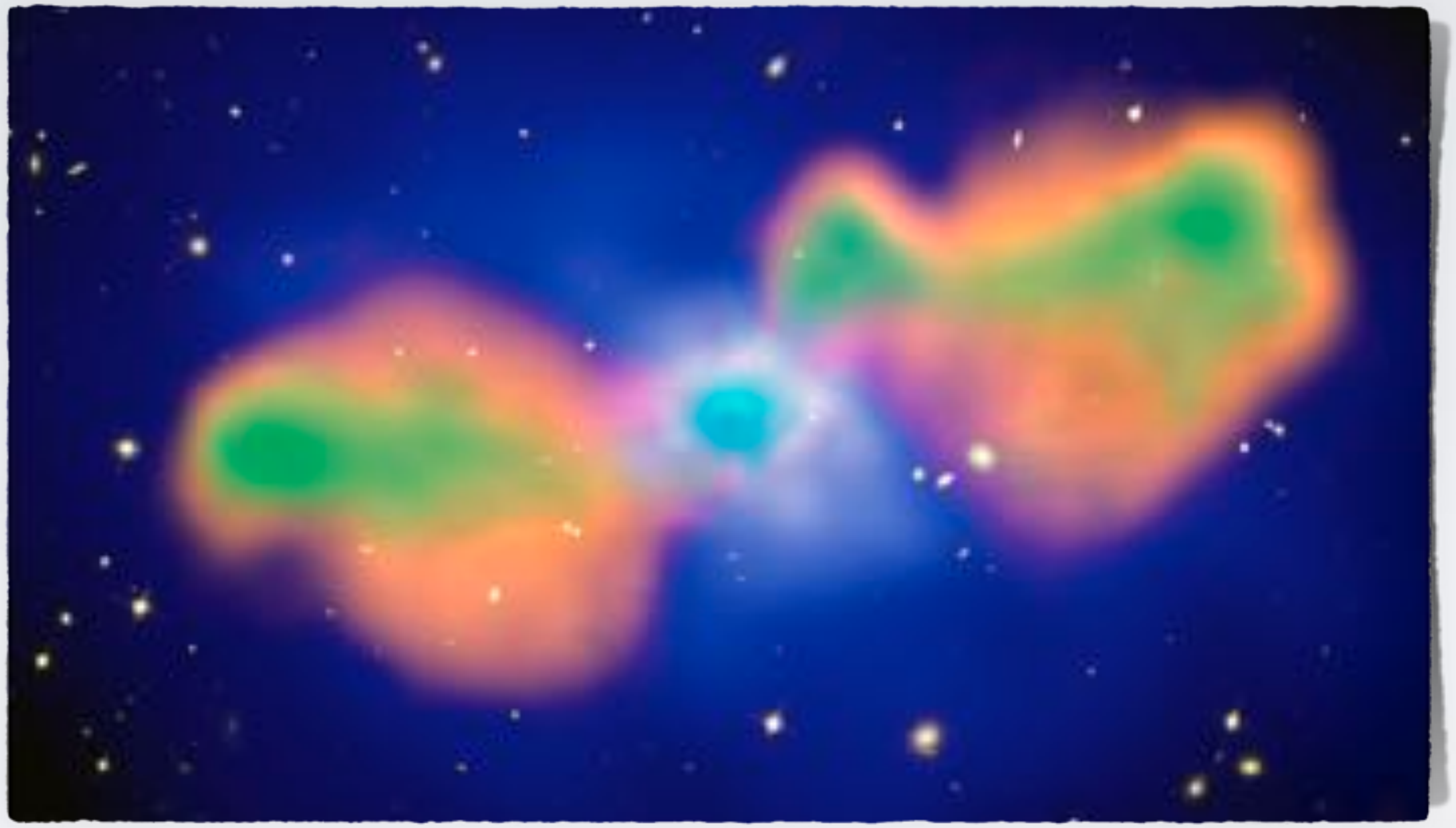
PARTICLE ACCELERATION AND THE HIGHEST ENERGY COSMIC RAYS



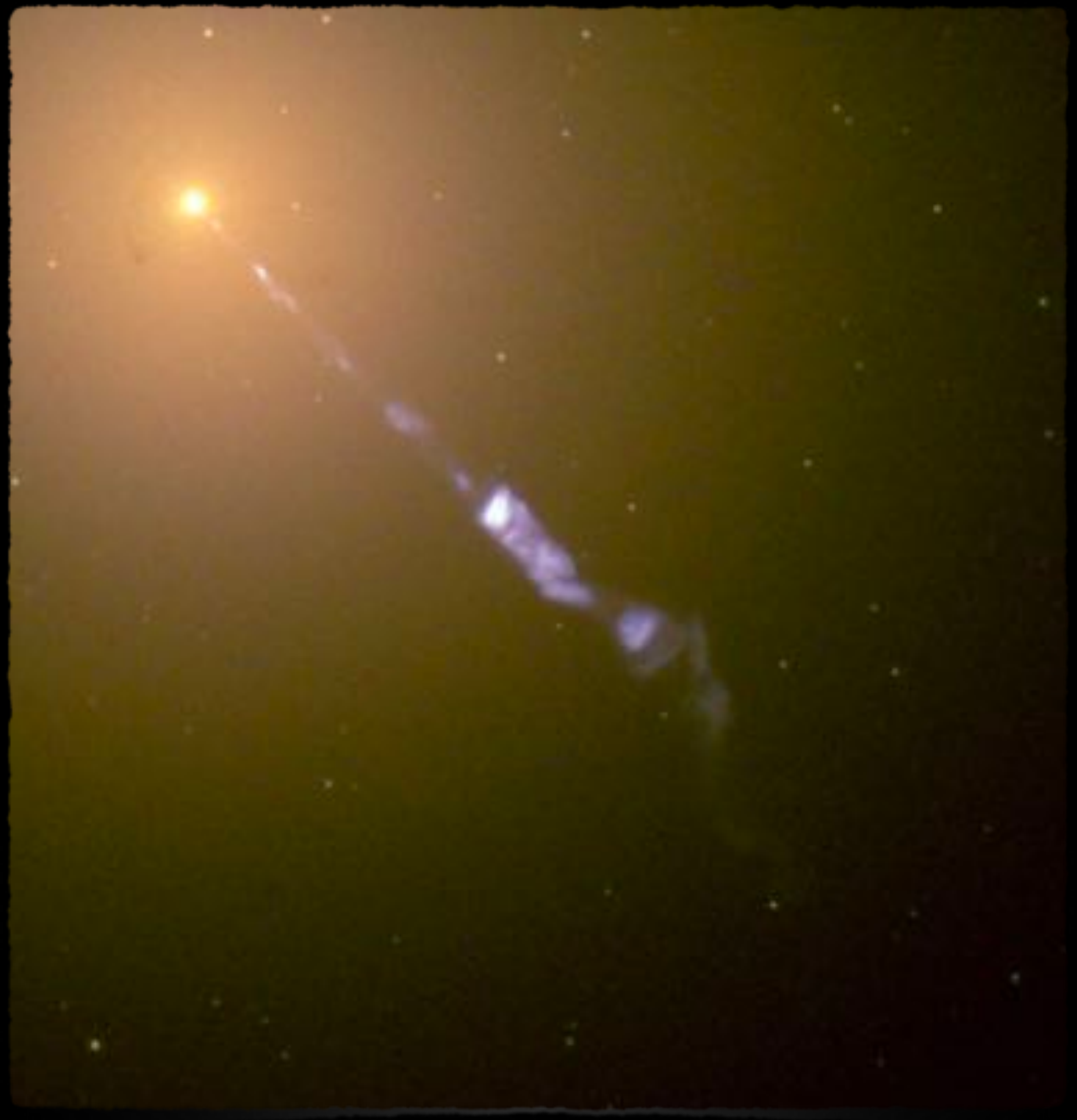
James Matthews
Grad Lecture, 21 Nov 2023

UNIVERSITY OF OXFORD

THE ROYAL SOCIETY

TWO 100-YEAR OLD PHYSICS PROBLEMS...

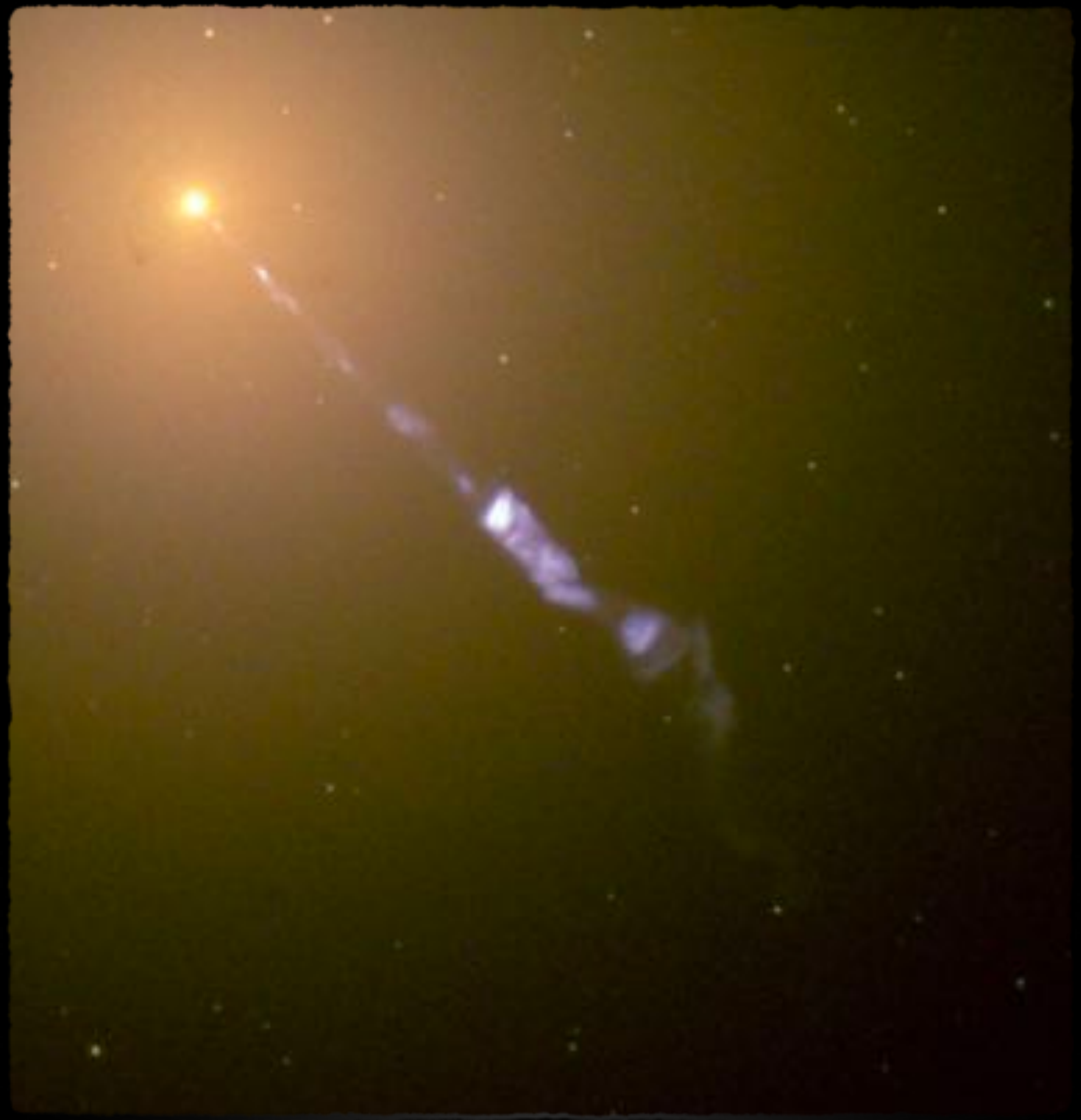
Discovery of cosmic rays
(Hess 1912)



Discovery of M87 jet
(Curtis1918)

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."

OUTLINE

1. Some key concepts

2. Motivation:

    i) Ultrahigh energy cosmic rays (UHECRs)

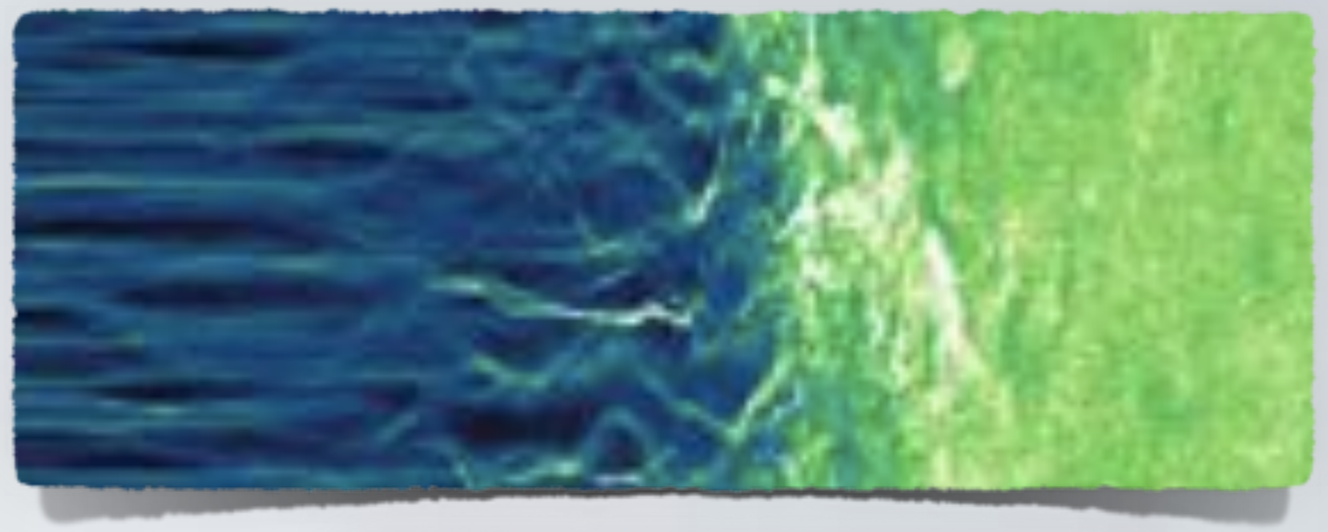
    ii) Radio observations of jets

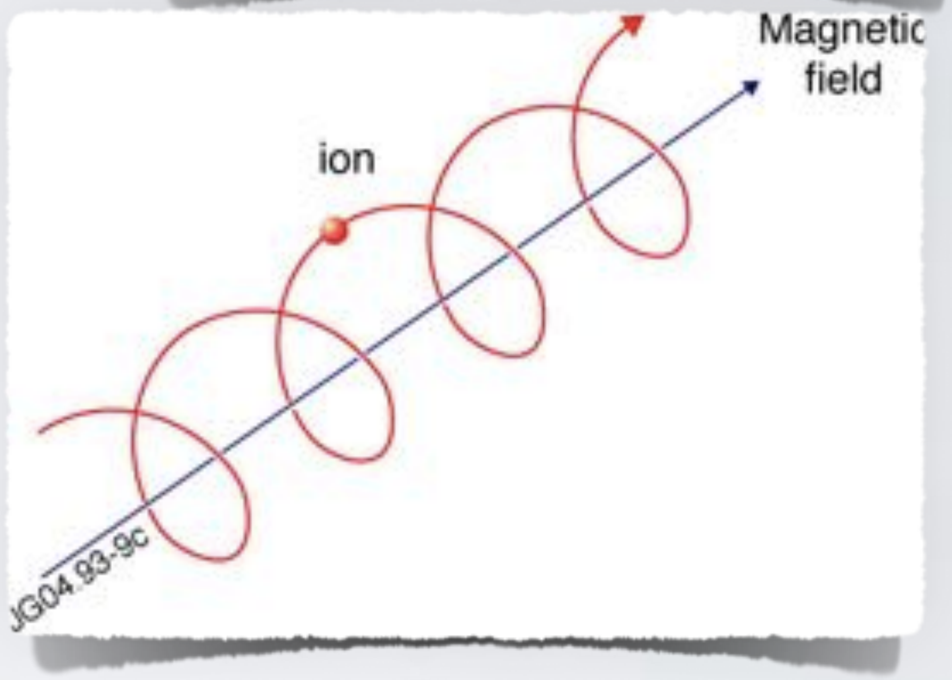
3. Particle acceleration physics

4. Where do UHECRs come from?

5. If time: modelling of black hole jets

Some Key Concepts





- **Collisionless plasmas**
  - Mean free path to Coulomb collisions > system size. Particle interactions are mediated by plasma waves
- **Shock**
  - Disturbance that propagates faster than the local speed of sound, leading to a discontinuous jump in T, P, ϱ.
- **Gyro/Larmor radius**
  - Radius of gyration of a charge particle in a magnetic field:
- **Electric fields**
  - Generally, electrostatic fields are hard to maintain in astrophysical settings, so E=-u x B

$$\frac{d}{dt}(\gamma m\vec{v}_p) = e(\vec{\mathcal{E}} + \vec{v}_p \times \vec{B})$$

$$-\vec{u} \times \vec{B}$$

Collisionality

Coulomb mean free path in, e.g., clusters:

$$\lambda_c \sim 23\ \mathrm{kpc}\ \left(\frac{T}{10^8\ \mathrm{K}}\right)^2 \left(\frac{n_e}{10^{-3}}\right)^{-1}$$

Phase	Volume Fraction	Mass Fraction	N (cm^{-3})	T (K)	c_s ($\times 10^5$ cm s^{-1})
Molecular Clouds	0.005	0.4	1000	10–30	0.6
Diffuse Clouds	0.05	0.4	100	80	0.9
Intercloud Medium	0.4	0.2	1	8000	9
Coronal Gas	0.5	0.001	0.001	10^6	100

$\lambda_c \sim 7$ m
$\lambda_c \sim 5$ km
$\lambda_c \sim 5$ million km
$\lambda_c \sim 2$ pc

COLLISIONALITY

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$$\lambda_c \sim 23\ \mathrm{kpc}\ \left(\frac{T}{10^8\ \mathrm{K}}\right)^2 \left(\frac{n_e}{10^{-3}}\right)^{-1}$$

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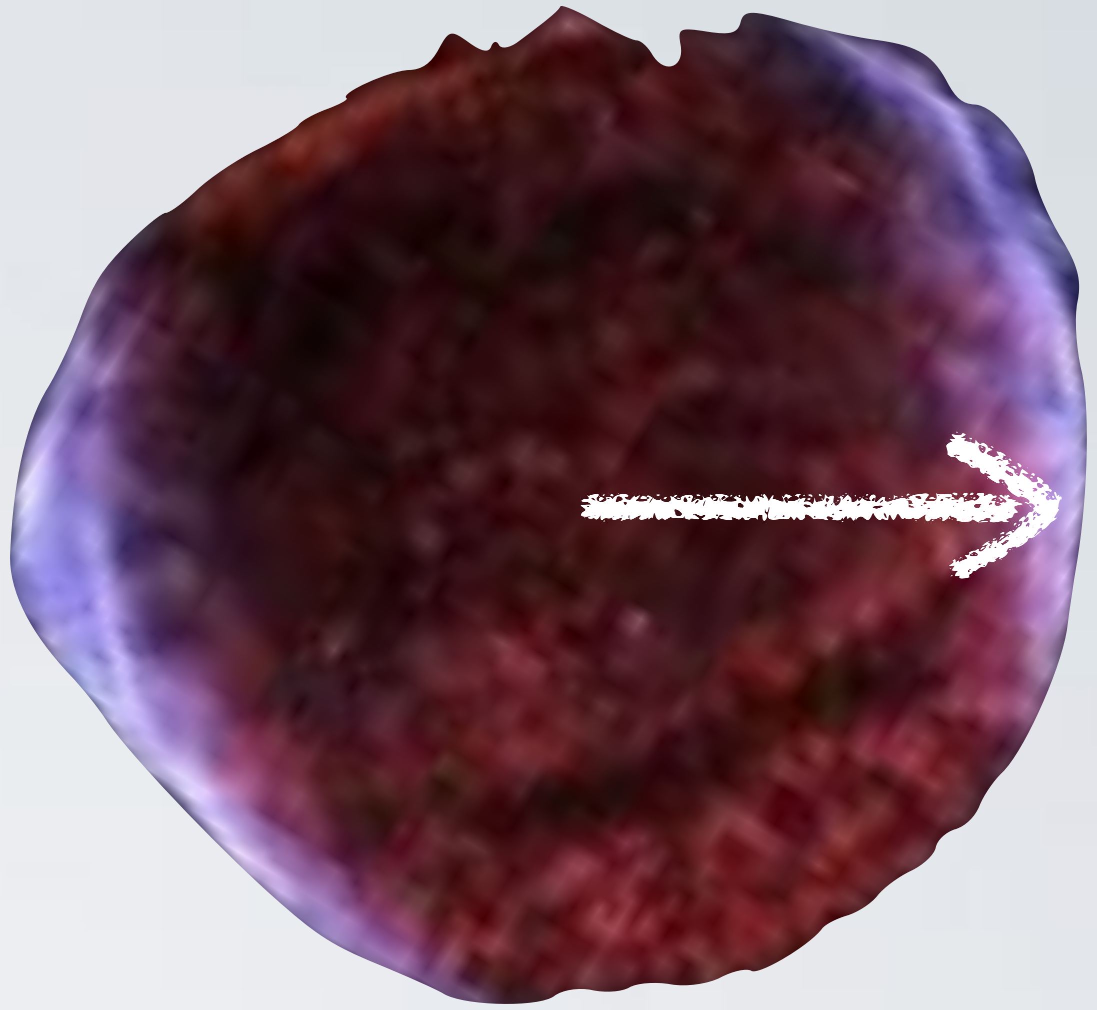
Molecular Clouds	0.005	0.4	1000	10–30	0.6	$\lambda_c \sim 7$ m
Diffuse Clouds	0.05	0.4	100	80	0.9	$\lambda_c \sim 5$ km
Intercloud Medium	0.4	0.2	1	8000	9	$\lambda_c \sim 5$ million km
Coronal Gas	0.5	0.001	0.001	10^6	100	$\lambda_c \sim 2$ pc

- Even if the length scale is smaller than system, it's still often larger than relevant microphysics (instabilities, gyro radius, 1/plasma frequency)
- Collisional plasmas will quickly redistribute any excess energy into a thermal distributions
- *Collisionless* shocks: particles can cross a shock many times more interesting as sites of particle acceleration

SHOCKS

- A shock is a disturbance that propagates faster than the local speed of sound
- "Ahead of the shock" the medium has no way of knowing what's about to hit it, so there is a discontinuity
- MHD equations permit this solution, results in big jump in pressure and density, corresponding drop in velocity (factor of 4 in high M shock)
- Shocks *dissipate* kinetic energy
- A "reverse" and "forward/external" double shock structure is common

Lab Frame



Shock frame

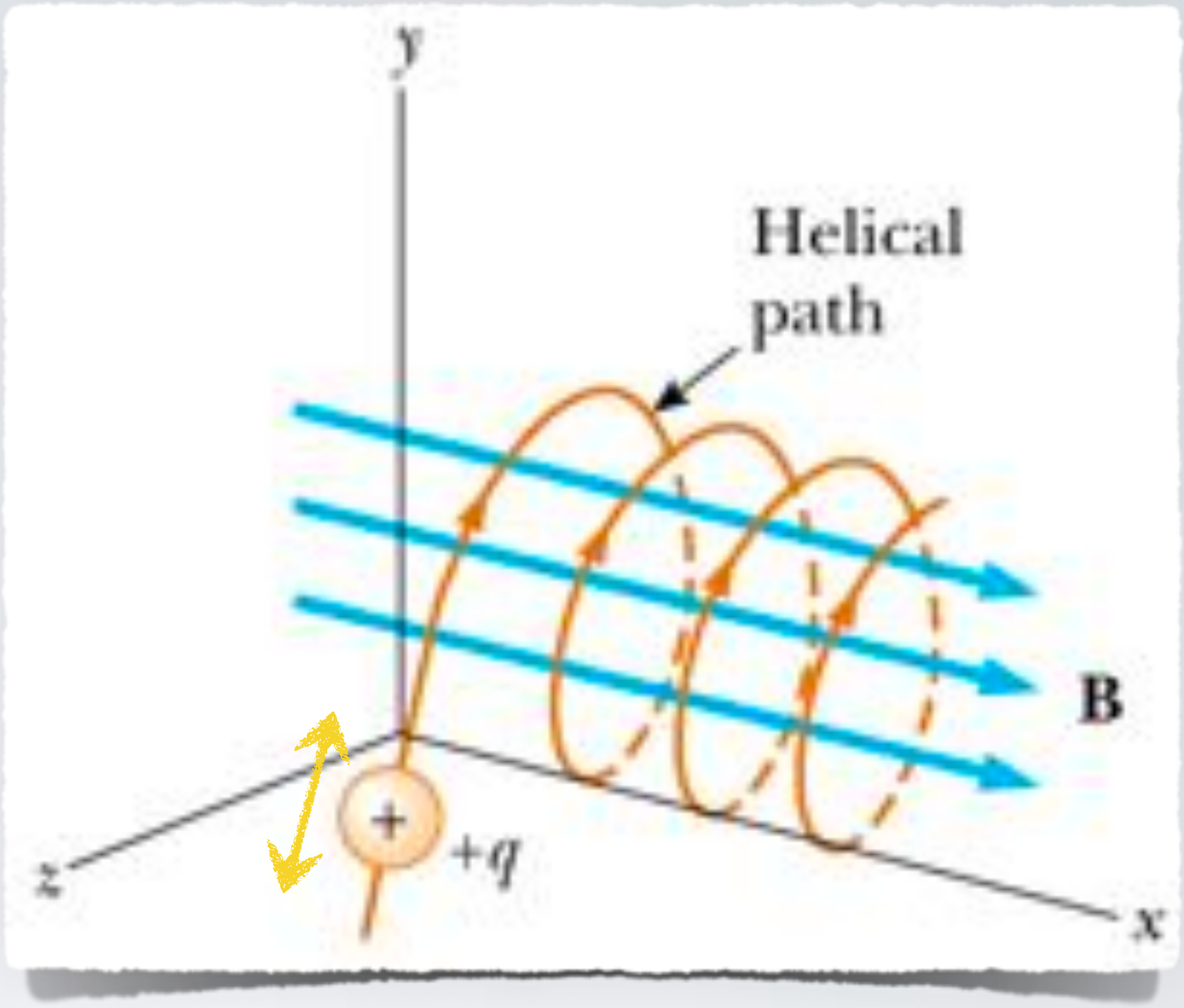
Shocked material	Unshocked ISM
$4\rho, u/4$	ρ, u
$\leftarrow$	$\longleftarrow$
Downstream	Upstream

THE LARMOR RADIUS OR GYRORADIUS

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

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

…so energetic particles gyrate in bigger cycles



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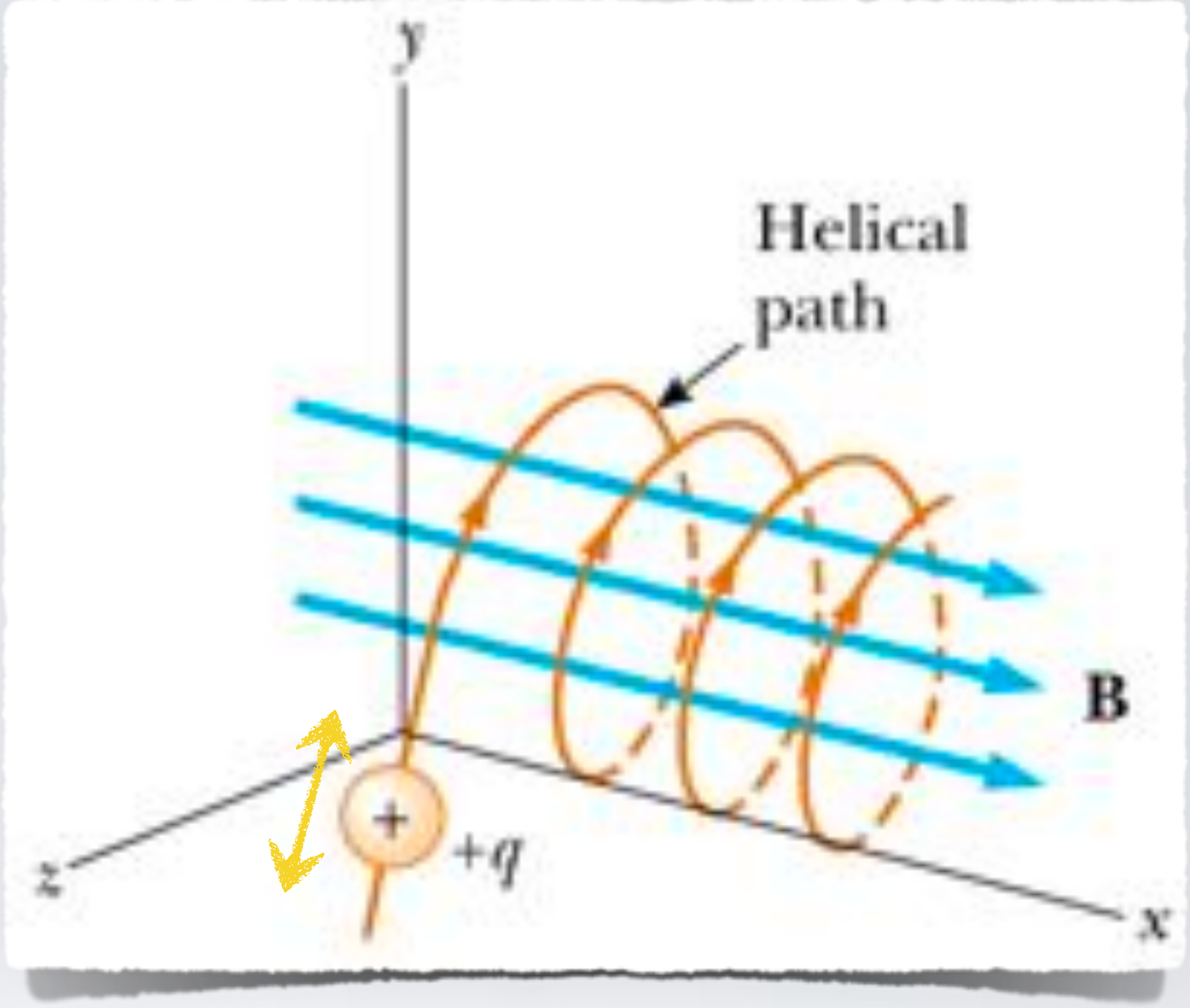
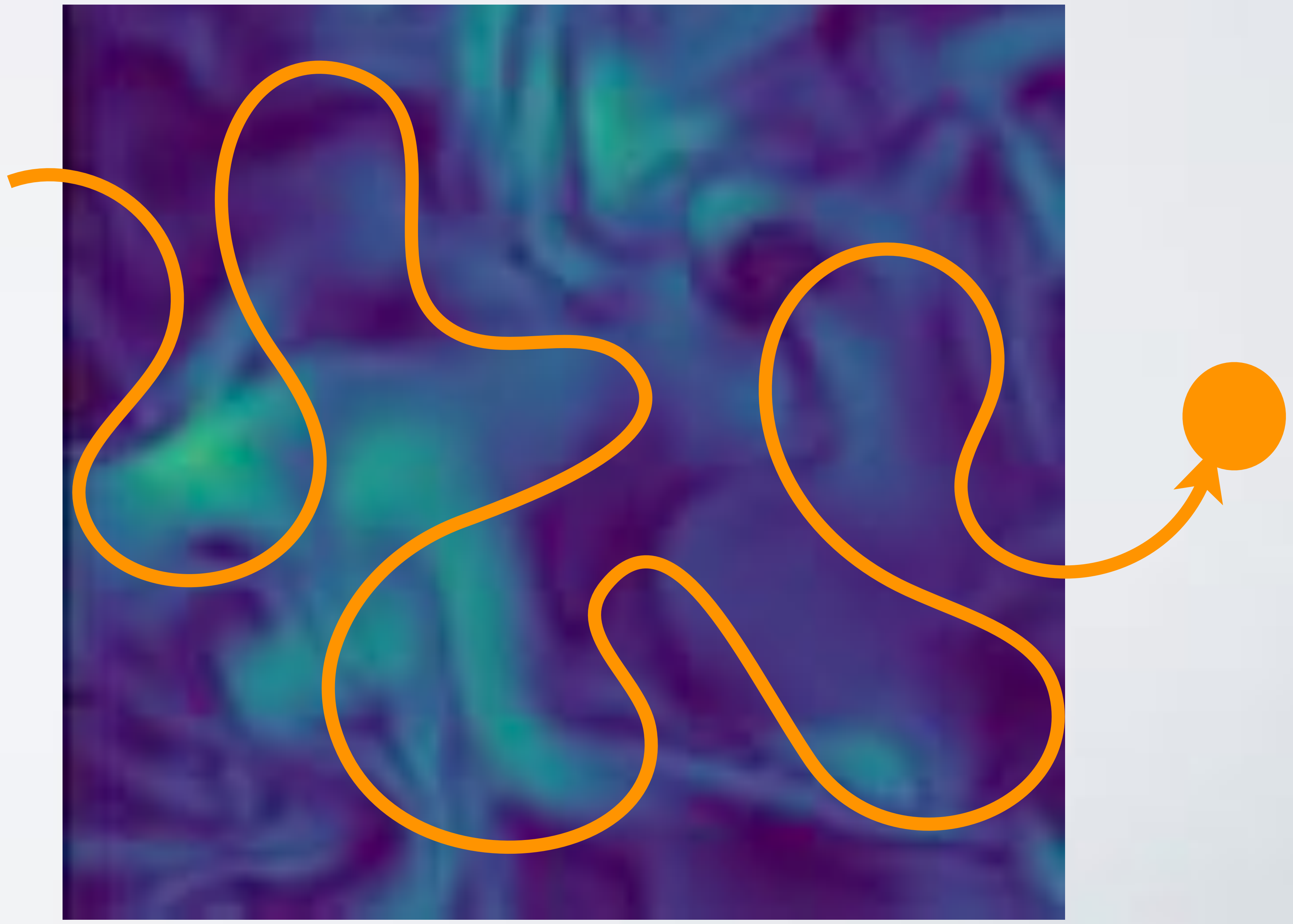


I'm going to talk about "scattering" and "diffusion" - what really happens:



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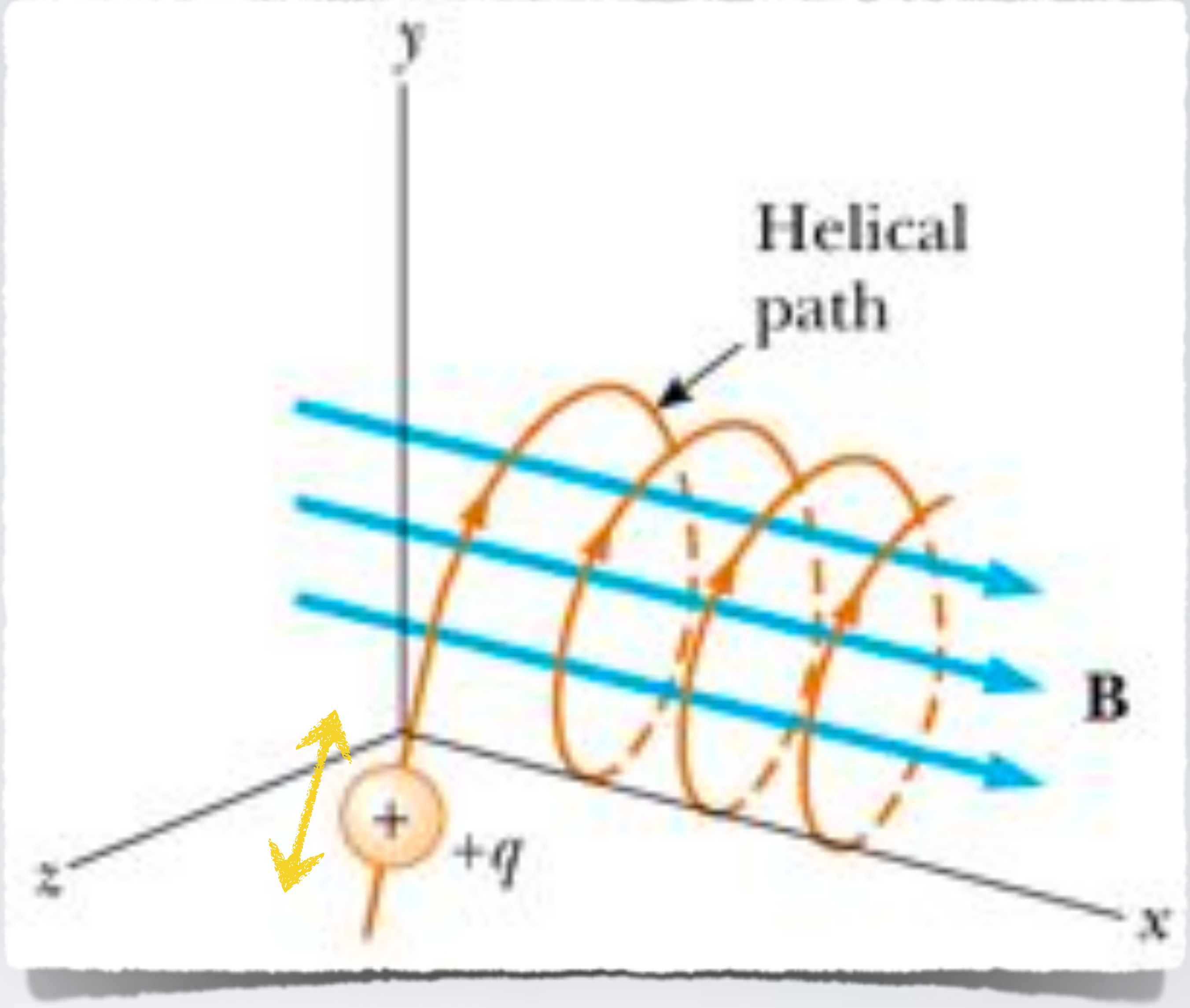
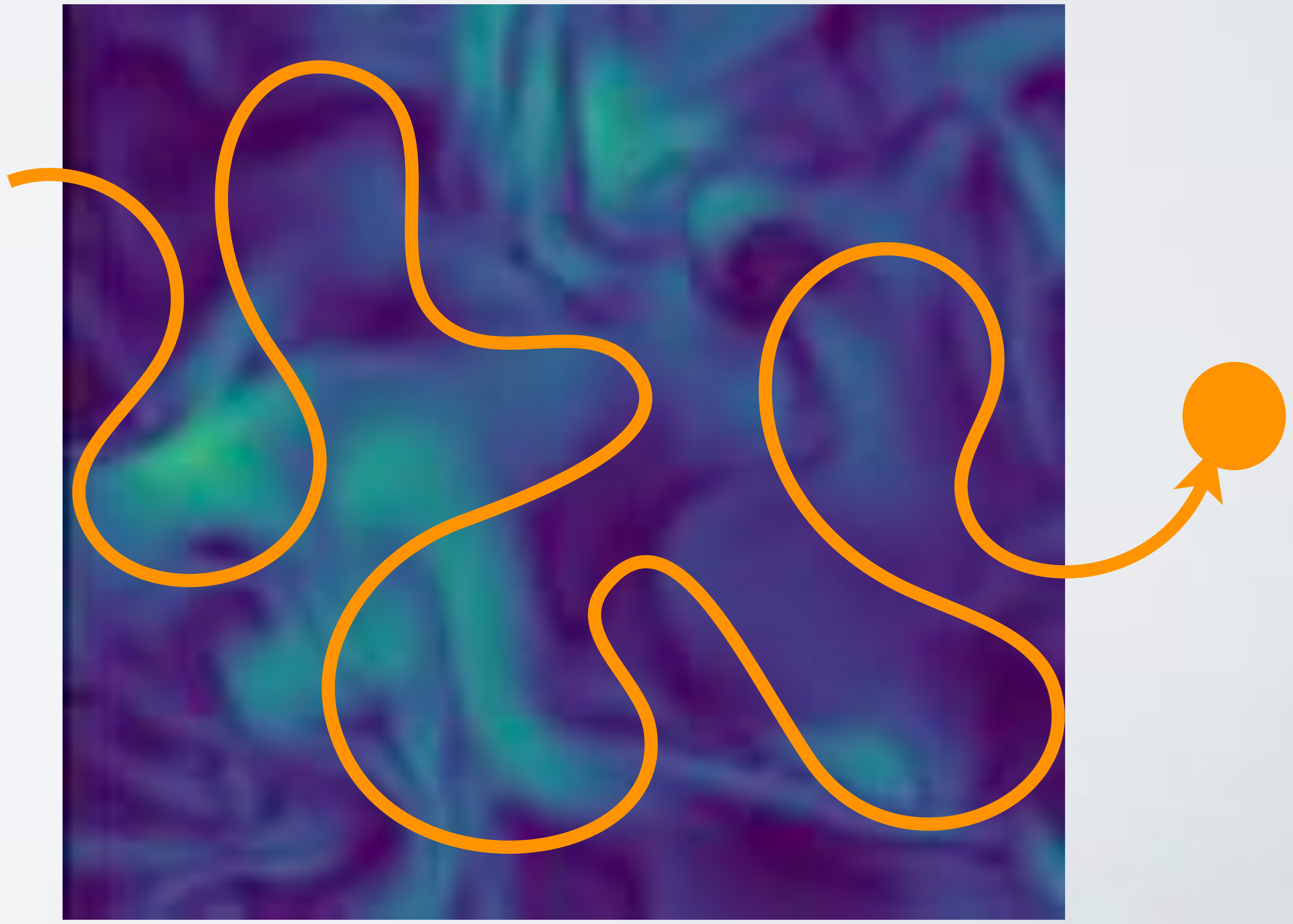


I'm going to talk about "scattering" and "diffusion" - what really happens:

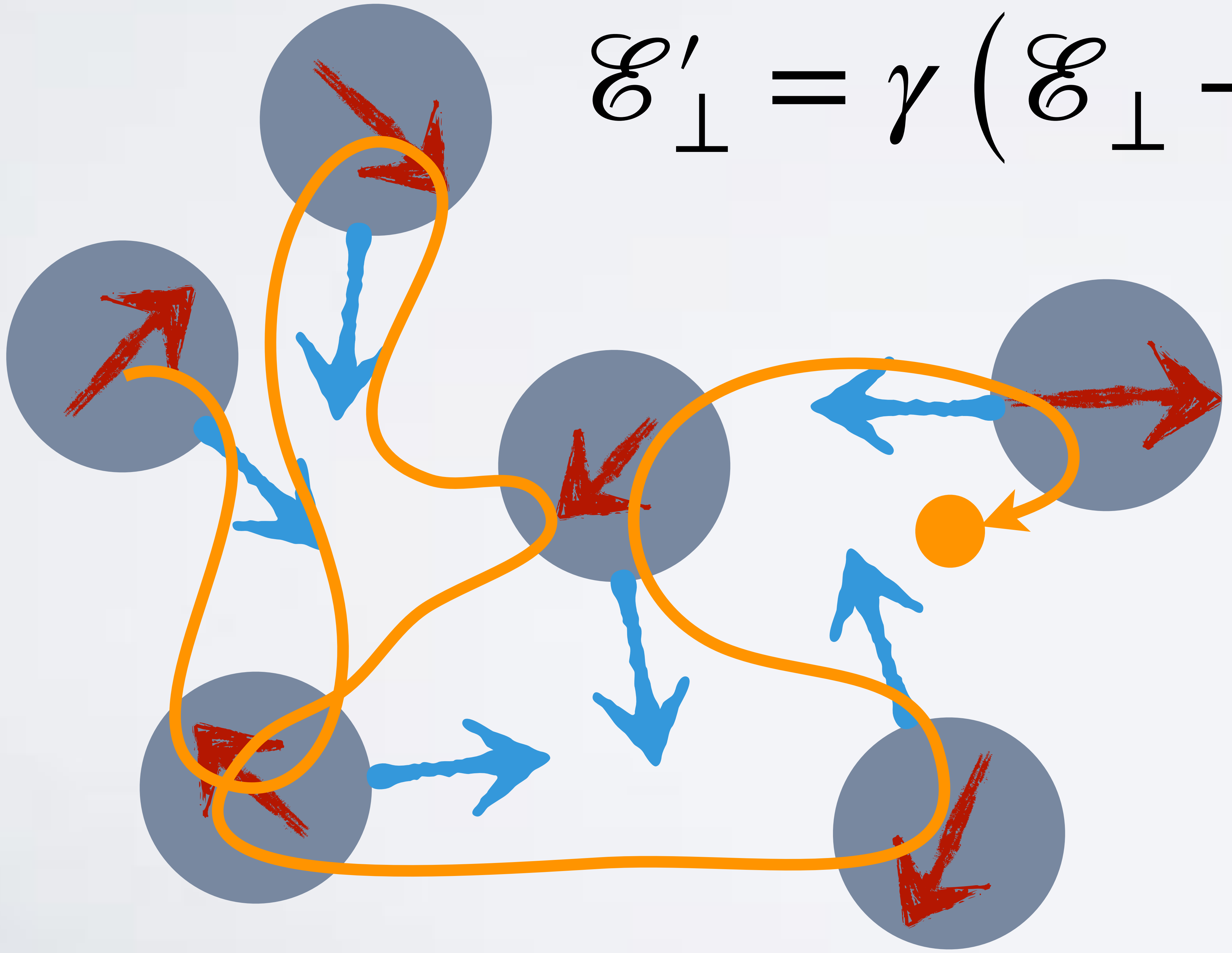
$$\frac{dn}{dt} = \nabla \cdot (D \nabla n)$$



Electric Fields

- Hard to have an electrostatic field in astrophysics
- But gyration in a magnetic field gives no acceleration…
- "A transformed magnetic field is an electric field (and vice versa)"

$$\mathcal{E}'_\perp = \gamma\left(\mathcal{E}_\perp + \mathbf{v} \times \mathbf{B}\right)$$

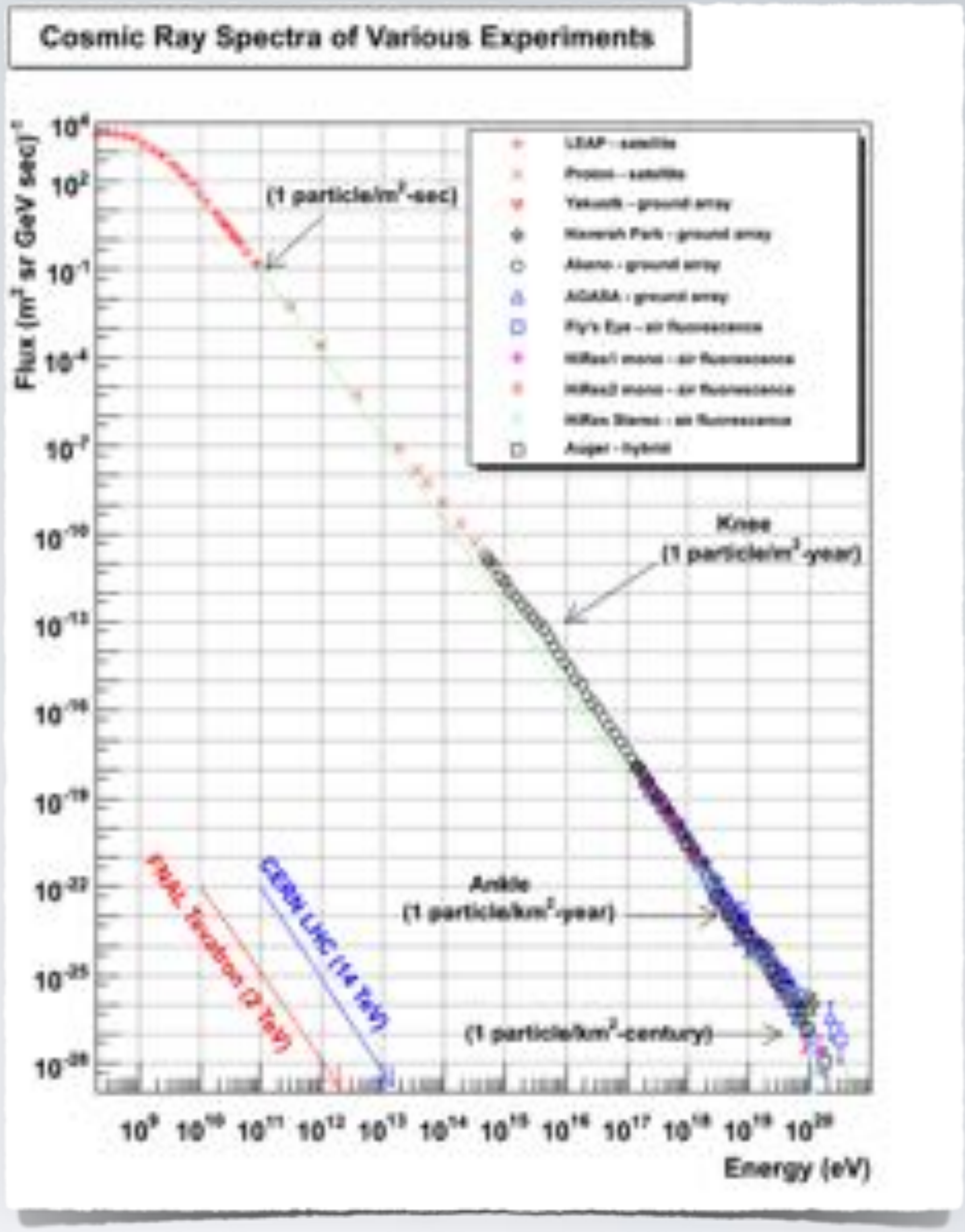


"Scattering off magnetic mirrors" $\equiv$ *"Moving through a stochastic electric field"*

2. MOTIVATION

The CR Spectrum

- 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.
- Huge range of Larmor radius scales!



The CR Spectrum

- The Cosmic Ray spectrum: The best power law in nature?
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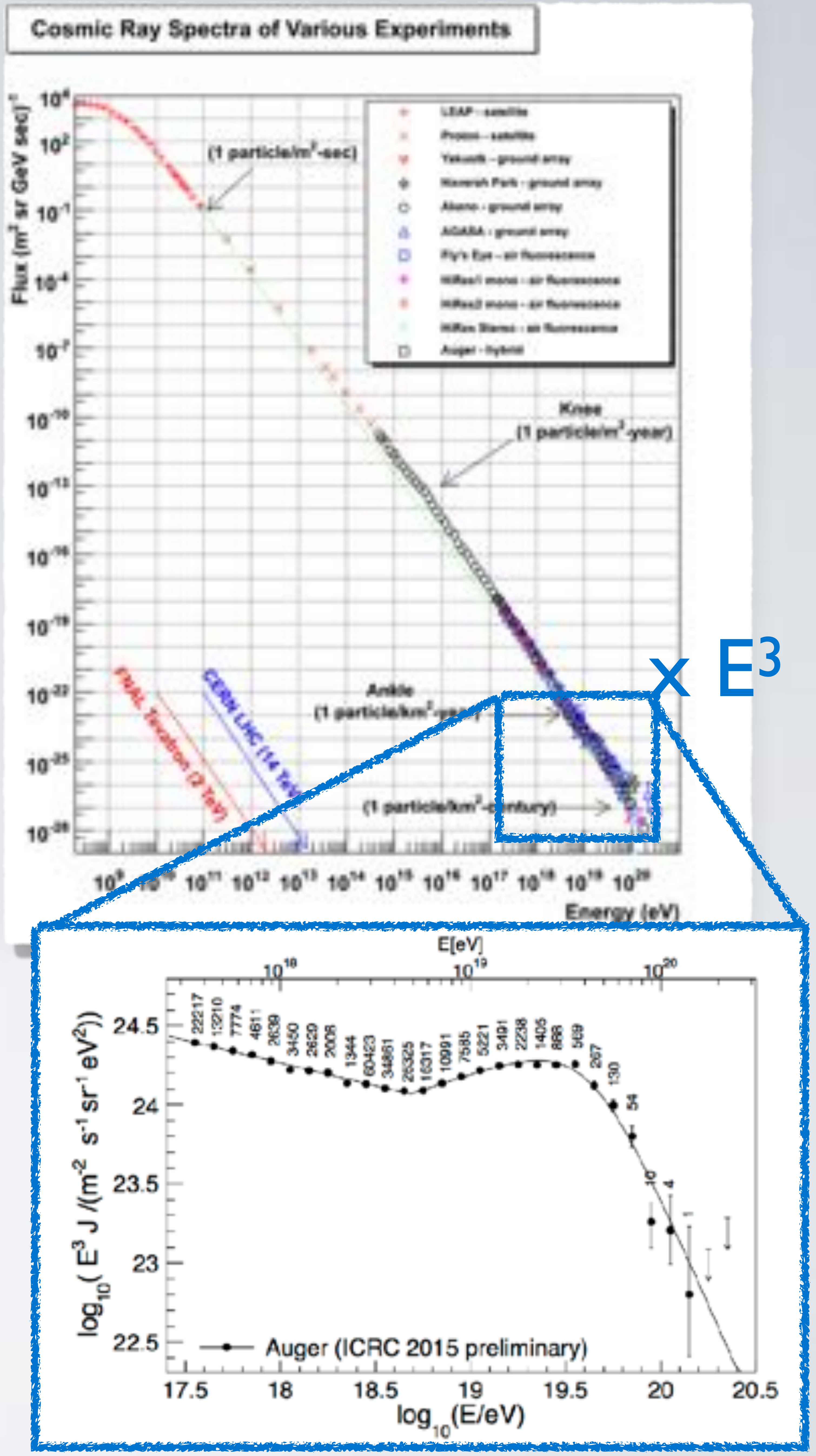
List of unsolved problems in physics

From Wikipedia, the free encyclopedia



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

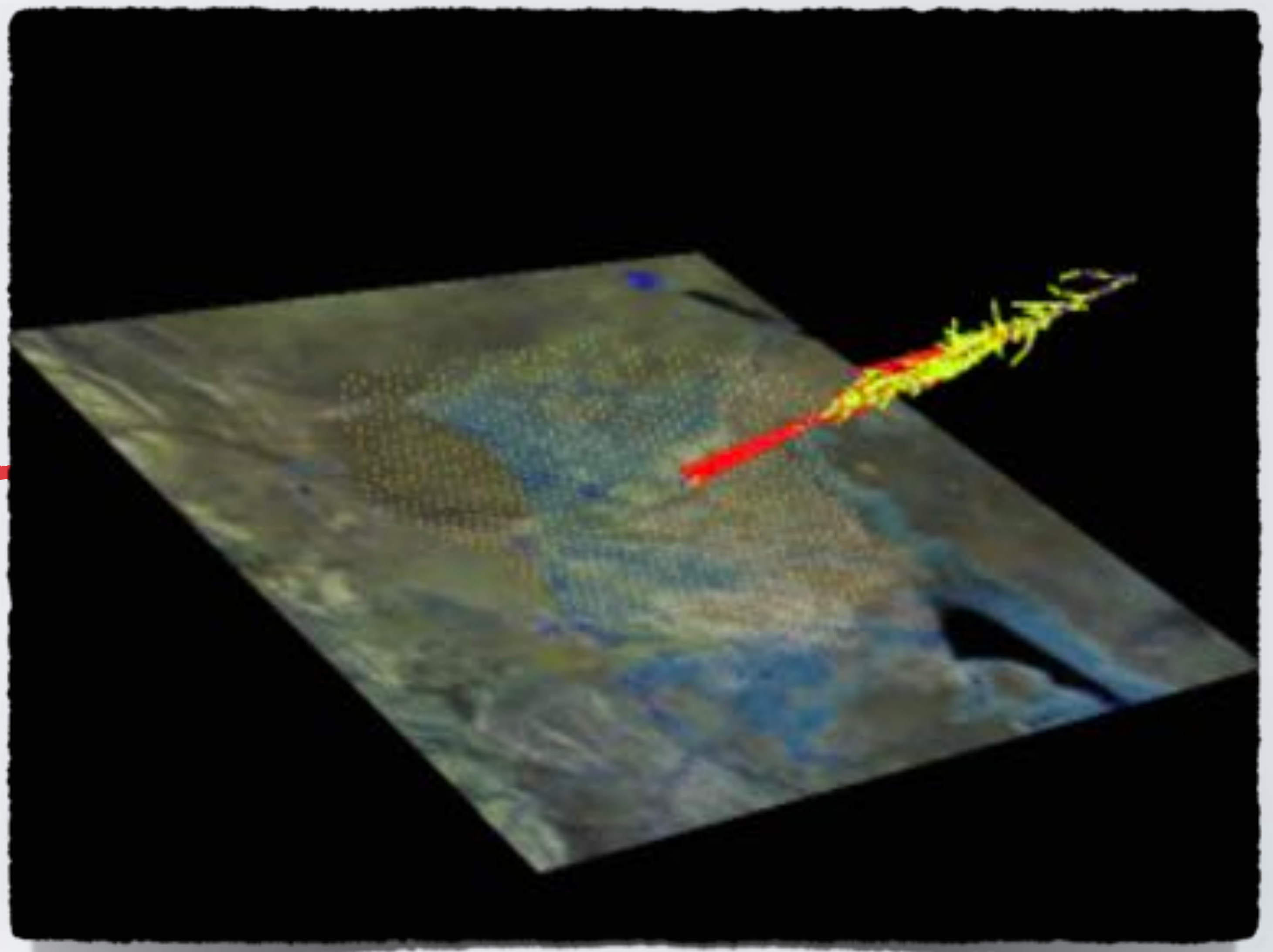
$$\mathcal{R} = \frac{E}{Z}$$

Illustration: Katie Savard

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



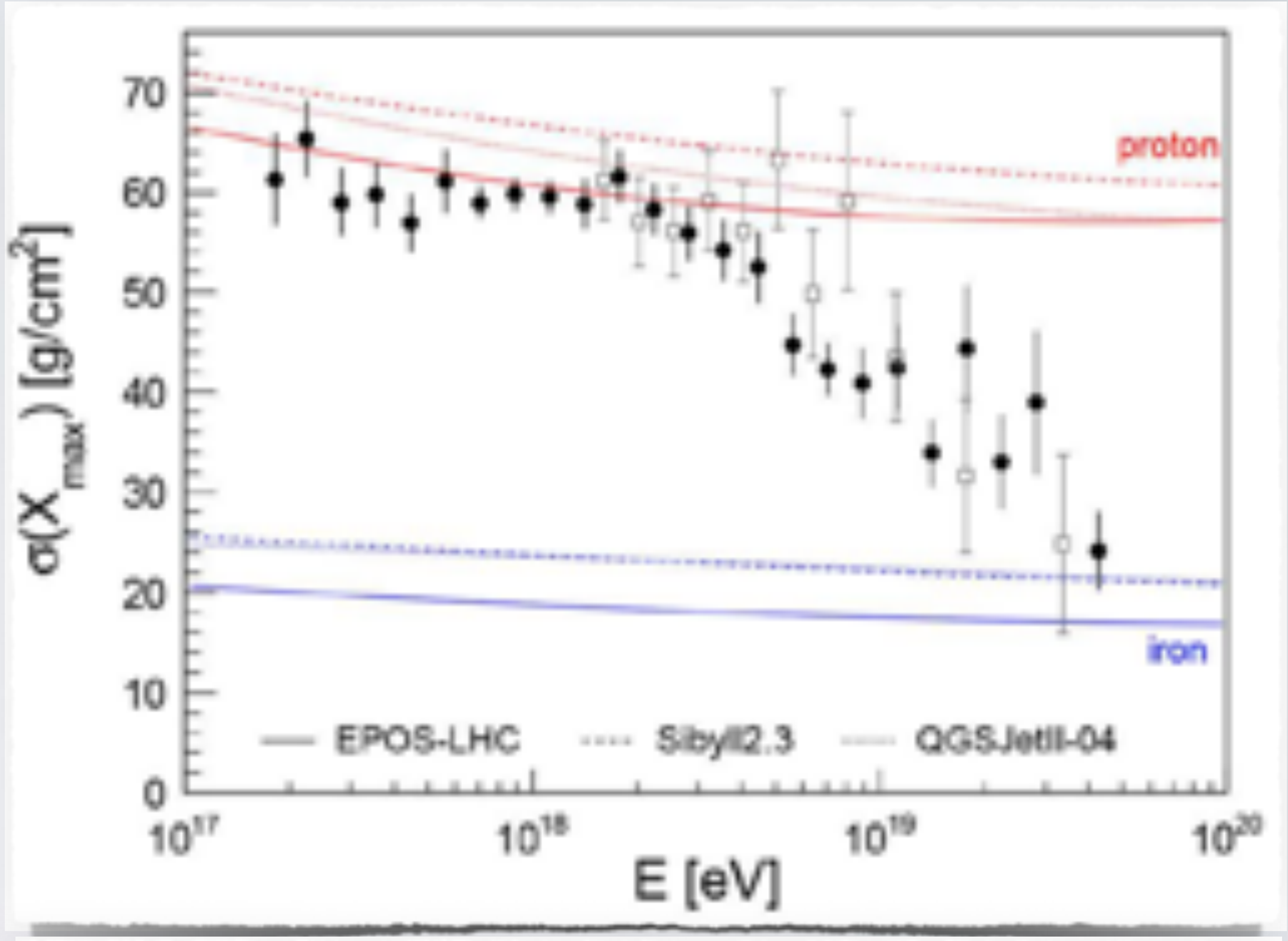
Both also measure ***directions*** and ***composition*** of UHECRs

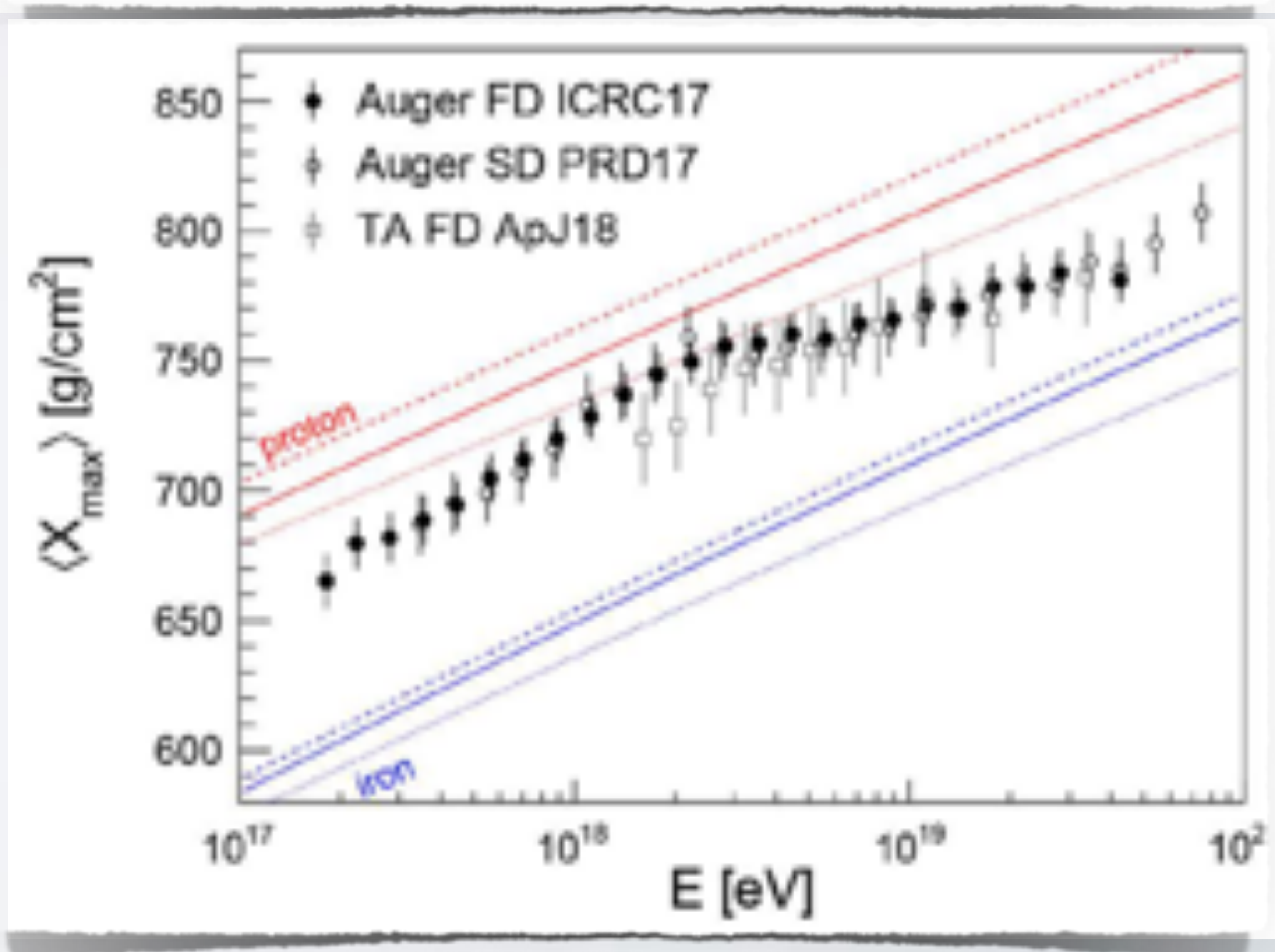
Composition and max rigidity

M. Unger

- Composition measured from distribution of "Xmax" - depth of air shower maximum
- General picture emerging that composition becomes heavier around 5 EeV
- In this talk I will assume we need to get protons to 10 EeV, which implies

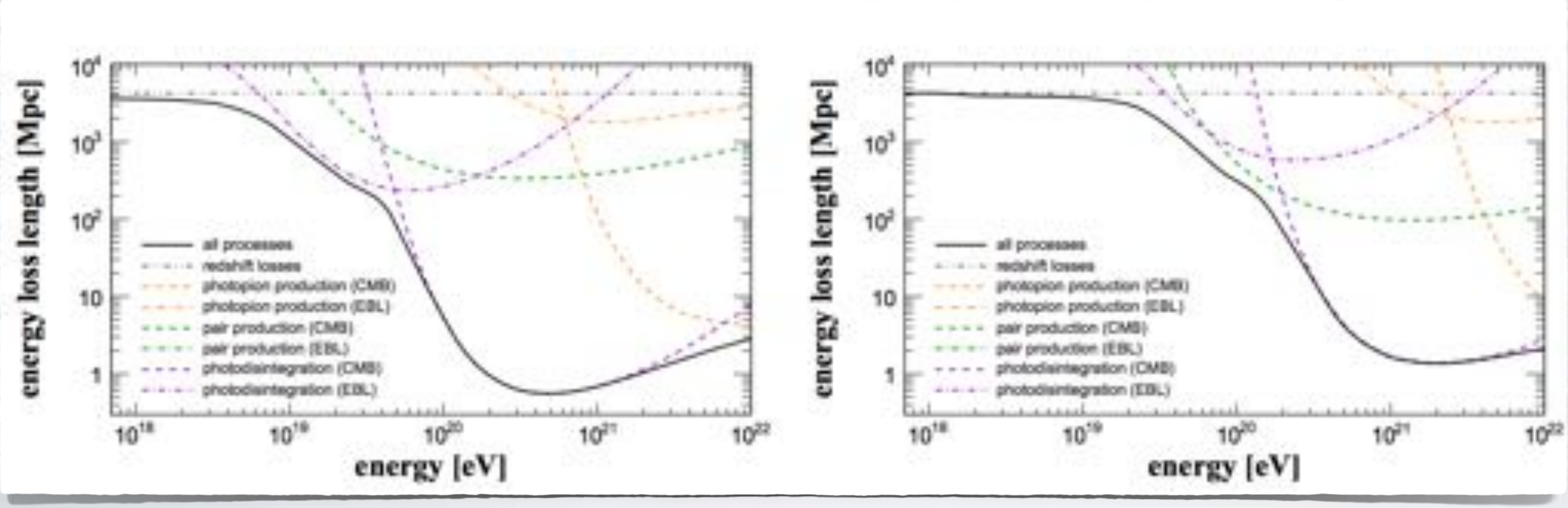
$$\mathscr{R}_{\max} = E/Z \sim 10^{19}\ \mathrm{eV}$$

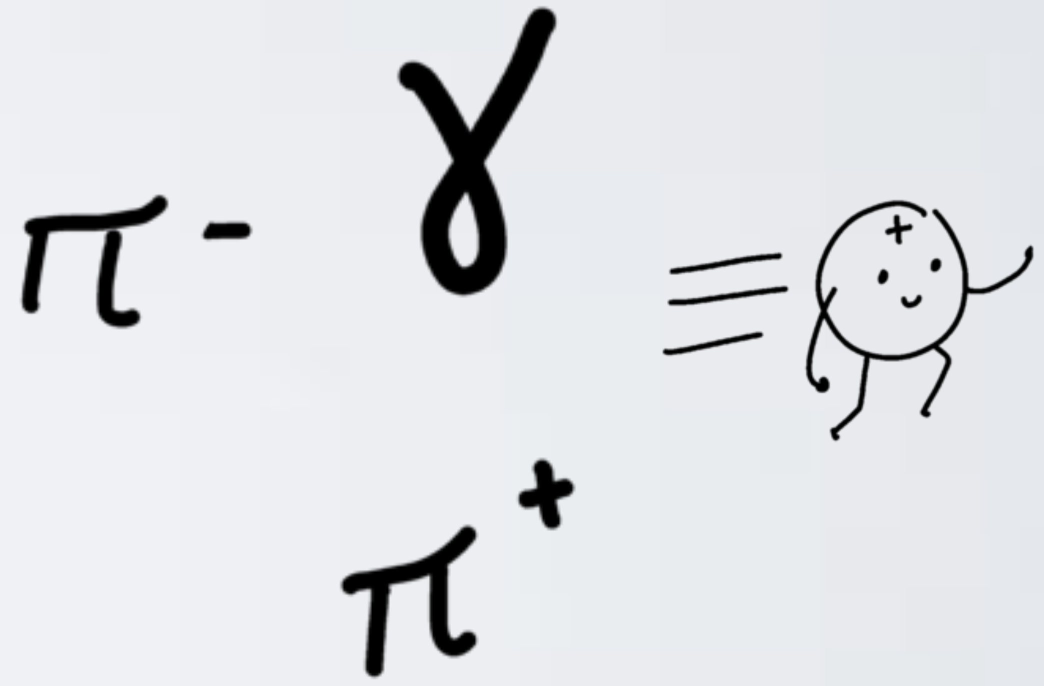




A HORIZON FOR UHECRS

- 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

PARTICLE ACCELERATION: PHYSICS TO OBSERVABLES

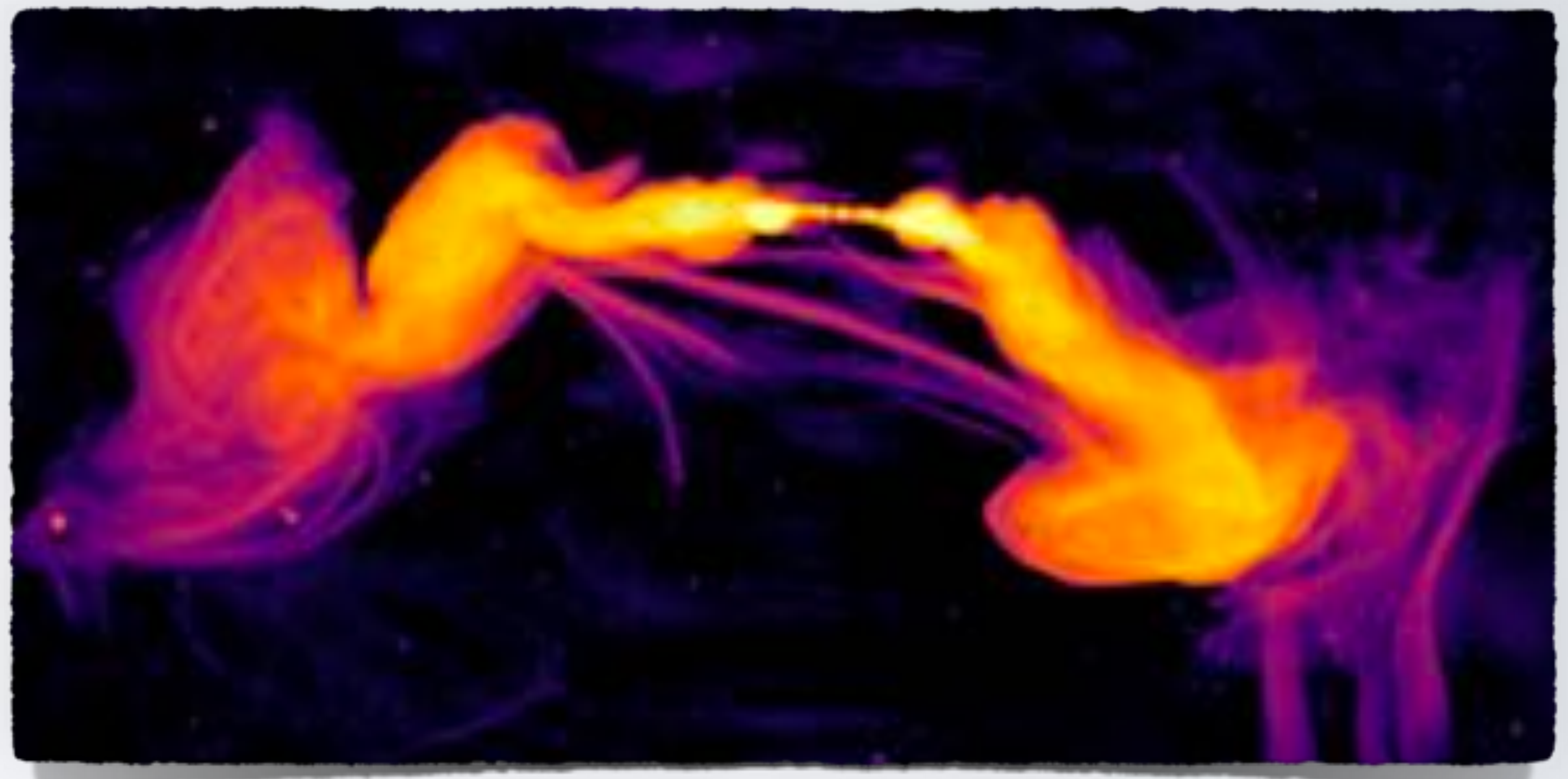
Power and energetics

In-situ conditions: density, pressure, etc.

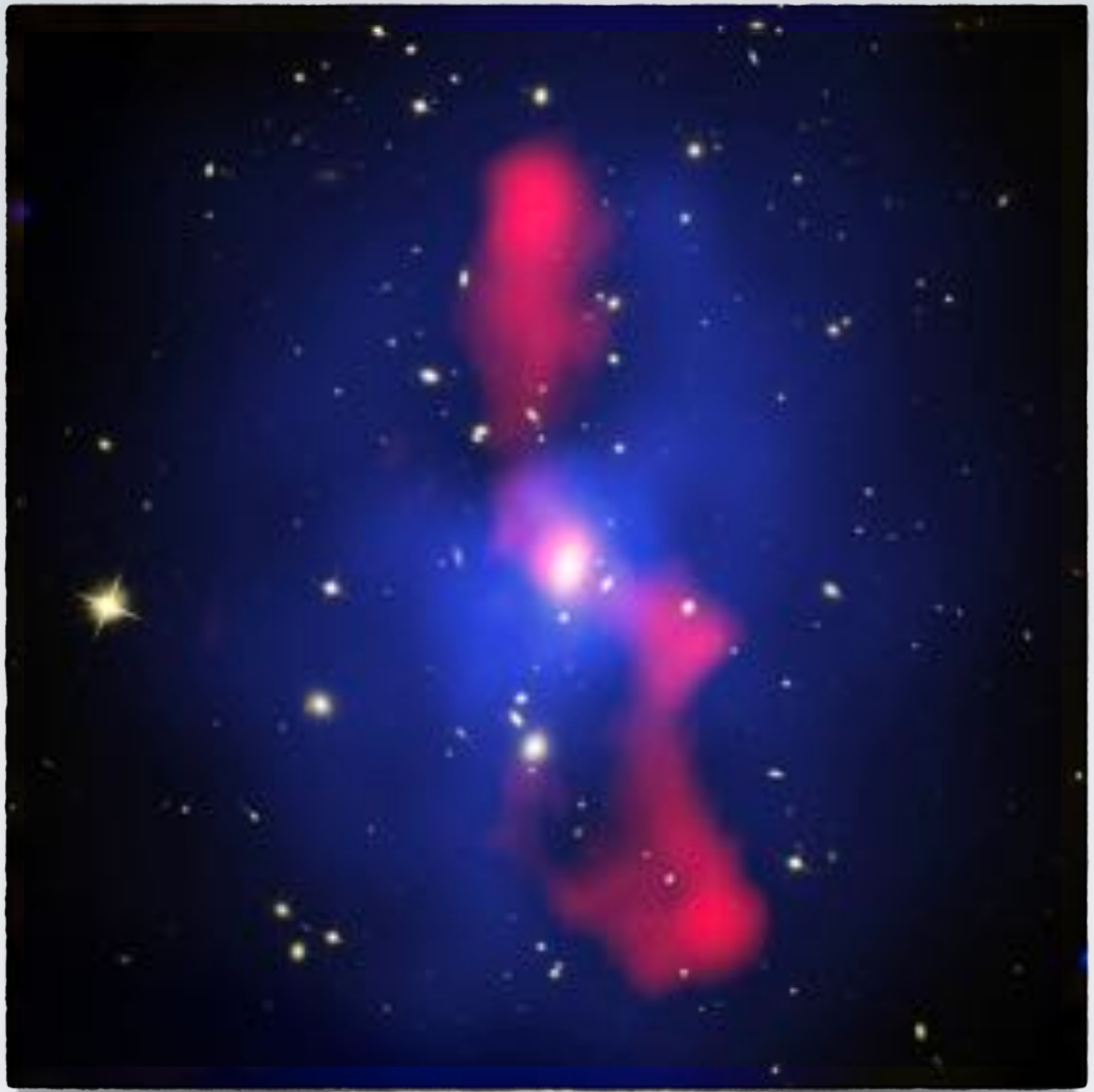
Magnetic field geometry and strength

Kinematics

Credit: SARAO



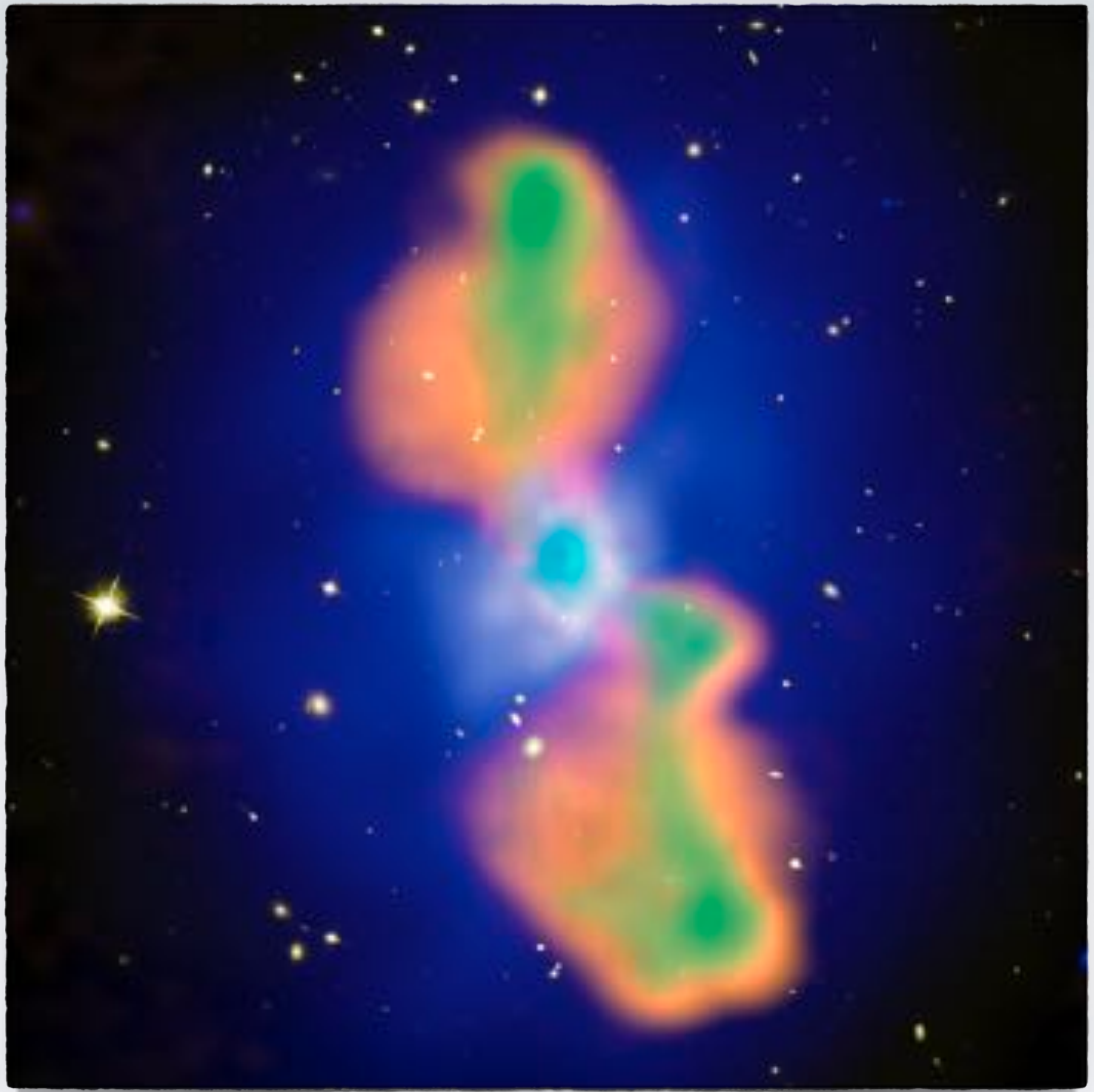
Synchrotron radiation (usually)



MS 0735+742

Chandra X-ray (blue) + VLA 330 MHz (red)

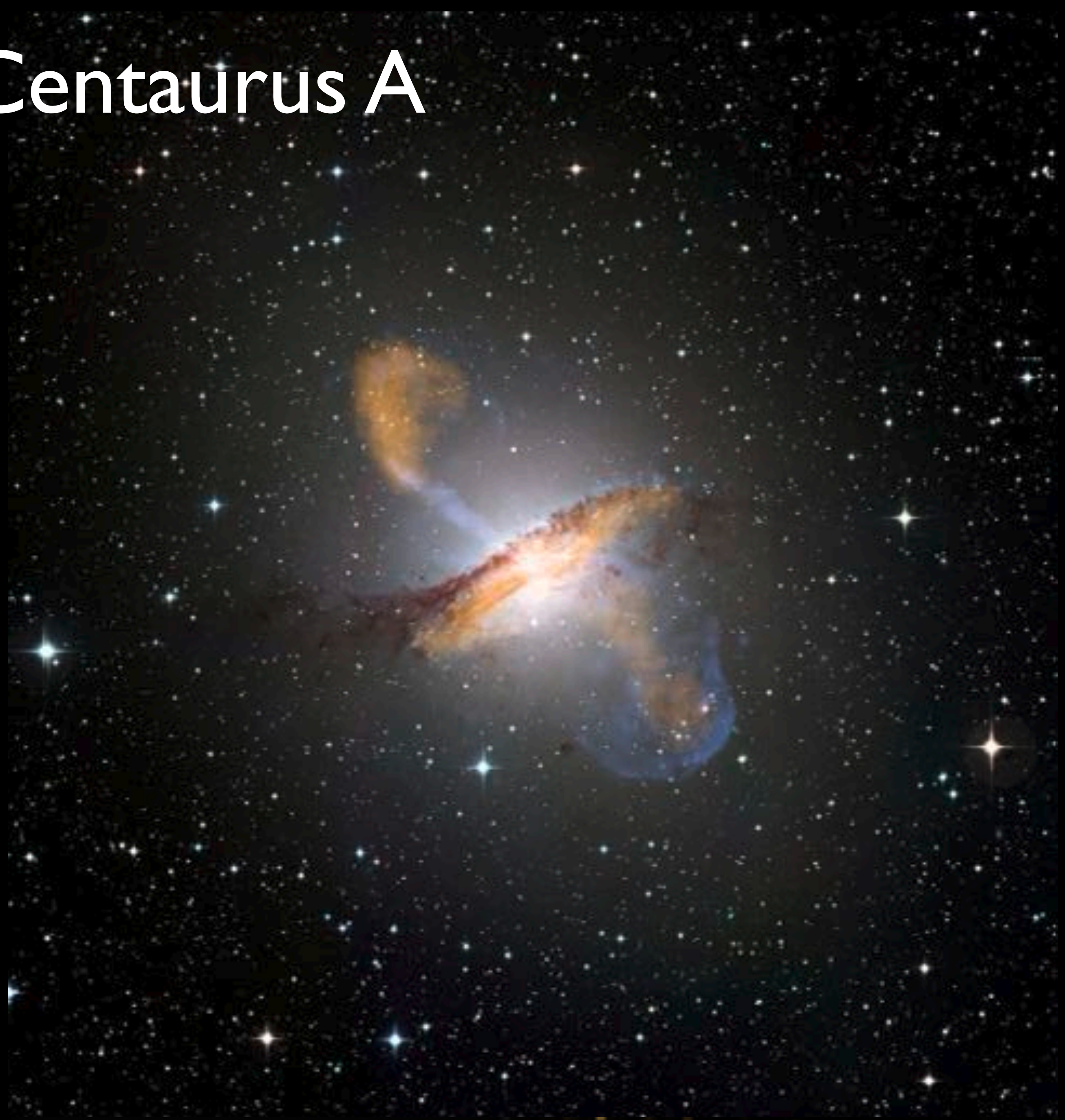
NRAO+Birzan et al.



MS 0735+742

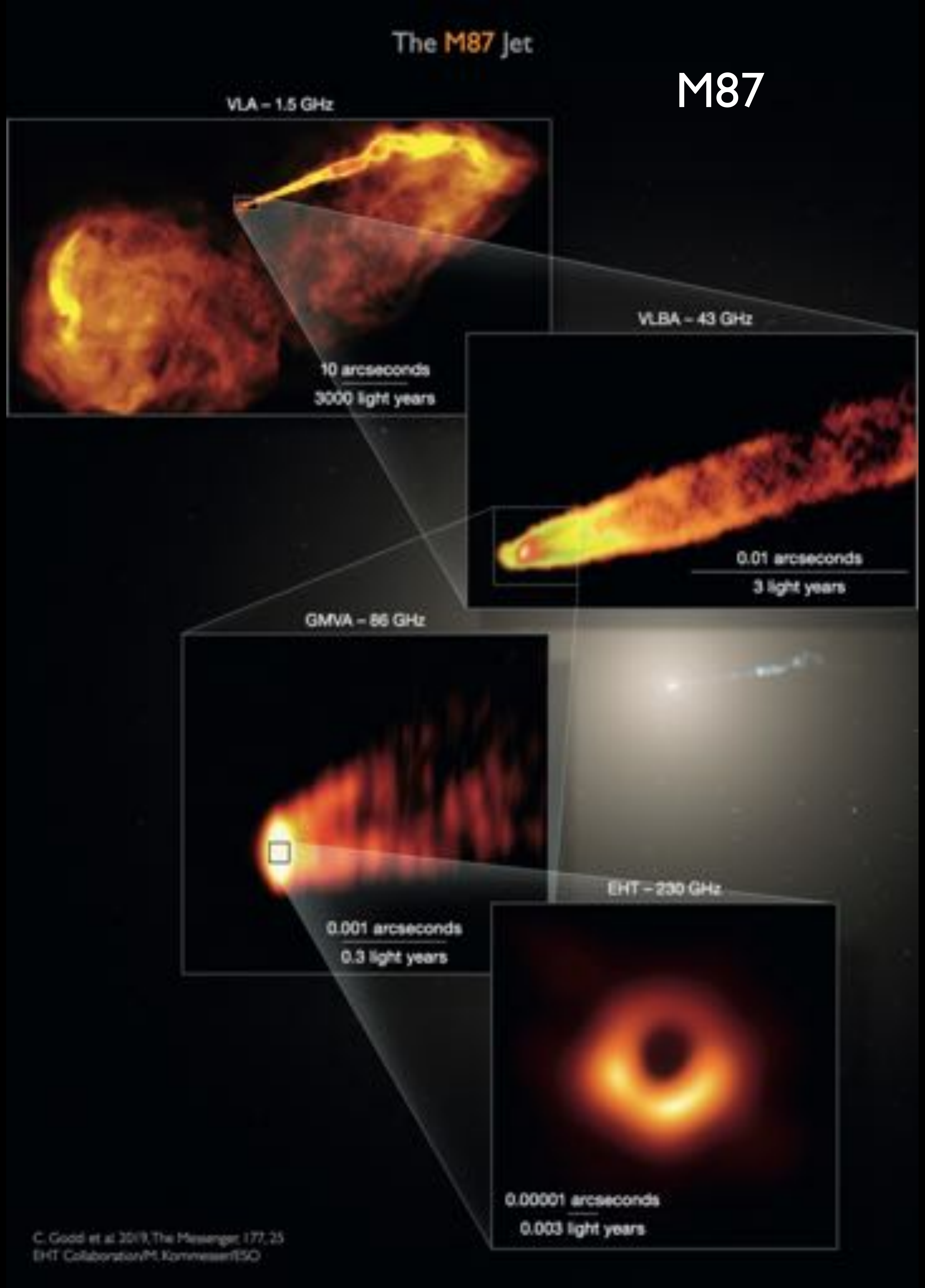
VLA 330 MHz (green) + LOFAR 150 MHz (orange)

Biava+ 2021

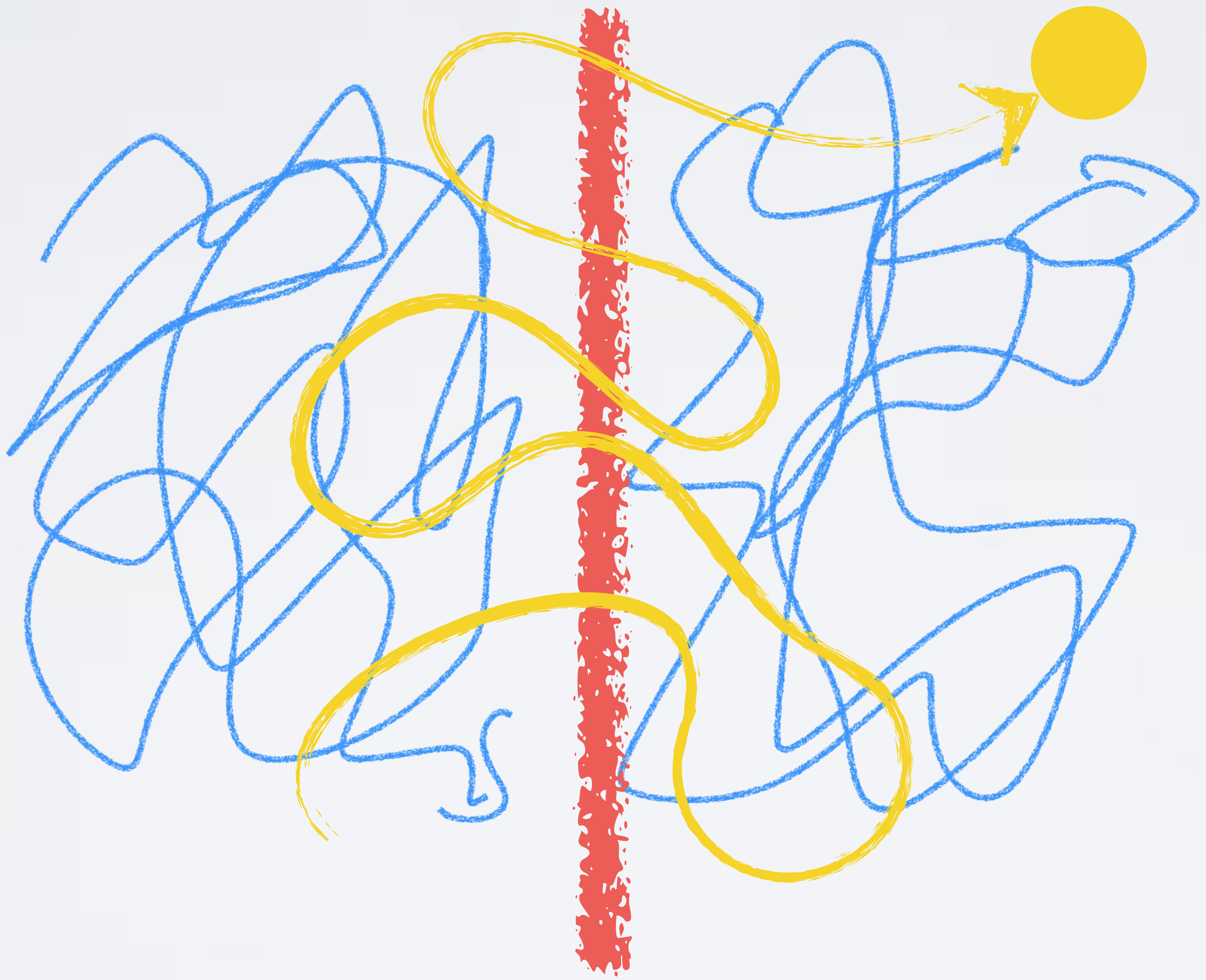

Centaurus A


Fornax A


Cygnus A


The M87 Jet
M87
VLA – 1.5 GHz
10 arcseconds
3000 light years
VLBA – 43 GHz
0.01 arcseconds
3 light years
GMVA – 86 GHz
0.001 arcseconds
0.3 light years
EHT – 230 GHz
0.00001 arcseconds
0.003 light years
C. Goddi et al 2019, The Messenger 177, 25
EHT Collaboration/M. Kornmesser/ESO

3. PARTICLE ACCELERATION PHYSICS



HOW TO ACCELERATE A PARTICLE

Maxwellian

HOW TO ACCELERATE A PARTICLE

Maxwellian

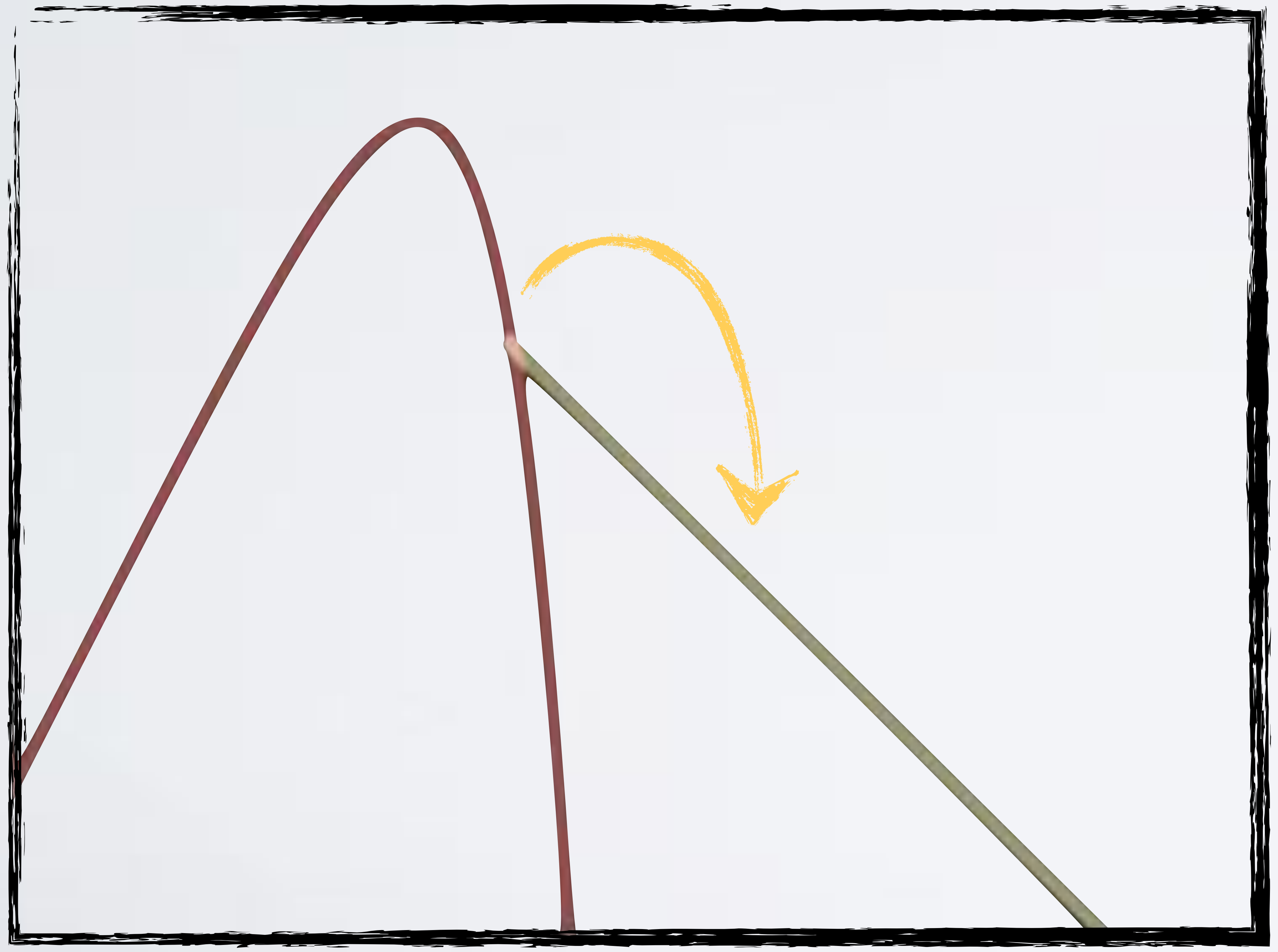
Log-scaled and shifted

HOW TO ACCELERATE A PARTICLE

Maxwellian

Log-scaled and shifted

With a non-thermal tail



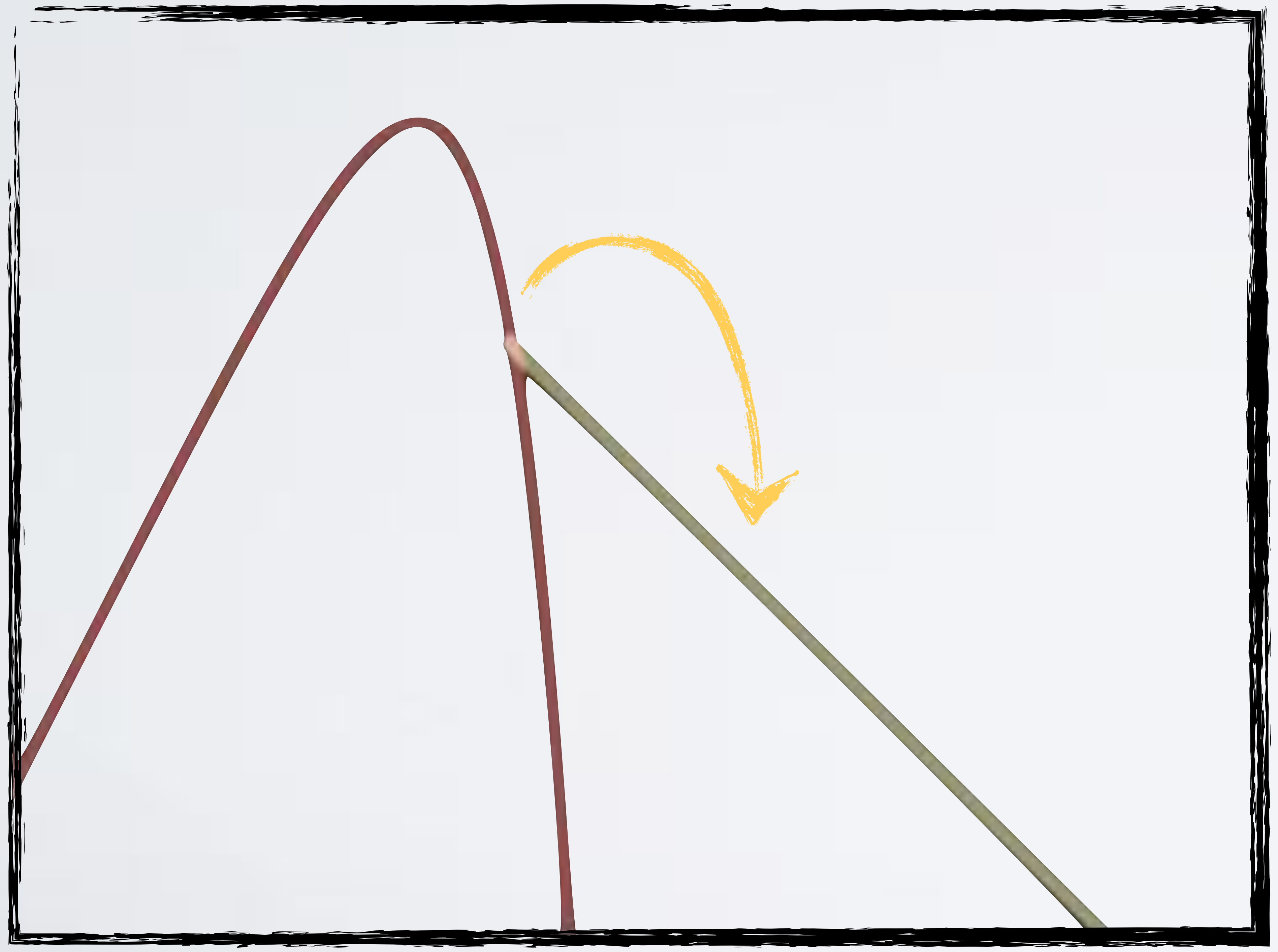
Particle acceleration is the process of "lifting" particles from thermal population onto non-thermal tail

HOW TO ACCELERATE A PARTICLE

Maxwellian

Log-scaled and shifted

With a non-thermal tail

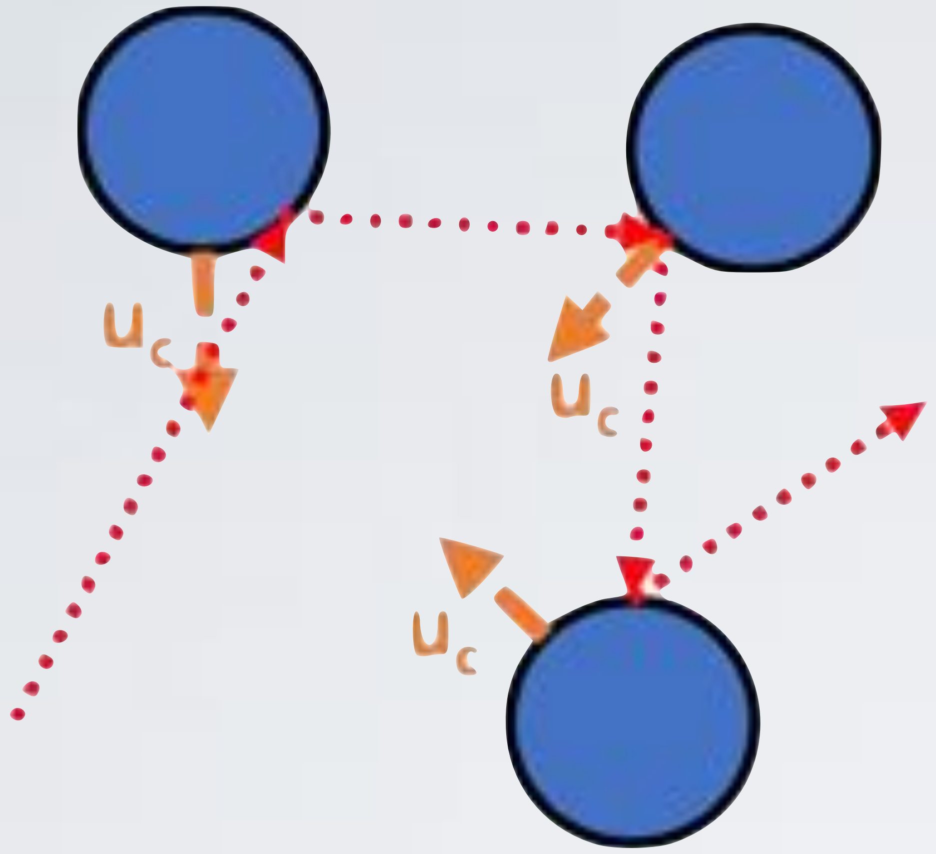


Particle acceleration is the process of "lifting" particles from thermal population onto non-thermal tail

How do we form a power-law?

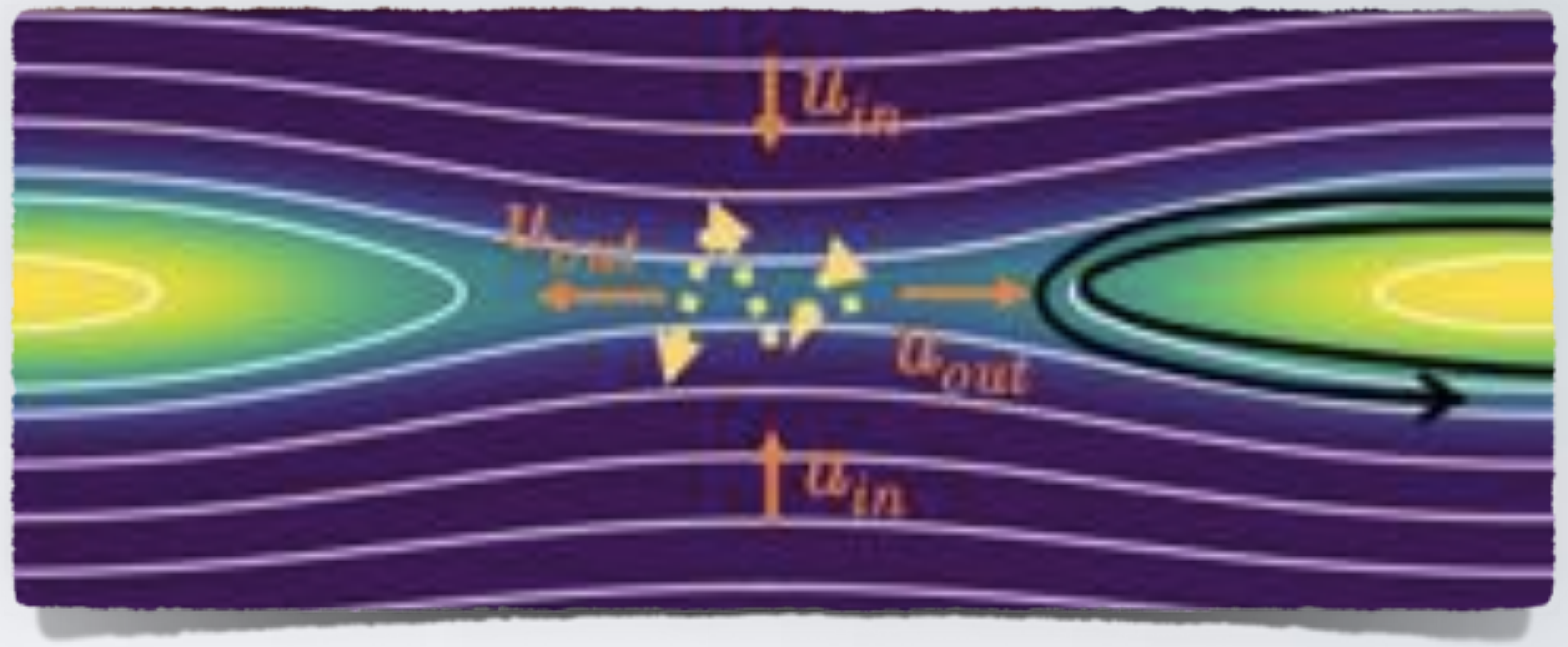
What sets the maximum energy?

PARTICLES ARE ACCELERATED IN SITES OF ENERGY DISSIPATION



Turbulence/Fermi II

Shocks



Reconnection

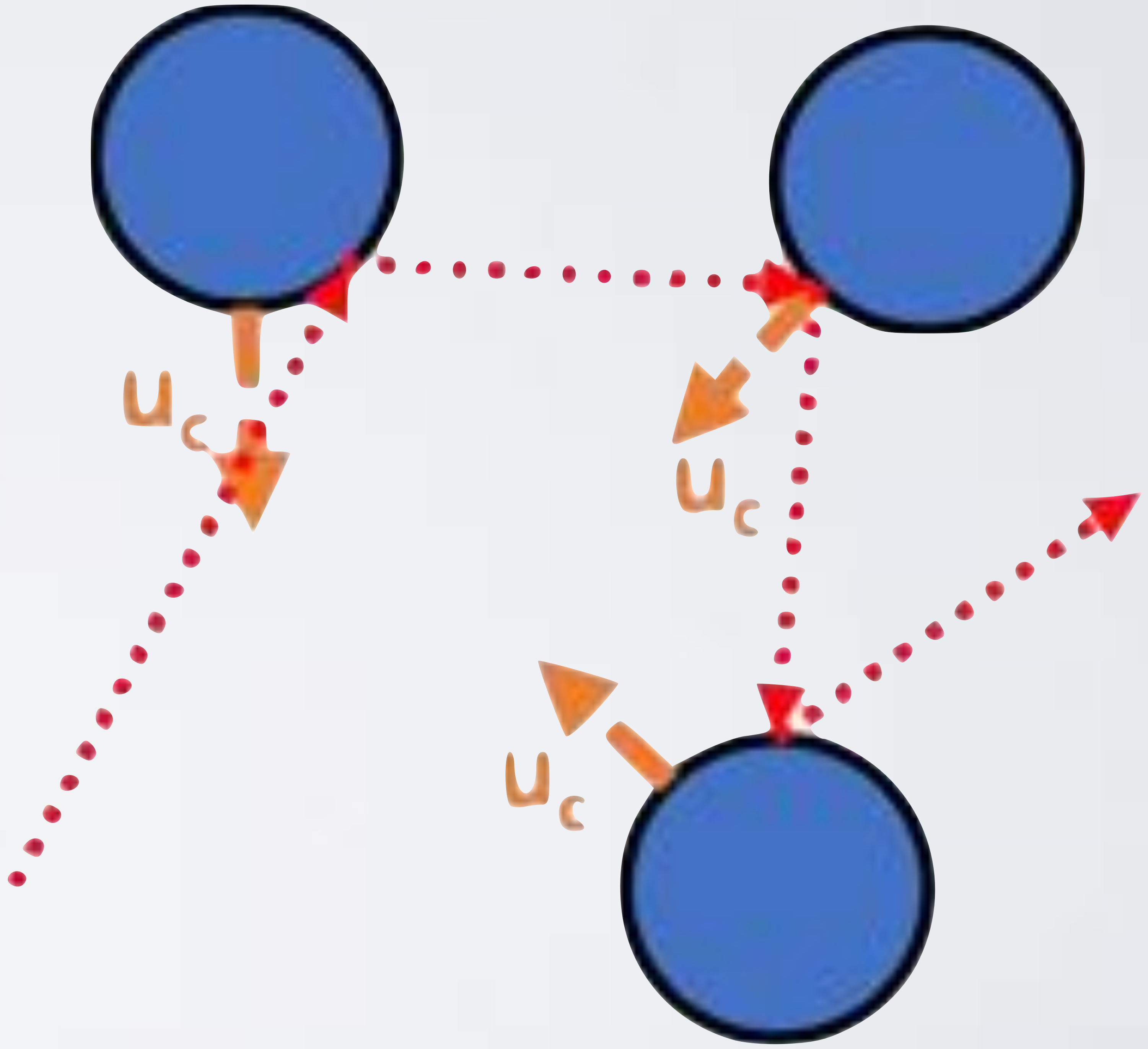
Also:

- 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

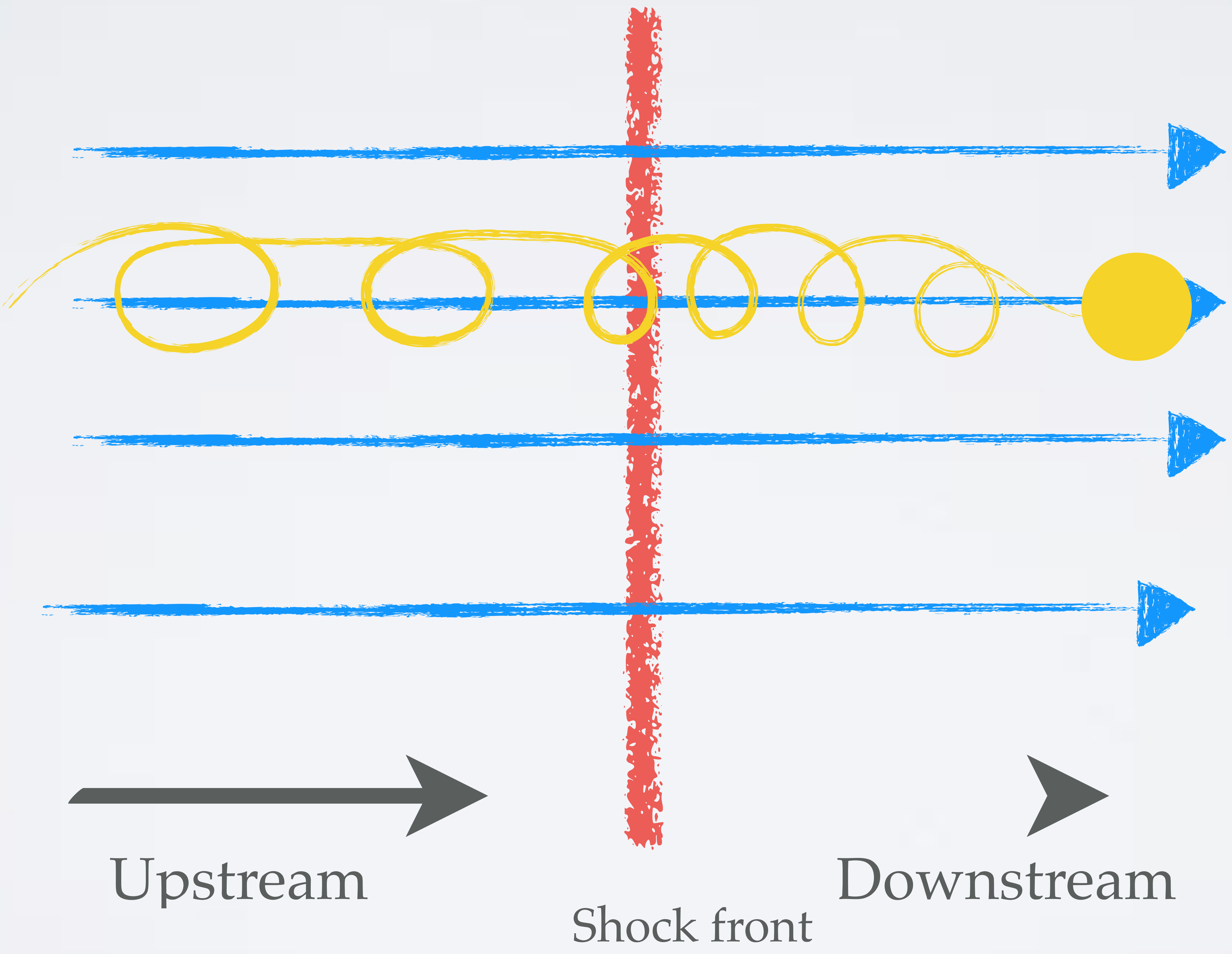
- Second-order Fermi acceleration was proposed in 1949 by Fermi
- Particles scatter off cloud/turbulence that acts as magnetic mirrors, particle gains or loses u/c on each collision, but head on collisions more likely
- Requires fine tuning to get a power-law, more fine-tuning for specific index
- Energy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



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

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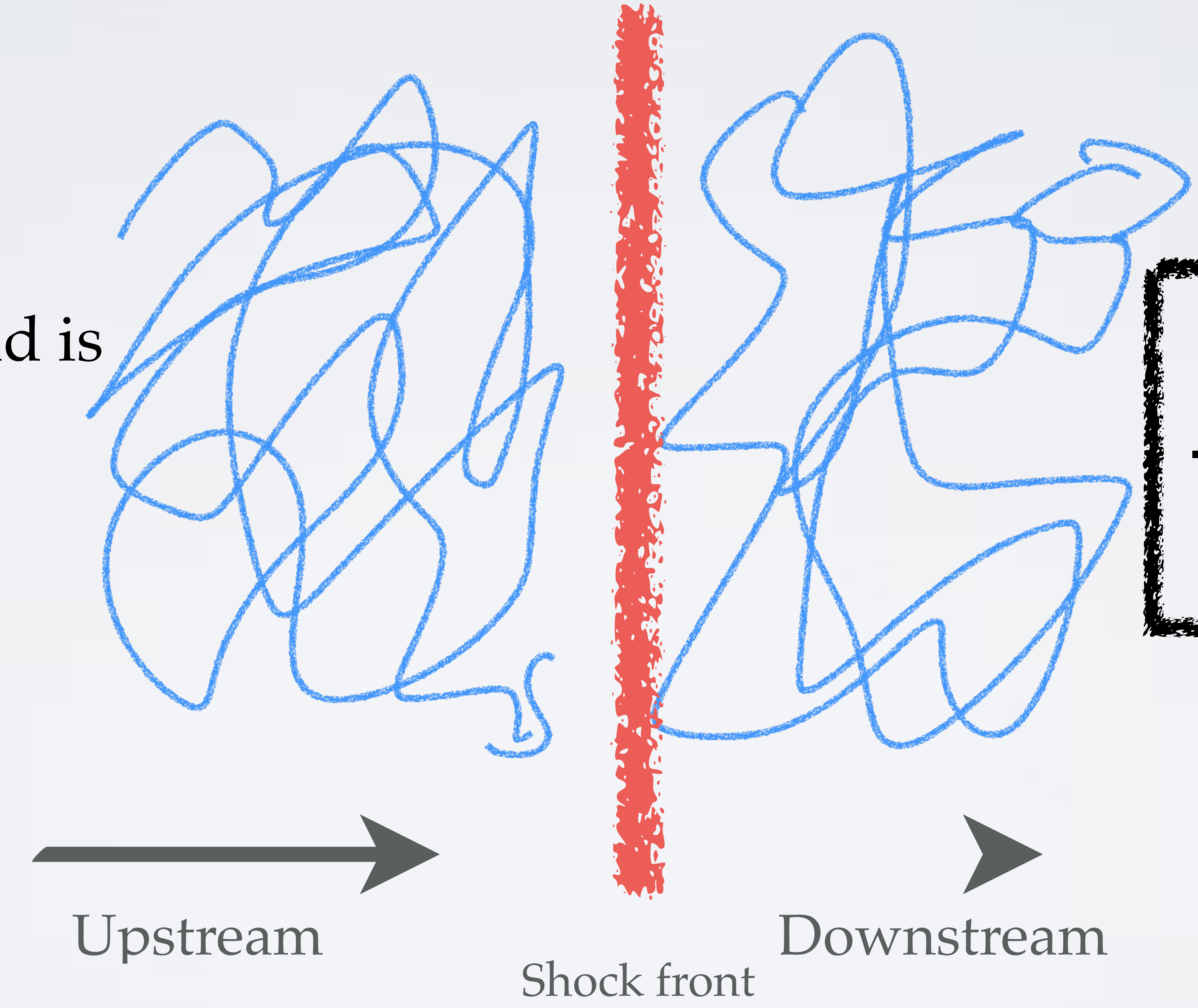
Turbulent B field is crucial!



$$\boxed{\frac{\Delta E}{E} \sim \frac{u_s}{c}}$$

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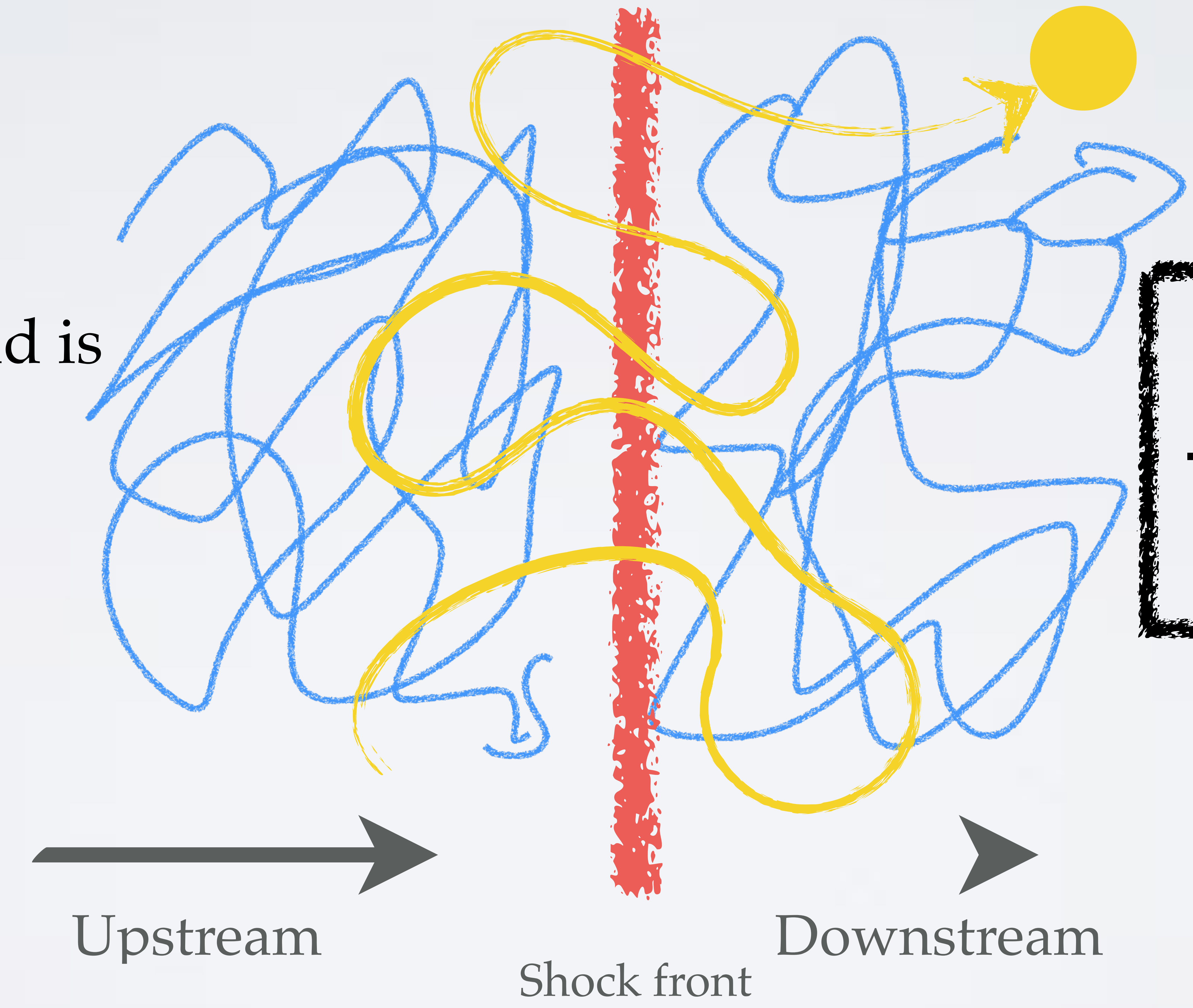
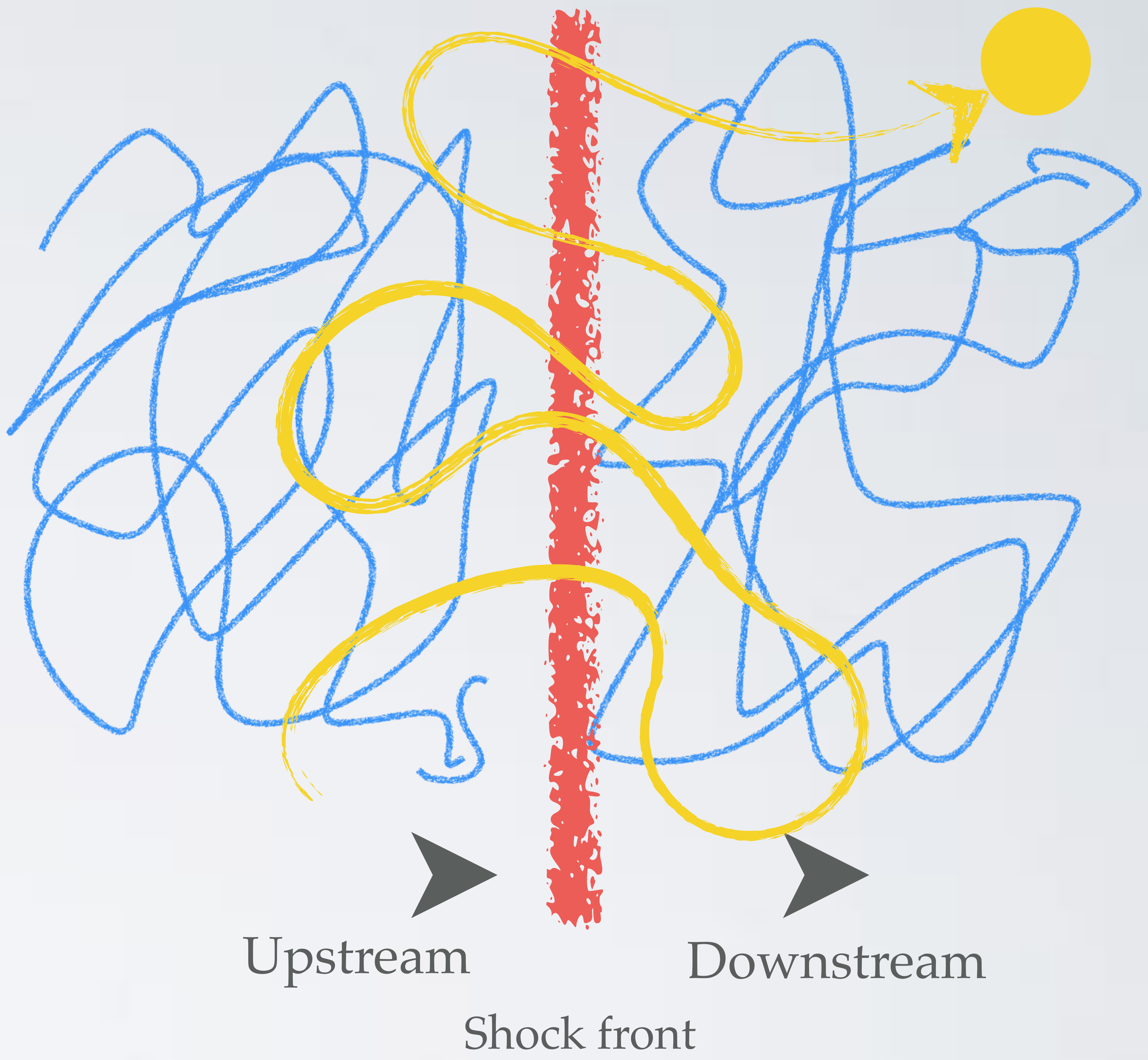


$$\boxed{\frac{\Delta E}{E} \sim \frac{u_s}{c}}$$

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

SHOCK ACCELERATION

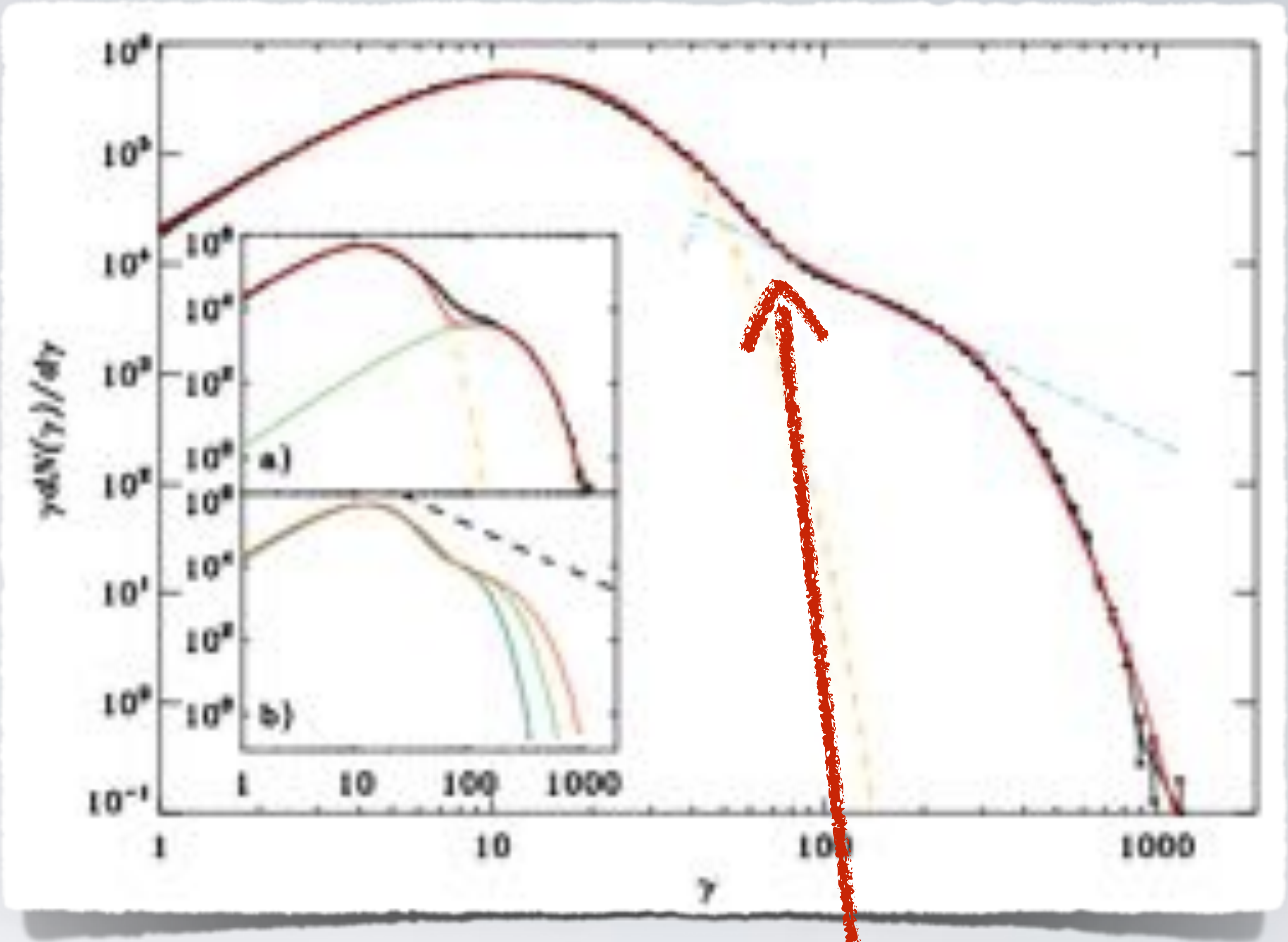
- Crucial aspect of shock acceleration:
  - escape prob (P) and energy gain (G) are hard-wired by shock jump conditions
- Good reason for a power-law to be produced!
- Well-motivated spectral index of ~2 or a bit steeper
- Relativistic shocks ~2.2-2.3
- Reviews: Drury 1981, Blandford & Eichler 1987, Bell 2014, Marcowith+ 2018, JM+ 2020.



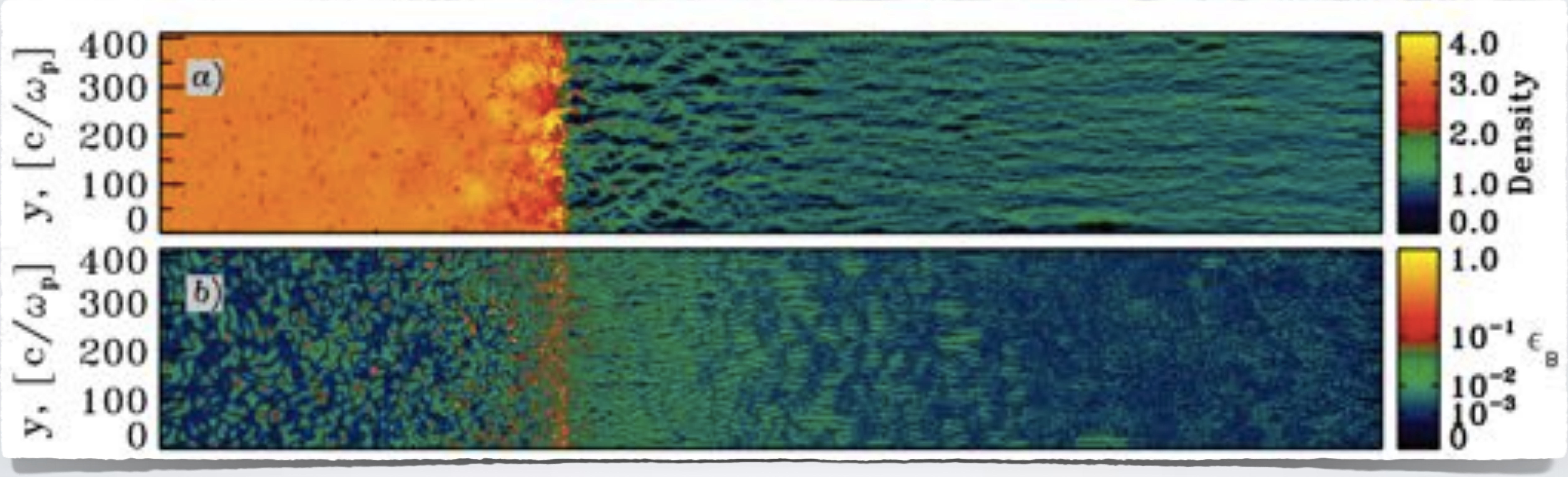
$$\frac{dN}{dE} \propto E^{(\ln P / \ln G - 1)}$$

Shocks with PIC

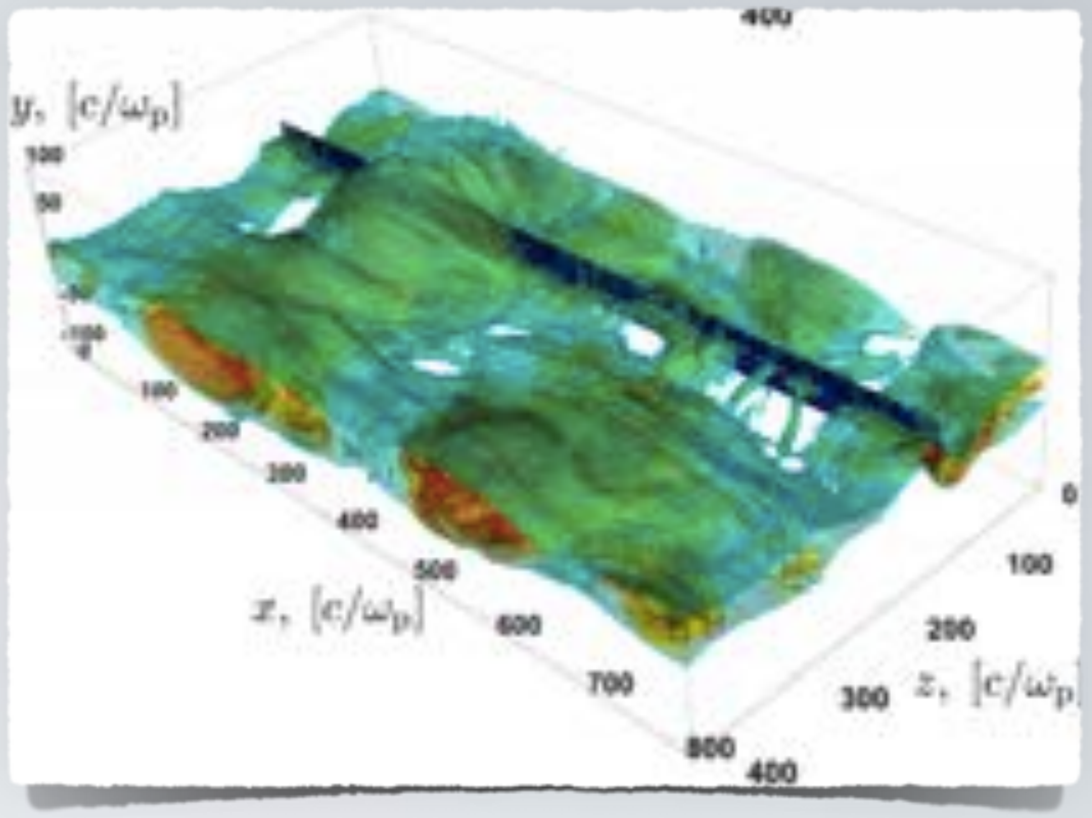
- Relatively simple theory where particle escape balances energy gain = power-law spectrum
- Verified by complex particle-in-cell (PIC) simulation (e.g. Spitkovsky 2008)
- Self-consistent generation of instabilities and power-law super thermal tail in momentum distribution



“Injection”

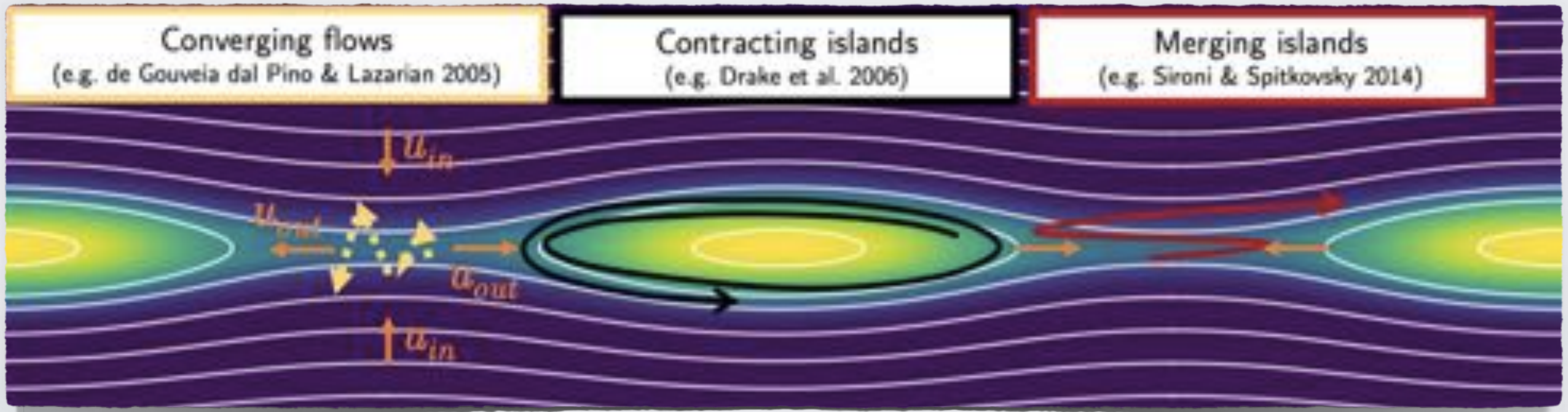


Magnetic Reconnection



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"



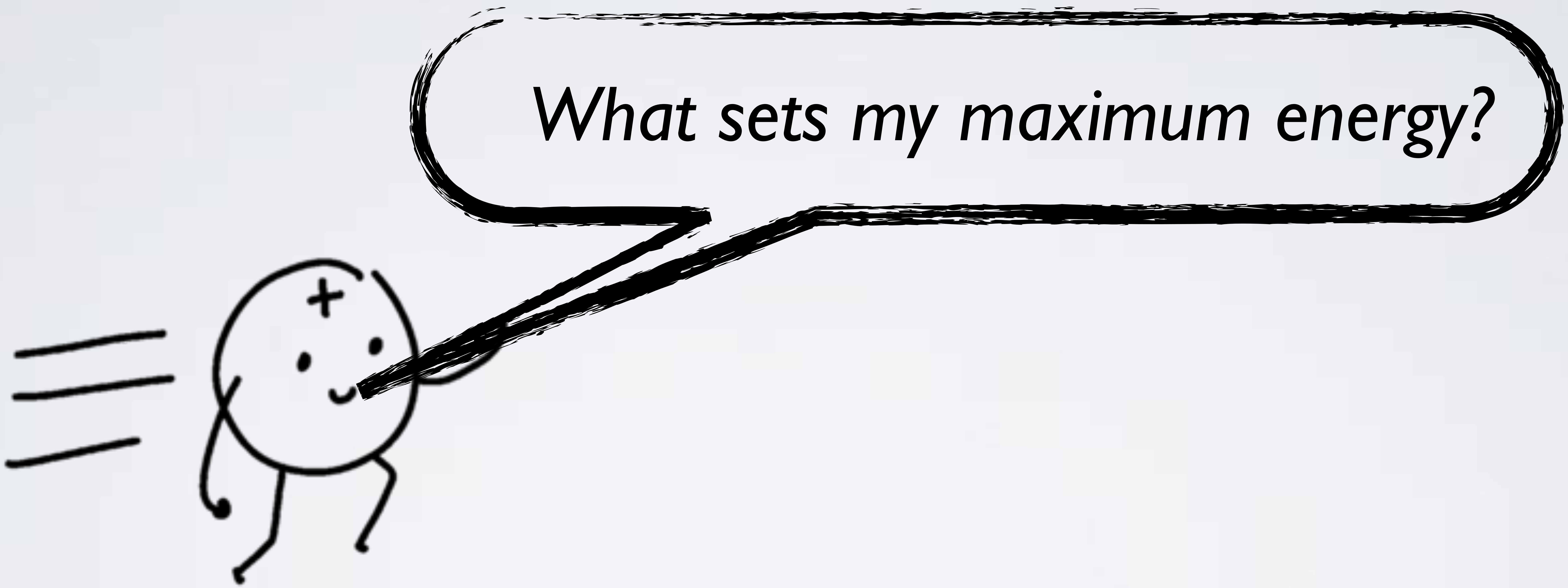
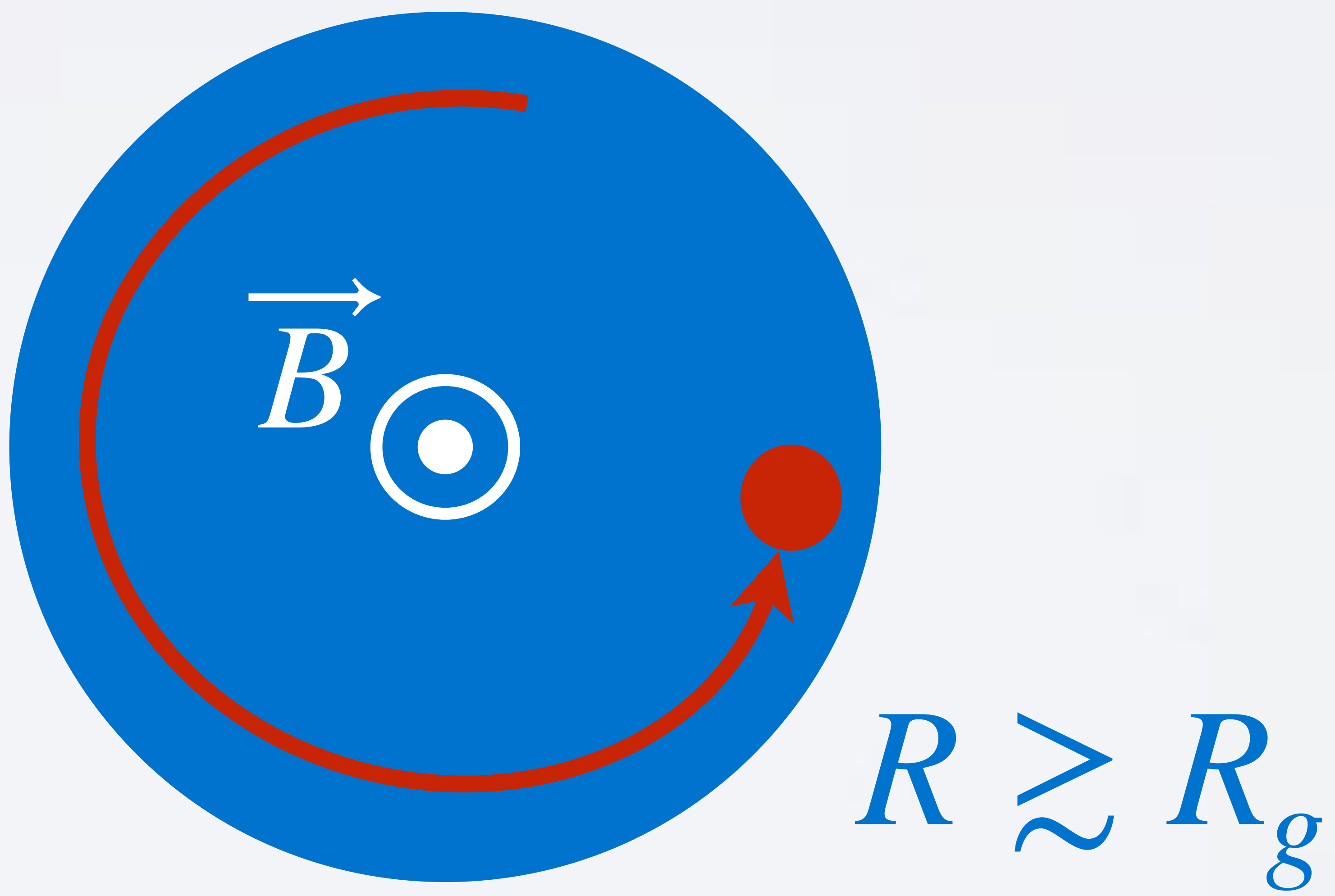


Illustration: Katie Savard

Confinement condition

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

$$E = ZBR$$



HILLAS ENERGY

Michael Hillas

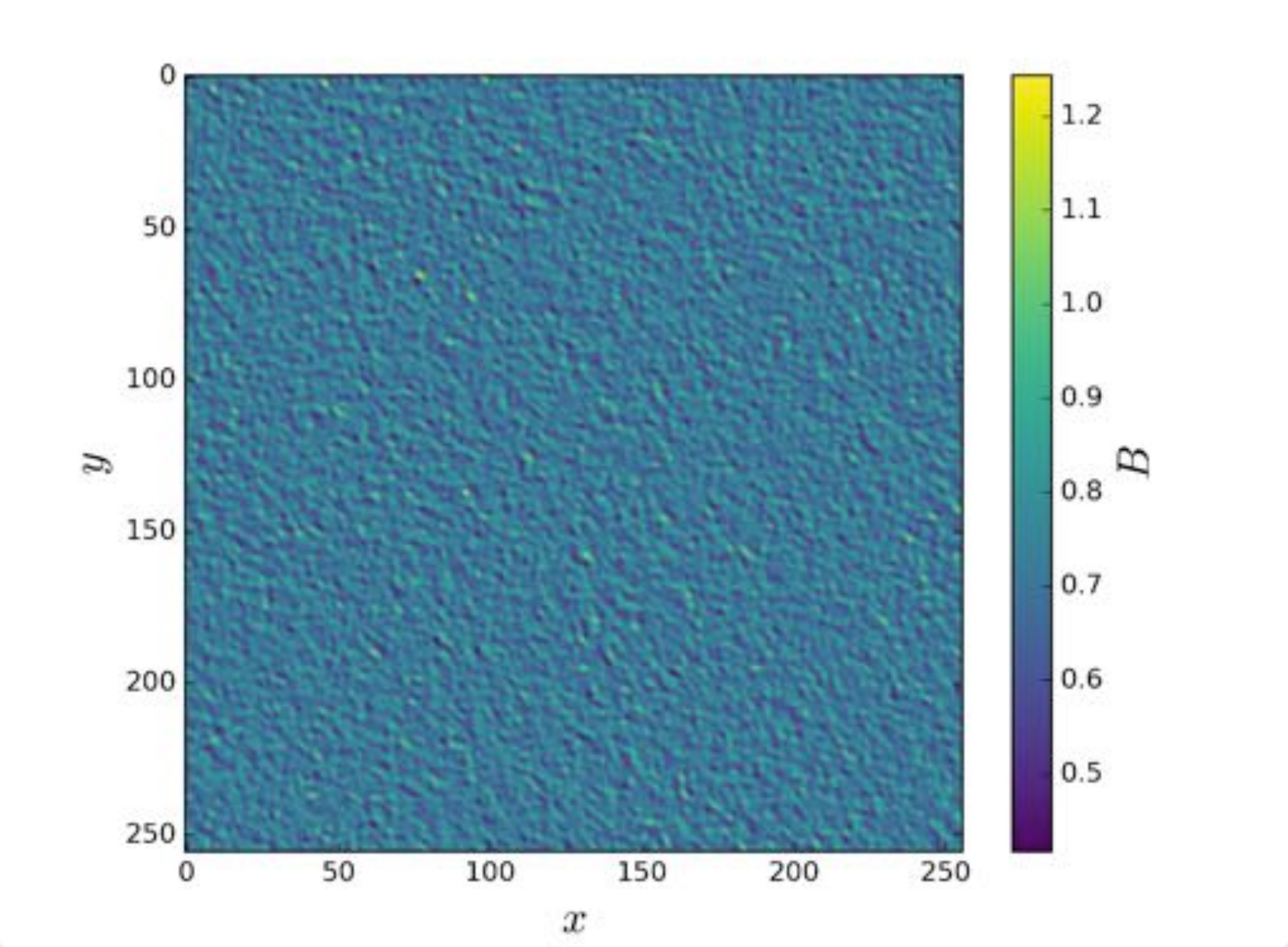
- Hillas energy: R bigger than Rg by factor $\beta^{-1} = c/u$

$$\boxed{E_H = Z\beta BR}$$

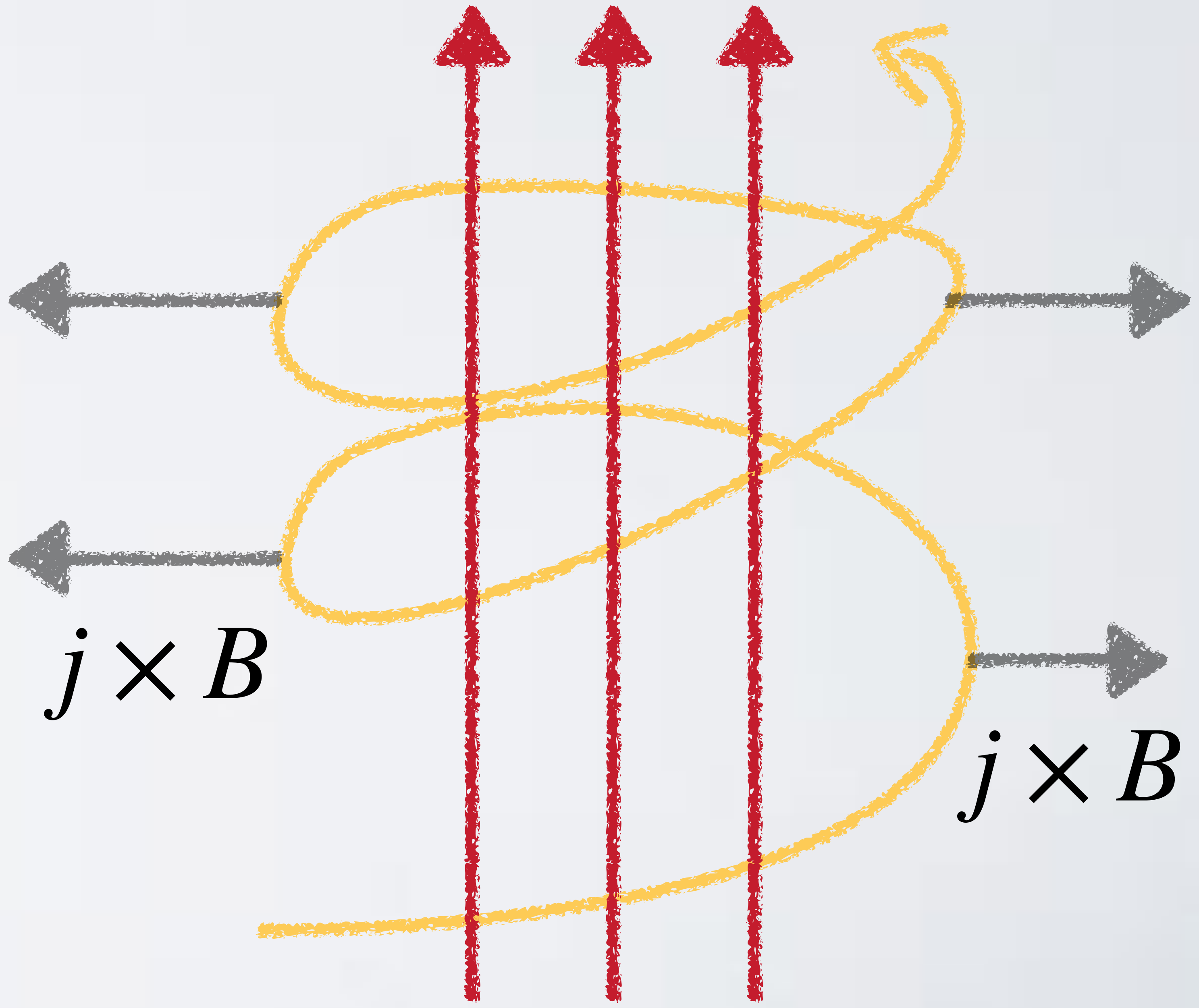
- Can be understood in various ways, e.g.:
  - Moving particle a distance R through -(u/c) x B electric field
  - Taking time derivative of magnetic flux BR^2 to give potential drop βBR

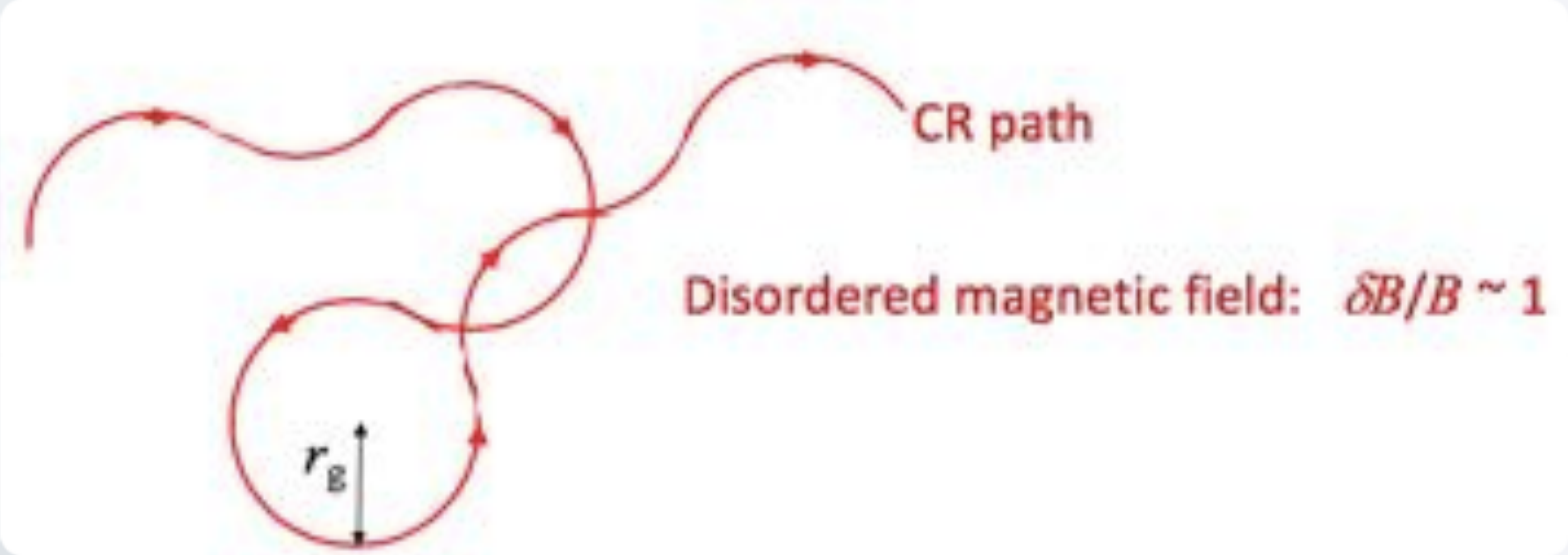
CR-driven instabilities

- Even without losses, 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

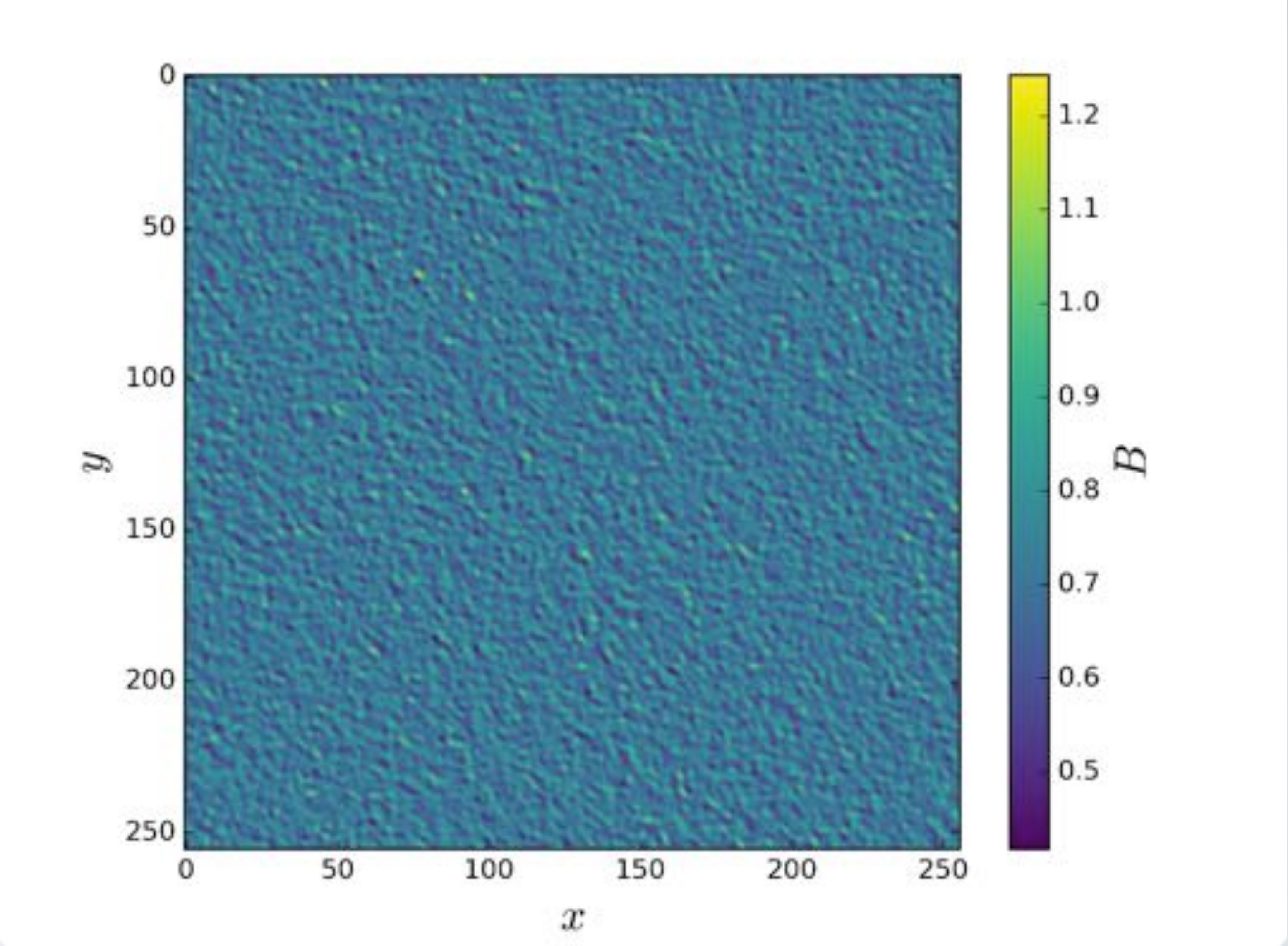




* Other instabilities are available

CR-driven instabilities

- Even without losses, 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.



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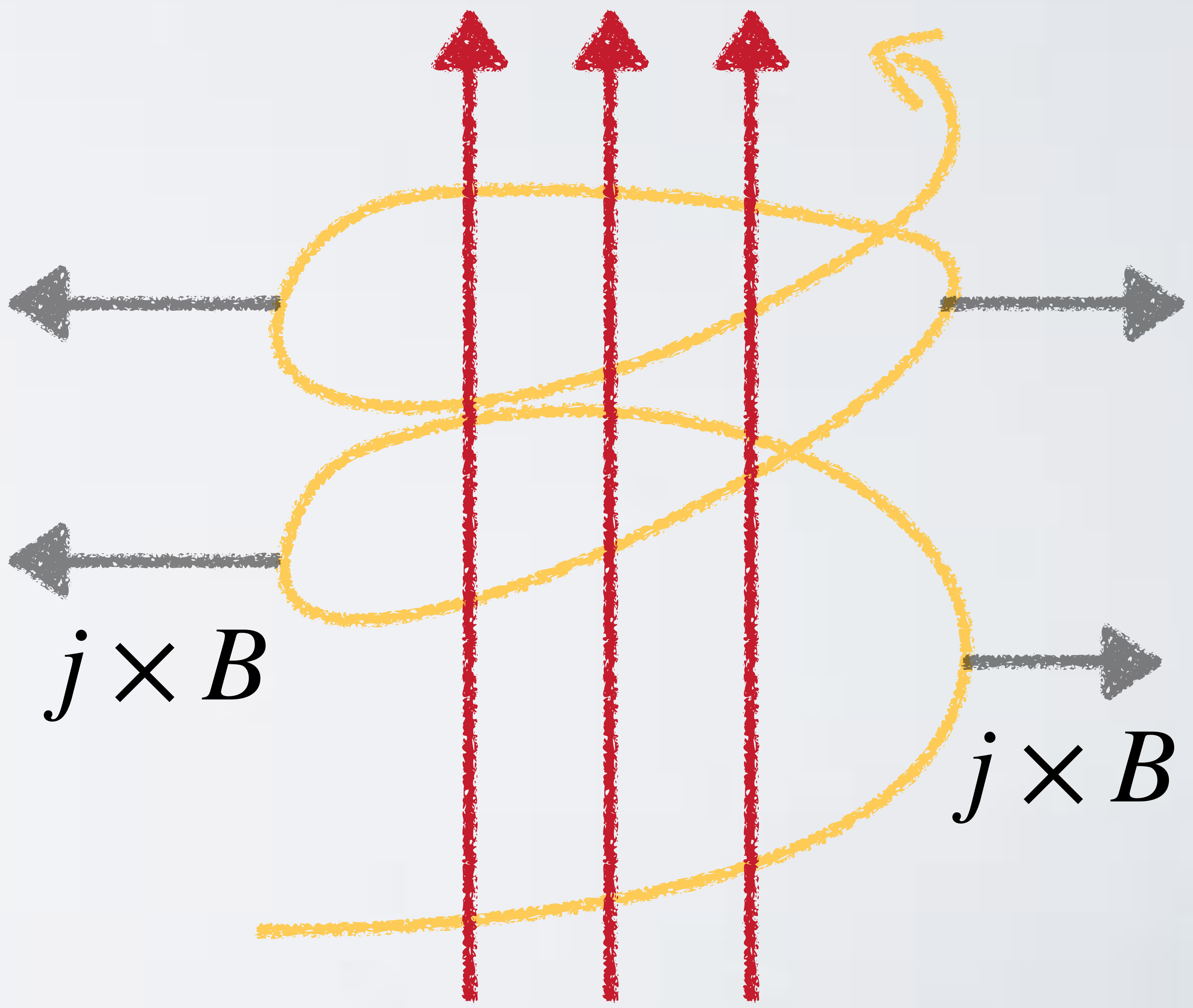

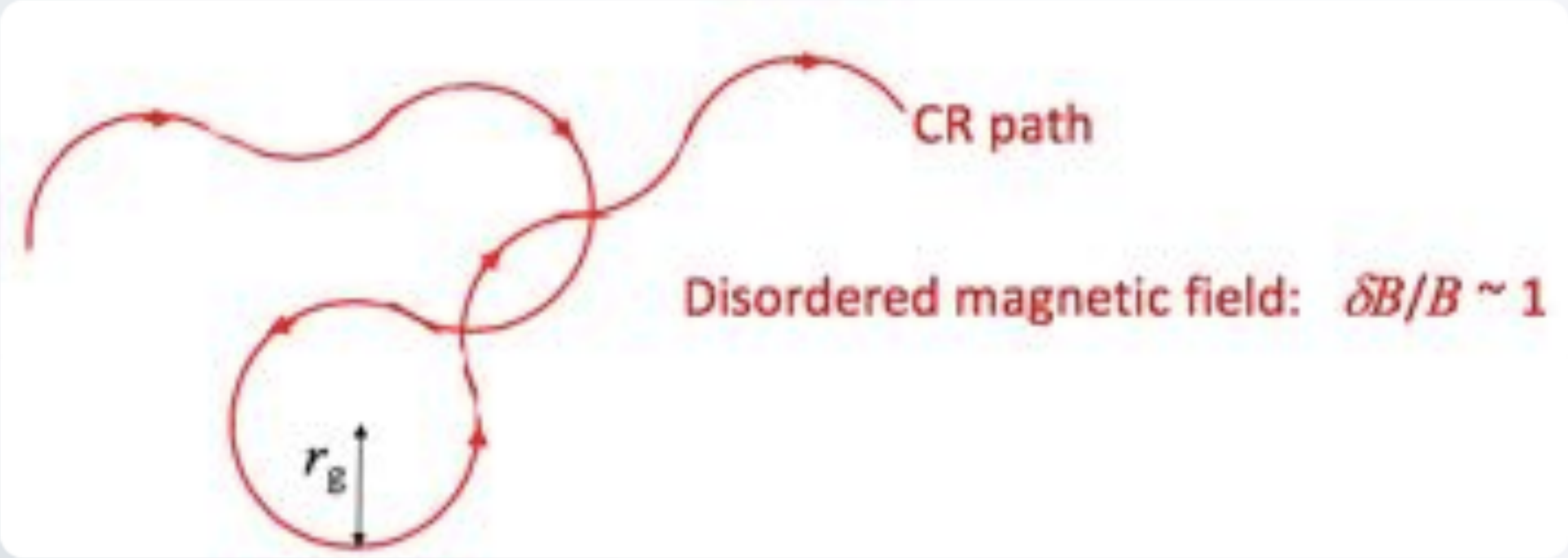

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Relativistic shocks

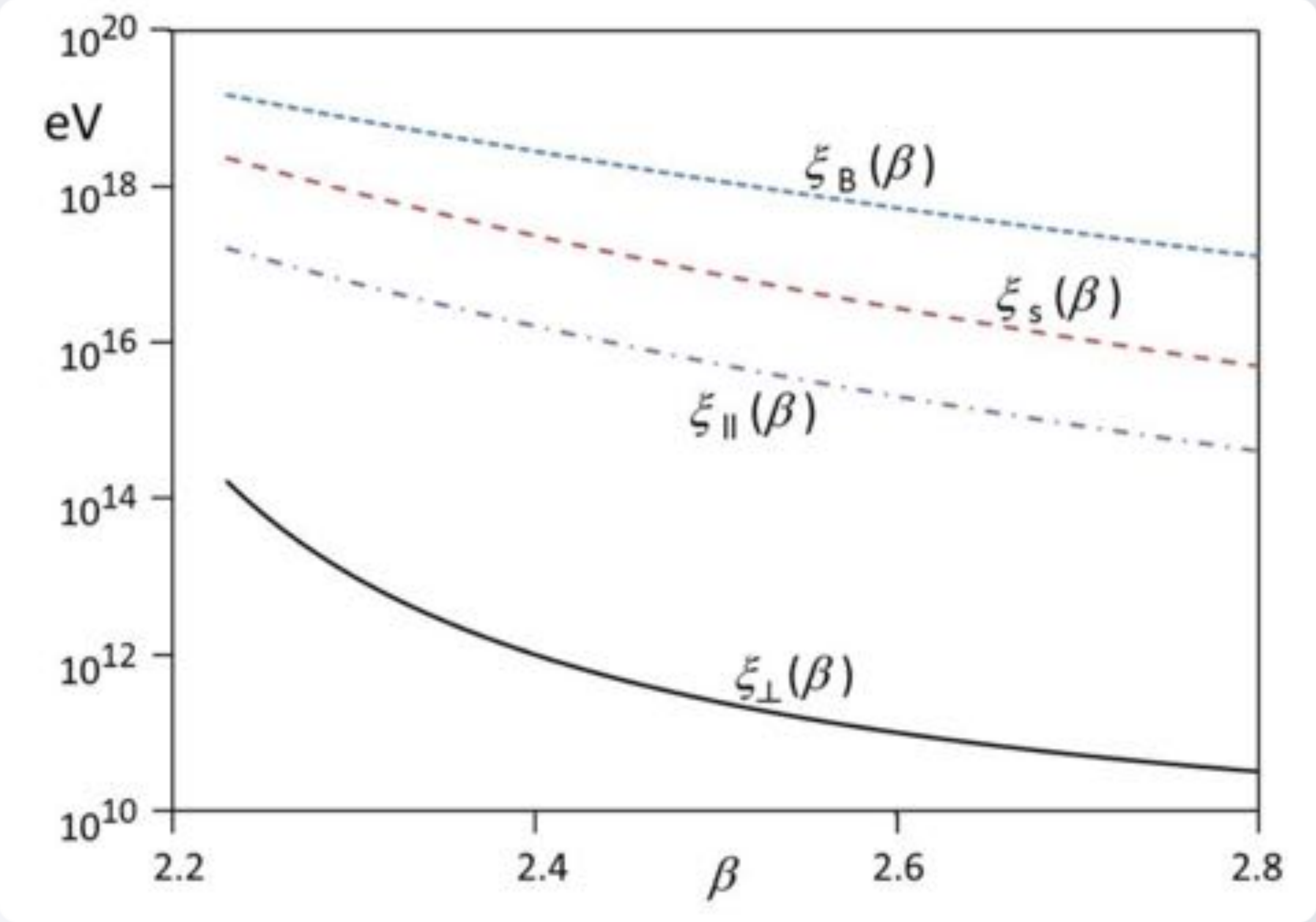
Bell+ 2018

- Relativistic shocks can be effective particle accelerators (e.g. Sironi & Spitkovsky 2011, Haugbølle 2011)
- Difficulty is getting particles to return from downstream - key is probably small-scale (skin depth) instabilities like Weibel instability
- Simple diffusion treatment breaks down, spectral index becomes steeper and shock is quasi-perpendicular
- Multiple authors have demonstrated that the maximum energy is limited in relativistic shocks (Lemoine & Pelletier 2010, Reville & Bell 2014, Bell et al. 2018)

$$E_{\max} \approx \left(\frac{\Gamma_{\rm sh}}{100}\right)^2 \left(\frac{\lambda_{\rm d}}{10c/\omega_{\rm pp}}\right) \left(\frac{\sigma_{\rm d}}{10^{-2}}\right) \left(\frac{\sigma_{\rm u}}{10^{-8}}\right)^{-1/2} \ \mathrm{PeV}$$

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?"



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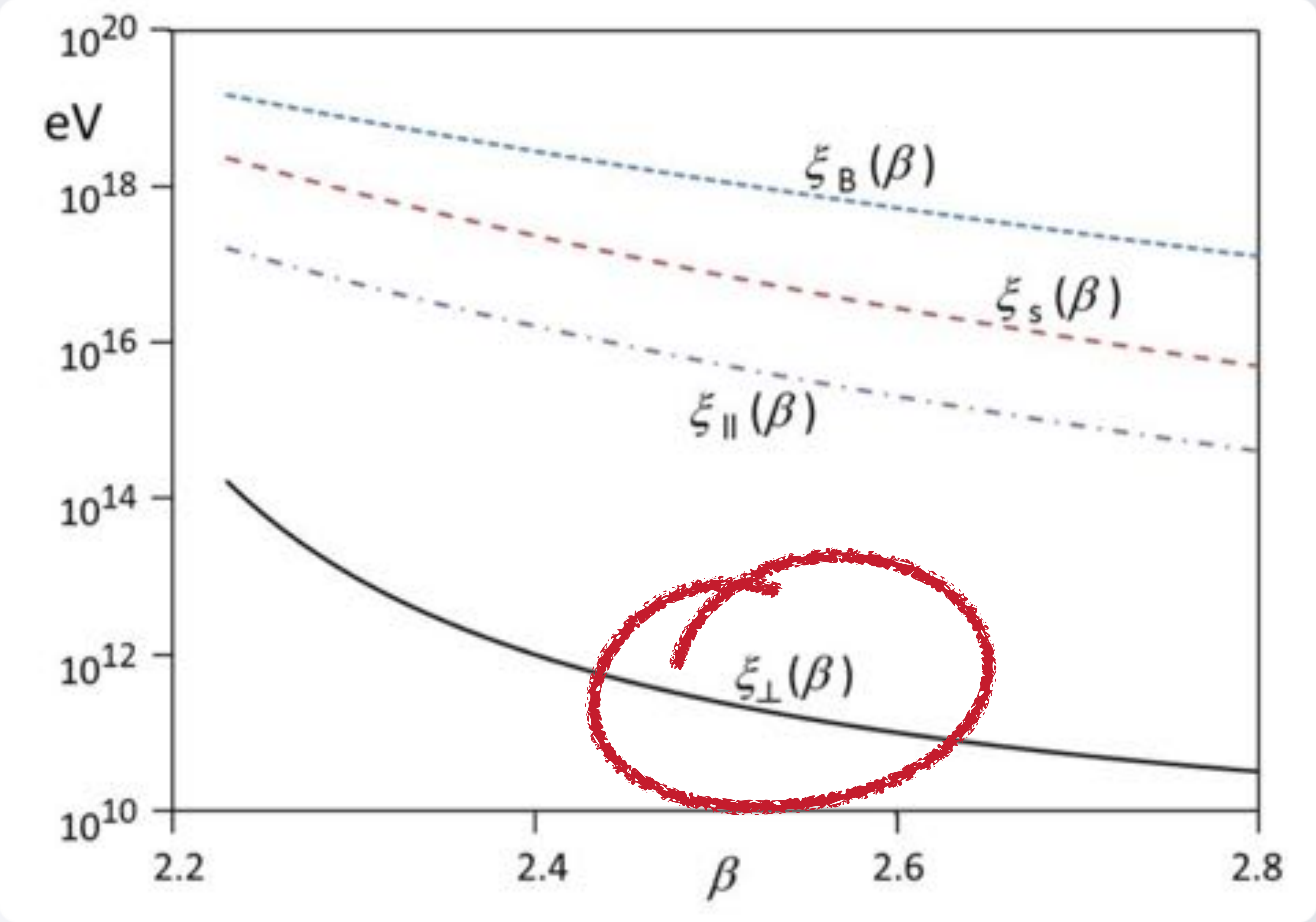
Shock and B-field physics

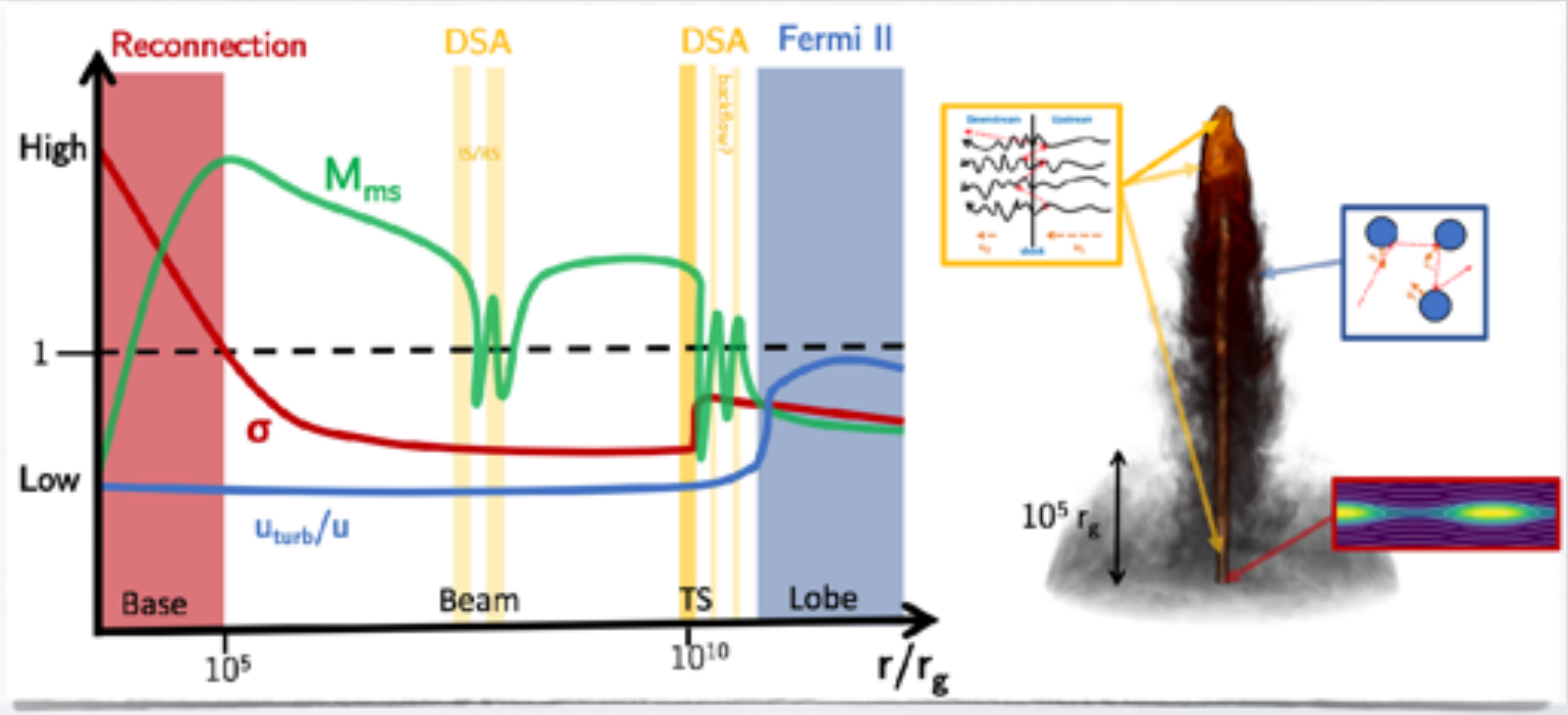


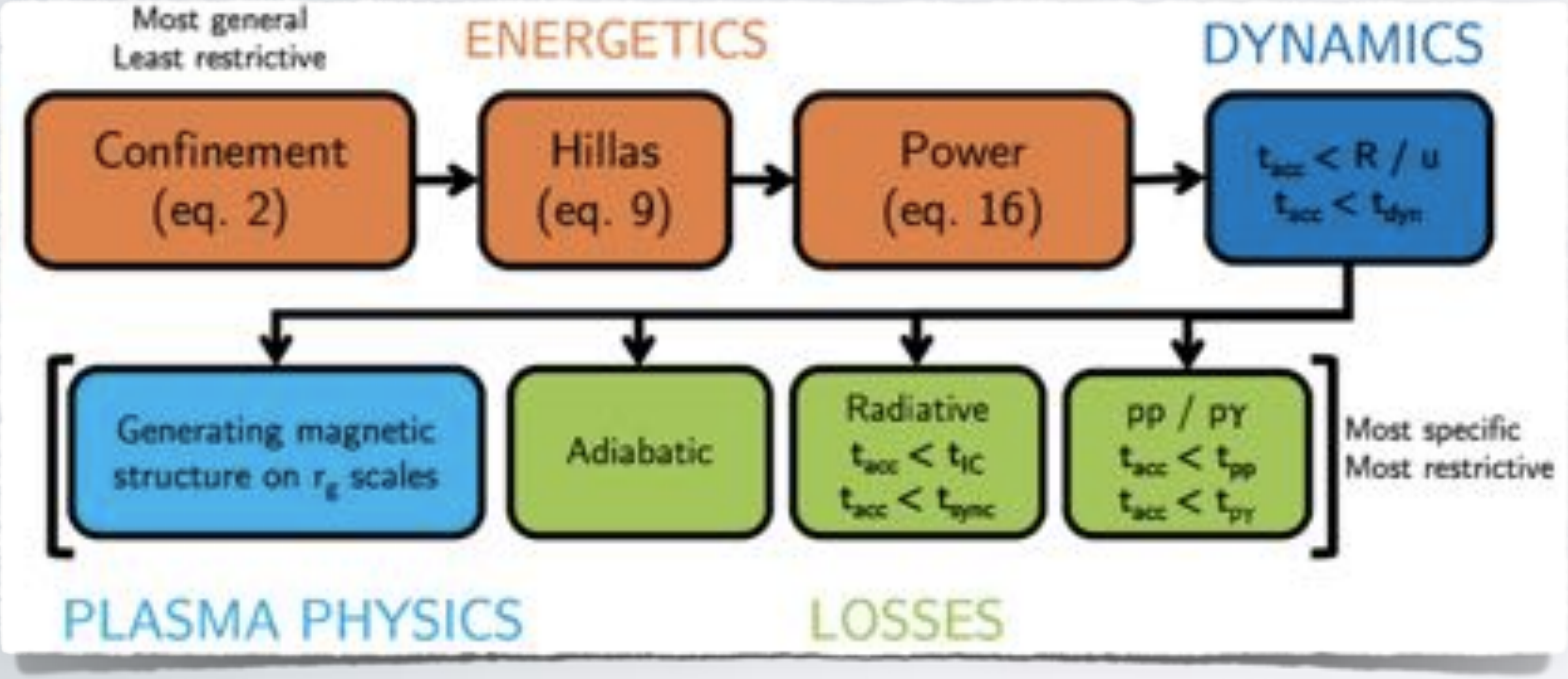
Steeper energy spectra

SCHEMATIC PHYSICS

"100 years of jets" anthology, Eds: Wijers, Fender.

In jets, which mechanisms operate where?





What sets the maximum particle energy?

Schematic Physics

"100 years of jets" anthology, Eds: Wijers, Fender.

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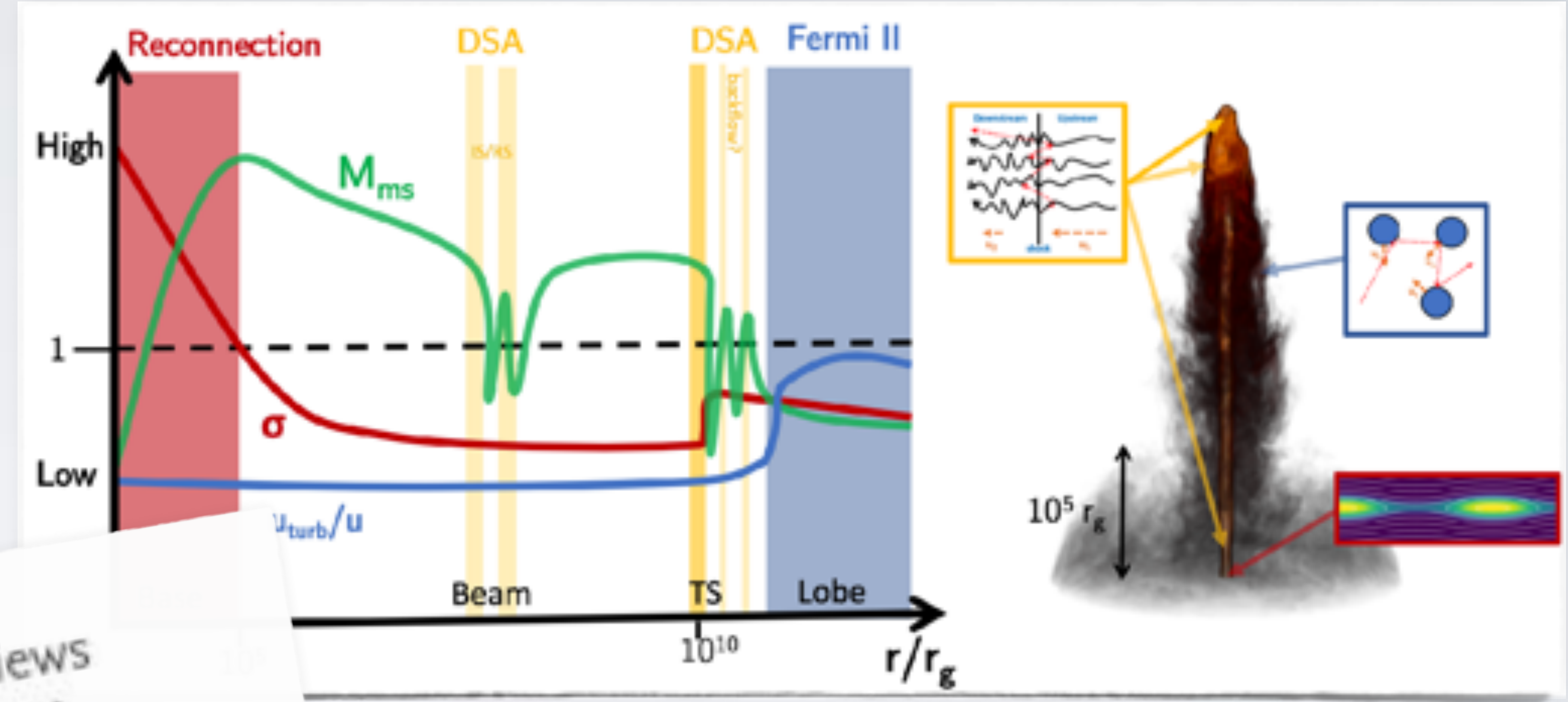
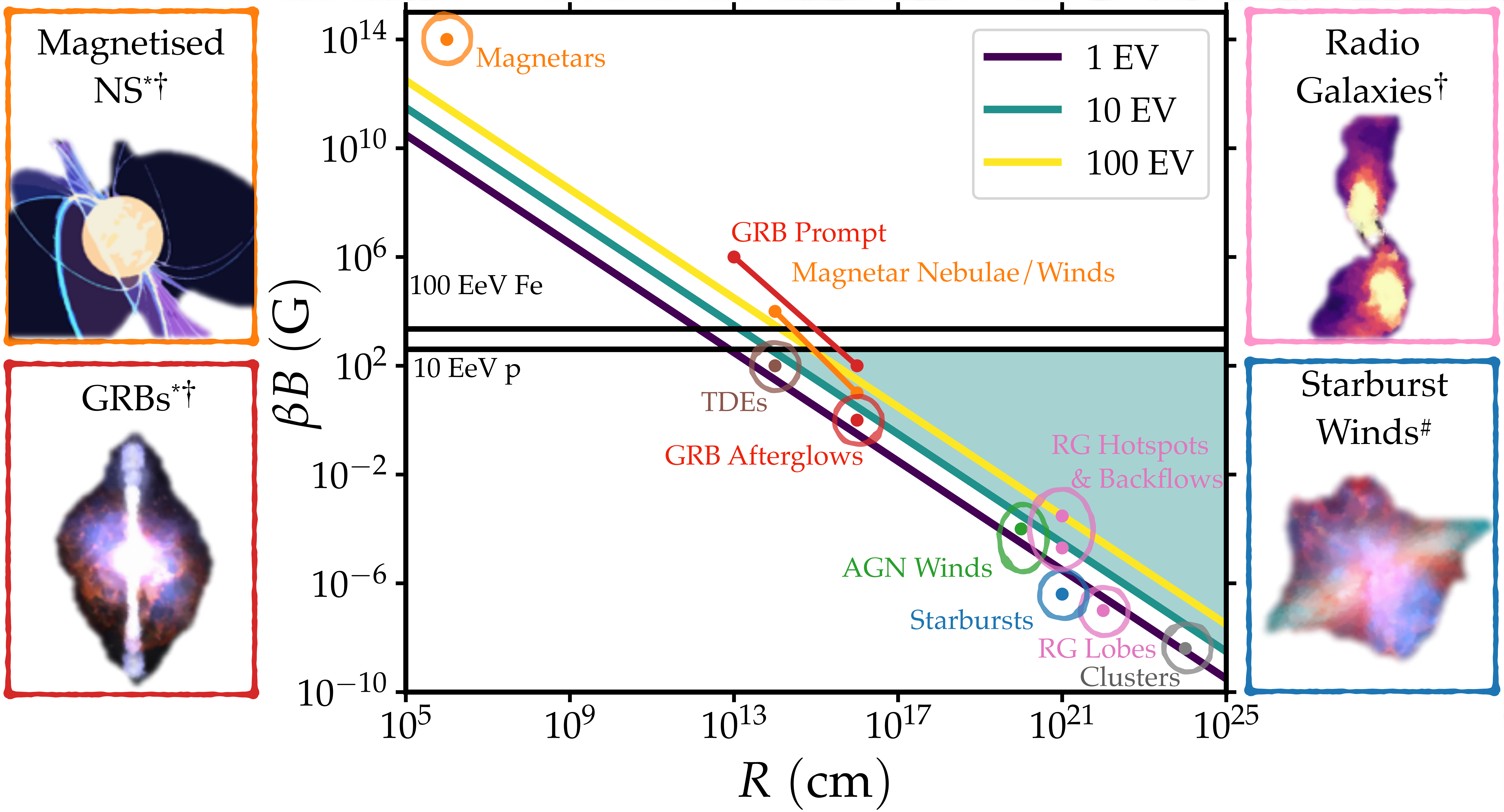


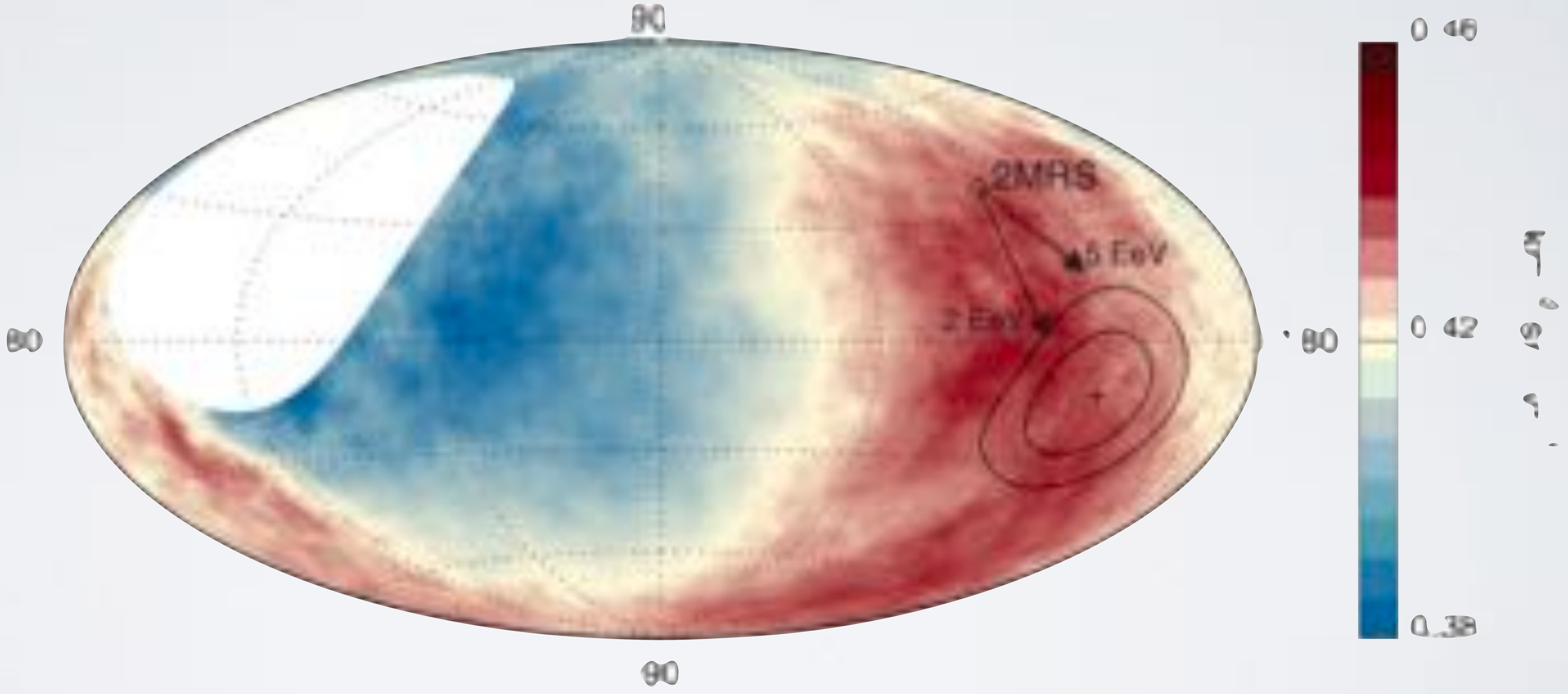
What sets the maximum particle energy?

A Modified Hillas Diagram

Matthews & Taylor 2023



4. Where do UHECRs come from?

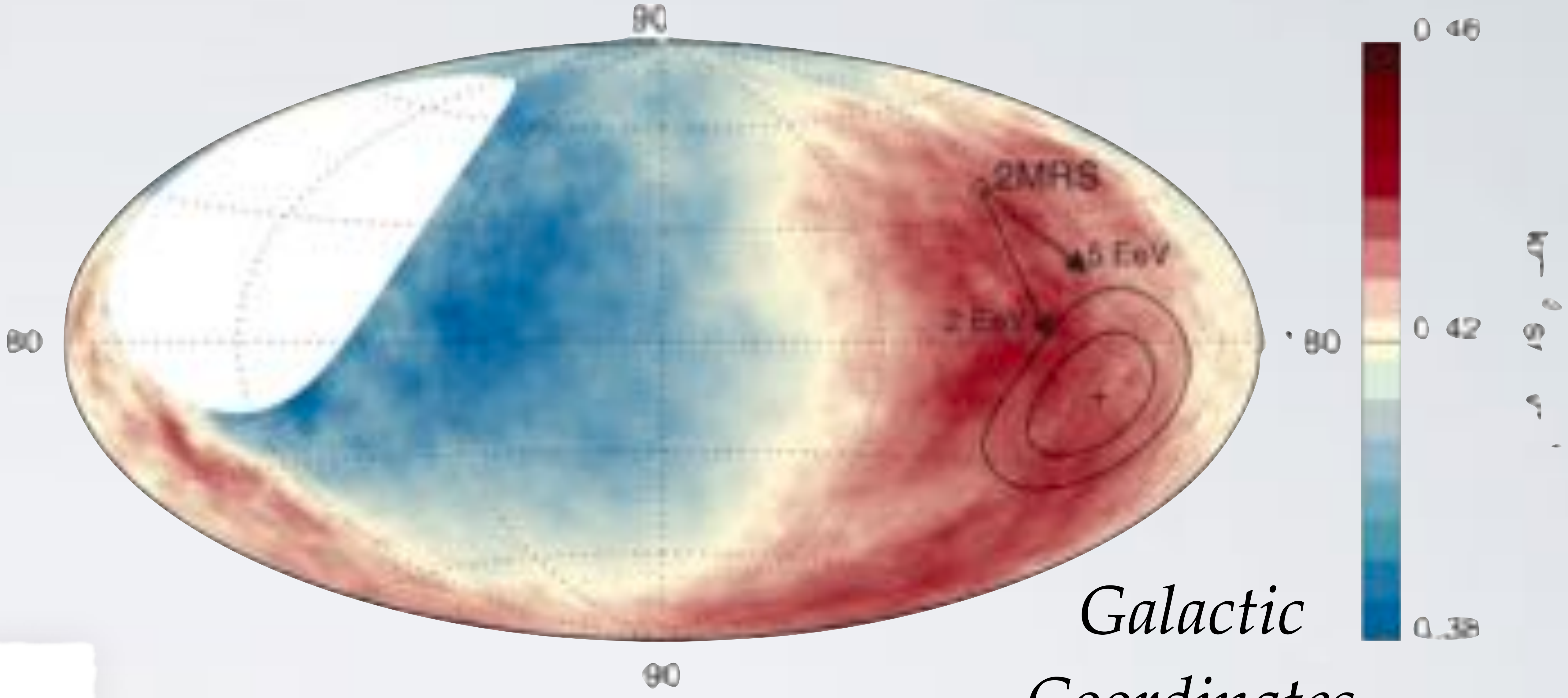


UHECR Anisotropies (Auger)

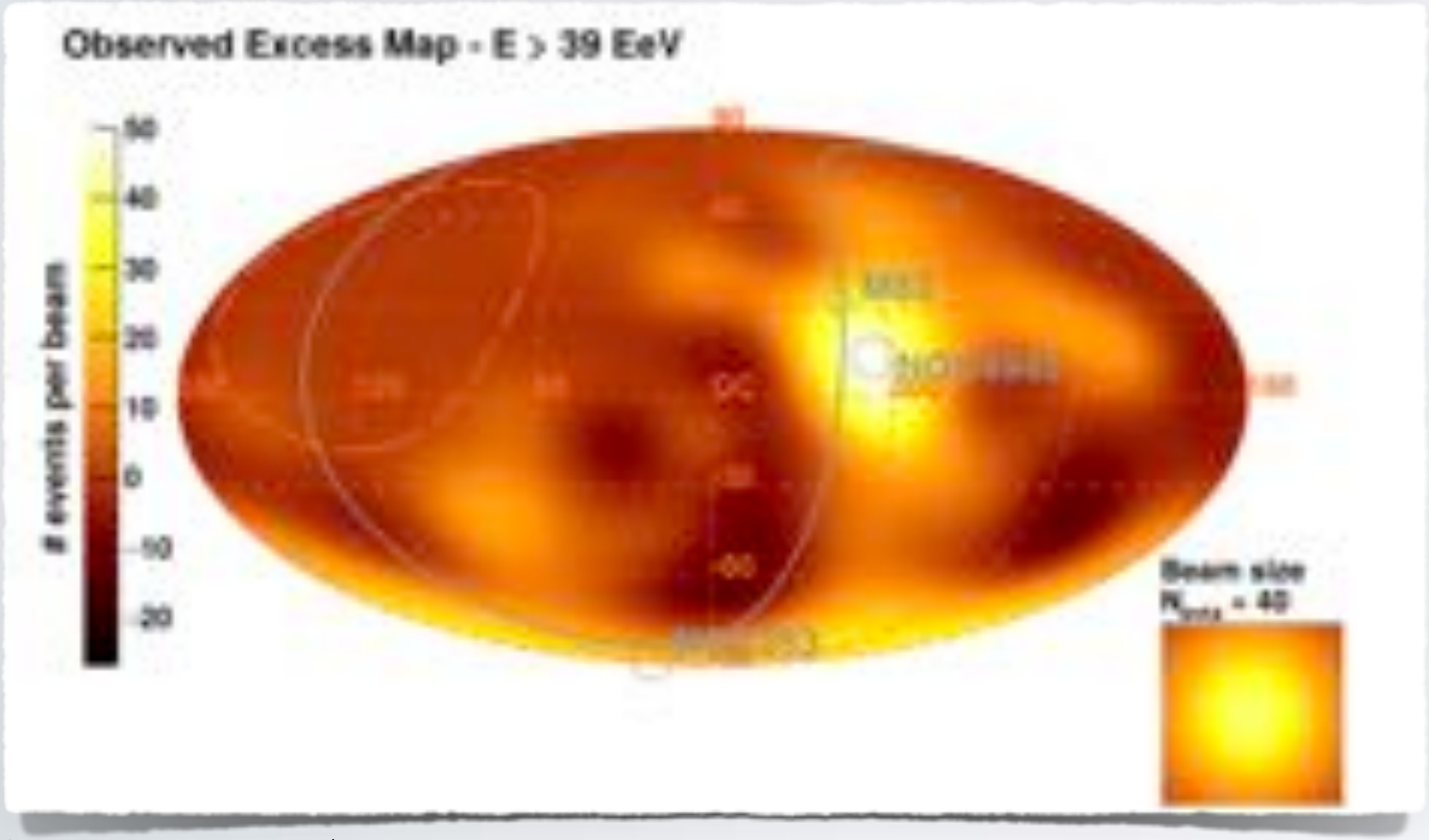
Dipole in Auger data at >8 EeV (PAO 2017)

5.2σ Significance

Spectacular!



Galactic Coordinates



Galactic Coordinates

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

Significance: ~3σ (AGN), ~4σ (SBGs)

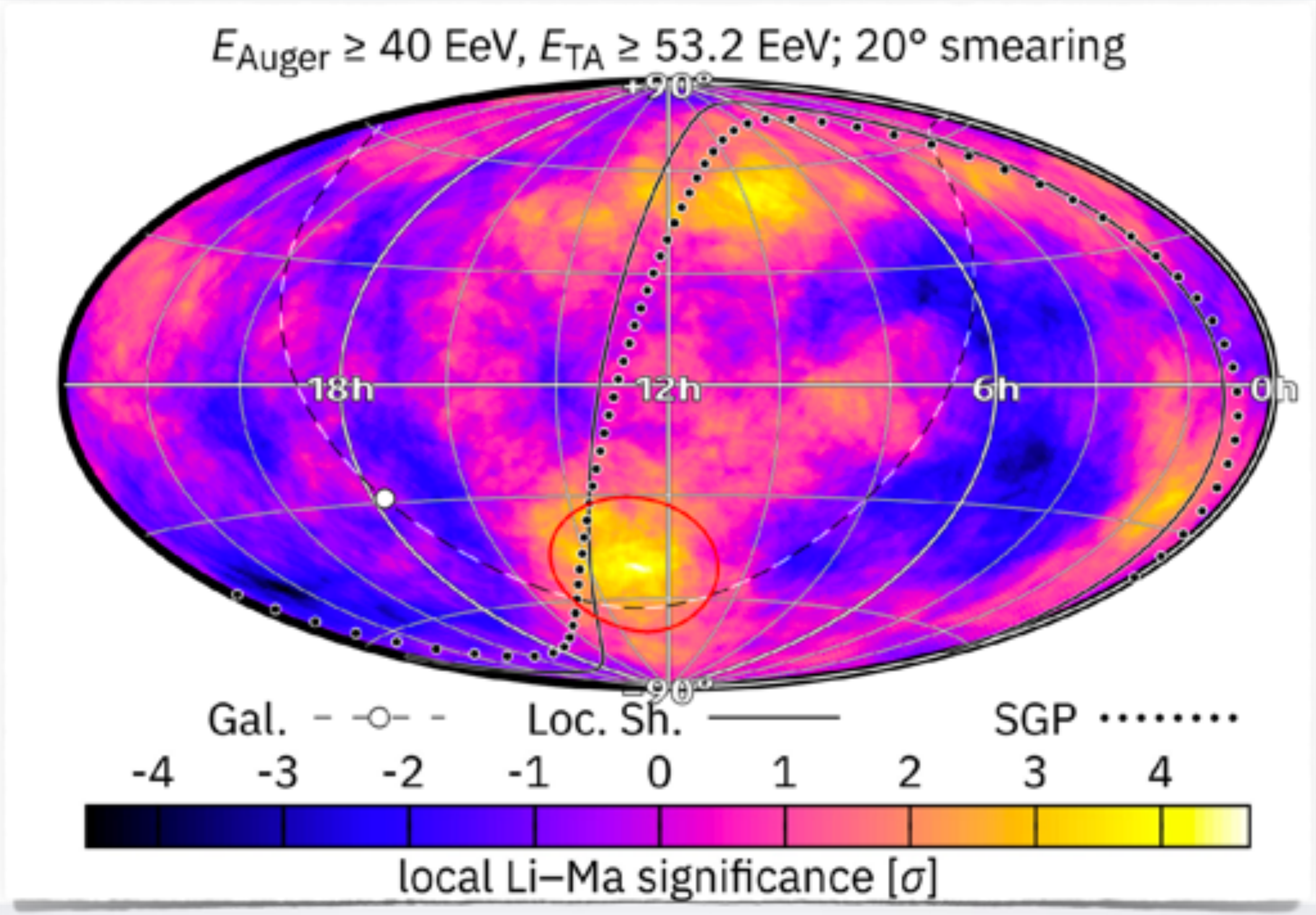
More model-dependent than dipole

UHECR Anisotropies (All-Sky)

Suggestive of an all-sky correlation with supergalactic plane or local sheet?

Di Matteo+, ICRC 2021

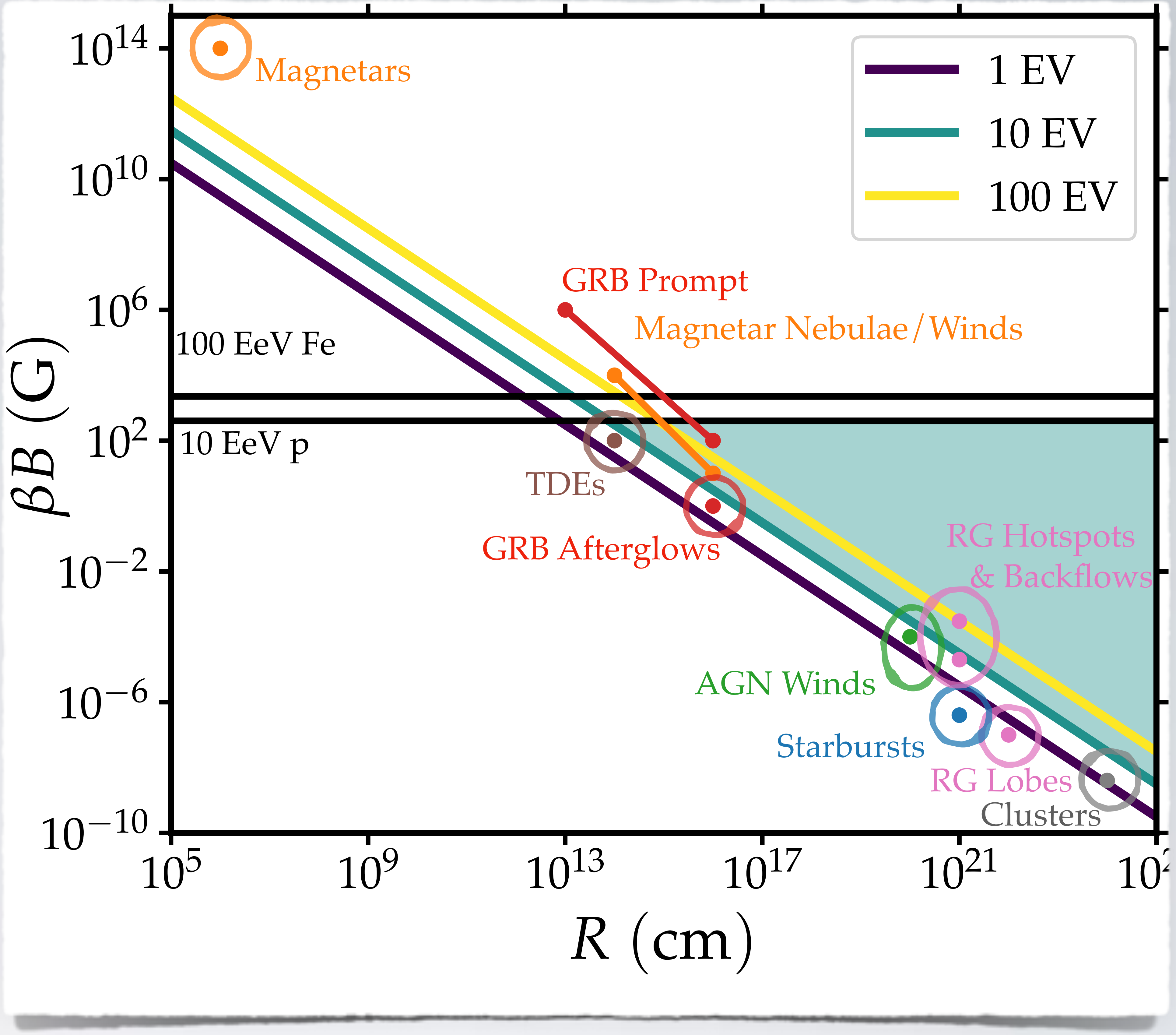
Unambiguous source IDs still not possible…



Equatorial Coordinates

UHECR CANDIDATES

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



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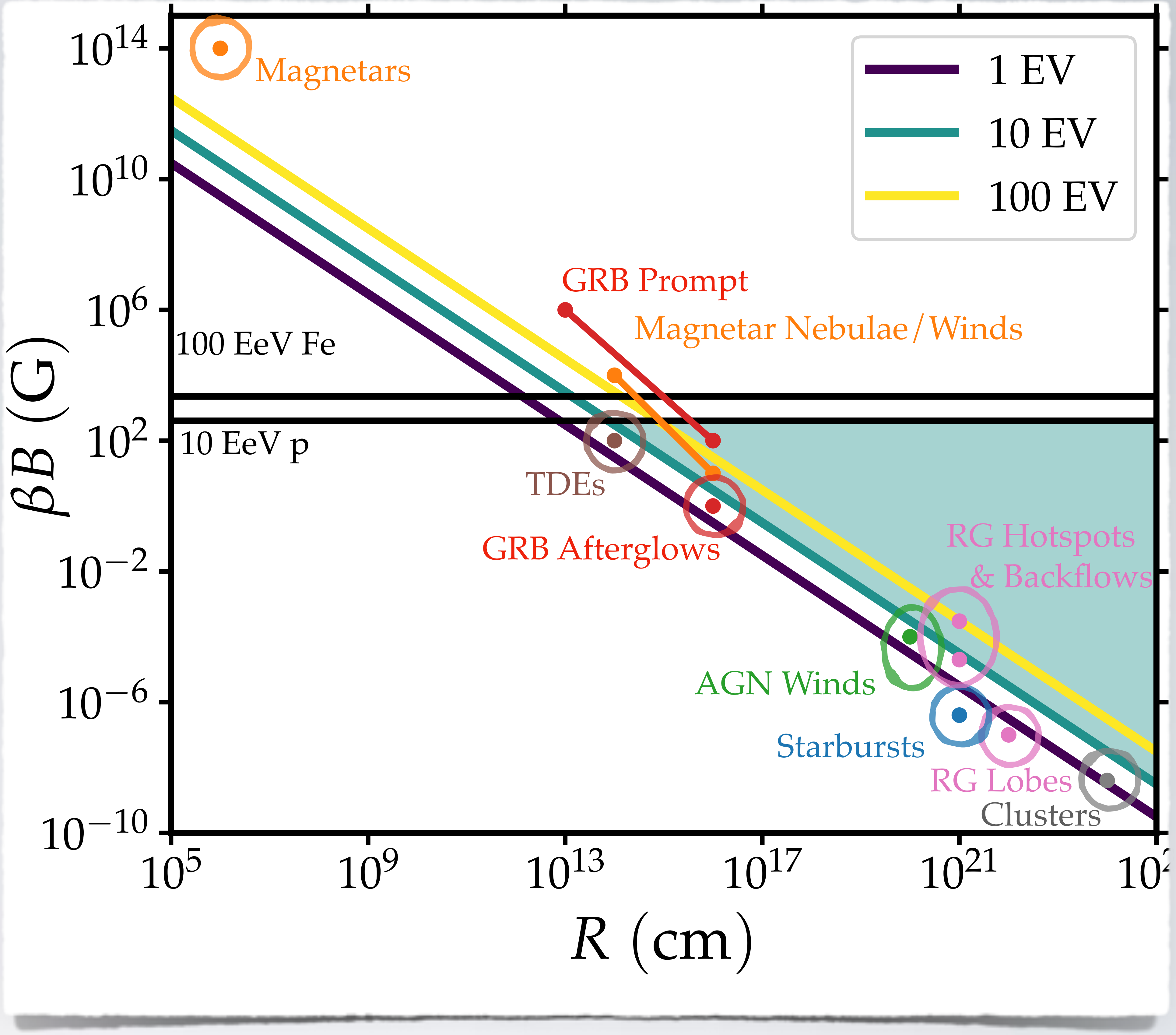
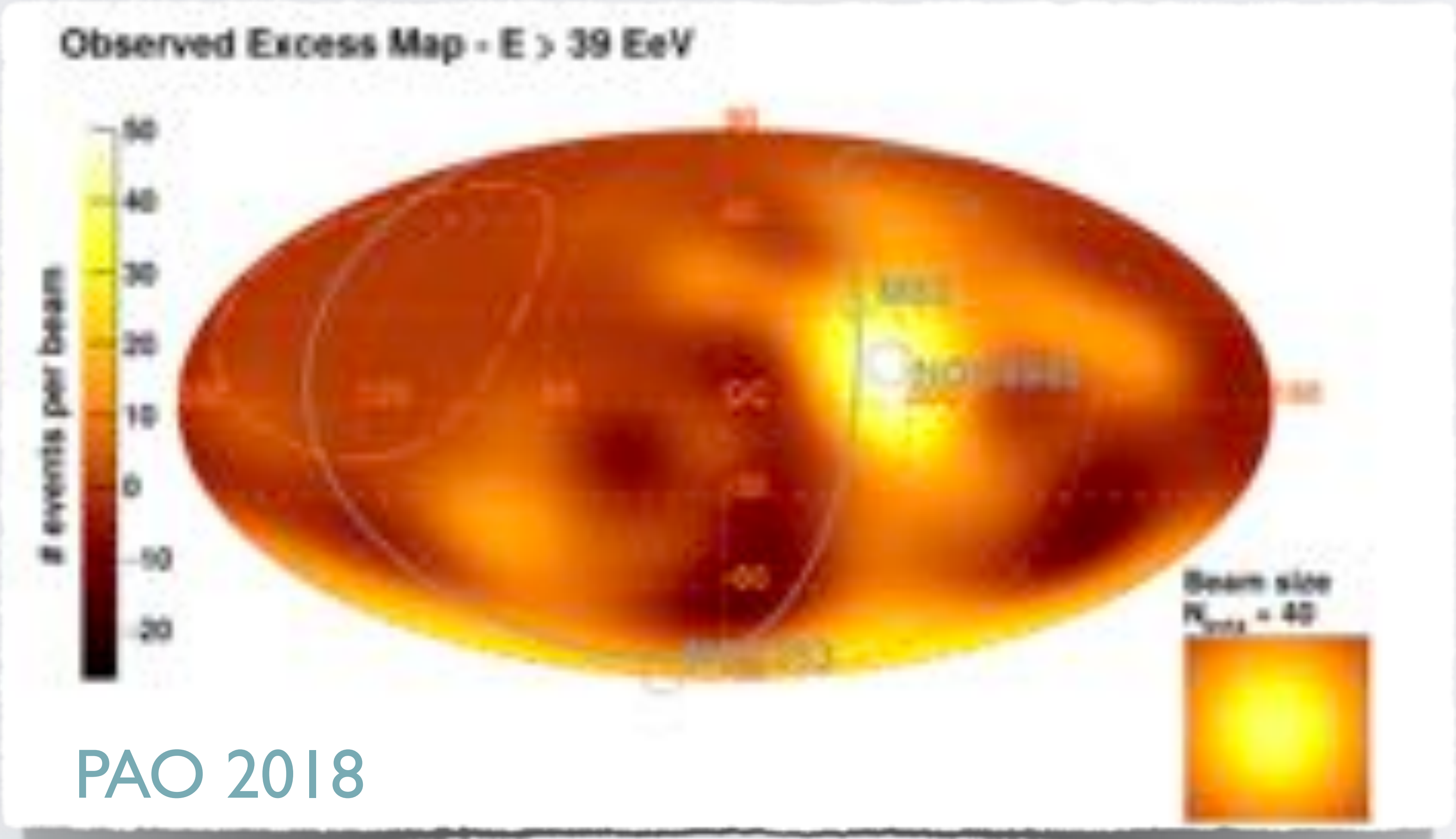


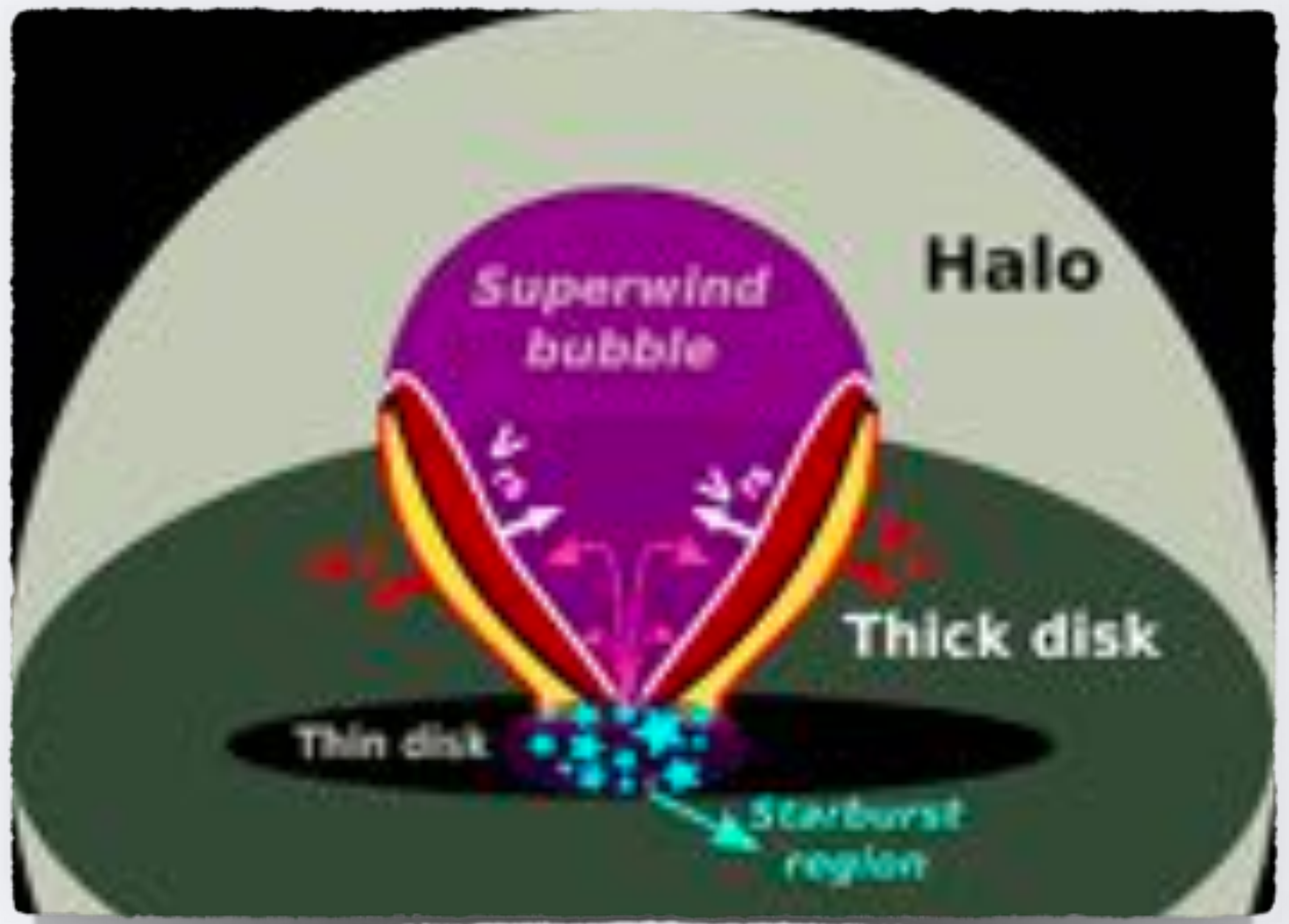
STARBURST WINDS

- 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)

Romero+ 2018



PAO 2018



Can Starburst Winds Do It?

- …I don't think so.

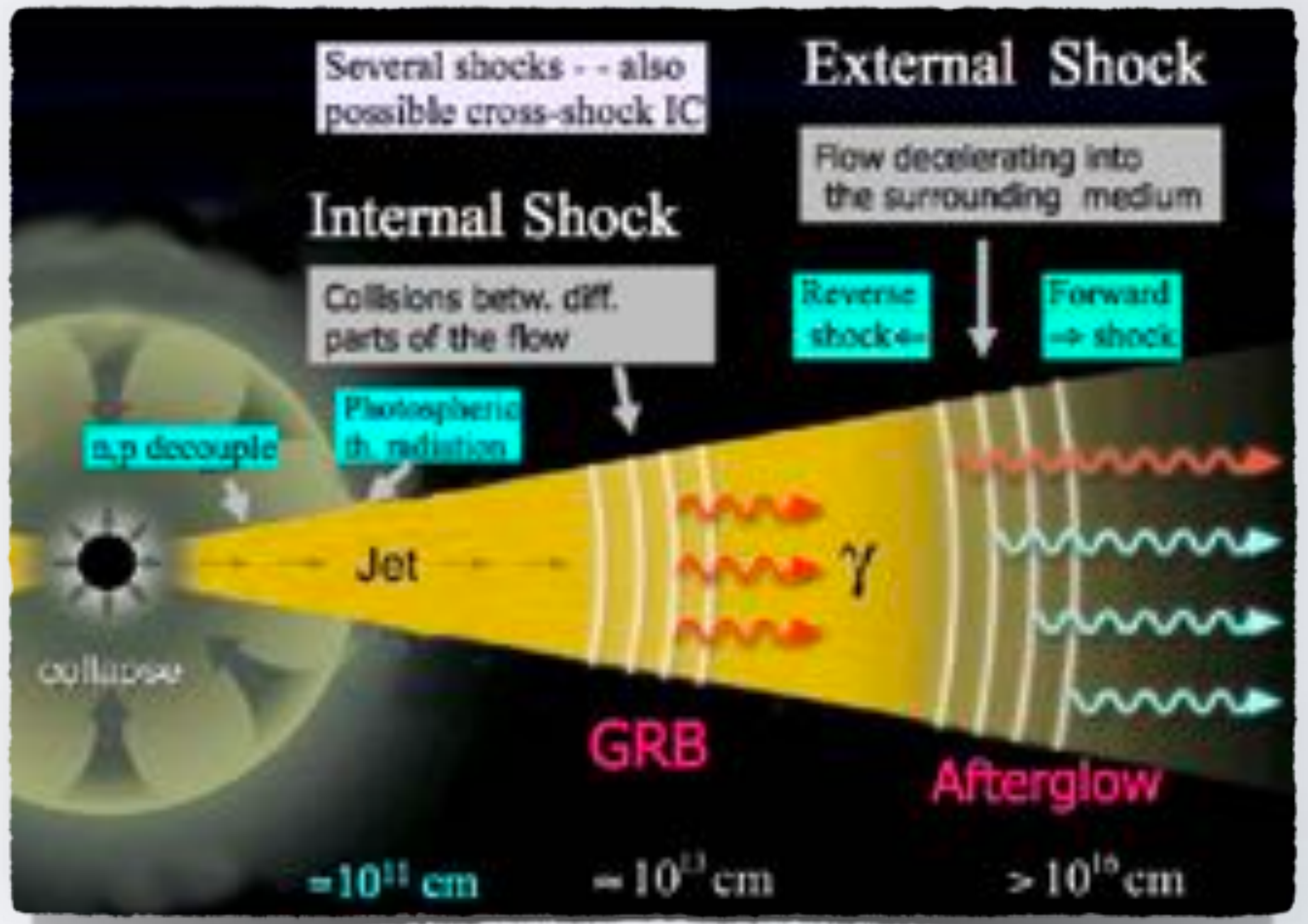
- Even assuming high efficiencies, superwinds in starburst galaxies like M82 have powers of ~10^{42} erg/s and shock velocities of ~1000 km/s (Heckman+ 1990; Strickland & Stevens 2000; Romero+ 2018)

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

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

GAMMA-RAY BURSTS

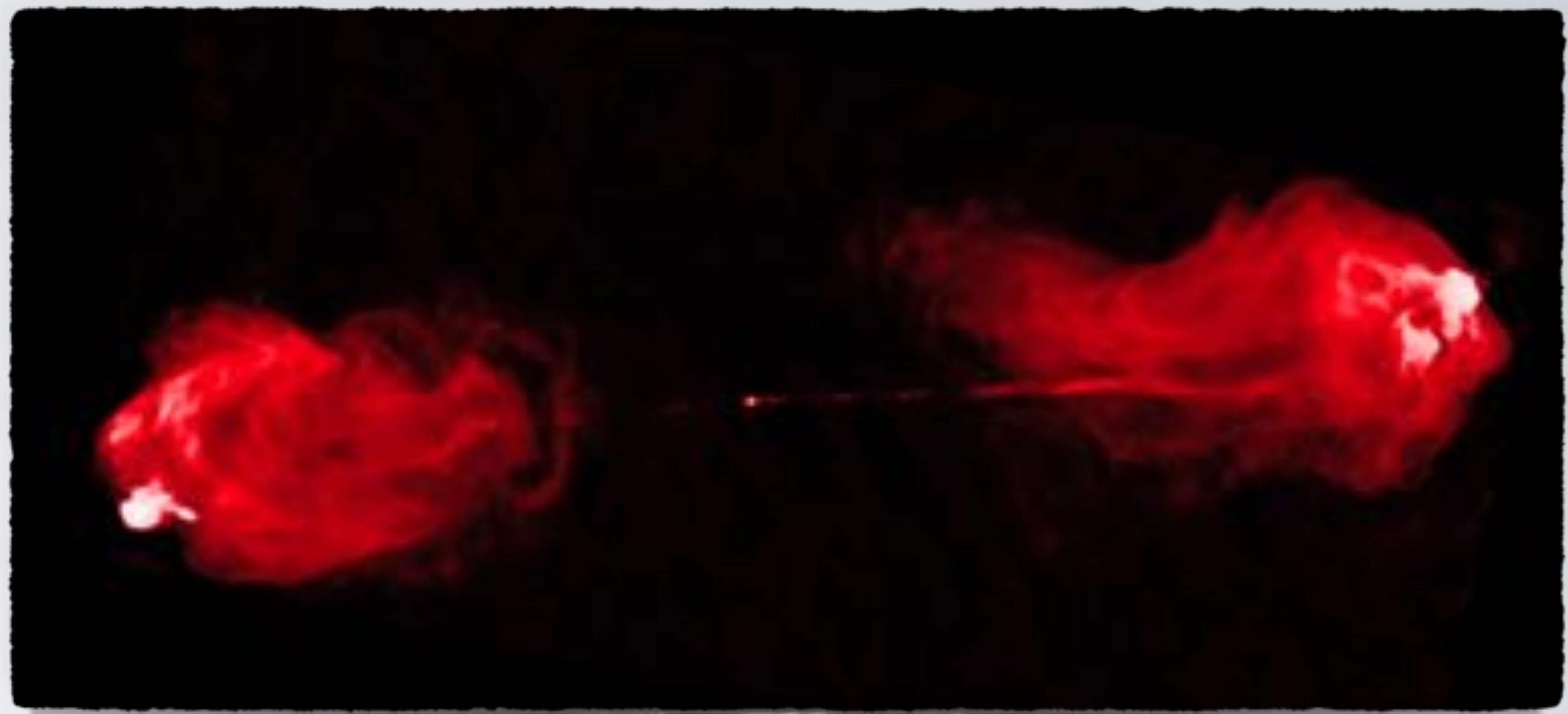
- Loads of power!!!
- Pioneering work by Waxman (1995) suggests GRB internal shocks as accelerators
- Need high baryon loading and high efficiencies to explain observed UHECR flux (e.g. Baerwald+ 2014, Globus+ 2015)
  - Although see GRB221009 results…
- Shocks are highly relativistic which prohibits UHECR acceleration (e.g. Reville & Bell 2014, Bell+ 2018)

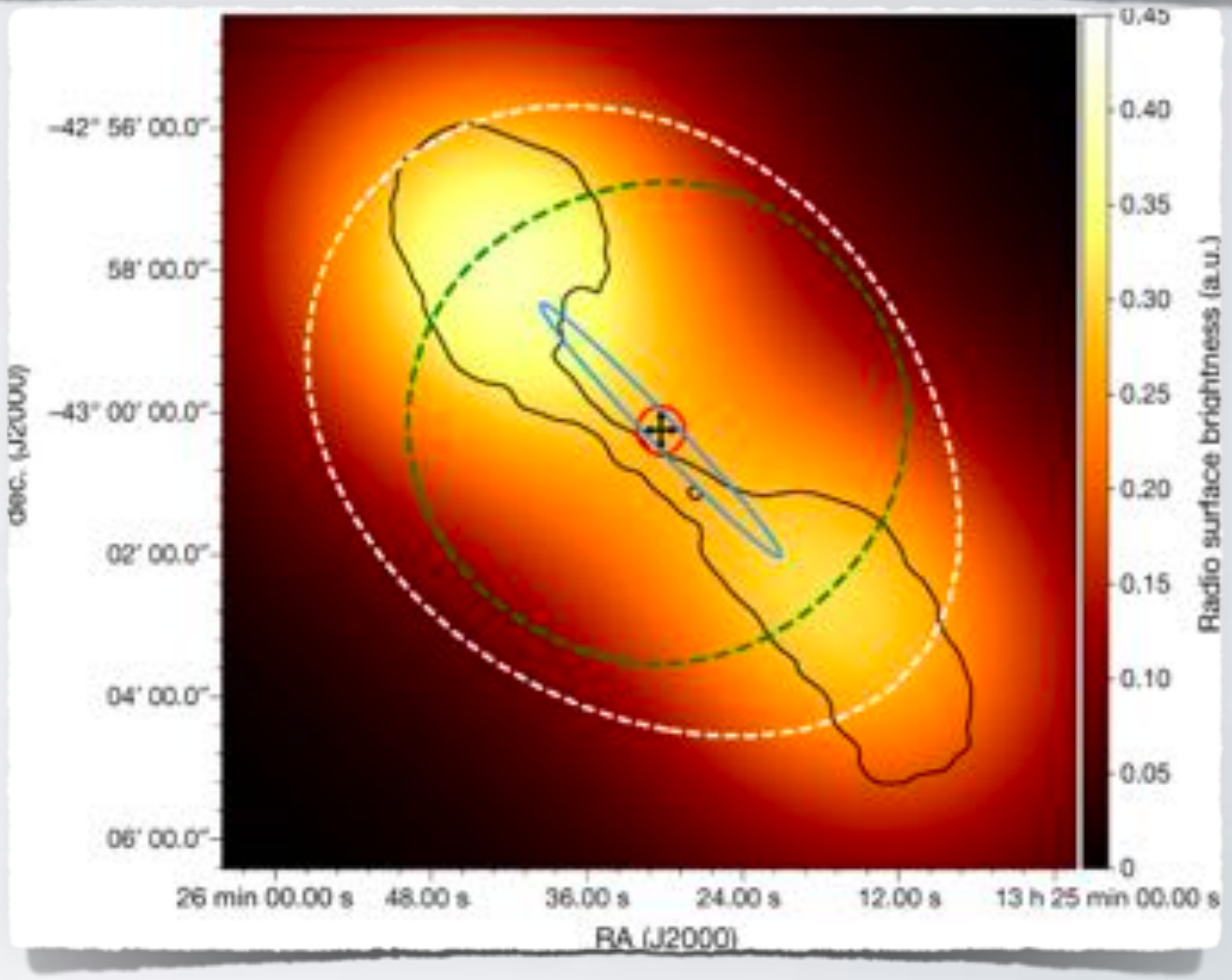


RADIO GALAXIES

- 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!

Cygnus A, VLA image





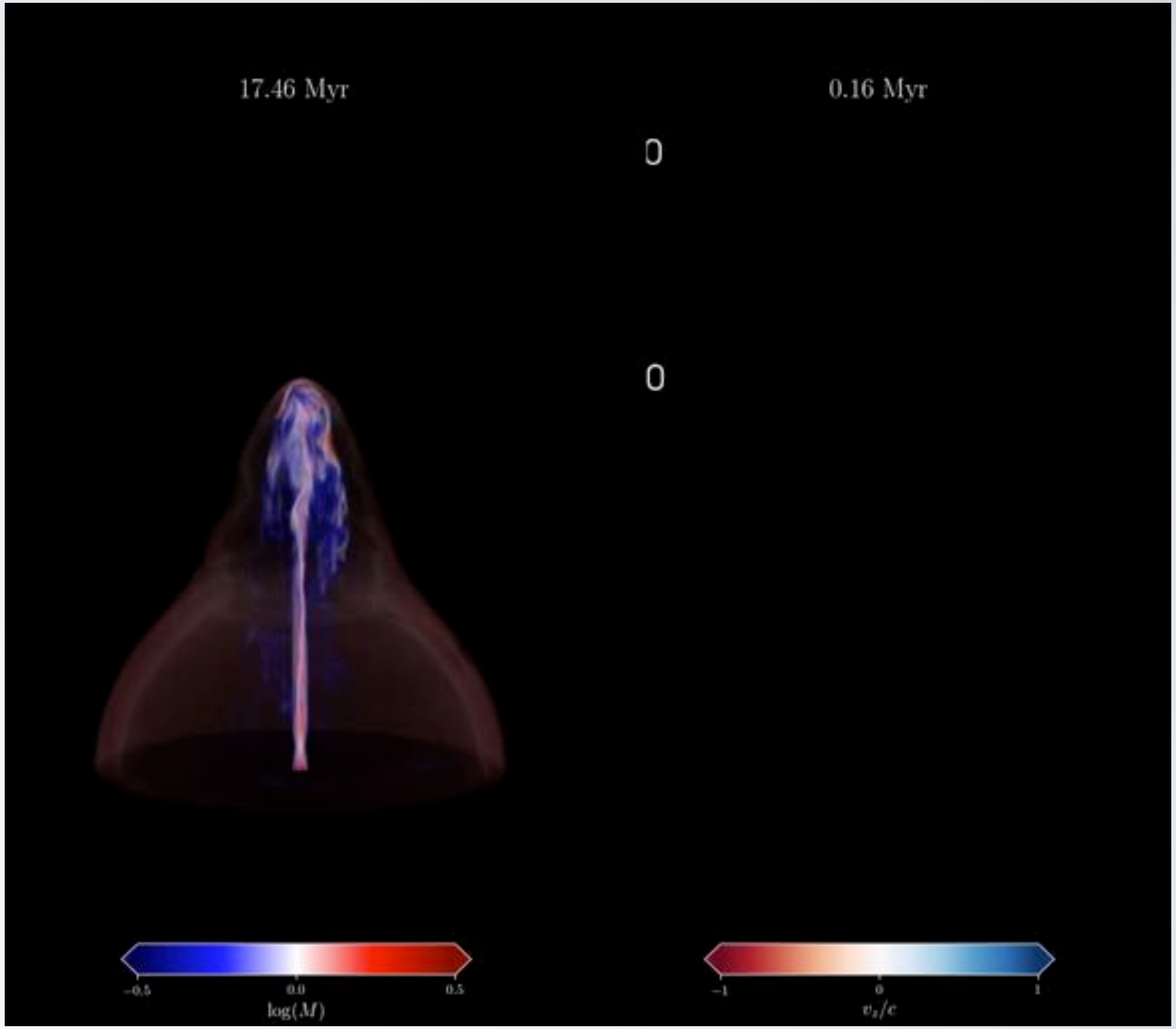
Cen A, H.E.S.S. collaboration

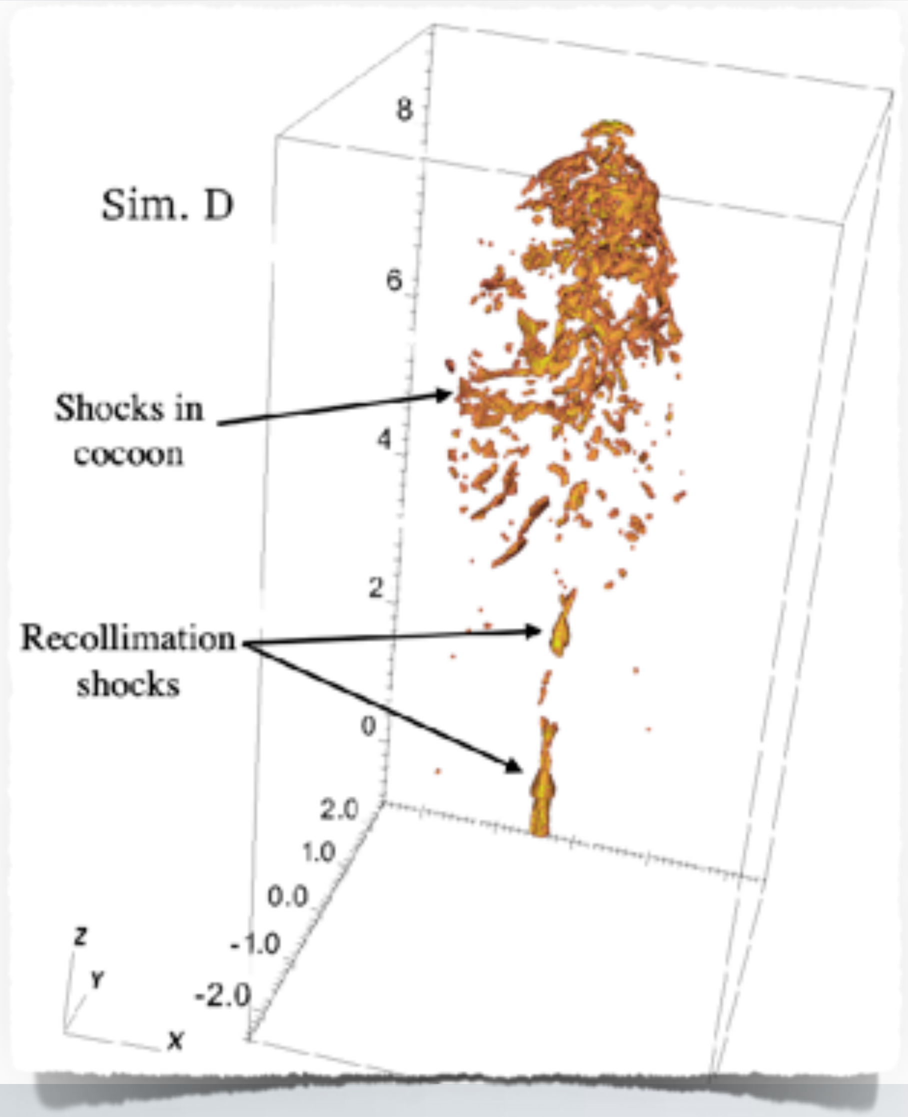
UHECRs from jet backflows

Matthews+ 2019a,b

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

- 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

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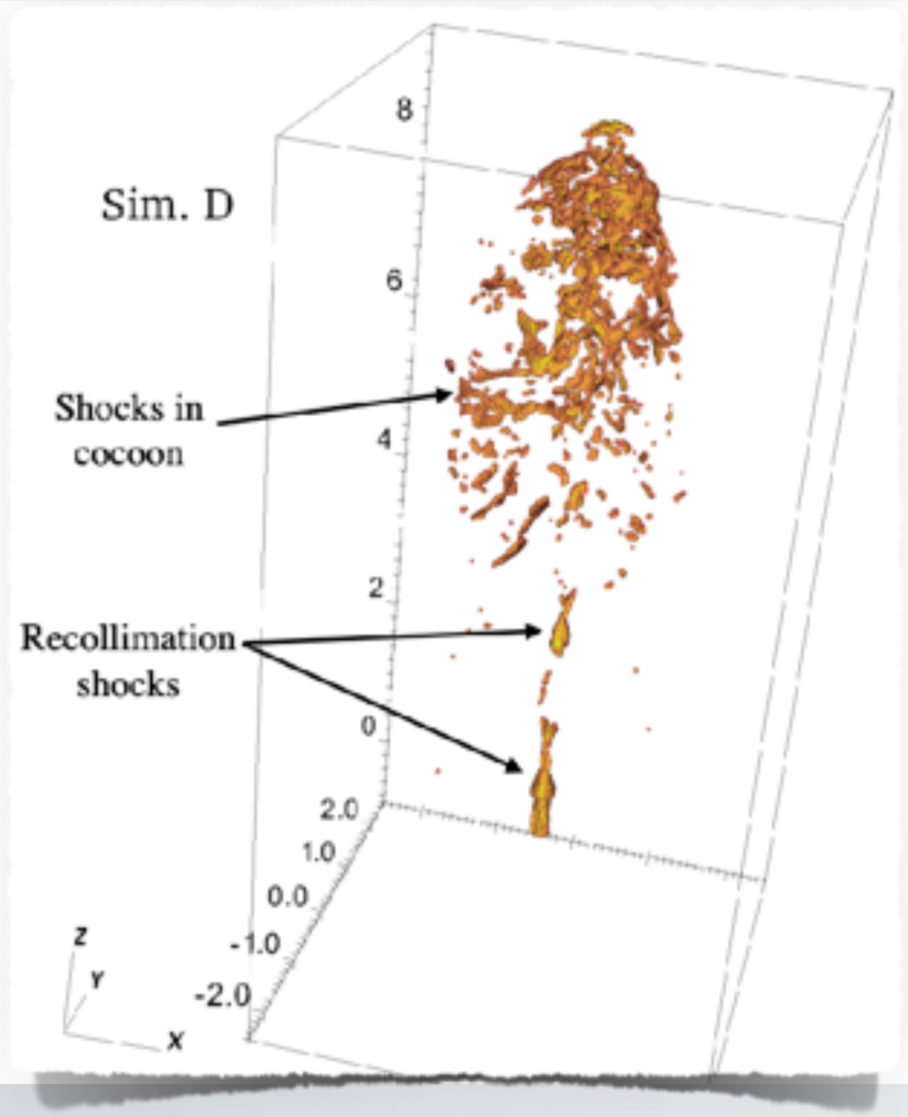
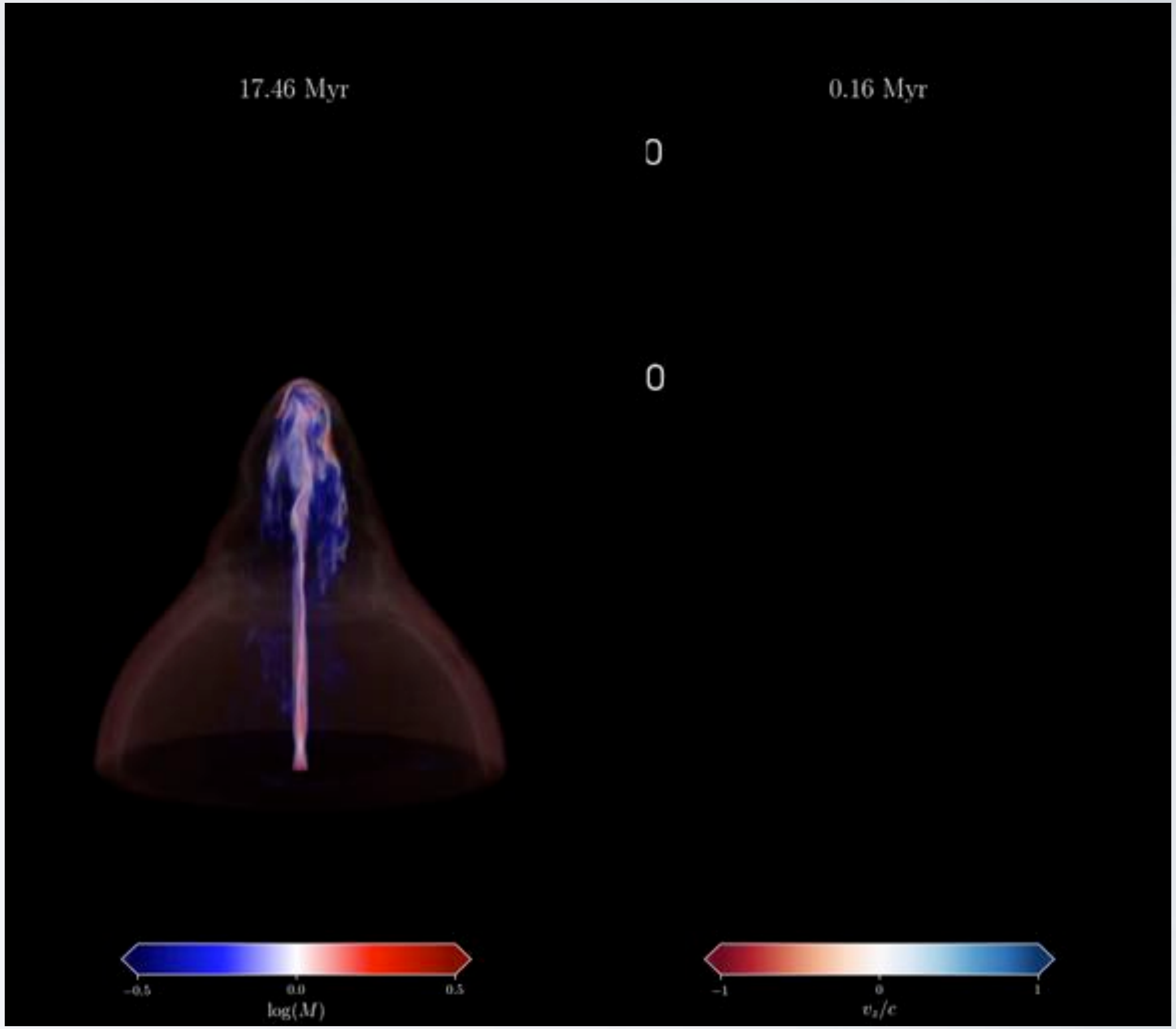


Mukherjee+ 2021



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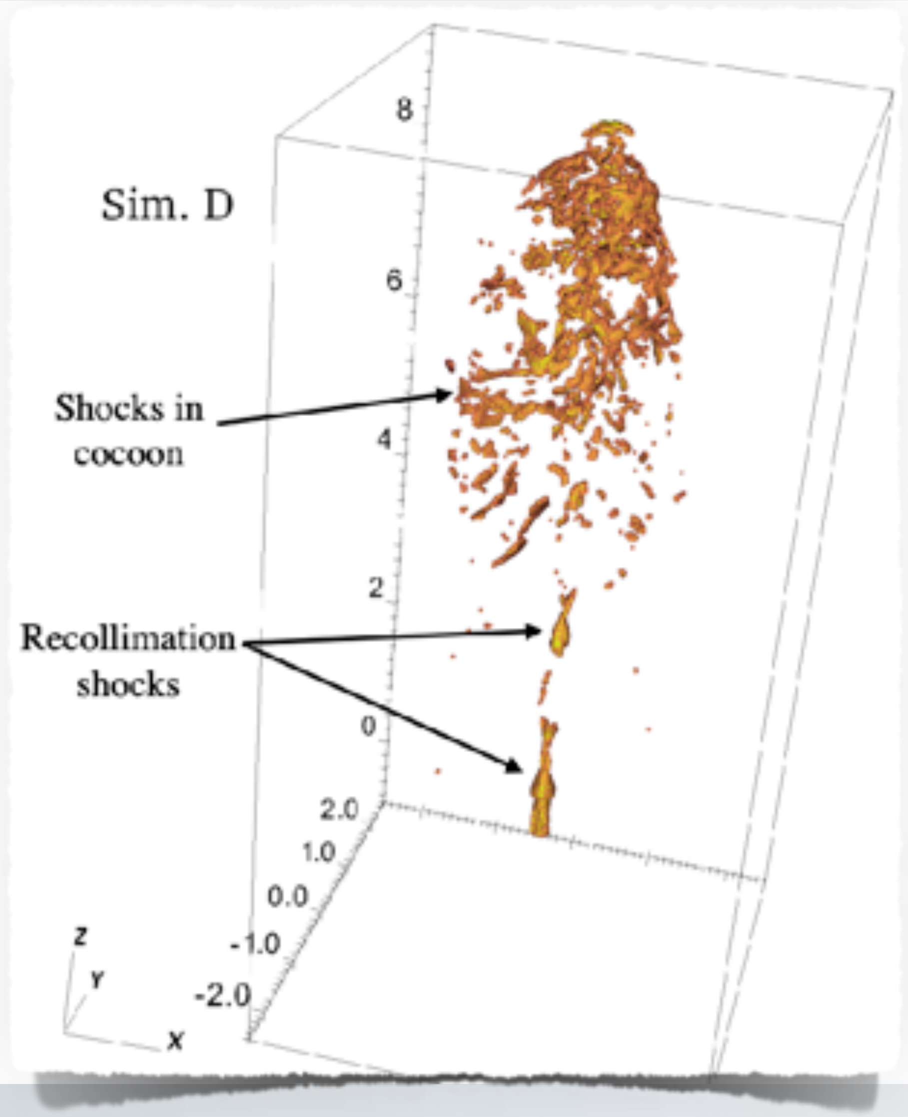

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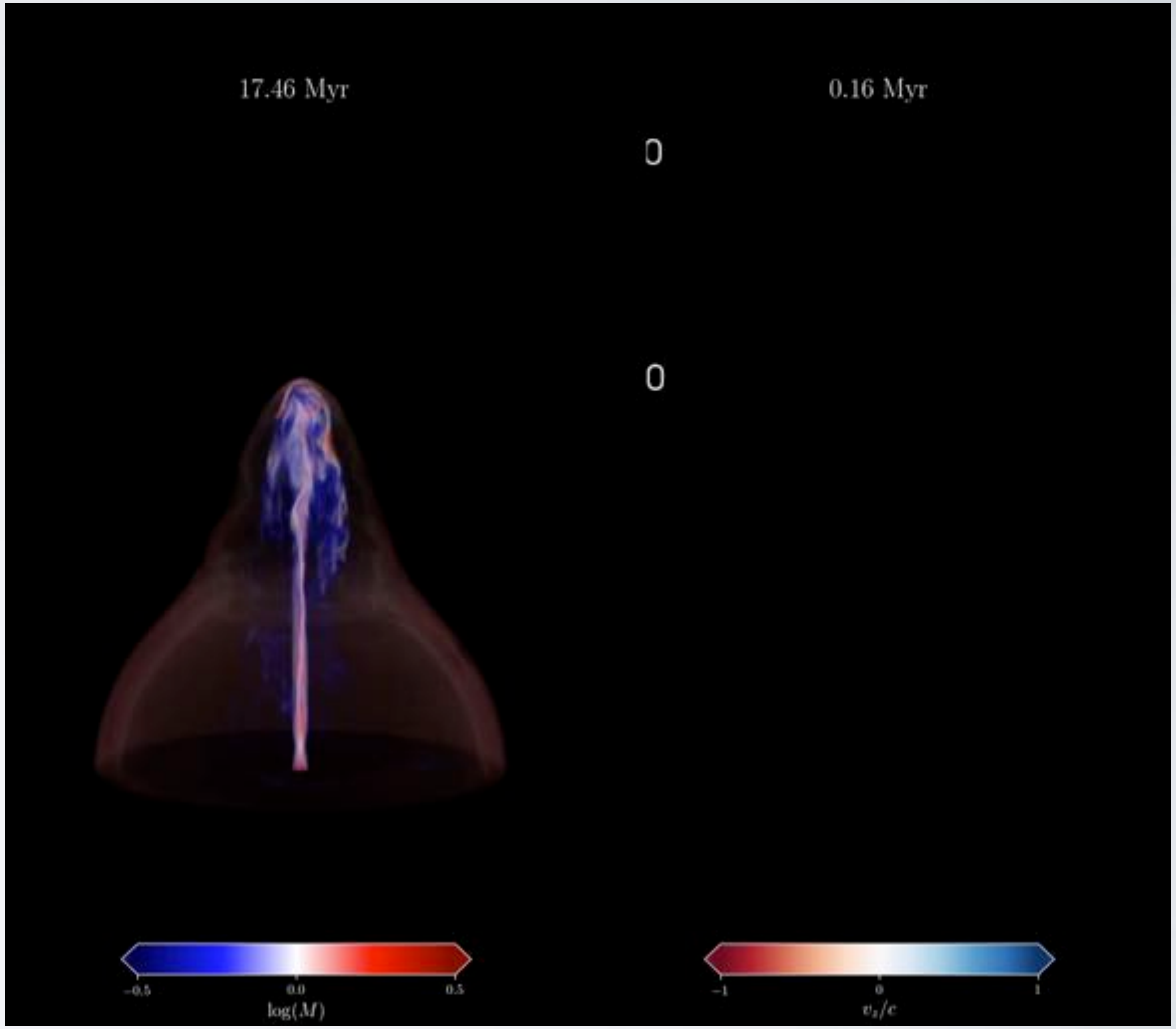
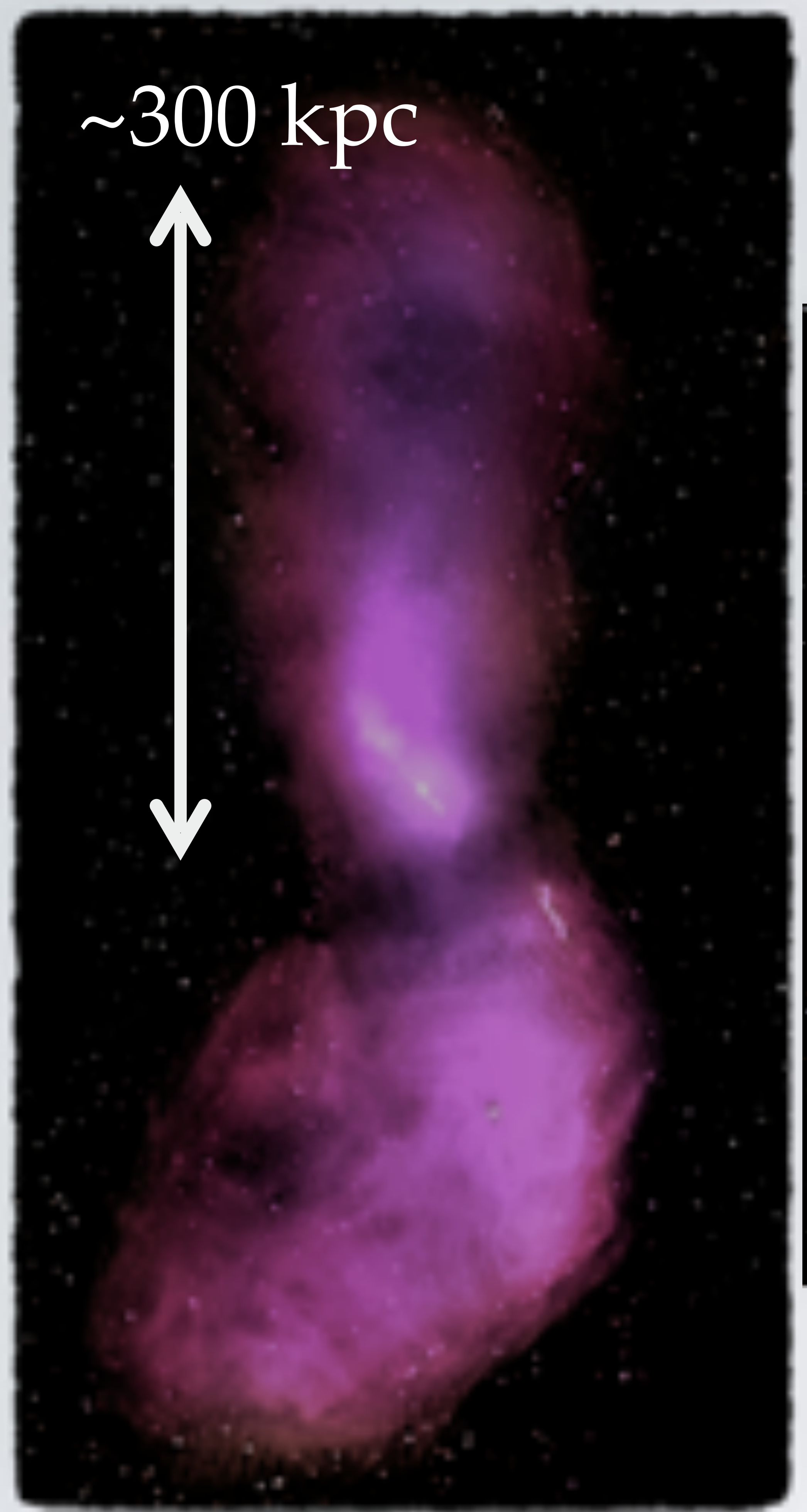
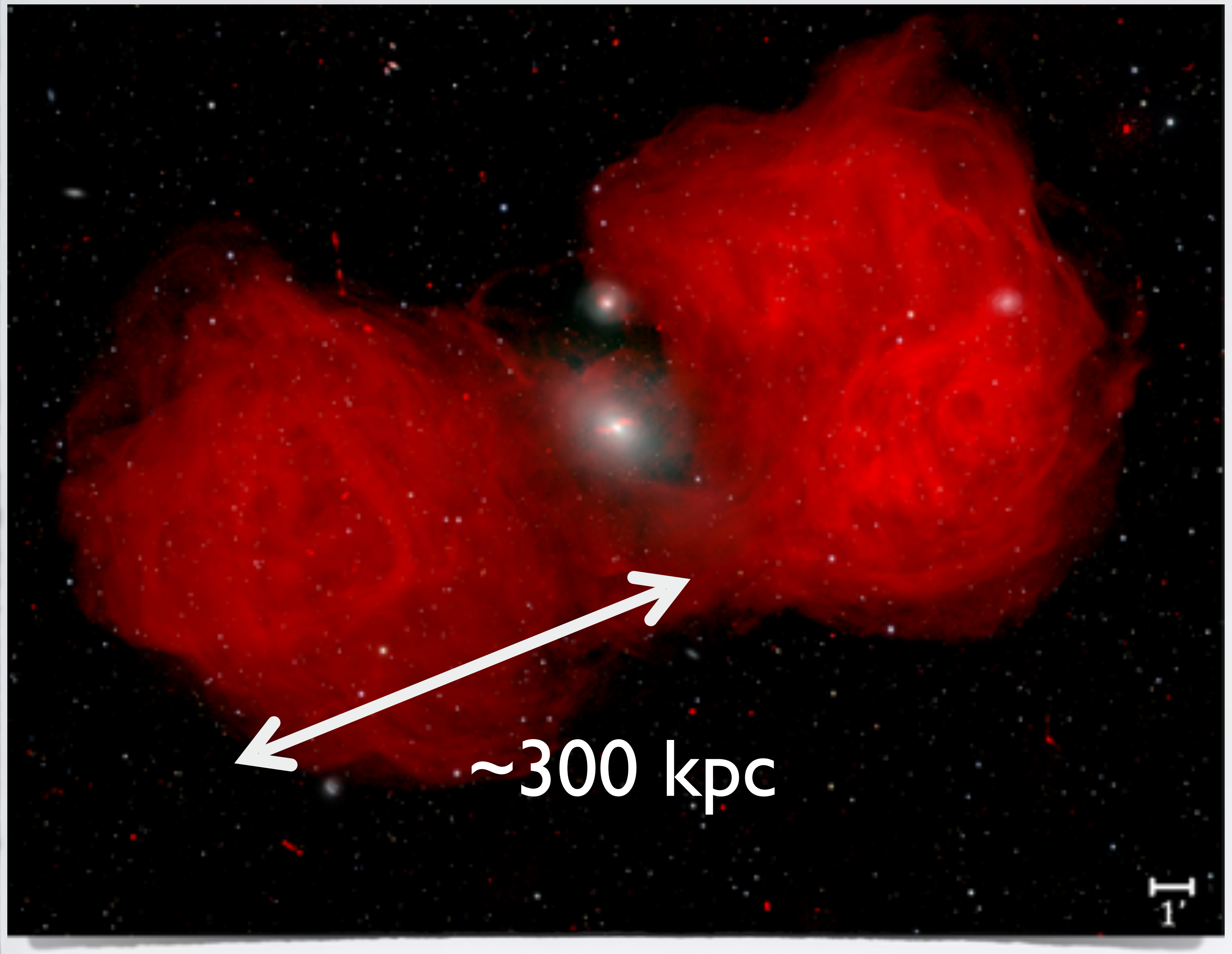


DORMANT RADIO GALAXIES?



Low-power jets

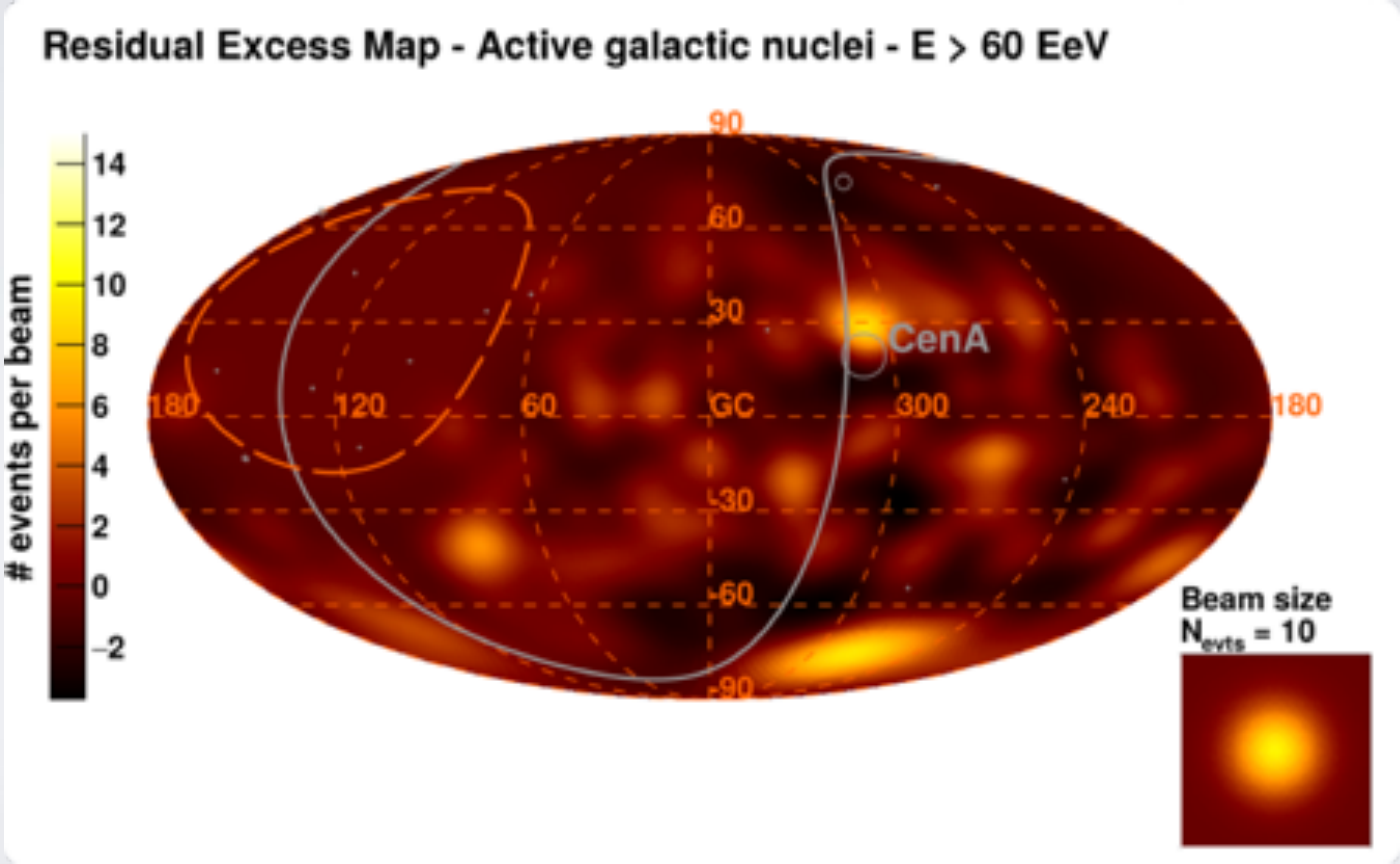
- Large lobes, energy content >10^{58} erg



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

Arrival Directions

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



ARRIVAL DIRECTIONS

Matthews+ 2018

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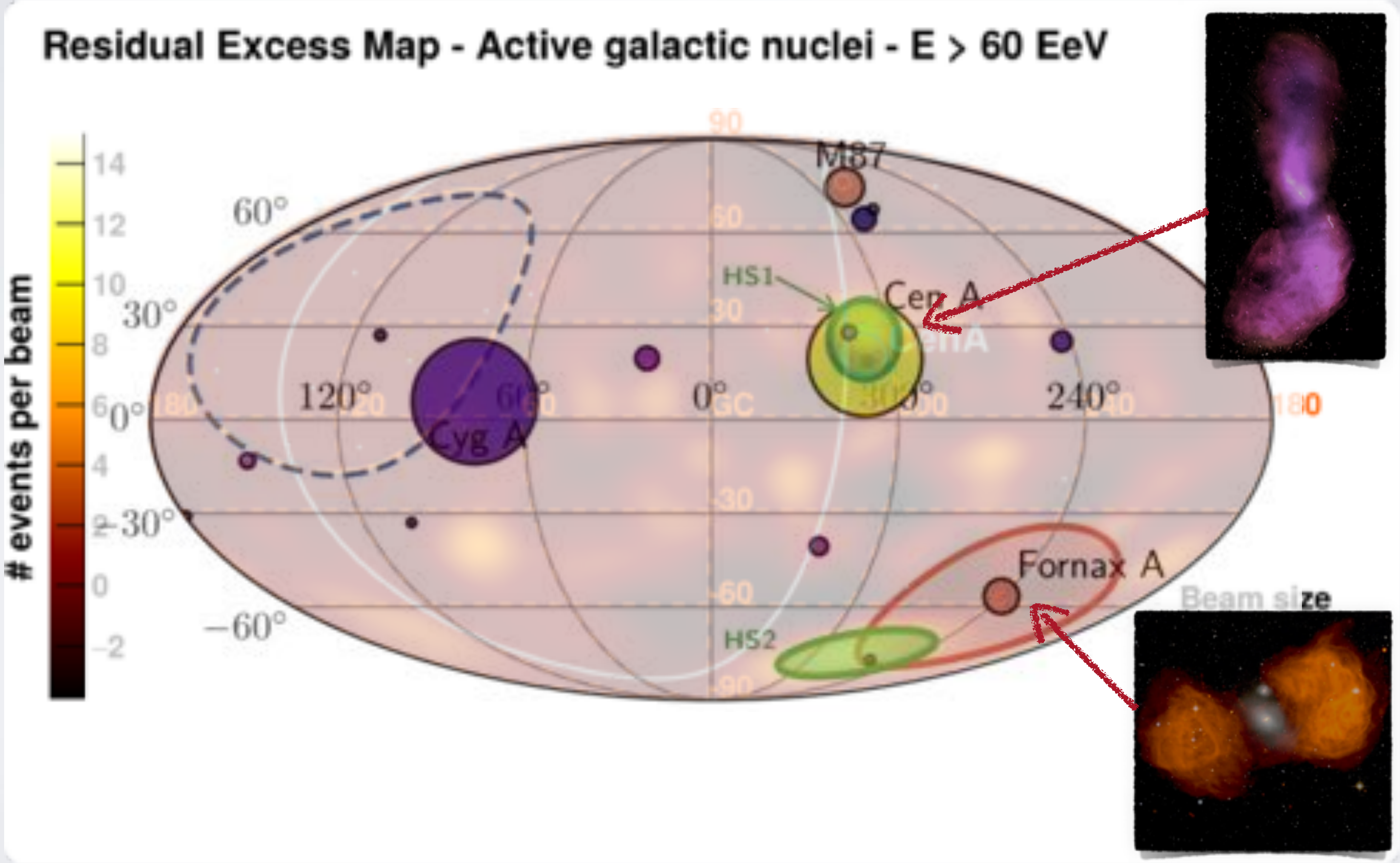


5. MODELLING BLACK HOLE JETS

Jet Launching and Accretion

- Blandford & Znajek (1977) showed that magnetic fields can extract BH spin energy to power a jet

- We expect the jet power to be determined by accretion physics and BH parameters

$$Q_{\rm jet} \sim (\eta_B \phi_B^2)\ a_*^2\ \dot{M}c^2$$

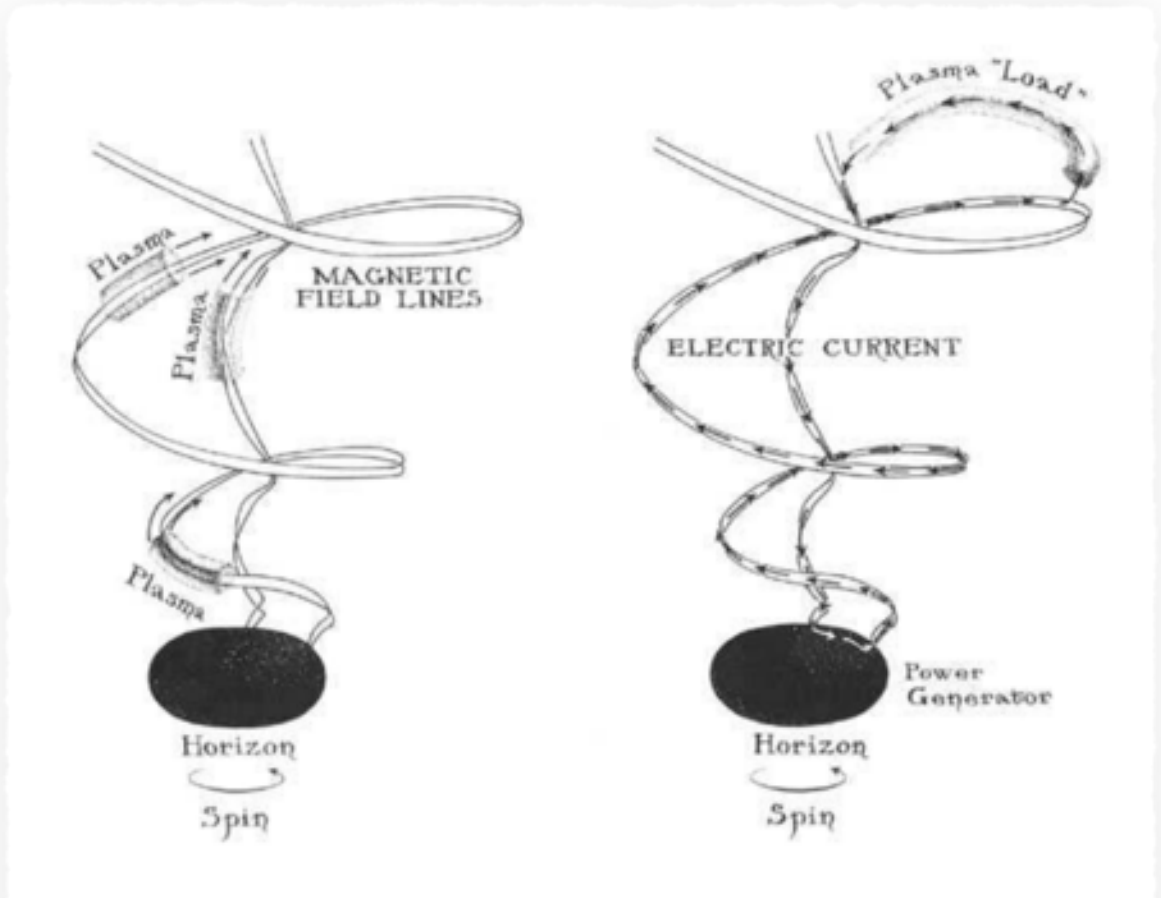
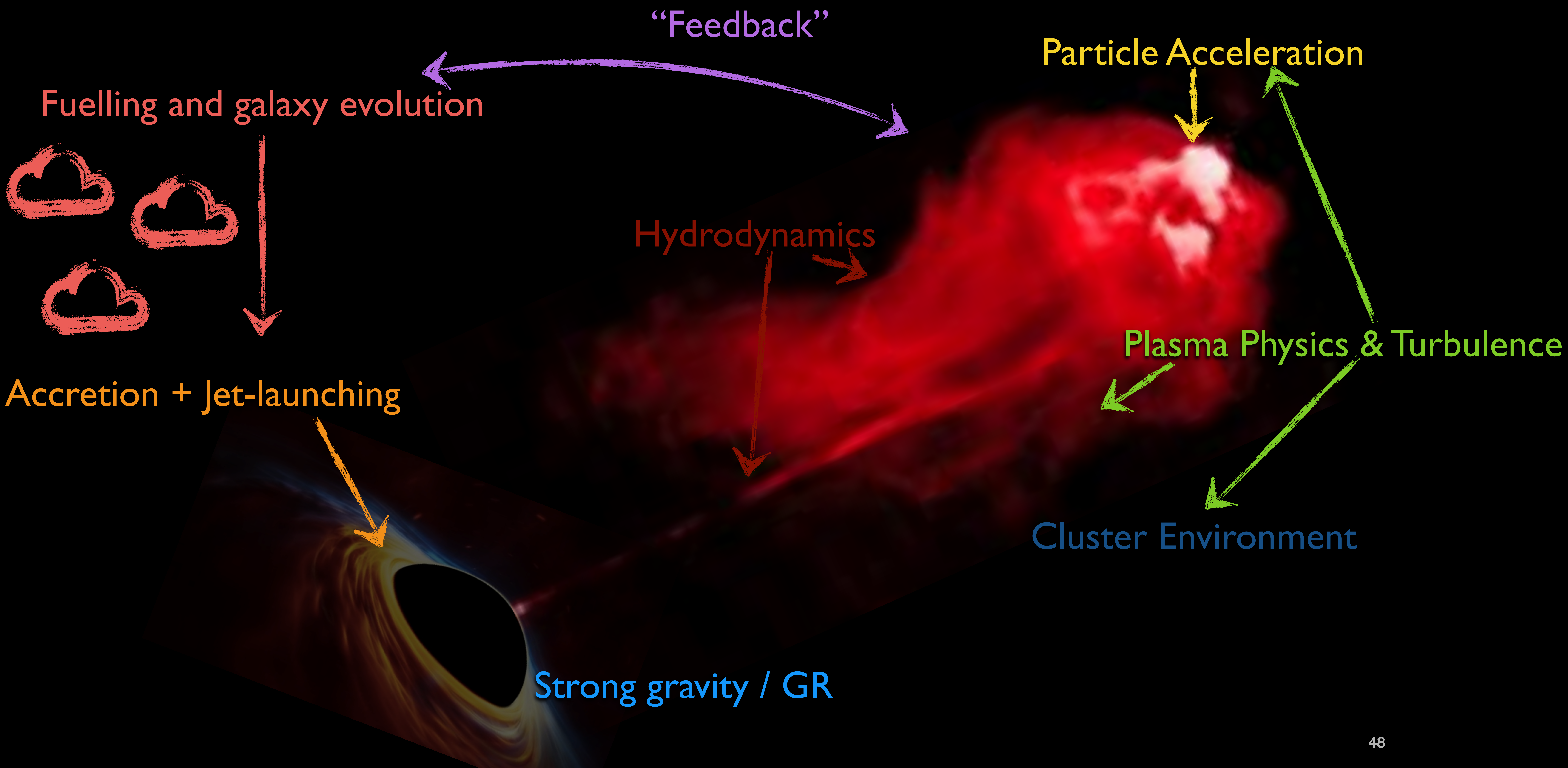


FIG. 4: Illustration of the Blandford-Znajek Process and cir-

PHYSICS OF RADIO-LOUD AGN



PHYSICS OF RADIO-LOUD AGN

“Feedback”

Particle Acceleration

Fuelling and

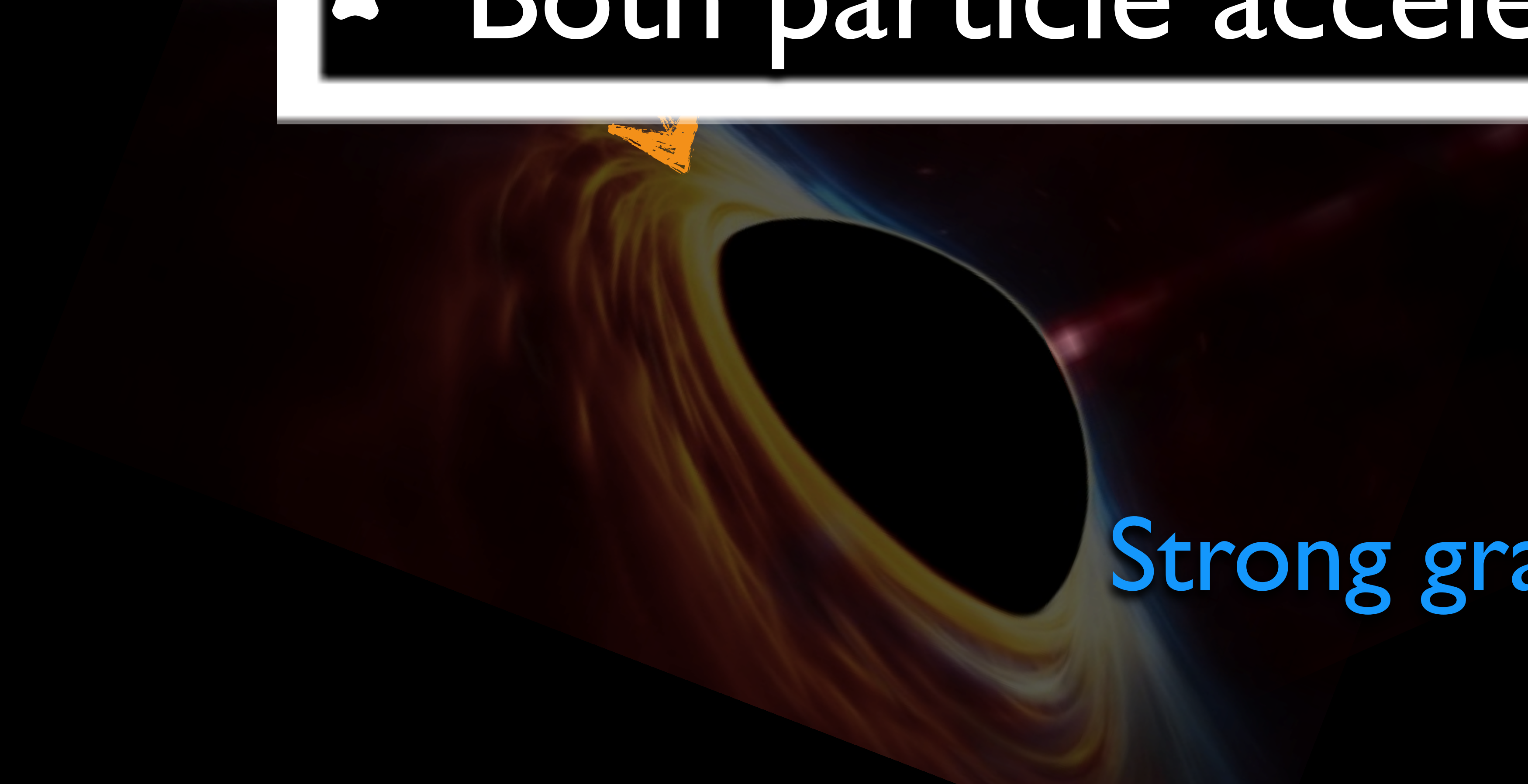
Challenges for modellers

- Huge *dynamic range* of scales, densities,
- Complex collisionless and collisional plasma physics
- Different fluid approximations valid in each regime
- Hard to know input/initial parameters
- Unresolved and “sub-grid” physics
- Both particle acceleration and magnetic fields matter

& Turbulence

Accretion + Je

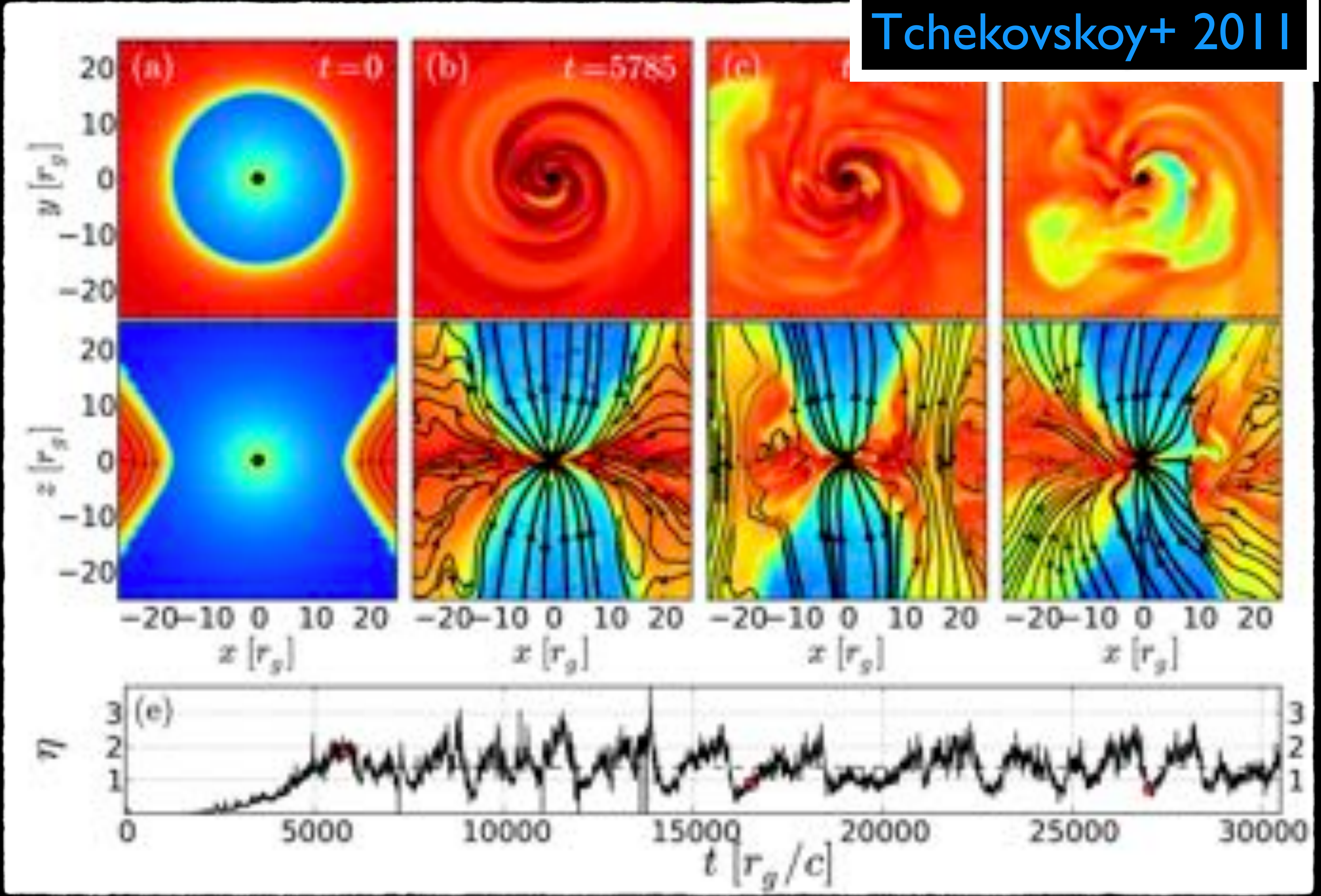
Cluster Environment



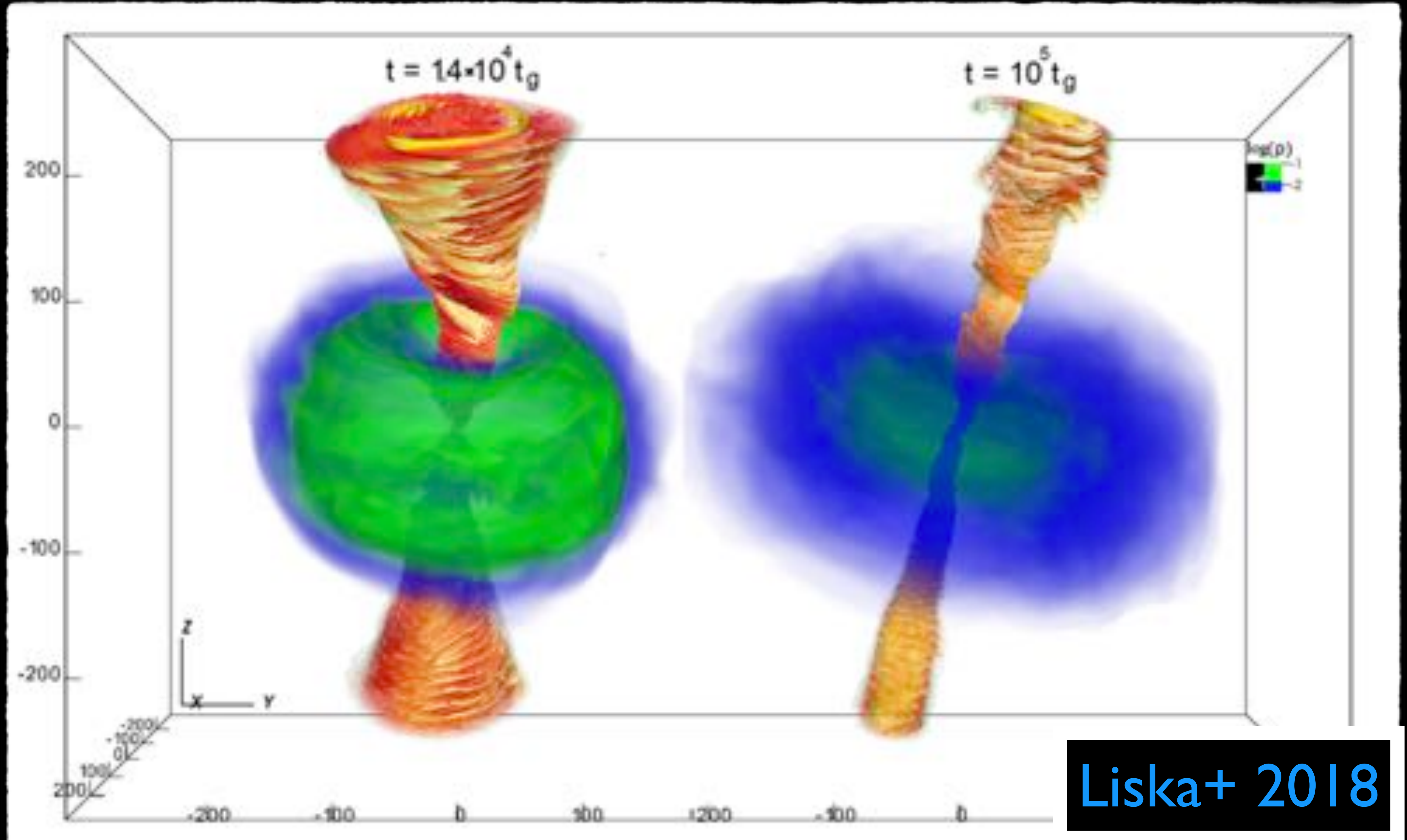
Strong gravity / GR

CLOSE TO THE HORIZON

- Last ~10 years has seen dramatic progress in General Relativistic Magnetohydrodynamic (GRMHD) simulations
- A range of configs - one common setup:
  - "Torus" of plasma with magnetic field
  - MRI develops and allows disc to form
  - Jet launched from extraction of BH spin energy
- Overall:
  - A spectacular verification of fundamental theories
  - Powerful jets shown to extract BH spin energy -> Blandford-Znajek type jets



Tchekovskoy+ 2011



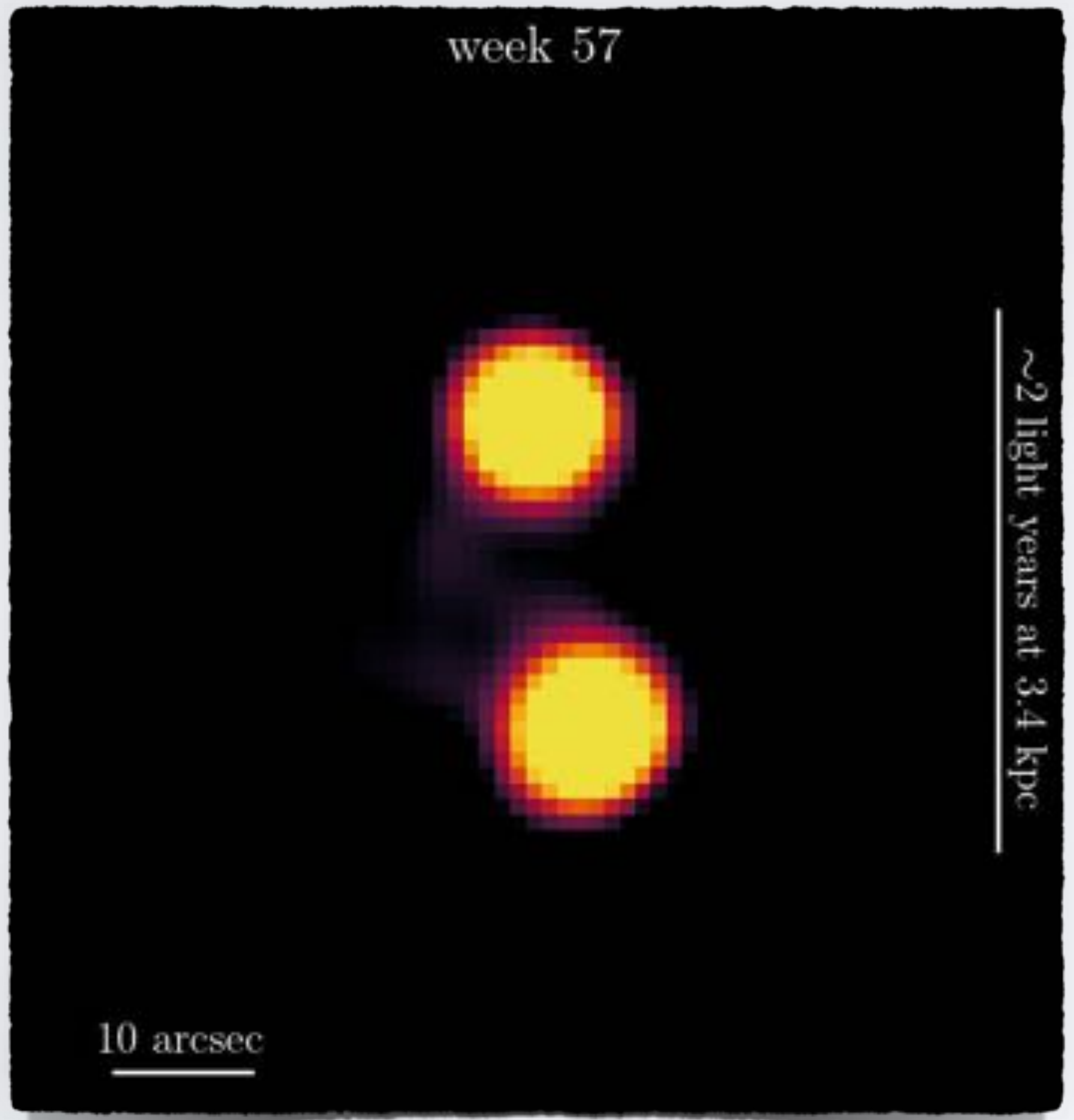
Liska+ 2018

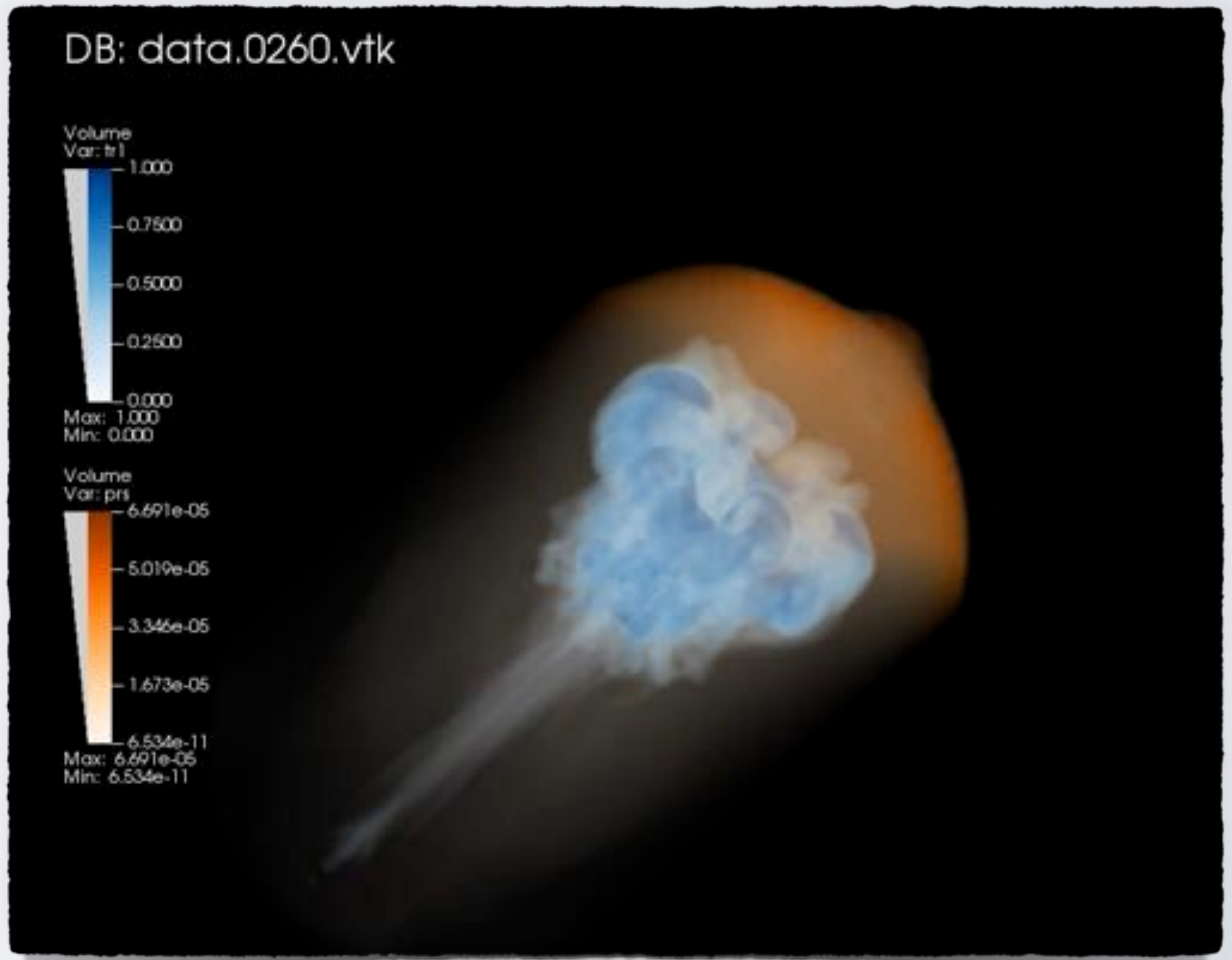
JETS IN STELLAR MASS BHS

Katie Savard

- Stellar mass black holes accrete from companion stars and produce jets
- Also produce "discrete ejecta" - relativistic blobs that move at the speed of light for ~a year, monitored through ThunderKAT collaboration
- We use hydrodynamic simulations to model the disruption and particle acceleration physics in these blobs

Arash Bahamian, MeerKAT observations of MAXI J1848 (Bahramian+ 2023)





Savard, JM+ in prep.

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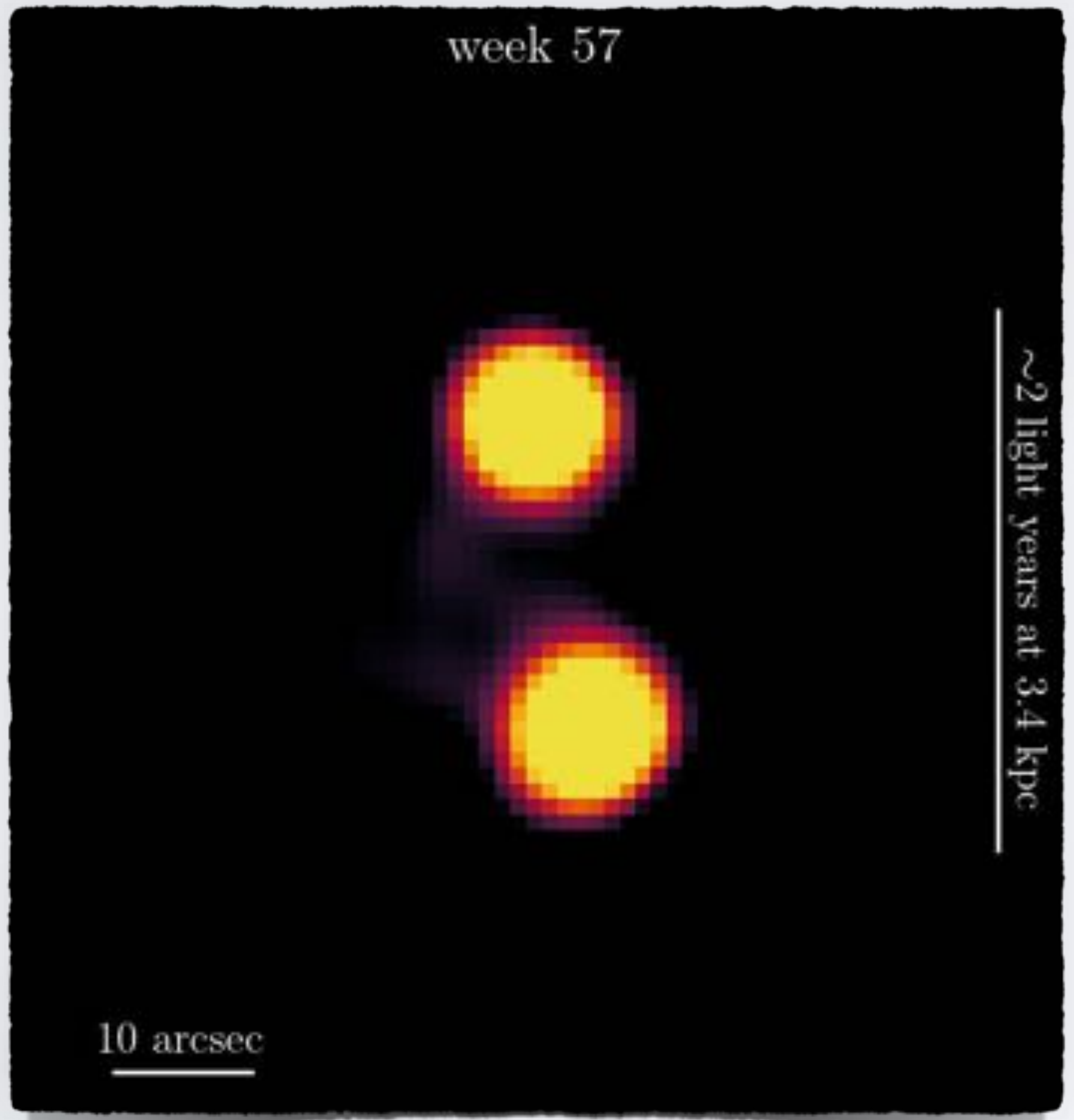

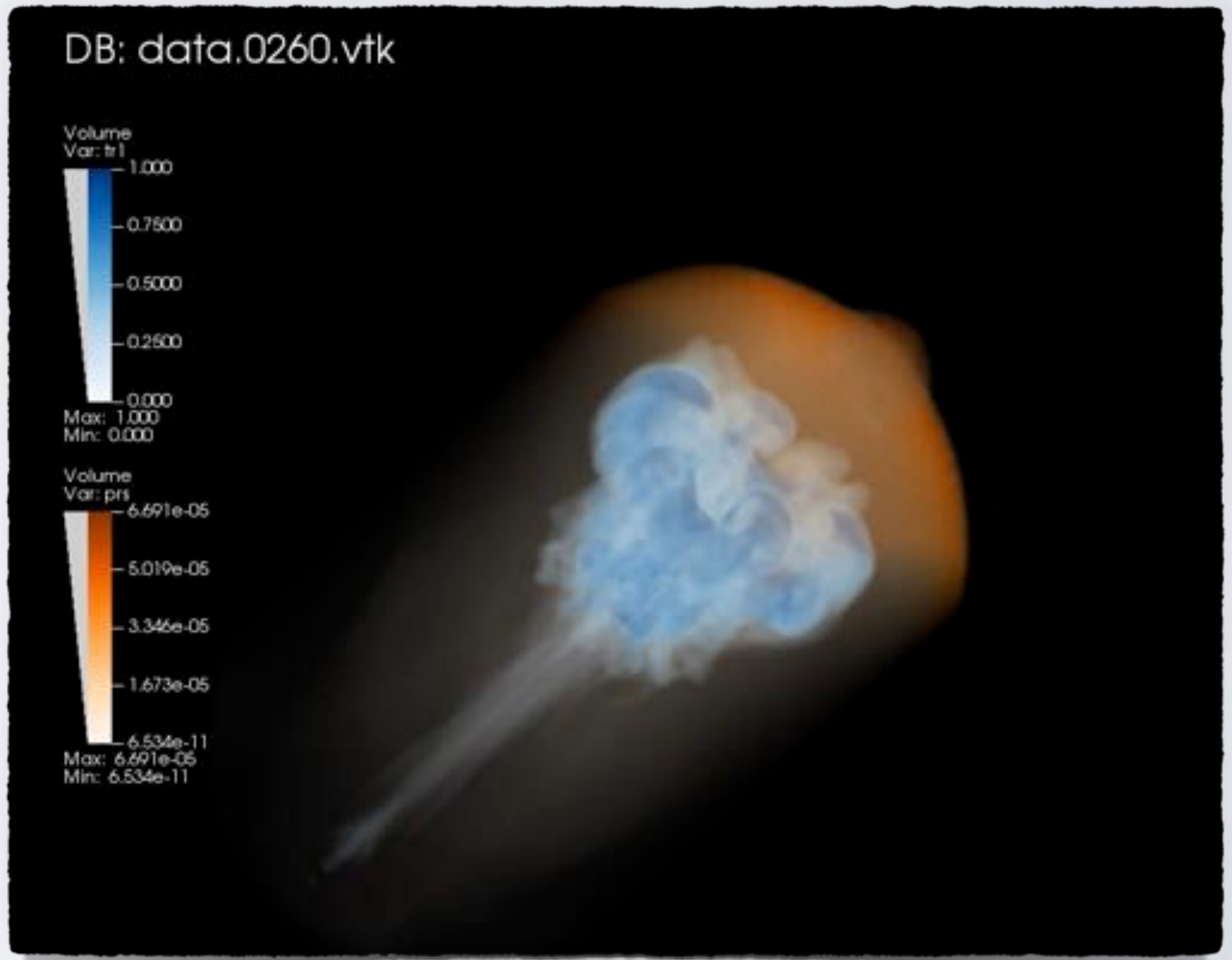

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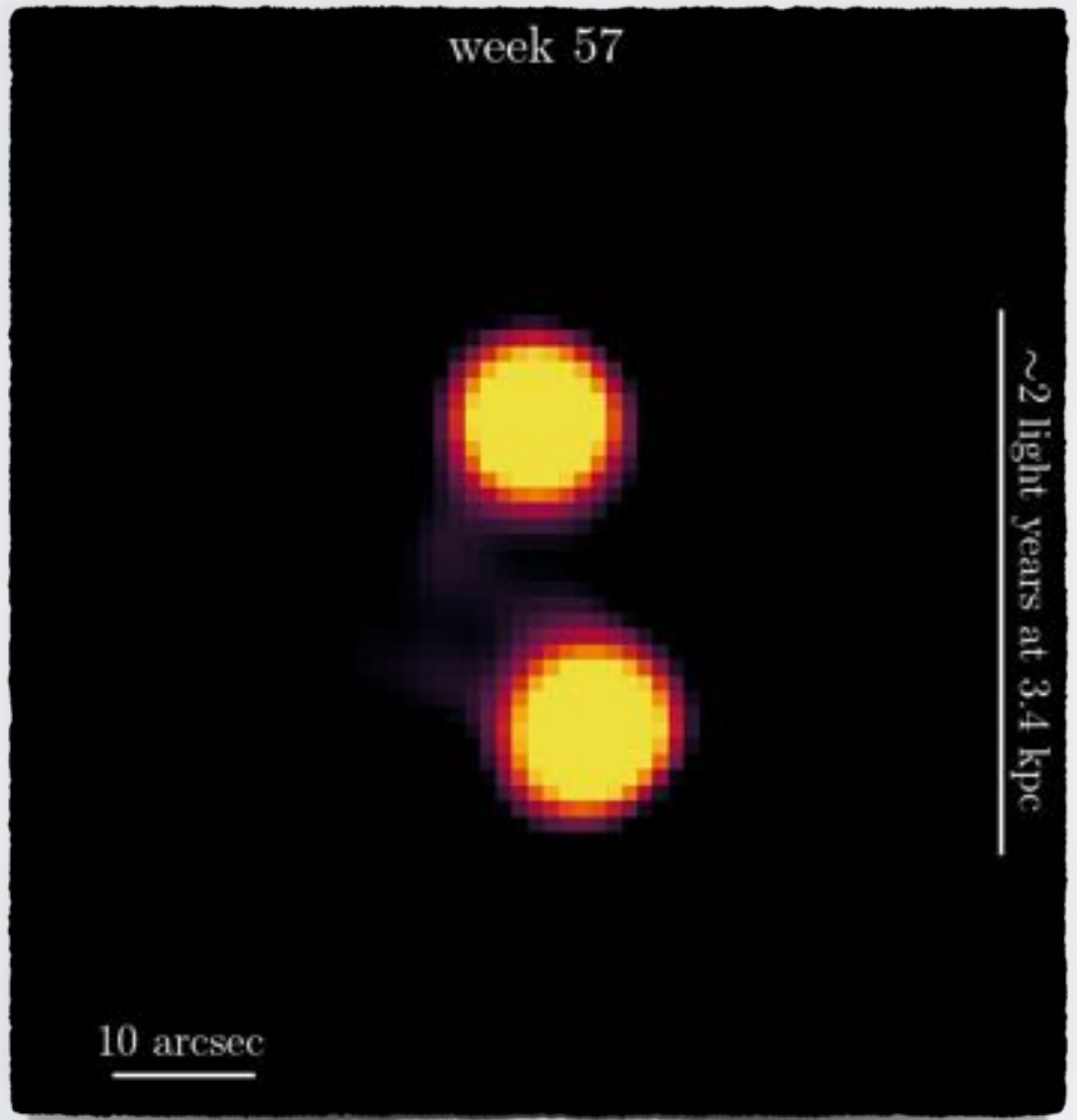

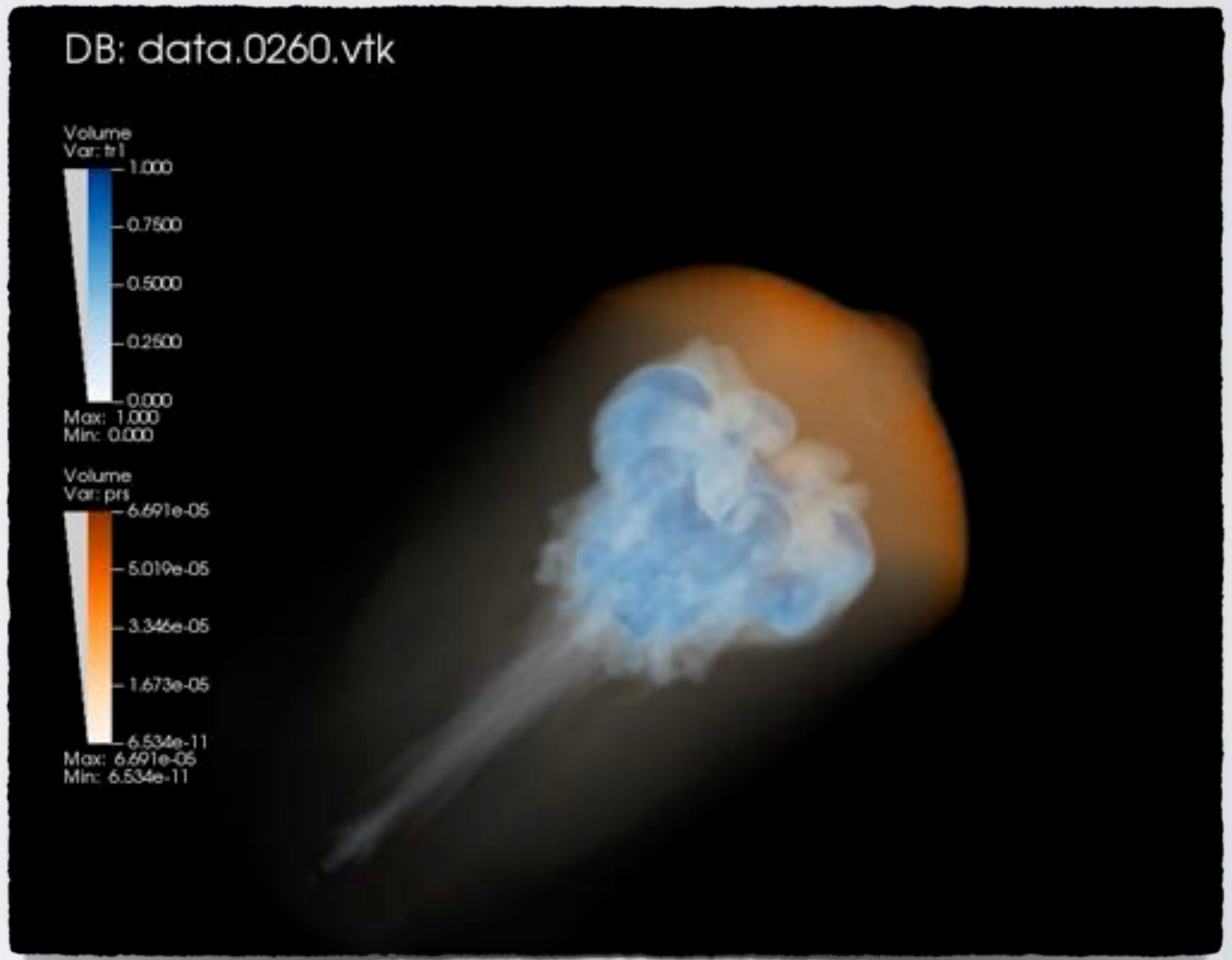

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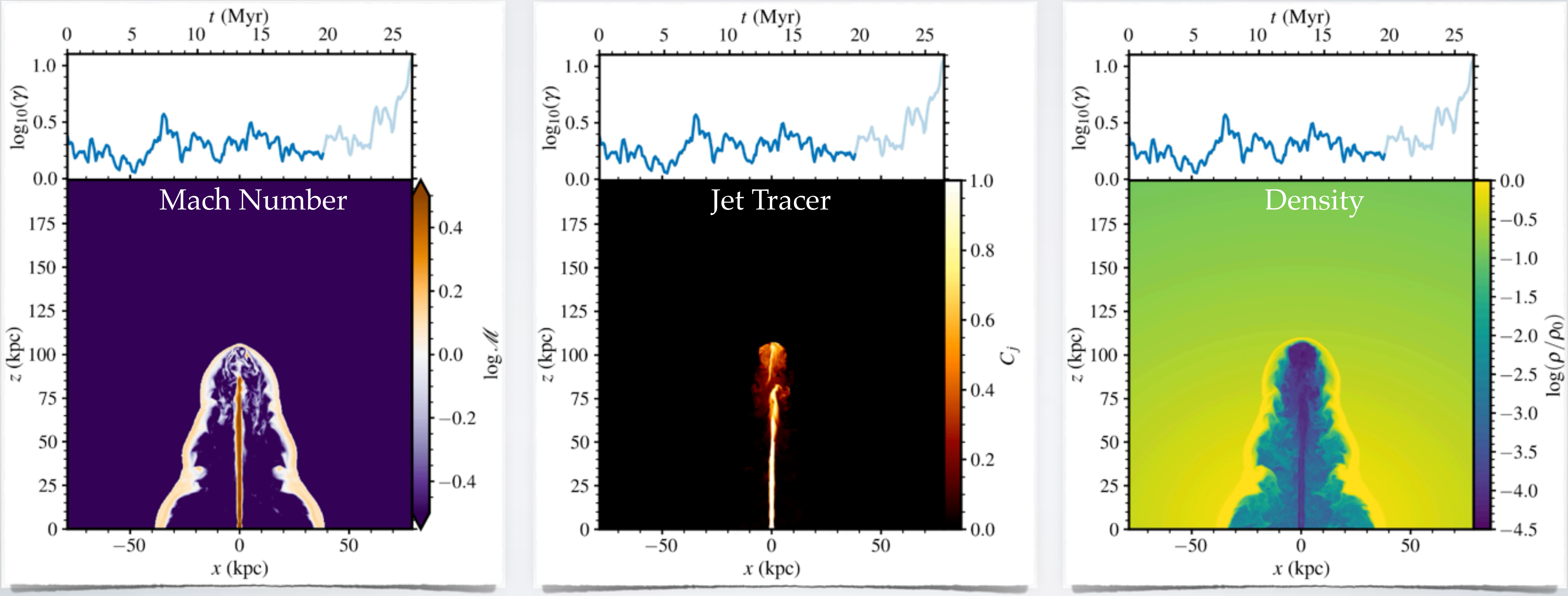
Flickering Jets

- 3D simulations produce similar behaviour, +additional phenomena e.g. discontinuities between jet and head
- Backflow maximised in high states, forms helical stream: could be an important region of particle acceleration (Matthews+ 2019)
- Propagating shock structures (“internal shocks”) could be responsible for knots in radio galaxies



Flickering Jets

Whitehead & Matthews 2023

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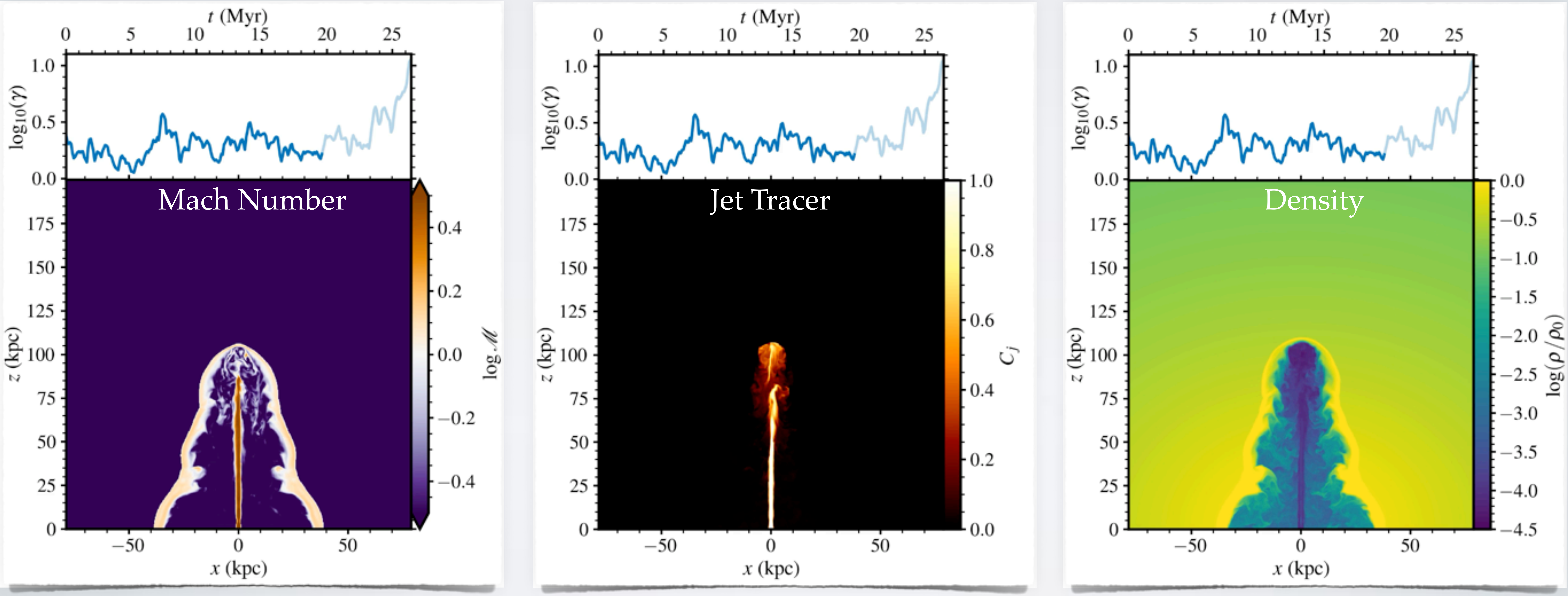
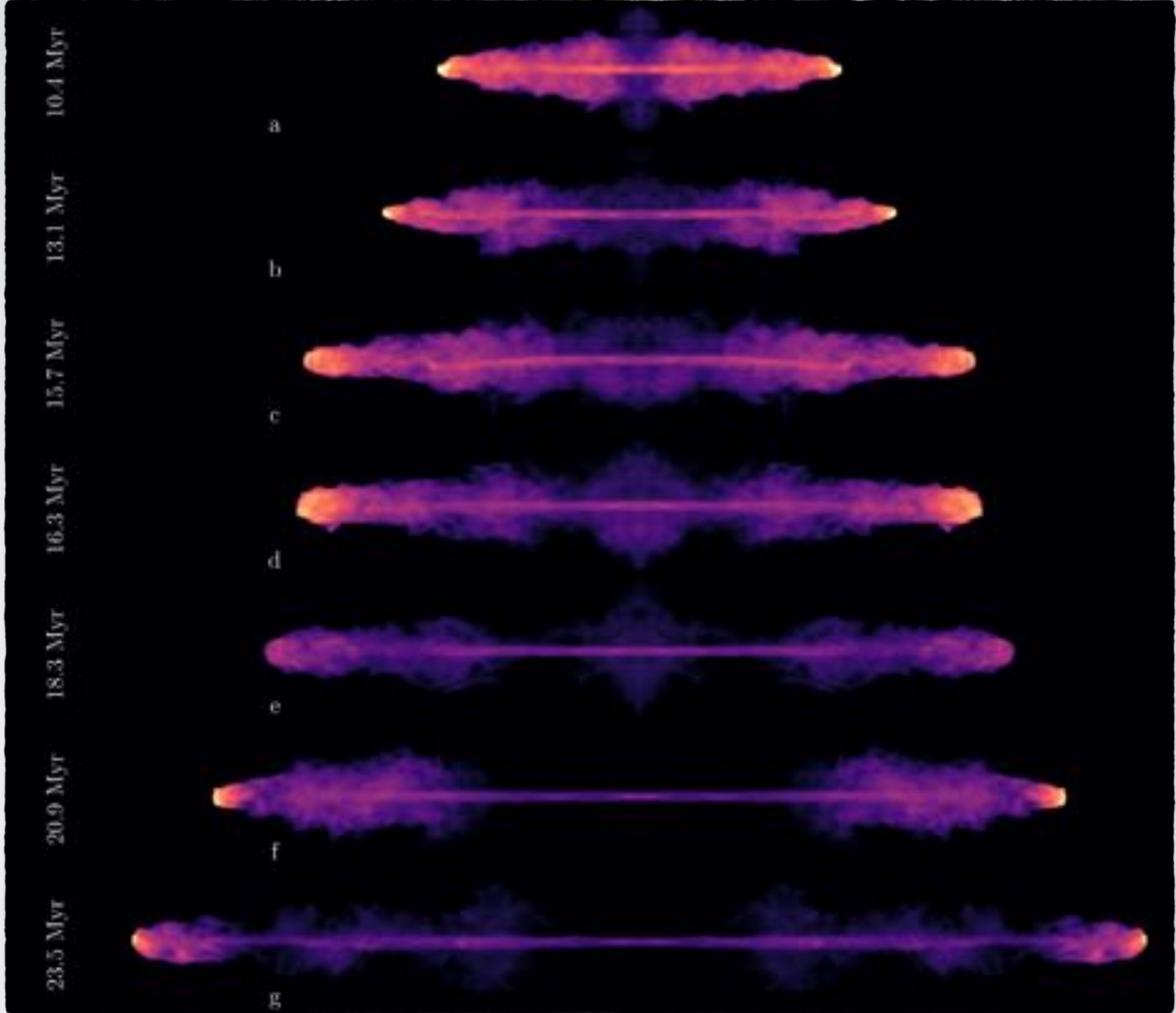


SYNTHETIC IMAGES

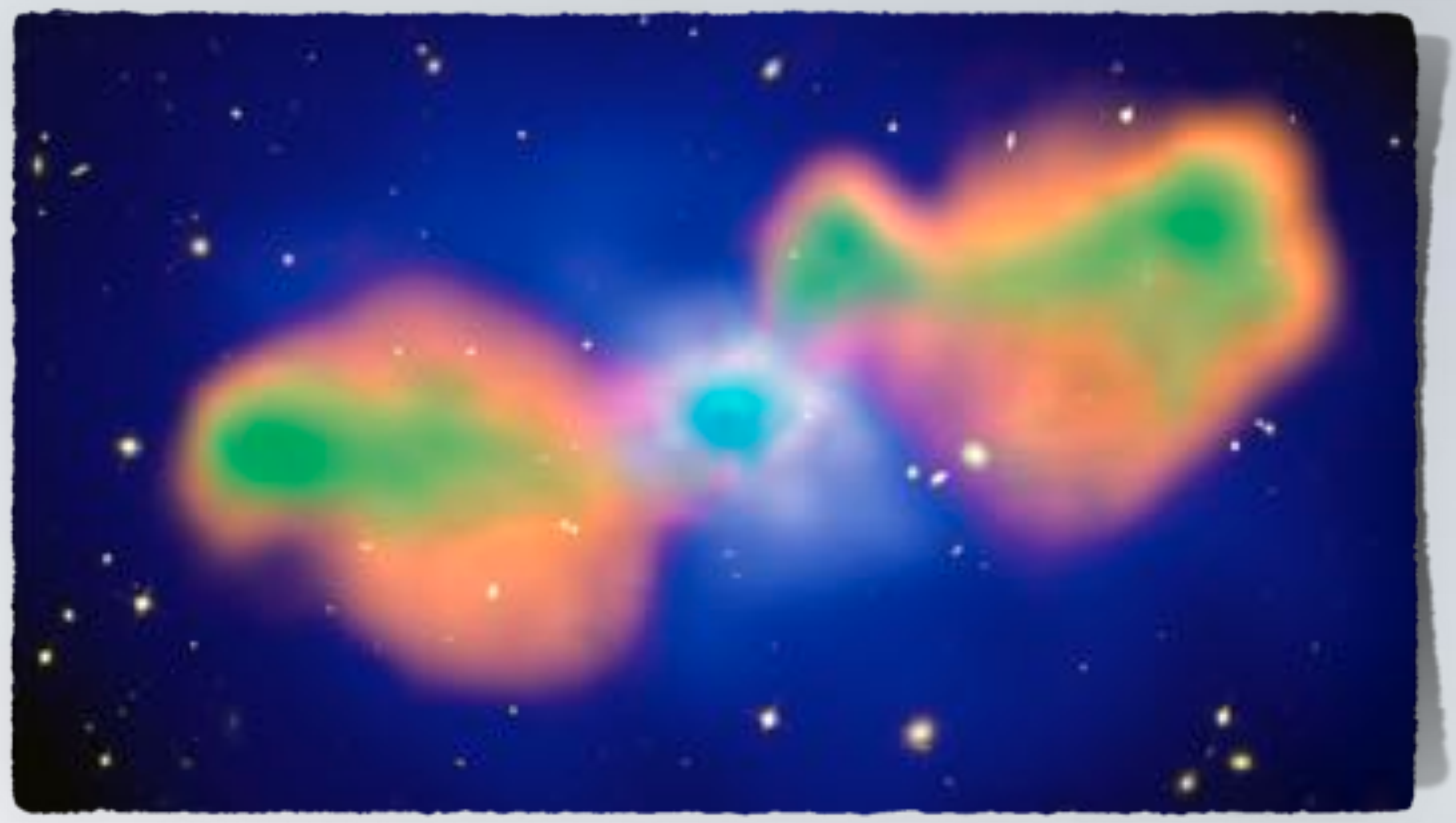
- Ray-traced images using 3D simulations and pseudo-emissivity
- Hotspots are intermittent and correlate with “high” states
- Changes in “edge-brightening” throughout history
- Patchy bright structures and relics of past activity - but nothing approaching, e.g., Hercules A: needs merger or “trigger?

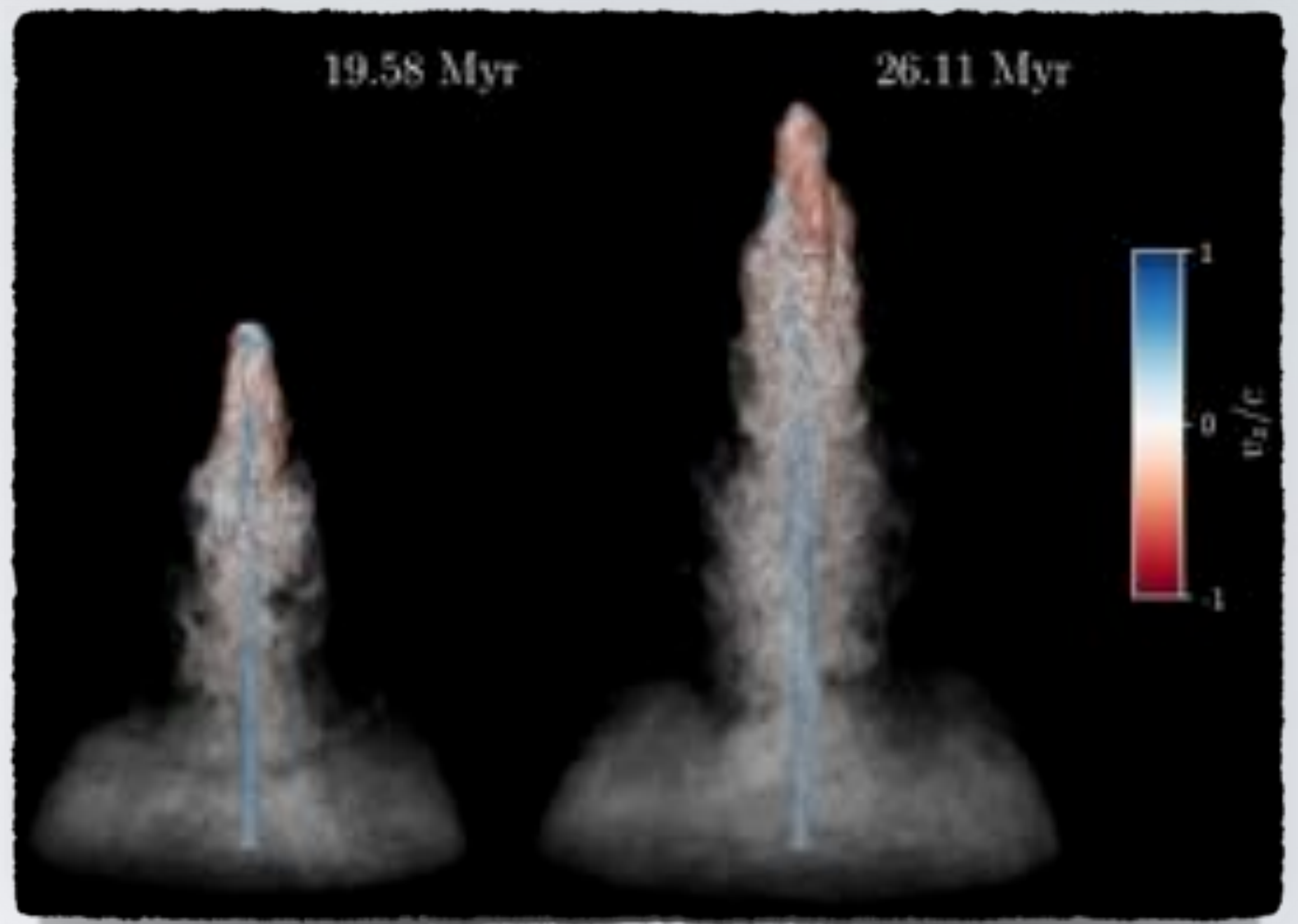
<u>*Implications for “dichotomies”?*</u>

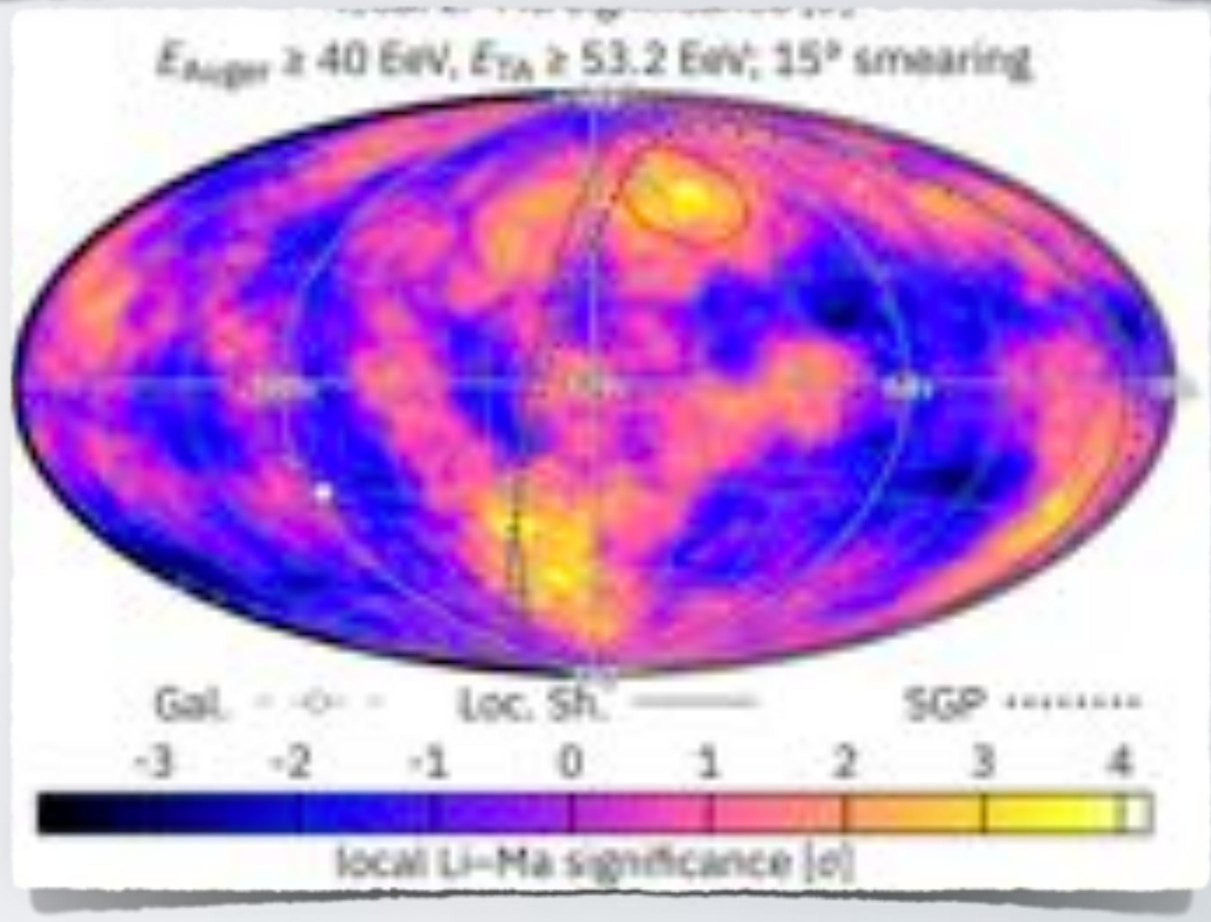


SUMMARY

- Nonlinear particle acceleration essential for mapping from observables to physics of jets
- Simple back of envelope calculations can be used to identify potential UHECR sources
- The maximum particle 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?
- *Understanding the physics of particle acceleration and origin of UHECRs is a perennial challenge*







EXTRA SLIDES

PARTICLE ACCELERATION

- Assume you undergo a series of scattering events (at this stage, agnostic about mechanism)

- Allow particles to gain a fractional gain of energy G in each scattering event

- Particles have a probability P of remaining in the interaction region after each scatter

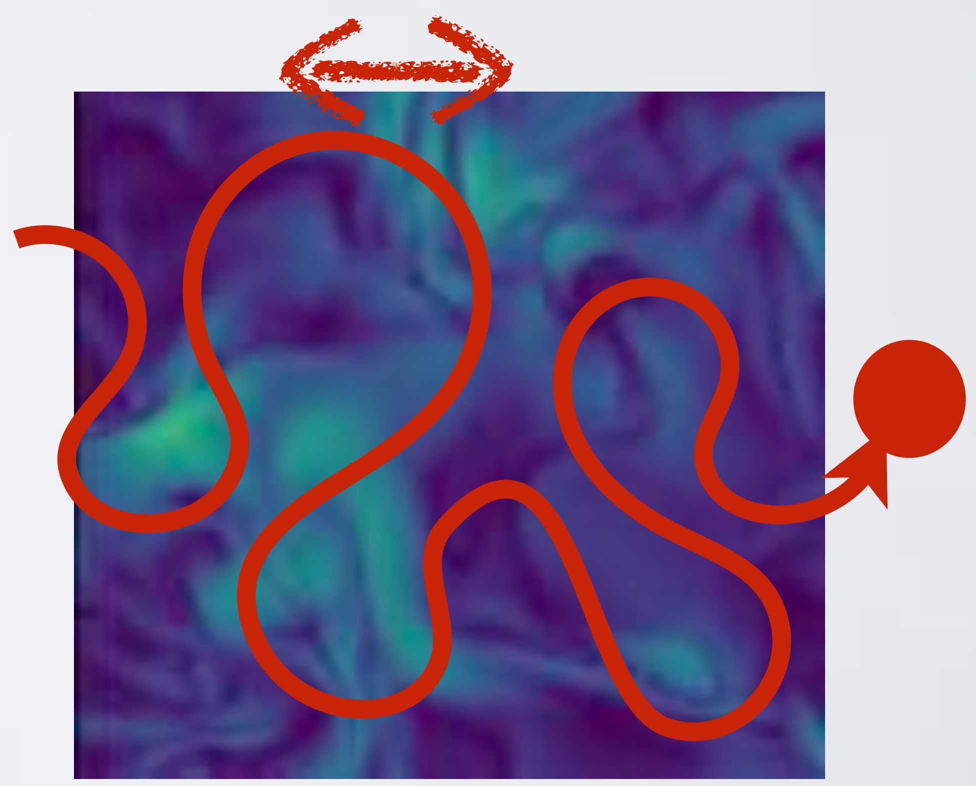
$$\frac{dN}{dE}\,dE = E^{(\ln P/\ln G)-1}dE$$

"Naturally produces a power-law spectrum of particle energies"

(Does it though?)

Hillas Energy Derivation in Shocks

- Except for special situations, particle cannot have a mean free path smaller than Larmor radius
- We call the situation when $\lambda_{\mathrm{mfp}} \sim R_g$ Bohm diffusion with diffusion coefficient D_B
- Write diffusion coefficient as $D = \eta D_B \sim \eta R_g c,\ \eta \geq 1$



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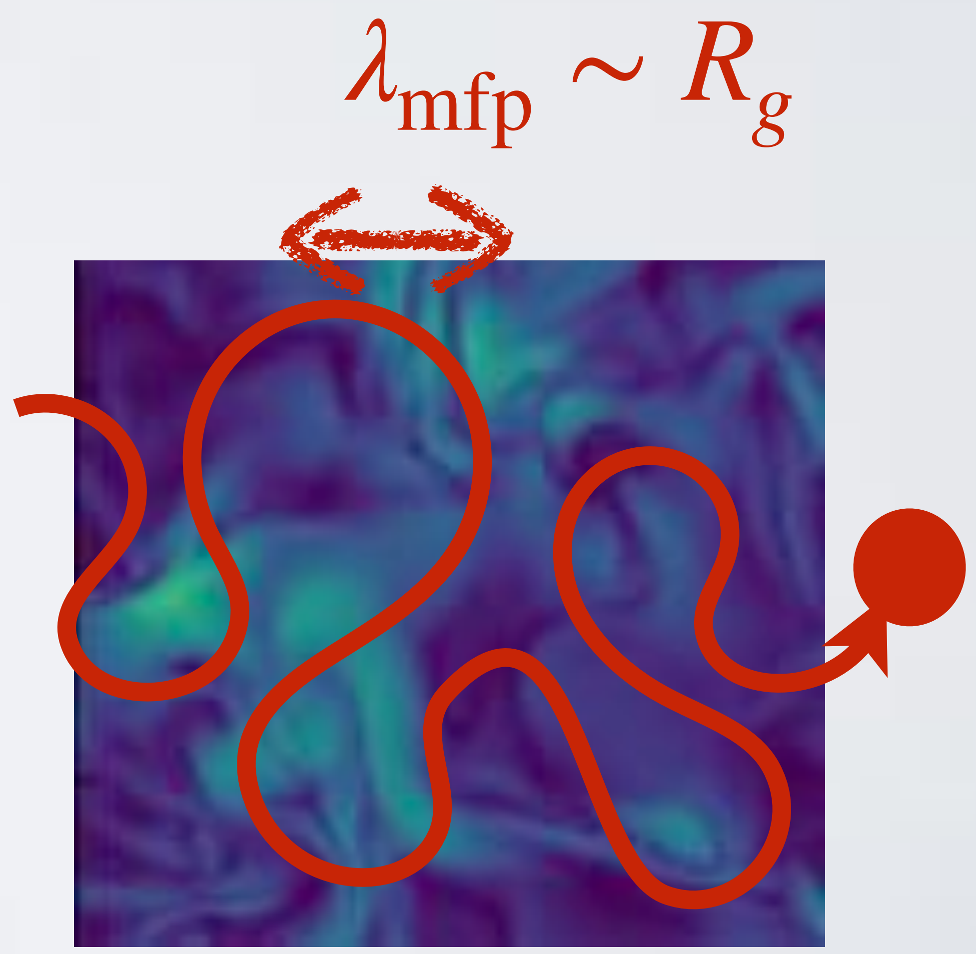

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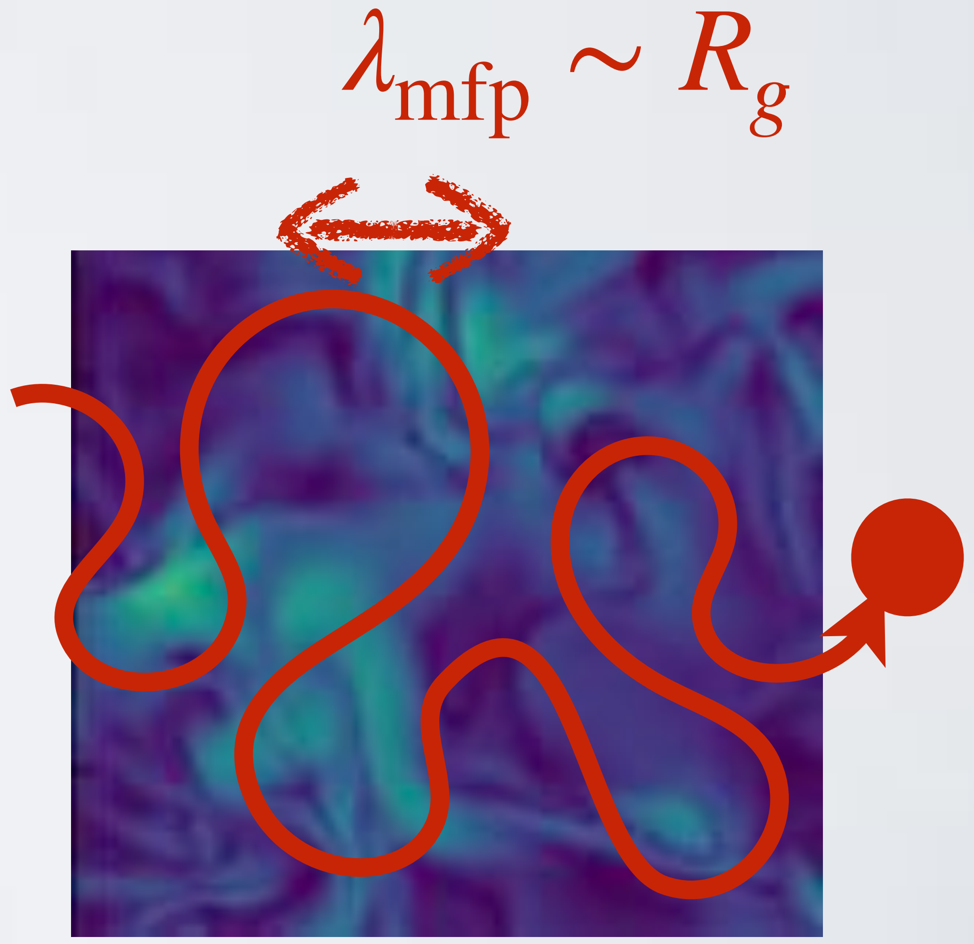
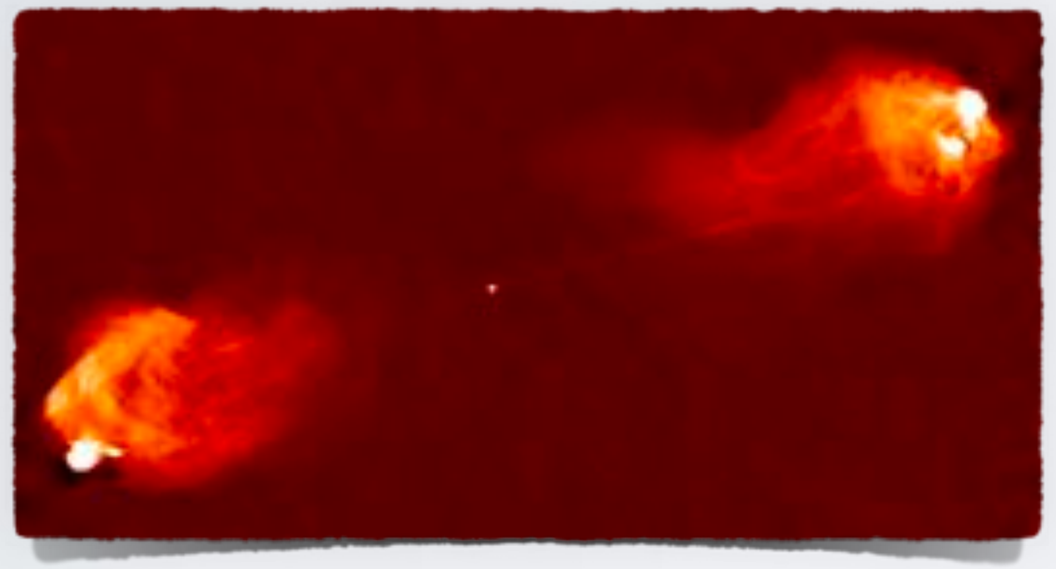


Hillas energy only reached when Bohm diffusion applies (Eta~1).

SCALES

Let's take BH jet scale as 50 Schwarzschild radii

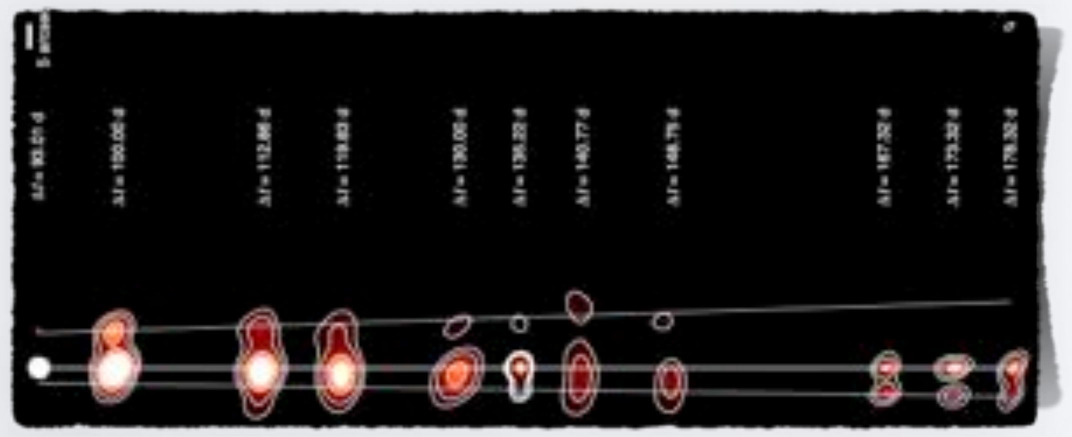
In AGN like Cygnus A:



$$\frac{100\text{kpc}}{50 \times 10^{-4}\text{pc}} \sim 20 \text{ million}$$

Throwing a tennis ball from Oxford to Sara

In XRB Jet Blob:



$$\frac{1\text{pc}}{50 \times 30 \text{ km}} \sim 20 \text{ billion}$$

Throwing a tennis ball to the moon

AGN JET PROPAGATION (1D)

- Imagine blowing low-density supersonic material into a high-density tube. Ram pressure means advance of jet head is slow
- Drives a forward shock into the ambient medium and a reverse shock into the "jet"
- Two-shocks are separated by contact discontinuity

- To model this, hydro code must be *conservative* and *shock-capturing* (Godunov-type codes now astro standard, e.g. PLUTO, ATHENA++, FLASH)

ANATOMY OF AN AGN JET