Episodic ejection of magnetic bubbles and jets

Andrea Ciardi
Laboratoire de Physique des Plasmas, Velizy
et
Laboratoire de Radioastronomie (LERMA), Ecole Normale Supérieure

Much of the work done while at the Observatoire de Paris and in collaboration with experimental Plasma Group at Imperial College.

Thanks to:
C. Stehle, S. Cabrit (Observatoire de Paris, LERMA)
S.V. Lebedev (Imperial College)
A. Frank (University of Rochester)

Overview

- Introduce jets from young forming stars
  → Jets are not homogeneous, steady flows

- Why laboratory experiments of astrophysical jets
  → Complementary to astrophysical simulations

- Results of magnetically driven jets from z-pinch machines
  → Unstable jets are not so bad
  → Episodic, unstable jets are actually quite good!

Jets from young stars

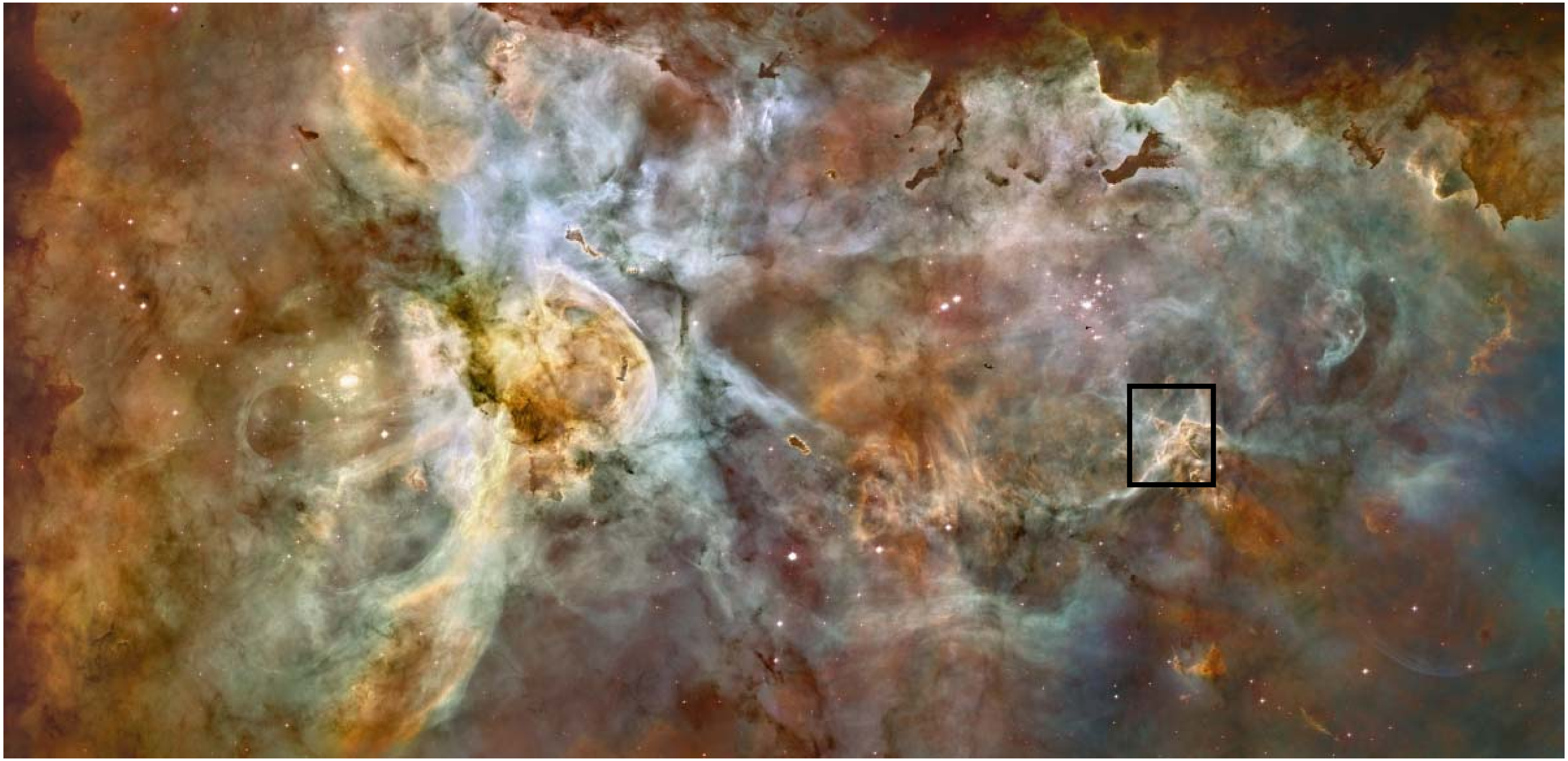
YOUNG STARS AND THEIR ENVIRONMENT: accretion, outflows and shocks

NASA, ESA, N. Smith (UCB)

50 light years ~ 3×10^6 AU

Star Forming Region: NGC 3372 Carina Nebula

YOUNG STARS AND THEIR ENVIRONMENT: accretion, outflows and shocks

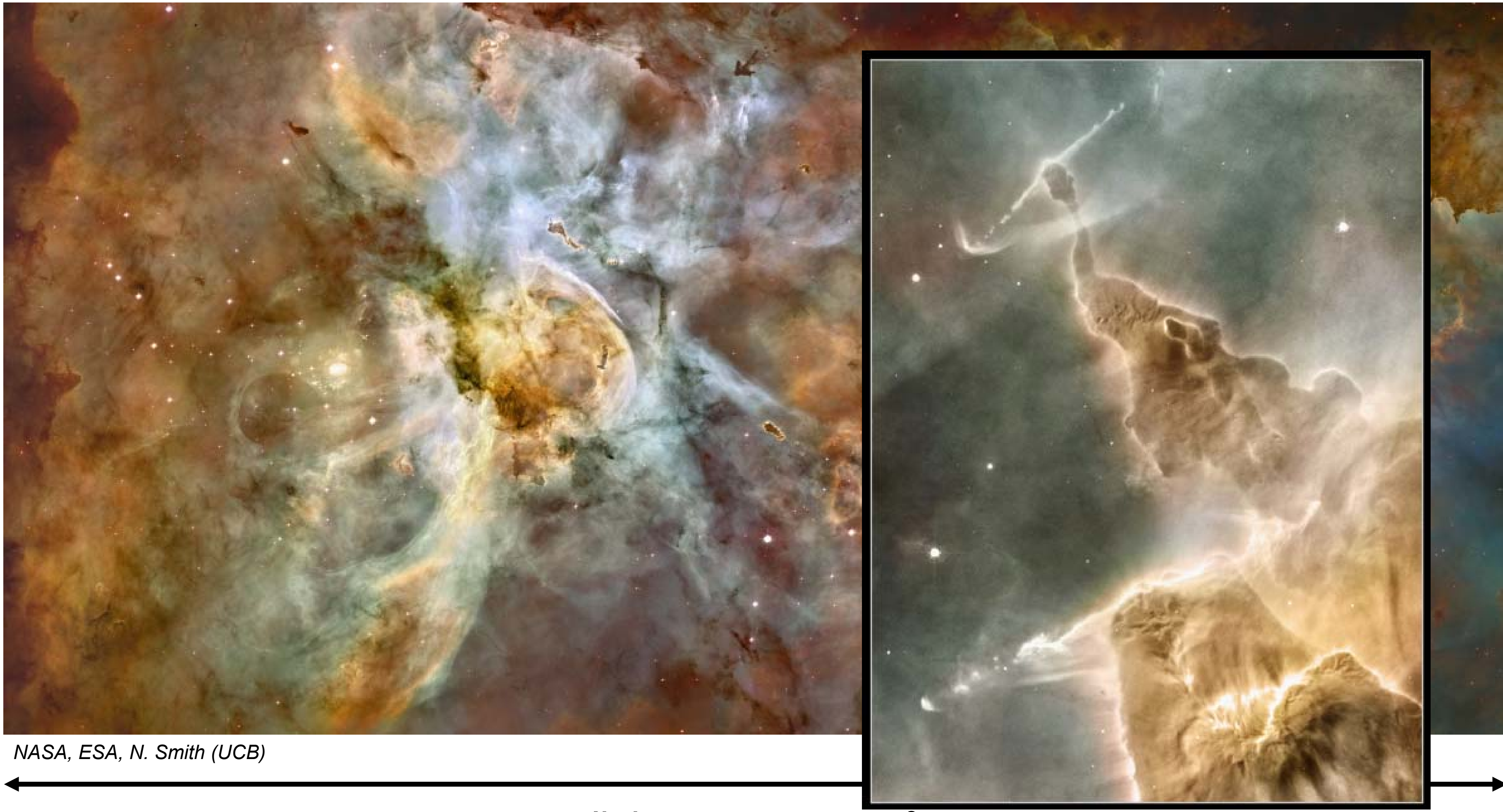


NASA, ESA, N. Smith (UCB)

50 light years ~ 3×10^6 AU

Star Forming Region: NGC 3372 Carina Nebula

YOUNG STARS AND THEIR ENVIRONMENT: accretion, outflows and shocks

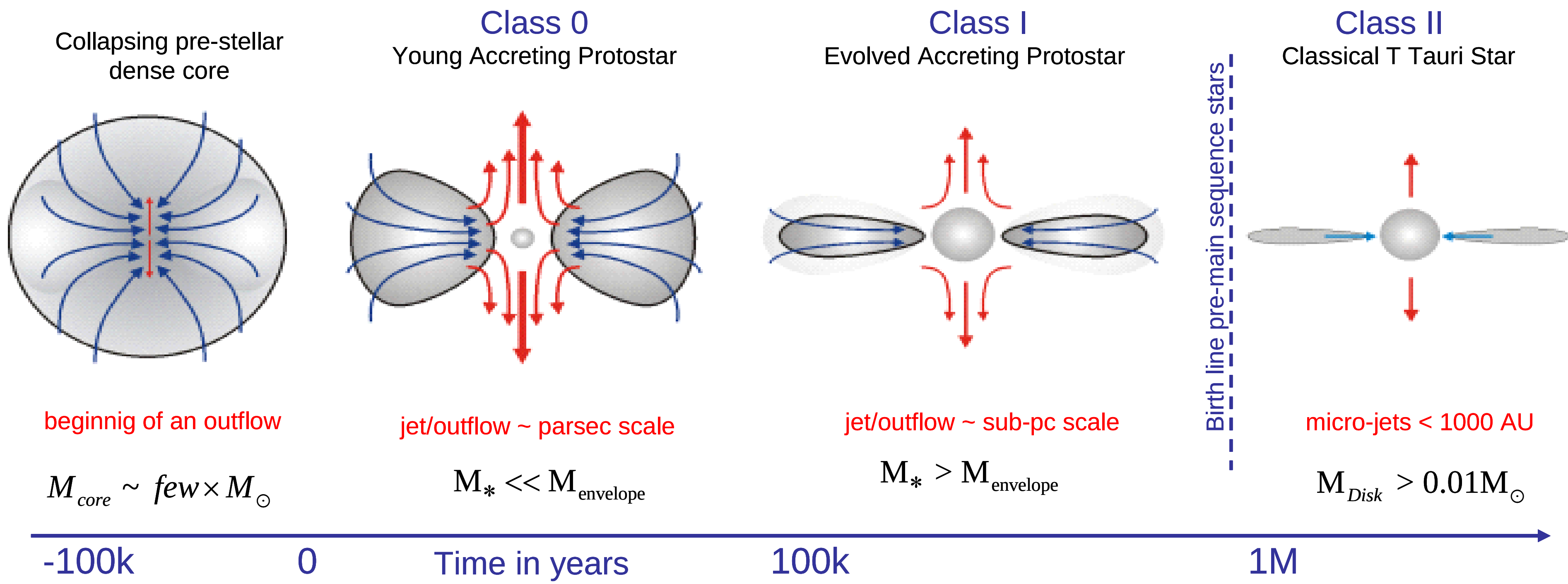


NASA, ESA, N. Smith (UCB)

50 light years ~ $3x10^6$ AU

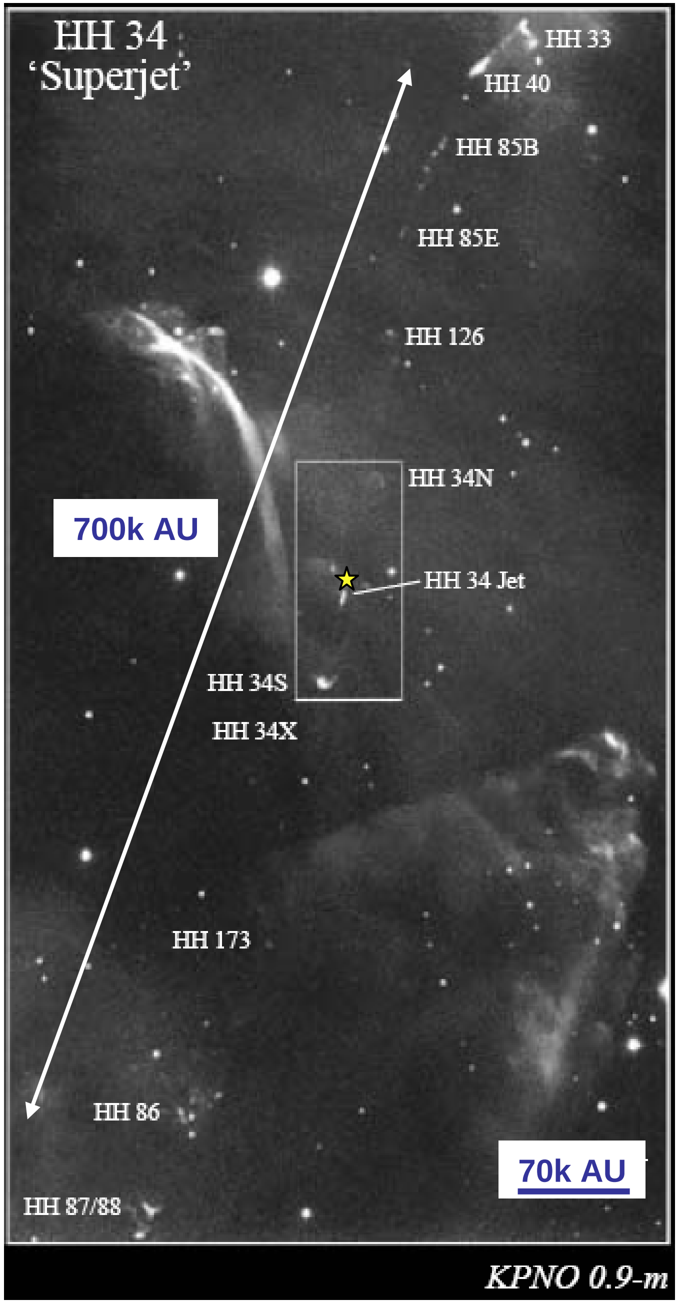
Star Forming Region: NGC 3372 Carina Nebula

From super-jets to micro-jets…

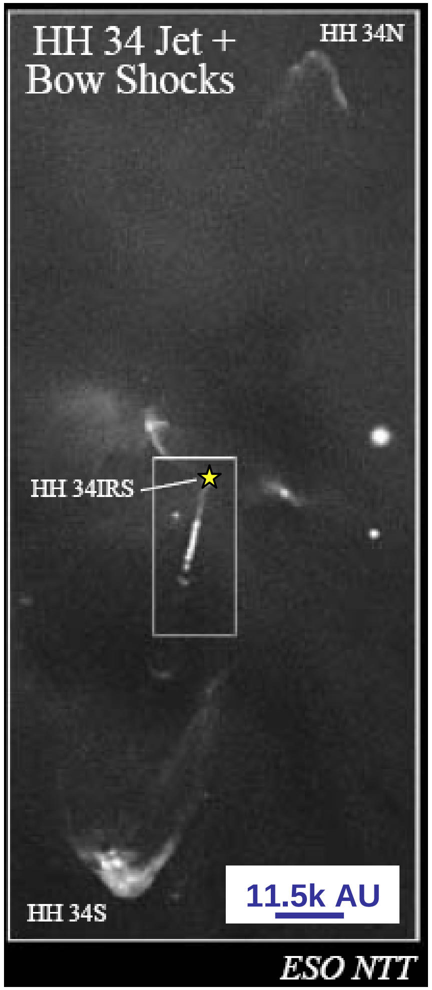


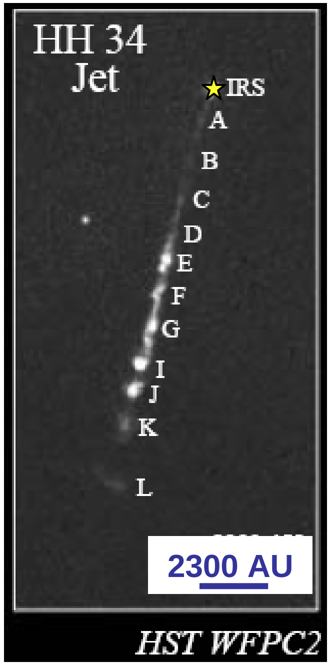
adapted from André 2002

From super-jets to micro-jets…



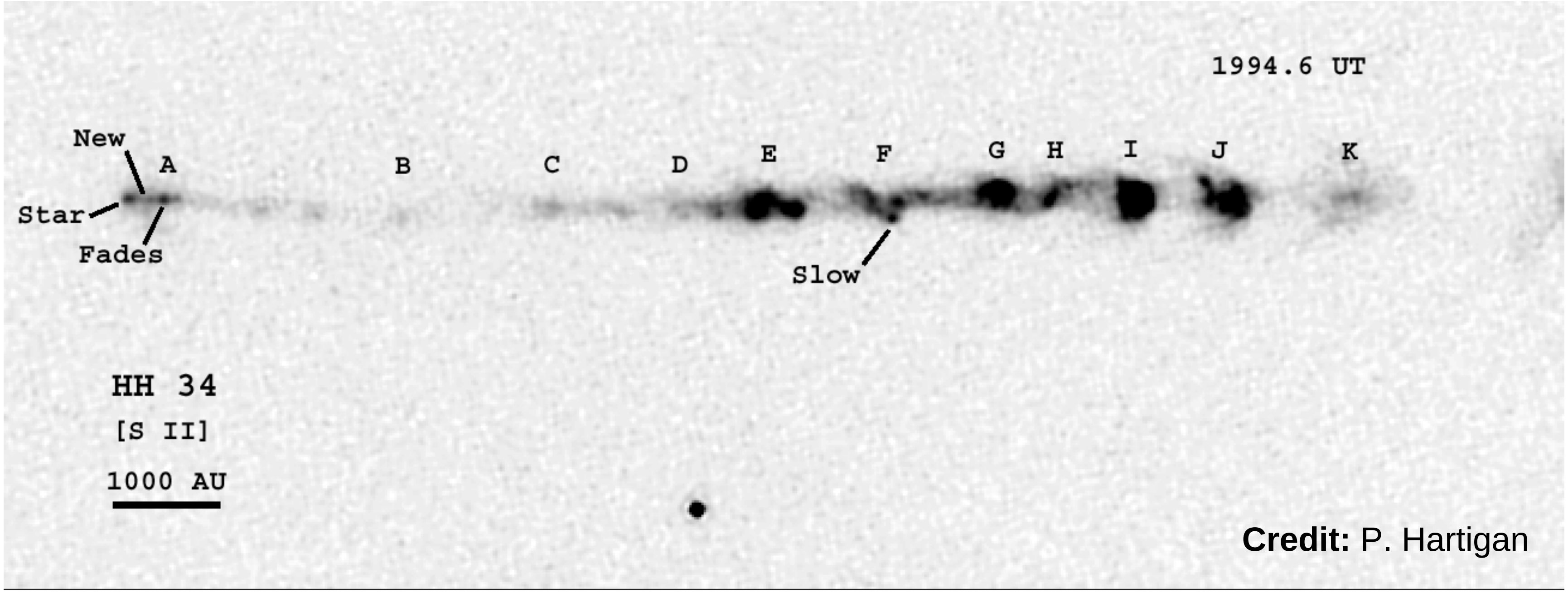
700k AU ~ 11 light years ~ 3.4 parsec ~ 10^{14} km





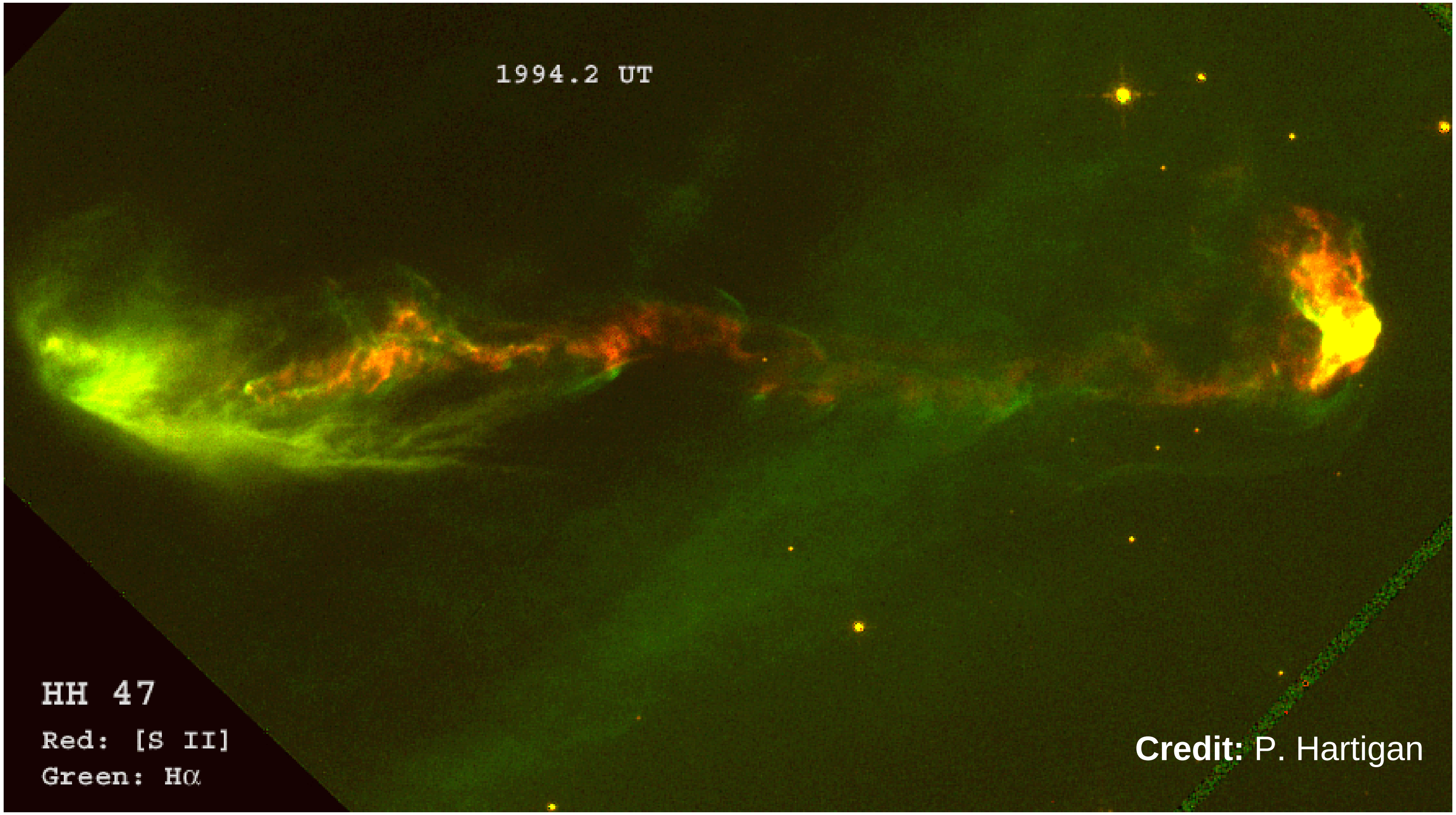
Bally & Morse 1996

For near by sources, proper motions can be directly observed



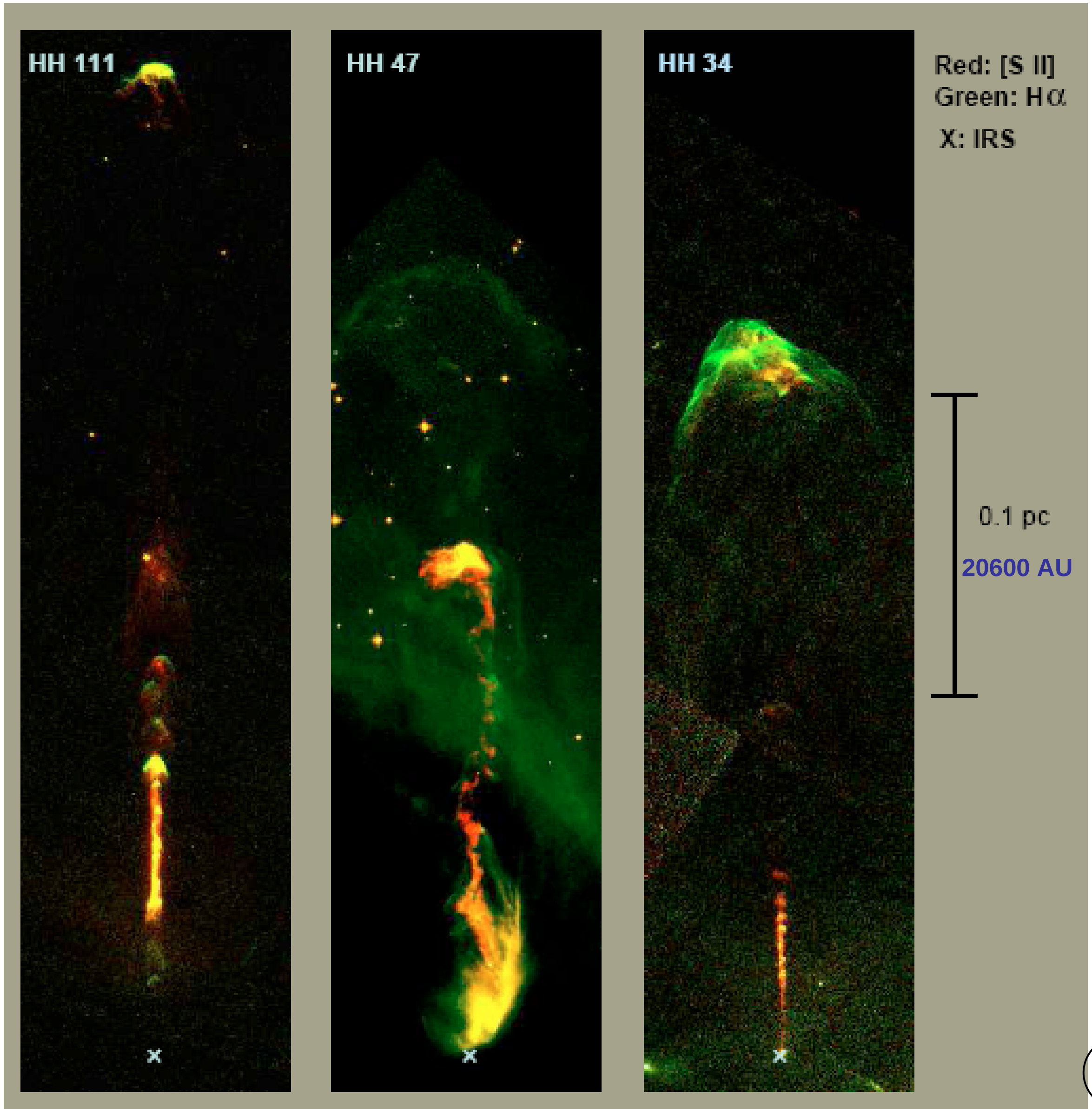
10k AU

For near by sources, proper motions can be directly observed



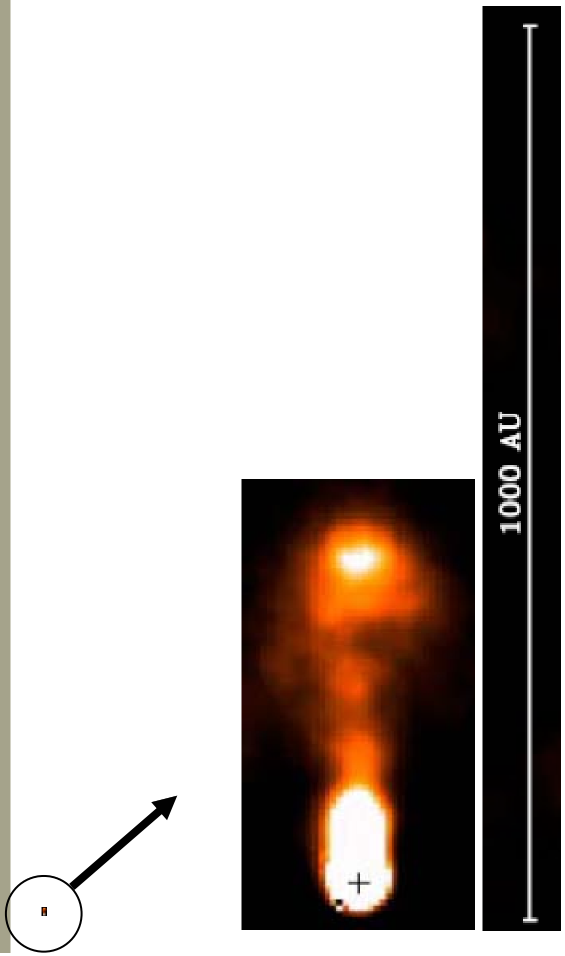
35k AU

From super-jets to micro-jets…



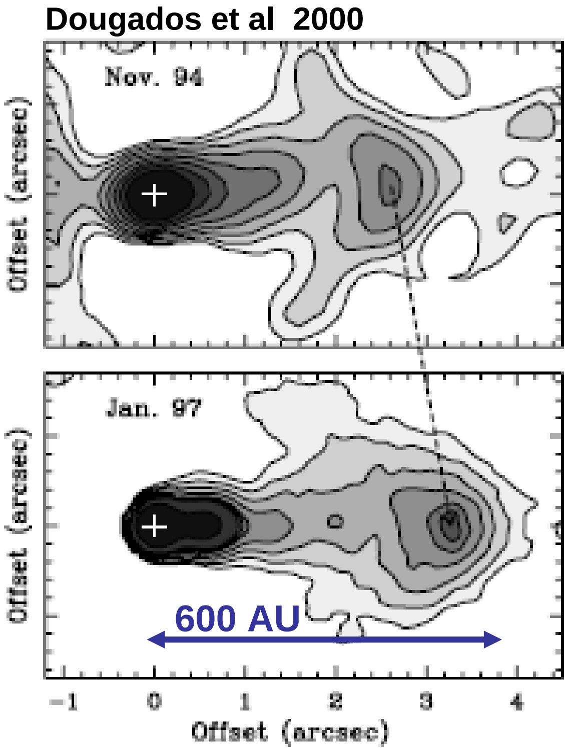
Cabrit 2000

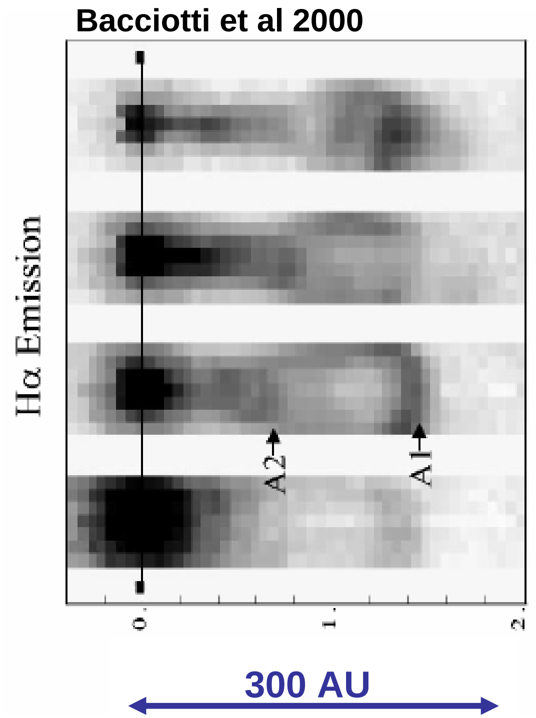
DG Tau

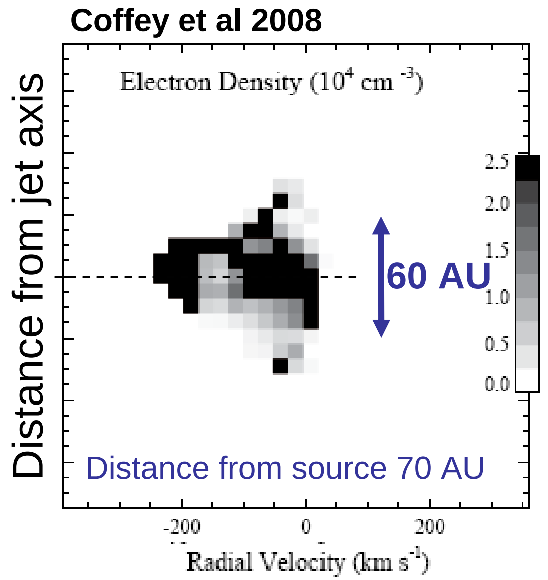


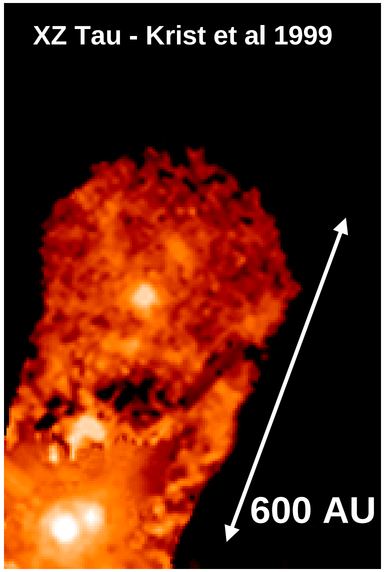
Dougados 2005

Asymmetries and internal structures very close to the source: the example of DG Tau and XZ Tau









"Typical" jet physical conditions:

velocities ~ few x 100 km/s → Mach > 10

densities ~ 10^6 to few x 100 particles / cc

temperatures ~ few x 1000 K (→ 10^6 K in strong shocks)

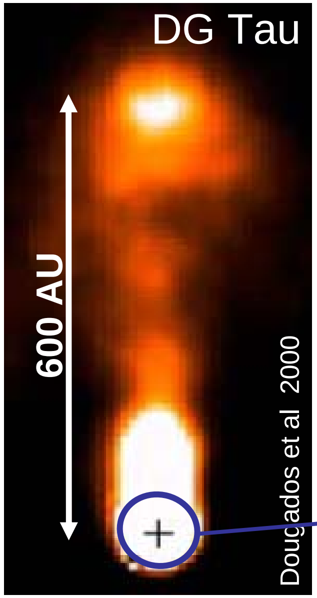
ionization fraction ~ 10%

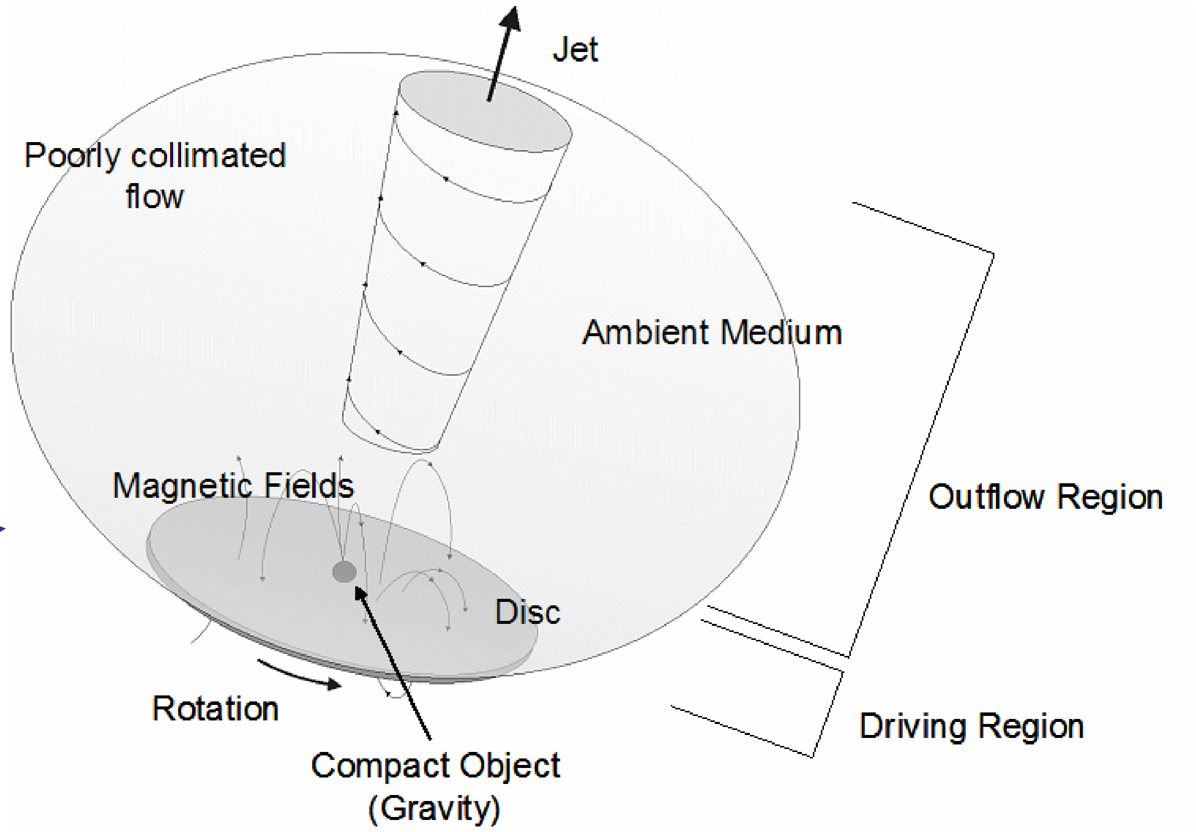
magnetic fields ~ ????? → 100 mG - few μGauss

Observations of jets: SUMMARY

Jets are not continuous streams of plasma but are time varying, heterogeneous flows

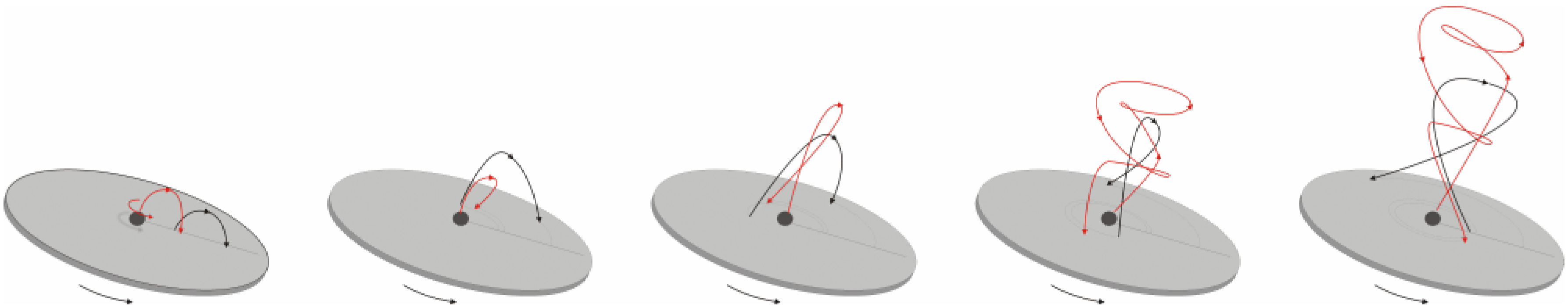
How are jets formed?



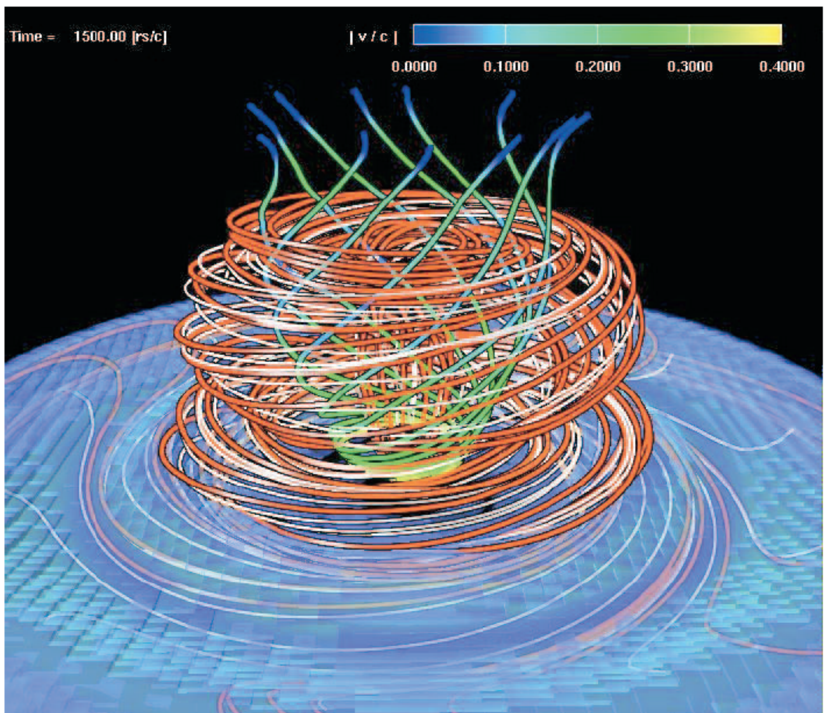


Blandford & Payne
Lynden-Bell
Lovelace
Ferreira
Camenzind
….

Twisting magnetic fields 1

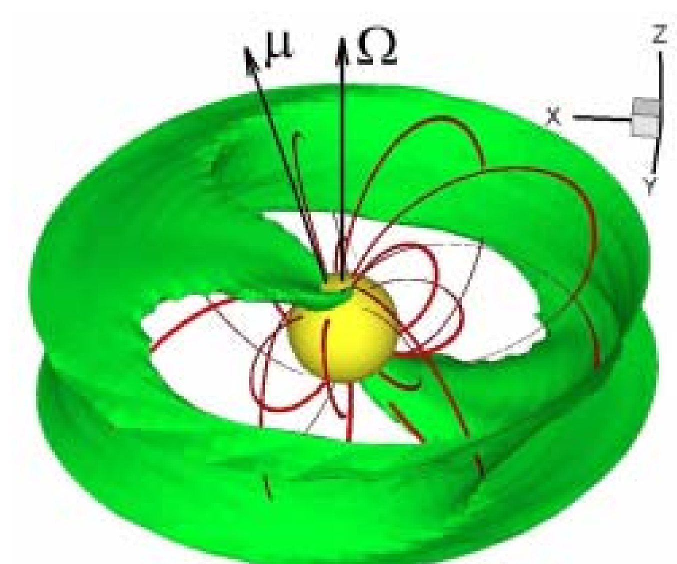


$B_{poloidal} \rightarrow B_{toroidal}$



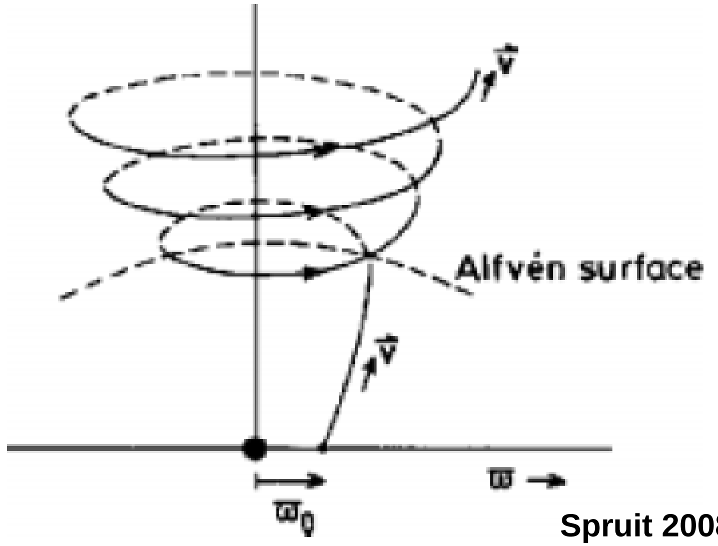
Kato et al 2004

star-disk interaction region



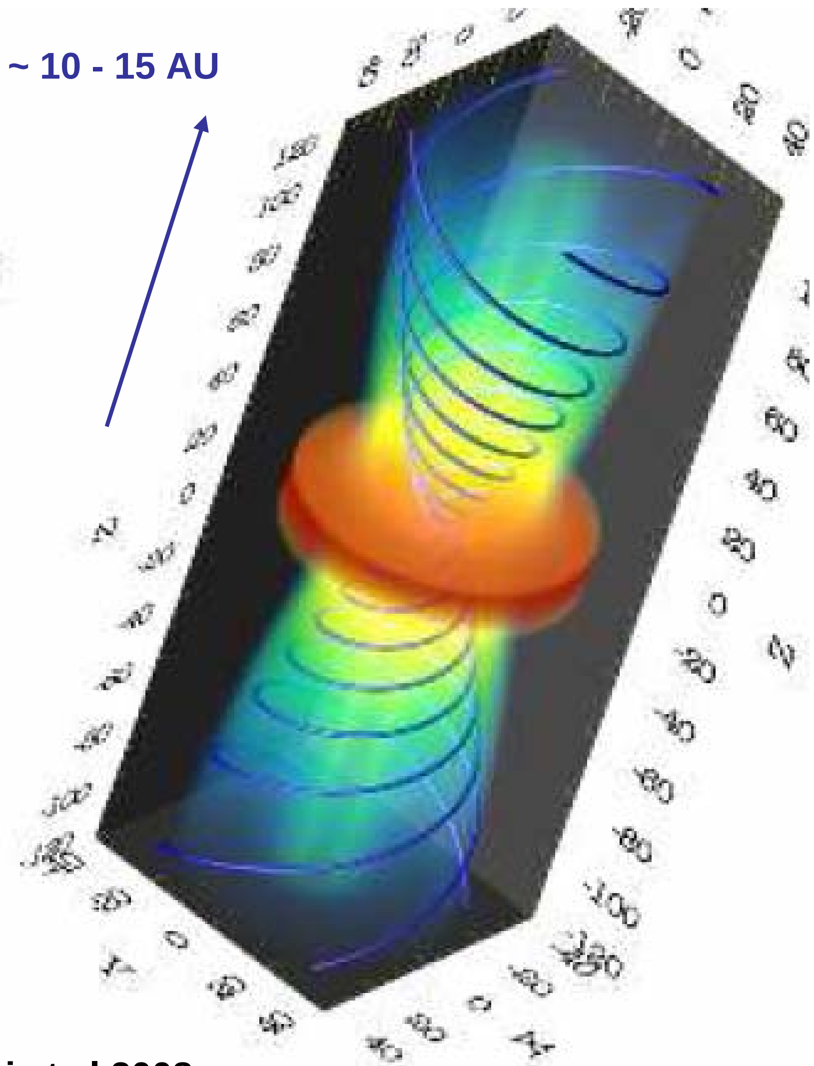
Romanova et al 2008

Twisting magnetic fields 2



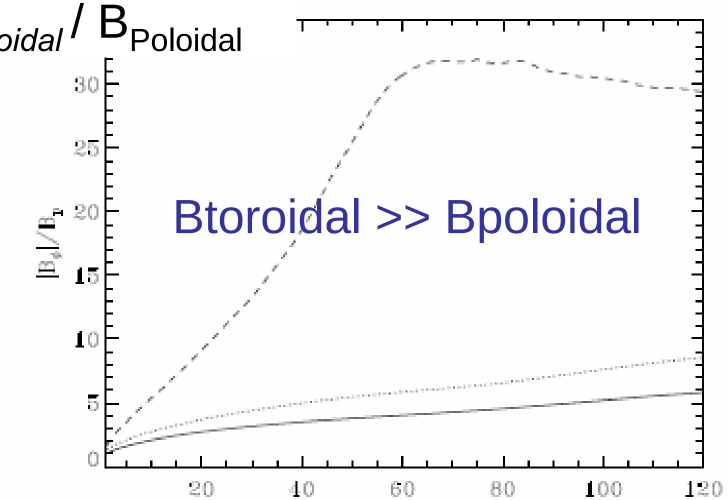
Spruit 2008

$B_{poloidal} \rightarrow B_{toroidal}$



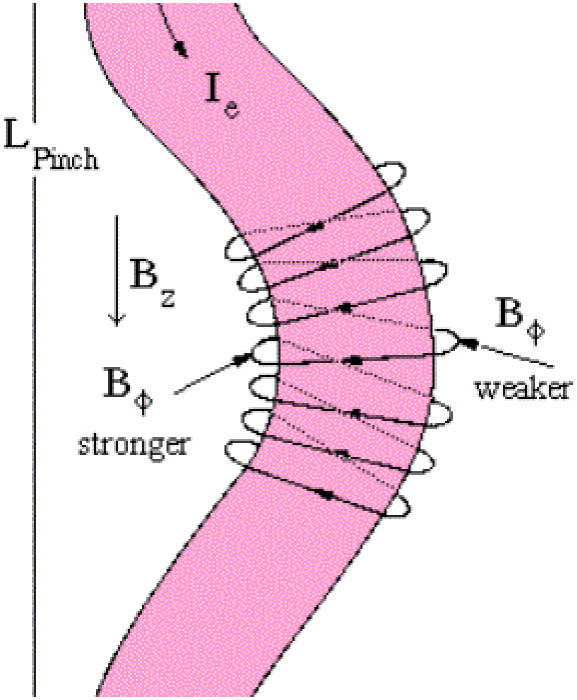
Zanni et al 2008

$B_{Toroidal}$ / $B_{Poloidal}$



height above source

Btoroidal >> Bpoloidal is unstable!



kink instability

Jets are not a continuous stream of plasma but are time varying, heterogeneous flows

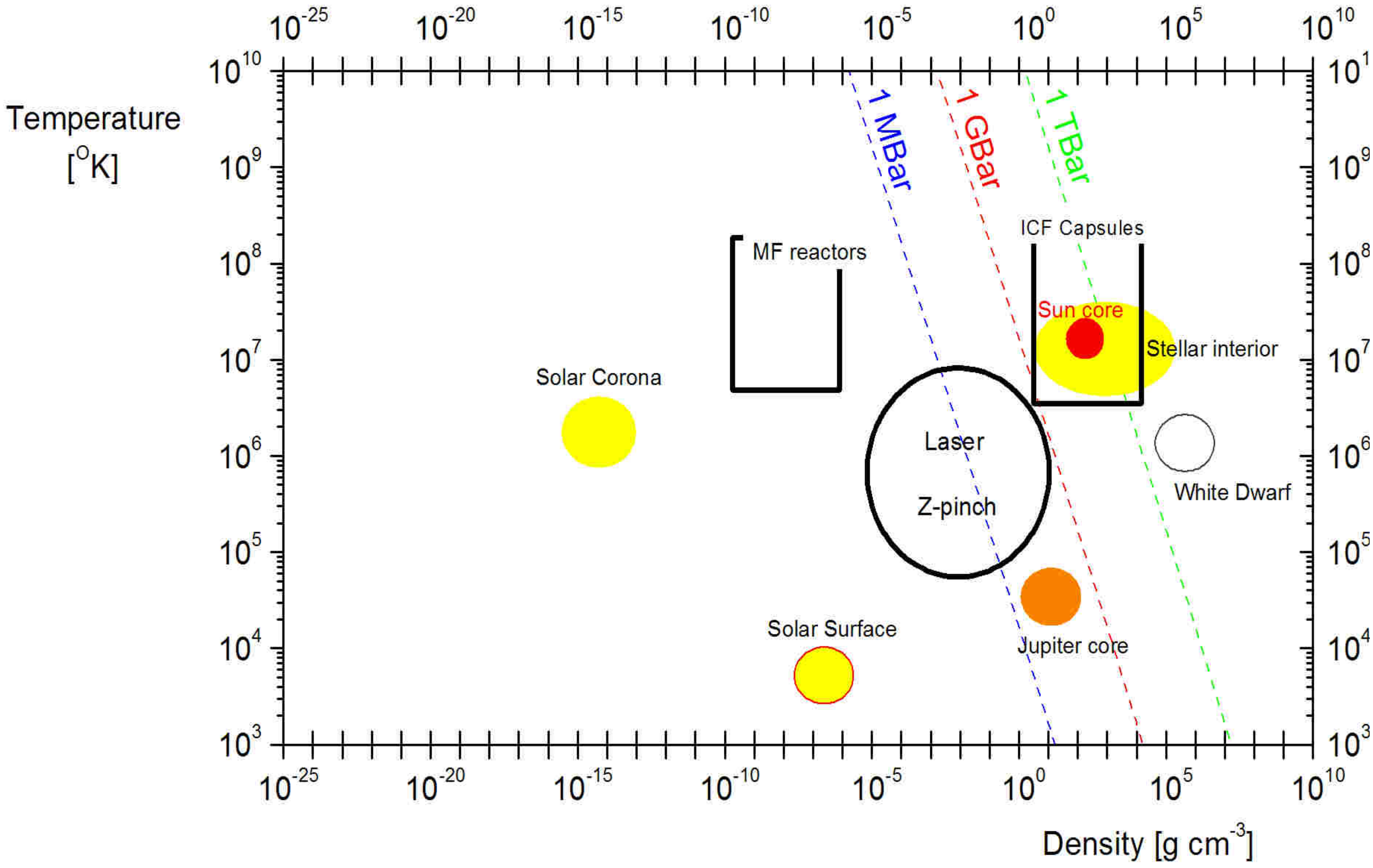
Magnetic fields are responsible for collimating and accelerating jets.

But the configuration is unstable....

Drawing credit: Roth et al 1997

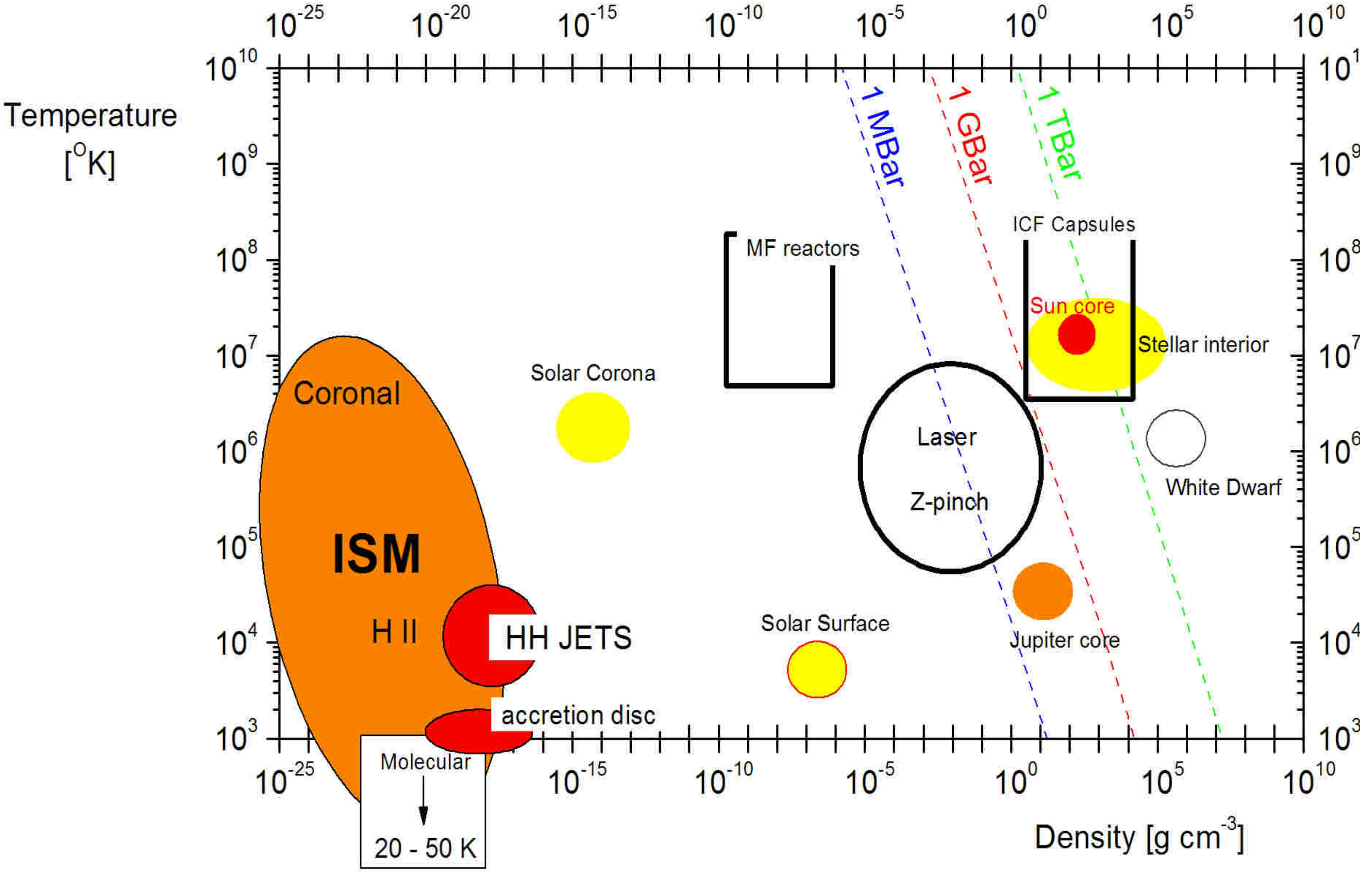
High-energy Density Laboratory Astrophysics

HIGH-ENERGY DENSITY PLASMAS



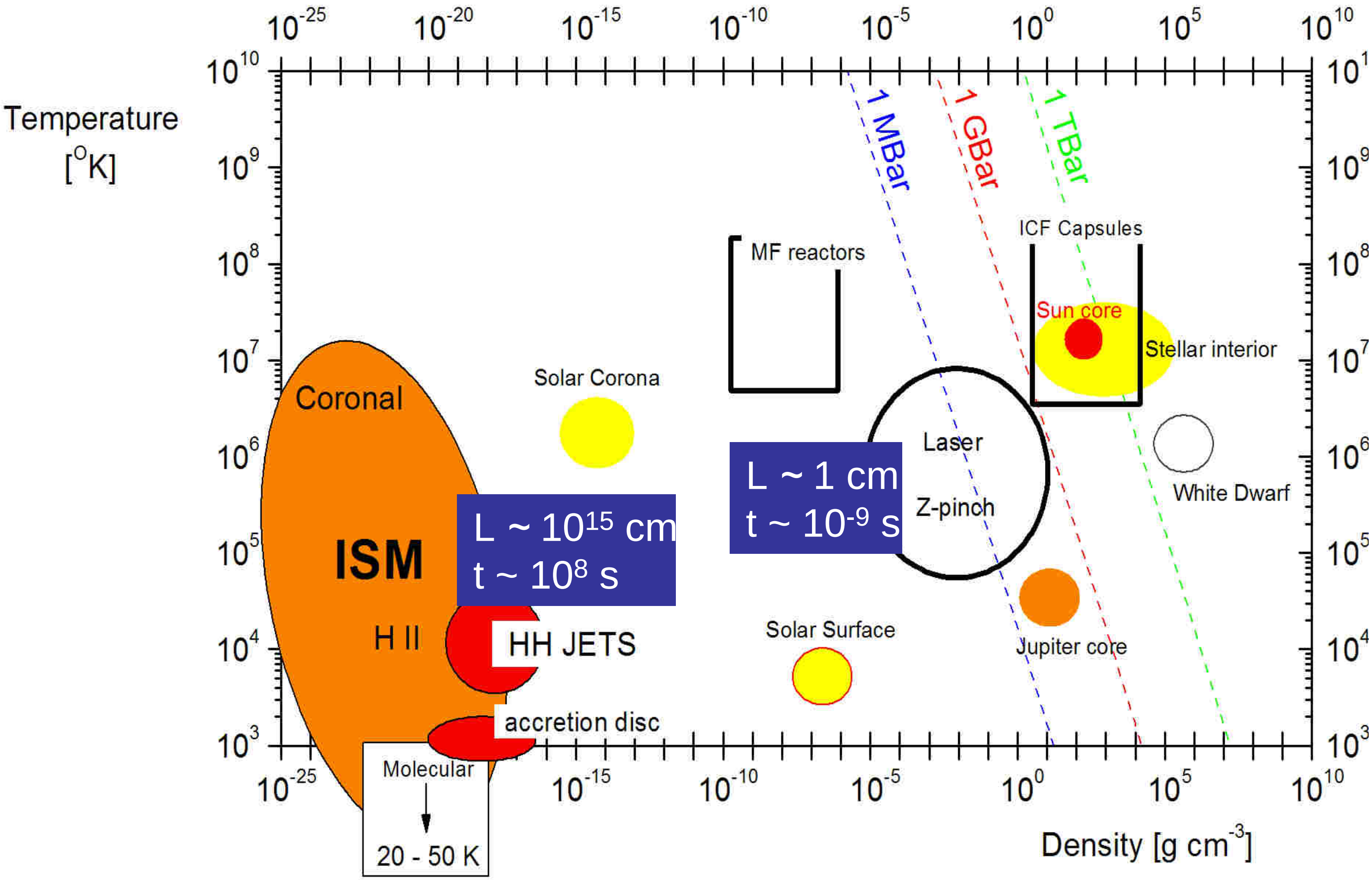
1 Mbar = 10^{11} J m^{-3} = 10^{12} erg cm^{-3}

HIGH-ENERGY DENSITY PLASMAS

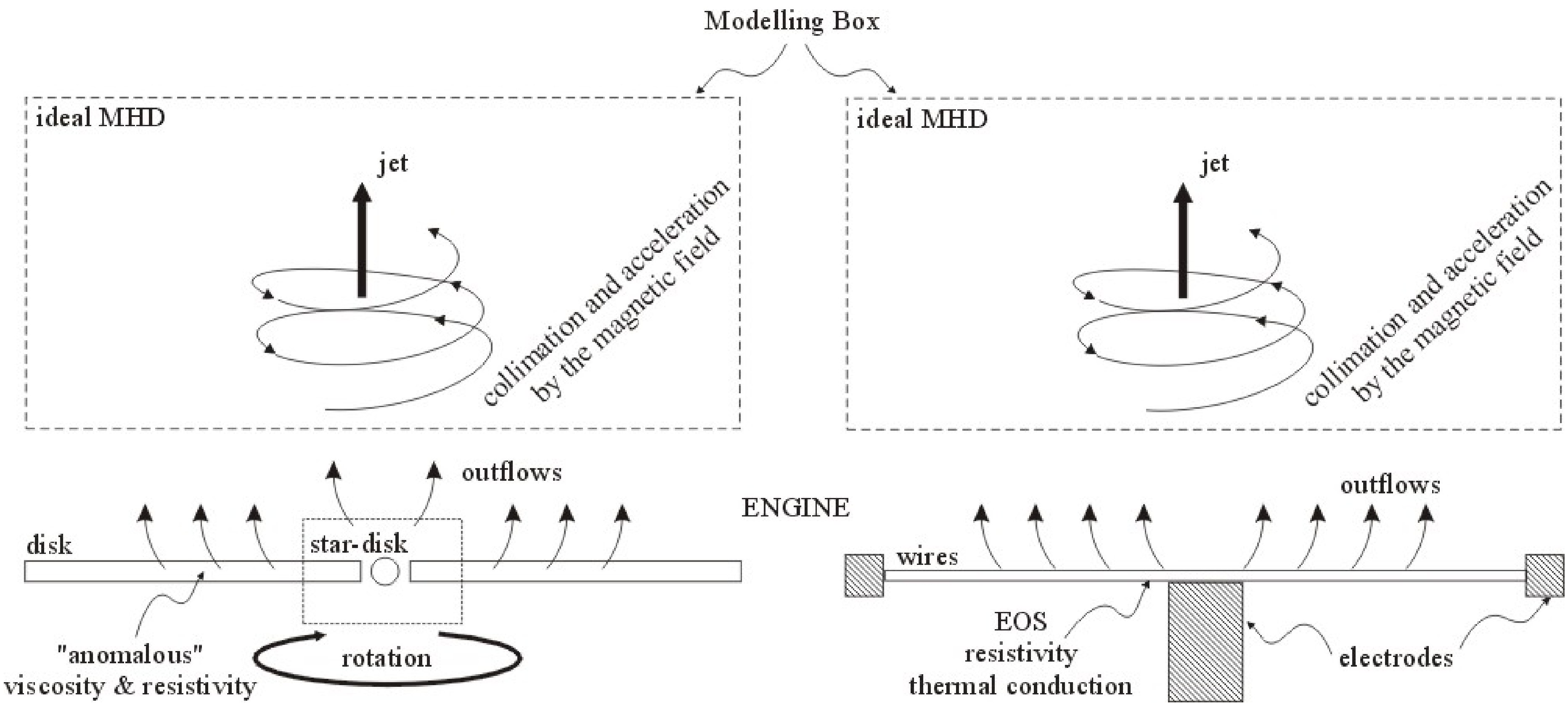


Ciardi, LNP, 2009

HIGH-ENERGY DENSITY PLASMAS



Scaling astrophysical phenomena by waving your hands



Ciardi, LNP, 2009

Experiments are designed to go from “non-ideal” to “ideal”

more ideal

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

$$\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) = -\nabla (p_i + p_e) + \mathbf{j} \times \mathbf{B}$$

$$\frac{\partial \varepsilon_i}{\partial t} + \nabla \cdot (\varepsilon_i \mathbf{v}) = -p_i \nabla \cdot \mathbf{v} - \cancel{\nabla \cdot \mathbf{q}_i} + \Delta_{ie}$$

$$\frac{\partial \varepsilon_e}{\partial t} + \nabla \cdot (\varepsilon_e \mathbf{v}) = -p_e \nabla \cdot \mathbf{v} - \cancel{\nabla \cdot \mathbf{q}_e} + \cancel{\eta |\mathbf{j}|^2} - \Lambda + \Delta_{ei}$$

EOS: perfect gas (+ LTE ionization)

not so ideal

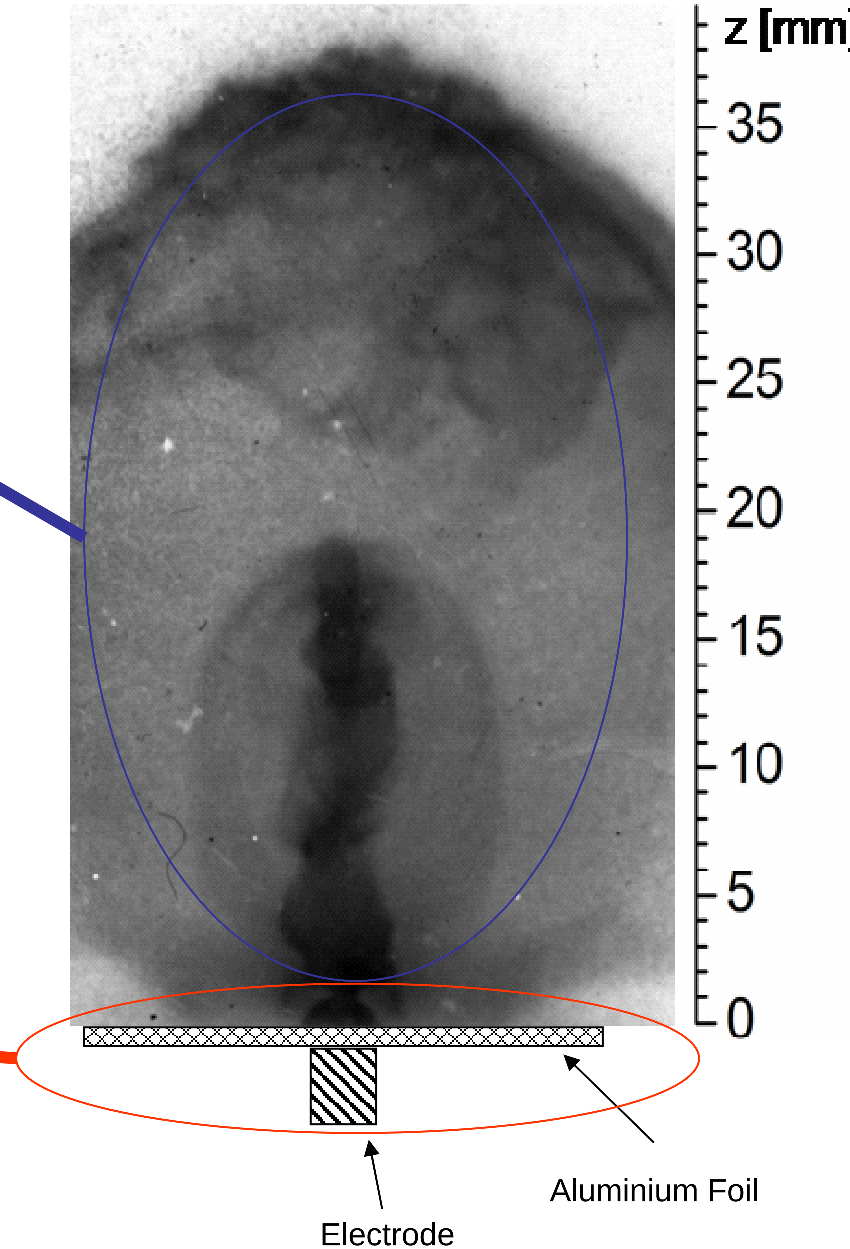
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) = -\nabla (p_i + p_e) + \mathbf{j} \times \mathbf{B}$$

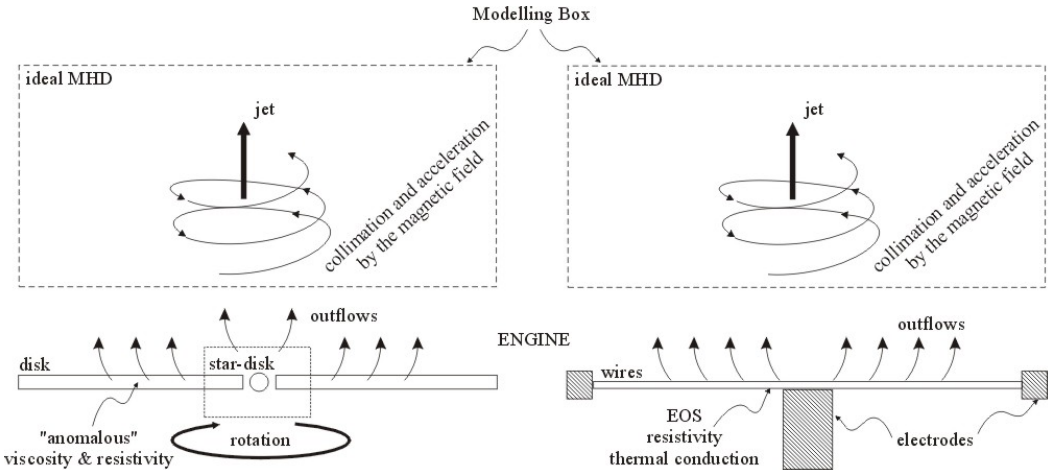
$$\frac{\partial \varepsilon_i}{\partial t} + \nabla \cdot (\varepsilon_i \mathbf{v}) = -p_i \nabla \cdot \mathbf{v} - \nabla \cdot \mathbf{q}_i + \Delta_{ie}$$

$$\frac{\partial \varepsilon_e}{\partial t} + \nabla \cdot (\varepsilon_e \mathbf{v}) = -p_e \nabla \cdot \mathbf{v} - \nabla \cdot \mathbf{q}_e + \eta |\mathbf{j}|^2 - \Lambda + \Delta_{ei}$$

EOS: solid → plasma
Thermal conduction, …



Scaling by invariance of the ideal MHD equations



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

$$\rho\left(\frac{\partial\mathbf{v}}{\partial t}+\mathbf{v}\cdot\nabla\mathbf{v}\right)=-\nabla p+\frac{1}{4\pi}(\nabla\times\mathbf{B})\times\mathbf{B}$$

$$\frac{\partial p}{\partial t}+\mathbf{v}\cdot\nabla p=-\gamma p\nabla\cdot\mathbf{v}\qquad\frac{\partial\mathbf{B}}{\partial t}=\nabla\times\mathbf{v}\times\mathbf{B}$$

$$r=L^*\tilde{r}$$

$$\rho=\rho^*\tilde{\rho}$$

etc...

$\Longleftrightarrow$

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

$$\tilde{\rho}\left(\frac{\partial\tilde{\mathbf{v}}}{\partial\tilde{t}}+\tilde{\mathbf{v}}\cdot\tilde{\nabla}\tilde{\mathbf{v}}\right)=-\tilde{\nabla}\tilde{p}+\frac{1}{4\pi}(\tilde{\nabla}\times\tilde{\mathbf{B}})\times\tilde{\mathbf{B}}$$

$$\frac{\partial\tilde{p}}{\partial\tilde{t}}+\tilde{\mathbf{v}}\cdot\tilde{\nabla}\tilde{p}=-\gamma\tilde{p}\tilde{\nabla}\cdot\tilde{\mathbf{v}}\qquad\frac{\partial\tilde{\mathbf{B}}}{\partial\tilde{t}}=\tilde{\nabla}\times\tilde{\mathbf{v}}\times\tilde{\mathbf{B}}$$

If the initial conditions are geometrically similar, then the two systems will evolve identically provided that:

$$v^*\sqrt{\frac{\rho^*}{p^*}}=inv\qquad\frac{B^*}{\sqrt{p^*}}=inv$$

Similarity conditions: see Ryutov et al 1999, 2001

The world is not perfect

Reynolds number Re >> 1 ($\sim 10^{12}$)
Neglect Viscosity

Magnetic Reynolds number Re_M >> 1 ($\sim 10^{16}$)
Neglect Resistivity

Peclet number Pe >> 1 ($\sim 10^{10}$)
Neglect Thermal Conduction

Laboratory	**Space**	**Numerical**
$Re \sim 10^5$	$Re \sim 10^{12}$	$Re \sim 10 - 10^3$
$Re_M \sim 10 - 10^3$	$Re_M \sim 10^{16}$	$Re_M \sim 10 - 10^3$
$Pe \sim 10 - 10^3$	$Pe \sim 10^{10}$	$Pe \sim 10 - 10^3$

Laboratory flows:

Three-dimensional

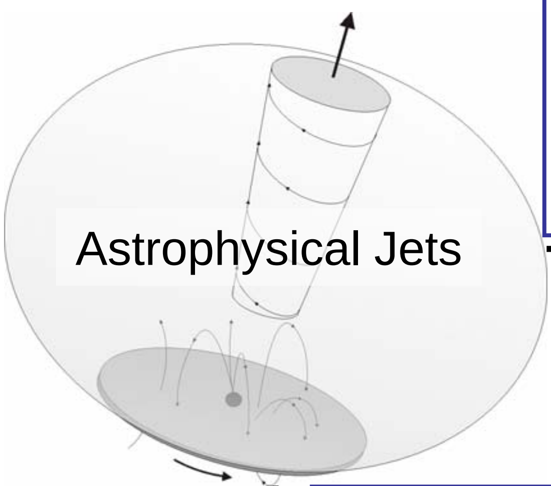
Mach numbers ~ 5 - 40

Radiative cooling is important

1 >> *plasma-β* >> 1

Laboratory jets are complementary to astrophysical simulations of jets

Laboratory astrophysics approach in practice



Study a subset of the problem

Make simplifying assumptions
- symmetry
- disregard physics by order of magnitude

Make an “educated” guess
- physical conditions/profiles

Analytical/Numerical Jets

Study an even smaller subset of the problem

No simplifying assumptions
cannot turn off a physical package! → *posteriori* sanity check

Make an “educated” guess → astrophysical system
- physical conditions/profiles

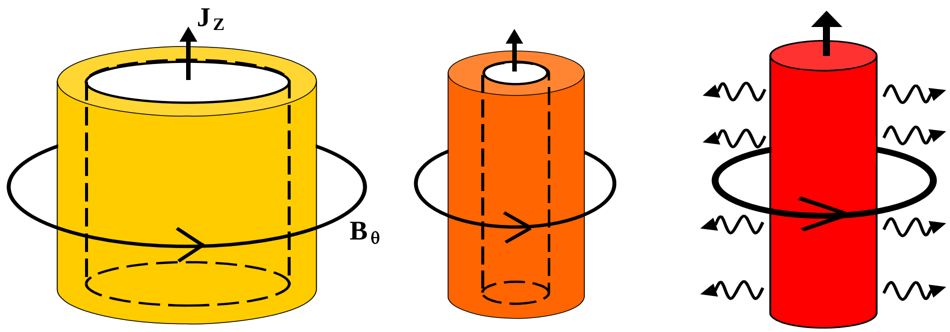
→ Good knowledge of initial conditions in the laboratory

Laboratory Jets

Jets in the Laboratory

WHAT IS A Z-PINCH?

The “dynamic” Z-pinch is an intense and efficient source of x-ray radiation



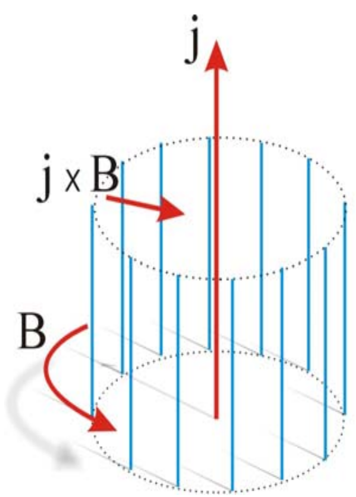
magnetic energy → kinetic energy → heat and radiation

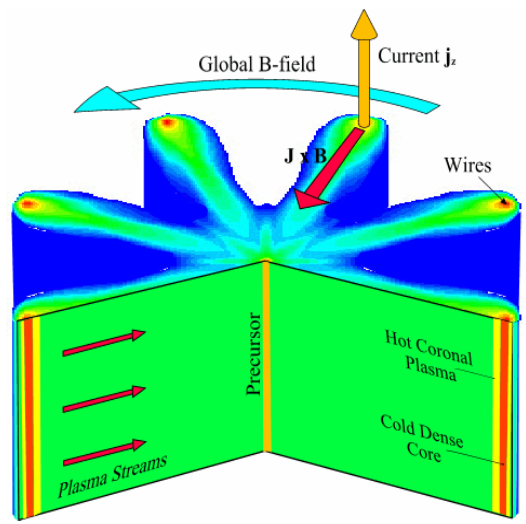
The magnetic energy drives the implosion of a plasma through a large current (20 MA)

Compression and shock heating thermalizes the kinetic energy of the ions.

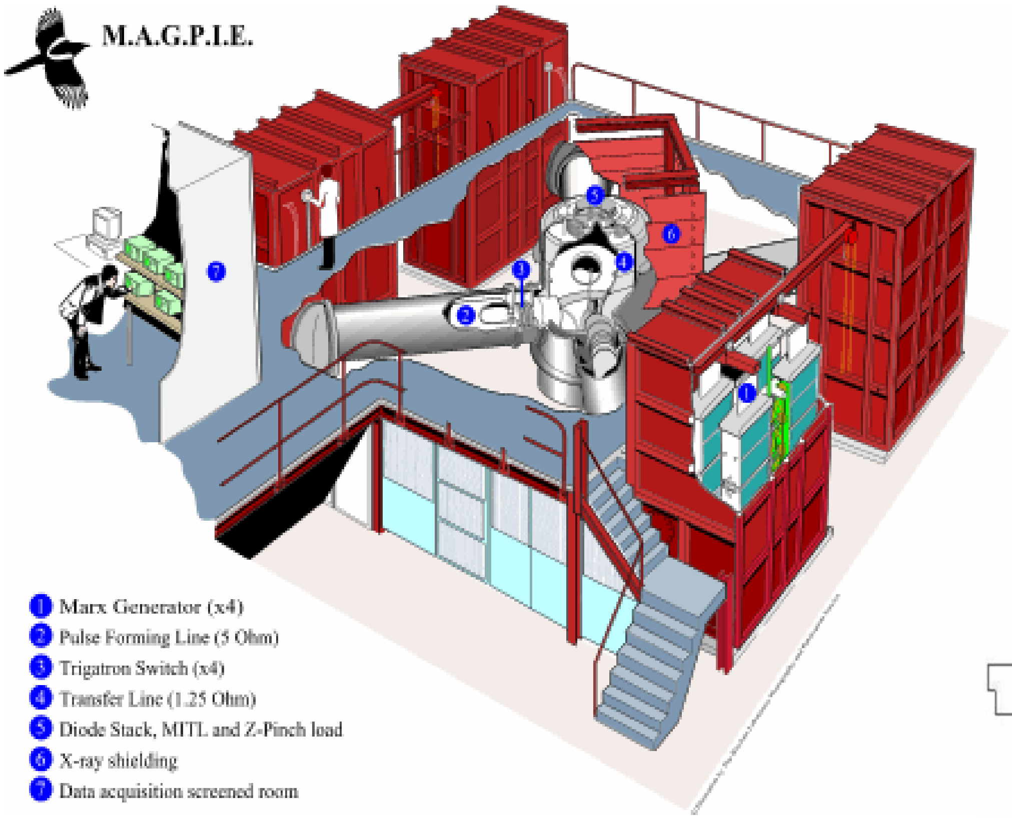
The plasma gets very hot (>1 keV) and radiates (280 TW - 1.6 MJ).

WIRE ARRAYS





MAGPIE EXPERIMENTAL FACILITY (Imperial College, UK)

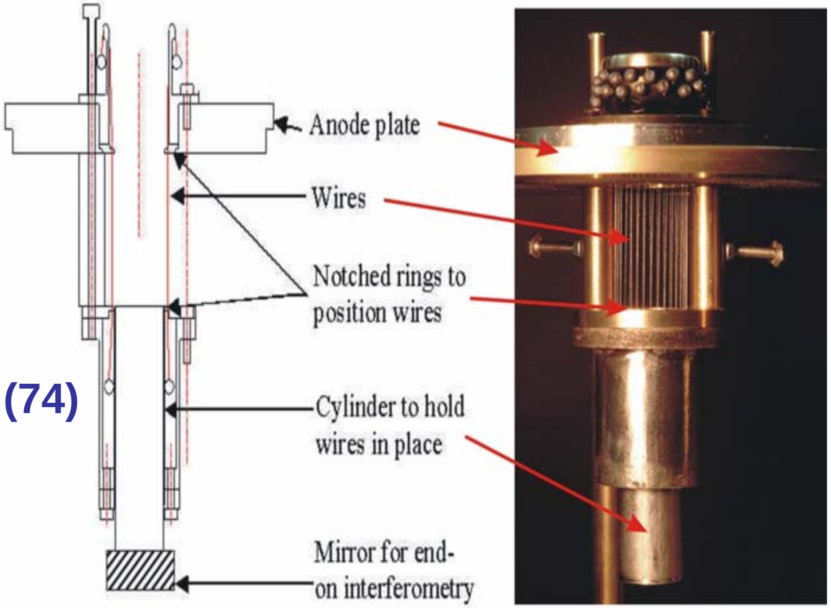


Load current ~ 1 - 1.4 Mega Amperes

Pulse duration of 240 ns

Energy ~ 300 kJ

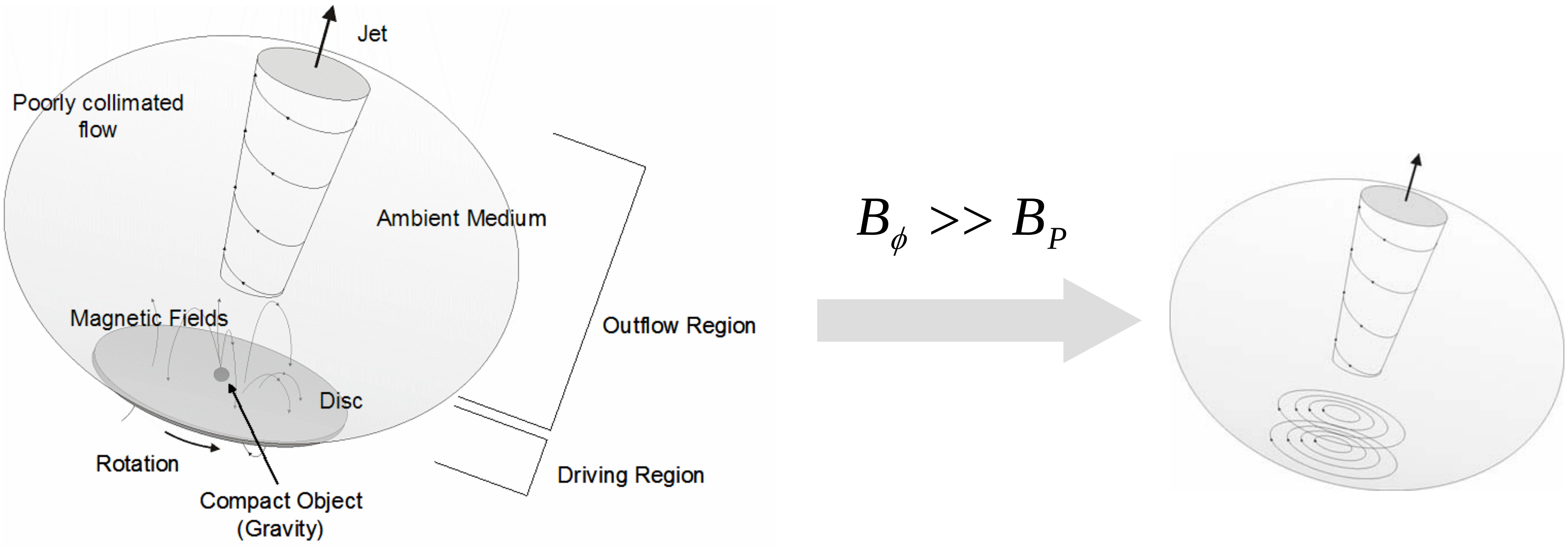
Characteristic powers ~ Tera Watts



Wire material: C (6), Al (13), Fe (26), Mo (42), W (74)

Typical volume ~ cubic centimetre

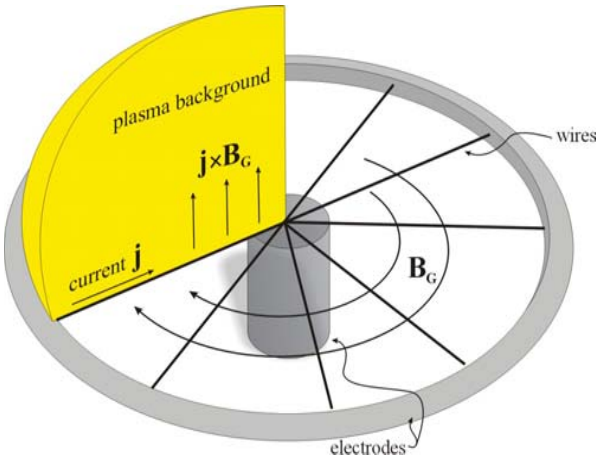
MAKING LIFE SIMPLE(R)

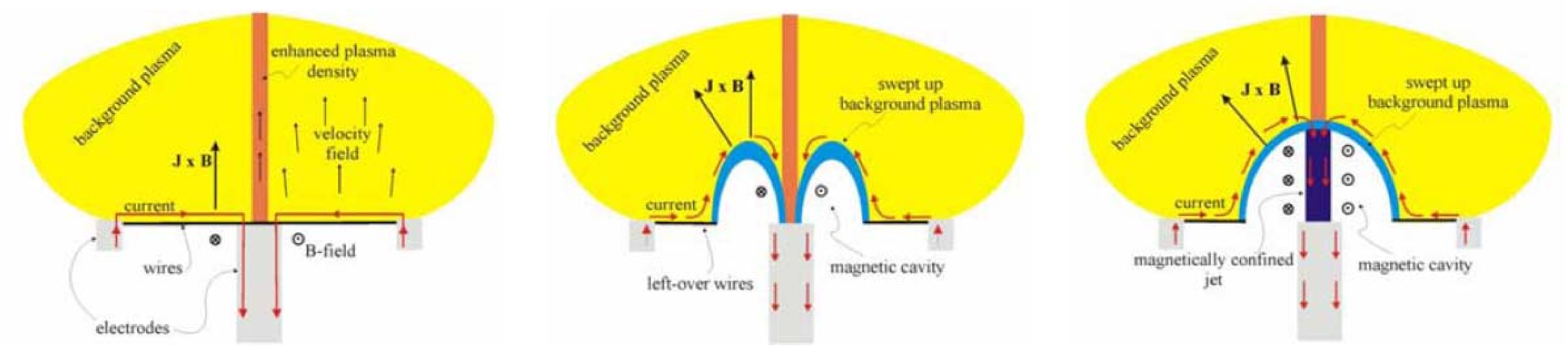


Is it too simplified? → Can jets be produced? → Are they relevant?

MAGNETICALLY DRIVEN JETS IN THE LABORATORY

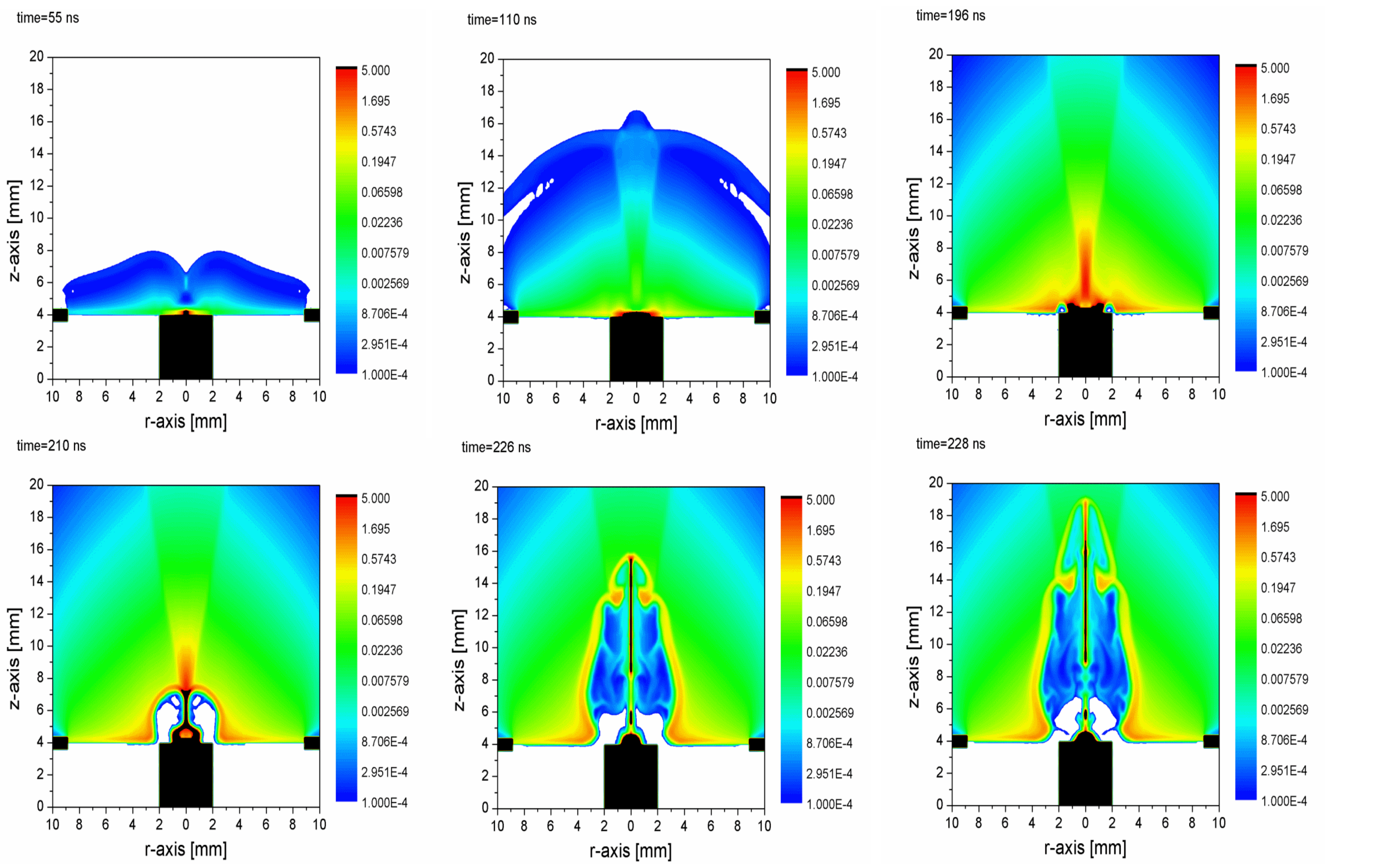
Radial wire arrays





Lebedev, MNRAS, 2005

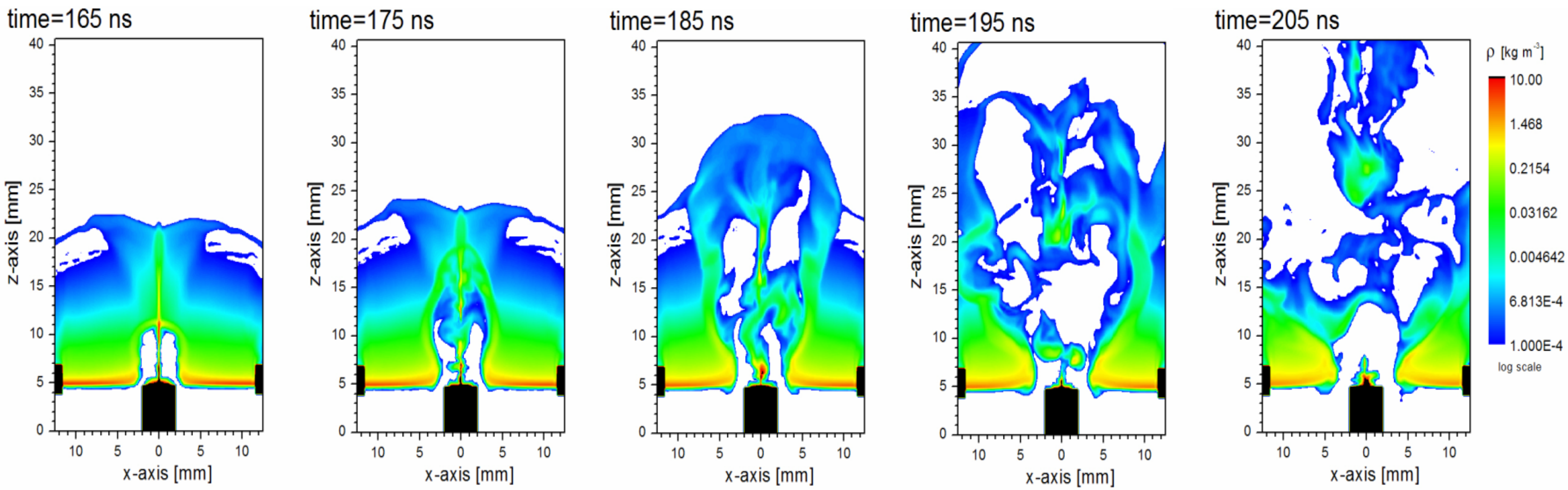
SIMULATING JETS IN THE LABORATORY: 2D AXIS-SYMMETRIC MHD

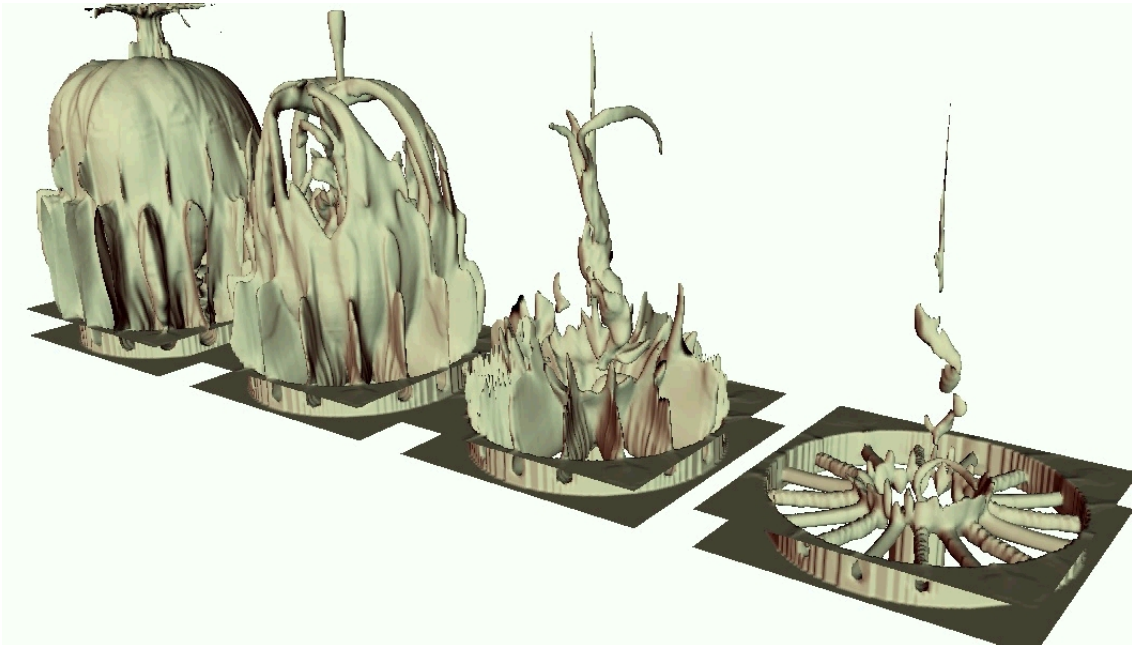


Logarithmic mass density contour plots
16 x 13 μm W wires.

Ciardi et al 2005

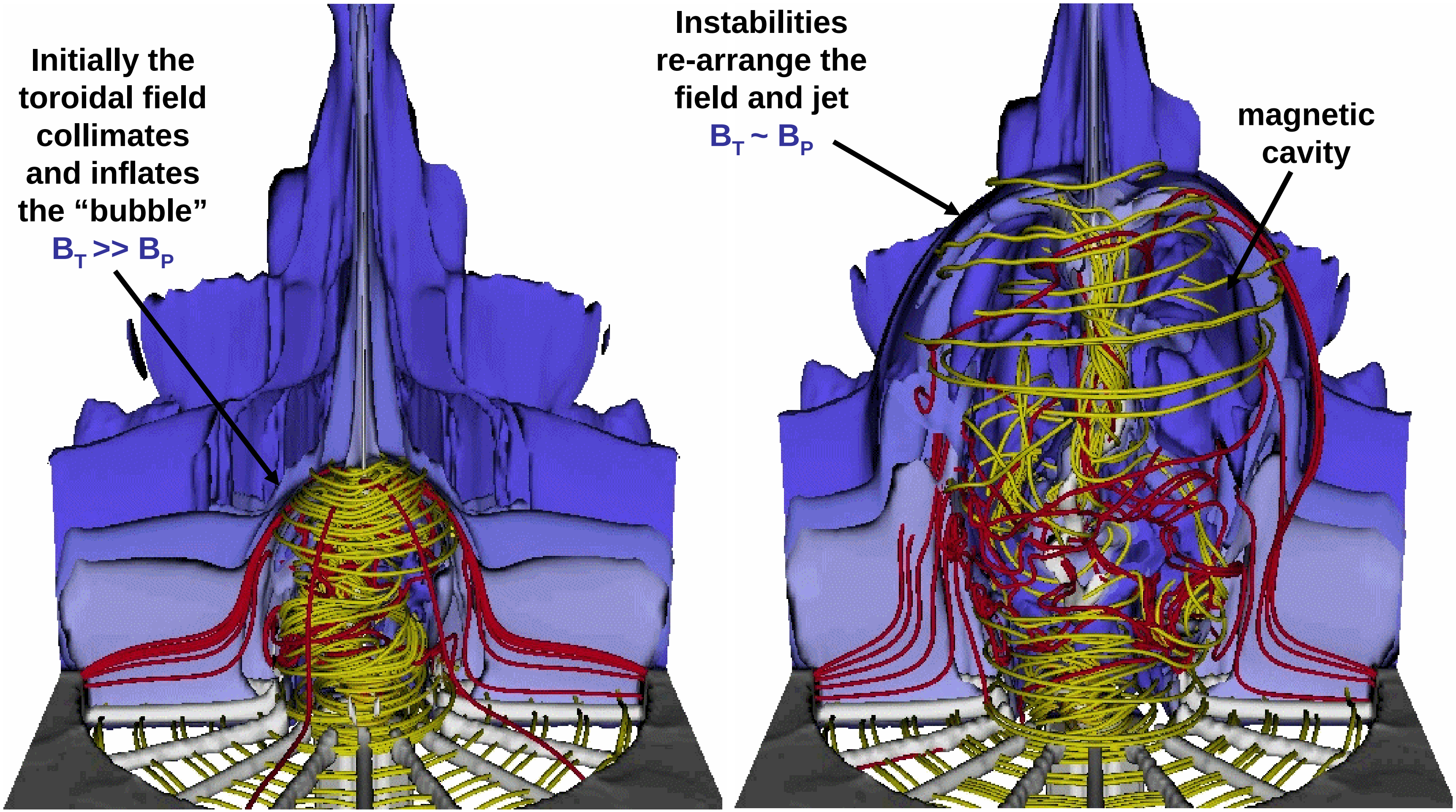
SIMULATING JETS IN THE LABORATORY: 3D MHD simulations





Ciardi et al 2007

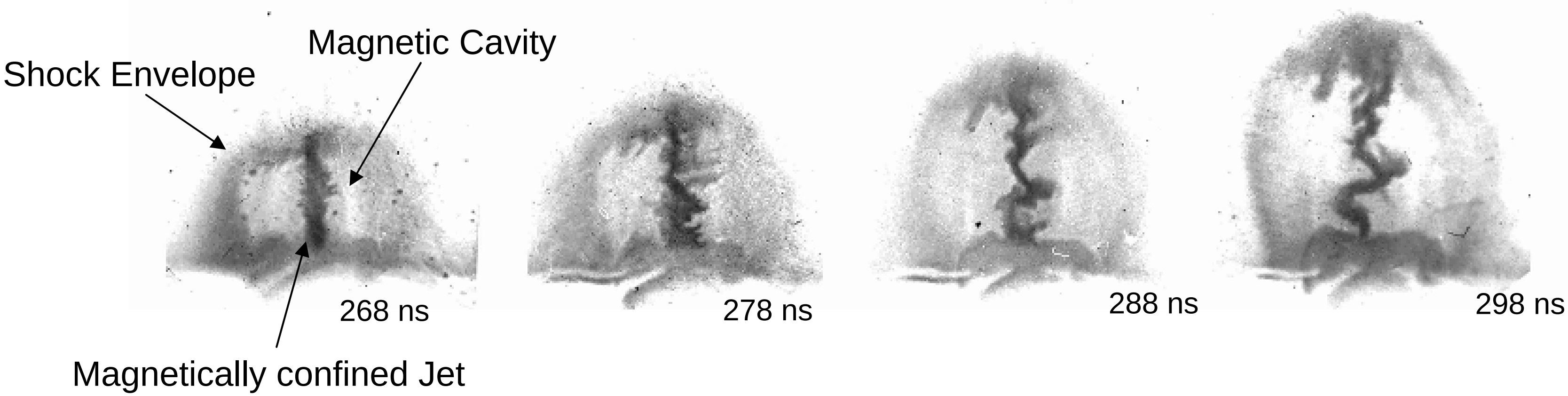
SIMULATING JETS IN THE LABORATORY: 3D MHD simulations



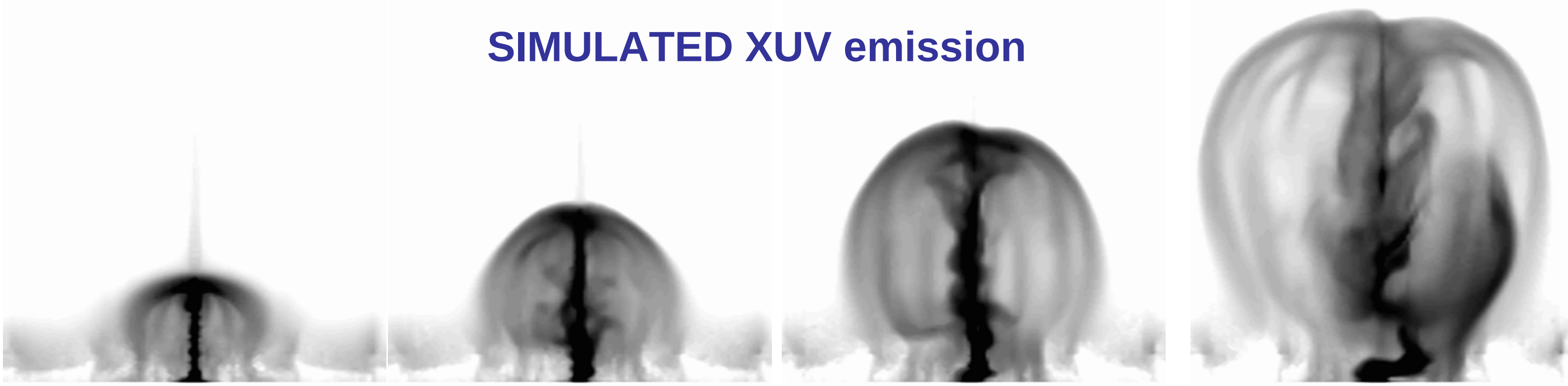
Ciardi et al 2007

SIMULATING JETS IN THE LABORATORY: the experiments

EXPERIMENTAL time resolved XUV images



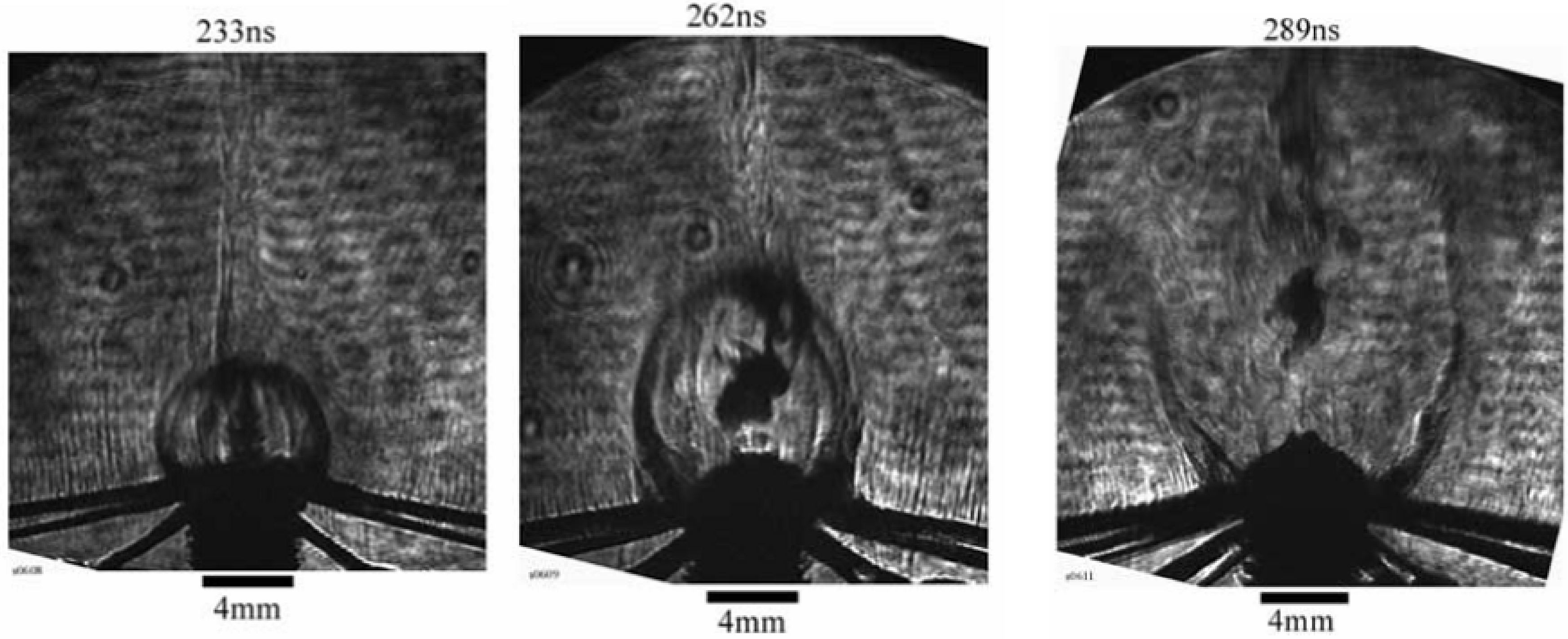
SIMULATED XUV emission



Ciardi et al 2007

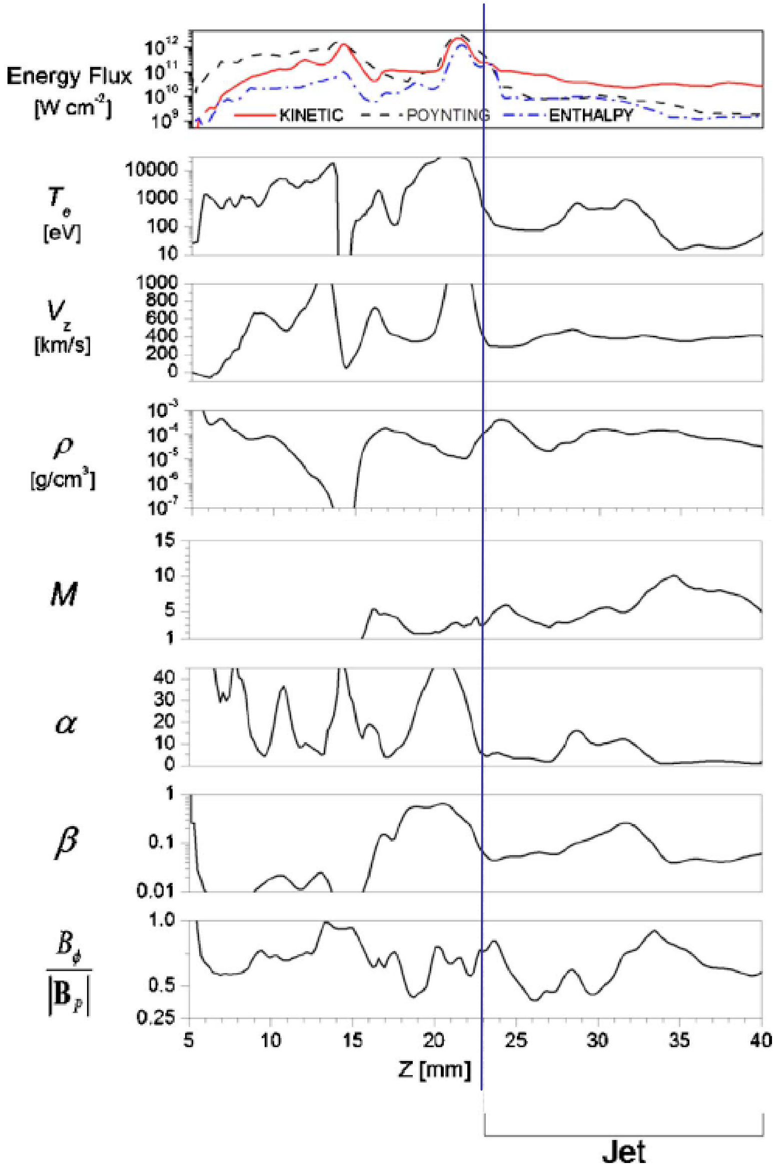
SIMULATING JETS IN THE LABORATORY: the experiments

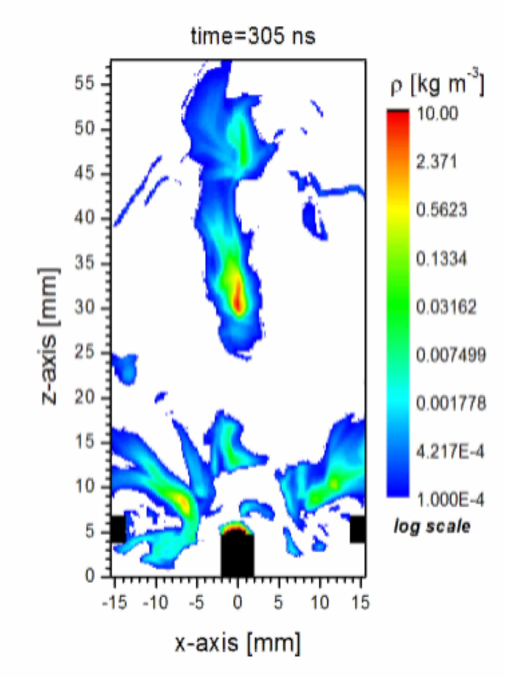
EXPERIMENTAL shadowgraph images

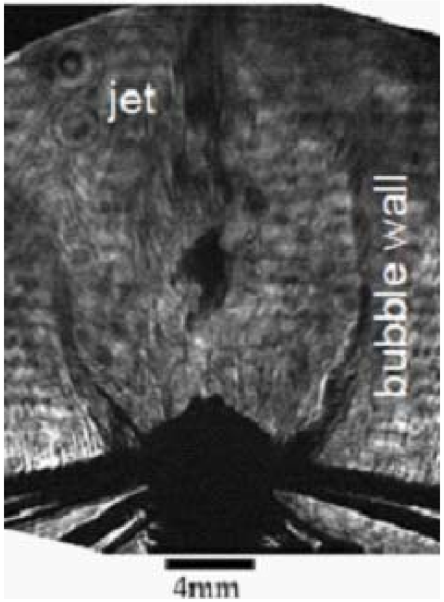


Lebedev et al 2005

Magnetically launched laboratory jets







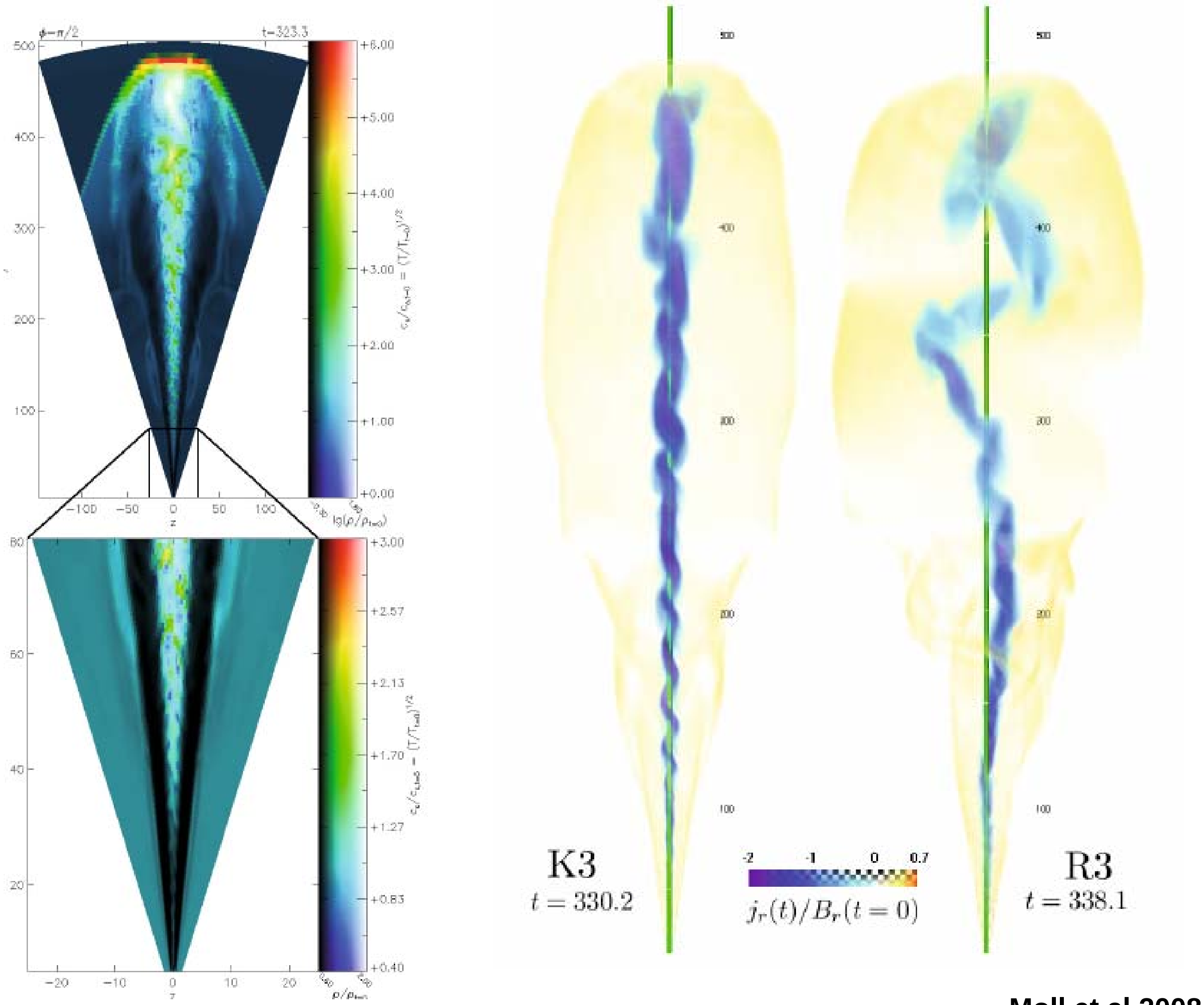
Instability is non-destructive.

Plasma and fields are rearranged into a clumpy, super-Alfvenic flow.

Emerging jet is still collimated.

Ciardi et al 2007

Astrophysical simulations of unstable jets



Moll et al 2008

Rotation may help to partially stabilize the jet

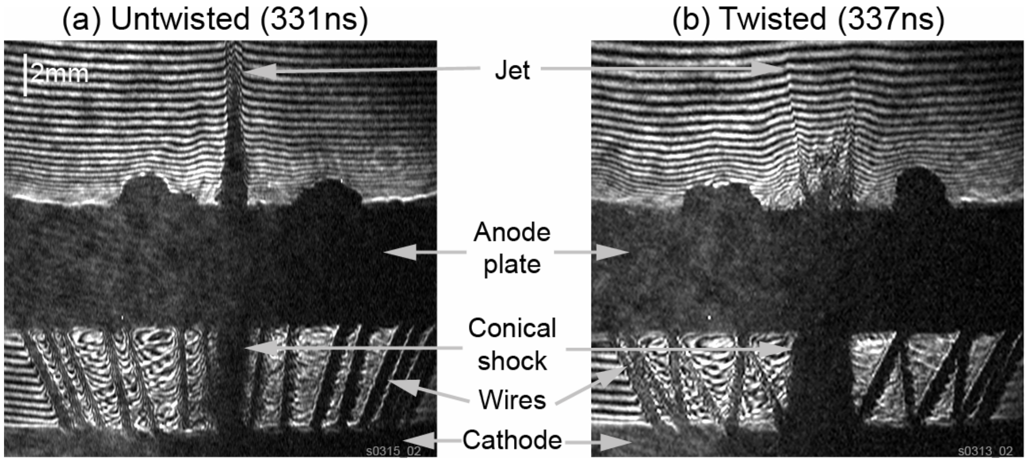
Testing astrophysical simulations predictions

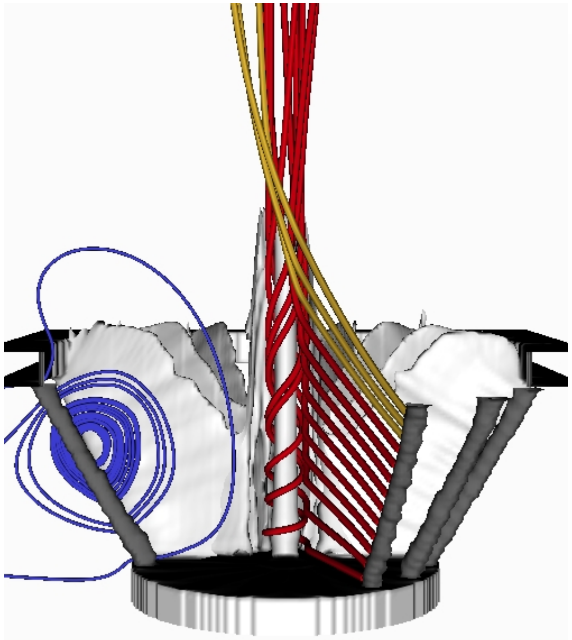
Using twisted conical arrays we obtained the first rotating laboratory jets.

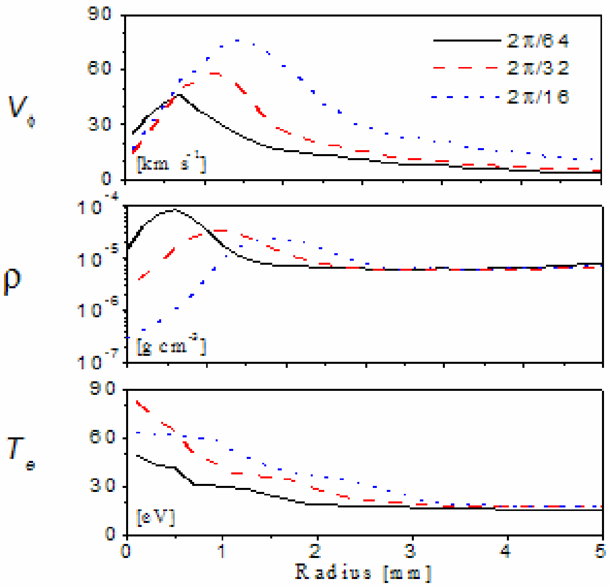
Measured rotation velocity ~ 10-20 % of axial velocity

Control over the level of angular momentum introduced in the flow. Proof-of-principle.

Modify radial arrays to introduce rotation in magnetically driven jets.

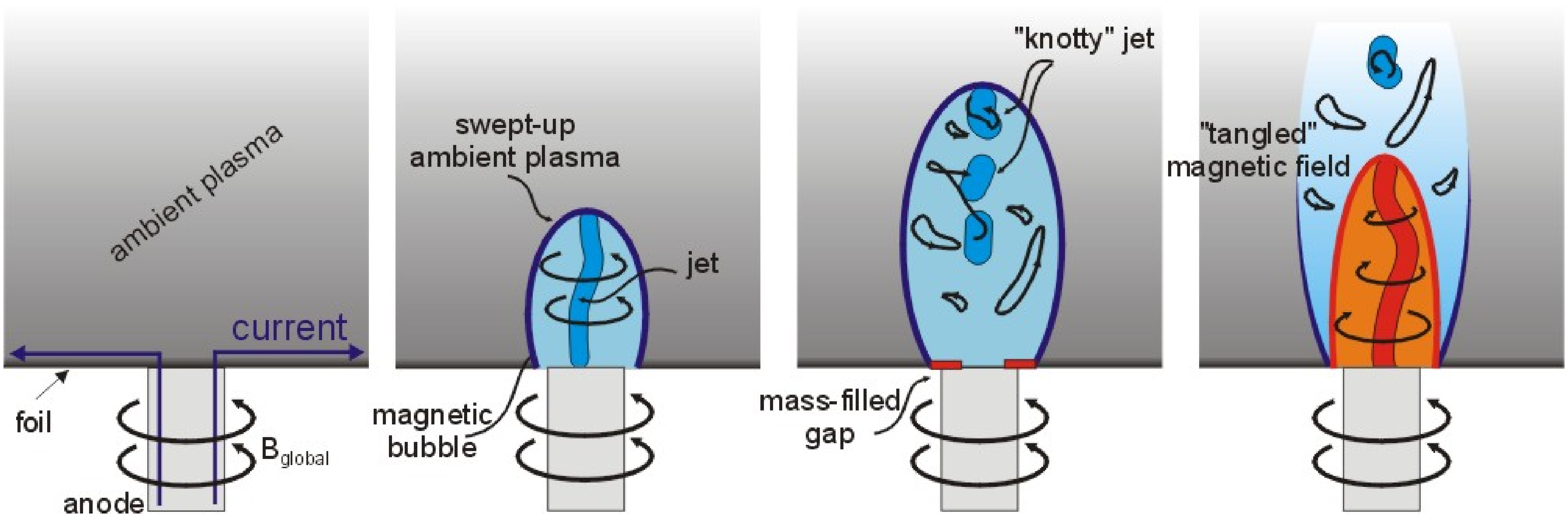






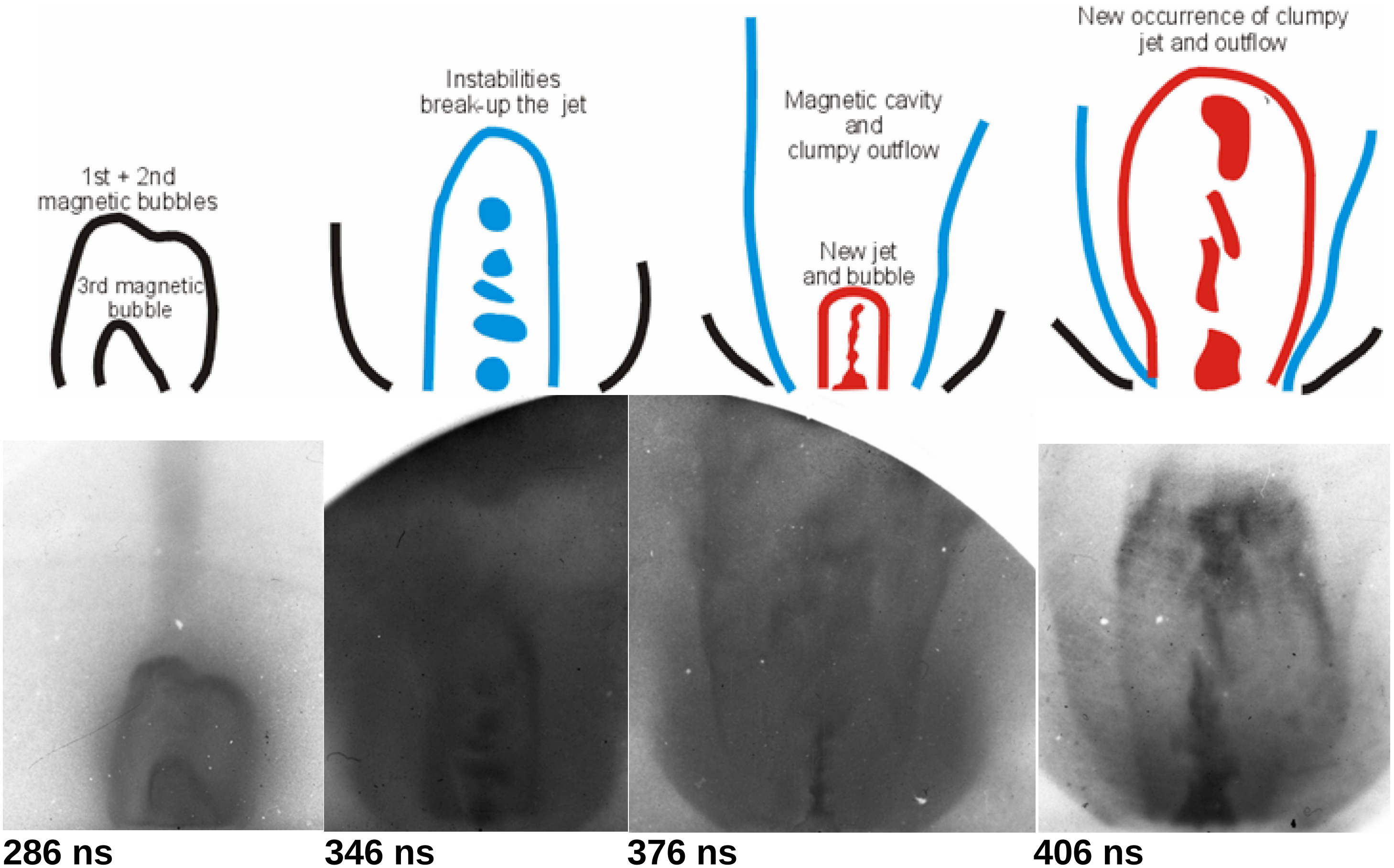
Ampleford et al 2008

Episodic jet launching and instabilities



Ciardi et al 2009

Episodic magnetic bubbles and jets



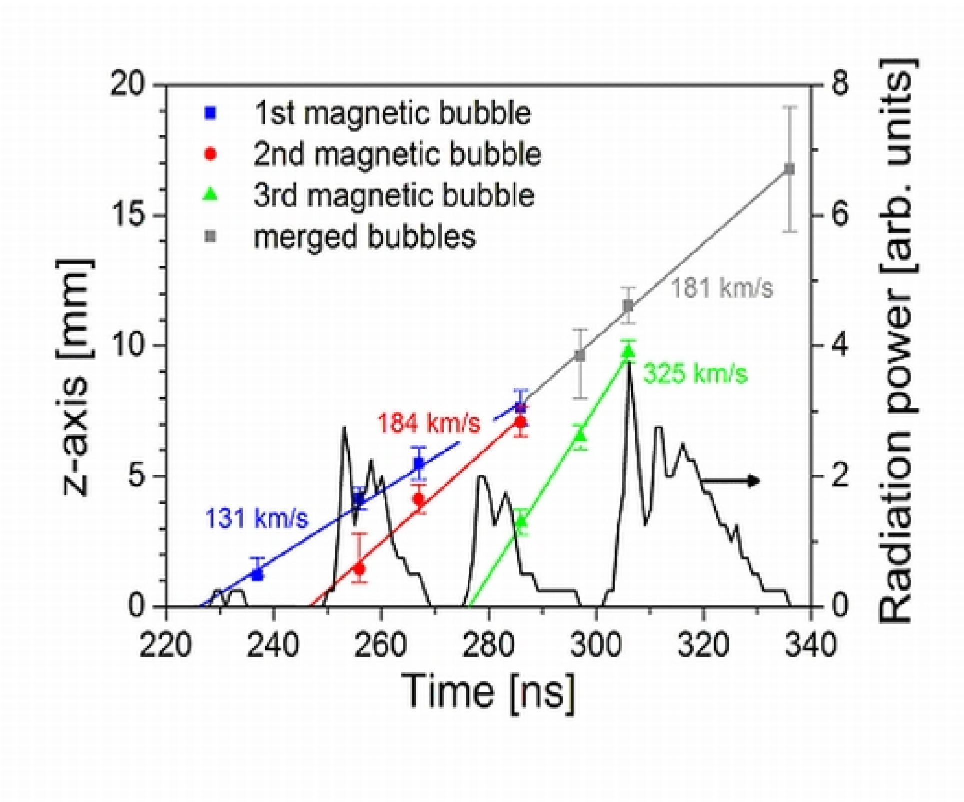
Jet temperature up to 3 x 10^6 K (time-integrated spatially resolved spectroscopy)

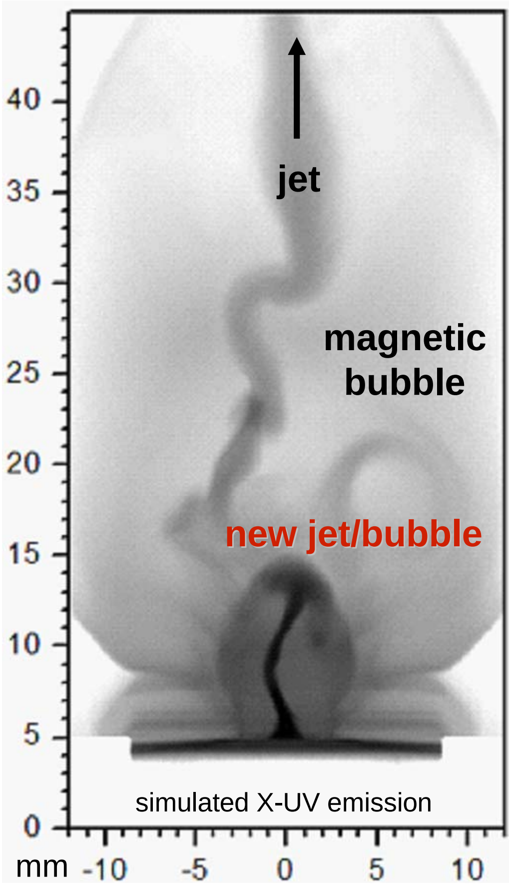
Measured trapped magnetic field in the bubble ~ 1 - 5 kG (far from jet)

Large Re_M ~ 150 - 400

Ciardi et al 2009

Episodic magnetic bubbles and jets



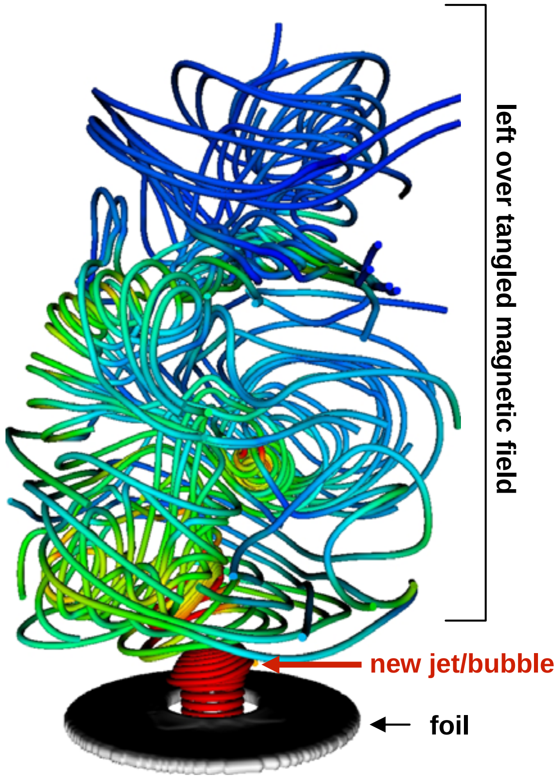


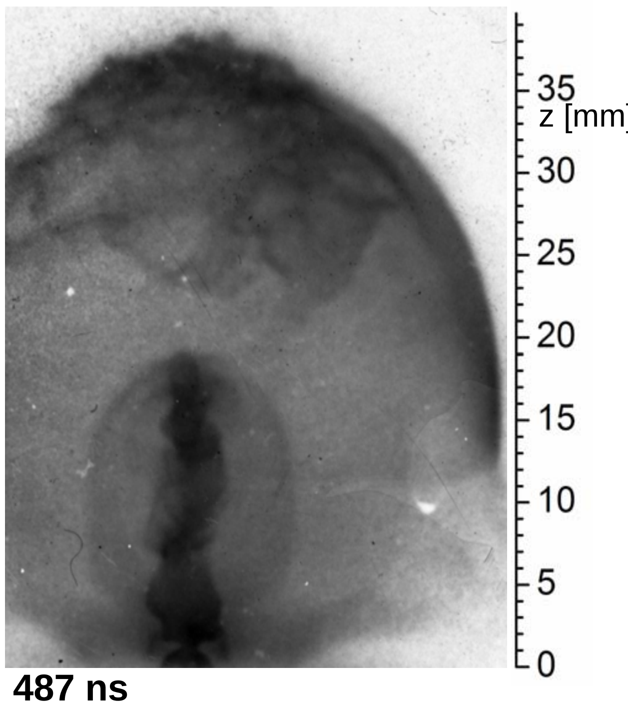
up to 5 episodes have been produced

Typical velocities ~ 100 - 400 km/s

Ciardi et al 2009

Episodic magnetic bubbles and jets





Episodic ejections of jets/bubbles produce a long-lasting, ***self-collimated*** channel with a ***clumpy flow and chaotic magnetic field*** inside.

Collimation of cavities is ***independent of initial ambient medium.***

Ciardi et al 2009

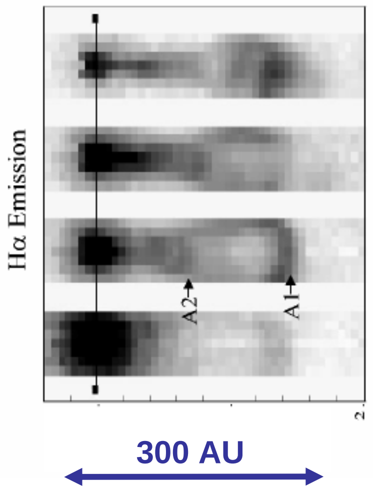
Astrophysical Implications from Laboratory Experiments

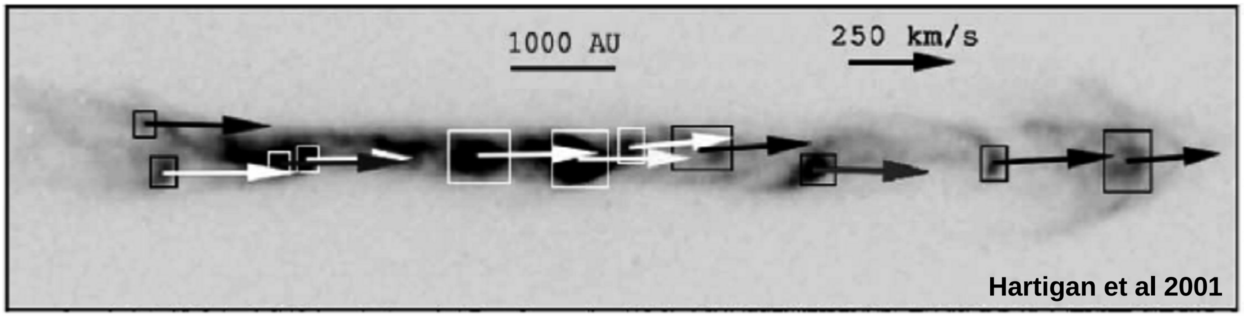
Two timescale of interest in the experiments:
Current-driven instabilities growth time ~ few nanoseconds
Episodic bubble/jet ejection ~ 30 nanoseconds

For the astrophysical jet the equivalent timescales of interest are:
Current-driven instabilities growth time ~ year
→ Simulations and from estimates of the Alfven speed crossing time

Episodic bubble/jet ejection ~ 5 - 20 years
→ From jet kinematics but the reason is unknown

Bacciotti et al 2000

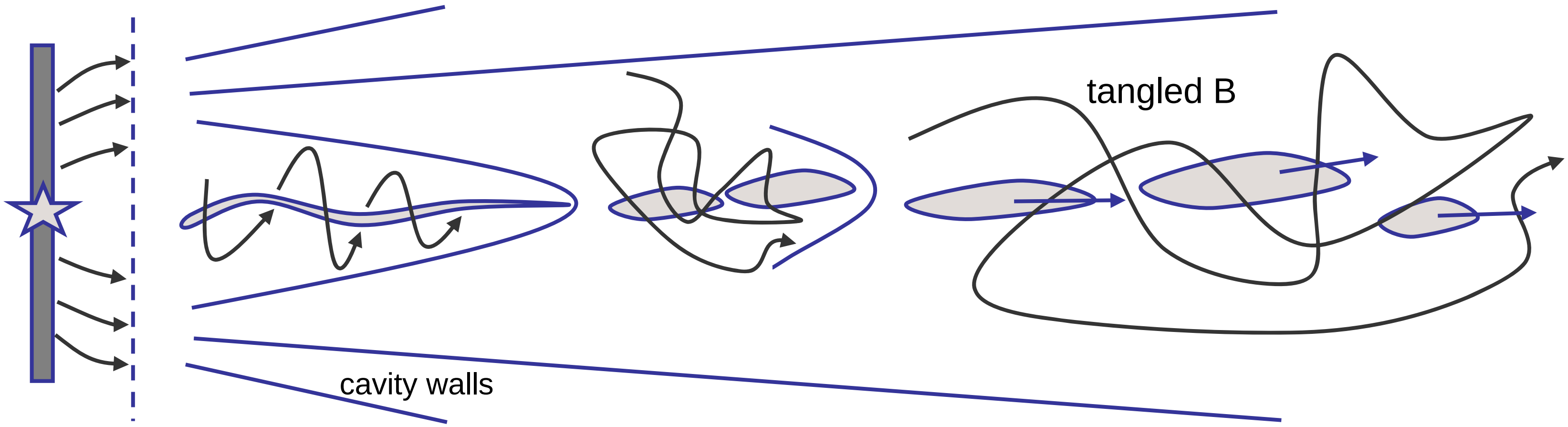




Hartigan et al 2001

Astrophysical Implications from Laboratory Experiments

Current-driven instabilities growth time = 1 year
Episodic bubble/jet ejection = 10 years
Nominal jet velocity = 200 km/s (~ 40 AU per year)



$B_\phi < B_P$ — Launching — < few AU

$B_\phi >> B_P$ … $B_\phi \sim B_P$ — Jet collimation and instabilities — ~ few x 100 AU

Jet Propagation

Inner disk orbit period << year
Jet launching should reach steady-state

Asymmetries already present in the jet.

Presence of bubble/cavity like features.

Dissipation and tangling of magnetic fields.

Clumpy jet
Interaction between clumps produces internal shocks

Ciardi et al 2009

Summary

Astrophysical jets are heterogeneous and time-dependent, and are expected to be collimated by a toroidal magnetic field, which may/should be unstable.

From laboratory *simulations* of astrophysical jets:

The collimation and acceleration to super-Alfvenic speeds by toroidal fields has been demonstrated in the laboratory.

Current-driven kink instability does not destroy jets, but produce clumpy, collimated jets.

Time-dependent ejections of bubbles/jets forms long-lasting, self-collimated channel, which is independent of the initial environment.

Combining the results together gives some very useful insights into the possible behaviour of astrophysical jets and indicates a possible way to follow.