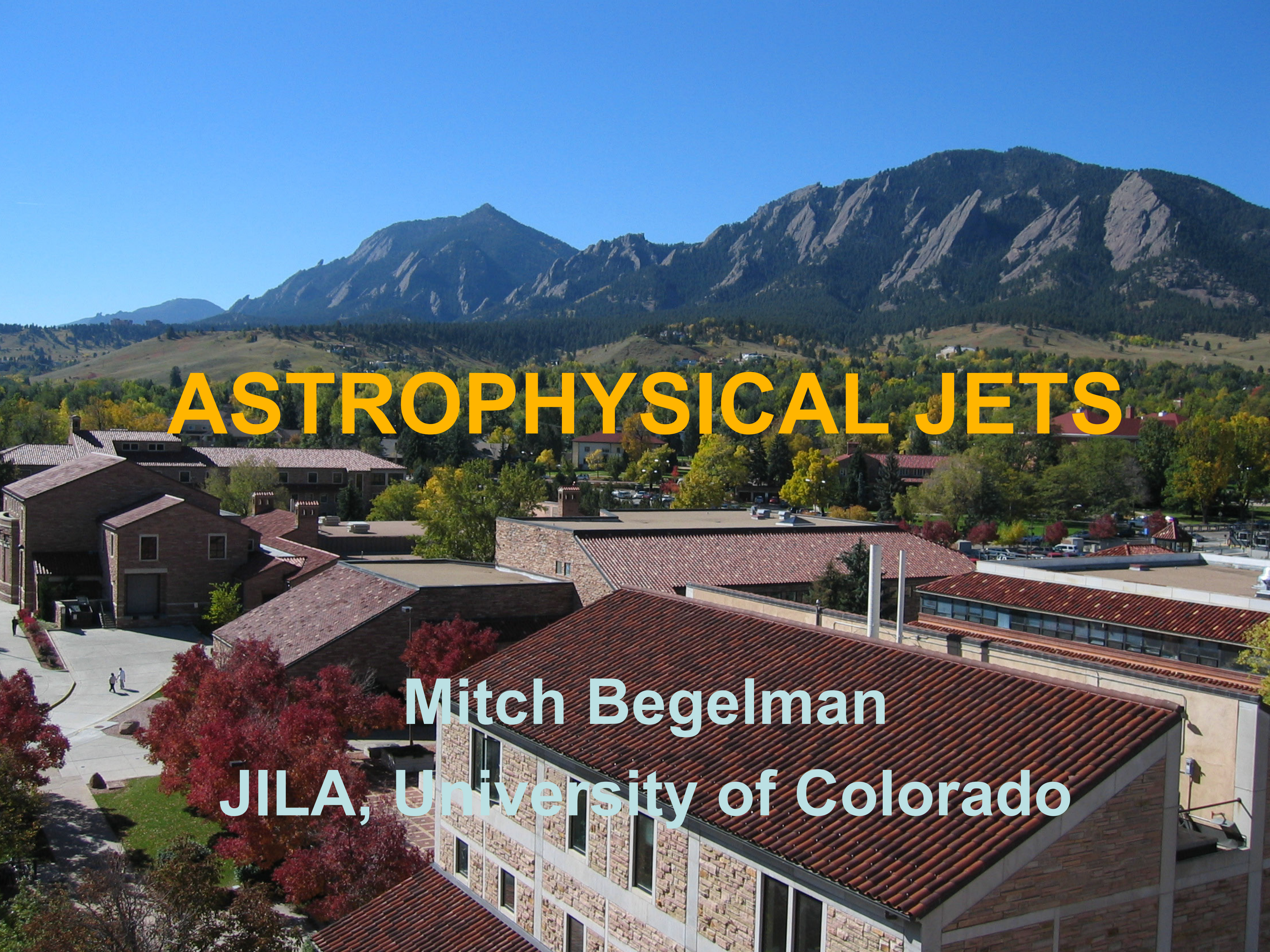


ASTROPHYSICAL JETS

Mitch Begelman

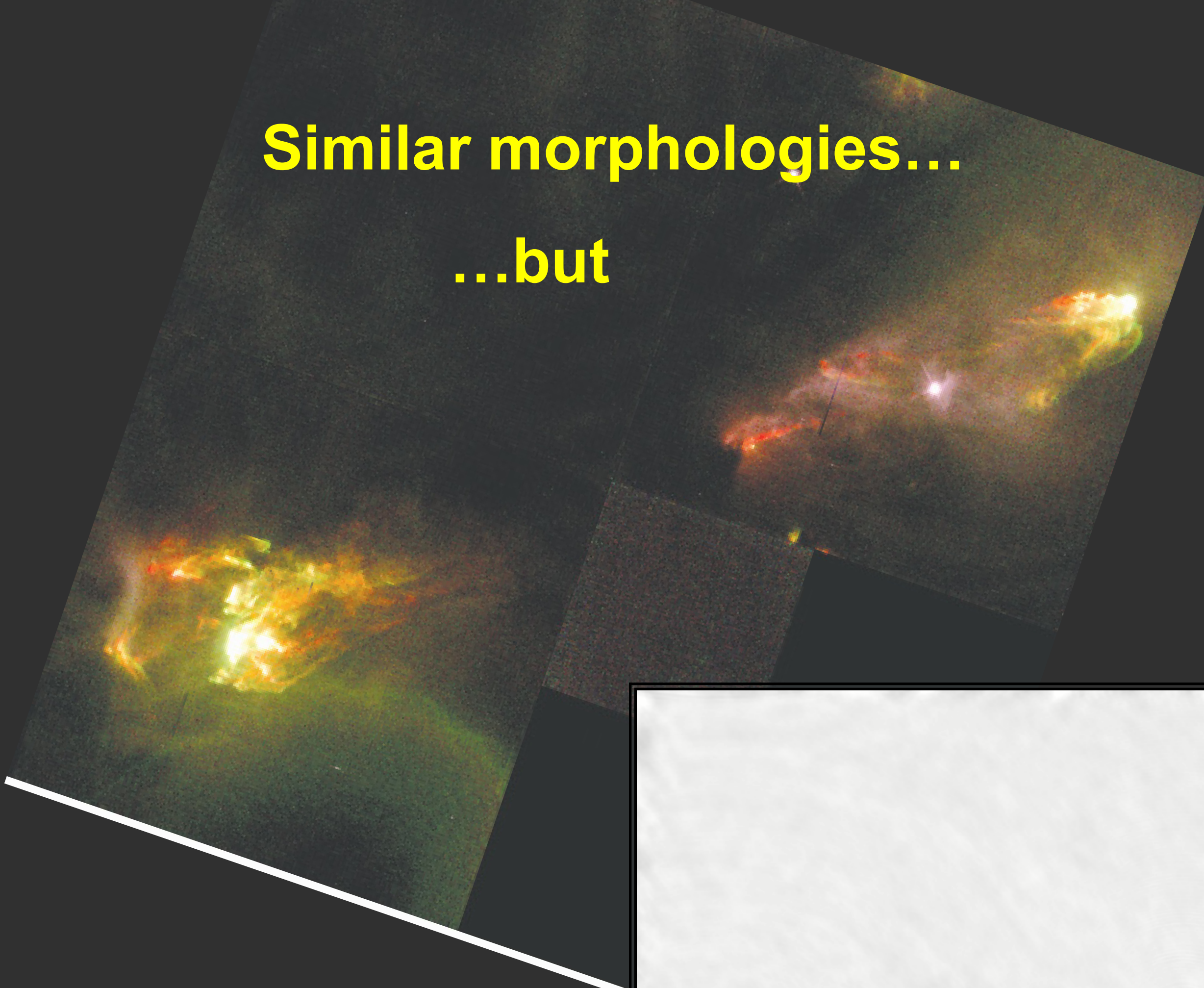
JILA, University of Colorado

Jets are common…

- Protostellar accretion disks
- Pulsars
- Gamma-ray bursts
  - Merging neutron stars
  - Black hole forming inside collapsing star
- X-ray binaries
  - BHs or NSs accreting from disks
- Active Galactic Nuclei
  - Accreting supermassive BHs

Similar morphologies…

…but



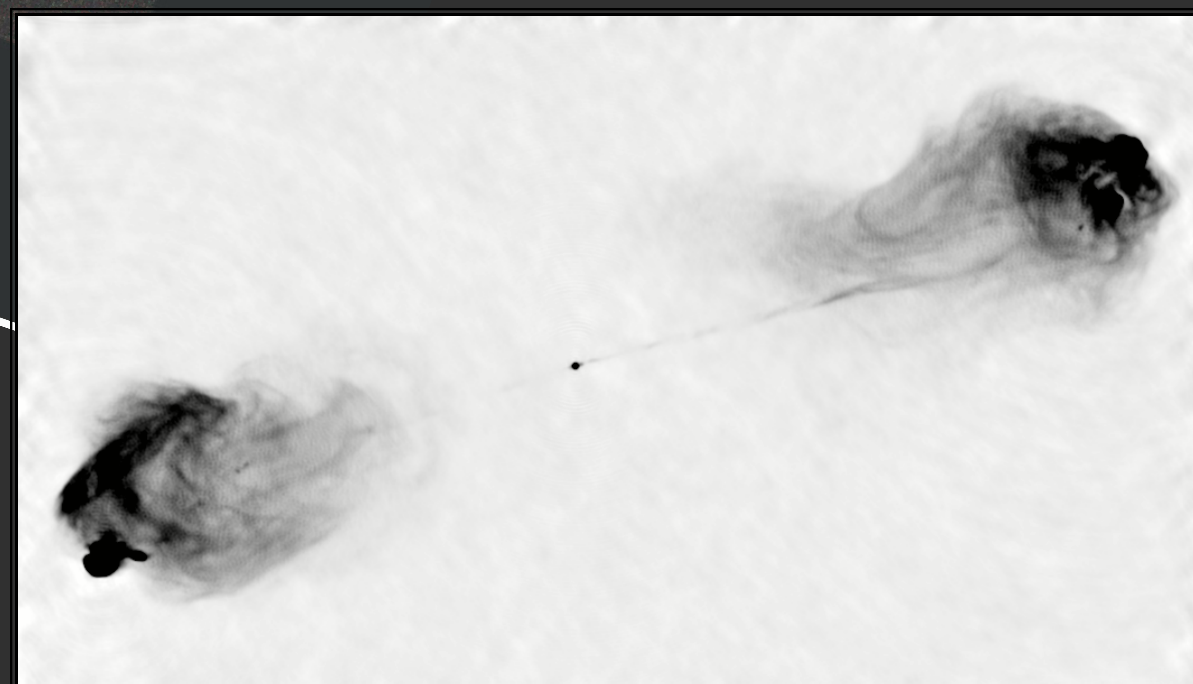
Jets from a protostar

Few light-years across

Speed few 100 km/s

Visible light

Atomic line emission



Jets from a quasar

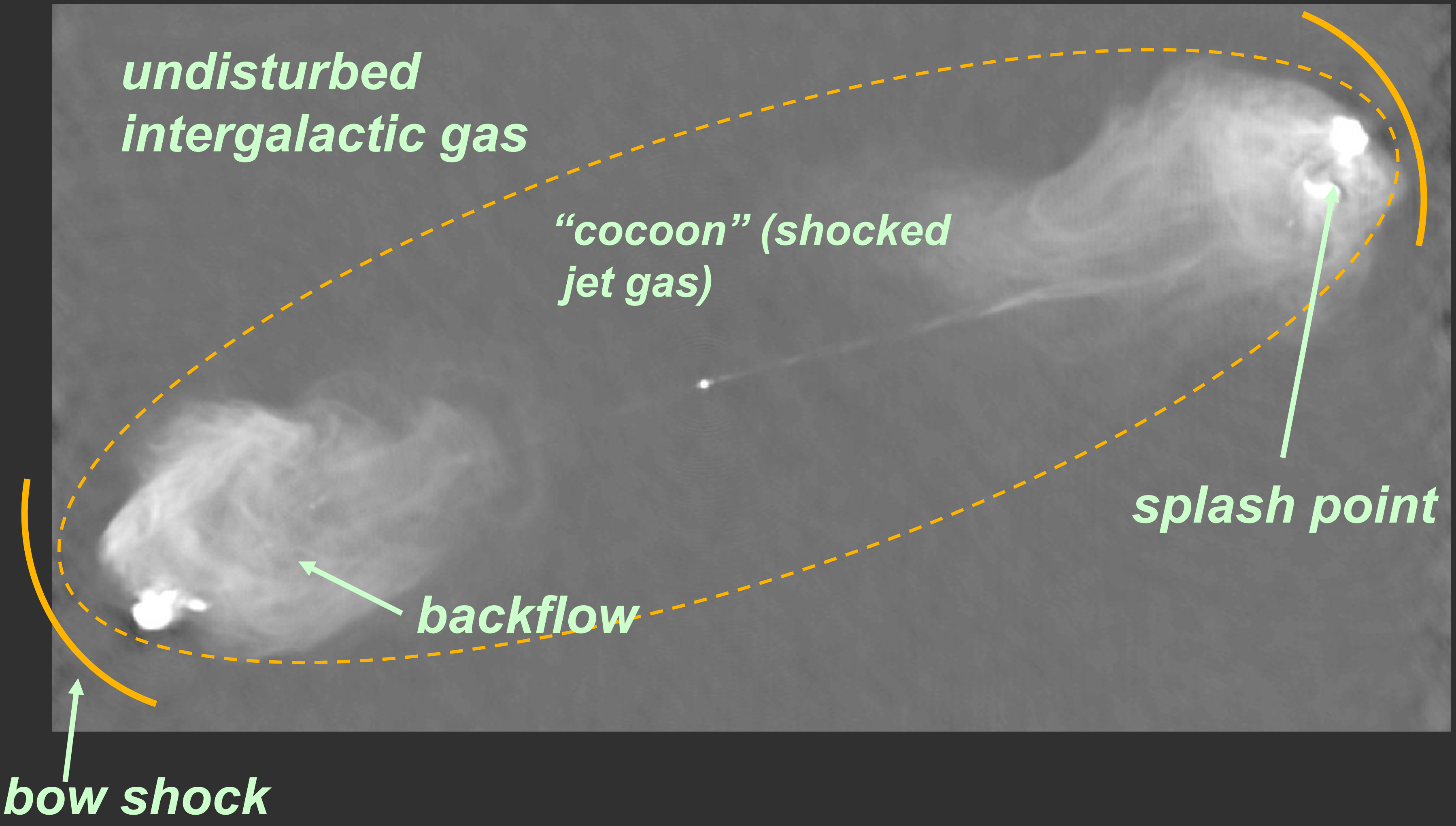
~ Million light-years across

Speed ~ c

Radio wavelengths

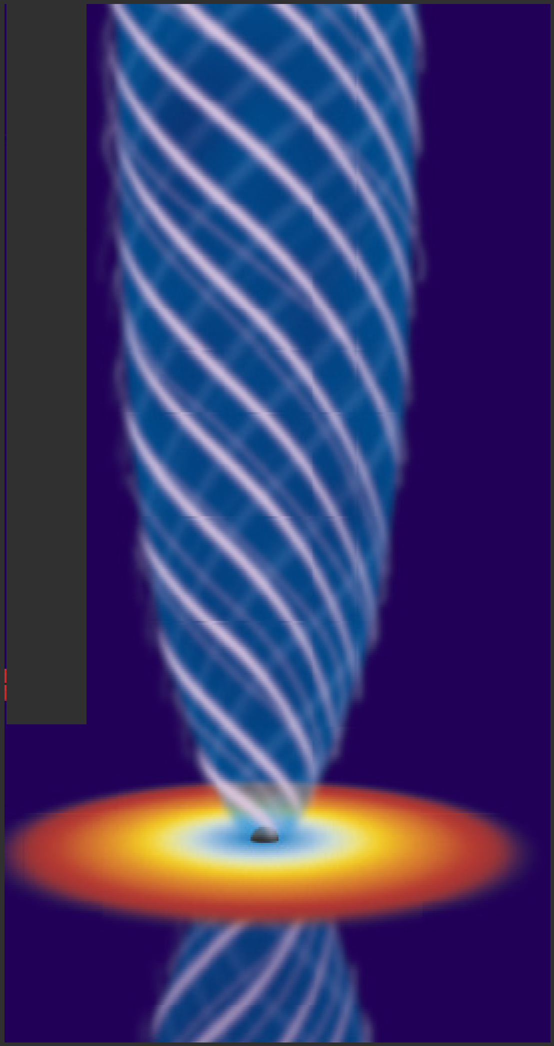
Synchrotron emission

LARGE-SCALE INTERACTION



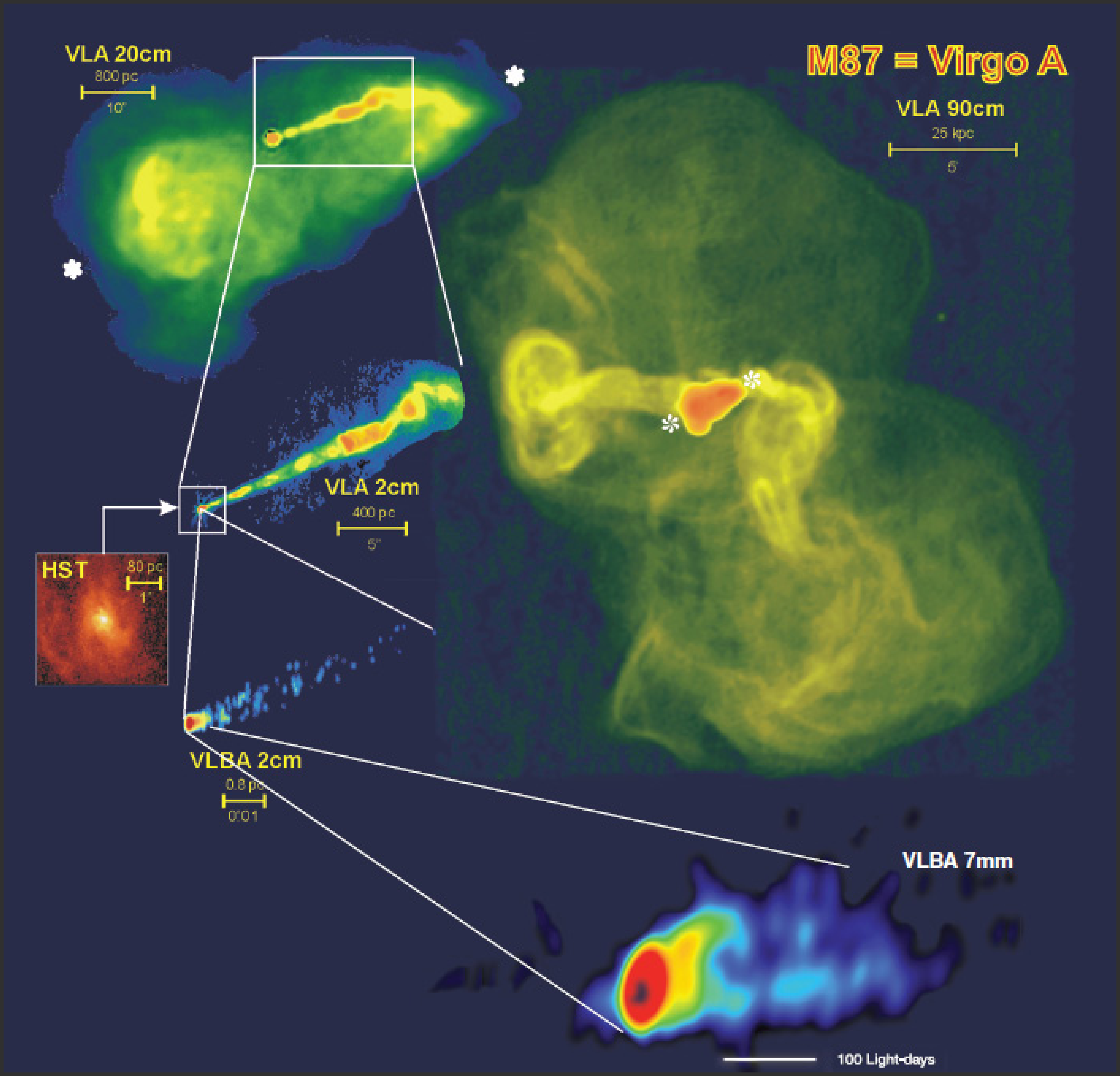
Ingredients for forming jets

- **Rotation**
  - axis determines direction
- **Accretion disk**
  - often, but cf. pulsars
- **Magnetic field**
  - likely but unproven



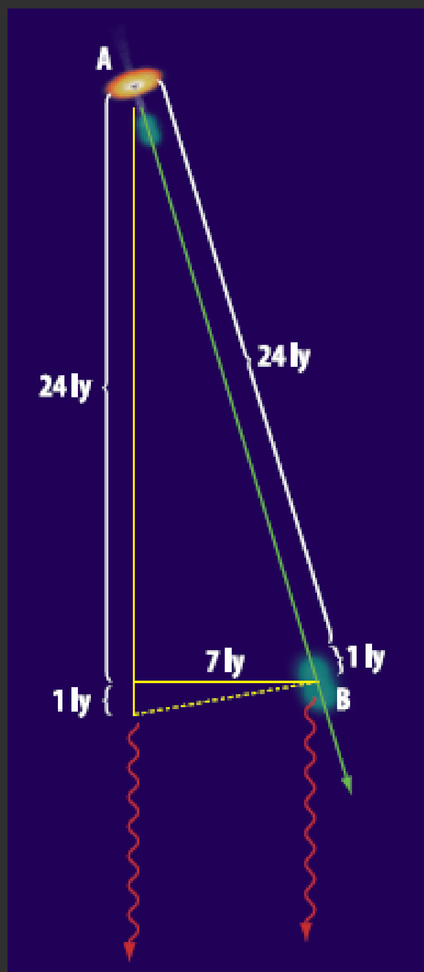
Jet speeds

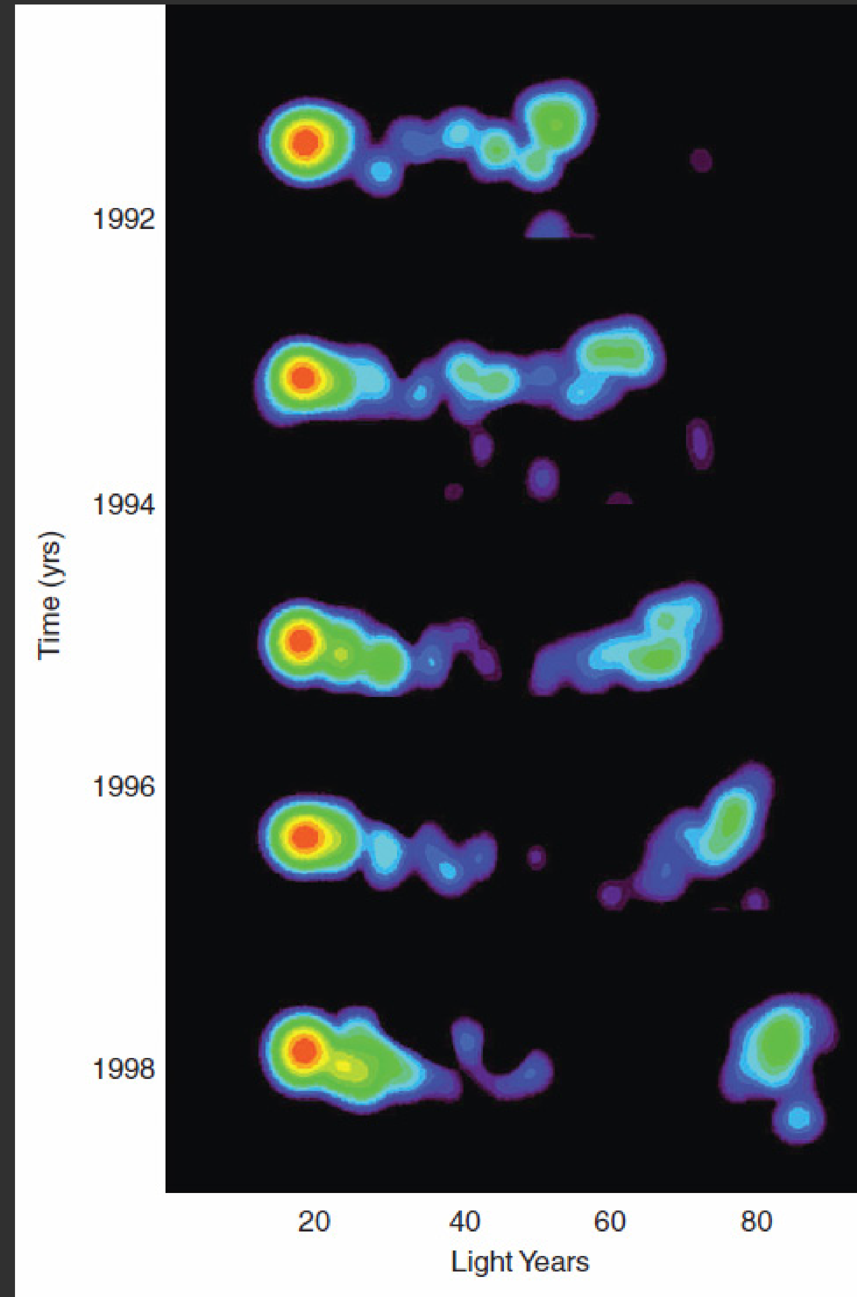
- **Subrelativistic:** protostars, $v/c \sim 10^{-3}$
- **Mildly relativistic:** SS433 XRB ($v/c = 0.26$)
  - Doppler-shifted emission lines
- **Highly relativistic:** X-ray binaries, ~10% of AGN ($\Gamma \sim 2\text{-}30$)
  - Doppler beaming (one-sidedness)
  - Illusion of superluminal motion
  - Gamma-ray flares (to avoid $\gamma\gamma$-pair production)
- **Hyper-relativistic:** gamma-ray bursts ($\Gamma \sim 300$)
  - Gamma-ray variability
- **Ultra-relativistic:** pulsar jets ($\Gamma \sim 10^6$)
  - Modeling of radiation and pulsar nebulae


M87 = Virgo A
VLA 20cm
800 pc
10'
VLA 90cm
25 kpc
5'
VLA 2cm
400 pc
5"
HST
80 pc
1"
VLBA 2cm
0.8 pc
0."01
VLBA 7mm
100 Light-days

Quasar 3C 279:

Apparently expanded 25 light-yrs in 6 years





Jet Acceleration Mechanisms

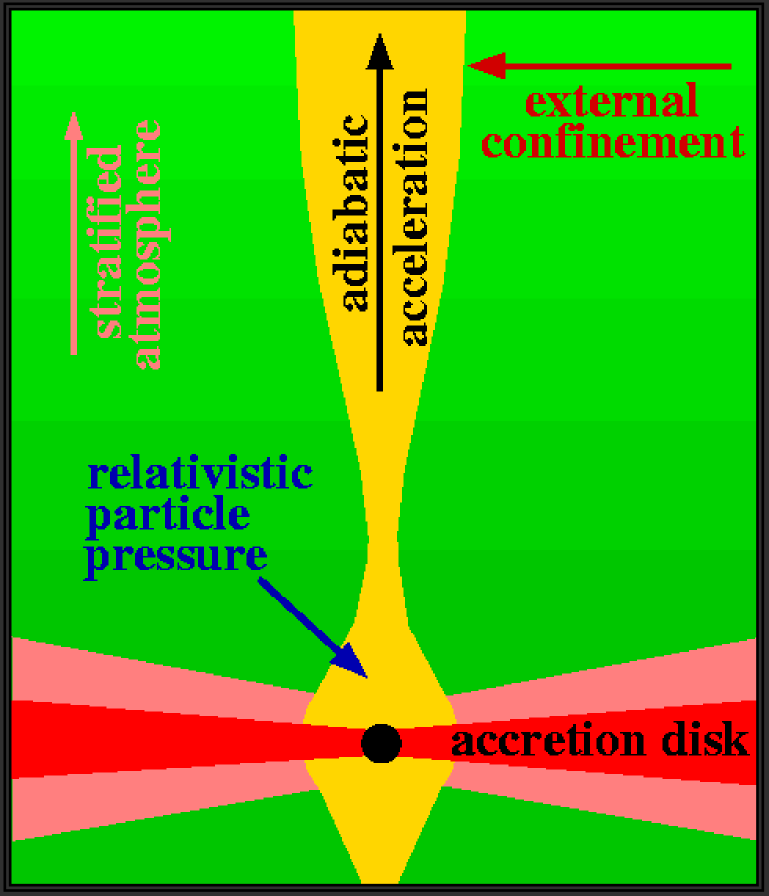
Hydrodynamic: "Twin-Exhaust" (Blandford & Rees 74)

Pros:

- Simple: adiabatic expansion through nozzle

Cons:

- Needs large external pressure
- Radiative losses
- Radiation drag



Jet Acceleration Mechanisms

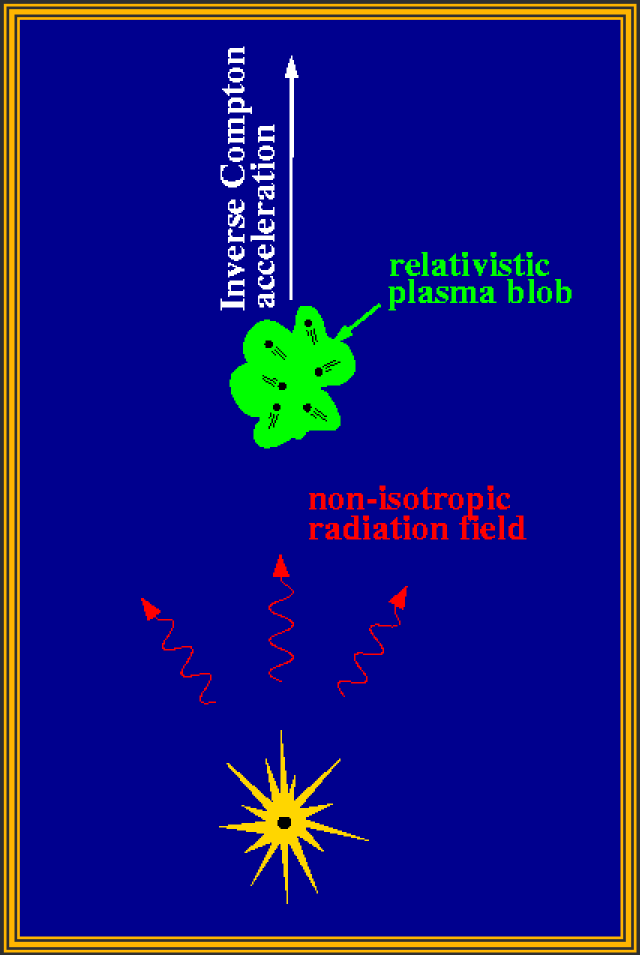
Radiative: “Compton Rocket” (O’Dell 81)

Pros:

- Fast acceleration
- Collimation by radiation

Cons:

- Radiative losses
- Aberration limited



Jet Acceleration Mechanisms

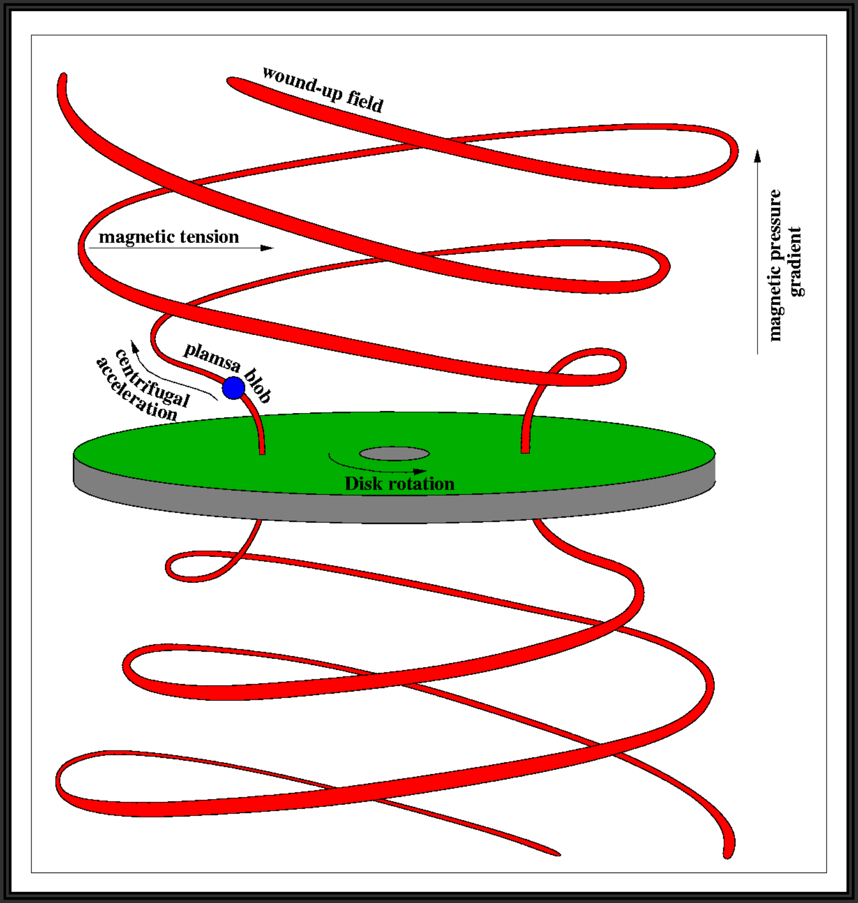
MHD: "Magneto-Centrifugal" (Blandford & Payne 82)

Pros:

- Self-collimation
- Immune to radiation

Cons:

- Unstable
- Field not ordered?



What propels jets?

Gas Pressure?

- Catastrophic cooling (but maybe OK for heated baryons)
- Particle production

Radiation Pressure?

- Insufficient luminosities
- Aberration limits max. Γ *

(*Unless highly opaque: e.g., GRBs)

Electromagnetic Stresses?

- Best bet by elimination, MHD limit
- Polarized synchrotron radiation shows presence of organized B-field
- Magnetic tension/pinch good for extracting rotational energy, collimating jet

Some (rough) numbers

Protostar	X-ray binary	Quasar
$M_*\sim 1\ M_\odot$	$M_{BH}\sim 10\ M_\odot$	$M_{BH}\sim 10^9\ M_\odot$
$R\sim 10^6$ km	$R\sim 10$ km	$R\sim 10^9$ km
$B\sim 10^3$ G	$B\sim 10^8$ G	$B\sim 10^4$ G
$R_{cyc,p}\sim 0.1$ m	$R_{cyc,p}\sim 0.1$ mm	$R_{cyc,p}\sim 1$ m
$\Omega_{rot}\sim 10^{-3}$ rad s^{-1}	$\Omega_{rot}\sim 10^{4}$ rad s^{-1}	$\Omega_{rot}\sim 10^{-5}$ rad s^{-1}
$\Phi\sim 10^{14}$ V	$\Phi\sim 10^{16}$ V	$\Phi\sim 10^{20}$ V

→ **MHD probably OK**

MAGNETOHYDRODYNAMICS

- **Near-perfect conductivity** $\vec{E} = -\frac{\vec{v}}{c} \times \vec{B}$
- **Magnetic flux-freezing** $\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{v} \times \vec{B} \right)$
- **EM force density**

$$\vec{F}_{EM} = \frac{\vec{j} \times \vec{B}}{4\pi c} = \frac{\vec{B} \cdot \nabla \vec{B}}{4\pi} - \nabla \left(\frac{B^2}{8\pi} \right)$$

TENSION FORCE (arrow to $\frac{\vec{B} \cdot \nabla \vec{B}}{4\pi}$)

PRESSURE FORCE (arrow to $\nabla \left(\frac{B^2}{8\pi} \right)$)

- **Think … currents follow field (not the other way around)**

Relativistic MHD (vs. non-Rel.)

- Must include inertia of internal energy
- Significant electric field $\vec{E} = -\frac{\vec{v}}{c} \times \vec{B}$
- Can't ignore charge density

$$\rho_e = \frac{\nabla \cdot \vec{E}}{4\pi} = -\frac{1}{4\pi} \nabla \cdot \left(\frac{\vec{v}}{c} \times \vec{B} \right)$$

- Partial cancellation of Maxwell stress under some conditions (thought to be attained naturally by jets)

$$\rho_e \vec{E} + \frac{\vec{j} \times \vec{B}}{c} << \frac{\vec{j} \times \vec{B}}{c}$$

Near-cancellation of Maxwell stress

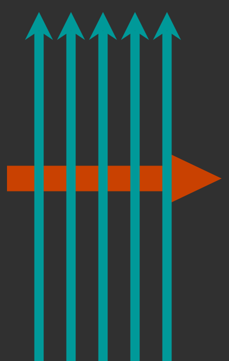
- **Thought experiment: What is the force density acting through the screen toward the observer?**

$$B,\ j$$

$$p_B = \frac{B^2}{8\pi}$$

$$E = 0$$

Γ



$$B' = \Gamma B \ \text{(Lorentz contraction)}$$

$$j' = \Gamma j$$

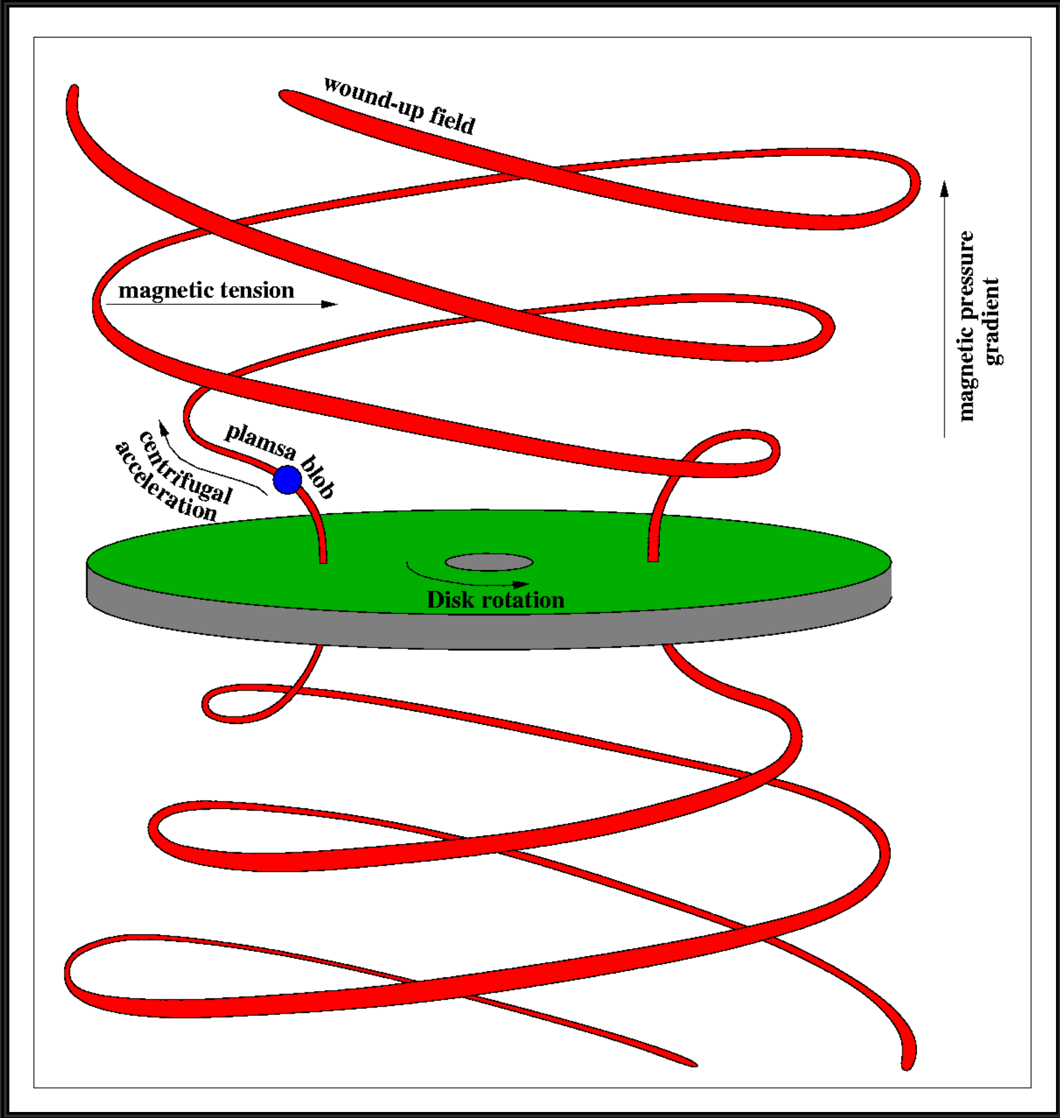
$$p'_{B'} = \Gamma^2 p_B$$

$$\rho'_e E' + \frac{j' \times B'}{c} = \frac{1}{\Gamma^2} \Gamma^2 \frac{j \times B}{c}$$

Pressure forces are unchanged by Lorentz transformations

Launching Jets

- Jet base: disk or rotating star (dense gas)
- Initial propulsion– several options
  - Gas or radiation pressure pushes flow through slow magnetosonic point
  - Expansion of “magnetic tower”
    - Mainly toroidal field from start
    - Acceleration by magnetic buoyancy, interchange instability
  - Magnetocentrifugal acceleration
    - Mainly poloidal field, anchored to disk or spinning star
    - Disk or star (or ergosphere of BH) acts like crank
    - Torque transmitted through poloidal field powers jet
- Jet power supply
  - Disk
    - Tap gravitational energy liberated by recent accretion
  - Spin of black hole (Blandford-Znajek effect)
    - use energy stored over long time (like flywheel)



wound-up field
magnetic tension
magnetic pressure gradient
plamsa blob
centrifugal acceleration
Disk rotation

Jet Energetics

Magnetic field a medium for transmission, not a source

GRAVITY, ROTATIONAL K.E.

↓ Efficient conversion to EM energy

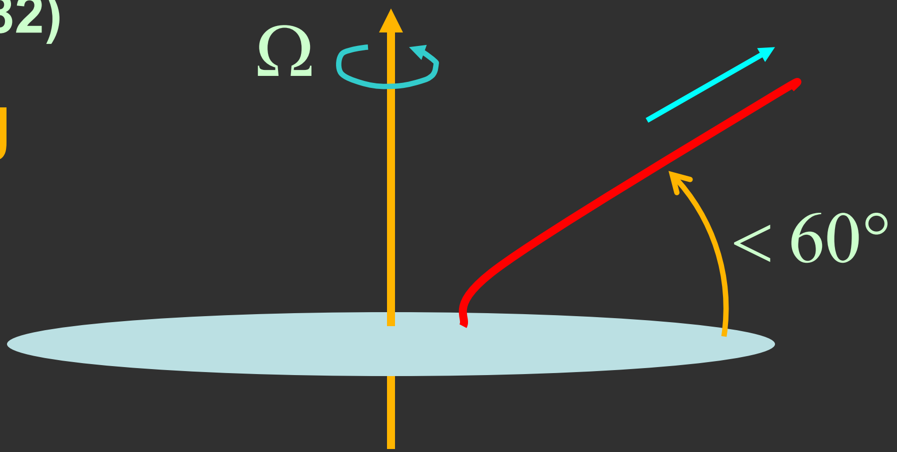
POYNTING FLUX

↓ Easy to get ~equipartition, hard to get full conversion

JET KINETIC ENERGY

“Magnetocentrifugal” acceleration

(Blandford & Payne 1982)

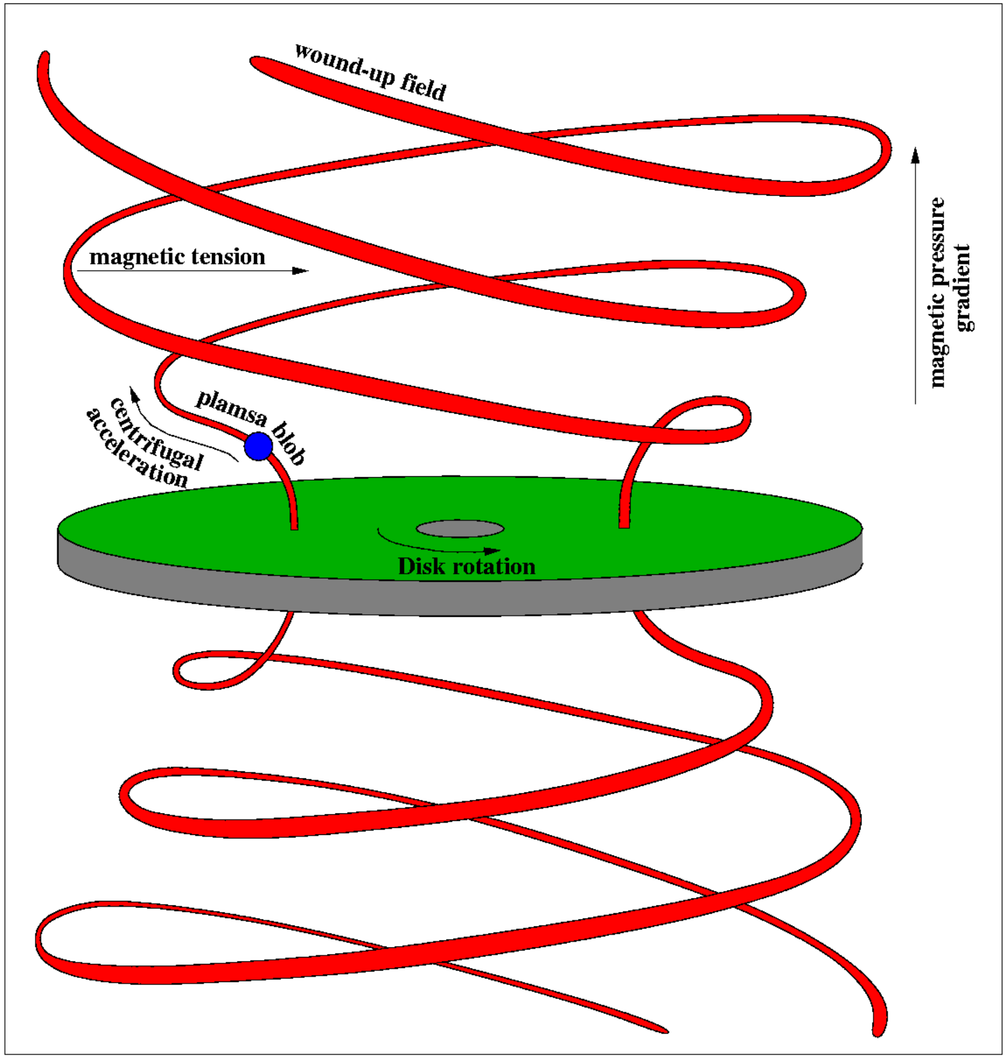


1 Gas flung outward along “stiff” field lines

2 Inertia of gas overcomes stiffness of field

→ field bent backwards into coils

3 Springlike behavior of coils can give further acceleration (?) + get collimation for free (magnetic pinch effect)


wound-up field
magnetic tension
magnetic pressure gradient
plamsa blob
centrifugal acceleration
Disk rotation

Analysis of magnetocentrifugal accel.

- **Power extracted from crank**

$$\dot{E} \sim \frac{\Phi^2 \Omega^2}{c}$$

  ☞ = magnetic flux

  ⌖ = ang. vel. of crank

- **Linear acceleration with radius** $v \sim \Omega R$

- **Non-rel. case: Centrifugal phase ends when torque exceeds tension of field**

$$v \sim \Omega R_A \sim v_A \sim \frac{\Phi}{R^2 \rho^{1/2}}$$

  – field bends and becomes mainly toroidal
  – this is called the “Alfvén point”
  – at this point Poynting flux and K.E. are roughly equal

..

Magnetocentrifugal Acceleration: Relativistic limit

- **Power and acceleration unchanged**

$$\dot{E} \sim \frac{\Phi^2 \Omega^2}{c} \qquad v \sim \Omega R$$

- **Alfvén radius located near "light cylinder"** $R_A \sim c / \Omega$

- **Terminal Lorentz factor** $\Gamma_\infty \sim \frac{\dot{E}}{\dot{M} c^2} >> 1$

- **At Alfvén point, flow Lorentz factor Γ_A ~ Lorentz factor of a (relativistic) Alfvén wave signal**

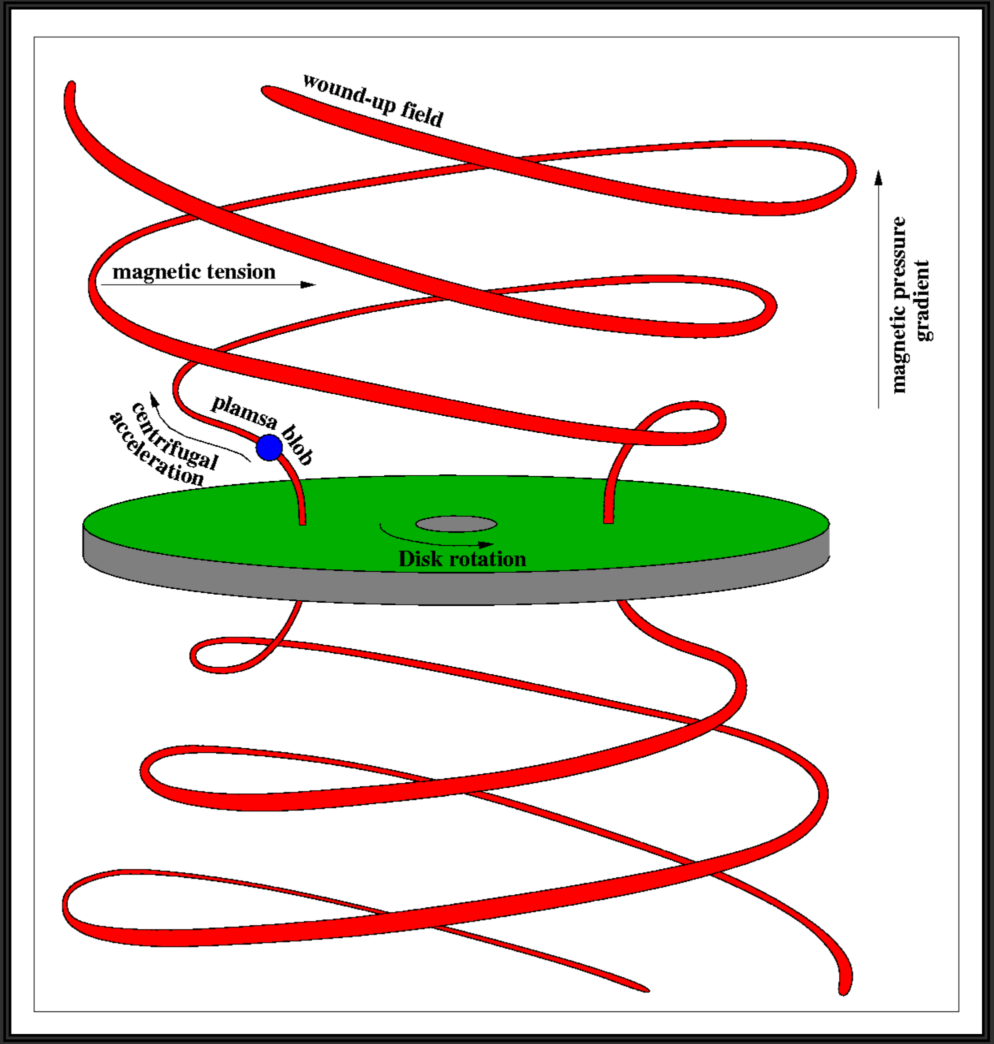
$$\Gamma(R_A) \sim \Gamma_\infty^{1/3} \qquad \frac{K.E.}{P.F.} \sim \Gamma_\infty^{-2/3} << 1$$

  – At end of centrifugal phase, energy is still mostly electromagnetic

Beyond the Alfvén point...

- Jet loses causal contact with disc/star via torsional Alfvén waves
- Further conversion of magnetic into kinetic energy must be by magnetic spring effect... but this is difficult…

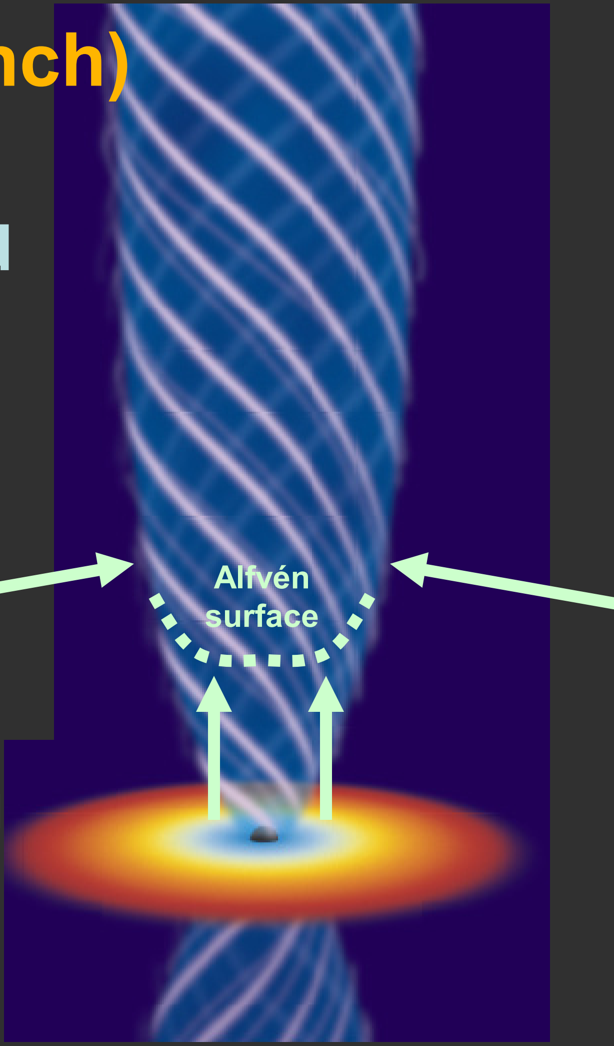
…and it is tightly tied to collimation



Jet collimation

- Self-collimation (by magnetic pinch) a myth!
  - Unconfined fields (and jets) expand
  - Need external confinement
- Sources of confinement:

Pressure of external medium



Inertia of disk (transmitted along jet by Alfvén waves)

Collimation vs. Acceleration

OPTIMAL COLLIMATION ⟷ PRESSURE DECREASES SLOWLY ALONG JET

OPTIMAL ACCELERATION ⟷ PRESSURE DECREASES RAPIDLY ALONG JET

BUT IT'S NOT A SIMPLE TRADEOFF, FOR TWO REASONS…

Reason 1: Relativistic acceleration is gradual

- Inside R_A energy "passes through" field lines; outside R_A energy is carried by flow
- But energy has <u>inertia</u>: $(E = Mc^2)$

→ – in relativistic version of $accel. = \frac{force}{mass}$

both numerator and denominator ✪ energy content

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

To go from $\Gamma \sim 1 \Rightarrow \Gamma = 10$ pressure must drop by factor ~10,000

Reason 2: Magnetic forces are anisotropic

- Reason 1 assumed acceleration by gas pressure
- **Magnetic fields also produce tension**

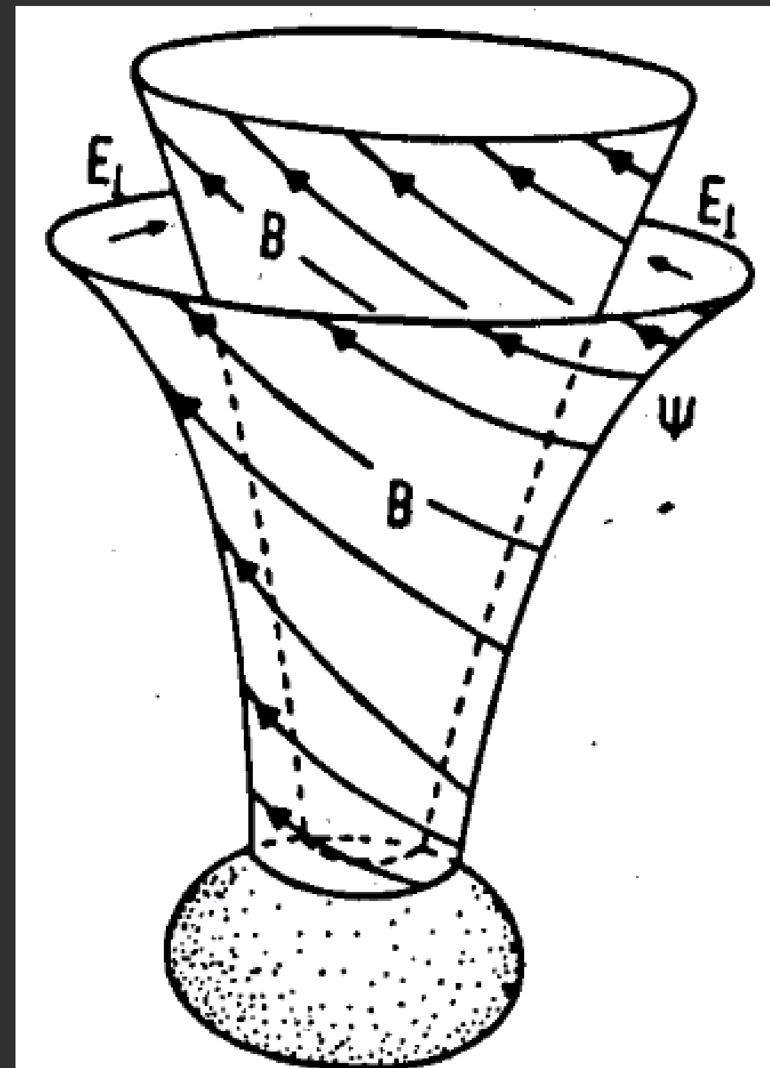
→ Nearly perfect cancellation of net EM force (outward pressure vs. inward tension) in jets dominated by magnetic fields

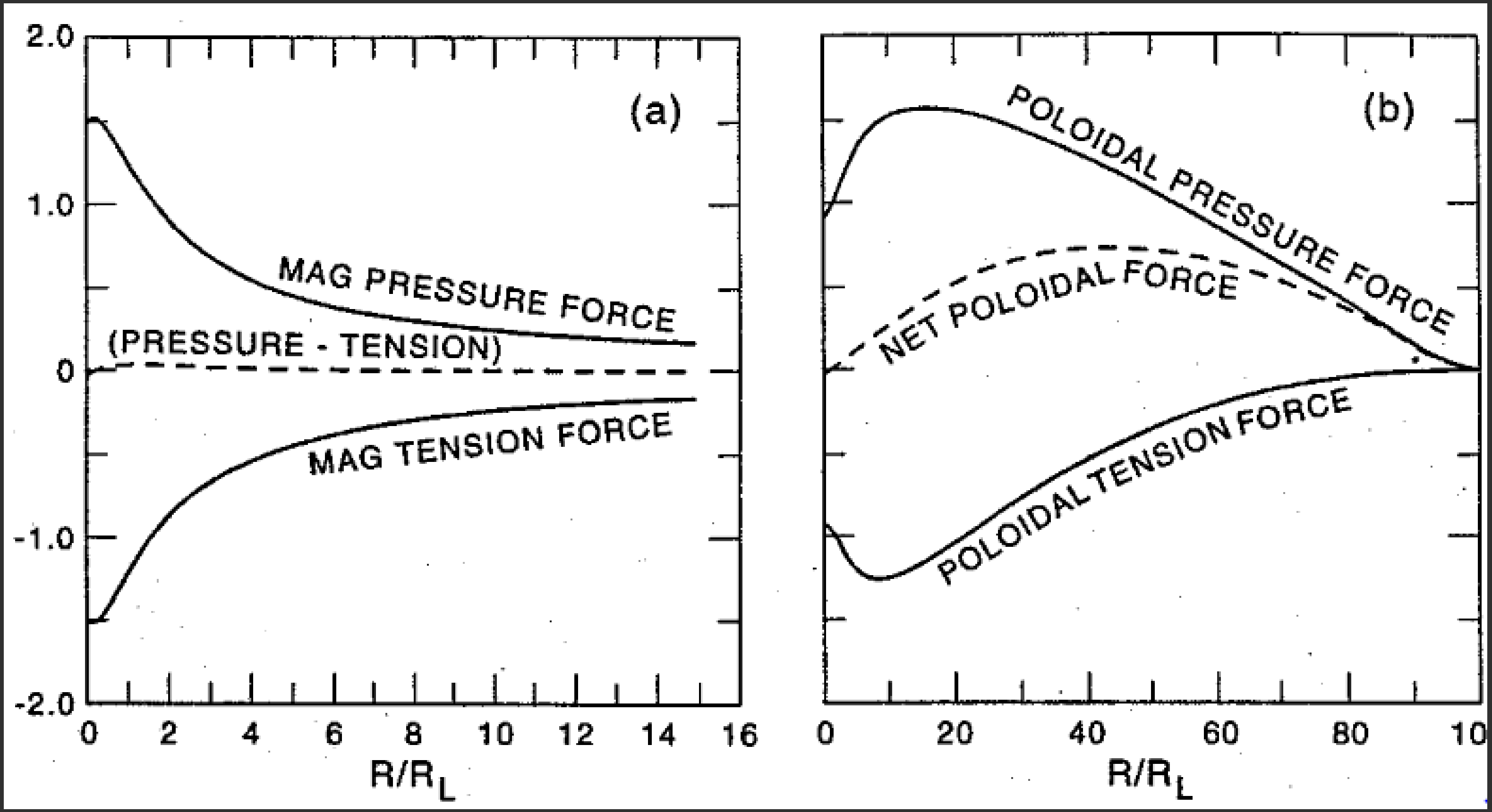
Need to examine internal (transverse) jet structure in detail

To get purely magnetic acceleration:

Depends on how rapidly flux surfaces separate from one another:

- **Faster than radial** $\Rightarrow$ K.E./P.F. $\propto \left(B_p R^2\right)^{-1}$ increases
- **Slower than radial** $\Rightarrow$ K.E./P.F. decreases





Conical flux surfaces:
force cancellation

Inner flux surfaces collimate
relative to outer flux surfaces:
P.F. converted to K.E.

Possible asymptotic arrangements of flux surfaces:

OPTIMAL FOR ACCELERATION

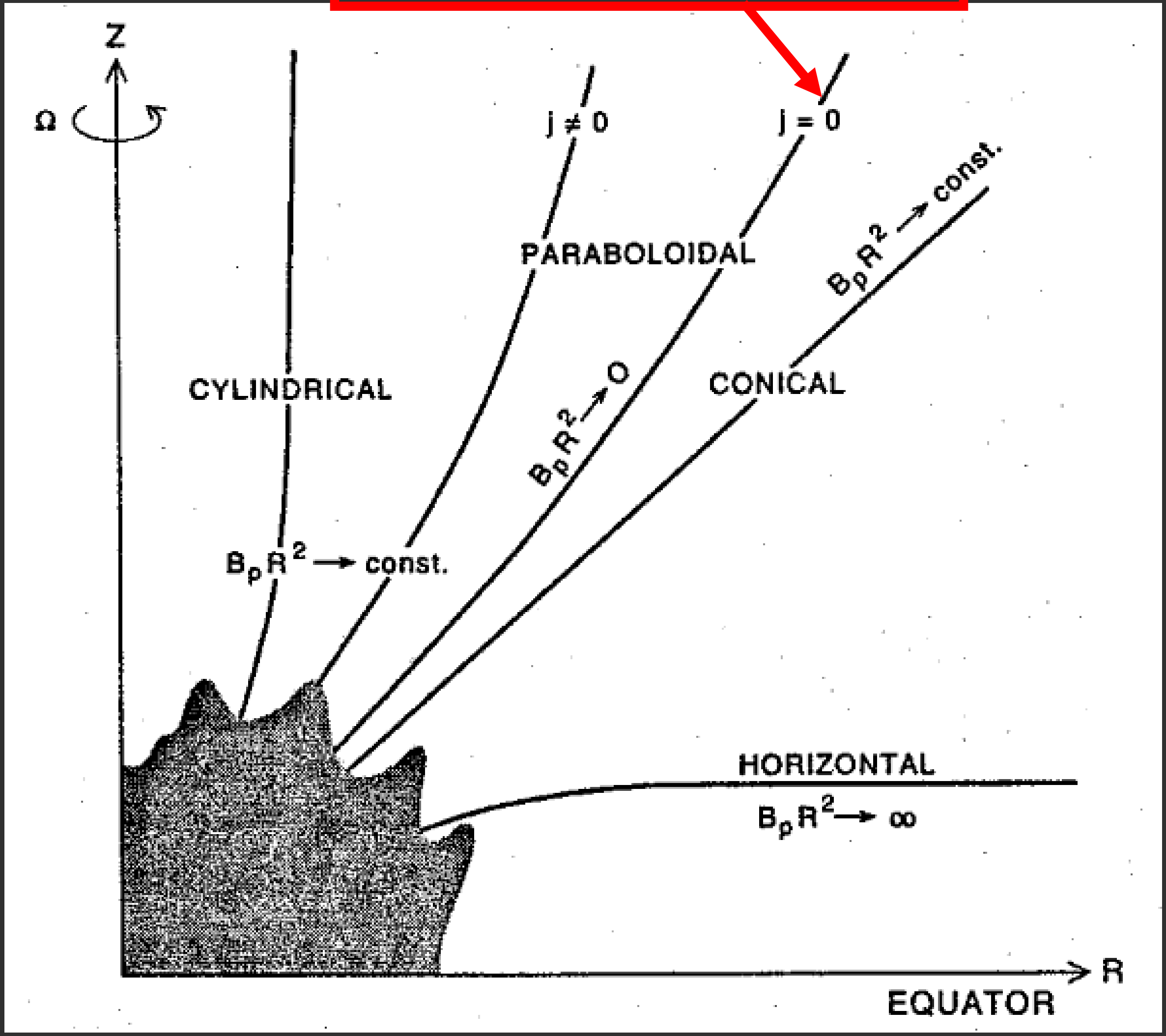
Which asymptote is chosen?

Depends on solution of the momentum equation transverse to the flux surfaces

a.k.a…

GRAD-SHAFRANOV EQUATION

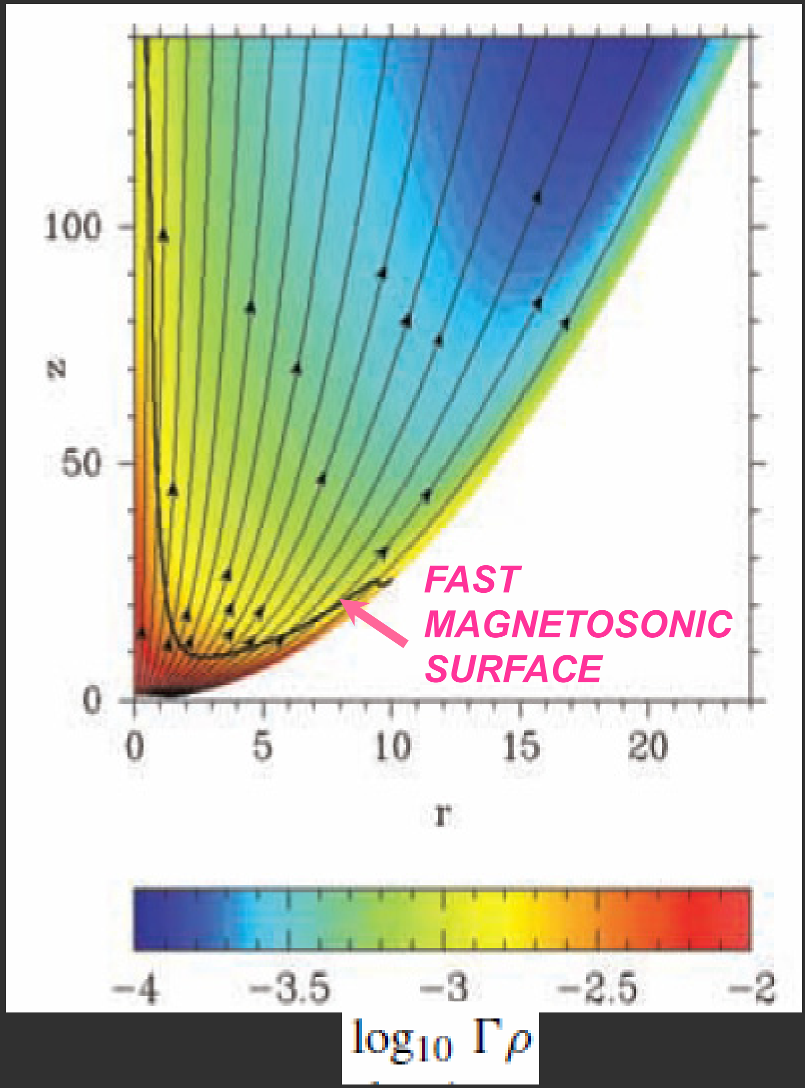
(modified to include relativistic internal energy and velocity field)



Numerical models…

- **Motion converts GS equation from elliptic to hyperbolic**
- **2 critical points:**
  - Alfvén (transverse momentum)
    – magnetic tension waves
  - Fast magnetosonic (longitudinal momentum) – magnetic pressure waves
  - Only one constraint
- **Result:** some flux surfaces can convert P.F. ➒K.E.

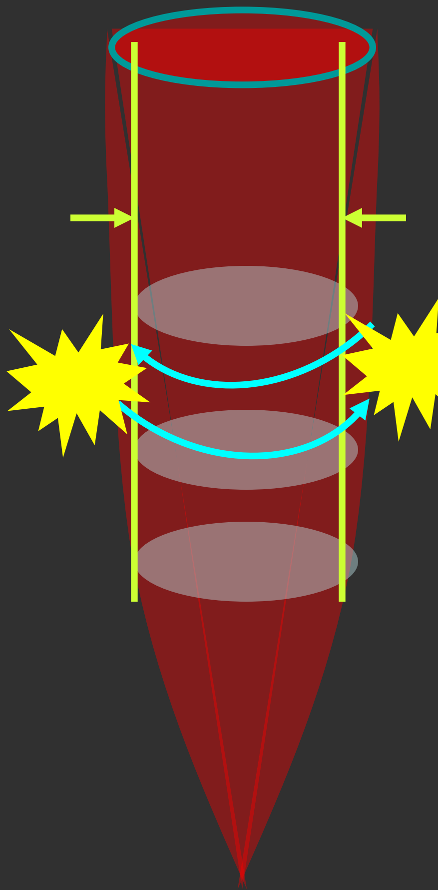
  but most can't



(Komissarov et al. 2007)

Dissipation in Jets: can result from

- **BOUNDARY CONDITIONS**
  - Time-dependence ❾ internal shocks
  - Loss of causal contact ❾ recollimation shocks
  - Magnetic field reversals ❾ current sheets, reconnection



- **INSTABILITIES**
  - Shear-driven
    - Kelvin-Helmholtz ❾ jet boundary
  - Current-driven
    - Pinch, kink ❾ jet interior

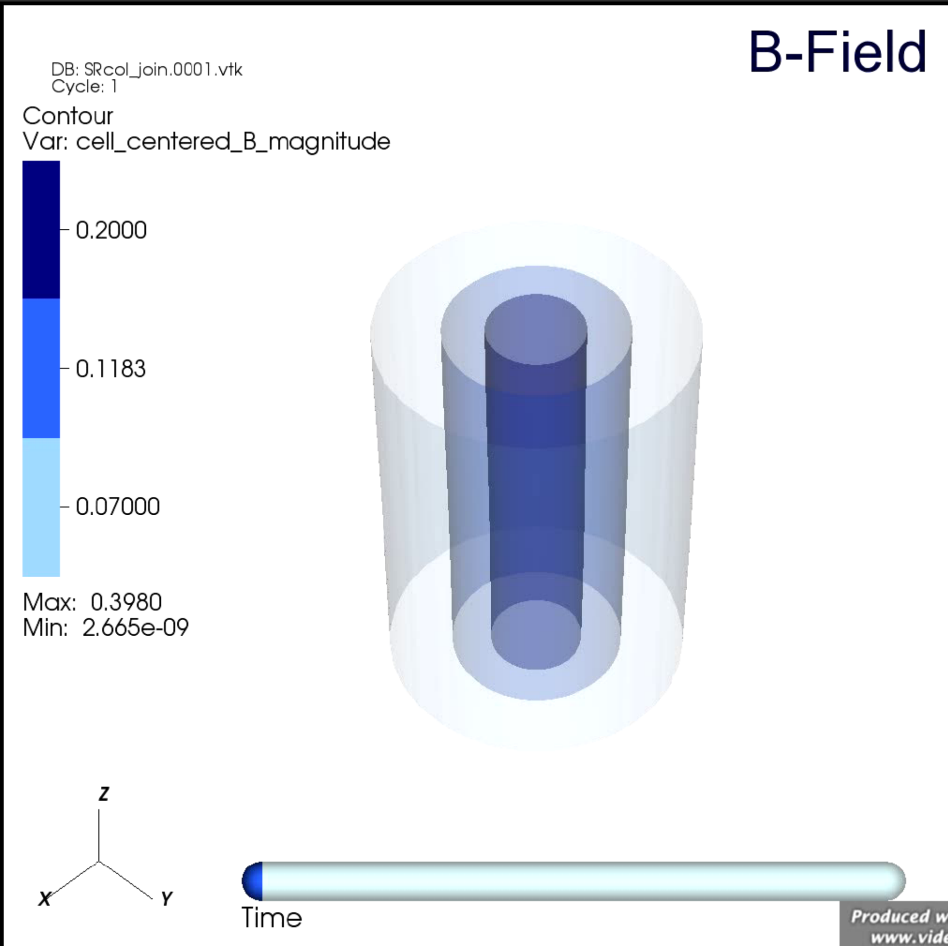
Dissipation in Jets: energetics

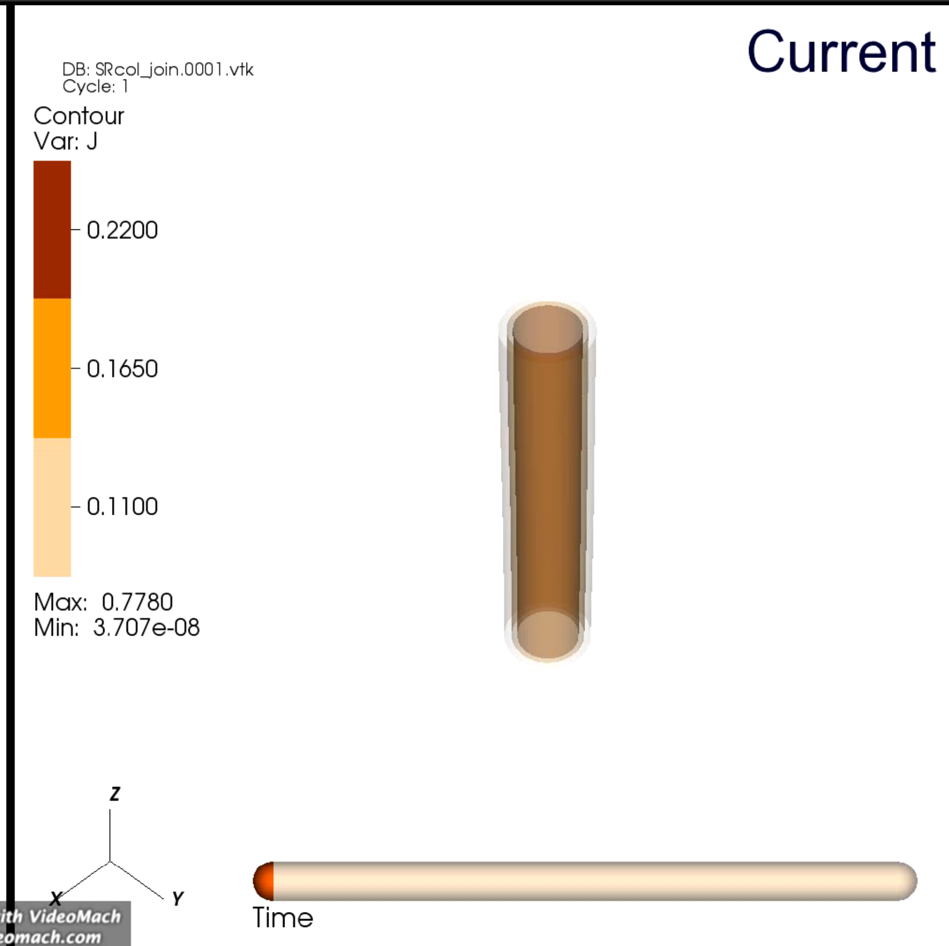
- **Tapping Kinetic Energy**
  - Internal shocks
  - Recollimation shocks
  - Shear-driven instabilities

- **Tapping Poynting Flux**
  - Magnetic field reversals
  - Current-driven instabilities

} CAN CATALYZE CONVERSION P.F. ❾ K.E.

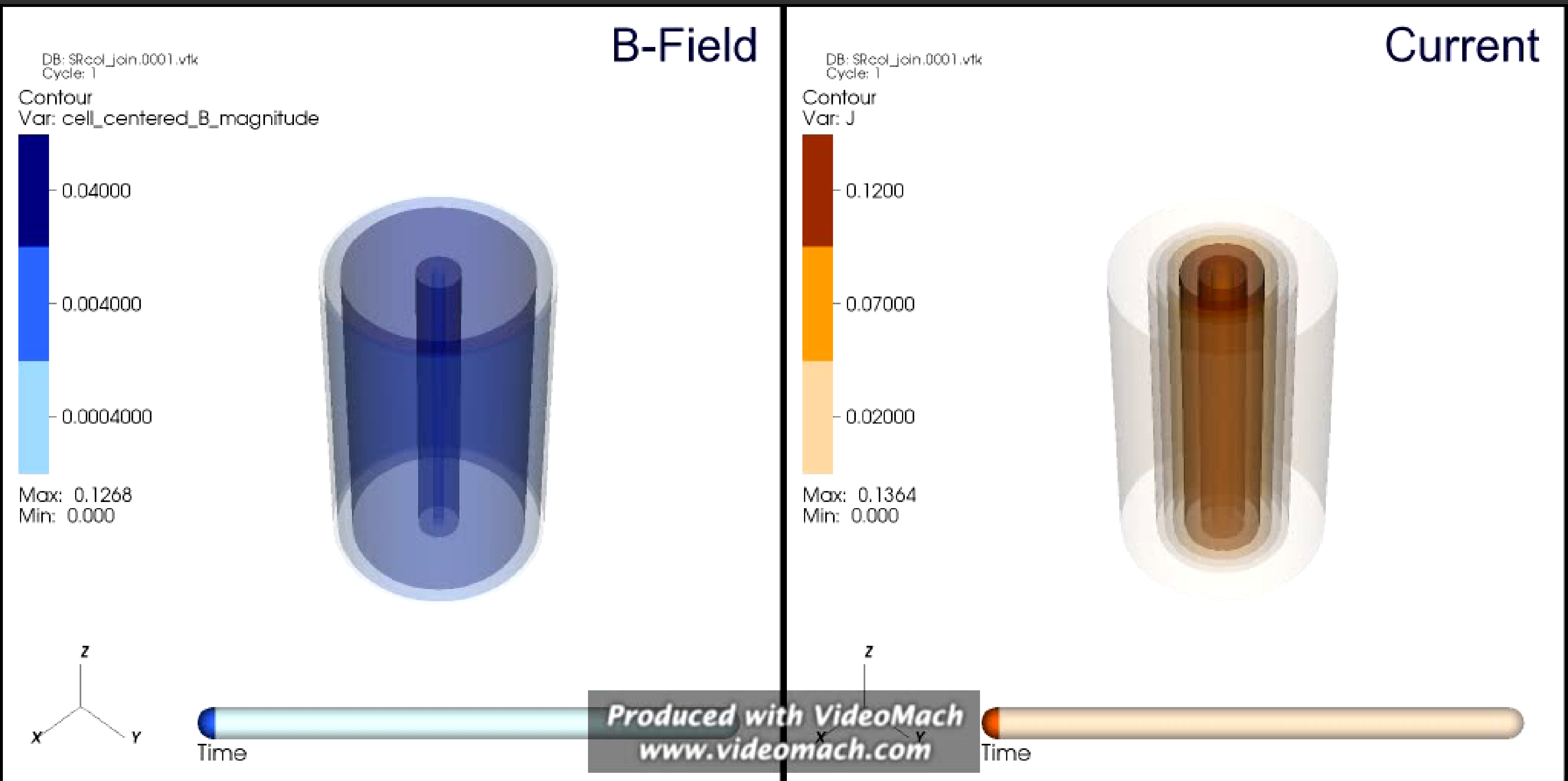
FORCE-FREE PLASMA COLUMNS - STABLE





Special relativistic MHD simulations – S. O'Neill et al., in prep.

PINCH BALANCED BY GAS PRESSURE - UNSTABLE



Special relativistic MHD simulations – S. O'Neill et al., in prep.

Conclusions

- **Jets plausibly accelerated by EM stresses in MHD limit**
- **Flow dominated by Poynting flux where it crosses Alfvén surface**
- **Conversion of P.F.→K.E. beyond R_A sensitive to flow geometry**
  - Easy to ~equipartition, hard beyond
  - Dissipation can help
- **Self-collimation a "myth": external confinement needed beyond Alfvén point**
- **Relativistic jets accelerate gradually: $\Gamma \propto P_{\rm ext}^{-(1/4-1/2)}$**

Still to be understood…

- **How are jets launched?**
  - Disk-launching vs. BH spin
  - How is mass loaded onto jets?
    - Ordinary plasma or pair-rich?
    - What determines ☝$_{◎}$?
- **How are jets collimated?**
  - Structure/origin of external medium?
  - Causal contact of jet interior with surroundings
- **Why do jets shine?**
  - Dissipative processes inside jets (shocks, reconnection, etc.)
  - Sensitivity to P.F./K.E. ratio (shocks weak if Poynting-dominated)
  - Nonlinear effects of local radiation field (synchrotron self-Compton...)
  - Instabilities
    - Shear-driven (Kelvin-Helmholtz) near jet-ambient interface
    - Current-driven near jet axis

Frontiers…

- **Numerical simulations**
  - GRMHD now possible
  - Need sufficient dynamic range to study boundary layers, dynamics of current sheets
    - Adaptive mesh codes
    - Modeling microphysics, e.g., reconnection
- **Effects of time-dependence, non-axisymmetry**
- **Boundary conditions**
  - Connections to disks
  - Modeling radiation environments
  - Disc-wind environments