

The Cosmic Engine

Physics of Black Holes and Active Galactic Nucleus Jets

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Opening Hook

A Jet Larger Than Its Galaxy

- This is a stream of plasma launched from the galaxy's center, extending over 30 kiloparsecs — well beyond the host galaxy's stars.
- It has traveled at close to the speed of light for millions of years.
- The knots and brightness changes along the jet reveal internal structure and particle acceleration.
- First noticed by H. D. Curtis in 1918 as a “curious straight ray” — long before anyone understood it.



Fig: The M87 jet. HST (optical)
Credit: NASA

Opening Hook

Zooming Toward the Central Engine

- This VLBI image shows the jet at parsec scales, close to the black hole itself.
- The jet stays narrow and relativistic down to the smallest scales we can resolve.
- As we zoom in, we approach the central engine — the supermassive black hole.
- Notice the one-sided appearance — a hint of relativistic beaming. We will return to this.

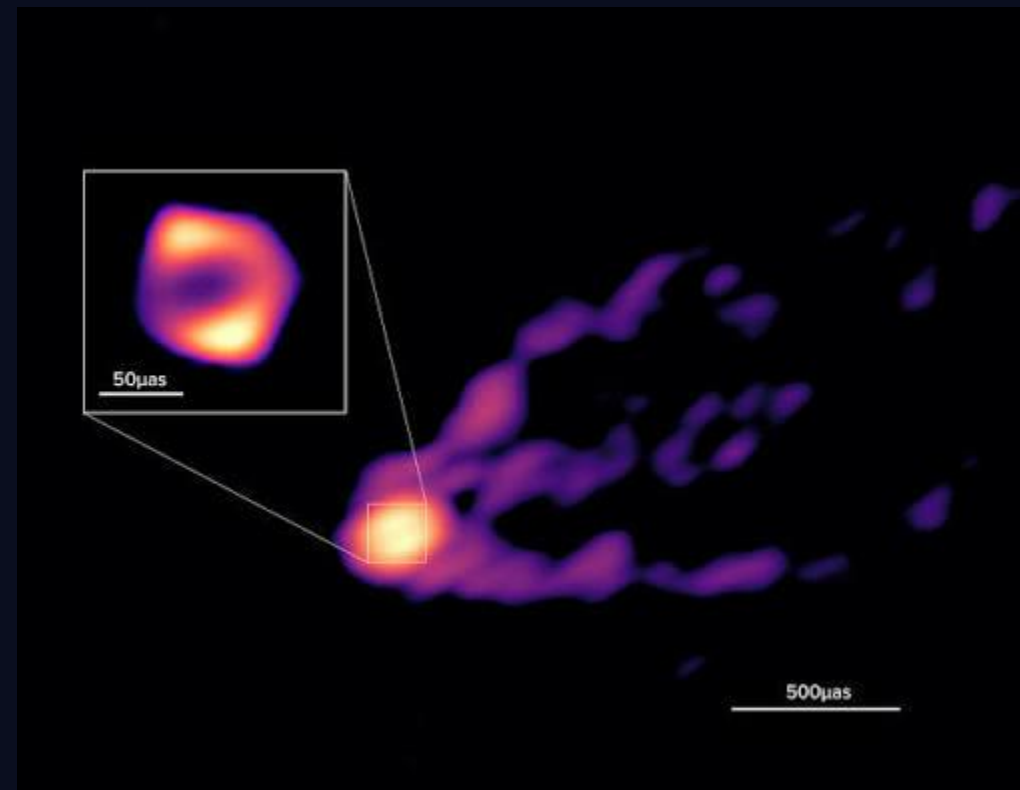


*Fig: VLBI image (86 GHz).
GMVA+ALMA+GLT
Lu + (2023) Nature 616, 686*

Opening Hook

Arriving at the Black Hole

- This is the EHT image of M87* (2019).
- 6.5 billion solar masses; gravitational radius ~ 120 AU — about the size of our solar system.
- The bright ring: the event-horizon shadow plus glowing accreting plasma; the asymmetry comes from relativistic motion in the disk.
- The jet points perpendicular to the ring — tied directly to the black hole's spin axis.

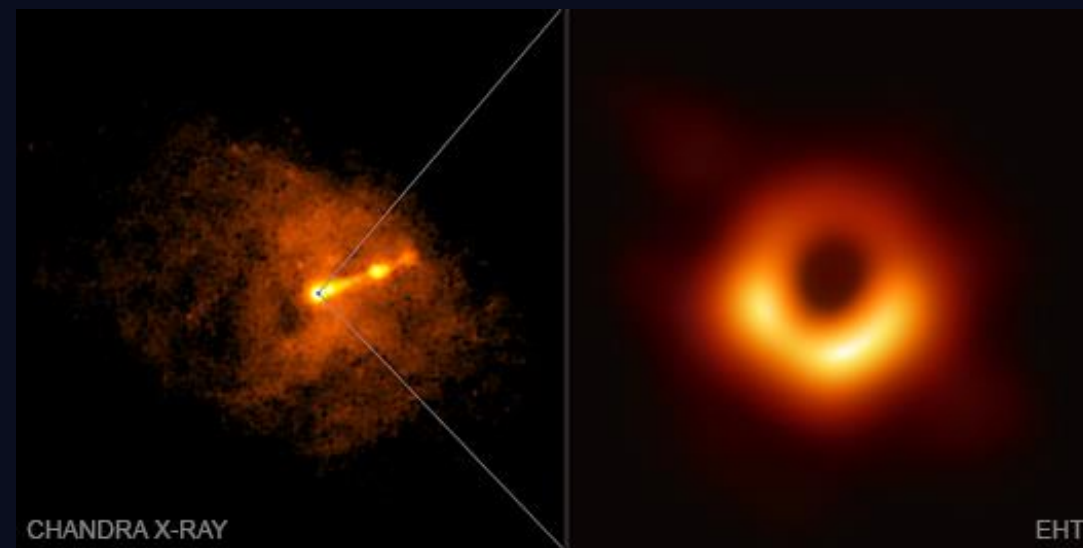


*Fig: Chandra X-ray (left) +
EHT shadow image (right) of
M87*
Chandra photo album.*

Opening Hook

The Central Paradox

“A black hole is defined as an object from which nothing — not even light — can escape. So how does this object, defined by absolute gravitational imprisonment, simultaneously drive a continuous outflow of plasma at $0.99c$, sustained over millions of years and extending far beyond the galaxy itself?”

“Answering this question will take us to the frontiers of general relativity, plasma physics, and high-energy astrophysics. That is what this lecture is about.”

What Is an Active Galactic Nucleus?

AGN: Two Engines, One Extraordinary Luminosity

- An AGN is a galaxy whose nucleus radiates far more luminosity than its stars can explain.
- **Mechanism 1** — Accretion: gravitational energy turns into radiation and kinetic energy as matter spirals into the black hole.
- **Mechanism 2** — Spin extraction: magnetic fields tap the black hole's own rotational energy.
- Combined efficiency: 10–40%, far above nuclear fusion's $\sim 0.7\%$.

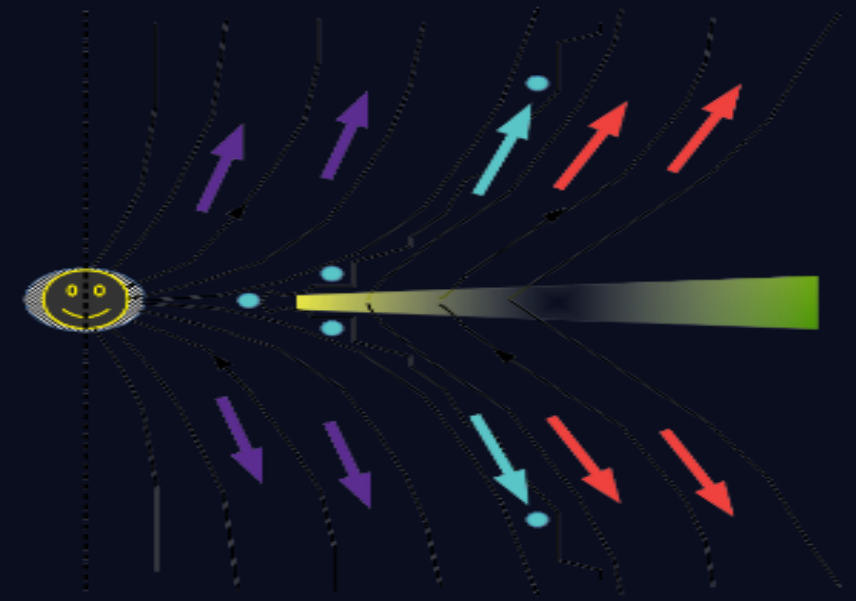


*Fig: energy extraction processes.
Blandford-Payne & **Blandford-Znajek** processes. Dihingia & Fendt
2024, astro-ph:2404.06140)*

What Is an Active Galactic Nucleus?

The Supermassive Black Hole Engine

- SMBHs range from 10^6 to 10^{10} solar masses and reside in nearly all massive galaxies.
- The accretion disk radiates intensely and amplifies the magnetic fields that power the jet.
- M87* sits 16.7 Mpc away, yet its jet is traceable out to ~ 30 kpc — larger than its host galaxy.
- Radio galaxies, blazars, and quasars: the same phenomenon, seen from different angles and accretion rates (fig.).



Fig: A unified picture of various kinds of AGNs (by L. C. Gallo).

Observational Phenomenology of Jets

One Jet, Four Wavelengths

- Jets are highly collimated relativistic outflows, from sub-parsec to megaparsec scales, seen across the full electromagnetic spectrum.
- Different bands reveal different physics — jets are not single-zone structures.

Skip below (see next slide)

Band	What we see	Implication
Radio	Full extent (~100,000 ly)	Synchrotron, low-E e^-
Optical	Bright knots (~5,000 ly)	Higher-energy synchrotron
X-ray	Compact knots (~18,000 ly)	Highest-E e^- / IC scattering
Gamma-ray	Compact core + flares	Extreme particle acceleration

Observational Phenomenology of Jets

Seeing the Jet Across the Spectrum

- Radio traces the full $\sim 100,000$ -light-year extent — synchrotron from low-energy electrons.
- Optical and X-ray show bright knots — higher-energy synchrotron and inverse-Compton emission.
- Gamma-rays trace the compact core and flares — extreme particle acceleration.

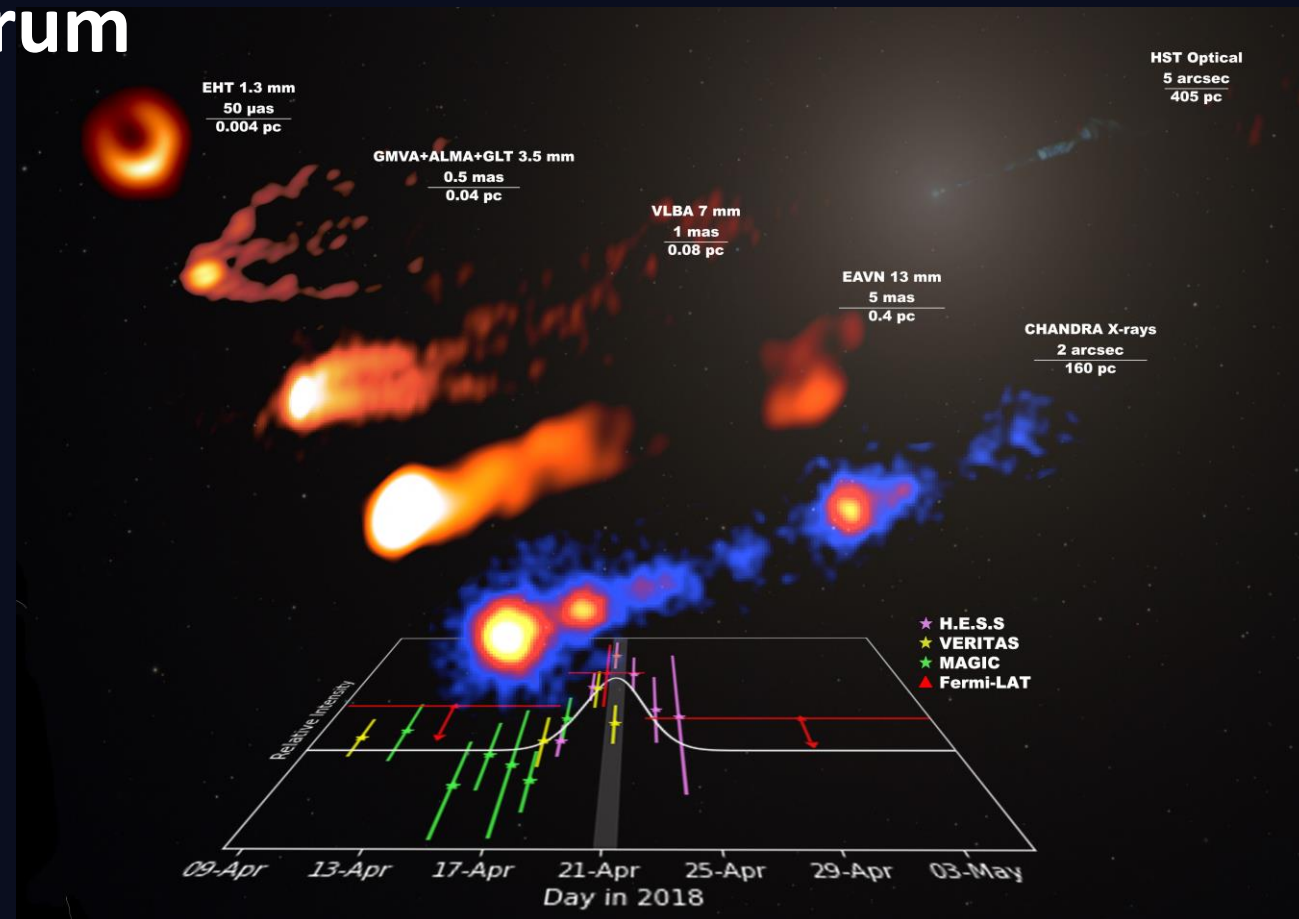


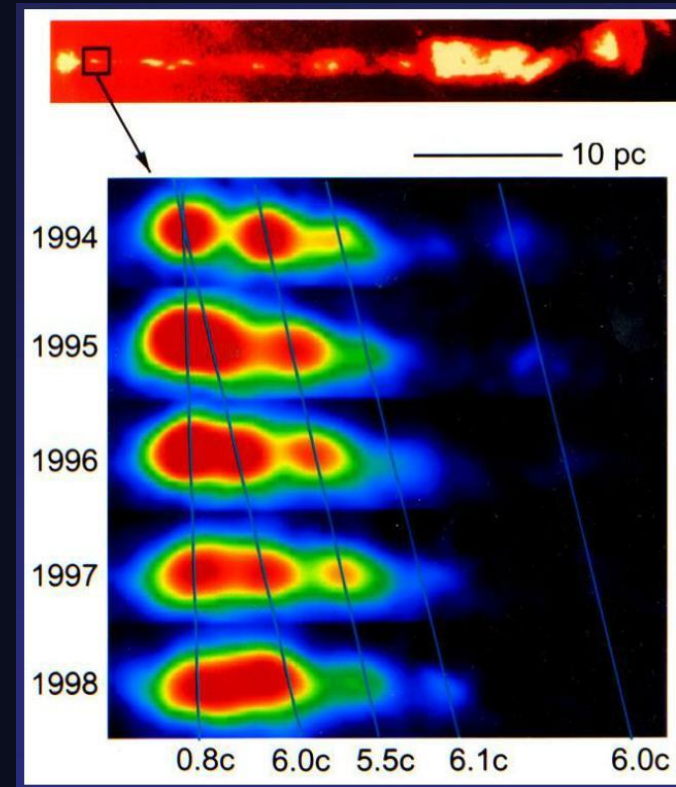
Fig: Multi-wavelength image of the M87 jet. Algaba+ (2024)

Observational Phenomenology of Jets

Superluminal Motion

- Optical & VLBI time-lapse images show plasma blobs moving apparently faster than light (up to $\sim 6c$ in M87 by VLBI).
- A geometric projection effect, not a violation of special relativity (Rees 1967)

$$\beta_{\text{app}} = (\beta \sin \theta) / (1 - \beta \cos \theta)$$



Superluminal
Motion in M87
HST-1

Do FR I radio
galaxies have
relativistic jets
like BL Lacs?

5

*Fig: superluminal knot
motion. Livio (2019).*

*“What mechanism accelerates plasma
to within 1% of c , sustained over
100,000 light-years?”*

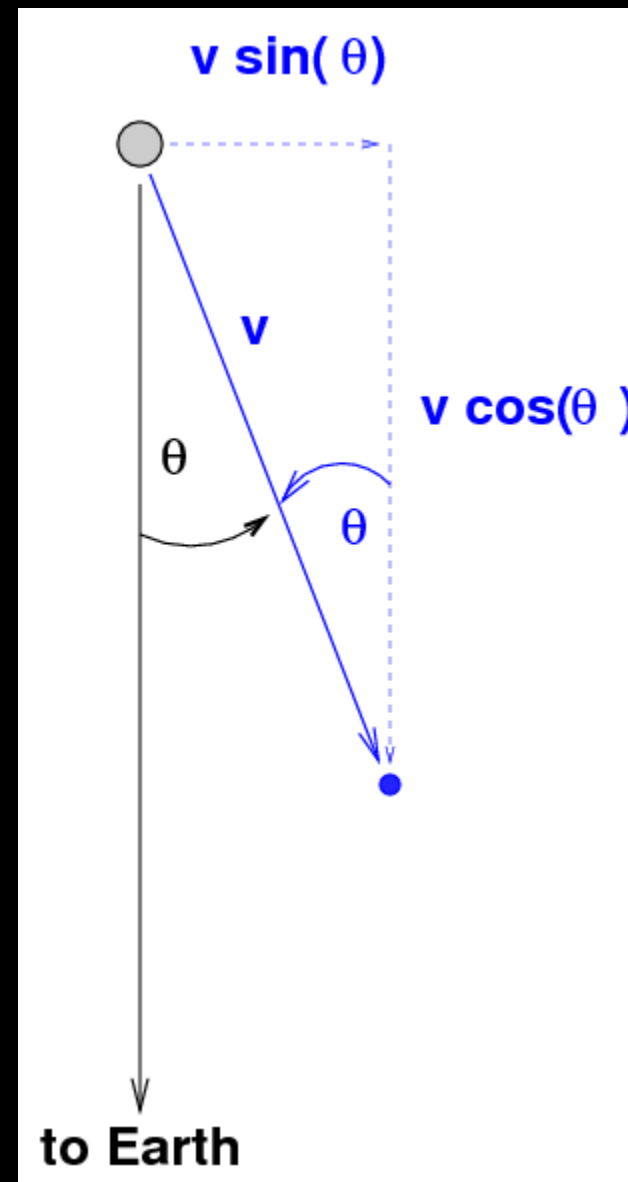
Observational Phenomenology of Jets

Superluminal Motion

- Optical & VLBI time-lapse images show plasma blobs moving apparently faster than light (up to $\sim 6c$ in M87 by VLBI).
- A geometric projection effect, not a violation of special relativity (Rees 1967)

$$\beta_{\text{app}} = (\beta \sin \theta) / (1 - \beta \cos \theta)$$

- For $\beta = 0.99$ at a small angle, β_{app} can greatly exceed 1 — direct proof that jet plasma moves at $v \gtrsim 0.99c$.



The Central Engine — Black Hole Basics

The Size Paradox

- M87*'s mass: 6.5×10^9 solar masses.

$$R_s = 2GM / c^2$$

- For M87*: $R_s \approx 120$ AU — about the size of our solar system, out to Pluto's orbit.

“An object the size of our solar system is powering a jet larger than its entire host galaxy — and outshining hundreds of billions of stars. This is the central mystery of AGN physics.”

The Central Engine — Black Hole Basics

What Is a Black Hole?

- Defined by its event horizon — a one-way boundary that nothing, not even light, can cross outward.
- Inside, every trajectory leads inevitably to the singularity.

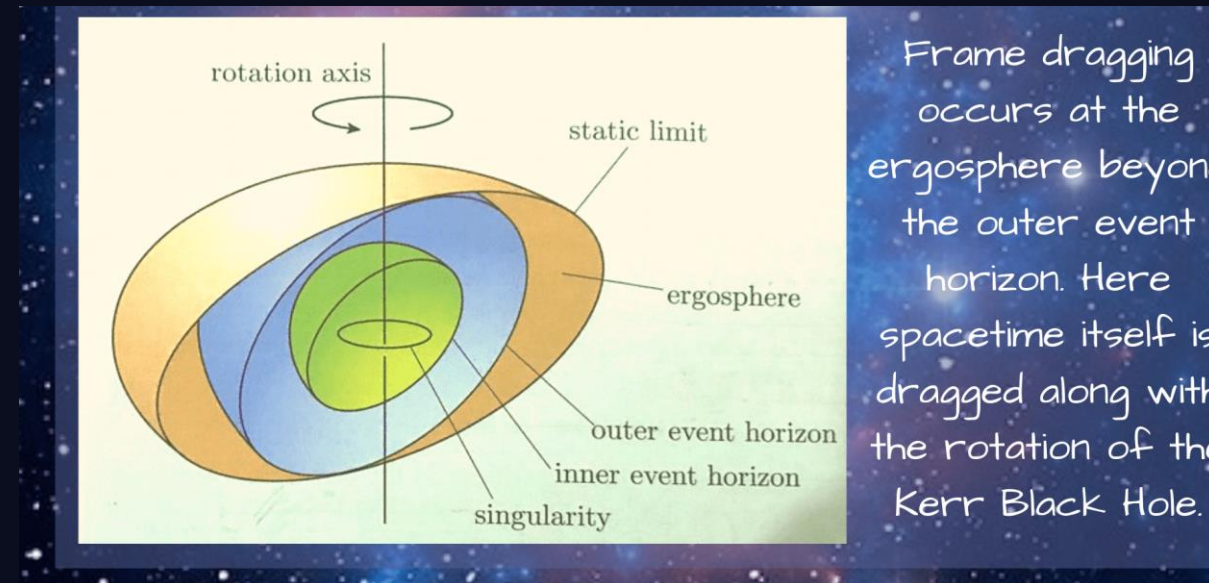
“A black hole is defined by absolute gravitational trapping. So how can it simultaneously launch continuous streams of matter at velocities exceeding $0.99c$ — not for a moment, but continuously, over millions of years?”

“This is not a contradiction — but resolving it requires going beyond Newtonian gravity.”

The Central Engine — Black Hole Basics

The Kerr Black Hole and Frame Dragging

- Real black holes rotate, described by the Kerr metric with spin parameter $a = J/Mc$ ($0 \leq a \leq M$).
- The ergosphere lies outside the event horizon — spacetime itself is dragged along with the hole's rotation.
- Inside it, nothing can stay static — even light co-rotates.



Frame dragging occurs at the ergosphere beyond the outer event horizon. Here spacetime itself is dragged along with the rotation of the Kerr Black Hole.

Fig: Anatomy of Kerr black hole. Lea (2021). From <https://cdn.zmescience.com/wp-content/uploads/2021/03/Frame-dragging-occurs-at-the-ergosphere-beyond-the-outer-event-horizon.-Here-spacetime-itself-is-dragged-along-with-the-rotation-of-the-Kerr-Black-Hole..png>

The Central Engine — Black Hole Basics

Extracting the Black Hole's Spin Energy

- Crucially, the ergosphere is outside the horizon — matter and energy CAN escape from it.
- Up to 29% of a black hole's rest-mass energy is stored as rotational energy and is, in principle, extractable.
- The accretion disk is magnetized plasma; frame dragging pulls field lines into the ergosphere, setting up electromagnetic energy extraction.

“The interplay of a spinning black hole, its ergosphere, and large-scale magnetic fields is what drives the jet. This is the Blandford–Znajek process — and it is where we begin.”

Road Map of the Lecture

Where We're Headed

Part	Topic	Central Question
1	Blandford–Znajek process	How is spin energy extracted to power the jet?
2	Jet collimation	How does a wide outflow become a narrow beam?
3	Matter composition	What is the jet actually made of?
4	Propagation & radiation	How do jets travel and shine across the universe?

Road Map of the Lecture

Theory, Observation, and the Journey Ahead

“At every stage, we will ask: what does theory predict, and what do observations tell us? In jet physics, theory and observation are in constant dialogue — and some of the most fundamental questions remain open.”

“We will follow energy and matter from the immediate vicinity of a spinning black hole — on solar-system scales — all the way out to structures larger than the galaxy itself. Each step of this journey is an active frontier of modern astrophysics.”

Section 2: Energy extraction from rotating black holes

What powers the jets? Two independent Energy Reservoirs

- **Reservoir 1:** Gravitational Binding Energy of AD
 - Energy released as accreting matter spirals inward through the black hole's potential.
 - Available power:
 - Tapped by the **Blandford–Payne (BP) process**.
- **Reservoir 2:** Rotational Spin Energy of BH
 - Energy stored in the rotation of the Kerr BH itself.
 - Available power: 29% of Mc^2 for maximal spin.
(for M87*, $E_{\text{spin}} \sim 10^{62}$ ergs)
 - Tapped by the **Blandford–Znajek (BZ) process**.

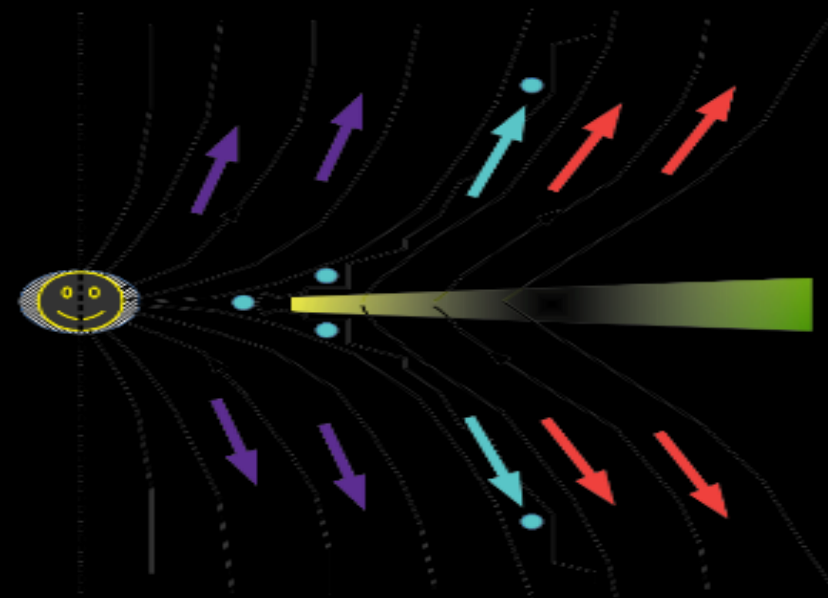


*Fig: **Blandford-Payne** & **Blandford-Znajek** processes.
Dihingia & Fendt 2024, astro-
ph:2404.06140)*

Section 2: Energy extraction from rotating black holes

What powers the jets? Two independent Energy Reservoirs

- Independent, yet coupled
 - These reservoirs are genuinely independent in origin, but the rate of spin extraction is regulated by accretion through the magnetic field.

The spin energy of M87 was accumulated over billions of years — but the rate at which we can extract it is regulated by today's accretion flow.

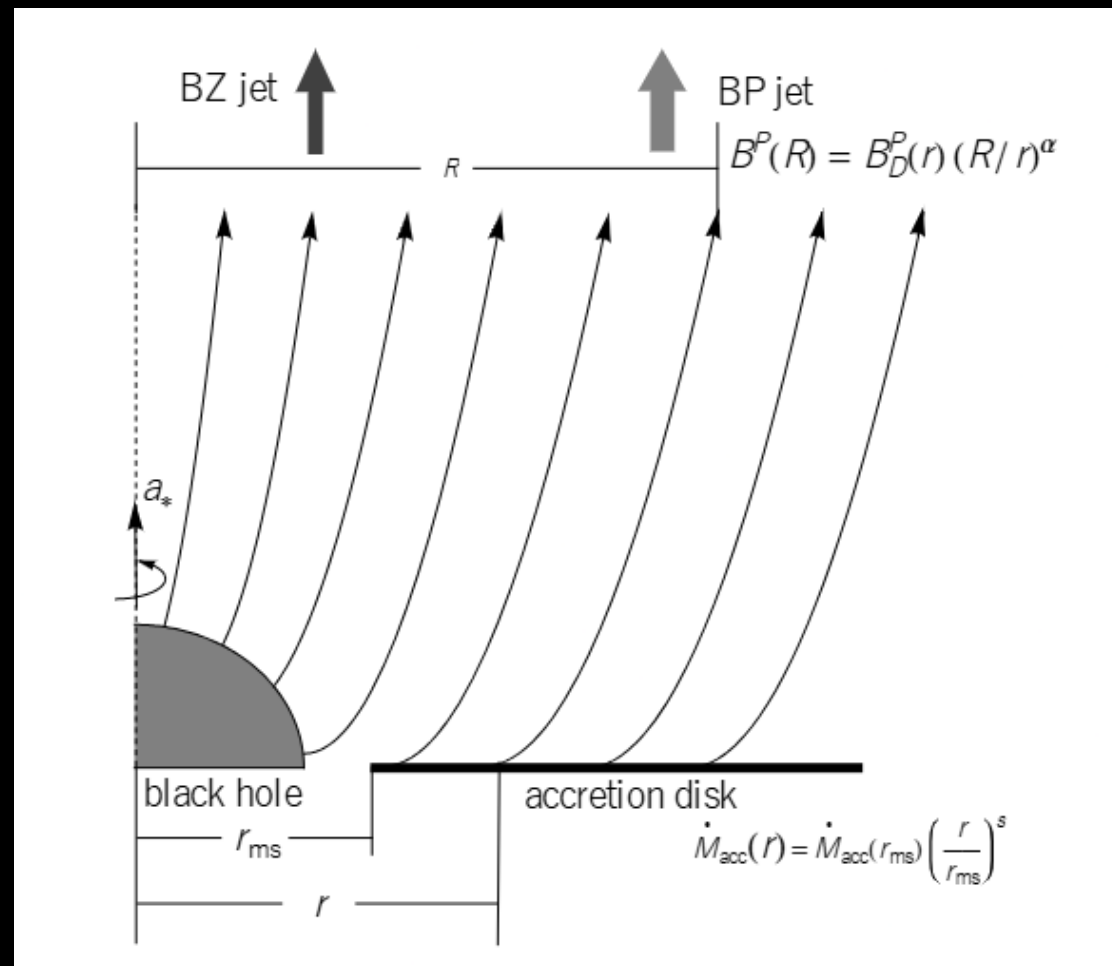


*Figure: The Blandford-Payne process
Xie + (2013).*

2-1: The **Blandford–Payne** Process — Tapping Reservoir 1

- **Physical Setup:** Large-scale poloidal magnetic field lines thread the Keplerian rotating accretion disk.
- Magnetocentrifugal Launching:
 - If a field line makes an angle $< 60^\circ$ with disk normal (fig.), plasma is flung outward centrifugally like a bead on a rotating wire.
- Below vs. Above the Alfvén Surface:
 - Below: Field lines rotate rigidly $\rightarrow$ matter is accelerated centrifugally outward.
 - Above: Toroidal field grows $B_\phi \gg B_p \rightarrow$ magnetic pressure provides additional acceleration and self-collimation.

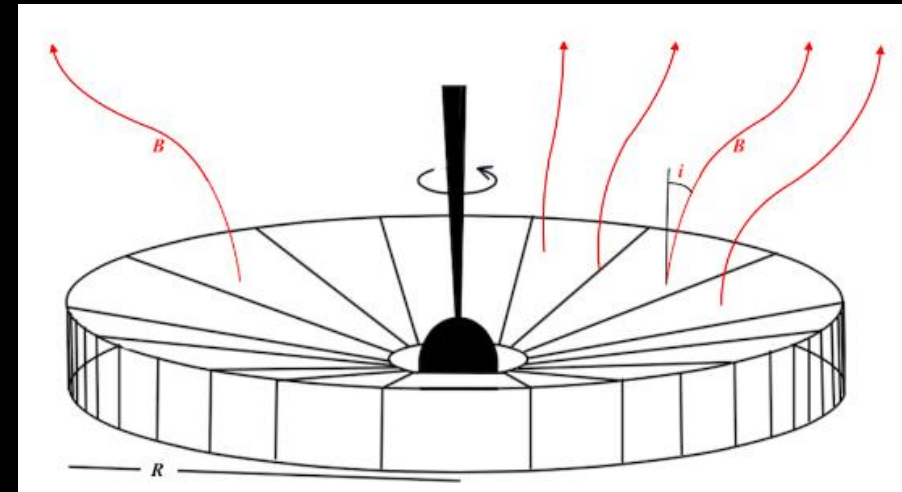


*Figure: The BP process
Jafari (2019).*

2-1: The **Blandford–Payne** Process — Tapping Reservoir 1

- Outflow properties: sub-relativistic ($v \sim 0.1\text{--}0.3\ c$) mass-loaded normal plasma wind carries the power

$$P_{\text{BP}} = \eta_{\text{BP}} \dot{M} c^2, \quad \eta_{\text{BP}} \approx 0.01\text{--}0.10$$

- *The ADIOS Scenario in M87:*
 - In radiatively inefficient accretion flows (ADAFs), most gravitational energy drives BP-type winds and advection rather than radiation.

2-2: The **Blandford–Znajek** Process — Tapping Reservoir 2

- **Physical Setup:** Large-scale poloidal (= meridional) magnetic field lines thread the rotating black hole.
- Unipolar inductor:
 - The poloidal B lines are dragged in the rotational direction, producing a toroidal (= azimuthal) B field.
 - Due to this toroidal B field, the Poynting flux is carried outward,

$$P_{\text{BZ}} = \frac{\kappa}{4\pi c} \Phi_{\text{H}}^2 \omega_{\text{H}}^2 \propto a^2 M^2 B^2$$

$$= \eta_{\text{BZ}} \dot{M} c, \quad \eta_{\text{BZ}} \approx 0.1 - 1.4$$

$$\text{Cf. } \eta_{\text{BP}} \approx 0.01 - 0.10$$

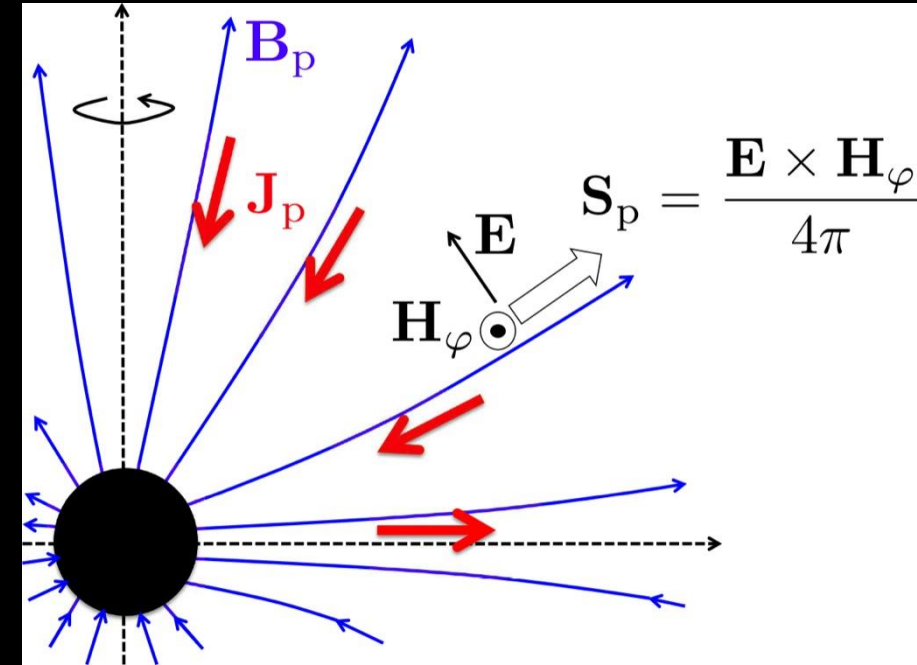


*Figure: image of the BZ process.
Toma & Takahara (2016)*

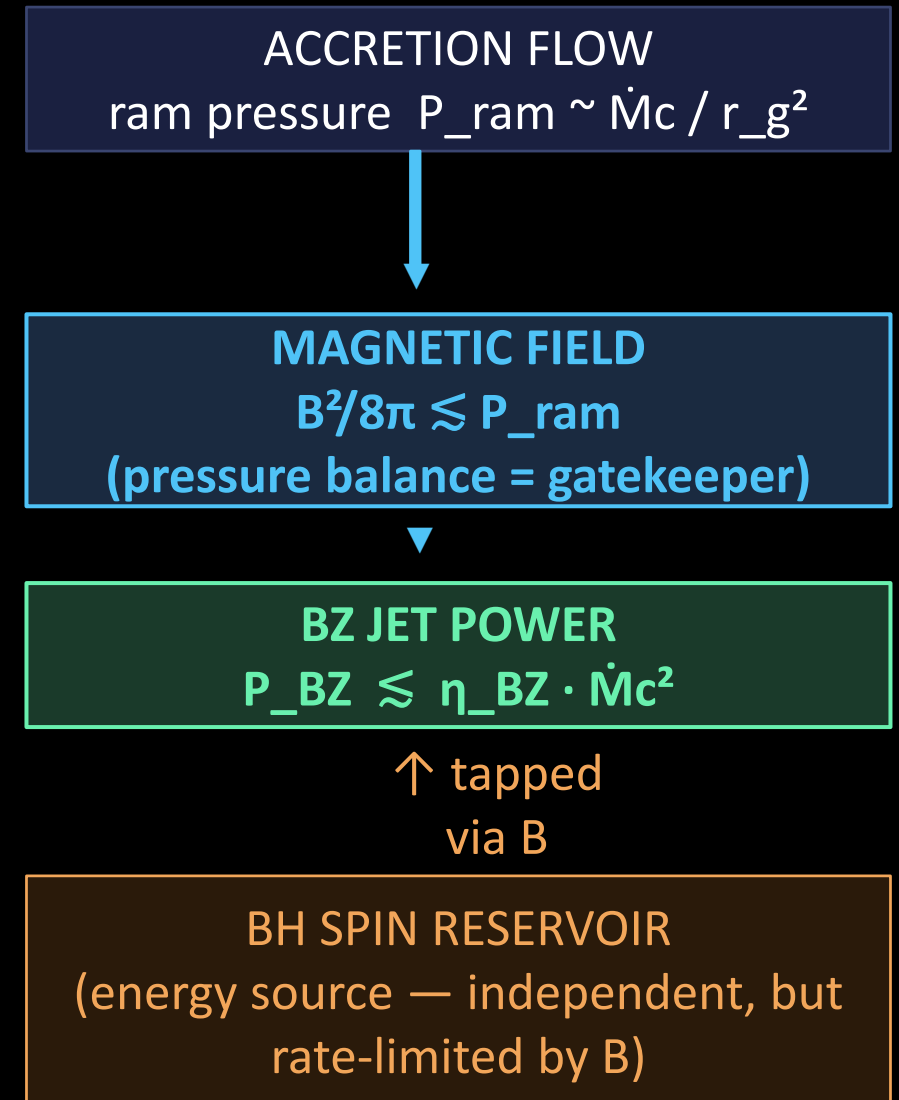
2-2: The Blandford–Znajek Process & Jet evolution

- **Mass loading:** Converting Poynting Flux to Kinetic one
 - Near the horizon, the jet is Poynting-dominated (magnetization $\sigma \gg 1$).
 - Initial mass loading occurs via electron-positron pair production via photon-photon annihilation or magnetic cascades.
- **Outward propagation:**
 - Mass is gradually loaded from the BP disk wind or pair cascades.
- **Large-scale kinetic-dominated jet ($\sigma \ll 1$).**
 - Electromagnetic energy is converted into bulk kinetic energy of particles.
 - Observed bulk Lorentz factors in M87*: $\Gamma \approx 3 - 10$ on parsec scales.
- **The open σ problem.**
 - How the jet converts from $\sigma \gg 1$ to $\sigma \ll 1$ remains debated. E.g., magnetic reconnection and resultant pair cascade? Inverse-Compton γ -ray cascades?

Section 2: Energy extraction from rotating black holes

2-3: The Magnetic Field — **Coupling Agent** Between the Two Reservoirs

- **BZ requires a strong B field threading the horizon**
 - This field is supplied & confined by the accreting plasma — cannot be maintained independently
- **Maximum sustainable field: pressure balance at the horizon**
 - $B^2/8\pi \lesssim P_{\text{ram}} \sim \dot{M}c / r_g^2$
- **Substituting into the BZ power formula:**
 - $P_{\text{BZ}} \lesssim \eta_{\text{BZ}} \cdot \dot{M}c^2$
- **Critical conclusion: BZ power cannot greatly exceed accretion power**
 - Accretion flow acts as the gatekeeper — it sets the rate of spin energy extraction
 - If B exceeds equipartition $\rightarrow$ accretion halted $\rightarrow$ MAD state (next slide)
 - If B is sub-equipartition $\rightarrow P_{\text{BZ}} < \dot{M}c^2$ — spin reservoir is bottlenecked

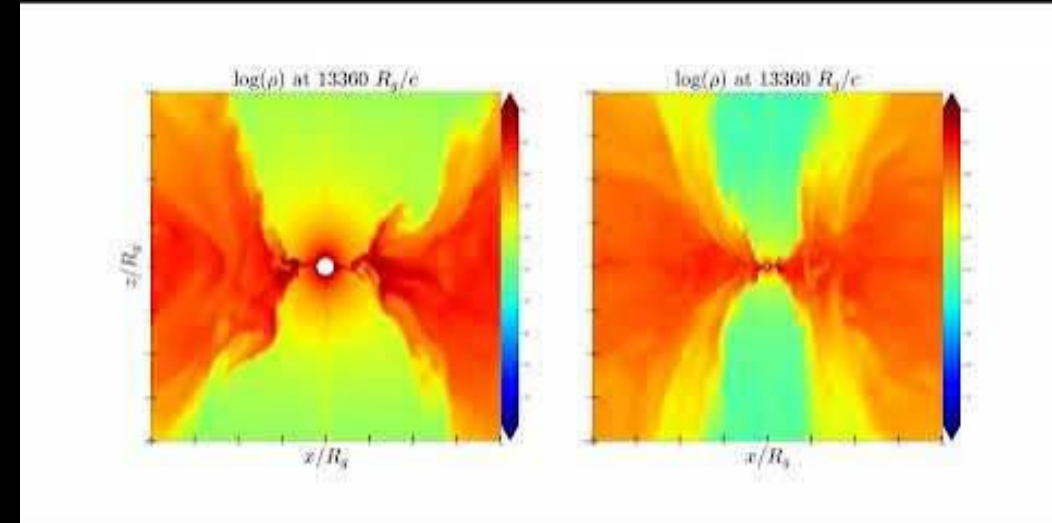


Section 2: Energy extraction from rotating black holes

2-4: The **MAD State** — Maximum BZ Power

- **MAD = Magnetically Arrested Disk**

- Narayan + (2003); Tchekhovskoy + (2011)
- Magnetic flux accumulates at the horizon as accretion brings field inward
 - When $B^2/8\pi \sim P_{\text{ram}}$: magnetic pressure $\approx$ ram pressure $\rightarrow$ accretion temporarily arrested
- **Maximum BZ efficiency state:**
 - $P_{\text{BZ}}(\text{MAD}) \sim \eta_{\text{MAD}} \cdot \dot{M}c^2$, w/ $\eta_{\text{MAD}} \sim 0.1\text{--}1.4$ for $a \rightarrow 1$
 - Even in MAD: P_{BZ} remains bounded by accretion power — gatekeeper principle holds
- Magnetic flux eruptions $\rightarrow$ quasi-periodic variability in P_{jet}
- **Evidence for M87* near MAD state:**
 - EHT Paper VIII (2021): magnetic flux at horizon consistent w/ MAD
 - High jet efficiency is inferred: $\eta \gtrsim 1$ (in units of $\dot{M}_{\text{horizon}} c^2$)



MAD condition: $B^2/8\pi \sim P_{\text{ram}}$
Gate fully open $\rightarrow$ maximum spin extraction

In M87 ADAF/ADIOS, $\dot{M}_{\text{horizon}} \ll \dot{M}_{\text{outer}}$ — but MAD maximizes BZ relative to the local horizon rate.

Section 2: Energy extraction from rotating black holes

2-5: Two-Component Jet Structure — What Do We Actually Know?

- **GRMHD simulations naturally produce a two-component outflow:**
 - Inner funnel: $\sigma \gg 1$, highly relativistic — clearly BZ-driven
 - Outer disk wind: denser, less magnetized, sub-relativistic — disk-driven
- **Tempting identification: BZ spine + BP sheath**
- **But this identification is NOT firmly established:**
 - Thick disk / ADAF sims (relevant to M87): outer wind may be toroidal pressure-driven, not classical BP
 - BP launching condition ($\theta < 60^\circ$) often NOT satisfied in GRMHD thick disk runs
 - Alternative: outer sheath = stratified BZ from field lines at larger horizon latitudes
 - Sub-relativistic BP wind may simply be undetected (too faint, too diffuse)
- **Observed VLBI morphology of M87: limb brightening**
 - Consistent with spine-sheath — but equally consistent with a stratified BZ jet
 - Tchekhovskoy, McKinney & Narayan (2008)

Inner BZ funnel jet is well-established. Nature of the outer component remains actively debated.

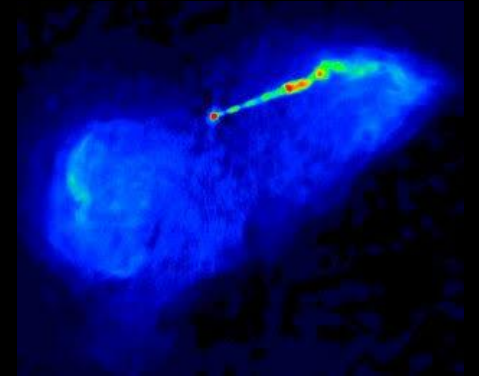
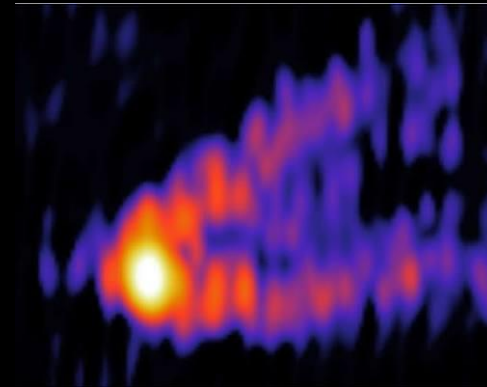
Jet Collimation

Section 3 — From a Wide Outflow to a Structured Relativistic Beam

Jet Collimation

The Collimation Problem — From Wide Outflow to Narrow Beam

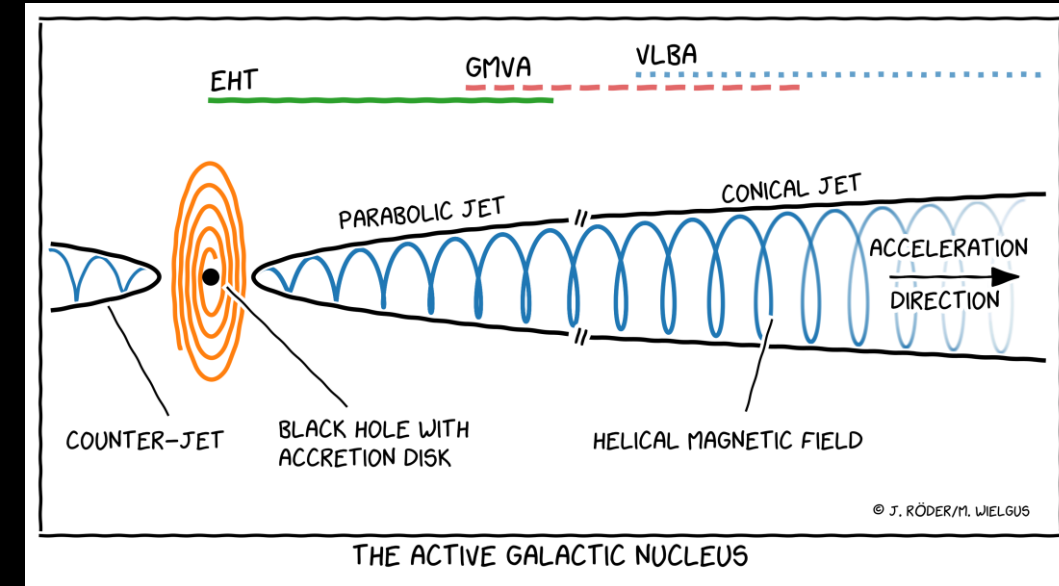
- A freshly launched jet near the black hole is wide and diverging.
- Observations demand jets stay narrowly collimated from kiloparsec to megaparsec scales — what confines them?
- Magnetic self-collimation: hoop stress from the toroidal field component.
- External pressure confinement: squeezed by the surrounding ambient medium.



Jet Collimation

Magnetic Self-Collimation — Hoop Stress & the Magnetic Nozzle

- As the outflow accelerates, differential rotation winds the field into tight toroidal loops.
- Hoop stress in B_ϕ acts like a magnetic pinch, squeezing the jet inward.
- This forms a magnetic nozzle that collimates the flow into a narrow beam.
- Near the black hole: poloidal-dominated ($B_p \gg B_\phi$). Farther out: toroidal-dominated ($B_\phi \gg B_p$).



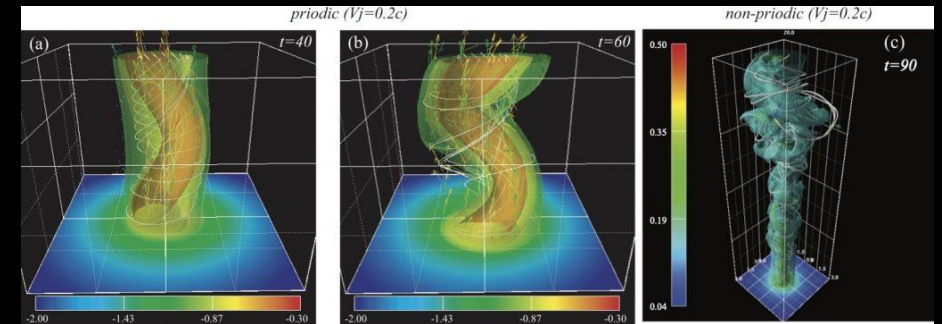
(Poloidal field lines winding into toroidal loops — inward hoop stress)

Nachrichten Informationsdienst Wissenschaft

Jet Collimation

The Threat to Collimation — Current-Driven Kink Instabilities

- A purely toroidal-dominated field column is prone to the current-driven kink instability ($m = 1$ mode).
- Unchecked, it bends the jet into a corkscrew and can disrupt it entirely.
- Velocity shear across the jet stretches out and suppresses the kink.
- External confinement from the surrounding medium also limits kink growth.



(3D MHD simulation of the $m = 1$ current-driven kink instability — periodic vs. non-periodic jet velocity; Mizuno et al. 2009, ApJ, 700, 684)

Jet Collimation

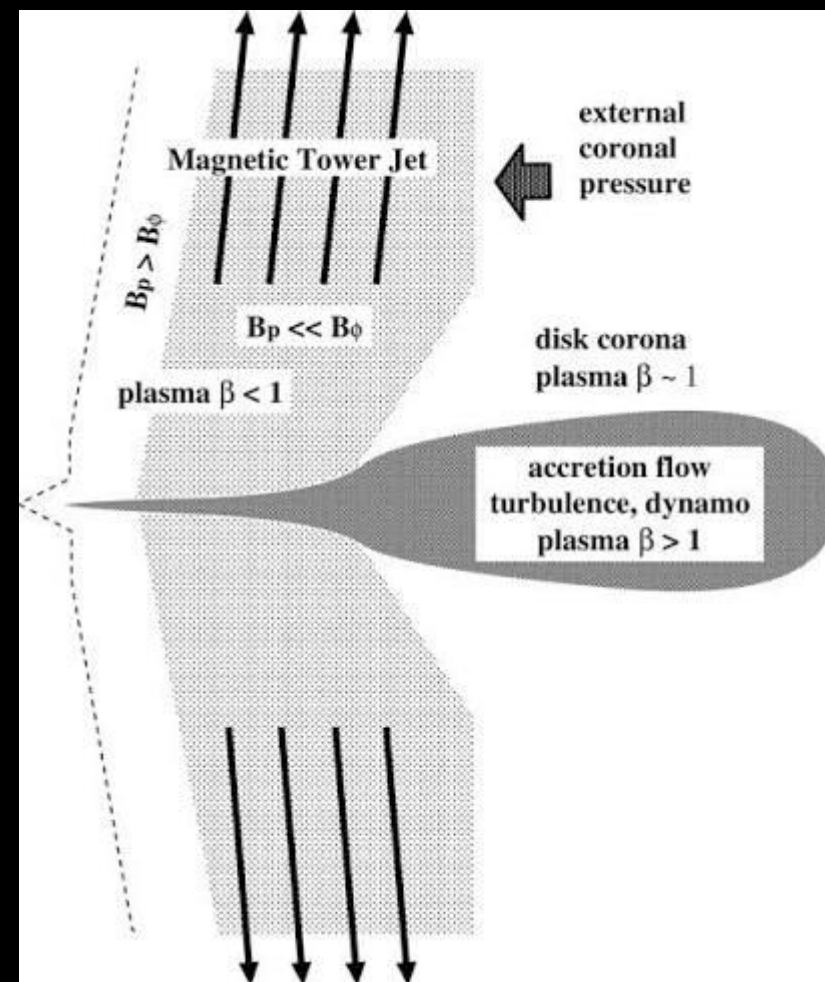
External Confinement — The Role of the Environment

- Magnetic hoop stress weakens as the jet expands to larger radii.
- The ISM (kpc scales) and ICM (tens—hundreds of kpc) press back against the jet boundary.
- This external pressure prevents lateral expansion and dispersal.
- The environment is an active structural partner, not just a passive backdrop.

Fig: confinement of jet by external pressure

[https://encrypted-](https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcRB3vsh6e1MsQdCDhnwLds3nD4DamuwNNLi0fcfQakXtg&s=105)

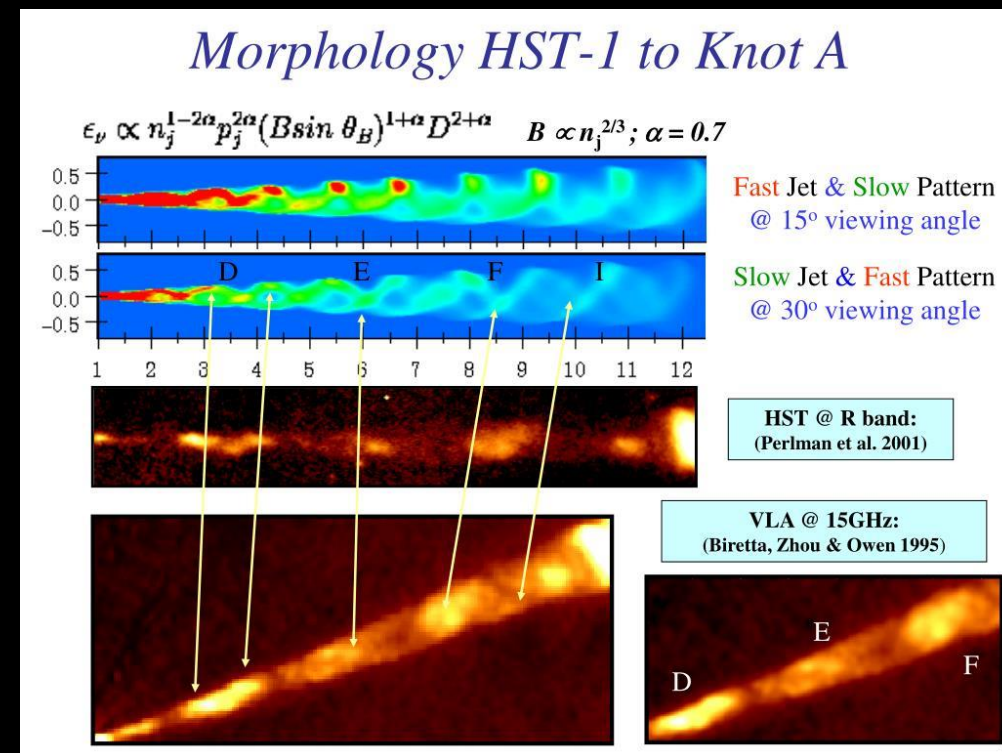
[tbn0.gstatic.com/images?q=tbn:ANd9GcRB3vsh6e1MsQdCDhnwLds3nD4DamuwNNLi0fcfQakXtg&s=105](https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcRB3vsh6e1MsQdCDhnwLds3nD4DamuwNNLi0fcfQakXtg&s=105)



Jet Collimation

Recollimation Shocks — Direct Observational Signatures

- Overpressured jet → lateral expansion → overshoot → internal shock → recollimation — a repeating cycle.
- These shocks compress plasma and accelerate particles, producing bright emission knots.
- Seen as stationary or semi-stationary knots in VLBI and optical images.
- Classic example: the HST-1 knot in the M87 jet, ~100 pc from the core.

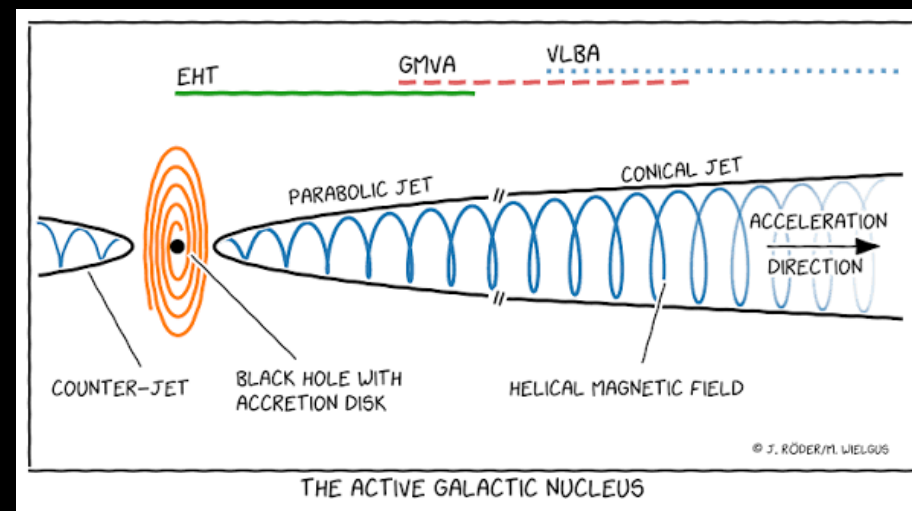


<https://image1.slideserve.com/3208581/morphology-hst-1-to-knot-a-l.jpg>

Jet Collimation

Transverse Jet Structure — Limb Brightening

- VLBI imaging of M87, Centaurus A, and Cygnus A often shows limb brightening — the edges glow brighter than the axis.
- Spine-sheath model: a fast inner spine plus a slower outer sheath; Doppler effects or shear brighten the edges.
- Angle-dependent BZ model: energy extraction peaks at mid-to-low horizon latitudes, channeling power to the outer jet.
- Transverse cuts of M87 and Cen A match this “hollow-pipe” emissivity profile.



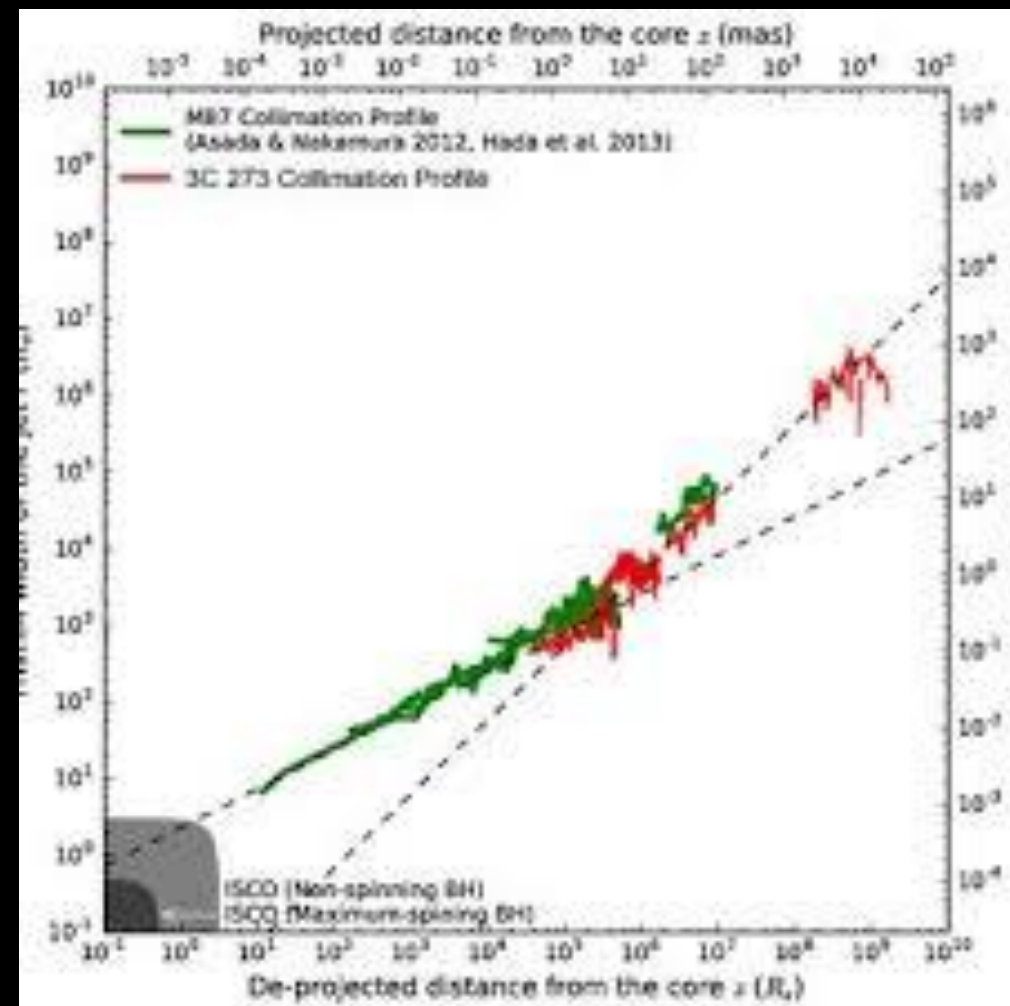
*(Schematic of the AGN jet:
parabolic-to-conical
transition and helical
magnetic field, with
EHT/GMVA/VLBA resolution*

Jet Collimation

Theory vs. Observation — The Parabolic-to-Conical Transition in M87

- M87's jet width follows a parabolic profile ($r \propto z^{0.58}$) from sub-parsec to kiloparsec scales.
- Near the Bondi radius ($\sim 10^5 r_g$), it transitions to conical expansion ($r \propto z$).
- Parabolic zone: hoop stress + ambient pressure collimate the flow. Conical zone: external pressure drops off and collimation saturates.
- GRMHD simulations reproduce this exact parabolic-to-conical transition.

*Fig: M87 jet radius r vs. distance z .
Parabolic $\rightarrow$ conical transition at the Bondi radius)
Asada & Nakamura (2012) ApJ 745, L28*



Jet Collimation

Summary & Open Questions

- Inner region: collimated by toroidal hoop stress — the magnetic nozzle.
- Outer region: confined by ISM/ICM pressure, producing recollimation shocks.
- **Confirmed observationally: transverse limb brightening and M87's parabolic-to-conical profile.**
- Open question 1: at what exact scale does magnetic collimation hand off to external confinement?
- Open question 2: how much of limb brightening is horizon-latitude BZ energetics vs. downstream velocity shear?

Jet Collimation

Bridge to Section 4

- We have examined how jets are launched (Section 2) and collimated into a structured beam (Section 3).

“What is this relativistic beam actually made of?”

- Section 4: Matter Composition of Jets — pair plasma ($e^+ e^-$) versus normal plasma ($e^- p^+$).

Matter Composition

Section 4 — What Is Flowing Inside the Jet?

Matter Composition

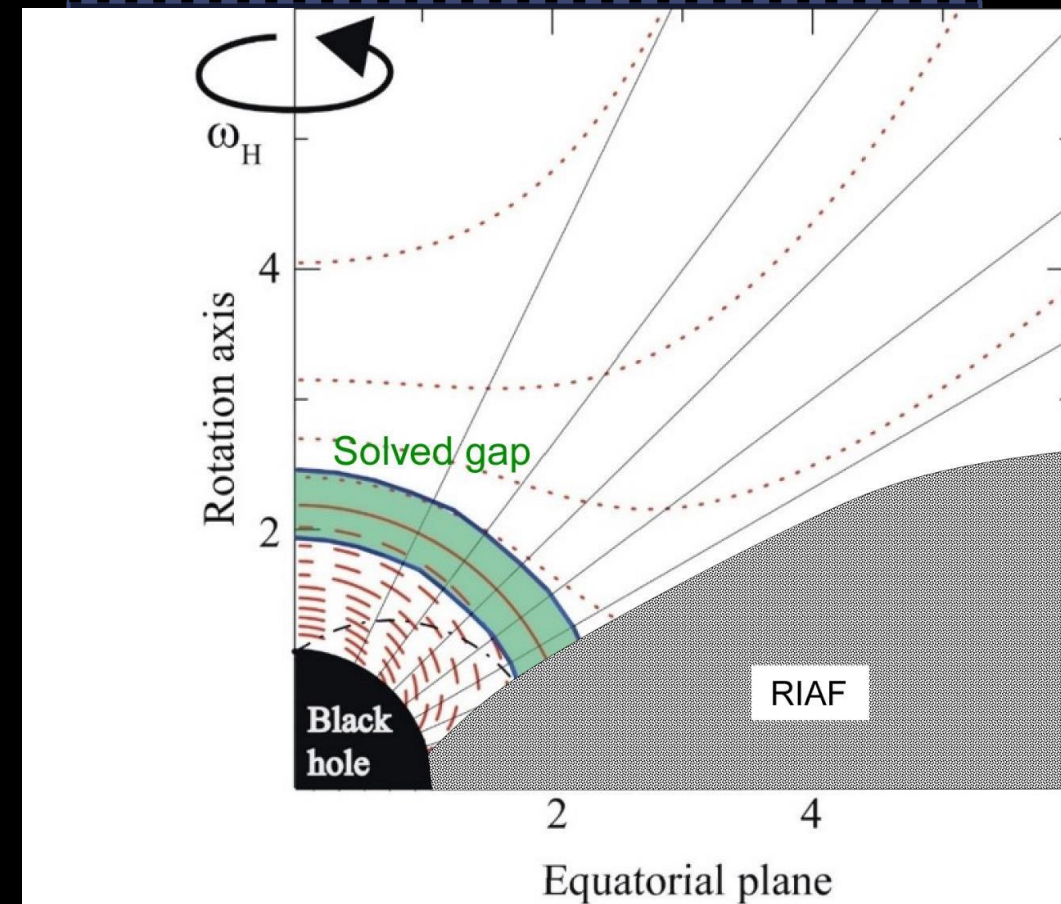
The Composition Puzzle — What Is Flowing Inside the Jet?

- We can image the jet and measure its radiation — but we cannot directly sample it.
- Composition must be inferred indirectly — one of the major unsolved problems in jet physics.
- It sets the jet's kinetic energy budget, particle acceleration mechanism, and cosmic-ray/neutrino output.
- Two extremes: leptonic $e^+ e^-$ pair plasma vs. hadronic $e^- p^+$ normal plasma.

Matter Composition

Pair Production Mechanisms — Filling the Magnetosphere

- The BZ process launches from a near-vacuum magnetosphere — plasma must be continuously supplied.
- $\gamma\gamma \rightarrow e^+ e^-$: MeV photons from the inner disk/corona collide to create pairs.
- Magnetospheric gap sparking: unscreened $E_{\parallel} \cdot B$ accelerates seed particles, triggering cascades.
- Result: the launch zone fills with dense, ultra-relativistic $e^+ e^-$ pairs.



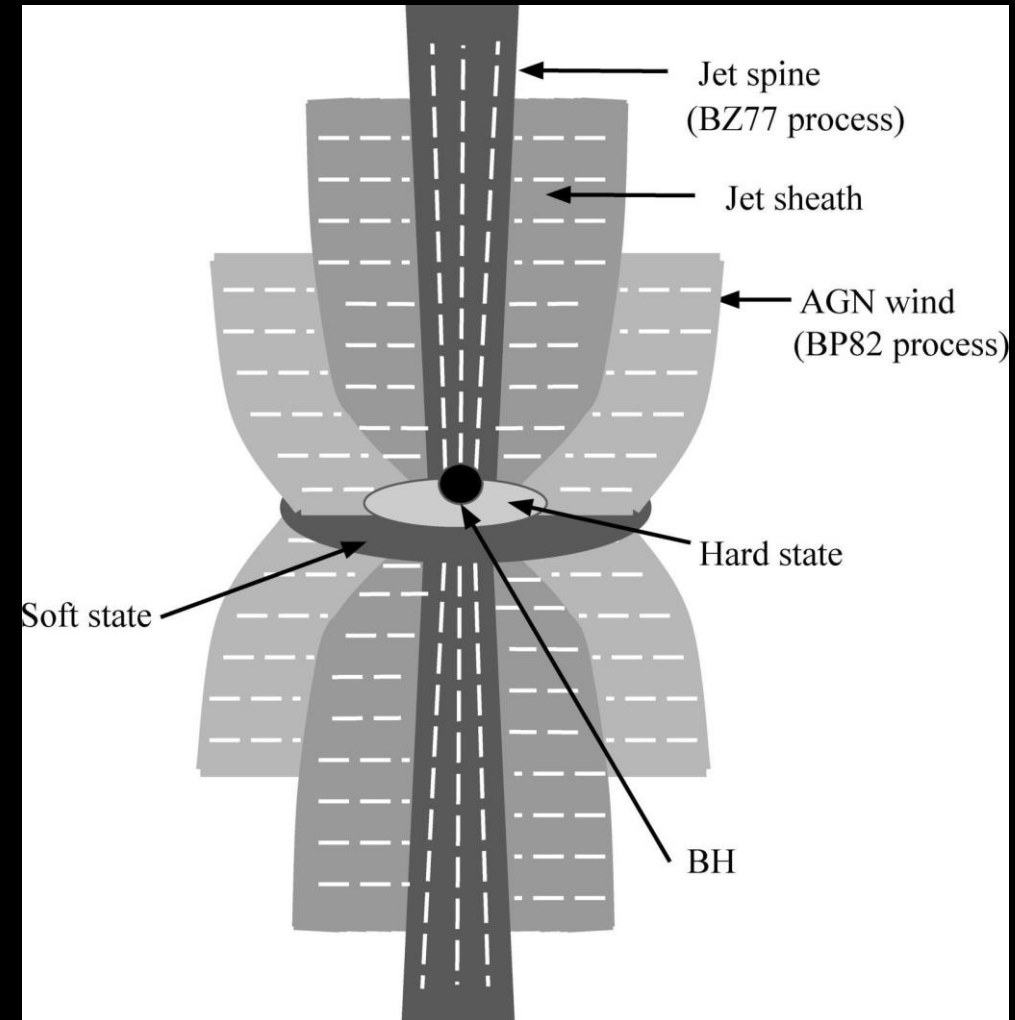
Matter Composition

Hadronic Entrainment — Loading Protons into the Outflow

- Jets don't travel in a vacuum — they interact with surrounding matter as they propagate.
- Accretion disk winds mix sub-relativistic protons into the jet boundary layer.
- Stellar winds, ISM clouds, and Kelvin–Helmholtz shear entrain more normal matter.
- Even a small proton fraction can dominate the jet's kinetic momentum ($m_p \approx 1836 m_e$).

Fig: jet-wind structure. BP disk wind may be entrained by the relativistic BZ jet.

https://cosmicvarta.in/assets/images/radio_quiet_agp_polarization_silpa/image4.jpg



• Significant Faraday Rotation

• some conversion

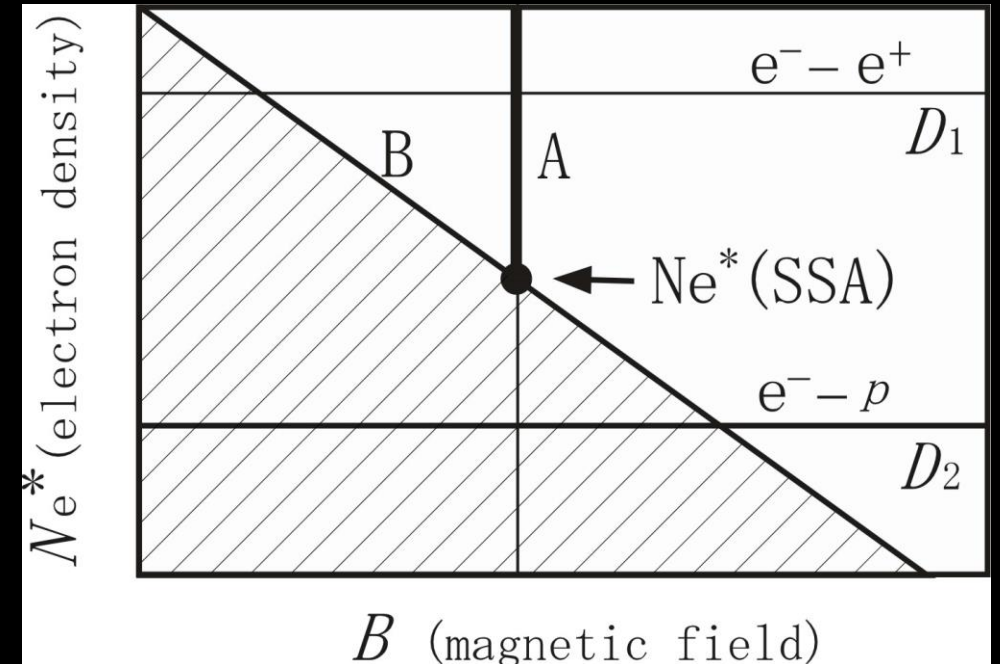
Matter Composition

Observational Diagnostics I — Faraday Rotation & Polarization

Matter Composition

Jet Energetics & the Leptonic “Mass Deficit”

- Multi-wavelength SEDs fix the required number density of radiating electrons, n_e .
- If $n_p = n_e$ (pure hadronic), $P_{\text{kin}} \approx \Gamma^2 n_p m_p c^3 A$ would vastly exceed the accretion power $\dot{M}c^2$.
- This “hadronic overpower limit” forces jets to be pair-rich.
- Models need $\sim 10\text{--}1000$ $e^+ e^-$ pairs per proton to match luminosity within energy limits.



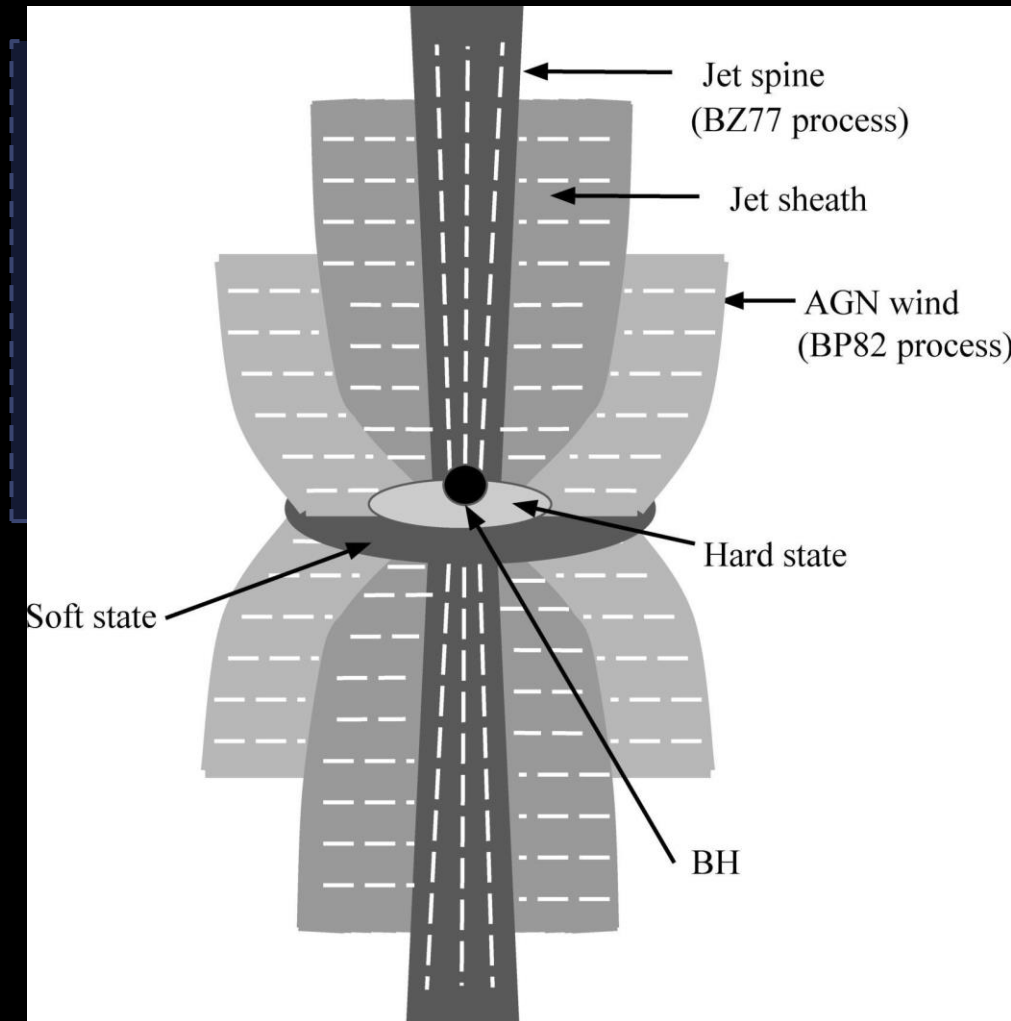
(Kinetic power required: pure hadronic vs. pair-dominated vs. Poynting-flux, against $\dot{M}c^2$)
KH (2005) ApJ 619, 73

Matter Composition

Synthesis — The Modern Consensus: Stratified Spine–Sheath Jets

- Inner spine: BZ-launched, $e^+ e^-$ -dominated, $\Gamma \sim 10\text{--}30$ — drives gamma-ray variability.
- Outer sheath: disk-wind entrained, $e^- p^+$ -loaded, $\Gamma \sim 2\text{--}5$ — provides confinement and Faraday screening.
- This two-component picture reconciles polarization diagnostics, energy budgets, and the limb-brightened VLBI structure from Section 3.

Fig: Stratified jet cross-section: pair-dominated inner spine ($\Gamma \sim 10\text{--}30$) + proton-loaded BP wind ($\Gamma \sim 1$)



Matter Composition

Summary & Open Questions

- Magnetospheric cascades inject $e^+ e^-$ pairs near the horizon; boundary entrainment adds $e^- p^+$ — together, a stratified spine-sheath jet.
- **Energetics and polarimetry mandate a pair-rich jet: 10–1000 pairs per proton.**
- Open question 1: what is the exact pair-to-proton ratio as a function of distance along the jet?
- Open question 2: do hadronic processes power IceCube neutrino detections (e.g., TXS 0506+056)?

Matter Composition

Bridge to Section 5

- We know how jets are launched (Sec. 2), collimated (Sec. 3), and structured in matter content (Sec. 4).

“How does this moving plasma produce the observed multi-wavelength radiation?”

- Section 5: Radiative Processes & Emission Mechanisms — synchrotron radiation, inverse Compton scattering, and hadronic emission channels.

Propagation & Radiation

Section 5 — From a Structured Jet to the Light We Observe

Propagation & Radiation

From Poynting Flux to Kinetic Flow

- Jets propagate as relativistic, supersonic, super-Alfvénic flows across ~ 9 orders of magnitude, horizon to megaparsec lobes.
- Launched with $\sigma \gg 1$ (Poynting-dominated); observed on pc–kpc scales with $\sigma \ll 1$ ($\Gamma \sim 3$ –10 in M87, ~ 10 –40 in blazars).
- The “ σ problem”: candidates are magnetic reconnection, kink instabilities, and recollimation shocks (Section 3).
- This section asks: how are particles accelerated, how does the jet terminate, and how does energy escape as light?

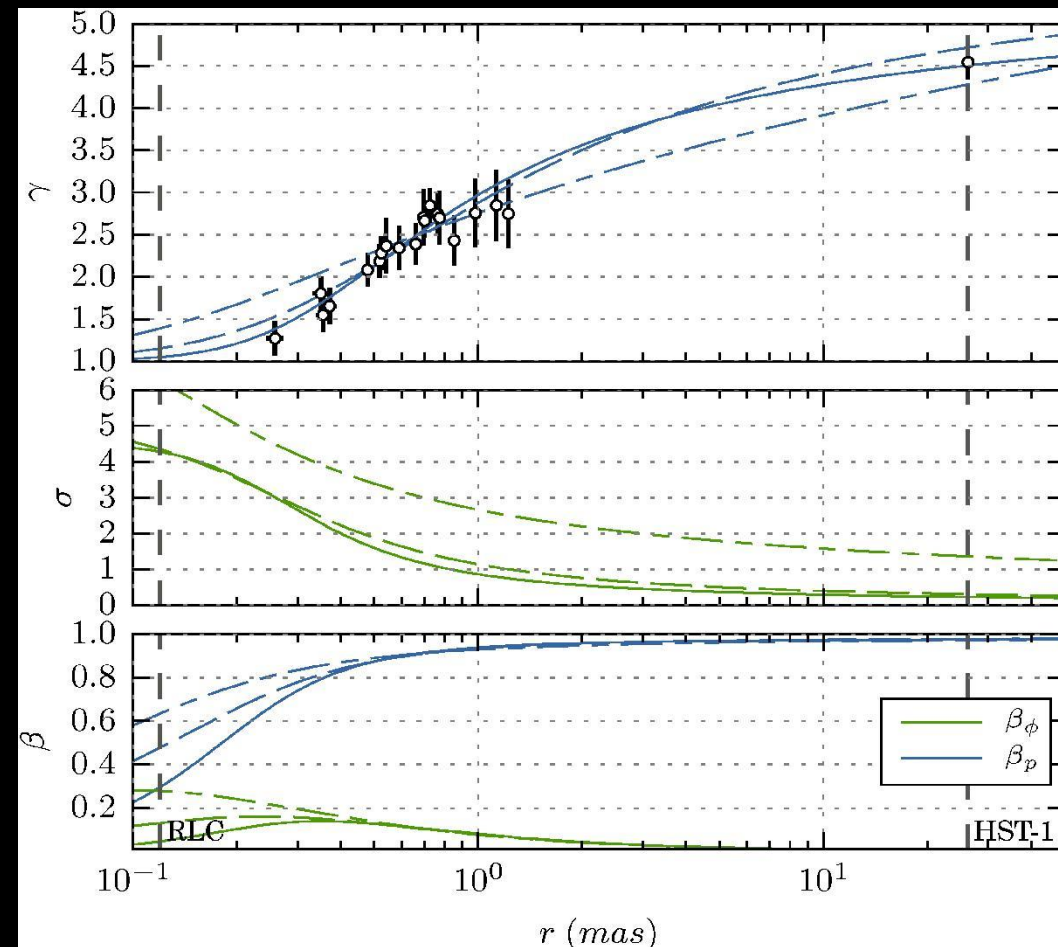
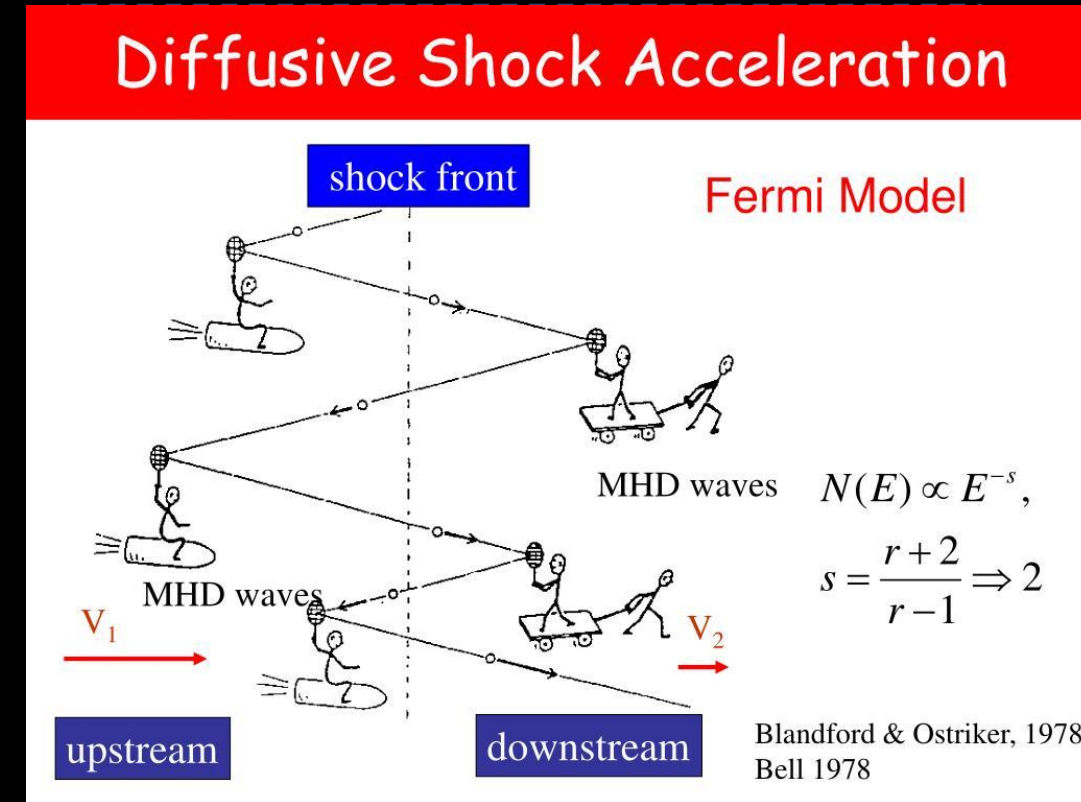


*Fig: Evolution of jet parameters
(bulk Lorentz factor, sigma
parameter, velocity/c).
Mertens + (2016) AA595, A54*

Propagation & Radiation

Particle Acceleration Mechanisms

- Diffusive shock acceleration (DSA): particles gain energy crossing shocks repeatedly — internal, recollimation, and termination shocks.
- Magnetic reconnection: converts field energy directly into particle energy — a natural site for σ -dissipation.
- Shear acceleration: the spine–sheath velocity gradient (Section 4) accelerates particles along the jet.
- These mechanisms likely coexist, dominating in different regions and epochs.



Propagation & Radiation

Jet Termination — Hotspots, Lobes & Feedback

- FR II jets stay supersonic to a strong hotspot shock where they ram into the IGM/ICM.
- Shocked plasma inflates giant radio lobes of relativistic plasma and field, tens to hundreds of kpc across.
- FR I jets instead decelerate and turn turbulent within the host galaxy.
- AGN feedback: mechanical energy from the jet suppresses cooling and star formation, self-regulating SMBH growth.

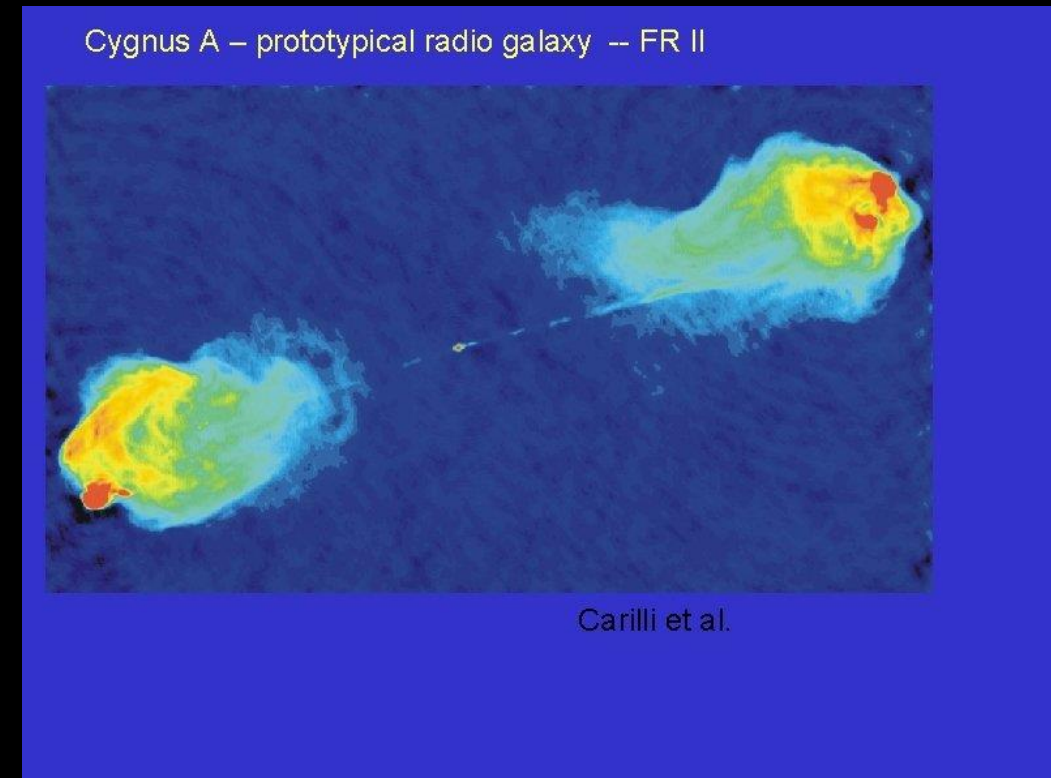


Fig: Cygnus A (VLA): twin jets terminating in hotspots, inflating giant radio lobes.
https://slidetodoc.com/presentation_image/538d733d7b23f60bc2da87de8bd6ec0a/image-12.jpg

Propagation & Radiation

Synchrotron Radiation — From Radio to X-rays

- Relativistic electrons gyrating in B fields emit synchrotron radiation, beamed into a cone of half-angle $\sim 1/\Gamma$.
- A power-law electron distribution $N(\gamma) \propto \gamma^{-p}$ gives a power-law spectrum, $F_\nu \propto \nu^{-(p-1)/2}$.
- Self-absorption flattens the spectrum at low frequency — the flat radio spectra of compact VLBI cores.
- Radiative cooling steepens the spectrum at high frequency — the synchrotron cooling break.

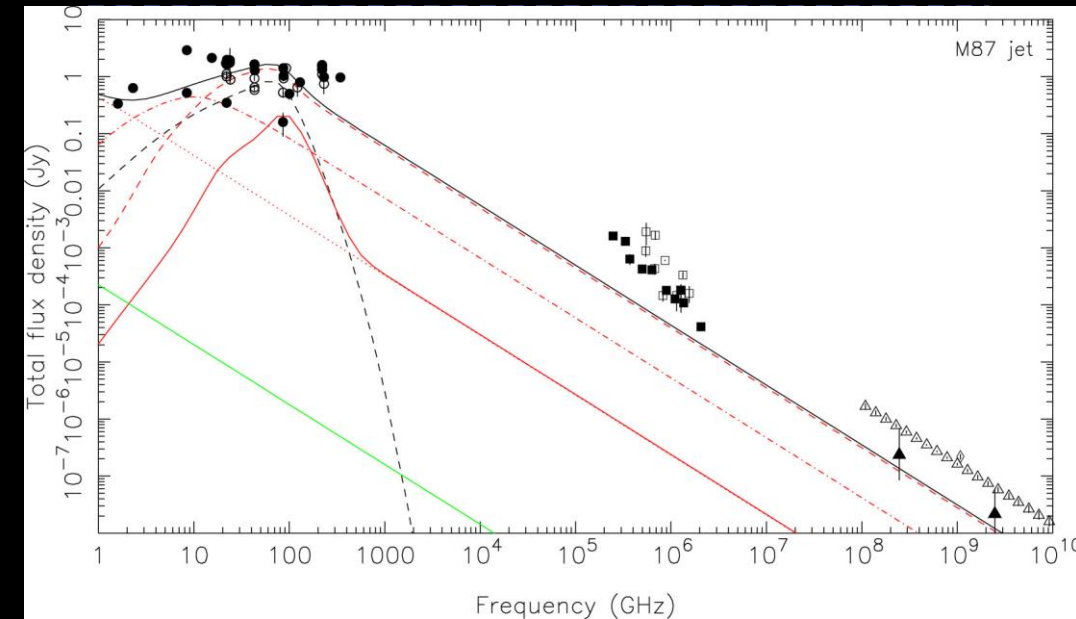


Fig: Synchrotron spectrum of the M87 jet (KH + 2025, ApJ 991, 117)

Propagation & Radiation

Inverse Compton Scattering — SSC & EC

- The same electrons upscatter photons to X-ray/gamma-ray energies via inverse Compton (IC) scattering.
- Synchrotron Self-Compton (SSC): electrons scatter the jet's own synchrotron photons — dominant in BL Lacs.
- External Compton (EC): electrons scatter external disk/BLR/torus photons — dominant in luminous FSRQs.
- SSC + EC produce the second, high-energy hump of the blazar spectral energy distribution.

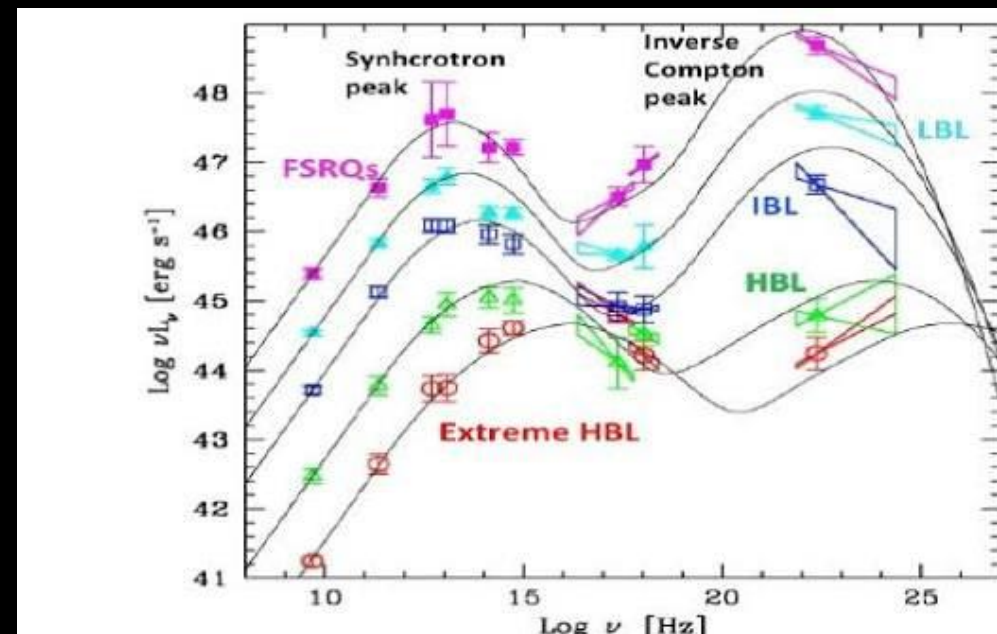


*Fig: The double-humped blazar SED: synchrotron peak plus an SSC/EC inverse-Compton peak.
Falomo + (2014) AAR 22, 1*

Propagation & Radiation

Hadronic Radiation — If Protons Are Along for the Ride

- If jets carry dynamically significant protons (Section 4), those protons can also accelerate and radiate.
- Proton synchrotron: very high-energy gamma rays, but requires extreme fields or proton energies.
- Photo-hadronic ($p-\gamma$) interactions produce pions: $\pi^0 \rightarrow$ gamma rays, $\pi^\pm \rightarrow$ high-energy neutrinos.
- 2017: an IceCube **neutrino** () traced to flaring blazar TXS 0506+056 — first plausible neutrino–blazar link.

Suppose relativistic protons encounter photons. (probability)

Propagation & Radiation

Doppler Boosting — Why Blazars Look So Extreme

- Observed flux is boosted by the Doppler factor $\delta = [\Gamma(1 - \beta \cos\theta)]^{-1}$.
- For small θ (blazars: jet points at us), $\delta \gg 1$ — flux boosted by orders of magnitude.
- The same δ compresses variability timescales and produces the superluminal motion seen in Section 1.
- The same jet viewed side-on de-boosts into an ordinary-looking radio galaxy.

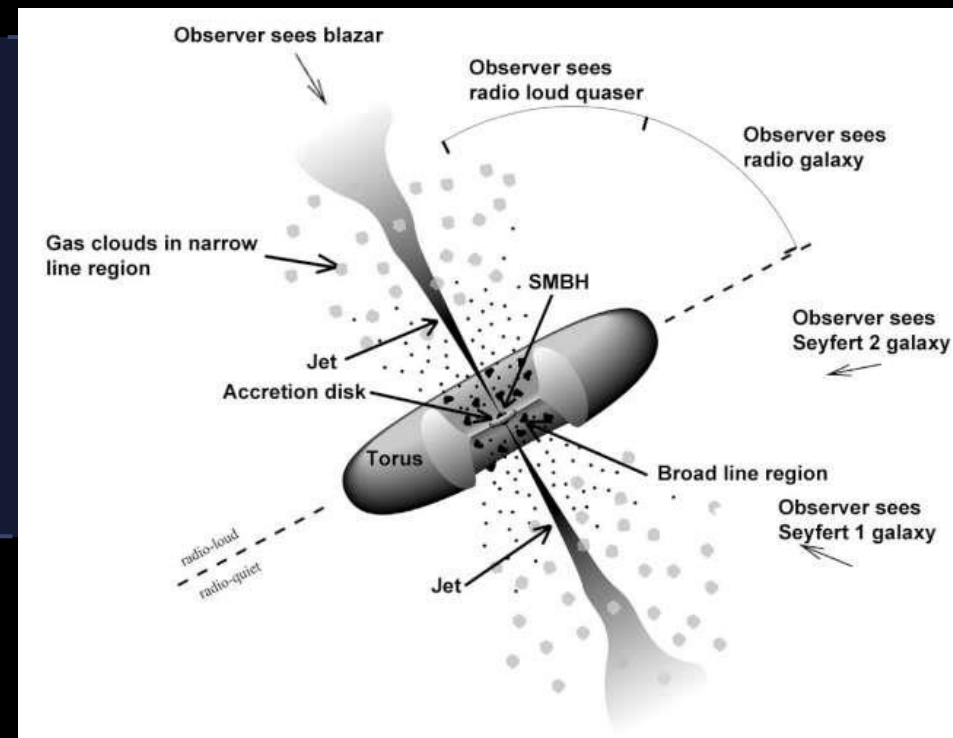


Fig: Relativistic beaming: a boosted blazar face-on, a de-boosted radio galaxy side-on)

Propagation & Radiation

Multi-wavelength Variability

- Jets vary on timescales from years (radio) down to minutes (blazar gamma-ray flares).
- Causality: $R \lesssim c \delta t_{\text{var}}$ — minute-scale flares imply an extraordinarily compact emission region.
- “Orphan flares” — gamma-rays with no radio/optical counterpart — challenge simple single-zone models.
- Modern picture: multi-zone models, with several compact regions contributing at different times and wavelengths.

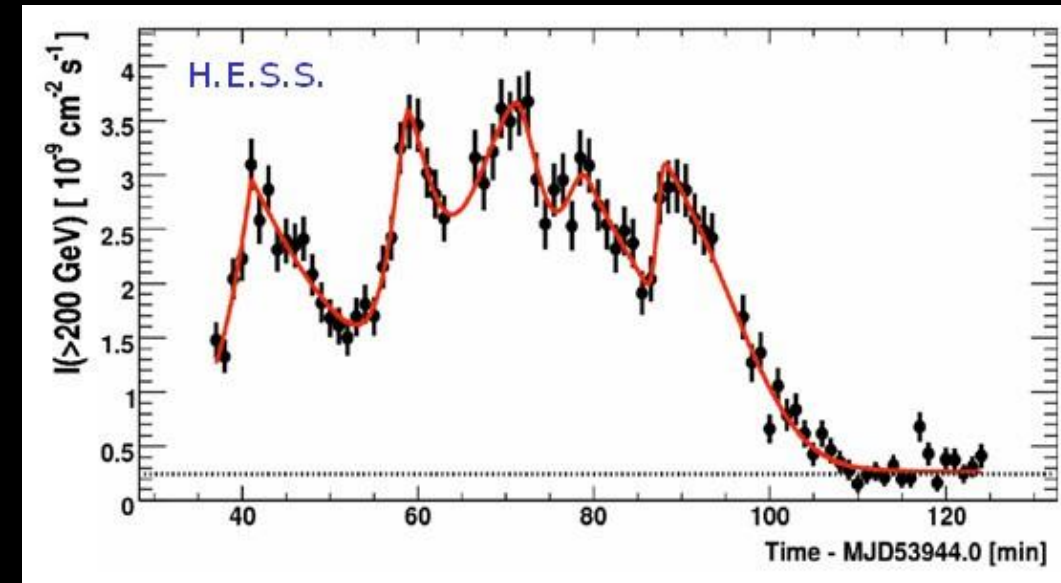


Fig: Minute-scale gamma-ray variability in blazar PKS 2155–304, observed with HESS

Propagation & Radiation

Theory vs. Observation — Fermi, VHE & the EHT

- Fermi-LAT: a decade of all-sky monitoring, thousands of AGN detected, revealing the “blazar sequence.”
- VHE (TeV) telescopes (MAGIC/HESS/VERITAS) probe extreme acceleration; EBL absorption also lets blazars probe cosmic starlight.
- The EHT resolves the jet base in M87/Cen A, linking the horizon-scale launch region to the radiating jet.
- Open question: where exactly are particles accelerated to the highest energies we observe?

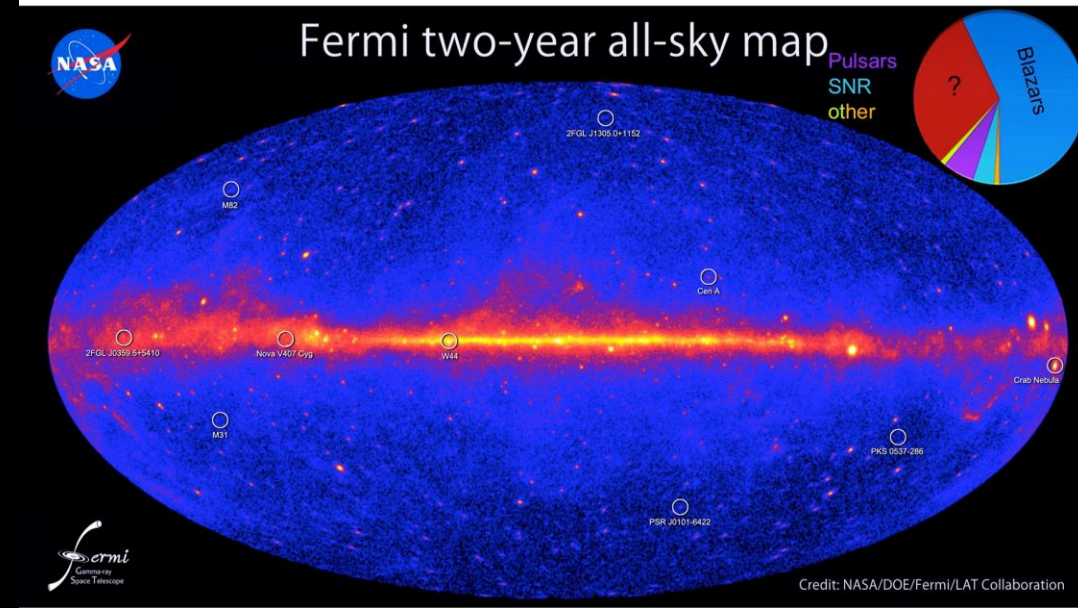


Fig: Fermi-LAT sky map
Credit: NASA

Propagation & Radiation

Bridge to the Conclusion

- We have followed the full journey: launching (Sec. 2) → collimation (Sec. 3) → matter content (Sec. 4) → propagation & radiation (Sec. 5).

“From a spinning black hole no larger than our solar system to a beacon visible across the observable universe.”

- Next: the Conclusion — pulling the whole picture together, and the open questions that remain.

Conclusion

The Physics of AGN Jets — From Horizon to Observation

- Section 1: a solar-system-sized black hole powers a galaxy-sized jet.
- Section 2 (Blandford–Znajek): black-hole spin plus threaded fields launch the jet.
- Section 3 (Collimation): hoop stress and ISM/ICM pressure confine the outflow.
- Section 4 (Matter): a pair-rich spine and proton-loaded sheath match the data.
- Section 5 (Radiation): acceleration and Doppler boosting produce the observed light.
- Open questions: the σ -conversion mechanism, the pair-to-proton ratio, and the peak-energy site.

“From a spinning black hole no larger than our solar system to a beacon visible across the observable universe — every step of that journey is written into the light we detect.”