

MHD simulations and forward modeling of Alfvénic waves in coronal holes



European Research Council

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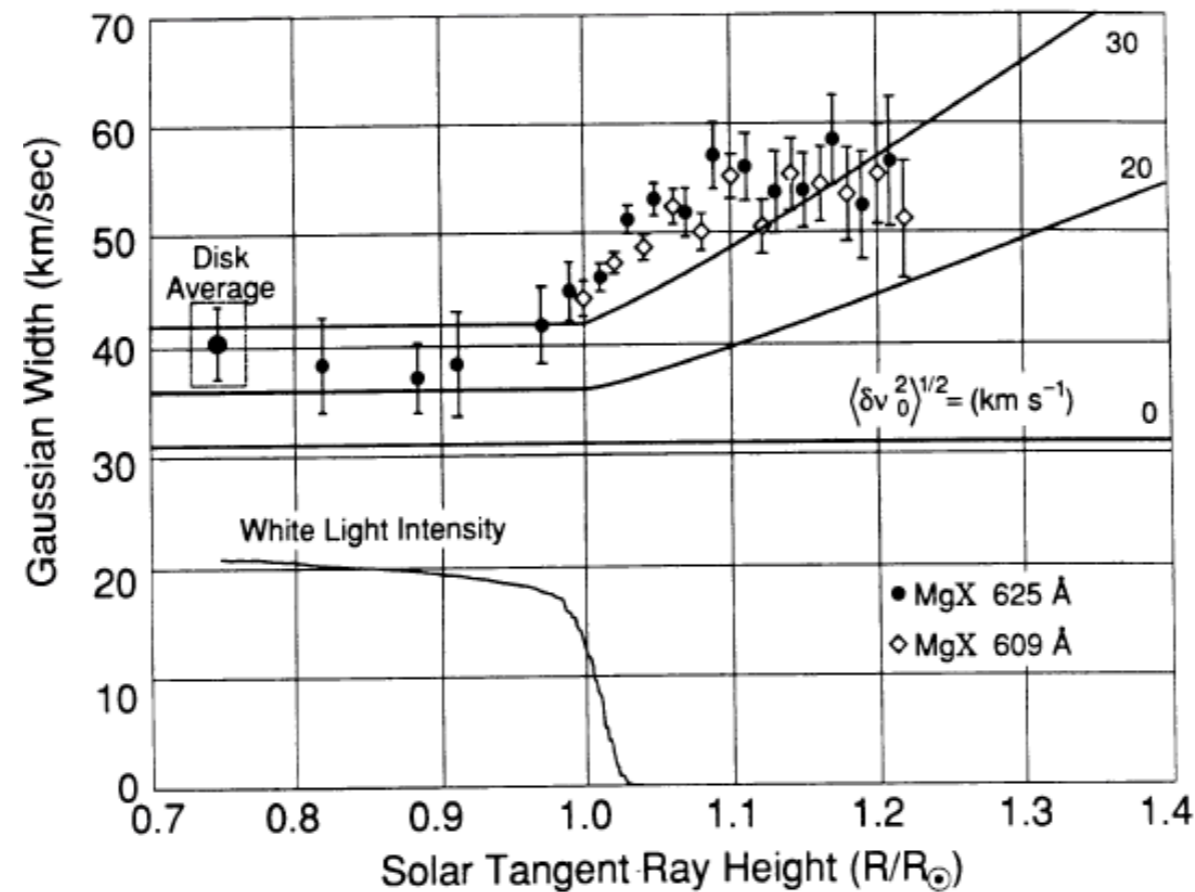


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CmPA, KU Leuven

in collaboration with
Tom Van Doorselaere, Norbert Magyar and Richard Morton

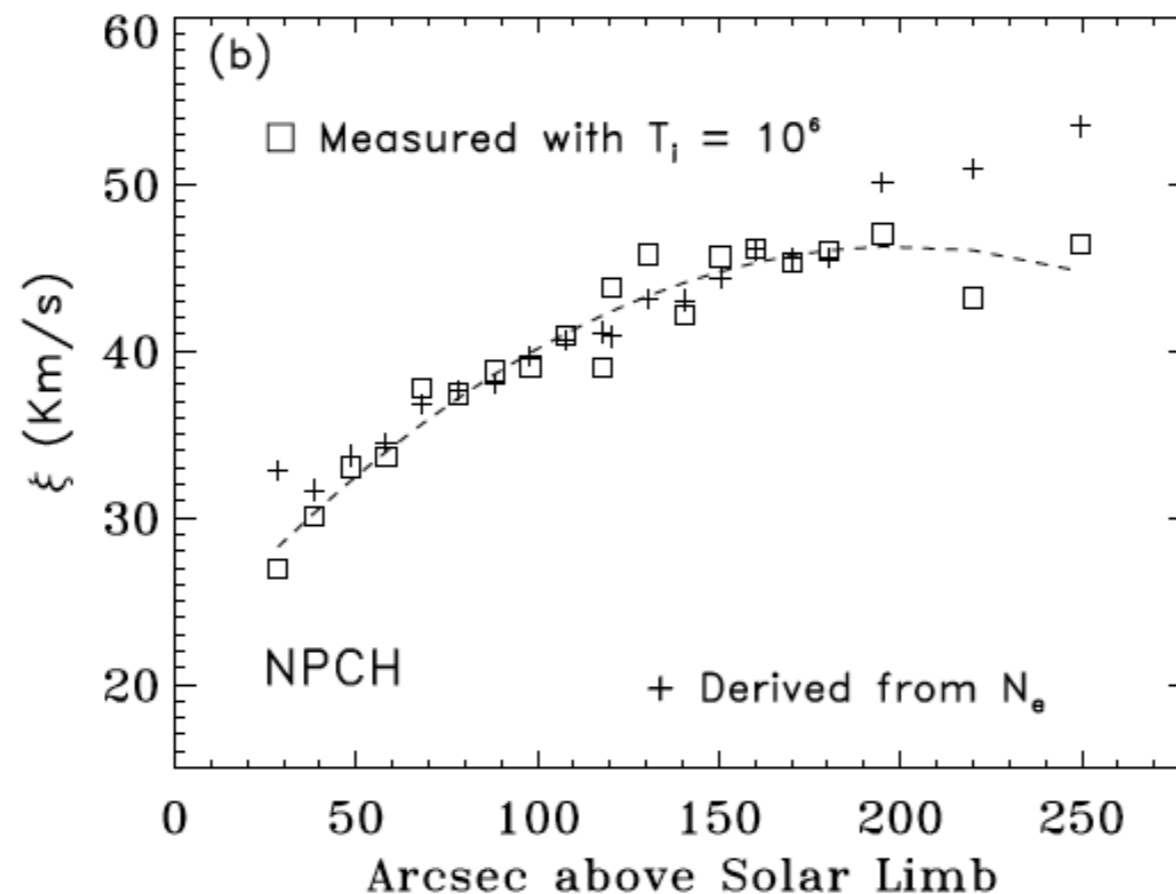


Introduction



Observations were made by EUV spectrometer in Mg X spectral lines

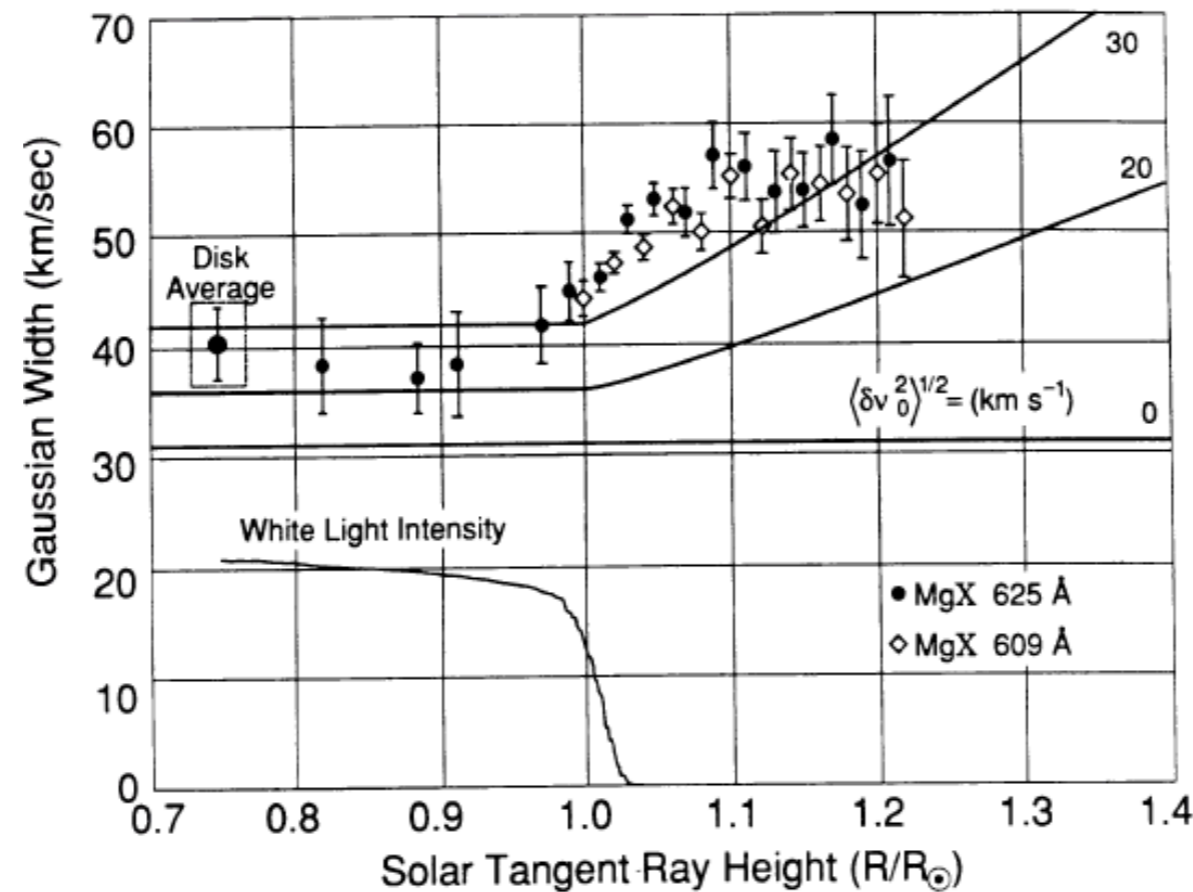
Hassler et al, 1990



Observations were made using Si VIII spectra. The spectra were obtained with SUMER onboard SOHO

Banerjee et al, 1998, Doyle et al, 1997, 1998

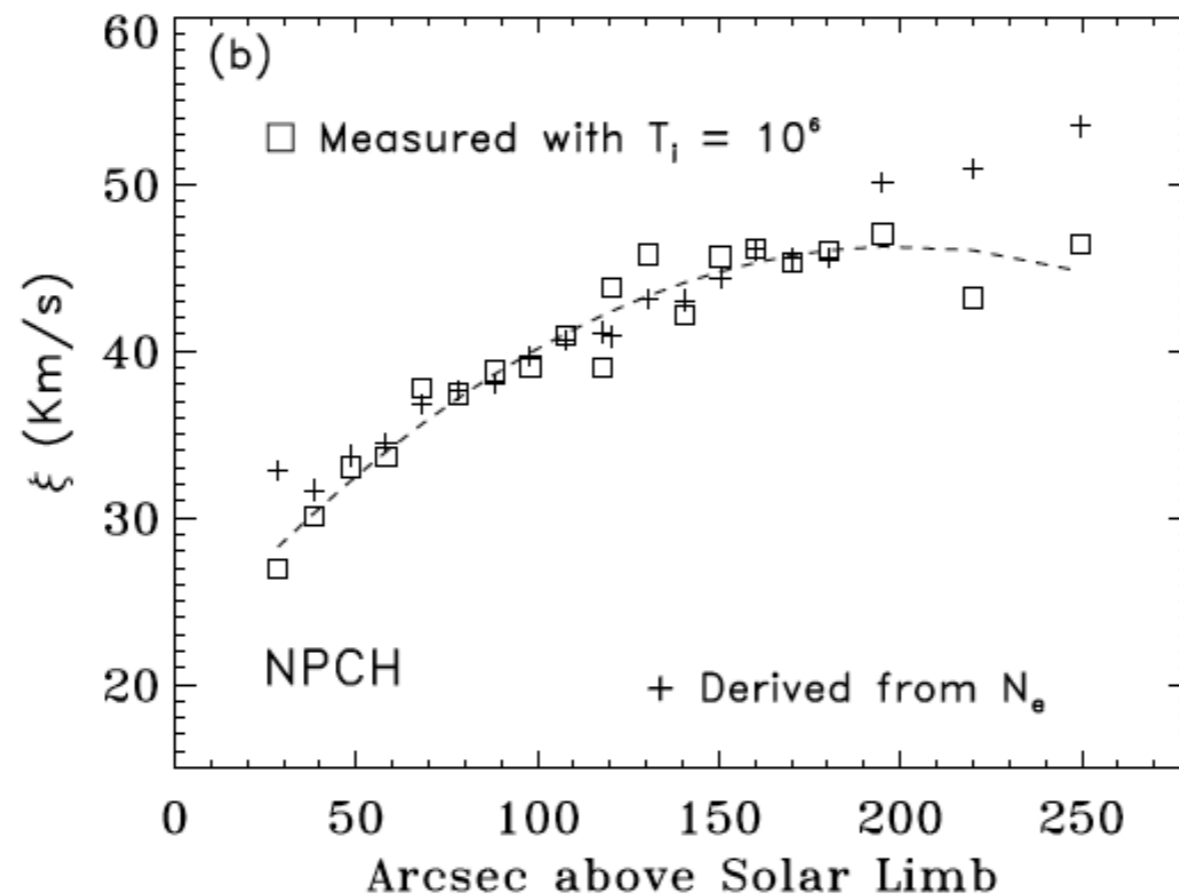
Introduction



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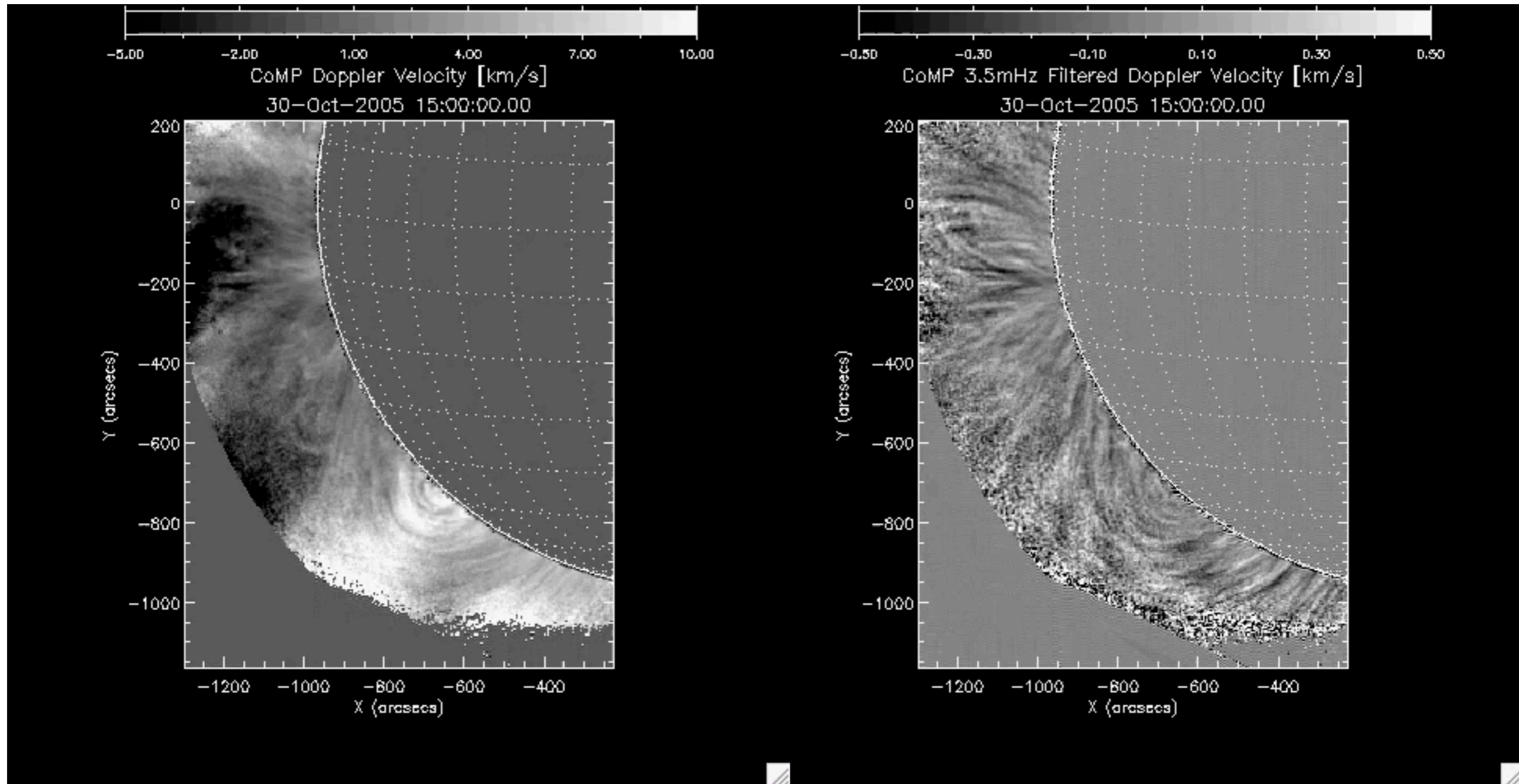
Signatures of Alfvén(ic) waves in the solar corona



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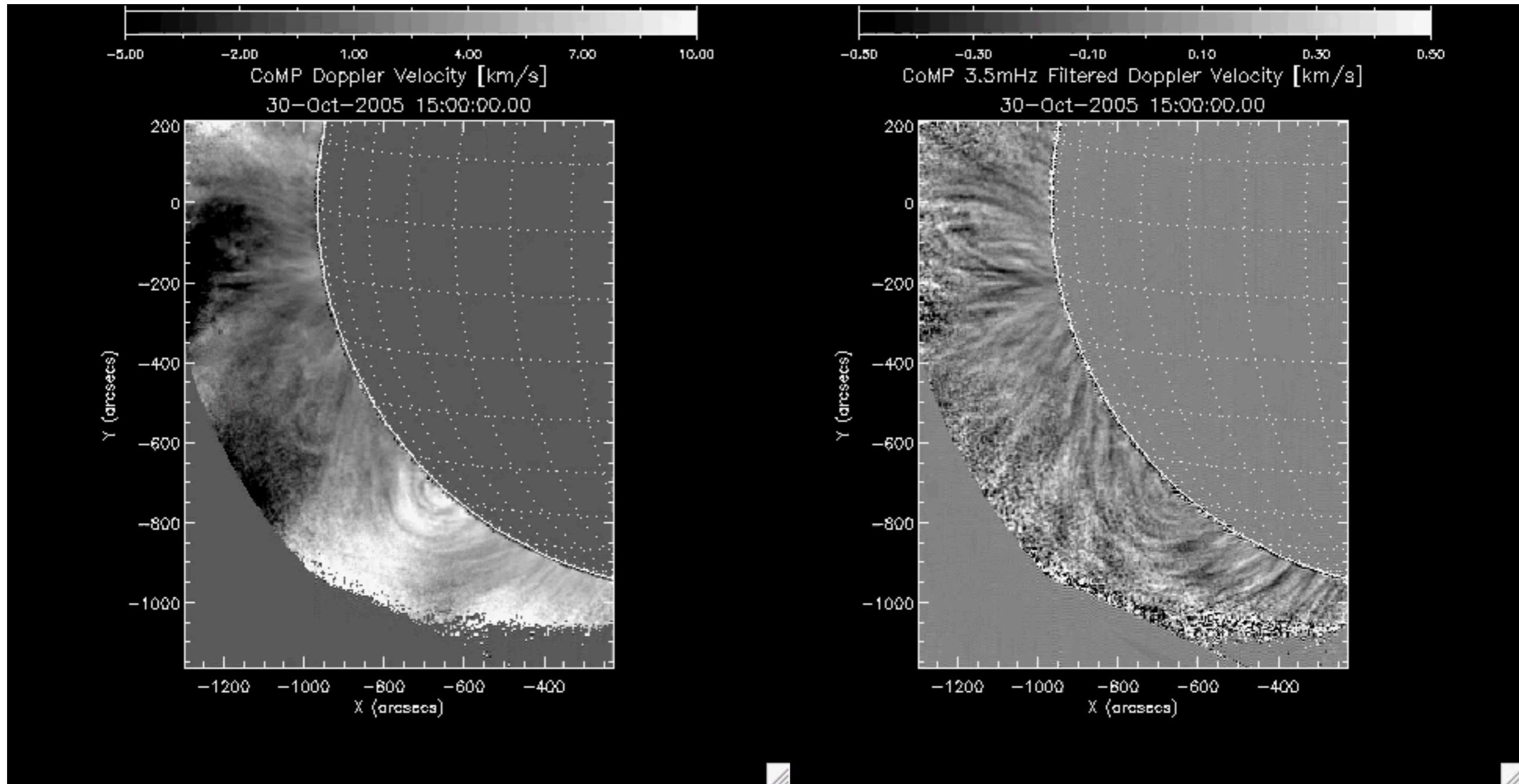
Kink (Alfvénic) waves in the solar corona



RMS Doppler velocities ~ 0.3 km/s
Phase speeds 2 Mm/s
Energy flux ~ 0.01 W/m²
non-thermal line width = 30 km/s

Tomczyk et al, 2007

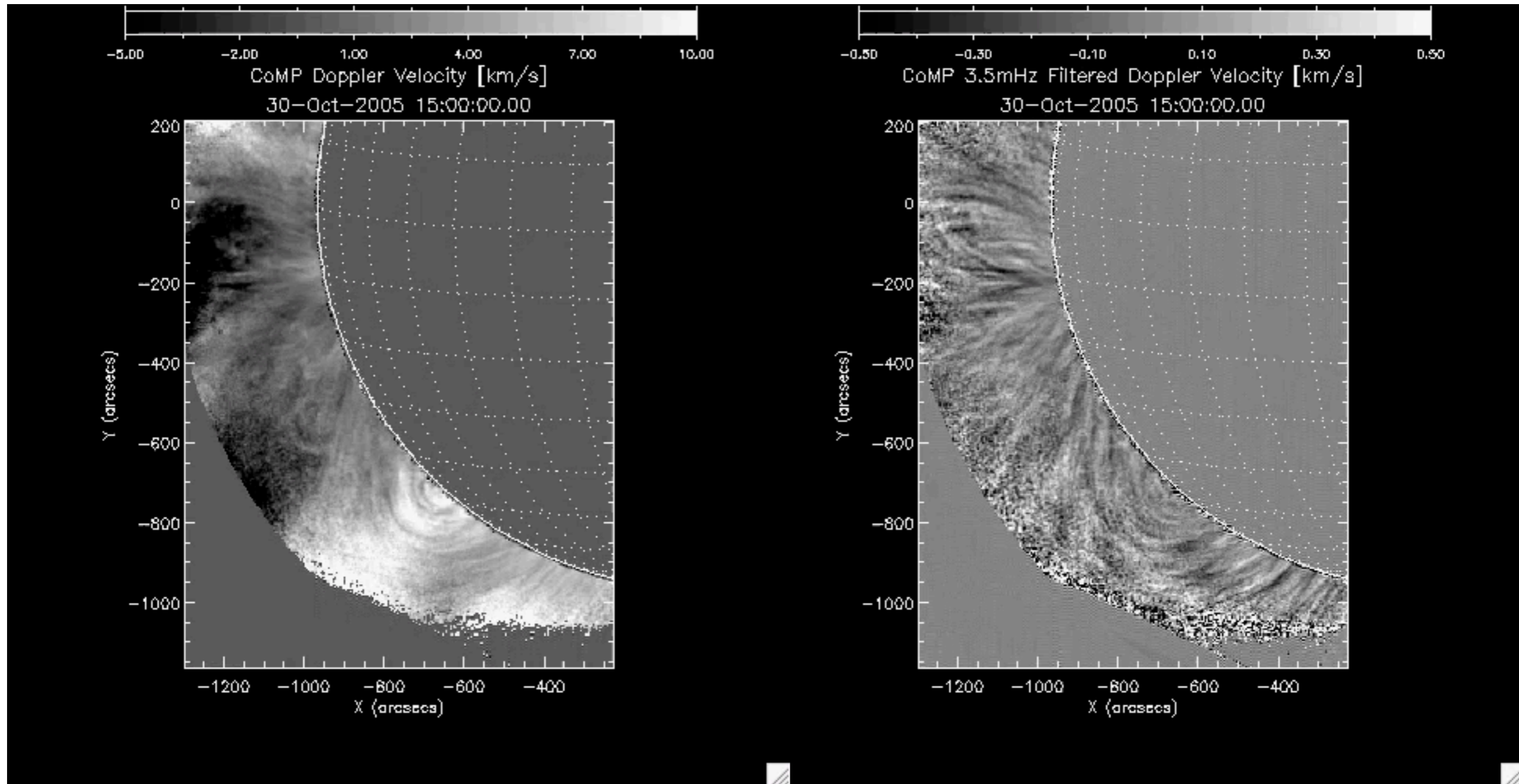
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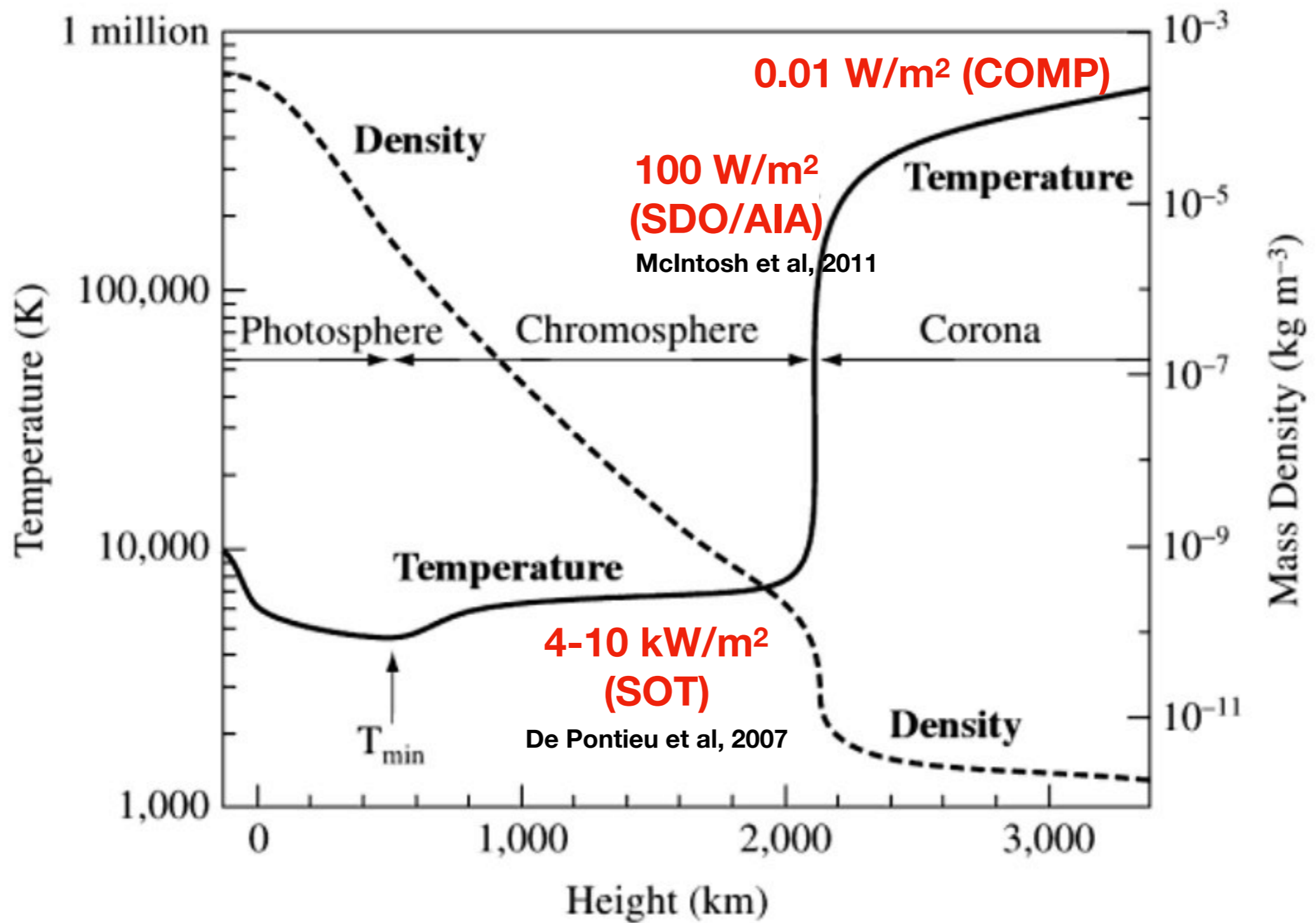
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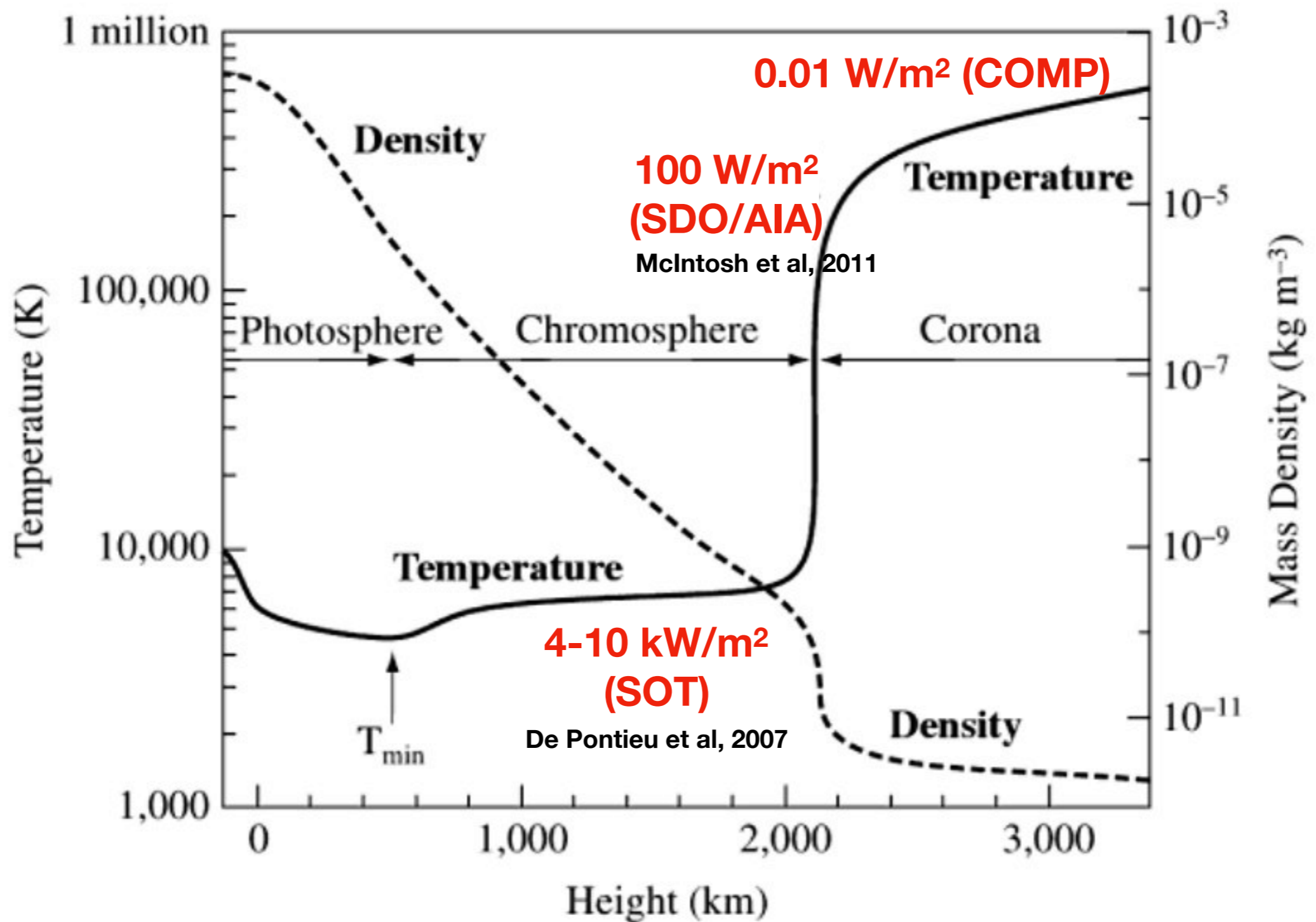
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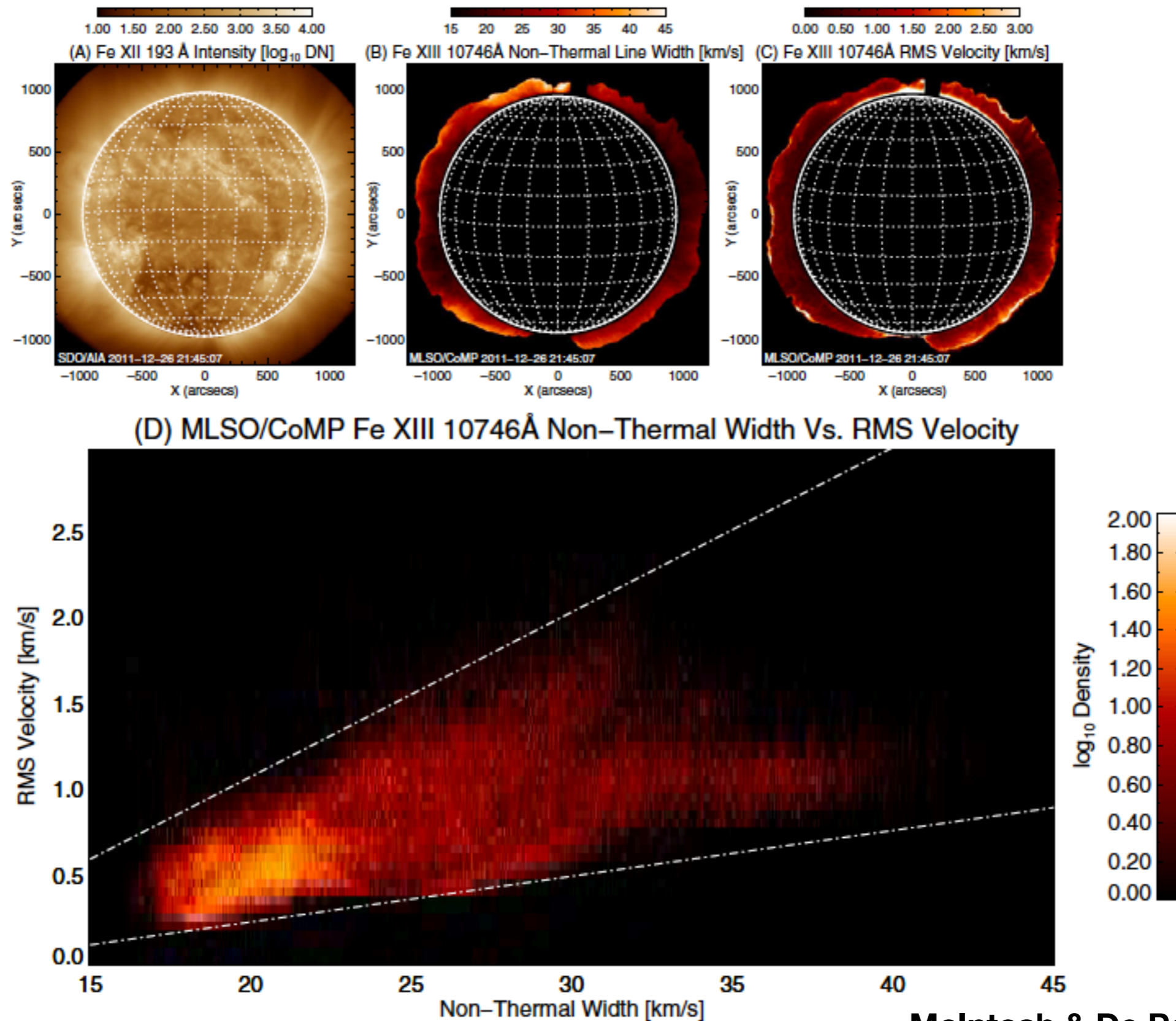
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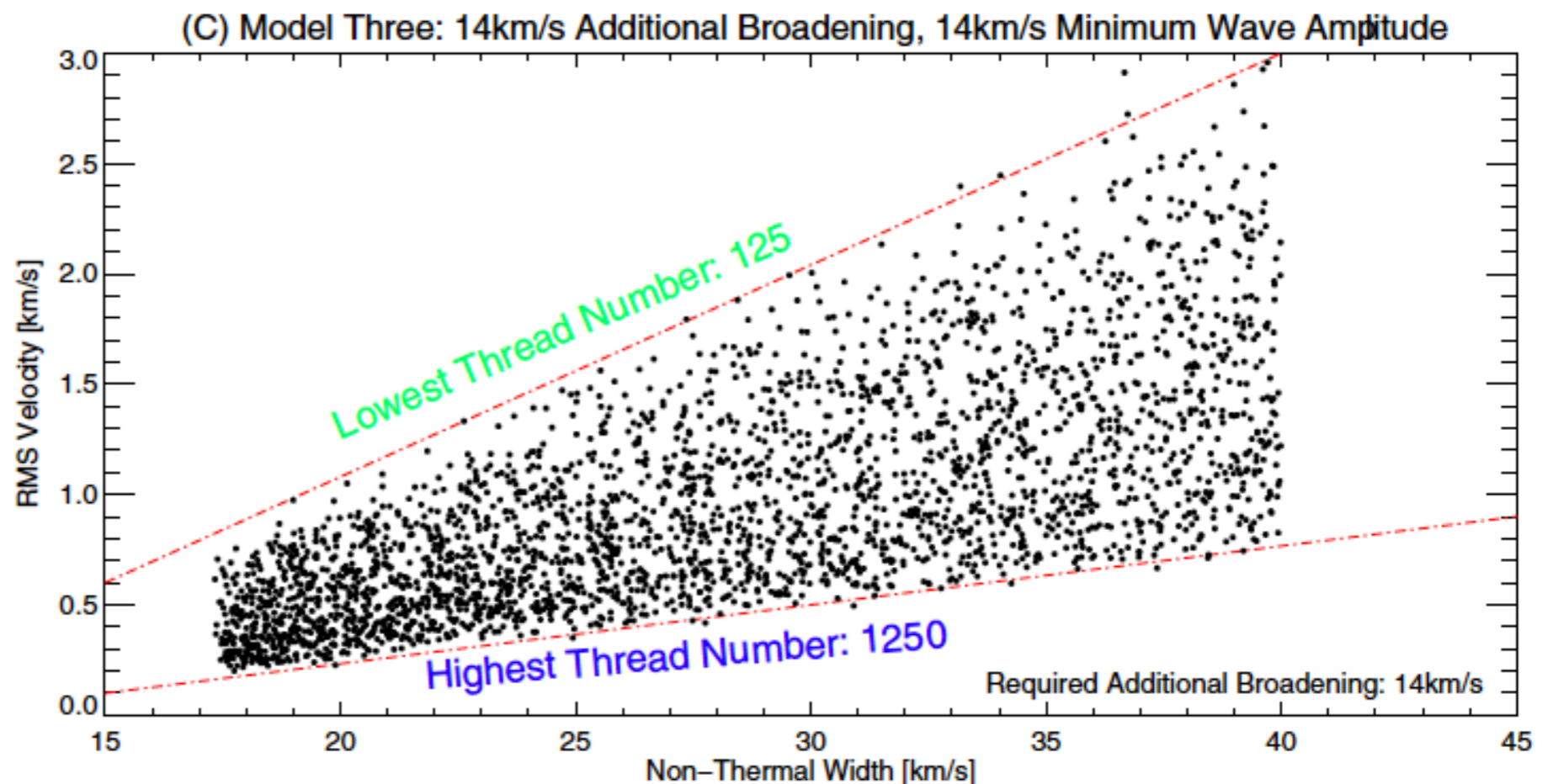
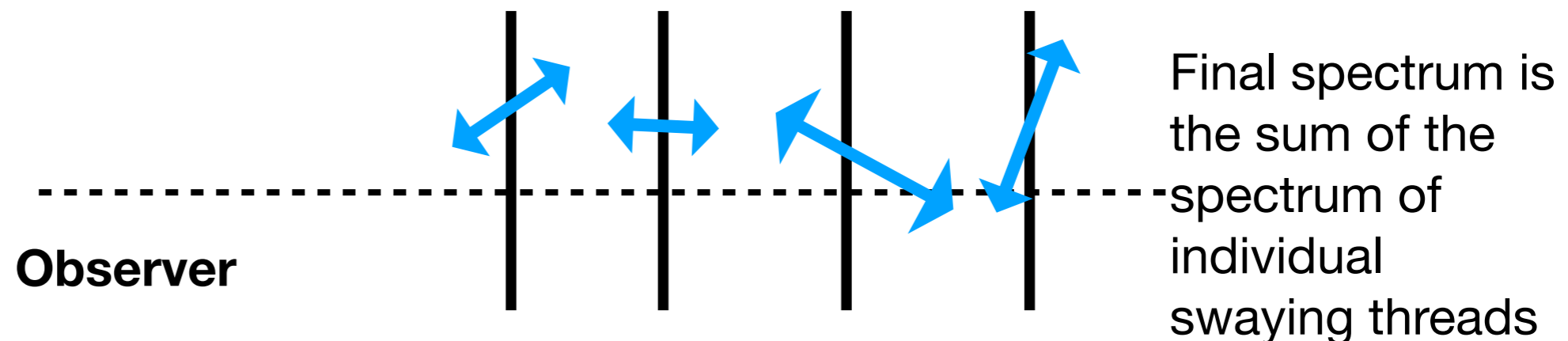
Underestimation of the observed energies due to line-of-sight integration (De Moortel & Pascoe, 2012)

Variation of Doppler velocities with non-thermal line widths



Monte Carlo method to forward model Alfvénic waves

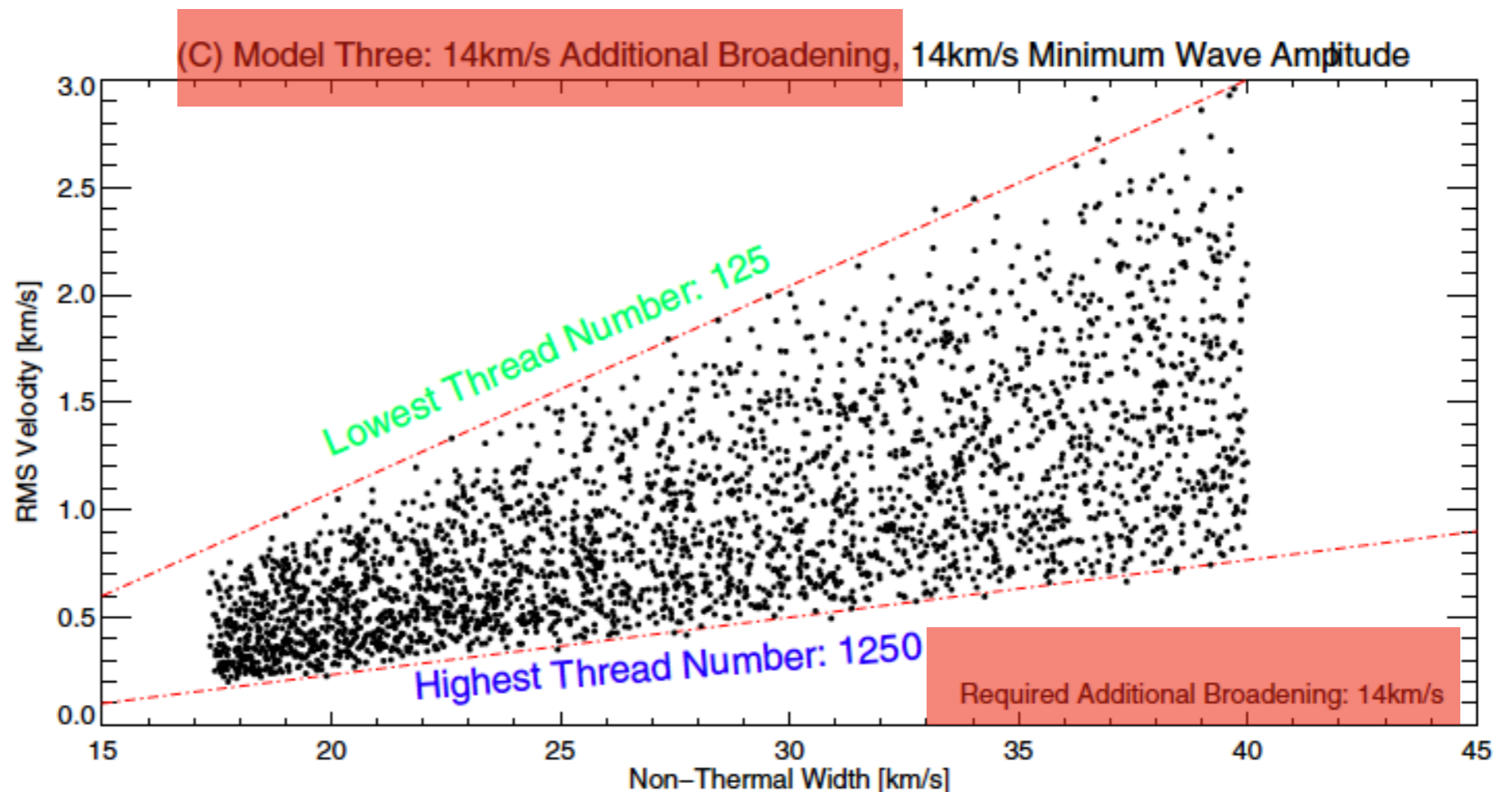
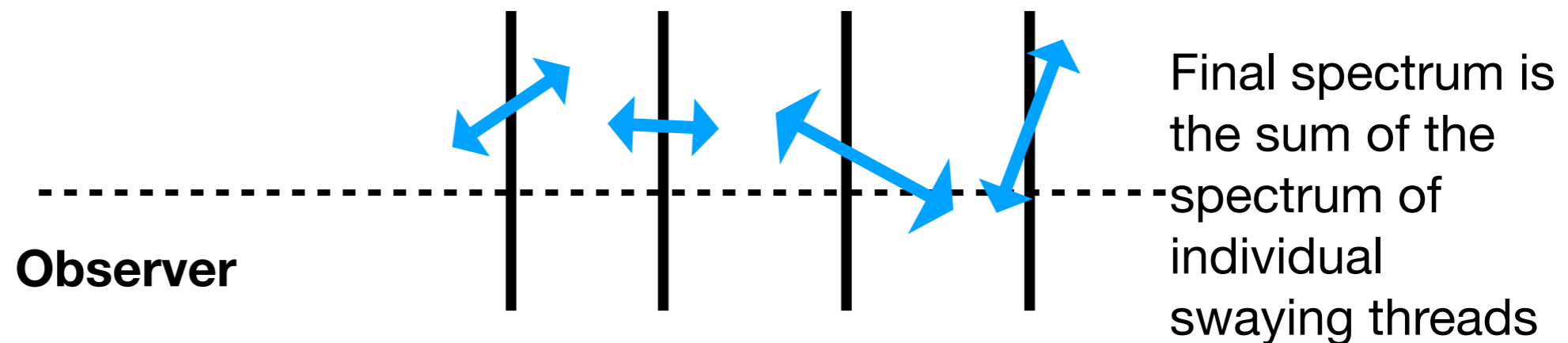
Solar corona consists of several swaying threads or “elementary oscillating structure”



- Lifetime of thread $\sim 100 \pm 20$ sec
- Uniform brightness
- Randomly chosen period, amplitude
- Polarisation angle $\sim 0-360$ degrees

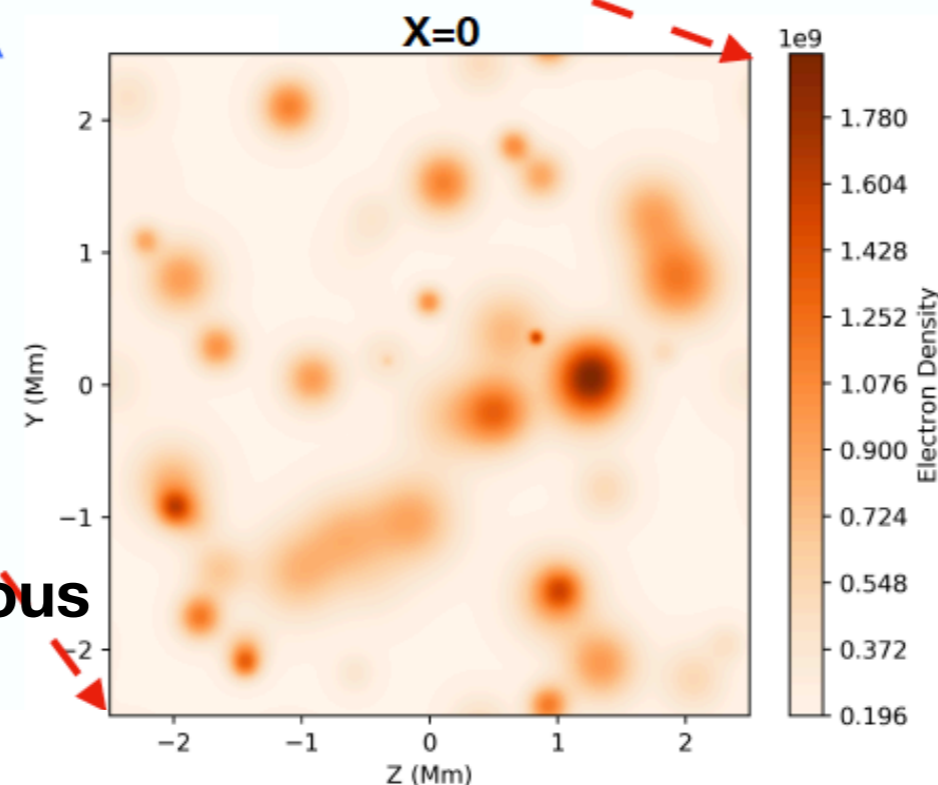
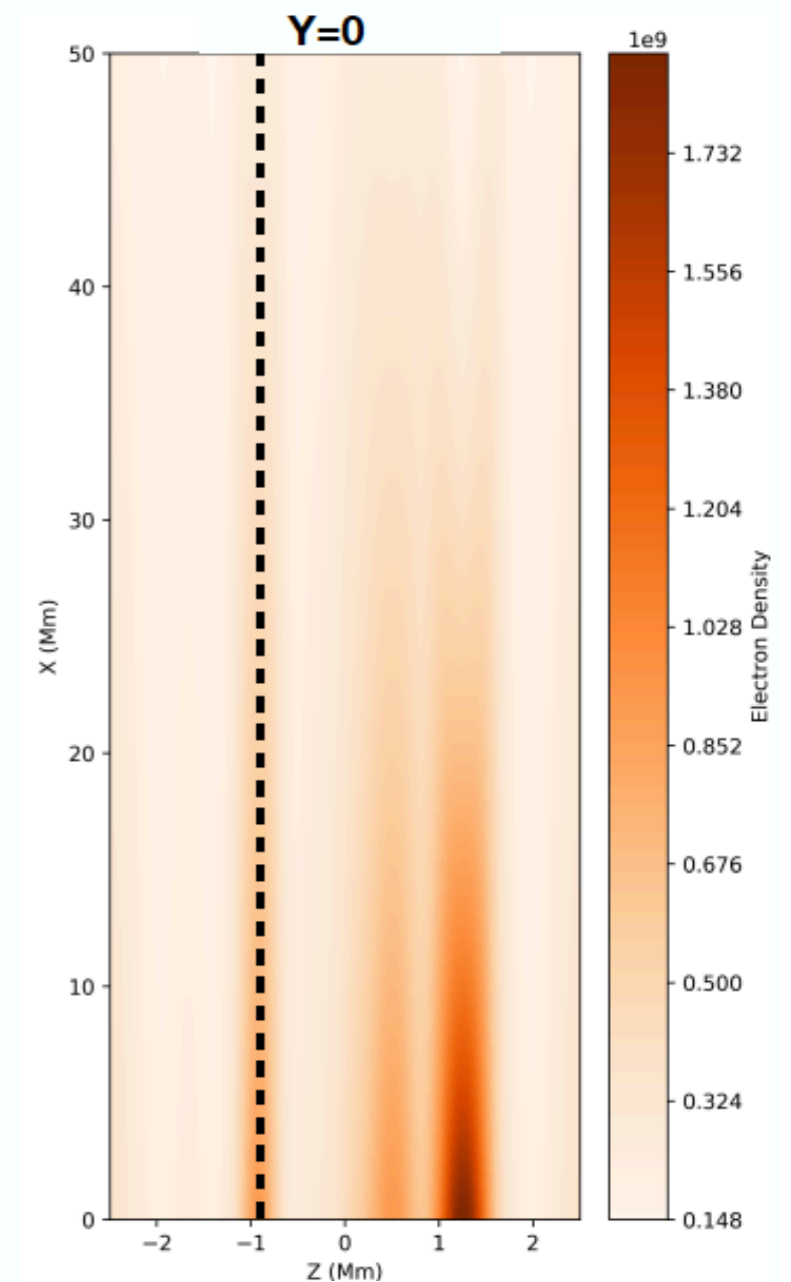
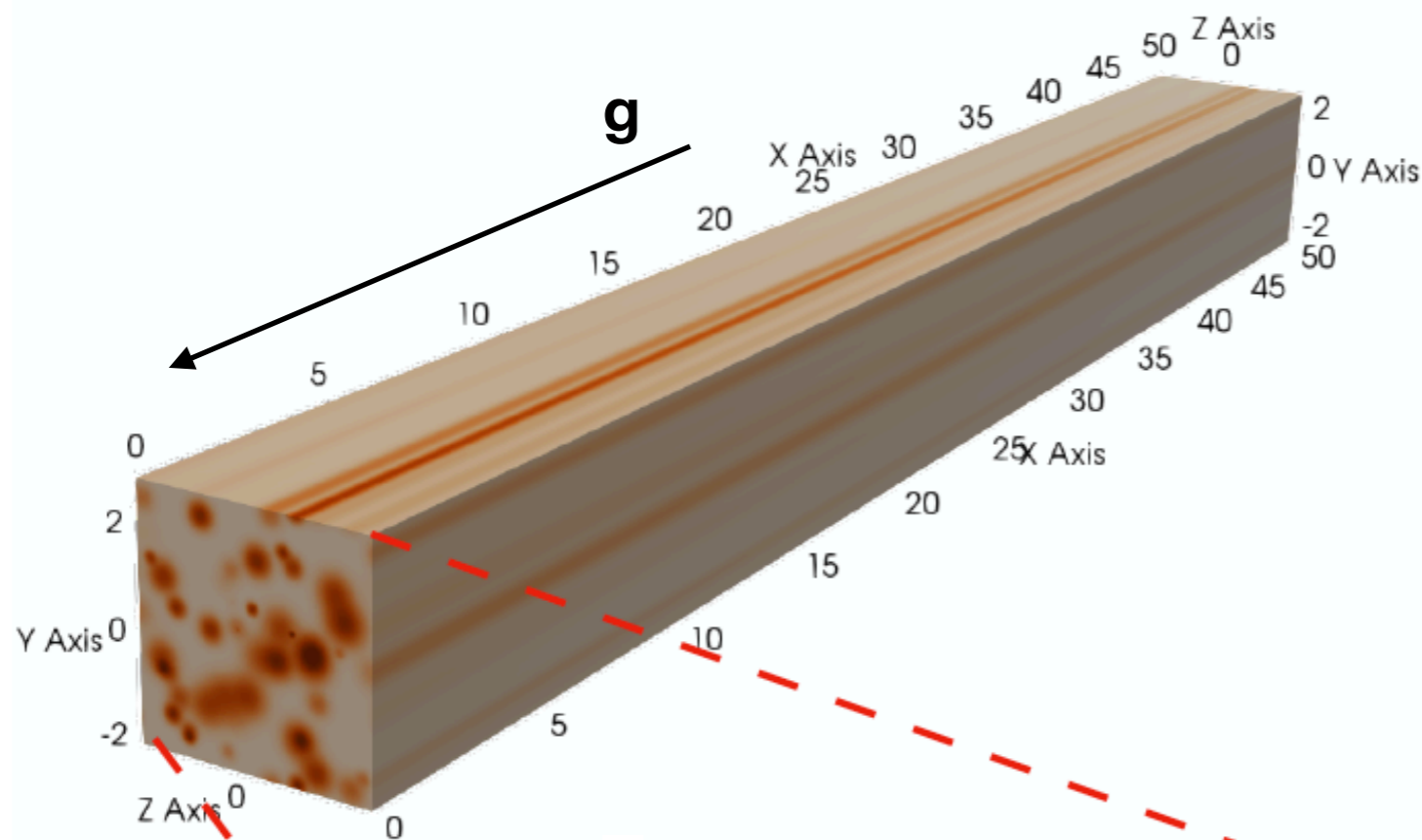
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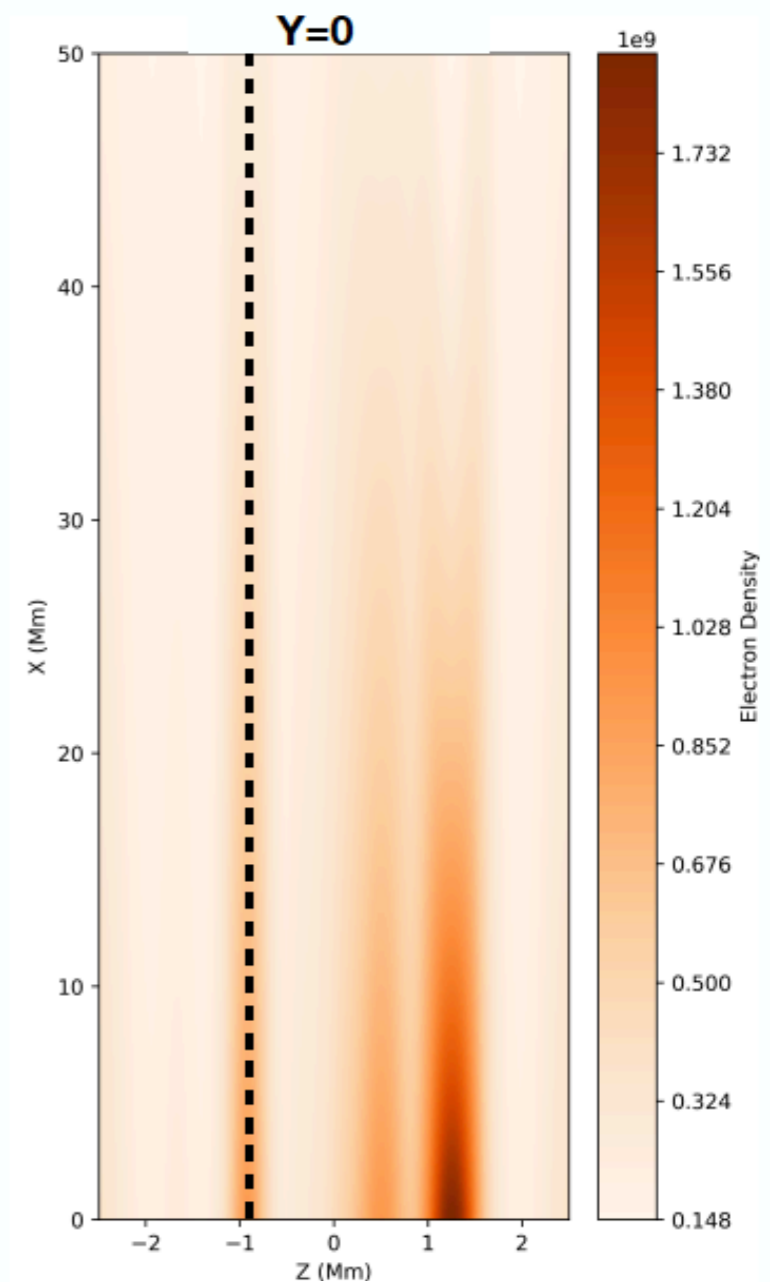
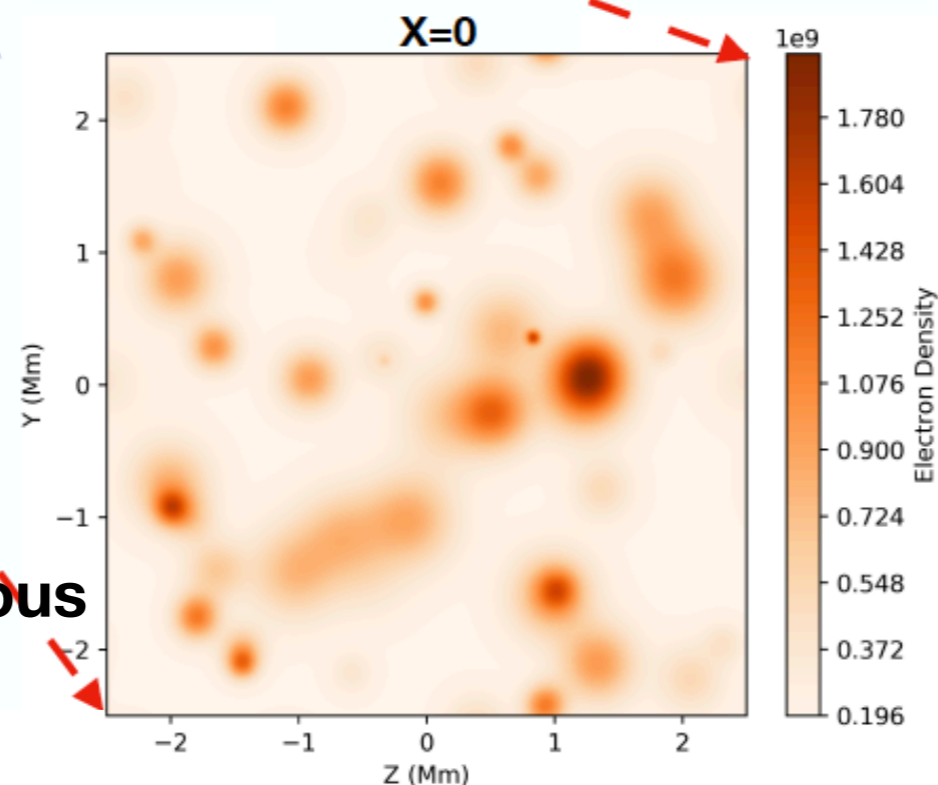
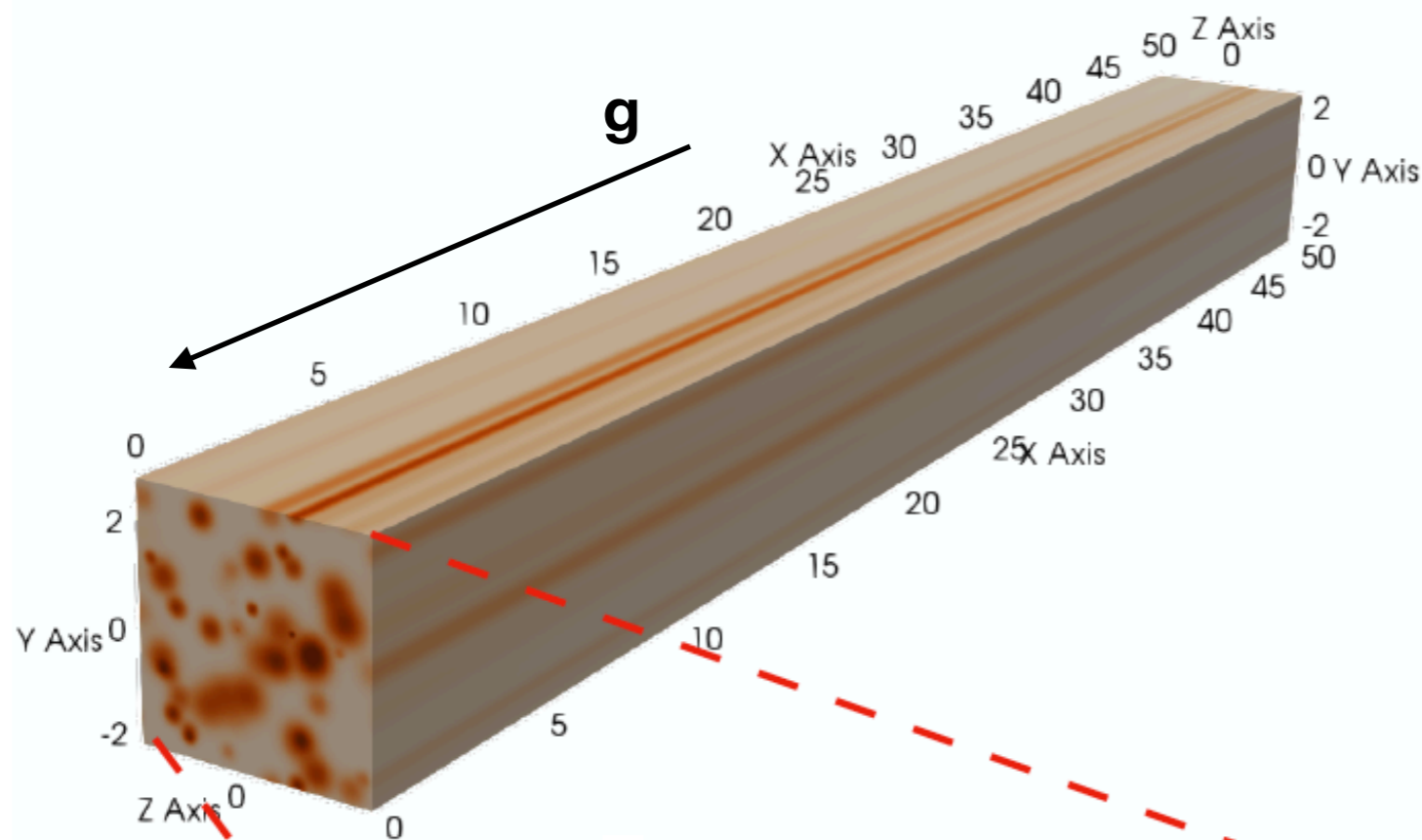
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Propagating waves in the gravitationally stratified plasma



- Gravitationally stratified
- Transversely inhomogeneous
- $B = 5 \text{ G}$
- $50 \text{ Mm} \times 5 \text{ Mm} \times 5 \text{ Mm}$

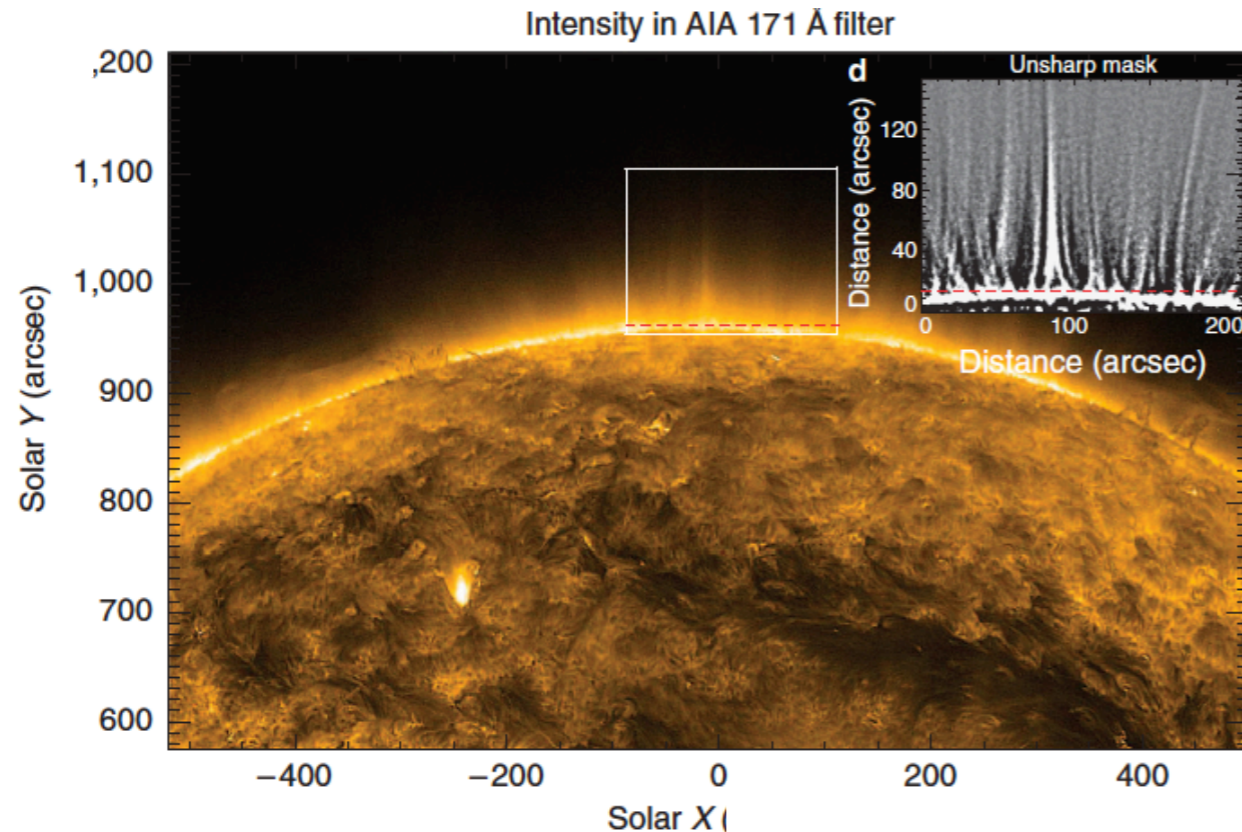
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Performed Ideal MHD simulations

Wave excitation at the bottom boundary



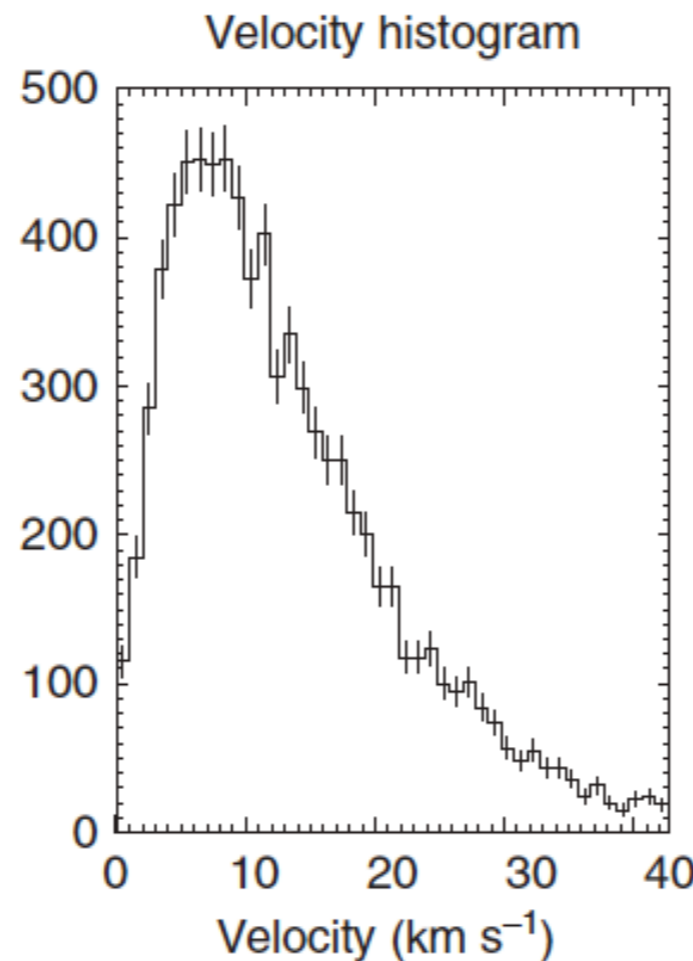
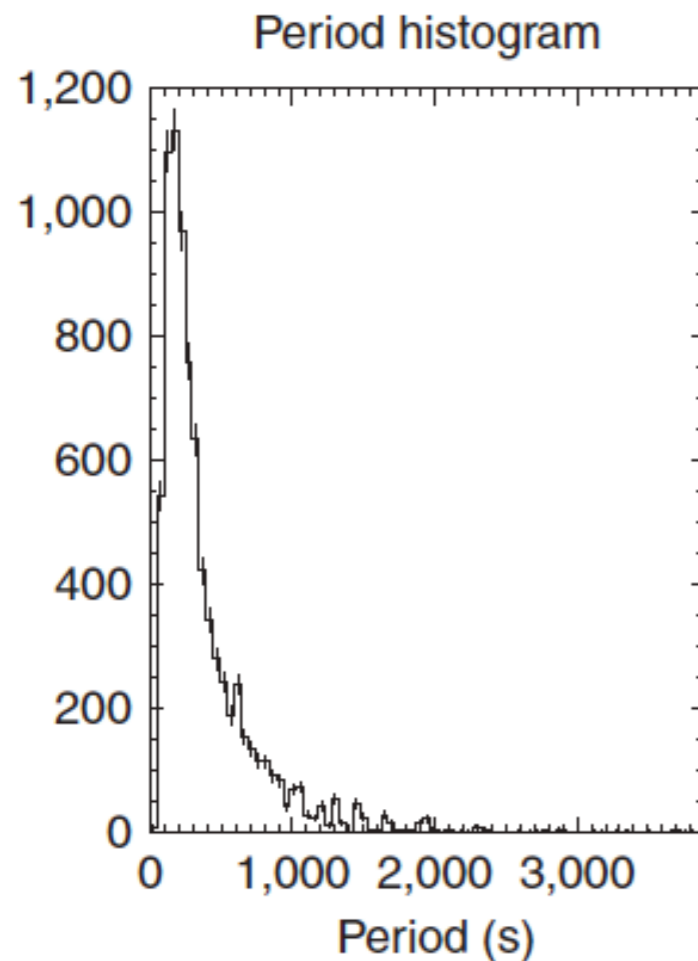
- Multiple periodic drivers of varying amplitude
- Velocity drivers in **perpendicular** directions to the background magnetic field

$$v_y(x=0, t) = \sum_{i=0}^{10} U_i \sin(\omega_i t)$$

$$v_z(x=0, t) = \sum_{i=0}^{10} V_i \sin(\omega_i t)$$

$$v_{rms} = \left\langle \sqrt{\frac{\sum_{t=0}^T [v_y^2(x=0, t) + v_z^2(x=0, t)]}{T}} \right\rangle_{y,z}$$

$v_{rms} = 7 \text{ km/s}, 15 \text{ km/s}$ and 26 km/s

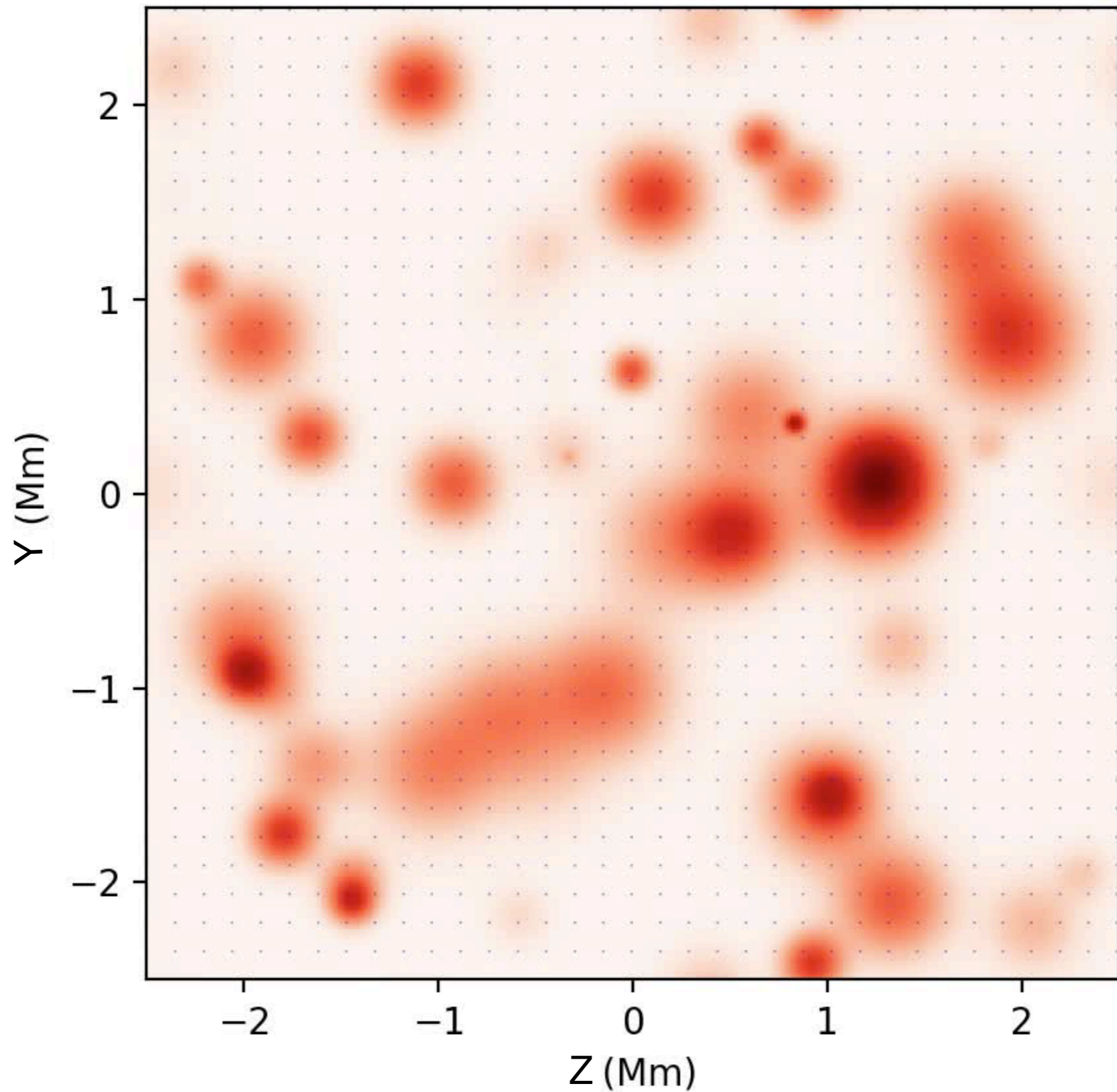


Morton et al, 2015

Generation of (uni)turbulence

$X = 25 \text{ Mm}$

10 km s^{-1}

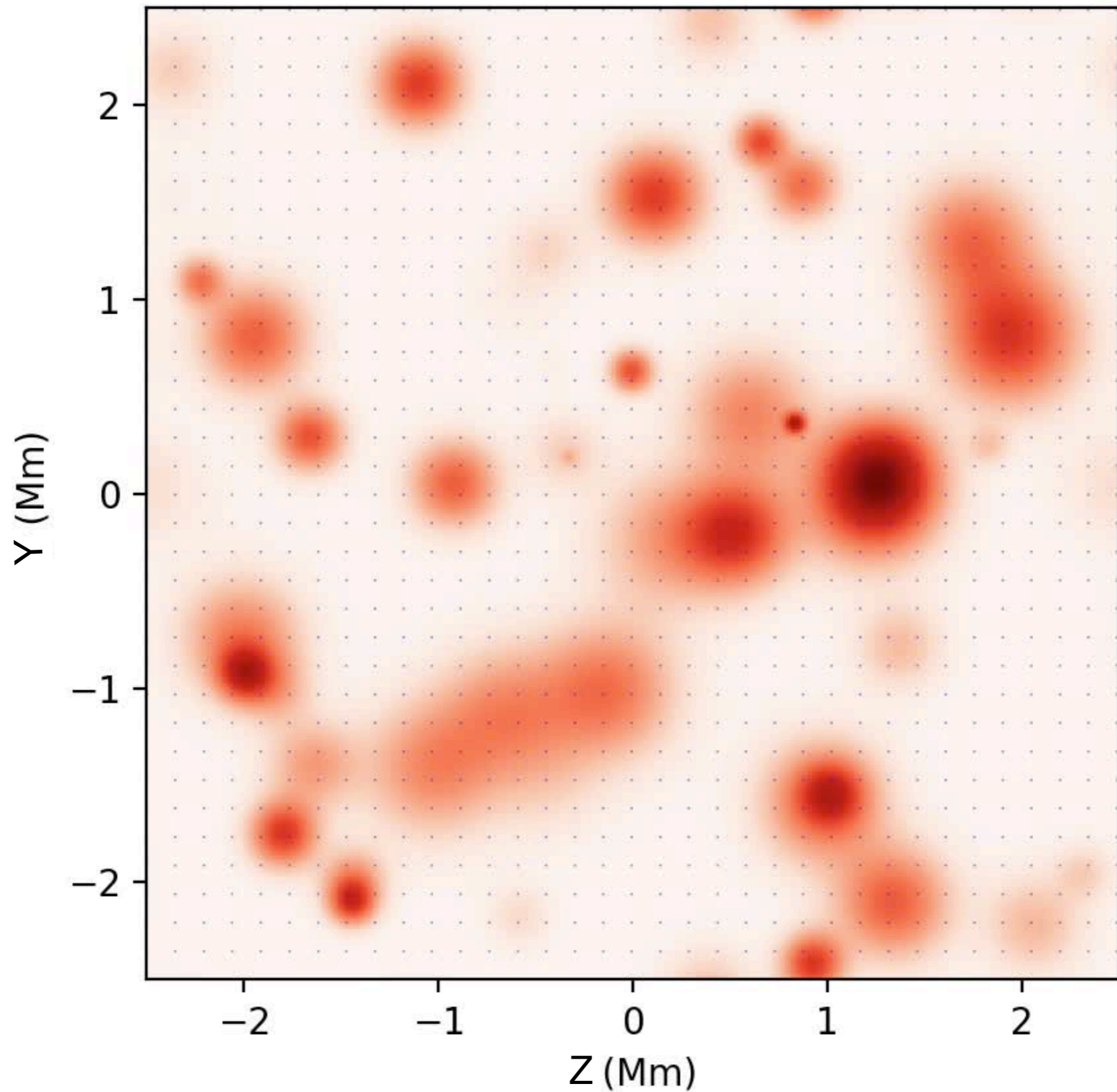


**Turbulence is
generated by
unidirectionally
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(Magyar, 2017 &
2019)**

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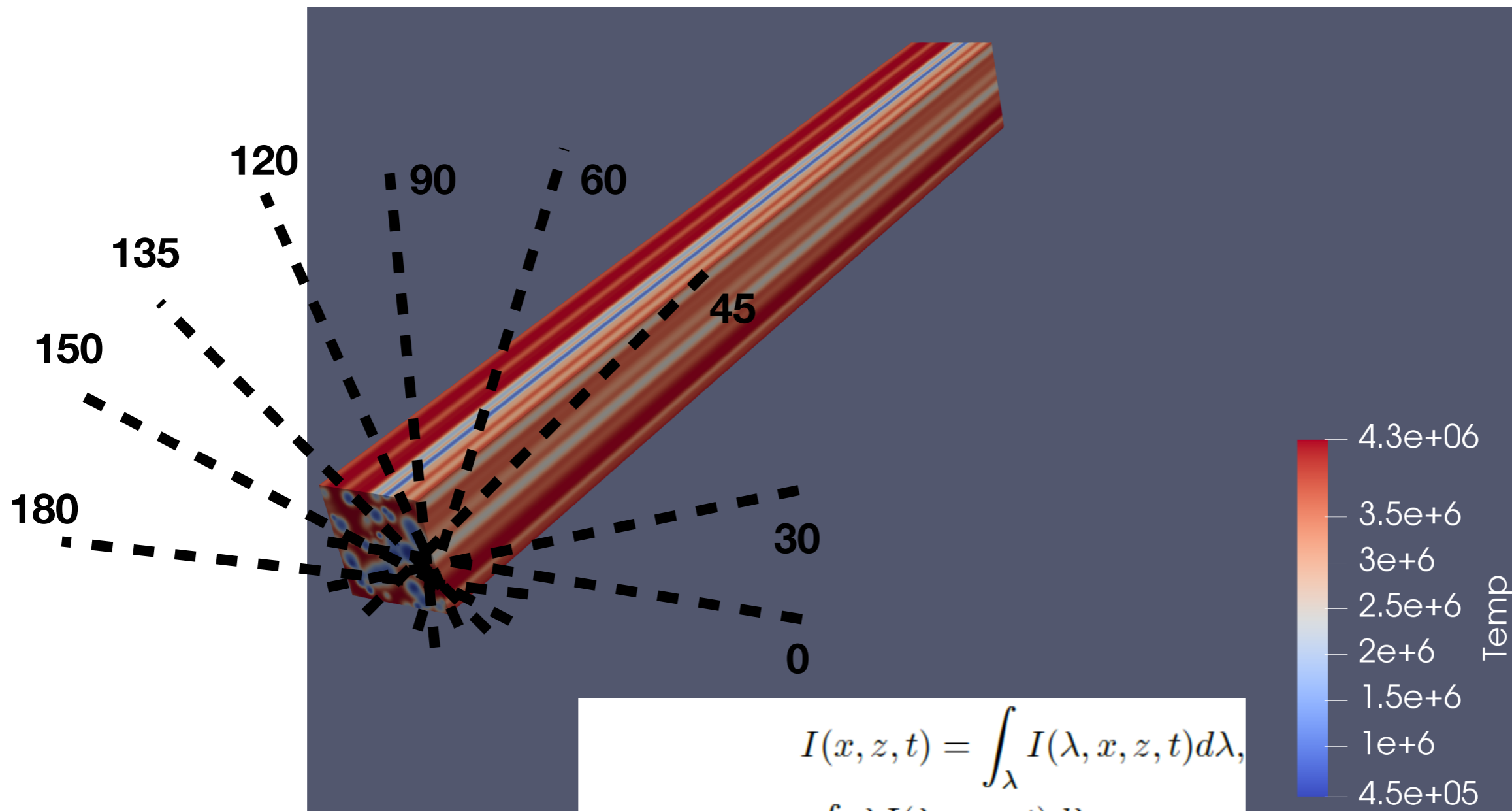
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Forward modeling with FoMo for Fe XIII (10749 Å)

Twelve different line-of-sights perpendicular to background magnetic field are chosen for the analysis

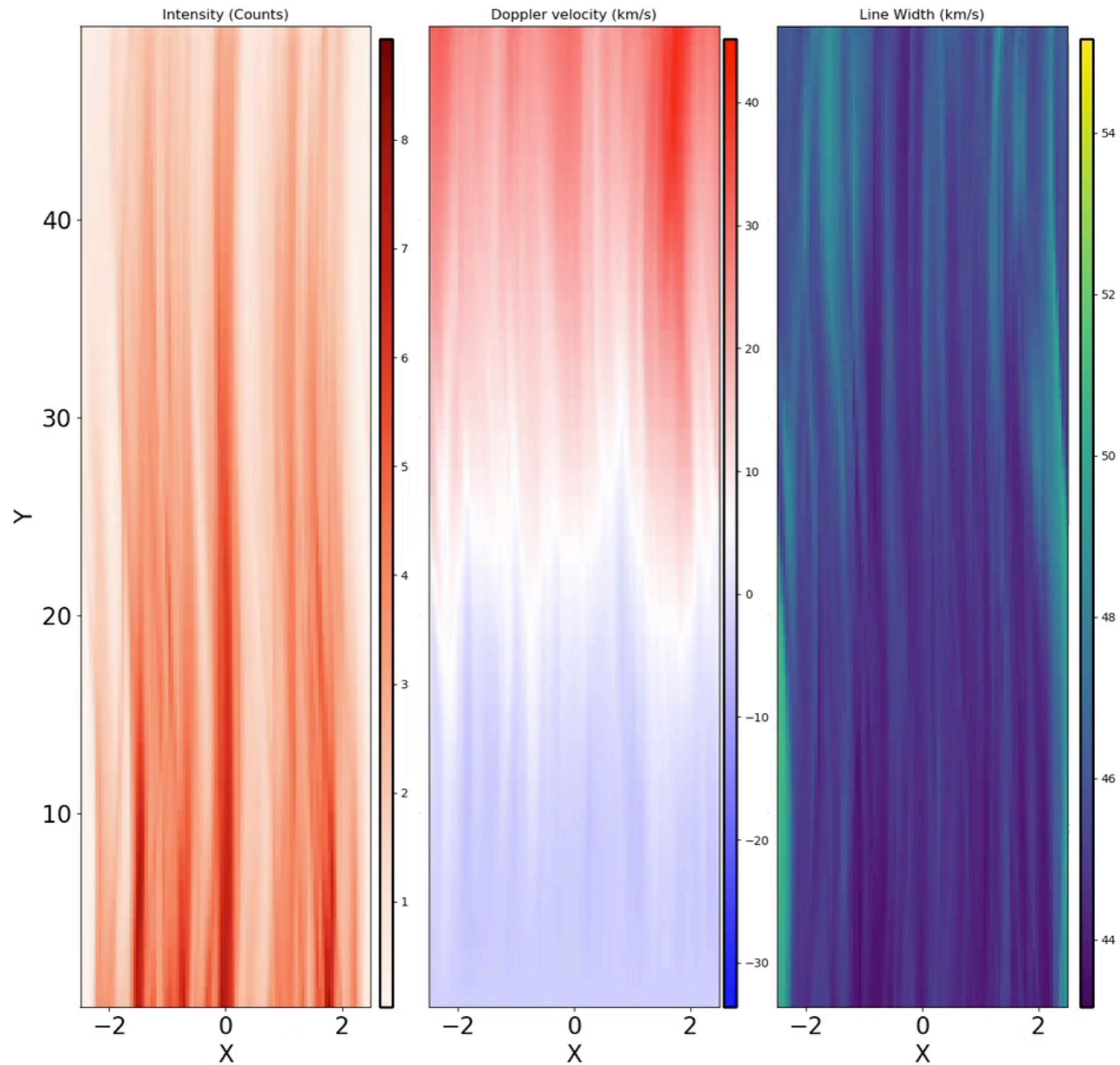


$$I(x, z, t) = \int_{\lambda} I(\lambda, x, z, t) d\lambda,$$
$$\lambda_D(x, z, t) = \frac{\int_{\lambda} \lambda I(\lambda, x, z, t) d\lambda}{\int_{\lambda} I(\lambda, x, z, t) d\lambda} - \lambda_{mean},$$
$$\sigma(x, z, t) = \sqrt{\frac{\int_{\lambda} (\lambda - \lambda_D)^2 I(\lambda, x, z, t) d\lambda}{\int_{\lambda} I(\lambda, x, z, t) d\lambda}}.$$

Application fo FoMo for Fe XIII (10749 A)

LOS = 0 degree

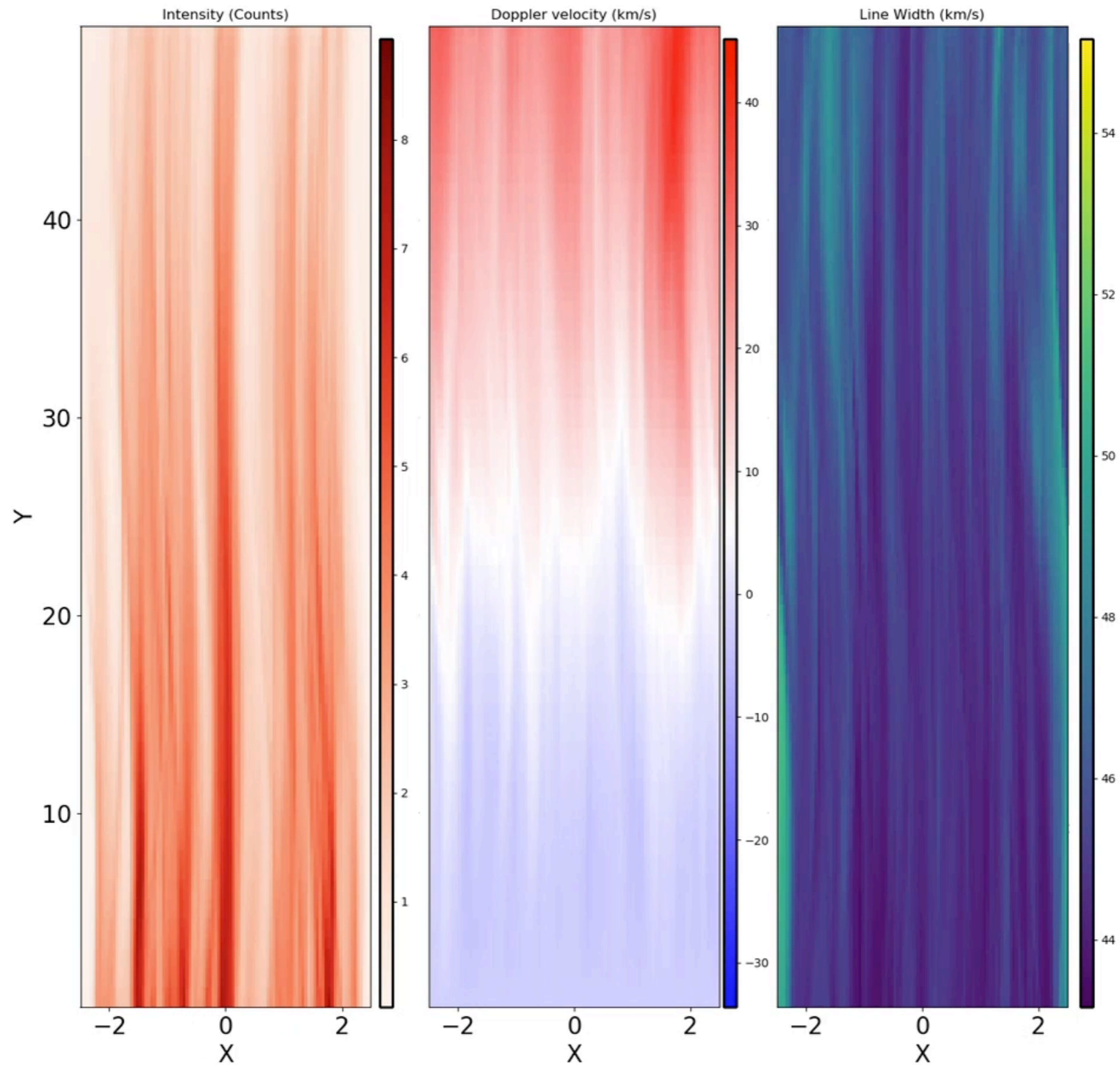
$v_{\text{rms}}=15$ km/s



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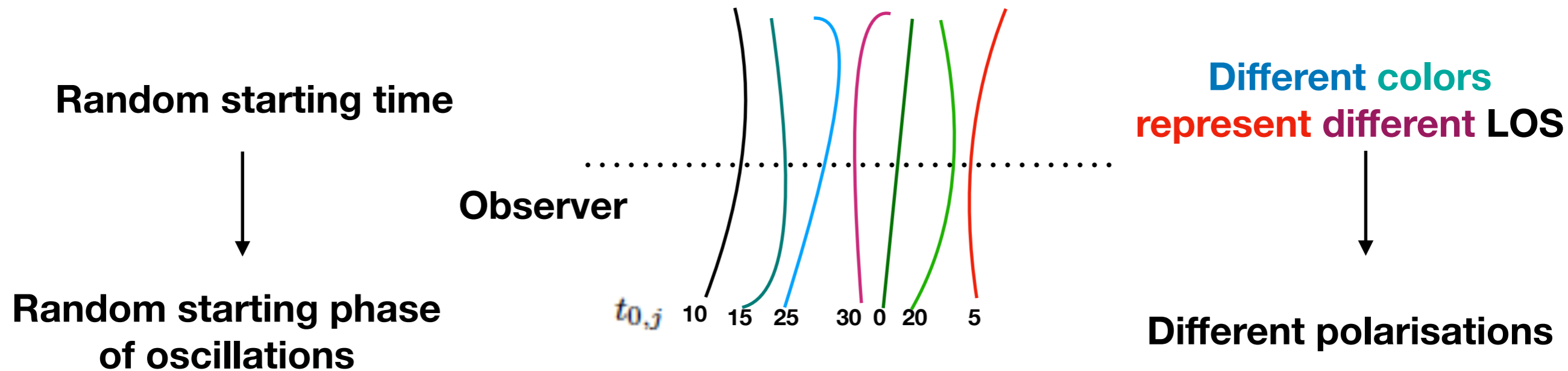
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Choosing random segments

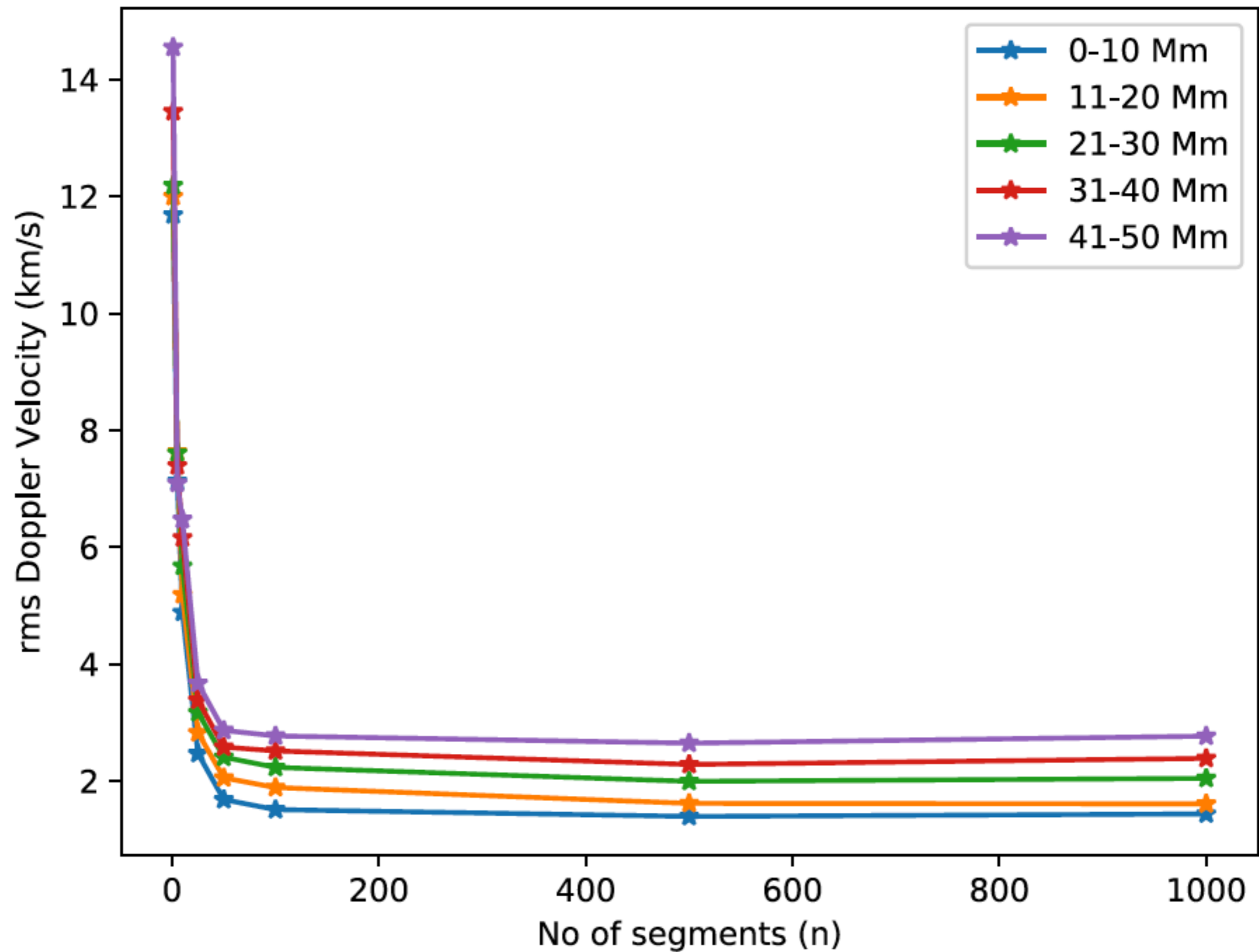
We chose 100 random segments and add their emission spectra

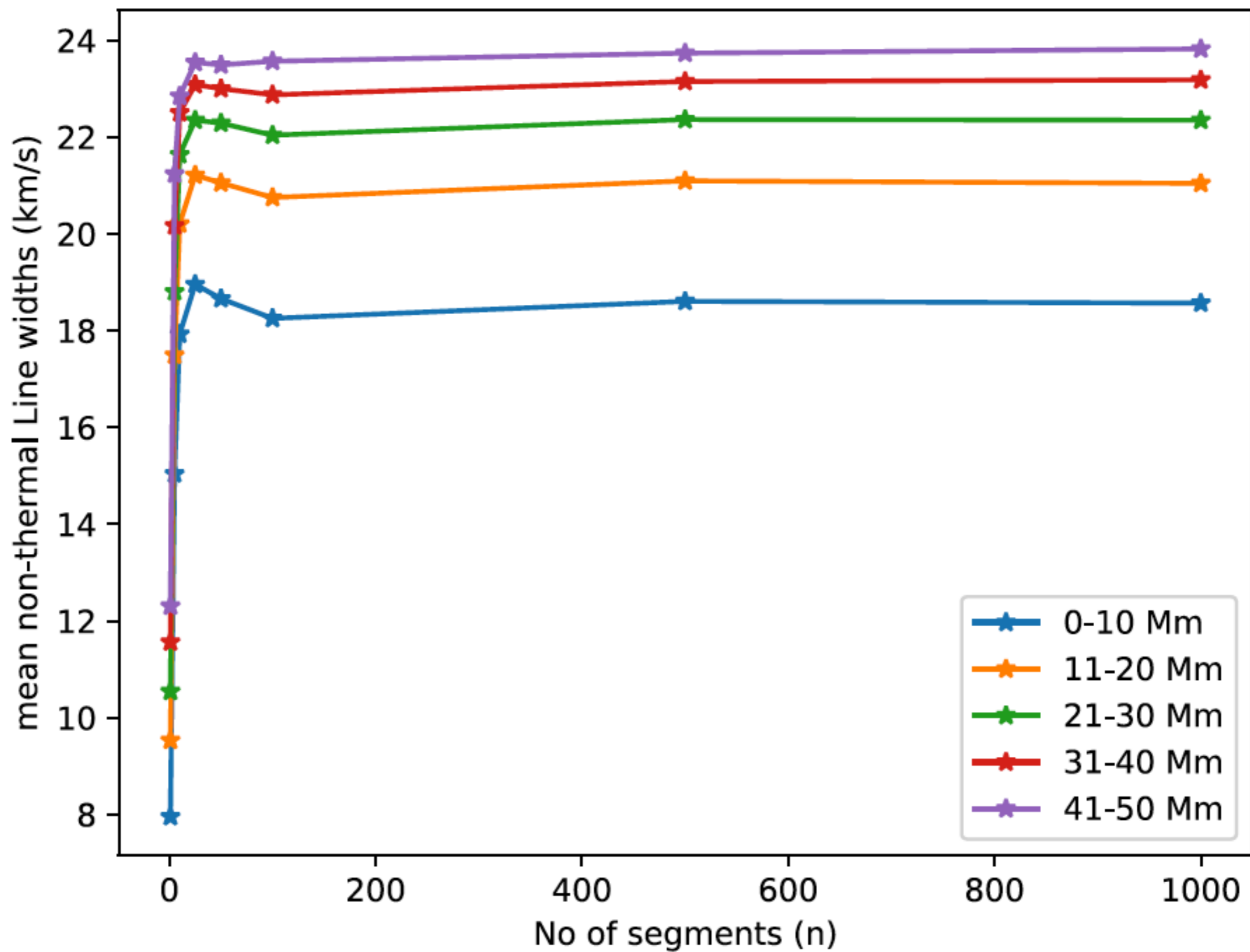
$$\epsilon(\lambda, x, z, t_n) = \sum_{j=1}^{100} \epsilon(\lambda, x, z, LOS_j, t_{0,j} + n\delta t); n \rightarrow 1 - 20$$



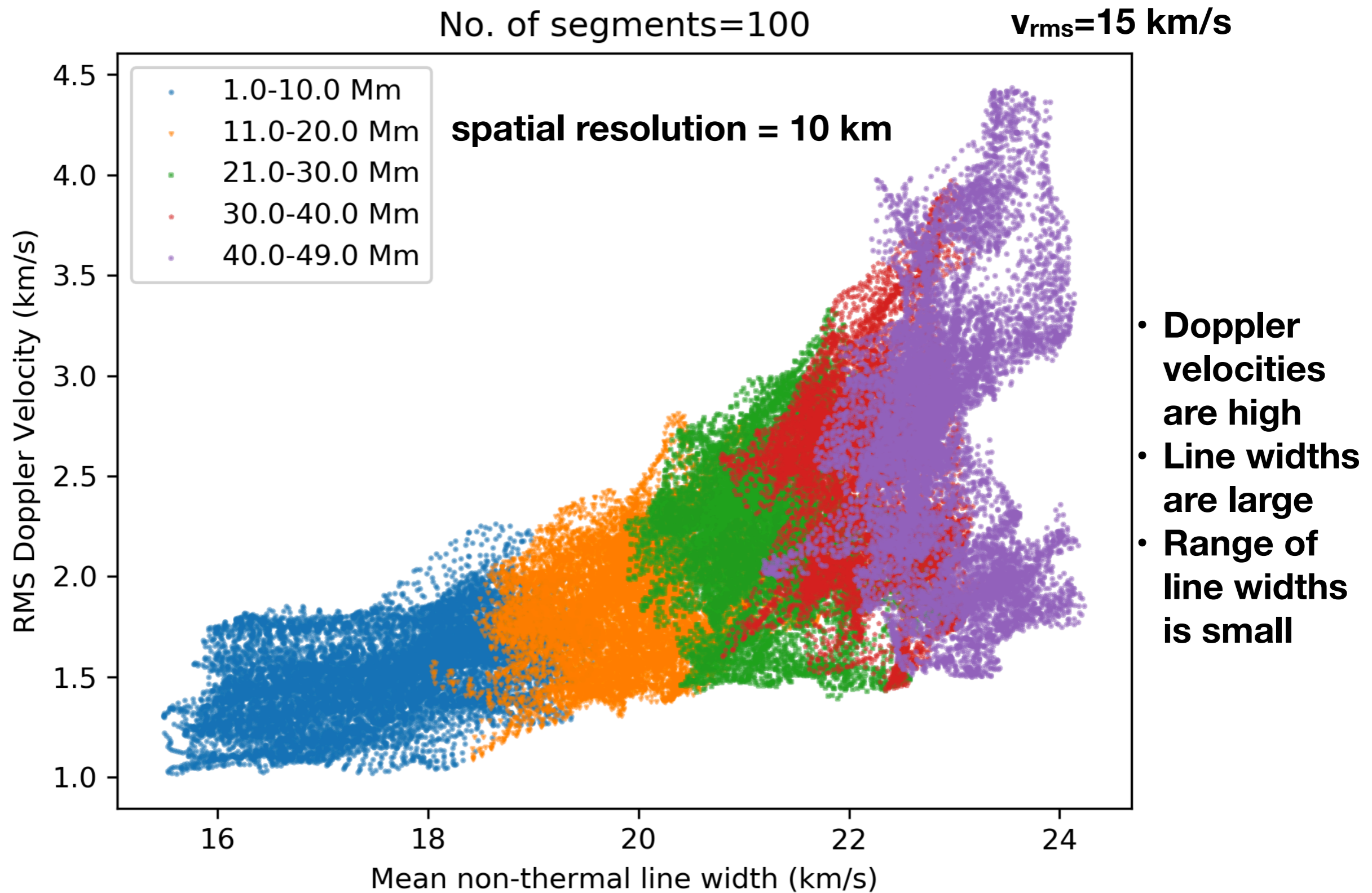
If n is large, allowed values of $t_{0,j}$ will be less

If n is less, allowed values of $t_{0,j}$ will be large but averaging due to superposition will be less





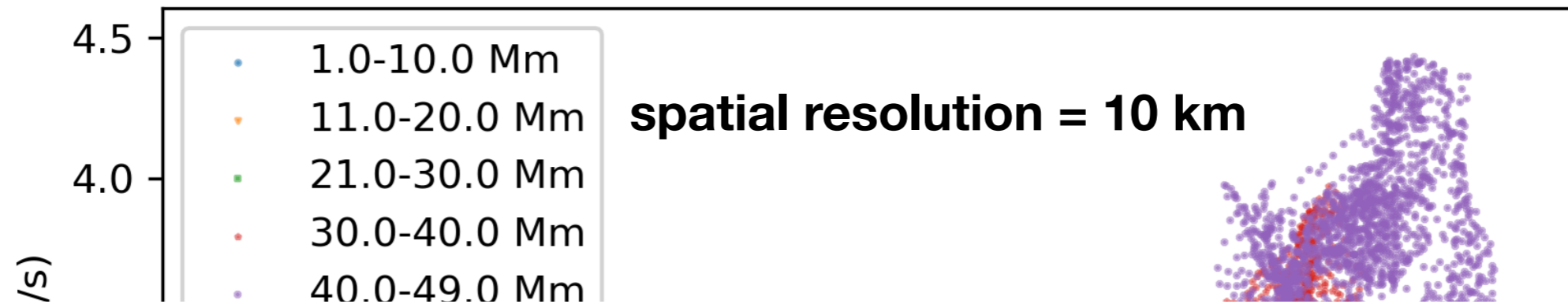
Wedge-shape correlation



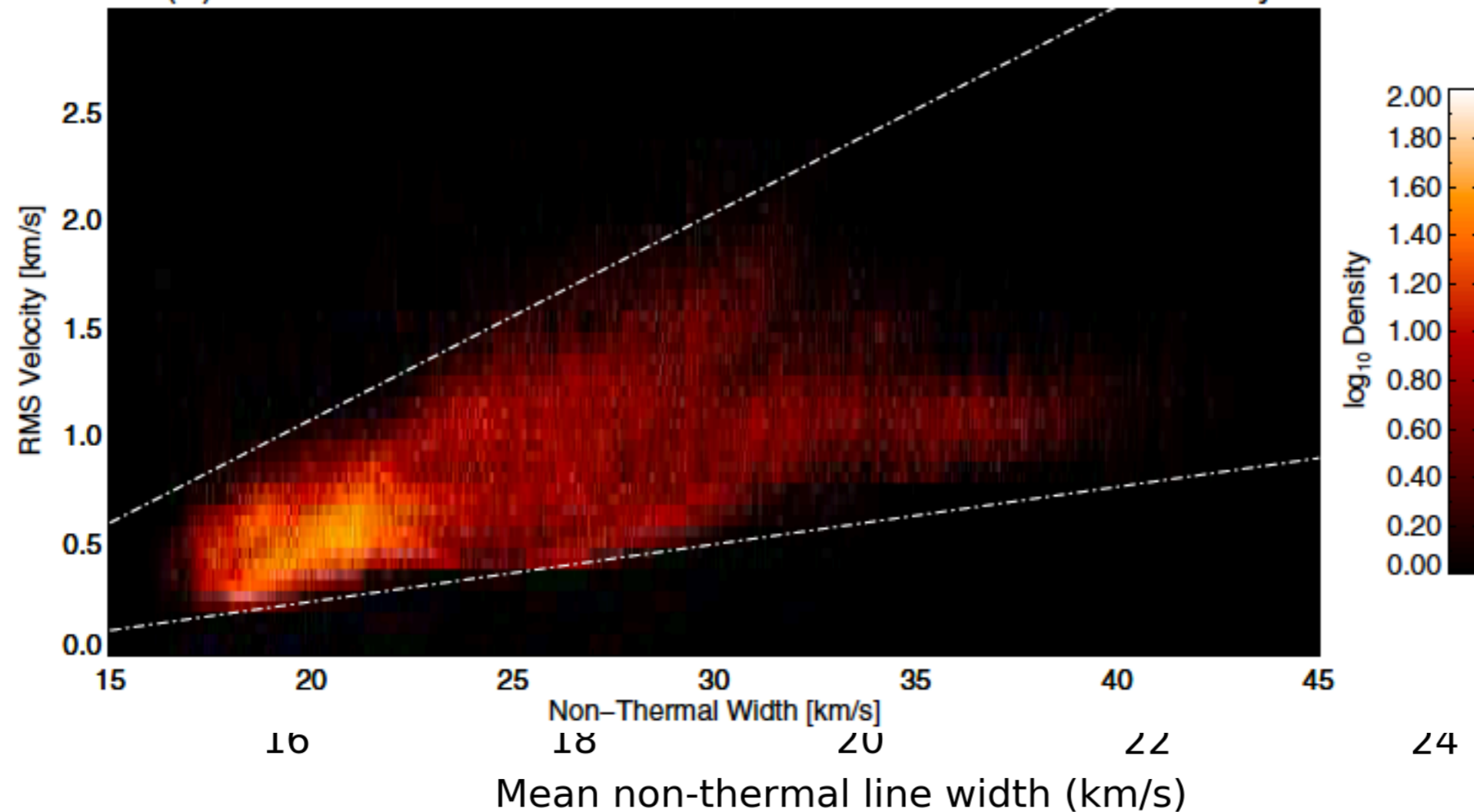
Wedge-shape correlation

No. of segments=100

$v_{\text{rms}}=15 \text{ km/s}$

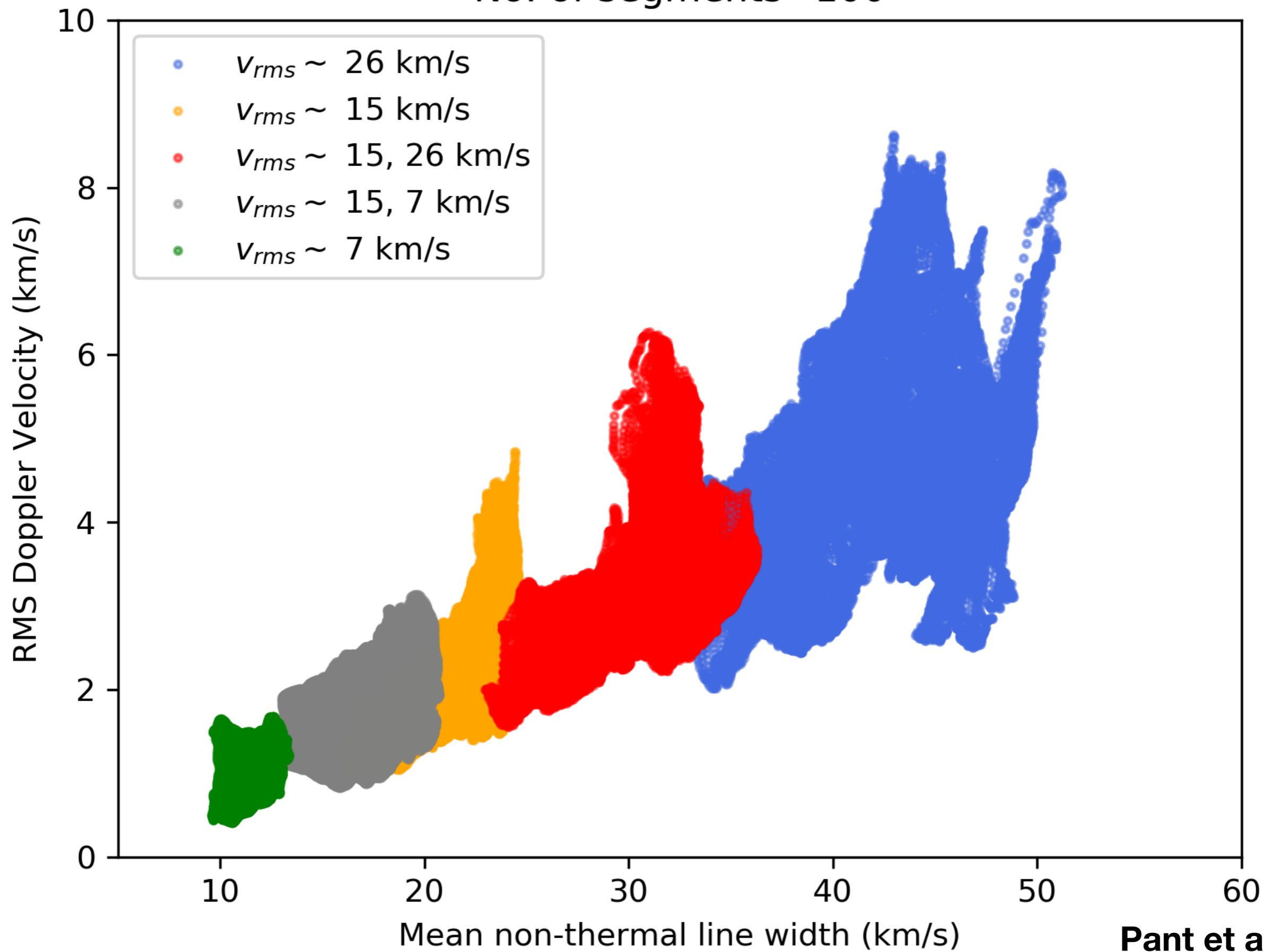


(D) MLSO/CoMP Fe XIII 10746Å Non-Thermal Width Vs. RMS Velocity

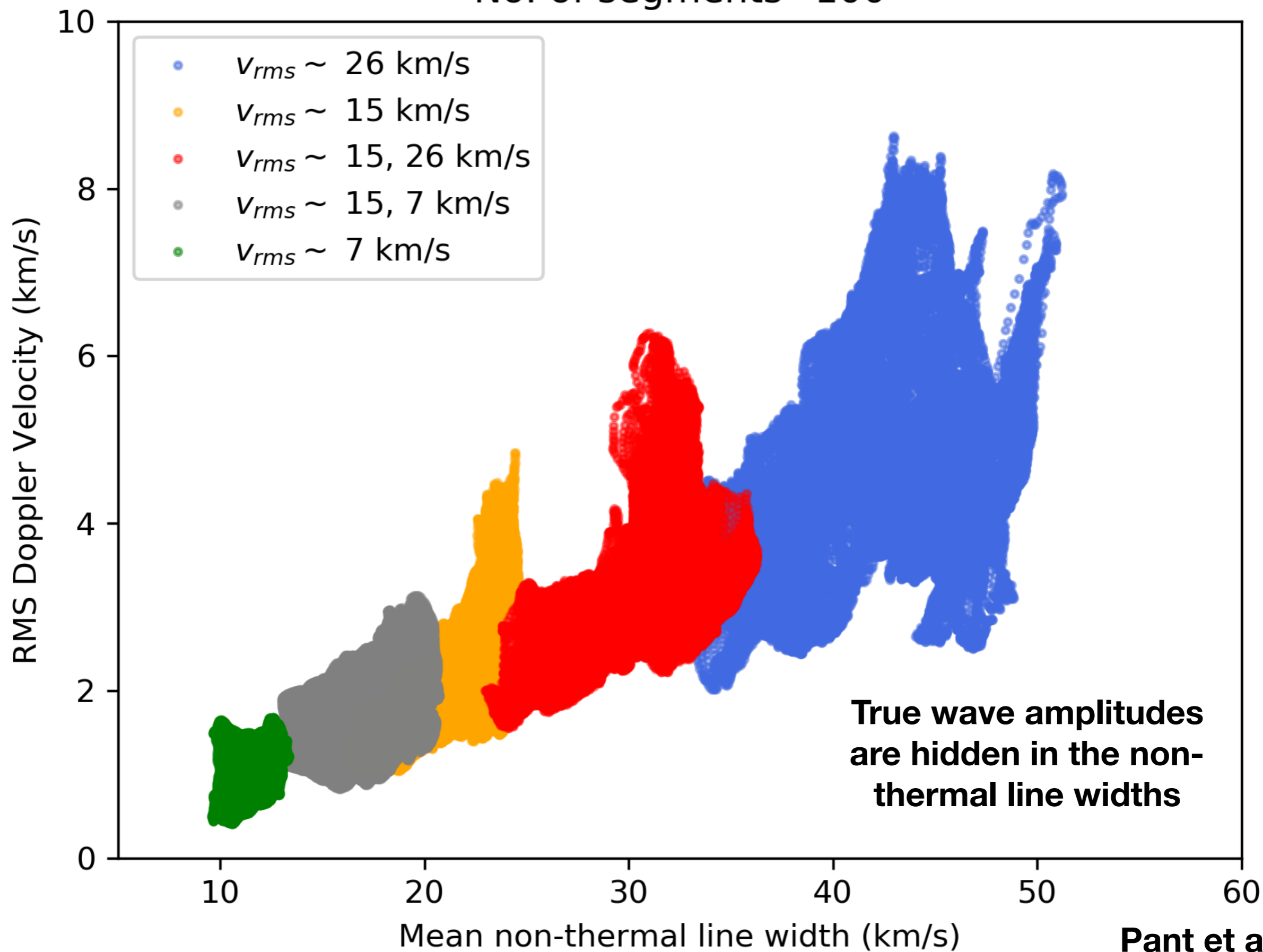


**Doppler
velocities
are high
Line widths
are large
Range of
line widths
is small**

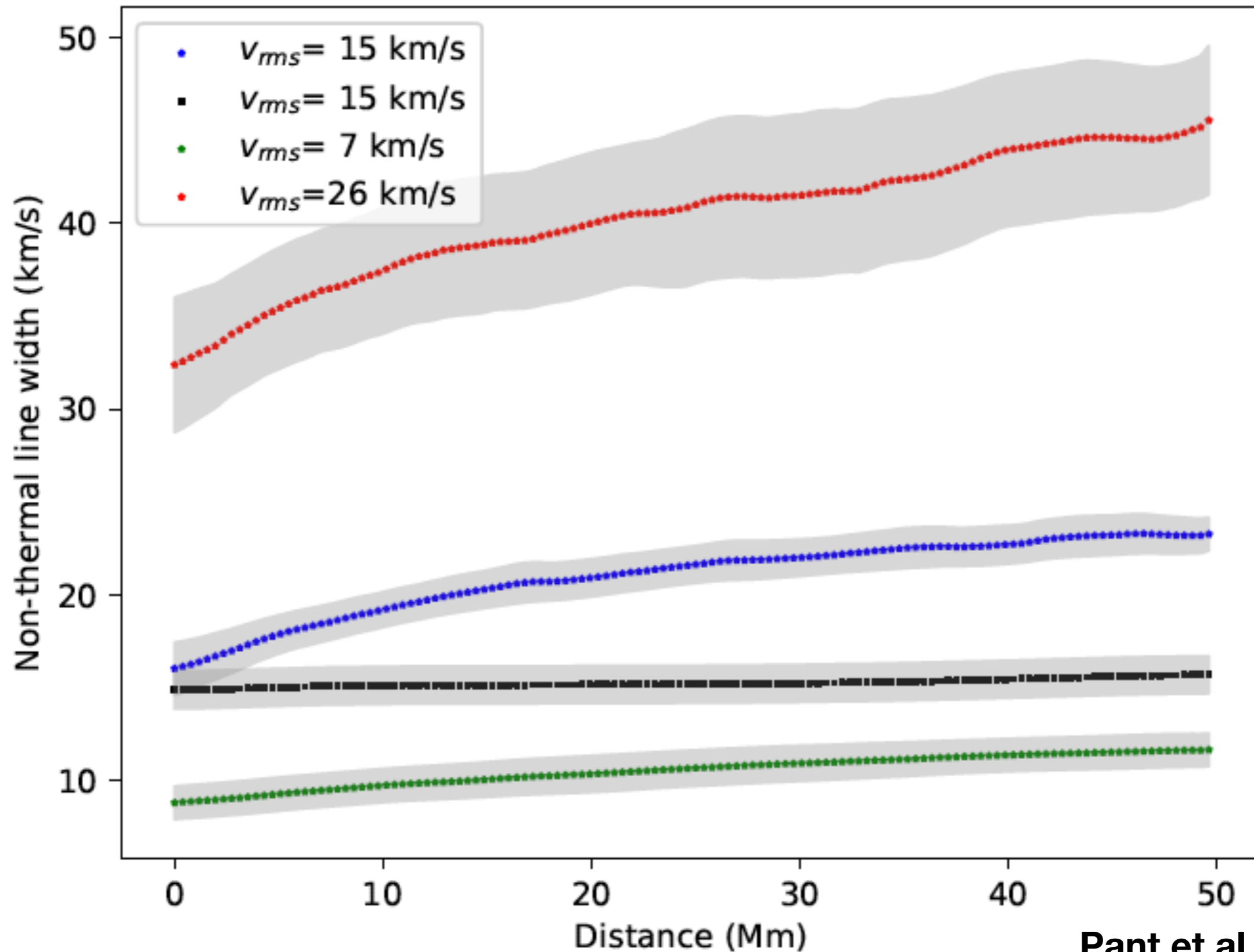
No. of segments=100



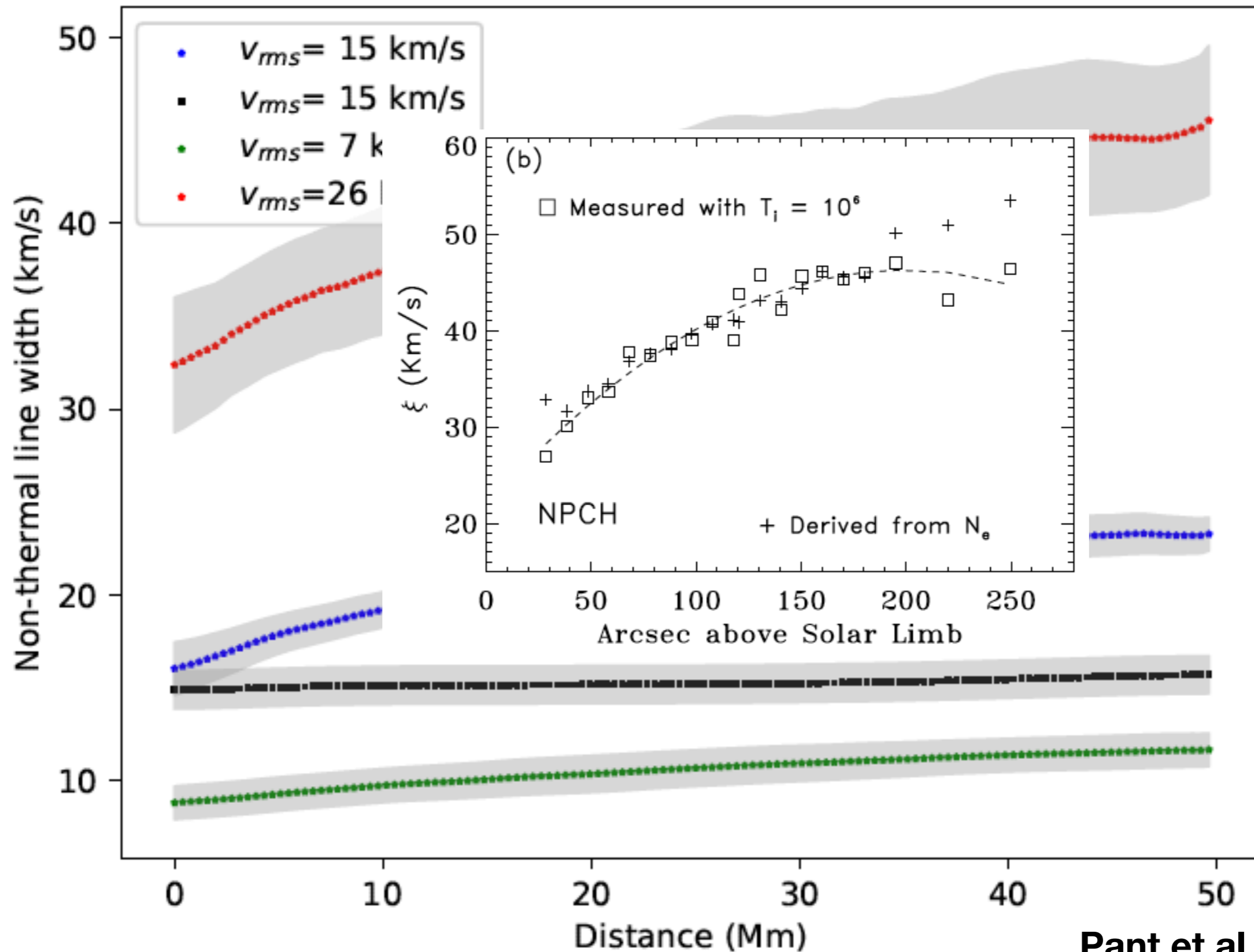
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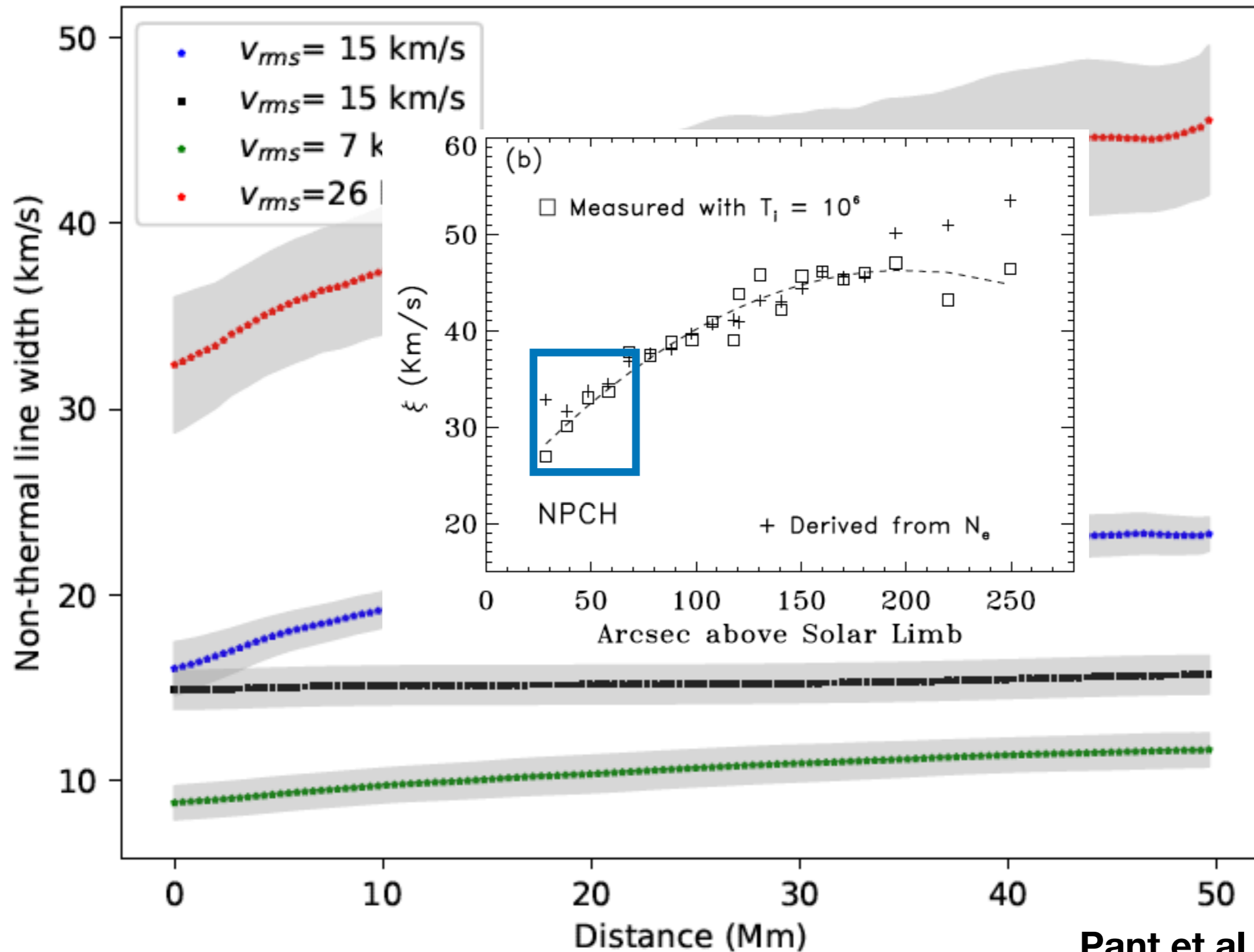
Variation of line widths with height



Variation of line widths with height



Variation of line widths with height



Energy estimates

MHD simulation

Energy flux

14 W/m²
51 W/m²
213 W/m²

Forward modelling

$\rho v_{\text{rms}}^2 v_A$

0.04 W/m²
0.21 W/m²
1.08 W/m²

Energy estimates

MHD simulation		Forward modelling	
Energy flux	14 W/m ²	$\rho v_{\text{rms}}^2 v_A$	0.04 W/m ²
	51 W/m ²		0.21 W/m ²
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- Uniturbulence model **can explain the energy discrepancy of 2-3 orders of magnitude observed in the CoMP**
- CoMP suffers from coarse spatial resolution and LOS integration thus energy estimated from the Doppler velocity measurements is underestimated

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In optically thin plasma, LOS superposition affects the observed wave amplitudes

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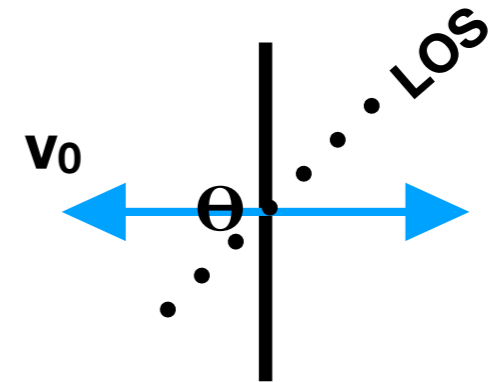
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True wave amplitudes are hidden in the non-thermal line widths

Relation between non thermal line width and rms velocity

$$\langle G(v, t') \rangle_t = \int_0^t \frac{1}{t\sigma\sqrt{2\pi}} \exp\left(-\frac{(v - v_0 \cos(\omega t'))^2}{2\sigma^2}\right) dt'$$

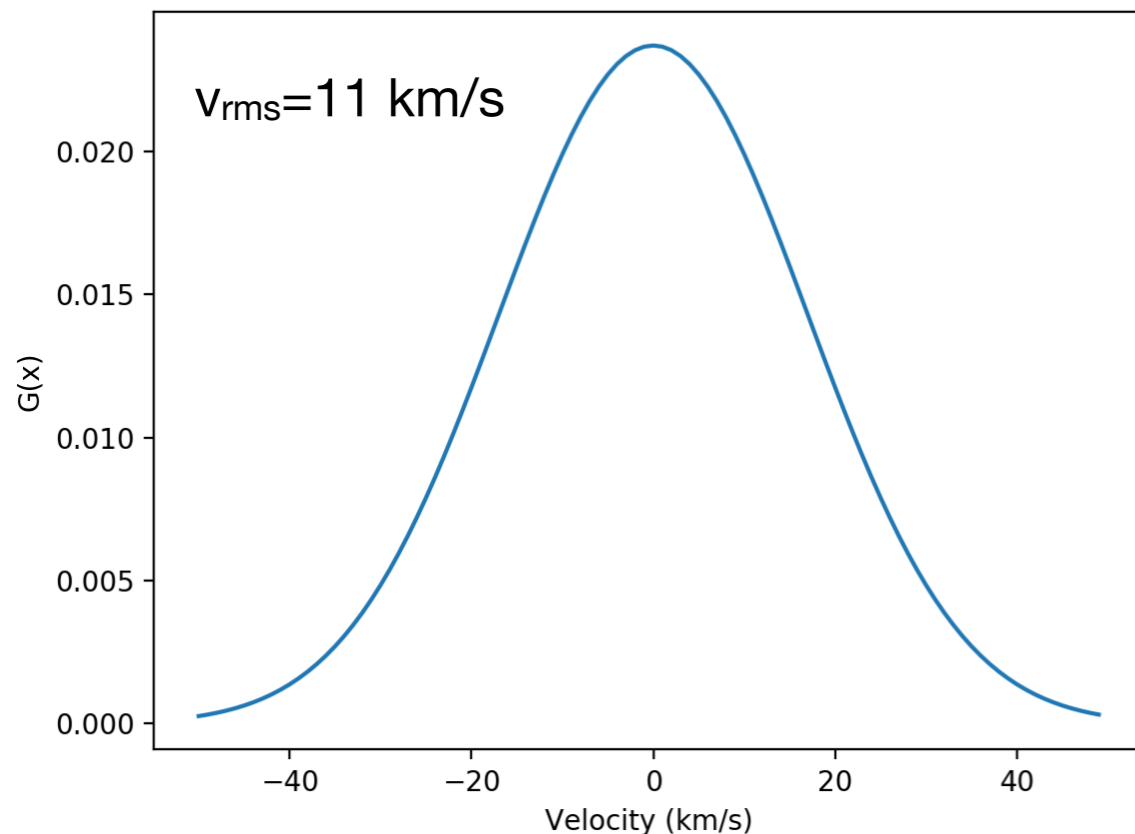


$$\sigma_{nt} \sim \sqrt{2} v_{rms}$$

$$\langle G(v, \theta', t') \rangle_{t, \theta} = \frac{1}{P\sigma(2\pi)^{3/2}} \int_0^{2\pi} \int_0^P \exp\left(-\frac{(v - v_0 \cos \theta' \cos(\omega t'))^2}{2\sigma^2}\right) dt' d\theta'$$

$$\sigma_{nt} \sim v_{rms}$$

$$\sigma_{nt} = 12 \text{ km/s}$$



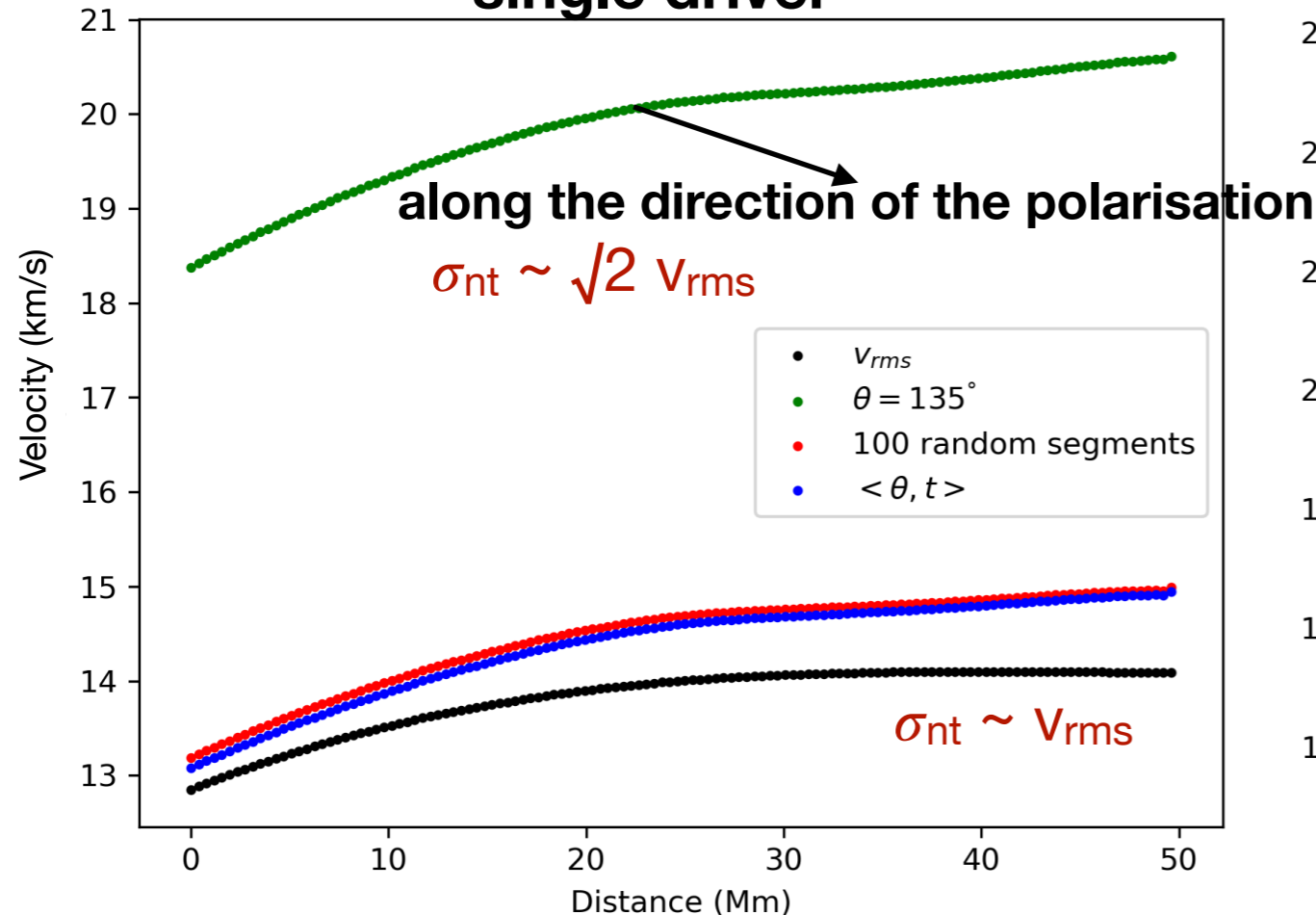
$$v_{rms} = \sqrt{\frac{1}{P} \int_0^P v(t')^2 dt'}$$

Transversely homogeneous MHD simulations

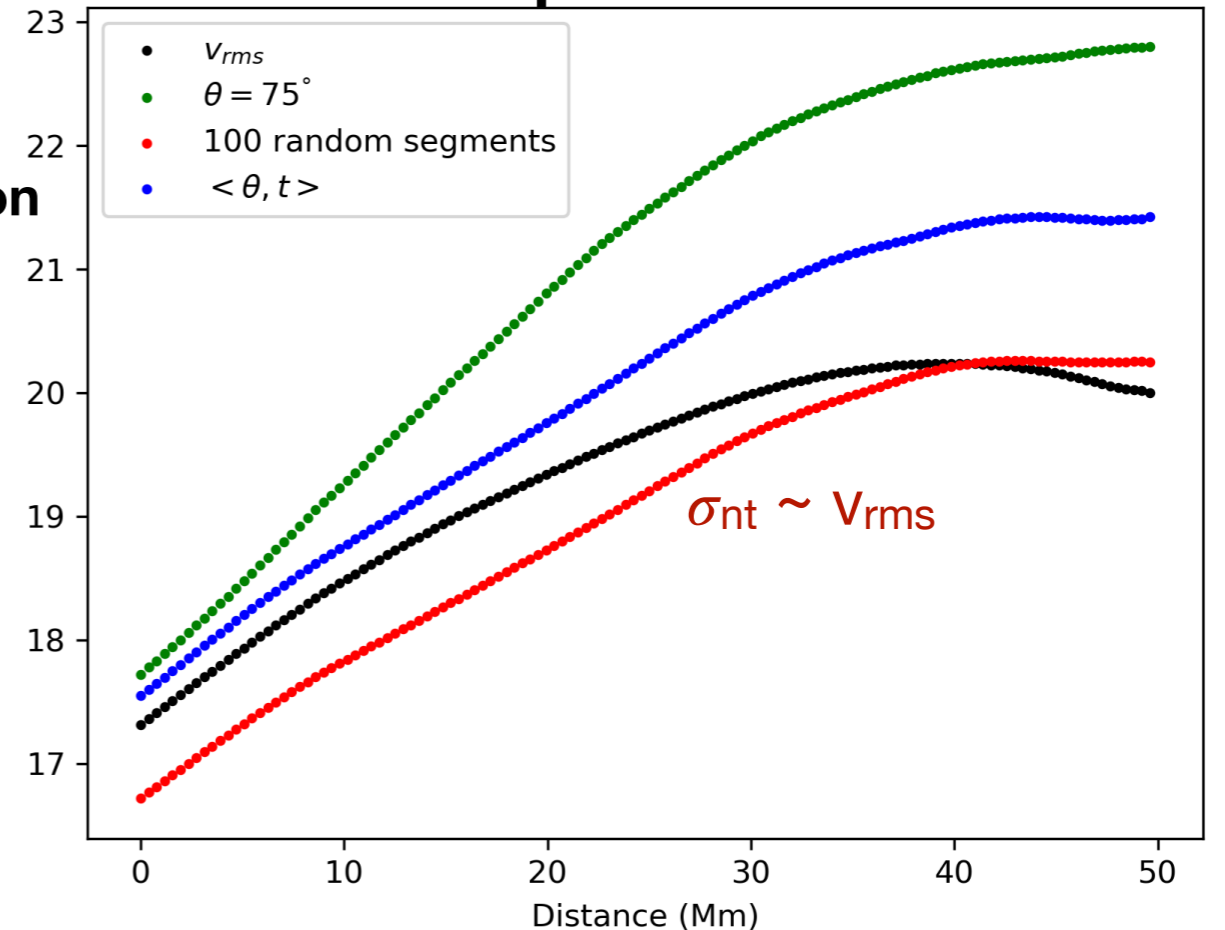
Alfvénic waves are excited at the bottom boundary

Temperature is kept constant around 1.2 MK

single driver



Multiple drivers

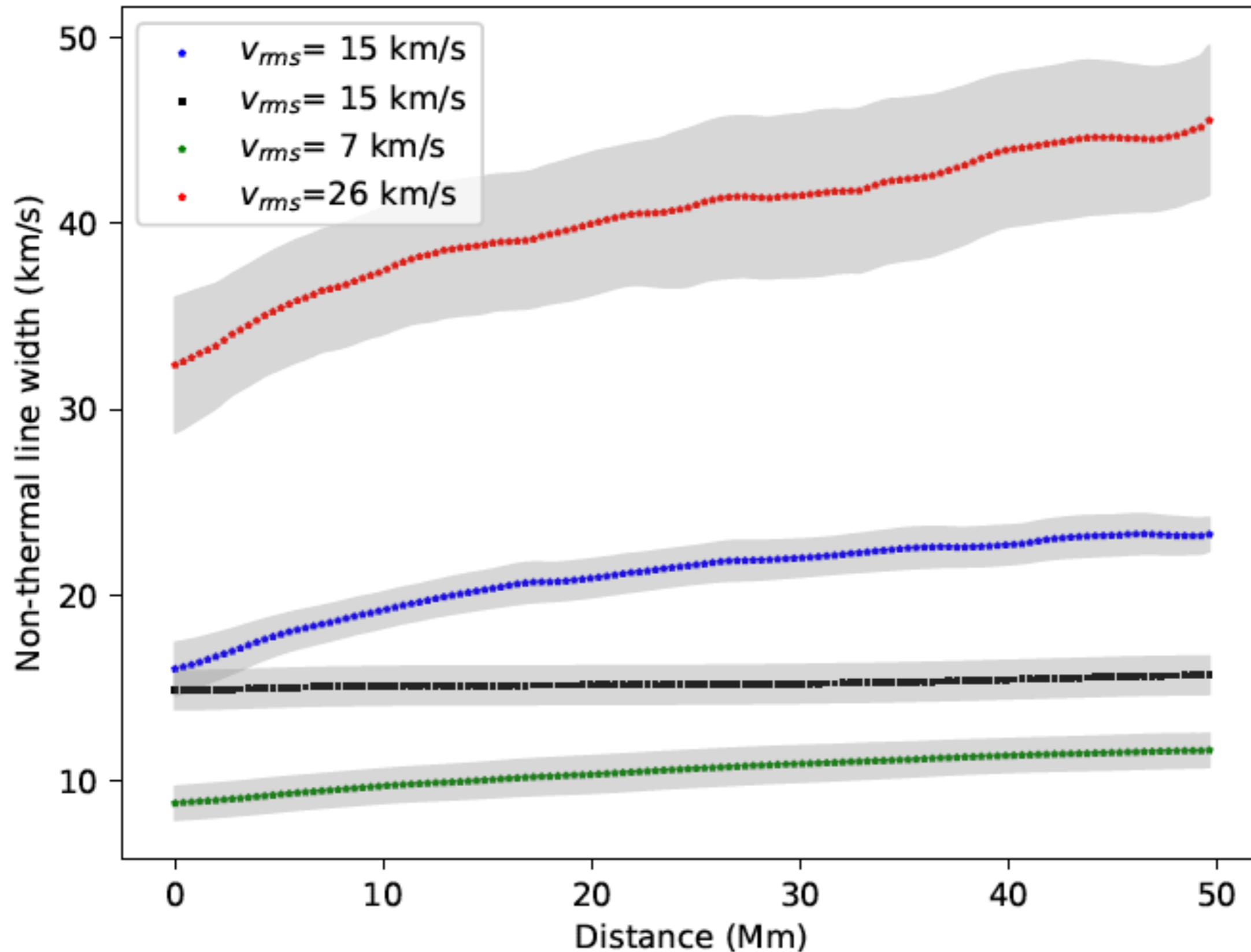


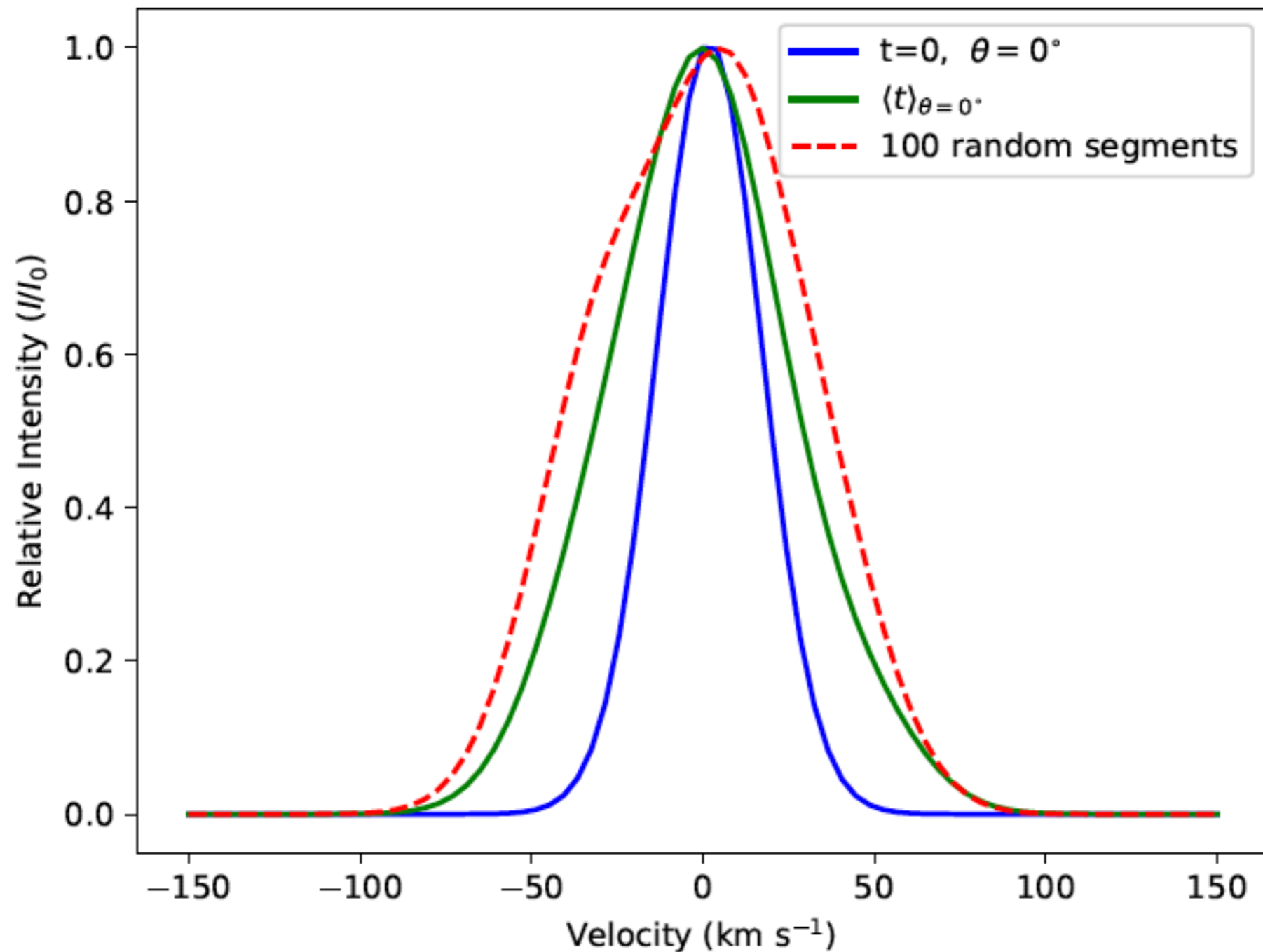
Nonthermal line width is equal to the rms wave velocity for linearly polarised, circularly polarised Alfvén(ic) waves

$$E = \rho v_{rms}^2 v_A = \rho \sigma_{nt}^2 v_A$$

$$E = \rho v_{rms}^2 v_A = \rho \sigma_{nt}^2 v_A / 2$$

Transversely inhomogeneous simulations





**Asymmetric line profile
at a specific instant due to the
choice of random segments**

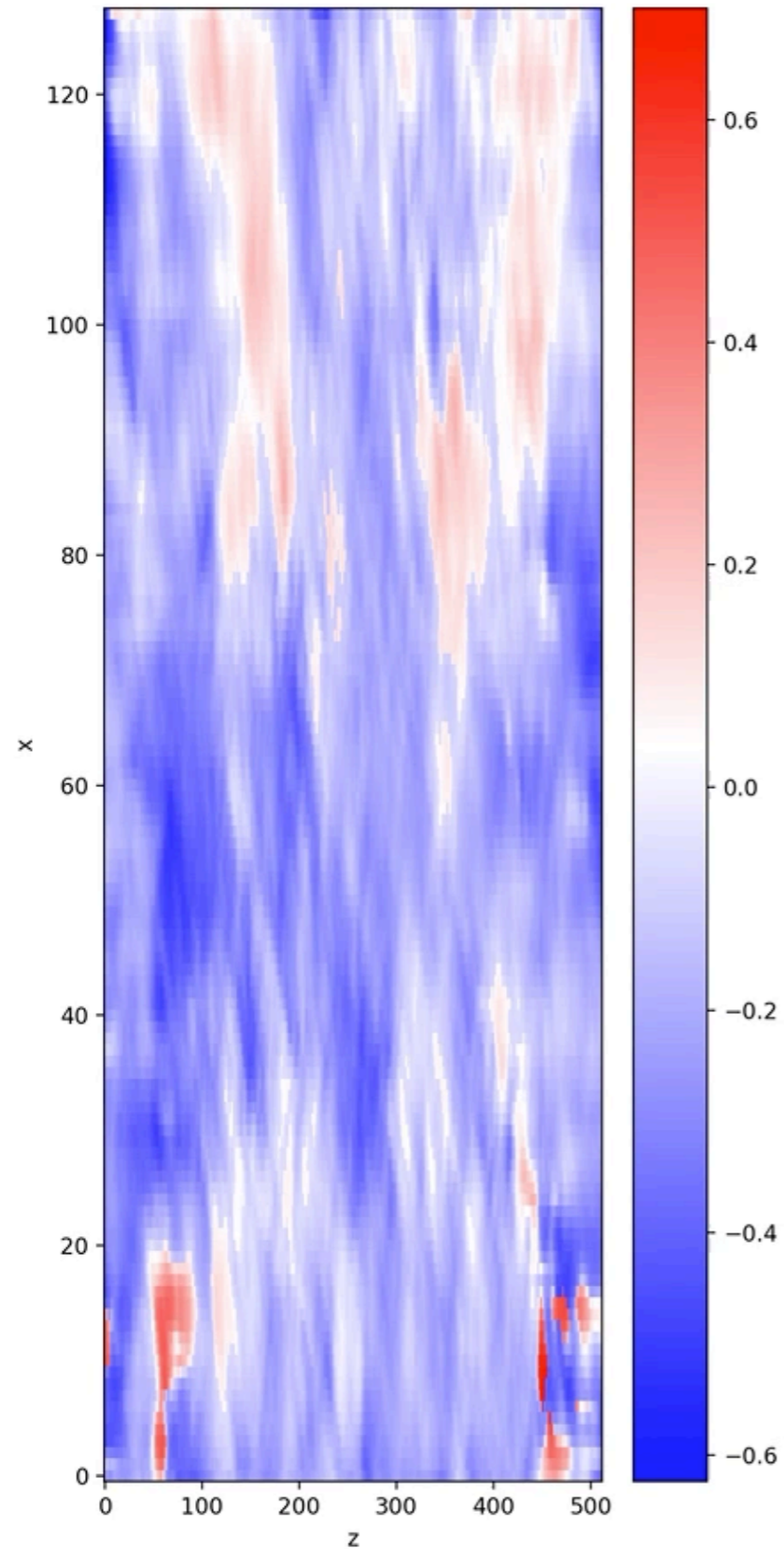
**+
turbulence**

For large wave amplitudes $\rightarrow \sigma_{\text{nt}} > v_{\text{rms}}$

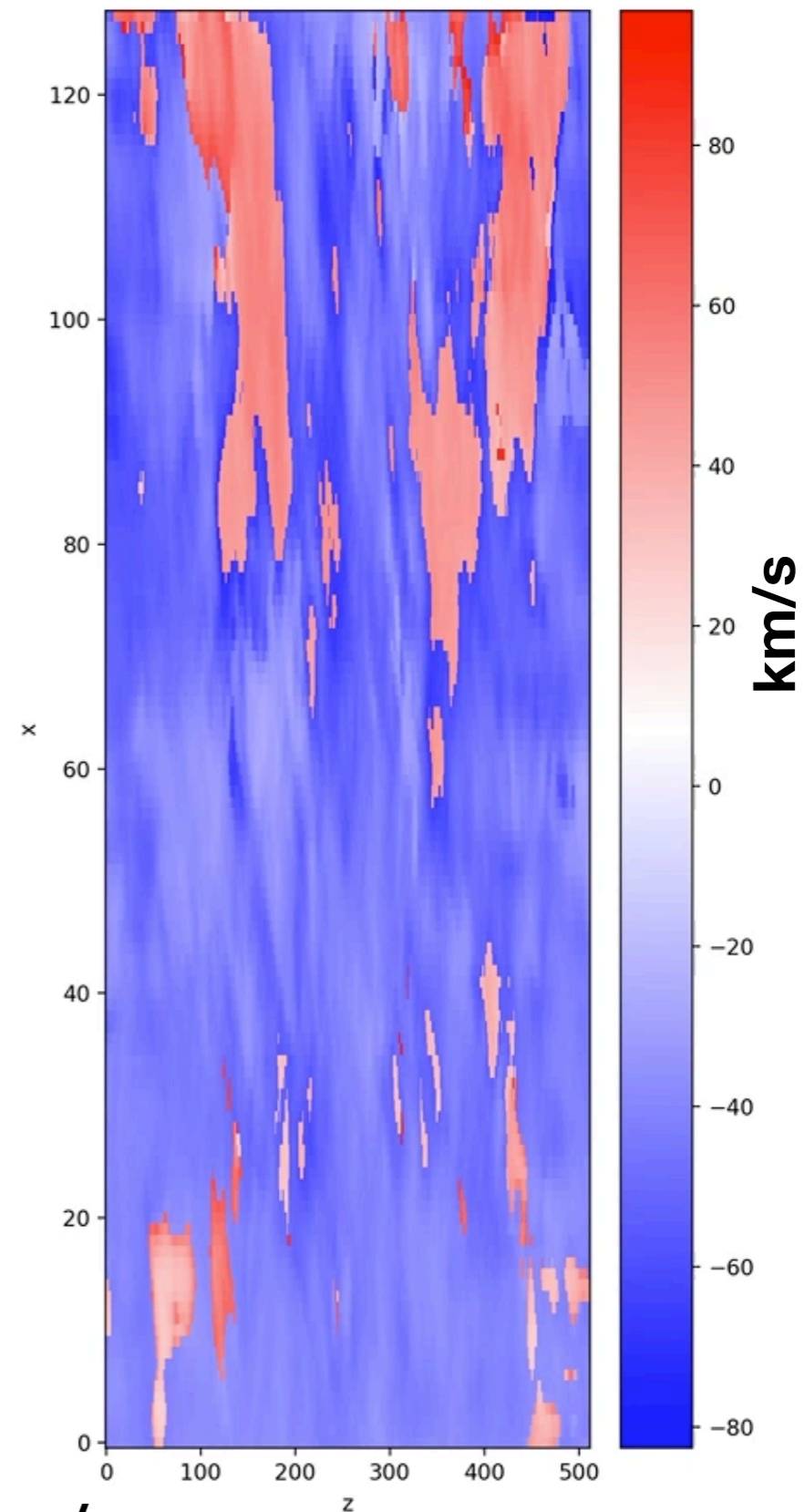
**large non-thermal line
widths**

Propagating spectral line asymmetry

Asymmetry peak



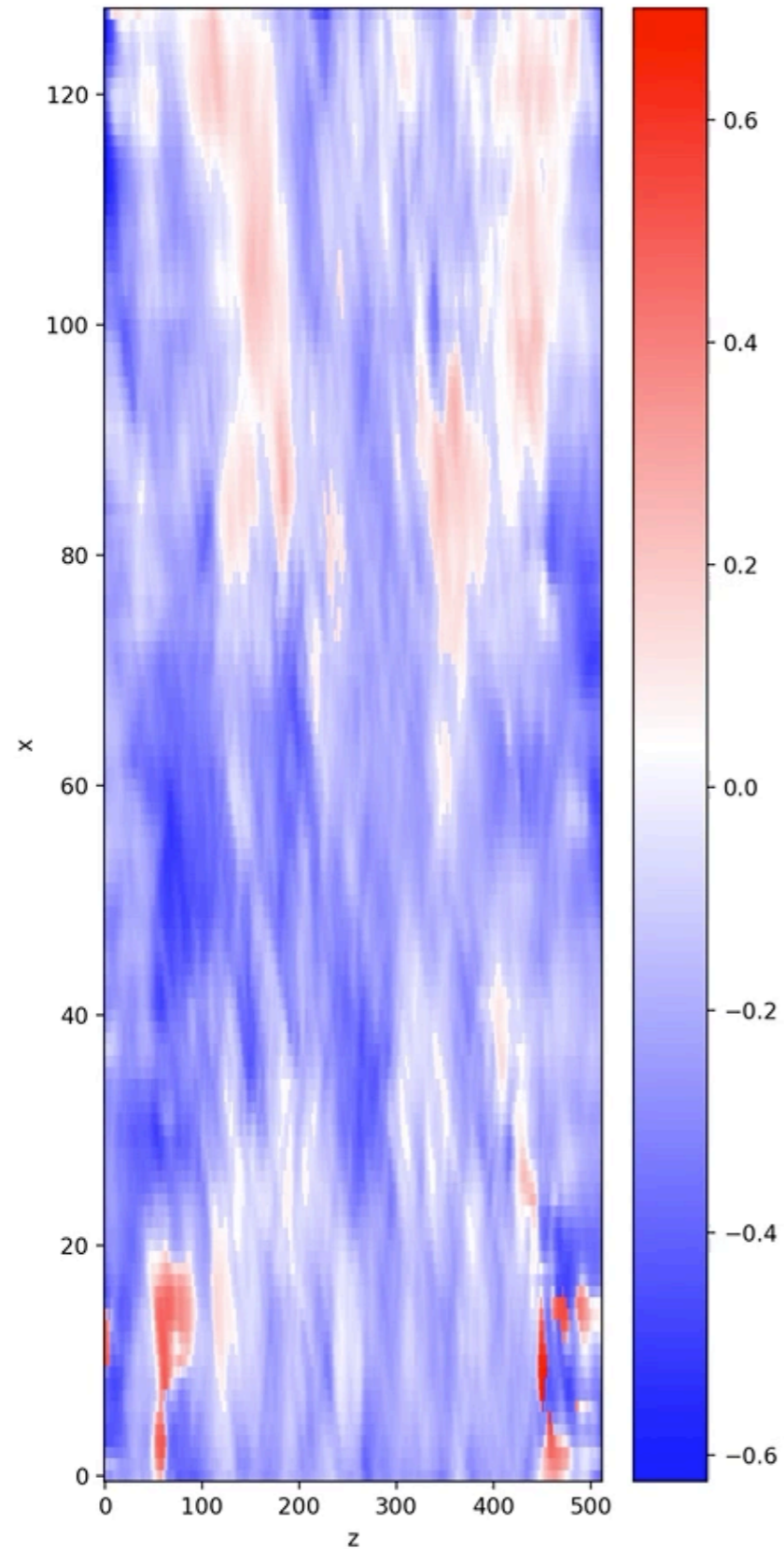
velocity of second component



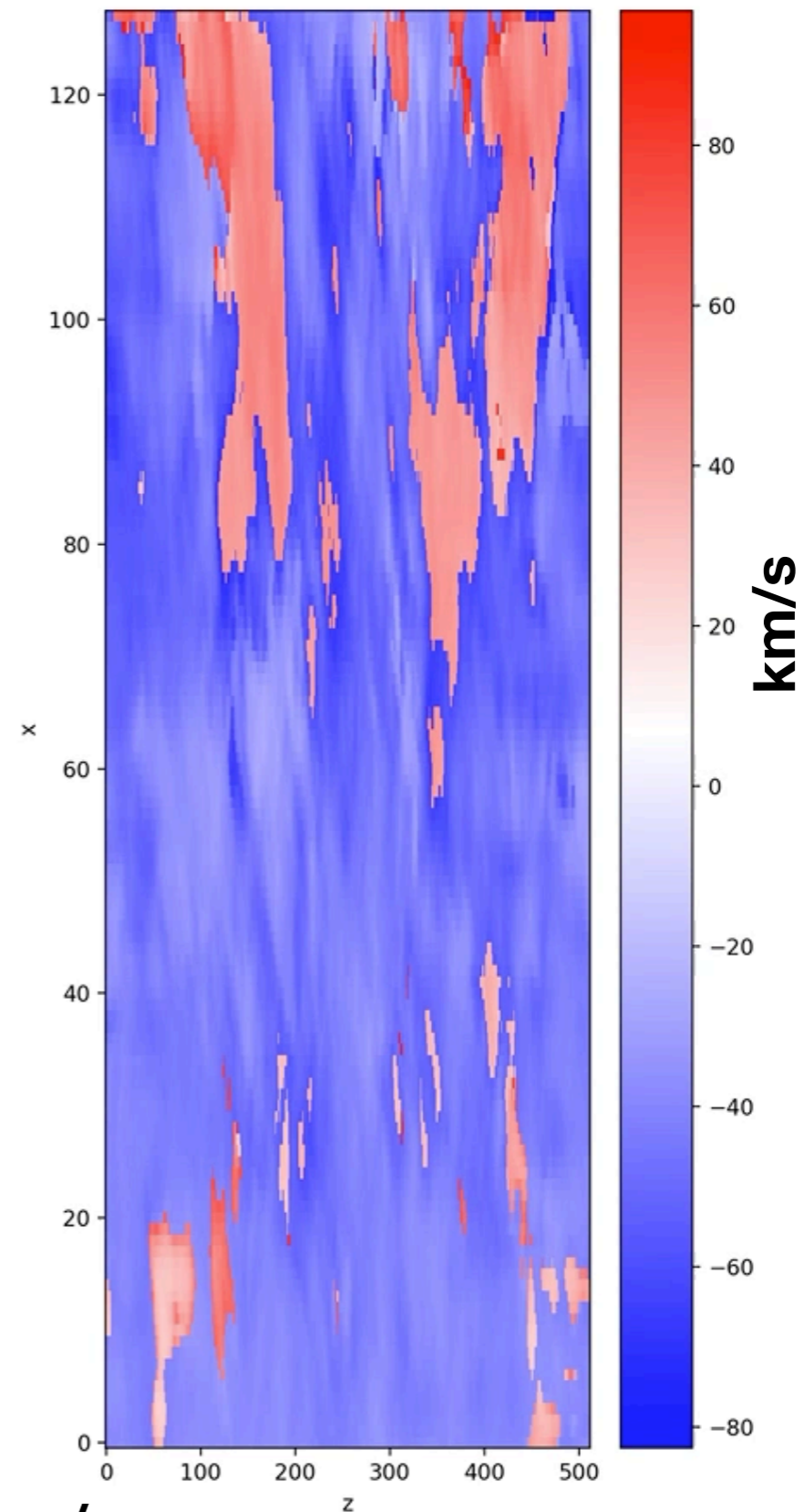
$v_{\text{rms}}=26 \text{ km/s}$

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Conclusions

- Investigated the variation of Doppler velocities with non-thermal line width in gravitationally stratified plasma
- Our model could **reproduce wedge-shape correlation** between line widths and Doppler velocities
- Our model could generate large non-thermal line widths as observed in the COMP data, **without adding any artificial non-thermal line widths**
- Using uniturbulence model we **can explain the energy discrepancy of 2-3 orders of magnitude**
- CoMP suffers from coarse spatial resolution and LOS integration thus energy estimated from the Doppler velocity measurements is underestimated
- **Nonthermal line widths are equal to rms wave velocity** when waves of different polarisations and phases are assumed to occur along the LOS
- Large amplitudes of the Alfvén(ic) waves **can generate asymmetries in the observed spectrum**

To be tested for closed magnetic field regions

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Thank you