Laboratory Plasma Astrophysics

Theory and Selected Topics

Introduction to Plasma and Fusion Course, Princeton Plasma Physics Laboratory, 6th of June 2025.

Vicente Valenzuela-Villaseca*

Postdoctoral Research Associate
Department of Astrophysical Sciences, Princeton University

*Moving to Lawrence Livermore National Laboratory and MIT in August

v.valenzuela@princeton.edu

A little bit about me…

Young me setting up a pulsed-power conical jet experiment in 2014

v.valenzuela@princeton.edu

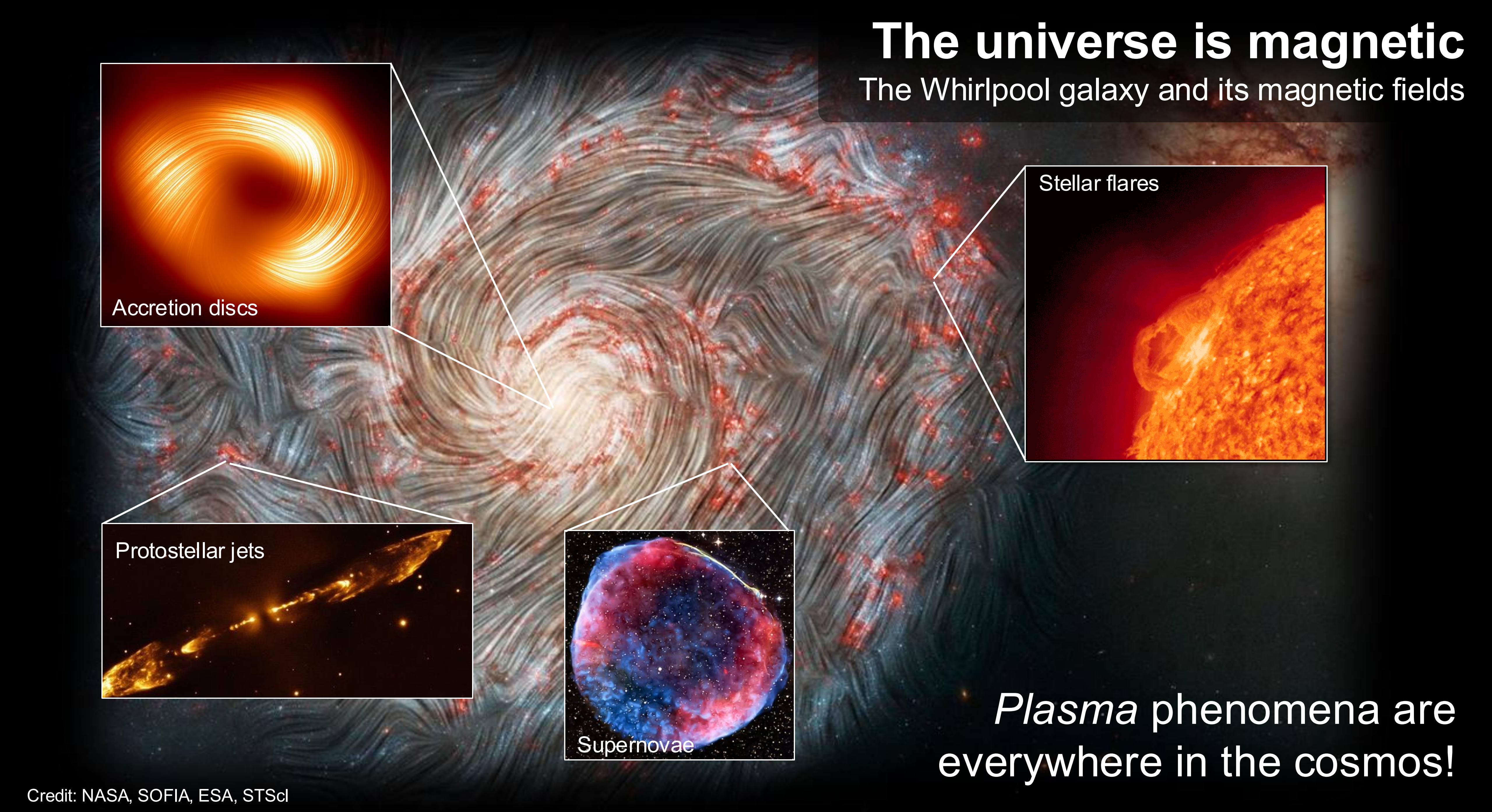
A little bit about me…

- Started as an astronomy student
- In January 2013 I joined the plasma physics lab at my university in Chile
- Fell in love with experimental plasma physics
- In 2018, I moved to London to do my PhD at Imperial College
- In 2022, I moved to Princeton Astrophysics as a postdoc
- Now I’m off to Livermore to kickstart my own research program, combining theory and experiments

v.valenzuela@princeton.edu

The universe is magnetic

The Whirlpool galaxy and its magnetic fields



Plasma phenomena are everywhere in the cosmos!

Credit: NASA, SOFIA, ESA, STScI

Outline

1. **Plasma Astrophysics**: Why is it important? Why is it difficult?
2. **Laboratory Plasma Astrophysics**: What is it? Where do we do it?
3. **Theory of MHD scaling:** From the cosmos to the lab
   a. When can a plasma be treated as a fluid?
   b. Dimensionless parameters and their meaning
4. **Selected topics**
   1. Plasma jets and radiative/MHD instabilities
   2. Turbulence and magnetic dynamo
   3. Magnetic reconnection and plasmoids
   4. Subcritical MHD shocks and collisionless magnetized shocks

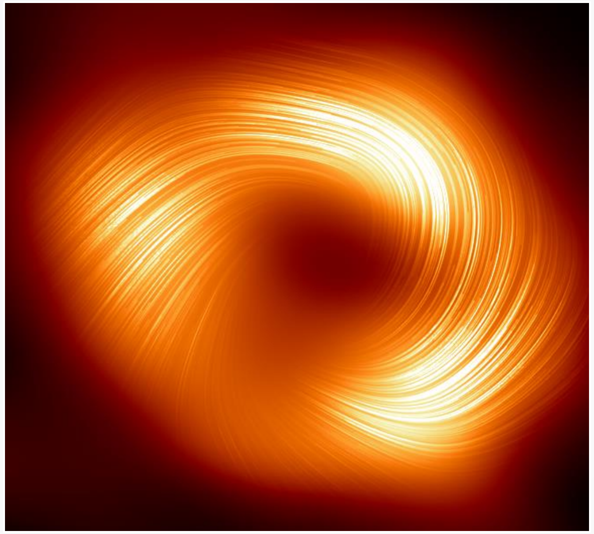
v.valenzuela@princeton.edu

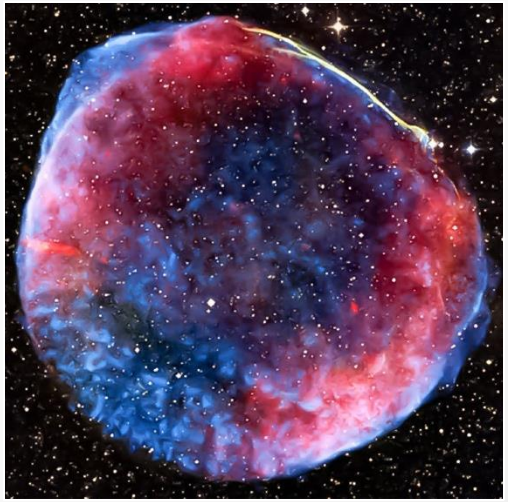
Laboratory Astrophysics with high-energy density (HED) facilities

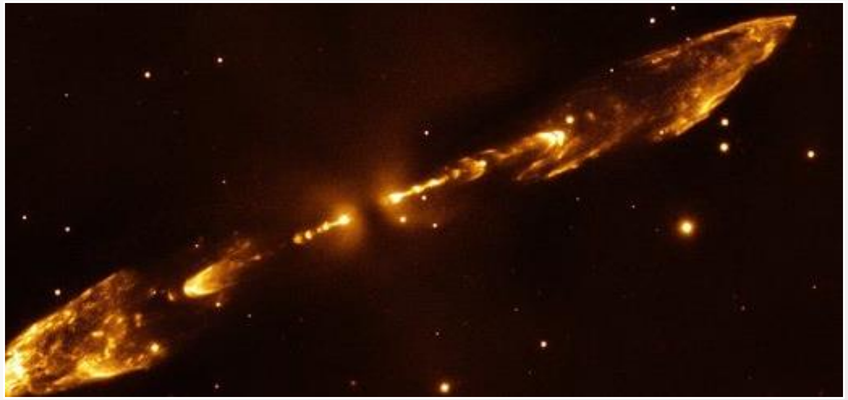
1. **Laboratory data providing important input parameters for astrophysical modelling**
    a. Spectral lines, excitation rates, recombination rates, etc. – “traditional” laboratory astrophysics
    b. Properties of matter in extreme conditions (temperature, density, pressure, etc) – e.g opacity, equation of state, warm dense matter
2. **Dynamical laboratory experiments:**
    a. Benchmarking hydrodynamics (compressible), radiation-hydrodynamics, magneto-hydrodynamics codes under scalable conditions
    b. Laboratory experiments may prompt the emergence of new concepts

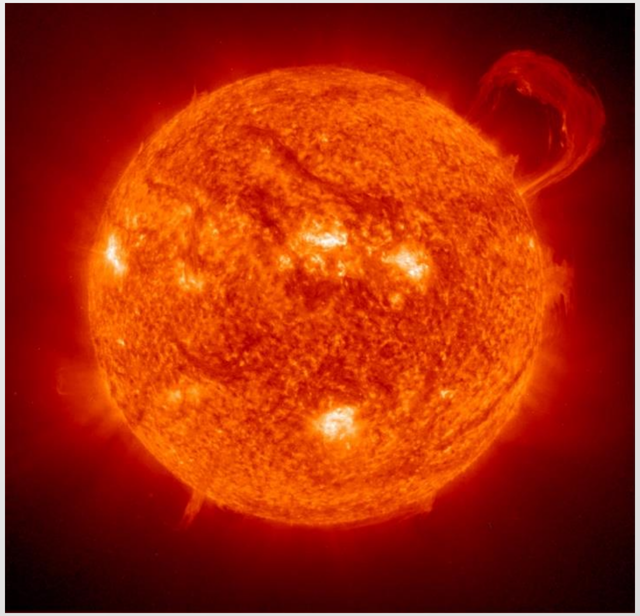
Topic of this lecture

Plasma astrophysics deals with fluids, fields and particles and how they behave in the universe







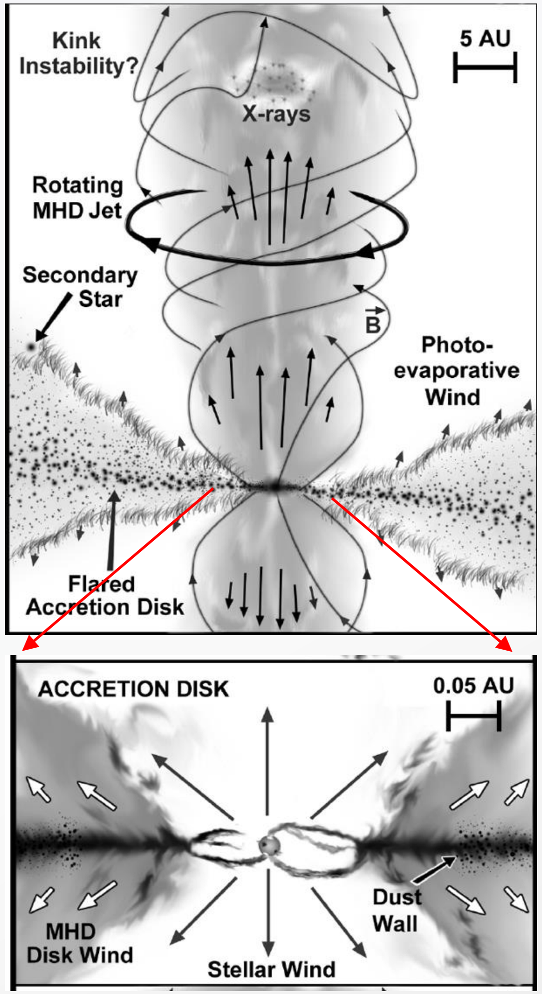


Fundamental processes in astrophysics are mediated by plasma effects

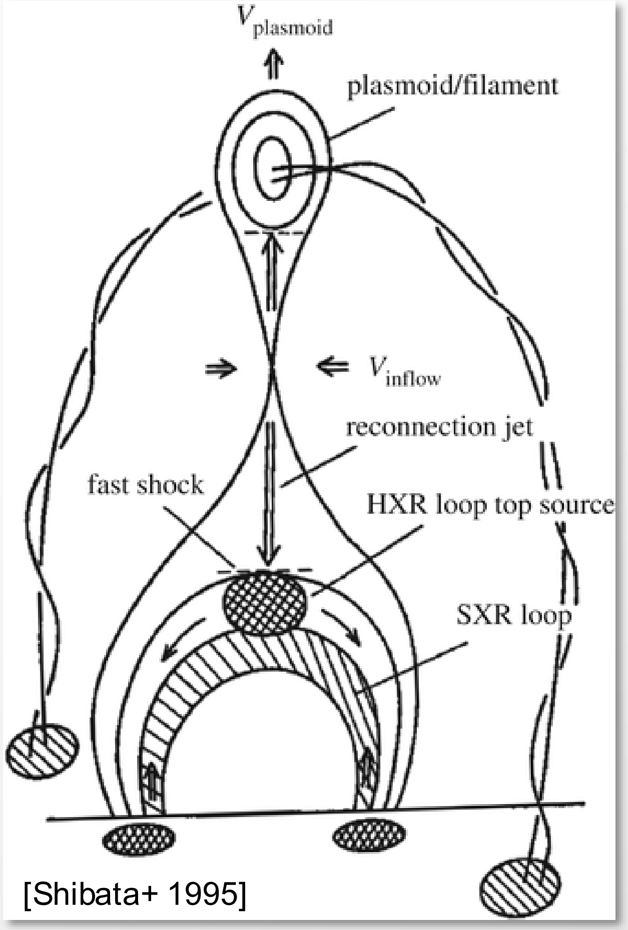
PRINCETON UNIVERSITY

PPPL

Accretion discs and jets

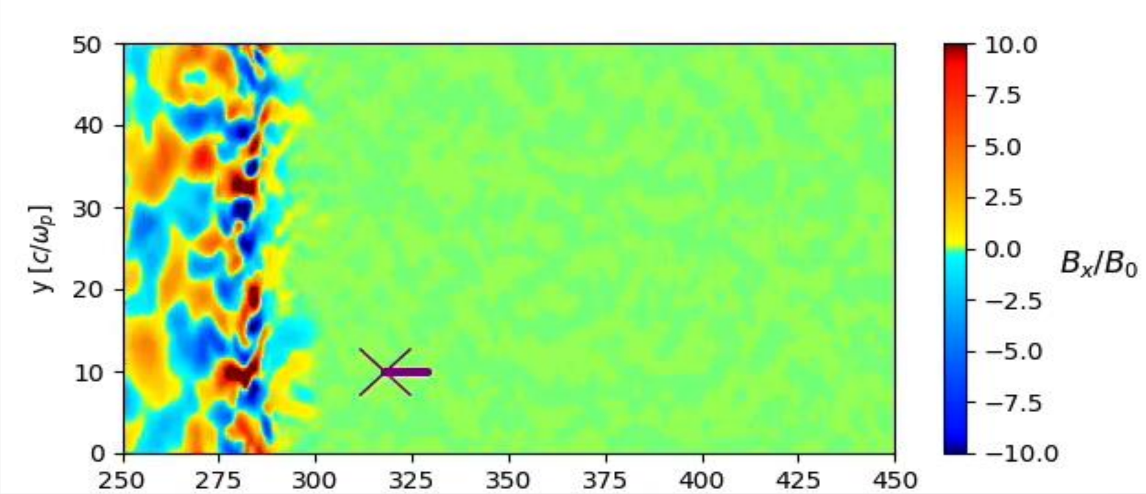


Coronal mass ejection



[Shibata+ 1995]

Cosmic ray acceleration in supernovae

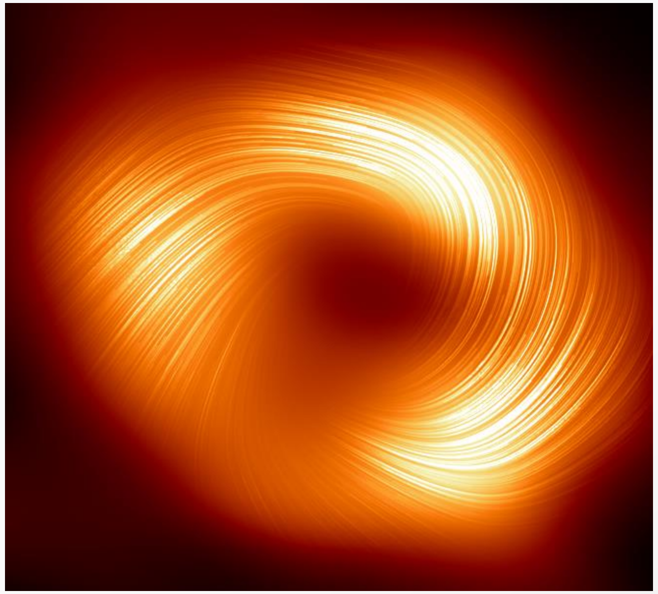


Plasma physics is crucial for understanding

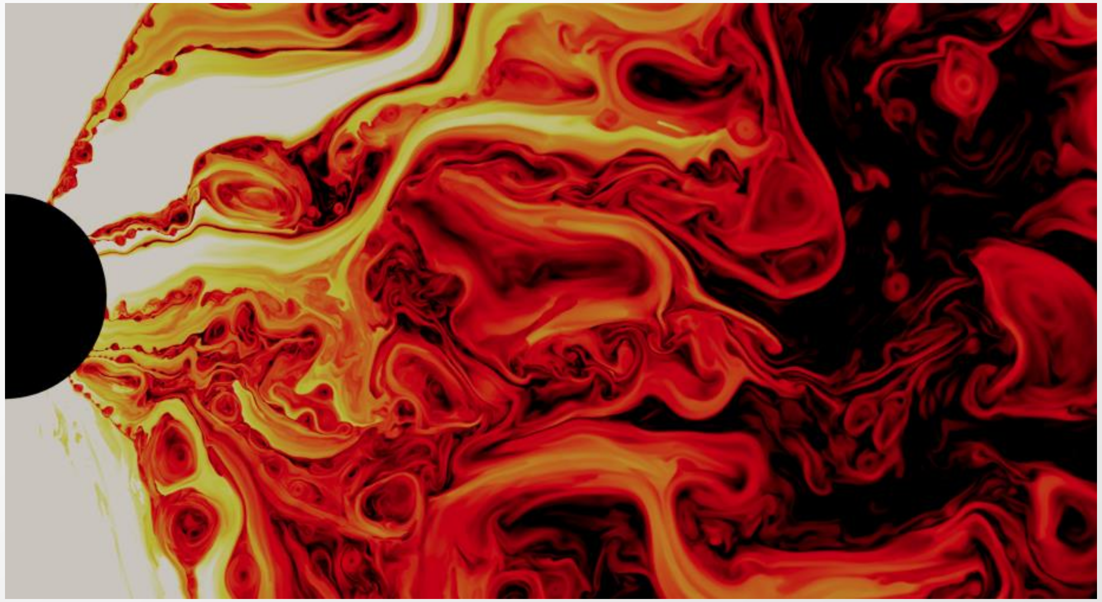
- **Formation and evolution of structures**
- **Electromagnetic sources sources** (e.g. stars, inter-stellar and -cluster medium, magnetospheres, compact objects)
- **Astro-particles** (e.g. cosmic rays)

Plasmas often are highly dynamical, nonlinear, and multi-scale: hard to interpret observations and model!

Observation of Sgr A* in the Milky Way

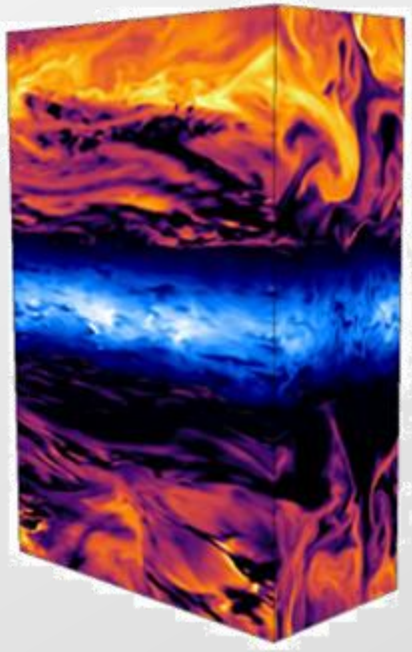


***Global* simulation of a turbulent black hole accretion disc**



Credit: Ripperda et al. (BHAC)

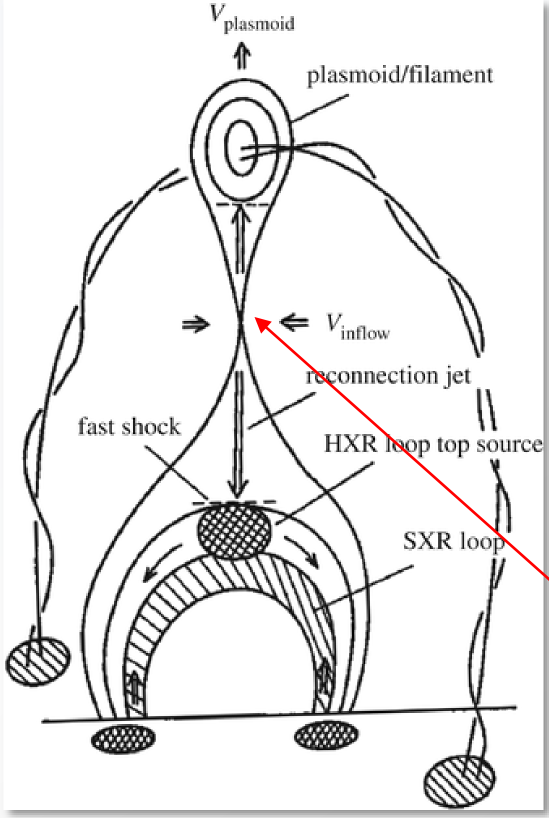
***Local* simulation of a turbulent black hole accretion disc**



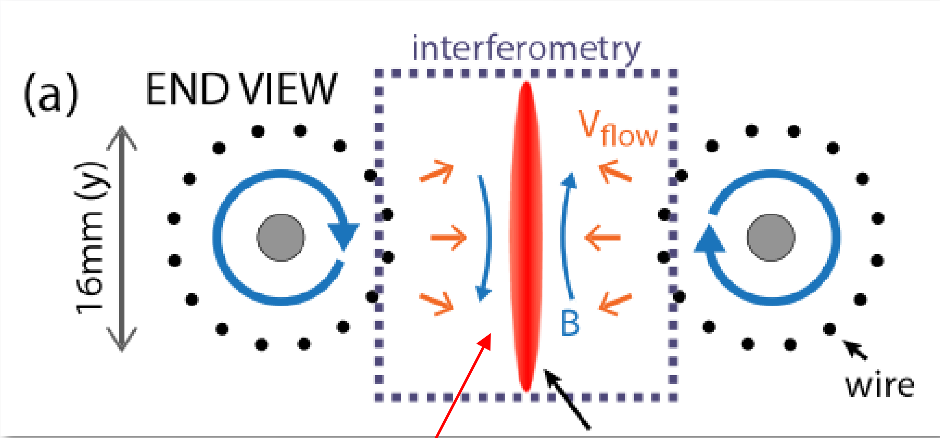
EHT Collaboration; Astrophys. J. (2024); Bambic et al., MNRAS (2024)

Laboratory Plasma Astrophysics: take a subset of an astrophysical problem and study it in detail

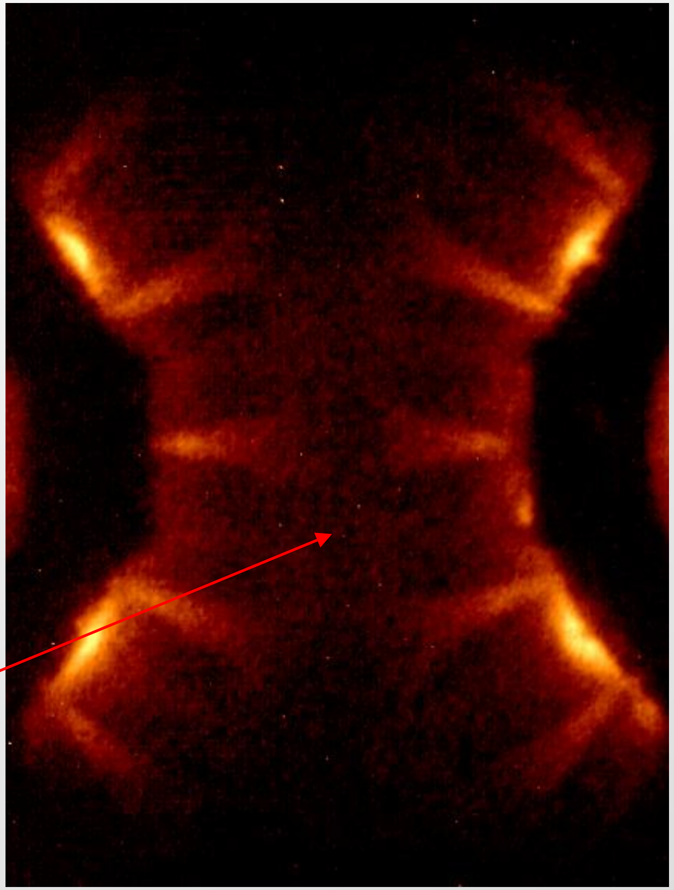
Ex: Theory of a CMS on the Sun



Experimental concept



Experimental realization



"Key" physics: magnetic reconnection

Reference (with hyperlink)

I work with *dynamical* laboratory astrophysics experiments on high-energy density facilities

High-energy density plasma (HEDP) facilities

Working definition: energy density $\varepsilon \geq 10^{12}$ erg cm^{-3}; pressure $p \geq 1$ Mbar

Lasers

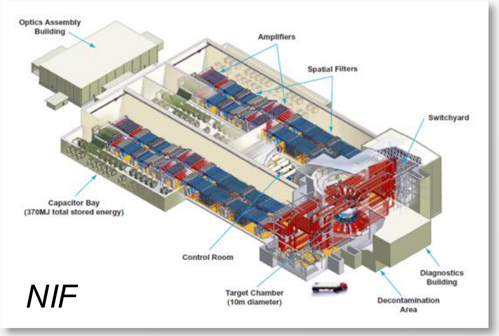
- Energy: $\sim 1 - 10^4$ J $\rightarrow$ MJ
- Timescales of ps to 10s of ns
- Plasma volumes ~ mm^3

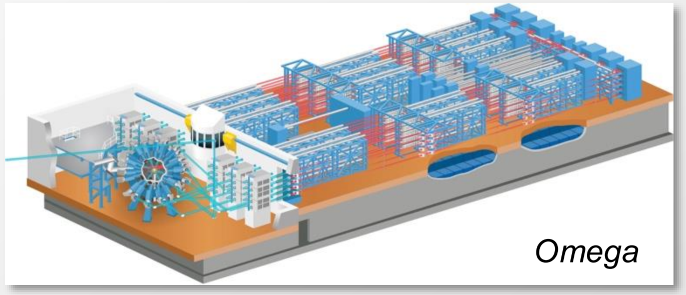
Pulsed-power generators

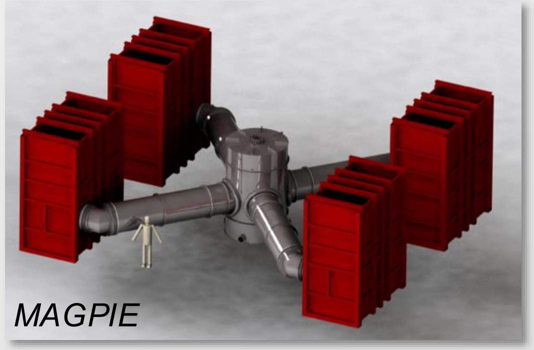
- Energy: ~ 100 J to several MJ
- Timescales of 100s of ns to μs
- Plasma volumes ~ cm^3

Laser facilities: Vulcan (UK), LIL (France), FIREX (Japan), Omega (USA), NIF (USA), LMJ (France), etc

Pulsed-power facilities: Z-machine (USA), MAGPIE (UK), COBRA (USA), PUFFIN (USA), etc

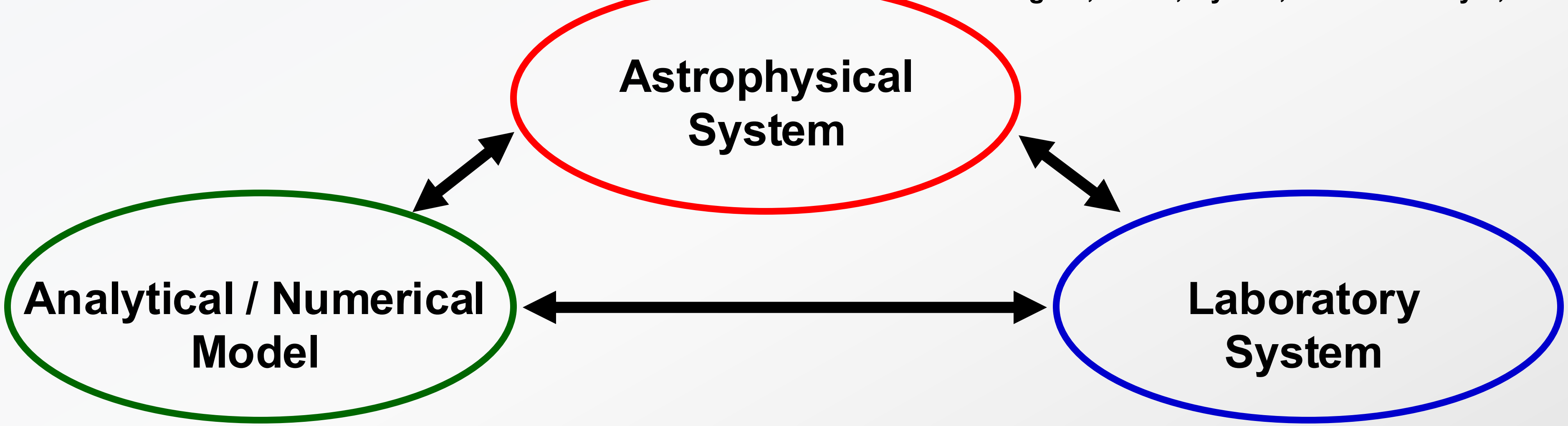






Laboratory experiments are good for investigating fundamental physics of astrophysical objects in detail

Remington, Drake, Ryutov, Rev. Mod Phys., 2006

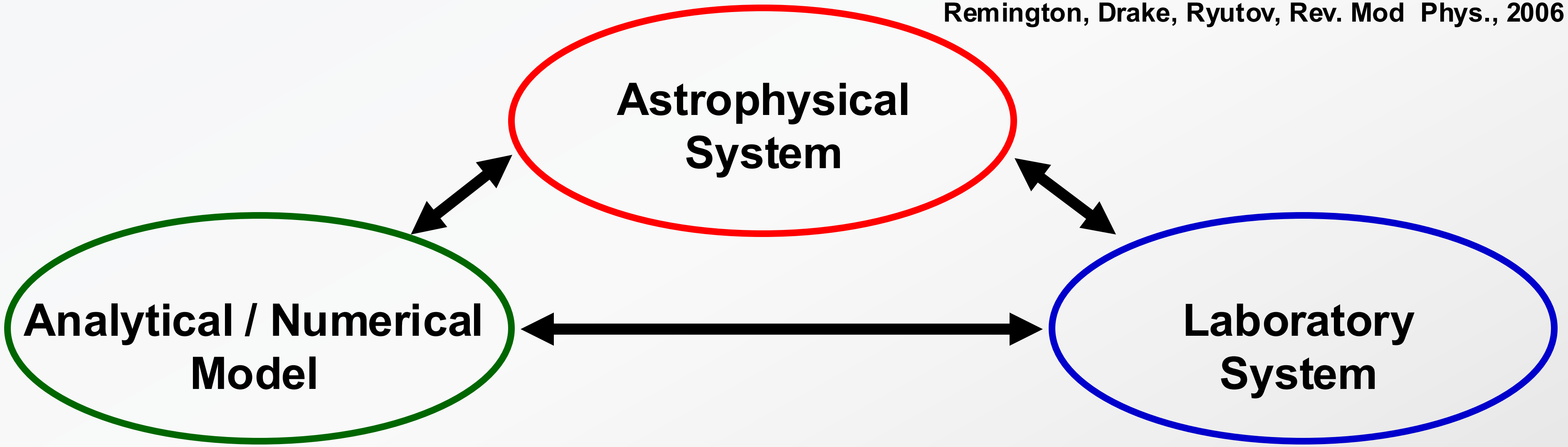


- **Study a subset of the problem**
- **Make simplifying assumptions** (symmetry, disregarding some "unimportant" physics)
- **Make educated guess on conditions / profiles**

- **Study a subset of the problem**
- **No simplifying assumptions** (difficult to turn-off a physical package)
- **Control of initial conditions**

Laboratory experiments are good for investigating fundamental physics of astrophysical objects in detail

Remington, Drake, Ryutov, Rev. Mod Phys., 2006



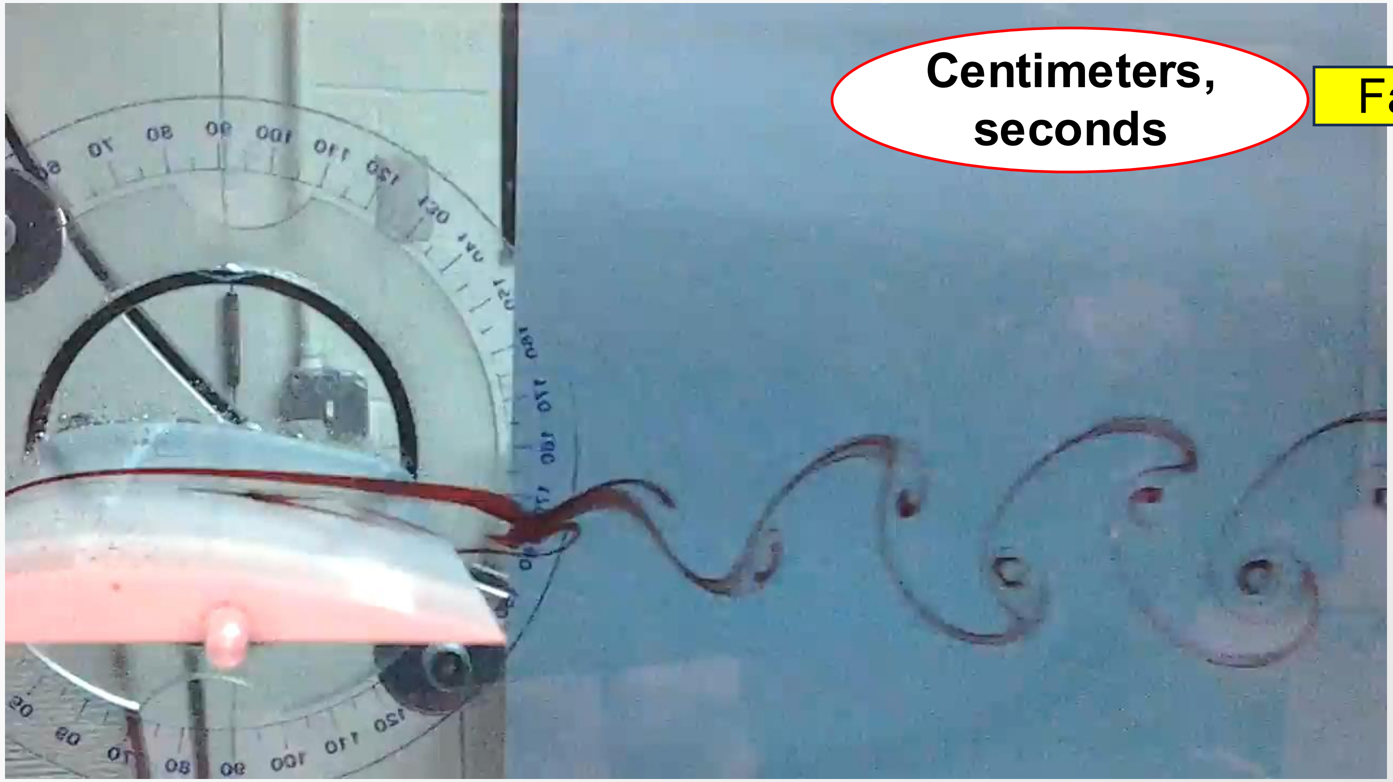
Scaled representation of astrophysical plasma dynamics:

- Laboratory and astrophysical phenomena are described by the same set of equations — ideal MHD: *Rm* >>1; *Re* >>1
- Creating appropriate initial conditions (morphology)
- Dimensionless numbers and similarity transformations — (M_S, M_A, β)

Lab experiment reproducing the evolution of an astrophysical system

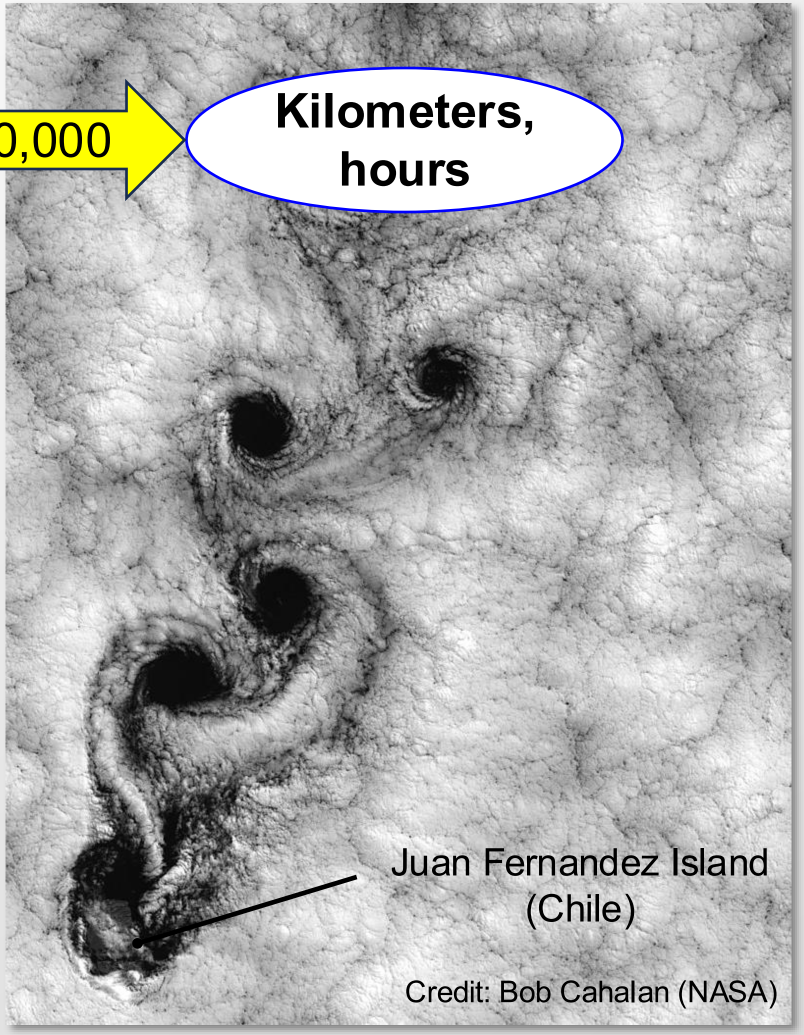
Hydrodynamic and magnetohydrodynamic flows often behave similarly despite their size

Von Karman vortex street in a wind tunnel



Credit: Sarwesh Narayan Parbat's Youtube channel

Von Karman vortex street in the atmosphere



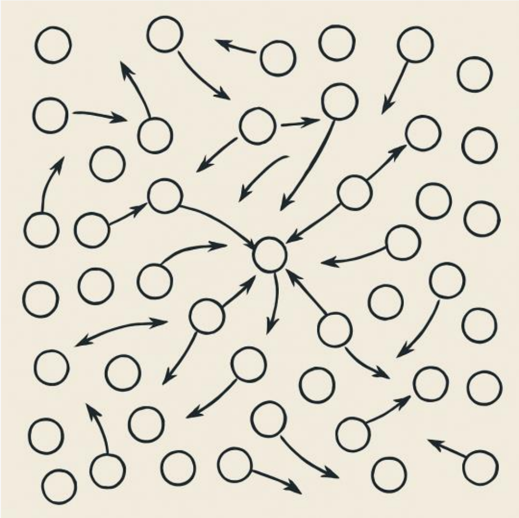
Centimeters, seconds → Factor x10,000 → Kilometers, hours

A plasma can be treated as a fluid when the particles within are localized

PRINCETON UNIVERSITY

PPPL

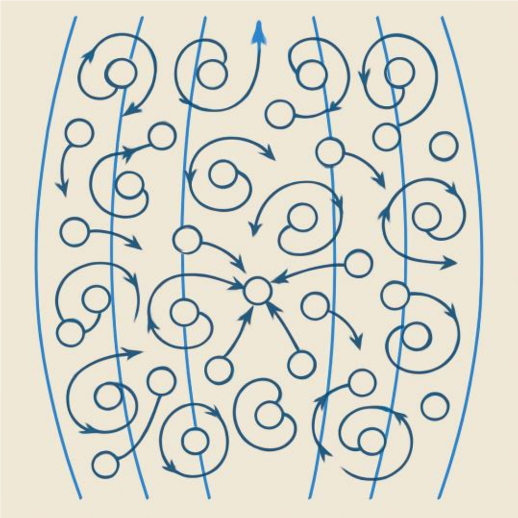
Collisional



- Particle-particle collisions are efficient

"Easy". Use Braginskii theory.

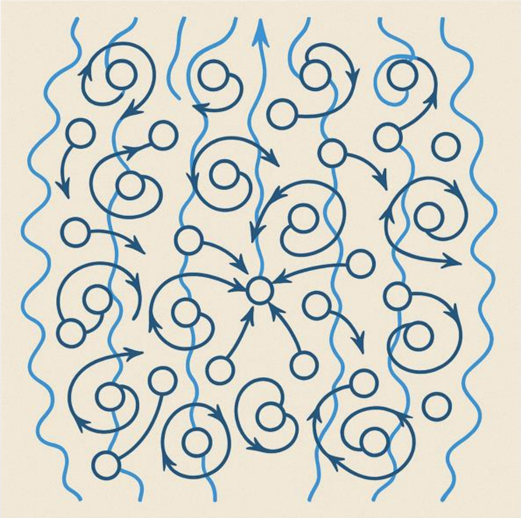
Semi-collisional



- Gyro-orbits are small
- Particle-particle collisions are efficient along B-field

Harder. Anisotropic. Can use Braginskii theory but handle with care.

Collisionless



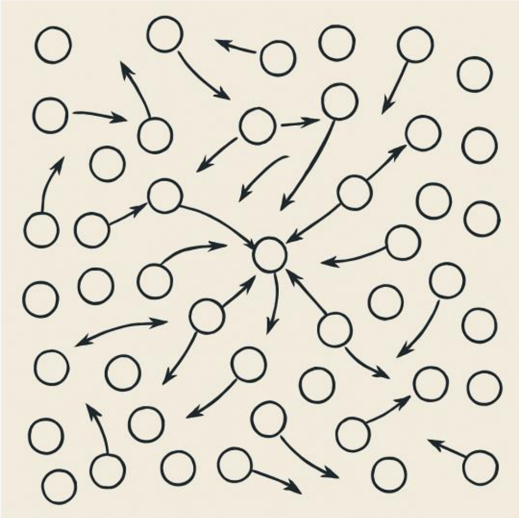
- Gyro-orbits are small
- Waves in the plasma efficiently pitch-angle scatter the particles (effective collisionality)

Very hard. Possibly not universal. Handle case-by-case.

Braginskii, in: Review of Plasma Physics (1965); Marcowith et al., Rep. Prog. Phys. (2016); Kempski et al., Astrophys. J. (2025)

A plasma can be treated as a fluid when the particles within are localized

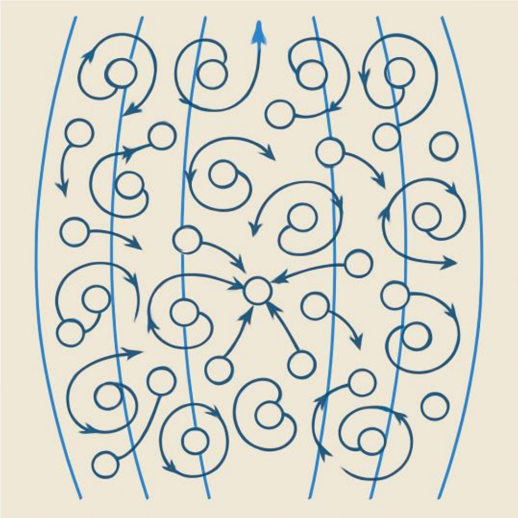
Collisional



- Particle-particle collisions are efficient

“Easy”. Use Braginskii theory.

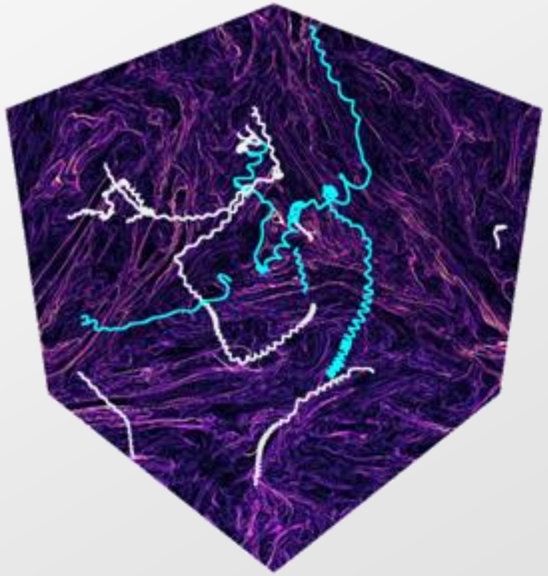
Semi-collisional



- Gyro-orbits are small
- Particle-particle collisions are efficient along B-field

Harder. Anisotropic. Can use Braginskii theory but handle with care.

Collisionless



- Gyro-orbits are small
- Waves in the plasma efficiently pitch-angle scatter the particles (effective collisionality)

Very hard. Possibly not universal. Handle case-by-case.

Braginskii, in: Review of Plasma Physics (1965); Marcowith et al., Rep. Prog. Phys. (2016); Kempski et al., Astrophys. J. (2025)

Let us write the MHD equations with explicit dependence on scale

Approach:

1. Write plasma and field quantities in terms of characteristic values and order-unity objects

Fluid/field scalar → ; Fluid/field vector →

$$\lambda = \lambda_0 \hat{\lambda}; \quad \boldsymbol{A} = A_0 \widehat{\boldsymbol{A}}$$

Characteristic value (with dimensions): λ_0, A_0

Order unity (dimensionless): $\hat{\lambda}$, $\widehat{\boldsymbol{A}}$

2. Write differential operators using characteristic global spatial and temporal scales explicitly

$$\nabla = \frac{1}{L}\widehat{\nabla}; \qquad \frac{\partial}{\partial t} = \frac{1}{t_0}\frac{\partial}{\partial \hat{t}} \equiv \frac{u_0}{L}\frac{\partial}{\partial \hat{t}}$$

L: global spatial scale of the system
t_0: hydrodynamic timescale
u_0: characteristic flow velocity

3. Apply in all MHD equations

4. Solve such that left-hand-side of each equation such that it is dimensionless (only hat objects)

Ryutov et al., Astrophys. J. (1999); Cross et al., Astrophys. J. (2016)

MHD scaling: continuity equation

- The conservation of mass is $$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0$$

- Introducing scaling variables
$$\rho = \rho_0 \hat{\rho}; \boldsymbol{u} = u_0 \hat{\boldsymbol{u}};$$
Fluid parameters
$$\nabla = \frac{1}{L}\hat{\nabla}; \frac{\partial}{\partial t} = \frac{u_0}{L}\frac{\partial}{\partial \hat{t}}$$
Differential operators

- The continuity equation becomes

$$\frac{\rho_0 u_0}{L}\frac{\partial \hat{\rho}}{\partial \hat{t}} + \frac{\rho_0 u_0}{L}\hat{\nabla} \cdot (\hat{\rho}\hat{\boldsymbol{u}}) = 0 \quad \rightarrow \frac{\partial \hat{\rho}}{\partial \hat{t}} + \hat{\nabla} \cdot (\hat{\rho}\hat{\boldsymbol{u}}) = 0$$

Continuity equation is always scale-invariant (no intrinsic $L, t_0 = L/u_0$)

Mass is conserved at all scales

Ryutov et al., Astrophys. J. (1999); Cross et al., Astrophys. J. (2016)

MHD scaling: momentum equation

- The conservation of momentum is $$\rho\frac{\partial \boldsymbol{u}}{\partial t}+\rho(\boldsymbol{u}\cdot\nabla)\boldsymbol{u}=-\nabla p+\frac{1}{\mu_0}\nabla\times\boldsymbol{B}\times\boldsymbol{B}+\rho\nu\nabla^2\boldsymbol{u}$$
- Introducing scaling variables

$$\rho=\rho_0\hat{\rho};\boldsymbol{u}=u_0\hat{\boldsymbol{u}};p=p_0\hat{p};\boldsymbol{B}=B_0\hat{\boldsymbol{B}}$$ Fluid + field parameters

$$\nabla=\frac{1}{L}\hat{\nabla};\ \frac{\partial}{\partial t}=\frac{u_0}{L}\frac{\partial}{\partial\hat{t}}$$ Differential operators

- Solving for dimensionless left-hand-side (good homework)

$$\hat{\rho}\frac{\partial\hat{\boldsymbol{u}}}{\partial\hat{t}}+\hat{\rho}(\hat{\boldsymbol{u}}\cdot\hat{\nabla})\hat{\boldsymbol{u}}=-\frac{p_0}{\rho_0}\frac{1}{u_0^2}\hat{\nabla}\hat{p}\quad+\quad\left(\frac{B_0^2}{\mu_0\rho_0}\right)\frac{1}{u_0^2}\hat{\nabla}\times\hat{B}\times\hat{B}\quad+\quad\frac{\nu}{u_0L}\hat{\rho}\hat{\nabla}^2\hat{u}$$

Sound speed: $c_s^2=p_0/\rho_0$

Alfven velocity: $\mathrm{V_A}=B_0/\sqrt{\mu_0\rho_0}$

Viscous term is the only one with spatial scales

Coefficient yields **sonic Mach number:** $M_s=u_0/c_s$

Coefficient yields **Alfvenic Mach number:** $M_A=u_0/V_A$

Coefficient yields the **Reynolds number:** $Re=u_0L/\nu$

In the limit $Re\gg1$, momentum is conserved on (global) scales L, and the momentum equation is scale-invariant

Ryutov et al., Astrophys. J. (1999); Cross et al., Astrophys. J. (2016)

MHD scaling: induction equation

- The evolution of the magnetic field is

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times \boldsymbol{u} \times \boldsymbol{B} + \eta \nabla^2 \boldsymbol{B}$$

- The dimensionless induction equation becomes (again, homework)

$$\frac{\partial \hat{B}}{\partial \hat{t}} = \hat{\nabla} \times \hat{u} \times \hat{B} + \underbrace{\frac{\eta}{u_0 L}} \hat{\nabla}^2 \hat{B}$$

Resistive term is the only one with spatial scales

Magnetic Reynolds number:
$Rm = u_0 L / \eta$

Resistive dissipation breaks the frozen-in condition of ideal MHD

In the limit $Rm \gg 1$, the magnetic field is coupled to the fluid on scales L, and the induction equation is scale-invariant

Ryutov et al., Astrophys. J. (1999); Cross et al., Astrophys. J. (2016)

MHD scaling: internal energy equation

- Adiabatic energy conservation

$$\frac{\partial p}{\partial t} + (\boldsymbol{u} \cdot \nabla)p = -\gamma p(\nabla \cdot \boldsymbol{u}) + \chi \nabla^2 p$$

→ Scales are coupled only to the **Peclet number:** $Pe = u_0 L/\chi$

In the limit $Pe \gg 1$, heat is advected along the flow, thermal diffusion is negligible on scales L, and the energy equation is scale-invariant

Ryutov et al., Astrophys. J. (1999); Cross et al., Astrophys. J. (2016)

MHD scaling is based on comparing a small set of dimensionless parameters in the lab and astrophysics

Dimensionless parameters

$\boldsymbol{M_s}$, $\boldsymbol{M_A}$, $\boldsymbol{\beta}$, $\boldsymbol{Re}$, $\boldsymbol{Rm}$, $\boldsymbol{Pe}$

Sonic Mach number:

$$M_s = \frac{u_0}{c_s}$$

Alfvenic Mach number:

$$M_A = \frac{u_0}{V_A}$$

- Compare flow speed to internal propagation of information
- Formation of (HD/MHD) shock waves
- Buoyancy

Supersonic (M_s >1) fighter jet creating a shock in the atmosphere

Related to the partition of internal and magnetic energy density, plasma-β parameter

$$\beta \equiv p/p_M; \quad p_M \equiv B^2/2\mu_0; \quad \beta = 2\,M_A^2/M_s^2$$

Ryutov et al., Astrophys. J. (1999); Cross et al., Astrophys. J. (2016)

Plasma flows are scale invariant when dissipation is negligible

Dimensionless parameters

M_s, M_A, β, Re, Rm, Pe

Reynolds number:

$$Re = \frac{u_0 L}{\nu}$$

"Dimensionless viscosity":
Ratio of inertial to viscous forces

Magnetic Reynolds number:

$$Rm = \frac{u_0 L}{\eta}$$

"Dimensionless resistivity":
Ratio of magnetic advection vs diffusion

Peclet number:

$$Pe = \frac{u_0 L}{\chi}$$

"Dimensionless heat diffusivity":
Ratio of heat advection vs diffusion

Dissipation sets a particular length-scale through terms of the form

$$\propto D\nabla^2 v,$$

breaking scale-invariance. Because of the Laplacian, when dissipation is a "small" number, it can only act on small scales << global scales

Ryutov et al., Astrophys. J. (1999); Cross et al., Astrophys. J. (2016)

Dimensionless numbers in the universe, the laboratory, and numerical simulations

Ideal MHD: Rm >> 1; Re >> 1

(frozen-in B-field)

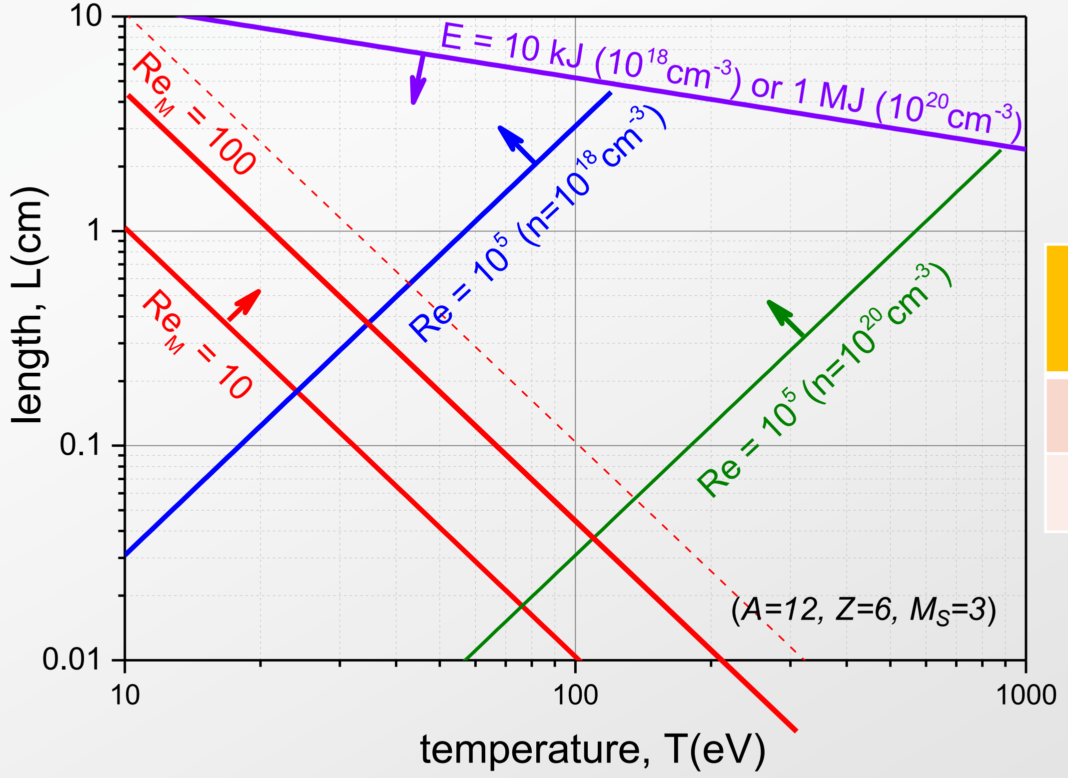
$$Rm = \frac{u_0 L}{\eta} \propto \frac{L \cdot T^2}{Z\sqrt{A}} \gg 1$$

(negligible viscosity)

$$Re = \frac{u_0 L}{\nu} \propto \frac{L \cdot Z^4 n_i}{T^2} \gg 1$$

Large *nT* ➔ HEDP

(there are non-HEDP lab astro experiments, but they are large!)



	Astro	Lab	Simulations
Rm	$>10^{10}$	10^3	$10\text{-}10^3$
Re	$>10^{10}$	10^5	$10\text{-}10^4$

Ryutov et al., Astrophys. J. (1999); Cross et al., Astrophys. J. (2016)

Dimensionless parameters as ratios of length- and time-scales

- A modern approach is to calculate **dissipation time- and length-scales**
- They are measurable in experiments (unlike dimensionless parameters), so they are practical/useful

Viscous timescale

Ex: take the Reynolds number $$Re = \frac{u_0 L}{\nu} = \frac{u_0/L}{\nu/L^2} = \frac{1/t_0}{1/\tau_\nu} = \frac{\tau_\nu}{t_0}$$

$$Re \gg 1 \leftrightarrow \tau_\nu \gg t_0$$

Conclusion: When Re is large compared to unity, time for viscous damping is much greater than hydrodynamic time. Viscosity is *inefficient* at dissipating *large-scale* momentum.

- Associated with this timescale there is a viscous length ℓ_ν at which large-scale momentum is dissipated

$$\tau_\nu(L = \ell_\nu) \sim t_0 \quad \leftrightarrow \quad \frac{\ell_\nu^2}{\nu} \sim \frac{L}{u_0} \quad \leftrightarrow \quad \ell_\nu^2 = \frac{\nu}{u_0 L} L^2 \quad \longrightarrow \quad \ell_\nu = Re^{-1/2} L$$

$Re \gg 1 \rightarrow \ell_\nu \ll L$: viscosity operates on small scales

Homework: what are the equivalent interpretations for Rm and Pe?

Ryutov et al., Astrophys. J. (1999); Cross et al., Astrophys. J. (2016)

In summary: what is the goal of dynamical laboratory astrophysics? (and what isn't)

PRINCETON UNIVERSITY

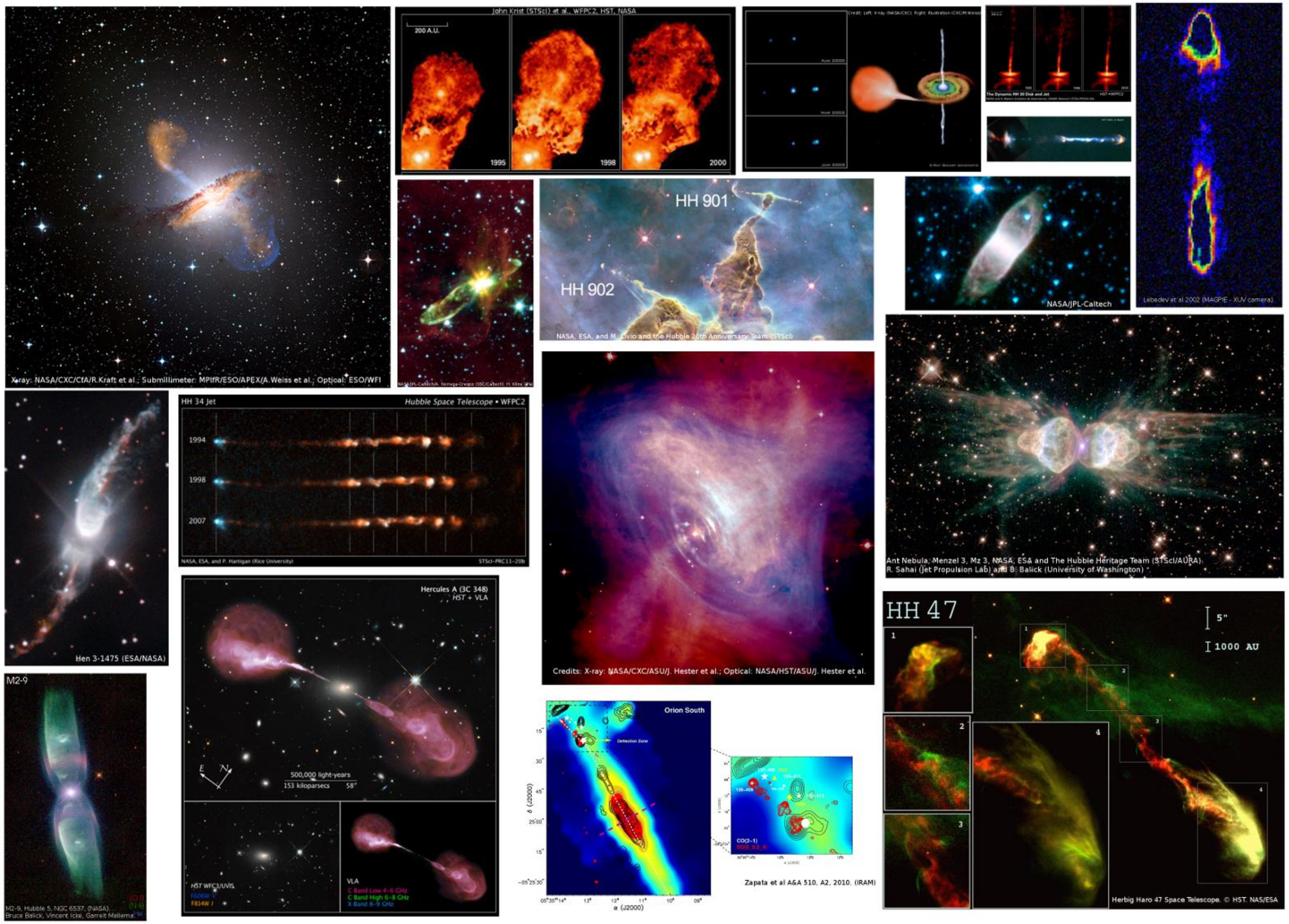
PPPL

- **Dynamical laboratory astrophysics: study of evolution of astrophysics-relevant plasma flows from well-known initial conditions**
- **Simplify a complicated astrophysics system, then make sure scaling is appropriate *(MHD, collisionless, Braginskii, etc)***
- **Make sure you measure all useful parameters:** what is their structure? How do they evolve? This is what is interesting
- **The universe is *very* large!**
  - ➢ Even if you realize after the experiment that you targeted the wrong system initially, there **probably is another system you can compare to**
  - ➢ **Collaboration** with astronomers/astrophysicists helps
- **Laboratory astrophysics is *not:***
  - ➢ **Recreation of full astrophysical systems**
  - ➢ **A loose morphological comparison between lab and astro** ("this looks like that")

Selected Topics

(the good stuff)

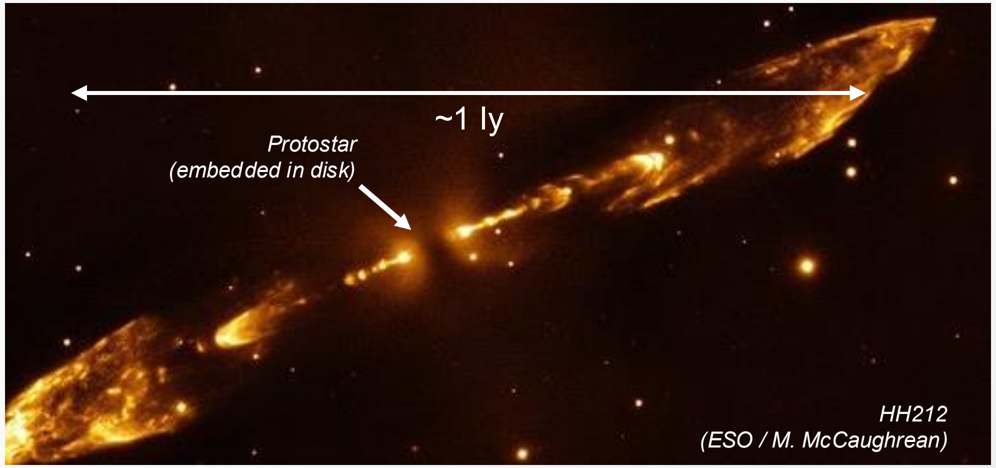
Plasma jets in the universe

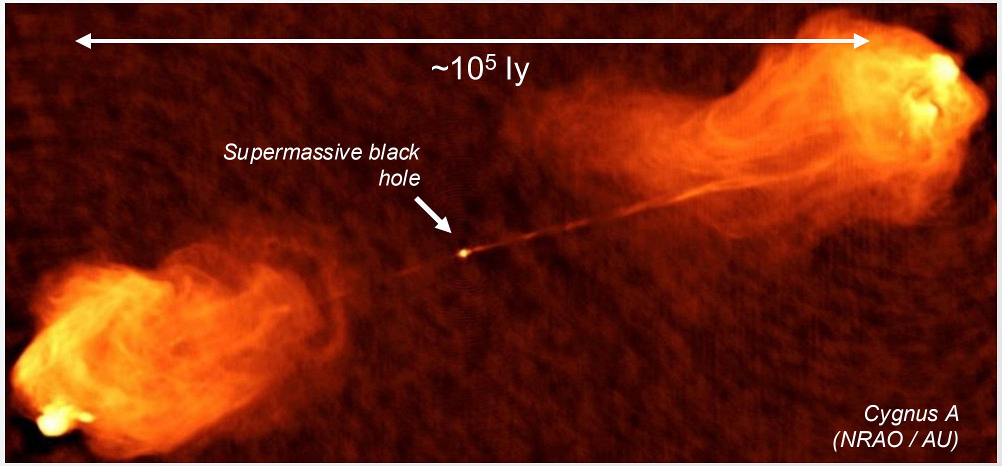


Plasma jets are full of substructures but remain collimated on large scales

They 'look' similar…

- Similar jet morphology
- Jets originate from a central source
- Spatial features along jet (shocks, knots)
- Terminal bow shocks





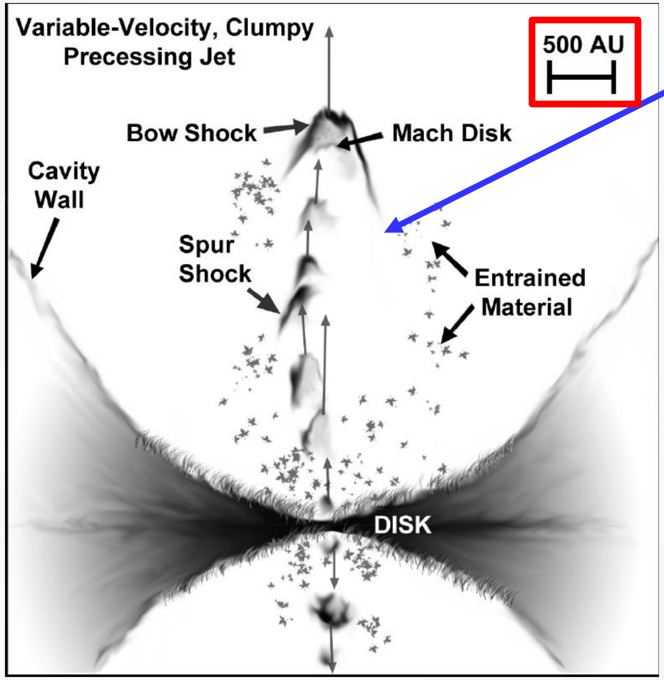
Protostellar jets

- Few light-years across
- Accretion into a protostar
- Speed ~ 100's km/s
- Optical emission (atomic lines)

Extragalactic jets

- Thousands light-years across
- Accretion into a supermassive black hole
- Speed ~ light
- Radio emission (synchrotron)

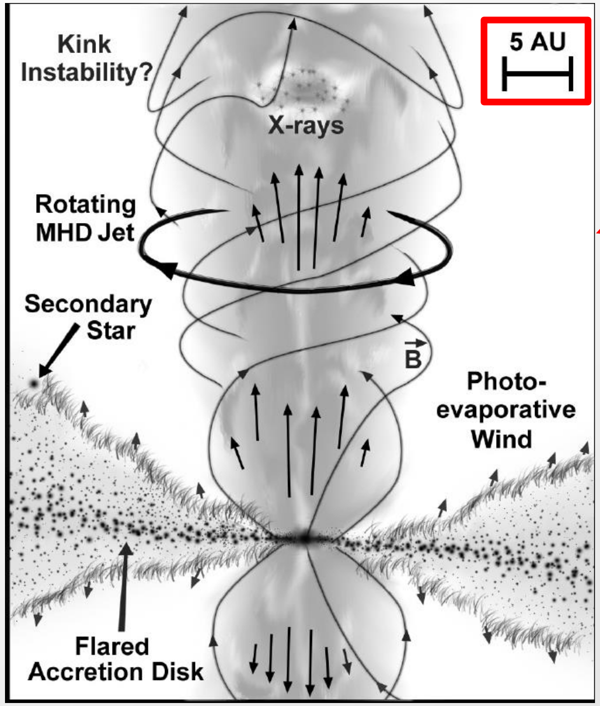
Plasma jets are multi-scale where different regions should be treated with a different approximation



Outflow region - hydrodynamic jet

"Hydrodynamic" jet (M>>1)
(resolved in observations)
(jet propagation,
interaction with interstellar medium)

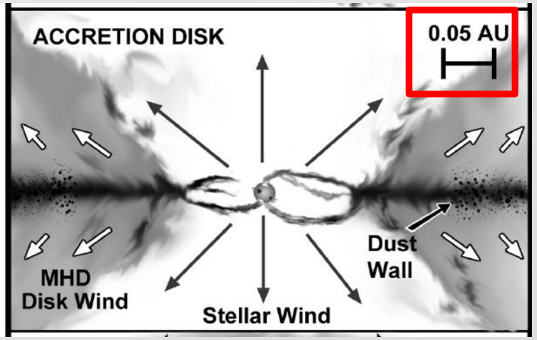
- Magnetic fields not important
- Supersonic flow Radiatively cooled
- Bow shock from jet-ambient interaction



Magnetically-driven jet (theory)

- Strong magnetic fields
- Highly-collimated jet
- Episodic ejections?

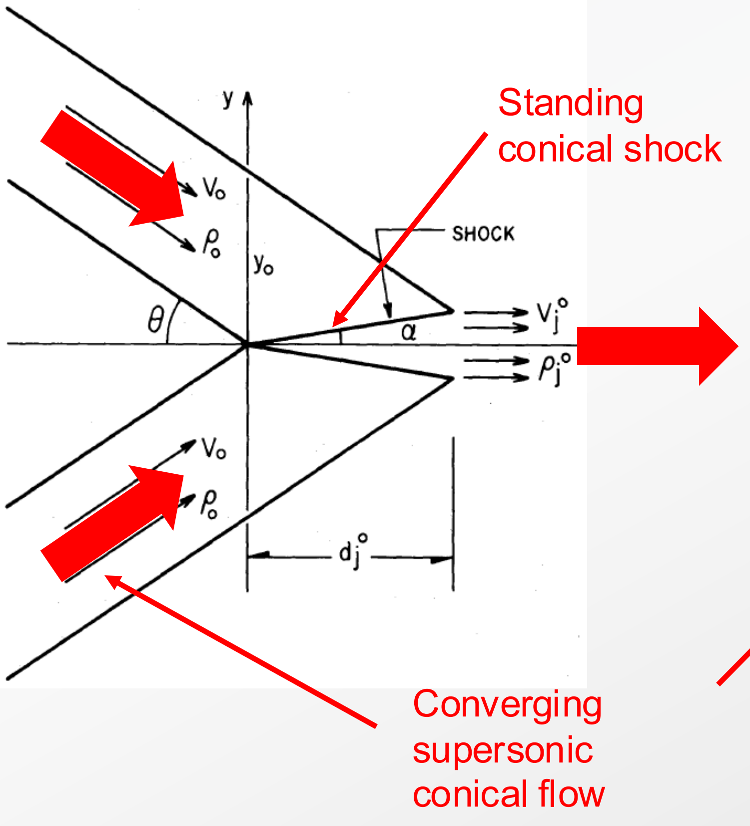
Launching region
(central source & accretion disk)



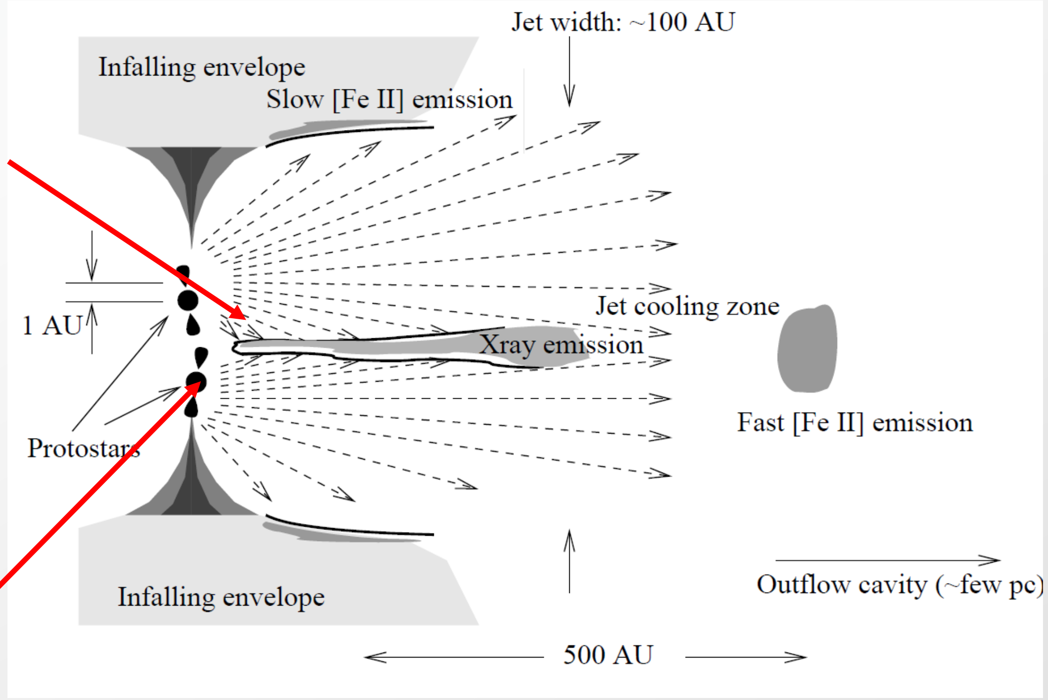
Frank et al., in: Protostars and Planets IV (2014); arXiv:14023553

Far from the source, in the hydrodynamical stage, jets can be collimated by conical shocks

[Canto et al., A&A 1988]



[Bally et al., ApJ 2003]

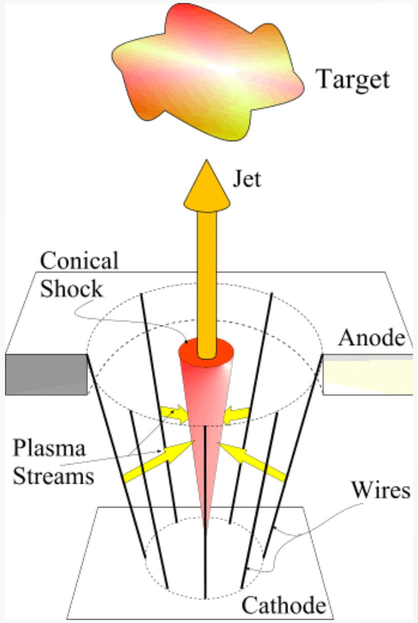


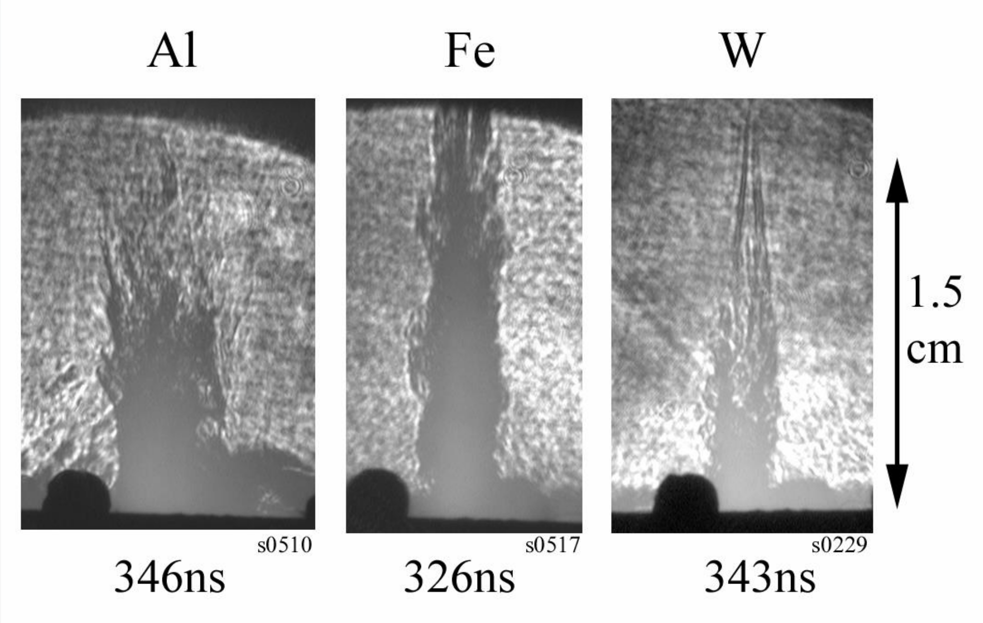
Cooling parameter:
ratio of radiative cooling time to hydrodynamic time

$$\chi \equiv \frac{\tau_{cool}}{R_j / V}$$

Pulsed-power experiments have shown the effect of radiative cooling in the structure of jets

Radiative cooling affects jet collimation





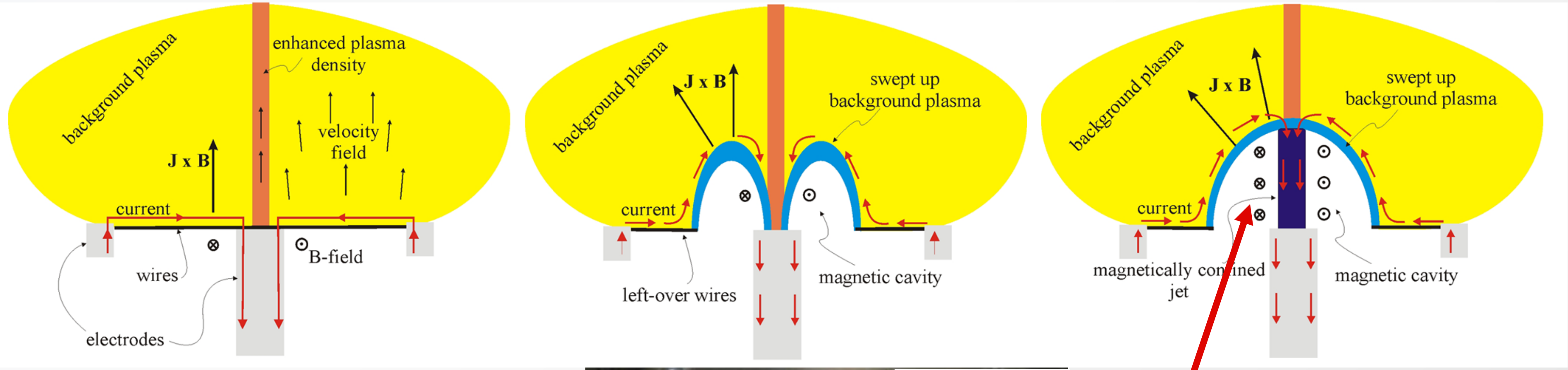
Stronger cooling

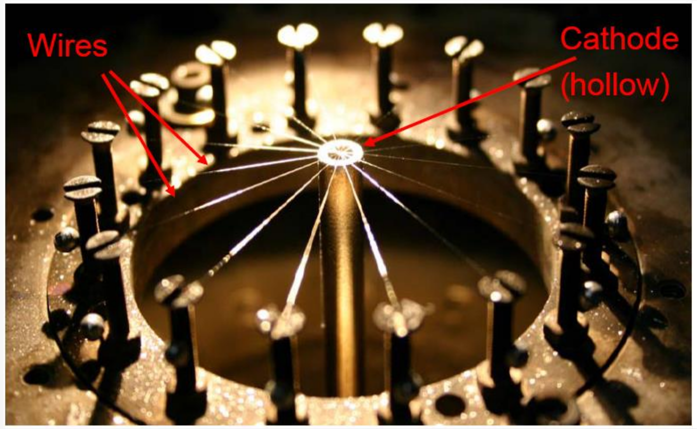
- Converging plasma flow, re-directed by a standing conical shock
- Radiatively cooled jet, M >10, χ <1
- Jet velocity ~ 200km/s
- Electron density 10^{18}-10^{19} cm^{-3}

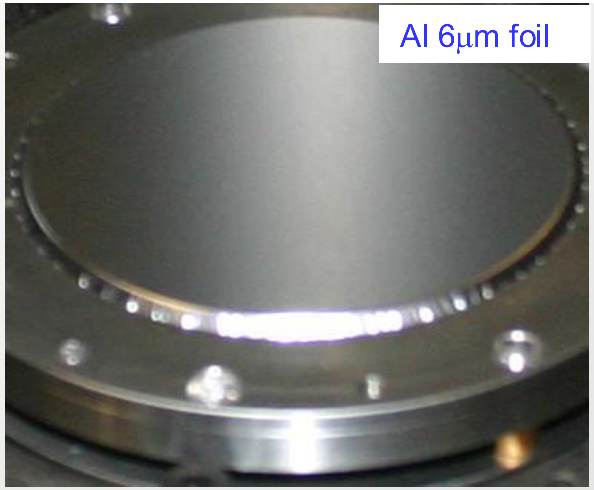
$\lambda/R < 10^{-4}$ Re > 10^4 Pe > 10-50

Lebedev et al., ApJ 2002

Magnetically-driven jets can be created by using foils in pulsed-power experiments



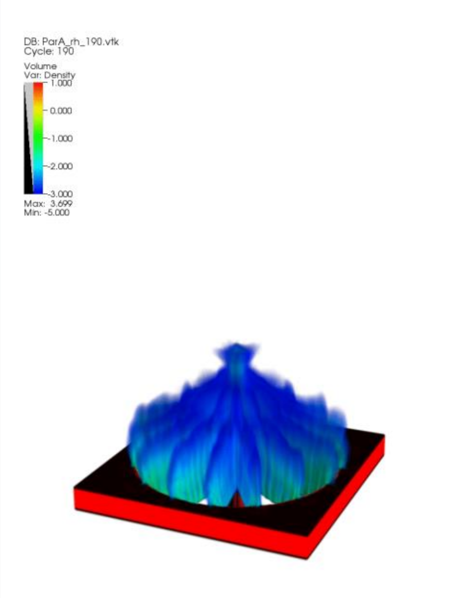




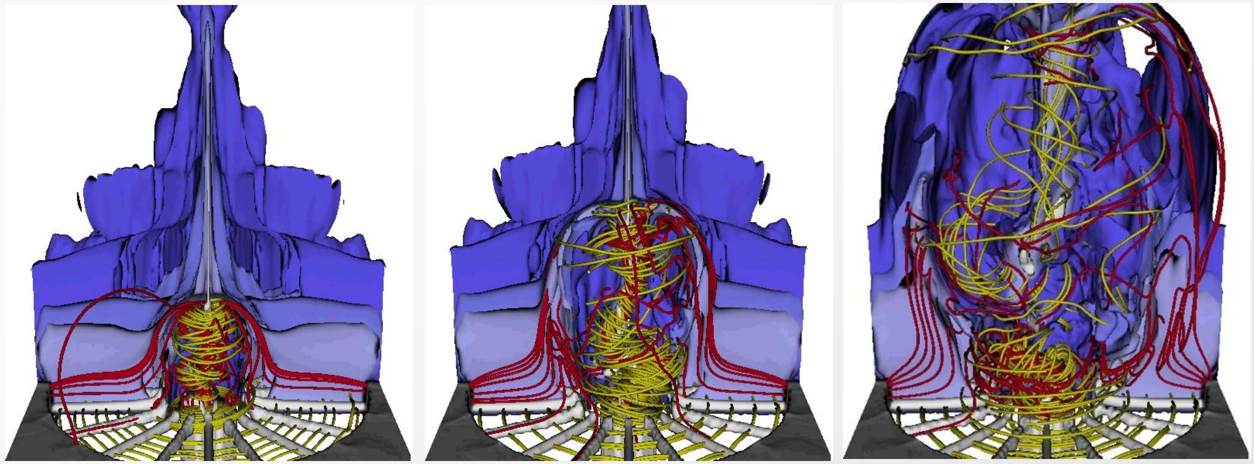
Magnetically confined jet on the axis of magnetic cavity expanding through ambient plasma

Lebedev et al, MNRAS (2005), Ciardi et al, ApJL (2009), Suzuki-Vidal et al, PoP (2010, 2012)

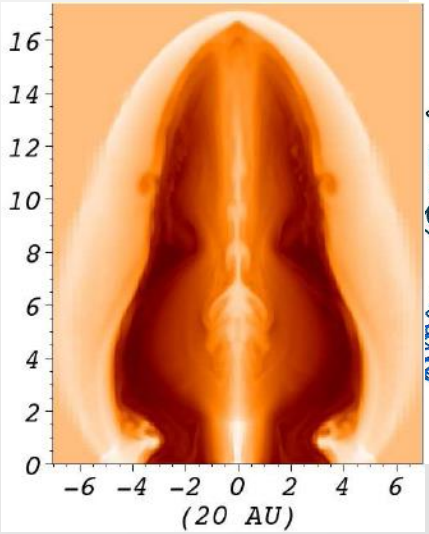
Well-known initial conditions in the experiments allow comparing with astrophysics codes

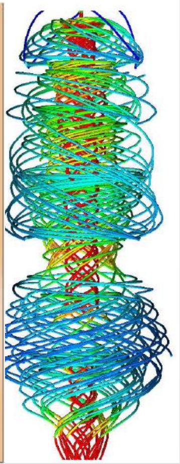


Simulations with laboratory code (GORGON)
Ciardi et al, PoP 2007



Astrophysical code (ASTROBEAR)
Huarte-Espinosa et al, 2012

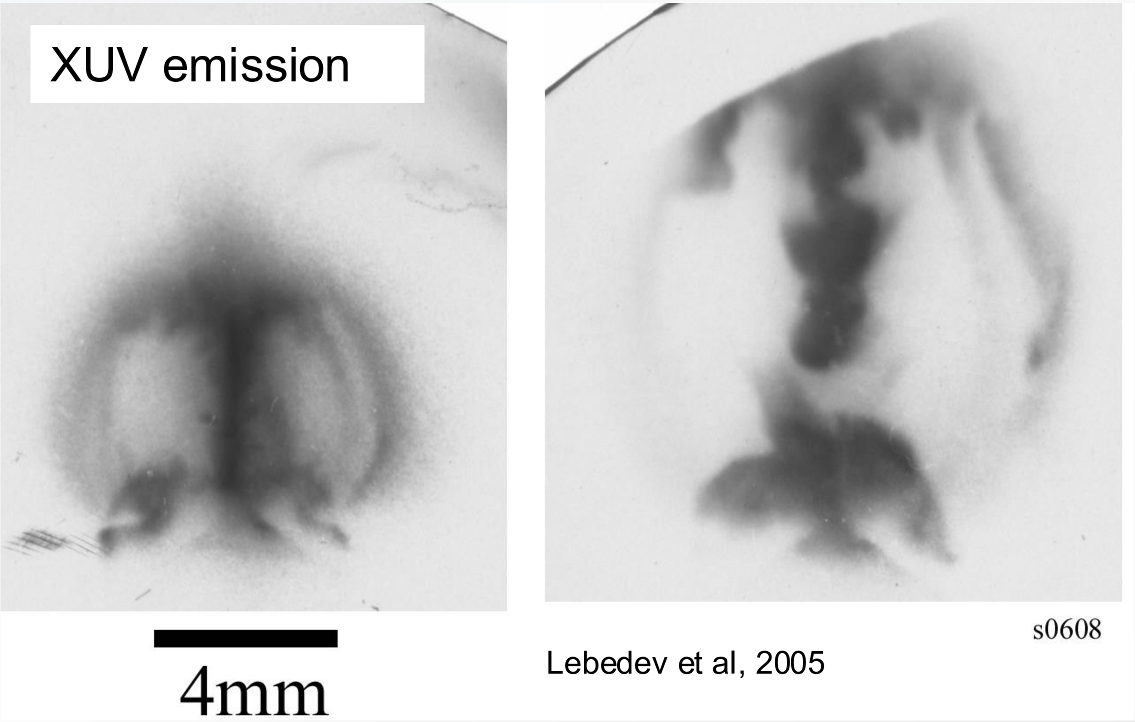




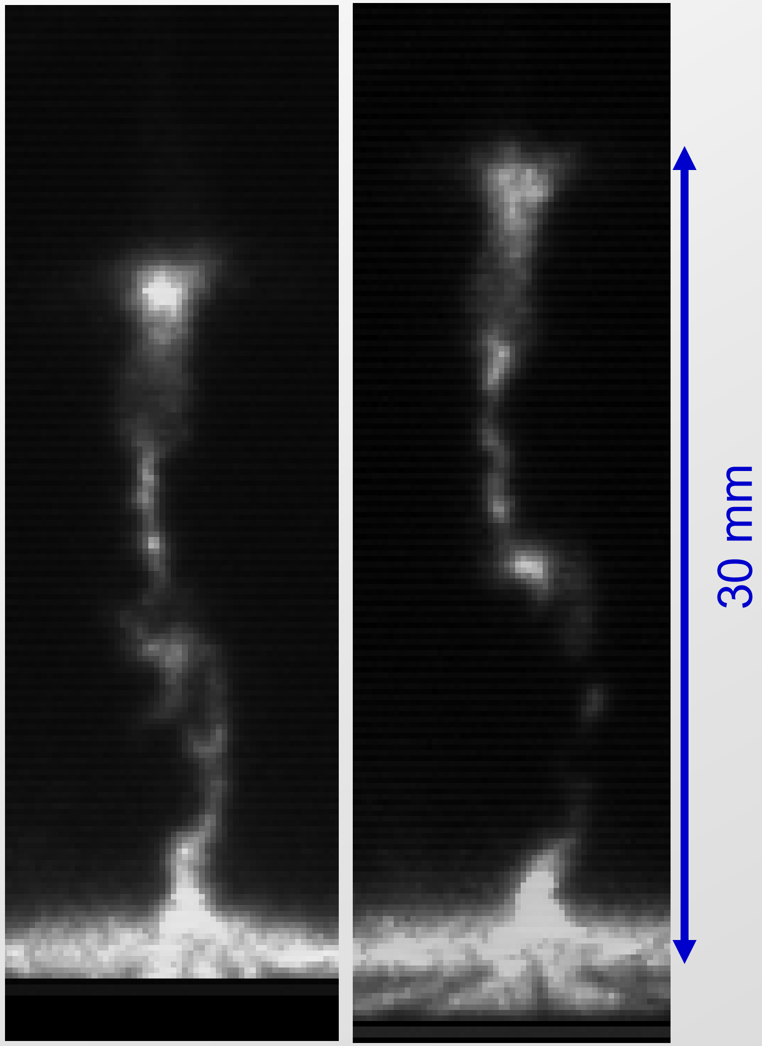
Magnetic cavity (β <<1) with dense jet on axis (β ~1)
MHD instabilities, change of magnetic field topology (B_φ ➔ B_z , B_r)
Energy balance: Poynting flux, magnetic energy, kinetic energy, radiation.

MHD instabilities can develop gradually over the evolution of the jet

H. Calamy et al, 2007



Lebedev et al, 2005

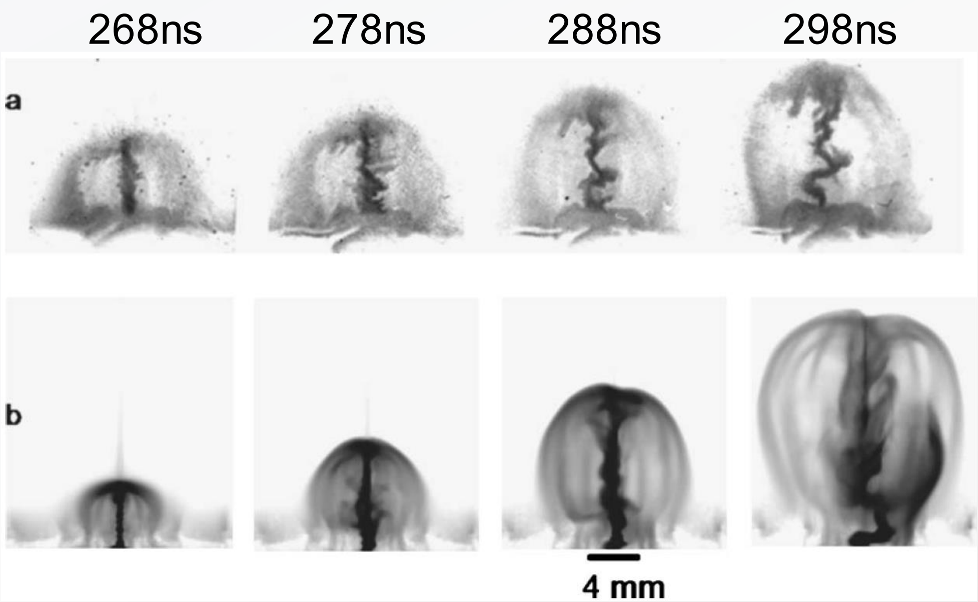


Instabilities produce “clumps” in the jet, but do not destroy collimation

Descriptive title

Experiment versus 3-D MHD

Ciardi et al, PoP 2007



Jet driven by the pressure of the toroidal magnetic field

Collimation of the central jet by the hoop stress

Collimation of the magnetic bubble by the ambient medium

Two temporal scales for outflow variability:

- fast – instability growth time (~1ns)
- slow – bubble growth time (~50ns)

Instabilities do not destroy the jet but produce a clumpy outflow

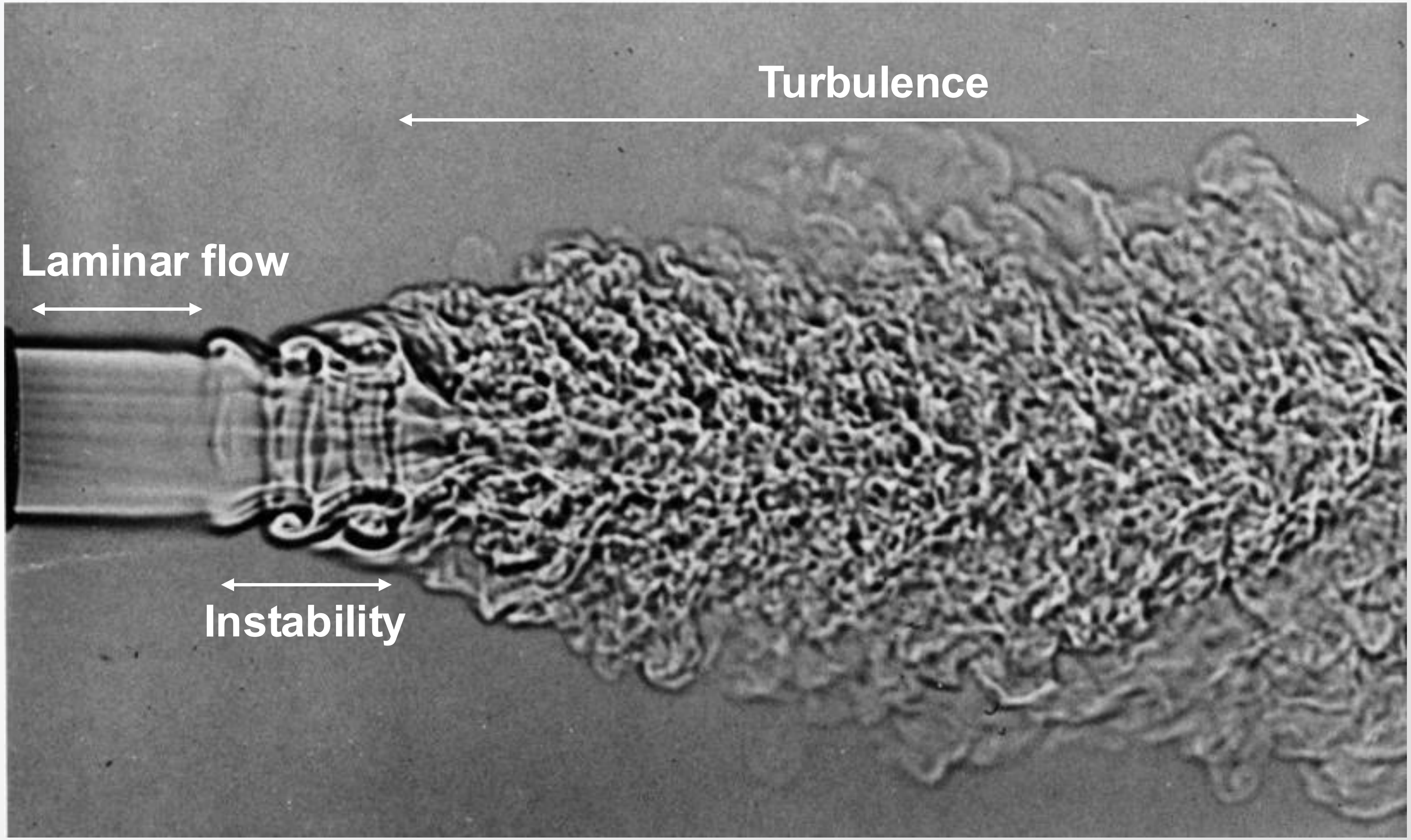
$n_i \sim 10^{19}\ cm^{-3}$, $T \sim 200$ eV,

$I \sim 1$ MA, $B \sim 100$ T

$Re > 10^4$, $\lambda/R \sim 10^{-5}$, $Pe > 10$

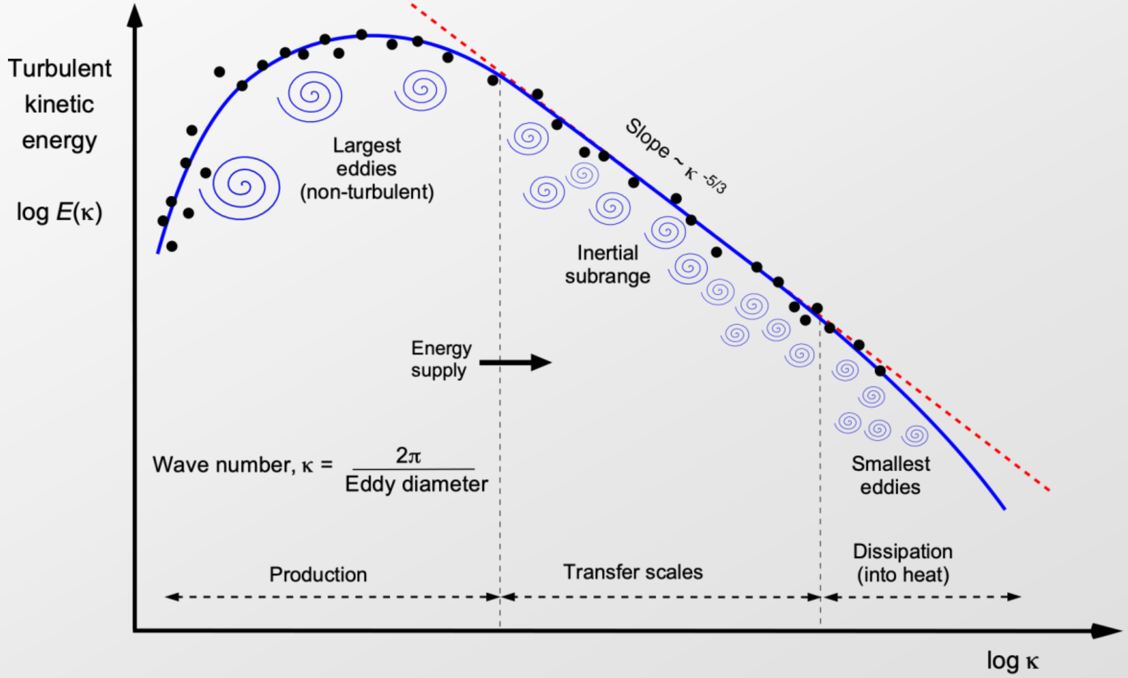
$\beta \sim 1$, $Re_M \sim 50\text{-}300$

Turbulent flows in a neutral fluid (liquid or gas)



Van Dyke, *An Album of Fluid Motion* (1988)

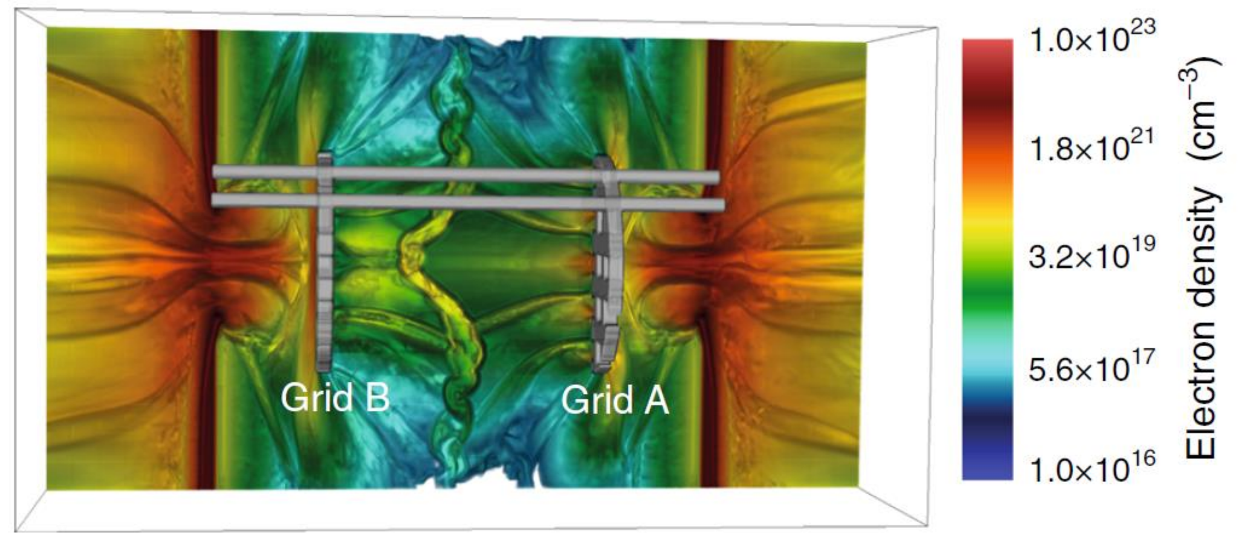
In a plasma, magnetic fields are entrained with the turbulence, producing much more complicated systems

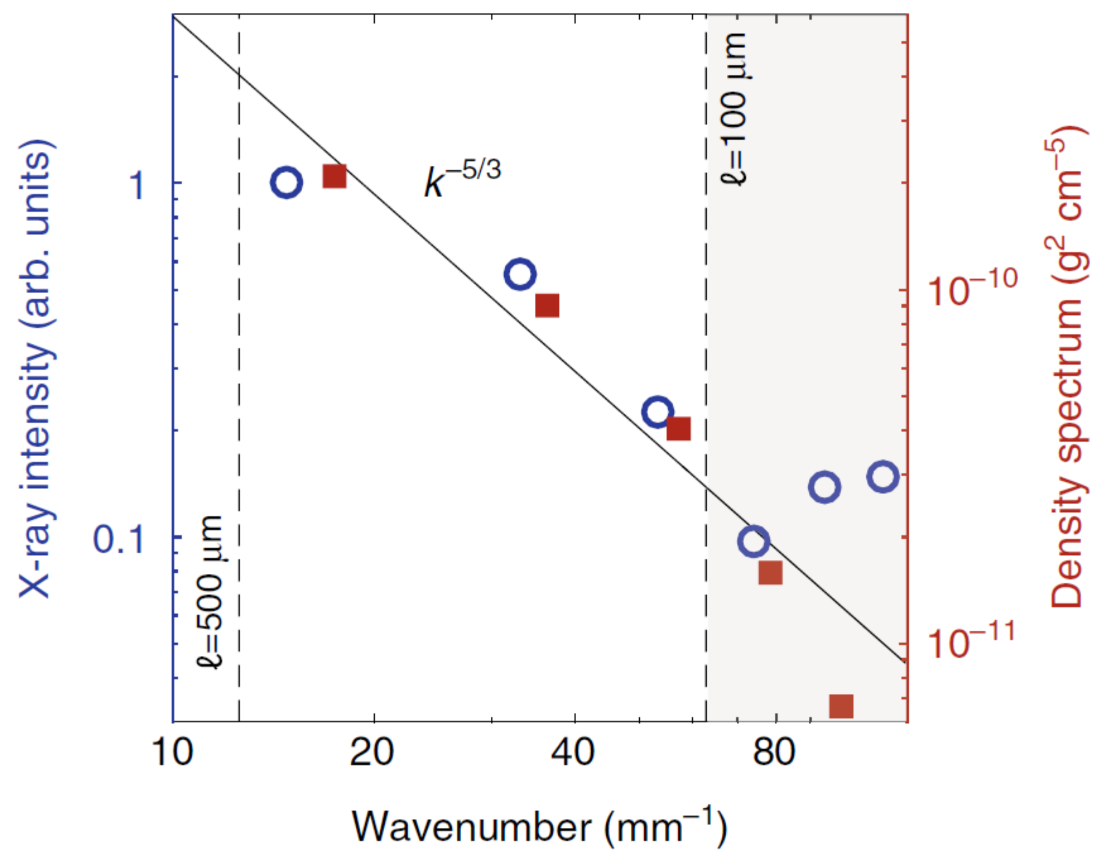


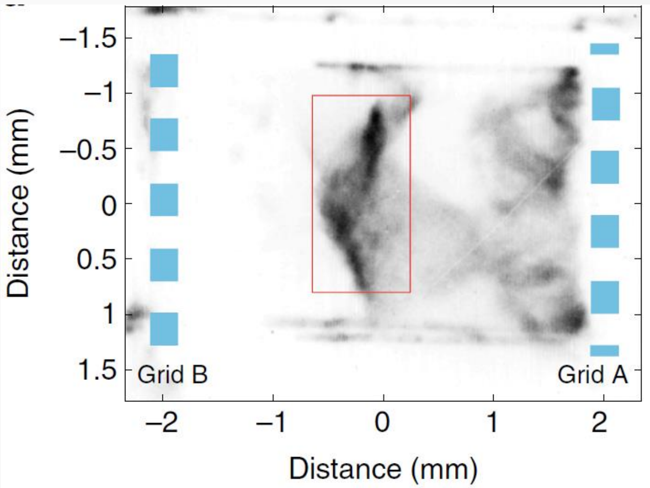
Dynamo: Magnetic fields can be amplified by line stretching (shear, compression, rotation)

Beattie et al., Phys. Rev. Lett. (2025, in review)

The TDYNO experiments create magnetized turbulence using lasers



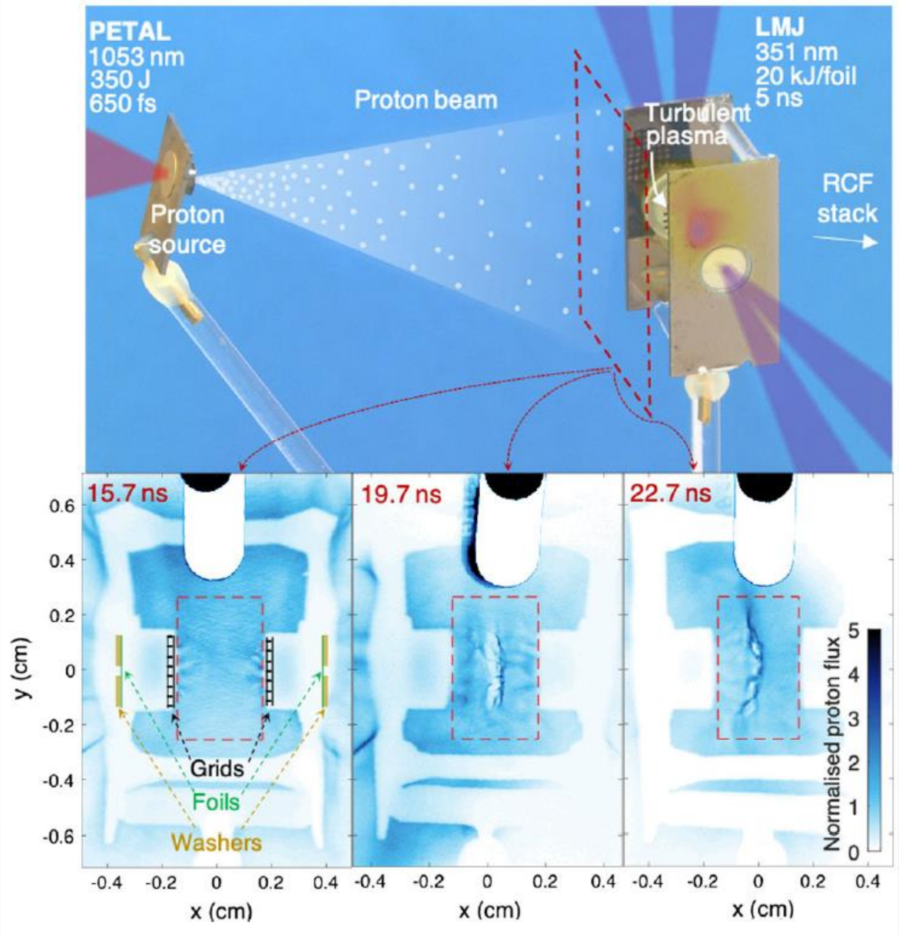




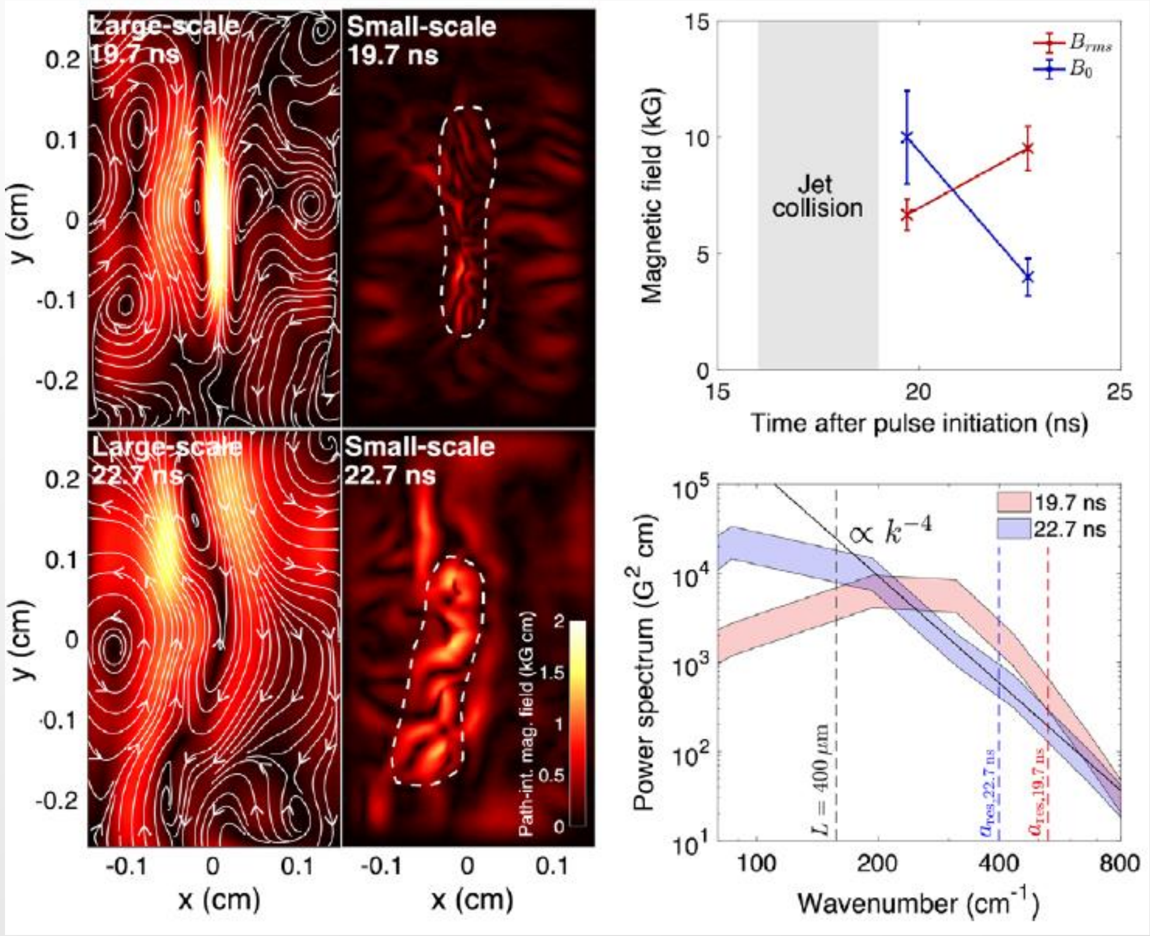
Tzeferacos et al., Nat. Comm. (2018); White et al., Nat. Comm. (2019); Bott et al., PNAS (2021)

First demonstration of fluctuation turbulent dynamo in the laboratory

LMJ-PETAL experiment: Bott et al, 2018

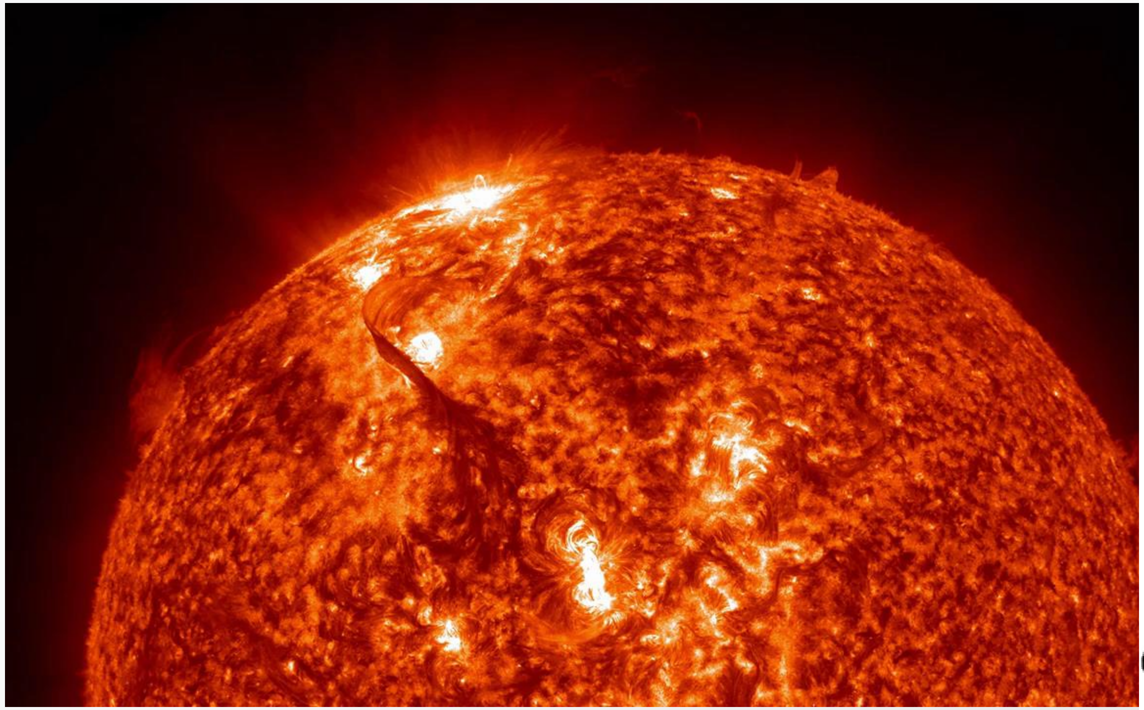


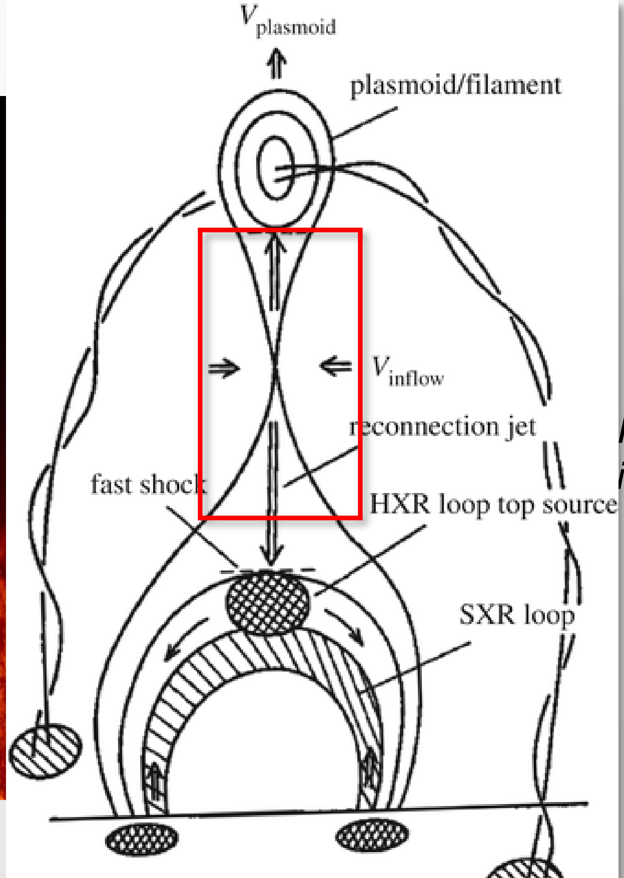
B-field reconstruction from proton probing



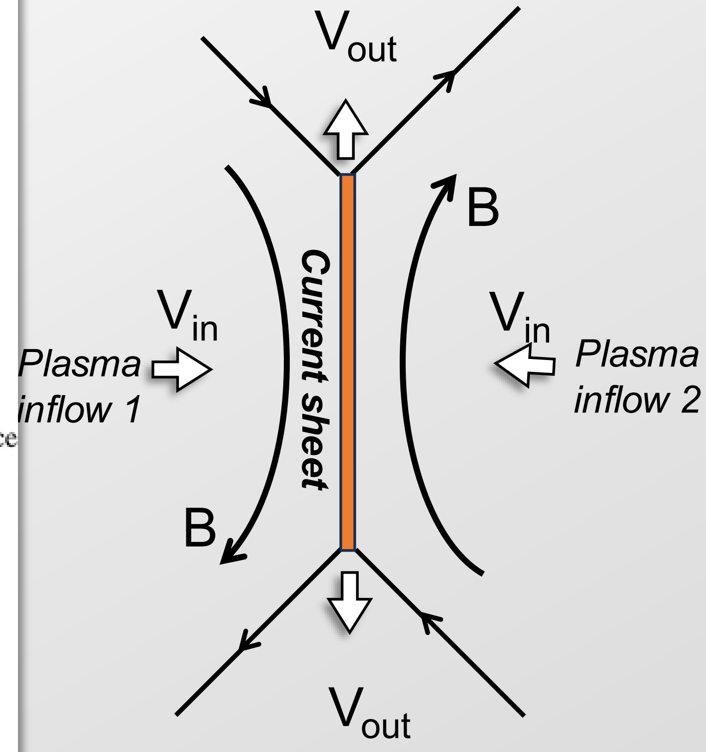
Magnetic reconnection is a common process in the universe that energizes the fluid from the field

Magnetic reconnection driven explosion on the surface of the Sun





[Shibata+ 1995]



The Sweet-Parker model of magnetic reconnection

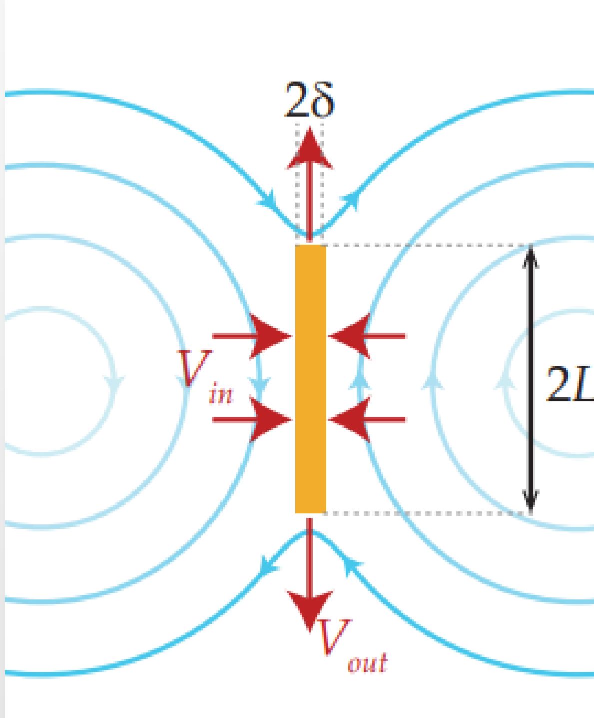
Reconnection rate: $\frac{\text{\# of lines out}}{\text{\# of lines in}} = \frac{V_{out}}{V_{in}}$

Conservation of mass:

$$\rho V_{in} L = \rho V_{out} \delta \quad \rightarrow \frac{L}{\delta} = \frac{V_A}{V_{in}}$$

Conservation of energy:
(max outwards speed)

$$\frac{B^2}{2\mu_0} = \frac{1}{2}\rho V_{out}^2 \rightarrow V_{out} = \frac{B}{\sqrt{\mu_0 \rho}} \equiv V_A$$



Ampere's law: $J_z \sim B/\mu_0 \delta$

Ohm's law $\mathbf{E} + \mathbf{u} \times \mathbf{B} = \eta \mathbf{J} \quad \rightarrow V_{in} B = \eta J_z$

$$\rightarrow \frac{V_{out}}{V_{in}} = \left(\frac{\mu_0 L V_A}{\eta}\right)^{1/2} \equiv S^{1/2}$$

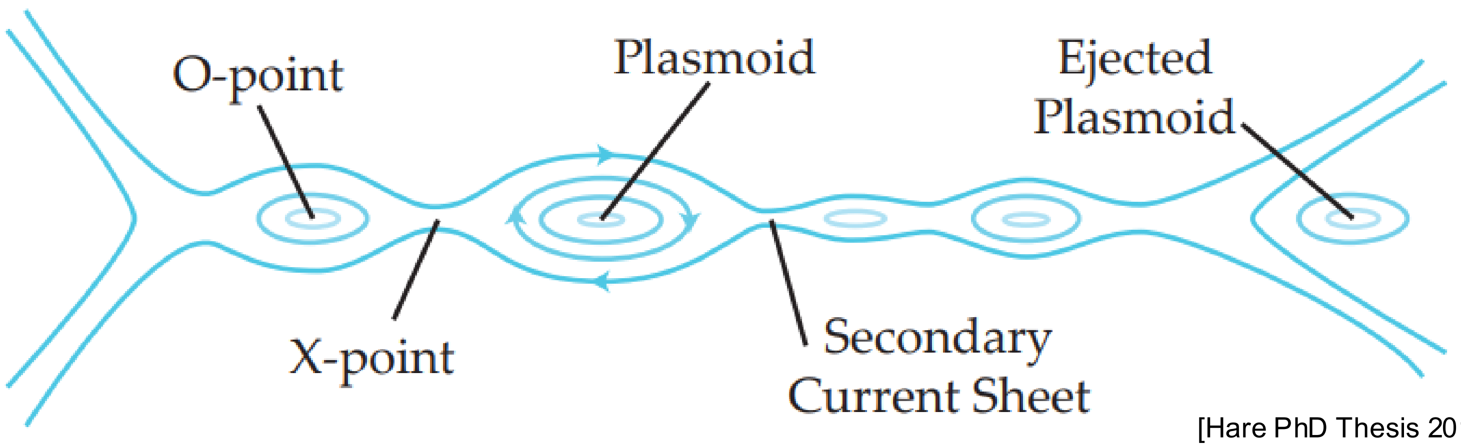
1. S is called **Lundquist number**, it is dimensionless (universal), and **sets the reconnection rate**

2. SP magnetic reconnection **dissipates energy through Spitzer resistivity**

Loureiro & Uzdensky, Plasma Phys. Control. Fusion (2015); Hare, PhD Thesis (2017)

Magnetic reconnection can be chaotic, bursty, and explosive when plasmoids are formed

$$S \sim \frac{L \cdot B \cdot T_e^{3/2}}{\sqrt{n_e}} > S_c$$



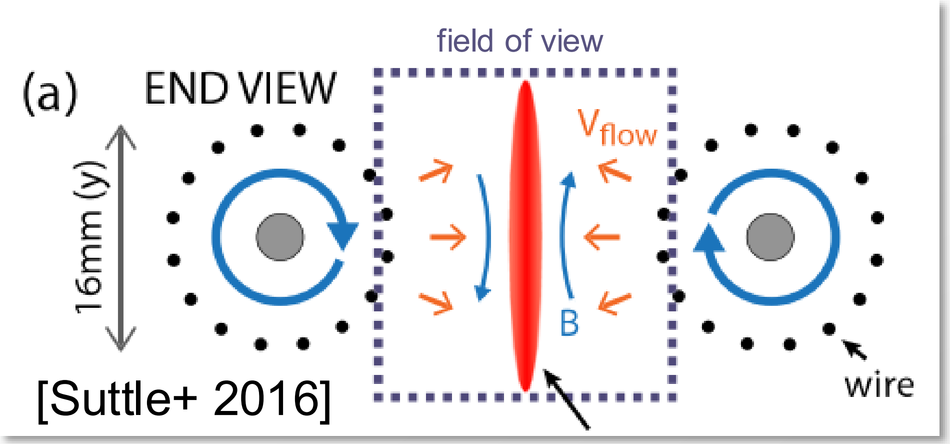
[Hare PhD Thesis 2017]

Current sheet length L is not a free parameter in Sweet-Parker reconnection

Loureiro & Uzdensky, Plasma Phys. Control. Fusion (2015); ; Hare, PhD Thesis (2017)

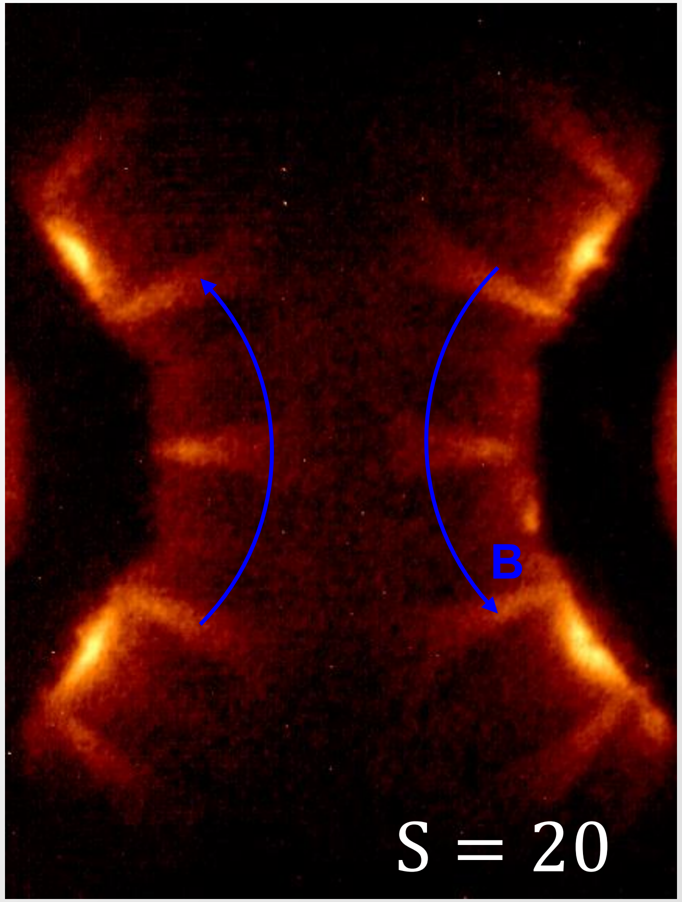
Plasmoid reconnection has been observed in pulsed-power experiments

Pulsed-power magnetic reconnection experiments

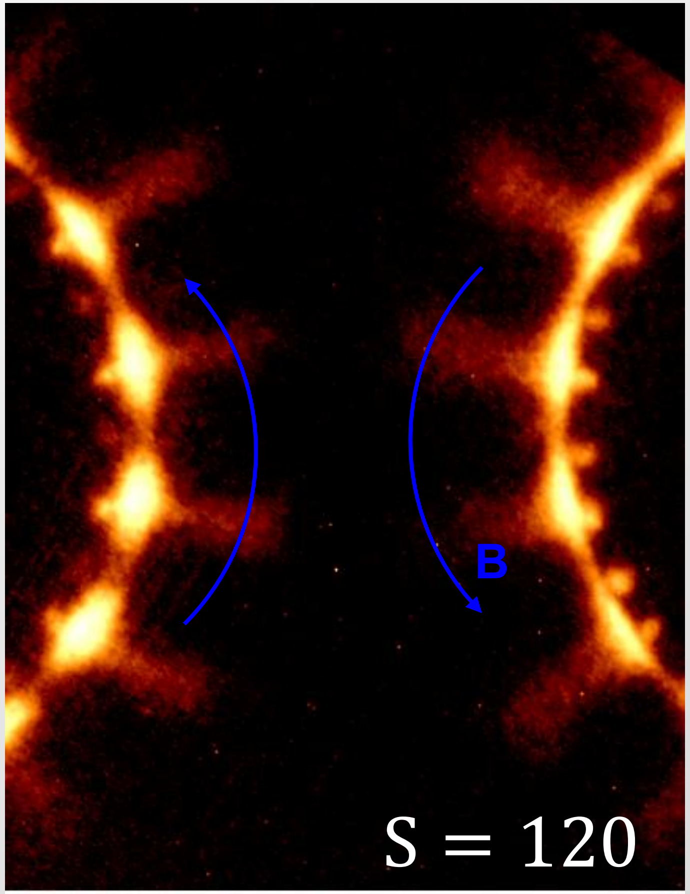


reconnection layer

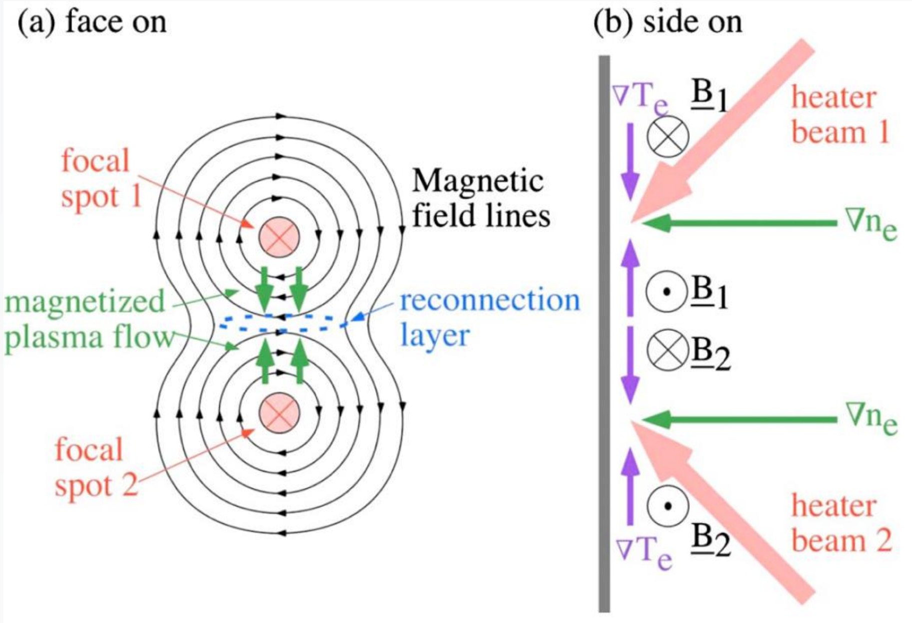
Stable SP with aluminium plasma experiments [Suttle+ 2016]

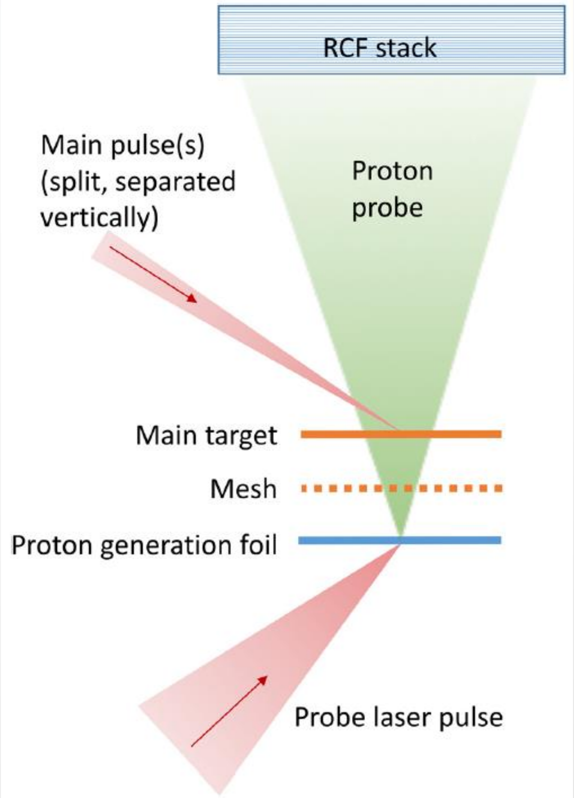


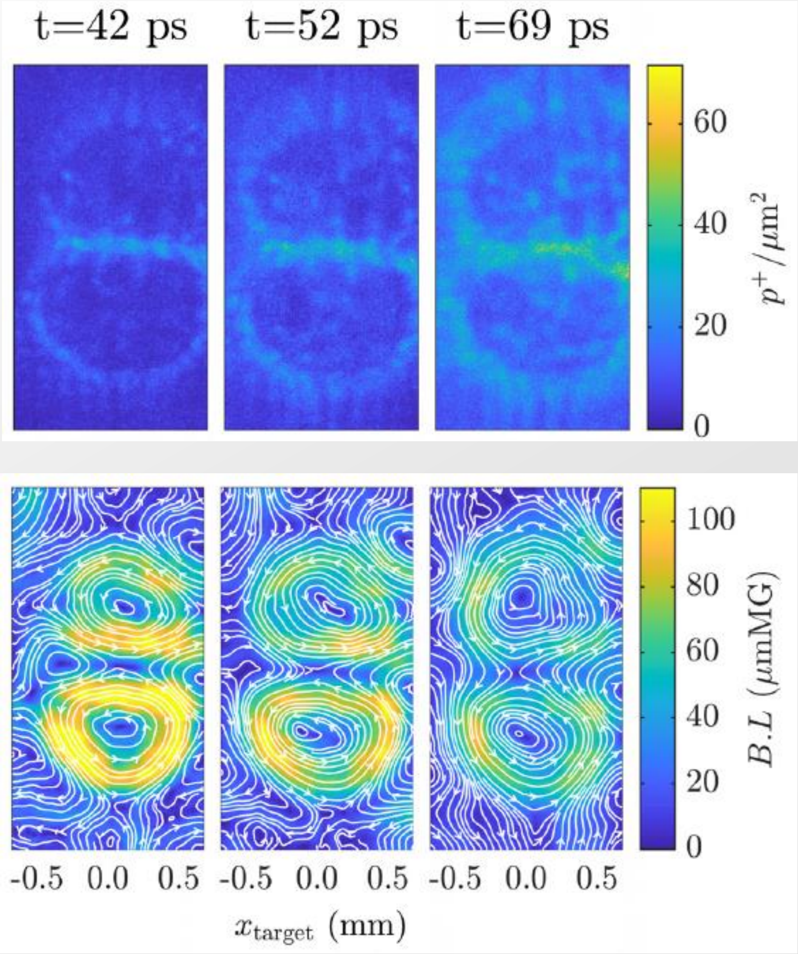
Plasmoid unstable layer in carbon plasma [Hare+ 2017]



Magnetic reconnection in laser-driven experiments

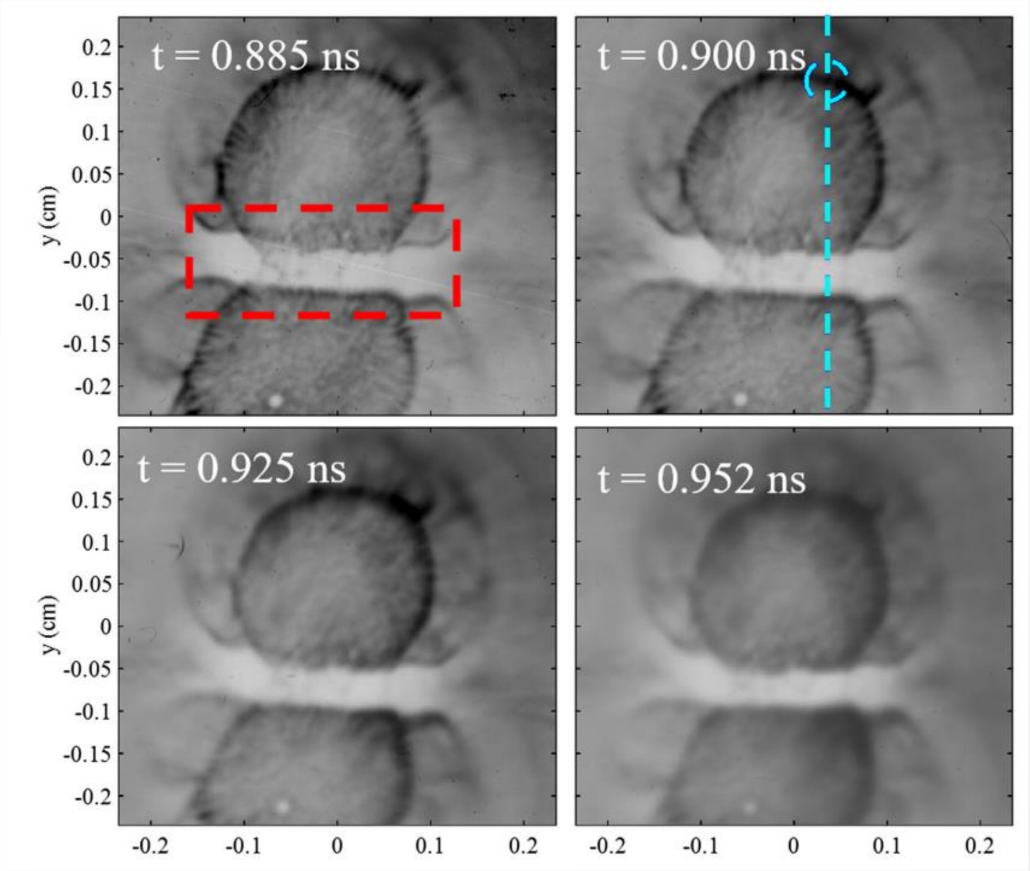


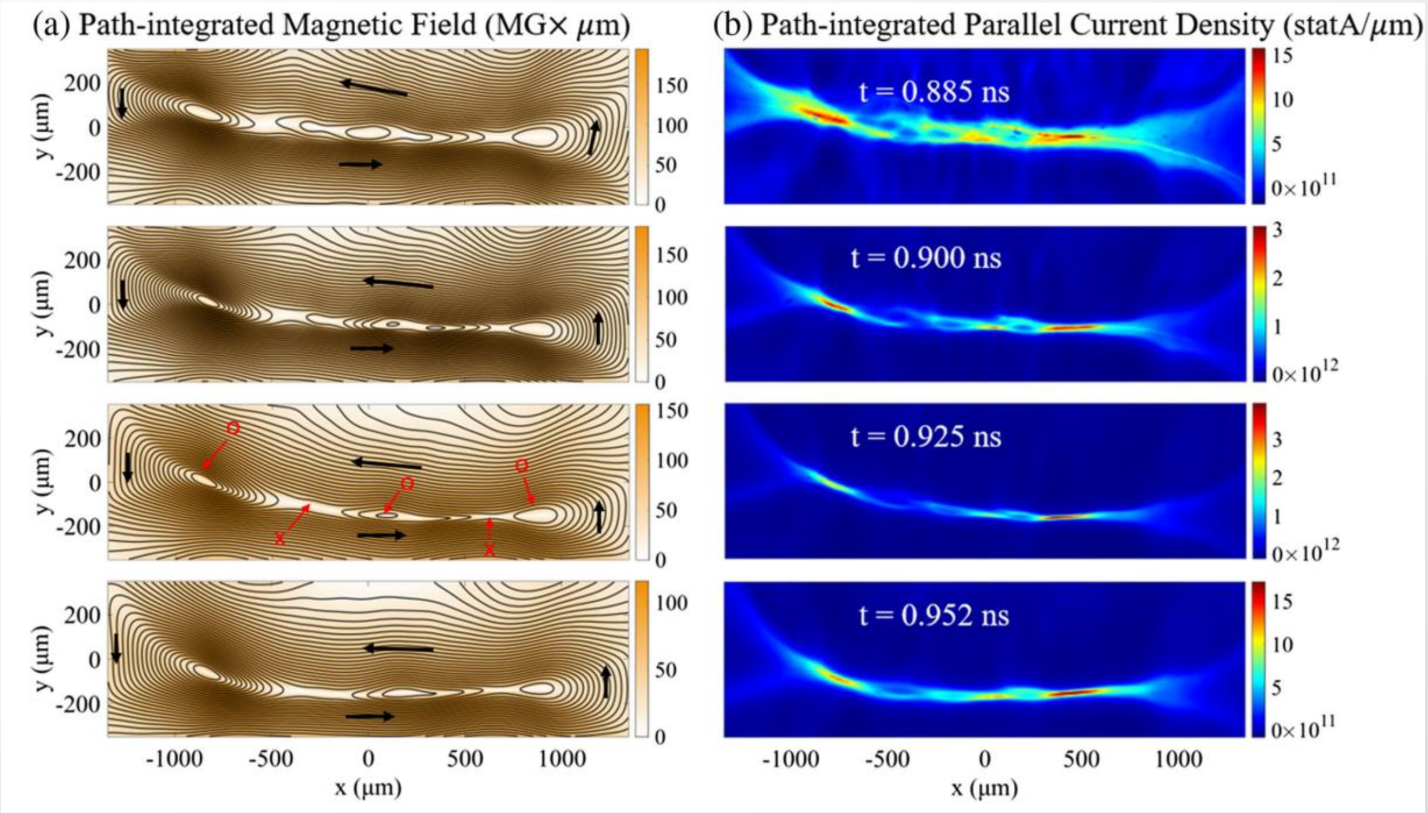




Willingdale et al., Phys. Rev. Lett. (2010)

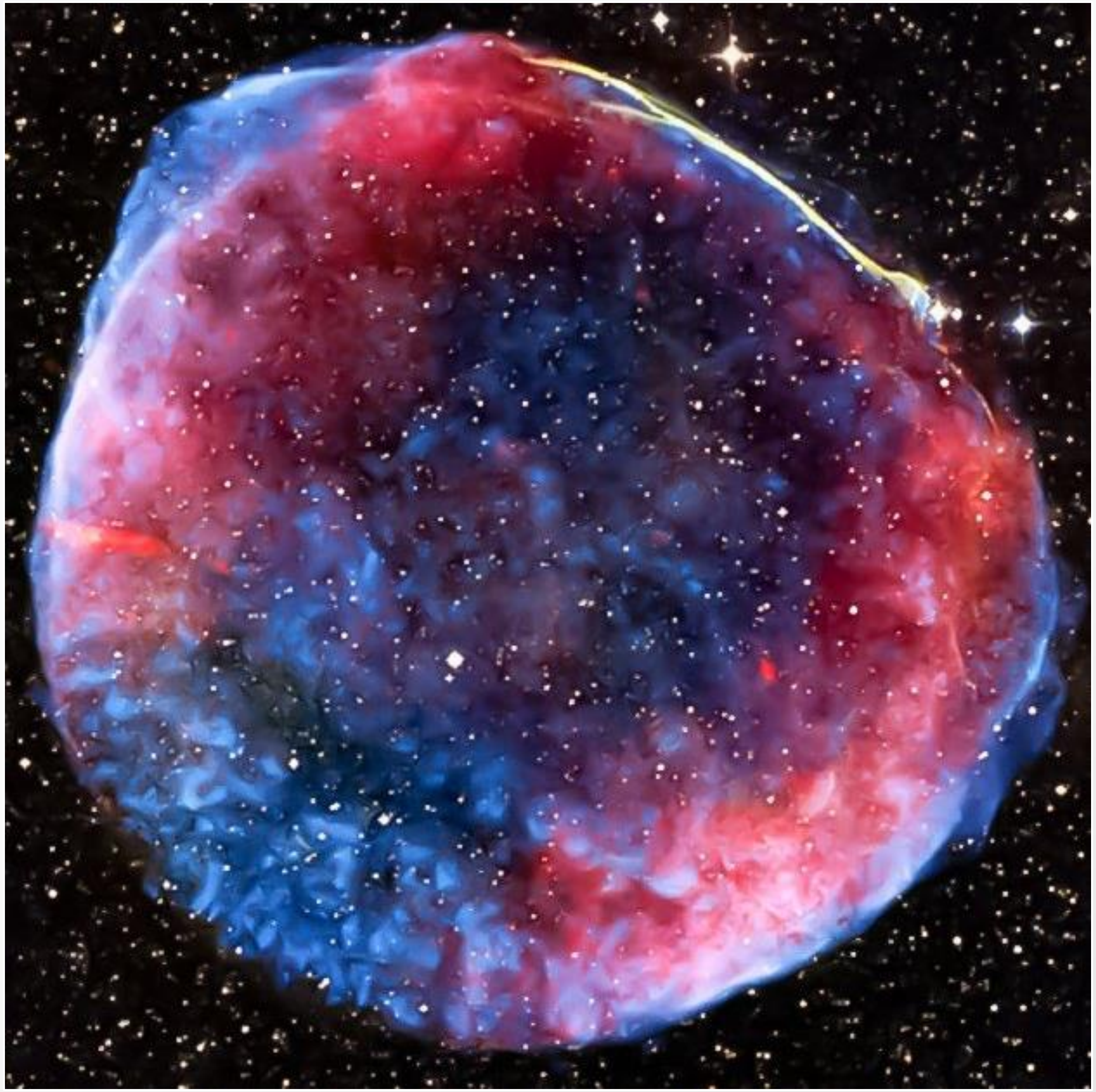
Plasmoid reconnection in laser-driven experiments

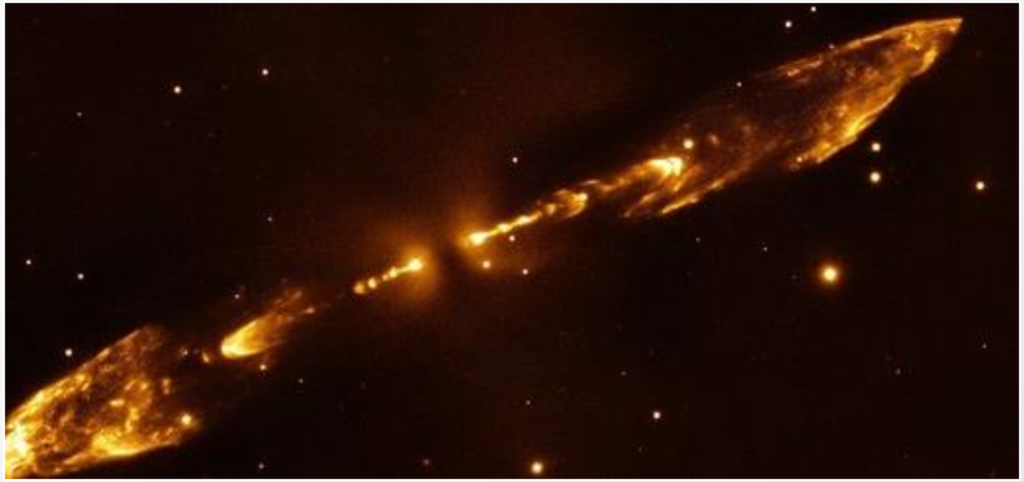


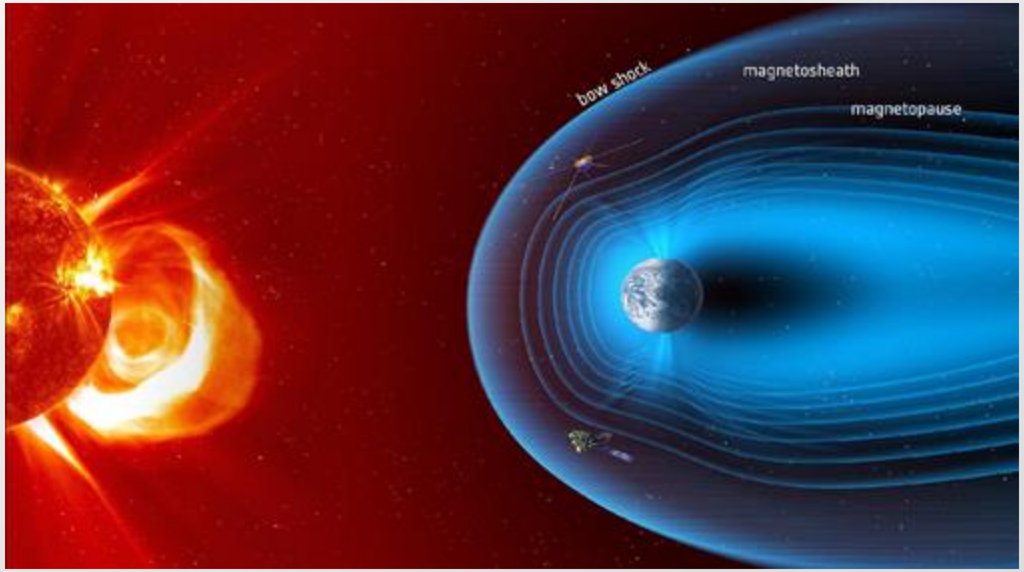


Pearcy et al., Phys. Rev. Lett (2024)

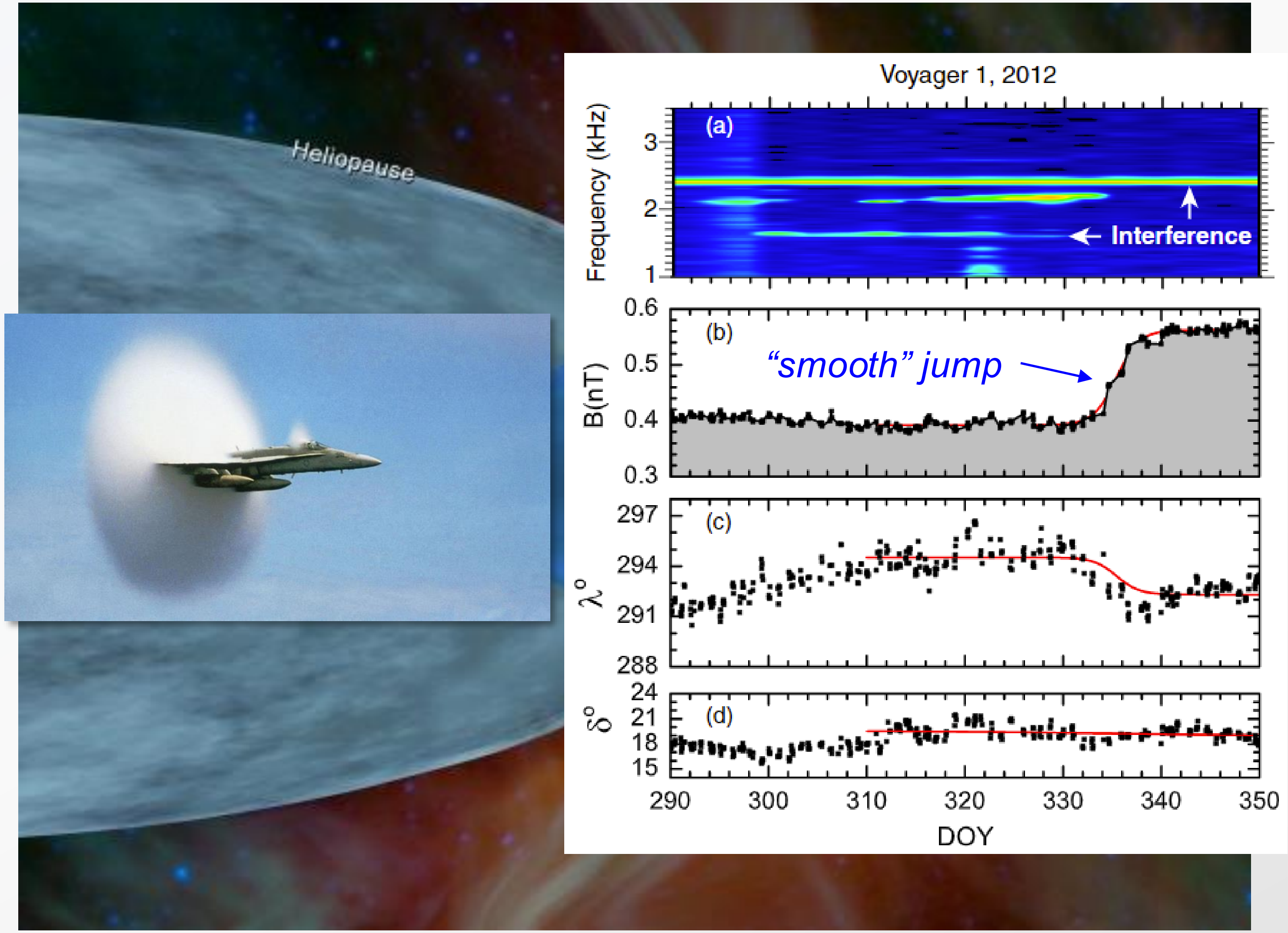
Magnetized shocks in the universe



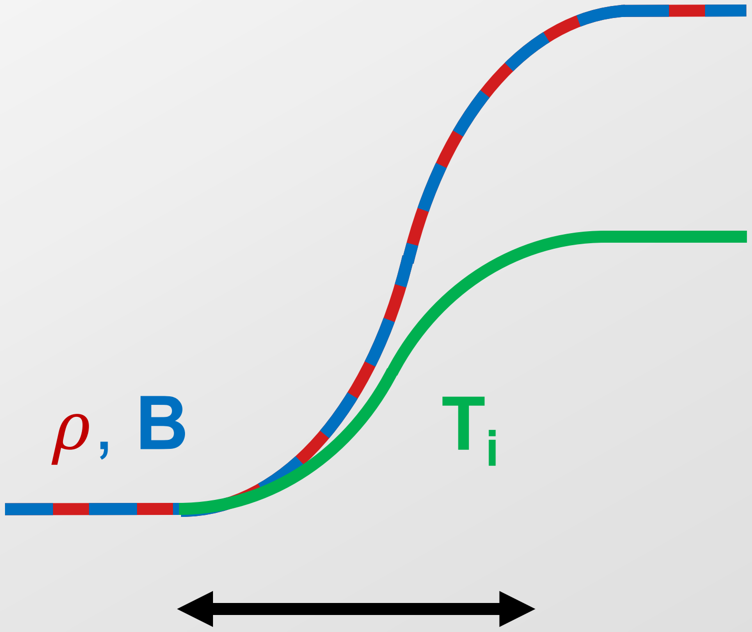




Observations of the transition from the heliosphere have shown a continuous shock around the solar system



Subcritical shock
(low Mach number)

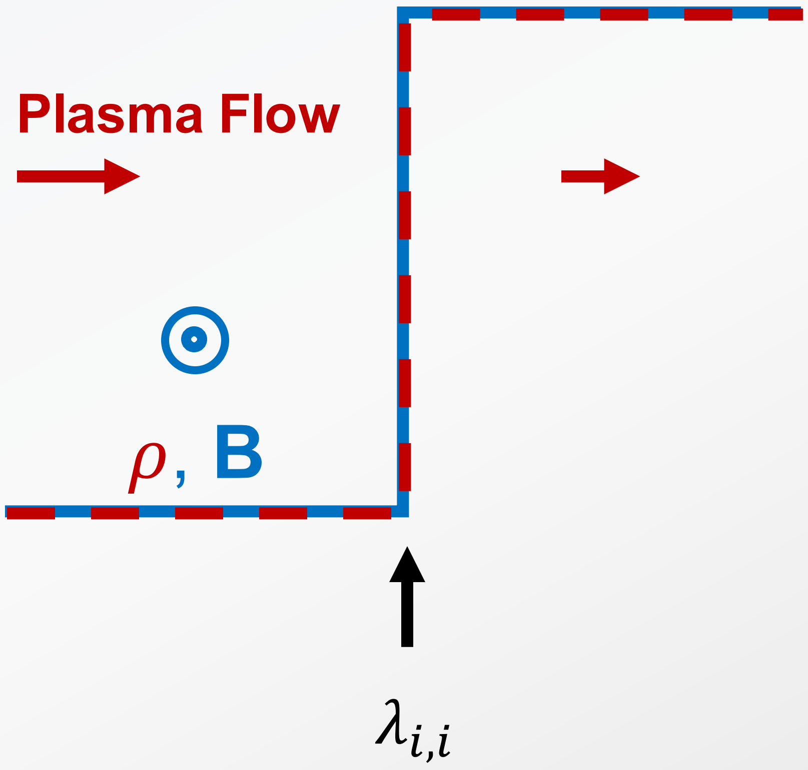


Resistive diffusion length

Burlanga et al., Astrophys. J. Lett. 2013

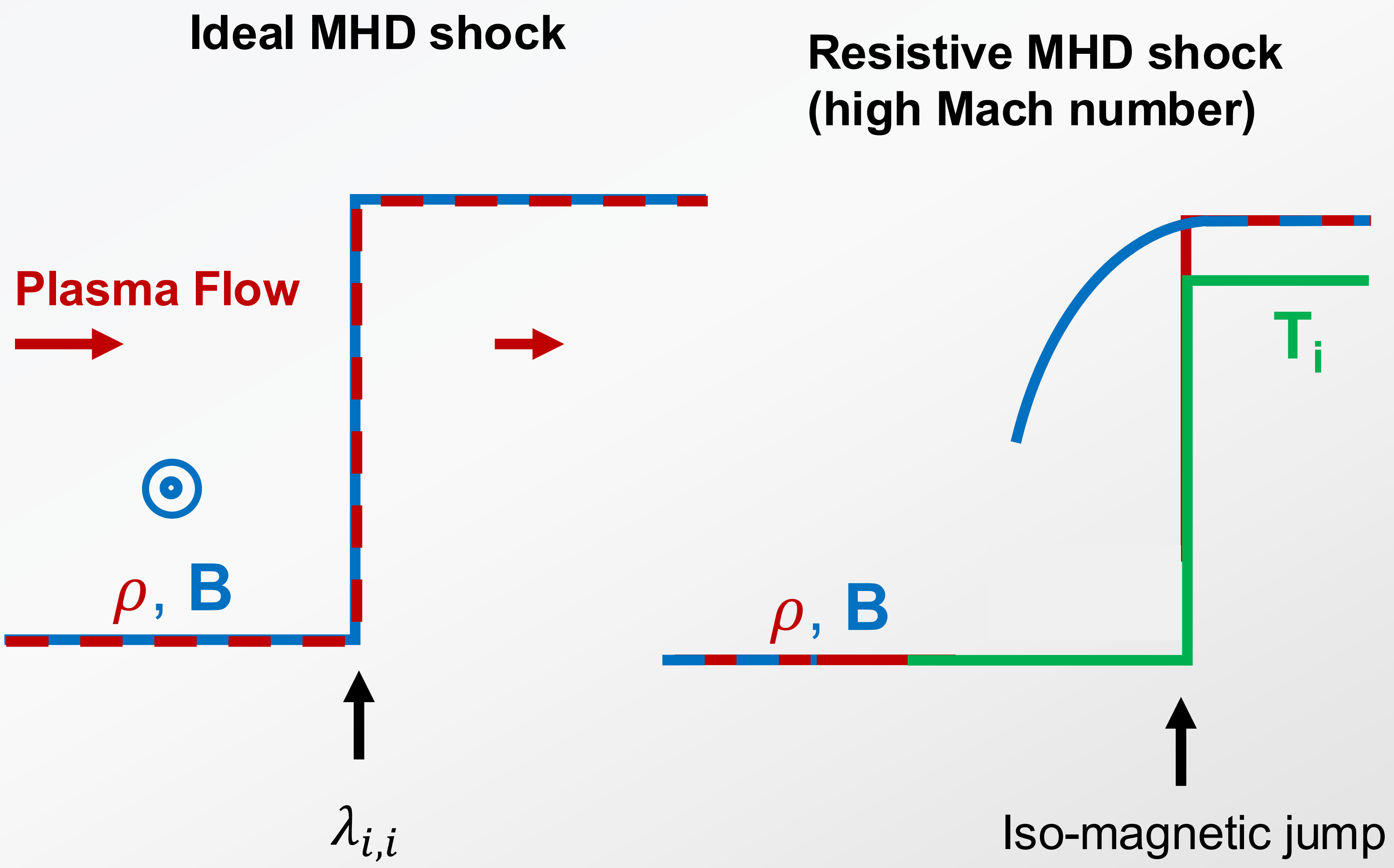
Magnetic fields and dissipation can drastically change the shape of a shock

Ideal MHD shock



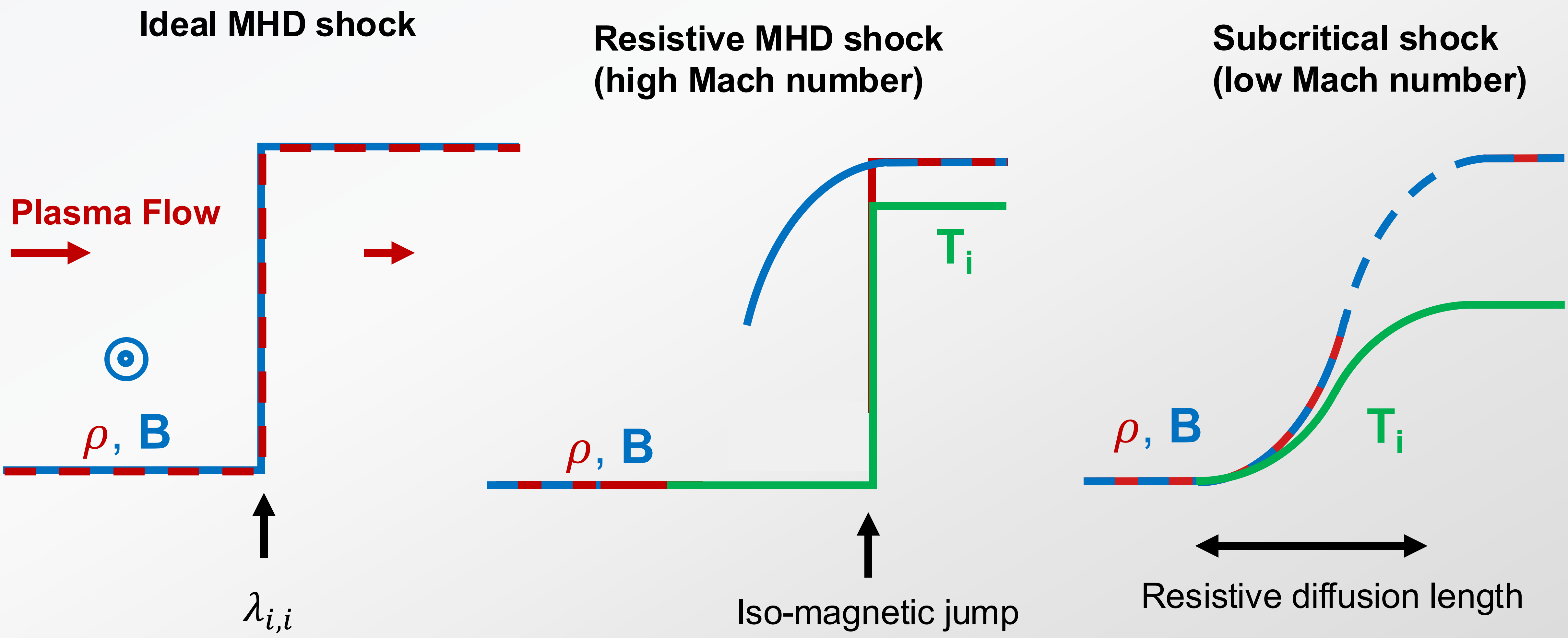
Slide credit: Danny Russell (Imperial)

Magnetic fields and dissipation can drastically change the shape of a shock



Slide credit: Danny Russell (Imperial)

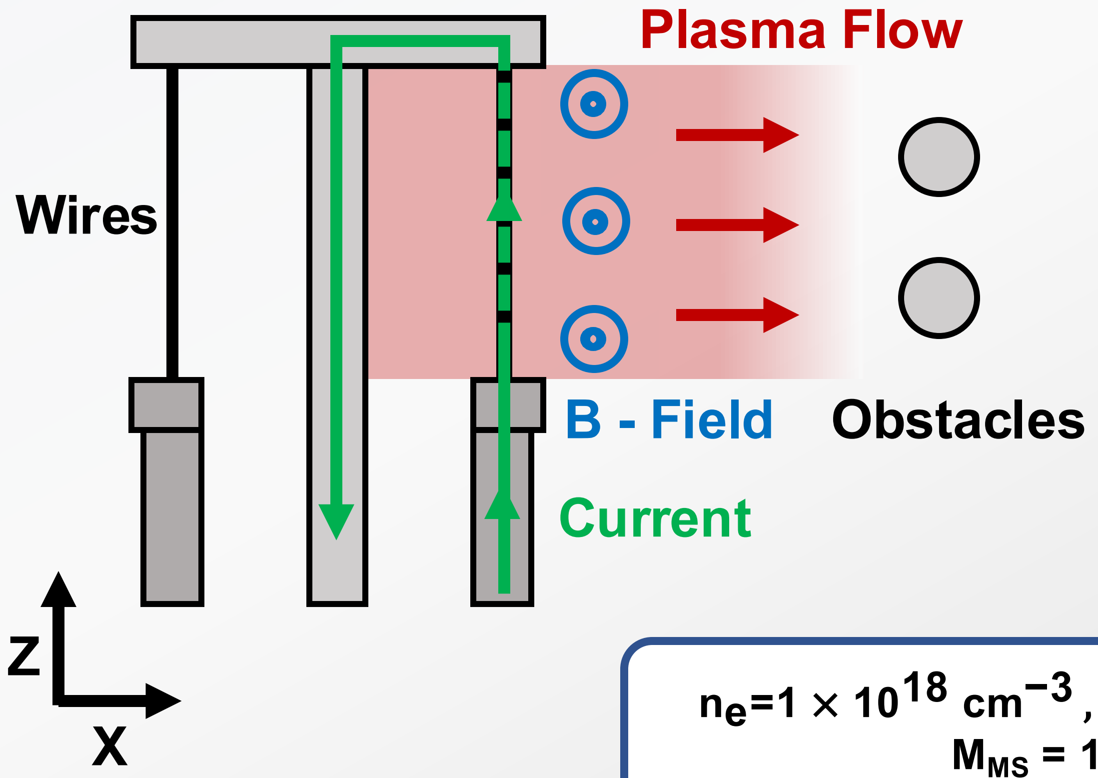
Magnetic fields and dissipation can drastically change the shape of a shock

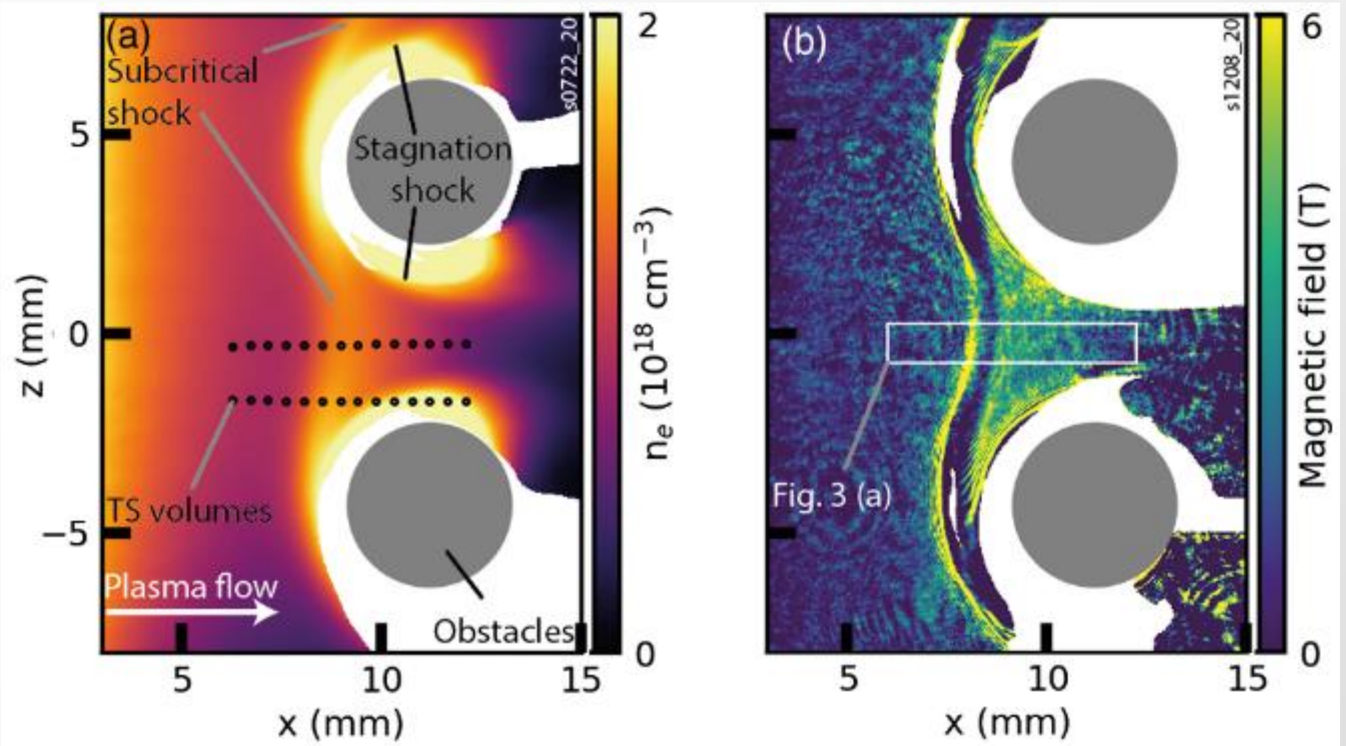


Slide credit: Danny Russell (Imperial)

To create subcritical shocks, an exploder wire array blew magnetized plasma winds onto two cylindrical obstacles

A supersonic, super-Alfvénic **Plasma Flow** with a frozen in **B – Field** is accelerated by the **J** × **B** force





n_e=1 × 10^{18} cm^{-3} , T=12 eV, V=45 kms^{-1} B = 1.5-2.5 T
M_{MS} = 1.9 $\beta_{th} = P_{th}/P_{mag}$ =1.7

Russell et al., Phys. Rev. Lett. (2022); Journal Plasma Phys. (2023)

The results show the formation of subcritical shocks where dissipation is given by resistivity

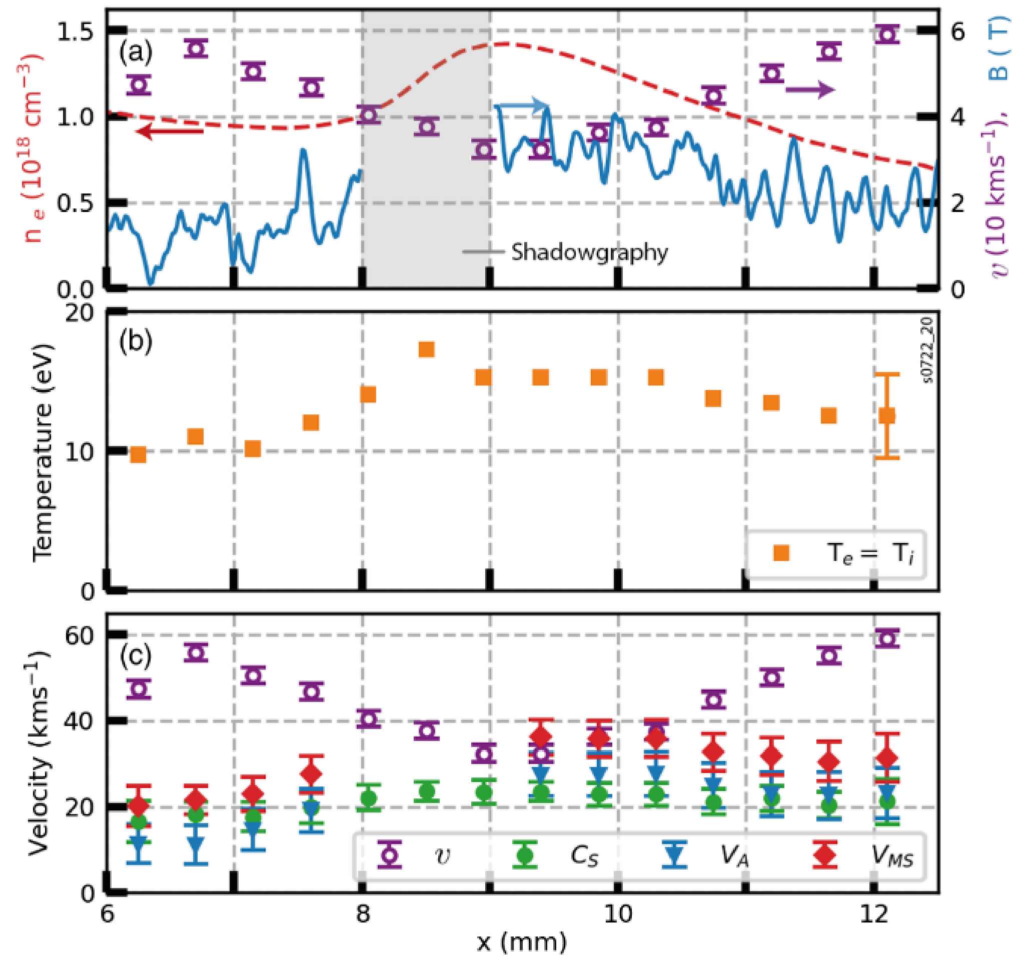


TABLE I. Characteristic plasma parameters upstream of the subcritical shock ~400 ns after current start (details in the Supplemental Material [34]). To evaluate the magnetic Reynolds number, a scale length of 10 mm, the distance between the wire array and the obstacles, gives $Re_M \sim 10$ while a distance of ~0.8 mm, the subcritical shock width, gives $Re_M \sim 1$.

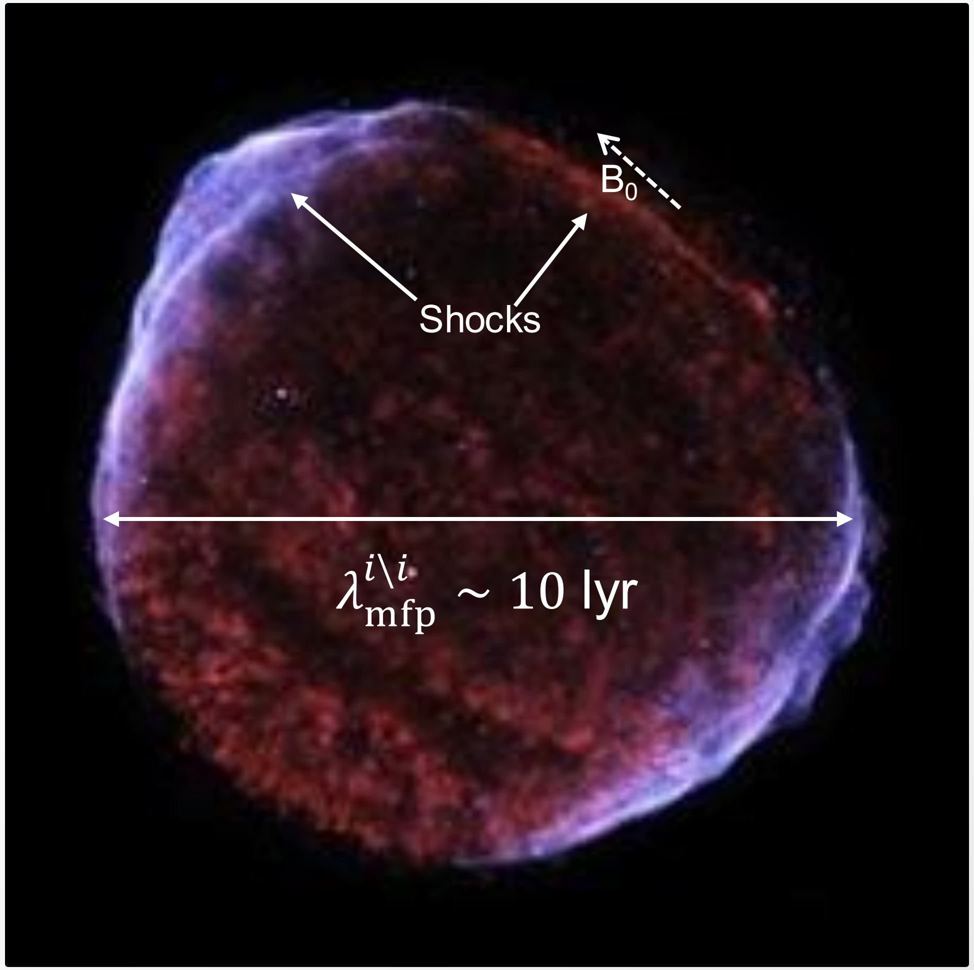
Dimensionless parameter		Value
Thermal beta	β_{th}	1.7
Dynamic beta	β_{ram}	18
Sonic Mach number	M_S	2.5
Alfvénic Mach number	M_A	3
Magnetosonic Mach number	M_{MS}	1.9
Reynolds number	Re	4×10^4
Magnetic Reynolds number	Re_M	$10 \rightarrow 1$

Shock width ~ resistive scale
Transition always happens at Rm = 1!

Russell et al., Phys. Rev. Lett. (2022); Journal Plasma Phys. (2023)

Often shocks in astrophysics are collisionless

Supernova Remnant SN 1006



Common features of collisionless shocks

1. Hierarchy of length-scales

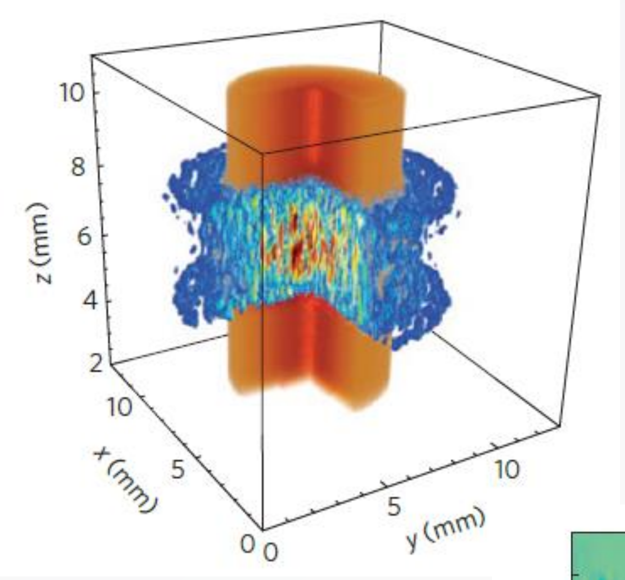
$$\underbrace{\lambda_{\text{mfp}}^{i\backslash i}}_{\text{Ion-ion mean free path}} \gg \underbrace{L_n}_{\text{Density gradient length-scale}}$$

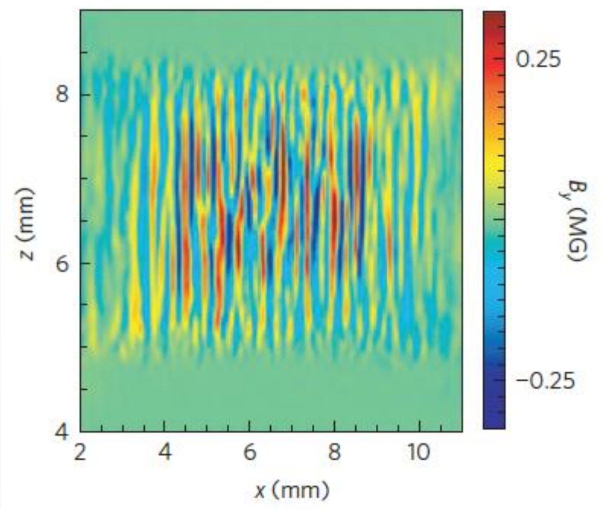
2. Interactions are mediated by collective EM fields

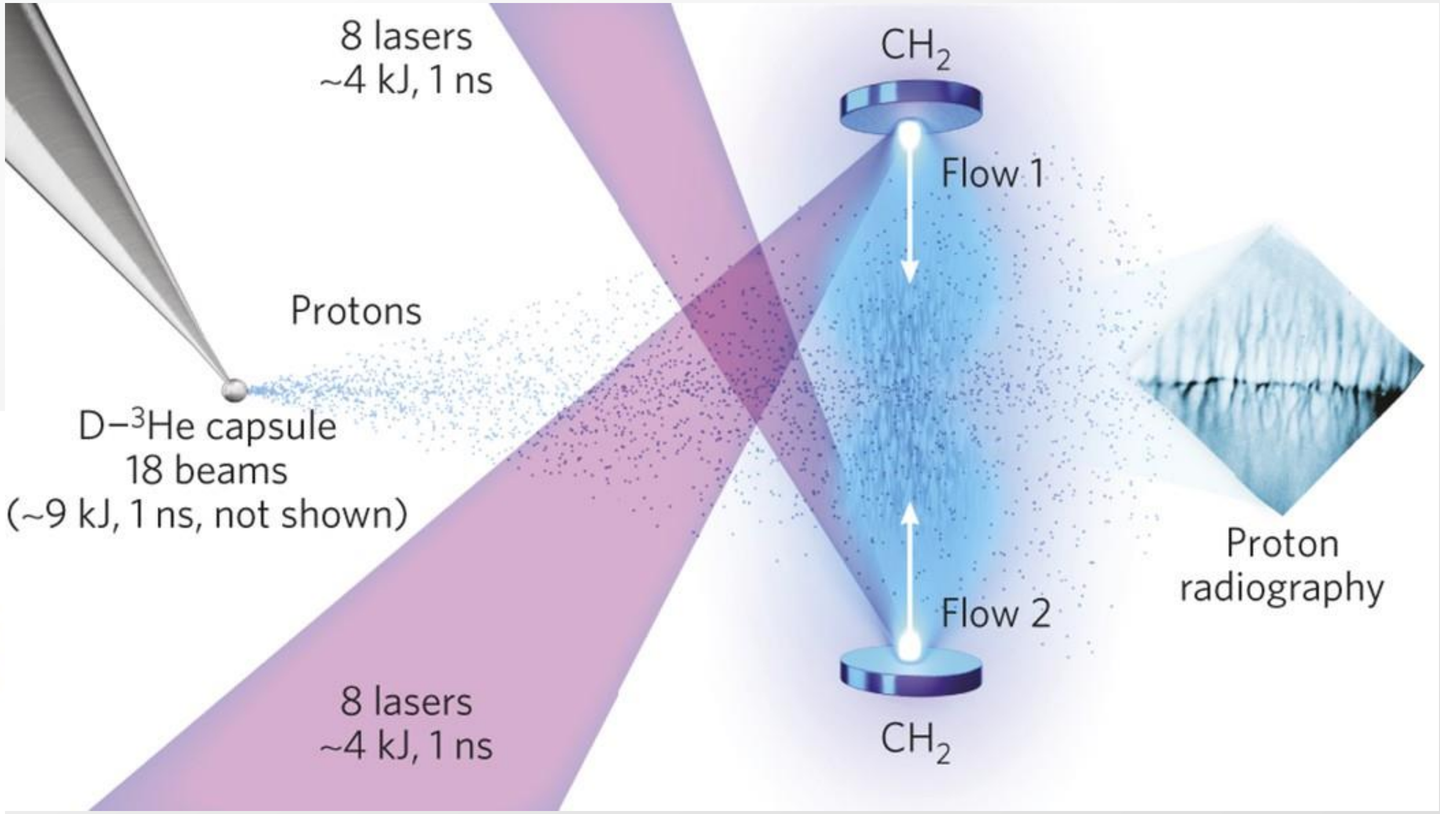
3. Efficient ultra high-energy particle accelerators

Marcowith et al. Rep. Prog. Phys. (2016)

Experiments at OMEGA and the NIF have created collisionless shocks mediated by the Weibel instability







Park et al., Phys. Plasmas (2015); Huntington et al., Nature Phys. (2015)

Experiments at the NIF have created fully-developed Weibel-mediated shocks

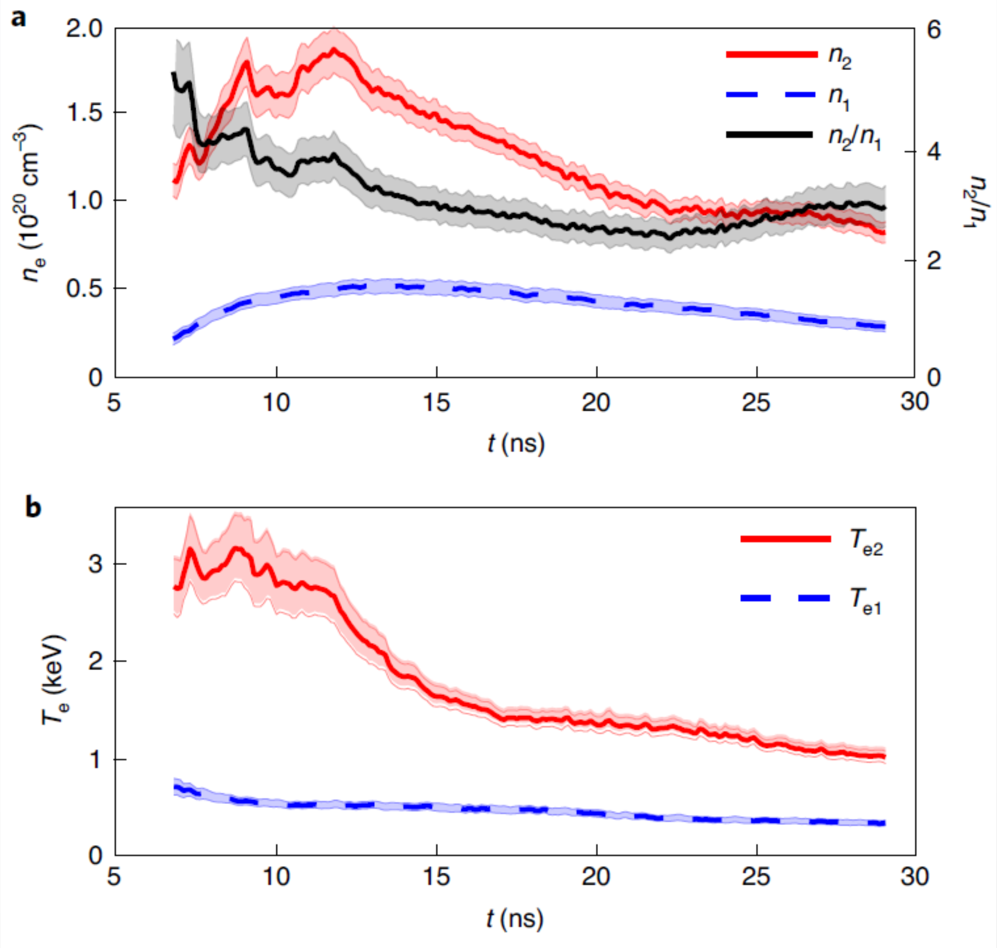


Table 1 | Comparison between plasma parameters in NIF experiments and young SNR shocks

Parameter	NIF experiments	Typical young SNR (for example, SN 1006)
Shock velocity (km s^{-1})	1,000–2,000	3,000–5,000
Ambient magnetic field (G)	2×10^4	3×10^{-6}
Ambient plasma density (cm^{-3})	5×10^{19}	0.2
Ambient plasma temperature (eV)	500	1
System size (cm)	2.5	3×10^{19}
Collisionality ($L_{system}/L_{m.f.p.}$)	0.03	0.01
Sonic Mach number (v_{sh}/c_S)	12	400
Alfvén Mach number (v_{sh}/v_A)	400	400

Fiuza et al., Nat. Phys (2020)

Conclusions

- HEDP facilities can create macroscopic quantities of matter at astrophysical conditions
- Dynamical laboratory experiments:
  a) benchmarking hydrodynamics (compressible), radiation-hydrodynamics, magneto-hydrodynamics codes under scalable conditions.
  b) laboratory experiments may prompt the emergence of new concepts

The "Grand Challenge": ability <u>to measure </u>all required parameters (n, T, V_{flow}, B, etc.), instead of inferring them from computer models