Fire hose instability in heliospheric and astrophysical plasmas: modeling, simulations and observations

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Thanks to collaborators: Petr Hellinger, Simone Landi, Marco Velli, Rob Wicks, Bruce Goldstein...

Motivation

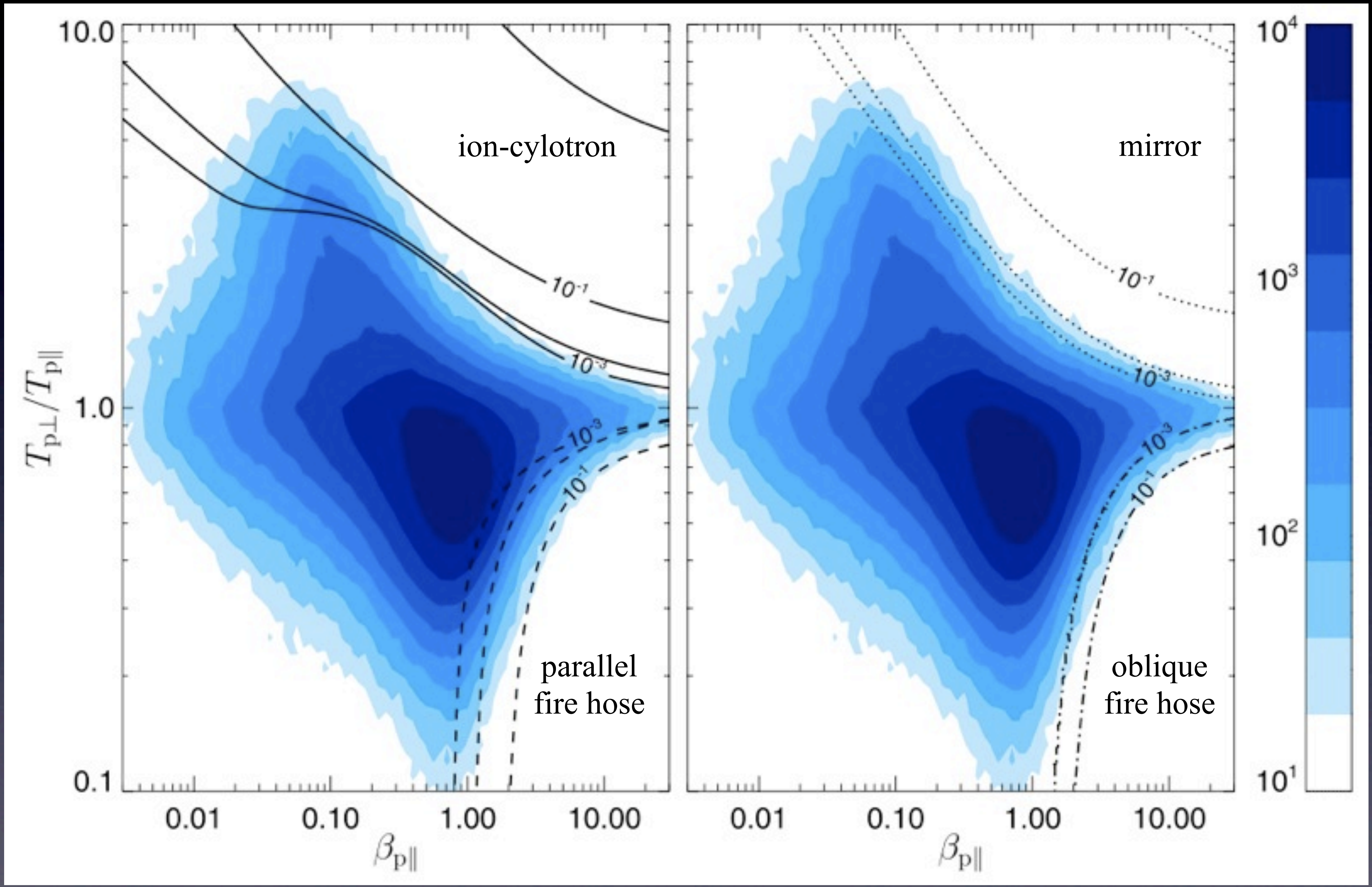
- Galaxy clusters
  (Cowley's talk)
- Accretion discs
  (MRI, Kunz's talk)
- Magnetic reconnection
  (Drake's talk)
- Solar wind: direct observations

Suggested outline

- SW observations of instabilities driven by anisotropy
- Kinetic simulations and expanding box
- Instabilities and current sheets*
  tearing with anisotropic protons
- Discussion/Conclusion

What does control thermodynamics in collisionless plasmas?

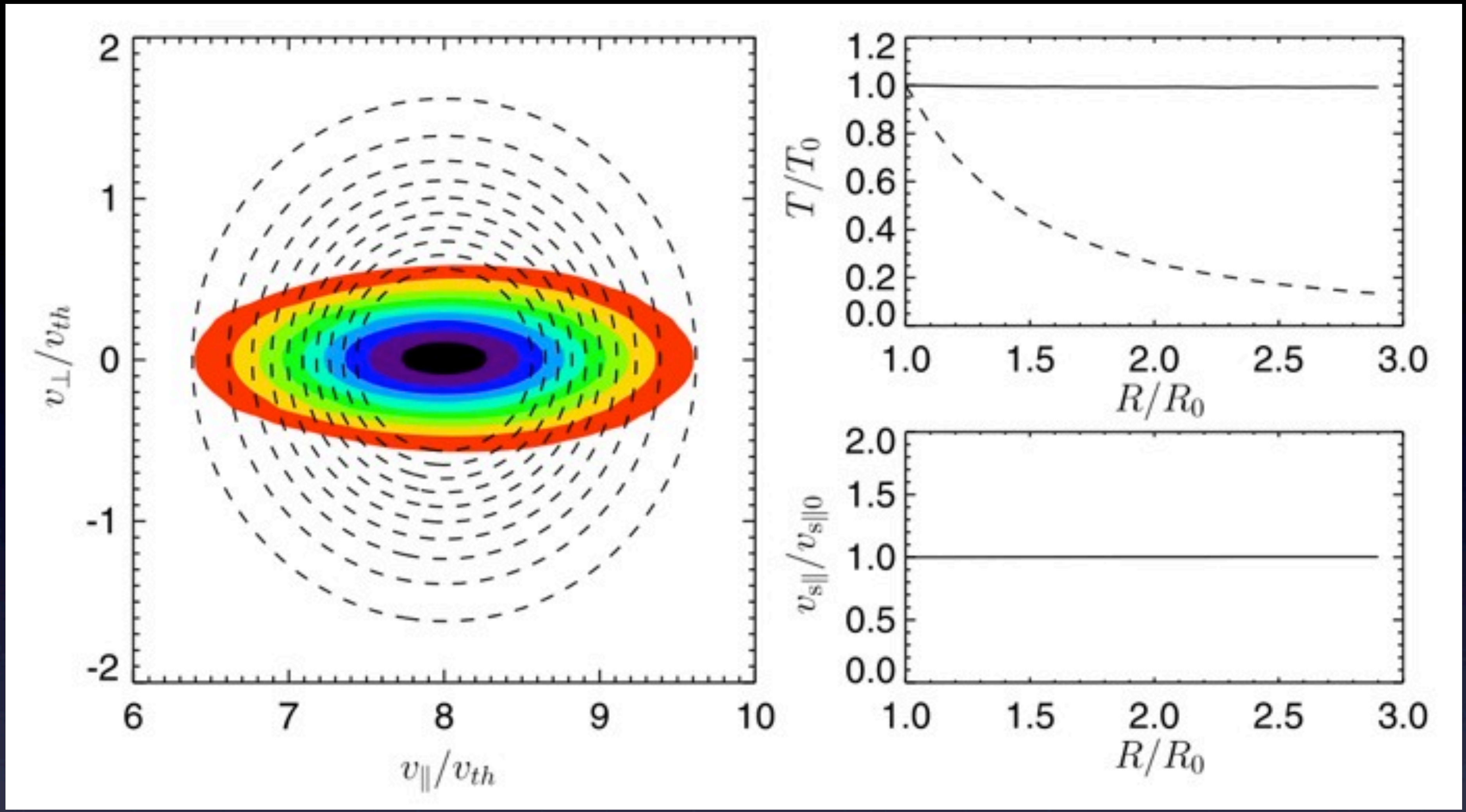
Microphysics (instabilities) constrain large scale evolution



Solar wind observations (WIND 1 AU) *Hellinger et al. 2006, Matteini et al. 2011*

Gary et al. 2001, Kasper et al. 2002, Marsch et al. 2006, Bale et al. 2009

Evolution of solar wind proton distributions



$$\mu = v_\perp^2/B$$

CGL or Double Adiabatic

$$\frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{P_\perp}{nB}\right) = 0 \quad \text{and} \quad \frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{P_\parallel B^2}{n^3}\right) = 0$$

$$P_{\parallel,\perp} = n k_B T_{\parallel,\perp}$$

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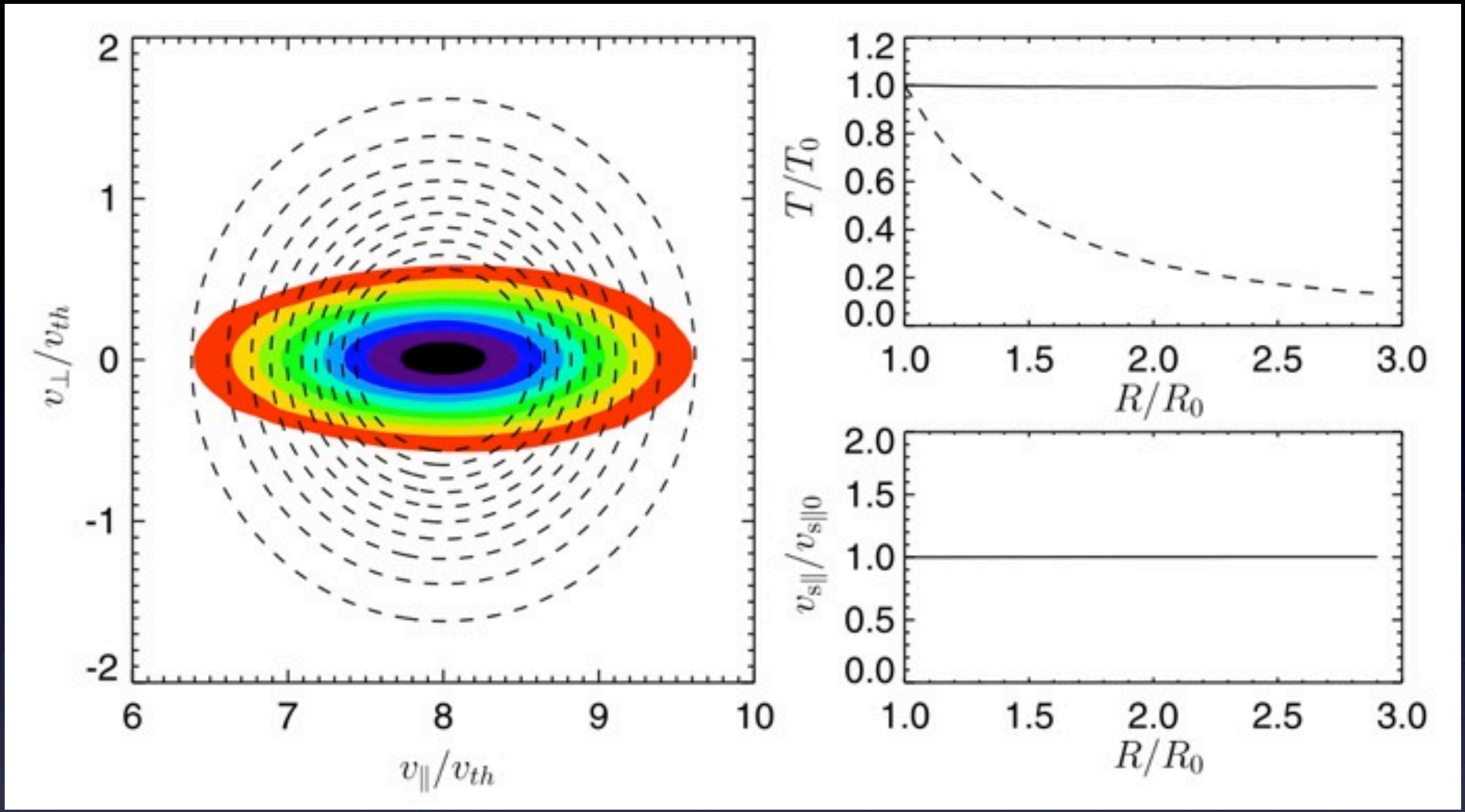

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Expansion in a radial magnetic field

$$T_{\perp p} \propto B \quad \text{and} \quad T_{\parallel p} \propto \frac{n^2}{B^2}\,;$$

$$T_{\perp p} \propto r^{-2} \quad \text{and} \quad T_{\parallel p} = \text{const.}$$

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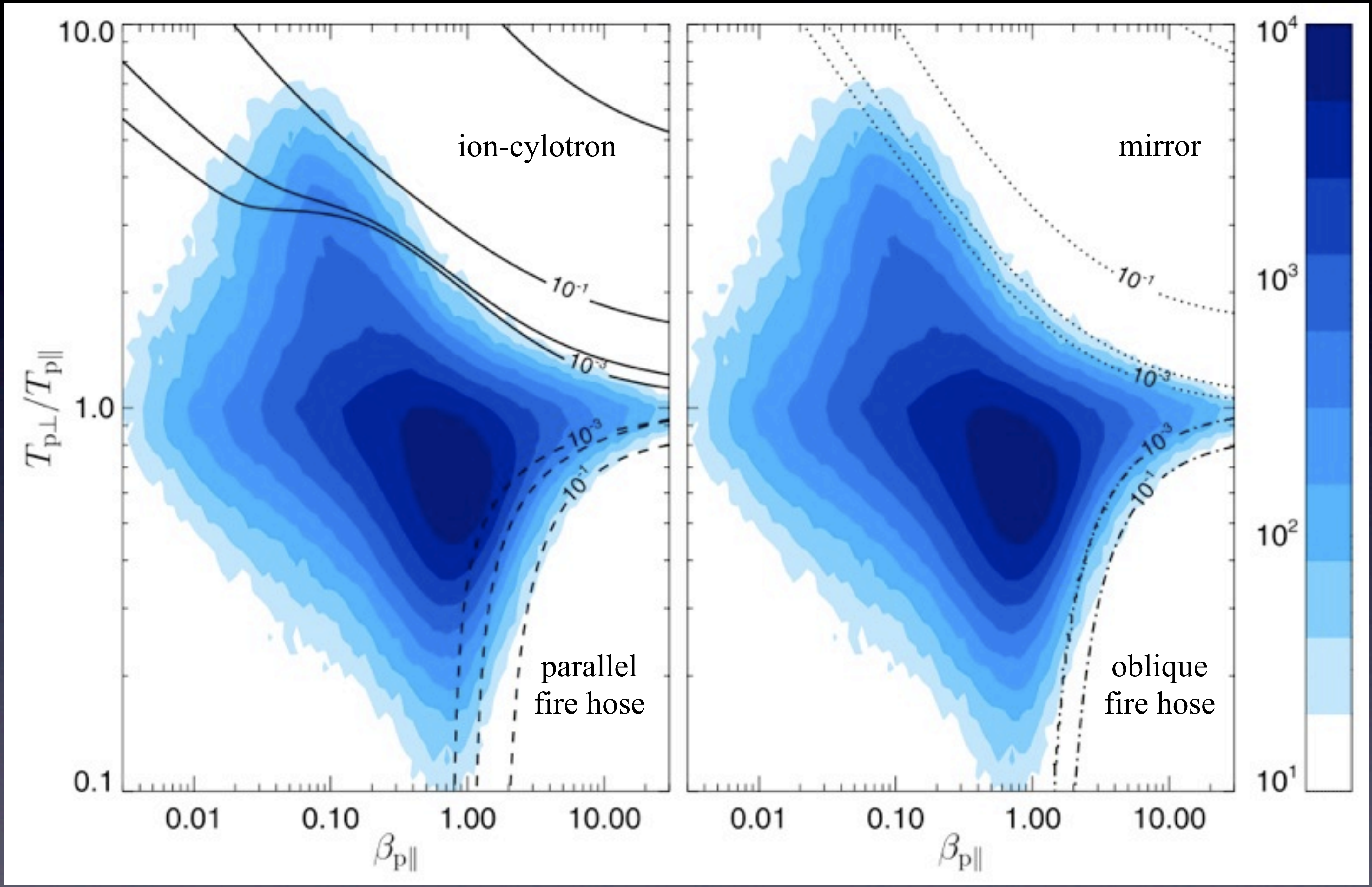

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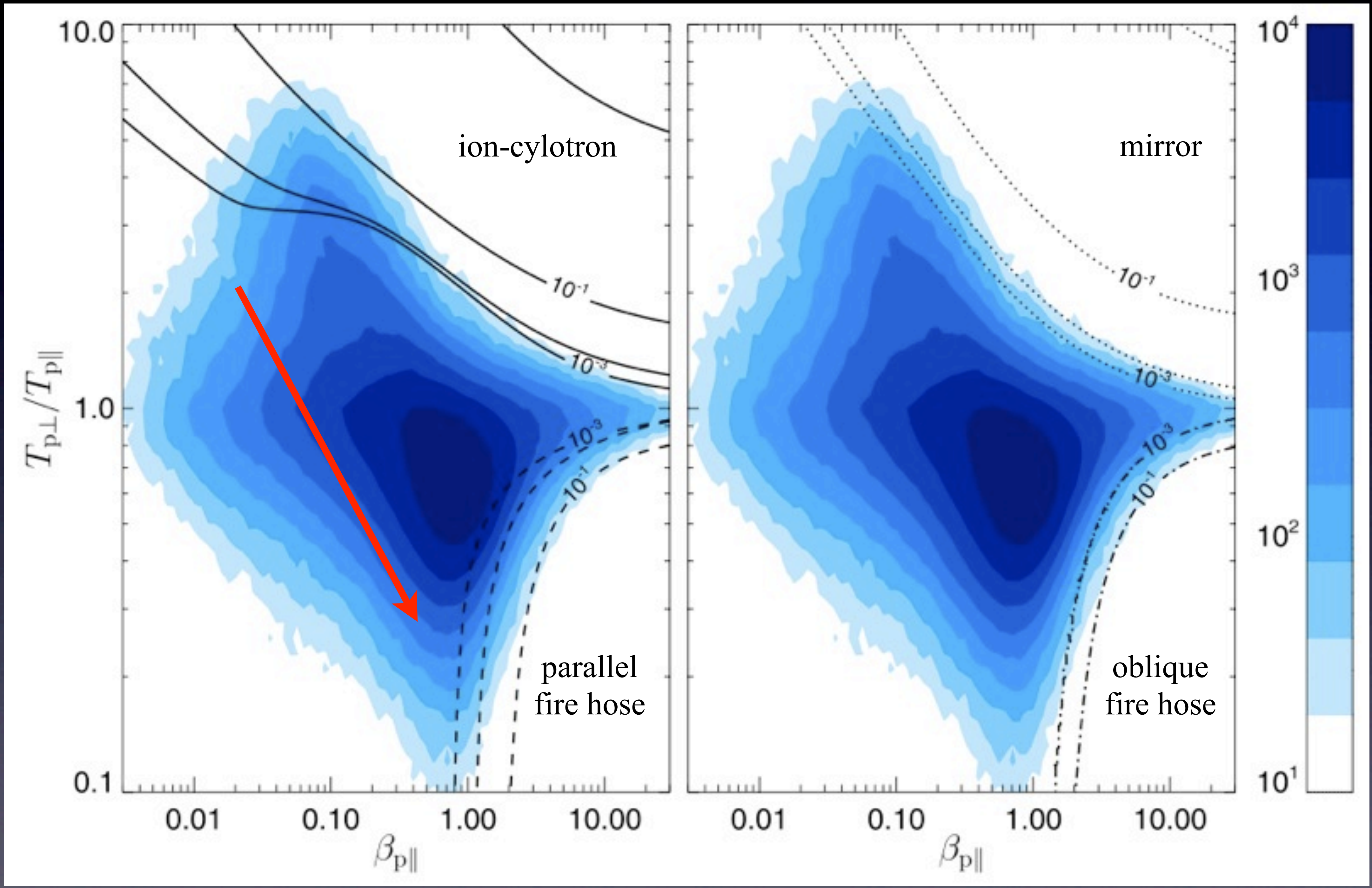

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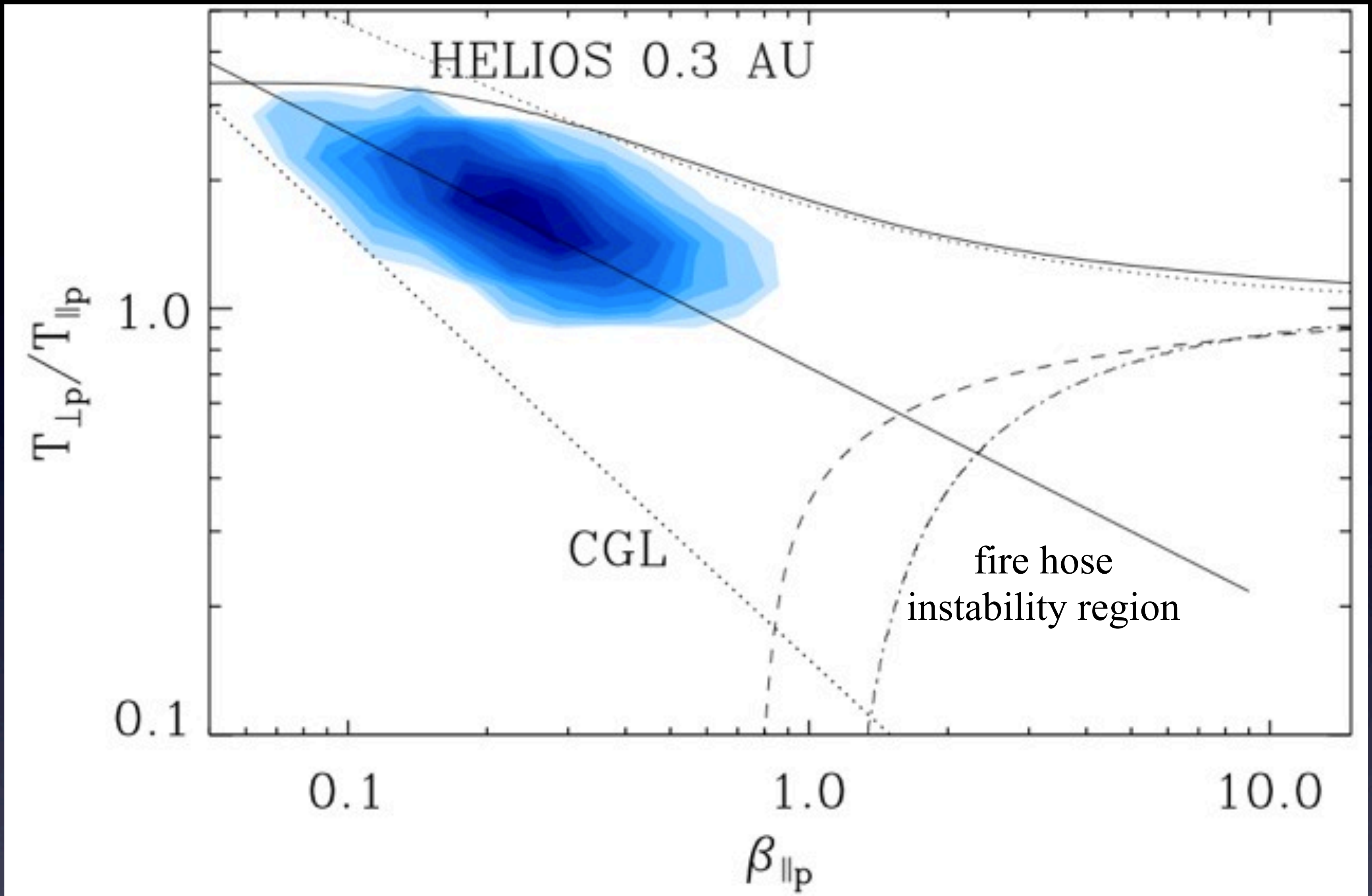
Evolution of anisotropy with distance (fast wind)



Matteini et al., GRL 2007

- Maximum of anisotropy close to the Sun: future observations?
- Non adiabatic evolution: perpendicular heating
- Evolution along a fire hose marginal stability path at large distance

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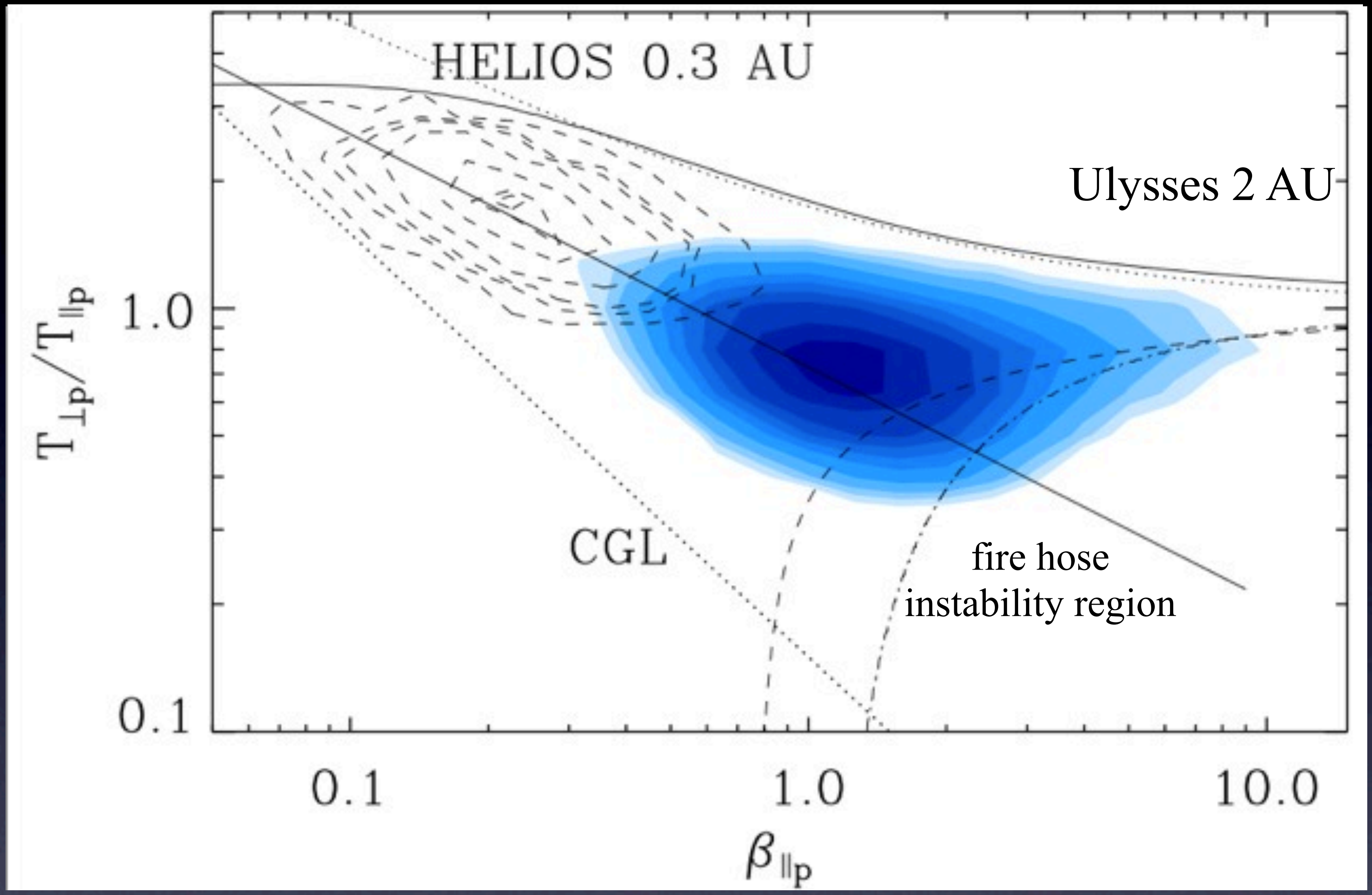

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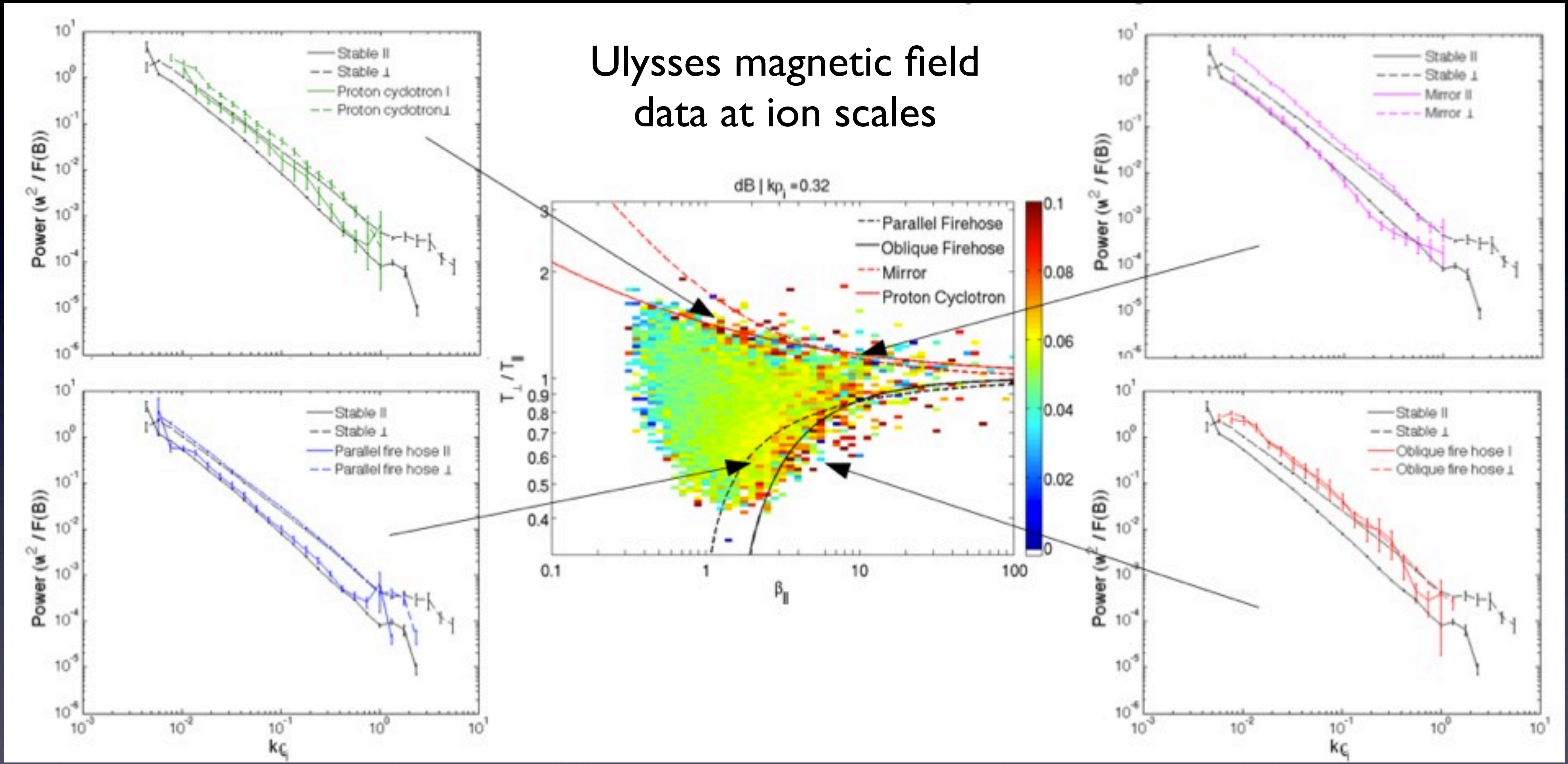
Signatures of kinetic instabilities in magnetic spectra?

generation of local fluctuations into the SW turbulent cascade



The magnetic power at parallel k-vectors is enhanced at the ion scales when protons are closer to a fire hose instability threshold

Wicks et al., in prep.

Different spectral shapes when protons close to an instability region

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, A10101, doi:10.1029/2006JA011667, 2006

Parallel proton fire hose instability in the expanding solar wind: Hybrid simulations

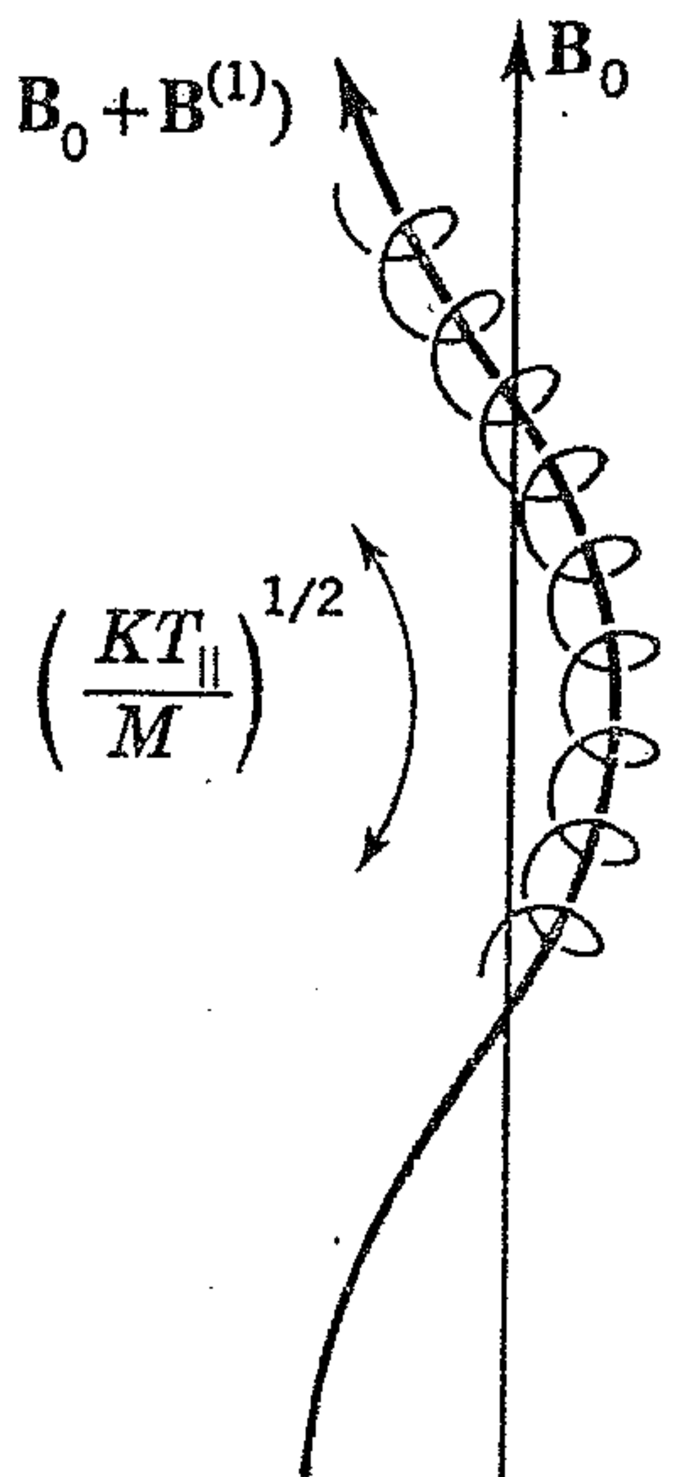
Lorenzo Matteini,[1,2] Simone Landi,[1] Petr Hellinger,[3] and Marco Velli[1,4]

Received 14 February 2006; revised 1 June 2006; accepted 30 June 2006; published 5 October 2006.

[1] We report a study of the properties of the parallel proton fire hose instability comparing the results obtained by the linear analysis, from one-dimensional (1-D) standard hybrid simulations and 1-D hybrid expanding box simulations. The three different approaches converge toward the same instability threshold condition which is in good agreement with in situ observations, suggesting that such instability is relevant in the solar wind context. We investigate also the effect of the wave-particle interactions on shaping the proton distribution function and on the evolution of the spectrum of the magnetic fluctuations during the expansion. We find that the resonant interaction can provide the proton distribution function to depart from the bi-Maxwellian form.

Citation: Matteini, L., S. Landi, P. Hellinger, and M. Velli (2006), Parallel proton fire hose instability in the expanding solar wind: Hybrid simulations, *J. Geophys. Res.*, *111*, A10101, doi:10.1029/2006JA011667.

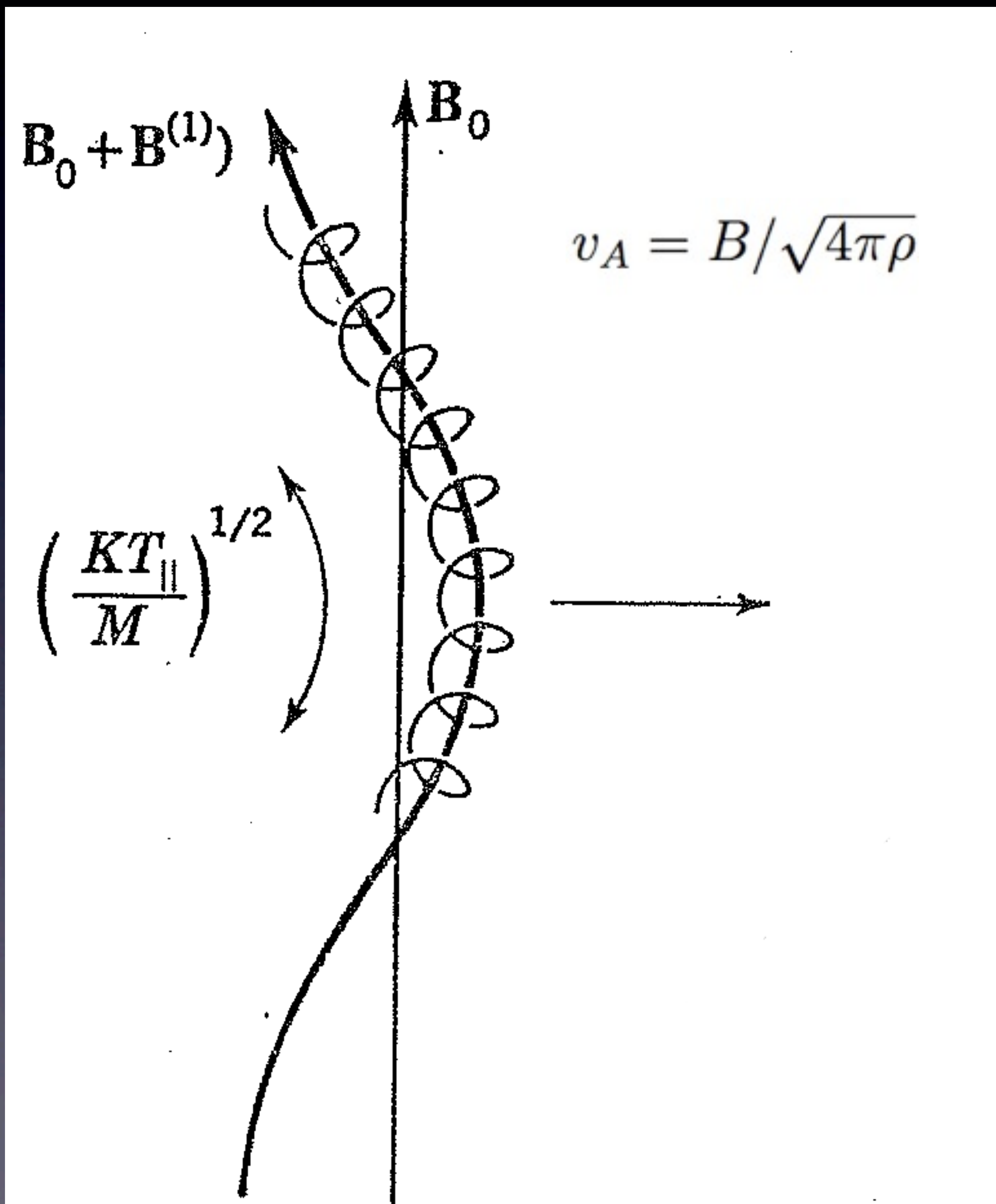
Alfvén wave in anisotropic plasmas



$v_A = B/\sqrt{4\pi\rho}$

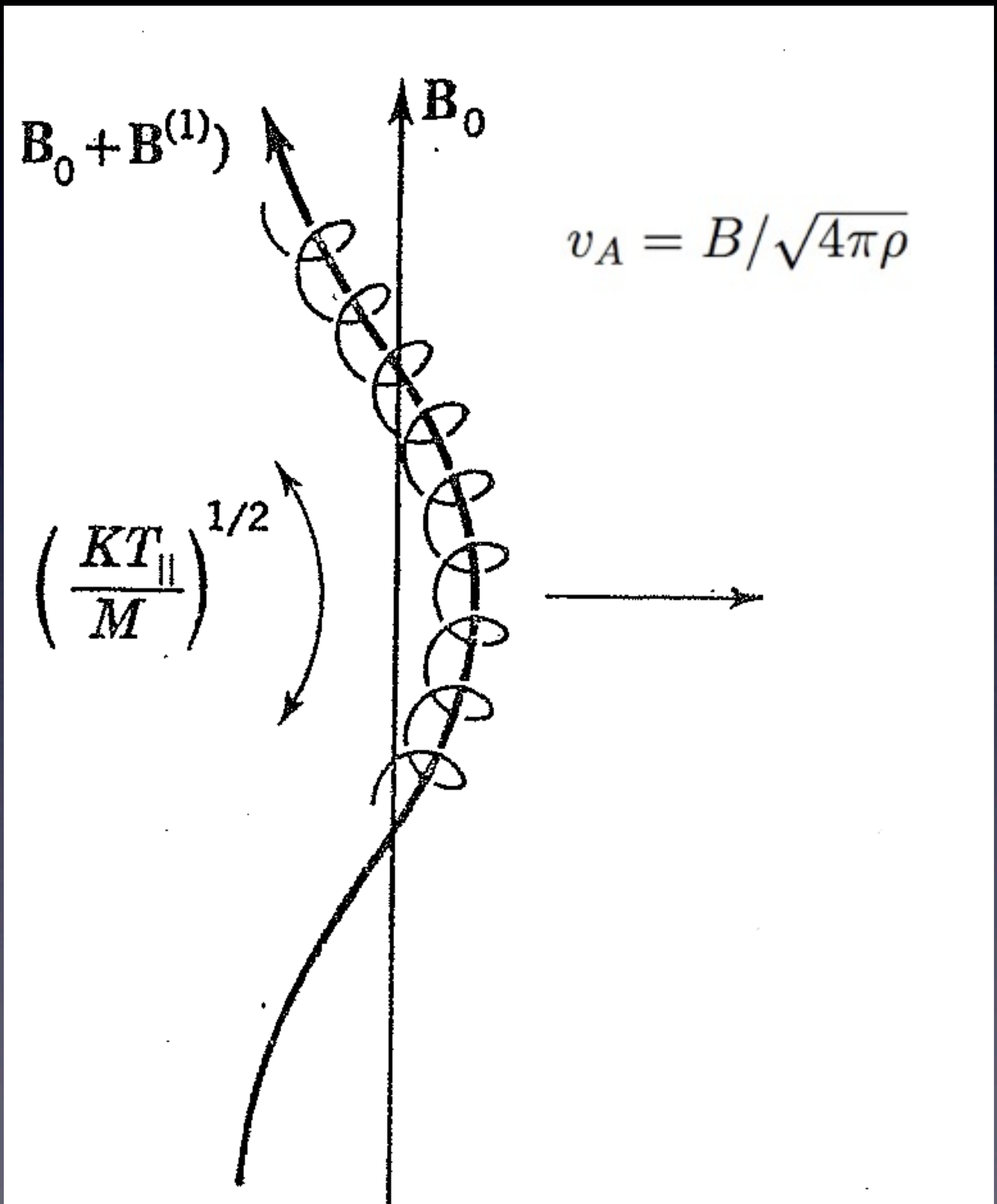
$$\omega^2 = k^2 v_A^2$$

Alfvén wave in anisotropic plasmas



$$\omega^2 = k^2 v_A^2 \left(\frac{B_0^2/4\pi + P_\perp - P_\parallel}{B_0^2/4\pi} \right)$$

Alfvén wave in anisotropic plasmas



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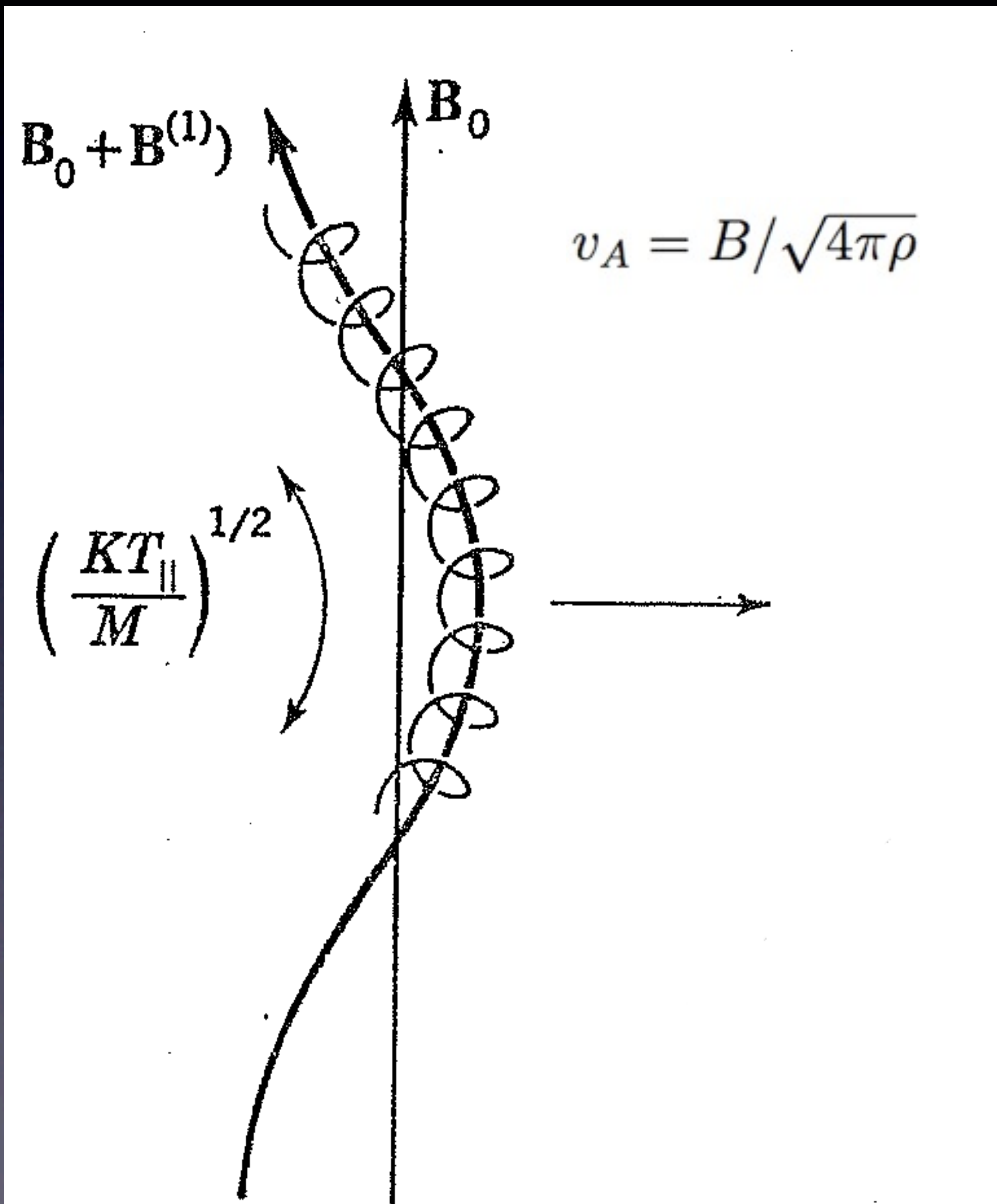

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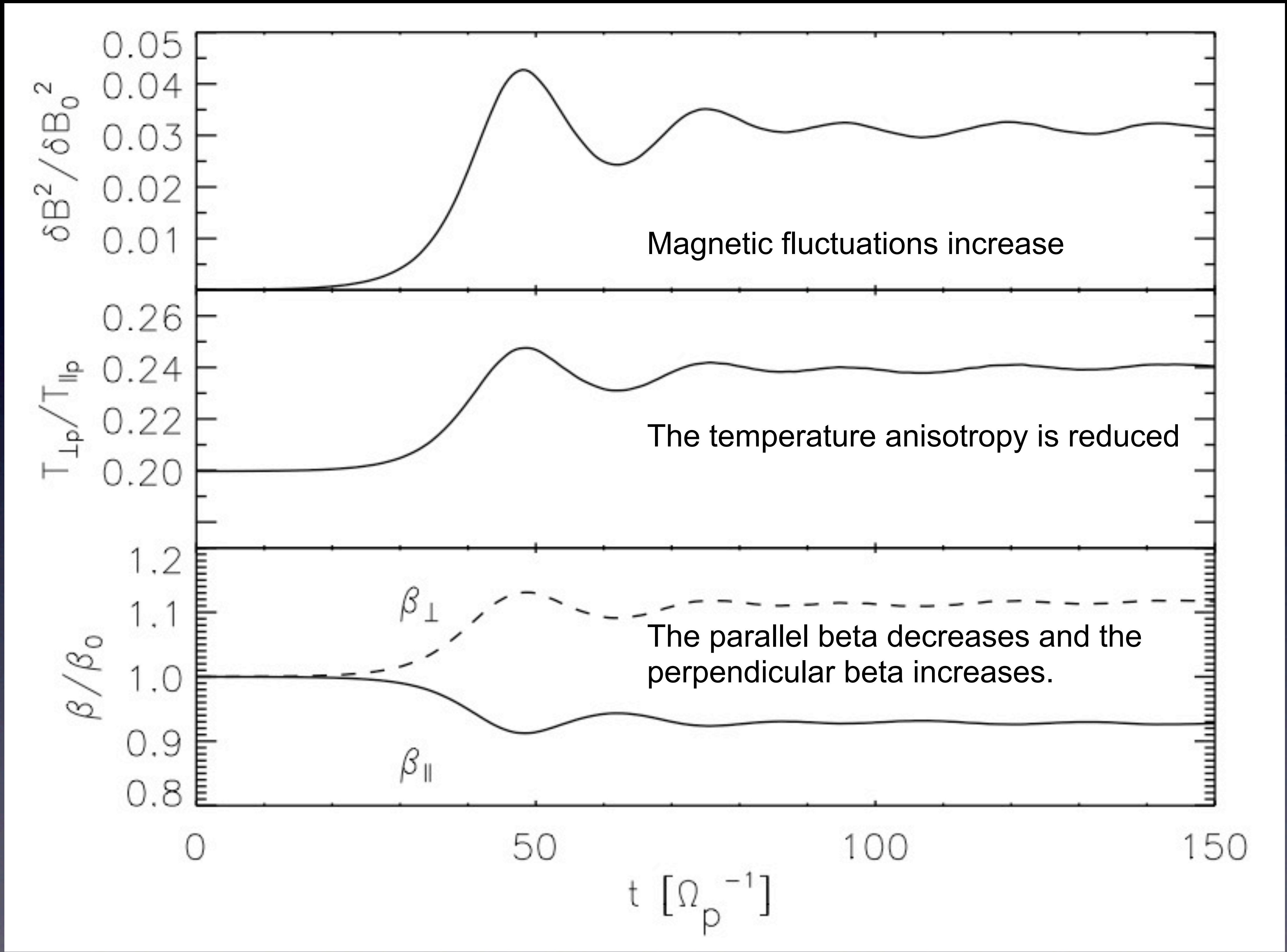
$$\beta_{\parallel,\perp} = \frac{P_{\parallel,\perp}}{B_0/8\pi} = \frac{8\pi n k_B T_{\parallel,\perp}}{B_0^2}$$

Fluid fire hose threshold condition:

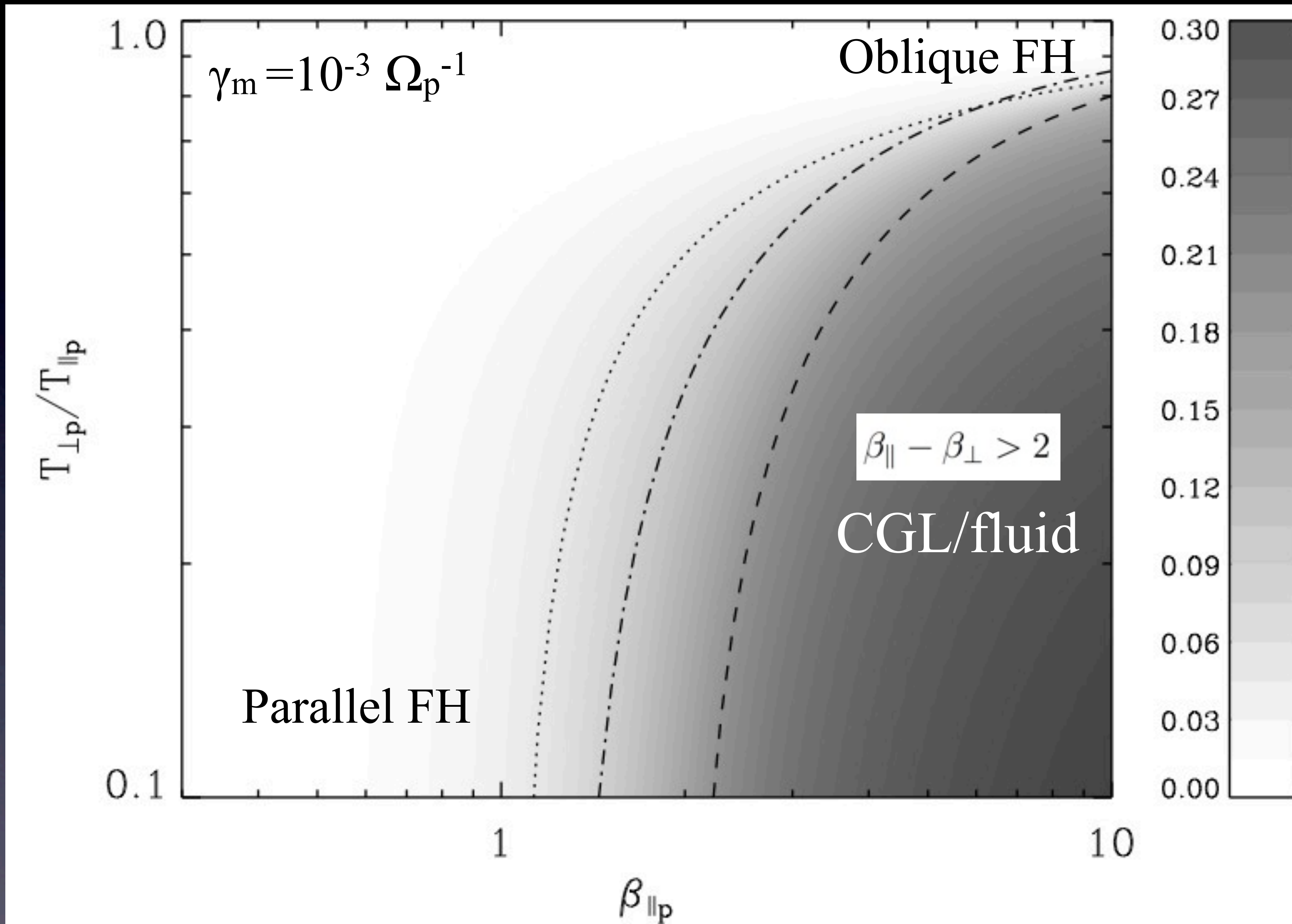
$$\beta_\parallel - \beta_\perp > 2$$

Typical evolution of the instability



Hybrid PIC simulation

Fire hose thresholds: fluid vs. kinetic

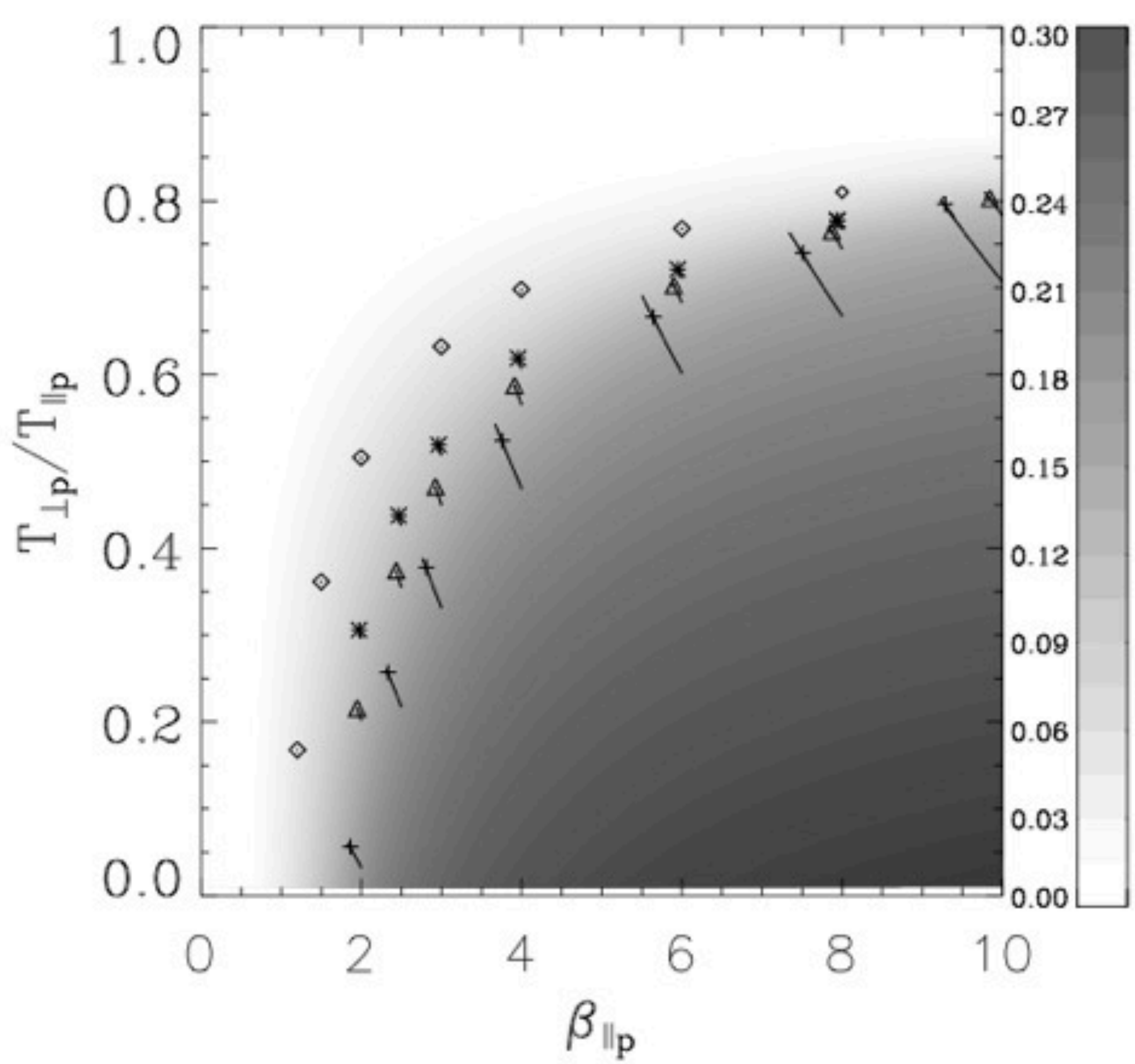


Vlasov linear theory: maximum growth rate

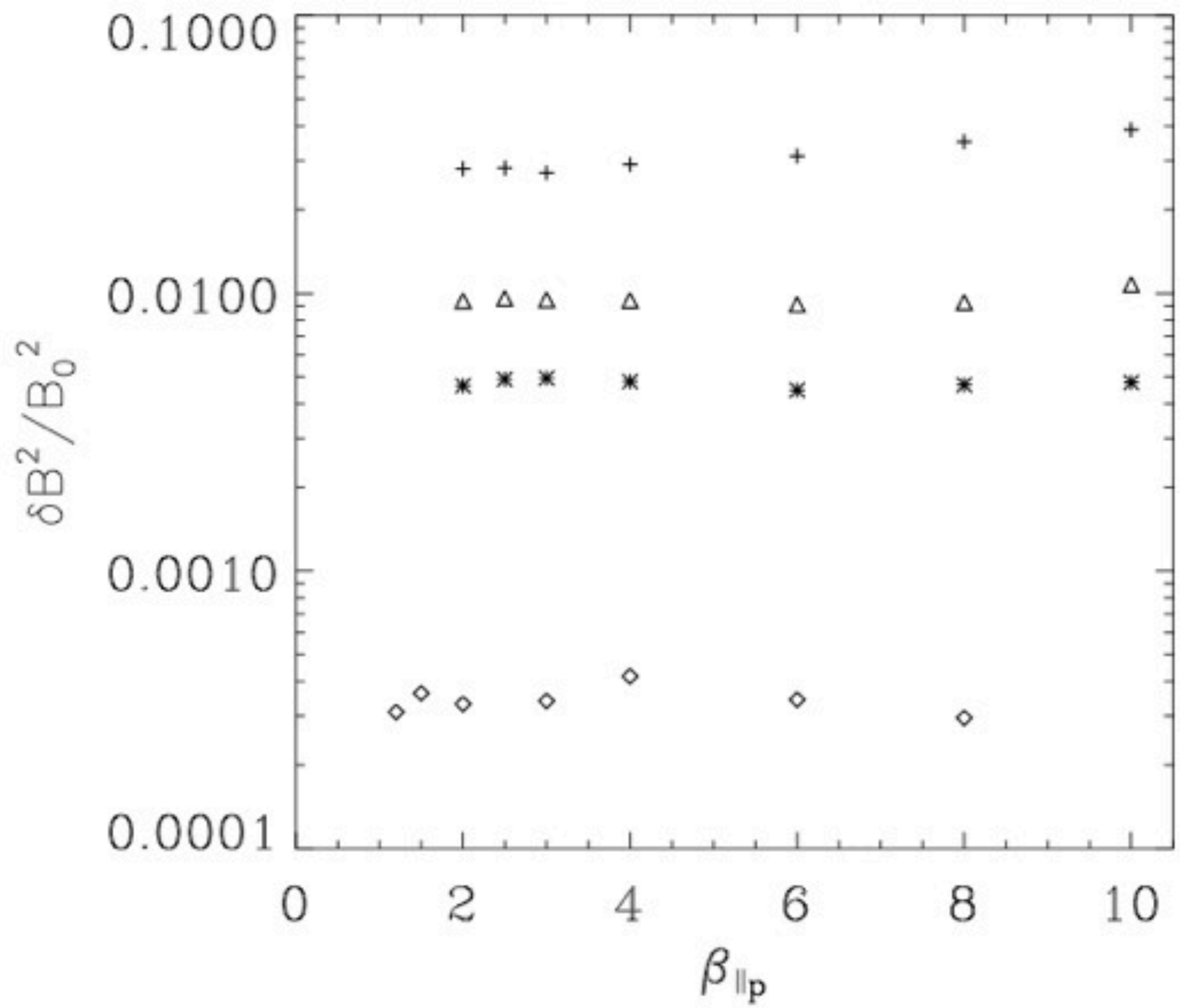
Standard hybrid runs

Normalizations: cyclotron frequency Ω_p^{-1} and ion inertial length $\rho_i=c/\omega_p=V_A/\Omega_p$

Typically: ~1000 points ; $\Delta x=0.5\text{-}1\rho_i$ => $L\sim 10^3\rho_i$ and $10^3\text{-}10^4$ ppc



Evolution in parameter space

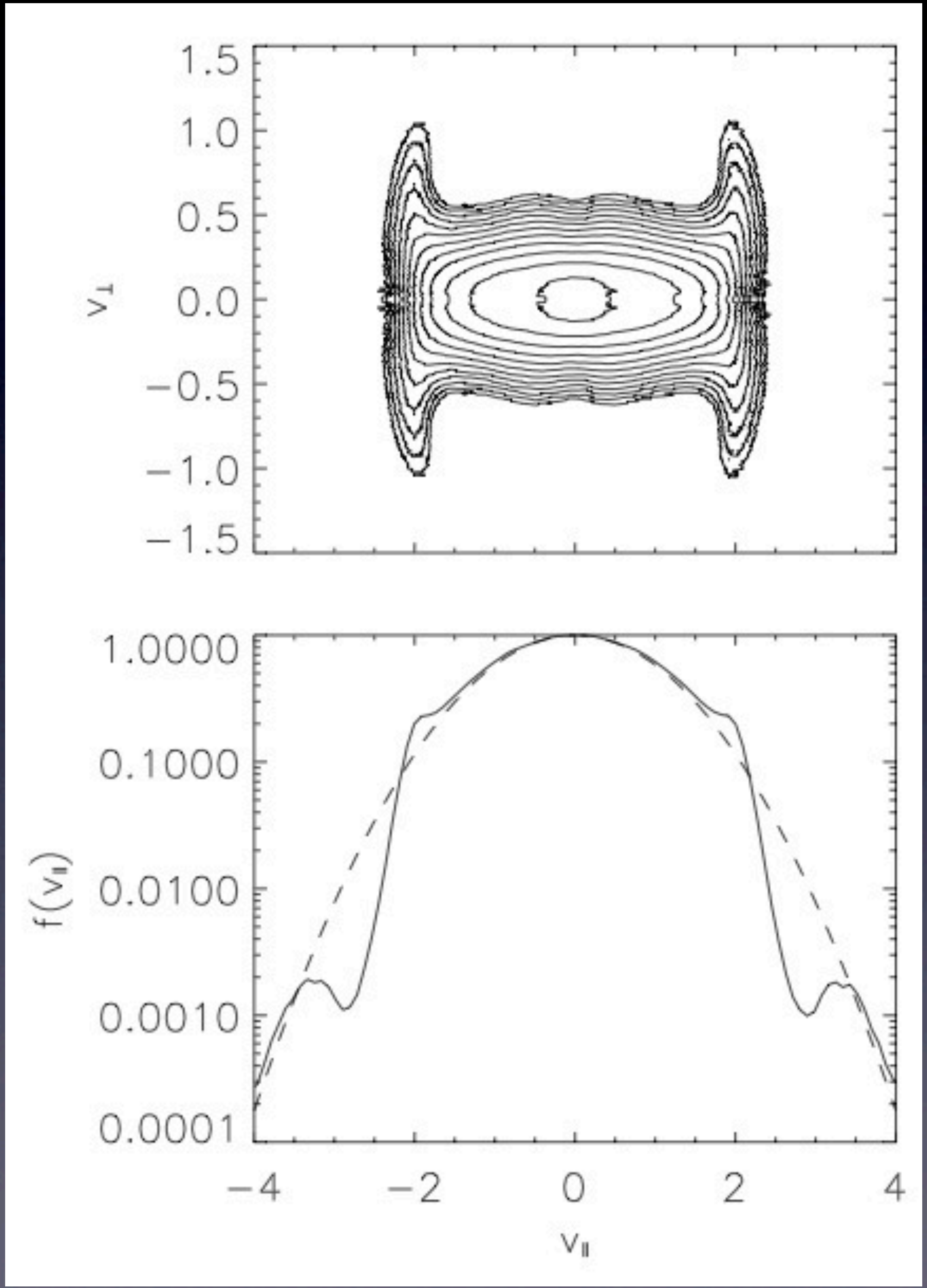


Level of fluctuations

Evolution of the proton vdf

Resonant fire hose

$$f(v_{\|p}, v_{\perp p})$$



$$f(v_{\|p})$$

Distribution modified by wave-particle interactions (resonances!)

$$\omega - k_\| v_\| = \pm \Omega_p$$

Proton fire hose is anomalous-doppler resonant thus with right handed waves

Evolution of the proton vdf

Resonant fire hose

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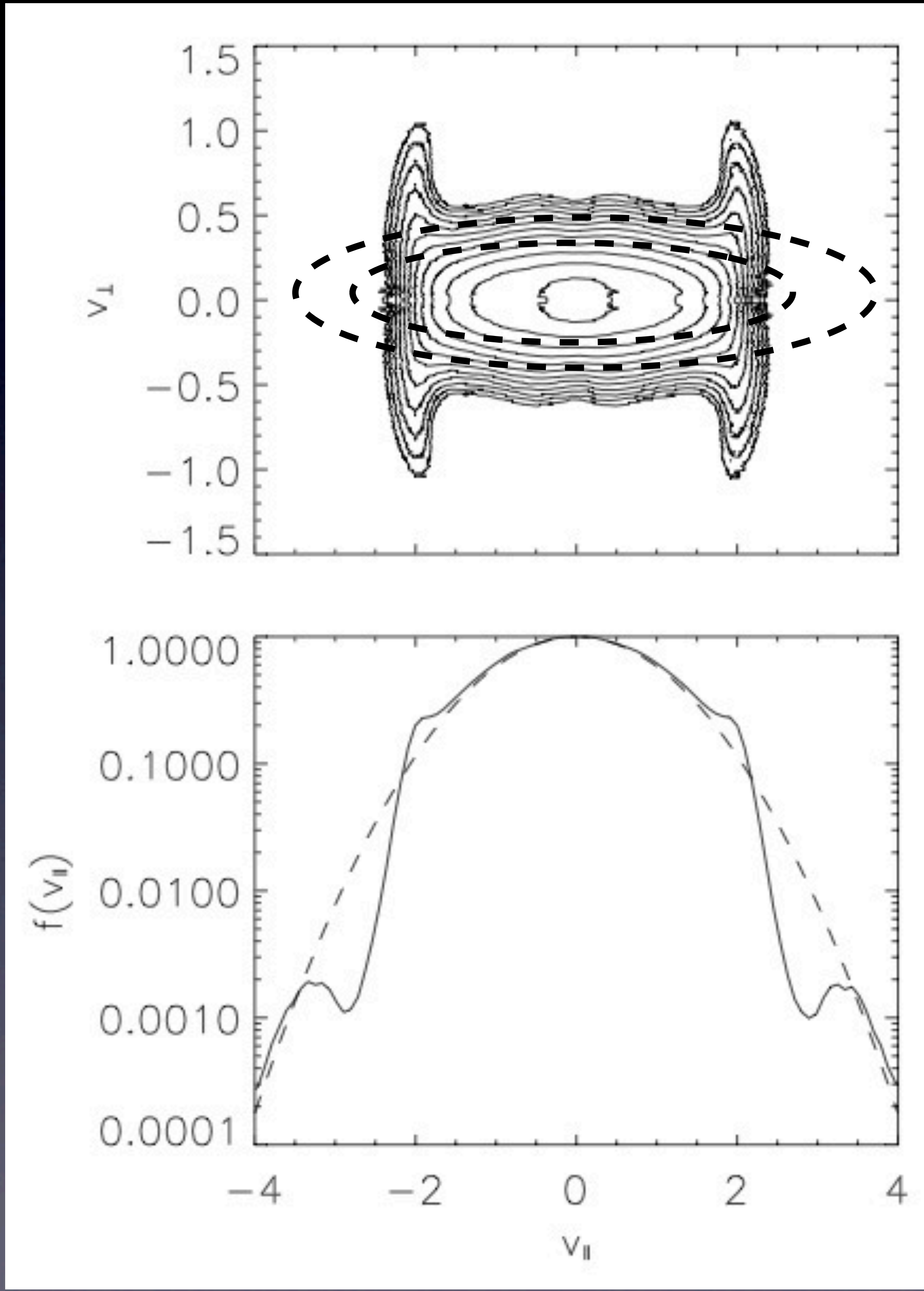

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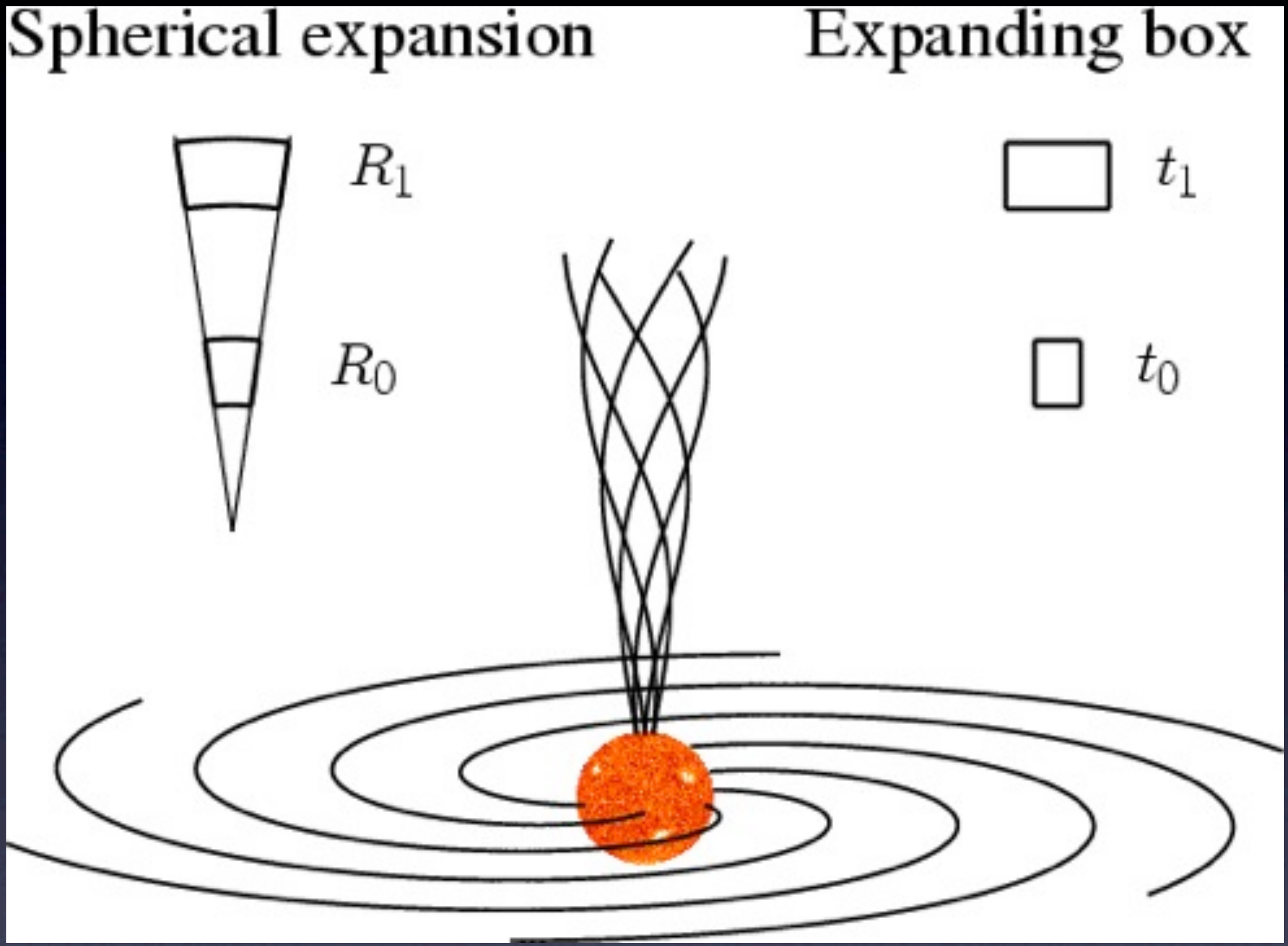
The Hybrid Expanding Box code (HEB)

Hybrid code implemented with an expanding box model (*Liewer et al. 2001, Hellinger et al. 2003*)

- Hybrid model (*Matthews 1994*):
  electrons as isotropic charged massless fluid
  ions as particles - PIC

- The expanding box model assumes a radial linearly driven evolution with a constant expansion velocity.
  (*Grappin et al. 1993, Grappin & Velli 1996*).

  Transverse dimensions of the box increase with distance: $\mathbf{x}(t)=L\mathbf{x_0}$



$L_{11} = 1,\ L_{22} = L_{33} = (1 + t/t_e)$ $\quad t_e = R_0/U$

$$R = R_0 + v_{sw}t = R_0(1 + t/t_e)$$

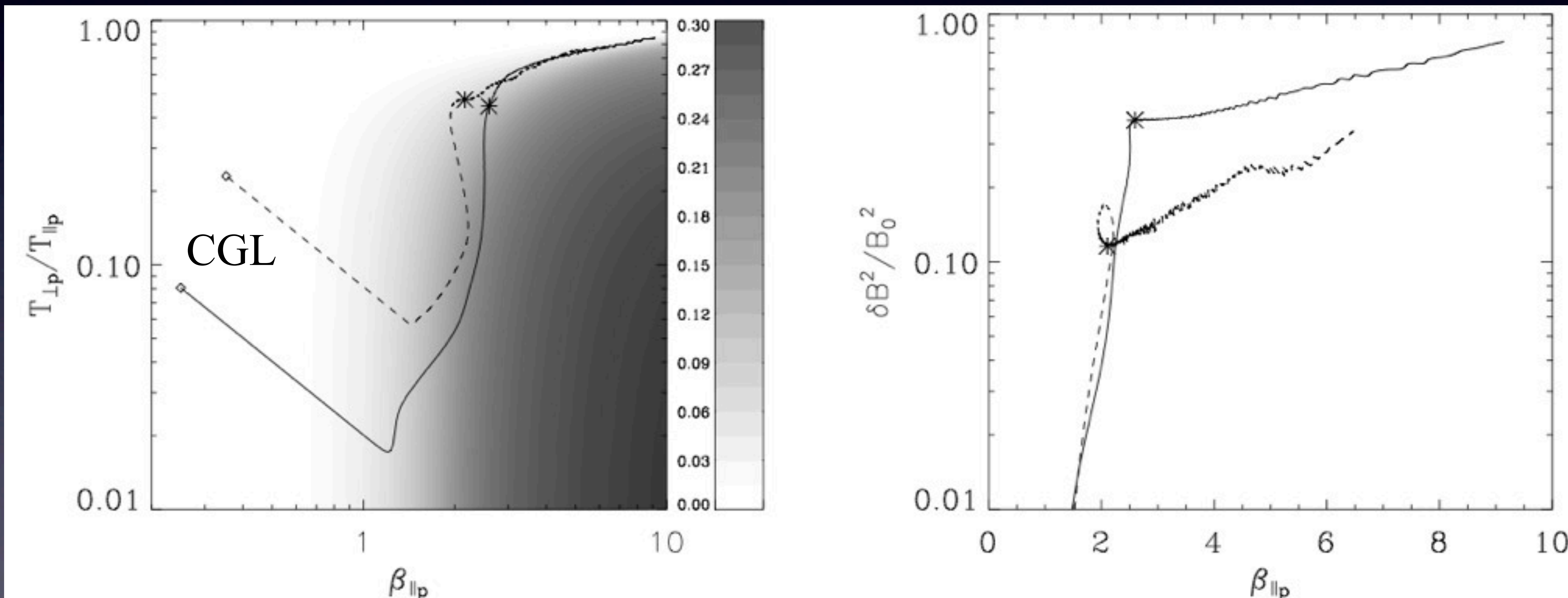
Adiabatic evolution for ions (CGL) and waves (WKB)

Self-consistent competition between expansion and local microphysics

1-D simulations: parallel fire hose

Expansion times:
$t_e = R/U = 2\text{x}10^3,\ 10^4\ \Omega_p^{-1}$

$$\frac{T_{\perp p}}{T_{\parallel p}} \propto \left(1+\frac{t}{t_e}\right)^{-2}, \quad \beta_{\parallel p} \propto \left(1+\frac{t}{t_e}\right)^{2}$$

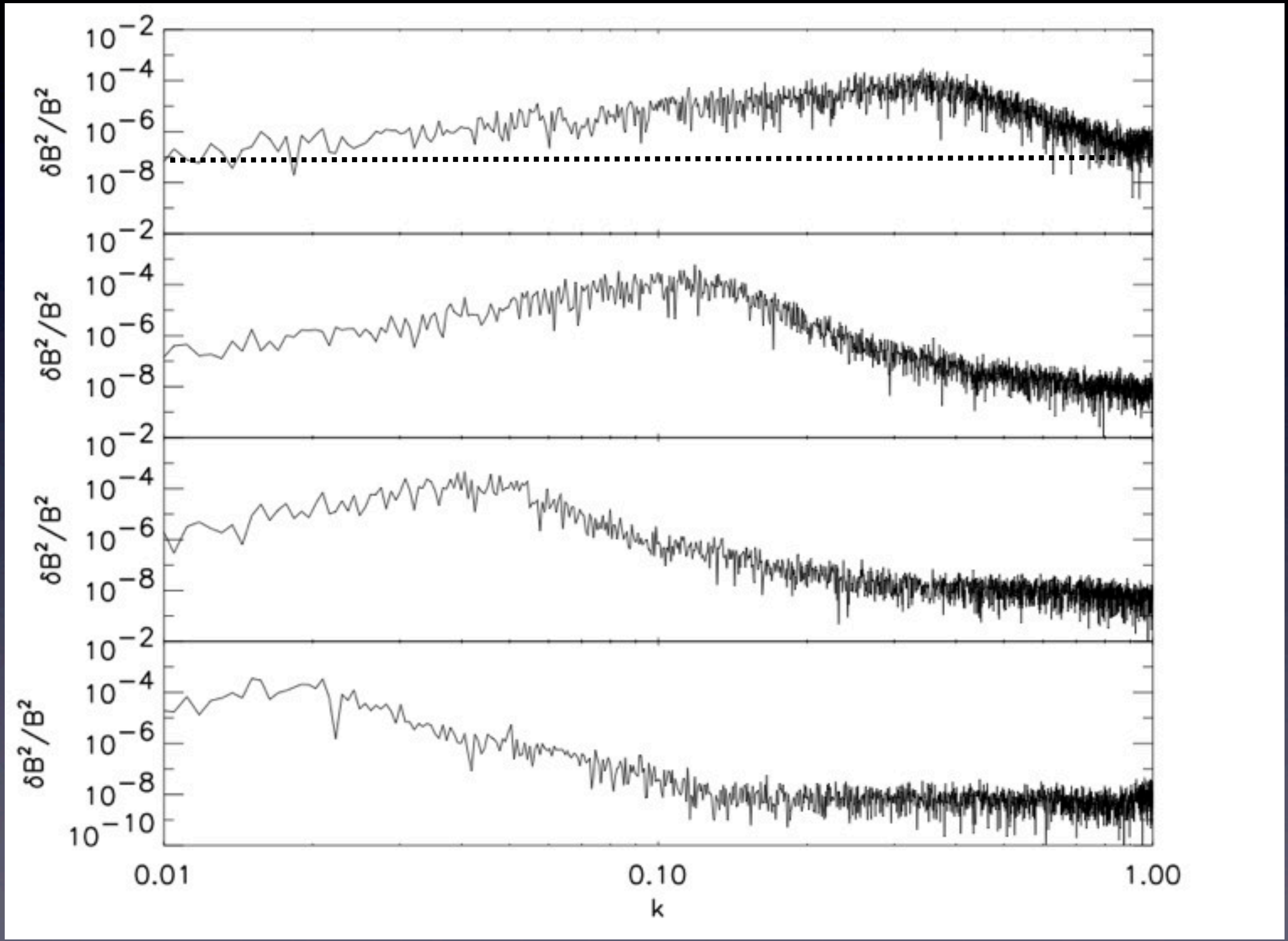


Evolution in parameter space

Level of fluctuations

Evolution of fire hose fluctuations

Simulation time (distance from Sun)



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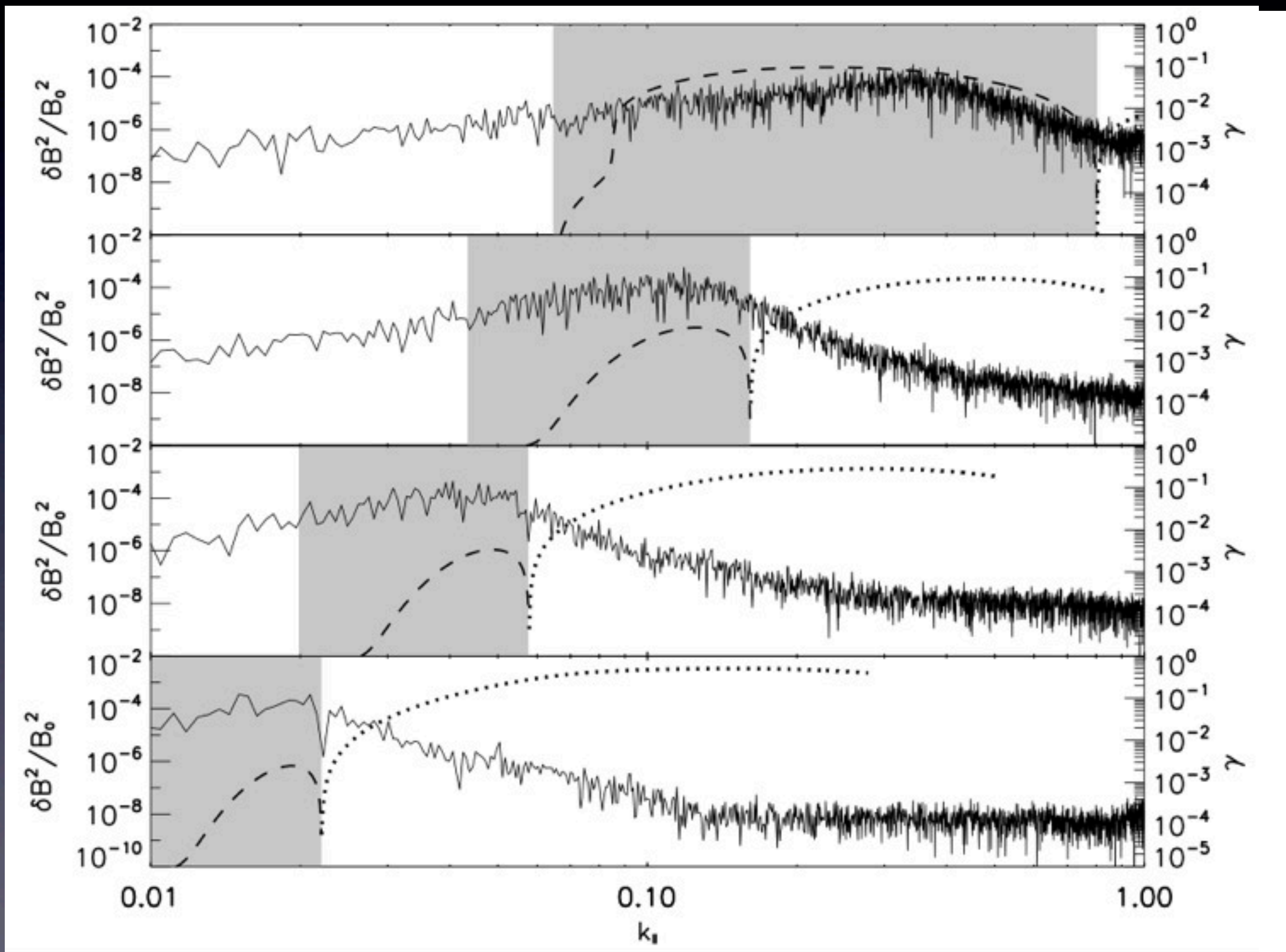
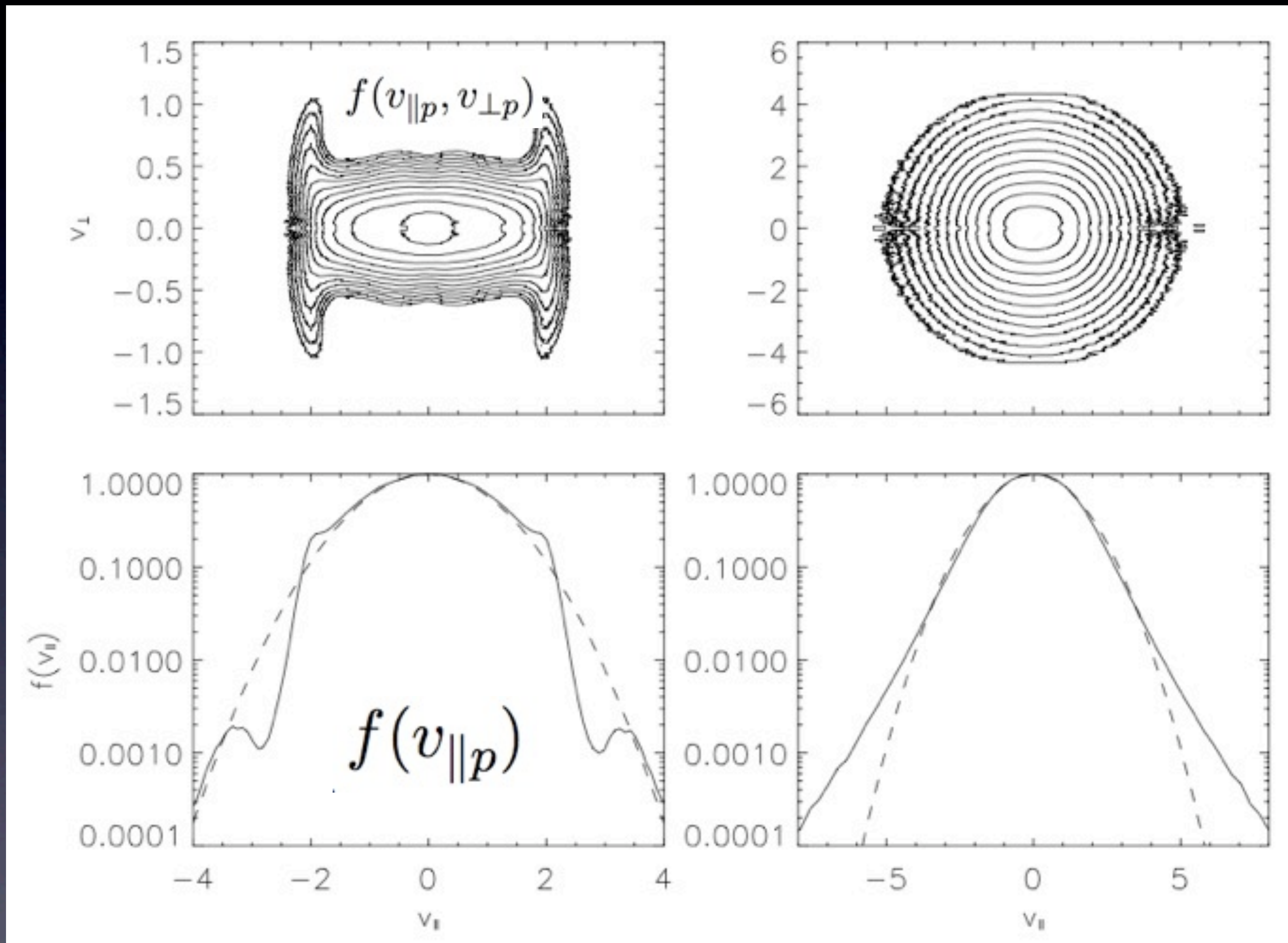


Evolution of particles during the expansion

Particles are scattered by unstable waves



Resonant fire hose

Later damping of fluctuations

Fluid view

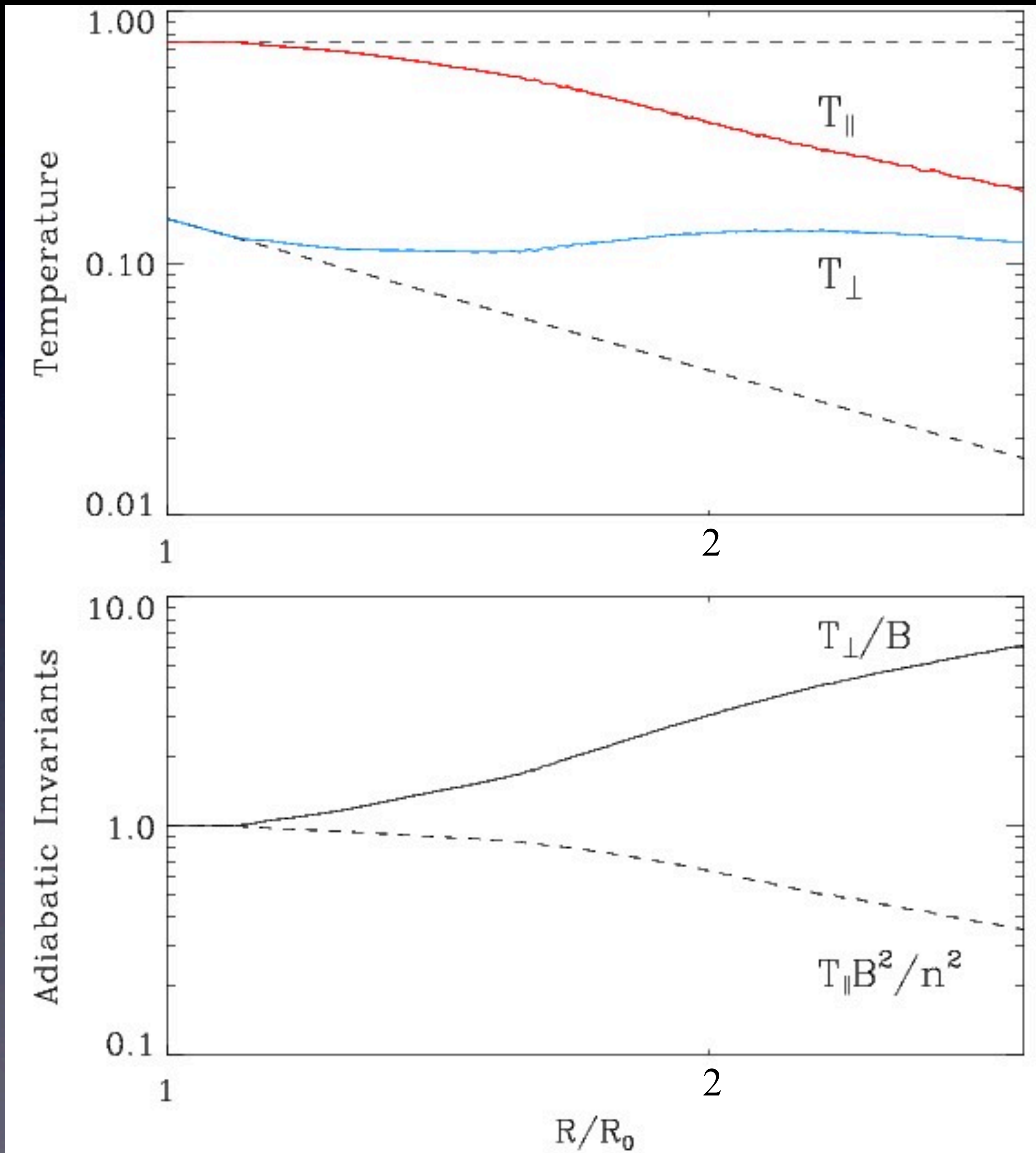
Plasma isotropization by fire hose instability

$$\frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{P_\perp}{nB}\right) = 0 \qquad \text{and} \qquad \frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{P_\parallel B^2}{n^3}\right) = 0.$$

The magnetic field intensity increases due to the growth of unstable waves, perpendicular and parallel pressures evolve according to the CGL invariants:

$P_\perp$ ↗ $\qquad$ $P_{||}$ ↘

Kinetic view



Temperatures depart from CGL prediction

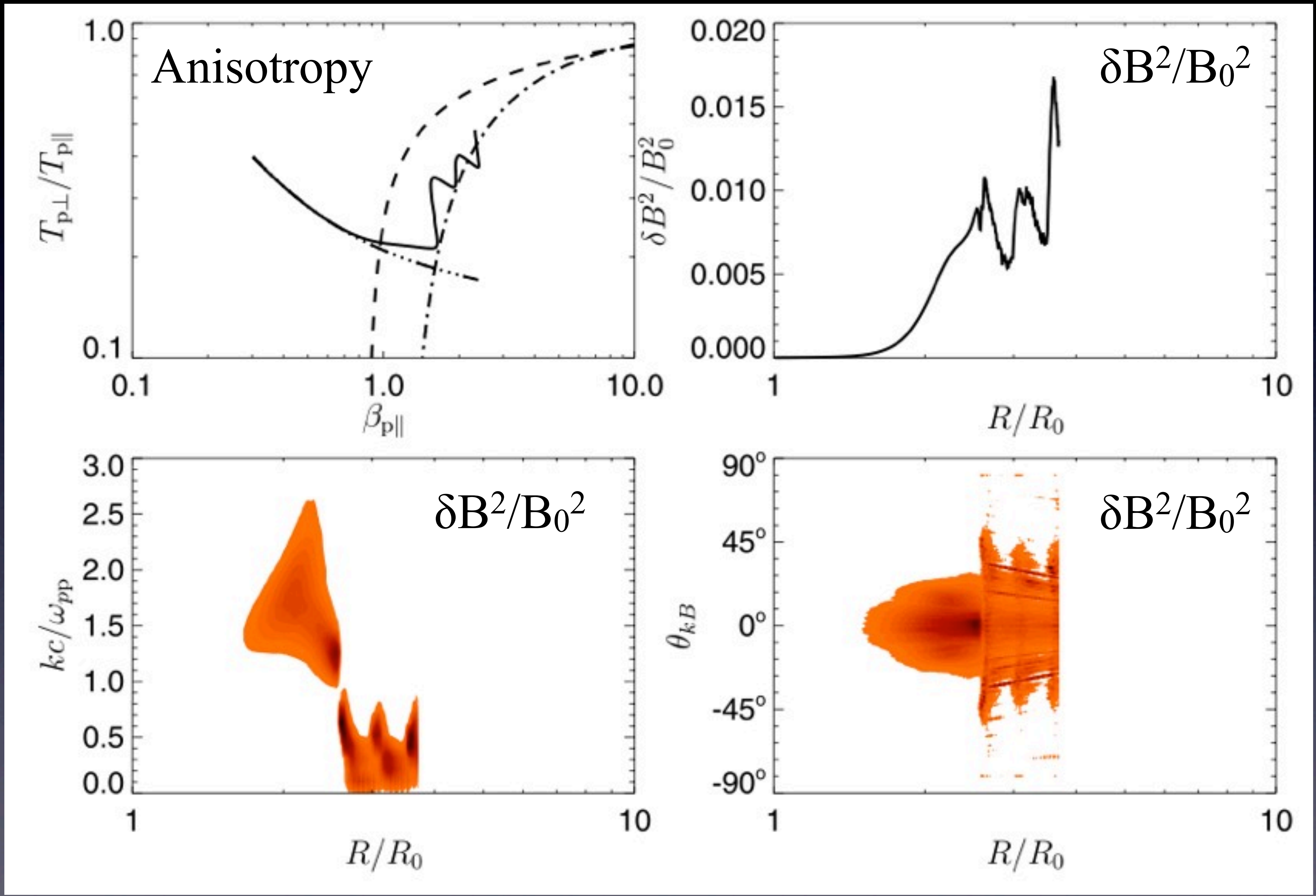
fire hose counteracts the perp cooling driven by expansion

Adiabatic invariants are not conserved

but $\perp$,$\parallel$ with respect B_0 ...
local direction of B should be used

moving to 2-D: oblique fire hose

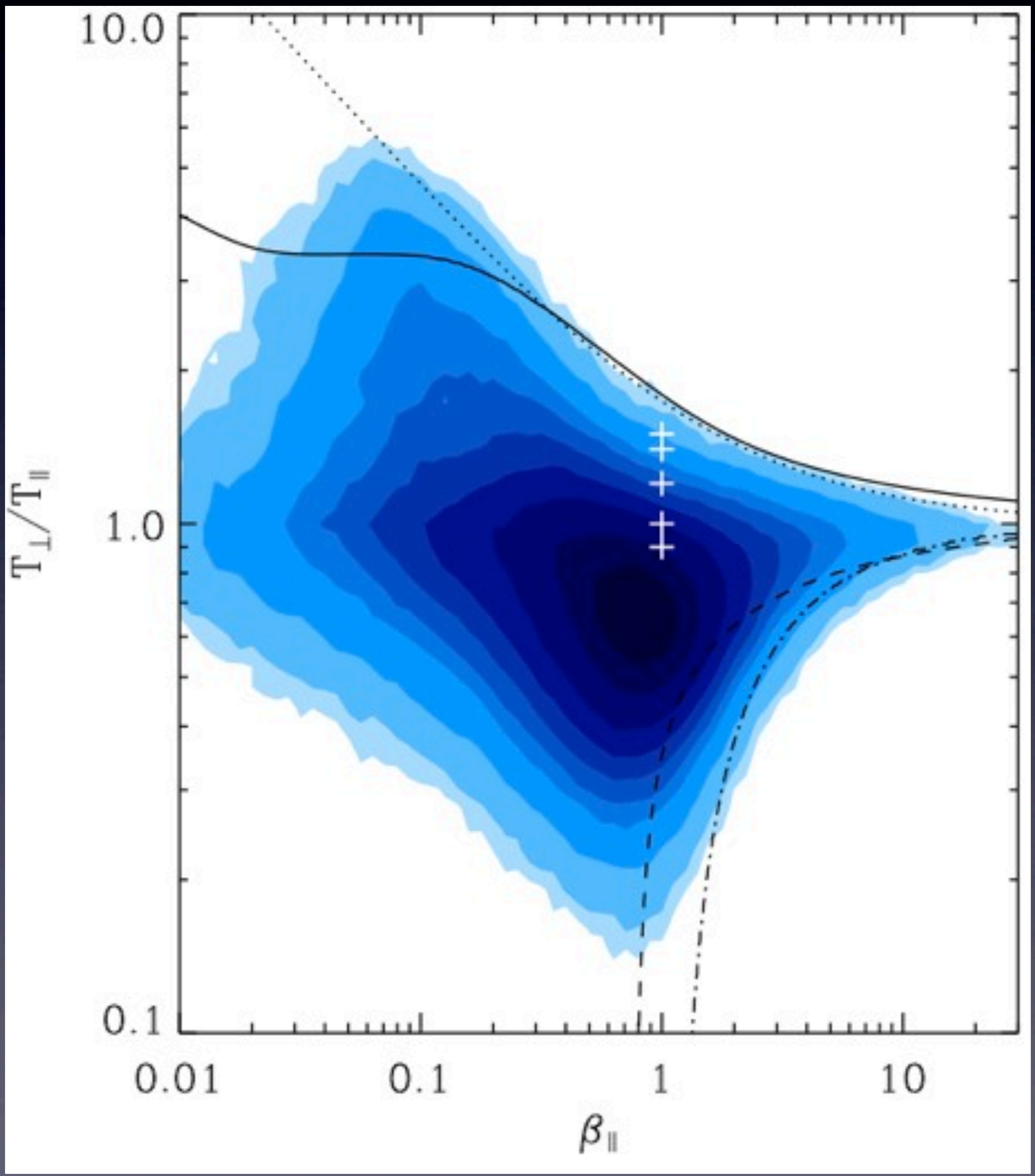
Hellinger and Matsumoto JGR 2000, 2001



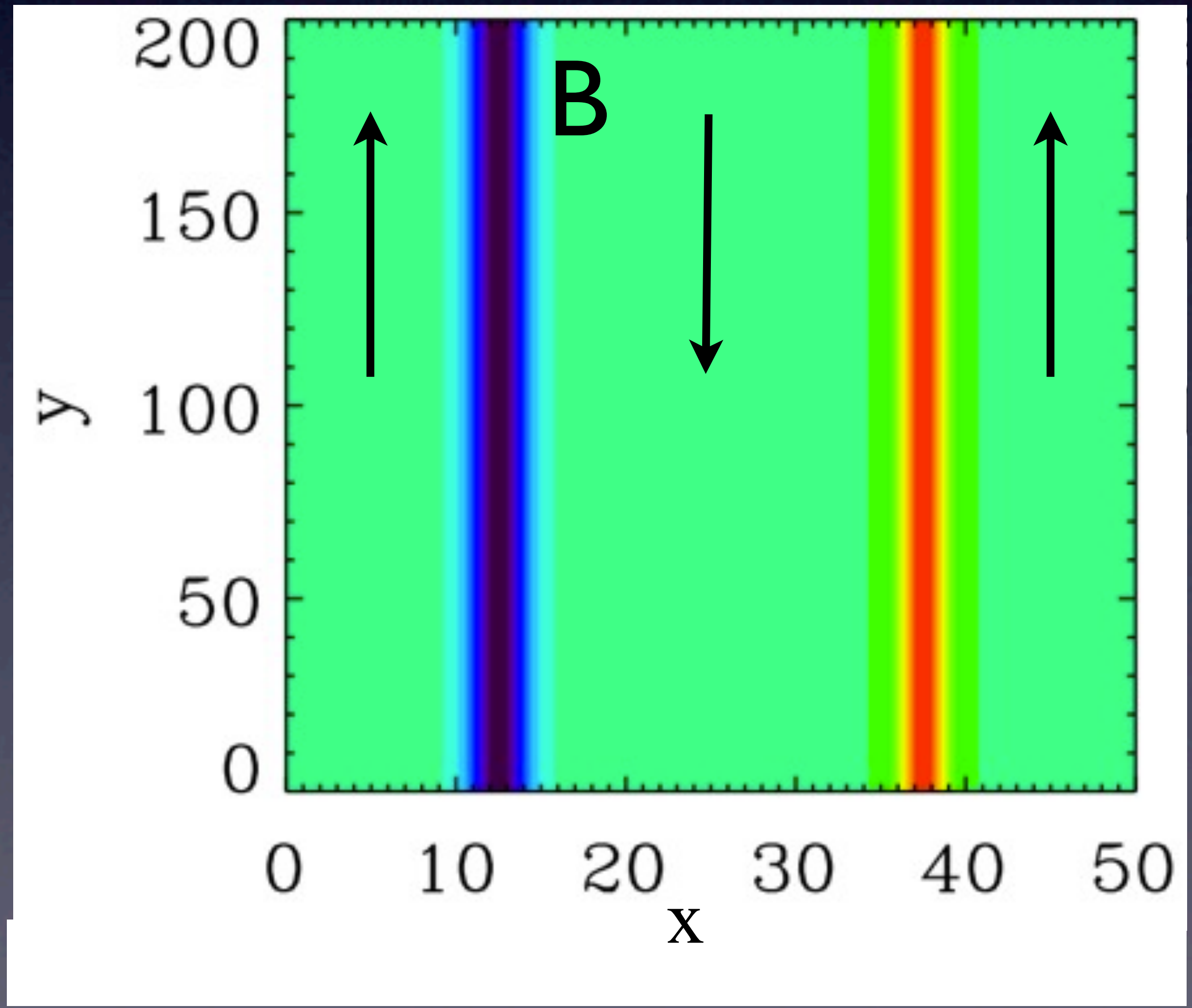
Hellinger et Travnicek JGR 2008, Matteini et al. SSR 2011

Fire hose in non homogeneous plasma

How instabilities evolve in the presence of structures?
how they affect current sheet stability?



Reconnection generates anisotropy
(Drake's talk)
Does anisotropy influence reconnection?



out-of-the-plane current J_z

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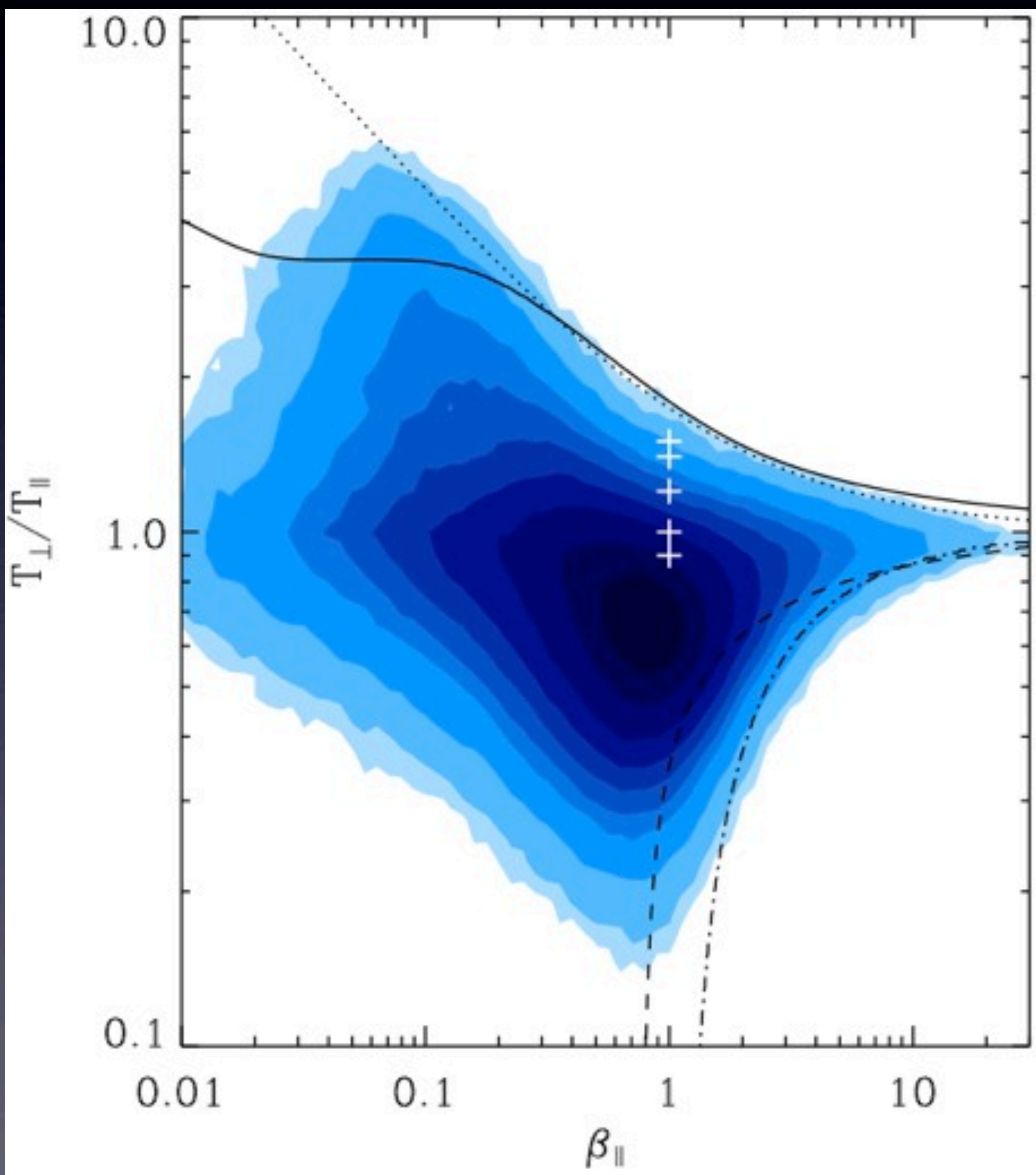
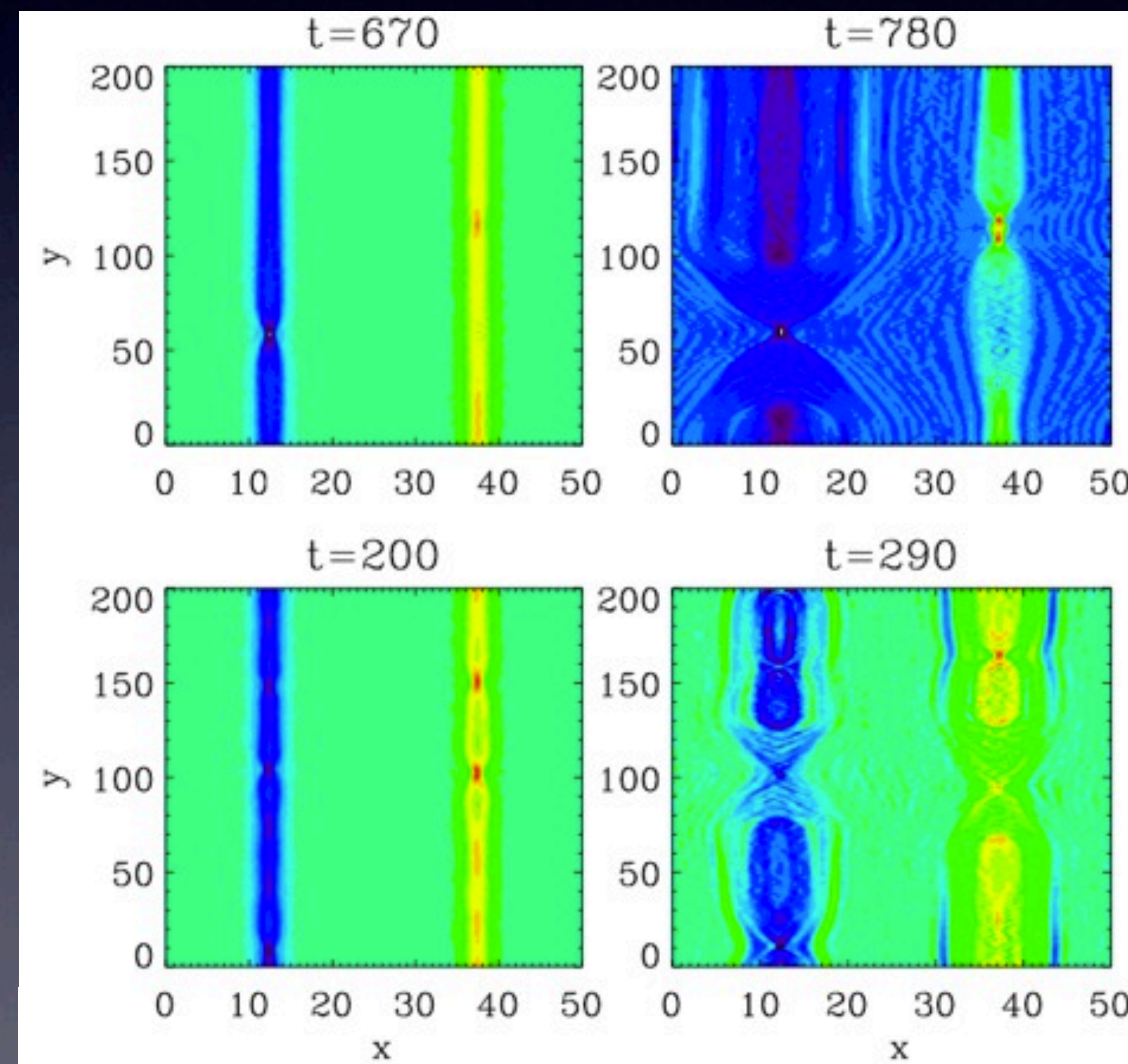


Linear phase

Nonlinear phase

Isotropic plasma

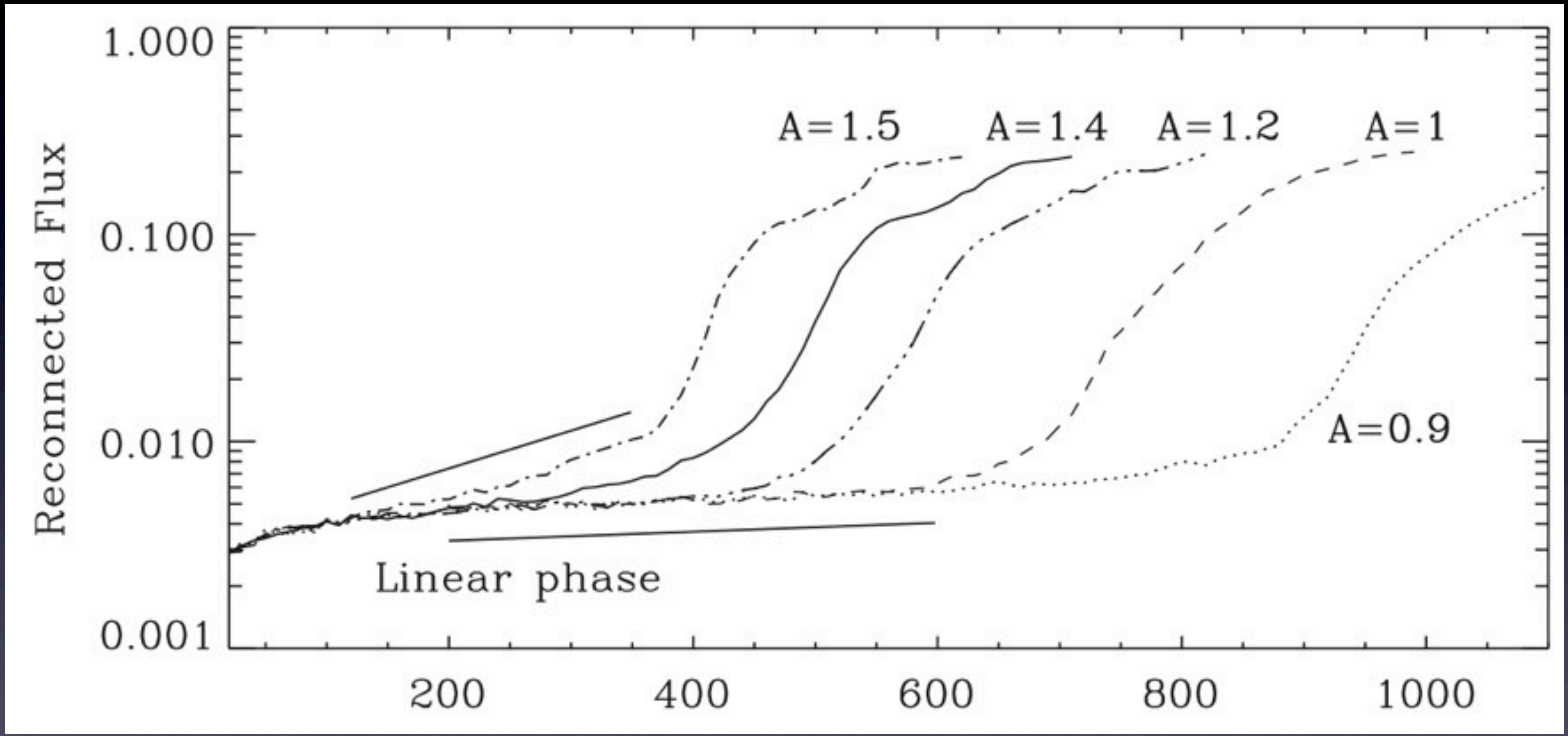
$T_\perp = 2T_\parallel$



out-of-the-plane current J_z

Tearing instability with anisotropic protons

Different runs with $\beta_{\parallel}$=1 and variable proton anisotropy in the current sheet
(the background isotropic)



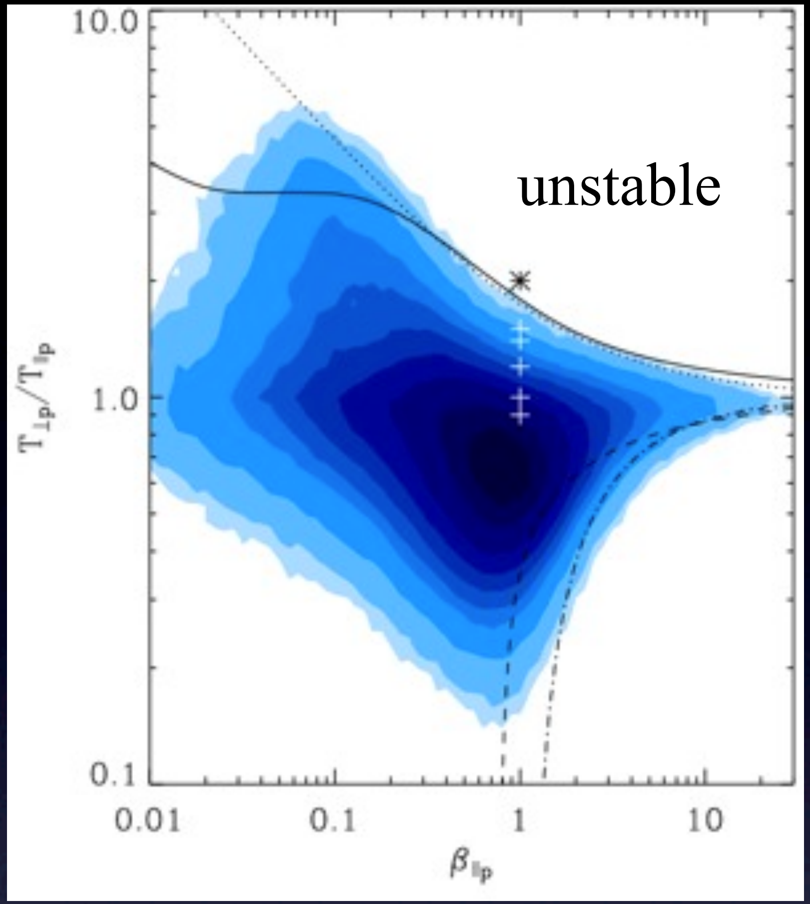
time (cyclotron periods)

The growth rate increases with $T_{\perp}>T_{\parallel}$ and decreases with $T_{\perp}<T_{\parallel}$

Laval and Pellat 1967, Coppi 1983, Chen and Palmadesso 1984,
Ambrosiano et al. 1986, Quest et al. 2010...

Increasing further the temperature anisotropy...

$T_\perp/T_\parallel = 2$



Instability develops in the regions of locally homogeneous magnetic field

Unstable modes propagate along the local magnetic field and modulate the current sheets

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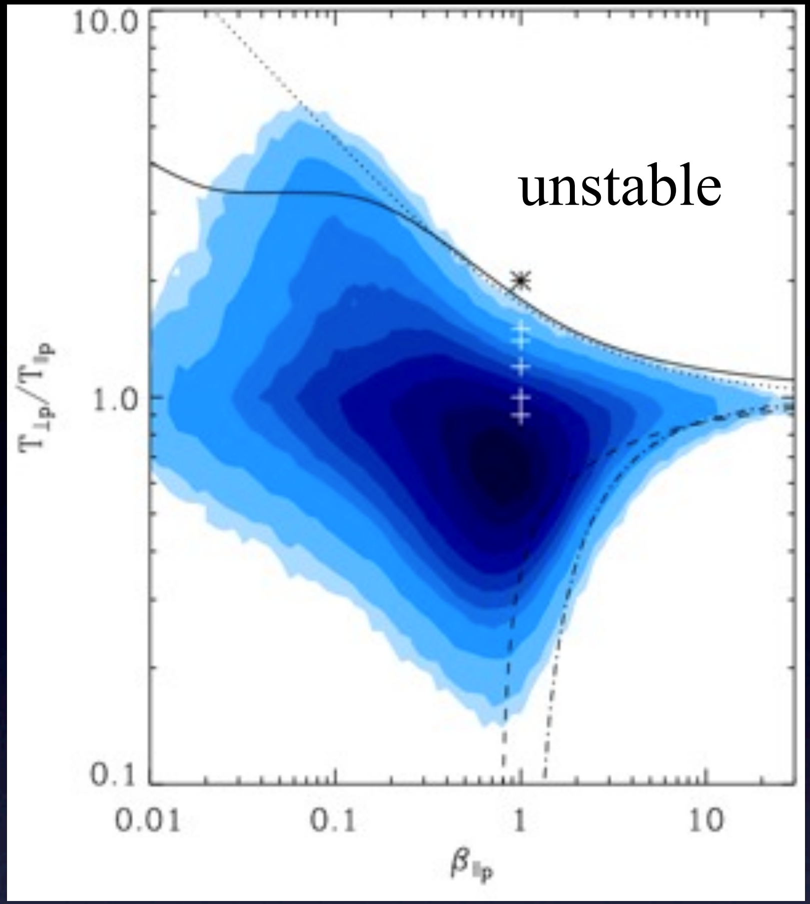

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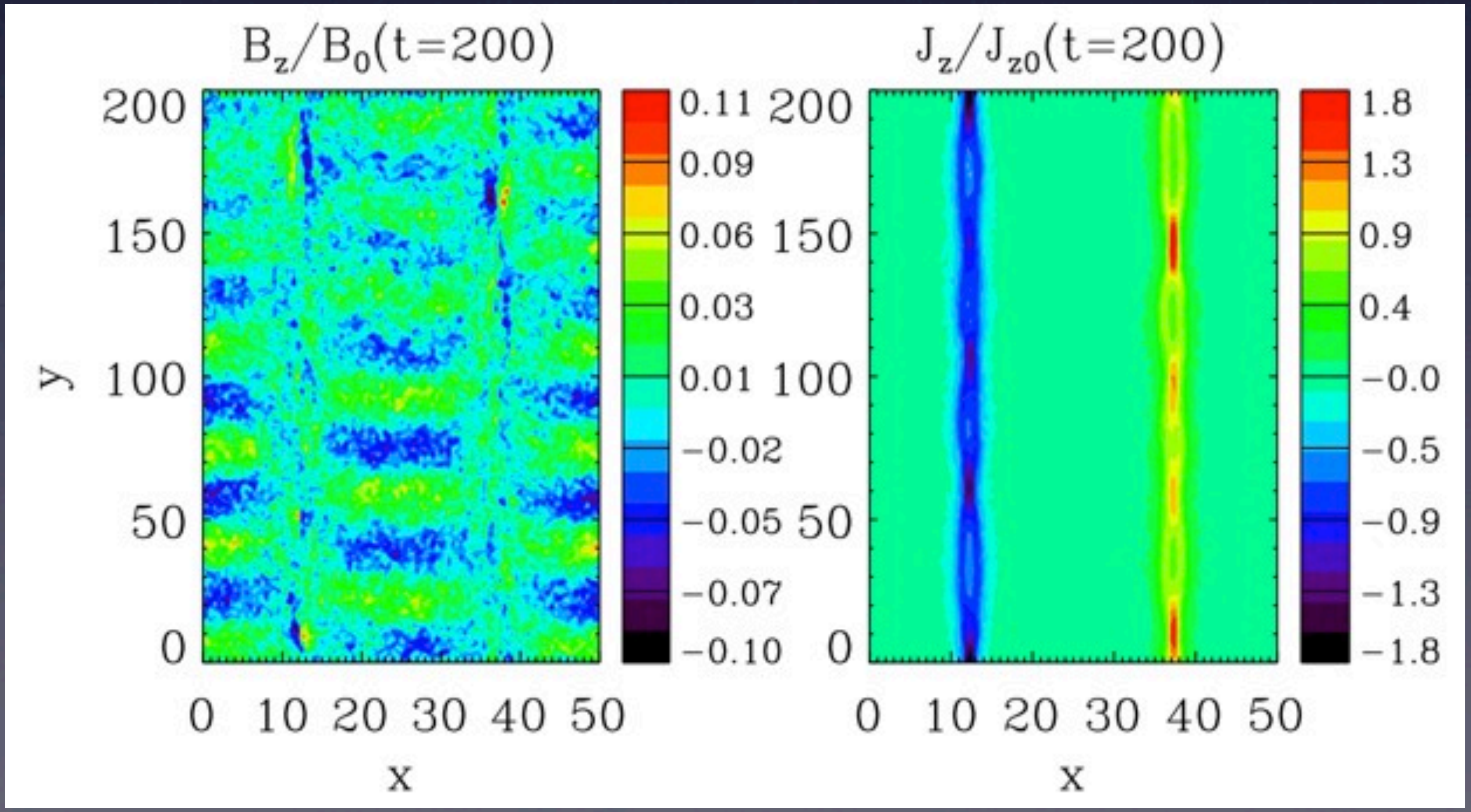
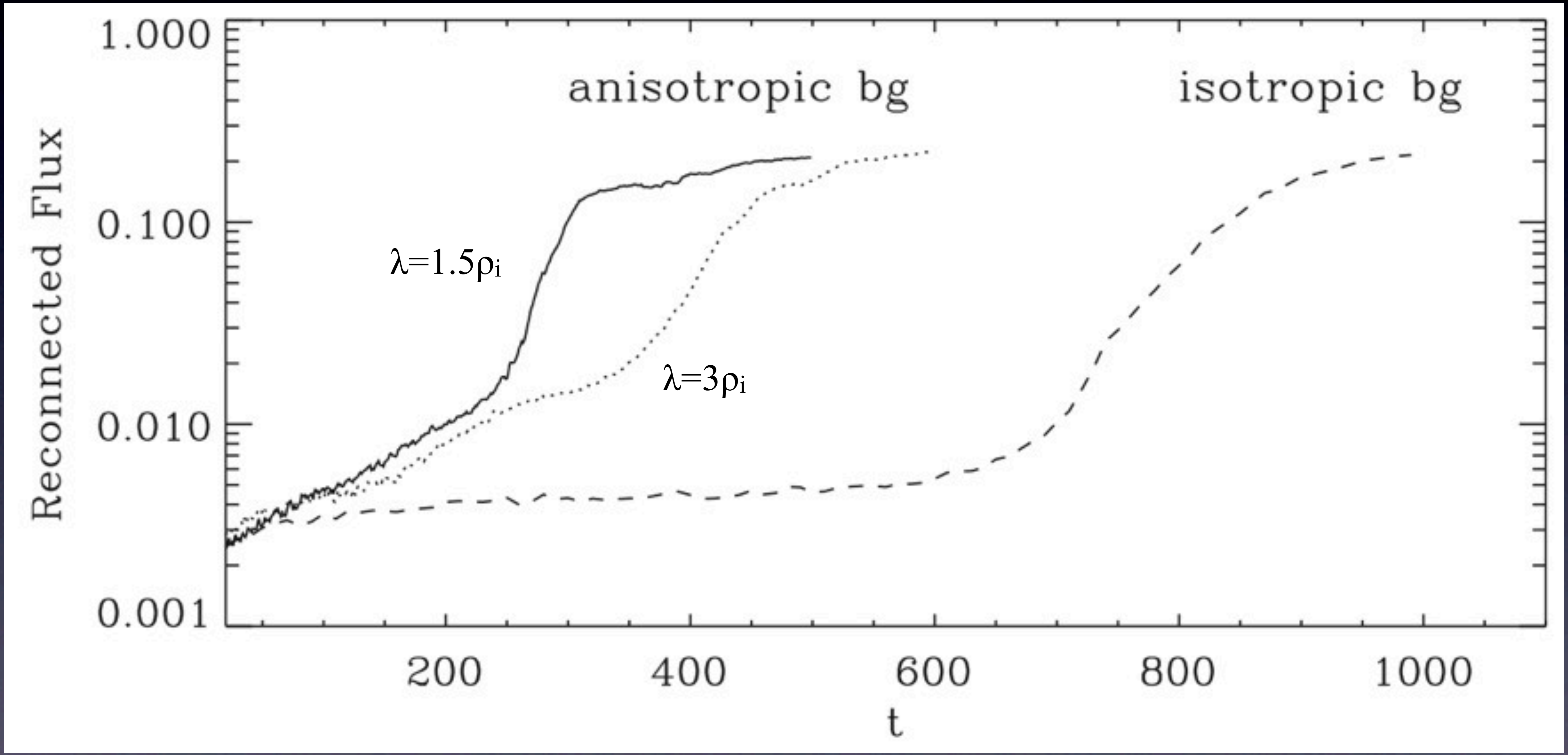
Background protons unstable for ion-cyclotron instability

External fluctuations drive the tearing instability of the current



Dependence on the thickness of the sheet

Ion-cyclotron fluctuations trigger the tearing and drive a faster onset of reconnection

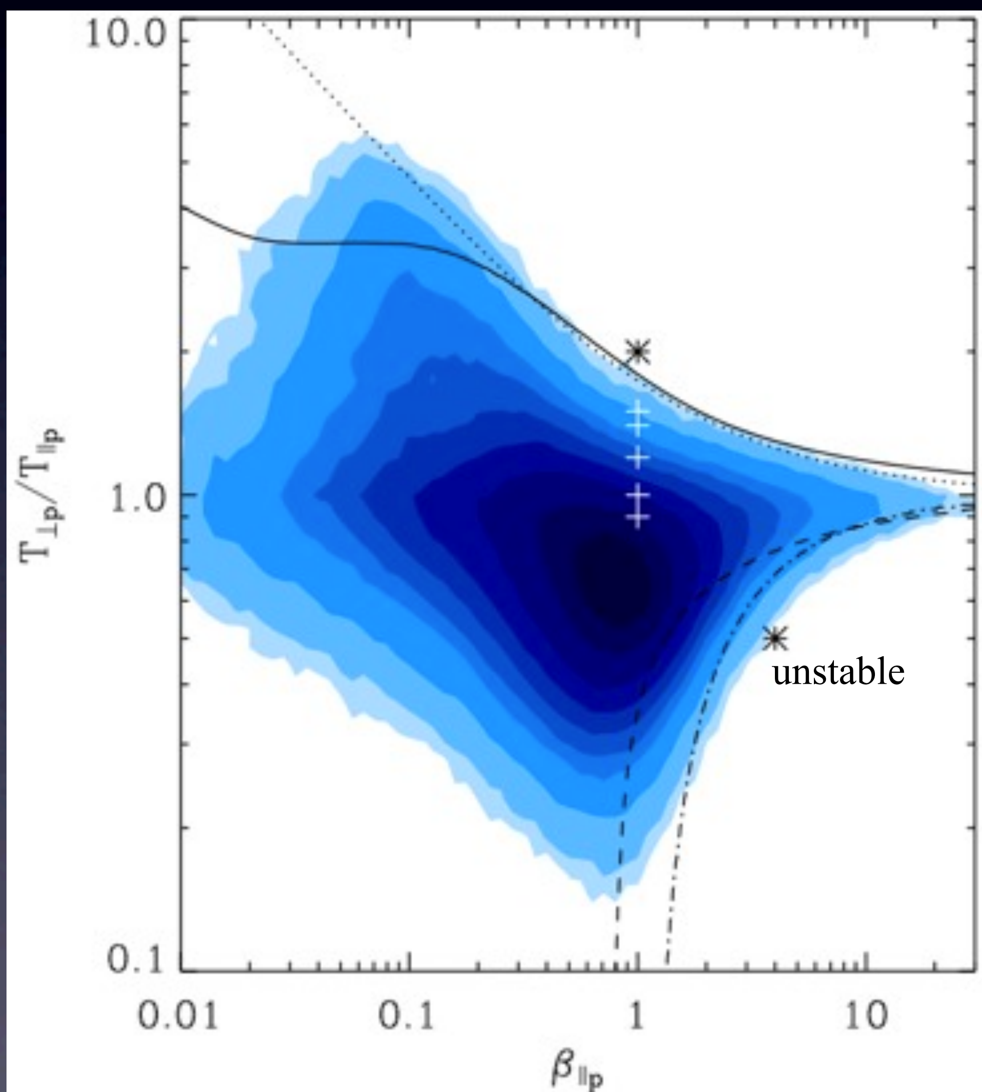


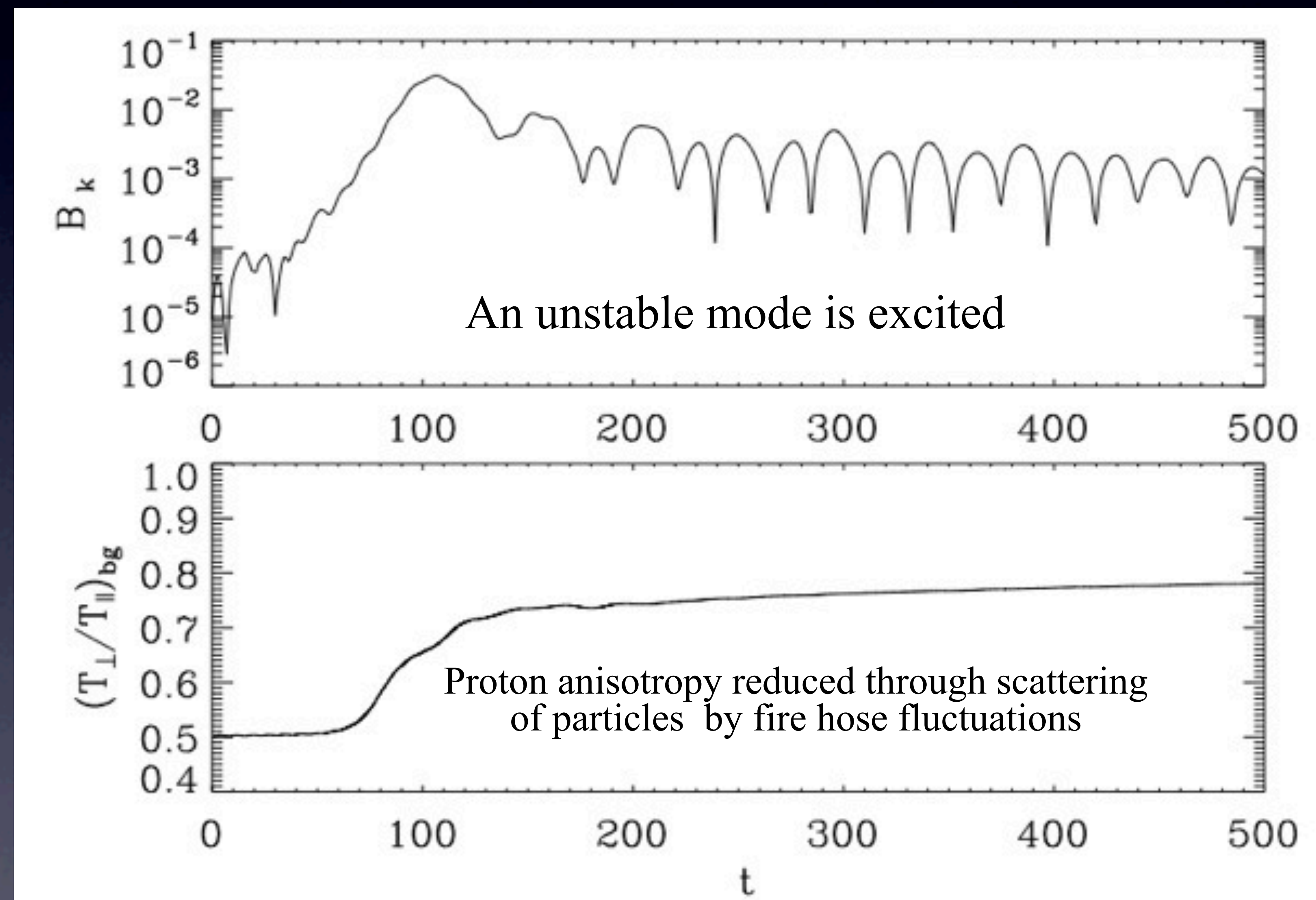
Unstable tearing mode is driven by the background plasma conditions (anisotropy and beta) and results then independent from thickness of the current sheet.

Is the presence of fluctuations enough?

Effects of the fire hose instability in the background plasma

Case $T_{||} > T_{\perp}$: fire hose unstable





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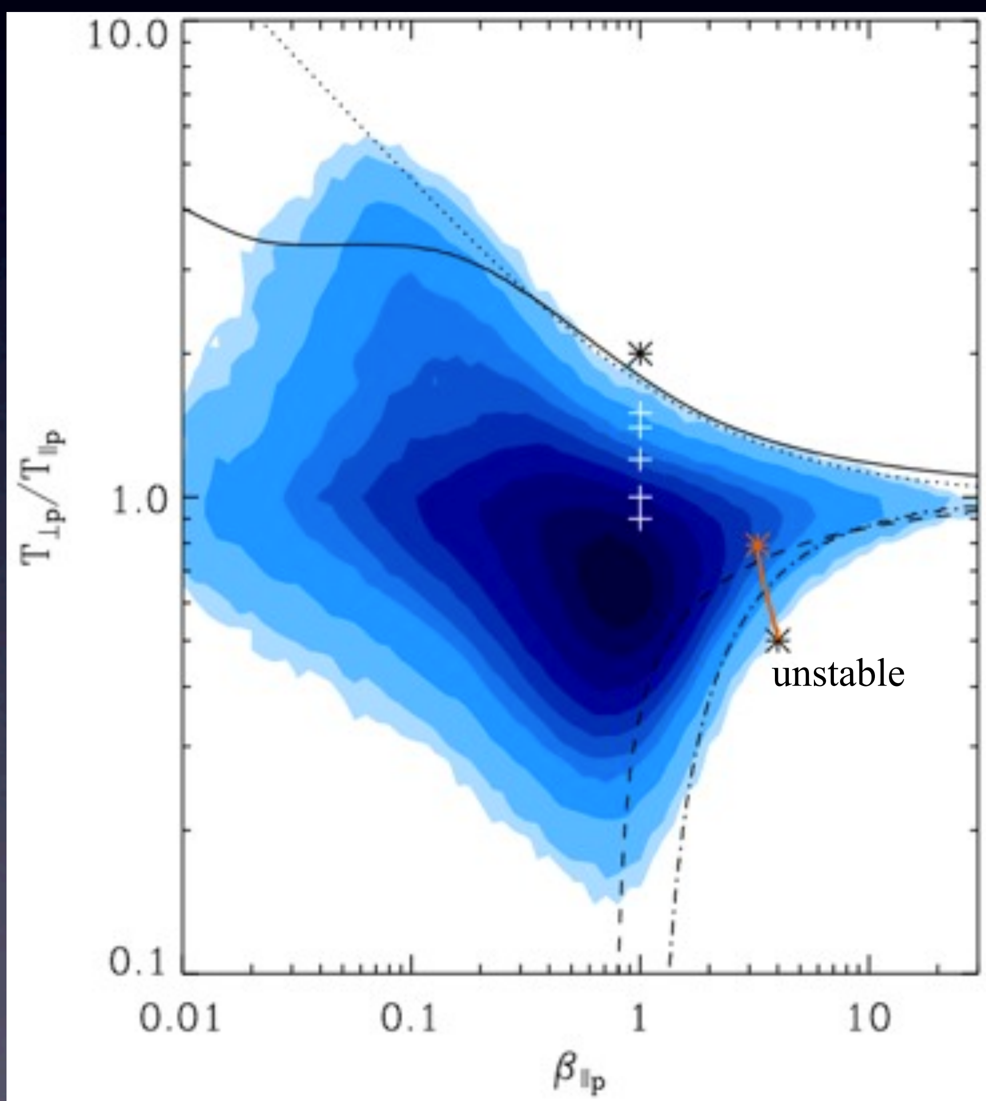
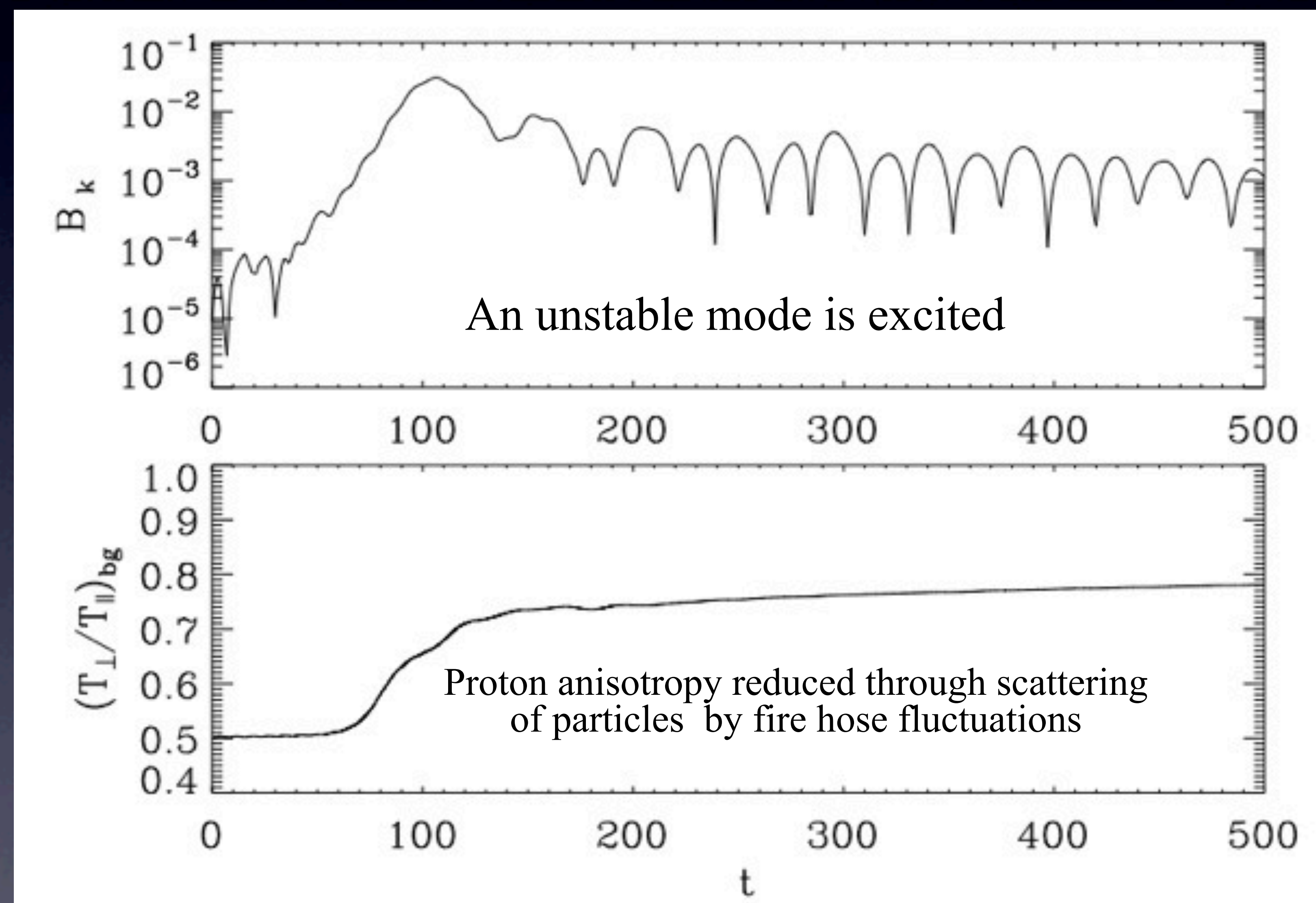


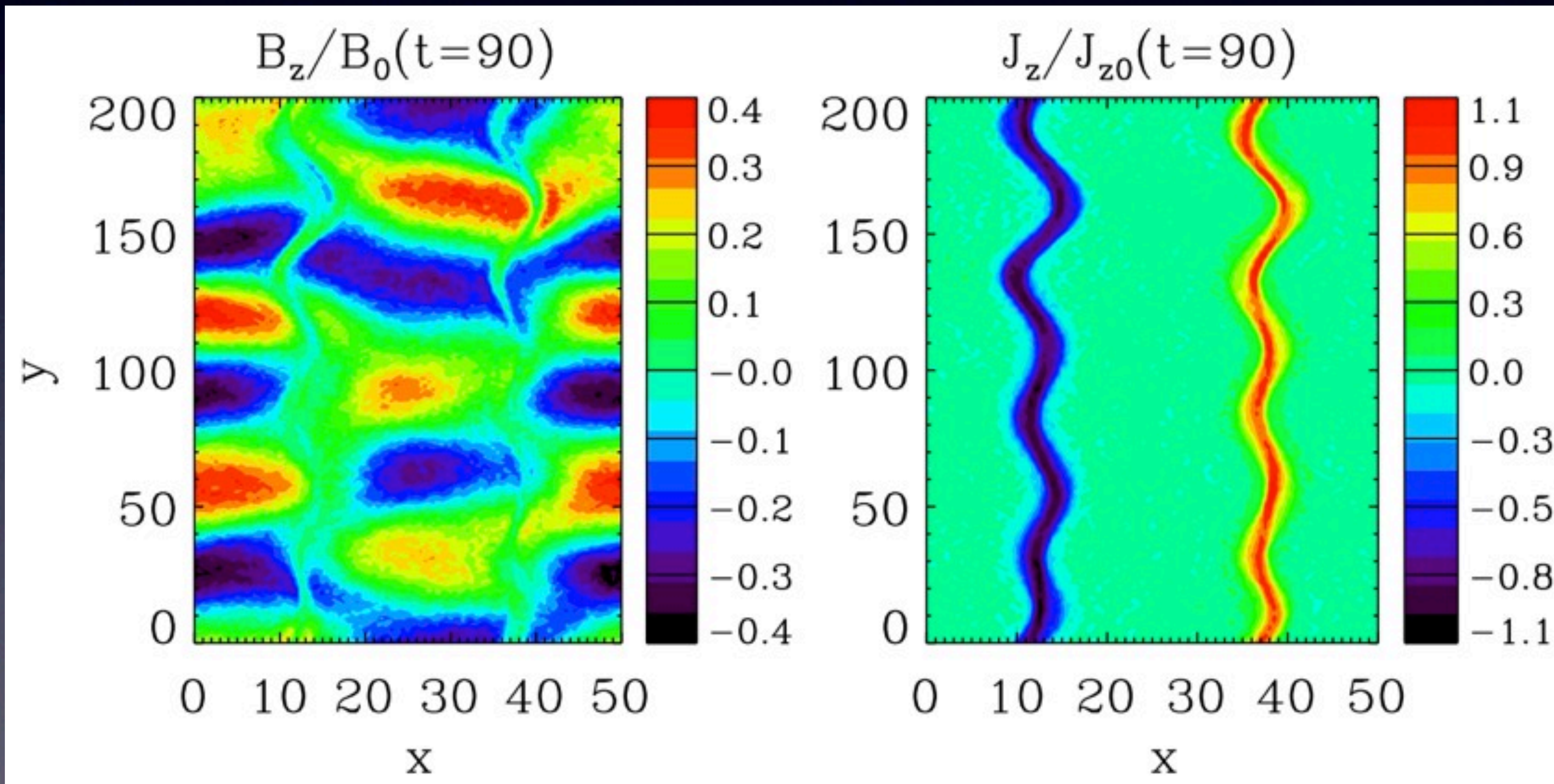


Is the presence of fluctuations enough?

Case $T_{\parallel} > T_{\perp}$: fire hose unstable

Generation of unstable fluctuations propagating along the main field, but kink deformation of the current sheet. Not tearing!

B_Z



J_Z

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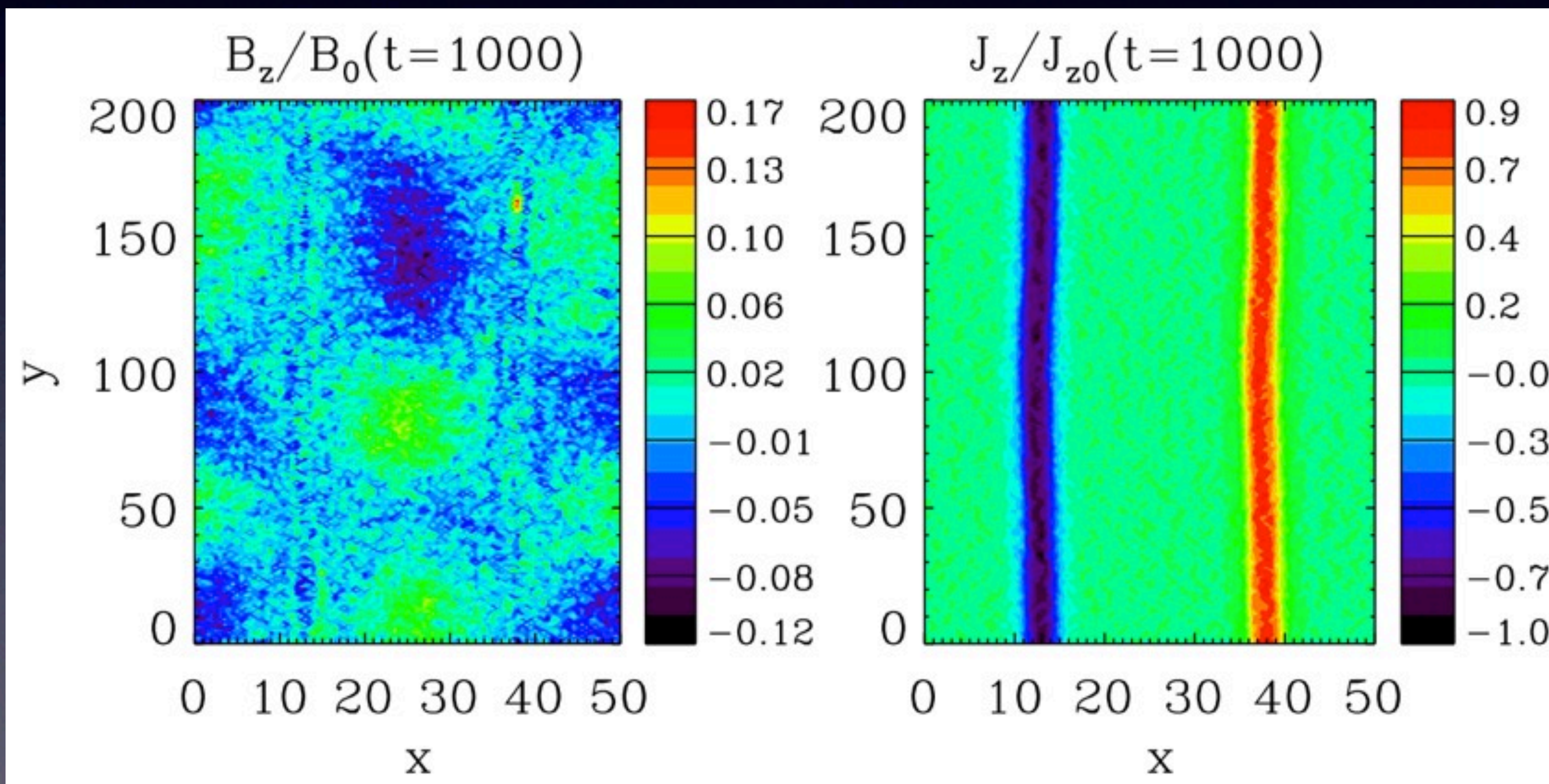

J_z

Matteini et al., ApJ 2013

Conclusions

- Signatures of fire hose activity in the solar wind in both particle and magnetic field data.
- Observations are in good agreement with predictions from theory and simulations. Expanding box simulations reproduce the observed path in the beta-anisotropy plane.
- Saturation of the instability occurs through resonant scattering and adiabatic invariants are not conserved (specially at low beta)
- Anisotropy play a role in the stability of current sheets and kinetic instabilities can further influence the evolution. This can be relevant for discontinuities in the solar wind.