

Optimum confinement regimes enabled by limit-cycle oscillations of Alfvénic modes near marginal stability

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1. York 2. Oxford 3. CEA 4. LPP-ERM/KMS 5. KIPT 6. UKAEA 7. A*STAR 8. Tokamak Energy 9. CFS 10. PPPL 11. Gridfire

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Understanding the nonlinear physics of energetic particles is essential for predicting next-generation burning plasmas



- Fusion-born alphas are expected to linearly destabilize modes (AEs, EPMs) by a resonant interaction
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- Simulations [1], theory [2], and experiments [3] have shown that EP-driven modes can generate zonal structures and have a positive effect on thermal confinement
- In this work, we focus on a recently-published experimental plasma condition in JET [4] which observed nonlinear coupling between TAEs, high-frequency sidebands, and a zero-frequency fluctuation :
 - Bursty alternating behavior of the Alfvénic modes and the microturbulence (ITG)
 - Nonlinear gyrokinetic simulations



- **Experimental observations**
 - Recap of JET plasma with MeV-range ICRF-heated ions
 - Alfvénic bursts in the DBS spectrum
- **Gyrokinetic modelling**
 - Linear gyrokinetic stability
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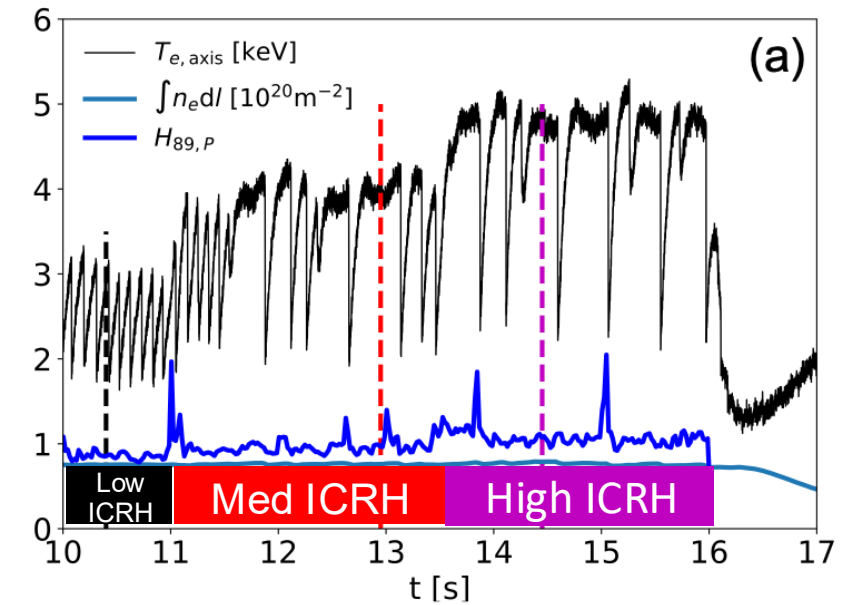


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- Confinement factor $H_{89,p}$ increase with ICRH power

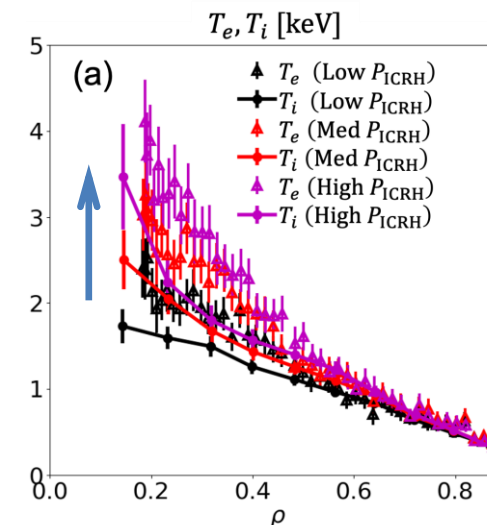
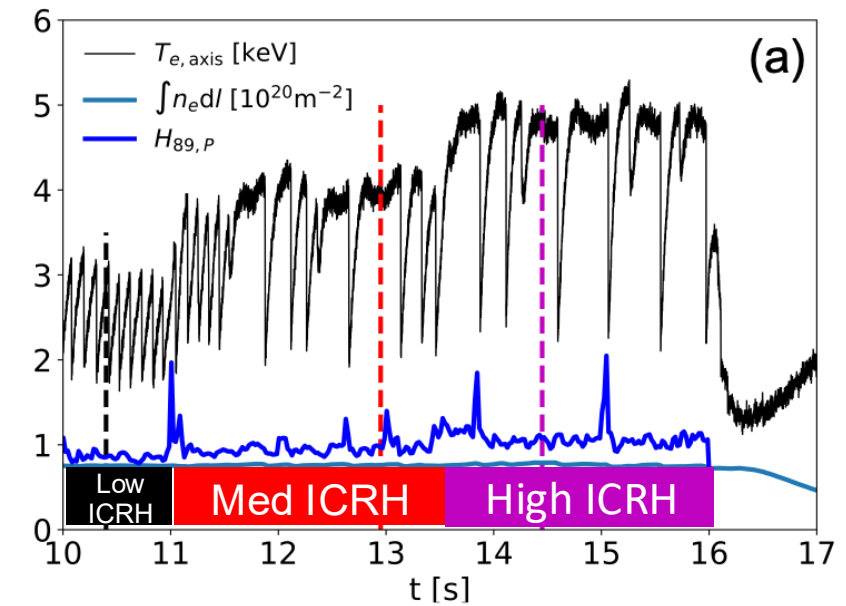


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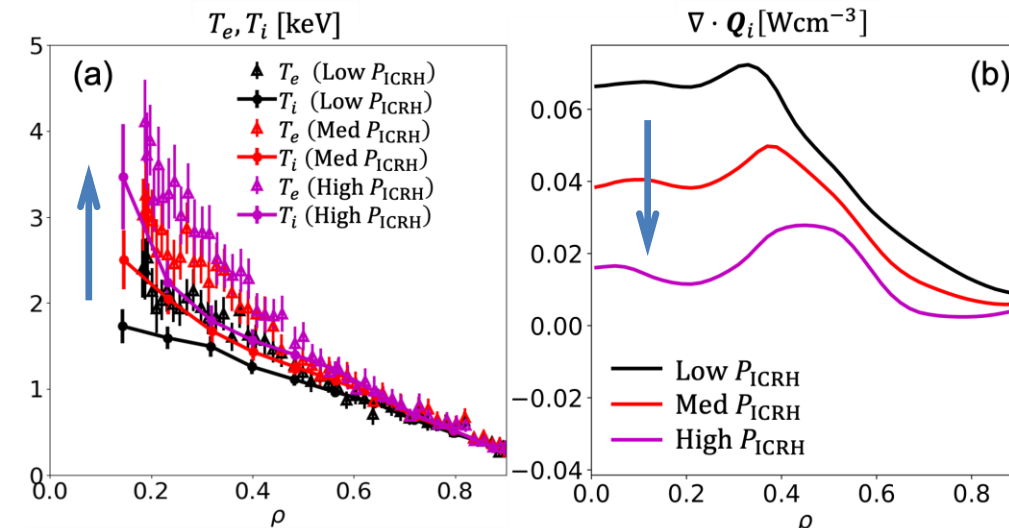
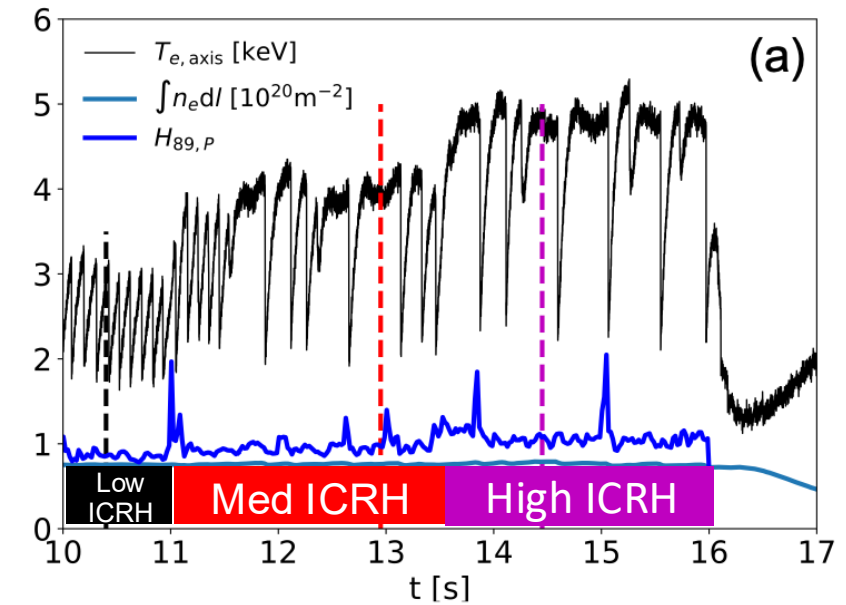
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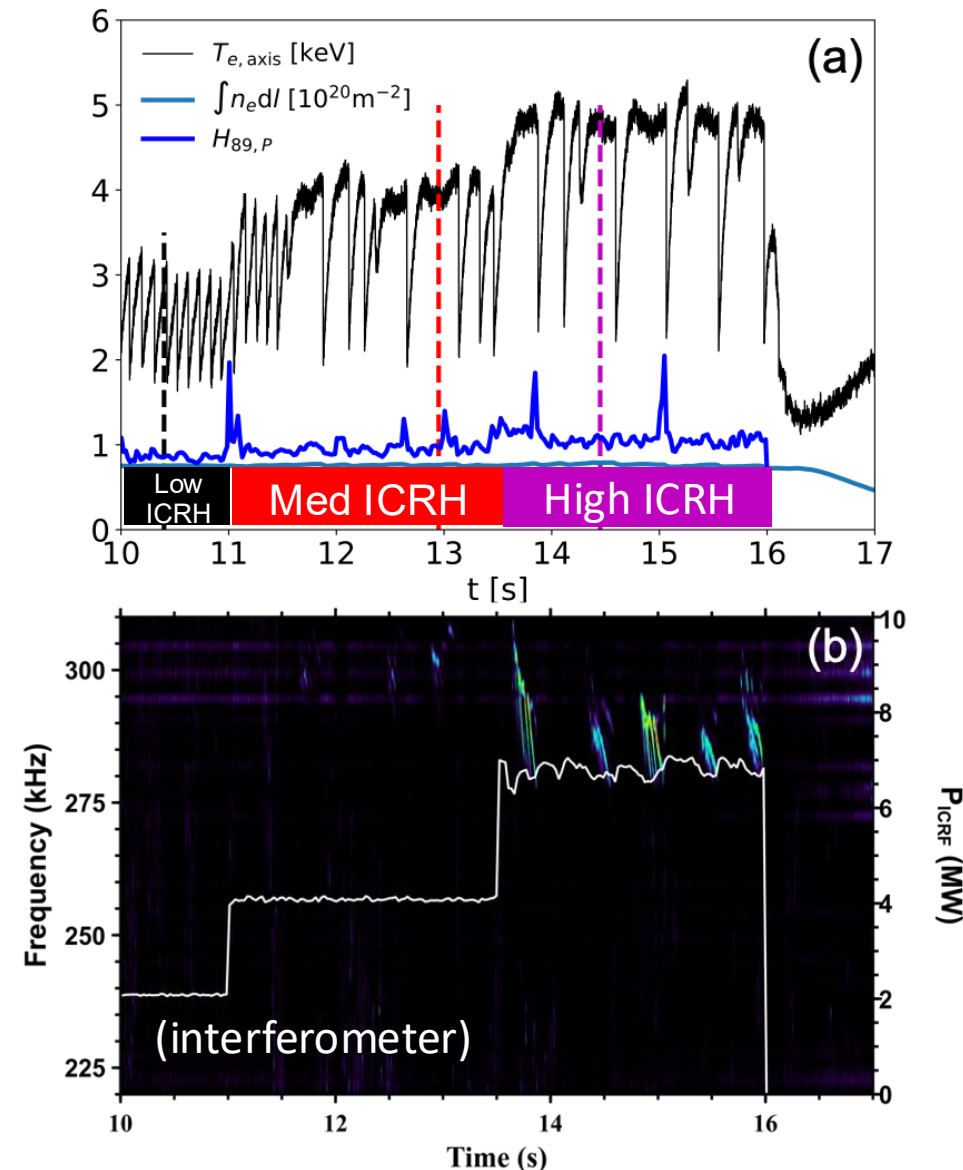


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- Unstable AEs (interferometer, SXR, DBS, faint in magnetics)



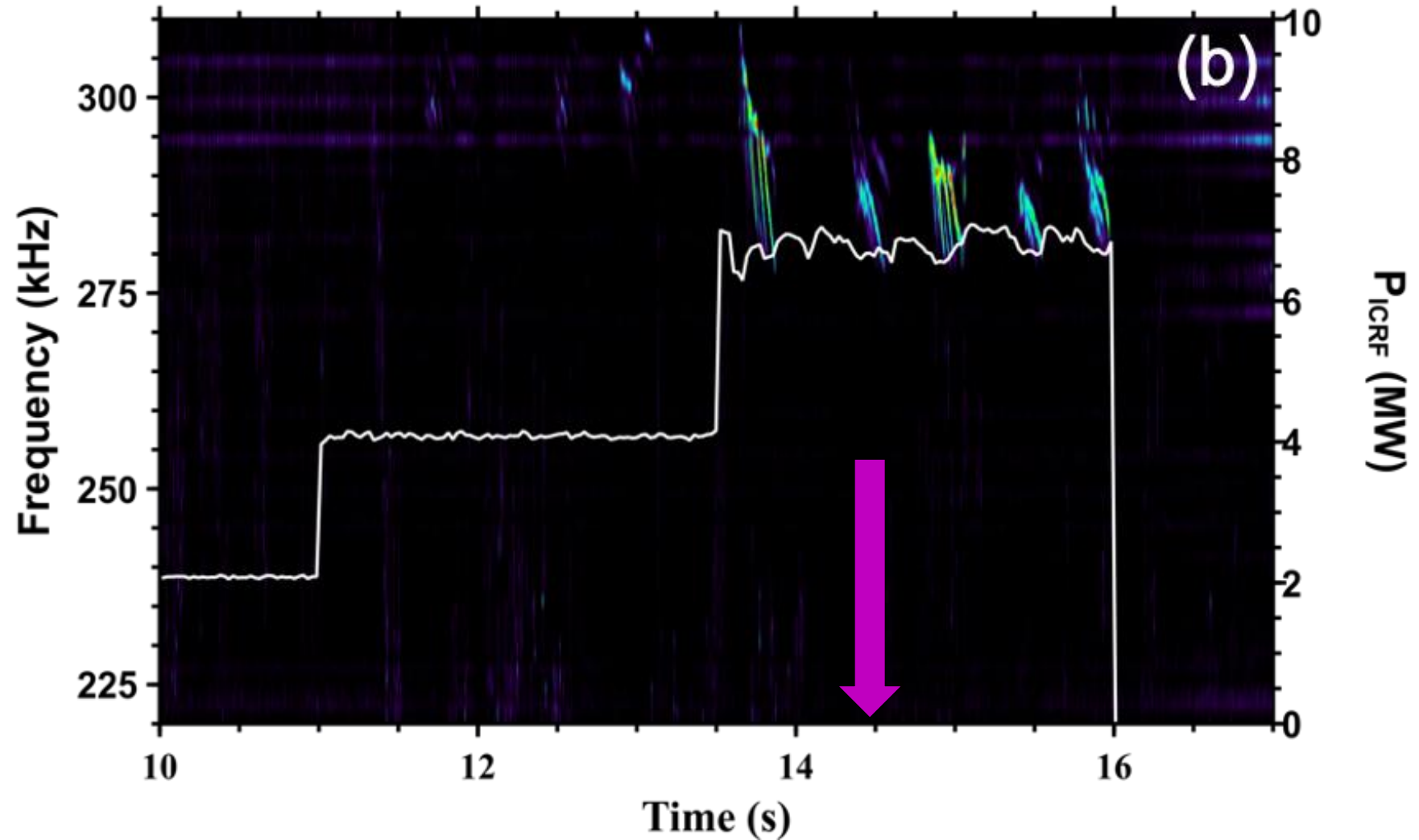
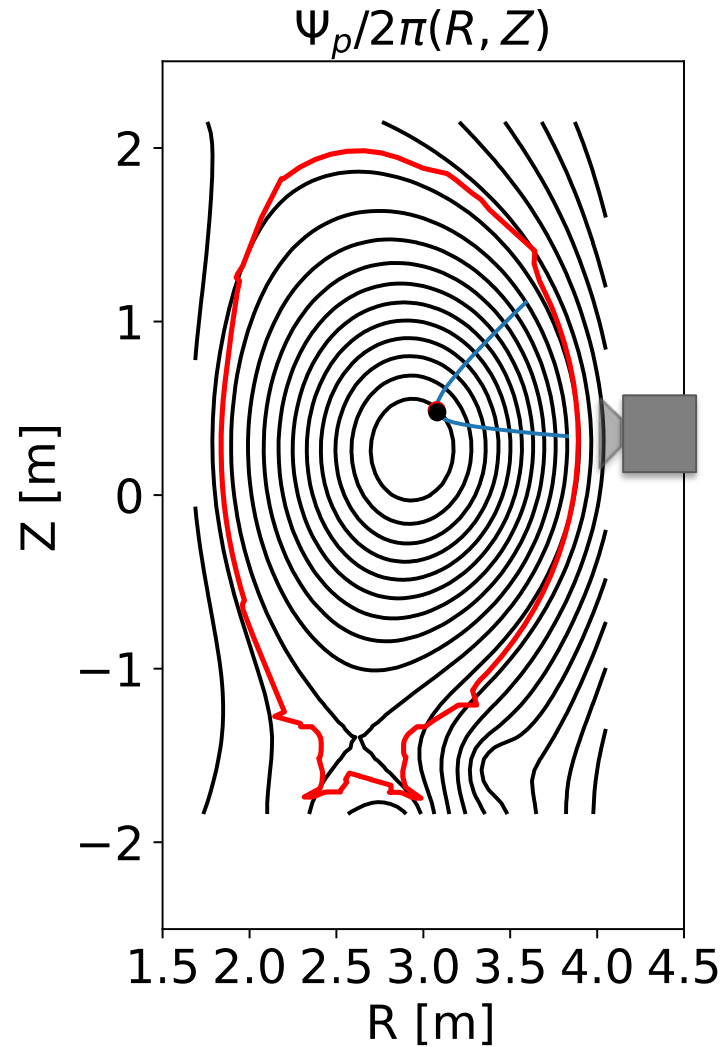
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Doppler Backscattering (DBS) measurements at high ICRH power

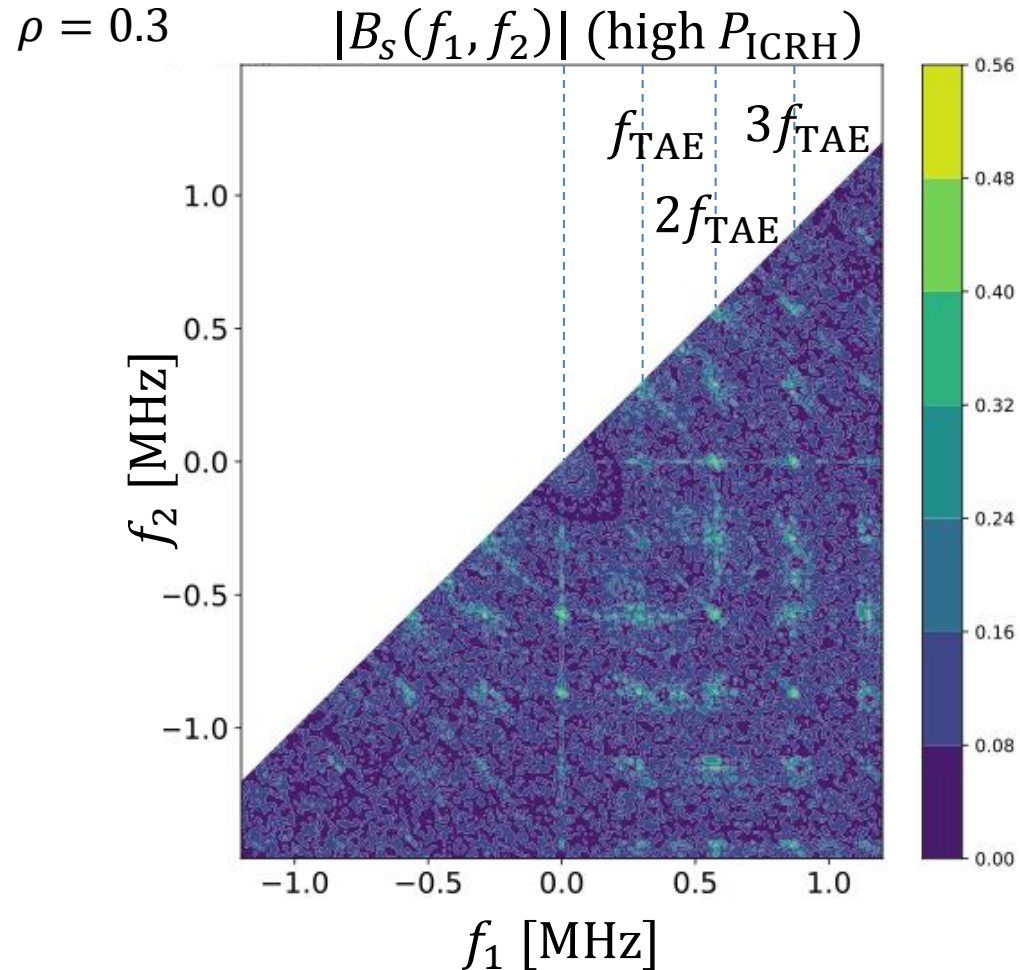


DBS ray path reaches $\rho = 0.3$

Interferometer signal

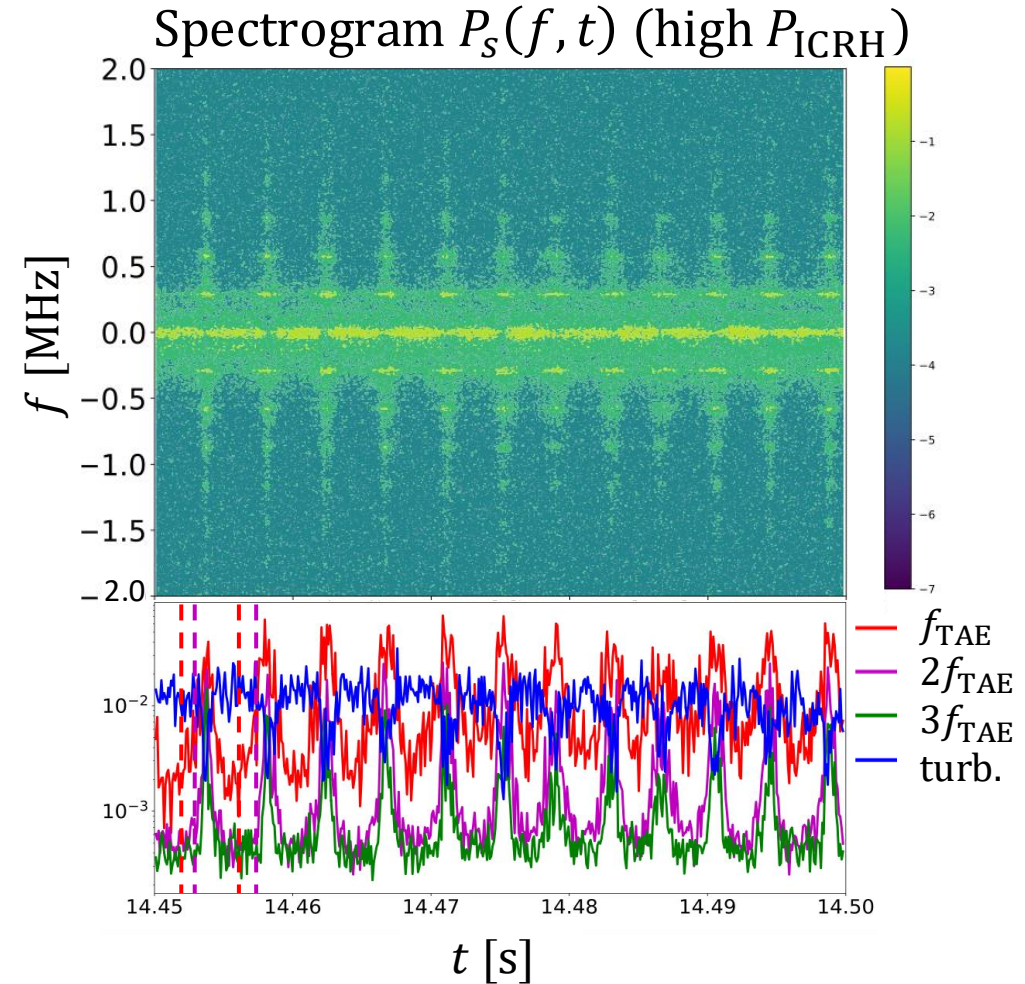
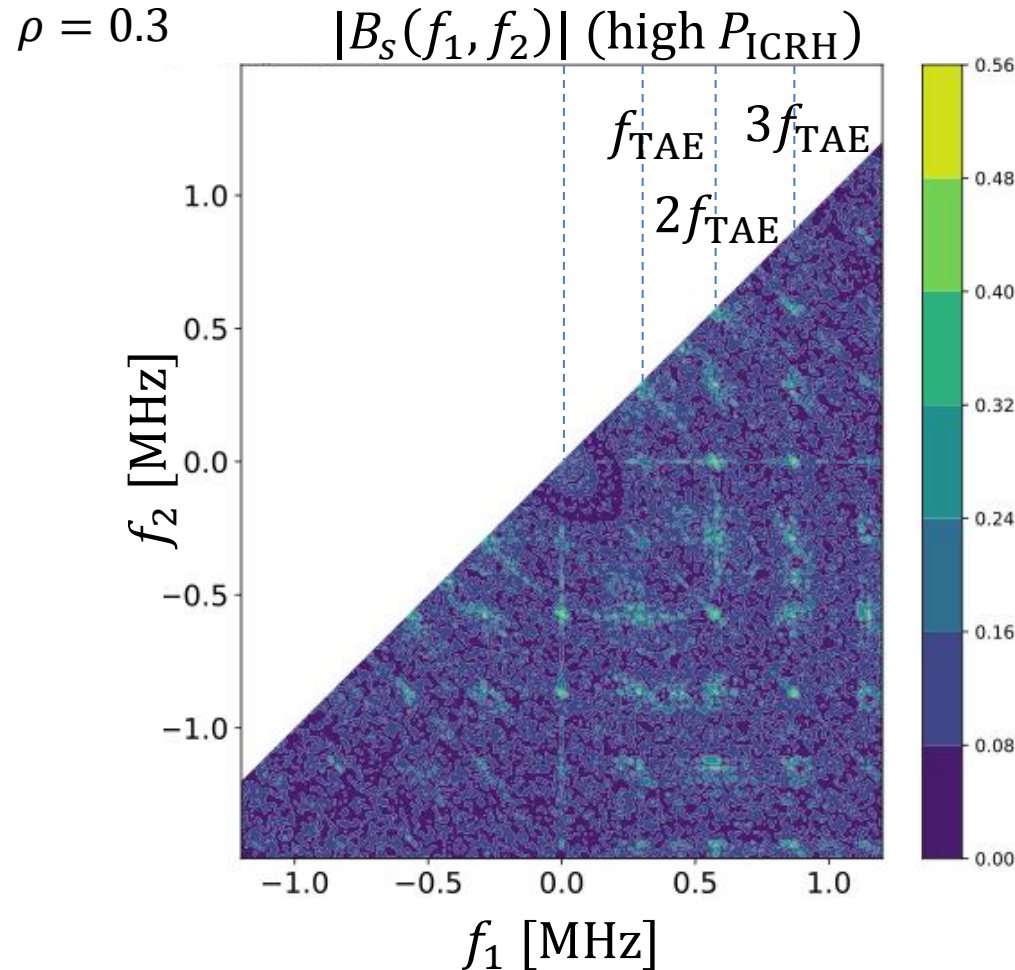


At high P_{ICRH} , DBS bicoherence exhibits nonlinear coupling between AEs and a zero-frequency fluctuation, spectrogram exhibits AE bursts



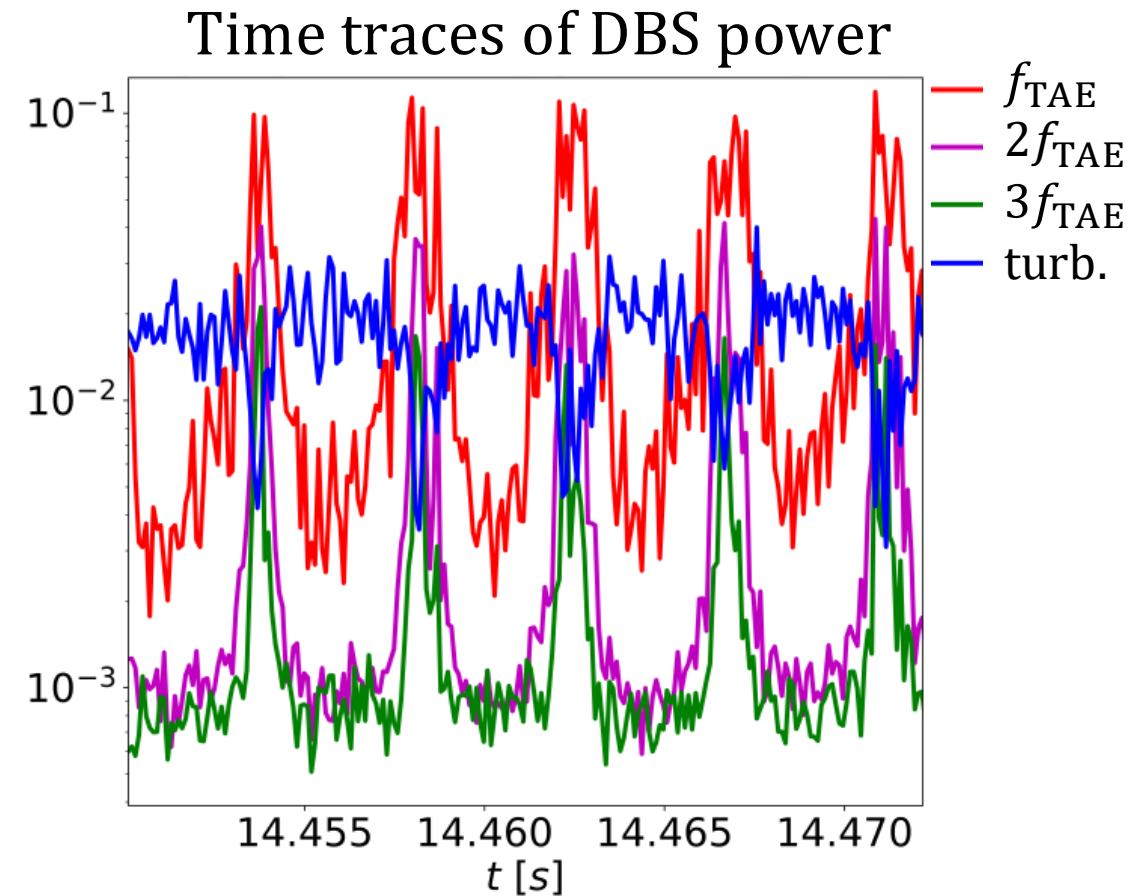
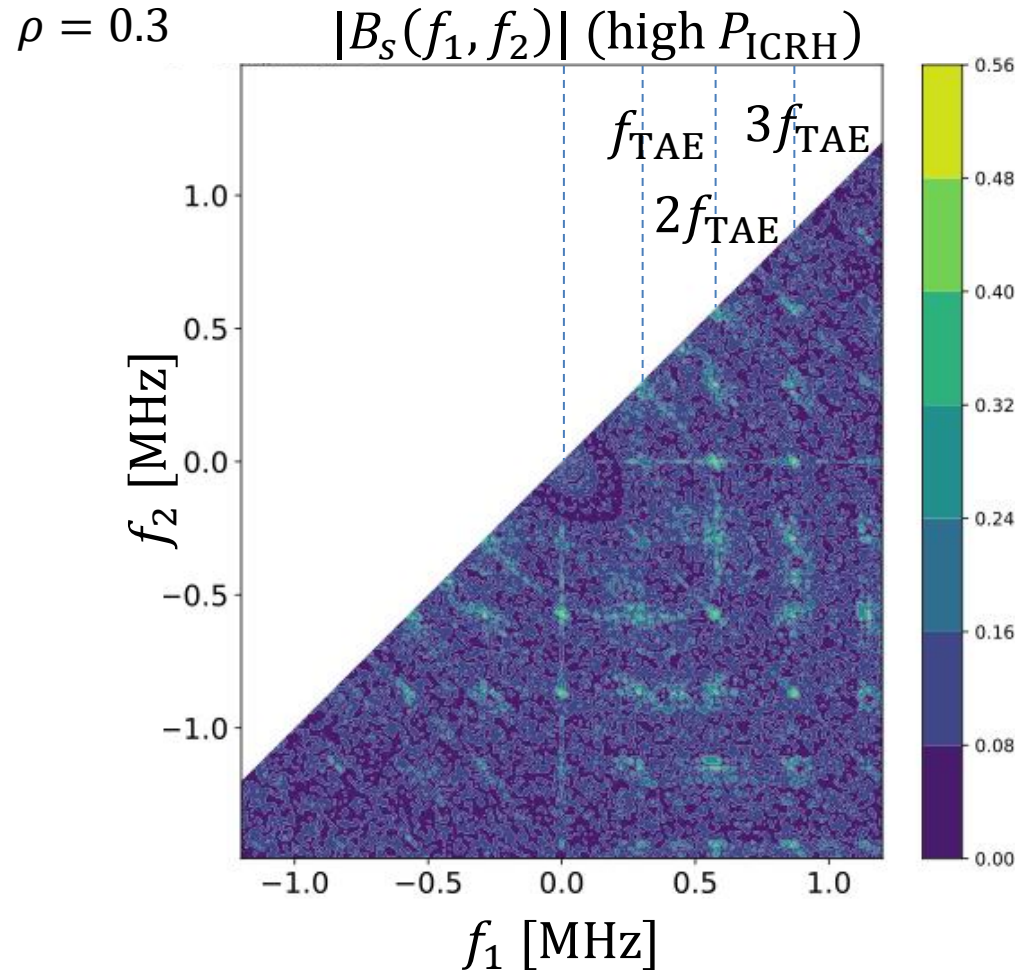
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- Spectrogram: quasi-periodic bursts of AEs at f_{TAE} + sidebands, and x5-10 decrease in microturbulence amplitude at f_{turb} . $\Delta t_{\text{DBS}} \approx 4$ ms

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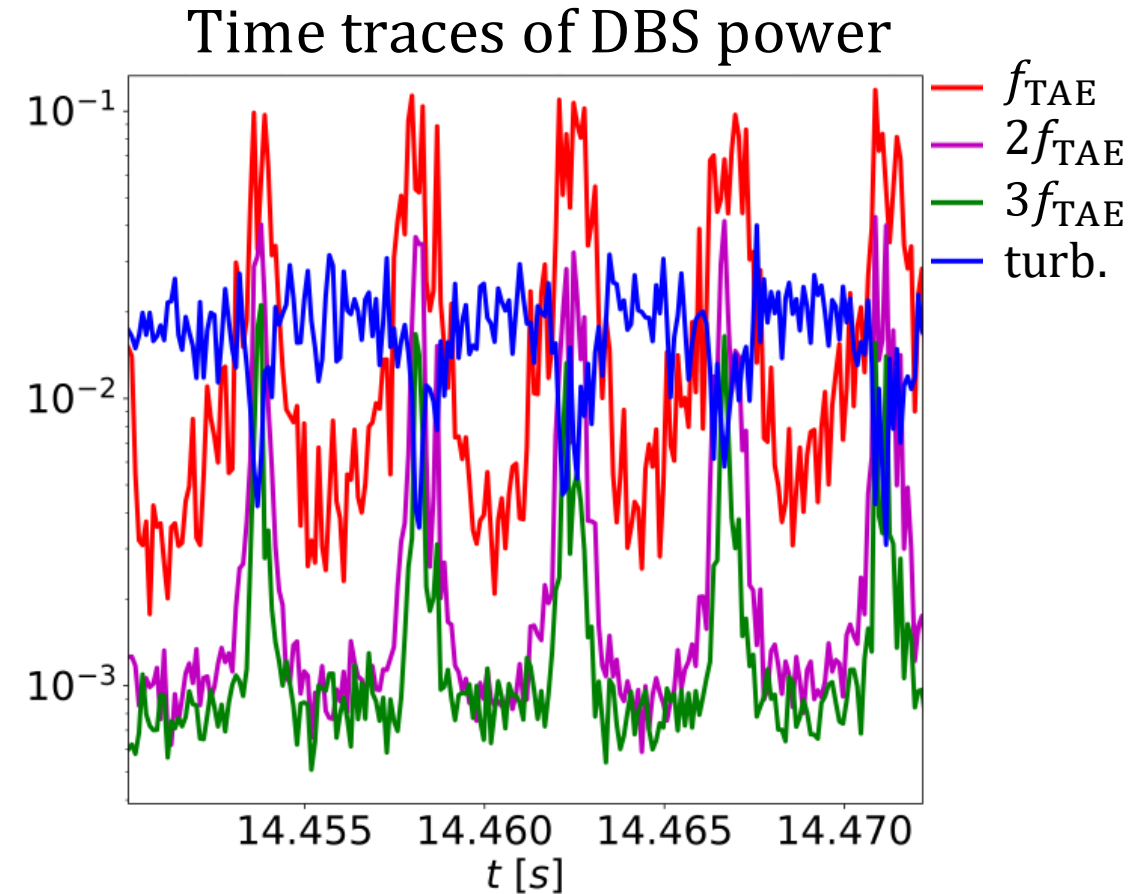
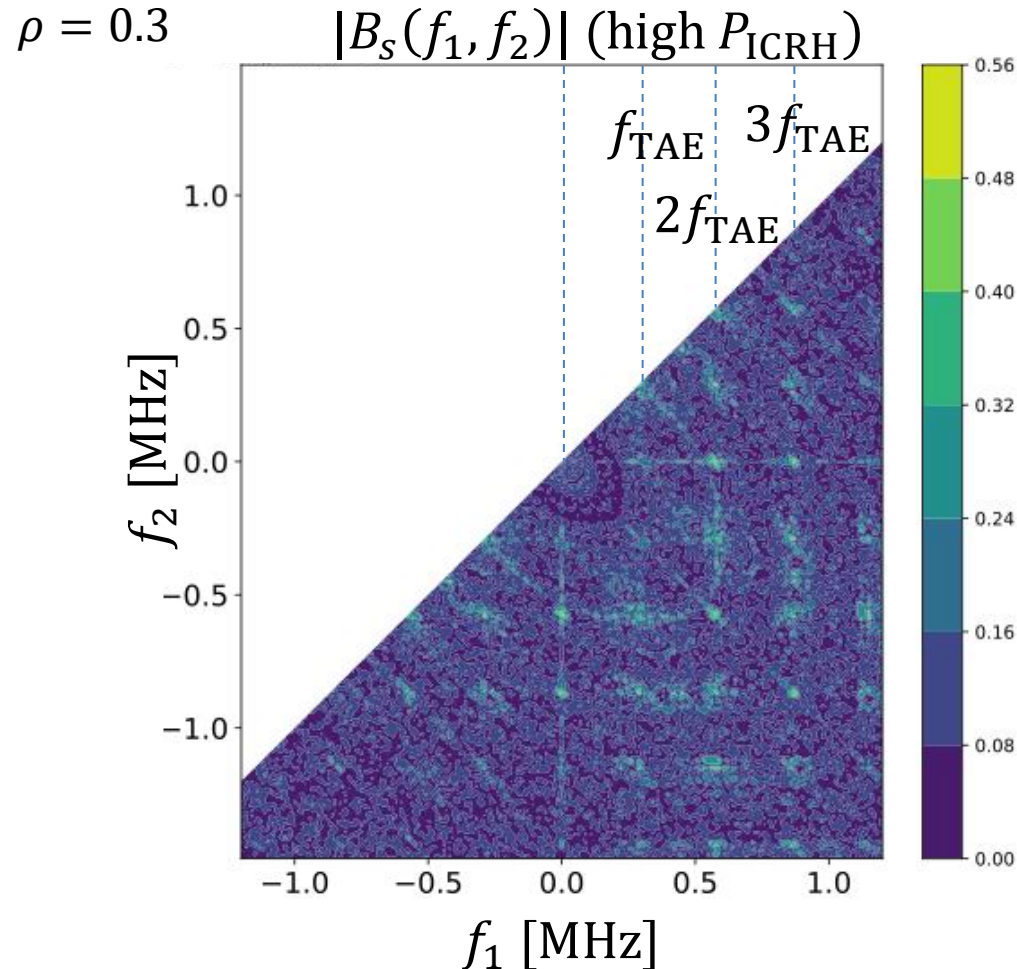
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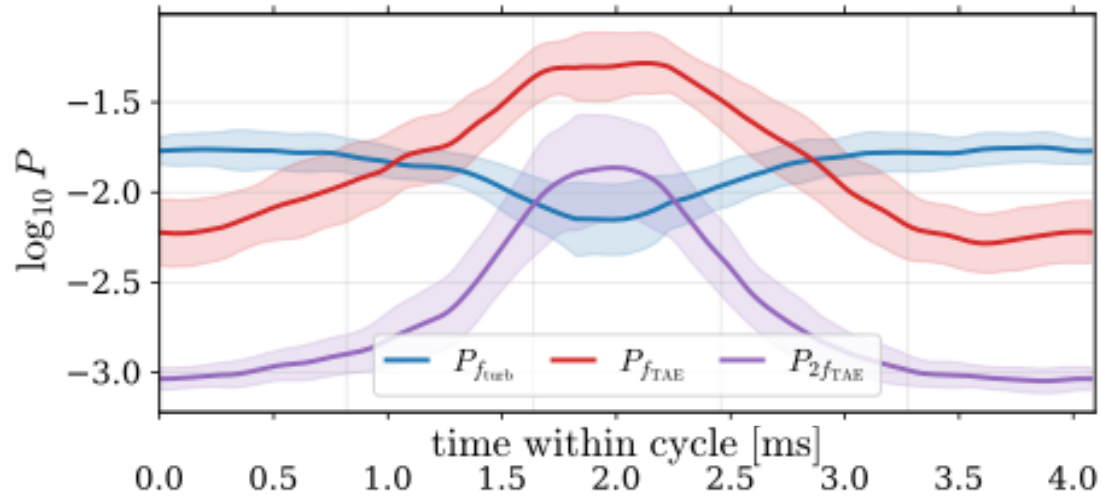
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In what follows, we give a candidate explanation behind the origin of the Alfvénic bursts

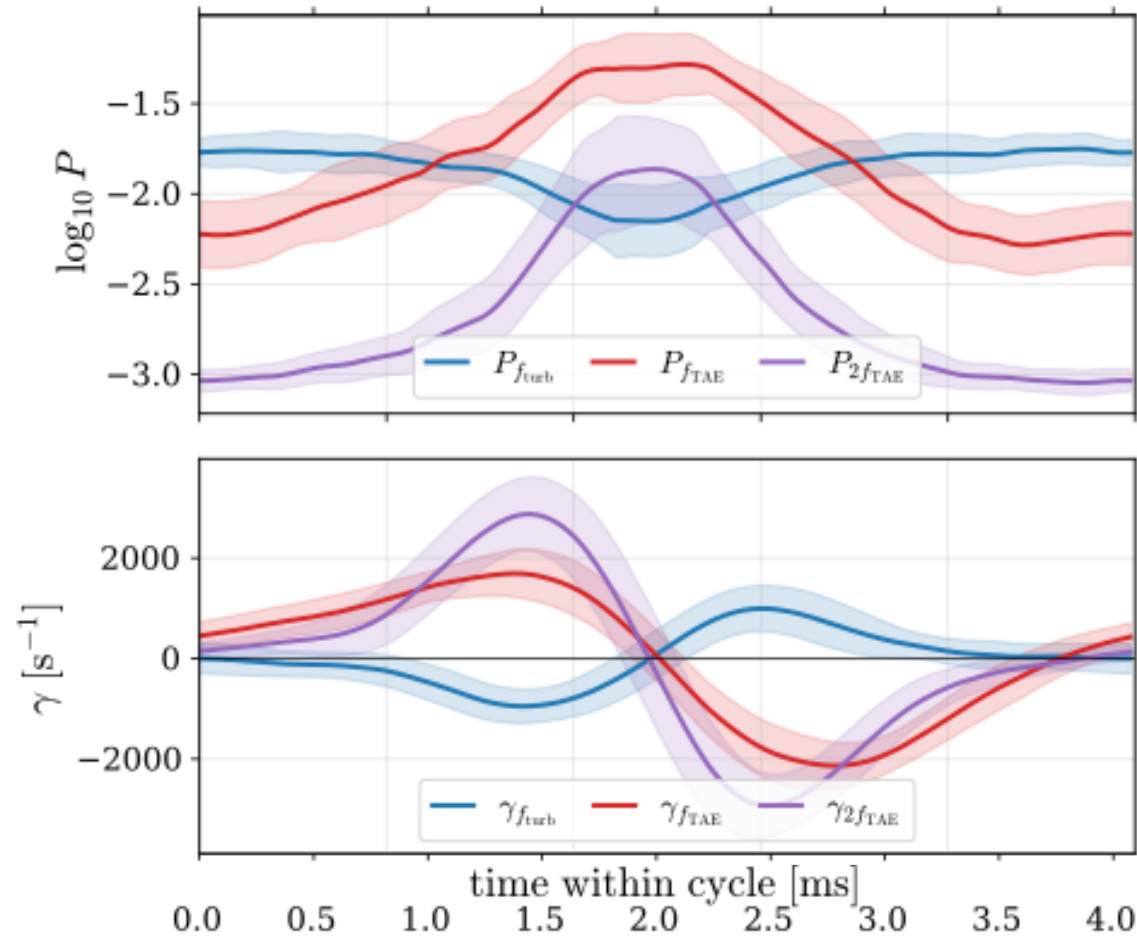
amplitude of f_{TAE} and DBS

Averaging the Alfvénic bursts over cycles yields linear growth rate and evidence of beat-driven generation of sideband



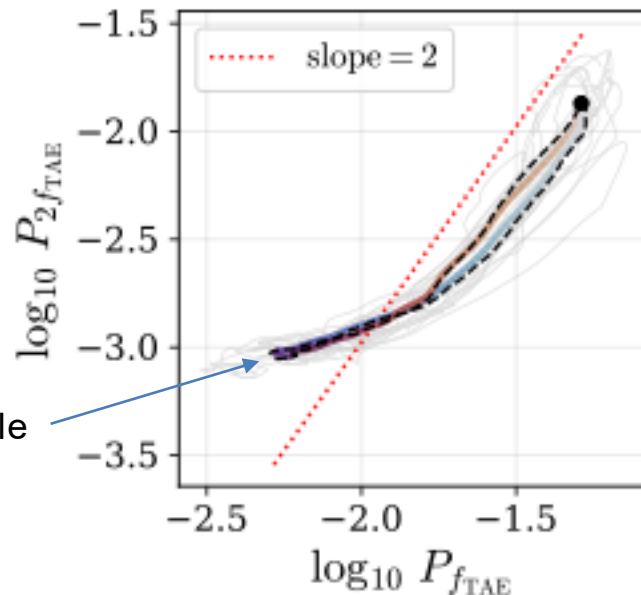
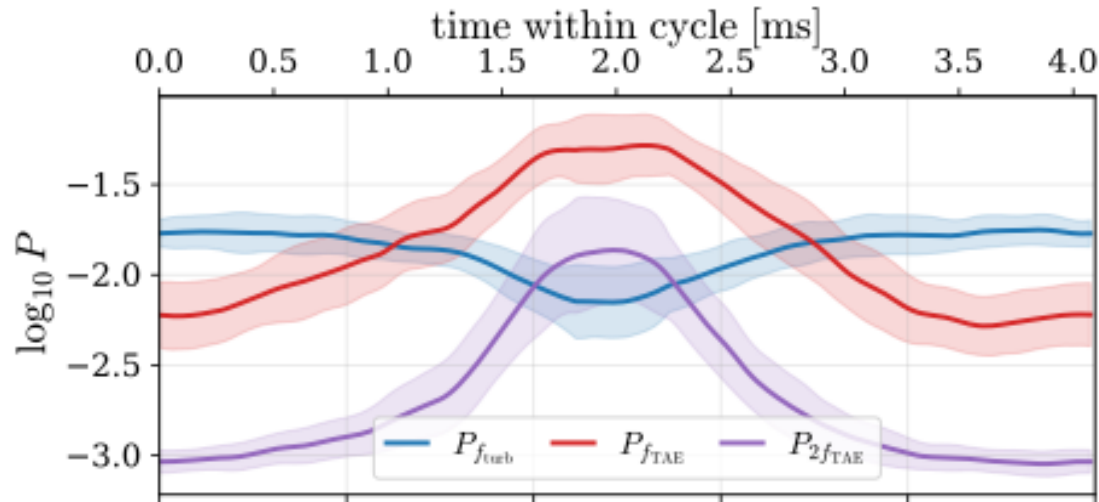
- Obtain average burst behavior by averaging over 12 cycles
 - $P_{f_{\text{TAE}}}$: power at f_{TAE} grows (primary)
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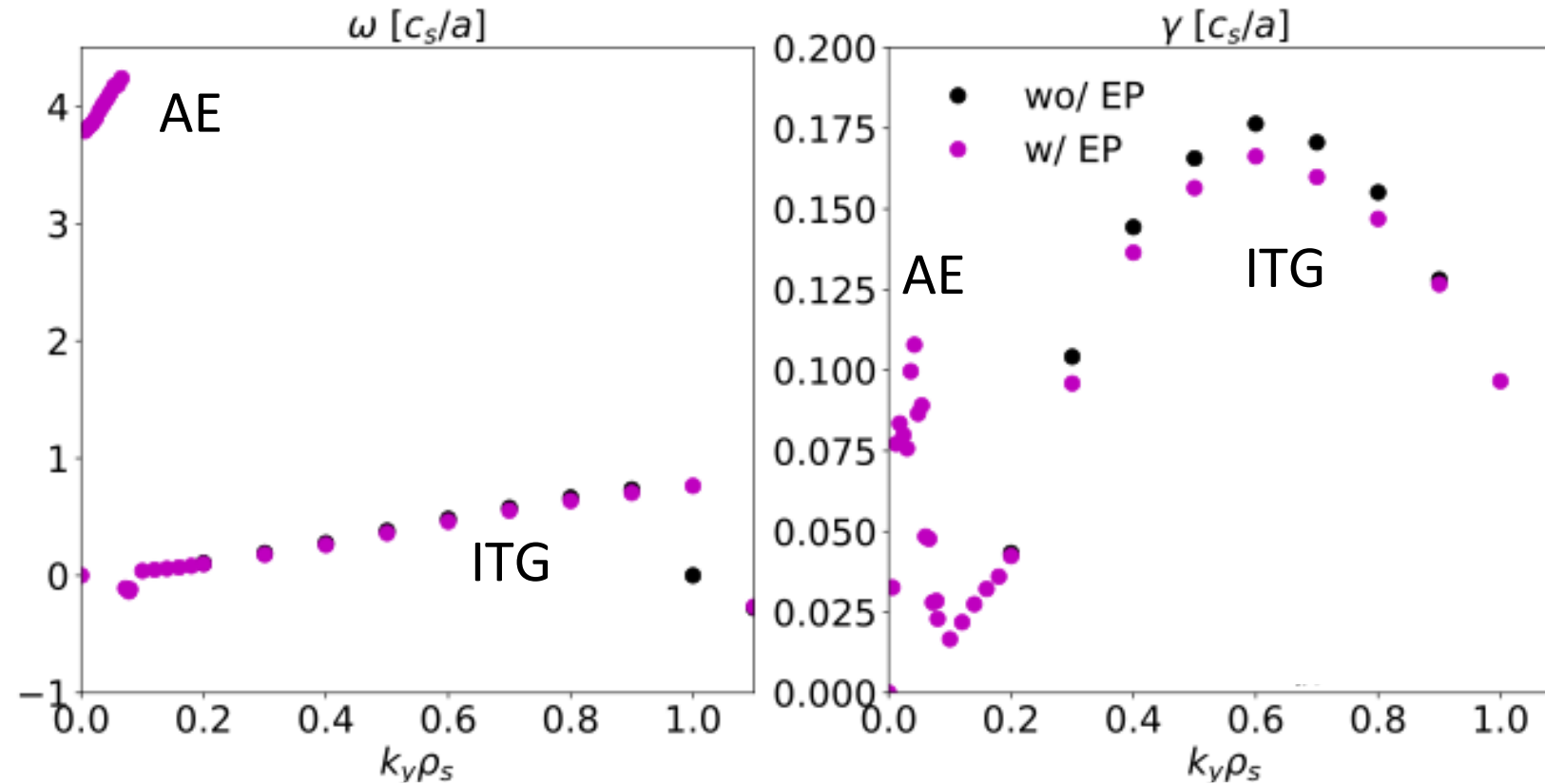


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- Find $\gamma_{2TAE}/\gamma_{TAE} \approx 2$ during growth of the sideband (burst): **sideband is generated by beat-driven process**



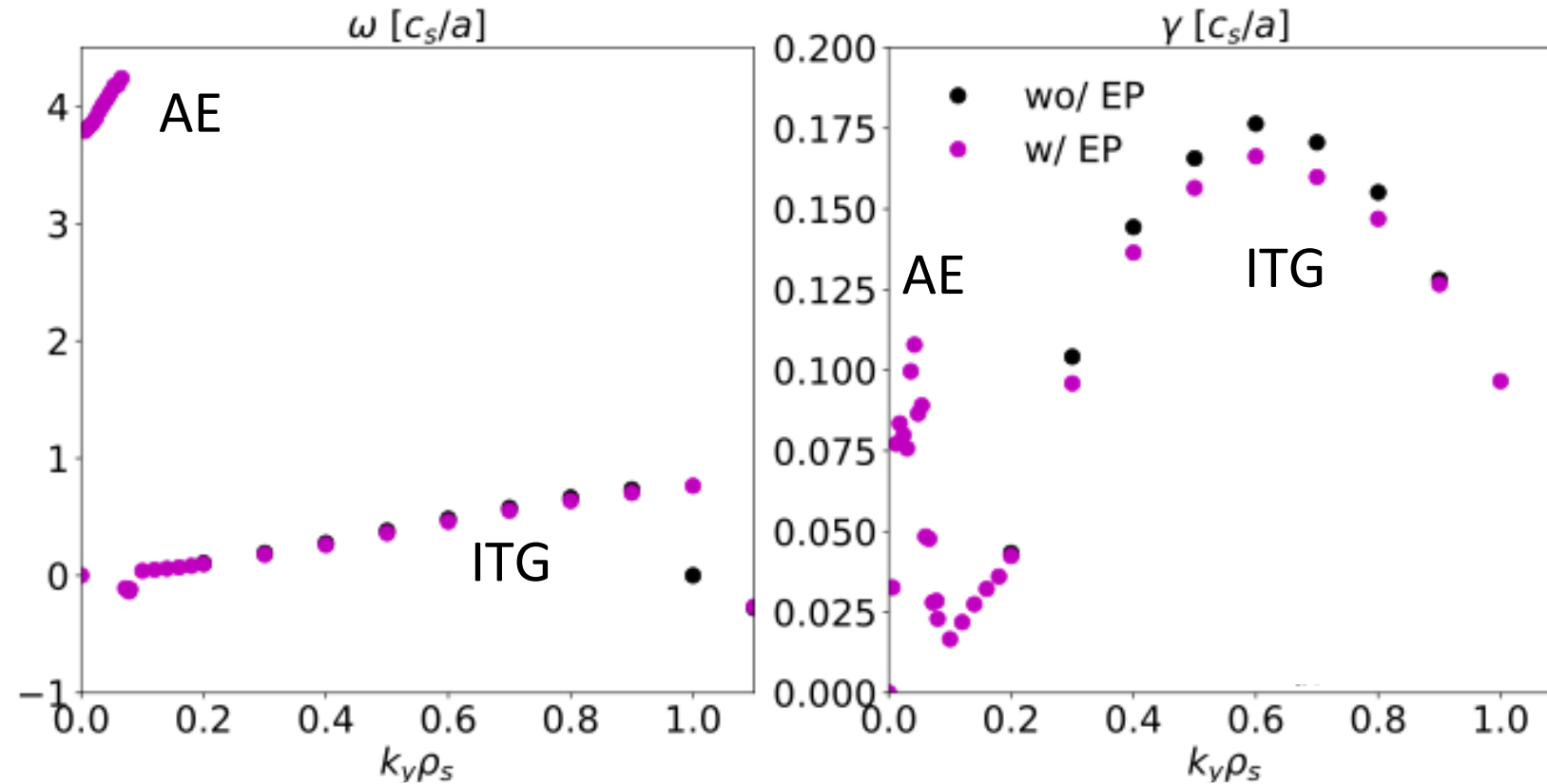
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Local linear CGYRO at high P_{ICRH} shows destabilization of fast-ion-driven instability consistent with an AE, and ITG



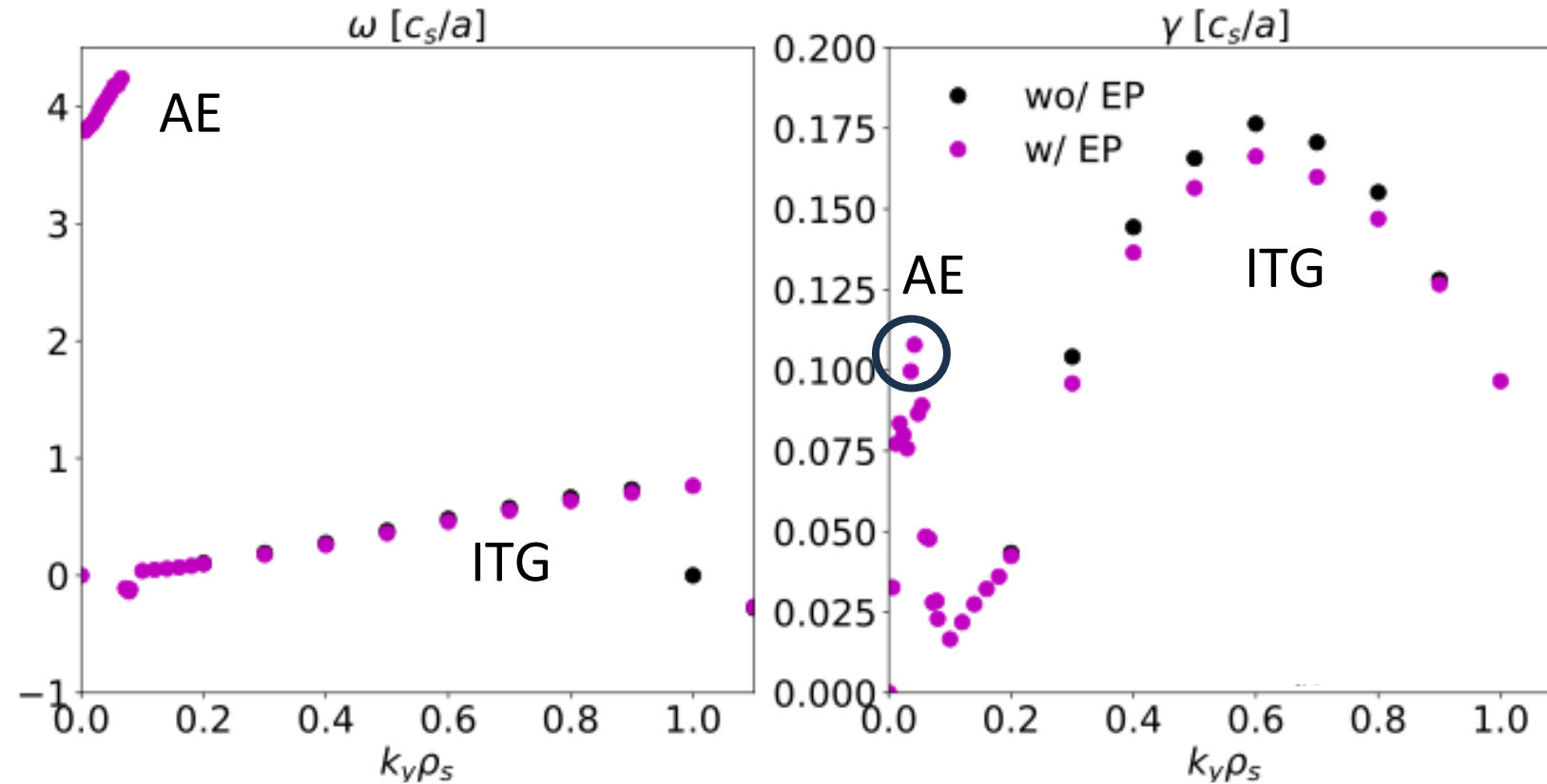
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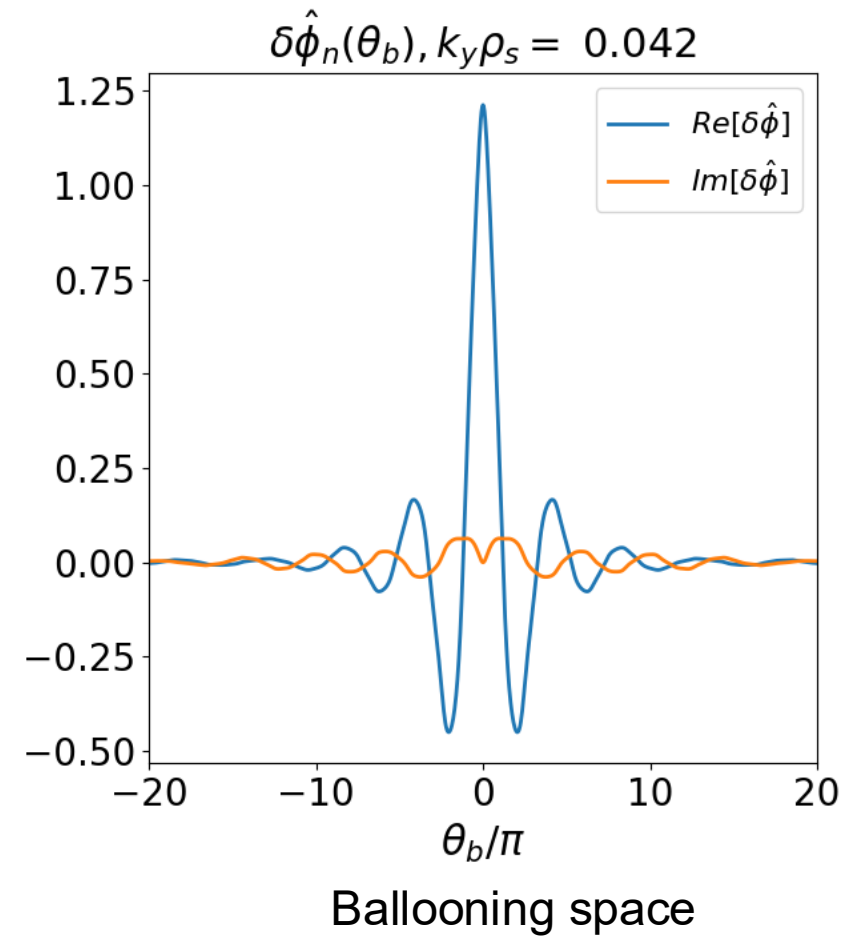
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 - CGYRO $\omega_{TAE} \approx 4 c_s/a$ matches DBS $f_{TAE} \approx 270 - 300 \text{ kHz}$, $n \approx 6$ ($k_y \rho_{sD} \approx 0.042$)
- Negligible effect of EPs on ITG $\rightarrow$ **linear** effects (dilution, β' , kinetic stabilization) are negligible
- No low- k_y AE without EP

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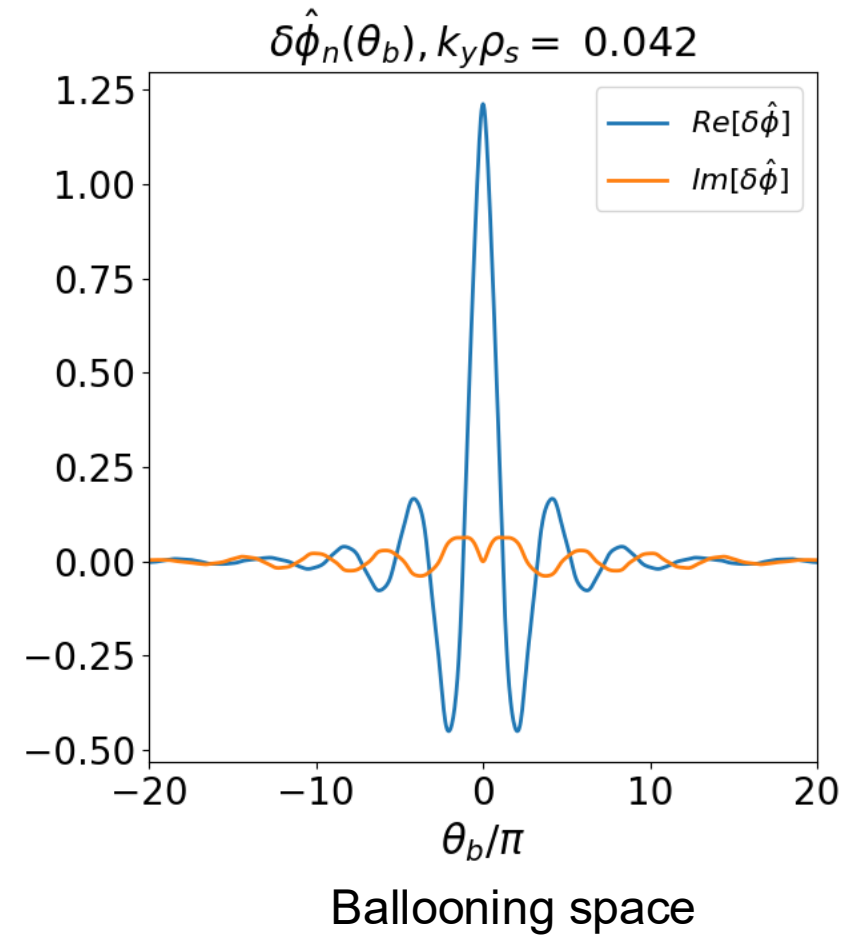


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Field-aligned coordinates (r, θ, α) :

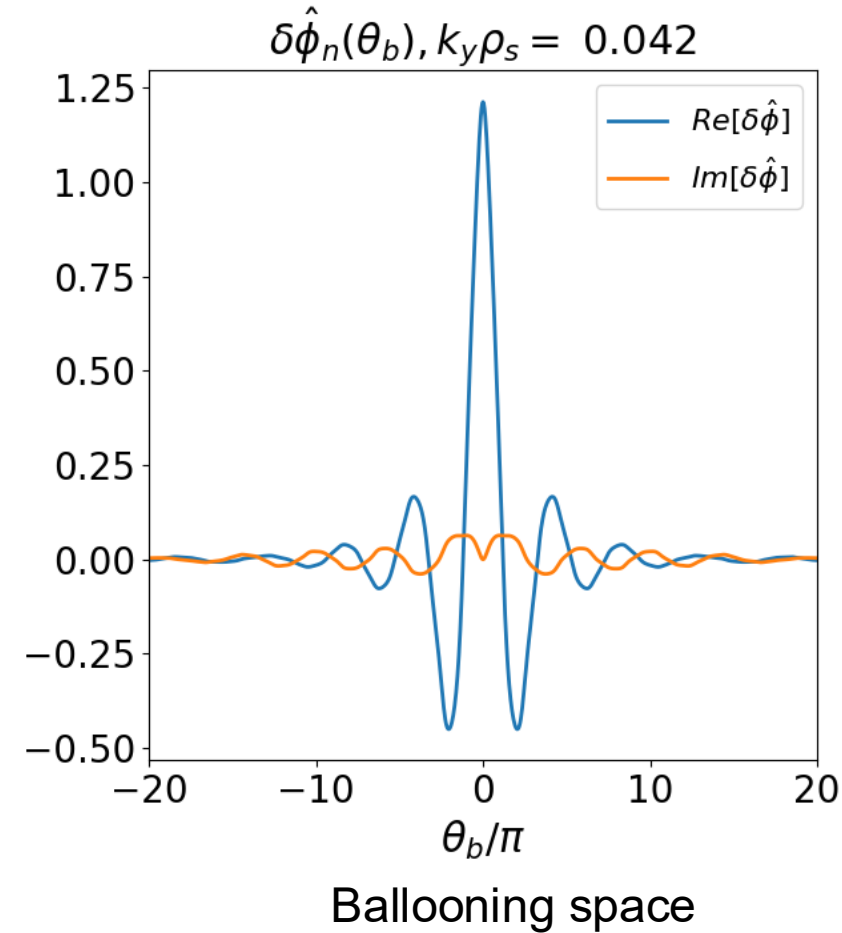
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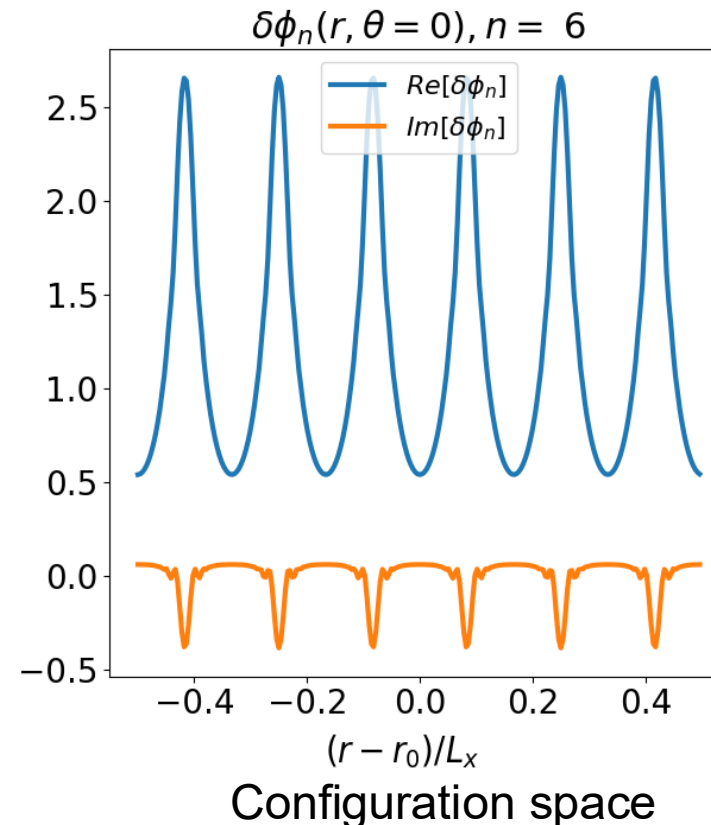
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- $n=6$ mode peaks 6 times

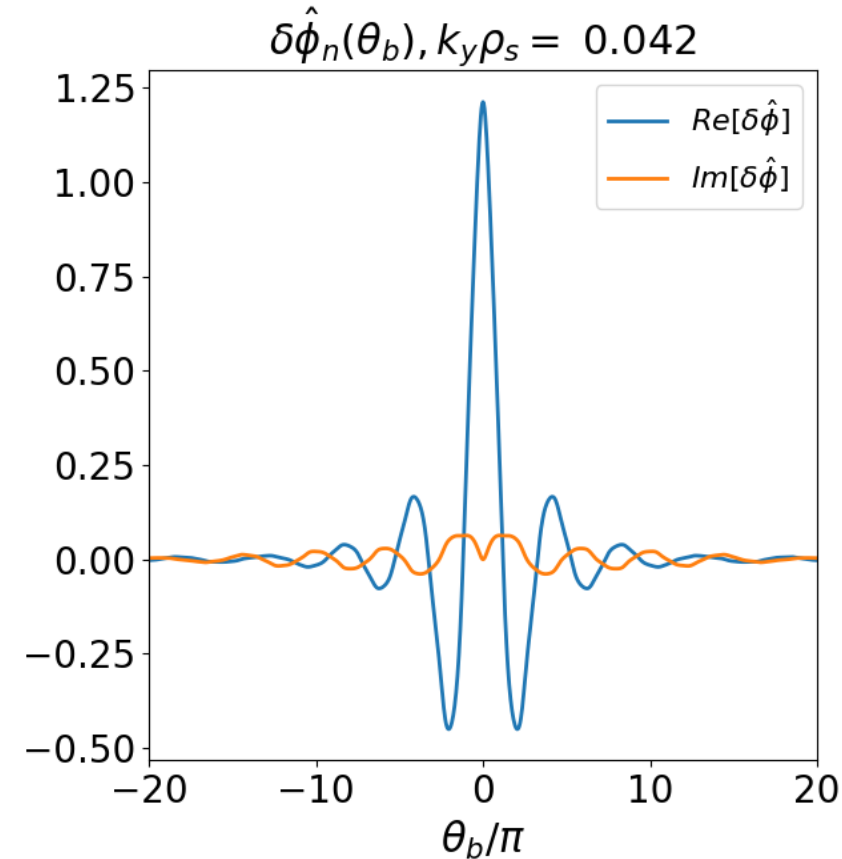
where $L_x = J_t / \Delta n q'$

$$\rightarrow \Delta r_{\text{rat}} / L_x = \Delta n / J_t n = 1 / j J_t$$

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$$\text{For } J_t = 1, j = 6 \rightarrow \Delta r_{\text{rat}} / L_x = 1/6$$

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Ballooning space



Rational surface $q=m/n$



Half-rational surface $q=(2m+1)/2n$

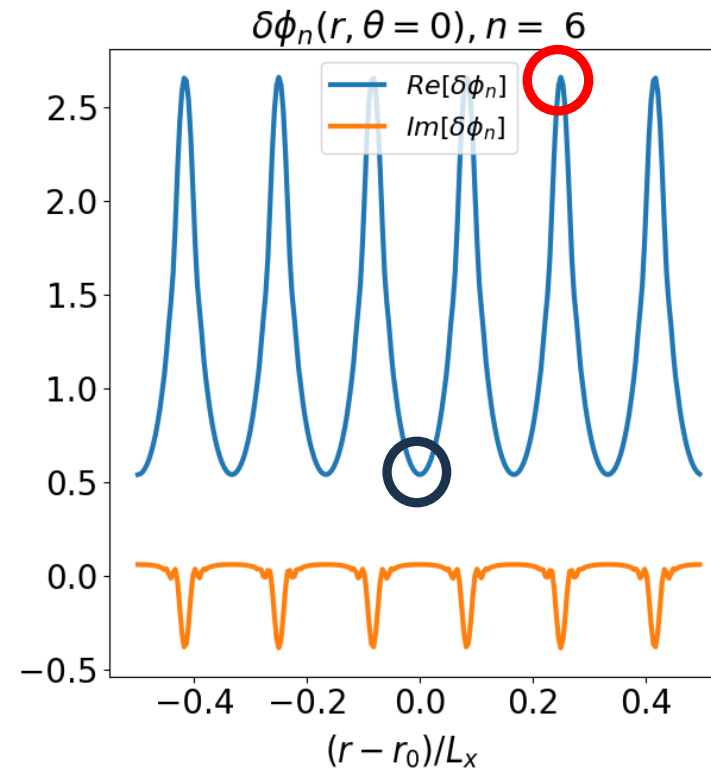
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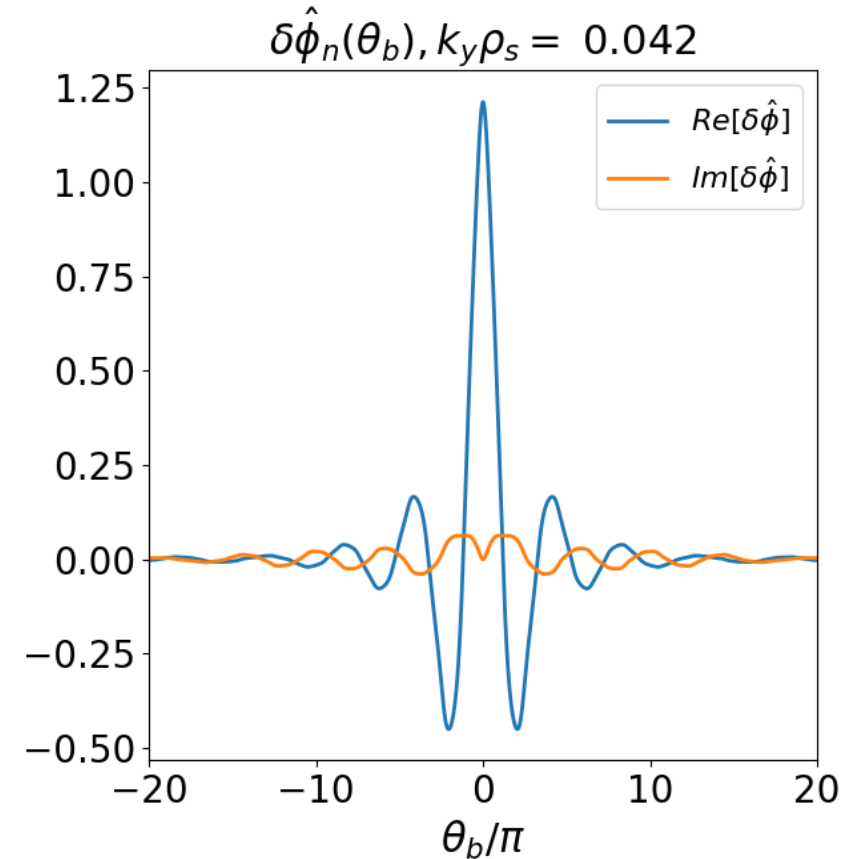
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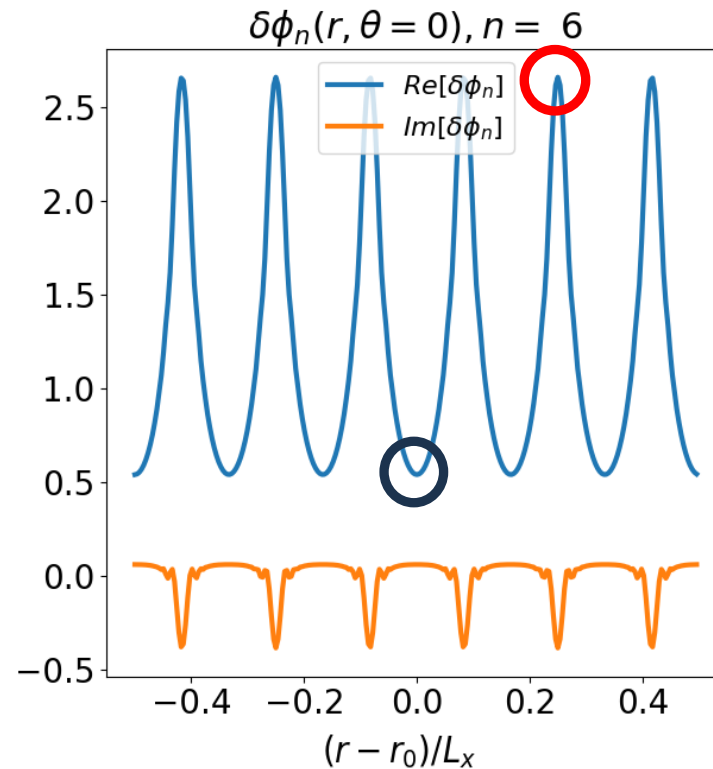
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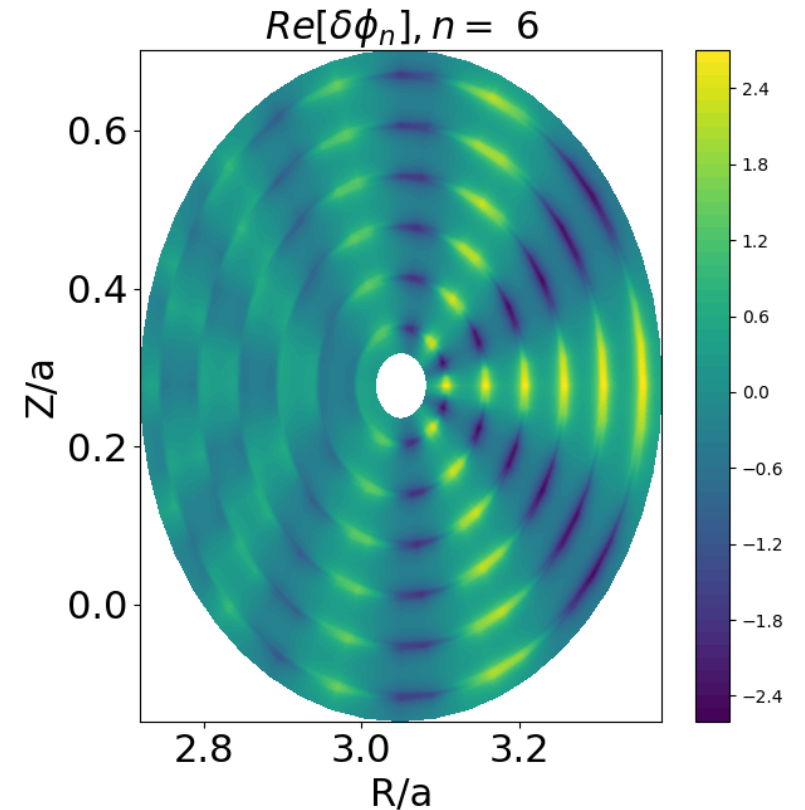
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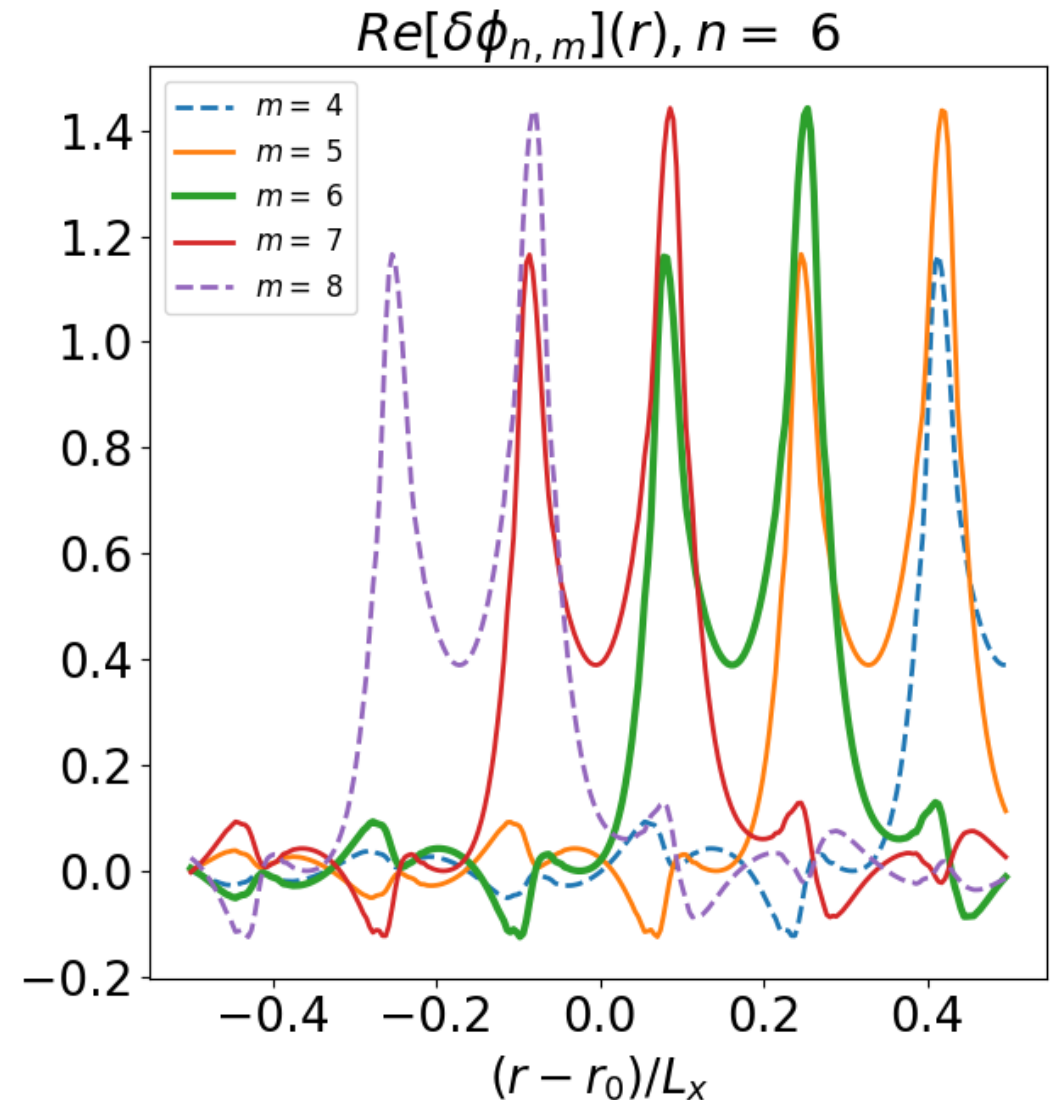
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Decompose $\delta\phi_n(r, \theta)$ into poloidal harmonics
→ overlap of neighboring m (TAE)



$$\delta\phi_{n,m}(r) = \int \frac{d\theta}{2\pi} \delta\phi_n(r, \theta) \exp(-im\theta)$$

This confirms that $n = 6$ here is a local TAE! [1]

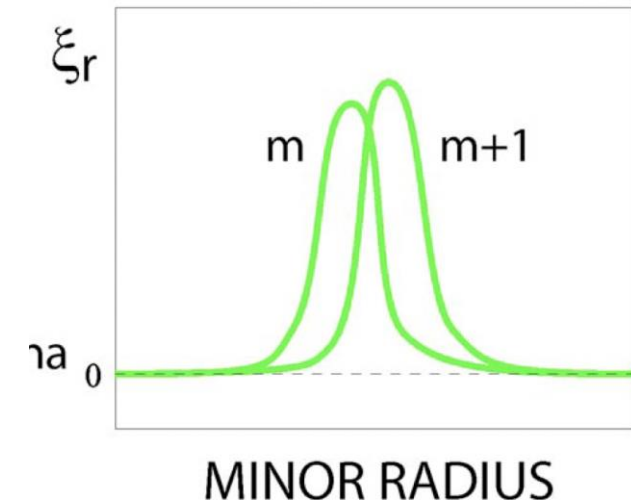
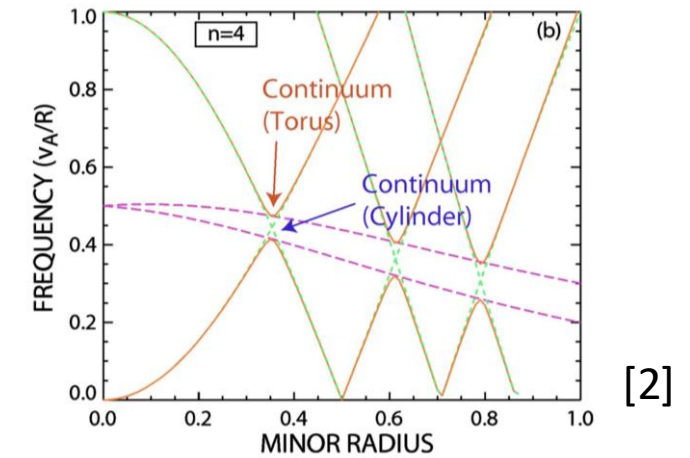


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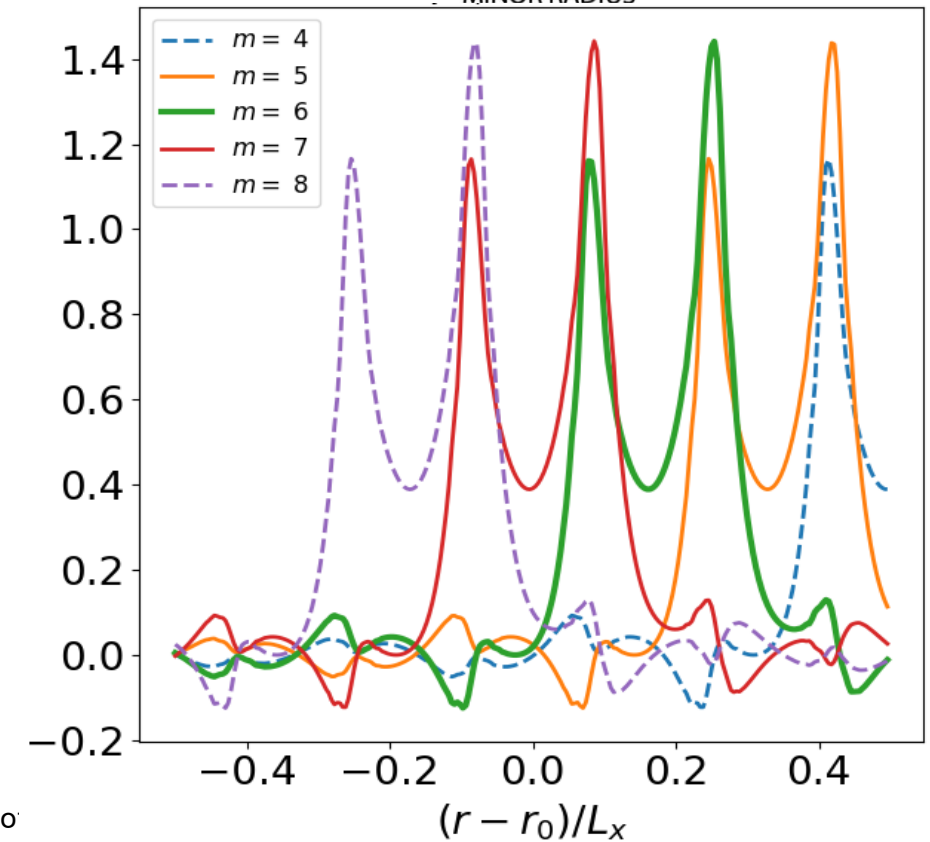
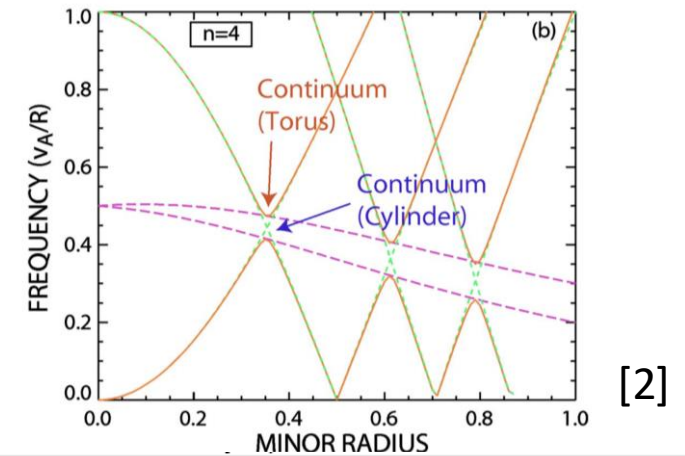


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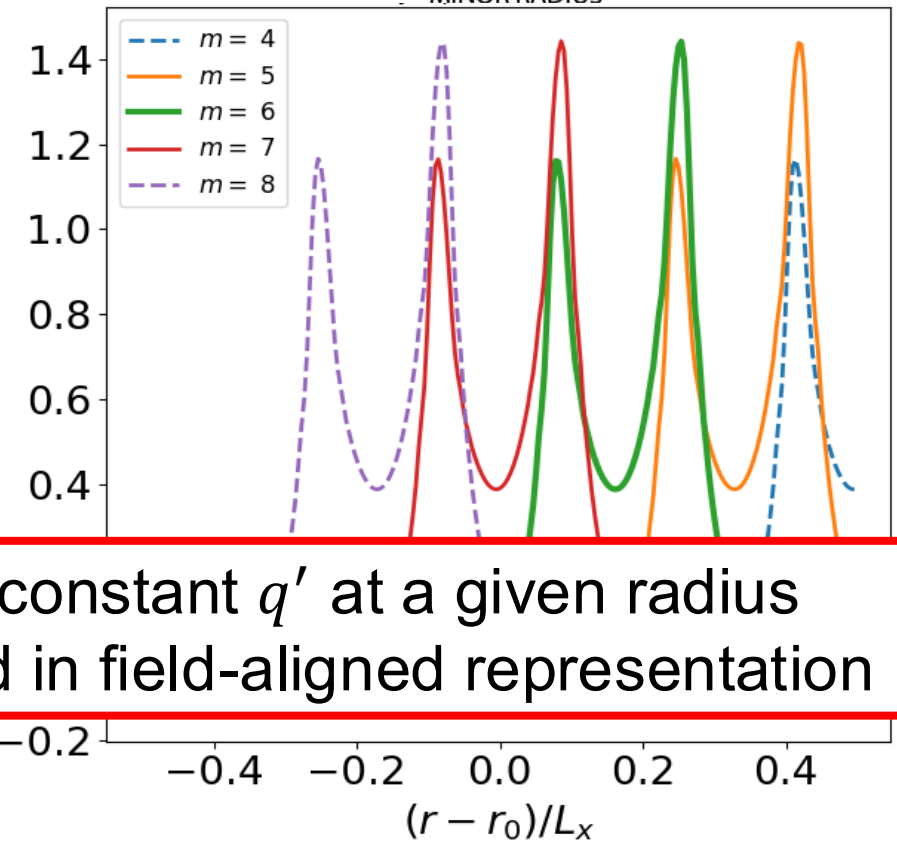
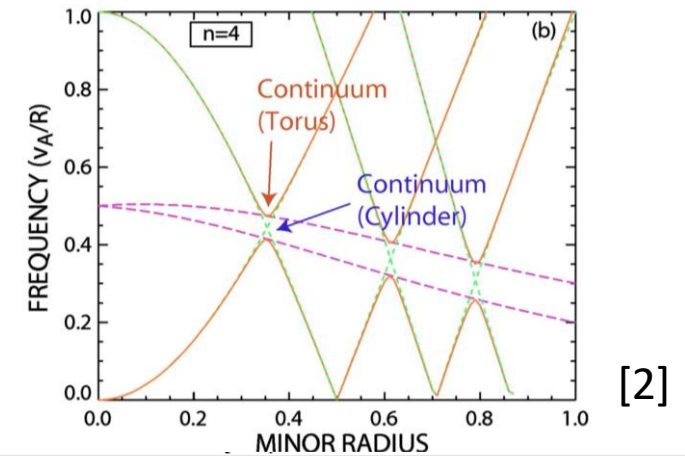


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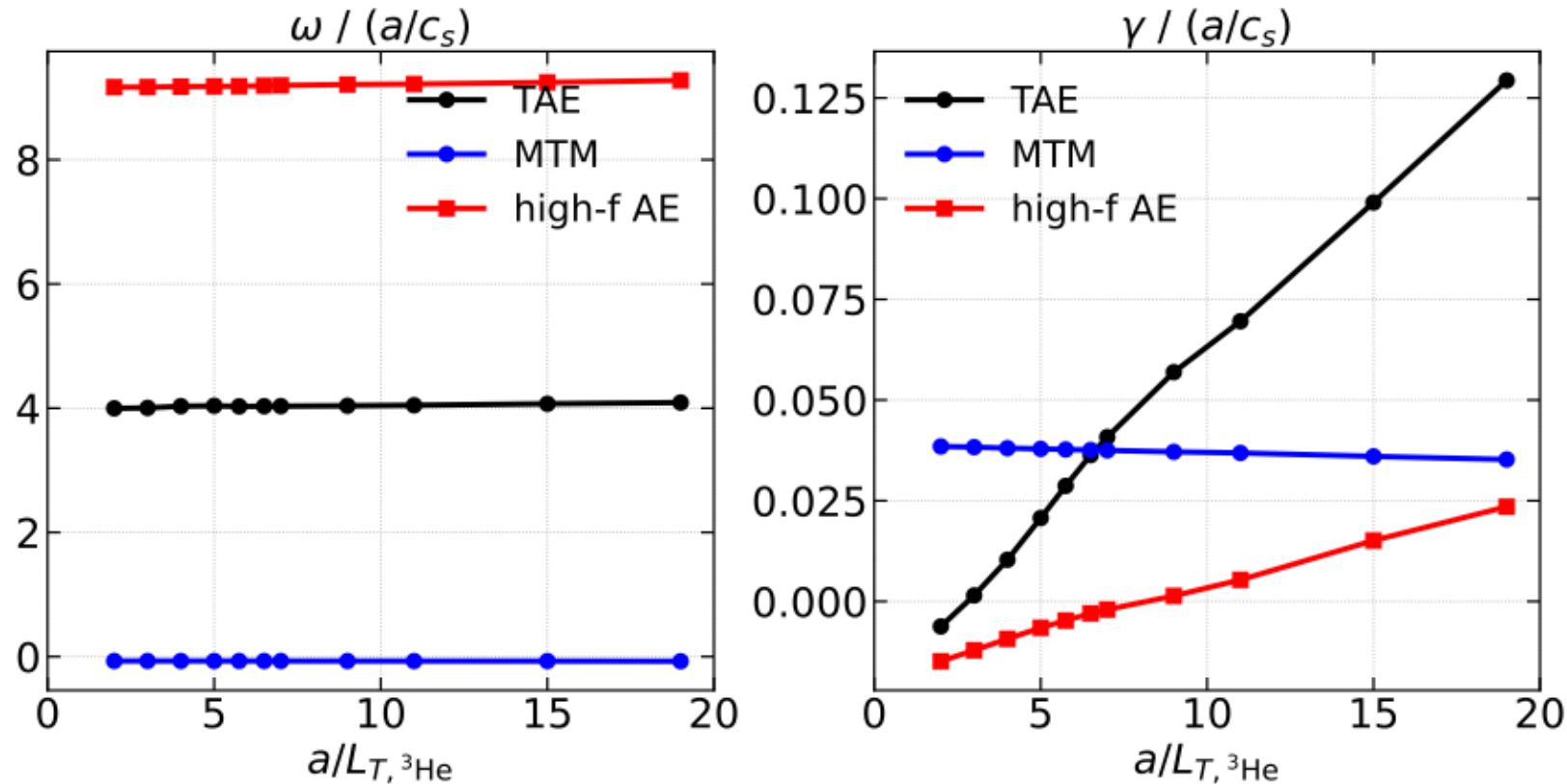
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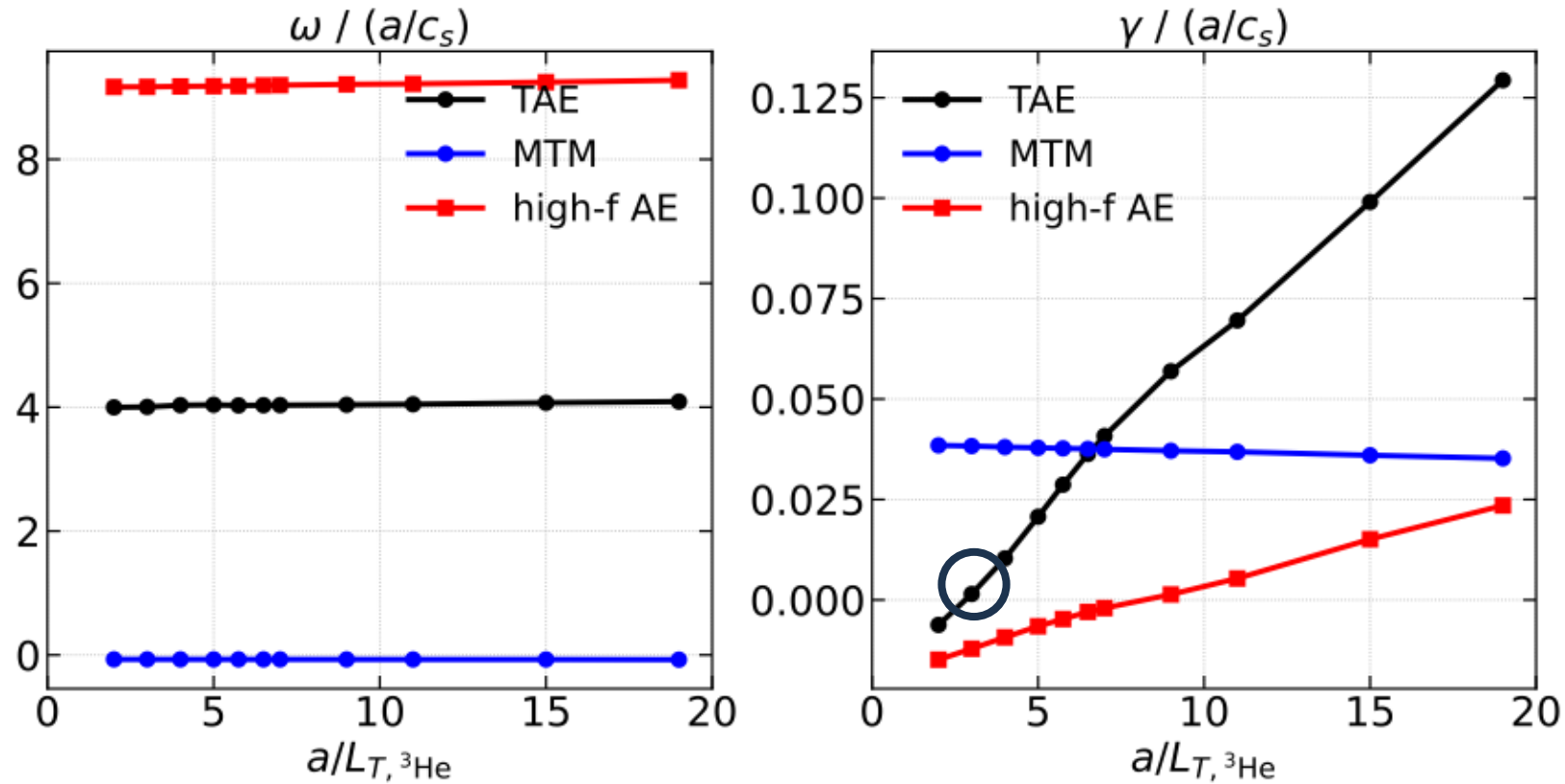
- Local CGYRO approximates continuum with a constant q' at a given radius
- Coupling of poloidal harmonics (TAEs) is encoded in field-aligned representation

CGYRO Dynamic-mode-decomposition (DMD*) for $k_y \rho_s = 0.042$ ($n = 6$) shows EP ^3He -driven TAE and high-f AE by $a/L_{T,3\text{He}}$



- Long-tail MTM-like mode independent of $a/L_{T,3\text{He}}$ is fastest growing for $a/L_{T,3\text{He}} \lesssim 7$
- TAE driven unstable for $a/L_{T,3\text{He}} \gtrsim 3$ (marginal stability)
- High-f AE potentially EAE driven by $a/L_{T,3\text{He}}$
- Experiment: $\gamma_{\text{TAE}}/f_{\text{TAE}} \approx 0.6\% \rightarrow \gamma_{\text{TAE}} \approx 0.004 c_s/a$
 → suggests that experiment is near TAE marginal stability

CGYRO Dynamic-mode-decomposition (DMD*) for $k_y \rho_s = 0.042$ ($n = 6$) shows EP ^3He -driven TAE and high-f AE by $a/L_{T,3\text{He}}$

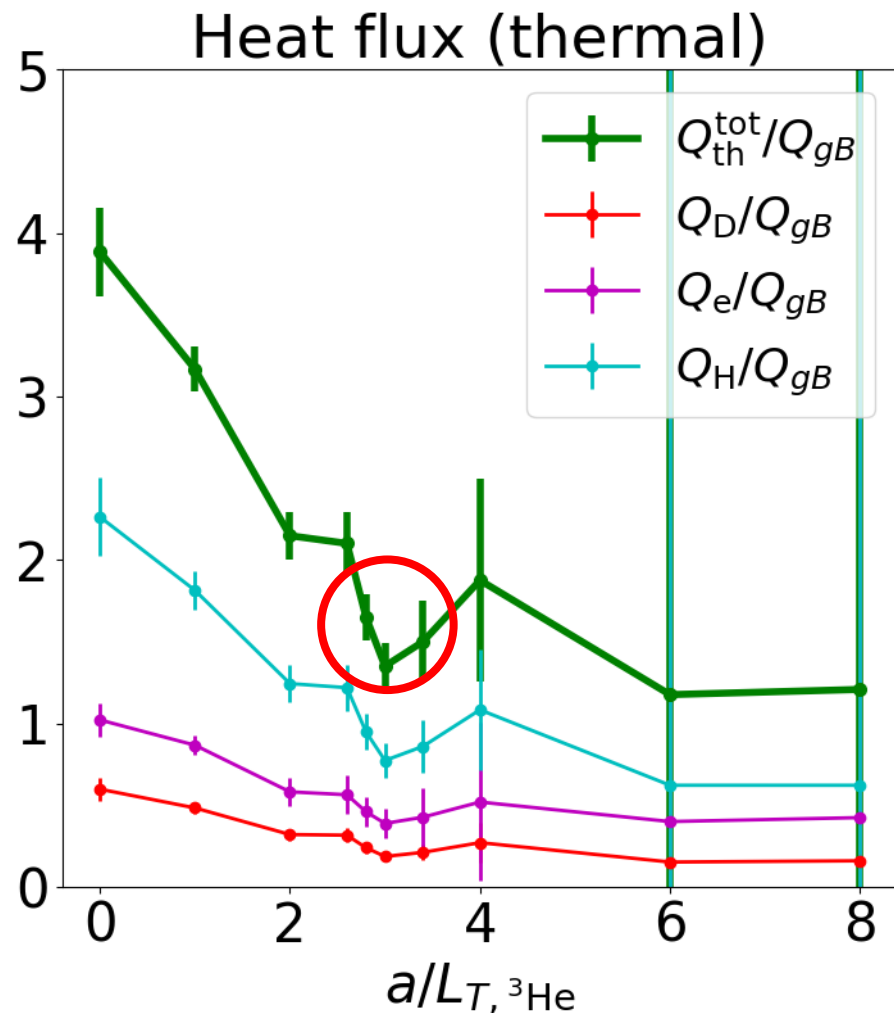


- Long-tail MTM-like mode independent of $a/L_{T,3\text{He}}$ is fastest growing for $a/L_{T,3\text{He}} \lesssim 7$
- TAE driven unstable for $a/L_{T,3\text{He}} \gtrsim 3$ (marginal stability)
- High-f AE potentially EAE driven by $a/L_{T,3\text{He}}$
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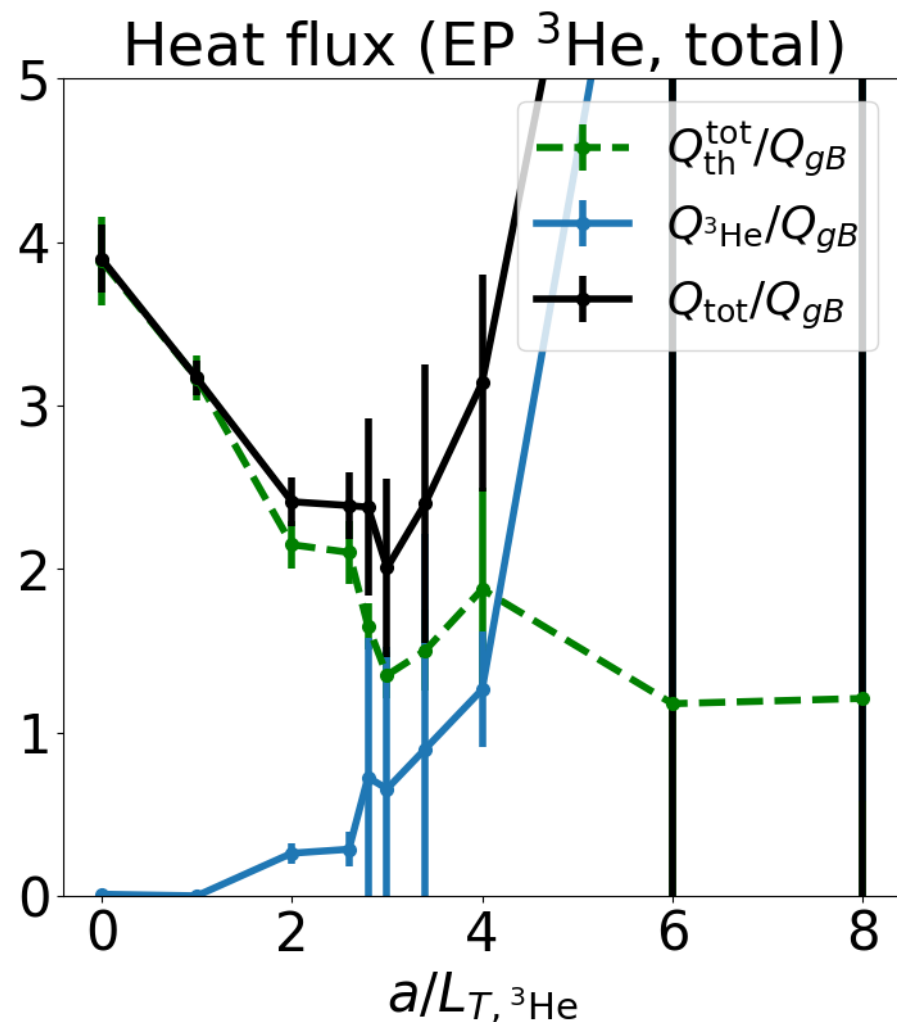
- **Experimental observations**
 - Recap of JET plasma with MeV-range ICRF-heated ions
 - Alfvénic bursts in the DBS spectrum
- **Gyrokinetic modelling**
 - Linear gyrokinetic stability
 - Local nonlinear gyrokinetic simulations (TAE+ITG)

Local nonlinear CGYRO for high P_{ICRH} : turbulence is stabilized when the TAE is *nonlinearly* driven unstable



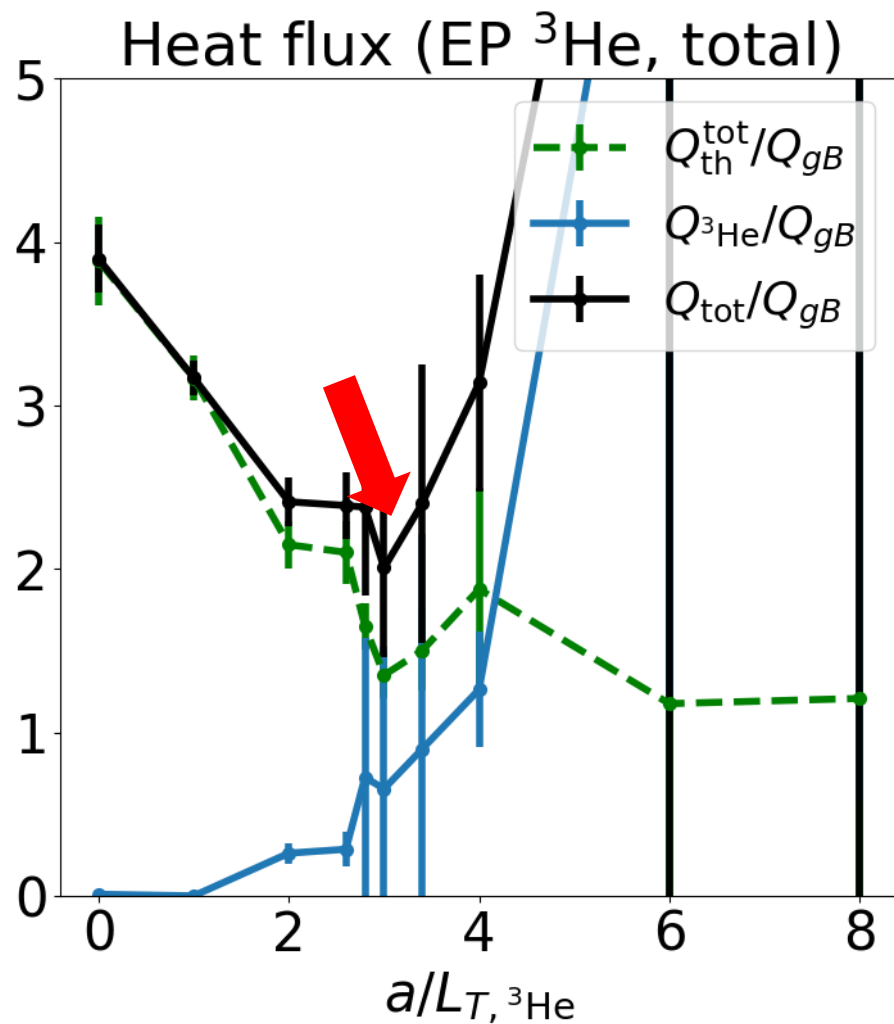
- Electromagnetic ($\delta\phi, \delta A_{||}$), fast-Maxwellian ^3He ($T_f \approx 168 T_i$)
- TAE+ITG scales:
 $k_y \rho_{SD} = [0.014, 0.994]$, $L_y = 449 \rho_{SD}$ ($\Delta n = 2$)
 $k_x \rho_{SD} = [0.021, 3.067]$, $L_x = 293 \rho_{SD}$
- Full Sugama collision operator
- Heat flux dominated by H ions for no EPs
- Near TAE marginal stability ($a/L_{T, 3He} \approx 3$):
 - Q_{th}^{tot} exhibits a 'dip'

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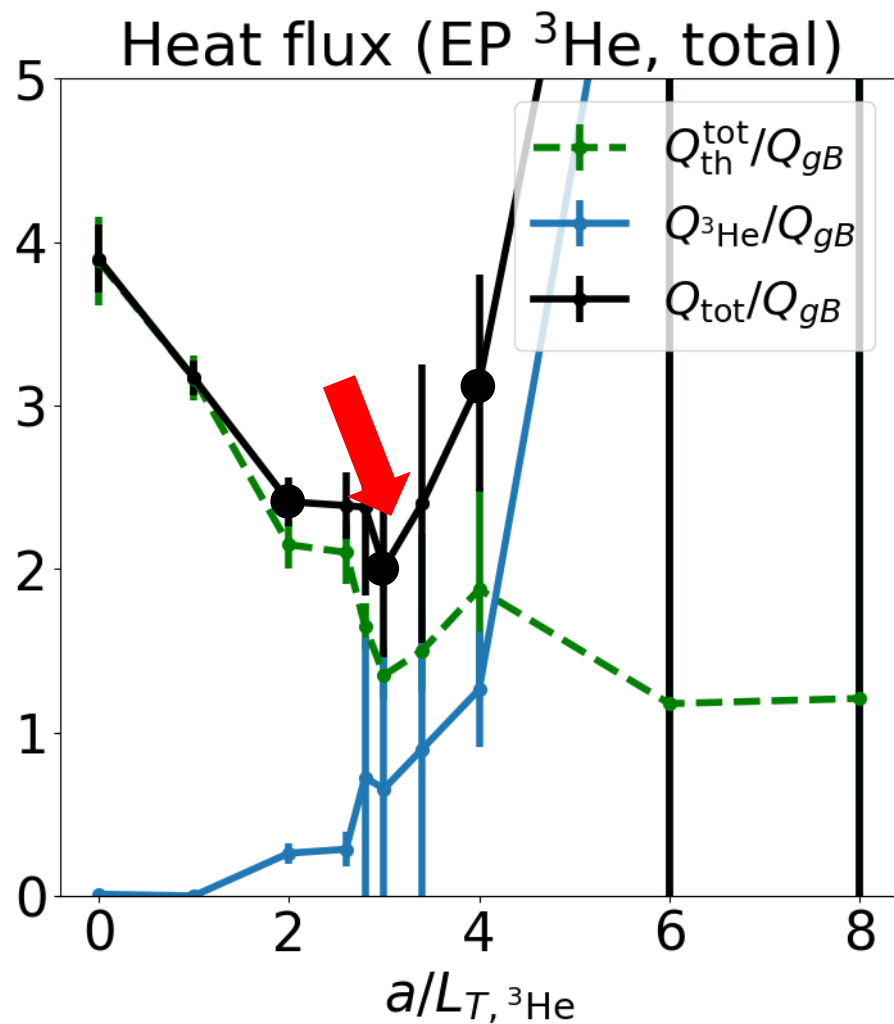
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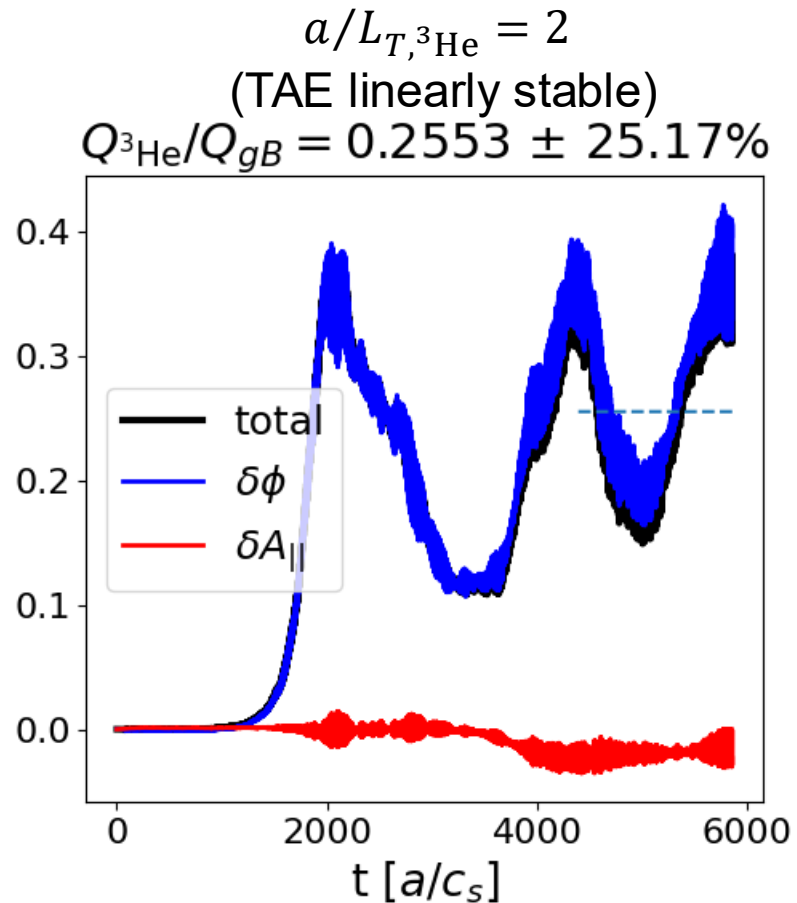
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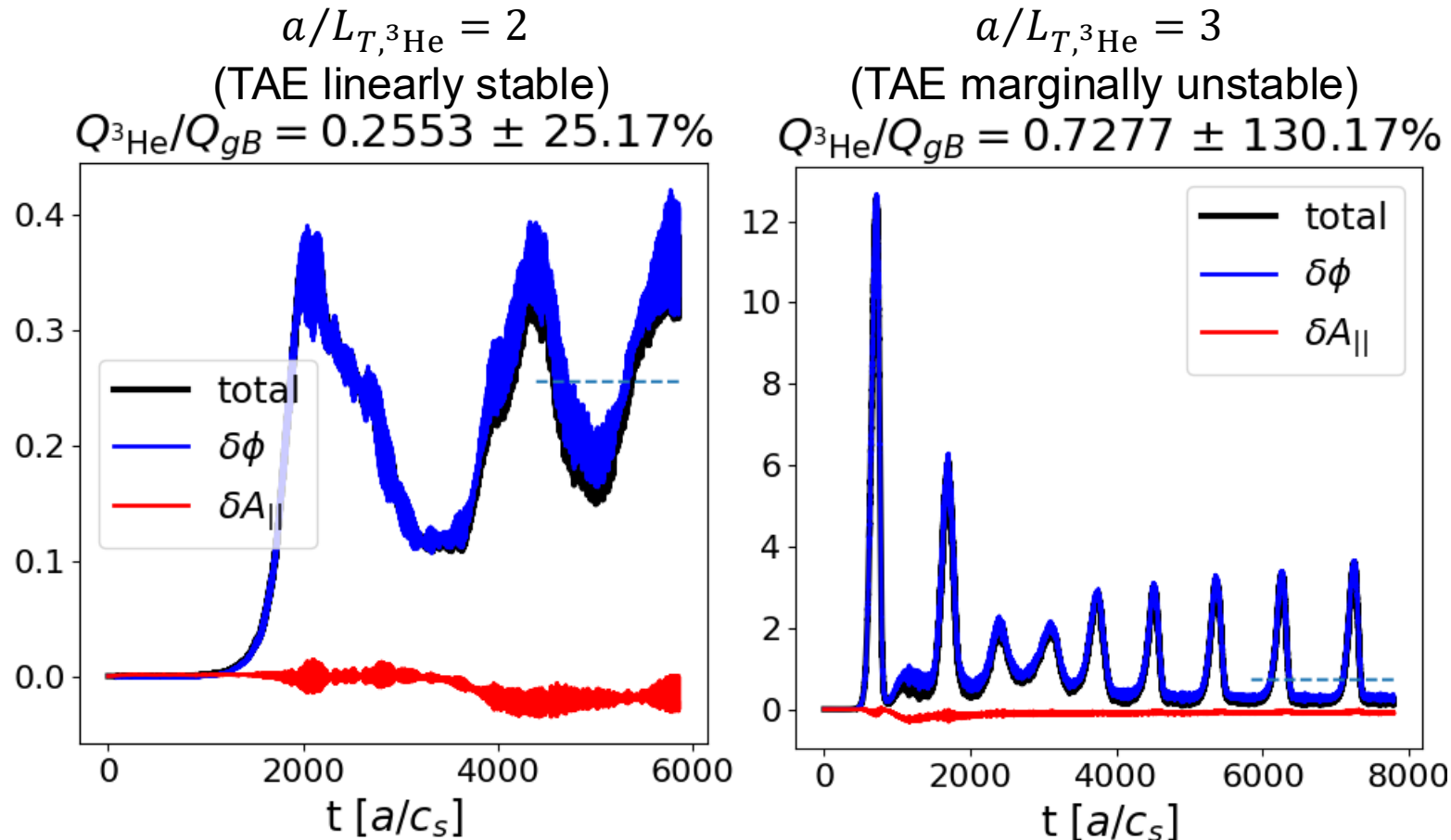
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Energetic ^3He heat flux exhibits bursty behavior that appears quasi-periodic for marginally-unstable cases ($a/L_{T,^3\text{He}} = 2.8 - 3.4$)



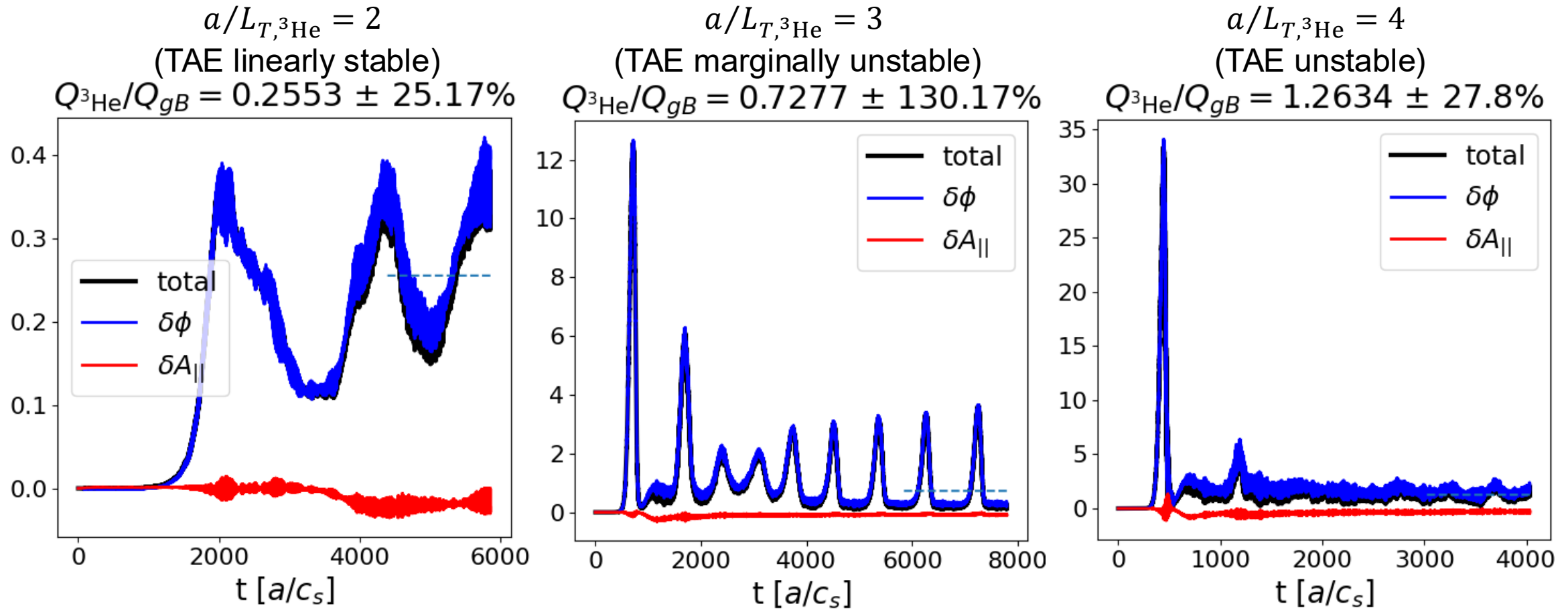
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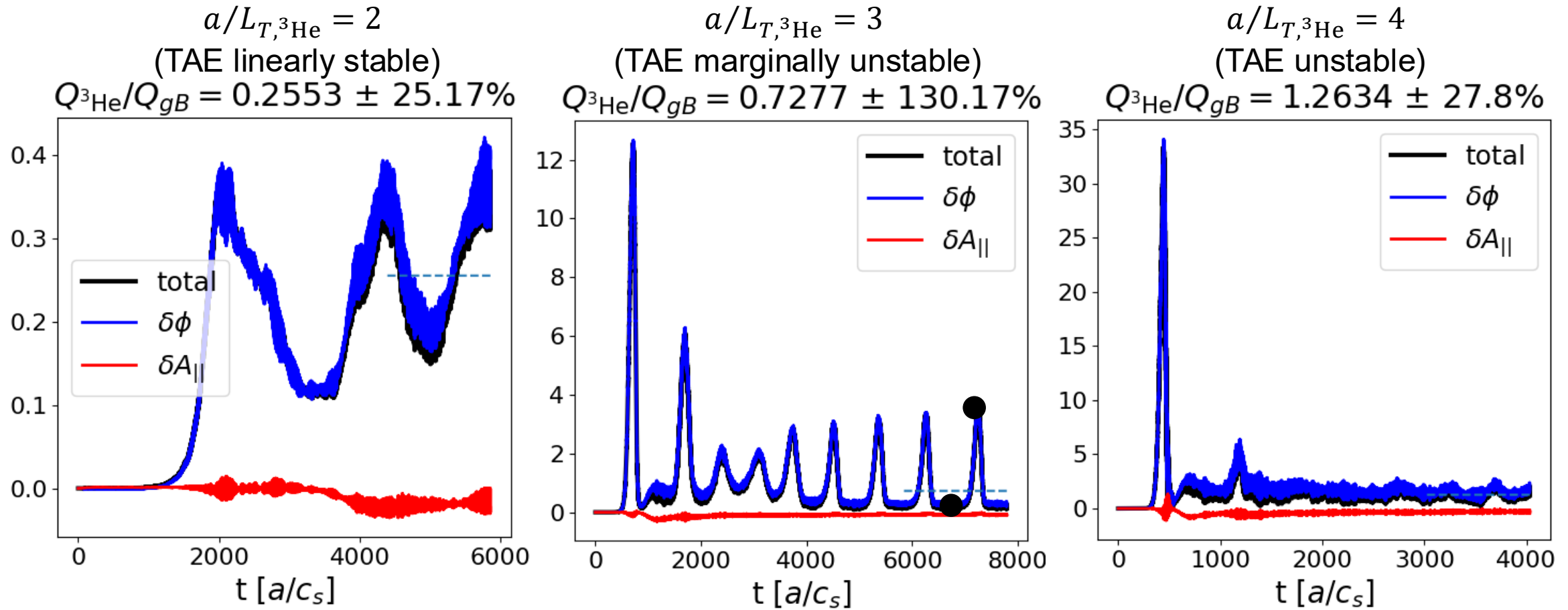
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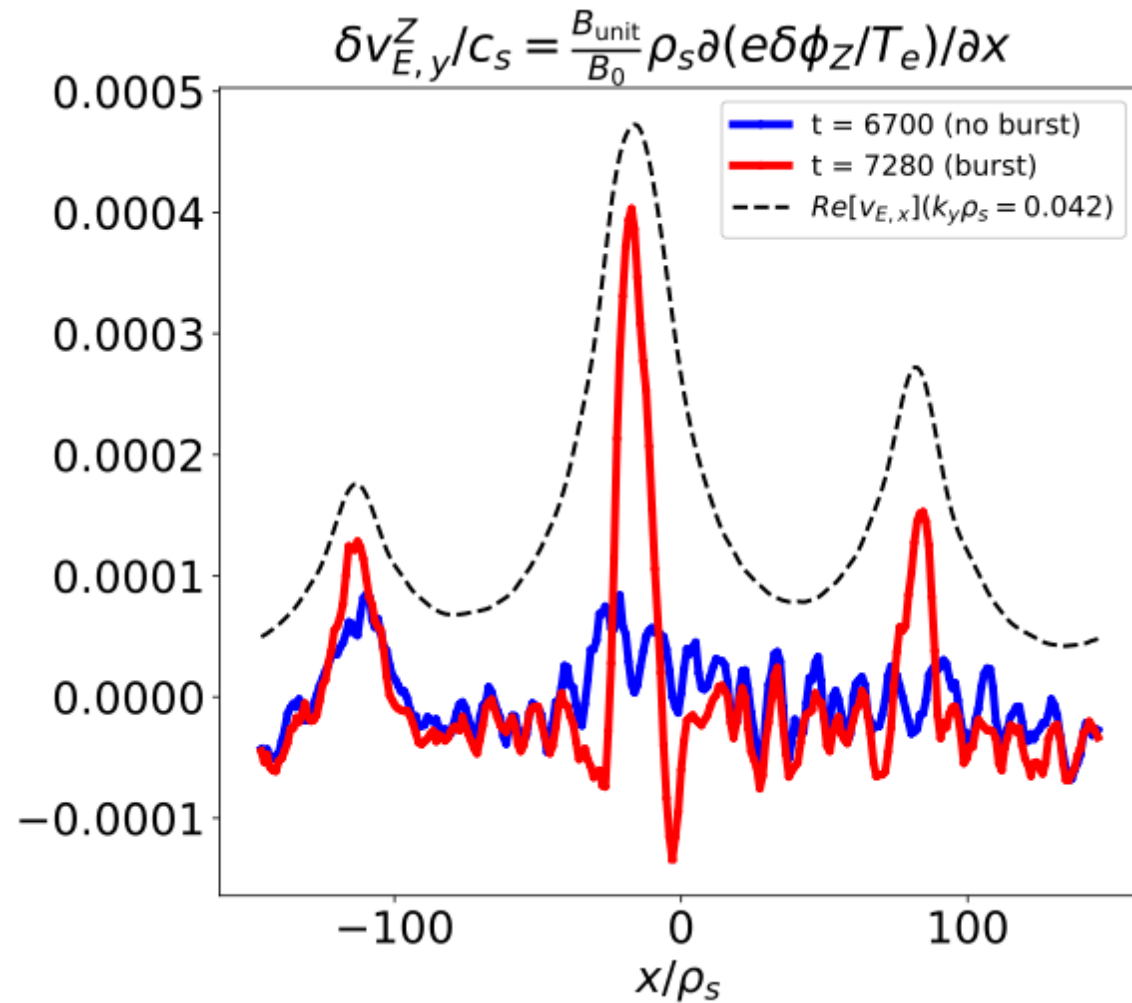
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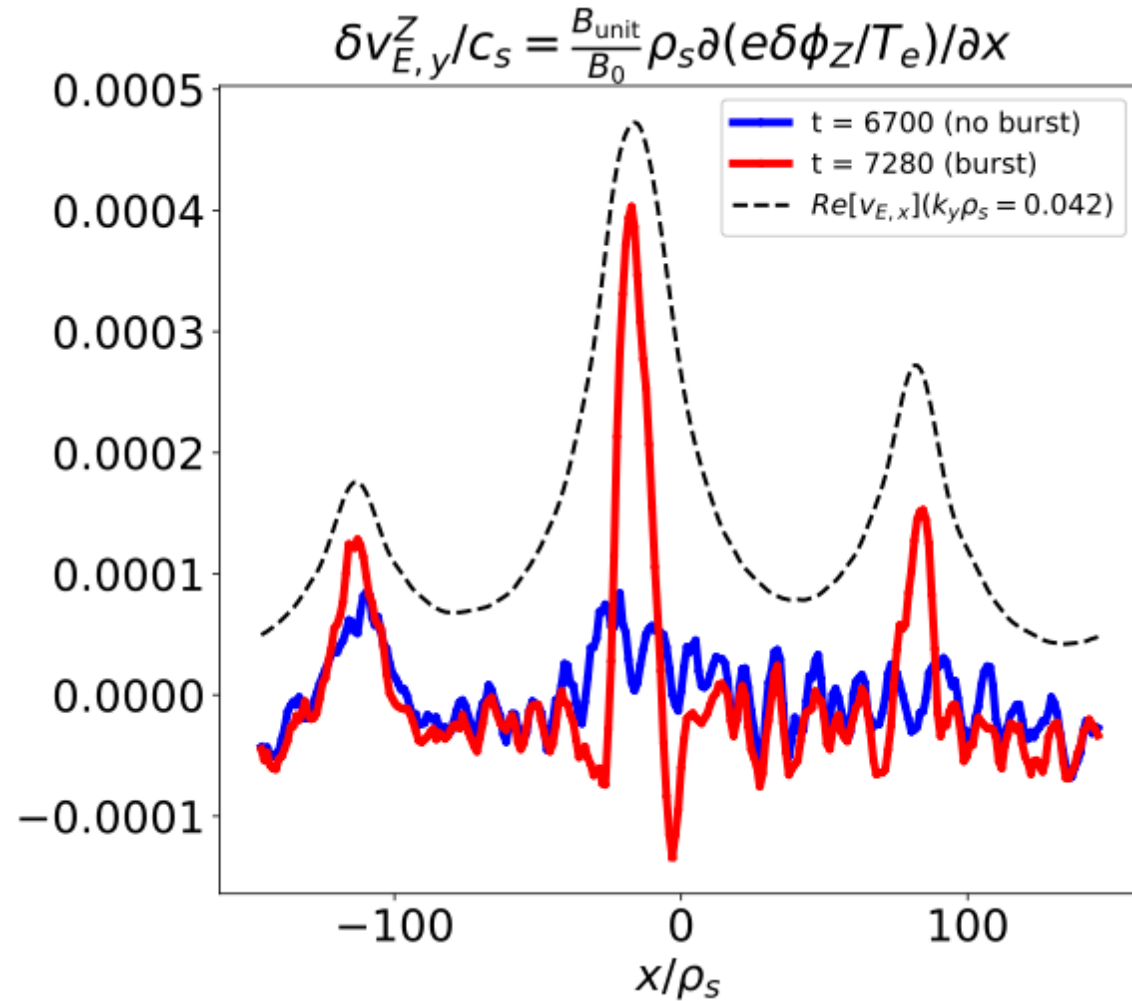
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Radial profile of $\delta \mathbf{v}_E = \mathbf{b}_0 \times \nabla_{\perp} \delta \phi / B_0$ reveals zonal flow is predominantly generated at TAE radial locations at the height of the burst



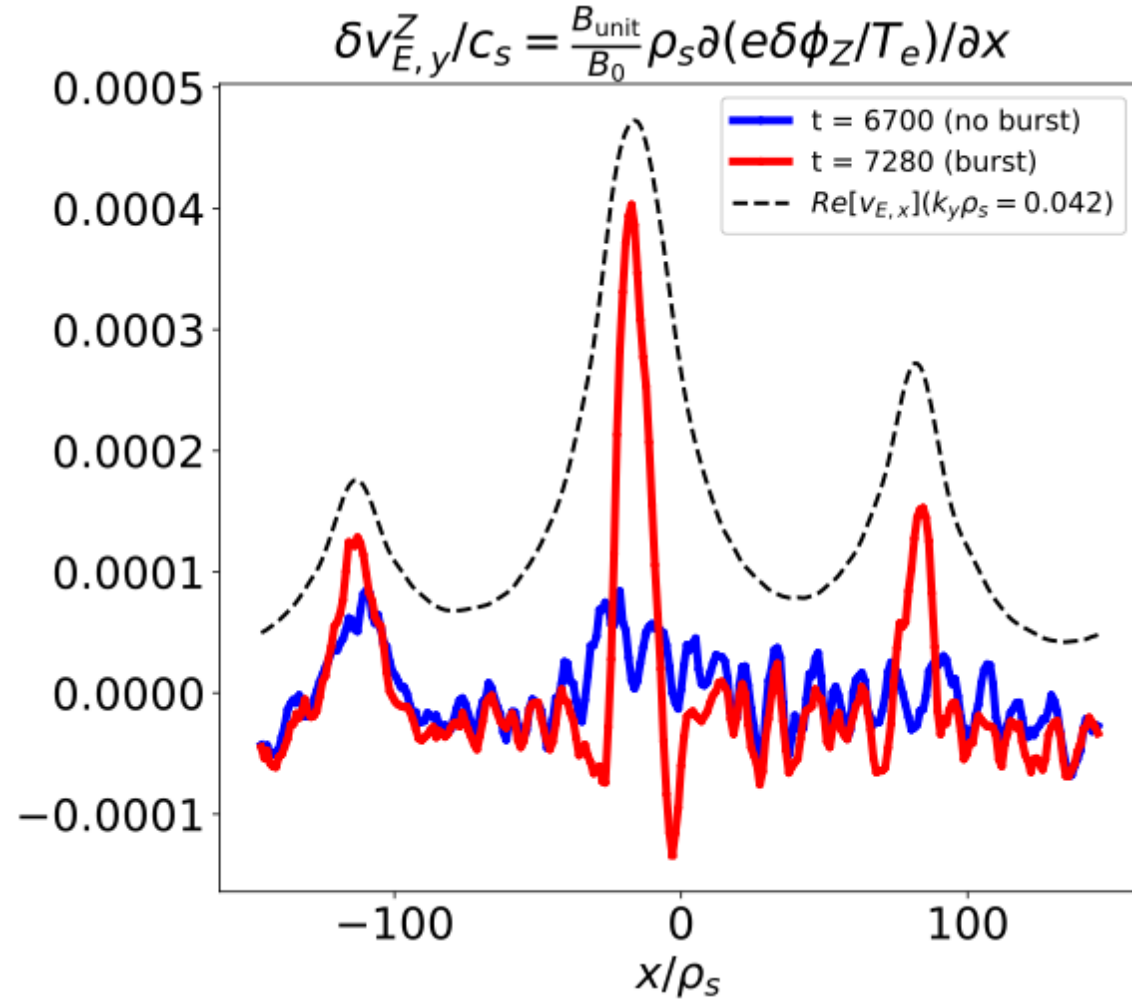
- $\delta v_{E,x} \propto \frac{\partial}{\partial y} \delta \phi$ ($k_y \rho_s = 0.042$ TAE)
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Height of the burst: $\delta v_{E,y}^Z$ is large at TAE radial locations
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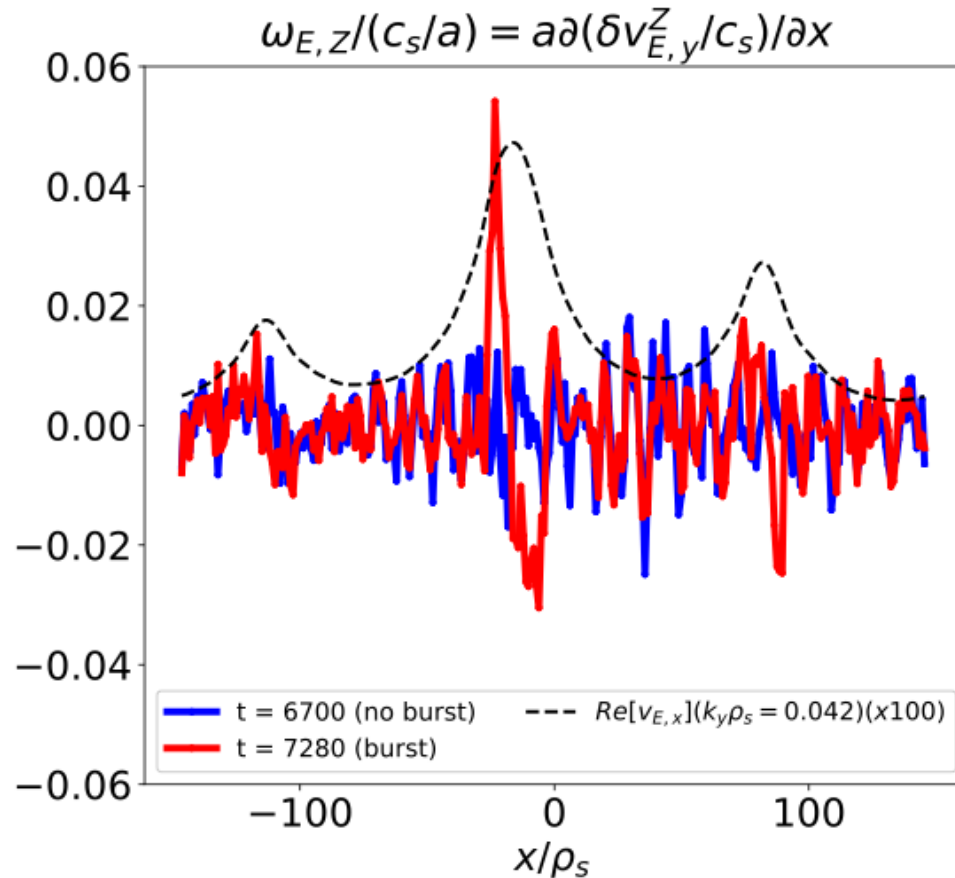
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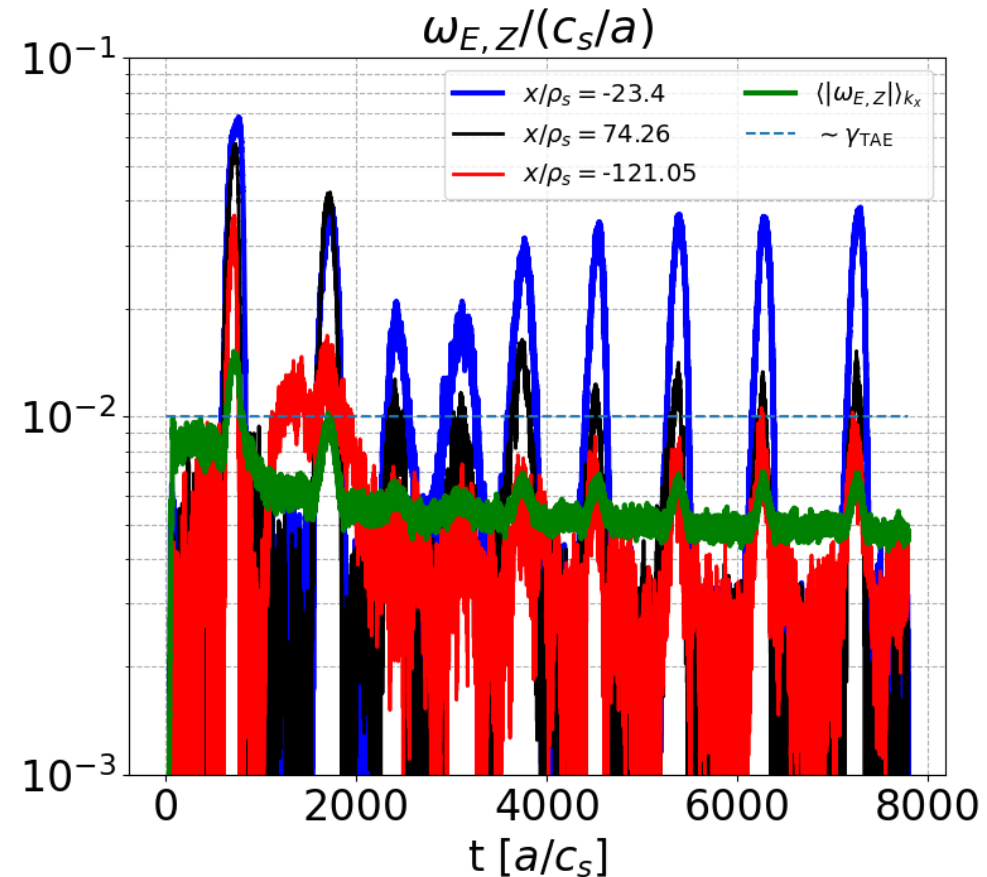
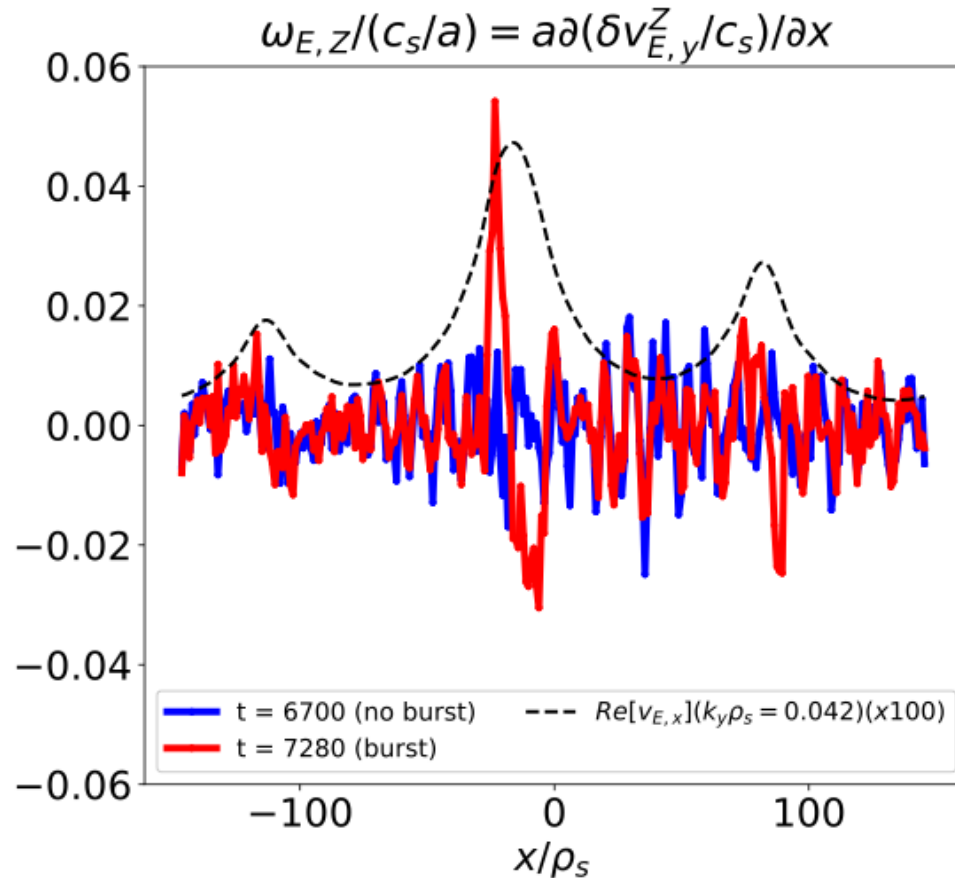
What matters is the $\mathbf{E} \times \mathbf{B}$ shearing rate ω_E produced by zonal flow

Phenomenology of burst near marginal stability: TAEs generate local zonal shearing rate $\omega_{E,Z}$ that overcomes γ_{TAE} ($\lesssim 0.01 c_s/a$)



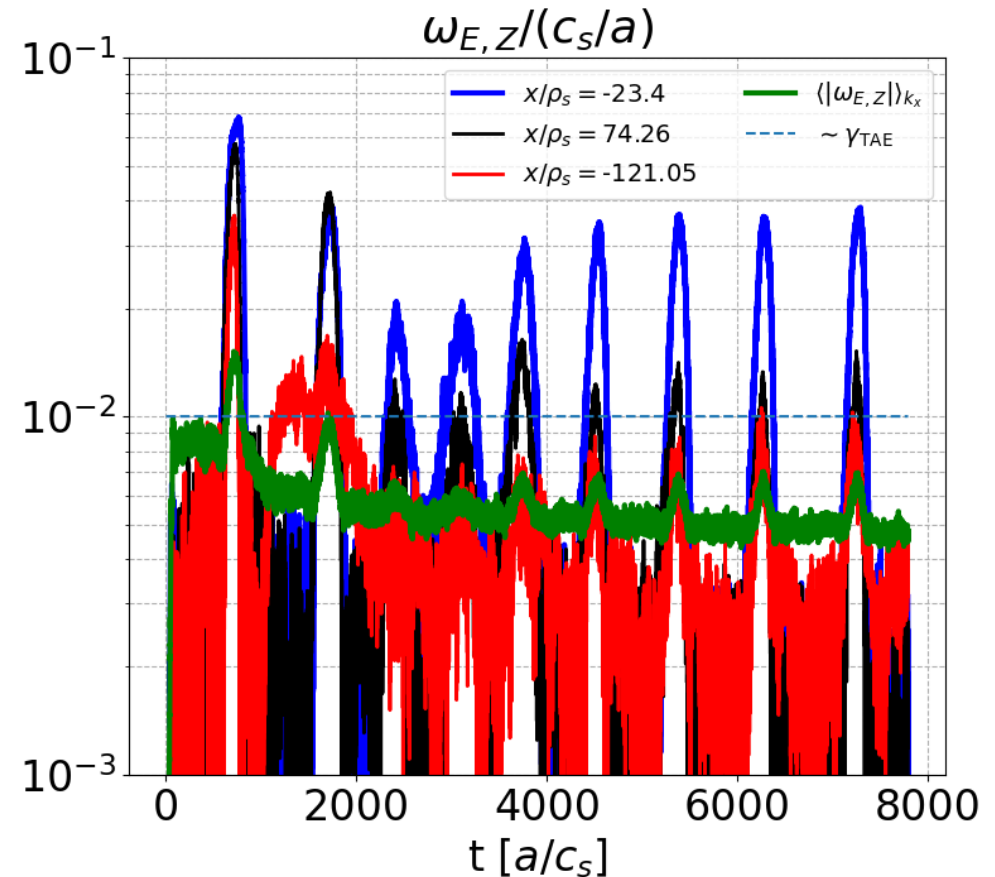
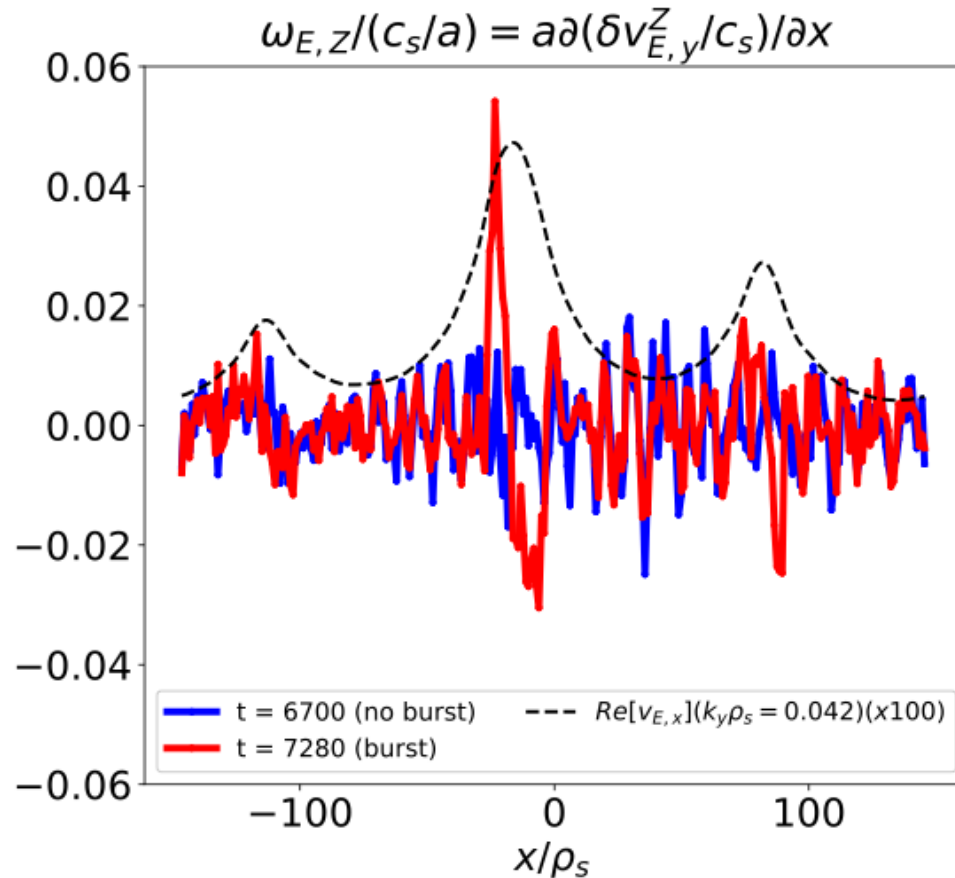
- $\omega_E^Z \approx [-0.03, 0.06] c_s/a \gg \gamma_{\text{TAE}} (\lesssim 0.01 c_s/a)$ at TAE radial locations! Suggests:
 - TAE generates zonal flow that shears it apart and saturates it
 - bursts in the CGYRO simulation might be predator-prey oscillations TAE-ZF

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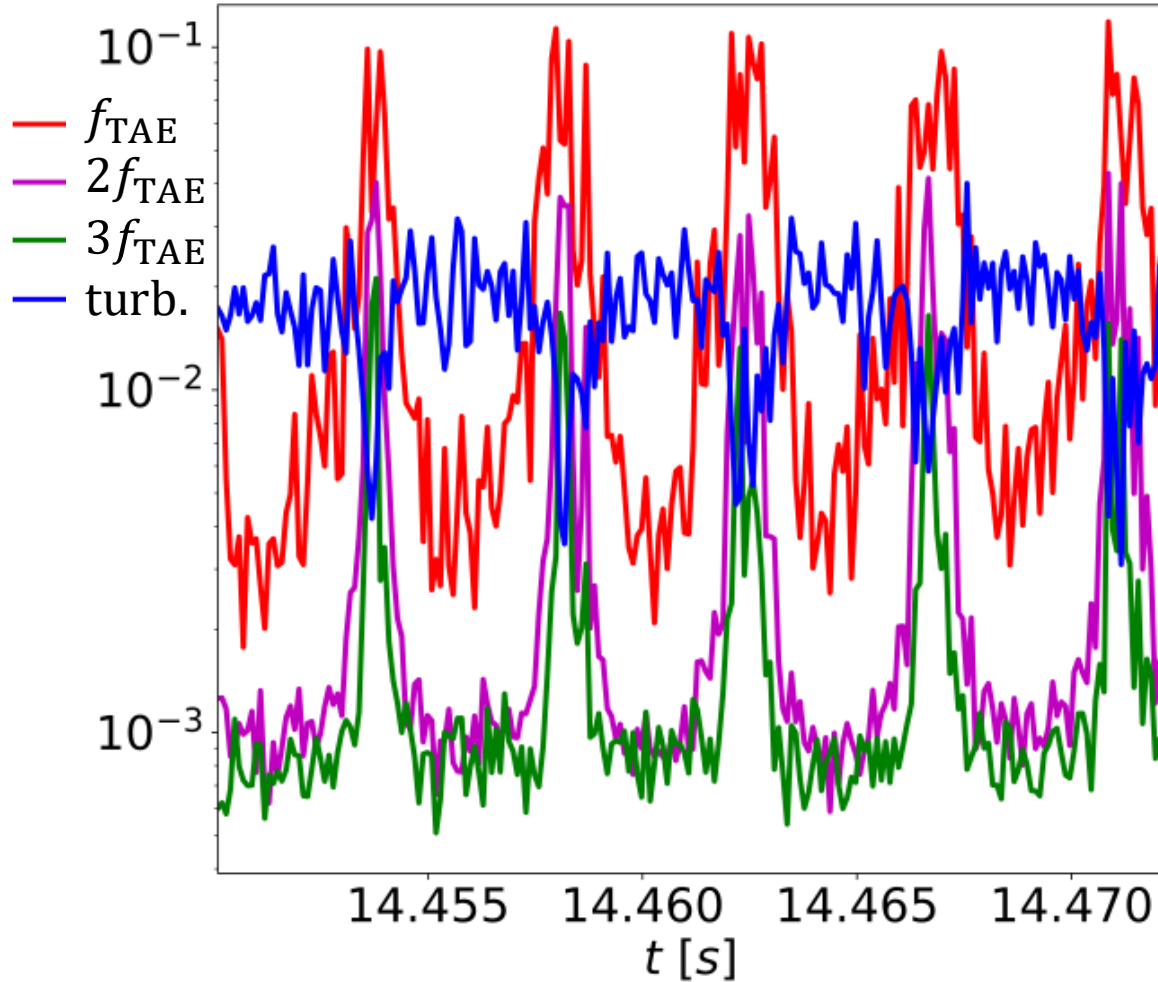


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- $\omega_E^Z \ll \gamma_{\text{ITG}} \approx 0.2 c_s/a$ and only at TAE radial locations → probably weak effect on ITG

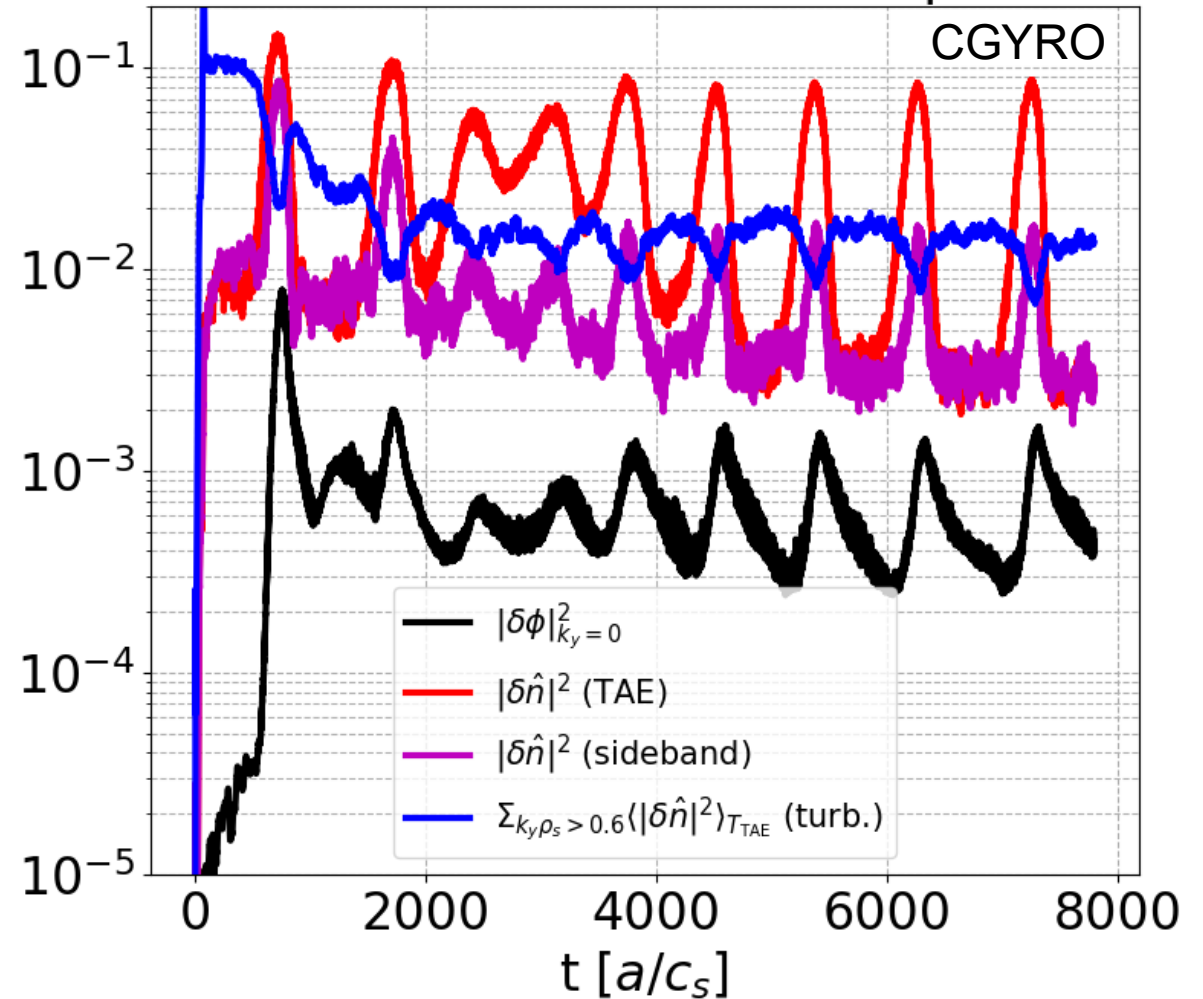
CGYRO simulation near TAE marginal stability can reproduce bursty quasi-periodic behaviour of TAEs+sidebands, alternating with turbulence power



Time traces of DBS power



Time traces of fluctuation power



ZF lags TAE, decays on $\nu_{ii}^{-1} \approx 1000 a/c_s \approx 2.5 \text{ ms} \rightarrow$ ZF collisional damping sets period between bursts

Conclusions from analysis of JET ICRH-heated L-mode with MeV-range 3He [*]



- DBS measurements show bursty alternating cycles of Alfvénic modes, high-f sidebands, and microturbulence, sustained and quasi-periodic at high ICRH power.
 - Growth rate of TAE $\gamma_{\text{TAE}}/f_{\text{TAE}} \approx 0.6\%$ is near marginal stability
- Local CGYRO shows that, near TAE **marginal stability** ($a/L_{T,3\text{He}} = 3$):
 - $Q_{3\text{He}}$ shows bursty cycles of TAEs with similar period to DBS ($\Delta t_{\text{DBS}} \approx 4\text{ms}$, $\Delta t_{\text{sim}} \approx 2.5\text{ms}$)
 - $\omega_{E,Z}$ is locally greater than γ_{TAE} at height of the burst $\rightarrow$ ZF saturates the TAE
 - ZF lags TAE and sideband growth, and decays on $\nu_{ii}^{-1} \approx 1000 a/c_s \sim$ time of burst
- Predator-prey limit cycles may be what was observed by DBS
- Q_{tot} is minimum near TAE marginal stability: EP and ExB flow profiles are not steady, but rearranged dynamically to yield an optimum confinement regime
- Open question: $\omega_E^Z \ll \gamma_{\text{ITG}}$, what is stabilizing ITG?

[*] Ruiz Ruiz *et al.*, PRL 2025