KINETIC WAVES & INSTABILITIES (II) Generation by turbulence

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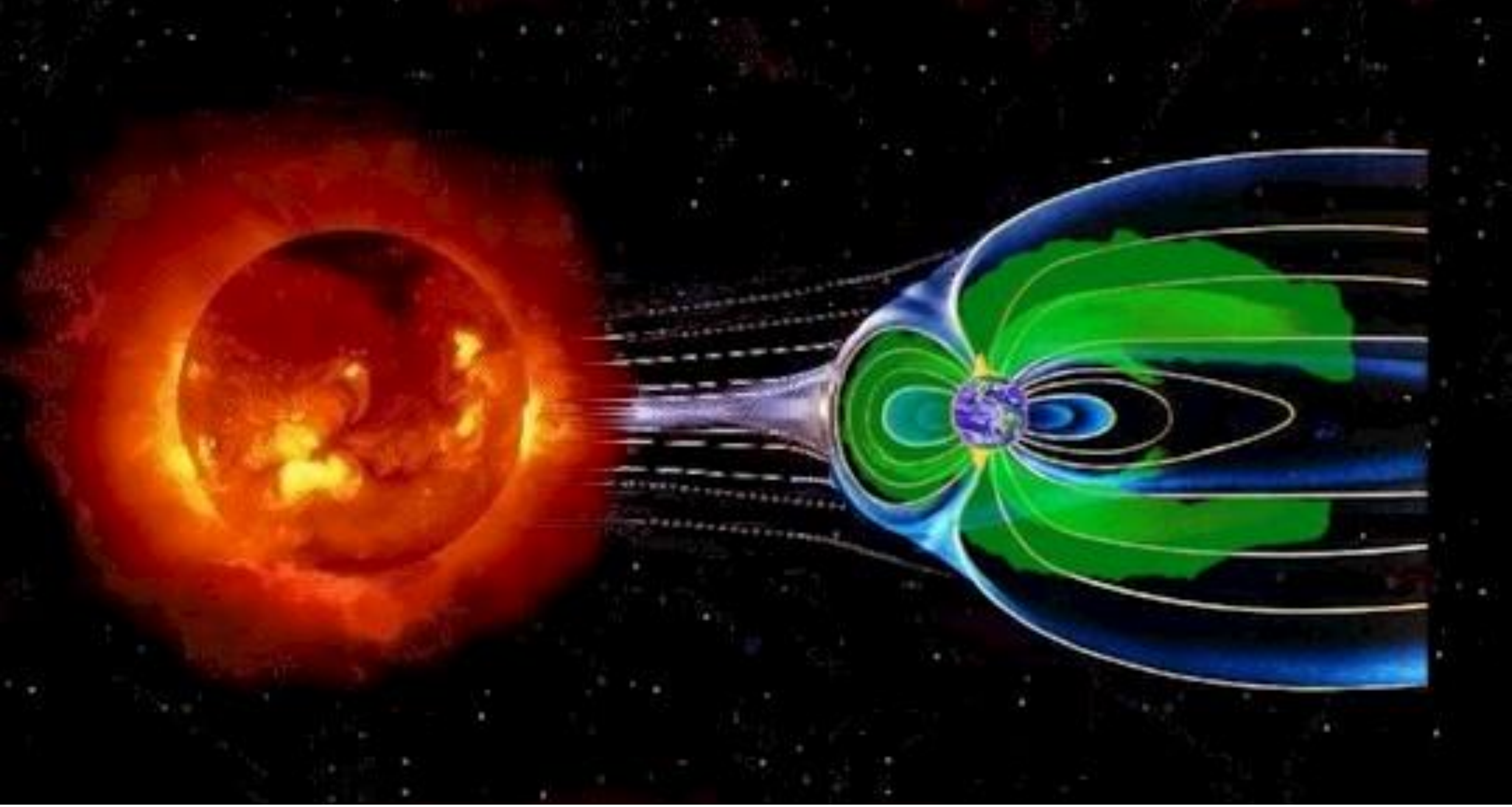
OUTLINE I

1. Introduction and motivation
2. Imbalanced turbulence
3. Analytical solution for turbulent spectrum
4. Double-kink spectral pattern
5. Application to solar-wind turbulence

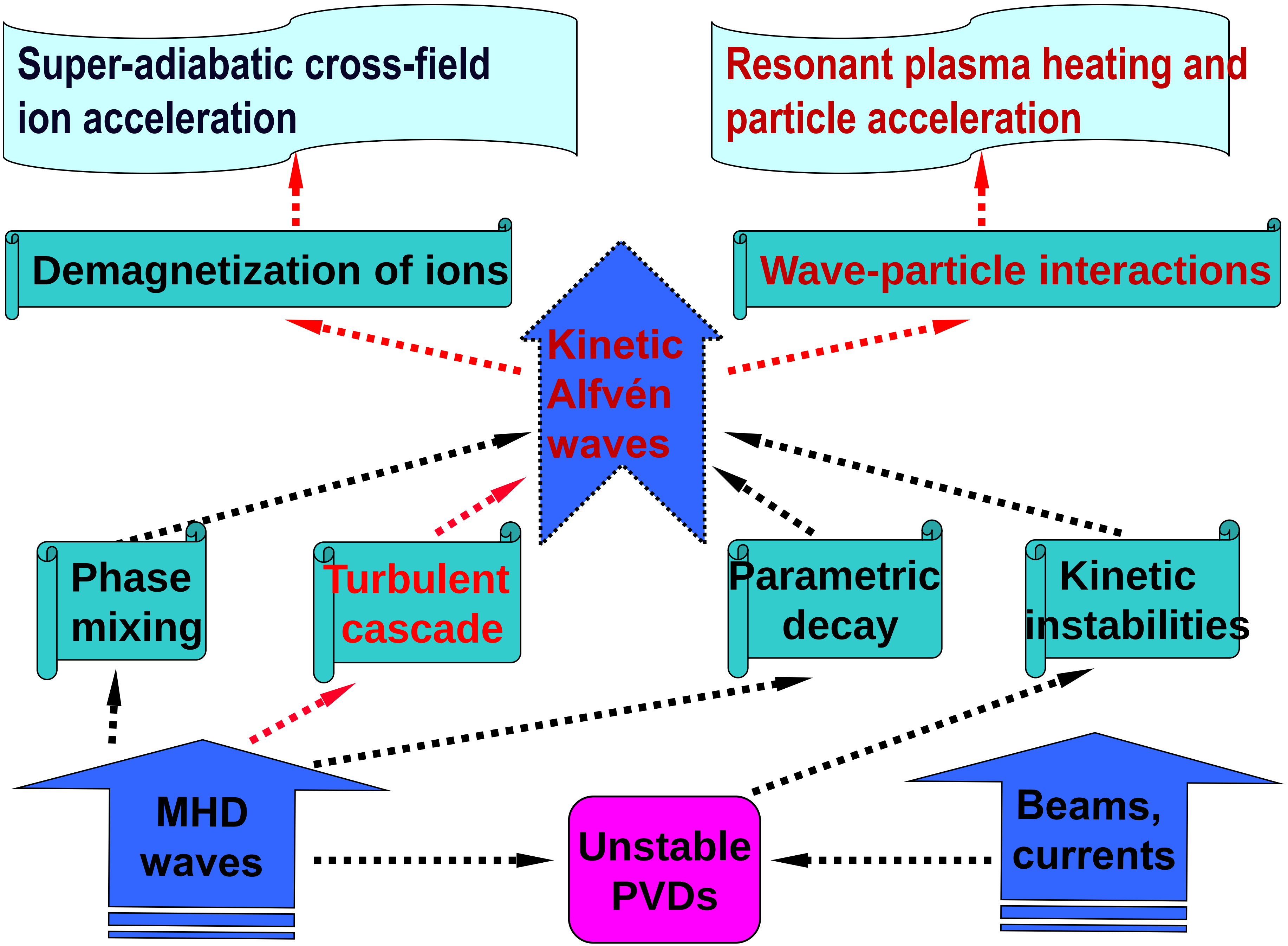


Solar-terrestrial example:

solar magnetic activity -> solar wind -> magnetosphere

-> space weather

WAVES & TURBULENCE !


Super-adiabatic cross-field ion acceleration
Resonant plasma heating and particle acceleration
Demagnetization of ions
Wave-particle interactions
Kinetic Alfvén waves
Phase mixing
Turbulent cascade
Parametric decay
Kinetic instabilities
MHD waves
Unstable PVDs
Beams, currents

OUTLINE

W. Heisenberg:

“When I meet God, I am going to ask him two questions: Why relativity? And why turbulence? I really believe he will have an answer for the first.”

H. Lamb:

“When I die and go to heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am rather optimistic.”

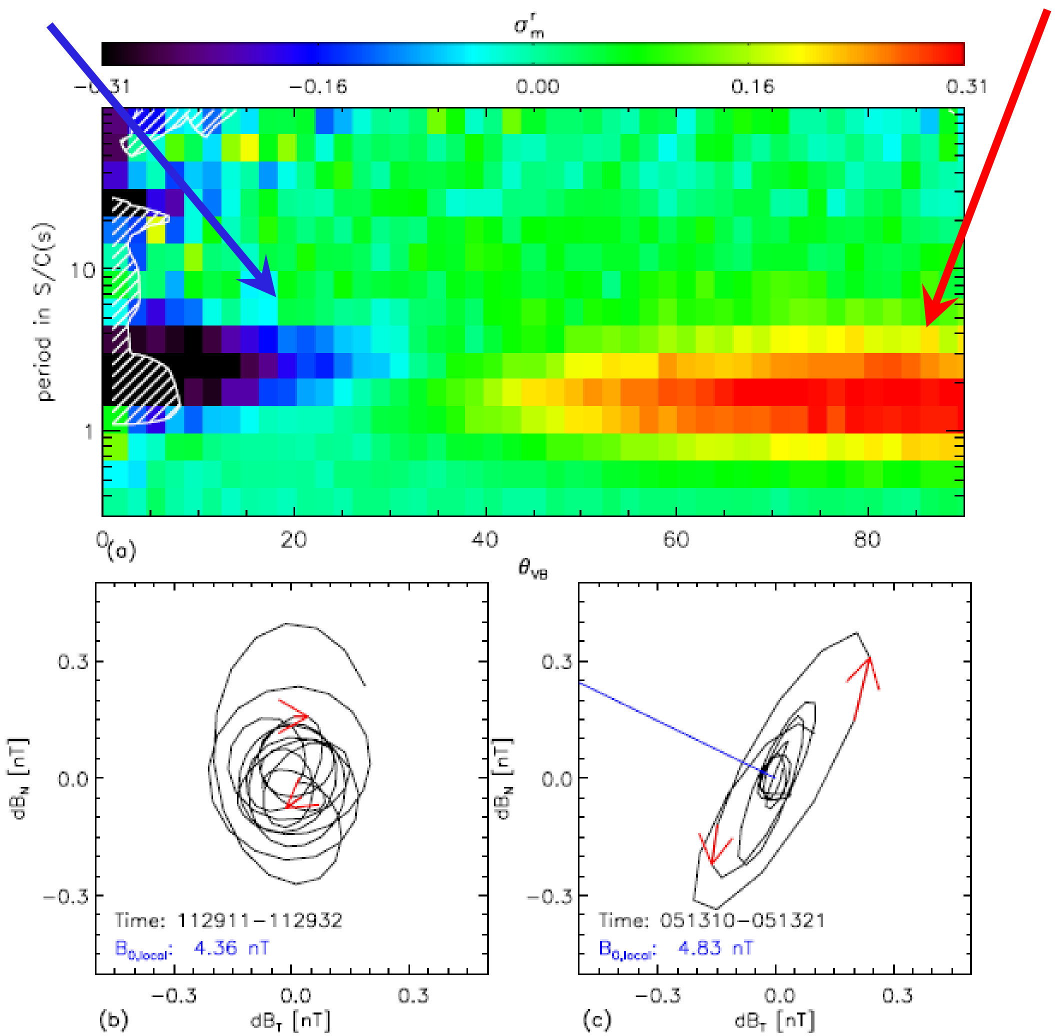
R. Feynman:

“Turbulence is the most important unsolved problem of classical physics”

SW TURBULENCE AT ION KINETIC SCALES

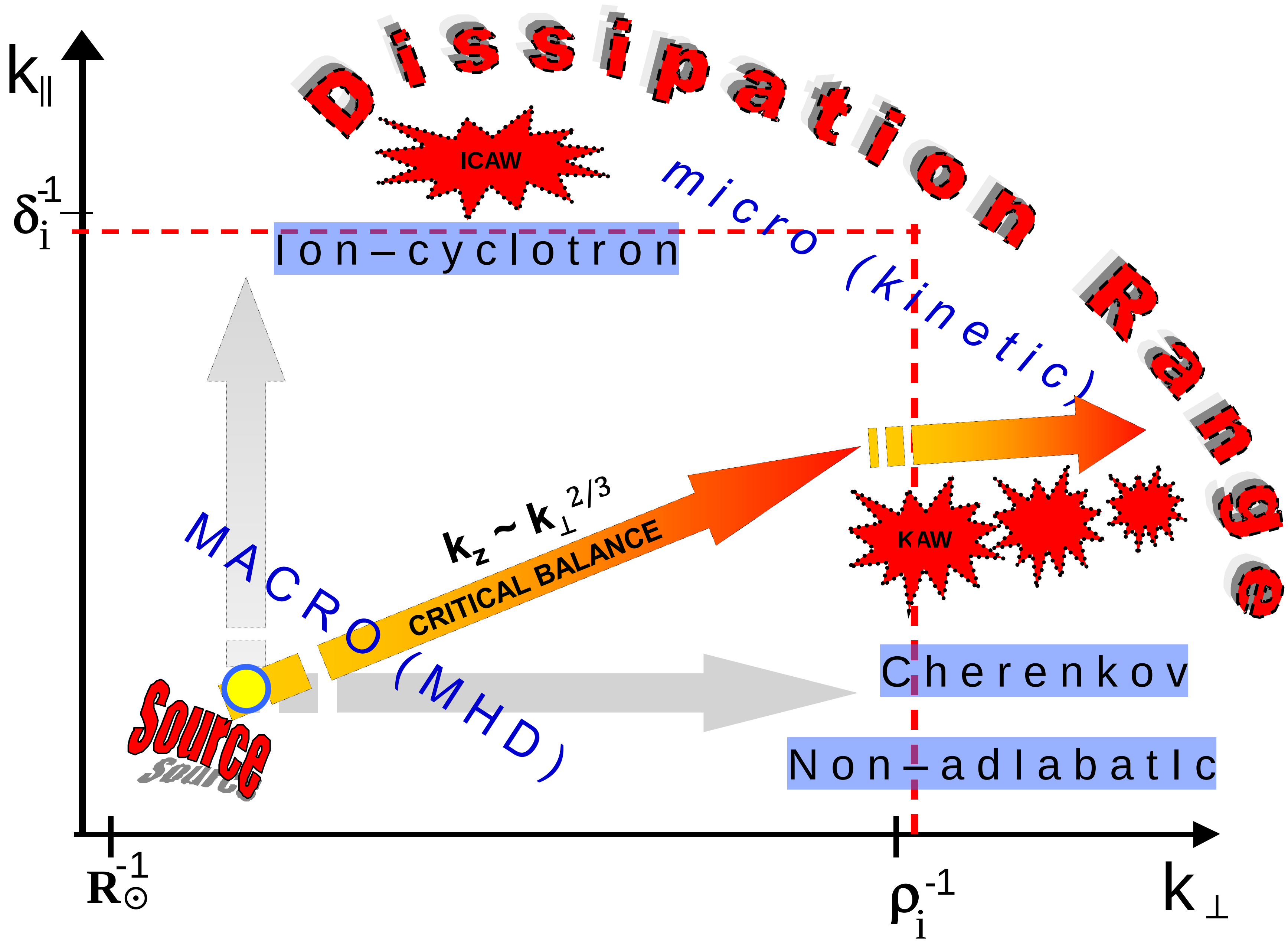
Analysis of polarization (*He et al. 2011,2012; Podesta & Gary 2011*):

TWO ALFVENIC COMPONENTS AT PROTON KINETIC SCALES :
LH QUASI-PARALLEL (15 %) & (DOMINANT) RH QUASI-PERP ALFVEN (85%)



He et al. (2011,2012)

ALFVENIC SPECTRAL TRANSPORT



INTRODUCTION

Strong Alfvénic turbulence:

→ Turbulence of electromagnetic fluctuations that can be approximately described as Alfvén waves

→ Time of nonlinear wave evolution is equal to time of wave collisions.

The latter can be re-formulated as

→ Spectral transfer is accomplished during one collision

or

→ Cascade rate is equal to nonlinear interaction rate

INTRODUCTION

Recent theory (Howes, Schekochihin, Boldyrev, …) and observations (He, Chen, Salem, Bruno, Telloni, …) suggest that MHD Alfvénic turbulence at a “sufficiently small kinetic” scale transforms into turbulence of kinetic Alfvén waves (KAWs). The relevant scale and nature of this transformation are currently subject of hot discussions.

INTRODUCTION

To reach kinetic scales, MHD Alfvénic turbulence undergoes a spectral transport from large to small scales. Standard theory assumes that the spectral transport in Alfvénic turbulence is due to collisions among counter-propagating waves (counter-collisions) (e.g. Goldreich & Sridhar 1995, Litwick et al. 2007, Schekochihin et al. 2009, Chandran 2008, Howes & Nelsson 2013, and references therein). This theory predicts power-law wavenumber spectra in asymptotic MHD and kinetic ranges with indexes -5/3 and -7/3.

BASIC ASSUMPTIONS

Similarly to the MHD AW turbulence, for the KAW turbulence it was assumed (Howes, Schekochihin, et al., 2007-2015):

- **locality** (only similar scales interact)
- **constant spectral flux at all** $k_\perp$ (no dissipation, no non-local interactions)
- **critical balance** (between nonlinear and linear time-scales)
- **counter-collisions** (only counter-propagating waves interact)

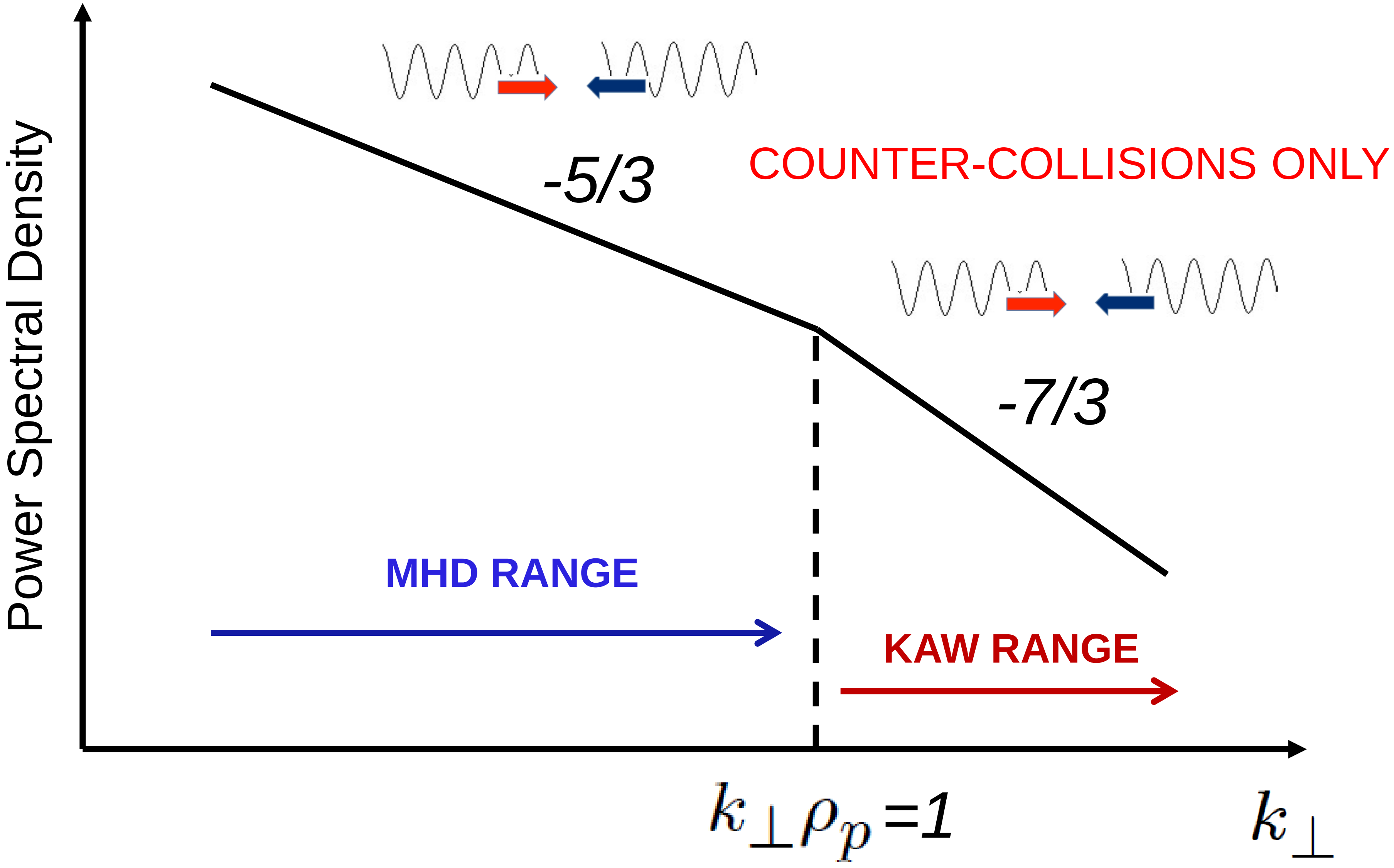
I will challenge the last assumption and argue that

co-collisions (collisions among co-propagating waves).

can establish a new dynamical range of turbulence at ion scales

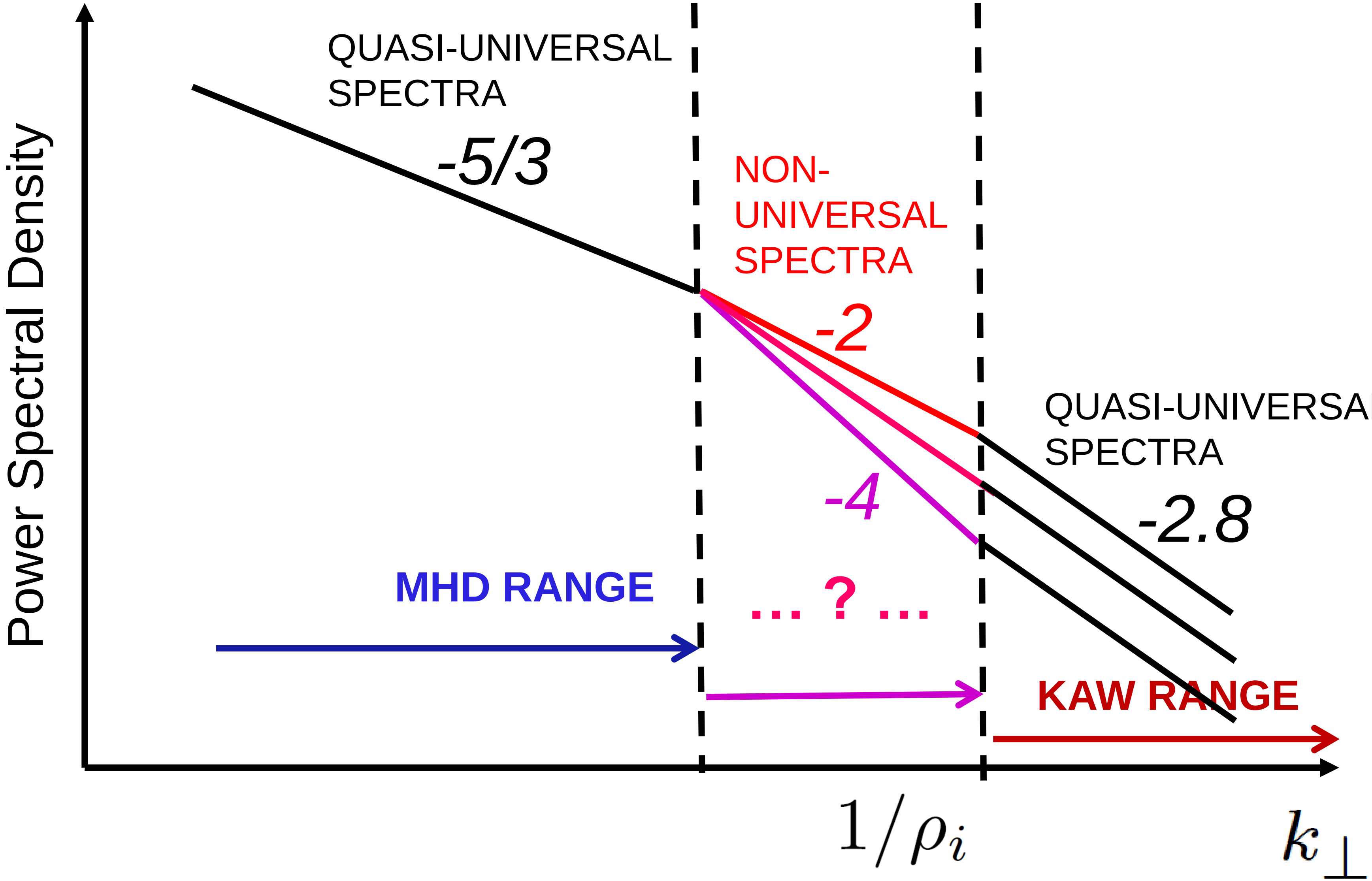
PREDICTED TURBULENT SPECTRA

Standard theory is based on counter-collisions (Goldreigh and Sridhar, Howes, Schekochihin, et al.) and predicts

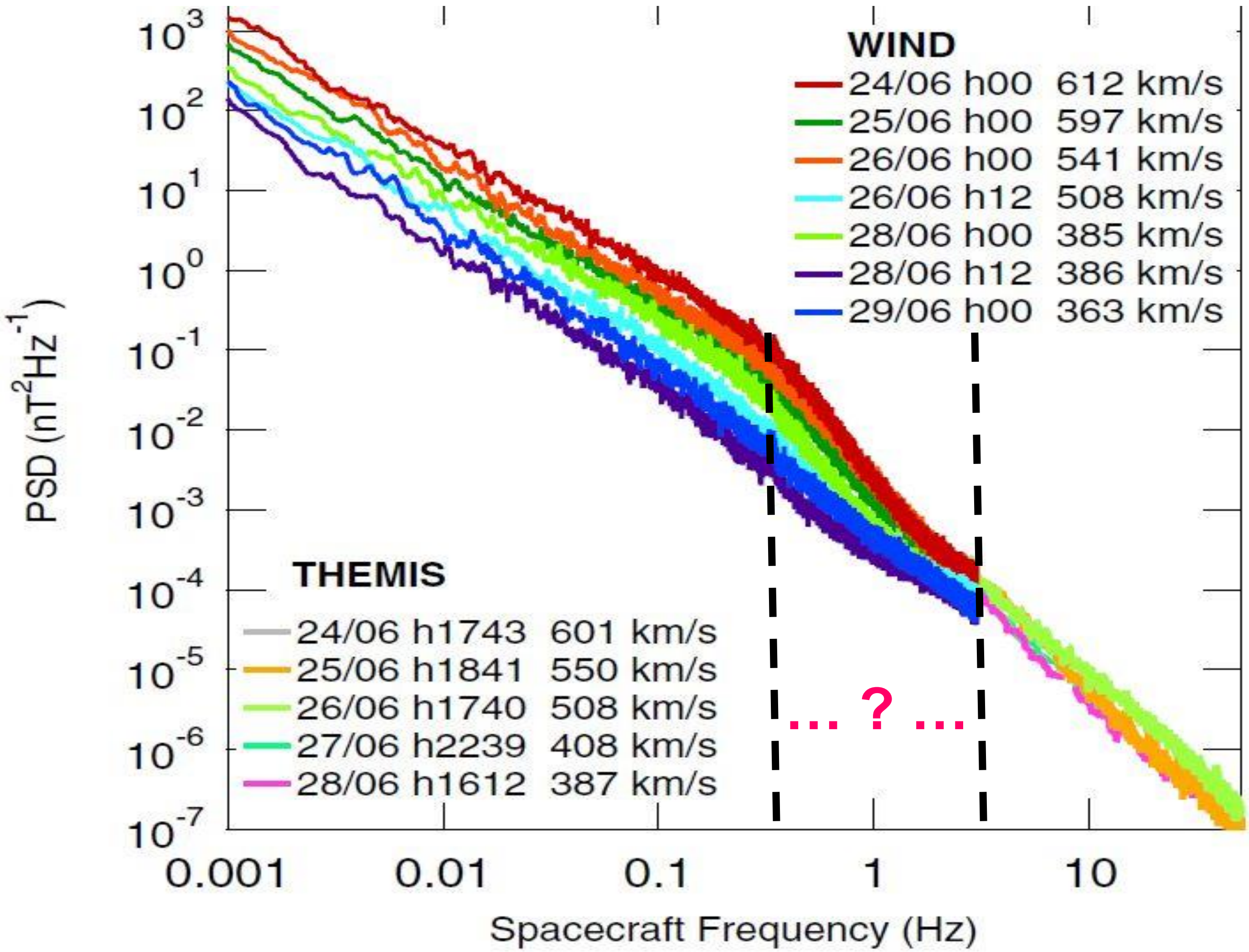


TURBULENT SPECTRA (OBSERVATIONS)

Leamon et al (1999), Smith et al (2007),
Sahraoui et al (2009), Alexandrova et al (2013) ...



NON-UNIVERSAL SPECTRA (OBSERVATIONS)



Spectral slopes after break are larger for larger solar wind velocities (Bruno, Trenchi, and Telloni 2014) … effect of Alfvénicity (imbalance) ?

INTERPRETATIONS OF OBSERVED SPECTRA

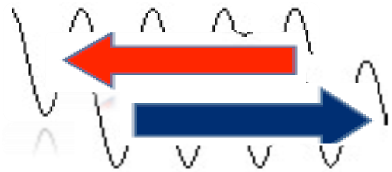
Bruno et al. (2014) suggested that the steeper spectra might be related to some dissipative mechanism, such as Landau damping and/or ion-cyclotron resonance.

We argue that there this steepening is mainly nonlinear, due to collisions among co-propagating waves (co-collisions).

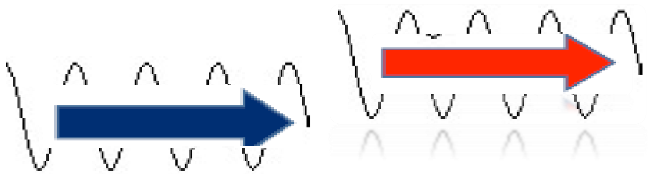
The resulting spectra are steep, non-universal, and depend on the turbulence imbalance.

CO-COLLISIONS OF KAWs

Counter-propagating MHD Alfvén waves can collide:



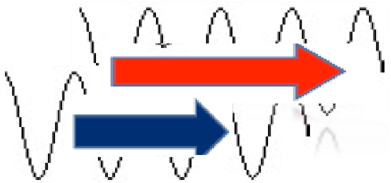
Co-propagating MHD Alfvén waves have the same Alfvén speed and cannot collide:



Co-propagating KAWs with different *k* have different speeds:

$$\frac{\omega}{k_{\|}} = V_k \approx V_{\mathrm{A}} \sqrt{1 + k_{\perp}^2 \rho_{\mathrm{T}}^2}$$

and can collide:



NONLINEAR INTERACTION RATE (nir)

The nonlinear interaction rate at any $k_\perp$ from MHD to kinetic scales is

$$\boxed{\gamma_{k\pm}^{\mathrm{NL}} = \frac{2+s}{4\pi} k_\perp V_A \Delta_{k,s} \frac{B_{k(\pm s)}}{B_0},} \qquad \text{\# (nir)}$$

where the wave velocity mismatch $\delta V_{ks}/V_A \equiv \Delta_{k,s} = \sqrt{1+(k_\perp \rho_T)^2} - s$ and magnetic amplitude $B_{k(\pm s)} = B_{k\pm}$ for co-collisions ($s = 1$) and $B_{k(\pm s)} = B_{k\mp}$ for counter-collisions ($s = -1$). (ref: nir) is obtained from nonlinear Maxwell-Vlasov equations assuming local interactions and separating dominant (+) and sub-dominant (-) waves propagating in opposite directions along $\mathbf{B}_0 \parallel \mathbf{z}$. Other definitions are: $\rho_T^2 \simeq (3/4 + T_{ez}/T_{i\perp})\rho_i^2$ at $k_\perp \rho_i < 1$ and $\rho_T^2 \simeq (1 + T_{ez}/T_{i\perp})\rho_i^2$ at $k_\perp \rho_i > 1$, T_{ez} - parallel electron temperature, $T_{i\perp}$- perpendicular ion temperature, $\rho_i = V_{Ti}/\Omega_i$ - ion gyroradius, Ω_i - ion gyrofrequency, $V_{Ti} = \sqrt{T_{i\perp}/m_i}$ - ion thermal velocity, $V_A = B_0/\sqrt{4\pi n m_i}$ - Alfvén velocity.

In what follows, we construct a semi-phenomenological model for the strong imbalanced Alfvénic turbulence from MHD to kinetic scales using this $\gamma_{k\pm}^{\mathrm{NL}}$.

MHD-KINETIC TRANSITION

A simple phenomenological interpretation of (ref: nir) can be given in terms of colliding waves 1 and 2. The straining rate experienced by wave 1 in the magnetic shear of wave 2, is proportional not only to the shear $\lambda_\perp^{-1}(B_{k2}/B_0) \sim (2\pi)^{-1}k_\perp(B_{k2}/B_0)$, but also to the relative velocity $V_{\rm ph1} - sV_{\rm ph2}$ defining how fast the wave 1 moves across the shear. Product of these two factors, accounting for locality $k_{\perp 1} \sim k_{\perp 2} \sim k_\perp$ and KAW's dispersion $V_{\rm ph} = V_A\sqrt{1 + (k_\perp \rho_T)^2}$, gives (ref: nir) within a factor of order one. The key element of (ref: nir) that distinguishes co- and counter-collisions is $\Delta_{k,s}$. Co-collisions ($s = 1$) exist only for finite $k_\perp\rho_T \neq 0$ making $\Delta_{k,s} \neq 0$ and allowing co-propagating waves to move with respect to each other undergoing mutual straining. Counter-collisions ($s = -1$) operate throughout, $\Delta_{k,s} \geq 2$ for all $k_\perp\rho_T \geq 0$, as the counter-propagating waves pass through each other even if they are non-dispersive.

SPECTRAL BREAK DUE TO MHD-KINETIC TRANSITION

For the dominant (+) component at $k_\perp \rho_T < 1$, interaction rate (ref: nir) reduces to

$$\gamma_{k+}^{\mathrm{NL}(\uparrow\uparrow)} \approx \frac{1}{2\pi}(k_\perp \rho_T)^2 k_\perp V_A \frac{B_{k+}}{B_0},$$

(c

for co-collisions (superscript $\uparrow\uparrow$), and

$$\gamma_{k+}^{\mathrm{NL}(\uparrow\downarrow)} = \frac{1}{2\pi} k_\perp V_A \frac{B_{k-}}{B_0}.$$

(co

for counter-collisions (superscript $\uparrow\downarrow$). A transition (spectral break) between MHD ($\uparrow\downarrow$) and kinetic ($\uparrow\uparrow$) occurs at

$$\rho_i k_{\perp *} \approx \sqrt{\frac{1}{\frac{3}{4}\left(\frac{3}{4} + \frac{T_{e\|}}{T_{p\perp}}\right)}} \left(\frac{B_{k*(-)}}{B_{k*(+)}}\right)^{1/2+q} < 1,$$

where $0 \le q \le 1$.

NEW DYNAMICAL RANGE

A new dynamical range is formed by the co-collisions at $0.5\sqrt{\epsilon_{(-)}/\epsilon_{(+)}} < k_\perp \rho_T < 1$ (in the weakly dispersive KAW range.

The magnetic amplitude ratio is here $k_\perp$-dependent,

$$\boxed{\frac{B_{k(-)}}{B_{k(+)}} \approx \sqrt{\frac{\epsilon_{(-)}}{\epsilon_{(+)}}}\,(k_\perp \rho_T),}$$

the (+) amplitudes scaling is

$$\boxed{\frac{B_{k(+)}}{B_0} \approx \left(\frac{2}{3}\bar{\epsilon}_{(+)}\right)^{1/3} (k_\perp \rho_T)^{-1},}$$

but the (-) amplitudes are constant, $B_{k(-)} \sim$ const.

The resulting magnetic power spectra of (+) and (-) waves

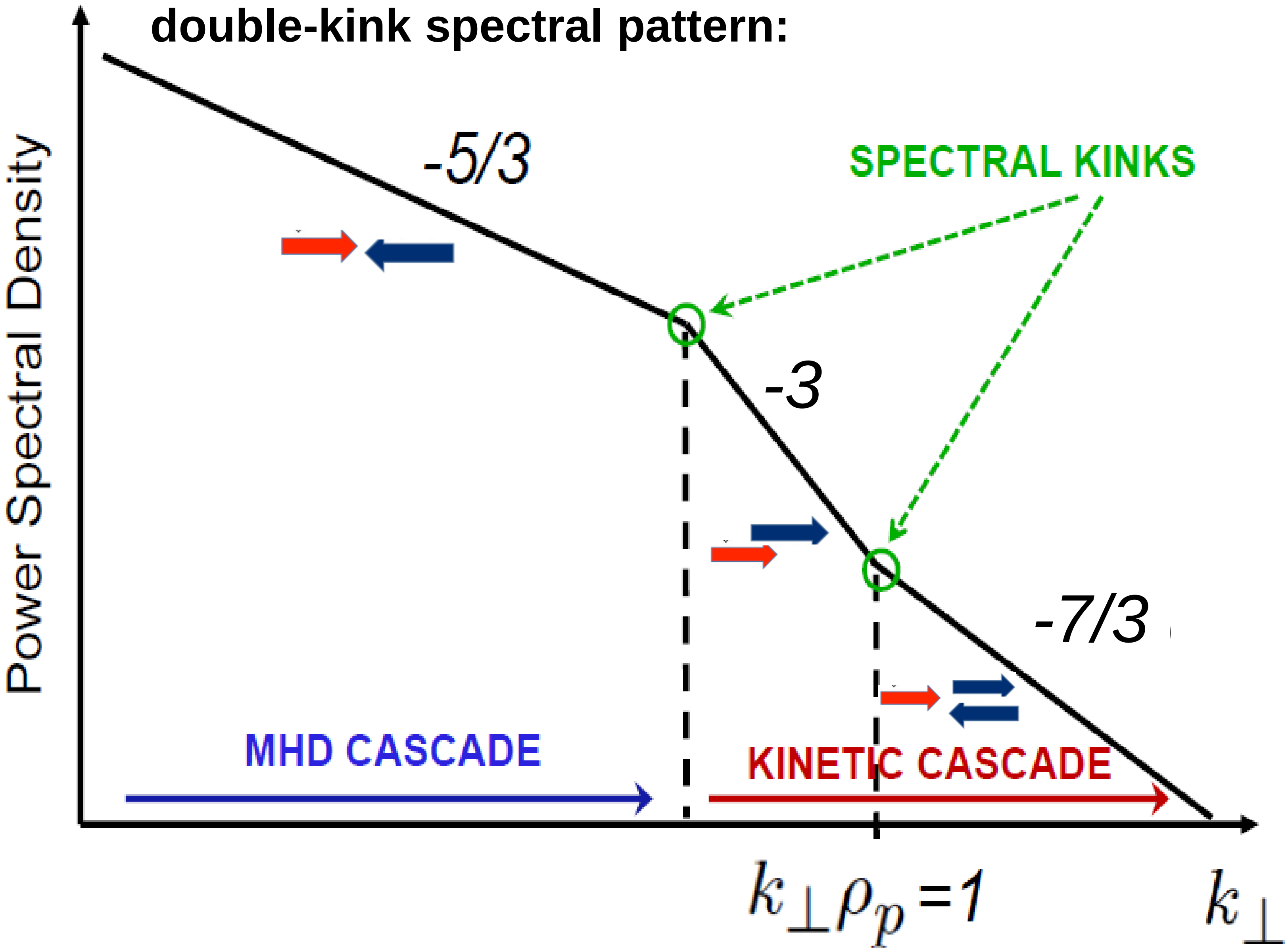
$$\boxed{P_{k\perp}^{(+)} \sim k_\perp^{-3};}$$

$$\boxed{P_{k\perp}^{(-)} \sim k_\perp^{-1}.}$$

Evolution of parallel scales is suppressed, $k_{z(-)} \sim k_{z(+)} \sim$ const.

DOUBLE-KINK SPECTRAL PATTERN

New theory (Voitenko and De Keyser 2016) predicts a double-kink spectral pattern:



ANALYTICAL SPECTRUM AT ALL SCALES

In the strong turbulence, energy fluxes $\epsilon_{\pm} = \left(\gamma_{k\pm}^{\mathrm{NL}(\uparrow\downarrow)} + \gamma_{k\pm}^{\mathrm{NL}(\uparrow\uparrow)}\right) B_{k\pm}^2/(4\pi)$ can be presented as

$$\boxed{\epsilon_{\pm} \approx \frac{B_0^2}{4\pi}\frac{k_{\perp}V_A}{4\pi} q_k \left(\frac{B_{k\mp}}{B_{k\pm}} + p_k\right)\left(\frac{B_{k\pm}}{B_0}\right)^3,}$$

(e+-

where $q_k = \Delta_{k,-1}$ and $p_k = 3\Delta_{k,1}/\Delta_{k,-1}$ are regular functions growing with $k_{\perp}$. Using (ref: e+-) we express the fluxes ratio as

$$\boxed{\frac{\epsilon_-}{\epsilon_+} = \frac{\left(1 + p_k \frac{B_{k-}}{B_{k+}}\right)}{\left(\frac{B_{k-}}{B_{k+}} + p_k\right)}\left(\frac{B_{k-}}{B_{k+}}\right)^2.}$$

(e/e

Real solution of this third-order equation for B_{k-}/B_{k+} is straightforward but too cumbersome to show explicitly. Denoting it by b_k, we find from (ref: e+-) the exact analytical spectrum for the turbulence at all scales, from MHD to kinetic:

$$\boxed{P_{k+} \equiv k_{\perp}^{-1} B_{k+}^2 \sim k_{\perp}^{-1}[k_{\perp} q_k (b_k + p_k)]^{-6}.}$$

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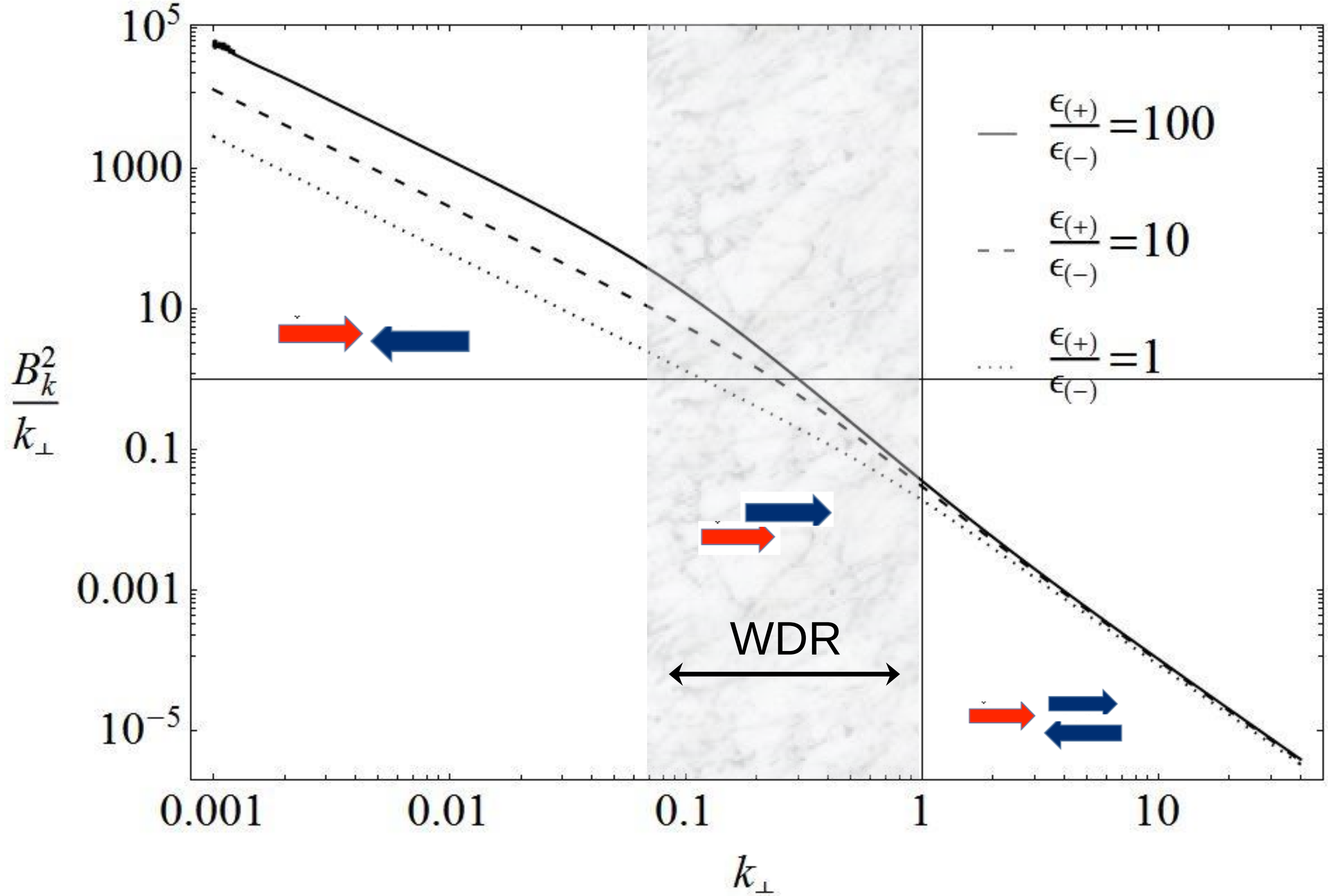
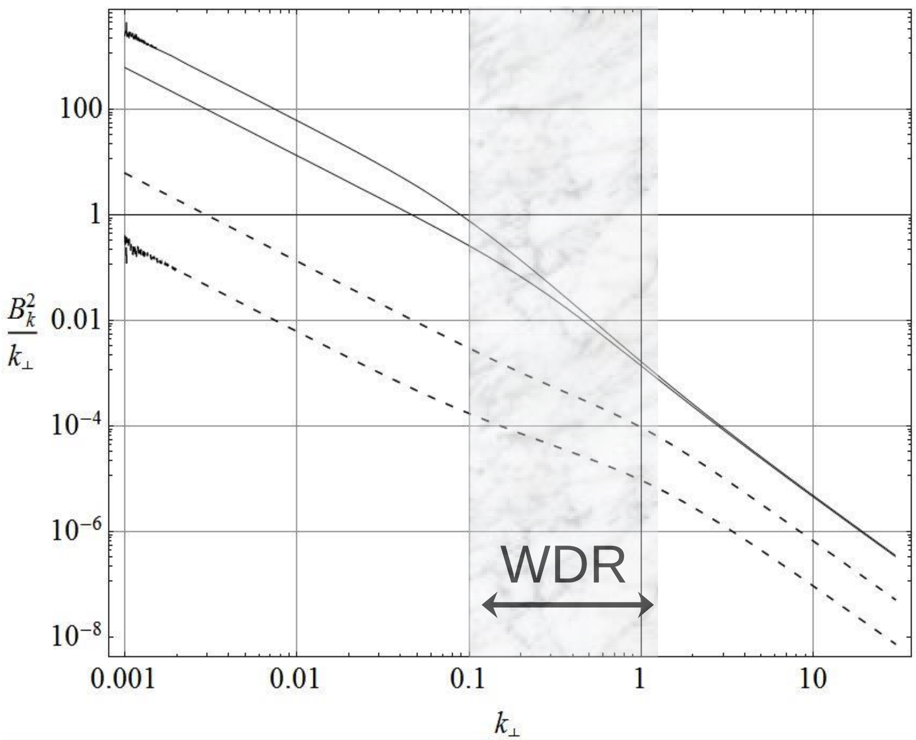
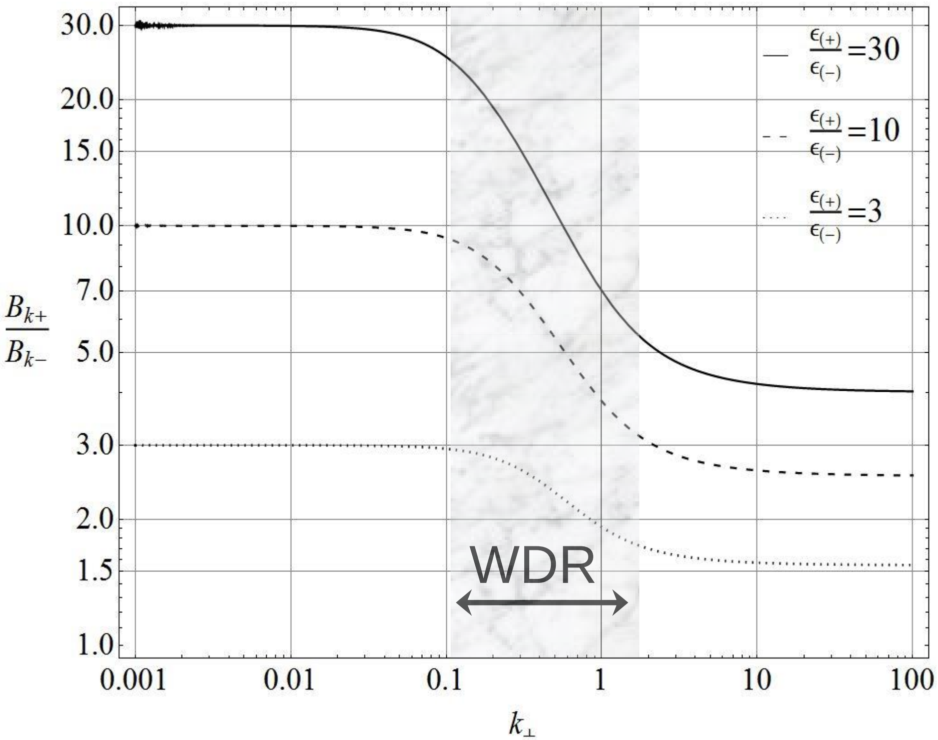
NON-UNIVERSAL SPECTRA (THEORY)



Effect of imbalance - steep non-universal spectra at $k_{\perp *} < k_\perp < 1/\rho_i$ plotted without using asymptotic expansions. Steeper spectra follow larger imbalances, spectral indexes ≥-3.

MAGNETIC AMPLITUDE RATIO



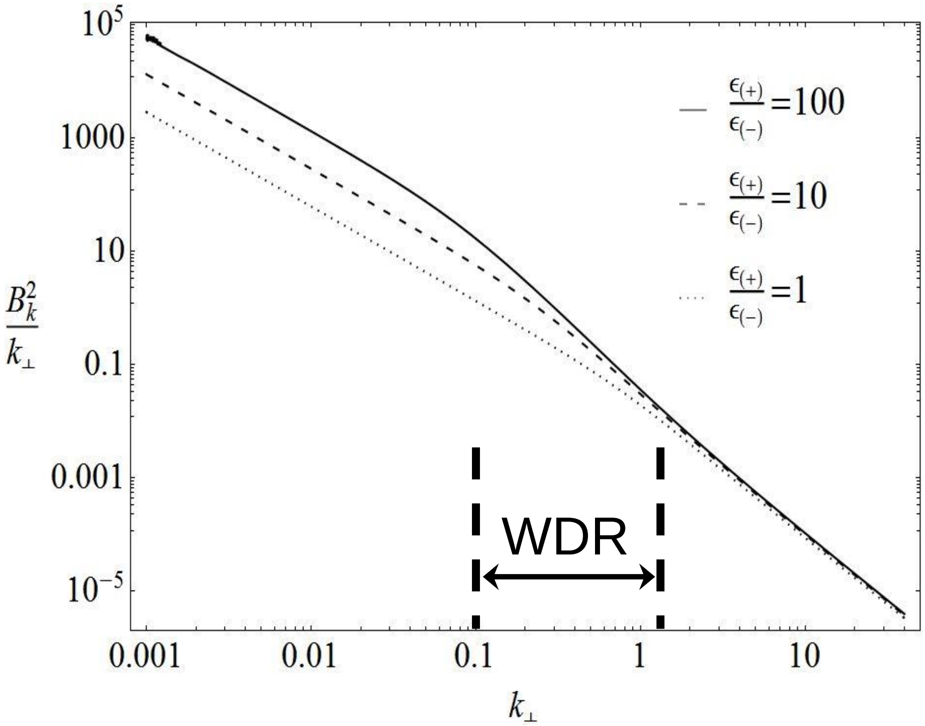


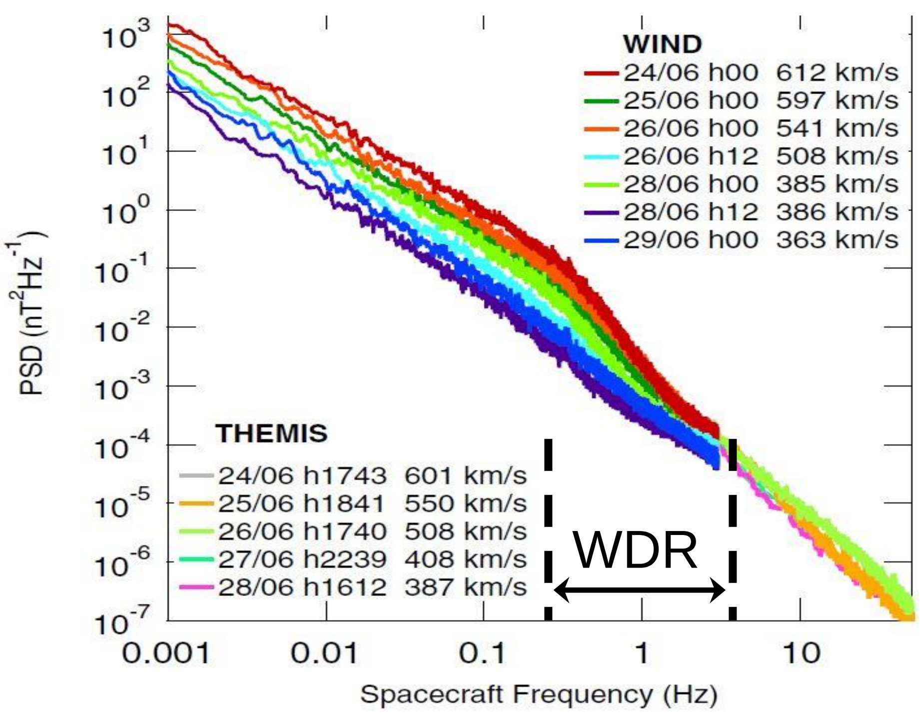
PINNING EFFECT
Convergence of dominant and subdominant spectra in WDR dominated by co-collisions

MAGNETIC AMPLITUDE RATIO
Magnetic amplitude ratio B_{k+}/B_{k-} is $k_\perp$ -dependent, decreasing in WDR

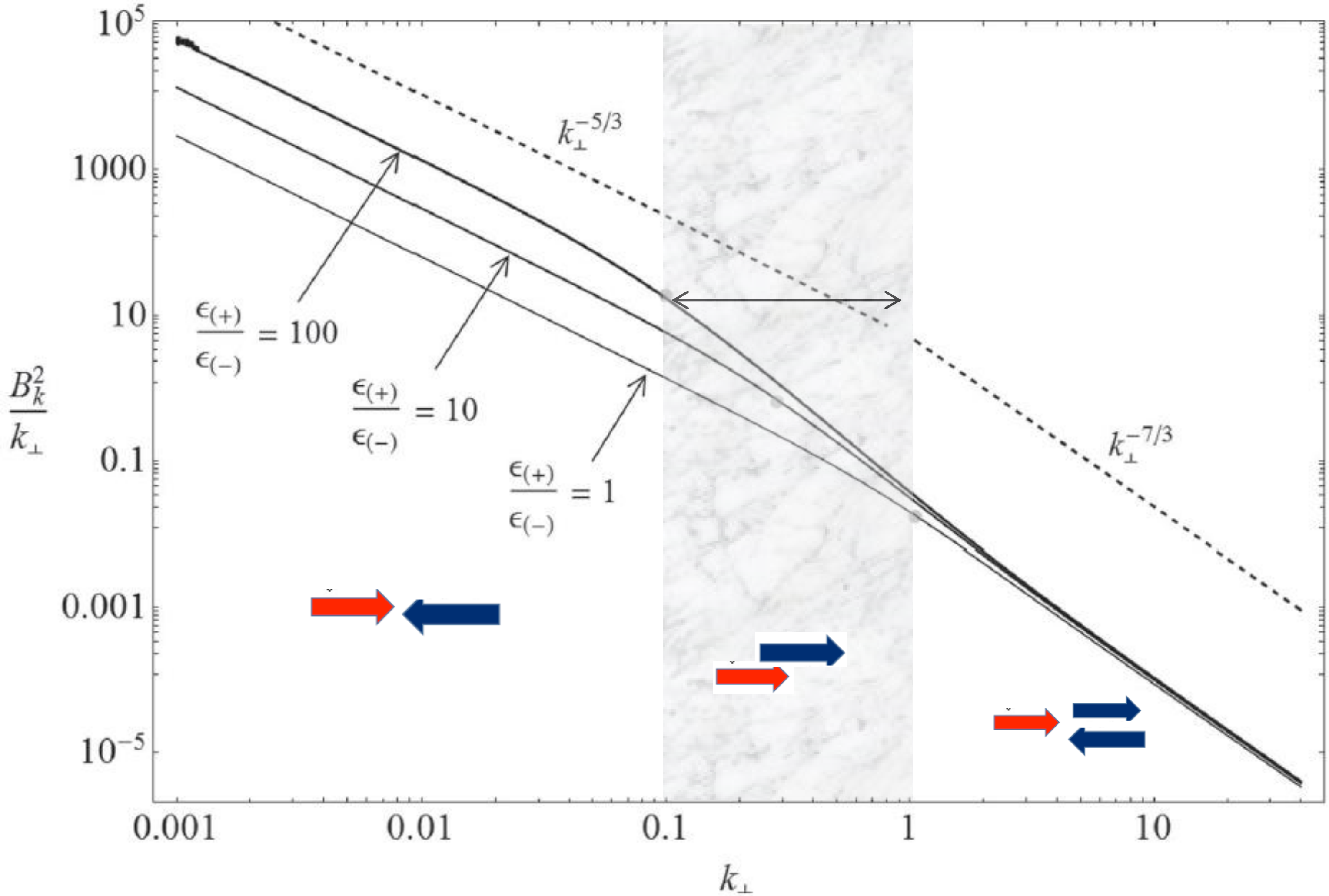
SUMMARY TURBULENCE (TO TAKE AWAY)

Collisions among co-propagating weakly dispersive KAWs establish a new dynamical range of the imbalanced turbulence $k_{\perp *} < k_\perp < 1/\rho_i$ (WDR) with steepest non-universal spectra. Larger imbalance → steeper spectrum.





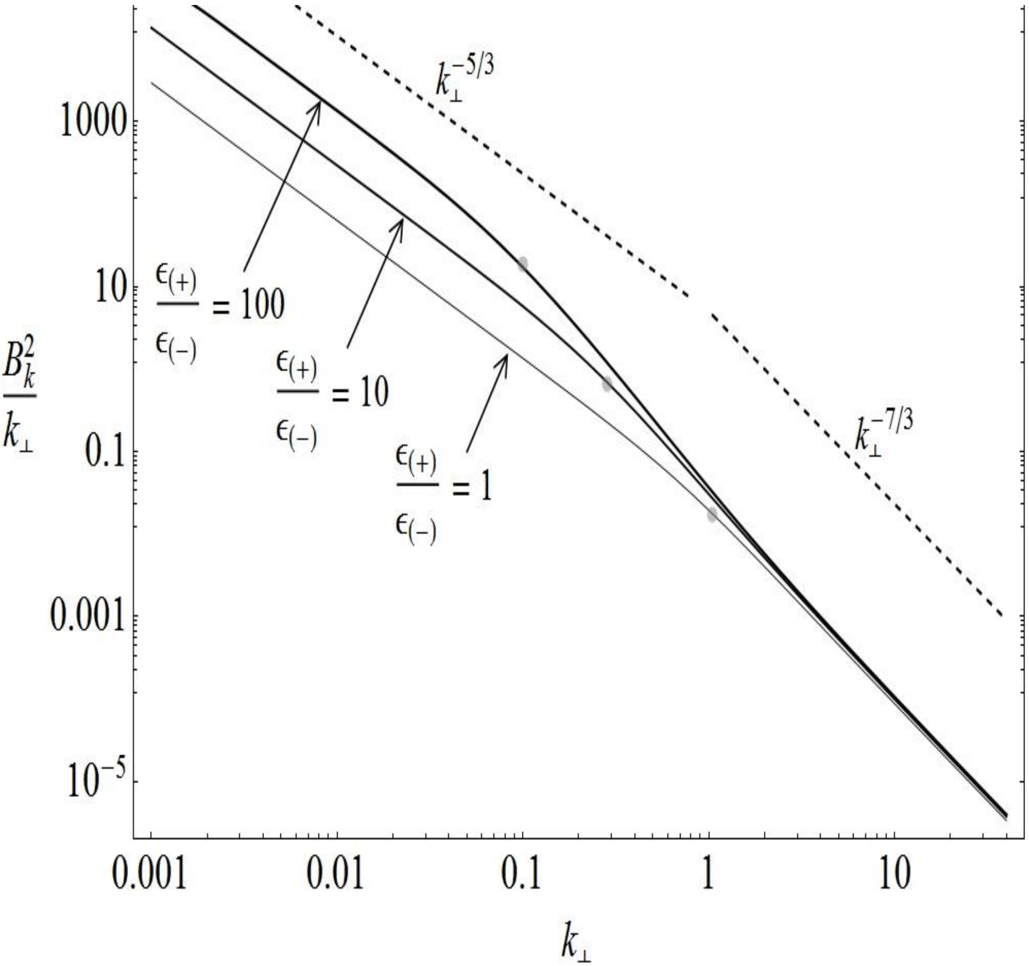
NON-UNIVERSALITY OF SPECTRA (THEORY)

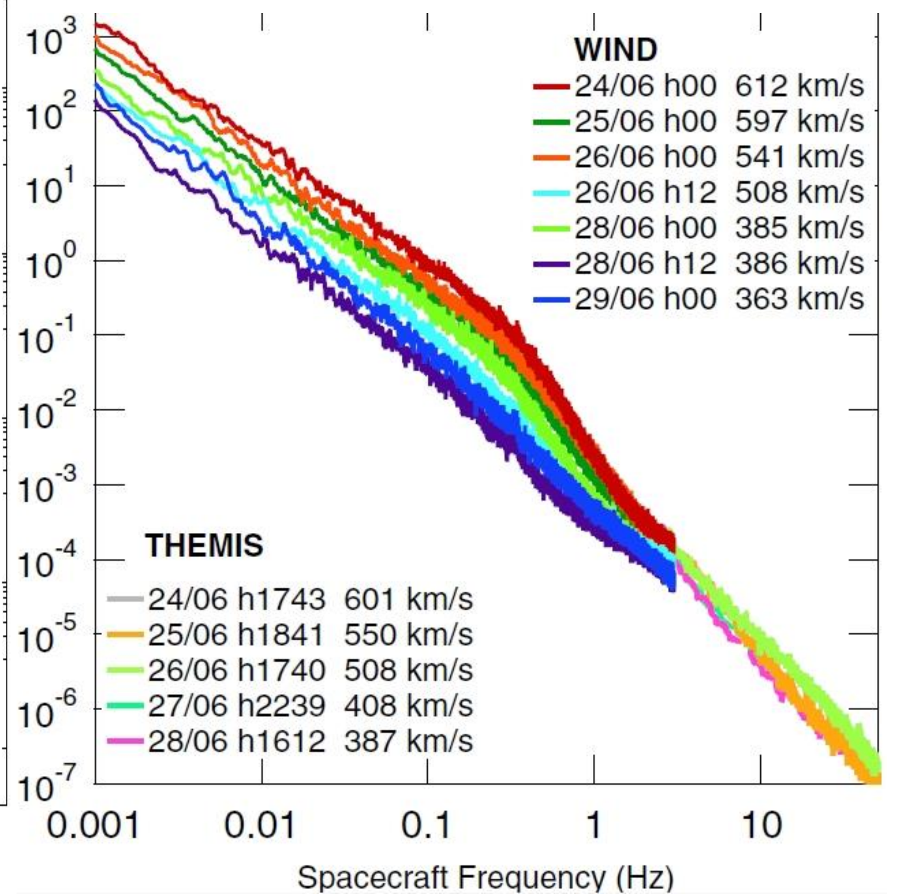


Turbulent spectra from MHD to kinetic scales without using asymptotic limits. Steepest non-universal spectra are found at $k_{\perp *} < k_\perp < 1/\rho_i$ Steeper spectra follow larger imbalances, spectral indexes ≥-3.

SUMMARY TURBULENCE (TO TAKE AWAY)

Collisions among co-propagating weakly dispersive KAWs establish a new dynamical sub-range of the imbalanced turbulence at perpendicular wavenumbers $k_{\perp *} < k_{\perp} < 1/\rho_i$ where the spectra are steepest and non-universal.





SUMMARY (IN MORE DETAIL)

Collisions among co-propagating weakly dispersive KAWs establish a new dynamical sub-range of imbalanced turbulence at perpendicular wavenumbers $k_{\perp *} < k_{\perp} < 1/\rho_i$ with steepest non-universal spectra the following properties:

1. Turbulence imbalance makes the transition (spectral break) wavenumber $k_{\perp *}$ smaller than the inverse ion gyroradius $1/\rho_i$
2. Collisions among co-propagating weakly dispersive KAWs. produce steepest non-universal spectra. The spectral indexes vary around -3 (strong turbulence) and -4 (weak turbulence)
3. Larger turbulence imbalances are followed by steeper ion-scale spectra (as observed by Bruno et al. 2014)
4. Magnetic amplitude ratio $B_{k(+)}/B_{k(-)}$ decreases with $k_{\perp}$ in the weakly dispersive KAW range
5. Parallel wavenumber k_z does not evolve in the weakly dispersive range, hence the wavenumber anisotropy $k_{\perp}/k_z$ grows faster

DISSIPATION OF TURBULENCE

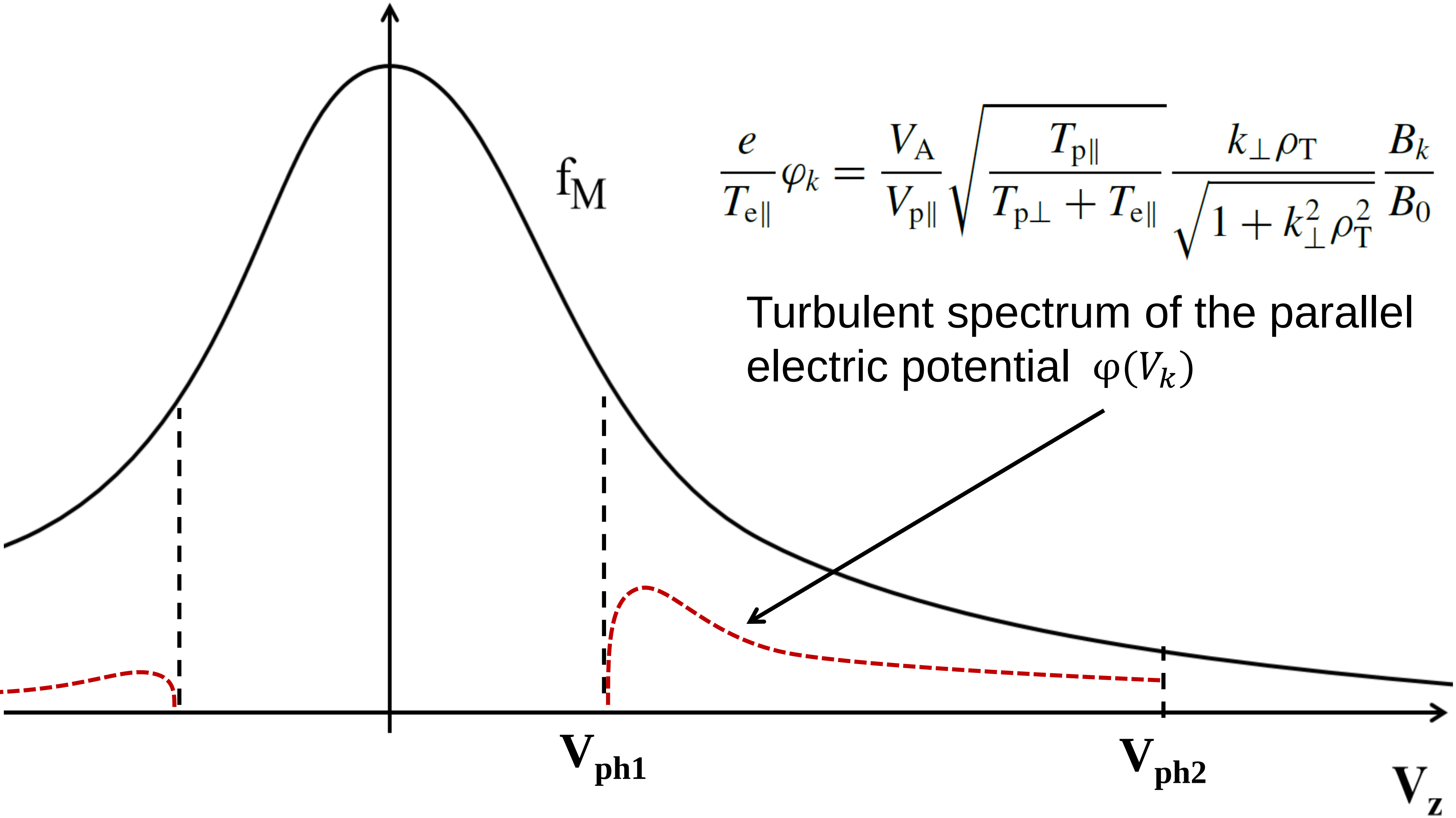
Energy deposition by turbulence:

- **Q1: How is plasma heated and particles accelerated?**
  - **heating mechanism: resonant, stochastic, reconnection, etc.**
  - **distribution throughout plasma, e.g. structures**

- **Q2: How is the dissipated energy partitioned?**
  - **electrons vs protons vs heavy ions**
  - **particle acceleration vs heating**

- **Q3: How does dissipation operate in different regimes of turbulence?**
  - **different environments: solar wind, foreshock, shock, magnetosheath**
  - **different plasma parameters: beta, temperature ratio, imbalance**

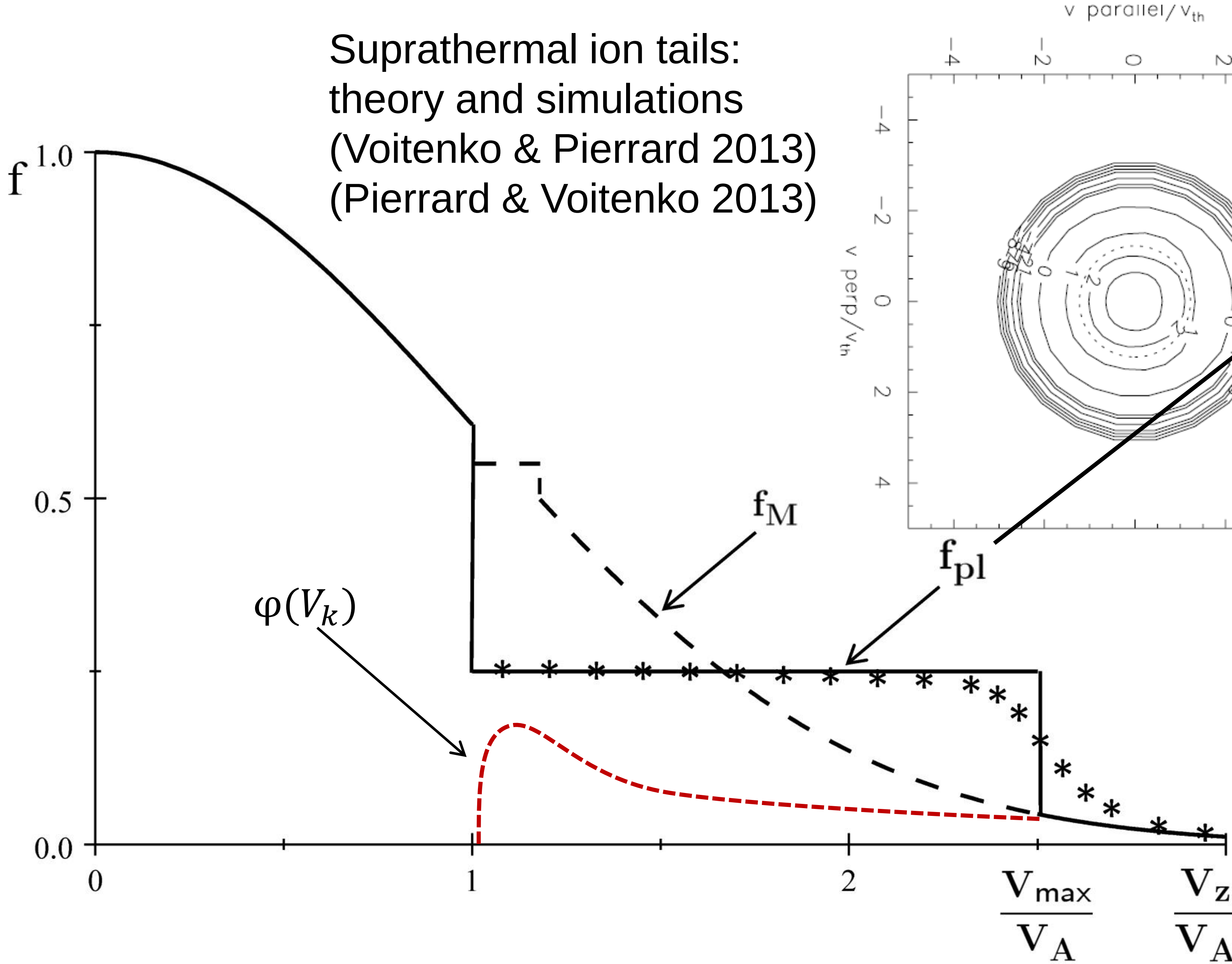
VELOCITY-SPACE DIFFUSION (THEORY)



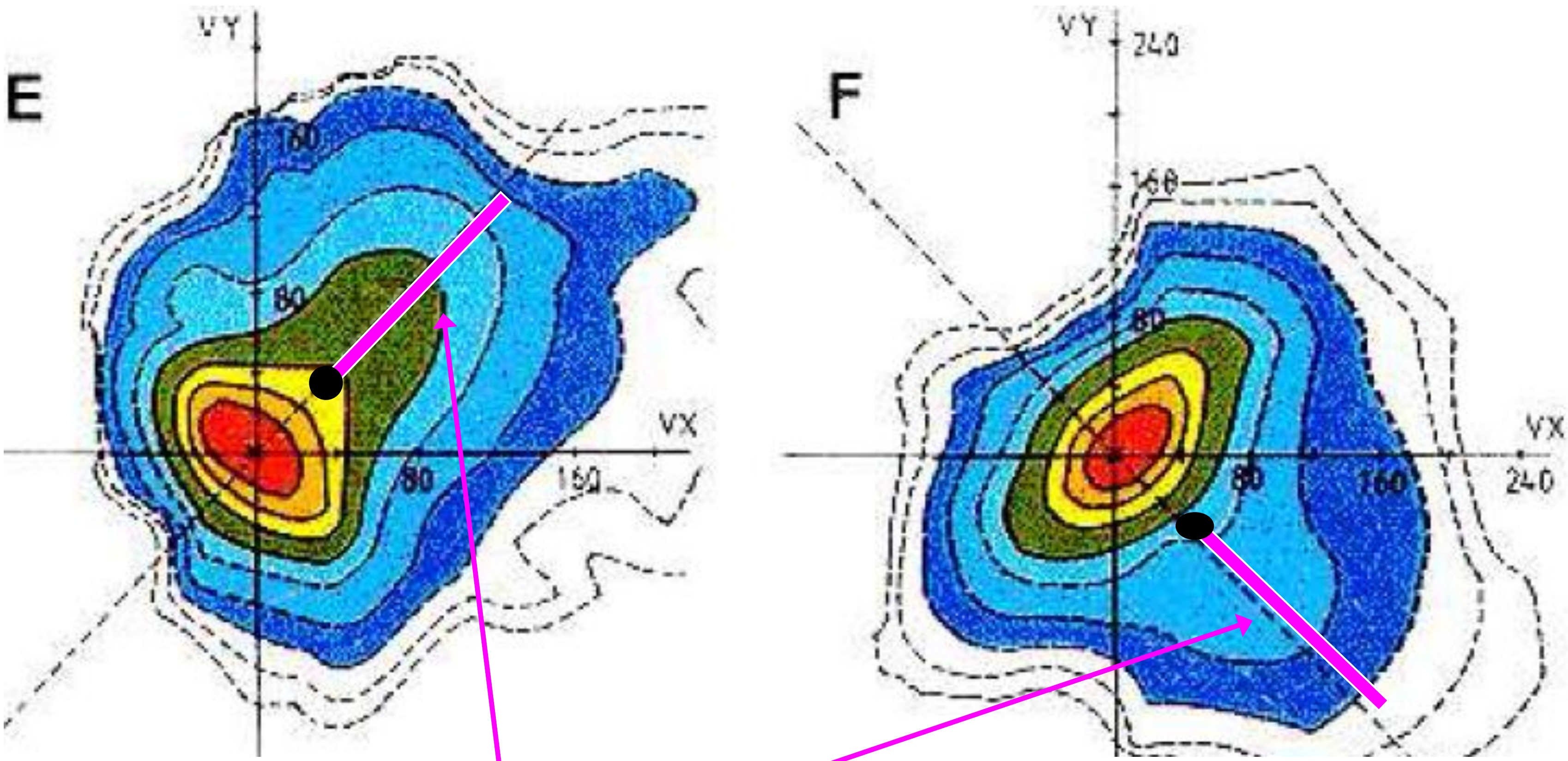
$$\frac{e}{T_{e\parallel}}\varphi_k = \frac{V_A}{V_{p\parallel}}\sqrt{\frac{T_{p\parallel}}{T_{p\perp}+T_{e\parallel}}}\,\frac{k_\perp \rho_T}{\sqrt{1+k_\perp^2\rho_T^2}}\,\frac{B_k}{B_0}$$

VELOCITY-SPACE DIFFUSION (THEORY)

Suprathermal ion tails:
theory and simulations
(Voitenko & Pierrard 2013)
(Pierrard & Voitenko 2013)

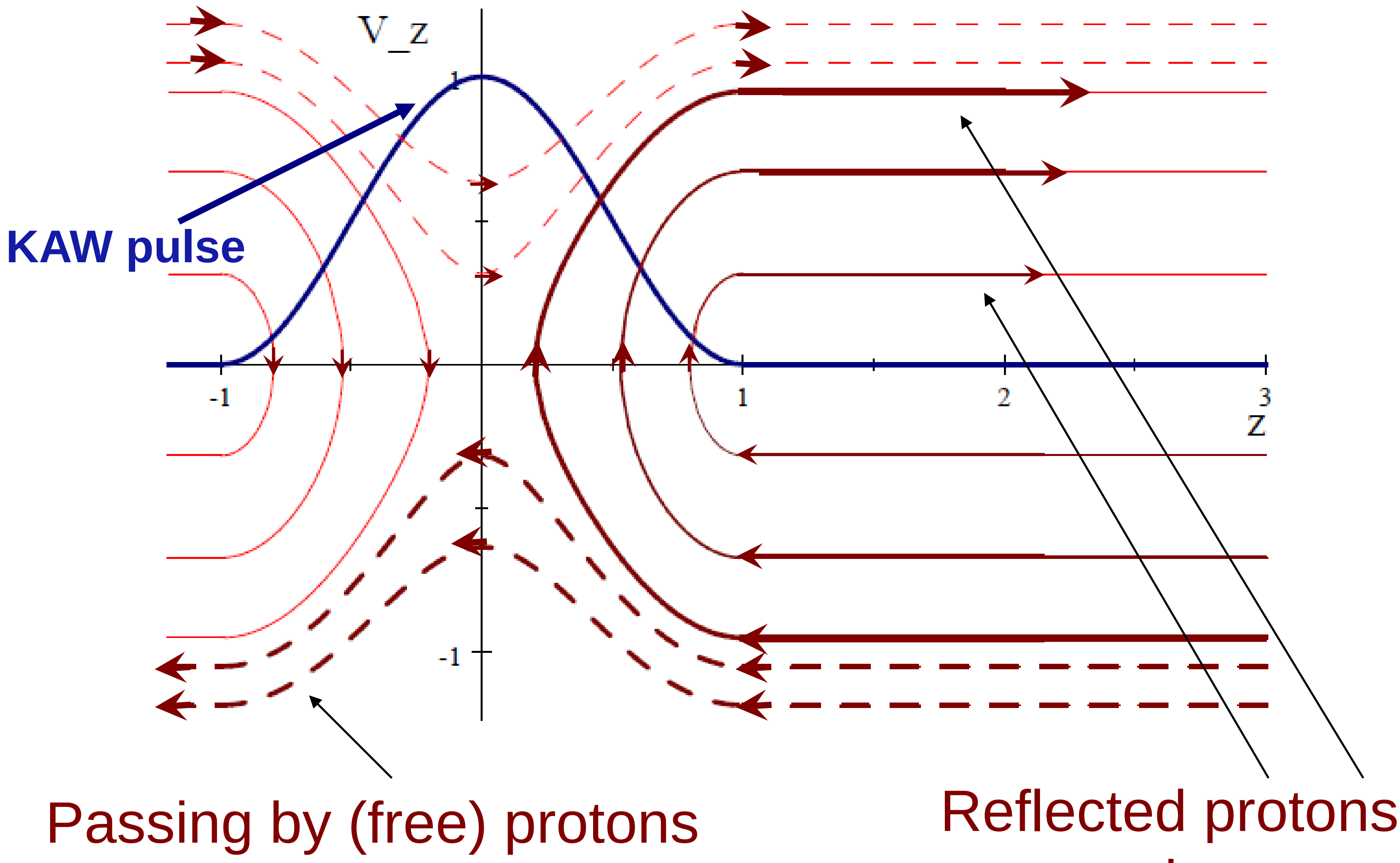


II. TURBULENCE → PARTICLES



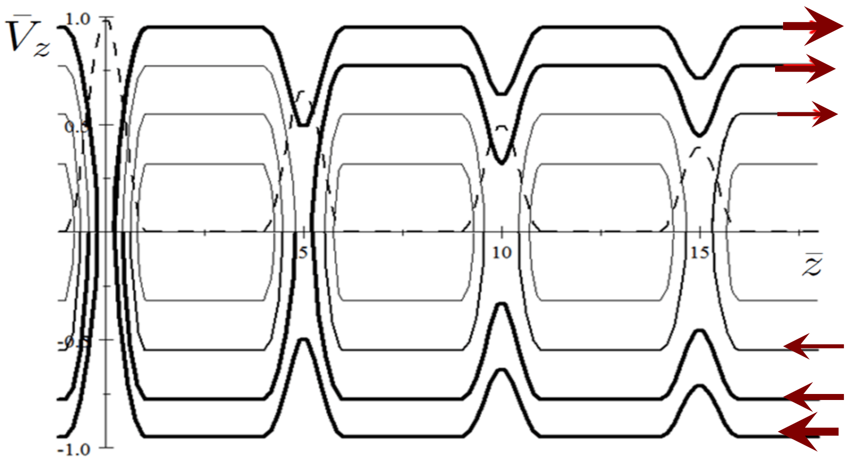
Velocities of KAWs cover the tail velocity range

PARALLEL PROTON ACCELERATION BY KAWs: NON-LINEAR CHERENKOV RESONANCE

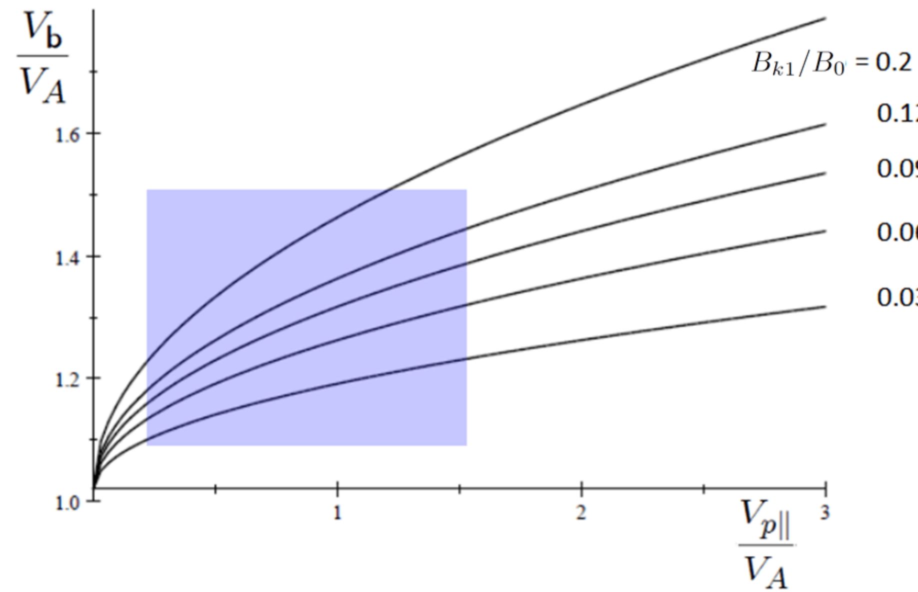


GENERATION OF ION BEAMS BY TURBULENCE

(Voitenko & Pierrard 2013)

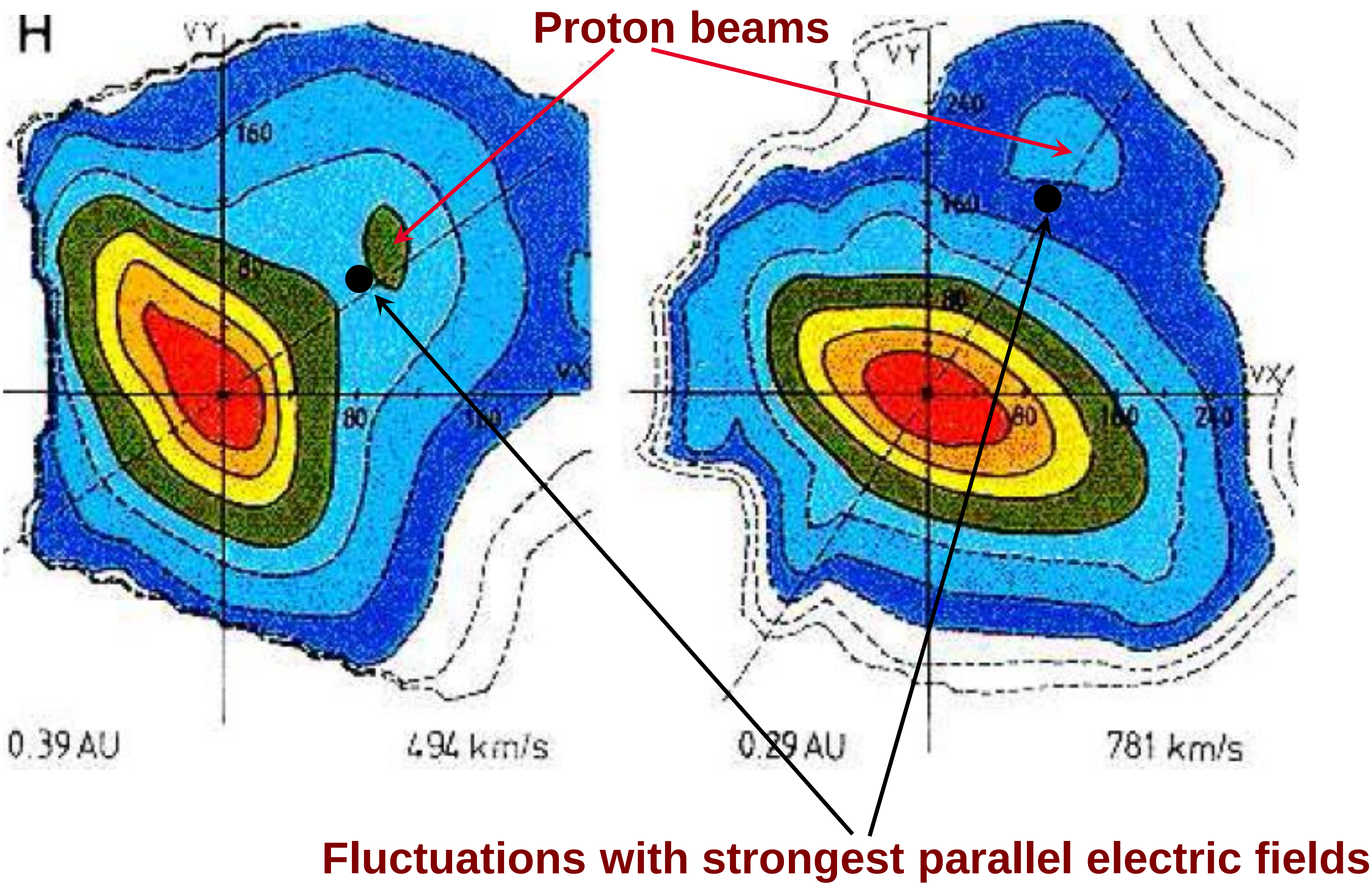


Phase-space map of the proton motion in the non-uniform series of pulses. The ratio of the proton energy to the maximum potential hill height is 0.1, 0.3, 0.6, and 0.9 from inner to outer solid curves. The outer proton trajectories become progressively released at larger z, where the pulse potentials decrease.



Proton beam velocity as function of thermal/Alfven velocity ratio. The relative magnetic amplitude is 0.03, 0.06, 0.09, 0.12, and 0.2 from bottom to top.
Blue box area shows values observed in the solar wind. Increasing beam velocity with increasing plasma beta has been observed by Tu et al. (2004)

GENERATION OF ION BEAMS BY TURBULENCE



NONADIABATIC ION ACCELERATION

Equation for cross-field ion velocity in the presence of KAWs:

$$\frac{d^2}{dt^2} v_x = \left[\boxed{\frac{q_i}{m_i} \left(\frac{\partial E_x}{\partial x} - \frac{V_{iz}}{c} \frac{\partial B_y}{\partial x} \right)} - \Omega_i^2 \right] v_x$$

In the vicinity of demagnetizing wave phases velocity grows exponentially:

$$v_x = v_{x0} \exp\left(\gamma_{\mathrm{n-a}} t\right)$$

- *--- non-resonant, frequency independent*
- *--- kick-like acceleration across the magnetic field*
- *--- threshold-like in wave amplitude and wavelength*
- *--- results in selective decay washing out highest amplitudes*
- *--- can produce 'dissipative' spectra*

NONADIABATIC ION ACCELERATION

Solution is $v_x = v_{x0} \exp(\gamma_{\mathrm{n-a}} t)$, with $\gamma_{\mathrm{n-a}}$ given by

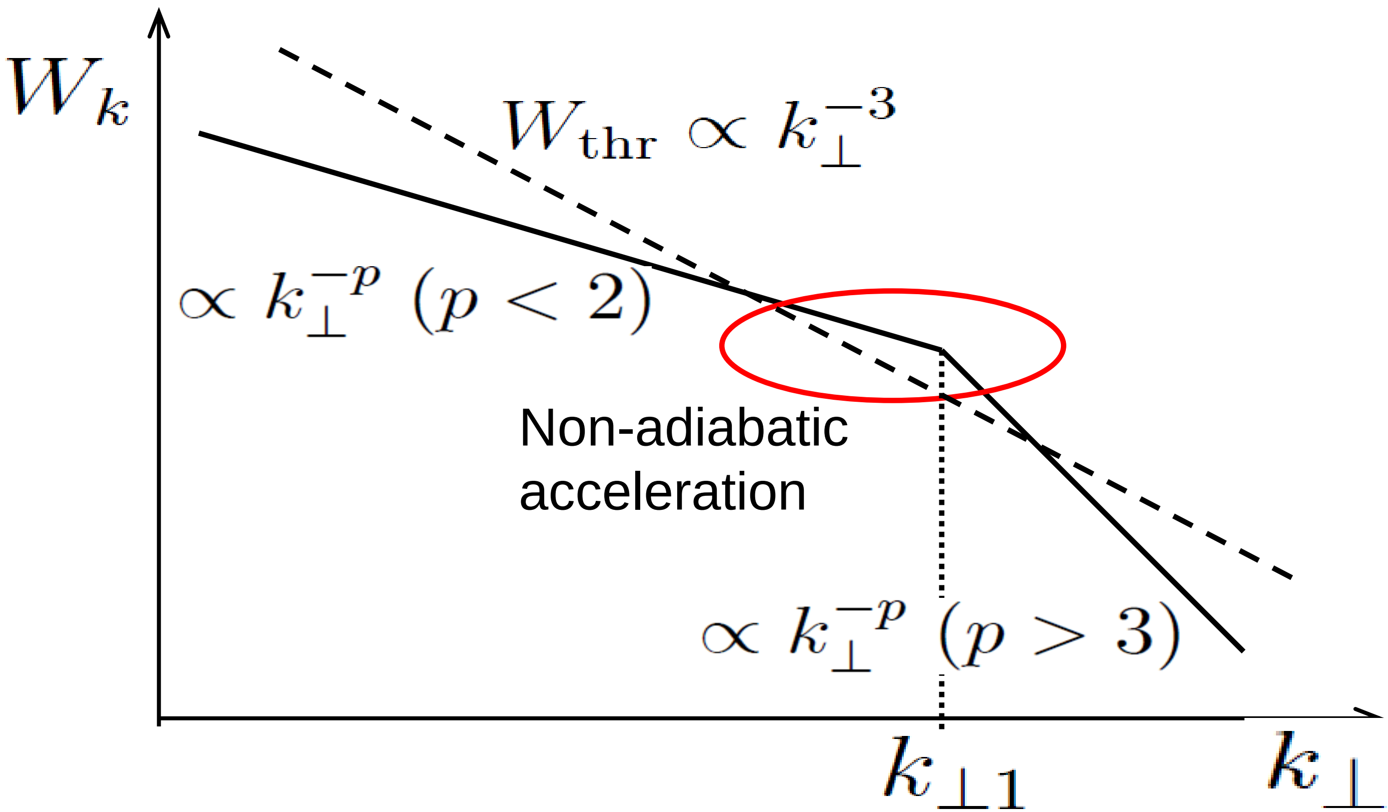
$$\frac{\gamma_{\mathrm{n-a}}}{\Omega_p} = \eta_i^{-1} \sqrt{A\eta_i - 1}.$$

$\gamma_{\mathrm{n-a}}$ becomes real for sufficiently large KAW's wavenumber and/or amplitude: threshold condition

$$A \equiv \frac{V_A}{V_{Tp}} \left(\frac{1 + \mu_p^2}{K} - \frac{V_{iz}}{V_A} \right) \mu_p \frac{B_{k0}}{B_0} > \eta_i^{-1}.$$

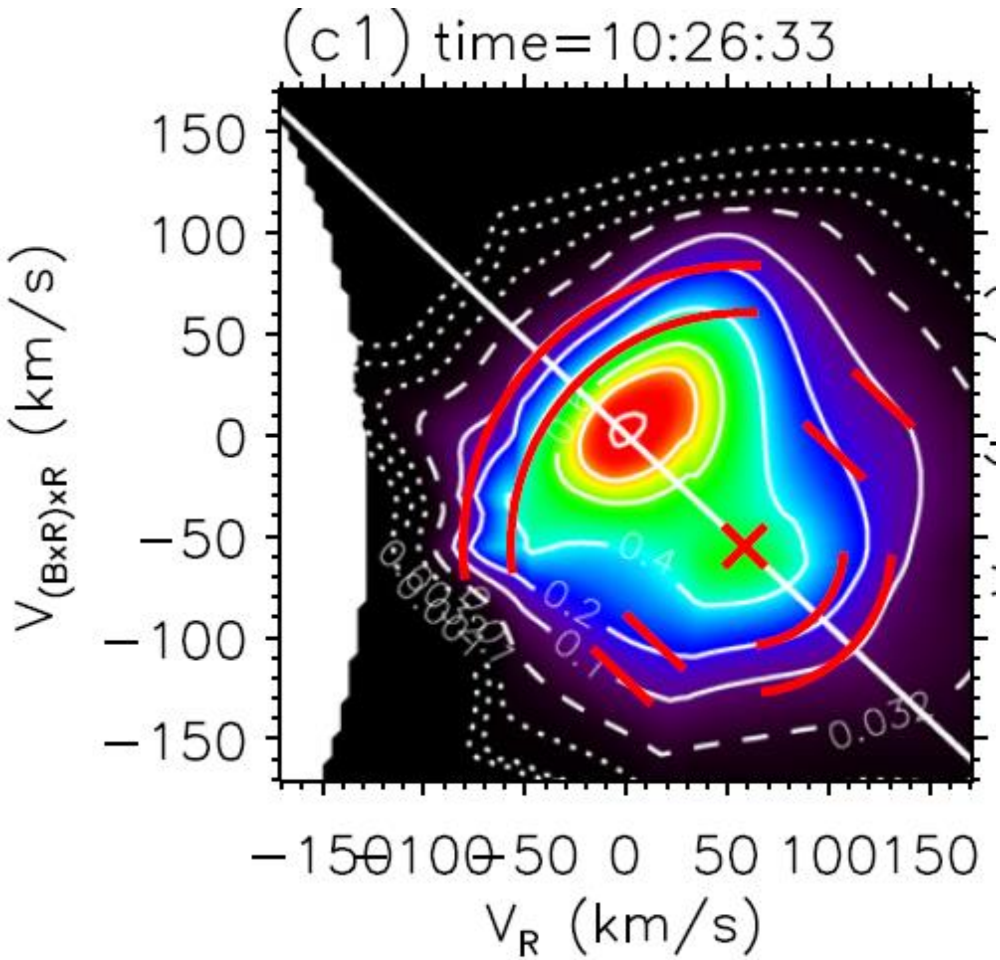
In this case the cross-field velocity of the ions grows exponentially, which leads to the energization and heating of the ions.

SPECTRAL LOCALIZATION OF NON-ADIABATIC



AW turbulent spectrum (solid line) and ”threshold” spectrum (dashed line). Super-adiabatic ion acceleration is possible around the ion-scale spectral kink, where the threshold spectrum can drop below the turbulent spectrum.

III. TURBULENCE → PARTICLES → TURBULENCE

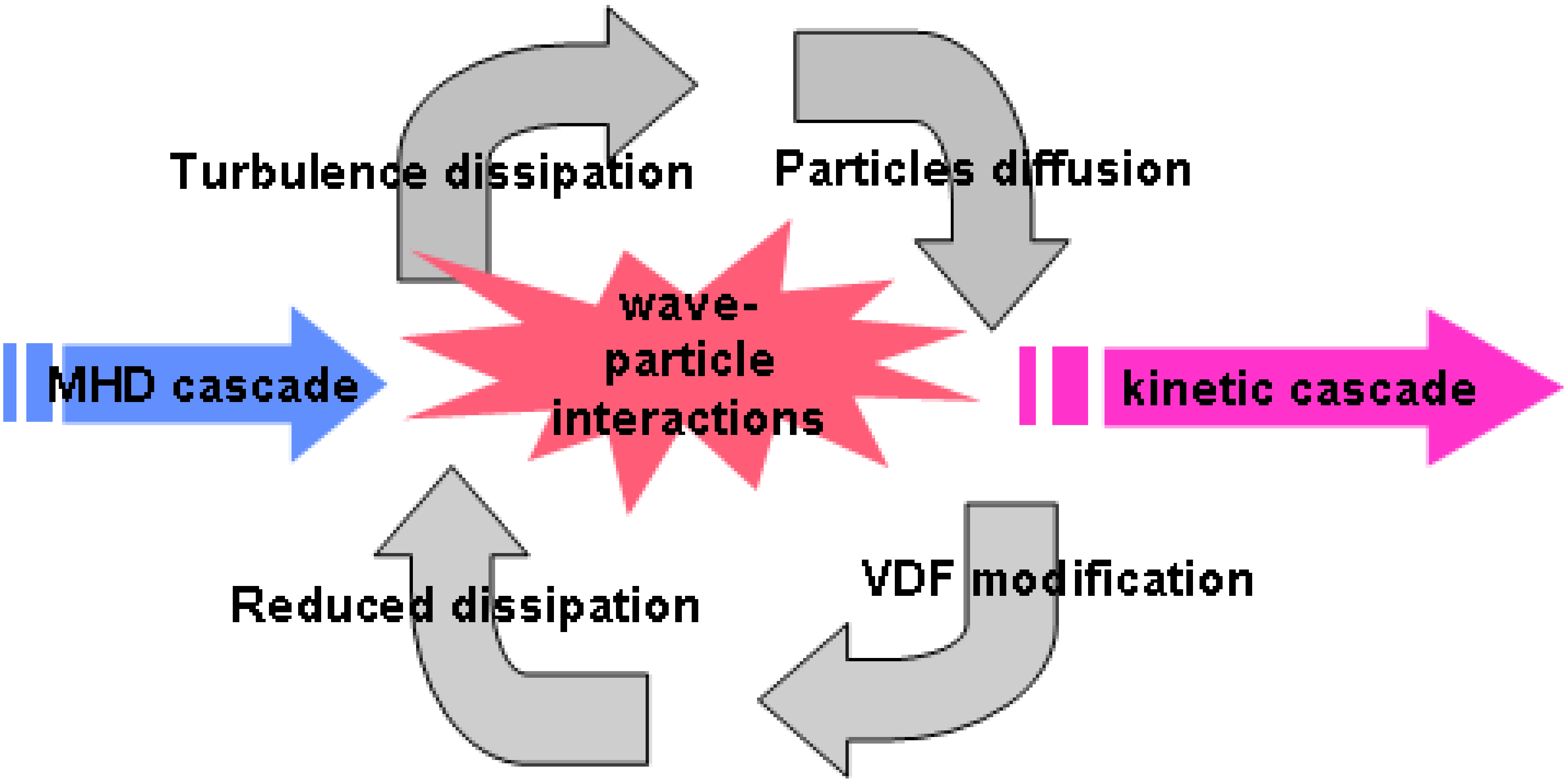


Velocity-space plateau in the solar wind (He et al. 2015)

Consequences for turbulence: kinetic damping is reduced!

$$\gamma_{\mathrm{L}} = \sum_{s} \gamma_{\mathrm{L}}^{\mathrm{M}} \left(1 + \frac{\tau_{\mathrm{C}}}{\tau_{\mathrm{KAW}}}\right)^{-1}$$

TURBULENCE / PARTICLES FEEDBACK LOOP



$$\gamma_{\mathrm{L}} = \sum_{s} \gamma_{\mathrm{L}}^{\mathrm{M}} \left(1 + \frac{\tau_{\mathrm{C}}}{\tau_{\mathrm{KAW}}} \right)^{-1}$$

SUMMARY

- Weakly dispersive dynamical range (WDR) of imbalanced turbulence is established by co-collisions among waves propagating in the same direction

- Larger imbalance → larger break scale → wider WDR → steeper WDR spectrum

- Spectral dynamics and scalings in WDR are dominated by co-collisions, with complimentary contribution of intermittency and damping.

- Damping is reduced by particles’ feedback (quasi-linear plateaus).

- **THOR – CSW measurements of velocity distributions will allow estimating the real damping and its role in the cascade generated by co-collisions**