Fast sausage modes in transversely continuous coronal tubes

Bo Li
Institute of Space Sciences
Shandong University

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S.-X. Chen, H. Yu, M.-Z. Guo @ Shandong U.
M. Xiong @ National Space Science Center

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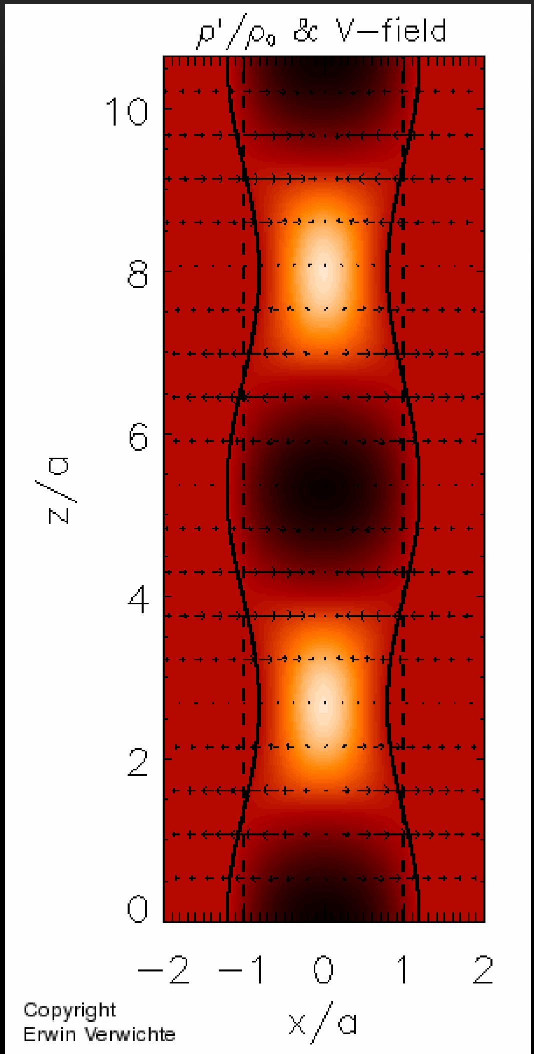
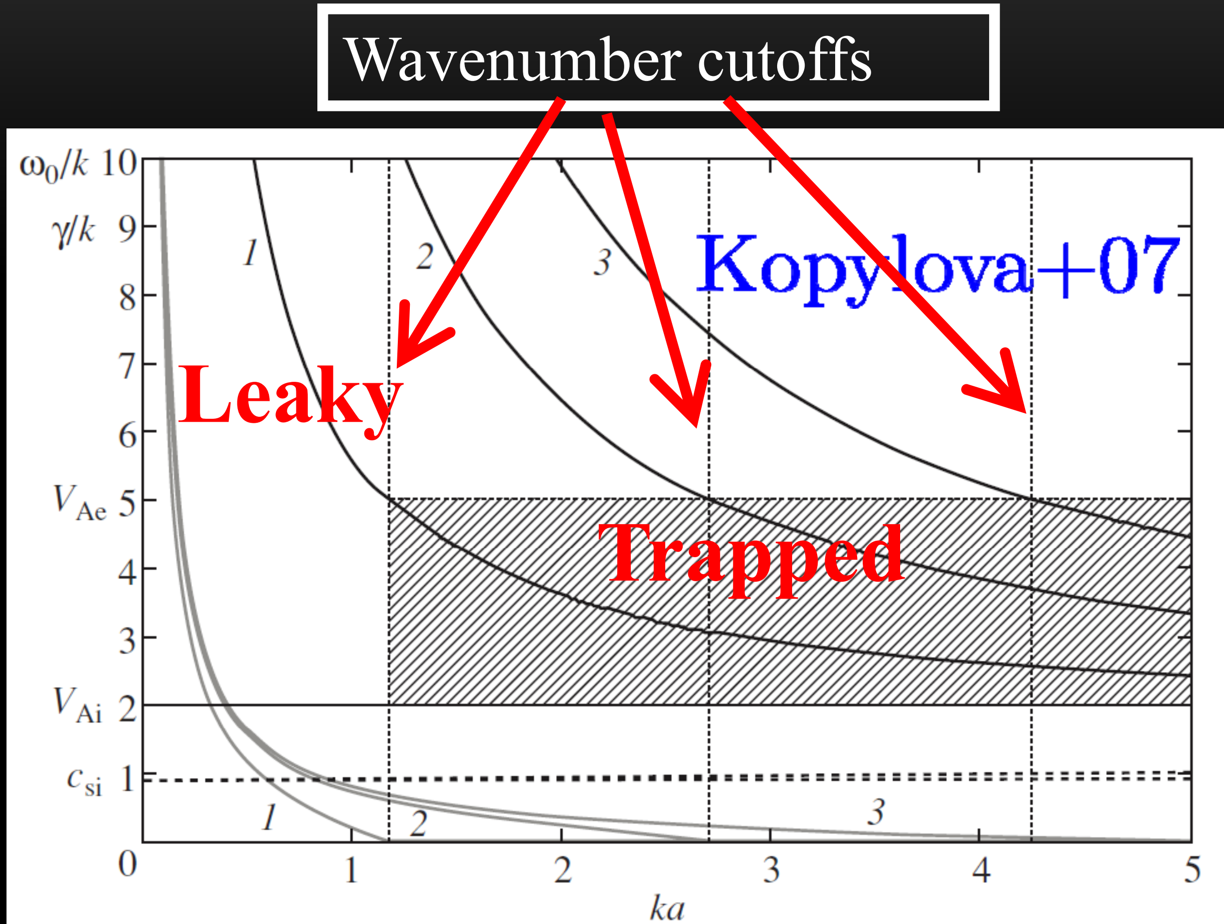
Fast sausage modes in transversely continuous coronal tubes

Contents

- Brief Intro to sausage modes
- Standing sausage modes in flare loops & their seismological applications
- Impulsively generated sausage wave trains in coronal tubes & implications for seismology

Fast sausage modes in tubes





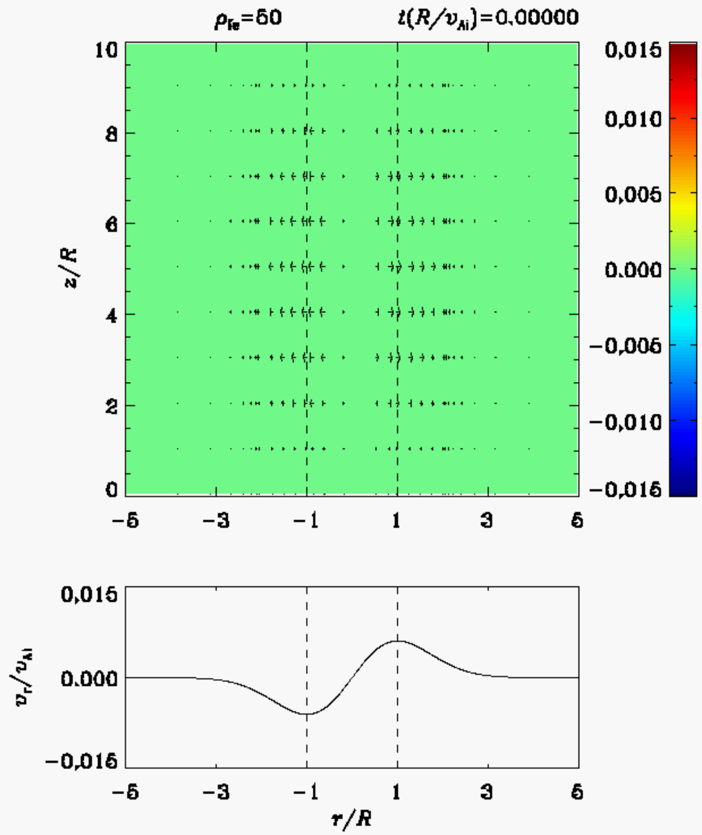
Stationary Prop. Waves [Nakariakov & Verwichte 05 LRSP]

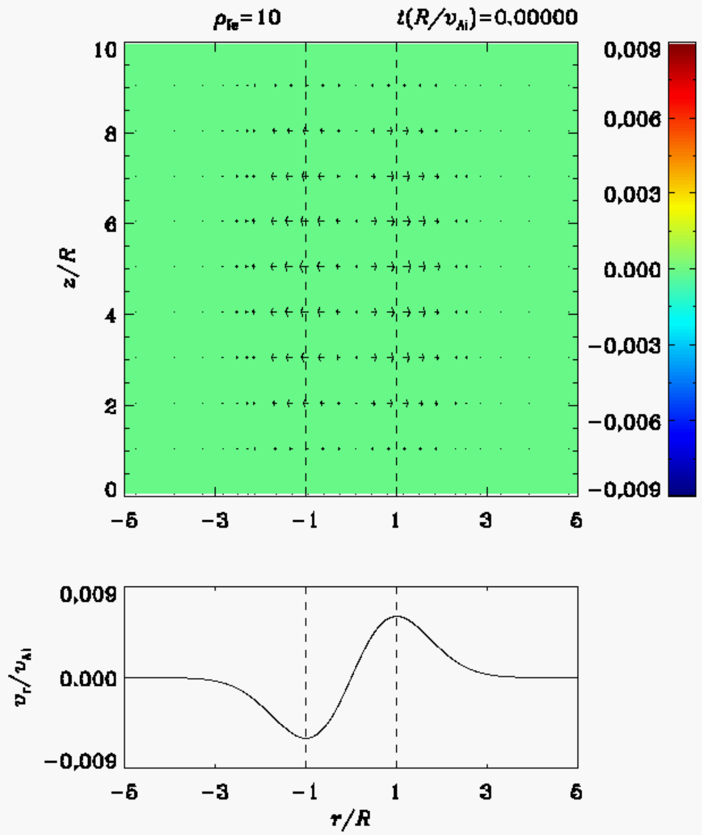
Phase speeds: real part (thick), imag. (thin) [Rosenberg 70; Zaitsev & Stepanov 75; Edwin & Roberts 83; Cally 86; …]

Fast standing modes: an initial-value-problem perspective

trapped

leaky

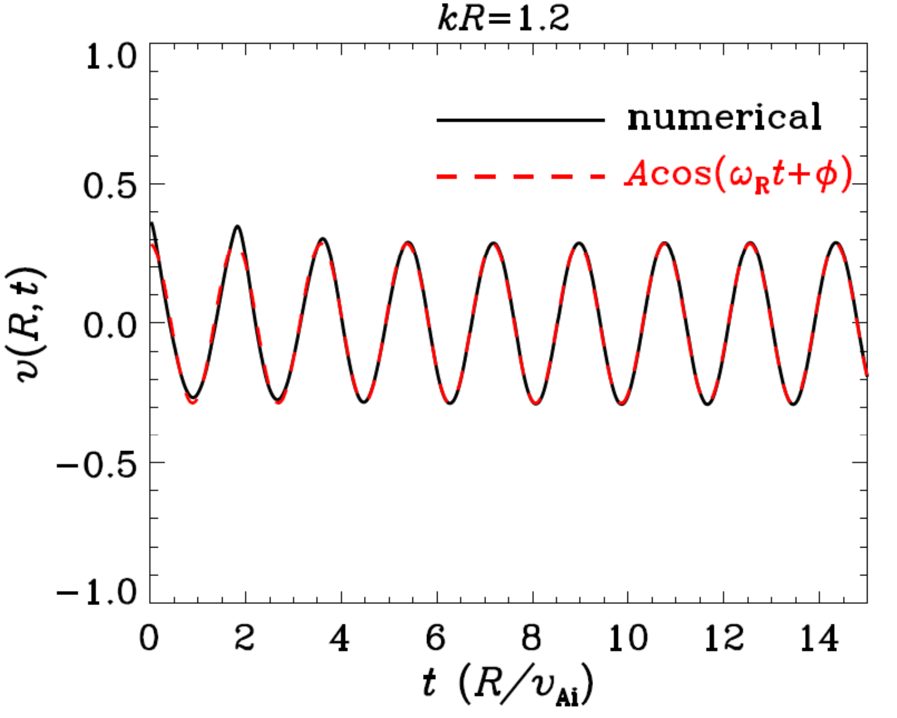




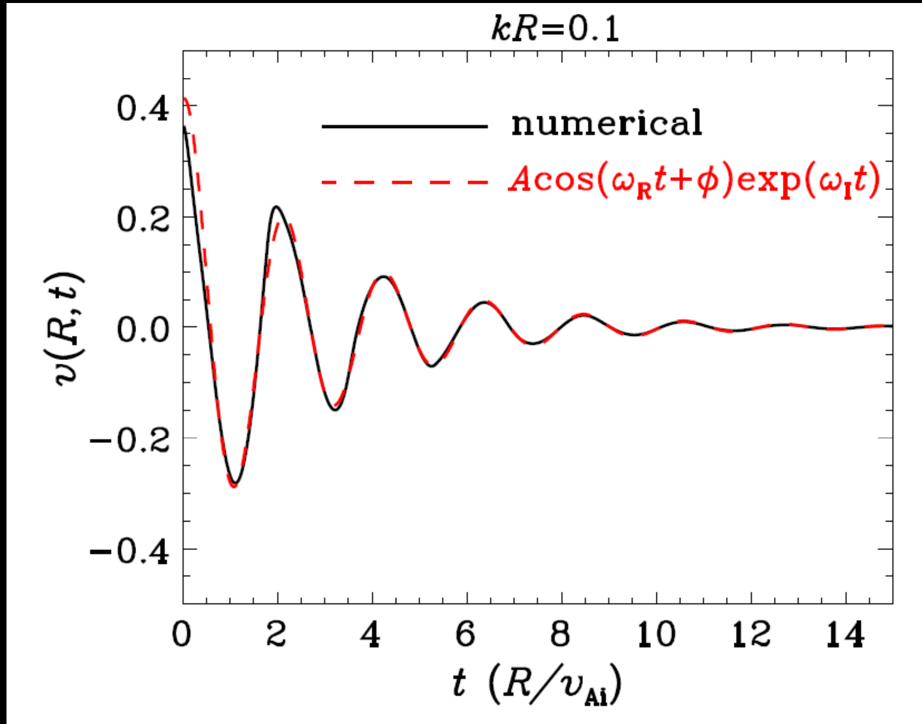
Upper row: Filled contours → density pert.; vectors → vel. Field
Lower row: radial distribution of radial velocity

Fast standing modes: an IVP approach

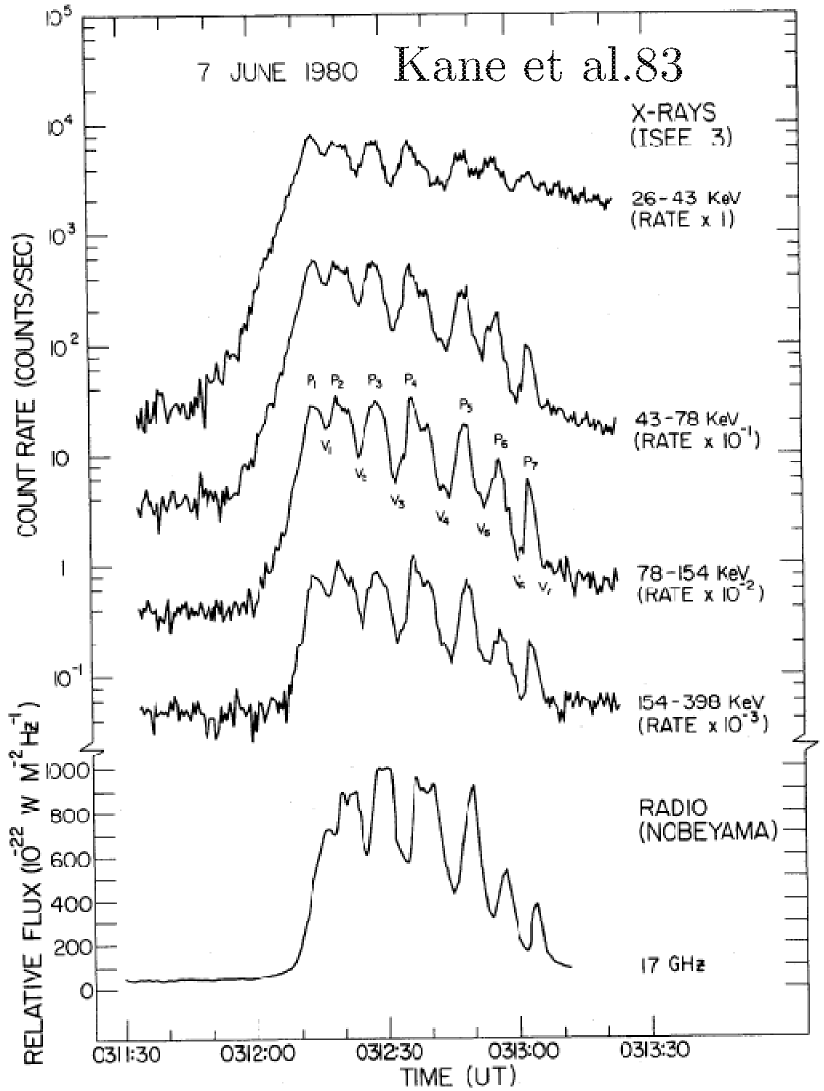
trapped



leaky

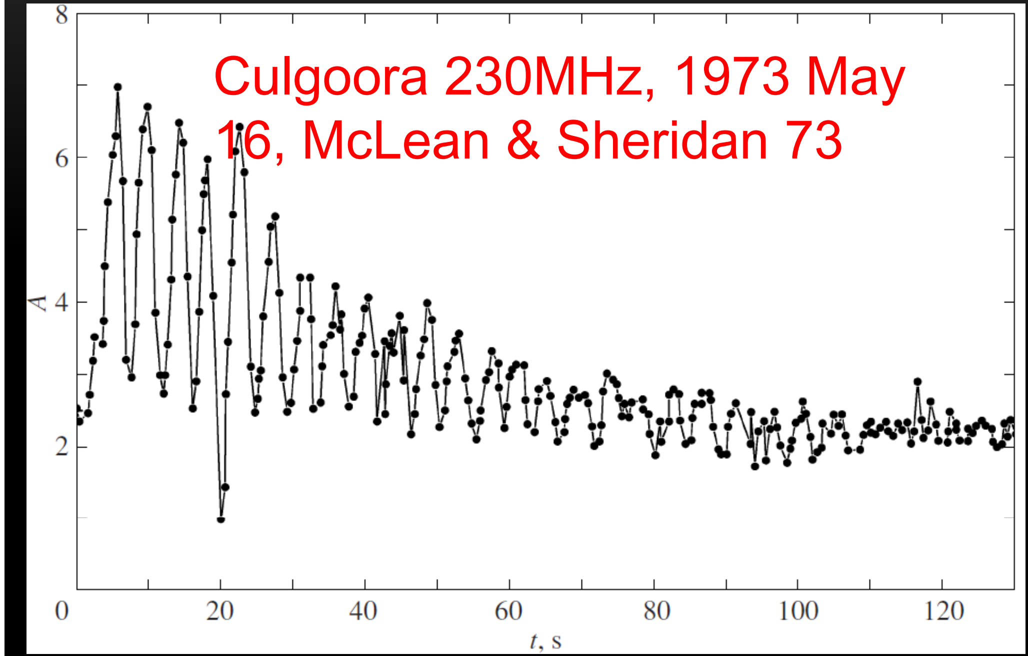


Quasi-periodic pulsations(QPPs) in solar flare lightcurves



- Discovered in late 1960's[Parks & Winckler 69, Frost 69, Rosenberg 70, …]
- Seen in all phases, in nearly all (? Inglis+16) flares [Nakariakov+09, Van Doorsselare+16]
- Imaging measurements possible
  - NoRH [e.g.,Asai+01, Nakariakov+03, Kolotkov+15]
  - SDO/AIA [e.g., Su+12, Li, Ning+16]
  - IRIS [Tian+16]
- Standing sausage modes → QPPs with periods ~ secs [e.g., Aschwanden+04]

Inferring flare loop parameters with QPPs



Kopylova+07

$$P \approx \frac{2.6a}{v_{Ai}} \qquad \tau/P \approx \frac{\rho_0/\rho_e}{\pi^2}$$

$$P \approx 4.3\text{s}, \ \tau/P \approx 10$$

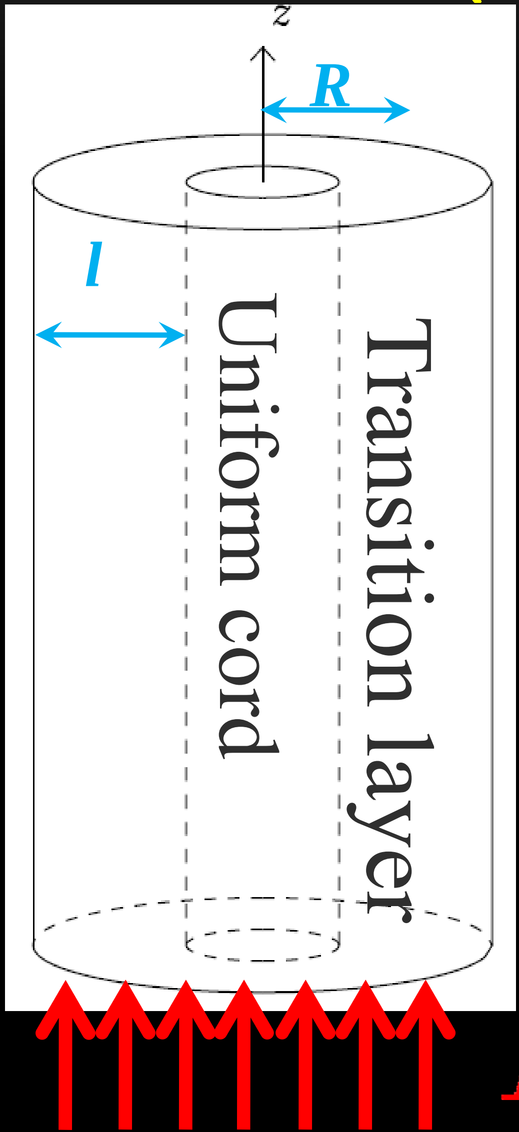
$$a/v_{\rm Ai} \approx 1.6\text{s}, \text{ den ratio} \approx 10$$

- Transverse Alfven time → B strength
- Key assumptions
  - Transverse ~~distributions of parameters: Discontinuous~~
  - (very often) gas pressure neglected

Dispersive Properties of Sausage Modes

	Transversely discontinuous	Transversely continuous
beta = 0	Eigenmode analysis: Rosenburg 70; Zaitsev & Stepanov 75; Meerson+78; Spruit 82; Cally 86; Vasheganhi Farahani+14; … Initial-value-problem (IVP) Terradas+07	Eigenmode analysis: Pneuman 65; Lopin & Nagorny 14, 15; Chen+15a, Yu+16; summarized in Yu+17 ApJ IVP Nakariakov+12; Chen+15a,b; Guo+16
beta ≠ 0	Eigenmode analysis: Edwin & Roberts 83; Kopylova+07; …	Eigenmode analysis: Chen+16 Initial-value-problem (IVP) Chen+16

Transversely continuous density profile (but still pressureless)



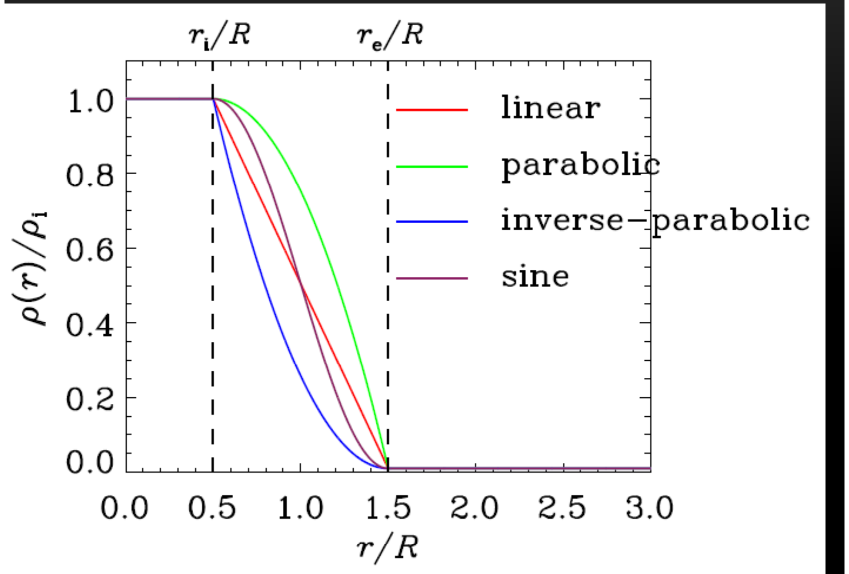
Analytical DR [Chen+15], applicable to

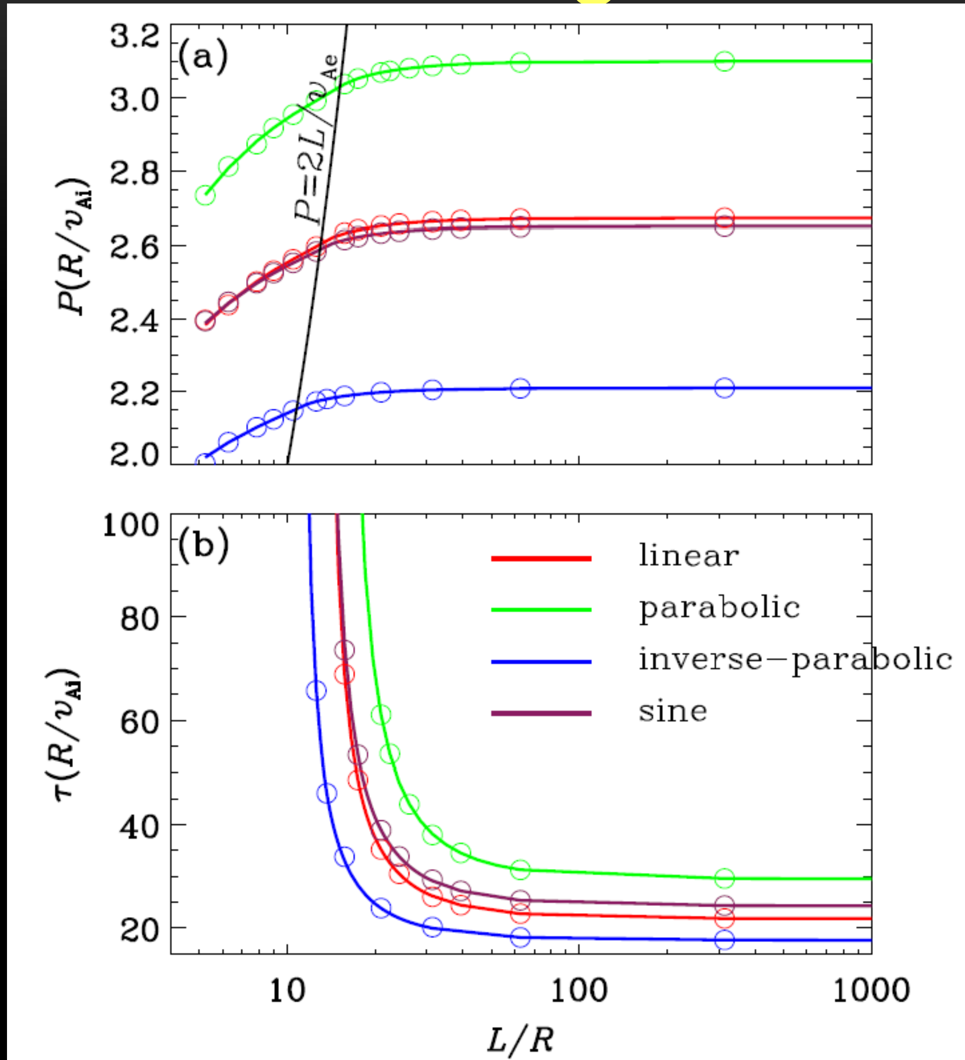
- ☐ arbitrary transition layer thickness (0, 2*R*)
- ☐ arbitrary profile prescription in the TL

$$\rho_{\rm tr}(r) = \begin{cases} \rho_{\rm i} - \dfrac{\rho_{\rm i} - \rho_{\rm e}}{l}\left(r - R + \dfrac{l}{2}\right), & \text{linear}, \\ \rho_{\rm i} - \dfrac{\rho_{\rm i} - \rho_{\rm e}}{l^2}\left(r - R + \dfrac{l}{2}\right)^2, & \text{parabolic}, \\ \rho_{\rm e} - \dfrac{\rho_{\rm e} - \rho_{\rm i}}{l^2}\left(r - R - \dfrac{l}{2}\right)^2, & \text{inverse} - \text{parabolic}, \\ \dfrac{\rho_{\rm i}}{2}\left[\left(1 + \dfrac{\rho_{\rm e}}{\rho_{\rm i}}\right) - \left(1 - \dfrac{\rho_{\rm e}}{\rho_{\rm i}}\right)\sin\dfrac{\pi(r - R)}{l}\right], & \text{sine}. \end{cases}$$

$\bar{B}$ Uniform external medium

Dispersive properties of sausage modes





Chen, Li+2015 ApJ, 812, 22

$$k = \pi/L$$

- Overall, similar to top-hat case

Re-analysis of the Mclean & Sheridan event

$$P_{\rm saus} = \frac{R}{v_{\rm Ai}} F_{\rm saus}\left(\frac{L}{R}, \frac{l}{R}, \frac{\rho_{\rm i}}{\rho_{\rm e}}\right),$$

$$\frac{\tau_{\rm saus}}{P_{\rm saus}} = G_{\rm saus}\left(\frac{L}{R}, \frac{l}{R}, \frac{\rho_{\rm i}}{\rho_{\rm e}}\right).$$

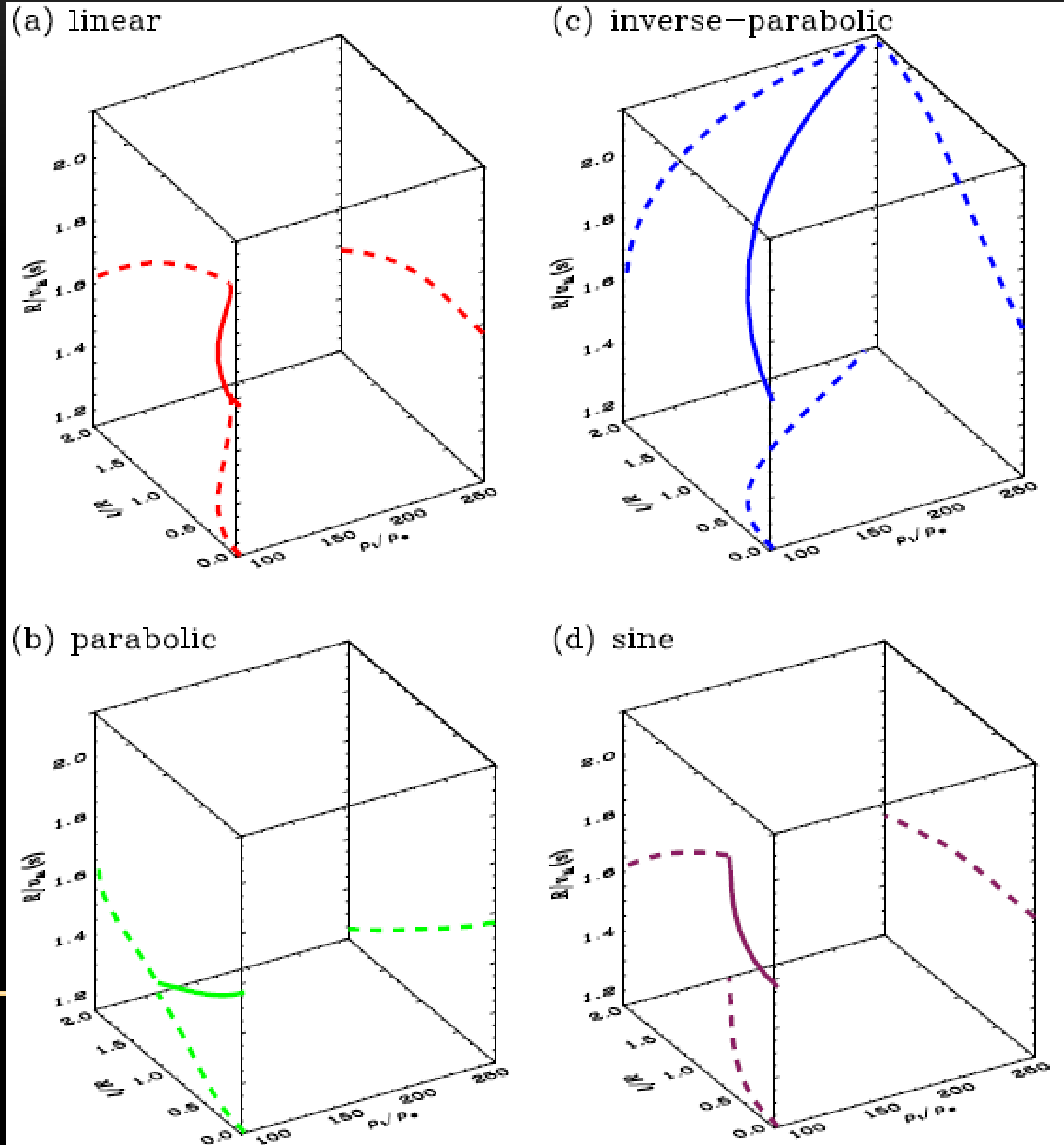
$$k = \pi / L$$

Chen+15 ApJ, 812, 22

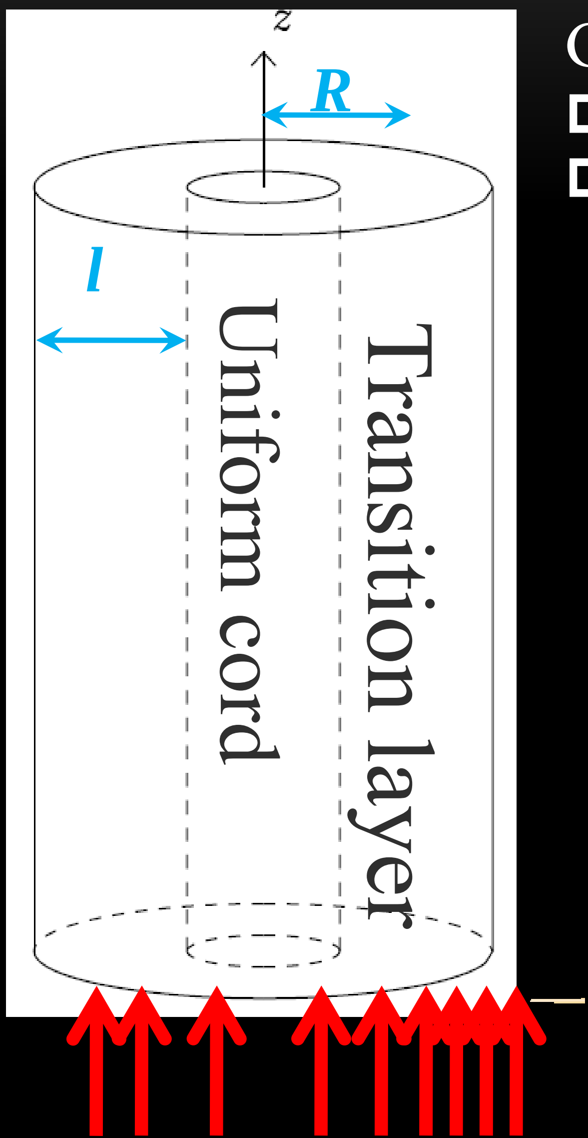
- Deduced transverse Alfven time: Max/Min = 1.8
- Not possible to constrain TL width

Guo+16, 2016 SoPh, 291, 877

- Possible to improve, if QPPs spatially resolved & involve multiple modes



Finite gas pressure & continuous distribution



Gas/magnetic pressure may reach unity

- Hot Active Region Loops [SUMER, Wang+07,…]
- Hot & Dense flare loops [Nakariakov+03, Melnikov+05]

$$\rho(r) = \begin{cases} \rho_i, & 0 \leqslant r \leqslant r_i = R - l/2, \\ \rho_{tr}(r) = \mathcal{F}(\rho_i, \rho_e; r), & r_i \leqslant r \leqslant r_e = R + l/2, \\ \rho_e, & r \geqslant r_e, \end{cases}$$

$$T(r) = \begin{cases} T_i, & 0 \leqslant r \leqslant r_i, \\ T_{tr}(r) = \mathcal{F}(T_i, T_e; r), & r_i \leqslant r \leqslant r_e, \\ T_e, & r \geqslant r_e. \end{cases}$$

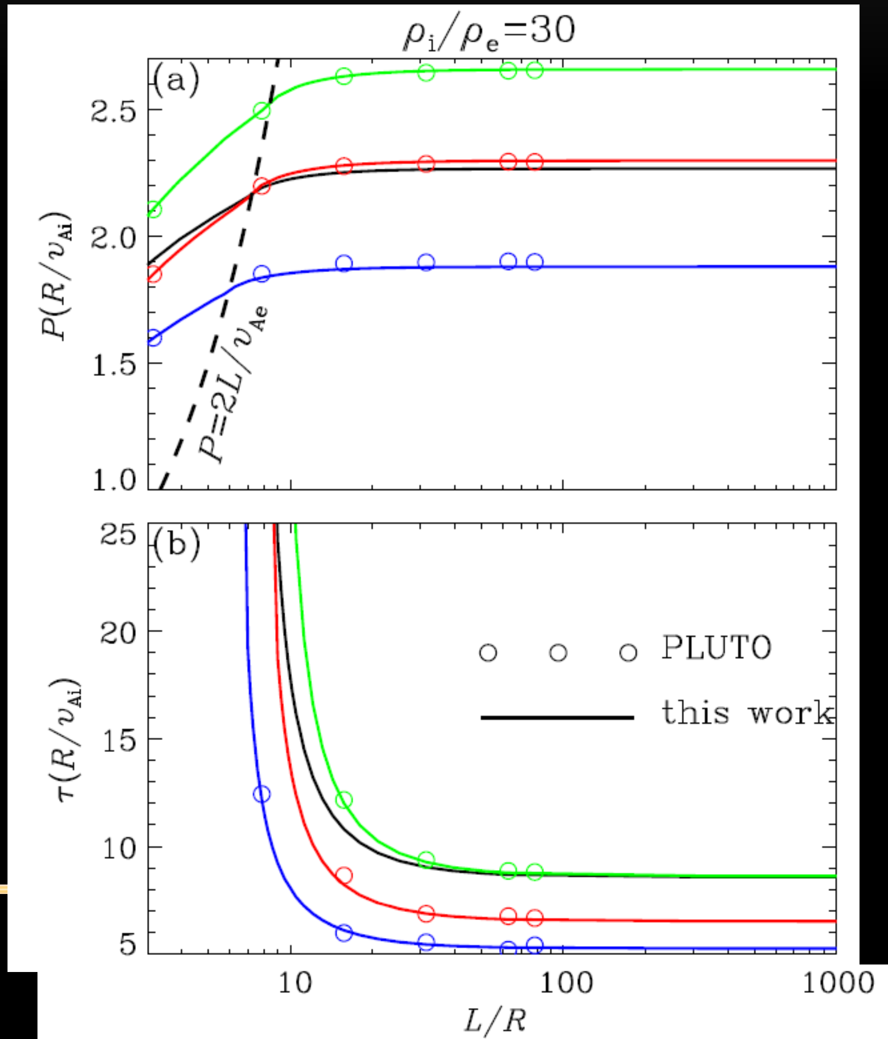
[Chen, Li, et al. 2016 ApJ 833, 114]

$$\frac{\dfrac{\rho_{\rm i} J_0(\mu_{\rm i} r_{\rm i})(\omega^2 - k^2 v_{\rm Ai}^2)}{\mu_{\rm i} r_{\rm i} J_1(\mu_{\rm i} r_{\rm i})} y_1(x_{\rm i}) + \Lambda_{\rm i} y_1'(x_{\rm i})}{\dfrac{\rho_{\rm i} J_0(\mu_{\rm i} r_{\rm i})(\omega^2 - k^2 v_{\rm Ai}^2)}{\mu_{\rm i} r_{\rm i} J_1(\mu_{\rm i} r_{\rm i})} y_2(x_{\rm i}) + \Lambda_{\rm i} y_2'(x_{\rm i})} - \frac{\dfrac{\rho_{\rm e} H_0^{(1)}(\mu_{\rm e} r_{\rm e})(\omega^2 - k^2 v_{\rm Ae}^2)}{\mu_{\rm e} r_{\rm e} H_1^{(1)}(\mu_{\rm e} r_{\rm e})} y_1(x_{\rm e}) + \Lambda_{\rm e} y_1'(x_{\rm e})}{\dfrac{\rho_{\rm e} H_0^{(1)}(\mu_{\rm e} r_{\rm e})(\omega^2 - k^2 v_{\rm Ae}^2)}{\mu_{\rm e} r_{\rm e} H_1^{(1)}(\mu_{\rm e} r_{\rm e})} y_2(x_{\rm e}) + \Lambda_{\rm e} y_2'(x_{\rm e})} = 0 \, ,$$

$$\frac{\omega R}{v_{\rm Ai}} = \mathcal{G}\left(\frac{L}{R}, \frac{l}{R}, \frac{\rho_{\rm i}}{\rho_{\rm e}}, \beta_{\rm i}, \beta_{\rm e}\right)$$

β_i=0.5, β_e=0.01, l/R=1.0

- step (black)
- linear (red)
- parabolic (green)
- inverse−parabolic (blue)

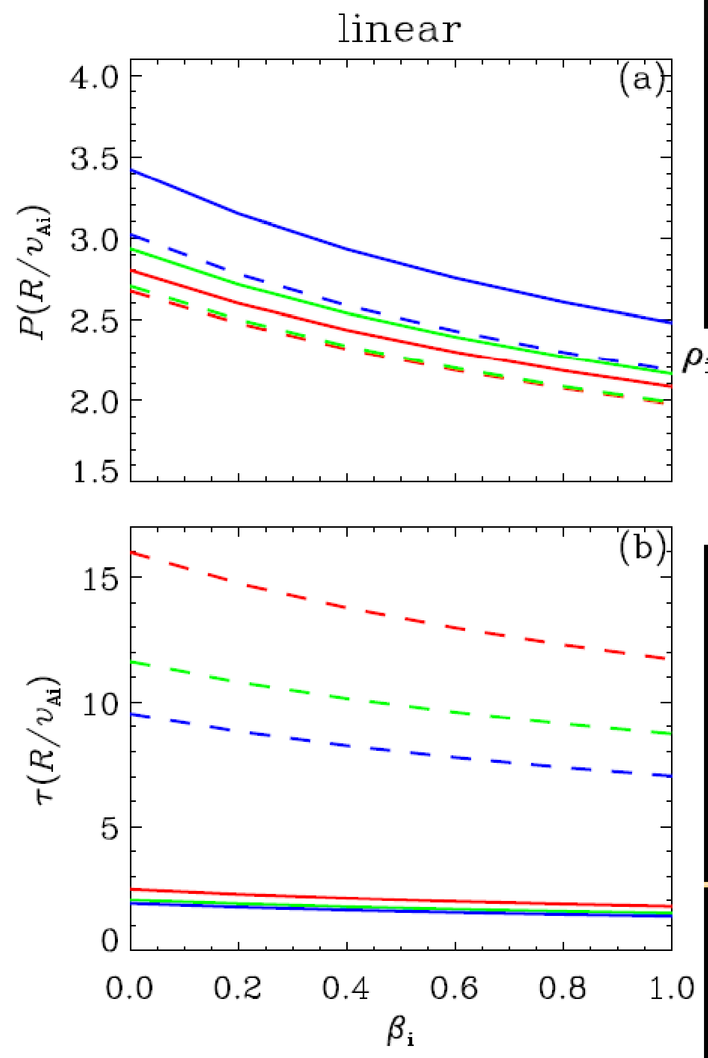


Importance of units of P & tau

$$\frac{\omega R}{v_{\rm Ai}} = \mathcal{G}\left(\frac{L}{R}, \frac{l}{R}, \frac{\rho_{\rm i}}{\rho_{\rm e}}, \beta_{\rm i}, \beta_{\rm e}\right)$$

$$\frac{\omega R}{v_{\rm fi}} = \mathcal{H}\left(\frac{L}{R}, \frac{l}{R}, \frac{\rho_{\rm i}}{\rho_{\rm e}}, \beta_{\rm i}, \beta_{\rm e}\right)$$

$$v_{\rm f}^2 = c_{\rm s}^2 + v_{\rm A}^2$$

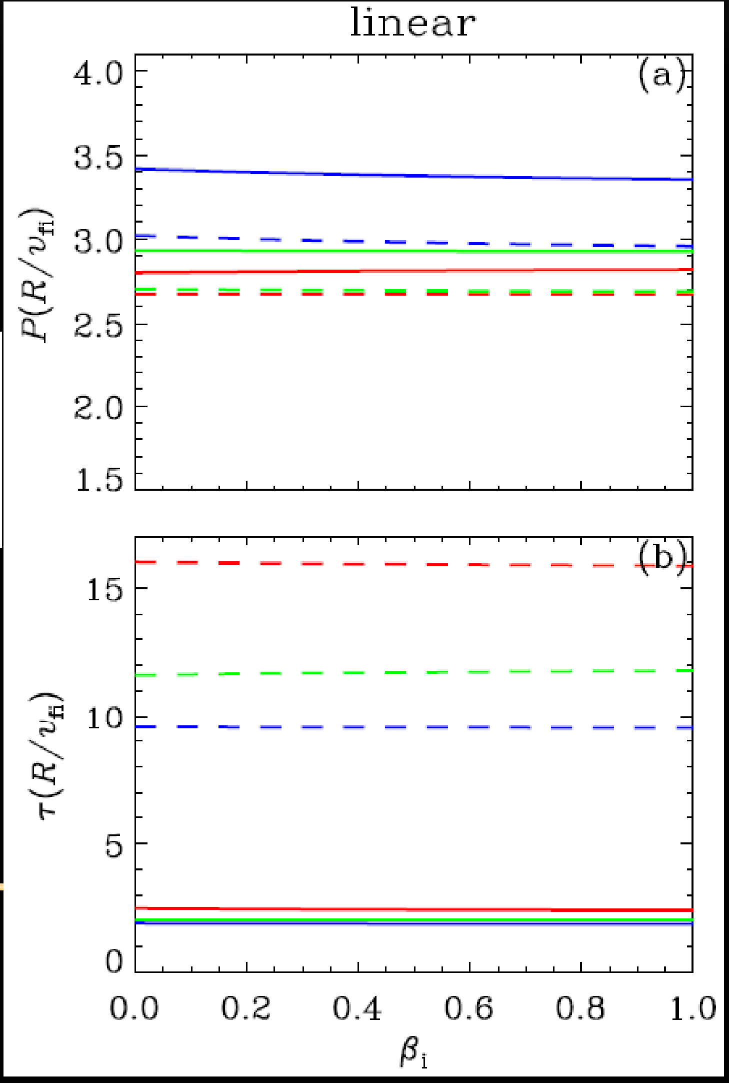


$\rho_{\rm i}/\rho_{\rm e}$ = 5 50

l/R=0.01

l/R=1.0

l/R=1.99



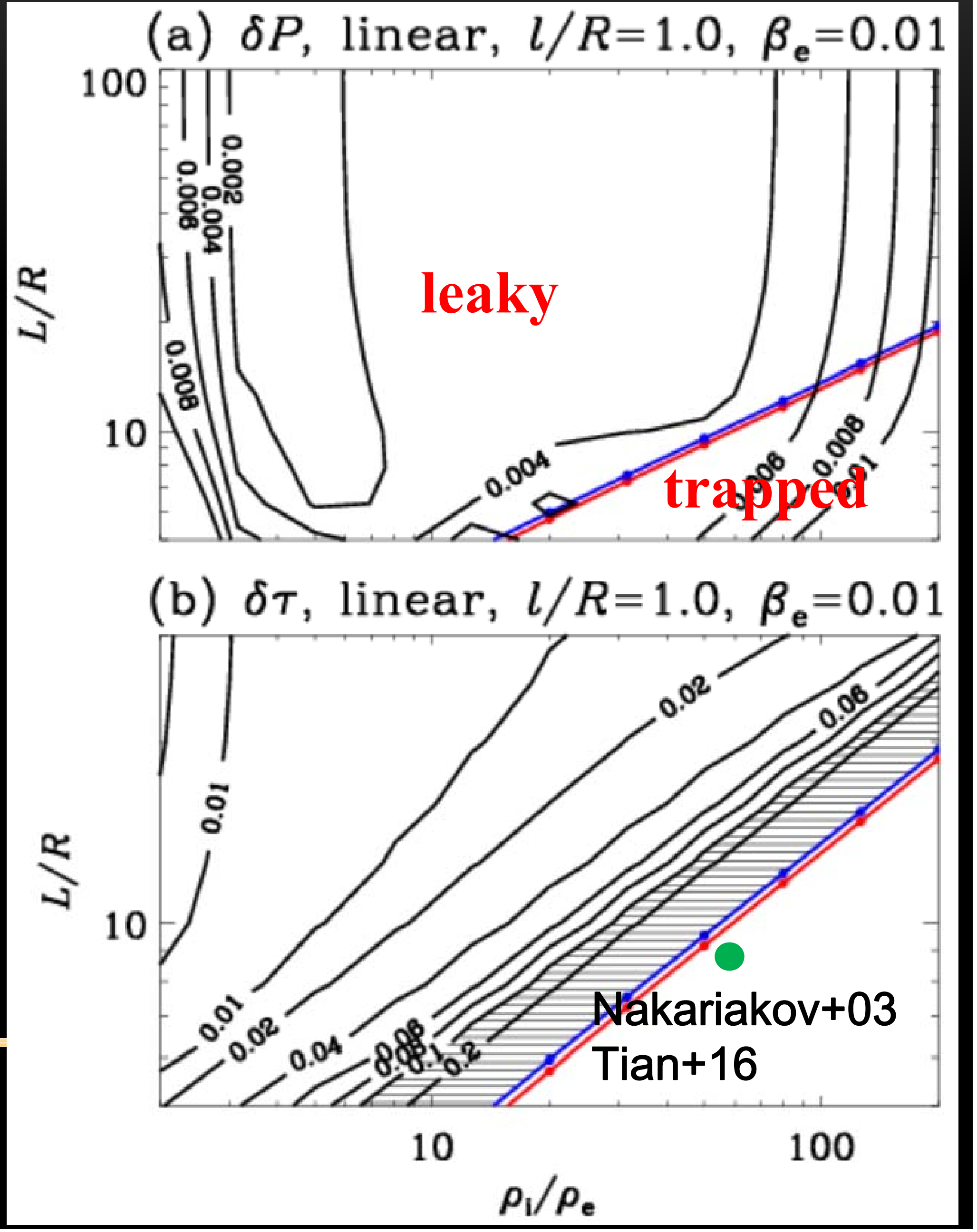
Finite vs. zero gas pressure

$$\frac{\omega R}{v_{\rm fi}} = \mathcal{H}\left(\frac{L}{R}, \frac{l}{R}, \frac{\rho_{\rm i}}{\rho_{\rm e}}, \beta_{\rm i}, \beta_{\rm e}\right)$$

$$\delta P = \max\left|\frac{P^{\beta\neq 0}(\beta_{\rm i}\in[0,1])}{P^{\rm cold}} - 1\right|$$

$$\delta \tau = \max\left|\frac{\tau^{\beta\neq 0}(\beta_{\rm i}\in[0,1])}{\tau^{\rm cold}} - 1\right|$$

- negligible changes to cutoff wavenumbers & periods
- Changes to damping times may be substantial

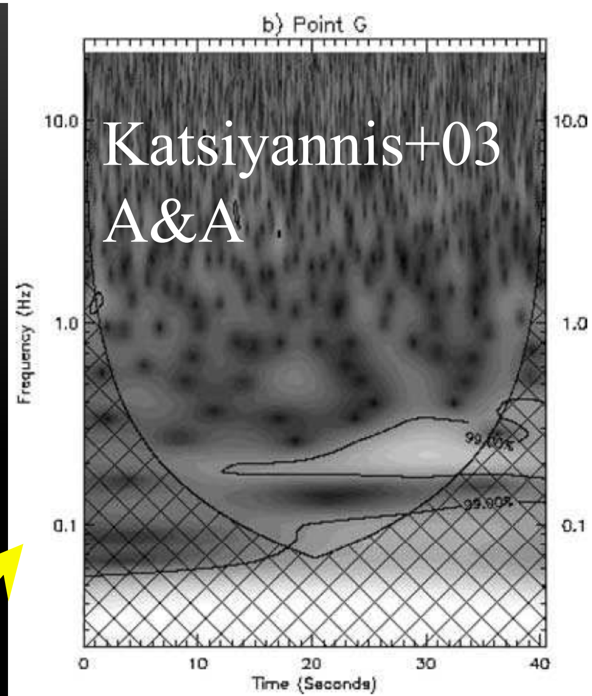


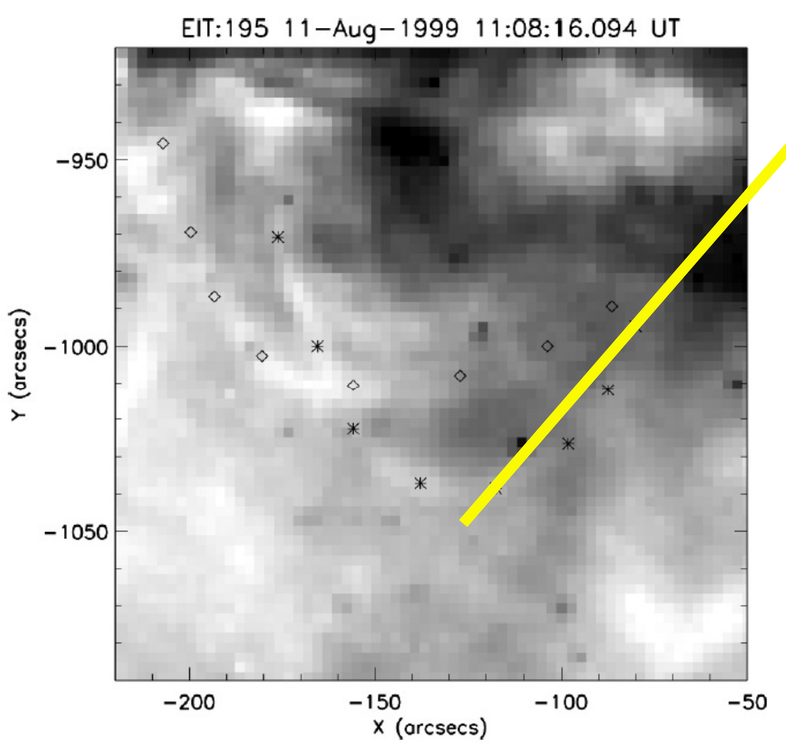
Sausage wave trains in coronal tubes

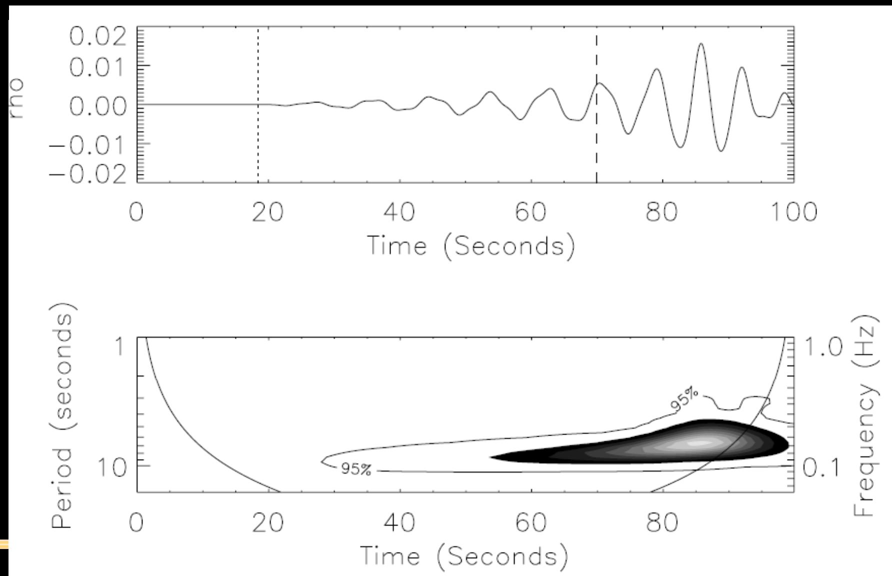
Oscillatory behavior in optical measurements of the corona

- Originated in Billings 59; Tsubaki 77… (5303; periods>minutes)
- Rapid oscillatory behavior at total eclipses
  - 5303; 0.5-2 secs (?) [Pasachoff & Landman 84; 1980 Hyderabad]
  - 5303; 0.5-4 secs (?) [Pasachoff & Ladd 87; 1983 Indonesian]
  - ……
  - 5303; 6 secs [Williams+01, 02; Katsiyannis+03; 1999 Bulgaria]
  - 5303 & 6374; 6-25 secs [Samanta+16, 2010 Chile]

“crazy tadpole”-like Morlet spectra

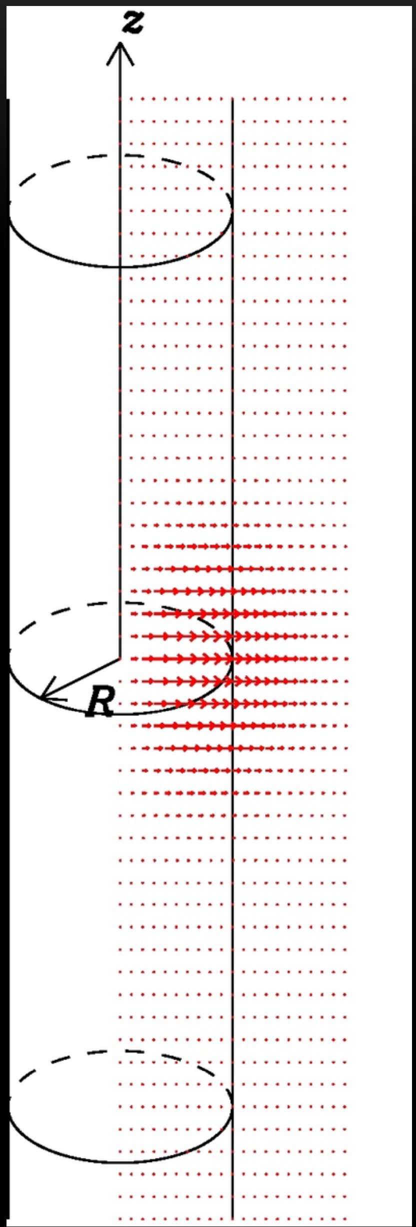


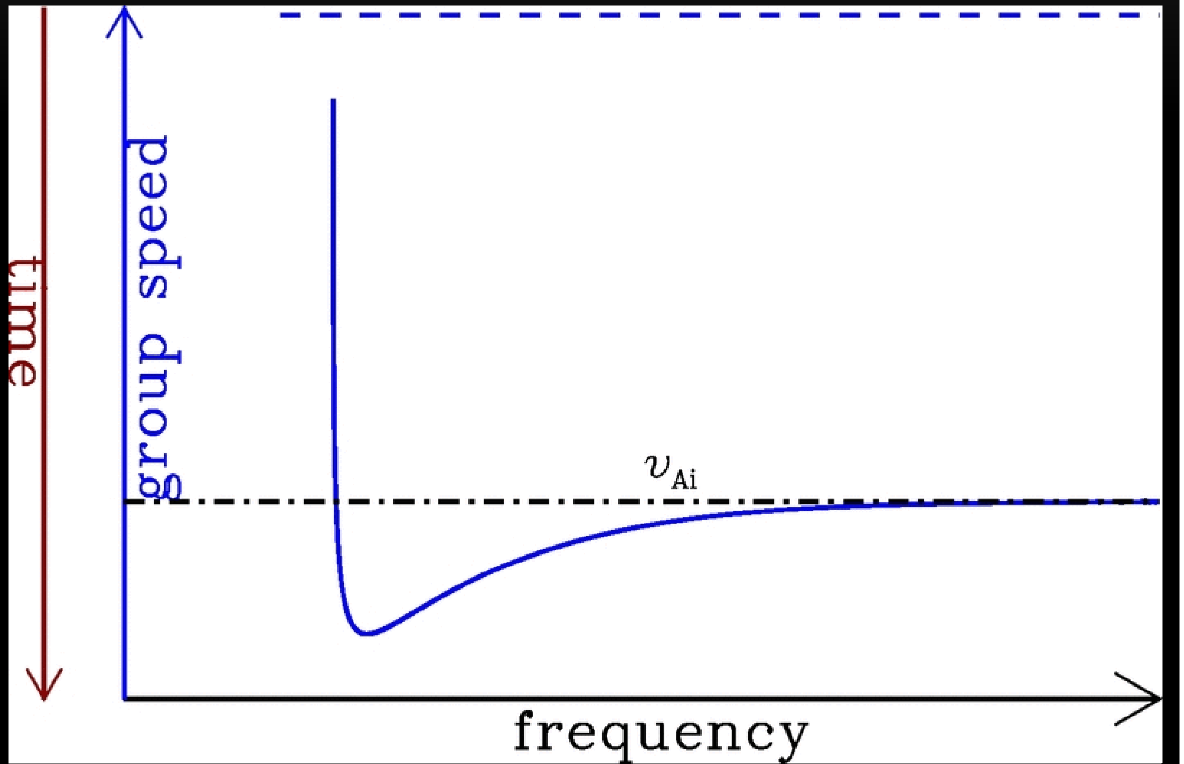




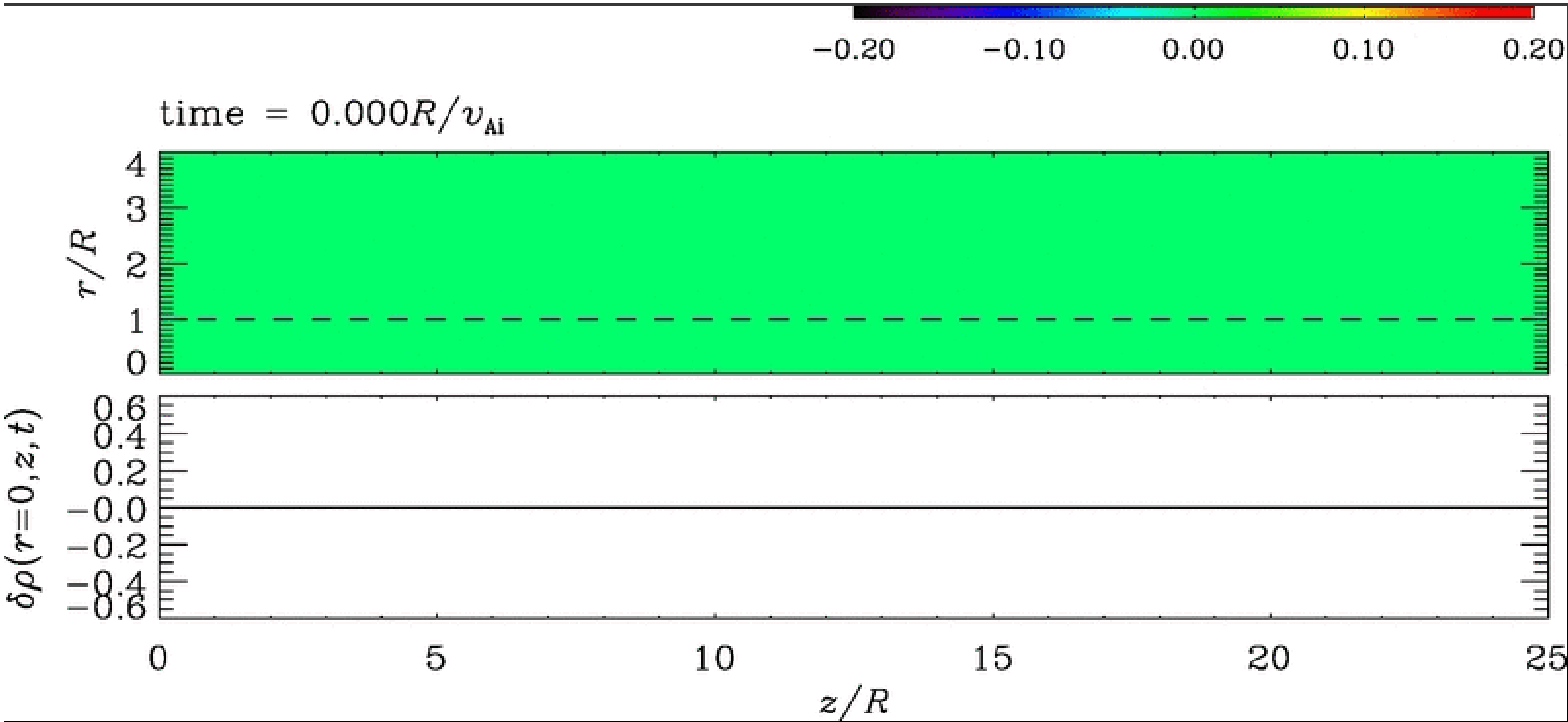
Slabs: Nakarikov+04
Tubes: Shestov+15

Interpretation in terms of sausage wave trains



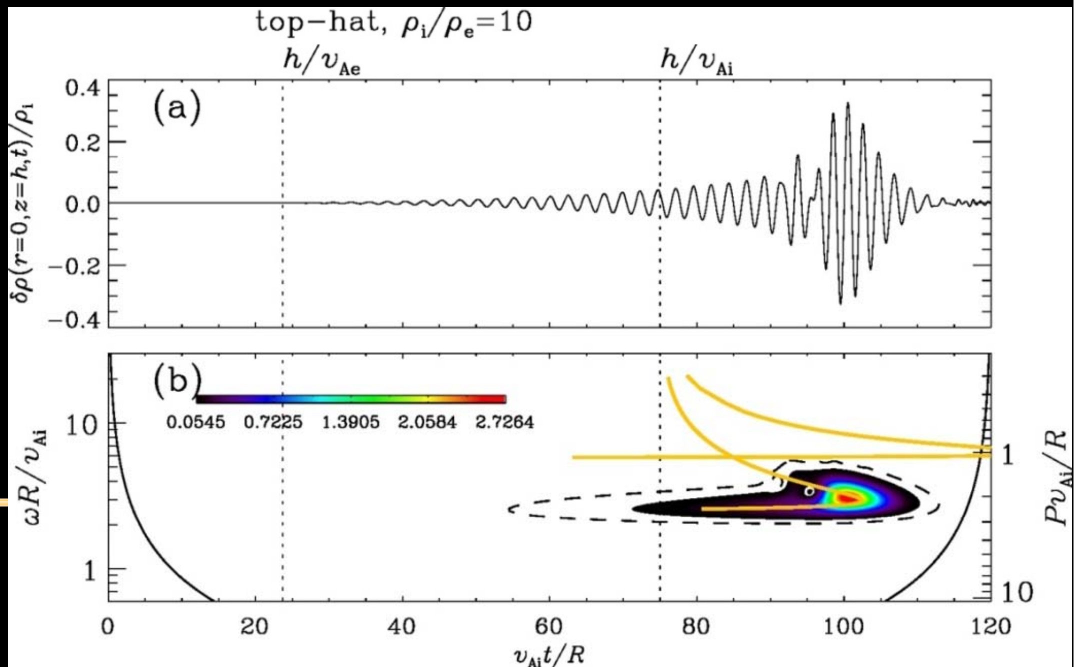


[Roberts+83, 84, Edwin & Roberts 86, 88; Nakariakov & Roberts 95, Oliver+15]



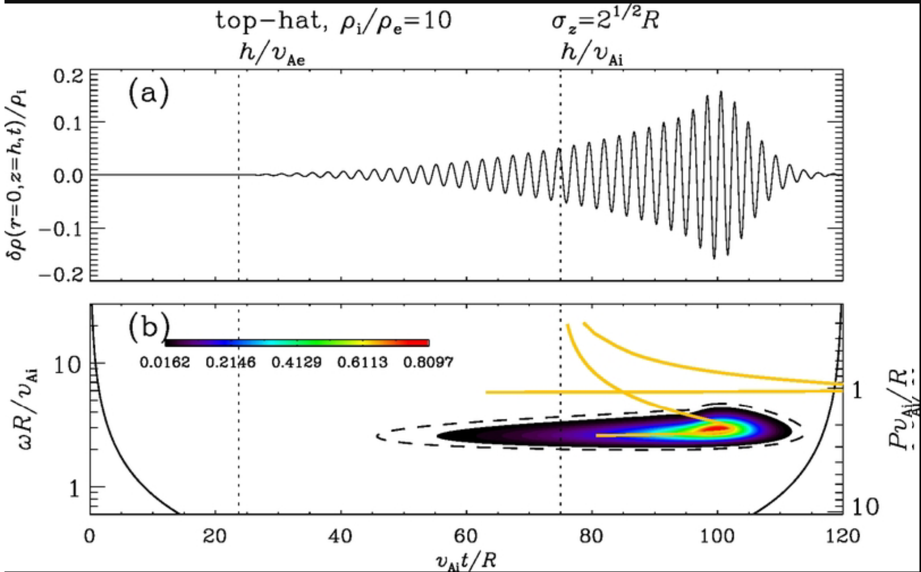
Yu, Li, et al. 2016ApJ 833, 51

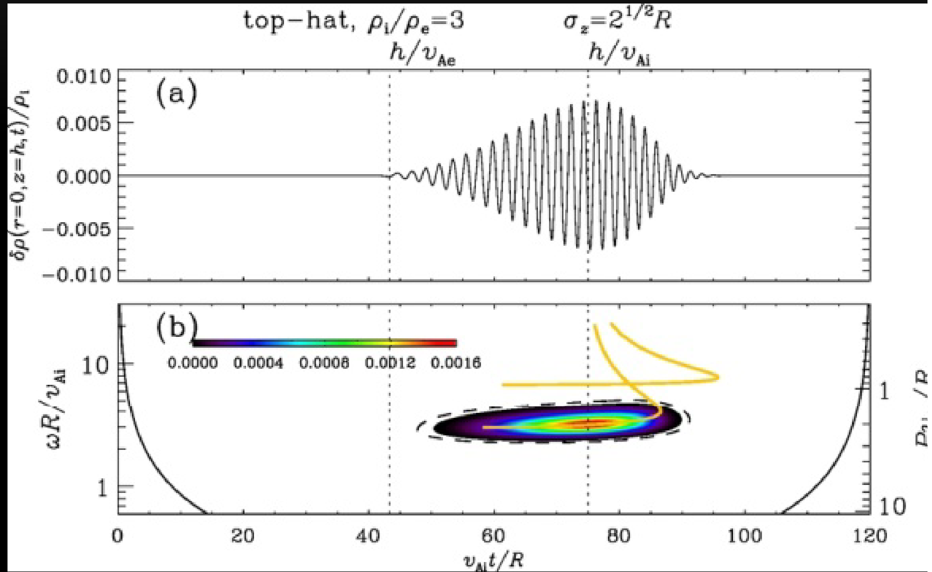
Yu, Li, et al. 2017ApJ, in press arXiv:1612.09479



yellow curves: $\omega - h/v_{gr}$

Spatial extent of initial perturbations

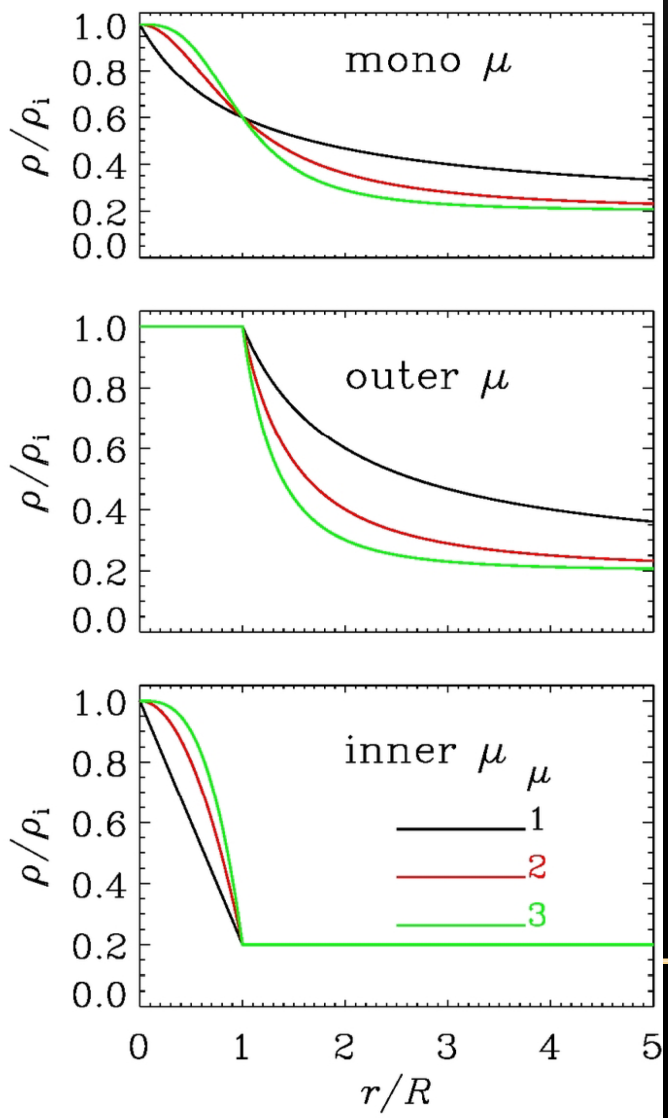




yellow curves: $\omega - h/v_{\rm gr}$

- Spatial extent of init. pert. important
- The reasoning by Roberts & co-workers?
- Group speed curves helpful for providing the context
  - Cutoff wavenumbers
  - Whether curves are monotonical

Continuous Transverse Structuring



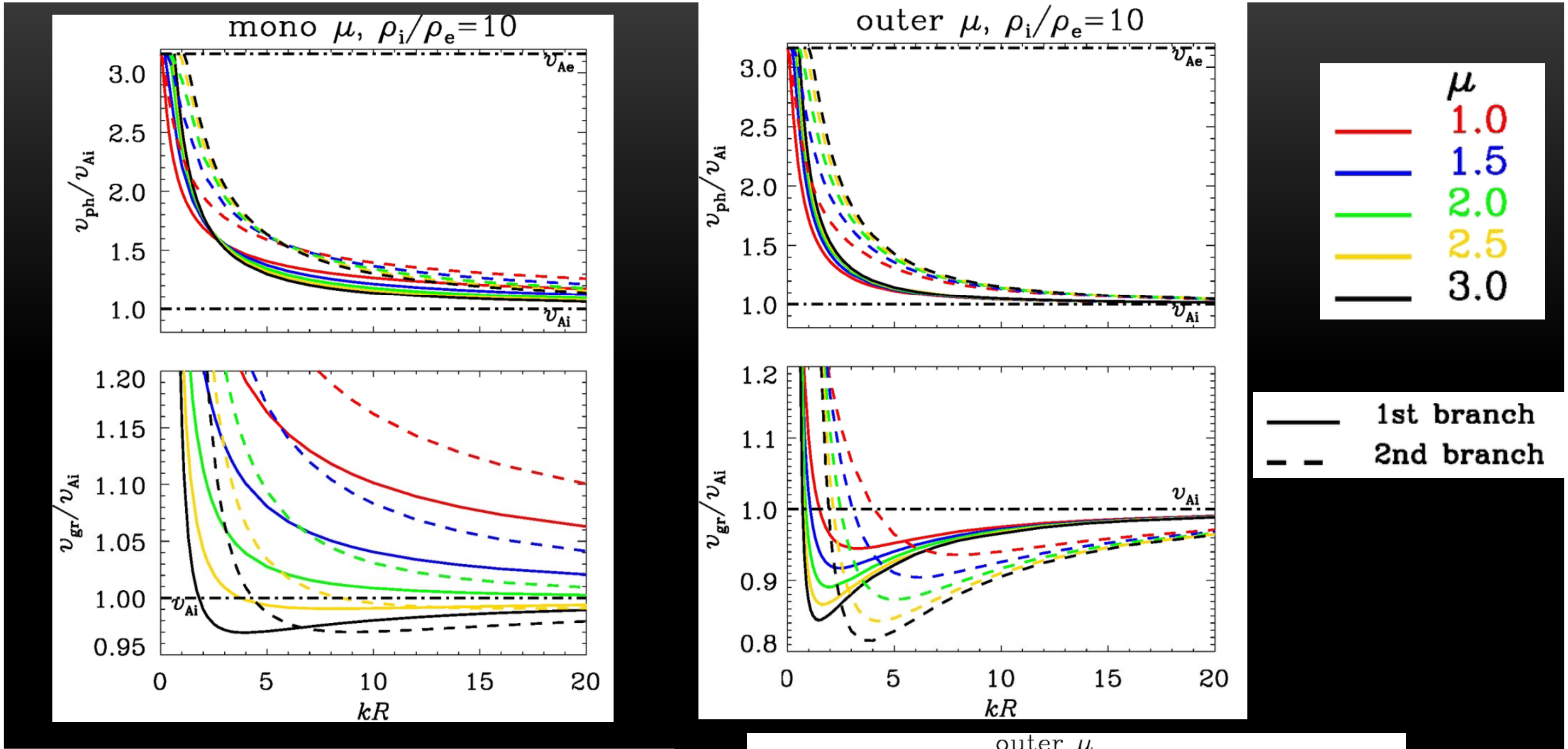
$$\rho(r) = \rho_e + (\rho_i - \rho_e) f(r)$$

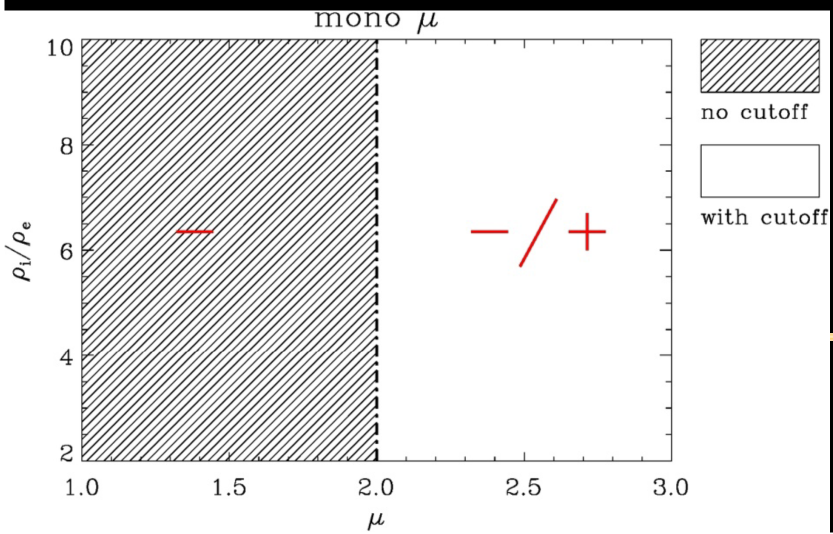
$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d\tilde{\xi}}{dr}\right) + \left(\frac{\omega^2}{v_A^2} - k^2 - \frac{1}{r^2}\right)\tilde{\xi} = 0$$

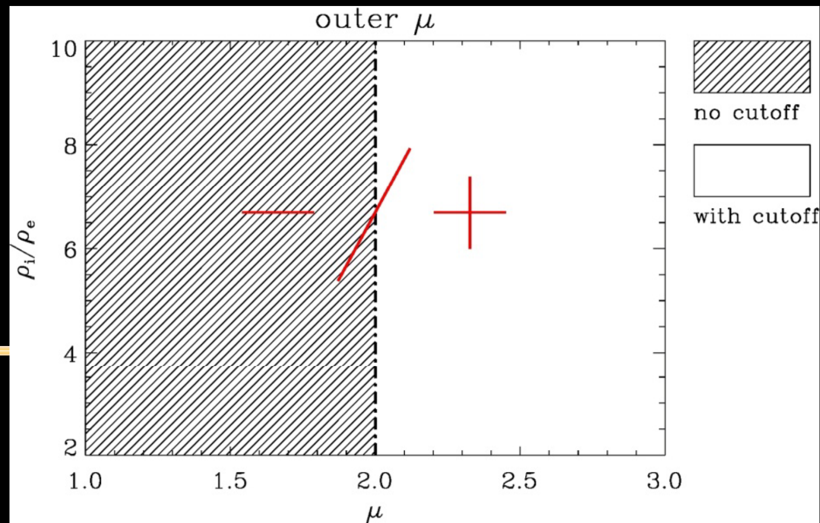
$$f(r) = \frac{1}{1 + (r/R)^{\mu}}$$

$$f(r) = \begin{cases} 1, & 0 \le r \le R \\ (r/R)^{-\mu}, & r \ge R. \end{cases}$$

$$f(r) = \begin{cases} 1 - \left(\frac{r}{R}\right)^{\mu}, & 0 \le r \le R, \\ 0, & r \ge R. \end{cases}$$

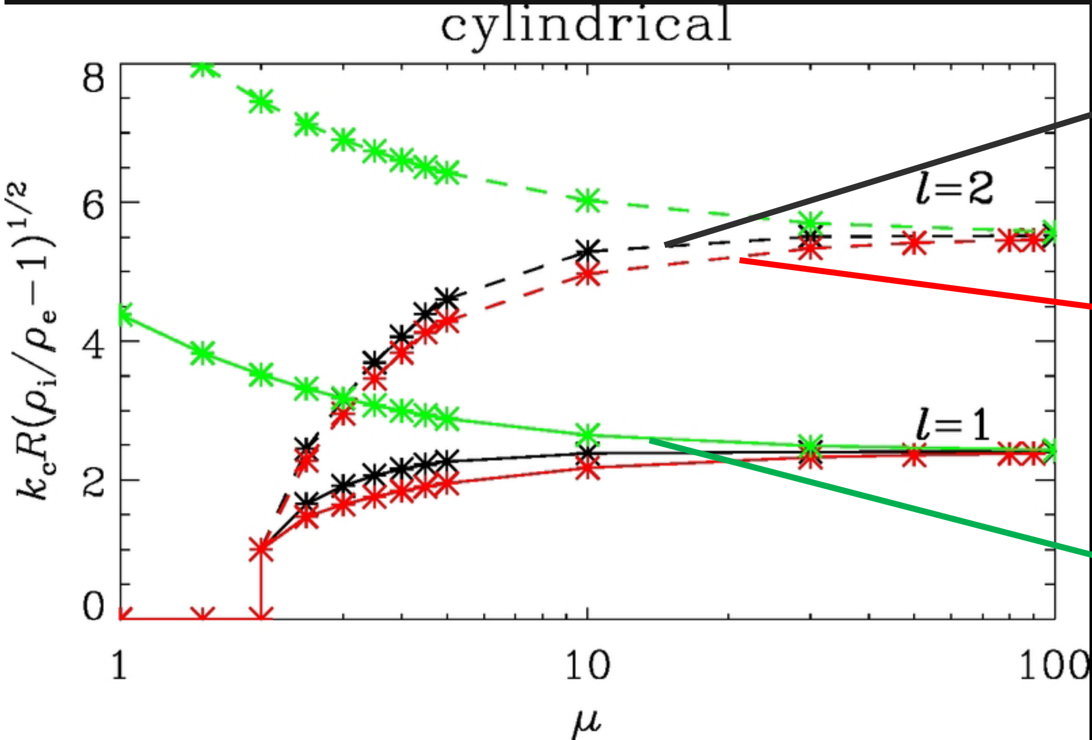

mono μ, $\rho_i/\rho_e=10$
outer μ, $\rho_i/\rho_e=10$
v_{ph}/v_{Ai}
v_{gr}/v_{Ai}
v_{Ae}
v_{Ai}
kR
μ
1.0
1.5
2.0
2.5
3.0
1st branch
2nd branch

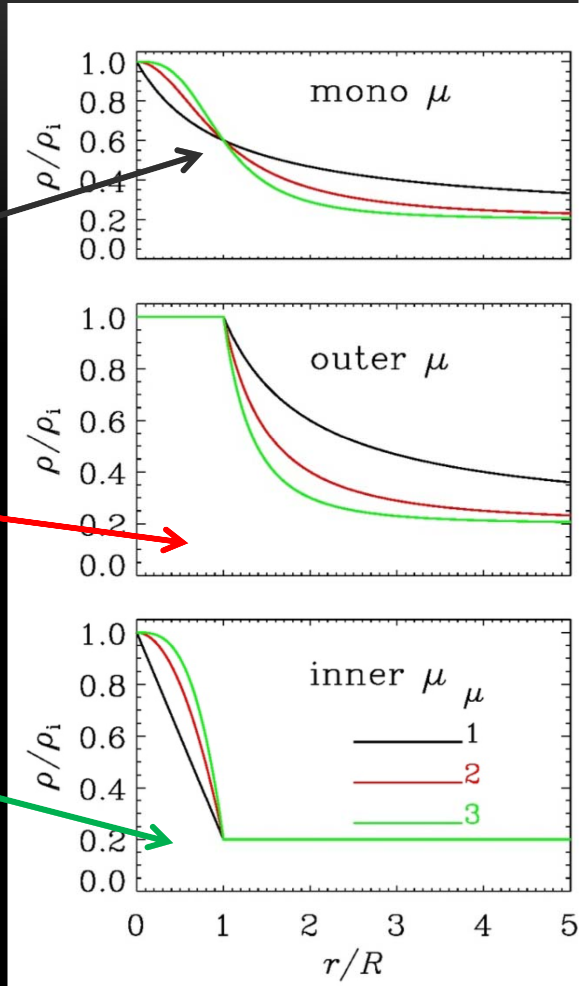

mono μ
ρ_i/ρ_e
μ
−
− / +
no cutoff
with cutoff


outer μ
ρ_i/ρ_e
μ
− / +
no cutoff
with cutoff

Cutoff wavenumbers

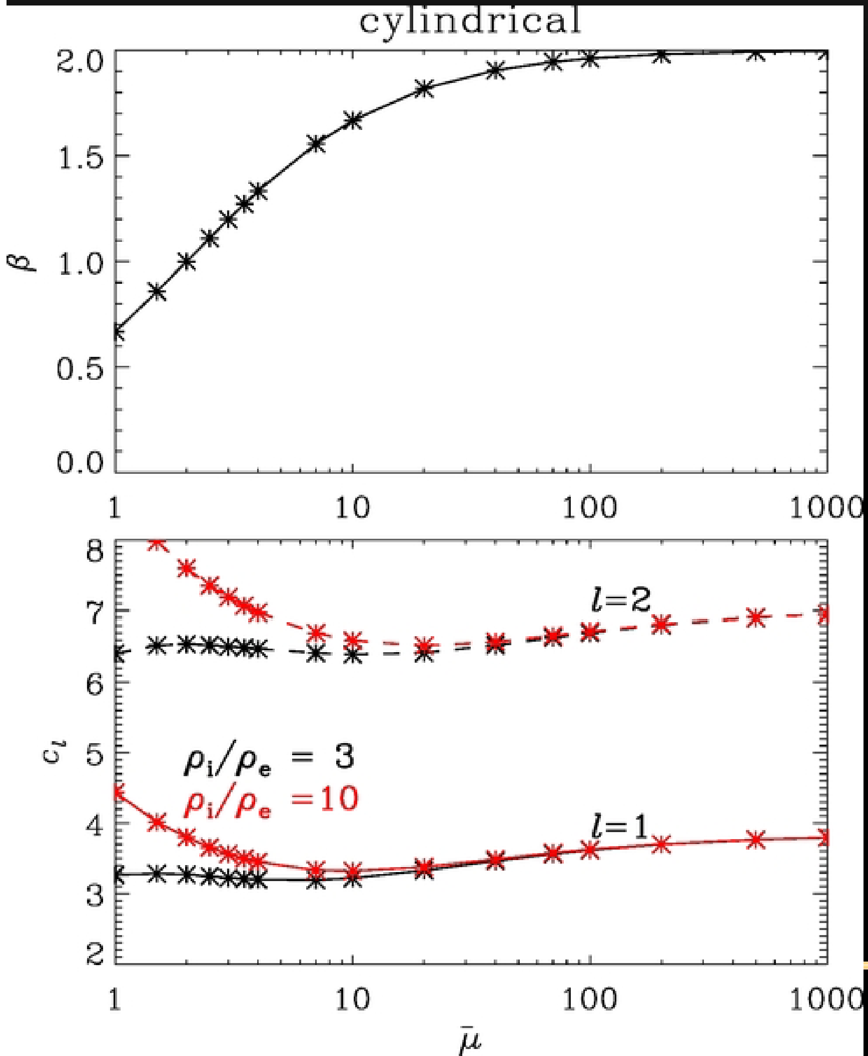
$$k_c R = \frac{d_l}{\sqrt{\rho_i/\rho_e - 1}}. \quad d_l = \text{func}(l, \mu)$$





- Exist only when $f(r)$ not less steep than r^{-2}(Lopin & Nagorny 15)
- When present
  - increases with l
  - but decreases with density contrast

Asymptotic *k*-dependence: Fact



when $kR \gg 1$

$$\frac{v_{\rm ph}^2}{v_{\rm Ai}^2} \approx 1 + \left(\frac{c_l}{kR}\right)^\beta, \quad \beta = \frac{2\mu}{\mu+2}$$

$$\frac{v_{\rm gr}^2}{v_{\rm Ai}^2} \approx 1 + (1-\beta)\left(\frac{c_l}{kR}\right)^\beta .$$

For both

$$f(r) = \frac{1}{1+(r/R)^\mu}.$$

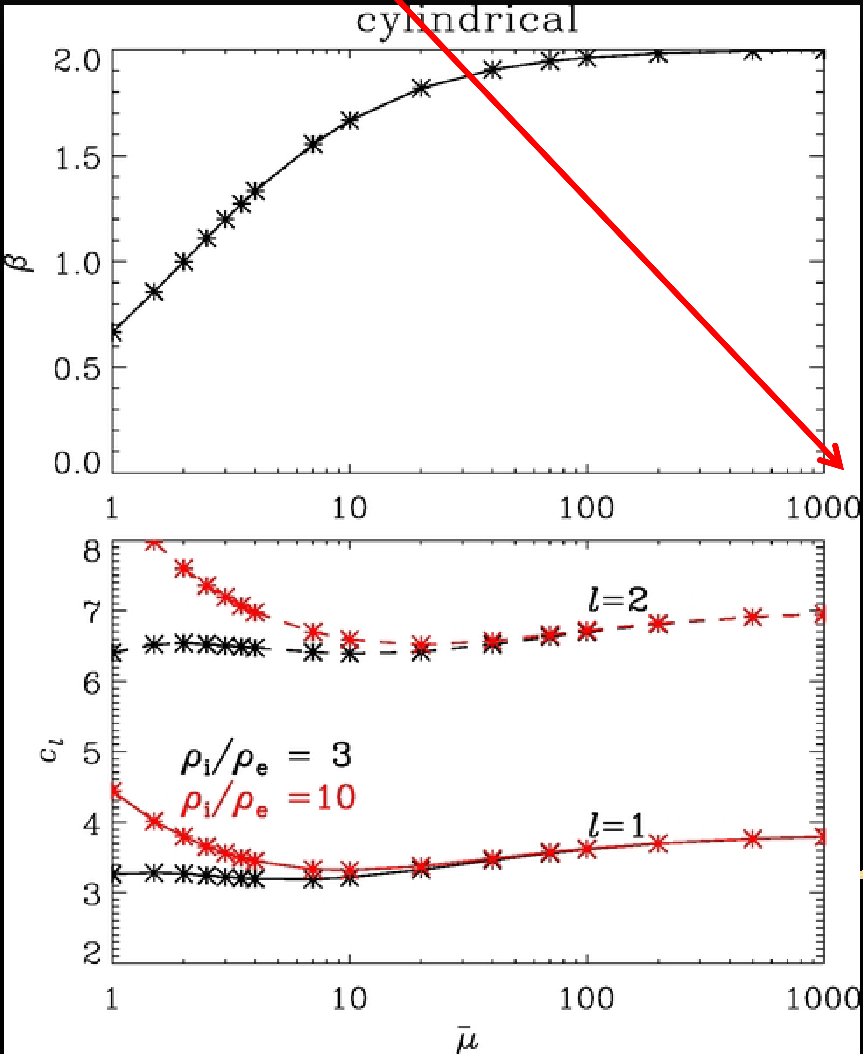
$$f(r) = \begin{cases} 1 - \left(\dfrac{r}{R}\right)^\mu, & 0 \le r \le R, \\ 0, & r \ge R. \end{cases}$$

Asymptotic *k*-dependence: Conjecture

Conjecture 1 *When $kR \gg 1$, the phase speed for arbitrary density contrast $\rho_{\rm i}/\rho_{\rm e} > 1$ or transverse harmonic number l is, to leading order, given by $v_{\rm ph} \approx 1 + [c_l/(kR)]^\beta]$ for any $f(r)$ that reads, to leading order, $1-(r/R)^{\bar{\mu}}$ when $r/R \ll 1$. Here $\beta = 2\bar{\mu}/(\bar{\mu}+2)$, and c_l depends on $\rho_{\rm i}/\rho_{\rm e}$ as well as $\bar{\mu}$.*

Support for this conjecture

$$f(r) \approx 1 - (r/R)^{\infty} \text{ for } r/R \ll 1$$



$$f(r) = \begin{cases} 1, & 0 \le r \le R, \\ 0, & r \ge R. \end{cases}$$

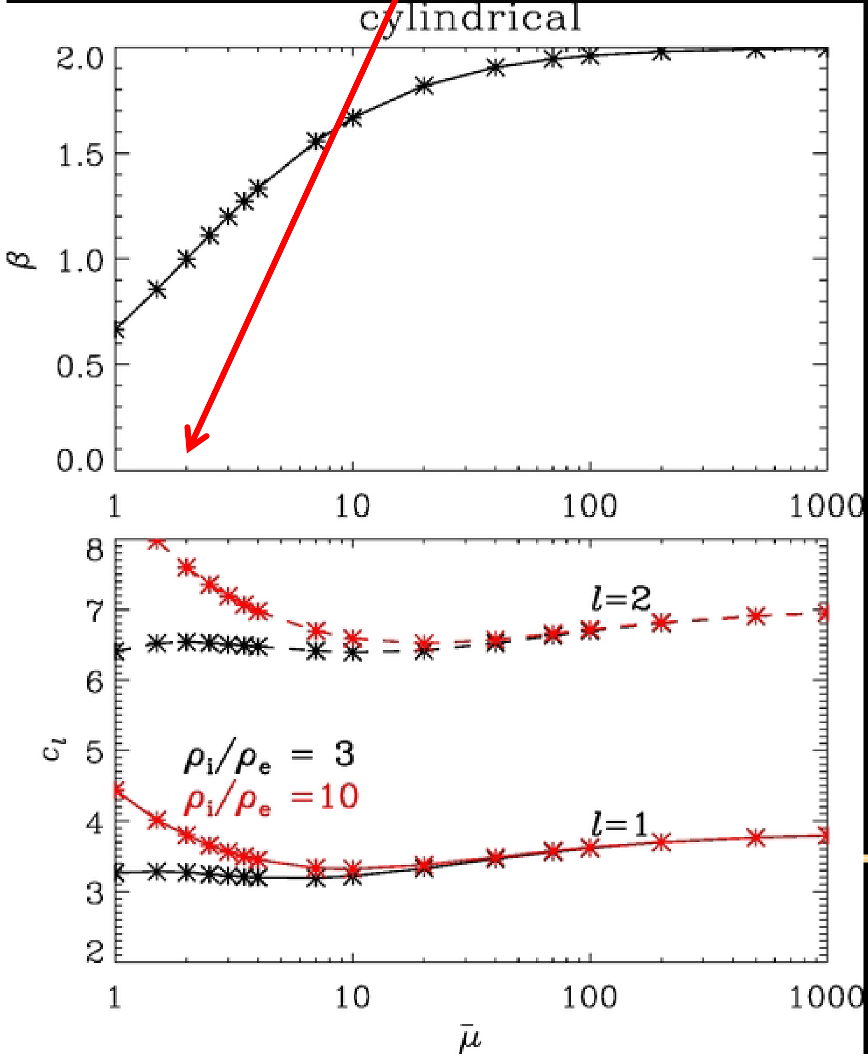
$$\frac{v_{\mathrm{ph}}^2}{v_{\mathrm{Ai}}^2} \approx 1 + \frac{j_{1,l}^2}{k^2 R^2}$$

also holds for (mu arbitrary)

$$f(r) = \begin{cases} 1, & 0 \le r \le R, \\ (r/R)^{-\mu}, & r \ge R. \end{cases}$$

Support for this conjecture

$$f(r) \approx 1 - (r/R)^2 \text{ for } r/R \ll 1$$



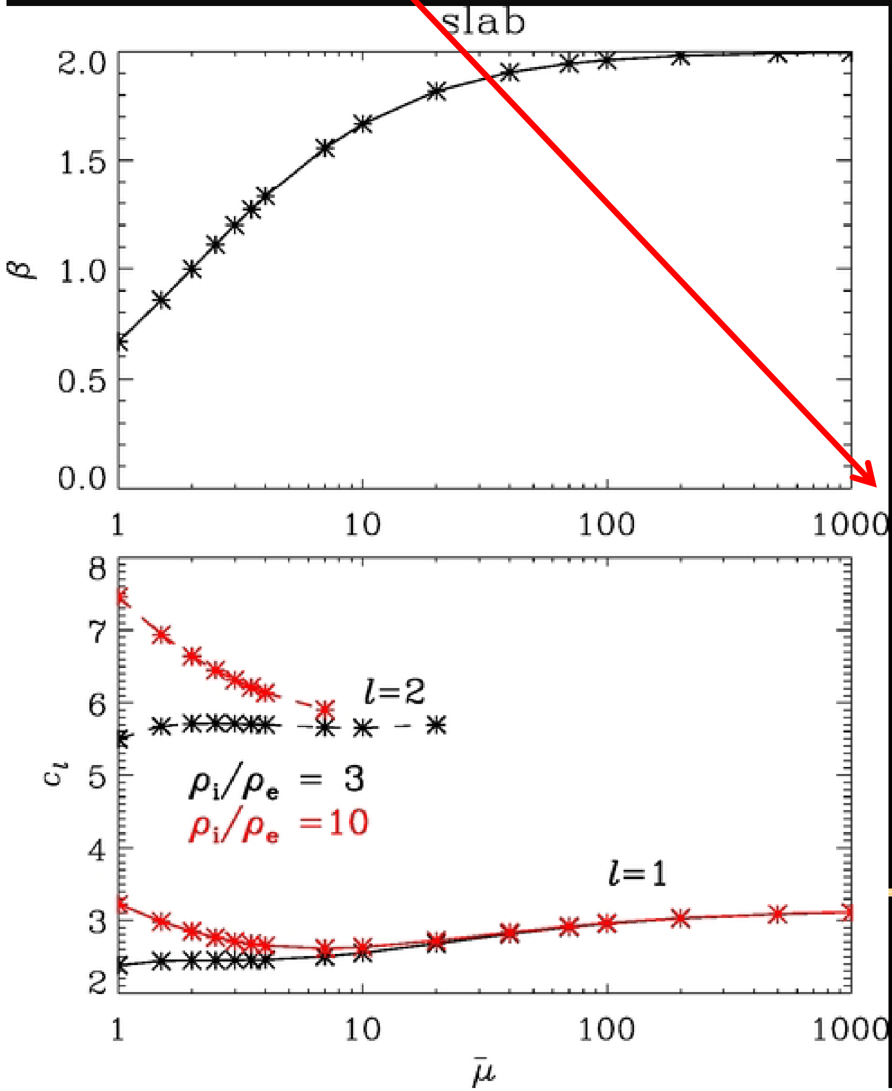
$$f(r) = \begin{cases} 1 - \left(\frac{r}{R}\right)^2, & 0 \le r \le R, \\ 0, & r \ge R. \end{cases}$$

$$\frac{v_{\rm ph}}{v_{\rm Ai}} \approx 1 + \frac{2l\sqrt{1-\rho_{\rm e}/\rho_{\rm i}}}{kR} + \frac{2l^2(1-\rho_{\rm e}/\rho_{\rm i})}{(kR)^2},$$

Further support for this conjecture

$f(x) \approx 1 - (x/R)^{\infty}$ for $|x/R| \ll 1$

Li et al. 2017 ApJ, to submit



$$f(x) = \begin{cases} 1, & 0 \le x \le R, \\ 0, & x \ge R. \end{cases}$$

$$\frac{v_{\rm ph}^2}{v_{\rm Ai}^2} \approx 1 + \left(\frac{l\pi}{kR}\right)^2$$

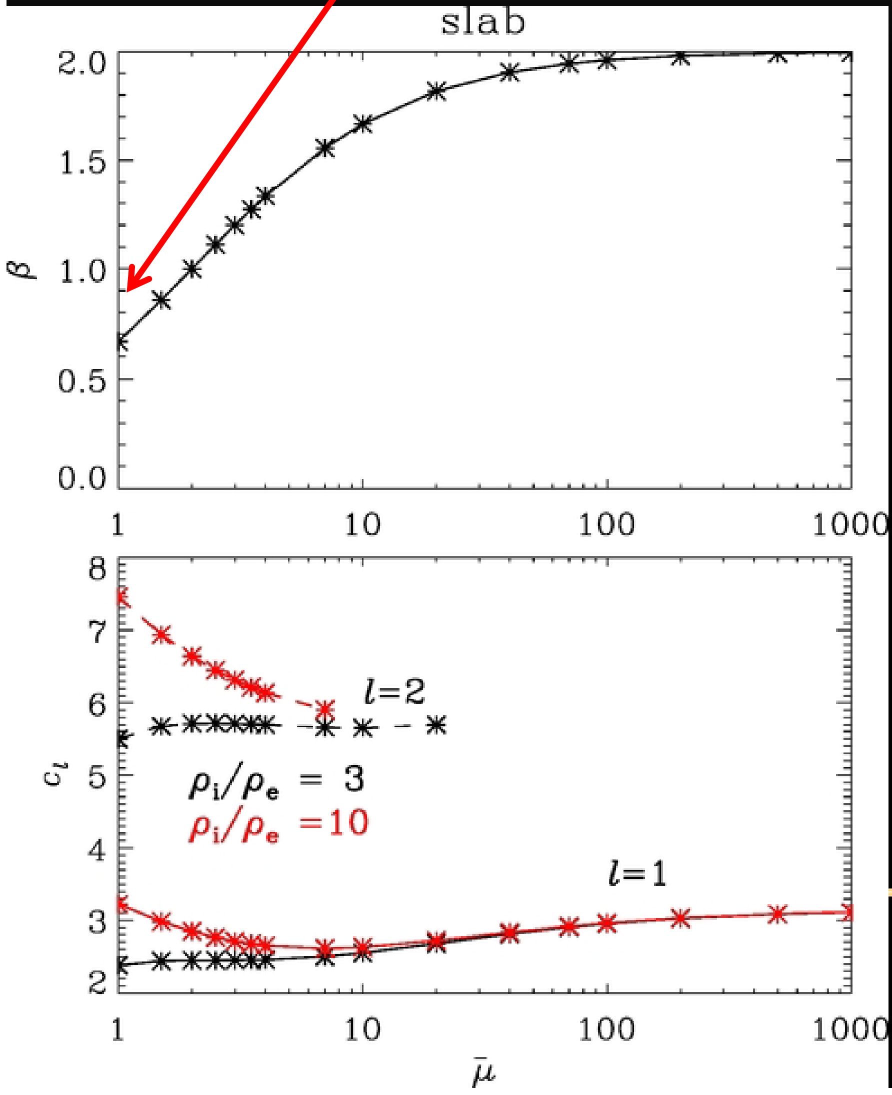
also holds for (mu arbitrary)

$$f(x) = \begin{cases} 1, & 0 \le x \le R, \\ (x/R)^{-\mu}, & x \ge R. \end{cases}$$

Further support for this conjecture

$f(x) \approx 1-(x/R)$ for $|x/R| \ll 1$

Li et al. 2017 ApJ, to submit



$$f(x) = \frac{1}{1+(x/R)}.$$

$$f(x) = \begin{cases} 1-\left(\frac{x}{R}\right), & 0 \le x \le R, \\ 0, & x \ge R. \end{cases}$$

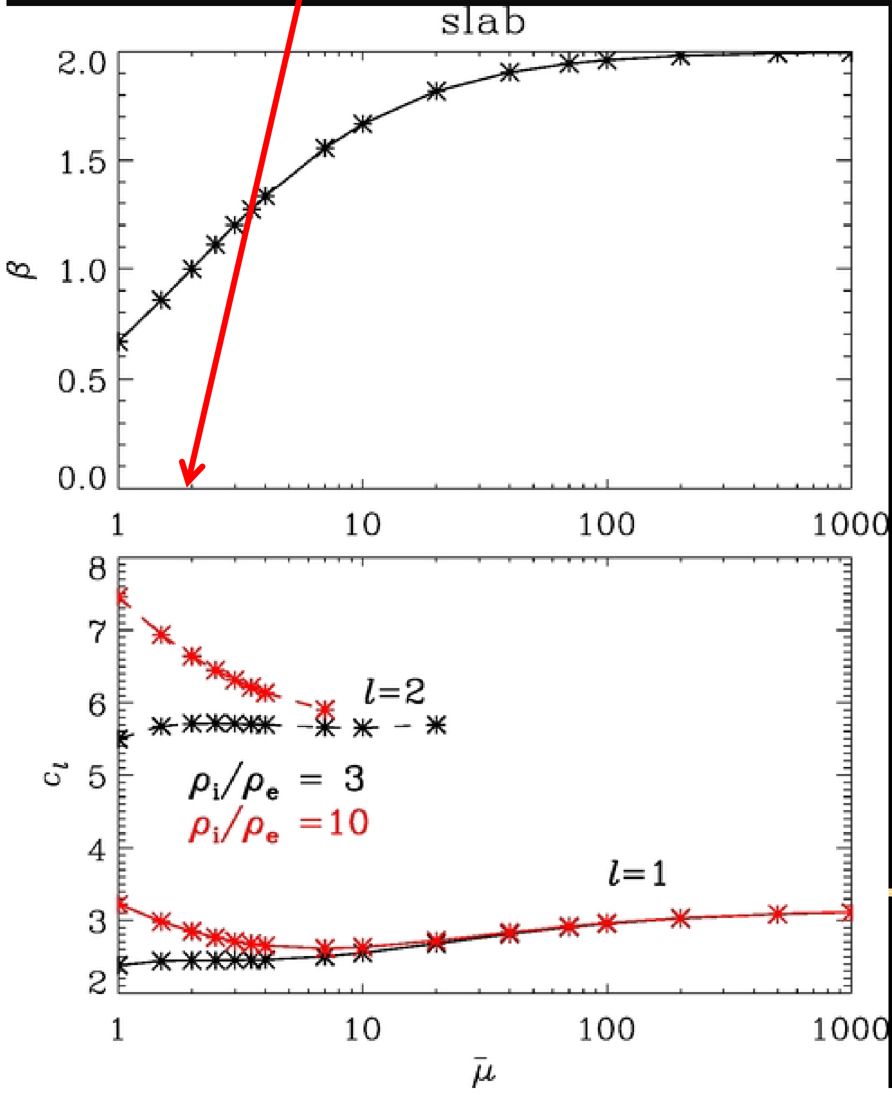
$$f(x) = \exp\left(-\frac{x}{R}\right)$$

$$\frac{v_{\rm ph}^2}{v_{\rm Ai}^2} \approx 1 + \left[\frac{3\,(4l-1)\,\pi(1-\rho_{\rm e}/\rho_{\rm i})}{8kR}\right]^{2/3}$$

Further support for this conjecture

$f(x) \approx 1-(x/R)^2$ for $|x/R| \ll 1$

Li et al. 2017 ApJ, to submit

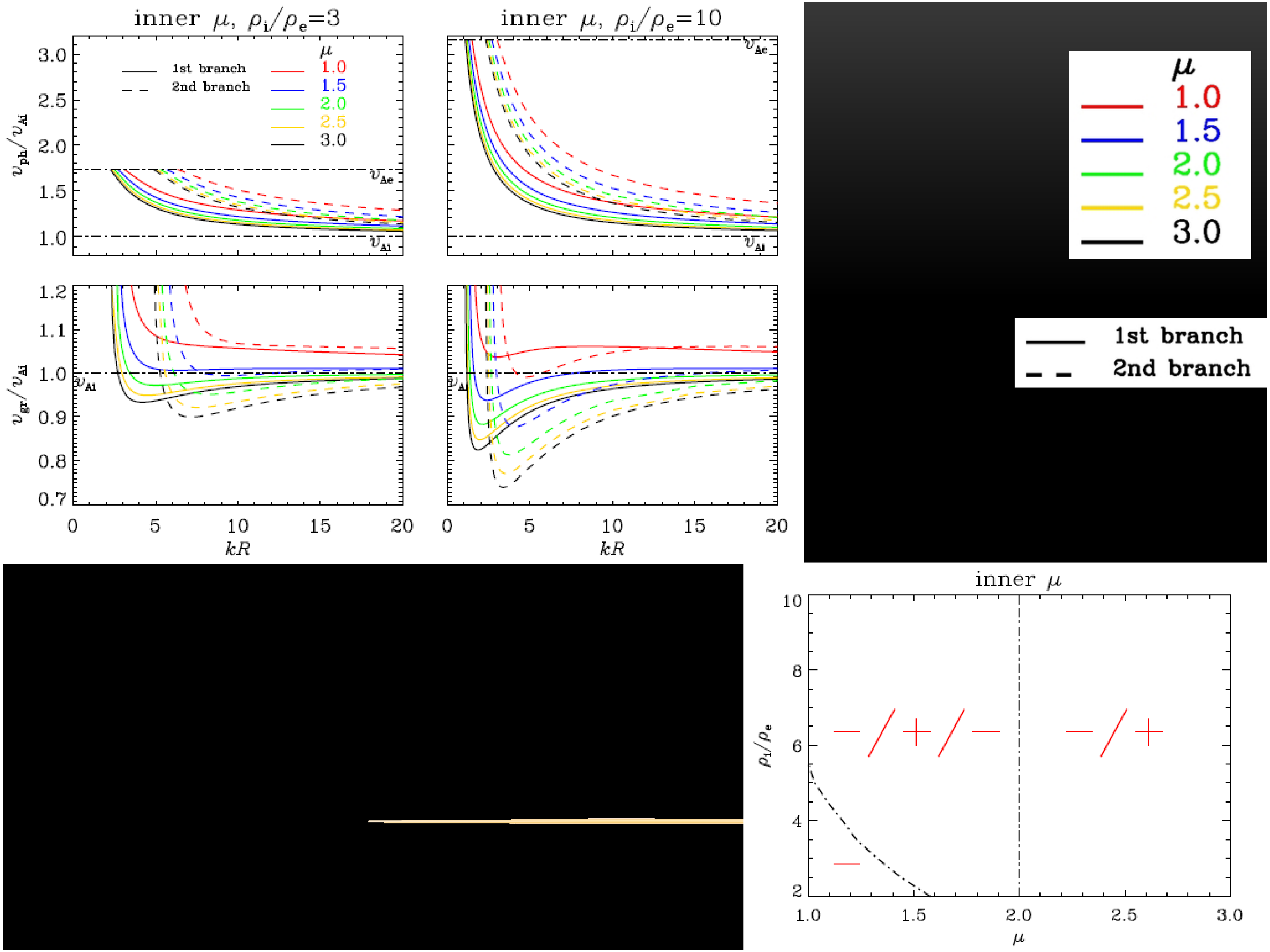


$$f(x)=\begin{cases}1-\left(\frac{x}{R}\right)^2, & 0\le x\le R,\\ 0, & x\ge R.\end{cases}$$

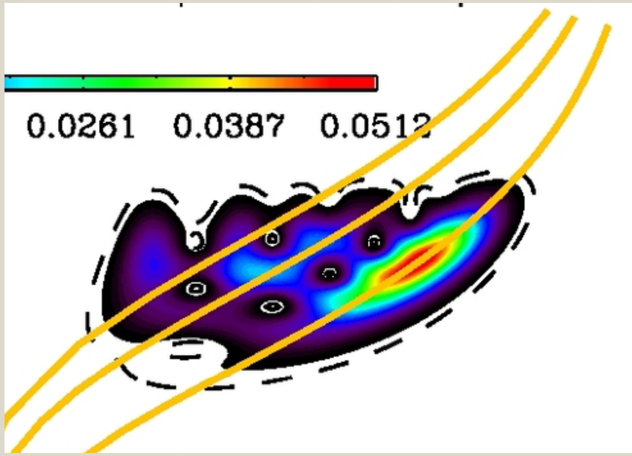
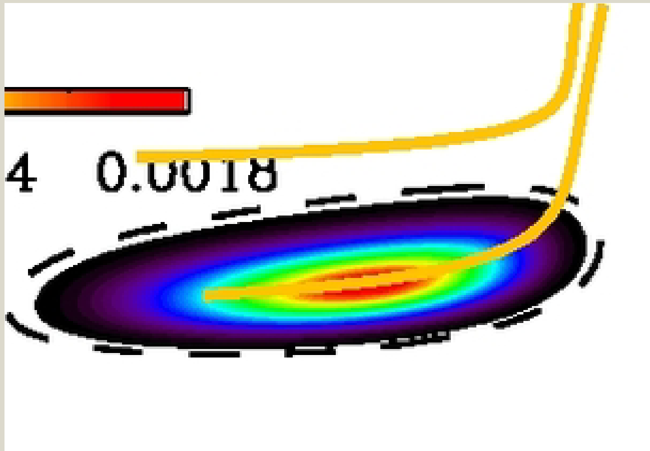
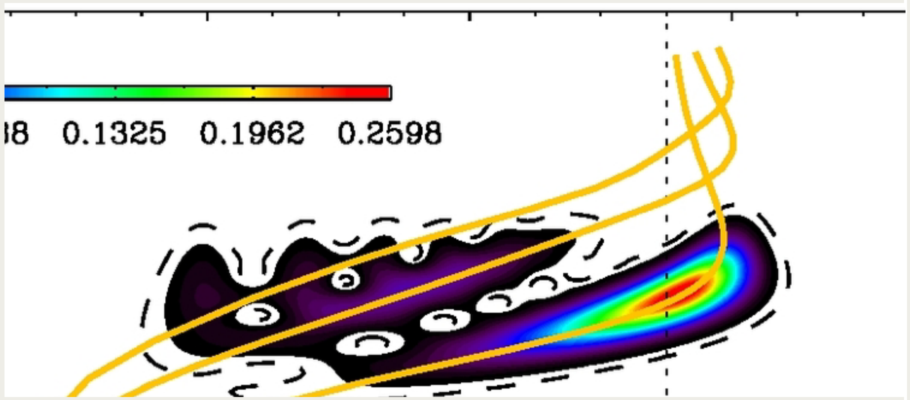
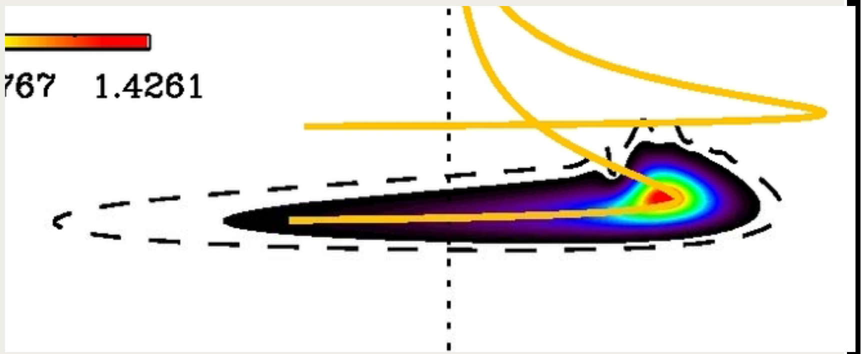
$$\frac{v_{\rm ph}}{v_{\rm Ai}} \approx 1+\frac{4l-1}{2}\frac{\sqrt{1-\rho_{\rm e}/\rho_{\rm i}}}{kR}+\frac{(4l-1)^2}{8}\frac{(1-\rho_{\rm e}/\rho_{\rm i})}{(kR)^2}$$

$$f(x)=\mathrm{sech}^2\left(\frac{x}{R}\right)$$

$$\frac{v_{\rm ph}}{v_{\rm Ai}} \approx 1+\frac{4l-1}{2}\frac{\sqrt{1-\rho_{\rm e}/\rho_{\rm i}}}{kR} - \frac{(2l-1/2)^2(1+\rho_{\rm e}/\rho_{\rm i})/2-l(2l-1)}{k^2R^2}$$


inner μ, ρ_i/ρ_e=3
inner μ, ρ_i/ρ_e=10
v_{ph}/v_{Ai}
v_{gr}/v_{Ai}
1st branch
2nd branch
μ
1.0
1.5
2.0
2.5
3.0
v_{Ae}
v_{Ai}
kR
inner μ
ρ_i/ρ_e
μ

Morlet spectra may look different from tadpoles

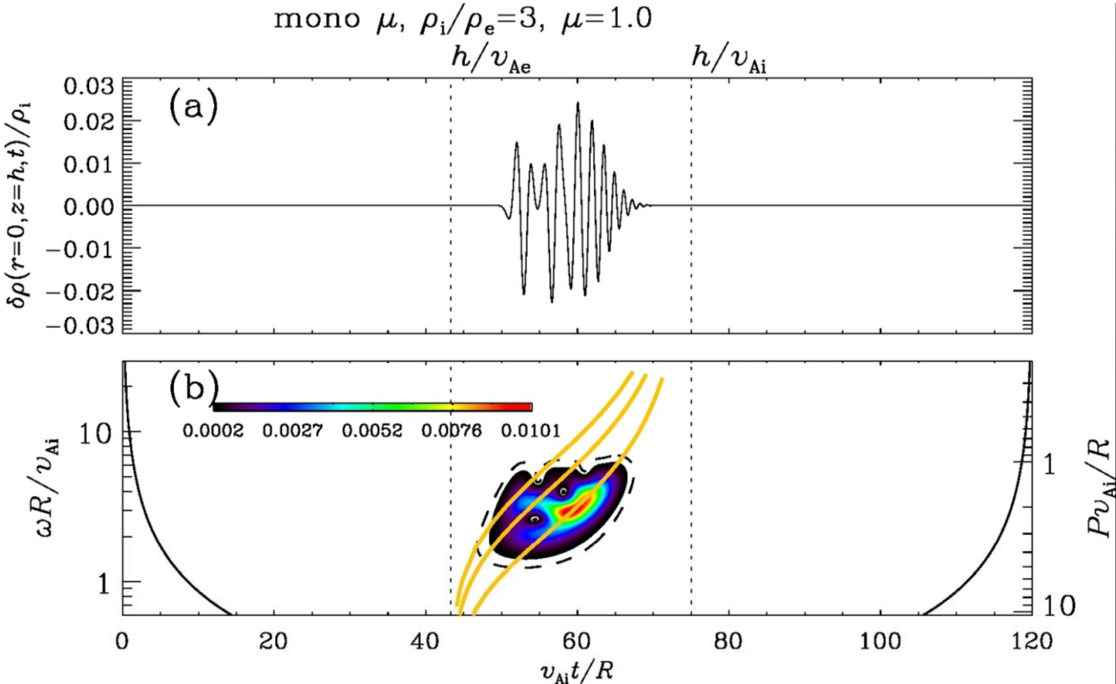
	Cutoff-free	With cutoffs
monotonical		
non-nonotonical		

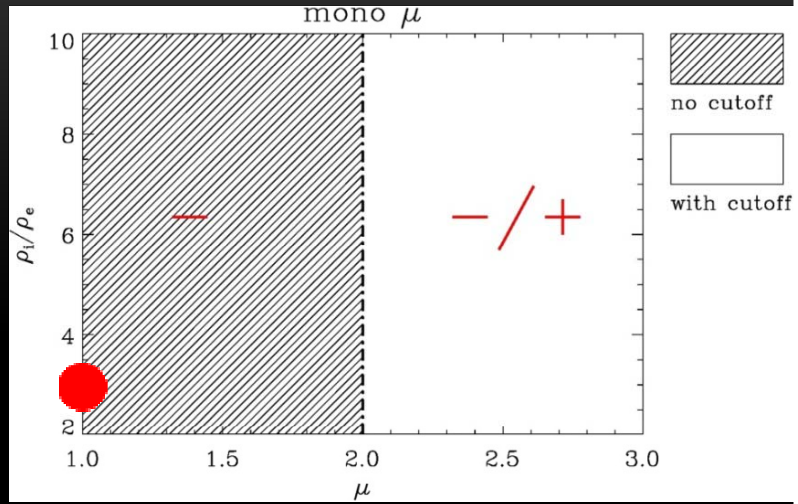
Summary

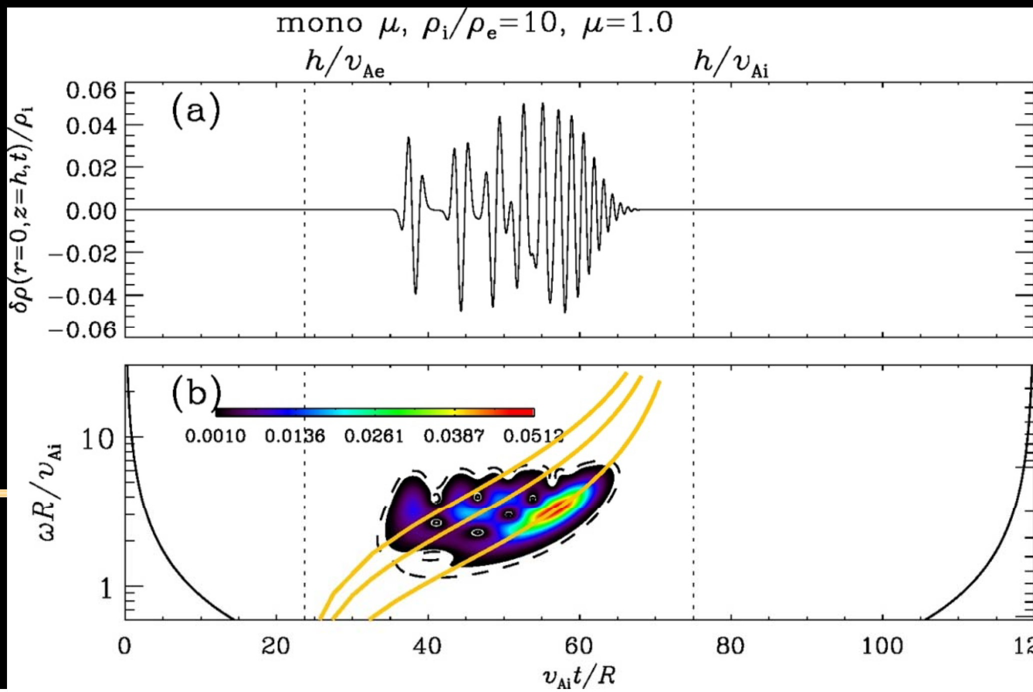
- Fast sausage waves in coronal tubes
  - axisymmetric, do not displace tube axis
  - (quasi-)periodic contractions & expansions
  - Strong compressibility & strong dispersion
- Fundamental, standing, fast sausage modes in flare loops
  - often invoked to interpret QPPs with periods of order seconds
  - uncertainties in density distribution leads to considerable uncertainties in the deduced transverse Alfven time
  - Gas pressure not important for periods →cold MHD theory can be used, but deduced Alfven time is actually transverse fast time
- Impulsively generated sausage wave trains in coronal tubes
  - invoked to interpret rapid oscillatory behavior
  - uncertainties in density distribution → Morlet spectra that look quite different from "crazy tadpoles" → worth digging into high-cadence data in optical and radio passbands

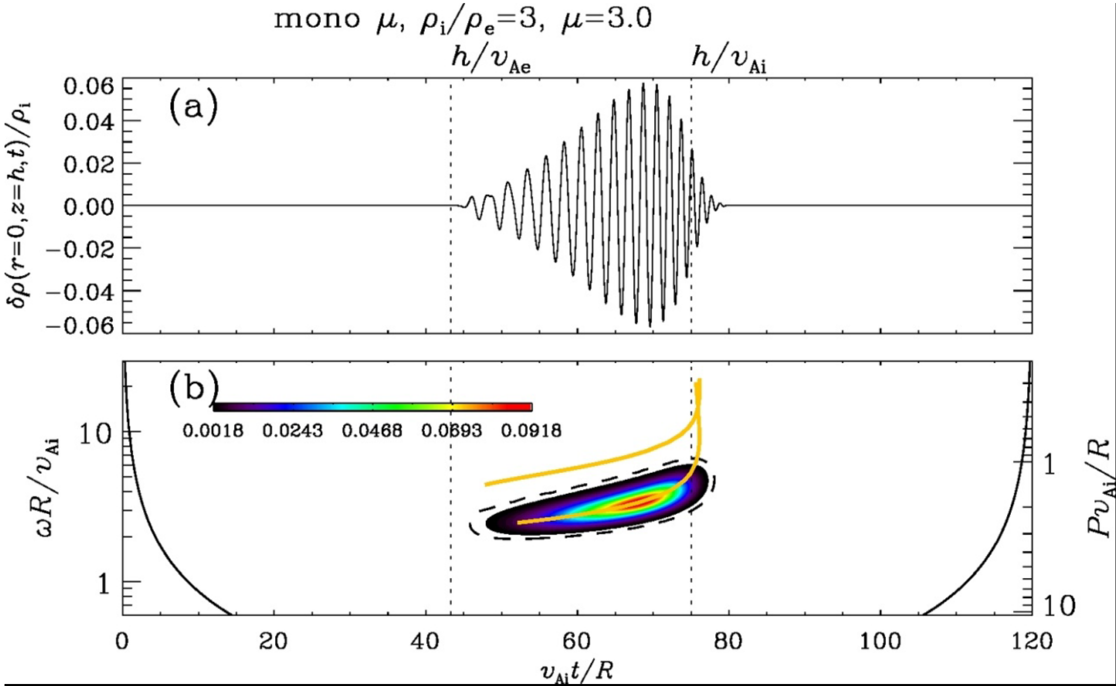
Chen, Li, et al.	2015 SoPh, 290, 2231
Chen, Li, et al.	2015 ApJ, 812, 22
Guo, Chen, Li, et al.	2016 SoPh, 291, 877
Chen, Li, et al.	2016 ApJ, 833, 114
Yu, Li, et al.	2016 ApJ, 833, 51
Yu, Li, et al.	2017 ApJ, in press, arXiv:161209479Y
Li, et al.	2017 ApJ, to be submitted soon

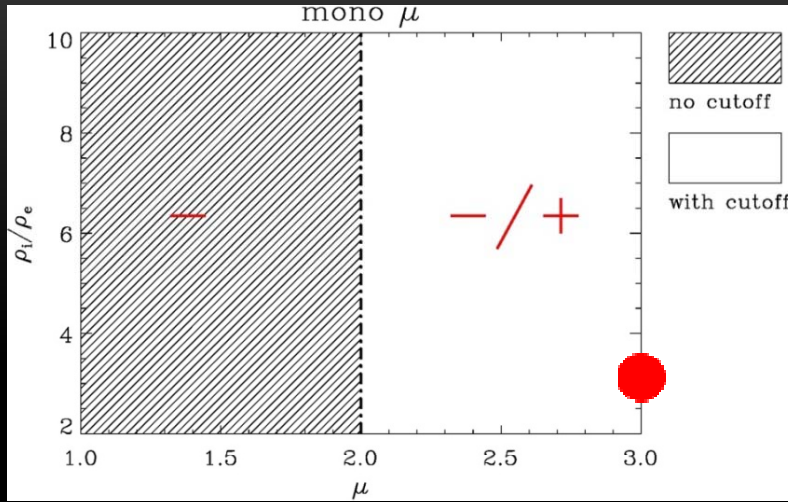
BACKUP SLIDES

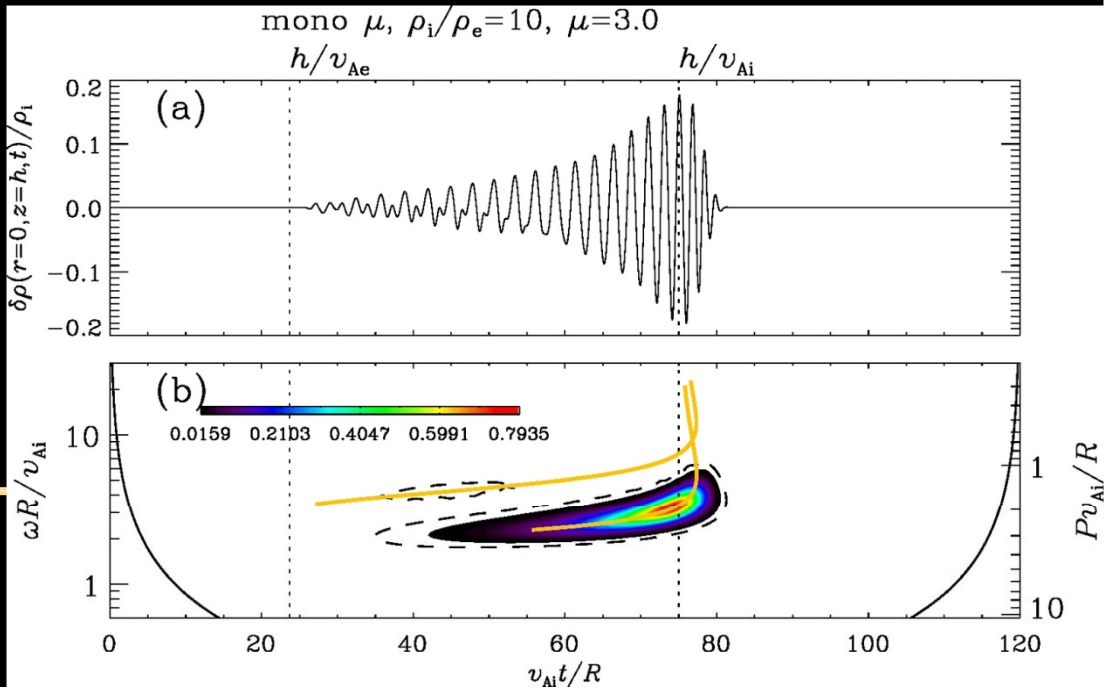

mono μ, ρi/ρe=3, μ=1.0
h/vAe
h/vAi
(a)
δρ(r=0,z=h,t)/ρi
(b)
0.0002 0.0027 0.0052 0.0076 0.0101
ωR/vAi
PvAi/R
vAit/R

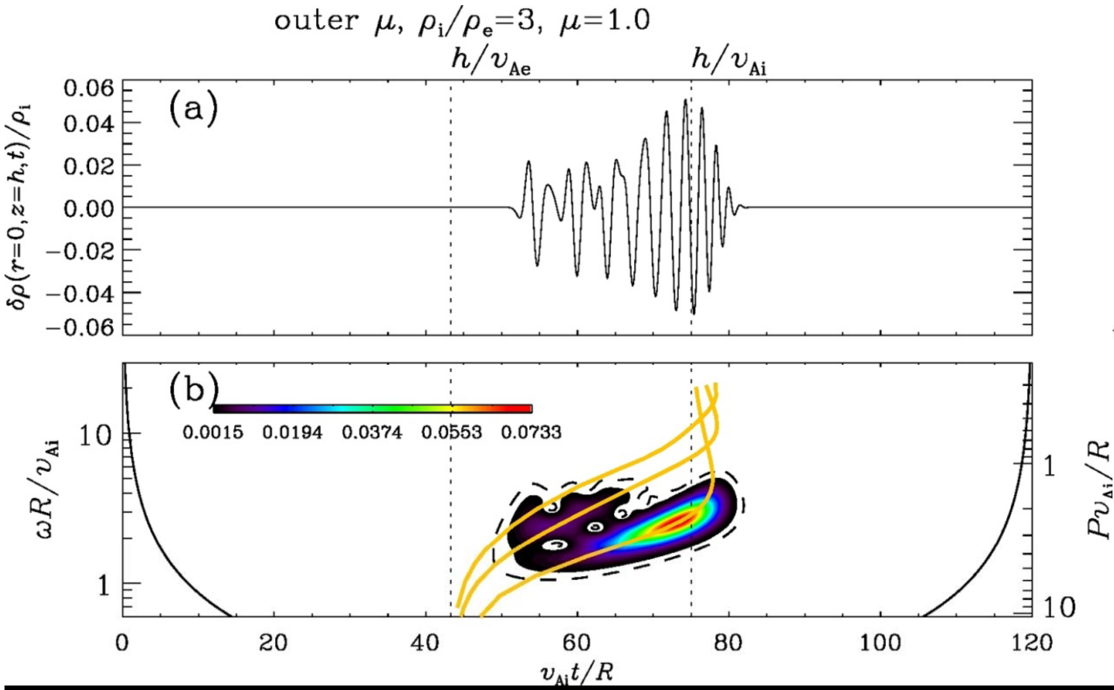

mono μ
no cutoff
with cutoff
ρi/ρe
μ
−
−/+

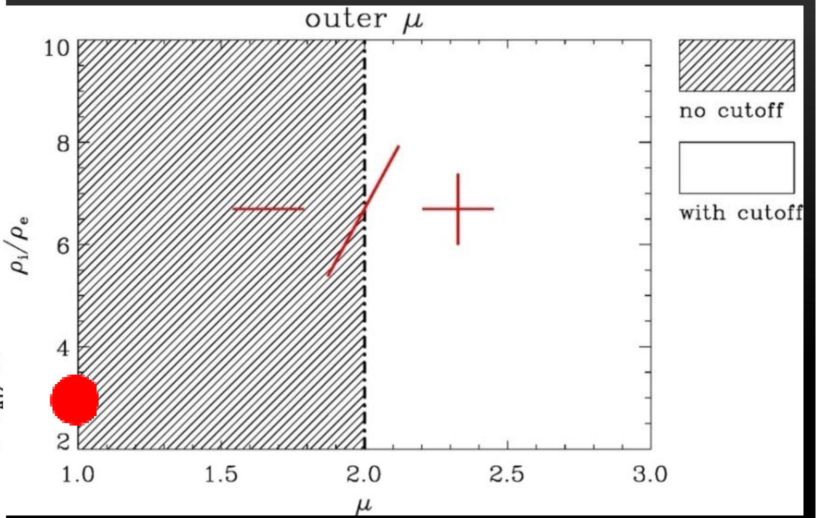

mono μ, ρi/ρe=10, μ=1.0
h/vAe
h/vAi
(a)
δρ(r=0,z=h,t)/ρi
(b)
0.0010 0.0136 0.0261 0.0387 0.0512
ωR/vAi
PvAi/R
vAit/R

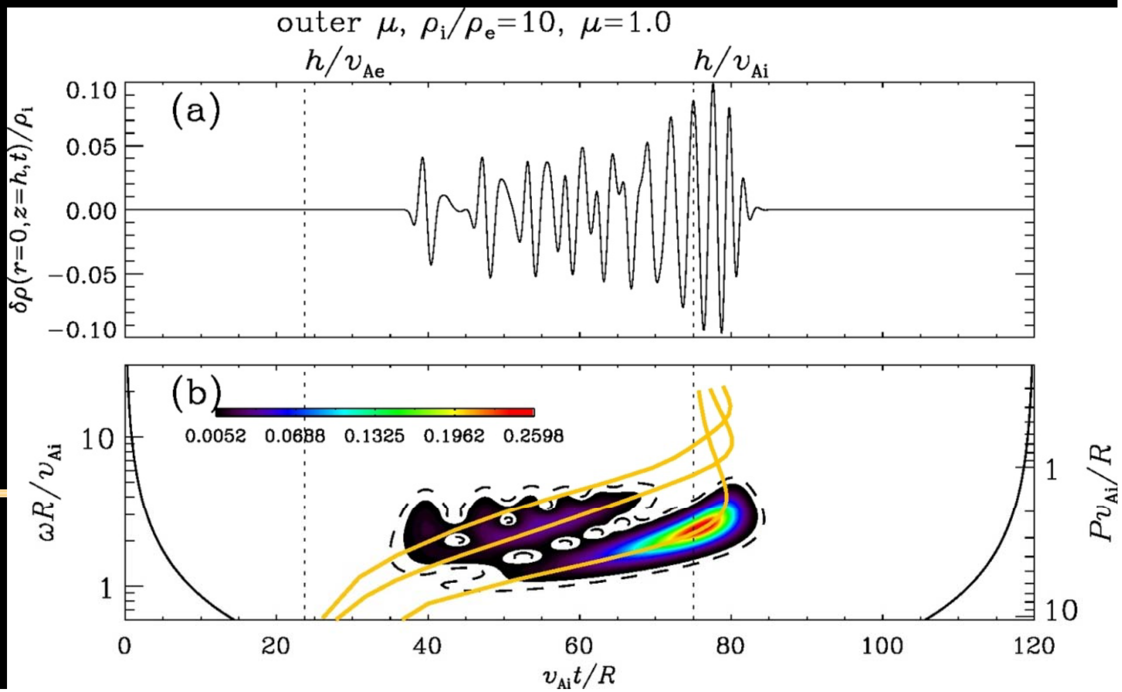

mono μ, ρ_i/ρ_e=3, μ=3.0
h/v_{Ae}
h/v_{Ai}
(a)
$\delta\rho(r=0,z=h,t)/\rho_i$
(b)
0.0018 0.0243 0.0468 0.0693 0.0918
$\omega R/v_{Ai}$
$P v_{Ai}/R$
$v_{Ai}t/R$

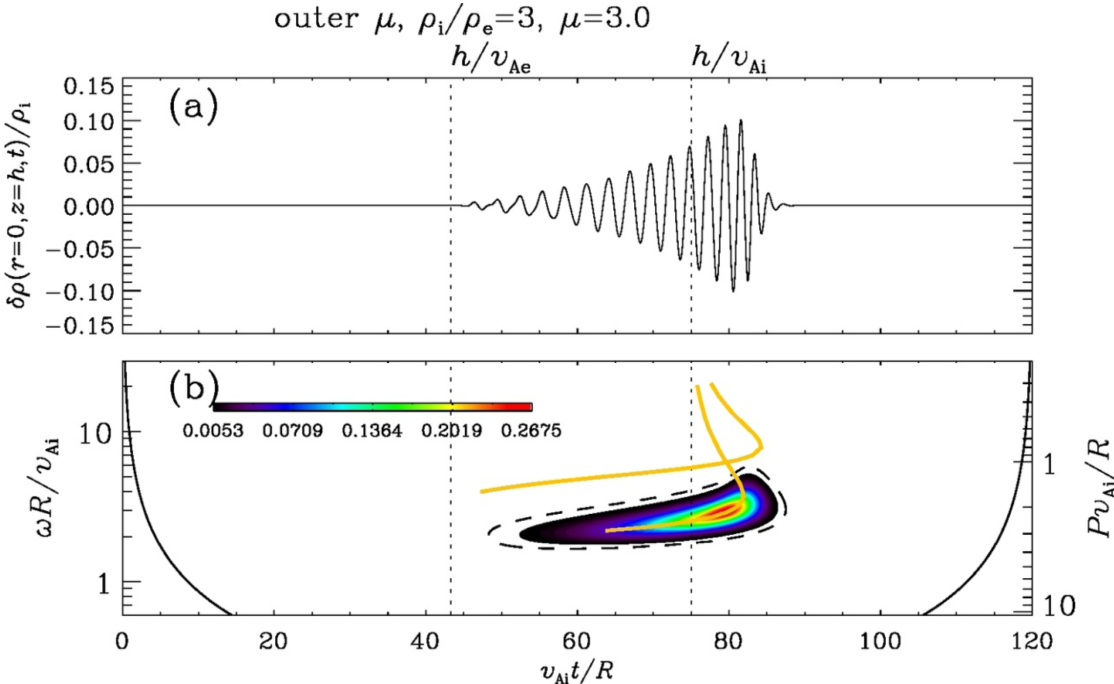

mono μ
no cutoff
with cutoff
ρ_i/ρ_e
μ
−
−/+

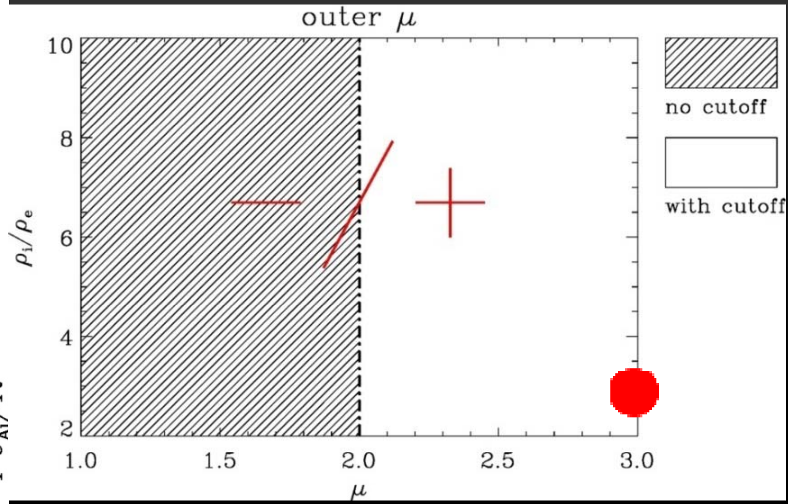

mono μ, ρ_i/ρ_e=10, μ=3.0
h/v_{Ae}
h/v_{Ai}
(a)
$\delta\rho(r=0,z=h,t)/\rho_i$
(b)
0.0159 0.2103 0.4047 0.5991 0.7935
$\omega R/v_{Ai}$
$P v_{Ai}/R$
$v_{Ai}t/R$

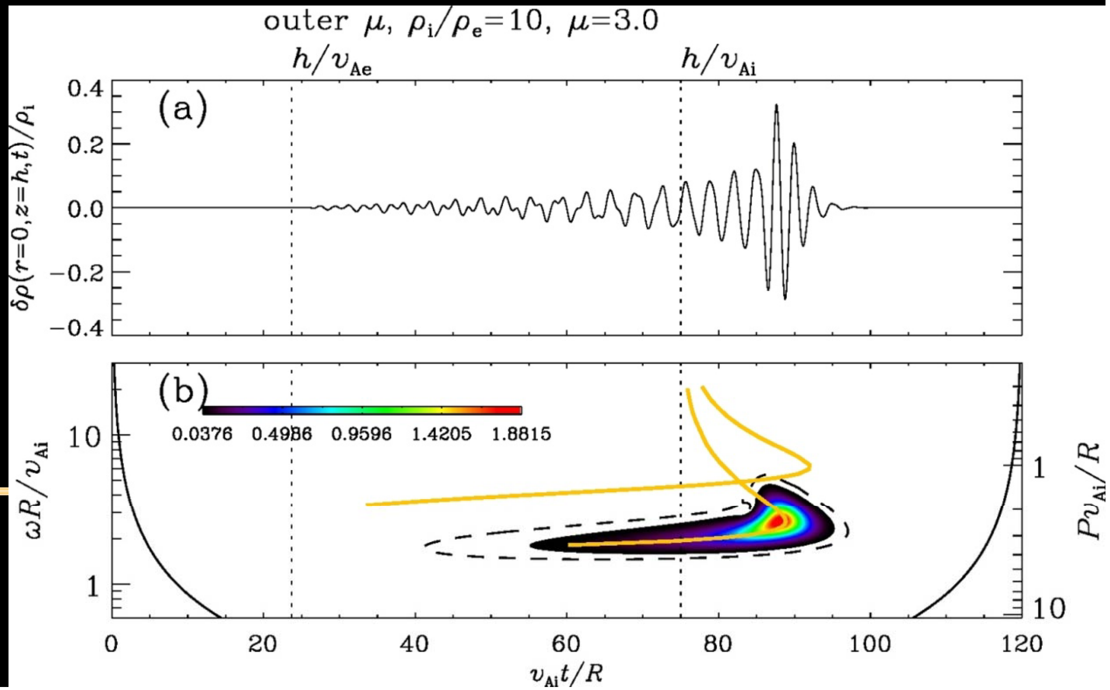

outer μ, ρ_i/ρ_e=3, μ=1.0
h/v_{Ae}
h/v_{Ai}
(a)
$\delta\rho(r=0,z=h,t)/\rho_i$
(b)
0.0015 0.0194 0.0374 0.0553 0.0733
$\omega R/v_{Ai}$
Pv_{Ai}/R
$v_{Ai}t/R$

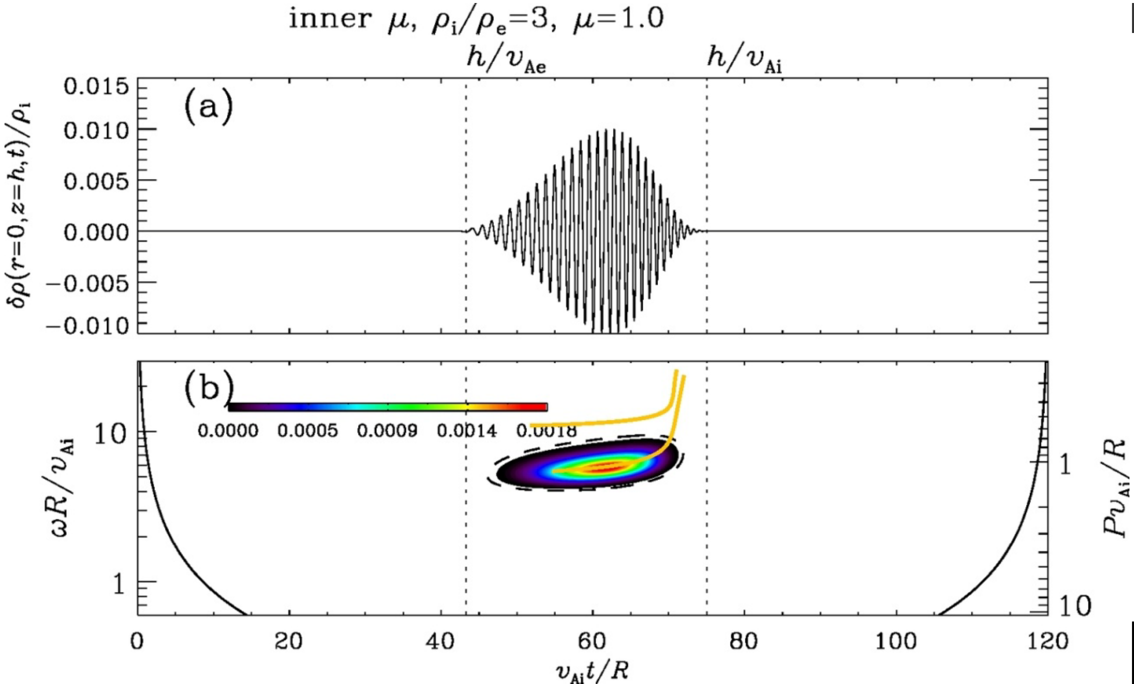

outer μ
ρ_i/ρ_e
μ
no cutoff
with cutoff

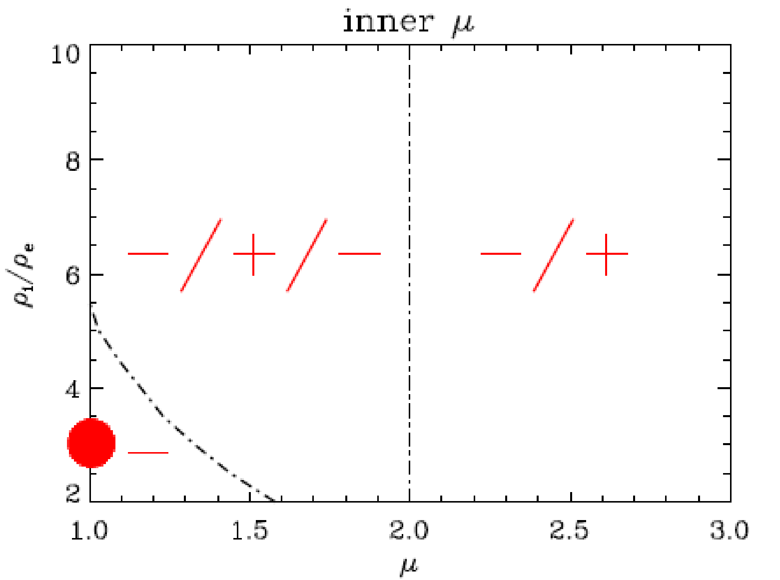

outer μ, ρ_i/ρ_e=10, μ=1.0
h/v_{Ae}
h/v_{Ai}
(a)
$\delta\rho(r=0,z=h,t)/\rho_i$
(b)
0.0052 0.0688 0.1325 0.1962 0.2598
$\omega R/v_{Ai}$
Pv_{Ai}/R
$v_{Ai}t/R$

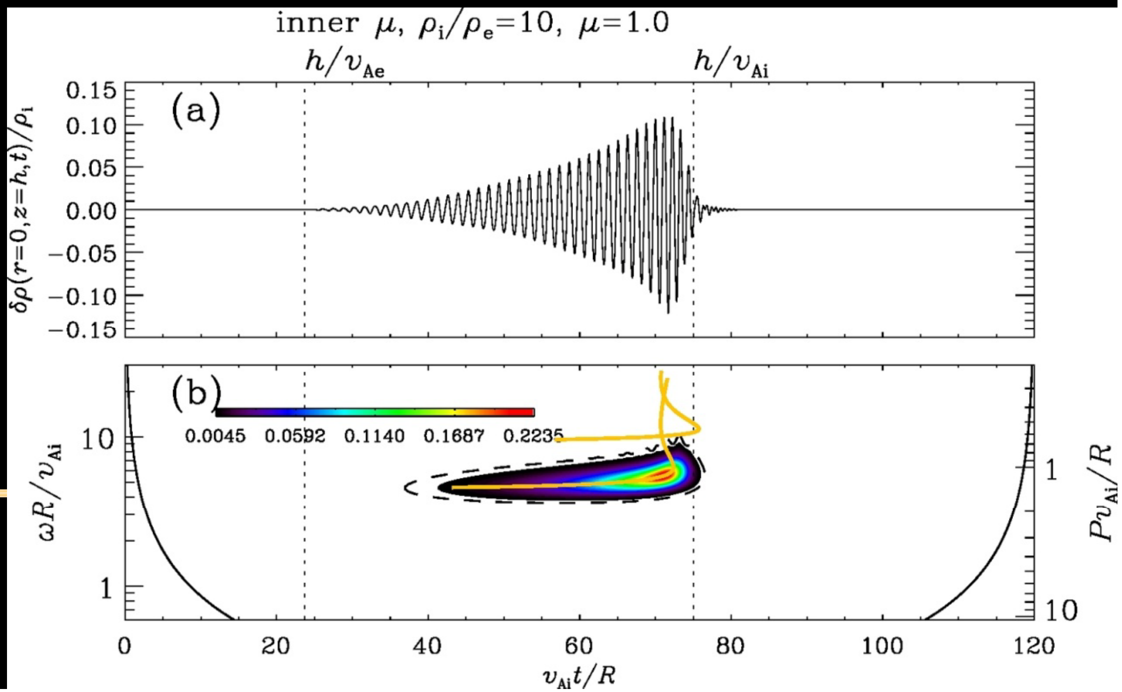

outer μ, ρ_i/ρ_e=3, μ=3.0
h/v_{Ae}
h/v_{Ai}
(a)
$\delta\rho(r=0,z=h,t)/\rho_i$
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
(b)
0.0053
0.0709
0.1364
0.2019
0.2675
$\omega R/v_{Ai}$
10
1
$P v_{Ai}/R$
1
10
0
20
40
60
80
100
120
$v_{Ai}t/R$

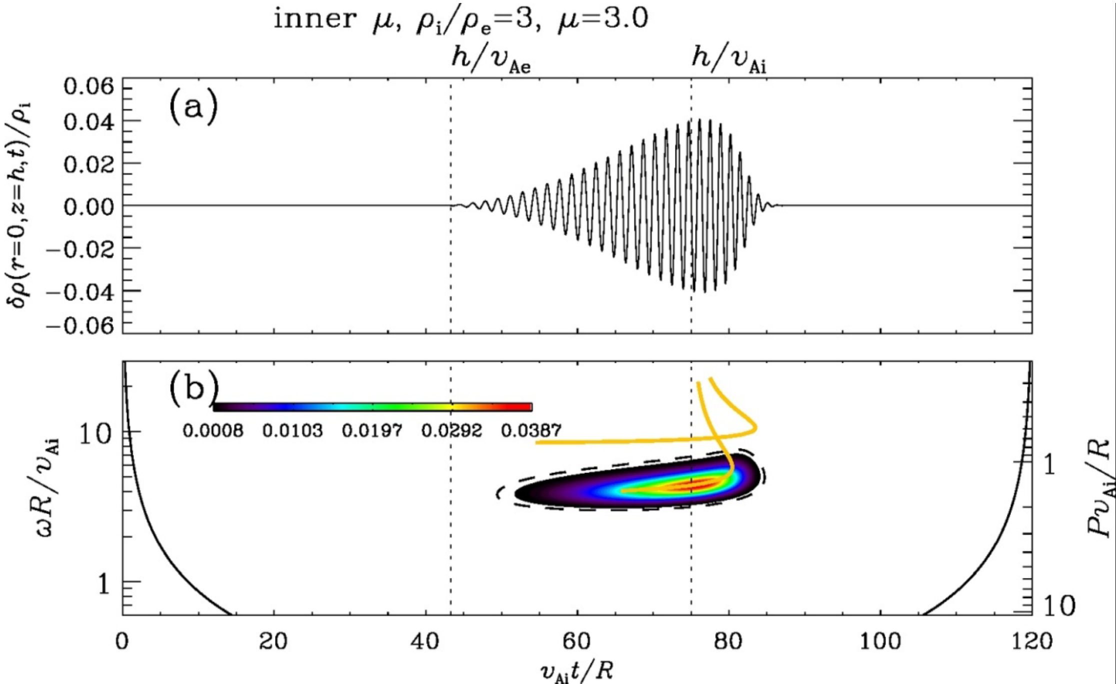

outer μ
ρ_i/ρ_e
10
8
6
4
2
1.0
1.5
2.0
2.5
3.0
μ
no cutoff
with cutoff


outer μ, ρ_i/ρ_e=10, μ=3.0
h/v_{Ae}
h/v_{Ai}
(a)
$\delta\rho(r=0,z=h,t)/\rho_i$
0.4
0.2
0.0
−0.2
−0.4
(b)
0.0376
0.4986
0.9596
1.4205
1.8815
$\omega R/v_{Ai}$
10
1
$P v_{Ai}/R$
1
10
0
20
40
60
80
100
120
$v_{Ai}t/R$

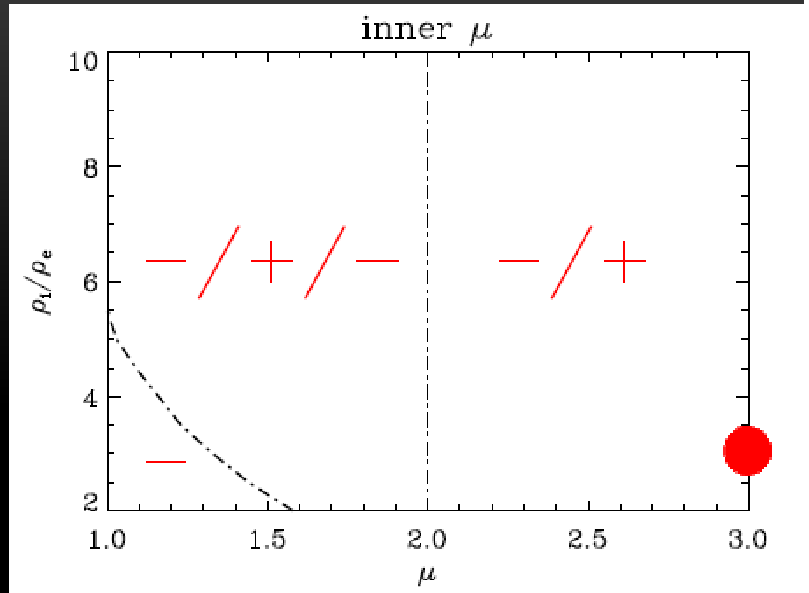

inner μ, ρi/ρe=3, μ=1.0
h/vAe
h/vAi
(a)
δρ(r=0,z=h,t)/ρi
0.015
0.010
0.005
0.000
−0.005
−0.010
(b)
0.0000 0.0005 0.0009 0.0014 0.0018
ωR/vAi
PvAi/R
vAit/R
0
20
40
60
80
100
120


inner μ
ρi/ρe
μ
10
8
6
4
2
1.0
1.5
2.0
2.5
3.0

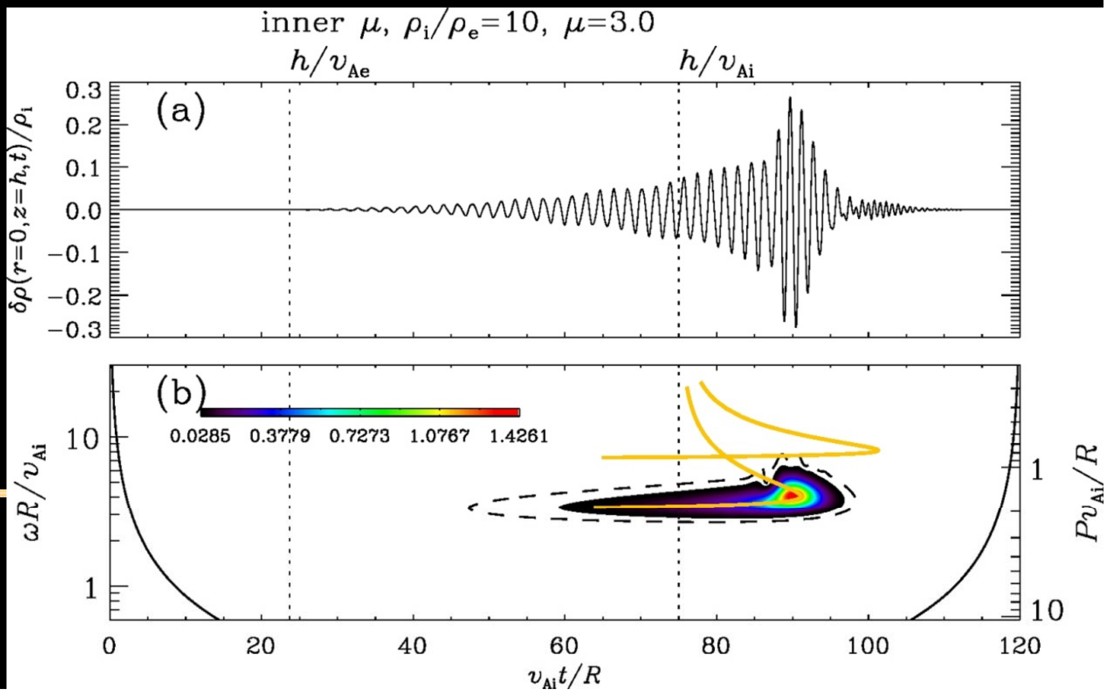

inner μ, ρi/ρe=10, μ=1.0
h/vAe
h/vAi
(a)
δρ(r=0,z=h,t)/ρi
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
(b)
0.0045 0.0592 0.1140 0.1687 0.2235
ωR/vAi
PvAi/R
vAit/R
0
20
40
60
80
100
120



inner μ, ρ_i/ρ_e=3, μ=3.0
h/v_{Ae}
h/v_{Ai}
(a)
$\delta\rho(r=0,z=h,t)/\rho_i$
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
(b)
0.0008 0.0103 0.0197 0.0292 0.0387
$\omega R/v_{Ai}$
10
1
Pv_{Ai}/R
1
10
0 20 40 60 80 100 120
$v_{Ai}t/R$

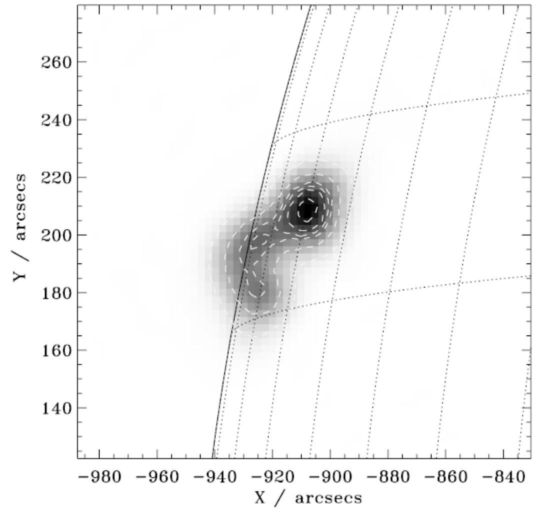


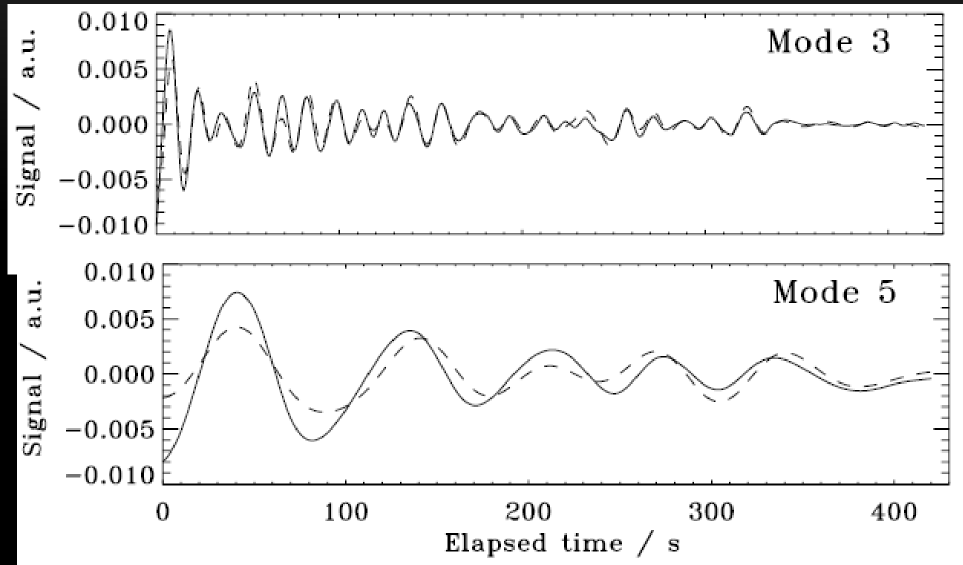
inner μ
ρ_i/ρ_e
10
8
6
4
2
− / + / −
− / +
−
1.0 1.5 2.0 2.5 3.0
μ



inner μ, ρ_i/ρ_e=10, μ=3.0
h/v_{Ae}
h/v_{Ai}
(a)
$\delta\rho(r=0,z=h,t)/\rho_i$
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
(b)
0.0285 0.3779 0.7273 1.0767 1.4261
$\omega R/v_{Ai}$
10
1
Pv_{Ai}/R
1
10
0 20 40 60 80 100 120
$v_{Ai}t/R$

NoRH QPP: 14 May 2014 [Kolotkov+15]





profile	l/R	ρ_i/ρ_e	v_{Ai} (km/s)	$P_{kink,theory}$ (s)
linear	0.167	28.5	653.8	91.5
parabolic	0.240	28.4	657.7	89.2
inverse-parabolic	0.277	31.1	593.7	102.5
sine	0.284	29.9	620.5	95.9

Guo et al. 2016 SoPh, 291, 877