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Particle Acceleration in (AGN) Jets

A biased, theory/phenomenology review

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Thanks to:
Tony Bell, Katherine Blundell (Oxford), Andrew Taylor (DESY Zeuthen)
Chris Reynolds (Cambridge), Anabella Araudo (Czech Academy of Sciences), Leah Morabito (Durham)

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Herchel Smith Fund

Structure

1. Historical Perspective and Motivation

2. Particle Acceleration Theory

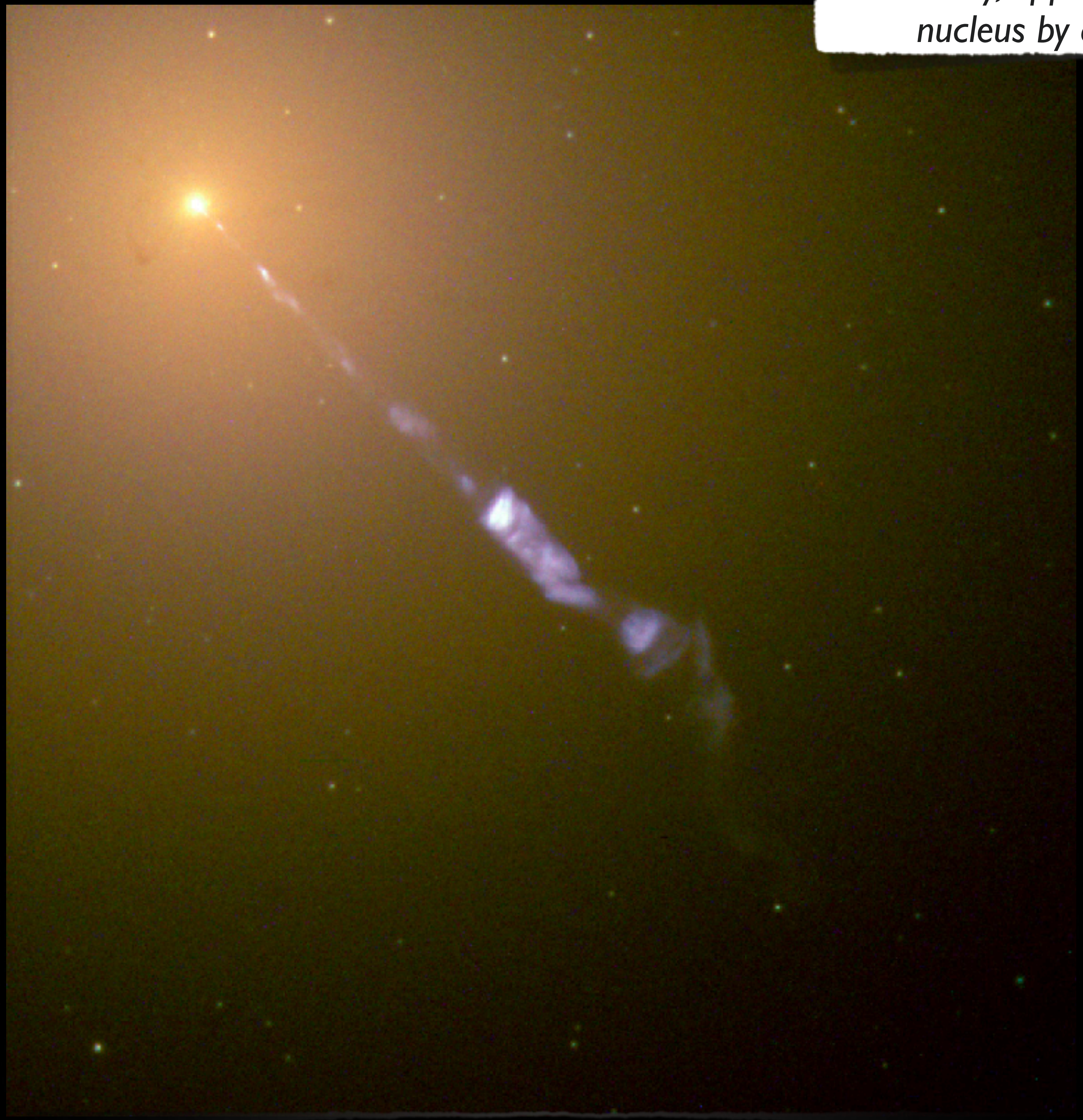
3. Interlude: Stability, Backflows and Variability

4. Recent Observational Highlights

5. Synergies, Big Picture and Concluding Remarks

Two 100-year old physics problems…

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



"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."

Discovery of cosmic rays
(Hess 1912)

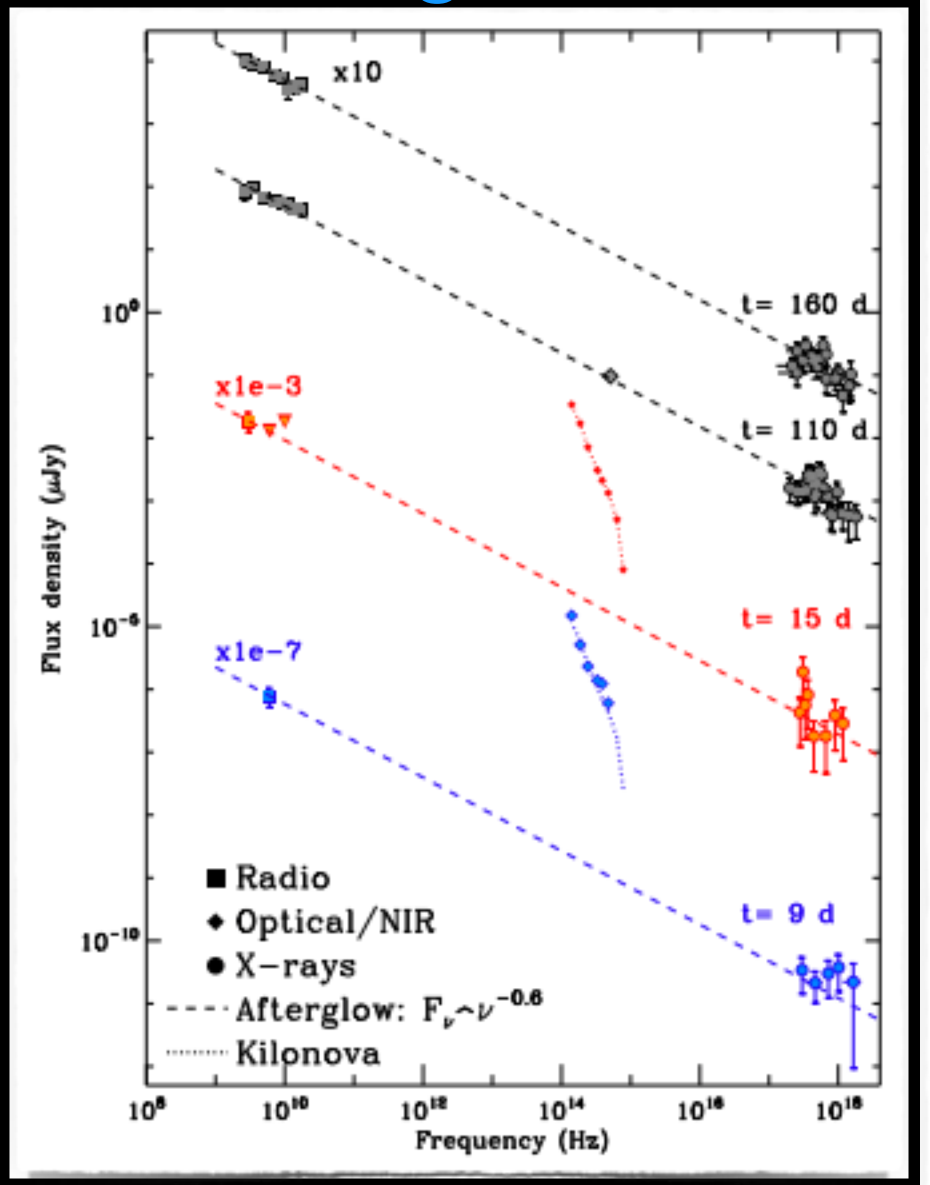
Discovery of M87 jet
(Curtis1918)

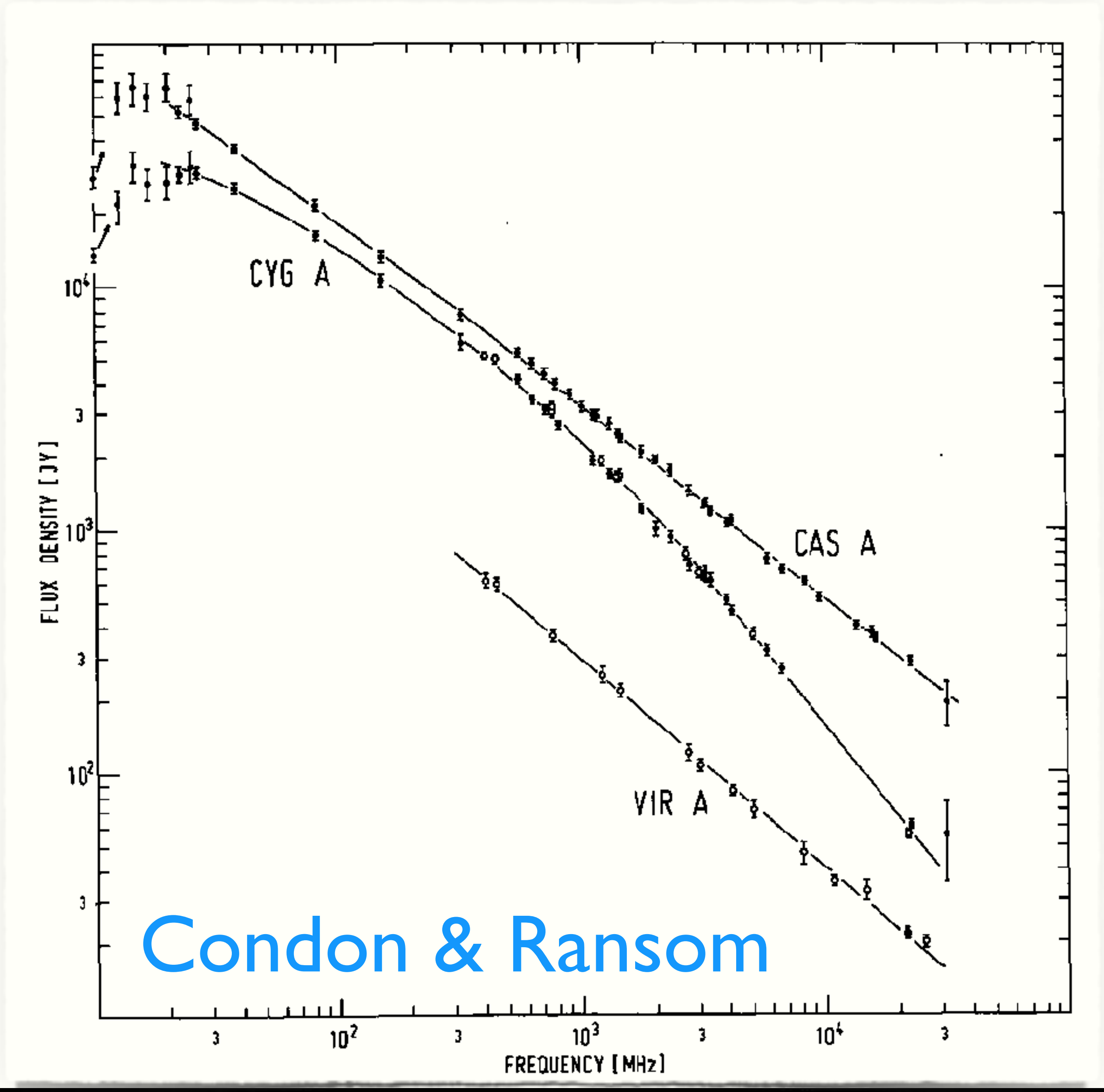
Natural power-laws

- CR Power-law smoothly extends over 11 OOM
- Intrinsic Galactic CR slope ~$E^{-2.3}$
- Synchrotron spectra with similar injection spectra in SNR, Radio galaxies, NS-NS/GRB afterglows, XRBs…
  - As with all rules of thumb, there are many exceptions!
- Huge range of Larmor radius scales

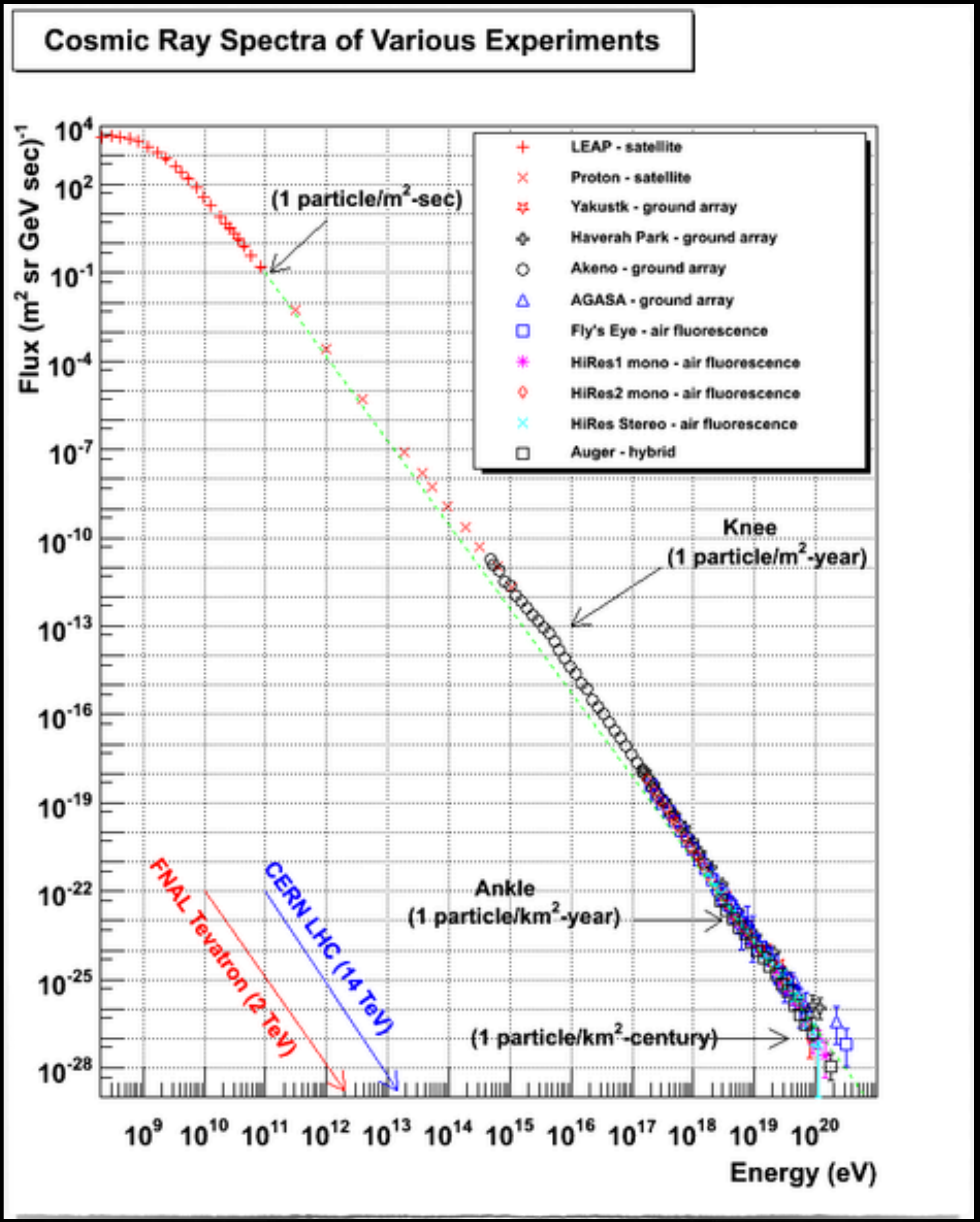
$$R_g = \frac{E}{ZeB}$$

GW170817
Margutti+ 2018

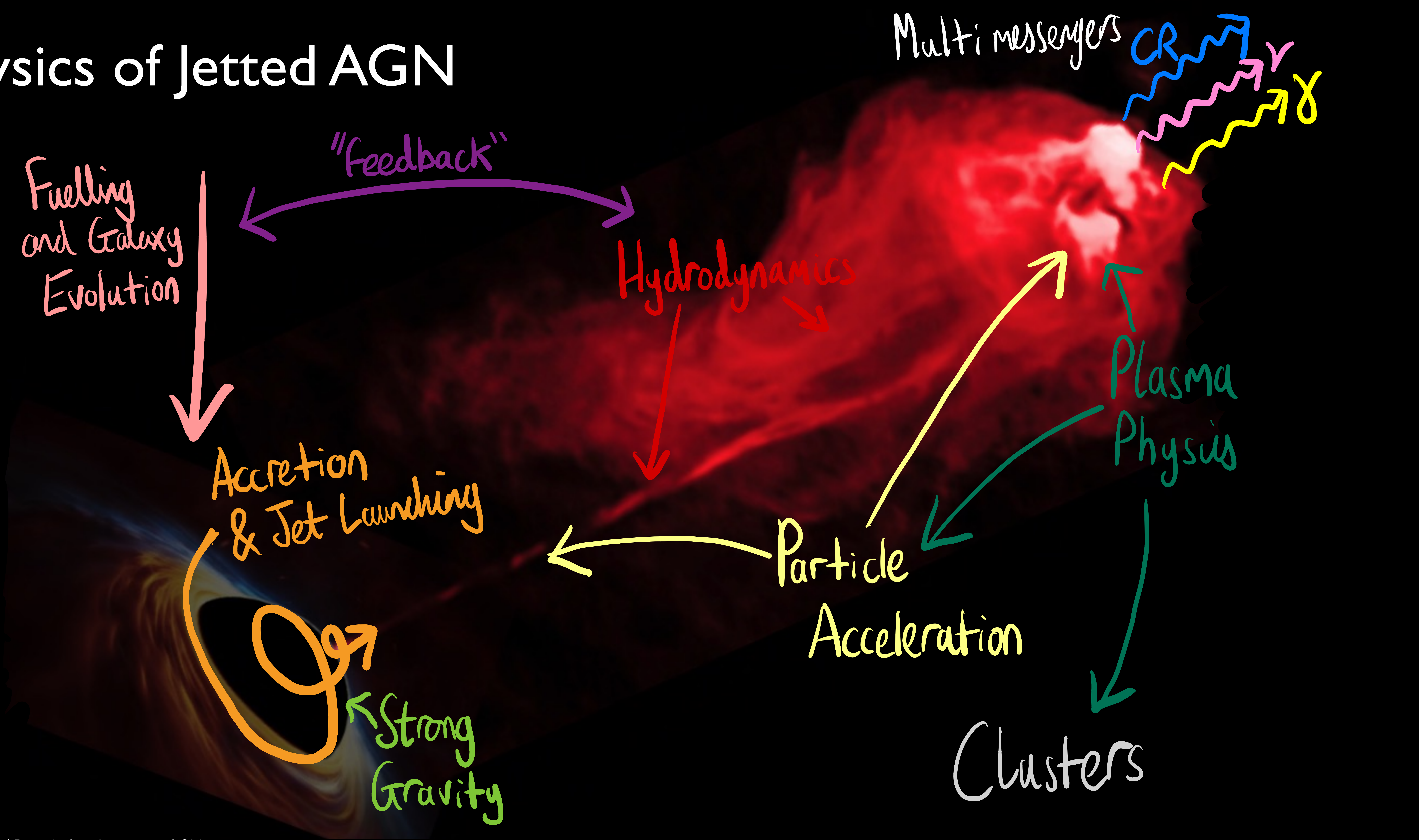




Condon & Ransom



Physics of Jetted AGN



Challenges

- Huge *dynamic range* of scales, densities, etc.
- Different fluid approximations appropriate in each regime
- Nonlinear, self-regulated processes
- Difficult "sub-grid" physics
  - Ideal MHD not enough
  - Complex plasma physics

Structure

1. Historical Perspective and Motivation

2. Particle Acceleration Theory

   a. Shocks and the Hillas energy
   b. Reconnection
   c. Others

3. Shocks, Backflows and Variability

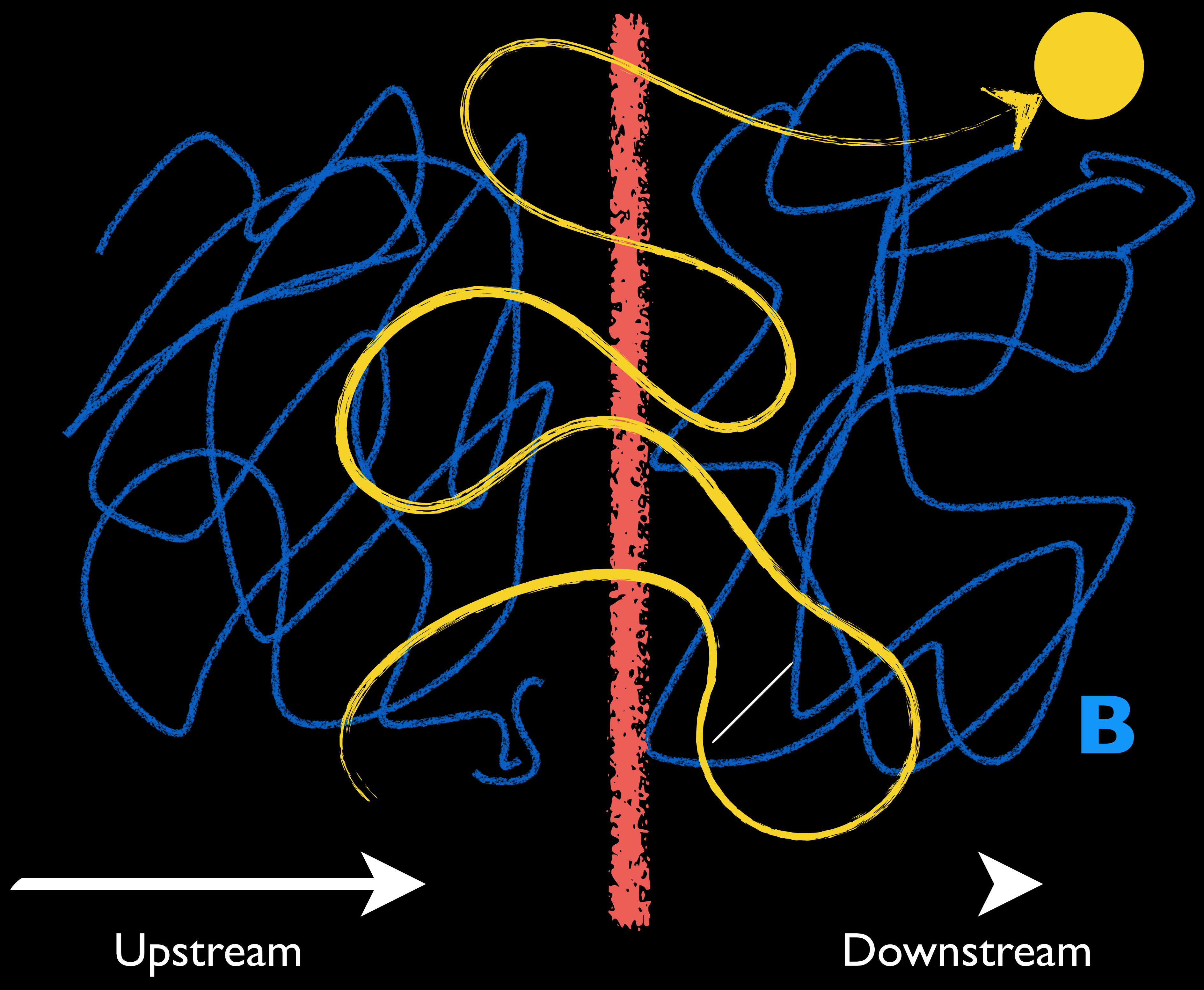
4. Recent Observational Highlights

5. Synergies, Big Picture and Concluding Remarks

Shock acceleration

- Relatively simple theory where particle escape balances energy gain = power-law spectrum (Bell 1978; Blandford & Ostriker 1978)

Turbulent B field is crucial!



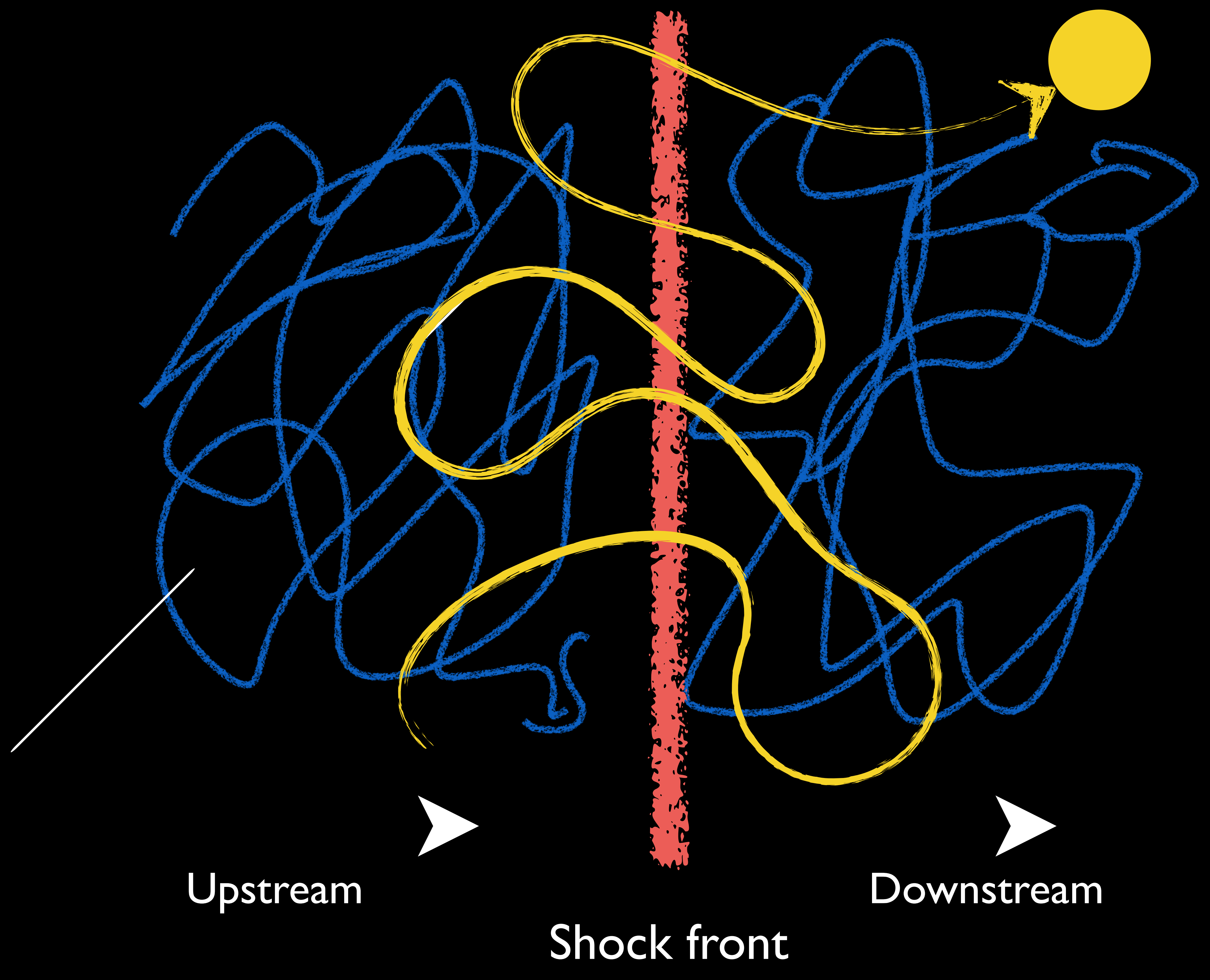
$$\frac{\Delta E}{E} \sim \frac{v_s}{c}$$

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

Shock Acceleration

- Crucial aspect of shock acceleration:
  - escape prob (P) and energy gain (β) 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
- Other flavours: shock drift acceleration, shock surfing acceleration - similar principle.

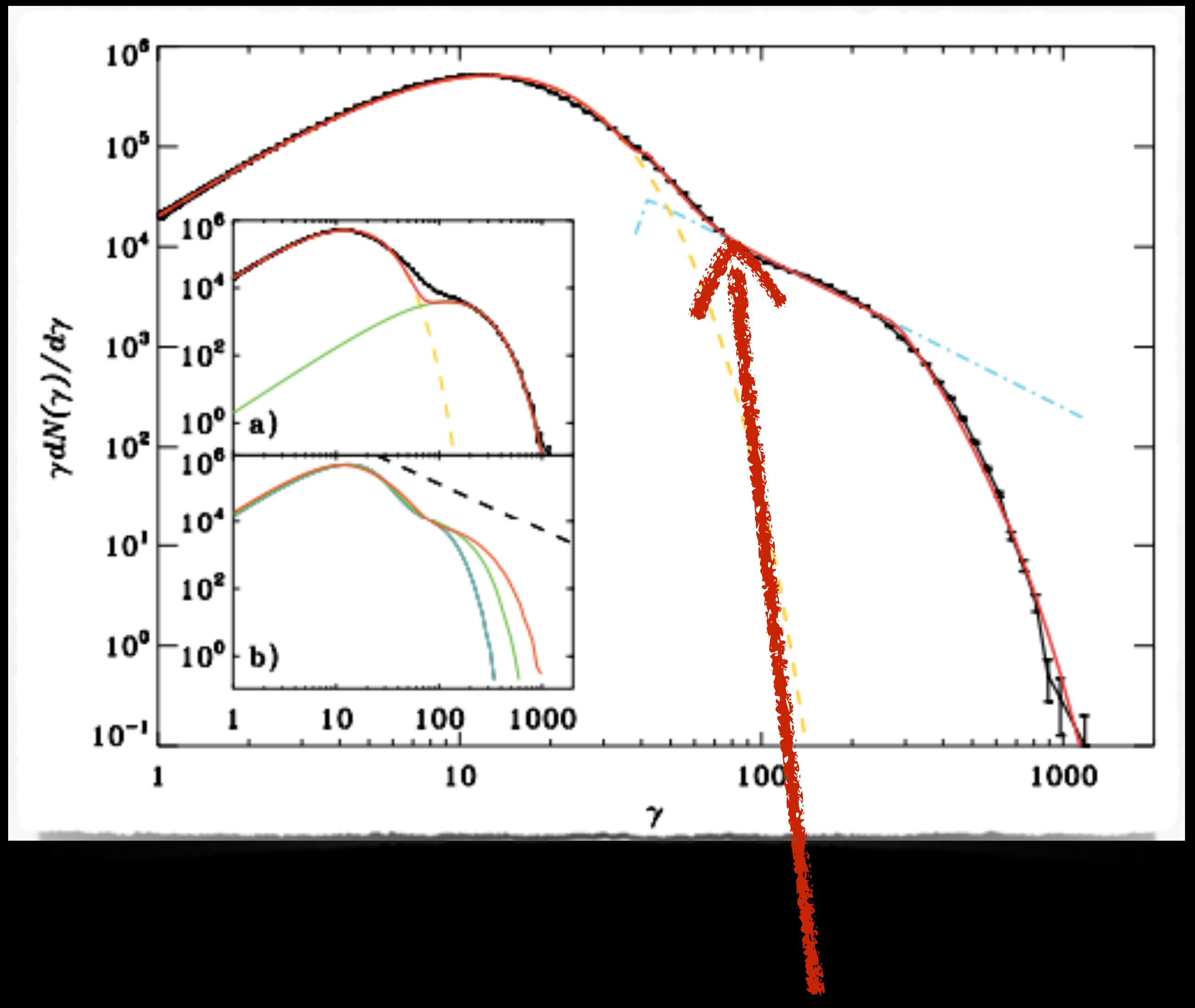
$$\frac{dN}{dE} \propto E^{(\ln P/\ln \beta_e - 1)}$$



Reviews: Drury 1981, Blandford & Eichler 1987, Bell 2014, Marcowith+ 2018, JM+ 2020.

PIC Simulations

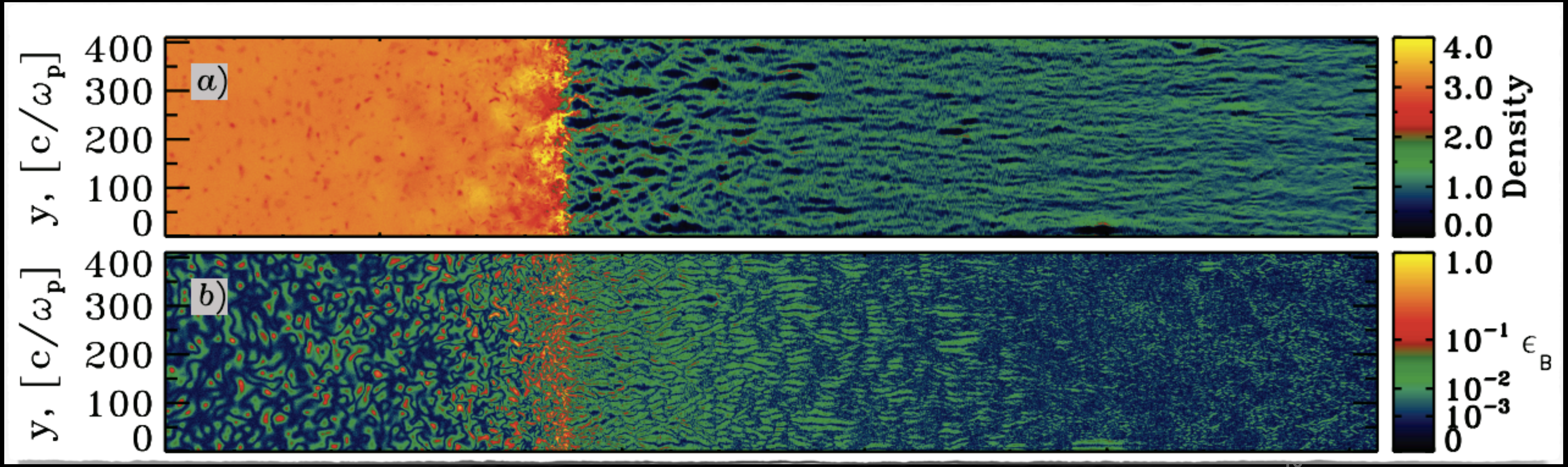
- Relatively simple theory where particle escape balances energy gain = power-law spectrum
- Verified by complex particle-in-cell (PIC) simulation (e.g. Spitkovsky 2008)
- Self-consistent generation of instabilities (e.g. Weibel, Bell, Whistler) and power-law superthermal tail in momentum distribution



"Injection"

Spitkovsky 2008

See also:, e.g. Sironi & Spitkovsky 2009, 2011 Riquelme & Spitkovsky 2011, Caprioli, Spitkovsky 2014a,b, , Caprioli+ 2015, Bai+ 2015, Crumley+ 2019)



Maximum Particle Energy

Hillas 1984

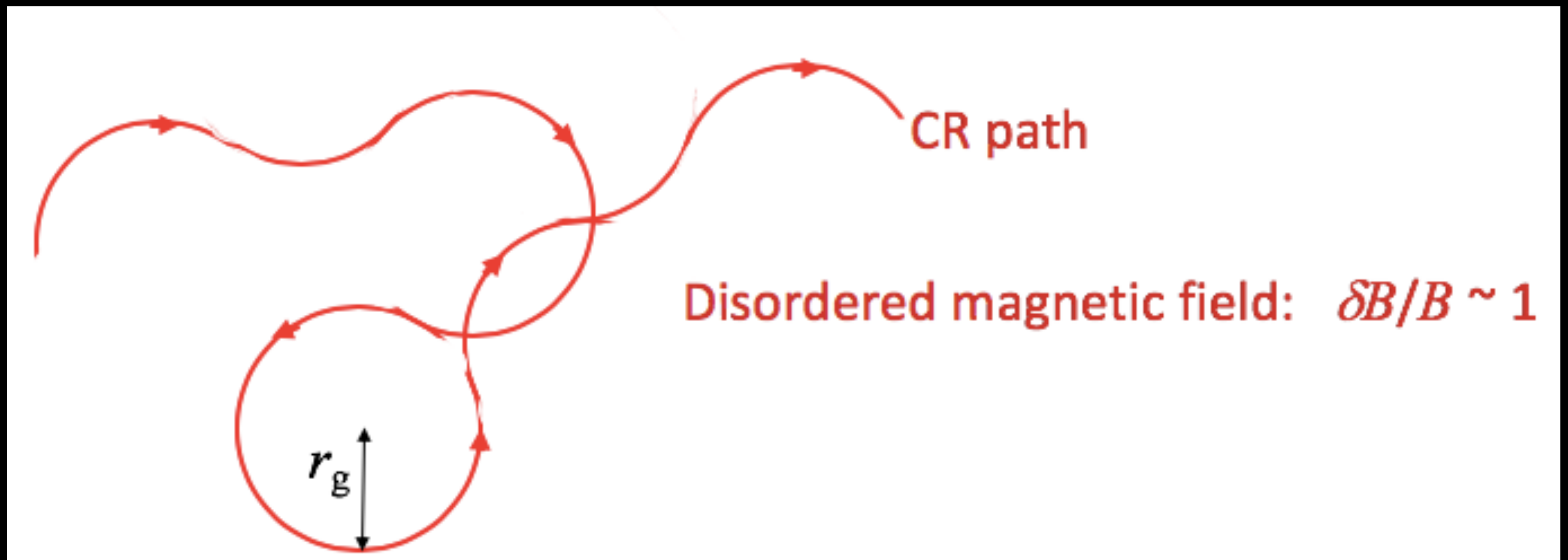
Ignoring factors of bulk Γ - depends on details of escape

- **Hillas energy:** lower by factor β=v/c, maximum characteristic energy

$$E = Ze\beta BR$$

- Intuition:
  - Moving particle a distance R through u x B electric field
  - Taking time derivative of magnetic flux BR^2 to give potential drop uBR
- Can derive a *power requirement:* $Q_k > 10^{43} Z^{-2} \beta^{-1} \left(\frac{E}{10^{19}\ \mathrm{eV}} \right)^2$

The Bohm Regime



- **Hillas is necessary, but not sufficient**
- Diffusion coefficient, D, controls how quickly particles diffuse
  - larger D means quicker diffusion and poorer confinement (D ~ mean free path x velocity)
- Shortest acceleration time for smallest D, which is *Bohm diffusion*

$$D_B \sim R_g c \qquad R_g = \frac{E}{ZeB} \qquad \tau \sim D/u^2$$

$$E \approx (3/8) Ze\beta BR$$

Hillas energy only reached when Bohm diffusion applies - need strong turbulence in the magnetic field on Larmor radius scale

CR-driven instabilities

- CRs produce a return current in a plasma that drives MHD turbulence - the non-resonant or Bell instability* (Lucek & Bell 2001; Bell 2004; Amato & Blasi 2009)

- Natural way to grow field to Larmor radius scales

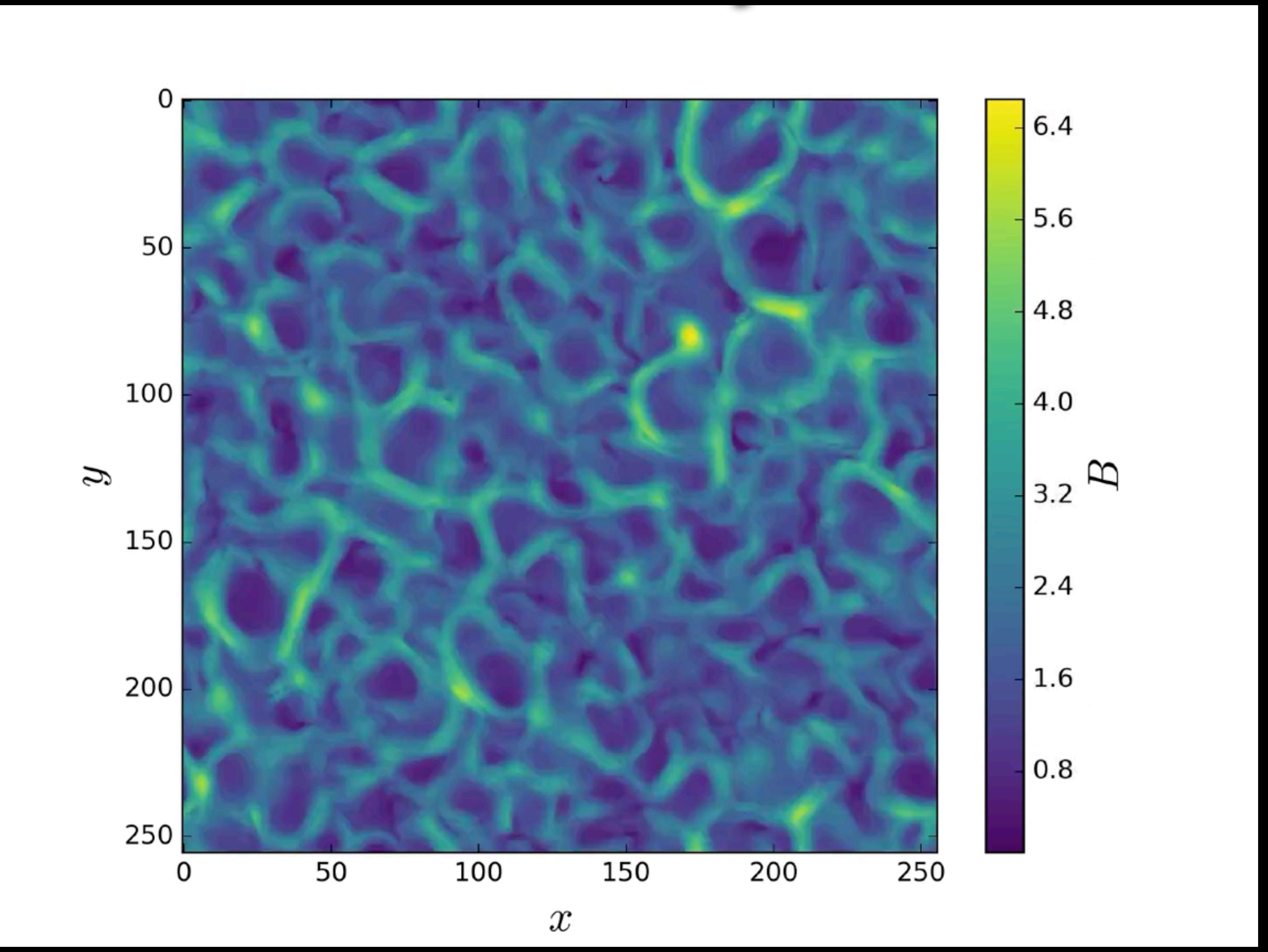
- Energy exchange with turbulence steepens CR spectrum (Bell, JM+ 2019, Osipov+ 2019, Malkov+ 2019, Caprioli 2019)

  - A general example of the *nonlinear nature of particle acceleration*

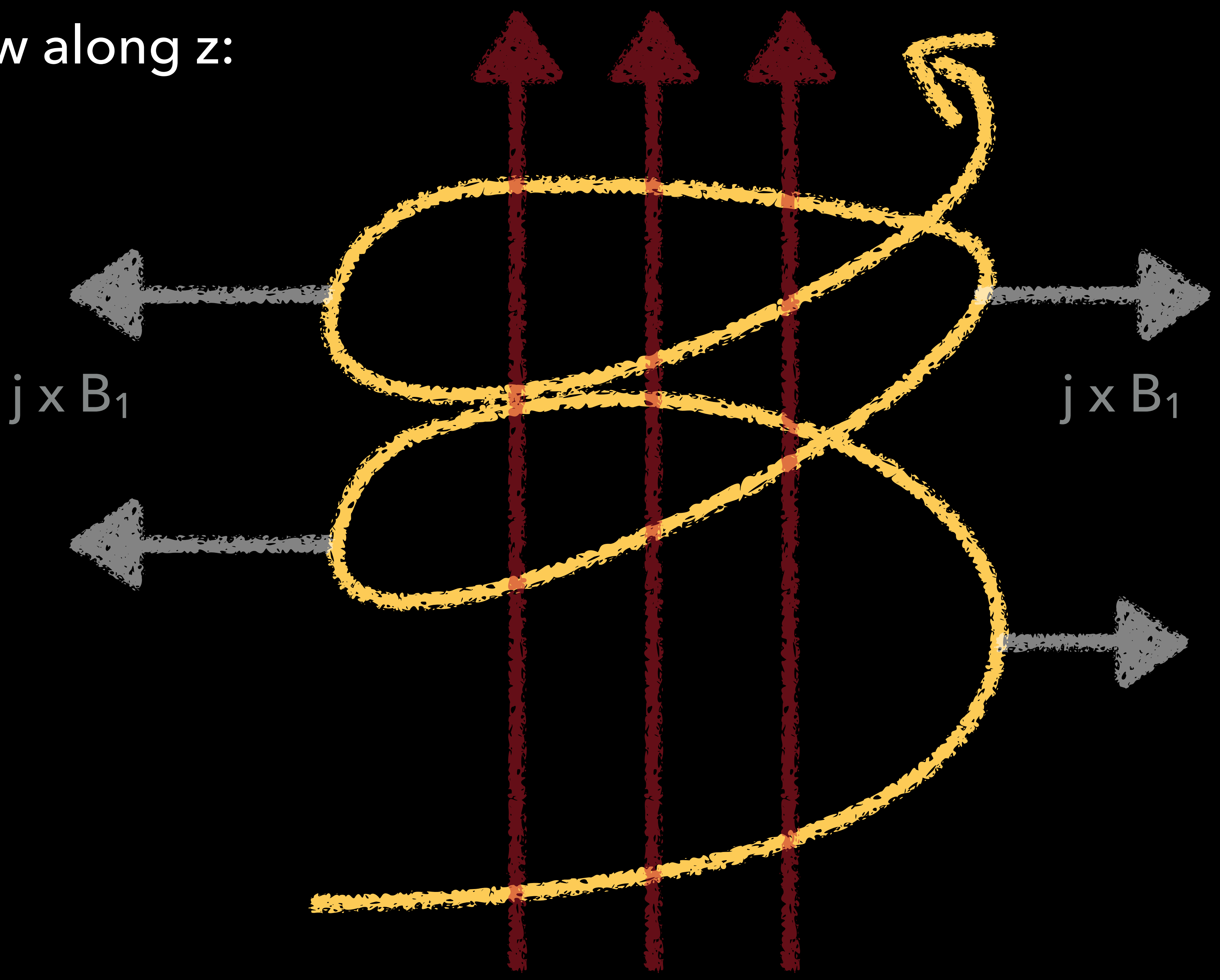
dependence of the radio spectral index on the shock velocity:

$$\alpha = \frac{1}{2 - 12u_s/c} \quad (32)$$

JM+ 2017



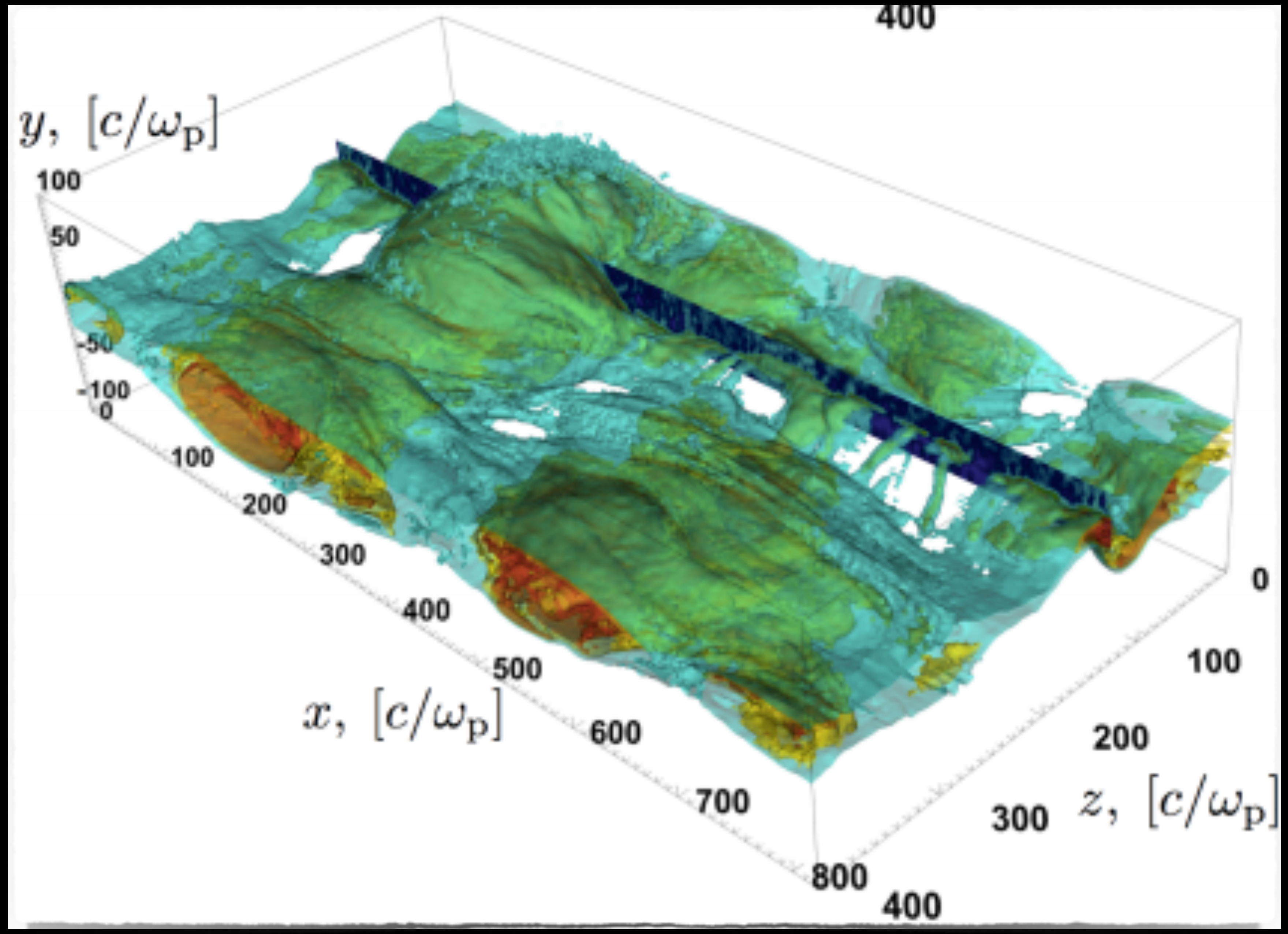
View along z:



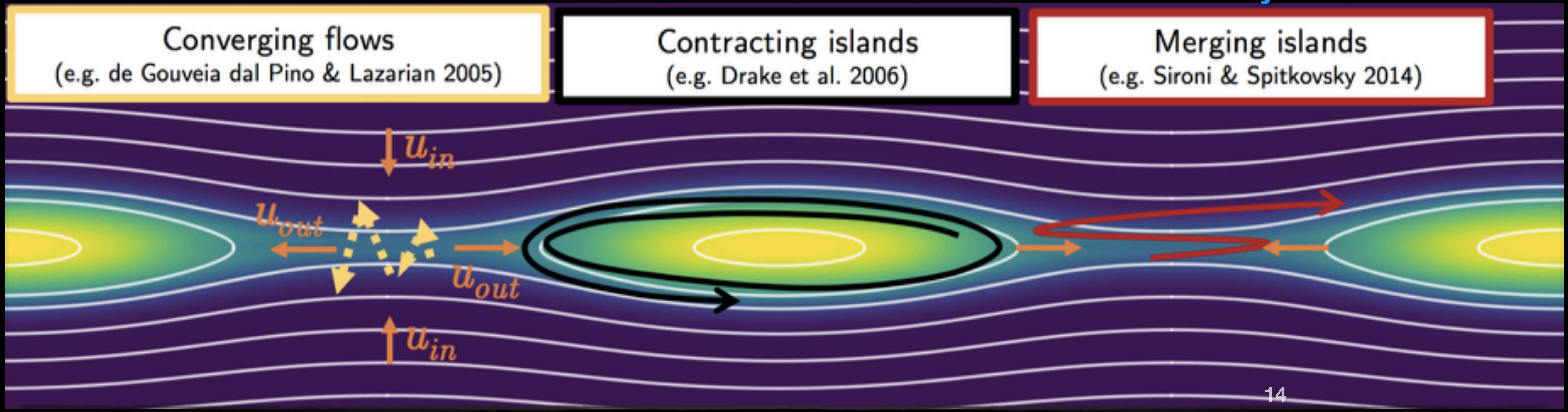
* Other instabilities are available

Magnetic Reconnection

- 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"



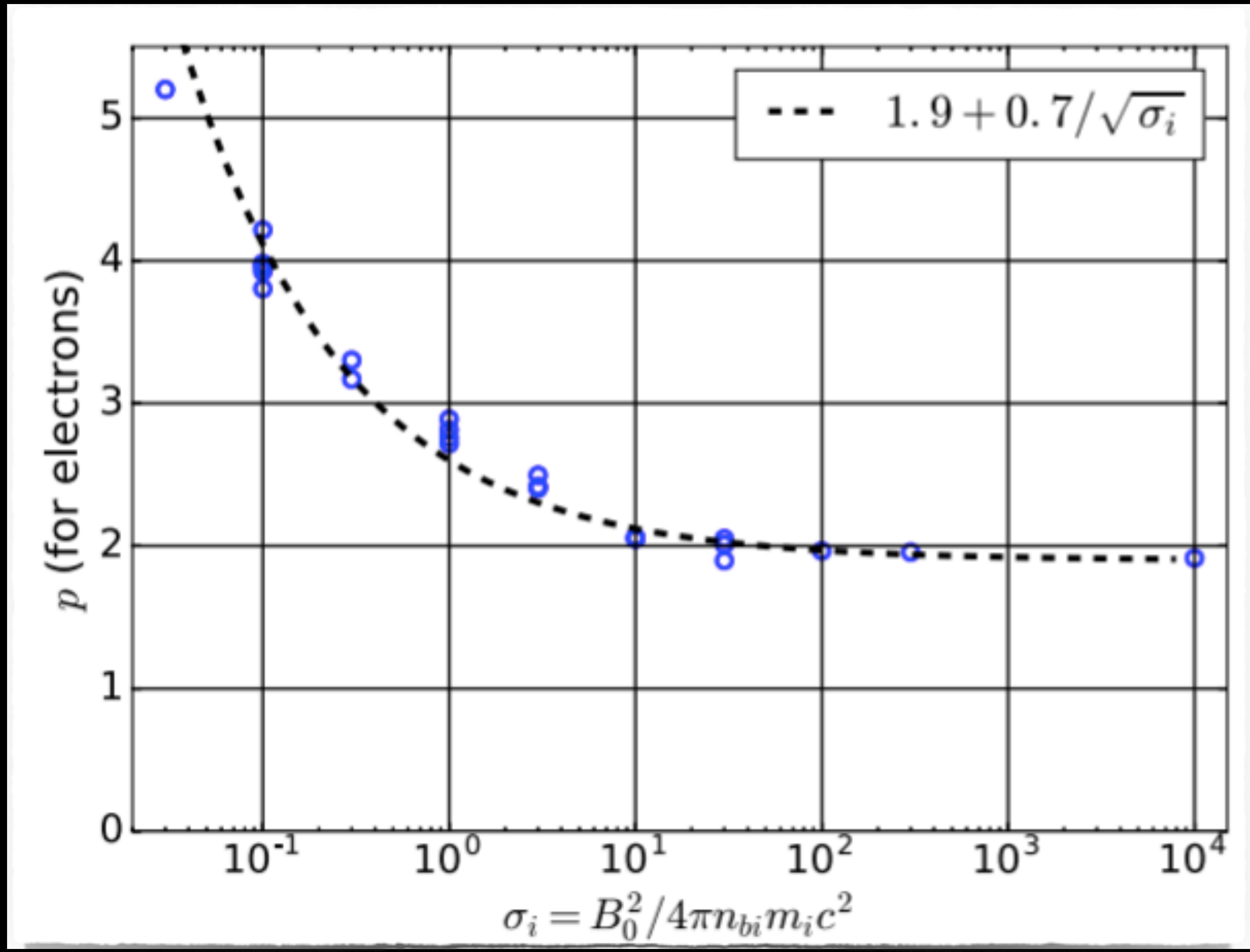
JM+ 20



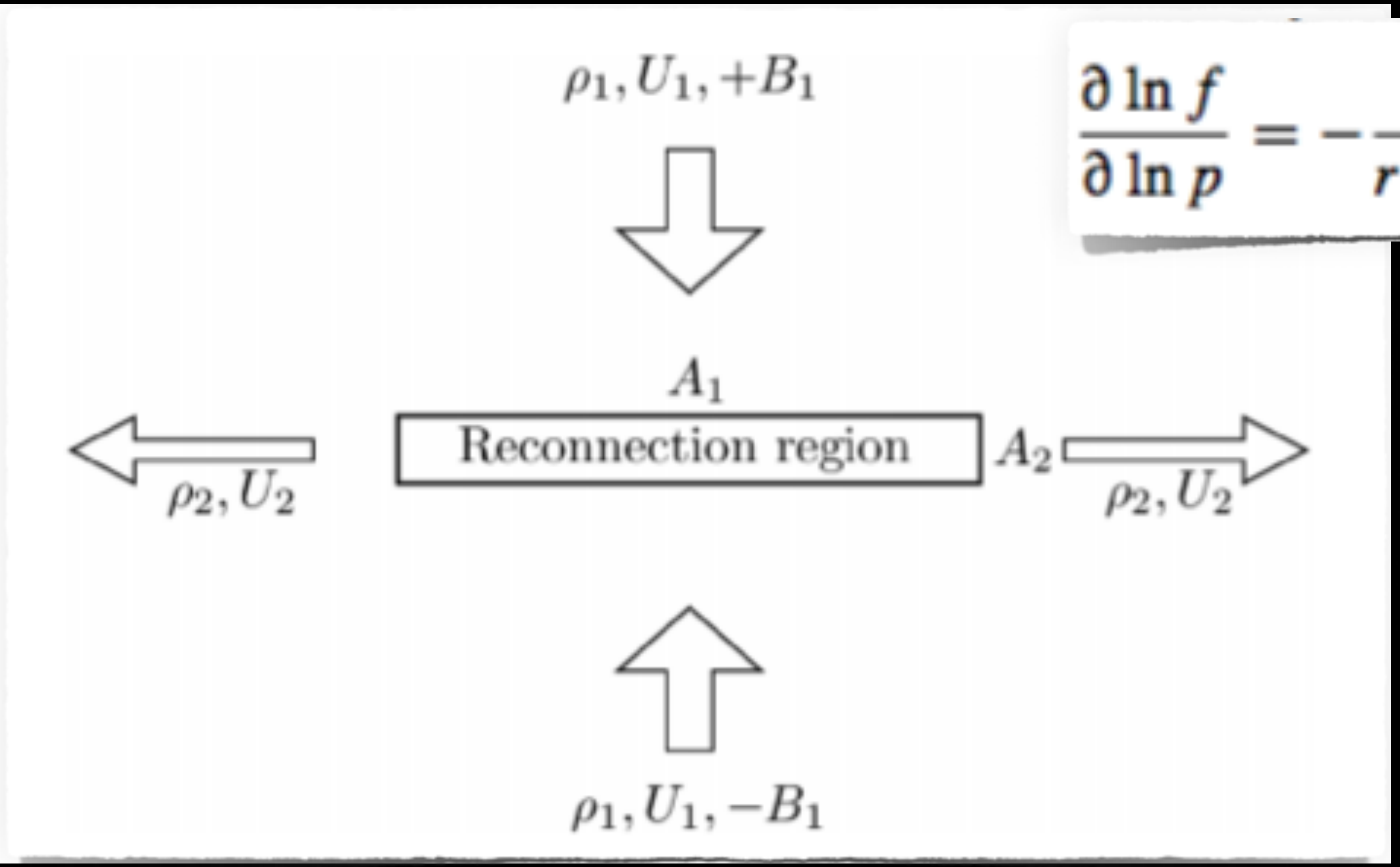
See reviews by Blandford+ 2017, Guo+ 2020

Magnetic Reconnection

- Interesting parallels with shocks
  - spectral index perhaps controlled by "compressivity" or magnetisation
- Connects macroscopic energy dissipation to non thermal particles?
- Explains "Magnetoluminescence"? (Blandford+ 2017)



Werner+ 2016



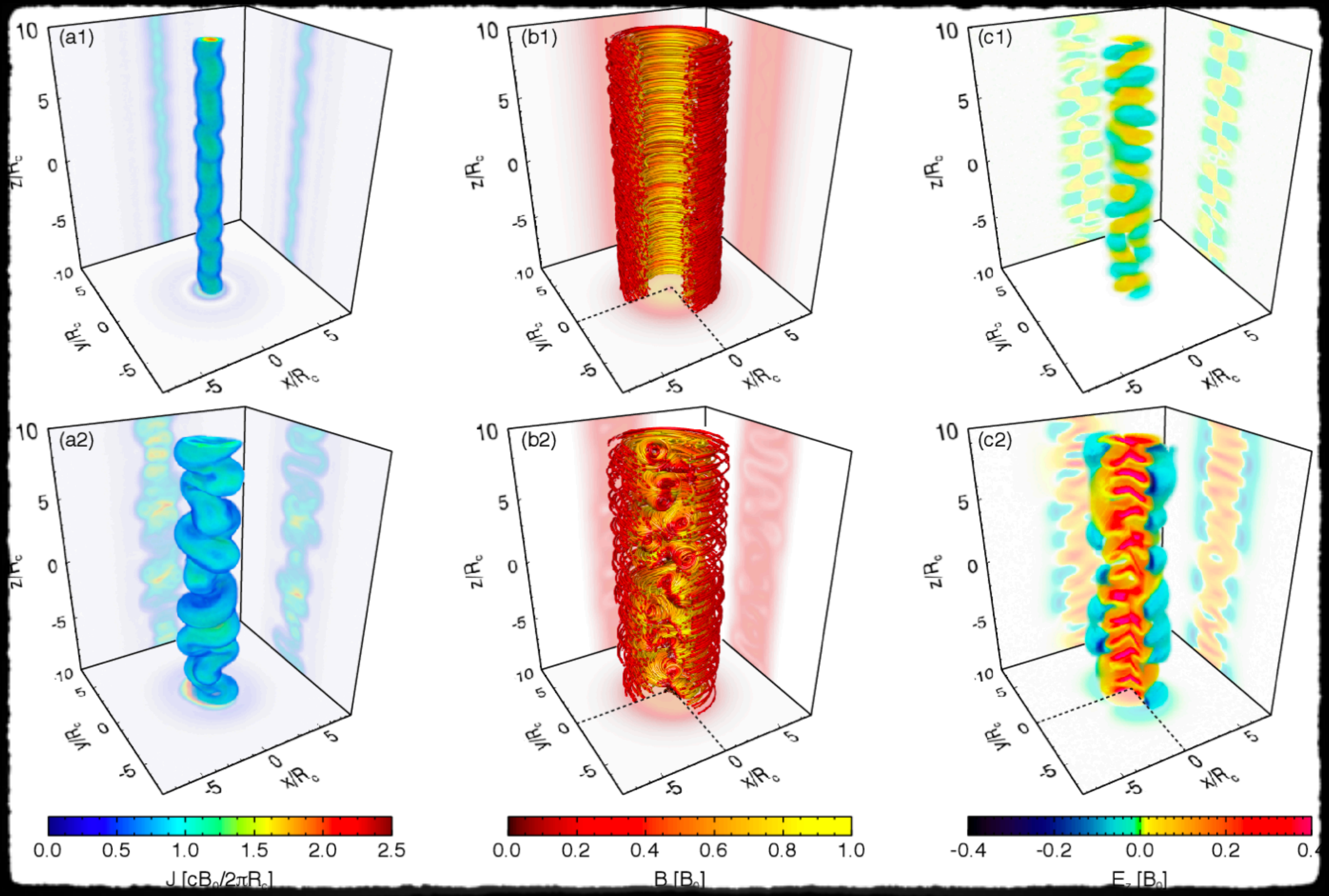
$$\frac{\partial \ln f}{\partial \ln p} = -\frac{3r}{r-1}, \qquad r = \frac{\rho_2}{\rho_1}$$

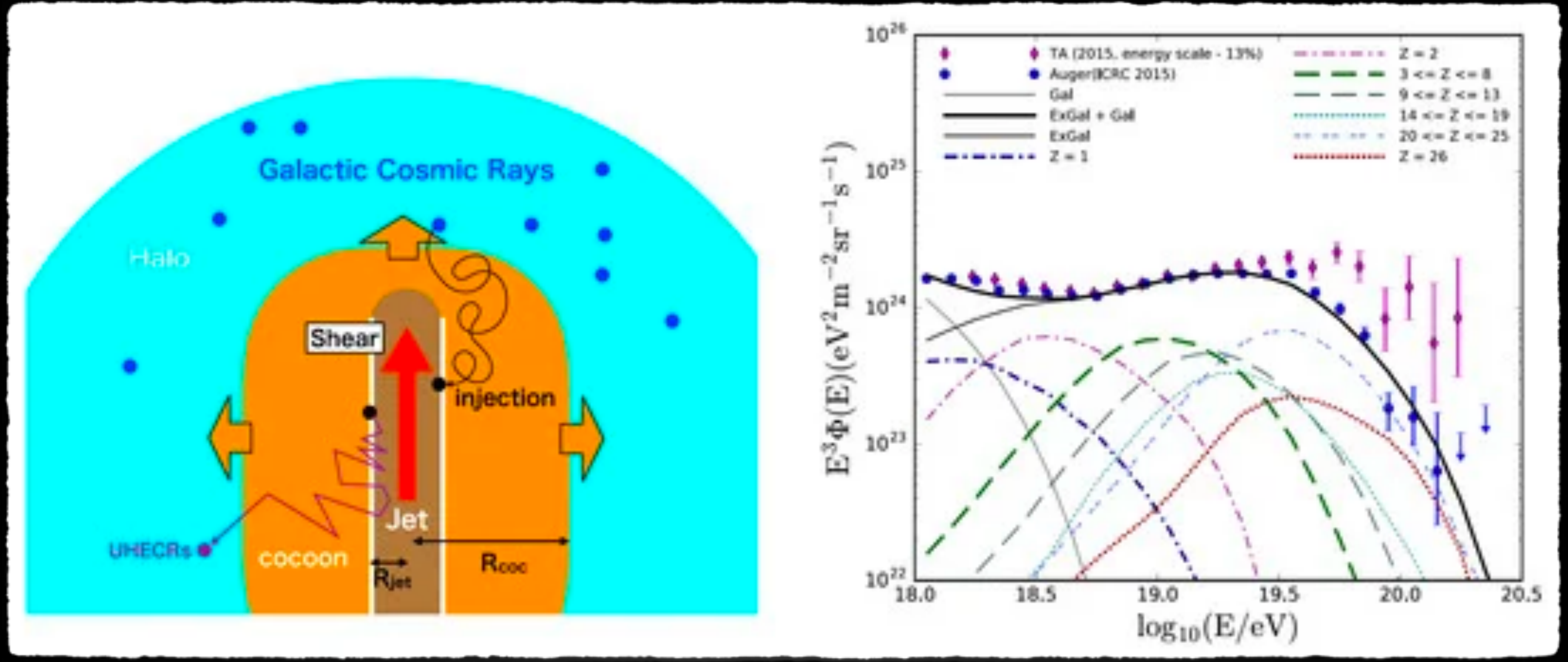
Drury 2012

Other mechanisms

- Shear acceleration (e.g. Rieger & Duffy 2004, Caprioli+ 2015,Kimura+ 2018, Rieger 2019)
- Magnetic Kink Instabilities (e.g. Alves et al. 2018, but see also lab Z-pinches)
- Fermi II (Fermi 1949; problems with fine-tuning)
- BH spark gaps / Magnetospheres / Direct E fields (e.g. BZ 1978, Crinquand+2020)

Alves+ 2018

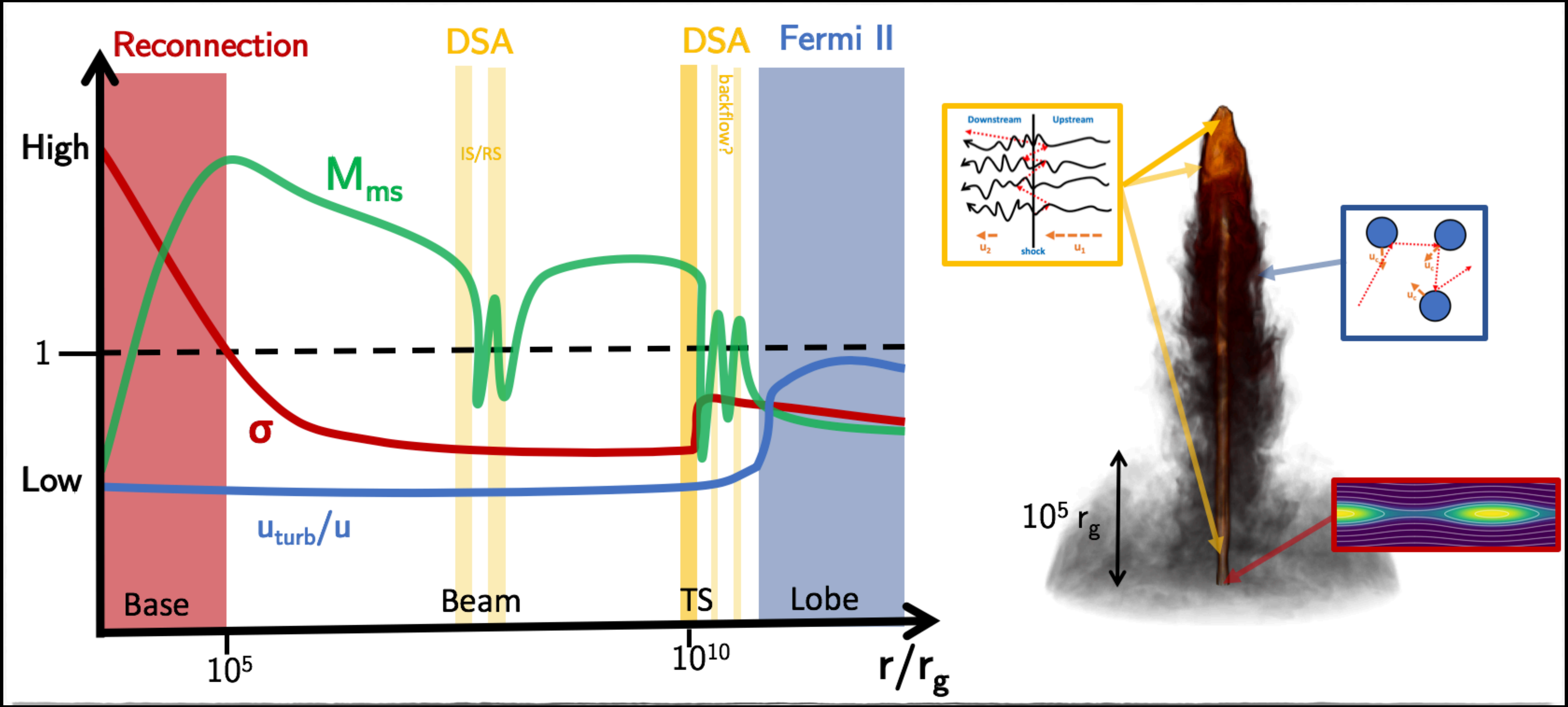




Kimura+ 2018

JM+ 2020 (review, 100 years of jets anthology)

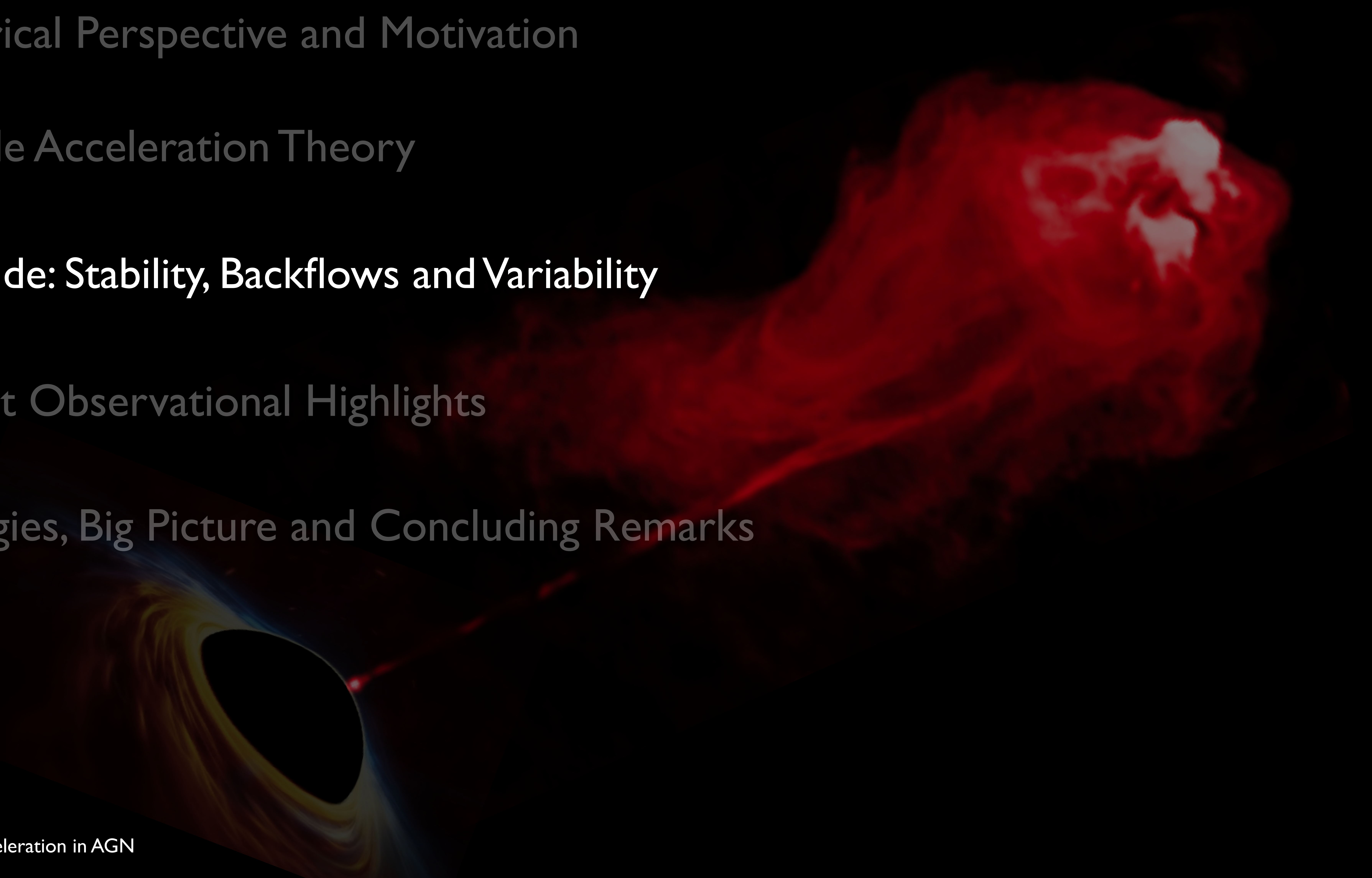
Acceleration Sites in Jets?



Key sites for particle acceleration are sites of *energy dissipation*

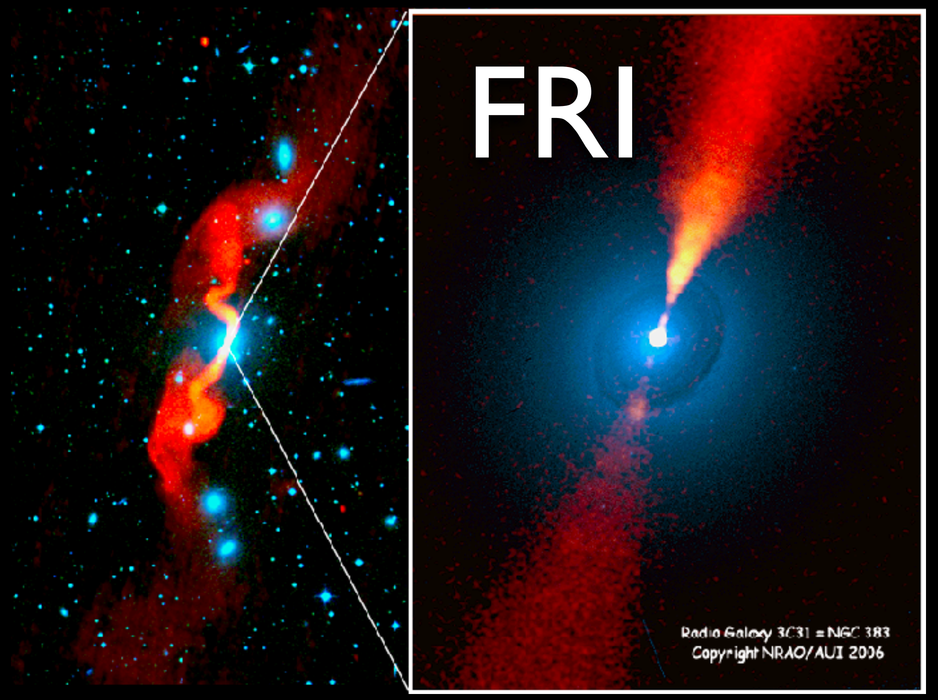
Hard to distinguish….

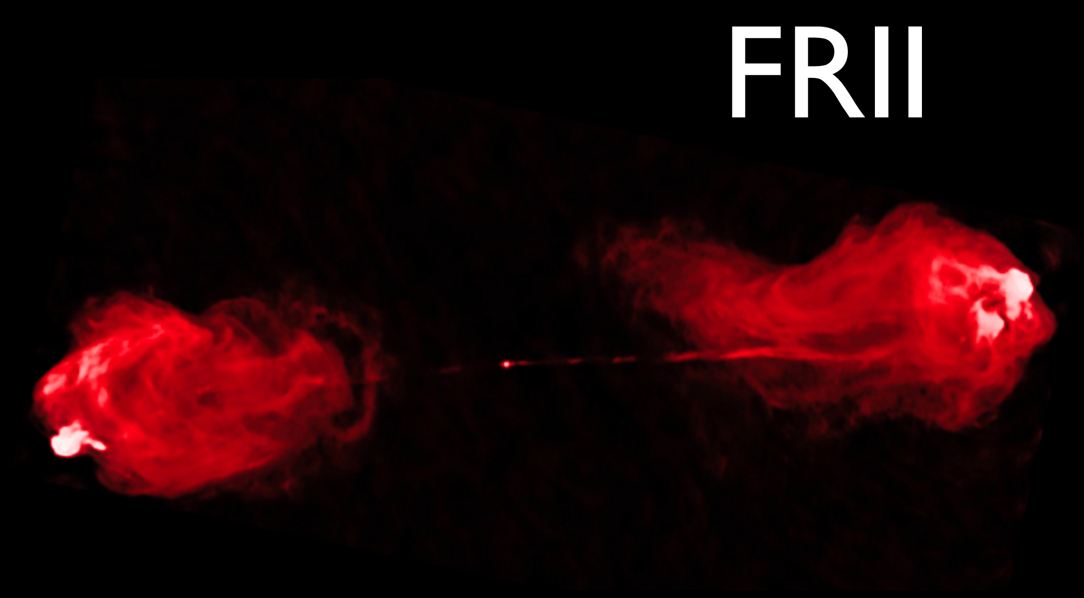
Structure



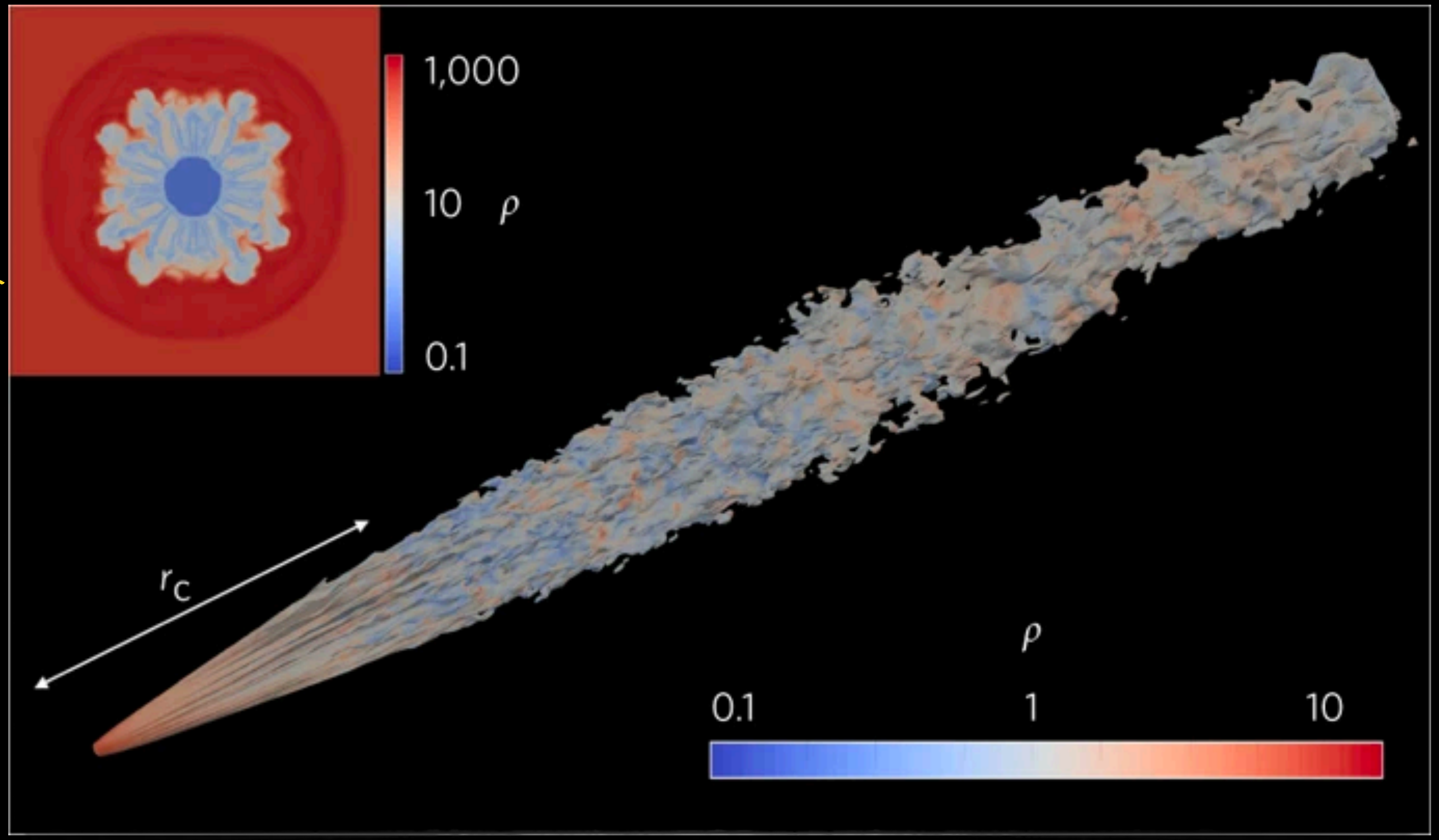
Jet Stability and Confinement

Fanaroff & Riley (1974)



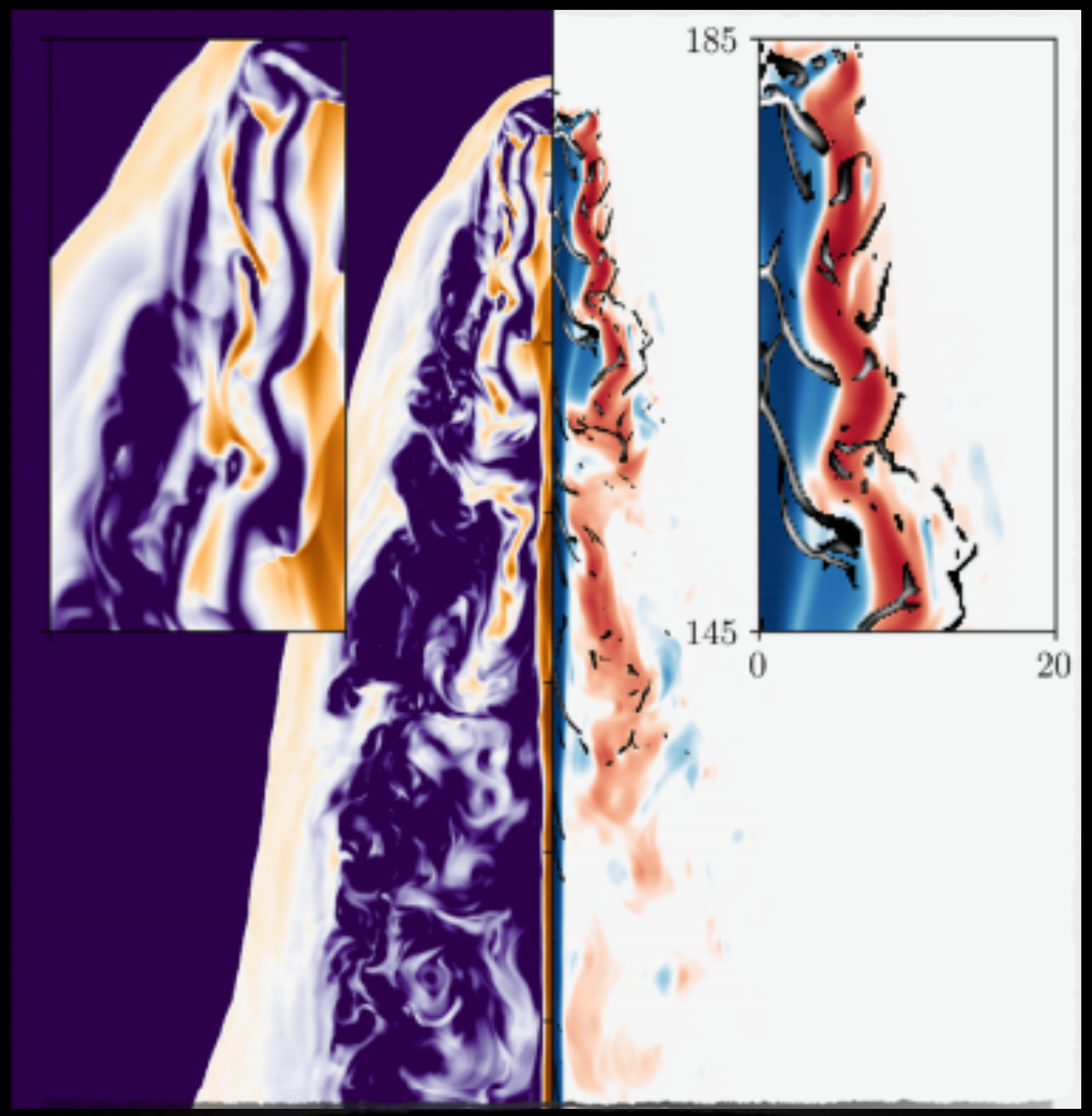


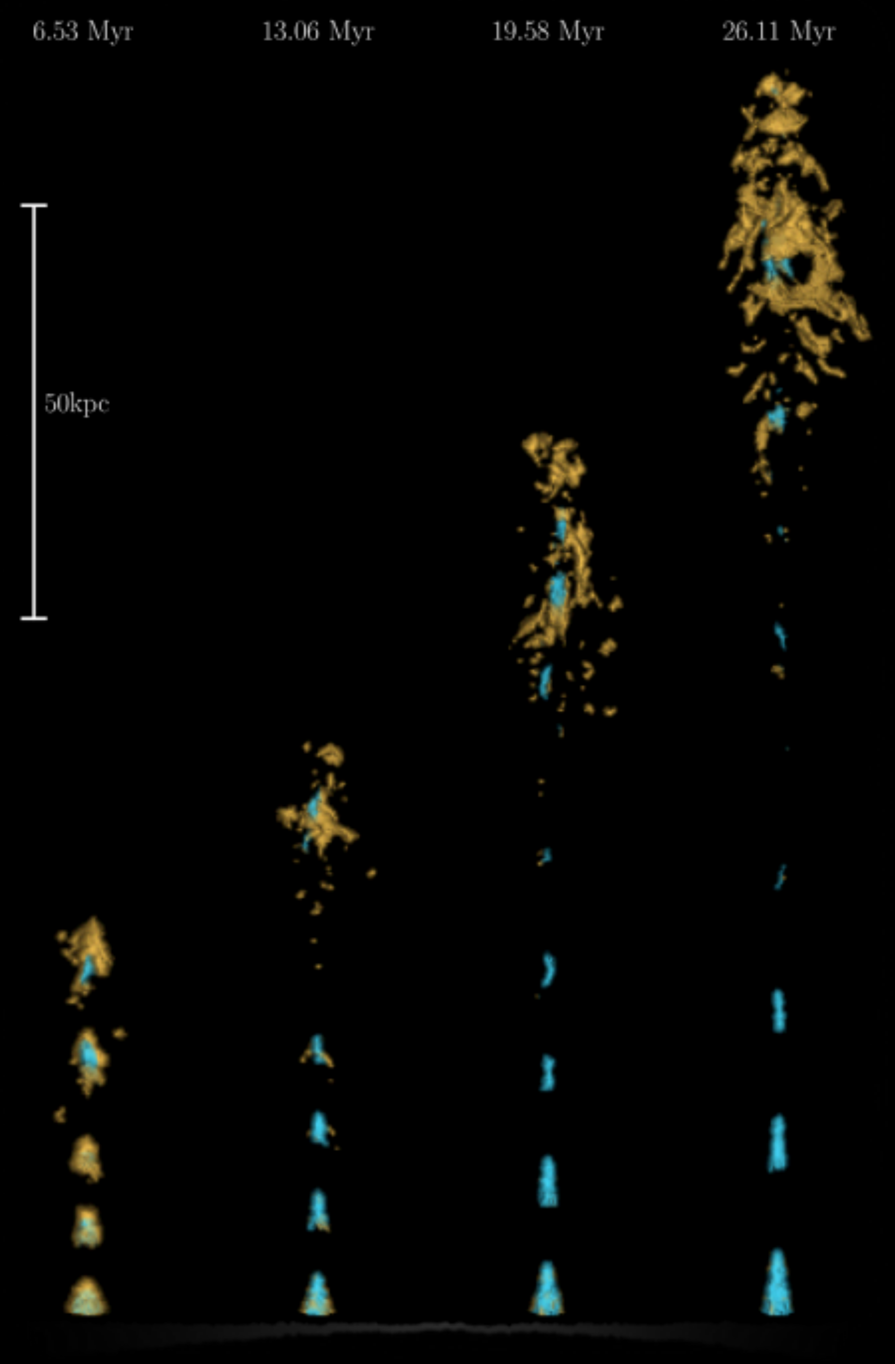
- Key question: why do some jets stay well-confined and others are disrupted?
  - FRI-FRII “dichotomy”
- Two of the (many) possibilities:
  - Magnetic kink instability (e.g. Tchekovskoy & Bromberg 2016)
  - Centrifugal-type instability (Gourgouliatos & Kommissarov 2018)
- Mixing and entrainment -> critical for composition (e.g. Wykes+ 2018, Chattejee 2019)

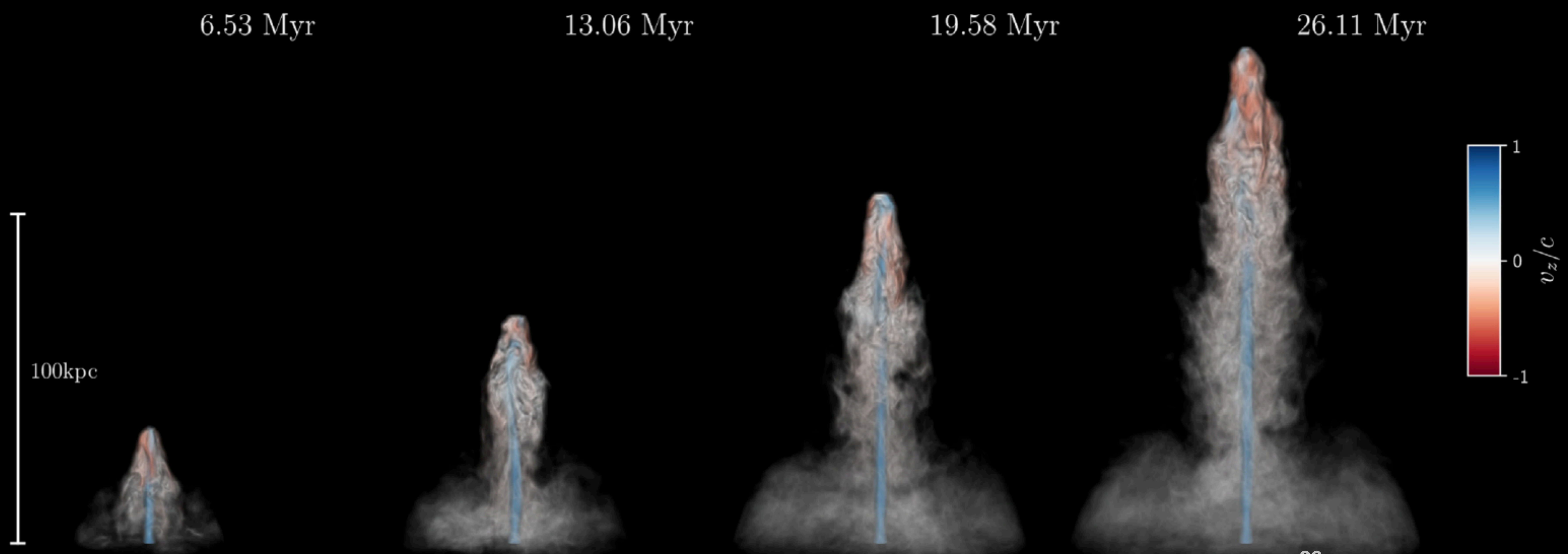


Backflow & Cocoon Shocks

- Jets produce strong backflow, which can be supersonic, v~0.1-0.5c
- Shocks produced in the cocoon from backflow
  - See also Reynolds+ 2003, Mignone+ 2007, Bell+ 2018l
- Estimate of maximum proton energy: 5e19 eV -> UHECRs!





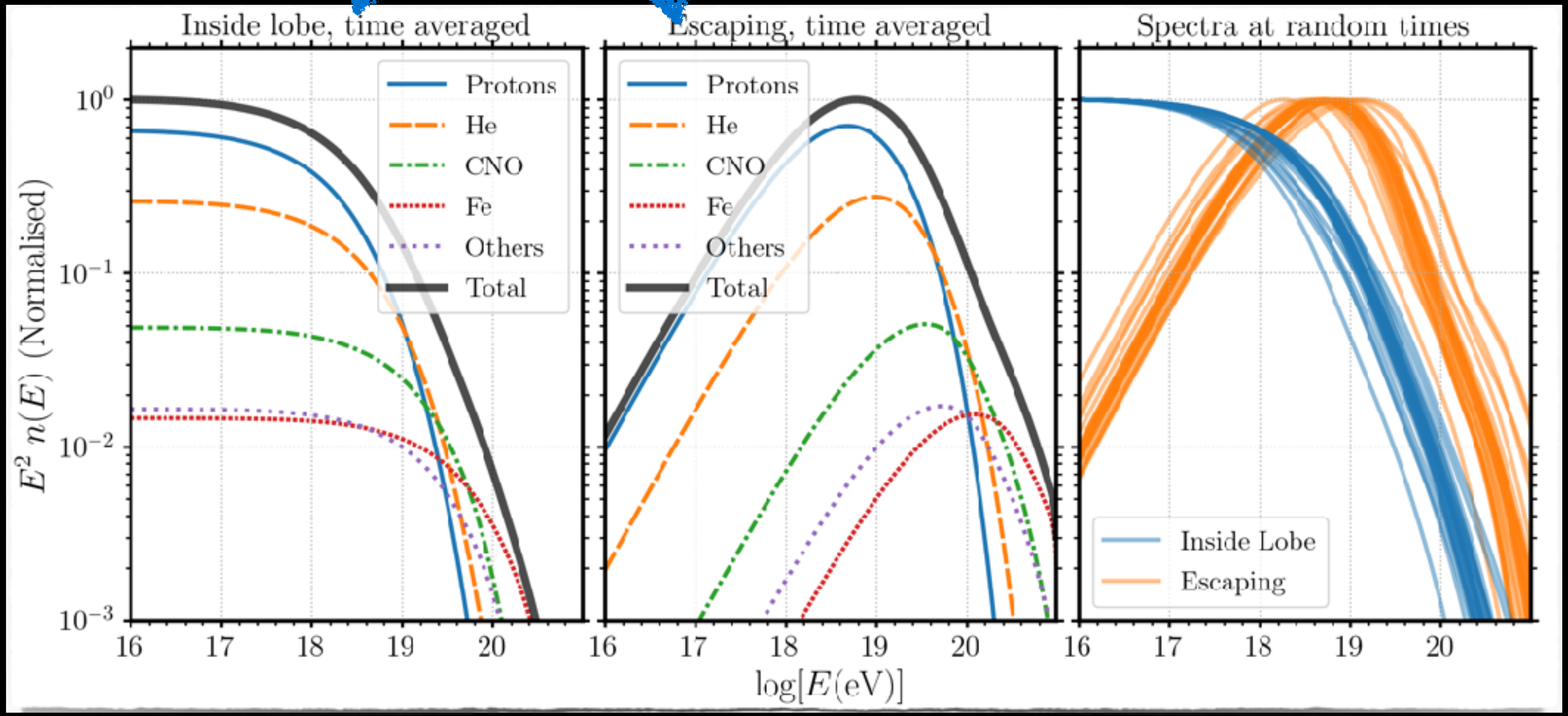


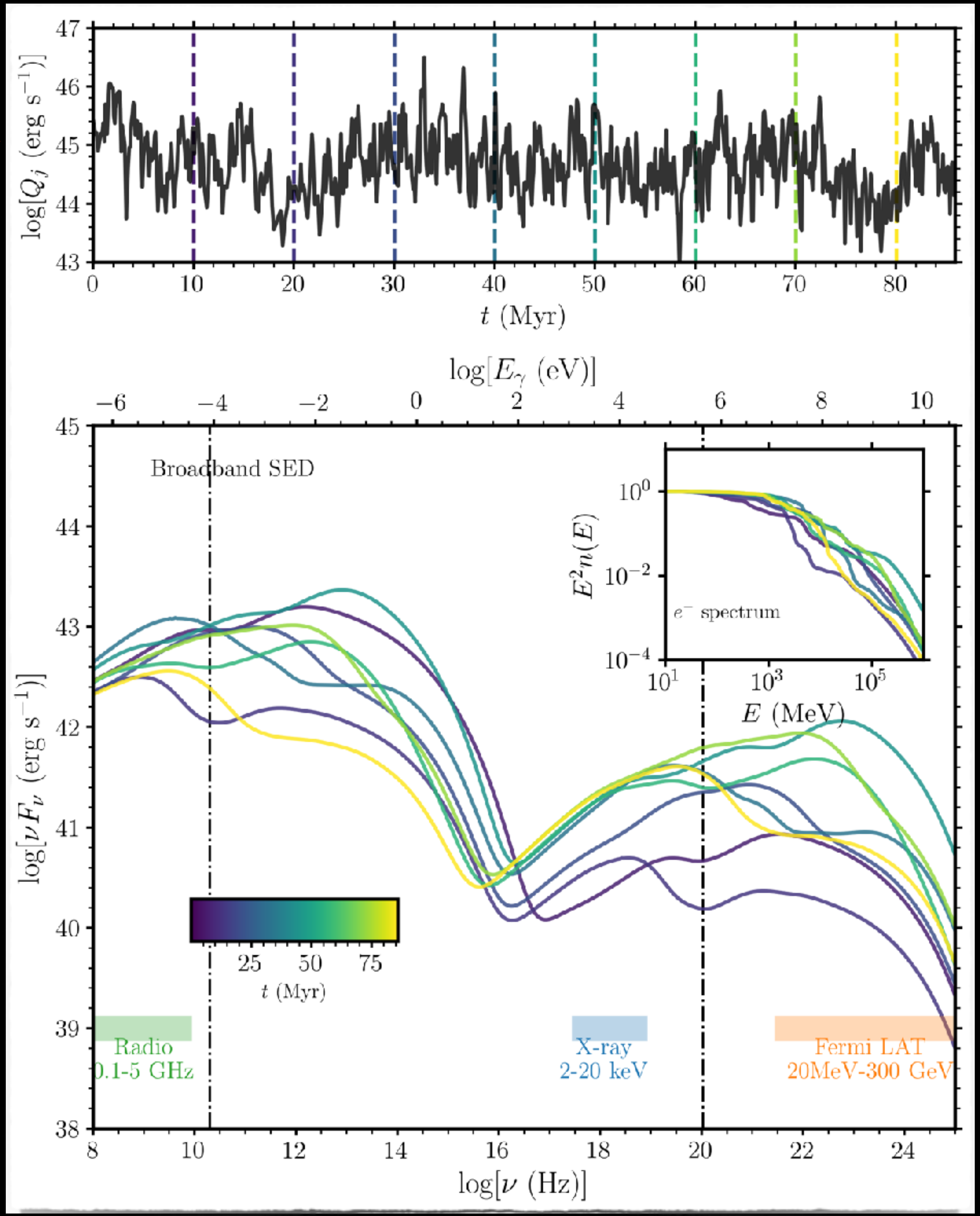
JM+ 2019
http://jhmatthews.github.io/uhecr-movies

Flickering Jets

JM & Taylor 2021

- Curvature and bumps in the electron spectrum and broadband SED when you vary the jet power
- Escaping CRs have different slope and composition to internal CRs -> stochasticity matters for UHECRs!



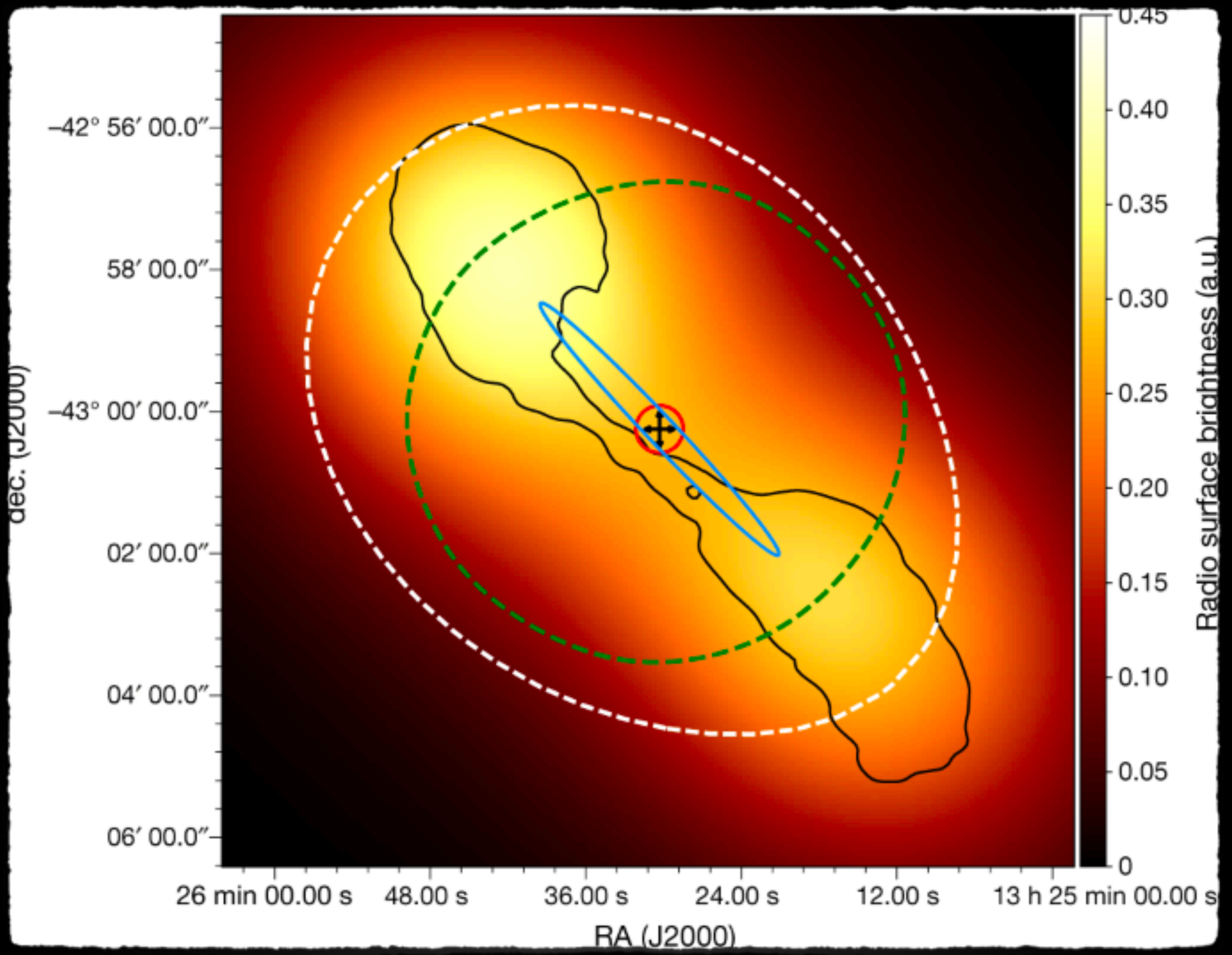


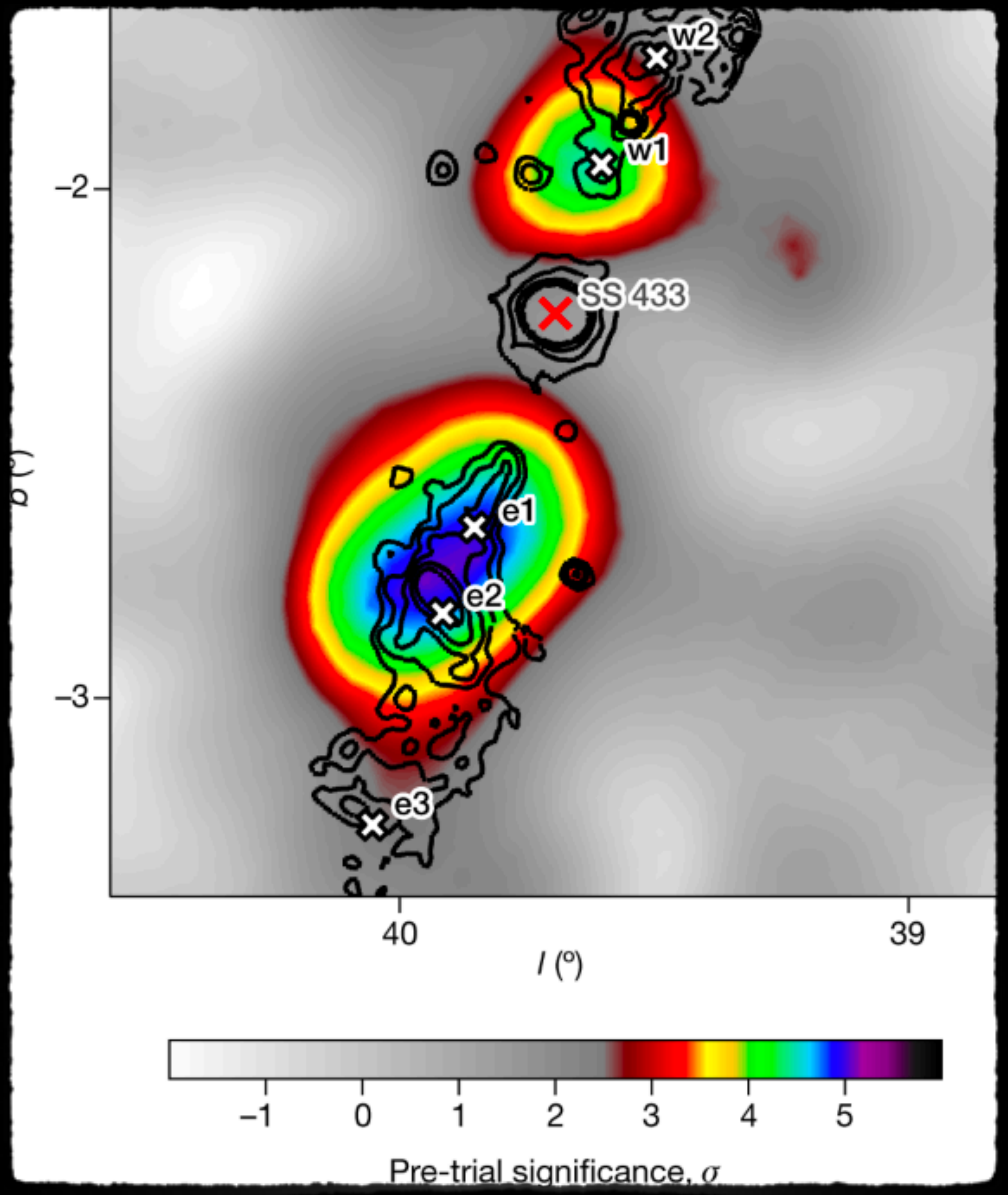
Structure

EM only! See Kotera, Bustamente, Lang talks for UHECRs + Neutrinos

TeV Gamma-rays from jets

Extended TeV gamma-ray emission in radio galaxy Cen A coincident with lobes (H.E.S.S. collab 2020)



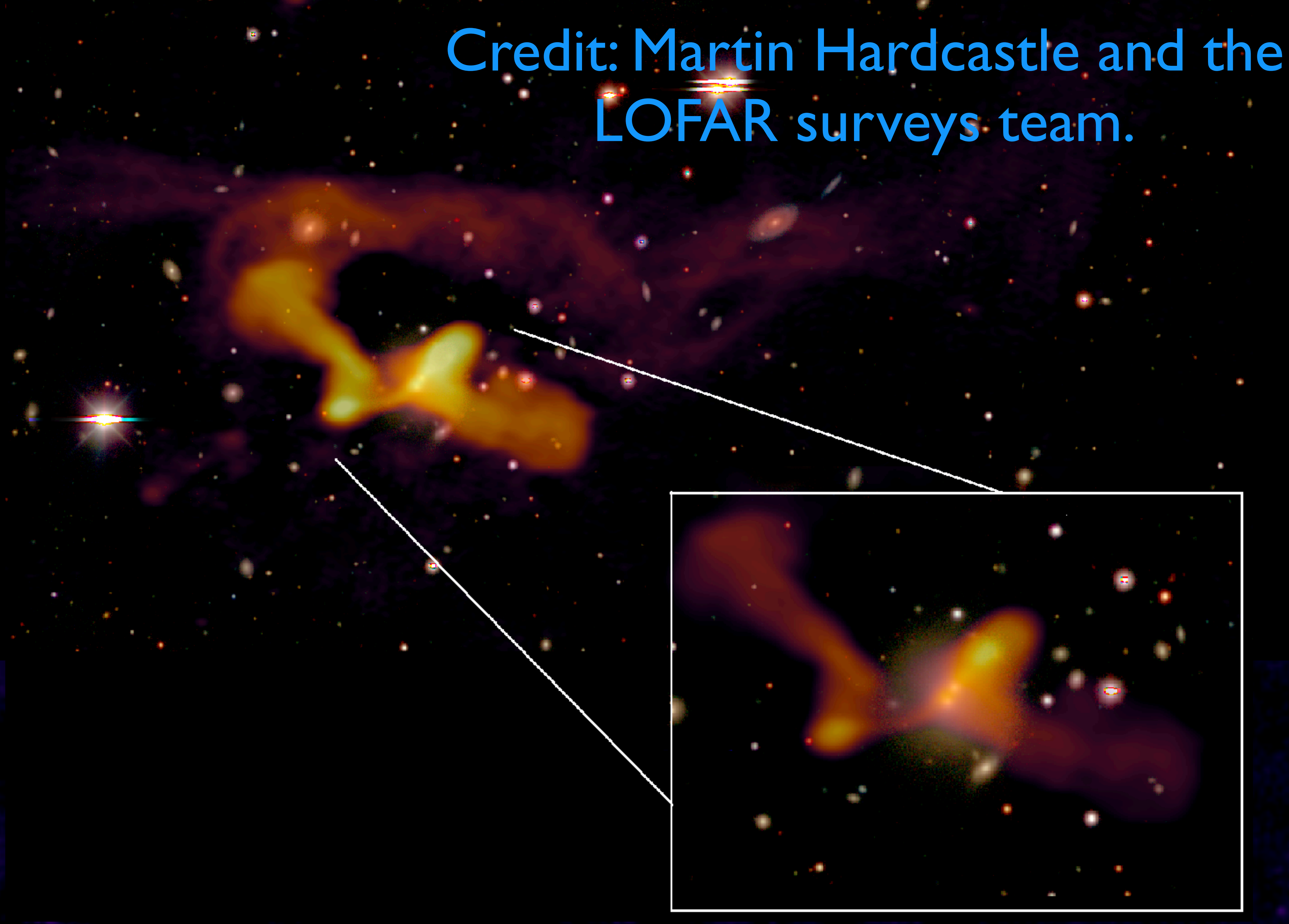


Extended TeV gamma-ray emission in galactic microquasar SS433 (H.A.W.C; Abeysekera+ 2018)

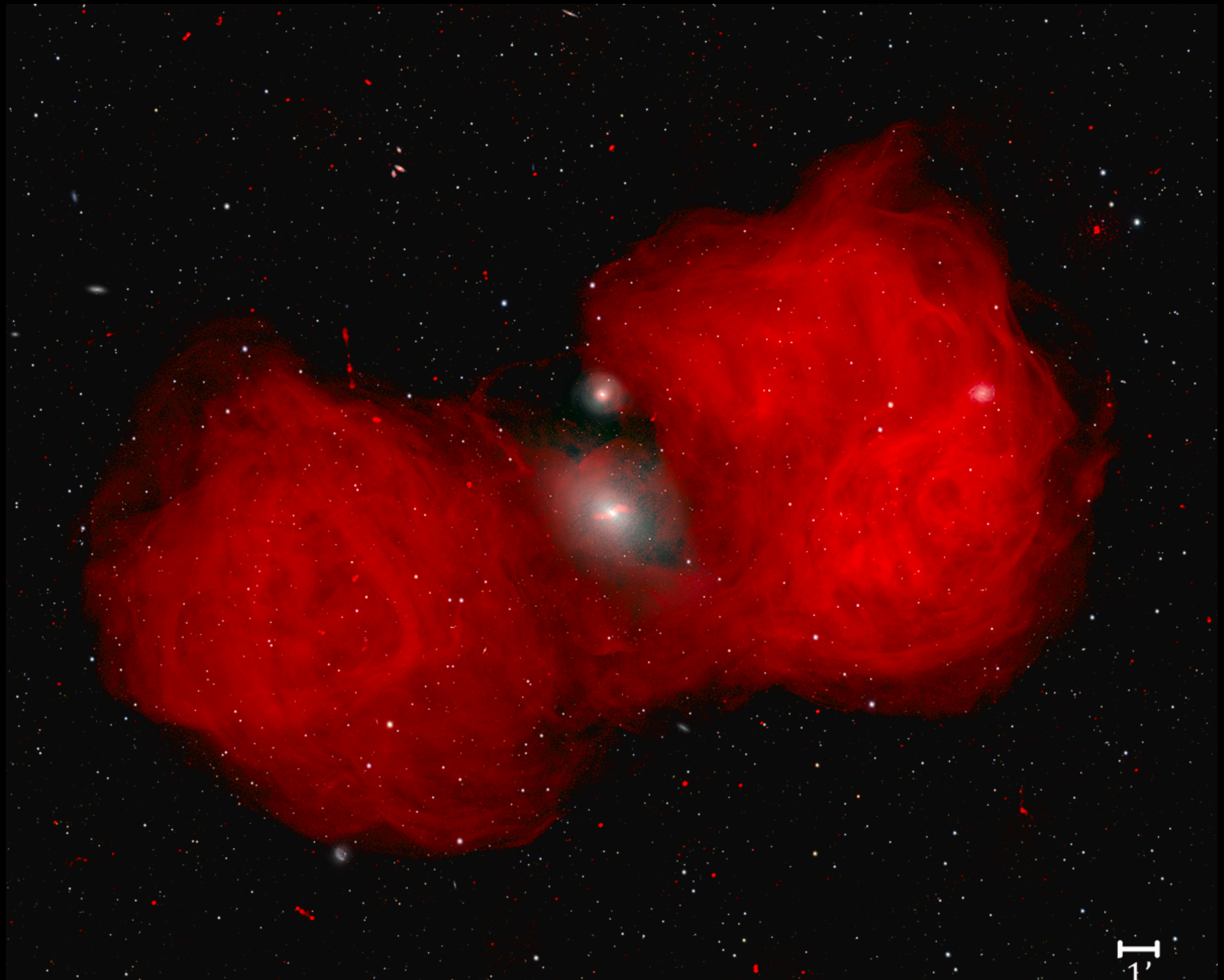
Challenge to jet/particle acceleration physics?
(e.g. Li+2020, Bordas 2020)

Sensitive, Hi-res Radio Images

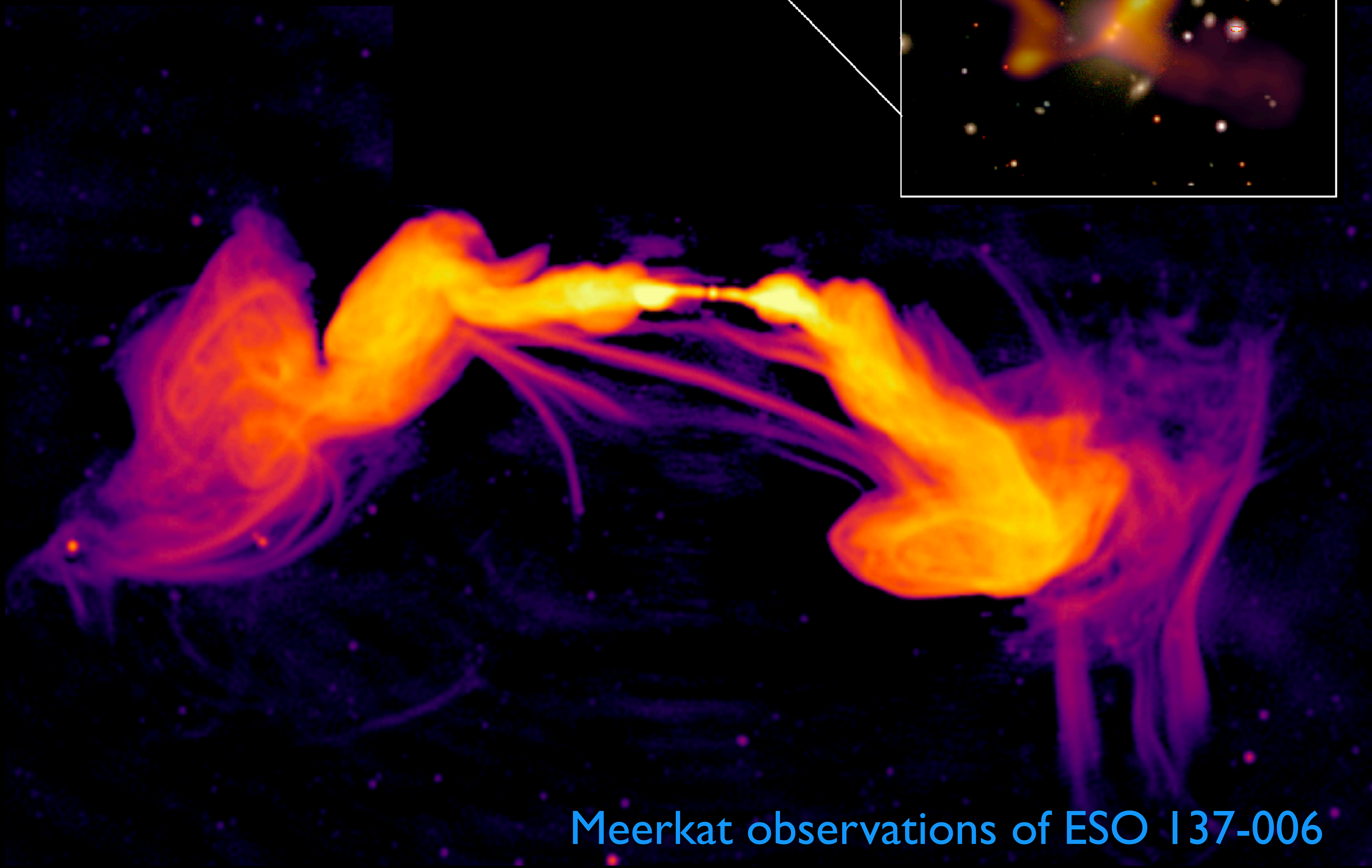
- Nextgen radio surveys are revealing new structure: stunning bridges and tails as well as flickering activity
- Shows importance of particle transport, B field structure and hydrodynamics!



Credit: Martin Hardcastle and the LOFAR surveys team.



Meerkat observations of Fornax A (Maccagni+ 2020)

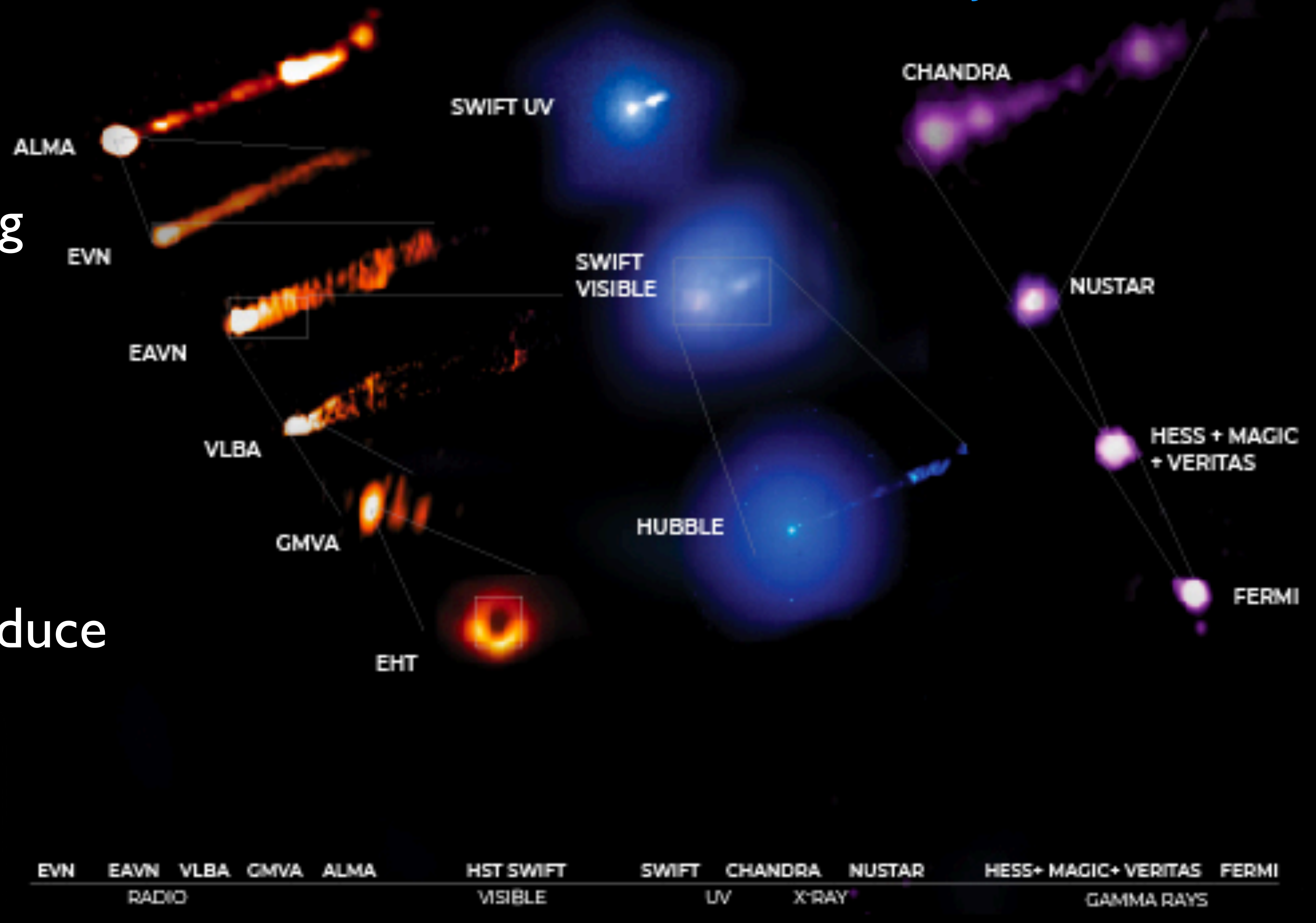


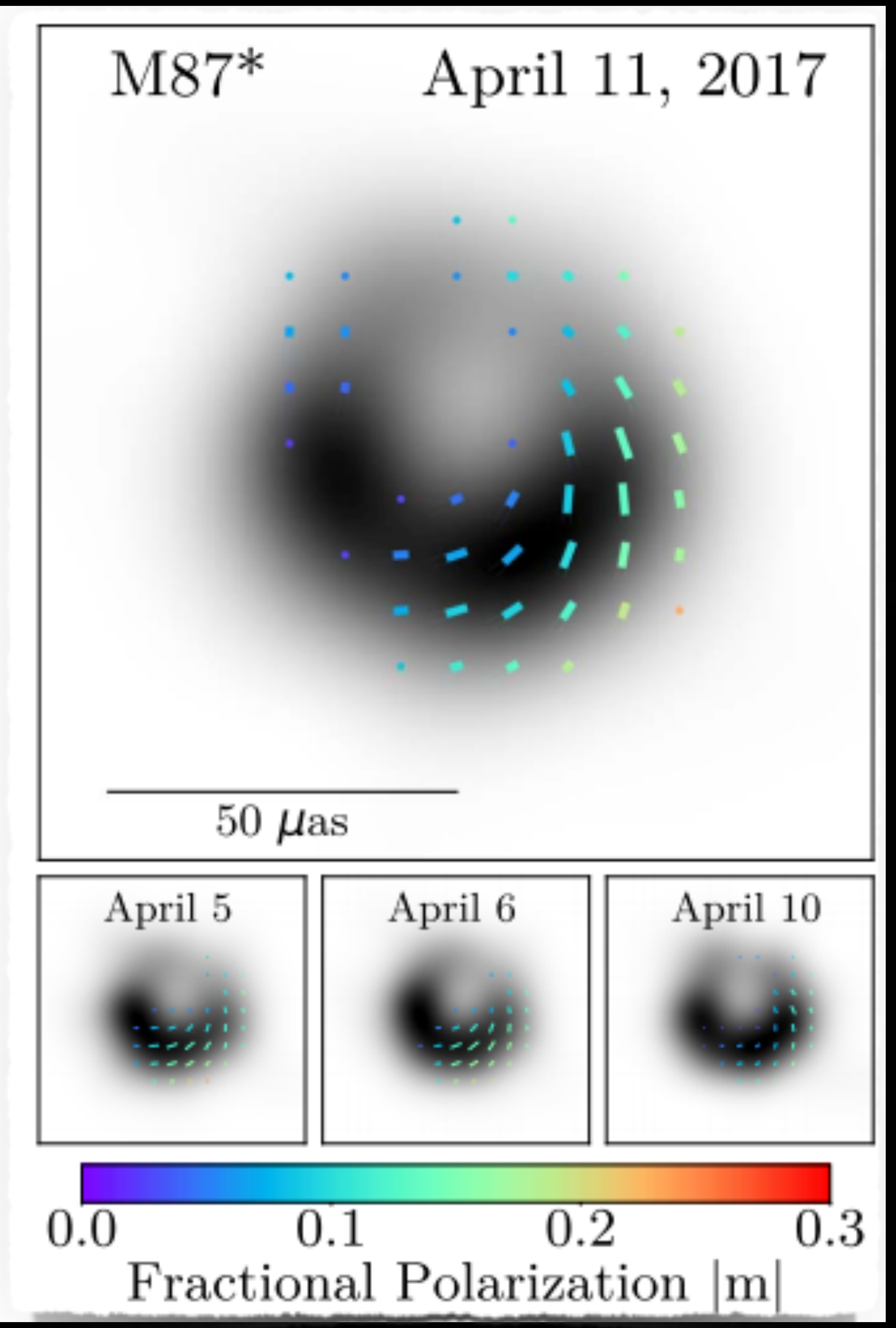
Meerkat observations of ESO 137-006

EHT+ observations of M87

- EHT provided first image of M87 BH (+now amazing multi wavelength coverage of jet!)
- Polarization maps probe B-field structure
- Degeneracies!
  - different particle acceleration treatments can produce similar images/polarizations

Credit: NASA/ESA/ESO/NAOJ/NRAO/CXC/EHT





EHT collab (paper VII; 2021)

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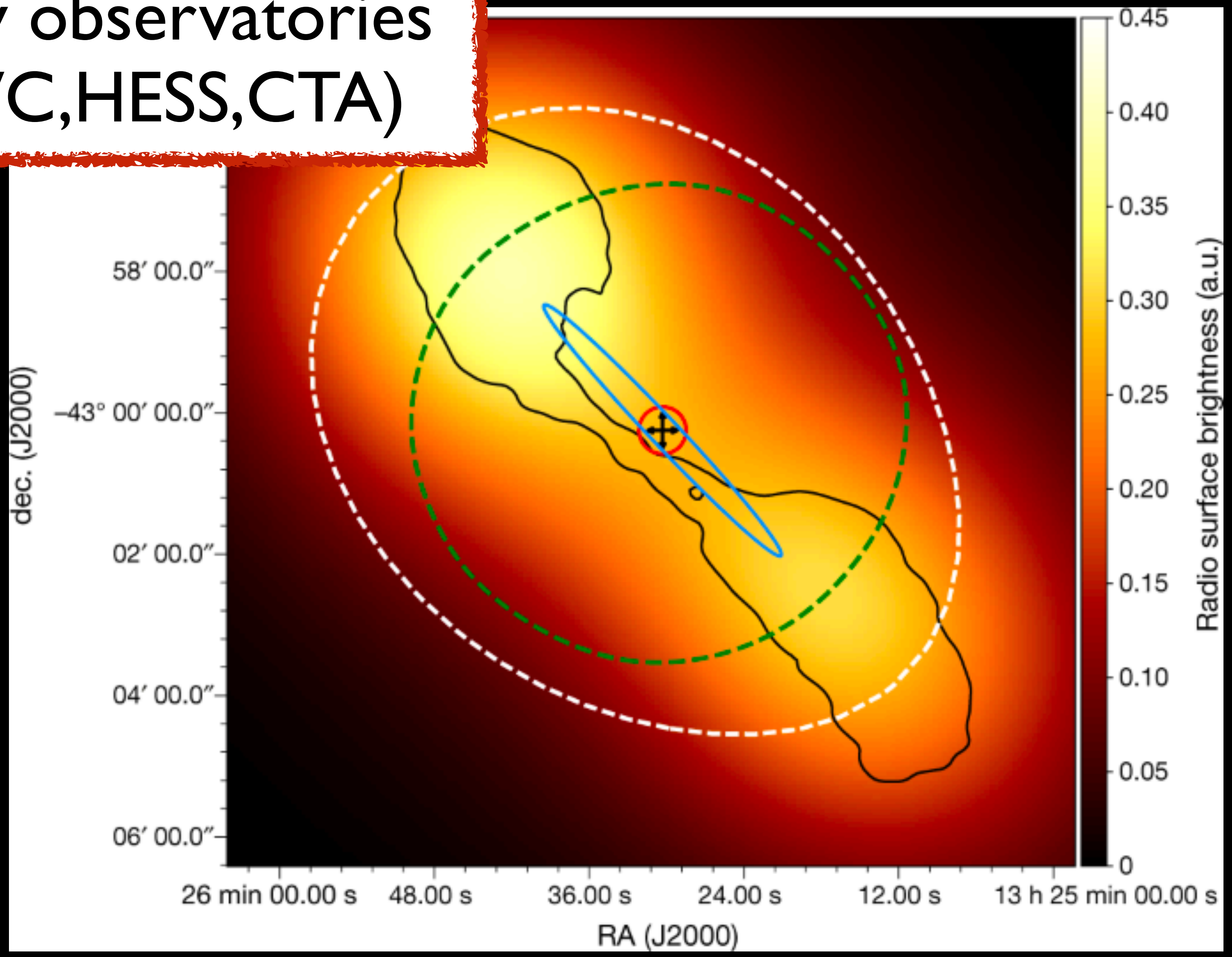
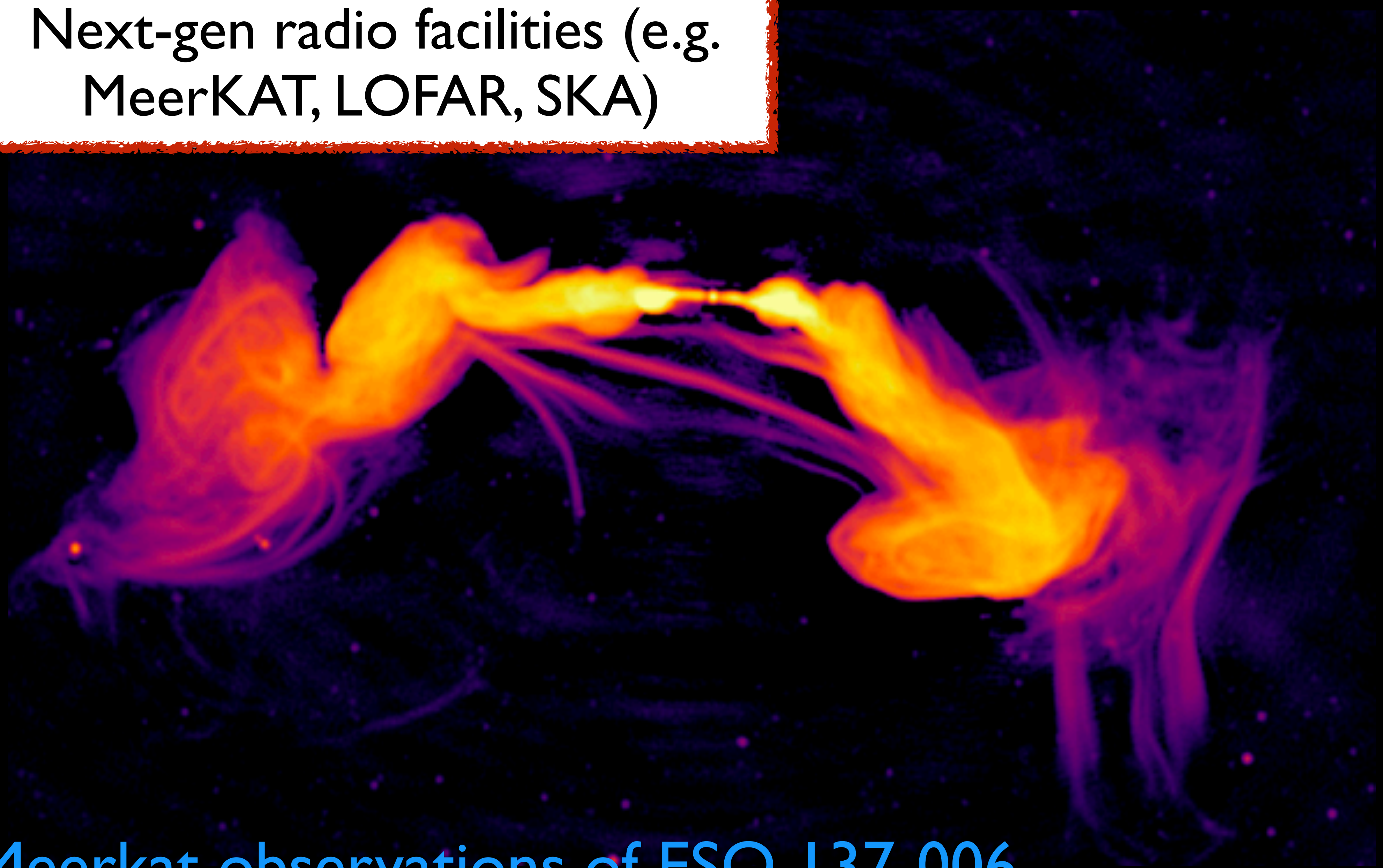
Astroparticle Synergies I

Gamma-ray observatories (e.g. HAWC,HESS,CTA)



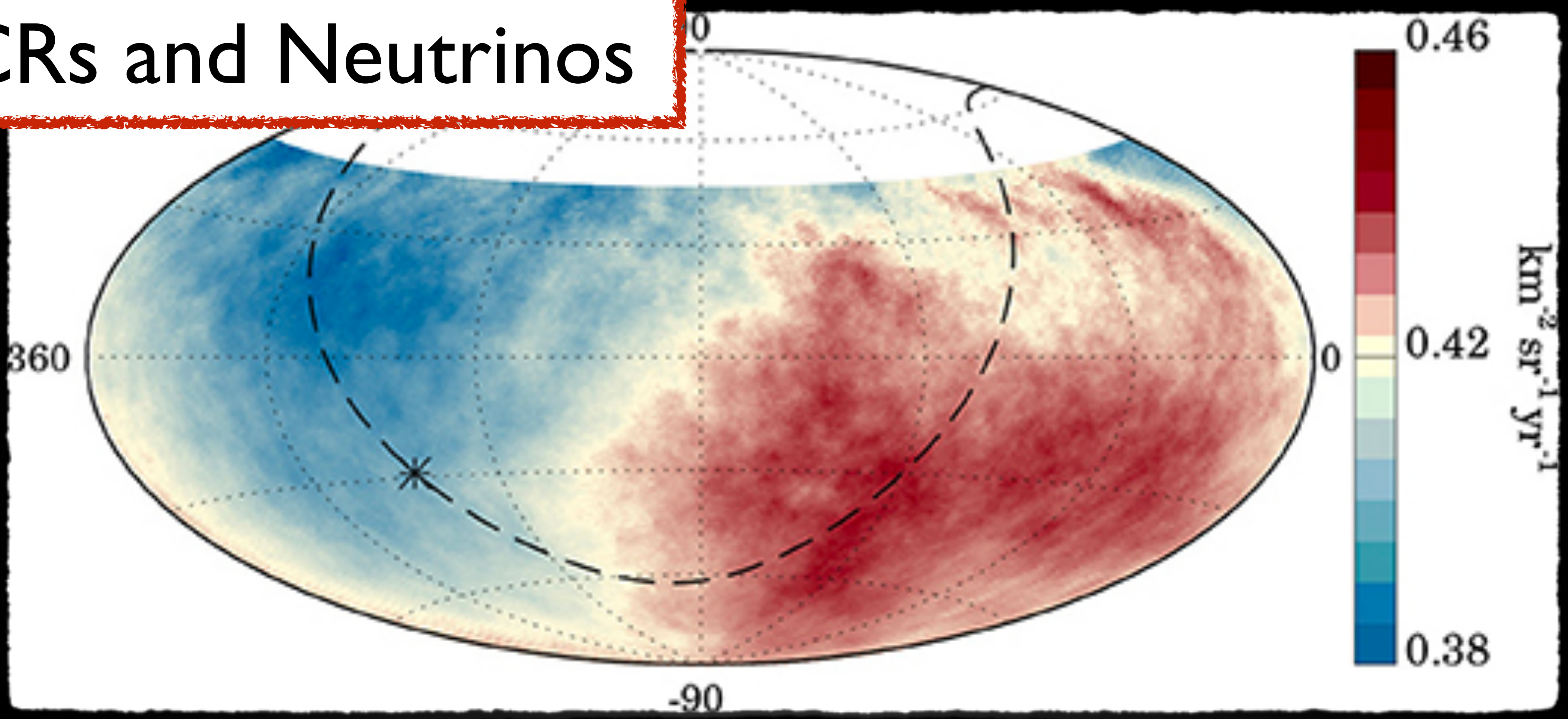
HESS observations of Cen A

Next-gen radio facilities (e.g. MeerKAT, LOFAR, SKA)



Meerkat observations of ESO 137-006

UHECRs and Neutrinos

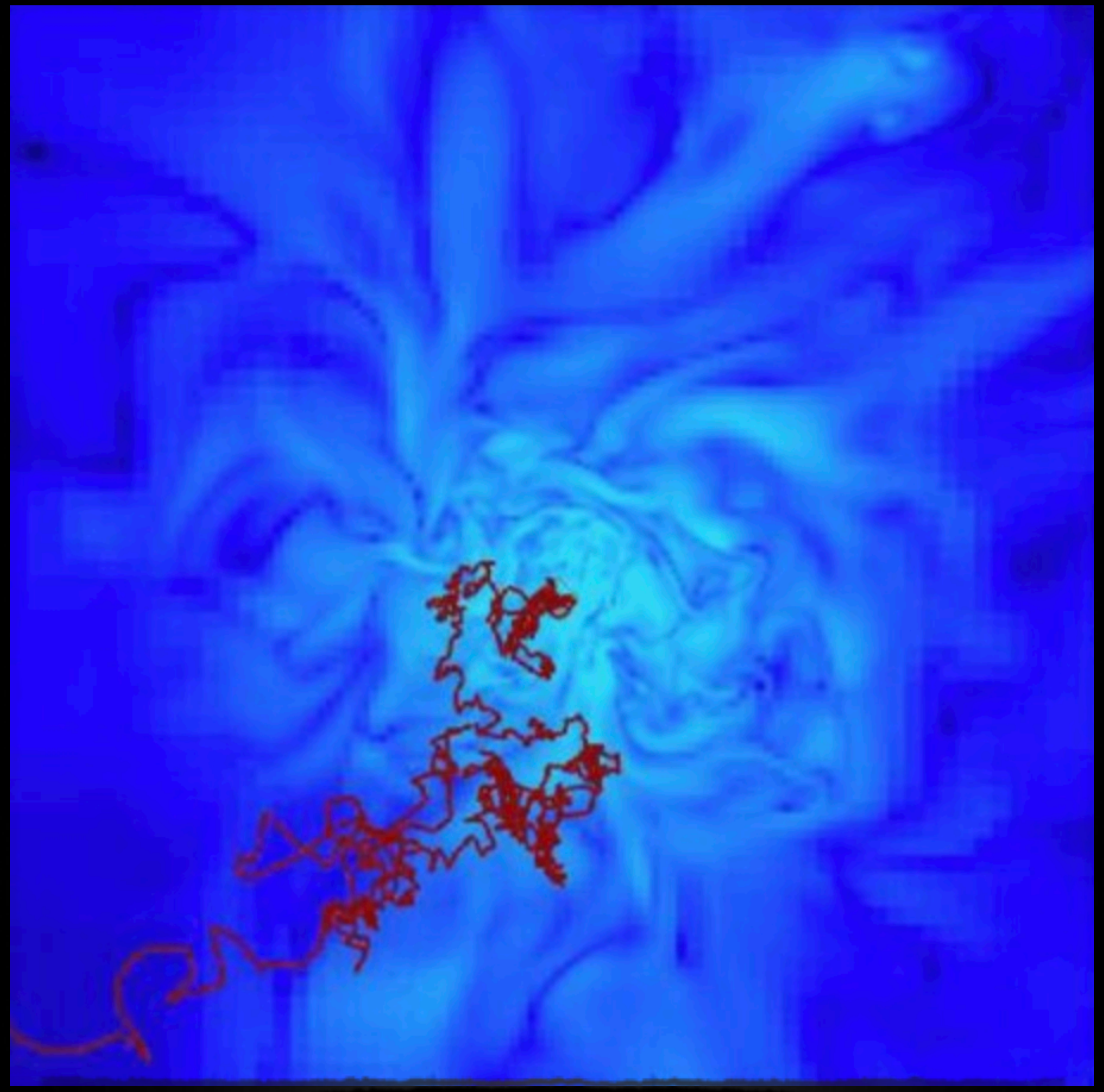


Pierre Auger Observatory

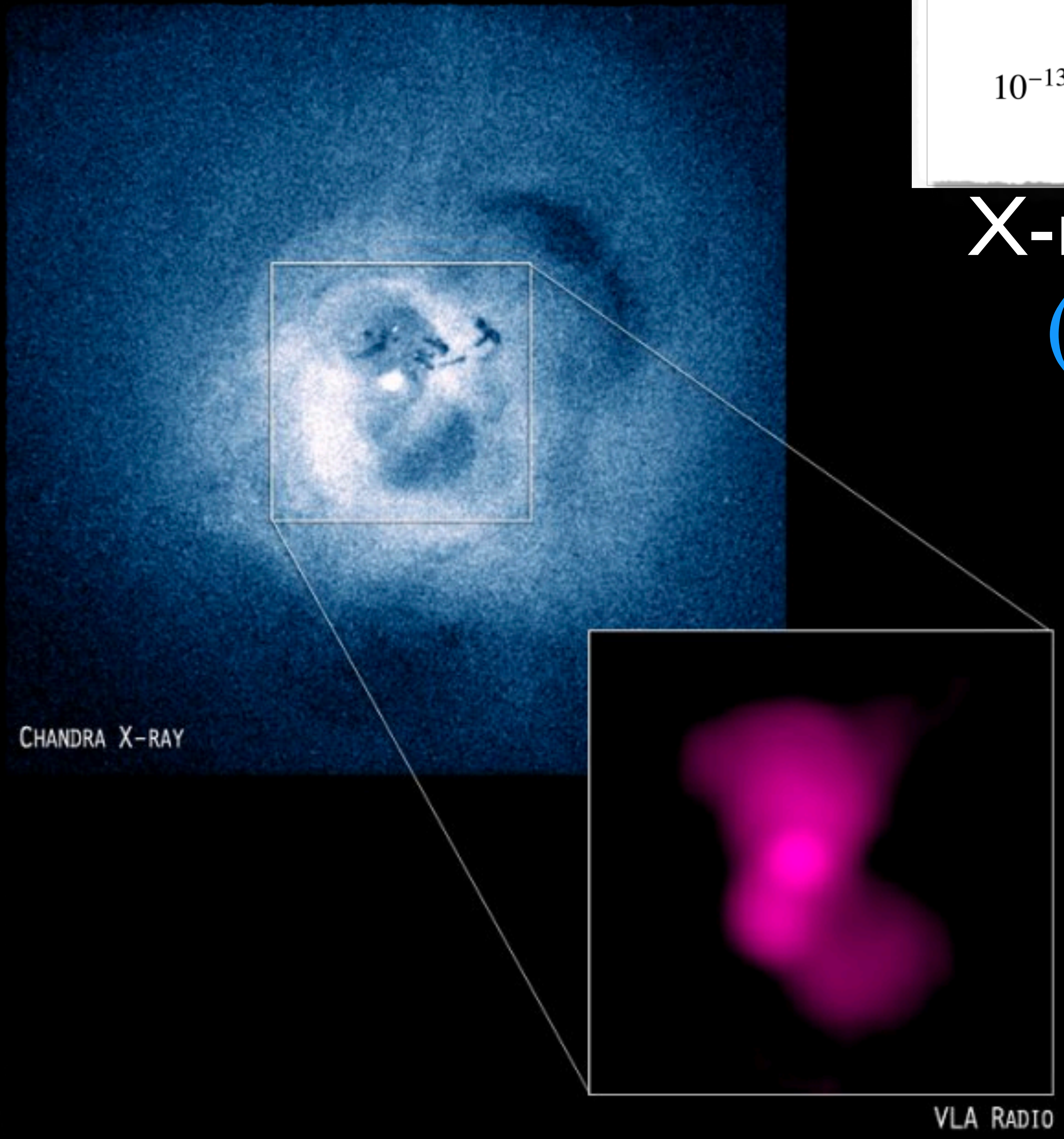
Lab-astro

Omega Laser Facility (Credit: Charlotte Palmer)

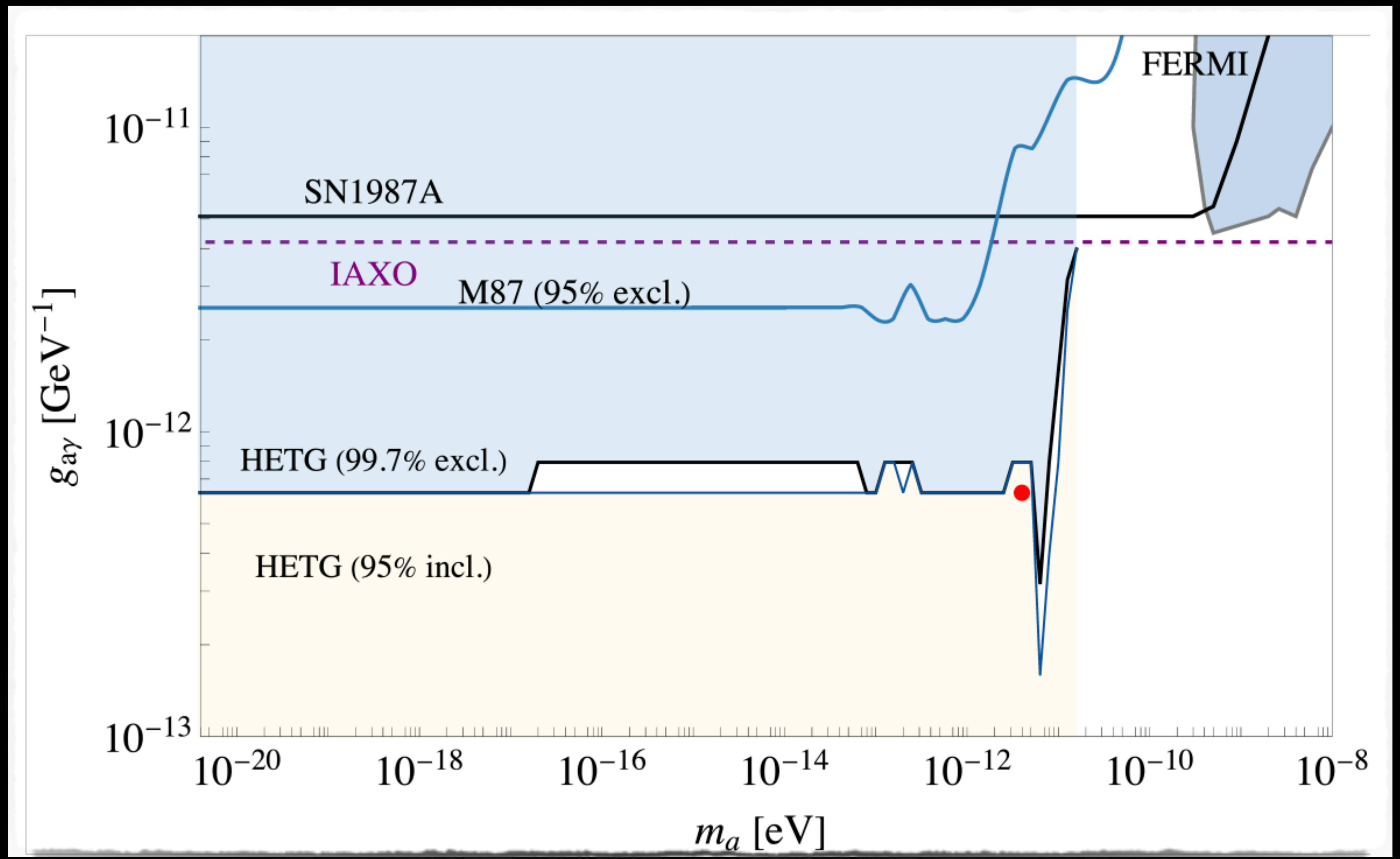
Astroparticle Synergies II: Cluster B-fields and Beyond SM



CR Propagation in clusters (Kotera et al. 2009)



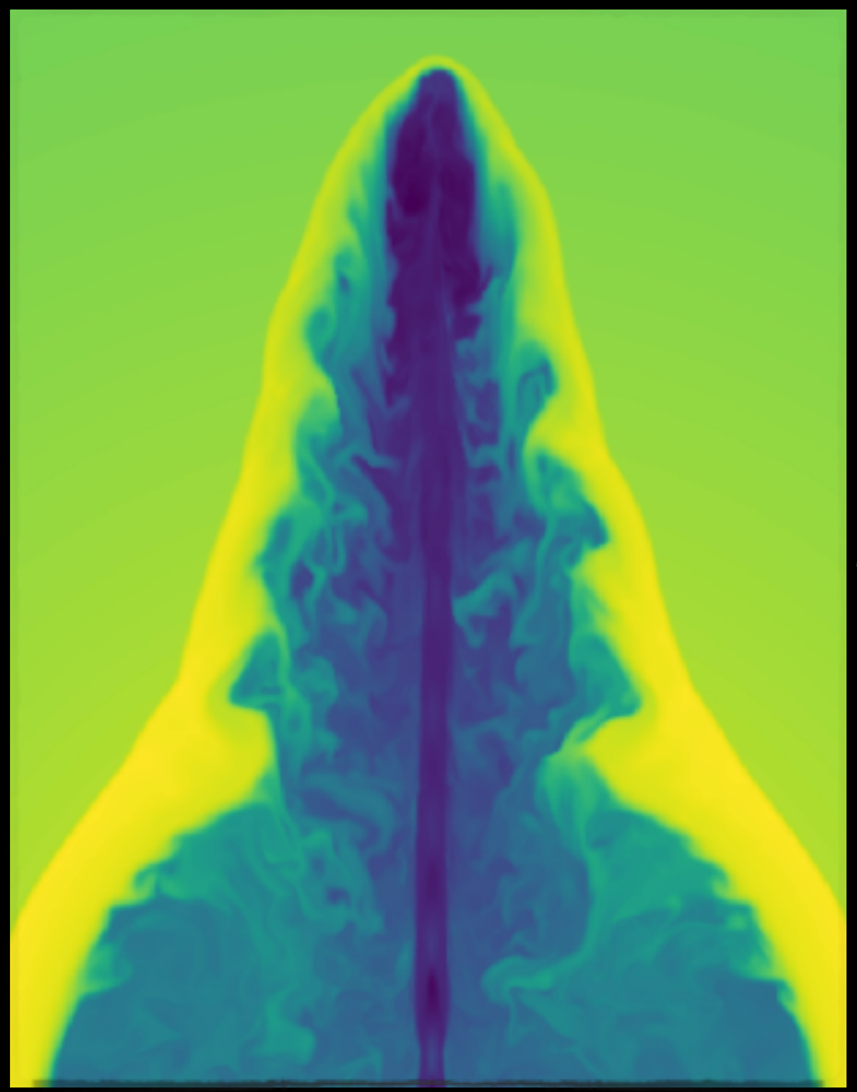
AGN jet feedback in clusters (e.g. Fabian 2006)



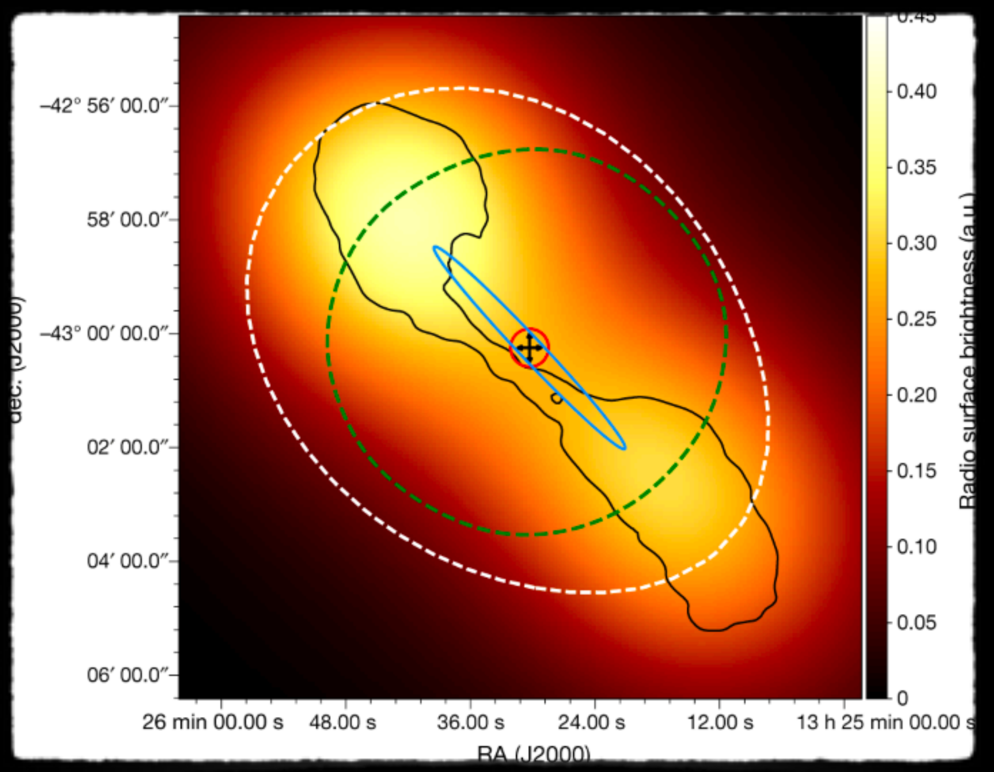
X-ray/gamma-ray ALP searches (e.g. Reynolds+ 2021, Sisk-Reynes, in prep)

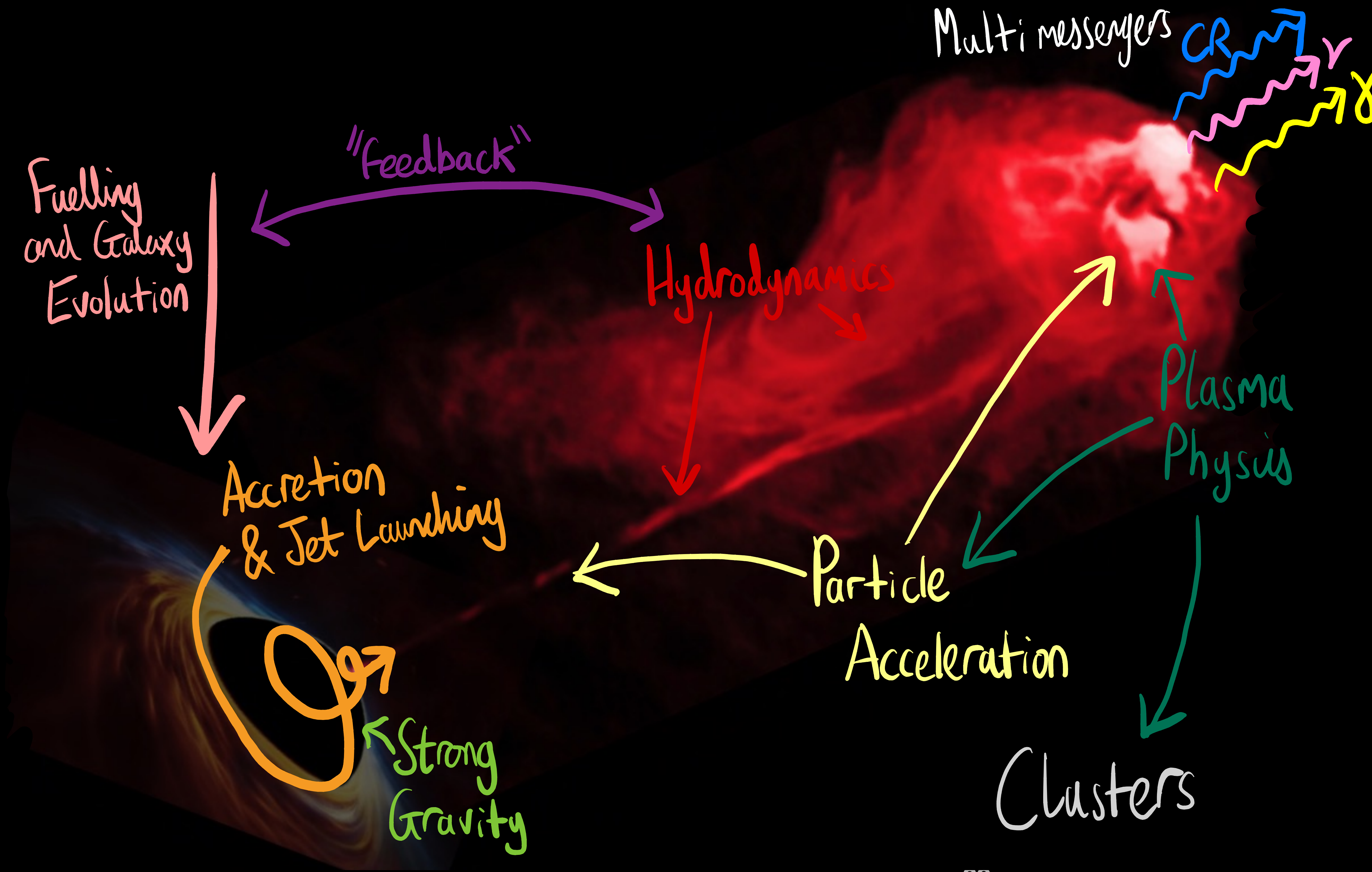
Bridging the gap

- We need to “Bridge the gap”!
  - Method gap: GRMHD/PIC/Radiation
  - Scale gap: critical plasma scales to UHECR Larmor radii
  - Obs/Theory gap: going from ab initio simulations observational predictions



Let’s talk more!

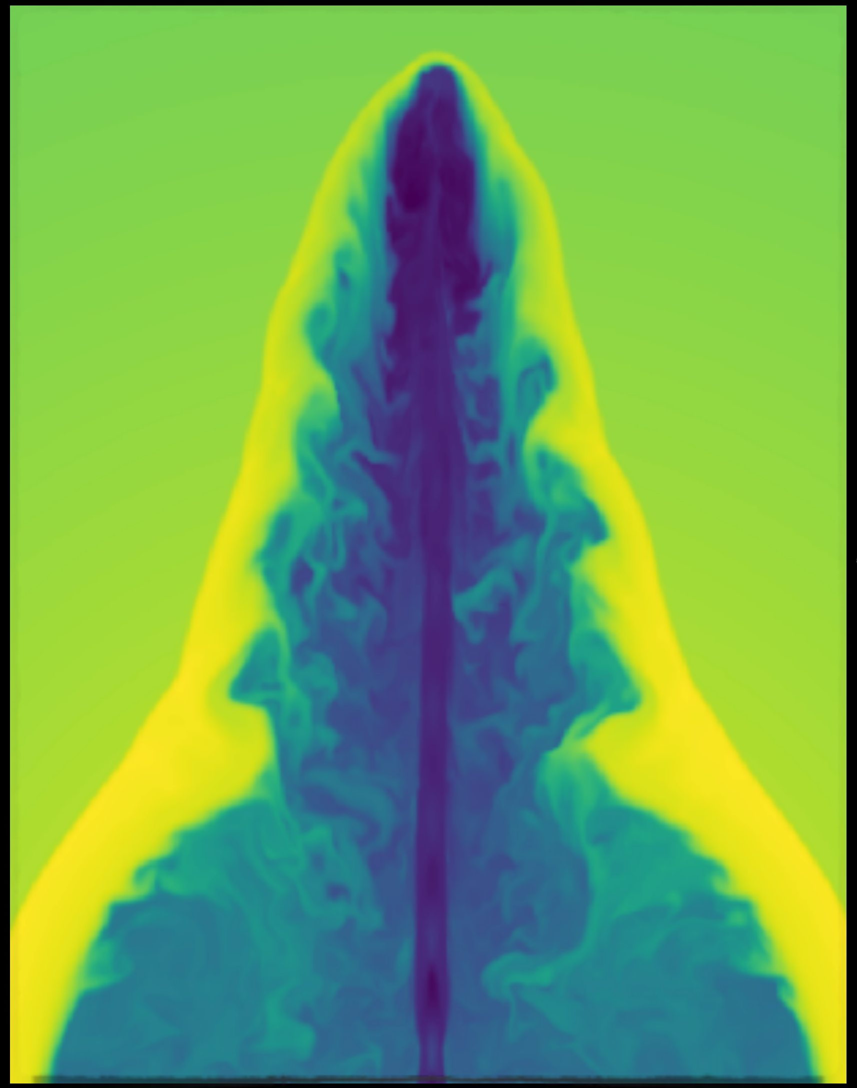




Feel free to get in touch on mattermost !

Summary

- Shock acceleration: inherently nonlinear, plasma physics is critical to understand
- Stunning recent progress in Particle-in-cell and hybrid MHD-PIC sims
- Sera Markoff: *"It's not just shocks!"* - reconnection sites are particle accelerators (+shear, kinks, etc?)
- Even shocks may form where we don't expect them
- Interdisciplinary work needed to "Bridge the gap"



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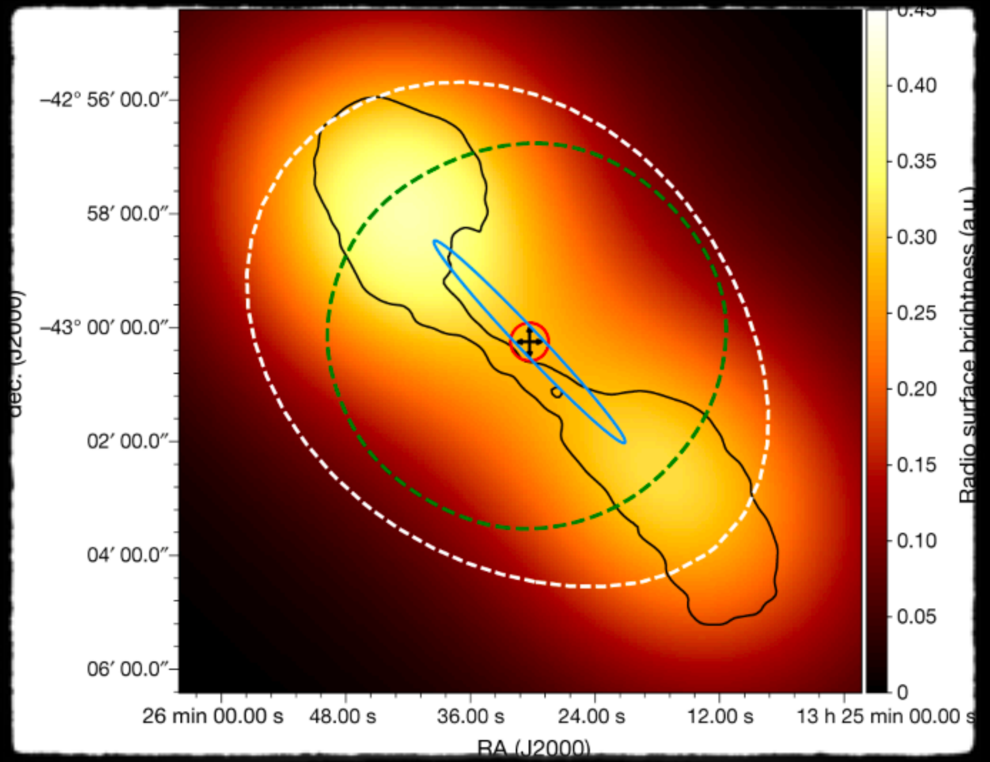

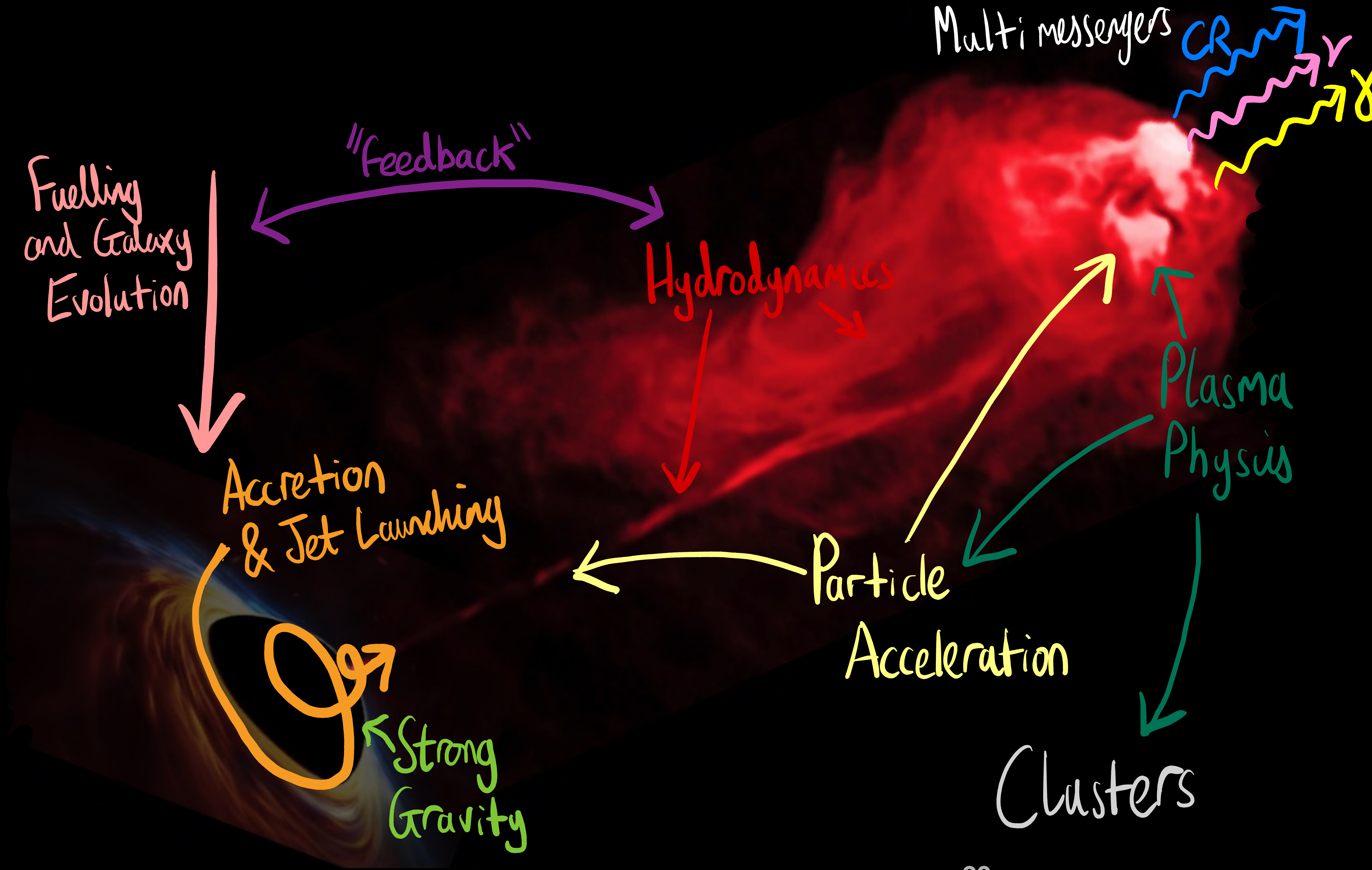

Some of this material appears in a review in "100 years of jets"(eds. Fender & Wijers), New. Astron. Rev., arXiv:2003.06587

UHECR work presented in Matthews+ 2018, MNLett, 479, 76 & 2019, MNRAS, 482, 4303, Matthews & Taylor 2021, MNRAS in press.