Laboratory Astrophysics on the SSX device

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with contributions from

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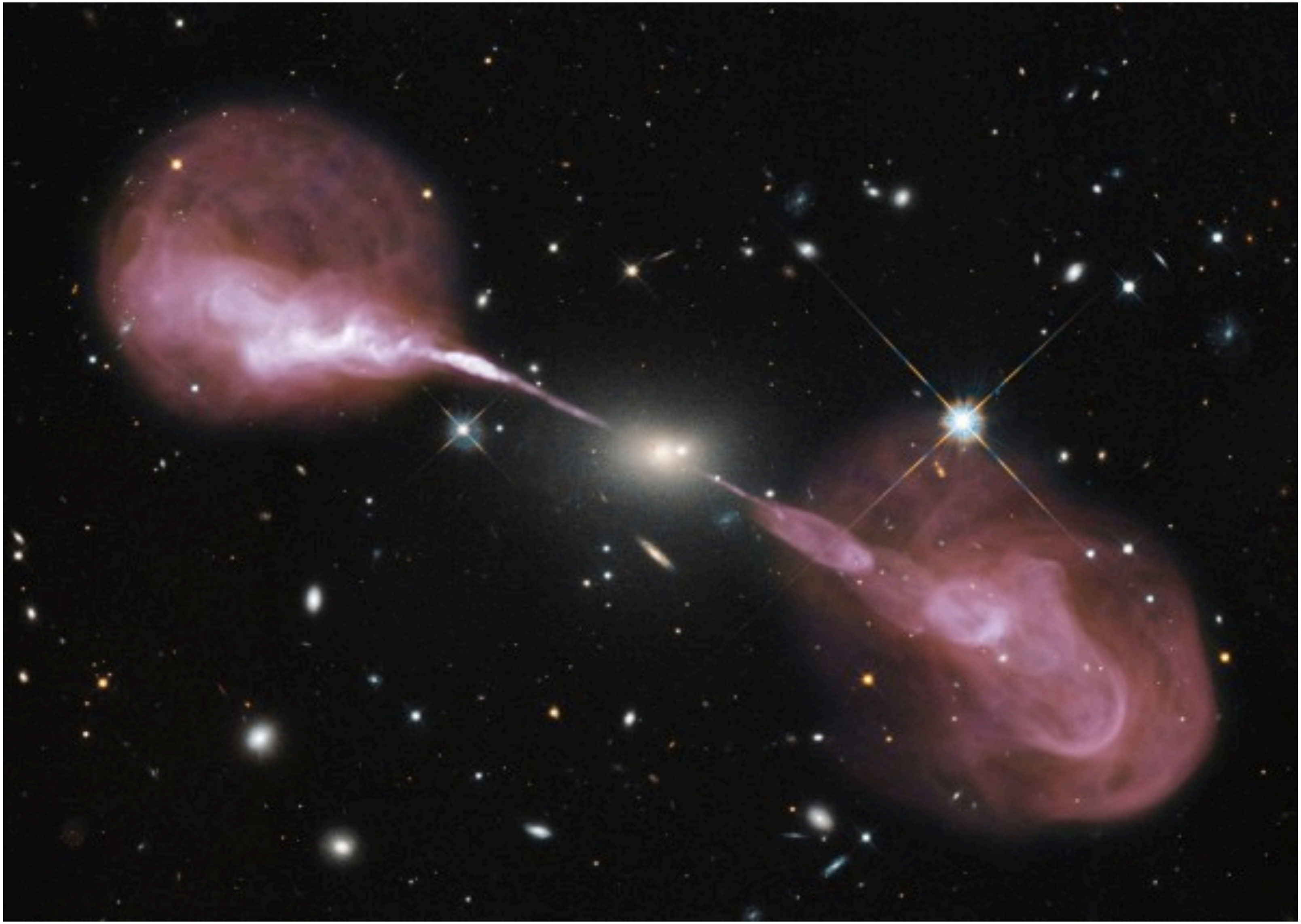
Laboratory Astrophysics on the SSX device

- Astrophysical examples

- Key physics: turbulence, reconnection, generation of relaxed magnetic structures… these are all coupled in astrophysics

- Some examples from SSX lab

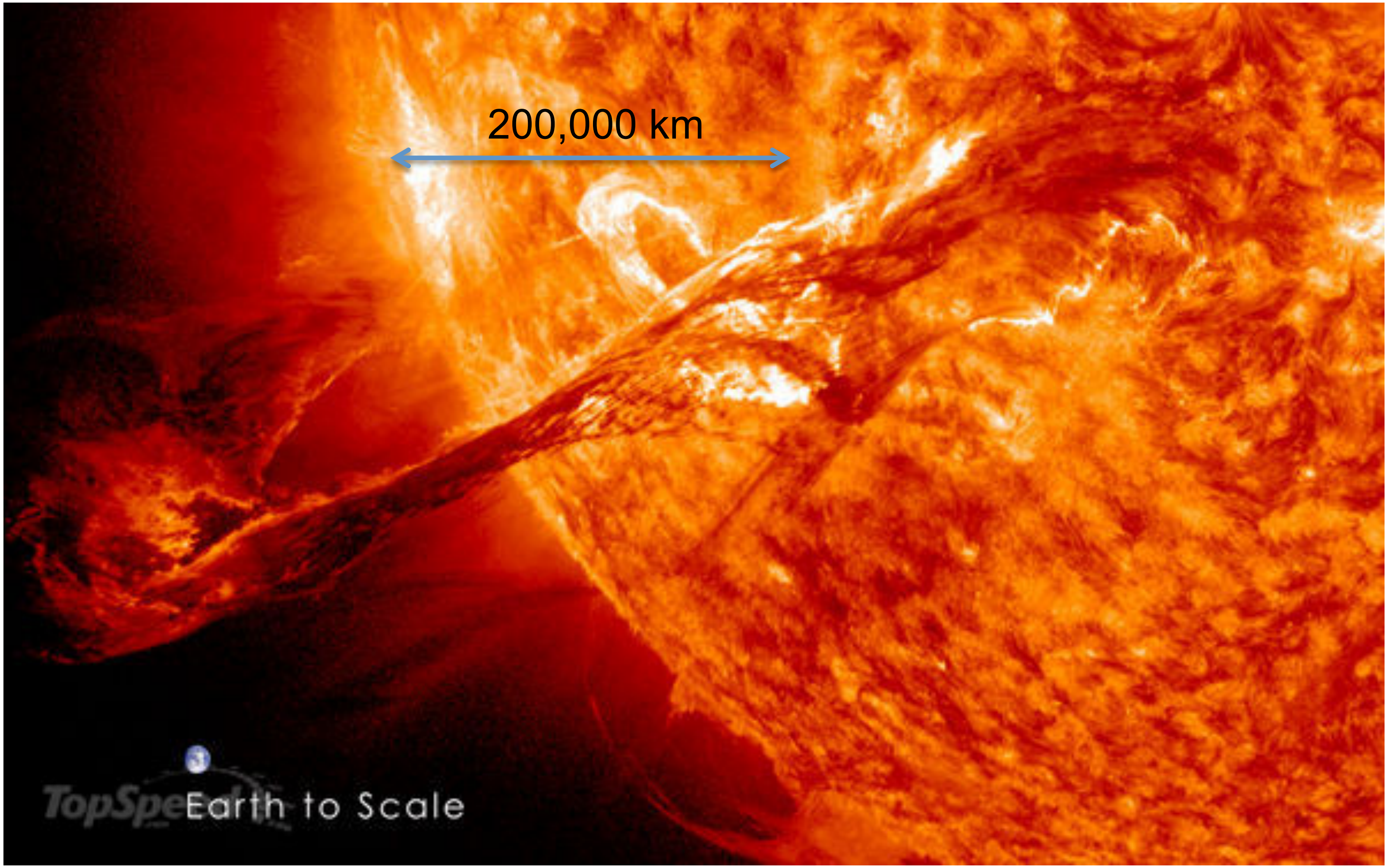
Galactic jet (Hercules A, 1 Mpc)



EHT image of plasma around black hole

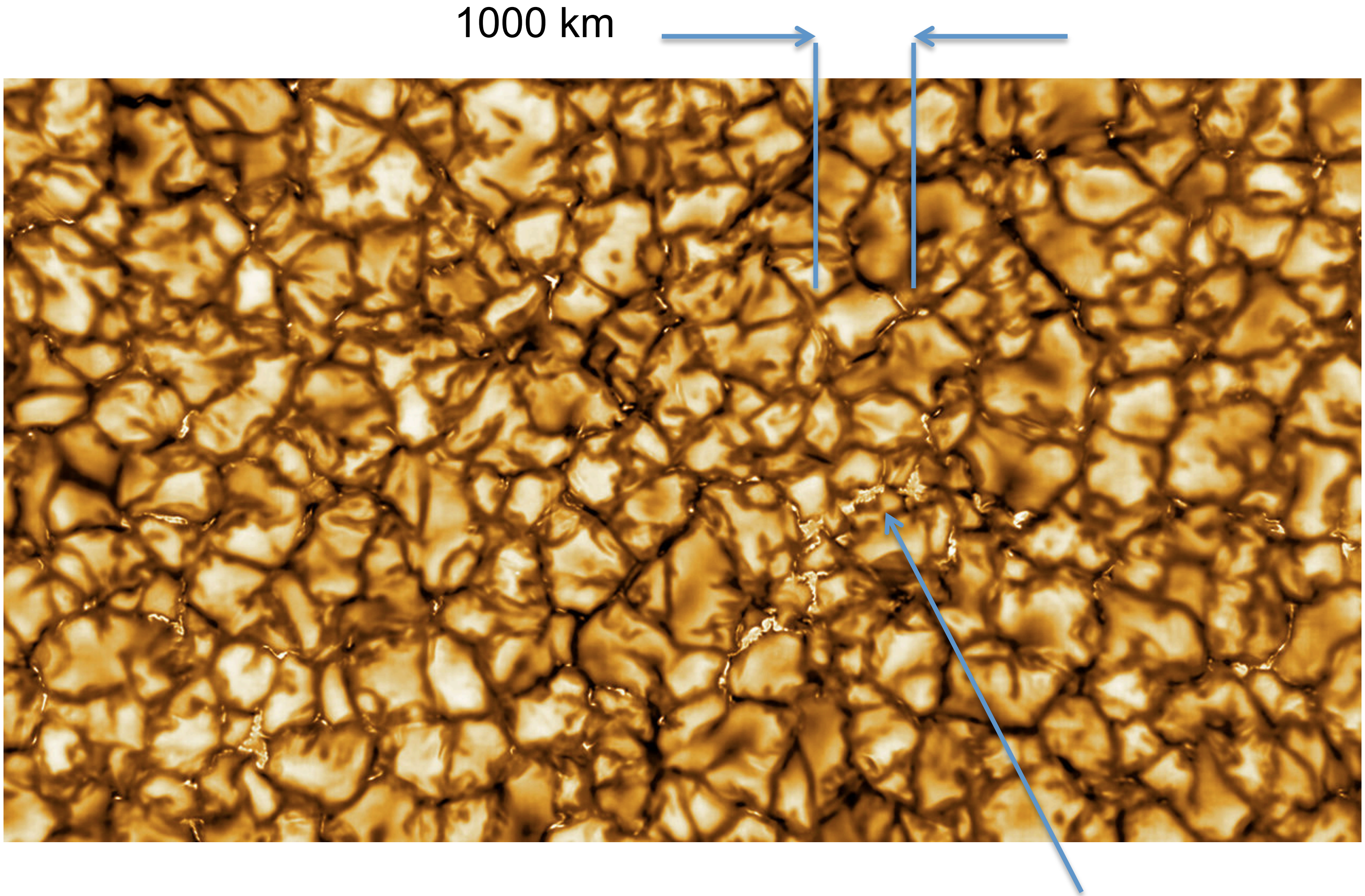
6×10^9 solar mass black hole, $T=10^{12}$ K, or 100 MeV
300 AU across

Solar plume (CME) and wind (plasma)



400 km/s plasma with entrained magnetic fields (SDO, 8/12)

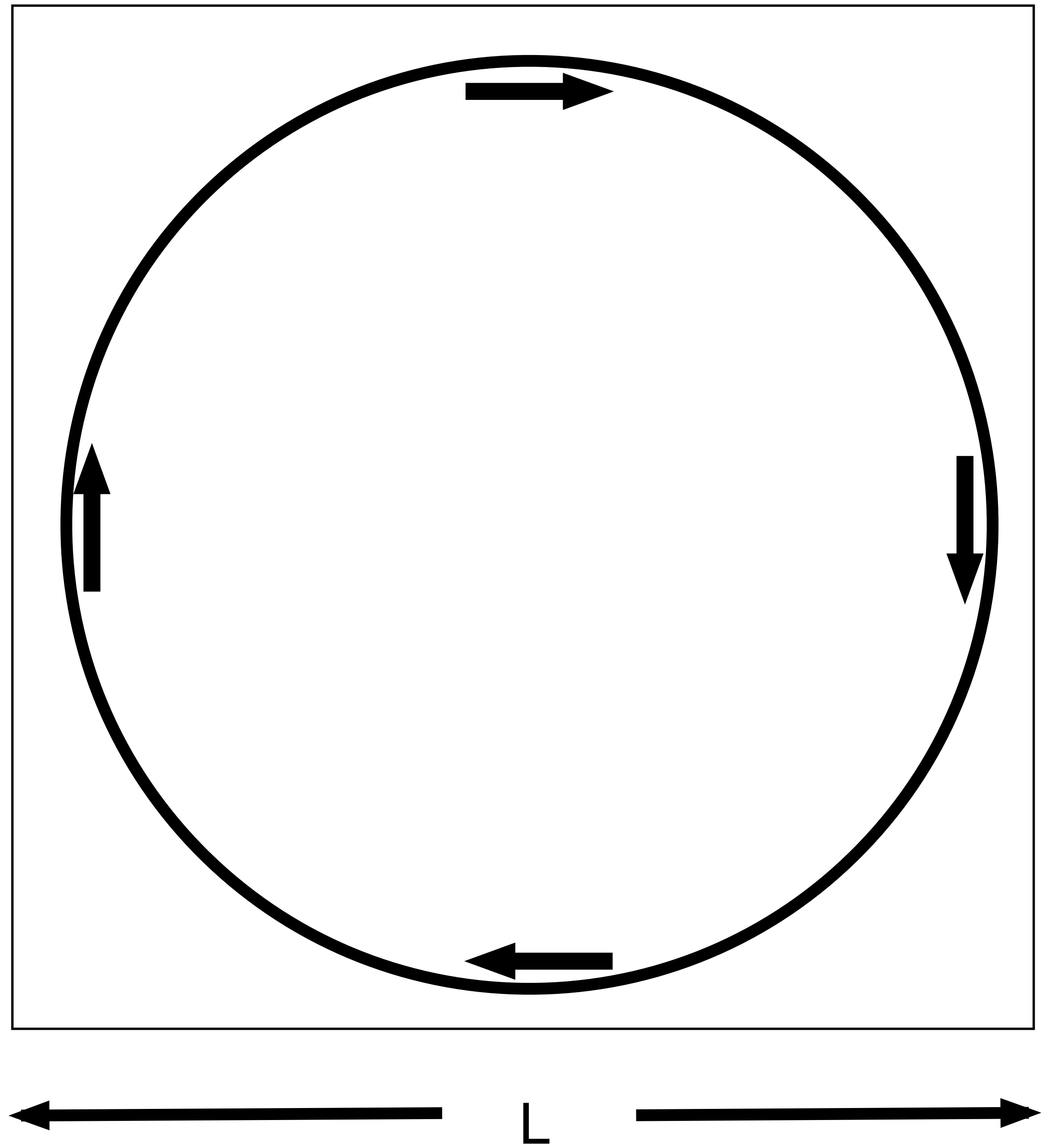
Solar granules and downflow lanes (DKIST)

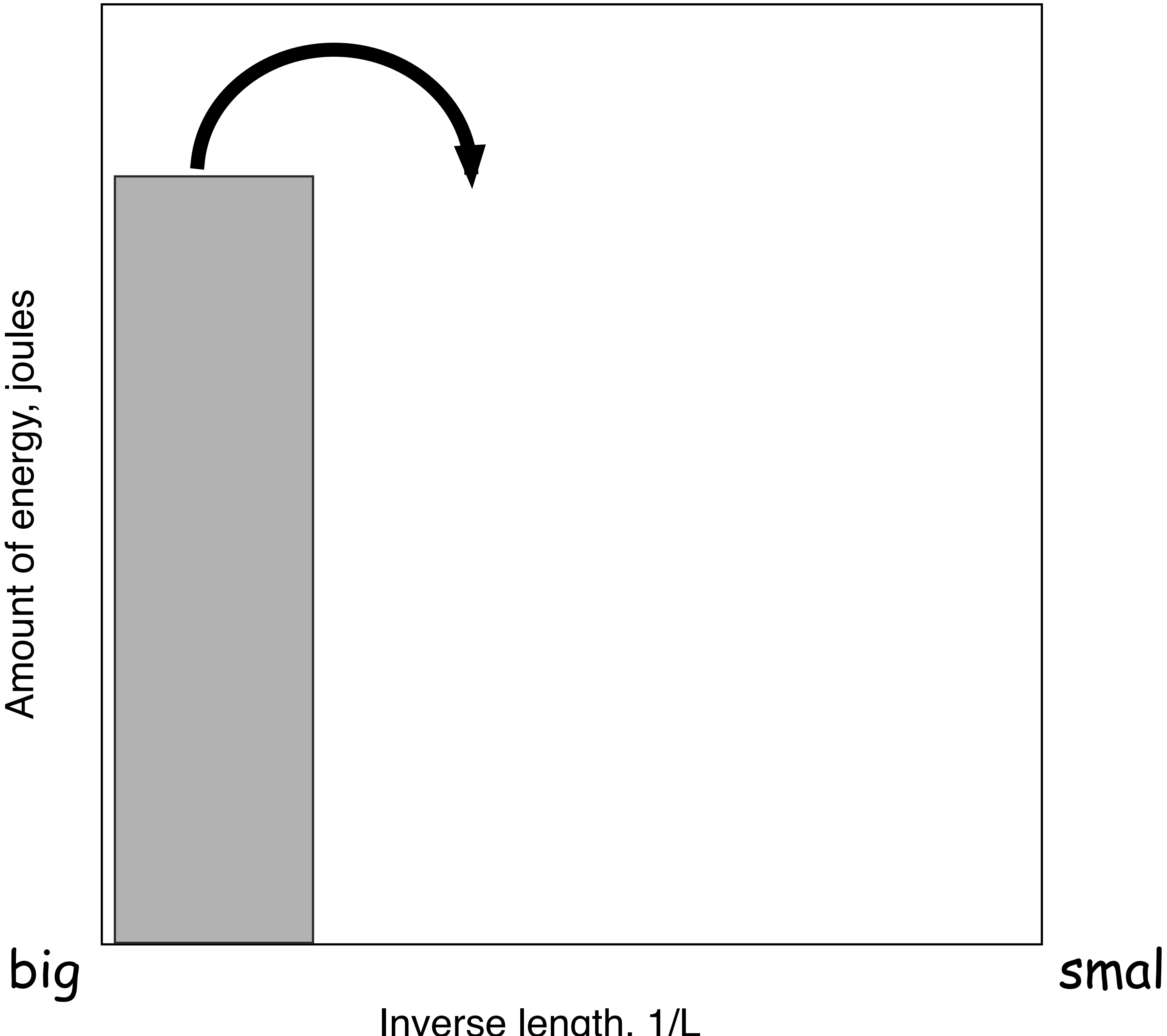


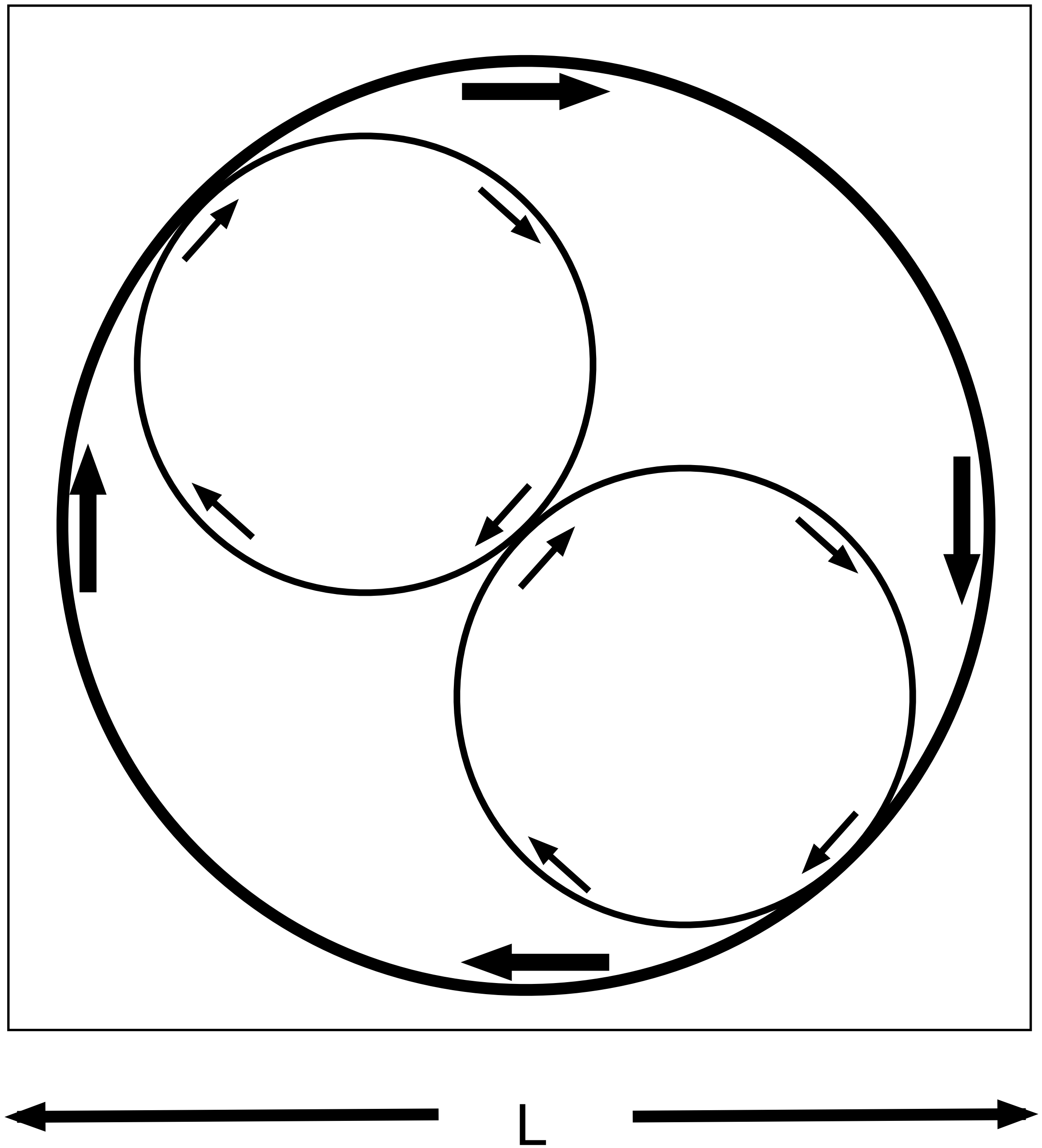
Granules 1000 km across, B=0.1T, lanes 30 km across, bright spots possibly small, twisted loop tops emerging every 20 minutes

Turbulence Primer

- Cascade from large scales to small
- Energy dissipated through viscosity and resistivity
- Kolmogorov scaling done on paper


L


Amount of energy, joules
big
small
Inverse length, 1/L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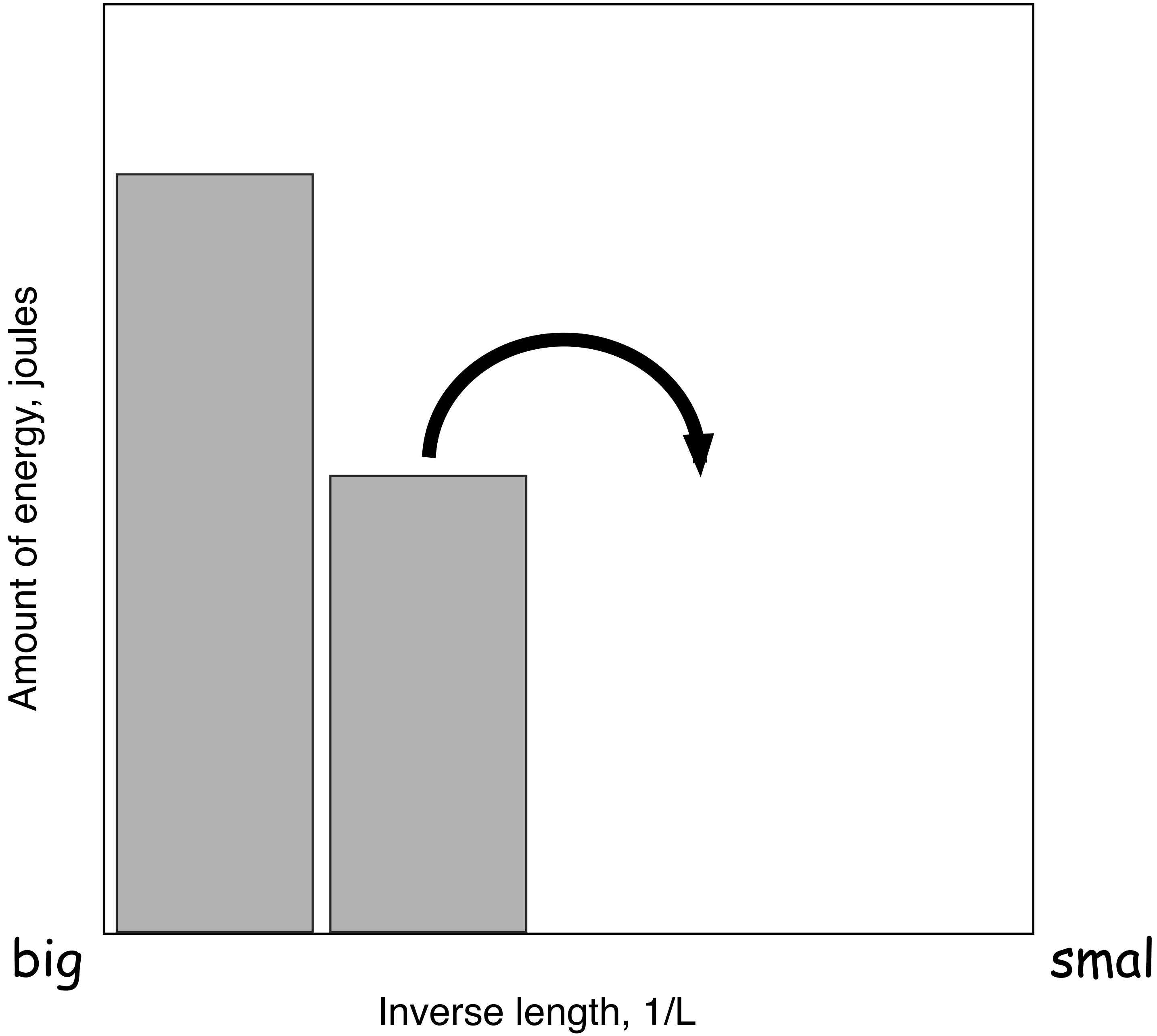
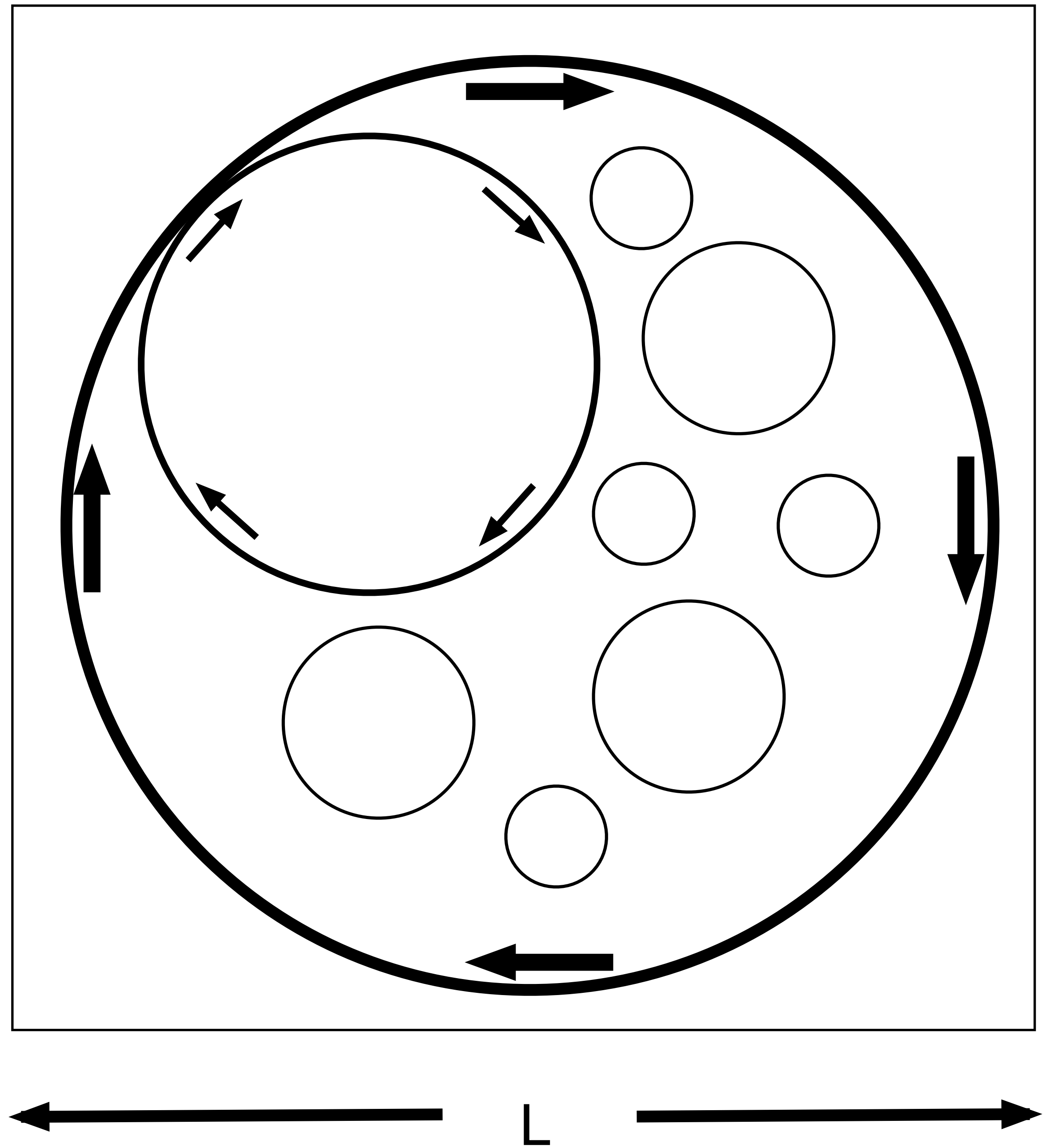
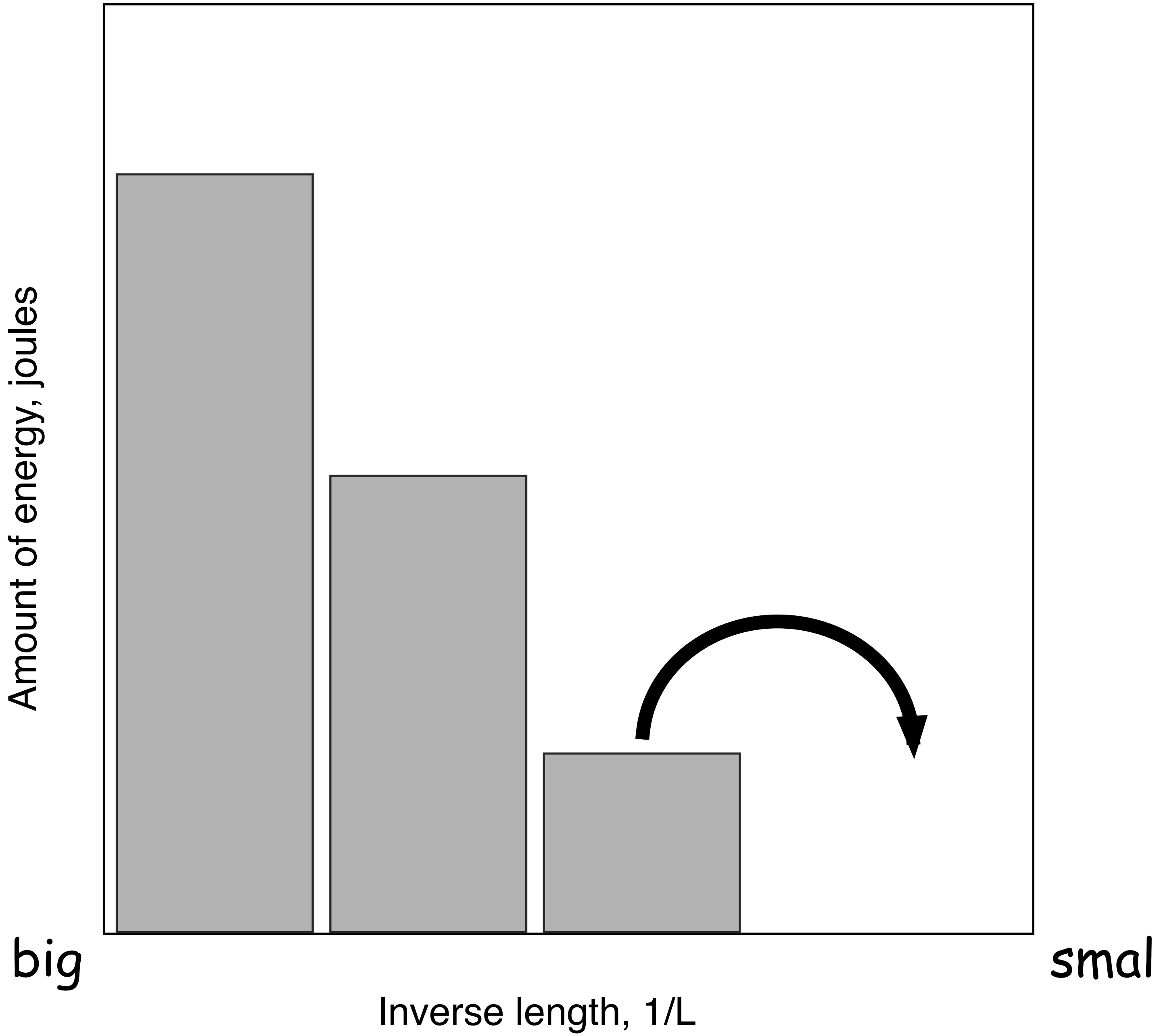
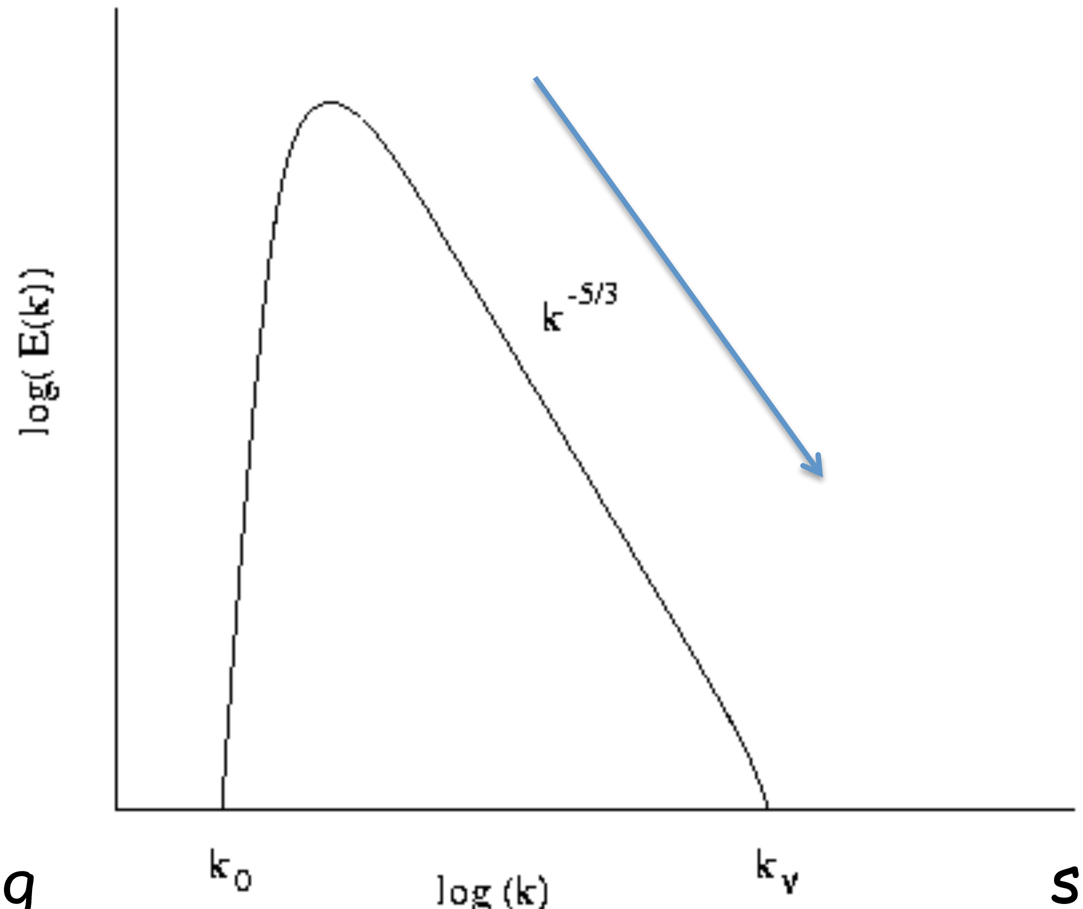

Amount of energy, joules
big
small
Inverse length, 1/L


L

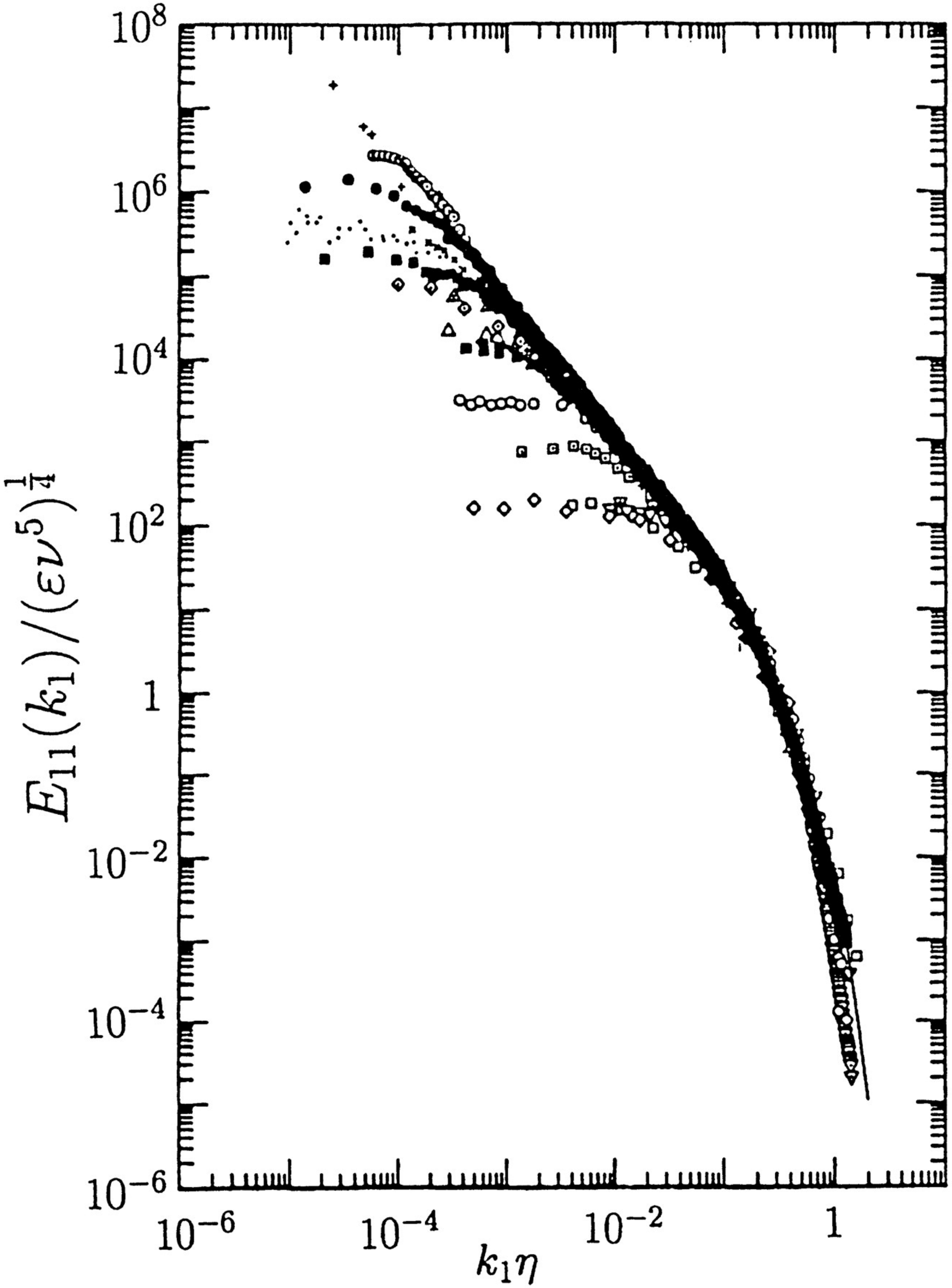

Amount of energy, joules
big
small
Inverse length, 1/L

Kolmogorov turbulence spectrum (1941)

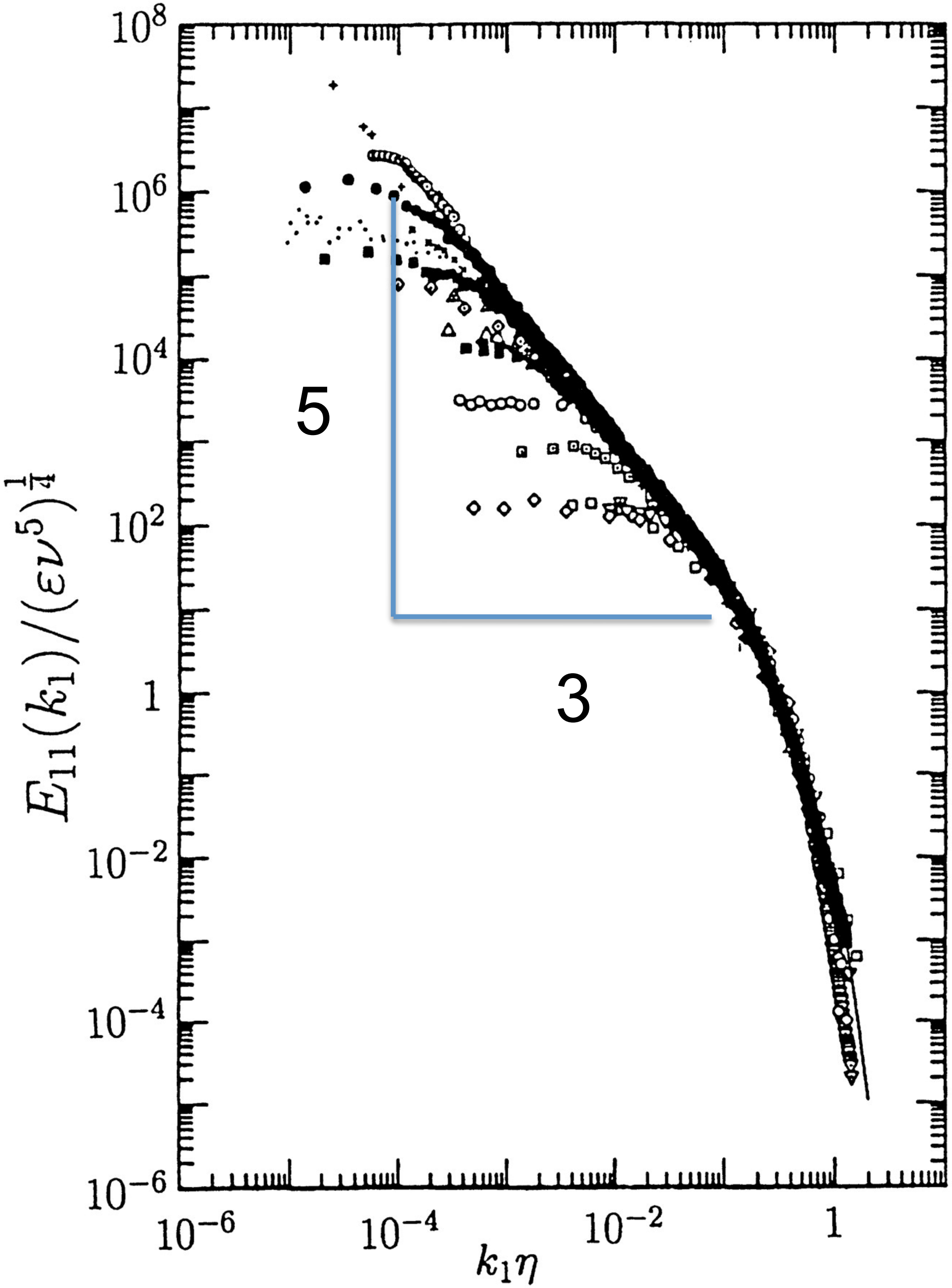


big small

Berkeley SSL



Saddoughi and Veeravalli, JFM 1994



Saddoughi and Veeravalli, JFM 1994

Kolmogorov spectrum

$$E(k) = C\epsilon^{\alpha} k^{-\beta}$$

Depends only on injection rate and k

$$E(k) \propto v^2/k$$

Energy per mass per wavenumber

$$\epsilon \propto k v^3$$

Energy per mass per time

$$v^2 k^{-1} \propto k^{\alpha} v^{3\alpha} k^{-\beta}$$

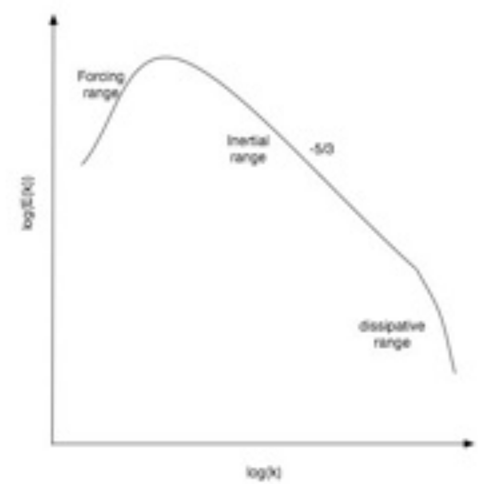
Dimensional analysis

$$2 = 3\alpha$$

$$-1 = \alpha - \beta$$

$$\alpha = 2/3$$

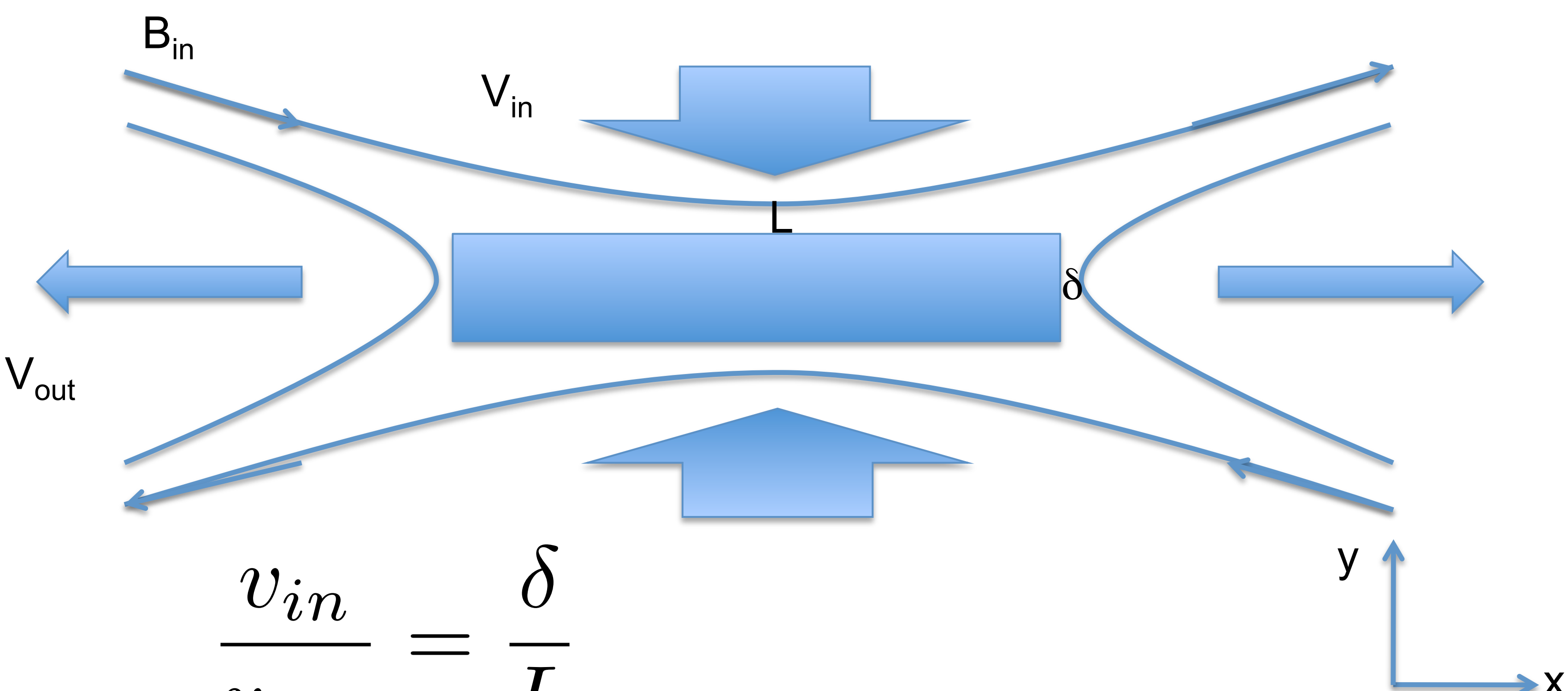
$$\beta = 5/3$$



Reconnection Primer

- Converts magnetic energy at large scales to flow and heat at small scales (ρ_i)
- Particle energization: ions, electrons, both heat and acceleration
- Re-organizes fields again on a large scale
- Calculation on paper

Reconnection (Sweet/Parker)

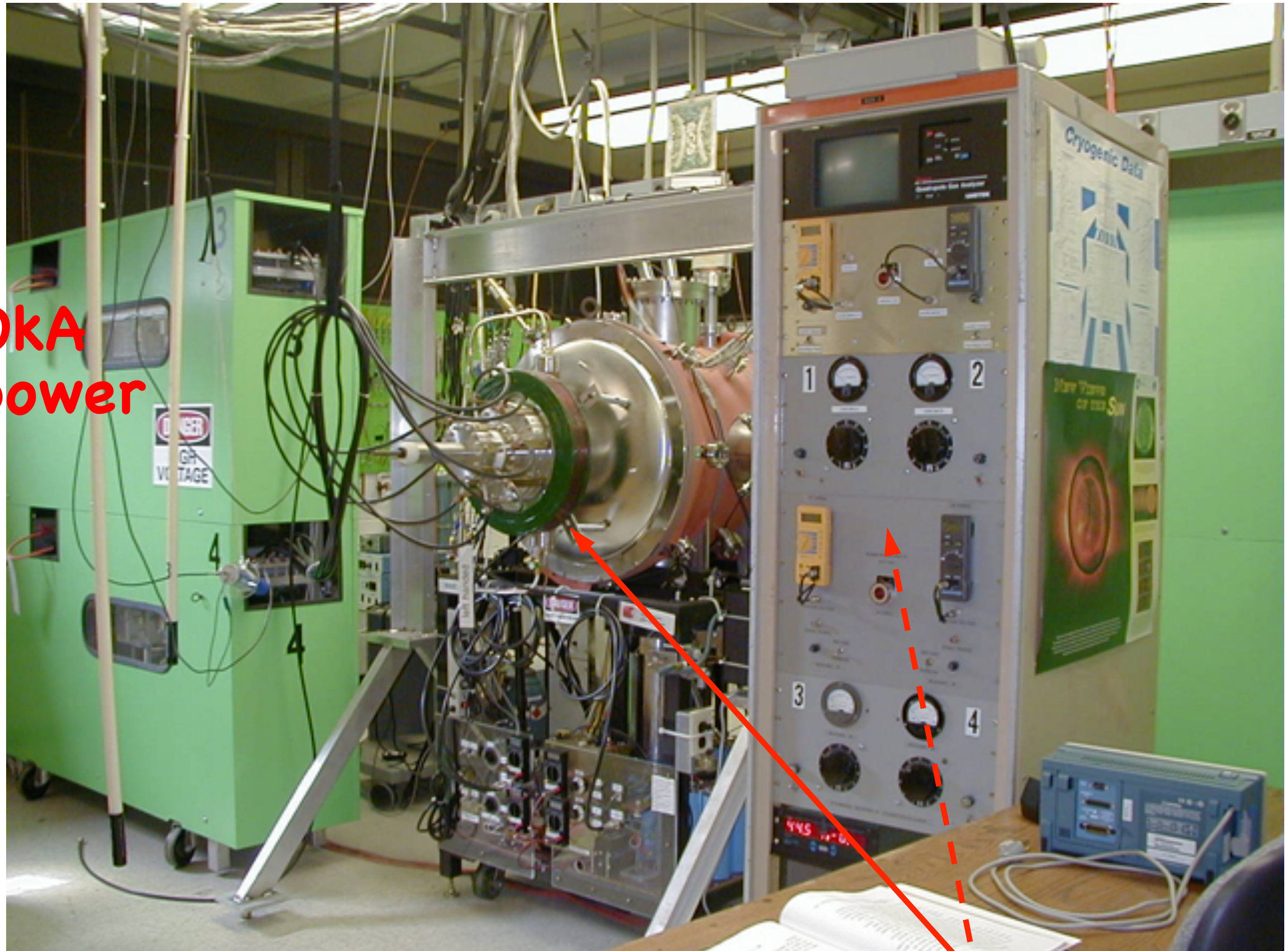


$$\frac{v_{in}}{v_{out}} = \frac{\delta}{L}$$

$$B_{in}(4L) = \mu_0 J_z (2L)(2\delta) \rightarrow B_{in} = \mu_0 J_z \delta$$

The SSX Laboratory

10kV/100kA
Pulsed power



Cylindrical vacuum chamber
(D = 0.5 m, L = 1 m)

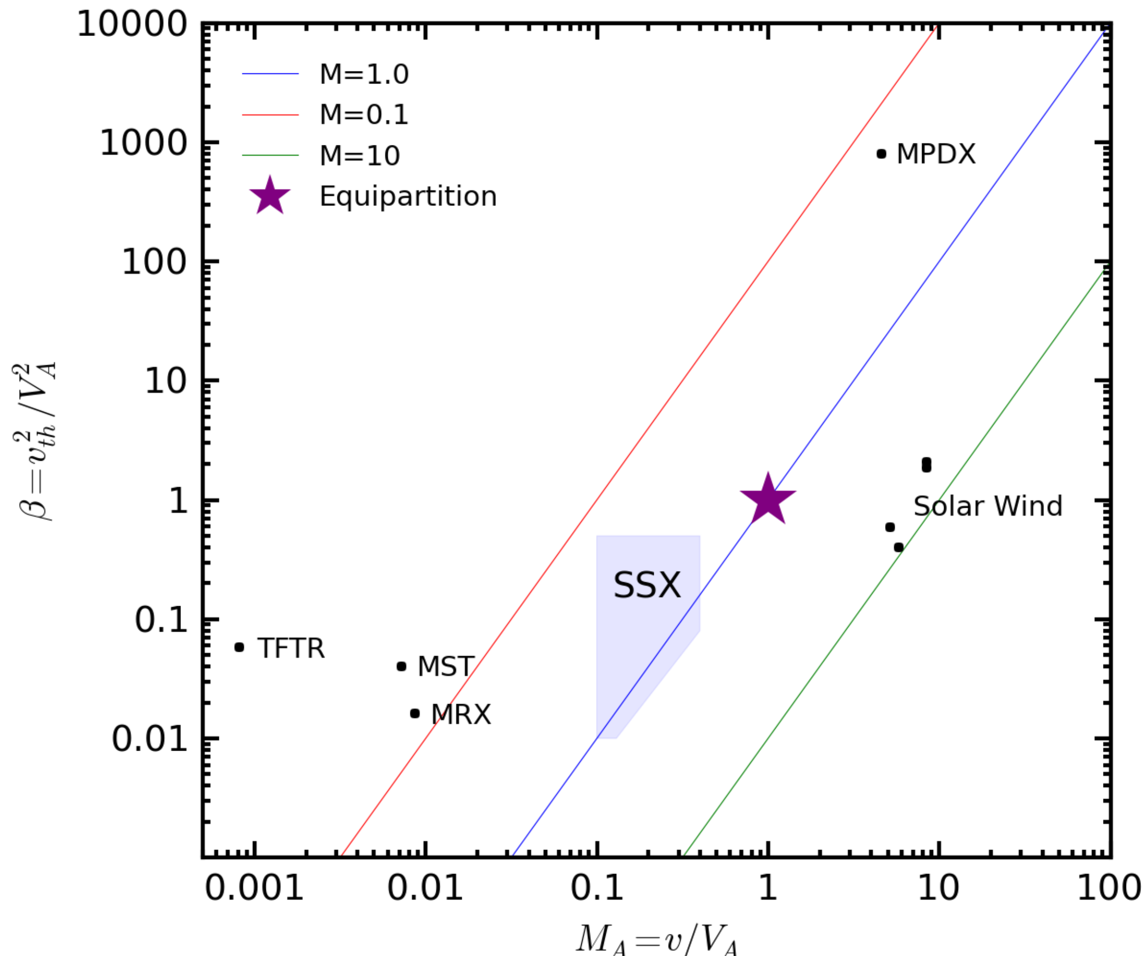
High voltage plasma
guns on each end

SSX parameters

Ion Density (protons)	10^{14} -10^{15} cm^{-3}
Temperature (T_e,T_i)	20 - 60 eV
Magnetic Field	> 0.1 Tesla
Ion gyroradius	< 0.5 cm
Alfvén speed	100 km/s
S (Lundquist number)	> 1000
Plasma β	0.1-1

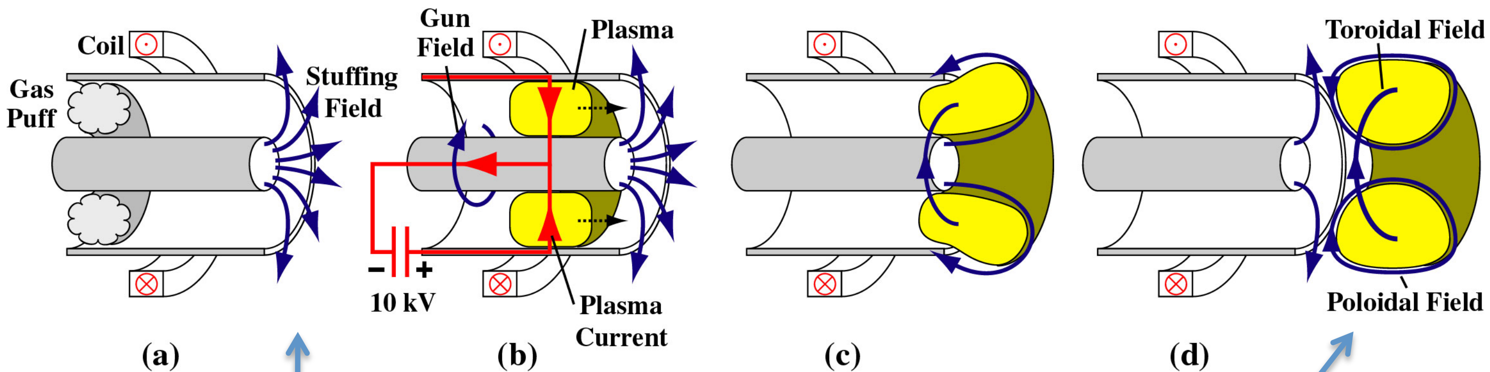
ρ<< R, so treat as MHD fluid… no intrinsic scale!

Equipartition of flow, thermal, and magnetic energy



plot_caryplot_forJPPpaper.py

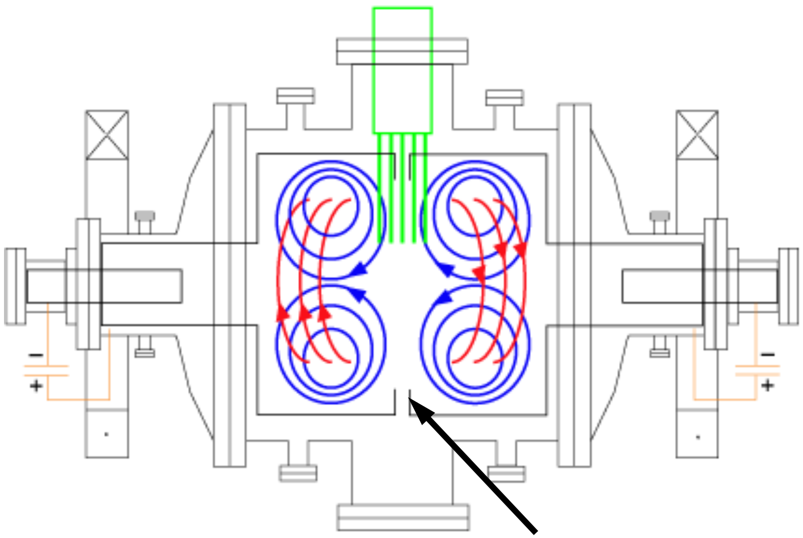
Spheromak formation



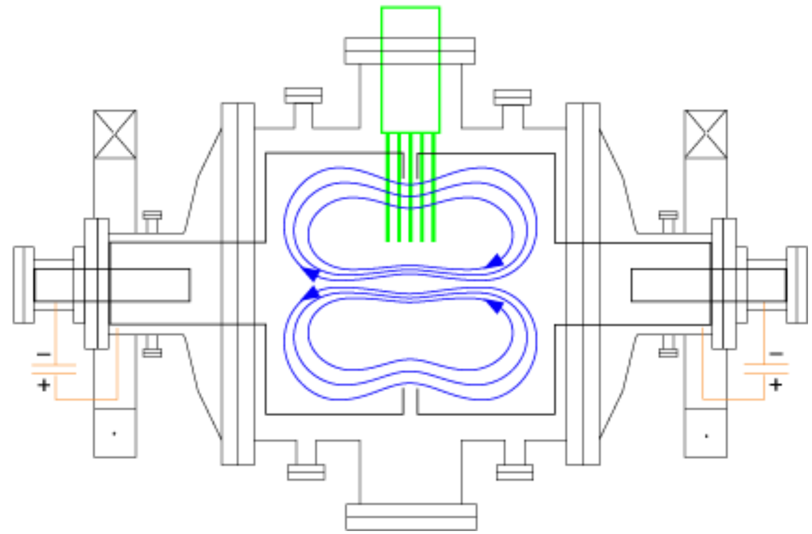
Spheromak

Stuffing flux acts like a nozzle

Plasma merging scenario (old SSX)



Rapid merging of two rings

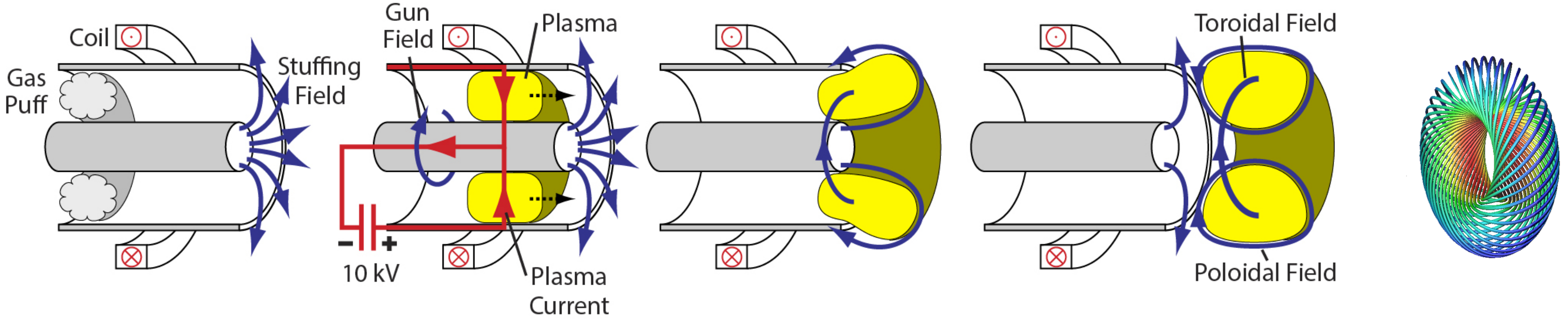


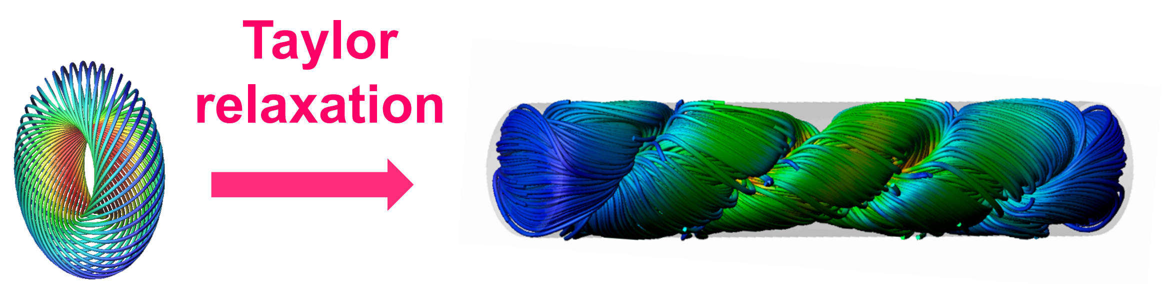
Single structure is formed

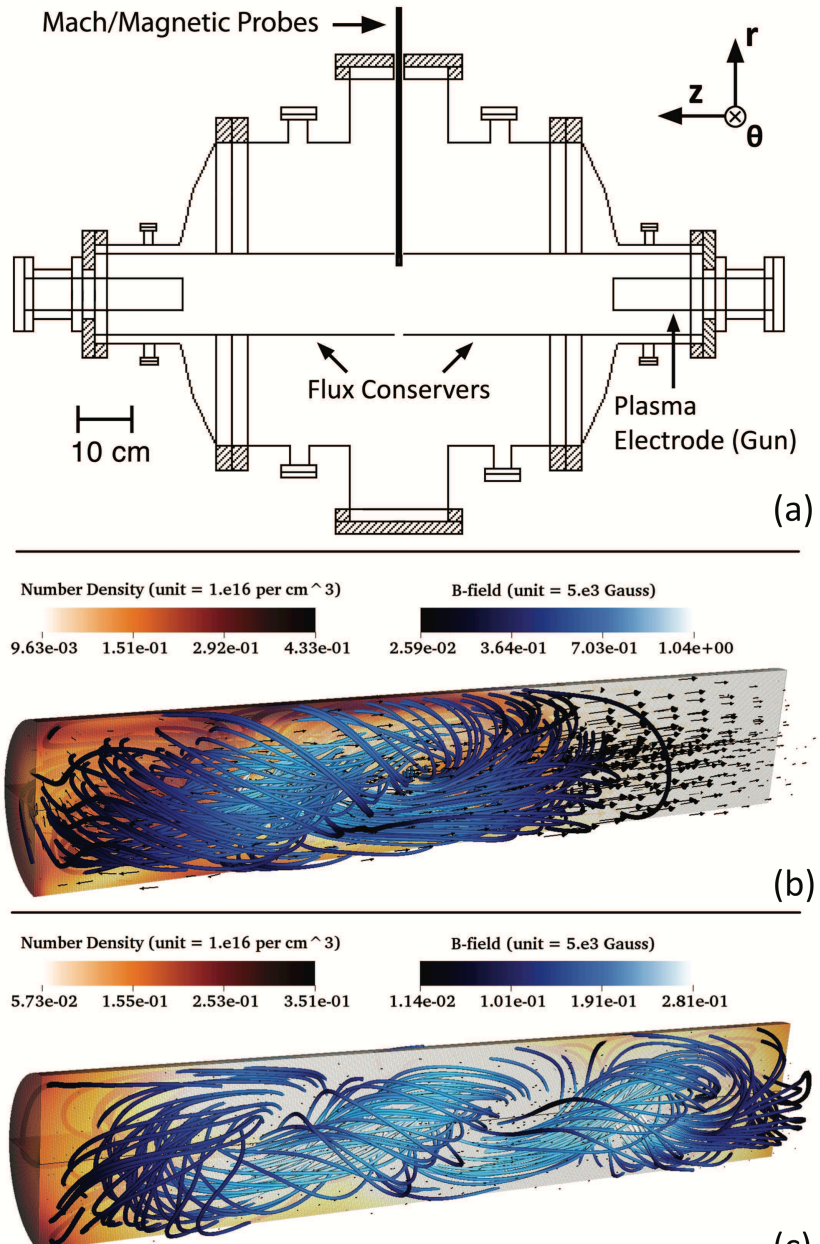
MHD wind tunnel (since 2014)

- 50 km/s flows, fully ionized and magnetized
- Kinetic, magnetic, thermal energies comparable
- Single plume (10 kJ)
- Characterization of MHD turbulence
- MHD simulation

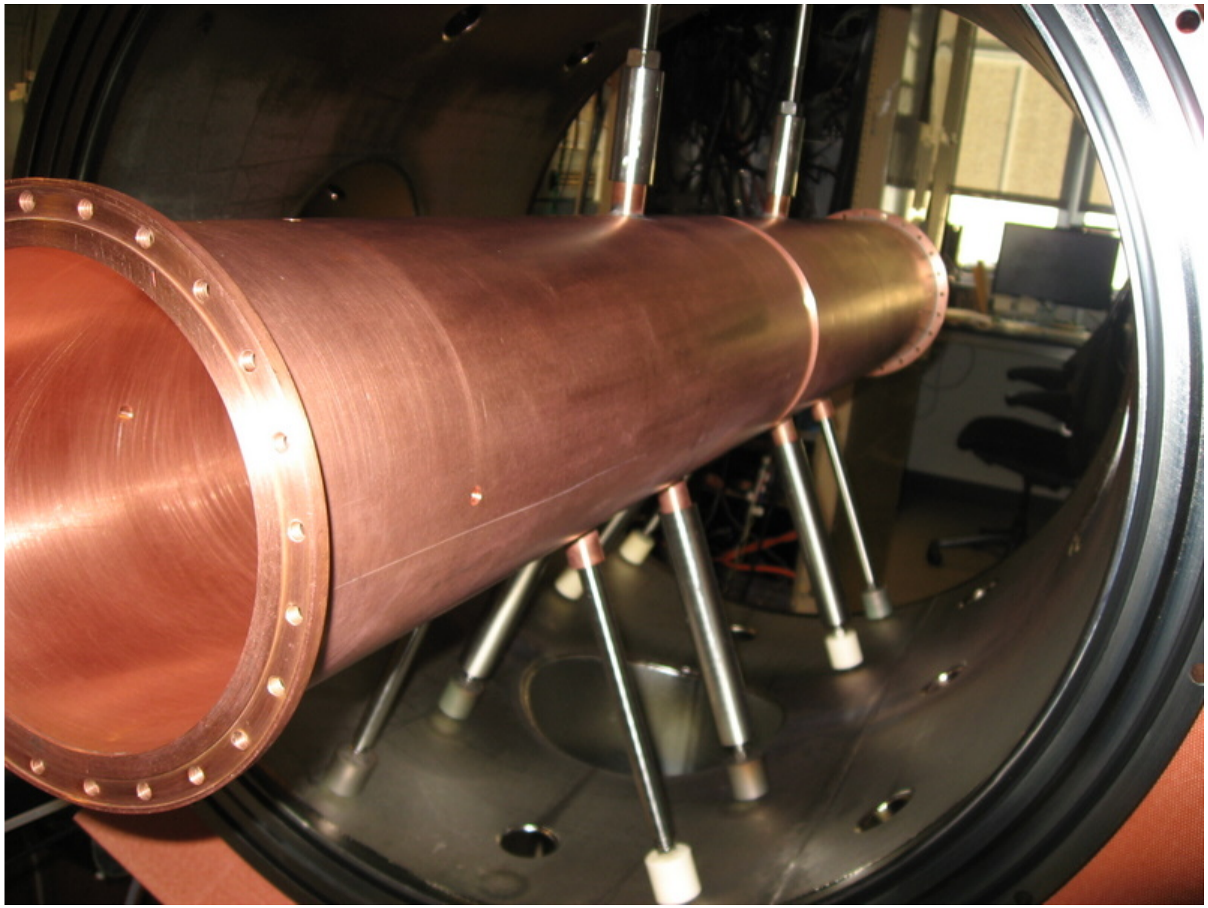
Taylor state formation





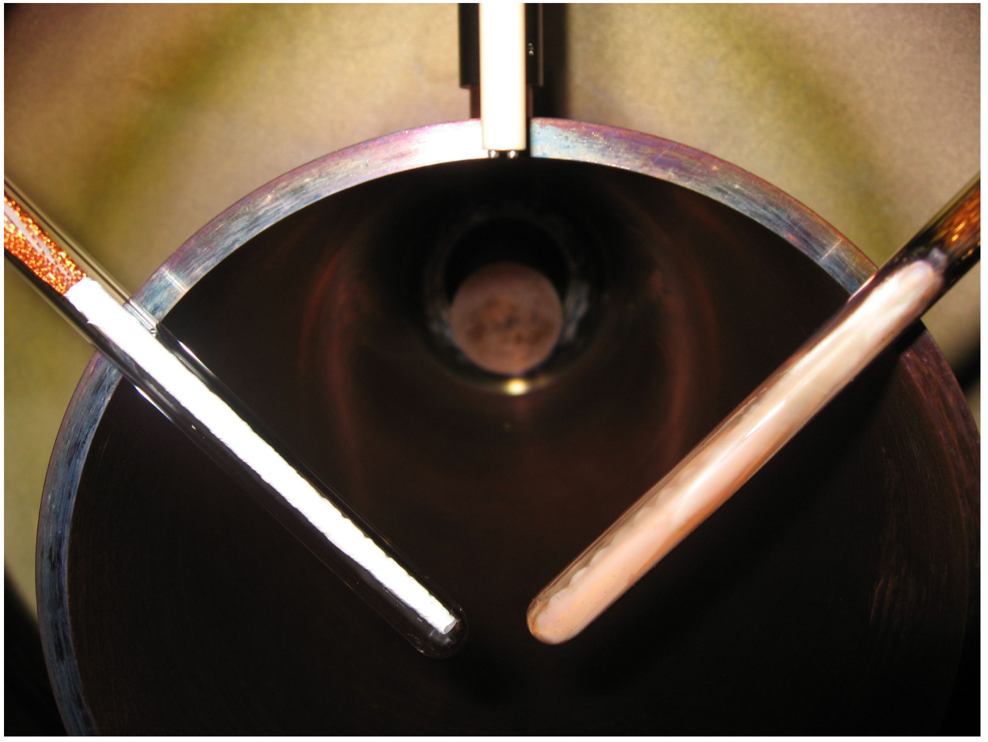

Mach/Magnetic Probes
r
z
θ
Flux Conservers
Plasma
Electrode (Gun)
10 cm
(a)
Number Density (unit = 1.e16 per cm^3)
9.63e-03
1.51e-01
2.92e-01
4.33e-01
B-field (unit = 5.e3 Gauss)
2.59e-02
3.64e-01
7.03e-01
1.04e+00
(b)
Number Density (unit = 1.e16 per cm^3)
5.73e-02
1.55e-01
2.53e-01
3.51e-01
B-field (unit = 5.e3 Gauss)
1.14e-02
1.01e-01
1.91e-01
2.81e-01
(c)

SSX MHD wind tunnel
50 km/s, magnetic and fluid turbulence



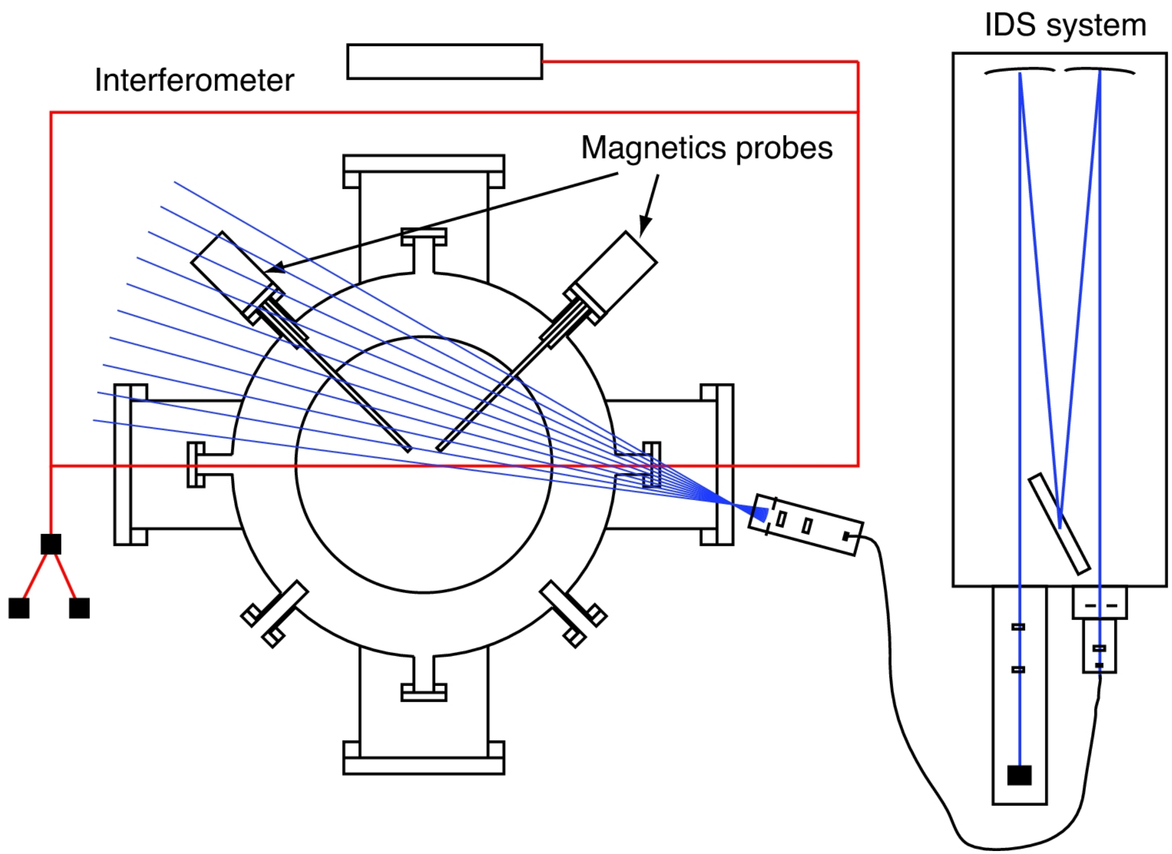
Diagnose with arrays of magnetic and velocity probes

Diagnostics at midplane (B and n_e)



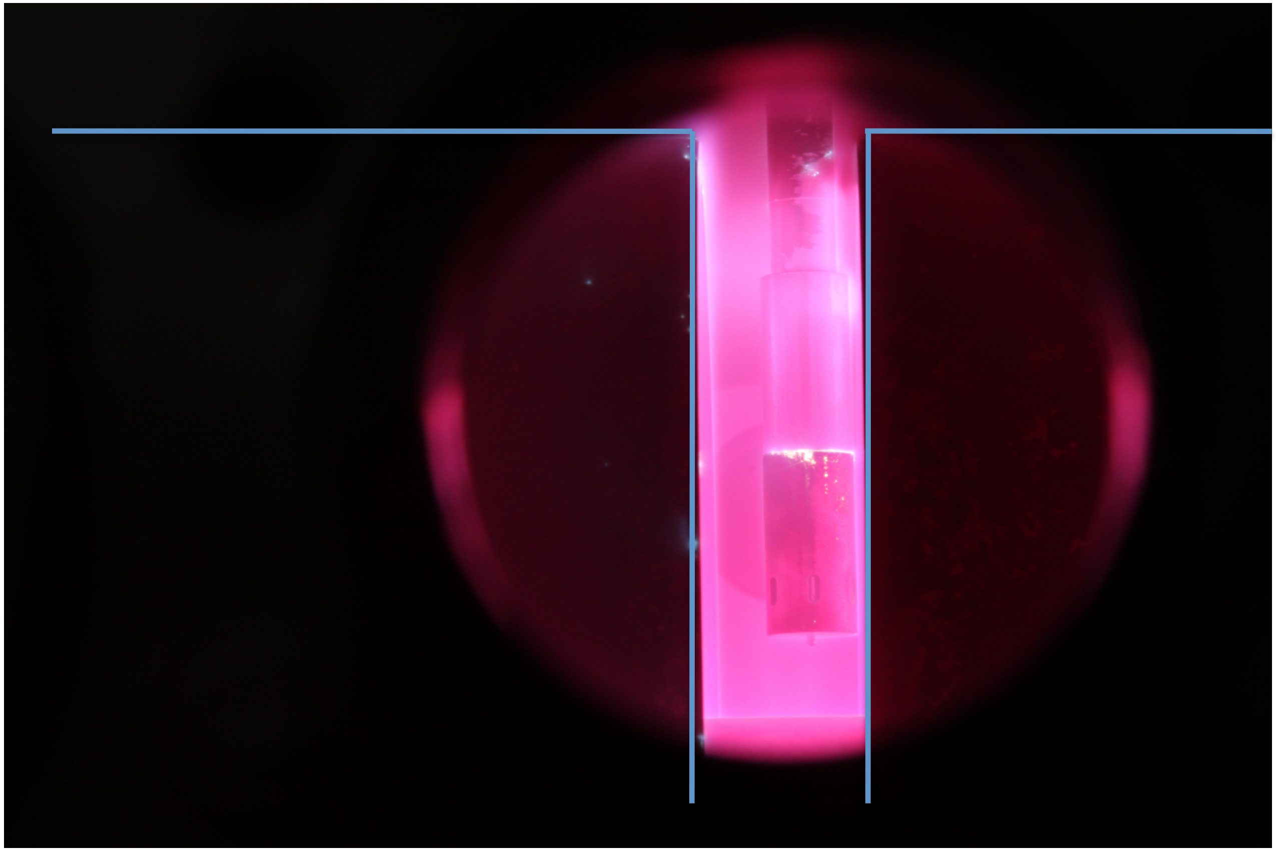
Line-averaged density with He-Ne, temperature from IDS

Ion Doppler spectrometer on SSX

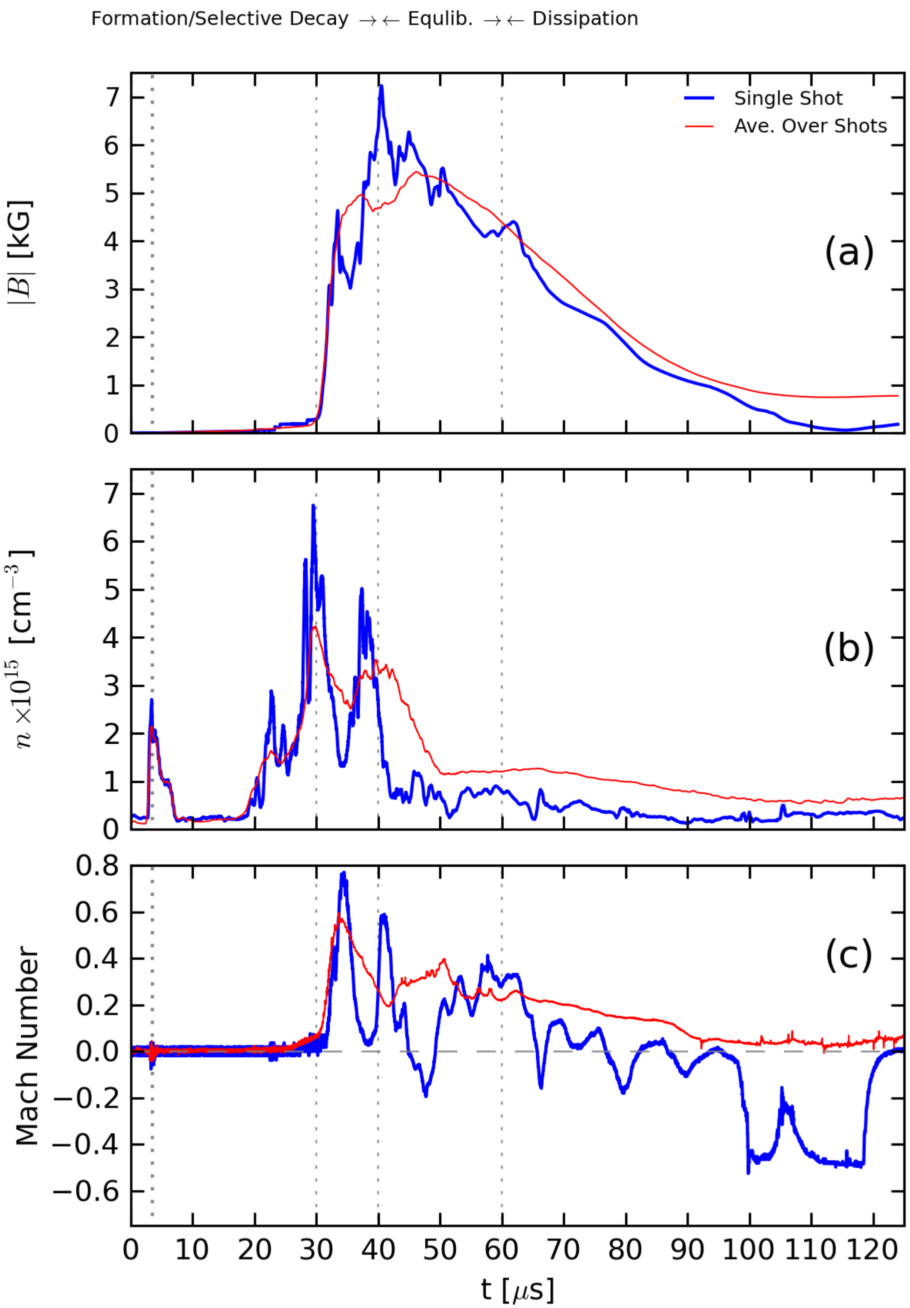


Interferometer chord and two magnetic probes also shown

Mach probe measures local flow

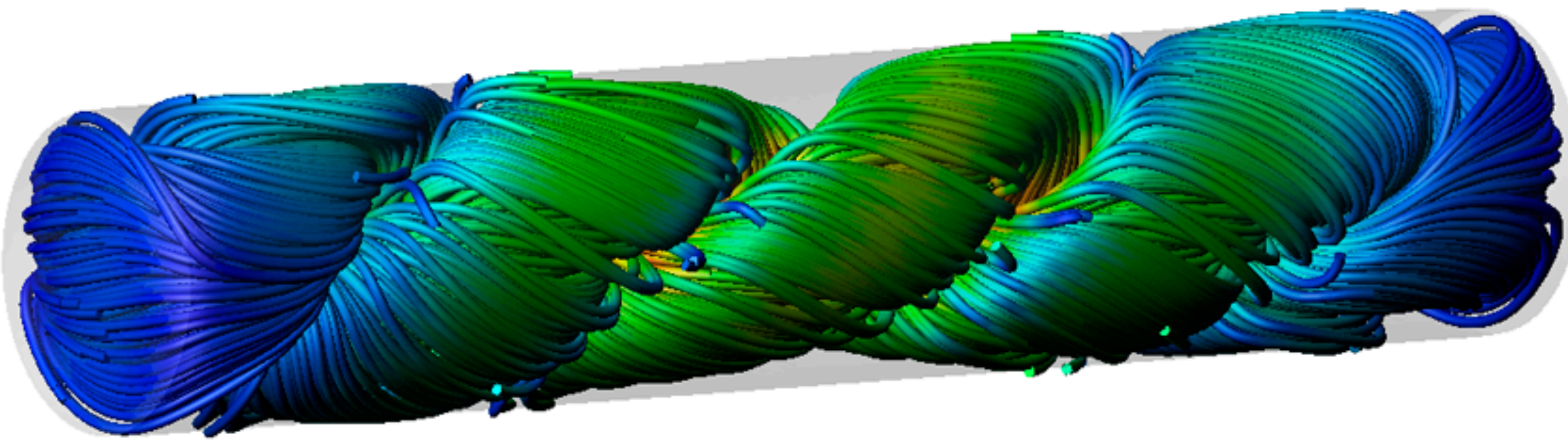


X. Zhang



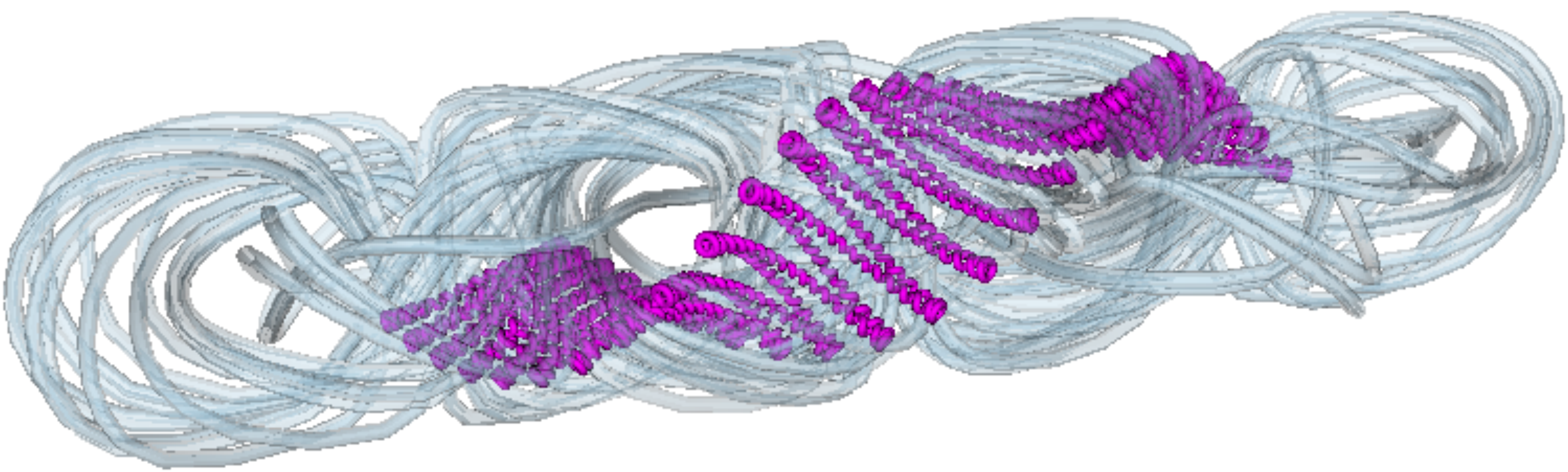
Formation/Selective Decay →← Equlib. →← Dissipation
Single Shot
Ave. Over Shots
|B| [kG]
(a)
n ×10^15 [cm^-3]
(b)
Mach Number
(c)
t [μs]

Comparison with predicted helical state



State with the minimum magnetic energy
(subject to certain constraints)
Originally predicted by J. B. Taylor

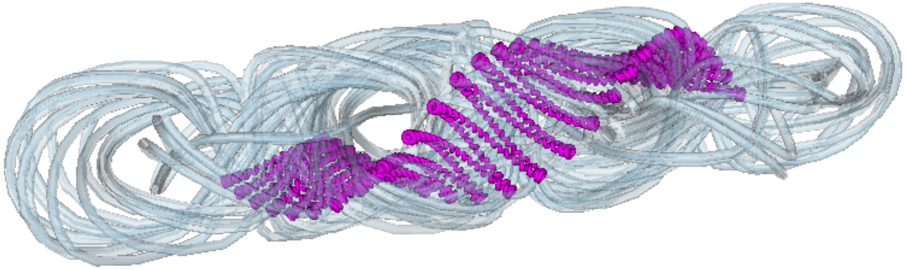
Trapped proton orbits



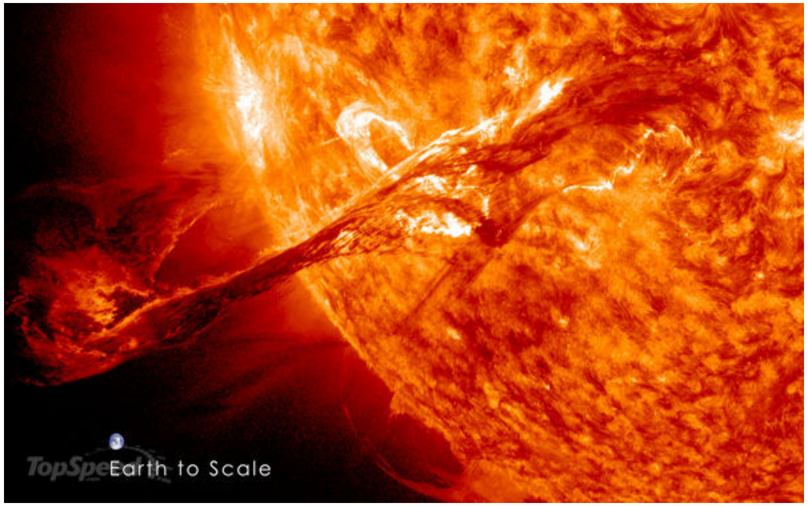
A. D. Light, H. Srinivasulu, et al (in preparation)

Summary

Turbulent relaxation (with magnetic reconnection) shows the emergence of a twisted helical magnetic structure in SSX that is a good trap for protons



Similar to magnetic structures observed in solar/space plasmas... turbulence, reconnection, heating, relaxation... all related.



Thank you!
Questions?