
Relativistic Jets:
Some Unsolved Problems
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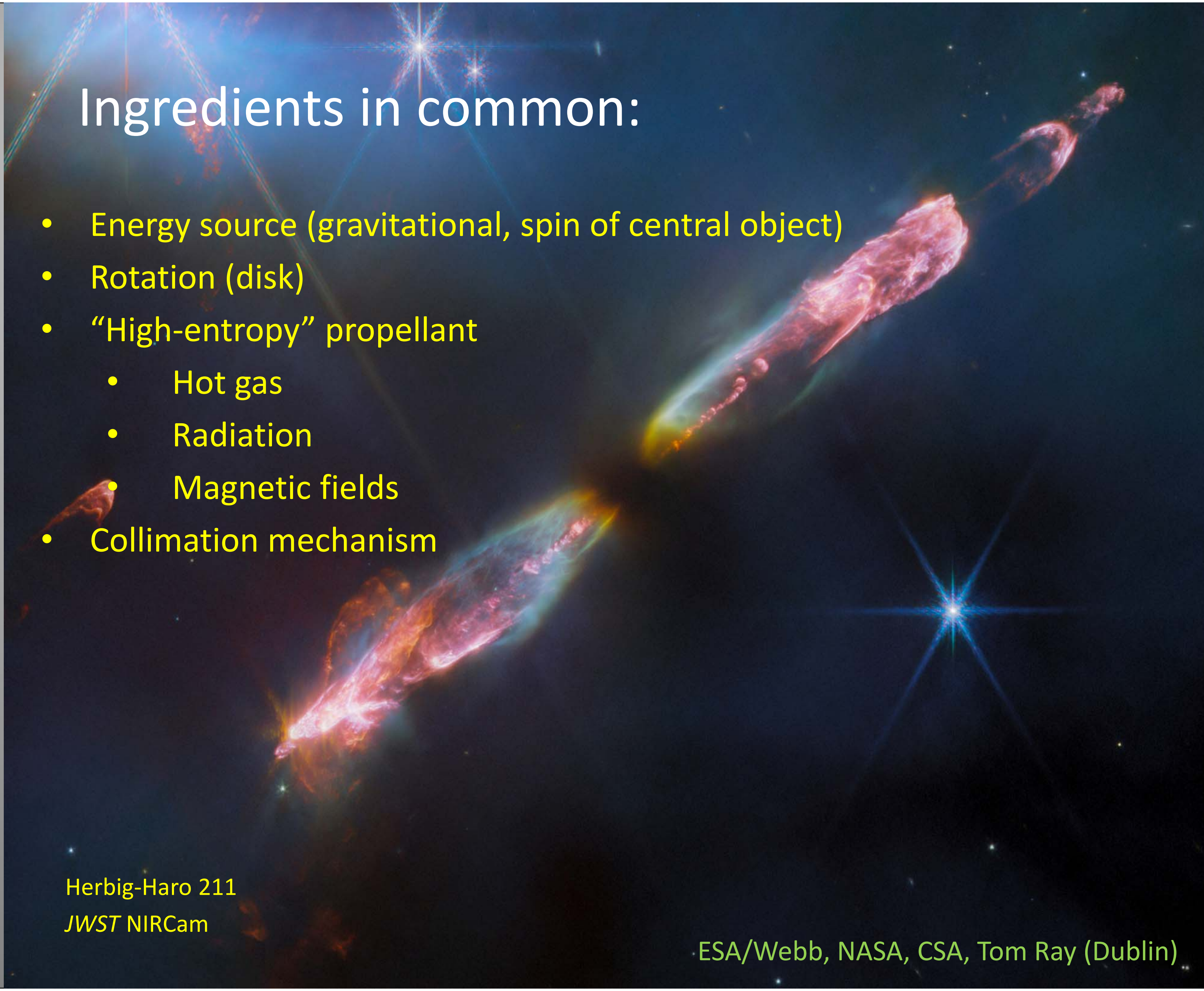
Reminder: jets are not intrinsically relativistic

Herbig-Haro 211
JWST NIRCam

ESA/Webb, NASA, CSA, Tom Ray (Dublin)

Ingredients in common:

- Energy source (gravitational, spin of central object)
- Rotation (disk)
- "High-entropy" propellant
    - Hot gas
    - Radiation
    - Magnetic fields
- Collimation mechanism



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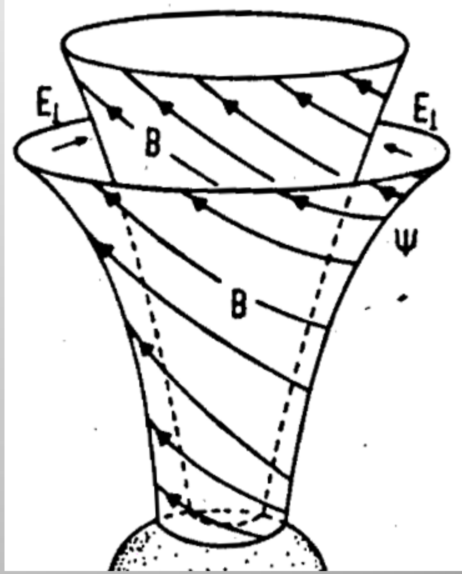
The Curious Demographics of Jet Speed

- Blazar jets: Γ ~ 10's
  - Low-density, optically thin
  - Likely propelled by BH spin
  - Mass-loaded by pair production in situ? – but density >> Goldreich-Julian
  - Entrainment at boundary with disk wind?
  - Core-sheath structure? Jet core faster but invisible?
- GRB jets: Γ ~ 100's $\longrightarrow$ ~ 10^3
  - Very dense environment – formed in stellar envelope

The Mixed Advantage of Magnetic Fields

Max terminal Lorentz factor $\Gamma_\infty = \frac{L_j}{\dot{M}_j c^2} >> 1$



- But Γ_∞ hard to reach with EM forces alone ...
  - Magnetorotational mechanism $\Gamma < \Gamma_\infty^{1/3}$
    - Rotational energy ⇒ Poynting flux + K. E.
    - Works inside Alfvén surface ~ light cylinder
    - Only region where jet could self-collimate without external medium
  - Magnetic nozzle $\Gamma \sim \Gamma_\infty^{1/3} \to \Gamma_\infty / 2$
    - Magnetic pressure ⇒ K. E.
    - Carries flow through fast magnetosonic surface but
    - "E"-forces nearly cancel "B"-forces in ultrarelativistic limit
  - Need dissipation to extract the remaining EM energy

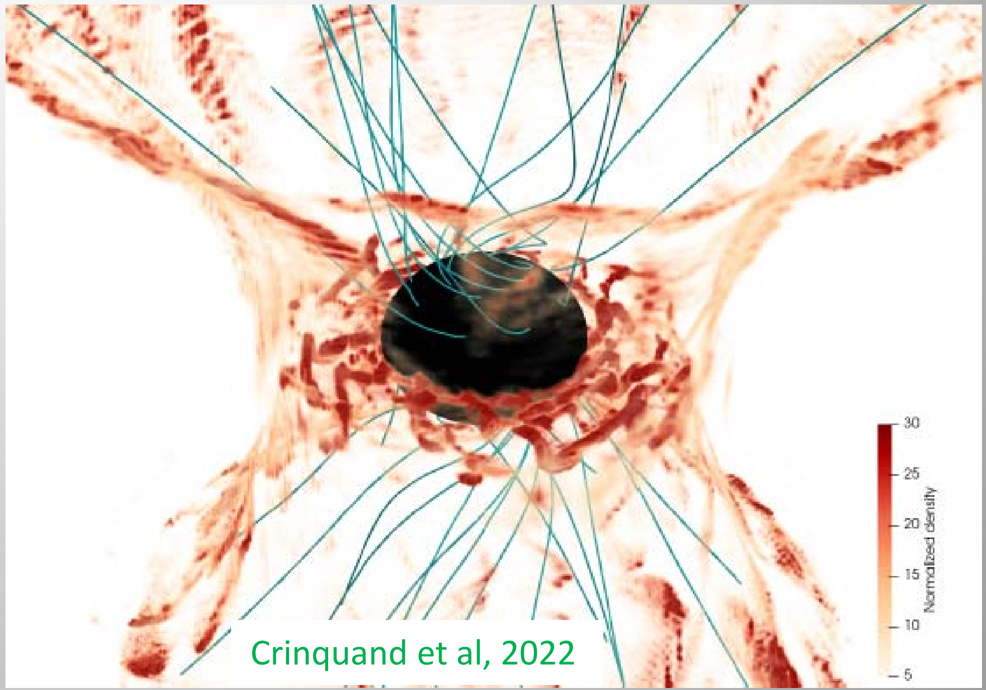
Adiabatic Acceleration: Slow But Reliable

Max terminal Lorentz factor $\Gamma_\infty = \frac{L_j}{\dot{M}_j c^2} >> 1$

- Relativistic fluid, γ=4/3 ...
  - Radiation
    - High efficiency if $\tau \gtrsim$ 1, radiation drag not a problem
    - Candidate for GRBs, maybe TDEs ... not blazars, pulsars, μQSOs, stars
  - Relativistically "hot" gas
    - No problem if protons!
  - Can ultimately extract all energy from isotropic expansion
    - ... but acceleration gradual

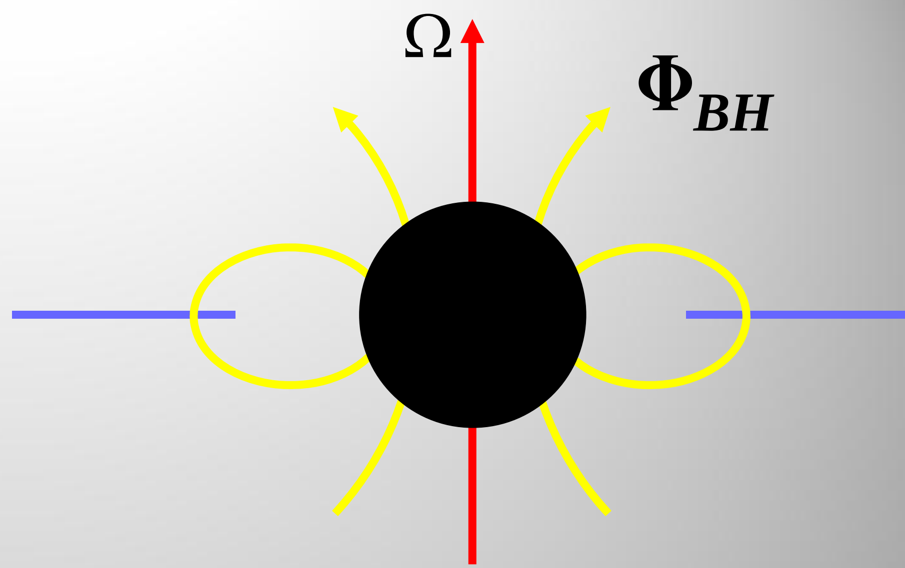
$$\Gamma \propto (external\ \ pressure)^{-1/4}$$

The Curious Demographics of Jet Speed



- Why does denser, messier environment produce the faster jet?
  - GRB jets: radiatively driven, more efficient energy conversion?
  - Blazar jets: conversion hung up by EM effects, ultimately more lossy?
    - Connection to dissipation/entrainment of ions at boundary layer?
    - Is there a faster, low-dissipation jet near the core?

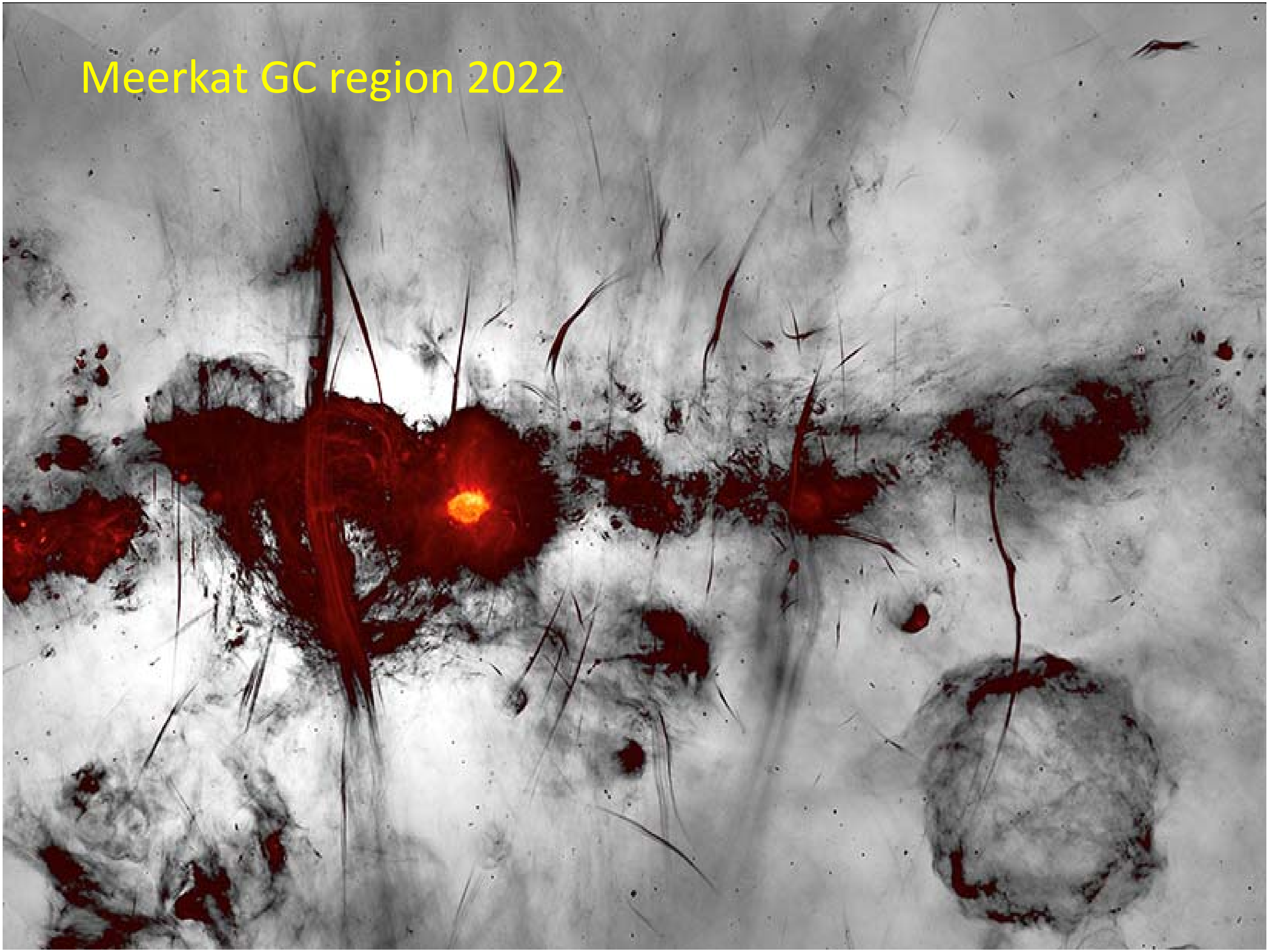
Why are jets so rare?



- Powerful jets ~ 10% of AGN
- The need for magnetic flux

$$L_j \sim \frac{\Phi^2\Omega^2}{c}$$

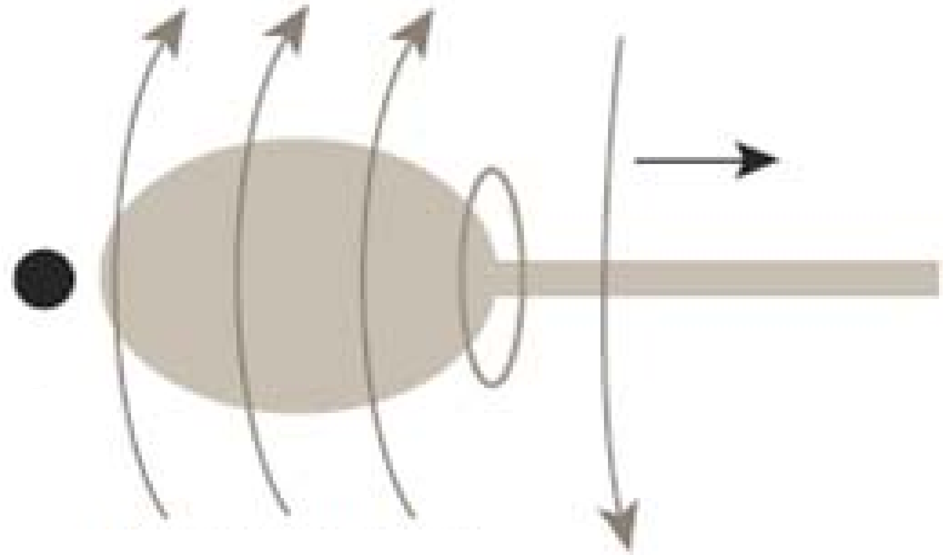
  - Which is more sensitive to environment/history: Ω or Φ?
- How to obtain flux?
  - Collect from environment: but can disk concentrate it?
  - Generate stochastically as large fluctuations?
- Not a large amount of flux *if* it can be accumulated


Meerkat GC region 2022

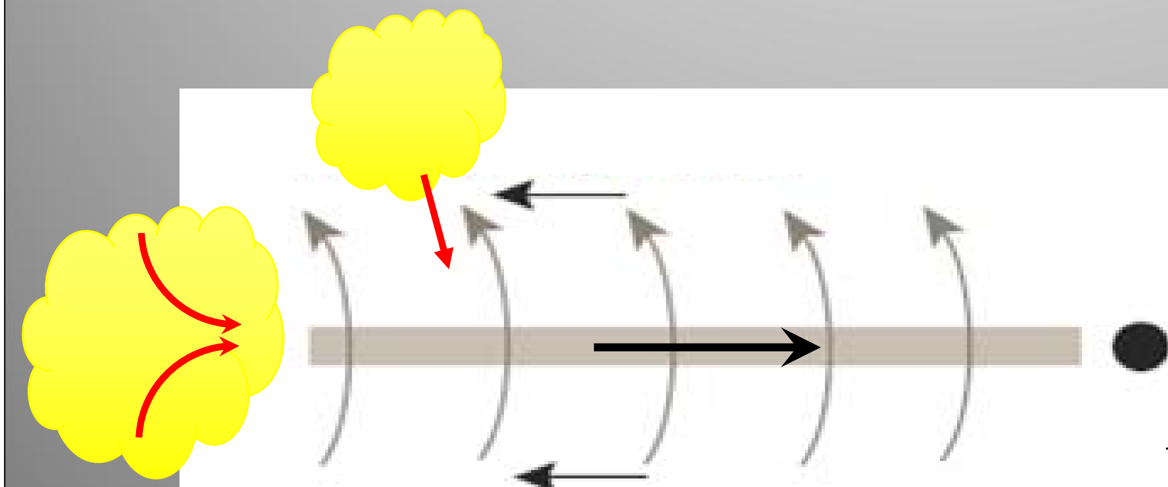
2 factors could lead to flux accumulation in disk:

Stochastic growth of large-scale field via dynamo

...not yet demonstrated in simulations



MCB & Armitage 14



Advection from source:

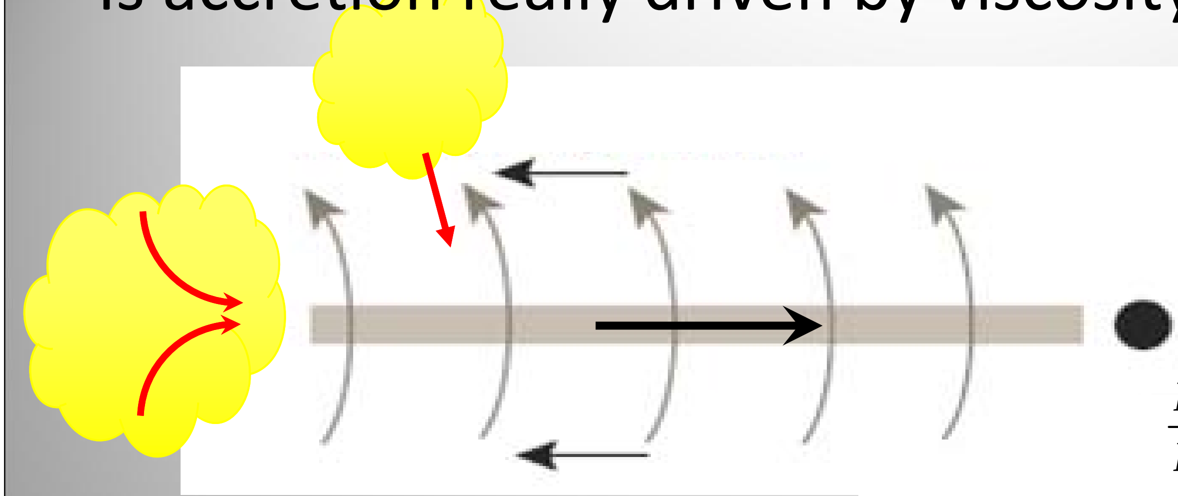
B-field of donor star, molec. clouds, etc.

... flux diffuses away unless

$\frac{B_r}{B_z} < \frac{H}{r}$ (for viscous disk)

Lubow et al. 94

Is accretion really driven by viscosity?



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Large-scale magnetic torque dominates if $\frac{1}{\Omega H}\frac{B_\phi B_z}{4\pi\rho} > \frac{\nu}{r}$

+ simple dynamo model

$\Rightarrow$ flux accumulates if $\mathrm{v}_{Az} = \left(\frac{B_z^2}{4\pi\rho}\right)^{1/2} > \frac{\nu}{H}$

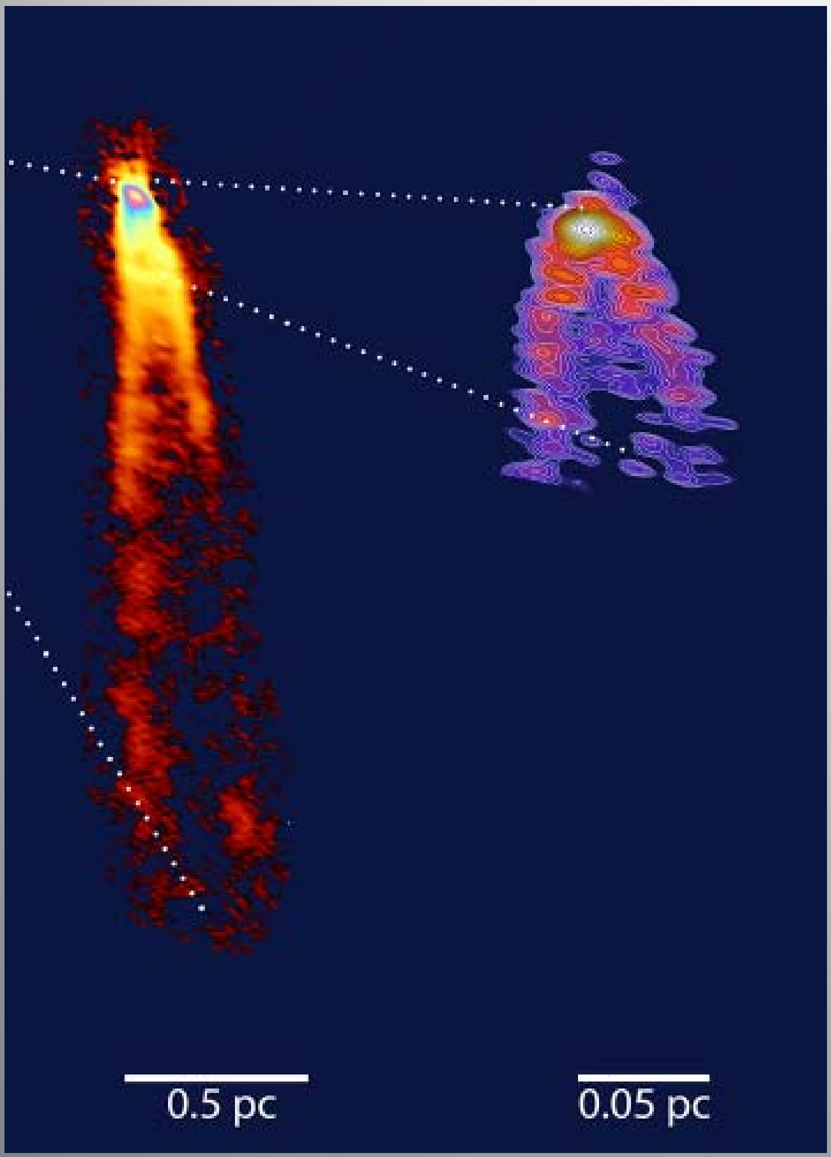
$\Rightarrow$ eventually reaches MAD (max. magnetic flux) state

Probably just requires B_z pressure $\gtrsim 0.01\ p_{gas}$ somewhere in disk

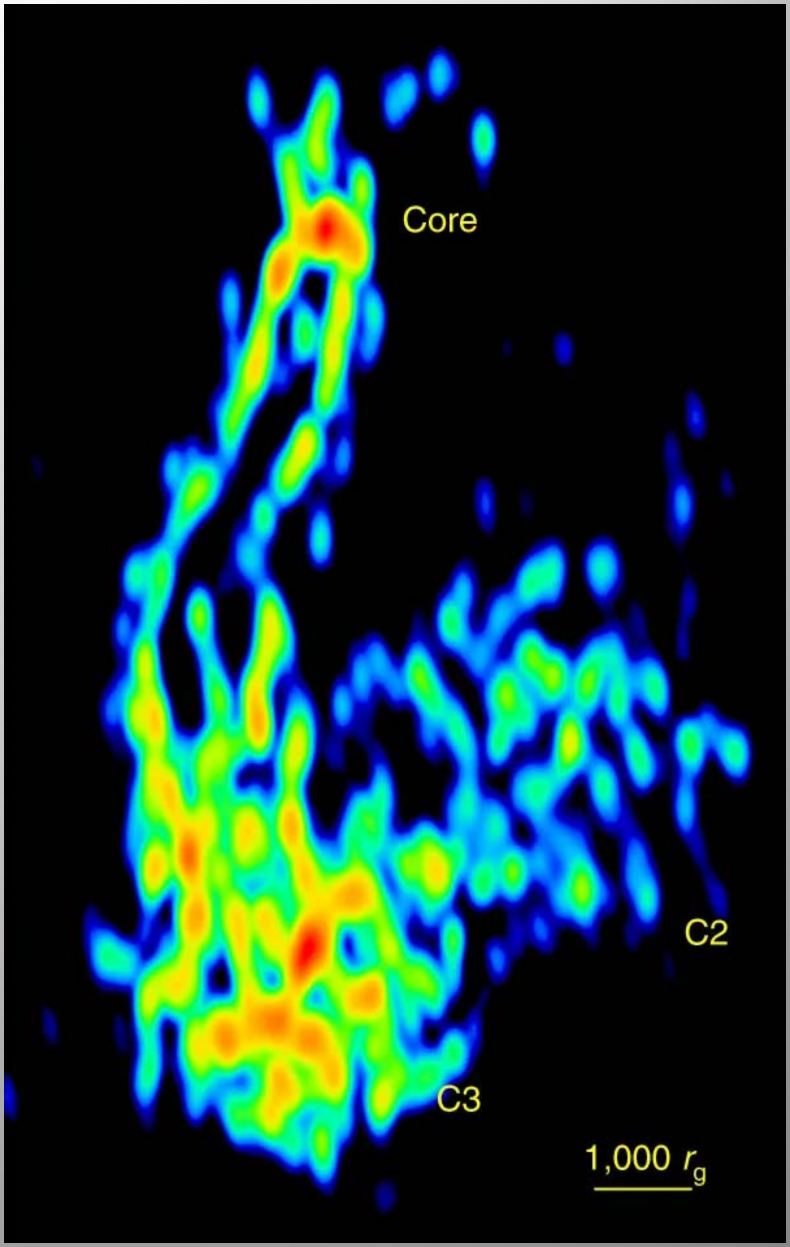
Ferreira + 90s, MCB & Silk 23

If field is easily advected,
why don’t we see more jets?

M87: Walker et al 2018 (l)
Kim et al 2018 (r)

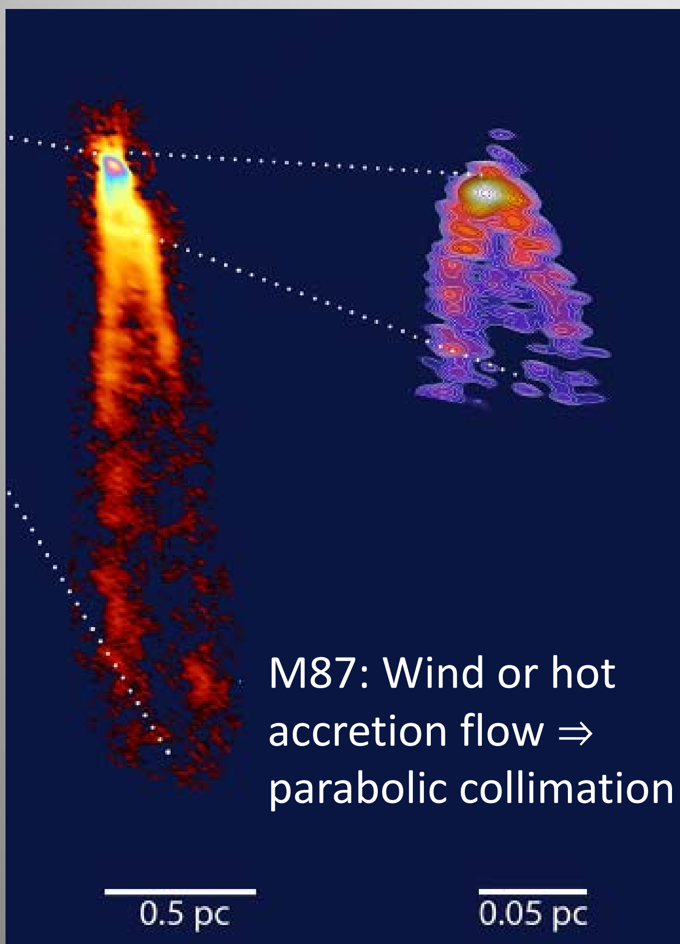


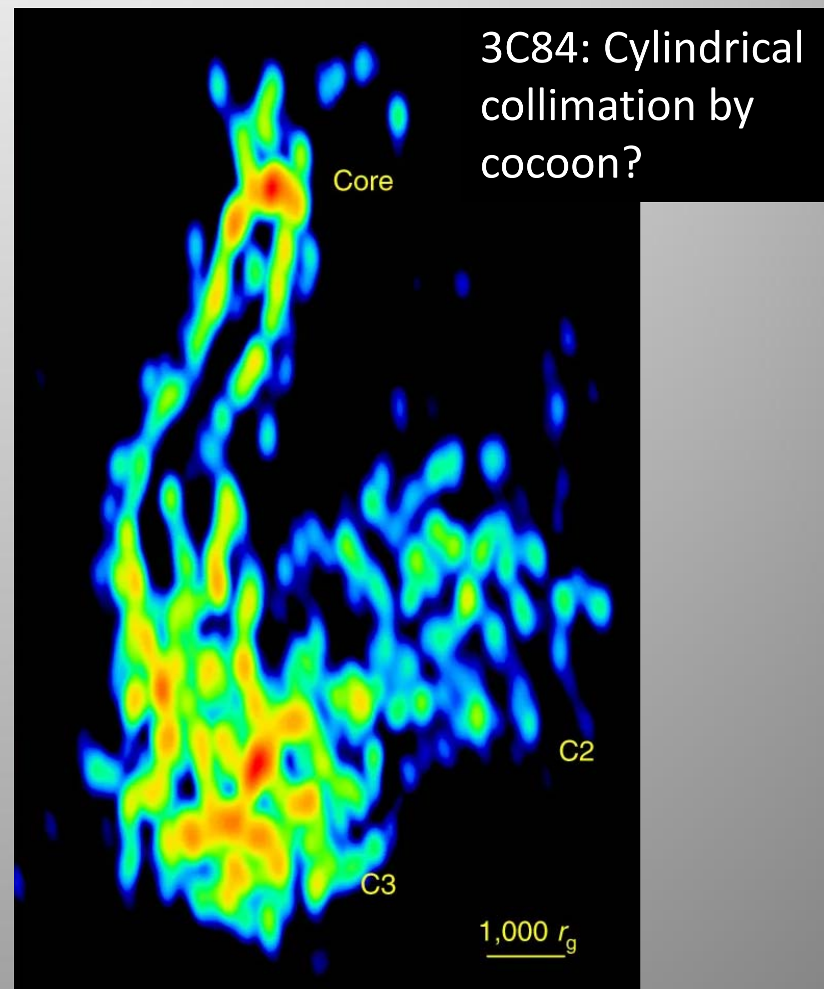
3C84: Giovannini et al 2018



Why don’t we see more jets?

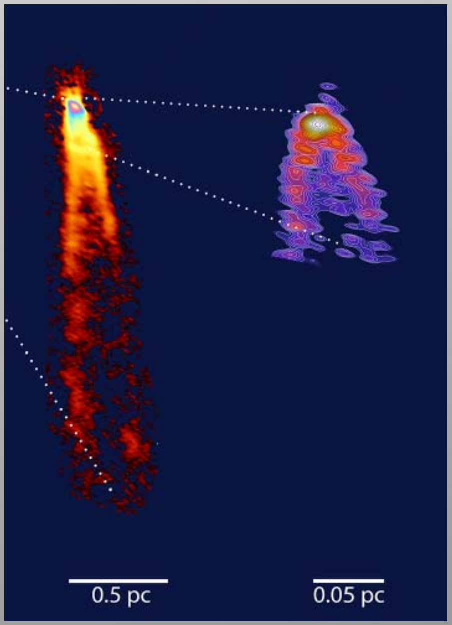
- External medium unable to confine/collimate jet?

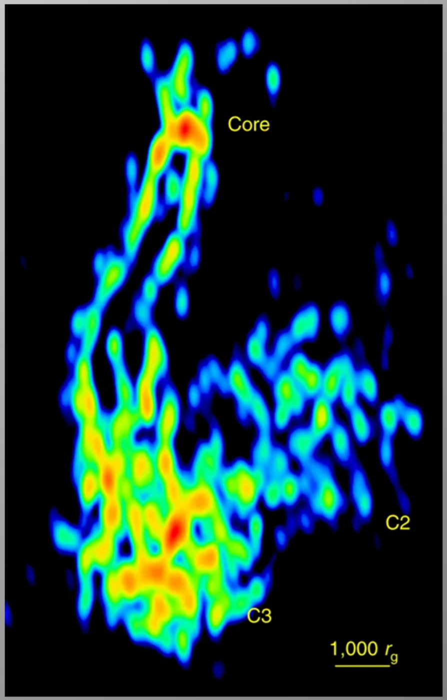




Why don't we see more jets?

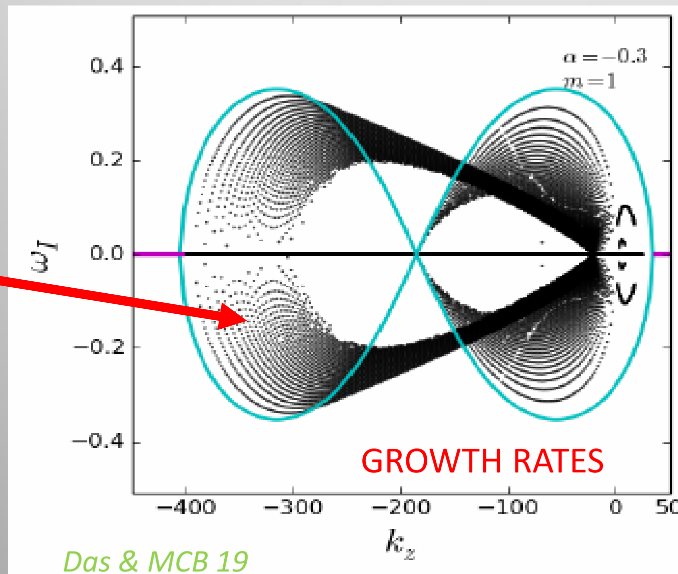
- External medium unable to confine/collimate jet?
- Need:
  - Shear instabilities along boundary
  - Turbulence, reconnection ⇒ Particle acceleration
- What about jet "spine"?
  - Too fast to see (beamed away)?
  - No instabilities
  - Or has magnetic field decayed?

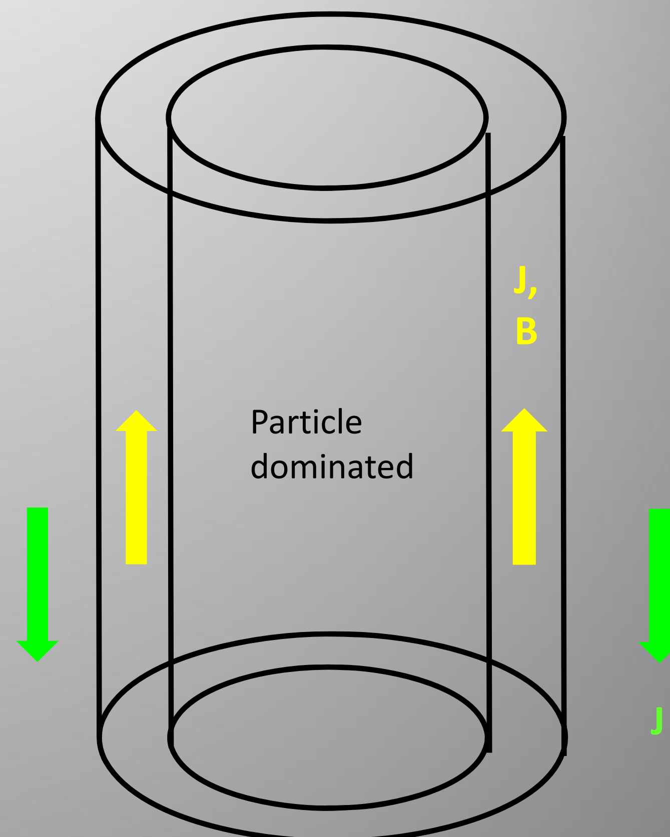




Current- and pressure-driven instabilities

- Global cause jets to wiggle (kink modes)
- Local (jet interior) ubiquitous, nondisruptive





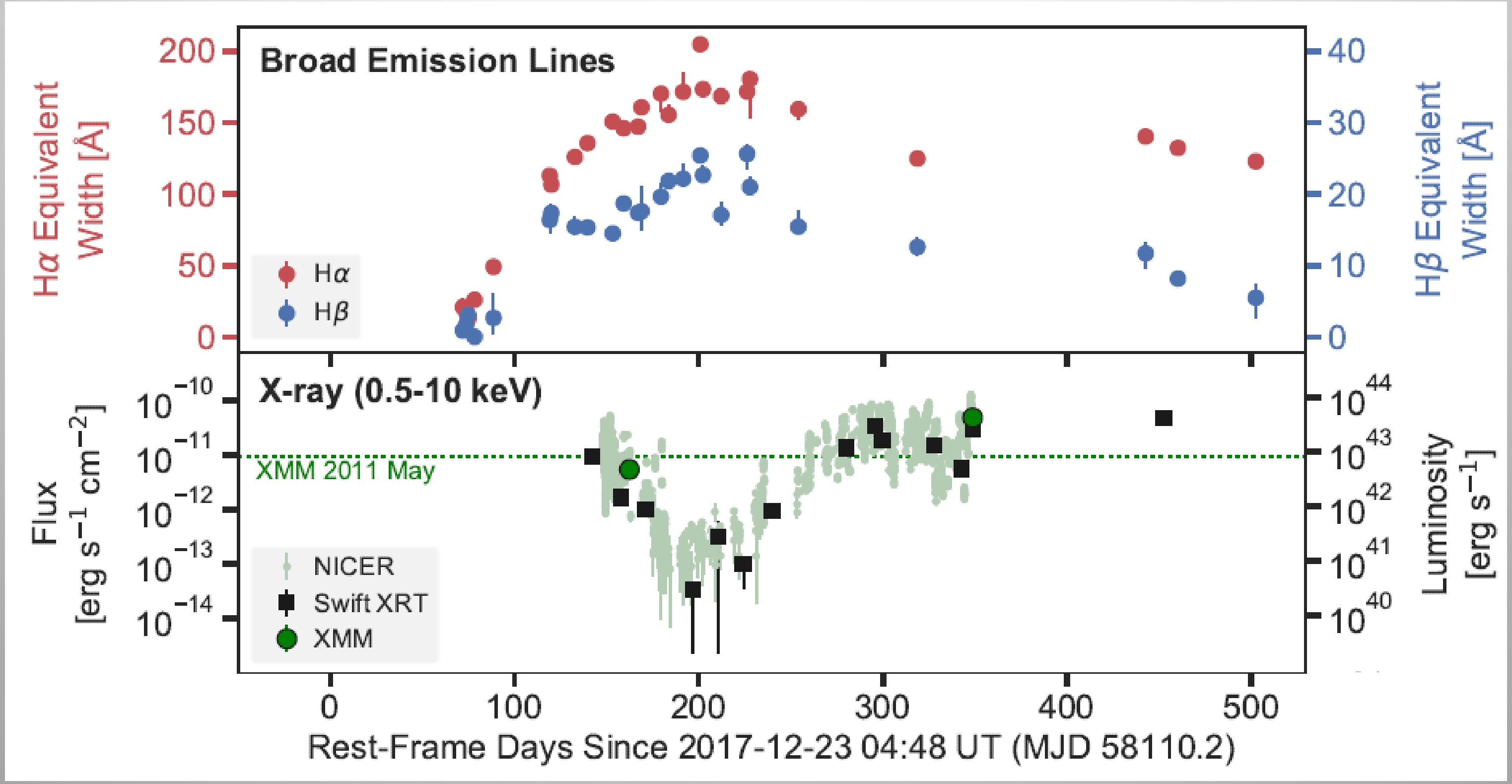
Conserved axial current migrates to jet wall, field and radiating particles confined to jet boundary if return current is just outside jet

$\Rightarrow$ could mimic shear boundary layer

What if the confining medium isn’t there (but the magnetic flux and BH spin are)?

Possible clue from a “changing-look” AGN

Changing-Look AGN 1ES 1927+654: a flux-reversing MAD?



1. X-ray dominant Seyfert 2

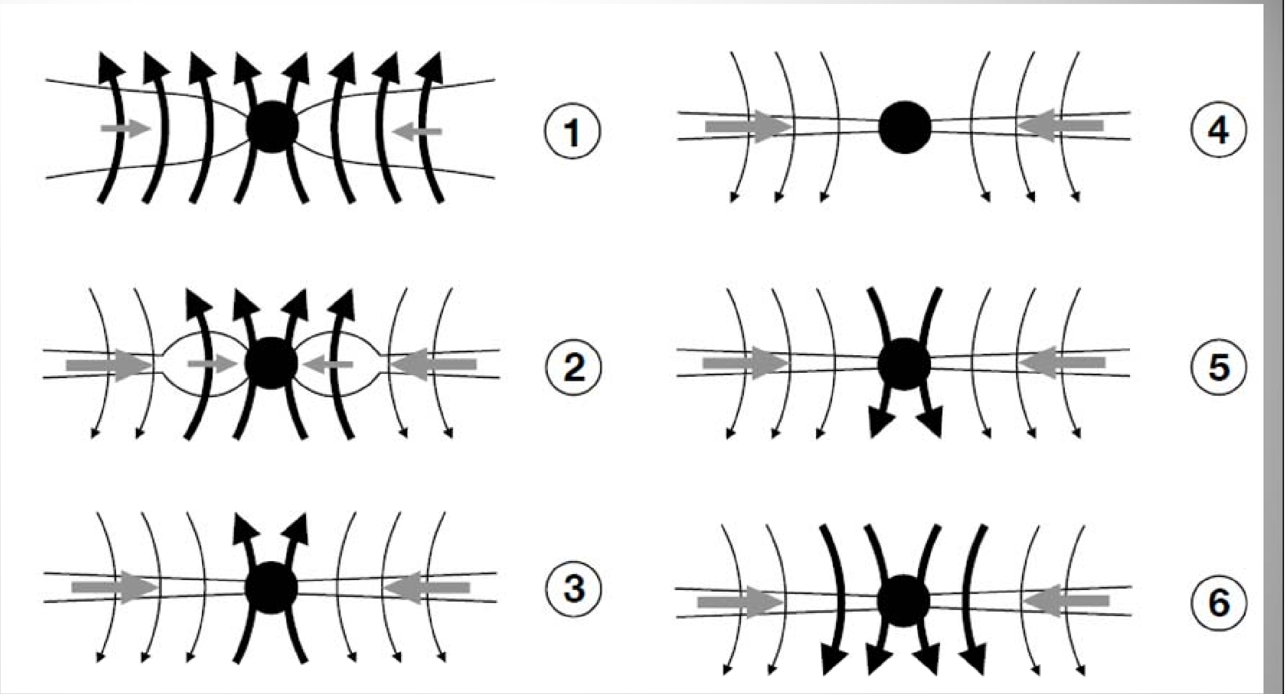
   UV/opt ≪ X ⇒ UV/opt ~ X in 100 d, BLR appears

2. X-rays drop by 10^3-10^4 in 100 d
3. X-rays recover to ~ 10x former level, UV/opt drifts lower

What accretion event switches the X-rays off, then on?

Suppose:

- Compact X-ray corona is powered by BH spin
- X-rays drop when newly accreted flux cancels existing flux threading BH
- X-rays rise when flux re-established with opposite sign



Theory: Dexter & MCB 2019, Scepi, Dexter, MCB 2021 Obs.: Laha et al '22

Are compact X-ray coronae powered by BH spin?

BZ power couples to disk

and/or

Jet exists but invisible due to lack of confinement/collimation

Suppose:

- Compact X-ray corona is powered by BH spin
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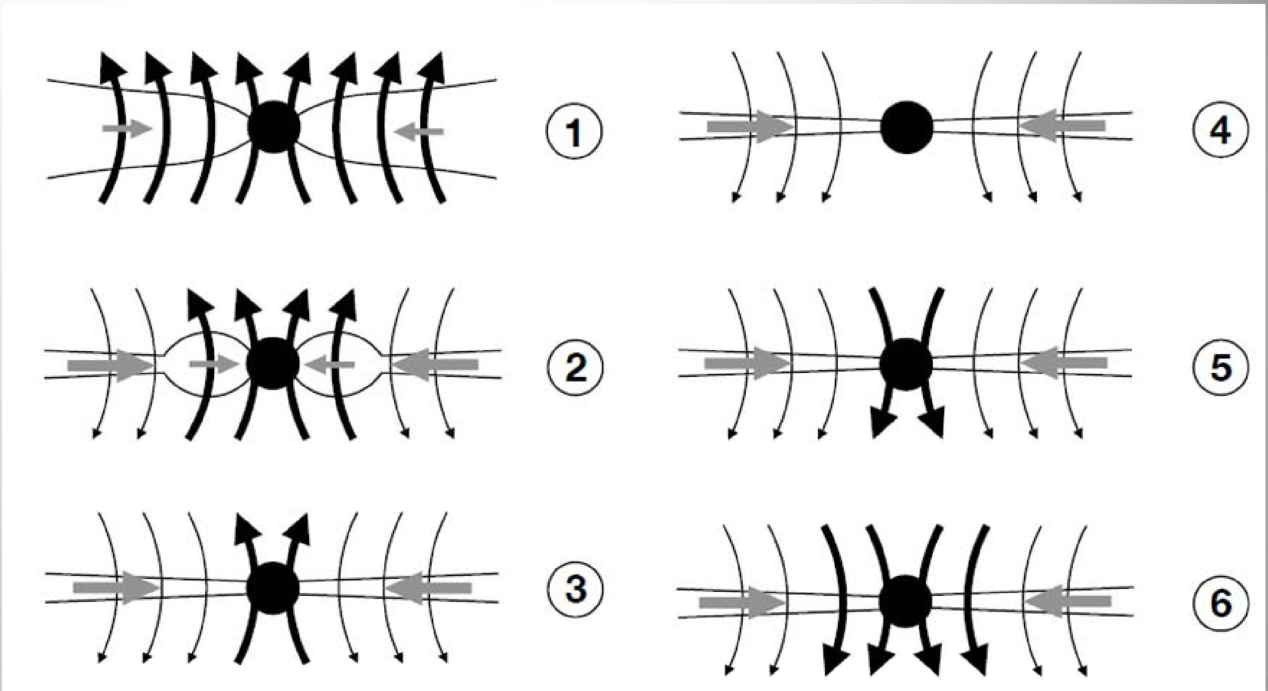

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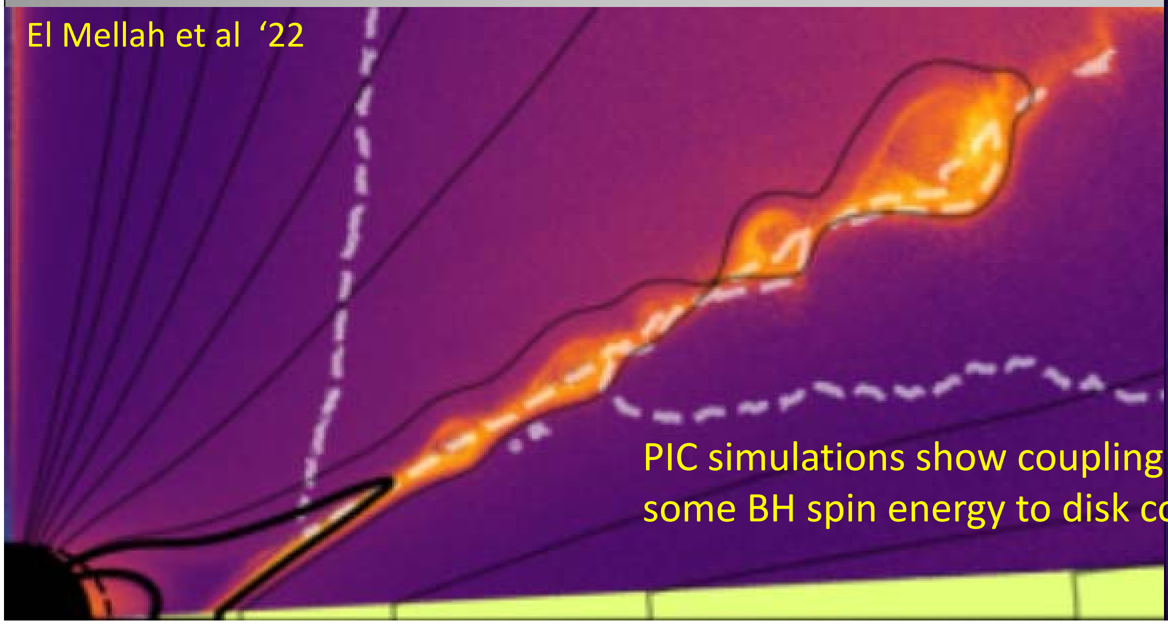
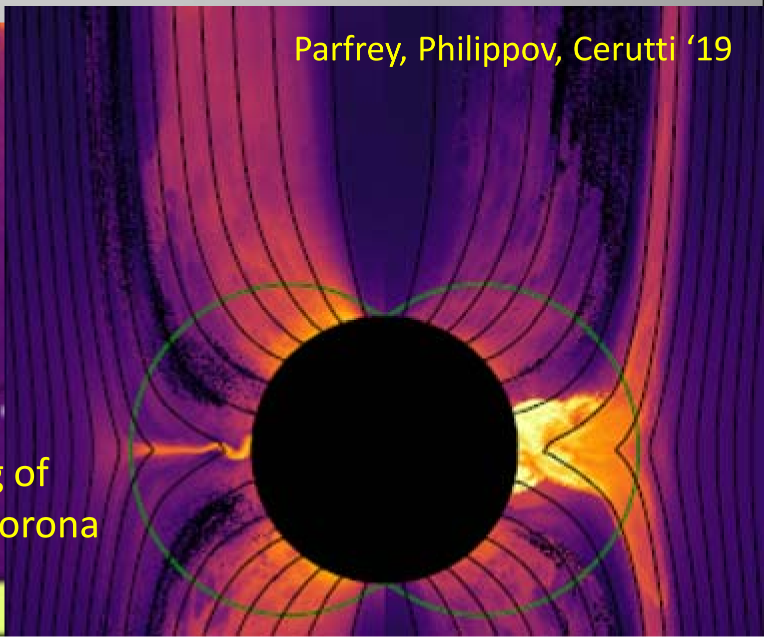
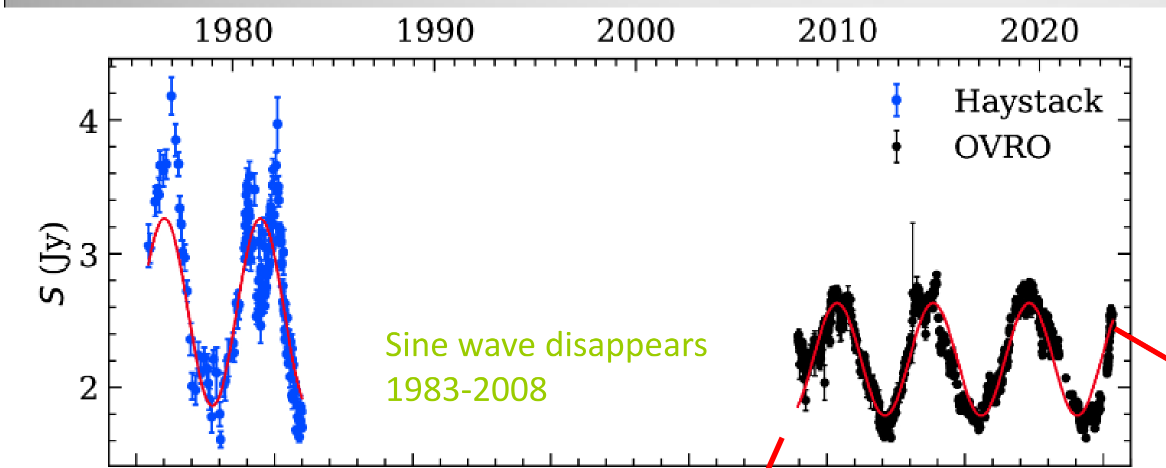




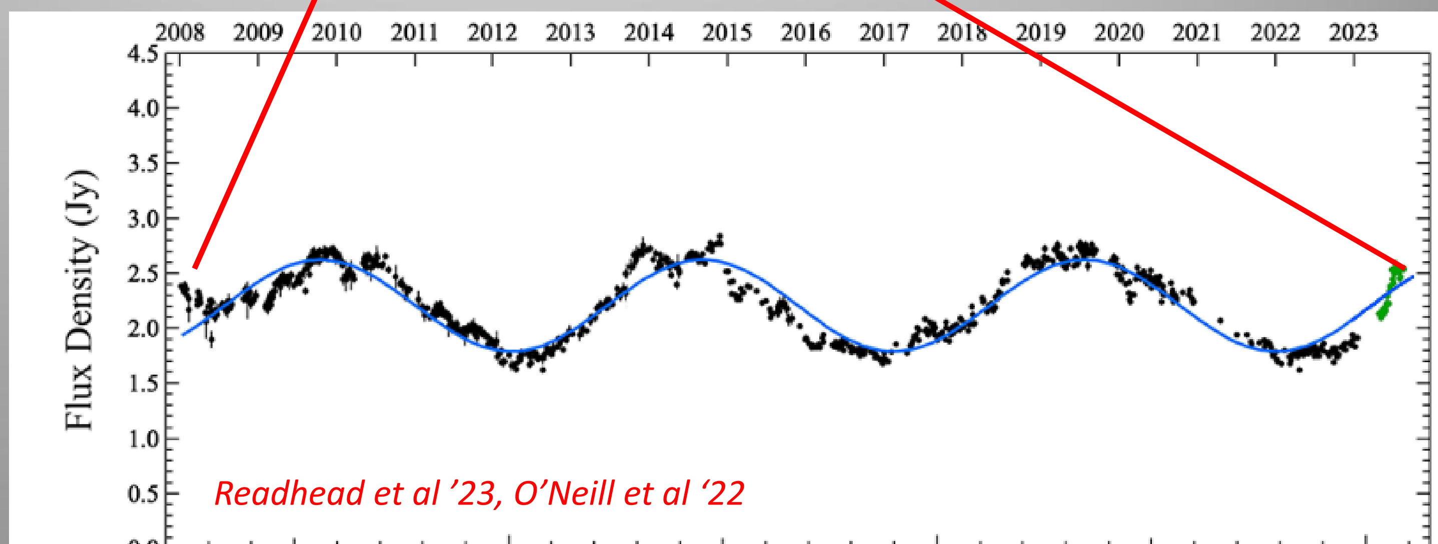
PIC simulations show coupling of some BH spin energy to disk corona

Jet diagnostics can come from unexpected sources



Blazar PKS 2131-021

- Monitored 1975-present
- Periodic 1975-83, 2008-23
- Sinusoidal: P=4.77 yr
- P_{rest}= 2.09 yr (z = 1.285)
- Phase drift <10% over 10 cycles



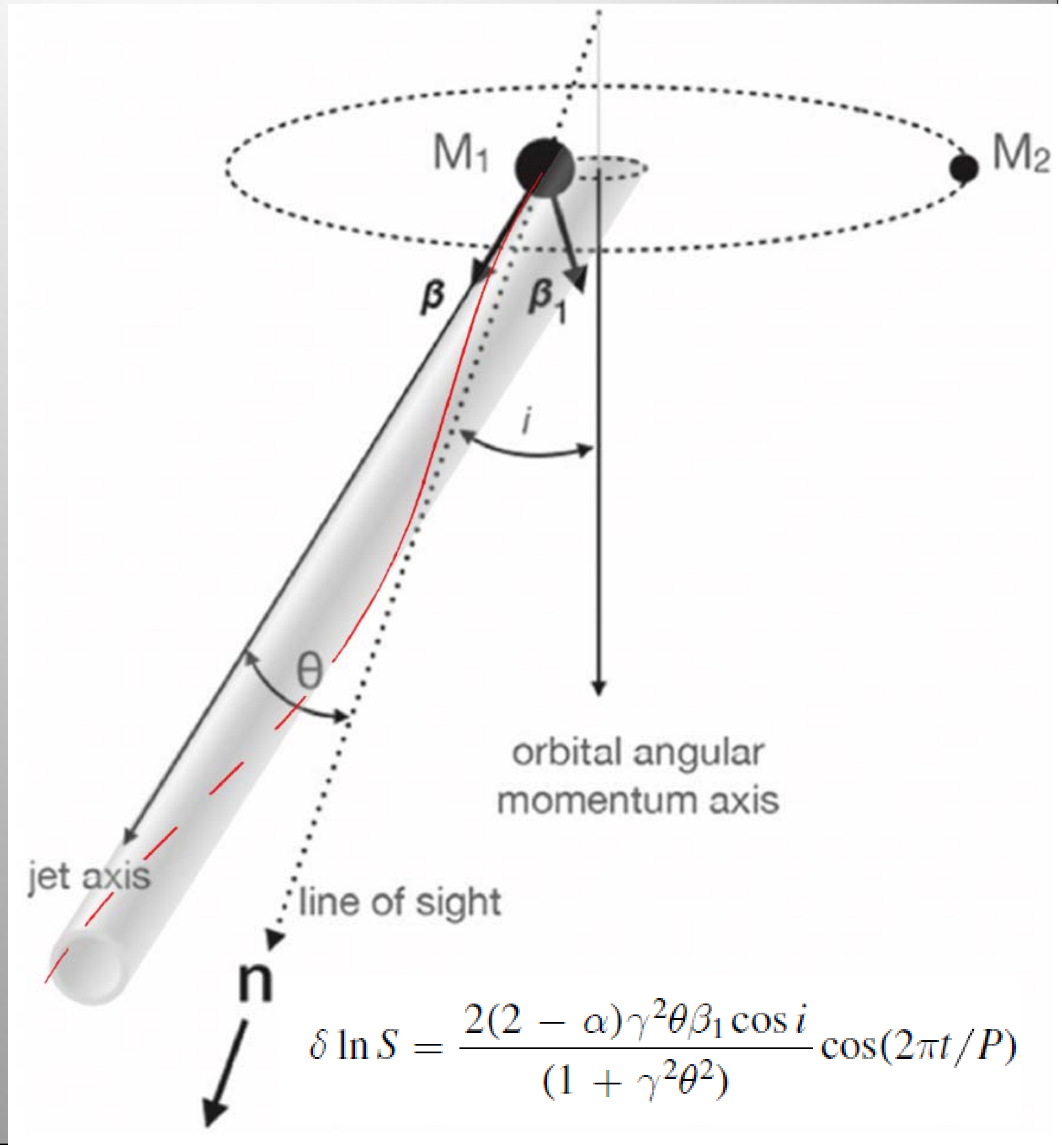
PKS 2131-021 as Black-Hole Binary candidate

- P_{rest}= 2.09 yr (z = 1.285)
- a = 0.004 $M_8^{1/3}$ pc
- $t_{GW} \approx 10^5 M_8^{-5/3}$ (M/m) yr
- $h_{GW} \sim 10^{-18}$
- $\beta_1 = 0.03 M_8^{1/3}$ [1, (M/m)]

Oscillating flux due to Doppler shift from orbital motion β_1

Sobacchi et al '23

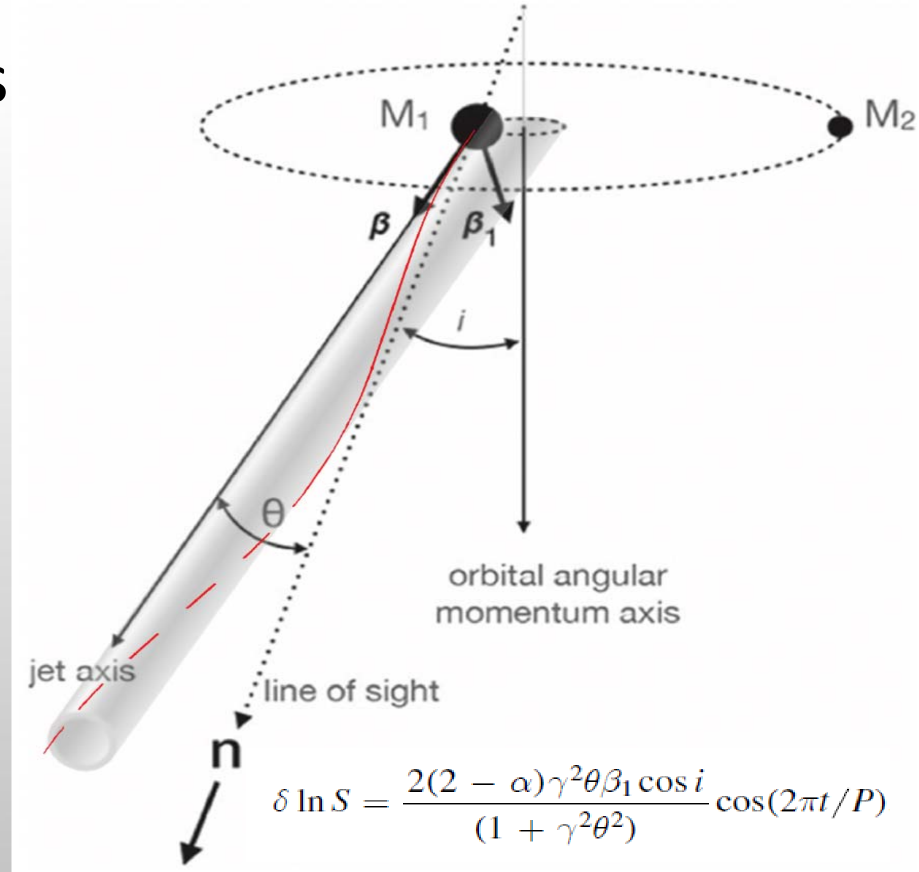
- nHz GW source
- Well inside "last pc"
- Too weak to detect with current PTA



$$\delta \ln S = \frac{2(2-\alpha)\gamma^2\theta\beta_1\cos i}{(1+\gamma^2\theta^2)}\cos(2\pi t/P)$$

Support for Binary Hypothesis

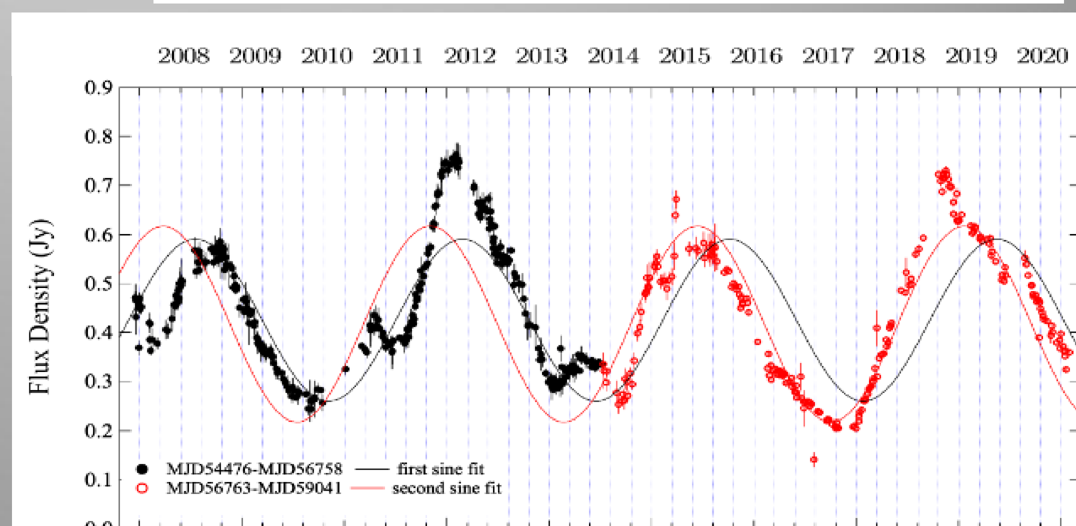
- Phase coherence over 48 yr
- Lack of harmonics
  - ~ perfect sine wave
  - predicted deviations ~ β_1^2 ~ 10^{-3}
- Amplitude consistent with Doppler model



Blazar PKS J0805-011

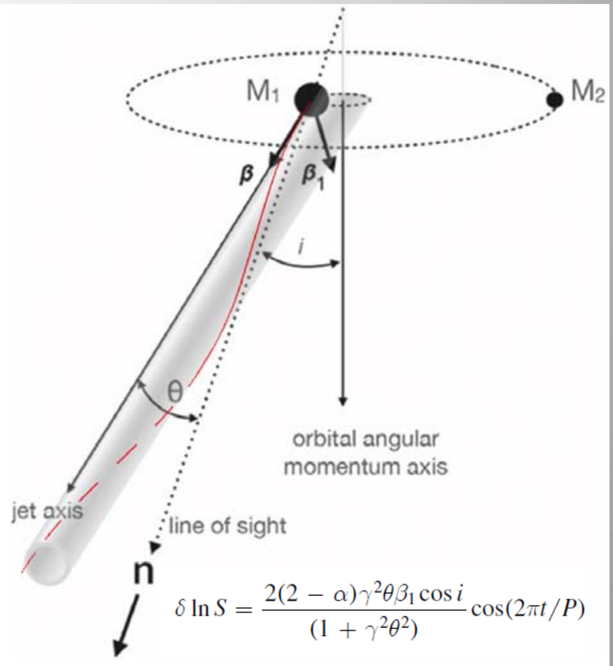
- Second example (so far)
- P=3.43 yr

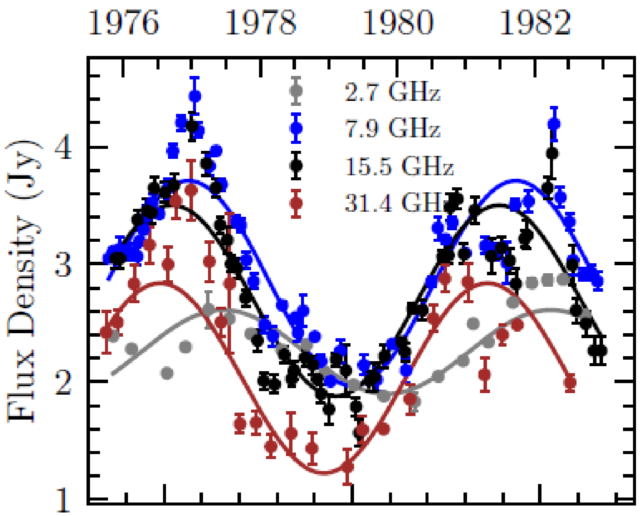
Vergara de la Parra et al, in prep.

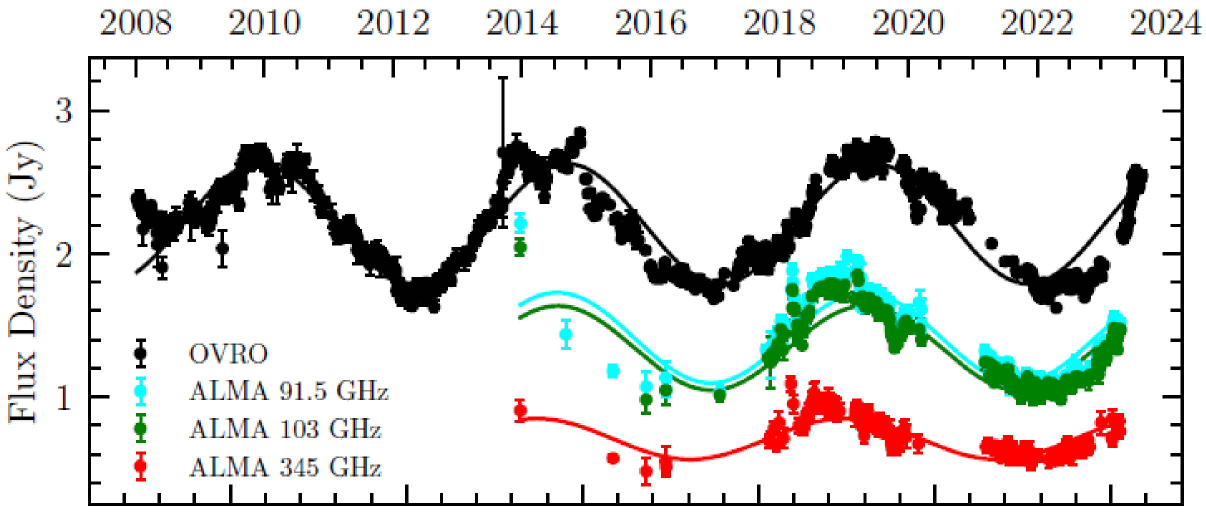


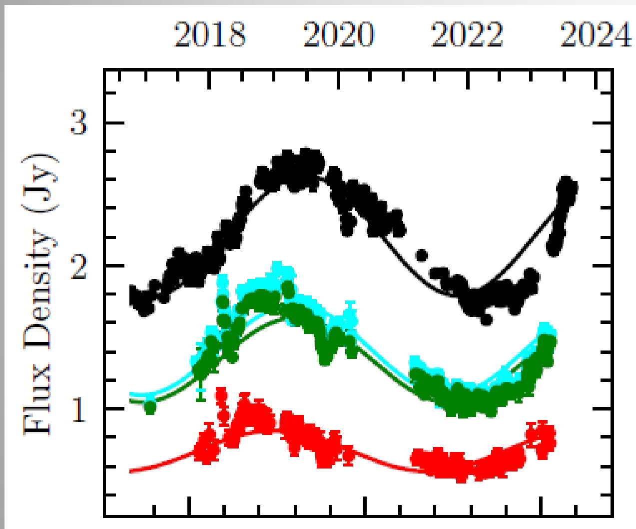
What can a BH Binary teach us about jet physics?

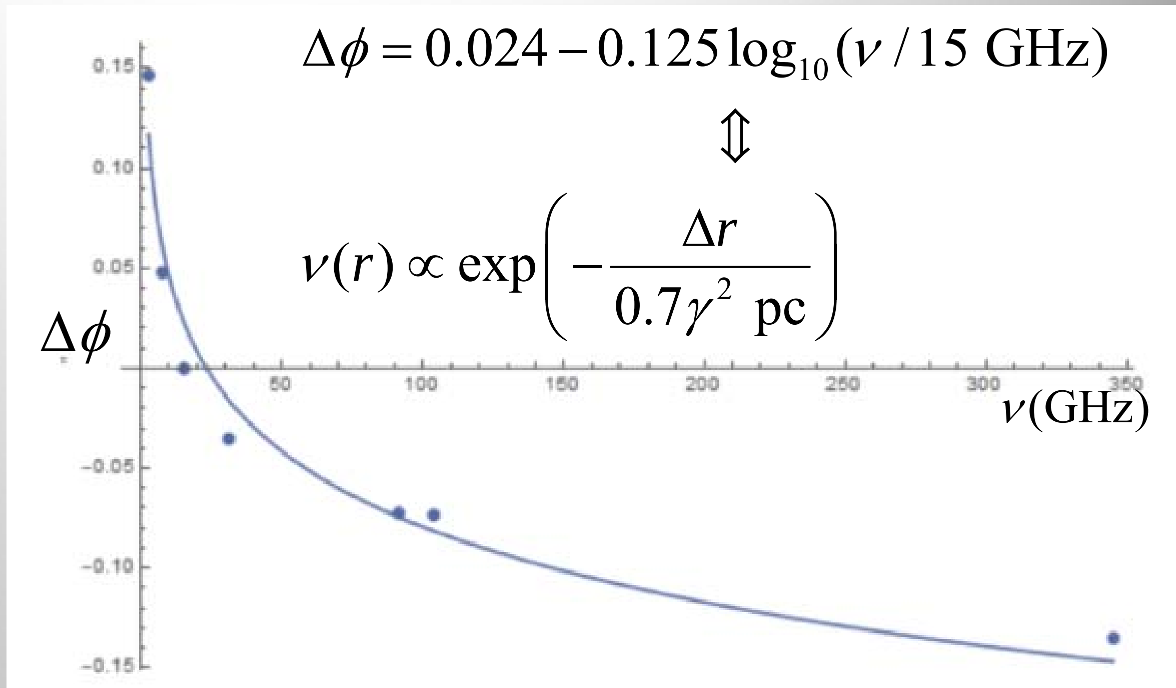
- Jet fluid is *ballistic*
  - "remembers" orbital motion out to emitting zone
  - Not averaged out by collimation, confinement
- Emitting zone is *localized* in radius
  - Otherwise sine wave would be washed out (phase-mixing)
- Peak radio frequency varies steeply with *r*
  - *Phase lags!*







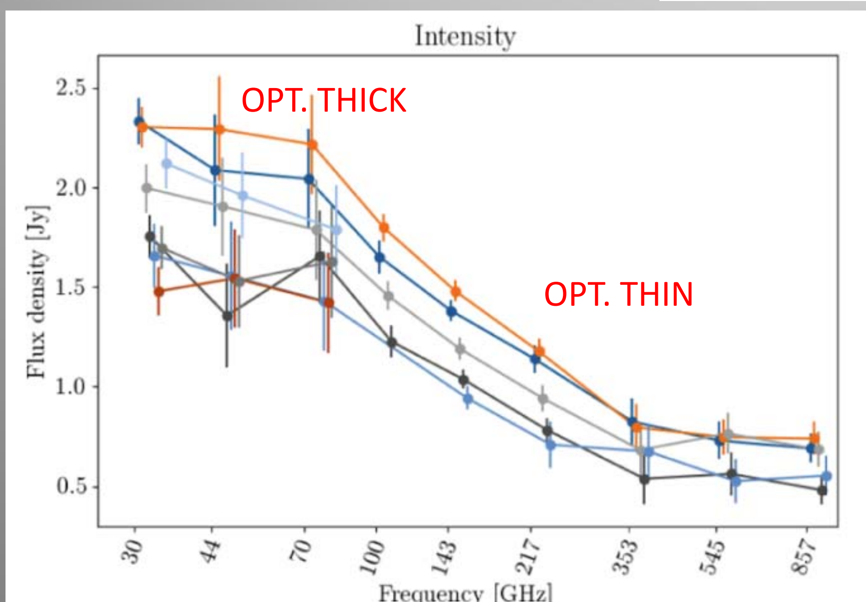




$$\Delta\phi = 0.024 - 0.125\log_{10}(\nu / 15\ \mathrm{GHz})$$

$$\Updownarrow$$

$$\nu(r) \propto \exp\left(-\frac{\Delta r}{0.7\gamma^2\ \mathrm{pc}}\right)$$



Localized jet emission with rapid evolution in frequency:

⇒ Recollimation shock?

Magnetic flux or current leakage? ... ?

SUMMARY
Some Unsolved Jet Problems

- Fundamental issues jet speed, prevalence, power, collimation, dissipation still unresolved
- These are “macro” (fluid-level) problems
  - “micro” (kinetic) level progress is fast, at least on the theory front
- Observations still rule
  - They continue to push our understanding of jets in new directions (e.g. BZ coupling to disk, binary BHs ...)