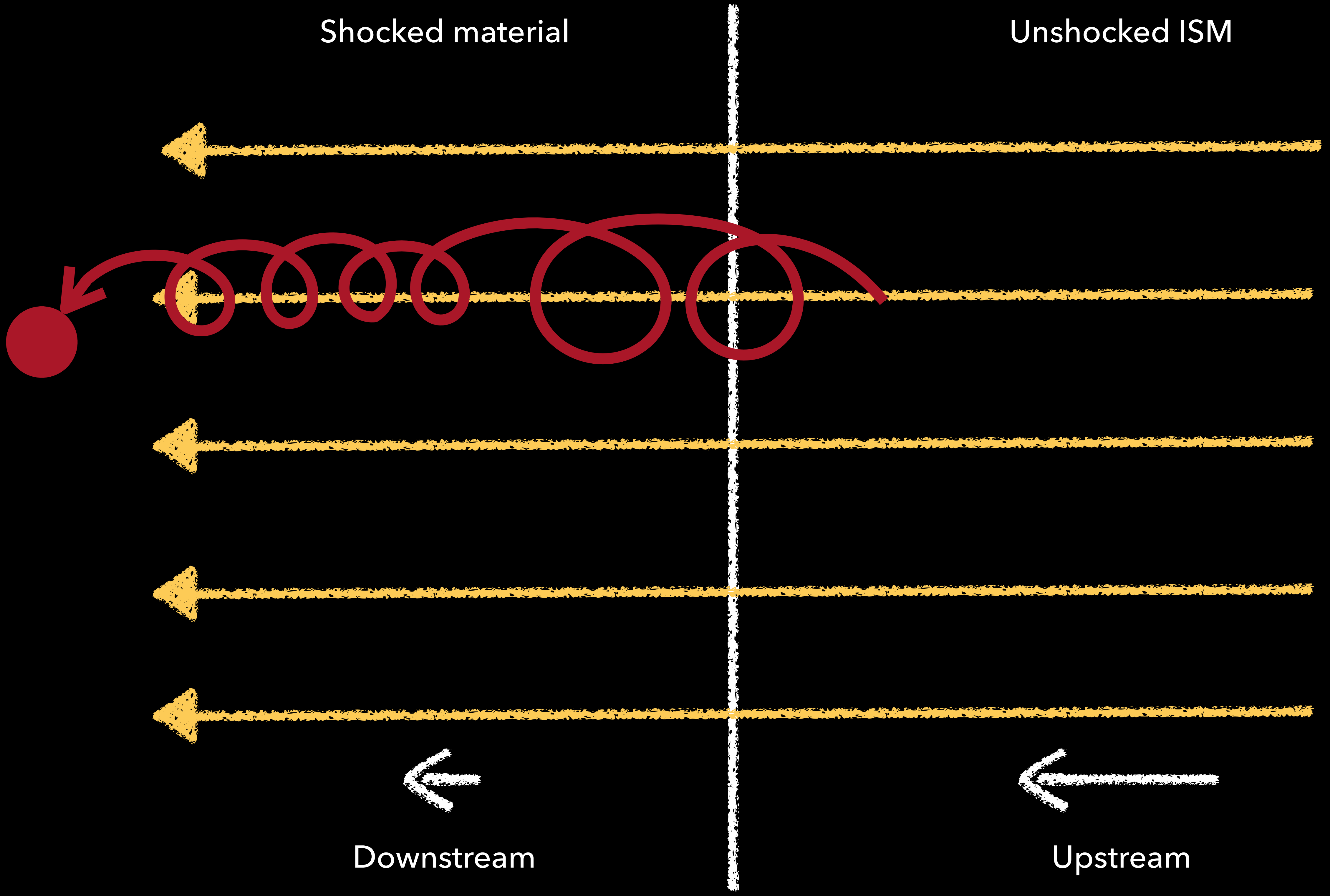
Downstream

Upstream

Shock Acceleration

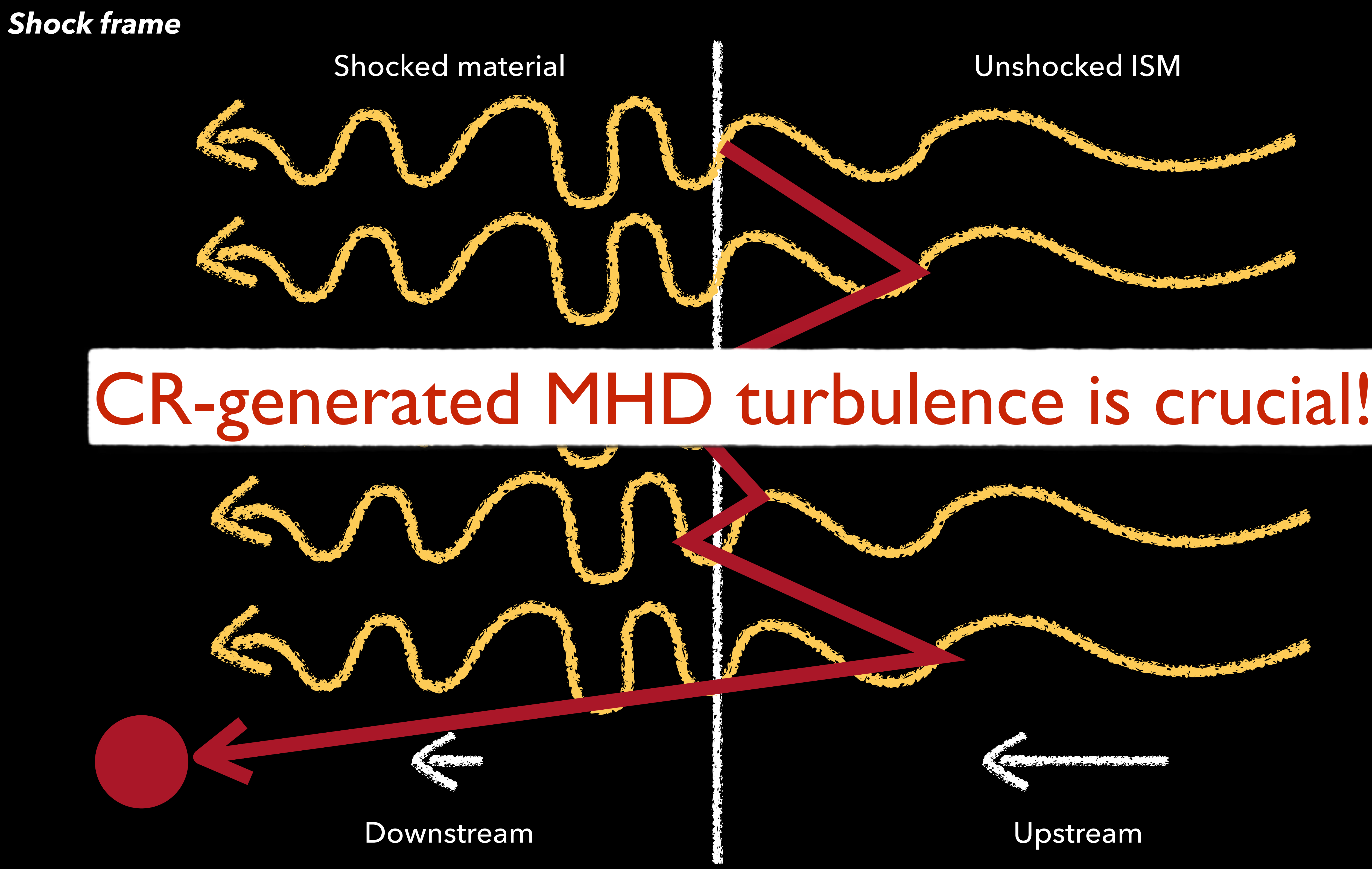
(Krymskii 1977; Axford+ 1977; Bell 1978; Blandford & Ostriker 1978)

Shock frame



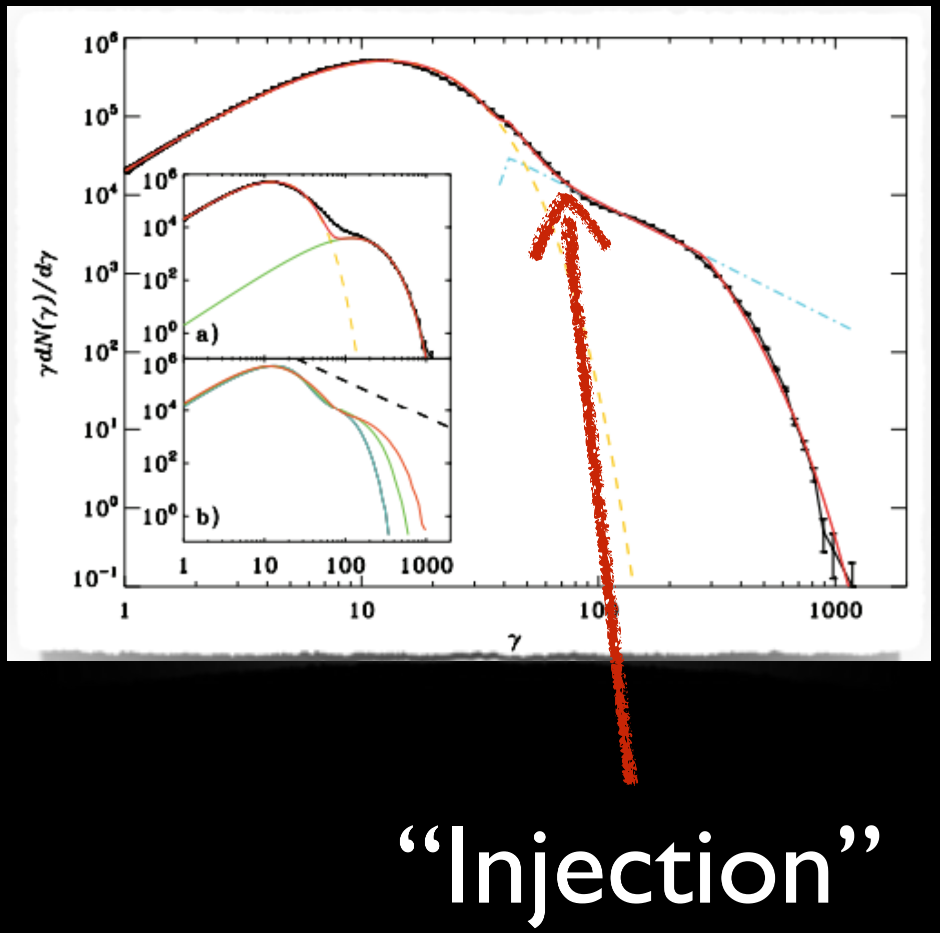
Shock Acceleration

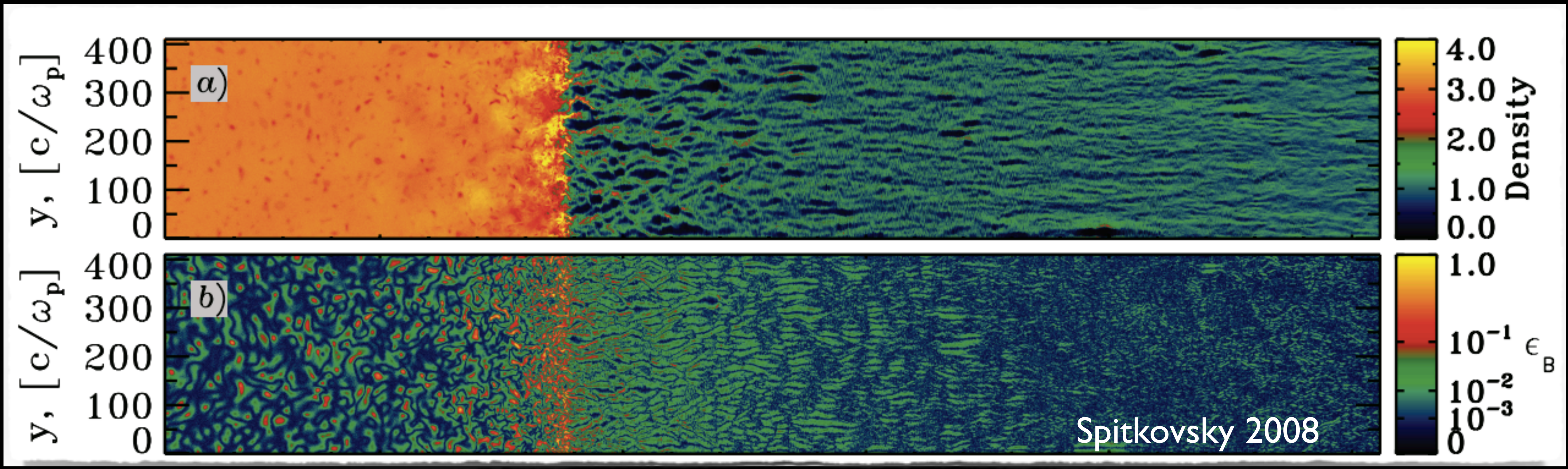
(Krymskii 1977; Axford+ 1977; Bell 1978; Blandford & Ostriker 1978)



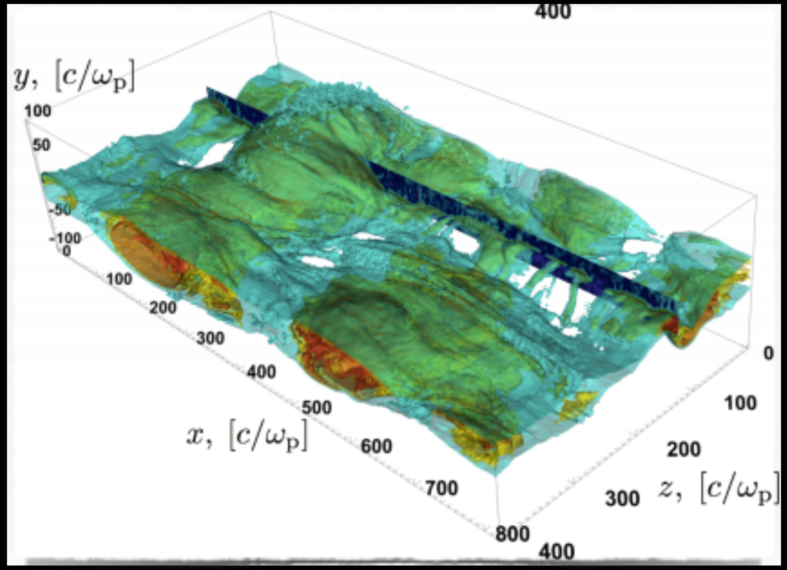
PIC Simulations

- 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



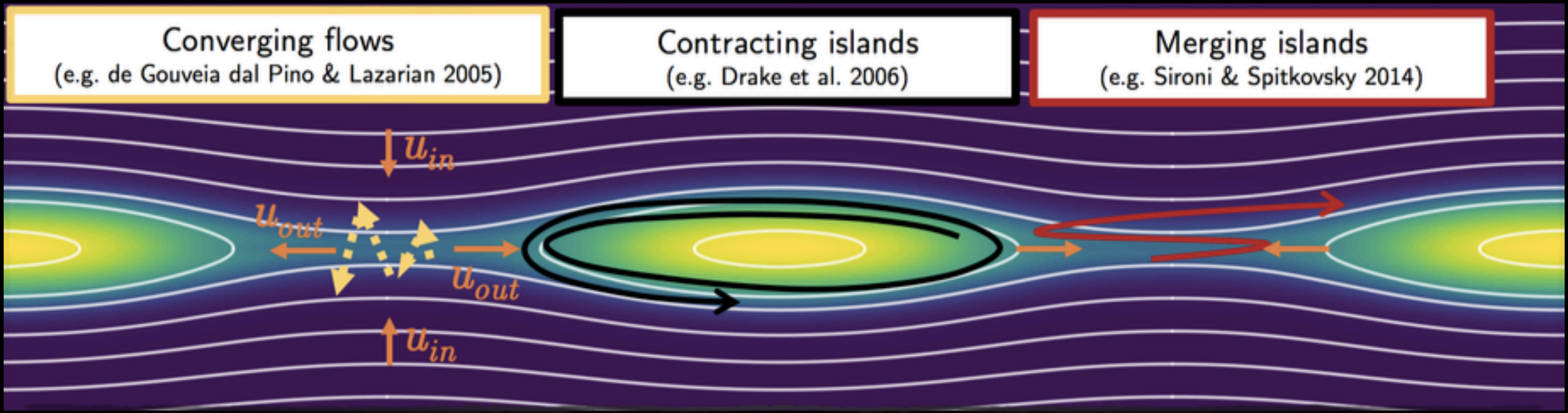


Magnetic Reconnection

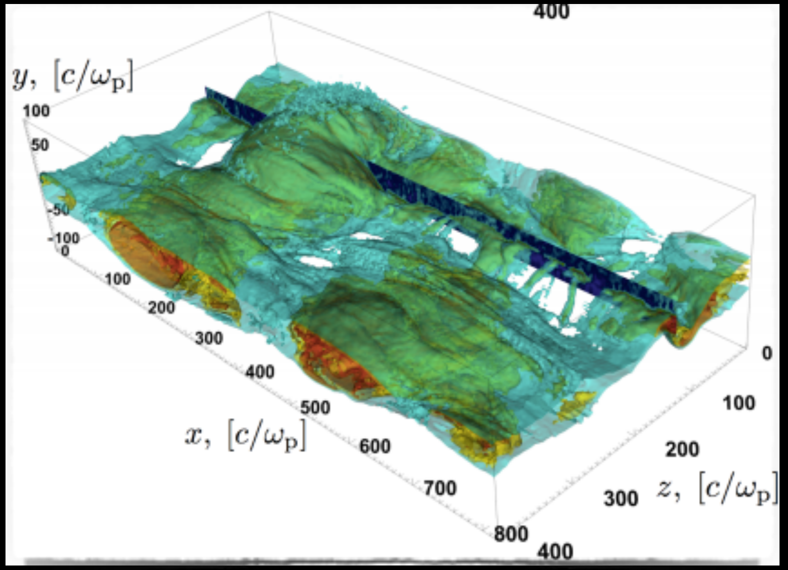


Sironi & Spitkovsky 2014

- 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”



Magnetic Reconnection



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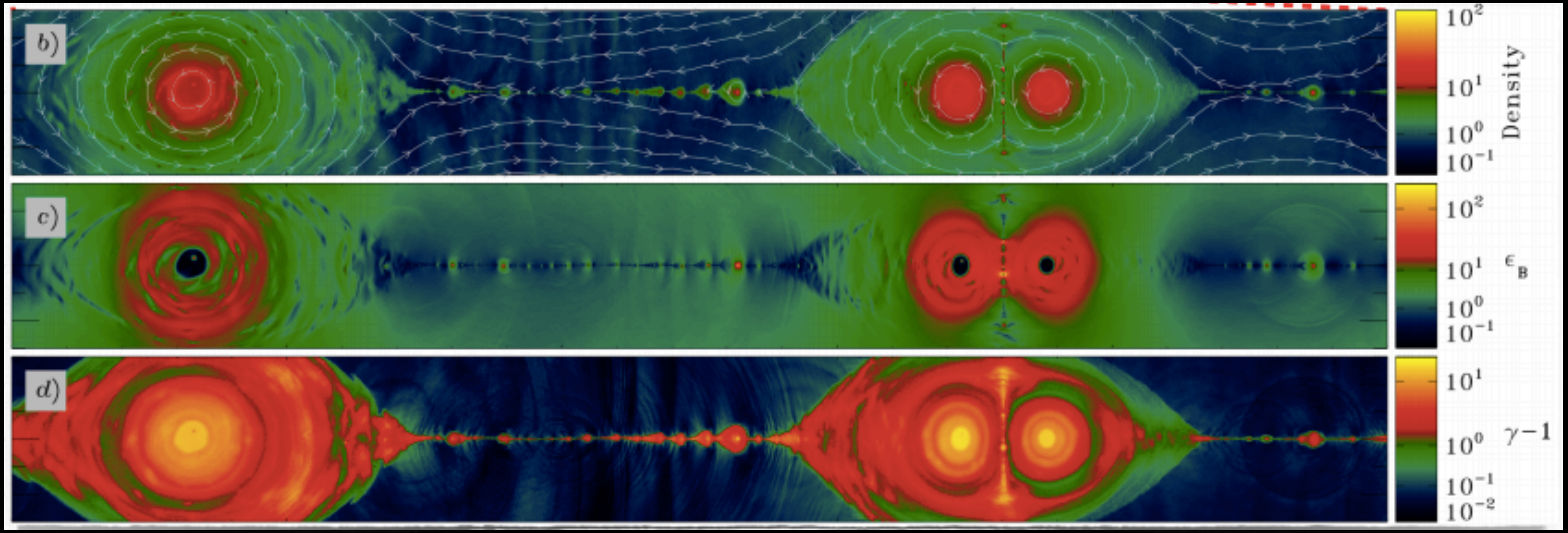
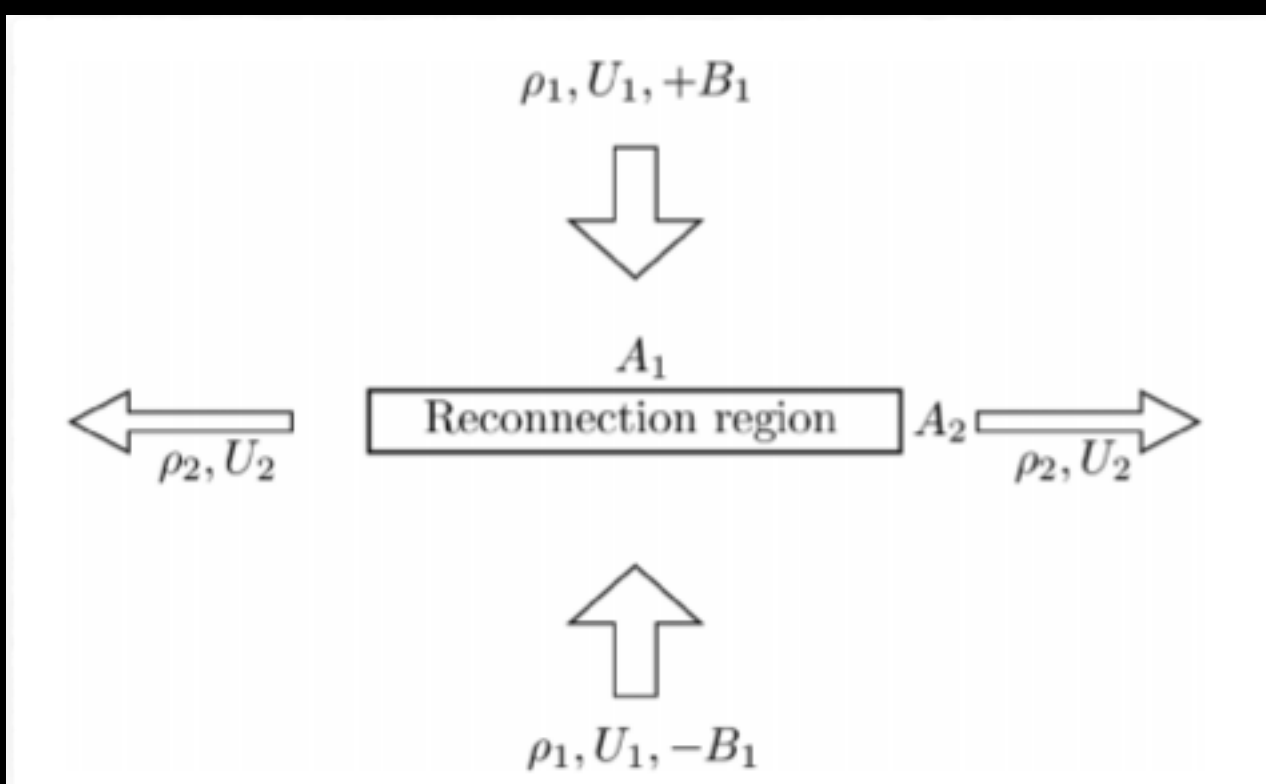


Magnetic Reconnection

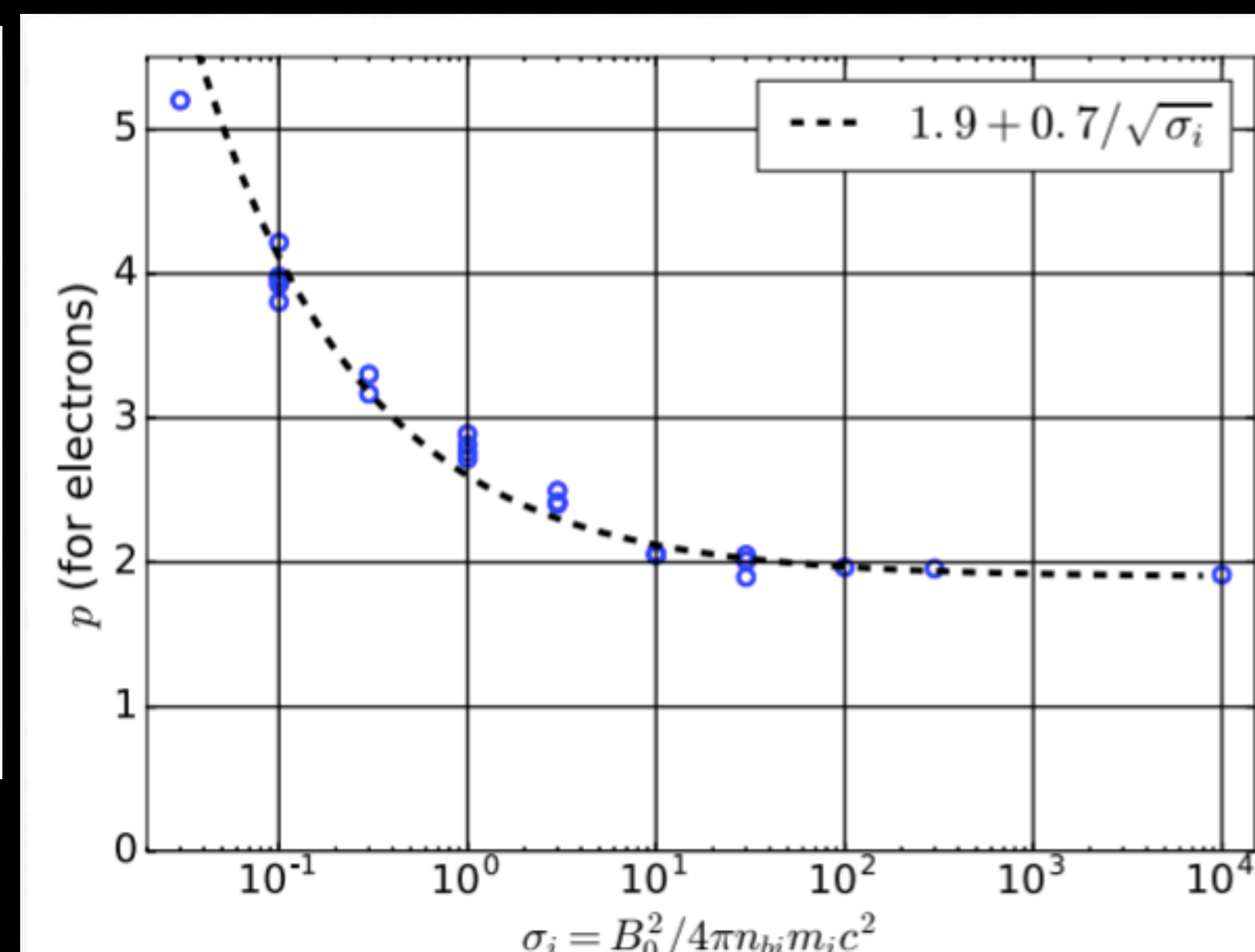
- Interesting parallels with shocks: escape and energy gain might be hardwired by either "compressivity" or magnetisation
- Connects macroscopic energy dissipation to non thermal particles? Explains "Magnetoluminescence"?

Drury 2012



$$\frac{\partial \ln f}{\partial \ln p} = -\frac{3r}{r-1}, \qquad r = \frac{\rho_2}{\rho_1}$$

Werner+ 2016



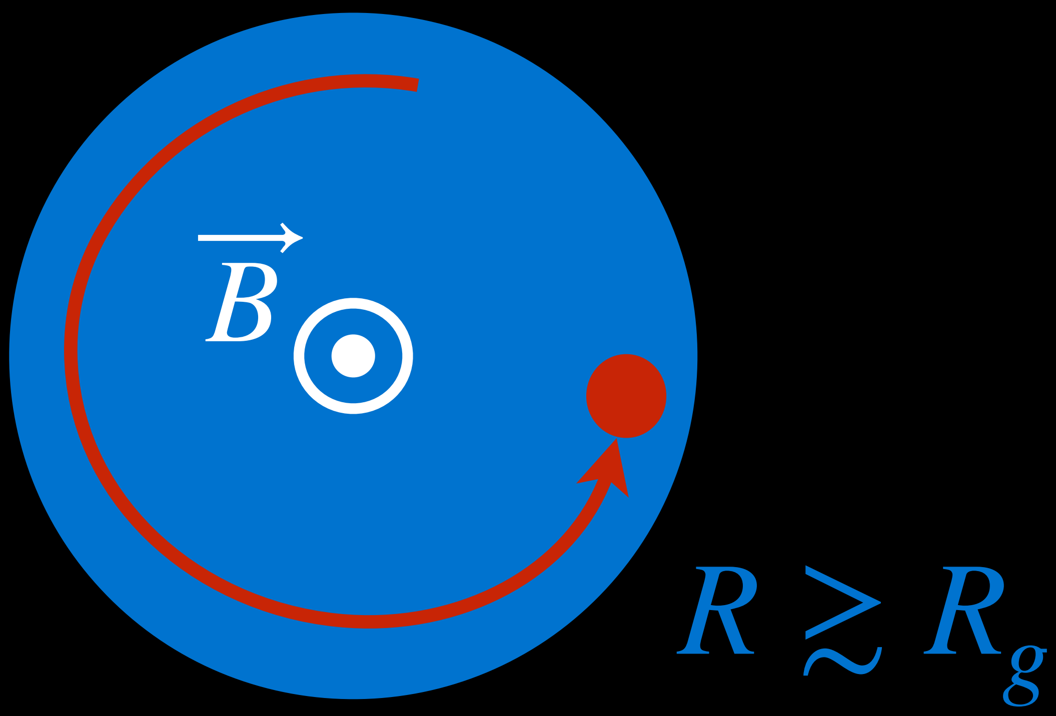
The Maximum Particle Energy

(How can we get protons to 10^{19} eV?)

Confinement condition

- Simplest condition on UHECR accelerators:
  - Larmor radius <= system size

$$E = ZcBR$$



Hillas 1984

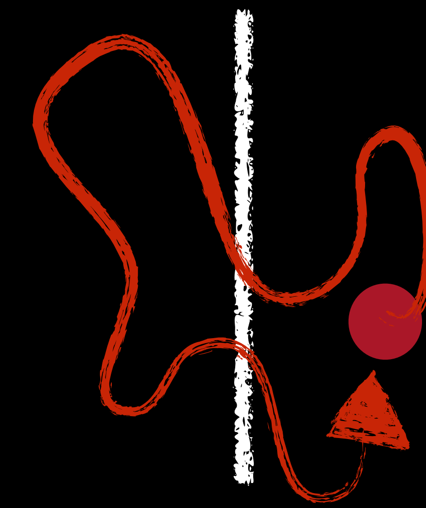
Hillas Energy

- Maximum characteristic 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

Hillas Energy Derivation in Shocks



- Recall that energy gain depends on u/c

$$\Delta E \sim E \frac{u_s}{c} \qquad \Delta t \sim \frac{D}{c u_s}$$

e.g. Drury (1983)

$$\frac{1}{E}\frac{dE}{dt} \sim \frac{u_s^2}{D}$$

- Acceleration time:

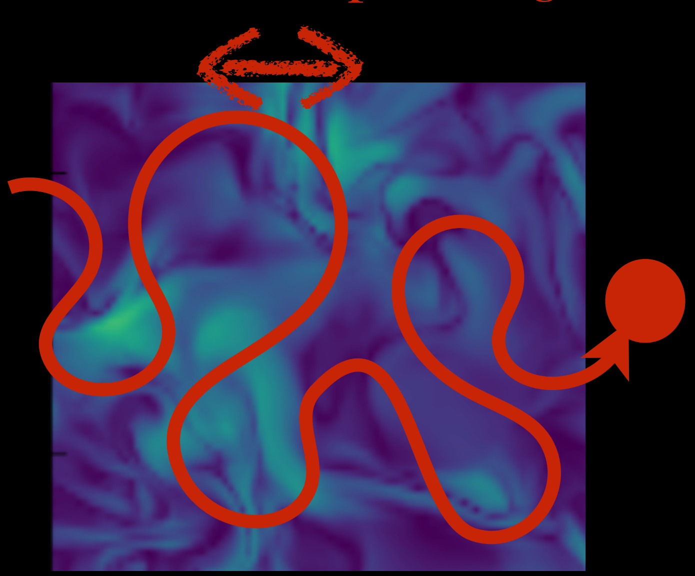
$$\tau_{\rm acc} \equiv \frac{E}{dE/dt} \sim \frac{D}{u_s^2}$$

Hillas Energy Derivation in Shocks

- Ecept for special situations, particle cannot have a mean free path smaller than Larmor radius
- We call the situation when $\lambda_{\rm mfp} \sim R_g$ Bohm diffusion with diffusion coefficient D_B
- Write diffusion coefficient as

$$D = \eta D_B \sim \eta R_g c, \; \eta \geq 1$$

$$\tau_{\rm acc} = \eta \frac{E}{ZB}\frac{1}{u^2}$$



Hillas Energy Derivation in Shocks

- Time available for acceleration at the shock $\tau_{\rm dyn} \sim R/u_s$

$$\tau_{\rm acc} = \eta \frac{E}{ZB}\frac{1}{u^2}$$

$$E_{\max} = \eta^{-1} ZuBR$$

Necessary but not sufficient

$$E_{\max} = \eta^{-1} ZuBR = \eta^{-1} E_H$$

Hillas energy only reached when Bohm diffusion applies (Eta~1).

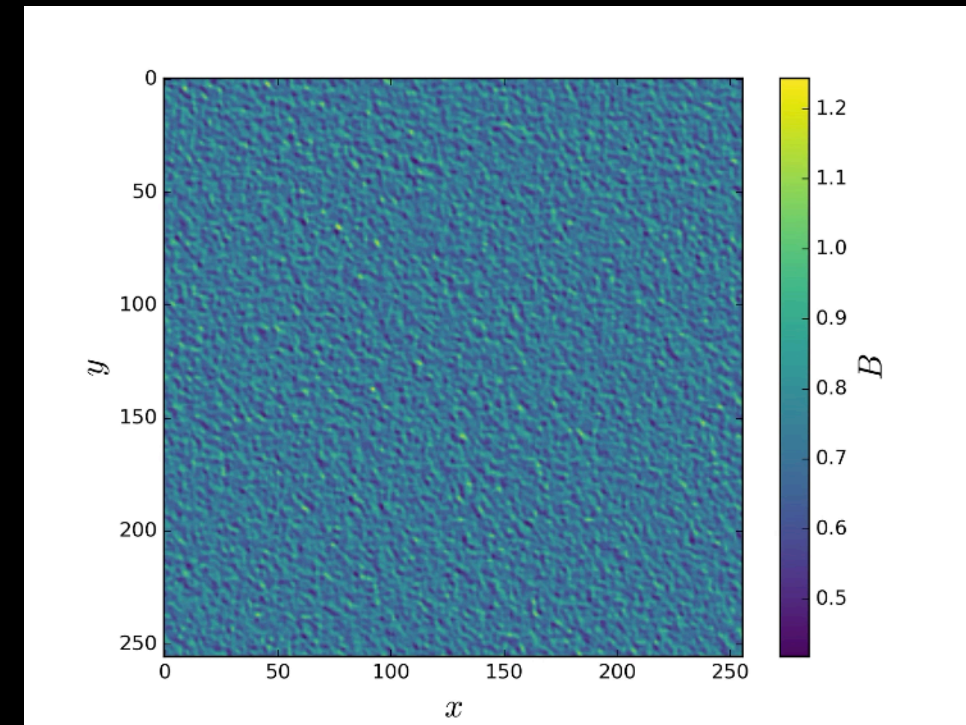
Requires:

- Structure in the magnetic field on scale of the Larmor radius
- Strong turbulence (dB/B ~ 1)

CR-driven instabilities

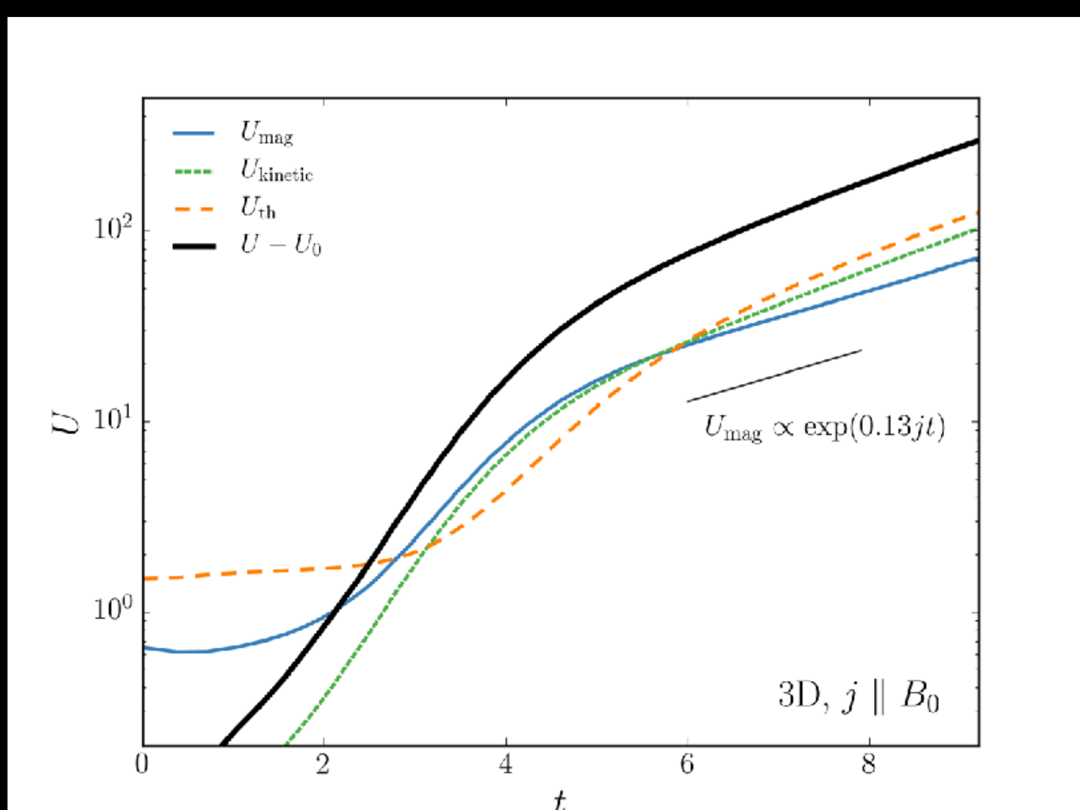
(Bell 2004, 2005)

- CRs produce a return current in a plasma that drives MHD turbulence - the non-resonant or Bell instability*
- Also amplifies magnetic field
- A natural way to grow turbulence to Larmor radius scales and reach the Hillas energy
- Similar instabilities in collisional form (Bell, JM+2020)

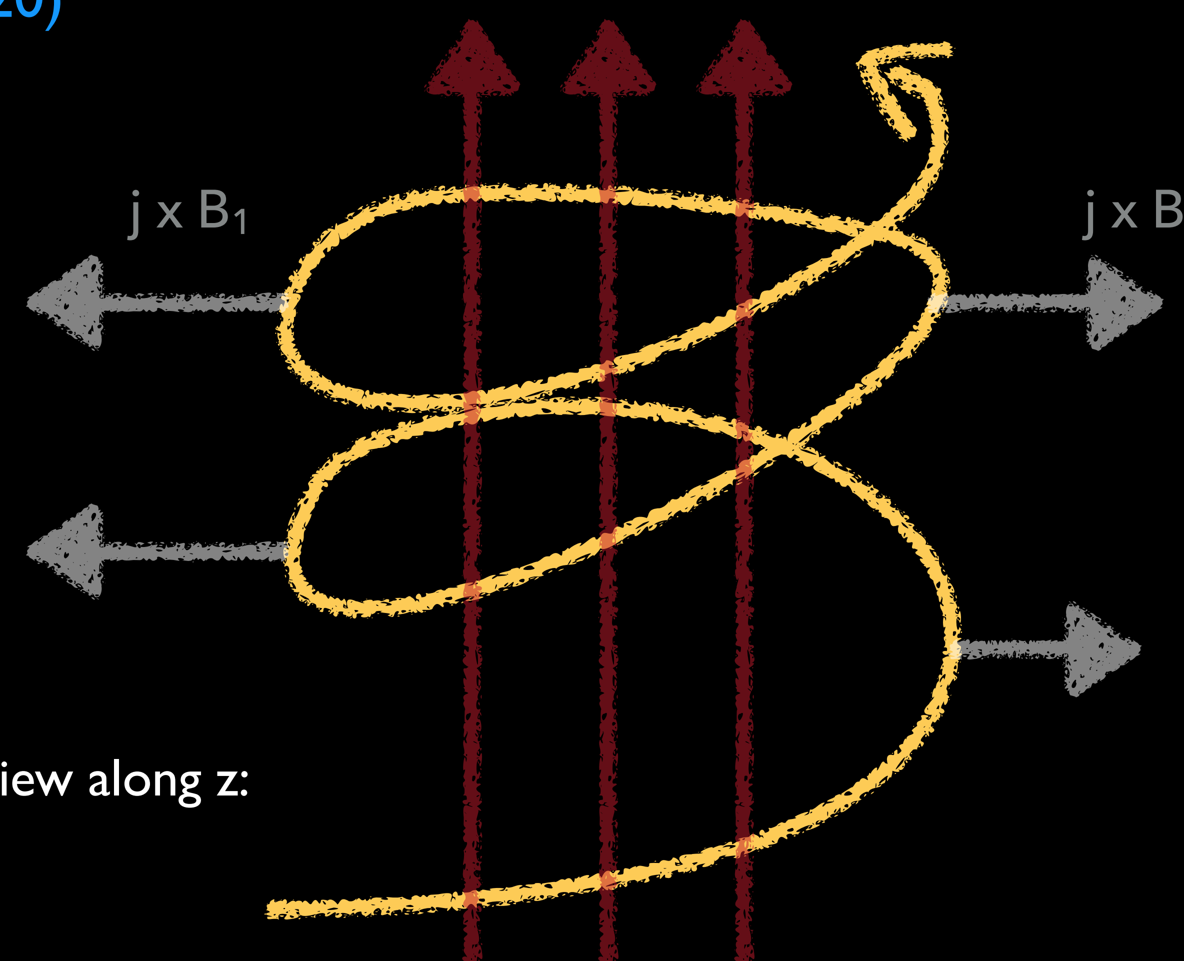


Matthews+ 2017

Energy



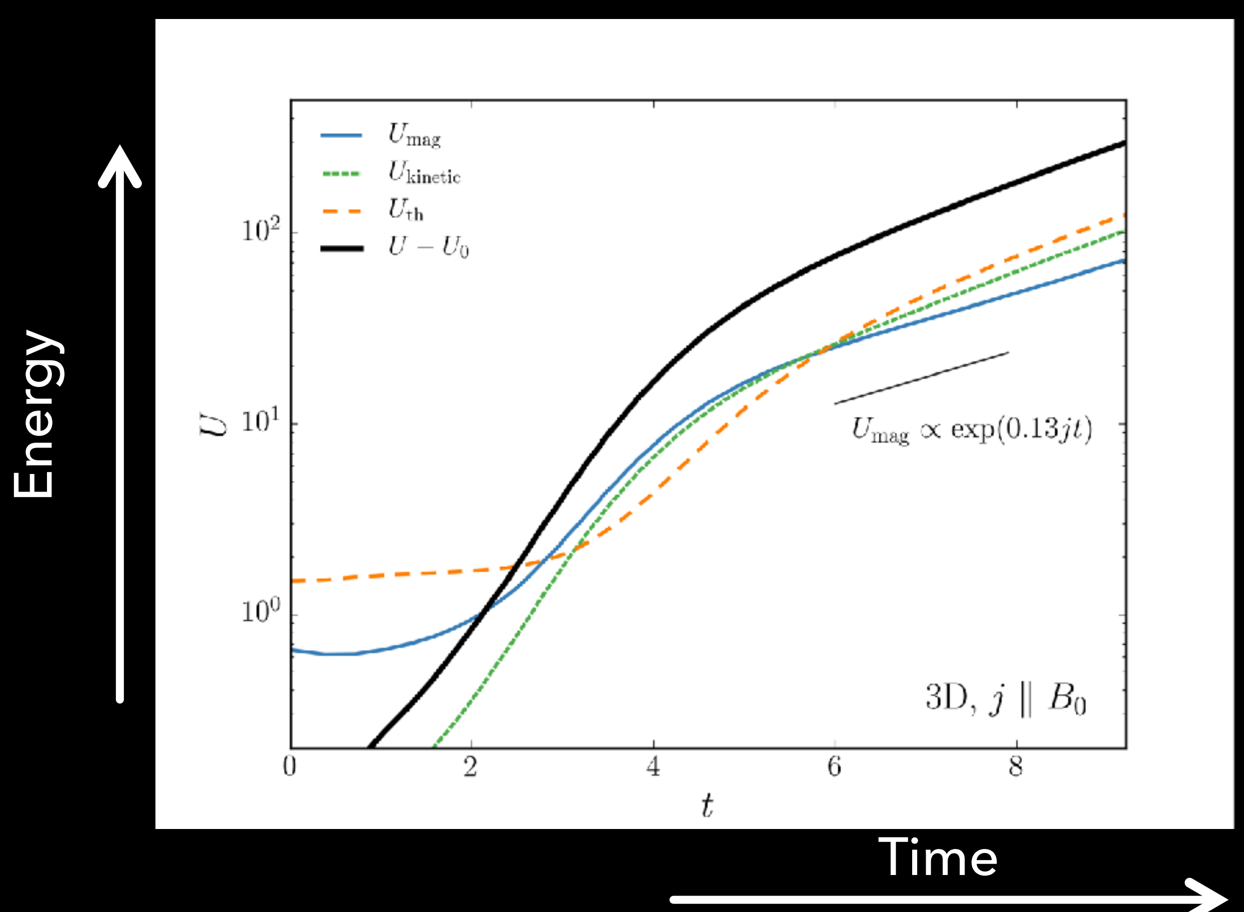
Time

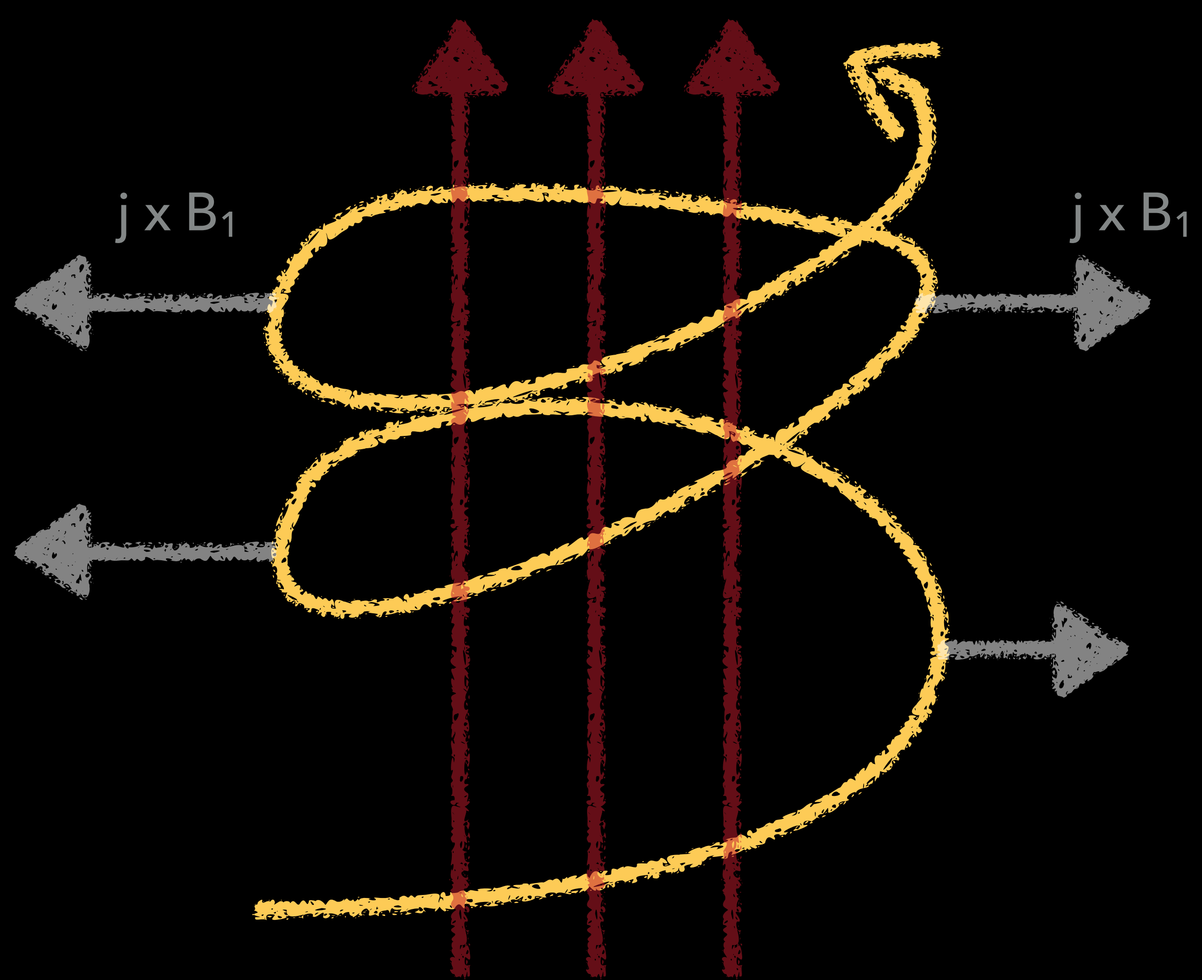


* Other instabilities are available

CR-driven instabilities

- Necessity for turbulence introduces additional time constraint
- Need enough time to drive instability - displacement of plasma set by $\mathbf{s = 1/2\, a\, t^2 = 1/2\, (j\, B\, /\, \rho)\, t^2 = r_g}$
- Limits maximum energy in SNRs to ~0.1PeV and ***severely*** limits maximum energy in relativistic shocks





Hillas 1984

Hillas energy

$$E_H = ZuBR$$

Highest when u ~ c??

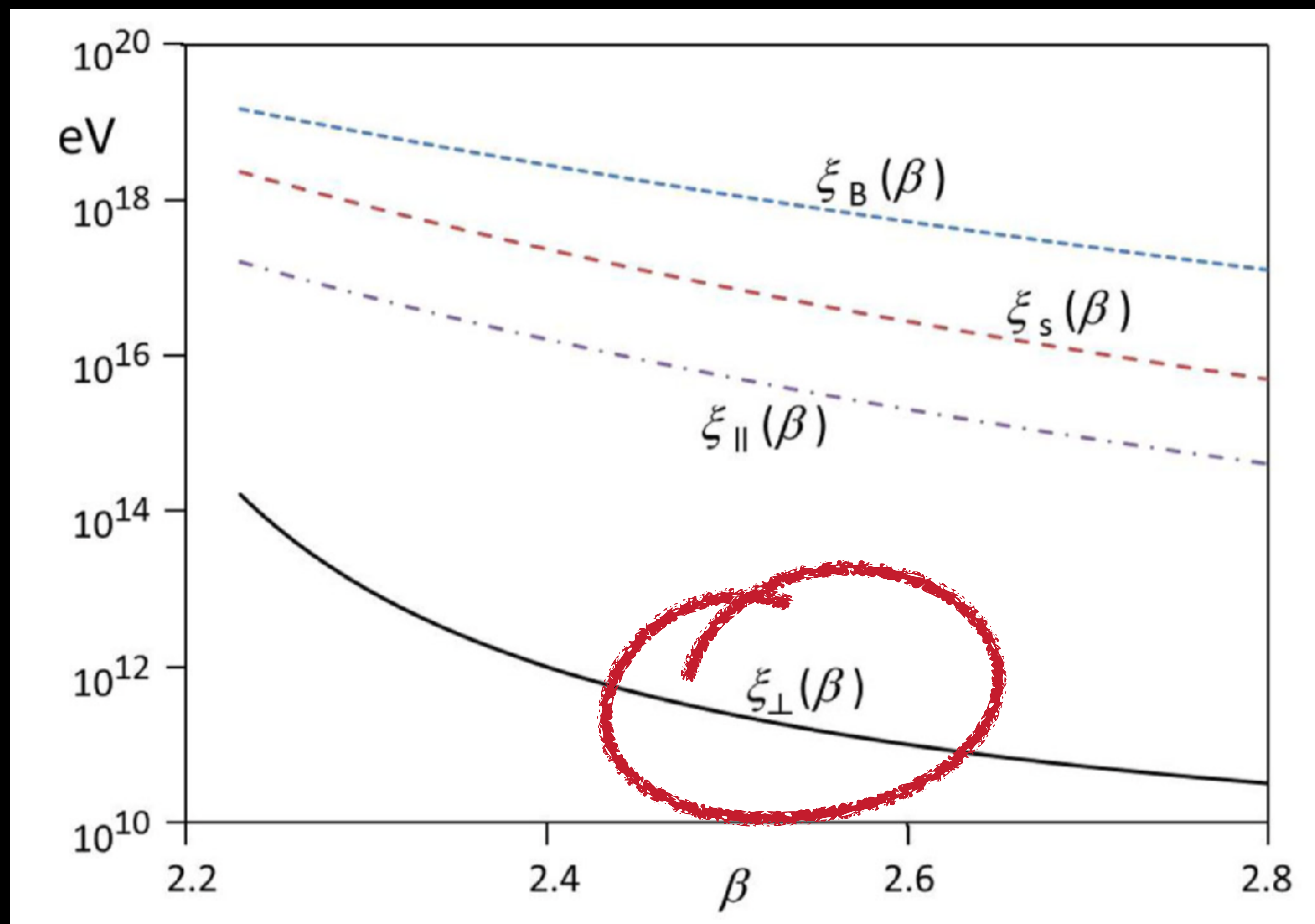
Observational support in Cygnus A
(Araudo+ 2018)

Relativistic shocks are problematic

> 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

Bell+2018

Shock and B-field physics

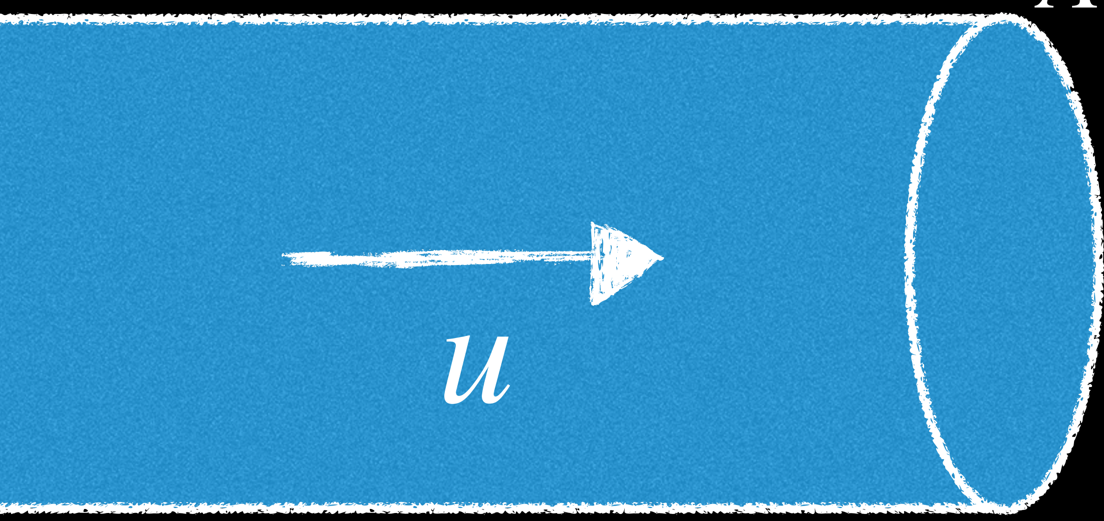


Steeper energy spectra

"Goldilocks shocks?"

Power Requirement (Hillas-Lovelace Limit)

$$A = \pi R^2$$



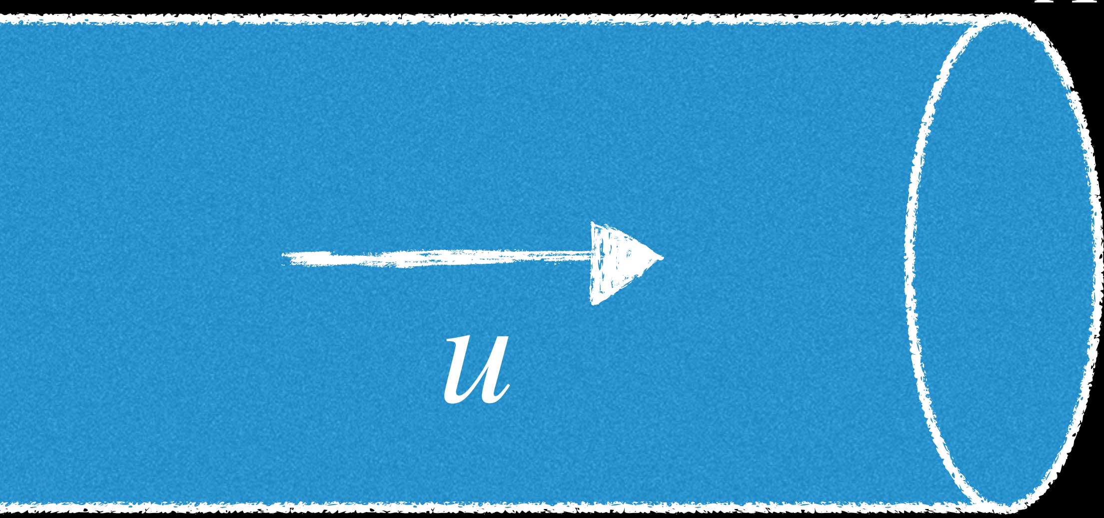
$$Q_B \sim \frac{B^2}{\mu_0} u \pi R^2$$

$$E_H = ZuBR$$

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

Power Requirement (Hillas-Lovelace Limit)

$A = \pi R^2$



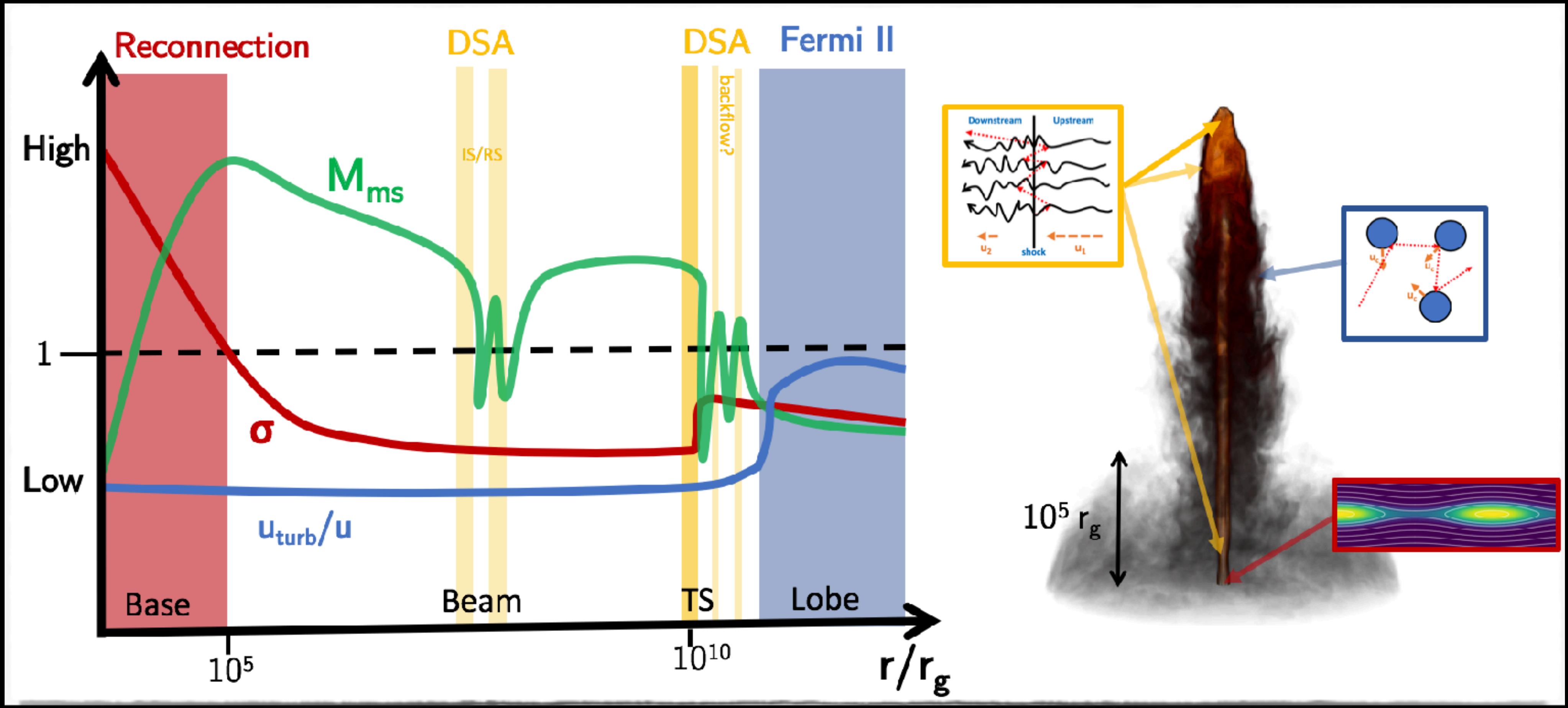
Assume kinetic power higher than magnetic power $Q_B \sim \epsilon Q_k$

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

‘Schematic Physics’

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

In jets, which mechanisms operate where?



What sets the maximum particle energy?

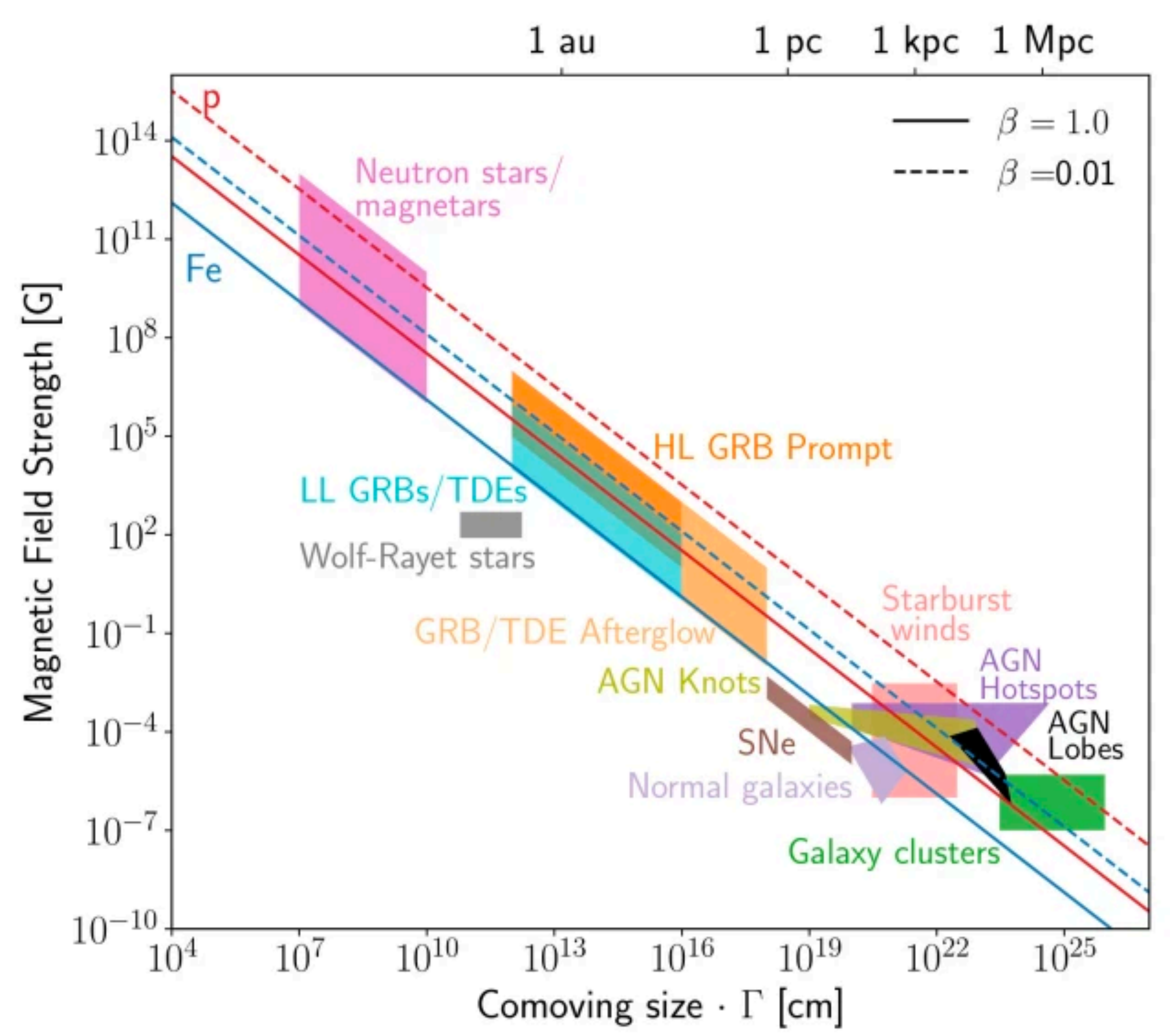
UHECR Checklist

- Hillas energy $$E_H = ZuBR$$ ☐
- Non-relativistic shocks $$u < f_{\rm crit} c$$ ☐
- Enough powerful sources $$Q_k \gtrsim 10^{43} \left(\frac{E/Z}{10^{19}{\rm eV}}\right)^2 \left(\frac{u}{c}\right)^{-1} \ {\rm erg \ s^{-1}}$$ ☐
- Powerful sources within “horizons” (e.g. GZK) ☐

UHECR Sources

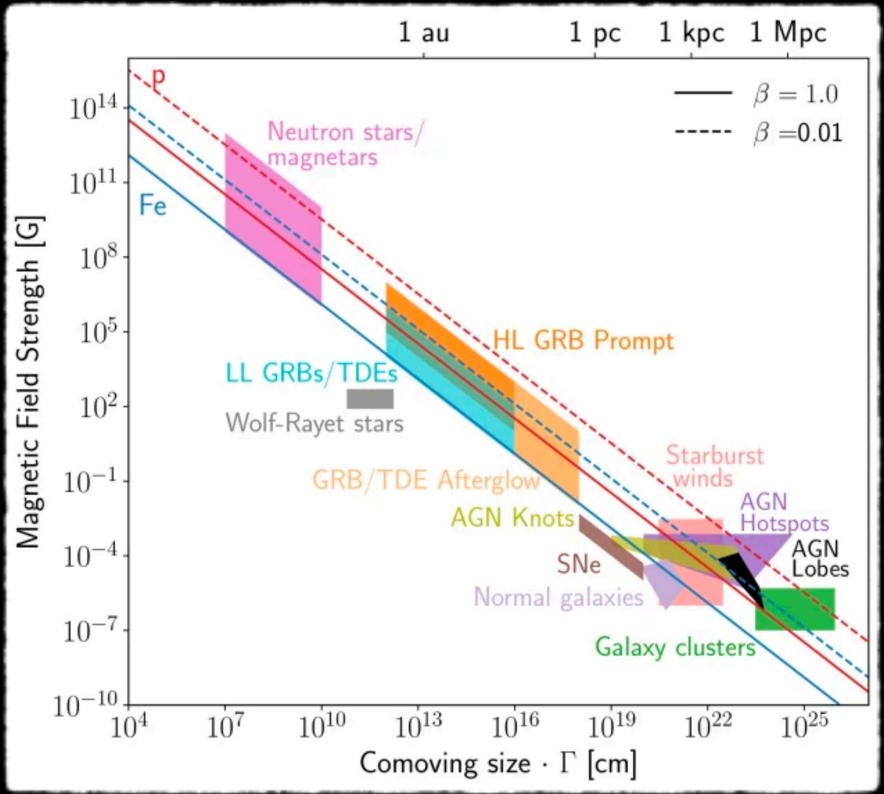
“Hillas Plot” (Hillas 1984)

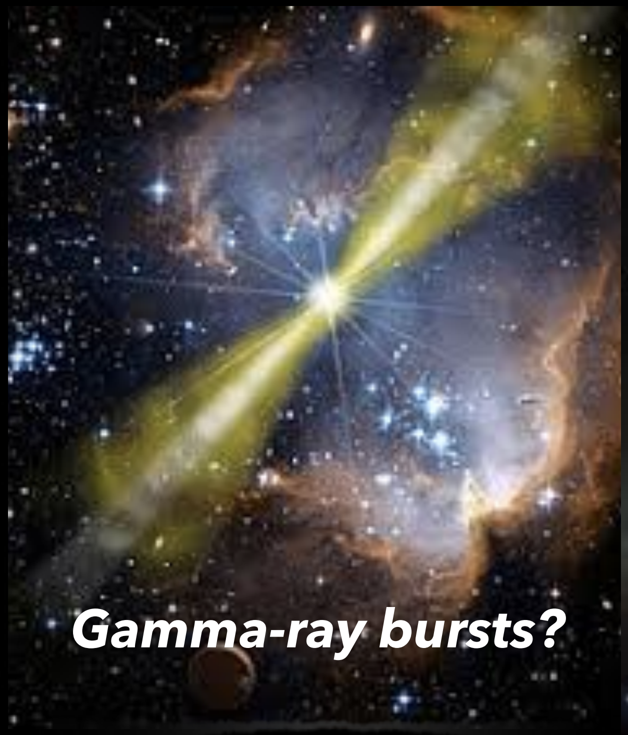
Update from Bustamente

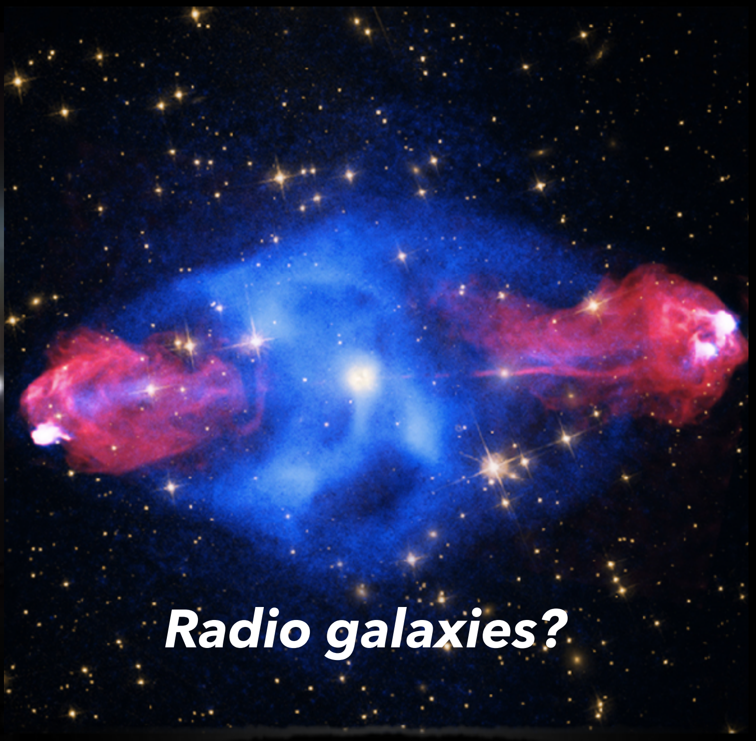


Getting to ultrahigh energies

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

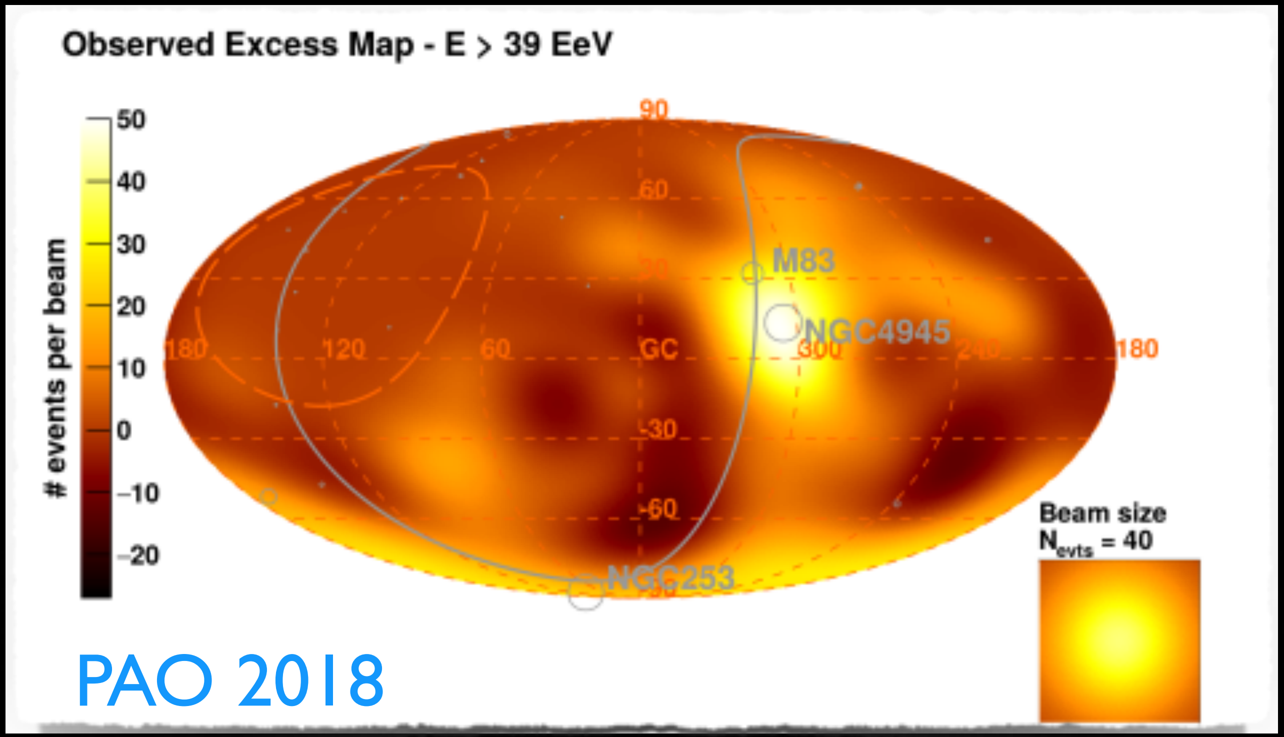






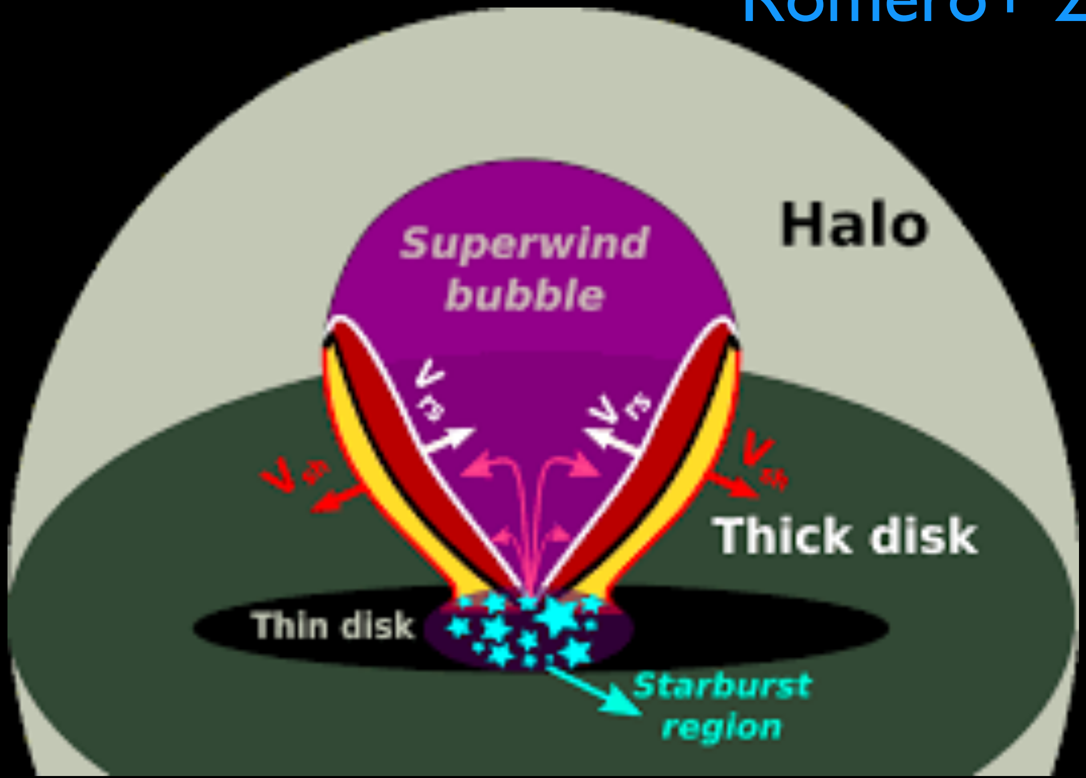
Starburst winds

- 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)
- but…power and velocity of wind way too low (see e.g. Romero+ 2018, Matthews+ 2018)
- *More or less ruled out on energetic grounds for highest energies*



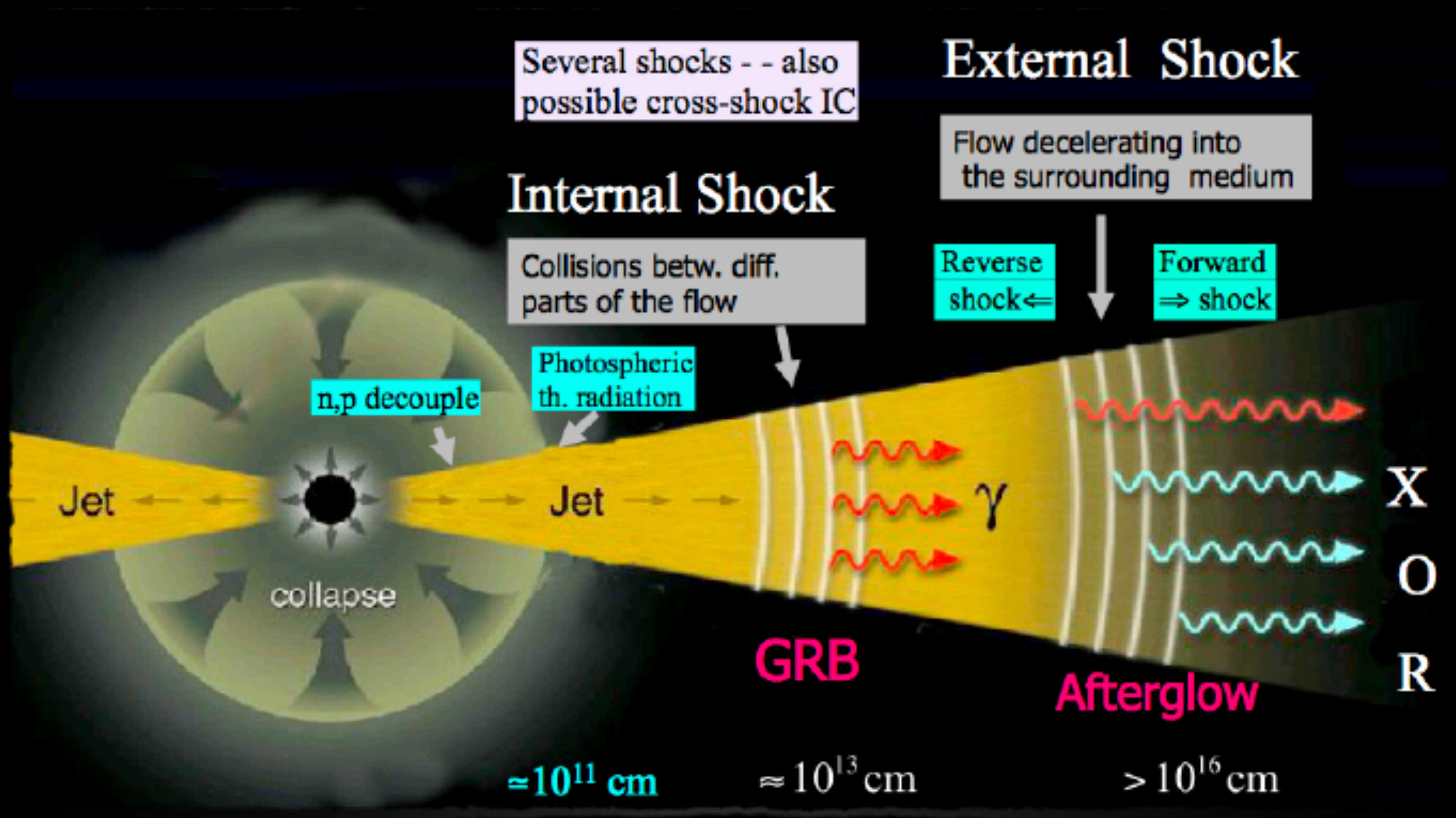
PAO 2018

Romero+ 2018



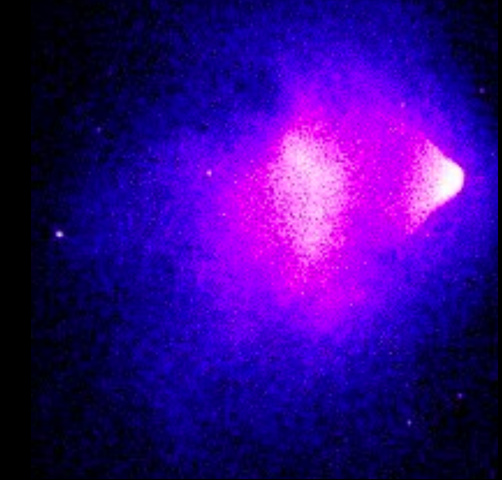
Gamma Ray Bursts

- 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)



Meszaros 2001,2015

Cluster Shocks



- Recent suggestion from TA that correlation with Perseus cluster observed (TA
- Cluster shocks are large (~Mpc) and have been proposed as UHECR (Kang, Blandford, Globus)
- Slow velocities means they only just reach the require energies
- Can acceleration to UHEs proceed in weak slow shocks?
- Hierarchical scheme with reacceleration of seed CRs?

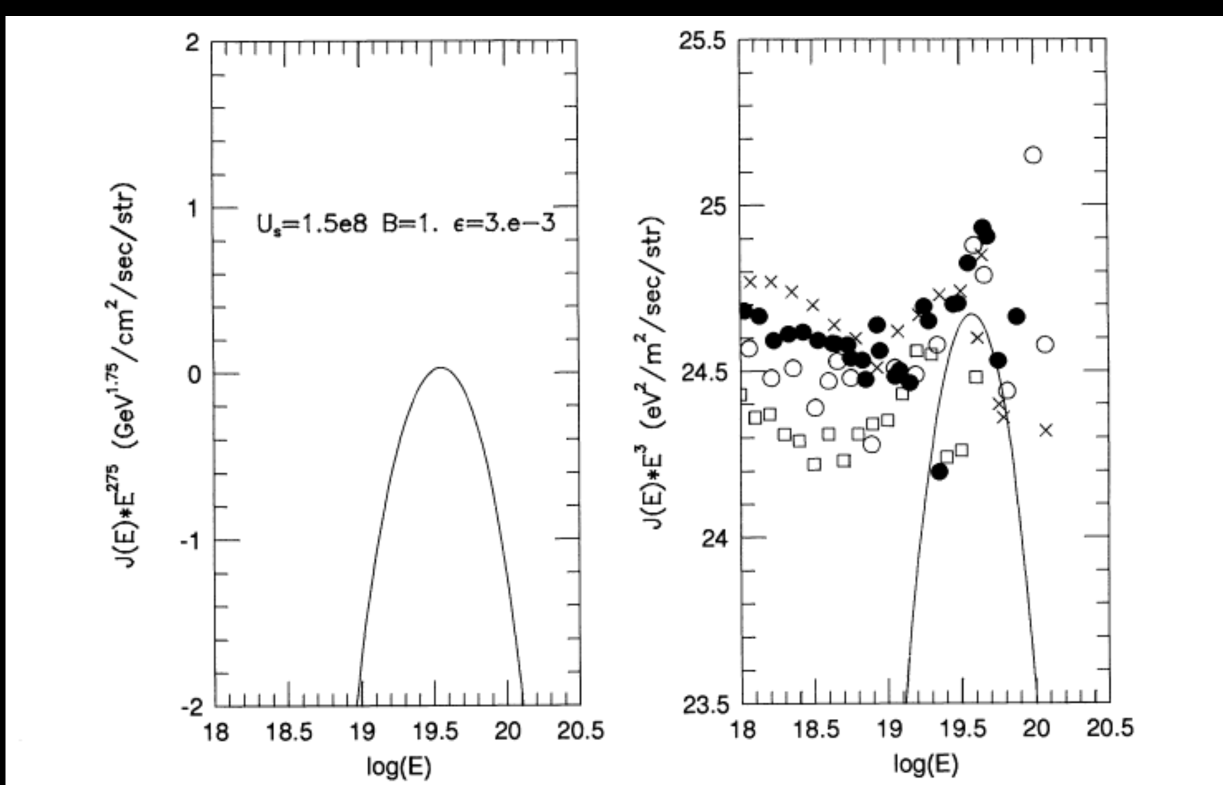
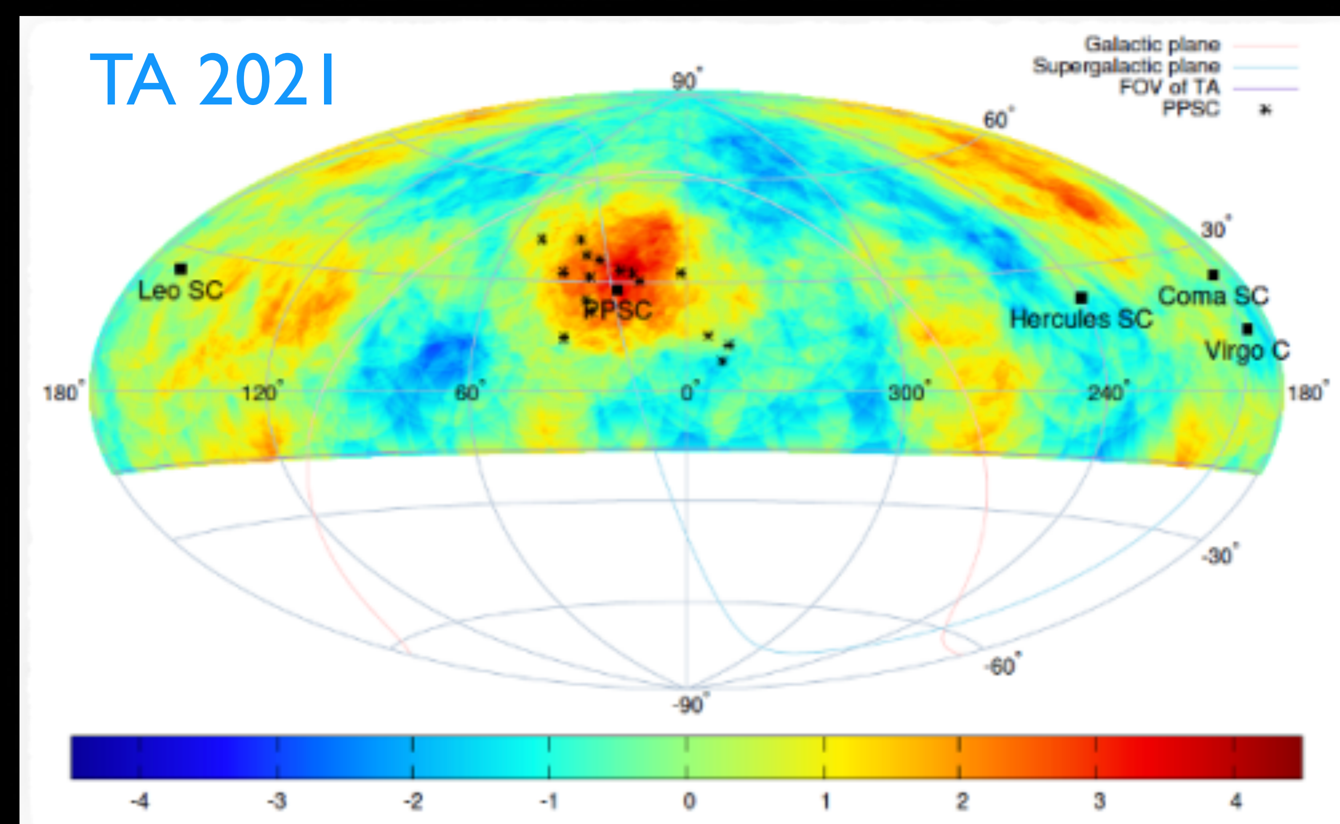
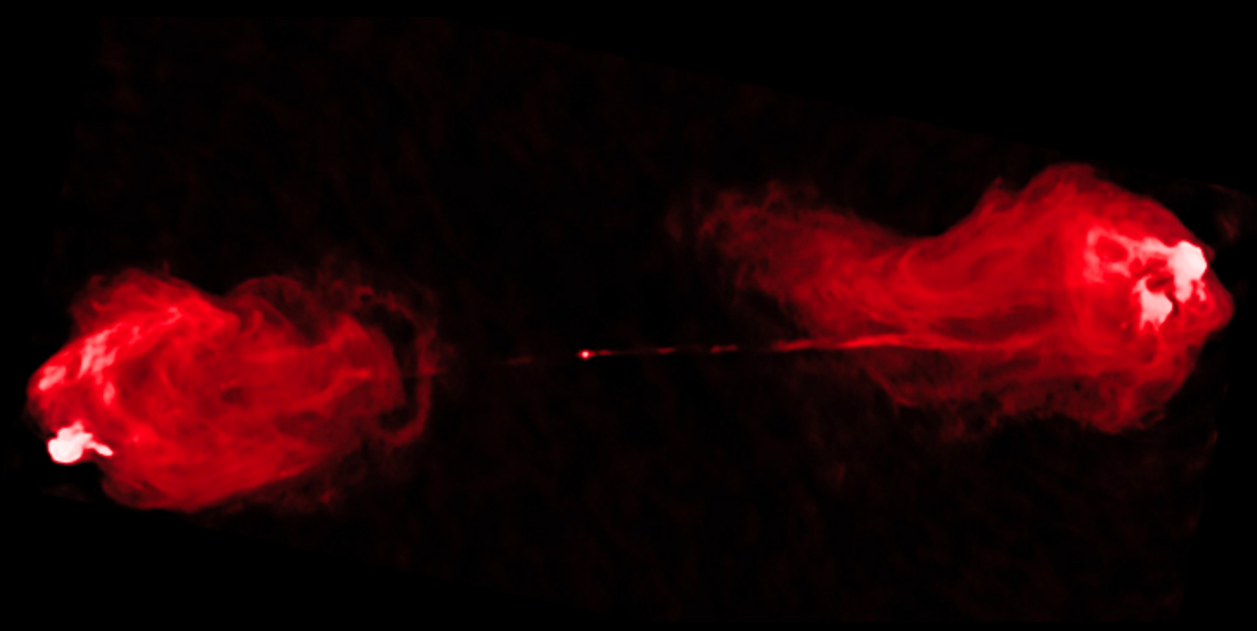


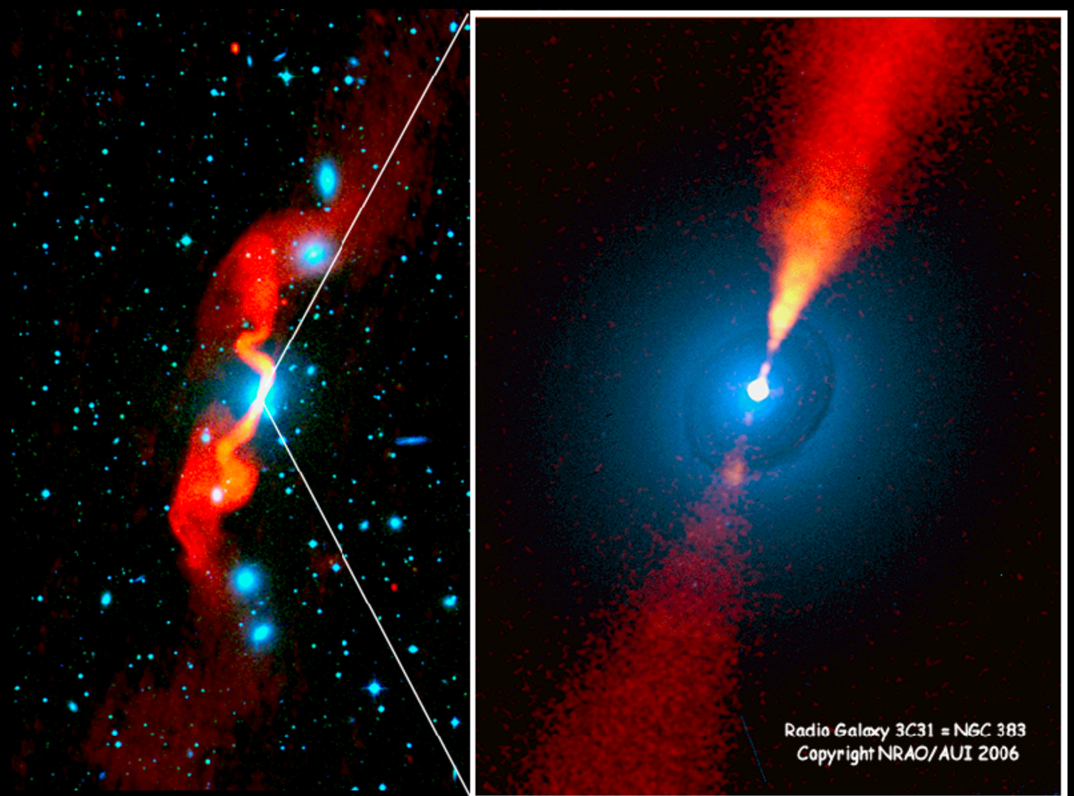
FIG. 2.—Estimated proton flux from the Virgo Cluster assuming that the accretion shock speed is 1500 km s^{-1}, the magnetic field strength is 1 μG, and $3 \times 10^{-3} \rho_{crit} u_s^2$ is transferred into CR energy density. The observed points (*cross*: Fly's Eye; *filled circles*: Akeno; *open circles*: Havera Park; *open squares*: Yakutsk) in the $J(E)E^3$ plot are taken from Teshima (1993).

Kang+ 1996



Radio galaxies





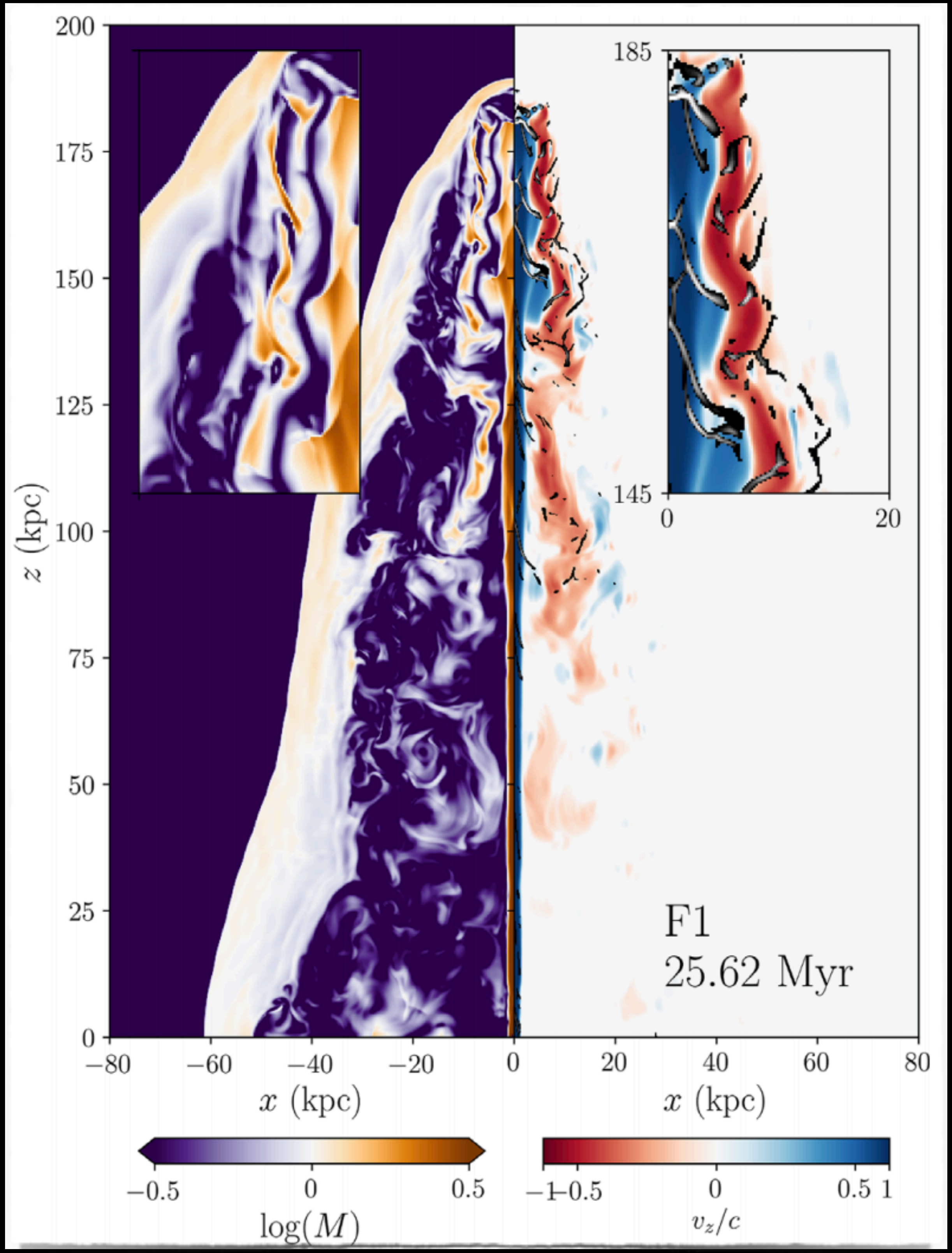
- Giant (kpc to Mpc) jets from AGN that produce lobes or cocoons of radio emitting plasma
- Two main morphologies – FRII, left, and lower power FRIs, right.
- Obvious UHECR candidates, since they are **big** and **fast**- See e.g. Hillas 1984, Norman+ 1995, Hardcastle 2010, but also many, many others!
- However - relativistic hotspots don't appear to reach high enough energies (Araudo+ 2015, 2016, 2018)
- *Basic idea: search for non-relativistic shocks that have high enough Hillas energy!*

Matthews+ 2019a,b

Jet simulations

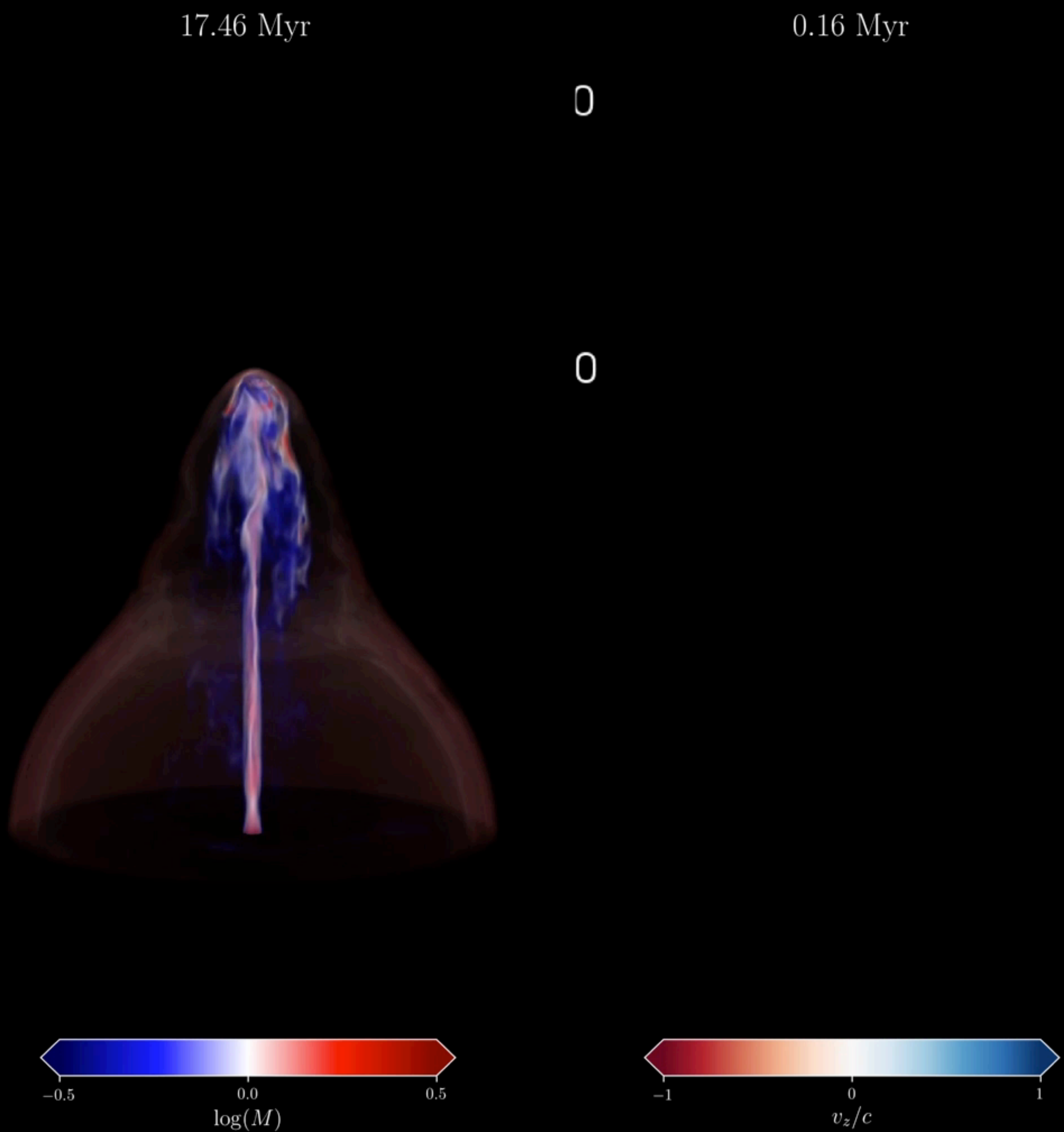
- We conducted relativistic hydro sims of light jets in a cluster
  - 2D and 3D, using PLUTO (Mignone+ 2007)
- Jets produce strong, supersonic *backflow* -> shocks
- Compression structures and pressure jumps seen
- Observed in other simulations (e.g. Saxton+ 2002, Reynolds+ 2002, Mignone+ 2009)

Mach number Vertical velocity



Jets in 3D

http://jhmatthews.github.io/uhecr-movies



Matthews+ 2019

UHECR Checklist (Radio galaxies)

- Hillas energy

$$E_H = ZuBR$$

- Non-relativistic shocks

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

- Enough powerful sources

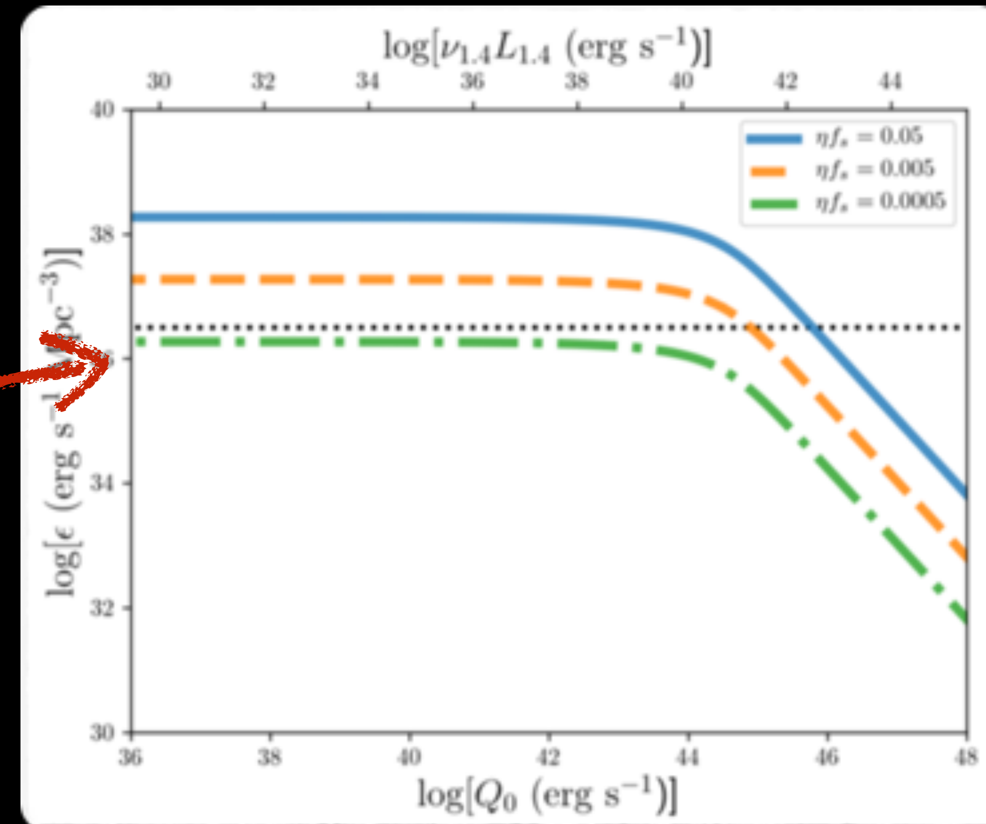
$$Q_k \gtrsim 10^{43} \left(\frac{E/Z}{10^{19}\mathrm{eV}} \right)^2 \left(\frac{u}{c} \right)^{-1} \ \mathrm{erg\ s^{-1}}$$

- Powerful sources within “horizons”

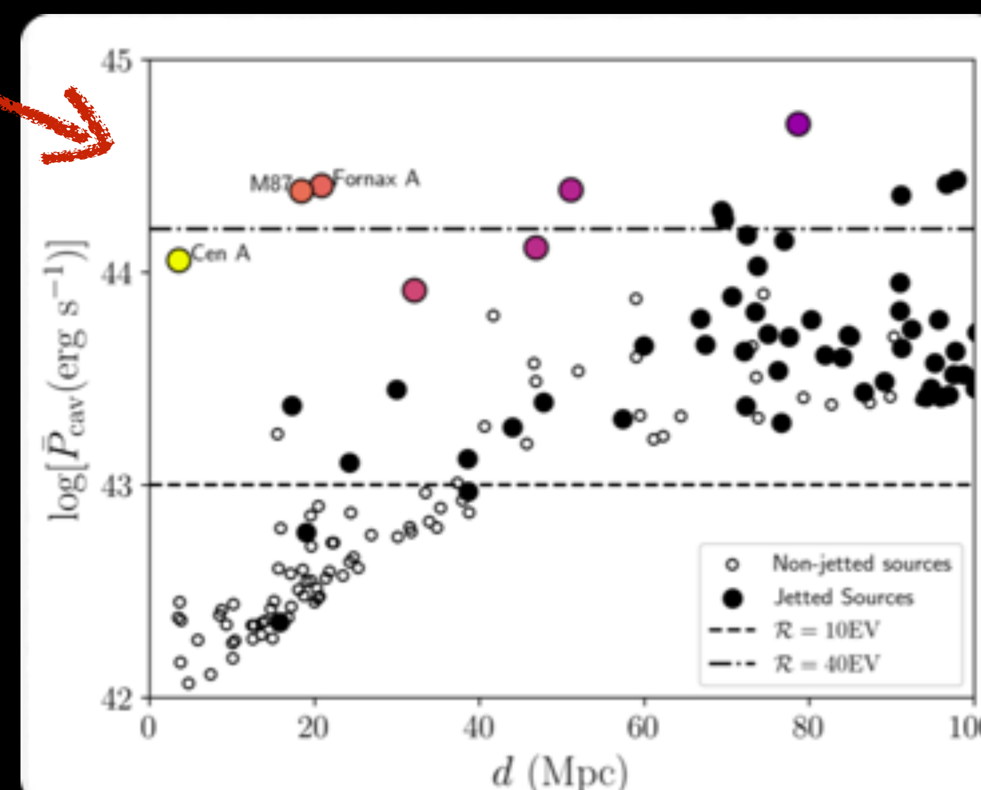
Matthews+ 2018, 2019

Are there enough powerful sources?

- Powerful RGs are on average common and energetic enough



- But, barely any currently active sources within GZK horizon powerful enough



- Are the sources variable / intermittent?

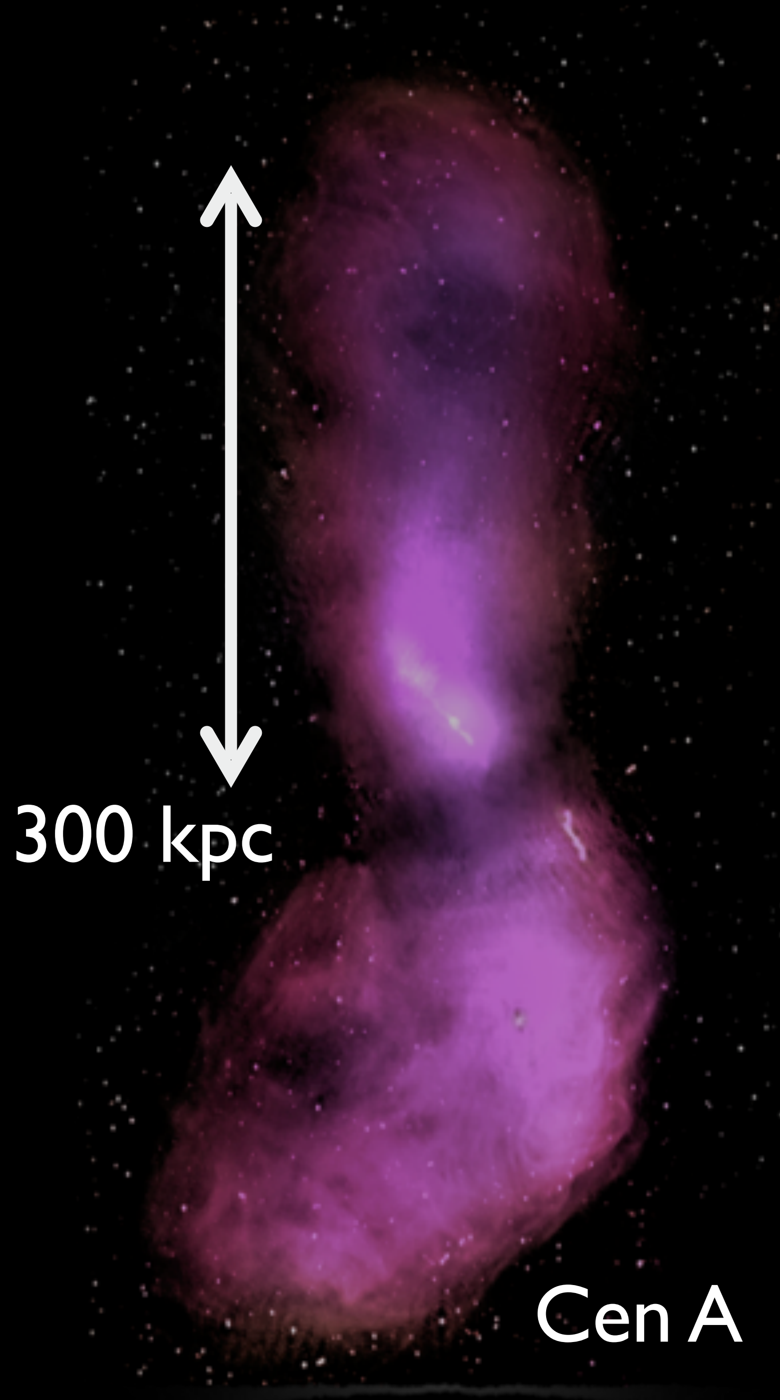
UHECR Checklist

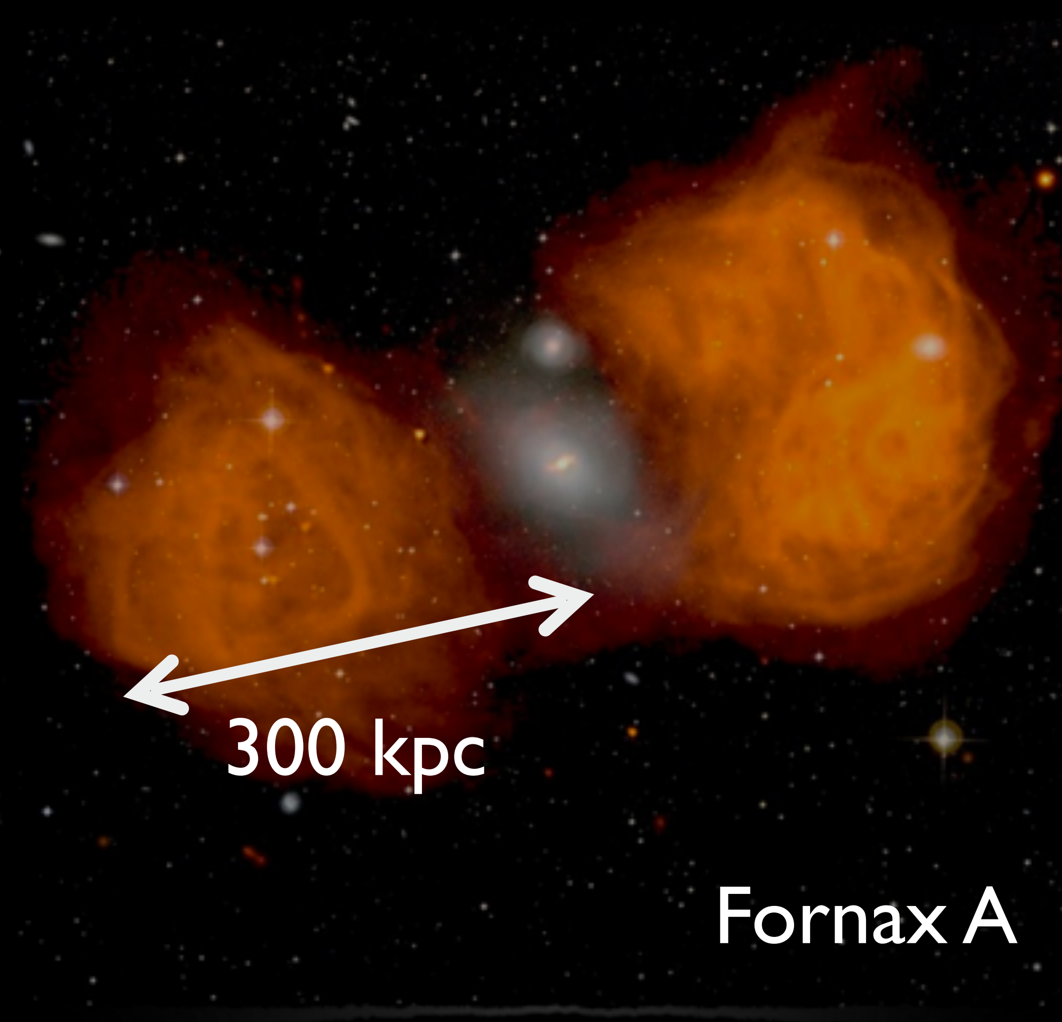
- Hillas energy $$E_H = ZuBR$$
- Non-relativistic shocks $$u < f_{\mathrm{crit}} c$$
- Enough powerful sources $$Q_k \gtrsim 10^{43} \left(\frac{E/Z}{10^{19}\mathrm{eV}} \right)^2 \left(\frac{u}{c} \right)^{-1} \mathrm{erg\ s^{-1}}$$
- Powerful sources within "horizons"

Matthews+ 2018

Dormant Radio Sources?

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





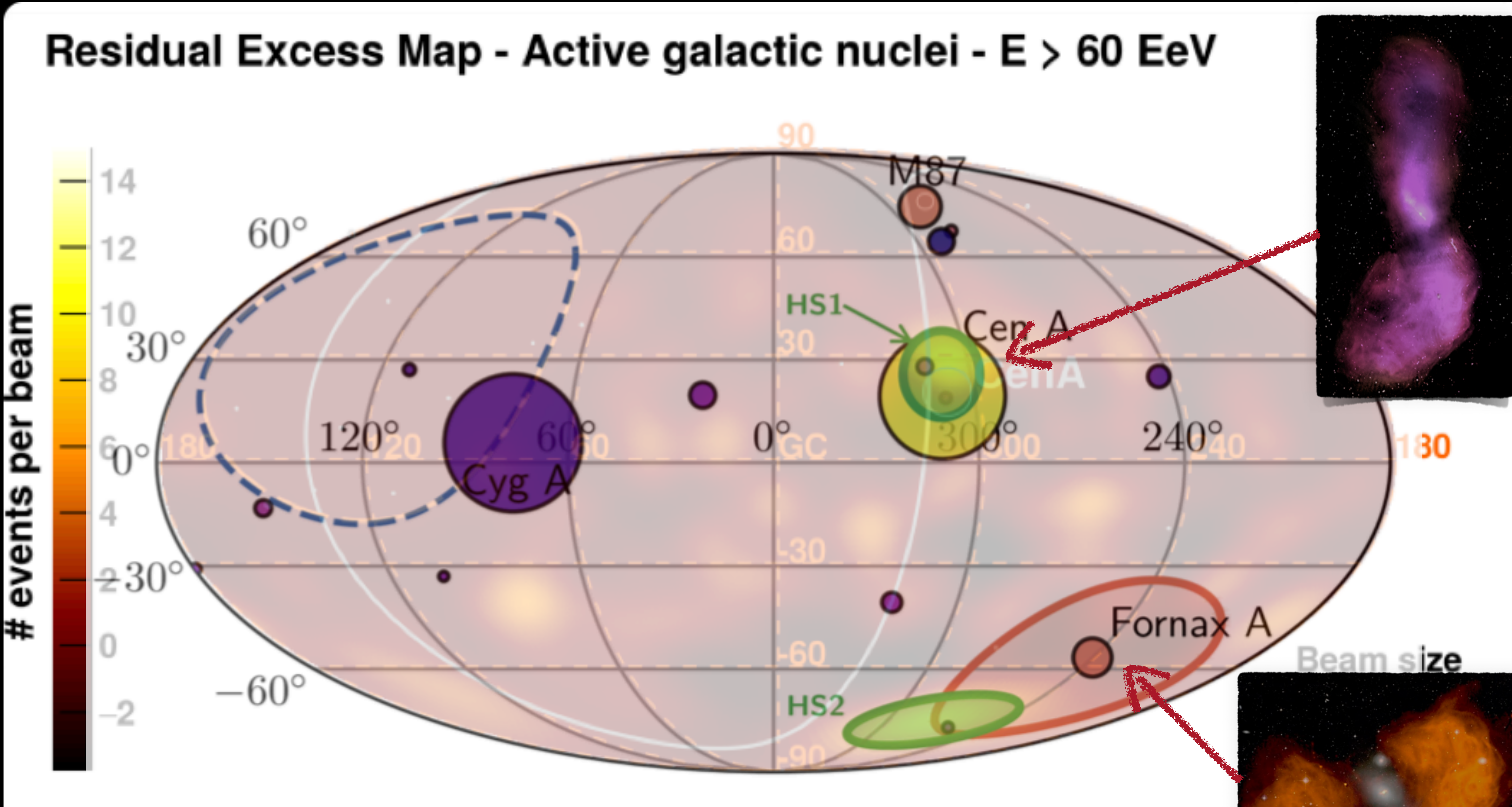
Low-power jets

- 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!

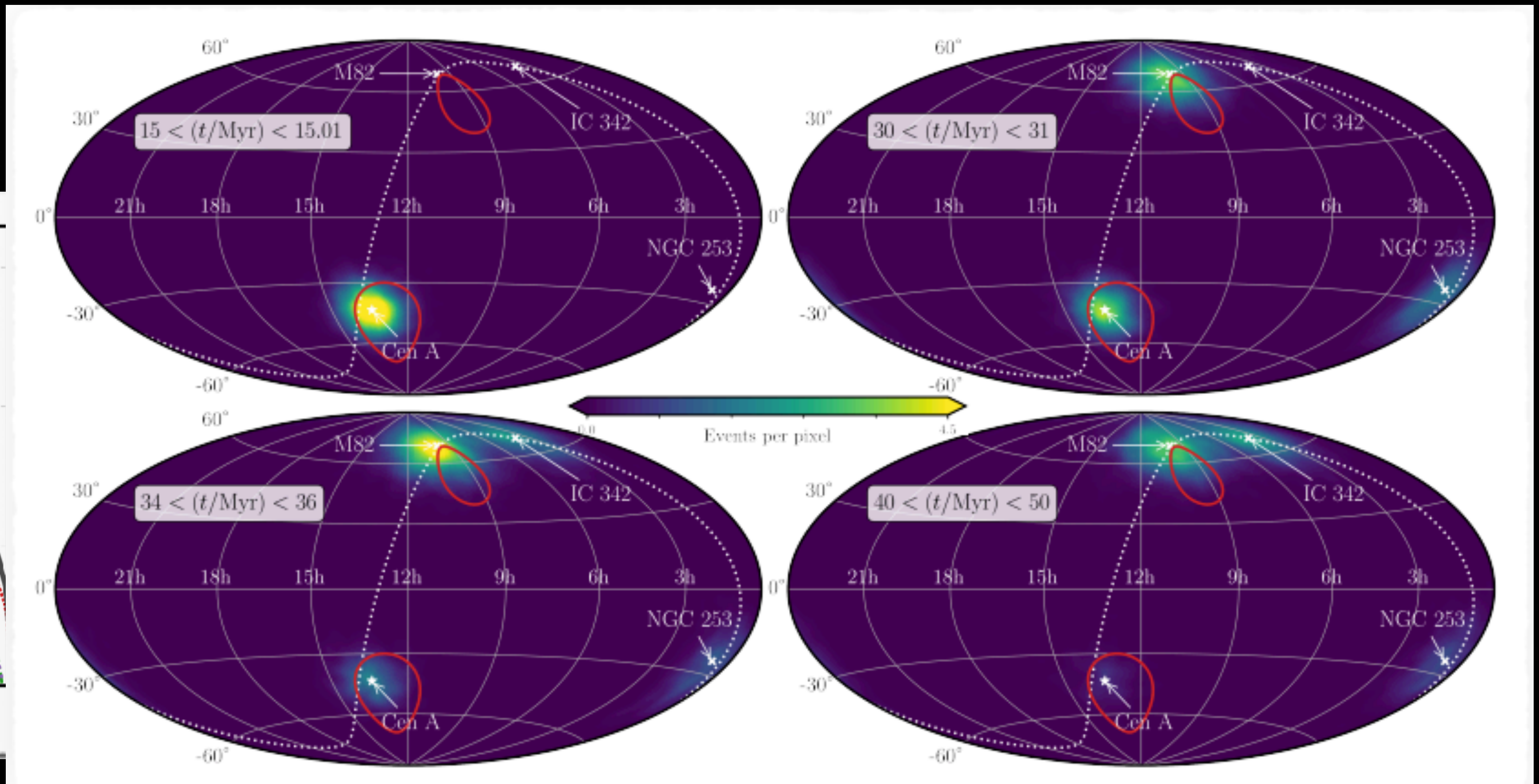


Fornax A offset from southern excess by 22.5 degrees

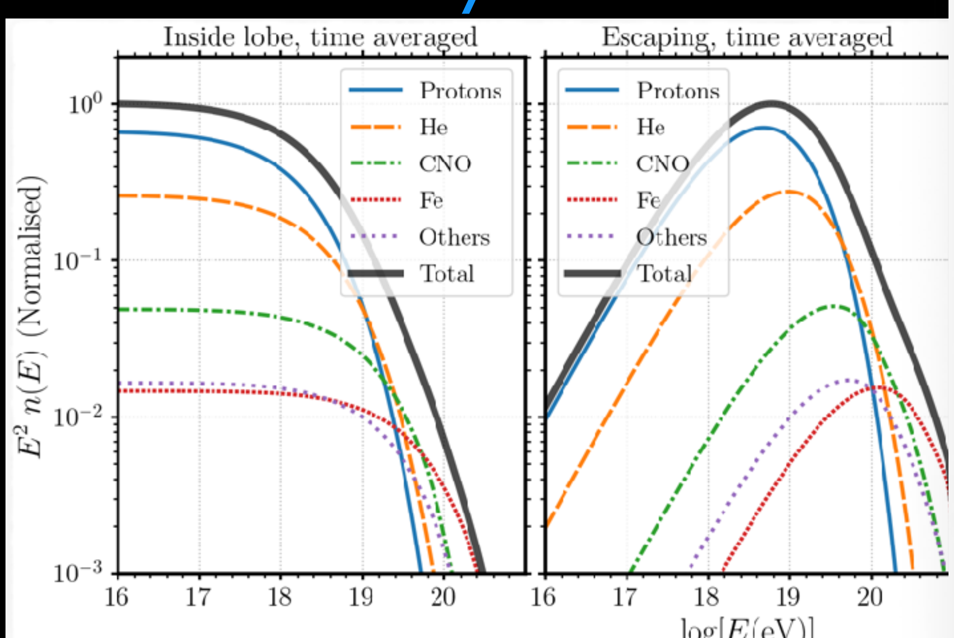
UHECR Echoes from the past

- Time variability important in determing UHECR spectrum and luminosity (e.g. Matthews & Taylor 2021)
- New idea: Cen A was 100x more luminous than it is know 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

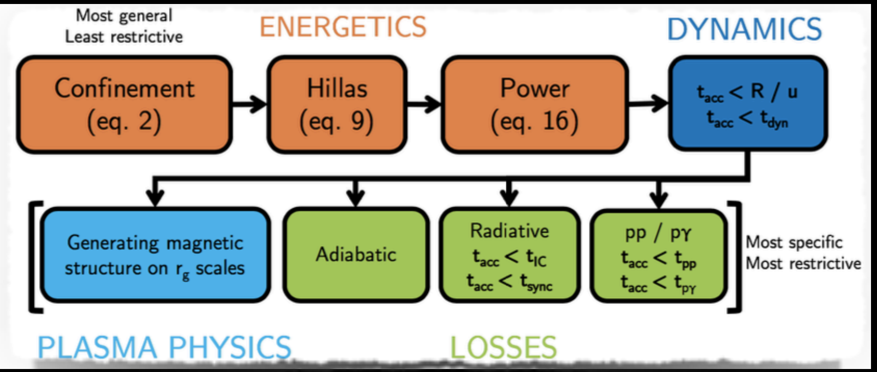
Bell & Matthews 2021



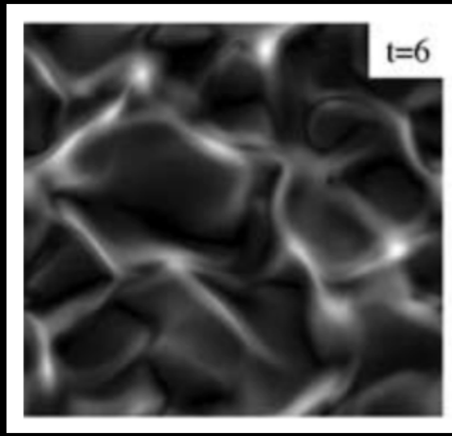
Matthews & Taylor 2021



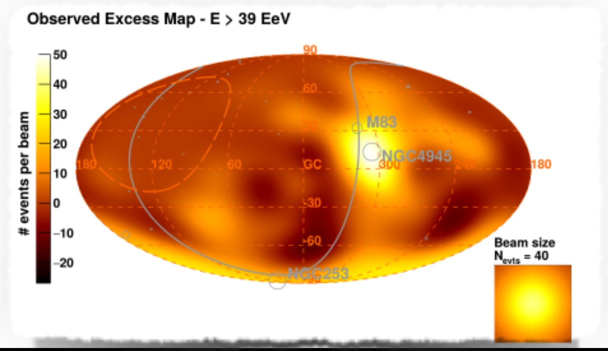
Summary



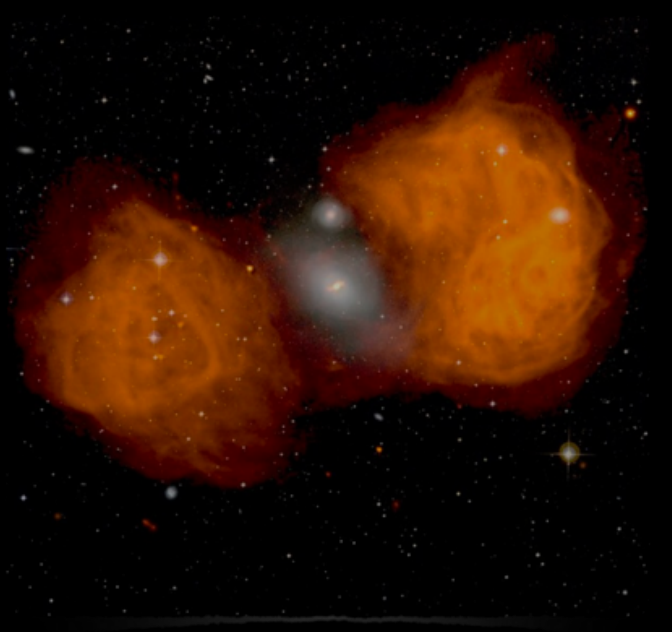
- Understanding UHECR origins is a perennial challenge



- Shocks and reconnection can both transfer energy to nonthermal particles and create power law particle distributions
- Simple back of envelope calculations can be used to identify potential UHECR sources
- The maximum CR energy is limited by a variety of factors - self-regulating acceleration process must be carefully considered



- UHECRs may be produced in the backflows of radio galaxies where the shock velocity is non-relativistic
  - Compelling associations between Cen A and Fornax A and UHECR excesses, variability critical



Main references:

Jets Review: Matthews+ 2020, New Astronomy Reviews, 89, 101543

Matthews+ 2018, MNLett, 479, 76

Matthews+ 2019, MNRAS, 482, 4303

Matthews & Taylor 2021, MNRAS, 503, 5948

Bell & Matthews, submitted, arXiv: 2108.080879