The Importance of Being Opportunistic

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Bringing Space Down to Earth:
Exploring the Physics of Space Plasmas in the Laboratory

Three types of experiments

1. Experiment to validate existing theory/model
2. Experiment to exploit new diagnostic
3. Experiment to survey parameter space

All three methods are good

- In lab experiments most attention has been given to theory validation
- Typically, theory person says to lab person “why don’t you look for such and such a phenomenon…”
- Proposals usually plan to validate a model

Other methods not used enough

- Other methods involve discovery
  - "following your nose", "curiosity", "opportunistic"

- Advantages of discovery:
  - Unbiased: not trying to verify a model
  - Seeing what really happens, not what one wants
  - Complex inter-relations become apparent: see how different phenomena influence each other, sequence of events, multi-scale, non-linear

Additional thoughts

- Research should have highs and lows
  - not an automobile assembly line with steady output
- Must take risks, not everything will work
- Experiments need to be clean, have clear results
- Importance of persistence & detective work
  - follow a trail where it goes
  - try again if not successful first time, iterative improvement
- Develop theory/models inspired by experiments
- Develop new diagnostics as required
- Incorporate advanced numerical models
  - by self or by collaborations

Space relevance

- Wasteful to attempt to duplicate space environment exactly, typically not possible
- Better to get similar regime
  - get new insights/understanding, not scale model
- Invert process: First get interesting results
  - then find a relevant space situation
  - often possible, since many space environments
  - i.e., get answer, then search for question
- Go to space plasma conferences
  - get out of comfort zone, be outsider
  - persistence needed, does not work first time

Caltech experimental program as example of this strategy

Topics

1. MHD-driven jets

2. Collisionless magnetic reconnection
   -associated whistler physics, heating, X-rays

3. 3D magnetic field measurement
   - axial thrust mechanism

4. Shocks from expanding loops colliding with target

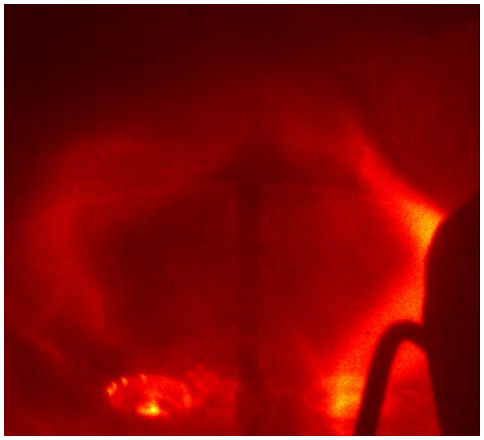
5. MHD simulation of single loop

6. Spacecraft method for measuring wave **k**-vector
   -used by MMS spacecraft, Nature Communications paper March 2017

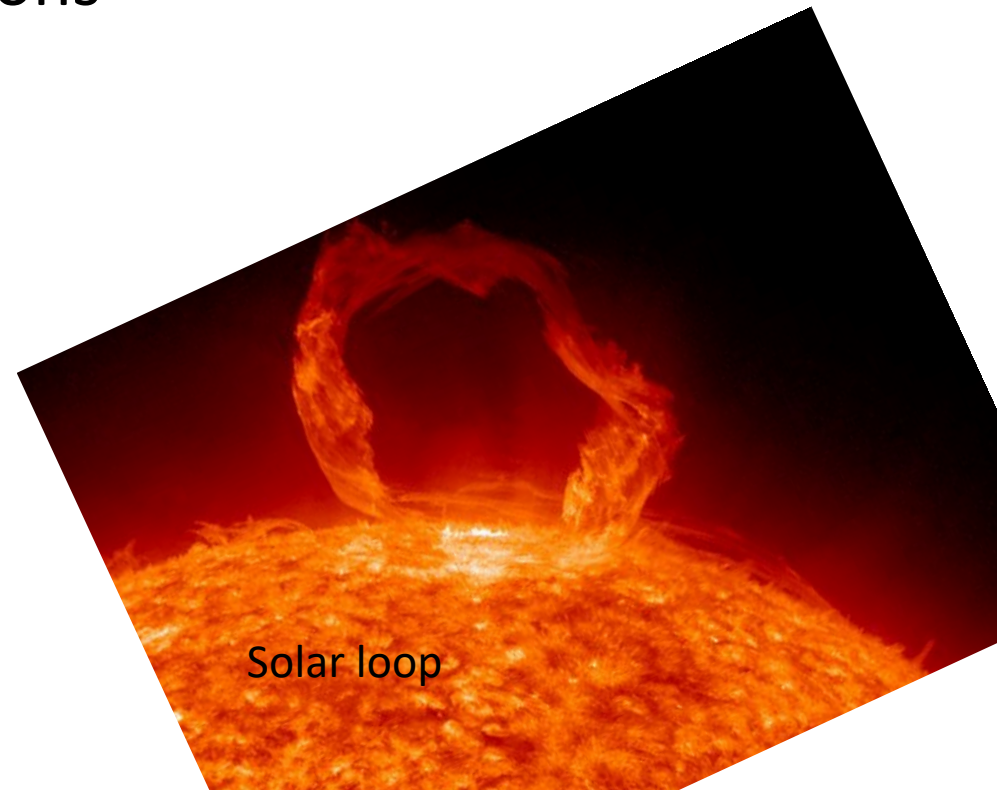
7. Ice dusty plasma

MHD has no intrinsic scale: exploit this

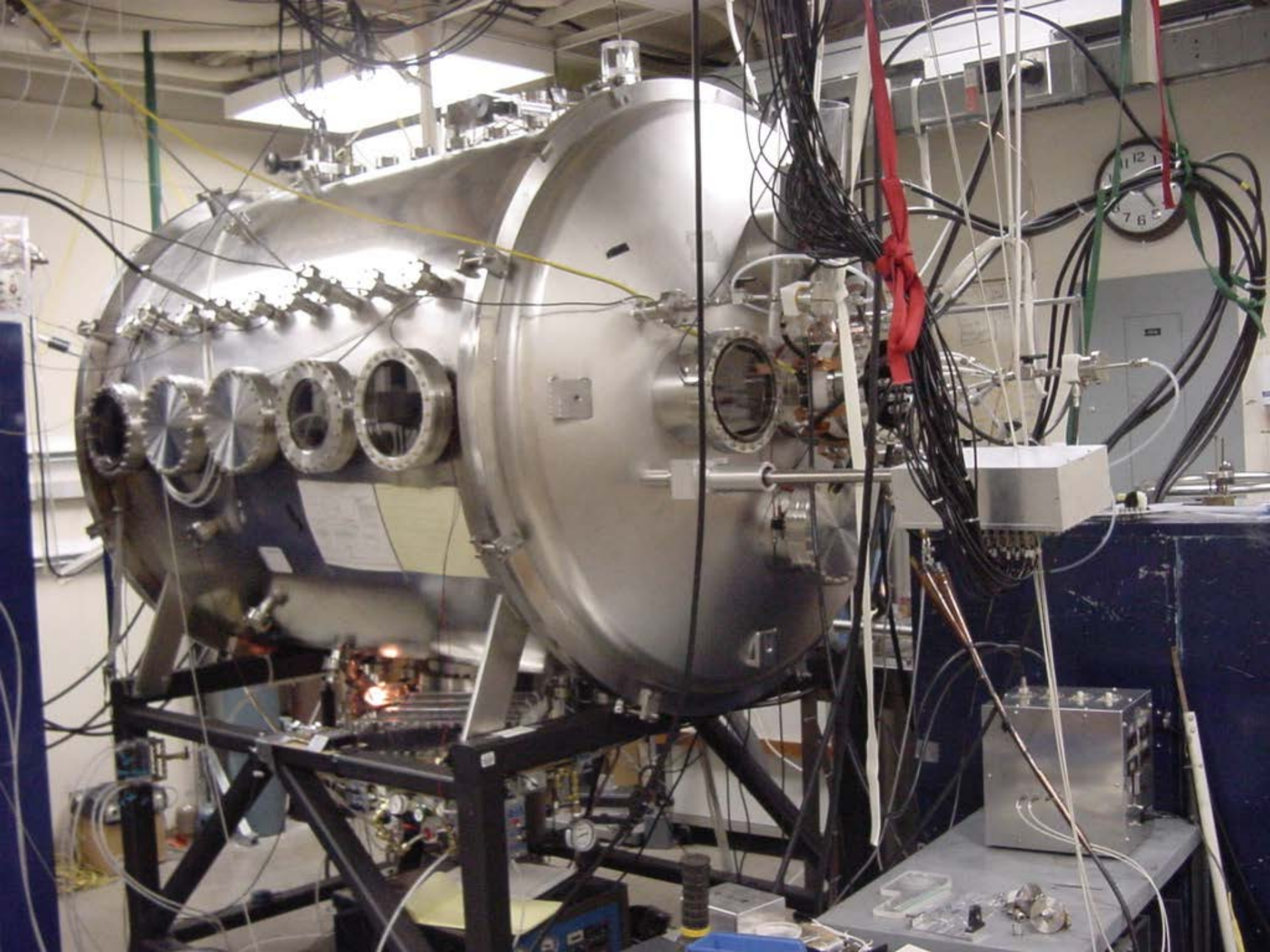
- Space relevant: physics/topology/dynamics:
  - frozen-in flux
  - magnetic forces dominate
  - boundary conditions



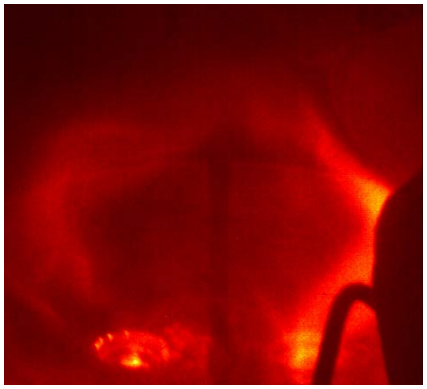
Laboratory loop



Solar loop

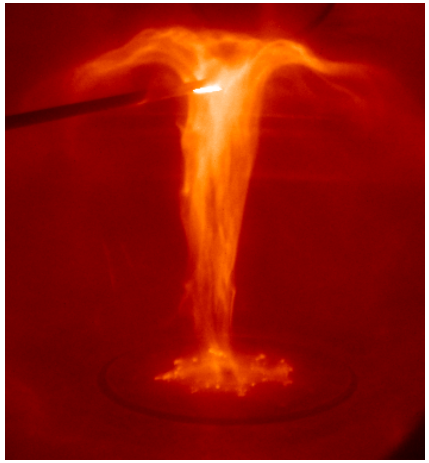


Nominal parameters

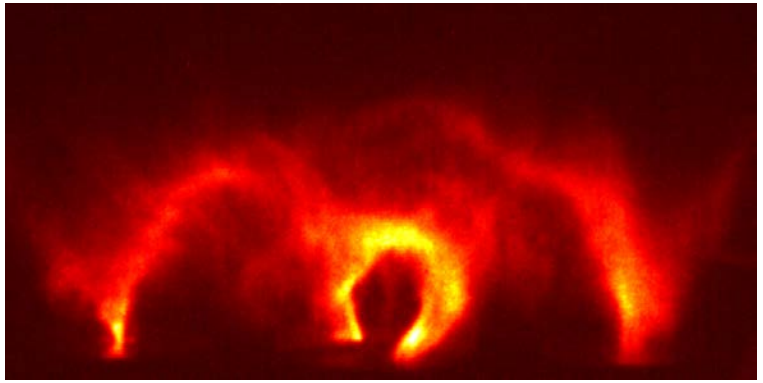


Single loop

- Duration =7-50 μs
- Scale size = 2-50 cm
- Species: H, D, He, Ar, N, Ne, Xe
- I = 50-100 kiloamp
- n = 10^{14}-10^{16} cm^{-3}
- B = 100-2000 G
- T = 2-3 eV
- Shot every 2 minutes, reproducible



Jet

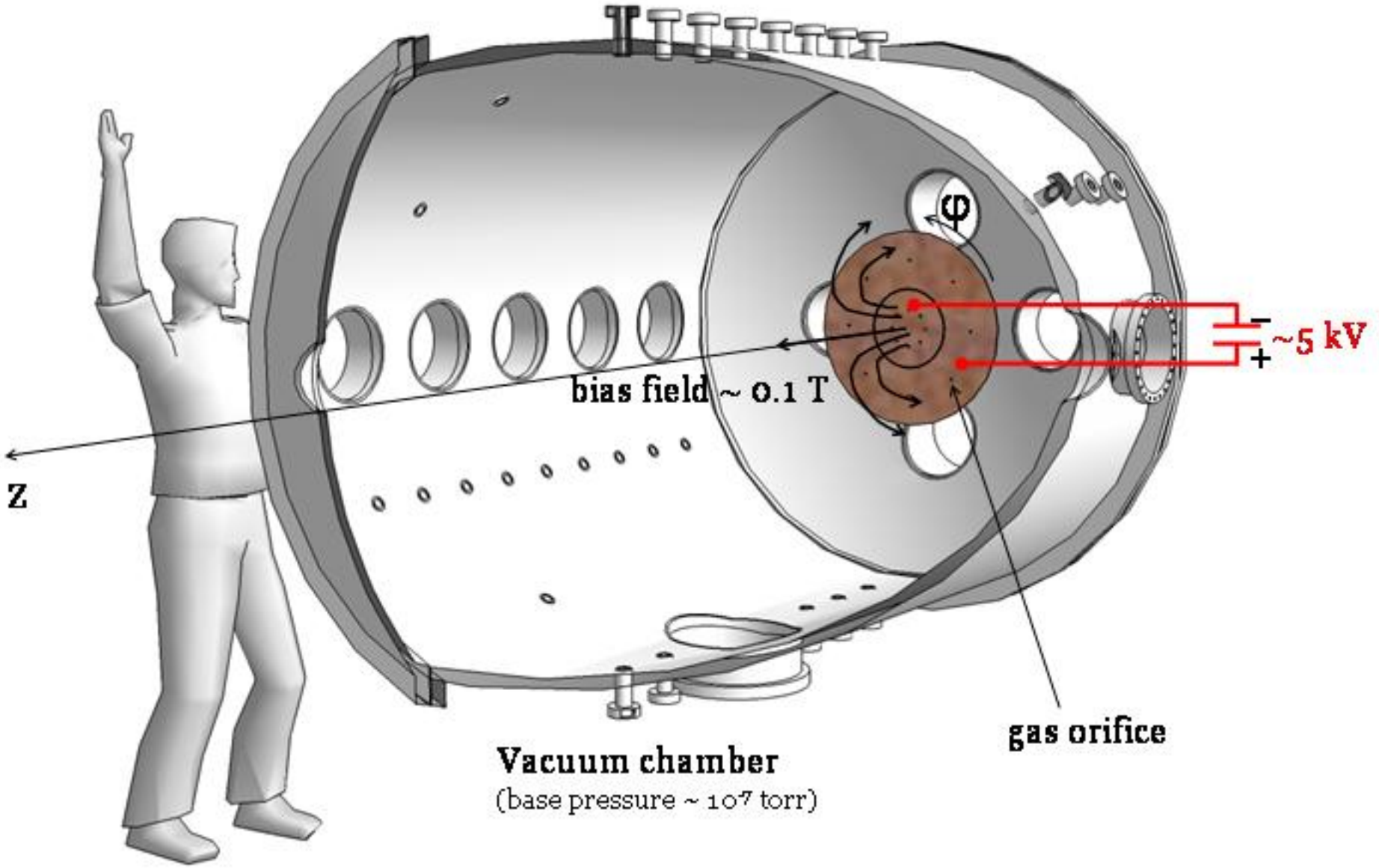


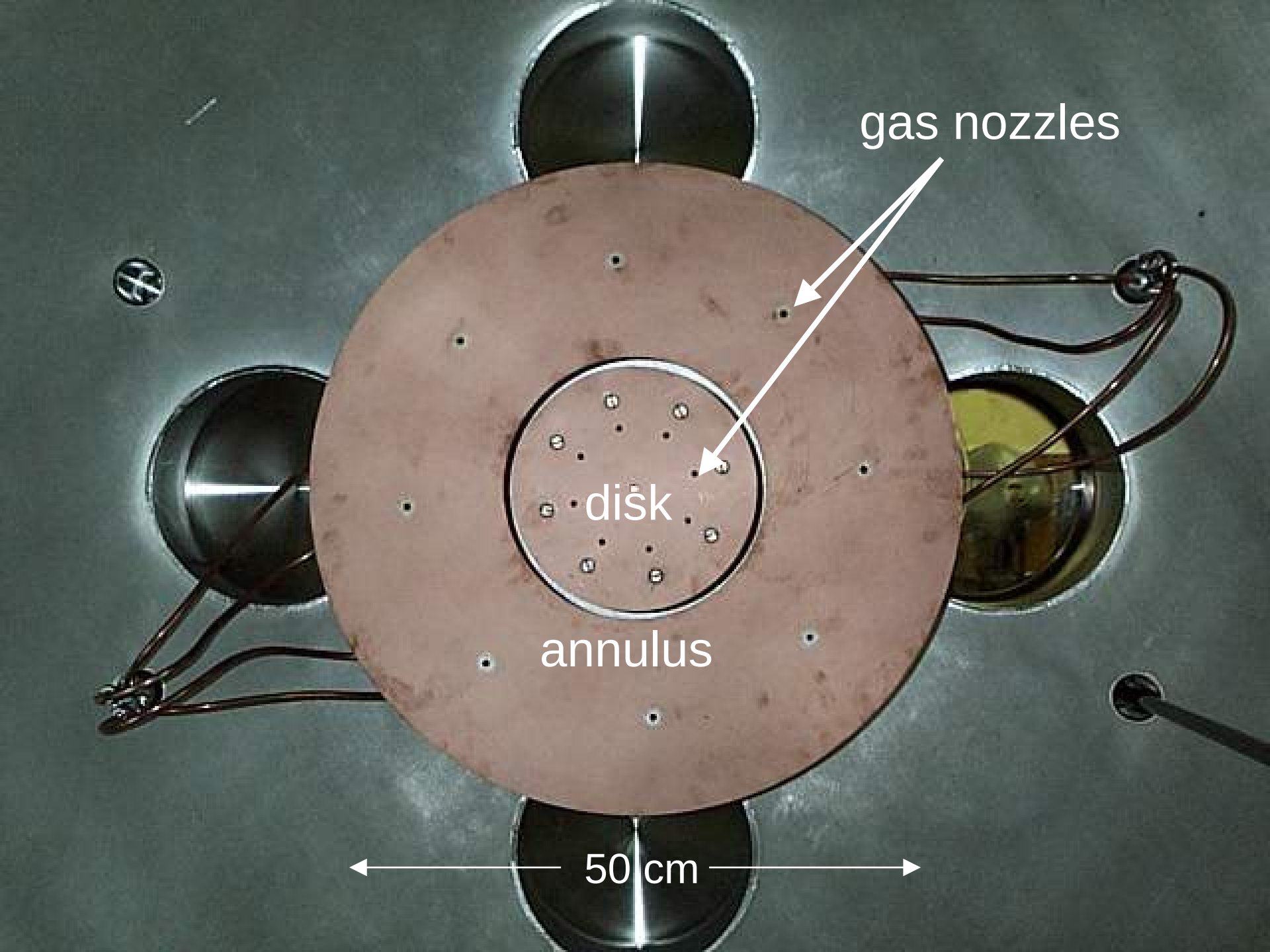
Double loop

Diagnostics

- High-speed imaging
  - White light
  - Filtered atomic lines
  - EUV
- Magnetic probe arrays
- Spectroscopy
  - Doppler velocities
  - Densities via Stark broadening
  - Ionization state
- EUV diode detectors
- X-ray scintillator
- Interferometry
- Voltage, current at electrodes

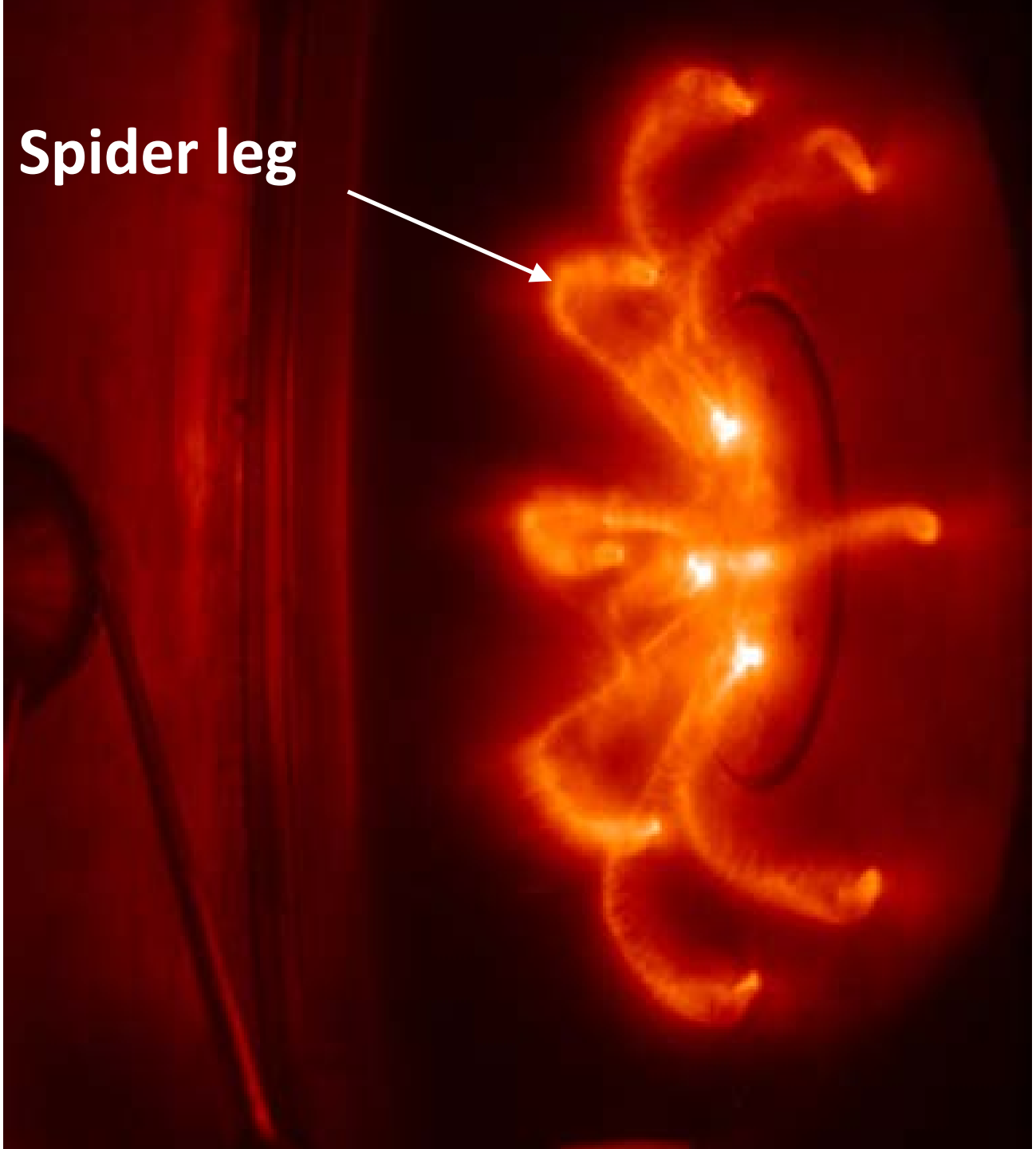
Coaxial setup




gas nozzles
disk
annulus
50 cm

Instability cascade from MHD to non-MHD regime

Jet forms from
merged spider legs



Hsu/Bellan
MNRAS 2002

You/Yun/Bellan
PRL 2005

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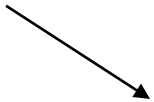
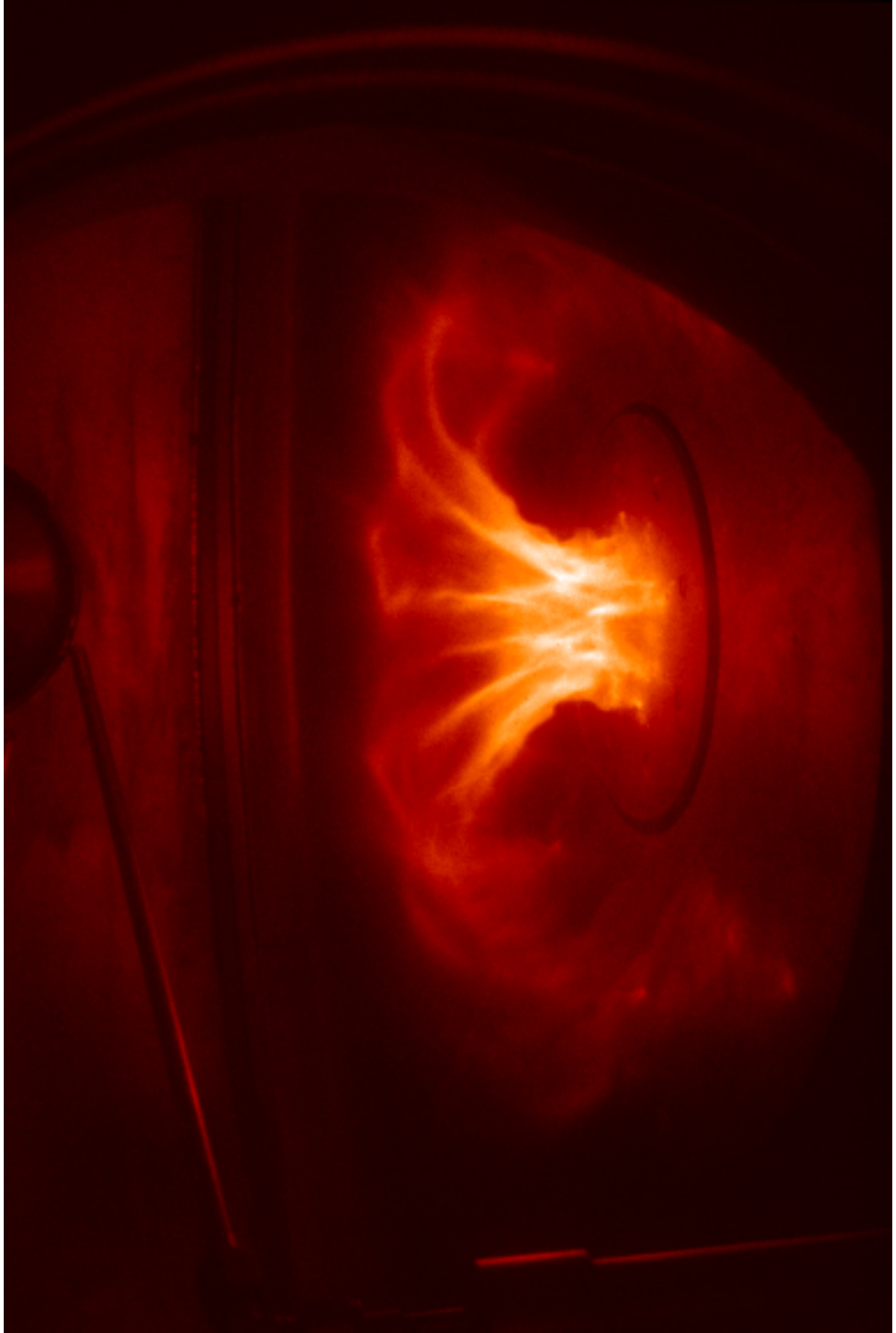


Jet collimates
and propagates



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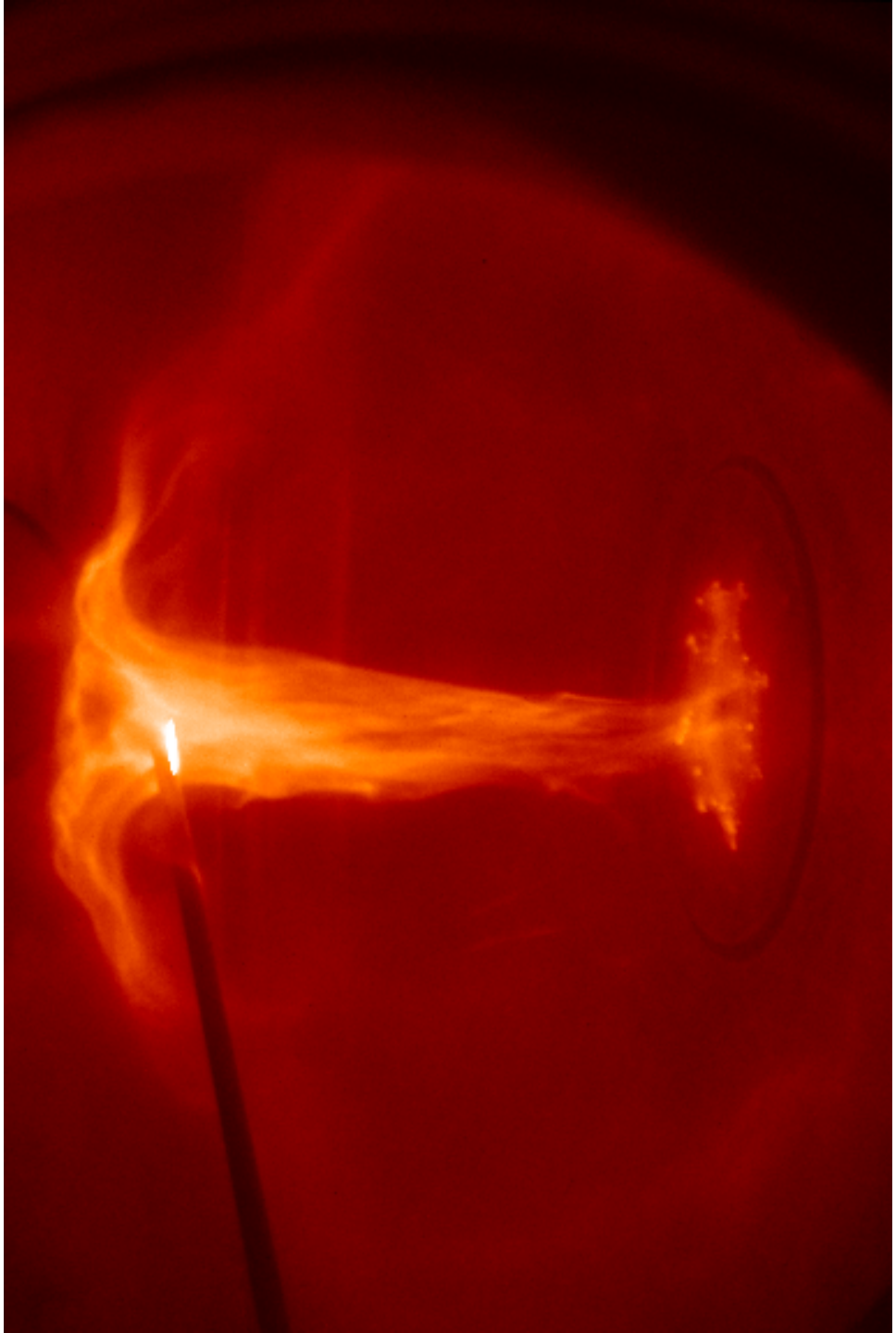
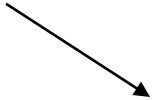


Instability cascade from MHD to non-MHD regime (Moser & Bellan, Nature 2012)

Jet forms from merged spider legs



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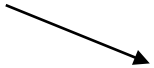
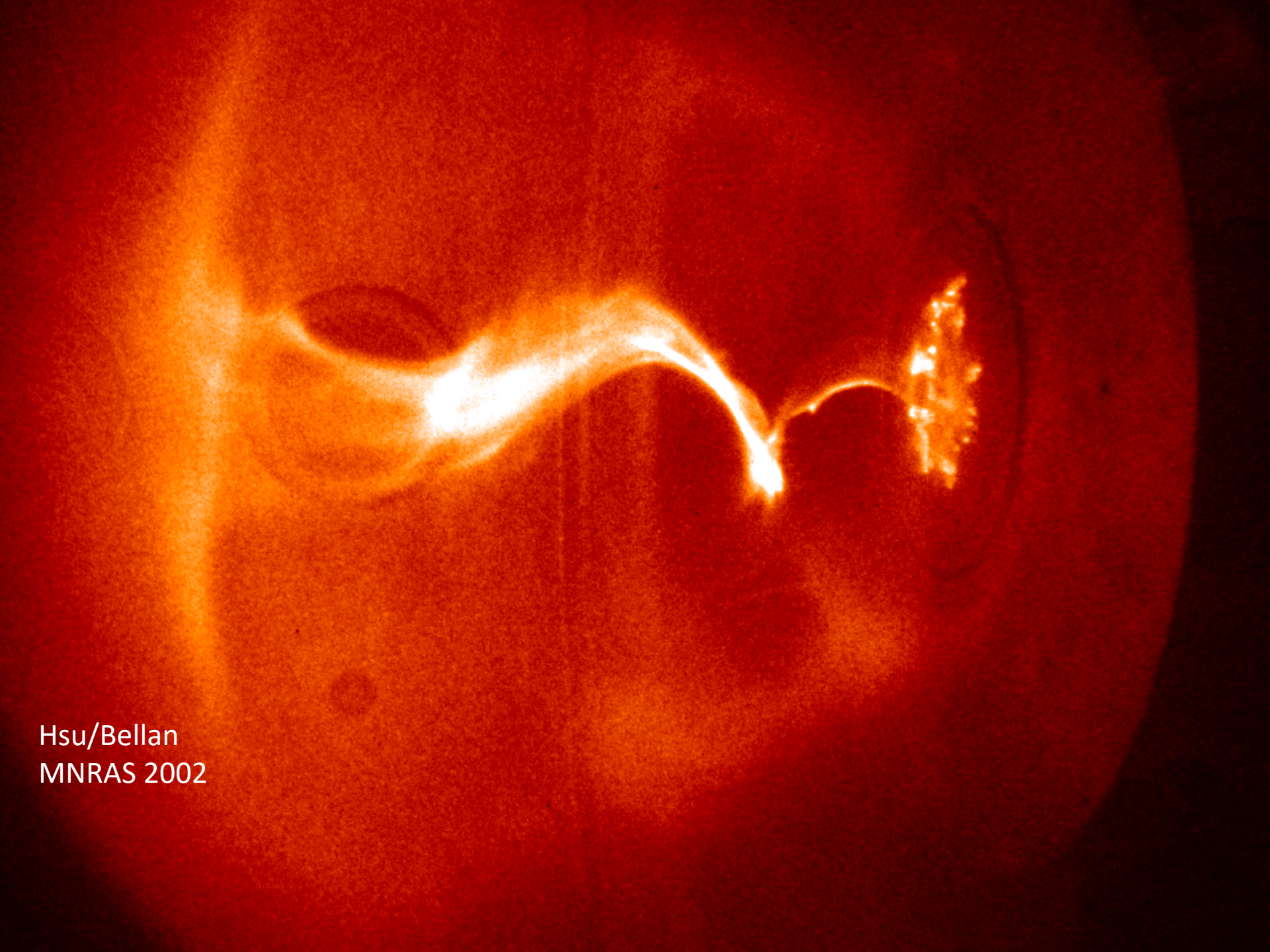


Jet kinks


Hsu/Bellan
MNRAS 2002

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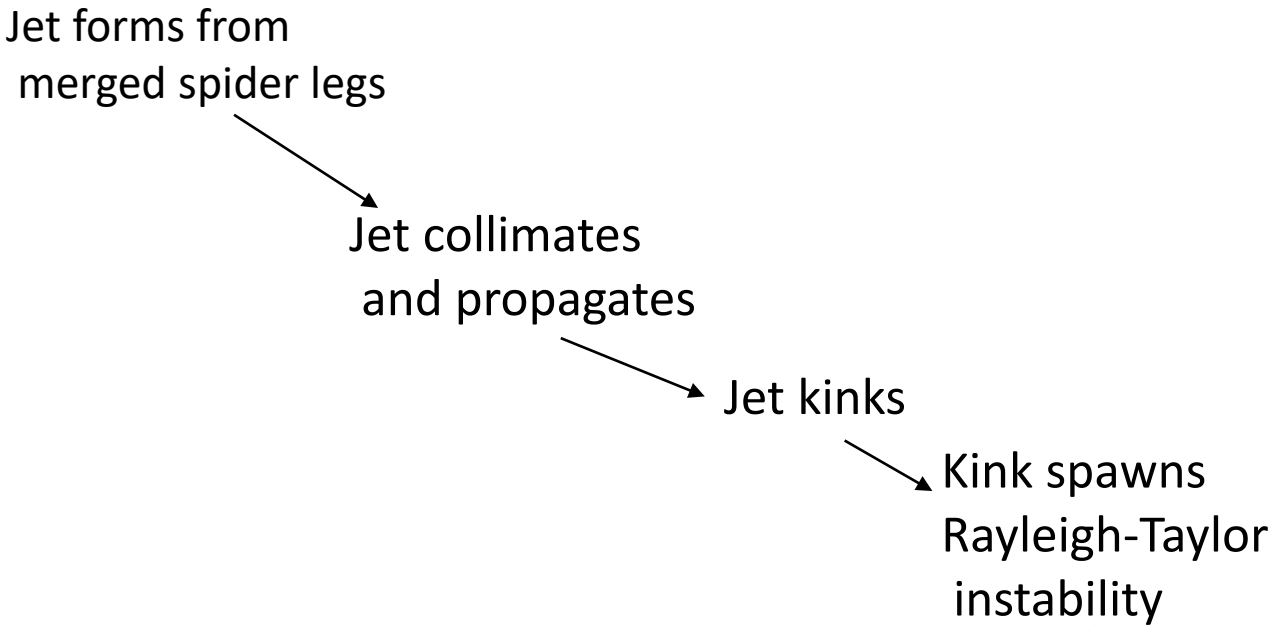
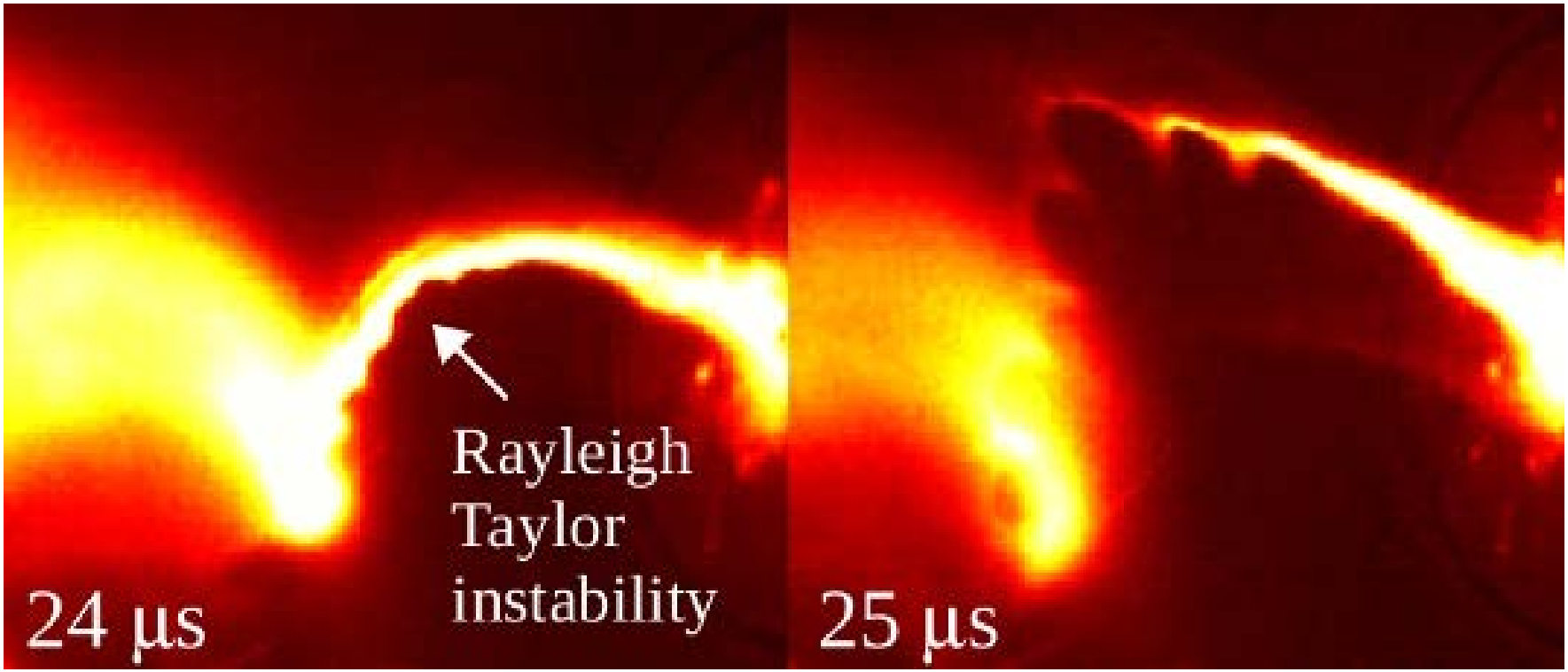




Moser/Bellan
Nature 2012

Instability cascade from MHD to non-MHD regime

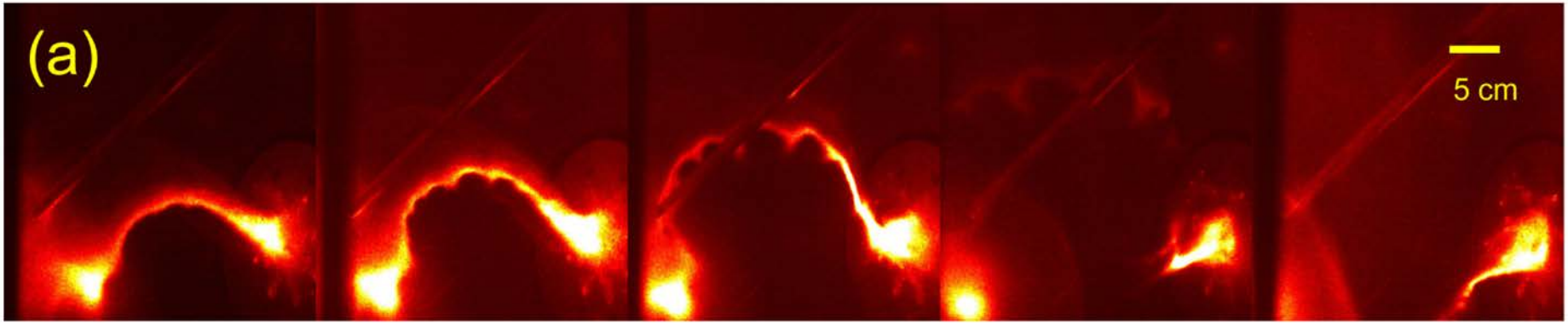
Jet forms from merged spider legs

→ Jet collimates and propagates

→ Jet kinks

→ Kink spawns Rayleigh-Taylor instability

→ Rayleigh-Taylor spawns localized magnetic reconnection



Chai, Zhai, Bellan
Phys. Plasmas 2016

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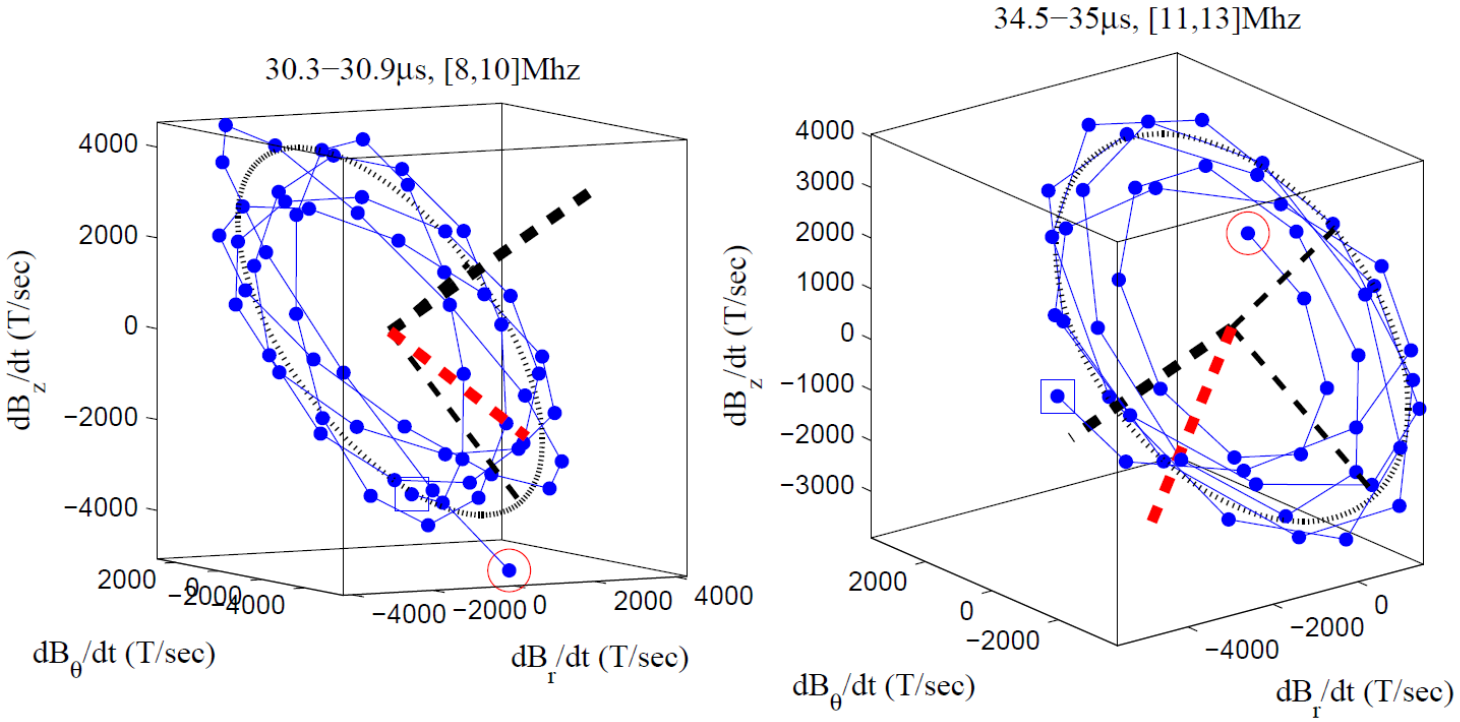
→ Whistler wave emission
Electron, ion heating
EUV emission
X-ray pulse

Whistler waves: Circular polarization

Chai, Zhai, Bellan
Phys. Plasmas 2016



- Hodograms of magnetic vector show circular polarization:
  -confirms whistler wave character
- Observation of whistler waves suggests Hall-MHD reconnection

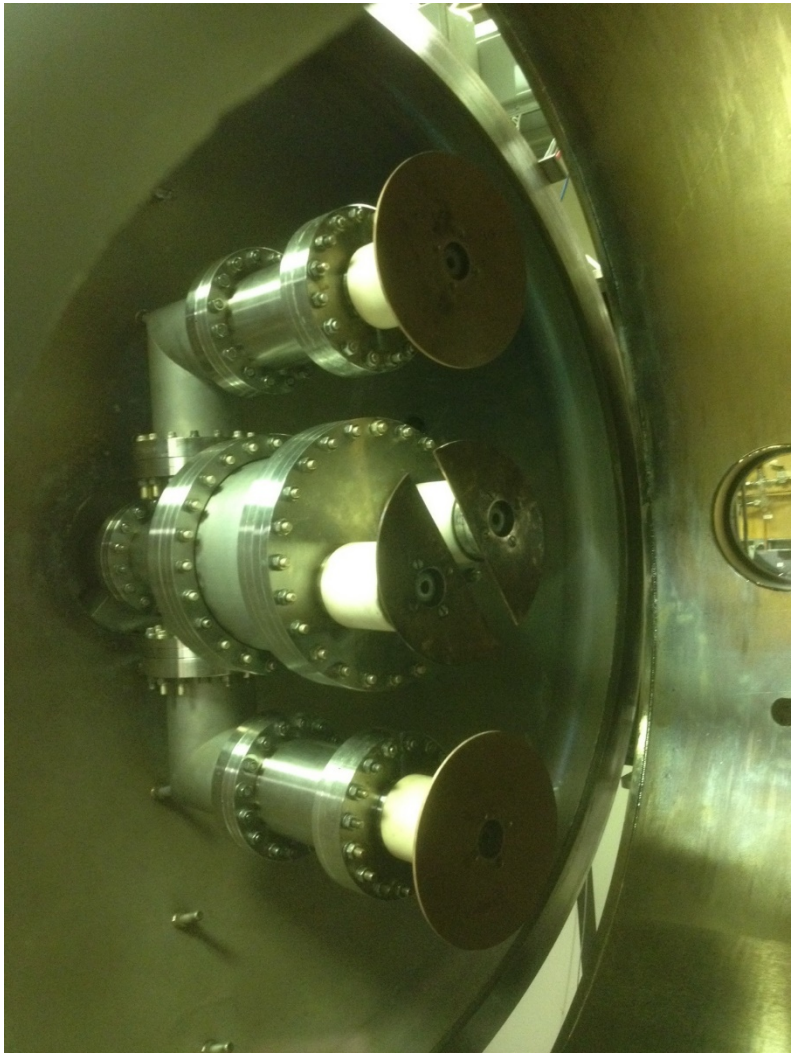
Measurement of **B**(**x**,t) over a 3D volume

to give **J**(**x**,t) and **J** x **B**

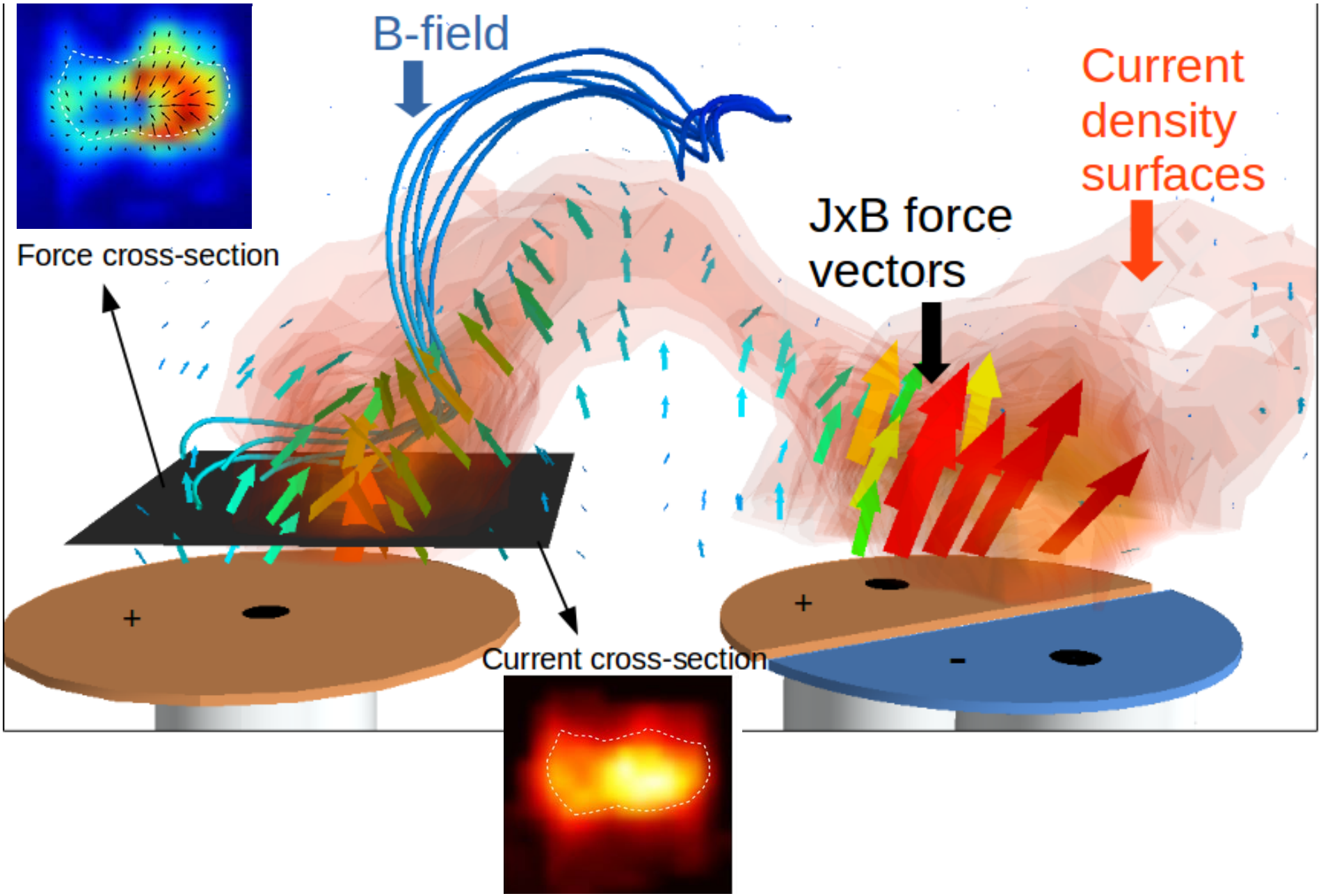
M. Haw and P. M. Bellan

B(**x**,t) Measurement Setup: Solar Loop Simulation

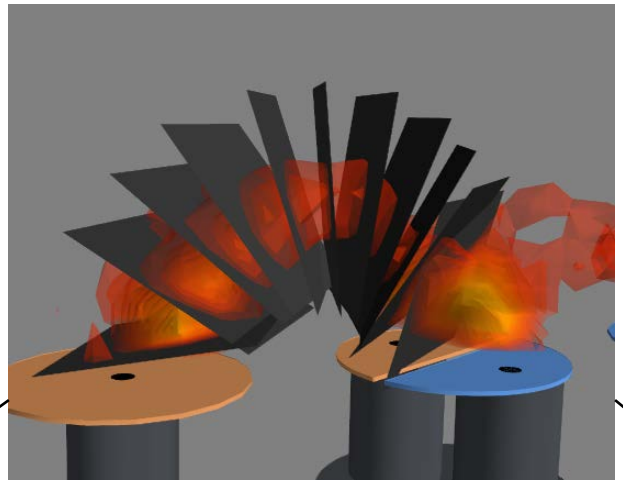
- Adjacent plasma loops
- Staggered instead of side by side
- “Candelabra” shape

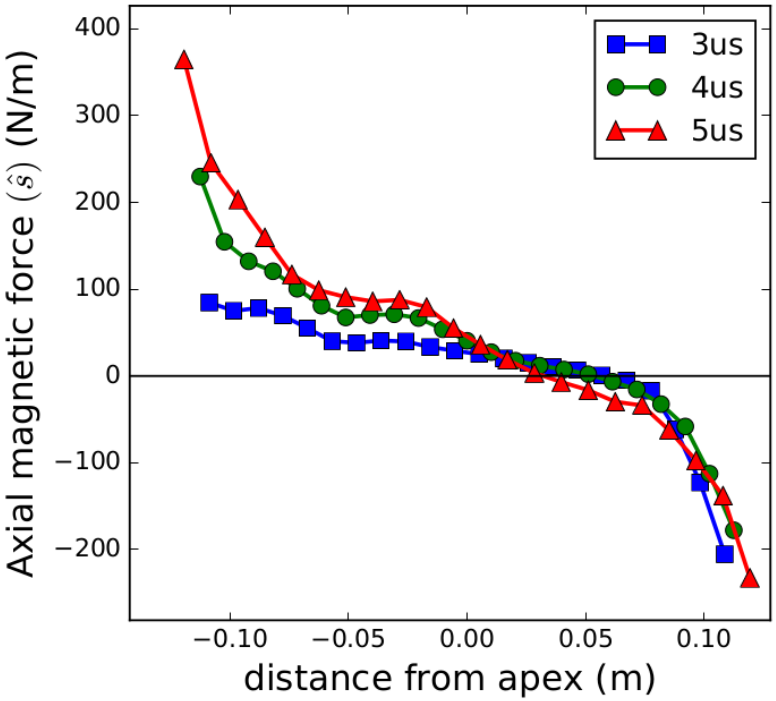


3D **Measurements** of B, J, and JxB forces

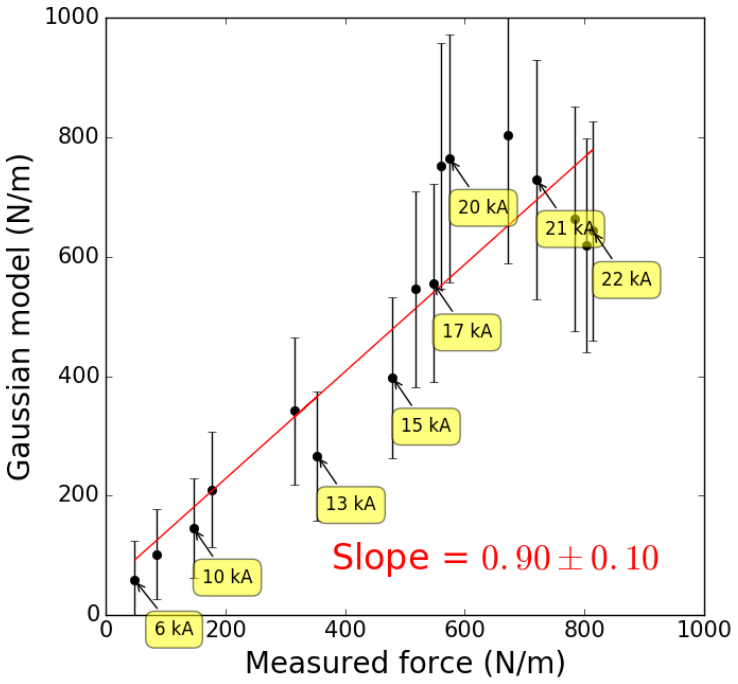


Measured Forces along the Loop Axis





relevant



Gershman et al. MMS KAW wave

http://www.nature.com/articles/ncomms14719

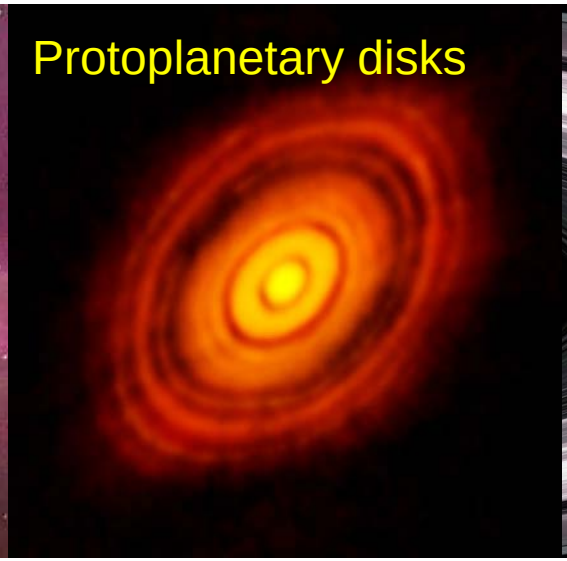
KAW wave MMMS last week

K vector obtained from single-point measurement
with no prior knowledge of dispersion relation

Bellan JGR 2016

Water-ice dusty plasma experiment

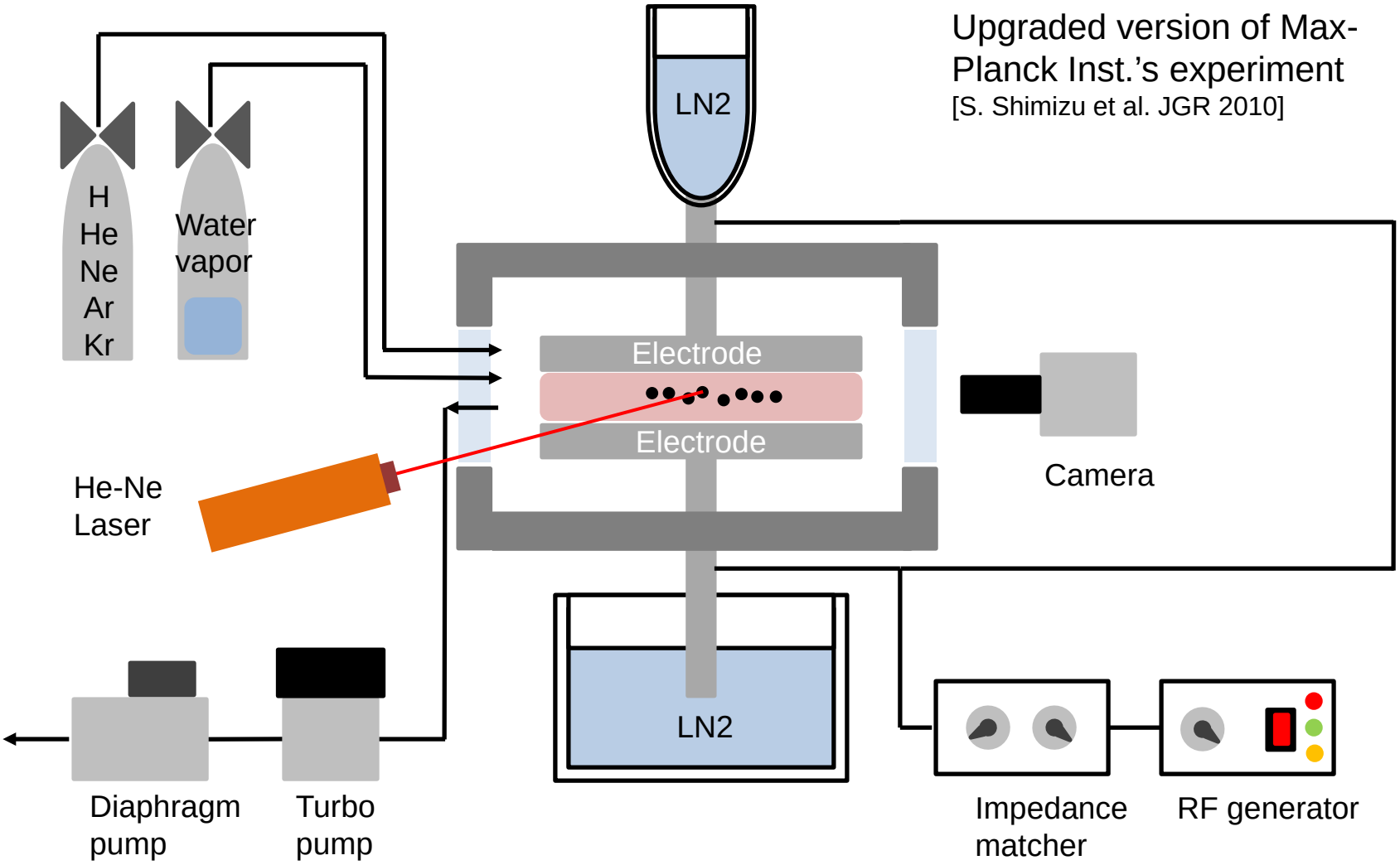
dusty plasmas in space



Polar mesospheric clouds

Plasma processing

Apparatus



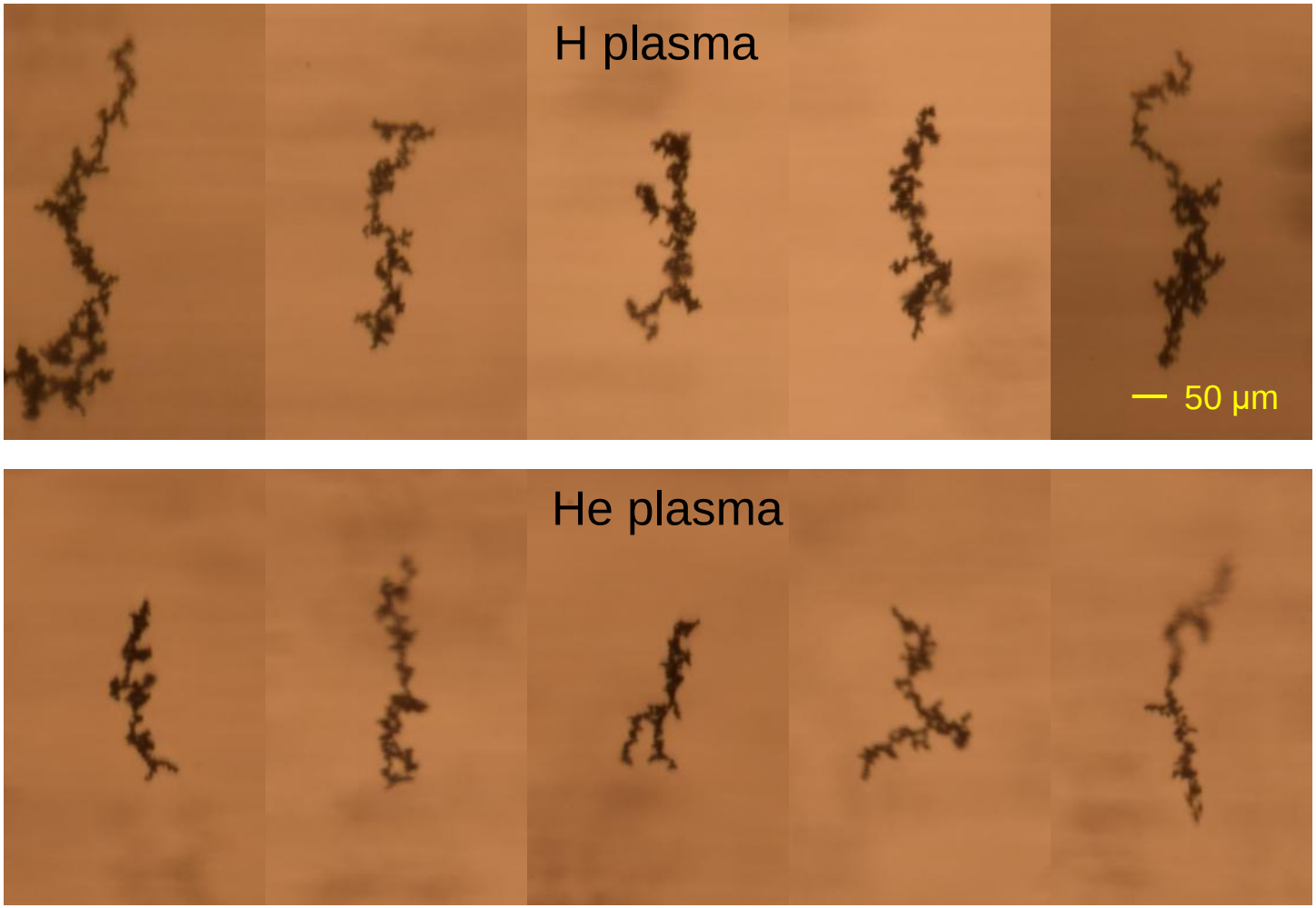
Upgraded version of Max-Planck Inst.'s experiment
[S. Shimizu et al. JGR 2010]

K.-B. Chai and P. Bellan, Geophys. Res. Lett, **40**, 6258 (2013)

Original goal

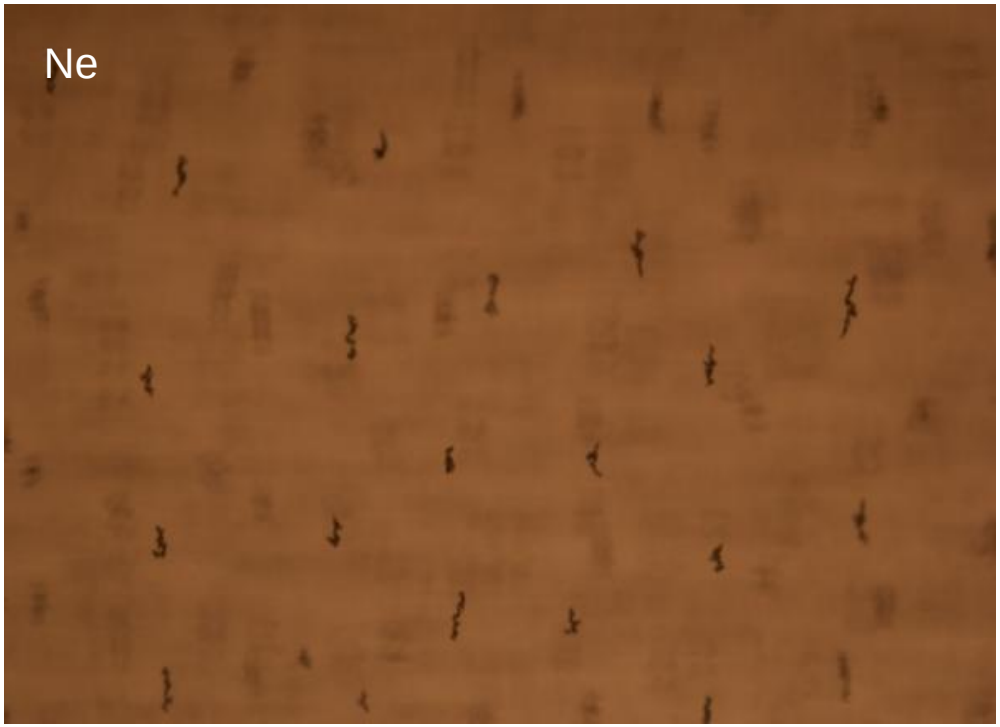
- see if ice grains are spherical
  - Theories typically assume spherical with power law distribution of radius
- result was very different
- many other phenomena observed also

Not spherical

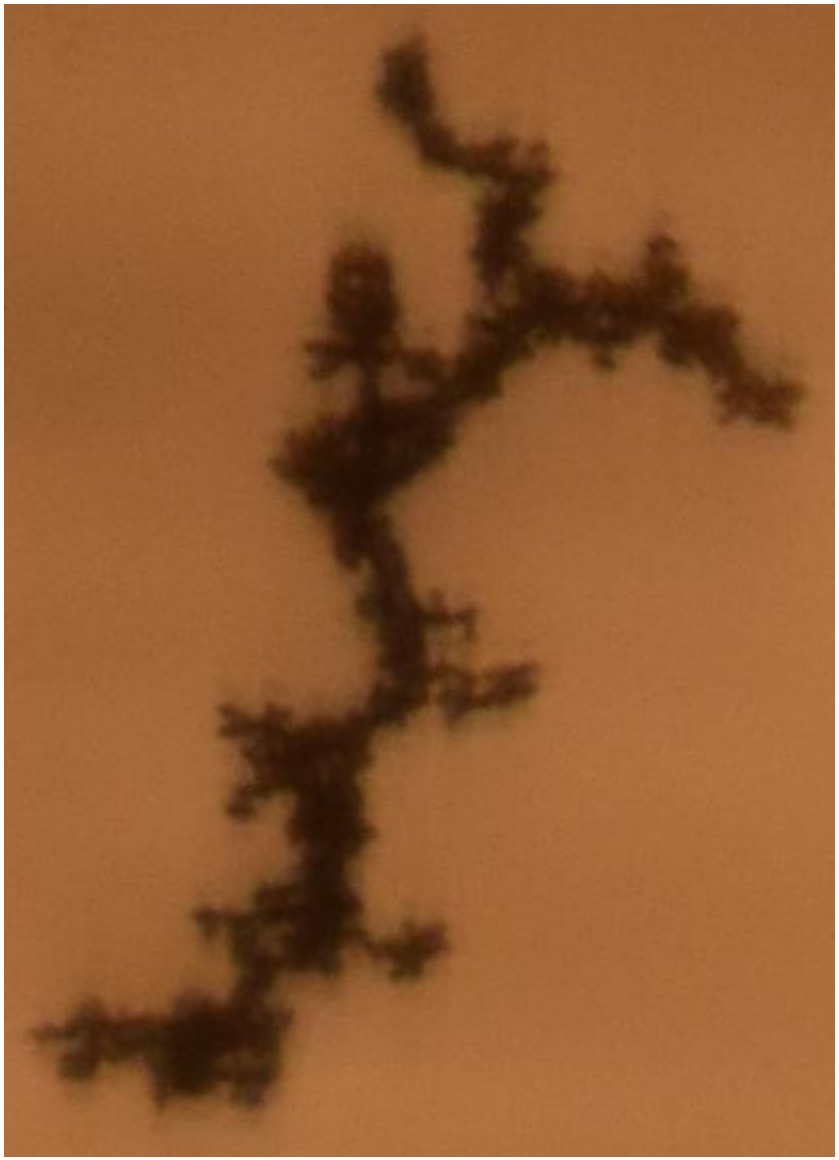


K.-B. Chai and P. Bellan, Astrophys. J. **802**, 112 (2015)

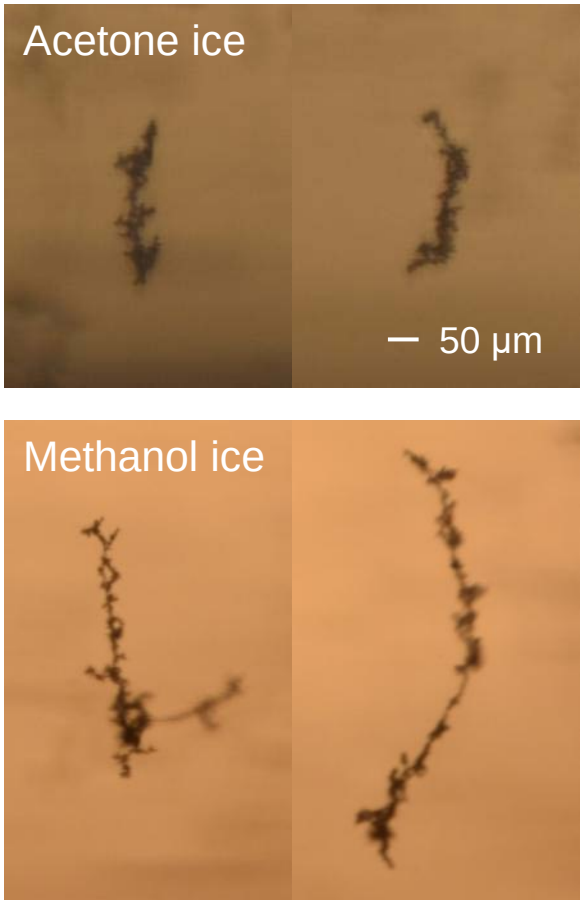
Alignment of elongated grains



Fractal nature



Methanol and acetone ice grains



Summary

- Explore many phenomena
  - See new relationships, interesting physics
  - Extrapolate to space situations after
  - Avoid getting stuck trying to duplicate specific space phenomenon or regime