# Astrophysical Plasmas in the Laboratory

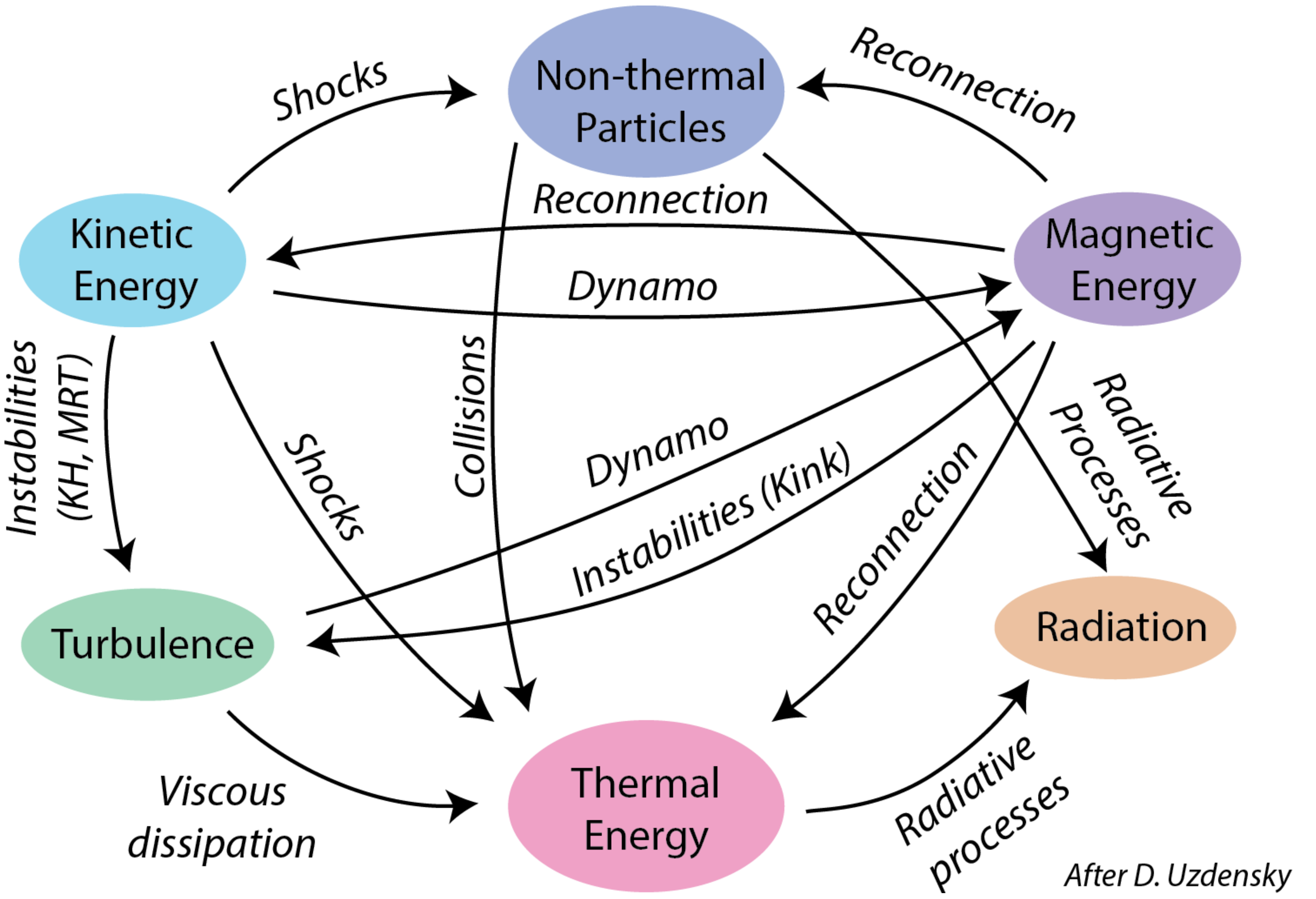
Jack D. Hare, *puffin.mit.edu*

# Introduction

- Undergrad at Cambridge University
- MA(!) in plasma physics at Princeton
- PhD at Imperial College London
- Postdocs at Imperial College and IPP Garching
- Assistant Professor at MIT since January 2021
- Member of APS DPP Pride (LGBTQ+) Committee [1]
- DPP Pride Mentoring Program coordinator [1]
- Outside of work: hiking, skiing, caving, boardgames

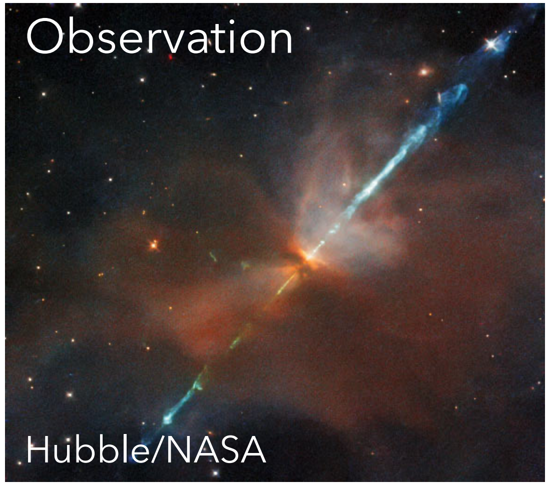
[1] https://engage.aps.org/dpp/programs/plasma-pride

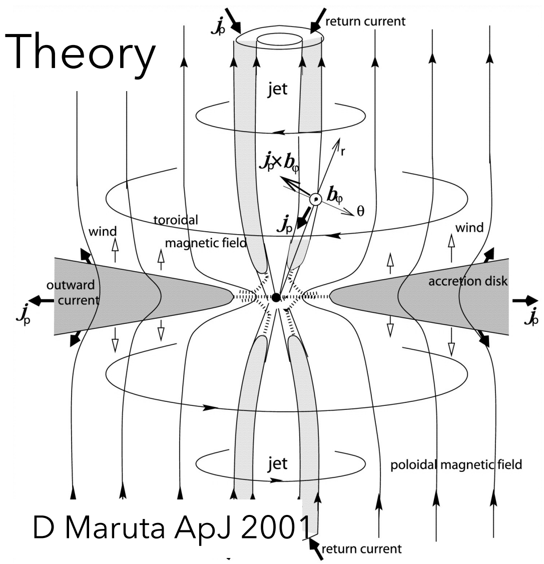
# Energy Flows in Plasma are Complex and Fascinating

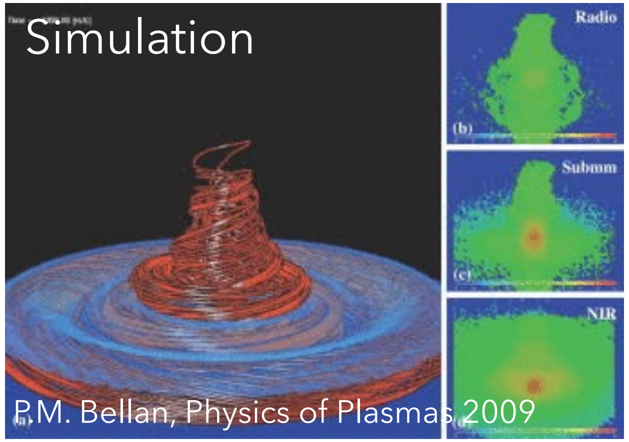


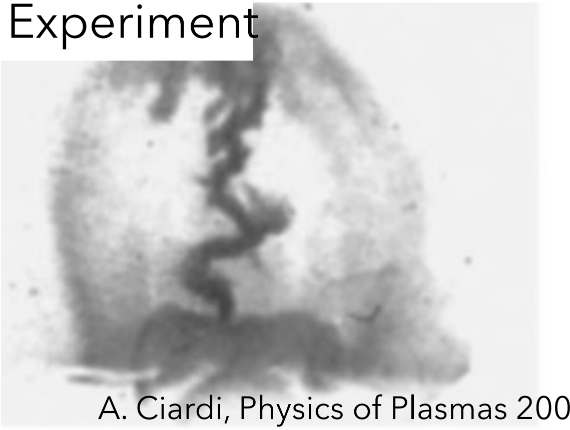
# Why Laboratory Astrophysics?

- Space is very (very) far away, hard to observe
- Astrophysical theories poorly constrained by observation
- Simulations only have the physics you put in – unknown unknowns
- Laboratory experiments are "easy" to diagnose, but less extreme




**Combine theory, observations, experiments and simulations!**

# Dimensionless scaling

*Wind tunnel experiments use dimensionless scaling*

- Rewrite governing equations in dimensionless form

$$\rho\left(\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v}\cdot\nabla\boldsymbol{v}\right) = -\nabla p\,,$$

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

$$\frac{\partial p}{\partial t} - \gamma\frac{p}{\rho}\frac{\partial \rho}{\partial t} + \boldsymbol{v}\cdot\nabla p - \gamma\frac{p}{\rho}\boldsymbol{v}\cdot\nabla\rho = 0\,,$$

$$\boldsymbol{r} = a\boldsymbol{r}_1\,;\quad \rho = b\rho_1\,;\quad p = cp_1\,;$$

$$t = a\sqrt{\frac{b}{c}}\,t_1\,;\quad \boldsymbol{v} = \sqrt{\frac{c}{b}}\,\boldsymbol{v}_1\,,$$

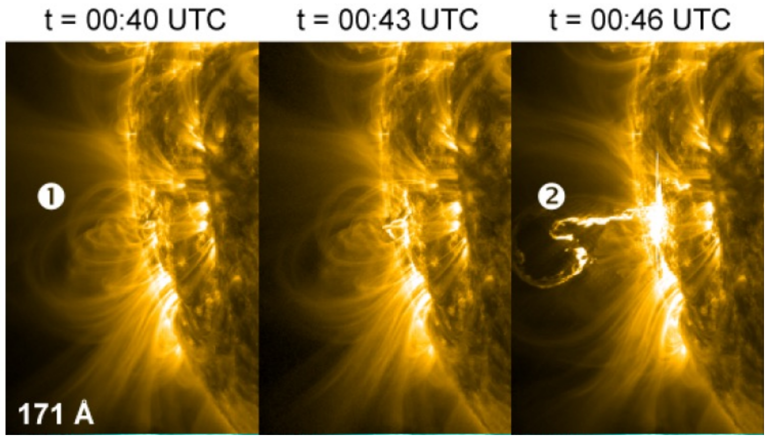
*3 eqns, 3 scaling variables*

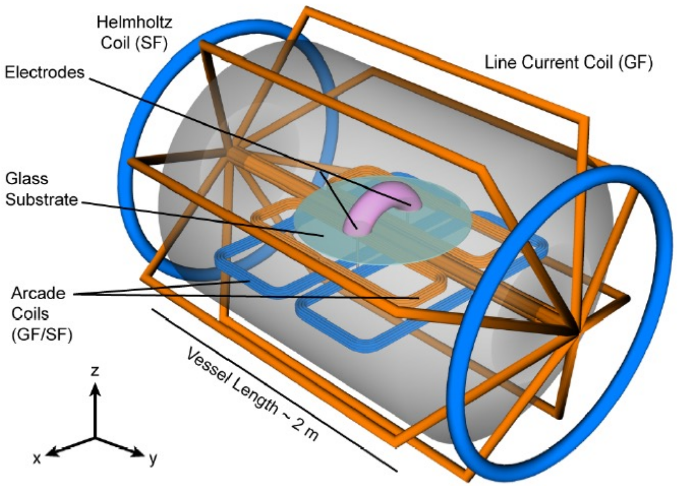
Ryutov et al (PoP 2001)

- Neglect viscosity, $Re = LV/\nu \gg 1$
- Two systems with matching dimensionless numbers and boundary conditions evolve similarly
- In practice, this is very, very hard:
  Resort to "weak" scaling where dimensionless parameters are either >>1 or <<1 in both systems

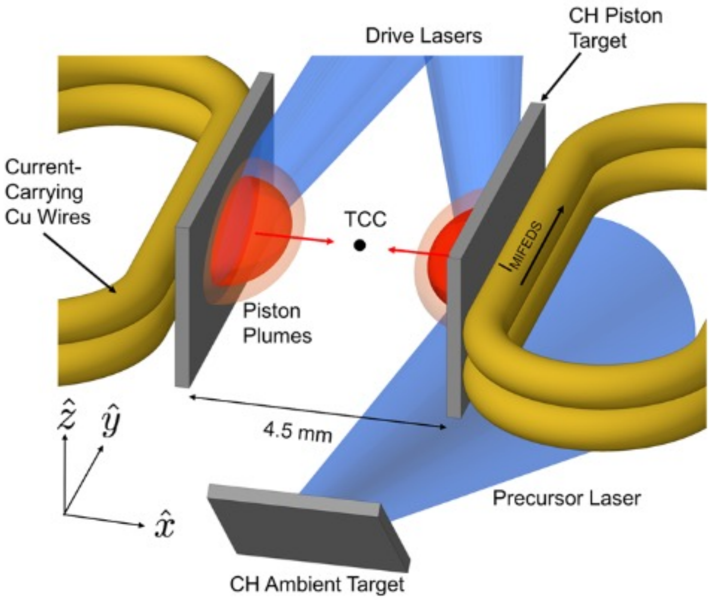
# Three laboratory astrophysics experiments

## Flux Rope Eruptions
*Myers, Nature (2015)*

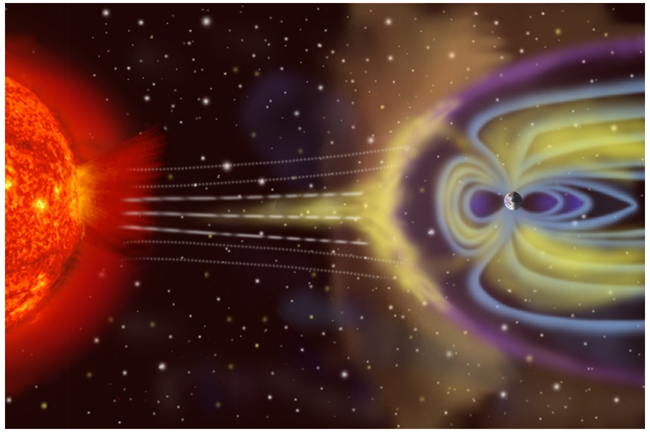


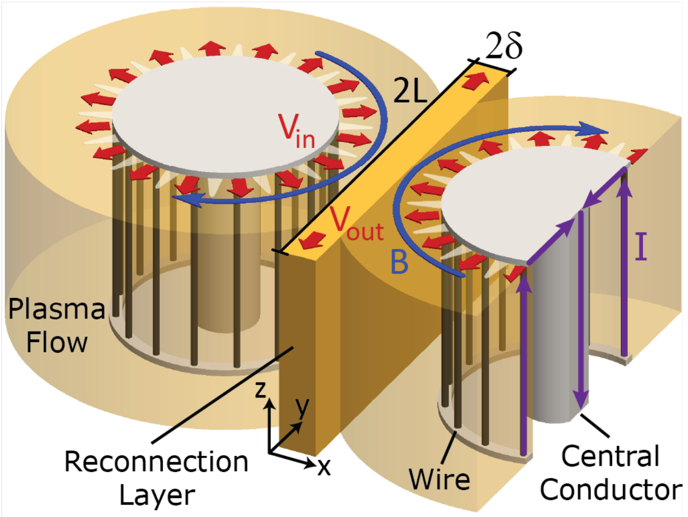




## Collisionless Shocks
*Schaeffer, PRL (2016)*

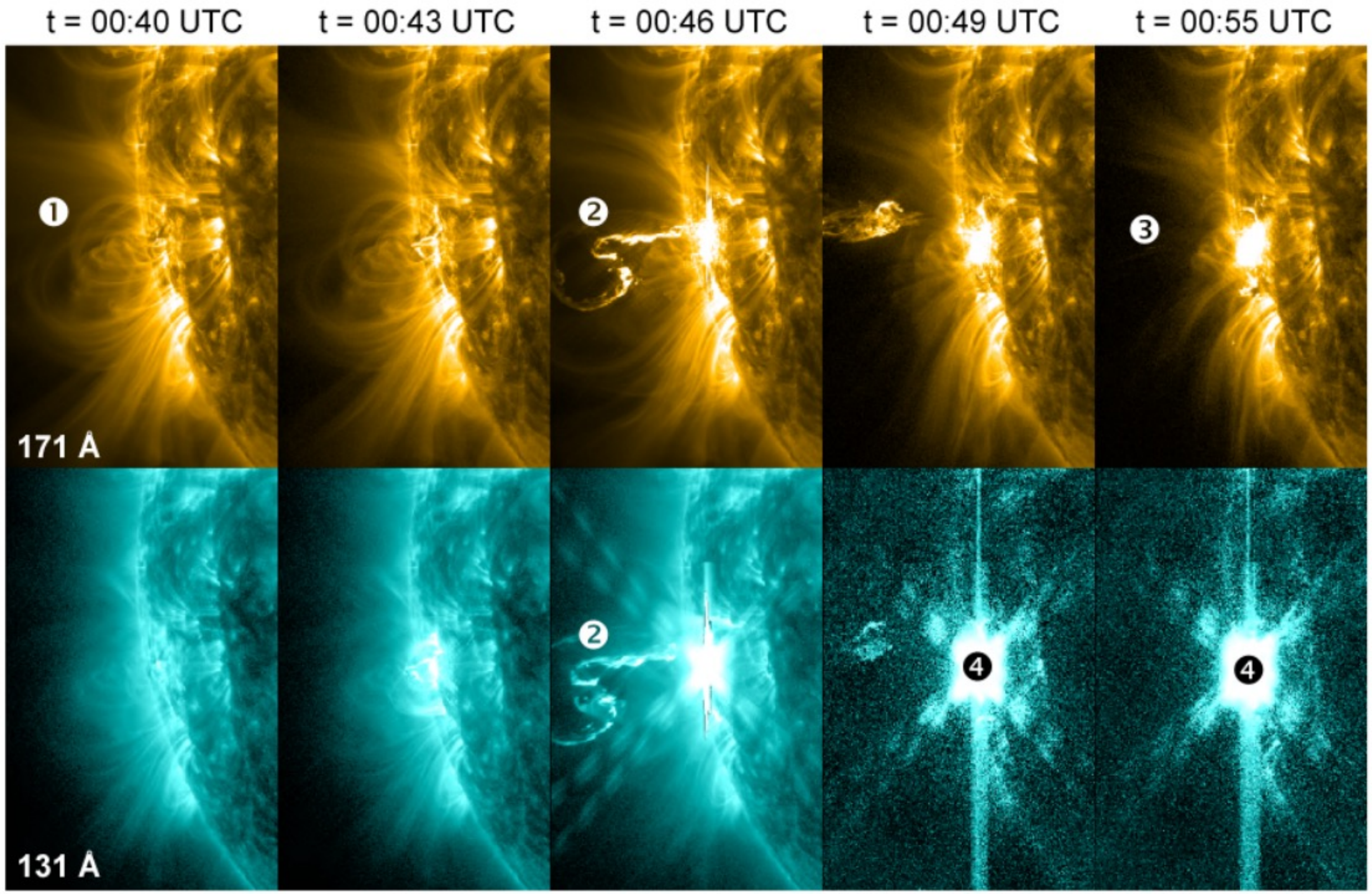



## Magnetic Reconnection
*Hare, PRL (2017)*





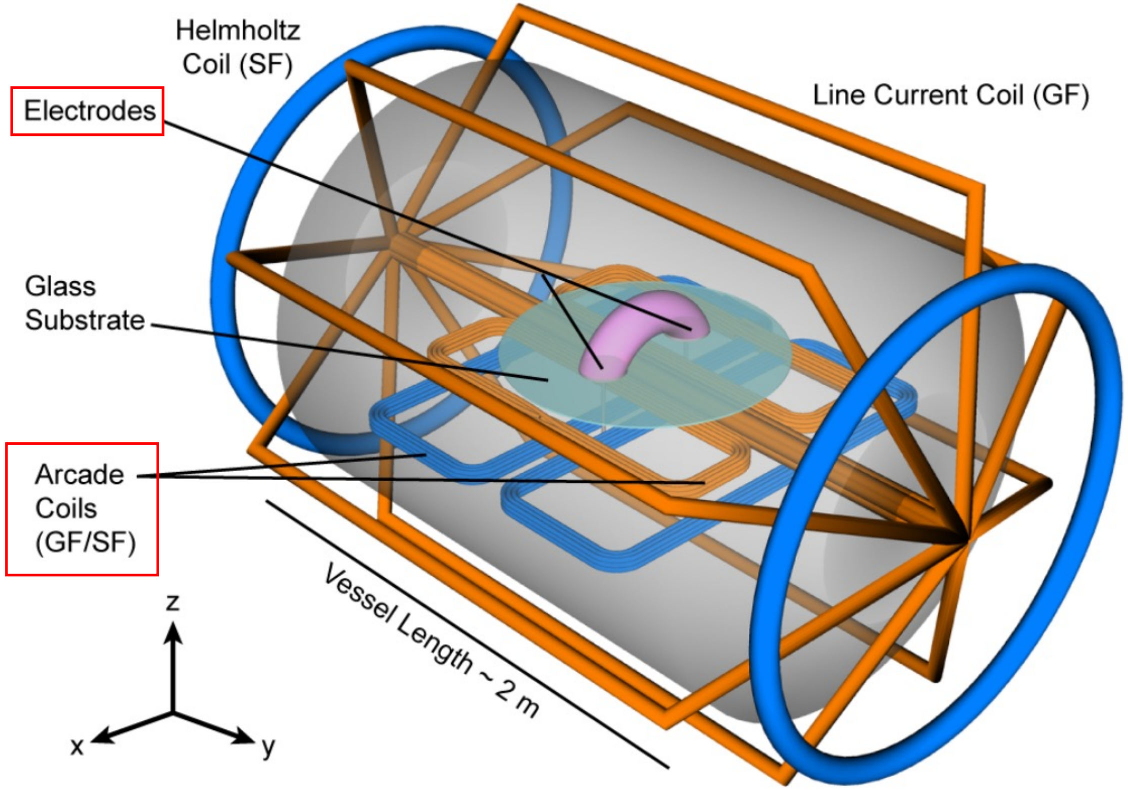
# Flux Rope Eruptions: astrophysical system




Astrophysical system:

- Satellites observe bright X-ray emission associated with coronal mass ejections
- Proposed mechanism is build up of magnetic energy and then sudden eruption through instability
- Problem: some theoretically unstable flux ropes appear stable

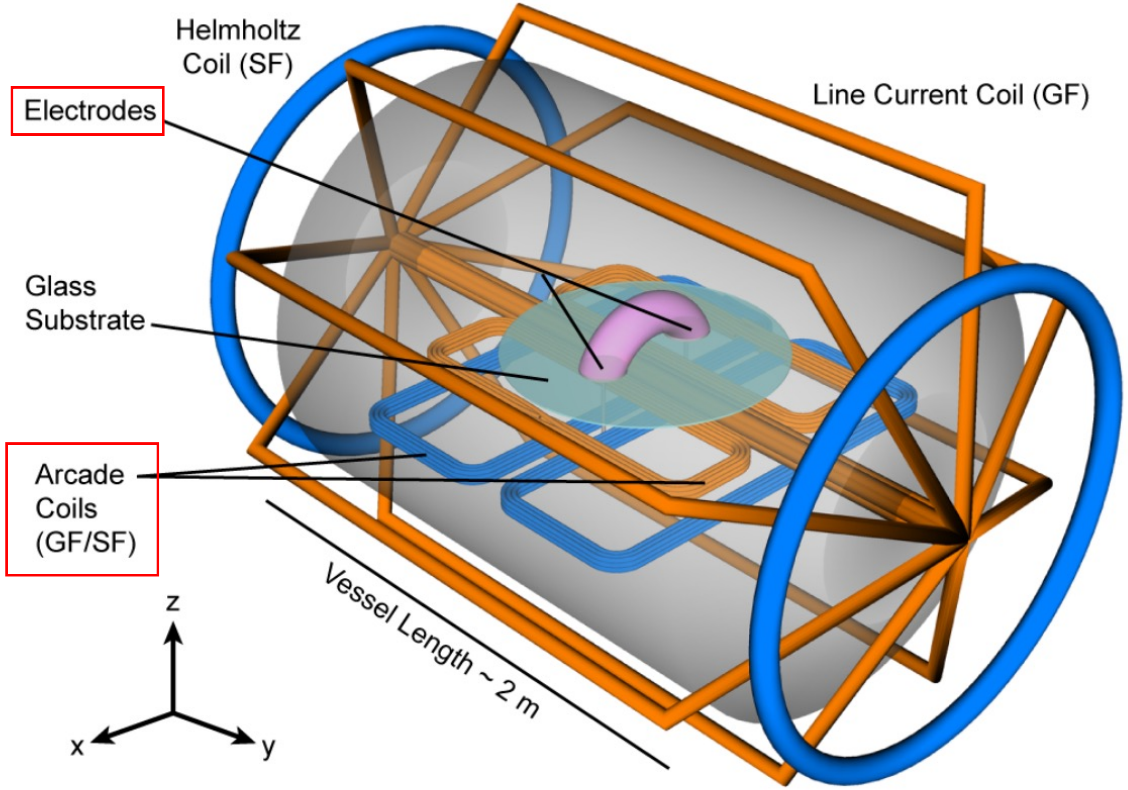
# Flux Rope Eruptions: experimental setup




Person for scale

*Myers, Nature (2015)*

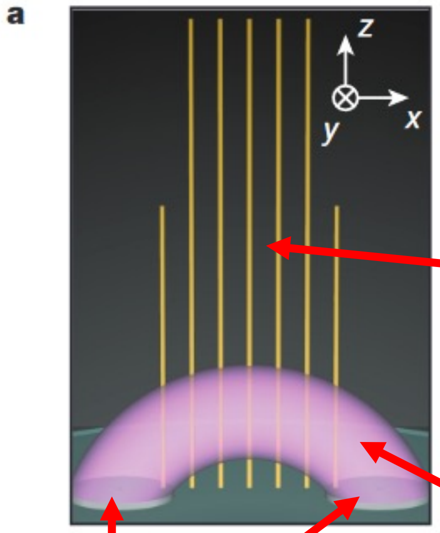
# Flux Rope Eruptions: experimental setup




- Used the vessel and coils from MRX (Magnetic Reconnection eXperiment, PPPL)
- Added new "arcade" coils and electrodes to produce flux rope
- Combination of magnetic field coils enables production of theoretical unstable and stable flux ropes
- Diagnostics: fast camera, magnetic probe array
- Both laboratory and solar plasma dynamics dominated by magnetic field

*Myers, Nature (2015)*

# Flux rope eruptions: experimental results



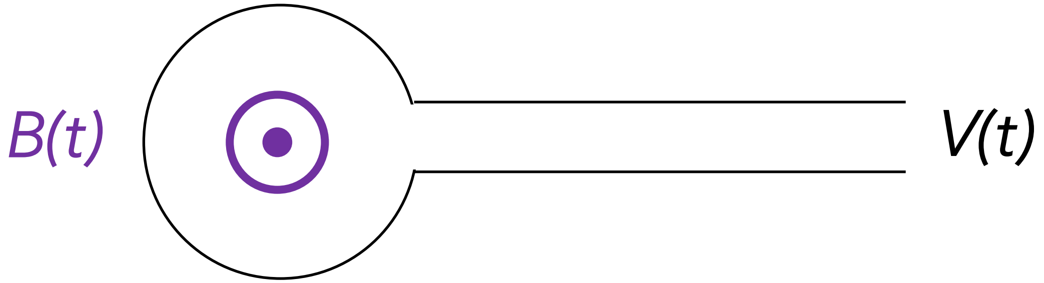

Magnetic probe array

Flux rope

Electrodes

Magnetic or “b-dot” probe:

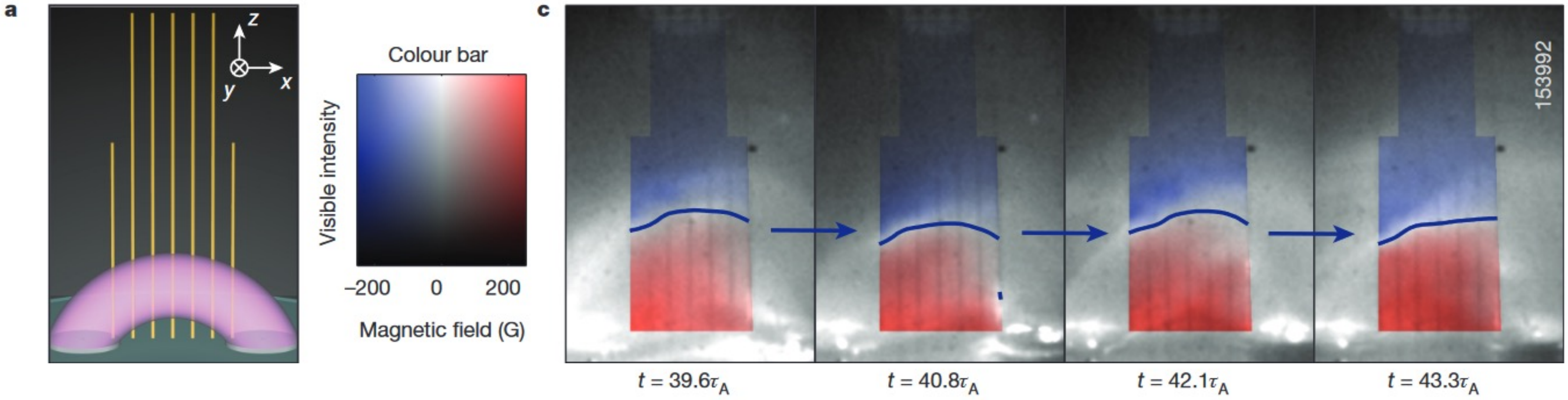
- Measures $V = Area \times \dot{B}$
- $\nabla \times \boldsymbol{E} = \partial \boldsymbol{B}/\partial t = \dot{\boldsymbol{B}}$
- $\int \nabla \times \boldsymbol{E} \cdot \boldsymbol{dA} = \int \boldsymbol{E} \cdot \boldsymbol{dl} = V = A\dot{B}$




Array of three-axis probes measures **B**(**X**, t)

*Myers, Nature (2015)*

# Flux rope eruptions: experimental results




- Note: time in "Alfvén times", so dimensionless – aids comparison to astrophysical object

*Myers, Nature (2015)*

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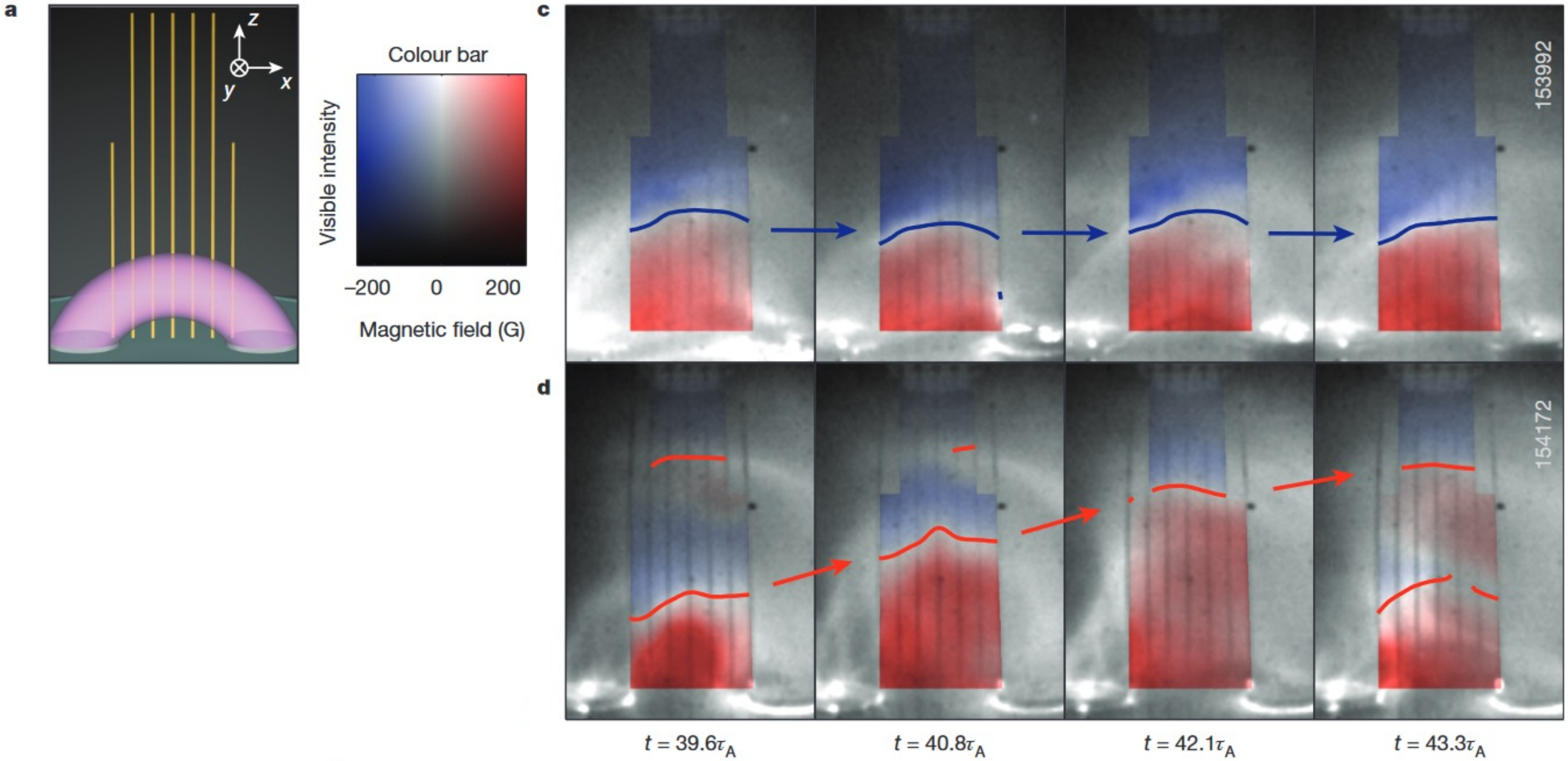


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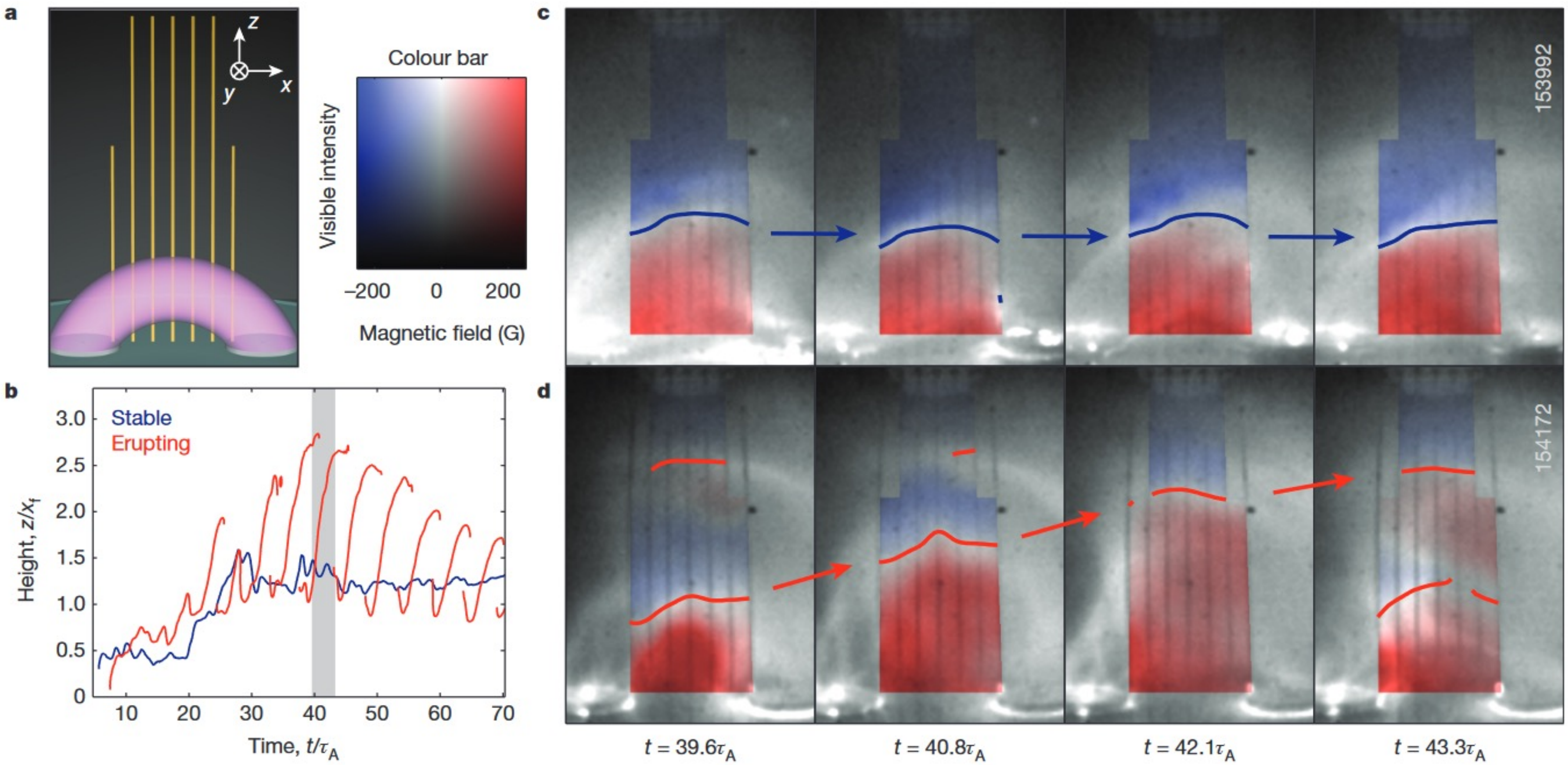


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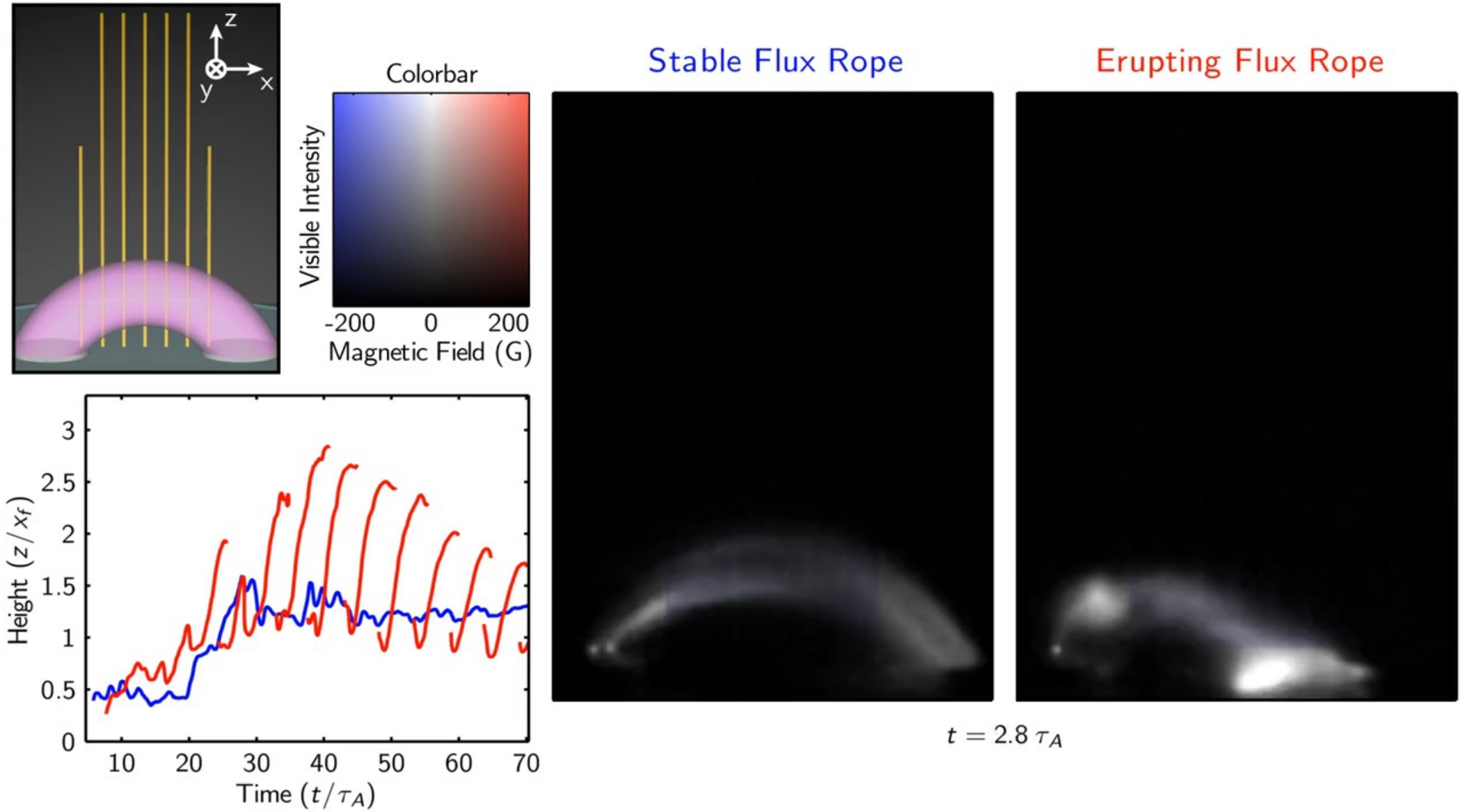
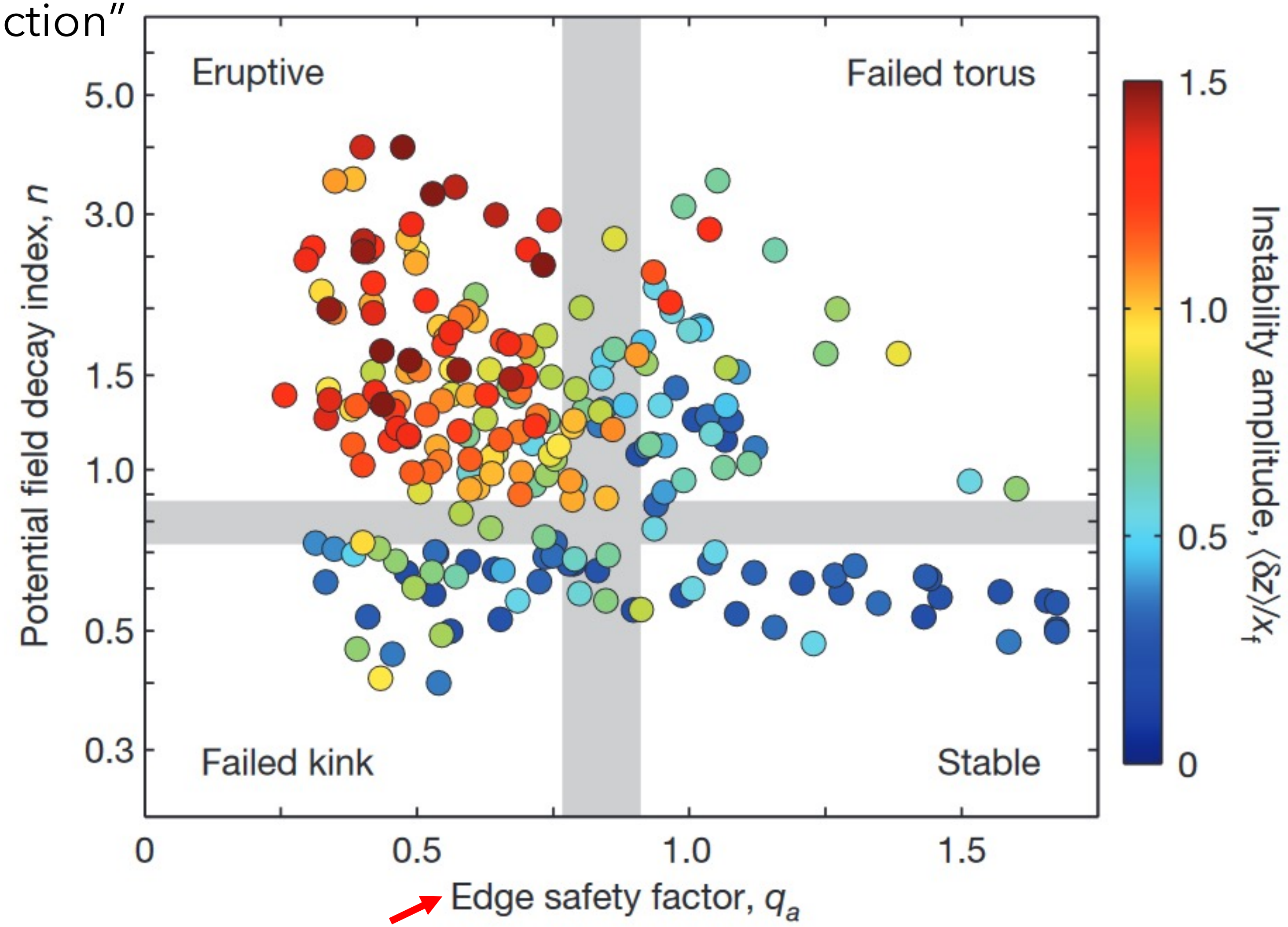


# Flux rope eruptions: experimental results

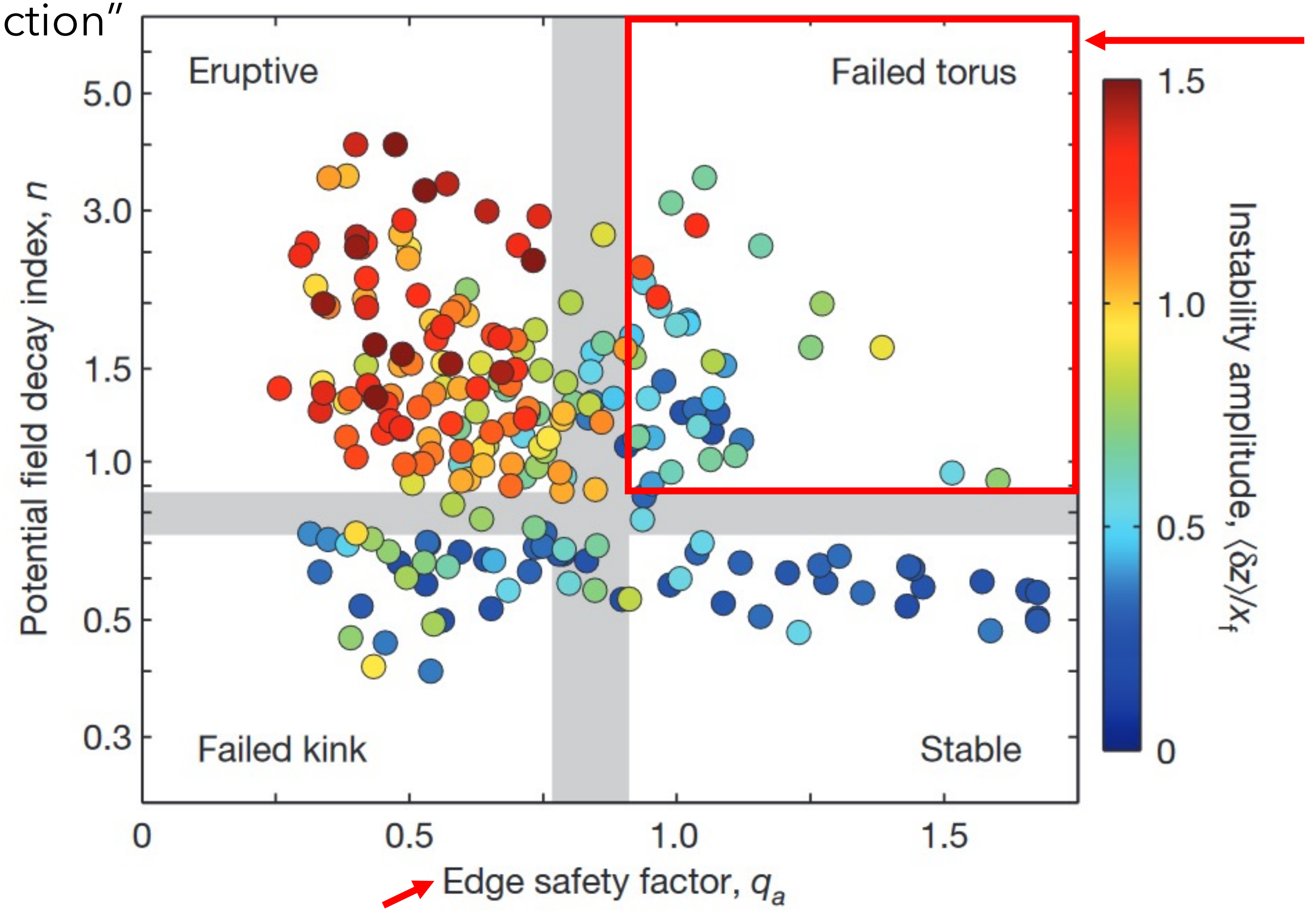
"How quickly field becomes smaller in vertical direction"




"1/Twistiness of magnetic field"

# Flux rope eruptions: experimental results

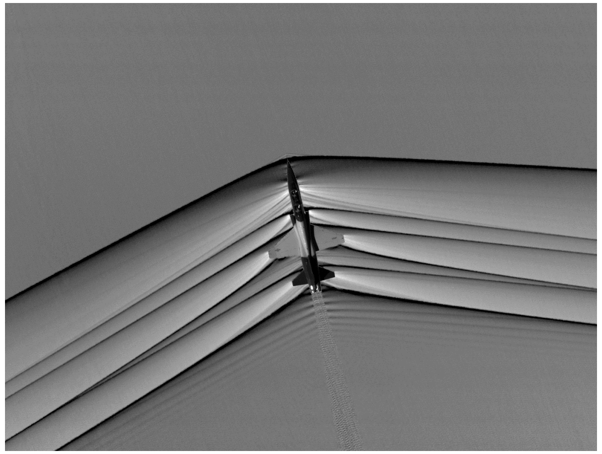
"How quickly field becomes smaller in vertical direction"




"1/Twistiness of magnetic field"

- New experimentally discovered regime!
- Thought to be unstable ($q_a$>0.8), found to be stable
- Plasma "self-organizes" and creates additional magnetic field which resists eruption

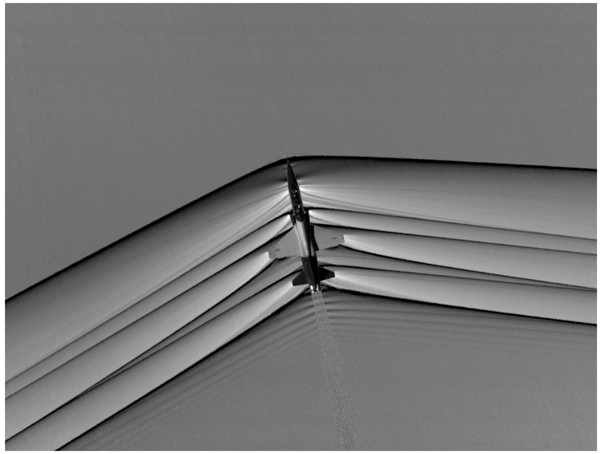
# Collisionless shocks: astrophysical setting



*Collisional shocks around a jet aircraft*

- Collisional (standard) shock: sudden change in density, velocity and temperature
  - Shocks mediated by particle collisions on very short length scales

# Collisionless shocks: astrophysical setting



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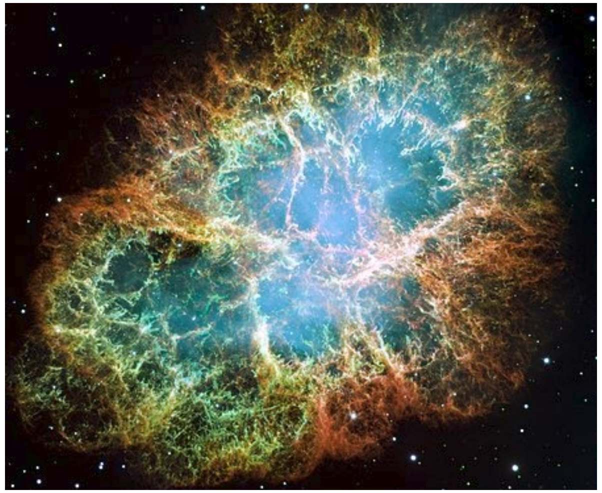
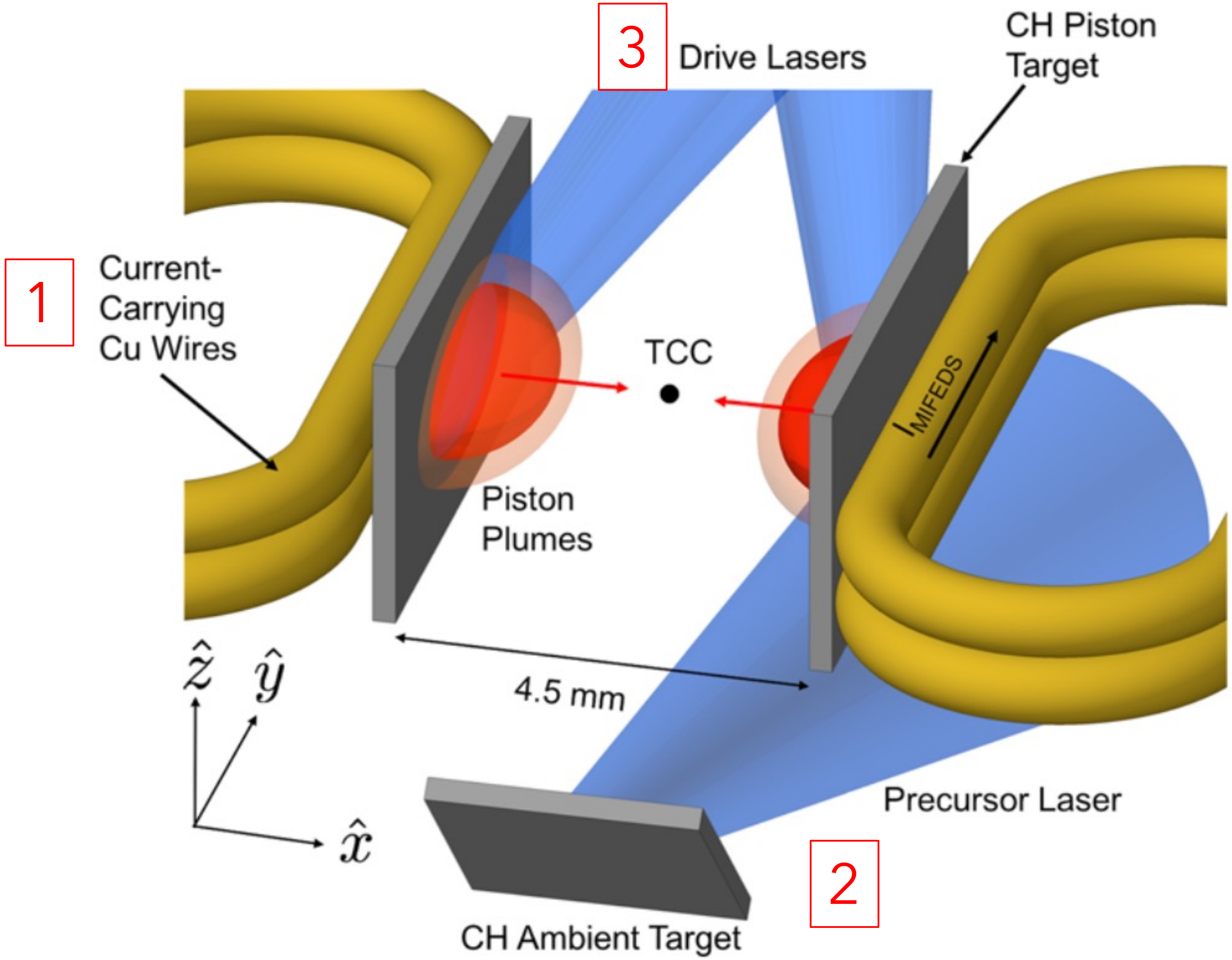


*Collisionless shocks around the Crab Nebula, a supernova remnant*

- Collisional (standard) shock: sudden change in density, velocity and temperature
  - Shocks mediated by particle collisions on very short length scales
- Collisionless shocks: accelerate particles to very high energies: source of cosmic rays which bombard Earth
  - Very fast hot plasma: particles do not collide! Shock is mediated by collective electromagnetic effects
  - Further complicated by existing magnetic fields!

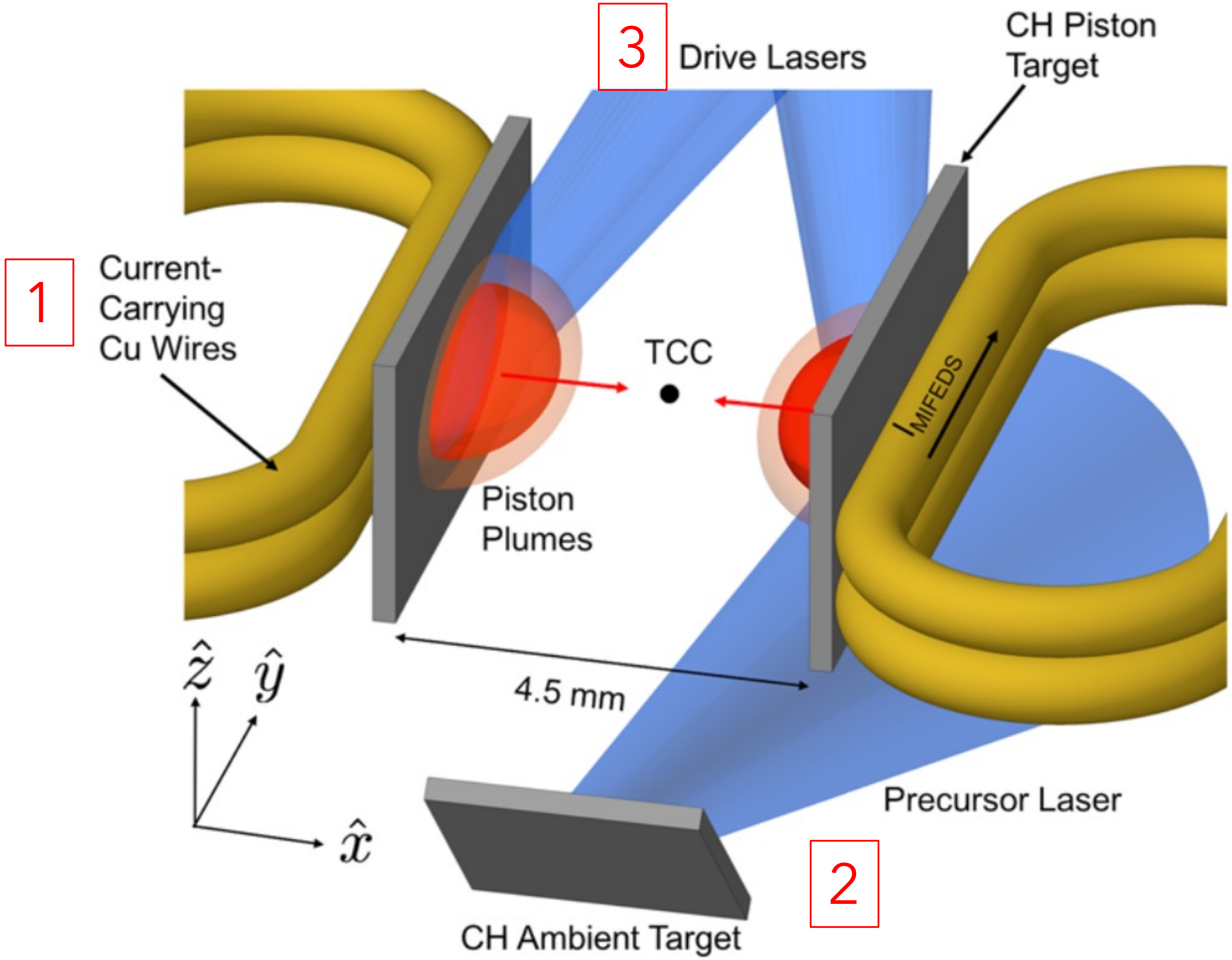
# Collisionless shocks: experimental setup




Grain of rice for scale

*Schaeffer, PRL (2016)*

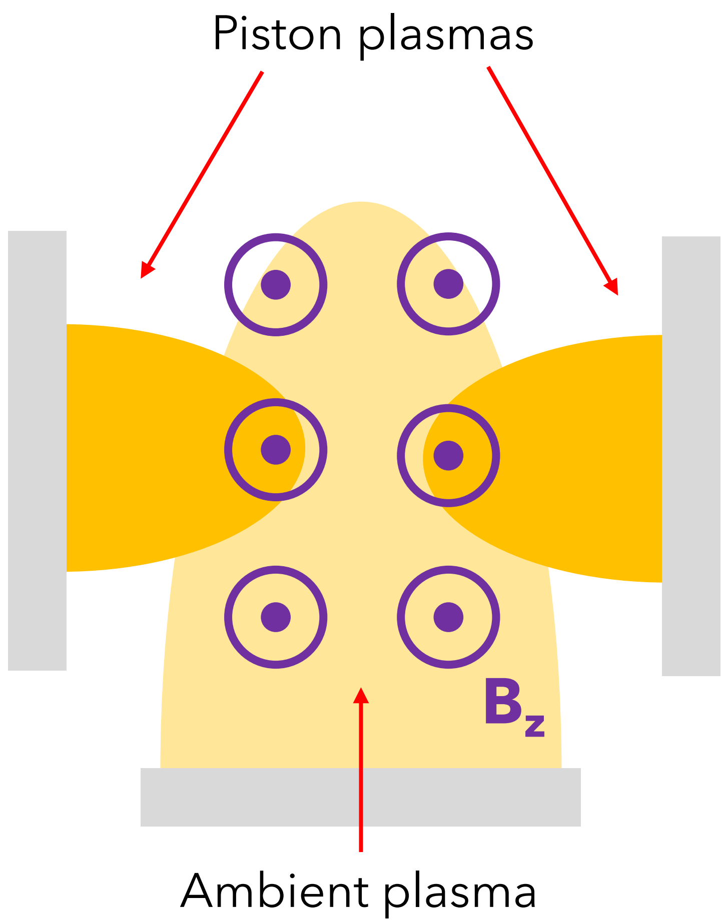
# Collisionless shocks: experimental setup




1. Magnetic coils fill volume with $B_z$ = 8 T field
2. Precursor laser creates ambient plasma between two targets
3. Drive lasers create counter-propagating pistons which drive collisionless shocks into ambient plasma

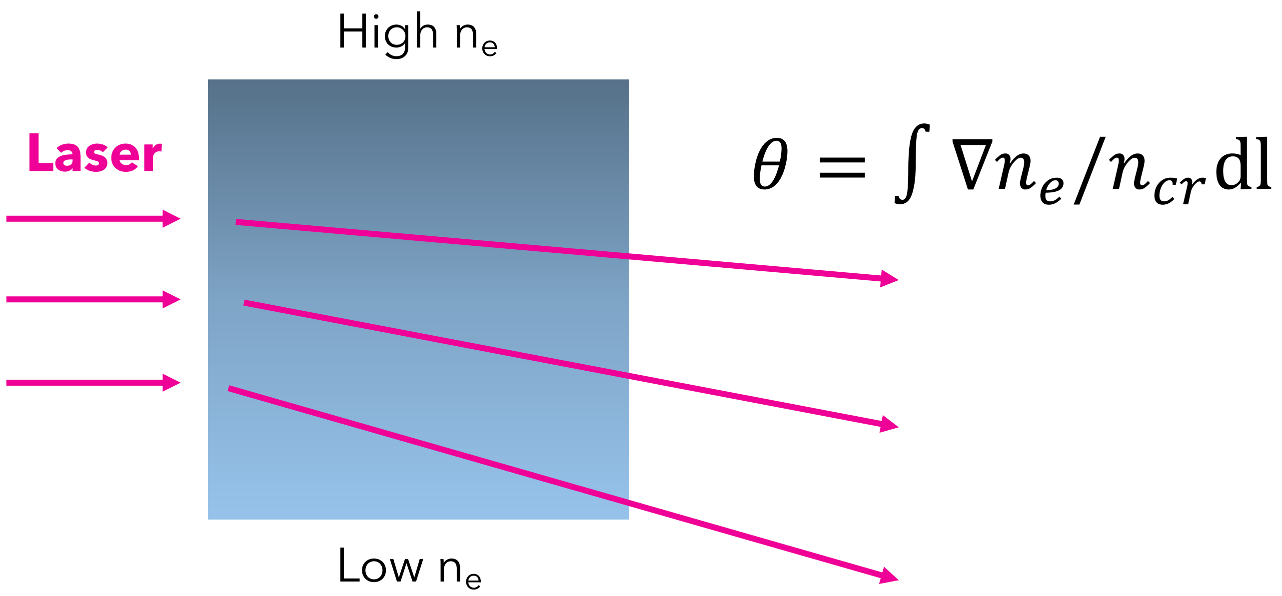
*Schaeffer, PRL (2016)*

# Collisionless shocks: experimental results




Angular Fringe Refractometry (AFR)

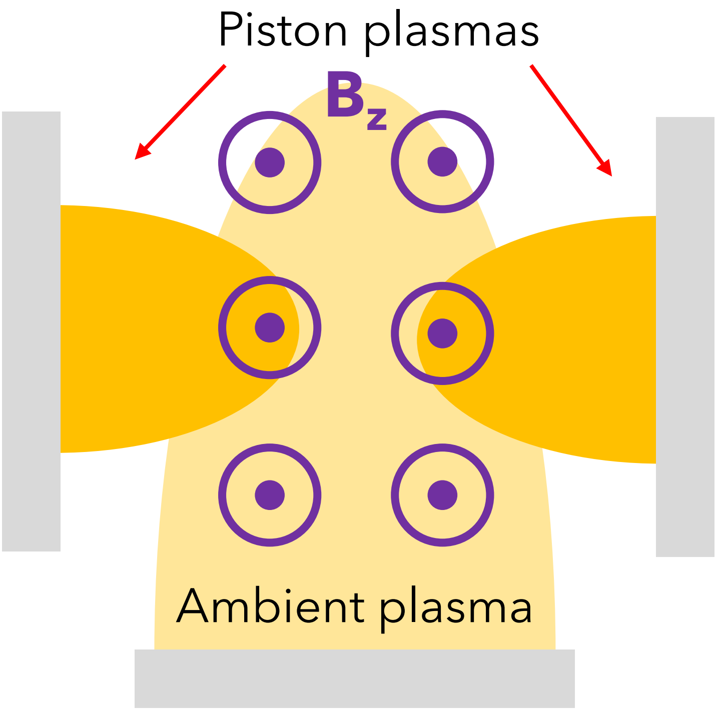
- Plasma refractive index $N \approx 1 - n_e/2n_{cr}$
- Rays of light deflected by refractive index gradients

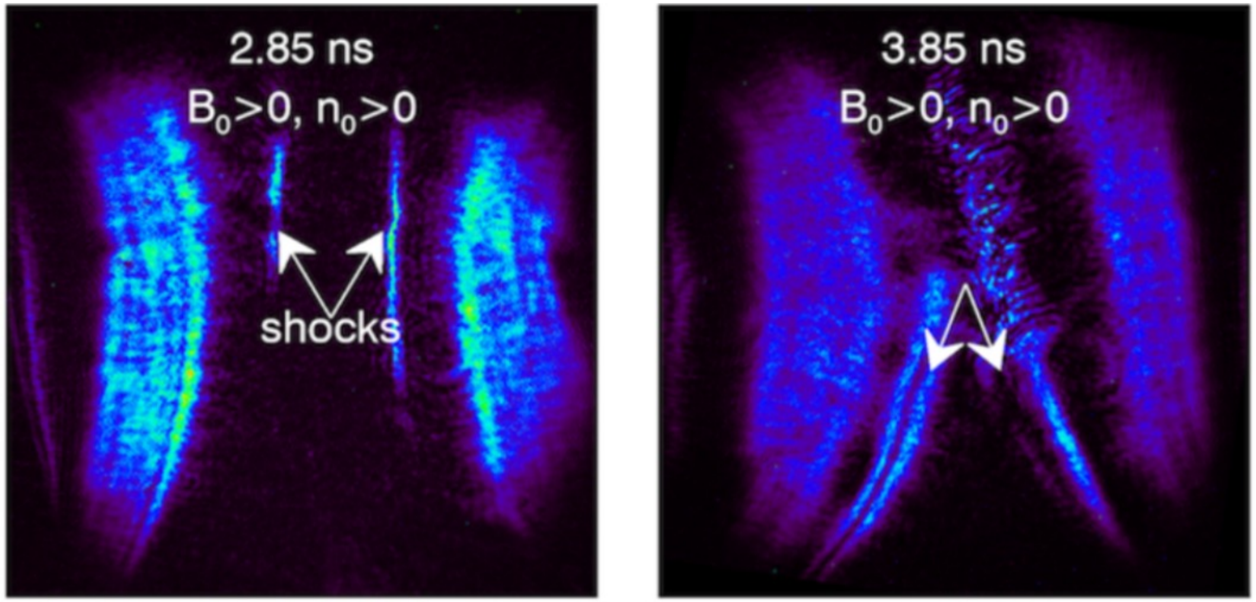



- AFR filters rays to have specific deflection angles, gives information on electron density gradient

*Schaeffer, PRL (2016)*

# Collisionless shocks: experimental results



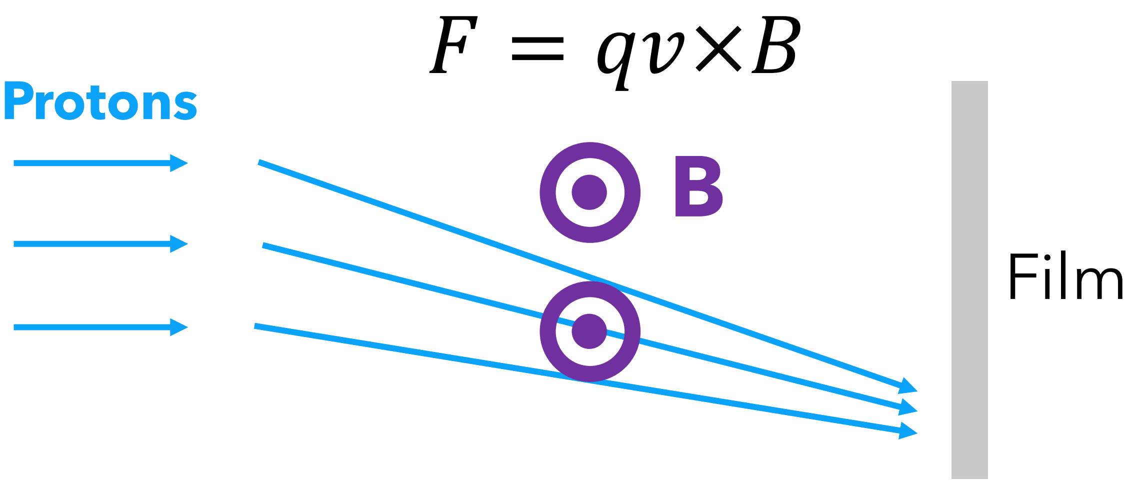

- Angular fringe refractometry (AFR): plasma density gradients bend light rays, AFR only allows rays with specific angles (corresponding to specific density gradients) to make it to camera.
- Two bright regions correspond to steep density gradient - two shocks!
- Track between frames: V = 700 km/s, ions collisionless

*Schaeffer, PRL (2016)*

# Collisionless shocks: experimental results

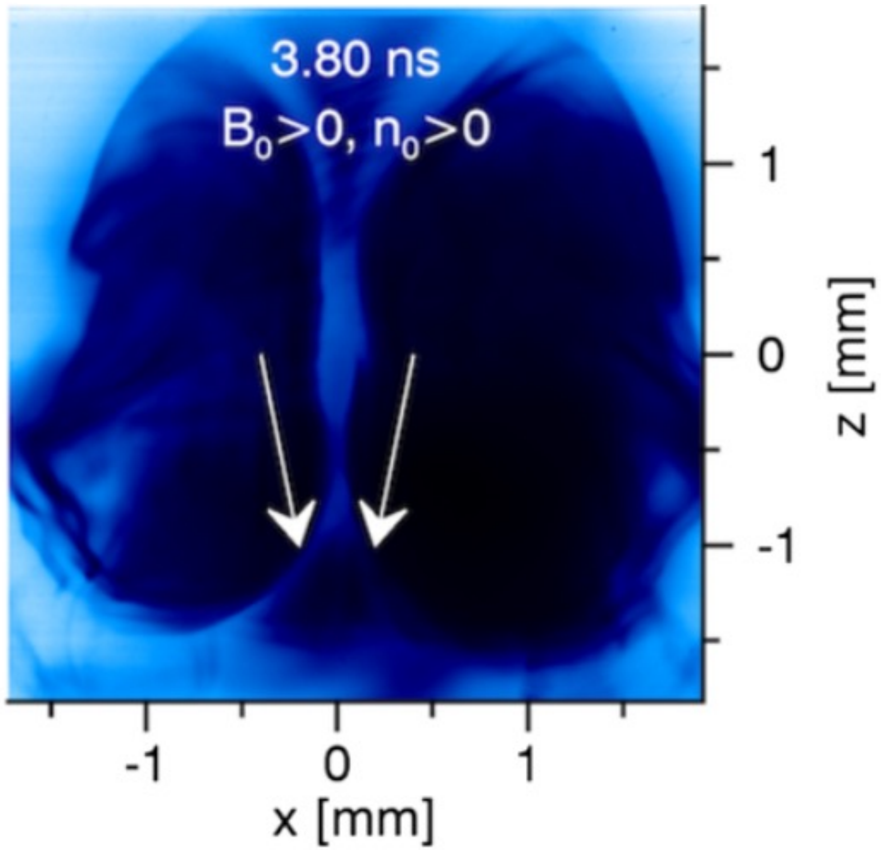
Proton imaging (or proton radiography)

- Charged particles deflected by magnetic fields
- Generate proton beam, measure proton location after plasma




- Deflection angle gives magnetic field strength (along proton path)

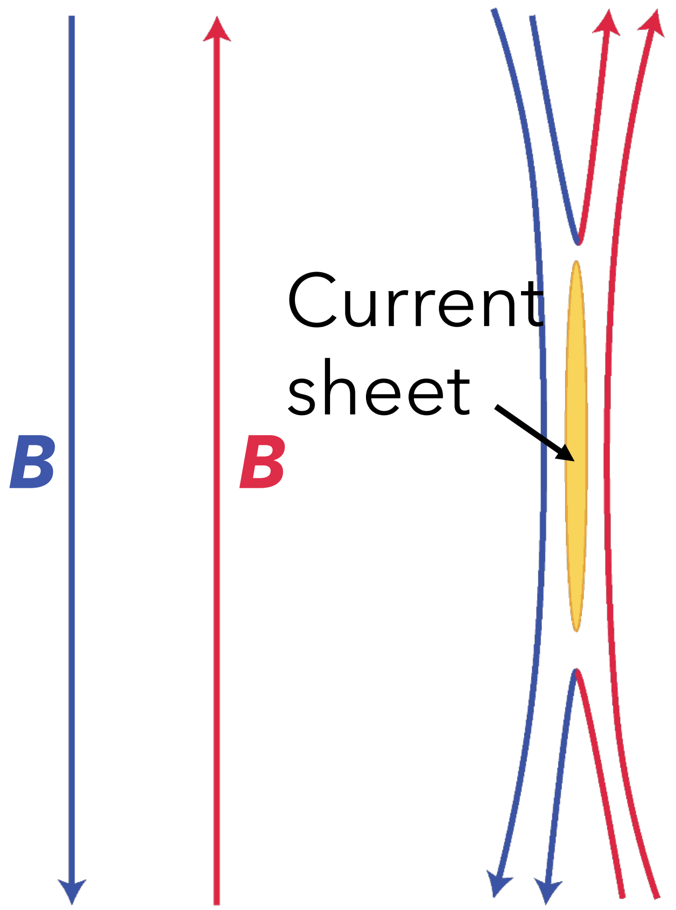
*Dark = more protons*




Magnetic field jump x2
Density jump x4
= a shock!

*Schaeffer, PRL (2016)*

# Magnetic Reconnection: astrophysical setting



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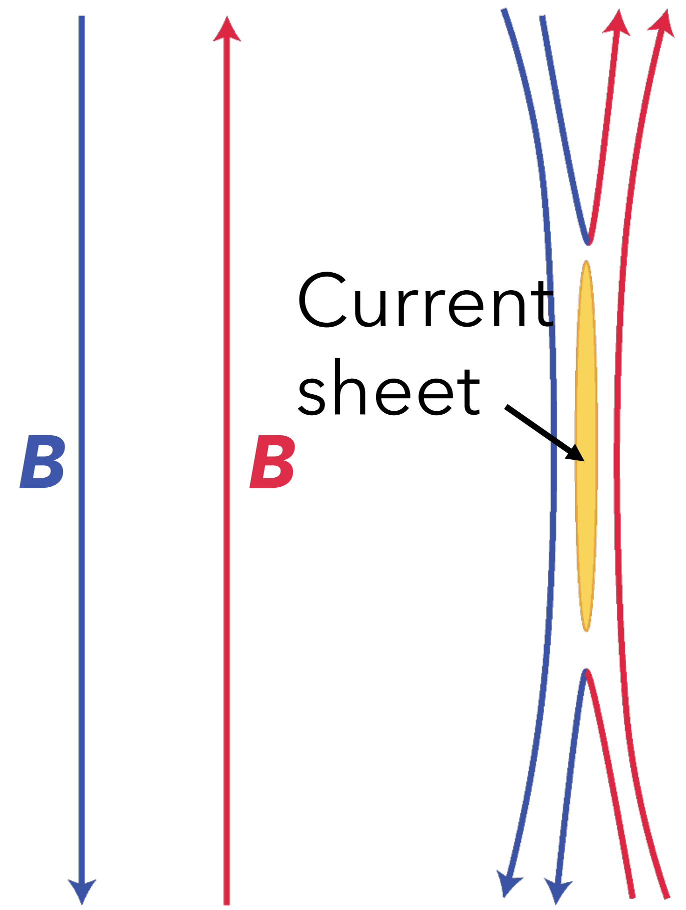
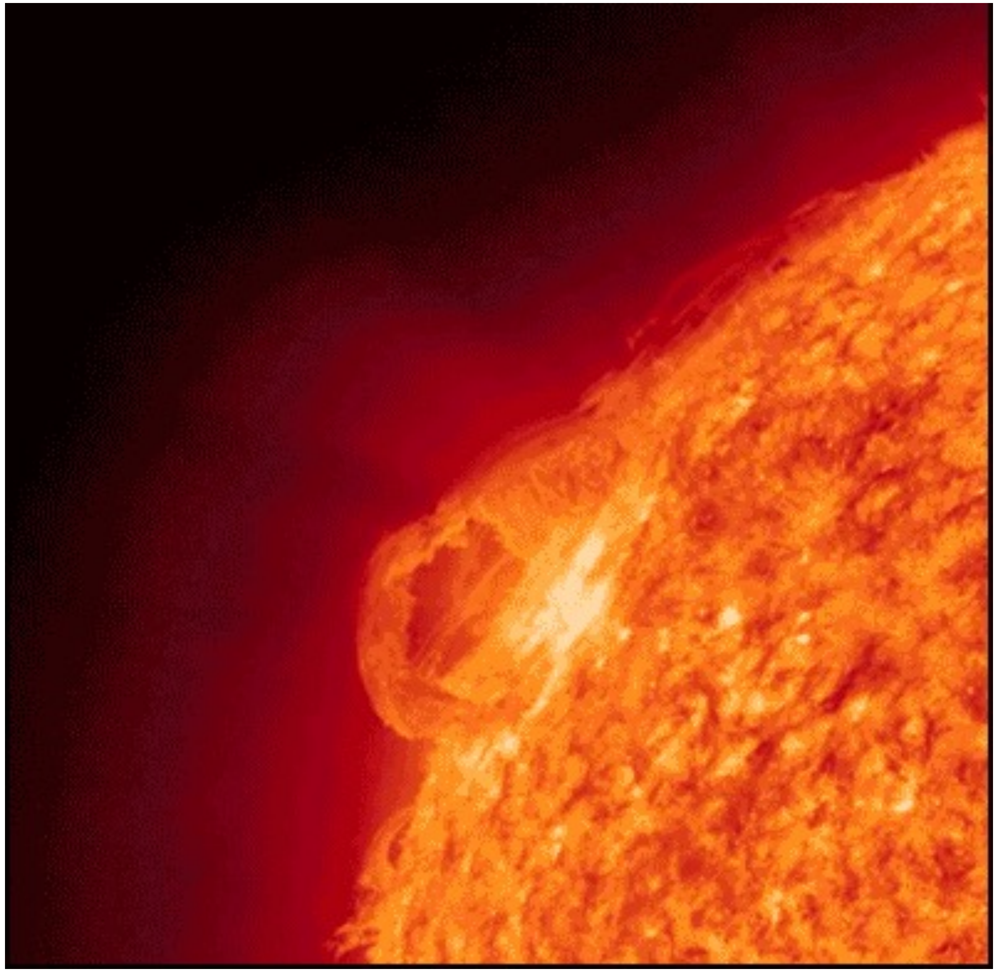



Prediction: 1000 yrs. Reality: 10 minutes!



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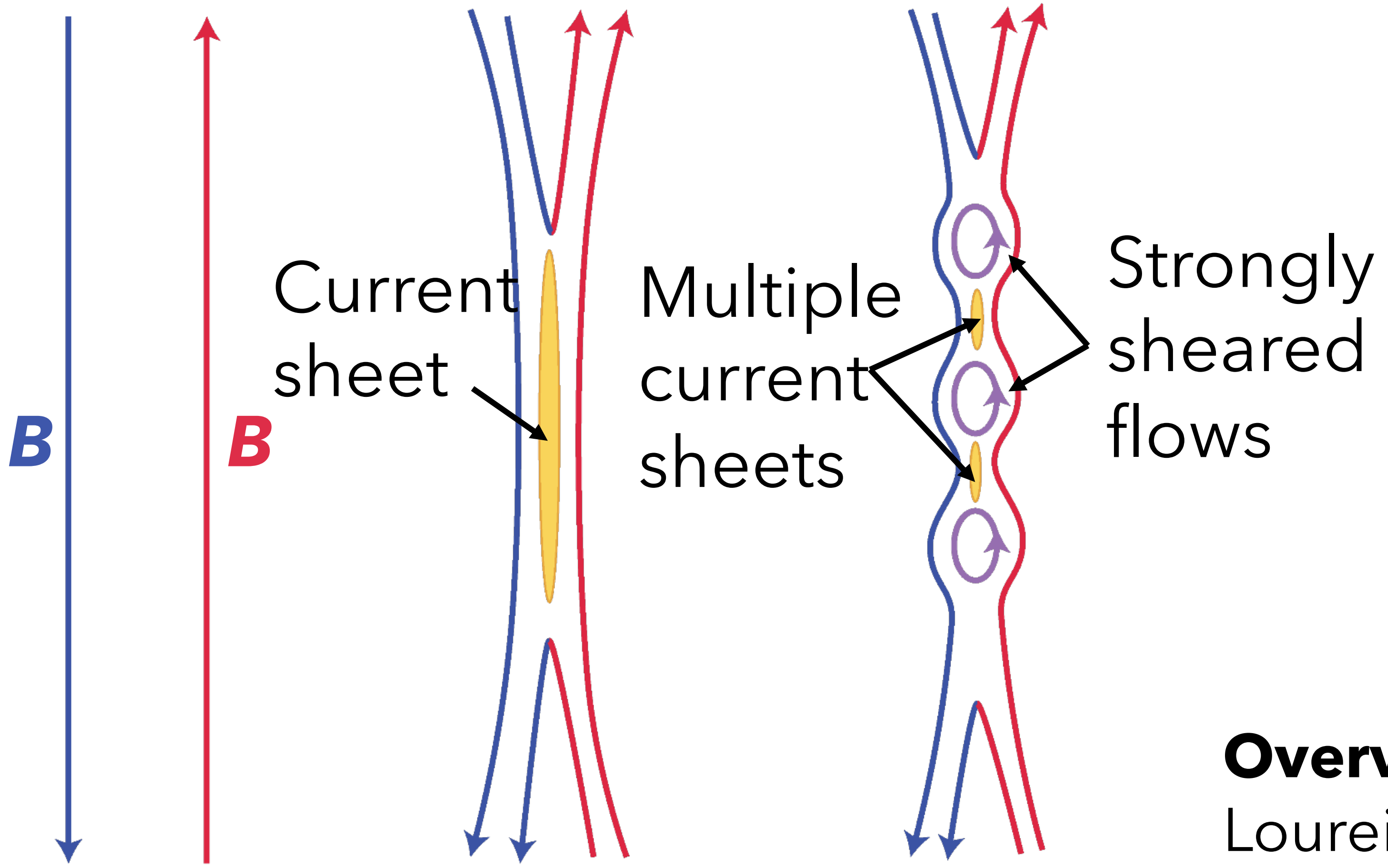
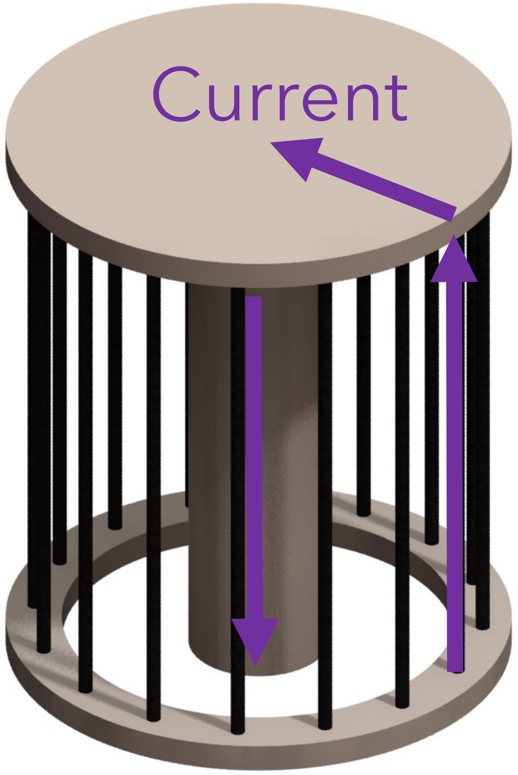



**Overview of recent theory:**
Loureiro, N. F., & Uzdensky, D. A.(2015). PPCF, *58*, 014021

# Magnetic reconnection: experimental setup

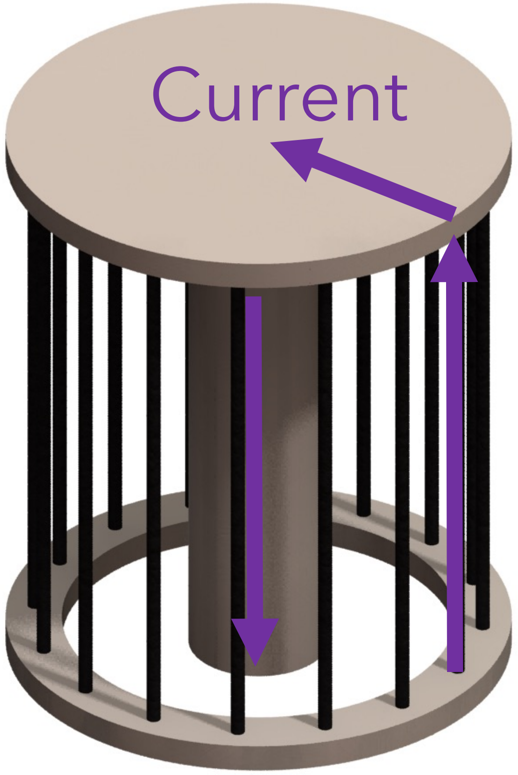



Dime for scale


I~1 MA,
100-300 ns
rise time

*Hare, PRL (2017)*

# Magnetic reconnection: experimental setup

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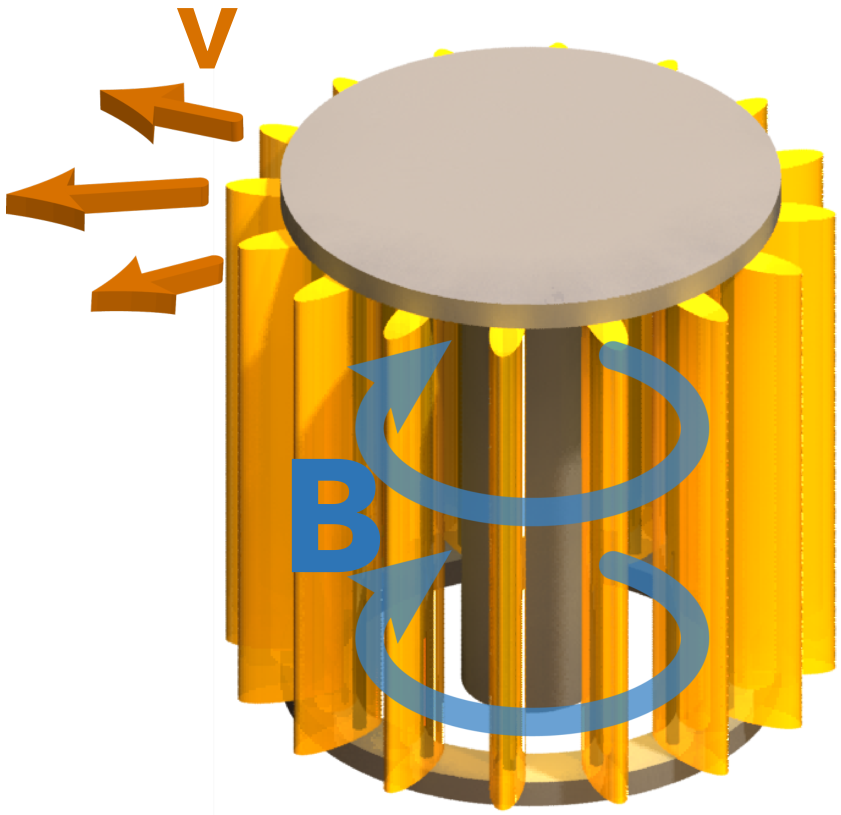



Current **heats** the wires & generates the **magnetic field** which **accelerates** the plasma

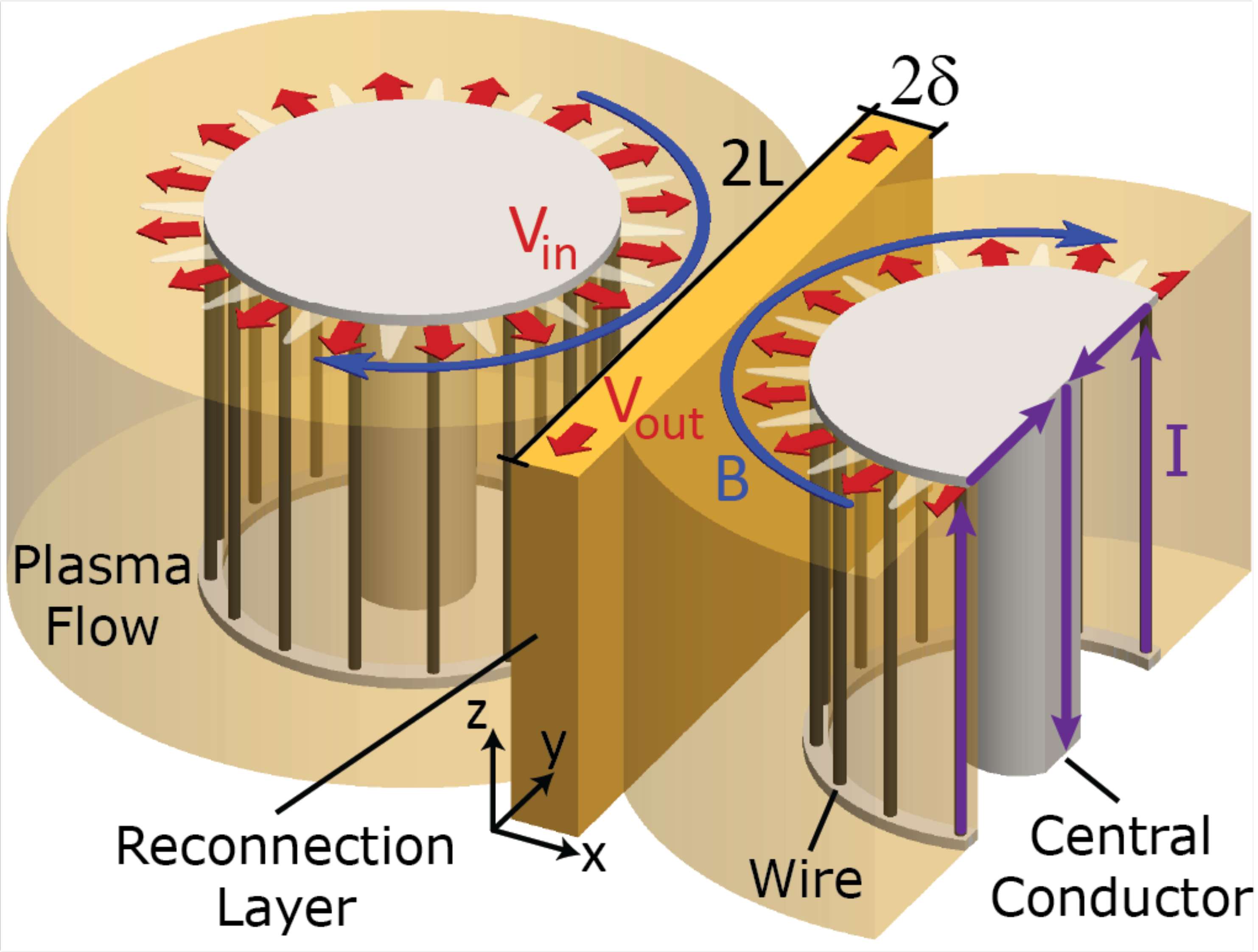
Result: energy components in rough equipartition,

$$U_B \approx U_{th} \approx U_{kin}$$

Similar to astrophysical systems

*Hare, PRL (2017)*

# Magnetic Reconnection from Double Exploding Wire Arrays

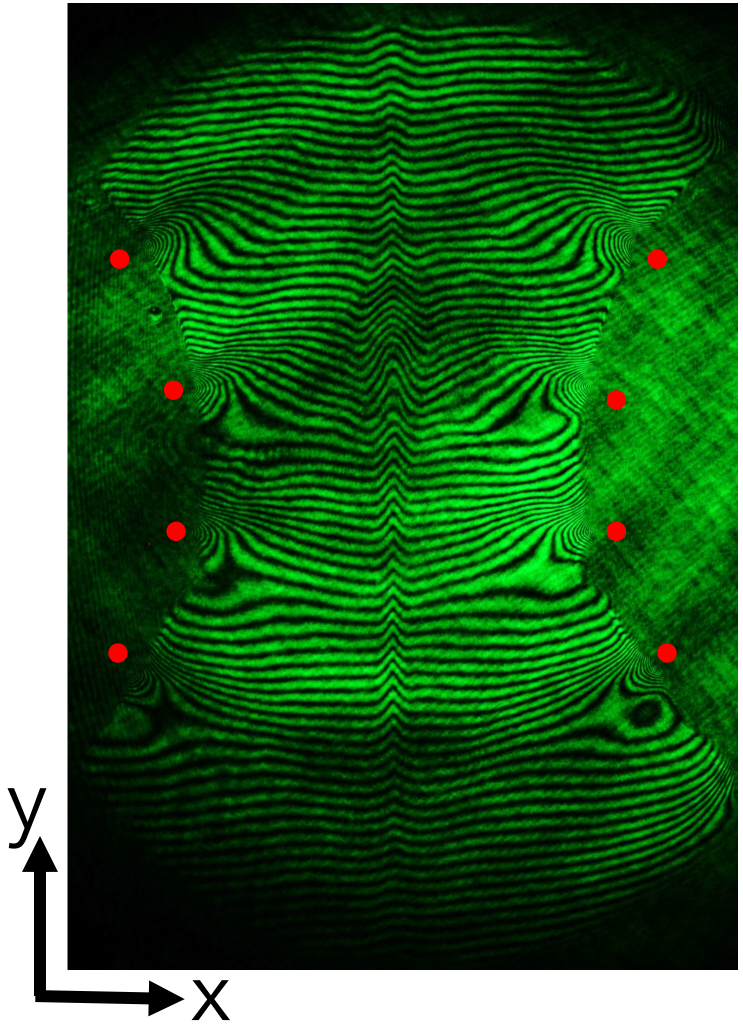



Drive two exploding arrays in **parallel**: collides flows with **opposite magnetic fields**, forming a **reconnection layer**.

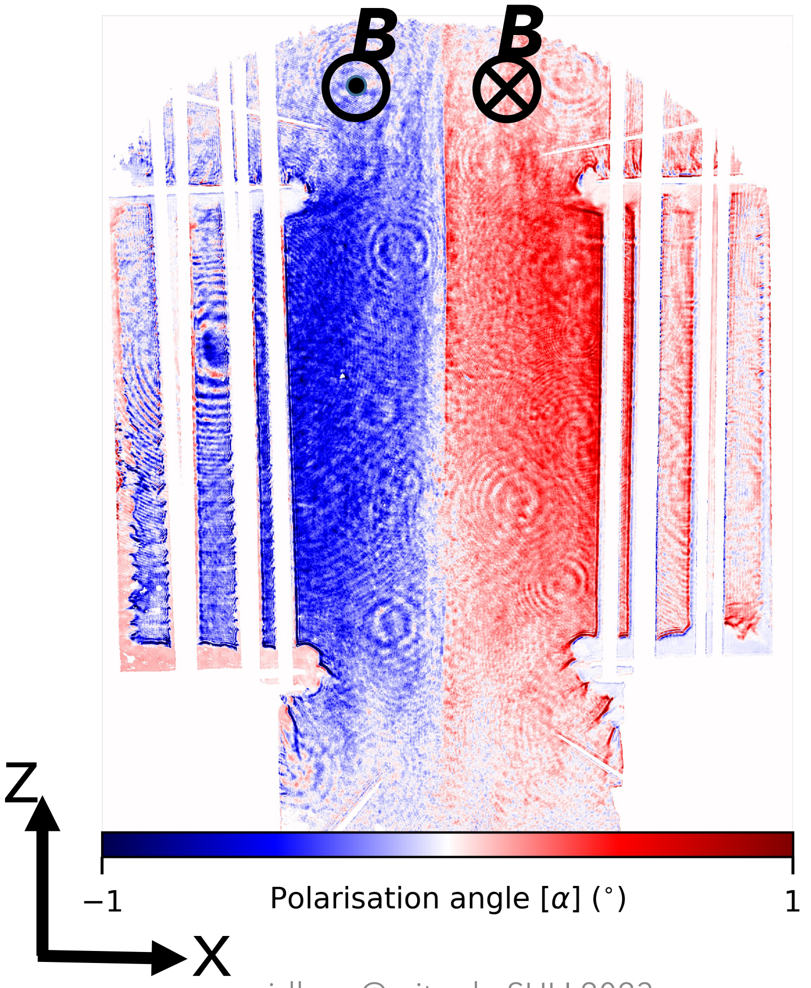
*Hare, PRL (2017)*

# Diagnosing reconnection in the laboratory

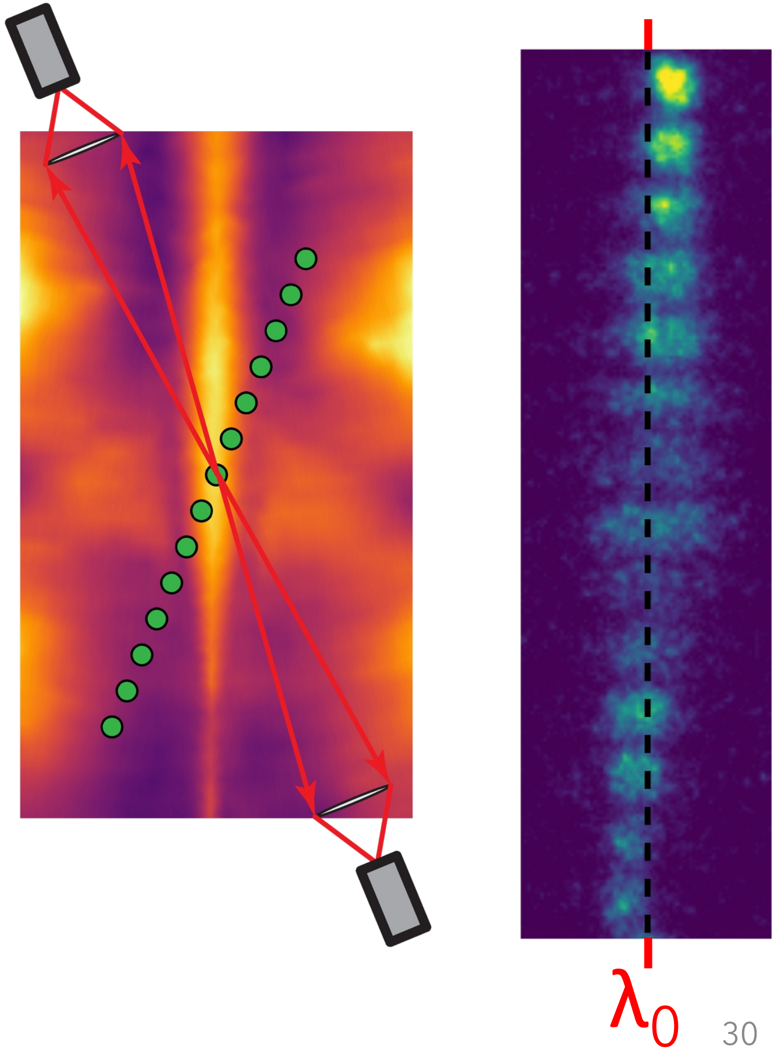
Laser interferometry:
$\int n_e dl$



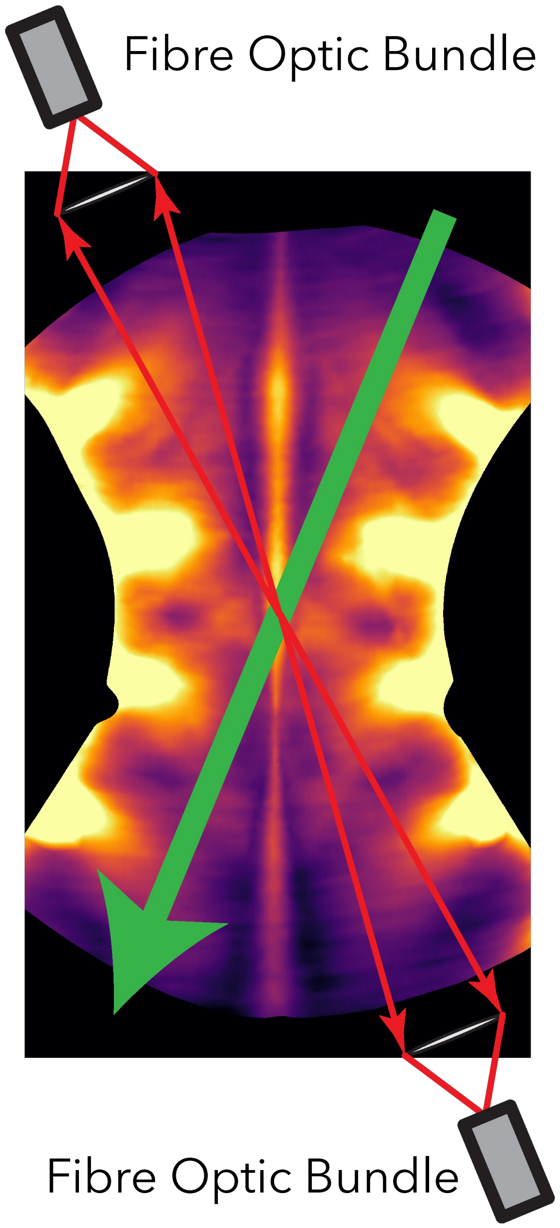

Faraday Imaging:
$\int n_e \boldsymbol{B} \cdot d\boldsymbol{l}$

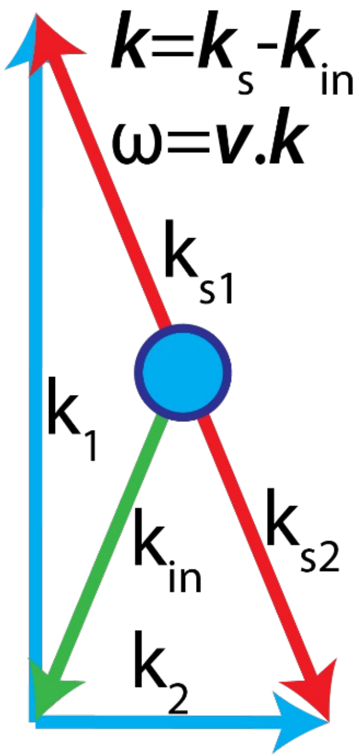



Thomson scattering:
$\boldsymbol{V}, ZT_e, T_i$



# Velocity and Temperature (Thomson Scattering)



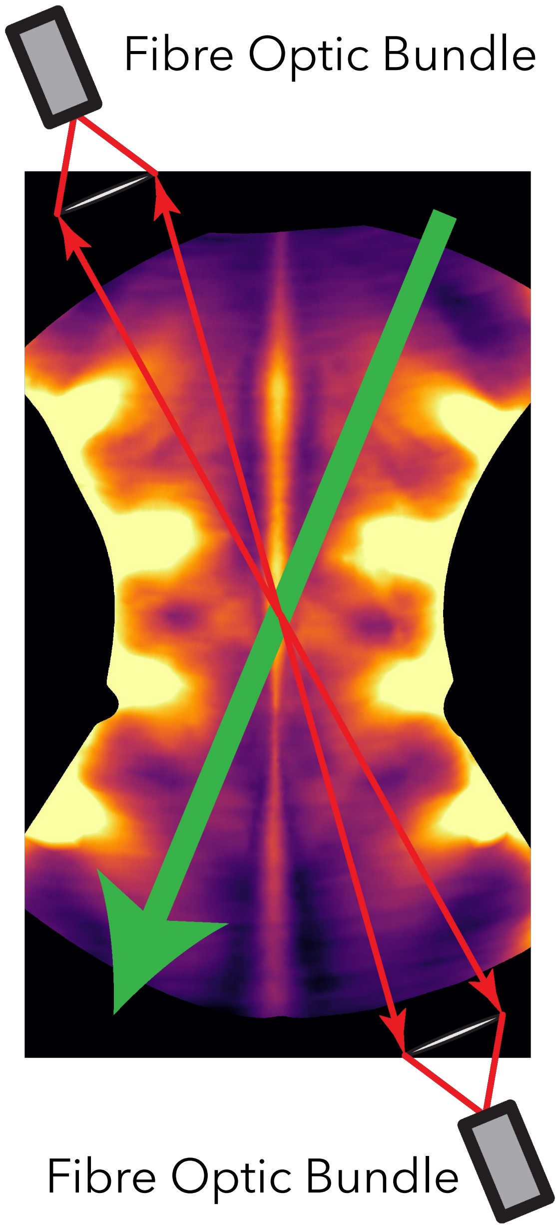



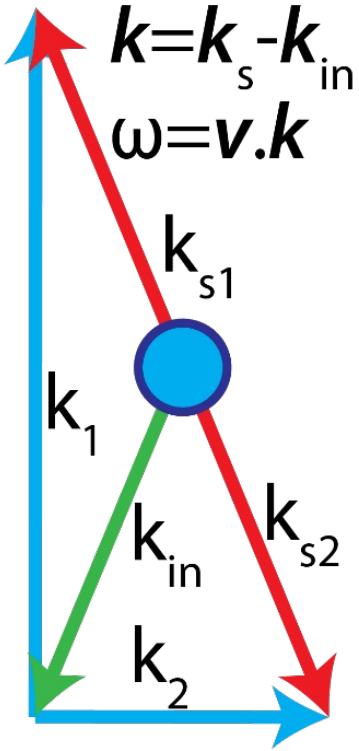

- Electrons in the plasma scatter light
- Light is Doppler shifted and scatters from waves in the plasma
- Resonance when $(\omega, k)$ or (energy/momentum) match

Ion acoustic waves:

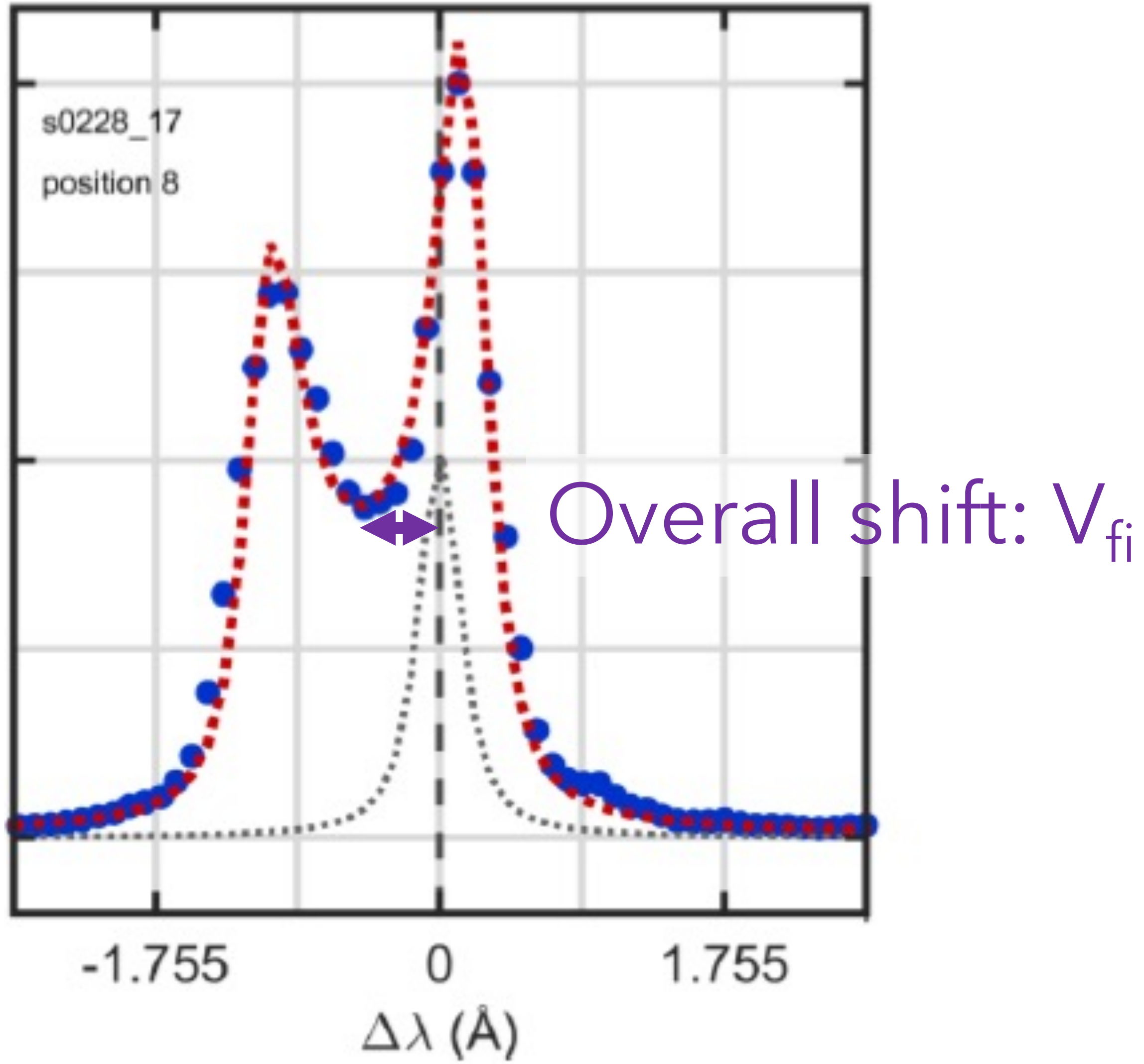
$$\omega = \pm C_{IA} k \text{ (two peaks)}$$
$$C_{IA} = \sqrt{(ZT_e + T_i)/m_i}$$

# Velocity and Temperature (Thomson Scattering)




Collective scattering from Ion Acoustic Waves



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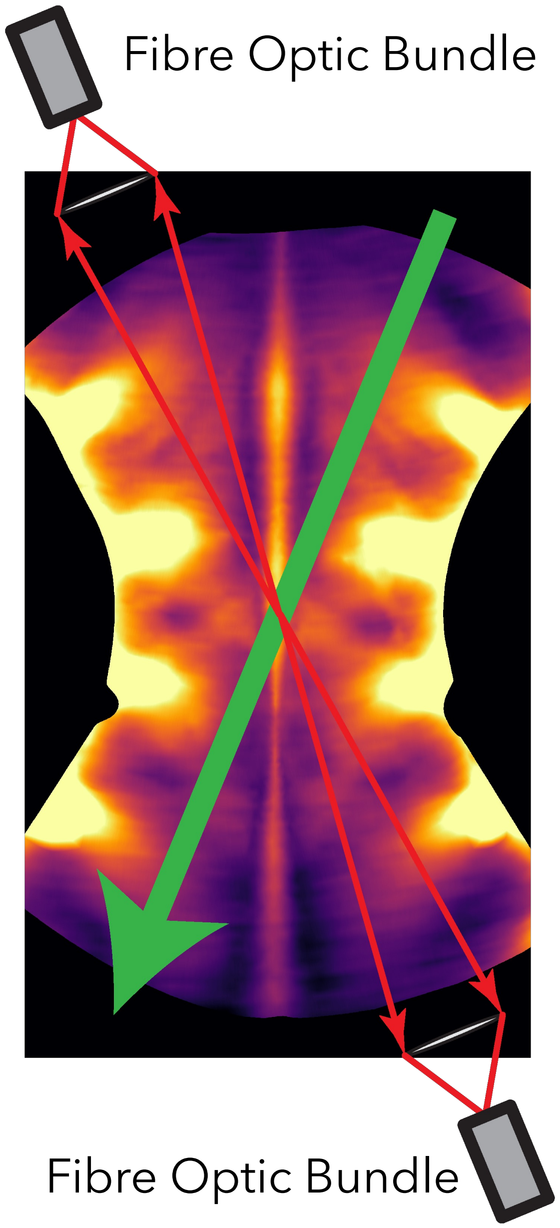


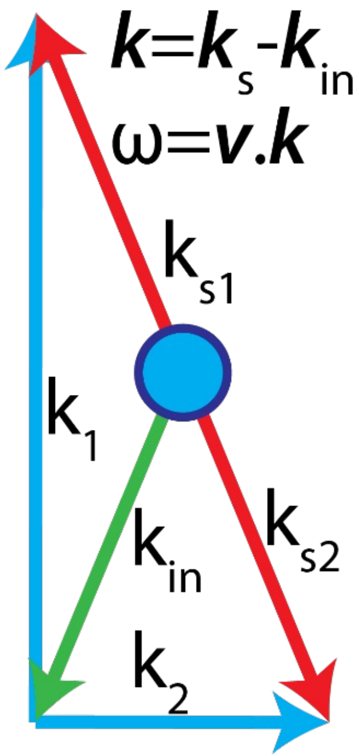


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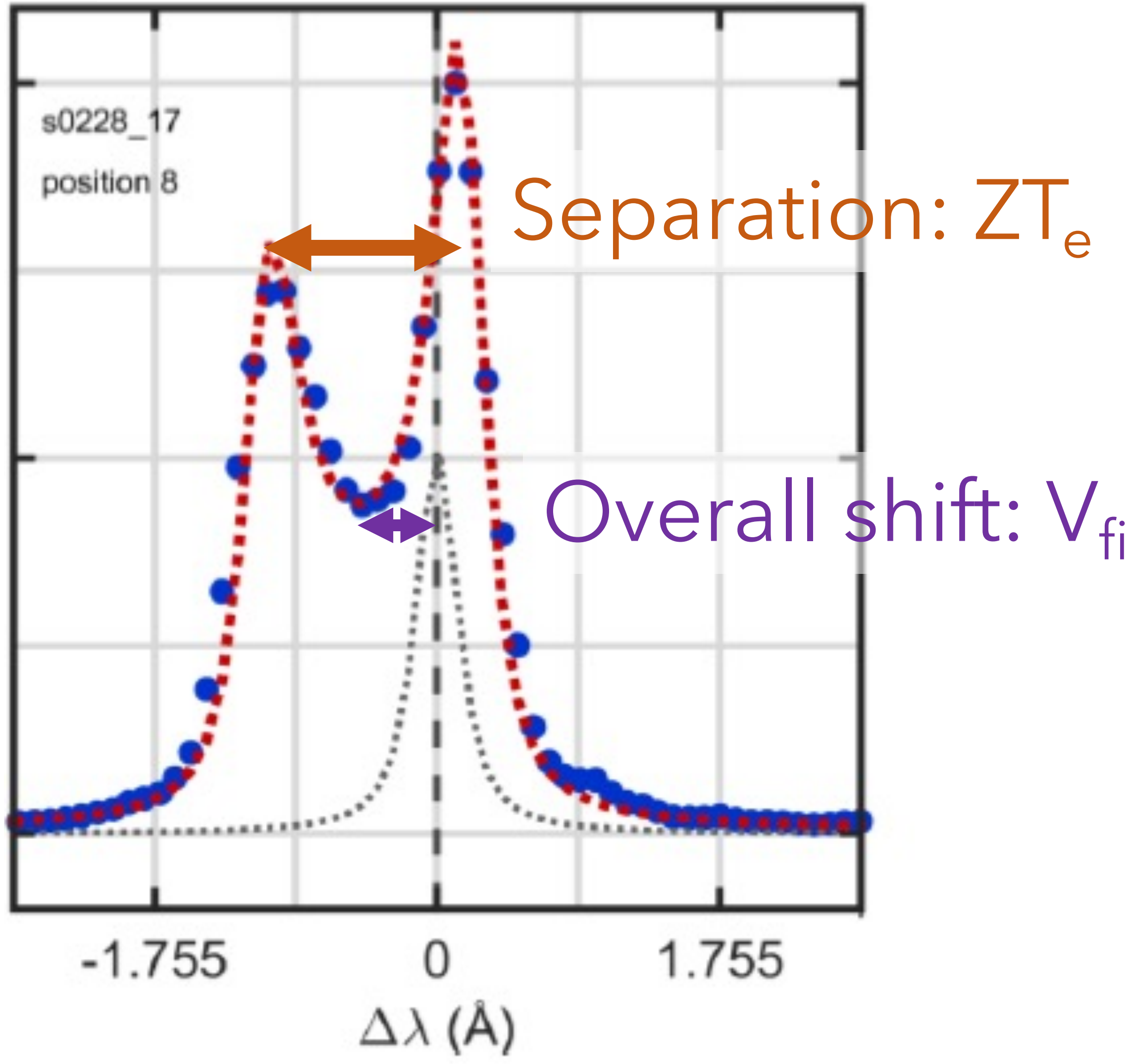

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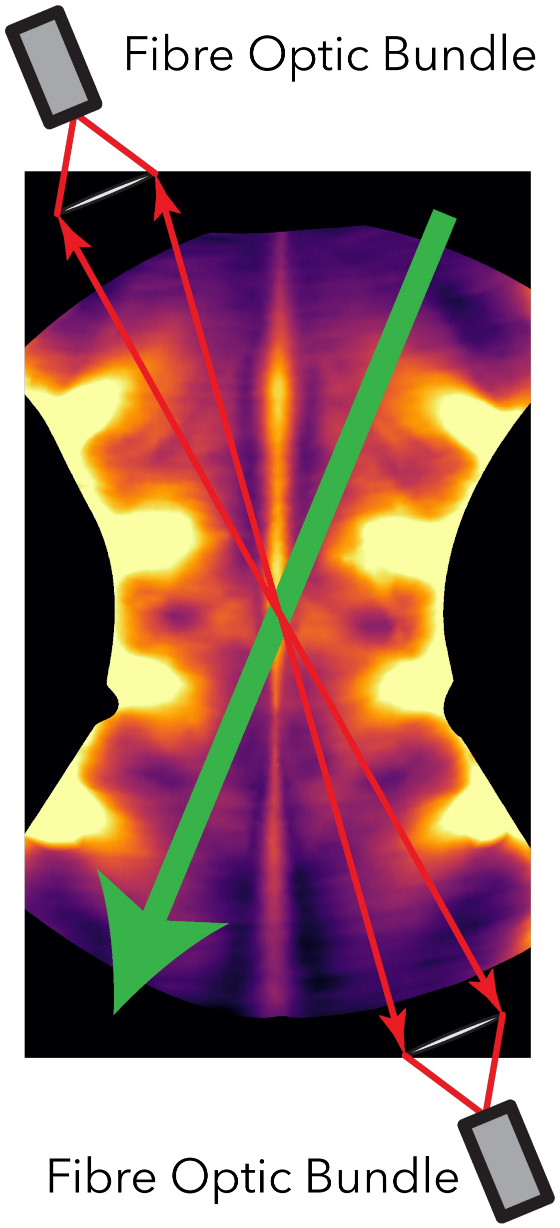


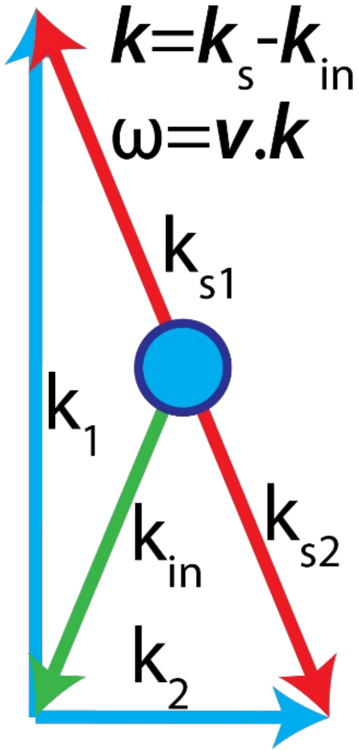


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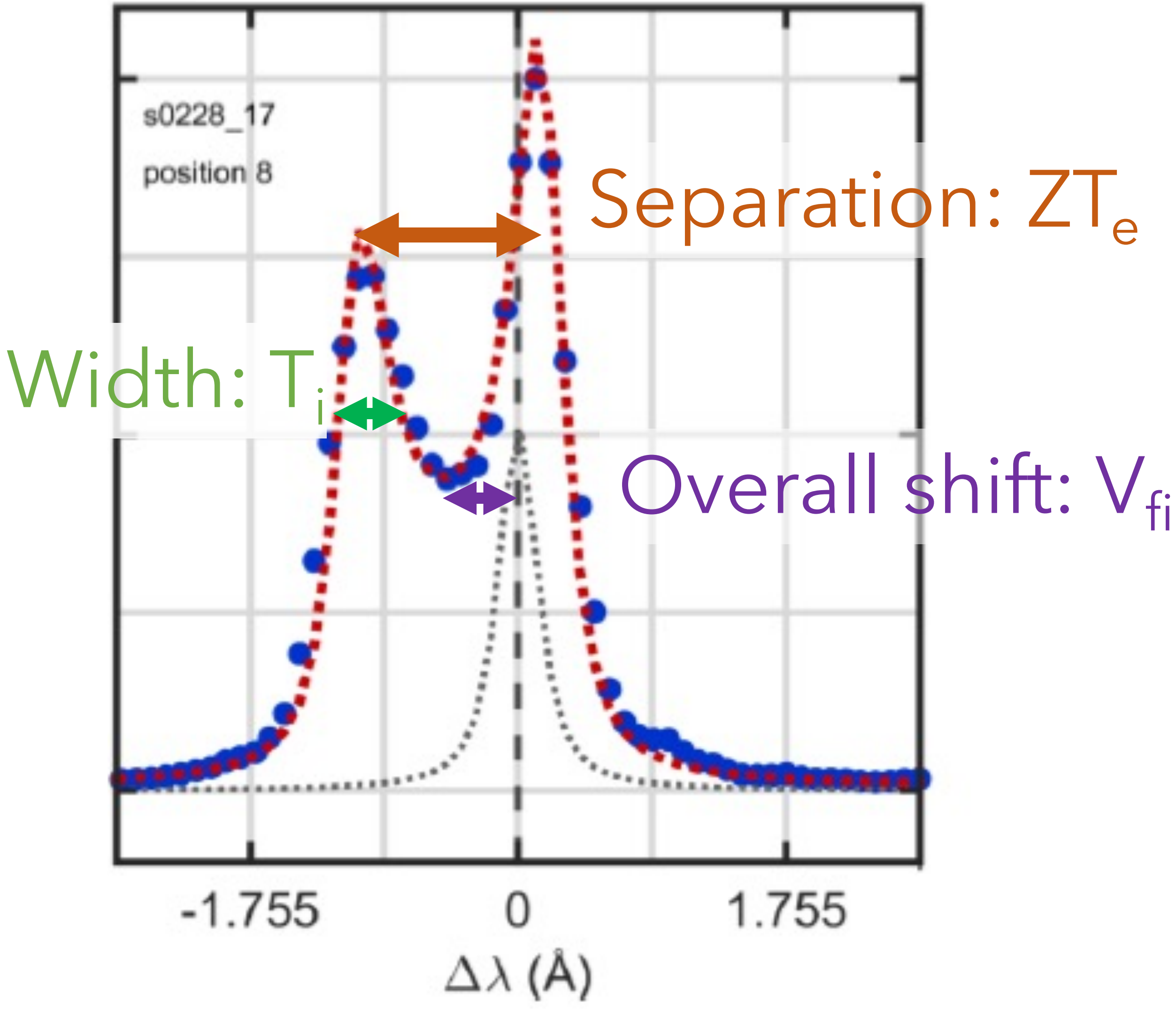

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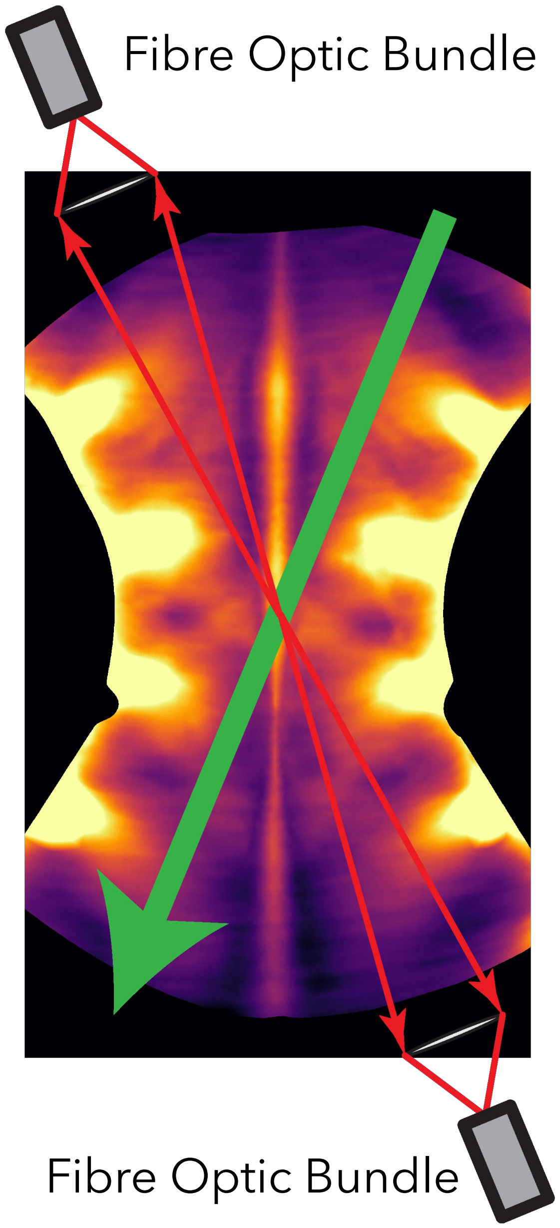
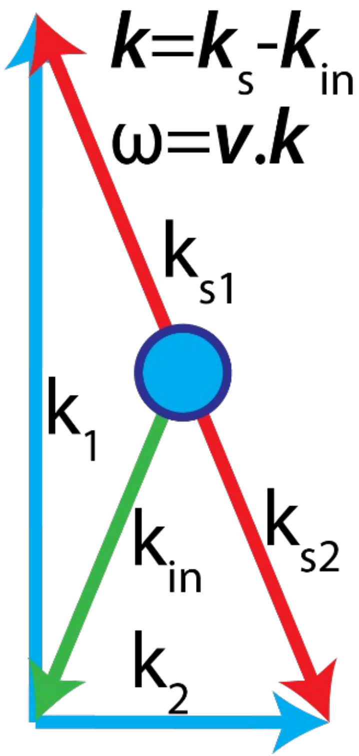
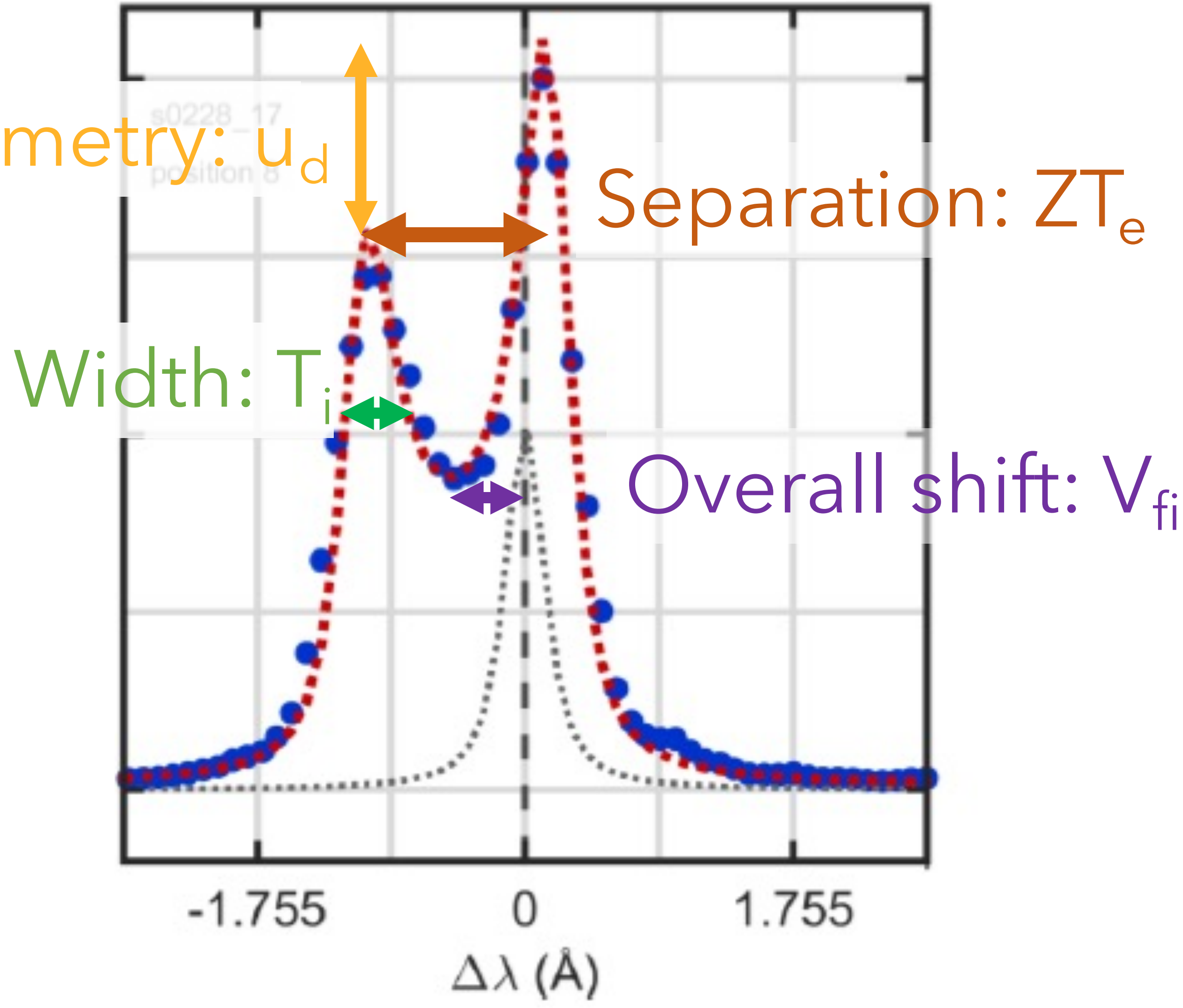


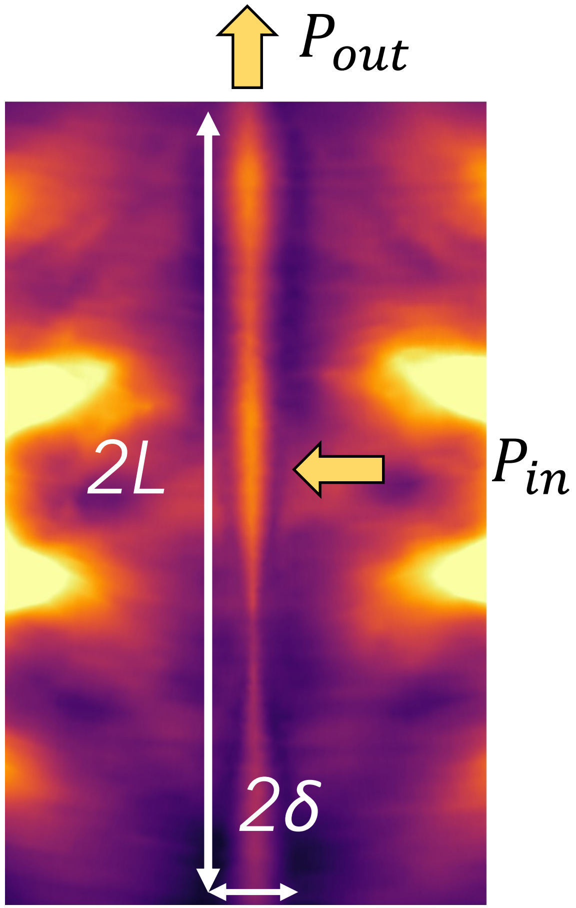

Collective scattering from Ion Acoustic Waves

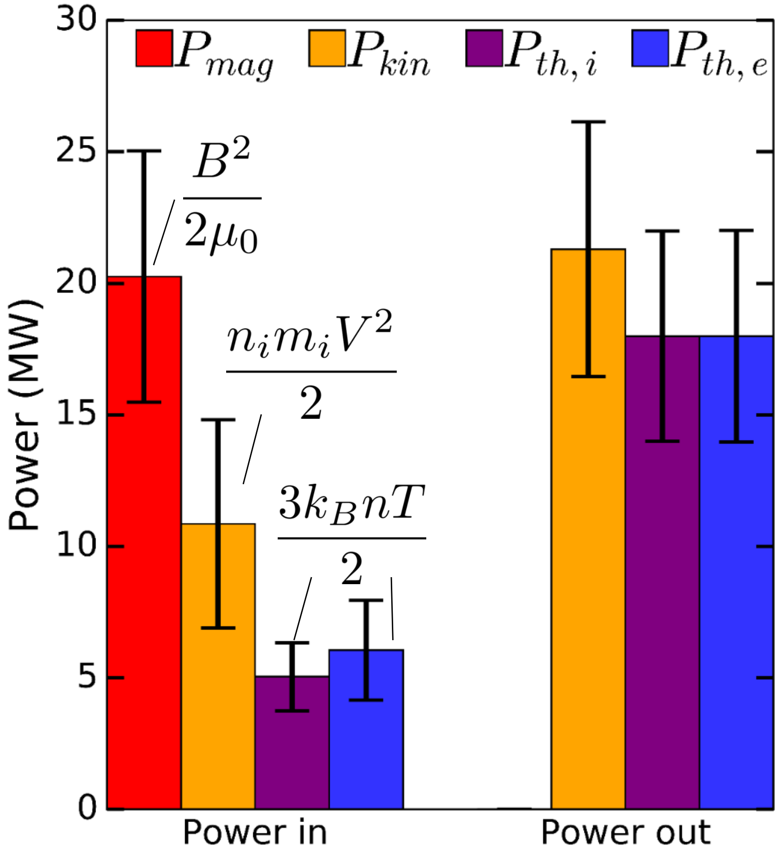


# Carbon: Anomalous Heating in the Reconnection Layer

$$V_{in} L h \left( E_{mag} + E_{kin} + E_{th,i} + E_{th,e} \right) \approx V_{out} \delta h \left( E_{kin} + E_{th,i} + E_{th,e} \right)$$

~50% ~25% ~25% ~40% ~60%




**Classical heating is too slow:**

$\tau_{exp} \approx 50$ ns

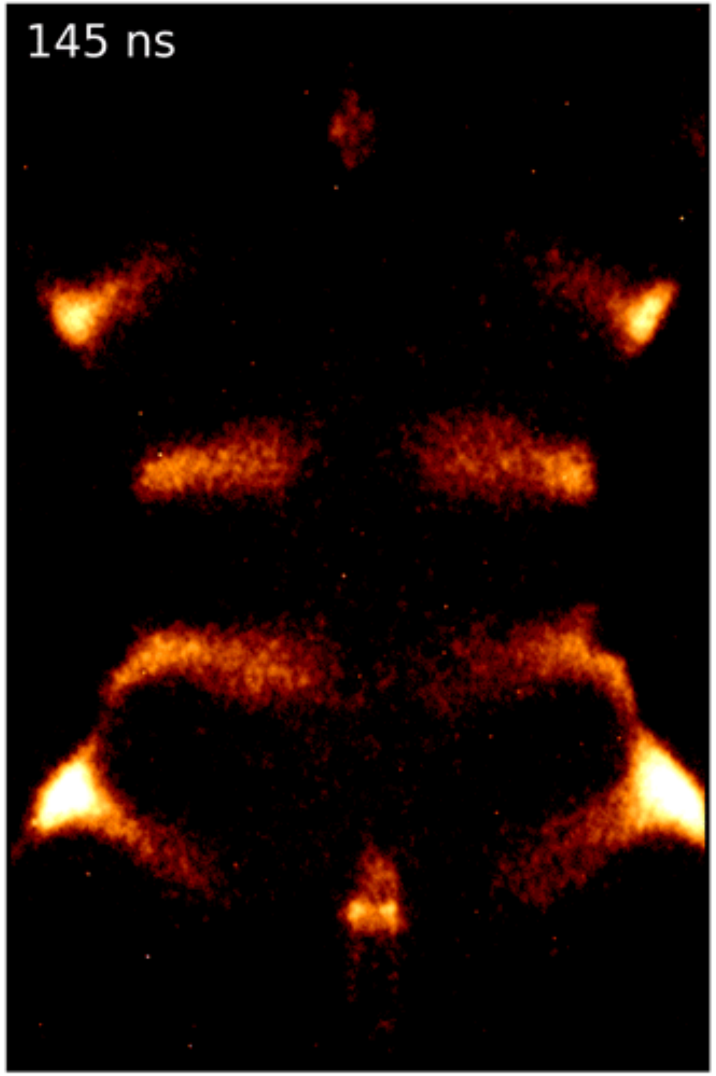
$\tau_{visc} \approx 800$ ns

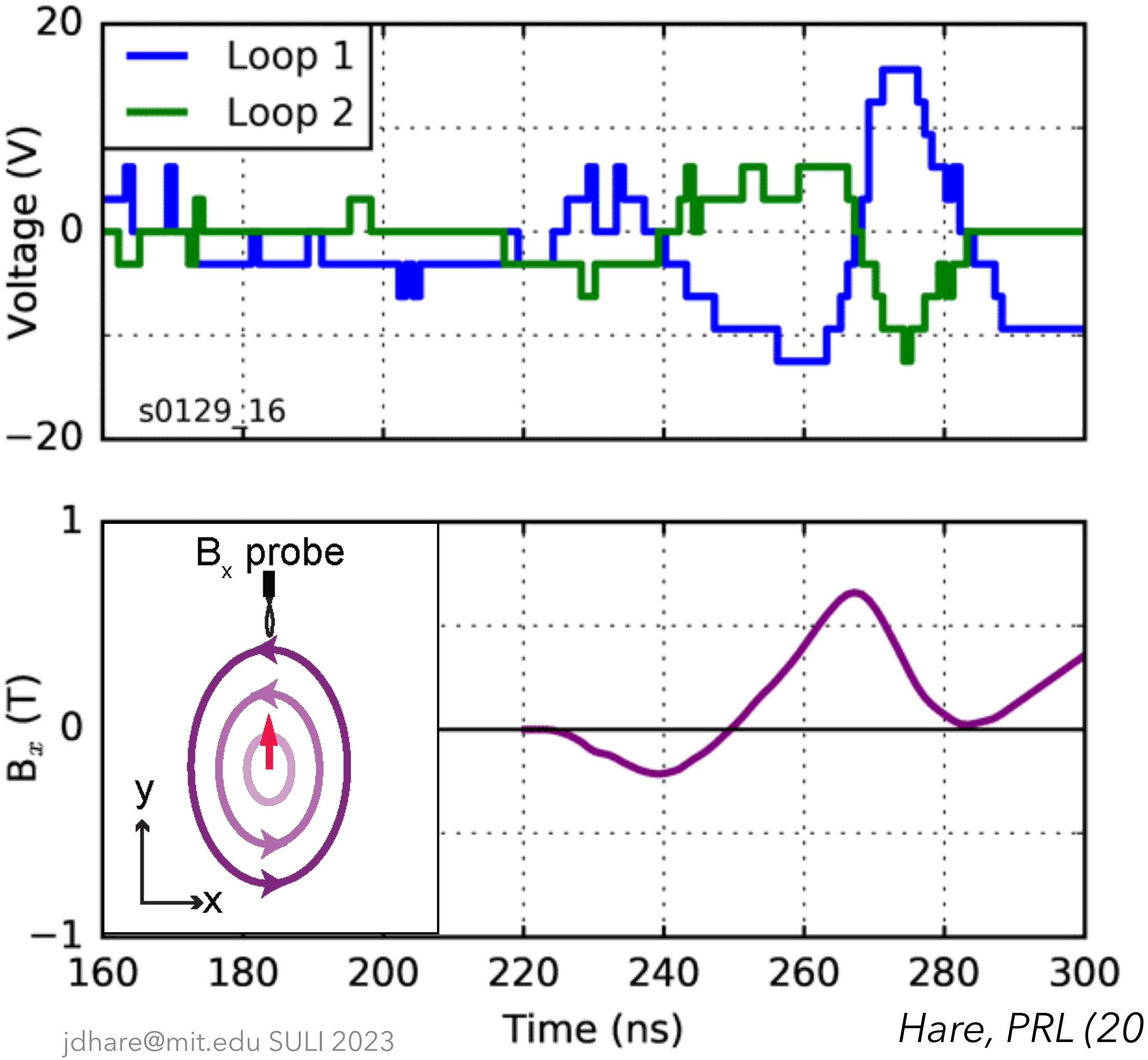
$\tau_{res} \approx 350$ ns

$\tau_{exp} \ll \tau_{visc}, \tau_{res}$

*Hare, PRL (2017)*

# Plasmoids observed in emission, density & B-field

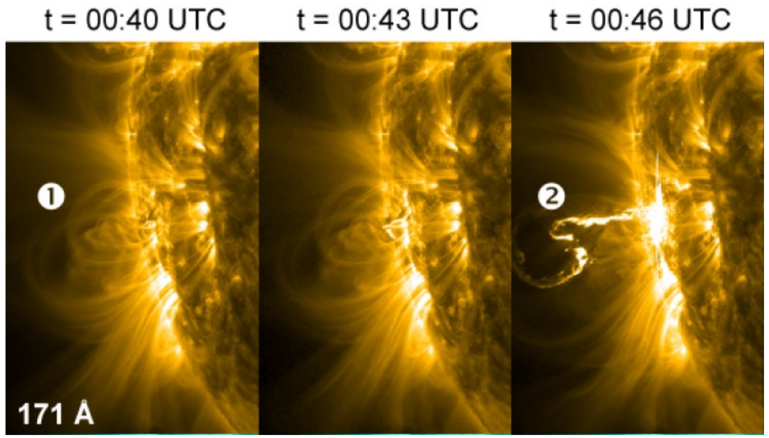


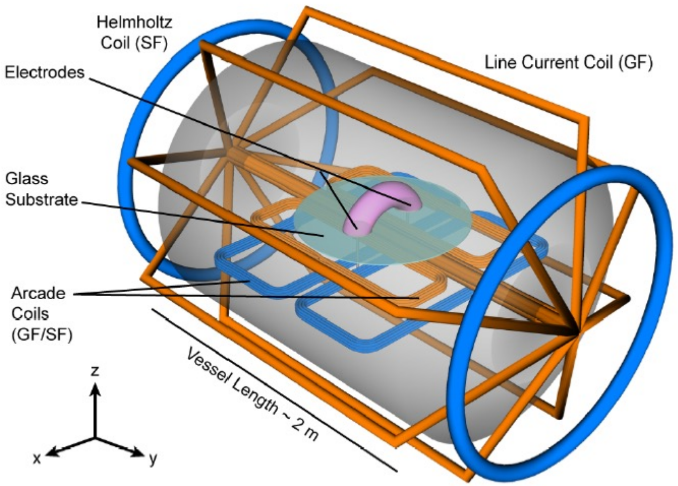




*Hare, PRL (2017)*

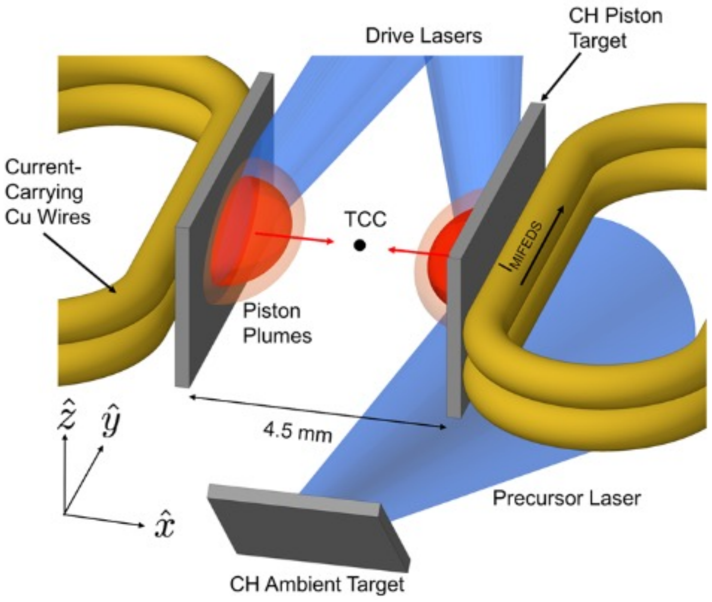
# Three laboratory astrophysics experiments

## Flux Rope Eruptions
*Myers, Nature (2015)*

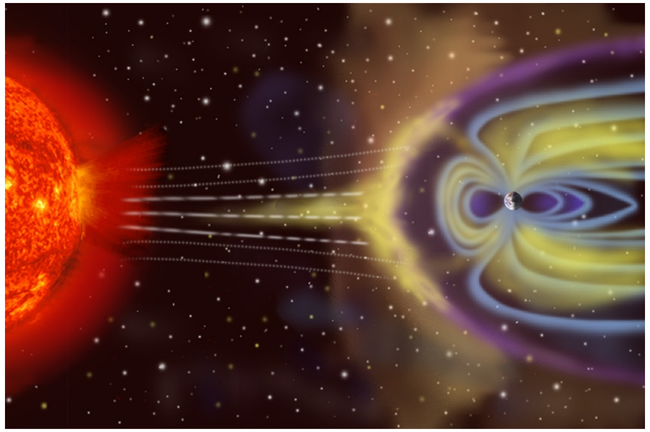


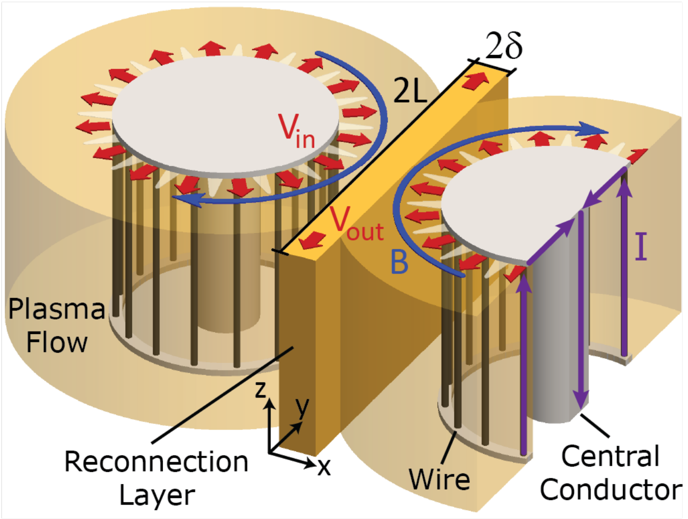




## Collisionless Shocks
*Schaeffer, PRL (2016)*

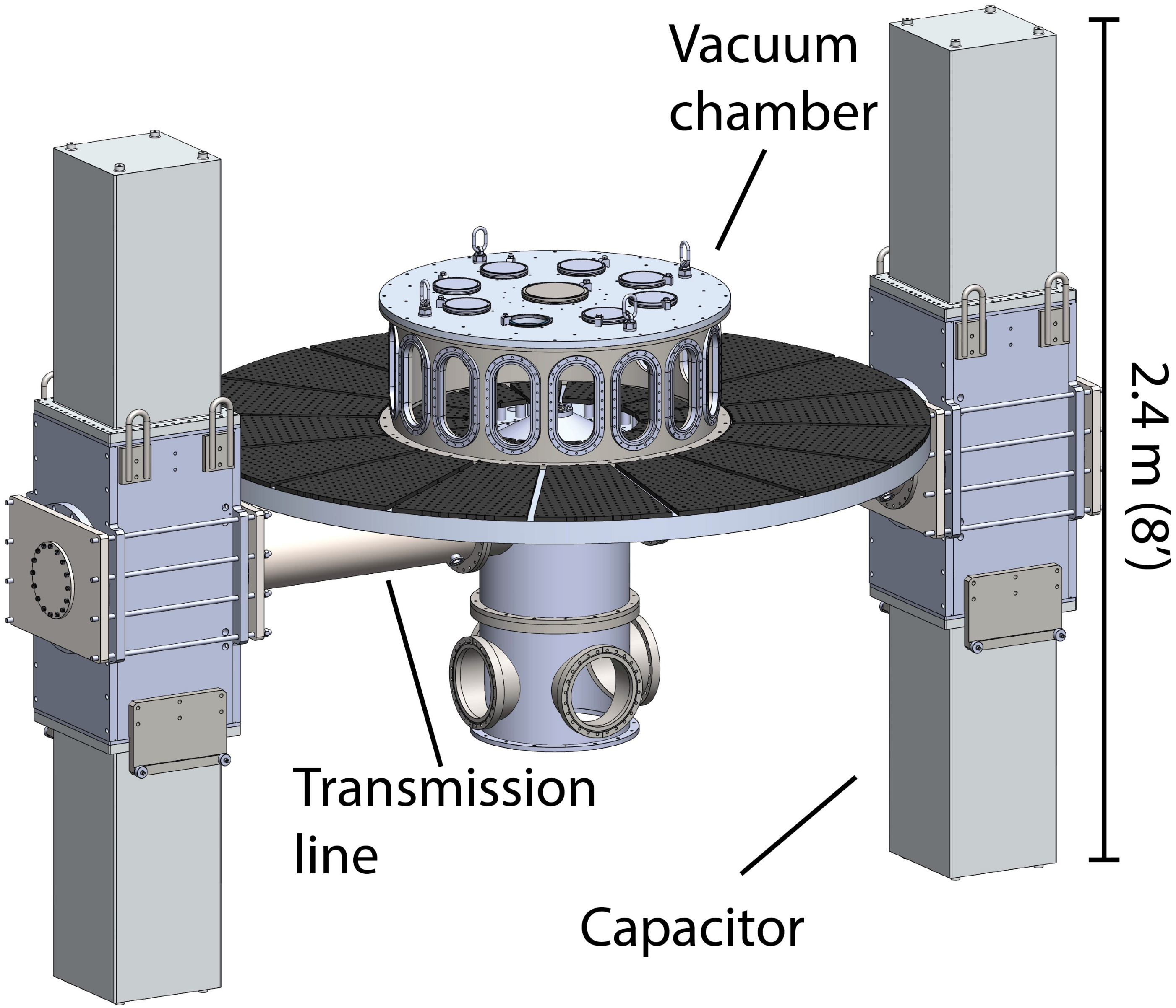


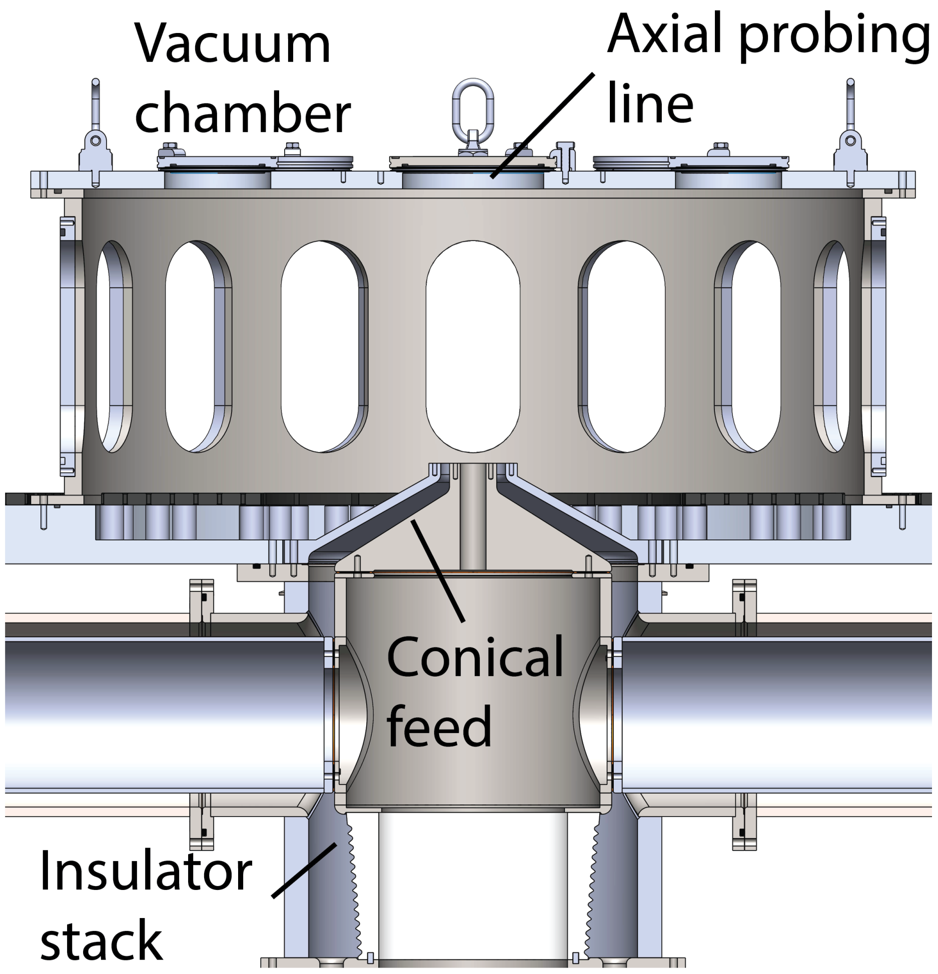

## Magnetic Reconnection
*Hare, PRL (2017)*





# PUFFIN will drive around 1 MA with a 1.5 μs rise time

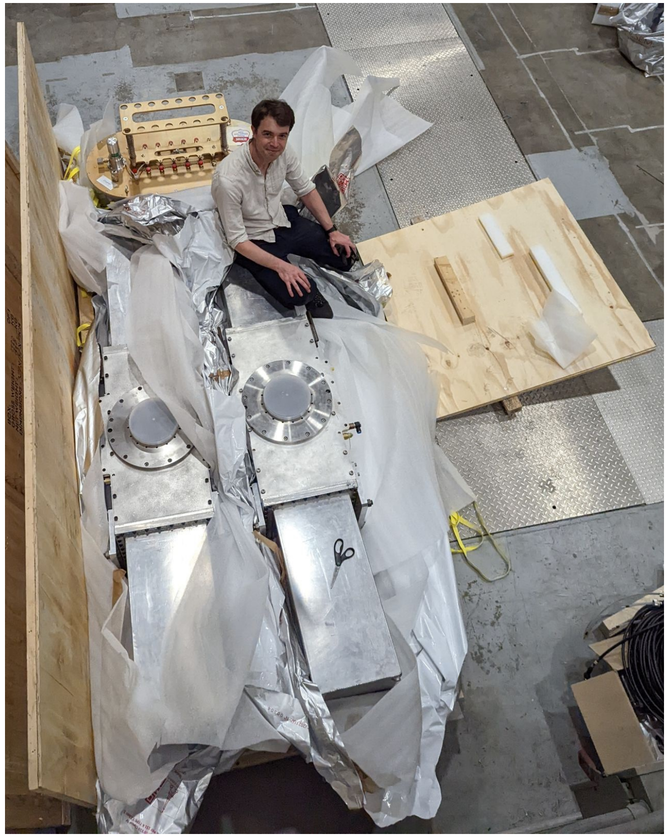



40 kJ energy to load

*puffin.mit.edu*

# Construction underway, aiming for first plasma in 2023



LTD5 modules arrived
May 2022

Mezzanine construction finished
September 2022

Laser barrier finished
March 2023

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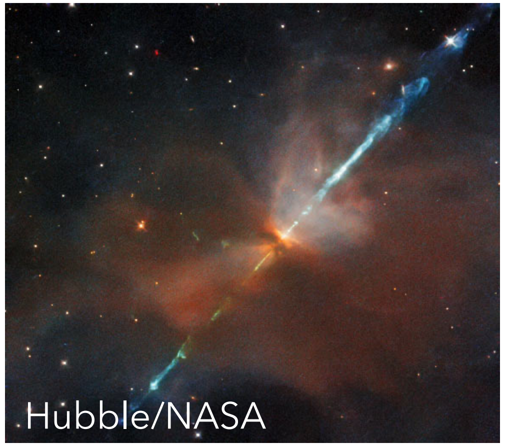
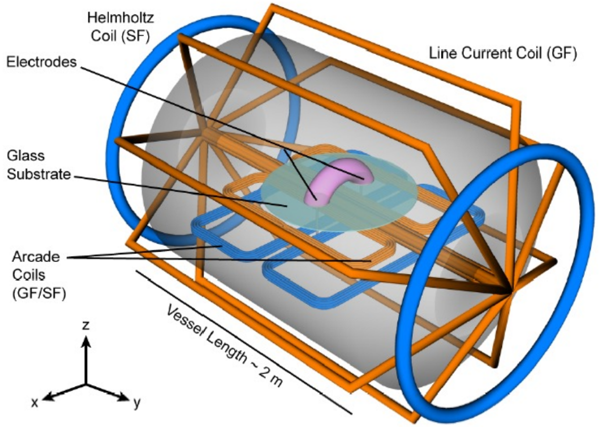
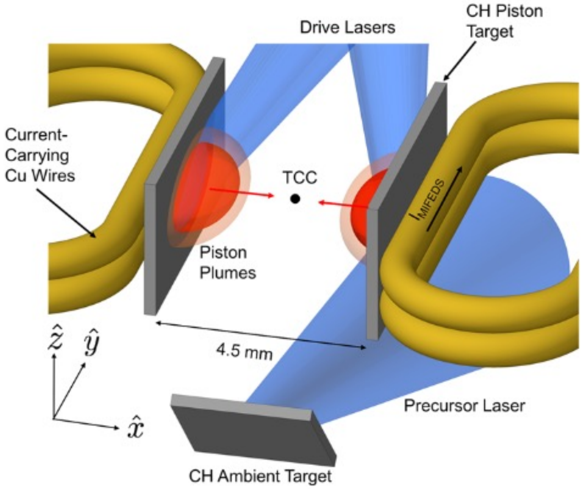
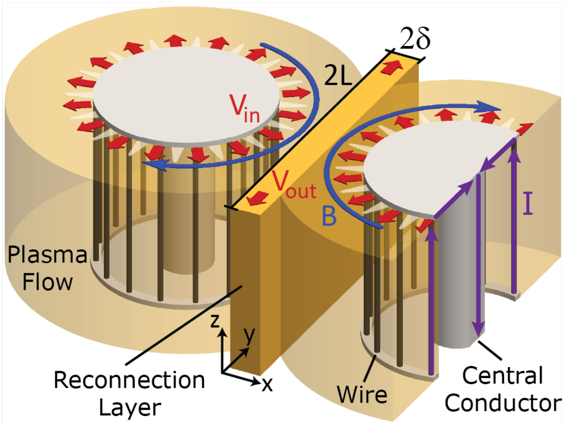
# Conclusions




- Laboratory experiments can give insight into astrophysical plasma processes
- Failed flux rope eruptions in gas discharge plasmas: a new regime!
- Collisionless magnetized shocks driven by lasers: first laboratory evidence!
- Magnetic reconnection driven by pulsed-power: fast heating and plasmoids!