Laboratory Experiments Relevant to Space, Solar, and Astrophysical Plasmas

Paul M. Bellan
Caltech

Importance

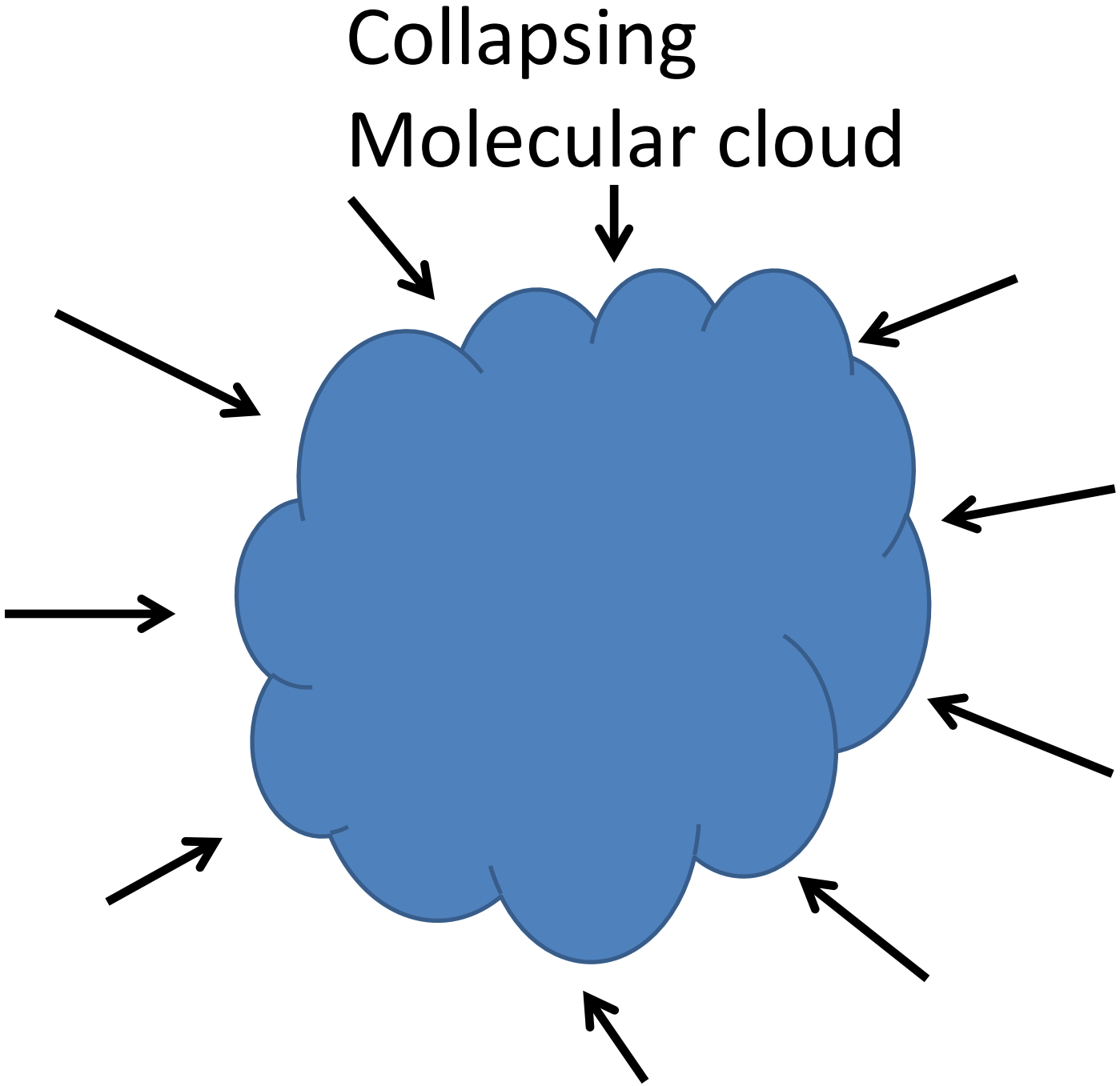
- Use acronym SSA to denote Space, Solar, and Astrophysical plasmas
- SSA plasmas are big (astronomical)
- Lab plasmas are human scale
- Despite size difference, lab plasmas can exhibit many phenomena relevant to SSA plasmas

Importance, cont'd

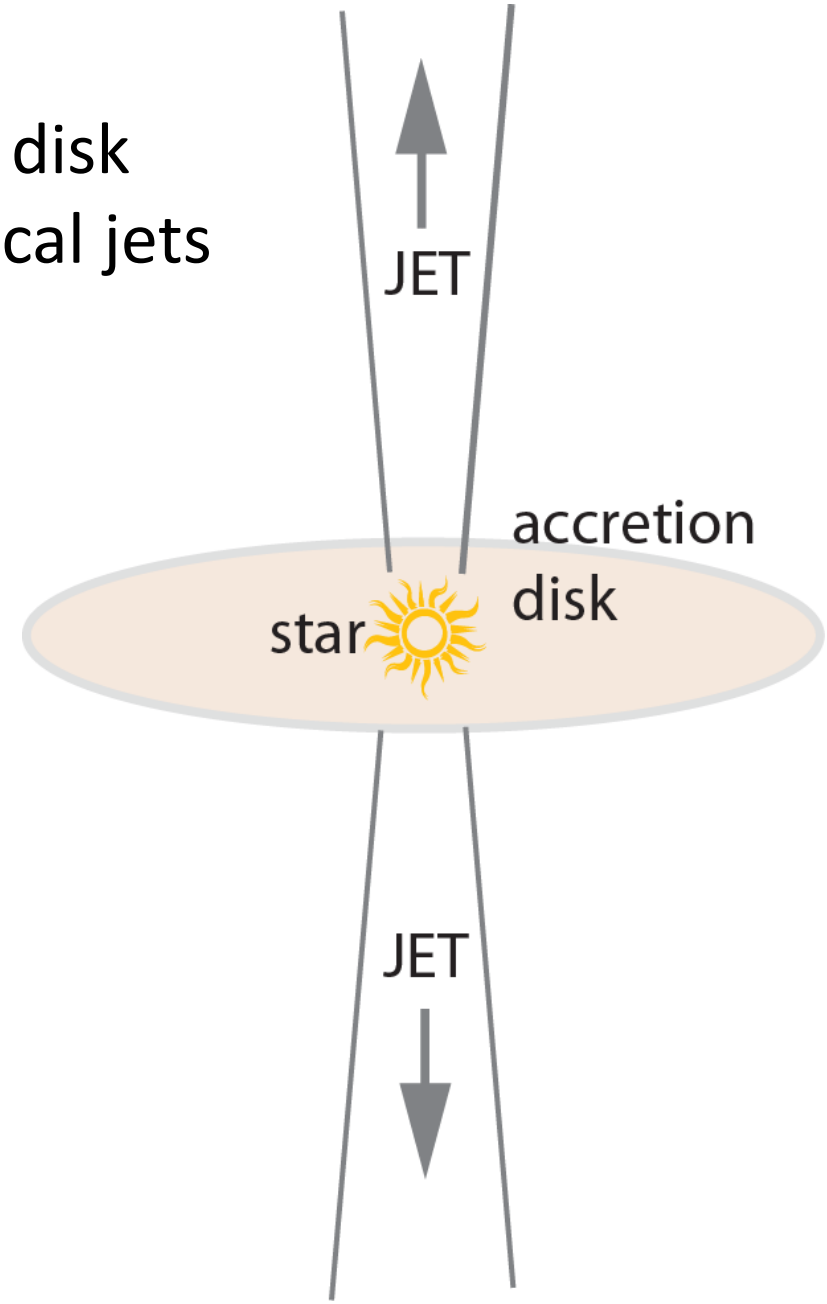
- Advantages of lab plasmas for studying SSA physics:
  - Reconfigurable
  - Controllable
  - Repeatable
  - Can be studied in great detail

Issues using lab plasma for SSA studies

- Making the plasma
- Diagnosing the plasma
- Modeling the observations
- Relevance to SSA plasmas

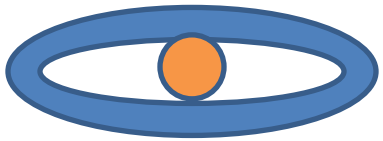

Collapsing
Molecular cloud

New-born star
with accretion disk
and astrophysical jets



Solar system

Planet with rings



Approach

- Make lab plasma governed by SSA physics
  - Similar dimensionless parameters
  - Similar geometry/topology boundary conditions
  - Do not expect exact match or precision
- Measure what is happening
- Compare to existing model

  or

  Construct new model
- When model and observation match, have confidence in model
- Can apply model to SSA situation

SSA plasmas differ from fusion and traditional lab plasmas

	Fundamental & fusion plasmas	**SSA plasmas**
State	Equilibrium	Non-equilibrium, dynamic
Geometry	High symmetry	Often not symmetric
Homogeneity	Quite uniform	Have interfaces
Wall interactions	Minimized	Critical
Topology	Set by chamber	Can change

Example SSA plasmas simulated at Caltech

1. Ice dusty plasmas (Saturn rings, noctilucent clouds)

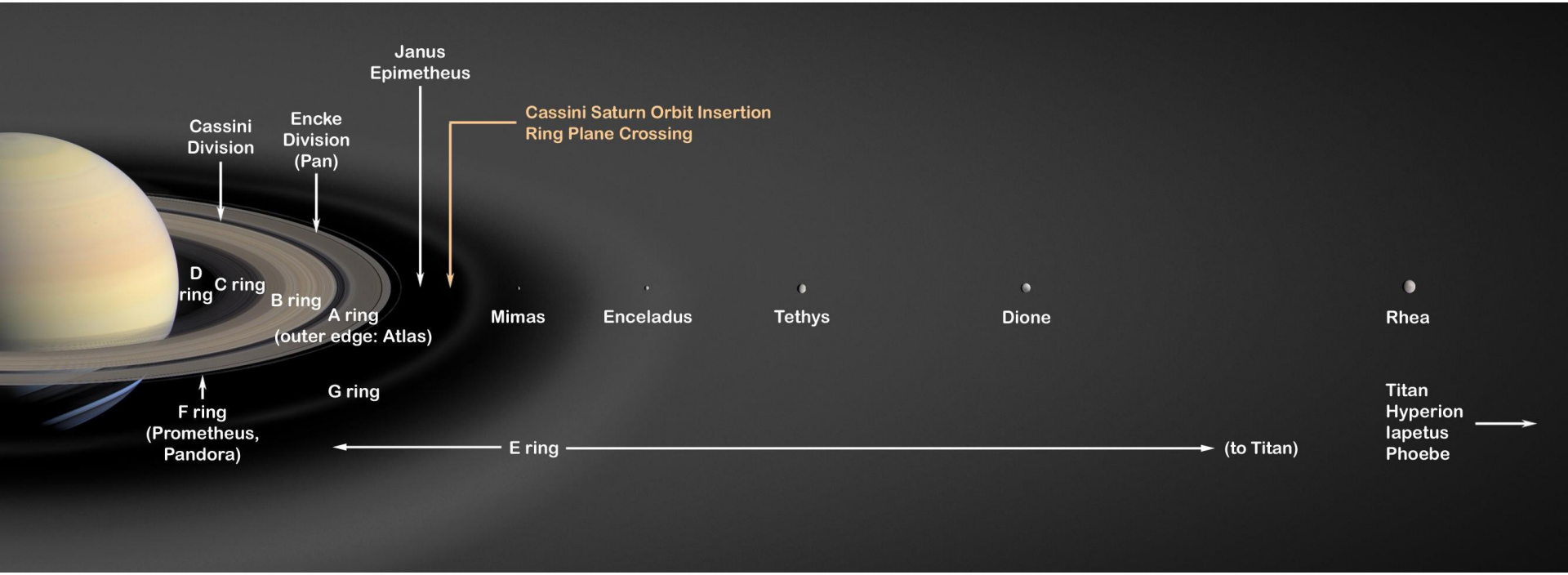
2. Solar corona loops (eruption causes space weather)

3. Astrophysical jets (from new-born stars, black holes)

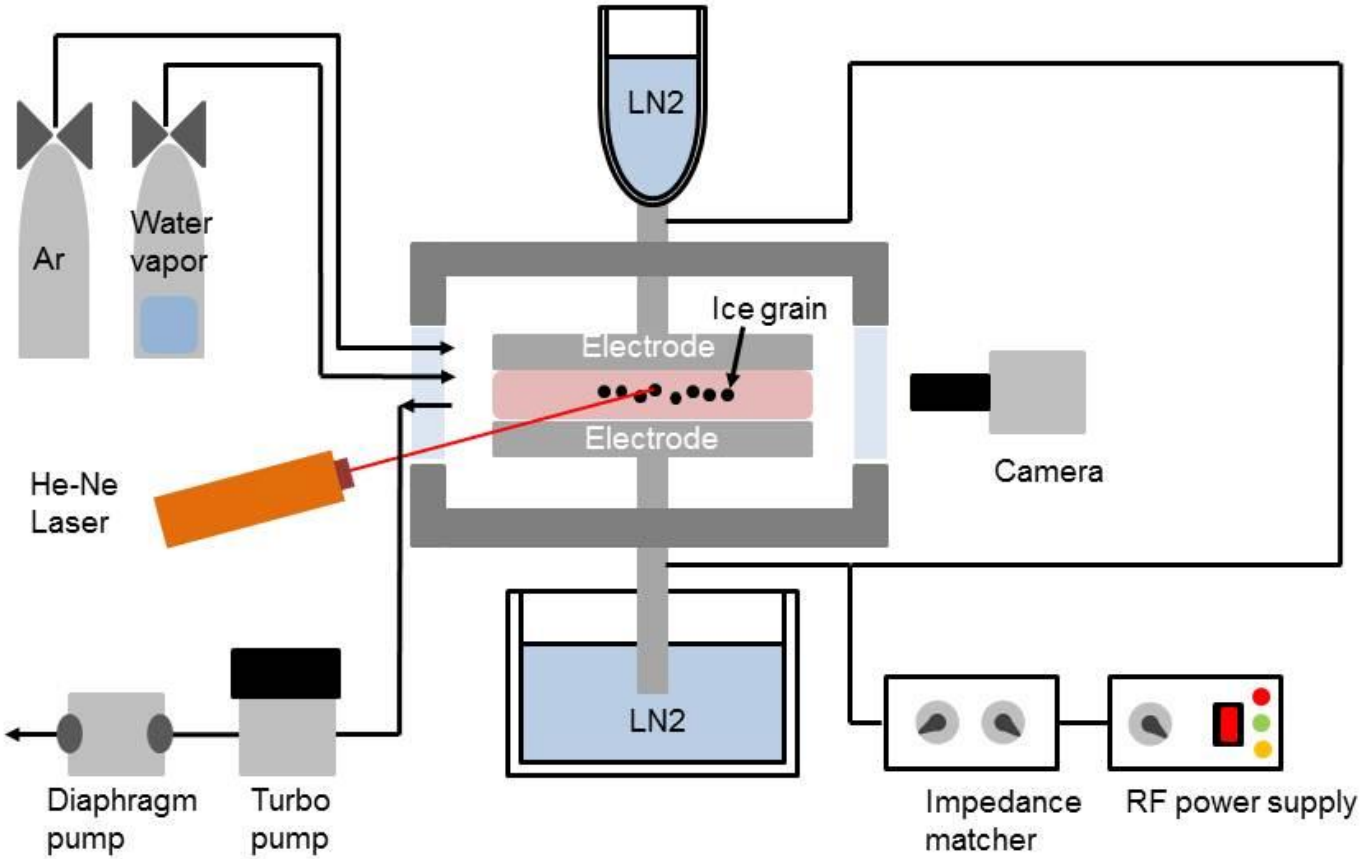
Ice Dusty Plasma

Noctilucent clouds

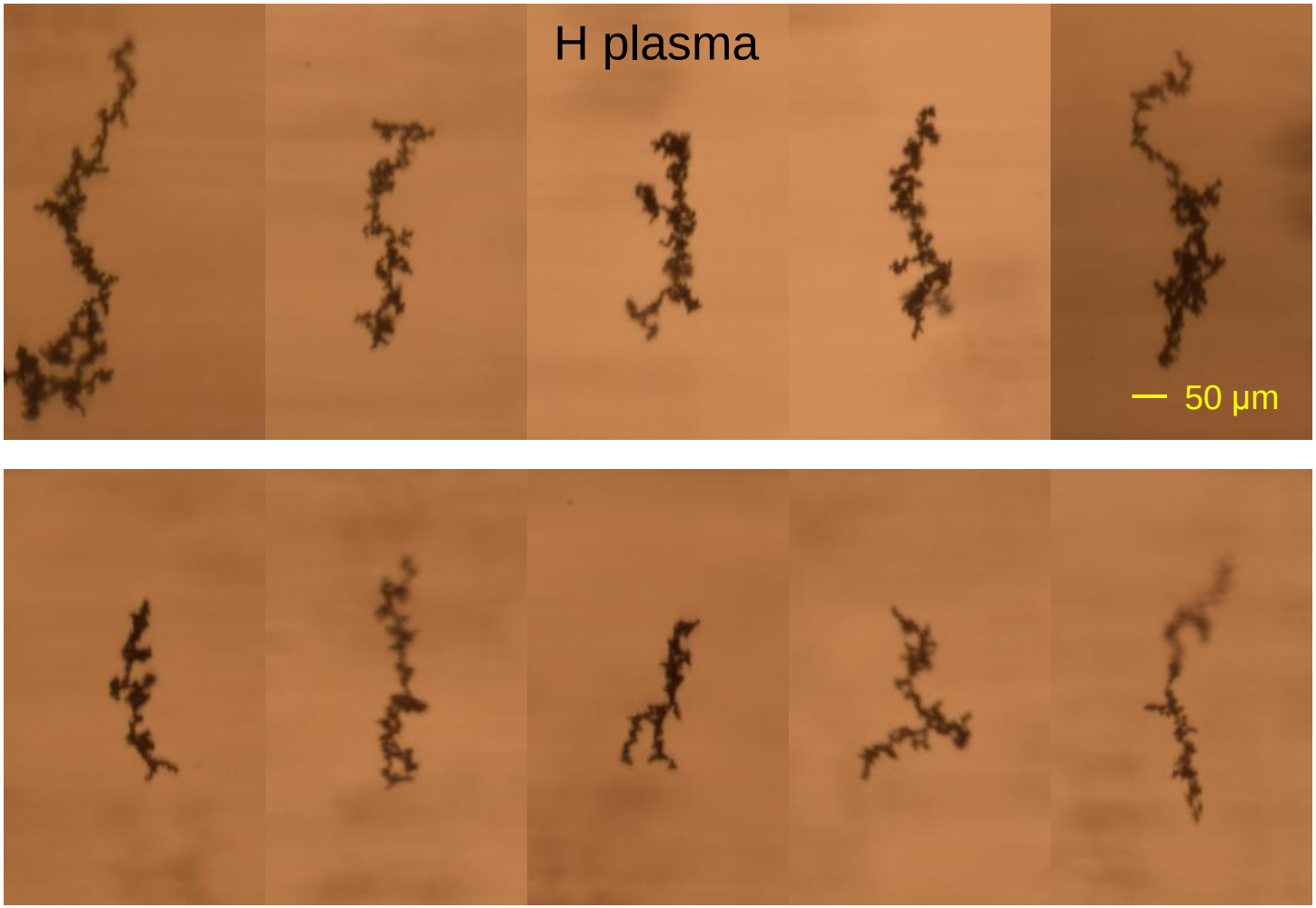
Diffuse rings of Saturn



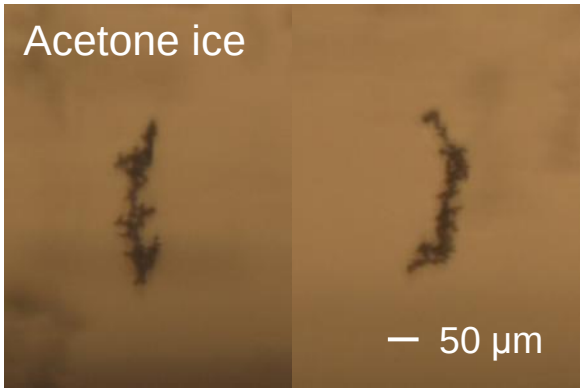
Ice dusty plasmas

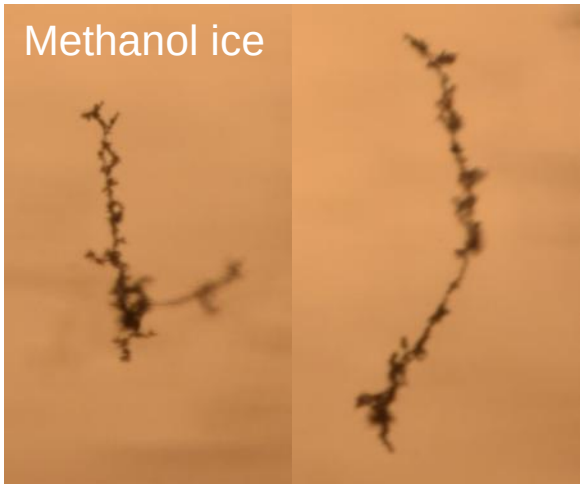


Spontaneously formed ice grains in plasma



Non-water ice dusty plasmas





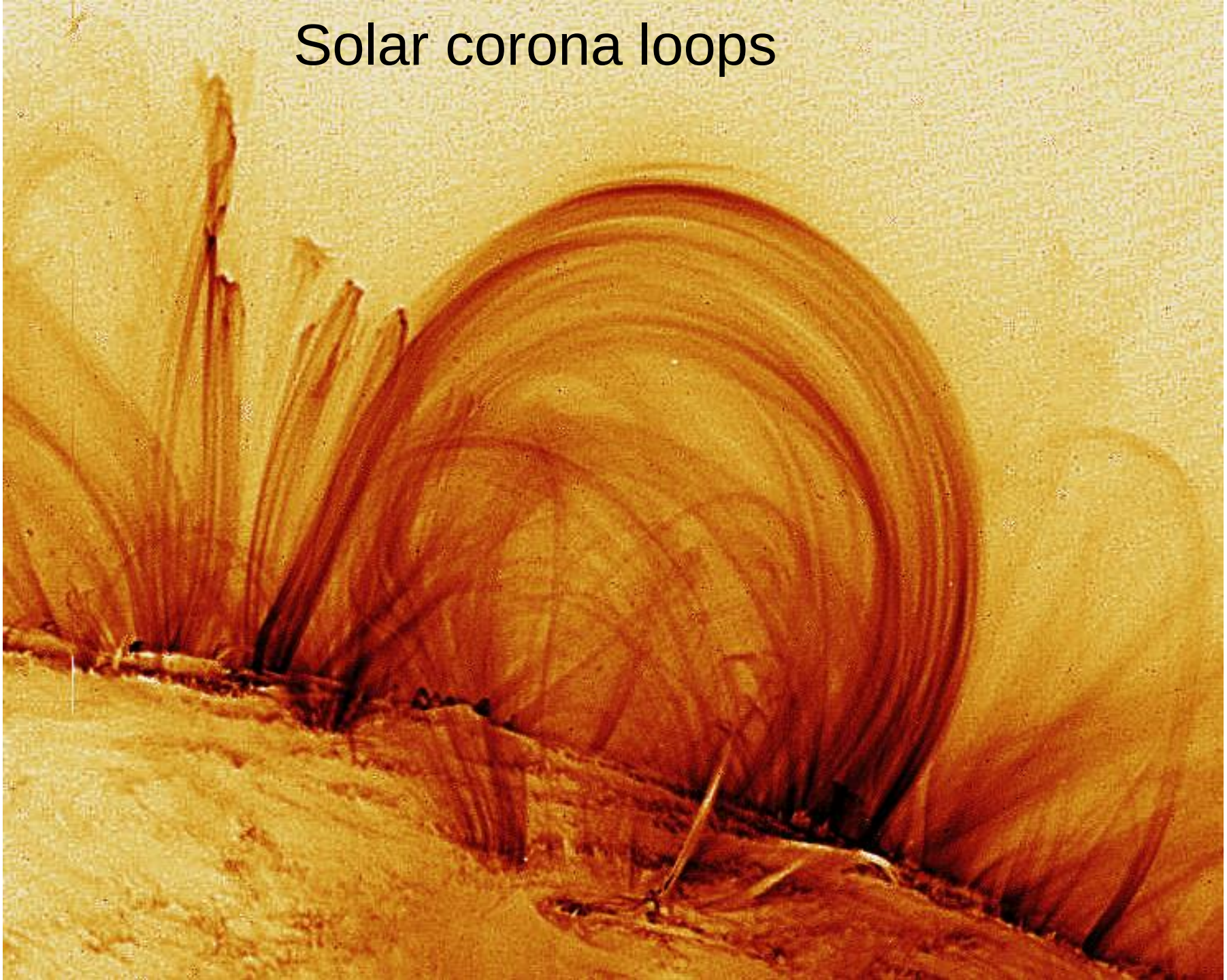
Questions

What determines non-spherical shape?
(most theories assume grains are spherical and argue about size)

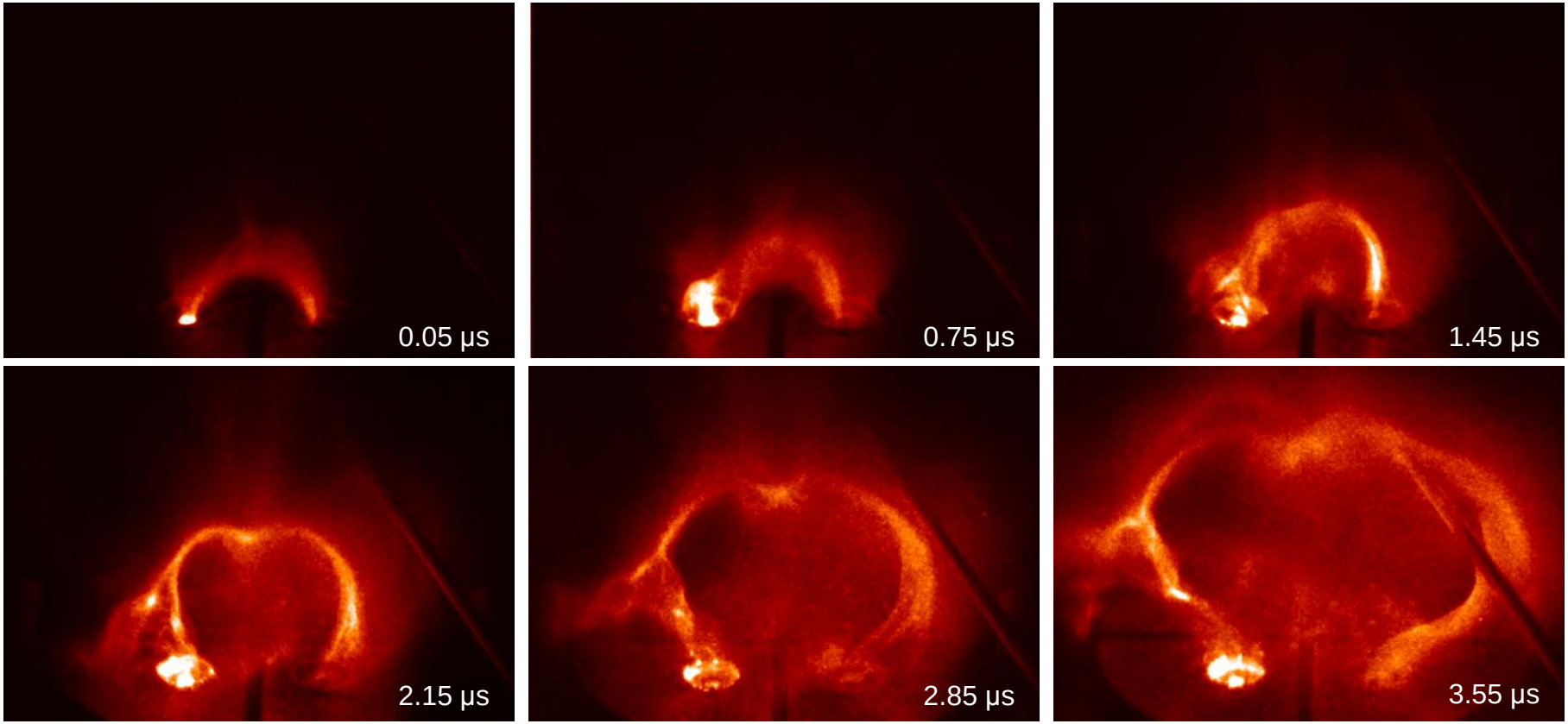
Is there some way they can still agglomerate to make large structures?
(Ice grains are charged with same sign so they repel)

How do ice grains interact with electromagnetic radiation?
(can this explain polarization of radiation)

Solar corona loops



Evolution of a lab plasma loop



What force or forces are behind this behavior?

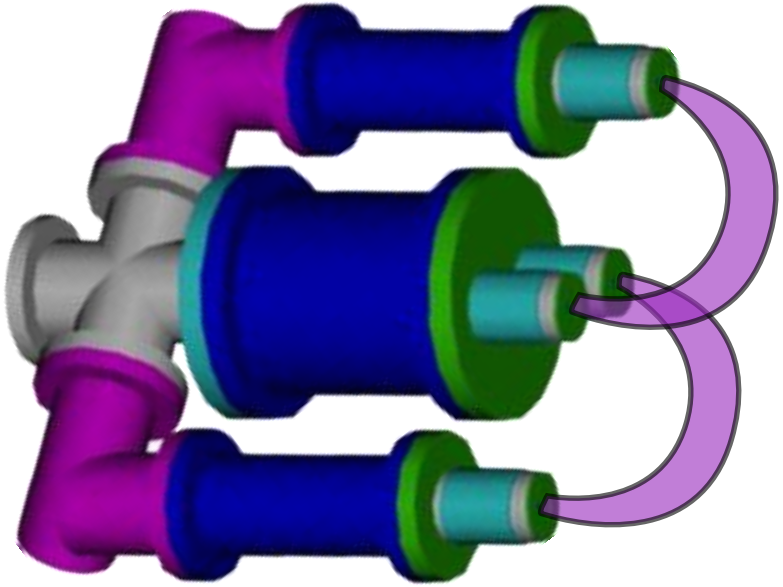
Where is plasma mass coming from?

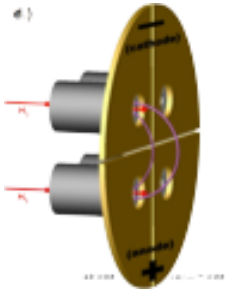
Solar corona loops

How do two solar loops interact?

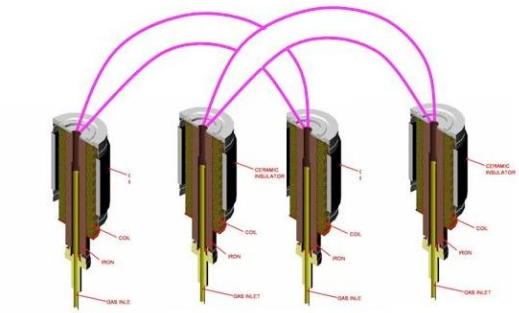
Crossed Flux Tube Experiment

- Adjacent plasma loops
- Staggered instead of side by side
- “Candelabra” shape
- Central electrodes pivot
- Observe reconnection dynamics

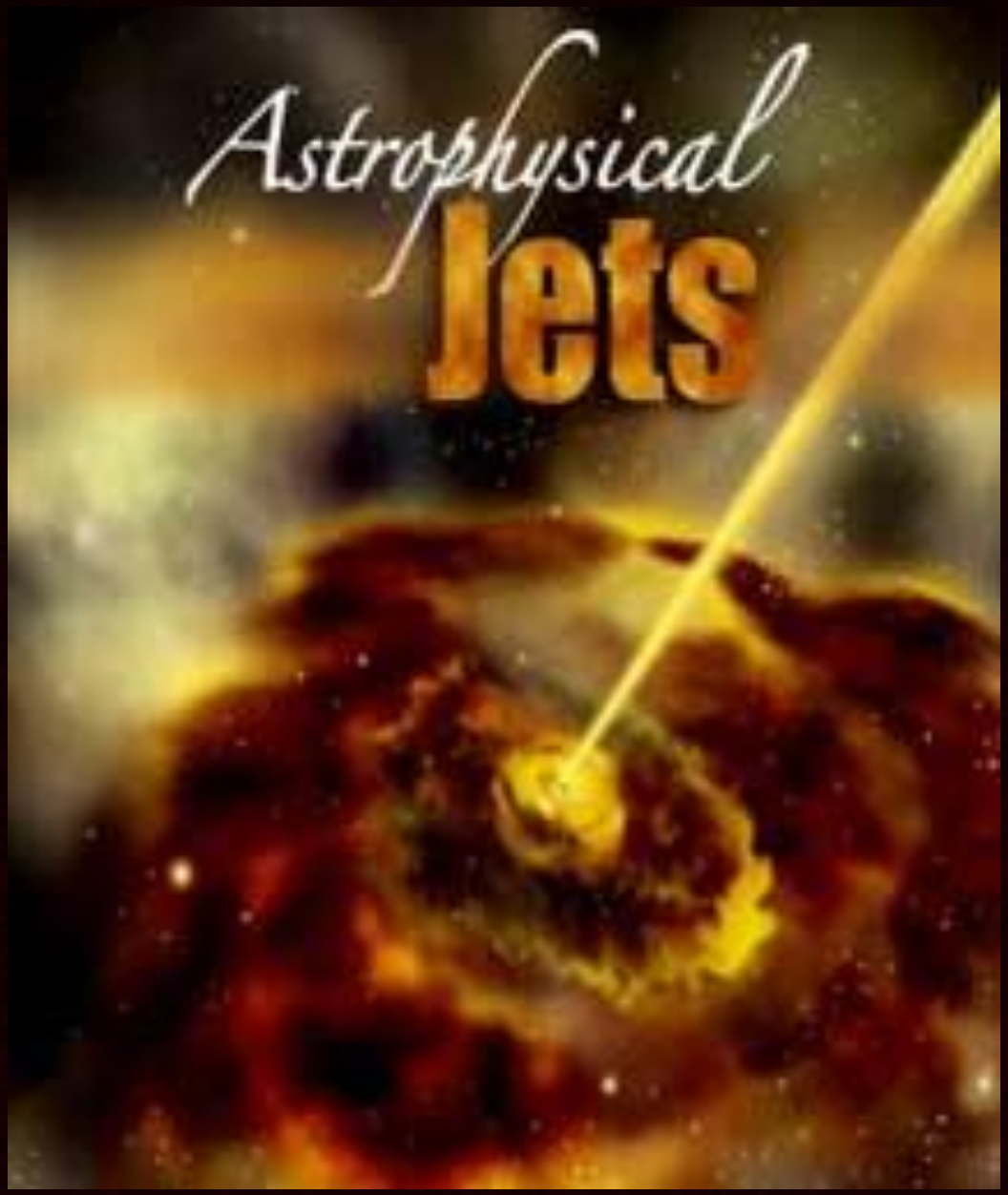


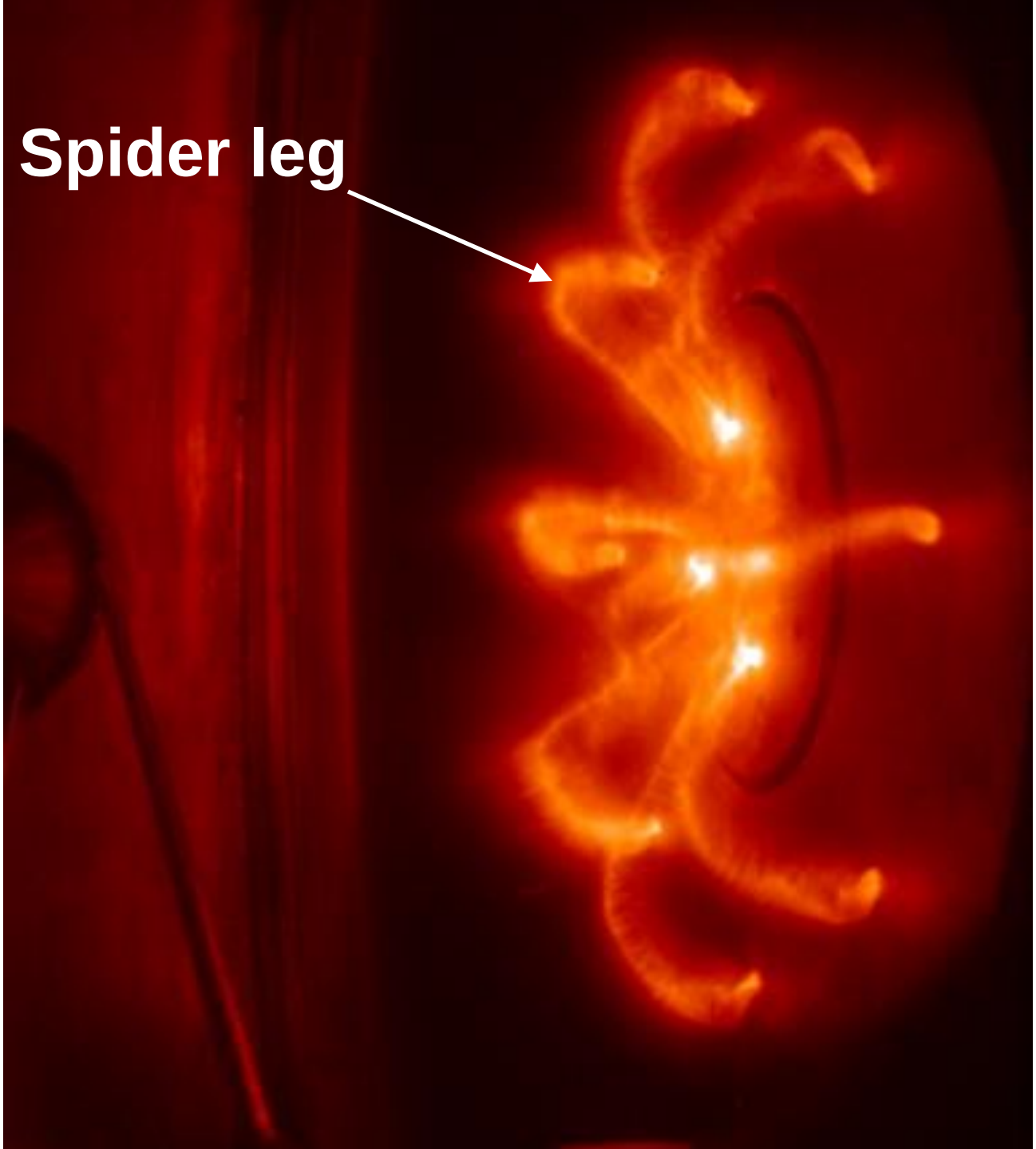


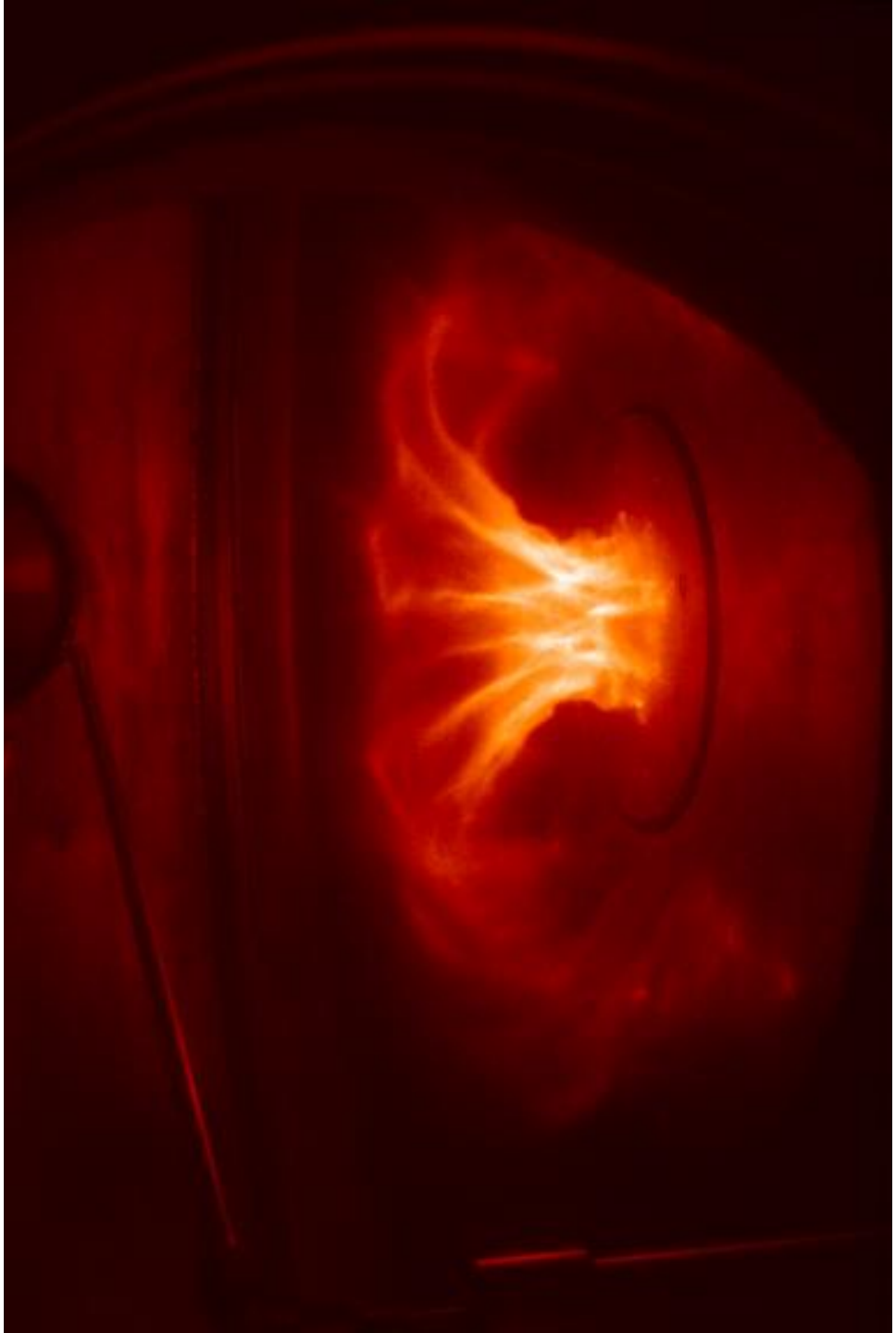
Schematic of experimental set-up (not to scale, not in 3D)

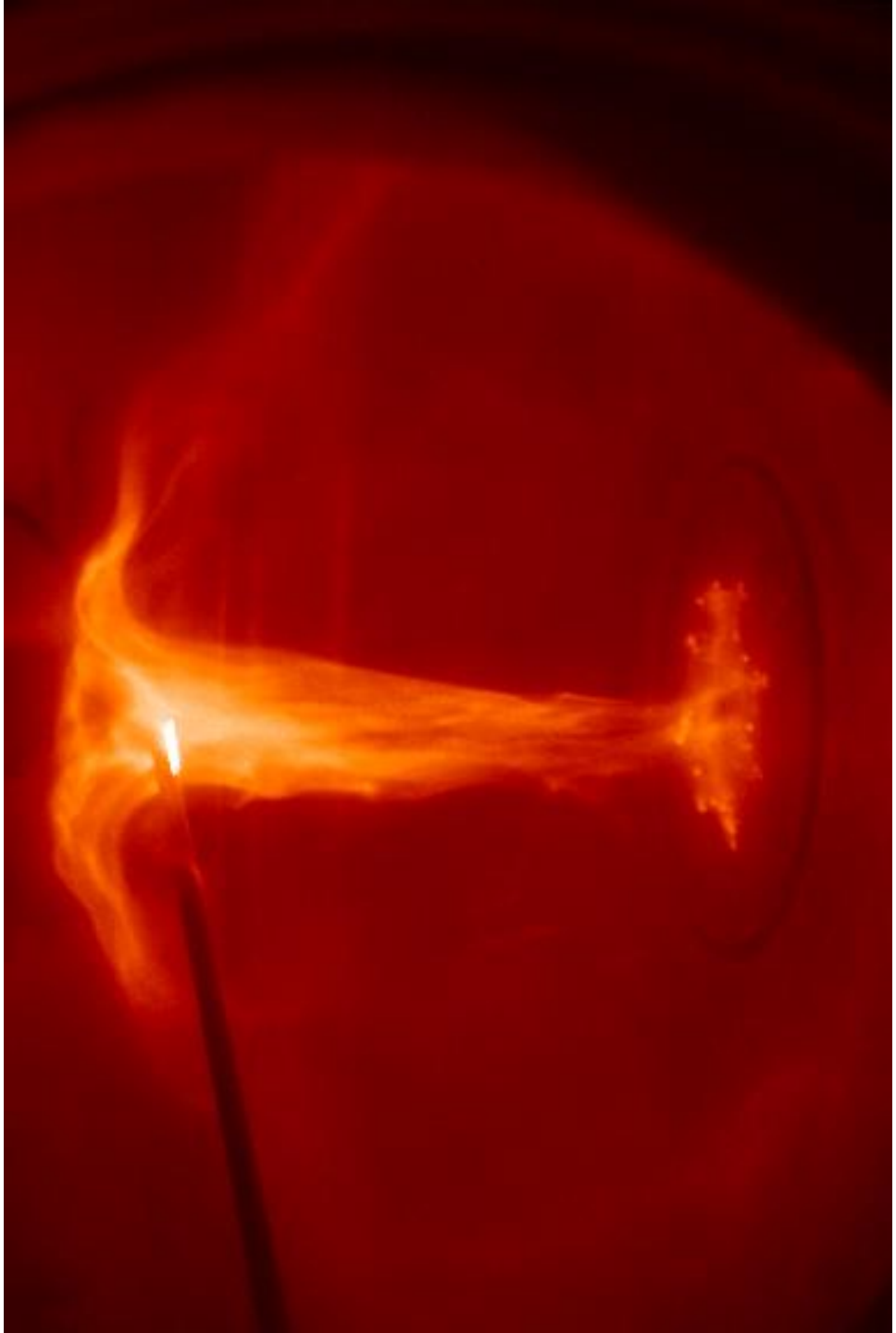


P1	P2	M1	M2
+5 kV	0 volts	0 volts	-5 kV
Positive magnetic polarity	Positive magnetic polarity	Negative magnetic polarity	Negative magnetic polarity


Astrophysical
Jets

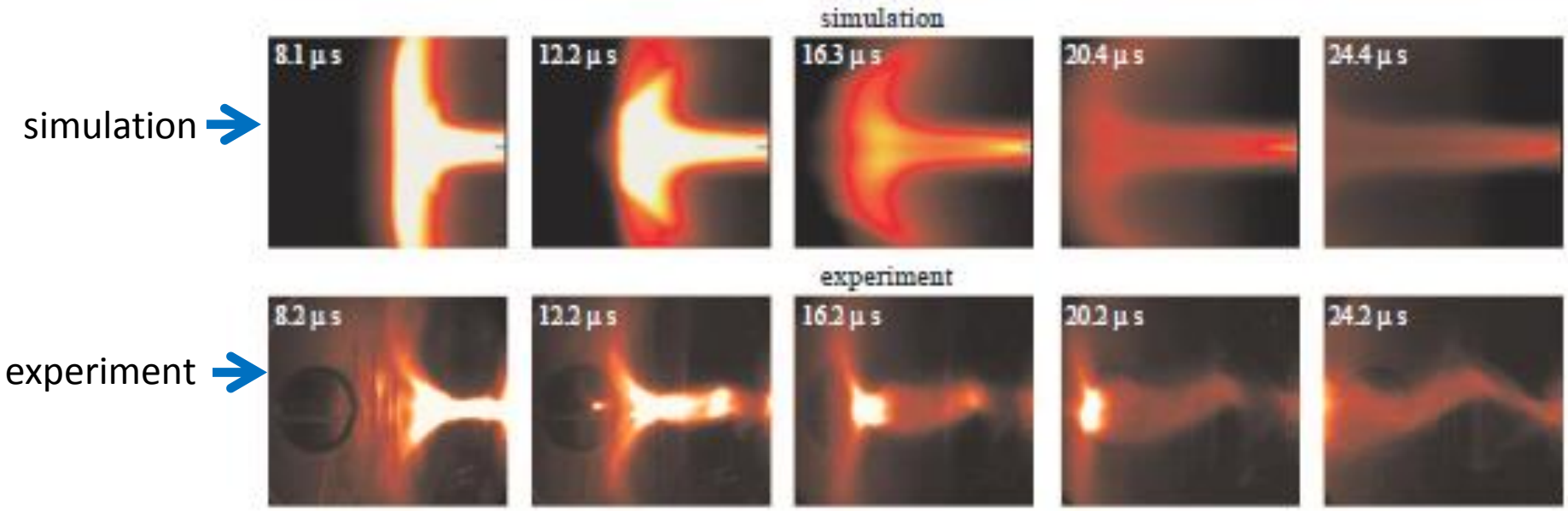

Spider leg





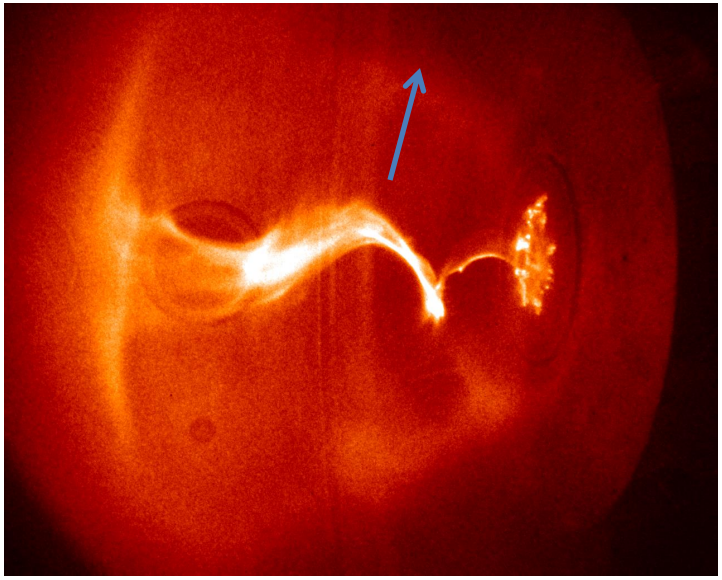
Numerical Simulation

- MHD equations solved on 800^3 3D grid
- Modified astrophysical jet code
- Axisymmetric regime (i.e., before kink)
- Good quantitative agreement (velocity, density, profiles, fields, current, Bernoulli relation,…)



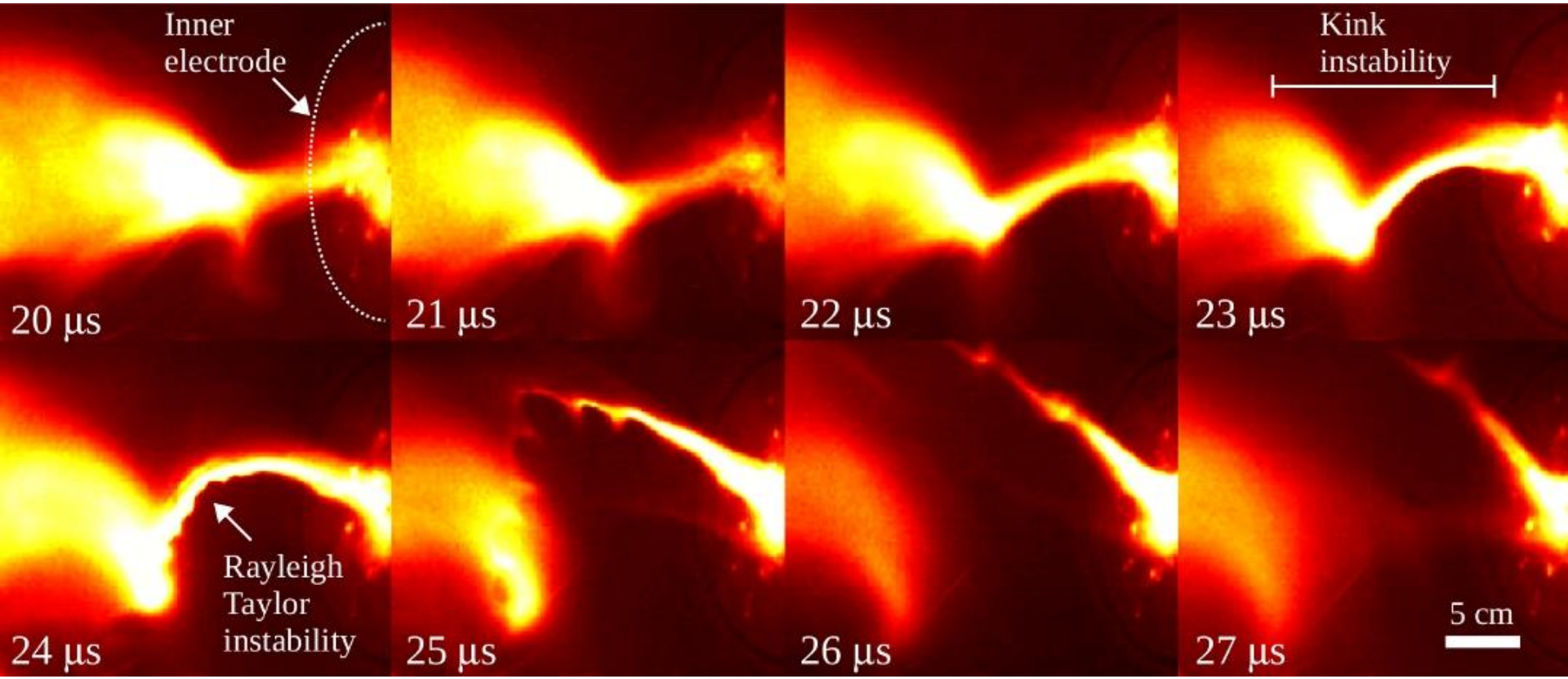
Zhai, Li, Bellan, Li, ApJ 2014

Kink instability involves lateral acceleration of plasma



Observer sitting on plasma would be in an accelerating frame
- would feel an effective gravity

- Heavy fluid on top of light fluid causes Rayleigh-Taylor instability


Inner
electrode
Kink
instability
20 μs
21 μs
22 μs
23 μs
Rayleigh
Taylor
instability
24 μs
25 μs
26 μs
27 μs
5 cm

Questions:

How are astrophysical jets related to accretion?

How are astrophysical jets related to removal of angular momentum of accreting material?

Are astrophysical jets describable by magnetohydrodynamics?

What happens when astrophysical jets become relativistic?

What happens when astrophysical jet impacts a molecular cloud target?

Different, unexplored Physics

- Solar loop, astrophysical jets:
  - -not in equilibrium
  - -strong interaction with boundary
  - -shape changing with time
  - -MHD and non-MHD physics interact
- Ice dusty plasma
  - -heterogenous, macro & micro combine
  - -ice size depends on plasma parameters
  - -ice self-organizes, captures electrons

Needs

- Better diagnostics
  - Non-perturbing imaging of magnetic field
  - Imaging of plasma
  - 3D measurements (not line-integrated)
- Exotic inputs
  - Improved cryogenics to cool ice dusty plasma
  - Laser tweezers to hold ice grains in place
  - High speed cameras to capture motion
- Do not need large experiments, just imaginative

Impact

<u>MHD jets, loops</u>

- Understanding highly heterogeneous plasmas gives predictive ability for real situations
  - E.g., mass flux from a surface into plasma
  - Two plasmas colliding
- Societal impact
  - Space weather can destroy power grids, damage spacecraft, endanger astronauts
- Star and planetary formation
  - Accretion disks associated with astrophysical jets
  - Planets form from accretion disks

Impact, cont'd

<u>Ice Dusty Plasma</u>

- Saturn's rings
  - Understand formation,
    interaction of ice with plasmas
- Accretion disks
  - Contain ice particles, dusty plasma
  - Agglomeration, planet formation
- Noctilucent clouds
  - Terrestrial phenomenon at edge of space
  - Interacts with sodium layer, big radar reflection

Conclusion

Lots of opportunity

Little has been done

Possibility for big impacts