Forward-modeling the Ultraviolet signatures of fundamental, standing, fast sausage modes in solar coronal loops

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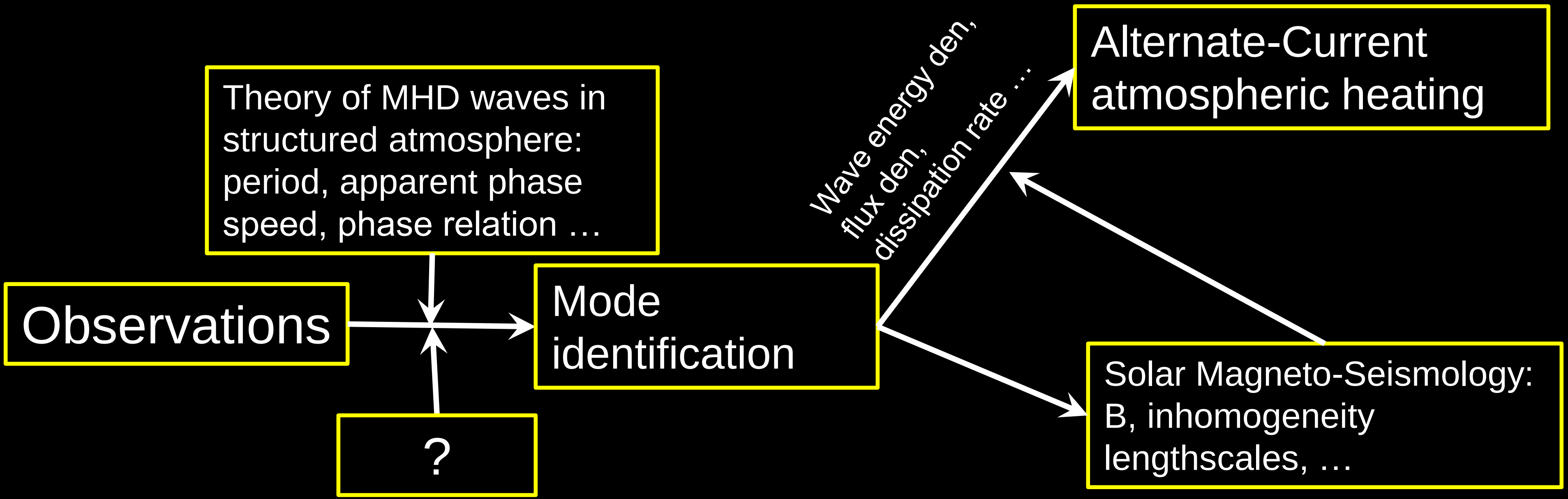
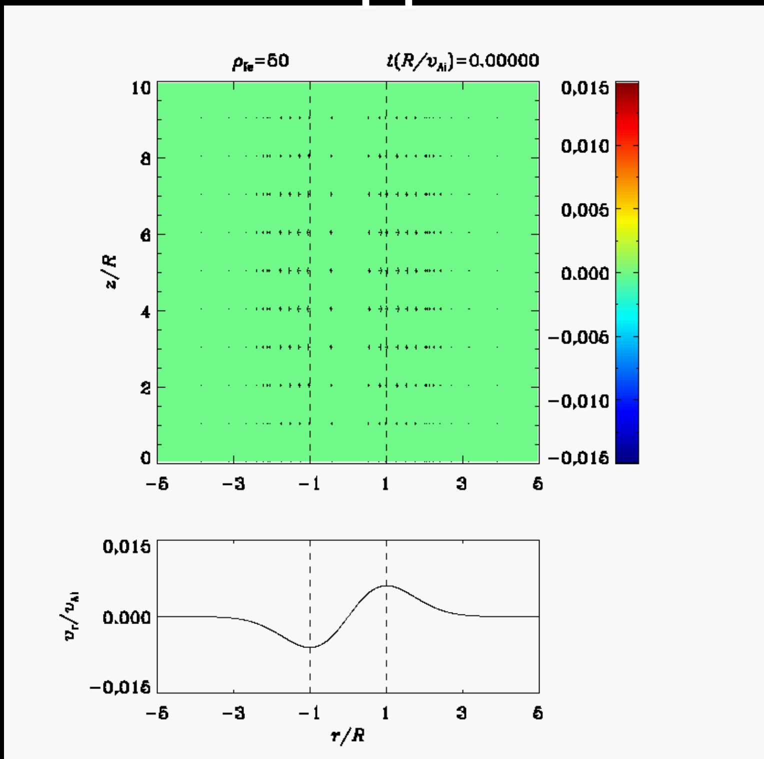
Motivation: why forward modeling?



- ? = forward modeling (atomic physics, LoS geometry, instrumental parameters)
- input: MHD parameters
- Output: synthesized
  - Images → intensity map recorded by an imager
  - Spectral profiles → specific intensity, Doppler shift & broadening…

Standing sausage modes (SSMs) in dense loops

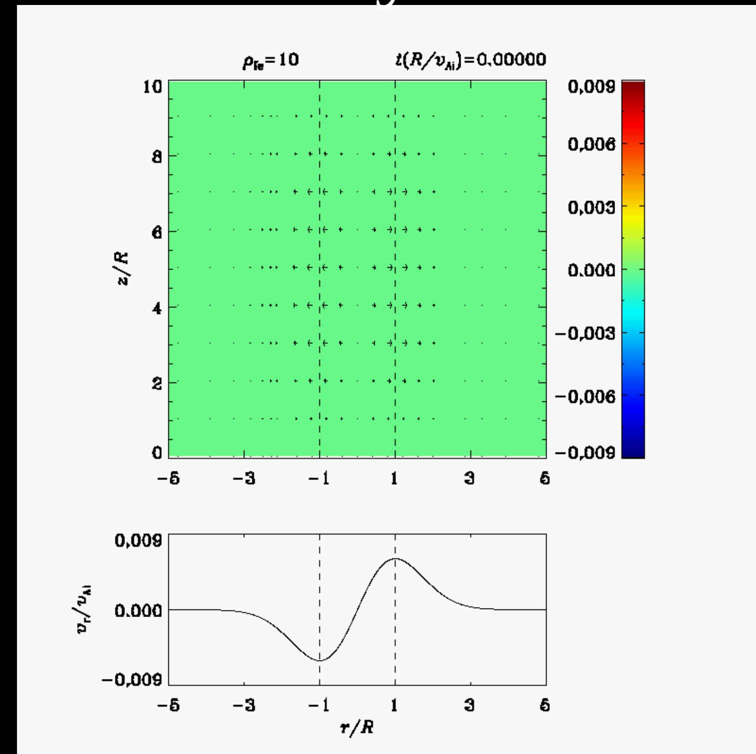
trapped



$\delta\rho/\rho_{\rm eq}$ map
$+\ \boldsymbol{v}$ arrows

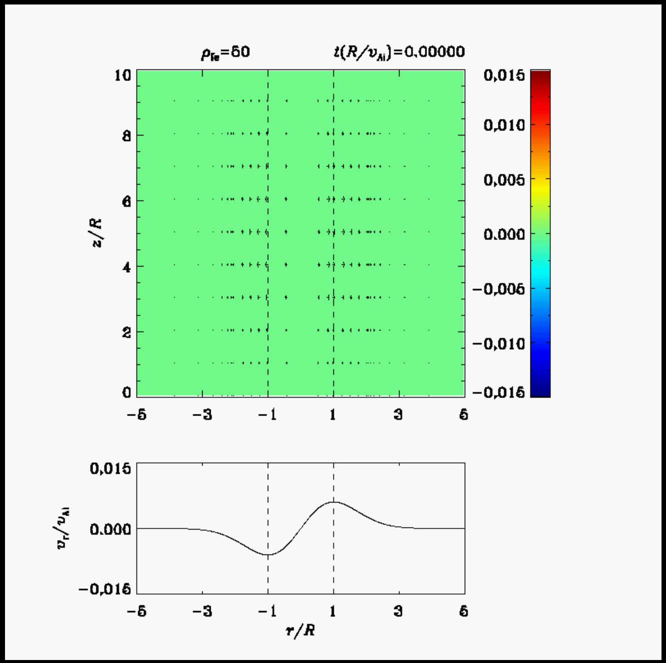
v_r vs r

leaky

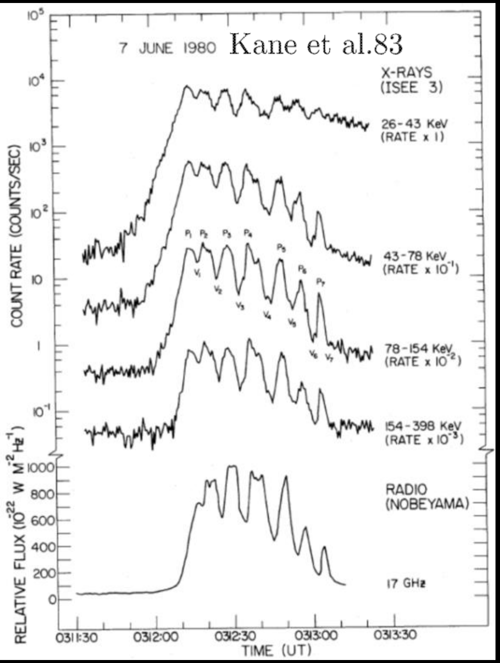


- Named by Edwin & Roberts 83: axisymmetric, strong compression
- Trapped for [exceptions? see Li+18 and references therein]
  - loops dense enough, when geometric parameters fixed
  - loops thick enough, when density contrast fixed
- leaky or trapped, $P \sim R/v_{\rm Ai} \sim$ secs

Connection to QPPs in flare light curves



[reviews by Nakariakov & Melnikov 09, Van Doorsselaere+16, McLaughlin+18]



- seismology $(P, \tau, \cdots) \rightarrow |\boldsymbol{B}|$, inhomogeneity length-scale [e.g., Chen, Li+15, 16, 18a]
- Possible detections in UV/EUV
  - Imaging: SDO/AIA [e.g.,Su+12]
  - Spectroscopic: IRIS [Tian+16, Dennis+17?]

Motivation: forward modeling (E)UV signiatures

- Coronal model approximation [e.g., Cooper+03, Gruszecki+12, Antolin & Van Doorsselaere+13]
  - Emission

ϵ: emissivity, $G_{\lambda 0}$: contribution function

f_q: ionic fraction of $q-1$ times ionized Fe

$$\epsilon = G_{\lambda 0}\boxed{N^2}$$

$$G_{\lambda 0} = h\nu_{ij} \cdot 0.83 \cdot Ab(\mathrm{Fe})\boxed{f_q}\boxed{\frac{n_j A_{ji}}{N}}$$

ϵ_λ: monochromatic emissivity

$$\epsilon_\lambda = \frac{2\sqrt{2\ln 2}}{\sqrt{2\pi}\boxed{\lambda_w}}\epsilon \exp\left\{-\frac{4\ln 2}{\boxed{\lambda_w^2}}\left[\lambda - \lambda_0\left(1 - \frac{\boxed{v_{\mathrm{LoS}}}}{c}\right)\right]^2\right\}$$

$$I = \int_{\mathrm{LoS}} \frac{\epsilon}{4\pi} dl \ , \quad \text{and} \quad I_\lambda = \int_{\mathrm{LoS}} \frac{\epsilon_\lambda}{4\pi} dl$$

I: specific intensity I_λ: monochramatic intensity

  - Ionization: equilibrium ionization (EI) → ionic fraction depends on *T* only → contribution func practically depends on *T only*

Expected signatures when EI assumed

- EI assumed implicitly (Cooper+03, Gruszecki+12) or explicitly (Antolin & Van Doorsselaere+13)
- Summary of spectroscopic signatures

input: MHD data – analytical or numerical		Output: spectral profile –intensity I, Doppler shift v_{Doppler}, Doppler width w_{Doppler}	
		Equilibrium Ionization	Spectroscopic Signatures
T R A P P E D	$\delta\rho$ at P	intensity modulation δI at P	1: **Note-** P short (secs to a couple 10s) ($L/P \gg$ sound speed)
	90° difference between $\delta\vec{v}$ and $\delta\rho$	90° difference between v_{Doppler} and δI	2
	δT and $\delta\mathbf{v}$ both at P	$\delta\mathbf{v}$ dominates Doppler width modulations for e.g., Fe IX 171Å hence w_{Doppler} at $P/2$	3

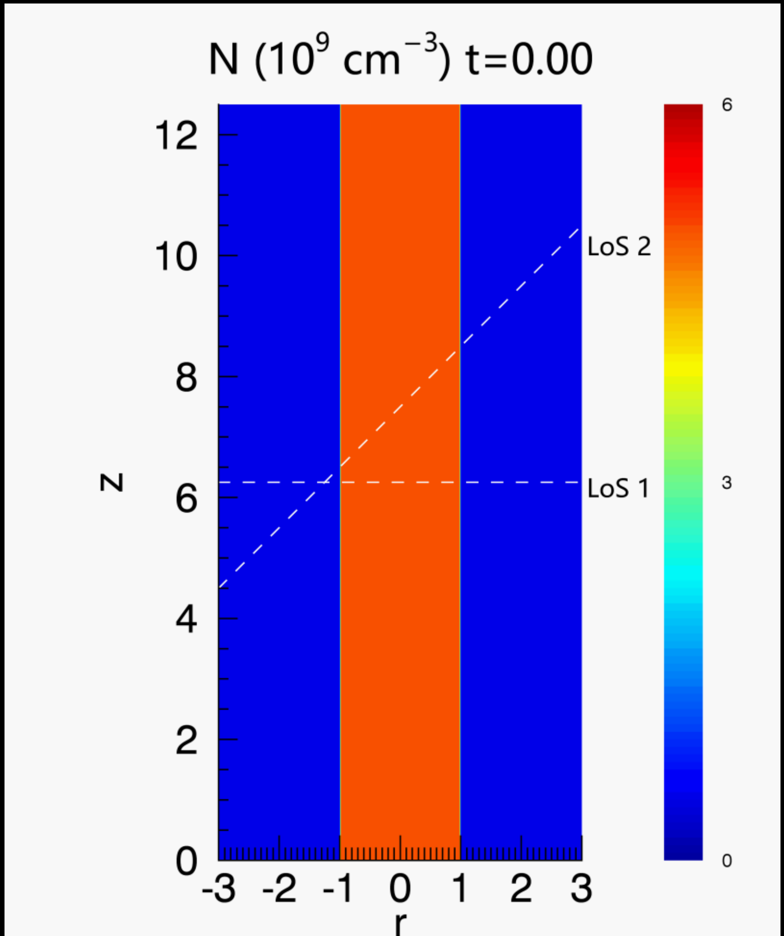
Questions to address: Non-EI effects

- Ionization-recombination eq. (I-R)

$$\left(\frac{\partial}{\partial t}+\boldsymbol{v}\cdot\nabla\right)f_q = N\left[f_{q-1}C_{q-1}-f_q\left(C_q+R_q\right)+f_{q+1}R_{q+1}\right]$$

  - EI applies when $\dfrac{P}{2\pi} \gg \dfrac{1}{NC}, \dfrac{1}{NR}$
- (E)UV signatures of standing sausage when NEI considered (Shi, Li+19a, 19b, 19c ApJ)
  - Approach
    - ✓ rate coefficients from Chianti
    - ✓ waves introduced at t=0, EI ionic fractions initiate solutions to I-R
  - Qs to address
    - ✓ Trapped modes: how known signatures affected by non-EI?
    - ✓ Leaky modes: $\delta I \to \tau_{\rm wave}$: damping time?

Fe IX 171 & Fe XII 193 as examples



Shi, Li+19a, ApJ, 870, 99

$$\mathrm{Length/radius} = 12.5$$

$$N_{\mathrm{int}}/N_{\mathrm{ext}} = 10, \; N_{\mathrm{int}} = 5 \times 10^9 \mathrm{cm}^{-3}$$

$$T_{\mathrm{int}} = 1 \mathrm{\ MK}, \; T_{\mathrm{ext}} = 0.74 \mathrm{\ MK}$$

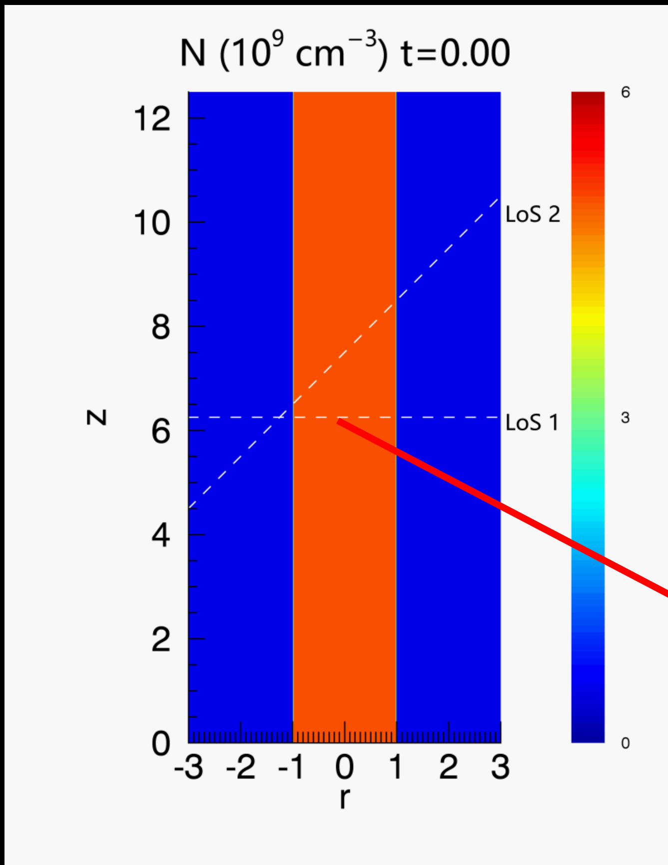
$$v_{\mathrm{Ai}} = 500 \mathrm{\ km\ s}^{-1}$$

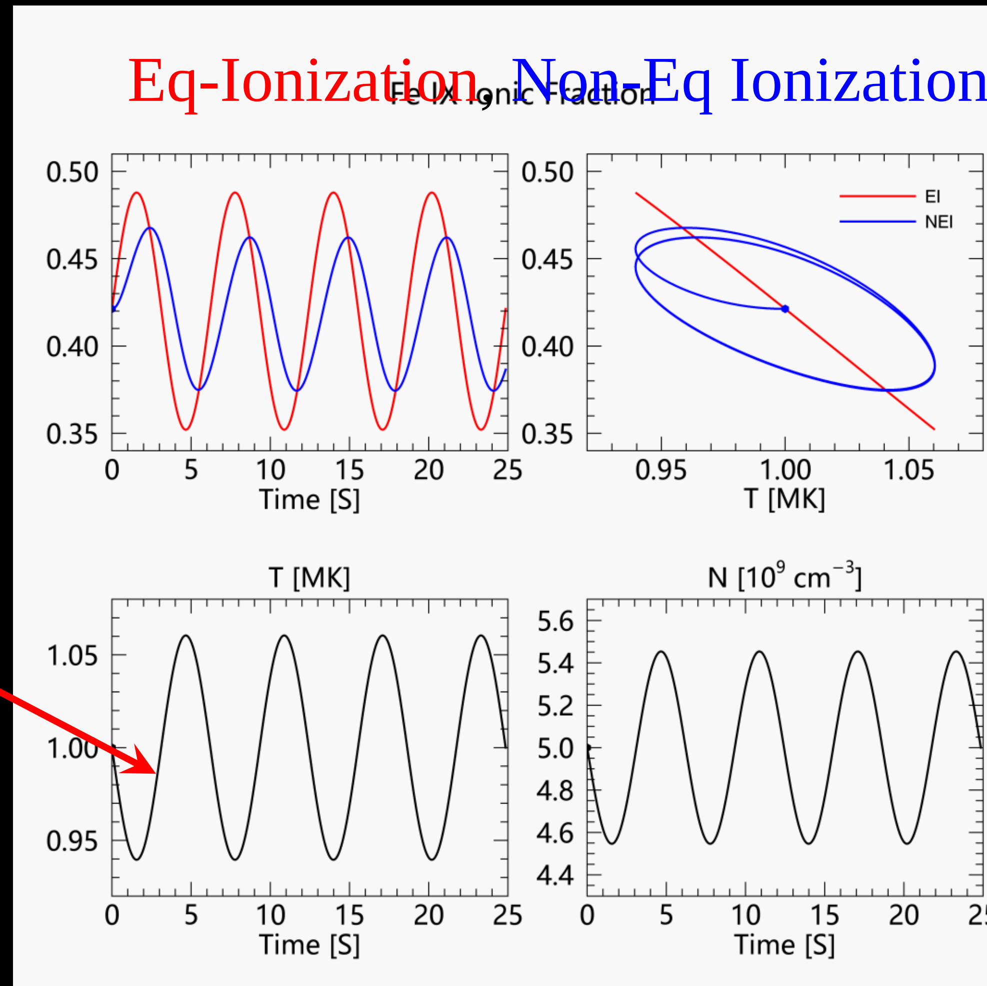
4th harmonic $P = 6.2$ sec

peak $v_r \approx 30$ km s^{-1}

- why 4th harmonic? to make sure the mode is trapped
- results for LoS 1 valid even for fundamental

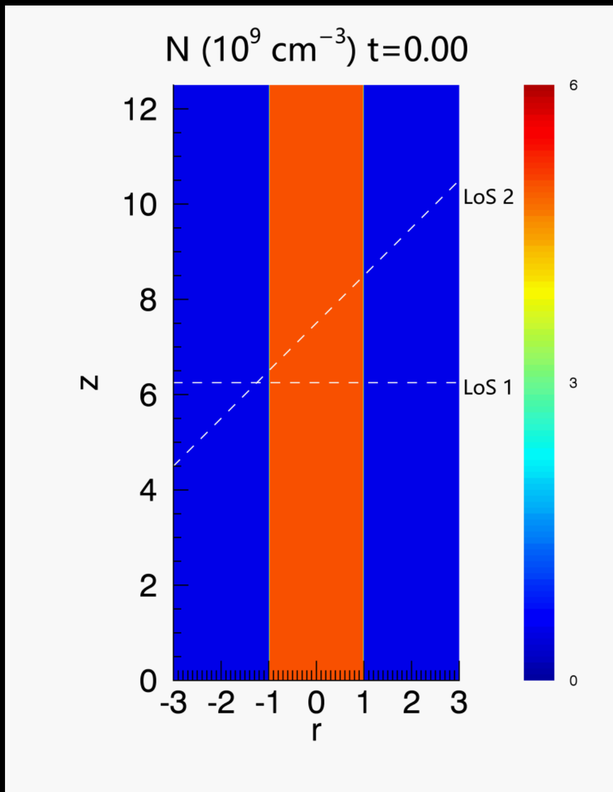
NEI impacts ionic fractions (*f*) substantially

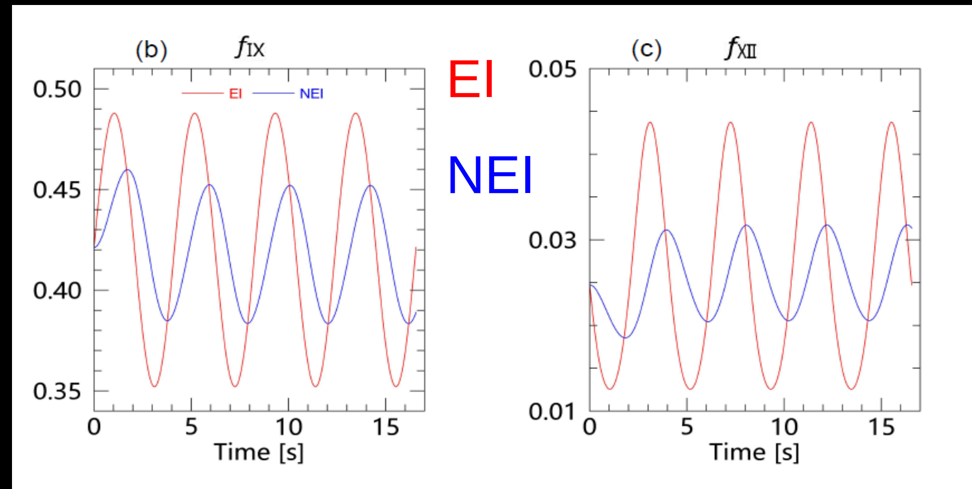


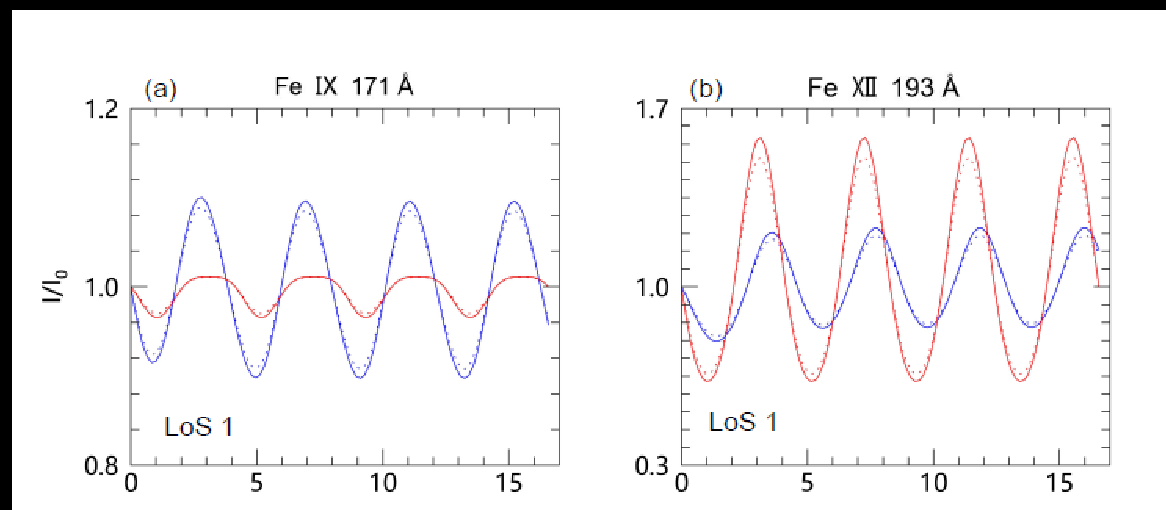


- T - N in phase
- Variations of ionic fraction *f*_IX weaker in NEI
- *f*_IX in anti-phase with T for EI, but not so for NEI

NEI may enhance or suppress intensity modulation

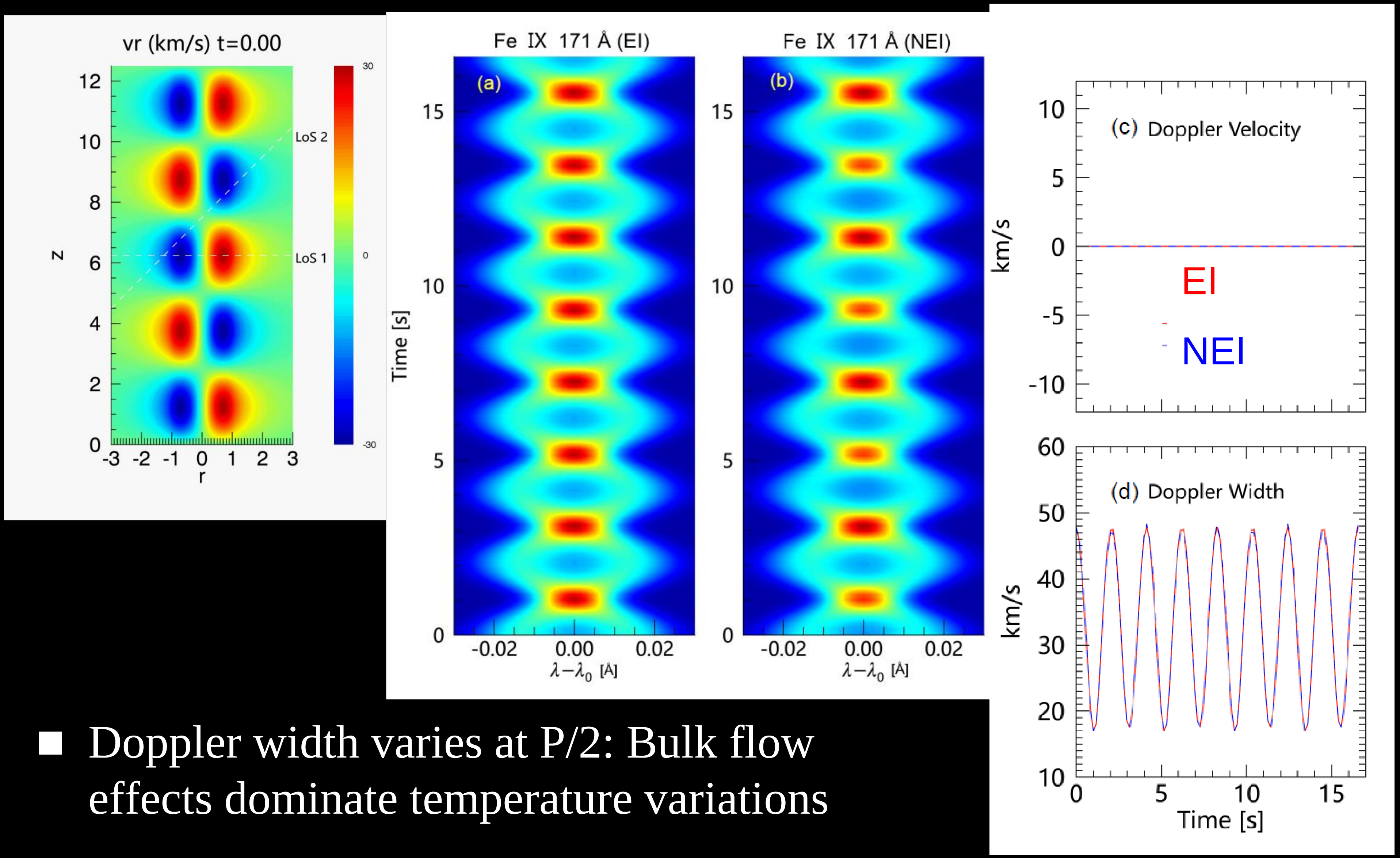






- Why? loop temperature is the key $\epsilon \propto f_q \frac{n_j}{N} N^2$

NEI no impact on Doppler shift & width

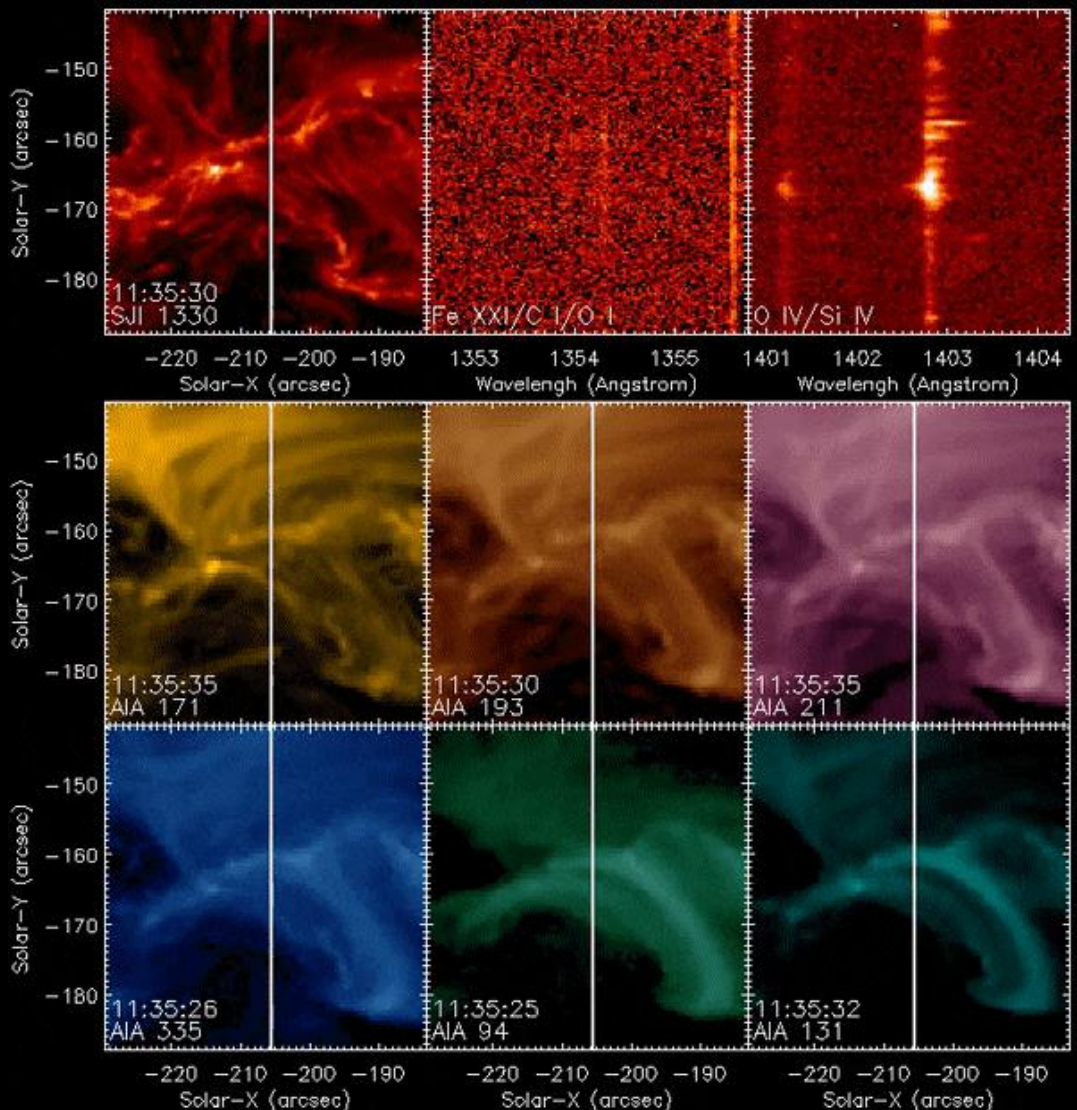


- Doppler width varies at P/2: Bulk flow effects dominate temperature variations

Oscillatory signal in Fe XXI 1354

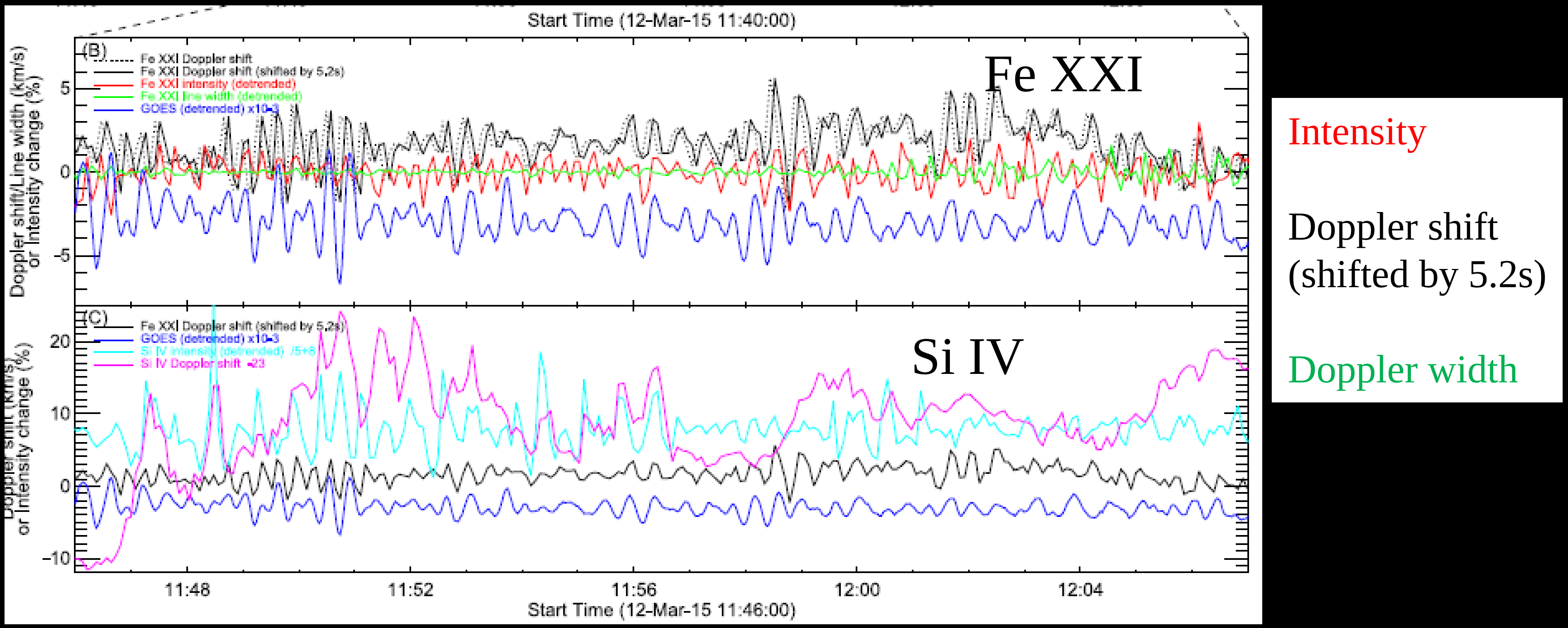
IRIS

SDO/
AIA



IRIS observations of an arcade of flare loops.
M1.6, 12 Mar 2015

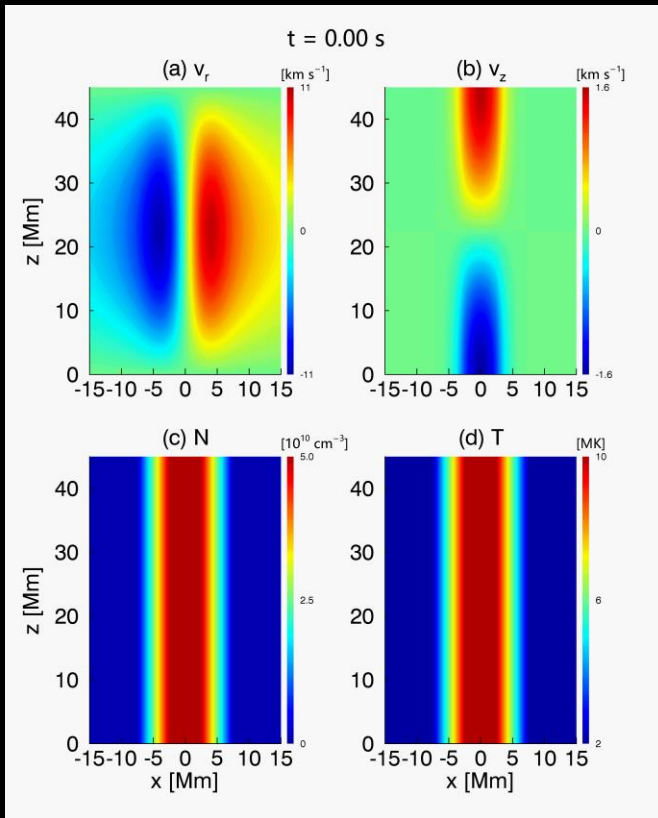
Tian+16 ApJ



Identified as a fundamental, fast sausage, because

1) fundamental: apparently no extra nodes
2) Fast: Apparent phase speed: 2L/P = 2 \times 42”/25 sec = 2420 km/s >> sound speed even in this hot line (525 km/s)
3) Sausage: weak Doppler width variation; Phase-shift by a quarter of period between line intensity & Doppler shift.

forward-modeling Fe XXI 1354 (Shi, Li+19b, ApJ, 874, 87)



$$\text{Length/radius} = 45 \text{ Mm}/5 \text{ Mm}$$

$$N_{\text{int}}/N_{\text{ext}} \approx 45, \;\; N_{\text{int}} = 5 \times 10^{10}\text{cm}^{-3}$$

$$T_{\text{int}} = 10 \text{ MK}, \;\; T_{\text{ext}} = 2 \text{ MK}$$

$$v_{\text{Ai}} = 420 \text{ km s}^{-1}$$

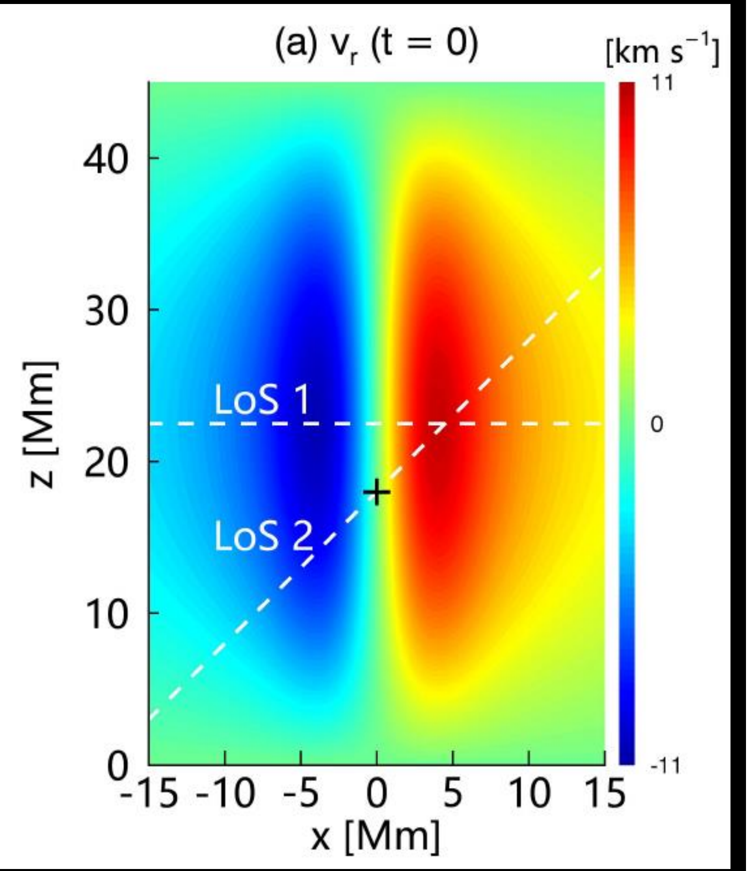
$$\tau_{\text{C,XXI}} = 1.6 \text{ sec} \;, \quad \tau_{\text{R,XXI}} = 0.8 \text{ sec}$$

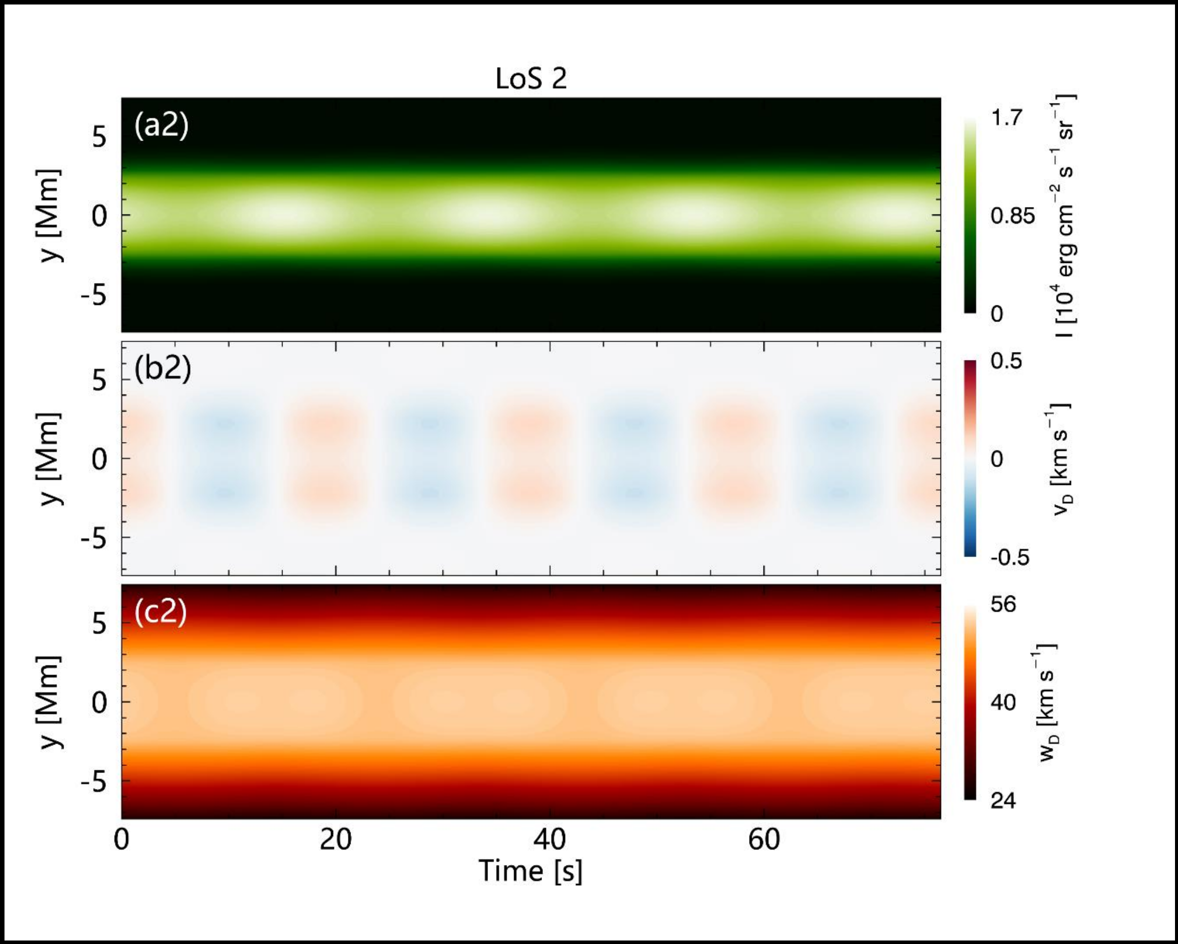
$$\text{fundamental } P = 19.2 \text{ sec}$$

$$\text{peak } v_r \approx 10.5 \text{ km s}^{-1}$$

- coronal model approximation still valid for this forbidden line (Landi+06, approximation breaks down when N 20x larger than adopted)

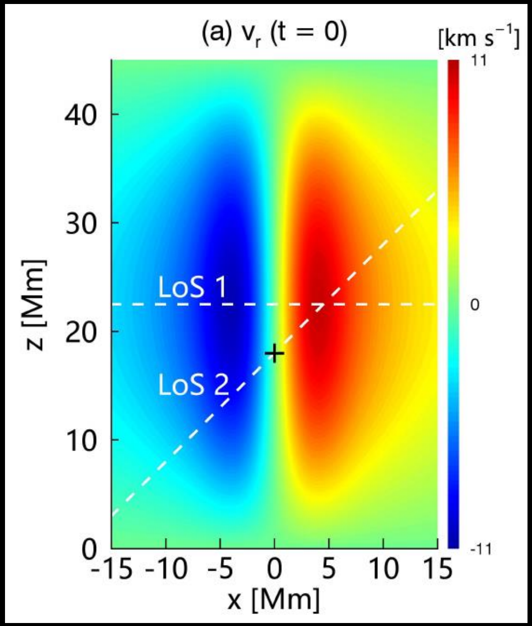
Spectral parameters for LoS 2

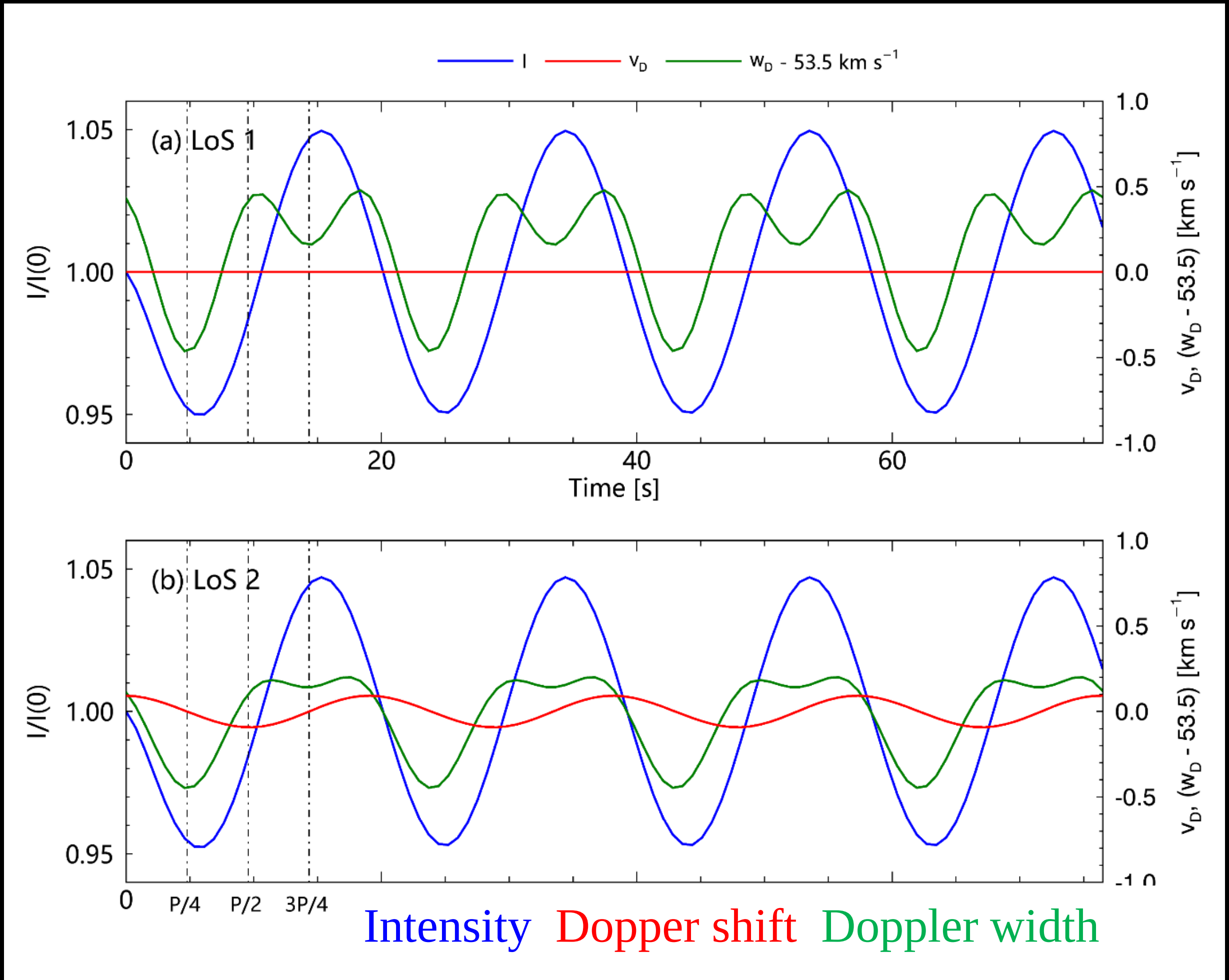




- intensity variation & Doppler shift : P
- Doppler width variation: predominantly P, but also P/2

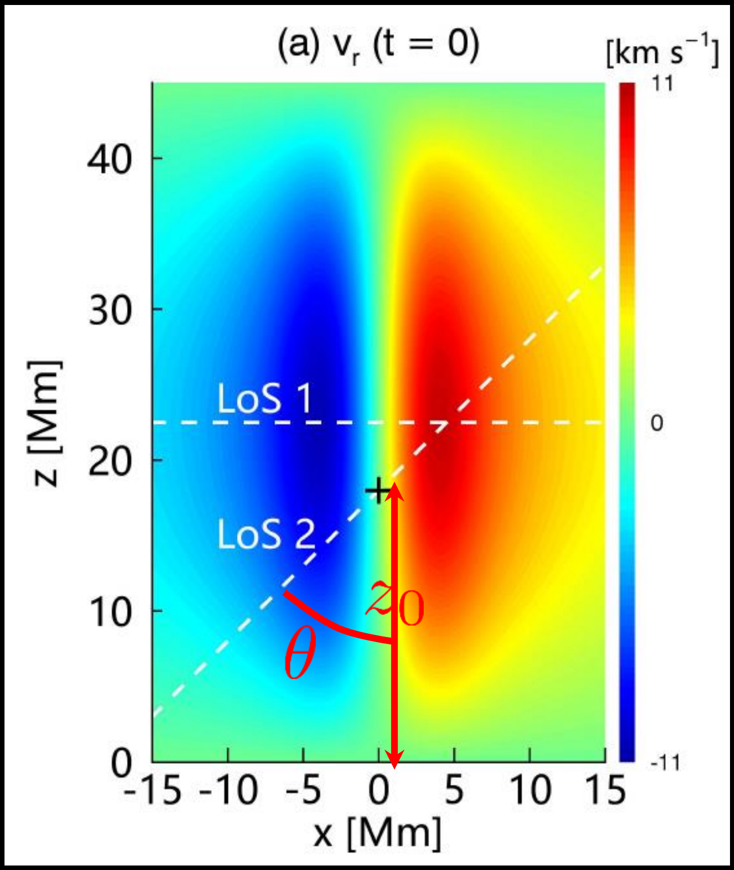
Parameters from slit-average profiles

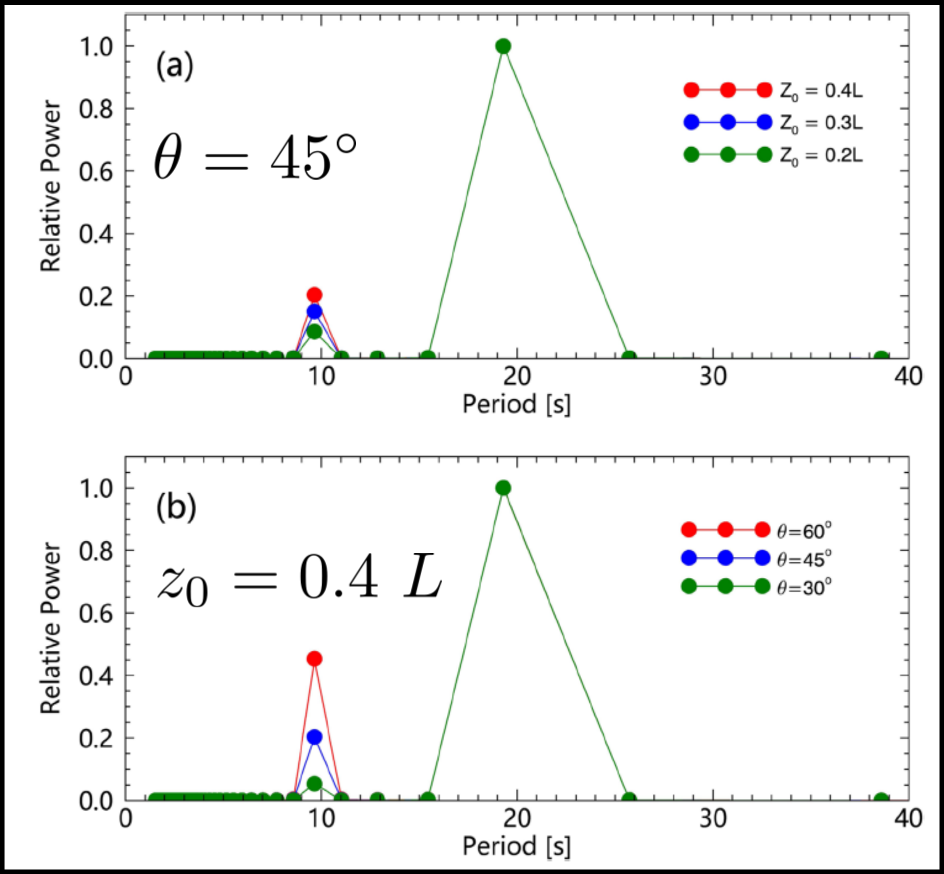




- Intensity & Doppler shift at *P*, phase shift 70 degrees: NEI effects
- Doppler width variation: predominantly P, but also P/2 (Temperature variation dominates, but not overwhelmingly so)

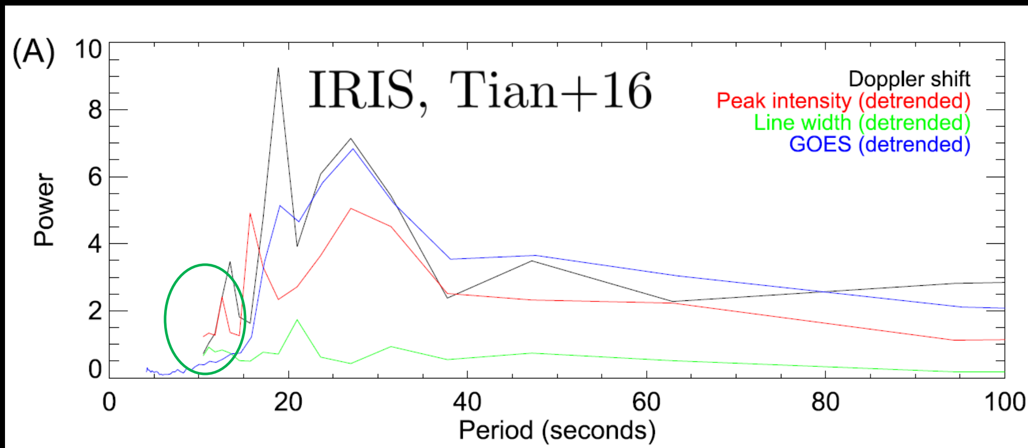
Fourier power spectra for Doppler broadening

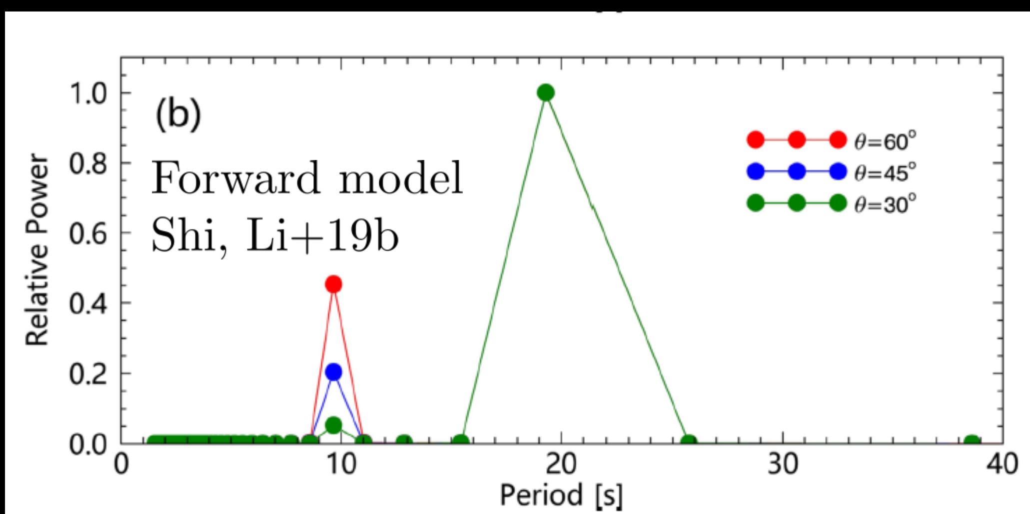




- $P/2$ component: $\nearrow$ when $z_0 \nearrow$ or $\theta \nearrow$
- Should be a more stringent criterion for id-ing sausage modes

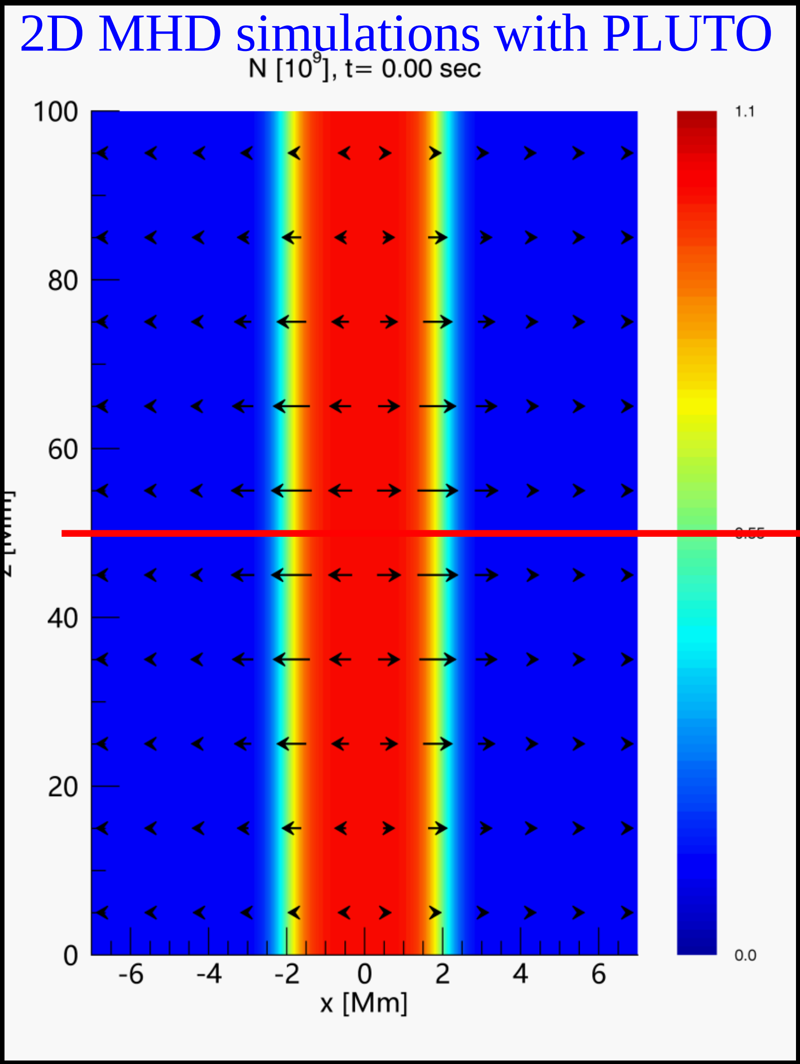
Some (inconclusive) evidence





- slight enhancement at P/2 in IRIS measurements (Nyquist? IRIS cadence~5.2 sec)
- Conclusive evidence requires a (much?) higher cadence

Leaky modes? (Shi, Li+19c, ApJ, 883, 196)



LOS

$\text{Length/radius} = 50$

$N_{\rm int}/N_{\rm ext} = 10, \;\; N_{\rm int} = 10^9 \text{cm}^{-3}$

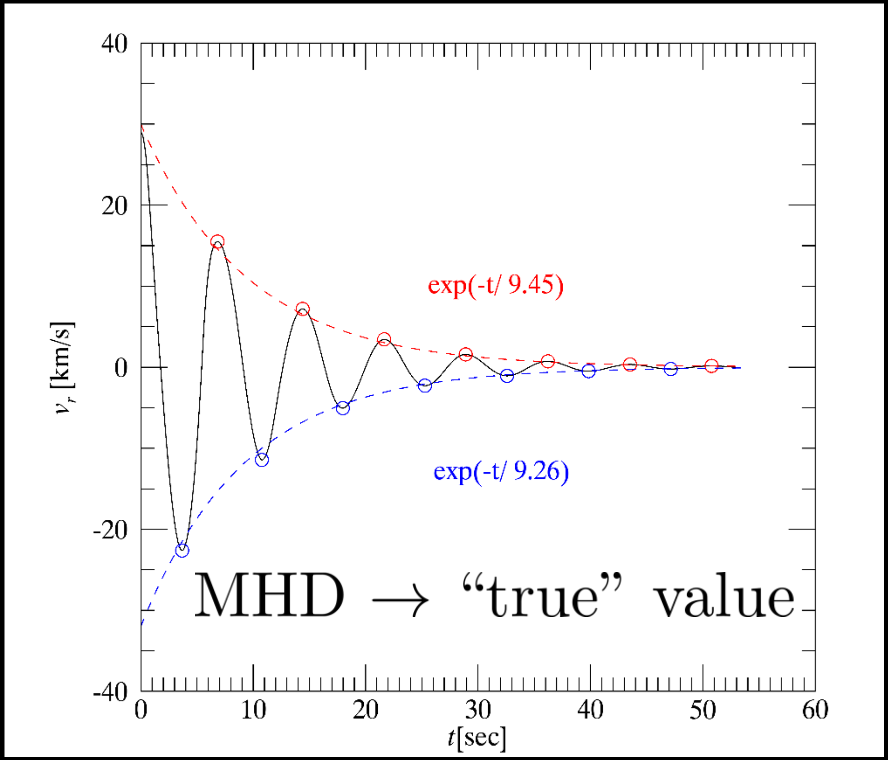
$T_{\rm int} = 0.9 \text{ MK}, \;\; T_{\rm ext} = 0.7 \text{ MK}$

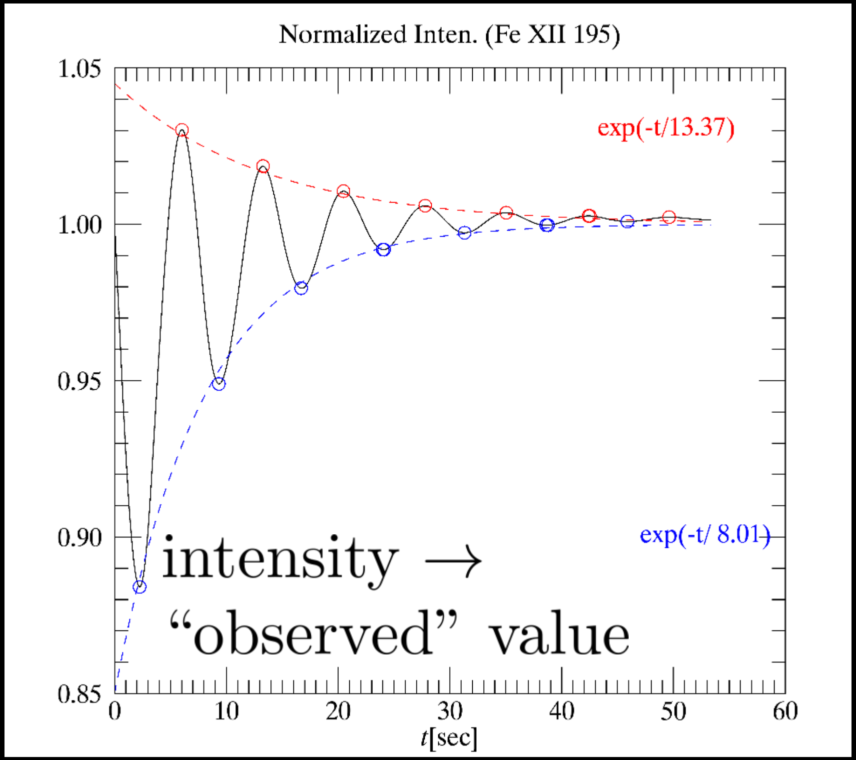
$v_{\rm Ai} = 750 \text{ km s}^{-1}$

$\text{fundamental } P = 7.28 \text{ sec}$

$\text{peak } v_r(t=0) \approx 30 \text{ km s}^{-1}$

Inferring damping time from intensity variations

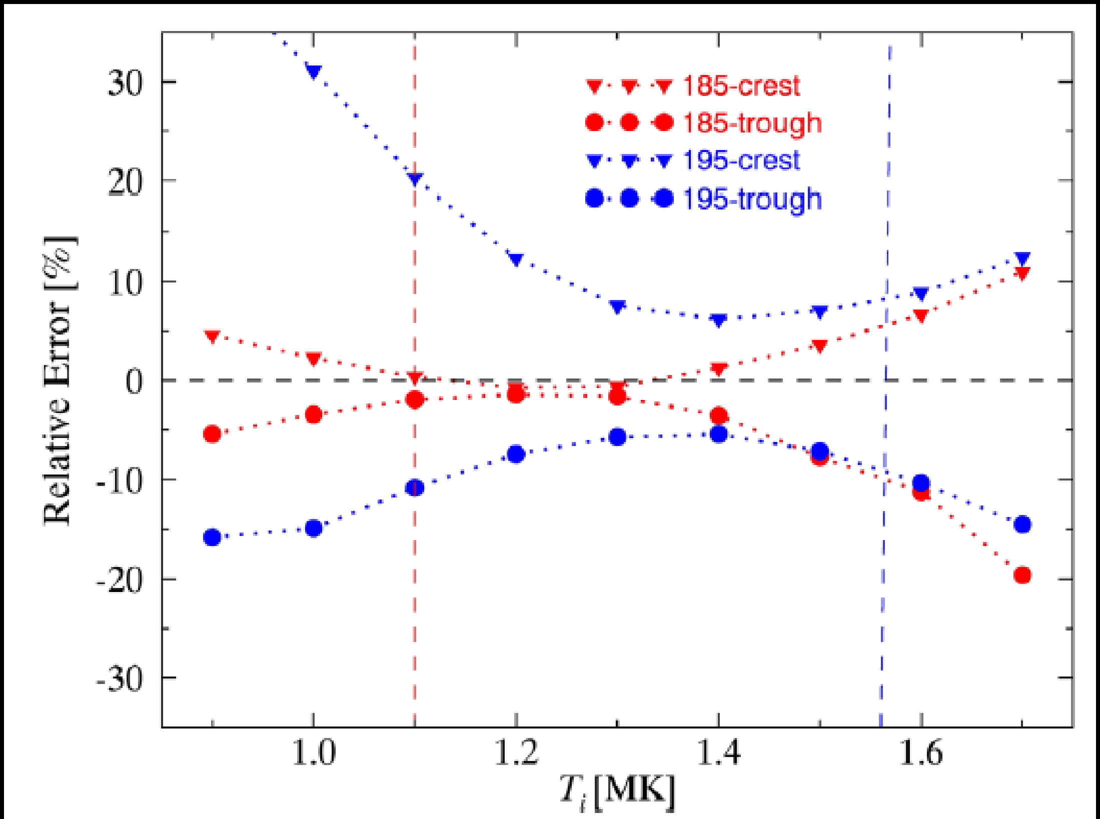




- Tau_damp from crests and troughs different; both are different from the wave damping rate
- Why? from nonlinear dependence of intensity on electron density & (implicitly) on temperature

When can tau_wave be reliably deduced?

$$\text{relative err} = \frac{\tau_{\text{intensity}}}{\tau_{\text{MHD}}} - 1$$



- when loop temperature not too far from nominal formation temperature expected under EI

Summary: (E)UV signatures of fundamental, standing, fast, sausage

- Forward modeling: Equilibrium Ionization not guaranteed
- Expected signatures

1 : a periodicity P common to int. & Doppler shift variations
Note 1- P short (secs to a couple 10s) ($L/P \gg$ sound speed)
Note 2- phase diff $\delta I - v_{\rm Doppler}$ not necessarily 90°

2 : periodicity in Doppler width dominantly

$$\begin{cases} P/2 & \text{coronal lines: e.g., Fe IX 171, X 185, XII 195} \\ P & \text{flare lines: e.g., Fe XXI 1354} \end{cases}$$

- Applications

1 : $\tau_{\rm intensity}$ largely reflects $\tau_{\rm MHD}$ if $T_{\rm loop}$ not too different from $T_{\rm EI}$

2 : $P, \tau, \cdots$ useful for seismology (e.g., Chen+15, 16, 18; Guo+16)