Multi-scale pressure-balanced fluctuations in the compressive solar wind

RPW meeting
Prague - October 2023

Luca Franci
Royal Society University Research Fellow
Imperial College London, UK

Emanuele Papini, INAF Institute for Space Astrophysics and Planetology, Italy
Daniele Del Sarto, Université de Lorraine, France
Georgios Nicolaou, University College London, UK
Julia Stawarz, Nortumbria University, UK
Milan Maksimovic, LESIA Observatoire de Paris, France
Alfredo Micera, **Maria Elena Innocenti**, Ruhr-Universität Bochum, Germany
Tim Horbury, **Lorenzo Matteini**, **Harry Lewis**, Imperial College London
Giovanni Lapenta, Katholieke Universiteit Leuven, Leuven, Belgium
Petr Hellinger, Astronomical Institute, Prague, Czech Republic
Simone Landi, University of Florence, Italy
and others…

Imperial College London
Science & Technology Facilities Council
THE ROYAL SOCIETY
DiRAC

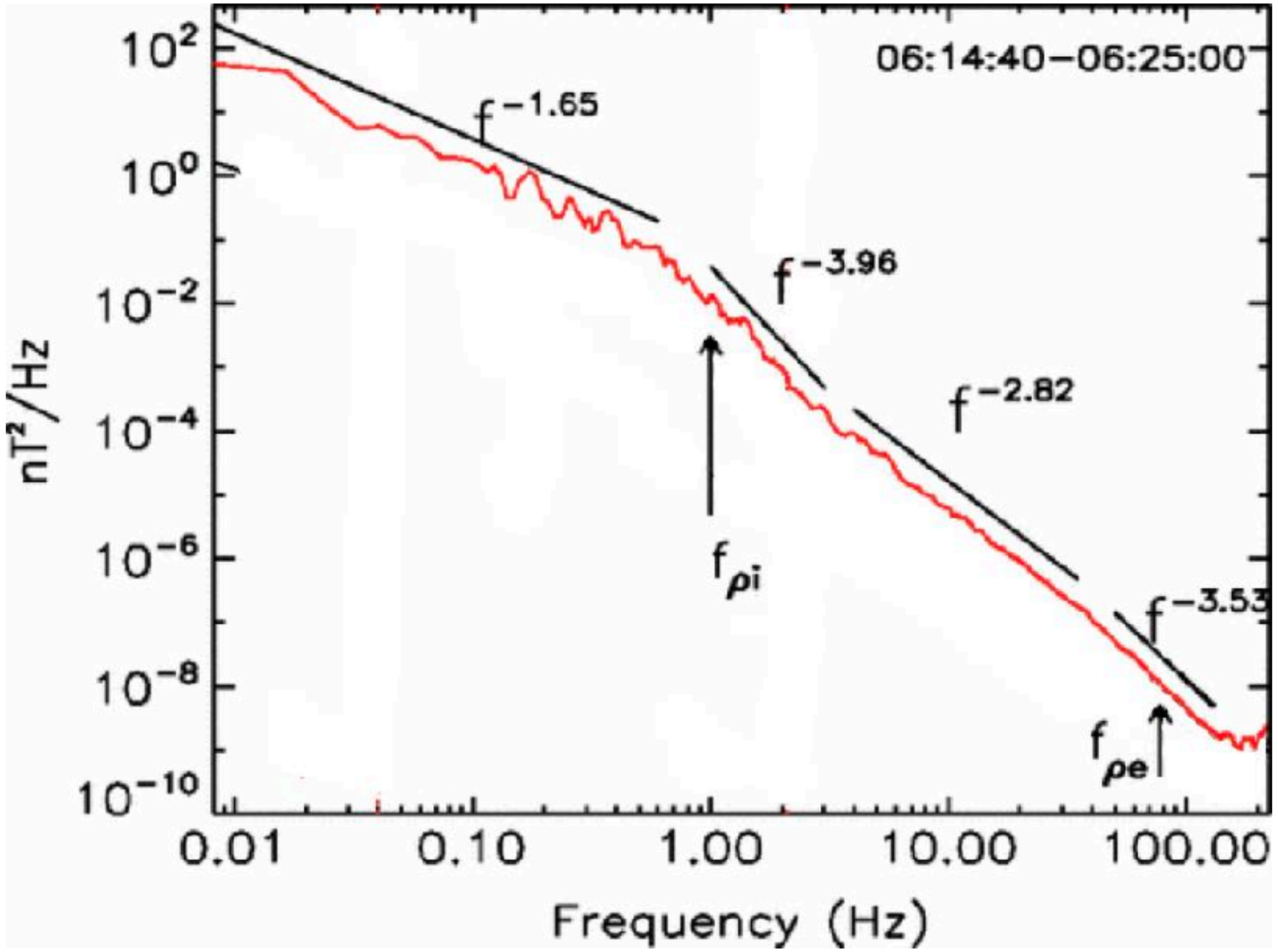
Scientific rationale

The magnetic field can carry a significant amount of fluctuation energy within a turbulent plasma but cannot do work on the plasma
The energy exchange between e.m. fields and particles is mediated by the electric field through a nonzero $\boldsymbol{j} \cdot \boldsymbol{E}$

The fluctuations of ***B*** have been extensively investigated, those of ***E*** much less so, both with observations and simulations!

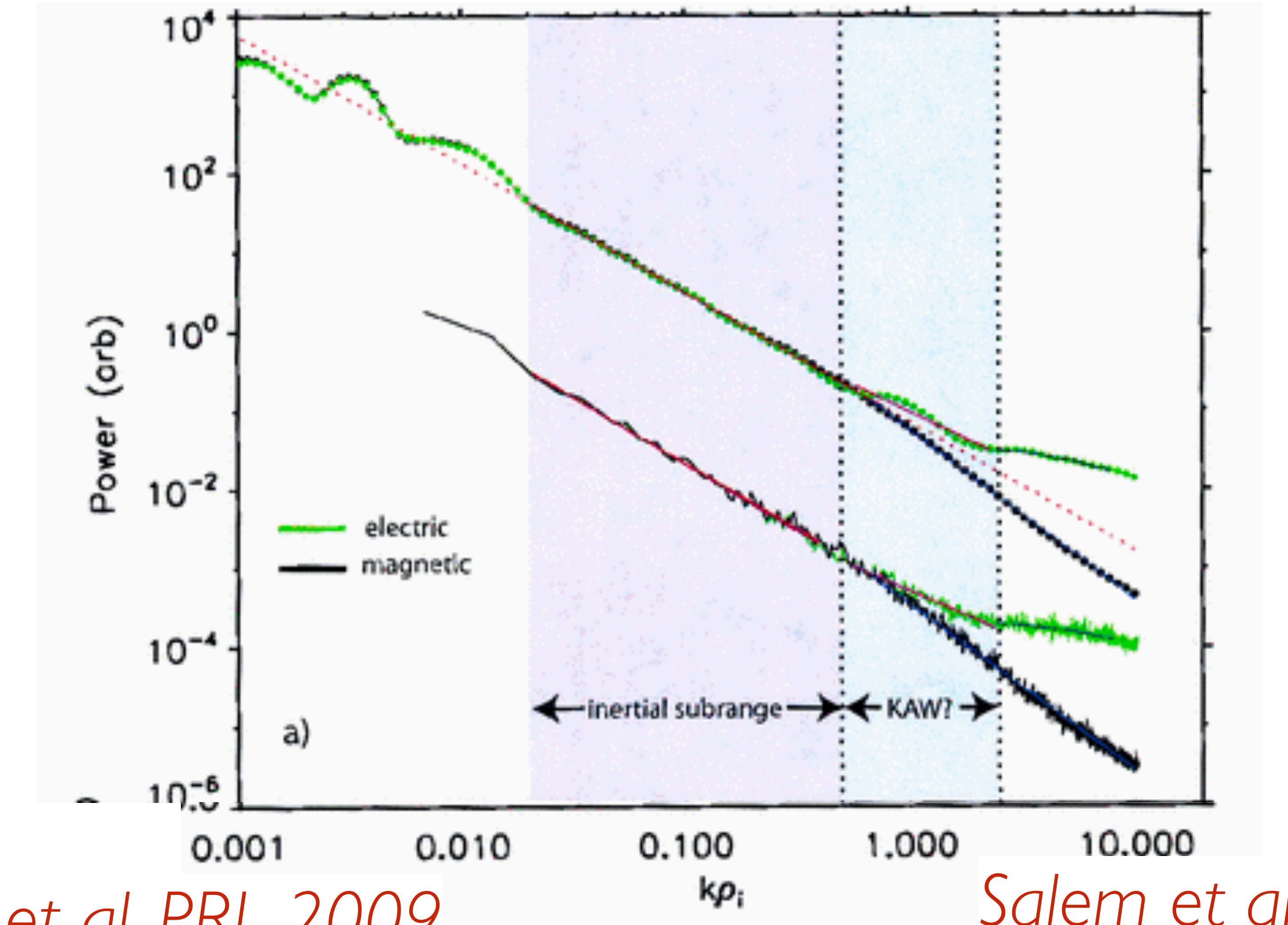
Adapted from Sahraoui PRL 2010

Power spectrum of the solar wind magnetic fluctuations at 1 au



Bale et al. PRL 2005

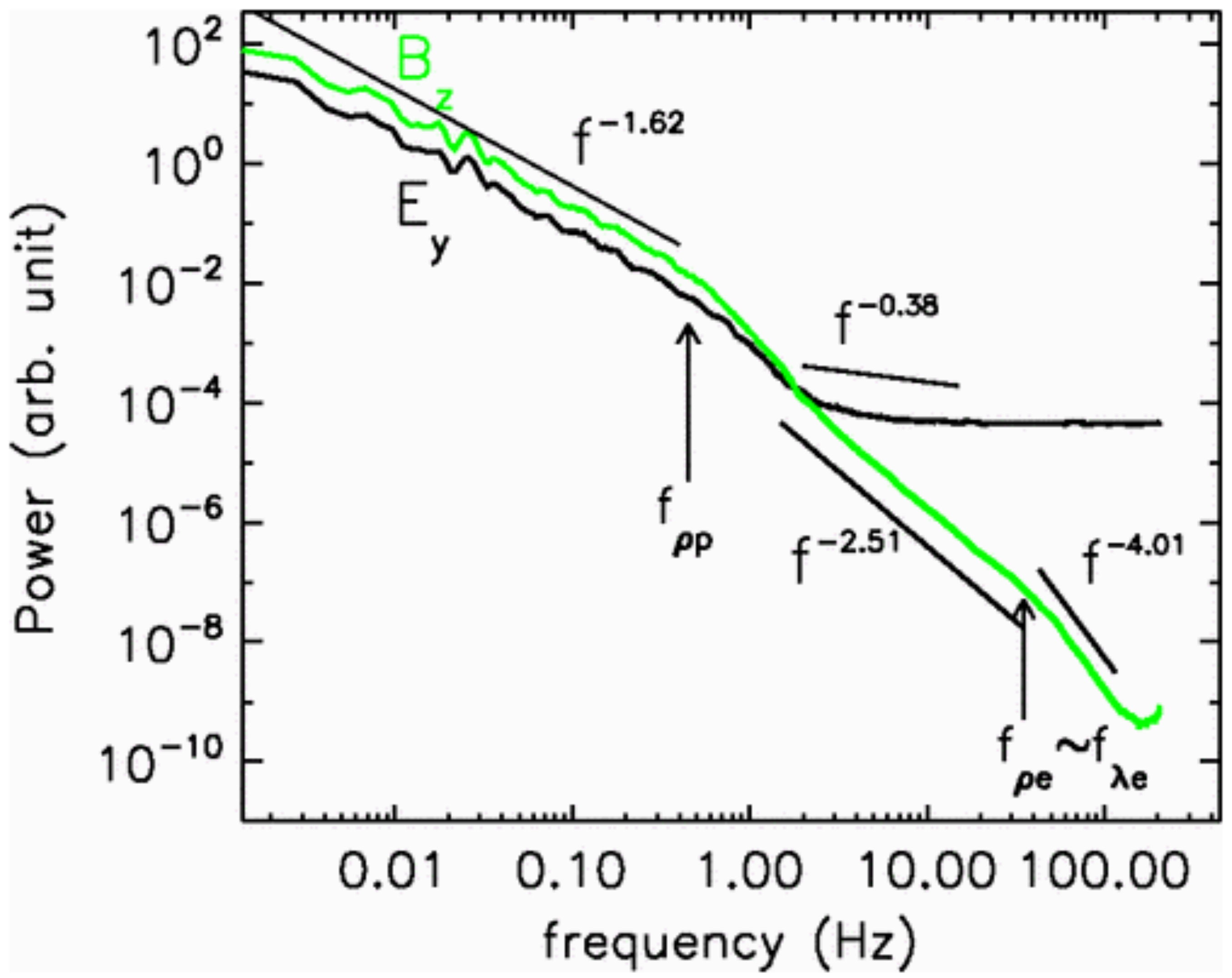
First measured power spectrum of electric fluctuations in solar wind turbulence



Not comprehensive

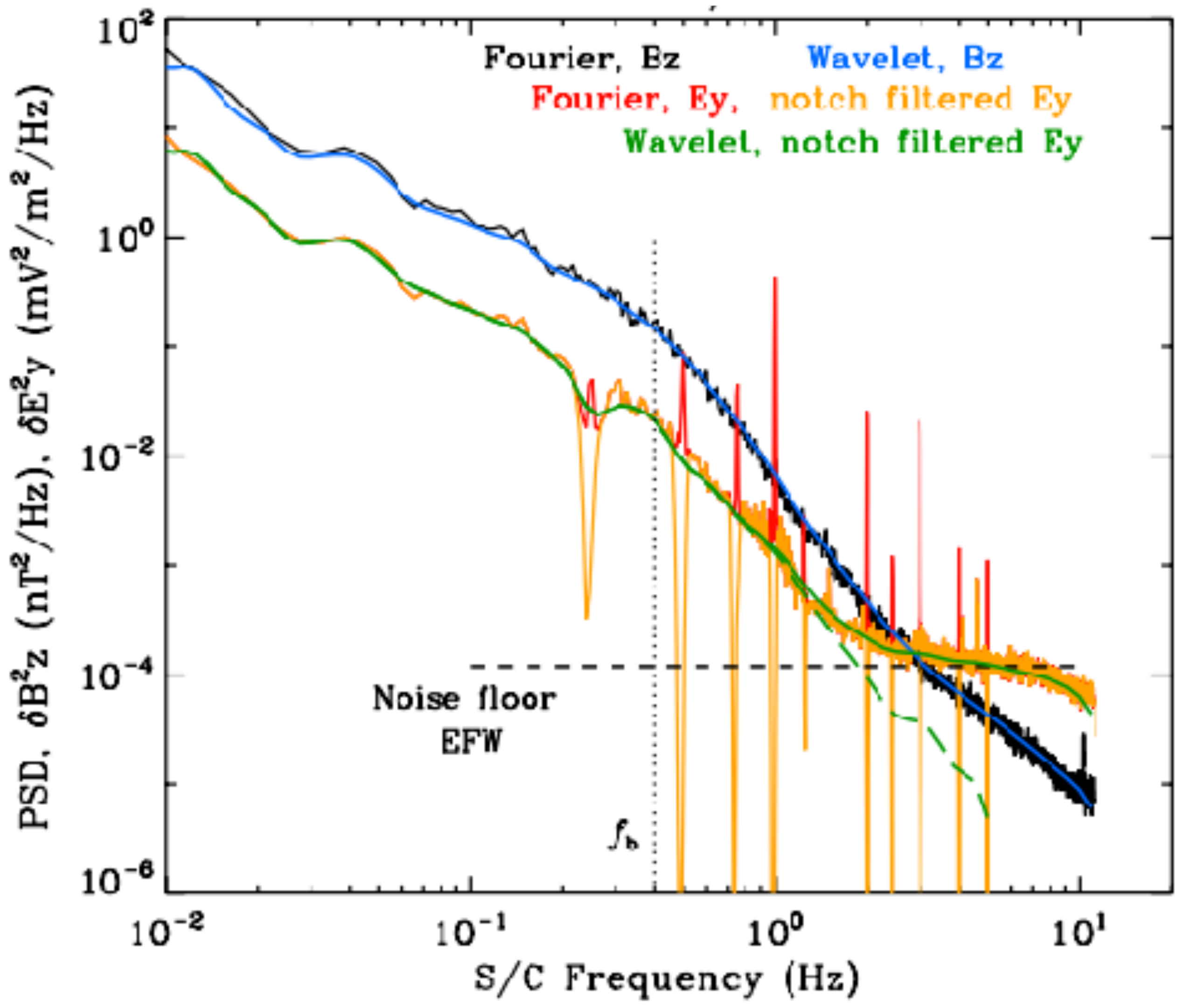
Sahraoui et al. PRL 2009

Cluster measurements in the solar wind



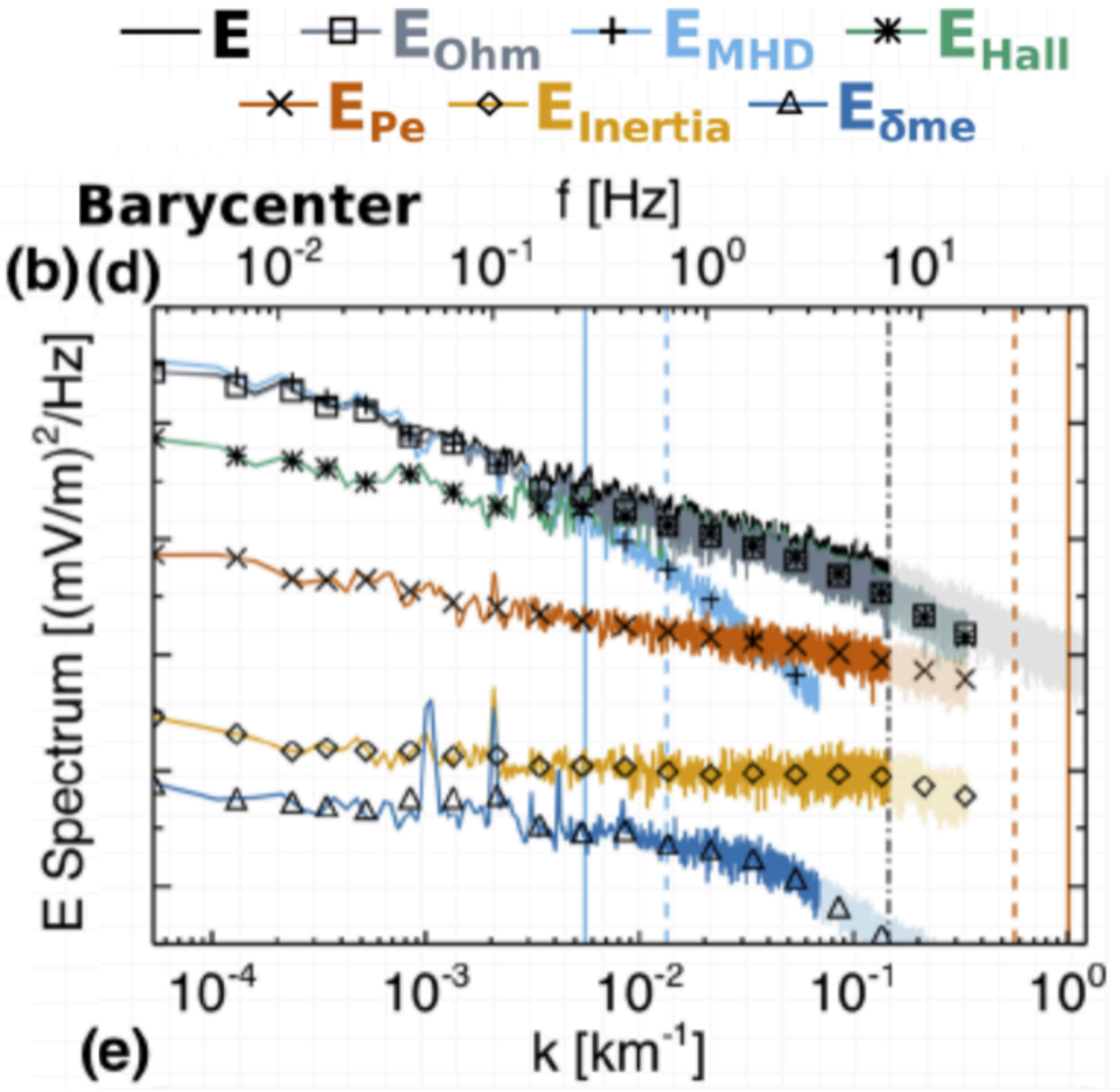
Salem et al. ApJL 2012

Cluster measurements in the solar wind



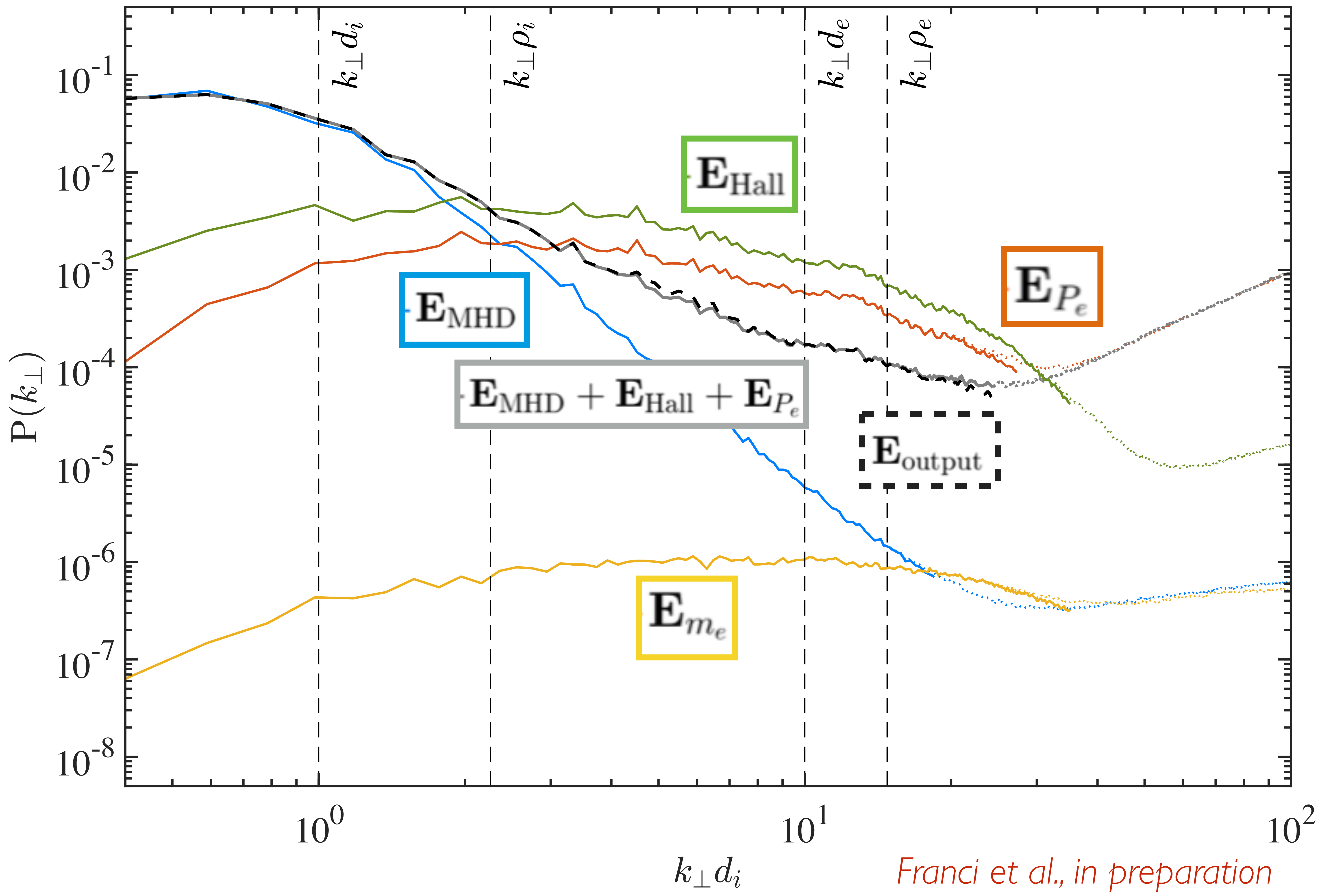
Contributions to the generalized Ohm's law in Fourier space

Stawarz et al. JGR 2020
MMS measurements in the magnetosheath



2D high-resolution fully kinetic simulation
Initial Alfvénic-like fluctuations + out-of-plane ambient magnetic field B_0

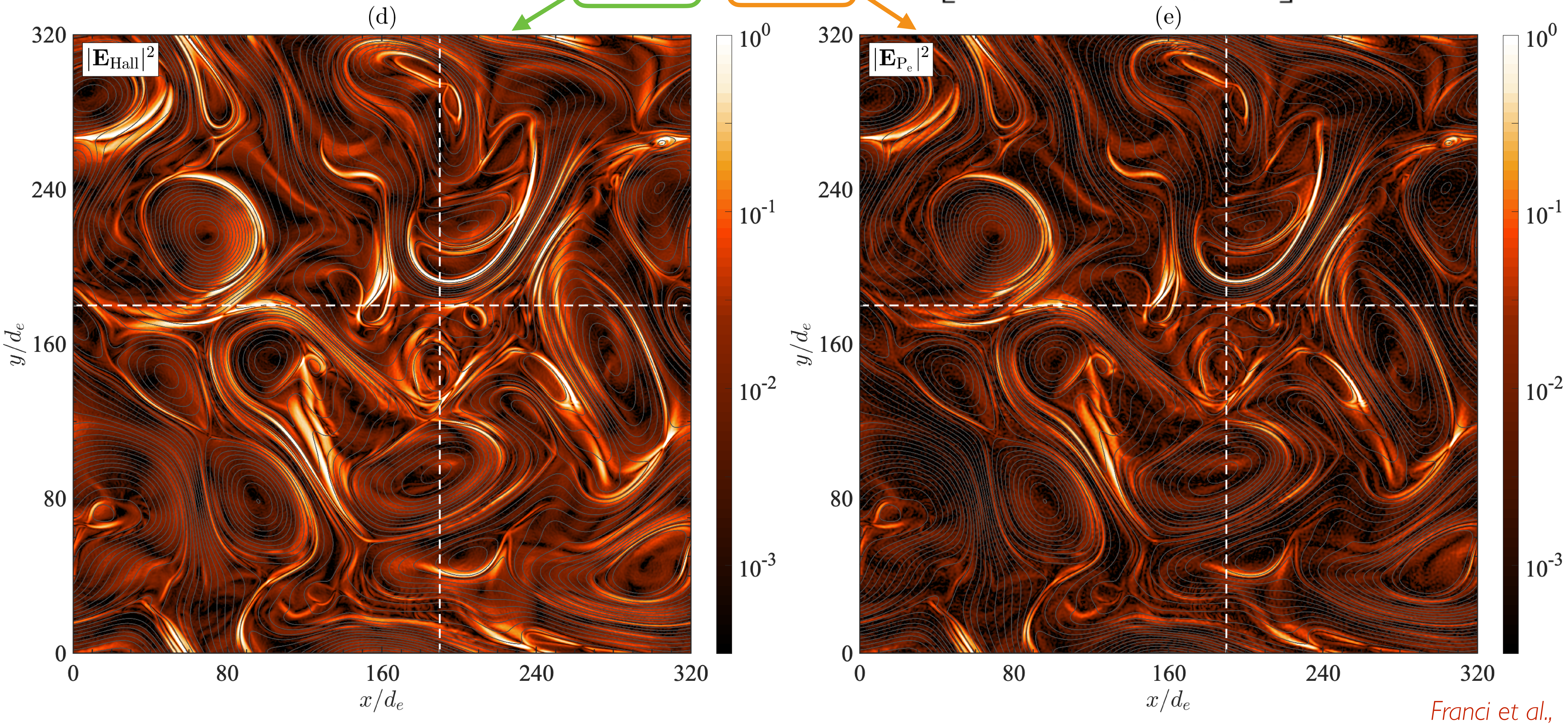
$$\boxed{\mathbf{E}} = \boxed{-\mathbf{u}\times\mathbf{B}} + \boxed{\frac{1}{en}\mathbf{j}\times\mathbf{B}} - \boxed{\frac{1}{en}\nabla\cdot\mathbf{p}_e} + \boxed{\cancel{\frac{m_e}{e^2 n}\left[\nabla\cdot\left(\mathbf{uj}+\mathbf{ju}-\frac{\mathbf{jj}}{en}\right)+\frac{\partial\mathbf{j}}{\partial t}\right]}}$$



Franci et al., in preparation

Dominant contributions to the generalized Ohm's law at sub-ion scales

$$\mathbf{E} = -\mathbf{u}\times\mathbf{B} + \boxed{\frac{1}{en}\mathbf{j}\times\mathbf{B}} - \boxed{\frac{1}{en}\nabla\cdot\mathbf{p}_e} + \frac{m_e}{e^2 n}\left[\nabla\cdot\left(\mathbf{uj}+\mathbf{ju}-\frac{\mathbf{jj}}{en}\right)+\frac{\partial\mathbf{j}}{\partial t}\right]$$

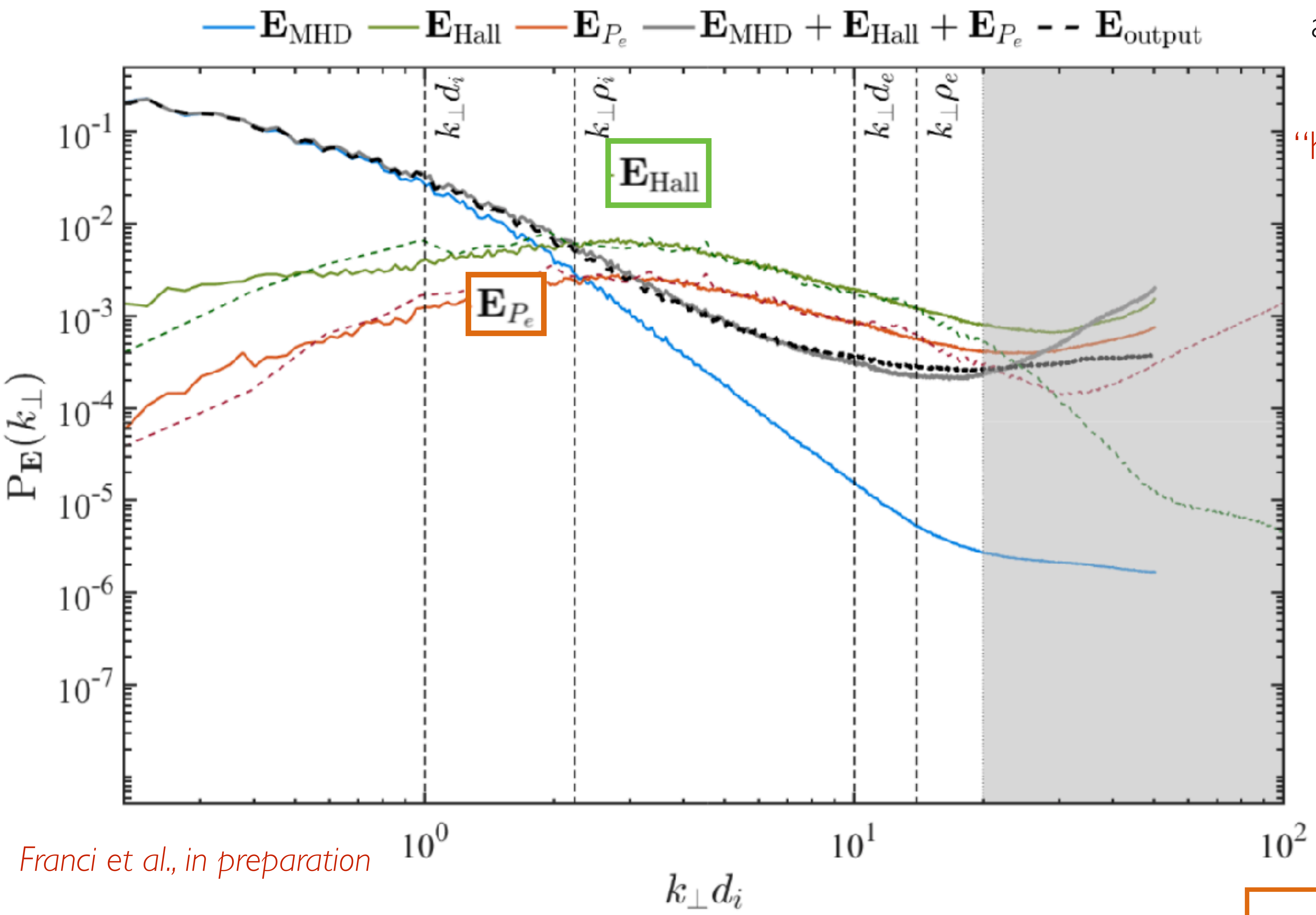


Franci et al., in preparation

l.franci@imperial.ac.uk

Hybrid and fully kinetic simulations with same plasma conditions

Hybrid (solid) vs Fully kinetic (dashed)



Franci et al., in preparation

No significant electron kinetic effects at scales larger than the electron gyroradius

The **Hall term** and the **electron pressure term** are almost exactly the **same above the electron scales**

⬇

"hybrid" approximation of isothermal electrons holds

$$\nabla \cdot P_e \sim \nabla \cdot (nT_e) = T_{e,0} \nabla(\delta n) + \cancel{n_0 \nabla \cdot (\delta T_e)} + \cancel{\nabla \cdot (\delta n\, \delta T_e)}$$

$$\boldsymbol{E}_{P_e} = -\frac{1}{en} \nabla \cdot P_e \xrightarrow[hybrid]{} \boldsymbol{E}_{P_e^{\mathrm{iso}}} = -\frac{1}{en} \frac{\beta_e}{2} \nabla n$$

If we now assume **force balance**

$$\nabla P = \boldsymbol{J} \times \boldsymbol{B}$$

and that also for ions the dominant term is

$$\nabla \cdot P_i \sim \nabla \cdot (nT_i) \simeq T_{i,0} \nabla(\delta n)$$

⬇

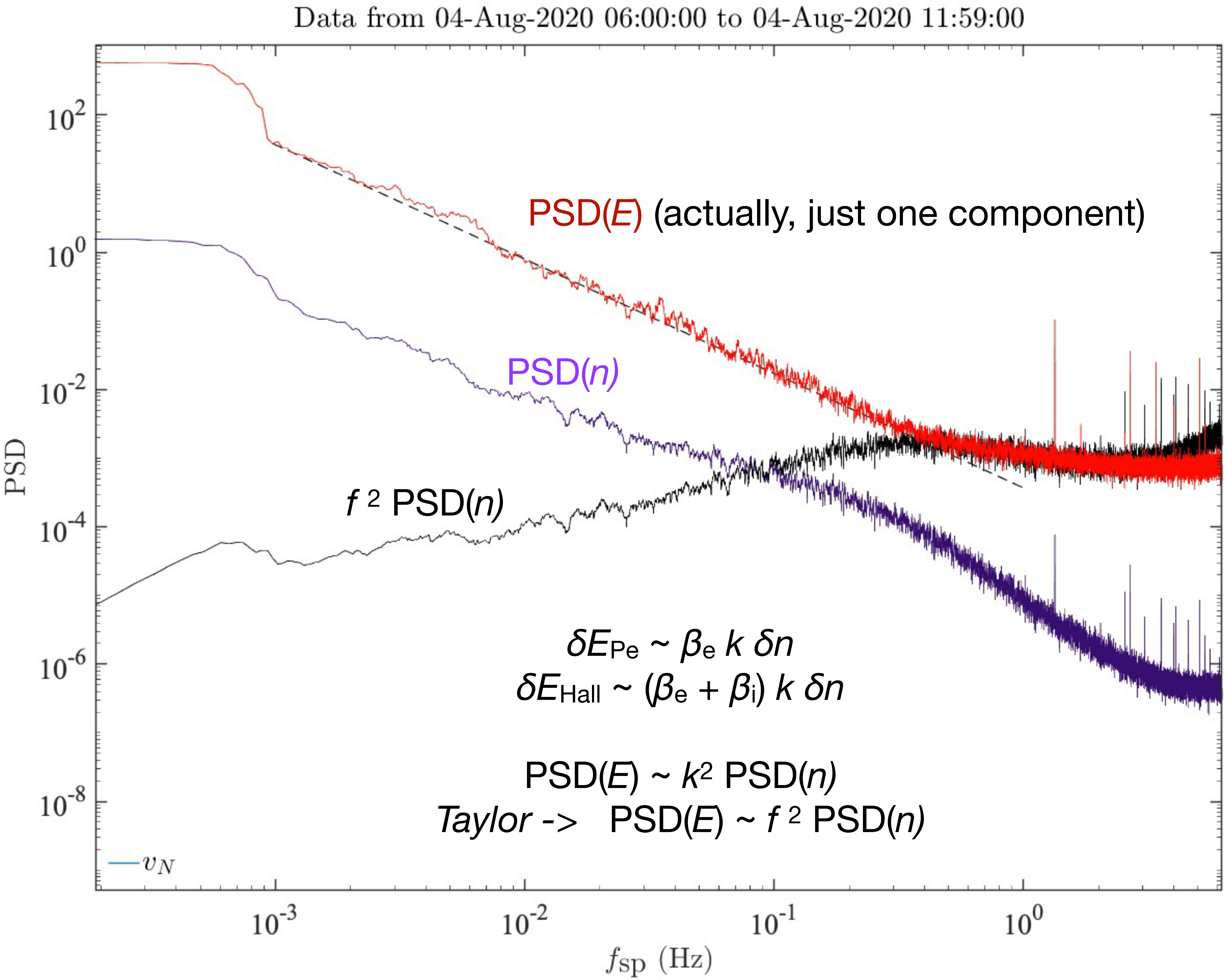
$$\boldsymbol{E}_{\mathrm{Hall}} \simeq \frac{1}{en} \frac{\beta_e + \beta_i}{2} \nabla n$$

$$\boxed{\boldsymbol{E}_{P_e^{\mathrm{iso}}} = -\frac{1}{en} \frac{\beta_e}{2} \nabla n} \qquad \boxed{\boldsymbol{E}_{\mathrm{Hall}} \simeq \frac{1}{en} \frac{\beta_e + \beta_i}{2} \nabla n}$$

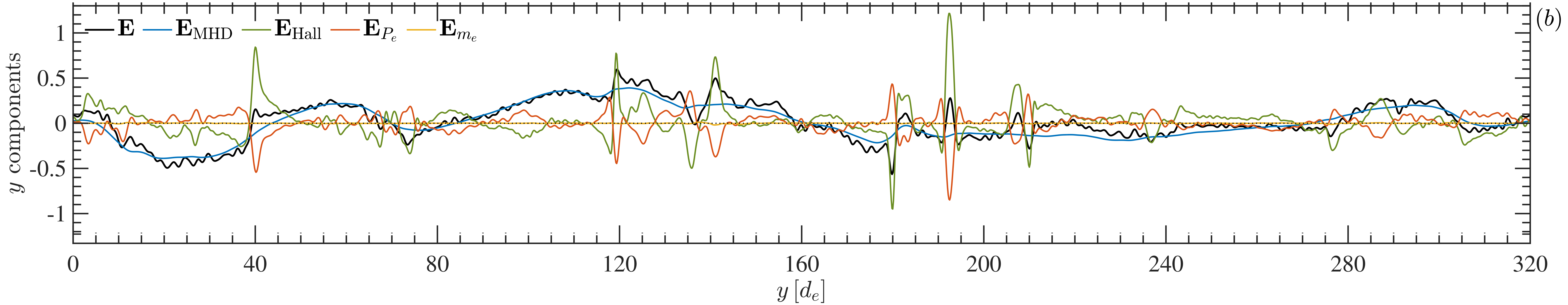
Scaling of electric field spectrum in Solar Orbiter data

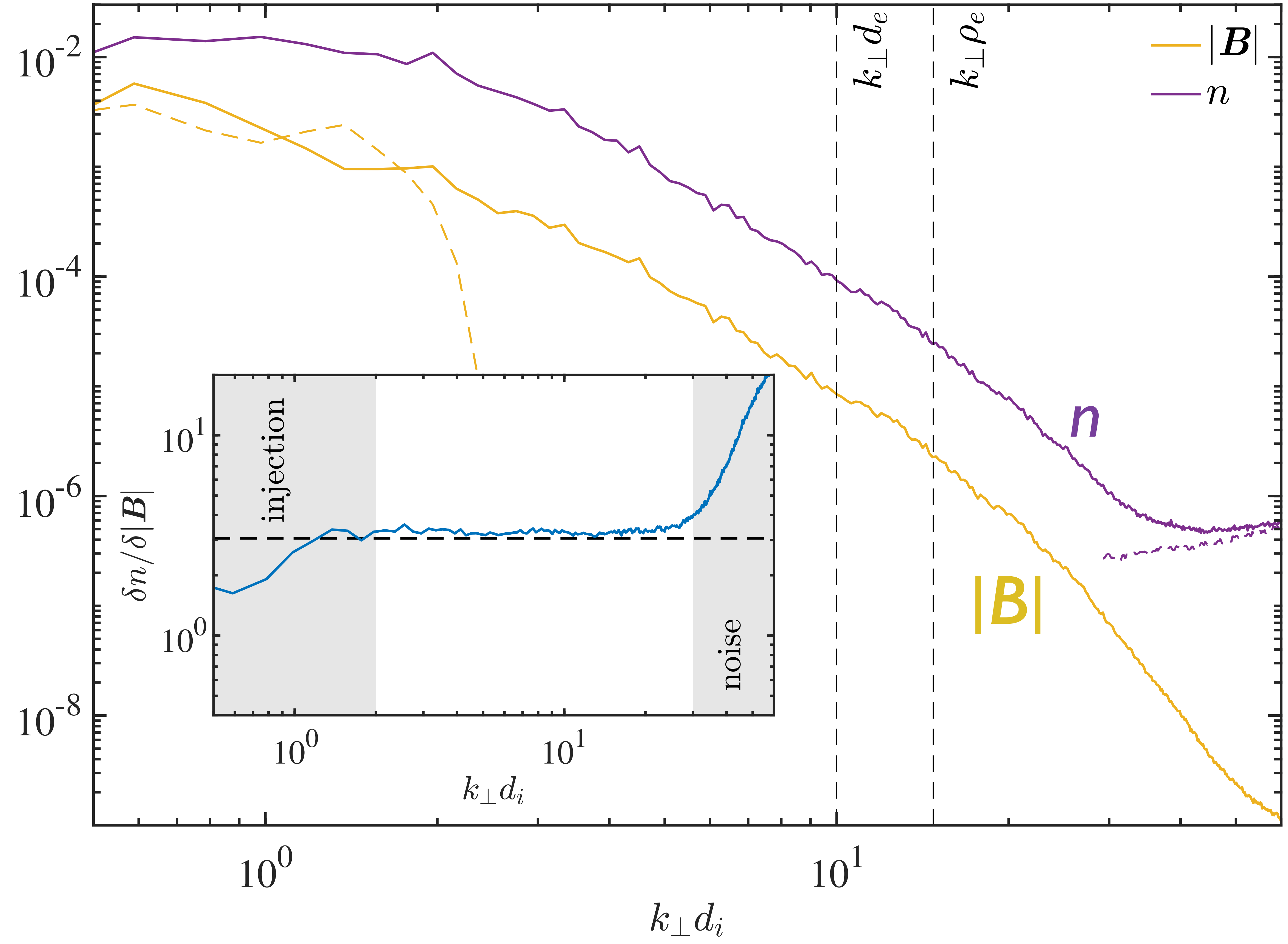
$$\boldsymbol{E}_{P_e} \simeq -\frac{1}{en}\frac{\beta_e}{2}\boldsymbol{\nabla} n$$

$$\boldsymbol{E}_{\mathrm{Hall}} \simeq \frac{1}{en}\frac{\beta_e+\beta_i}{2}\boldsymbol{\nabla} n$$



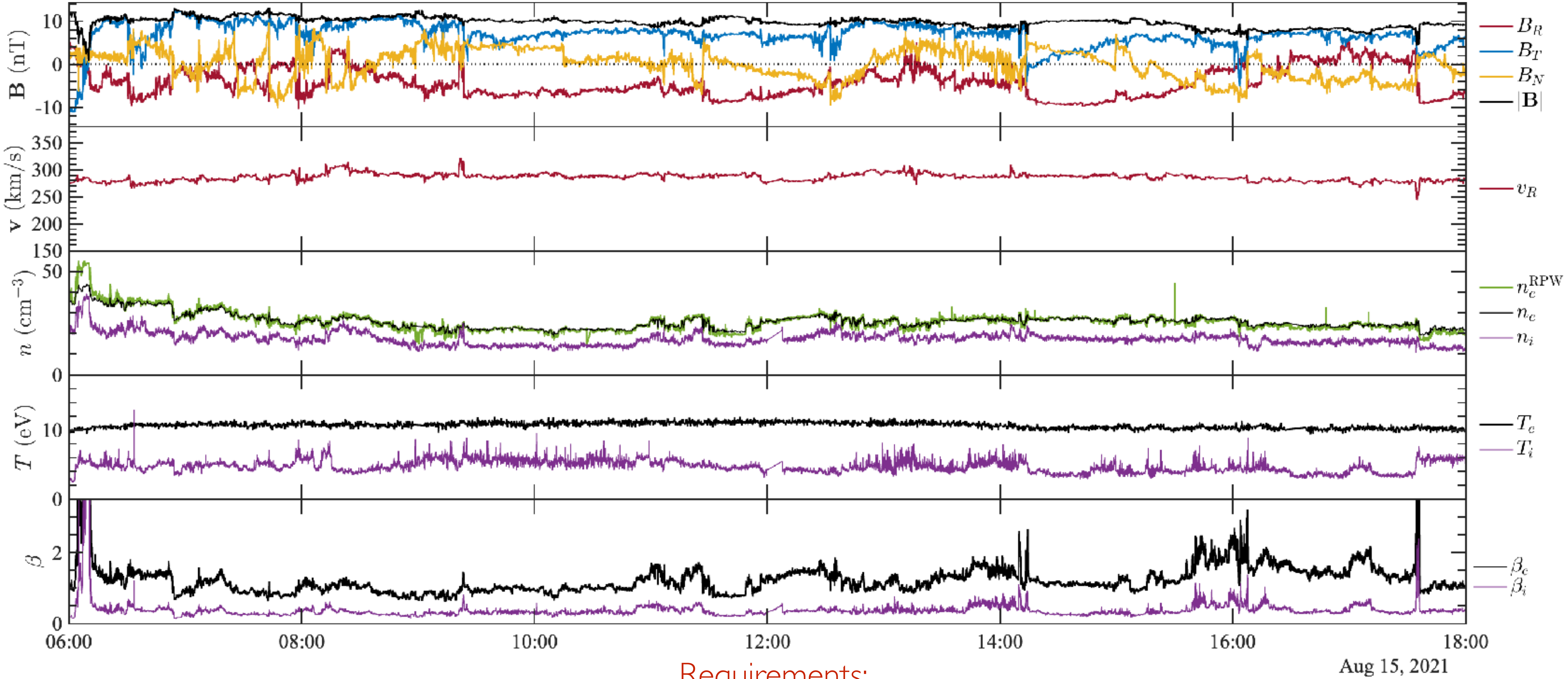
Anti-correlation between δn and $\delta|\mathbf{B}|$ in fully kinetic simulation





Franci et al., in preparation

Looking at anti-correlation between *n* and |***B***| in Solar Orbiter data



Requirements:

(i) slow solar wind (as we are interested in analysing compressive fluctuations)

(ii) solar wind speed > 280 km/s (in order to avoid PAS issues when ion energy is too low)

(iii) MAG, PAS, EAS, RPW operating

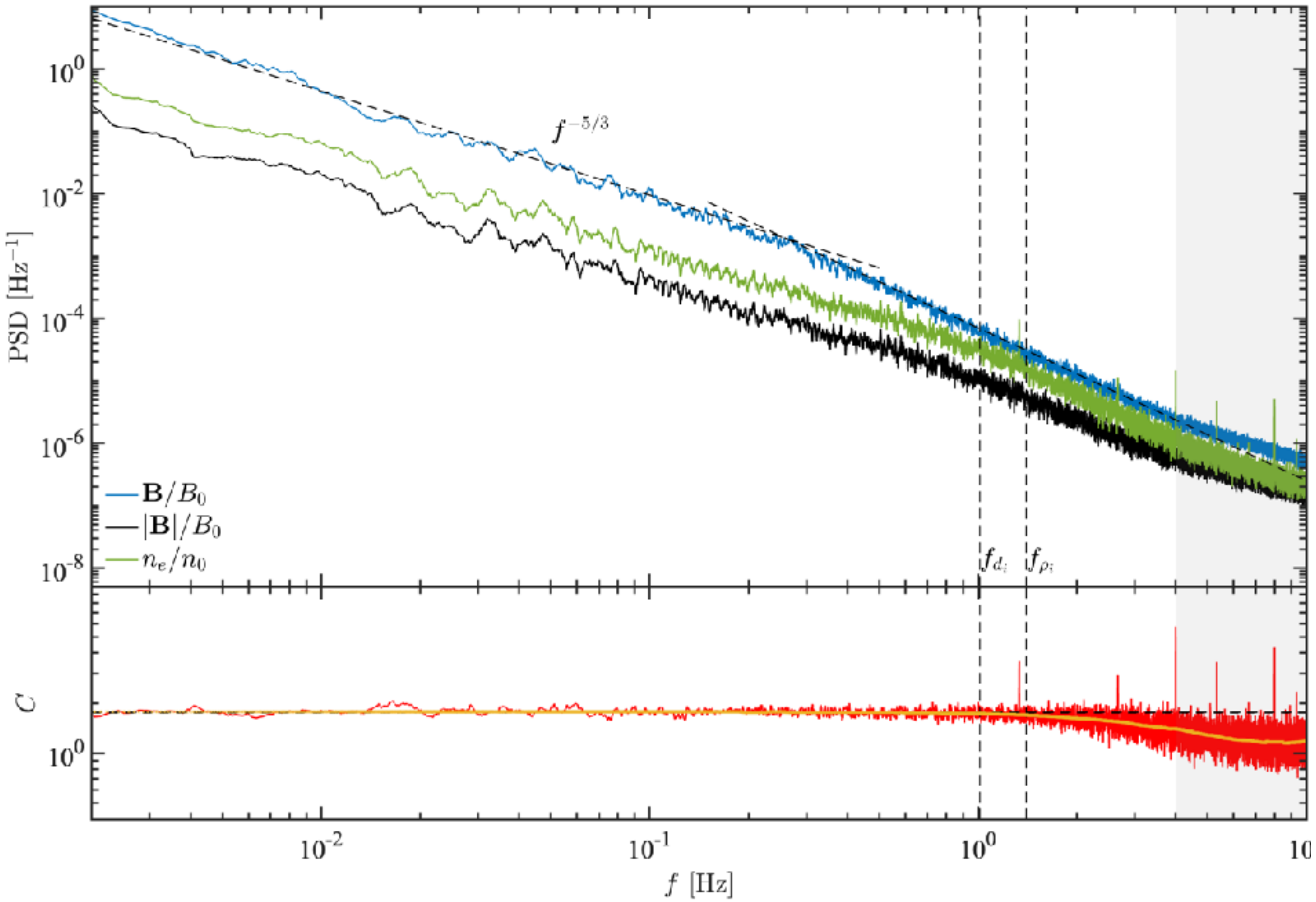
(iv) ideally, MAG is operating in burst mode

Franci et al., in preparation

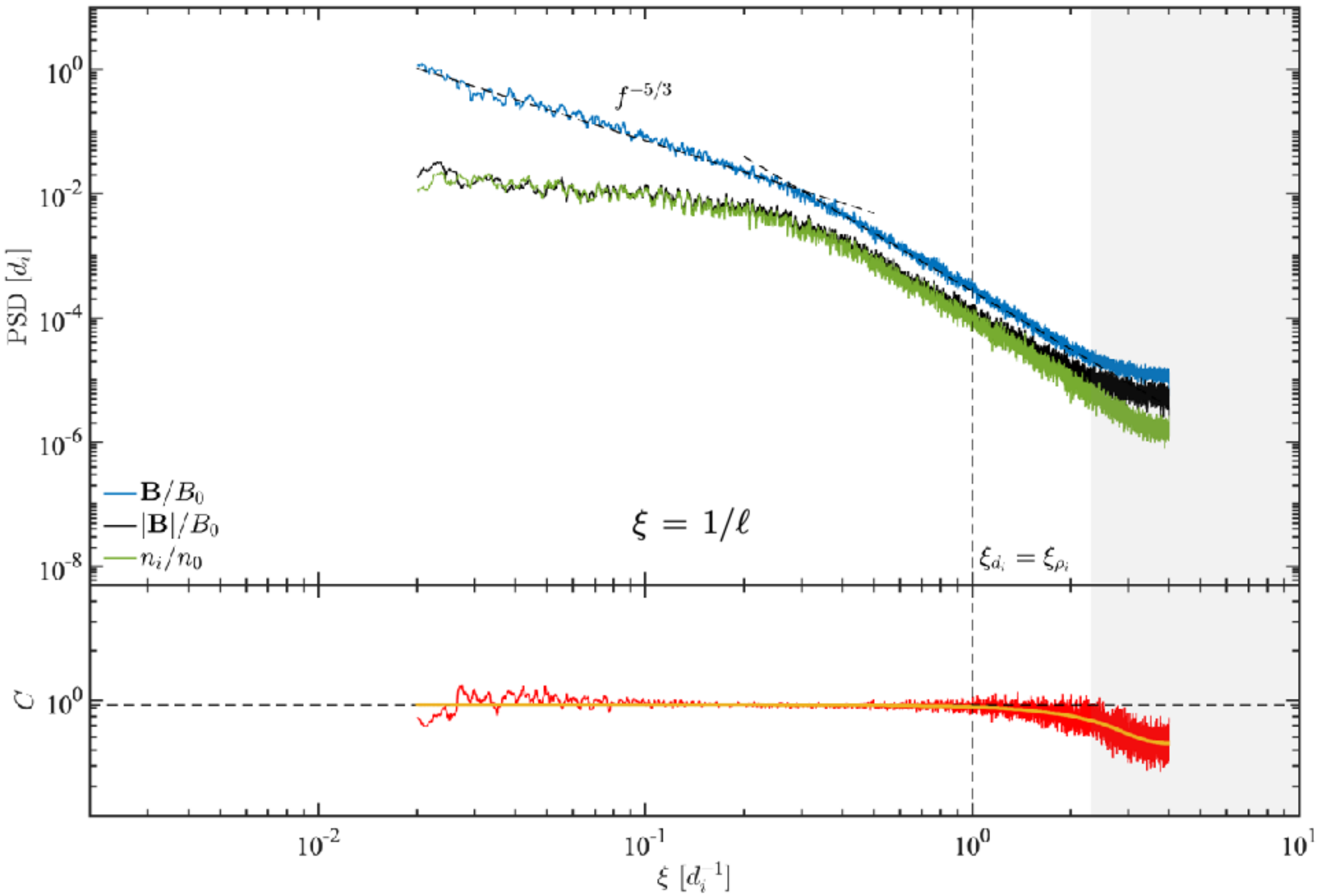
l.franci@imperial.ac.uk

(Anti-)correlation between n and |*B*| in frequency/spatial frequency

SOLAR ORBITER



2D HYBRID SIMULATION



Compressibility ratio

$$C_{\Delta t}(t) \equiv \frac{\delta n_e/n_0}{\delta|\mathbf{B}|/B_0}$$

$$|\tilde{C}_{\Delta t}(f)| \equiv \frac{\mathcal{F}(\delta n_e/n_0)}{\mathcal{F}(\delta|\mathbf{B}|/B_0)} = \sqrt{\frac{\mathrm{PSD}(n_e/n_0)}{\mathrm{PSD}(|\mathbf{B}|/B_0)}}$$

$$\delta n_e = n_e - n_0, \text{ with } n_0 = \langle n_e \rangle|_{\Delta t}$$

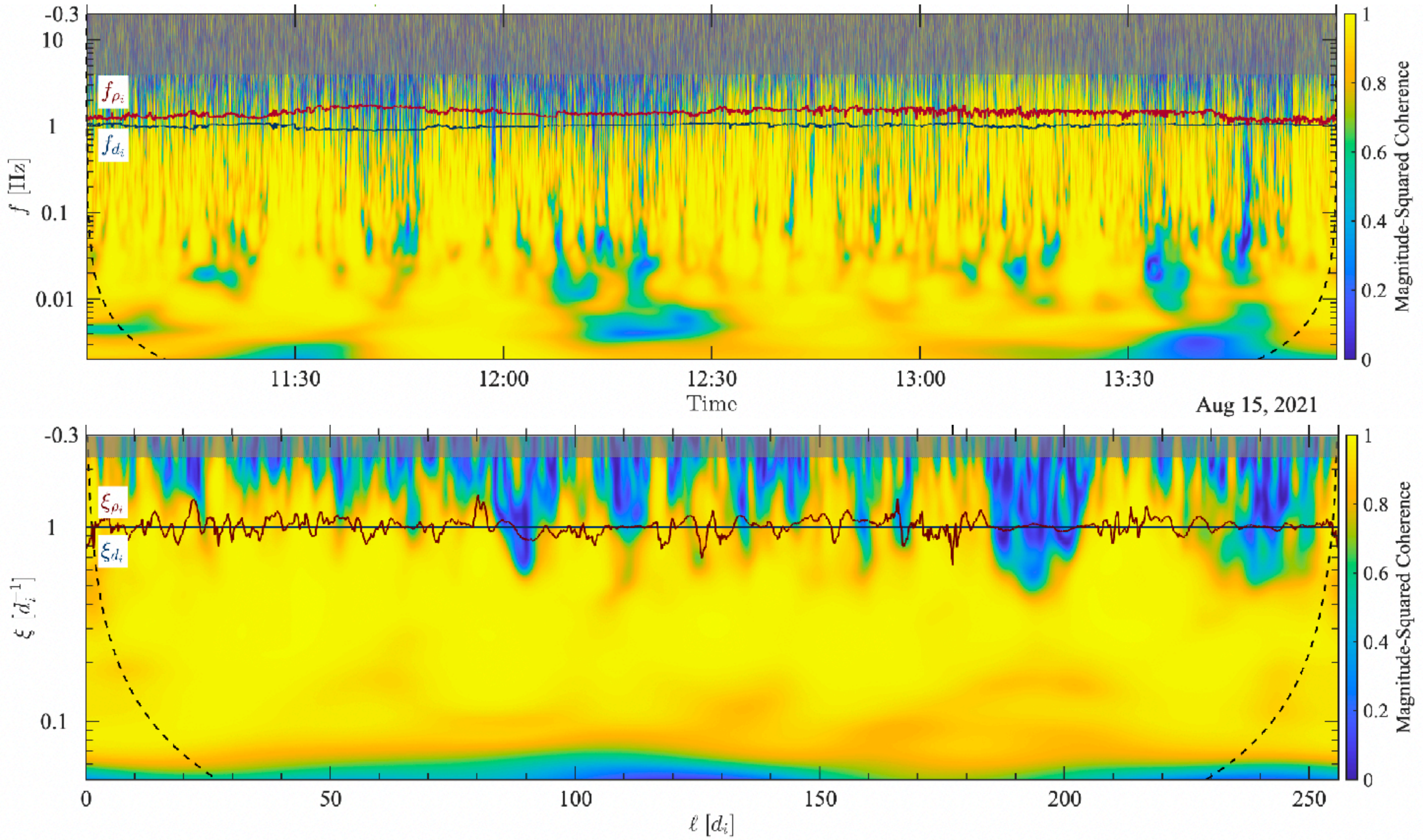
Franci et al., in preparation

l.franci@imperial.ac.uk

Anti-correlation between *n* and |***B***| across a range of temporal/spatial scales

SOLAR ORBITER

2D HYBRID SIMULATION



We observe a remarkable anti-correlation between *n* and |***B***| over 2-3 decades above the ion scales

The anti-correlation is observed to break around the ion scales in both SolO and simulation data

Franci et al., in preparation

l.franci@imperial.ac.uk

Theoretical interpretation

$$nm_i \cancel{\left[\frac{\partial \mathbf{u}_i}{\partial t} + (\mathbf{u}_i \cdot \boldsymbol{\nabla})\mathbf{u}_i\right]} = \mathbf{J} \times \mathbf{B} - \boldsymbol{\nabla} \cdot \mathcal{P} \qquad \mathcal{P} = \mathcal{P}_i + \mathcal{P}_e$$

HYP 1: Strong guide field (weak turbulence)

$$|\delta \mathbf{B}| \ll B_0 = |\mathbf{B}_0|$$

HYP 2: Spectral anisotropy (quasi-2D turbulence)

$$\nabla_{\|} \ll |\boldsymbol{\nabla}_{\perp}|$$

$$\boxed{\frac{B_0 \boldsymbol{\nabla}_{\perp}(\delta|\mathbf{B}|)}{\mu_0} = -(\boldsymbol{\nabla} \cdot \mathcal{P}_i) - (\boldsymbol{\nabla} \cdot \mathcal{P}_e)}$$

HYP 3: Negligible non-diagonal terms of the pressure tensor

$$\mathcal{P}_\alpha = \begin{pmatrix} P_\alpha^{\perp} & 0 & 0 \\ 0 & P_\alpha^{\perp} & 0 \\ 0 & 0 & P_\alpha^{\|} \end{pmatrix}$$

$$\boxed{\frac{B_0 \boldsymbol{\nabla}_{\perp}|(\delta \mathbf{B}|)}{\mu_0} = -(\boldsymbol{\nabla}_{\perp} P_i^{\perp} + \boldsymbol{\nabla}_{\perp} P_e^{\perp})}$$

HYP 4: Negligible temperature fluctuations

$$\delta P_i + \delta P_e = k_{\mathrm{B}} \delta n (T_{i,0} + T_{e,0}) + \cancel{+ k_{\mathrm{B}} n_0 (\delta T_i + \delta T_e) + k_{\mathrm{B}} \delta n (\delta T_i + \delta Te)}$$

$$\frac{\delta T}{T_0} \ll \frac{\delta n}{n_0}$$

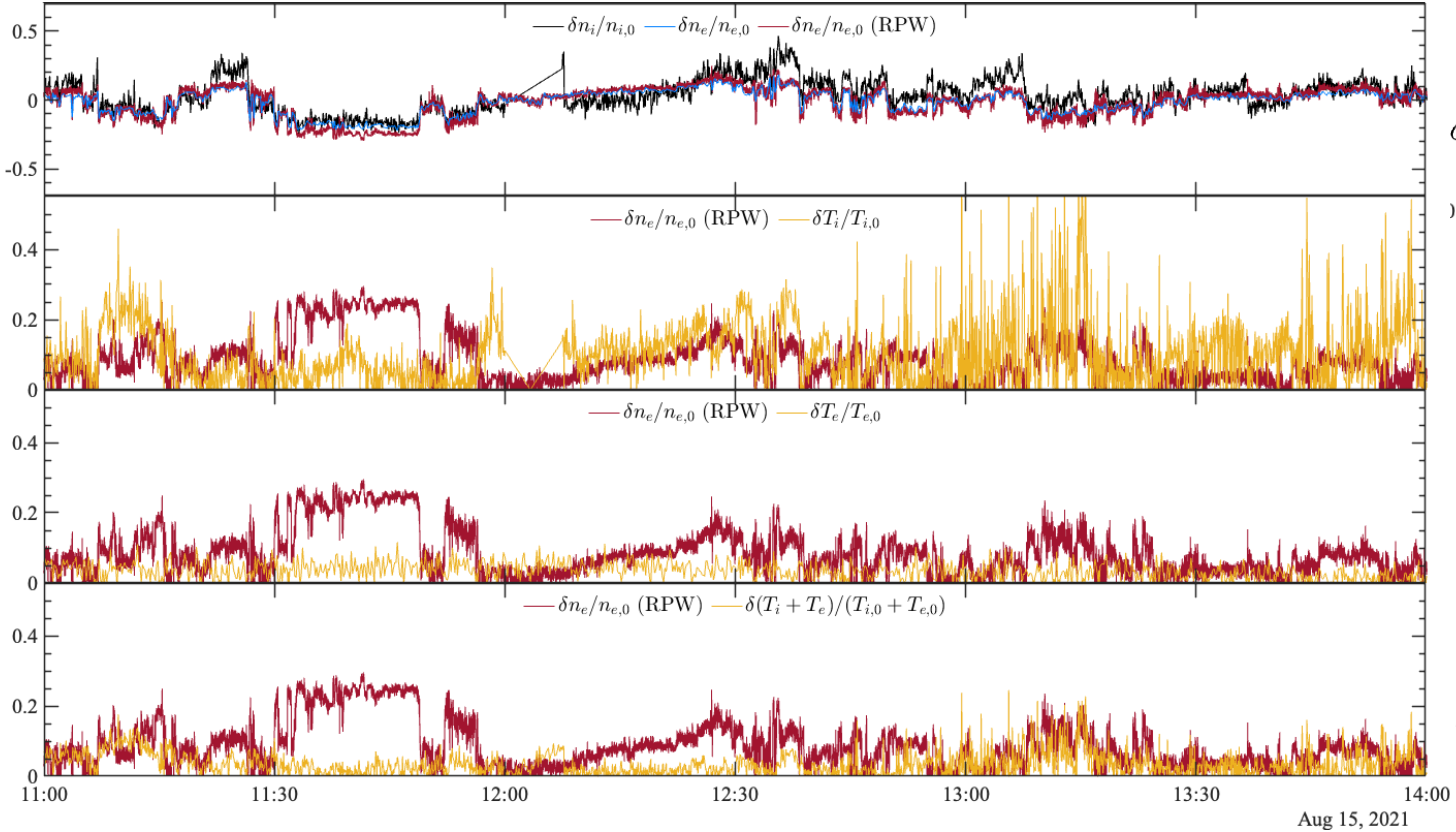
$$\boxed{\boldsymbol{\nabla}_{\perp} \left(\frac{\delta|\mathbf{B}|}{B_0}\right) = -\frac{\beta_{i,0} + \beta_{e,0}}{2} \boldsymbol{\nabla}_{\perp} \left(\frac{\delta n}{n_0}\right)}$$

$$\frac{\delta|\mathbf{B}|}{B_0} = -\frac{\beta_0}{2} \frac{\delta n}{n_0} + c \qquad \beta_0 = \beta_{i,0} + \beta_{e,0} \qquad \beta_{\alpha,0} = \frac{k_{\mathrm{B}} n_0 T_{\alpha,0}}{B_0^2/2\mu_0}$$

$$\boxed{\left.\frac{\delta|\mathbf{B}|}{B_0}\right|_{\mathrm{HPF}} = -\frac{\beta_0}{2} \left.\frac{\delta n}{n_0}\right|_{\mathrm{HPF}} \longrightarrow C_{\mathrm{HPF}} = \left(-\frac{\beta_0}{2}\right)^{-1}}$$

Franci et al., in preparation

Comparing density and temperature fluctuations



$$n_0^{\mathrm{PAR}} \neq n_{e,0}^{\mathrm{RPW}}$$

$$\delta n^{\mathrm{PAR}} \sim \delta n_e^{\mathrm{RPW}}$$

$$\frac{\delta T}{T_0} \lesssim \frac{\delta n}{n_0}$$

$$T_0 = T_{i,0} + T_{e,0}$$

Franci et al., in preparation

Theoretical predictions vs. observations

$$\left.\frac{\delta|\mathbf{B}|}{B_0}\right|_{\mathrm{HPF}} = -\frac{\beta_0}{2}\left.\frac{\delta n}{n_0}\right|_{\mathrm{HPF}} .$$

$$C_{\mathrm{HPF}} = \left(-\frac{\beta_0}{2}\right)^{-1} .$$

1. *Theoretical prediction.* We compute $\beta_{i,0}$ and $\beta_{e,0}$ from the background plasma quantities n_0, $T_{i,0}$, $T_{e,0}$, and B_0:

$$\boxed{C_{\mathrm{the}} = \left(-\frac{\beta_{i,0}+\beta_{e,0}}{2}\right)^{-1}} \qquad (30)$$

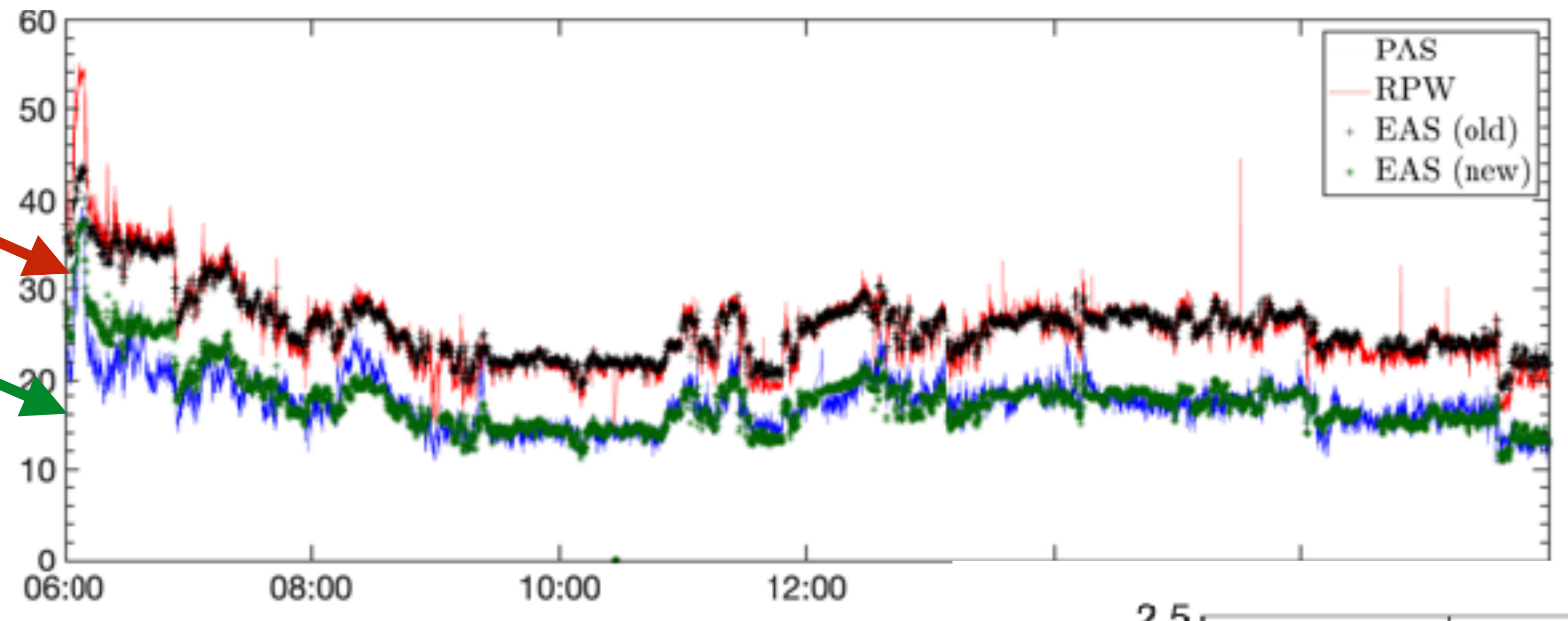
$$n_0^{\mathrm{RPW}} = n_{e,0}^{\mathrm{RPW}} \neq n_0^{\mathrm{PAR}}$$

$$n_0^{\mathrm{PAR}} = n_{i,0}^{\mathrm{PAS}} \sim n_{e,0}^{\mathrm{EAS}}$$

$$C_{\mathrm{the}}^{\mathrm{RPW}} = -\frac{B_0^2}{\mu_0 k_{\mathrm{B}}}\frac{1}{T_{i,0}+T_{e,0}}\frac{1}{n_0^{\mathrm{RPW}}},$$

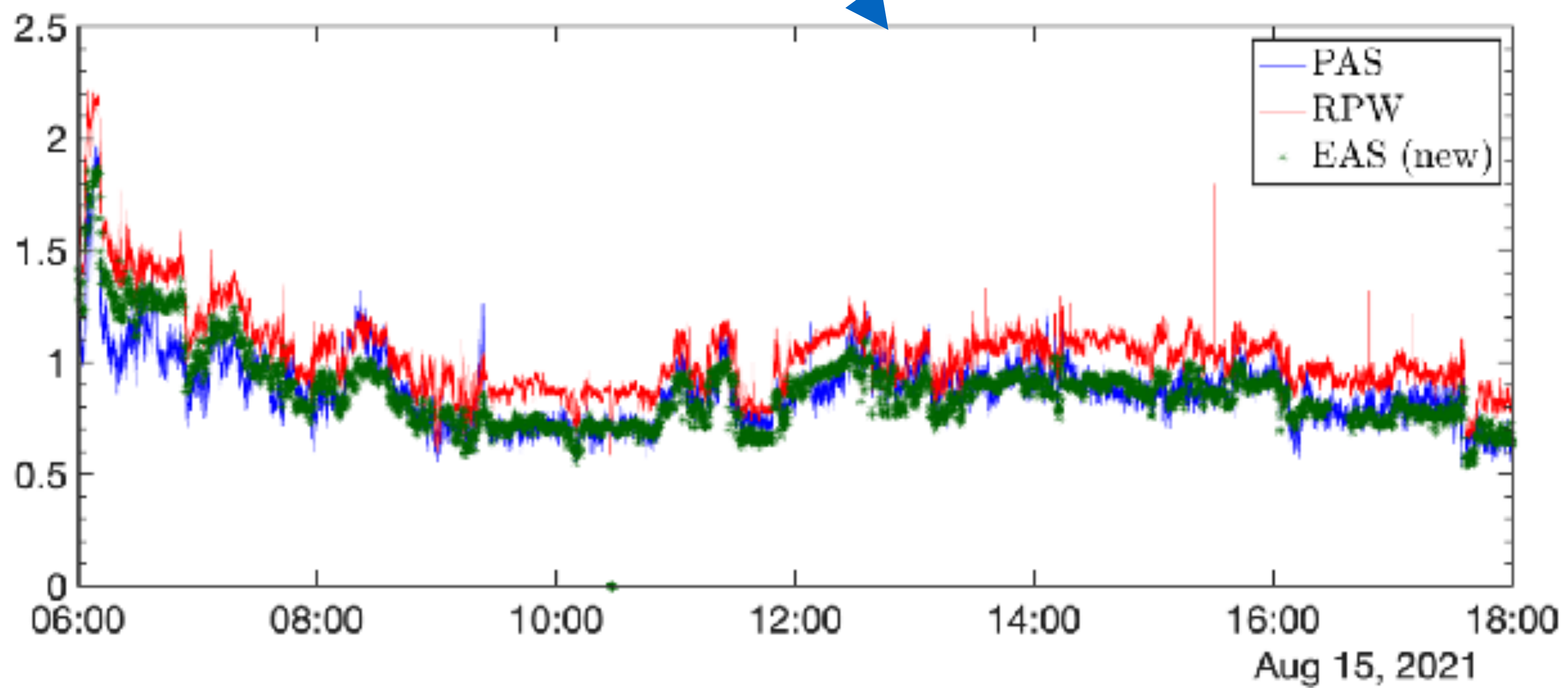
$$C_{\mathrm{the}}^{\mathrm{PAR}} = -\frac{B_0^2}{\mu_0 k_{\mathrm{B}}}\frac{1}{T_{i,0}+T_{e,0}}\frac{1}{n_0^{\mathrm{PAR}}},$$

such that $C_{\mathrm{the}}^{\mathrm{PAR}}/C_{\mathrm{the}}^{\mathrm{RPW}} = n_0^{\mathrm{RPW}}/n_0^{\mathrm{PAR}}$



2. *Observational measurement.* We estimate the ratio between the normalized fluctuations of n_e measured by RPW and those of $|\mathbf{B}|$ measured by MAG after high-pass filtering them:

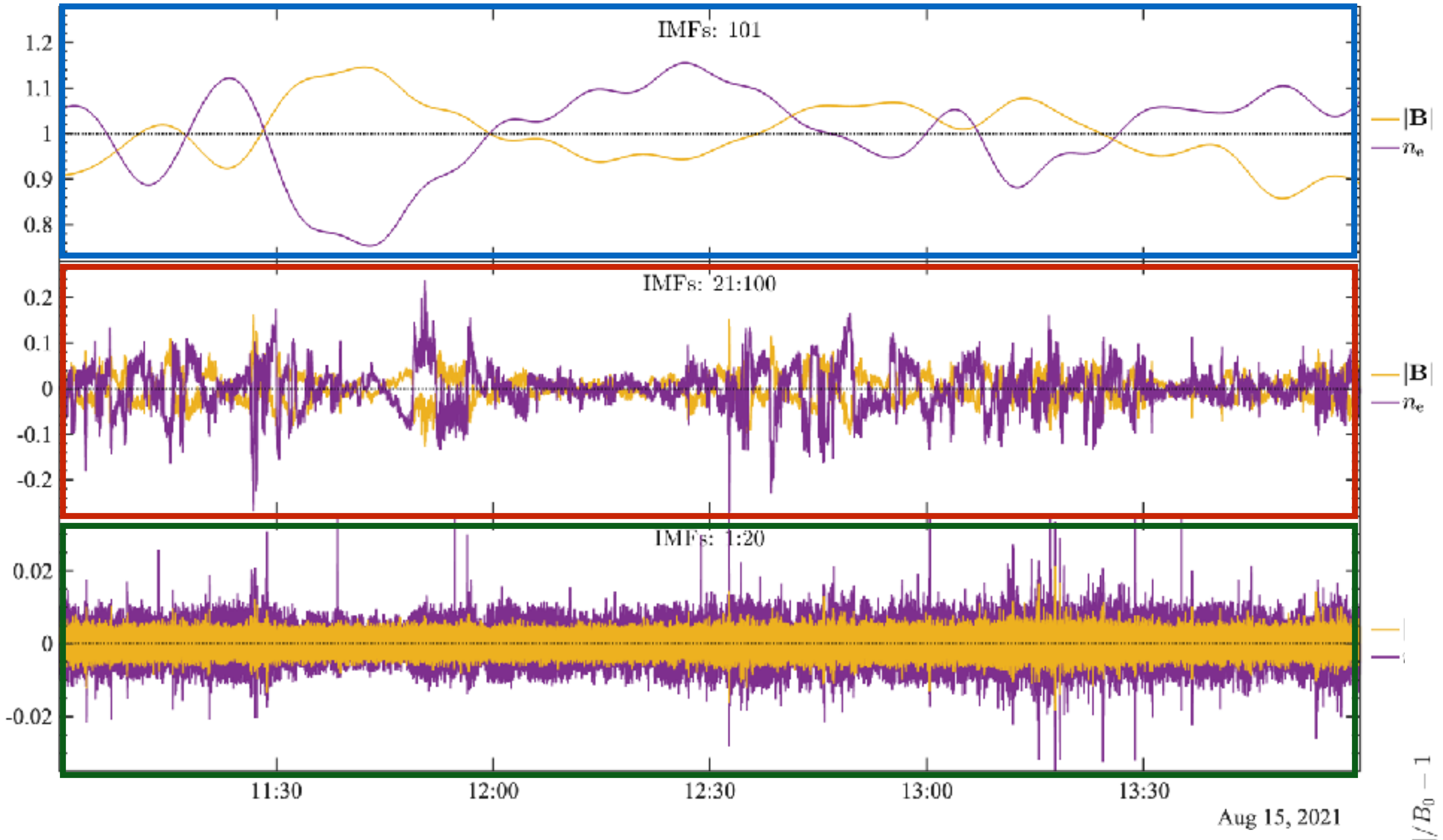
$$\boxed{C_{\mathrm{obs}} = \frac{(\delta n_e/n_0)|_{\mathrm{HPF}}}{(\delta|\mathbf{B}|/B_0)|_{\mathrm{HPF}}},} \qquad (32)$$

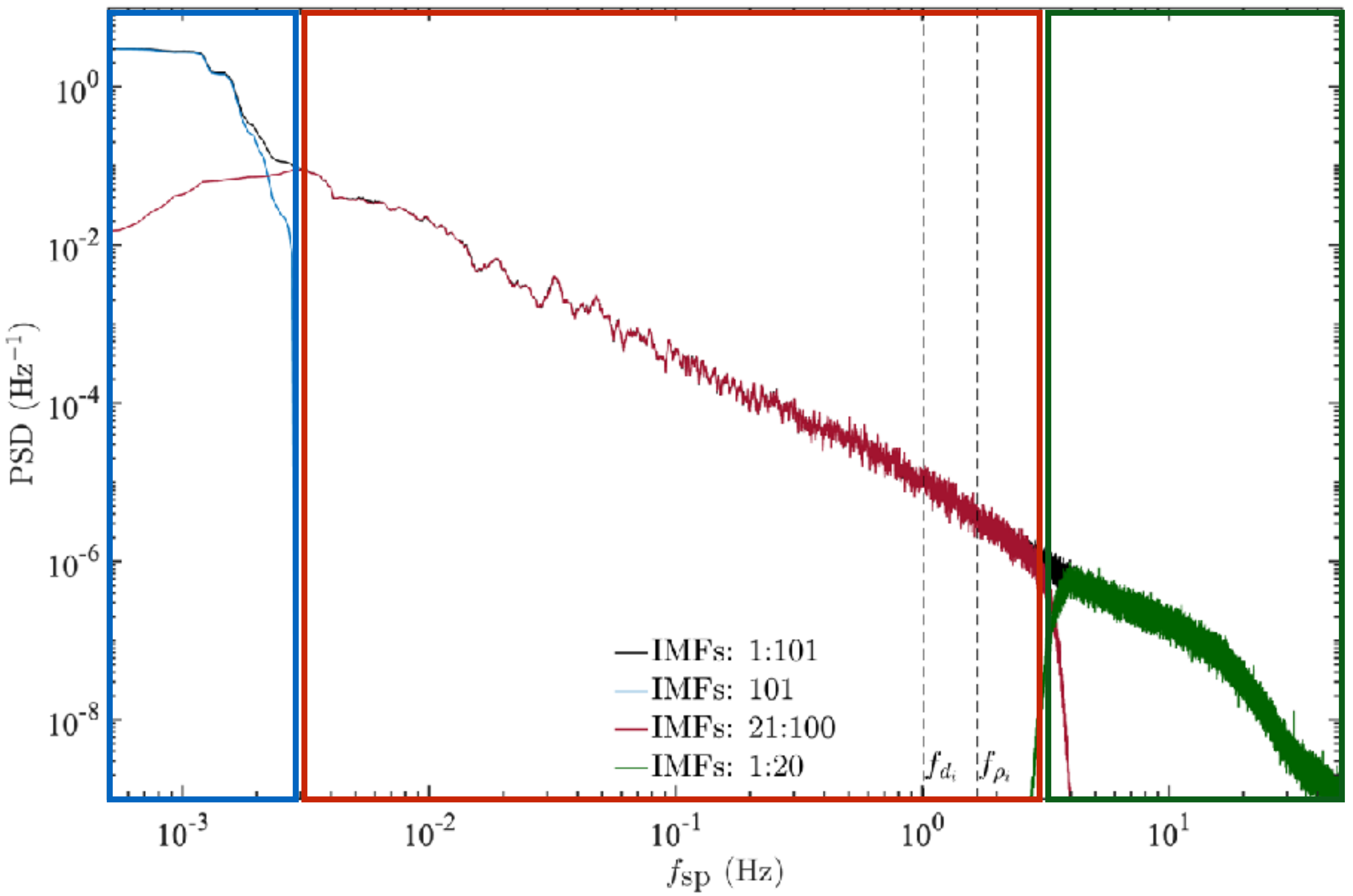


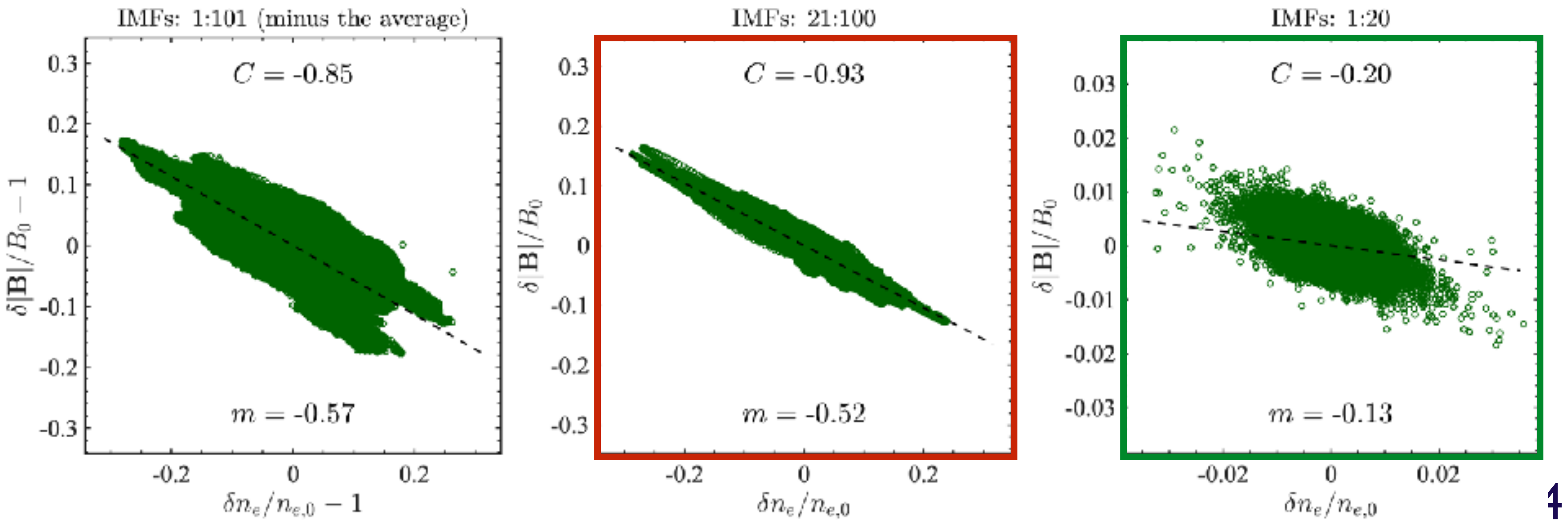
Observational value: filtering

$$\frac{\delta|\mathbf{B}|}{B_0} = -\frac{\beta_0}{2}\frac{\delta n}{n_0} + c \longrightarrow \left.\frac{\delta|\mathbf{B}|}{B_0}\right|_{\mathrm{HPF}} = -\frac{\beta_0}{2}\left.\frac{\delta n}{n_0}\right|_{\mathrm{HPF}}.$$

We decompose the time series using the
Multi-Variate Fast Iterative Filtering (MvFIF) algorithm





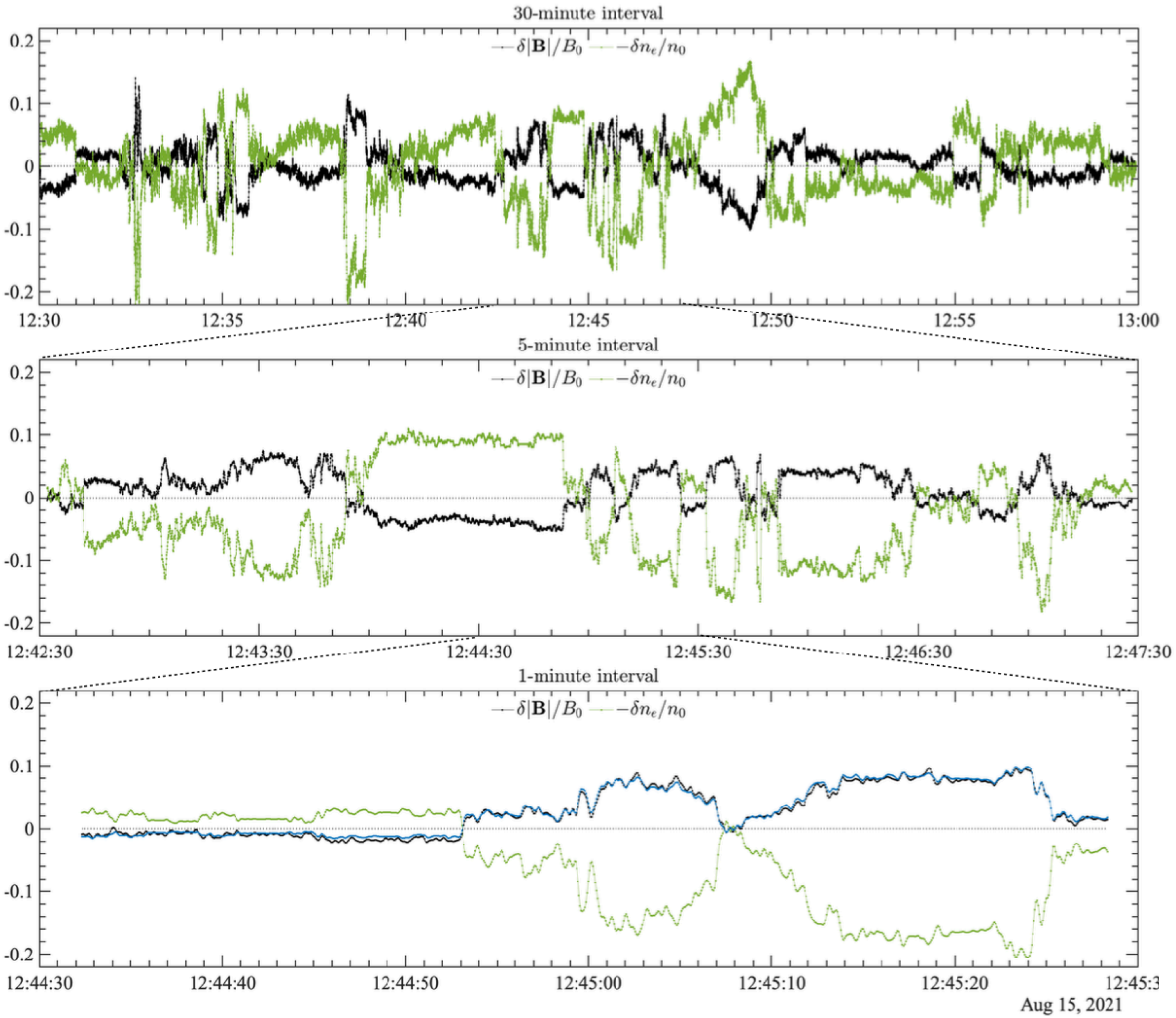


Franci et al., in preparation

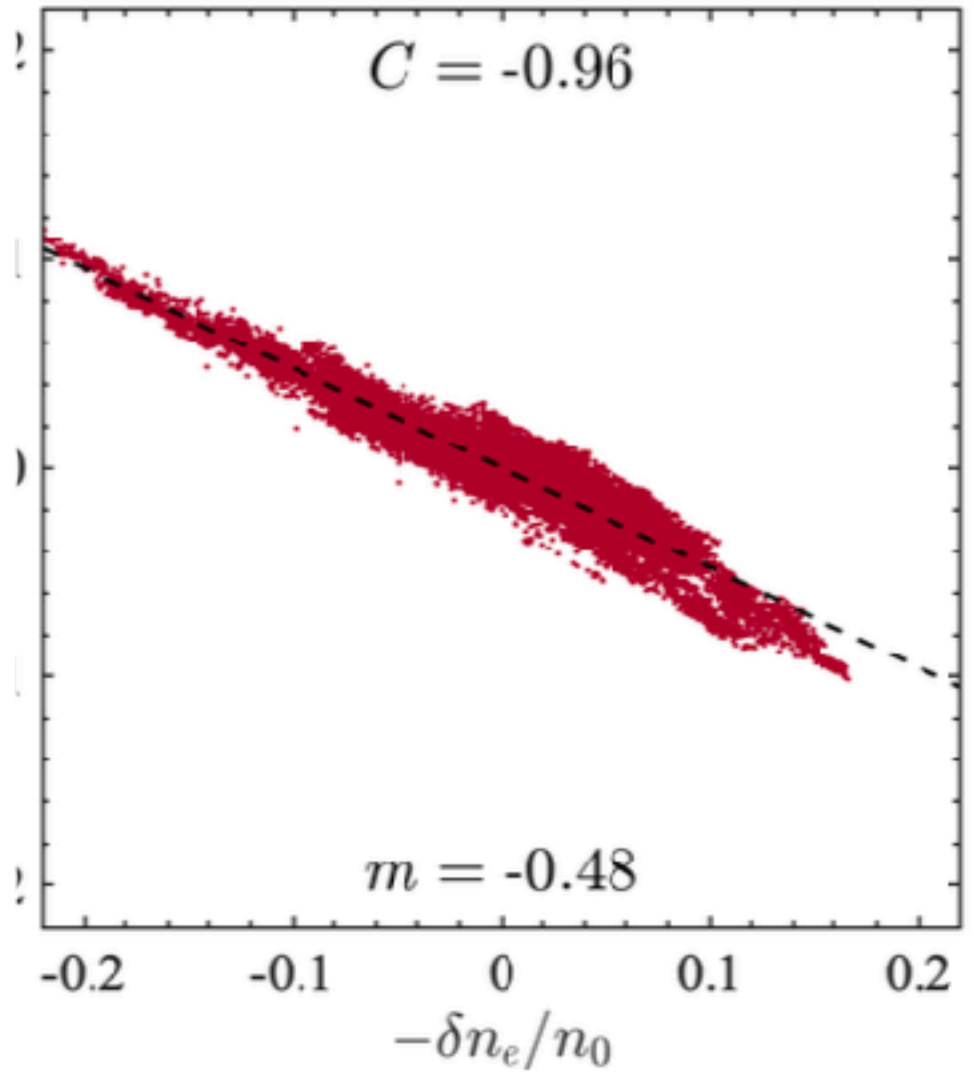
l.franci@imperial.ac.uk

Observational value: MAG vs RPW

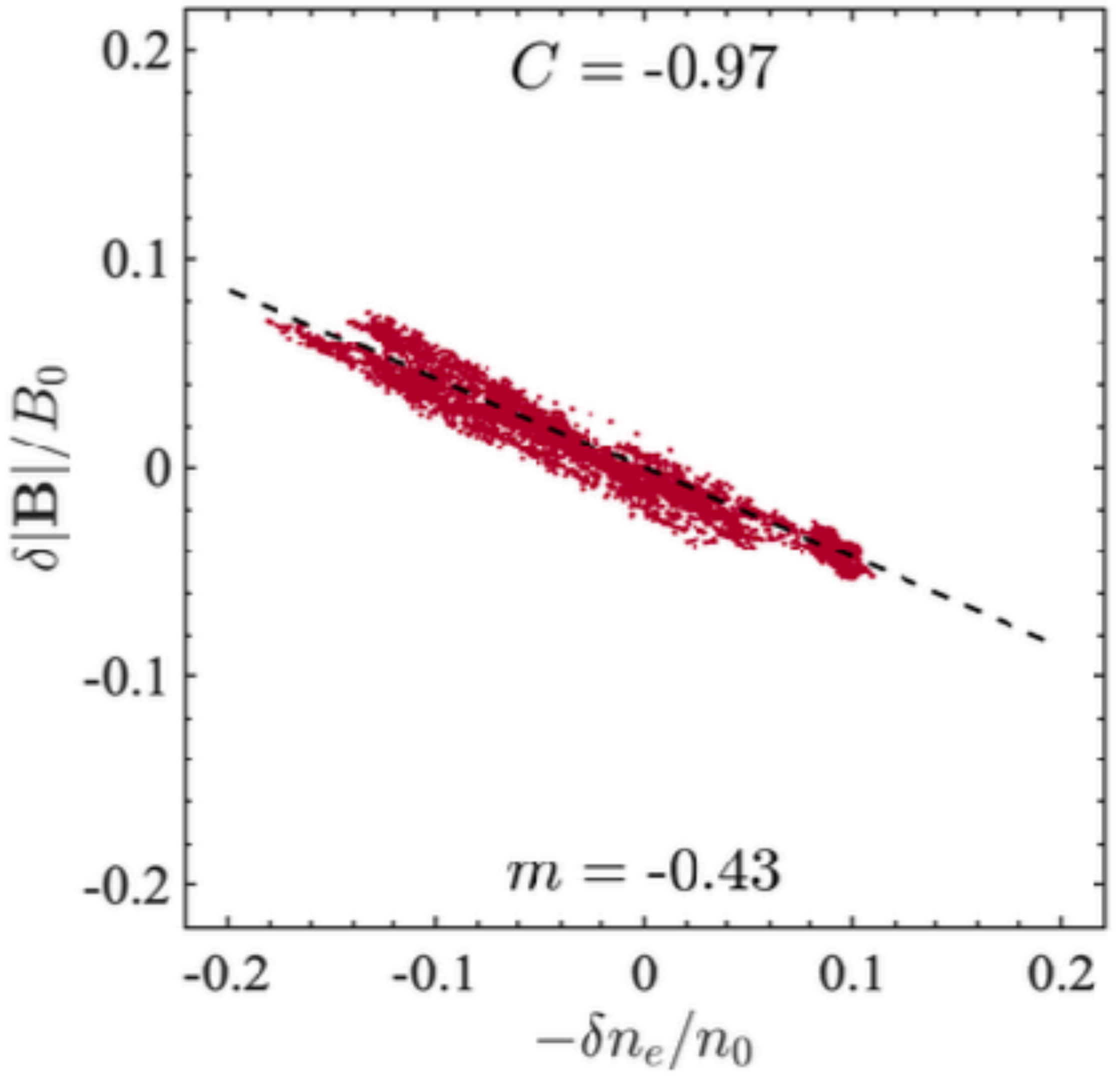
$$\left.\frac{\delta|\mathbf{B}|}{B_0}\right|_{\mathrm{HPF}} = -\frac{\beta_0}{2}\left.\frac{\delta n}{n_0}\right|_{\mathrm{HPF}}, \qquad C_{\mathrm{obs}} = \frac{(\delta n_e/n_0)|_{\mathrm{HPF}}}{(\delta|\mathbf{B}|/B_0)|_{\mathrm{HPF}}},$$



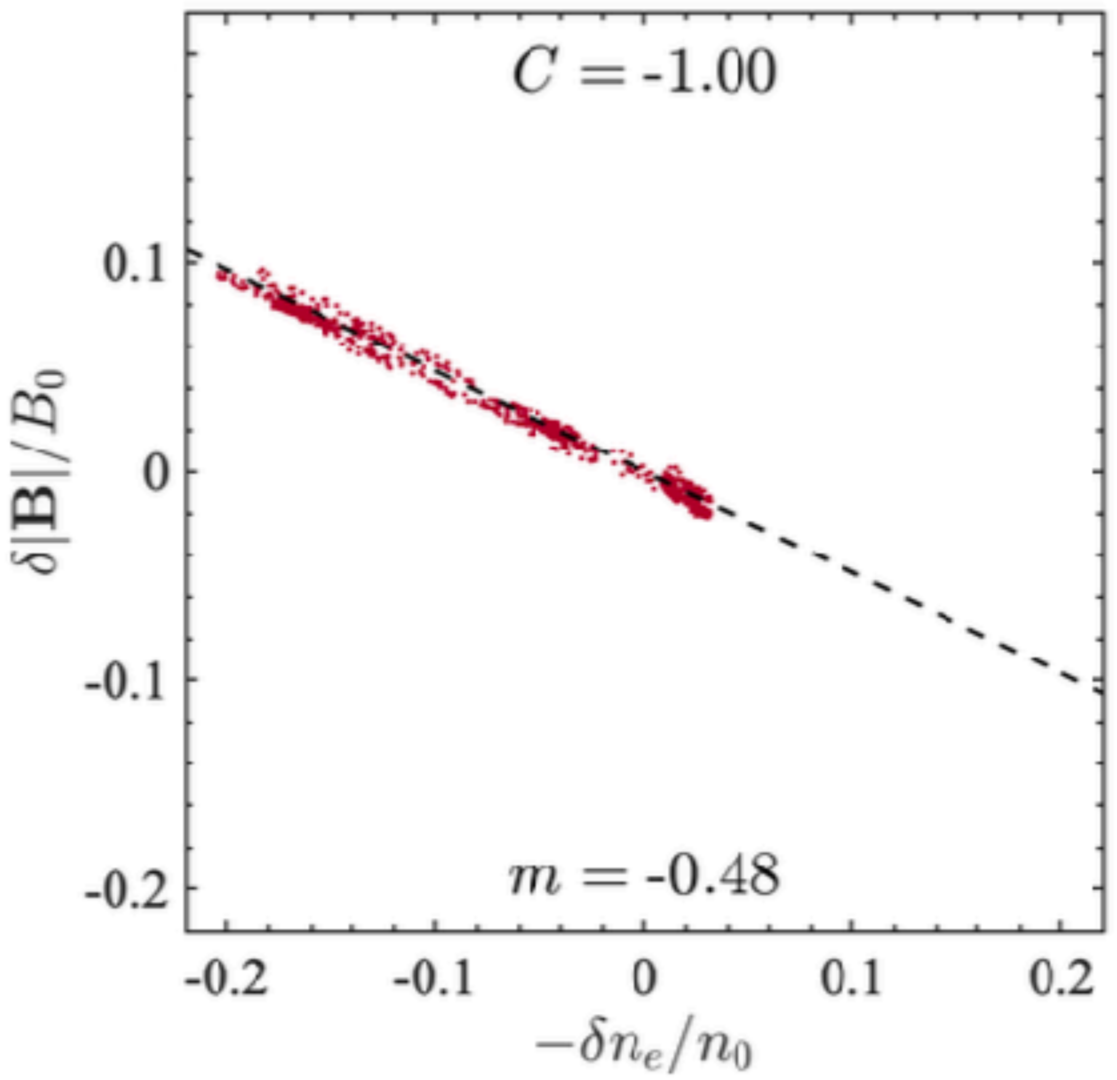
30-minute interval



5-minute interval



1-minute interval



Franci et al., in preparation

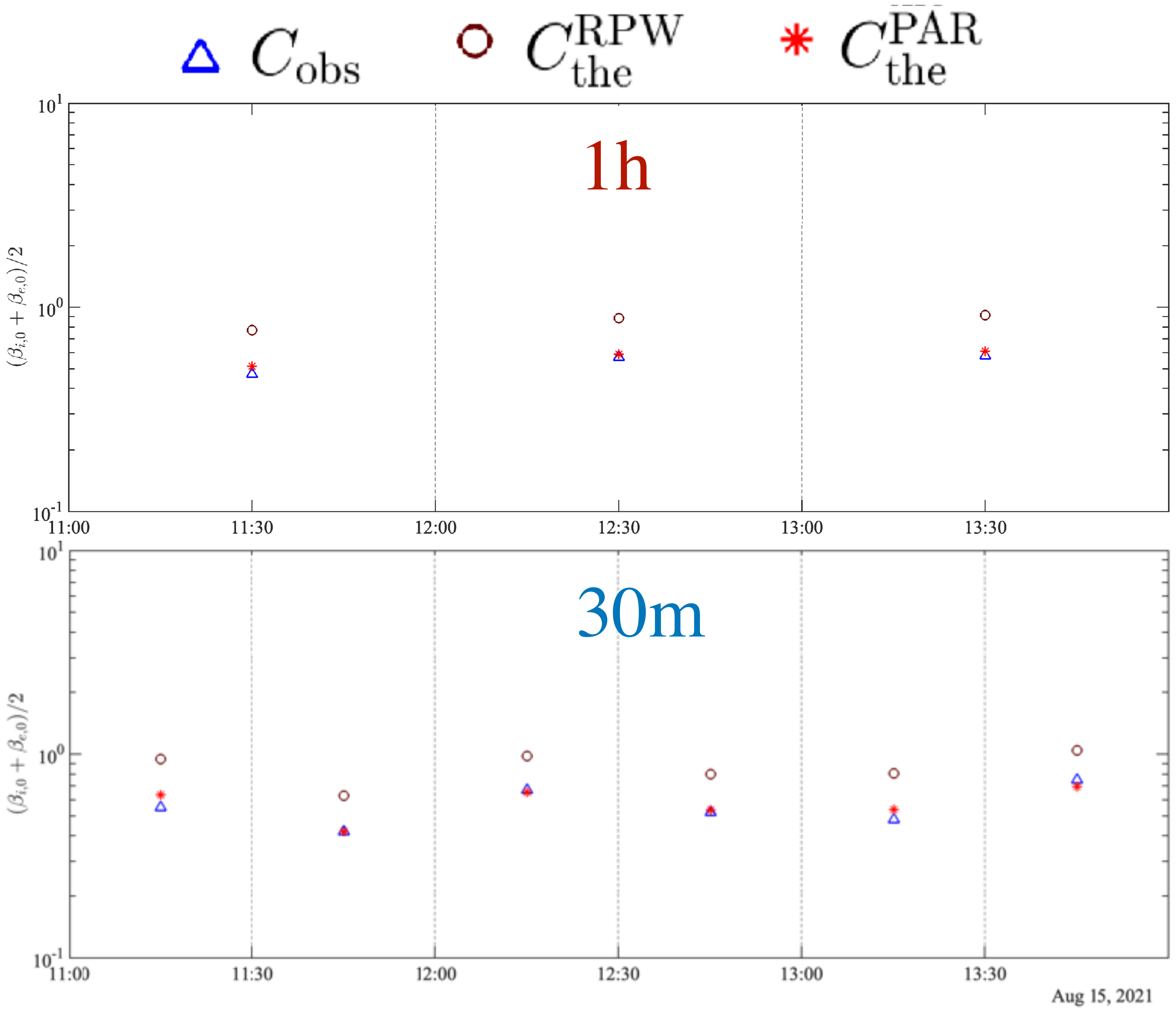
Theoretical vs. observations values

$$\boxed{C_{\text{obs}}} = \frac{(\delta n_e/n_0)|_{\text{HPF}}}{(\delta|\mathbf{B}|/B_0)|_{\text{HPF}}}$$

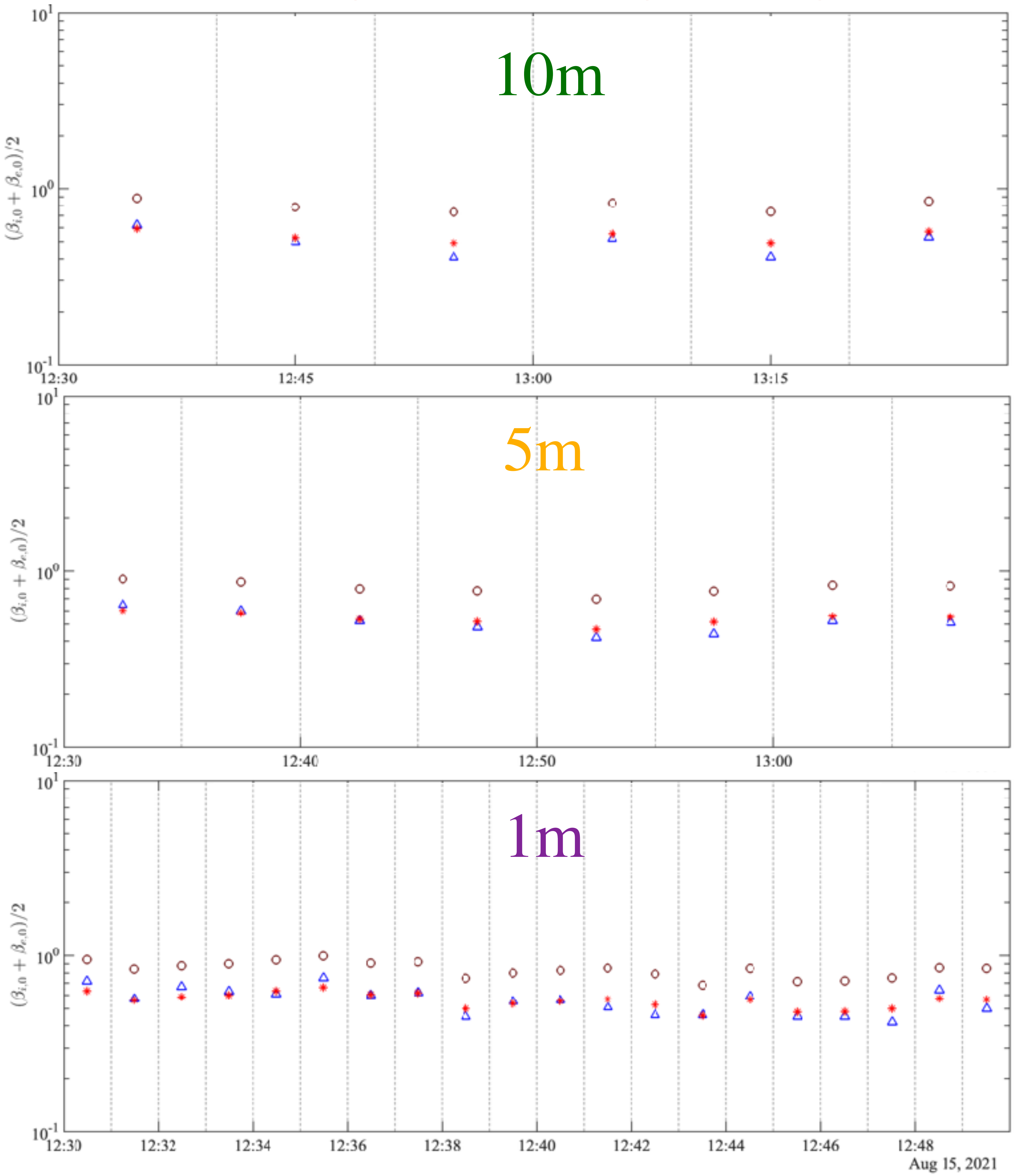
$$C_{\text{the}} = \left(-\frac{\beta_{i,0}+\beta_{e,0}}{2}\right)^{-1}$$

$$\boxed{C_{\text{the}}^{\text{RPW}}} = -\frac{B_0^2}{\mu_0 k_{\text{B}}}\frac{1}{T_{i,0}+T_{e,0}}\frac{1}{n_0^{\text{RPW}}},$$

$$\boxed{C_{\text{the}}^{\text{PAR}}} = -\frac{B_0^2}{\mu_0 k_{\text{B}}}\frac{1}{T_{i,0}+T_{e,0}}\frac{1}{n_0^{\text{PAR}}},$$



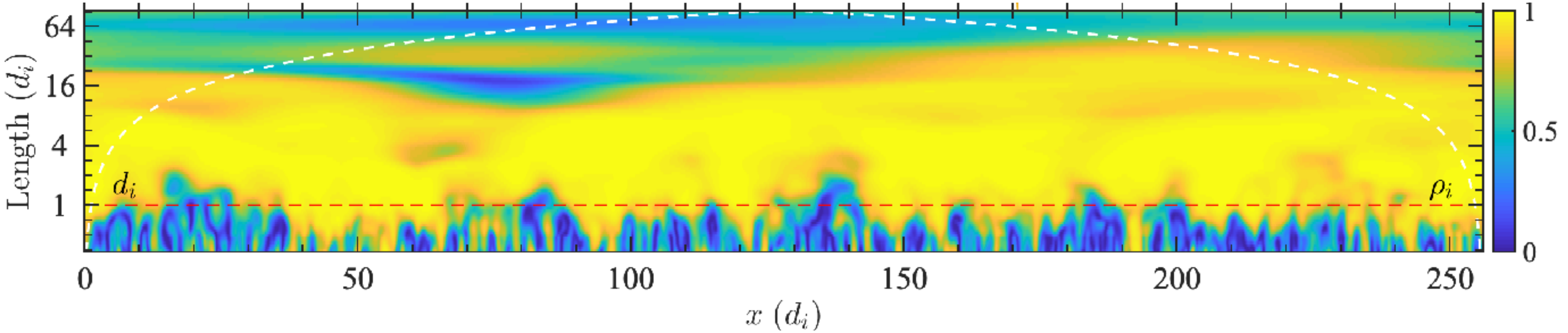
NB: the plots are actually showing C^{-1}



Franci et al., in preparation

Why does the anti-correlation break? 2D Hybrid vs. 2D Hall-MHD simulations

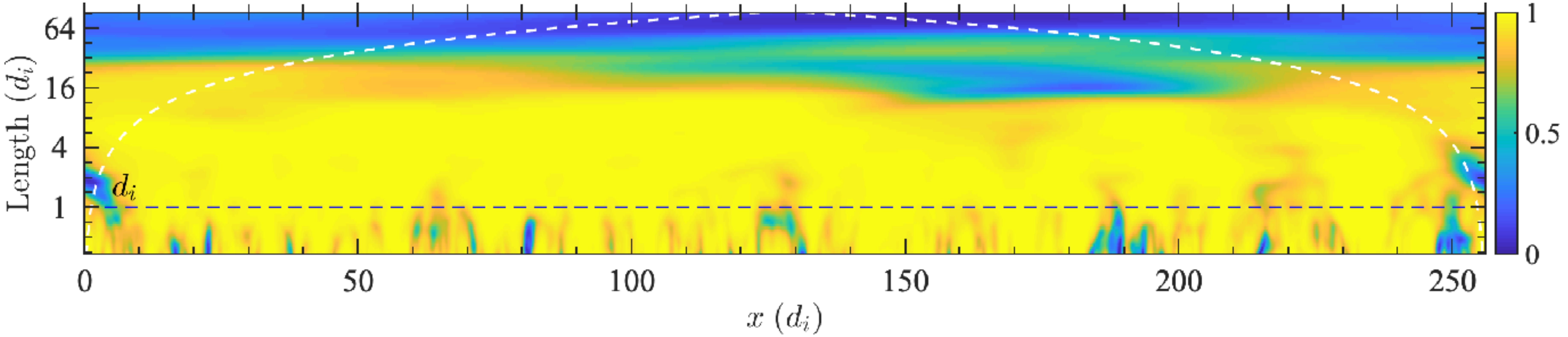
2D HYBRID
$\beta_i = \beta_e = 1$



In the hybrid simulation, the anti-correlation breaks at scales comparable to $d_i \sim \varrho_i$

At these scales, ion velocity shears can induce to non-gyrotropic deformations of the ion pressure tensor

2D HALL-MHD
$\beta = 2$



In the Hall-MHD simulation, the the pressure is isotropic by construction → the anti-correlation extends below d_i

	HYP 1: Strong guide field (weak turbulence)	HYP 2: Spectral anisotropy (quasi-2D turbulence)	HYP 3: Negligible non-diagonal terms of the pressure tensor	HYP 4: Negligible temperature fluctuations
2D HYBRID	$B^{\mathrm{rms}}/B_0 \sim 0.25$	2D	Not necessarily	Not necessarily
2D HALL-MHD	$B^{\mathrm{rms}}/B_0 \sim 0.25$	2D	Imposed by the model	Imposed by the model

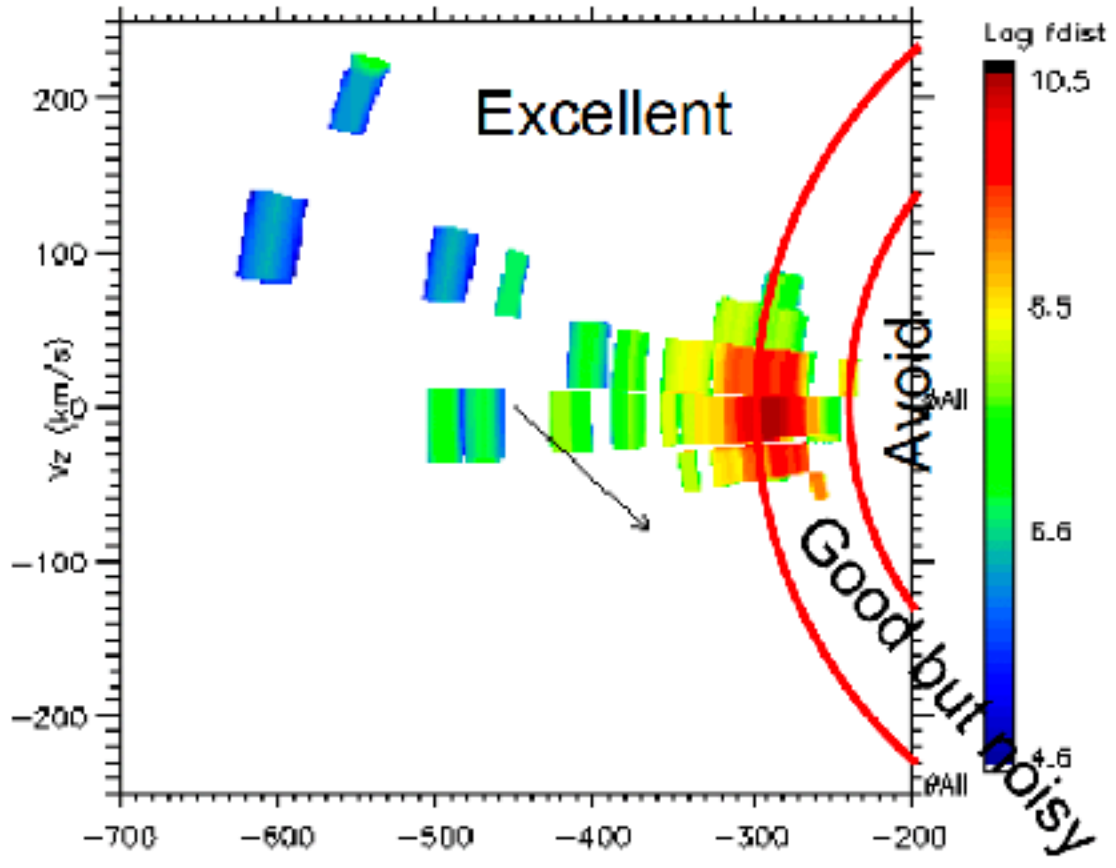
l.franci@imperial.ac.uk

Possible reasons for the discrepancy between predictions and measurements

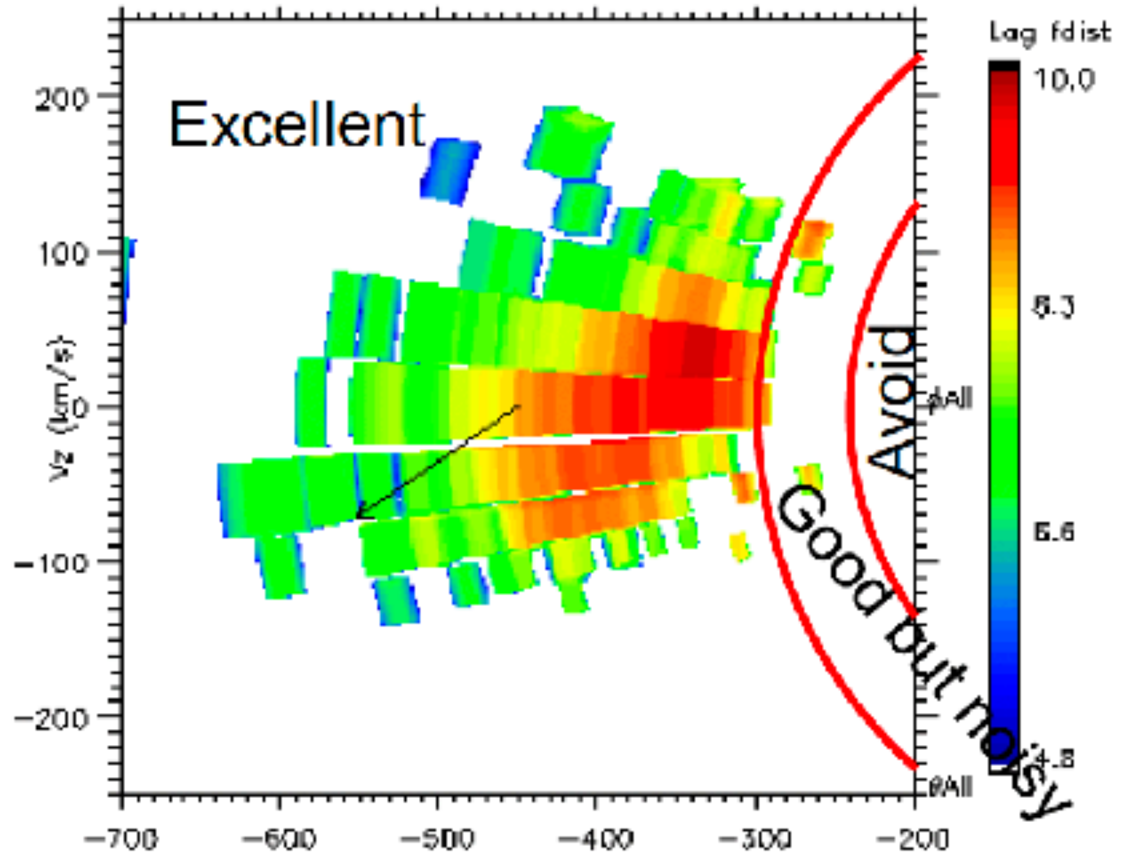
Low energy issue on PAS data
(from Philippe Louarn's slides for the SWA meeting – Bordeaux 02/2023)

The 'low energy' issue: The geometrical factor appears to be smaller than expected at energies below 400 eV (280 km/s). To correct this, an intensive data analysis was performed (Andrei's work).

1) **Above 400 eV (or 280km/s):** the calibration does not require specific correction. **Good measurements**. Everything you see on VDF are real. ***Just be careful in case of 'beam' in side channeltrons (ghost counts, see next)***.
2) **From 400 eV to 320 eV (250 km/s),** a specific correction needs to be applied, now included in calibration. It increases as energy decreases. **The correction is reliable and calibrated VDF (N2) are very good**. ***Note, however, that noise level increases.***
3) **Below 320 eV (250 km/s). Too large decrease of geometrical factor -> impossible to get a good correction factor.** Do not intend 'sophisticated' scien



Slow wind (280 km/s) with low temperature (< 4 eV)
Most of SW population is in the 'corrected' area.
Less statistics, more noise. See Andrei' quality factor: Fraction of counts that are not measured

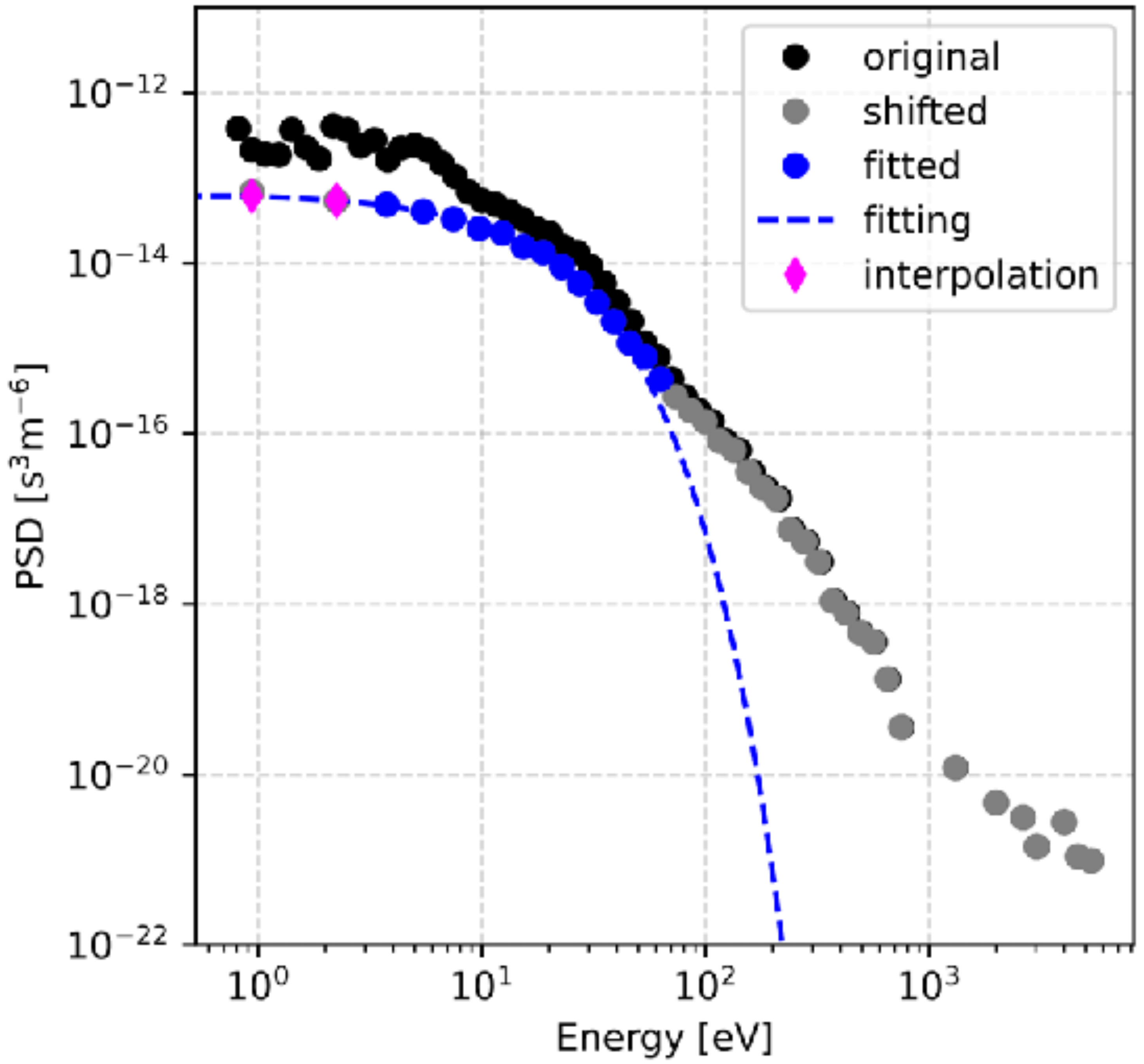


Faster wind (> 320 km/s)
Most of the VDF is perfectly measured.

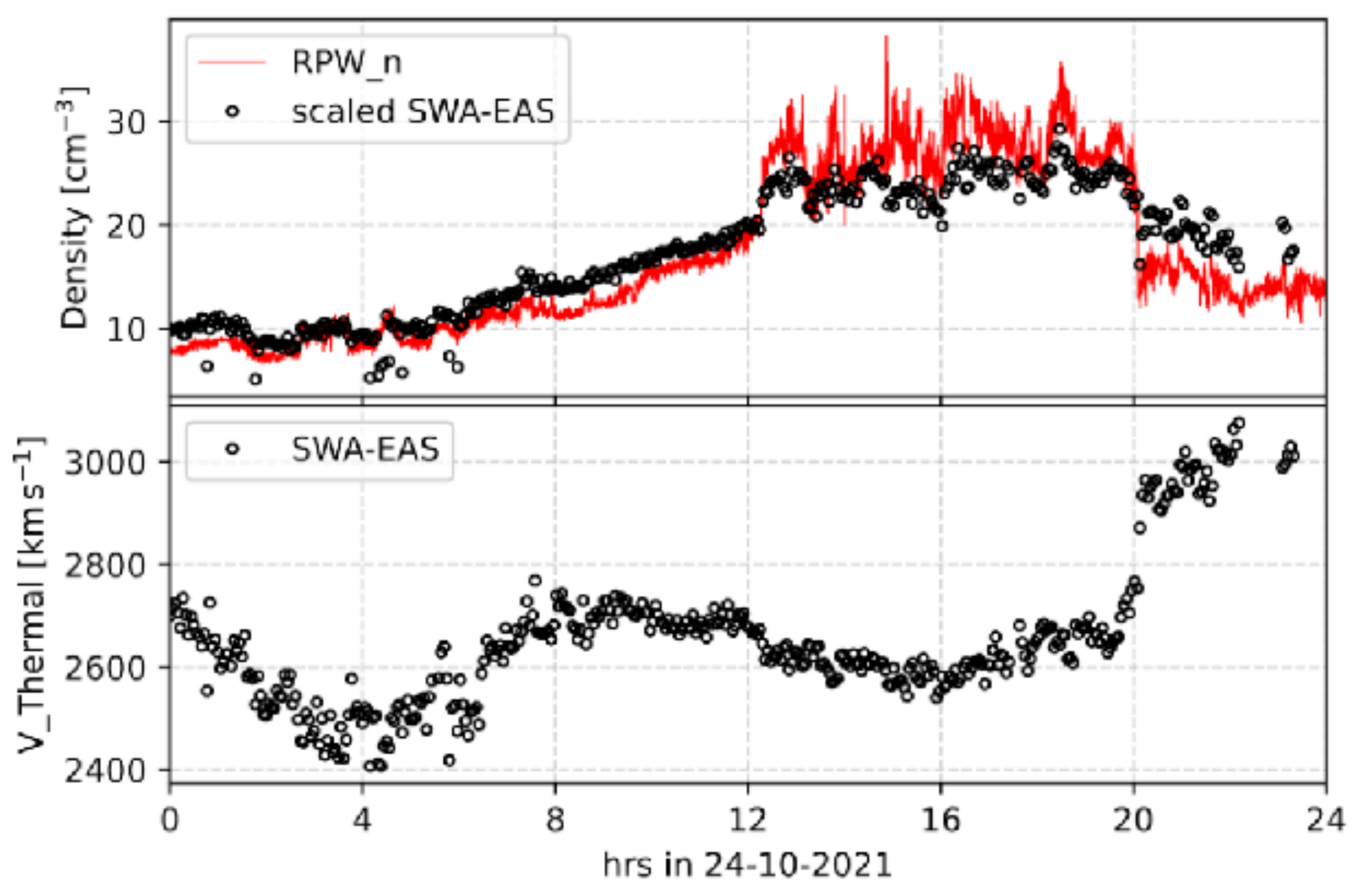
Possible reasons for the discrepancy between predictions and measurements

S/C potential treatment on EAS data
(Courtesy of Georgios Nicolaou'sslides, SWA meeting – Rome 09/2023)

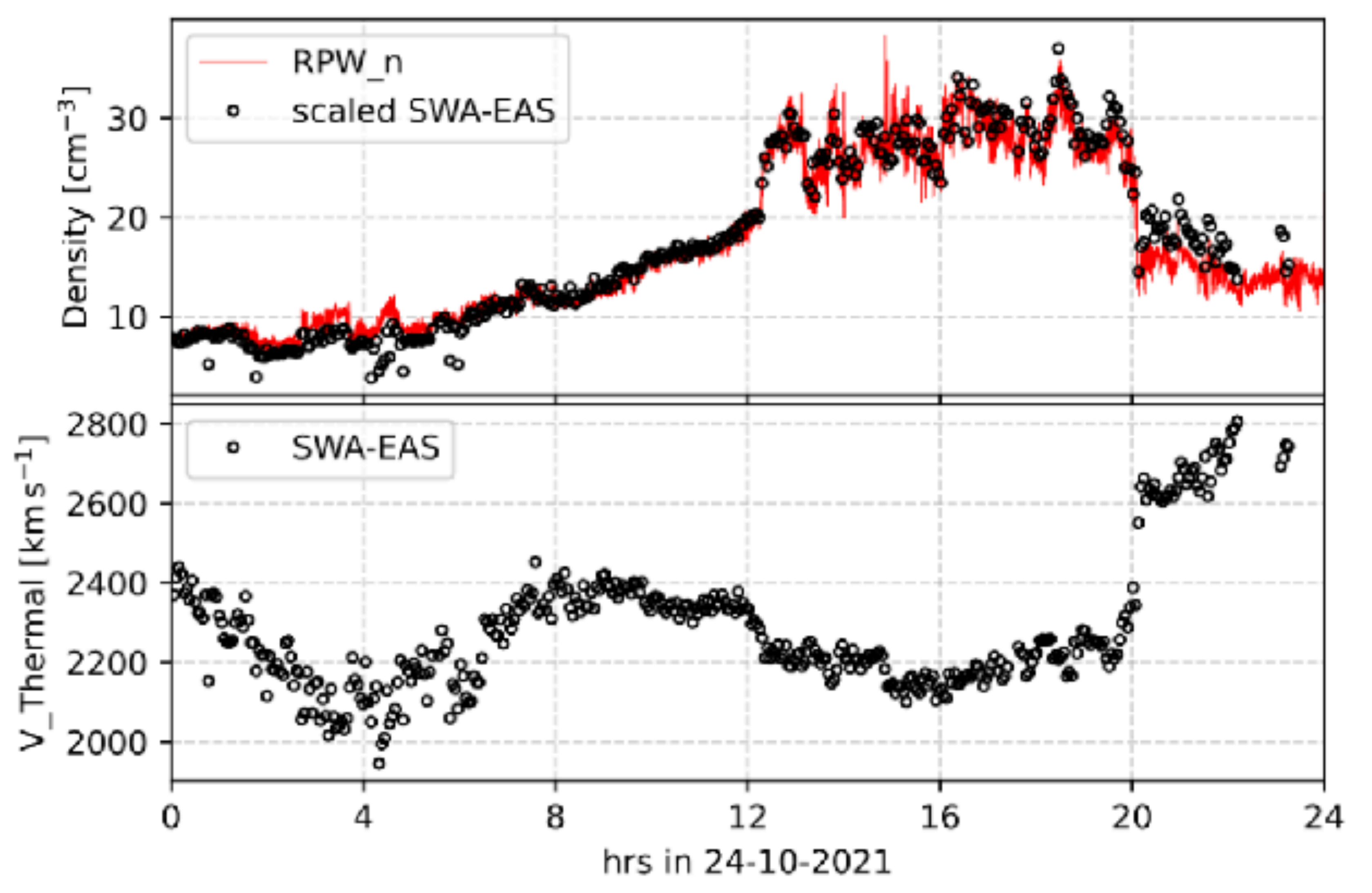
core fit parameters from EAS

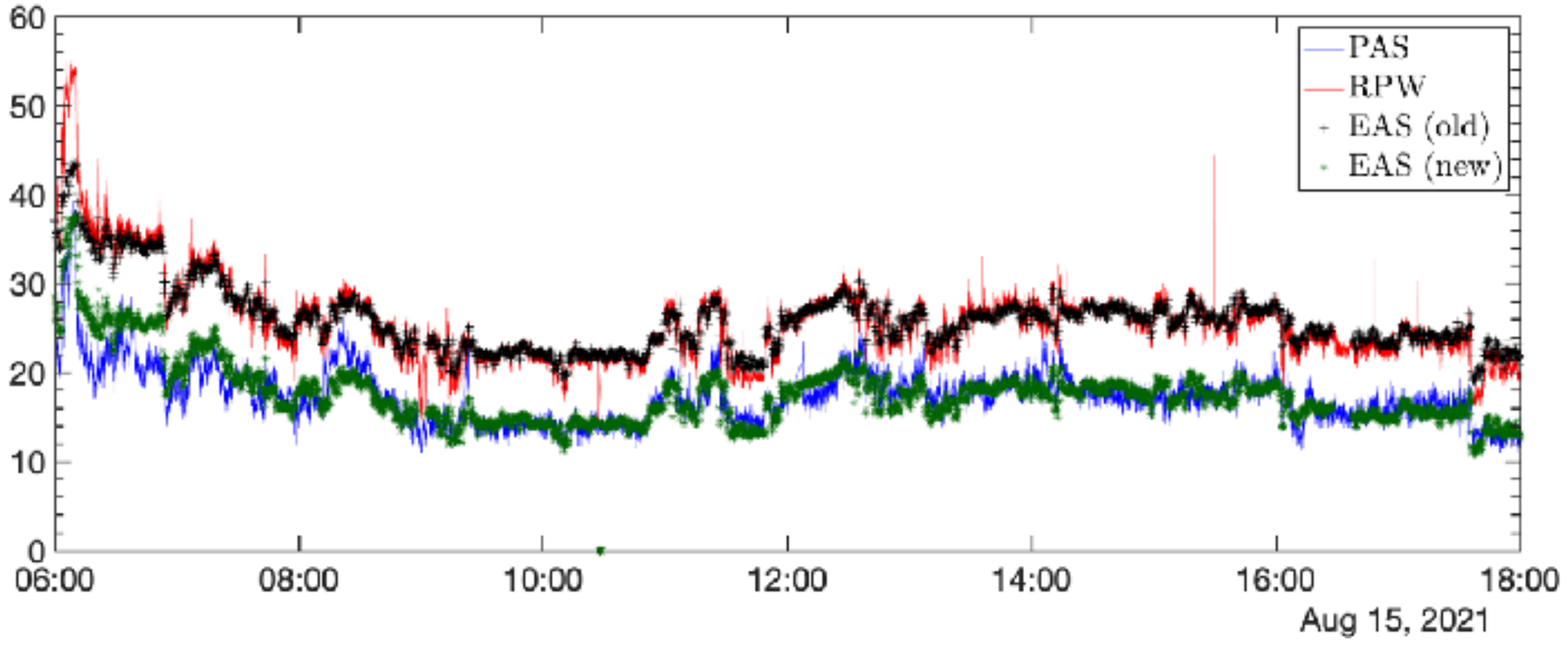


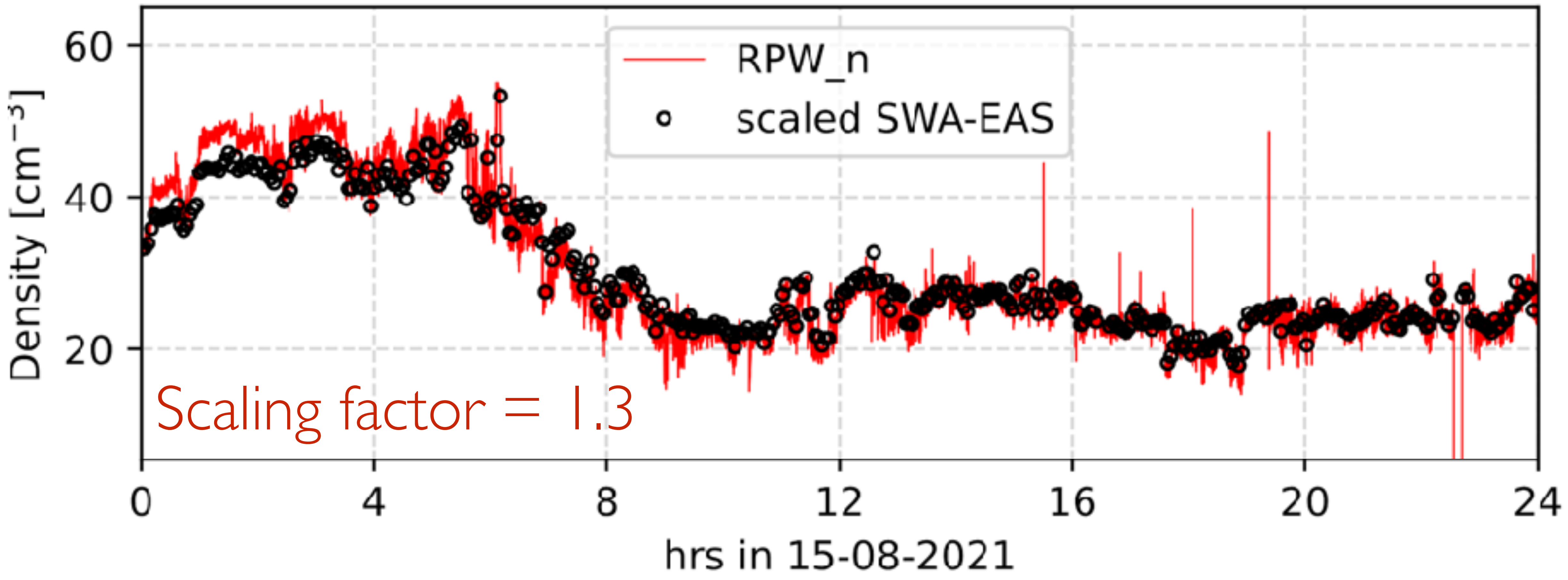
Old method



New method

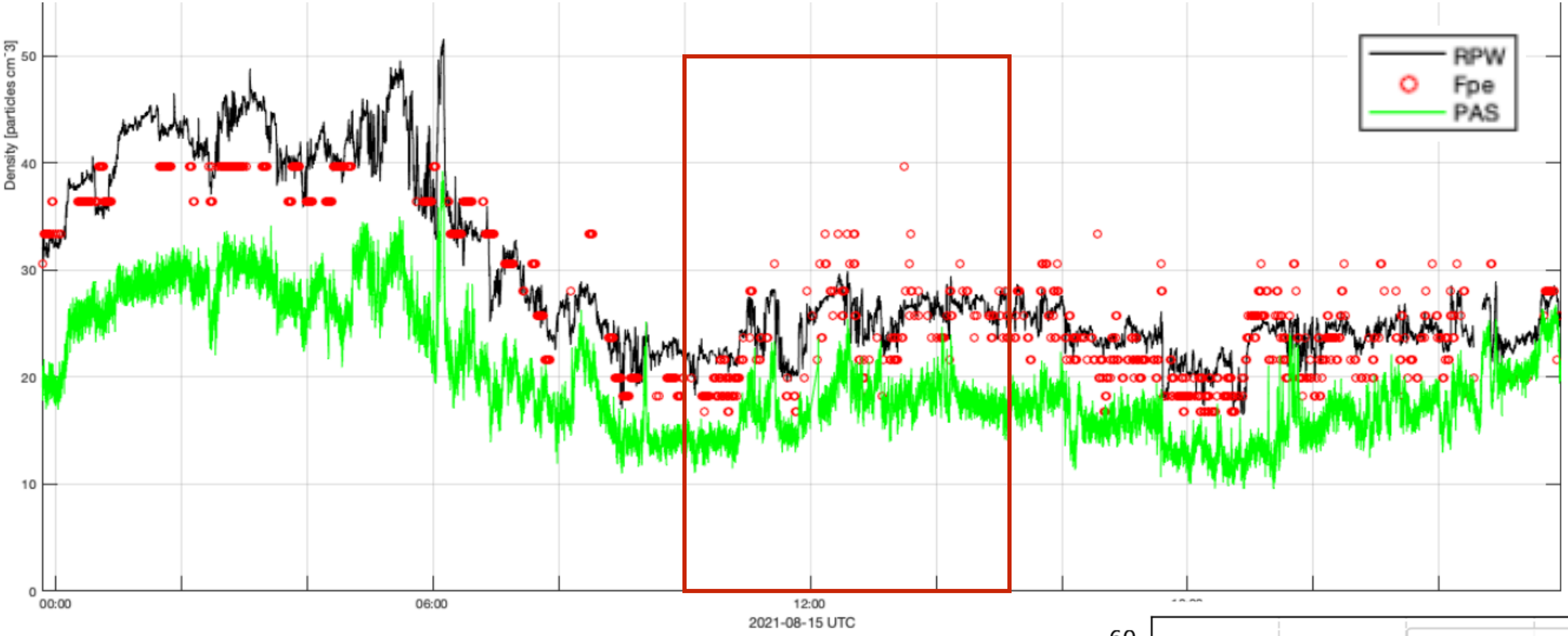




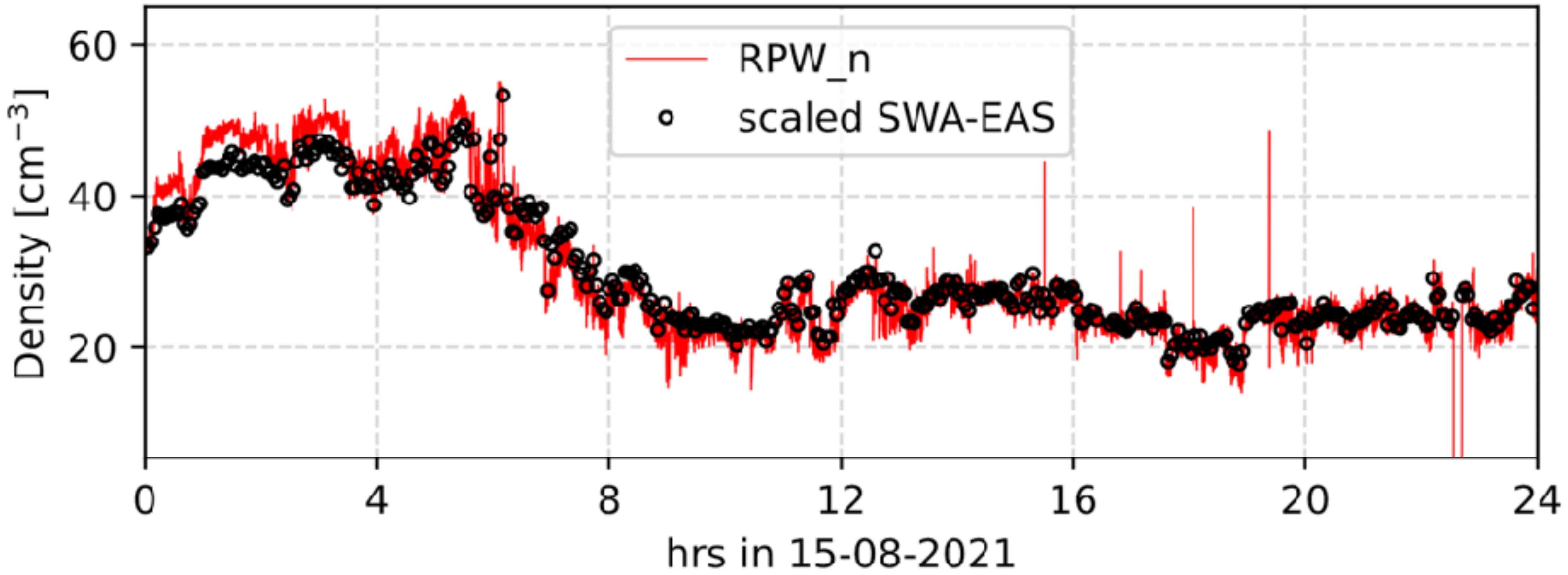


Possible reasons for the discrepancy between predictions and measurements

Calibration on RPW data
(Courtesy of Jordi Boldu)



Scaling factor = 1.3



Possible reasons for the discrepancy between predictions and measurements

Correction(s) required on theoretical prediction?

e.g., Pressure anisotropy?

$$\nabla_\perp \left(\frac{B_0 |(\delta \mathbf{B}|)}{\mu_0} + \delta P_i^\perp + \delta P_e^\perp \right) = 0$$

$$\frac{\delta |\mathbf{B}|}{B_0} = -\frac{\beta_0^\perp}{2} \frac{\delta n}{n_0} + c, \qquad \beta_{\alpha,0}^\perp = \frac{k_B n_0 T_{\alpha,0}^\perp}{B_0^2/2\mu_0}.$$

The perpendicular beta should be used

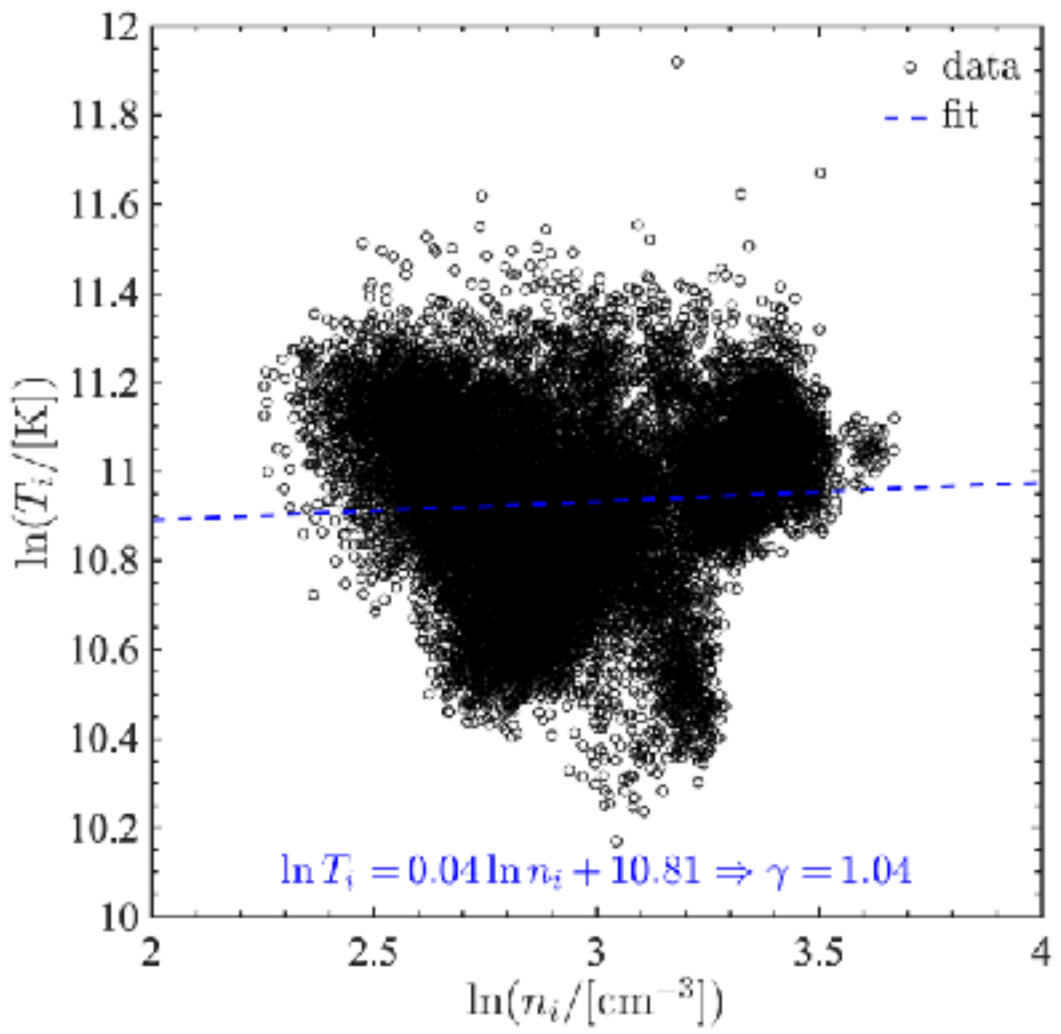
For the protons, I observe temperature anisotropy, such that the perpendicular temperature is smaller than the isotropic temperature. However, a correction to the ion beta would not change the total beta significantly, as the electron contribution is quite larger.

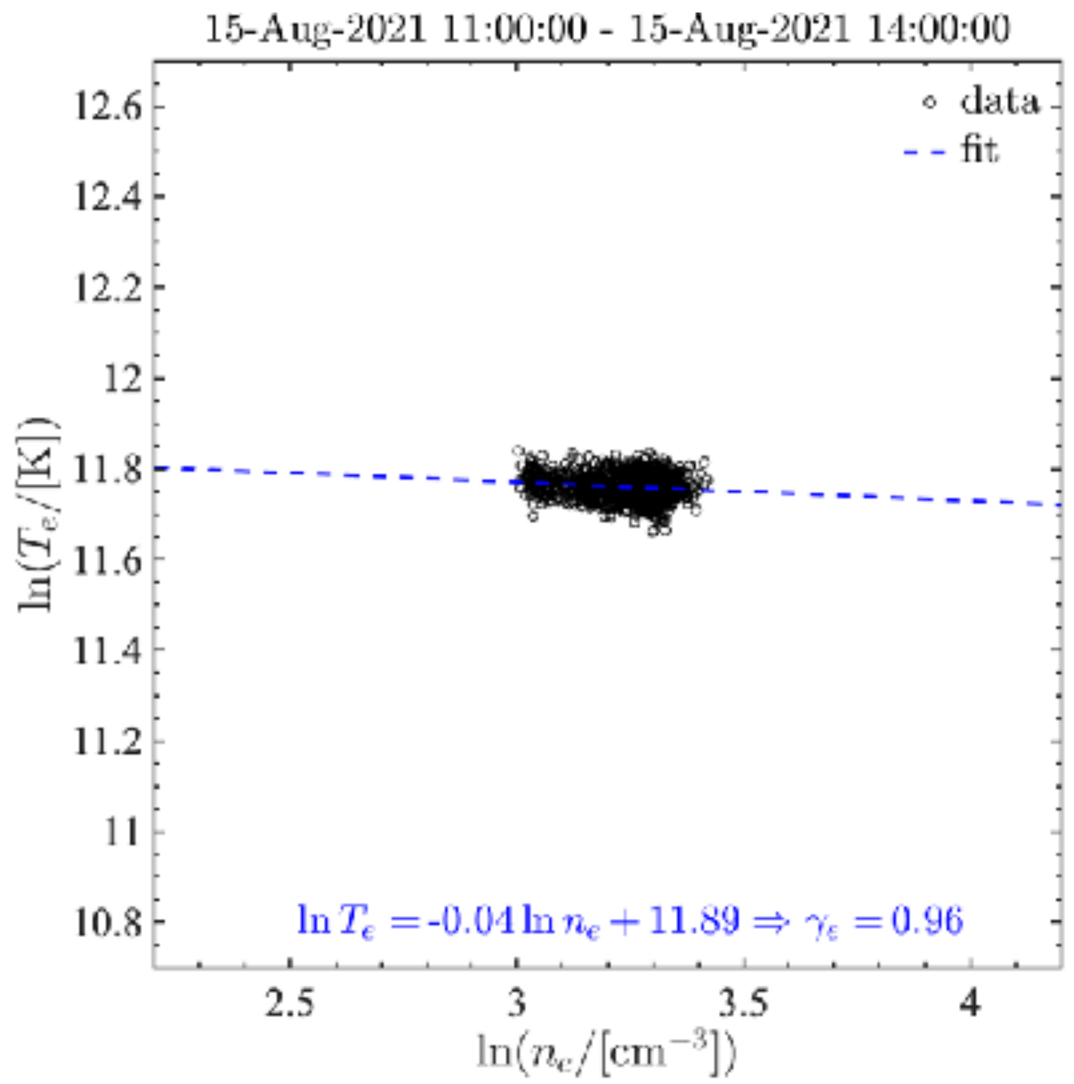
I am using the isotropic electron temperature obtained from core fit of EAS data, as I don't have data for the electron temperature components at the moment

Non-negligible temperature fluctuations with a polytropic closure?

$$\frac{\delta |\mathbf{B}|}{B_0} = -\frac{\gamma_i \beta_{i,0} + \gamma_e \beta_{e,0}}{2} \frac{\delta n}{n_0} + c.$$

The ratio should be corrected with the polytropic indexes…





For the protons, the situation is not very clear, even when considering smaller time intervals… but again, the proton correction would not contribute significantly.
For the electrons, they polytropic index from both data and simulation seem to be 1, regardless of the time interval duration.

Summary & Conclusions

- The density fluctuations play a major role in shaping the electric field spectrum at sub-ion scales and thus the cascade
- We observe an anti-correlation between the Hall and the electron pressure term in the generalised Ohm's law
- Using a force balance argument, this leads us to expect multi-scale pressure balances fluctuations
- We indeed observe them through the anti-correlation between the fluctuations of n and $|\boldsymbol{B}|$ in:
  - ✓ Solar Orbiter data (from MAG and RPW)
  - ✓ 2D numerical simulations (both hybrid and Hall-MHD)
- The anti-correlation breaks at ion scales (frequencies or wavenumber) in SolO data and hybrid simulations
- The anti-correlation is maintained below the ion scales in Hall-MHD simulations instead (where the pressure is constrained to be isotropic by the model)
- This supports our idea that the anti-correlation breaks at the ion scales (gyrofrequency/gyroradius) due to non-gyrotropic or agyrotropic deformations of the ion pressure tensor
- We can use the presence and the disruption of the anti-correlation to infer, respectively:
  - ✓ the total plasma beta without using particle instruments (useful for cross-calibration?)
  - ✓ the scale at which non-gyrotropic/agyrotropic deformations of the pressure tensor become important

Our results suggest a key role of pressure-balanced fluctuations in mediating the turbulent cascade below MHD scales