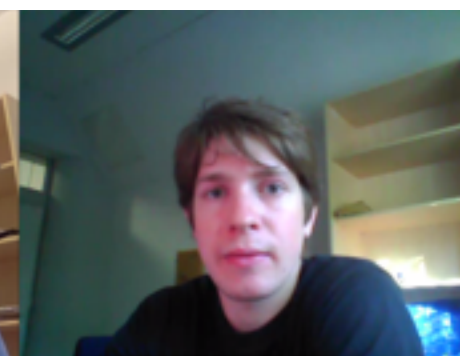
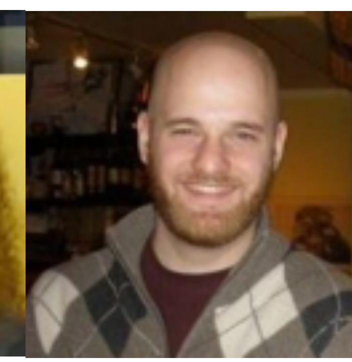
Viscosity, Conduction, Dynamo, and Convection in a Weakly Collisional Magnetized Plasma


Schekochihin


Churazov


Komarov


Melville


St-Onge

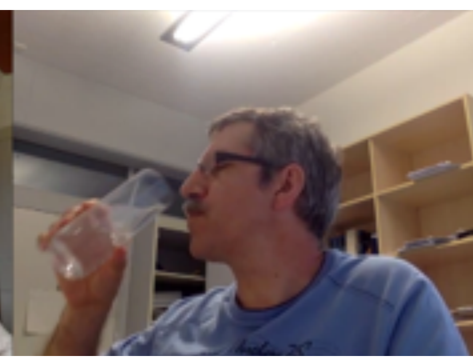

Xu

Xu & Kunz, *JPP* (2016)
Komarov, Churazov, Kunz, & Schekochihin, *MNRAS* (2016)
Melville, Schekochihin, & Kunz, *MNRAS* (2016)
Kunz, Schekochihin, & Stone, *PRL* (2014)

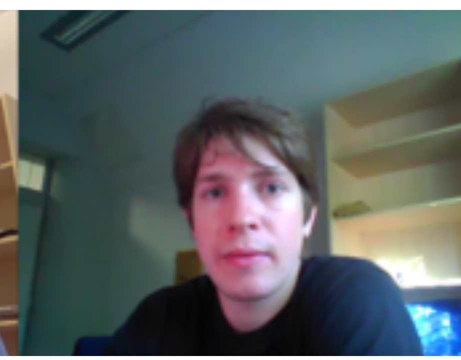
Matthew Kunz
Princeton University

or, *What is the response of a plasma in which the long-wavelength ("fluid") and small-wavelength ("kinetic") scales are simultaneously driven unstable by the same free-energy source?*

Schekochihin

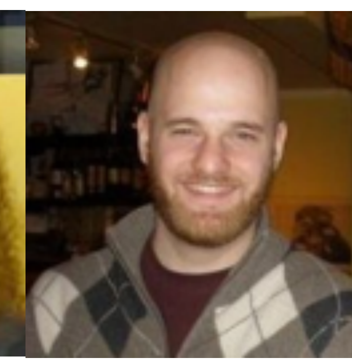


Churazov



Komarov

Melville



St-Onge

Xu

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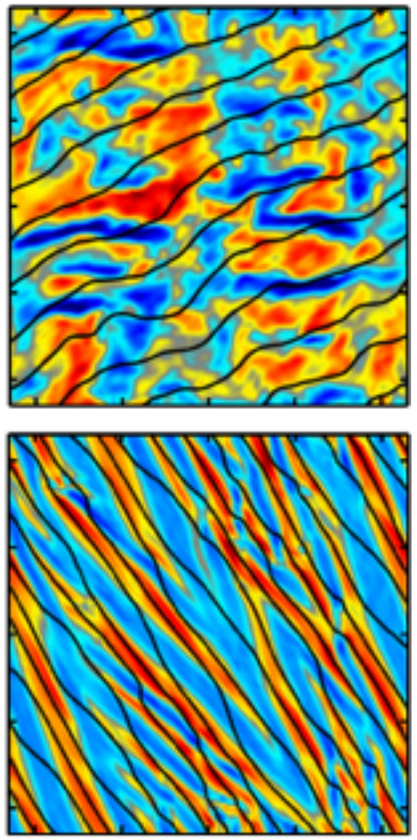
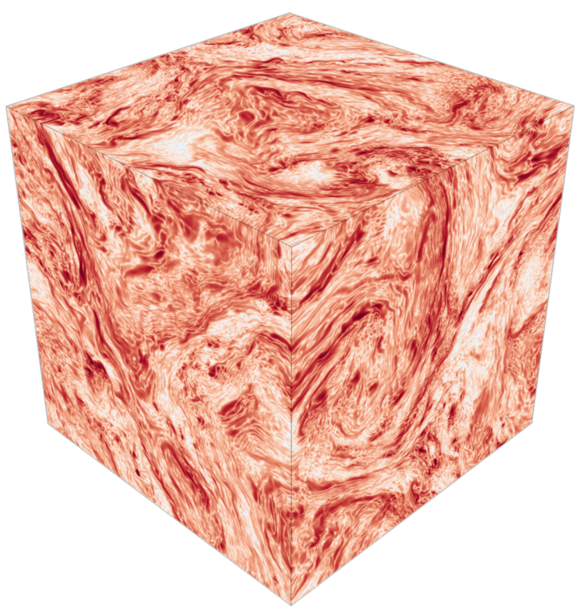
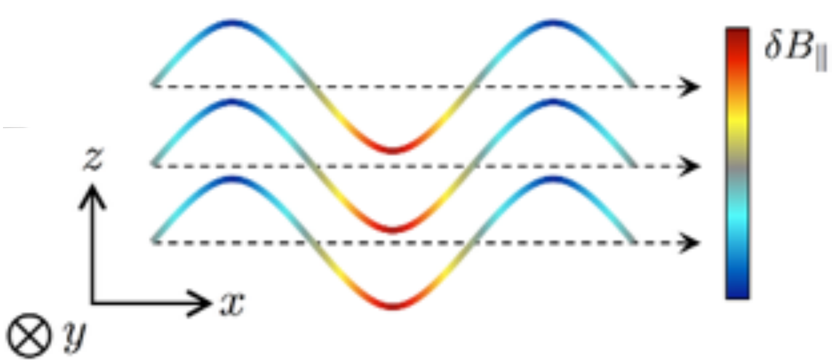
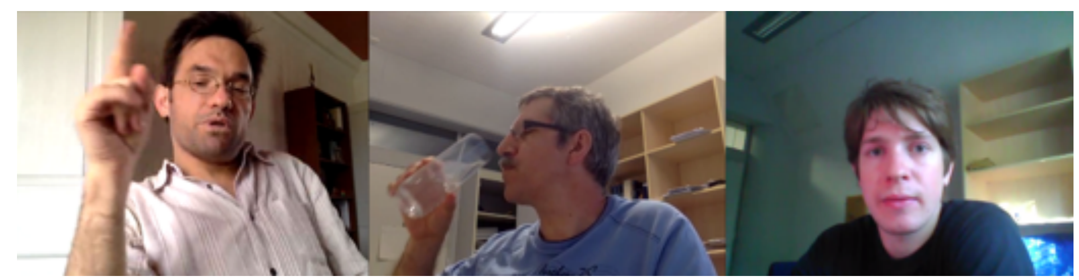






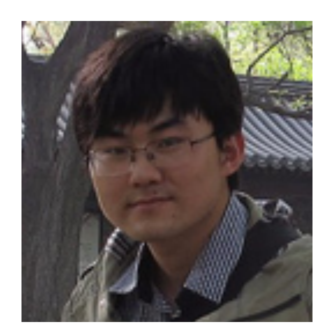
1) regulation of viscous transport by ion-Larmor-scale kinetic instabilities

2) efficacy of electron heat transport in ion-Larmor-scale magnetic mirrors



3) turbulent dynamo in a collisionless plasma

4) linear theory of convective stability in a collisionless plasma

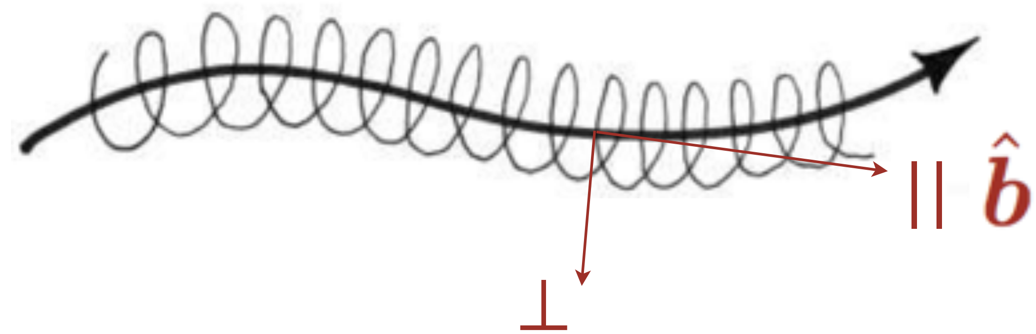


$$\mathrm{Kn} \doteq \frac{\lambda_{\mathrm{mfp}}}{H}$$ expansion parameter in Chapman-Enskog

In ICM, $\frac{\lambda_{\mathrm{mfp}}}{H} \sim 0.001 - 0.1$, with ~0.01 being typical.

$$\Longrightarrow \left| \frac{f}{f_{\mathrm{Maxw}}} - 1 \right| \sim 0.01$$ deviations from isotropic Maxwell distribution function are allowed, at levels that are (*deceivingly*) small

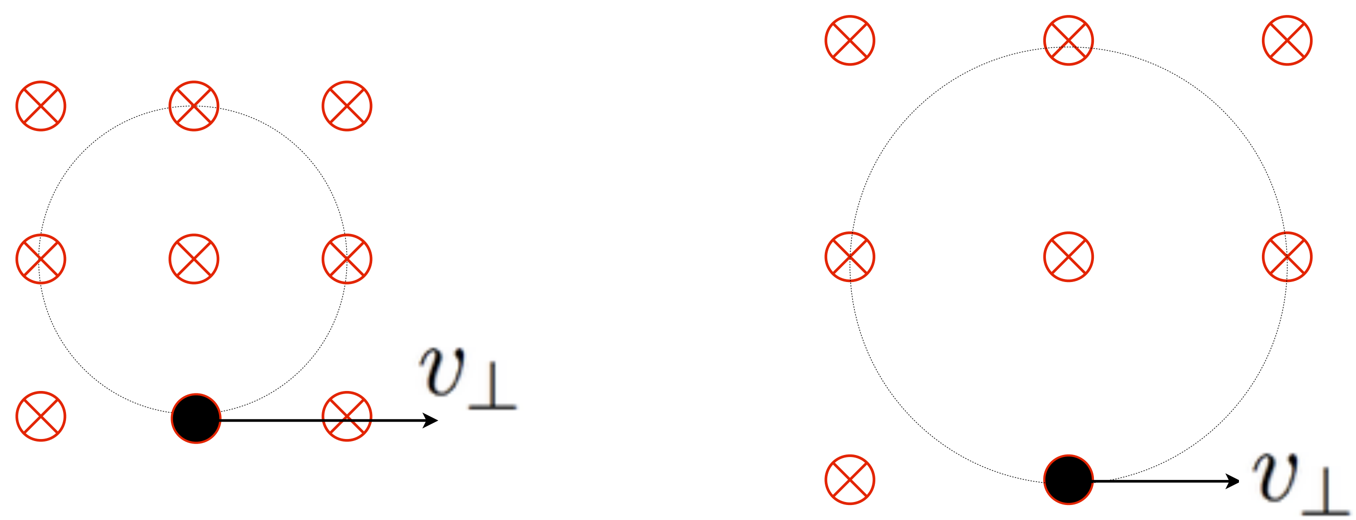
ICM is magnetized;
magnetic-field direction
biases anisotropy
(cross-field transport stifled)



change B $\implies$ produce pressure anisotropy $p_\perp \neq p_\parallel$

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

Kruskal (1958)



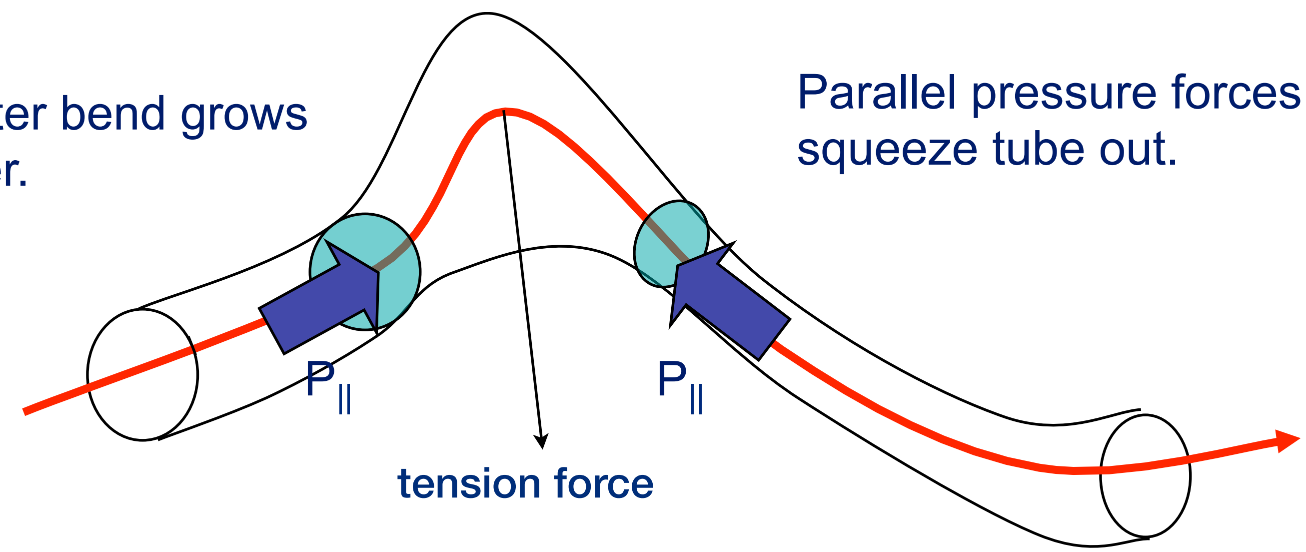
anisotropies in the distribution function produce "viscous" stresses, which also serve as free-energy source for kinetic instabilities

~1% deviations are enough, since ß ~ 100 or more

…when you try to propagate an Alfvén wave in a pressure-anisotropic plasma

firehose instability

$$p_{||} - p_{\perp} \gtrsim \frac{B^2}{4\pi}$$

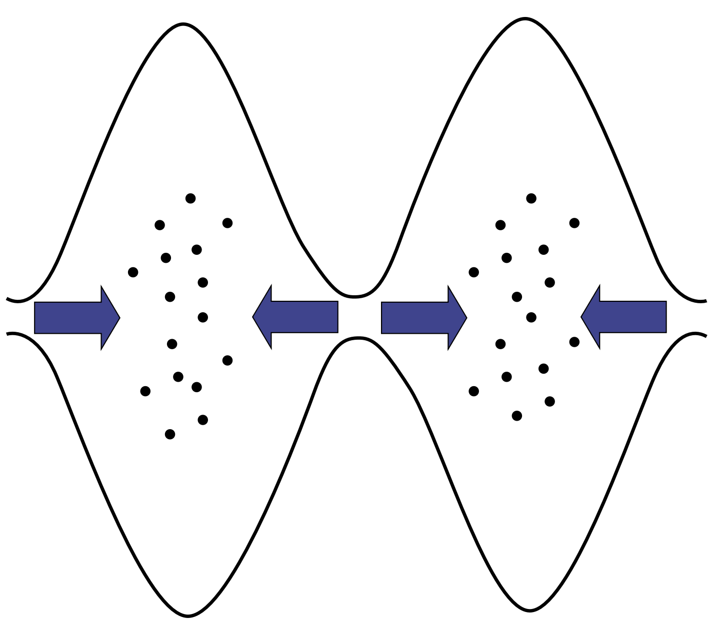


Rosenbluth 1956
Parker 1958

…when you try to Barnes-damp a slow mode in a pressure-anisotropic plasma

mirror instability

$$p_{\perp} - p_{||} \gtrsim \frac{B^2}{8\pi}$$

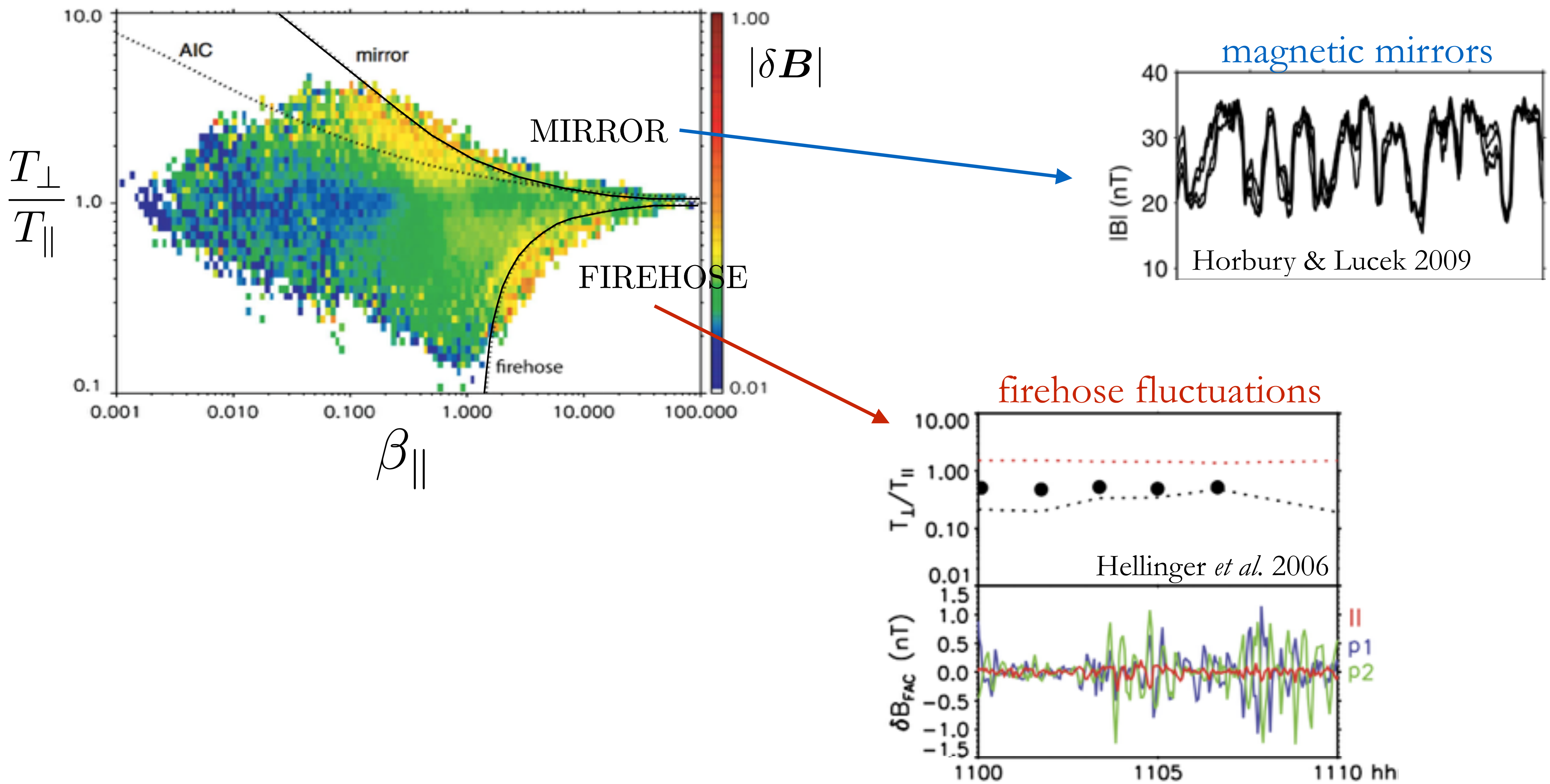


Perpendicular pressure forces blow out field lines.

$$-\hat{\boldsymbol{b}}\,(p_{\perp} - p_{||})\nabla_{||}\delta B_{||}$$

Rudakov and Sagdeev 1961
Southwood & Kivelson 1993

These limit pressure anisotropies, as seen in solar wind:

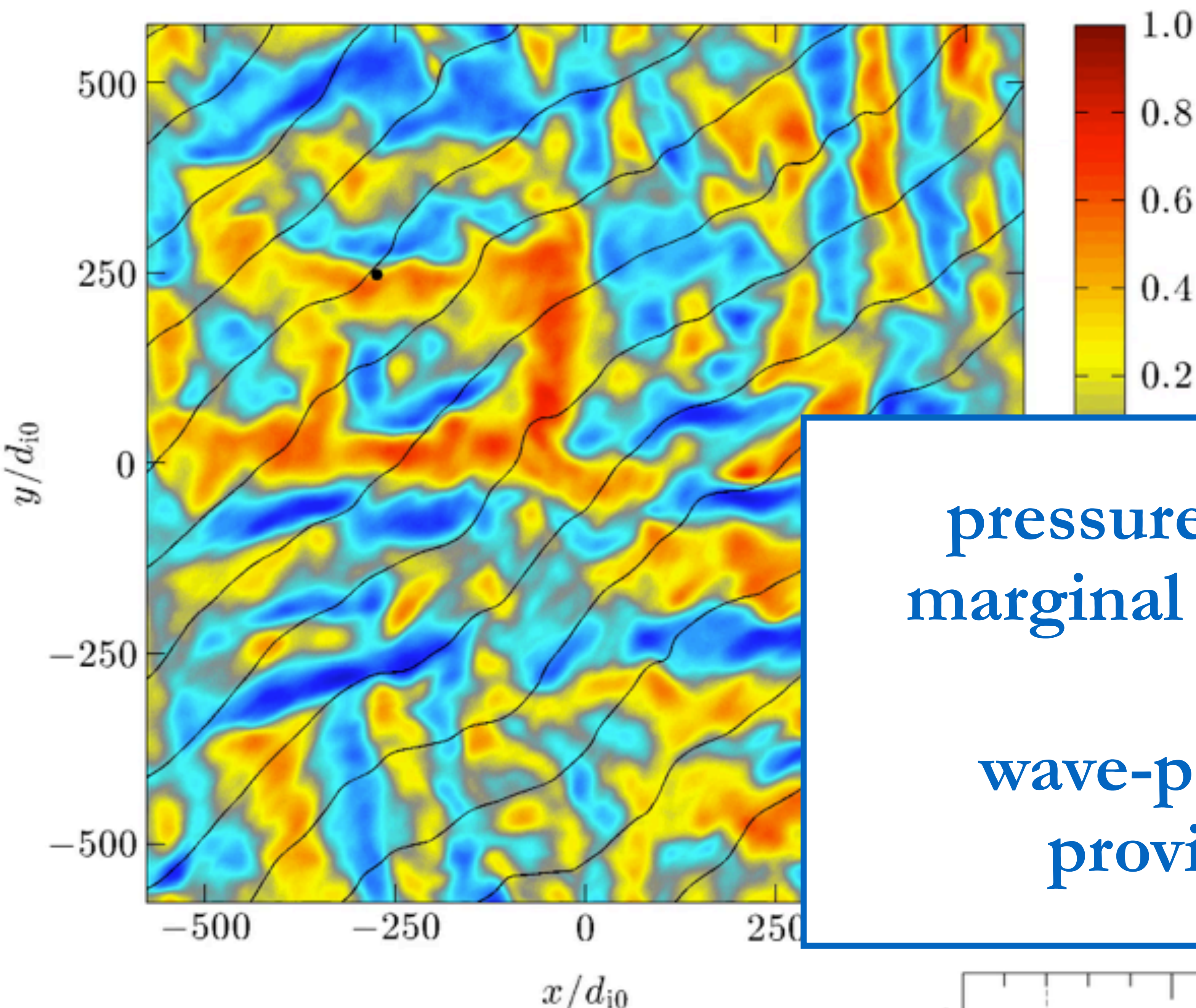


and as seen in kinetic simulations

(Hellinger & Trávníček 2008, 2015; Kunz *et al.* 2014; Riquelme *et al.* 2015; Sironi & Narayan 2015; Melville *et al.* 2016)

FIREHOSE

- initial Larmor radius

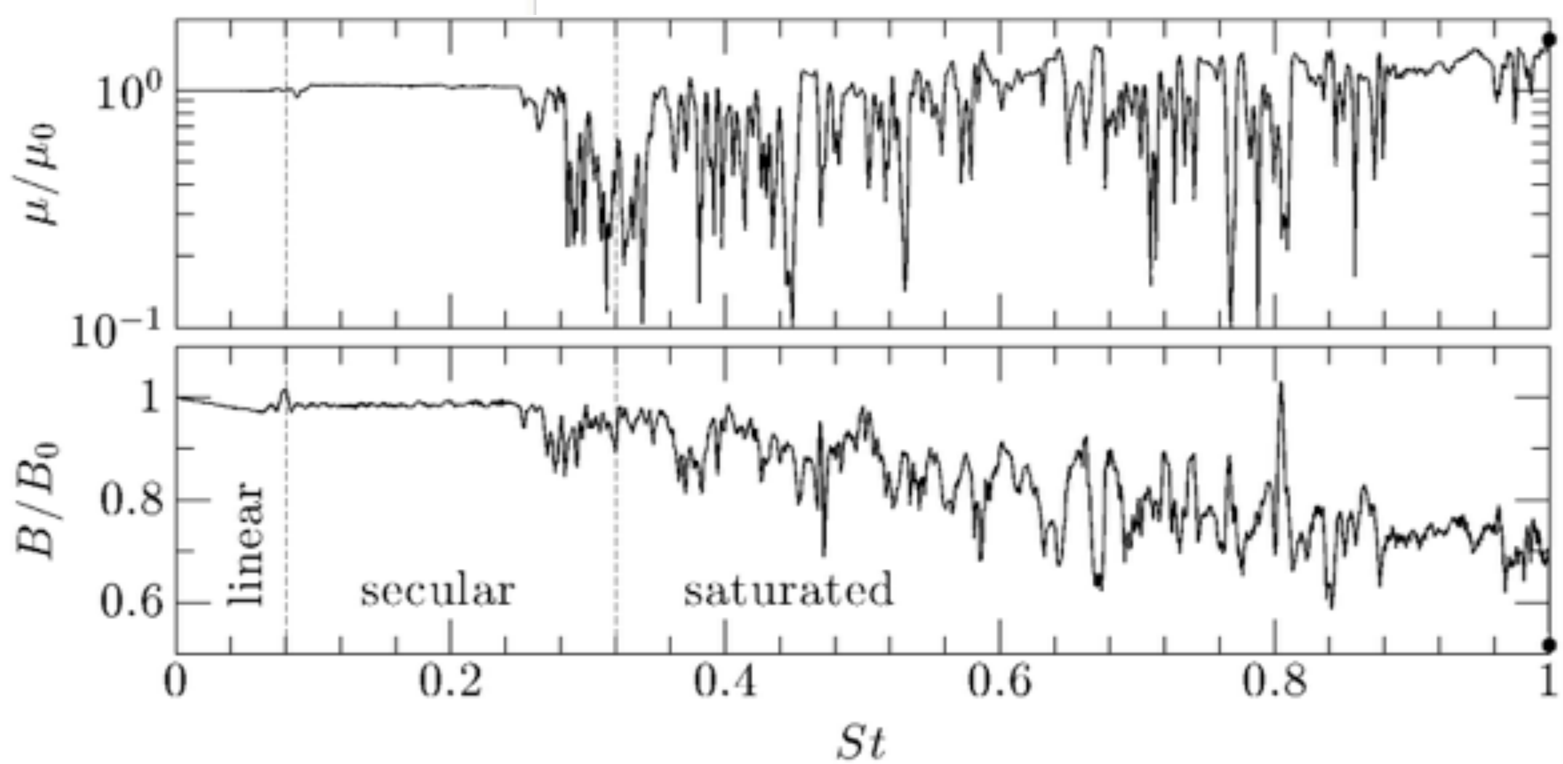


pressure anisotropy pinned at marginal stability by breaking μ

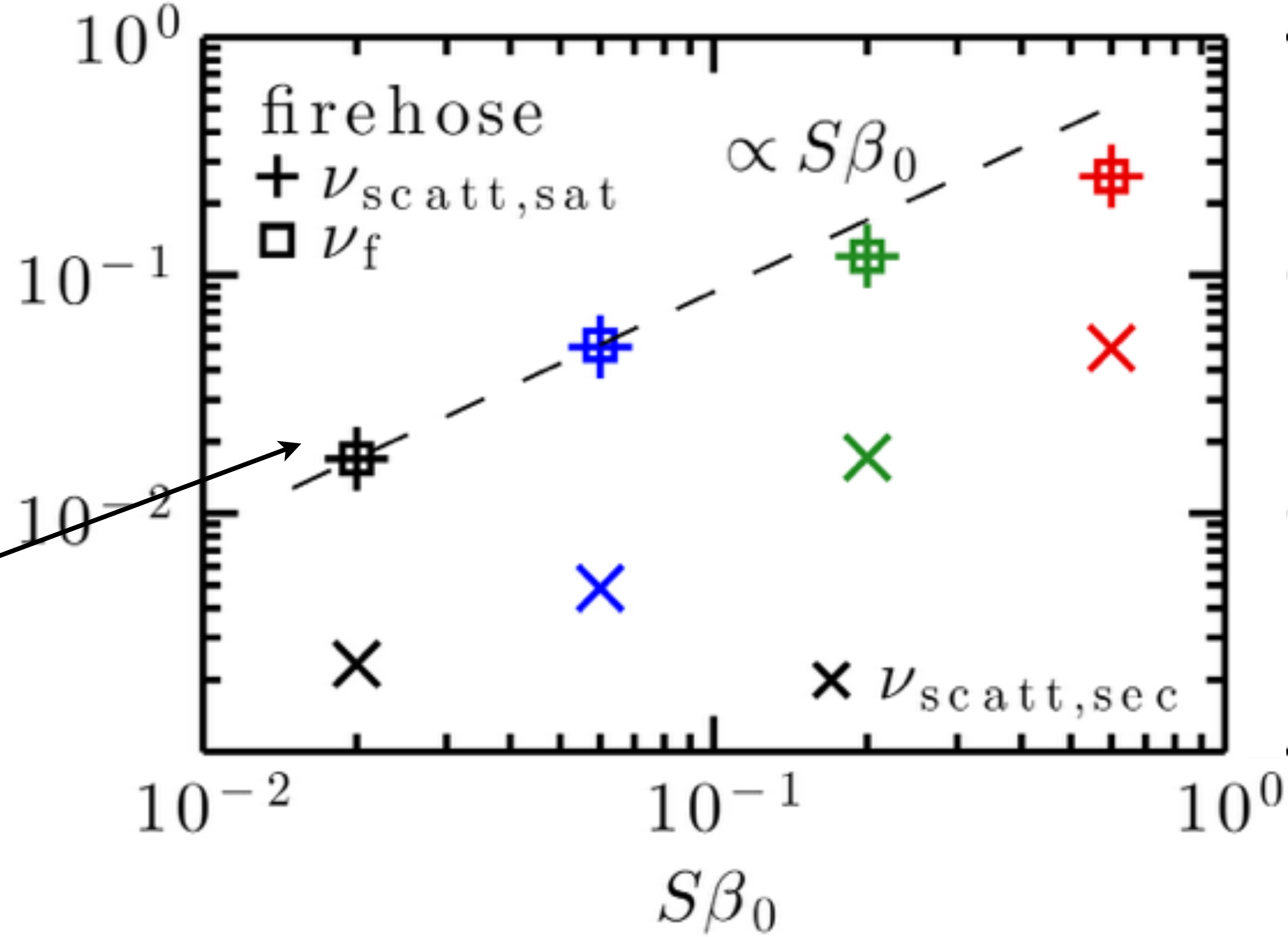
wave-particle interactions provide "collisionality"

magnetic moment of particle:

field strength at particle position:

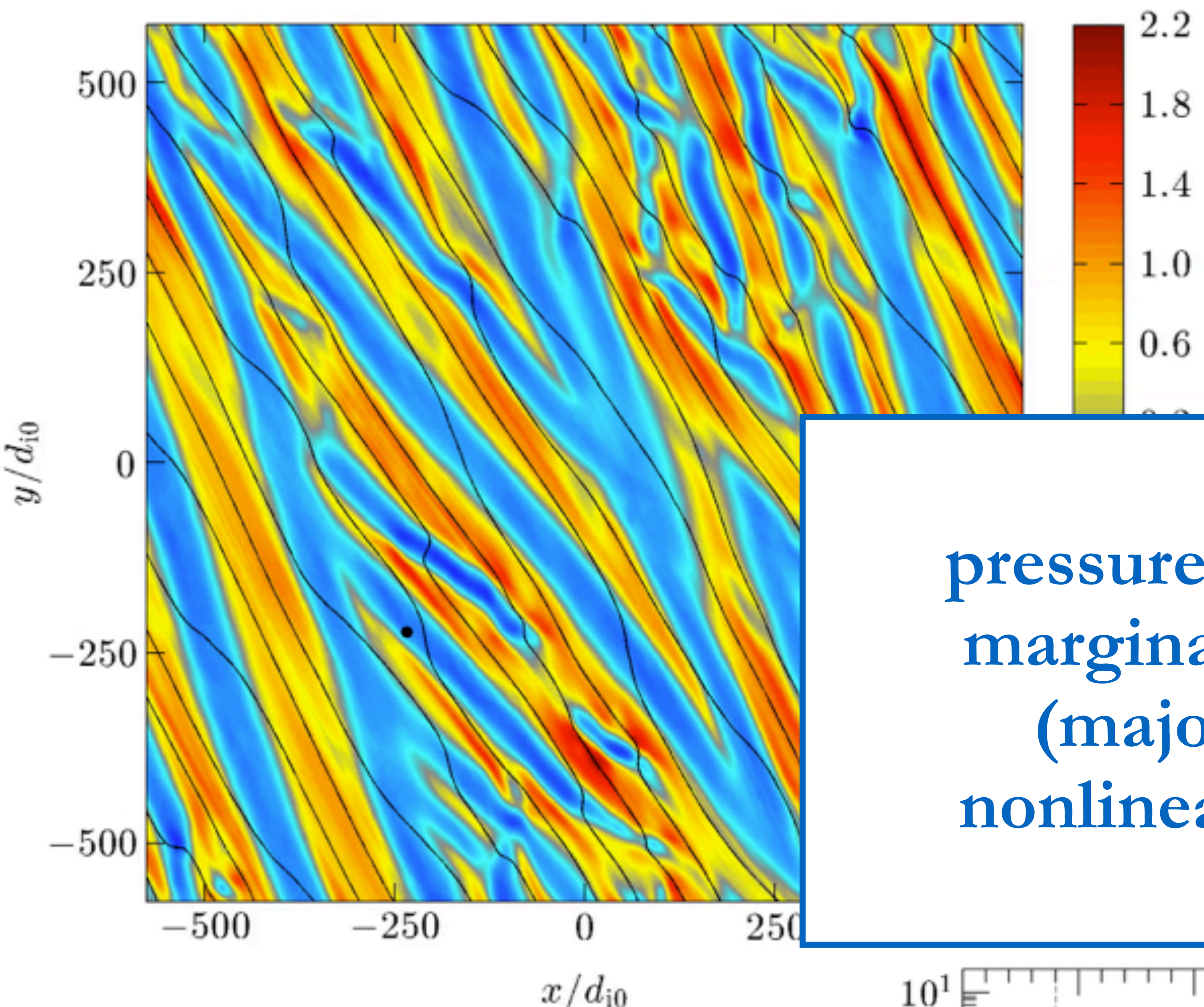


small-amplitude firehose turbulence scatters particles and thereby regulates departures from Maxwellian



$\nu_{\rm scatt,sat} \sim S\beta$

Try to decrease field strength, trigger firehose, and nearly instantaneously create an effective viscosity $\sim v_{\rm A}^2 / S$.



MIRROR

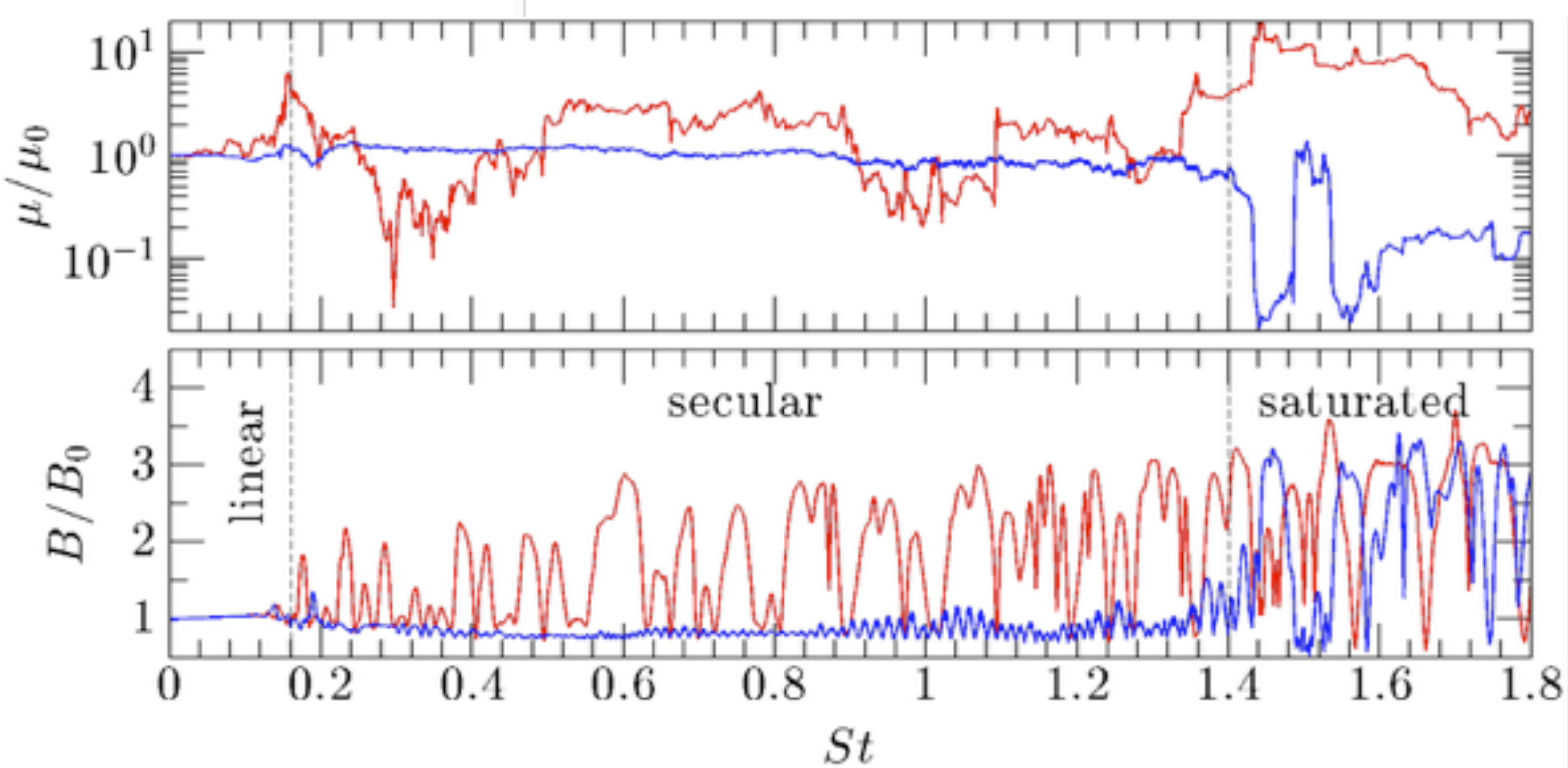
○ initial Larmor radius

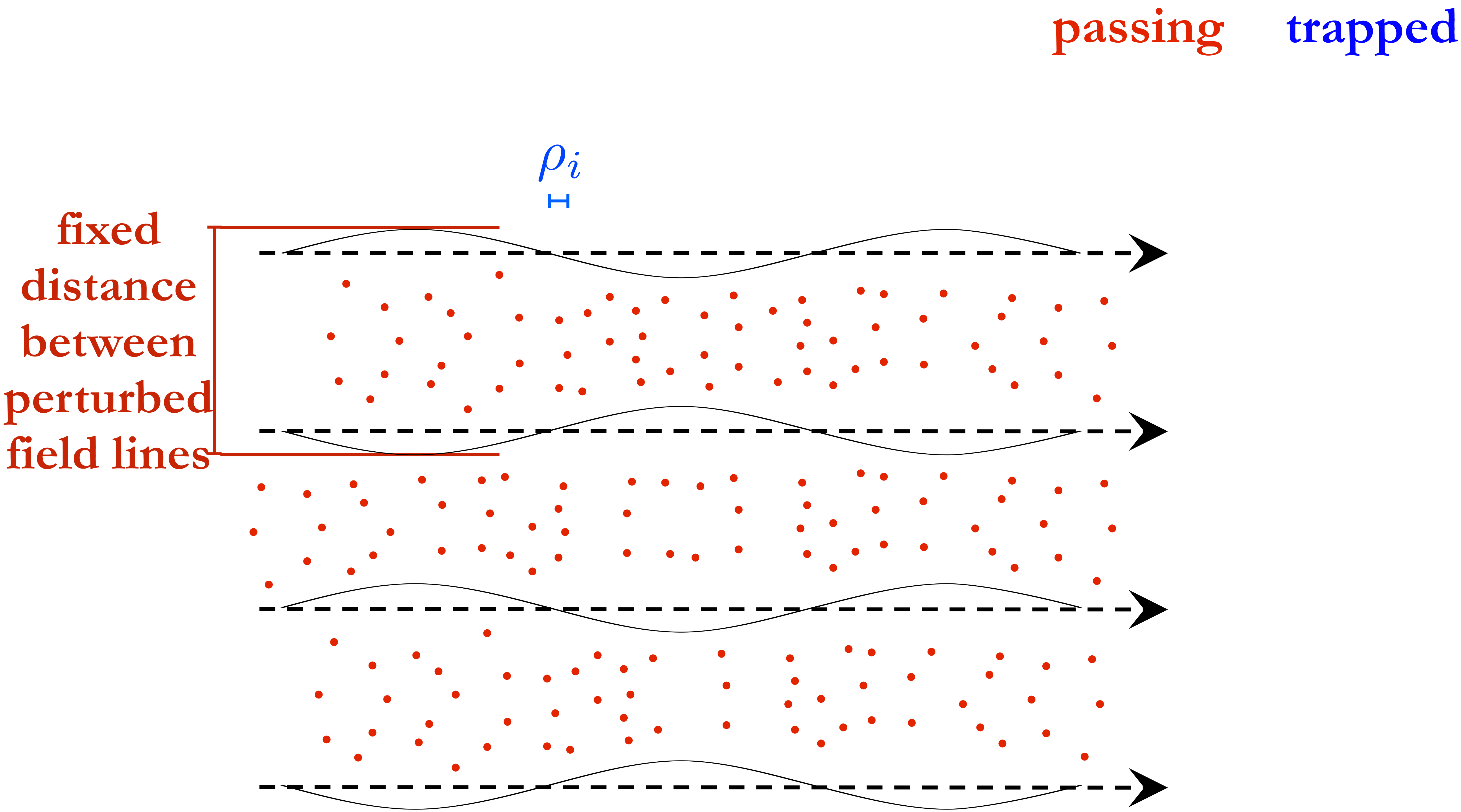
pressure anisotropy pinned at marginal stability by cooling (majority) population of nonlinearly trapped particles

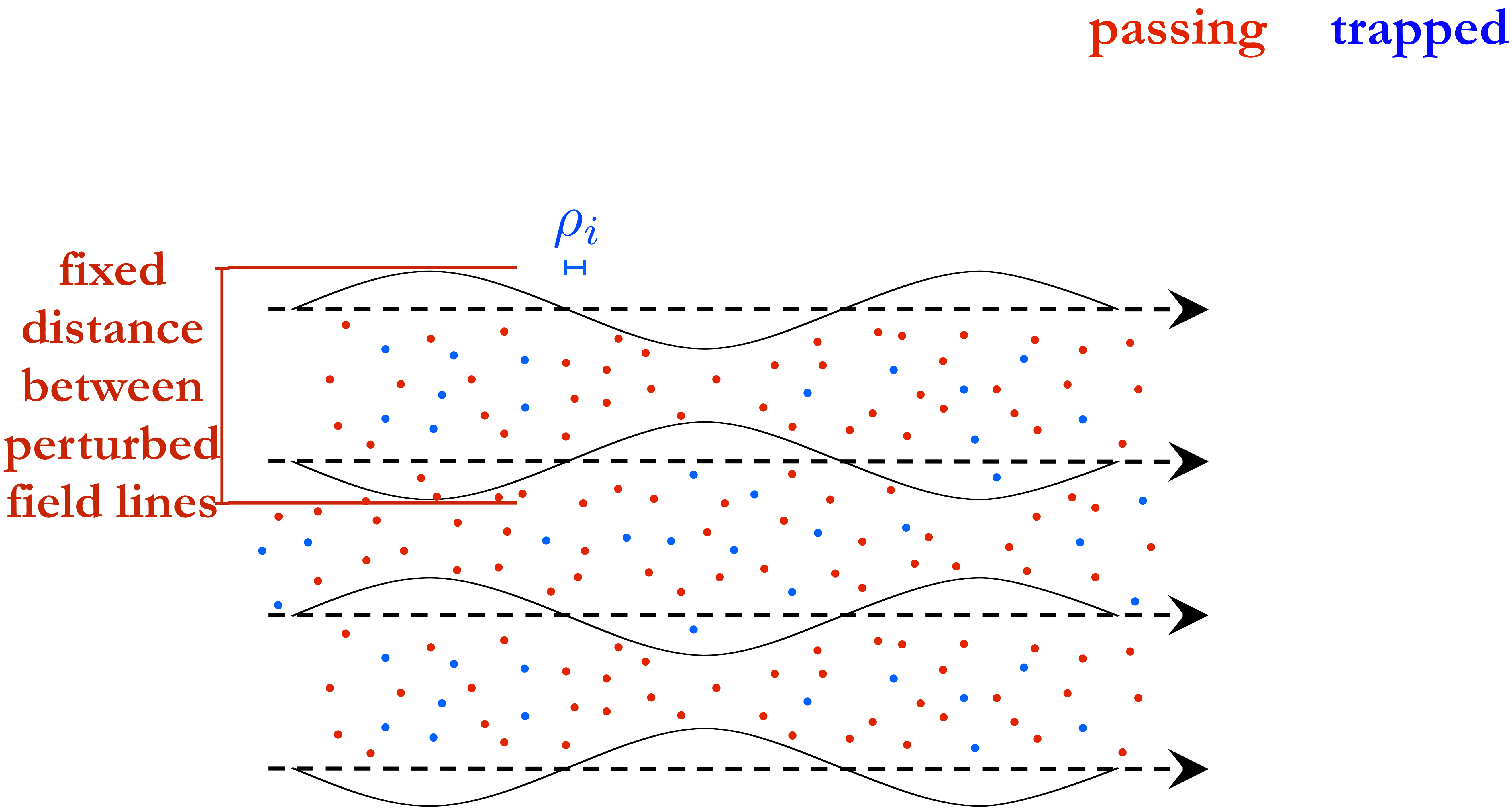
magnetic moment of particle:

passing   trapped

field strength at particle position:

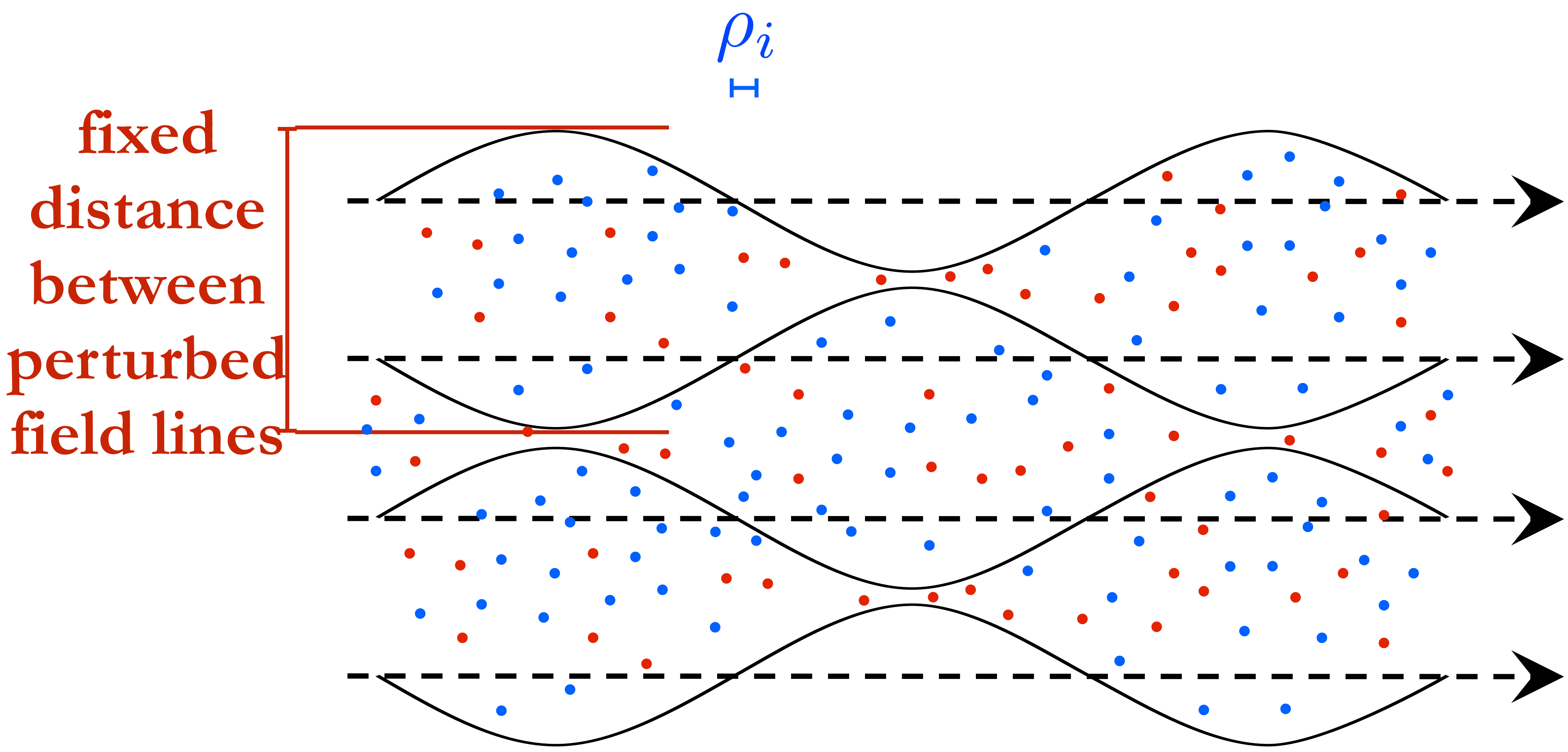



passing
trapped
ρ_i
fixed distance between perturbed field lines



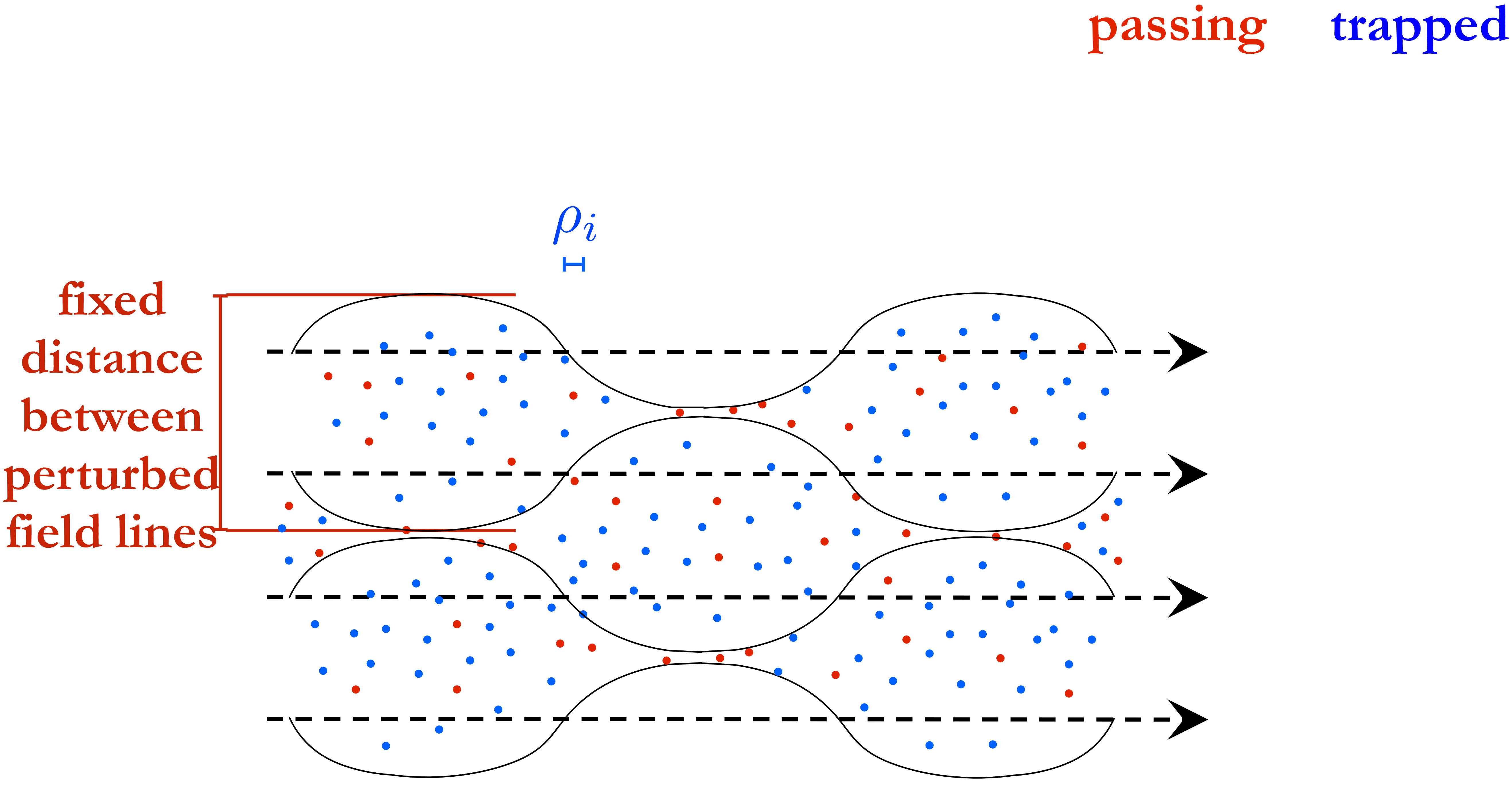
passing
trapped
ρ_i
fixed distance between perturbed field lines

passing **trapped**

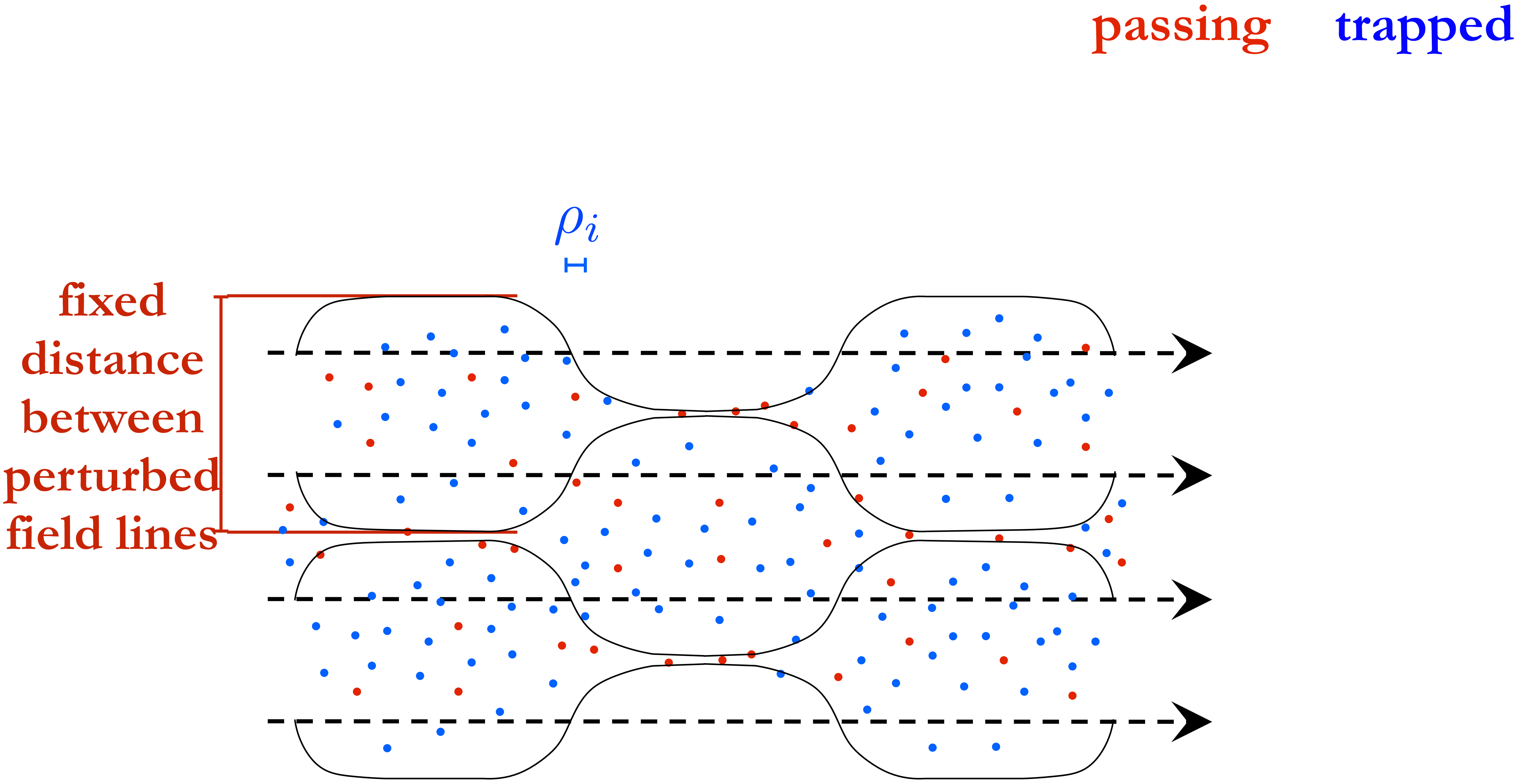


most particles do not even know that the mean field is increasing!

What does this mean for ion viscosity? I'm not sure…

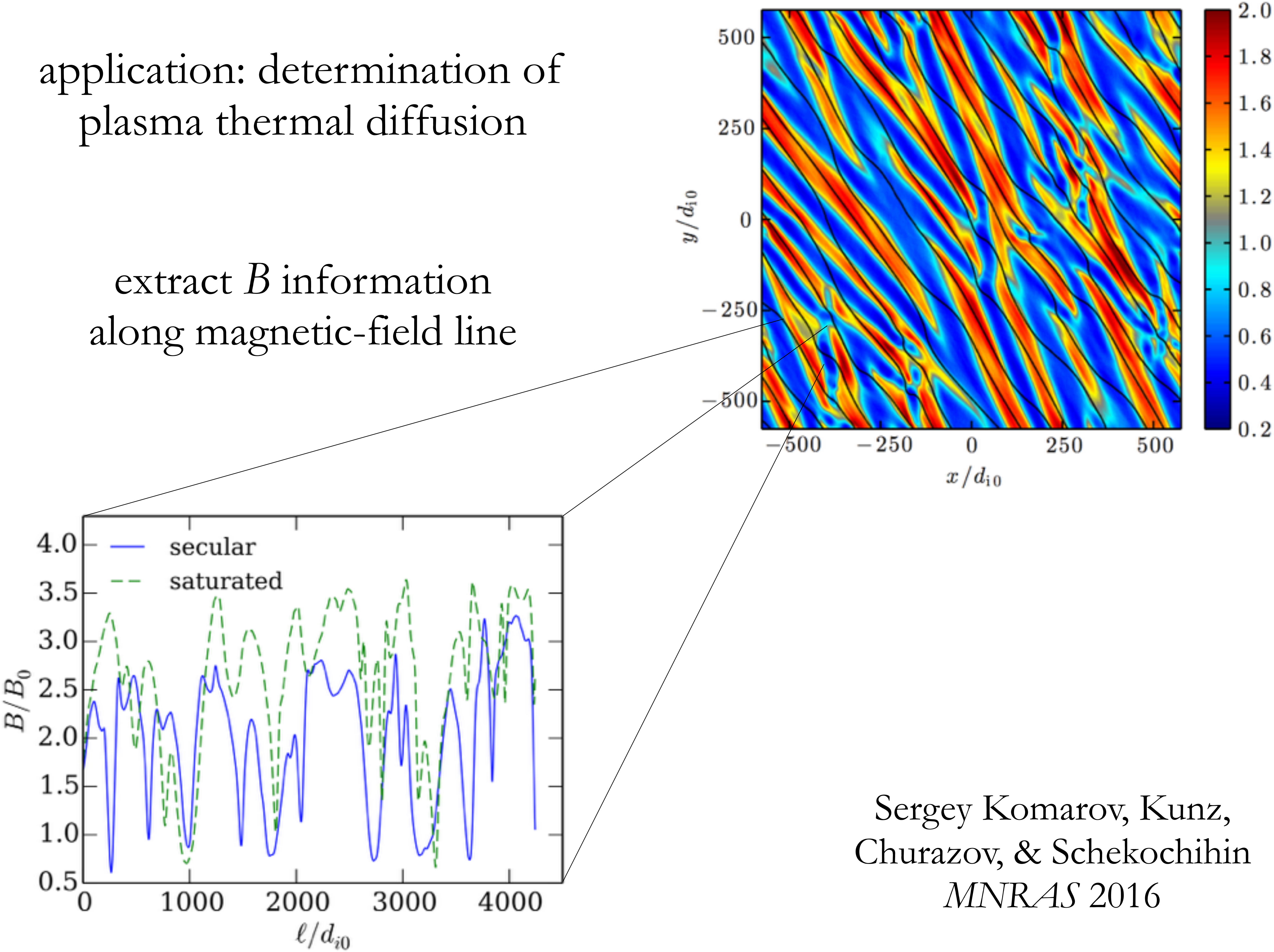


passing
trapped
ρ_i
fixed distance between perturbed field lines

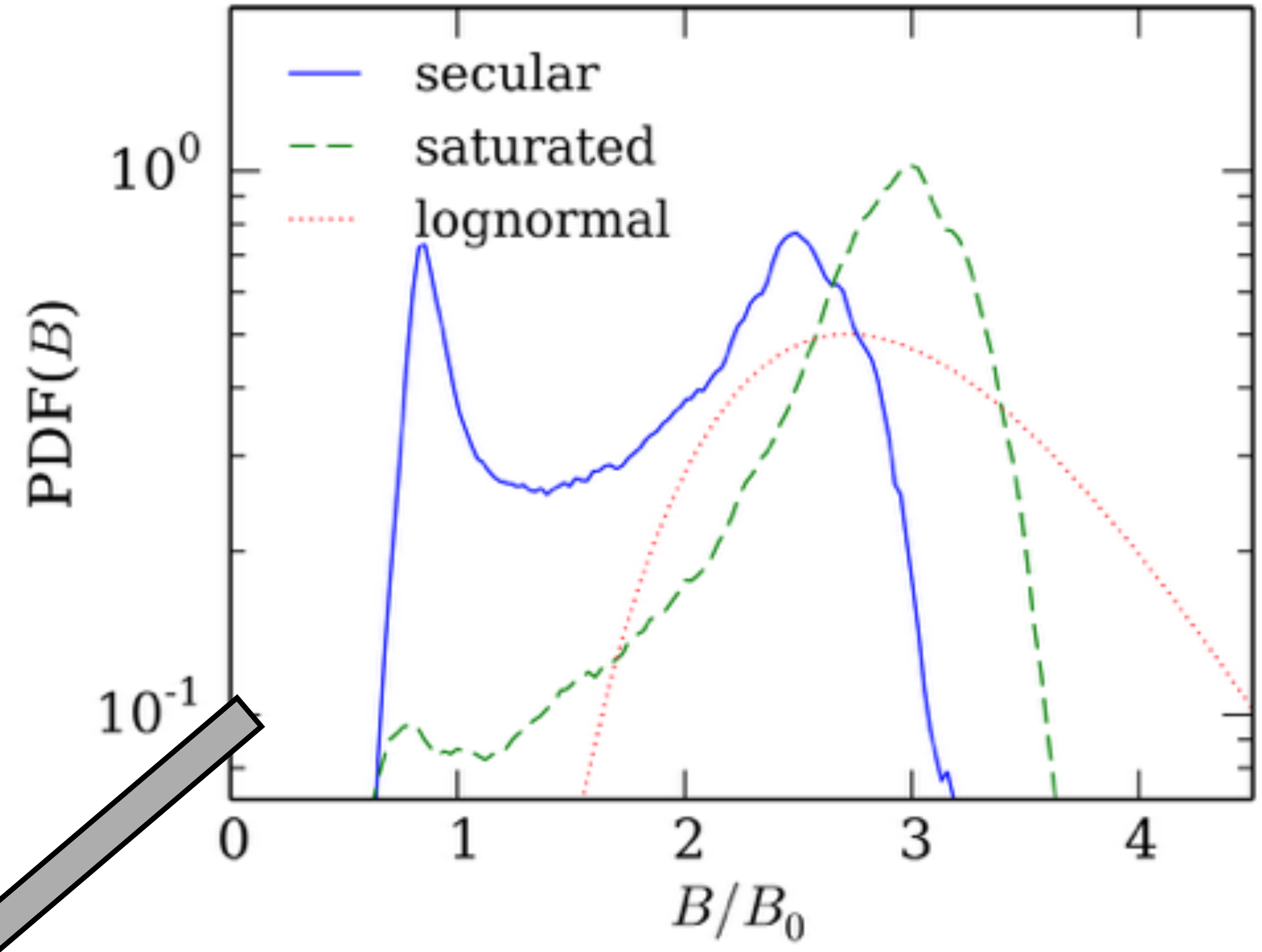


start pitch-angle scattering and leaking trapped particles application: determination of plasma thermal diffusion

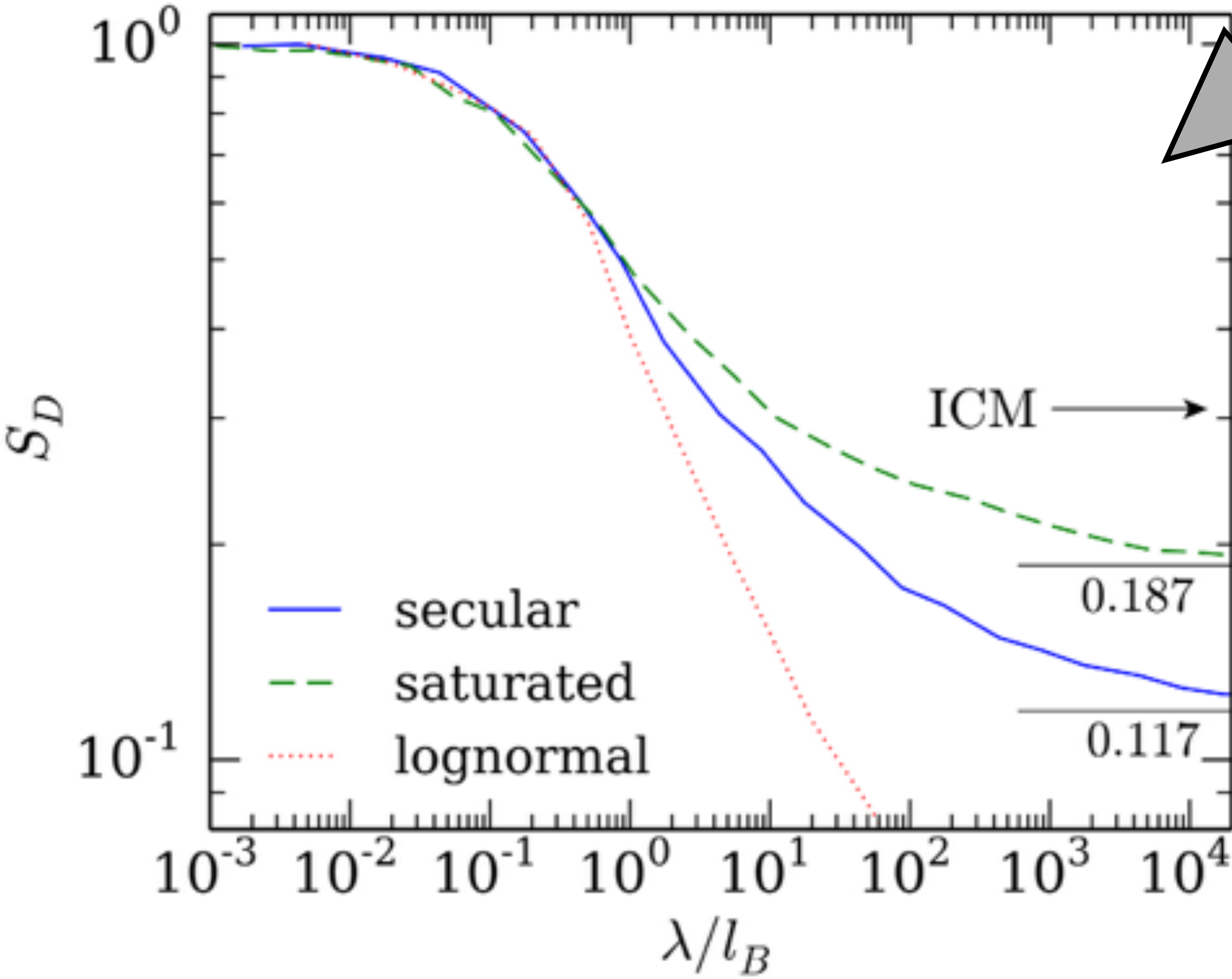
extract B information along magnetic-field line



Sergey Komarov, Kunz, Churazov, & Schekochihin *MNRAS* 2016 compute PDF(B):



suppression of electron diffusion as a fraction of unbridled Spitzer



suppression of electron conduction as a fraction of unbridled Spitzer

$$S_\kappa \sim 0.2$$

see also Gareth Roberg-Clark's poster & recent work by Riquelme *et al.* (2016)

another example application:
plasma dynamo

Try to **decrease field** strength, trigger firehose, and nearly instantaneously create an **effective viscosity** $\sim v_A^2 \,/\, S$.

This implies dynamo is nonlinear as soon as threshold is crossed, in that viscosity knows about ß;
hardly any kinematic phase, even when field is "weak"

Try to **increase field** strength, trigger mirror, the result being that most **particles don't** even **know** that the **mean field is increasing**!

explosive? Effective Re increases as B is changed.
Turbulent cascade can then get to smaller scales where field amplification is faster

working this out is a daunting task
(which is why my Ph.D. student, Denis St-Onge, is doing it)

just a taste of what we're doing…

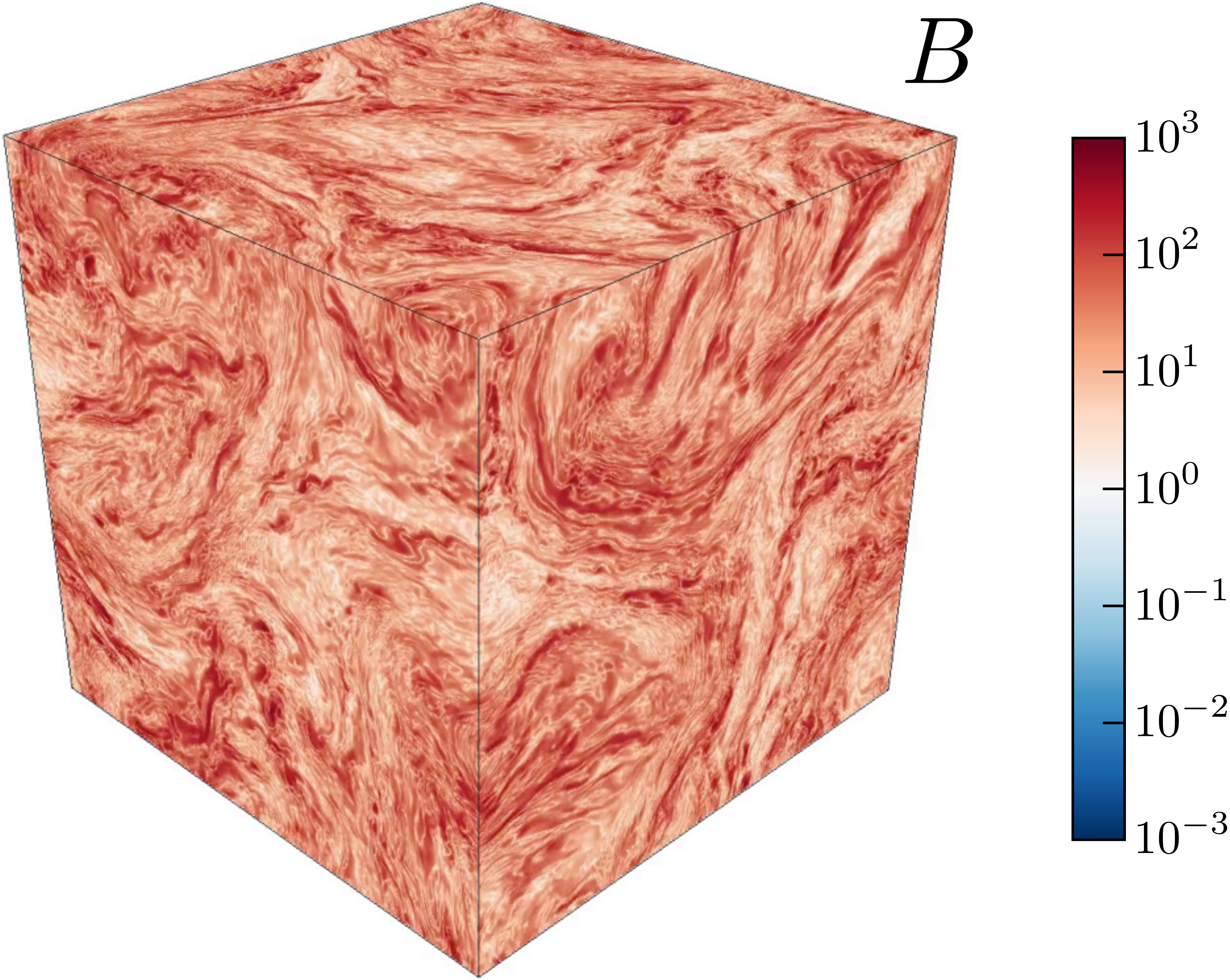
$$\frac{\partial f_i}{\partial t} + \boldsymbol{v}\cdot\boldsymbol{\nabla} f_i + \left[\frac{Ze}{m_i}\left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c}\times\boldsymbol{B}\right) + \frac{\boldsymbol{F}}{m_i}\right]\cdot\frac{\partial f_i}{\partial \boldsymbol{v}} = 0$$

$$\boldsymbol{\nabla}\cdot\boldsymbol{F} = 0 \qquad k_f \in [1,2] \times (2\pi/L)$$

forcing is time-correlated, with $\Omega_i t_{\rm corr} \ll 1$.

$$\Delta x \ll \rho_{i0} \ll L \qquad \beta_{i0} = 10^4 - 10^8$$

$\sim 500^3$ and $\sim 1000^3$ cells $\qquad \sim 30$ billion particles


B
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}

some results embargoed here

Linear Vlasov theory of a magnetised, thermally stratified atmosphere

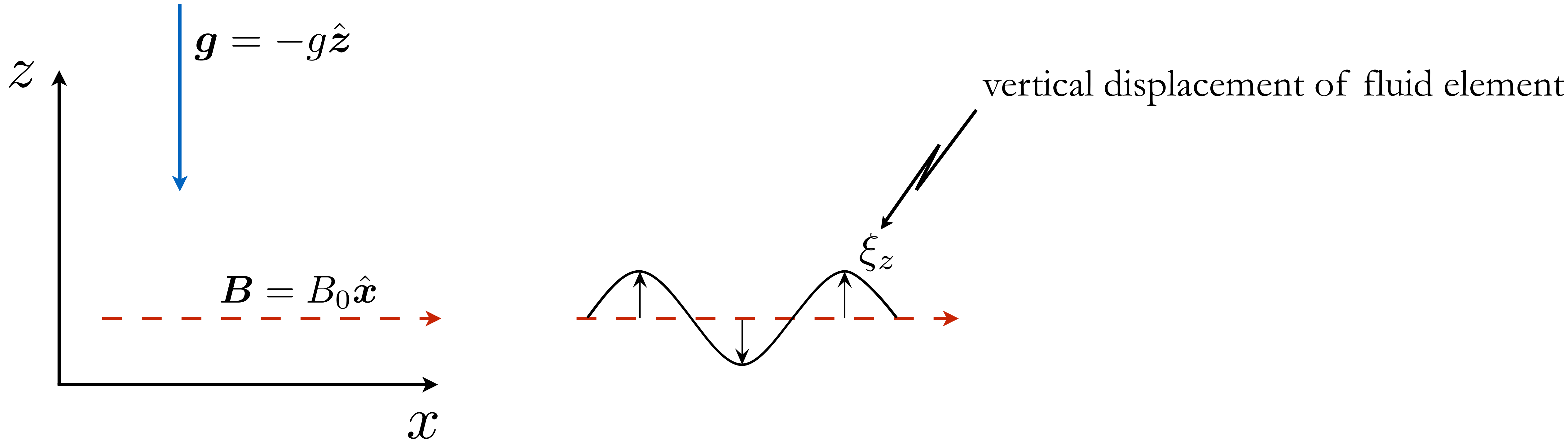
R. XU[1] AND M. W. KUNZ[1,2]†

arXiv:1608.05316; to appear in *J. Plasma Phys.*

contains:

1) Review of convection in magnetized, collisional plasma
2) Discussion of convection in magnetized, collisionless plasma
3) Linear Vlasov theory:
   i. Drift-kinetic limit
   ii. Gyroviscous limit
   iii. Gyrokinetic limit
4) Comparison with fusion-relevant convection (ITG/ETG)
5) Character-building algebra and unnecessarily long appendices

we worked *really* hard to make this clear and pedagogical!

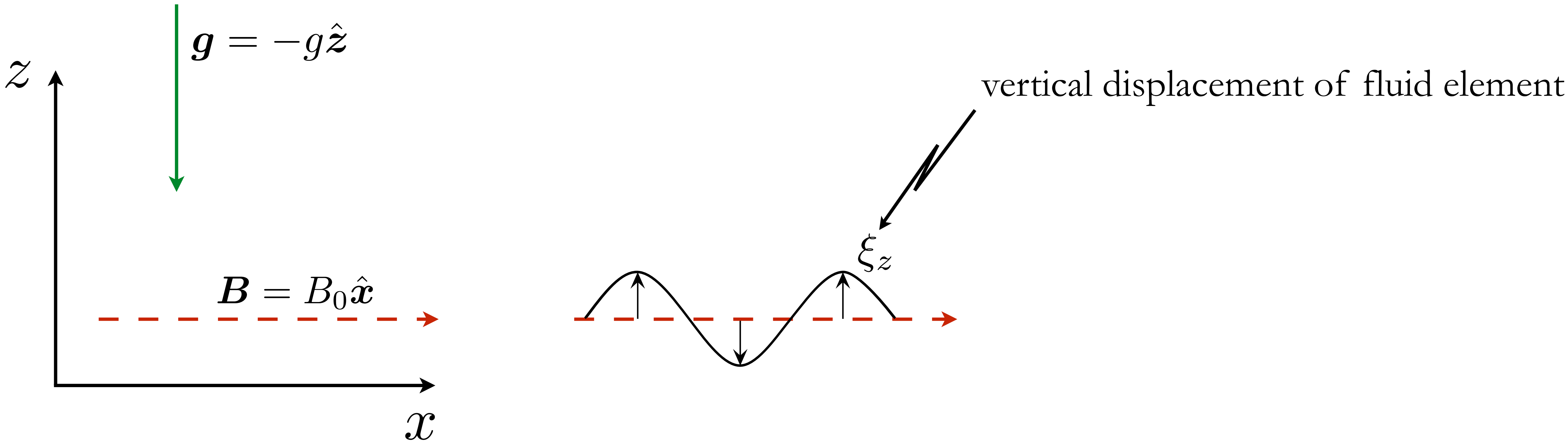


take limit $\omega \ll k v_{th}$:

$$\left(\frac{\partial}{\partial t} + \omega_{cond}\right)\frac{\delta T}{T} = -\left(\frac{N^2}{g}\frac{\partial}{\partial t} + \omega_{cond}\frac{\mathrm{d}\ln T}{\mathrm{d}z}\right)\xi_z$$

$$\omega_{\mathrm{cond}} \to 0 : \frac{\delta T}{T} = -\frac{N^2}{g}\xi_z$$

$$\frac{\partial^2 \xi_z}{\partial t^2} = -N^2 \xi_z$$



take limit $\omega \ll k v_{th}$:

$$\left(\frac{\partial}{\partial t} + \omega_{cond}\right)\frac{\delta T}{T} = -\left(\frac{N^2}{g}\frac{\partial}{\partial t} + \omega_{cond}\frac{\mathrm{d}\ln T}{\mathrm{d}z}\right)\xi_z$$

$$\omega_{\mathrm{cond}} \to \infty : \frac{\delta T}{T} = -\frac{\mathrm{d}\ln T}{\mathrm{d}z}\xi_z \implies \frac{\Delta T}{T} = 0$$

$$\frac{\partial^2 \xi_z}{\partial t^2} = -g\frac{\mathrm{d}\ln T}{\mathrm{d}z}\xi_z$$

Review of convection in magnetized, collisional plasma ©

Frozen magnetic
fields serve as conduits
along which heat flows

from tethered fluid
elements, one to the next;
the rate of transport

increases as B
becomes more aligned with the
gradient of T.

Magnetothermal
instability ensues.
Balbus would be glad.

Balbus (2000, 2001)

Review of convection in magnetized, collisional plasma ©

But viscous transport
is also channeled along
magnetic-field lines,

coupling Alfvénic
fluctuations to slow modes;
P is a tensor.

This time Alfvén waves
are buoyantly unstable.
Now Kunz is happy.

Kunz (2011)

That this carries over to a collisionless plasma is not obvious.

1) Inertia-bearing ions and conducting electrons need not remain in thermal equilibrium as the plasma is perturbed. (No collisional equilibration.)

That this carries over to a collisionless plasma is not obvious.

2) Changes in temperature cannot be made independently of changes in magnetic-field strength when μ is conserved.

$$\frac{\Delta T_{\perp s}}{T_s} \doteq \frac{\delta T_{\perp s}}{T_s} + \xi_z \frac{\mathrm{d} \ln T_s}{\mathrm{d} z} = \left[1 - Z_1(\zeta_s)\right] \frac{\delta B_{\|}}{B},$$

$$\frac{\Delta T_{\| s}}{T_s} \doteq \frac{\delta T_{\| s}}{T_s} + \xi_z \frac{\mathrm{d} \ln T_s}{\mathrm{d} z} = \frac{2 Z_3(\zeta_s) - Z_1(\zeta_s)}{Z_1(\zeta_s)} \left(\frac{\Delta n_s}{n_s} - \frac{\delta B_{\|}}{B} \right)$$

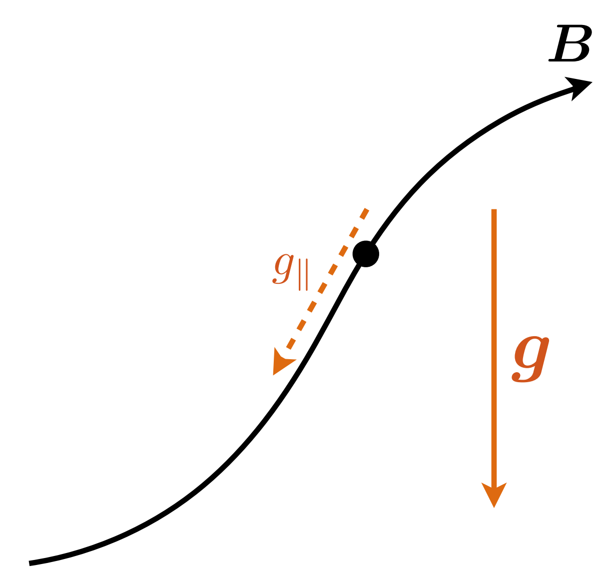
kinetic physics

That this carries over to a collisionless plasma is not obvious.

3) Collisionless damping!

$$\delta f_s(v_\parallel, w_\perp) = \overbrace{\boxed{\frac{\mathrm{i}}{k_\parallel}\frac{\partial f_s}{\partial z}\frac{\delta B_z}{B}}}^{\textbf{MTI}} + \overbrace{\boxed{\frac{w_\perp^2}{v_{ths}^2}\frac{\delta B_\parallel}{B} f_s}}^{\boldsymbol{\mu}\textbf{ conservation}}$$

$$- \frac{\mathrm{i}}{k_\parallel}\left(\underbrace{\boxed{\frac{q_s \delta E_\parallel}{T_s}}}_{\textbf{Landau damping}} + \underbrace{\boxed{\frac{\mathrm{d}\ln P_s}{\mathrm{d}z}\frac{\delta B_z}{B}}}_{\textbf{collisionless damping of MTI mode}} \underbrace{\boxed{- \mathrm{i}k_\parallel \frac{w_\perp^2}{v_{ths}^2}\frac{\delta B_\parallel}{B}}}_{\textbf{Barnes damping}}\right)\frac{v_\parallel}{v_\parallel - \omega/k_\parallel} f_s$$



That this carries over to a collisionless plasma is not obvious.

4) Pressure balance with surroundings usually maintained by radiating sound waves faster that fluid elements rise/sink; but sound waves are collisionlessly (Landau) damped.

That this carries over to a collisionless plasma is not obvious.

5) Conduction and buoyancy in a collisionless plasma are inextricably linked, a feature not present in a collisional fluid. Approximately isothermal displacements are tandem with the ability of those displacements to maintain pressure balance with their surroundings.

With $k_\perp = 0$ and $\zeta_i \doteq \omega/|k_\parallel|v_{thi} \ll 1$,

$$\frac{\delta P_\perp}{P} \sim \mathcal{O}(\zeta_i), \; \frac{\delta P_\parallel}{P} \sim \mathcal{O}(\zeta_i^2), \; \frac{\Delta T_\perp}{T} = 0, \; \frac{\Delta T_\parallel}{T} \sim \mathcal{O}(\zeta_i) \quad \text{(collisionless, magnetised).}$$

vs.

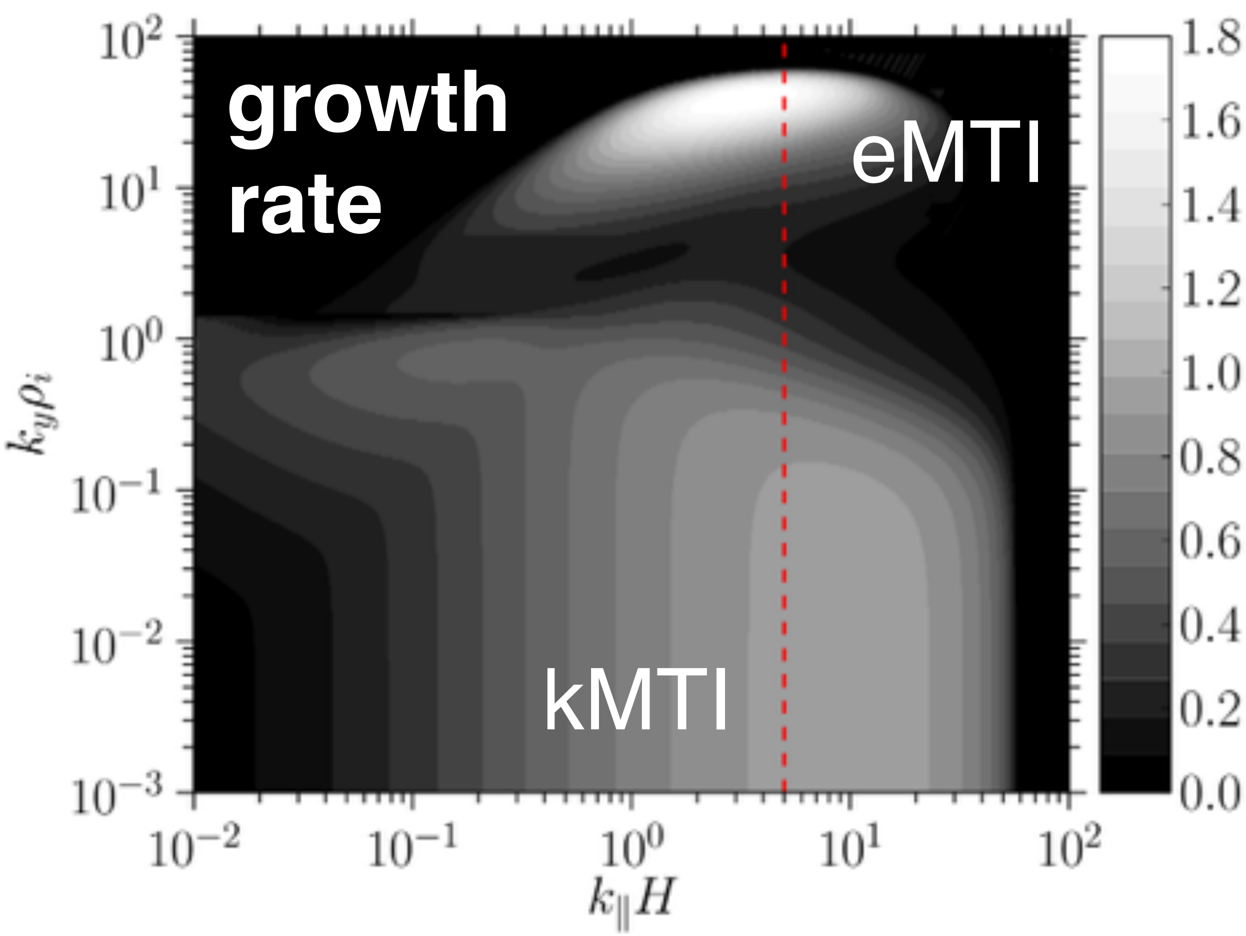
$$\frac{\delta P}{P} \sim \mathcal{O}(\zeta_i^2), \; \frac{\Delta T}{T} \simeq \xi_z \frac{\mathrm{d}\ln P}{\mathrm{d}z} \frac{-\mathrm{i}\omega}{k_\parallel^2 \kappa - (5/2)\mathrm{i}\omega} \quad \text{(collisional, magnetised).}$$

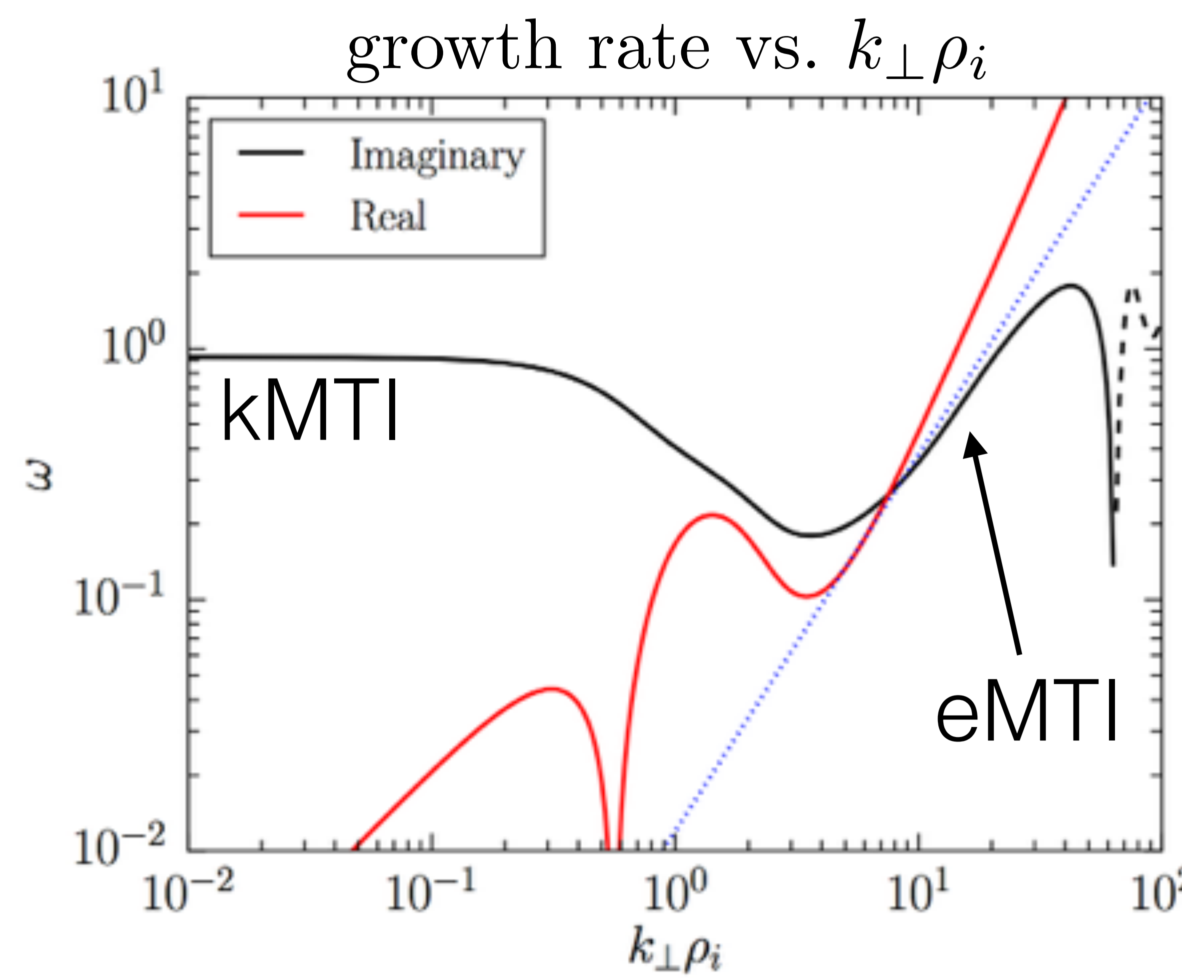
Won’t go through details here (read the paper!), but
MTI and Alfvénic-MTI basically carry over to collisionless case
(with some really fun physics and interesting differences)

and a surprise…

Finite Larmor Radius effects:

1) Vertical momentum can be transported in the (cross-field) horizontal direction — bad.
2) Gyroaveraging weakens fluid response at Larmor scales — bad.
3) Drift waves! Kinetic Alfvén waves! — good!
   Leads to new kind of magnetothermal instability.

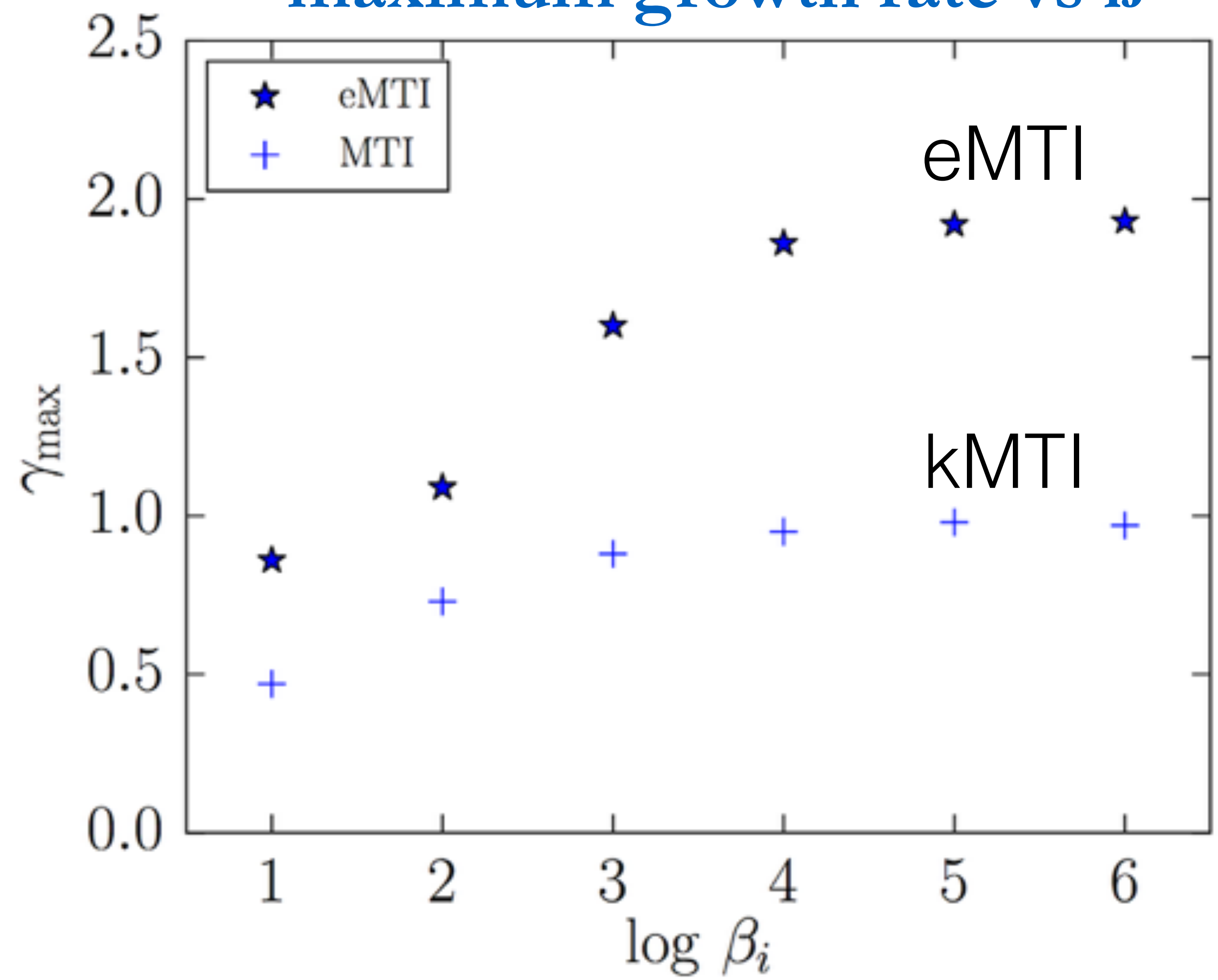




Larmor scales are more convectively unstable than are the large scales!

(drift wave coupled to a KAW)

maximum growth rate vs ß



same temperature gradient drives growth simultaneously at two disparate scales; implies large-scale MTI will likely depend upon saturation of Larmor-scale eMTI.

Summary

(1) Micro-scale physics can play a fundamental role in dictating what macro-scale dynamics are allowed in a given system;

(2) Ought to include effects of pressure anisotropy in studies of ICM:
- reduces parallel transport of momentum and heat
- accompanies and influences dynamo (possibly explosive at first)

(3) Linear Vlasov theory still has some surprises in it.

Same temperature gradient drives growth simultaneously at large scales (drift-kinetic MTI) and small scales (electron-MTI), the latter with growth rates larger than the former.

Xu & Kunz, *JPP* (2016)
Komarov, Churazov, Kunz, & Schekochihin, *MNRAS* (2016)
Melville, Schekochihin, & Kunz, *MNRAS* (2016)
Kunz, Schekochihin, & Stone, *PRL* (2014)