NONLINEAR MHD WAVES

THE INTERESTING INFLUENCE OF FIREHOSE AND MIRROR IN ASTROPHYSICAL PLASMAS

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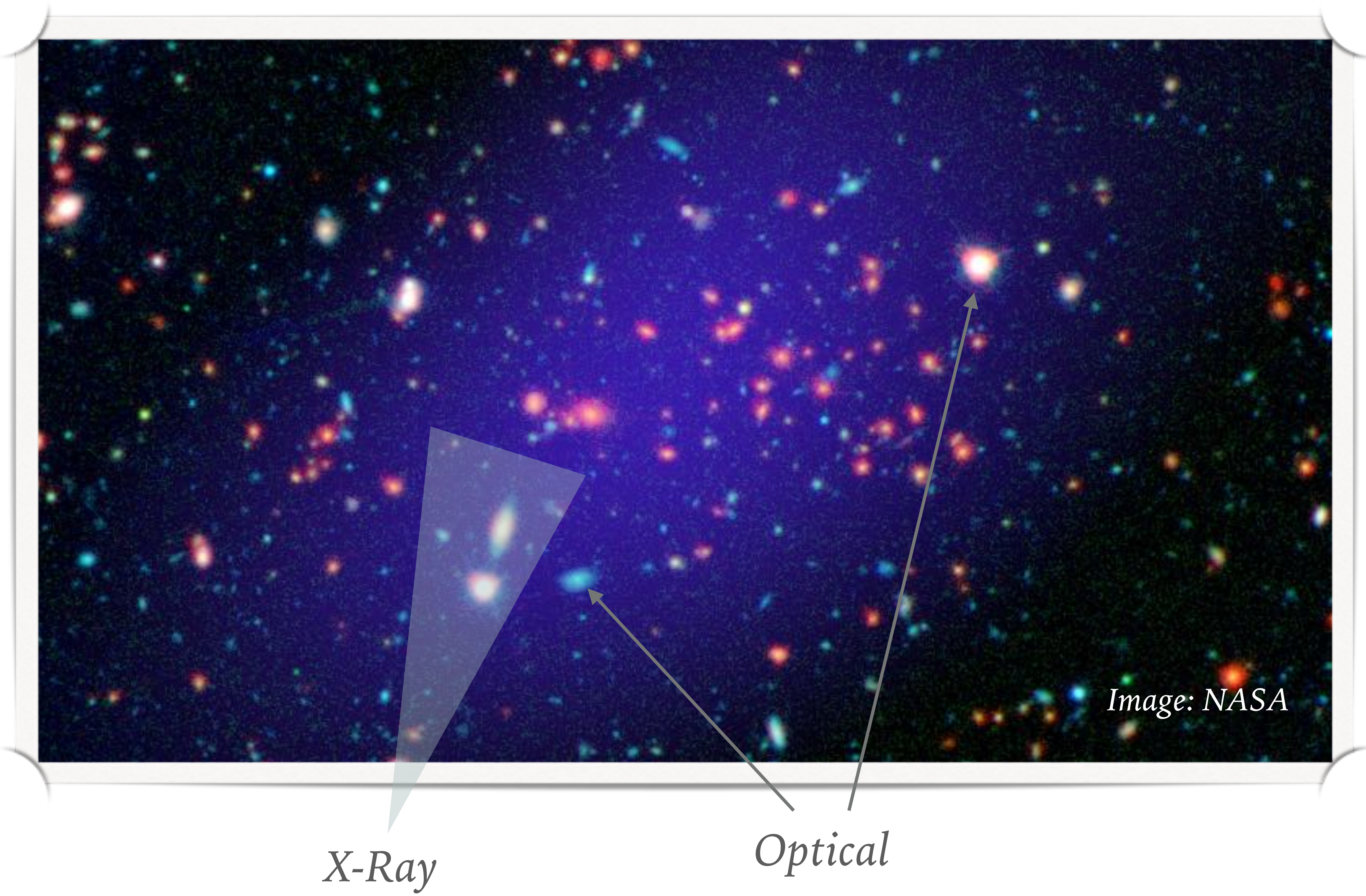
INTRACLUSTER MEDIUM (ICM)



LET'S LOOK AT A FEW PARAMETERS

e.g., Rosin et. al 2010, Hydra A
Kunz et. al 2010

$$n \sim 6 \times 10^{-2}\mathrm{cm}^{-3} \quad T \sim 3 \times 10^{7}\mathrm{K} \sim 3\mathrm{keV}$$

$$B \sim 7\,\mu\mathrm{G} \quad \Omega_i \sim 0.07\mathrm{s}^{-1} \quad v_{th,i} \sim 700\,\mathrm{kms}^{-1}$$

$$\nu_{ii} \sim 5 \times 10^{-13}\,\mathrm{s}^{-1}$$

Plasma motions

$$U \sim 250\,\mathrm{kms}^{-1} \quad L \sim 2 \times 10^{22}\mathrm{cm}$$

Dimensionless

$$\frac{\Omega_i}{\nu_{ii}} \sim 10^{11}$$ *Strongly magnetized*

$$\mathcal{M} \sim 0.3$$ *Incompressible?*

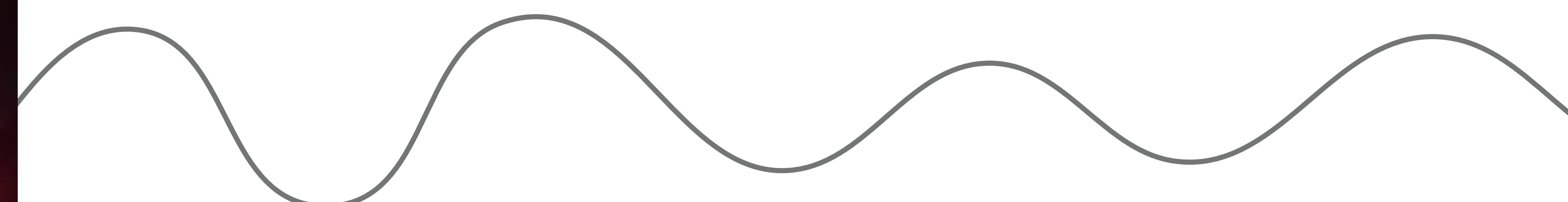
$$\beta = \frac{P_{\mathrm{magnetic}}}{P_{\mathrm{thermal}}} \sim 100$$ *Approximate equipartition*

$$\mathrm{Re} \sim 60 \quad \mathrm{Pm} \sim 2 \times 10^{26}$$ *Turbulent?*

$$\frac{\nu_{ii}}{|\nabla \boldsymbol{u}|} \sim 400$$ *Not very collisional*

PERTURB MAGNETIC FIELD?

e.g., sound (ion-acoustic) wave



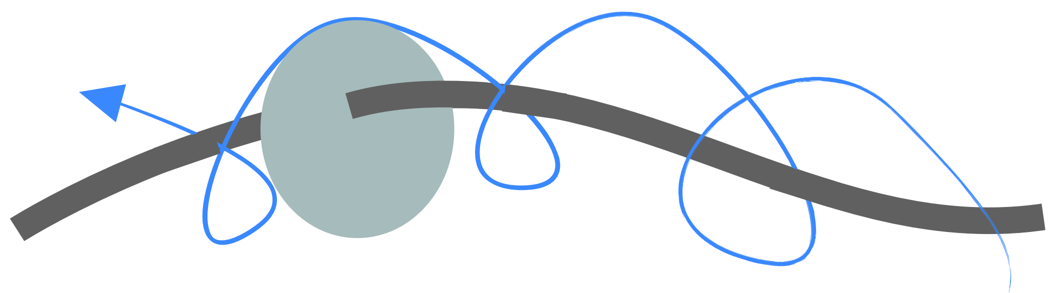
see also Verscharen et al. (2016)

PERTURB MAGNETIC FIELD?

If $\omega \gtrsim \nu_{ii}$ (wavelength < 0.01*galaxy size)

$$\mu = \frac{m v_\perp^2}{2B}$$

conserved



$L \ggg \rho_i \Rightarrow$ distribution function *f* is gyrotropic

$$p_\perp = \int d\boldsymbol{v}\, v_\perp^2 f \qquad p_\parallel = \int d\boldsymbol{v}\, v_\parallel^2 f \qquad \Delta p = p_\perp - p_\parallel$$

$$|\boldsymbol{B}| \uparrow \;\Rightarrow\; p_\perp \uparrow \;\Rightarrow\; \Delta p \uparrow$$

$$|\boldsymbol{B}| \downarrow \;\Rightarrow\; \Delta p \downarrow$$

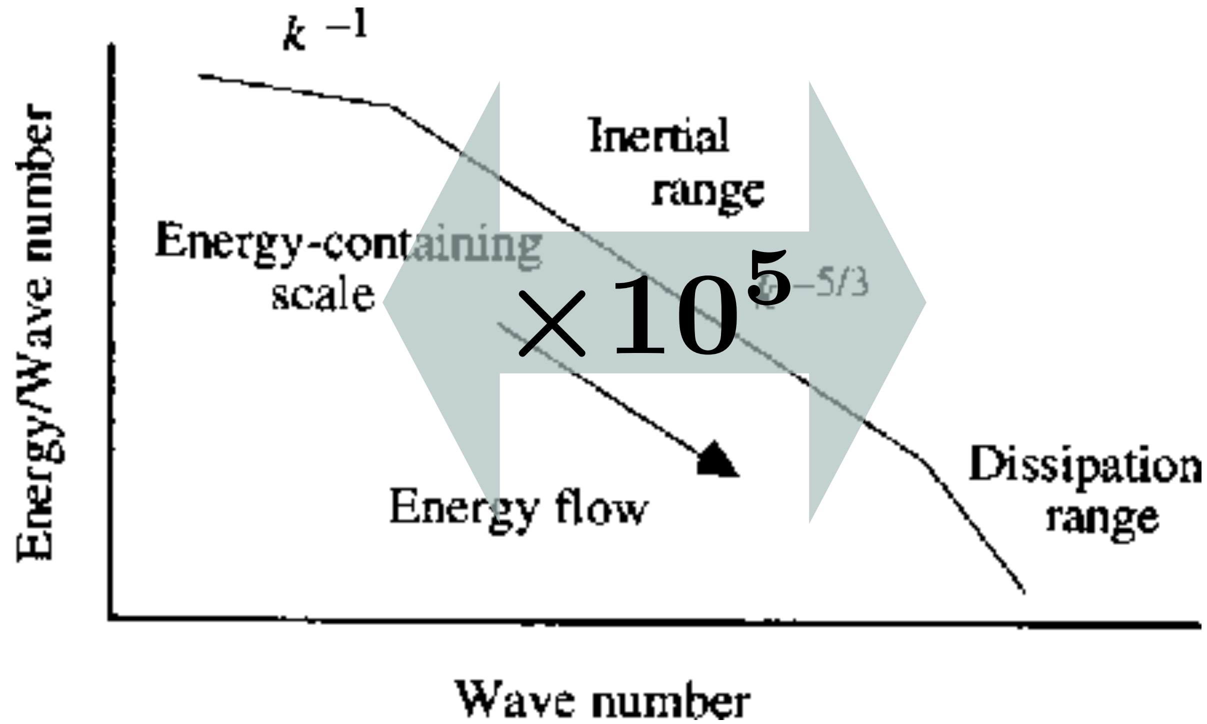
PERTURB MAGNETIC FIELD?

$$\delta B \sim \delta p \sim \Delta p$$

Momentum stress due to Δp $\sim$ *100*magnetic pressure*

MHD completely wrong?

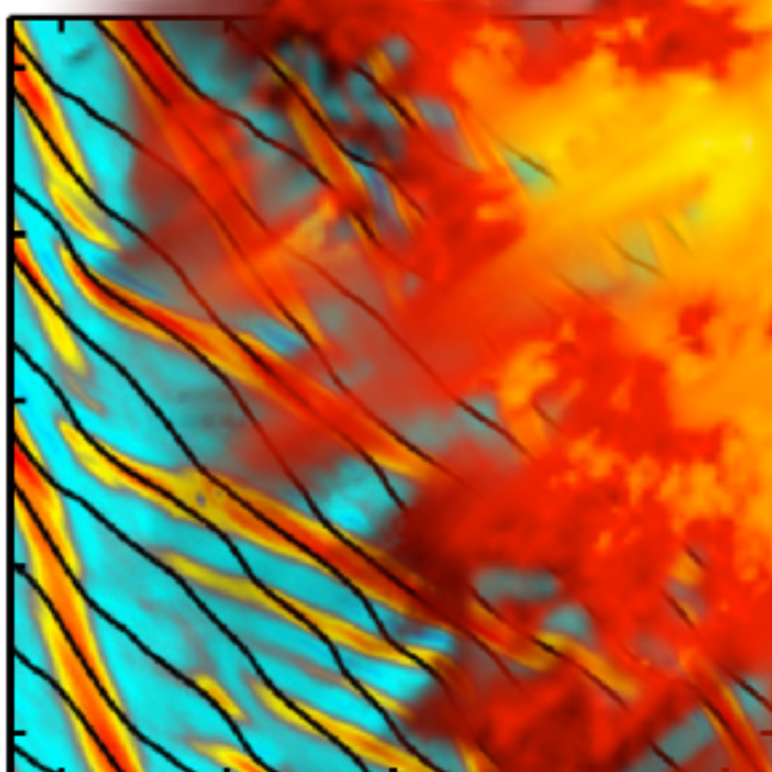
Even though
$L \ggg \rho_i$

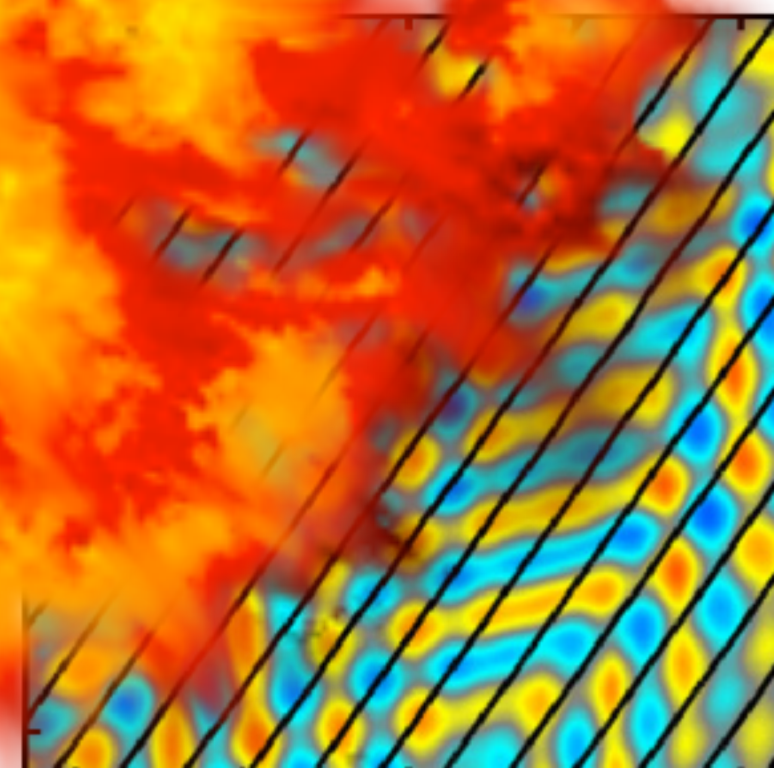


PRESSURE ANISOTROPY INSTABILITIES

$$\frac{\Delta p}{p} \gtrsim \frac{1}{\beta} \qquad \frac{\Delta p}{p} \lesssim -\frac{2}{\beta}$$

Mirror Instability **Firehose Instability**

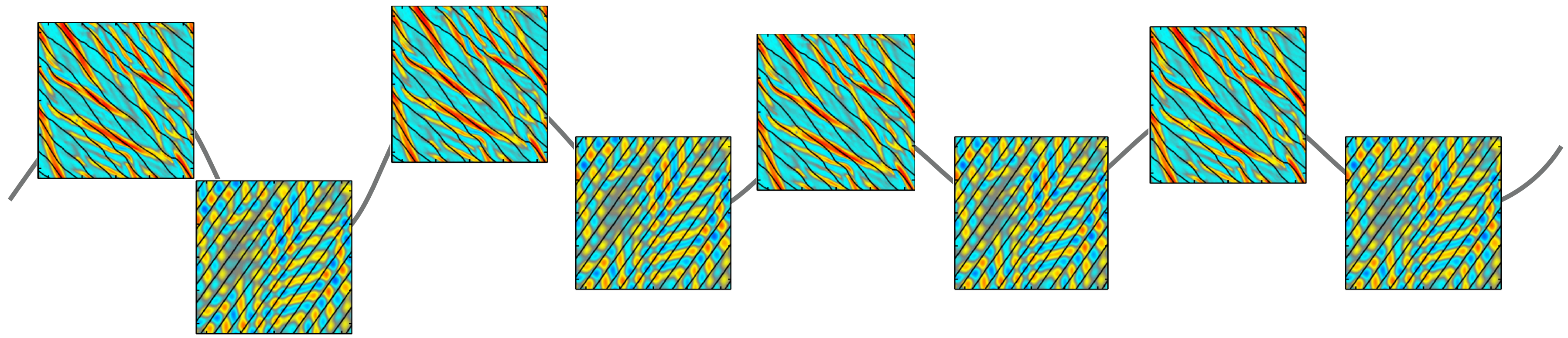




Kunz et al. 2014

ICM WAVE

$$\frac{\delta n}{n} > 0.01 \text{ ??}$$



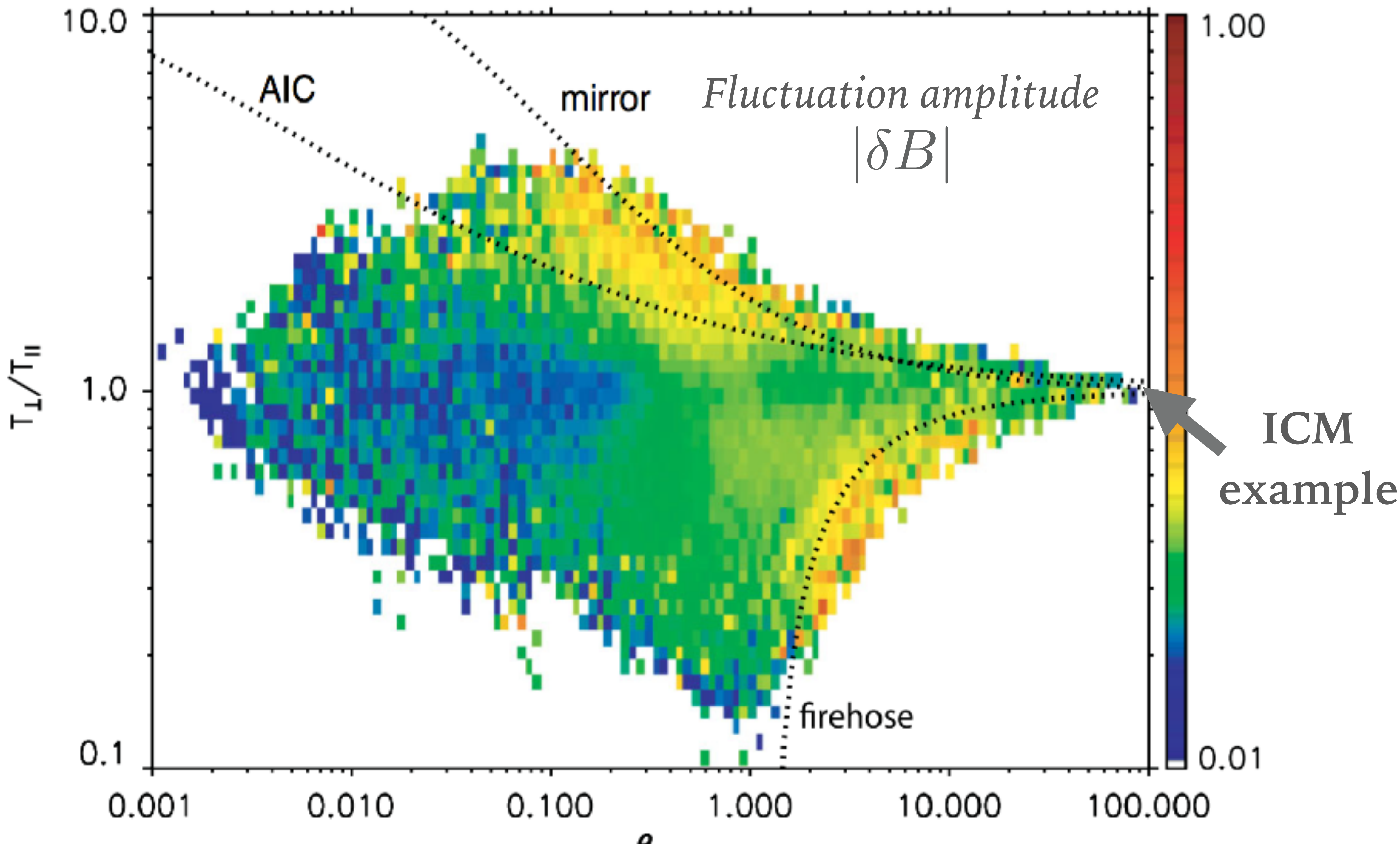
- Firehose/mirror excited *very* easily.
- Act to limit Δp
- Saturation controls large-scale dynamics

$$\Omega_i/|\nabla \boldsymbol{u}| \sim (k\rho_i)^{-1} \sim 10^{11}$$

they act instantaneously, enormous scale separation

COLLISIONLESS HIGH-β PLASMAS ARE ALWAYS UNSTABLE

Melville et al. 2016



Bale et al. 2009

A COMPLETELY DIFFERENT TYPE OF FLUID DYNAMICS

where the nonlinear behavior of mirror/firehose instability control the plasma's viscosity/conductivity/resistivity…?

THIS TALK *Firehose+mirror fundamental to plasma physics*

- Dynamics can differ (a lot) from MHD. Simplest to study: waves (but we really care about turbulence).
- Explore some parameters required to see such effects in the laboratory.

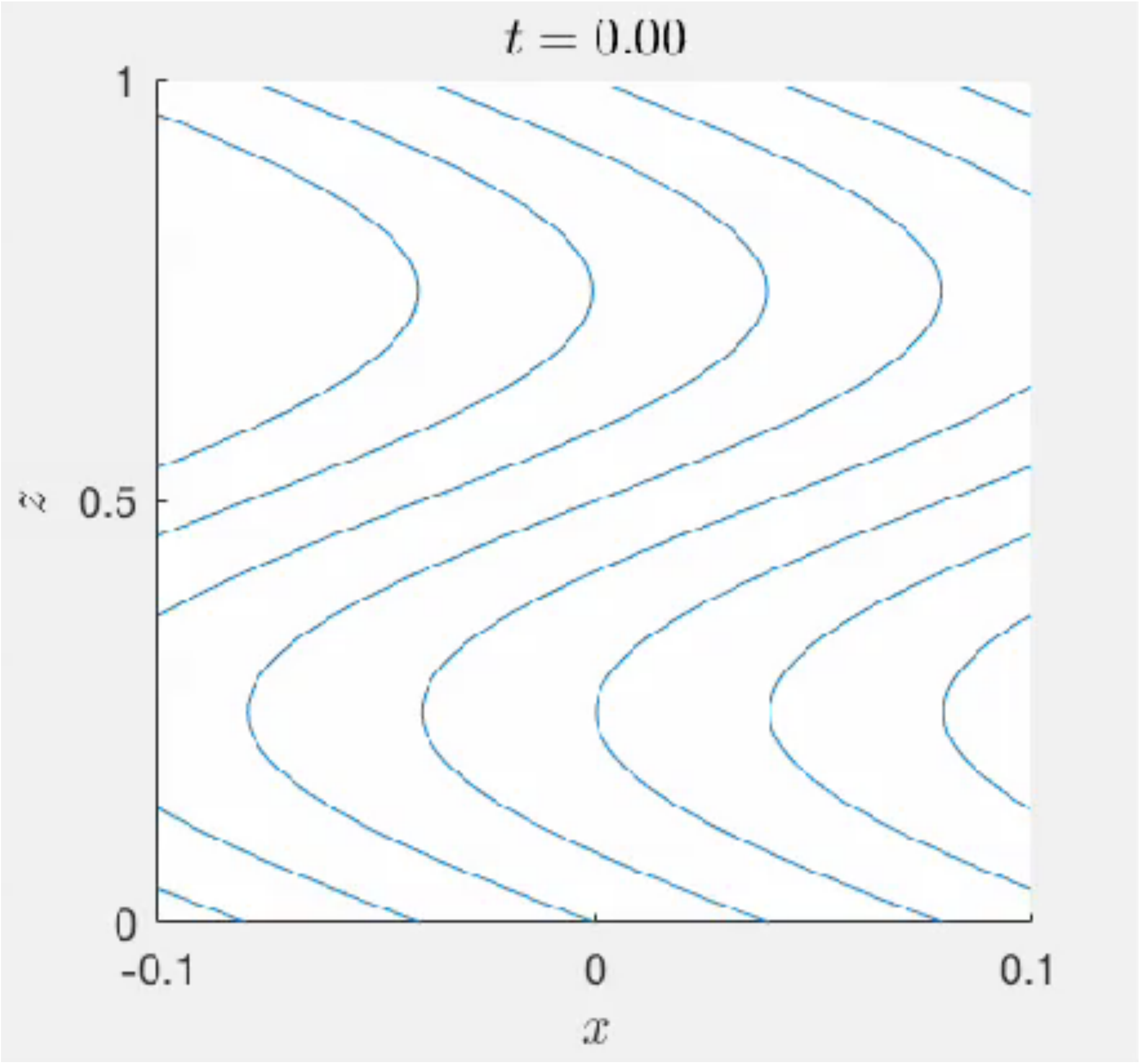
MHD WAVES THE SHEAR-ALFVÉN WAVE

- Fundamental to turbulence (Goldreich & Sridhar 1996)
- Ubiquitous in the solar wind and experiments
- Magnetic tension acts as spring

e.g., linearly polarized standing wave

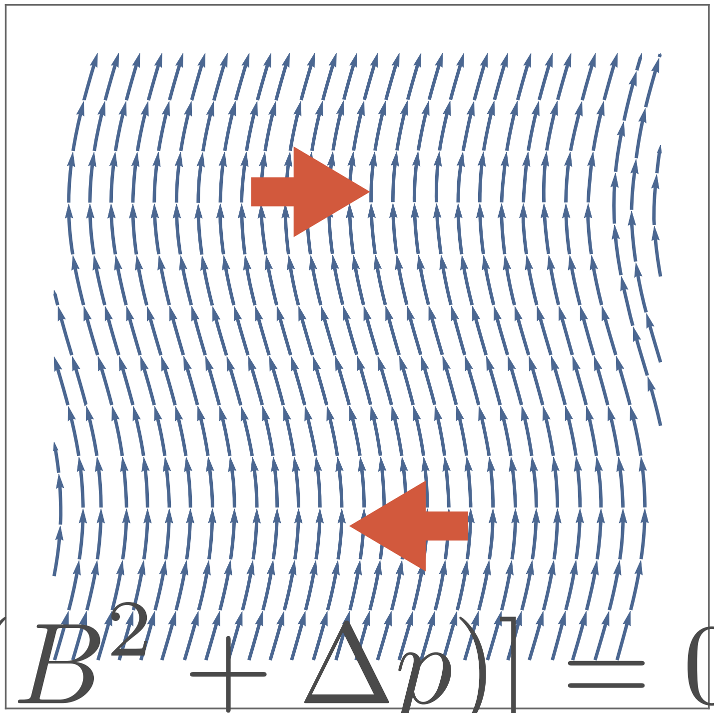
$$\boldsymbol{B} = B_0\hat{\boldsymbol{z}} + \delta B_\perp(z)\hat{\boldsymbol{x}}$$

$$\boldsymbol{u} = \delta u_\perp(z)\hat{\boldsymbol{x}}$$



COLLISIONLESS WAVES INTERRUPTION

$$\frac{dB}{dt} < 0 \;\Rightarrow\; \Delta p < 0$$



IF $\Delta p = -B^2 \;\Rightarrow\; \nabla \cdot [\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}(B^2 + \Delta p)] = 0$

Firehose limit $\frac{\Delta p}{p} = -\frac{2}{\beta}$

Magnetic tension

THE WAVE HAS REMOVED ITS OWN RESTORING FORCE

COLLISIONLESS WAVES INTERRUPTION

$$\mu \propto \frac{p_\perp}{B}$$

$$\Delta p \sim \Delta B \sim \Delta(\delta B_\perp^2)$$

$$\Delta p = -B_0^2$$

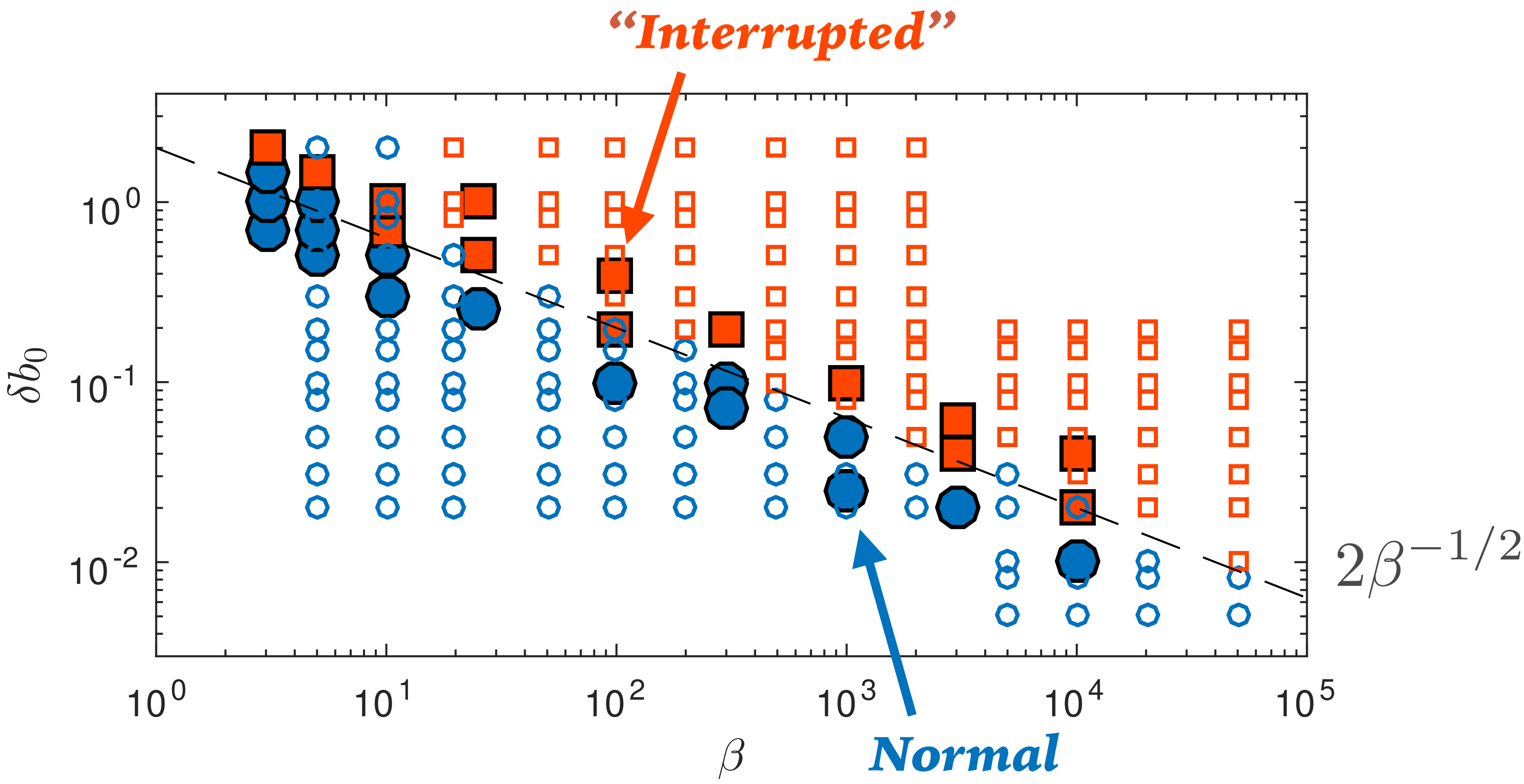
IF

$$\frac{\delta B_\perp}{B_0} \gtrsim \beta^{-1/2}$$

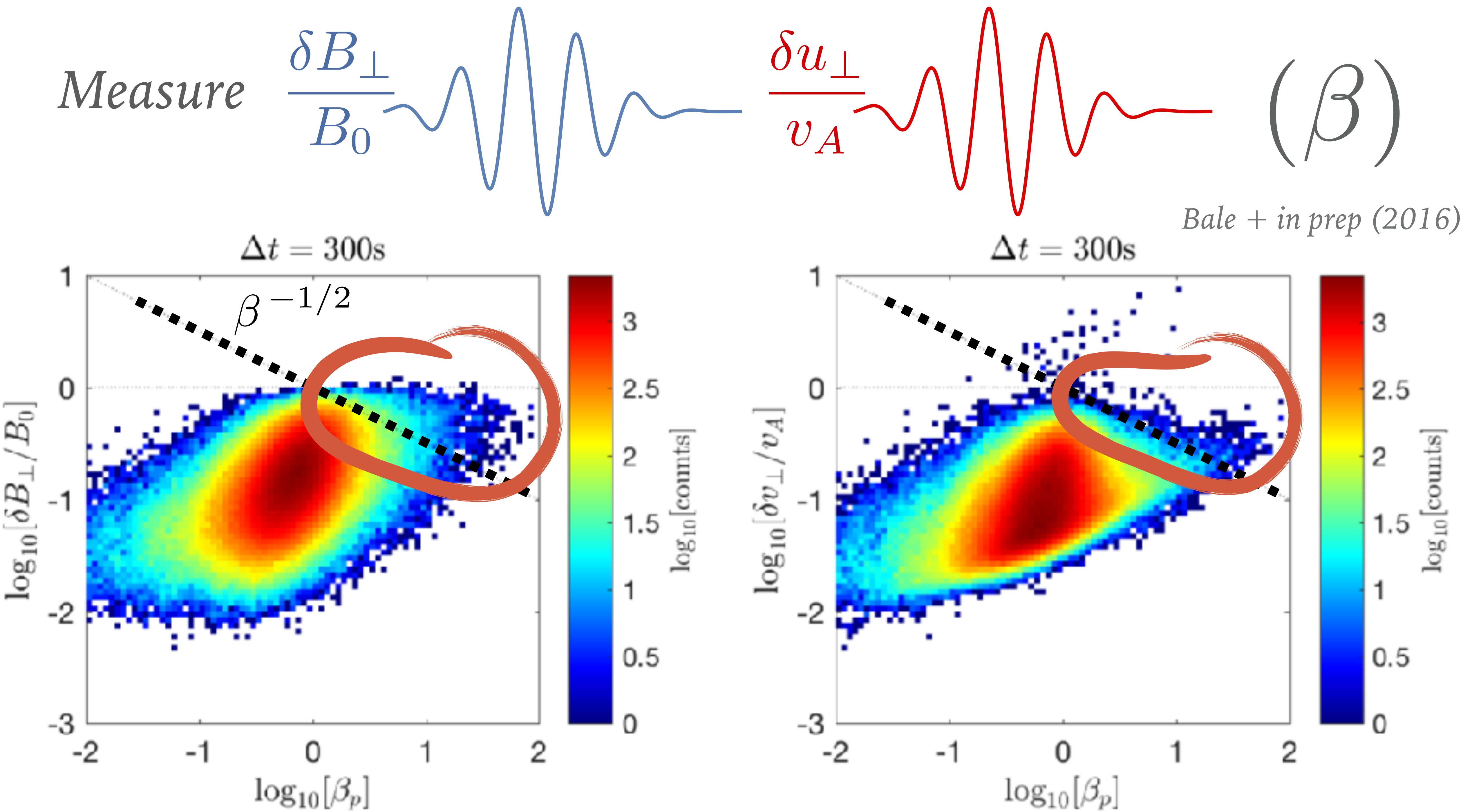
Firehose excited just as the wave loses restoring force

Squire+2016,2017

COLLISIONLESS WAVES INTERRUPTION



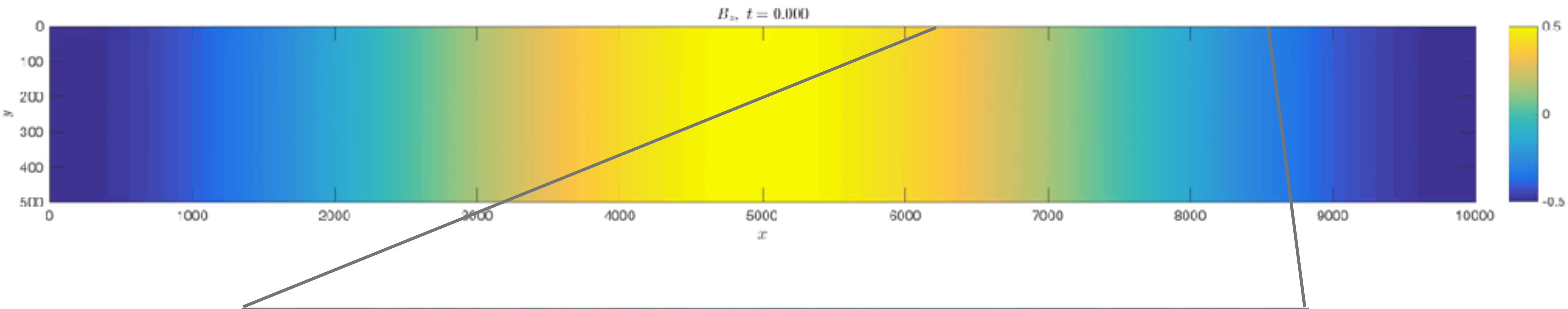
WE CAN SEE THIS EFFECT IN THE SOLAR WIND



MEASUREMENT SUPPORTS THEORY

2D–3V HYBRID SIMULATIONS

- Illustrate how firehose saturation controls MHD scales
- Transfer of energy directly from large to small — no turbulence

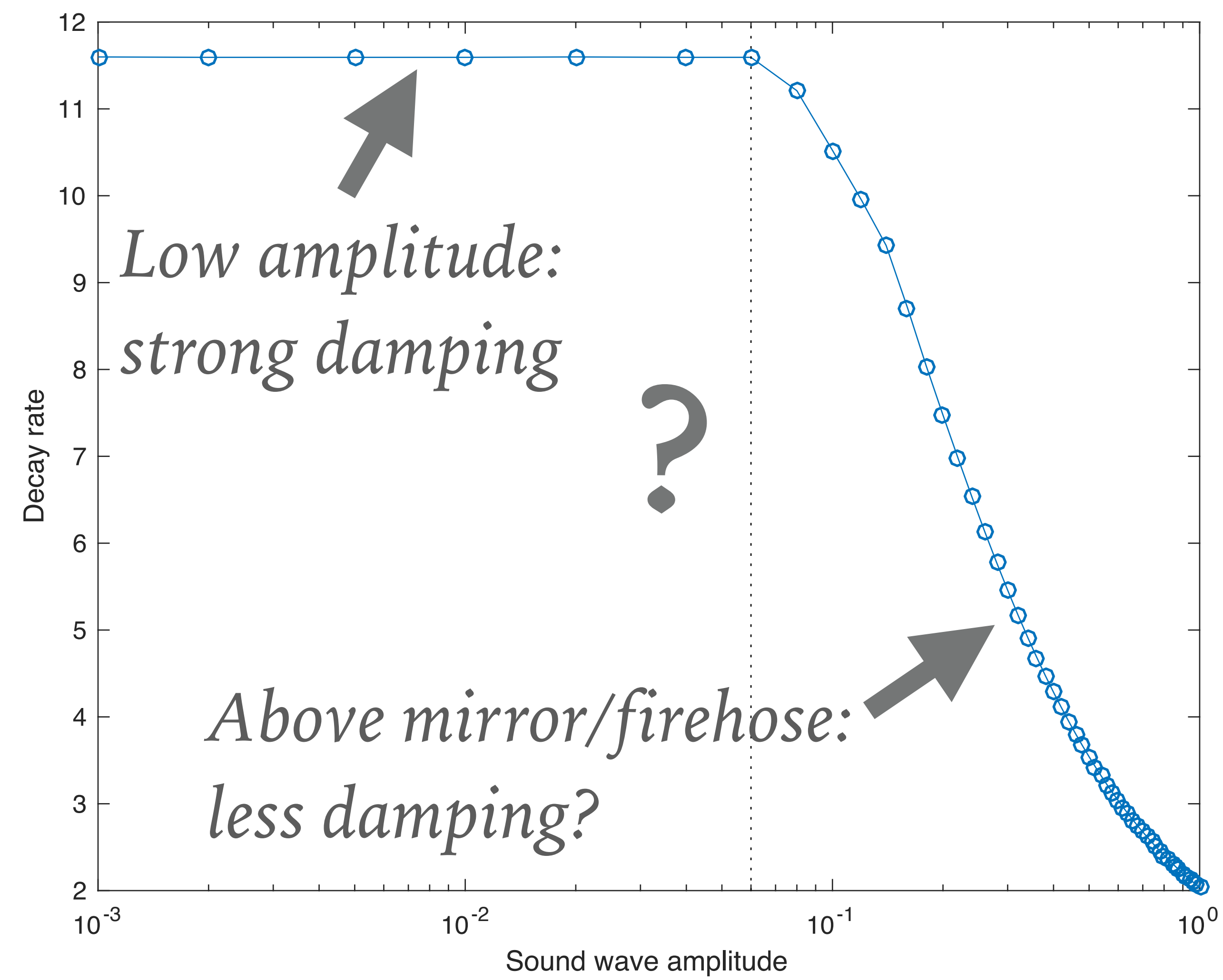


***Details** of firehose mode's saturation and decay controls the MHD wave*

(e.g., Quest+1996, Matteini+2006, Hellinger+2008, Kunz+2014, Seough+2015, Melville+ 2016,…)

OTHER MHD WAVES

- Slow and fast waves: pressure restoring force
- Can likely still propagate if they excite mirror/firehose
- Damping may *decrease* when this occurs?
- Verscharen et al. (2016): large-scale slow waves help isotropize the solar wind?



IN THE LAB?

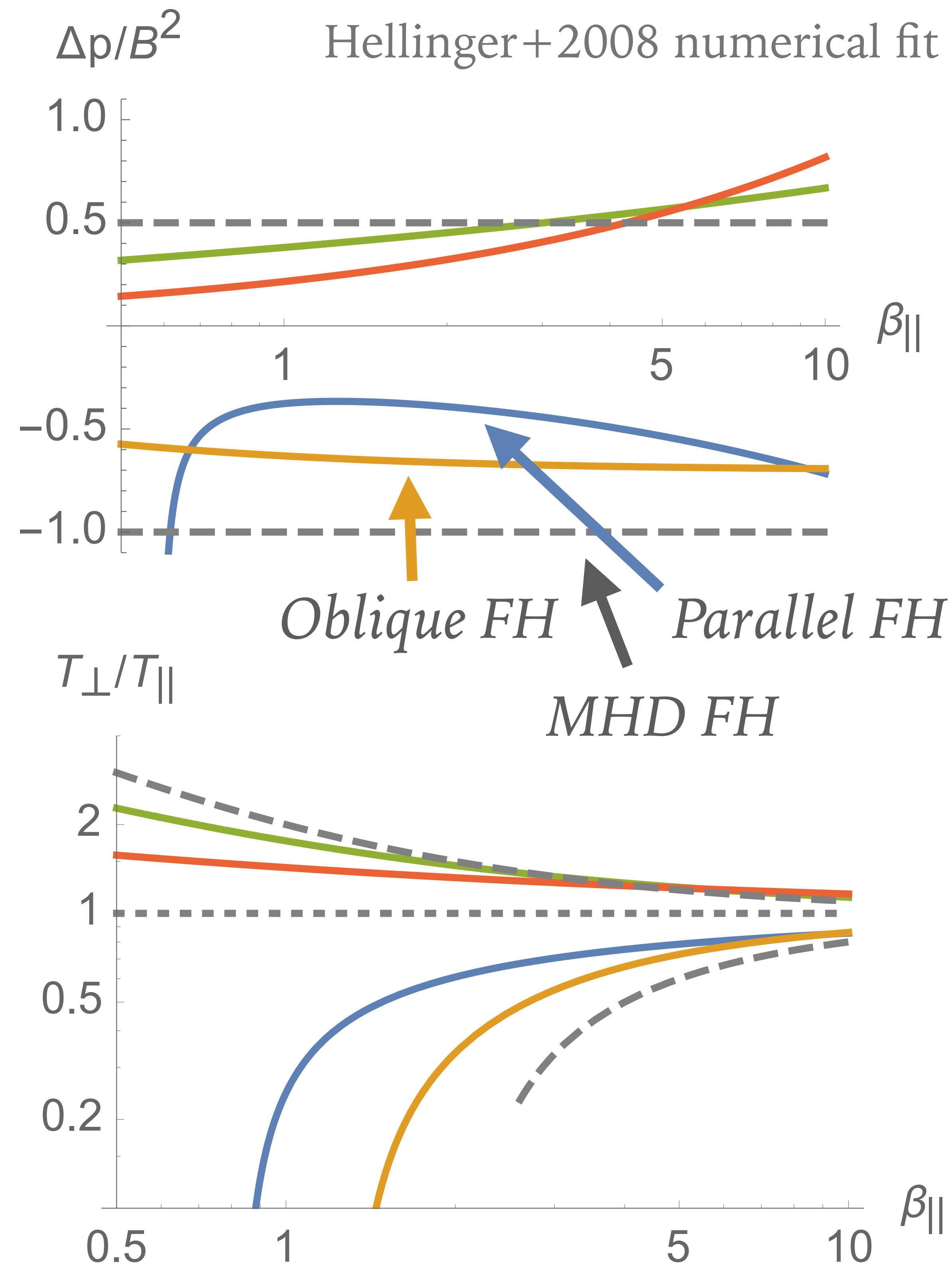
NEED

- $\beta \gtrsim 1$
- Magnetized — $\Omega_i > \nu_i$
  - *and* $\rho_i < L$
- Ability to create large-amplitude waves/turbulence
  - *Shear-Alfvén waves* — $\dfrac{\delta B_\perp}{B_0} \gtrsim \beta^{-1/2}$
  - *Sound waves* — $\dfrac{\delta B}{B} \sim \dfrac{\delta p}{p} \gtrsim \beta^{-1}$
  - *and* $\lambda_{\rm wave} > \rho_i$

IN THE LAB?

Some things to help

- Compared to B^2, instability thresholds reduced at moderate β
  (e.g., Hellinger+2008, Klein+2015)
- Need MHD firehose to "interrupt" wave, but would still see interesting fluctuations at kinetic thresholds



IN THE LAB?

Some things to help

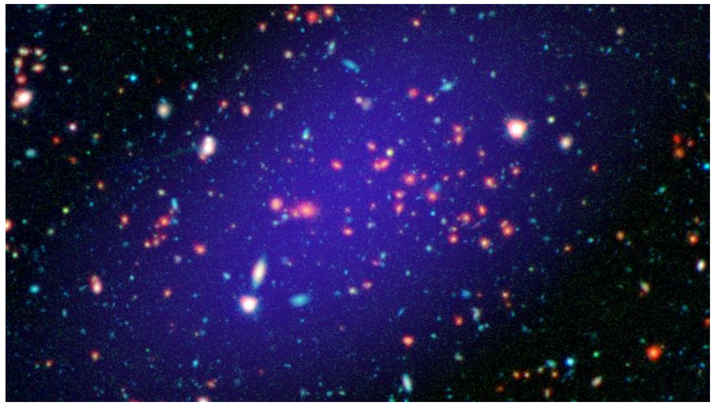
Combine waves/perturbations with other methods?

- E.g., near firehose threshold, launch shear-Alfvén wave
  - Reduced wave speed ($\Delta p<0$)
  - "Interrupt"+excite firehose at much lower amplitude

- E.g., long wavelength density wave near mirror threshold
  - Wave excites mirrors (or IC) as it passes, study their decay.

TO CONCLUDE

- Lots of astrophysical plasmas follow a different fluid dynamics, which we don't yet understand

e.g.,   

- Firehose/mirror fundamental — *control* the dynamics on the largest scales
- Fundamental aspect of plasma physics not yet studied in the lab