High-Energy-Density Physics Experiments: Creating astrophysically relevant conditions in the laboratory

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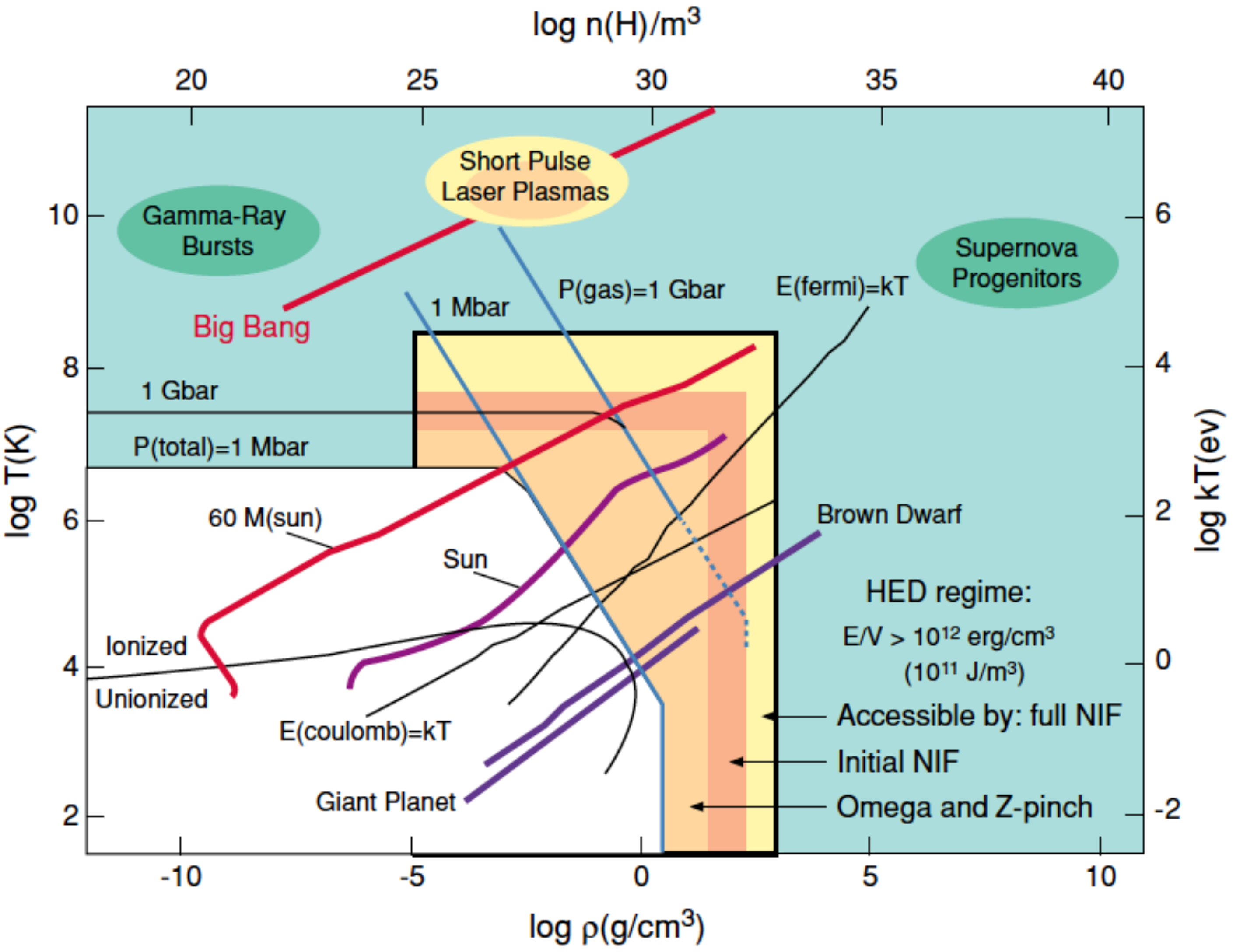
Summary

- What is the high-energy-density physics (HED) regime?
- Relevant astrophysical systems
- High-energy-density magnetized plasmas and important dimensionless numbers
- Scaling a lab experiment to an astrophysical phenomenon

What is High-Energy-Density Physics (HEDP)?

Systems with a pressure of over 1 million atmospheres (10^6 atm = 1 Mbar = 0.1 TPa)

- Materials become ionized under pressure
- Materials are generally dense plasmas
- Causes temperatures of 100 million Kelvin



From *Frontiers in High Energy Density Physics: The X-games of Contemporary Science*

Where do we create HEDP conditions?

Lasers

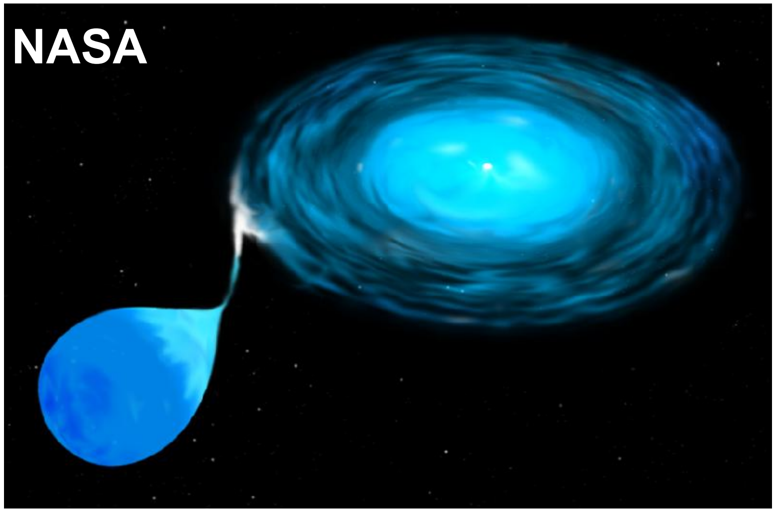
- Omega (University of Rochester)
- ORION (UK)
- Hercules (University of Michigan)
- NIF (Lawrence Livermore National Lab)
- Gekko (Japan)
- SGII (China)

Pulse power (Z-pinches)

- Z machine (Sandia National Lab)
- Maize (Michigan)
- MAGPIE (Imperial College)
- COBRA (Cornell)

HED experiments can uniquely address dynamics that matter for astrophysics

- High Mach number
- Low viscosity
- Dynamically important magnetic pressure
- Magnetic fields are advected with the flow
- **The dynamic systems can be scaled in terms of the physically important dimensionless parameters**



Key Dimensionless Parameters: Plasma β

Ratio of ram pressure to magnetic pressure

$$\beta \sim \frac{\rho U^2}{B^2}$$

U - velocity scale (m/s)

ρ − mass density (kg/m^3)

B − magnetic field strength (gauss)

Many astrophysical systems have β ~ 1

Key Dimensionless Parameters:
Reynolds number

Ratio of inertial forces to viscous forces

$$\mathrm{Re} = \frac{UL}{\nu}$$

U - velocity scale (m/s)
L - length scale (m)
ν - kinematic viscosity (m^2/s)

What happens at high *Re*?

- Systems can become turbulent
- Turbulent systems have fluctuations on a wide range scales
- Energy is transferred from large scale vortices l_0 to the viscous dissipation scale $\boldsymbol{l_v \sim Re^{-3/4*} l_0}$

Re	10^3	10^5
l_0	1 m	100 µm
l_v	5 mm	.01 um

Dimotakis P E 2000 The mixing transition in turbulent flows J. Fluid Mech. 409 69

Key Dimensionless Parameters: Magnetic Reynolds number

Ratio of inertial forces to magnetic diffusivity

$$\mathrm{Re}_m = \frac{UL}{\eta}$$

U - velocity scale (m/s)
L - length scale (m)
η - magnetic diffusivity (m^2/s)

What happens at high Re_m?

- The magnetic field is advected with the fluid flow
- The field lines become “frozen in” to the plasma and are carried with the flow
- Dissipation scale for magnetic fields $l_\eta \sim Re_m^{-1/2} Re^{-1/4} l_0$

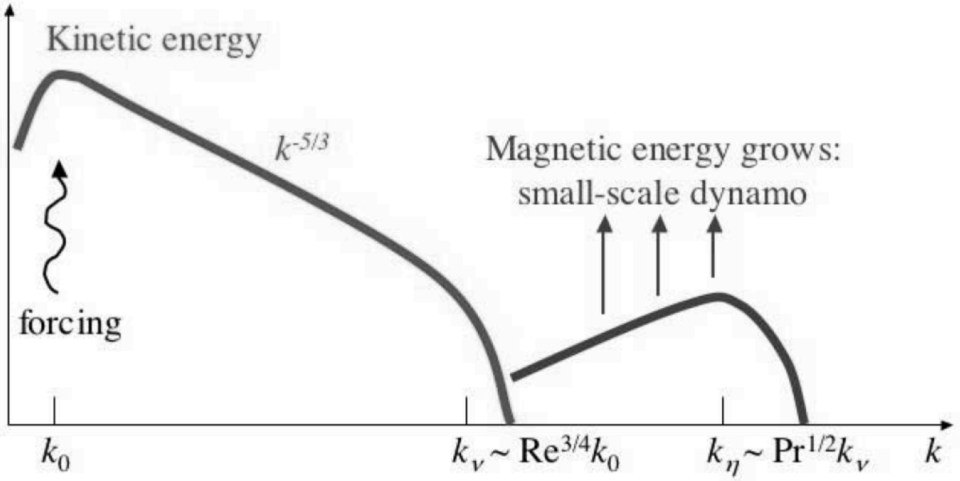


FIG. 1.—Sketch of scale ranges and energy spectra in a large-Pr_m medium.

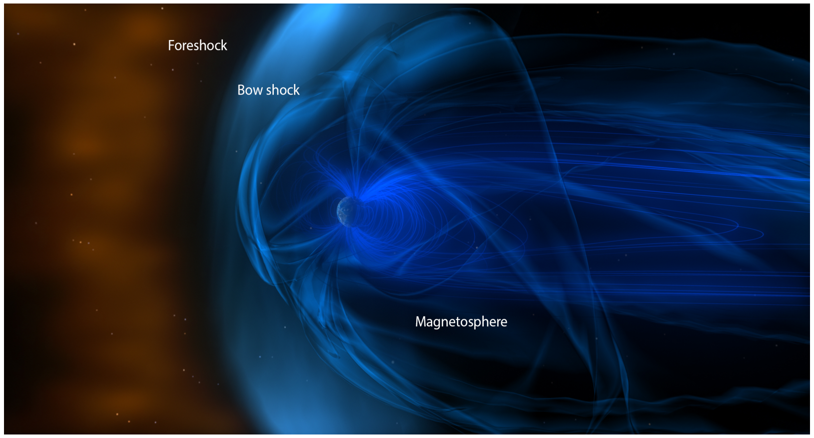
A. A. Schekochihin, Astrophysical Journal, 2004

High *Re* and Re_m flows are complex

- There exists an interplay of the velocity and magnetic field vectors and the dissipative parameters, viscosity, and resistivity
- Sufficient theory does not exist in this regime
- Computational simulations require significant resources and all scales cannot be resolved and are limited in *Re* and Re_m due to numerical diffusivity
- Experiments can help advance the understand of these systems

Where can high *Re* and *Re$_m$* flows be found in nature?

Stars and during star formation, galaxies and galactic evolution, accretion disks, planet formation, magnetosphere and more



Structure of the Earth's magnetosphere

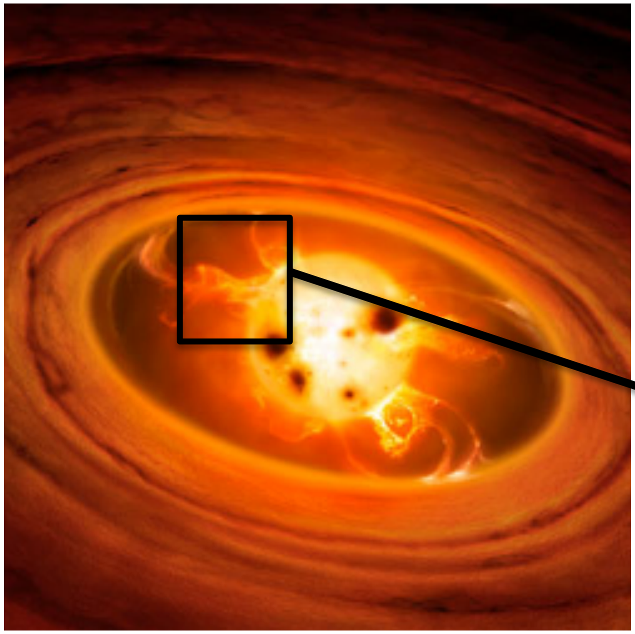
Examples of *Re* and *Re_m* for some astrophysical systems

	Re	Re_m
Intergalactic medium	10^{13}	10^{27}
Magnetized jets	10^{14}	10^{19}
Galaxy cluster	10^{25}	10^{25}
Solar dynamo	10^{11}	10^{8}
Accretion disks	10^{9}	10^{8}

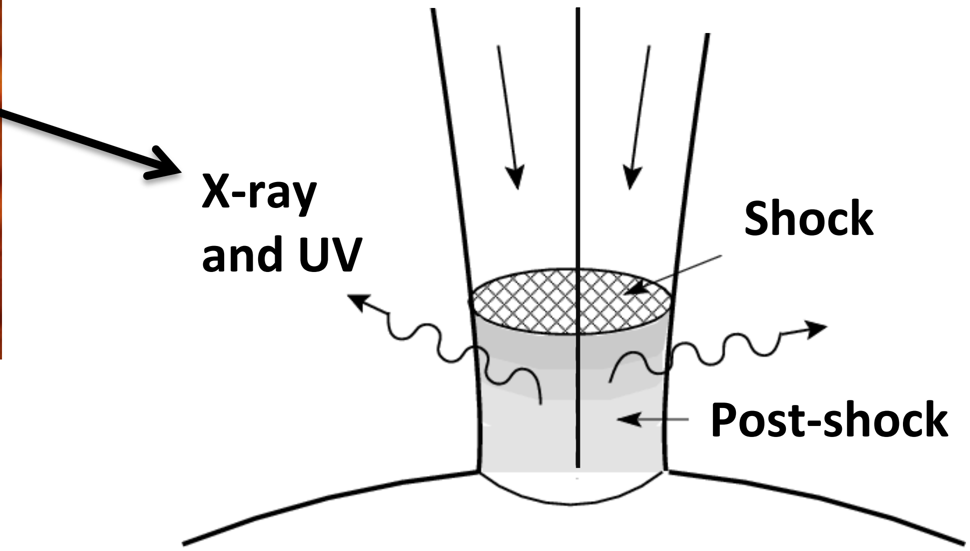
What is the scale, structure, and evolution of these systems and how is it affected by the magnetic field?

Well-scaled lab experiments can help answer these questions.

Accreting material funnels along magnetic field lines and forms a shock at the T Tauri star's surface



Figures by Mark Garlick and adapted from Suleimanov et al. (2008)



Pre-shock material falling to surface

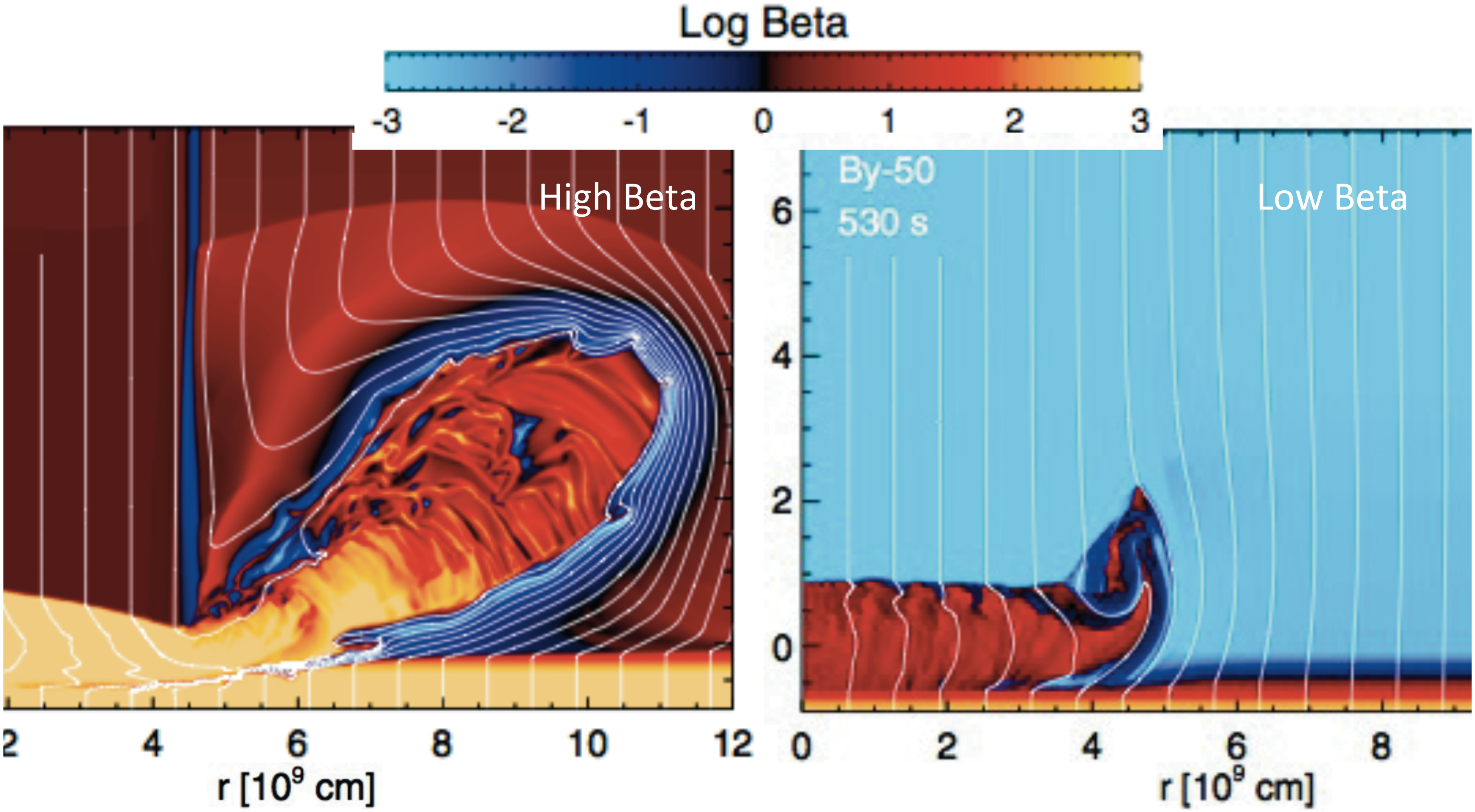
X-ray and UV

Shock

Post-shock

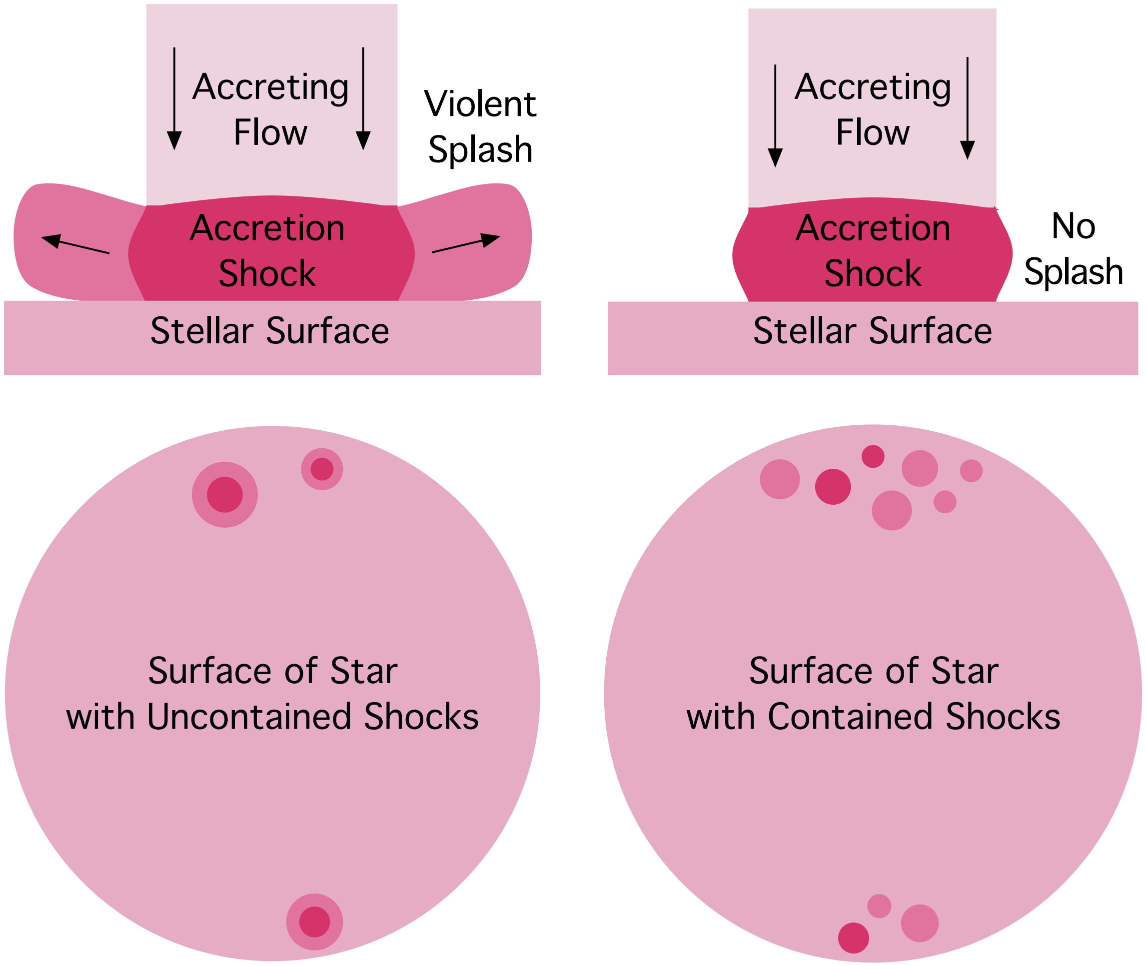
Surface of T Tauri star

How does a magnetic field affect the structure of the accretion shock and accreting stream of a T Tauri star?



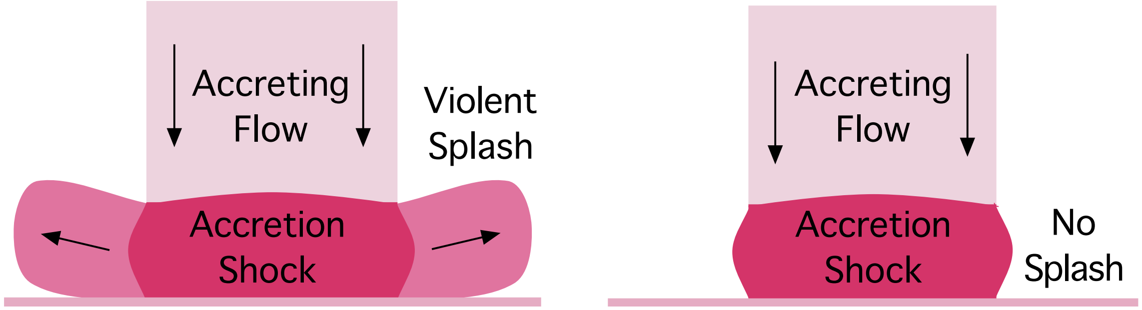
Orlando et al., Astronomy and Astrophysics, 2010

Understanding accretion shock structure is necessary to determine mass accretion rates



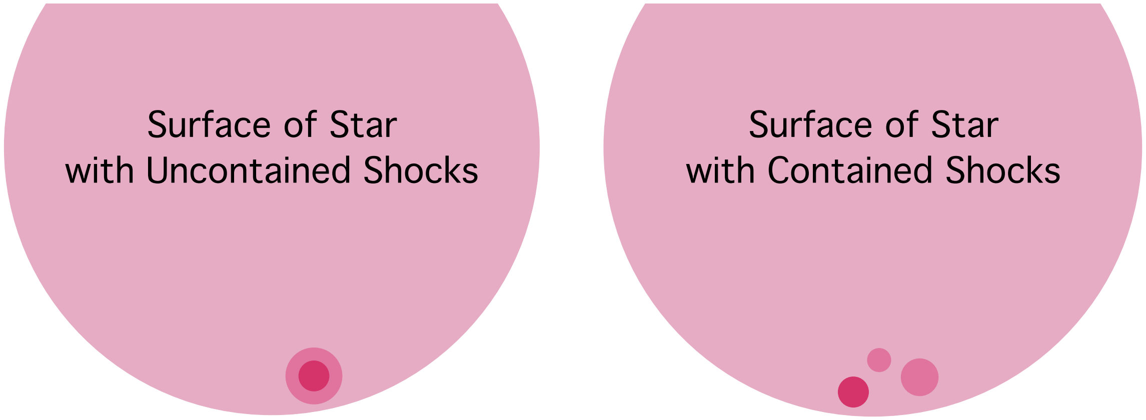
Observationally, these look the same

Understanding accretion shock structure is necessary to determine mass accretion rates

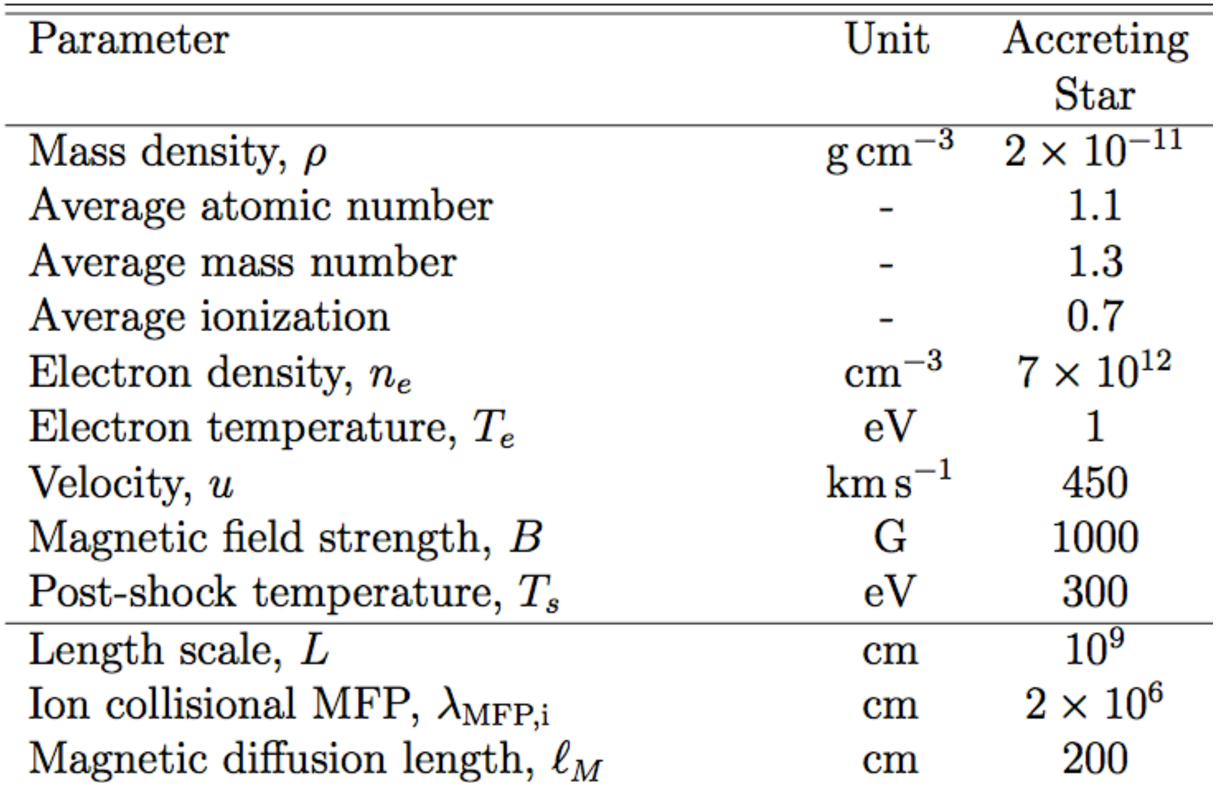


Observationally, these look the same

How can we use laboratory experiments to explore this phenomenon?

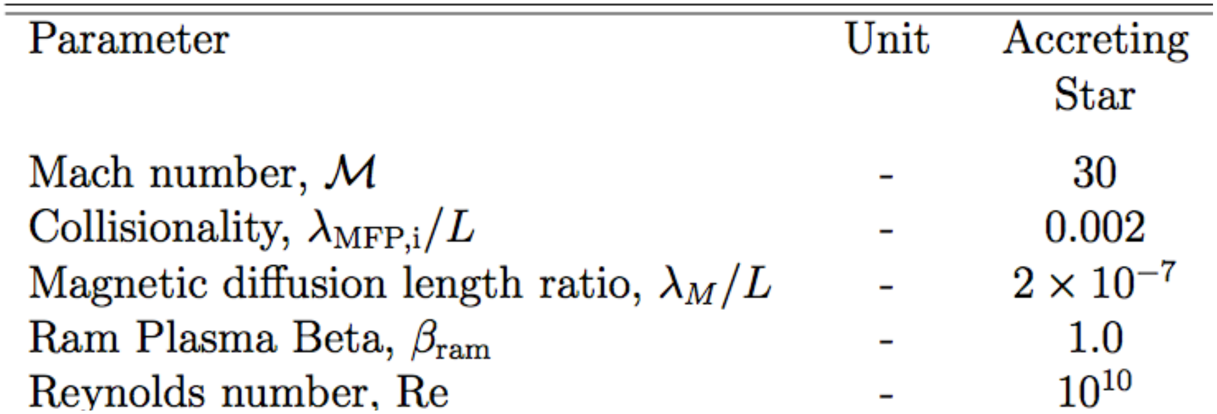


Parameters for accreting star from astrophysical observations and theory



Parameter	Unit	Accreting Star
Mass density, ρ	$\mathrm{g\,cm^{-3}}$	2×10^{-11}
Average atomic number	-	1.1
Average mass number	-	1.3
Average ionization	-	0.7
Electron density, n_e	$\mathrm{cm^{-3}}$	7×10^{12}
Electron temperature, T_e	eV	1
Velocity, u	$\mathrm{km\,s^{-1}}$	450
Magnetic field strength, B	G	1000
Post-shock temperature, T_s	eV	300
Length scale, L	cm	10^9
Ion collisional MFP, $\lambda_{\mathrm{MFP,i}}$	cm	2×10^6
Magnetic diffusion length, ℓ_M	cm	200

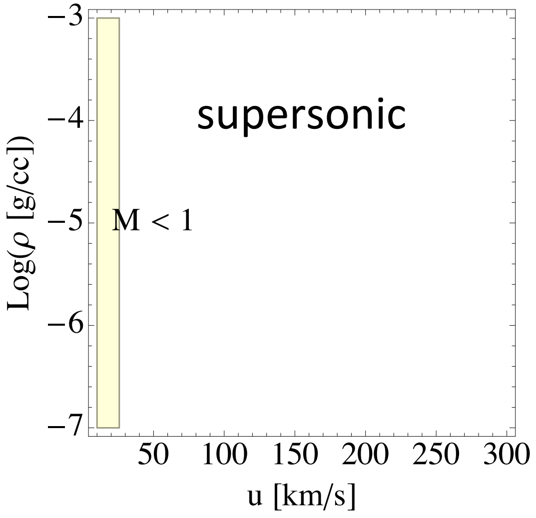
Dimensionless numbers connect the accreting star and the experiment

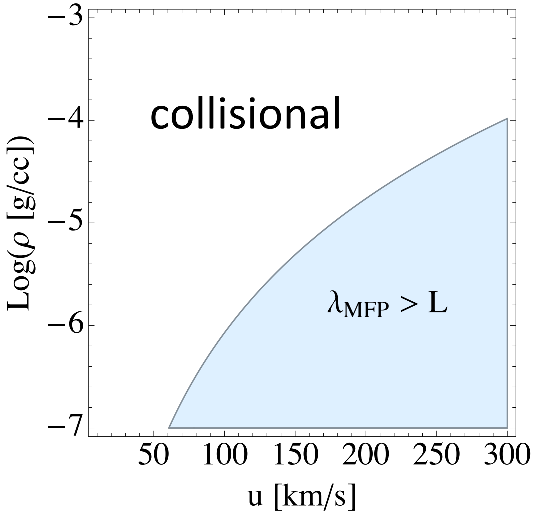


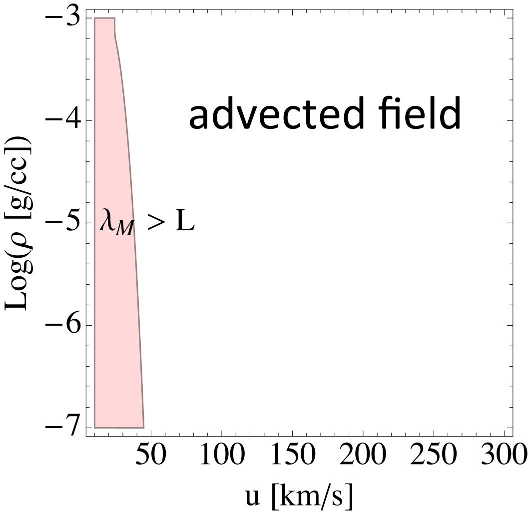
Parameter	Unit	Accreting Star
Mach number, $\mathcal{M}$	-	30
Collisionality, $\lambda_{\mathrm{MFP,i}}/L$	-	0.002
Magnetic diffusion length ratio, λ_M/L	-	2×10^{-7}
Ram Plasma Beta, β_{ram}	-	1.0
Reynolds number, Re	-	10^{10}

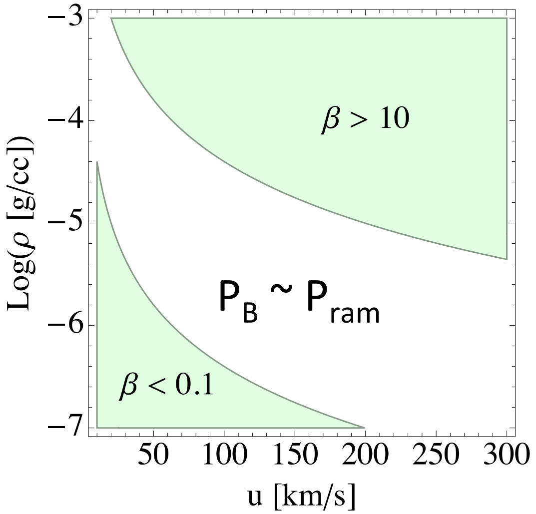
To create a similar system in the lab require a supersonic, collisional (shock forms) system, with an advected magnetic field, where the magnetic pressure is equal to the ram pressure and there is low viscosity

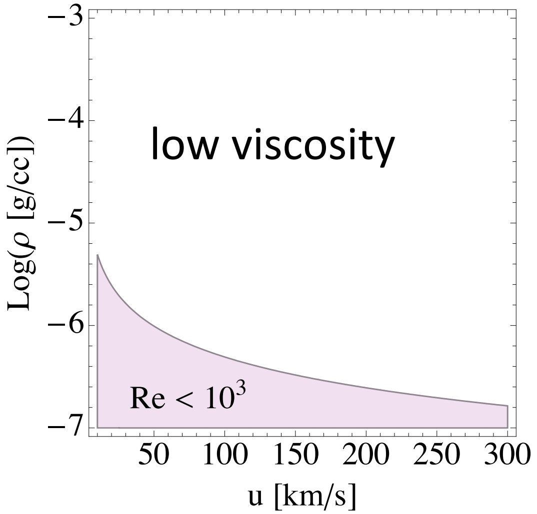
We can define a experimental space where these requirements are met









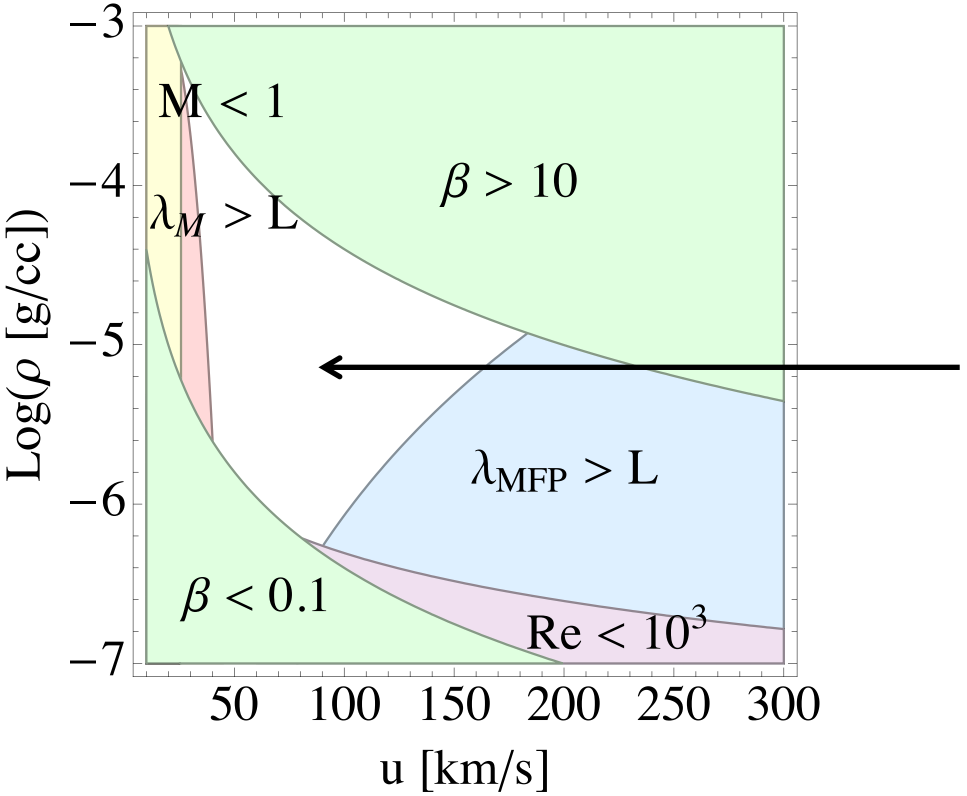


Constraints:

- $M > 1$
- $\lambda_{MFP} < L$
- $\lambda_{mag} < L$
- $0.1 < \beta_{ram} < 10$
- $Re > 1000$

Young, Kuranz, Drake, Hartigan, *High Energy Density Physics,* 2017

These constraints define the plasma and field requirements for a well-scaled experiment



$\rho = 10^{-5}$ g/cm^3

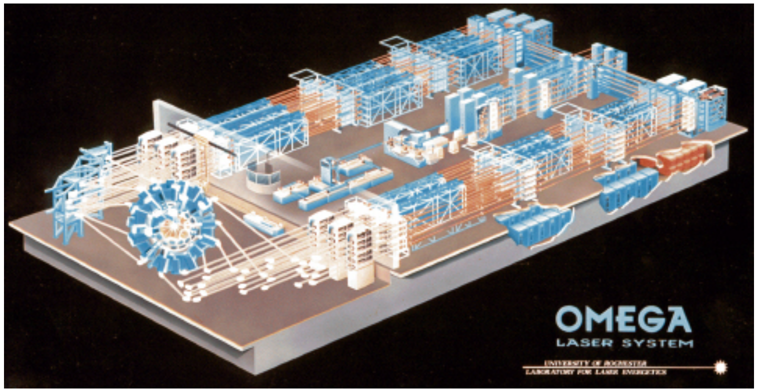
$u = 100$ km/s

$T_e = 10$ eV

$B = 10$ T

Young, Kuranz, Drake, Hartigan, *High Energy Density Physics,* 2017

We can create these conditions at the Omega laser with a seeded magnetic field

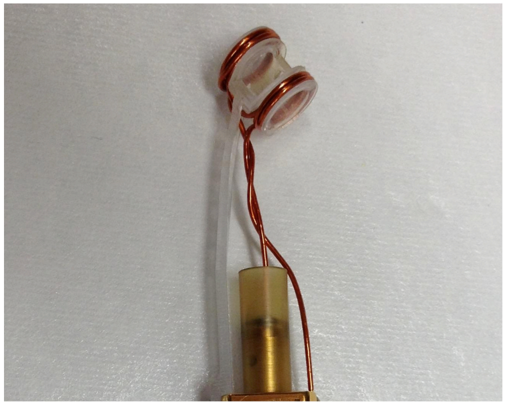


60 laser beams

UV light

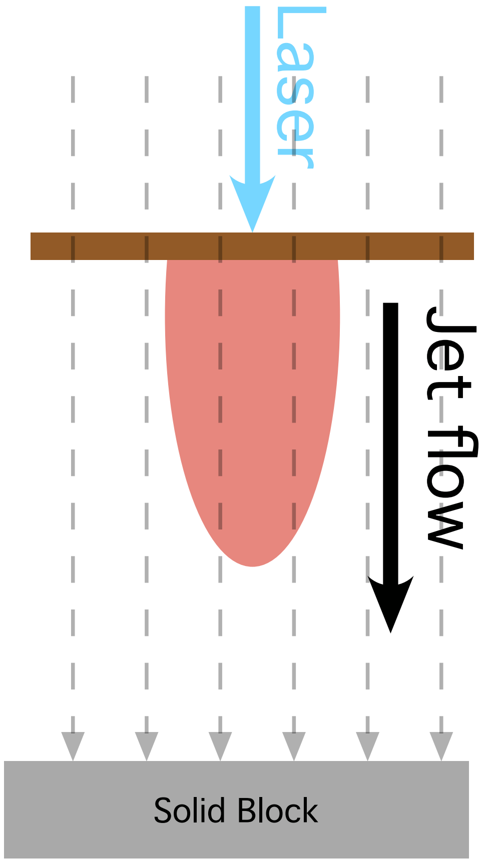
30 kJ of energy

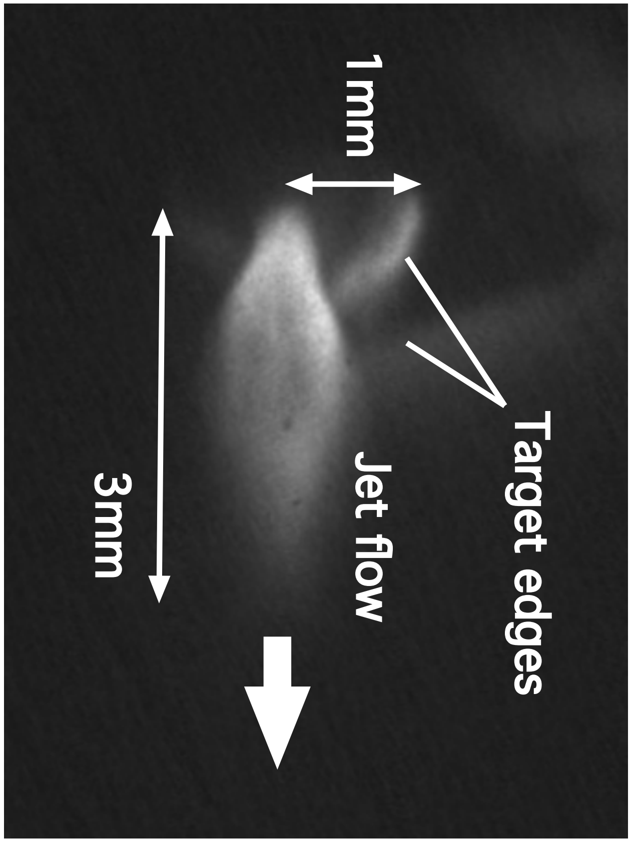
Omega target chamber



MIFEDs coil provide magnetic field strength and configuration

We irradiated the rear surface of a CH target with 3.5 kJ of UV laser energy in a 1 ns pulse





Optical image of jet

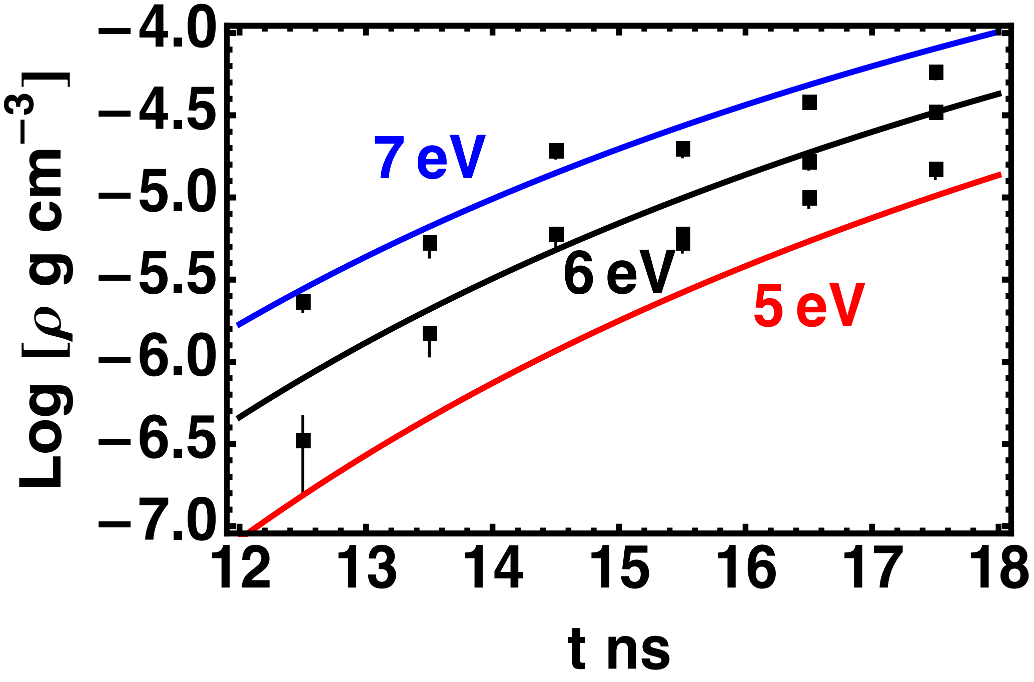
Not to scale

We used UV Thomson scattering to characterize the plasma

V = 100 to 300 km/s

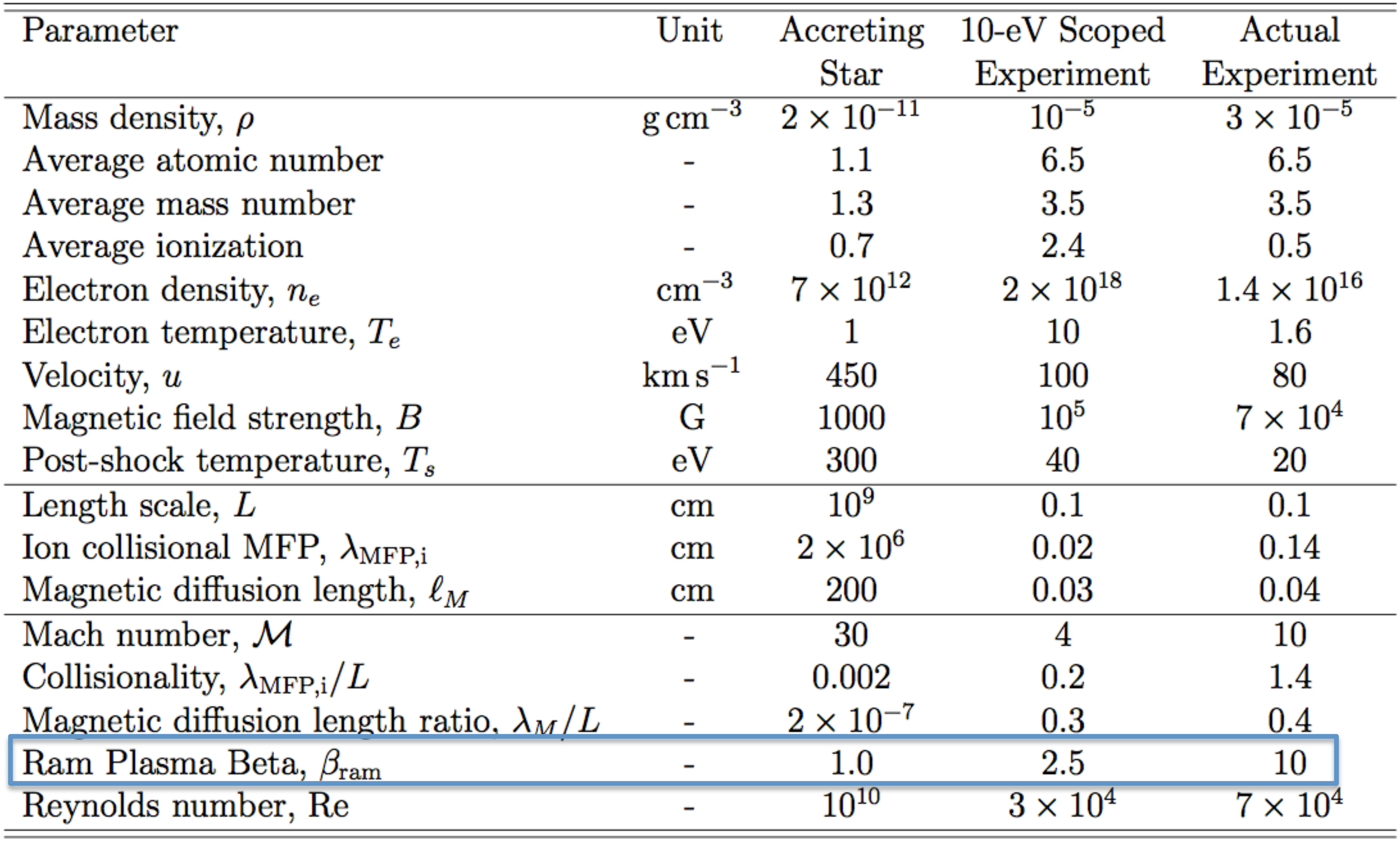
$\rho = 10^{-6.5}$ to 10^{-4} g cm^{-3}

T_e = ~6 eV



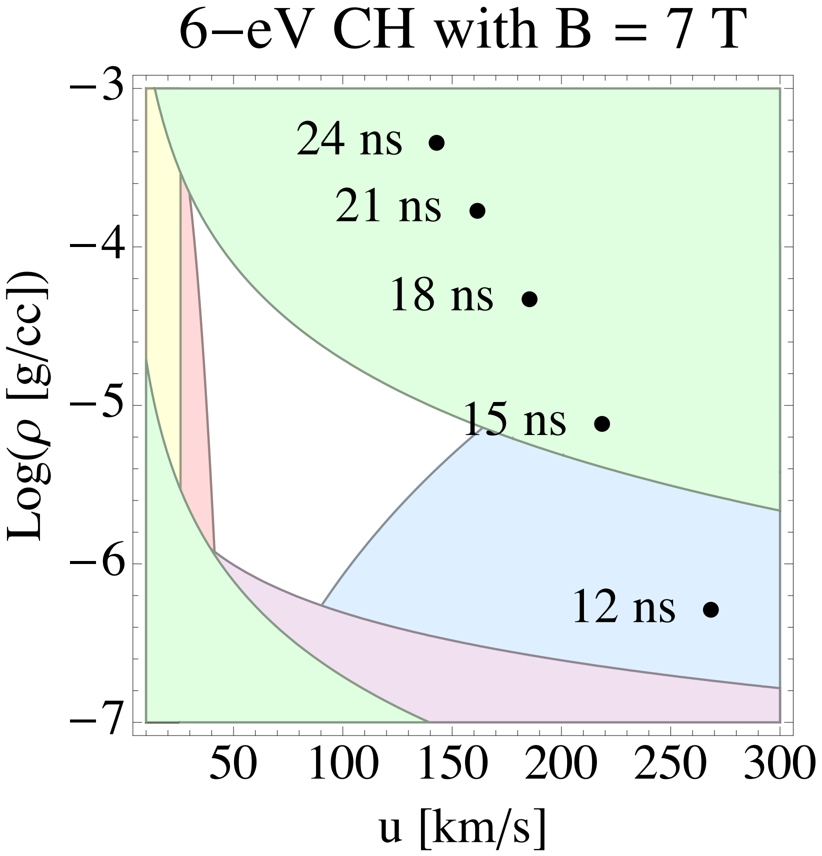
Analysis by Dr. Rachel Young

Compared to the optimal experiment, the actual experiment has a higher β_{ram}



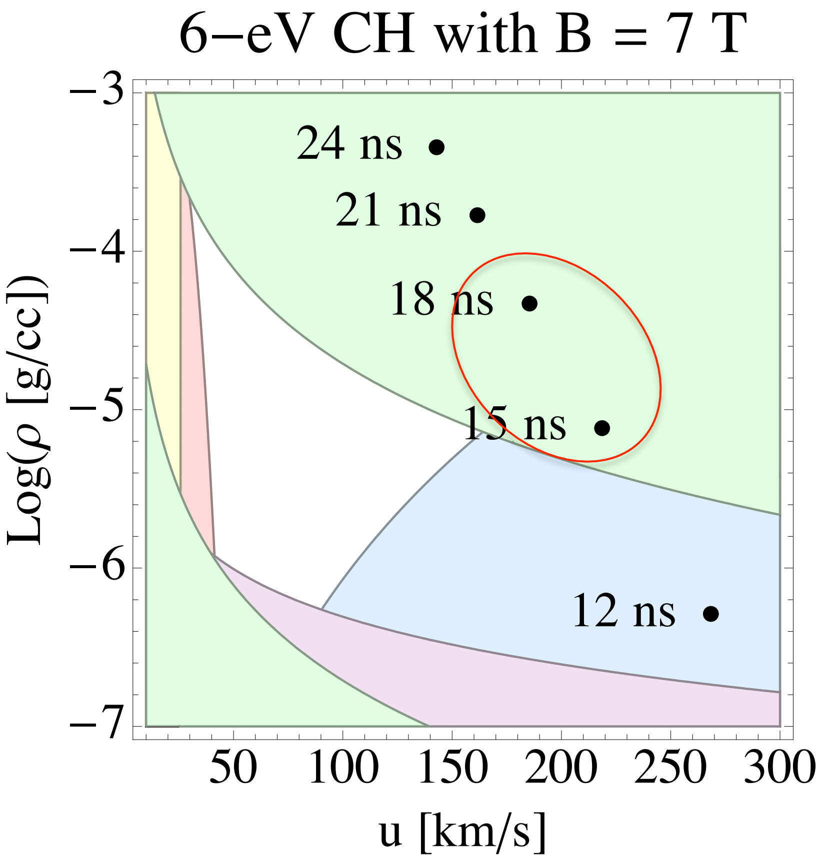
Parameter	Unit	Accreting Star	10-eV Scoped Experiment	Actual Experiment
Mass density, ρ	$\mathrm{g\,cm^{-3}}$	2×10^{-11}	10^{-5}	3×10^{-5}
Average atomic number	-	1.1	6.5	6.5
Average mass number	-	1.3	3.5	3.5
Average ionization	-	0.7	2.4	0.5
Electron density, n_e	$\mathrm{cm^{-3}}$	7×10^{12}	2×10^{18}	1.4×10^{16}
Electron temperature, T_e	eV	1	10	1.6
Velocity, u	$\mathrm{km\,s^{-1}}$	450	100	80
Magnetic field strength, B	G	1000	10^5	7×10^4
Post-shock temperature, T_s	eV	300	40	20
Length scale, L	cm	10^9	0.1	0.1
Ion collisional MFP, $\lambda_{\mathrm{MFP,i}}$	cm	2×10^6	0.02	0.14
Magnetic diffusion length, ℓ_M	cm	200	0.03	0.04
Mach number, $\mathcal{M}$	-	30	4	10
Collisionality, $\lambda_{\mathrm{MFP,i}}/L$	-	0.002	0.2	1.4
Magnetic diffusion length ratio, λ_M/L	-	2×10^{-7}	0.3	0.4
Ram Plasma Beta, β_{ram}	-	1.0	2.5	10
Reynolds number, Re	-	10^{10}	3×10^4	7×10^4

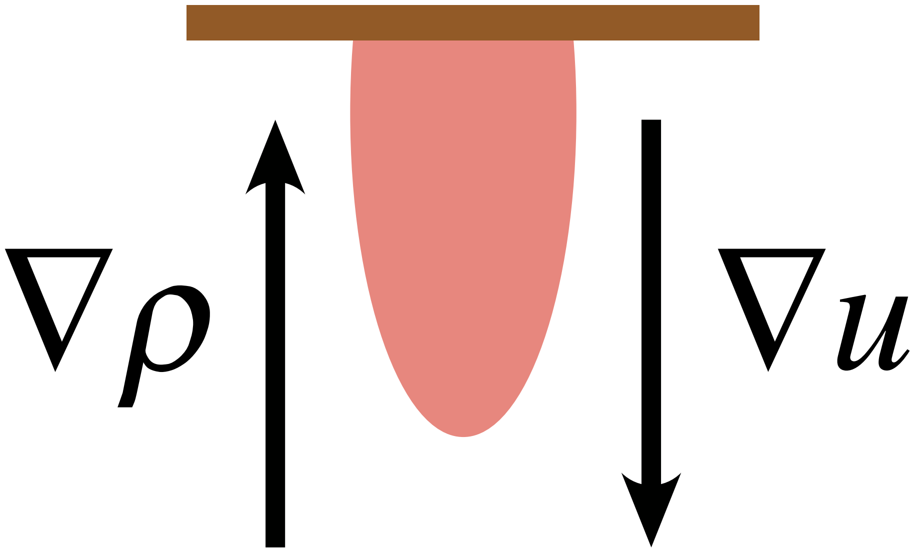
We are just nearly out of the desired parameter space



Analysis by Dr. Rachel Young

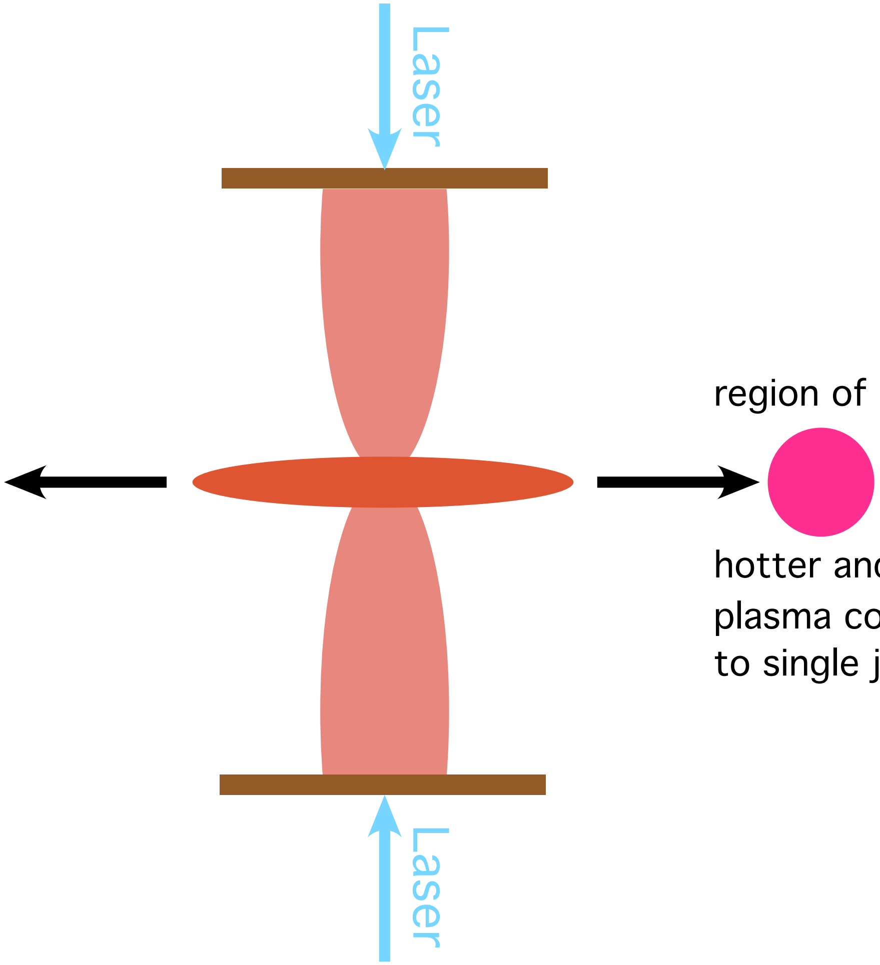
Large density and velocity indicate that the experiment could be scaled for a very short time





Analysis by Dr. Rachel Young

We need a slower, less dense, steadier flow

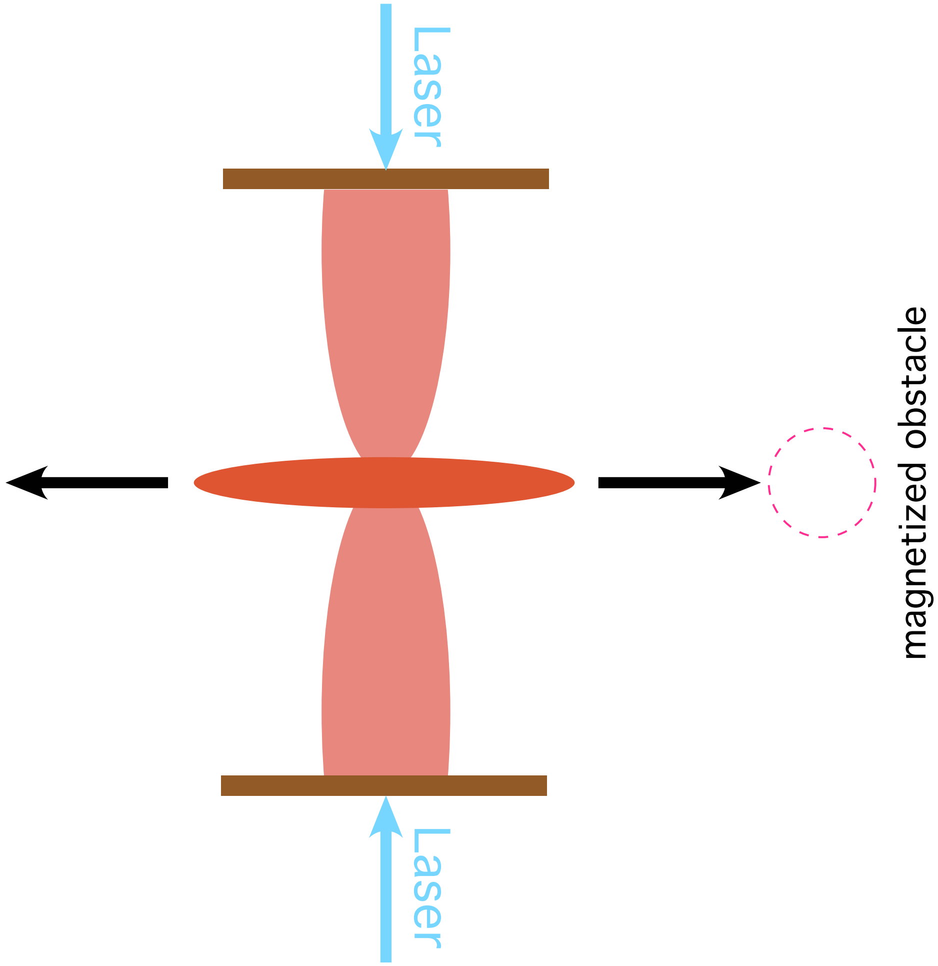


region of interest

hotter and slower
plasma compared
to single jets

Not to scale

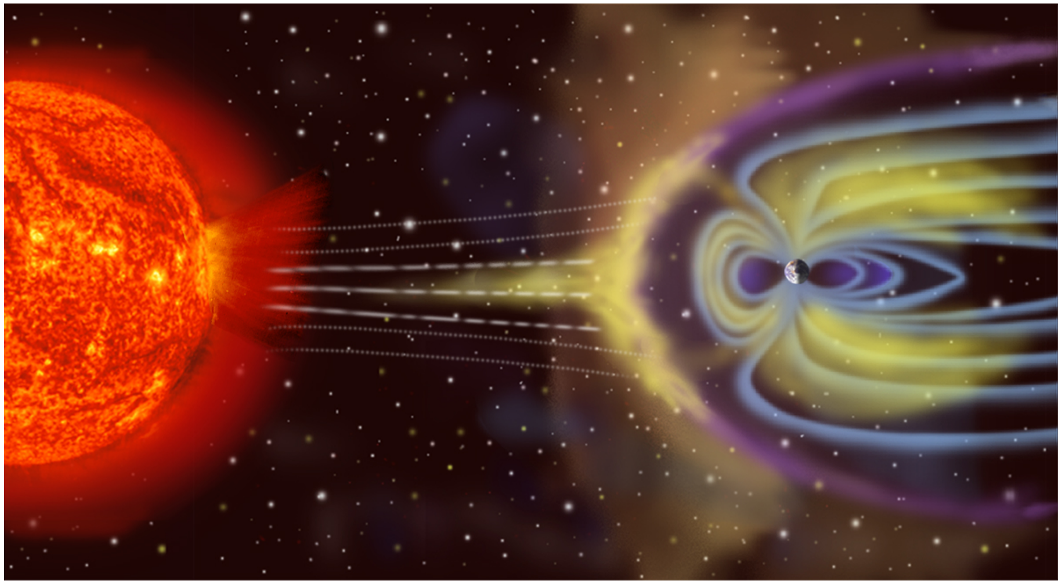
We need a slower, less dense, steadier flow



This setup is more relevant to bow shocks in the magnetosphere, which is in a similar regime, and a simpler experiment

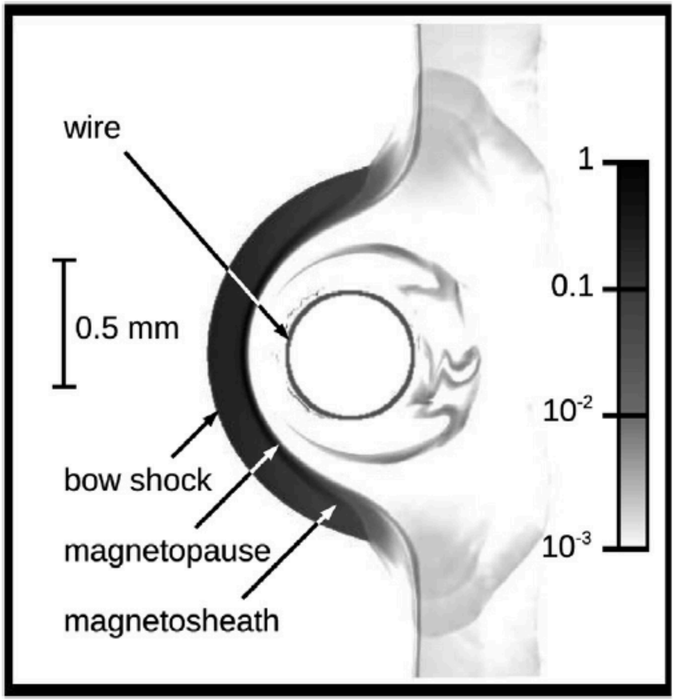
Not to scale

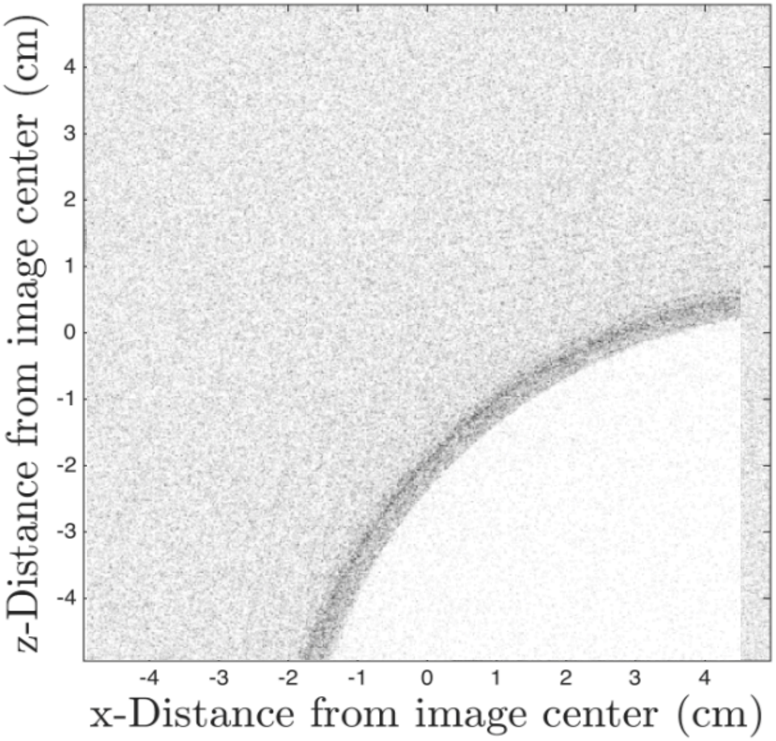
The Earth's bow shock forms when the P_{ram} of the solar wind equals the P_{mag} of the Earth's magnetic field



An artist's rendition of the solar wind interacting with a magnetosphere. From nasa.gov.

Simulations aided in experimental planning





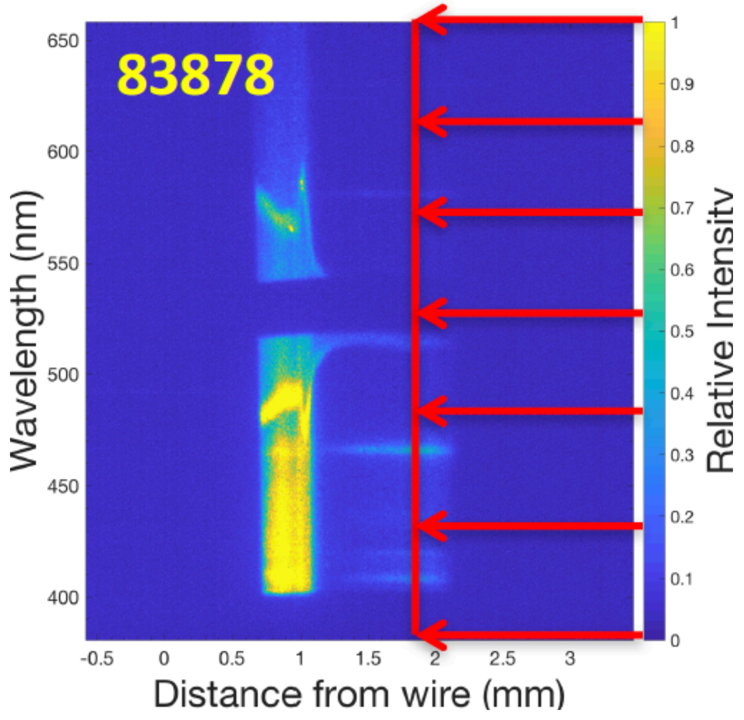
Simulated shock formation by Andy Liao (Rice)

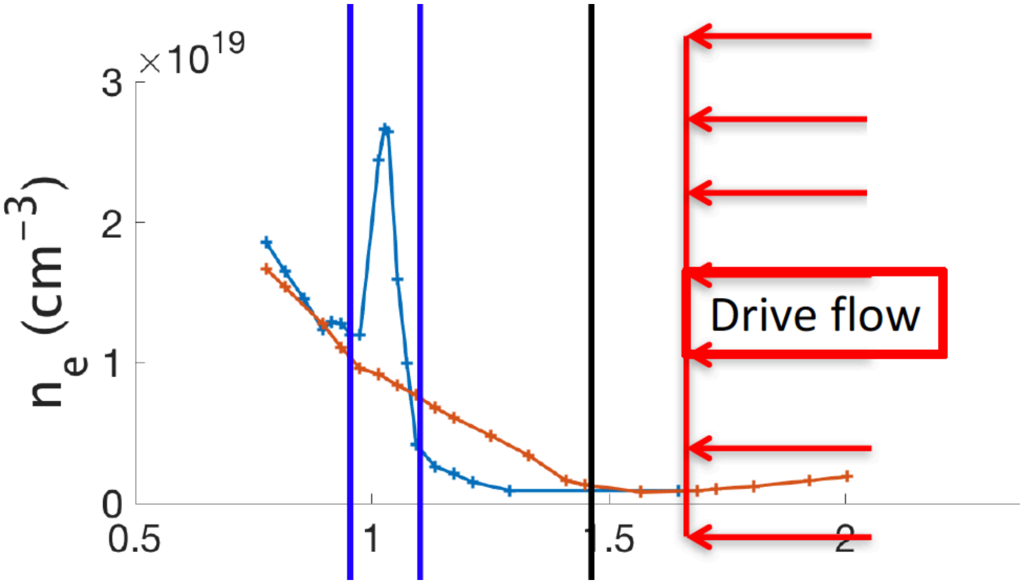
Simulated proton radiograph by Joseph Levesque

Liao et al, *High Energy Density Physics*

The new schematic creates a lower density, steady flow

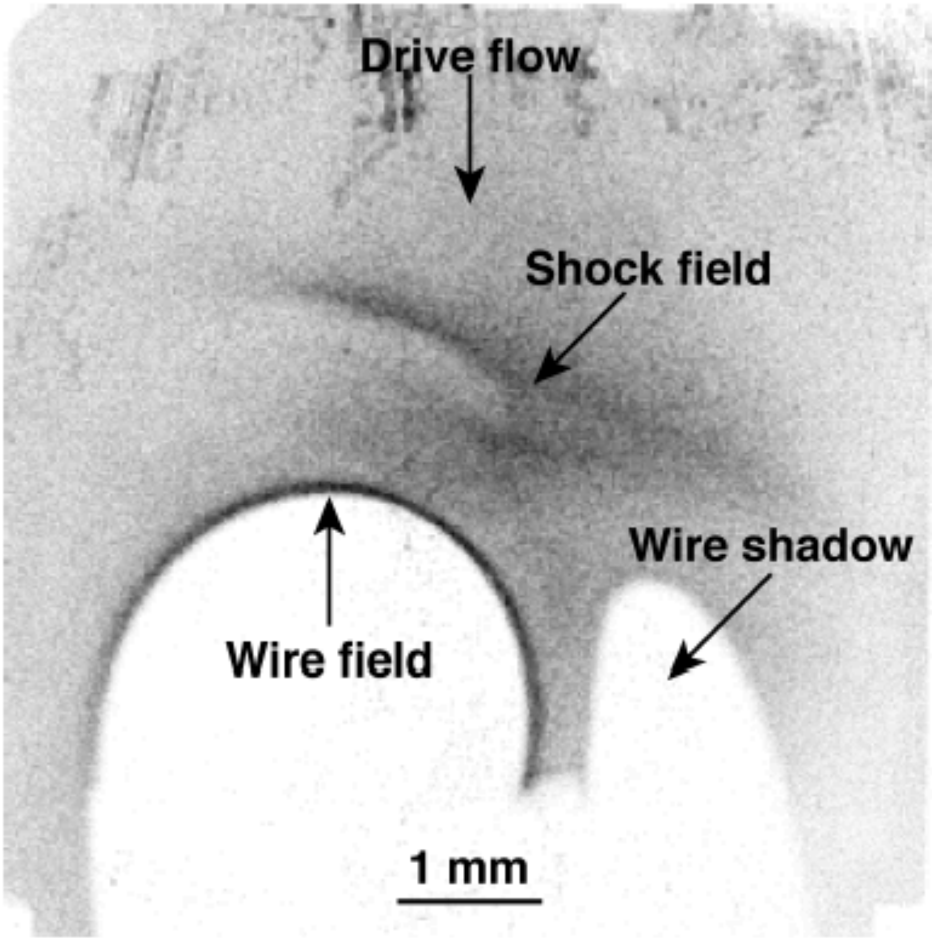
Spatially resolved Thomson scattering





Analysis by Joseph Levesque

Proton radiography images the shock formation



Proton radiography has aided in observing the shock location

Preliminary estimate of field compression is underway

Summary and Future Direction

- We study magnetized flows relevant to astrophysical systems
  - Accretion shocks
  - Magnetospheric dynamics
- Characterizing plasma is essential
- We recently developed a relatively steady, low pressure flow
- We are continuing to study shock formation in magnetized high-energy-density flows