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Alfvénic waves in the structured corona

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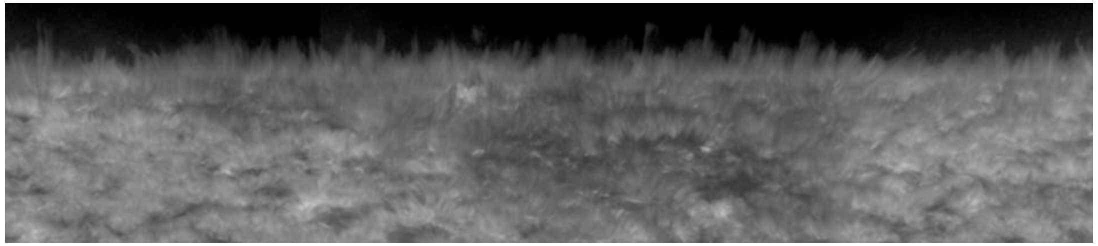
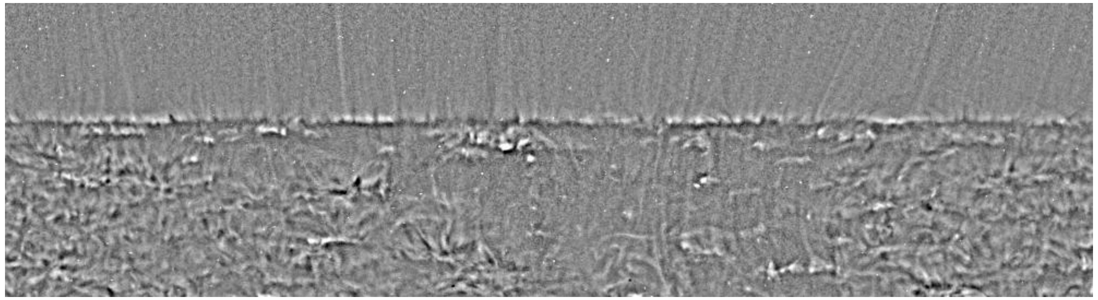
Transverse Alfvénic waves in Spicules

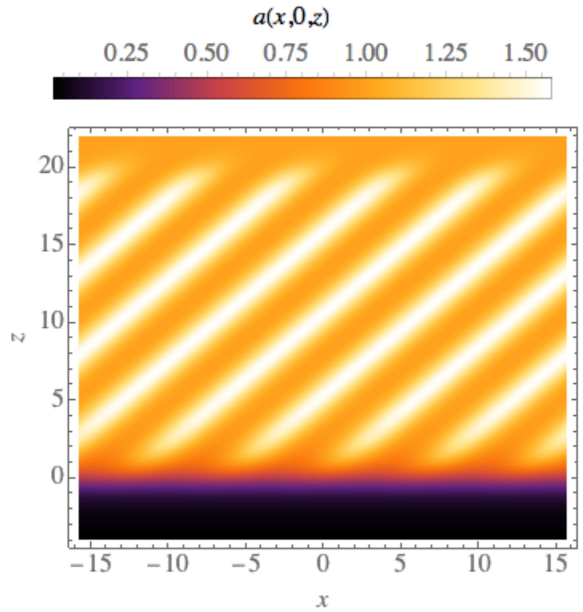
- ***"Alfvén Waves in the Solar Corona"***, Tomczyk et al (2007)
- ***"Alfvénic waves with sufficient energy to power the quiet solar corona and fast solar wind***", McIntosh et al (2011)
- But …
- ***"Are There Alfvén Waves in the Solar Atmosphere?"***, Erdelyi & Fedun (2007)
- ***"Detection of Waves in the Solar Corona: Kink or Alfvén?***", Van Doorsselaere et al (2008)

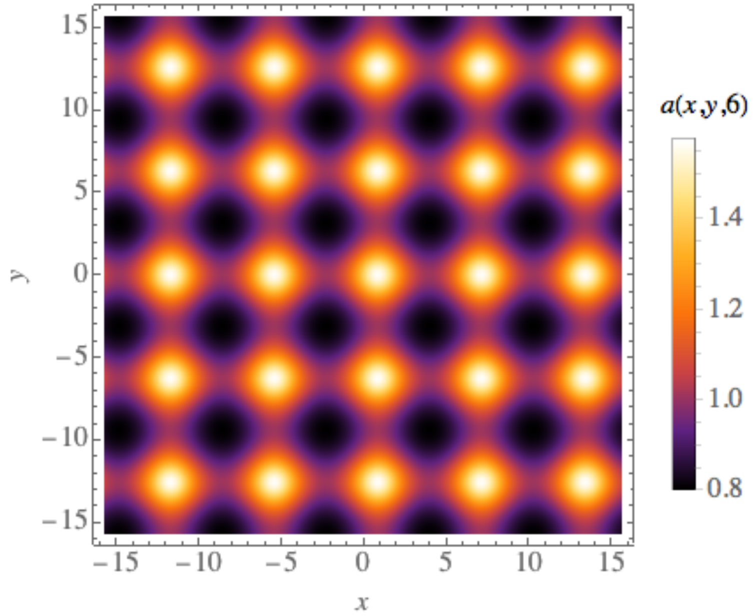




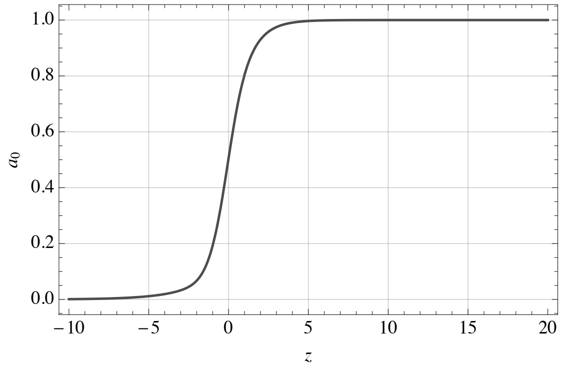
Are these simple Alfvén waves, or simple kink waves, or is it more complicated?
Yeh, I know you all know the answer, but hopefully my model and calculations will still be instructive …

Simple Inclined-Field Model with Periodic Tube-like Alfvén Speed: β=0 plasma





$$\frac{1}{a^2} = \frac{1}{a_0^2(z)} - \frac{\epsilon_0}{2}\left(1 - \tanh\left[\frac{z-L}{W}\right]\right)\left[\cos(x - z\tan\theta) + \cos y\right]$$



$$\max a_0 = 1$$

$$a_0^2 = \frac{1 + \delta + (1-\delta)\tanh\left(\frac{z}{h_2}\right)}{2(e^{-z/h_1} + 1)}$$

Wave Equations

$$\left(\partial_{\parallel}^2 - \frac{1}{a^2}\partial_t^2\right)\boldsymbol{\xi} = -\nabla_p \chi$$

perpendicular to **B**

where $\chi = \nabla \cdot \boldsymbol{\xi}$

Displacement

$$\boldsymbol{\xi} \perp \boldsymbol{B}$$

Helmholtz decompose into irrotational and incompressive parts

$$\boldsymbol{\xi} = \nabla_p \Phi - \nabla \times \Psi \hat{\boldsymbol{e}}_{\parallel}$$

Then

$$\left(\nabla^2 - \frac{1}{a^2}\partial_t^2\right)\partial_{\perp}\Phi = \left(\partial_{\parallel}^2 - \frac{1}{a^2}\partial_t^2\right)\partial_y \Psi$$

Fast operator $\mathcal{F}$

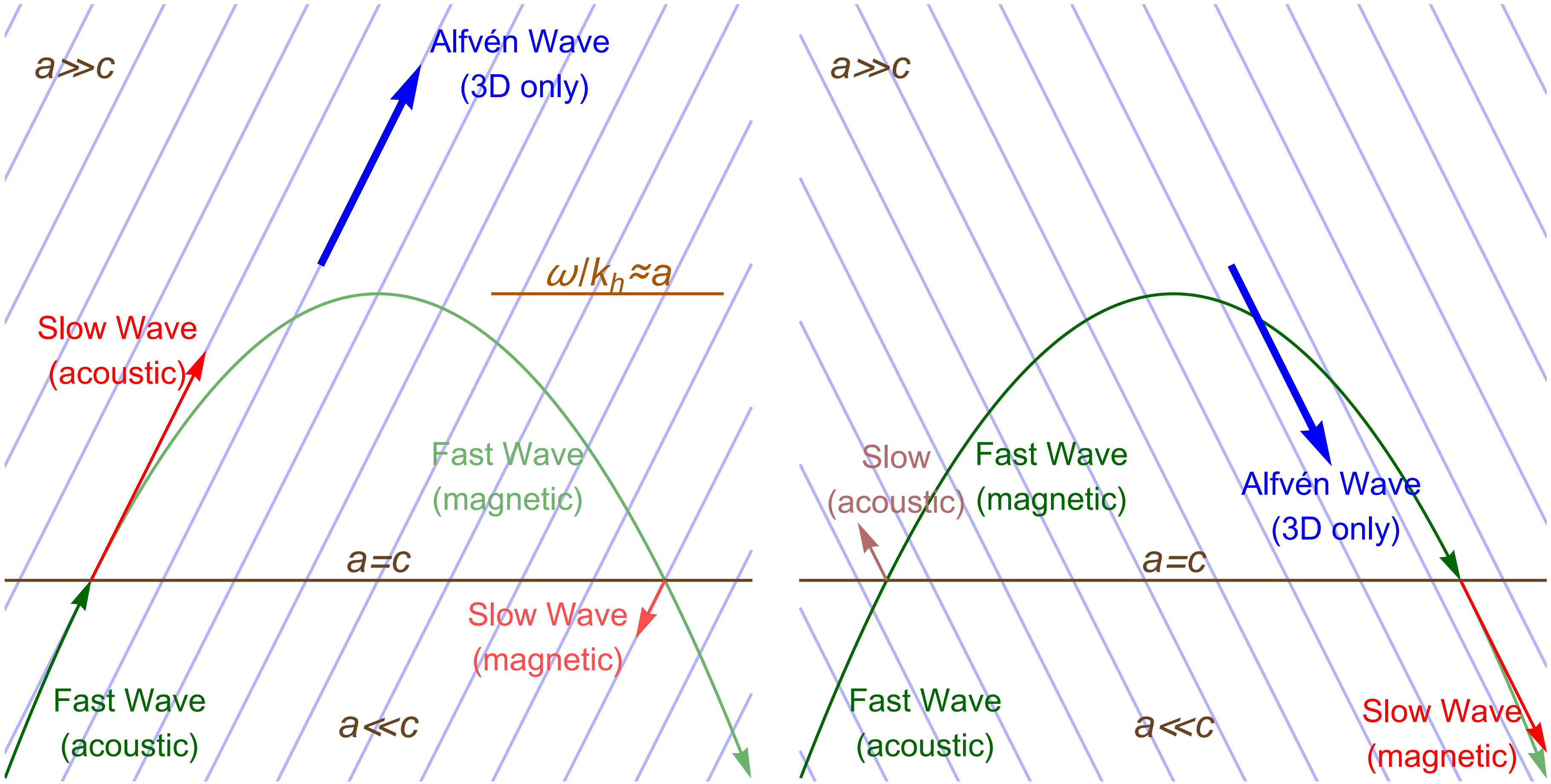
Coupling terms vanish if ∂_y=0

$$\left(\partial_{\parallel}^2 - \frac{1}{a^2}\partial_t^2\right)\partial_{\perp}\Psi = -\left(\nabla^2 - \frac{1}{a^2}\partial_t^2\right)\partial_y \Phi$$

Alfvén operator $\mathcal{A}$

These equations govern energy transfer between "fast" and "Alfvén" waves.

perpendicular to **B** in *x*-*z* plane


a≫c
Alfvén Wave
(3D only)
ω/k_h≈a
Slow Wave
(acoustic)
Fast Wave
(magnetic)
a=c
Slow Wave
(magnetic)
Fast Wave
(acoustic)
a≪c
a≫c
Slow
(acoustic)
Fast Wave
(magnetic)
Alfvén Wave
(3D only)
a=c
Fast Wave
(acoustic)
a≪c
Slow Wave
(magnetic)

Fourier decompose in *x* and *y*

Fourier expansion

$$\Phi(\boldsymbol{x},t) = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \phi_{mn}(z,t) e^{i[(m+r)x+(n+s)y]}$$

$$\Psi(\boldsymbol{x},t) = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \psi_{mn}(z,t) e^{i[(m+r)x+(n+s)y]}$$

- Leads to set of coupled ODEs in *z* for each (*m*,*n*)
- BCs:
  - Injected fast wave at bottom with $k_x = r$, $k_y = s$ (both rational)
  - No incoming Alfvén wave at bottom
  - Outgoing or evanescent waves at top
- Solved using high-order finite differences in *z* and Jacobi or line-Jacobi iteration in (*m*,*n*)
- Tubes scatter by integer increments

Fast waves trapped in dense tubes

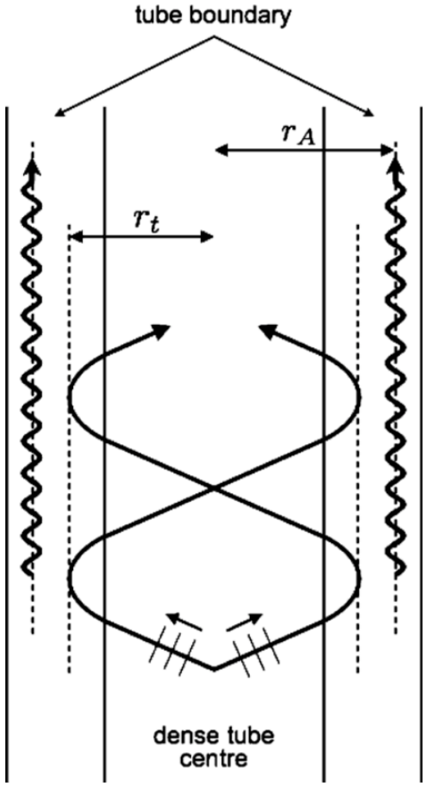
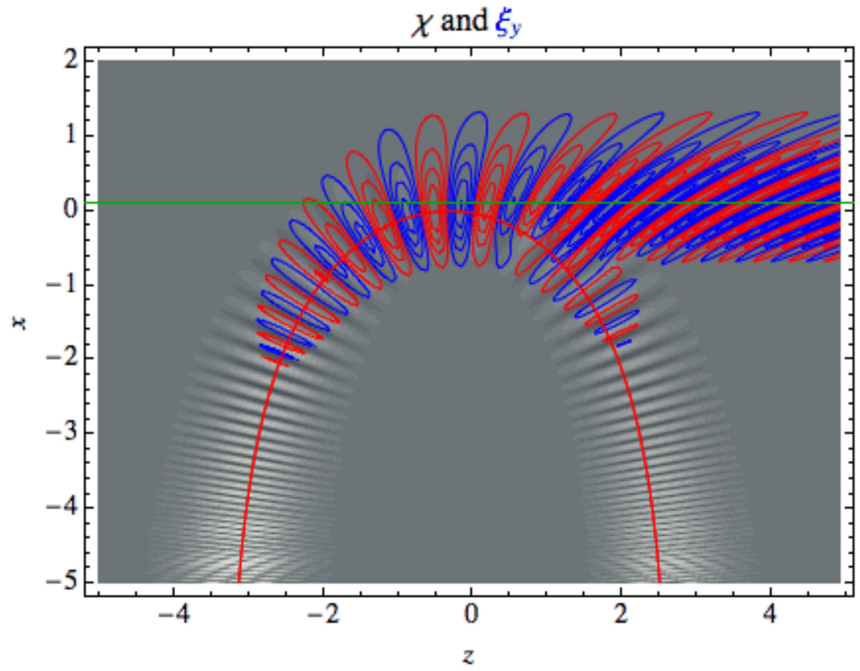


Figure 2. Ray tracing sketch showing the trapping of magnetoacoustic energy in a dense tube with turning point r_t. Energy can tunnel to r_A where it couples to Alfvén waves.

Pascoe et al (2010)

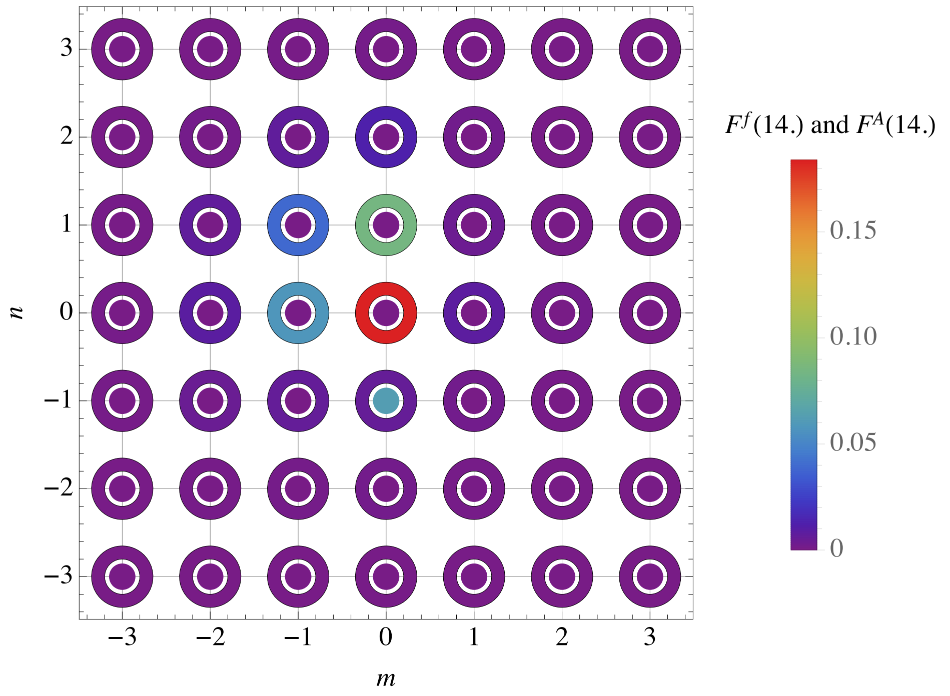


Particular case

- $r = \frac{1}{11}, s = \frac{3}{5}, \theta = 50°, L = 12, W = 1, z_{bot} = -8, z_{top} = 14$
- $\epsilon_0 = 0.3$, i.e., $0.79 < a < 1.58$ in "corona"
- Set $\alpha = \frac{\omega}{\sqrt{r^2+s^2}} = 0.85$, so incident fast wave $m = n = 0$ can propagate in the tubes $a < \alpha$; trapped kink wave
- However, incident fast wave reflects before reaching tubes
- Only other propagating fast wave is $m = 0, n = -1$, for which $\alpha = 1.26 > 1$; propagates in most of ensemble (contiguous). All other $\alpha < 0.79$.

Injected flux=1

Fast (inner) and Alfvén (outer) fluxes at various *m*, *n*

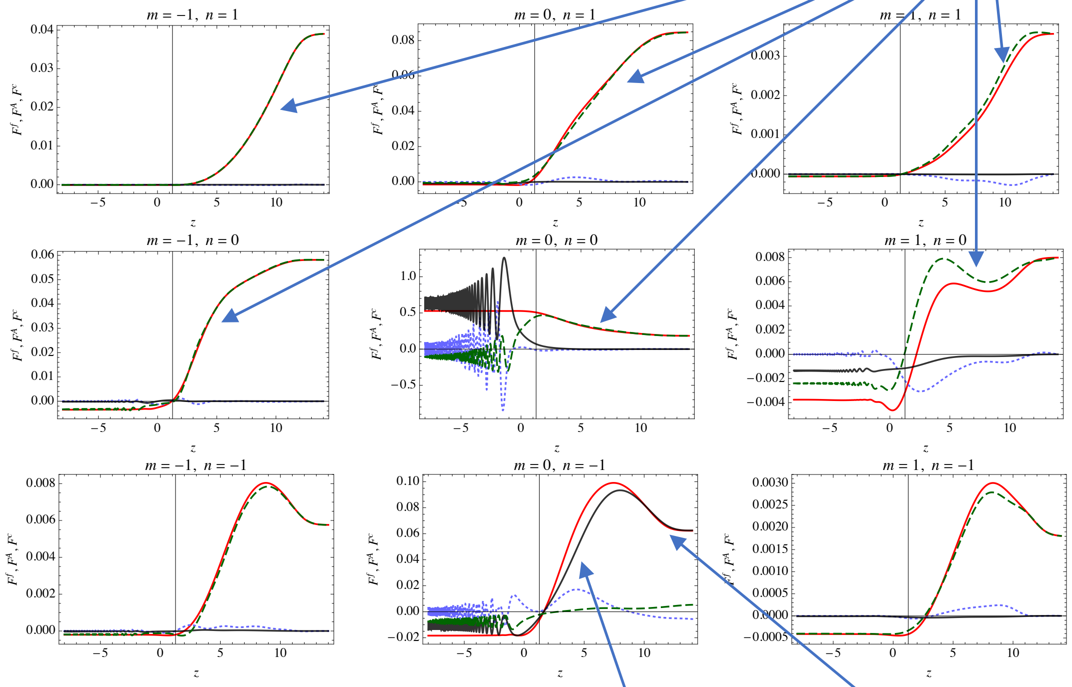


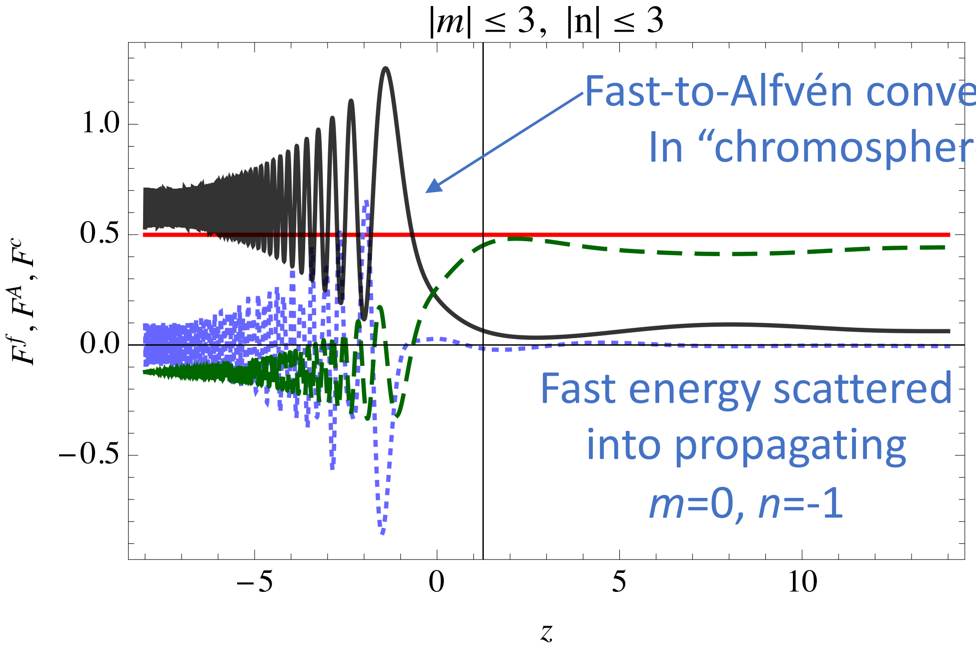
Fluxes: fast, Alfvén, cross (hybrid), total

Fluxes in central Fourier modes

Phase mixing Alfvén wave scattering into other modes

Total flux





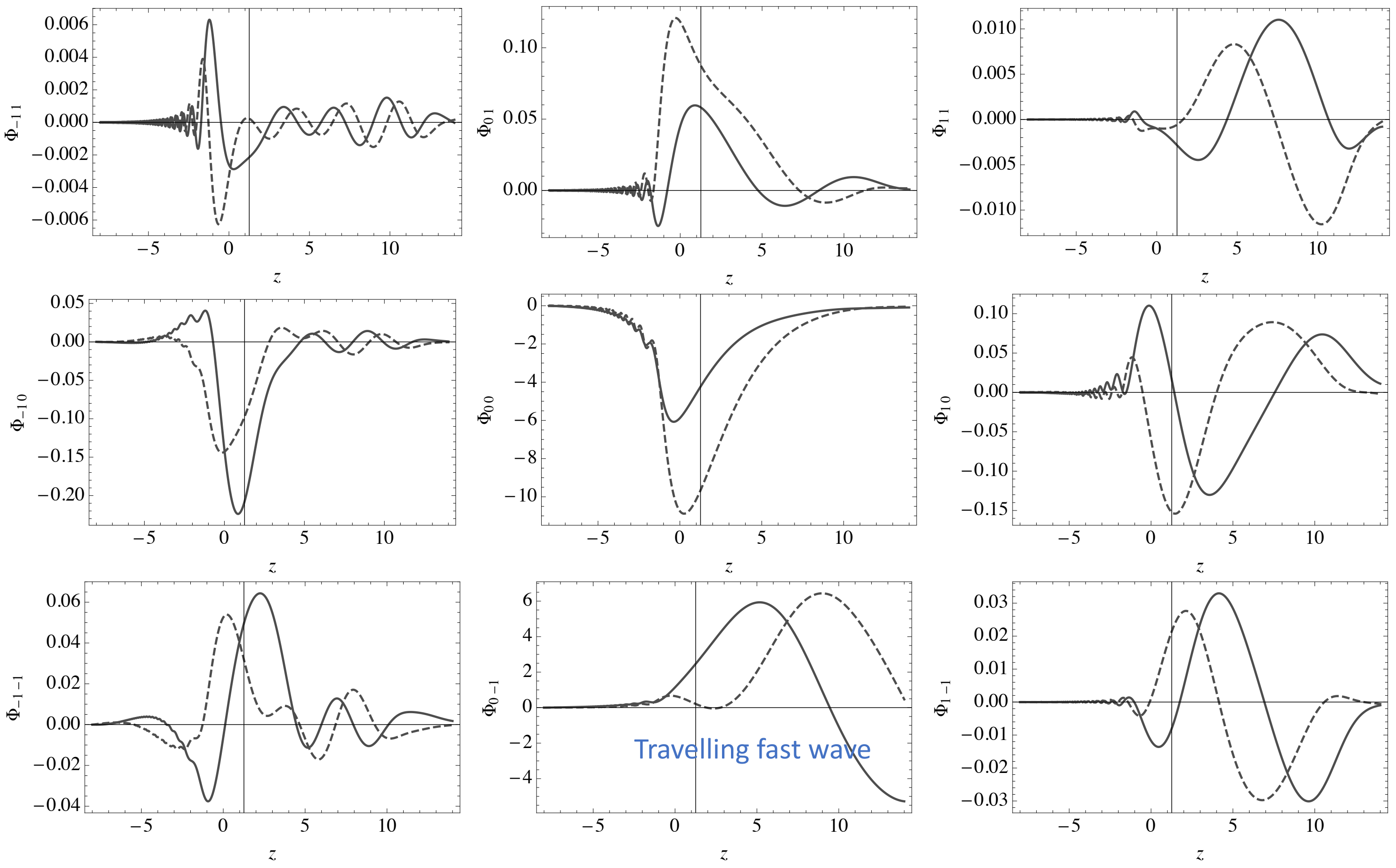
Fast-to-Alfvén conversion In "chromosphere"

Fast energy scattered into propagating *m*=0, *n*=-1

Fast energy scattered into propagating *m*=0, *n*=-1

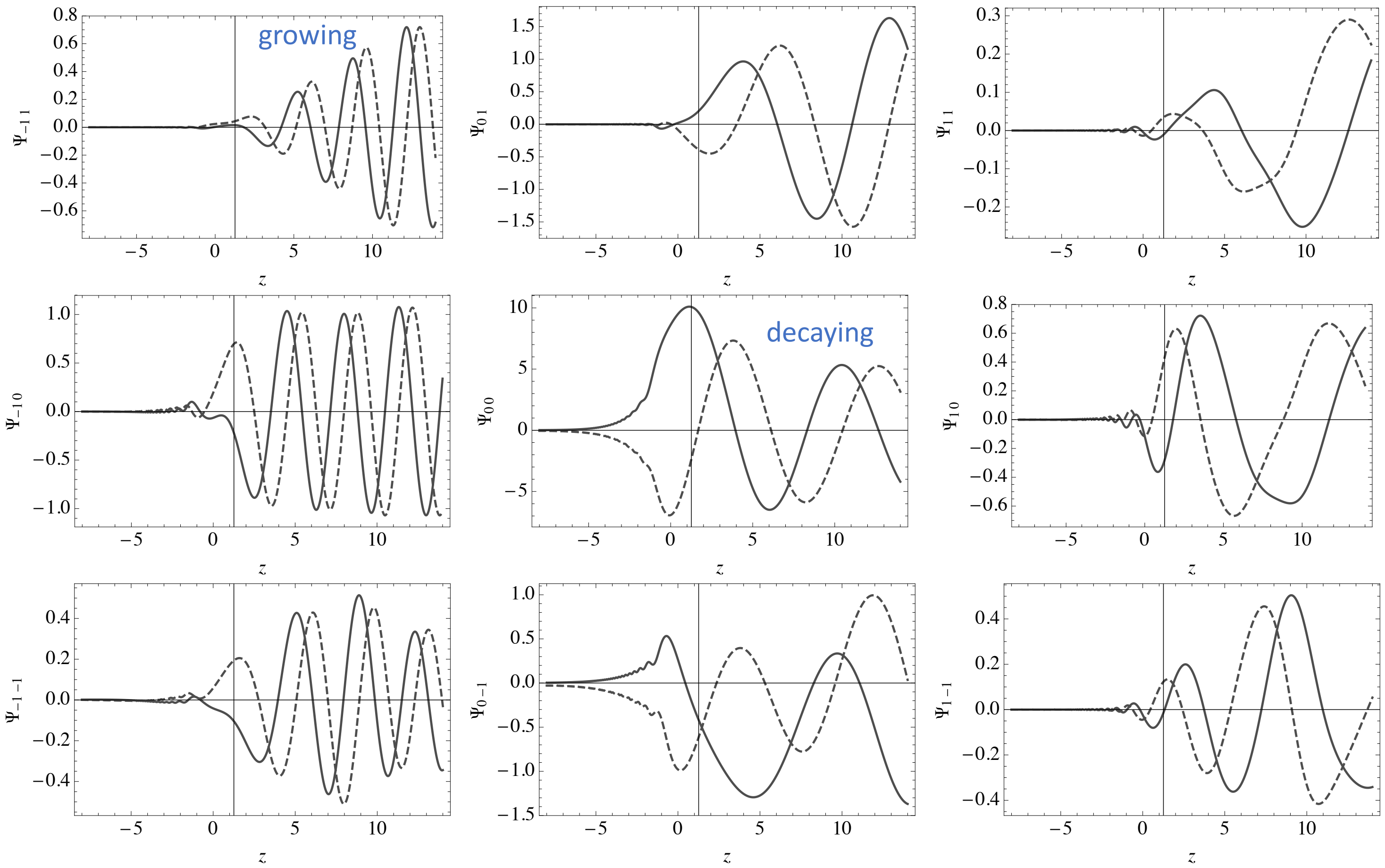
Resonant absorption of fast wave ceases where flux tubes fade out

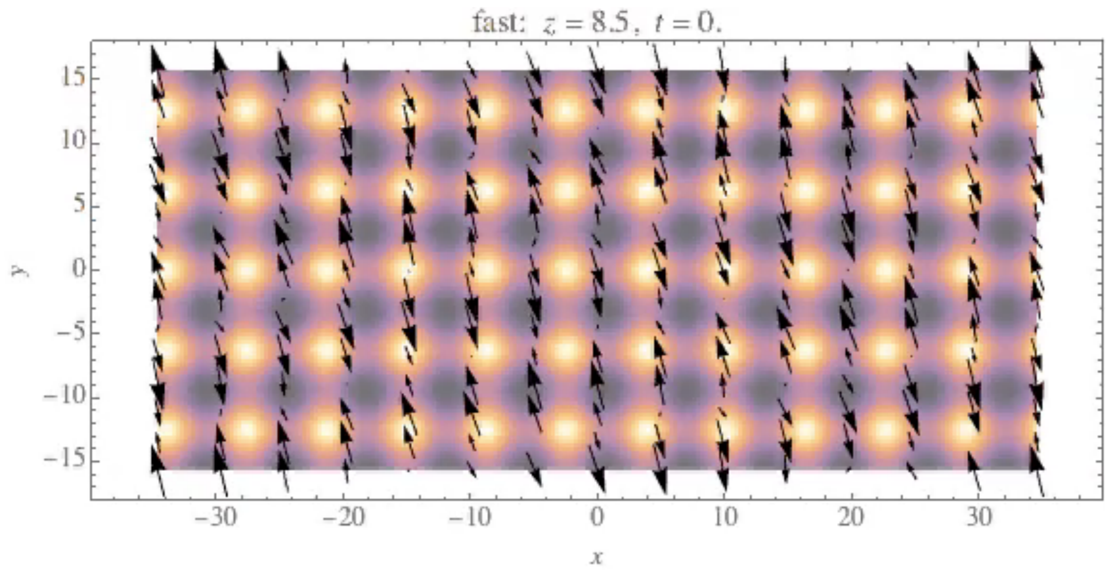
Φ (fast)

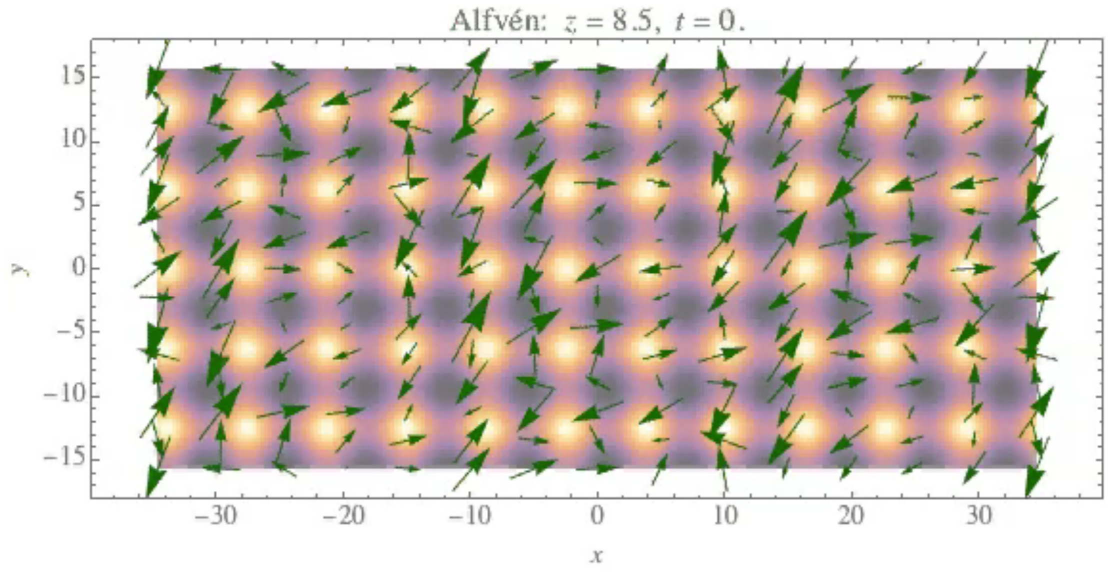


$\Phi_{-1\,1}$
$\Phi_{0\,1}$
$\Phi_{1\,1}$
$\Phi_{-1\,0}$
$\Phi_{0\,0}$
$\Phi_{1\,0}$
$\Phi_{-1\,-1}$
$\Phi_{0\,-1}$
$\Phi_{1\,-1}$
z
Travelling fast wave

Ψ (Alfvén)

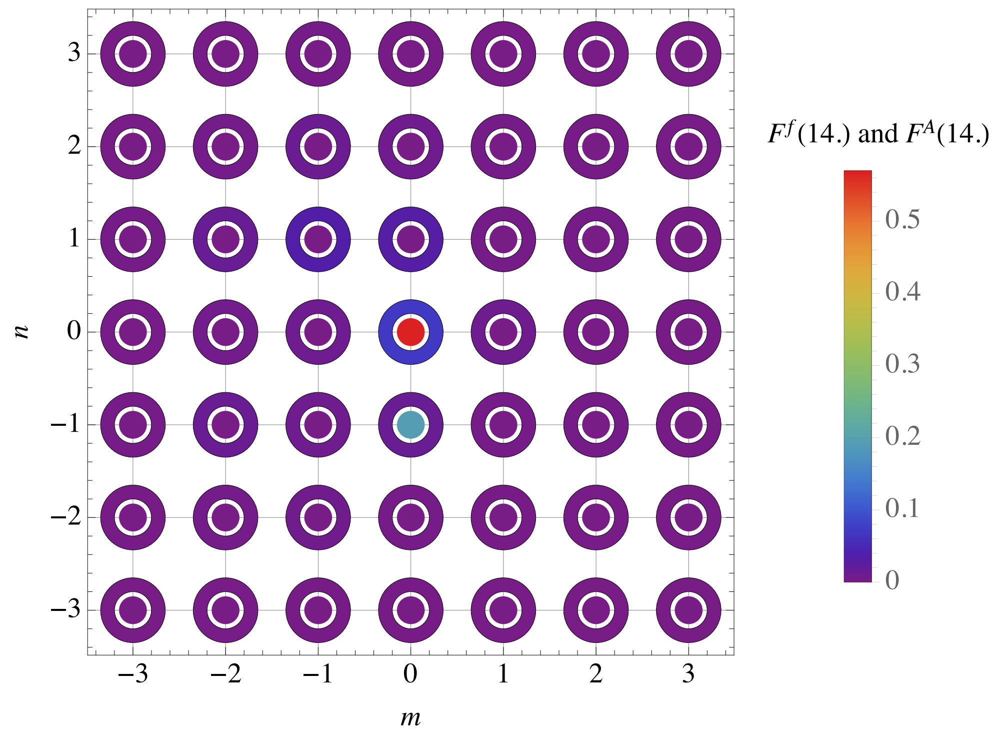

growing
decaying
$\Psi_{-1\,1}$
$\Psi_{0\,1}$
$\Psi_{1\,1}$
$\Psi_{-1\,0}$
$\Psi_{0\,0}$
$\Psi_{1\,0}$
$\Psi_{-1\,-1}$
$\Psi_{0\,-1}$
$\Psi_{1\,-1}$
z


fast: $z = 8.5,\ t = 0.$
15
10
5
0
−5
−10
−15
y
−30
−20
−10
0
10
20
30
x


Alfvén: $z = 8.5,\ t = 0.$
15
10
5
0
−5
−10
−15
y
−30
−20
−10
0
10
20
30
x

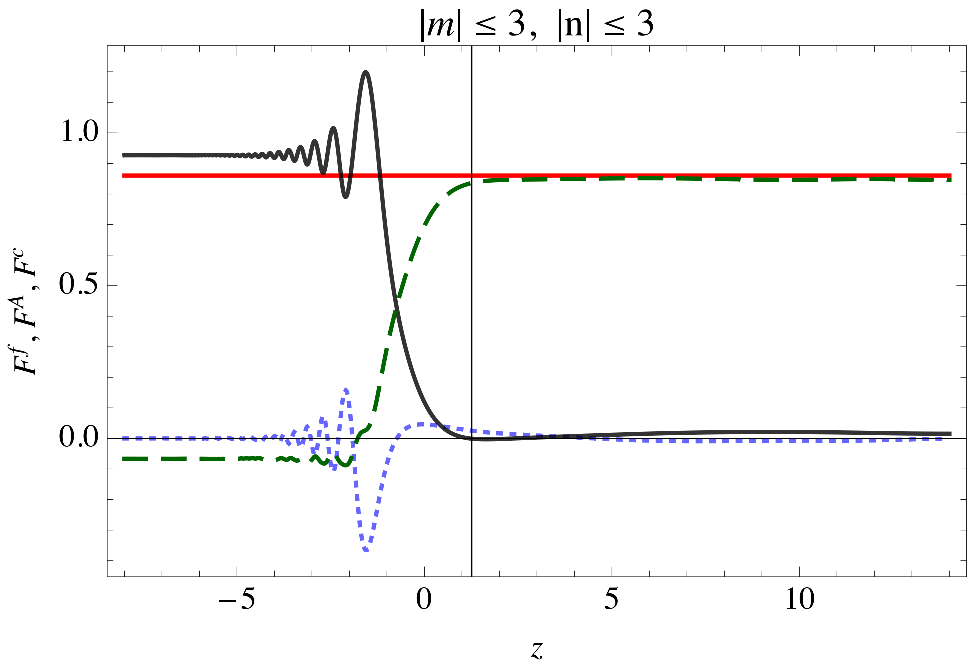
Swiss Cheese

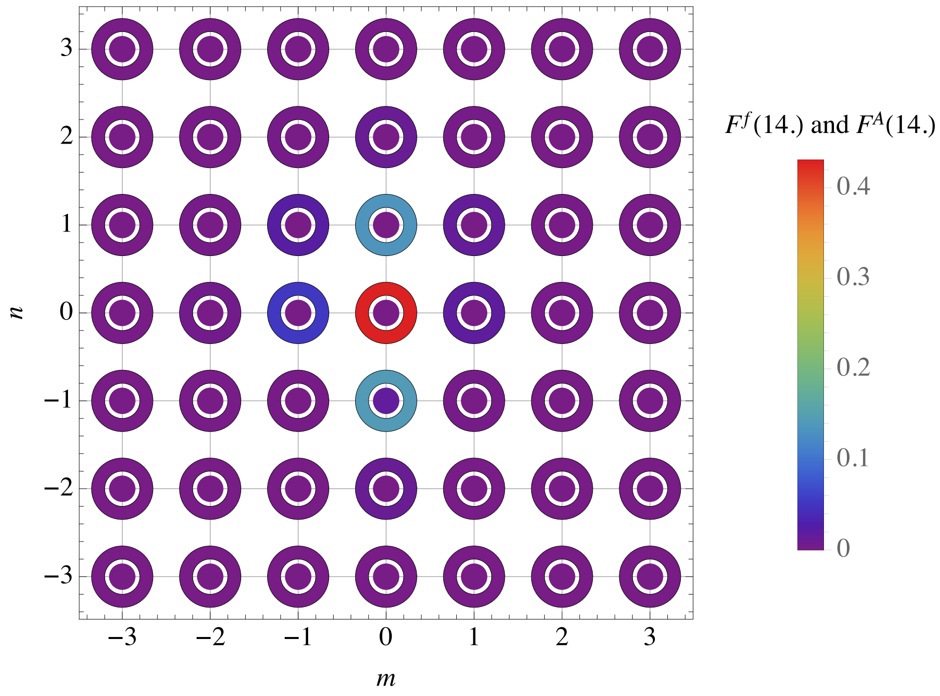
- $\alpha = 1.15$, but other parameters unaltered
- Fast wave does not reflect before reaching tubes
- *m*=*n*=0 fast wave now propagating in contiguous 69% of corona: not tubes, but Swiss cheese.
- Still some scattering to *m*=0, *n*=-1



Less inclined field

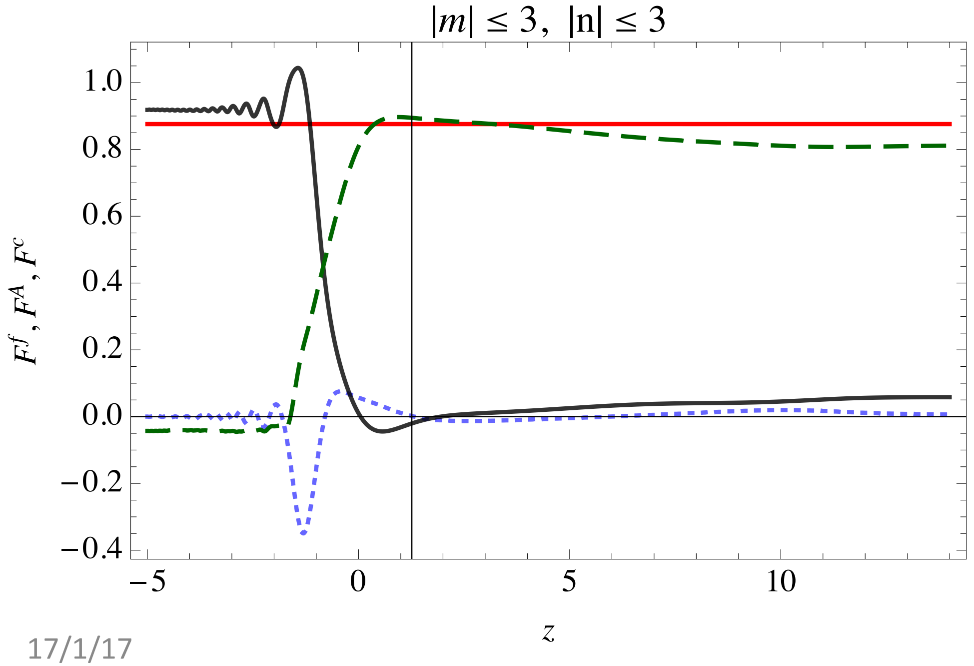
- $\theta = 20°$, other parameters unaltered ($\alpha = 0.85$)
- Nothing left in fast mode

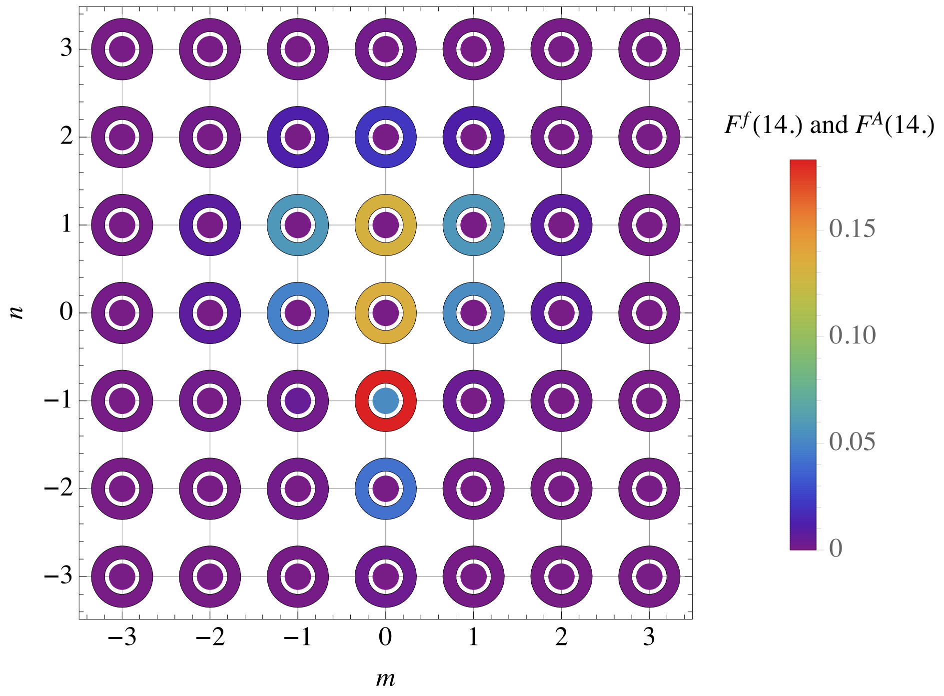




Less inclined field, different *r*, *s*

- $\theta = 20°$, other parameters unaltered ($\alpha = 0.85$), $r = \frac{1}{3}, s = \frac{5}{6}$
- Some fast mode returns
- Alfvén spread more widely in mode number space





Conclusions

1. Flux tube structure scatters in Fourier space
2. Fast waves generally reflect before reaching corona. But scattering makes travelling fast waves possible in tubes.
3. However, fast wave decays via resonant absorption (conversion to Alfvén); stops in model where tubes fade out.
4. Tubes also scatter Alfvén waves, but these are all propagating. Takes energy from m=n=0 though (phase mixing).
5. Significant wave flux penetration of transition region.