Wave-particle and wave-wave interactions in the Solar Wind: simulations and observations

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In collaboration with Petr Hellinger, Simone Landi, and Marco Velli

“*Ion kinetics in the solar wind: coupling global expansion to local microphysics*”
in press at Space Sci. Rev.

Outline

- Adiabatic expansion of a plasma
- Role of Coulomb collisions
- Wave-particle interactions:
  instabilities and plasma heating
- Wave-wave interactions:
  Non-linear evolution of Alfvén waves
- Evolution at oblique propagation

Why wave-particle interactions?

- In collisionless plasmas, collisions between particles are not able to maintain the equilibrium (Maxwellian distributions). Wave-particle interactions control the plasma thermodynamics.
- Particle distribution far for equilibrium can excite instabilities and generate fluctuations.
- Wave-wave interactions (3-w couplings, turbulence) can also produce fluctuations that involve particle dynamics.

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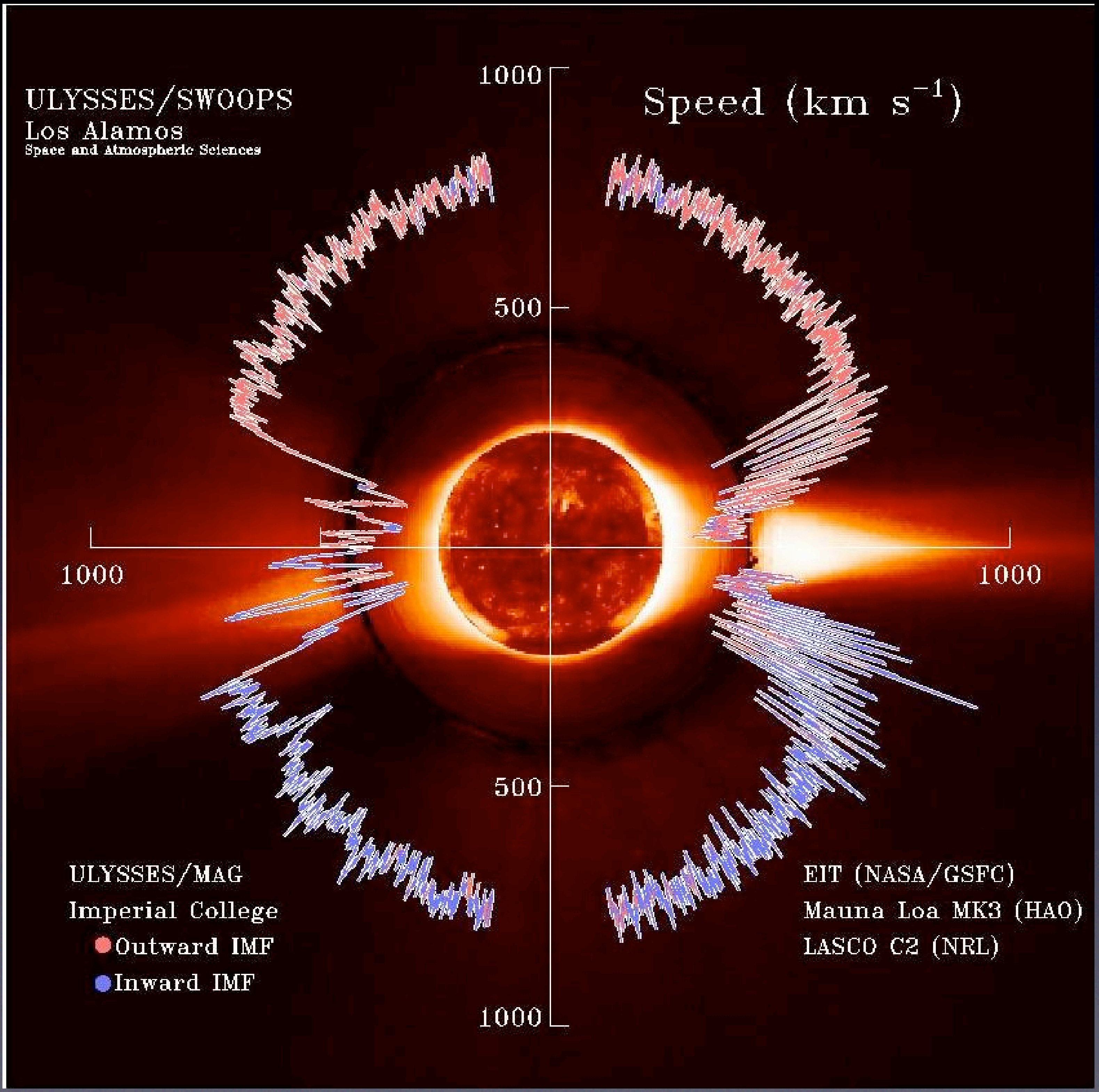
Interesting for many astrophysical plasmas

The solar wind



- High latitudes

Fast wind: 750 km/s and density of 3 particles/cm^3 at 1AU; regular.

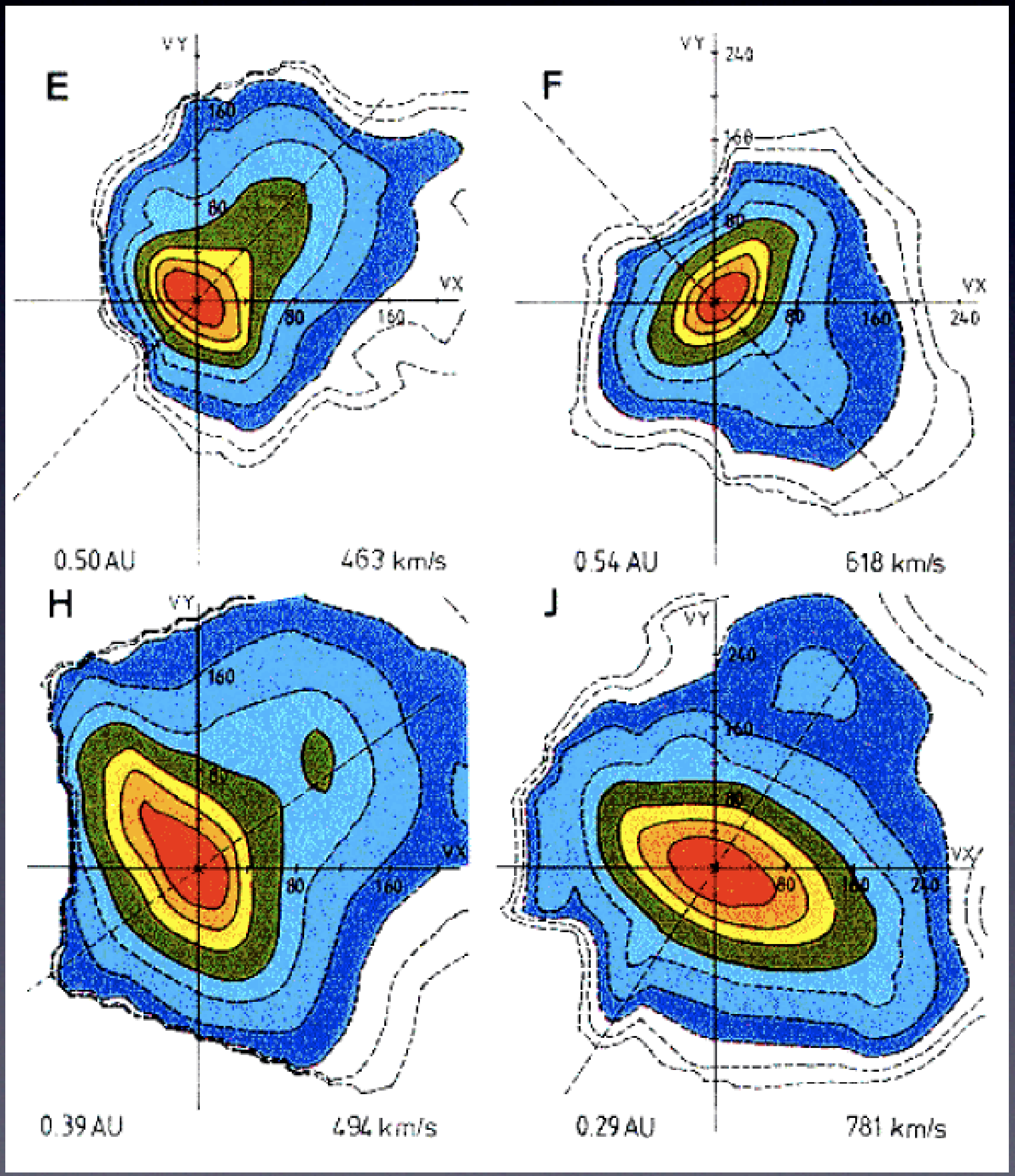
- Equatorial regions

Slow wind: bulk speed 350 km/s 10 particles/cm^3 at 1 AU; irregular.

Particle distribution functions are not Maxwellian, far from the LTE!

Solar wind proton distribution functions

Helios observations in the solar wind



(*Marsch et al. 1982*)

- Temperature anisotropy between parallel and perpendicular directions with respect to the ambient magnetic field

$$T_{\perp} \neq T_{\parallel}$$

- Velocity beam in the parallel direction

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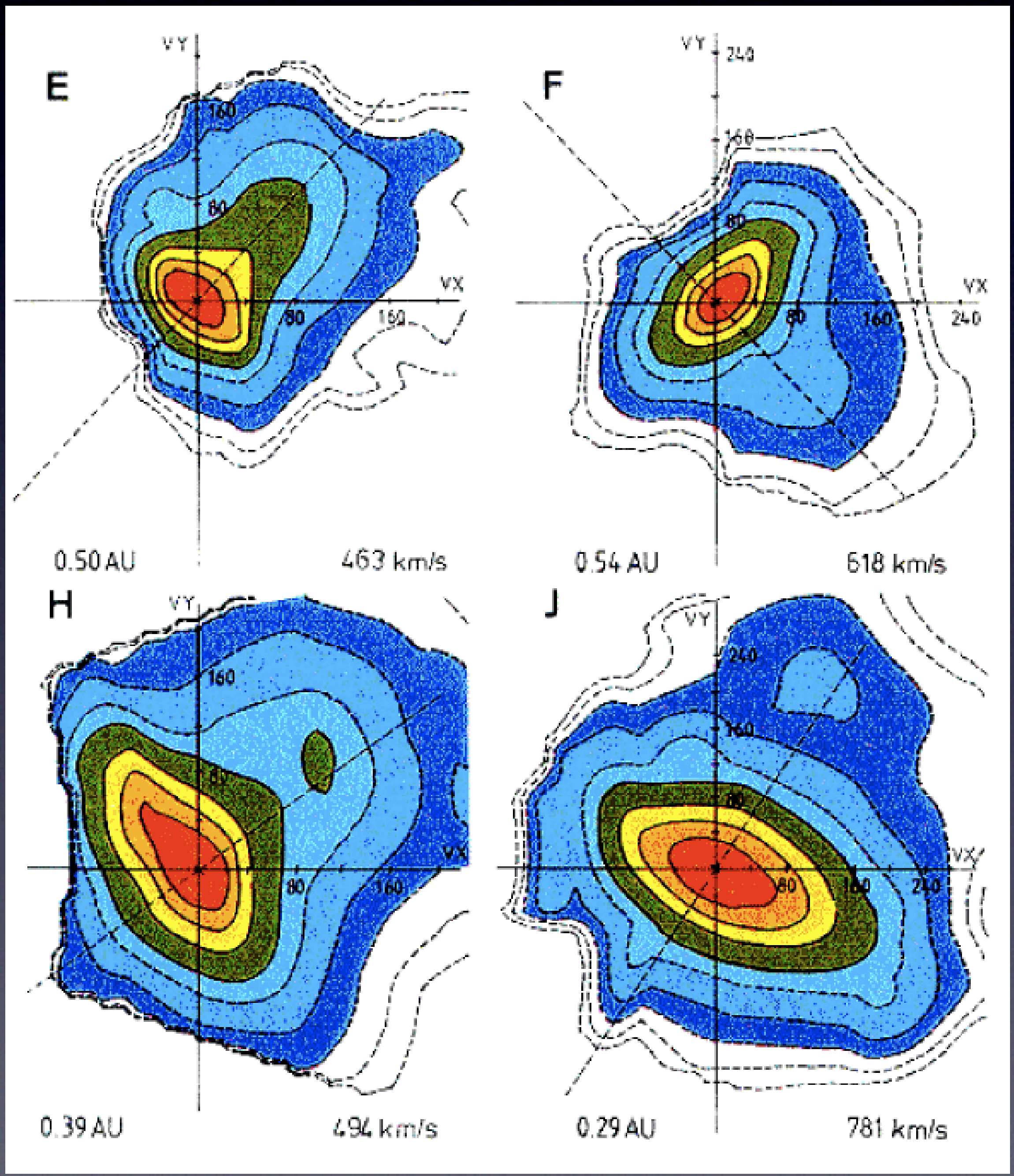

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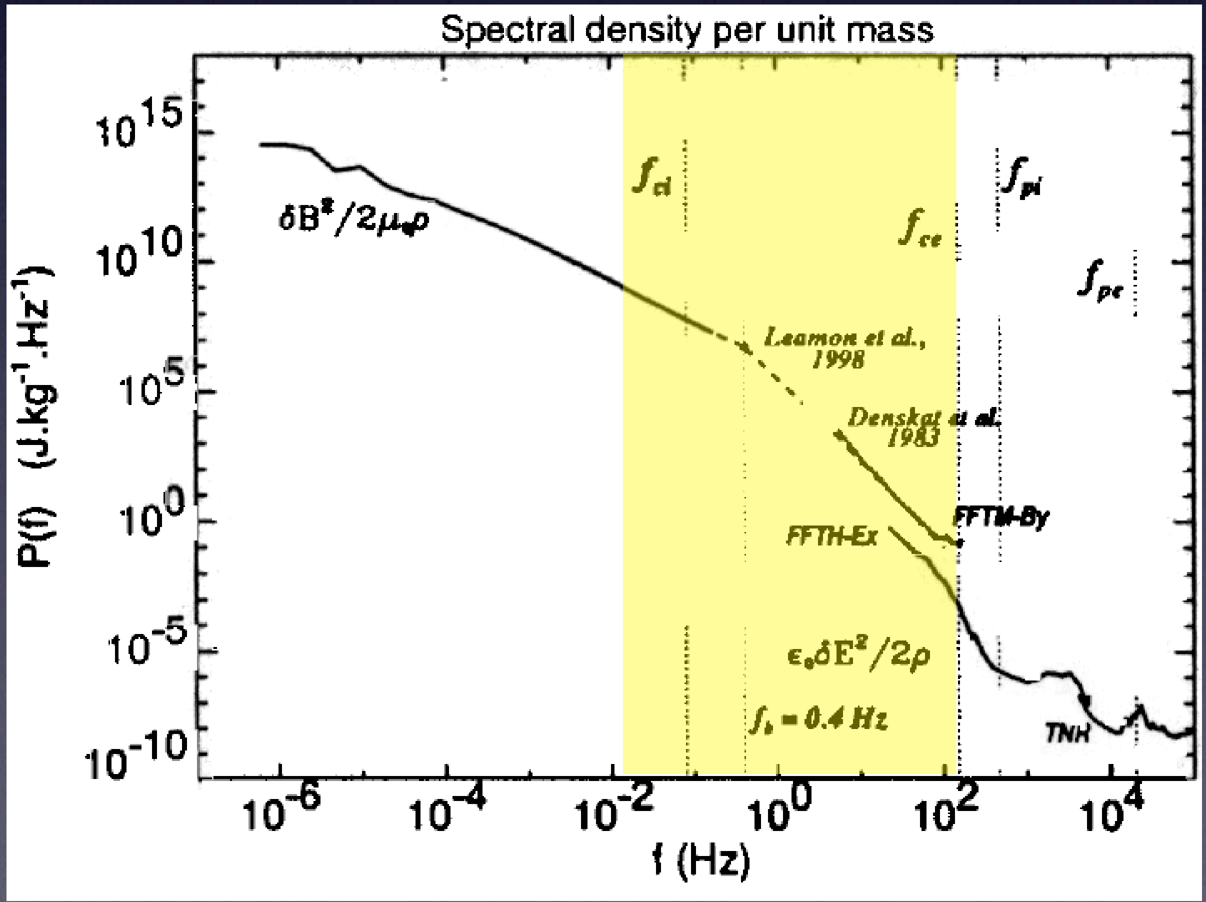

(*Marsch et al. 1982*)

(*Salem 2001*)

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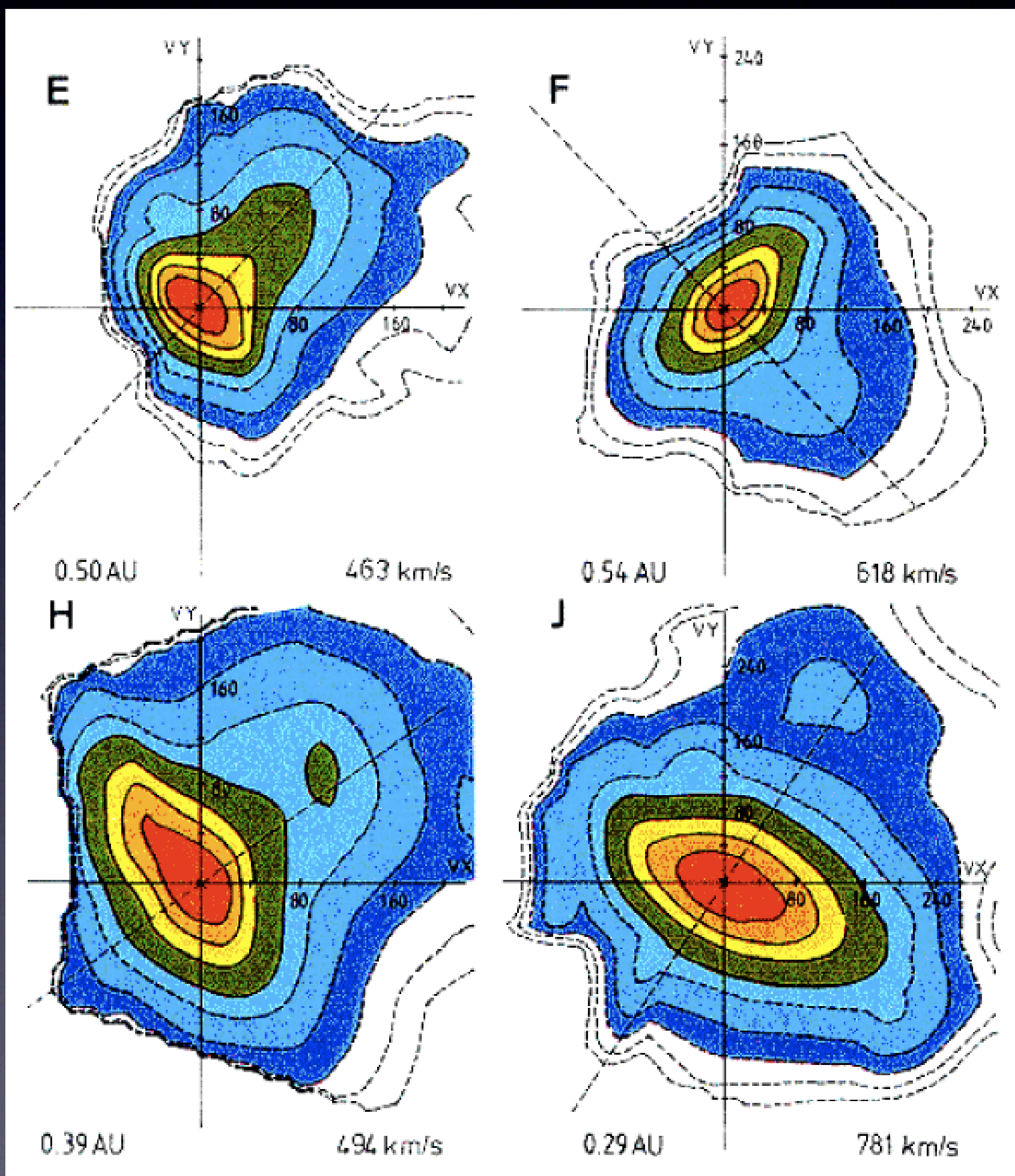

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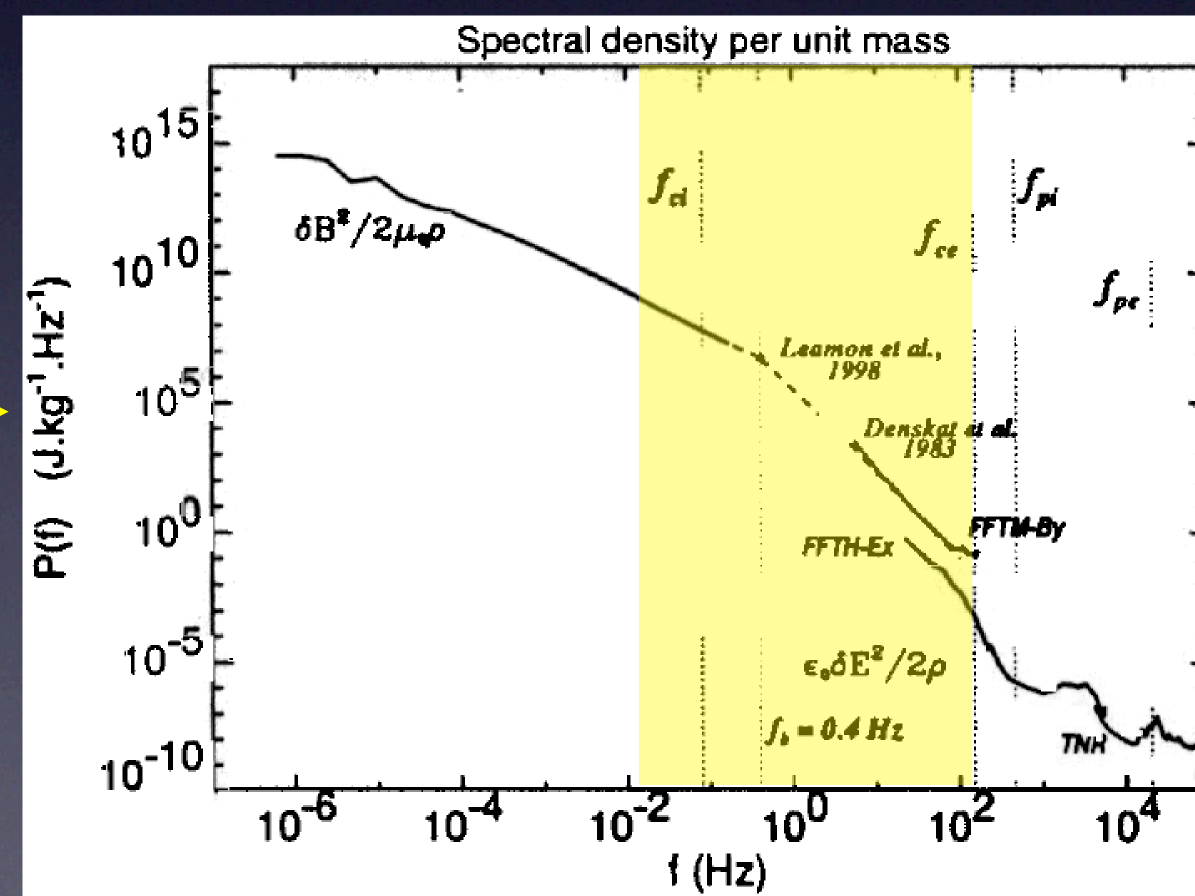
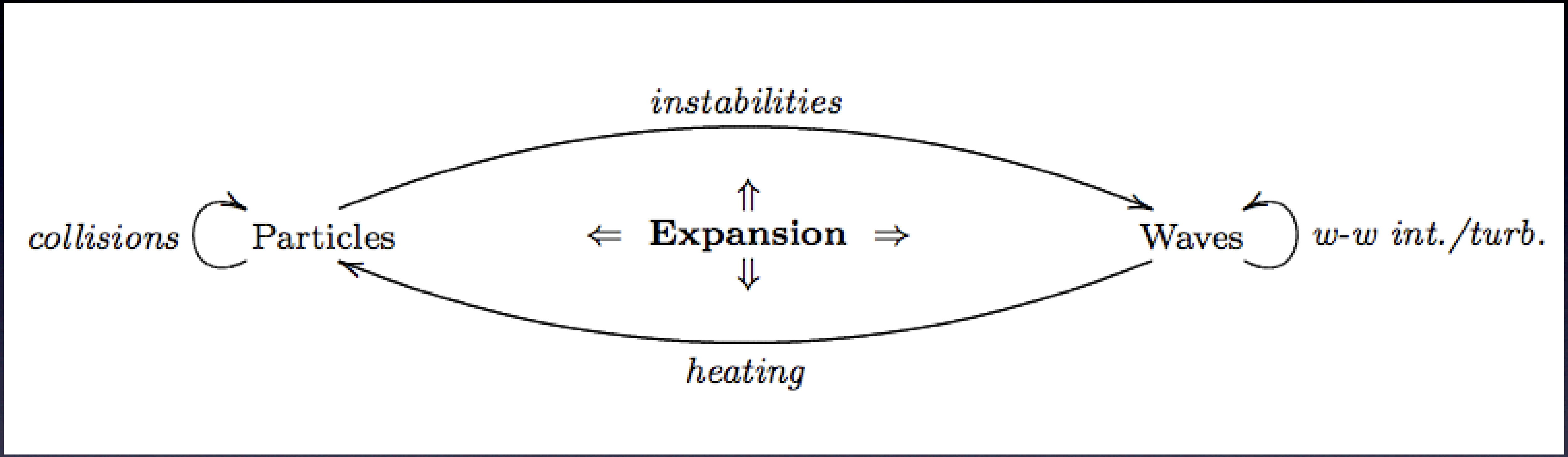


(*Salem 2001*)

Interactions in a plasma - Schematic view



(e.g., Alexandrova 2010, Araneda 2008&2009, Bourouaine 2010&2011, Califano 2008, Kunz 2011, Henri 2008, Passot&Sulem 2003&2006, Schekochihin 2009&2010, Valentini 2008&2009...)

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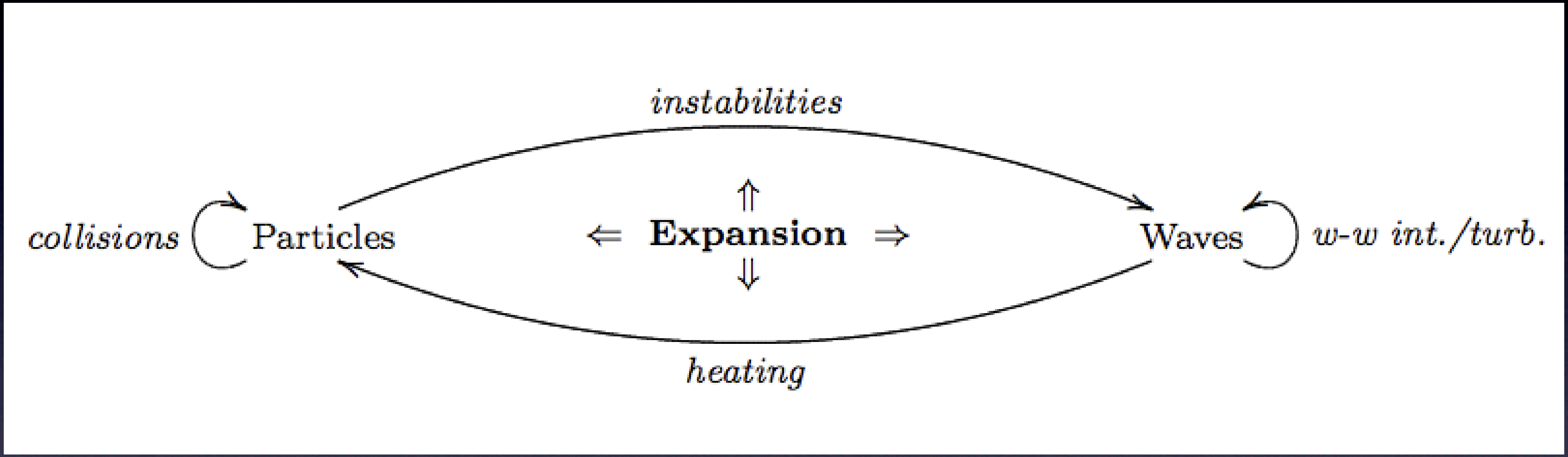

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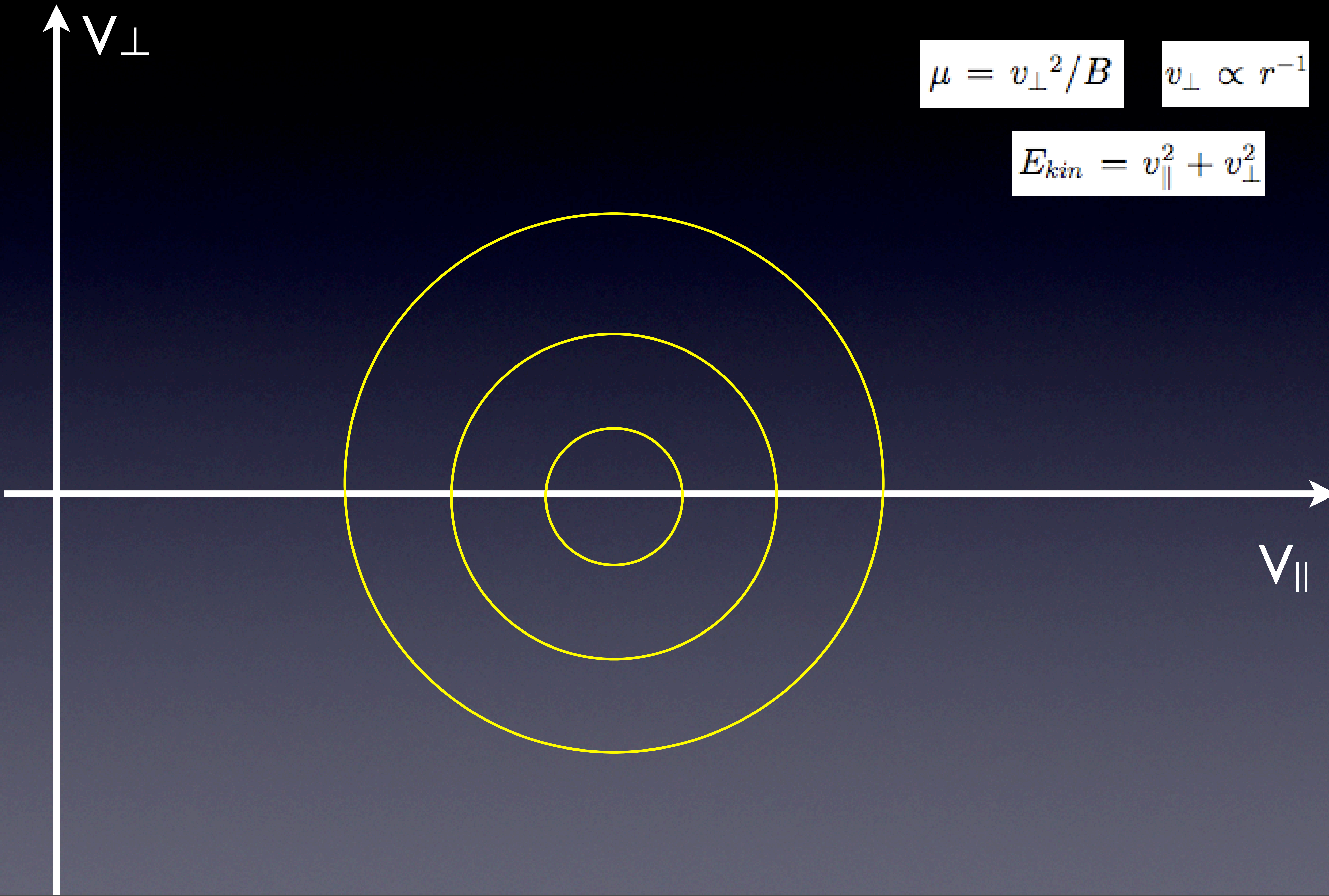
... but spherical expansion!

Adiabatic expansion

$\mu = v_\perp{}^2 / B$ $\quad v_\perp \propto r^{-1}$

$E_{kin} = v_\parallel^2 + v_\perp^2$



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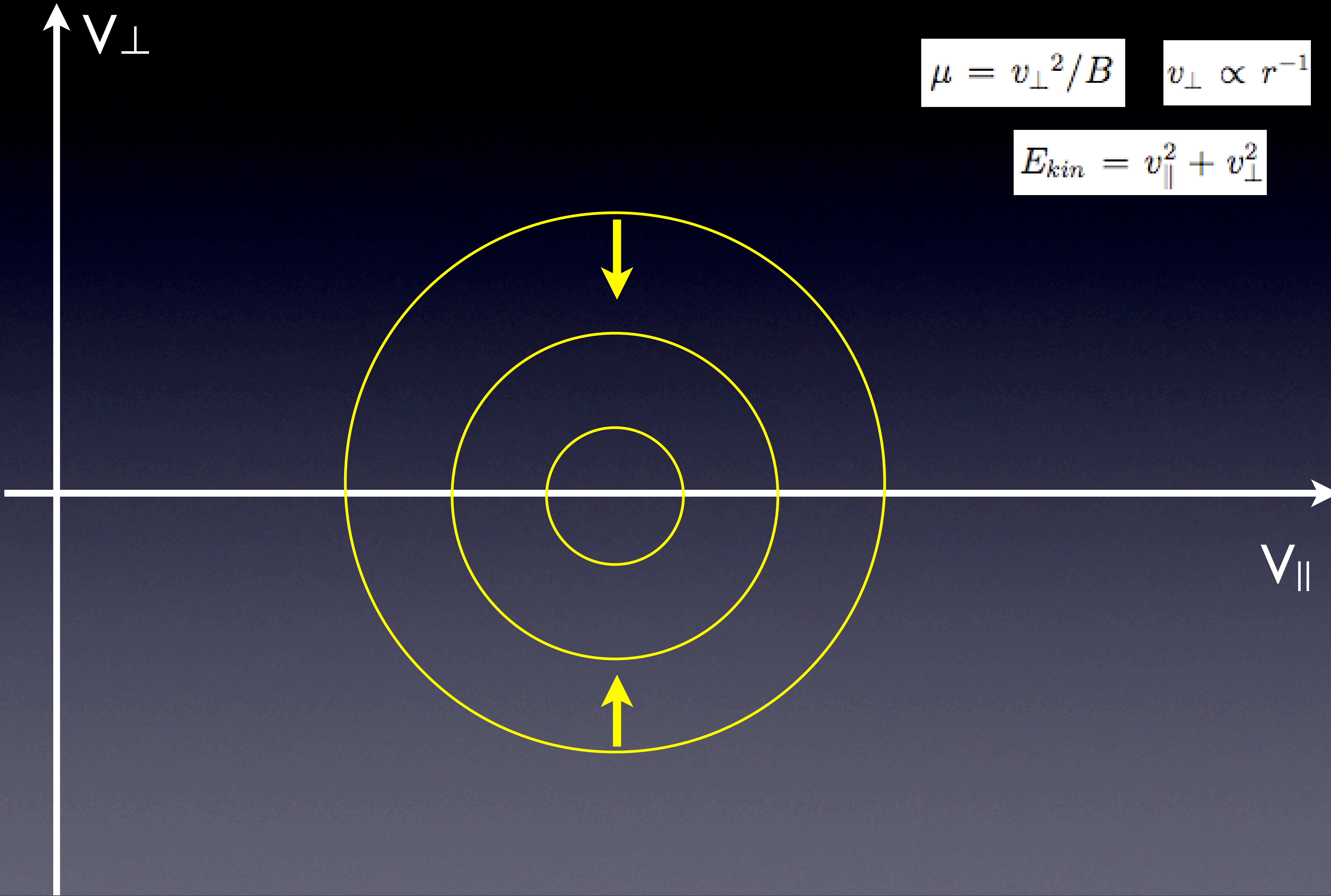

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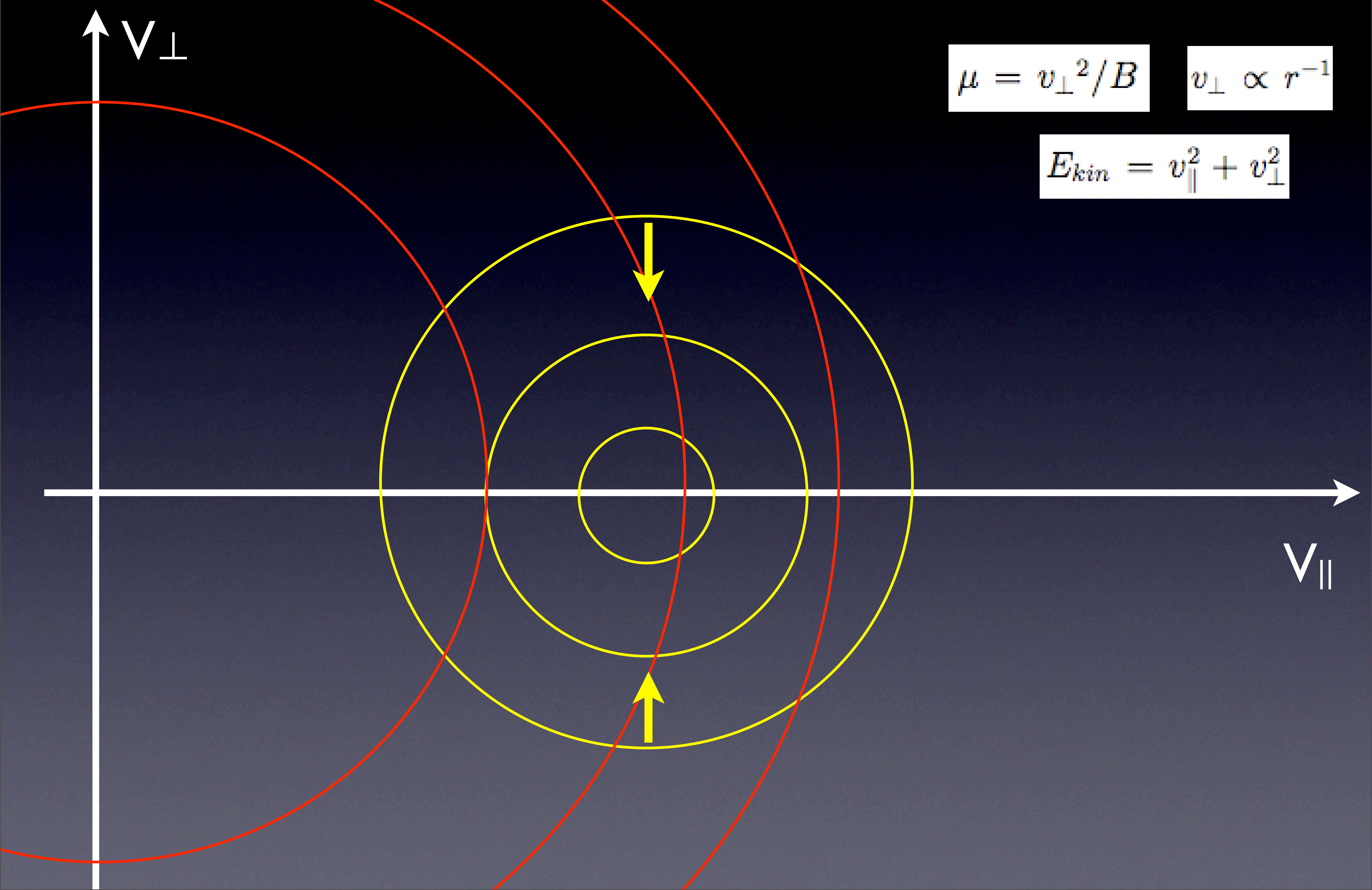

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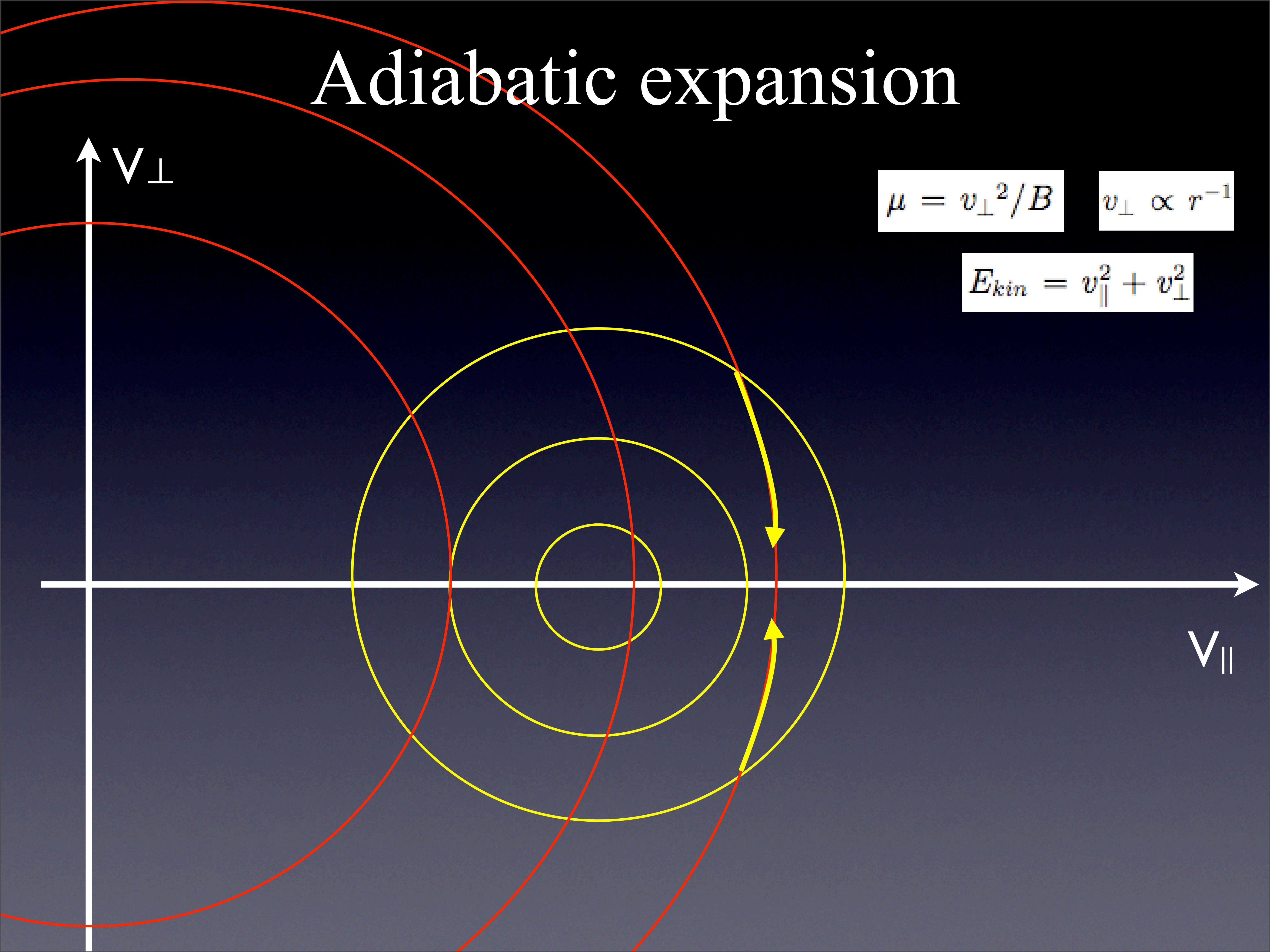

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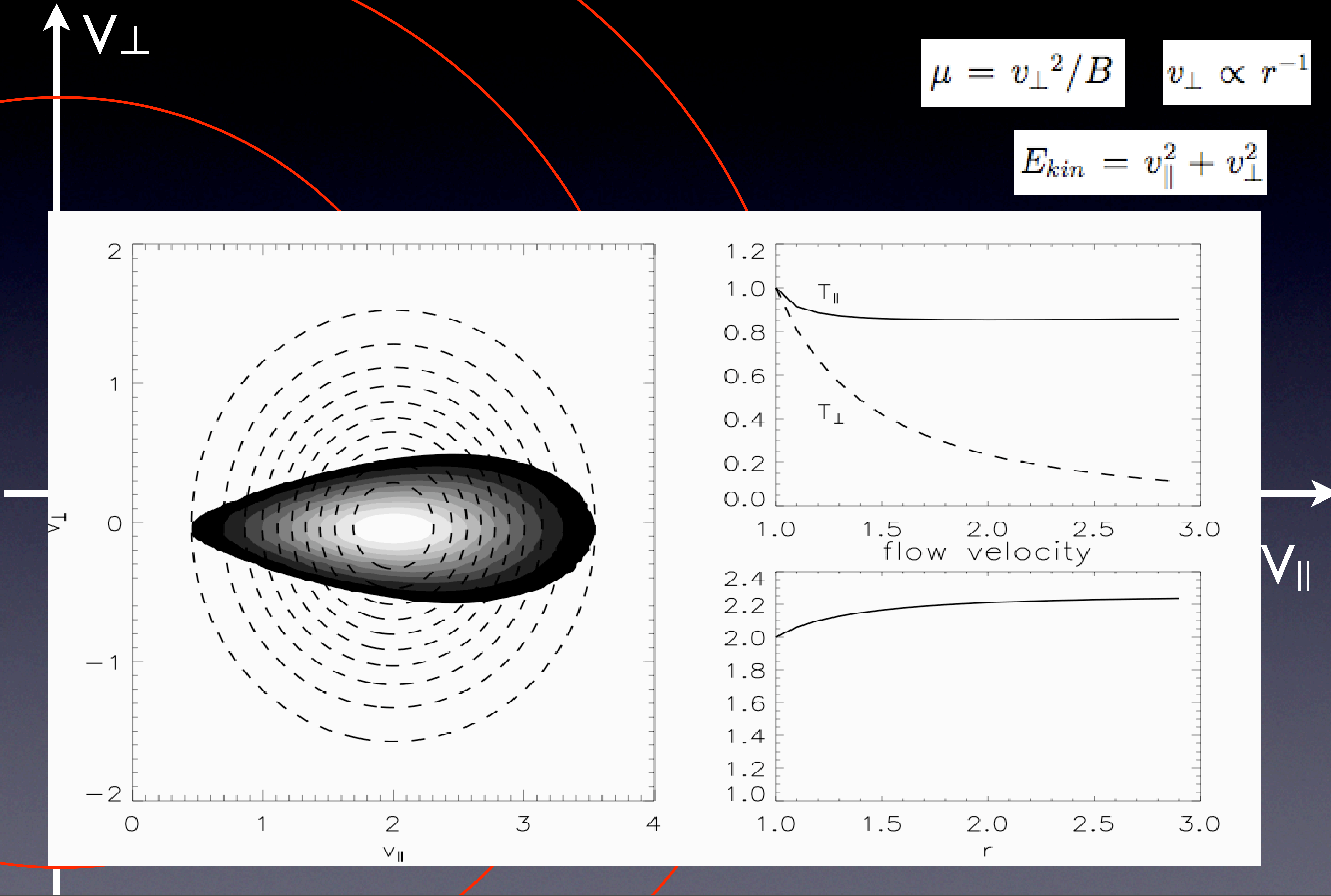
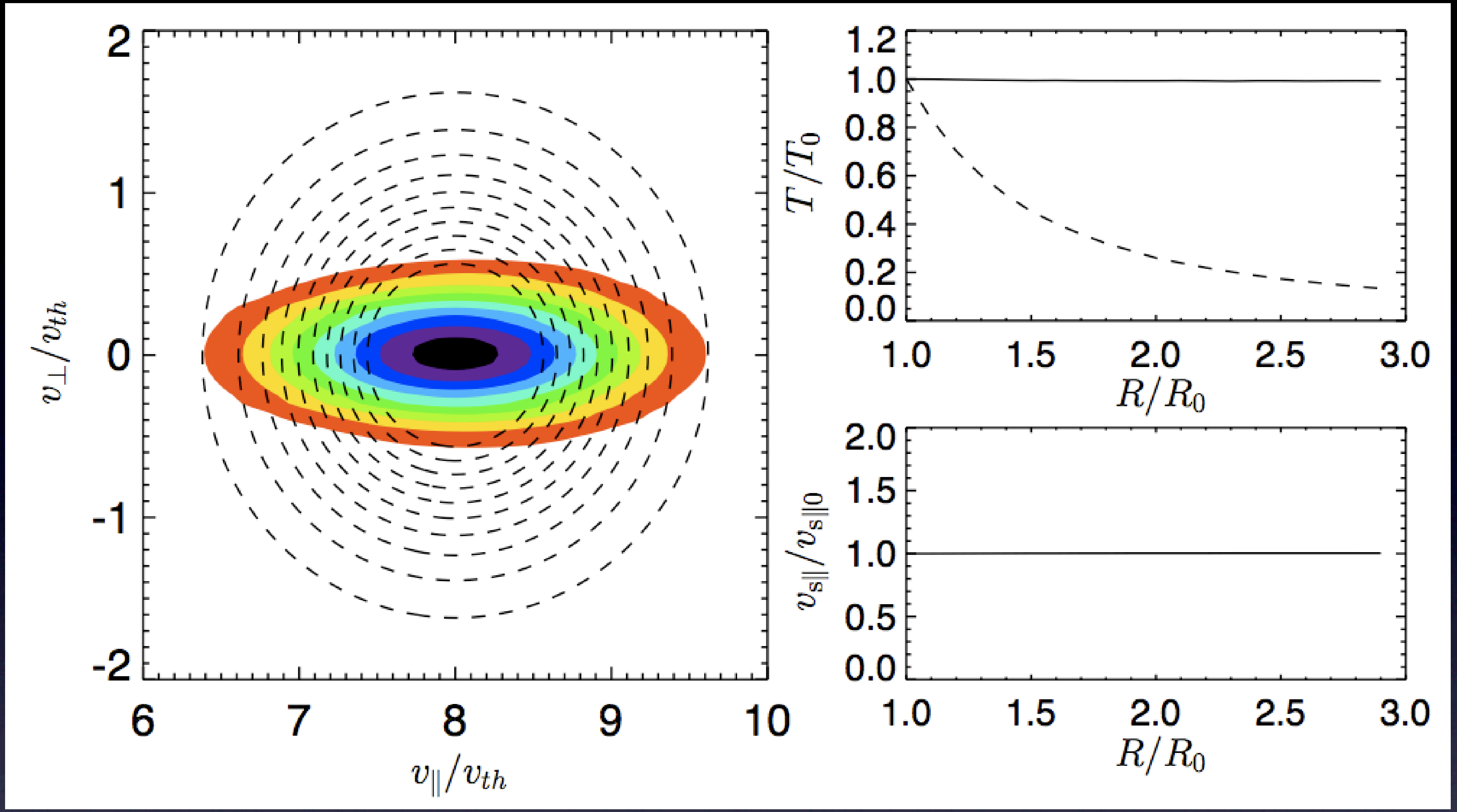


Evolution of solar wind proton distribution functions



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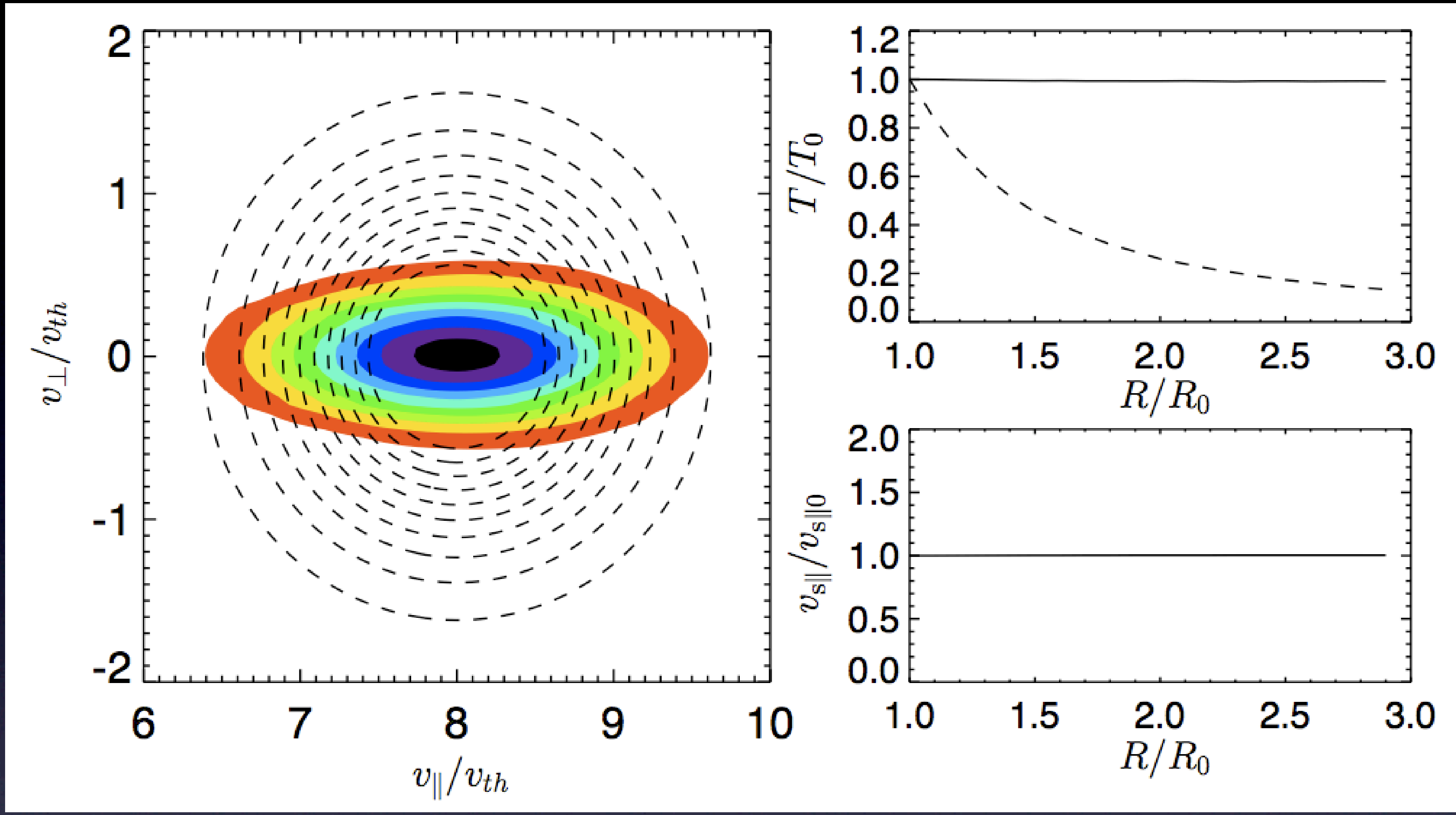

CGL or Double Adiabatic

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

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

$$\left(\frac{\mathrm{d}v_{s\parallel}}{\mathrm{d}t}\right)_{\mathrm{CGL}} = \frac{v_{s\parallel}}{n}\frac{\mathrm{d}n}{\mathrm{d}t} - \frac{v_{s\parallel}}{B}\frac{\mathrm{d}B}{\mathrm{d}t}$$

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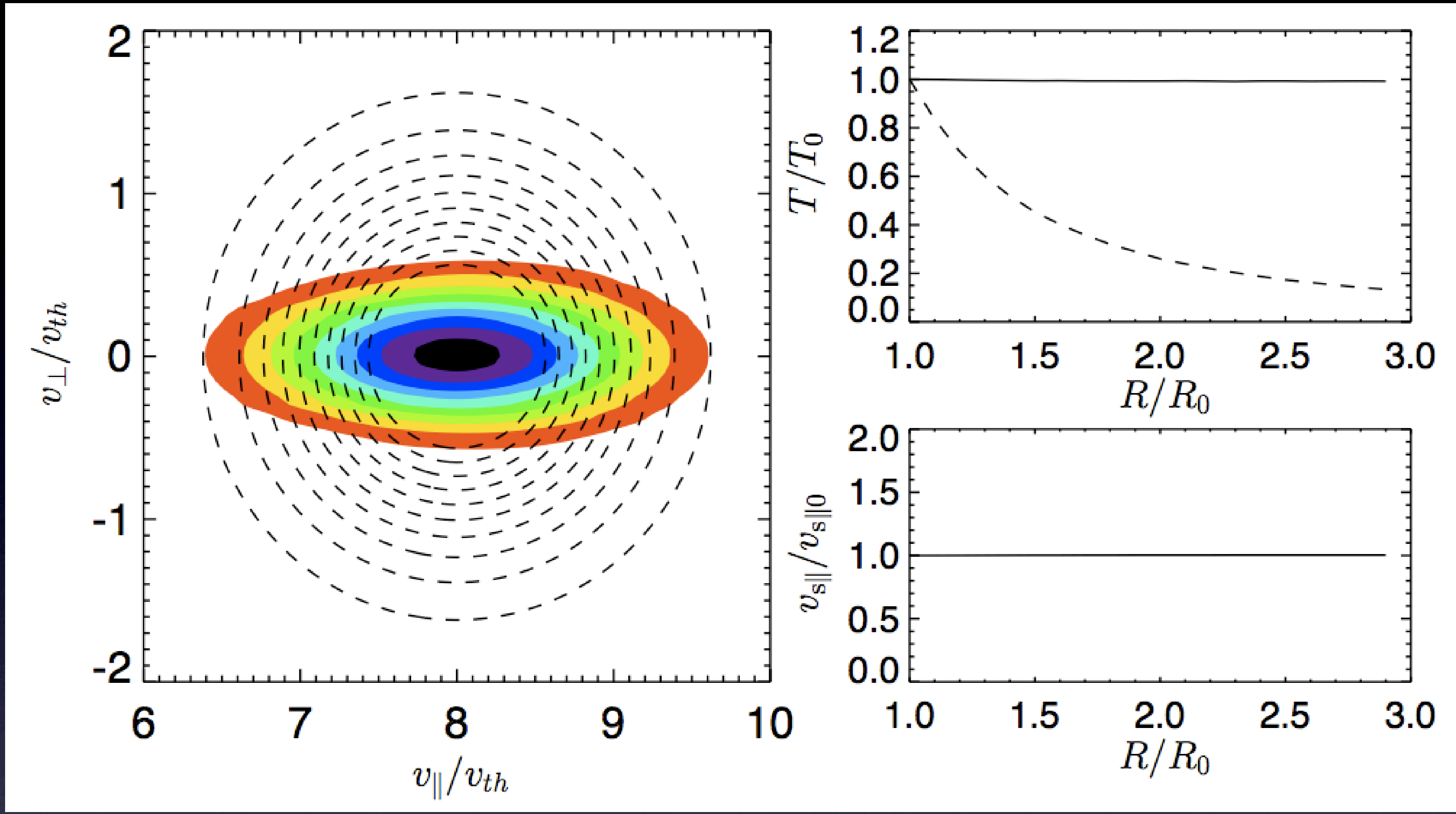

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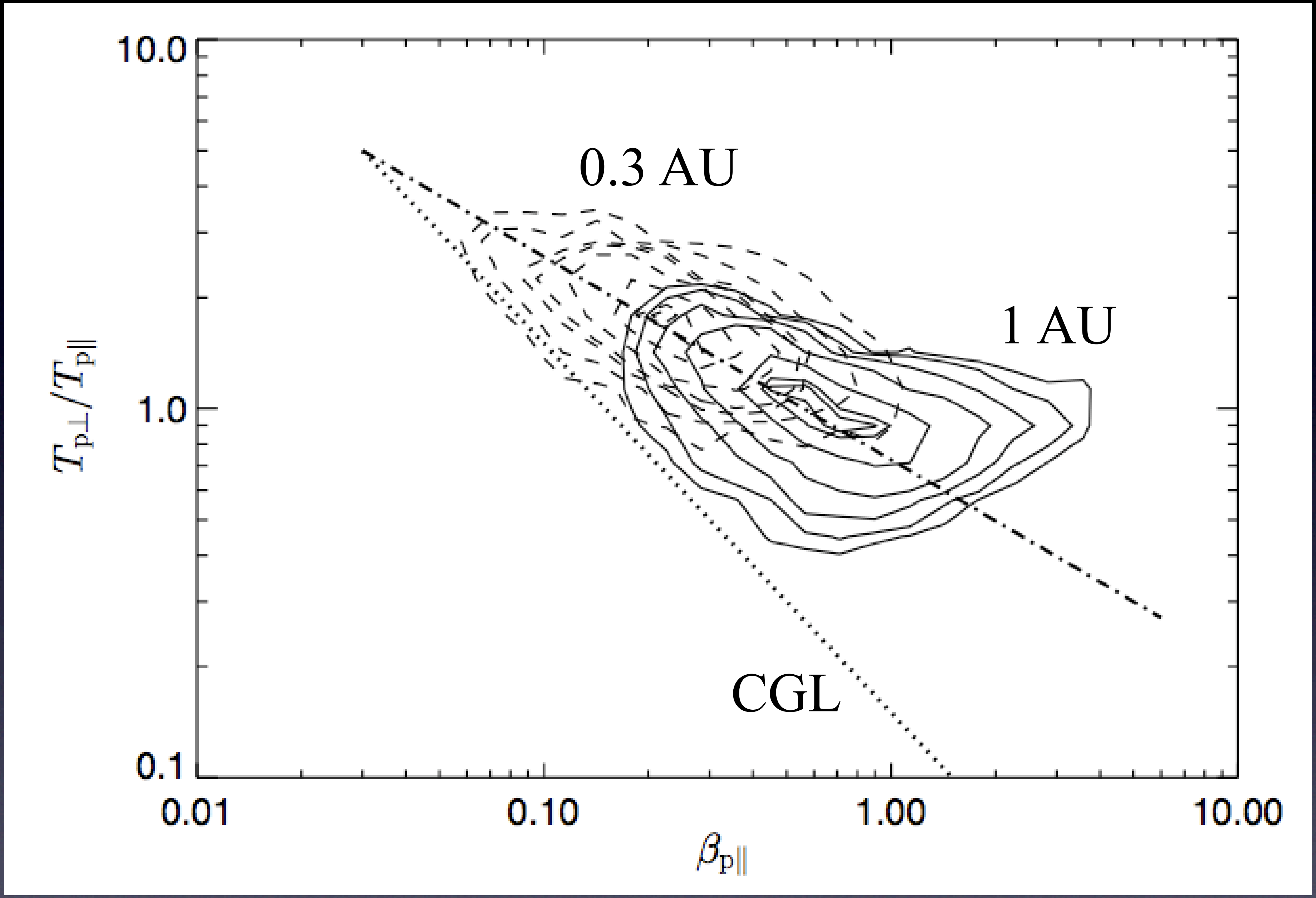
Expansion in a radial magnetic field

$$T_{\mathrm{p}\perp} \propto R^{-2} \qquad \text{and} \qquad T_{\mathrm{p}\parallel} = \mathrm{const}$$

$$v_{s\parallel} = \mathrm{const}$$

only if $T_\parallel = T_\perp = T$ then $T \propto R^{-4/3}$

The observed evolution of protons between 0.3 and 1 AU



Helios observations

$$\beta_{p\parallel} \propto \frac{nT_{p\parallel}}{B^2} \propto R^2 \propto T_{p\parallel}/T_{p\perp}$$

- Non-adiabatic, presence of perpendicular heating
- Change of slope observed at 1 AU (β>1)

Estimated number of collisions at 1 AU

Protons

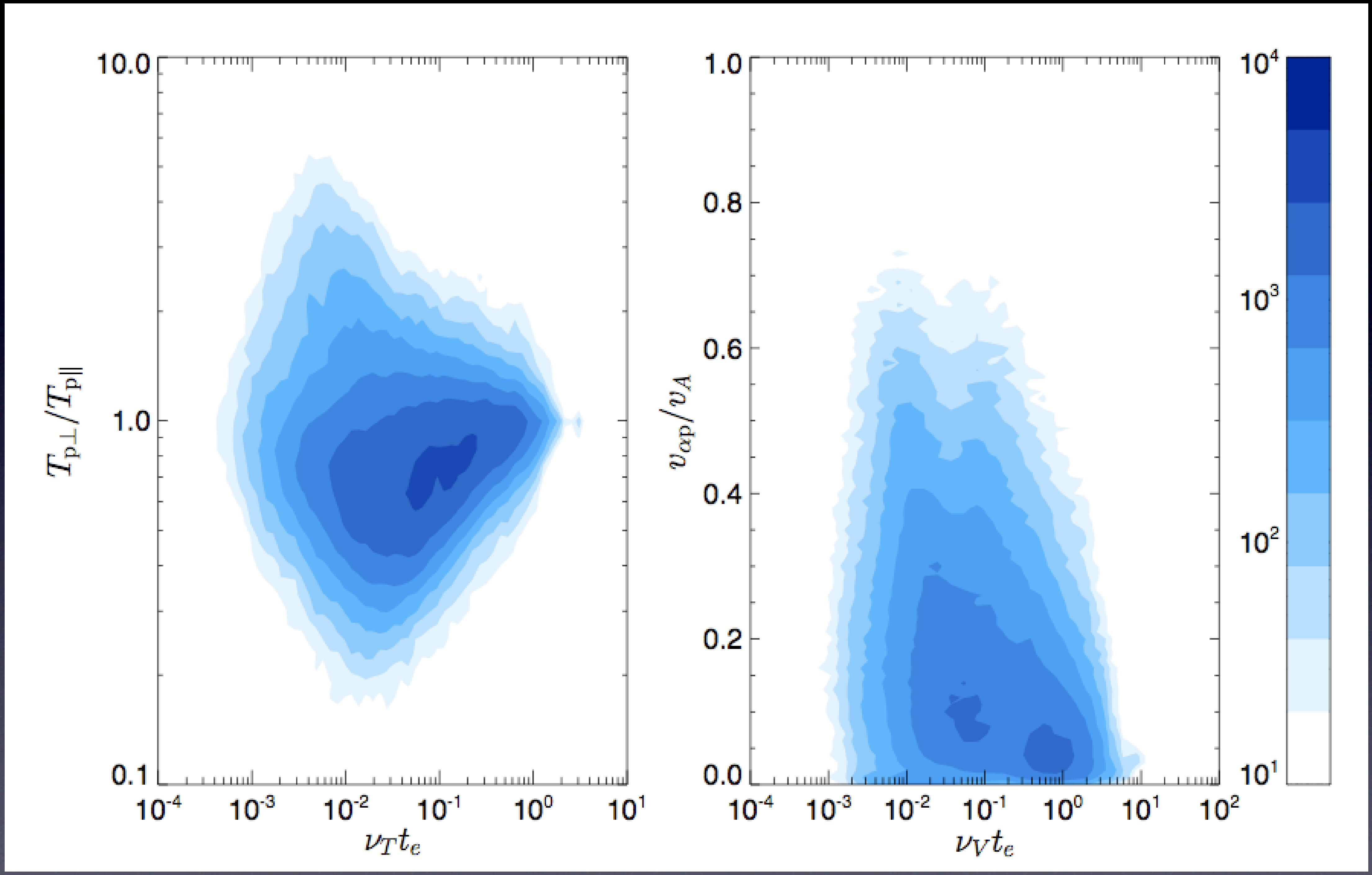
$$N = \frac{\tau_{exp}}{\tau^p_{coll}} = \frac{L}{\lambda} \frac{v^p_{th}}{v_{sw}} = K_n^{-1} \frac{v^p_{th}}{v_{sw}} < 1$$

Electrons

$$N = \frac{\tau_{exp}}{\tau^e_{coll}} = \frac{L}{\lambda} \frac{v^e_{th}}{v_{sw}} = K_n^{-1} \frac{v^e_{th}}{v_{sw}} > 1$$

WIND observations

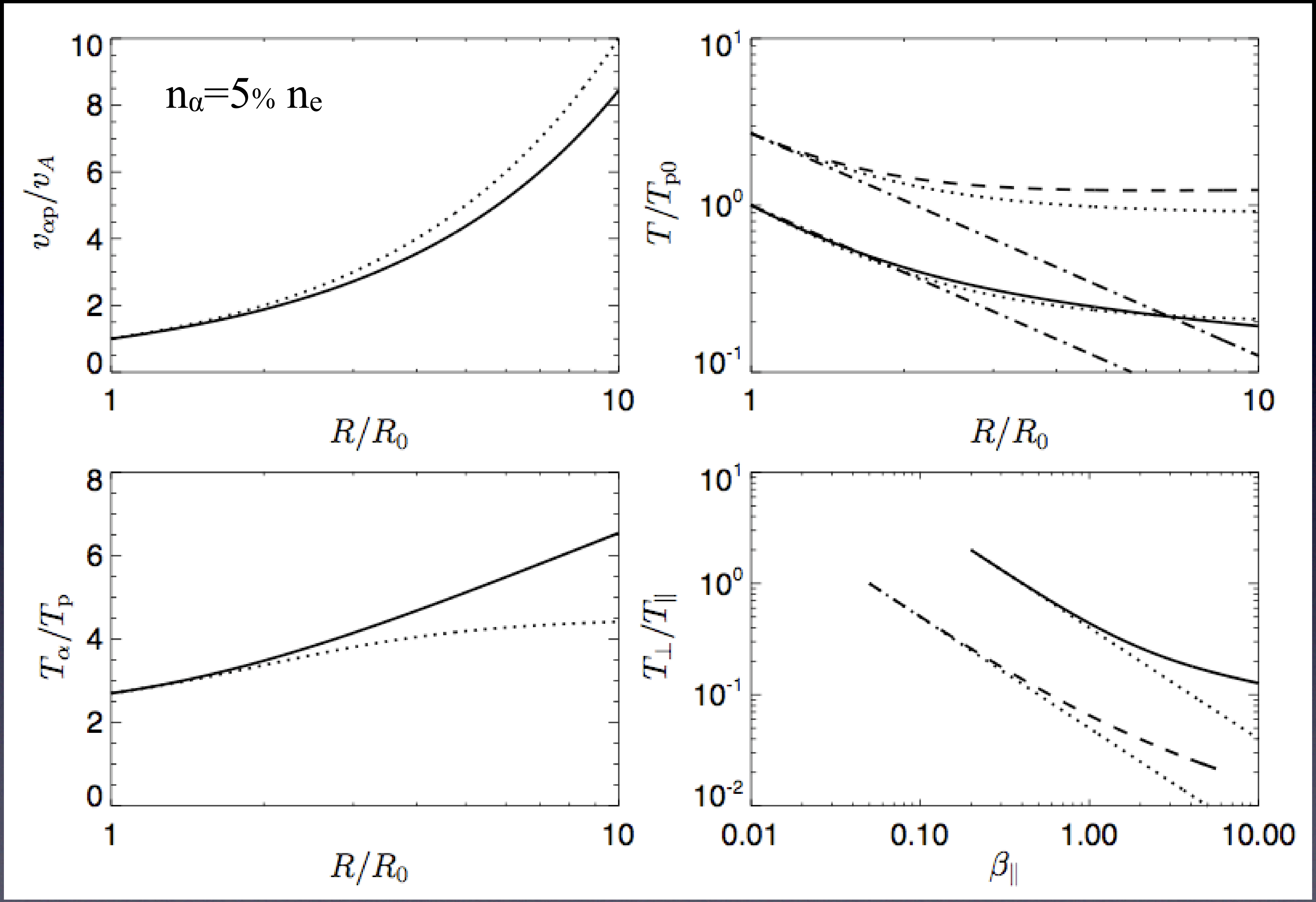
(after *Kasper et al. PRL 2008, Bale et al. PRL 2009*)



See also Bourouaine's presentation
and *Bourouaine et al. ApJ 2011*

Evolution of a plasma with an alpha-proton drift

(adiabatic vs. weakly collisional)



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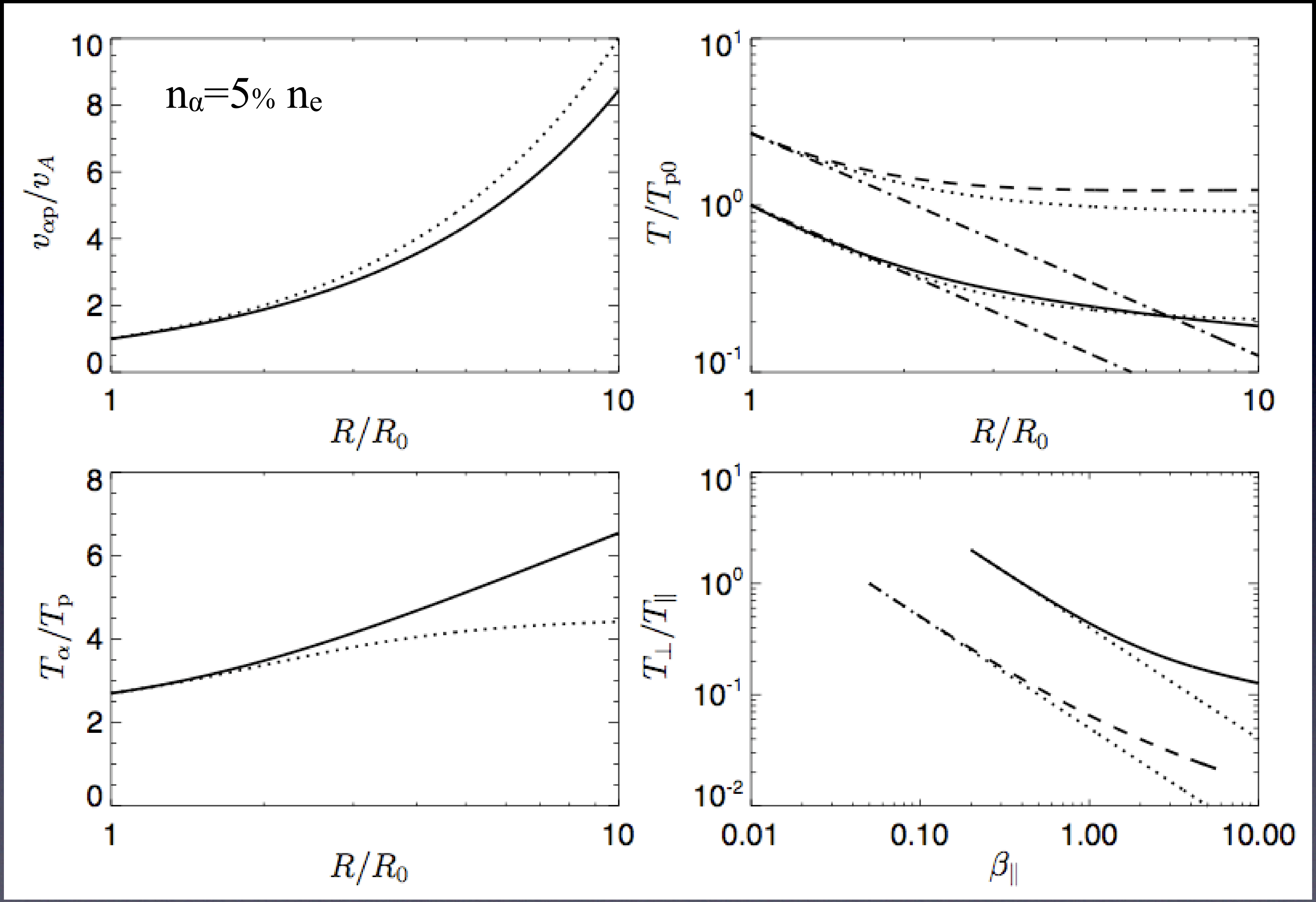
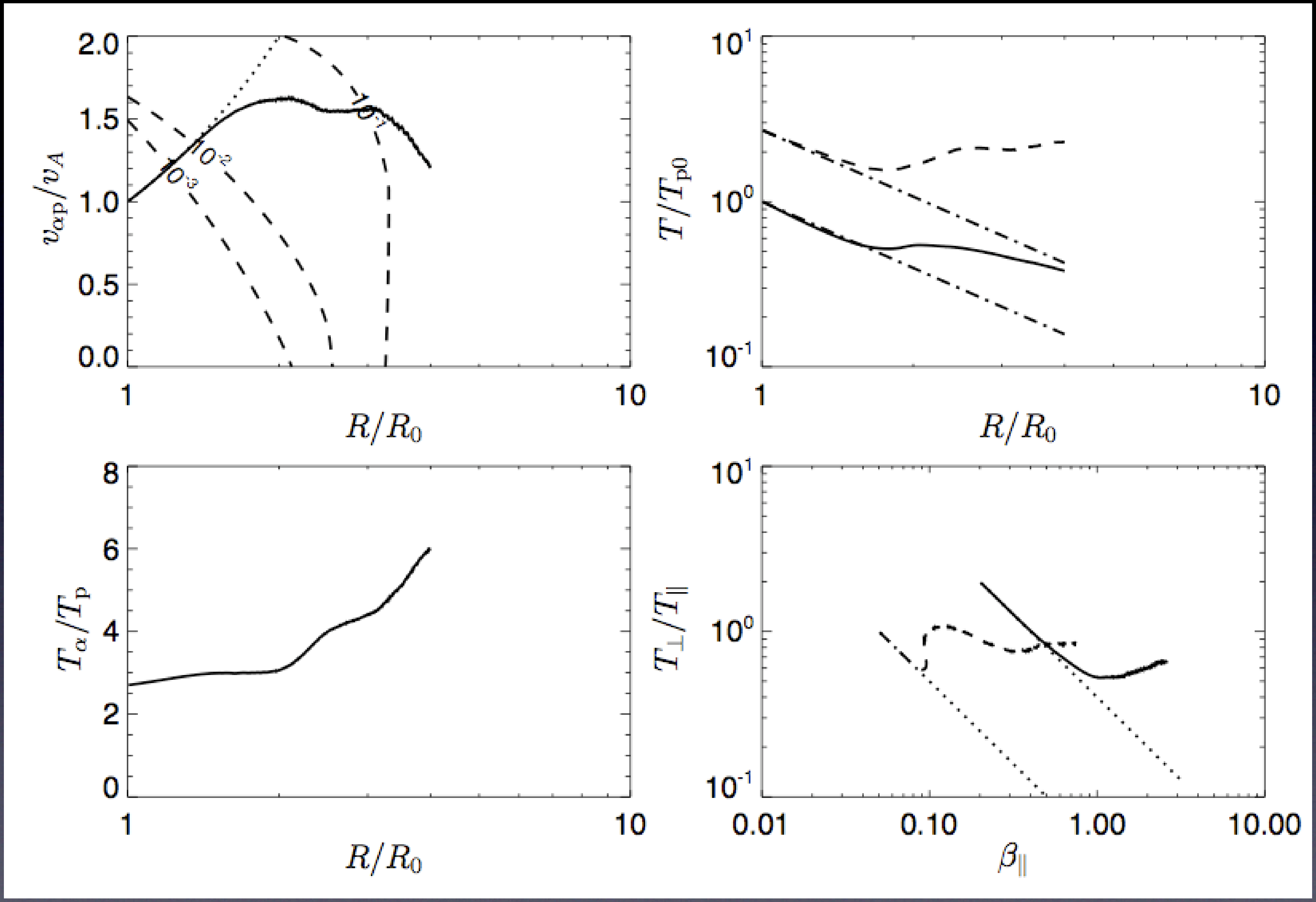


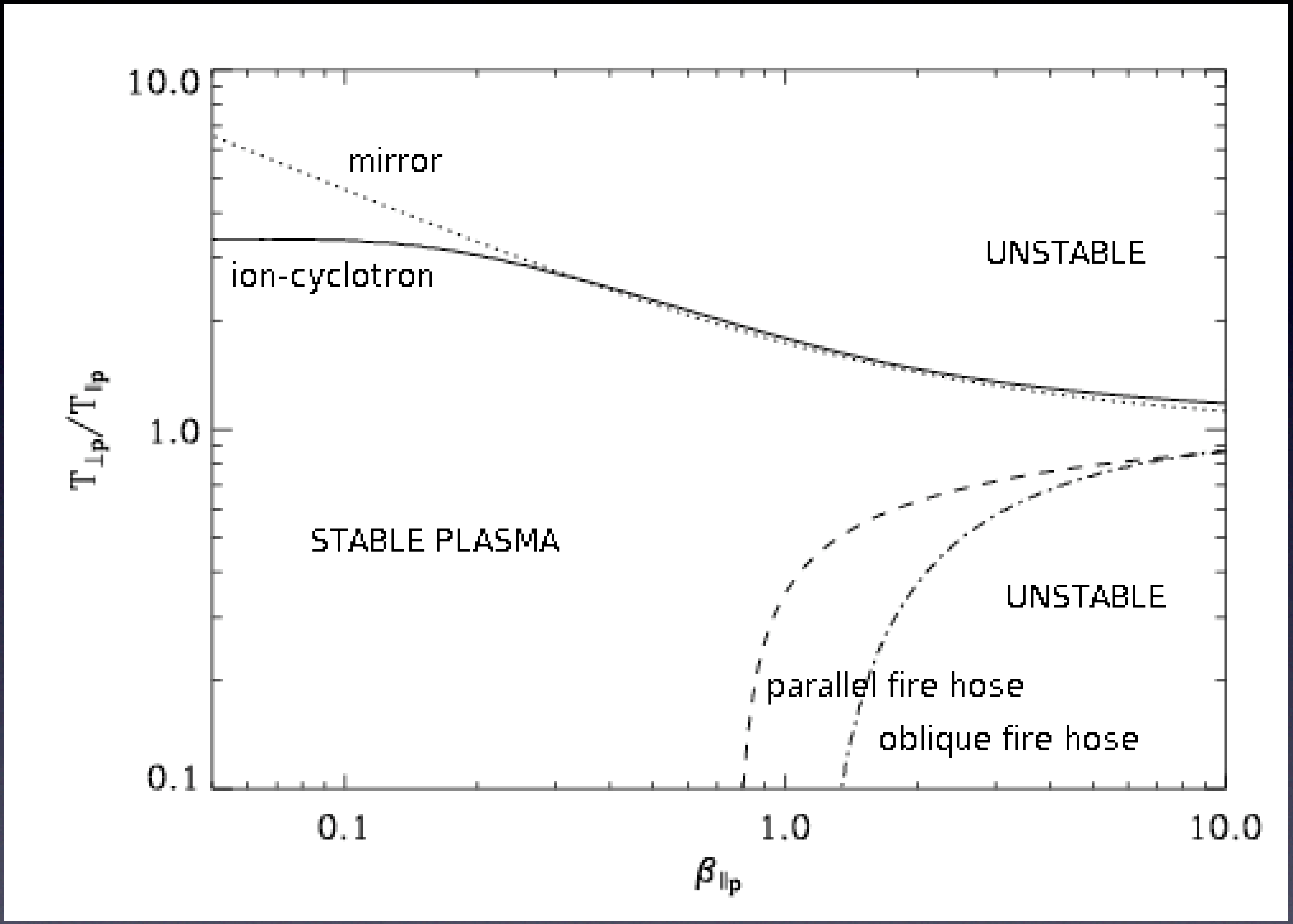
The decrease of the velocity drift by collisions tends to increase the alpha to proton temperature ratio!

Evolution of a plasma with an alpha-proton drift
(Hybrid numerical simulations)



Proton temperature anisotropy in the fast wind from 0.3 to 2.5 AU: Helios & Ulysses data

Linear theory with a 5% of alpha particles



Matteini et al., GRL 2007

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

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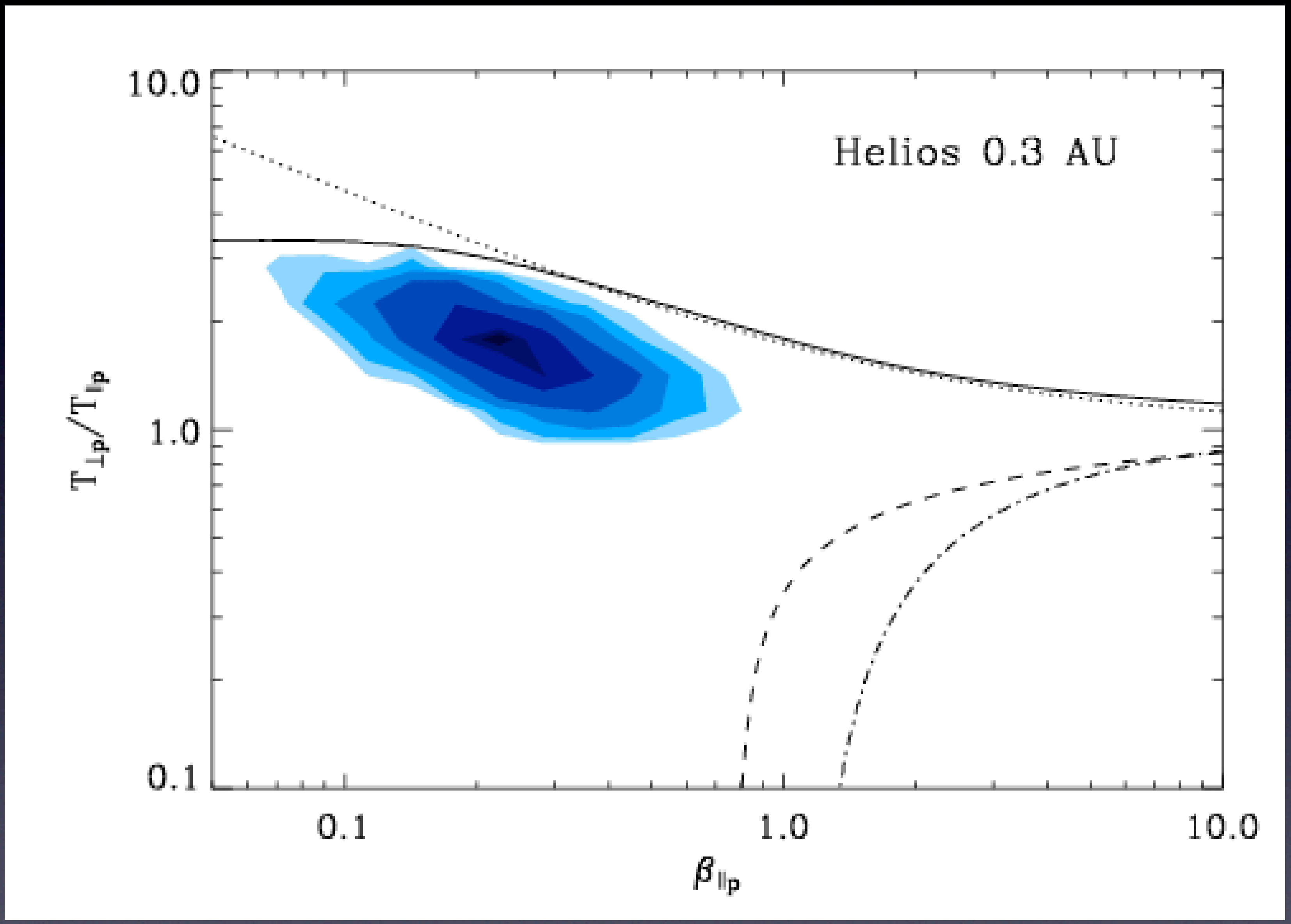

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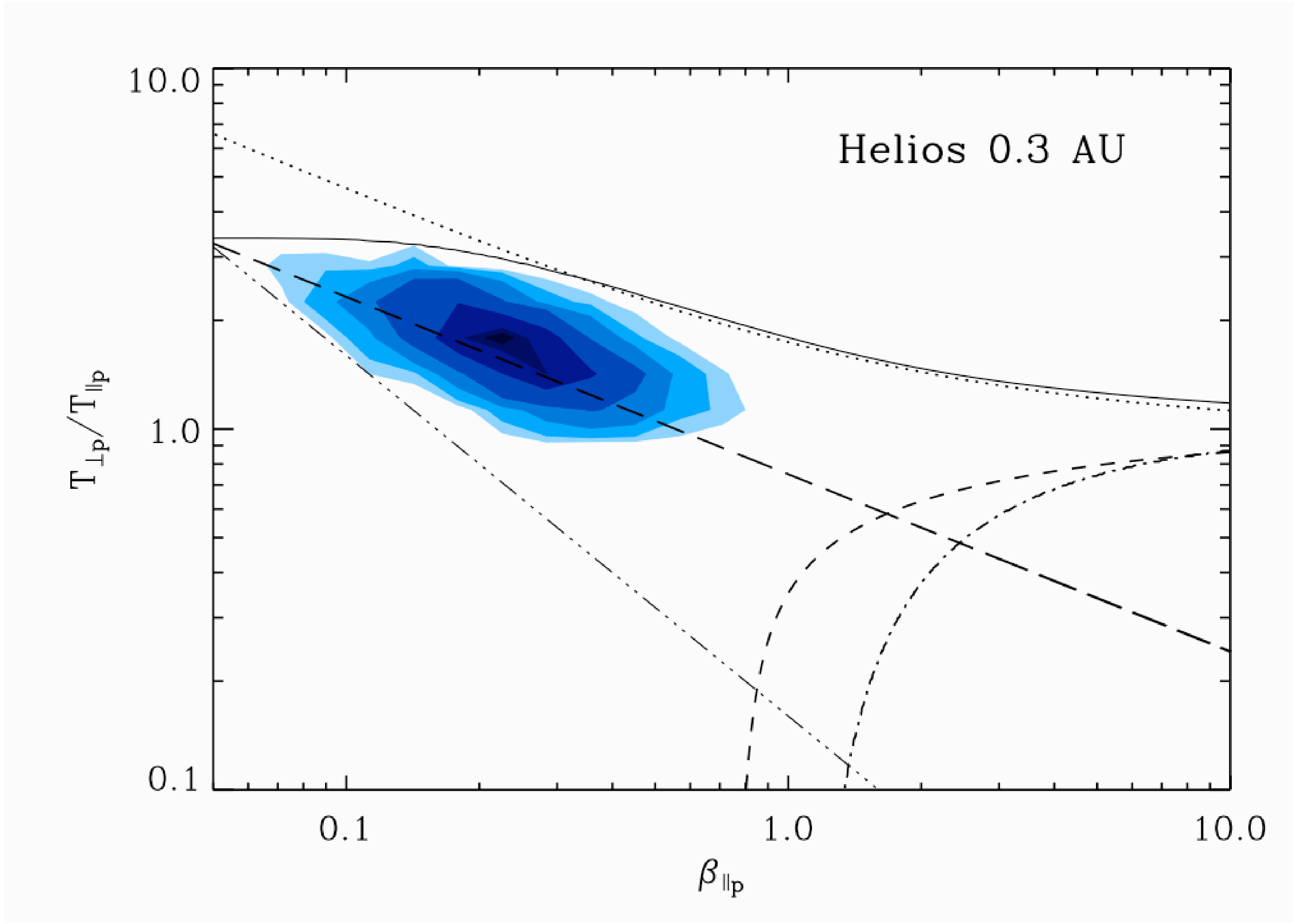

$$\frac{T_{\perp c}}{T_{\parallel c}} \sim \frac{a}{\beta_{\parallel c}^{b}}$$

Marsch et al. 2004

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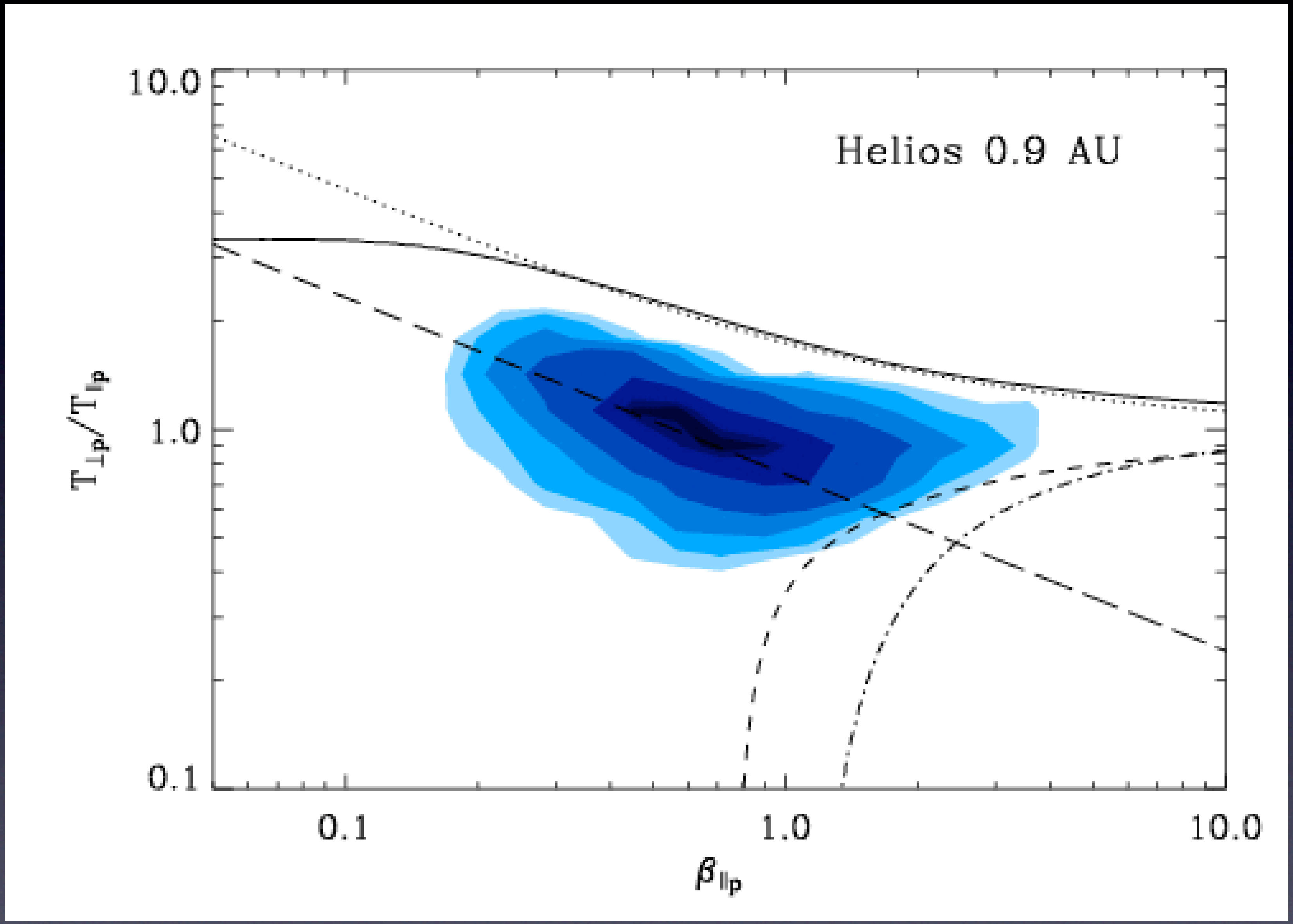

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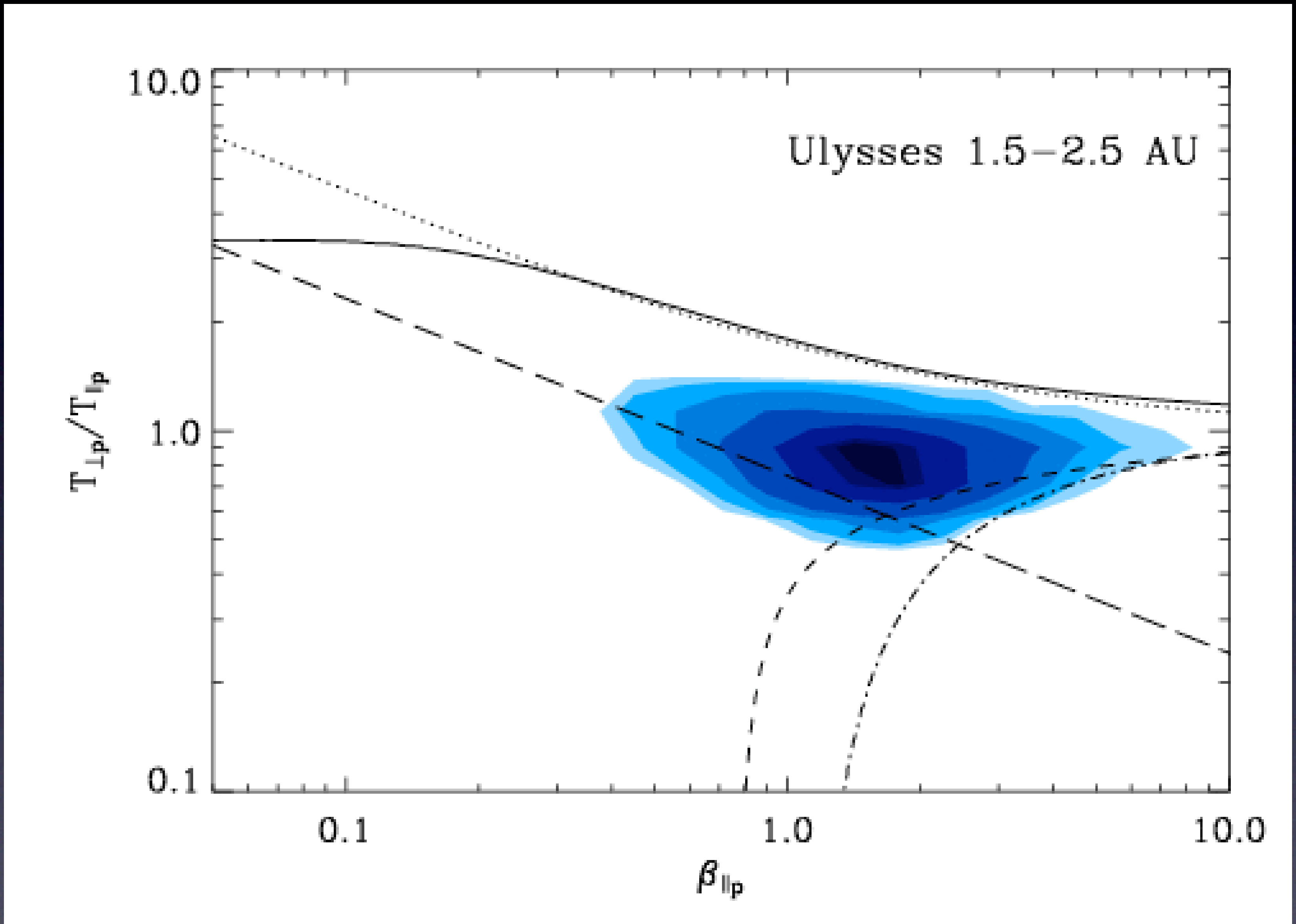

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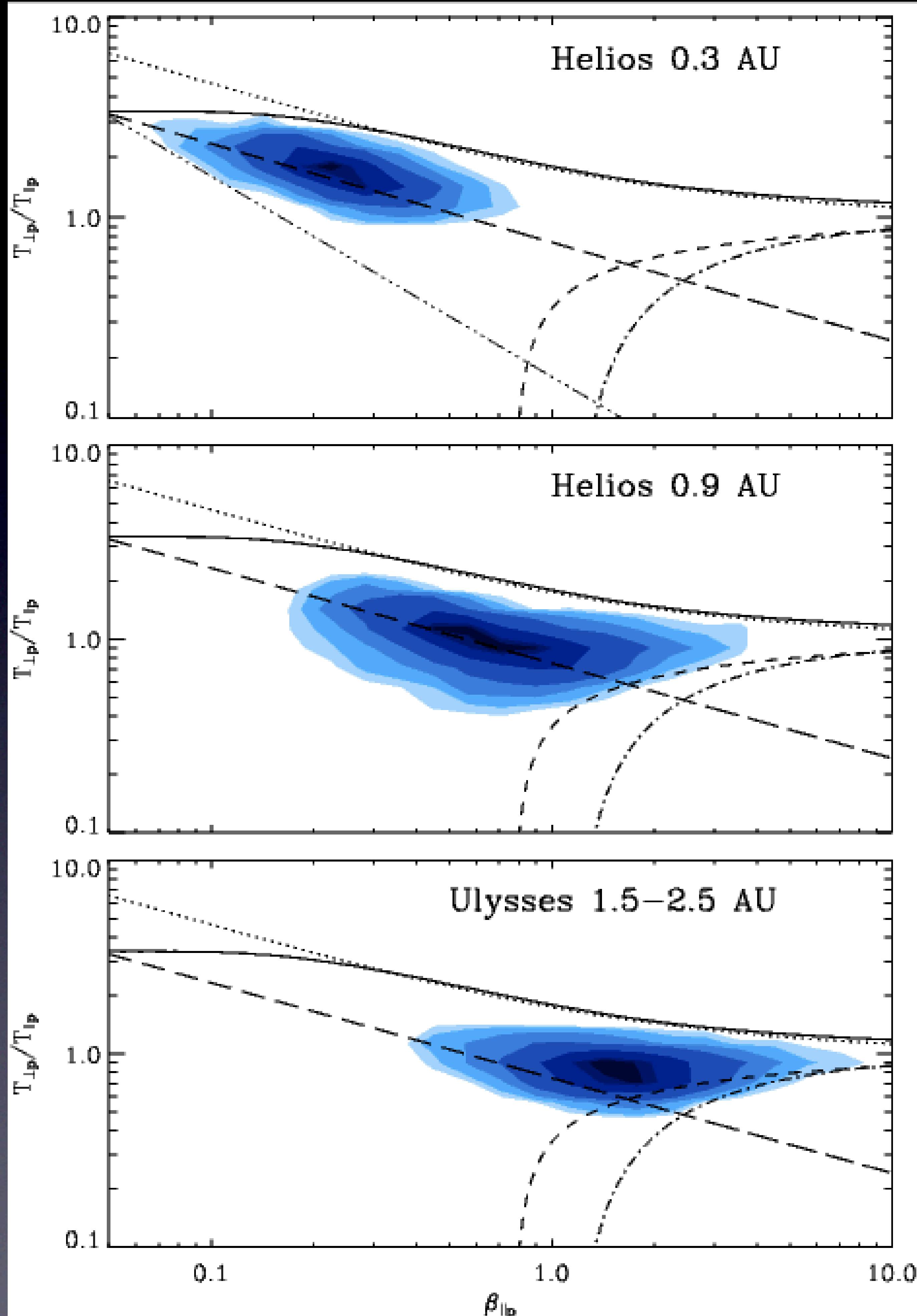
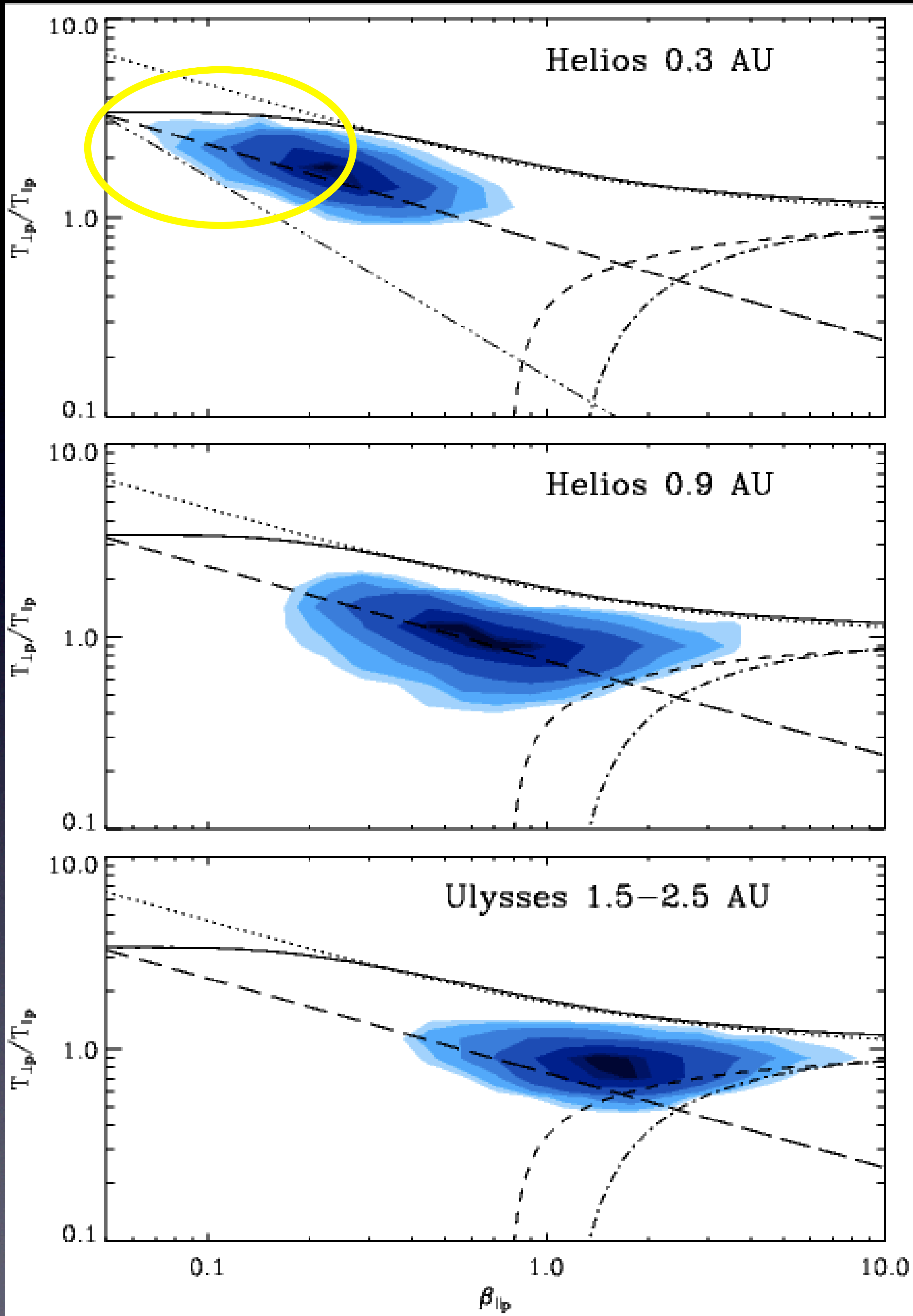


Helios 0.3 AU
Helios 0.9 AU
Ulysses 1.5–2.5 AU
$T_{\perp p}/T_{\parallel p}$
$\beta_{\parallel p}$
10.0
1.0
0.1

At which distance is the maximum of the anisotropy? (Solar Orbiter, Solar Probe)



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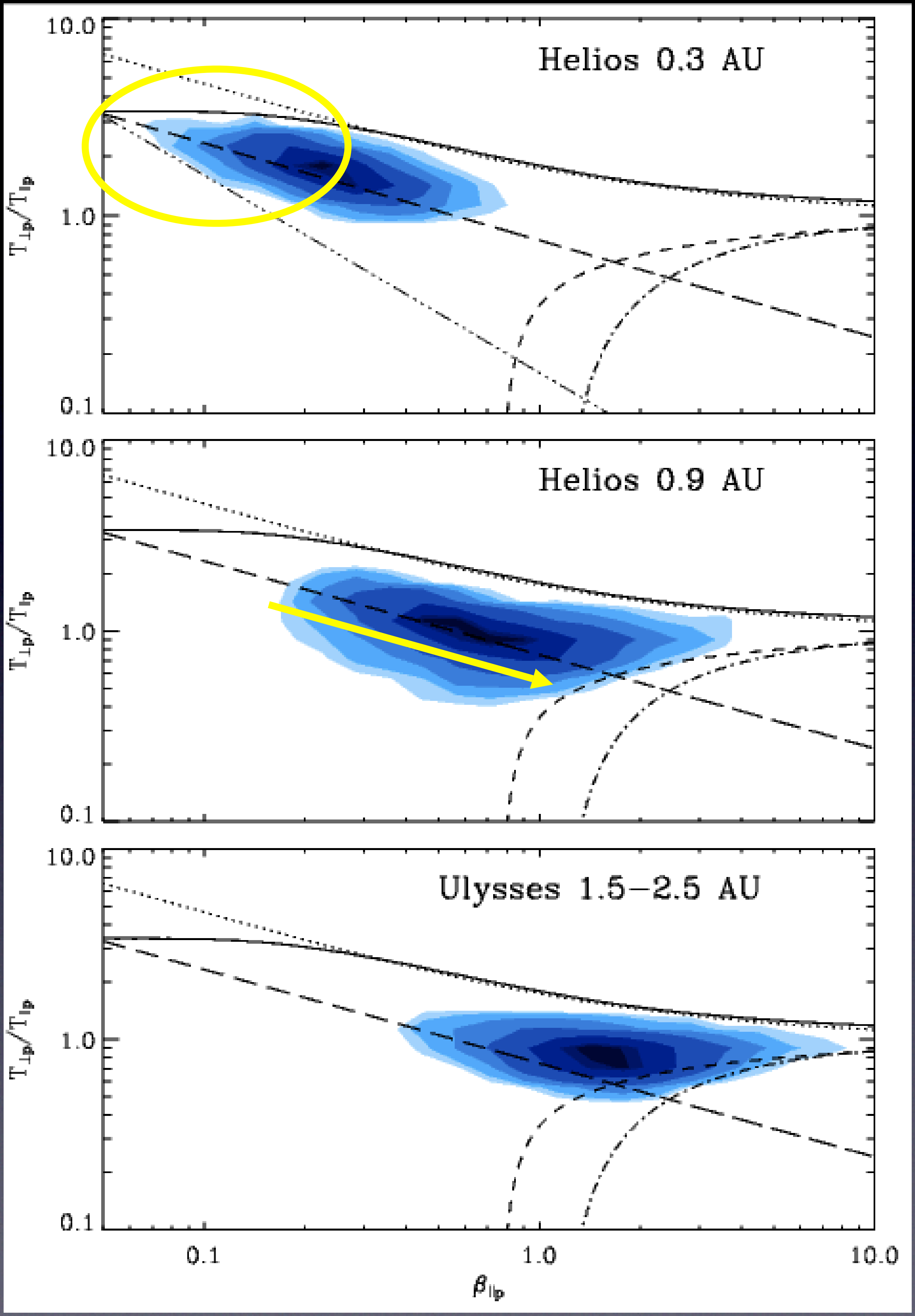
Non-adiabatic evolution, local perpendicular heating.



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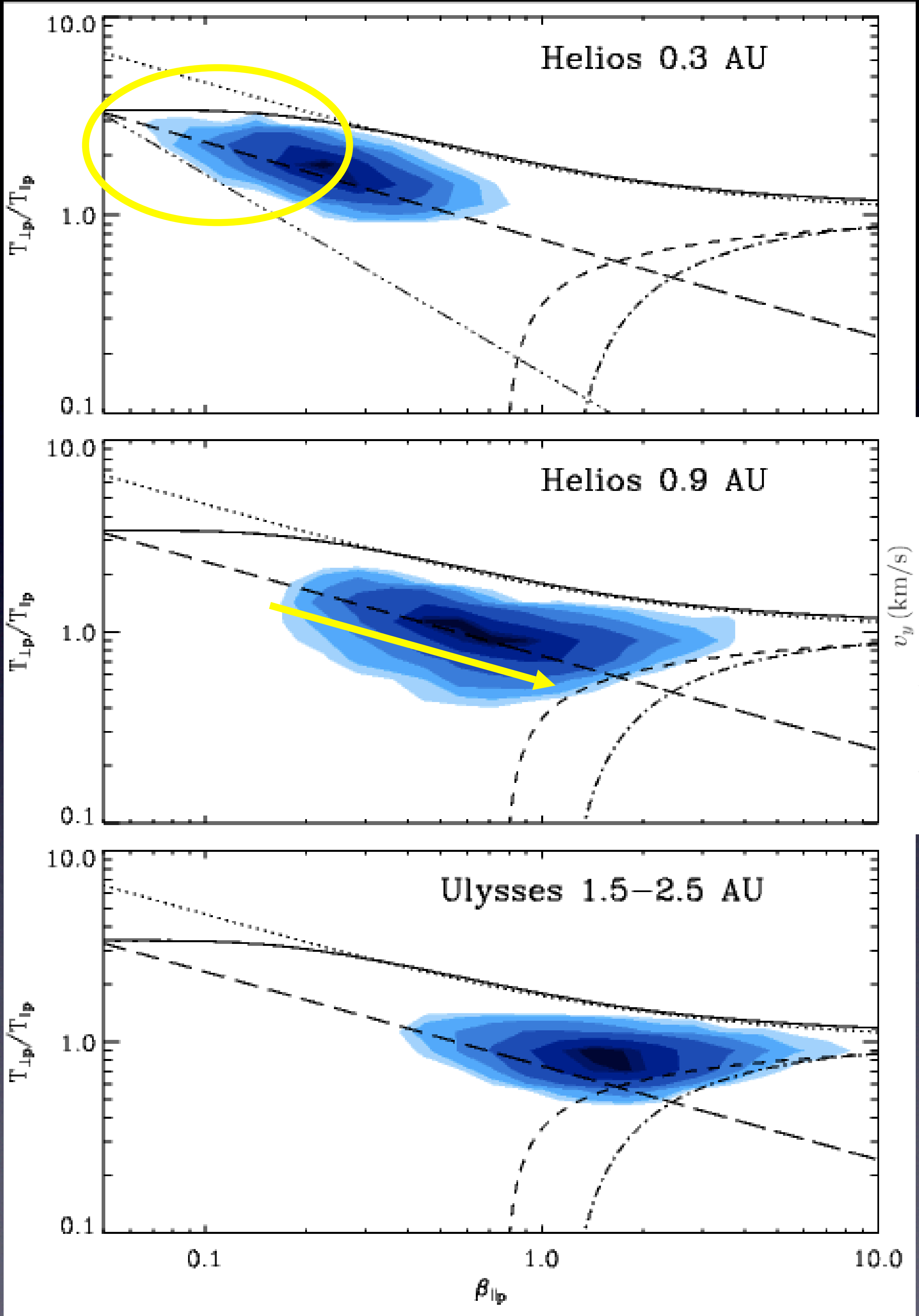

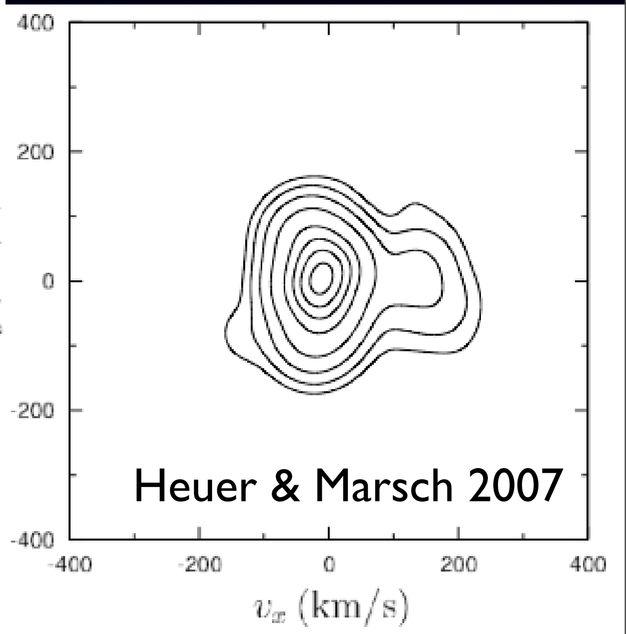

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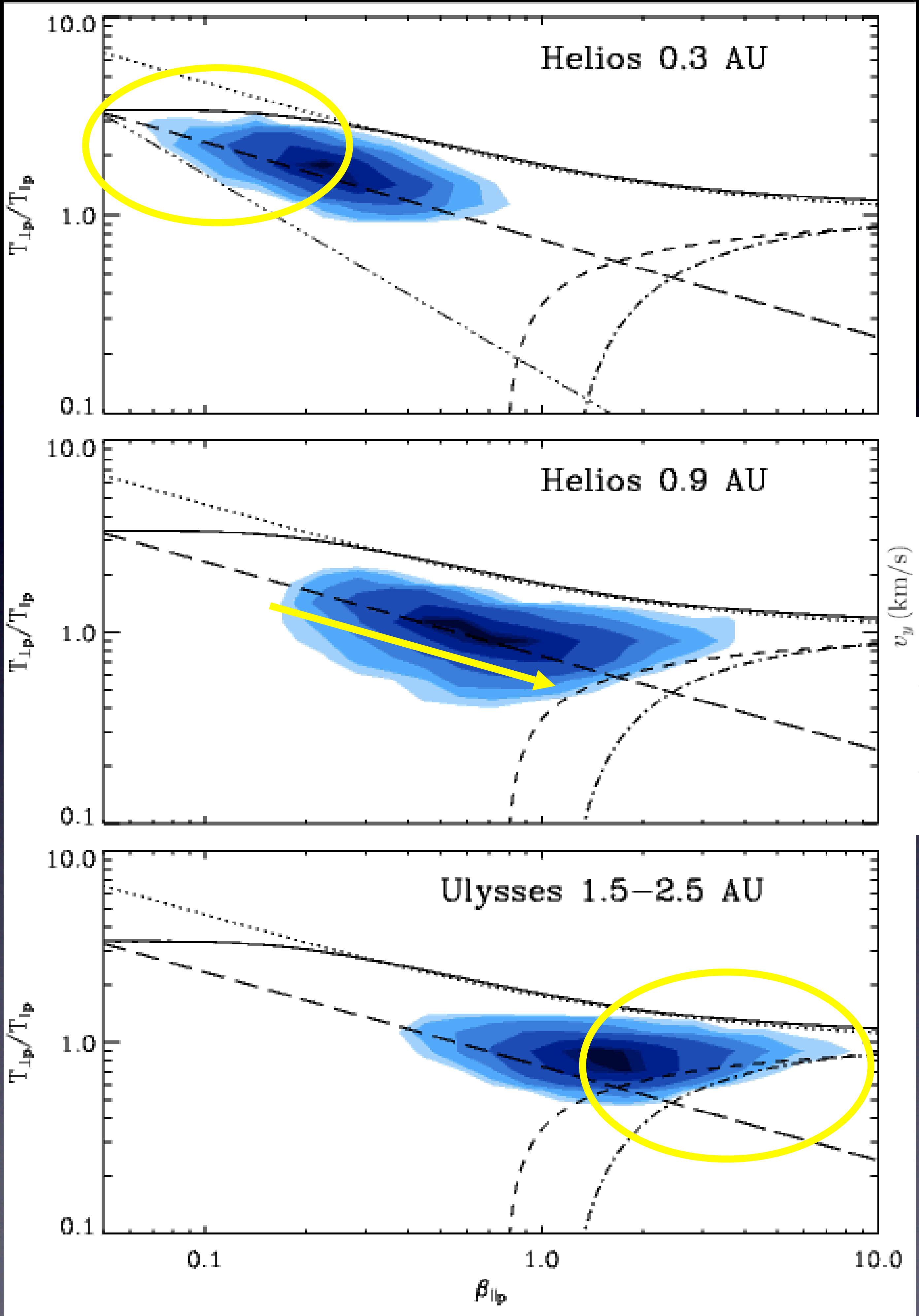
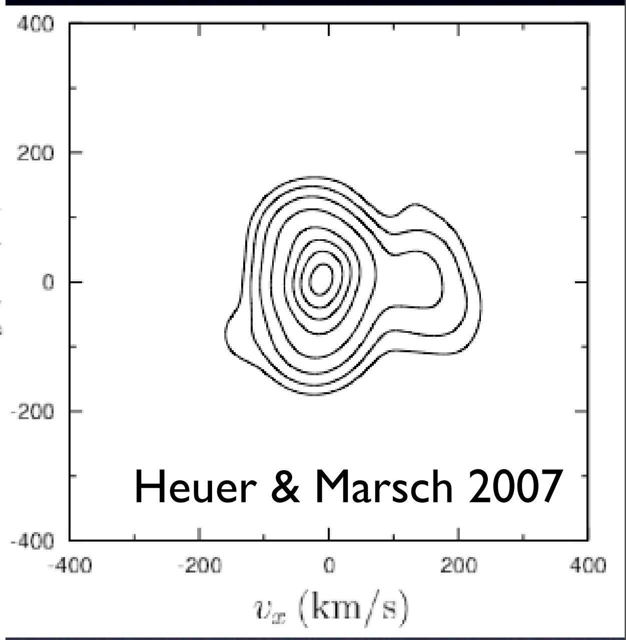
Non-adiabatic evolution, local perpendicular heating.

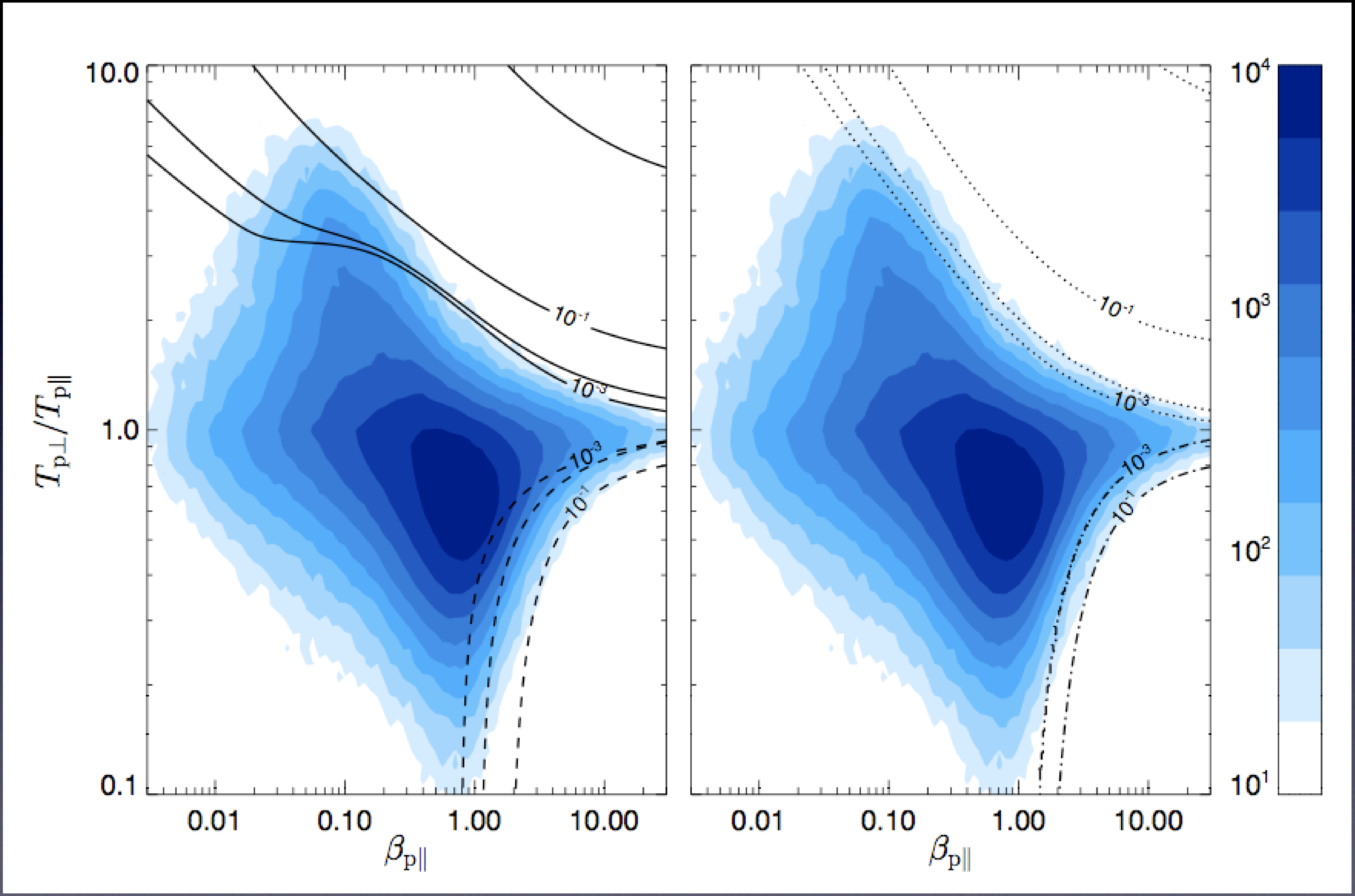
Local generation of fluctuations. Enhancement of wave activity observed by WIND (*Bale et al. 2009*) and Ulysses (Wicks et al. 2010)





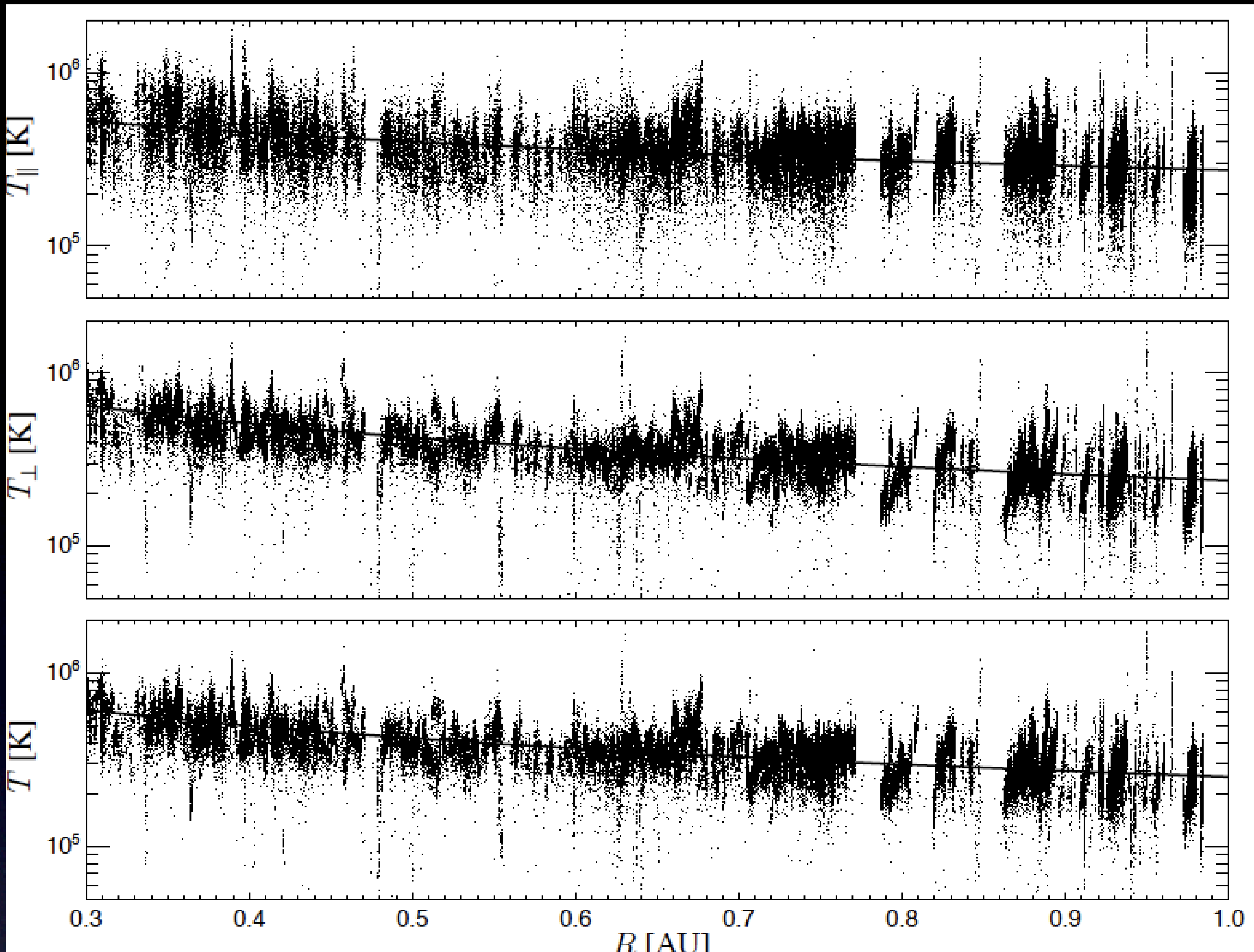
Slow wind: WIND data

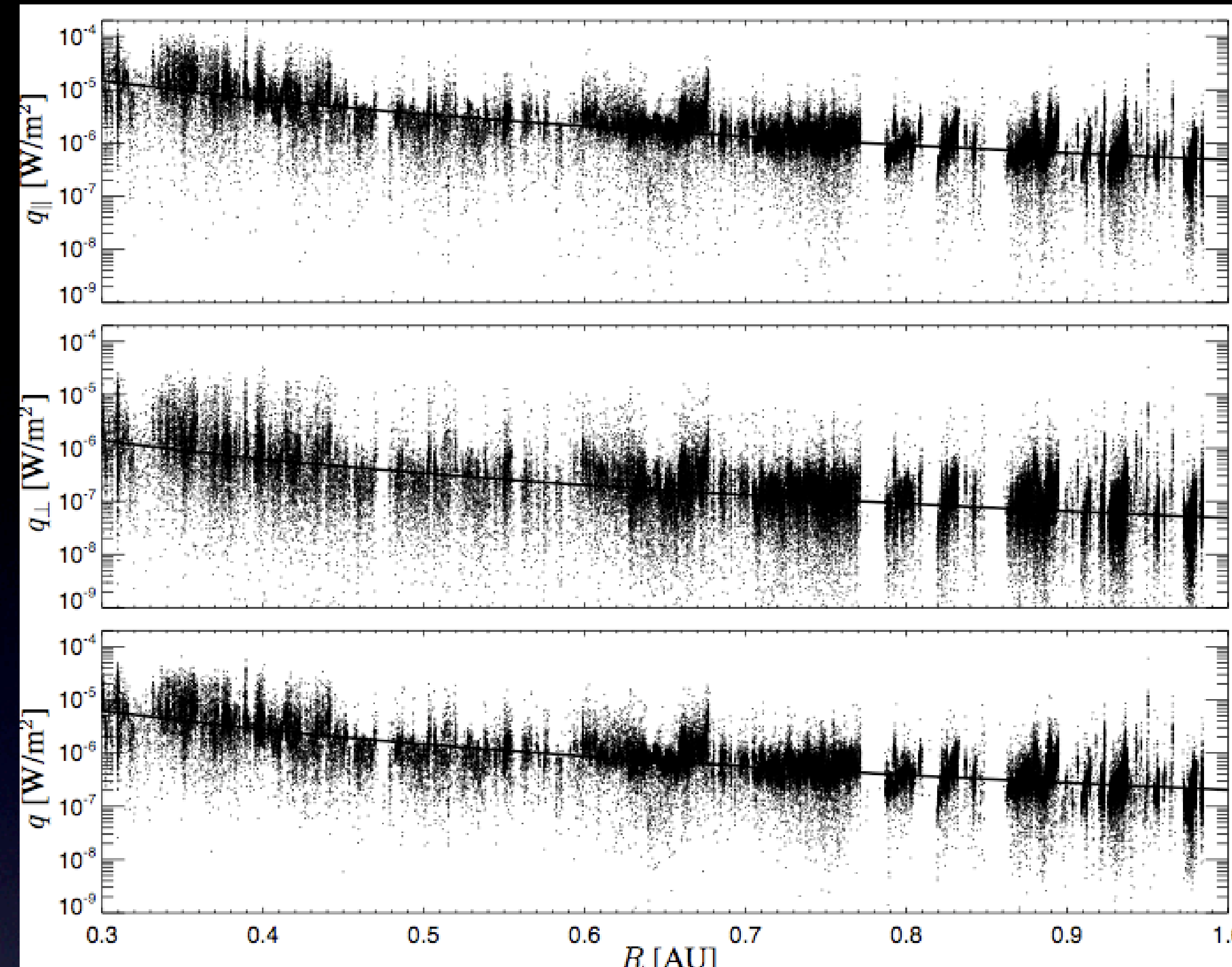
(*Kasper et al. 2002, Hellinger et al. 2006, Matteini et al. 2011*)



Ion-cyclotron
Parallel fire hose

Mirror
Oblique fire hose





$$T_{\|} \simeq 2.7 \cdot 10^5 (R/R_0)^{-0.54} \text{ K},$$

$$T_{\perp} \simeq 2.4 \cdot 10^5 (R/R_0)^{-0.83} \text{ K},$$

$$T \simeq 2.5 \cdot 10^5 (R/R_0)^{-0.74} \text{ K},$$

$$q_{\|} \simeq 4.8 \cdot 10^{-7} (R/R_0)^{-2.9} \text{ W/m}^2,$$

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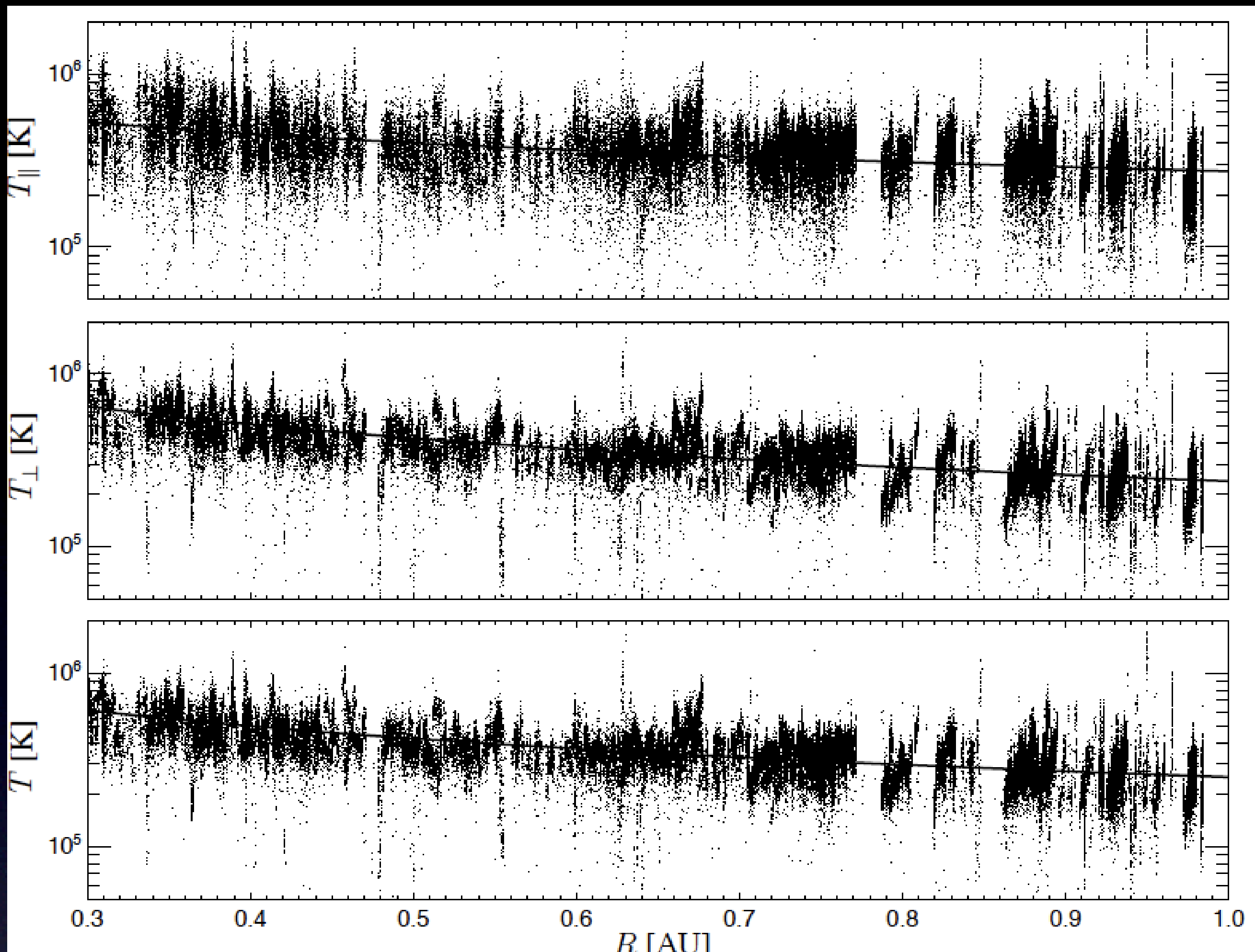
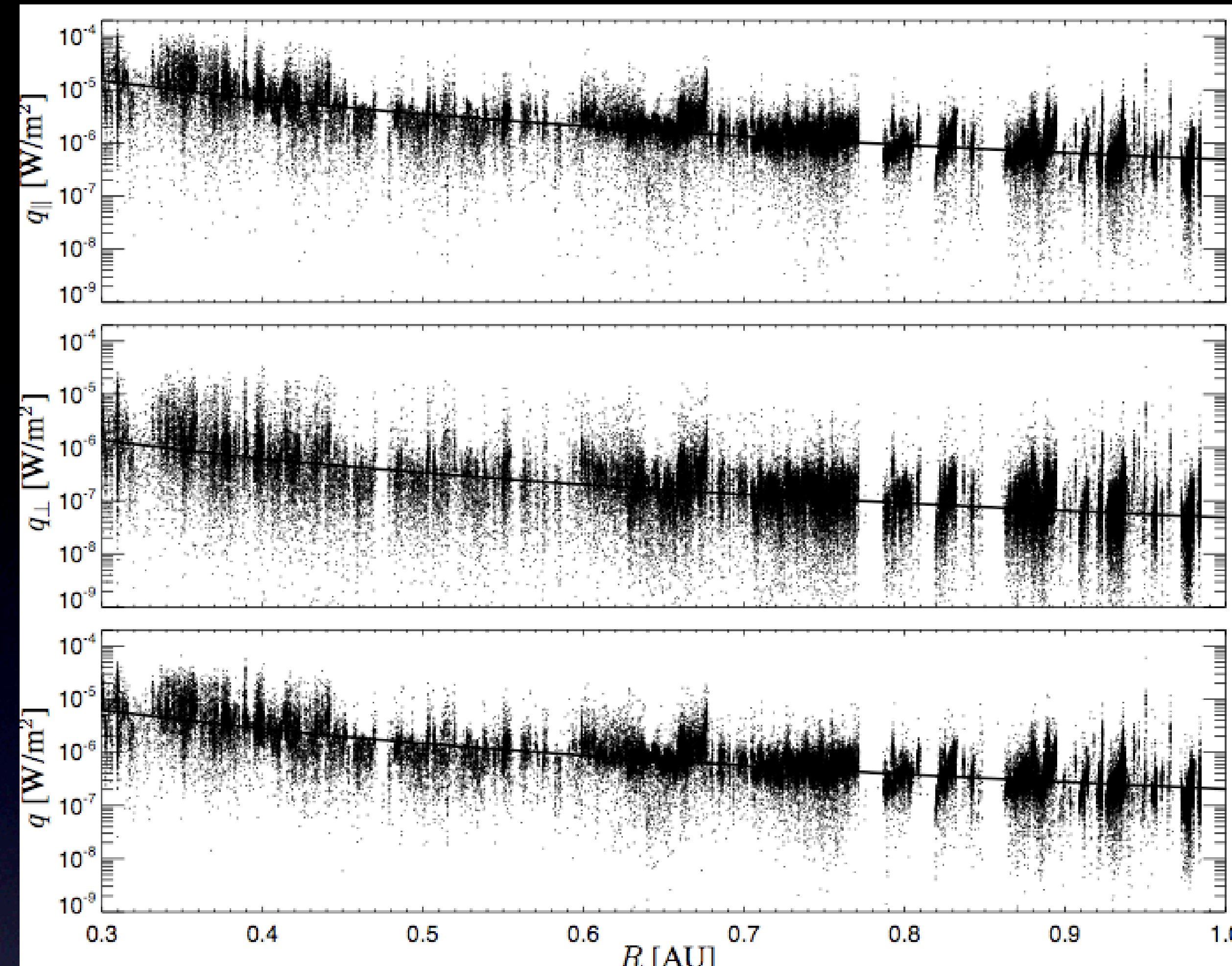
Hellinger, Matteini et al. JGR submitted





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nk_\mathrm{B}\left(\frac{\partial}{\partial t} + \boldsymbol{u}\cdot\boldsymbol{\nabla}\right) T_{\|} &= nk_\mathrm{B}\left[-2T_{\|}\boldsymbol{\nabla}_{\|}\cdot\boldsymbol{u} + \left(\frac{\mathrm{d}T_{\|}}{\mathrm{d}t}\right)_\mathrm{c}\right]\\
&\quad -\boldsymbol{\nabla}\cdot(q_{\|}\boldsymbol{b}) + 2q_{\perp}\boldsymbol{\nabla}\cdot\boldsymbol{b},\\
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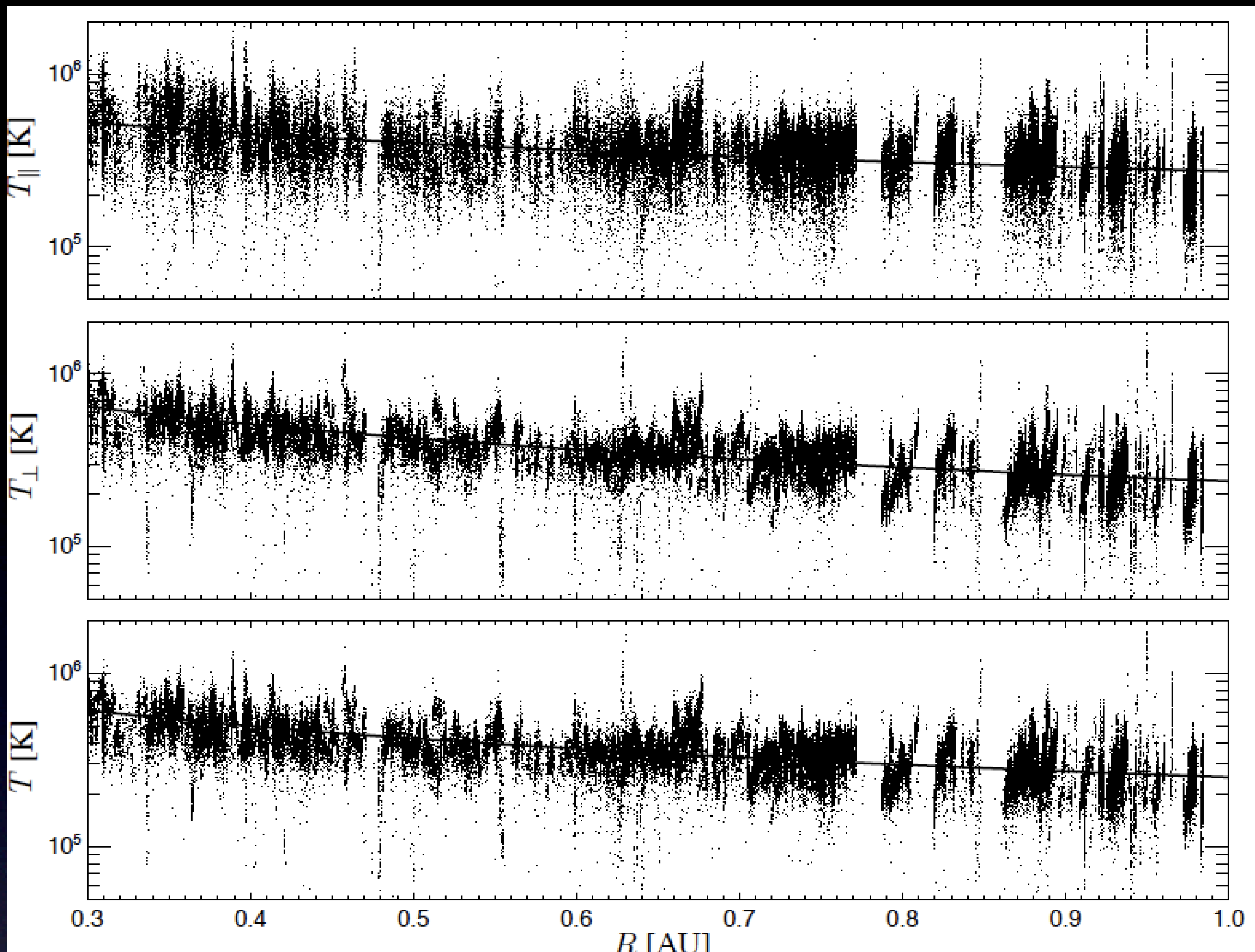

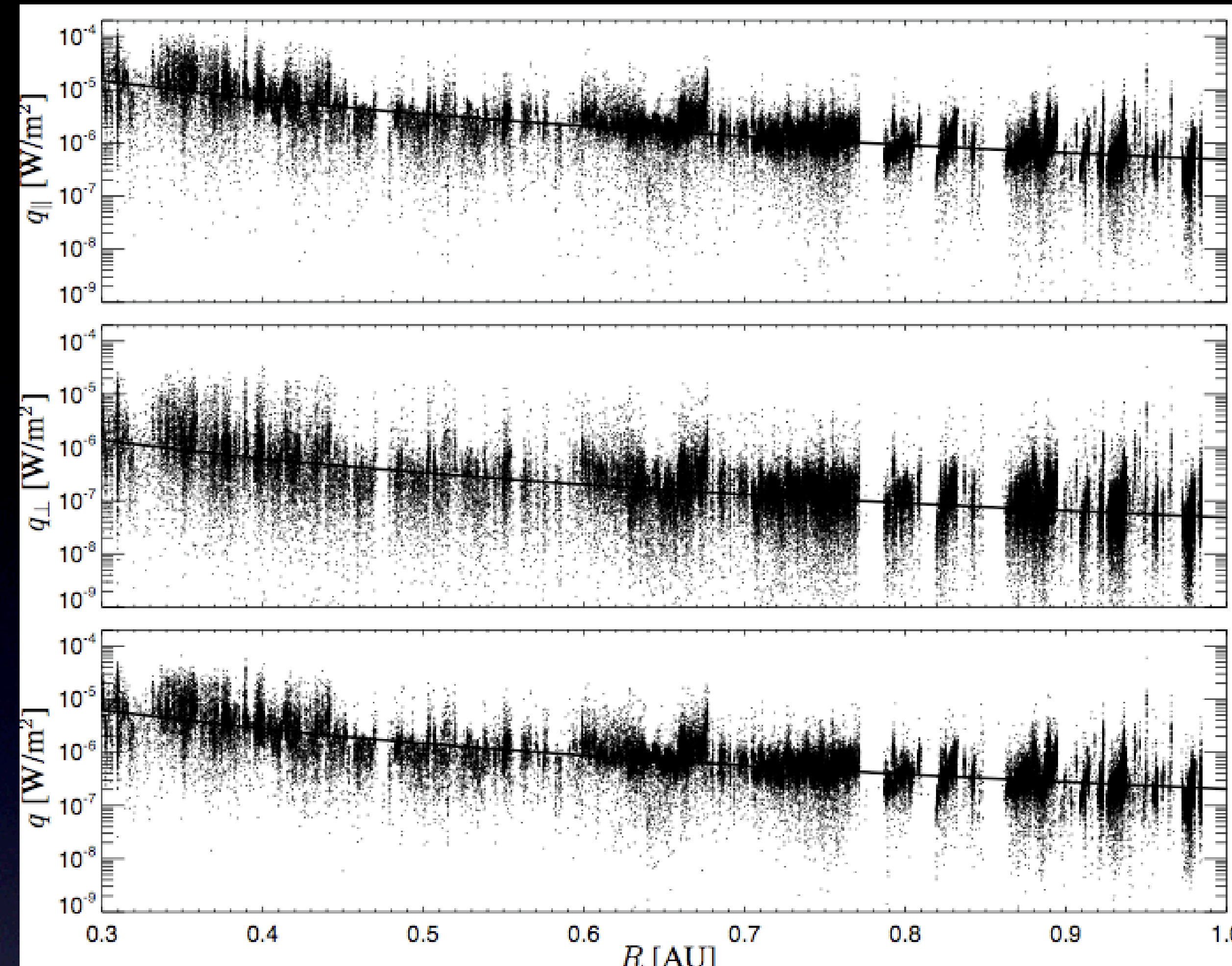

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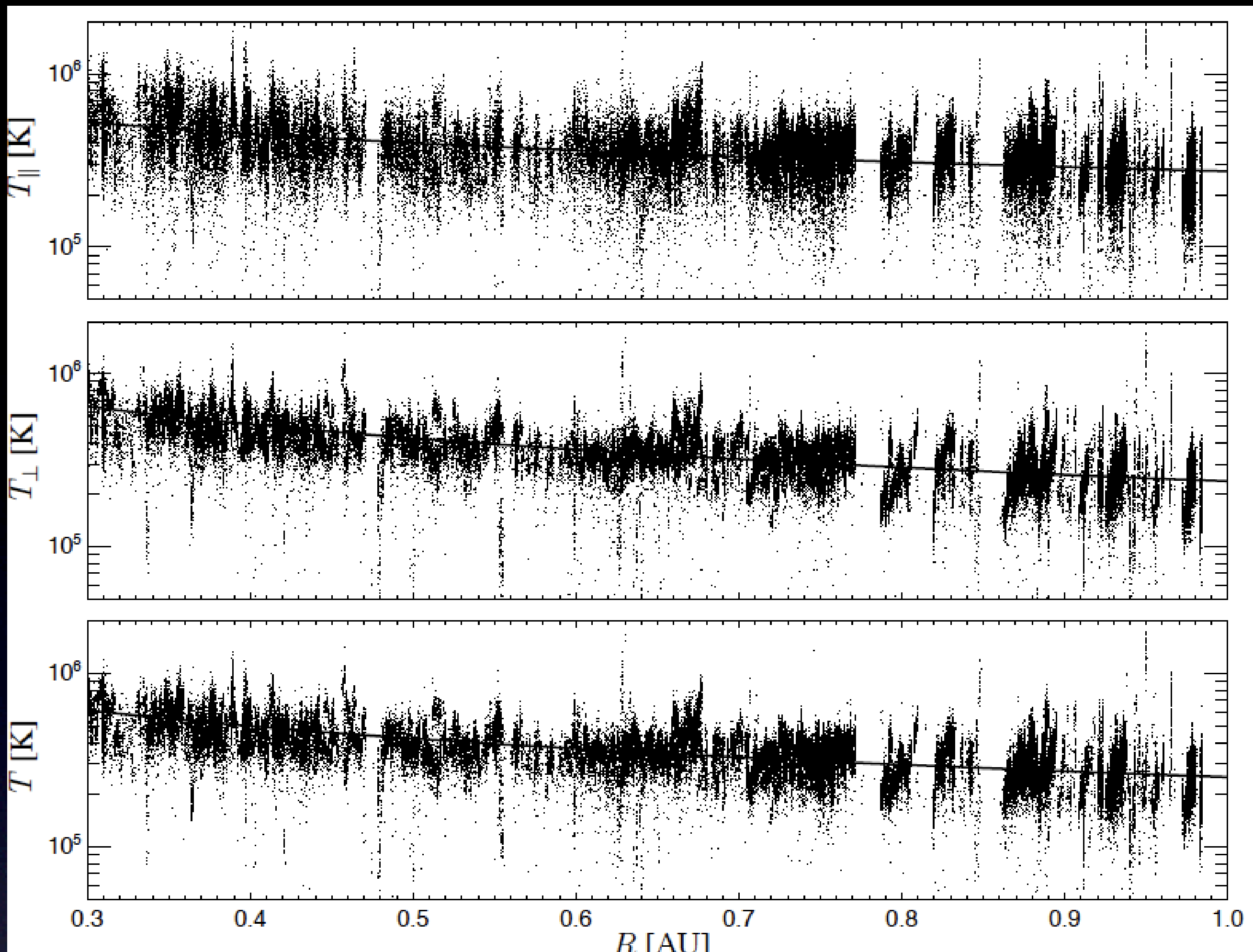
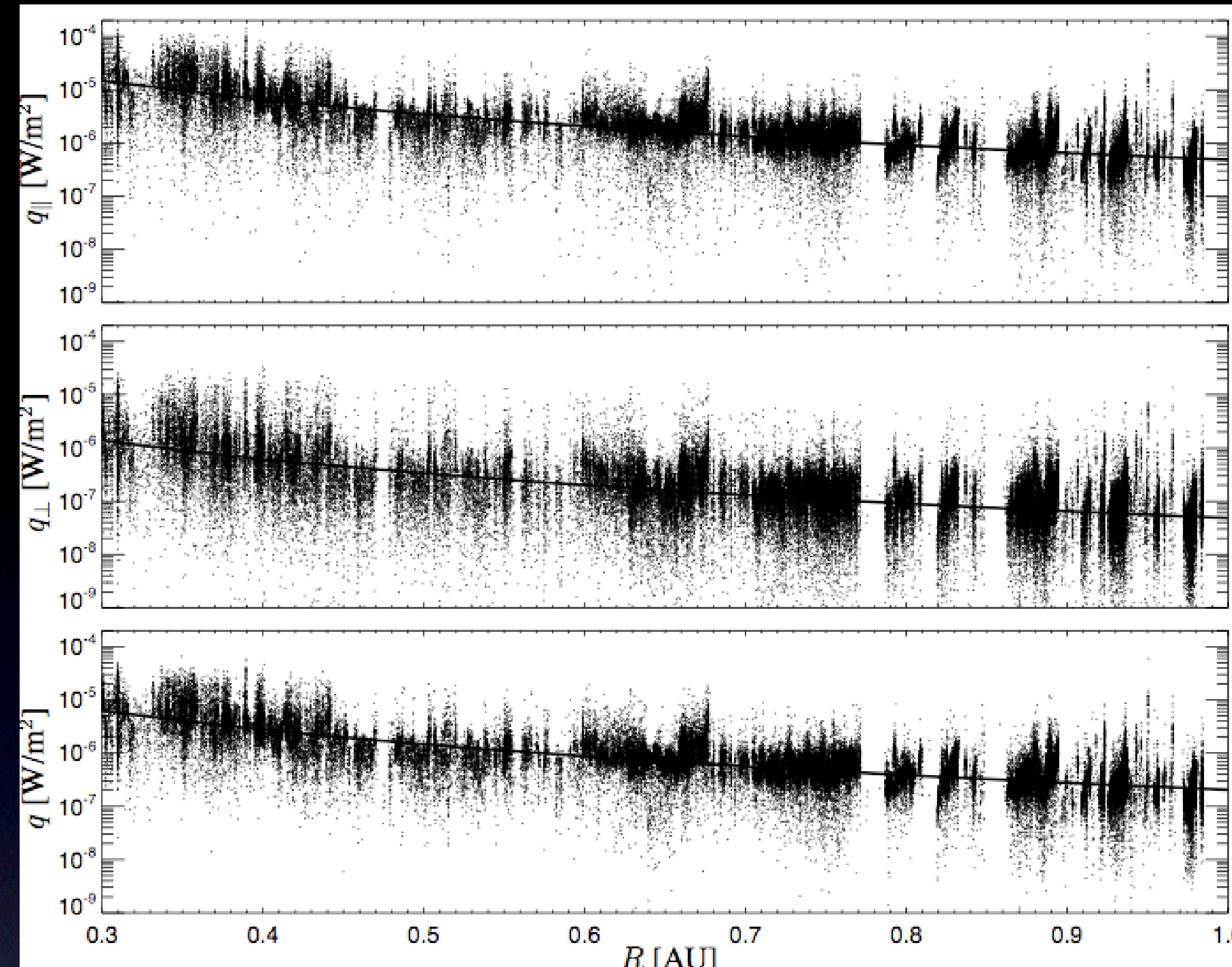
n k_B \left(\frac{\partial}{\partial t} + \boldsymbol{u}\cdot\boldsymbol{\nabla}\right) T_{\|} &= n k_B \left[-2T_{\|} \boldsymbol{\nabla}_{\|} \cdot \boldsymbol{u} + \left(\frac{\mathrm{d}T_{\|}}{\mathrm{d}t}\right)_{\mathrm{c}}\right] \\
&\quad - \boldsymbol{\nabla}\cdot(q_{\|}\boldsymbol{b}) + 2q_{\perp}\boldsymbol{\nabla}\cdot\boldsymbol{b}, \\
n k_B \left(\frac{\partial}{\partial t} + \boldsymbol{u}\cdot\boldsymbol{\nabla}\right) T_{\perp} &= n k_B \left[-T_{\perp} \boldsymbol{\nabla}_{\perp} \cdot \boldsymbol{u} + \left(\frac{\mathrm{d}T_{\perp}}{\mathrm{d}t}\right)_{\mathrm{c}}\right] \\
&\quad - \boldsymbol{\nabla}\cdot(q_{\perp}\boldsymbol{b}) - q_{\perp}\boldsymbol{\nabla}\cdot\boldsymbol{b},
\end{aligned}
$$

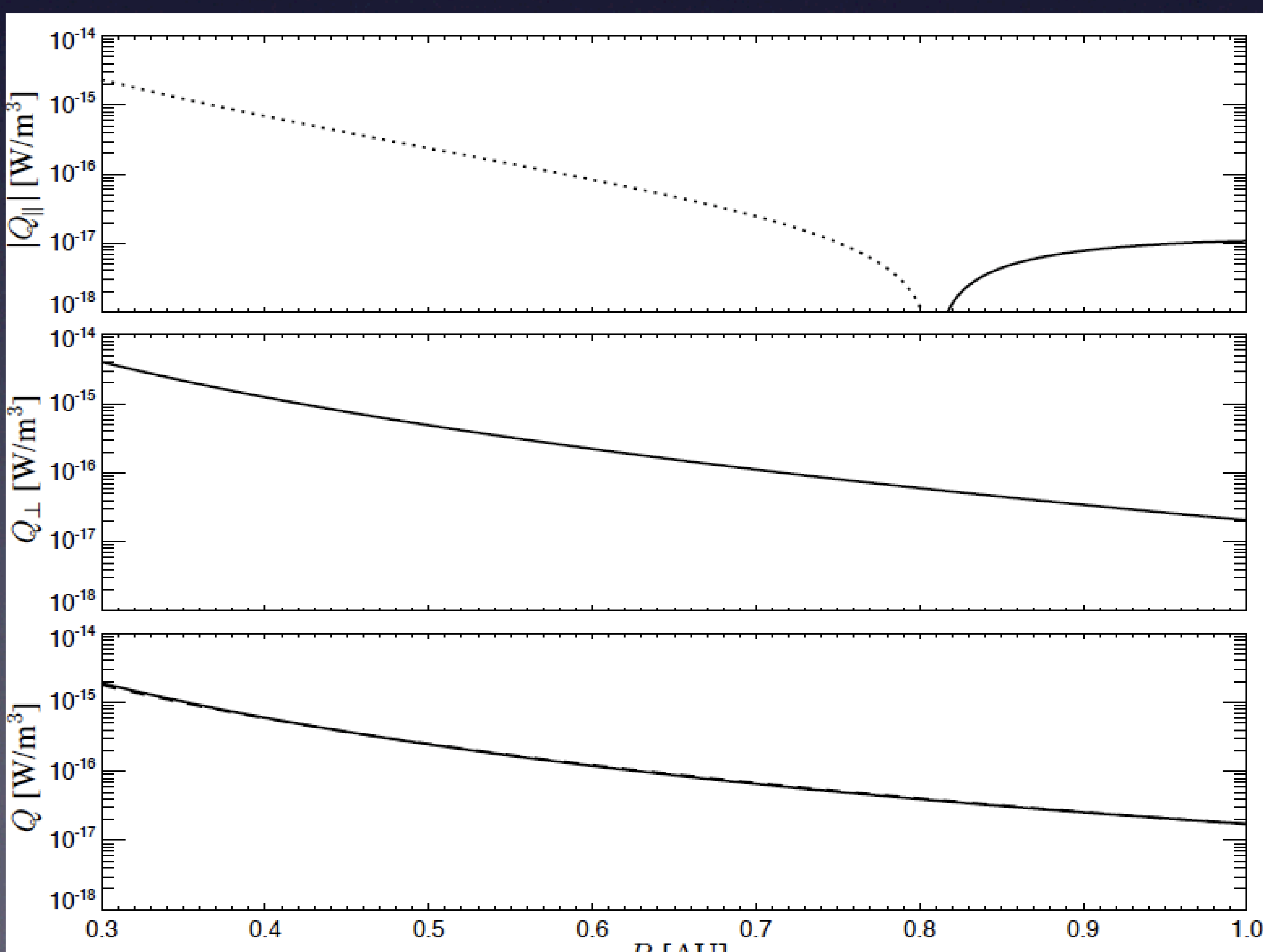
$$
\begin{aligned}
Q_{\|} &= n k_B (\boldsymbol{u}\cdot\boldsymbol{\nabla}T_{\|} + 2T_{\|}\boldsymbol{\nabla}_{\|}\cdot\boldsymbol{u}), \\
Q_{\perp} &= n k_B (\boldsymbol{u}\cdot\boldsymbol{\nabla}T_{\perp} + T_{\perp}\boldsymbol{\nabla}_{\perp}\cdot\boldsymbol{u}),
\end{aligned}
$$

"Heating and cooling of protons in the fast solar wind between 0.3 and 1 AU: Helios revisited"

Hellinger, Matteini et al. JGR submitted







$$
\begin{aligned}
nk_\mathrm{B}\left(\frac{\partial}{\partial t}+\boldsymbol{u}\cdot\boldsymbol{\nabla}\right)T_\parallel &= nk_\mathrm{B}\left[-2T_\parallel\boldsymbol{\nabla}_\parallel\cdot\boldsymbol{u}+\left(\frac{\mathrm{d}T_\parallel}{\mathrm{d}t}\right)_\mathrm{c}\right] \\
&\quad -\boldsymbol{\nabla}\cdot(q_\parallel\boldsymbol{b})+2q_\perp\boldsymbol{\nabla}\cdot\boldsymbol{b}, \\
nk_\mathrm{B}\left(\frac{\partial}{\partial t}+\boldsymbol{u}\cdot\boldsymbol{\nabla}\right)T_\perp &= nk_\mathrm{B}\left[-T_\perp\boldsymbol{\nabla}_\perp\cdot\boldsymbol{u}+\left(\frac{\mathrm{d}T_\perp}{\mathrm{d}t}\right)_\mathrm{c}\right] \\
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$$
\begin{aligned}
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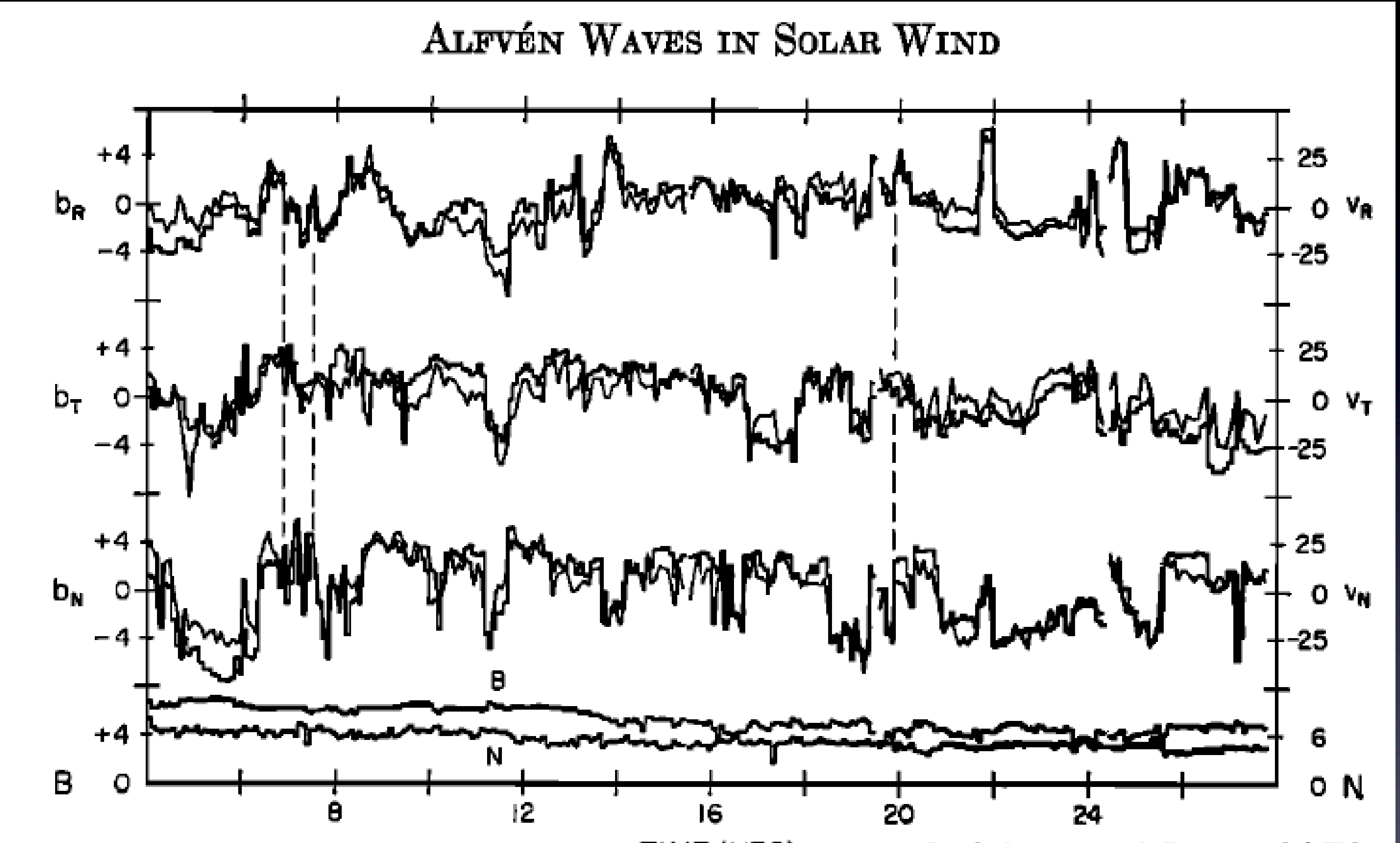
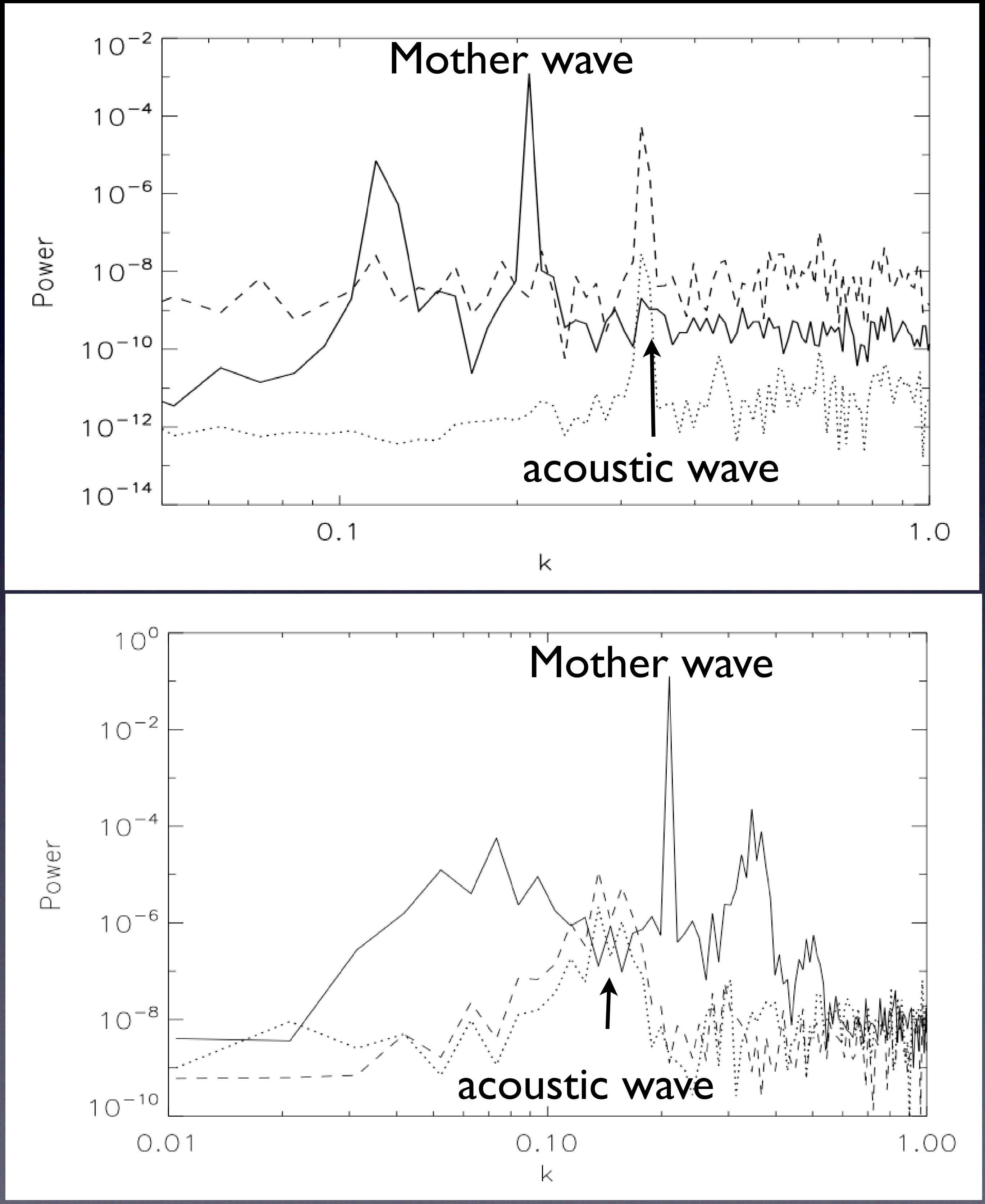
Alfvén waves in space plasmas



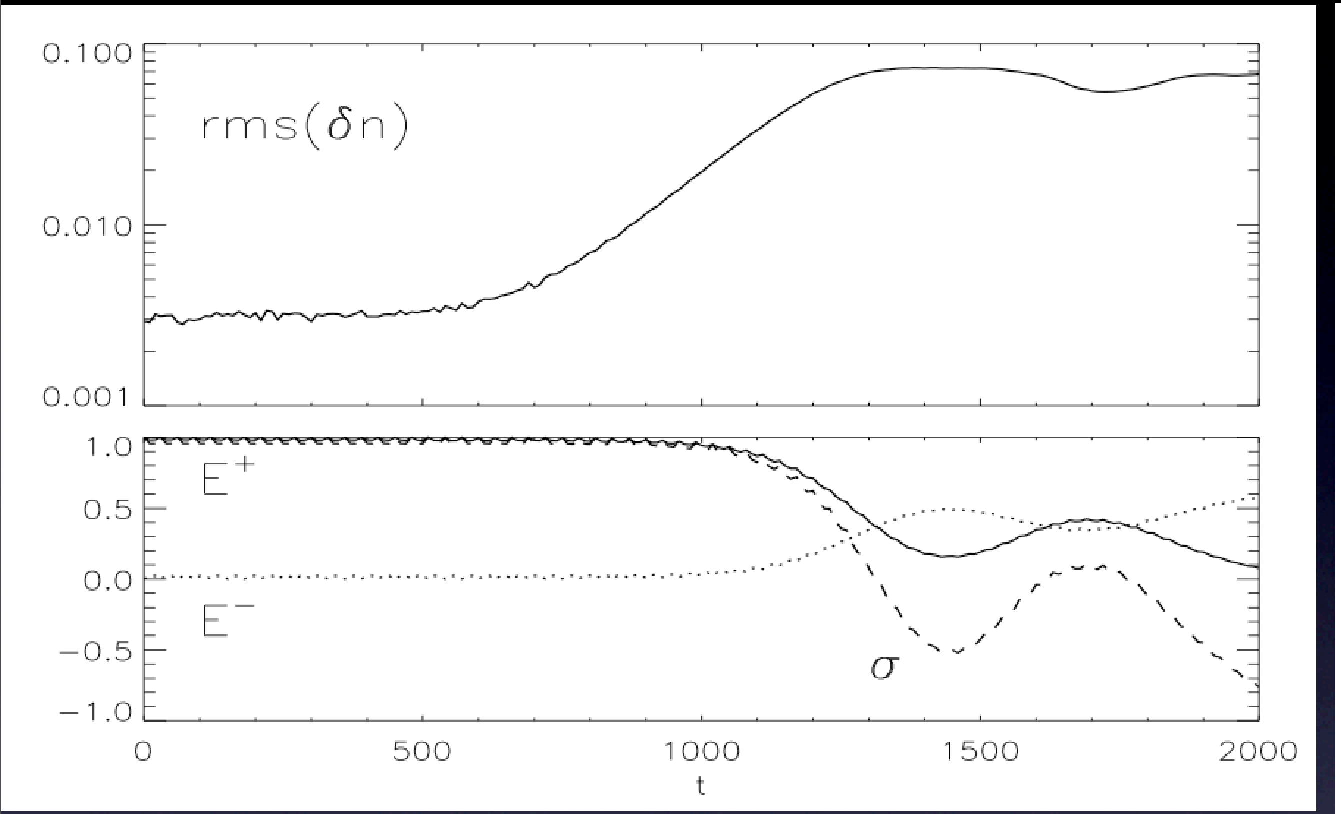
Belcher and Davis 1971

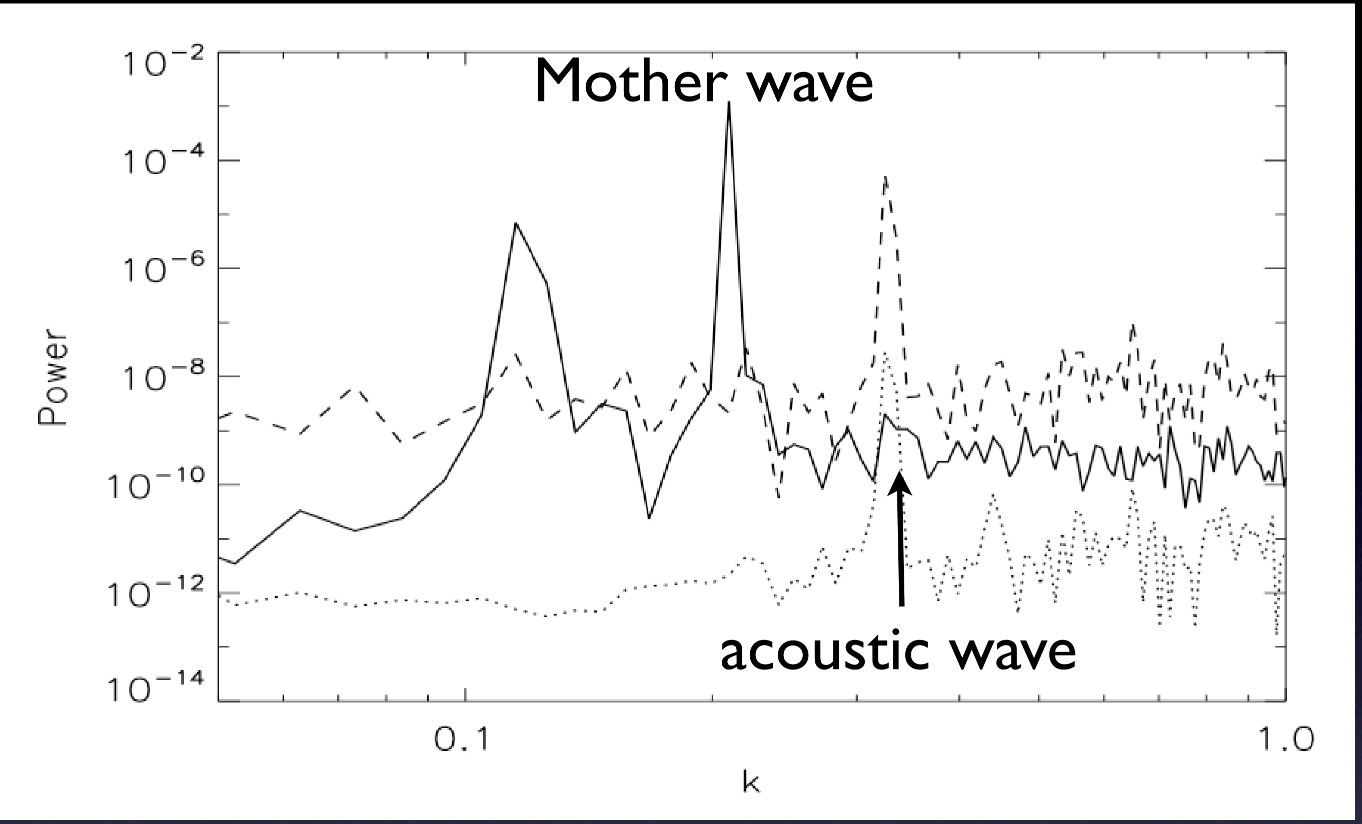
B-v correlation, |B| and n almost constant, E(z+)>E(z-)

Wave-wave coupling: Parametric instability
Field and spectrum signatures



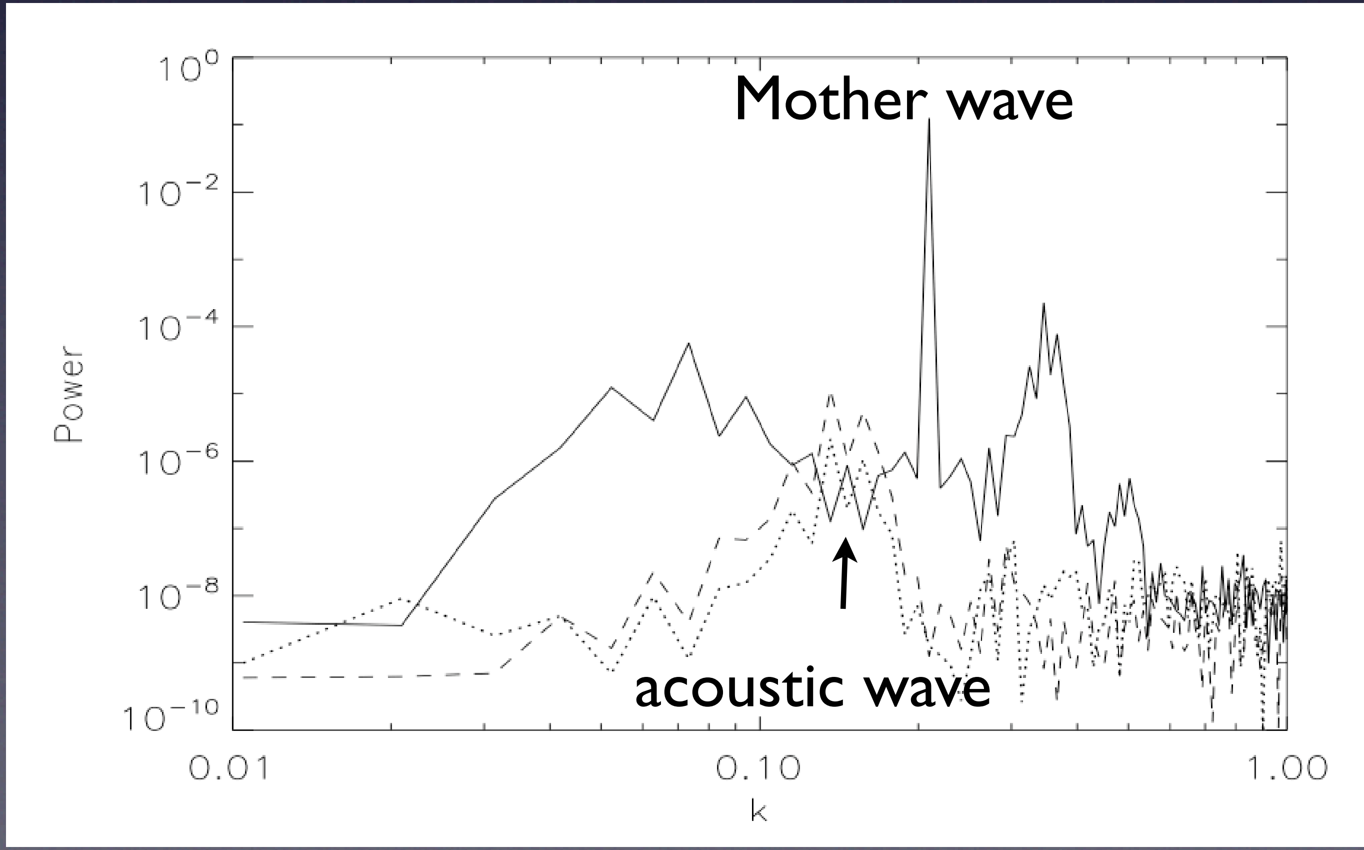
Wave-wave coupling: Parametric instability
Field and spectrum signatures





Decay E- >0

Modulational E- =0



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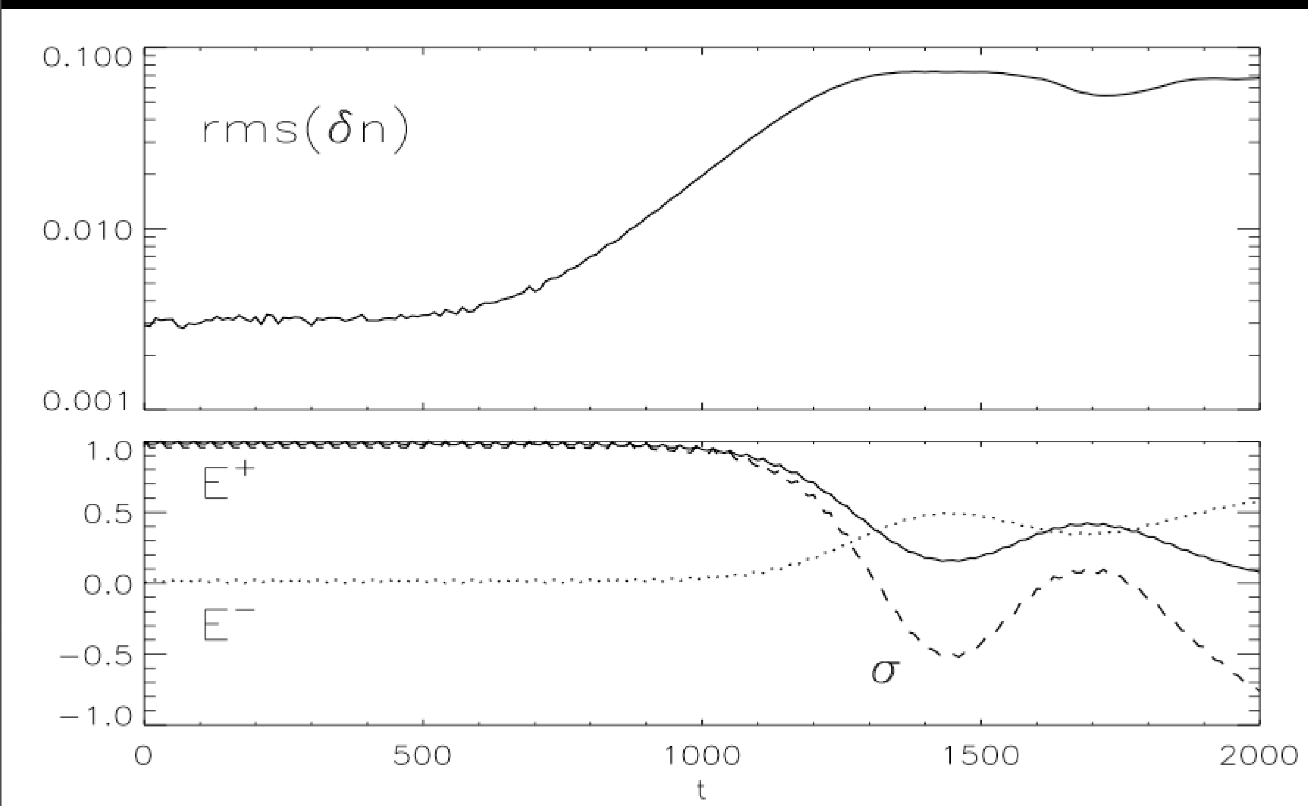

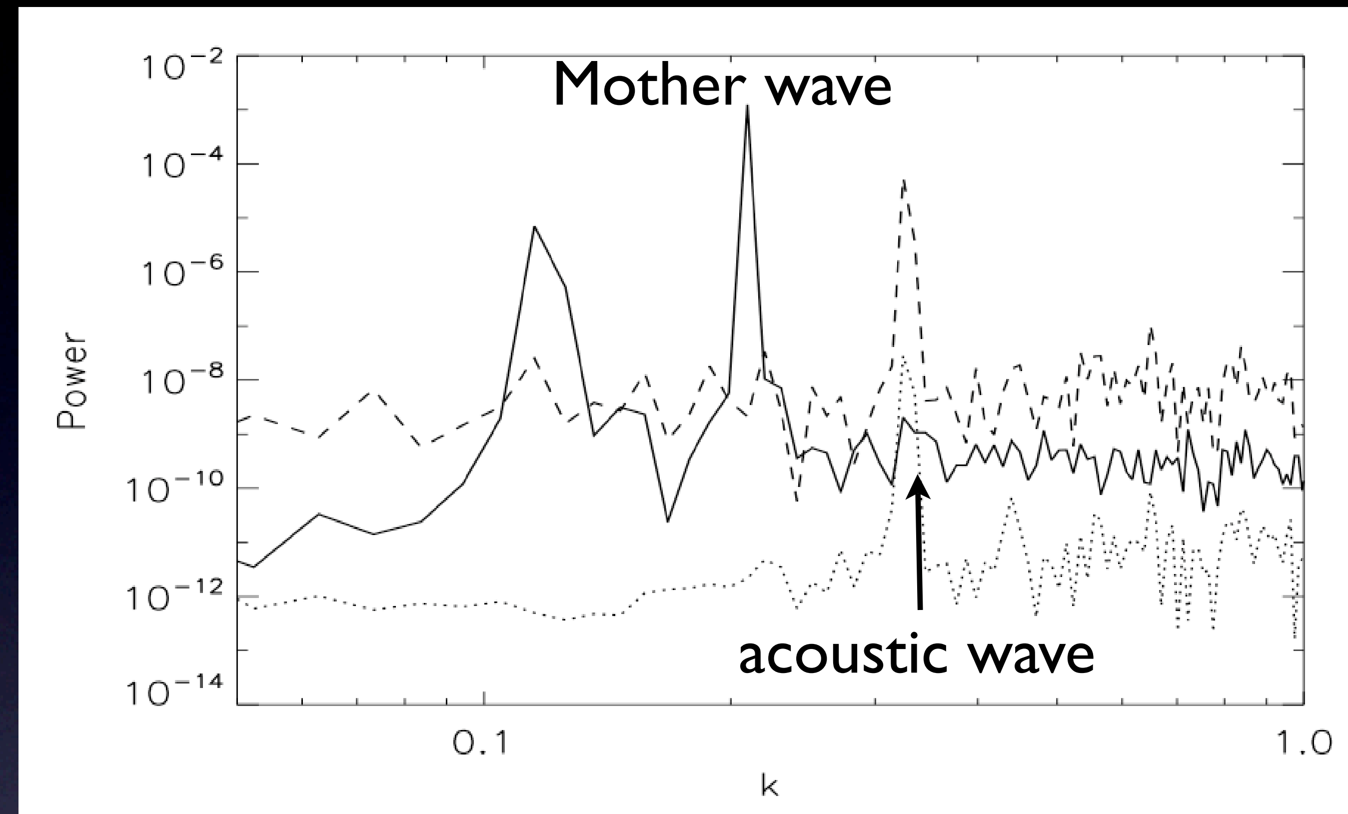

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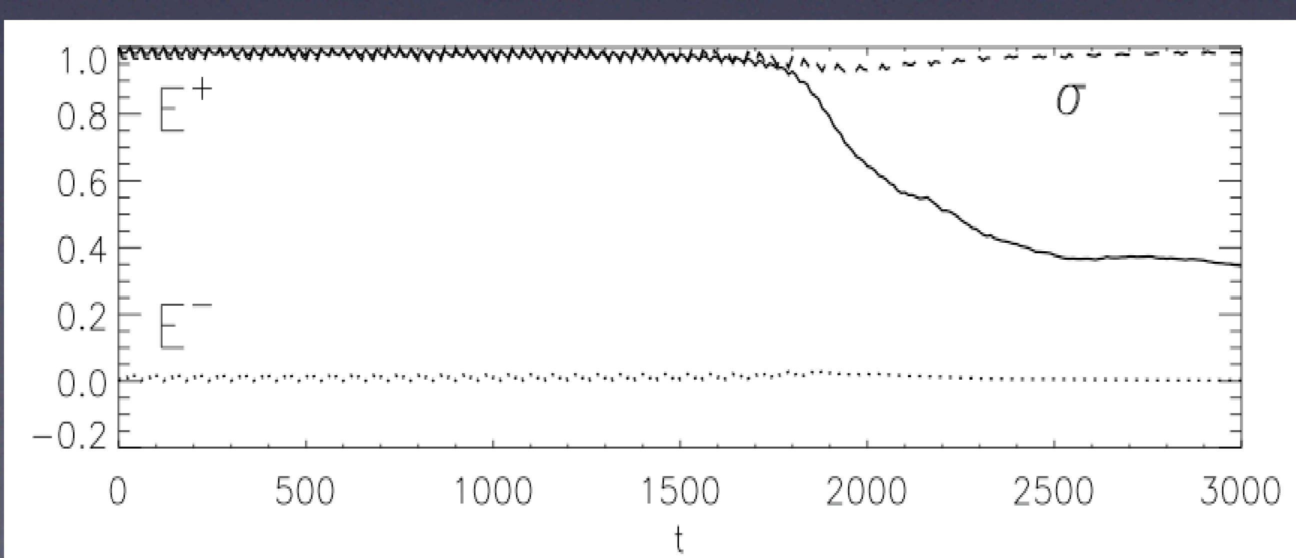
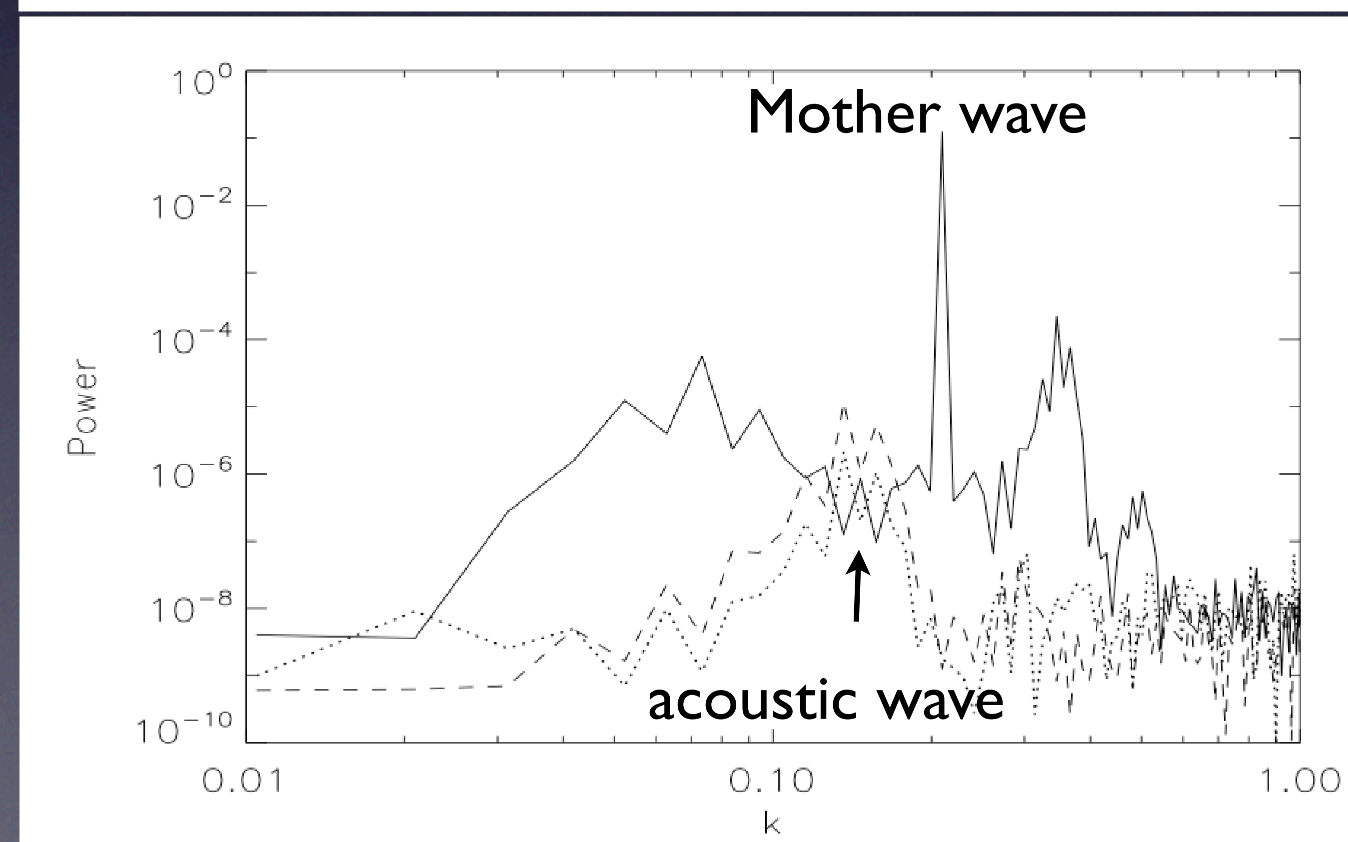
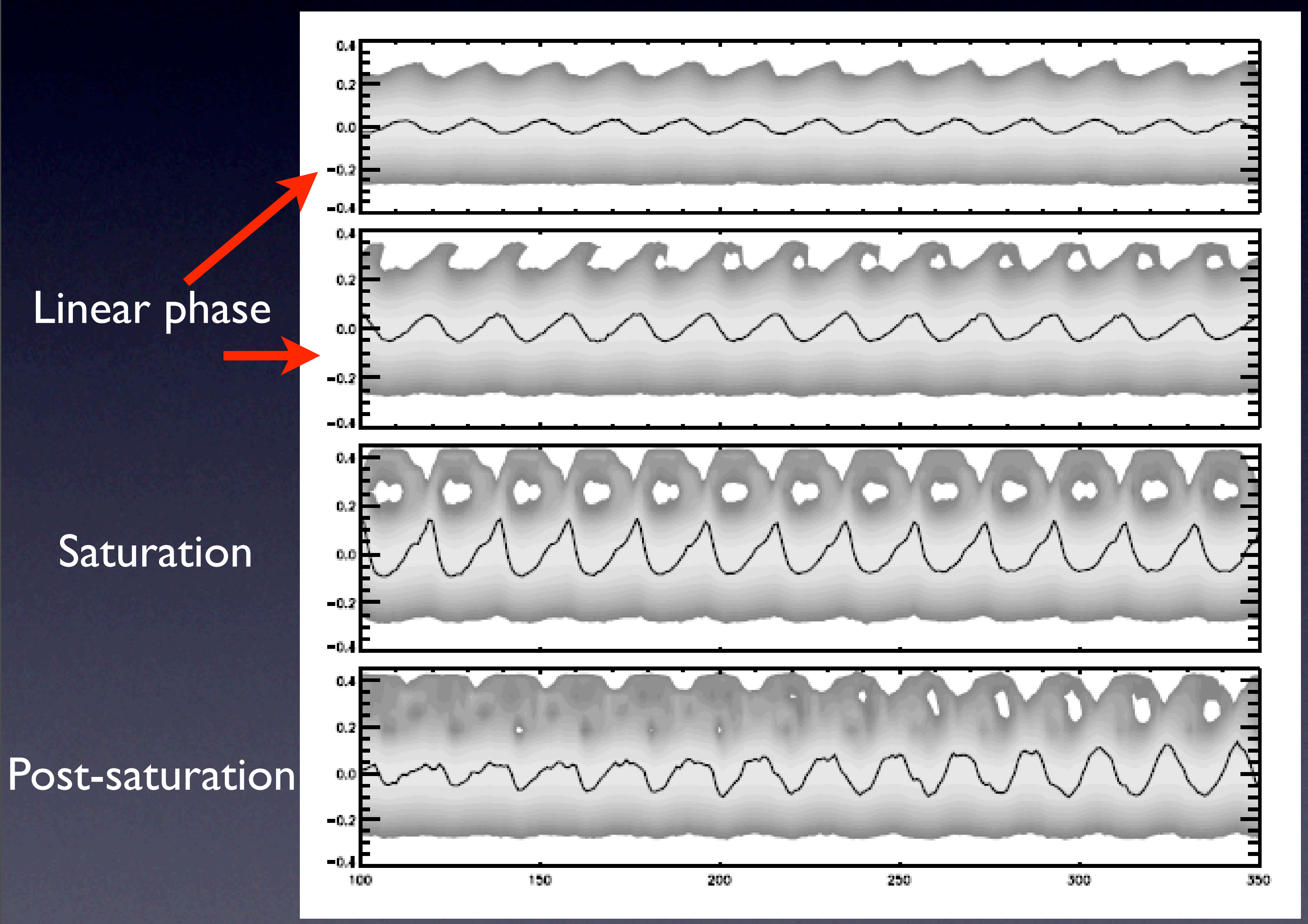




Wave-wave coupling:
Parametric instability and beam generation

(see also Araneda's talk et *Araneda 2008*)

Proton phase space x-vx



Parametric decay of a monochromatic Alfvén wave
(*Matteini et al. JGR 2010*)

Wave-wave coupling: Parametric instability and beam generation

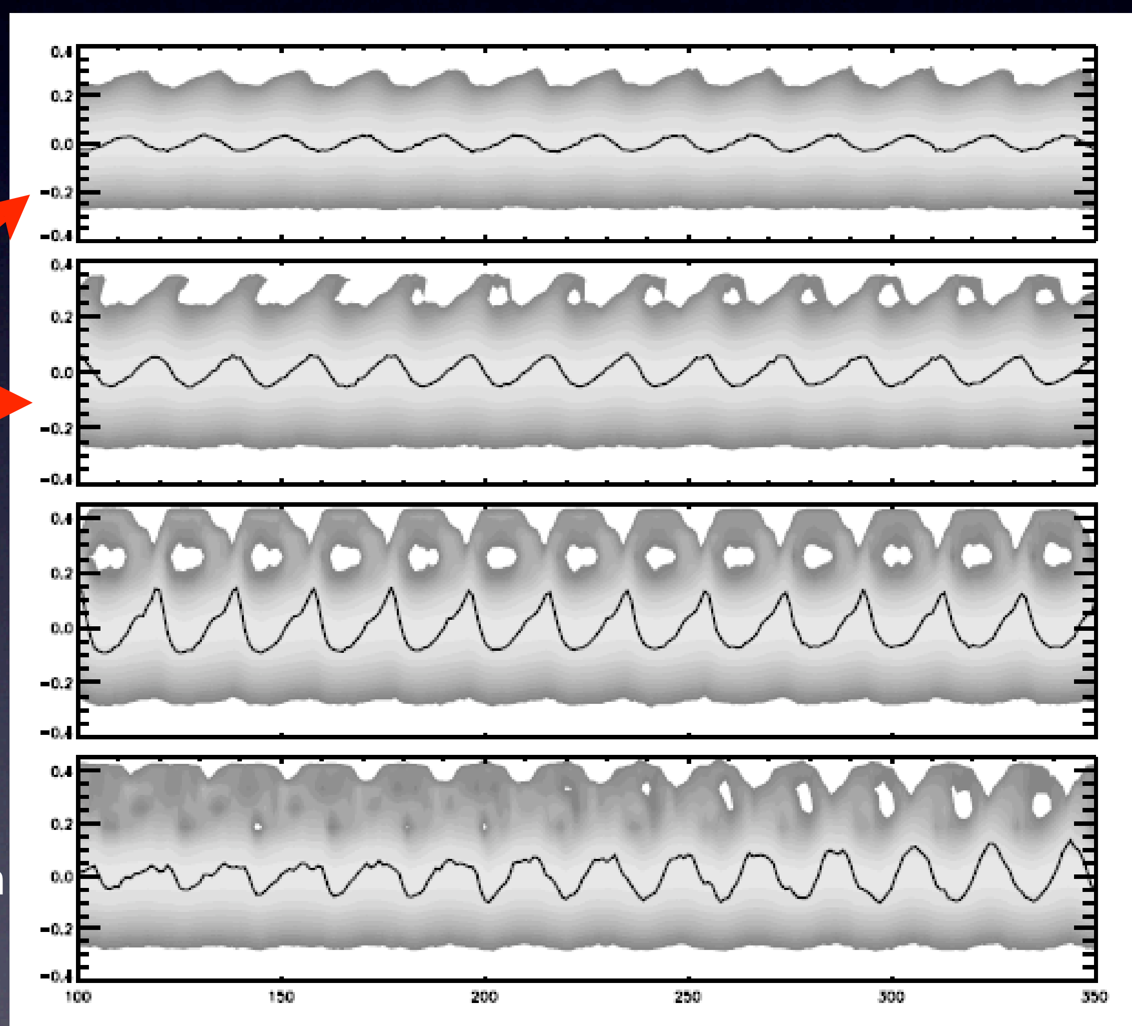
(see also Araneda's talk et *Araneda 2008*)

Proton phase space x-v_x

Linear phase

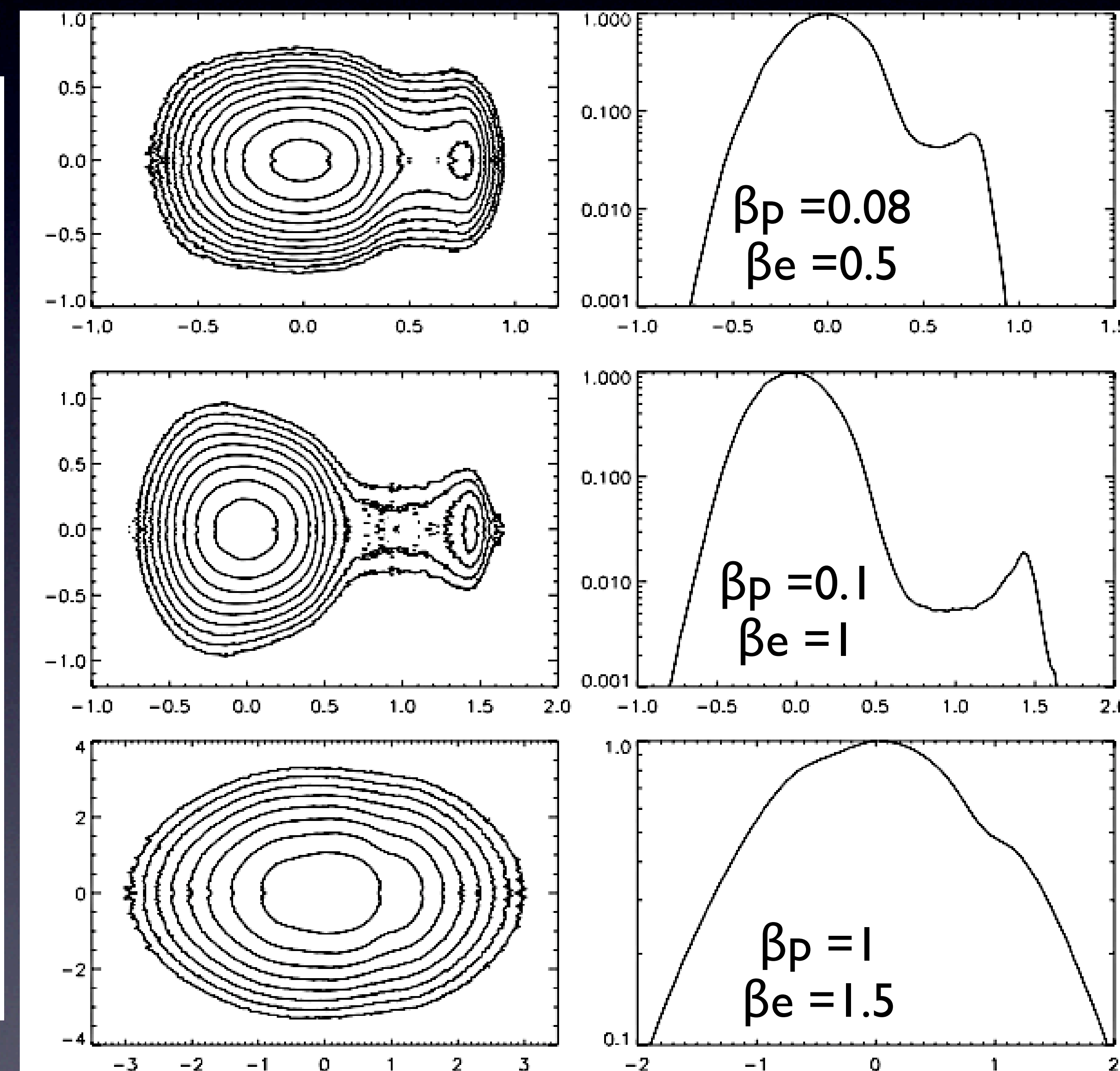
Saturation

Post-saturation



Parametric decay of a monochromatic Alfvén wave (*Matteini et al. JGR 2010*)

Beam properties with different betas



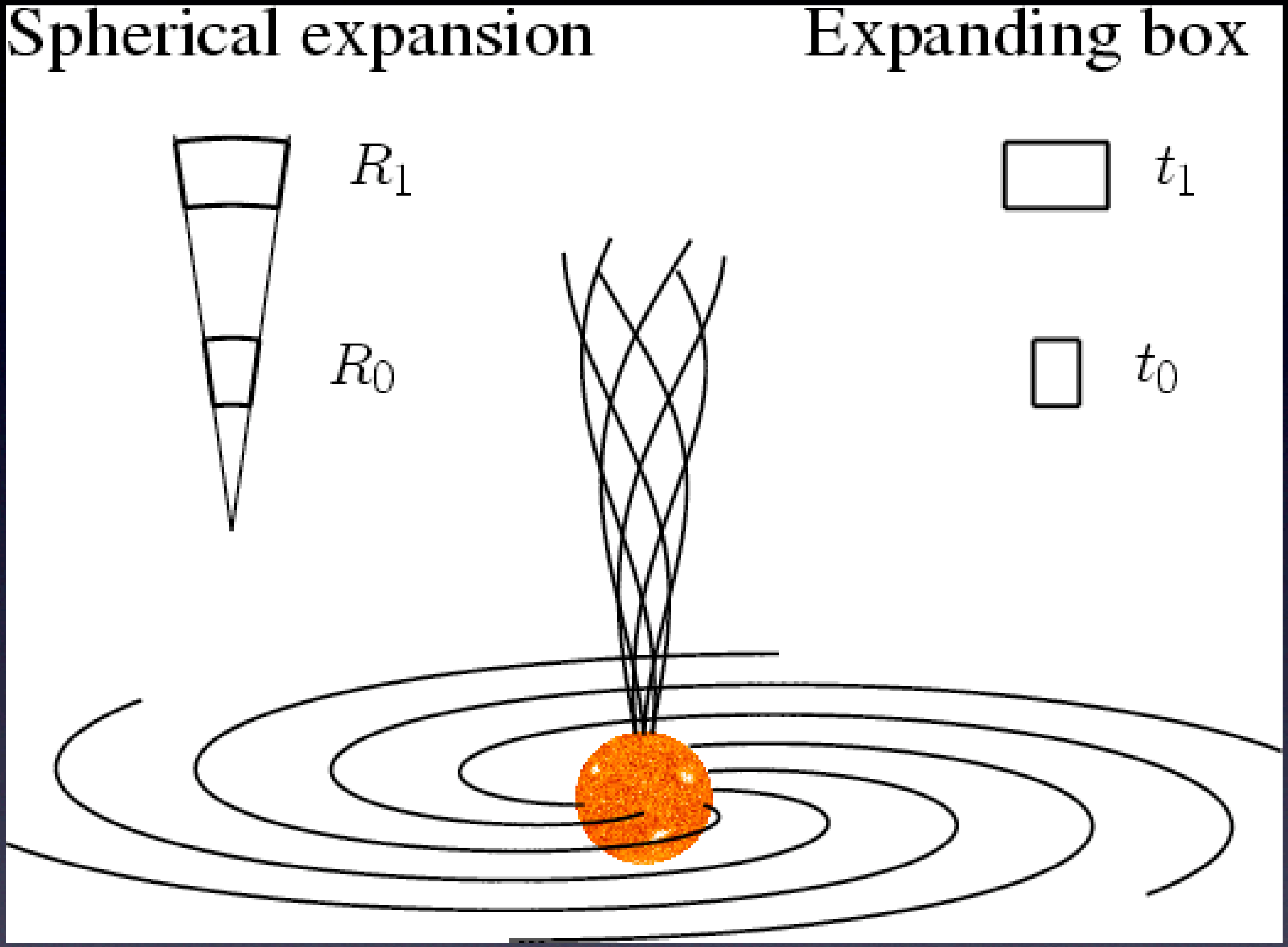
Drift velocity increases with increasing beta, in agreement with observations (*Tu et al., 2004*)

The Hybrid Expanding Box code (HEB)

To study non-linear wave-particle interactions during the solar wind expansion, we perform numerical simulation using a hybrid code implemented with an expanding box model (*Liewer et al. 2001, Hellinger et al. 2003*).

- Hybrid model: electrons are described as an isotropic massless fluid and protons (ions) as particles (*Matthews 1994*).

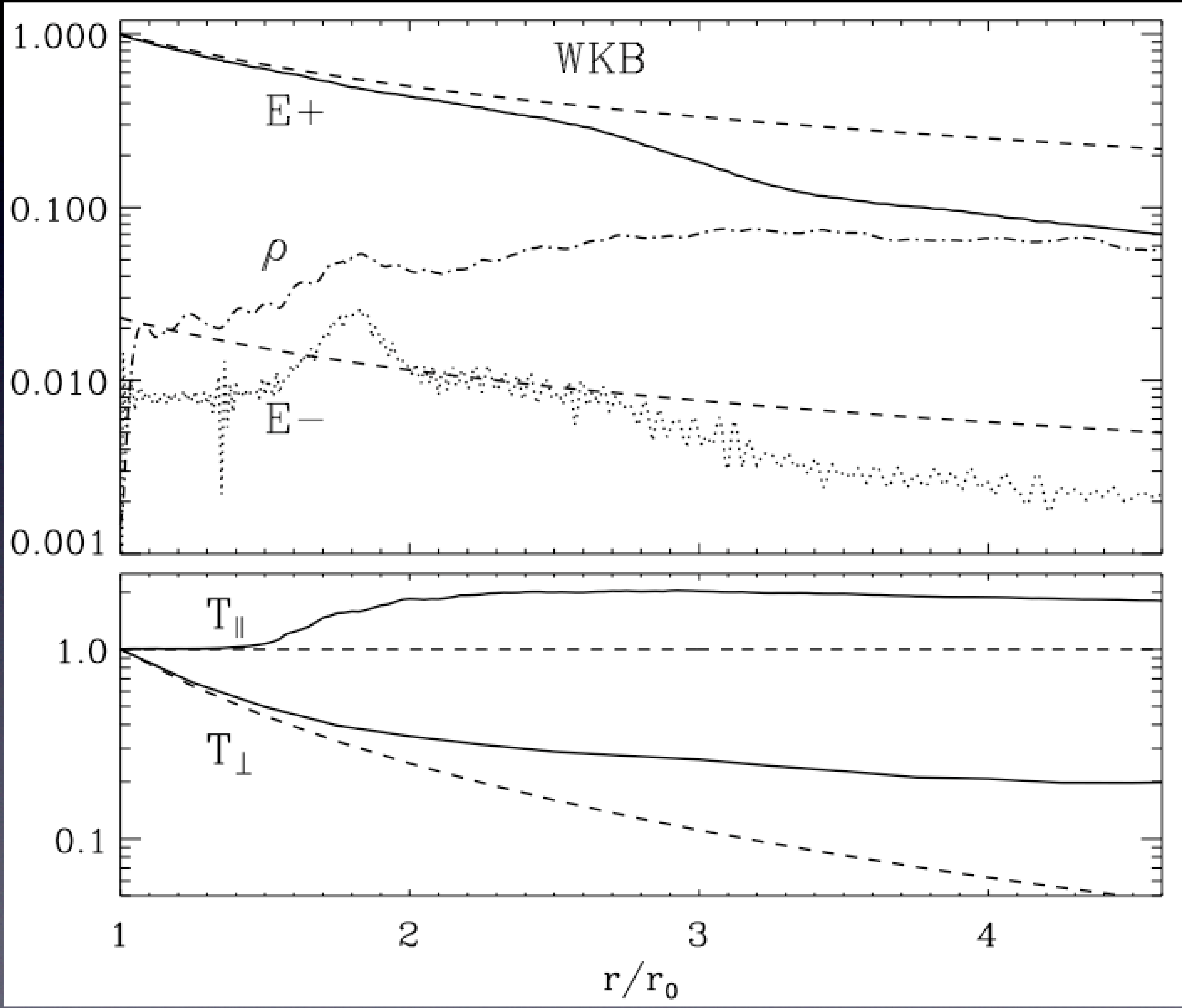
- The expanding box model assumes a radial linearly driven evolution with a constant expansion velocity; the transverse dimensions of the box (which co-moves with the wind) increase with distance (*Grappin et al. 1993*).



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

Self-consistent competition between the cooling driven by the expansion and the heating provided by wave-particle interactions and wave-wave instabilities

Evolution of a spectrum of outward Alfvén waves
Expanding simulation



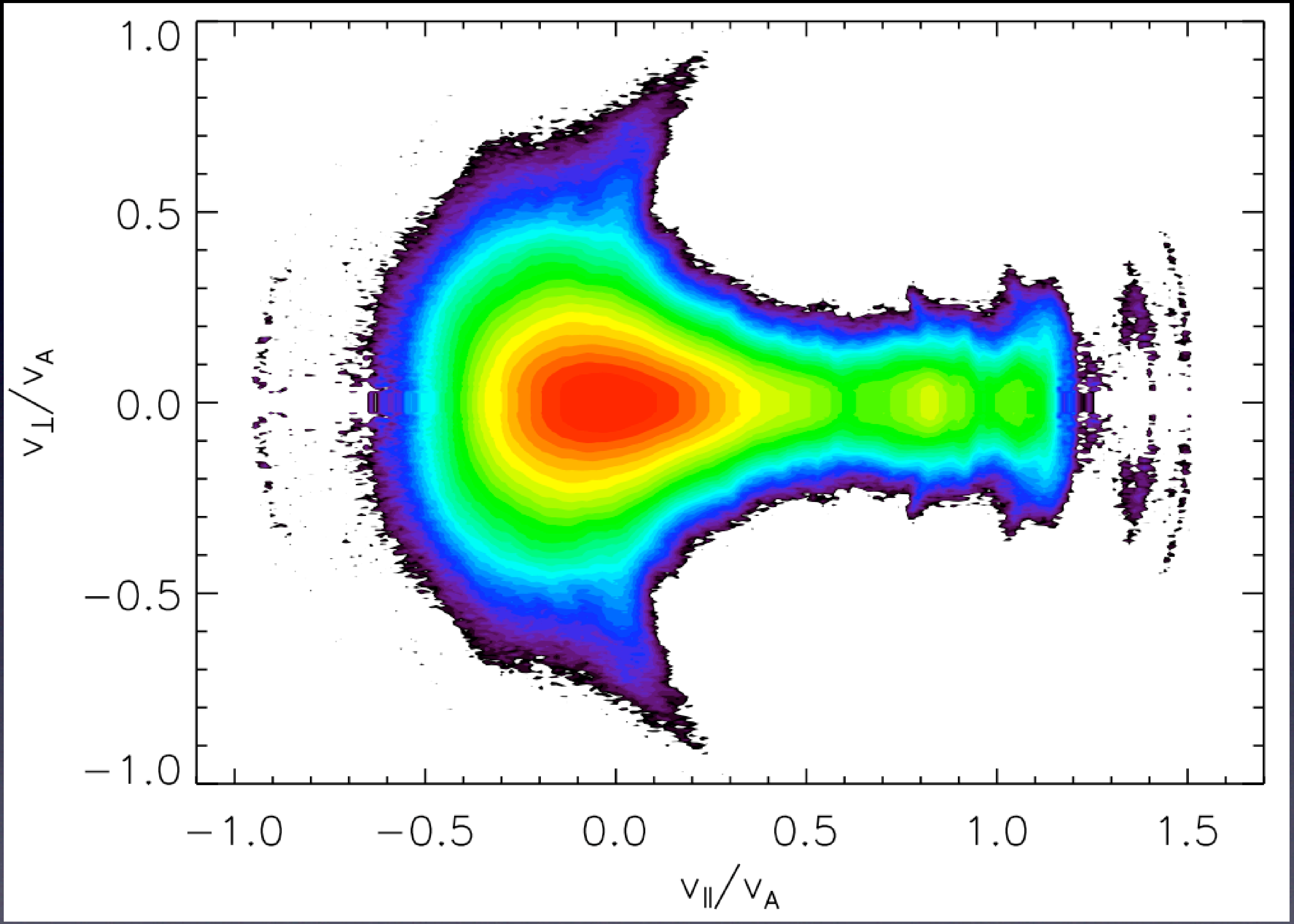
Wave energy decreases faster than the WKB and reveal the presence of parametric interactions

Parallel temperature increases due to the generation of a velocity beam

Protons are perpendicularly heated by waves

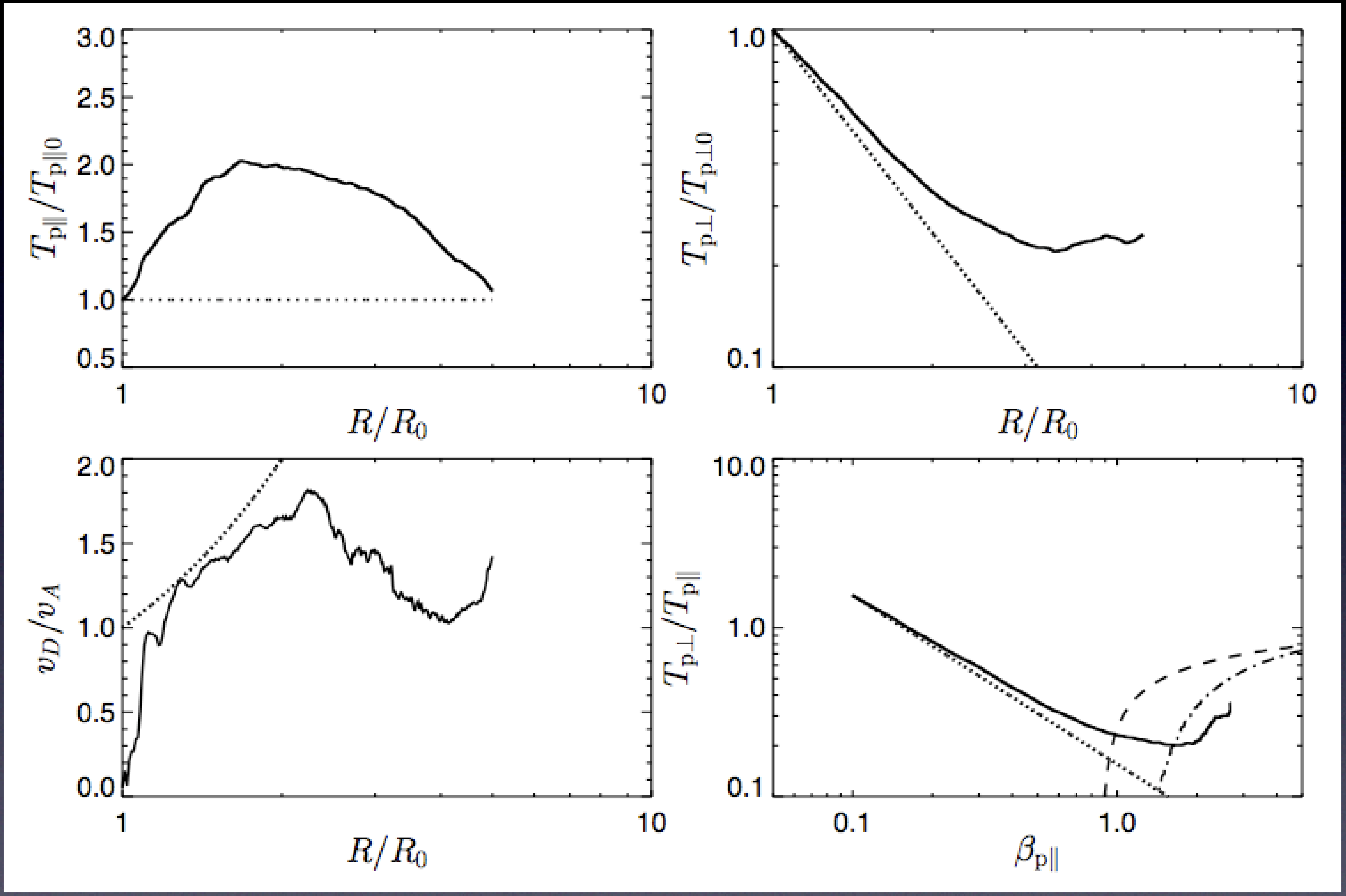
Evolution of the proton distribution function

Wave-particle interactions provide signatures in the proton distribution function



- Perpendicular heating due to ion-cyclotron interactions
- Parallel acceleration due to non-linear interactions with parametric instability

Generation and evolution of a proton beam



Acceleration and deceleration of the beam

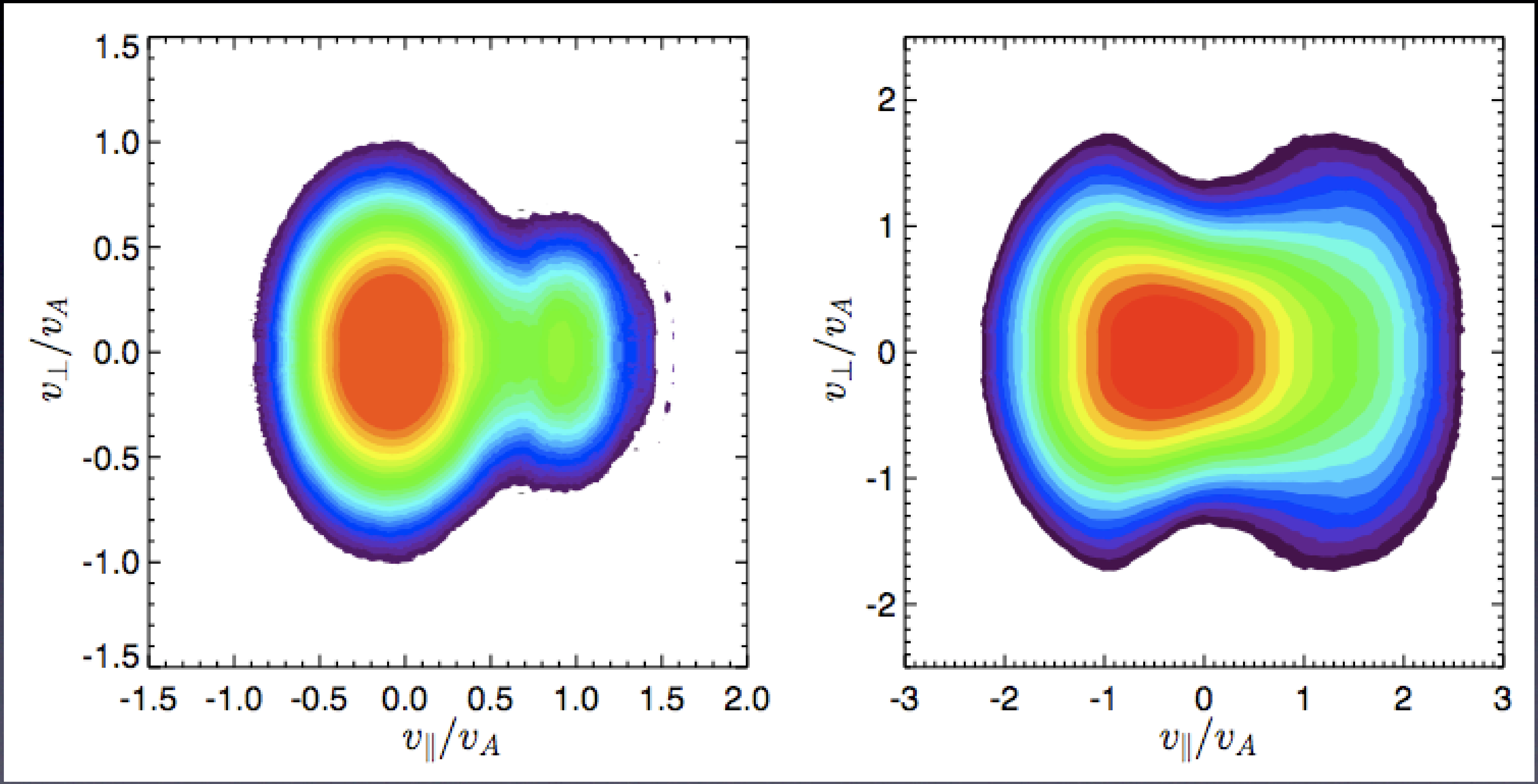
Perpendicular heating

Drift controlled by ion-beam instability

Fire hose

Matteini et al. SSR 2011

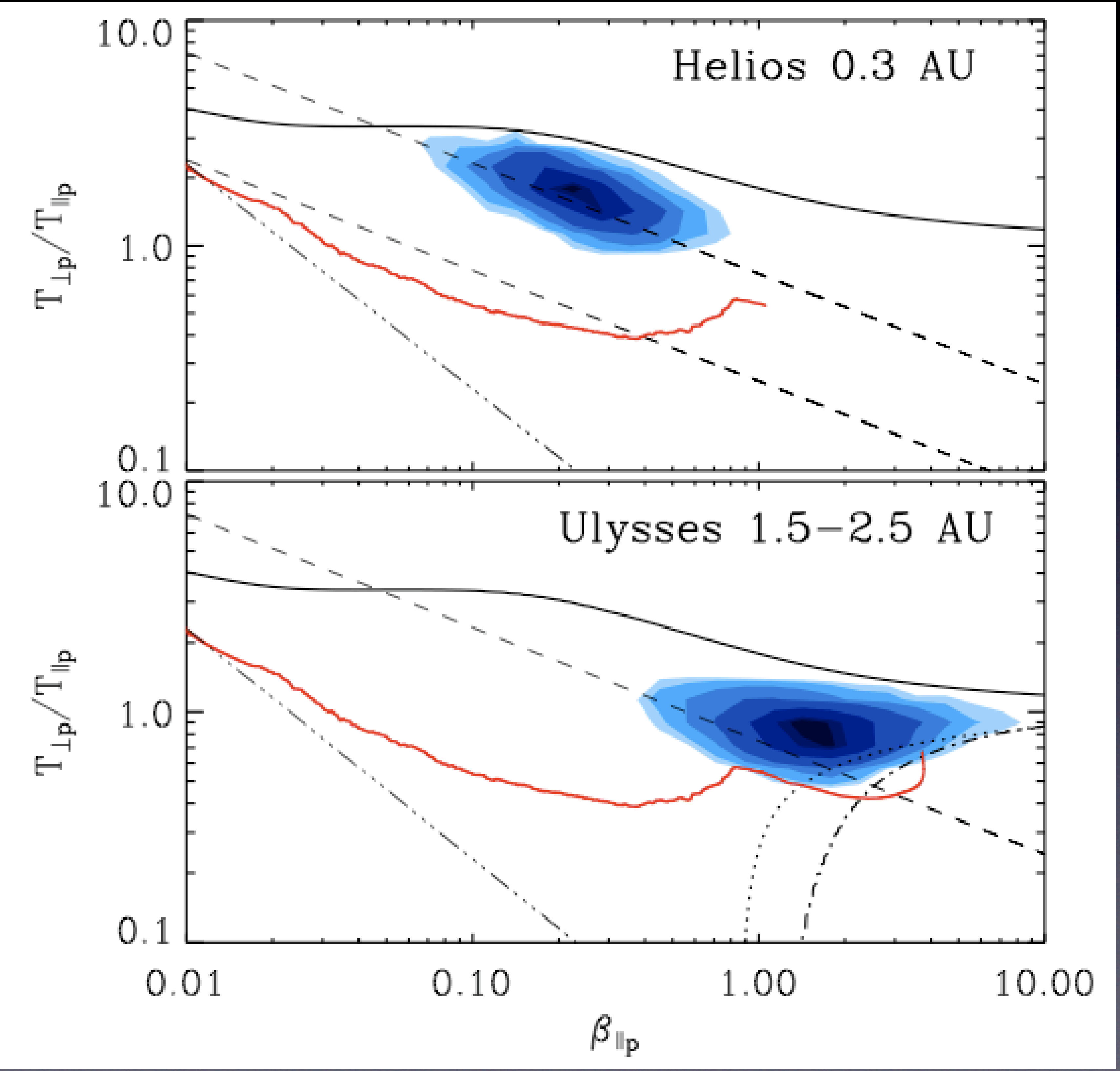
Evolution of proton distribution and ion-beam anisotropic heating



The kinetic energy of the beam drift is converted in anisotropic proton heating through ion-beam instability (*Schwartz et al. 1981, Daughton and Gary, 1998*)

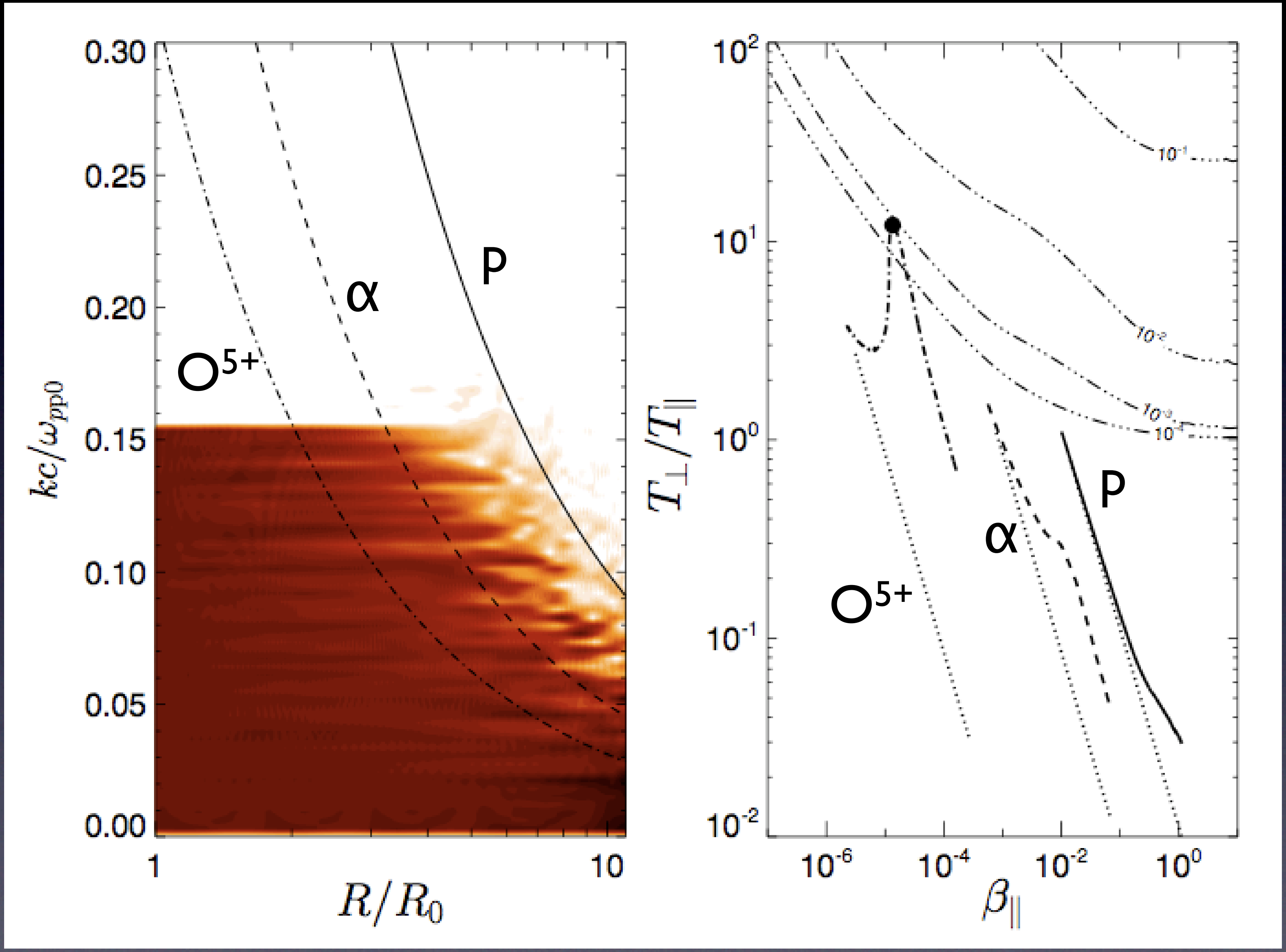
Evolution in the parameter space

The presence of a cyclotron perpendicular heating changes the trajectory of the system in the parameter space with respect the adiabatic case.



Cyclotron heating in the presence of minor ions

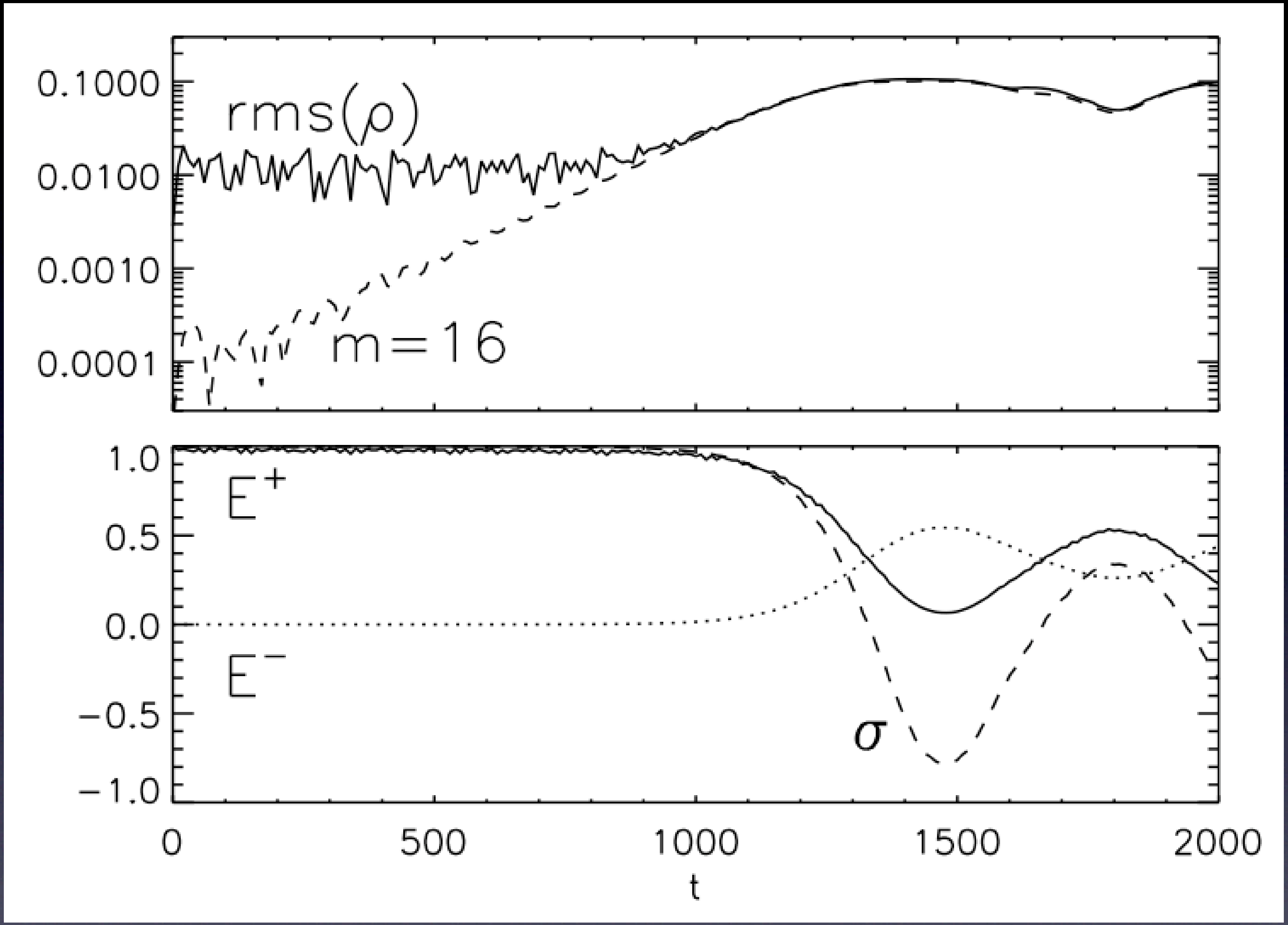
(*Hellinger et al. 2005, Matteini et al. 2011*)



Power absorbed by different species through frequency sweeping

Perpendicular preferential heating of minor ions

Oblique propagation: Parametric Decay 1-D



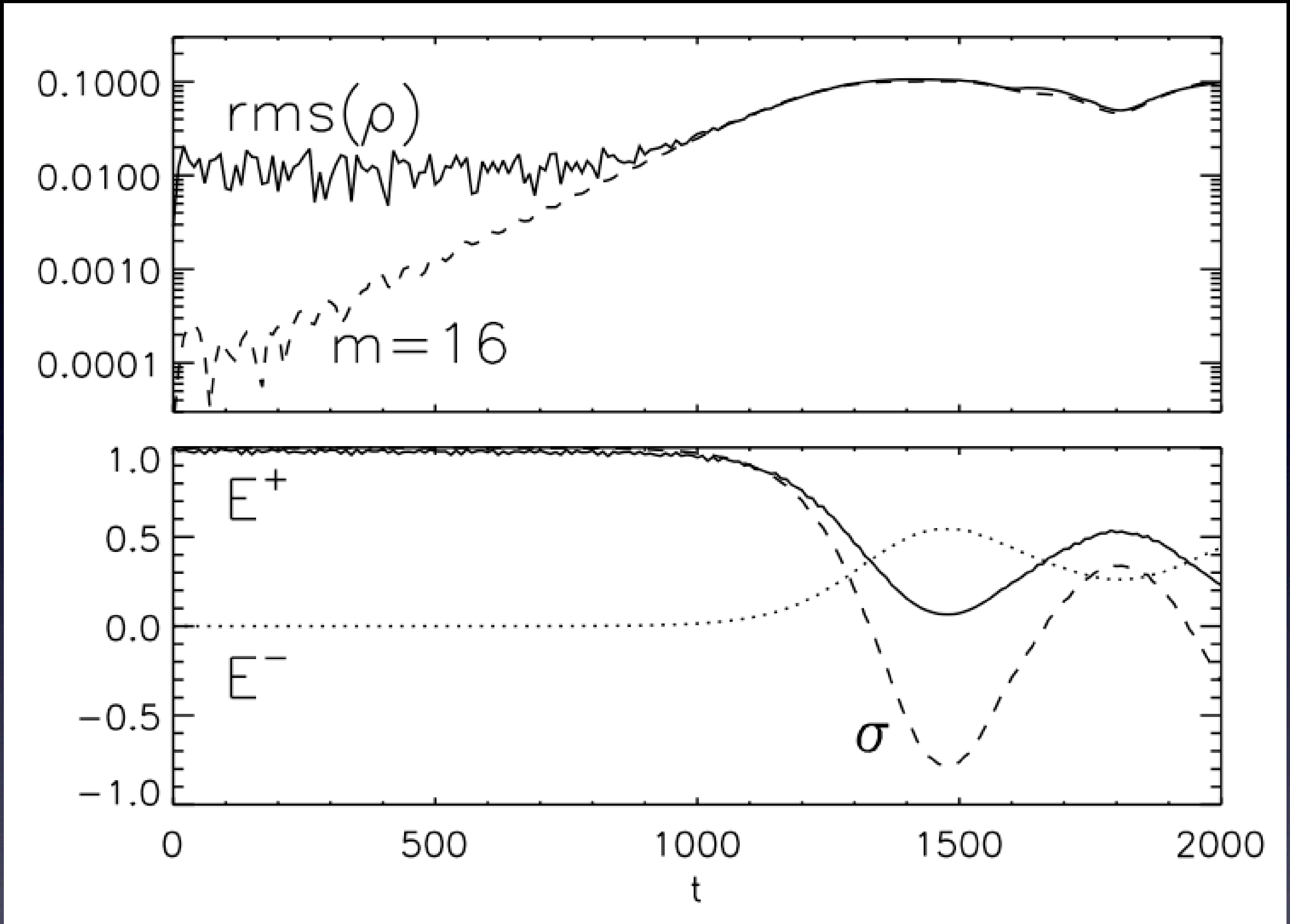
Enhancement of density fluctuations

Growth of an ion-acoustic mode

Damping of the mother wave

Generation of a backward propagating daughter Alfvén wave

Oblique propagation: Parametric Decay 1-D



Enhancement of density fluctuations

Growth of an ion-acoustic mode

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Generation of a backward propagating daughter Alfvén wave

Growth rate at different angles

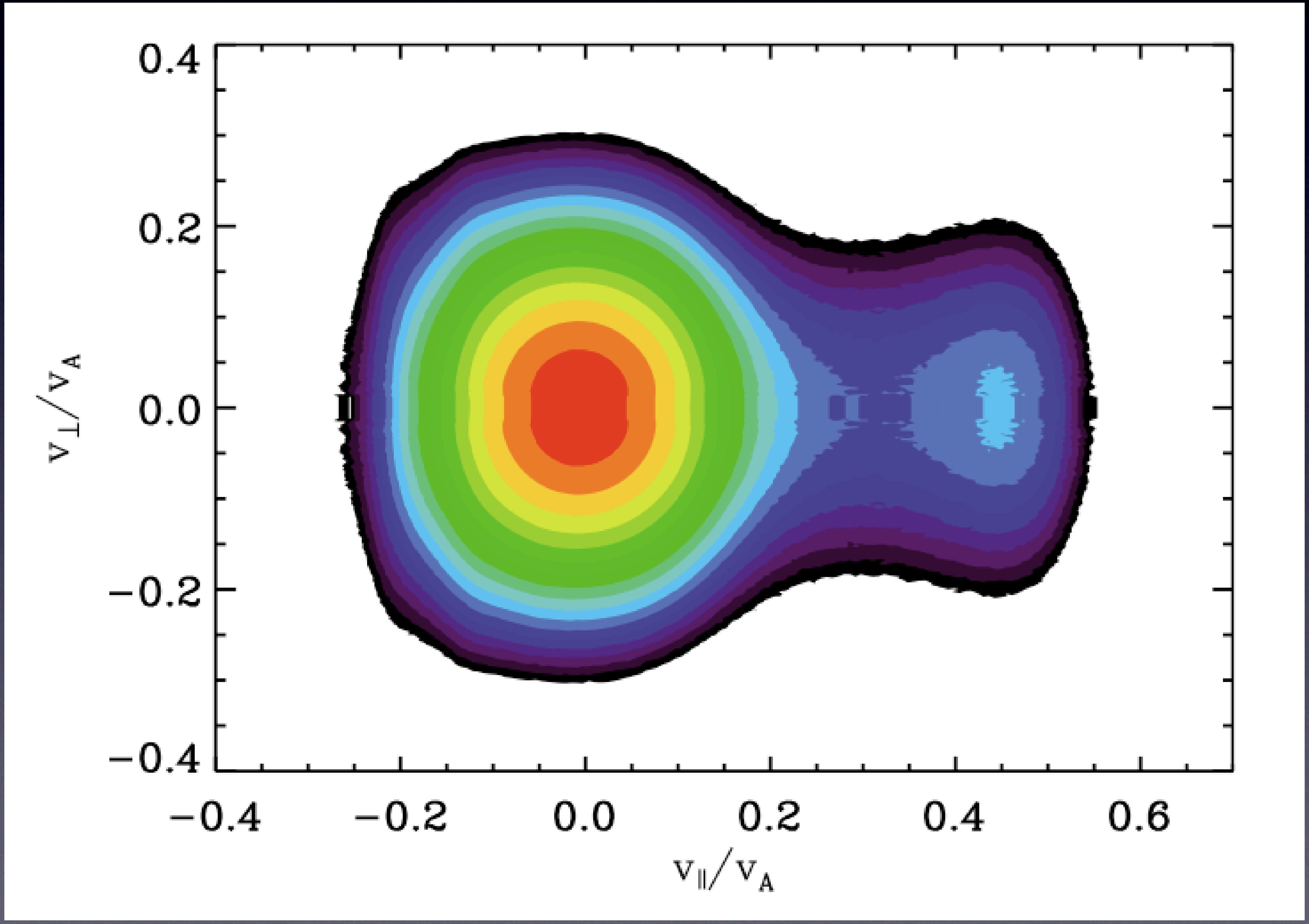
The instability growth rate decreases with increasing θ_{kB}

Table 1. Growth rate of parametric decay at various angles. For each angle we report the measured growth rate γ and the corresponding $\gamma_{||} = \gamma/\cos(\theta)$

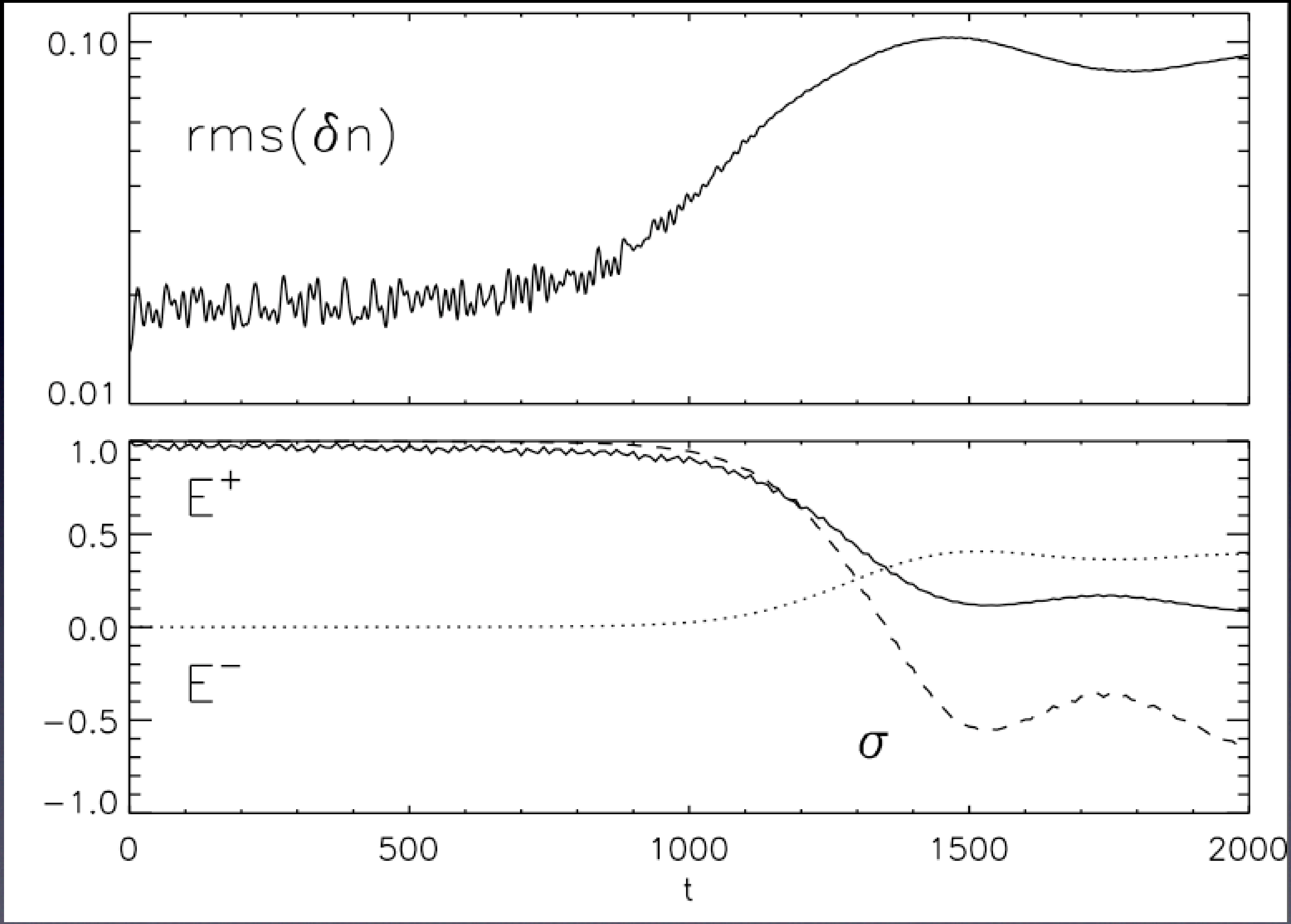
Run	θ_{kB}	k_0	k_s	k_-	γ	$\gamma_{\|\|}$
A	30	0.21	0.33	0.12	0.15	0.17
B	45	0.21	0.33	0.12	0.12	0.17
C	60	0.21	0.33	0.12	0.08	0.16

Evolution of proton distribution

Non-linear trapping by ion-acoustic waves generates velocity beams, like in the case of parallel mother waves (*Matteini et al., JGR 2010*)

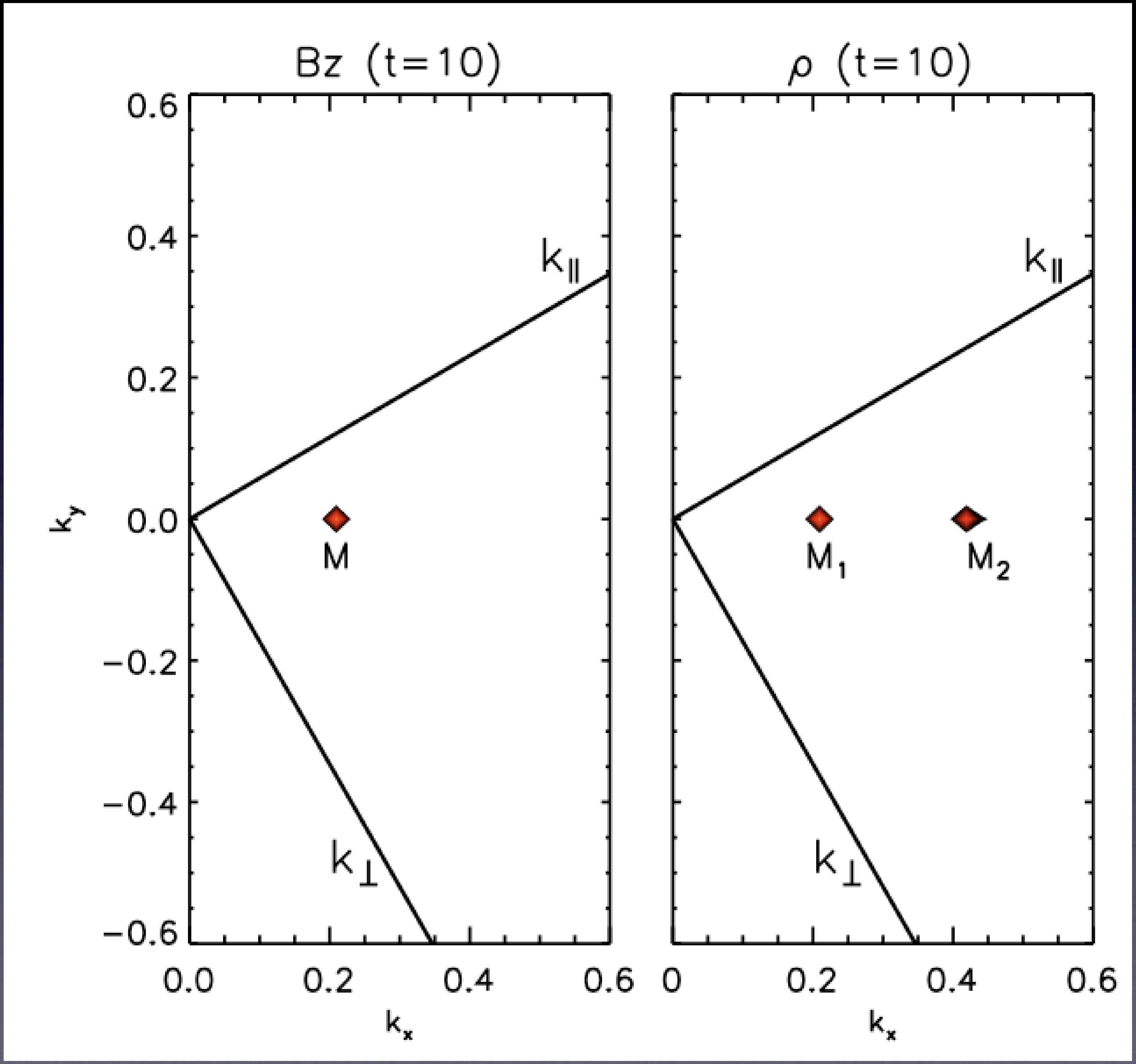


Oblique Decay 2-D



Any role of transverse couplings?

Perpendicular couplings and transverse modulation of B



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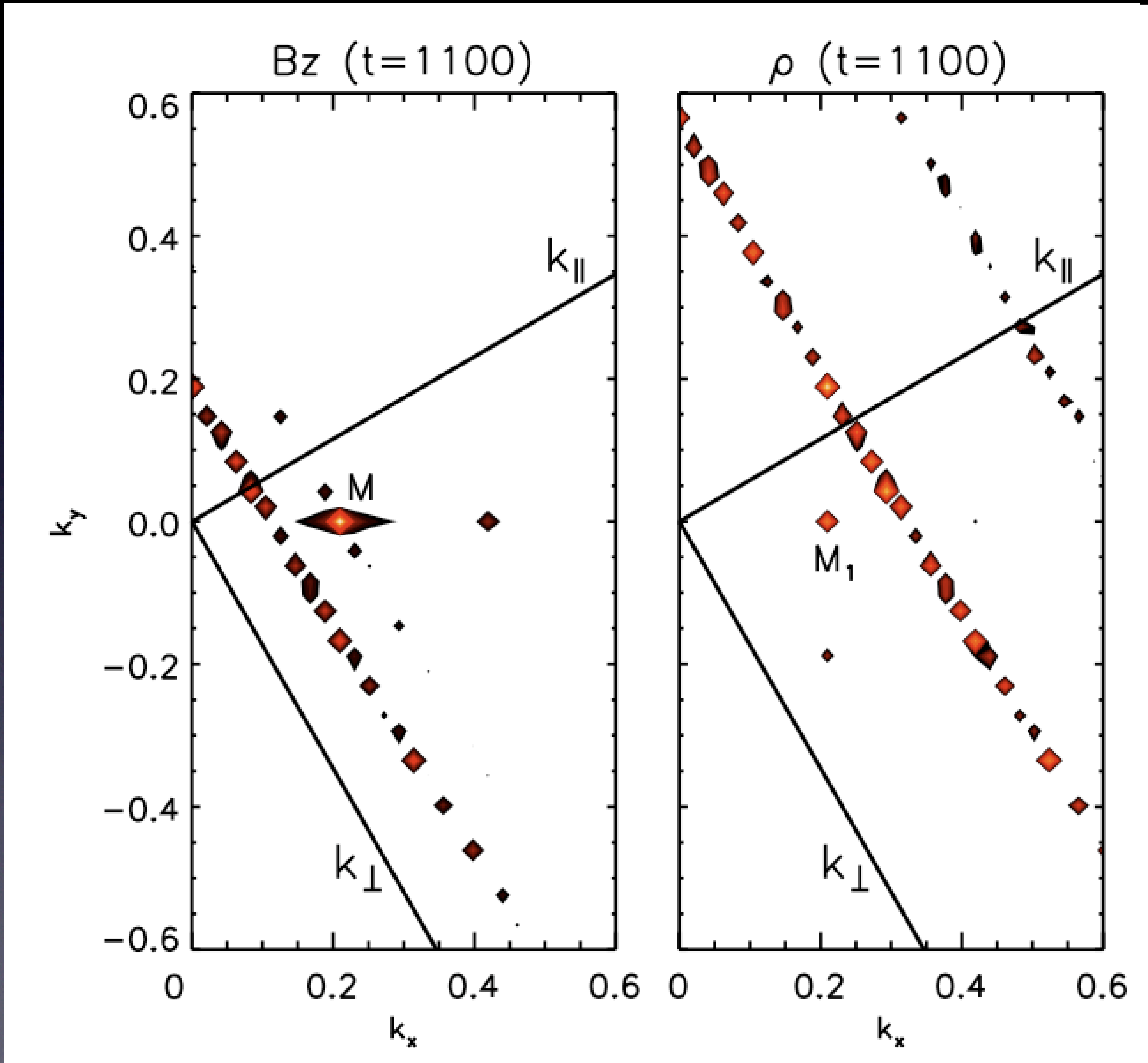

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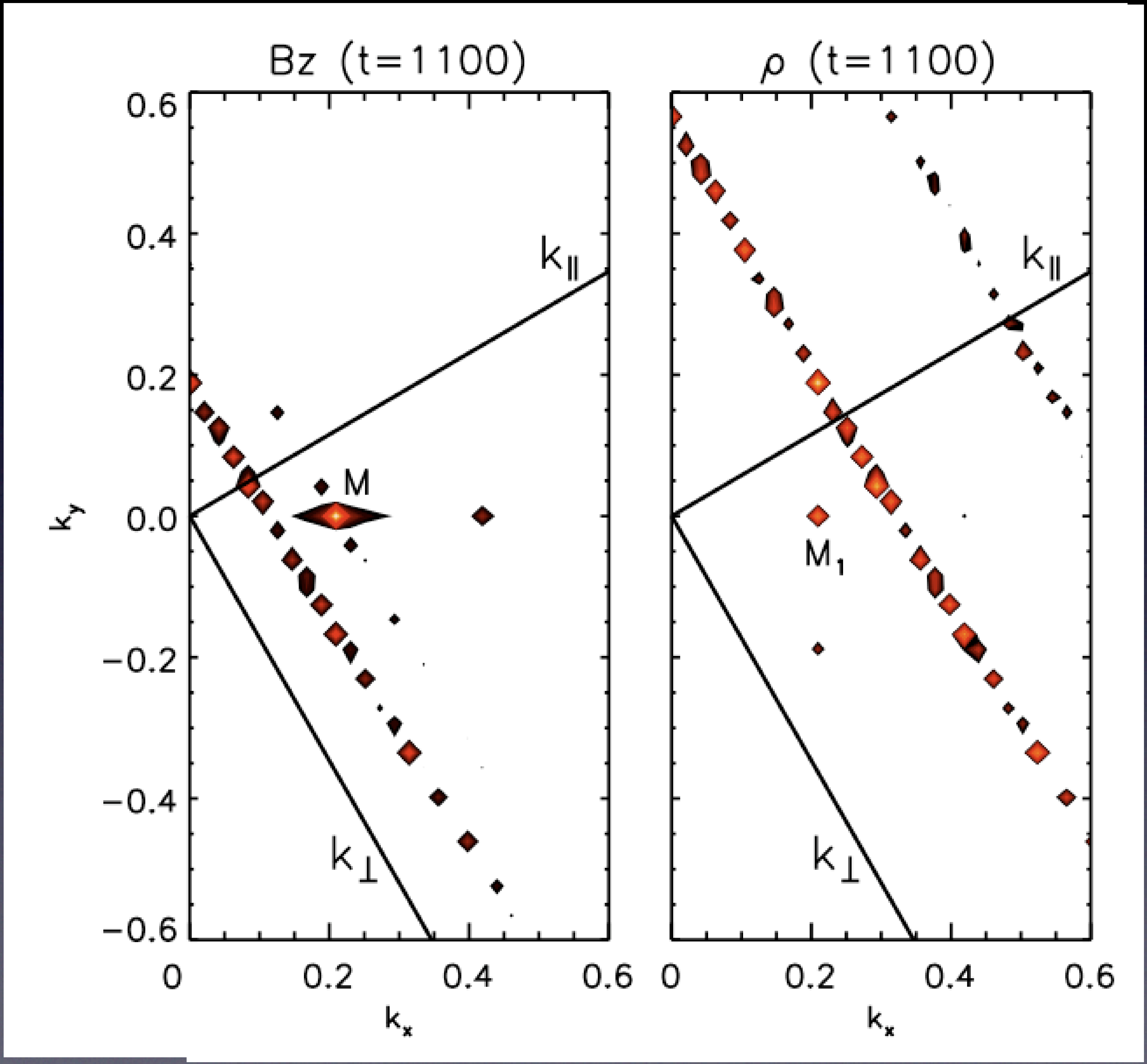


3-wave resonance along B

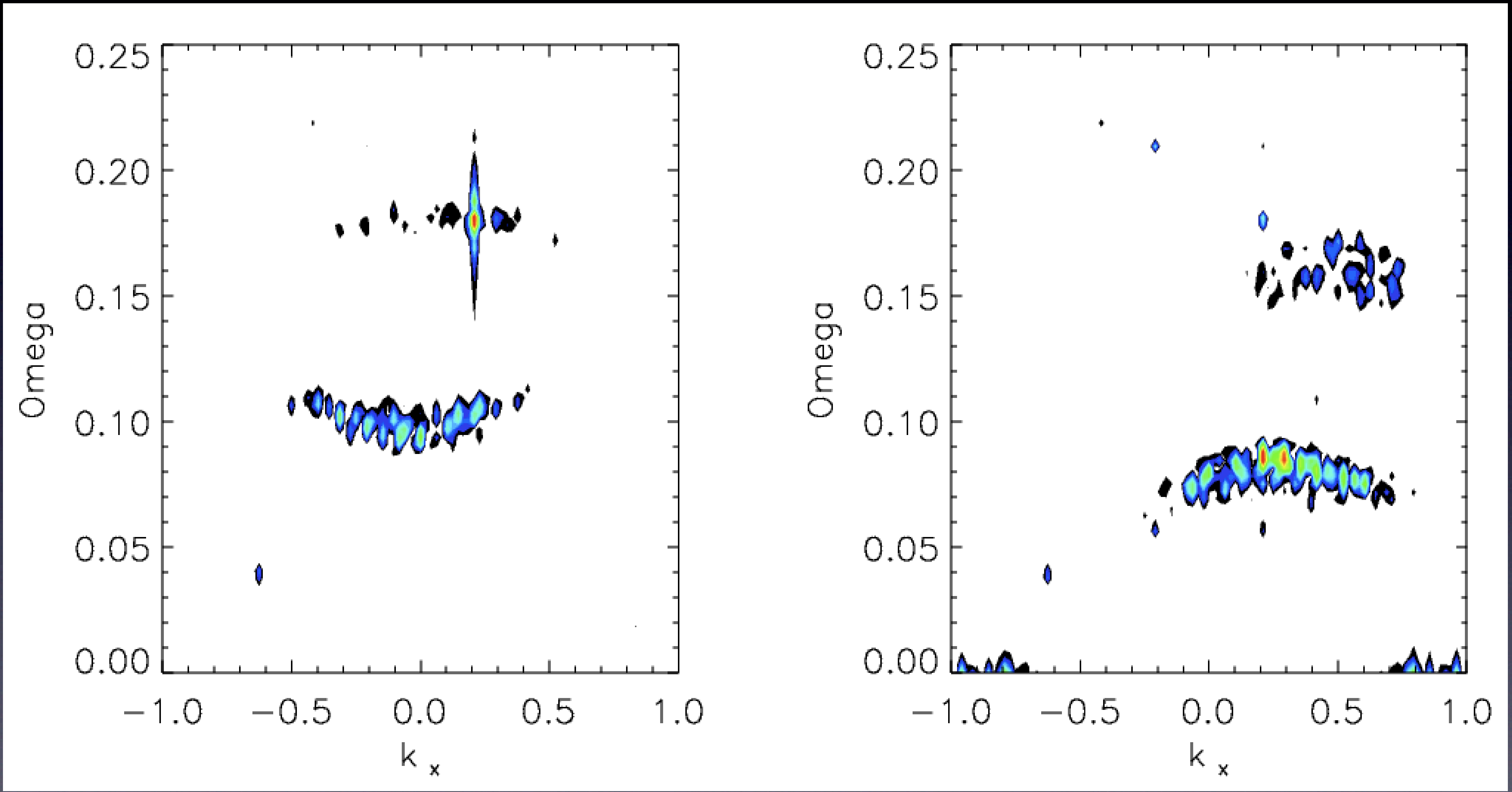
$$k_{\parallel}^{-} = k_{0\parallel} - k_{s\parallel},$$

$$k_{\perp}^{-} = k_{0\perp} - k_{s\perp}.$$

no constraint across B

Resonant condition satisfied also for frequencies

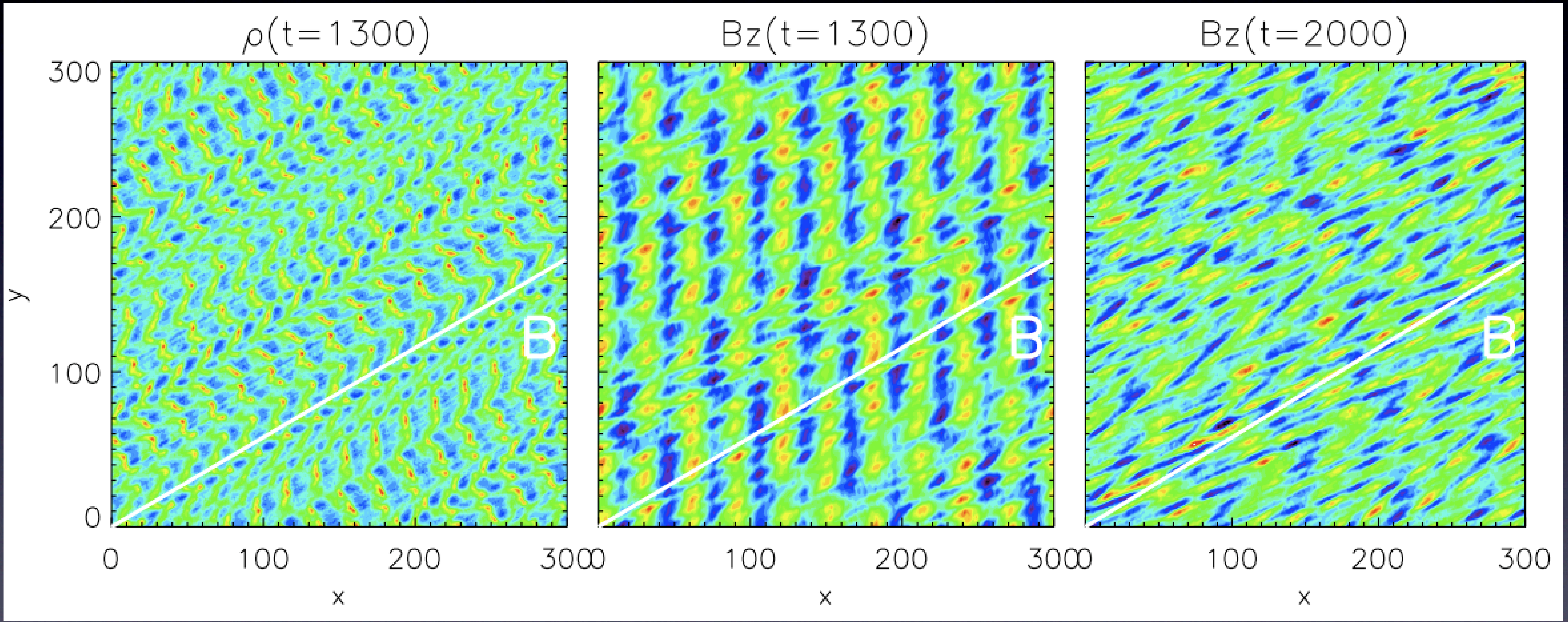
(phase velocity depends only on $k_{||}$)



B_z density

Evolution of fields

linear phase post-saturation



Main modulation occurs across the magnetic field B_0

Conclusions

- Adiabatic evolution (i.e., absence of interactions and dissipation) does NOT mean to keep Maxwellian distributions and can also be quite complicated.

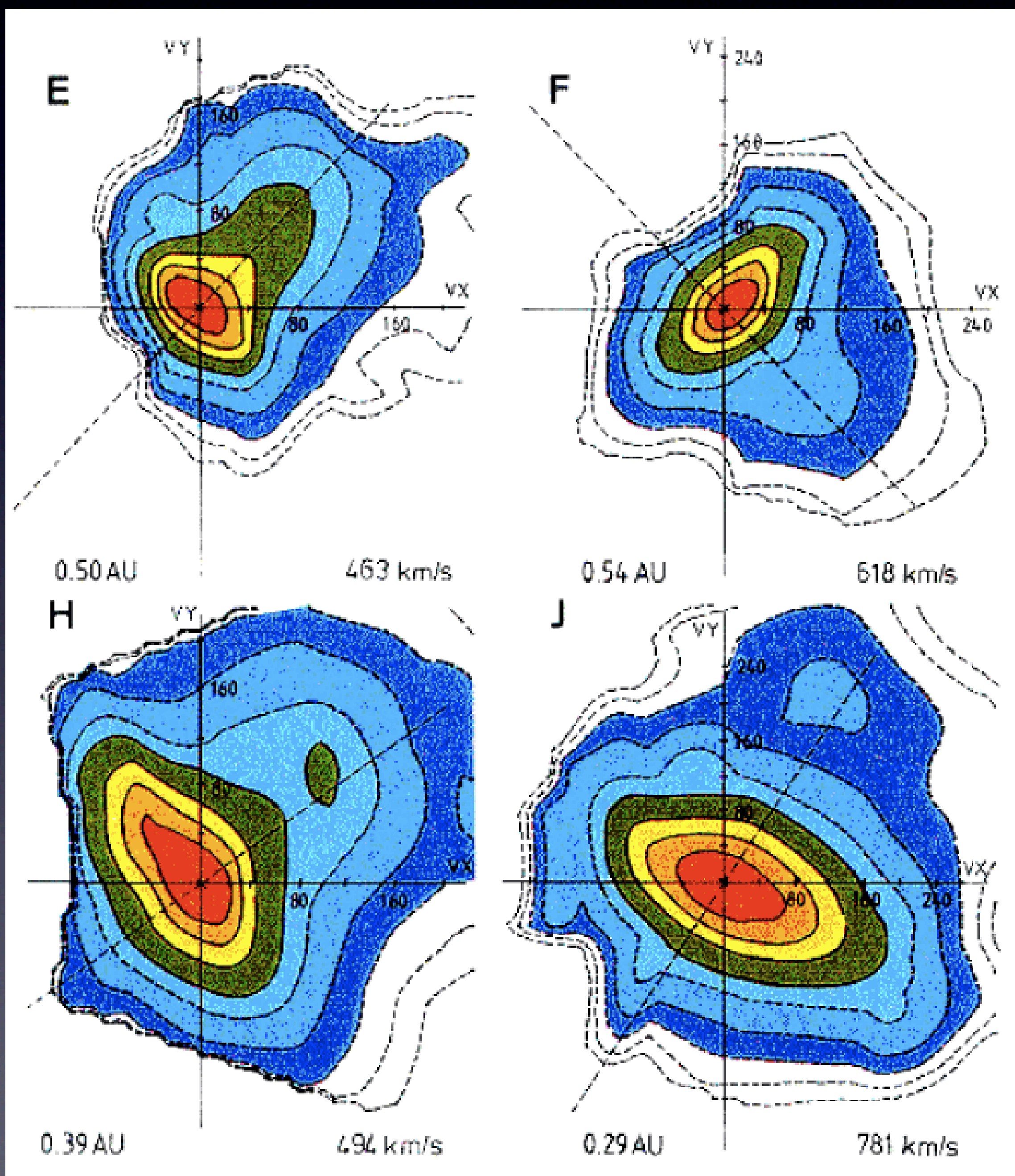
- Anisotropy of distribution functions is an important aspect that has to be taken into account. Plasma instabilities driven by temperature anisotropies or secondary beams play a role in the solar wind thermodynamics and possibly influence turbulence, reconnection, and cosmic rays acceleration.

- Data suggest the presence of a proton perpendicular heating in the solar wind, while a parallel cooling (or beam deceleration) is observed along the magnetic field. Constraints on heating models!

- Wave-wave interactions driven by parametric instabilities also contribute to the proton evolution with the generation of a velocity beam.
The presence of oblique mother waves leads to broadband couplings for the daughter waves and large oblique spectra, with strong modulation across the mean magnetic field.

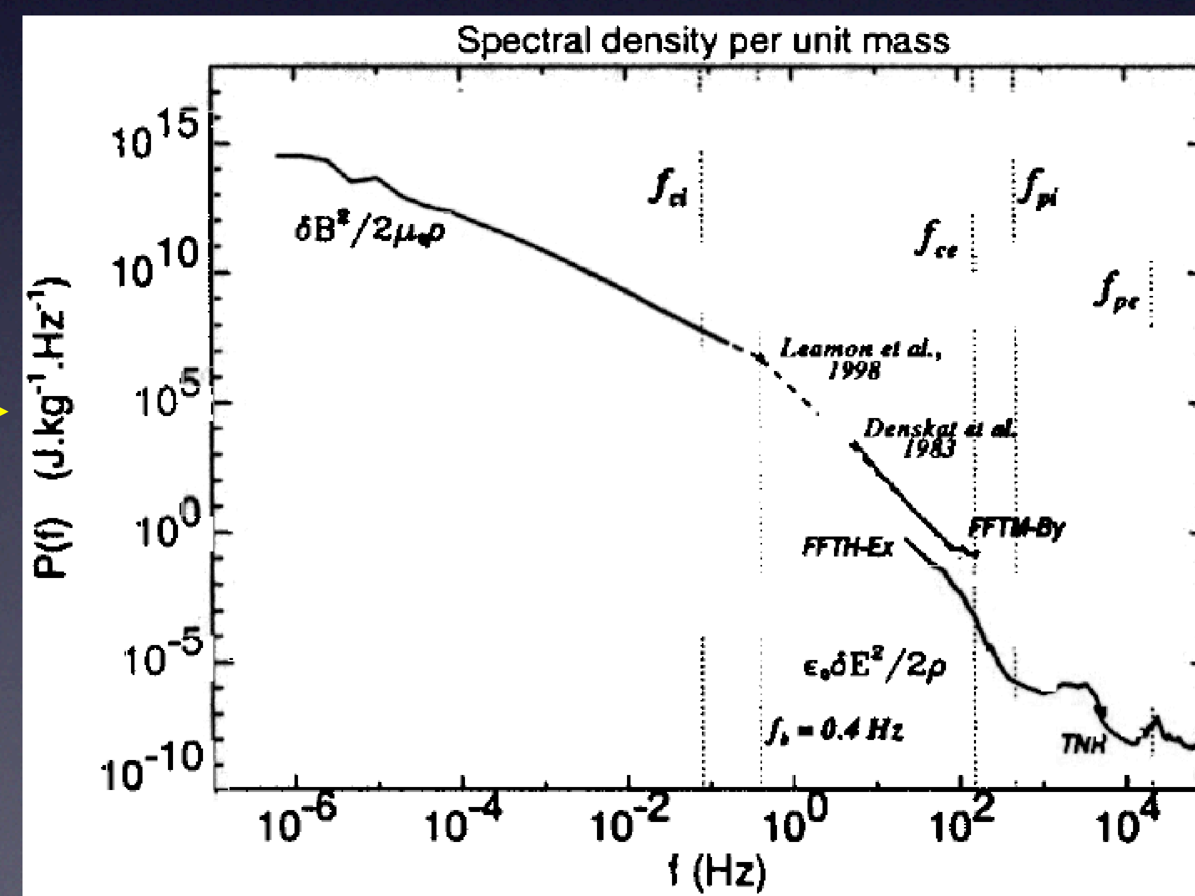
Solar wind proton distribution functions

Helios observations in the solar wind



- Temperature anisotropy between parallel and perpendicular directions with respect to the ambient magnetic field $T_{\perp} \neq T_{\parallel}$

- Velocity beam in the parallel direction



(*Marsch et al. 1982*)

(*Salem 2001*)

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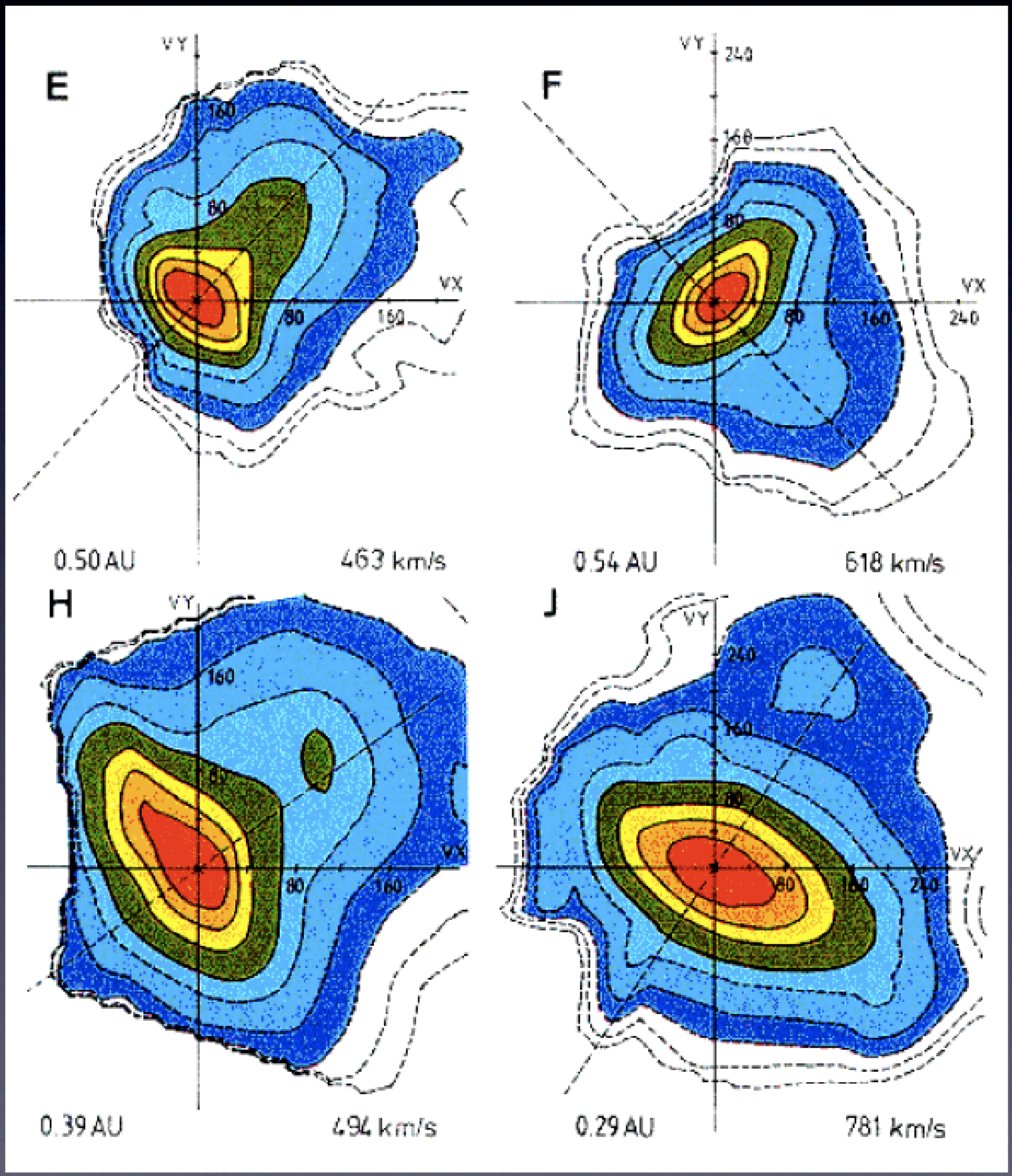

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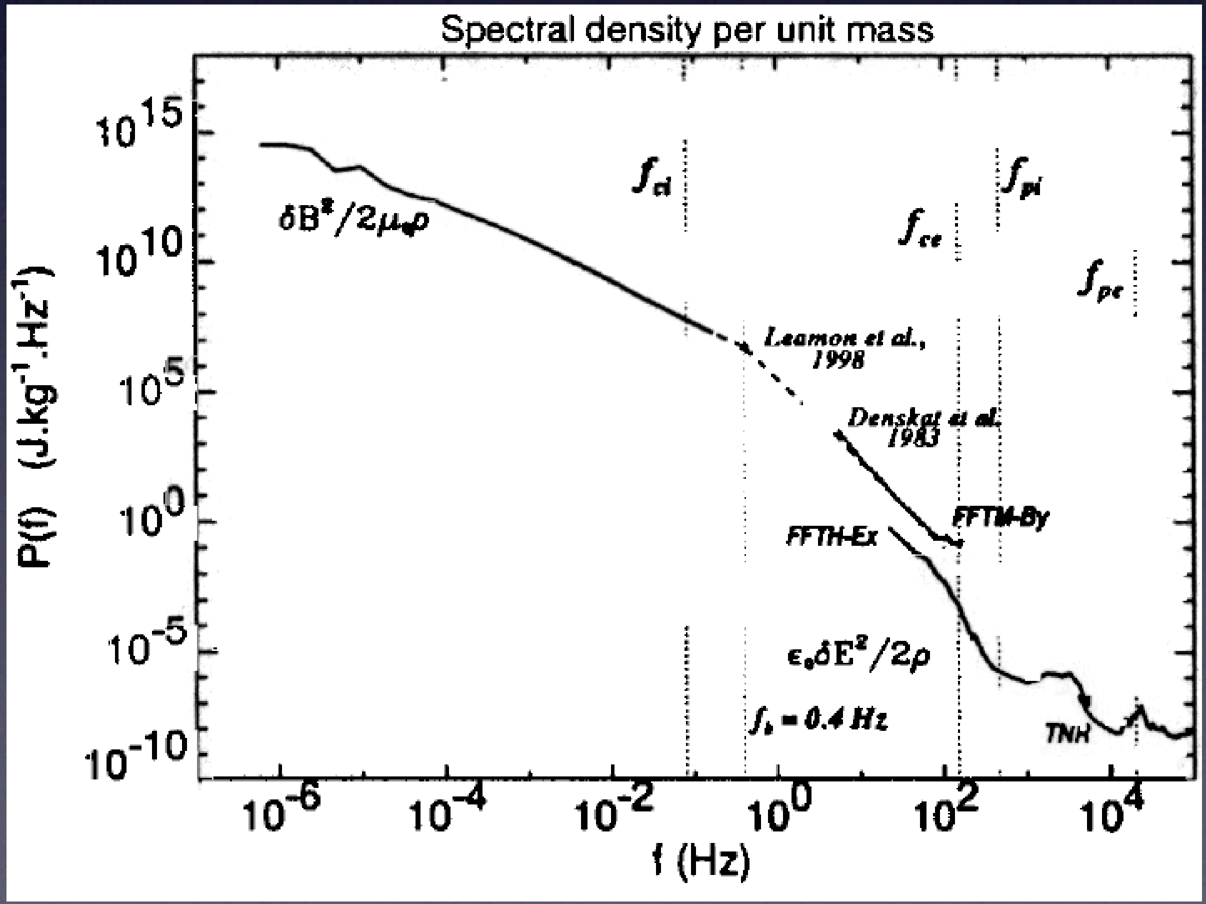

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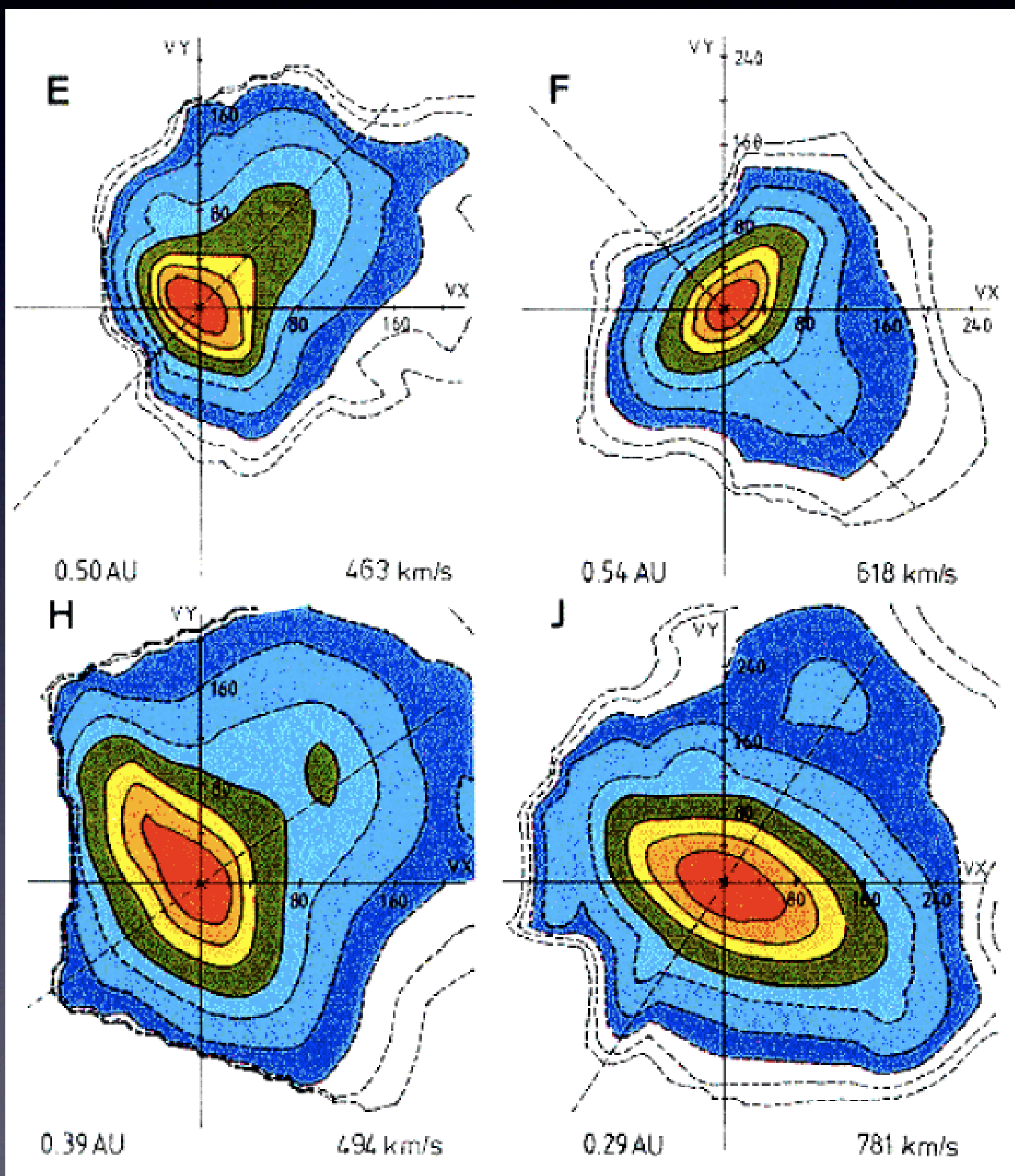

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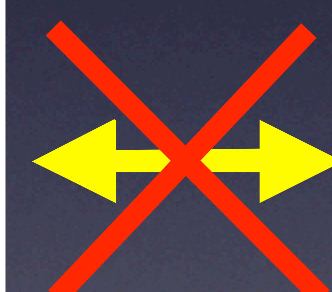

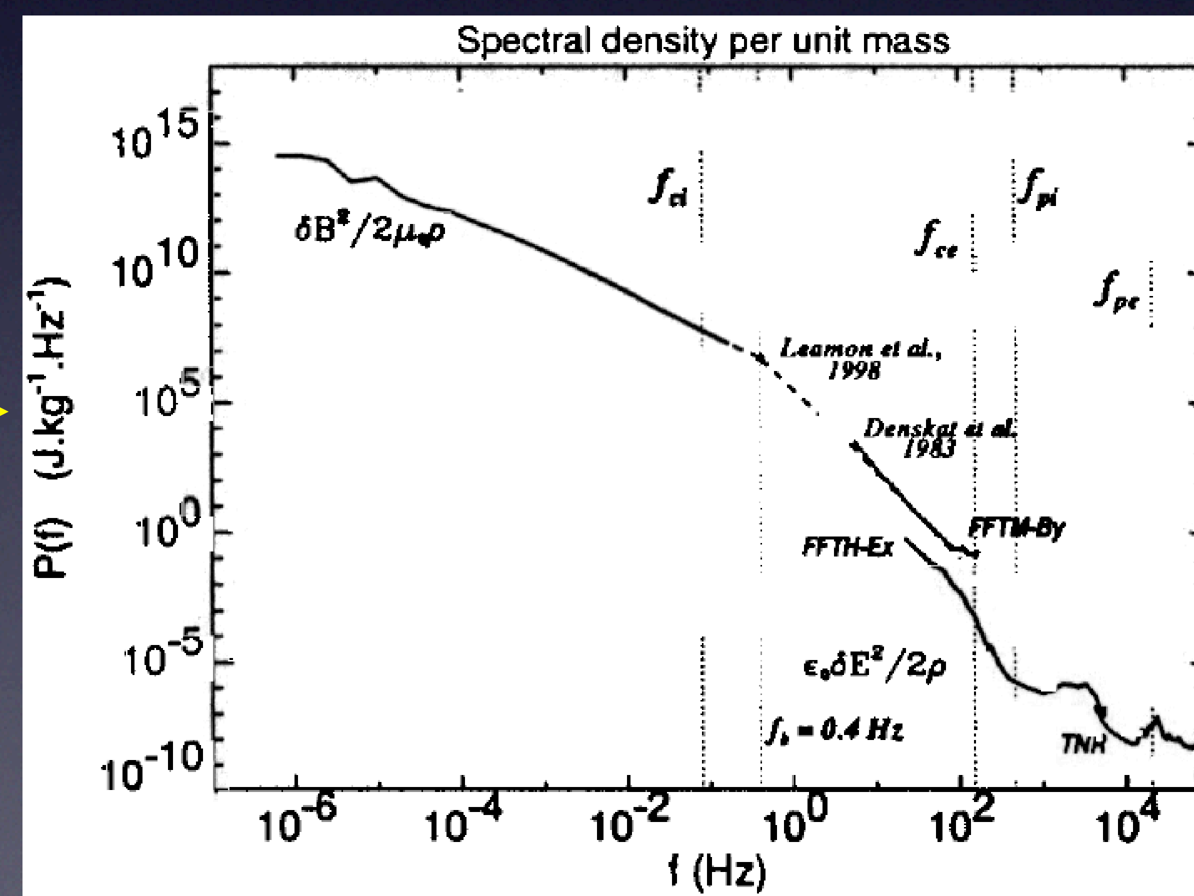

(*Salem 2001*)