IMPRS June 2013

lecture goals @
http://www.mpa-garching.mpg.de/~henk/IMPRSgoals.pdf

excercises @
http://www.mpa-garching.mpg.de/~henk/IMPRSexc.pdf

Jets

IMPRS June 2013

- Examples

  knots, precession, superluminal motion, connection with disks
- magnetic jet model
- problem areas

introduction:

http://www.mpa-garching.mpg.de/~henk/pub/jetrevl.pdf (somewhat old)

current issues:

arXiv:0804.3096

This presentation:

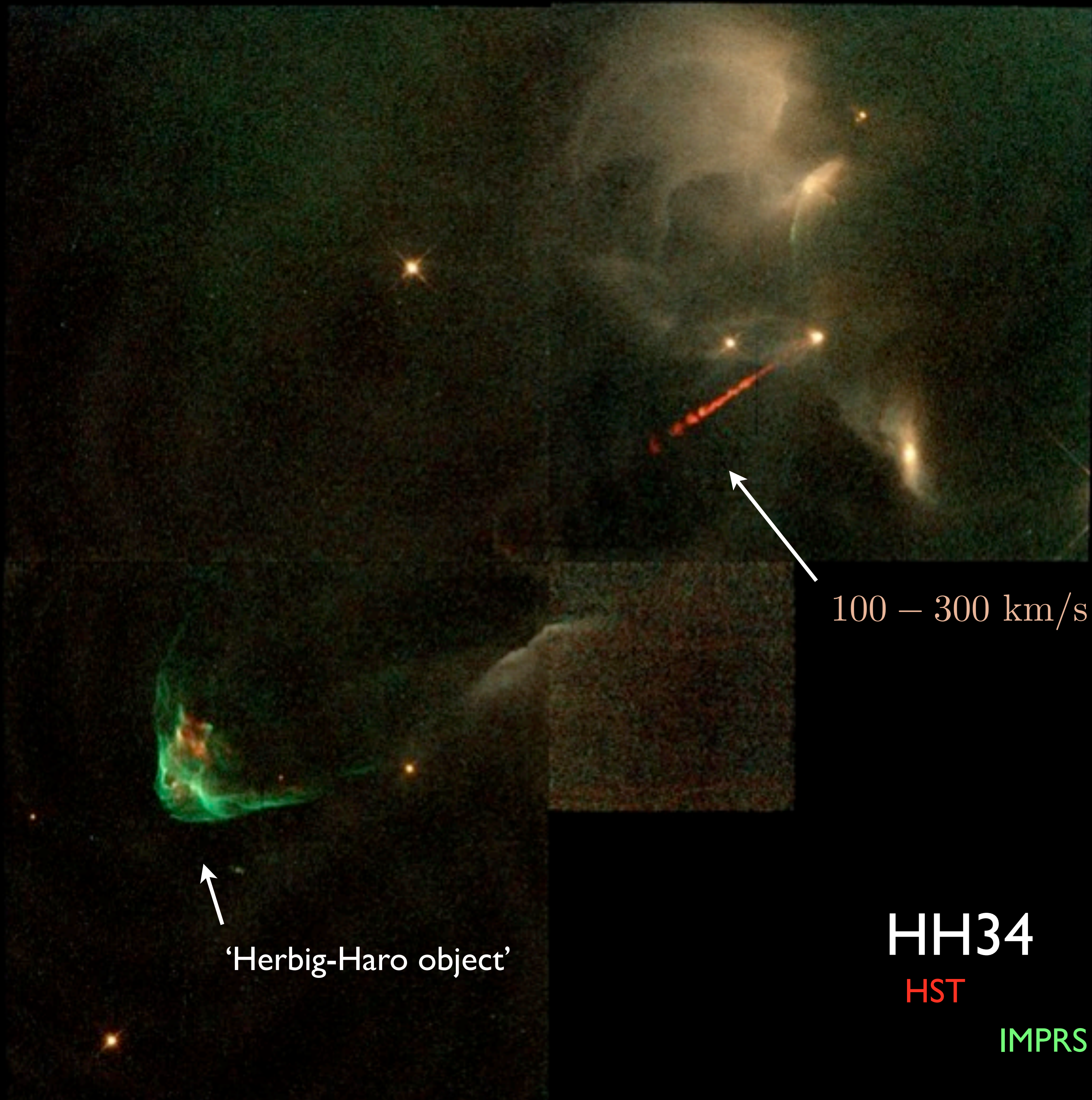
http://www.mpa-garching.mpg.de/~henk/imprsjets.pdf

Jets observed in:

- protostars
- ‘symbiotic’ binaries
- ‘supersoft’ X-ray sources
- neutron star binaries (Cir X-1)
- black hole binaries (‘microquasars’)
- SS433
- active galaxies

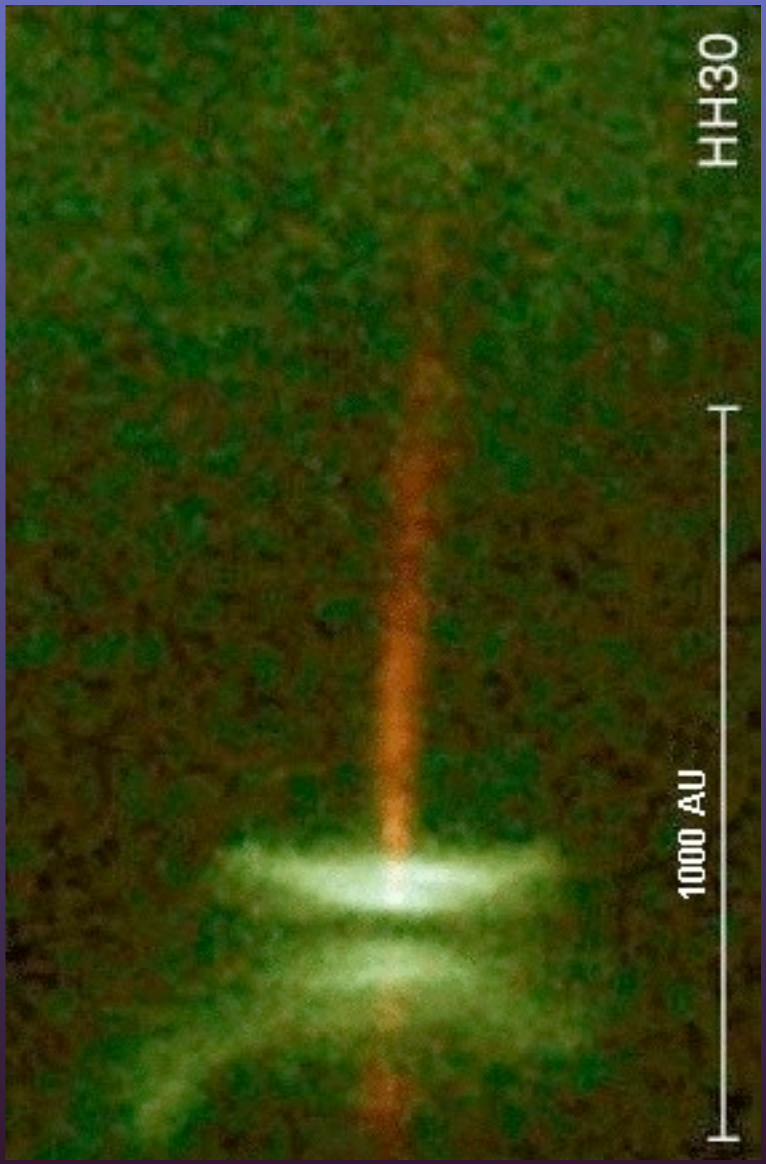
Common: all involve accretion and disks

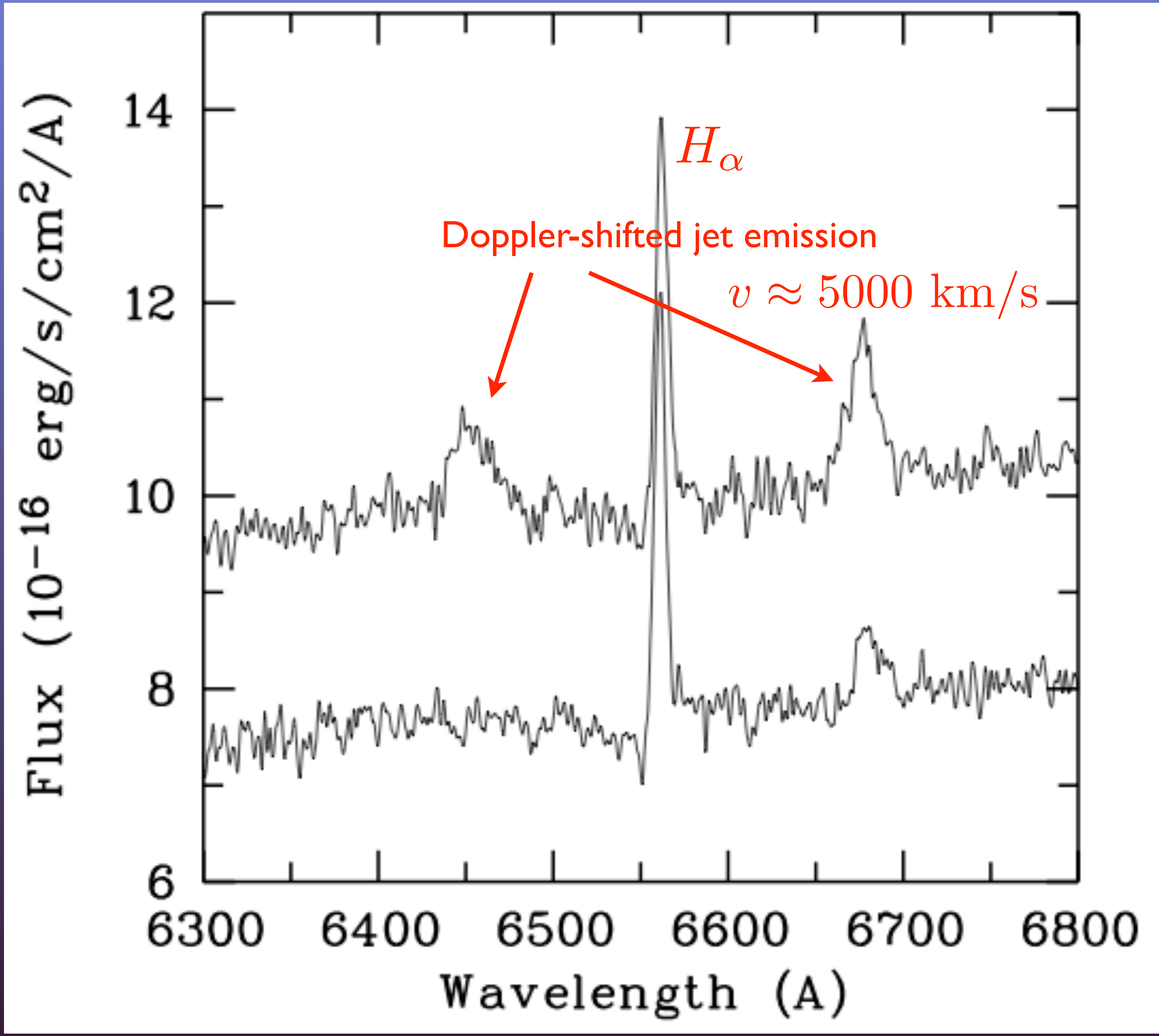
exceptional case (?) : planetary nebulae



HH34

HST

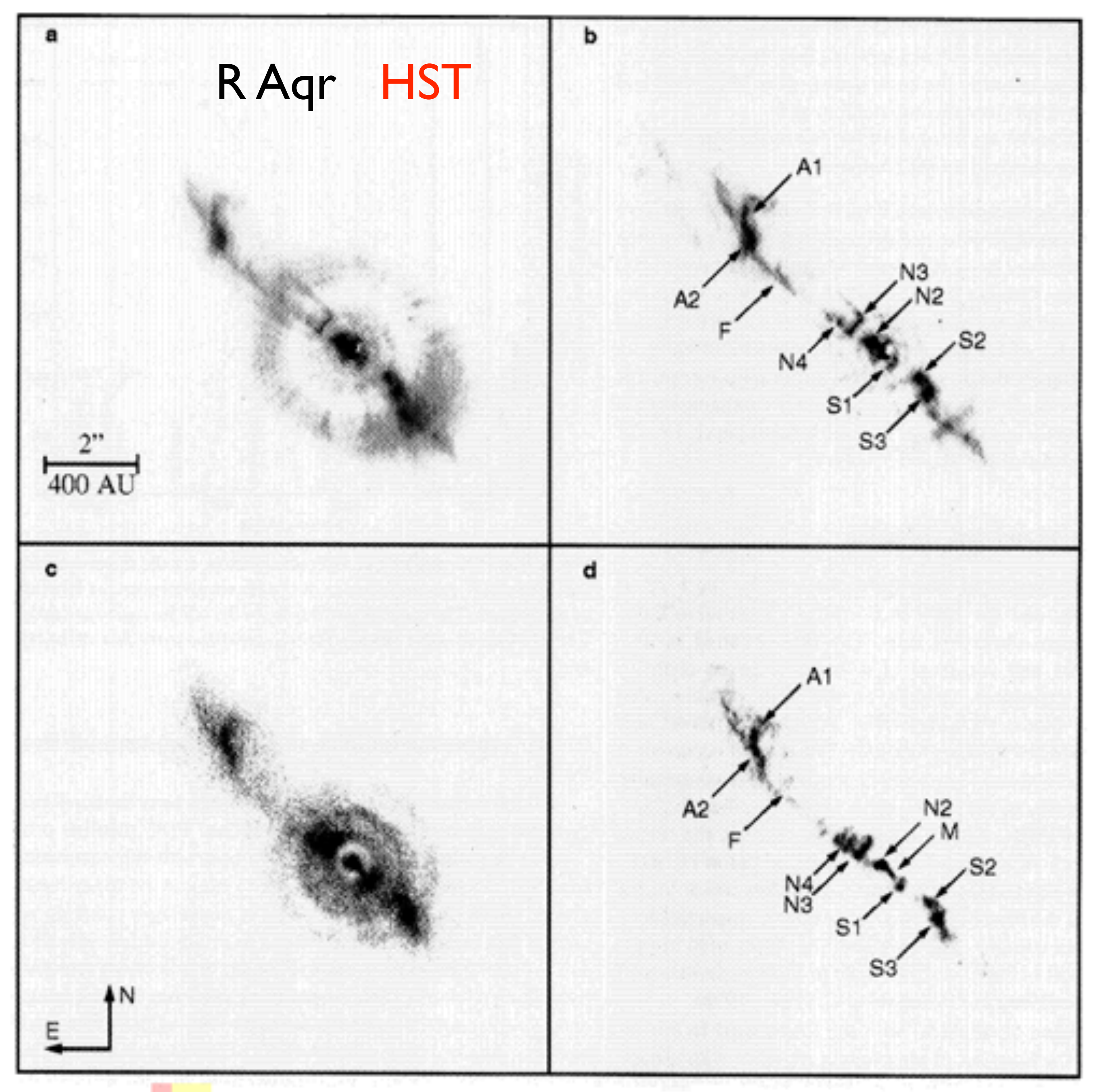

HH30
1000 AU



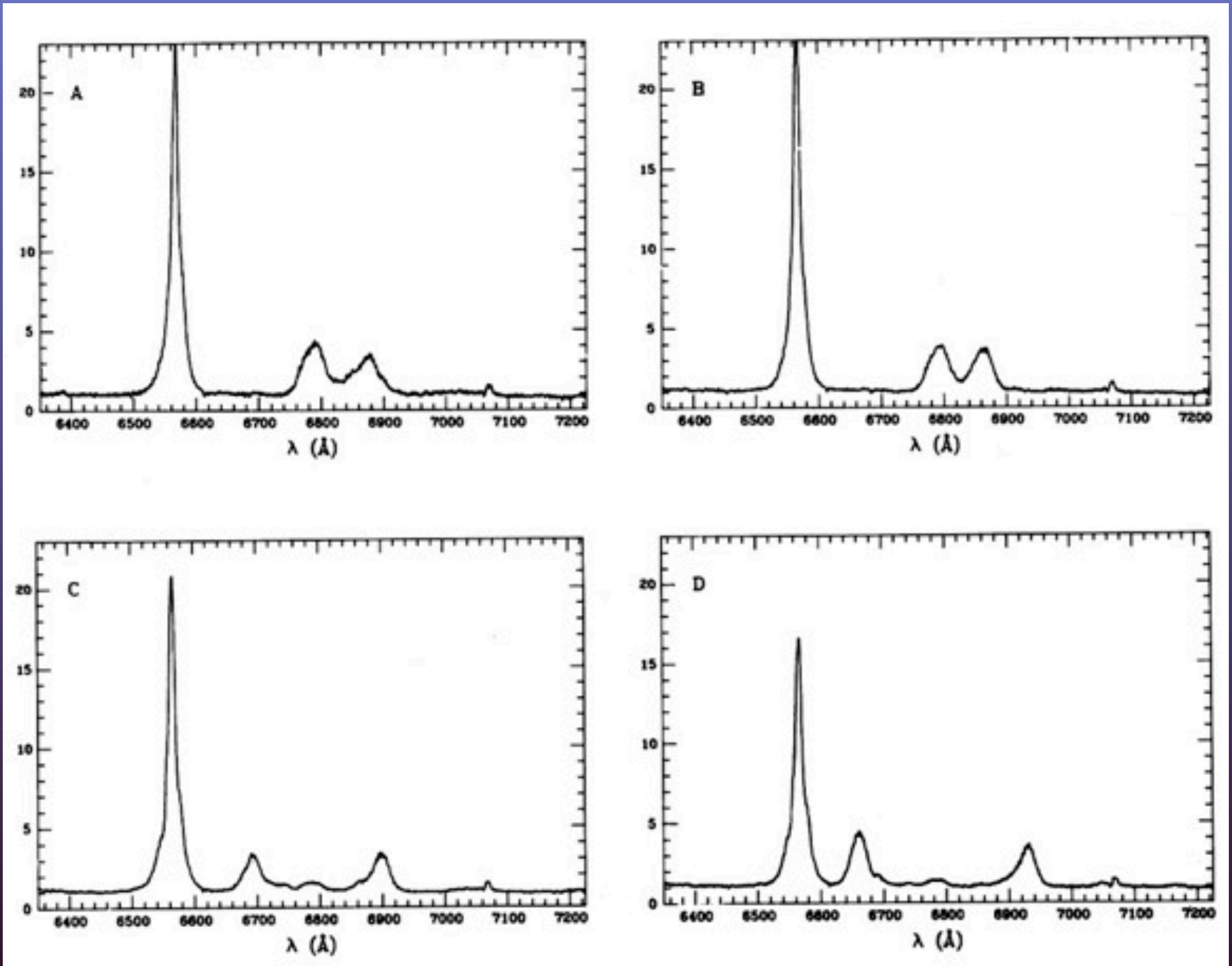
'Supersoft source': accreting WD, burning H on its surface

↔ symbiotics & CVs

C. Motch: The transient jet of the galactic supersoft X-ray source RX J0925.7-4758


a
R Aqr
HST
2"
400 AU
b
A1
A2
F
N3
N2
N4
S2
S1
S3
c
N
E
d
A1
A2
F
N2
M
N4
N3
S2
S1
S3

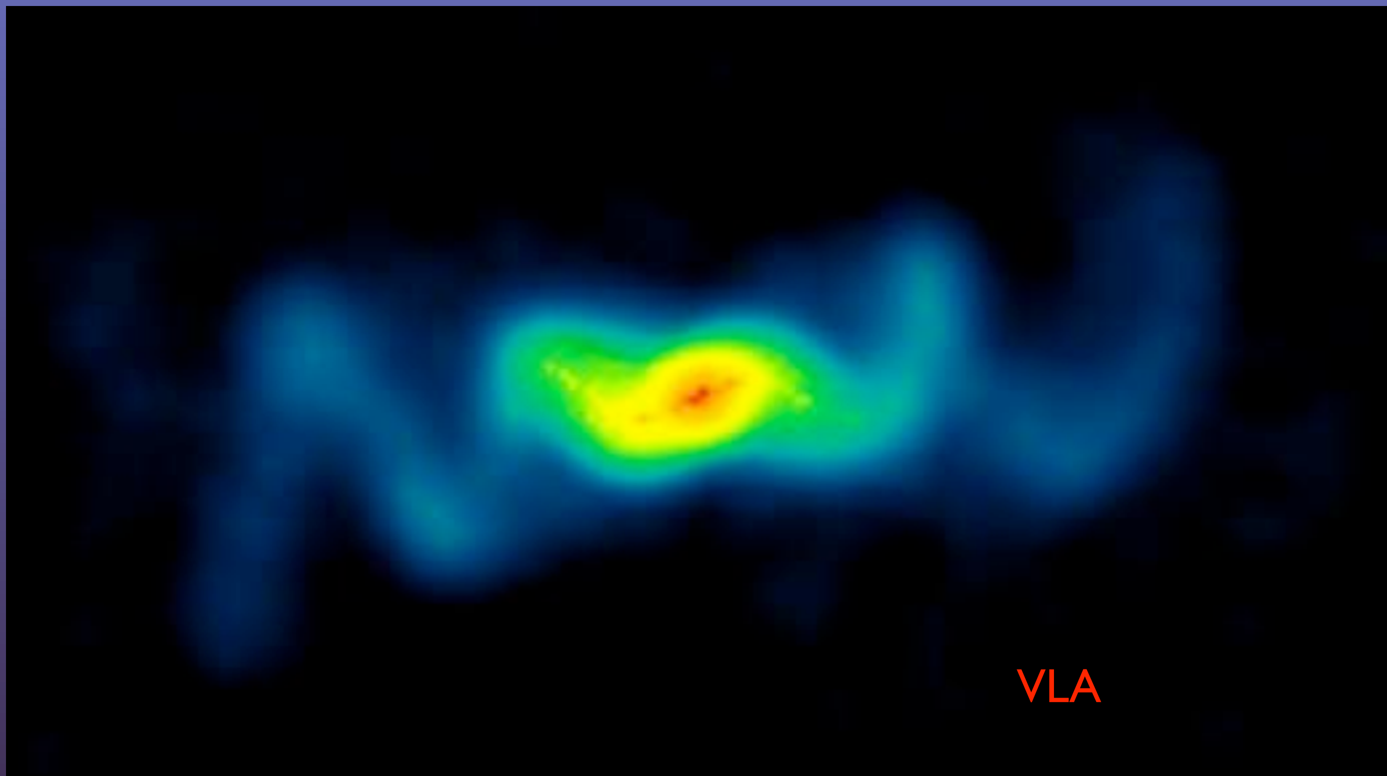
Jet precession



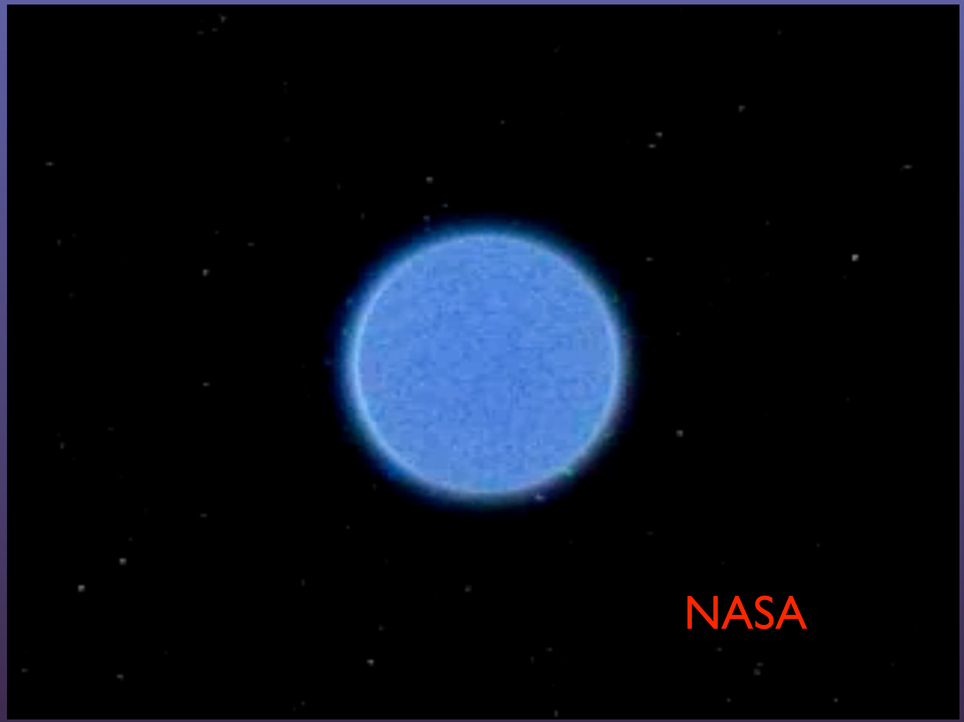
SS433 INT

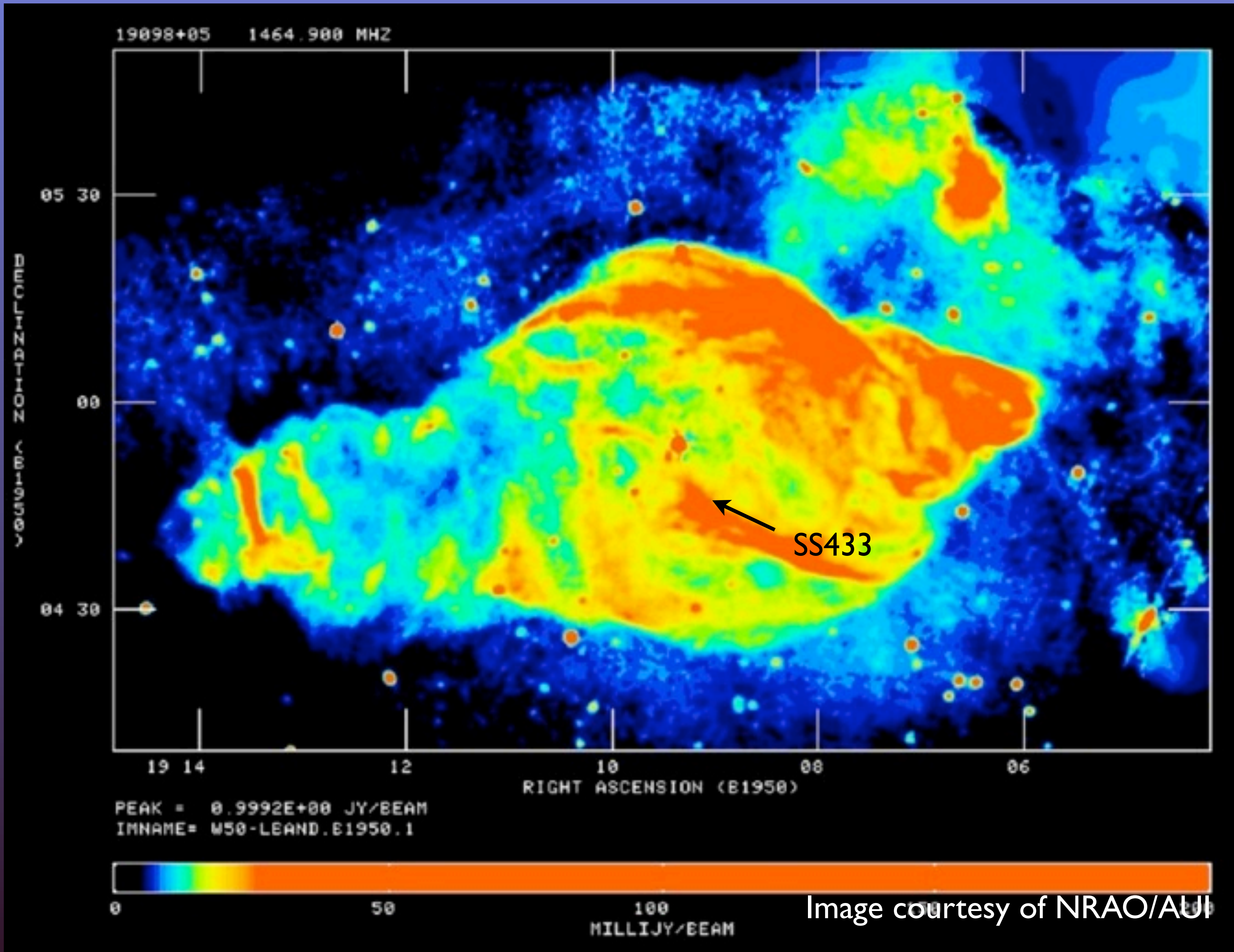
$v = 0.26c$

The precessing jet of SS433 (Precession period =164d)



Artist's view of SS433




19098+05 1464.900 MHZ
05 30
00
04 30
DECLINATION (B1950)
19 14
12
10
08
06
RIGHT ASCENSION (B1950)
SS433
PEAK = 0.9992E+00 JY/BEAM
IMNAME= W50-LEAND.B1950.1
0
50
100
MILLIJY/BEAM
Image courtesy of NRAO/AUI

Jet precession

SS 433
AGN : - hot spot morphology
- lack of correlation jet axis ↔ galactic plane

interpretation: precession of warped disk

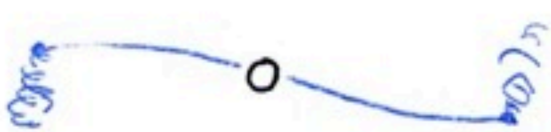
Warps by instability due to irradiation

→ direct : radiation pressure
(Petterson 75(?) ; Pringle '95)

→ indirect : radiation-driven wind reaction
(Schandl & Meyer '94)

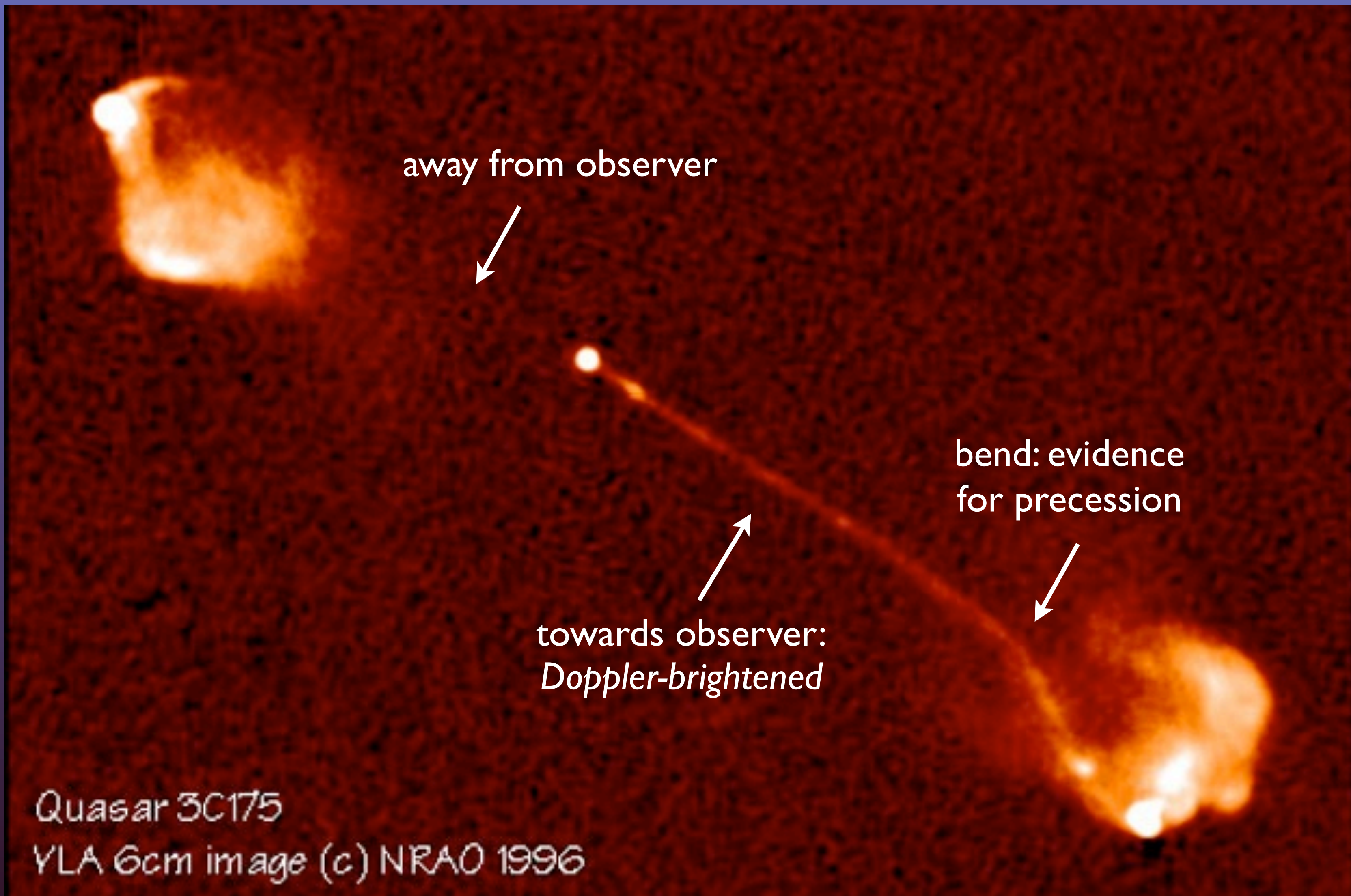
Definitive formalism: Ogilvie MNRAS 1999

slow precession : apparently "bent" jet :

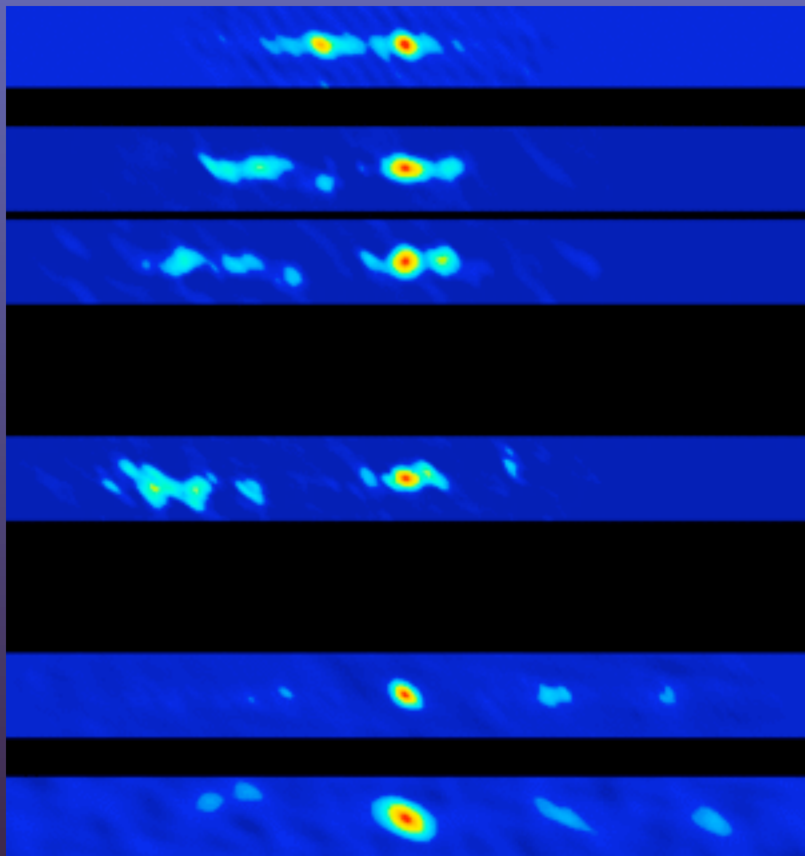


IMPRS 06 - 2013 Jets

One-sided jets (but *not* one-sided radiolobes): evidence of relativistic flow speeds



Microquasars: black hole binaries with radio jets

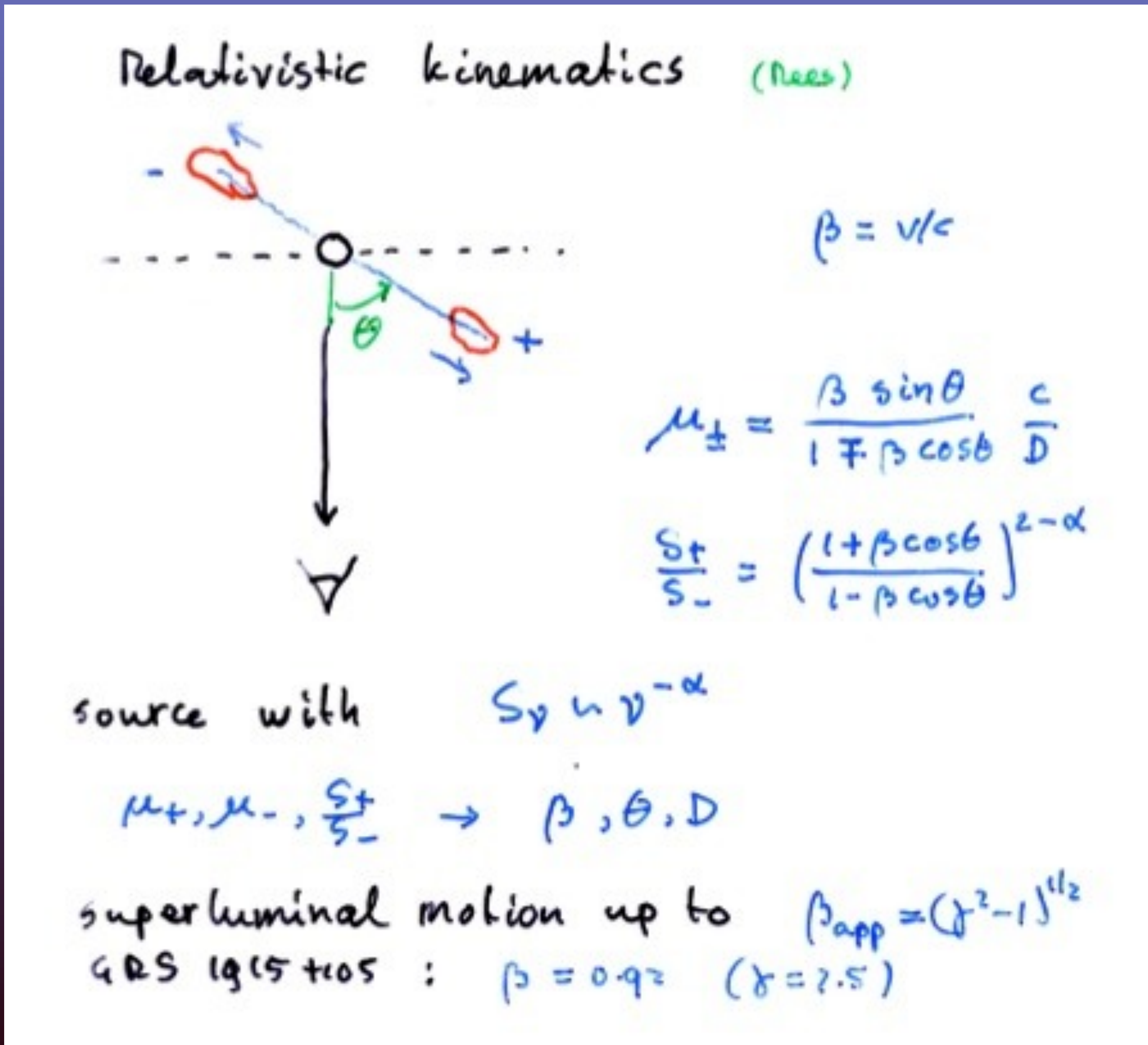


GRS 1655-40 VLBA (NRAO/AUI)

$\sim 10 M_\odot$ instead of $10^7 - 10^9$

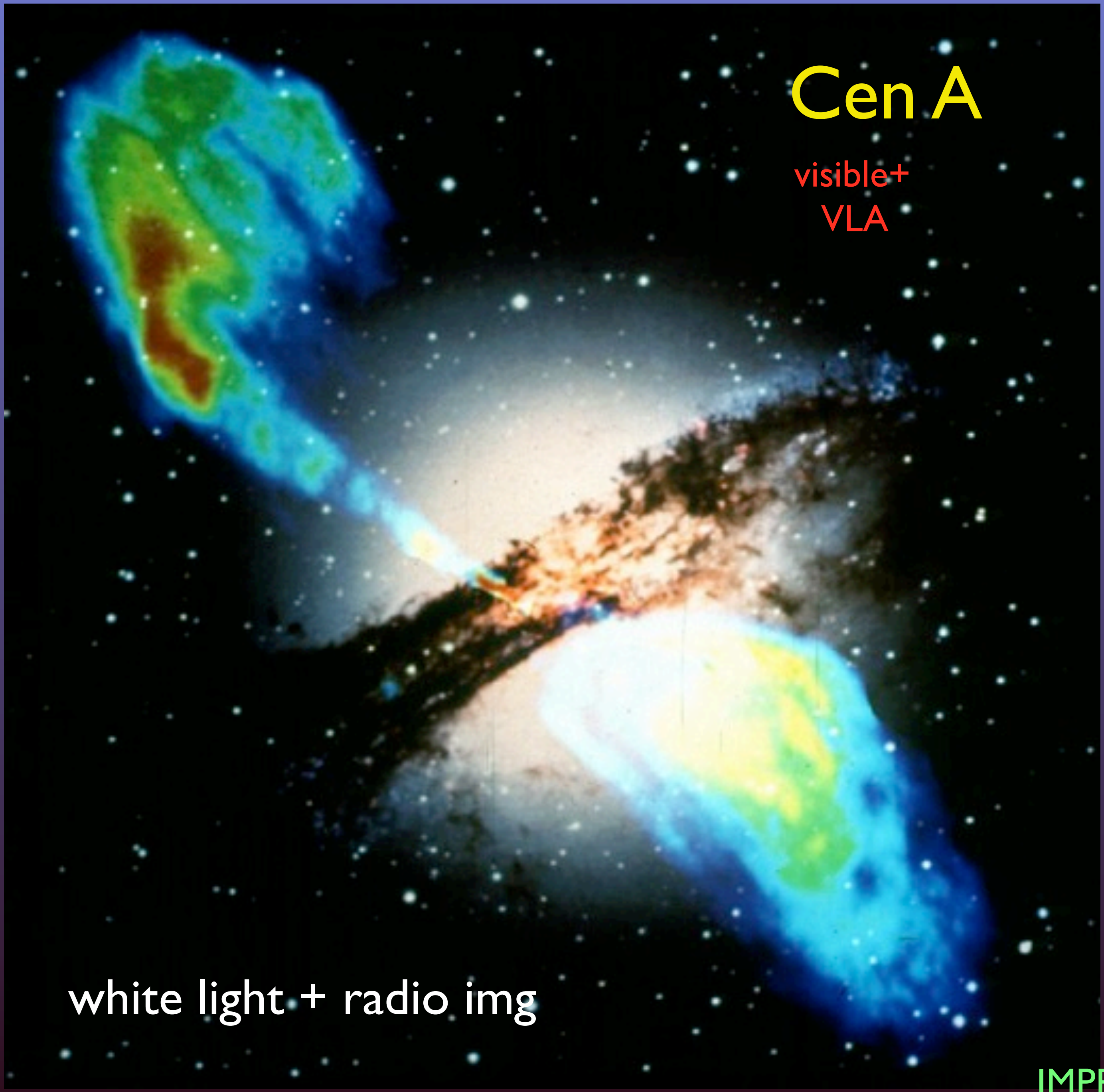
'blobs' moving at 'superluminal' apparent speed $\gamma \sim 2 - 10$

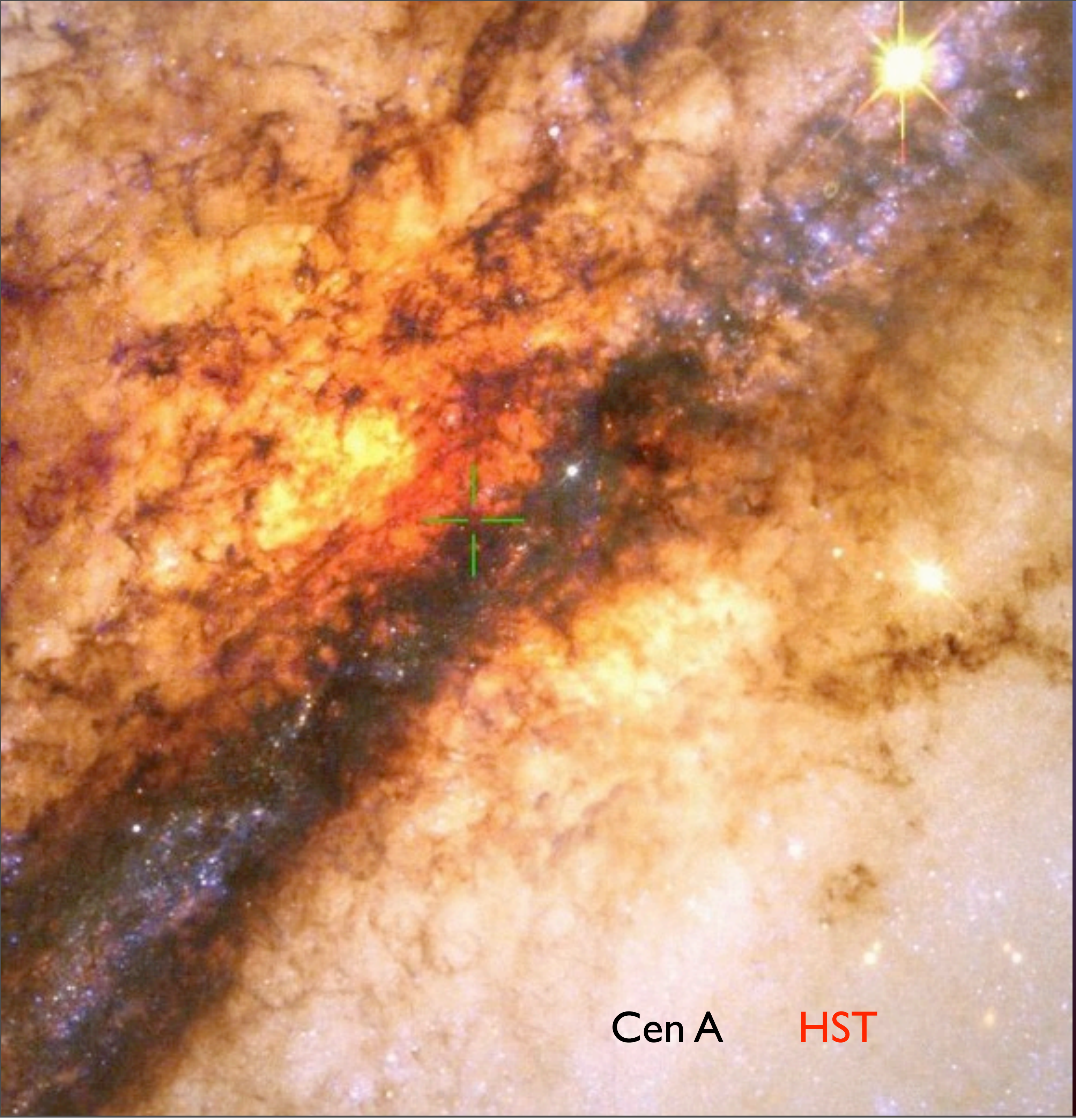
Apparent 'superluminal' motion



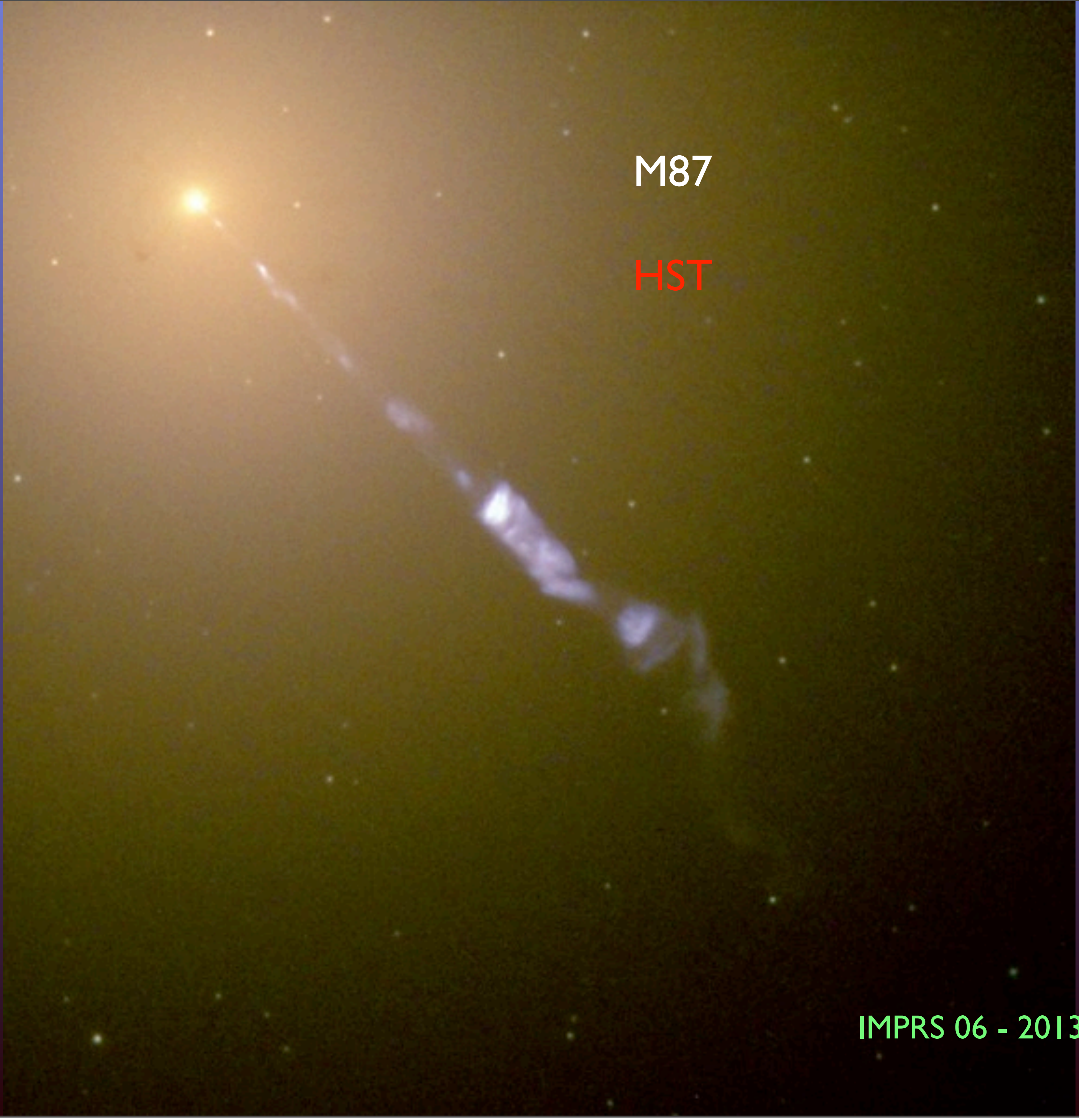
Doppler effect increases apparent proper motion of proximal jet (and slows down distal jet)

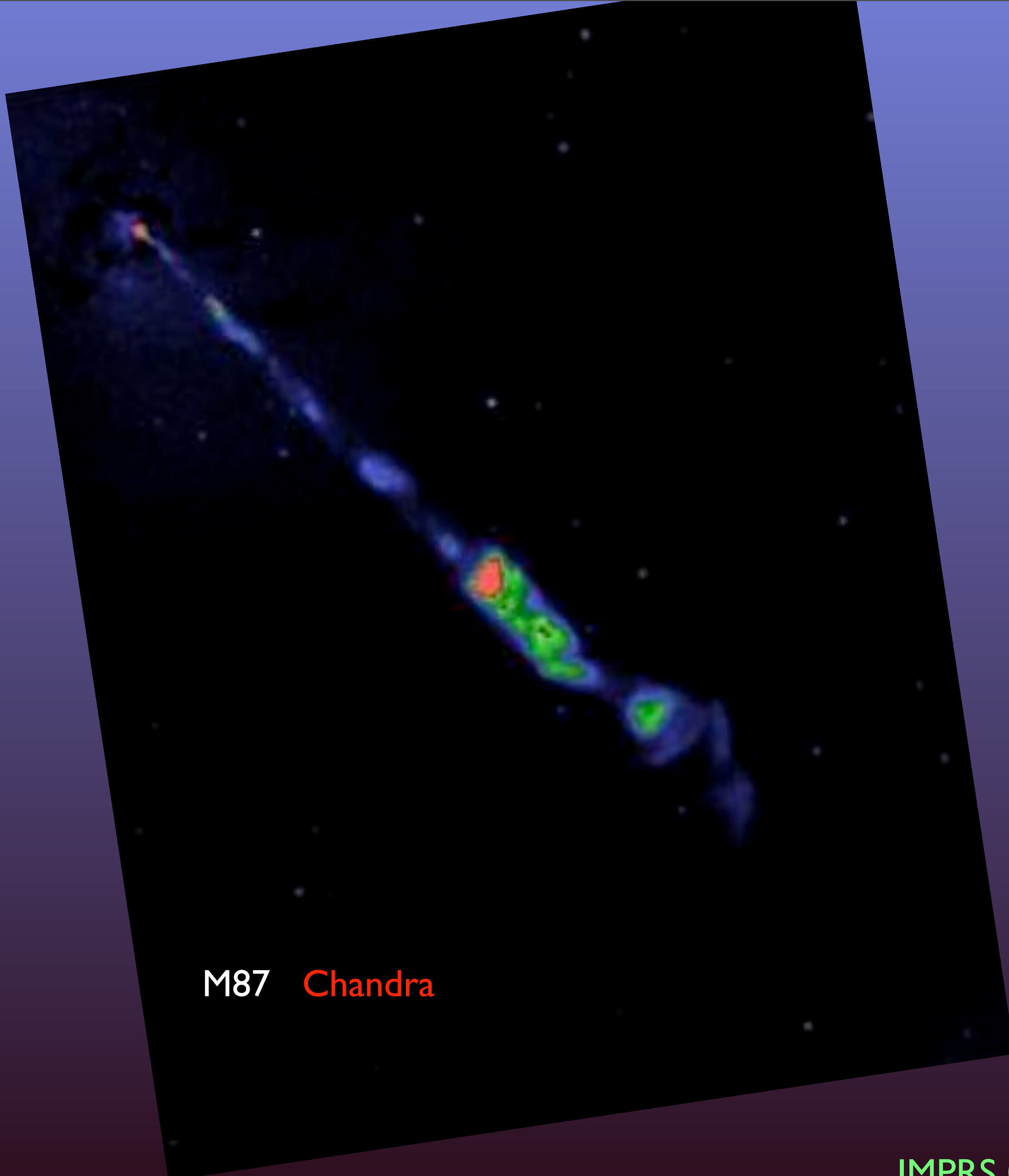
Lorentz factor and angle to line of sight derived from asymmetric proper motions and brightness


Cen A
visible+
VLA
white light + radio img


Cen A
HST

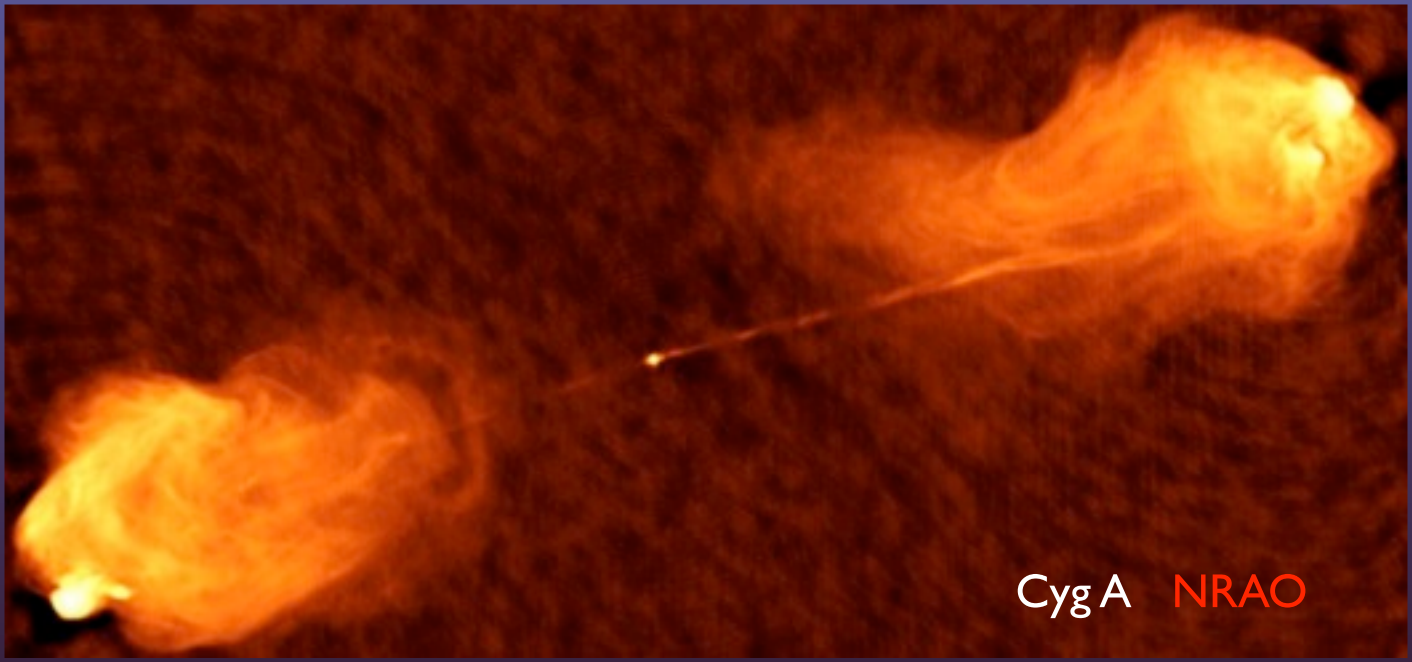

Cen A
Chandra

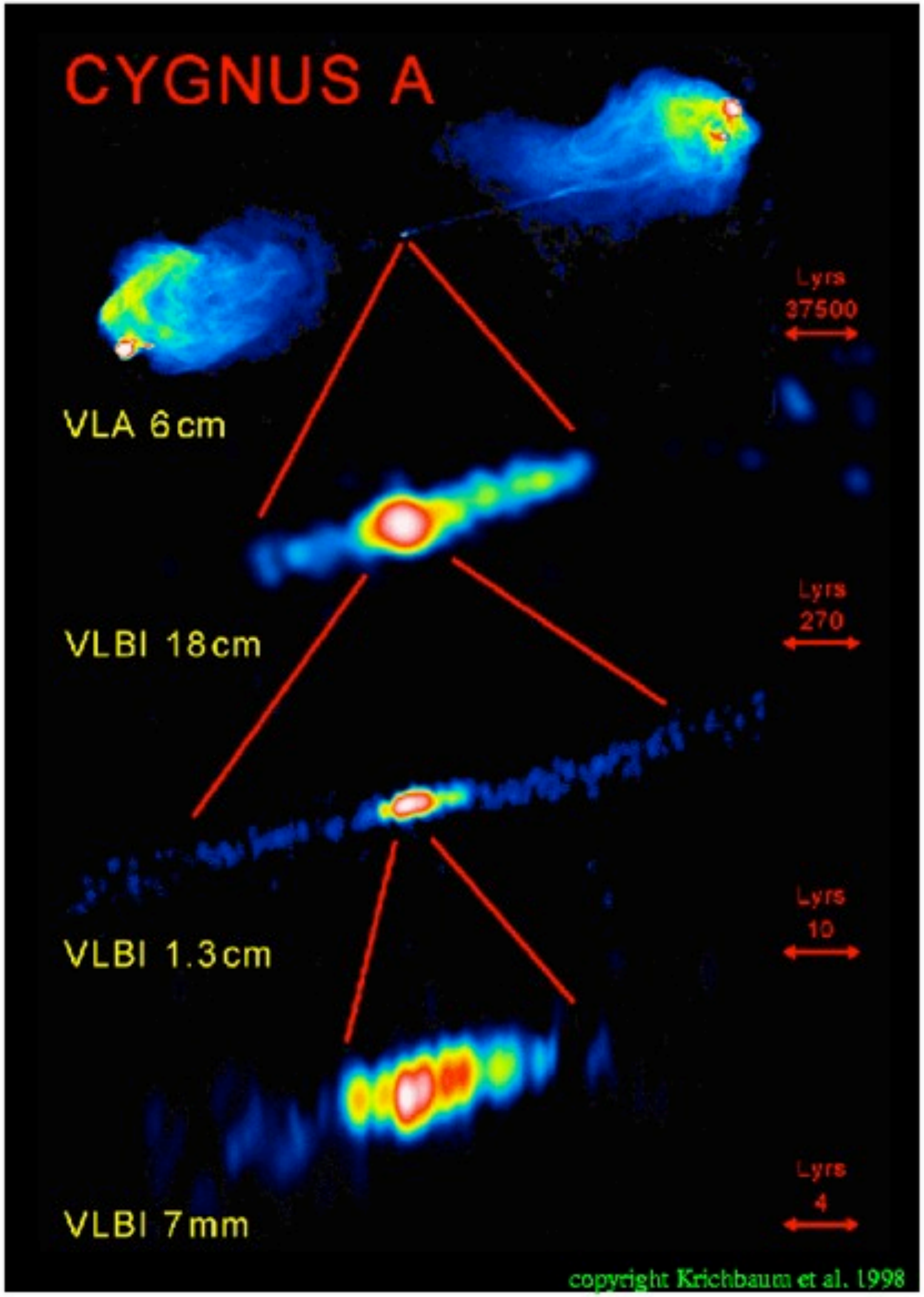

M87
HST

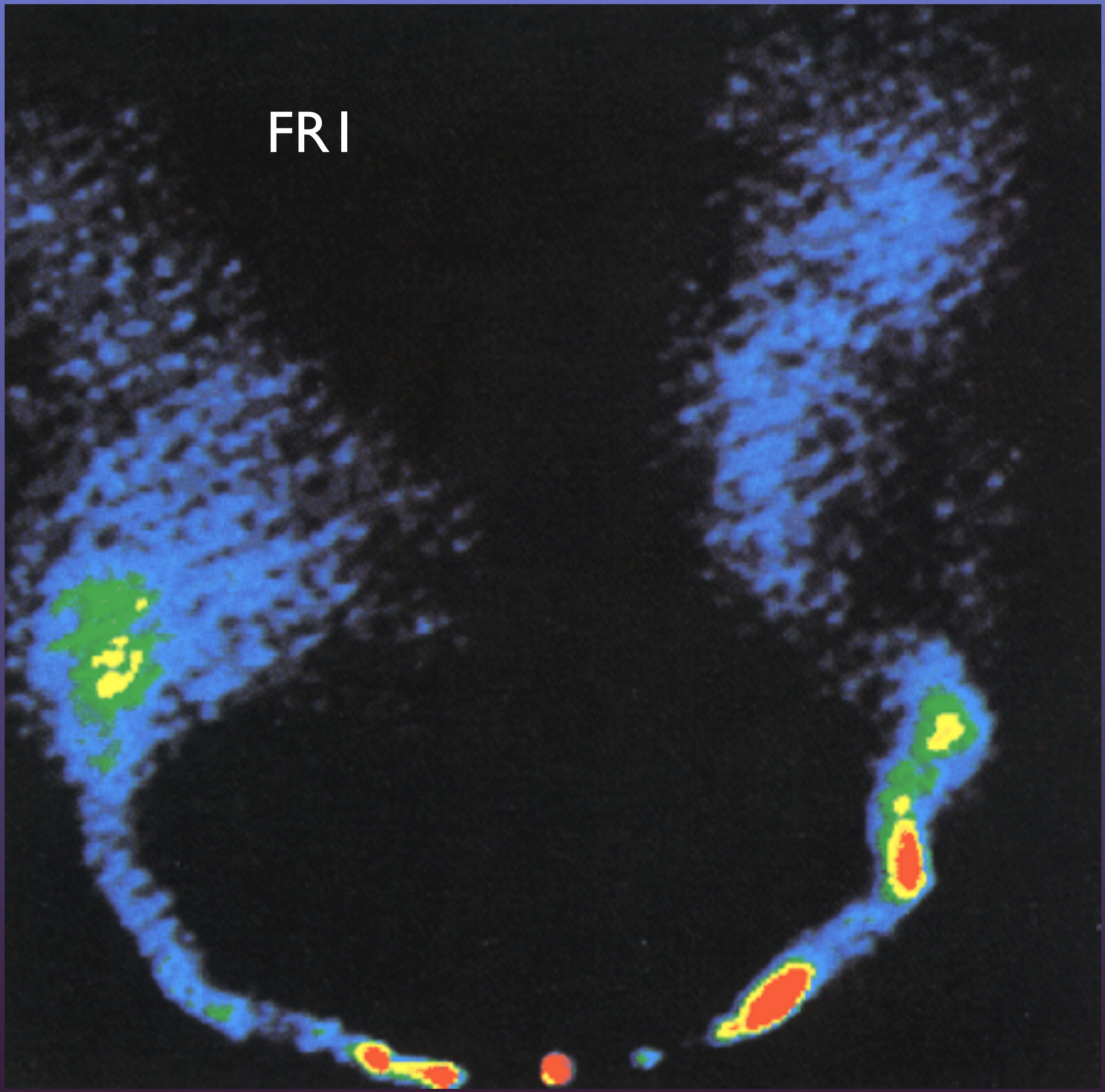

M87 Chandra

classical double-lobed, FR II radio source with jets visible

$\gamma \sim 10 - 30$

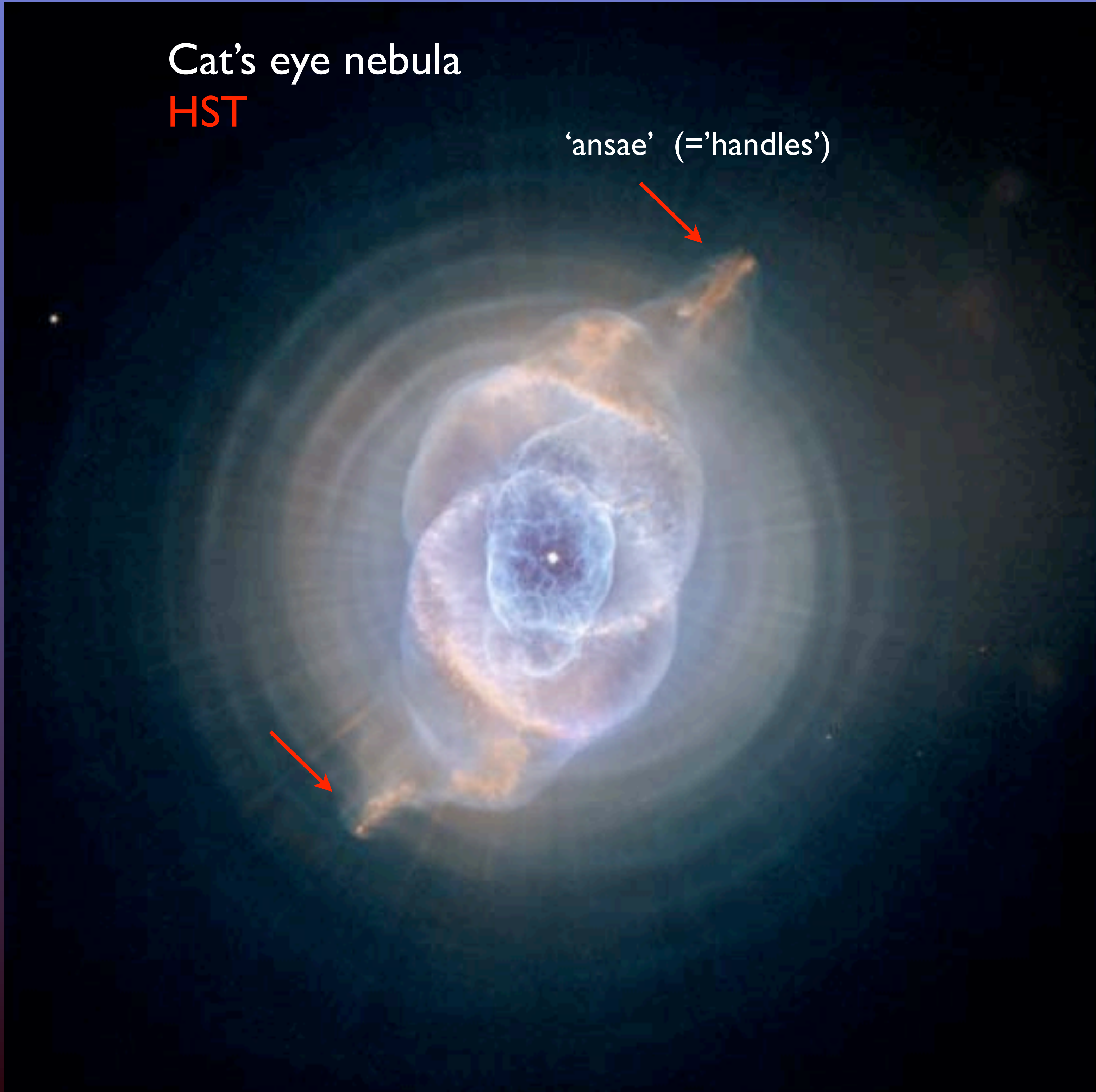



CYGNUS A
VLA 6cm
Lyrs
37500
VLBI 18cm
Lyrs
270
VLBI 1.3cm
Lyrs
10
VLBI 7mm
Lyrs
4
copyright Krichbaum et al. 1998

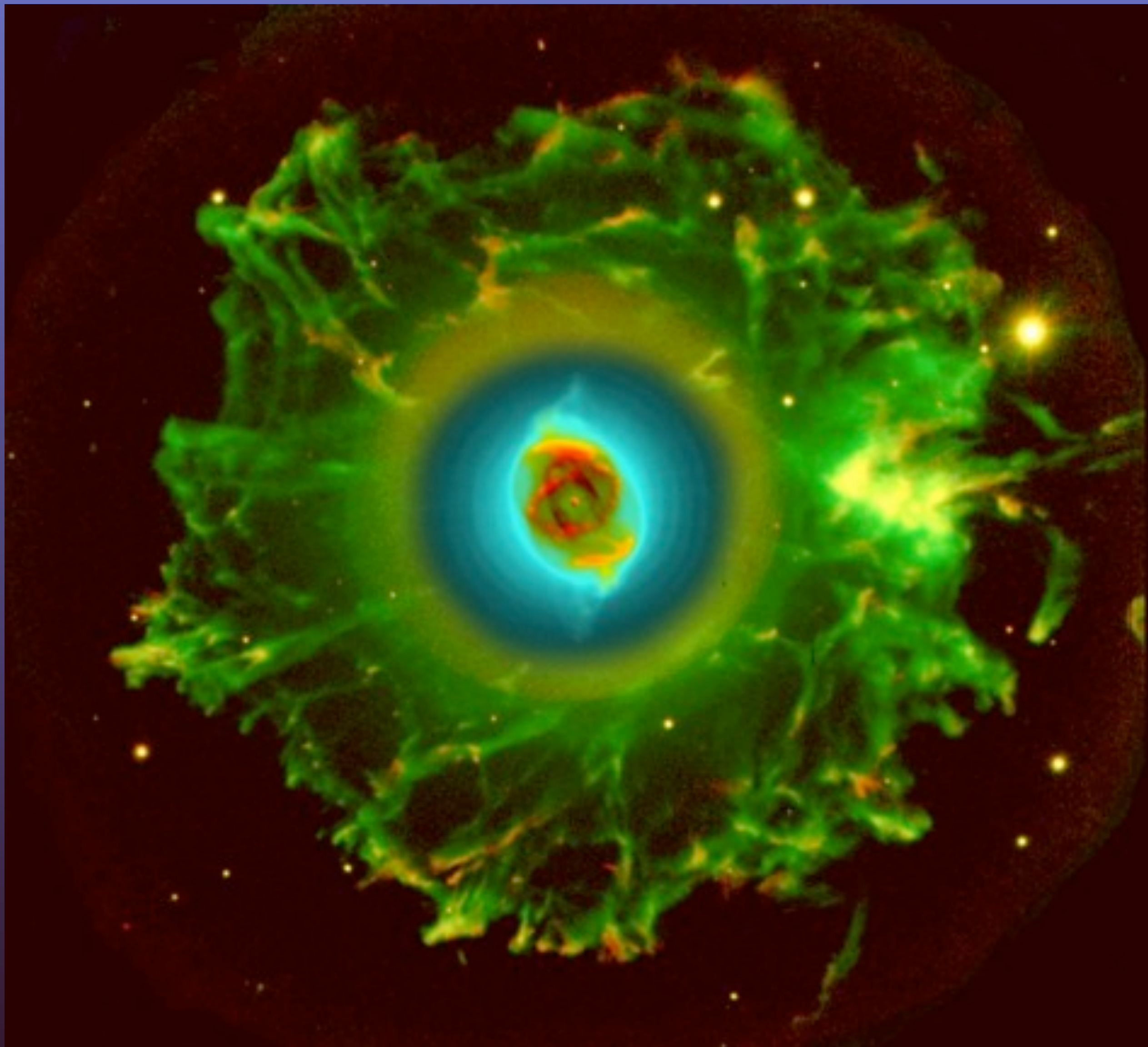


FR I vs FR I I classification
FRII: lobes fed by narrow relativistic jet

FRI: jet slowed by interaction with intergalactic medium


Cat’s eye nebula
HST
‘ansae’ (=’handles’)

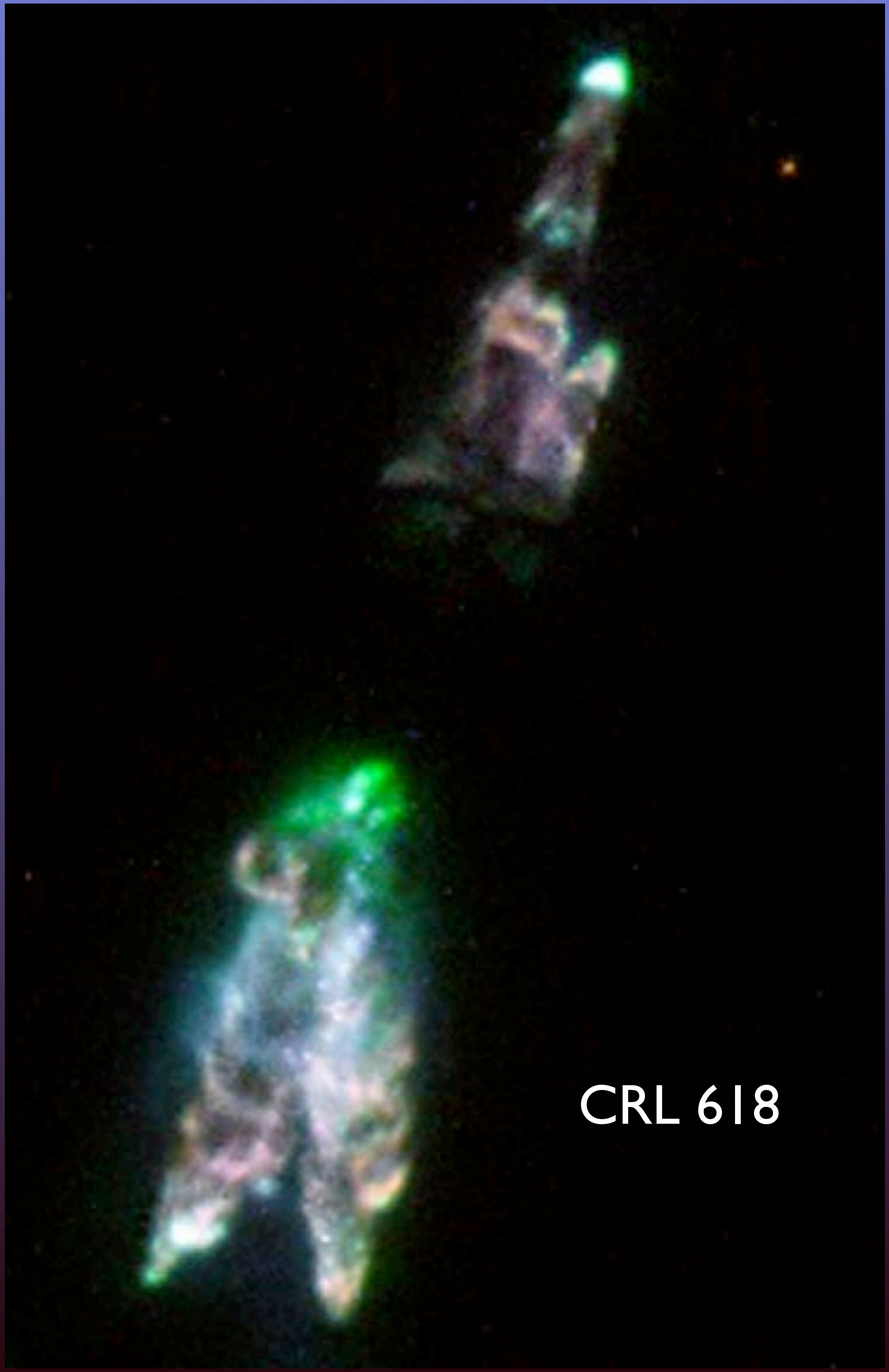
Nordic optical telescope



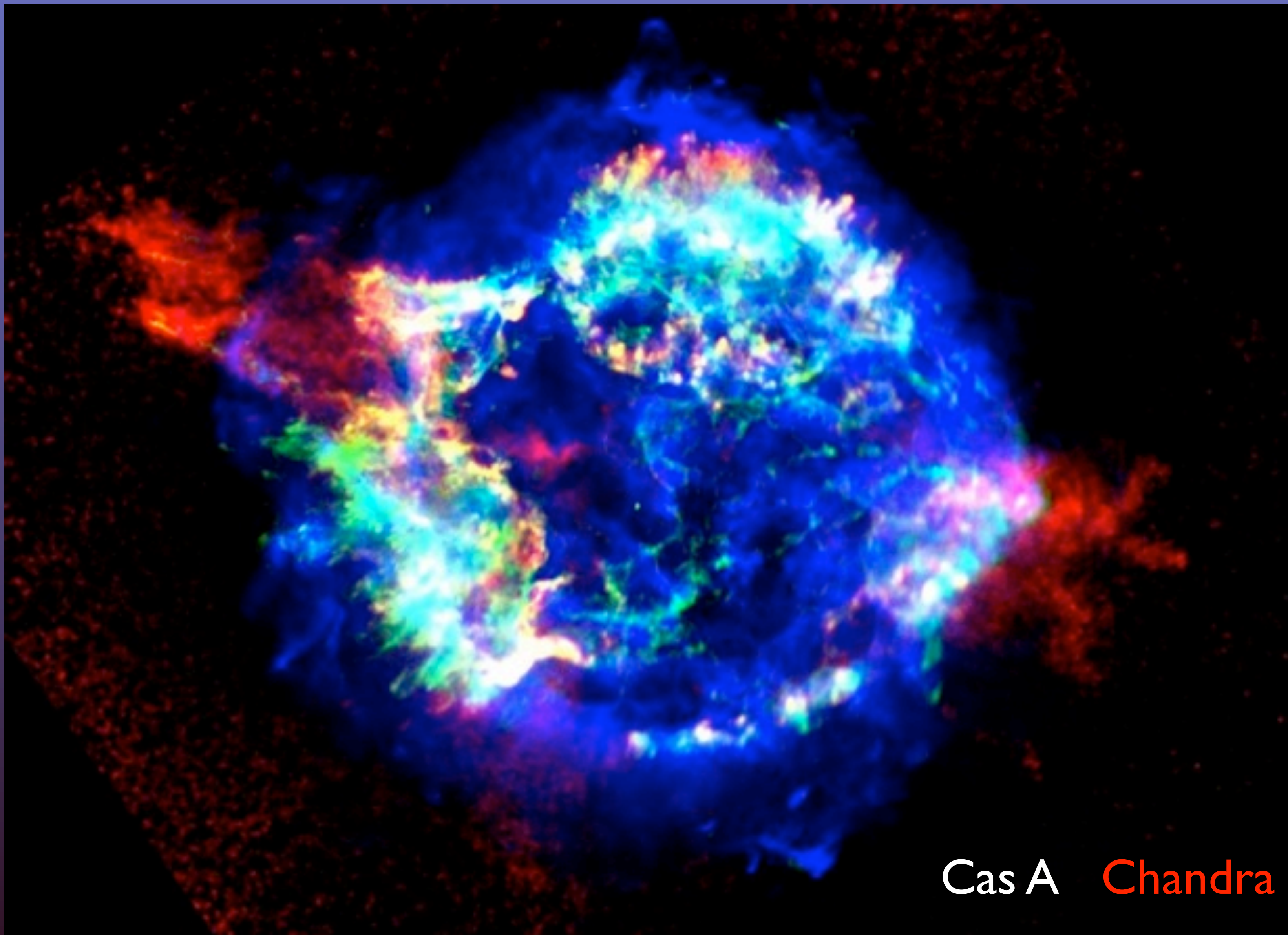
Planetary nebula: red supergiant star (AGB) loosing its envelope

some are in binaries, but 'jets' probably not due to mass transfer or accretion

$$v \sim 100 \text{ km/s}$$



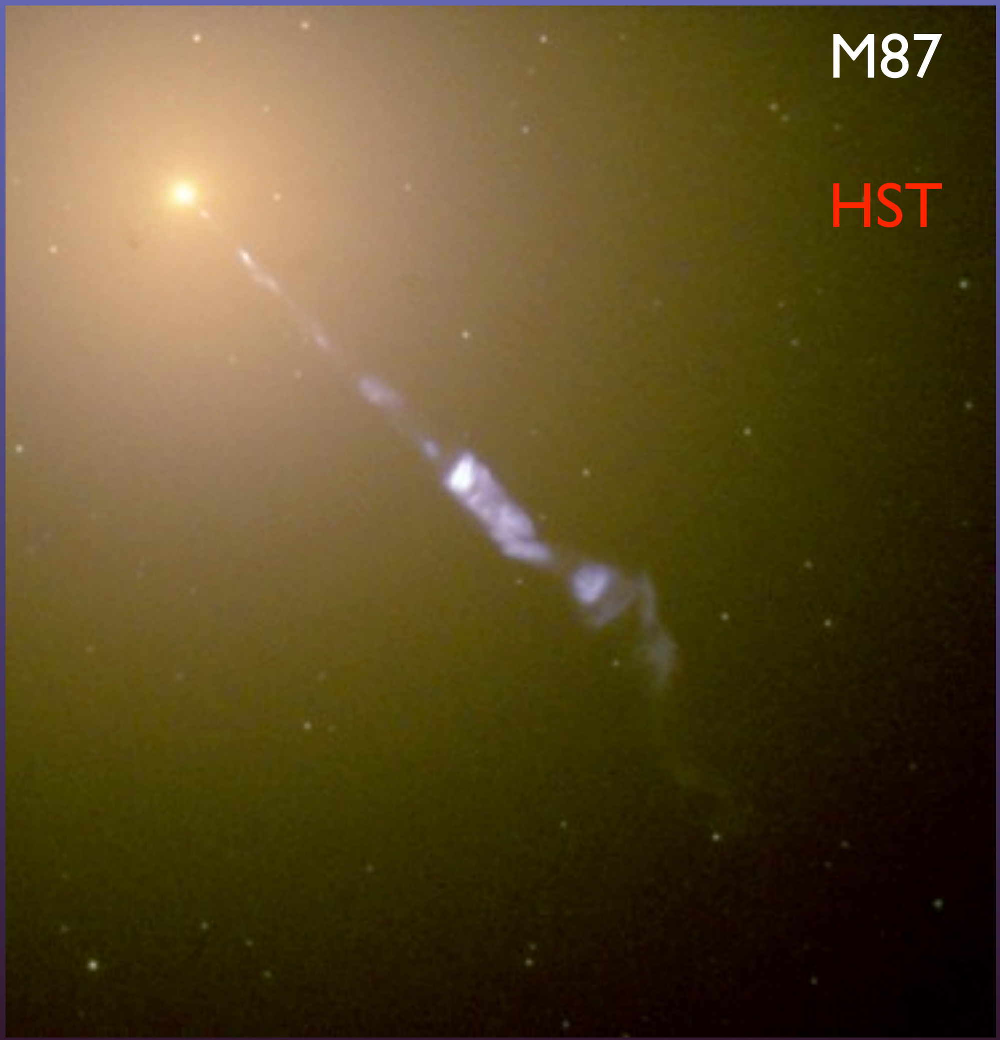
First phases of the formation of a planetary nebula ‘ansae’ in a supernova remnant



‘Observability’ of the source of the jet

	inner radius of disk	distance	angular scale (”)
	r_0	D	$100\ r_0/D$
nearby protostar	$3R_\odot$	500 pc	0”.003 ←
nearby AGN	10 AU	10 Mpc	0”.0001
galactic BHC	100 km	2 kpc	$3\,10^{-8}$ ”

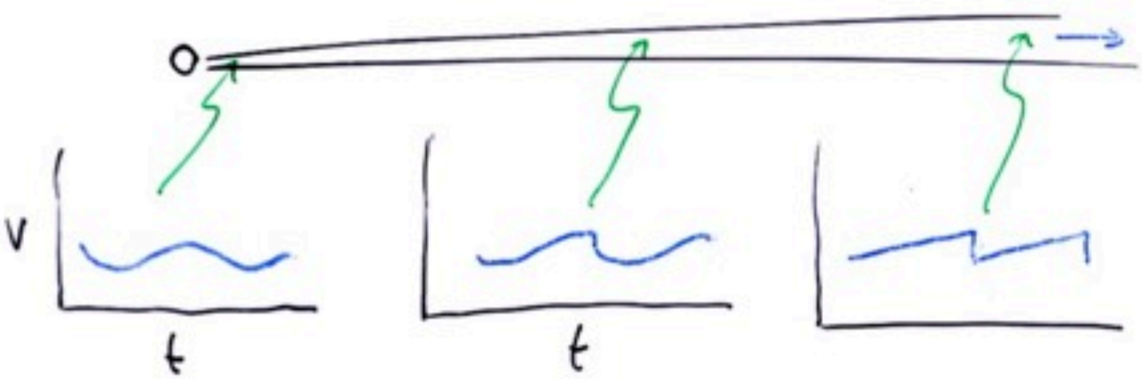
knots in jets



Knots in jets.

M 87

Proposed :
- internal instability (kink, sausage)
- interaction environment (K-H. inst., recollimation)
- jet-speed modulation (Rees '78)



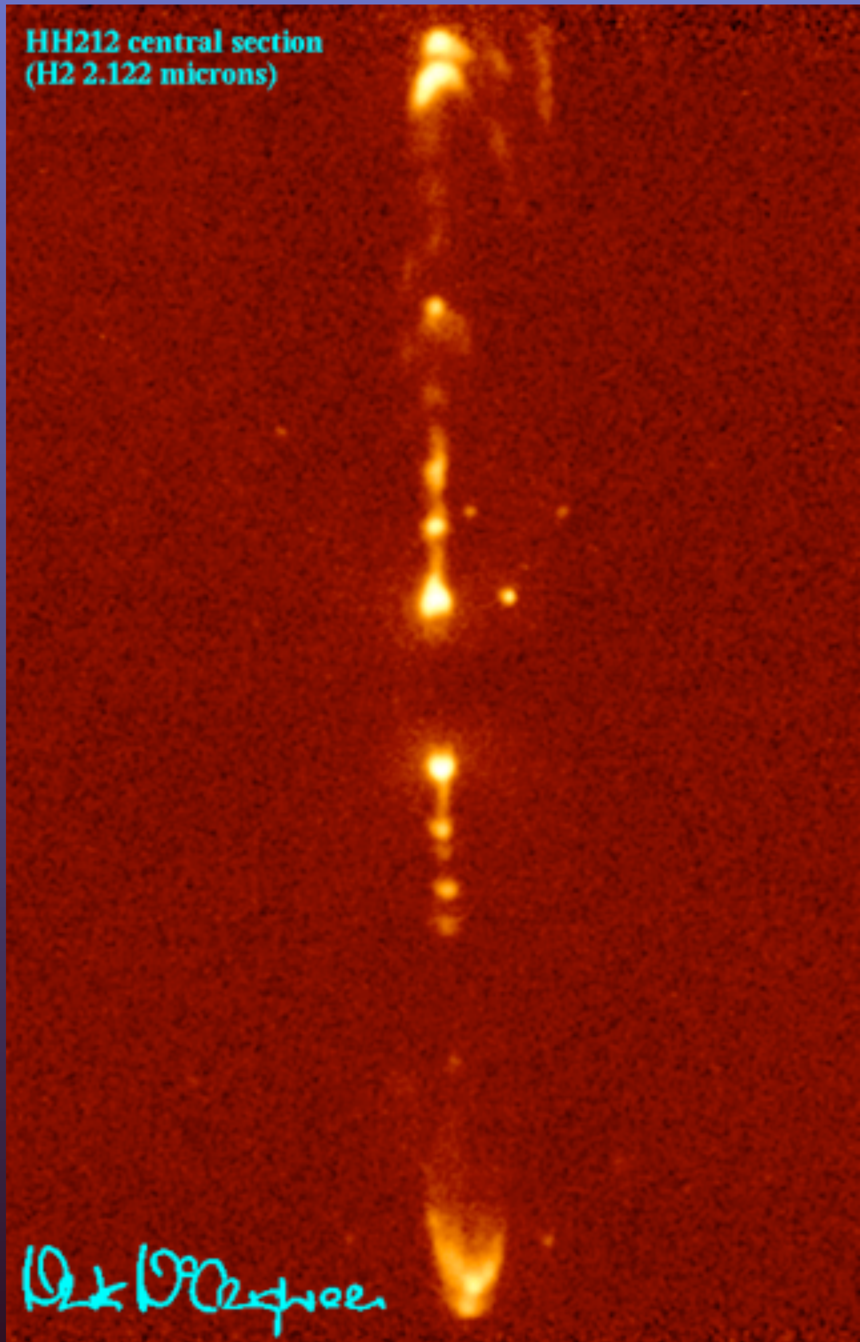
- can happen on many time scales
- produces strong shocks from modest modulation

Obs. support : symmetric ejection (μ-QSO's, protostellar jets)

HH 212

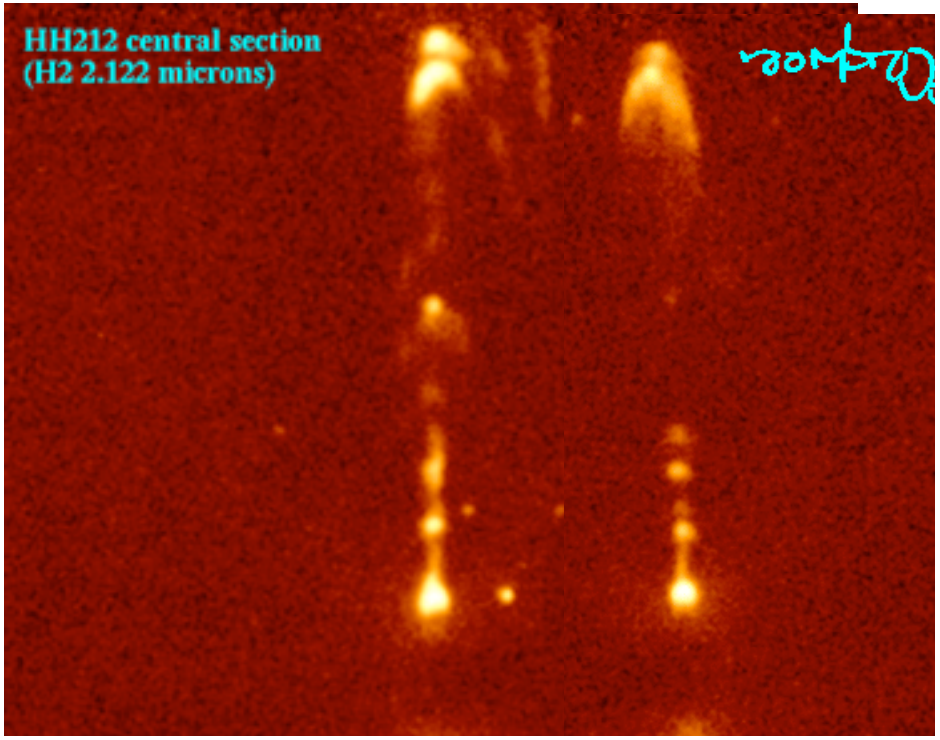
⇒ knot radiation from internal shock dissipation

Knot formation by modulation of flow speed:
internal shocks
- model for time variability in blazars and GRB



Knots in protostellar jets

- often symmetric
- source produces variable mass outflow
- flow speed from proper motion of knots



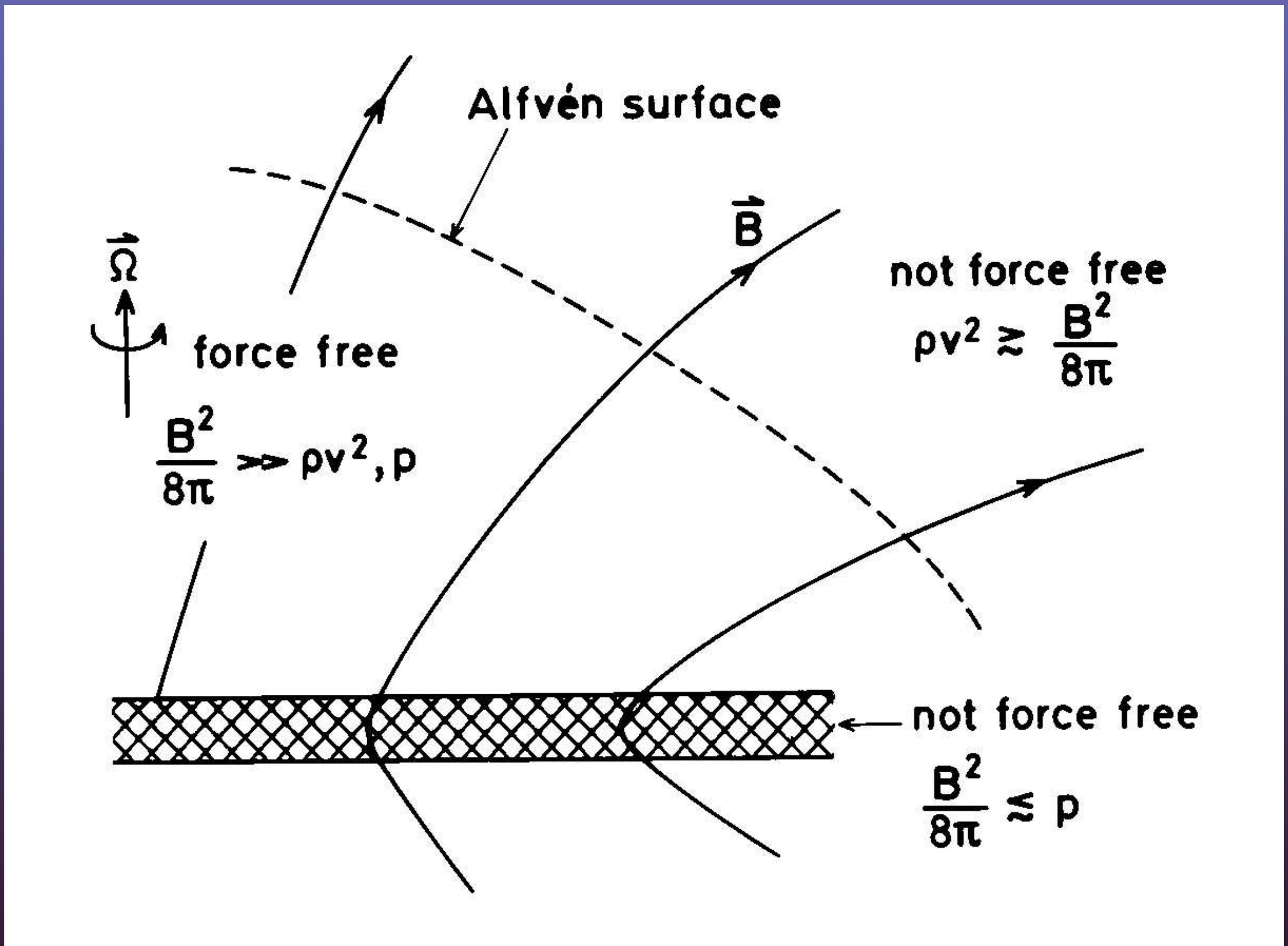
Next: magnetically powered jets

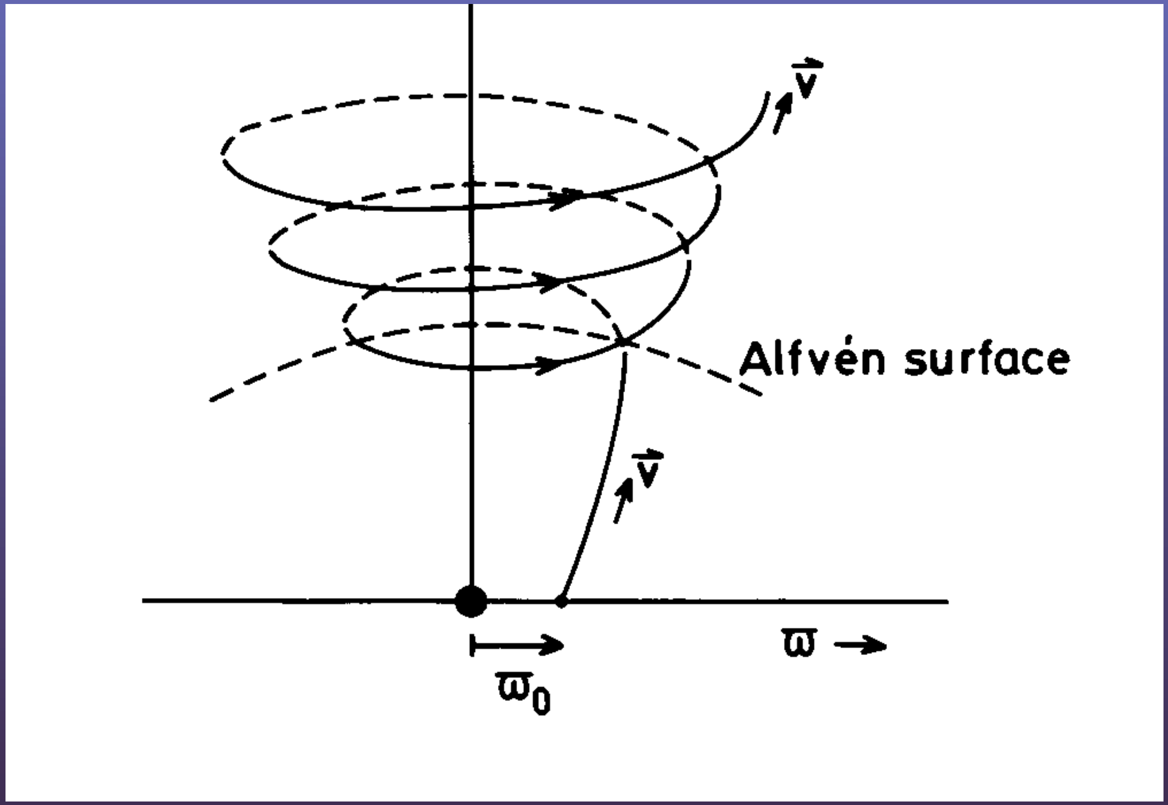
Magnetic jets: history

- Schatzman 1962 proposes spindown of the Sun
  by magnetic field in the solar wind
- Weber & Davis ’67, Mestel ’61-’67 formal
  MHD theory developed
- F.C. Michel ’69, ’73: relativistic wind from pulsars
- 1976: application to jets (Blandford, Bisnovatyi-Kogan &
  Ruzmaikin
- Blandford & Payne 1982: selfsimilar model
- ’80s, ’90s 2-D (axisymmetric numerical simulations)
- ’00s: 3-D simulations

The magnetic model

Gravitation → rotation → magnetic → kinetic




$\vec{v}$
Alfvén surface
$\vec{v}$
ϖ_0
$\varpi \rightarrow$

magnetohydrodynamics

`www.mpa-garching.mpg.de/~henk/mhd12.zip`

Fluid mechanics

fluid density

fluid velocity

gravity

$$\rho \frac{\mathrm{d}\mathbf{v}}{\mathrm{dt}} = -\nabla p + \rho \mathbf{g}$$

(Euler equation)

'Lagrangian' time derivative

'Eulerian' time derivative

'advection' term

$$\frac{\mathrm{d}f}{\mathrm{dt}} \equiv \frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

'continuity equation'
(= mass conservation)

Equations of (ideal) MHD

(Gaussian units)

$$\rho \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\nabla p + \frac{1}{4\pi}(\nabla \times \mathbf{B})\times\mathbf{B} + \rho\mathbf{g} \qquad (v \ll c)$$

$(\nabla \times \mathbf{B})$: current

$(\nabla \times \mathbf{B})\times\mathbf{B}$: Lorentz force

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$ MHD induction equation

2 equations for 2 vectors

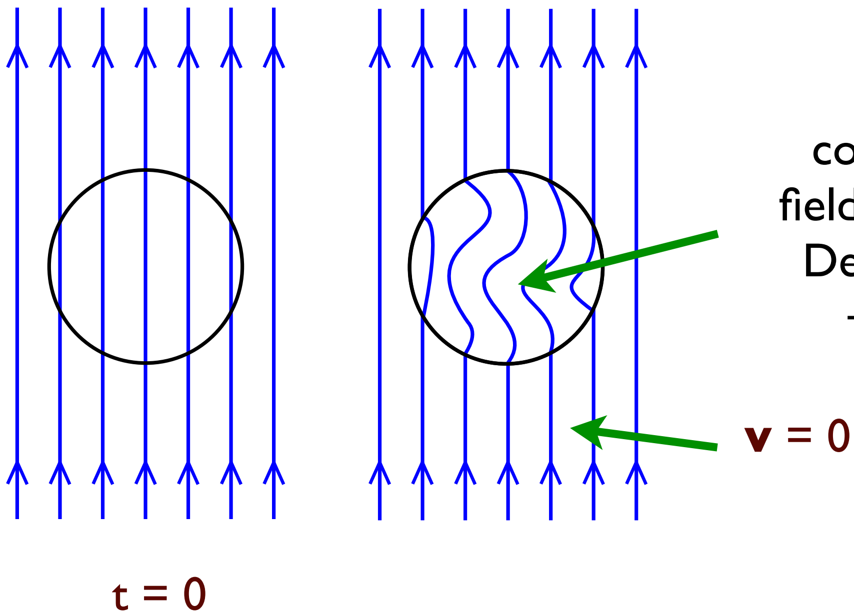
no currents, electric fields, charges appear in eqs.

$\mathbf{E}' = 0$ in a frame comoving with the flow ($v' = 0$)

$\mathbf{E} = -\mathbf{v} \times \mathbf{B}/\mathbf{c}$ (arbitrary $v/c < 1$)

Field amplification by fluid flows

as before: assume perfect conductivity

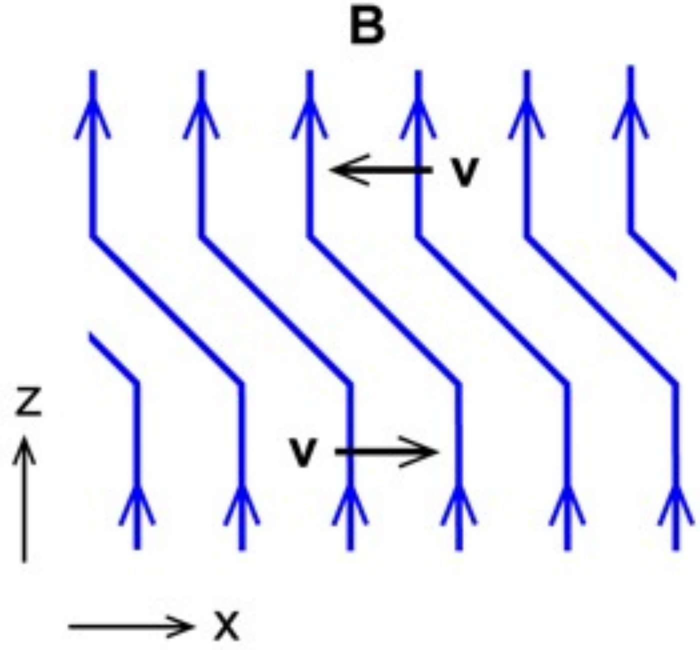


complex fluid motion:
field lines become longer.
Density of field lines ↑
→ field strength ↑

Cargese 3-5-13

‘shear amplification’ of field lines

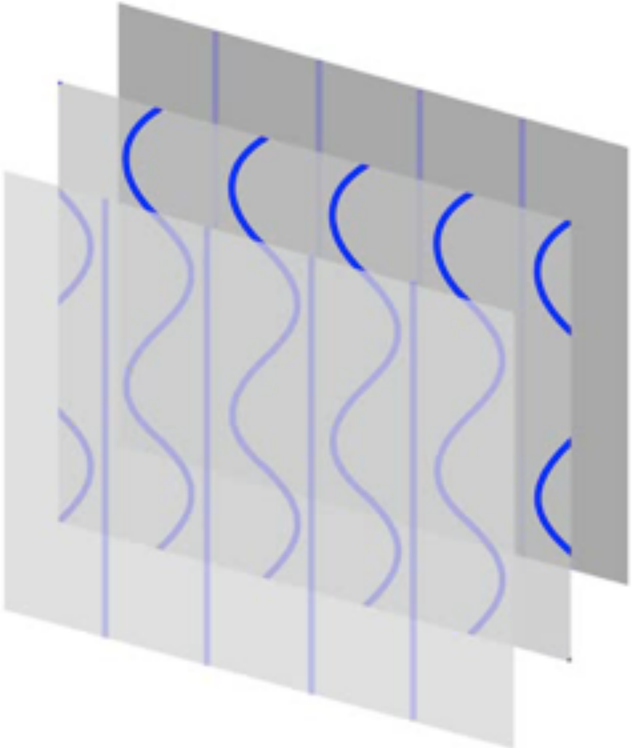
field initially weak

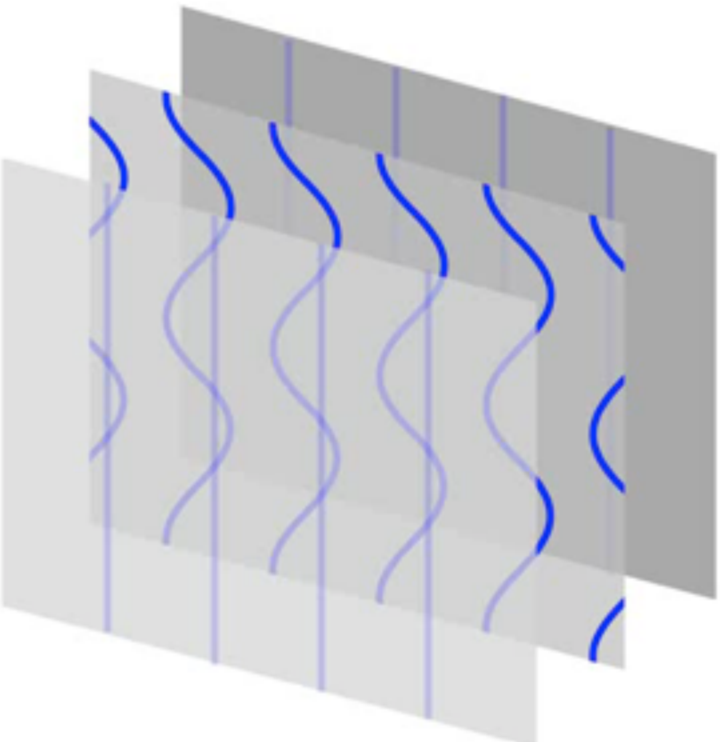


B increases ~ t

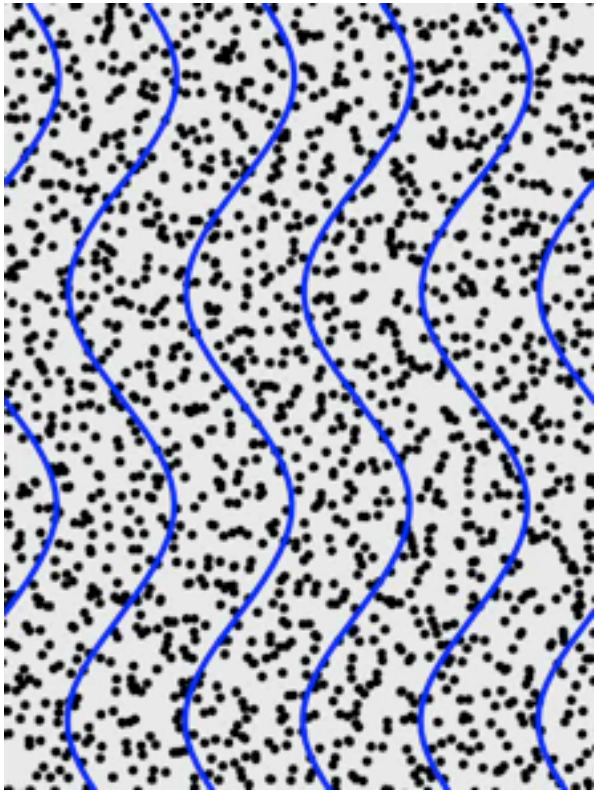
Field lines bent by the flow exert a restoring force

SHAO 13-6-12

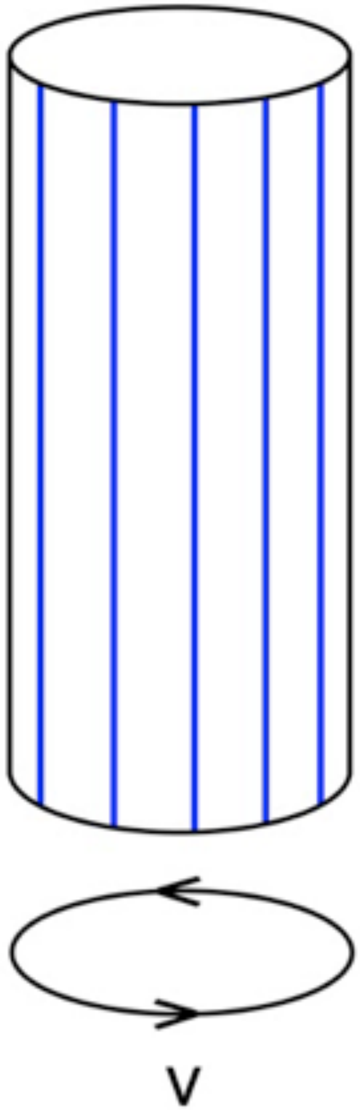




Alfvén waves

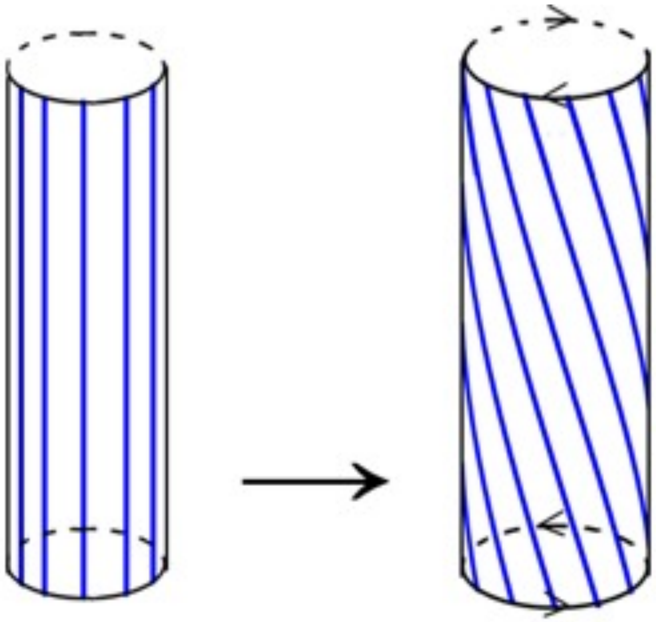


torsional Alfvén wave

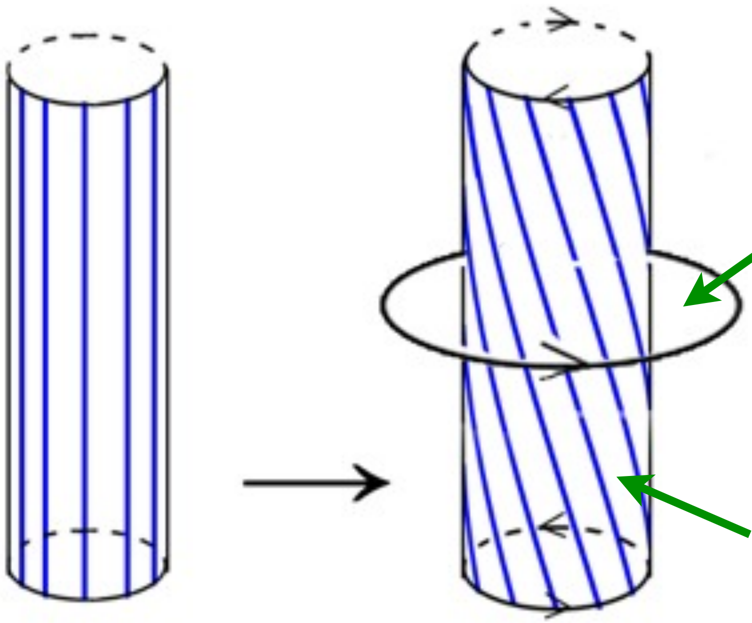


torsional Alfvén wave

Twisted flux tubes



Twisted flux tube in a field-free plasma



$$\oint_S \mathbf{j} \cdot \mathrm{d}\mathbf{S} = \int_l \mathbf{B} \cdot \mathrm{d}\mathbf{l} = \mathbf{0}$$

magnetic pressure on boundary increases due to B_ϕ^2

1. the net current along the tube *vanishes*
2. the tube *expands*

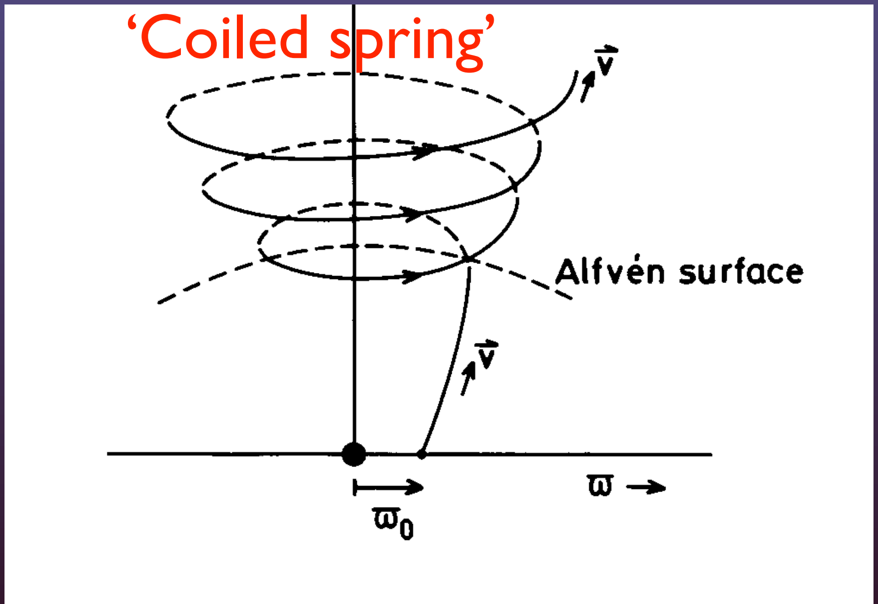
Magnetic acceleration

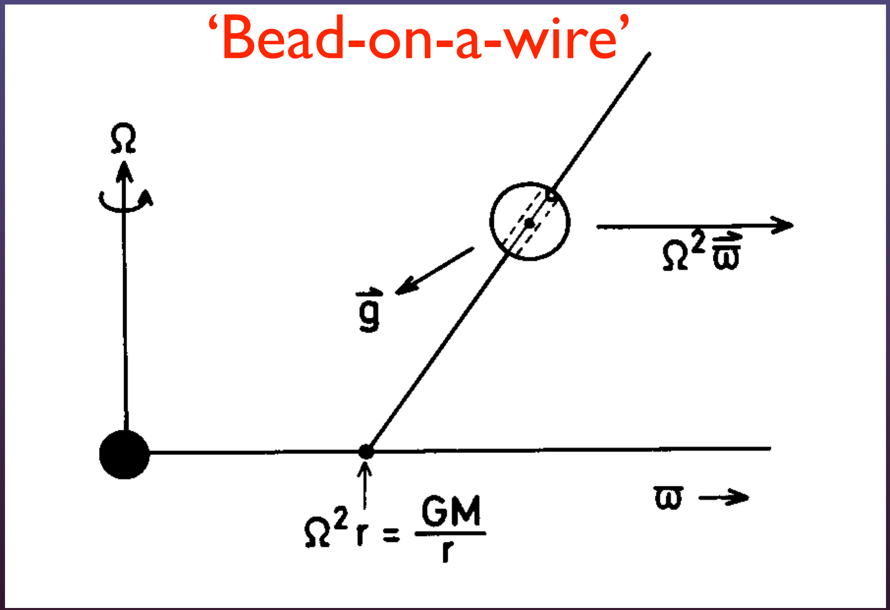
rotation → magnetic → kinetic

region $r \sim r_{\text{Alfven}}$

- Magnetic pressure
- Centrifugal acceleration
- Poynting flux conversion
- 'Magnetic towers'

} *Equivalent*





Steady, rotating, axisymmetric magnetic flow
- flow accelerated along field lines
- compute asymptotic speed

Model: 'Weber-Davis' (1967)

derivation: Mestel, L. Stellar magnetism, Oxford U Press, 1999
Sakurai, T. 1985, A&A 152, 121
http://www.mpa-garching.mpg.de/~henk/pub/jetrevl.pdf

Cold Weber-Davis model

Simple model:

- radial field ⊥ $\vec{\Omega}$
- cold limit $P_g = 0$
- $B_p \sim \frac{1}{r^2}$

(cold Weber & Davis model)

Visualize: equatorial plane. (Applies at all latitudes.)

Assumed:
- poloidal field fixed
- gas pressure neglected

compute:
- azimuthal field B_ϕ
- flow speed

Question: how does V_∞ depend on $\dot{M}$?

Mass-flux "per field line": $\dot{m} = \frac{\rho v_p}{B_p}$ [ ]: $(g\, cm^{-3})^{1/2}$

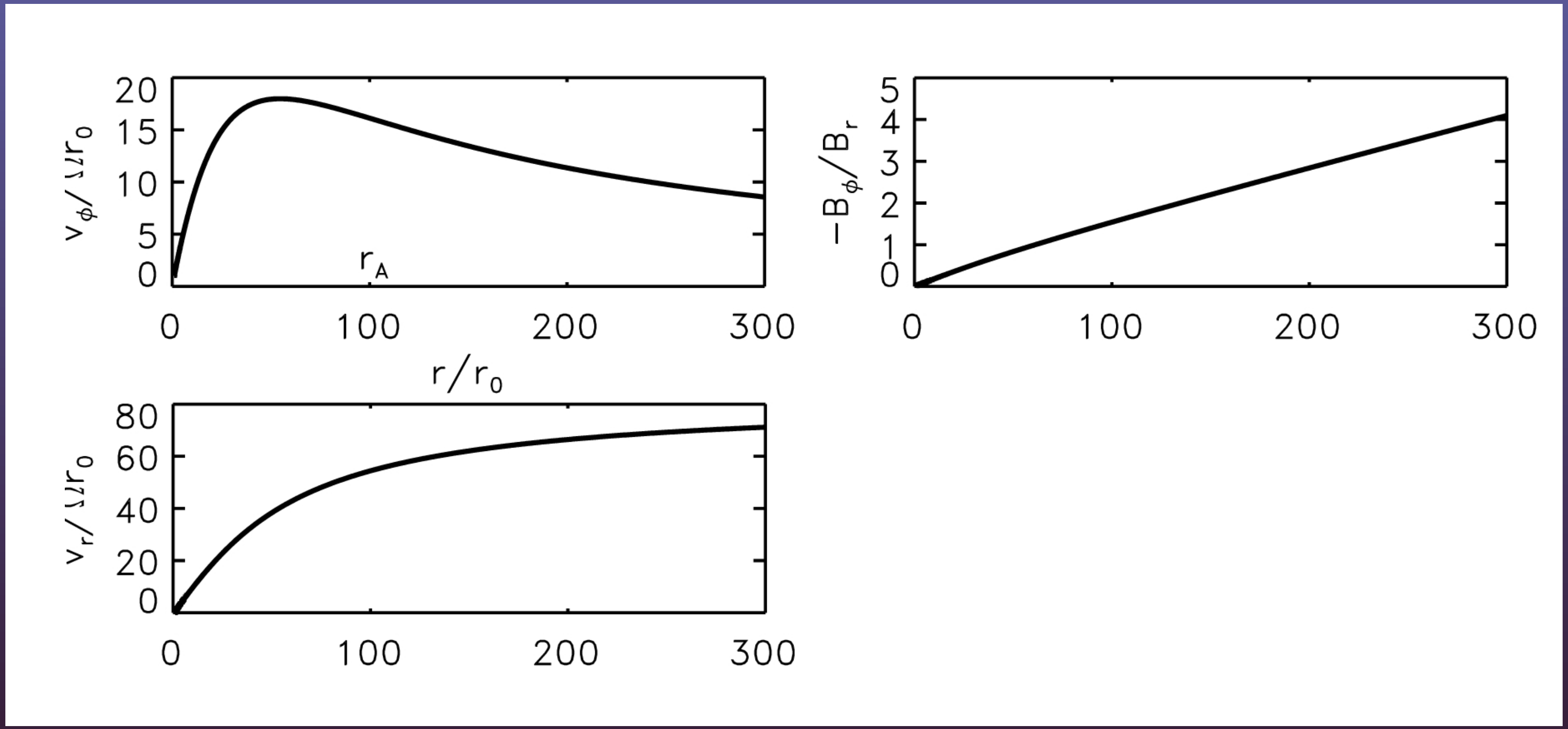
Natural unit for $\dot{m}$: $\dot{m}_0 = \frac{B_0}{4\pi \Omega r_0}$

Let $\eta = \dot{m}/\dot{m}_0$.

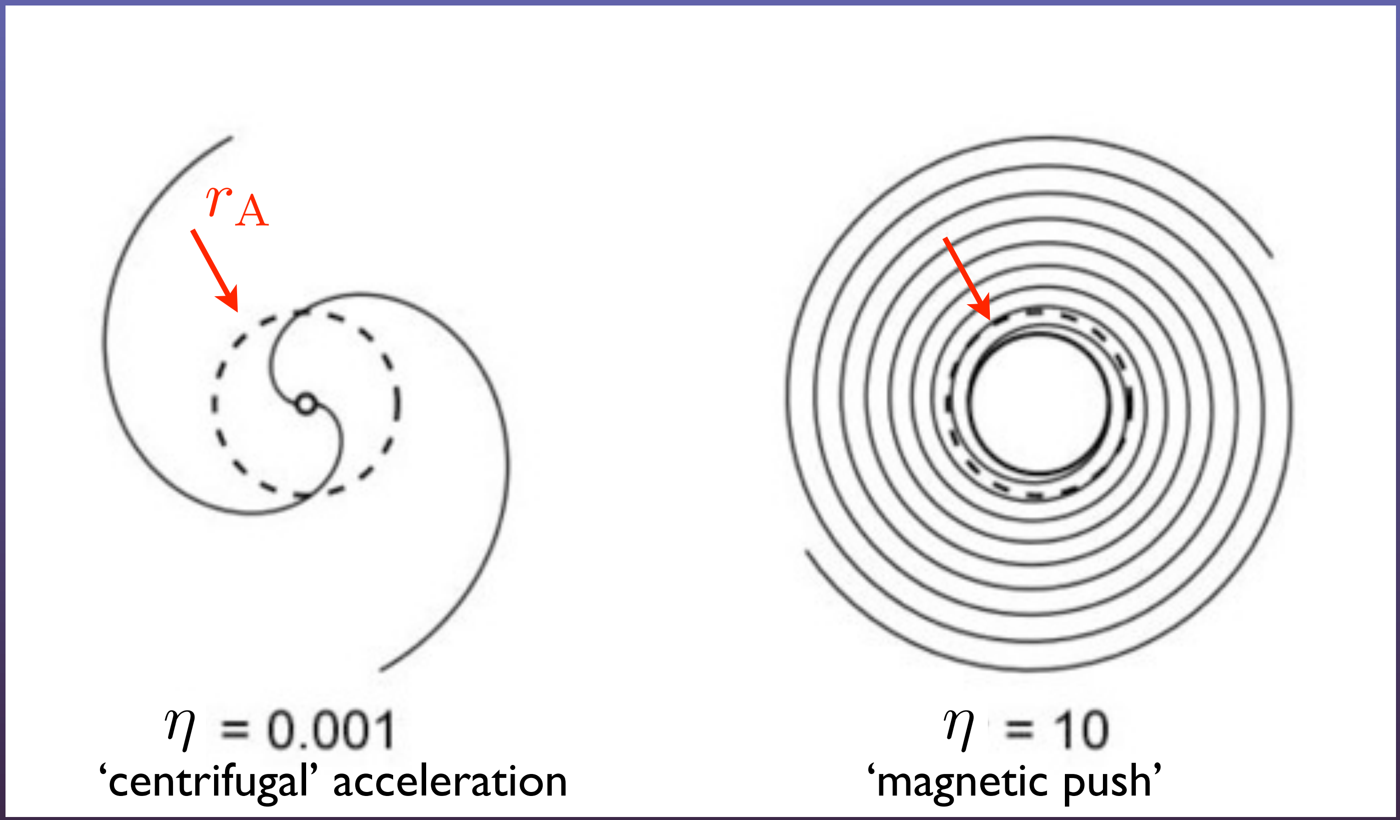
Solution:

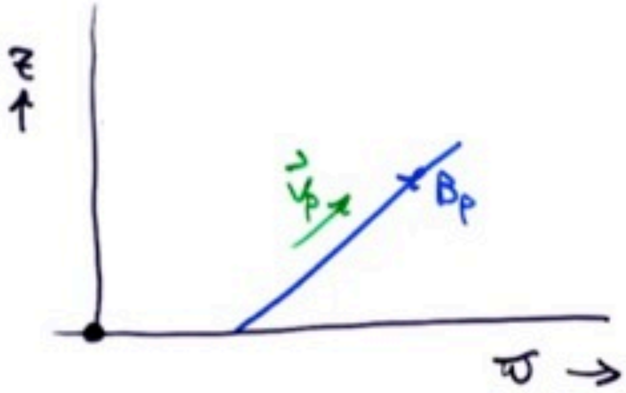
		$\eta \ll 1$	$\eta \gg 1$
$\frac{r_A}{r_0}$	$= \left(\frac{3}{2} + \eta^{-2/3}\right)^{1/2}$	$\eta^{-1/3}$	$\left(\frac{3}{2}\right)^{1/2}$
$\frac{V_\infty}{\Omega r_0}$	$= \eta^{-1/3}$		$\eta^{-1/3}$
$\frac{J}{\dot{m}_0 \Omega r_0^2}$	$= \eta\left(\frac{3}{2} + \eta^{-2/3}\right)$	$\eta^{1/3}$	$\frac{3}{2}\eta$
$\frac{V_\infty}{\Omega r_A}$	$= \eta^{-1/3}\left(\frac{3}{2} + \eta^{-2/3}\right)^{-1/2}$	1	$\left(\frac{2}{3}\right)^{1/2}\eta^{-1/3}$

Cold Weber-Davis model: example



Shape of the field lines





Acceleration (in inertial frame):

a) $(j \times B)_p$

$$-\hat{i}\cdot\left(\nabla \frac{B_\varphi^2}{8\pi} + \frac{B_\varphi^2}{4\pi\varpi}\vec{e}_\varpi\right)$$ (>0 for acceleration)

equiv.

b) In corotating frame: Bernoulli integral:

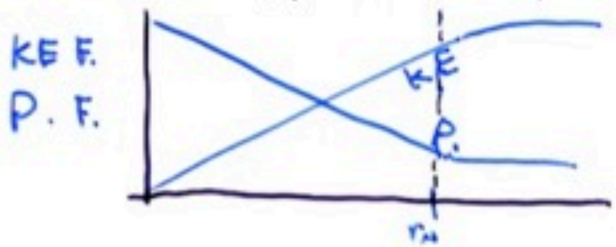
$$\frac{1}{2}v_p^2 - \frac{1}{2}\Omega^2\varpi^2 + \frac{1}{2}(v_\varphi - \Omega\varpi)^2 - \frac{GM}{r} + \text{enthalpy} = E = \text{cst}$$

centrifugal acceleration

small if corotating

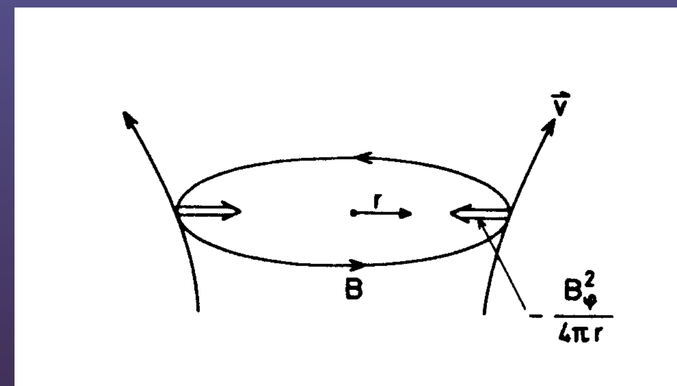
c) "Energy fluxes":

kinetic energy flux ↔ poynting flux



Equivalent descriptions of magnetic acceleration

- ‘centrifugal’
- magnetic pressure
- ‘Poynting flux conversion’



Poynting flux in MHD

$$\mathbf{S} = \frac{c}{4\pi}\mathbf{E}\times\mathbf{B}$$ (Gaussian units)

in MHD: $\mathbf{E} = -\mathbf{v}\times\mathbf{B}/c$

$$\rightarrow \quad \mathbf{S} = \frac{1}{4\pi}\mathbf{B}\times(\mathbf{v}\times\mathbf{B}) = \mathbf{v}_\perp\frac{B^2}{4\pi}$$

$$u_\mathrm{m} = \frac{B^2}{8\pi}$$ magnetic energy density

$$P_\mathrm{m} = \frac{B^2}{8\pi}$$ magnetic pressure

$$\mathbf{S} = \mathbf{v}_\perp(u_\mathrm{m} + P_\mathrm{m})$$ 'magnetic enthalpy flux'

Poynting flux in MHD

$$\mathbf{S} = \frac{c}{4\pi}\mathbf{E}\times\mathbf{B}$$ (Gaussian units)

in MHD: $\mathbf{E} = -\mathbf{v}\times\mathbf{B}/c$

$$\rightarrow \quad \mathbf{S} = \frac{1}{4\pi}\mathbf{B}\times(\mathbf{v}\times\mathbf{B}) = \mathbf{v}_\perp\frac{B^2}{4\pi}$$

$$u_\mathrm{m} = \frac{B^2}{8\pi}$$ magnetic energy density

$$P_\mathrm{m} = \frac{B^2}{8\pi}$$ magnetic pressure

$$\mathbf{S} = \mathbf{v}_\perp(u_\mathrm{m} + P_\mathrm{m})$$ 'magnetic enthalpy flux'

Steps in jet formation

1 "launching".

Transition from disk to flow

- how much mass flows into the jet?

2 Acceleration

- magneto-centrifugal picture
- 'push' from magnetic pressure B_ϕ^2

3 collimation

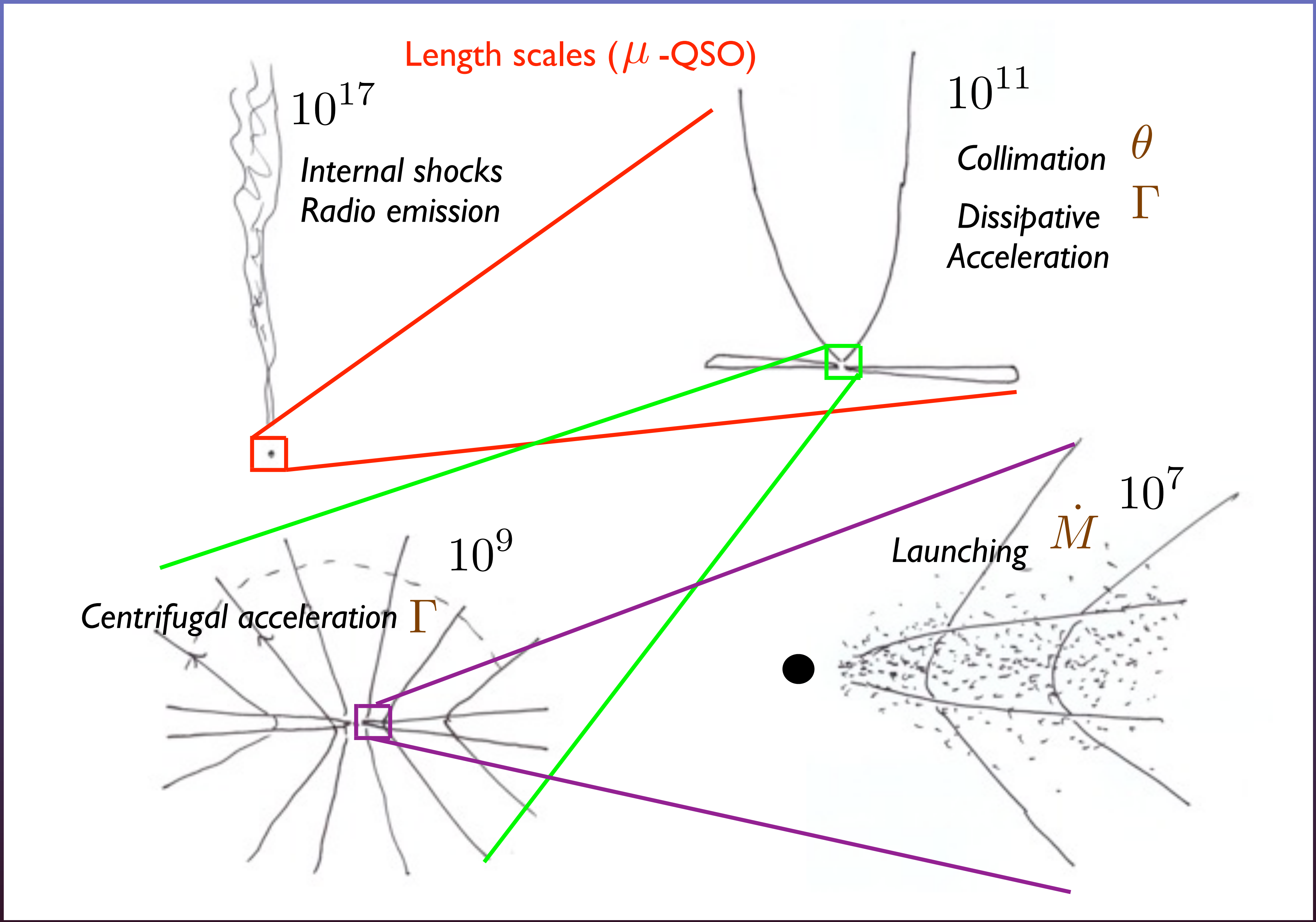
- how/where does external medium determine opening angle of flow?

Problem areas and current topics

arxiv.org/abs/0804.3096

- ‘length scales’
- net magnetic flux of a disk
- ‘hoop stress’ collimation
- acceleration ‘by dissipation’
- 3-D stability of jets
- disk-jet transition

length scales (microquasars/X-ray binaries)



launching

How much mass is launched?
(In num. simulations: $\dot{m}$ is set by hand)

Depends on
- details of temperature structure of disk atmosphere
  → need to know energy dissipation in atmosphere
- strength and inclination of field lines at disk surface

Better defined in hot (near virial) accretion:
flow already 'loosely bound' in gravitational potential
→ perhaps only radiatively inefficient flows make jets ?

launching

How much mass is launched?
(In num. simulations: $\dot{m}$ is set by hand)

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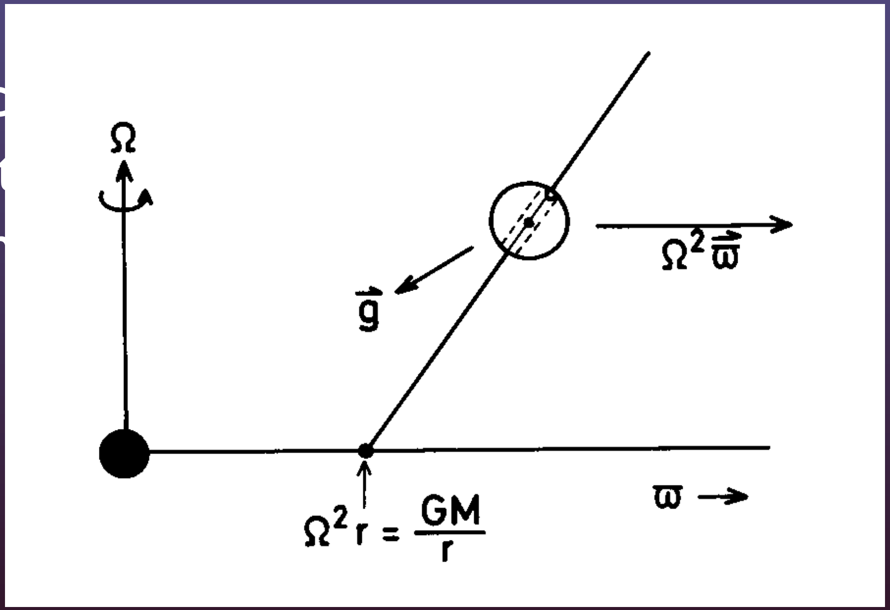
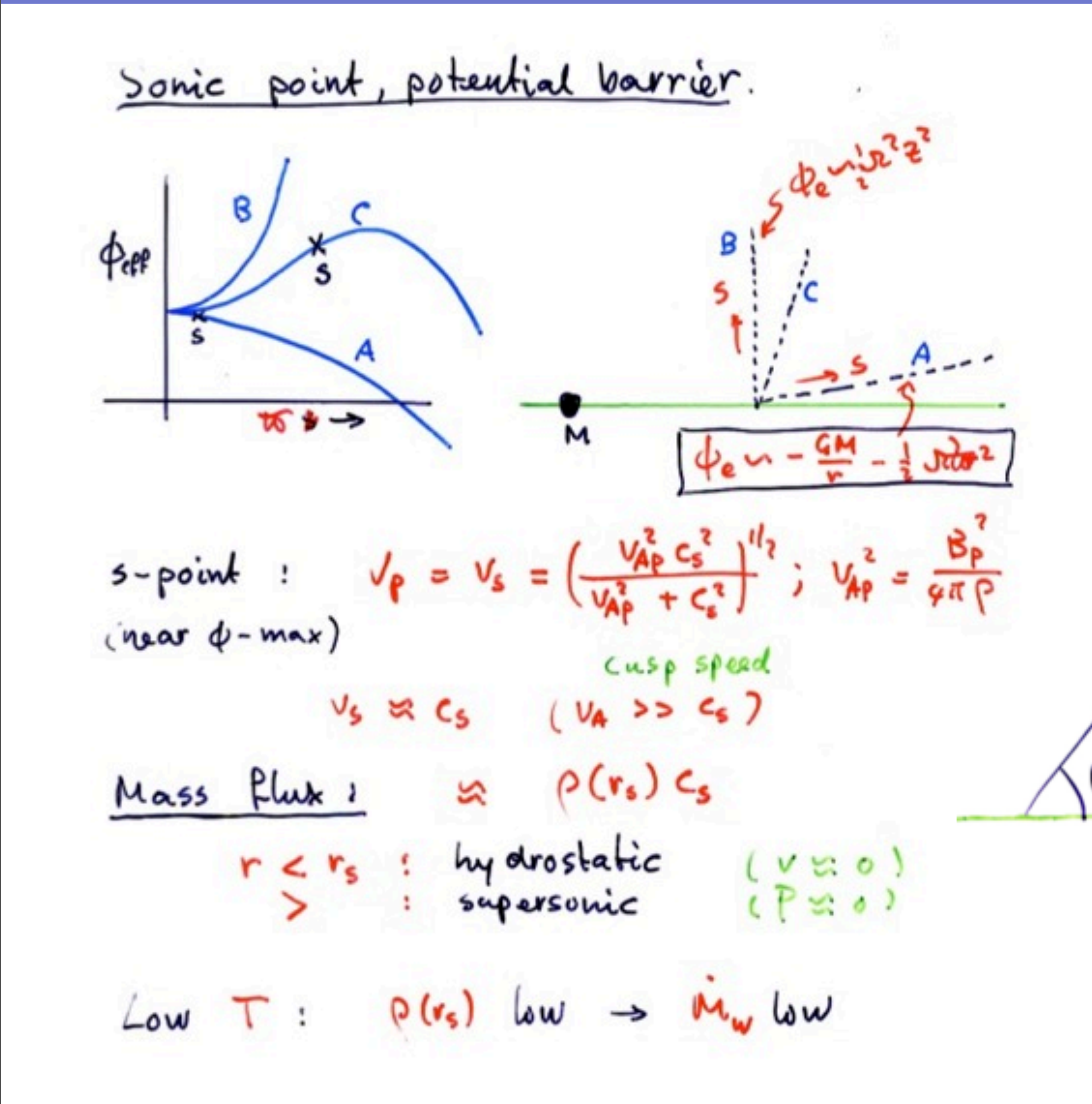
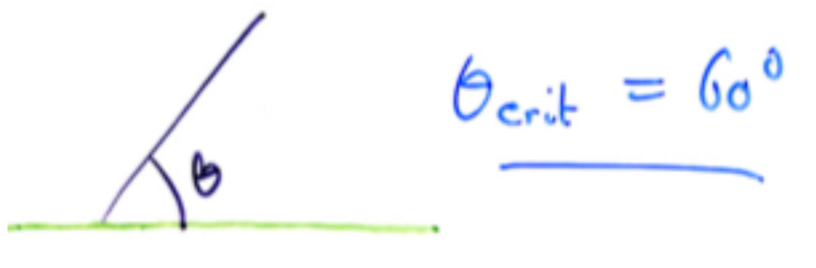
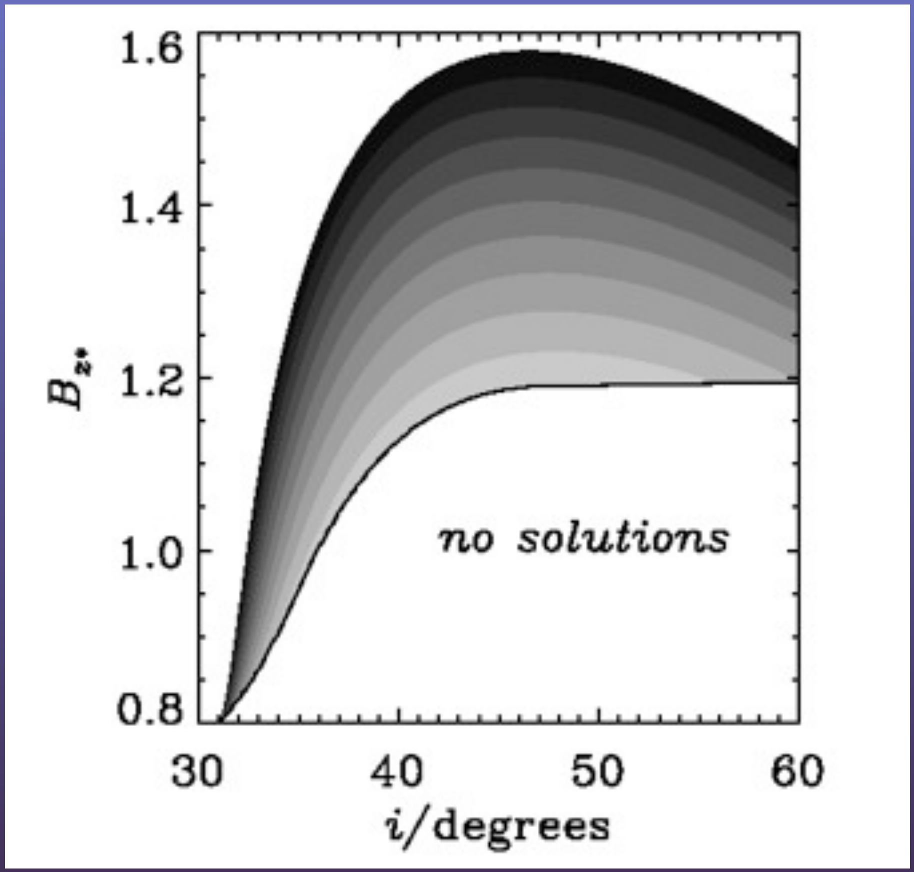




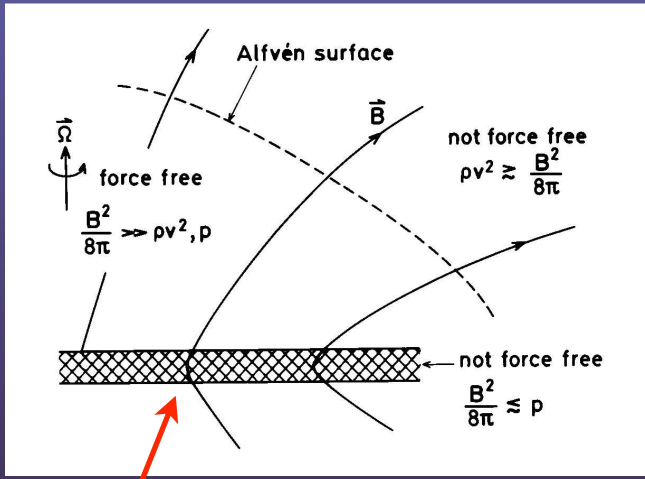
Transition between disk and jet, the 'launching region'





Dependence of mass flux
on strength and inclination of $\mathbf{B}$

Ogilvie and Livio 2001



tension force (outward) reduces rotation rate
→ centrifugal force less
→ potential barrier increased

Below a minimum field strength no steady flow solutions

launching

‘Poloidal’ (p): in a plane containing the rotation axis
‘toroidal’ = azimuthal (ϕ)

Shape of field above the disk

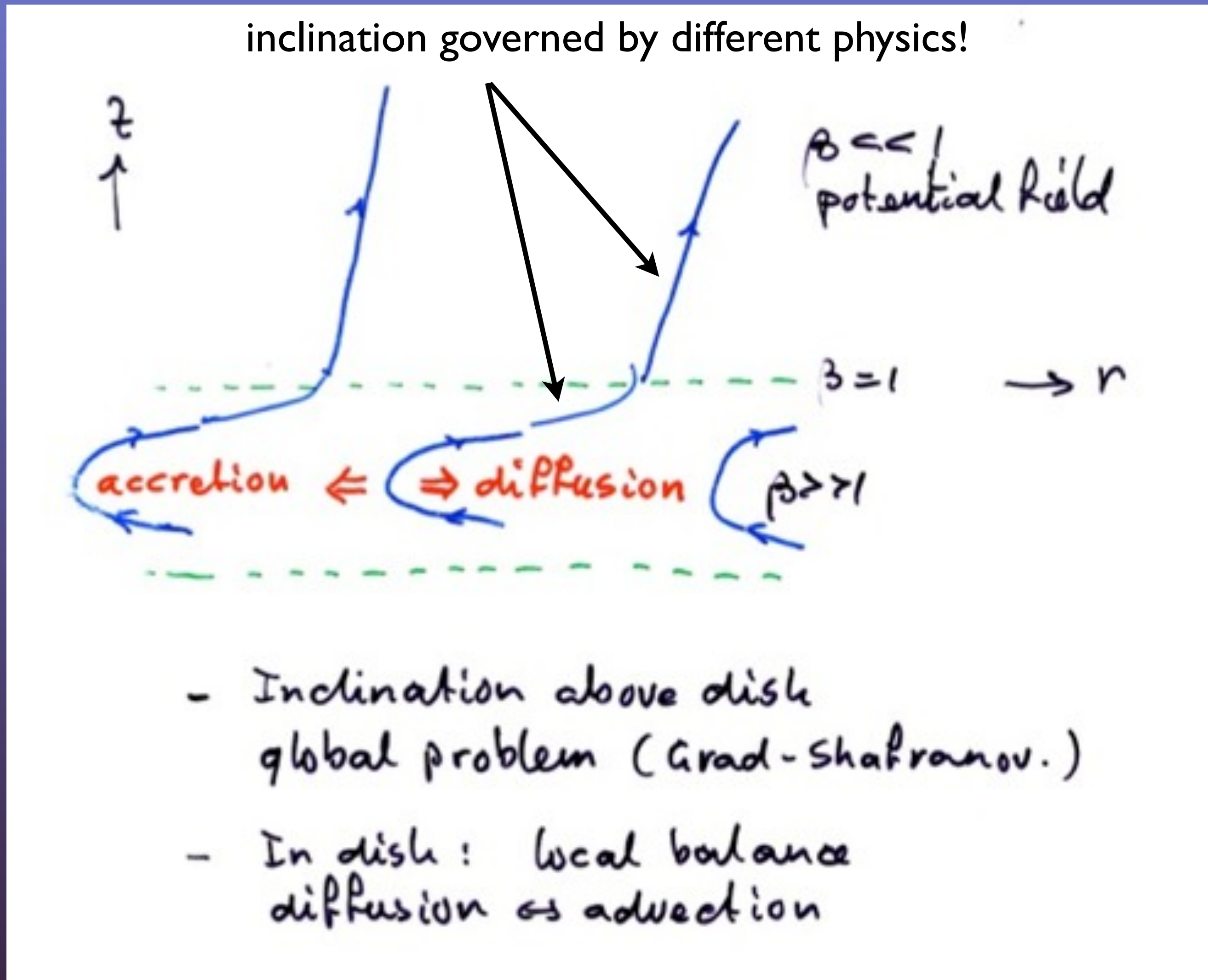
- (well) inside $r_{\rm A}$:

  Magnetic field dominates over other forces
  → field *force free*, $(\nabla \times \mathbf{B}) \times \mathbf{B} = 0$
  (well) inside $r_{\rm A}$: $B_\phi \ll B_{\rm p}$, neglect.

- → field approx. *potential*, $\nabla \times \mathbf{B} = 0$, $\mathbf{B} = -\nabla \Phi_{\rm m}$

- potential field: field lines fan out away from concentrations (like bar magnets)

→ field line shape, inclination at surface are *global* problem



beware: literature confusing

centrifugal acceleration ↔ collimation

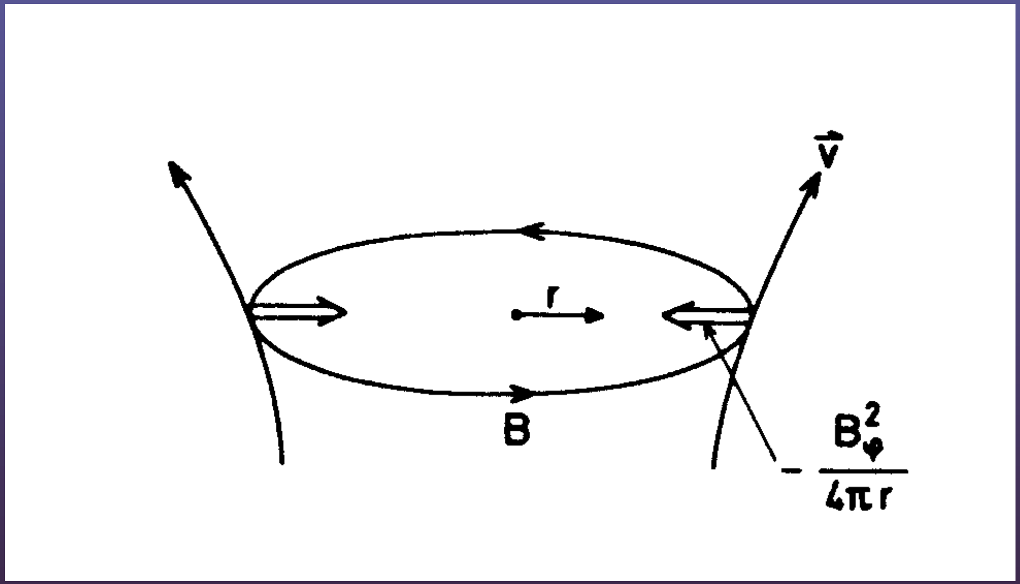
centrifugal acceleration requires field bent outward
→ need collimation after acceleration
demanding: AGN jets often < 3 degrees

‘Hoop stress

$(\nabla \times \mathbf{B}) \times \mathbf{B}$: tension *along* field lines

: pressure $\perp$ field lines

loop of field lines wants to contract



Field beyond r_A mostly azimuthal

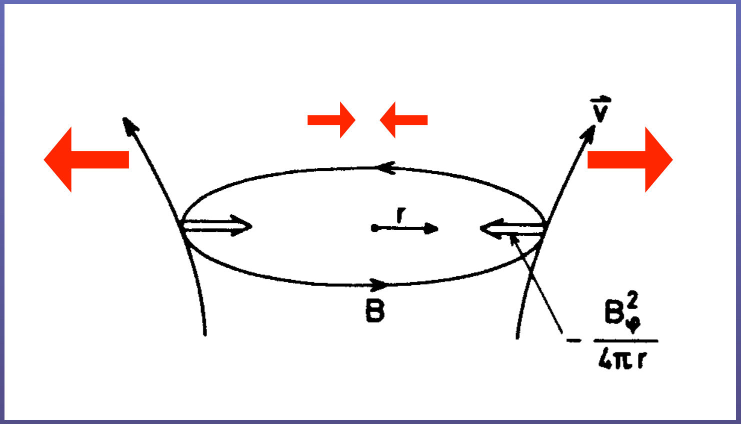
contraction towards:

jet ‘collimated by hoop stress’?

‘self-collimation’?

collimation

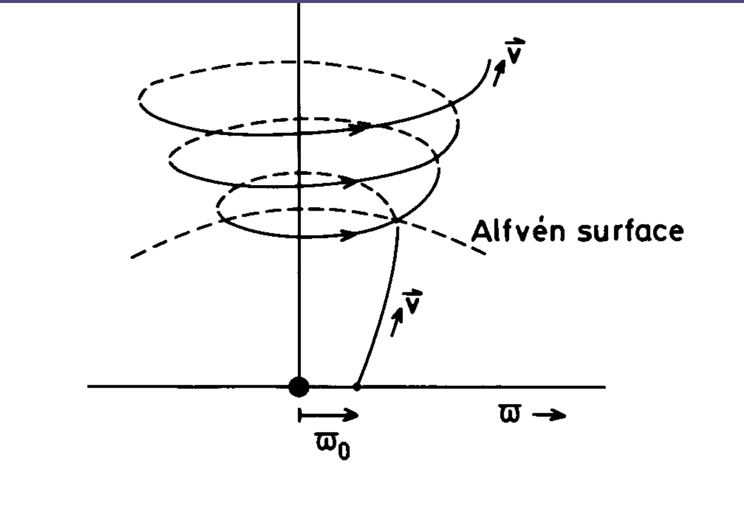
Def. *Collimation*: angle between flow lines
not *width* of jet



Magnetic fields are expansive
(↔ 'tensor virial theorem')

Azimuthal field adds energy density

azimuthal field *decollimates*



B_ϕ can collimate a jet *core*, but only at expense of overall expansion (*cf.* E.N. Parker 1979)

collimation ultimately
due to something external

Expansive nature of magnetic fields

Useful theorem ('the vanishing force-free field'):

A field which is force free $(\nabla \times \mathbf{B}) \times \mathbf{B} = 0$
everywhere (and finite) *vanishes identically*

Physics: there has to be a boundary that takes up the stress in the field and keeps it together.

The twisted field of a magnetically powered jet is not good for collimation

(beware of the literature)

collimating agents?

- disk surface $\rightarrow$ *toroidal field has to extend all the way from axis to disk surface*
- gas in the star-forming cloud
- material in the broad line outflow (AGN)
- a poloidal magnetic field in (the outer parts of) the disk

- Nothing. Ballistic flow, sideways expansion unconfined.
  (relativity helps: sideways expansion reduced by time dilatation)

observed opening angle, nonrelativistic: $\theta = v_{\rm expansion}/v_{\rm jet}$

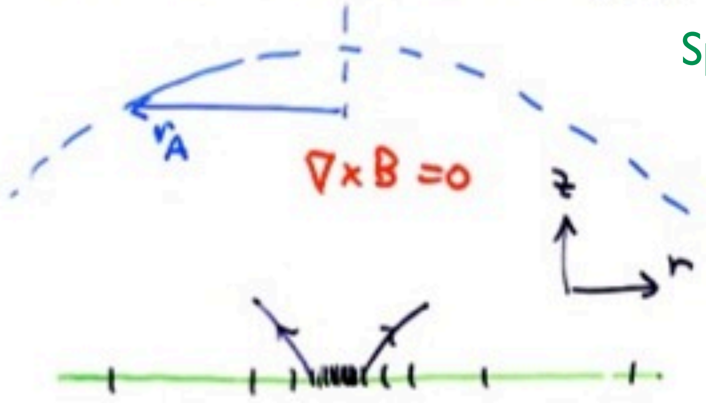
" " flow at Lorentz factor Γ : $\theta = \frac{1}{\Gamma} v_{\rm exp,comoving}/c$

flow of relativistic plasma: ($v_{\rm expansion} \approx c_{\rm s} = c/\sqrt{3}$):

$$\theta \approx \frac{1}{\Gamma\sqrt{3}}$$

* "Poloidal" collimation, by disk field.

Spruit, Foglizzo & Stehle 1997

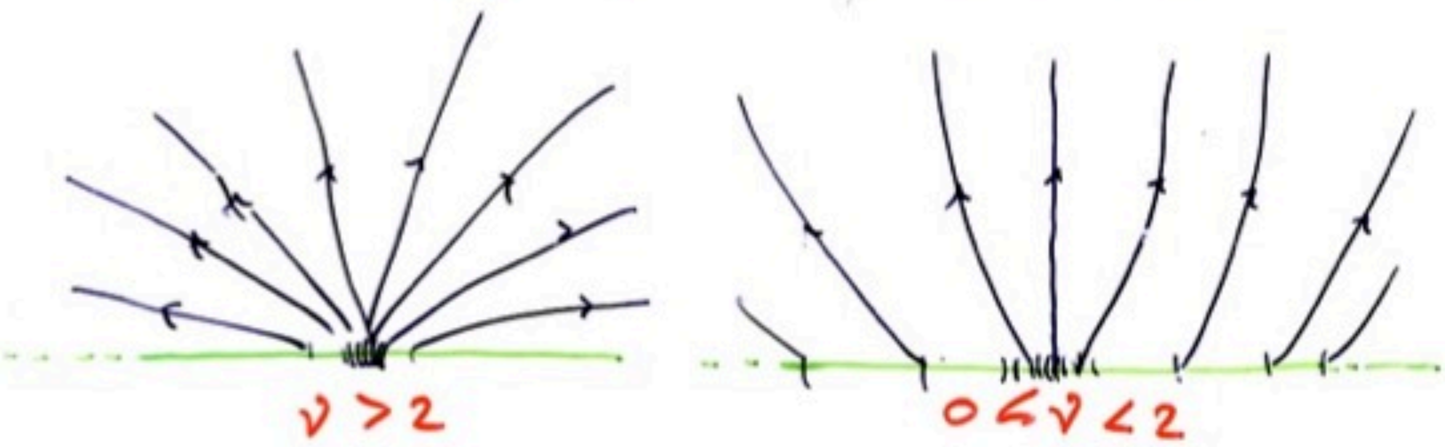


Magn. flux: $\phi(r) = r^2 B_z(z=0, r)$

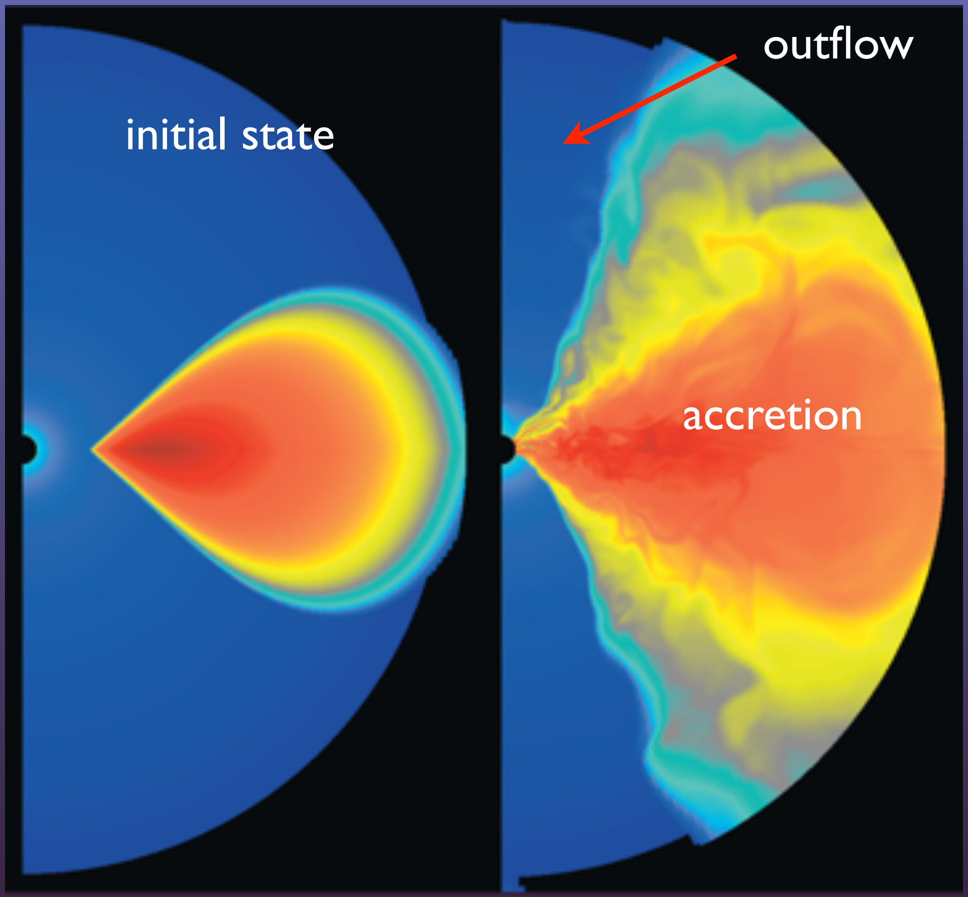
Assume $B_z \downarrow$ as $r \uparrow$

$\phi \uparrow$ as $r \uparrow$

exa: $B_z = (r^2 + r_c^2)^{-\nu/2}$ $\quad 0 < \nu < 2$



Collimation in numerical simulations



Equilibrium at boundary between flow and surroundings (assume field dominated by B_ϕ :

$$P_{\rm in} + B_\phi^2/8\pi = P_{\rm ext}$$

→ toroidal field increases pressure on boundary of the flow, *widens* the flow.

core *of flow can be collimated by tension force in* B_ϕ *but stress must be taken up by an external medium*

Origin of ‘ordered’ magnetic fields

ordered: - net flux crossing the disk,
- sufficiently strong

How strong can such a field be?
$\mathbf{B}$ must be less than orbital KE:

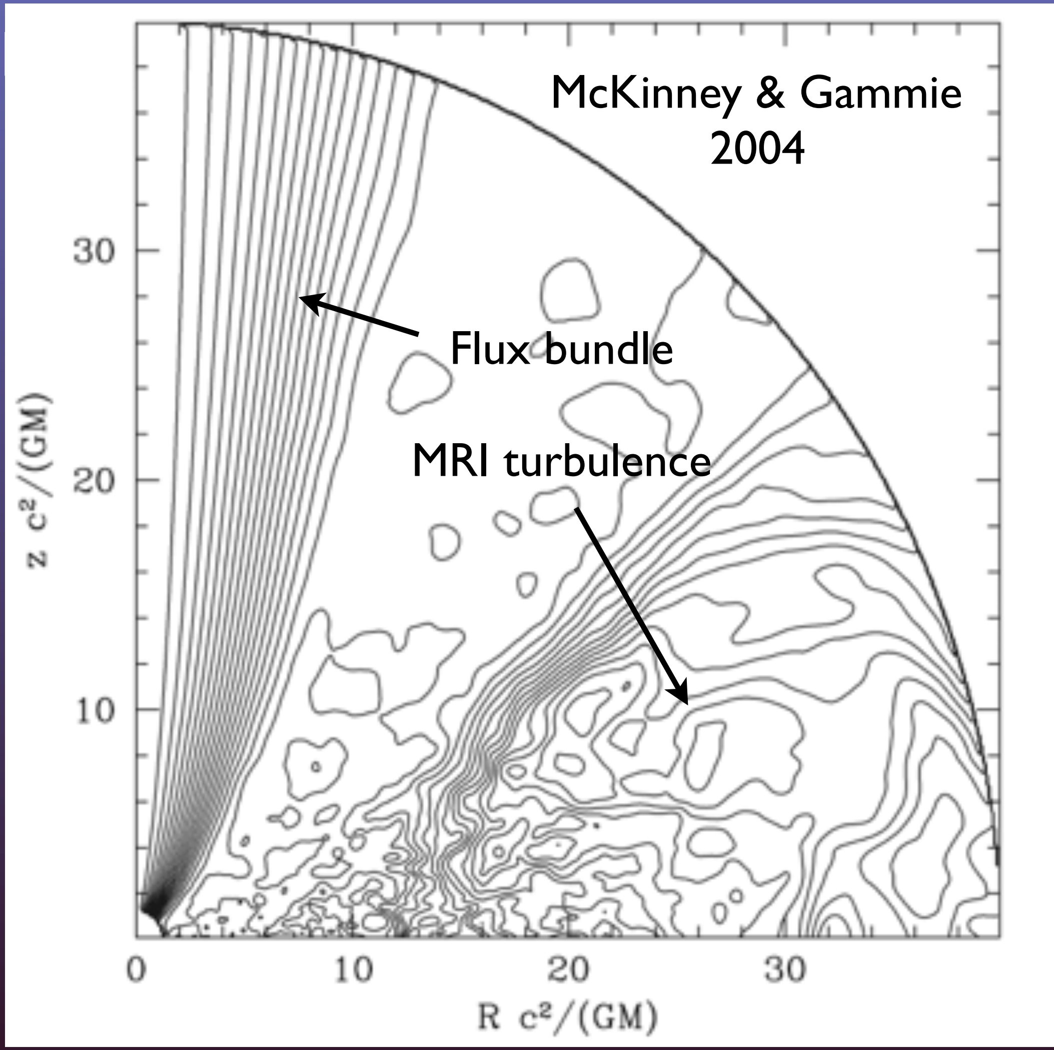
$$\frac{B^2}{8\pi} < \frac{1}{2}\rho\Omega^2 r^2 \qquad = \frac{1}{2}\frac{P}{c_s^2}\Omega^2 r^2 = \frac{1}{2}P(\frac{r}{H})^2$$

Magnetorotational turbulence: $\frac{B_{\rm turb}^2}{8\pi} < P$

is *suppressed* in an ordered external field $B_{\rm ordered}$ when

$$\frac{B_{\rm ordered}^2}{8\pi} > P$$

How do ‘good’ field configurations come about?



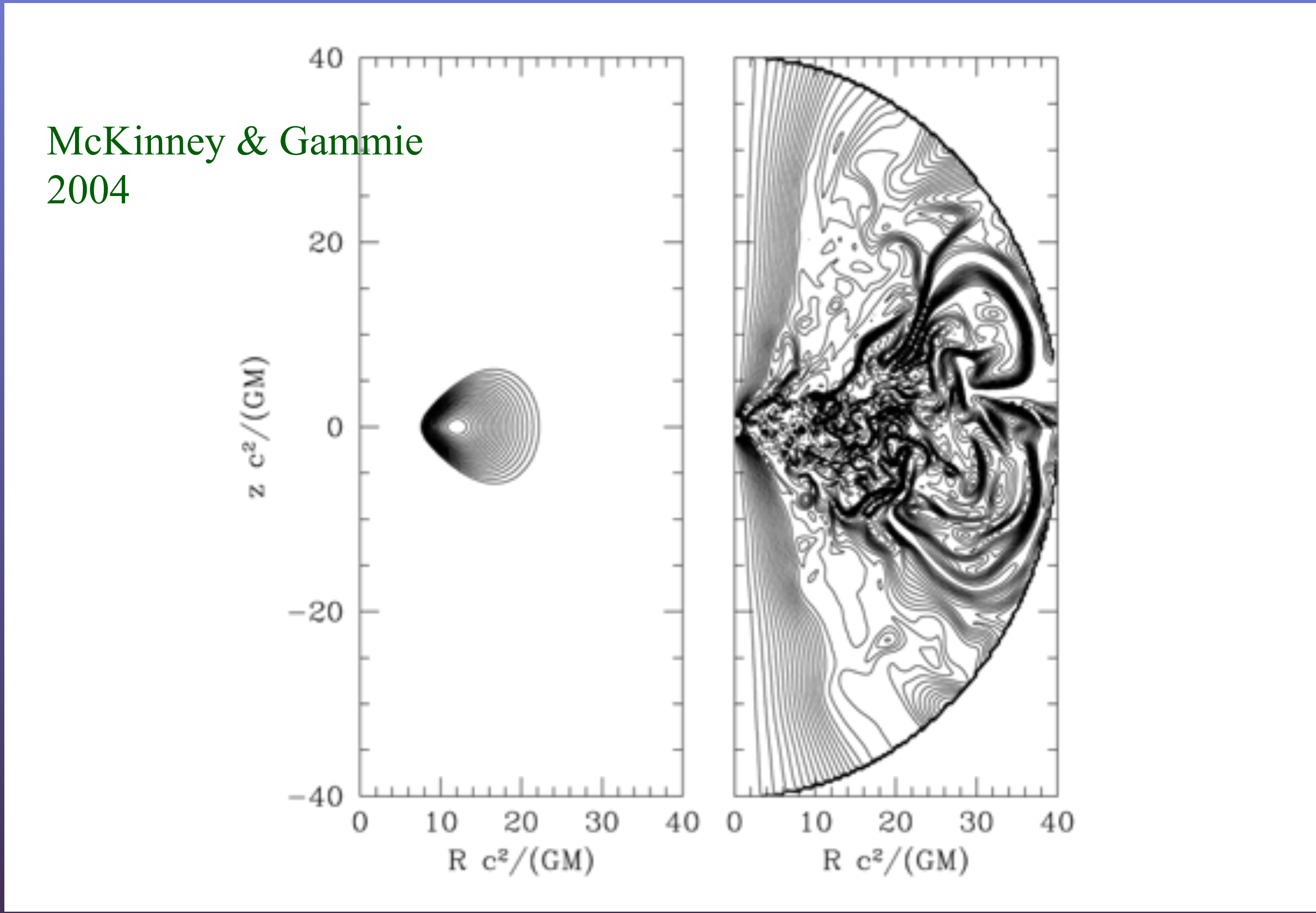
$\mathrm{div}\mathbf{B} = 0$: Net magnetic flux Φ through the disk surface
cannot change by internal processes.
Φ can only enter or leave through outer disk boundary.
→ net flux is *inherited,*
or advected in at outer boundary:

$$\partial_t \Phi = \int \mathrm{d}r\mathrm{d}\phi \; r[\nabla \times (\mathbf{v} \times \mathbf{B})]_z \qquad \Phi = \int B_z r \mathrm{d}\phi \mathrm{d}r$$

$$v_r(0,\phi,z) = B_r(0,\phi,z) = 0$$

$$\rightarrow \quad \partial_t \Phi = -\int \mathrm{d}\phi \; R[\underline{v_z B_r - v_r B_z}]$$

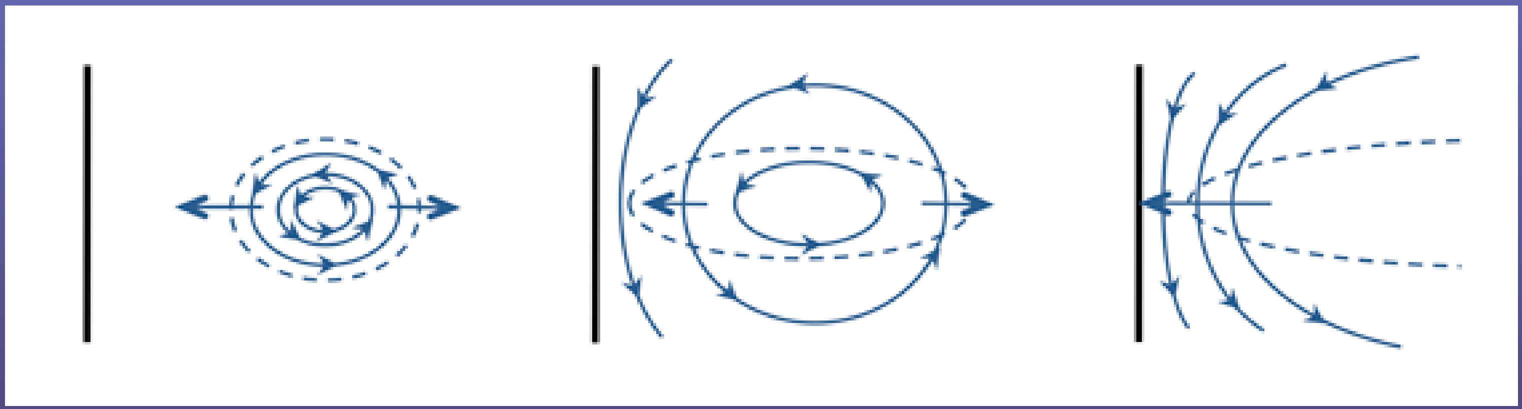
$$= \mathbf{v}_\perp B_\mathrm{p}$$



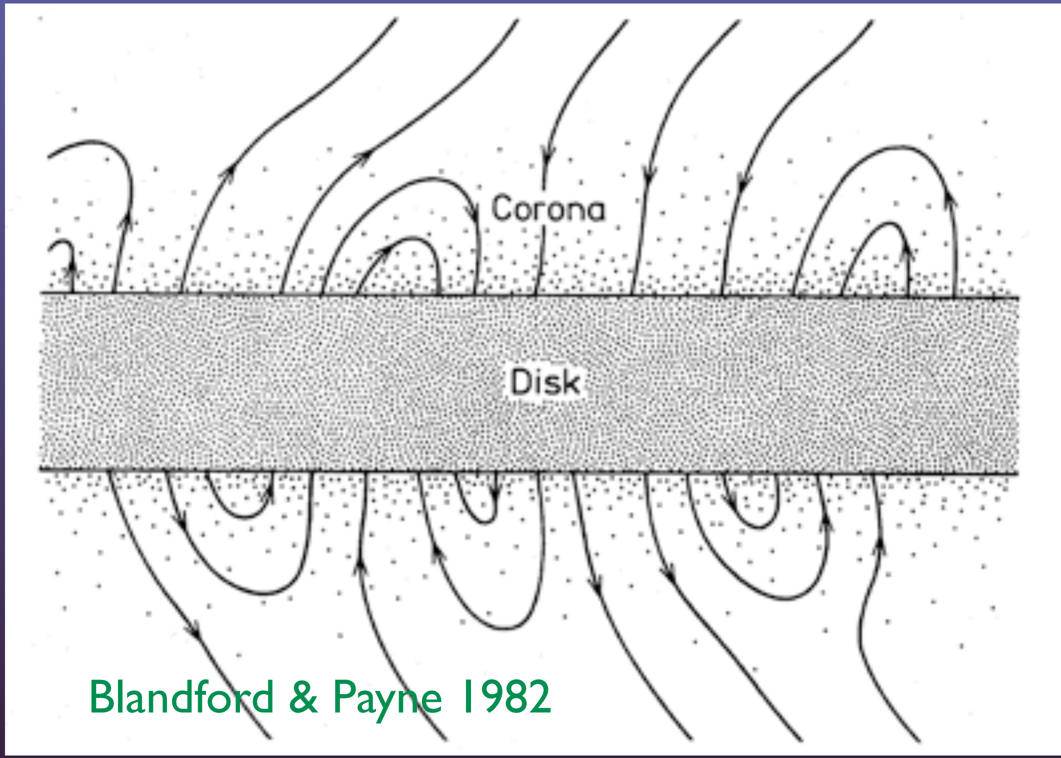
Ordered poloidal flux reflects initial conditions (deVilliers et al 2004)

→ *origin of poloidal flux (if needed) still t.b.d.*

Formation of a magnetic flux bundle through the hole



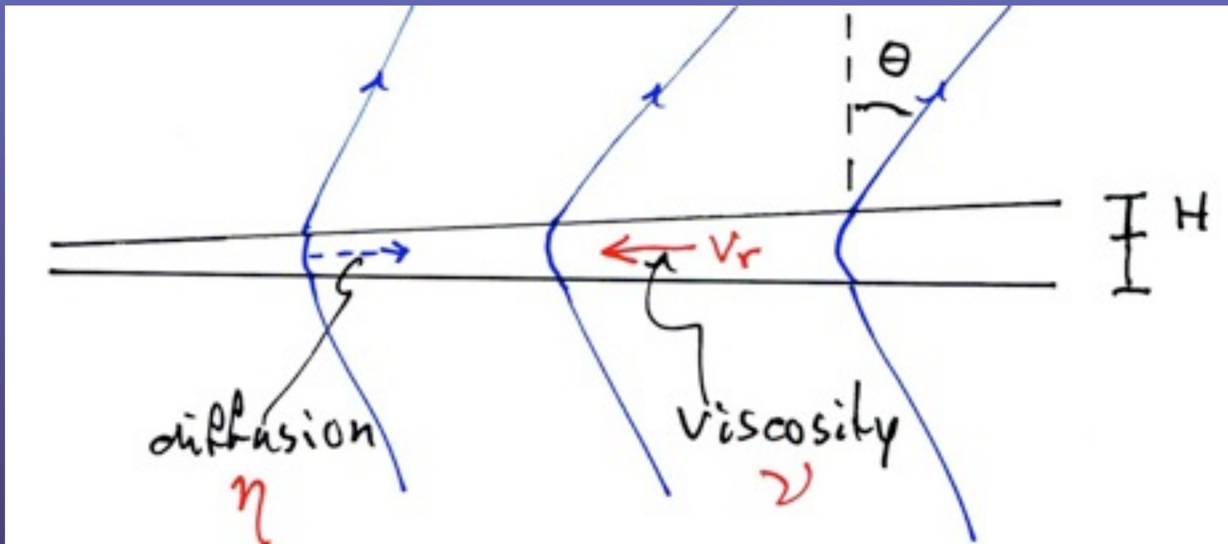
Magnetic jets from chaotic field?
Not seen in simulations, so far



Blandford & Payne 1982

Accretion of external flux

Accretion of ordered (net, poloidal) magnetic flux from environment



If accretion due to (magnetic) turbulence,

$$\eta \approx \nu$$

Balancing outward diffusion vs accretion of field, find

$$\Theta_{\rm max} \approx H/r$$

Reason: diffusion acts on curvature of field where it crosses the disk:

$$\rightarrow v_{\rm diff} \sim \frac{\eta}{H}\frac{B_r}{B_z} \qquad\qquad v_{\rm acc} \sim \nu/r$$

→ accretion of external field difficult in a diffusive disk model

Accretion of external flux

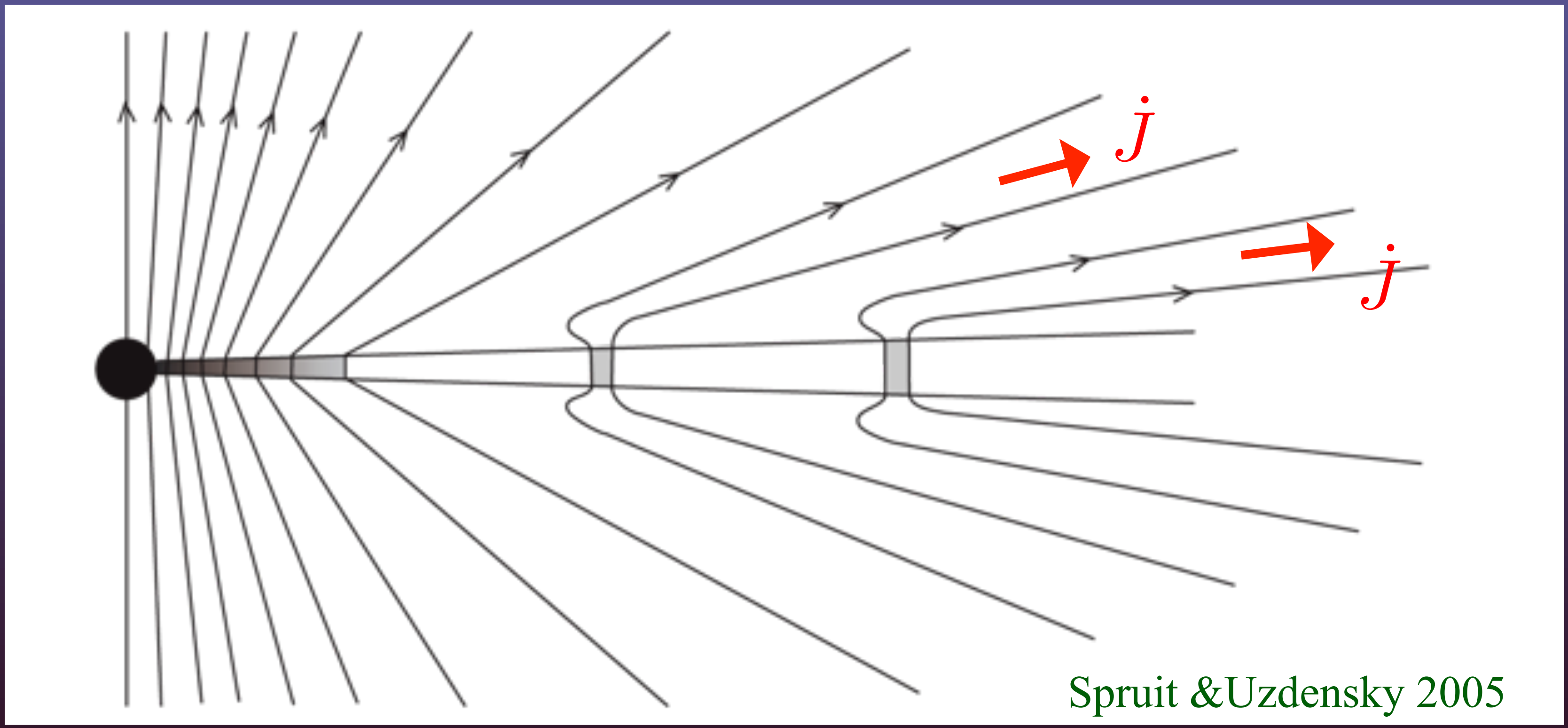
Diffusive disk model. Viscosity ν, magnetic difusion η:

$\eta \approx \nu$ $\rightarrow$ no flux accreted

Alternative: patchy magnetic field

seen in MRI simulations

Fromang, Papaloizou. Lesur, Heinemann 2008



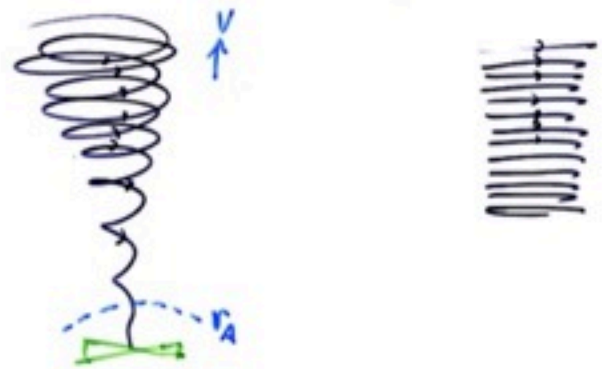
Why need disks with net magnetic flux?

- geometry good for jets
- could be stronger than internally generated fields
- could be involved as ‘second parameter’ in the X-ray states of X-ray binaries

Instability of toroidal field in jets.

(Choudhuri & Königl '86 ; Eichler '94)

*



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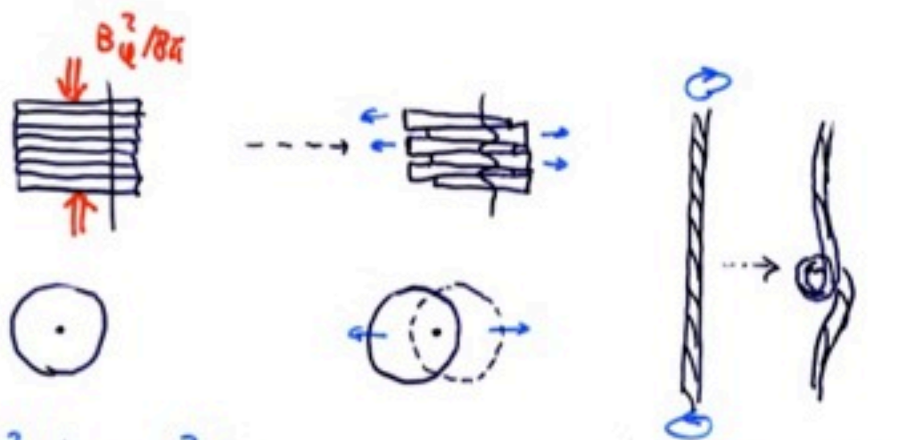
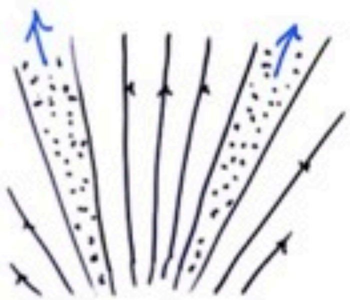


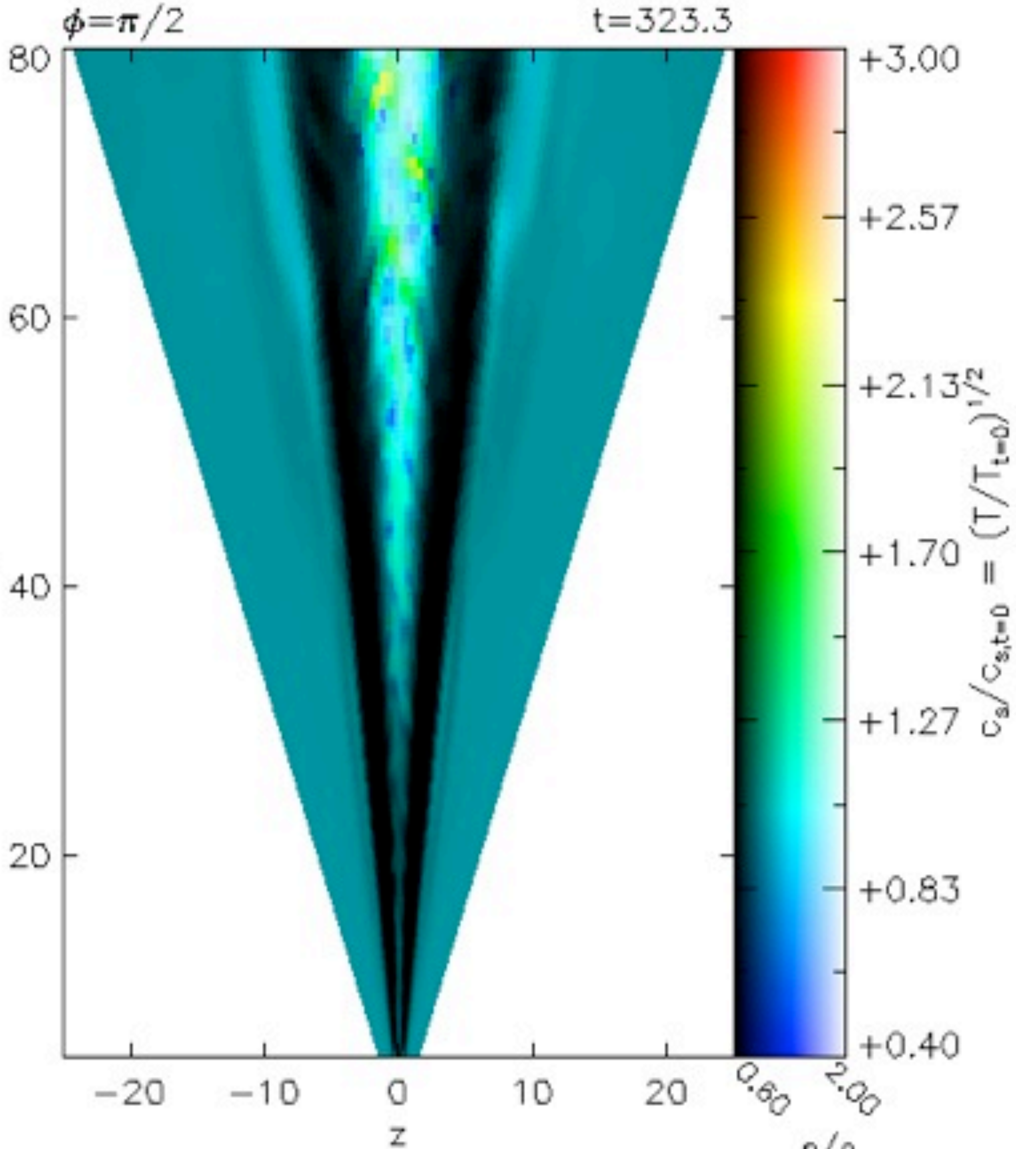
$B_\varphi^2 \downarrow$, $B_z^2 \uparrow$, net energy release if $B_\varphi \gtrsim B_z$

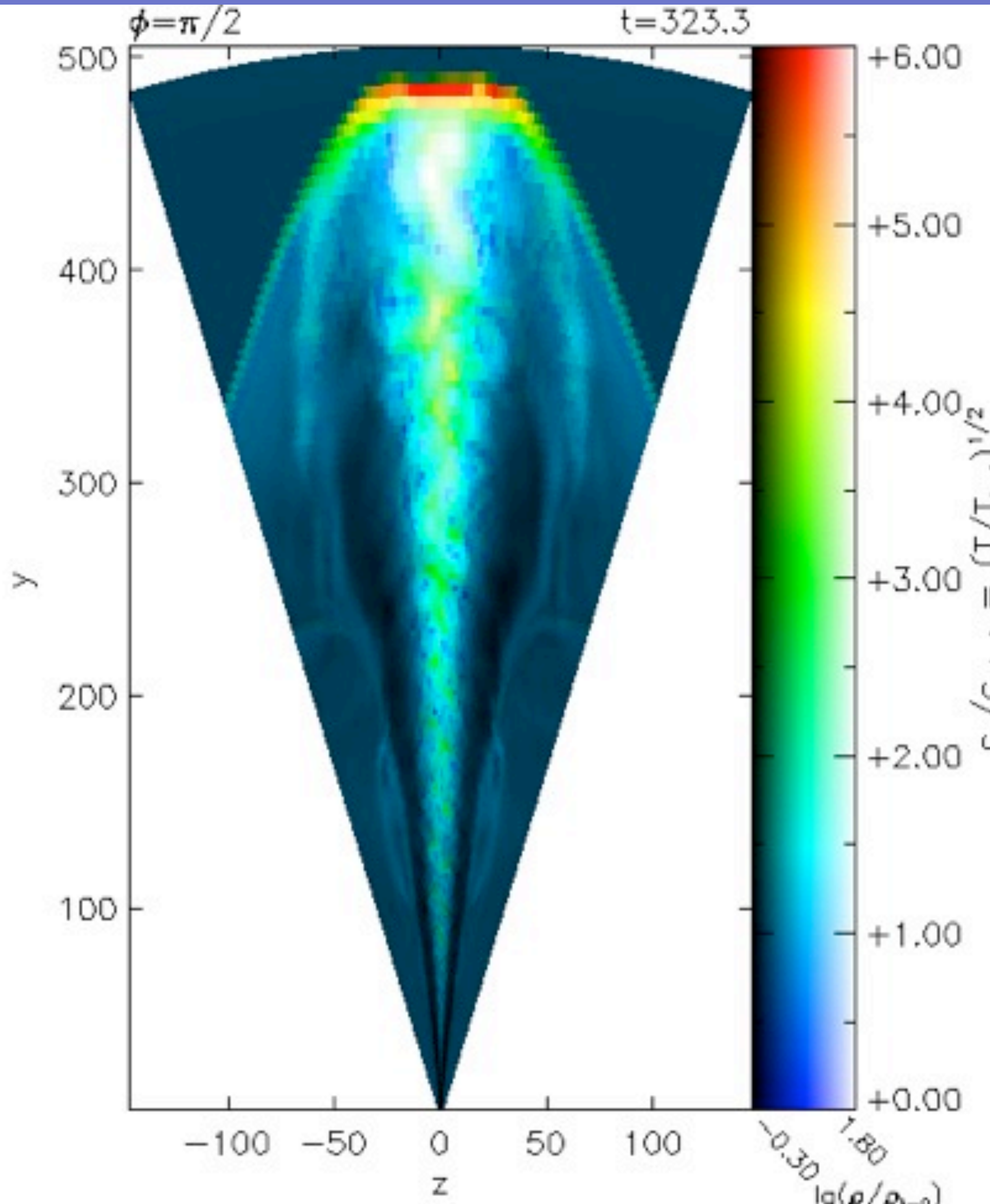
* Stabilizing effect of neighboring untwisted fields:



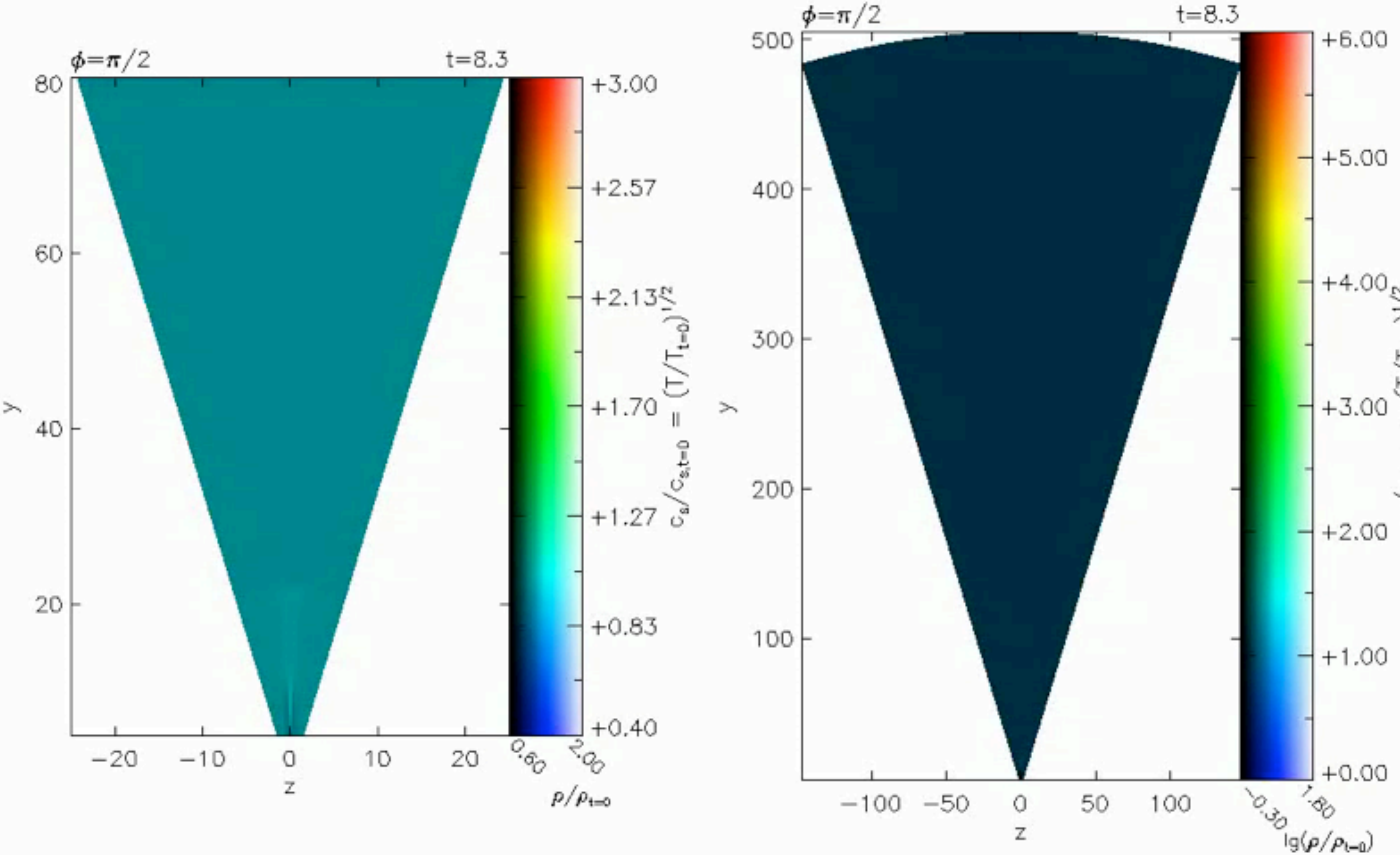
Consequences of kink instability

- Flow highly time dependent
- collimation influenced
- dissipation of magnetic energy source for radiation
- *increases the flow speed*

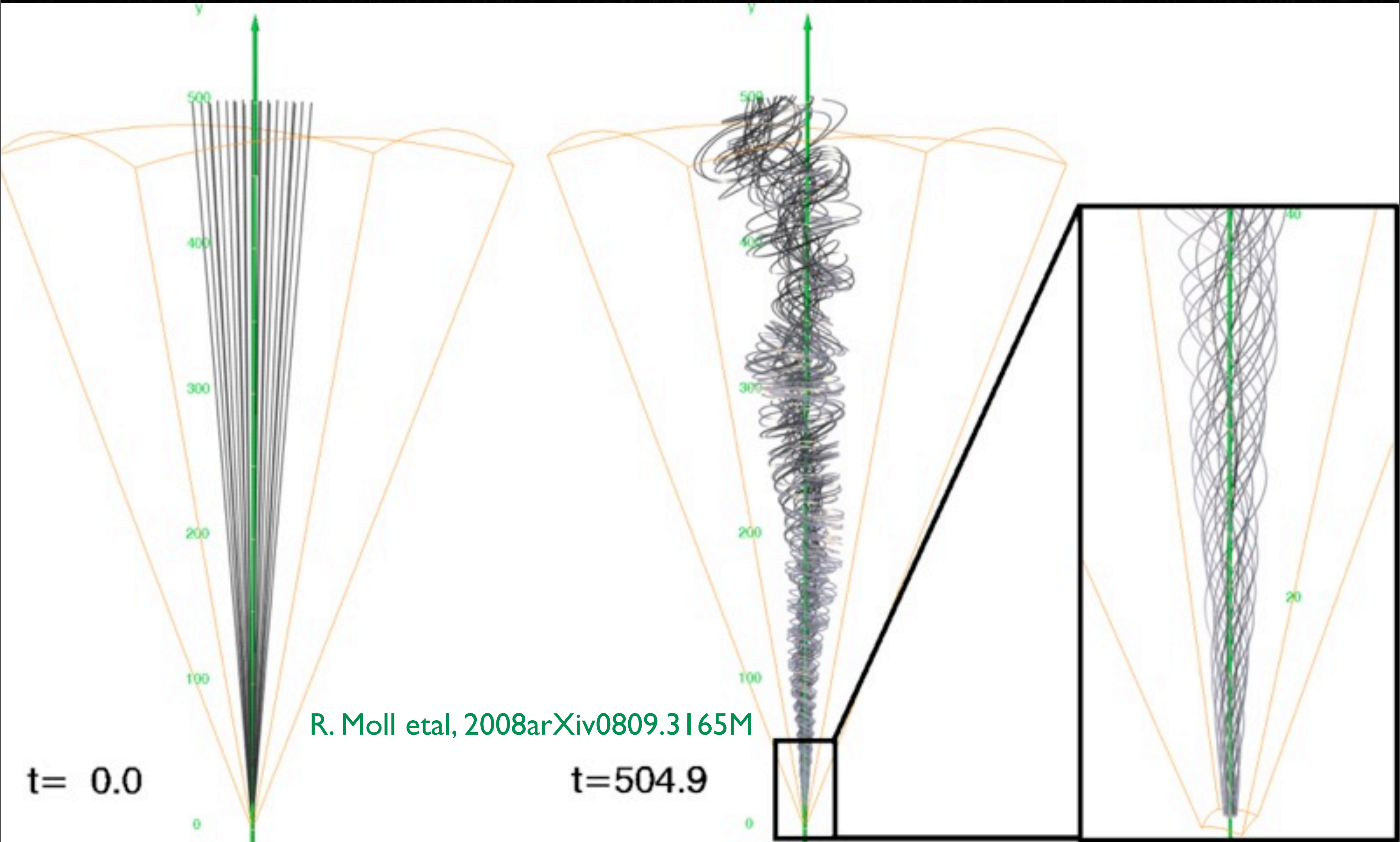




R. Moll etal, 2008arXiv0809.3165M

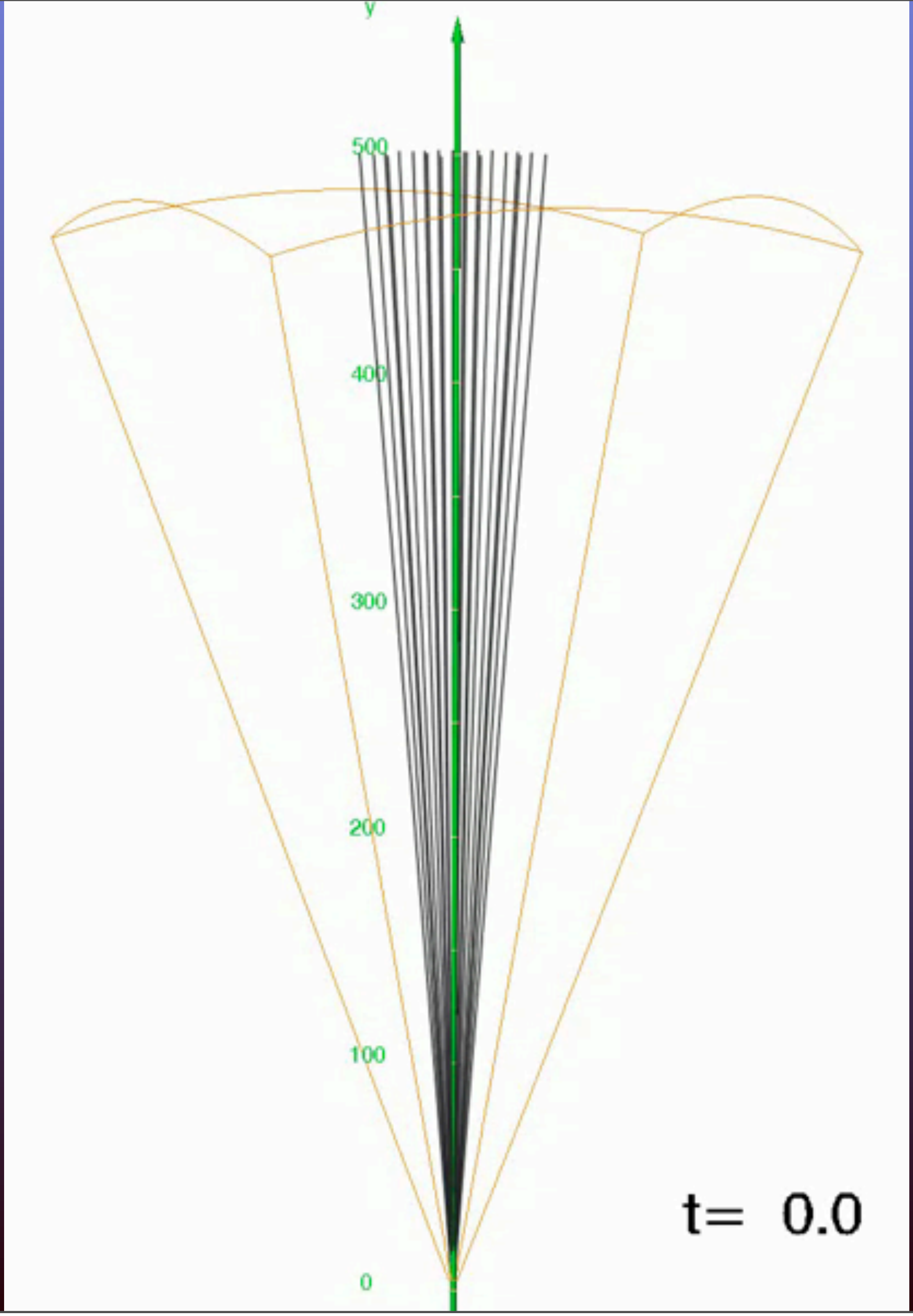


ϕ=π/2
t=8.3
80
60
40
20
y
−20
−10
0
10
20
z
+3.00
+2.57
+2.13
+1.70
+1.27
+0.83
+0.40
0.60
2.00
ρ/ρt=0
cs/cs,t=0 = (T/Tt=0)1/2
ϕ=π/2
t=8.3
500
400
300
200
100
y
−100
−50
0
50
100
z
+6.00
+5.00
+4.00
+3.00
+2.00
+1.00
+0.00
−0.30
1.80
lg(ρ/ρt=0)
cs/cs,t=0 = (T/Tt=0)1/2

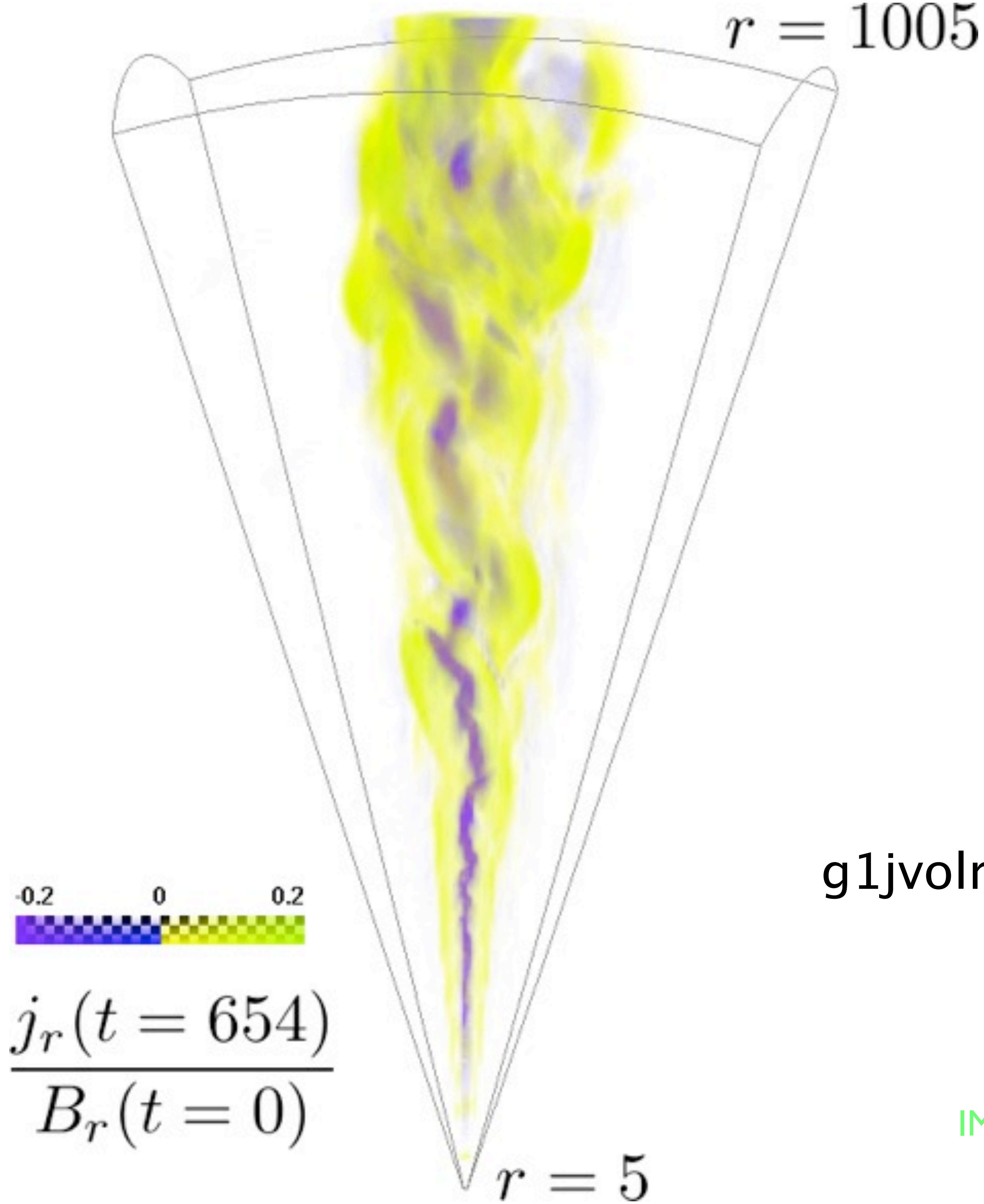


R. Moll etal, 2008arXiv0809.3165M

R. Moll, 2009, A&A 507, 1203

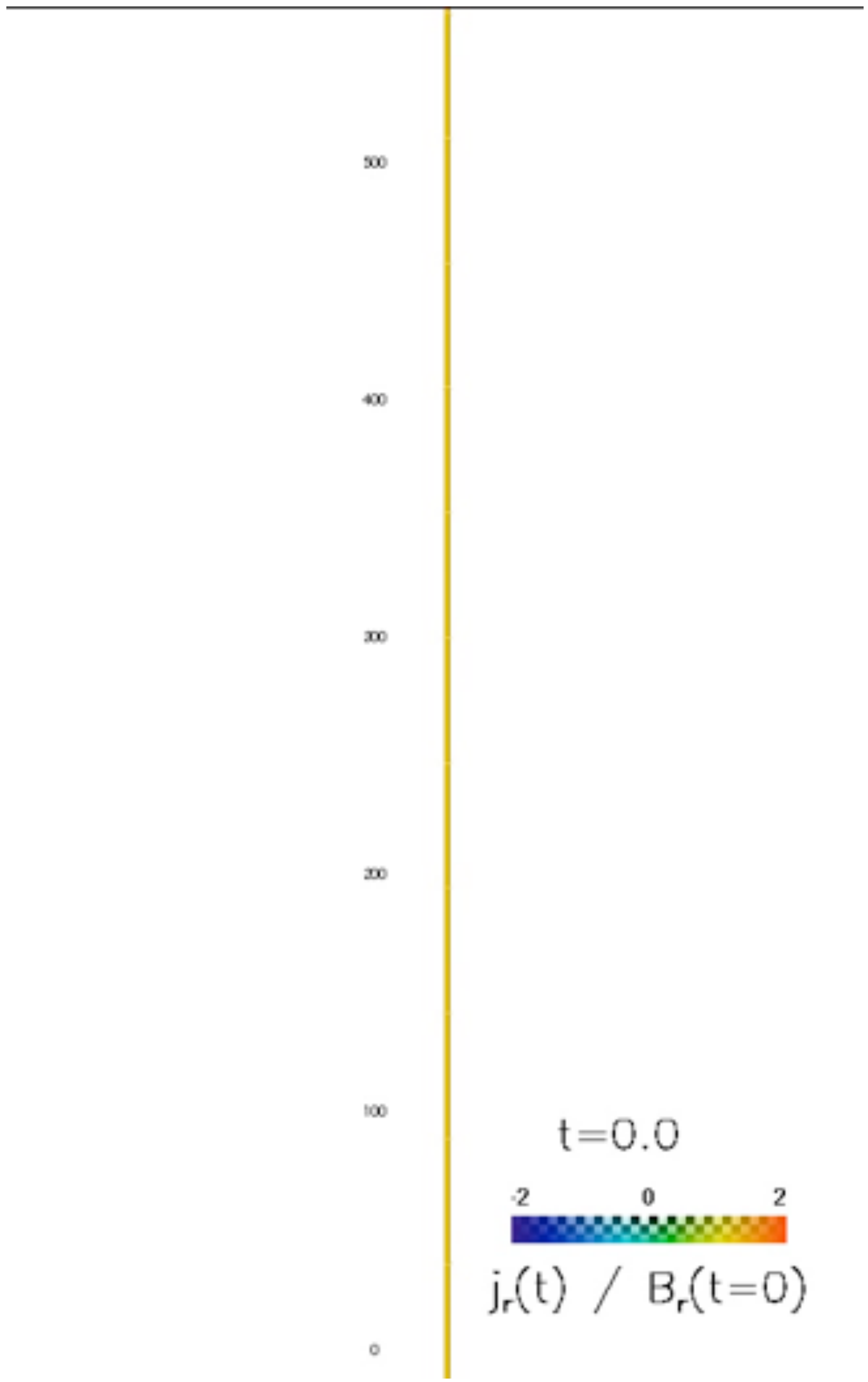


R. Moll, 2009, A&A 507, 1203



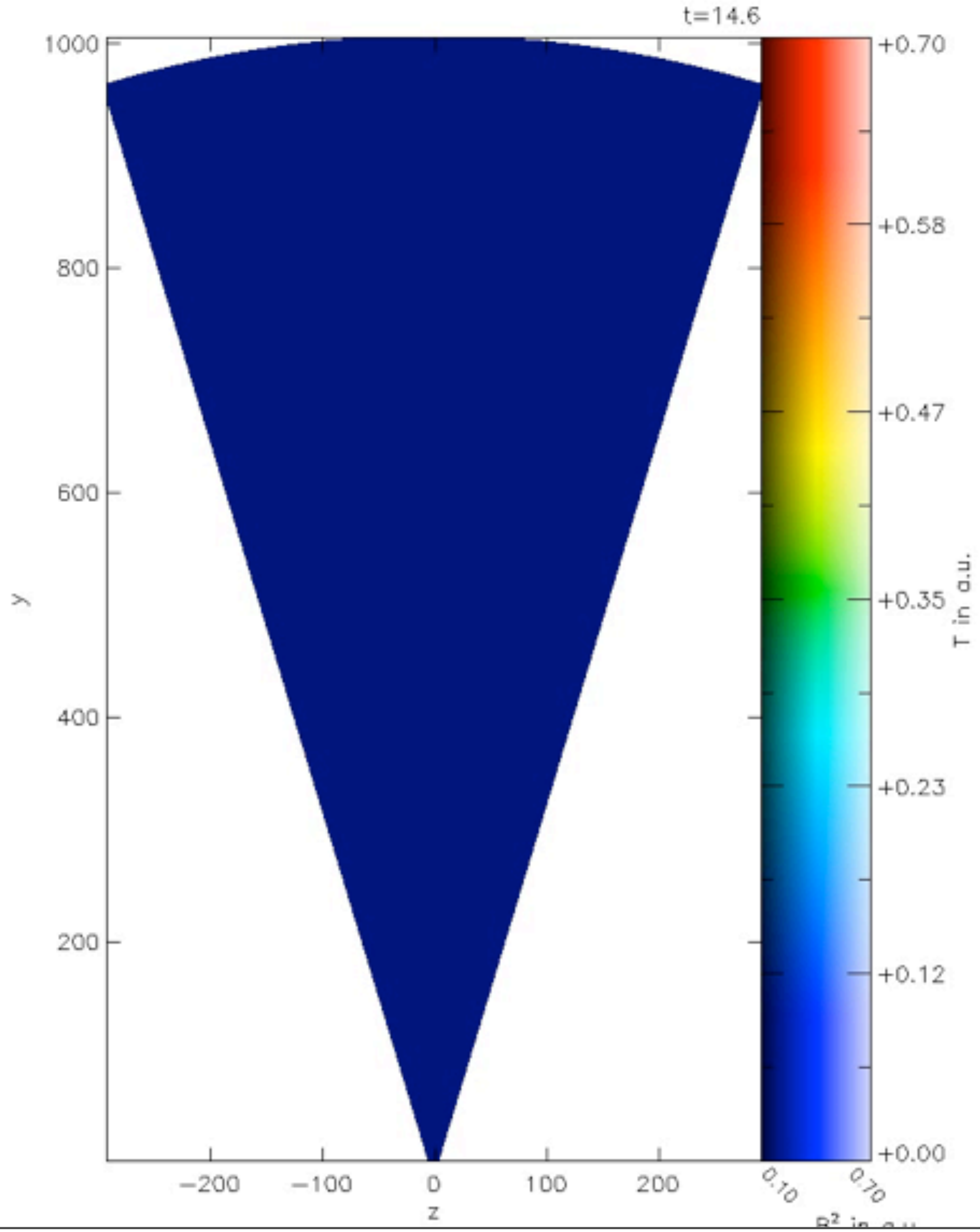
g1jvolren.avi

g1jvolren.avi

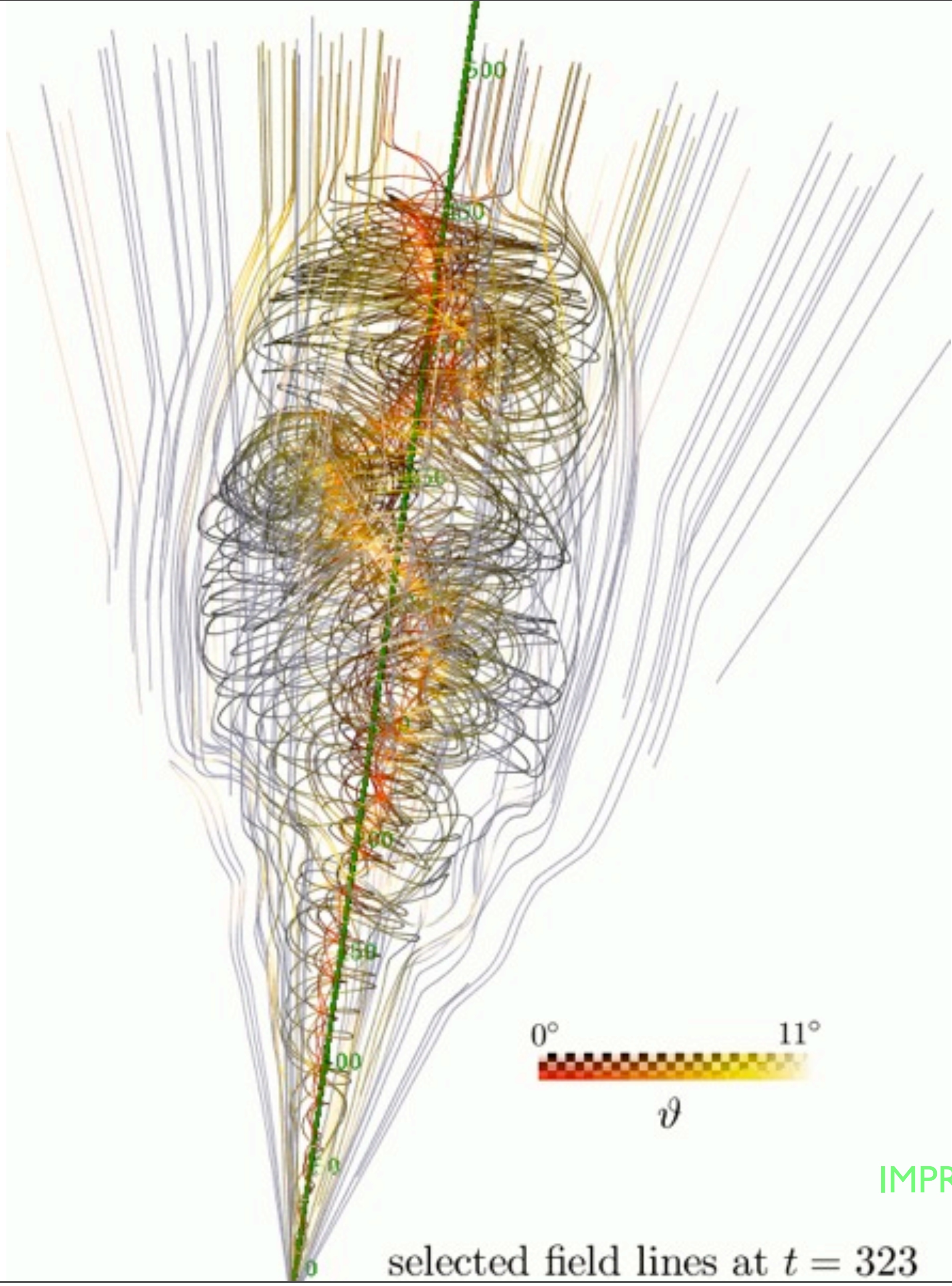


g1jvolren.avi

IMPRS 06 - 2013 Jets



volren_smooth.avi
K1Tvolren.avi



IMPRS 06 - 2013 Jets

Poynting flux conversion

Steady magnetic outflow, in axisymmetric models, (ϖ, ϕ, z)
tend to have poor conversion of B_ϕ^2

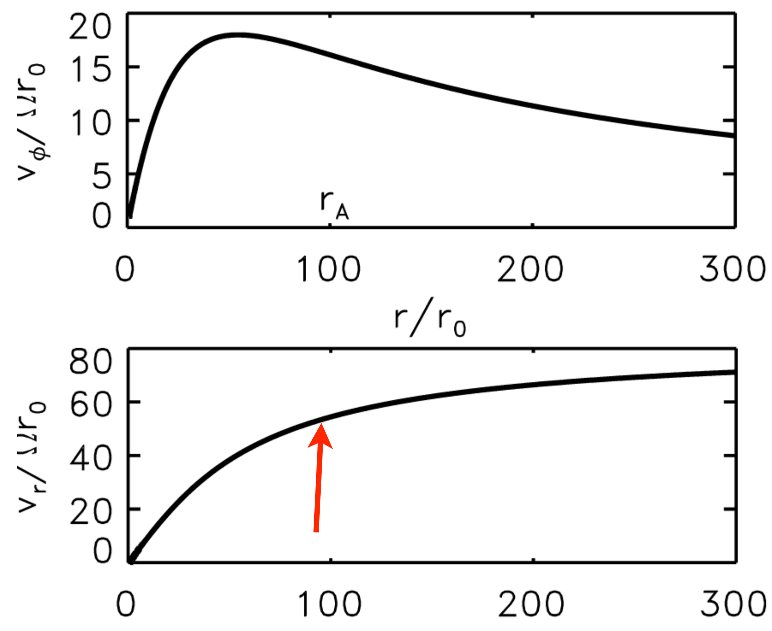
$S = v \frac{1}{4\pi} B_\phi^2$ (per unit area).

Integrated over jet cross section: $F_{\mathrm{P}} = \int S \, 2\pi\varpi \, \mathrm{d}\varpi \sim v \, \varpi^2 B_\phi^2$

If the (poloidal) purely radial, $B_\phi \sim 1/\varpi$ → $F_{\mathrm{P}} \sim \mathrm{cst.}$

Also: if flow converges/diverges uniformly!
problem worse in relativistic flows.

Cold Weber-Davis model



at rA still ~ 50% in magnetic energy

Magnetic flow acceleration

Does not work well in steady, axisymmetric flow.

Need: a sufficiently steep decline of B_ϕ^2 with distance z

better:

- (nonsteady:) at the head of the jet: *'magnetic tower'* picture
- by *dissipation of magnetic energy (:* nonaxisymmetric)

Flow acceleration by dissipation

plane flow: $v(x), \quad B^2(x)$

dissipation: $\partial_x B^2(x) < 0$

→ pressure gradient accelerates in flow direction

faster dissipation → steeper gradient

hydro: Bernoulli: $\frac{1}{2}v^2 + w = E\,, \;\; w = p + e$

shock tube analogy

IMPRS 04-2010 GBR

Poynting flux

$$S = \frac{c}{4\pi} E \times B$$

$$|S| = c(\frac{E^2}{8\pi} + \frac{B^2}{8\pi})$$

in MHD: $E = -v \times B/c\,,\quad S = v_\perp \frac{B^2}{4\pi}$

magnetic energy flux: $F_{\rm m} = v_\perp \frac{B^2}{8\pi}$

$$S = 2F_{\rm m} = v_\perp w_{\rm m}, \qquad w_{\rm m} = P_{\rm m} + e_{\rm m}$$

→ max Poynting flux conversion by magnetic dissipation: 50%

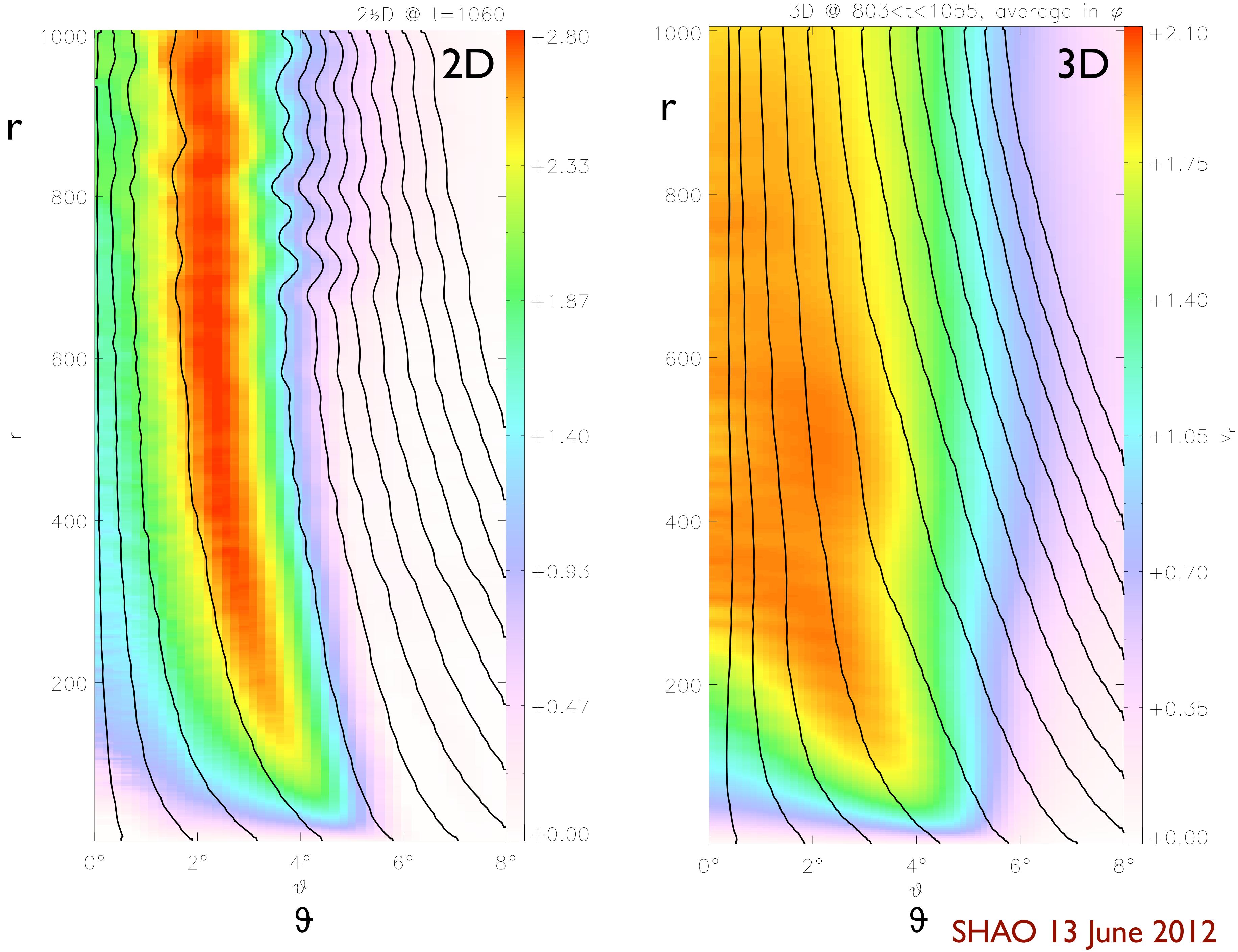
Acceleration mechanism: comparison 2D vs 3D

both: acceleration is by B_ϕ^2 (not by poloidal component)
centrifugal: equivalent to acceleration by B_ϕ^2

accelerating force: $F = - \nabla B_\phi^2/8\pi - B_\phi^2/(4\pi\ r)$

steady axisymmetric:
constant opening angle ('radial' flow): *the two terms cancel exactly*

2D: net acceleration by first term due to 'overdivergence' in *part* of the flow
3D net acceleration by first term due to *decay of the toroidal field*


2½D @ t=1060
2D
r
1000
800
600
400
200
0°
2°
4°
6°
8°
ϑ
+2.80
+2.33
+1.87
+1.40
+0.93
+0.47
+0.00
3D @ 803<t<1055, average in φ
3D
+2.10
+1.75
+1.40
+1.05
+0.70
+0.35
+0.00
v_r
SHAO 13 June 2012

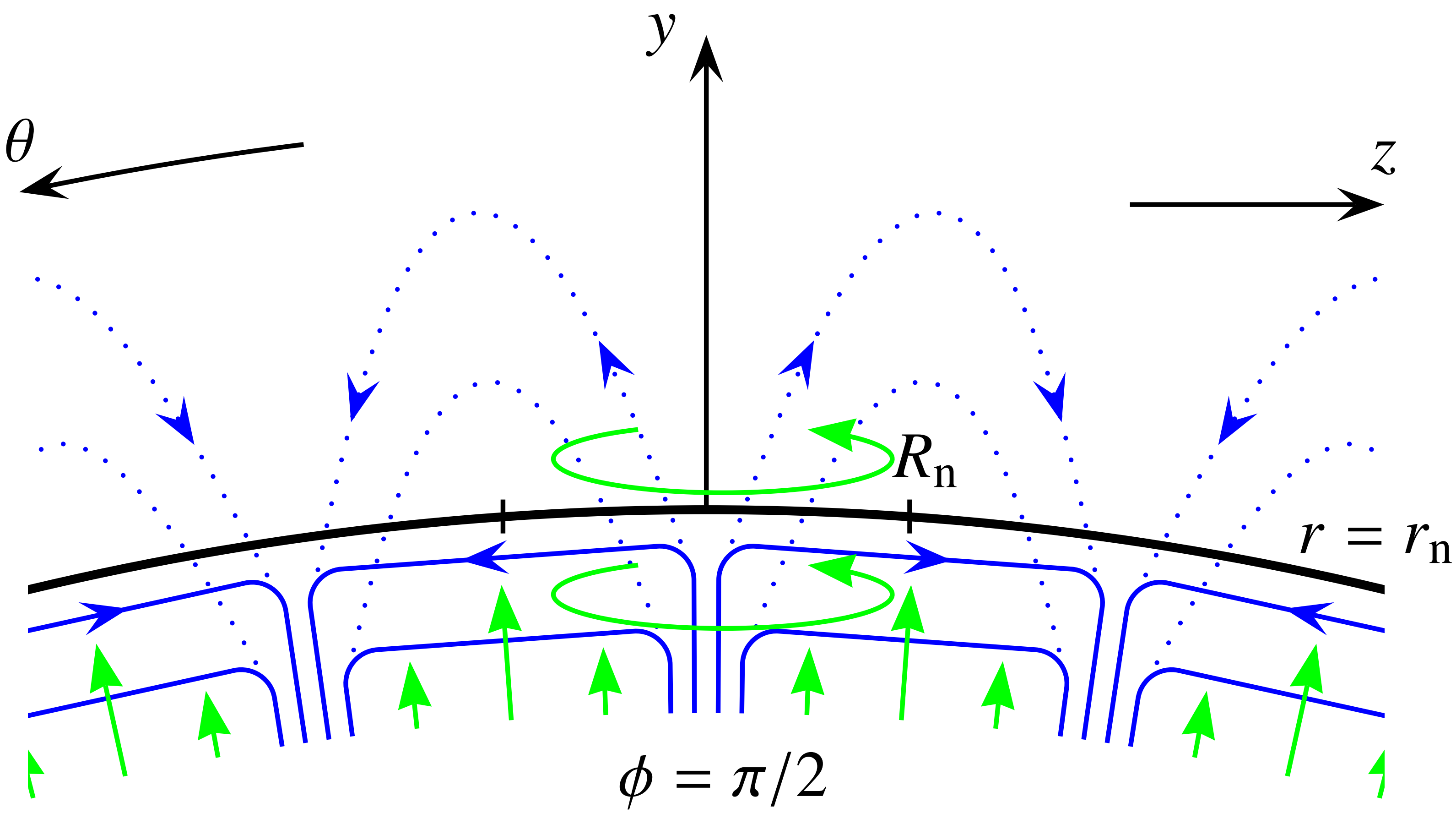
- strong time-dependence due to kink instability
- azimuthal field destroyed after ~ 10 Alfvén radii
- if all dissipated magnetic energy radiated, radiation is about 10% of initial Poynting flux
- acceleration in 3D case similar as in 2D, but by *different mechanism*
- *central 'spine' gets 'diffused out' in 3D*

Simulations without external field

setup:
- stratified background ('star')
- rotating field at center
  field consists of closed loops
  field strength decreases exponentially from center

application: GRB (collapsar scenario)

Initial field ~ sin(kθ) exp(-ky)



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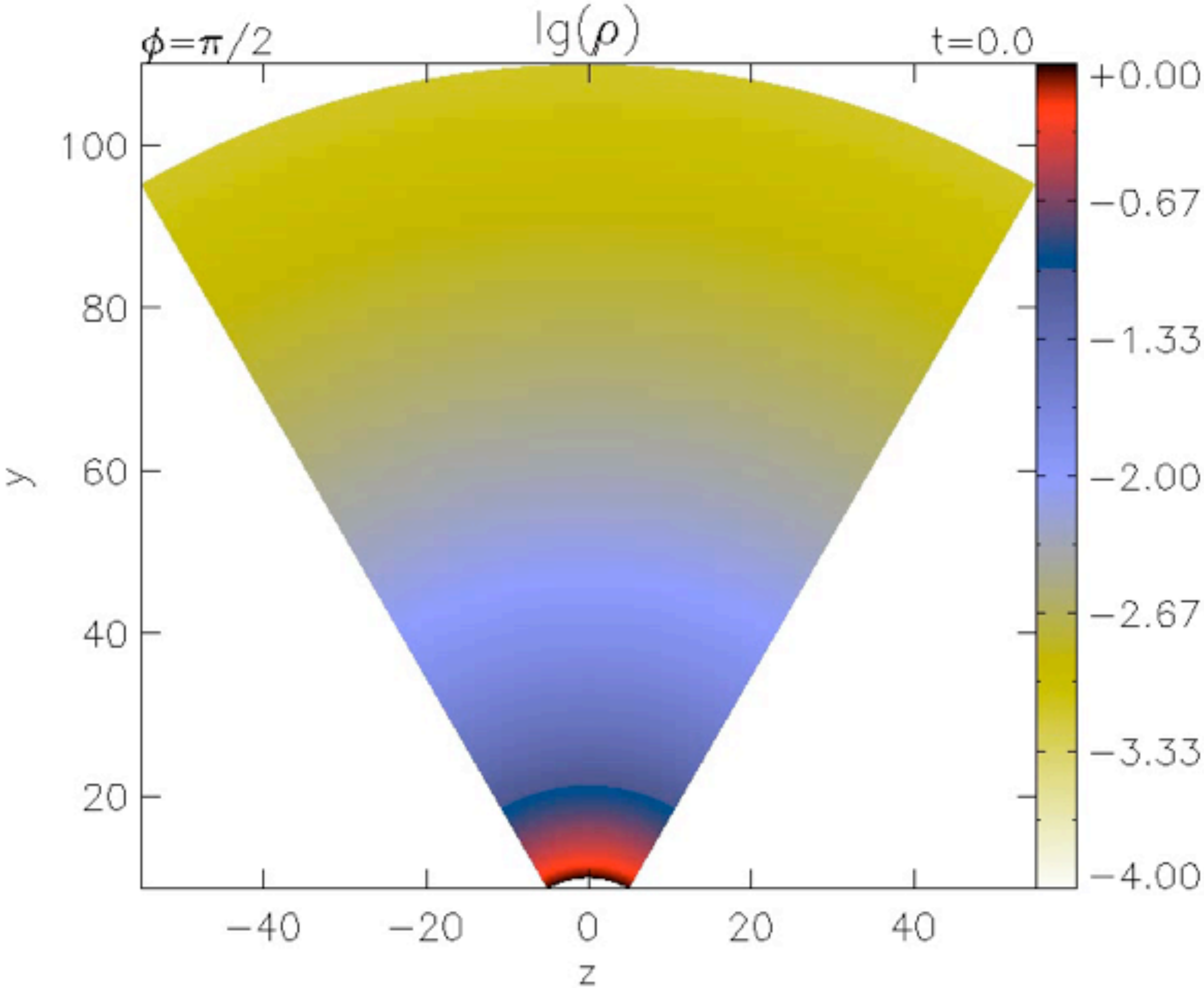
rho.avi, vr.avi



rho.avi, vr.avi

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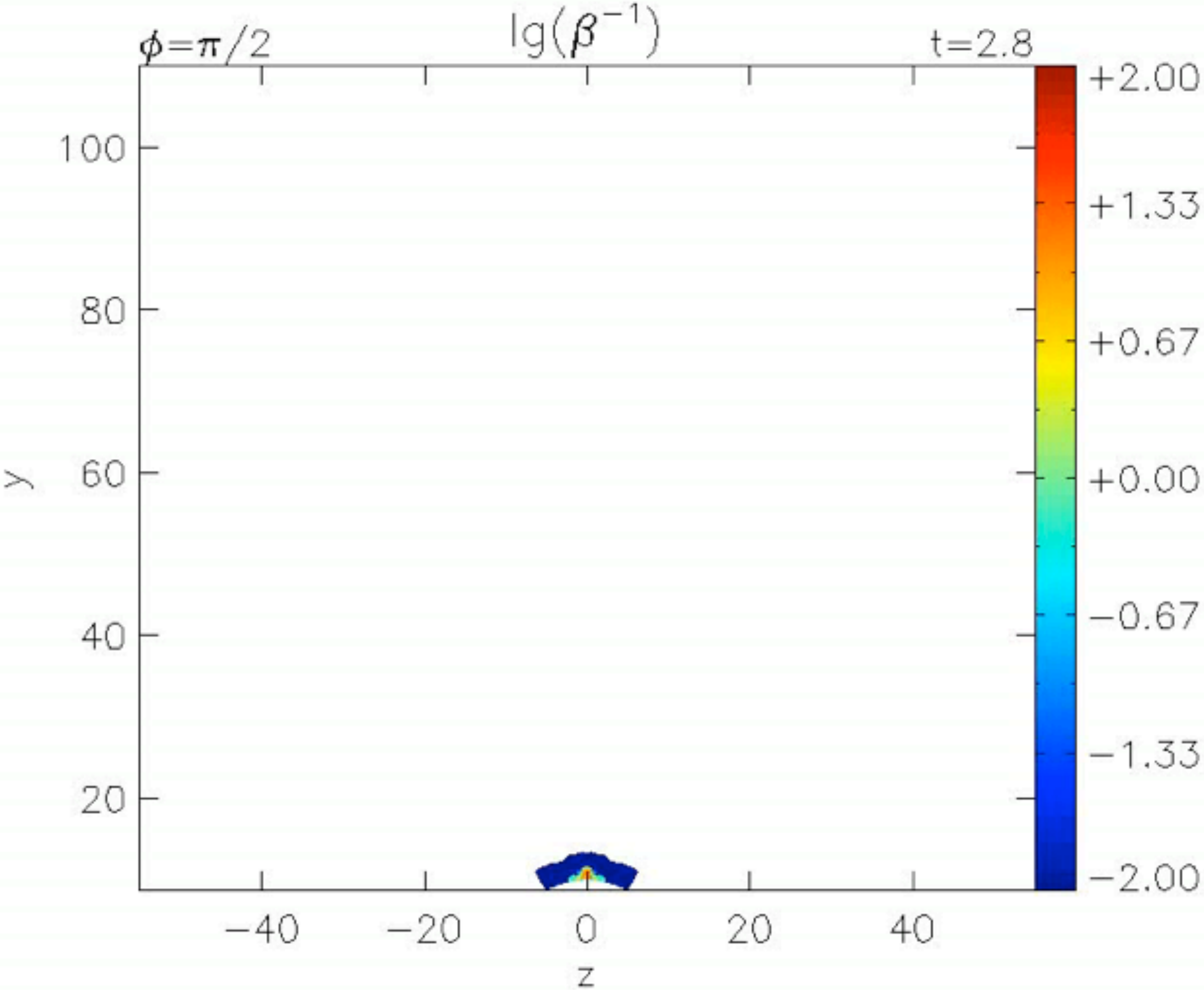

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Recent 3D GR MHD simulation:

http://arxiv.org/abs/1201.4163

summary (acceleration)

- steady axisymmetric models need special conditions for efficient conversion of Poynting flux to kinetic energy
- problem particularly acute at high Lorentz factors
- efficient conversion requires sufficiently steep decrease of B_ϕ^2 with distance

possibilities:
- jet head
- decrease of B_ϕ^2 by instability + dissipation (reconnection)