Strongly non-linear energetic particle dynamics in ASDEX Upgrade scenarios with core impurity accumulation

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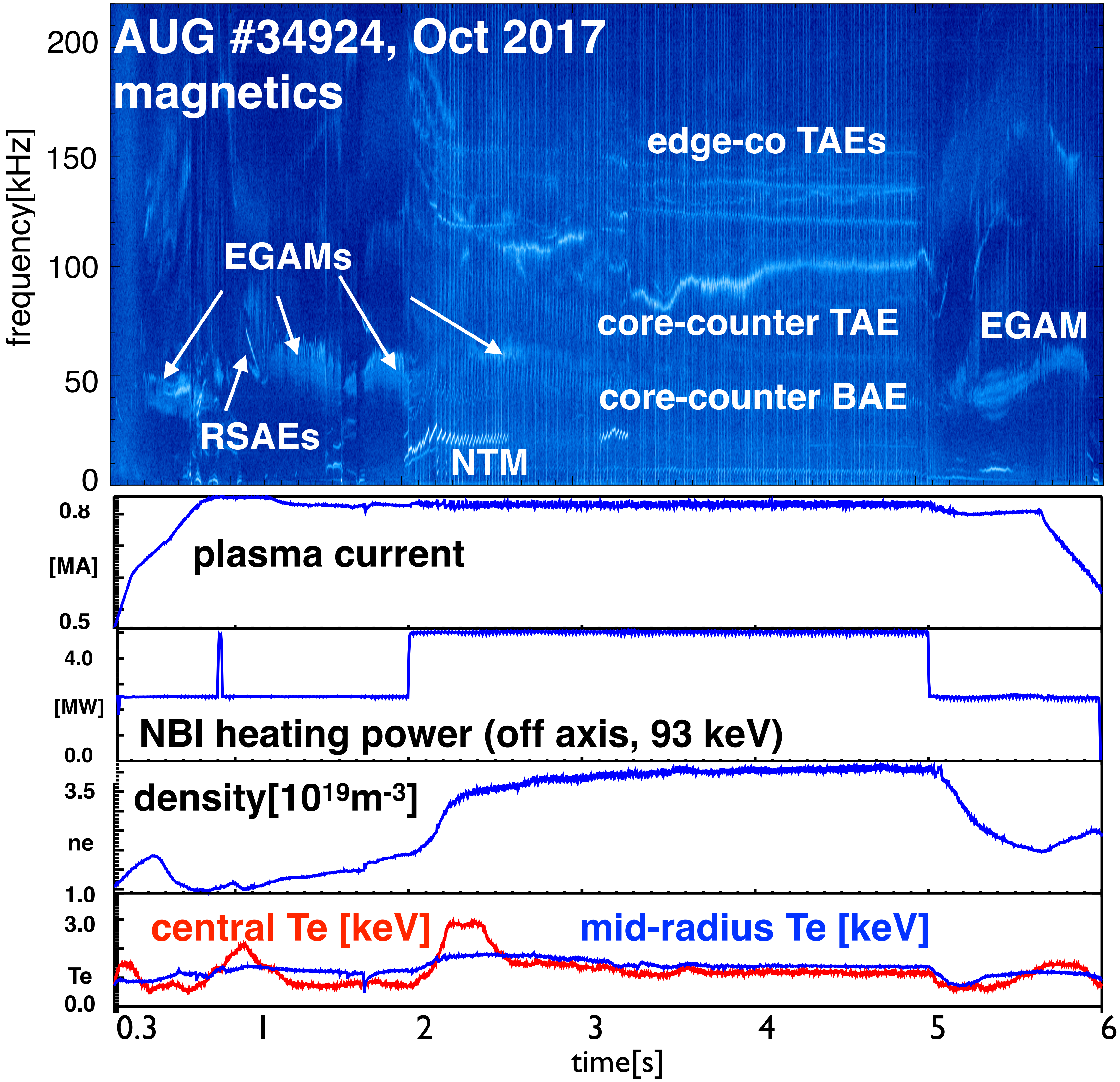
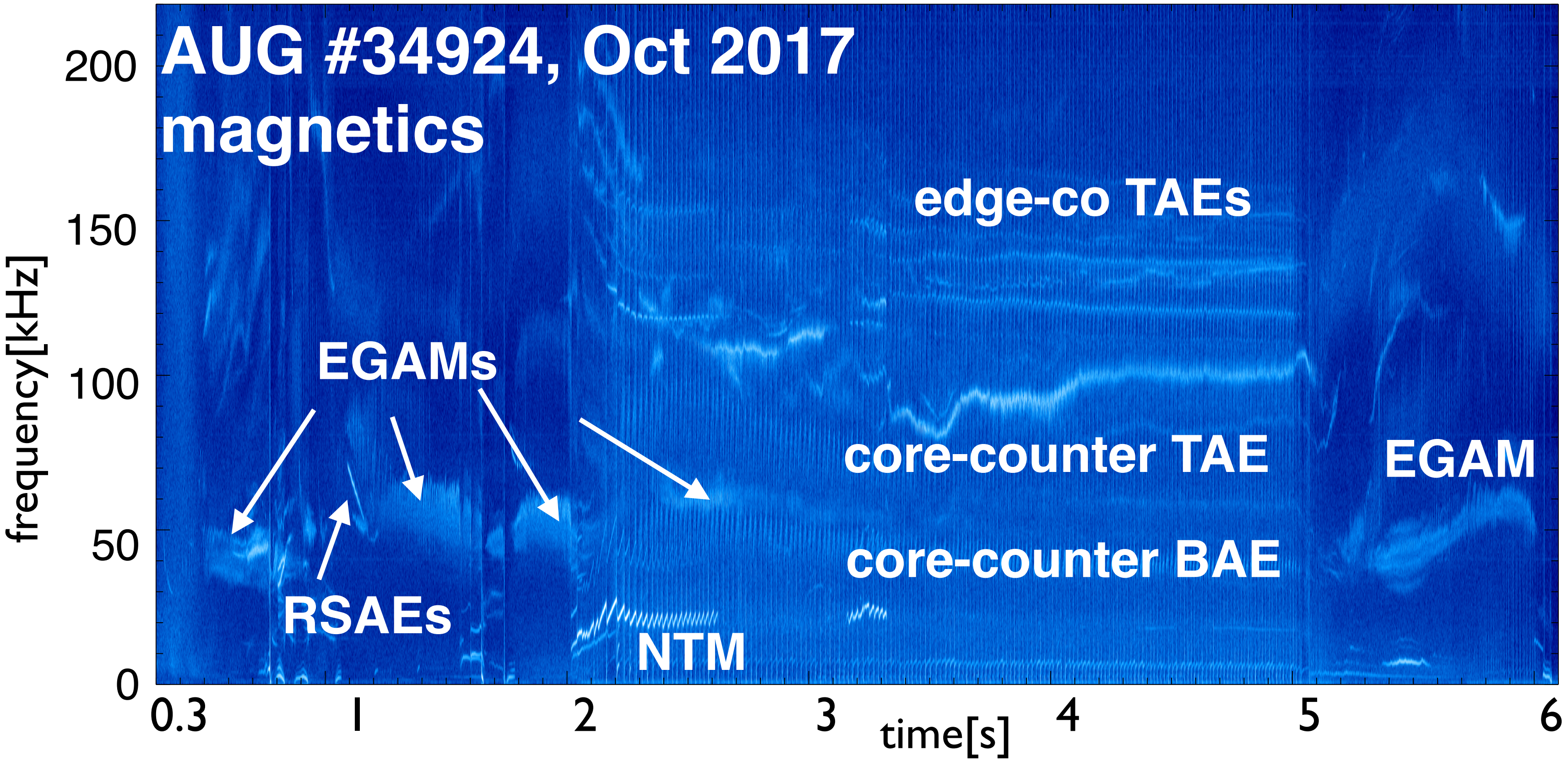
new scenario with strong mode activity induced by energetic particles (EPs) was established at ASDEX Upgrade



I=800kA
B=-2.5T

q≥2
slightly
reversed

new scenario with strong mode activity induced by energetic particles (EPs) was established at ASDEX Upgrade



investigation of strongly non-linear EP dynamics at ASDEX Upgrade is now possible:

- with sub-Alfvénic beams (2.5-5MW)
- in current flat top with stationary plasma conditions
- compatible with tungsten wall
- for EP physics relevant parameters:
  $\beta_{EP}/\beta_{thermal} \sim 1$, $E_{NBI}/T_{i,e} \approx 100$

motivation: predicting self-organisation of burning fusion plasmas

- one crucial physics element: transport properties of energetic particles (EPs) are determined by non-linear saturation level of EP-driven modes

- mechanism: mode-induced flattening of EP phase space gradients by non-linear wave-particle interaction vs. recovery of depleted gradients by collisional slowing down processes

- these ingredients lead to several non-linear saturation states: steady state, bifurcation, chaotic, bursting (typically super-Alfvénic drive *[JT-60SA,NSTX,MAST]*) that are determined by linear drive, damping, effective collisionality *[O'Neill, Berk&Breizman]* and radial non-uniformity of resonances *[Briguglio, X.Wang 2015; Duarte 2017]*

- less studied: wave-wave coupling processes and formation of zonal structures (ZS) caused by EP-driven modes influence the saturation and the overall plasma state *[Hahm 1995; Todo 2010-12, 2015; Bierwage Nature 2018; Chen&Zonca 2012, Qui 2018]*

- on long time scales: average EP profile close to -slightly upshifted - marginally stable state (stiff EP profiles, DIII-D *[Collins 2016]*); on short and intermediate time scales: steady, intermittent ('ALE', *[Shinohara, JT-60U]*) or even ballistic (EPM [G. Vlad 2004]) transport possible

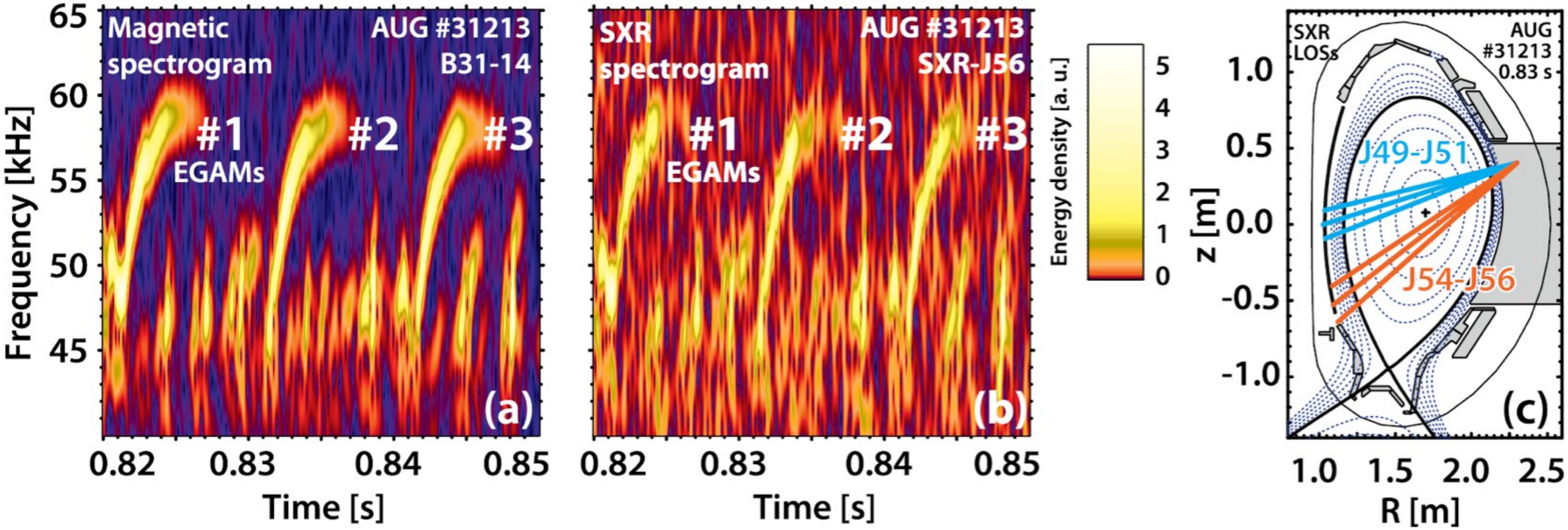
- challenge: predict properties of EP dynamics and EP profile relaxation

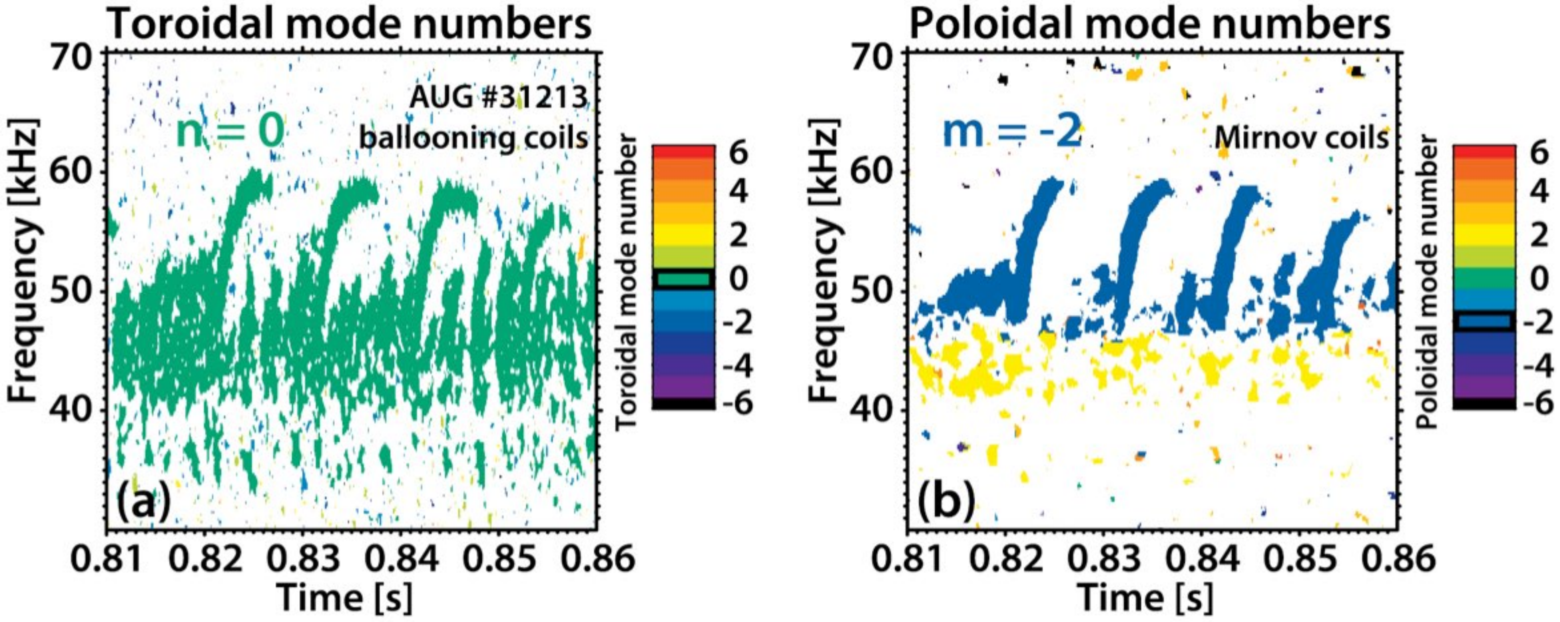
outline

- the dynamics of EP-driven geodesic acoustic modes (EGAMs) and excitation conditions under various experimental conditions
- interaction EGAMs and Alfvén eigenmodes (AEs)
- discussion & conclusions

EGAM properties: radial location and mode numbers

- one the most prominent modes in this scenario: EP-driven geodesic acoustic mode *[other exp. observations: Boswell, Berk Nazikian, Ido, Chen, Horvath,…]*
- visible in magnetics, soft-X ray: toroidal mode number n=0; dominant poloidal mode number n=2 *[Wahlberg 2008]*; global mode, peaked in core $\rho_{pol} \sim 0.2\text{-}0.4$



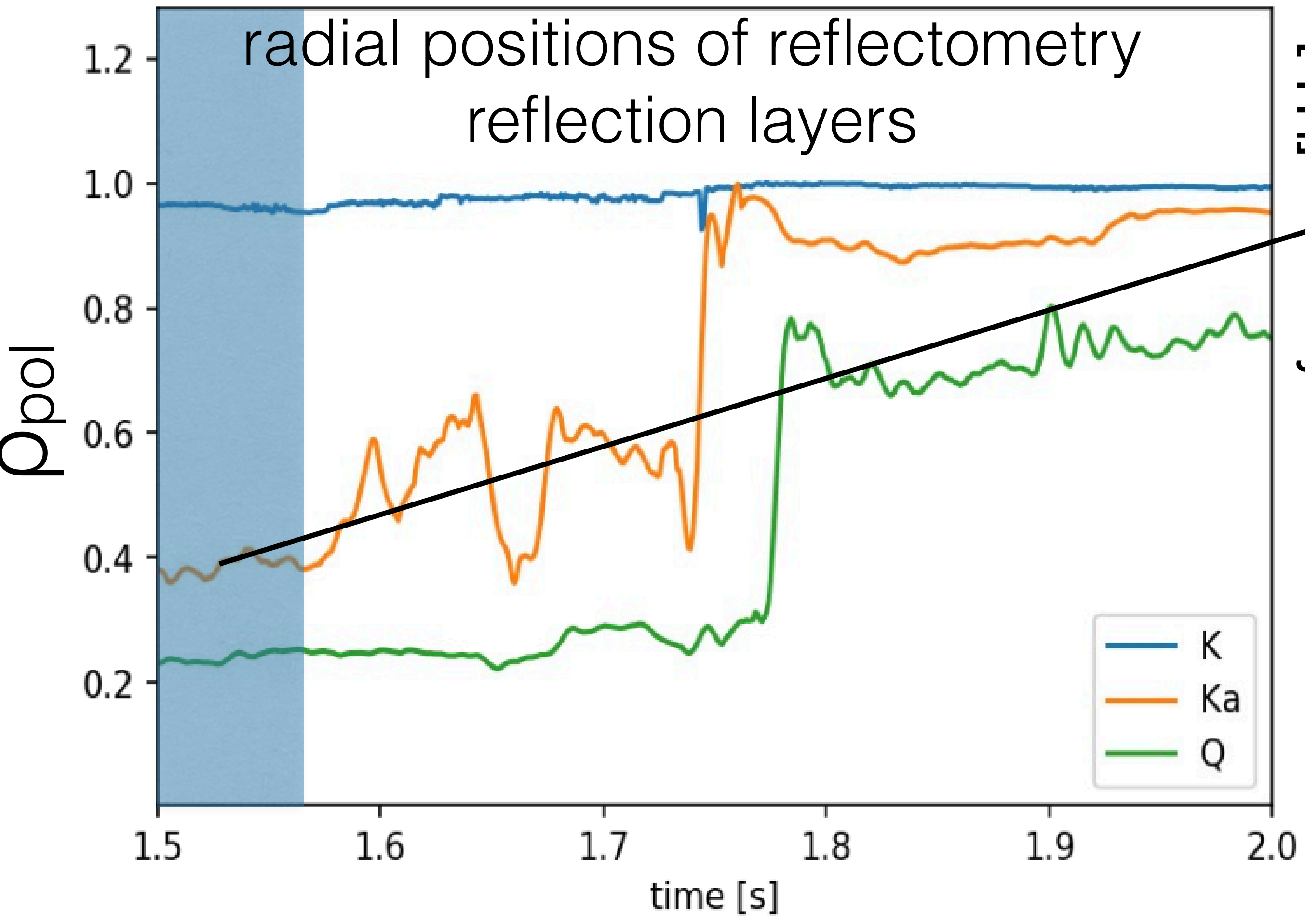


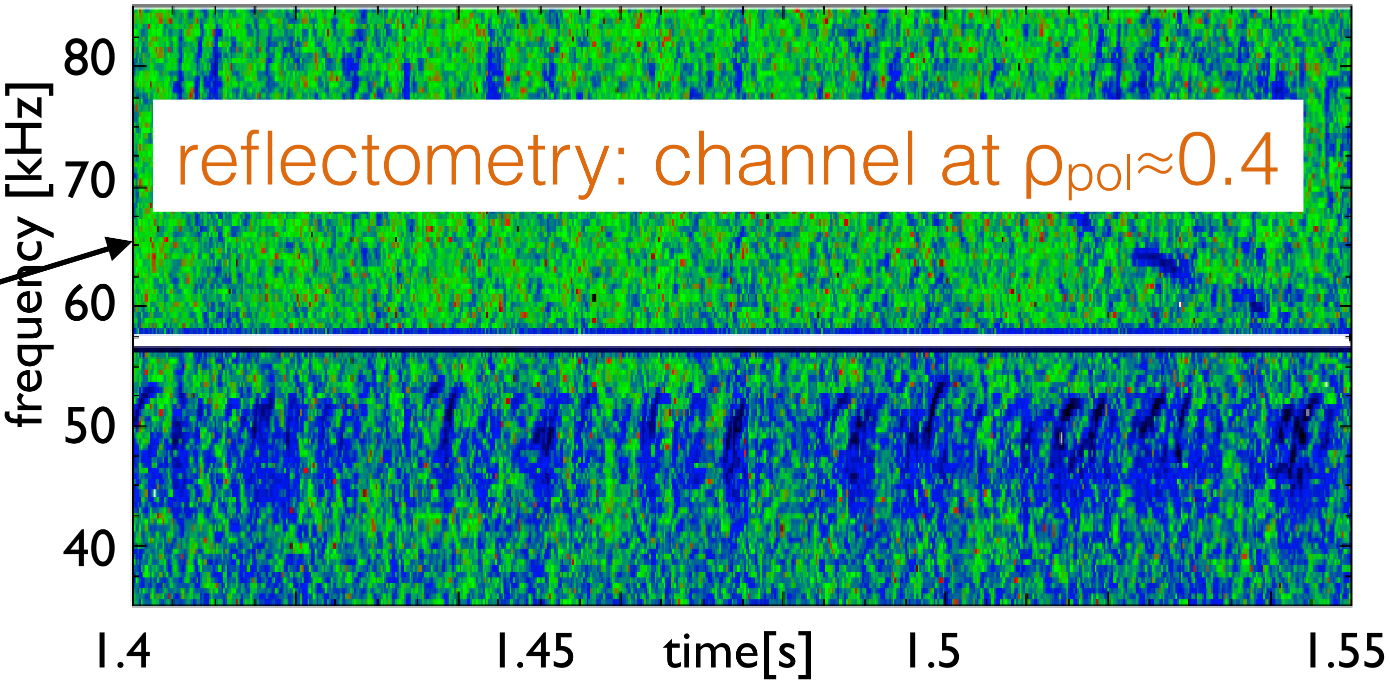
also change of radial EGAM mode structure in non-linear phase was observed

[Horvath et al,NF 2016]

EGAM properties: radial location and amplitude as measured by reflectometry

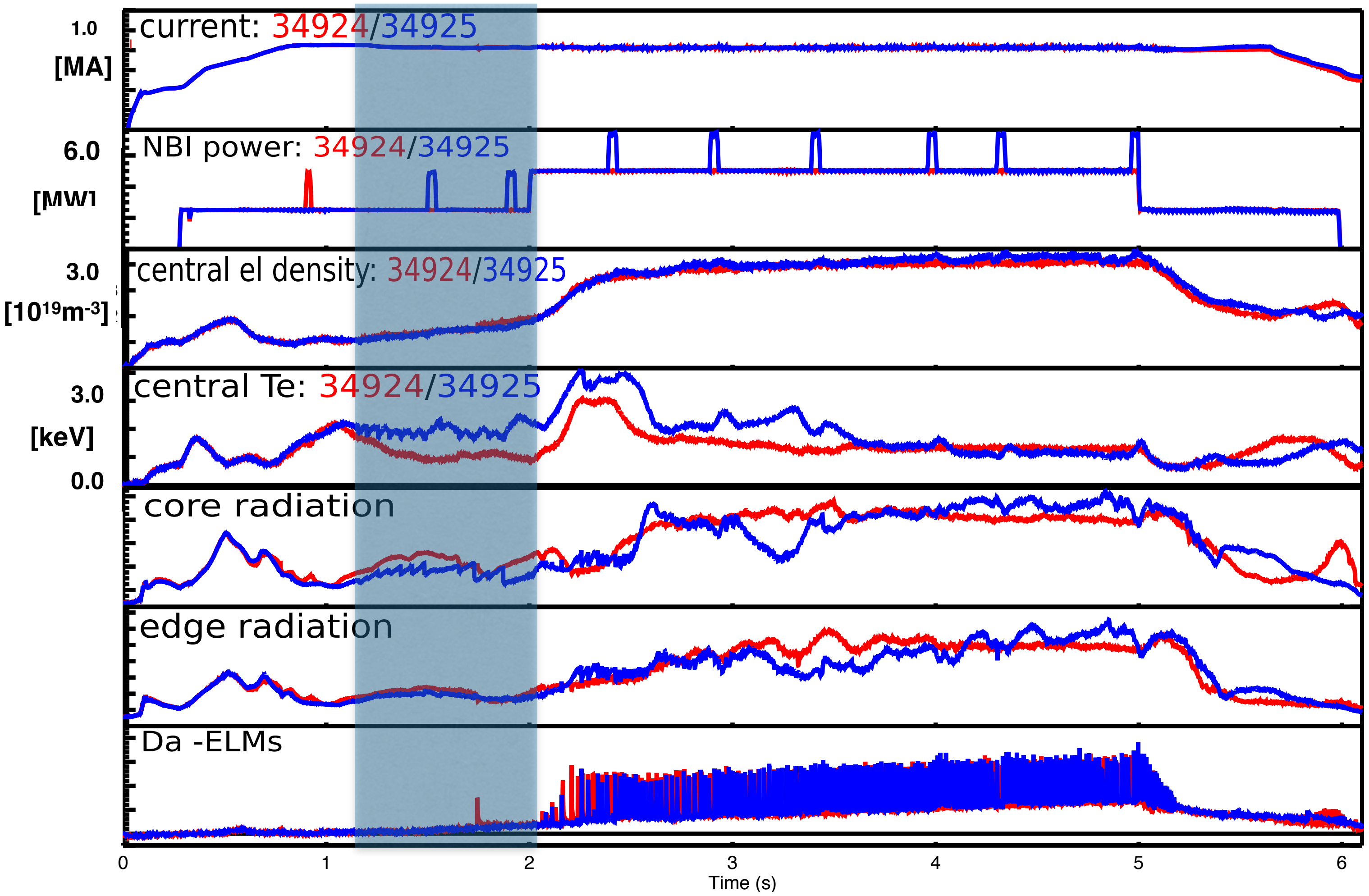
- one the most prominent modes: EP-driven geodesic acoustic mode
  [other exp. observations: Boswell, Berk Nazikian, Ido, Chen, Horvath,…]
- visible in magnetics, soft-X ray: toroidal mode number **n=0**; dominant poloidal mode number **n=2** *[Wahlberg 2008]*; global mode, peaked in core $\rho_{pol} \sim 0.2\text{-}0.4$
- visible also in interferometer and reflectometry, confirming mode location and giving estimate about $\delta n/n \sim 1\text{-}4\%$
- EGAMs only found in frequency band between 40-70kHz

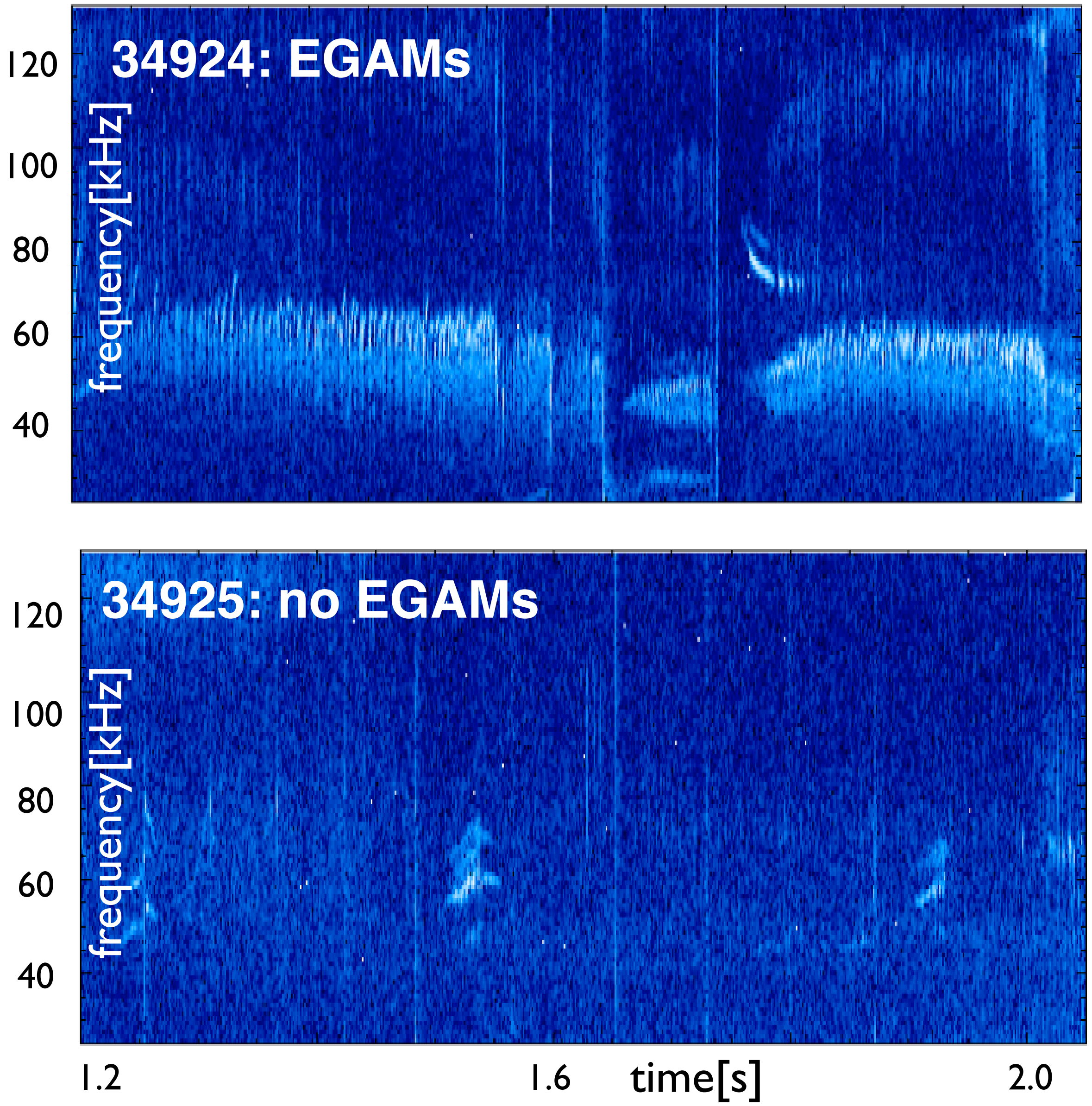

radial positions of reflectometry reflection layers


reflectometry: channel at $\rho_{pol} \approx 0.4$

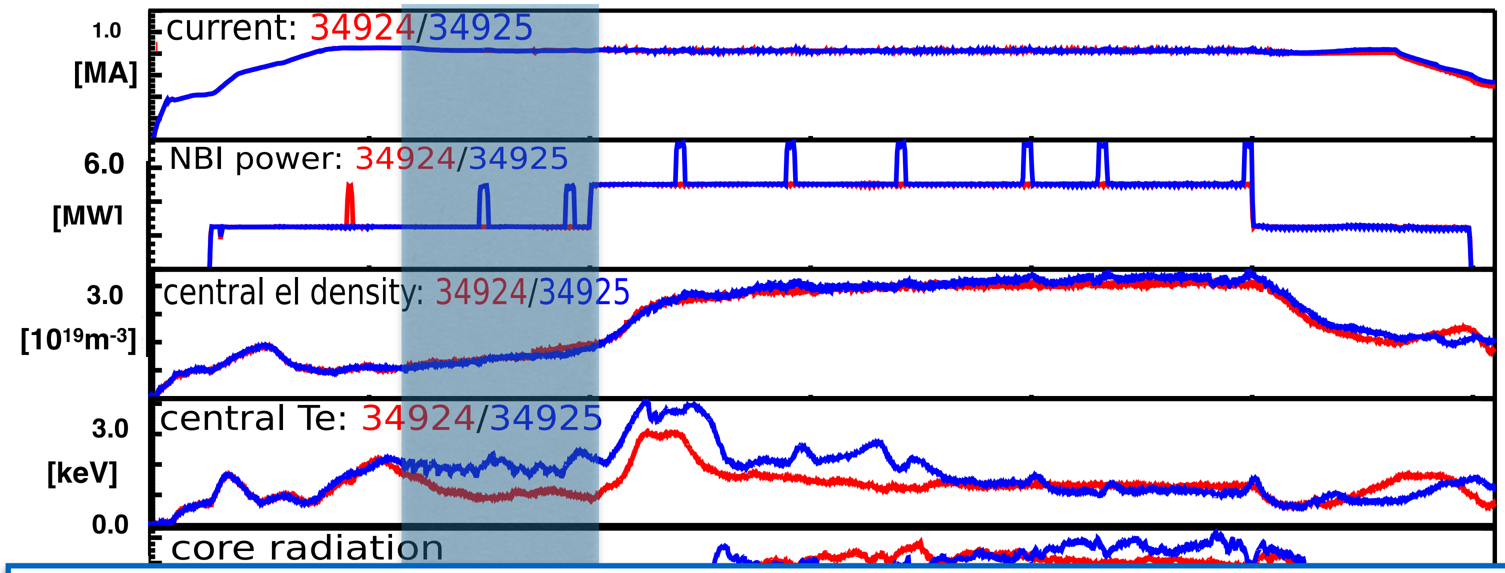
$\delta n/n \sim 1\text{-}4\%$

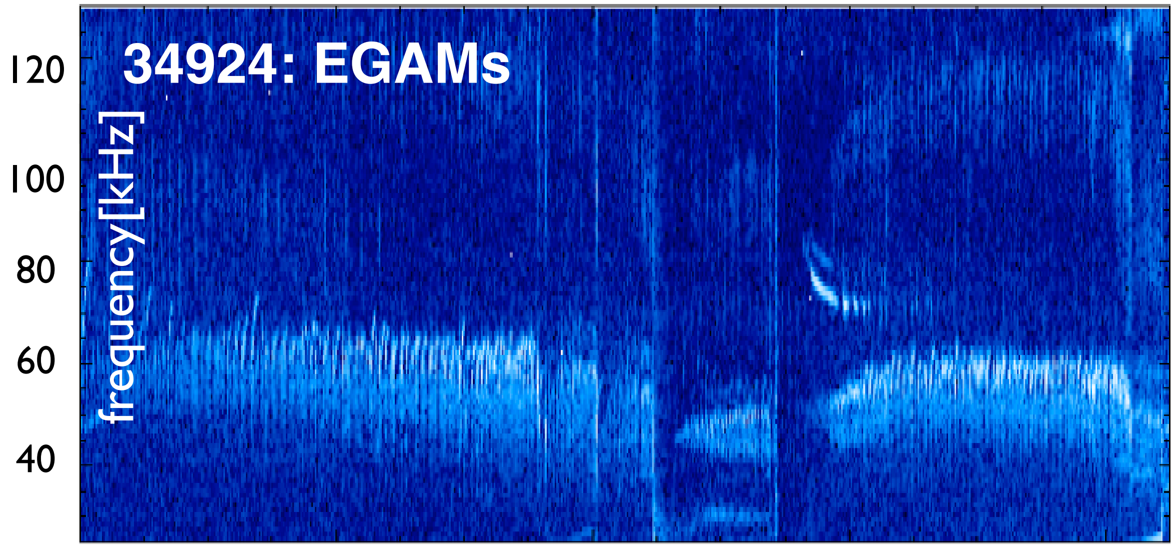
EGAM excitation conditions: comparison of discharges w/o EGAMs

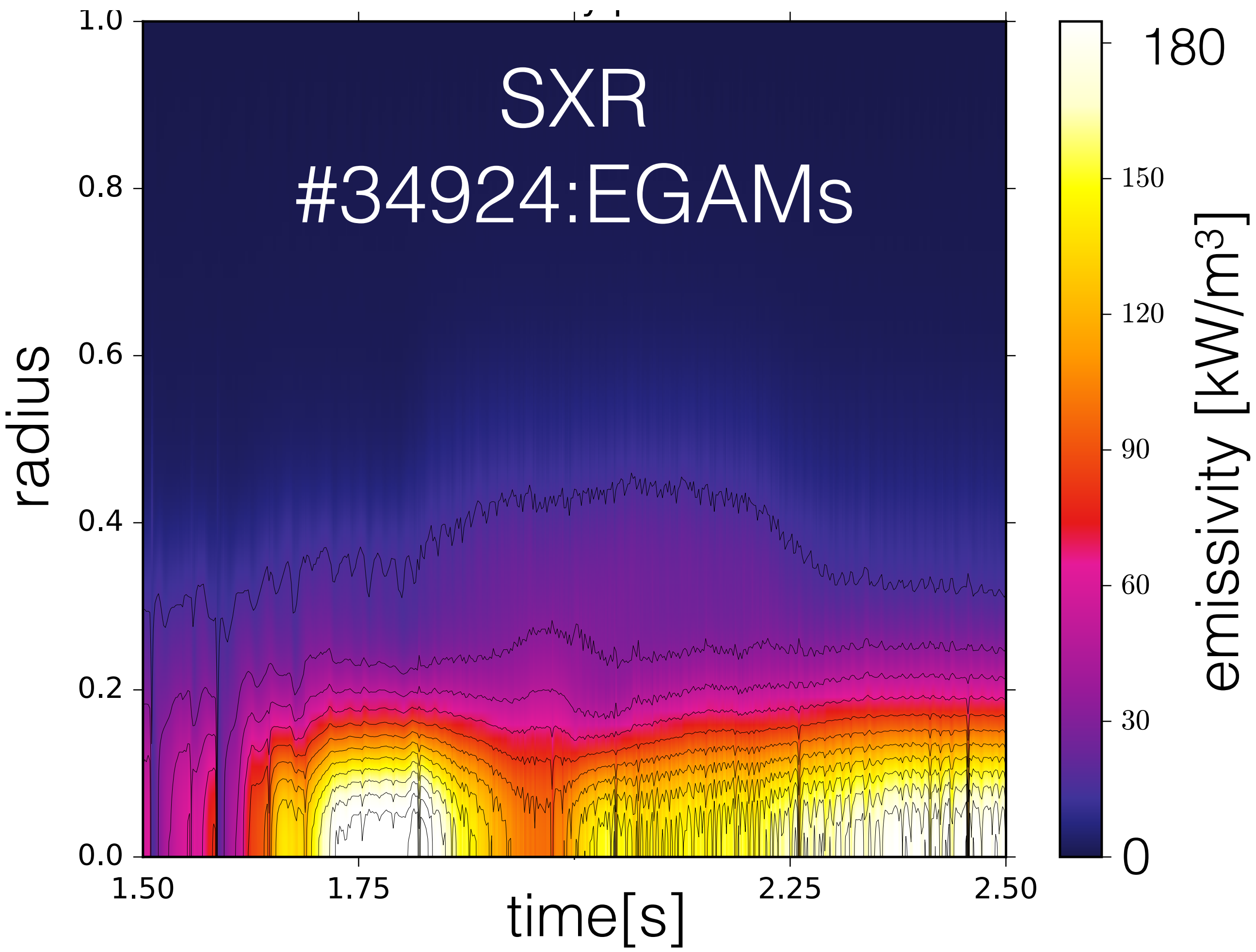


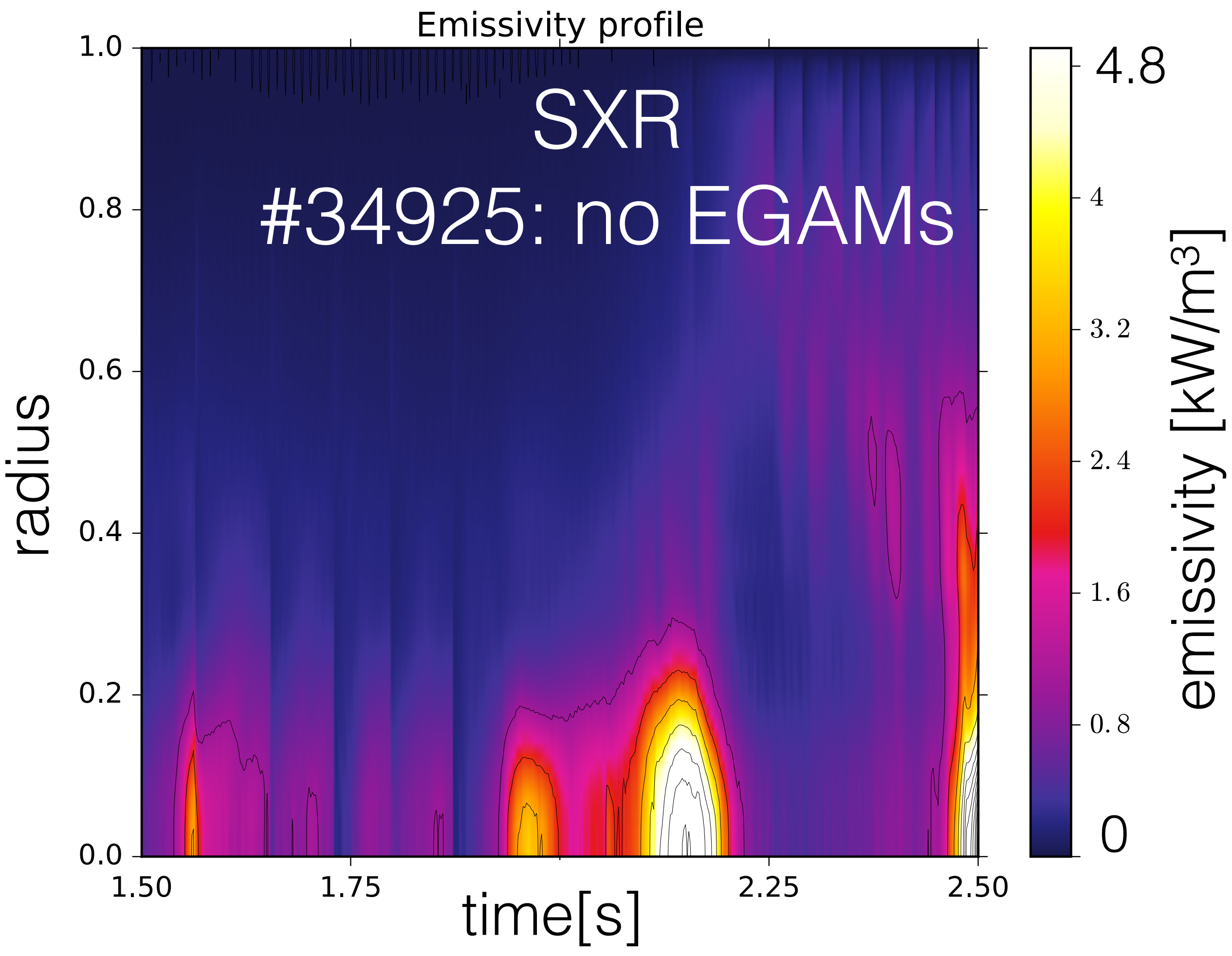


EGAM excitation conditions: comparison of discharges w/o EGAMs

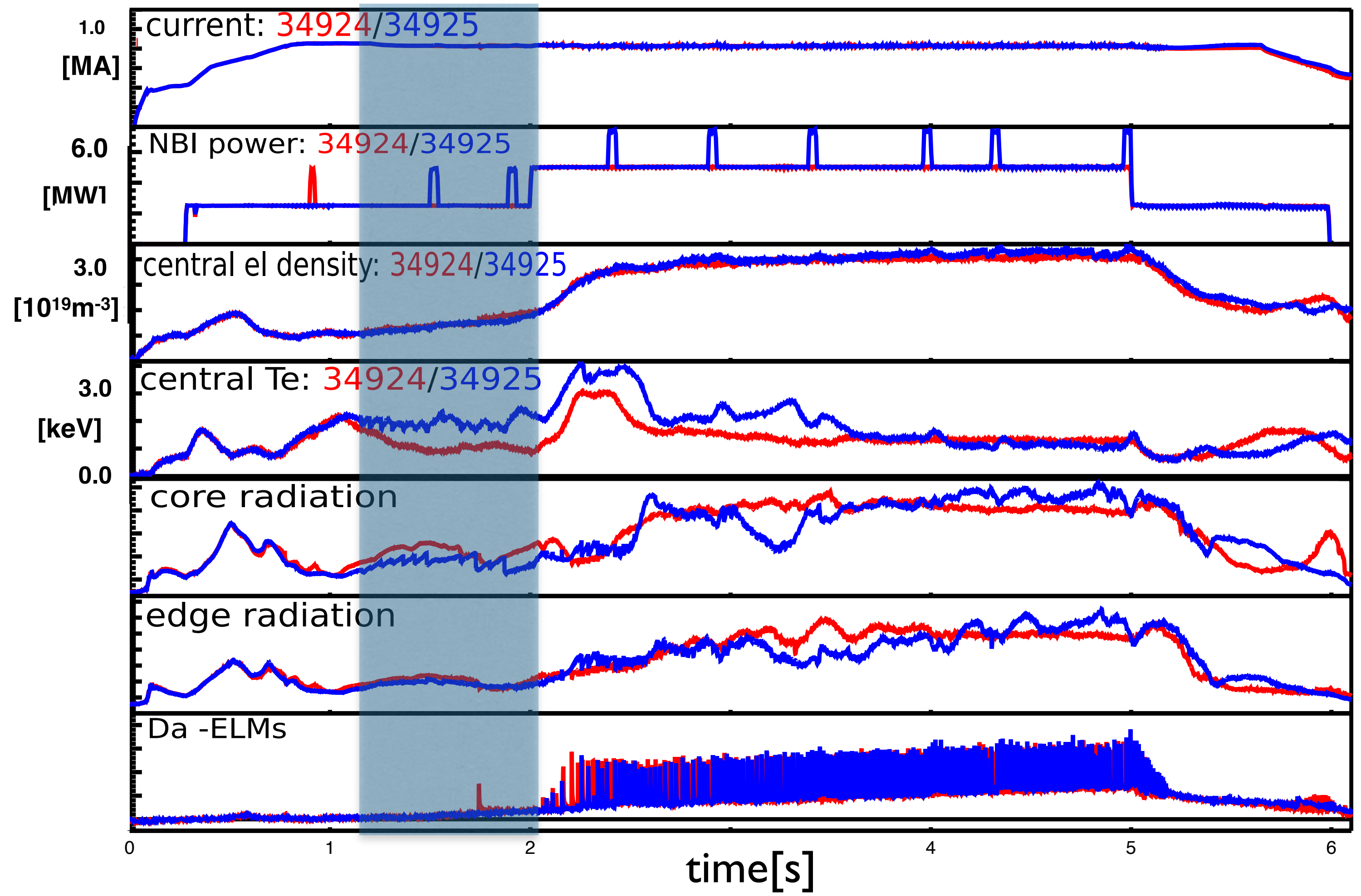


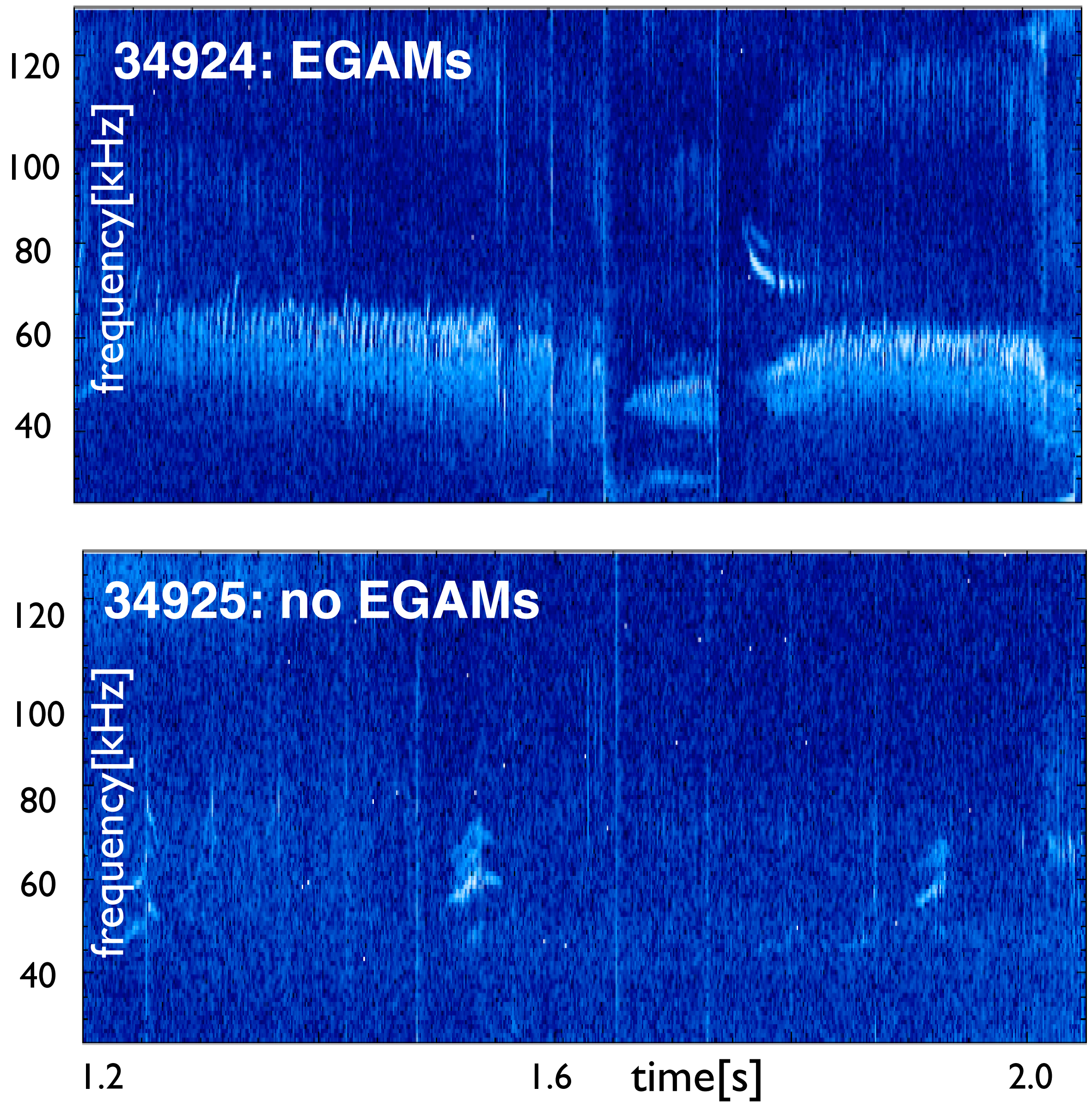


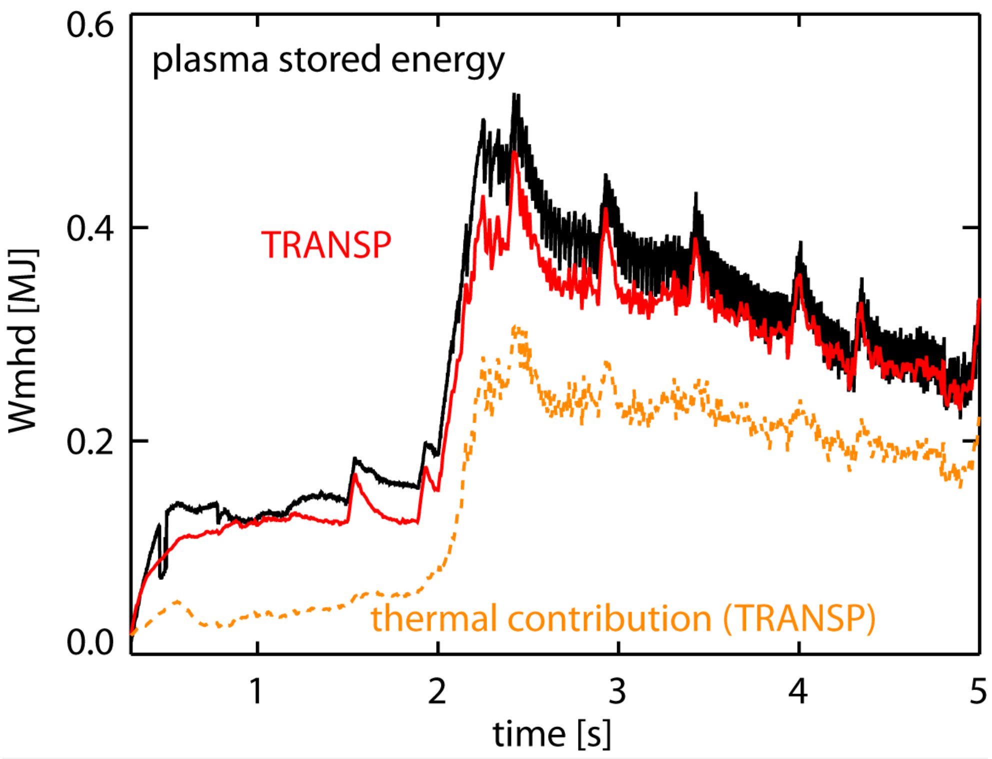




EGAM excitation conditions: comparison of discharges w/o EGAMs







interpretative TRANSP analysis: fast particle pressure contribution dominates in phase with one beam; in 2-beam phase ~ 30-50% of total β

EGAMs: linear theory

1. ω_{GAM} depends mainly on T_i,T_e,local curvature (R); damping strongly on q; simplest local formula underpredicts damping by orders of magnitude:

$\omega_{ti} = v_{th,i}/(qR)$

$$\omega_G^2 = v_{th,i}^2/R^2 \{(7/4+T_e/T_i) - i\,\pi\,(\omega_G/\omega_{ti})^5 \exp-(\omega_G/\omega_{ti})^2[1+(1+2\,T_e/T_i)/(\omega_G/\omega_{ti})^2\,]\}$$

any deviation of the geodesic curvature drift from **$\sin(\theta)$** dependence introduces **$\exp-(\omega/(2\omega_{ti}))^2$** terms that dominate the damping:

- plasma shaping in particular elongation *[Gao,NF 2009]* changes both ω and γ
- finite orbit width and finite Larmor radius effects *[Sugama 2006, Zonca 2008]*

trapped electrons increase the damping considerably *[Zhang 2010, Biancalani & Novikau 2017, Garbet, Varenna 2018]*

2. EGAMs are driven by the anisotropy in velocity space *[Fu 2008];* realistic F_{NBI} has to be included:

$$\gamma \sim \frac{\omega\,\partial F/\partial E - n\,\partial F/\partial P_\Phi}{\omega-\omega_t}$$

3. modes are global, have electromagnetic halo *[Wahlberg 2008]*

global, electromagnetic calculations in realistic geometry with a realistic EP distribution function are needed

modeling has been started with ORB5, GENE [di Siena, Biancalani 2018], HYMAGYC [G. Vlad] MEGA [H Wang]

EGAM modeling: linear gyrokinetic eigenvalue solver LIGKA

- LIGKA library comprises several local and global models for kinetic Alfvén mode (AE) physics and low frequency global modes based on the same linear gyro-kinetic model *[Qin 1998, Lauber 2007,2013,2018]*

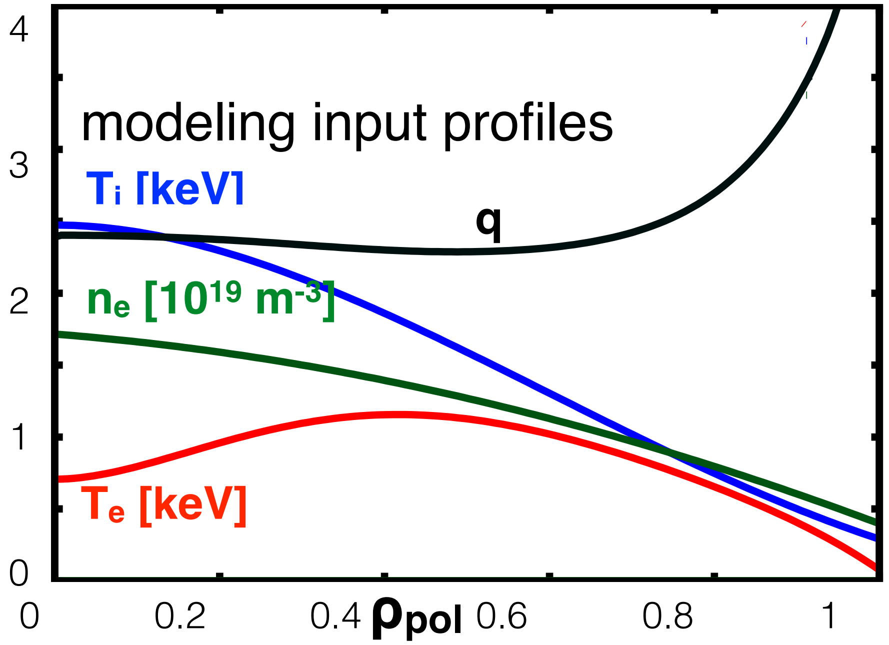
- various dispersion relations in literature (e.g. BAE, GAM, KGAM dispersion relation including FLR and FOW effects *[Lauber, Varenna 2018]* were directly derived from model equations

- fully numerical (based on HAGIS *[S.D. Pinches, 1996]* particle orbit information) and analytical evaluation of resonance integrals possible

- local and global solvers using either analytical or numerical v-space integrals

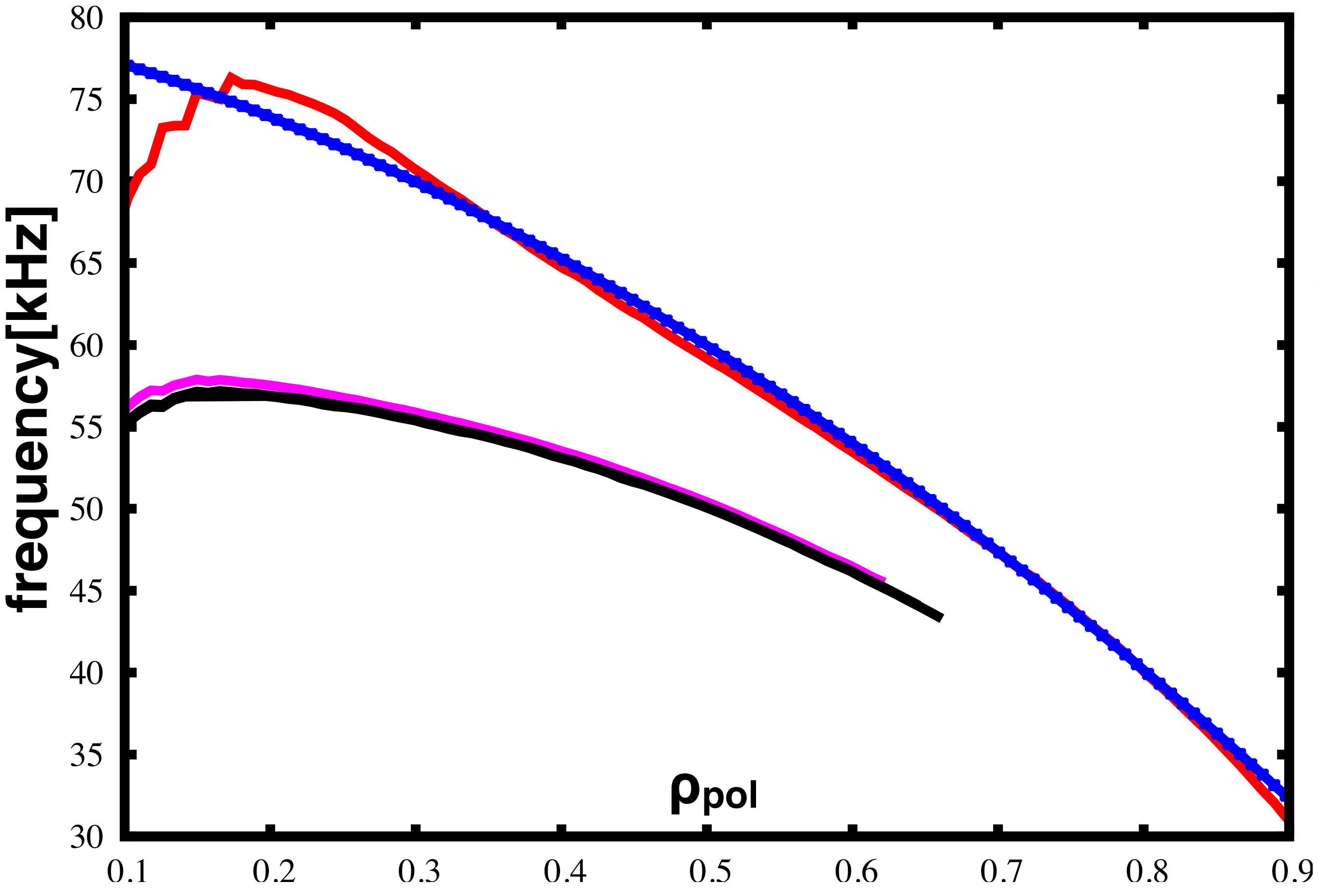
- in combination with non-linear HAGIS code, fast and automated stability and non-linear saturation evaluations for AE physics possible *[Hayward-Schneider & Lauber 2017/18]*

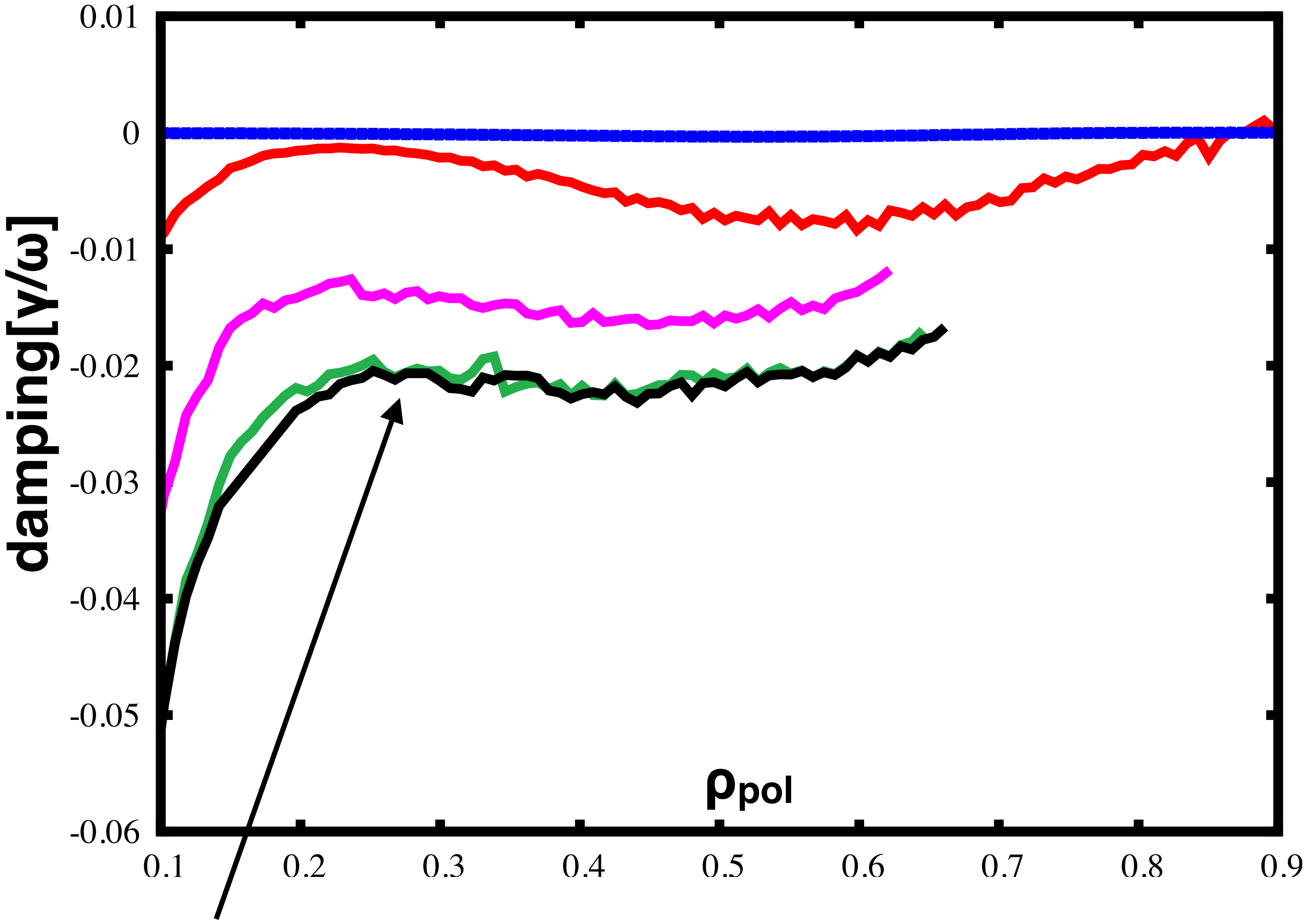
GAM continuum: local calculations



at each radial position, solve linear dispersion relation:

- analytical, circular equilibrium
- numerical, circular eq., all ion resonances
- numerical, shaped equilibrium $\kappa\sim 1.6$; $\omega\sim\sqrt{2}/(1+\kappa^2)$
- numerical, add trapped electrons
- numerical, trapped + circulating electrons

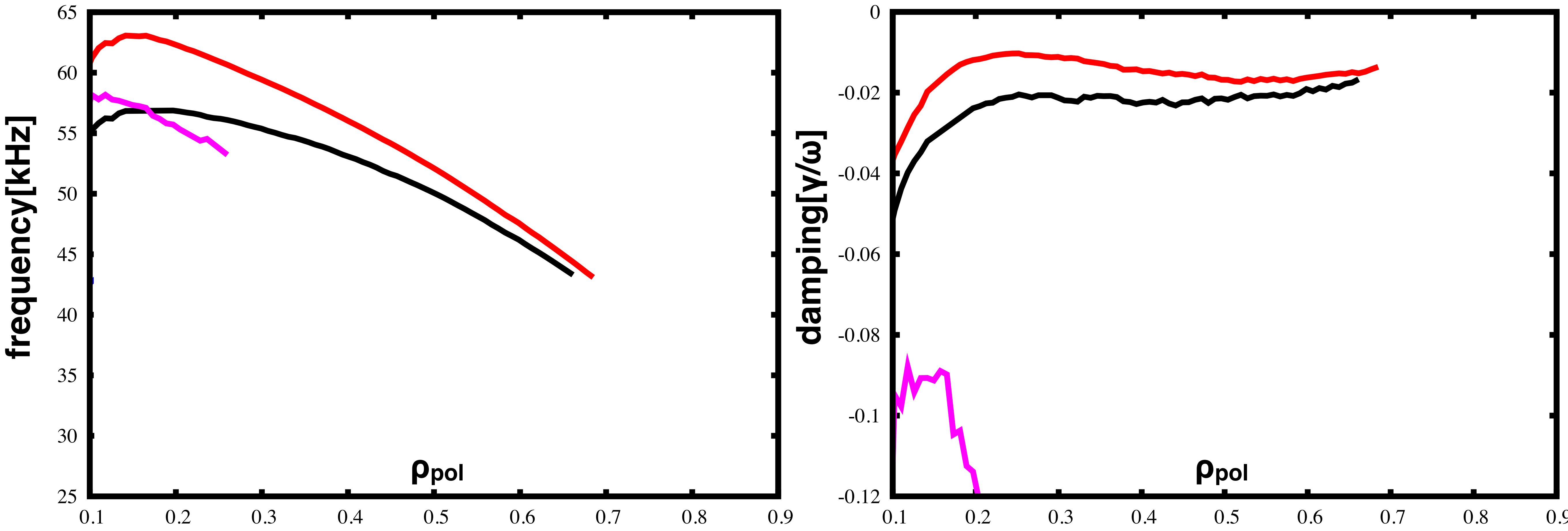




profiles (q,Ti,Te) create (flat) minimum in GAM damping rate

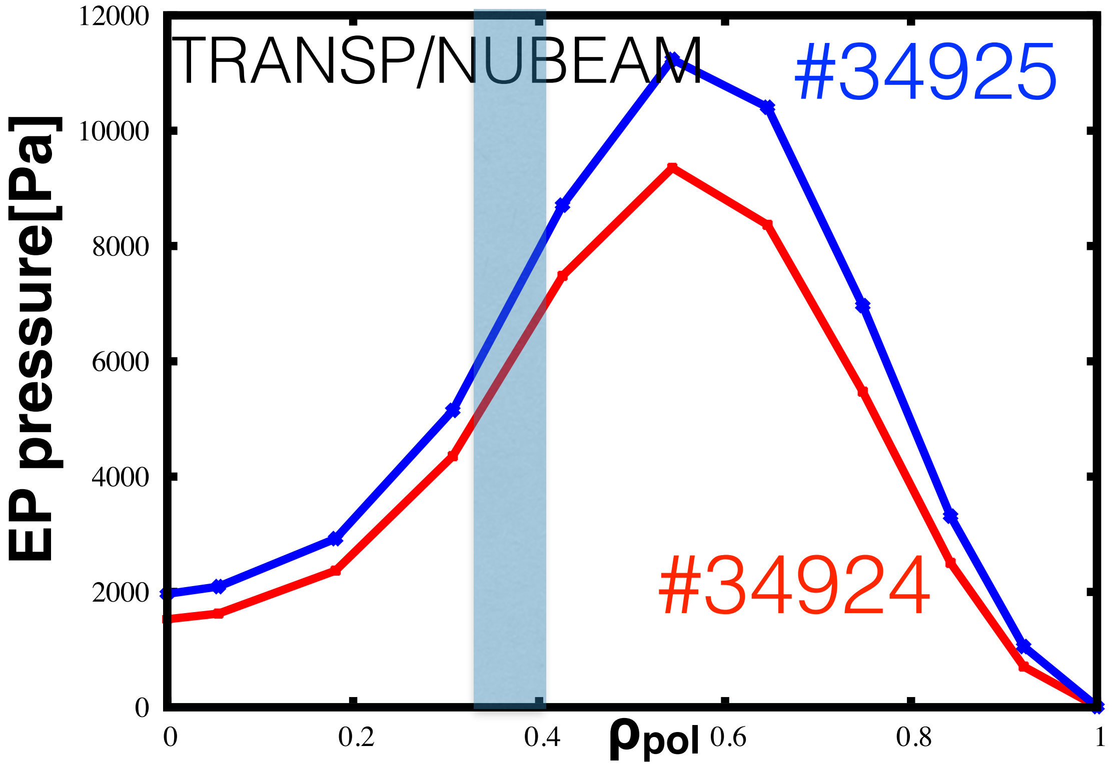
control cases: lower q, set T_e=T_i

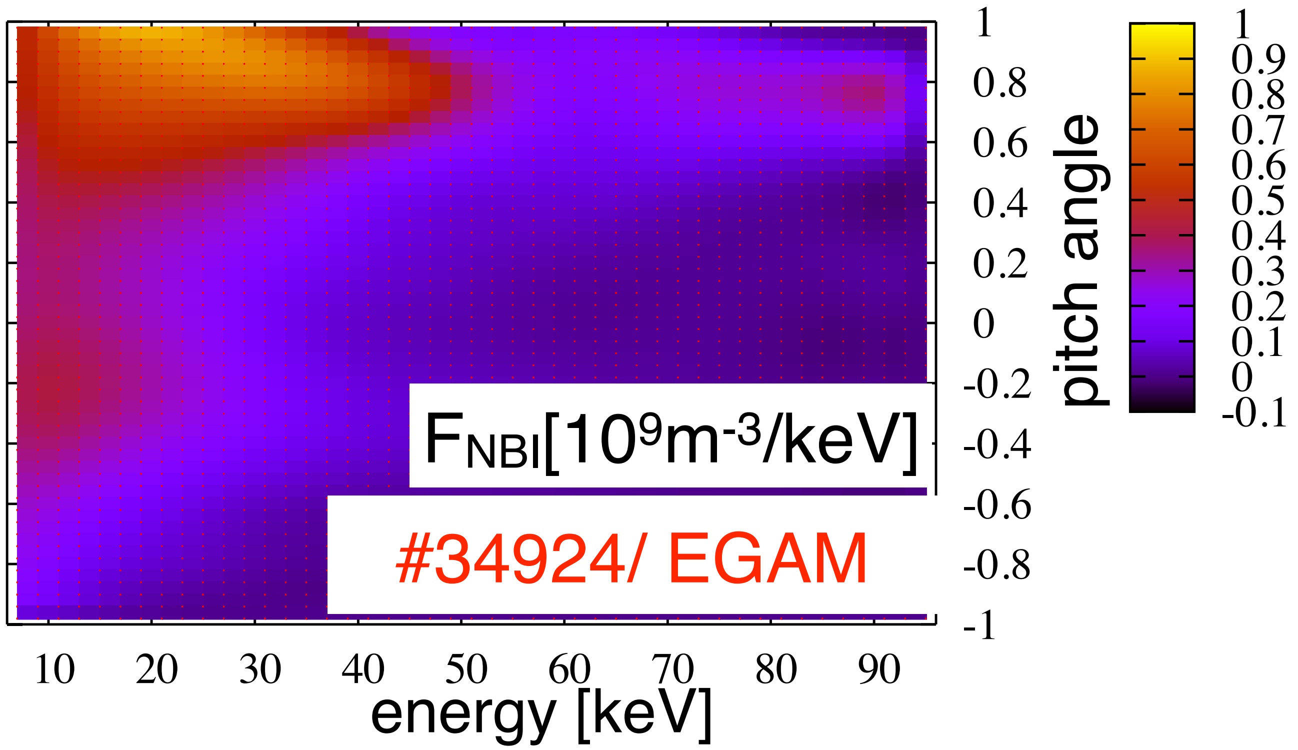
- reference parameters (last slide)
- lower q_0 from 2.4 to 1.99 (so far EGAMs were never observed for q<2)
- set T_e=T_i: increases f_{GAM}, reduces damping! Te inversion not a necessary ingredient for EGAM excitation (as experimentally confirmed)

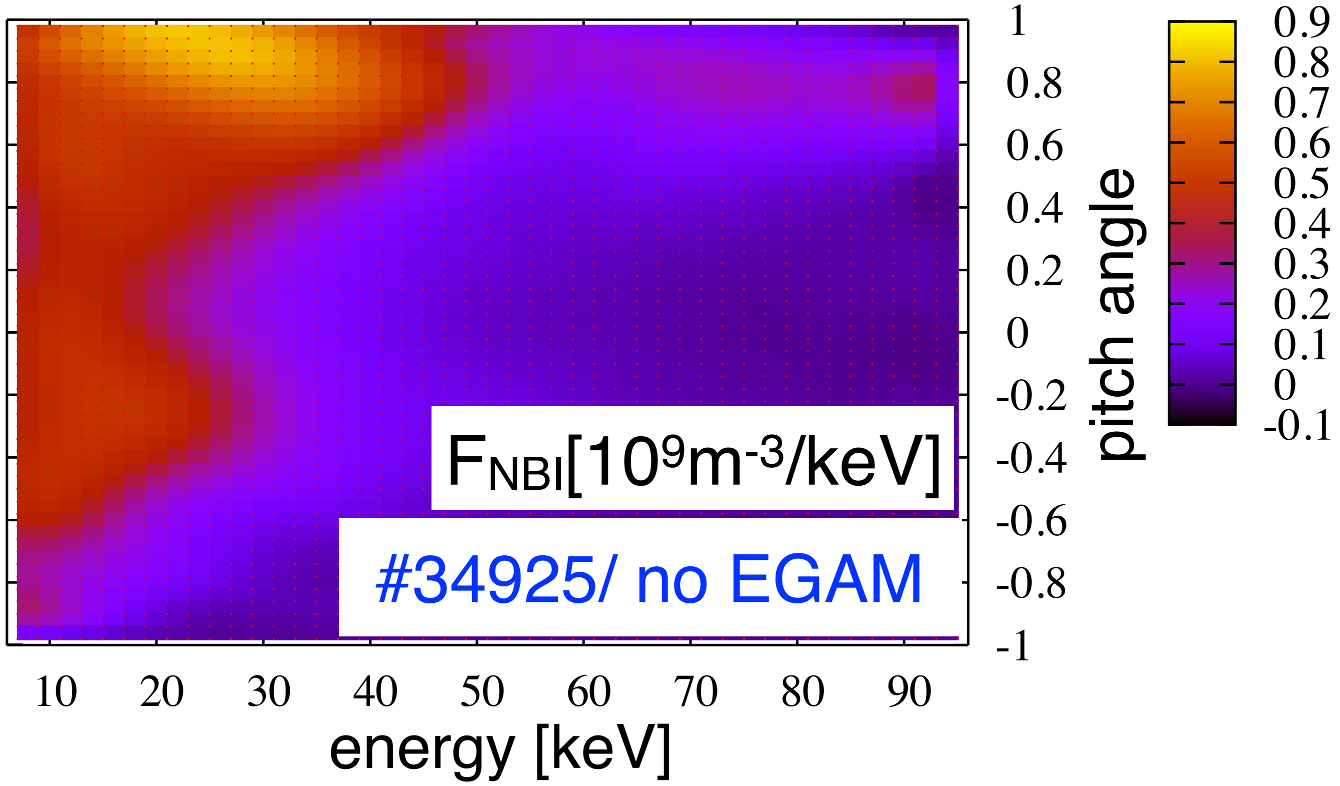


damping analysis alone does not explain EGAM excitation conditions

EP phase space analysis



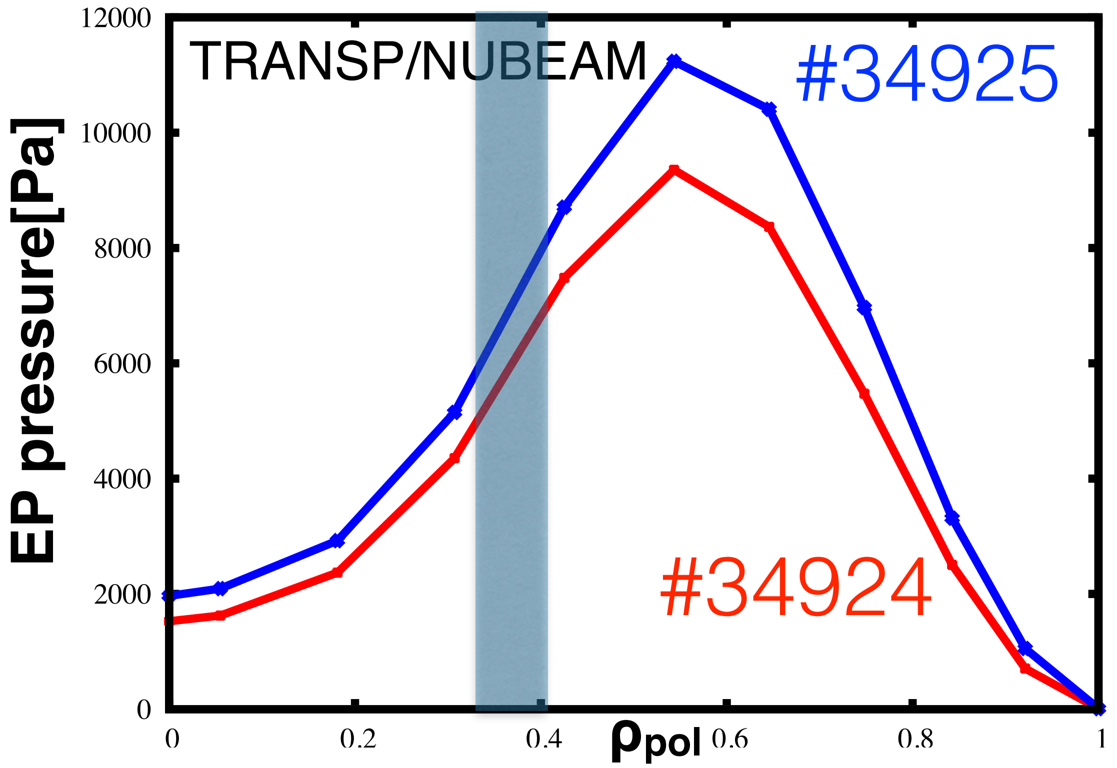




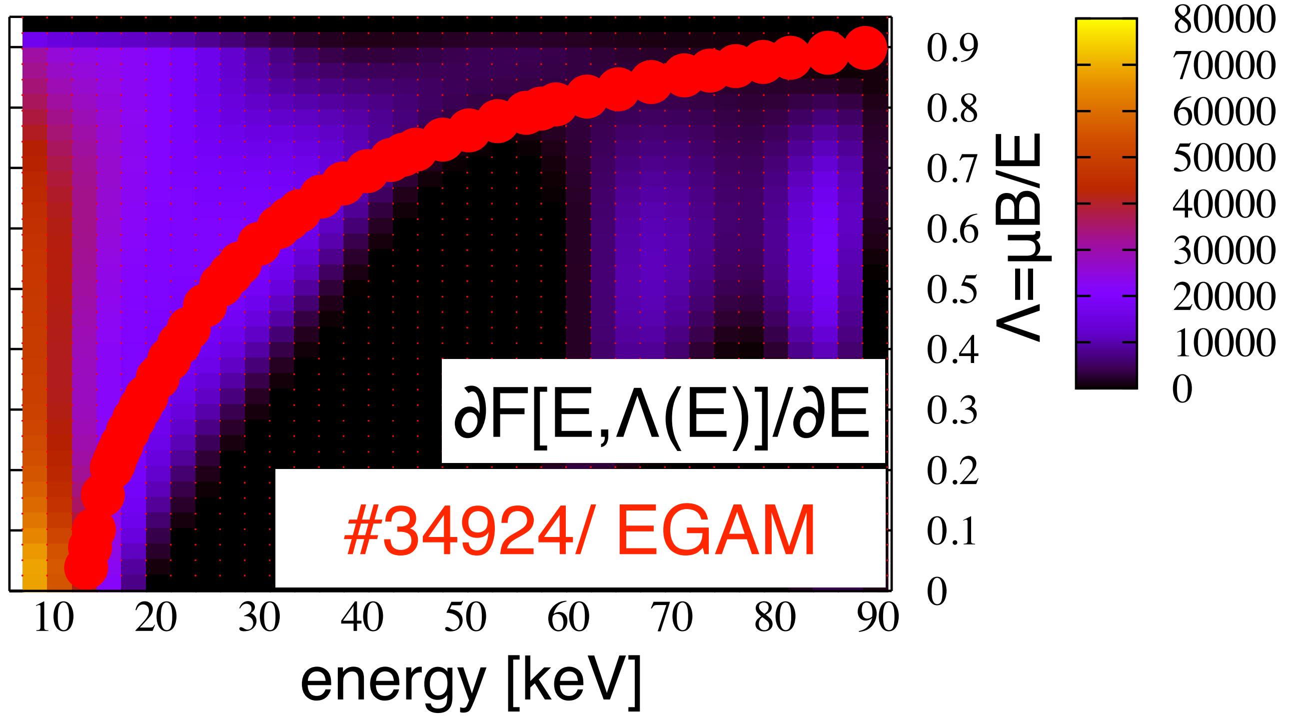
- as expected, $T^{-3/2}$ dependence of slowing down processes leads to higher EP pressure for case with higher background temperatures (and without EGAMs)

- at first glance: similar distribution in phase space structure

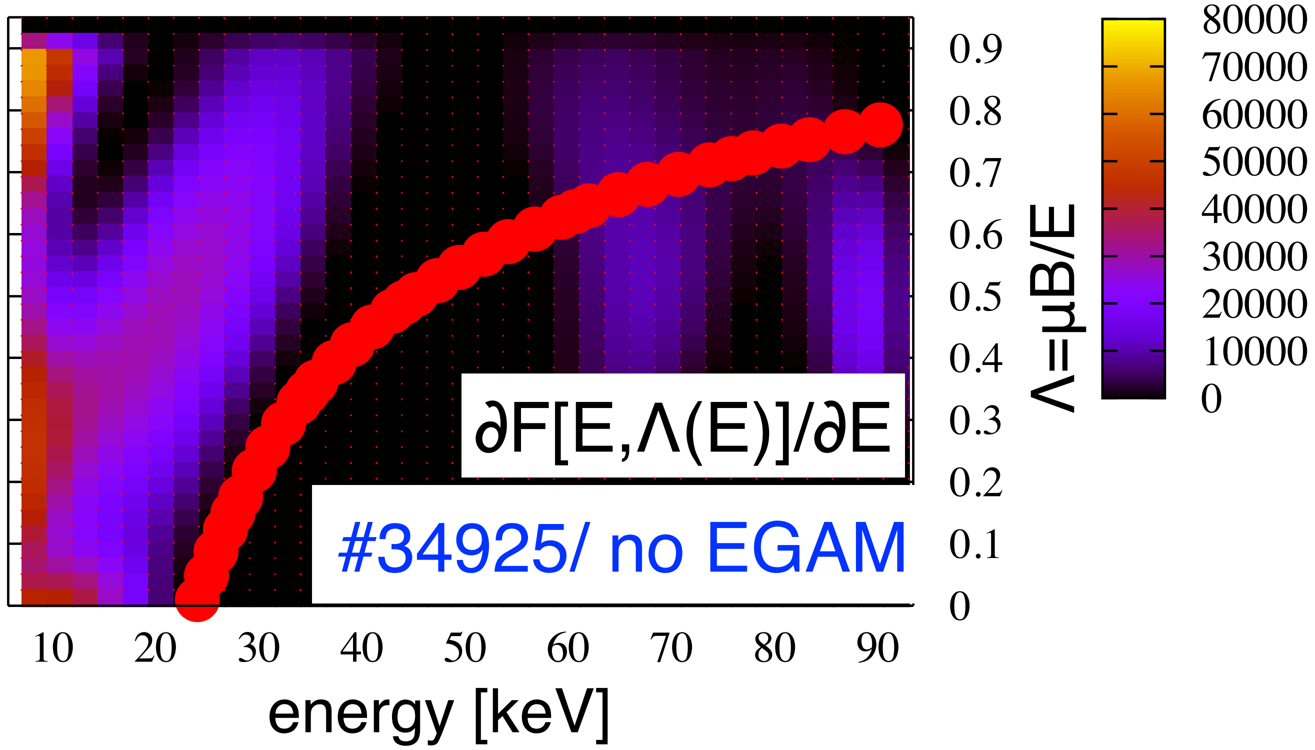
EP phase space analysis: ∂F/∂E



resonance with local f_{GAM}



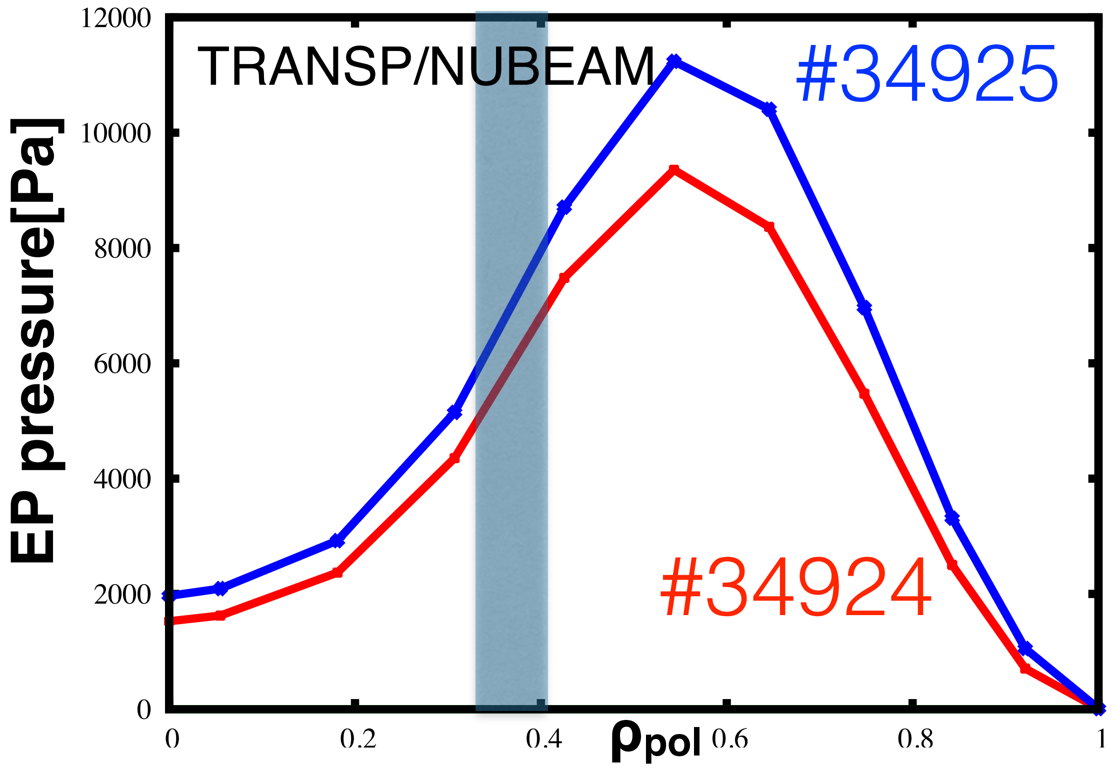
resonance with local f_{GAM}



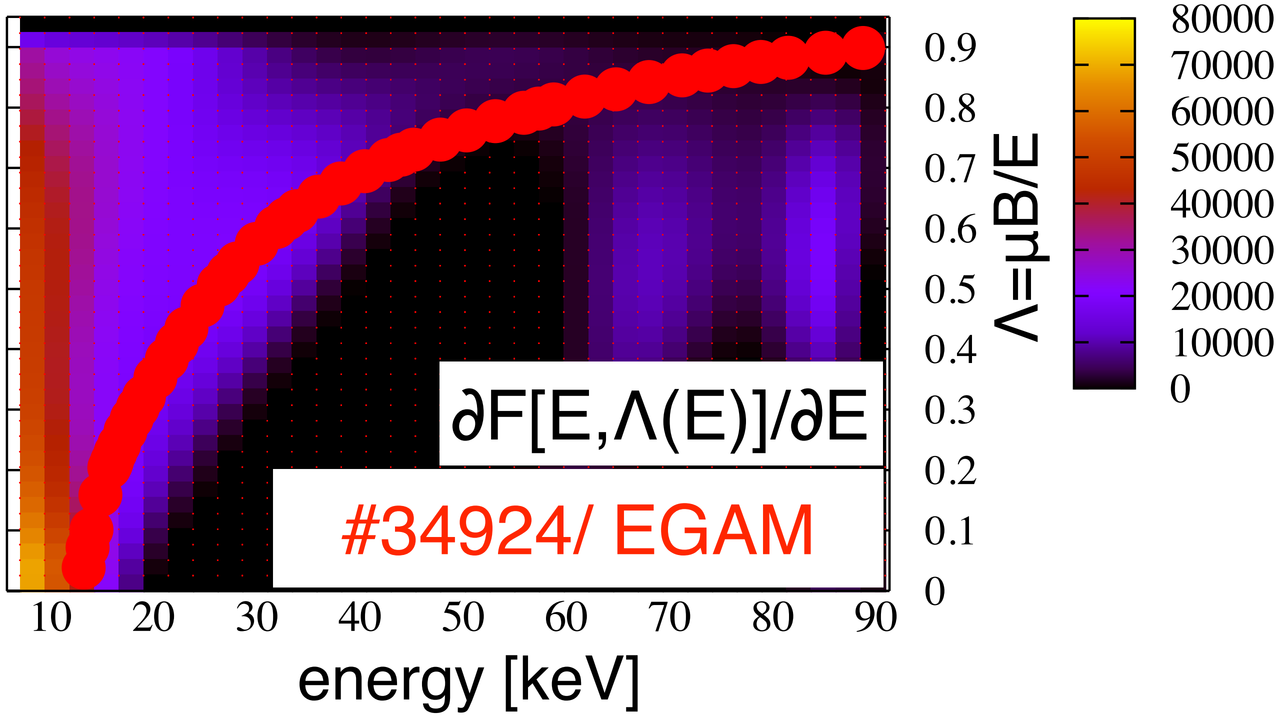
∂F[E,Λ(E)]/∂E< 0 is coloured as black with value 0

- EGAM drive is determined by integral along resonance line $\omega - \omega t = 0$
- no drive due to mismatch of drive region and local GAM frequency

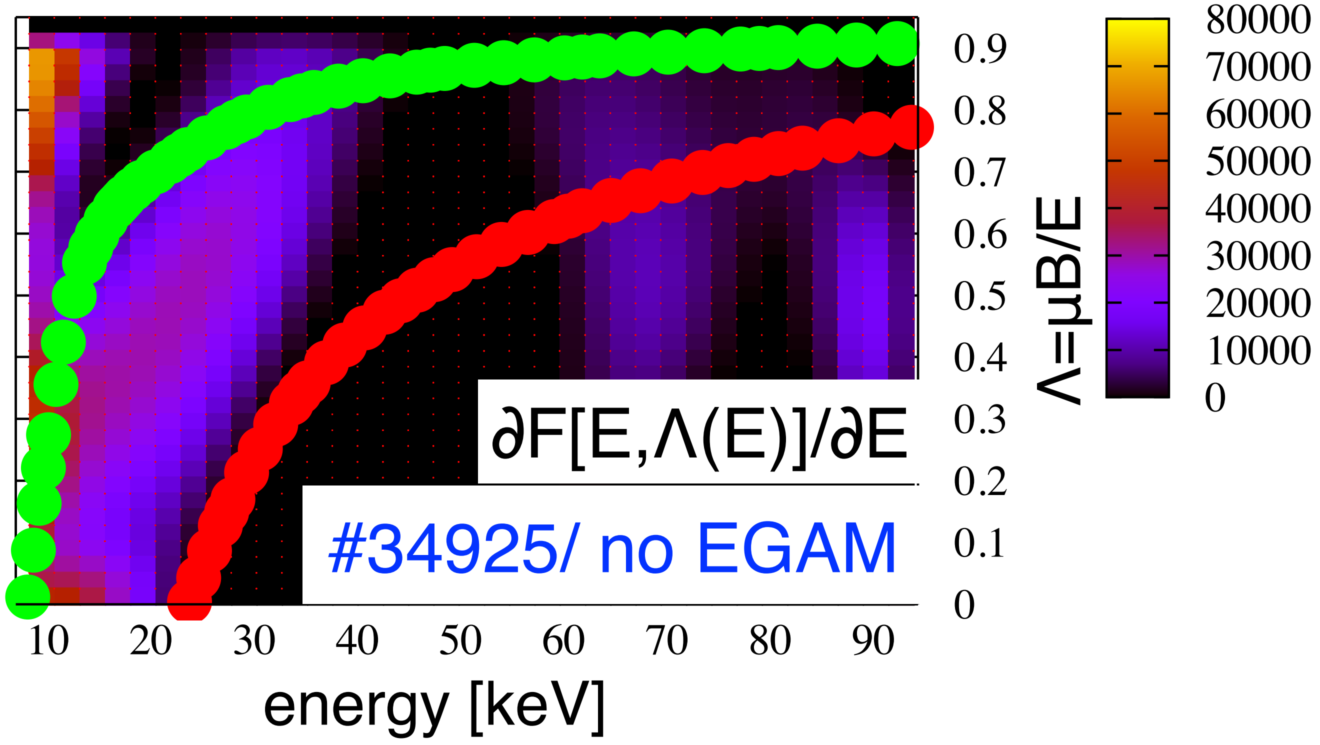
EP phase space analysis: ∂F/∂E



resonance with local f_{GAM}

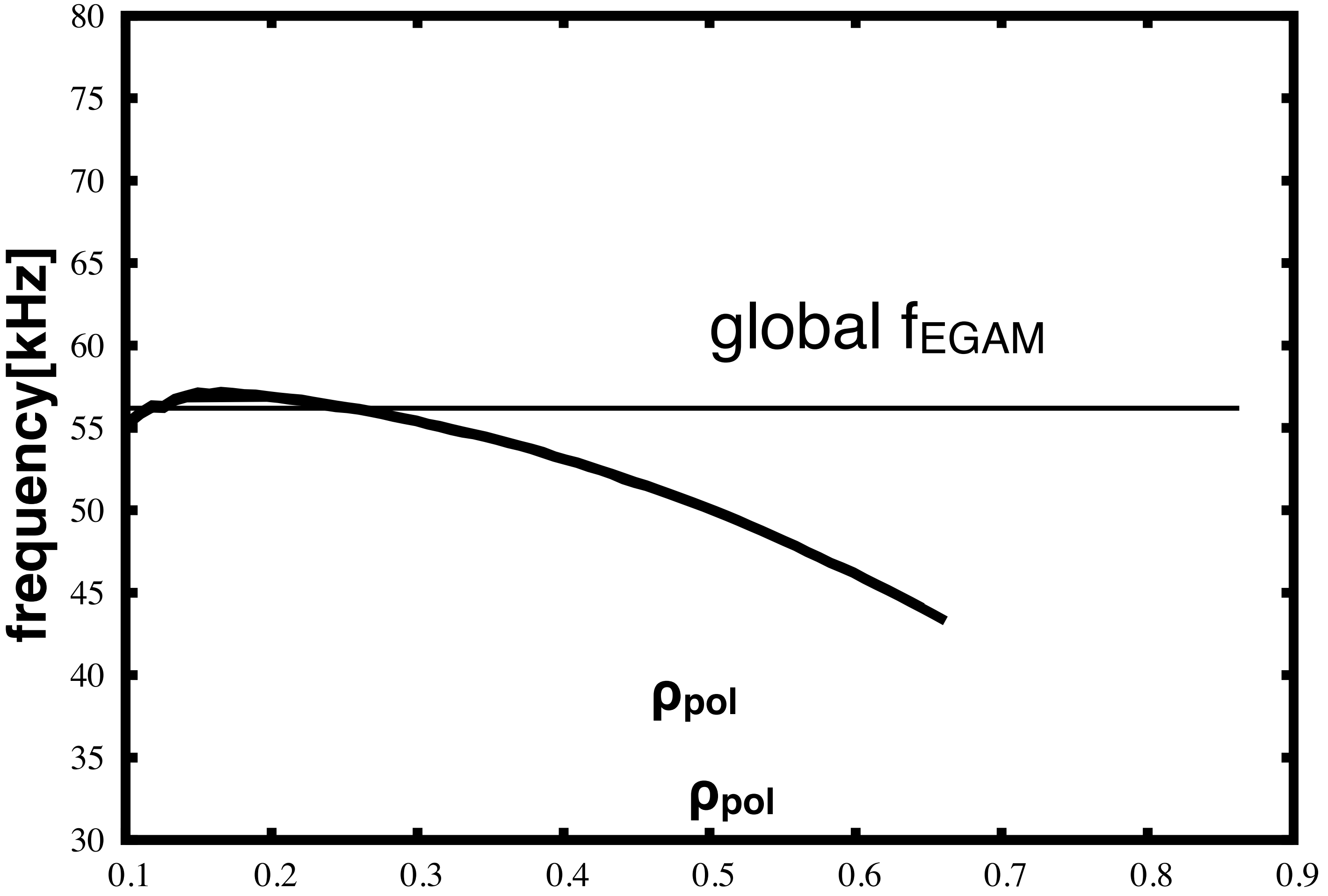


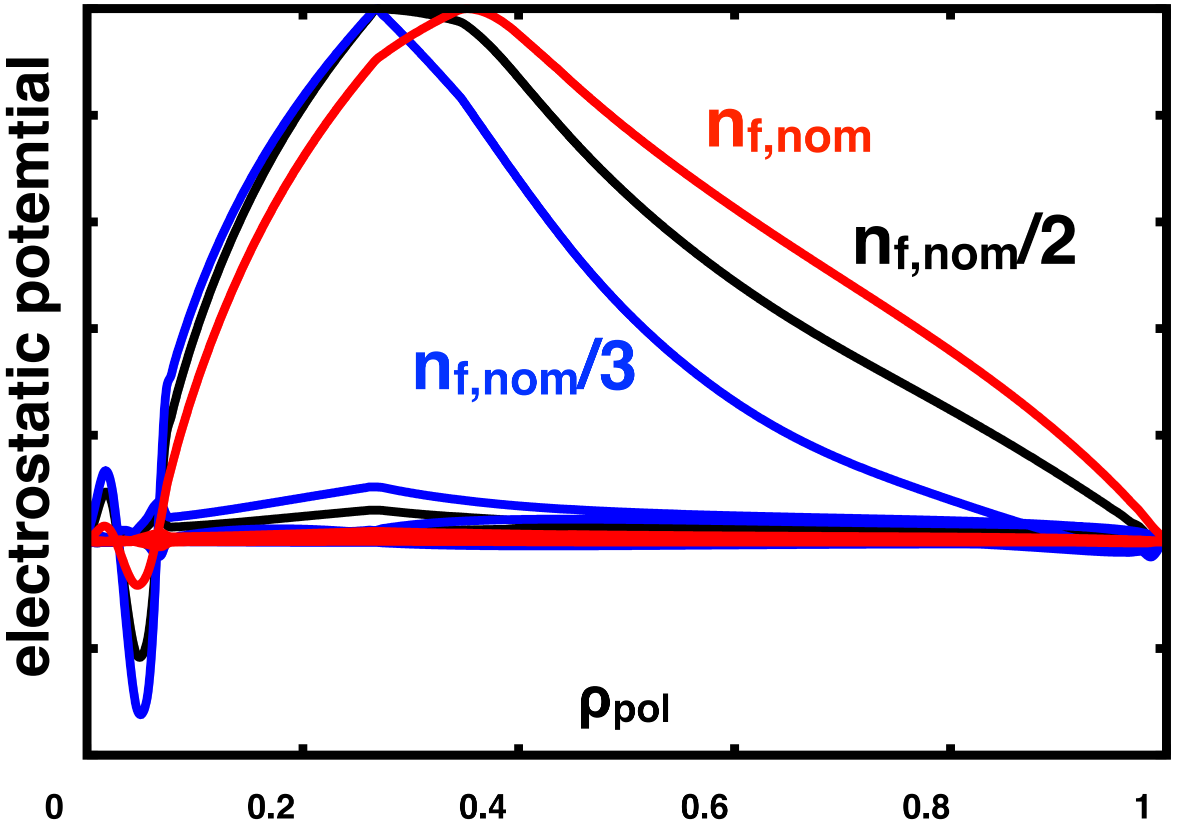
resonances with local f_{GAM}

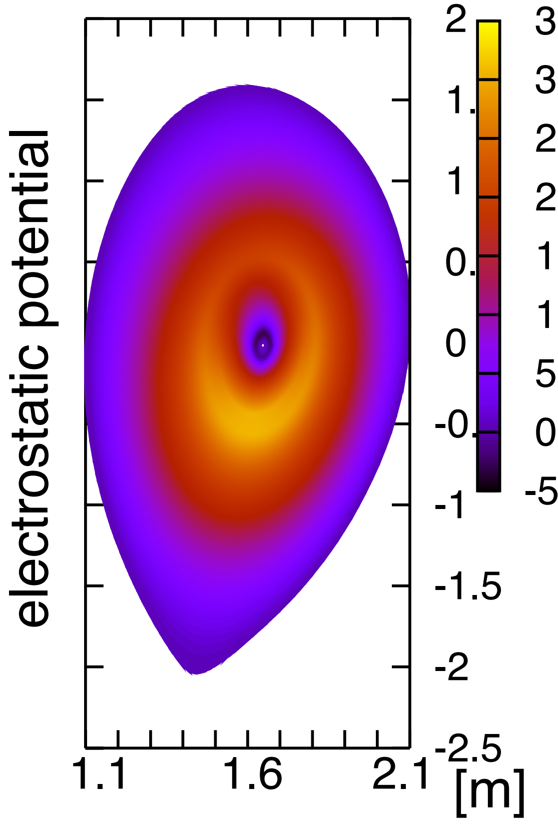


- EGAM drive is determined by integral along resonance line $\omega-\omega_t=0$
- no drive due to mismatch of drive region and local GAM frequency
- 2nd resonance $\omega - 2\omega_t=0$ suffers from damping of thermal background - ‘anomalous ion heating’ *[LHD, Ido 2014, H. Wang 2018]*

global EGAM structure [LIGKA]

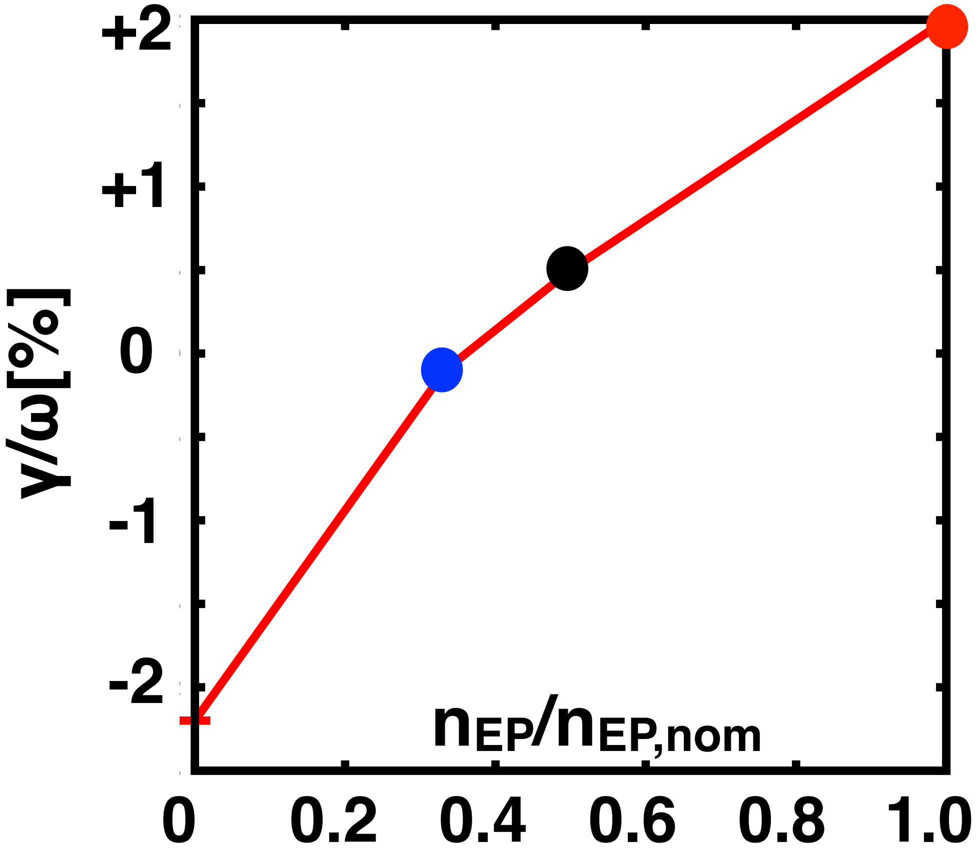


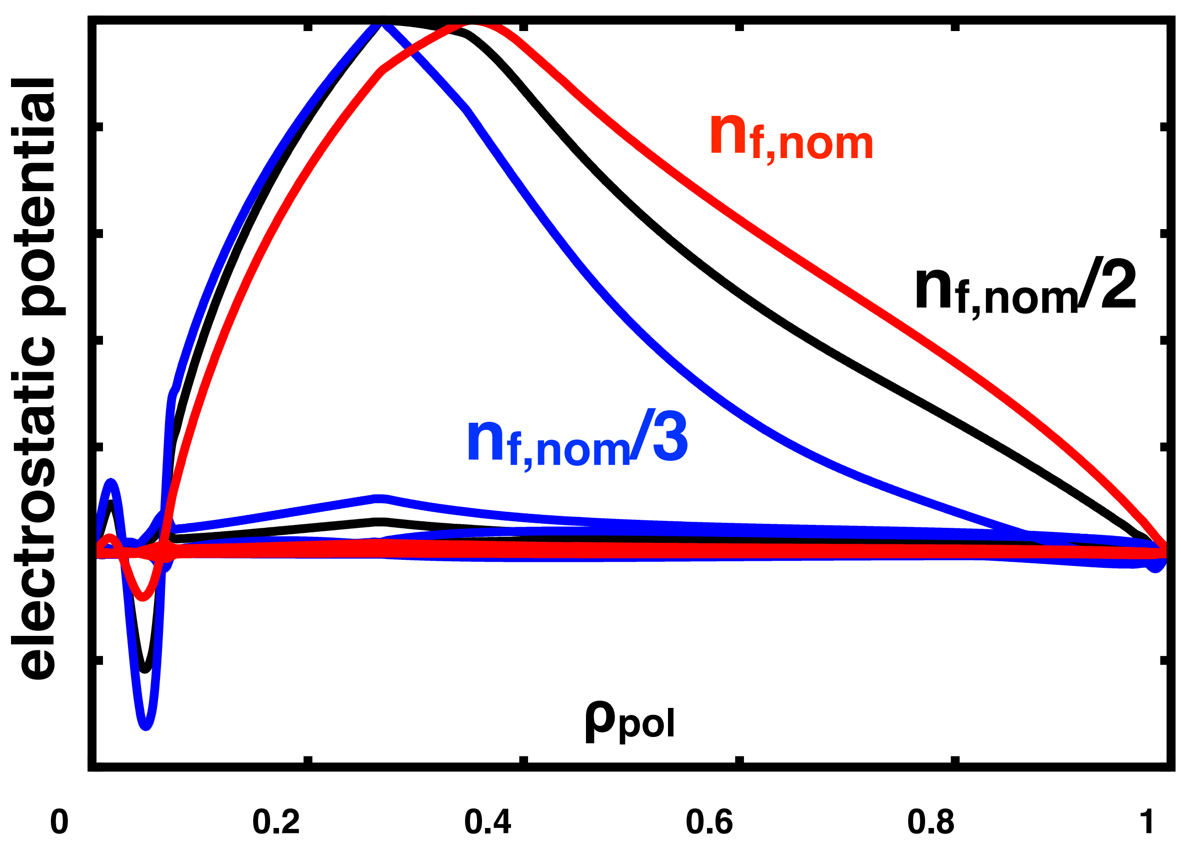




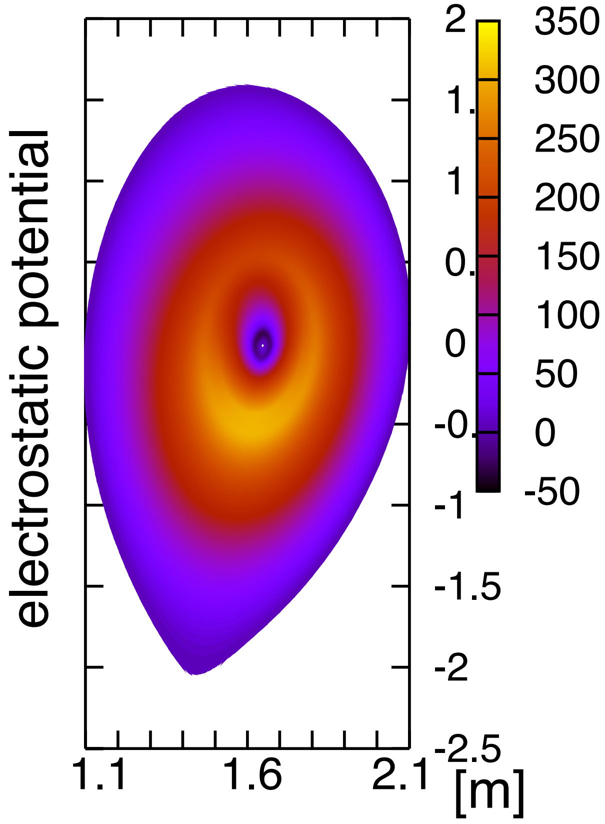
- global EGAM frequency stays roughly constant with increasing n_{EP}, and close to flat part of the GAM continuum
- change in mode structure is observed with increasing n_{EP}

global EGAM structure





- mode is destabilised with increasing n_{EP}
- asymmetries of poloidal sidebands observed when anisotropic EP drive is present *[Z. Lu, Varenna 2018]*
- mode stays in flat continuum region - avoid continuum damping $\sim \partial\omega_{GAM}/\partial r$ *[Biancalani, Palermo, 2016,17]*



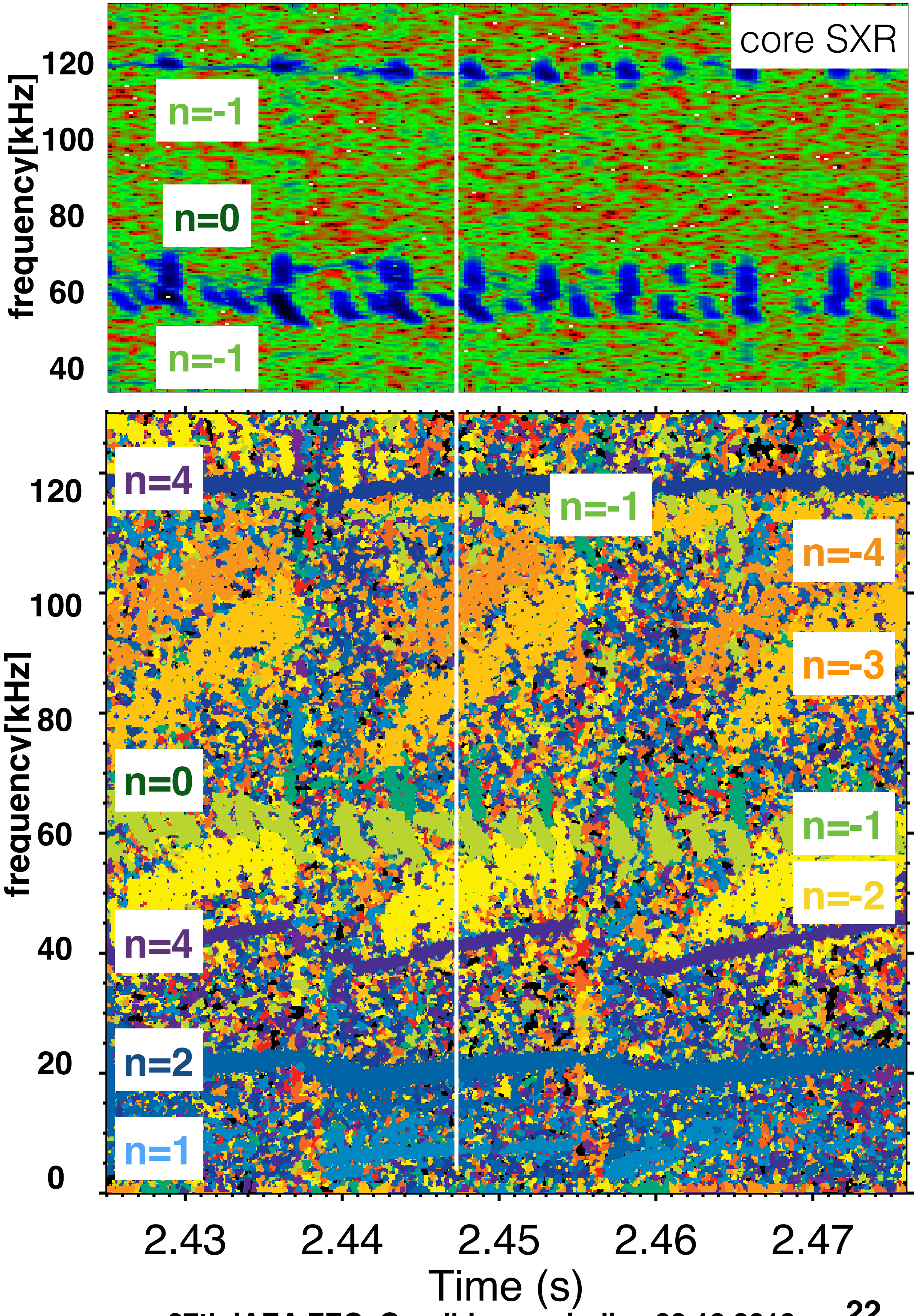
outline

- the dynamics of EP-driven geodesic acoustic modes (EGAMs) and excitation conditions under various experimental conditions
- interaction of EGAMs and Alfvén eigenmodes (AEs)
- discussion & conclusions

interaction with Alfvén modes

3 types:

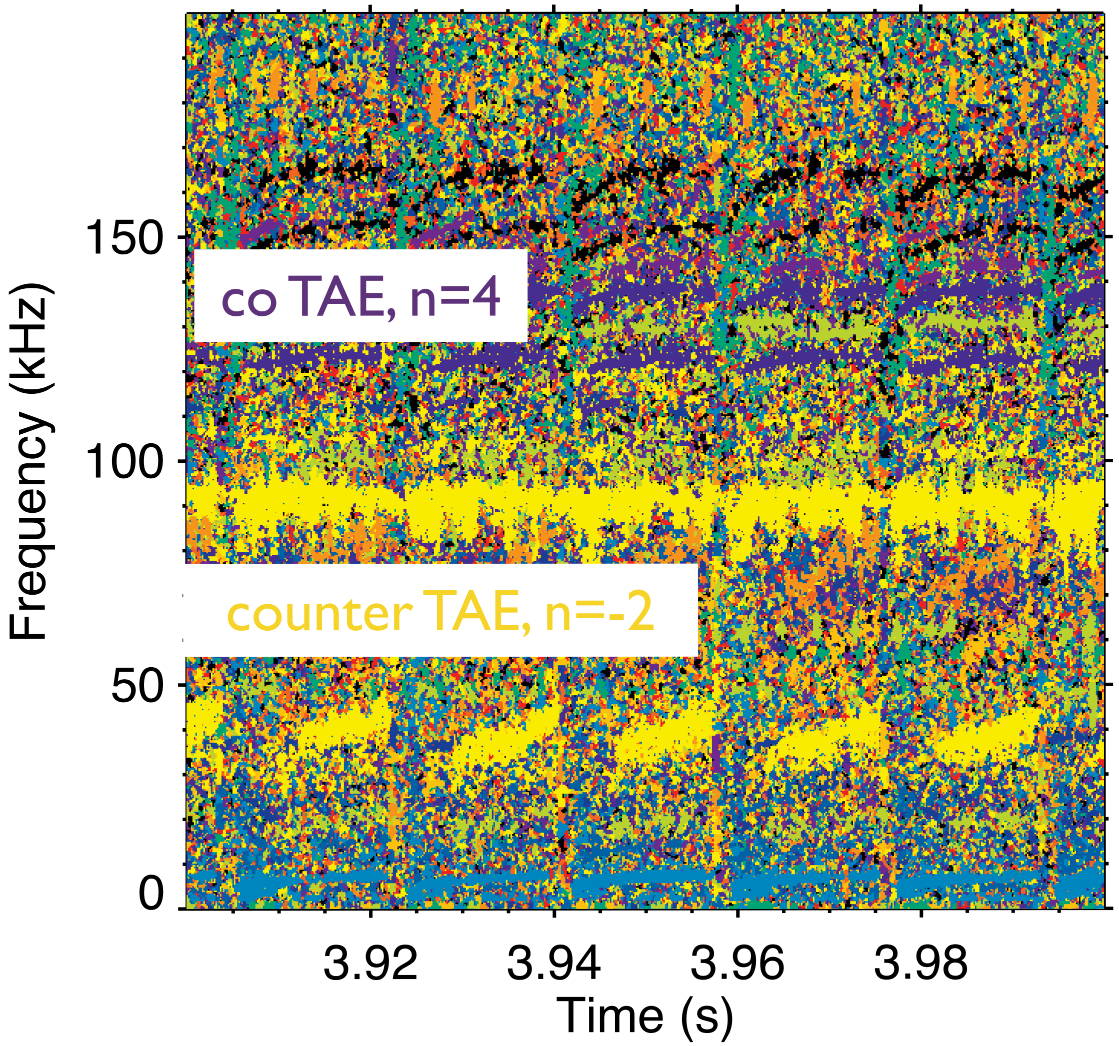
1. nearly simultaneous mode onset- but no phase correlation between different frequency bands, i.e. no significant bicoherence: triggering via non-linear phase space relaxation

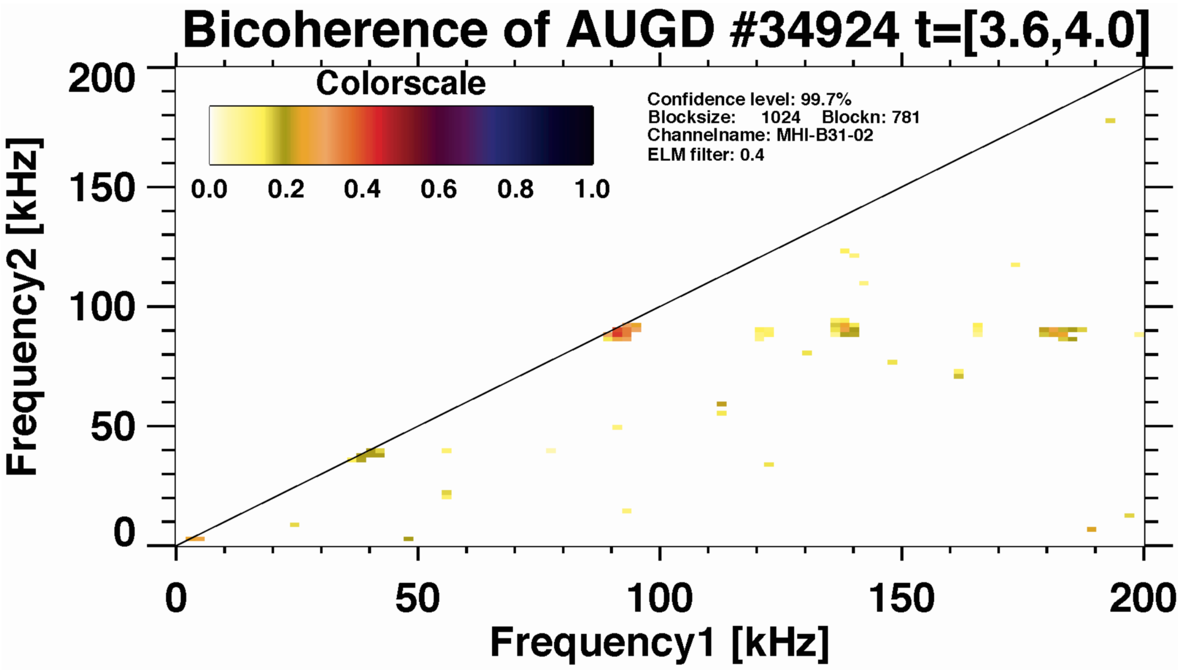


interaction with Alfvén modes

3 types:

1. simultaneous mode onset, no phase correlation: triggering
2. phase correlation between different frequency bands: **significant bicoherence** indicating wave-wave non-linear coupling

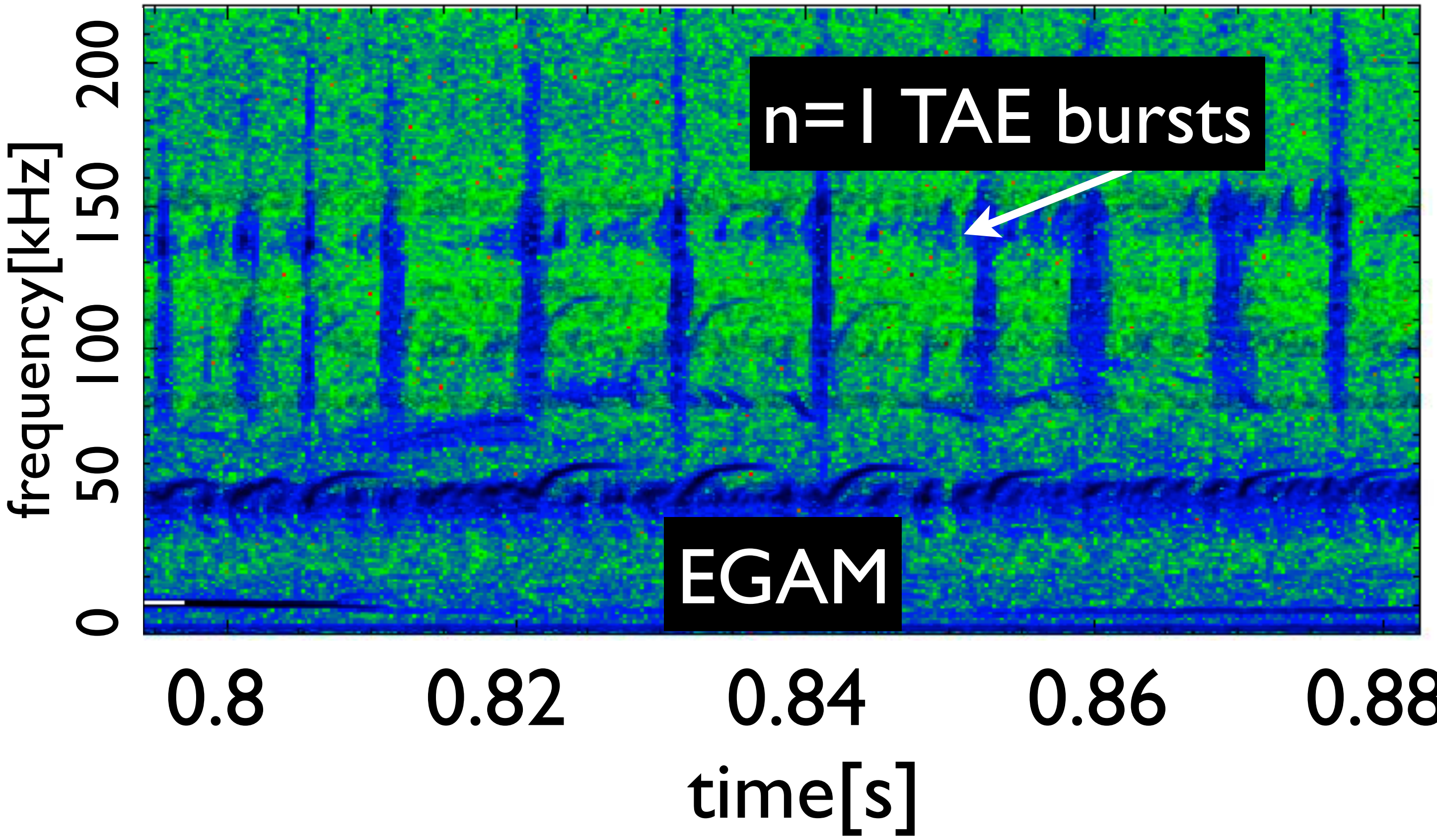




interaction with Alfvén modes

3 types:

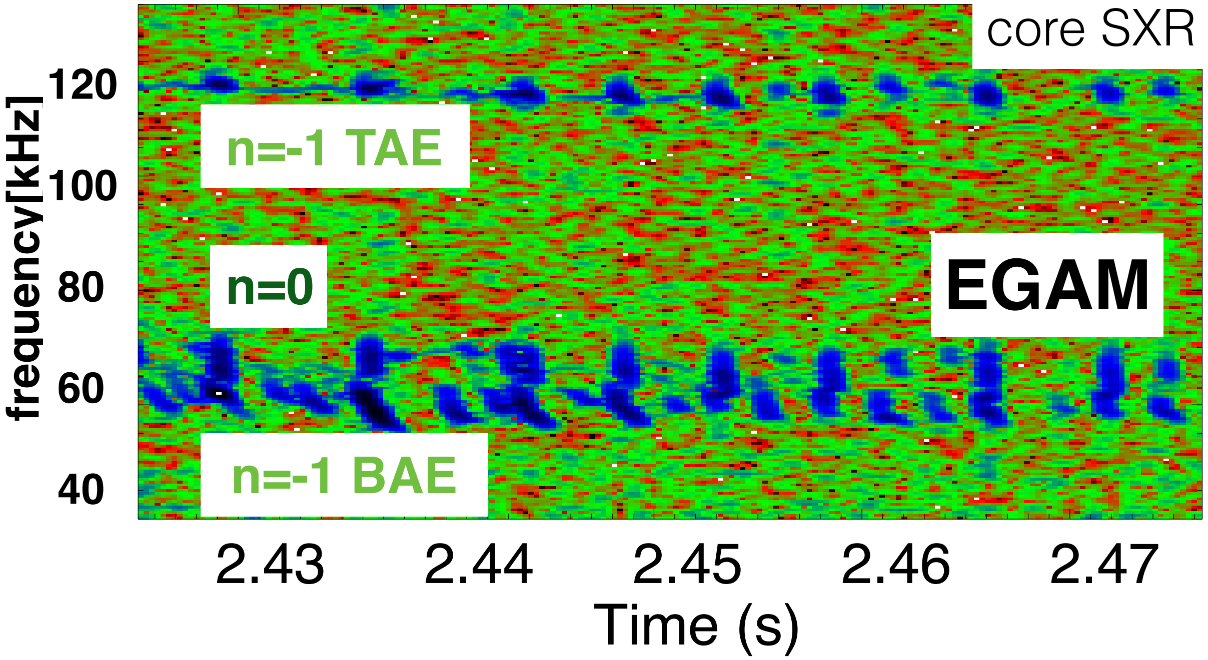
1. simultaneous mode onset, no phase correlation: triggering
2. phase correlation between different frequency bands: significant bicoherence indicating nonlinear wave-wave coupling
3. **both** mechanism can be observed together



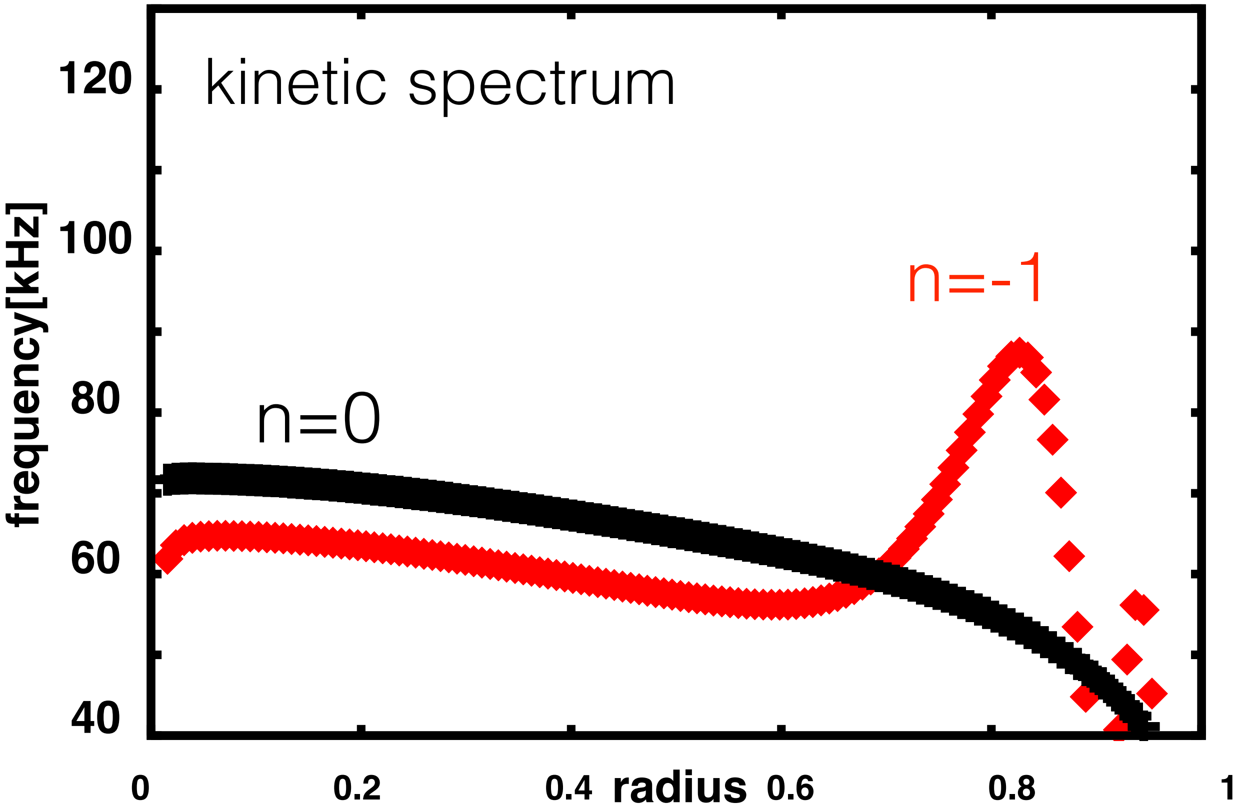
[P Poloskei et al, IAEA TCM 2017]

local and global LIGKA analysis

1st type:



calculate kinetic shear Alfvén and kinetic GAM spectrum for n=0 and n=-1 (LIGKA):



local and global LIGKA analysis

1st type:

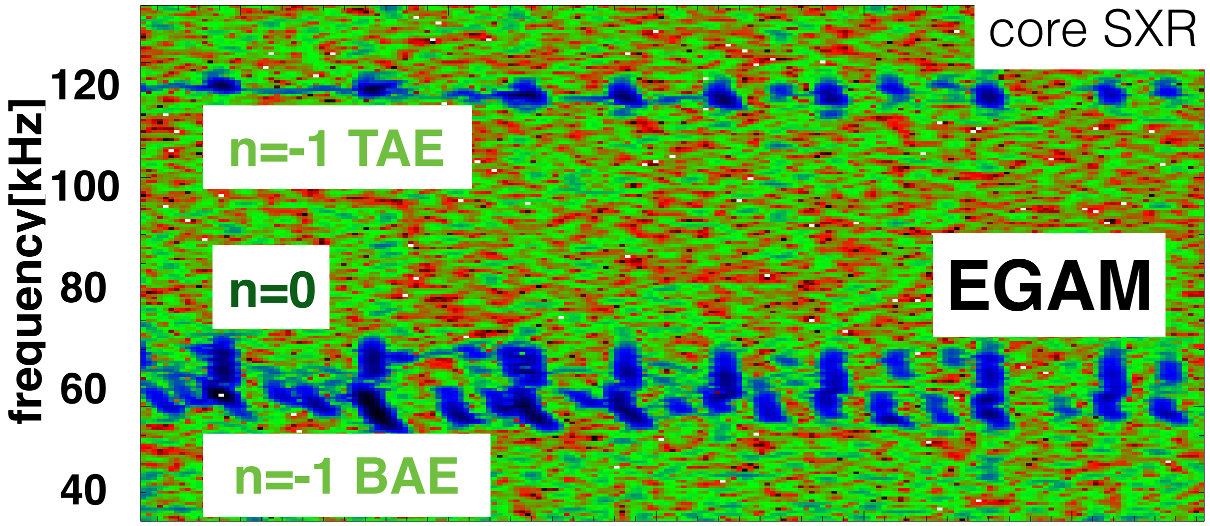
global mode structures:
[arb units for amplitudes]

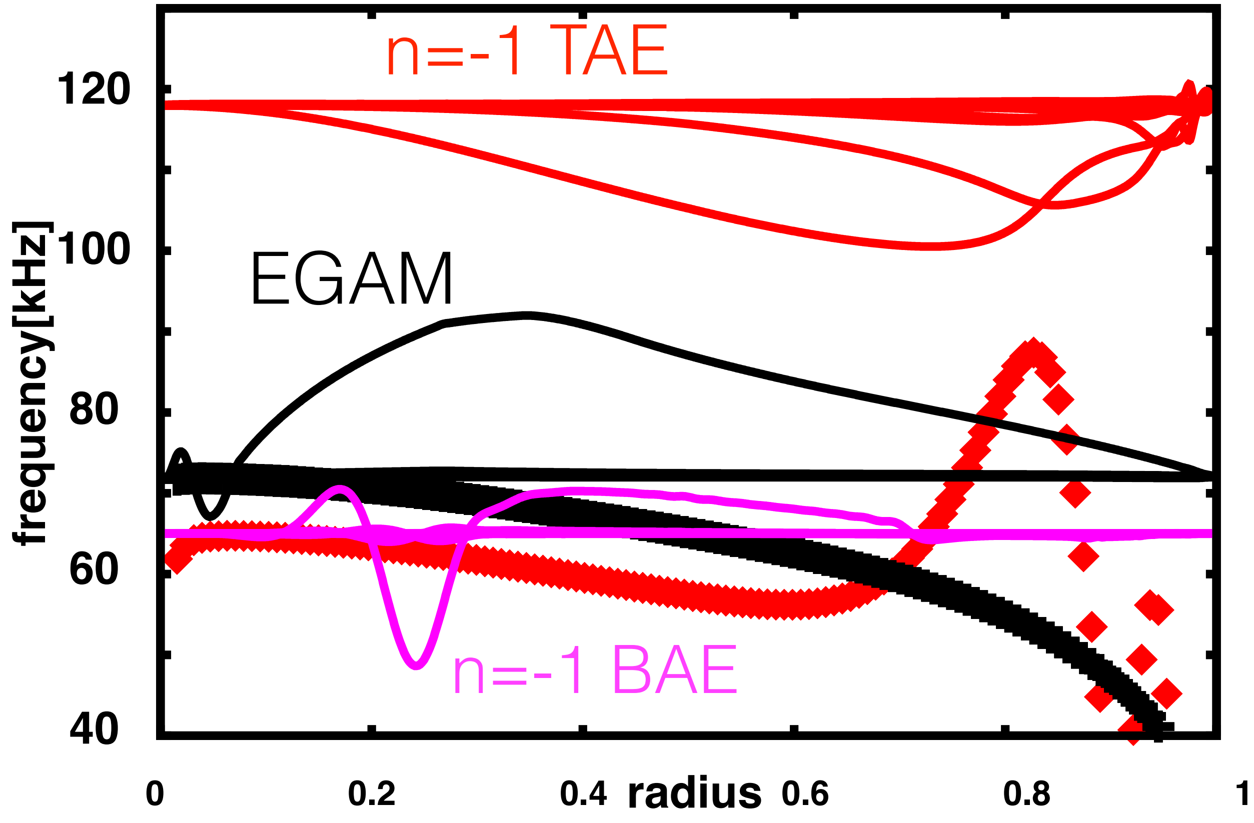
resonance analysis shows that:

- BAEs can tap energy from gradient both in velocity space and real space: most unstable mode

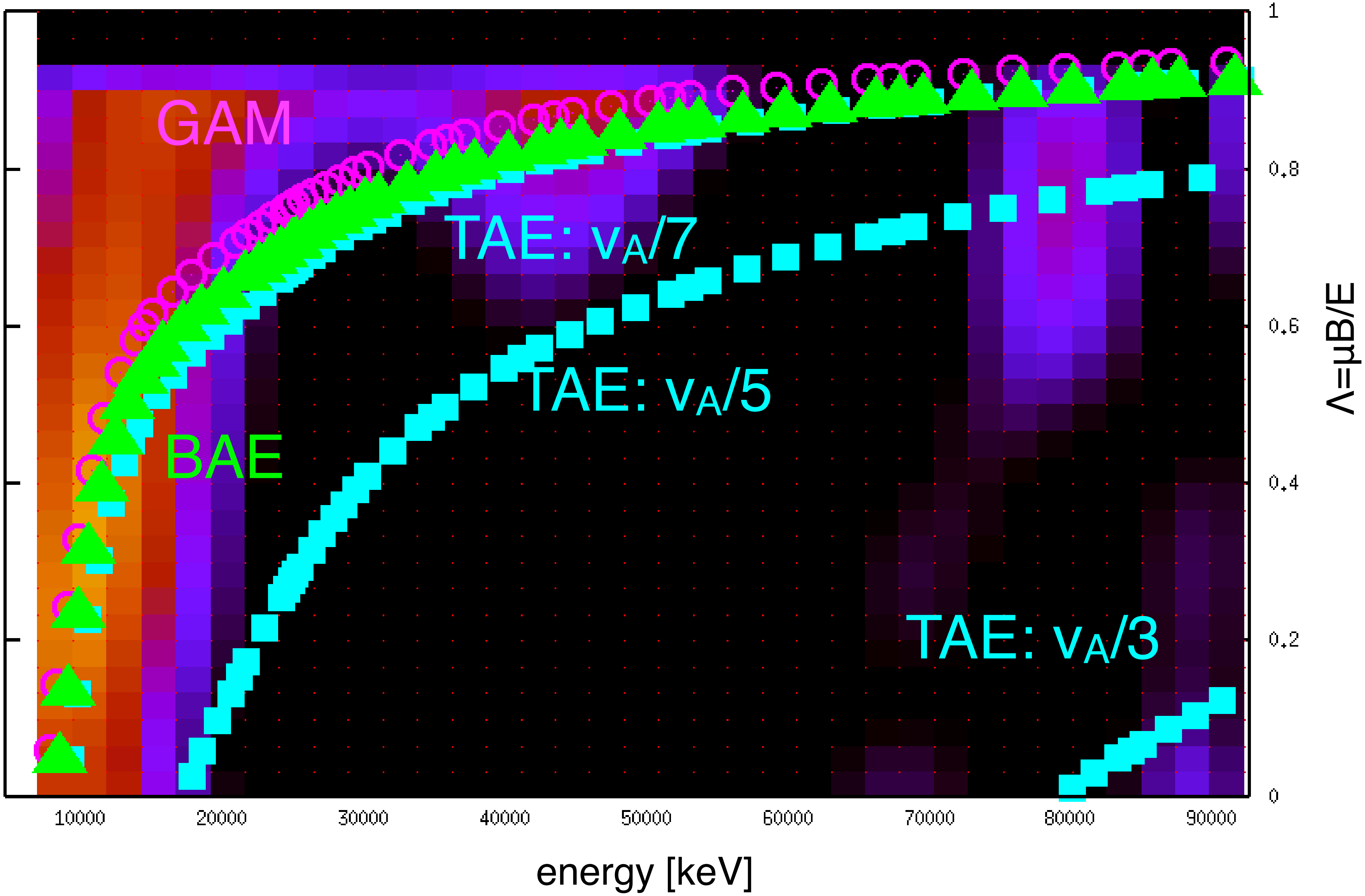
$$\gamma \sim \frac{\omega\, \partial F/\partial E - n\, \partial F/\partial P_\Phi}{\omega - \omega_t}$$

- BAE redistributes mainly in radial direction and thus triggers the EGAM (increased EP density) and TAE (higher order resonances)

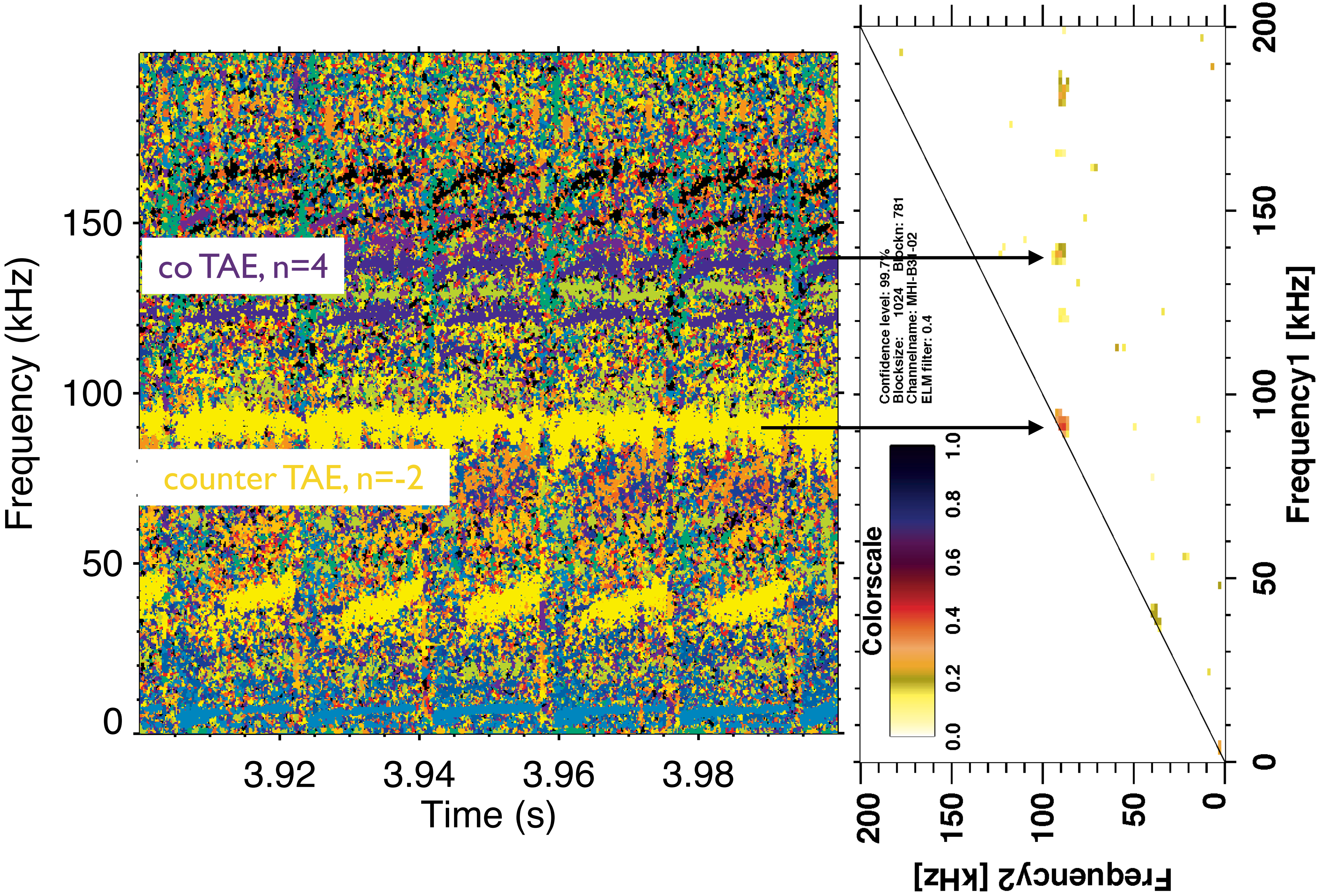




local and global LIGKA analysis
1st type: phase space analysis (@ρ_{pol}=0.35)



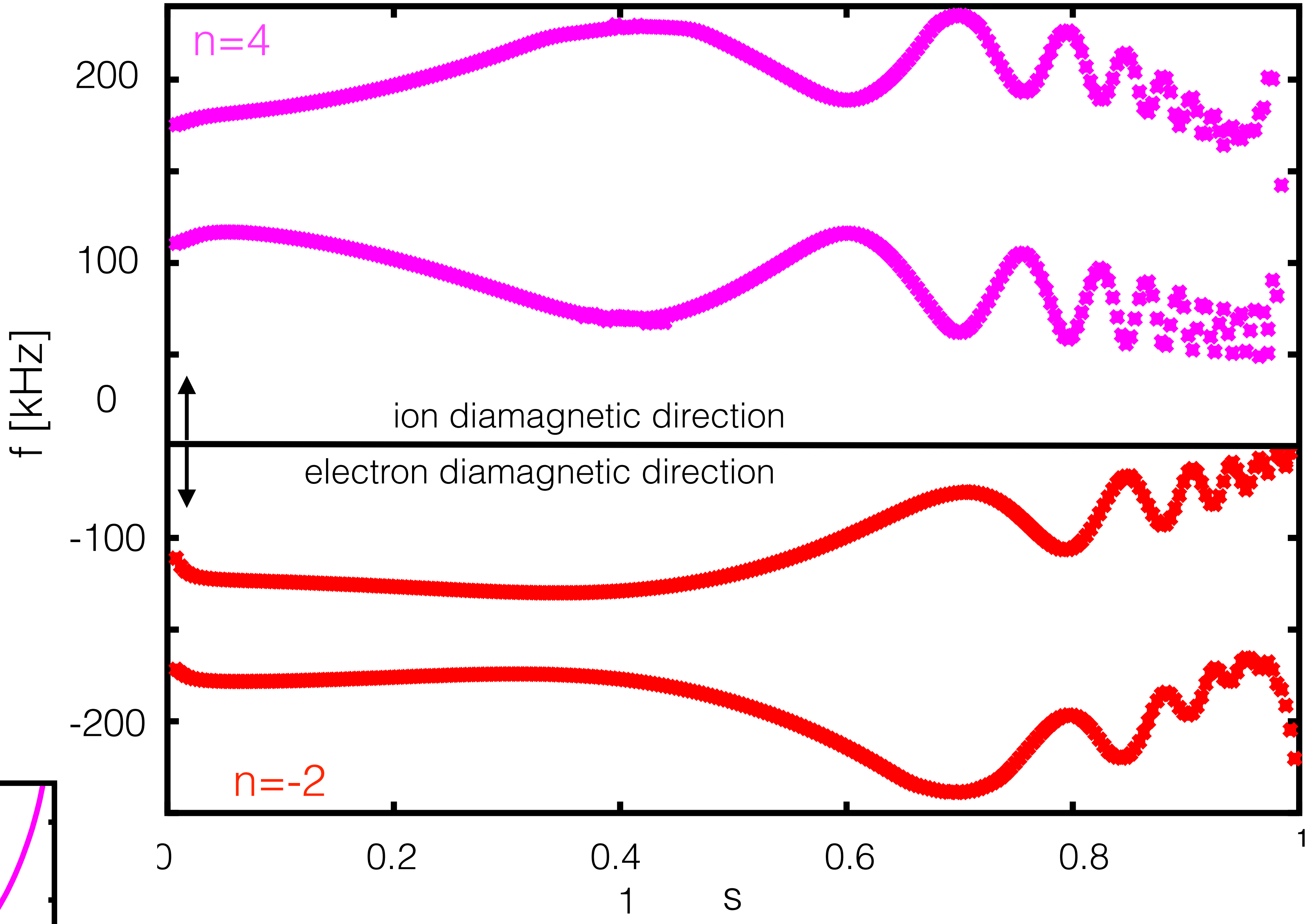
2nd type: ELM filtered bicoherence analysis shows evidence of mode-mode interaction

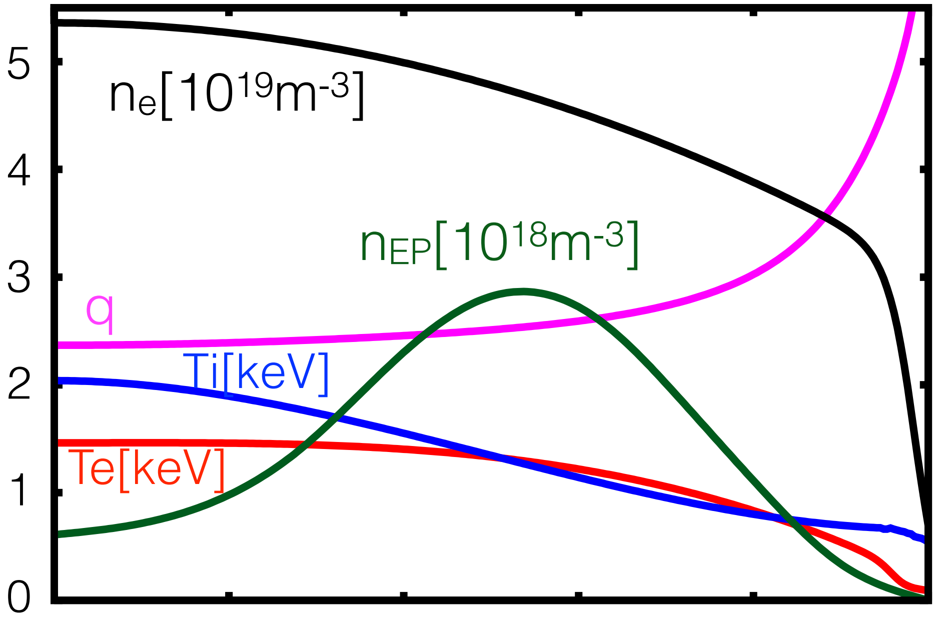


bicoherence measures phase coherence between the frequency bands that indicates a **non-linear (i.e. quadratic) interaction: n=-2 TAE and n=4 TAE bands**

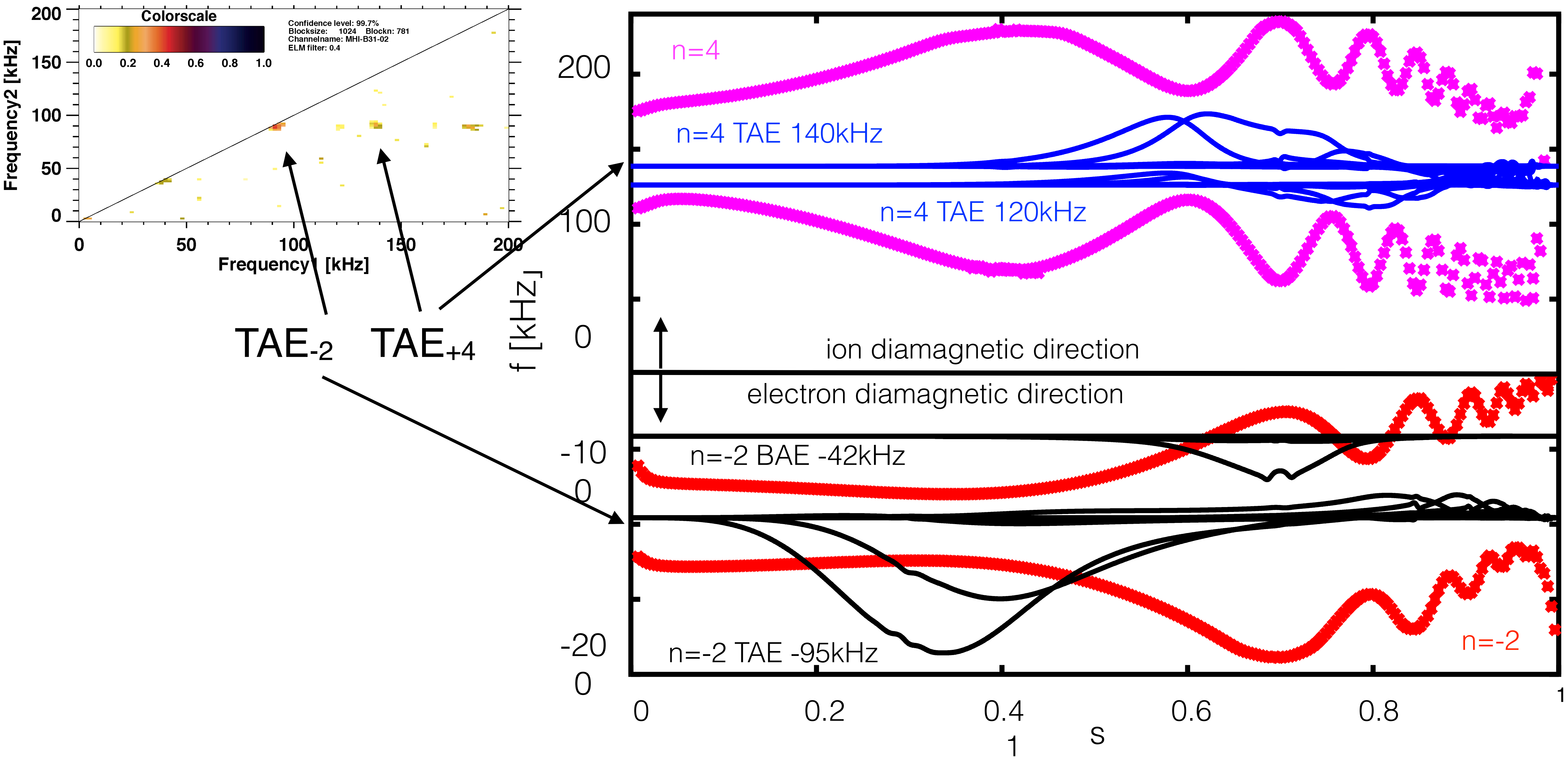
LIGKA: unstable modes, 3 wave coupling analysis

calculate kinetic shear Alfvén and GAM spectrum for n=4 and n=-2 (LIGKA):





LIGKA: unstable modes, 3 wave coupling analysis

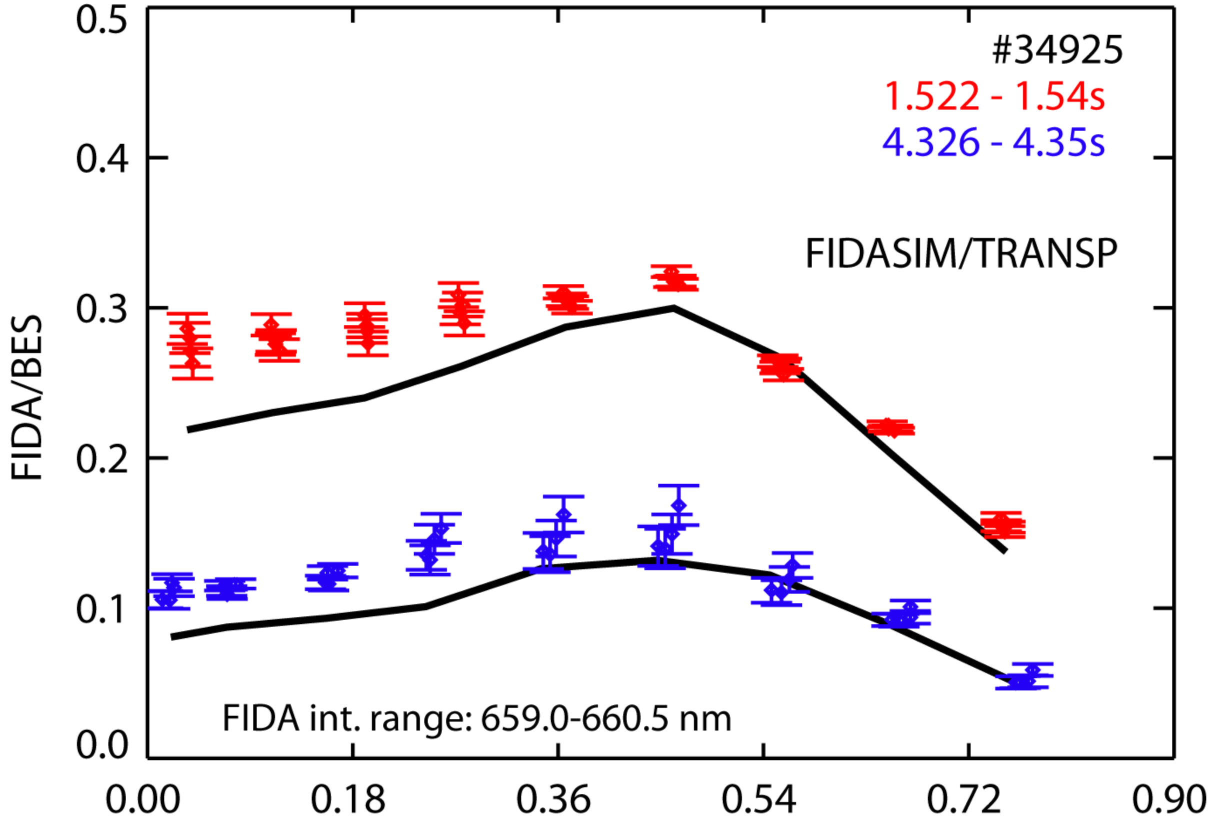


- after subtracting/adding rotation (7kHz): $\omega_{TAE-2}-\omega_{TAE+4}=0$
- also: $k_{\parallel TAE-2}+k_{\parallel TAE+4}= 1/(2\ q_{TAE-2}\ R)-1/(2\ q_{TAE+4}\ R)=0.222-0.211\approx 0$
- fulfil matching conditions with zero frequency zonal structure: modified parametric decay constellation

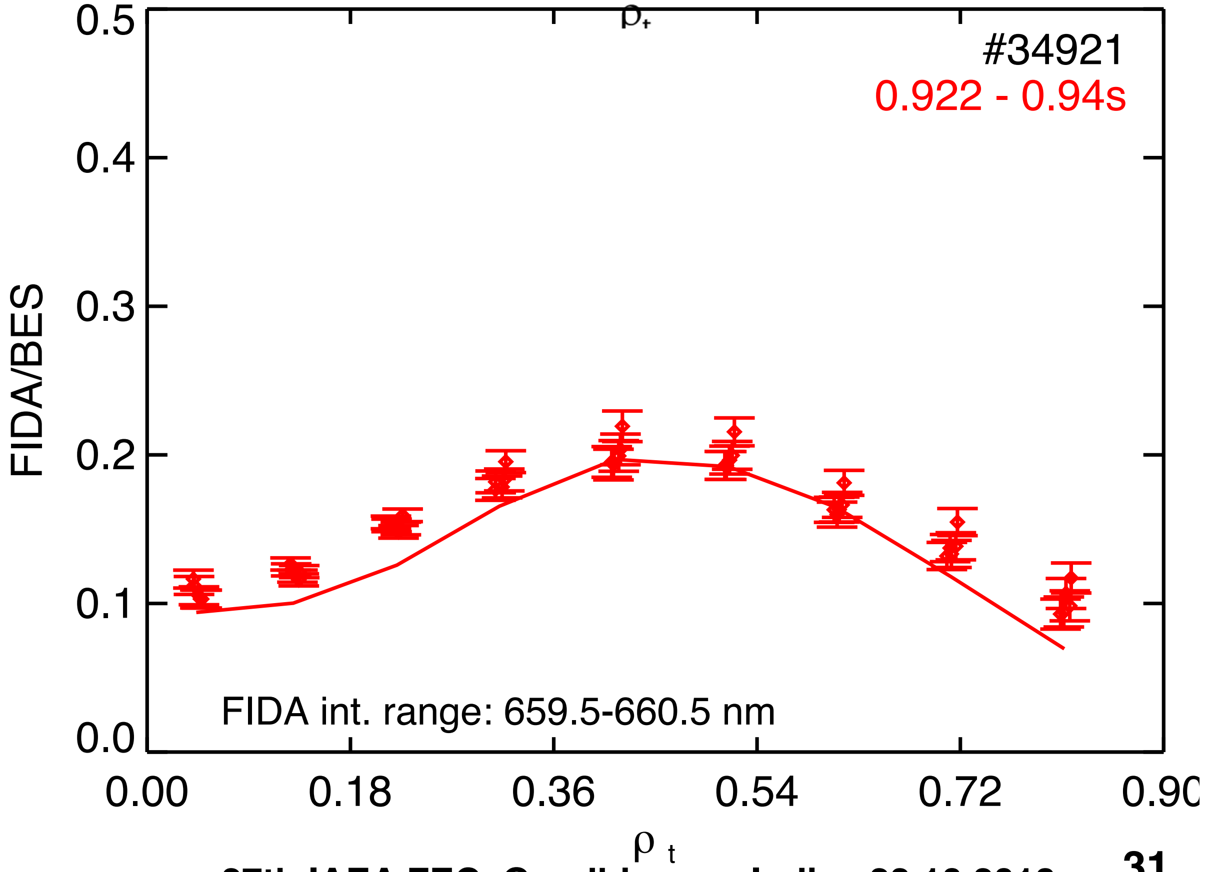
[Biancalani FEC 2016,TH/P2-9 2018]

radial flattening of EP gradient observed - inwards transport

TAE and BAE redistribute particles radially: FIDA measurements in comparison to neoclassical TRANSP/NUBEAM calculations



control case, where no strong Alfvénic mode activity is observed (#34921): strongly inverted EP gradient, small EP transport

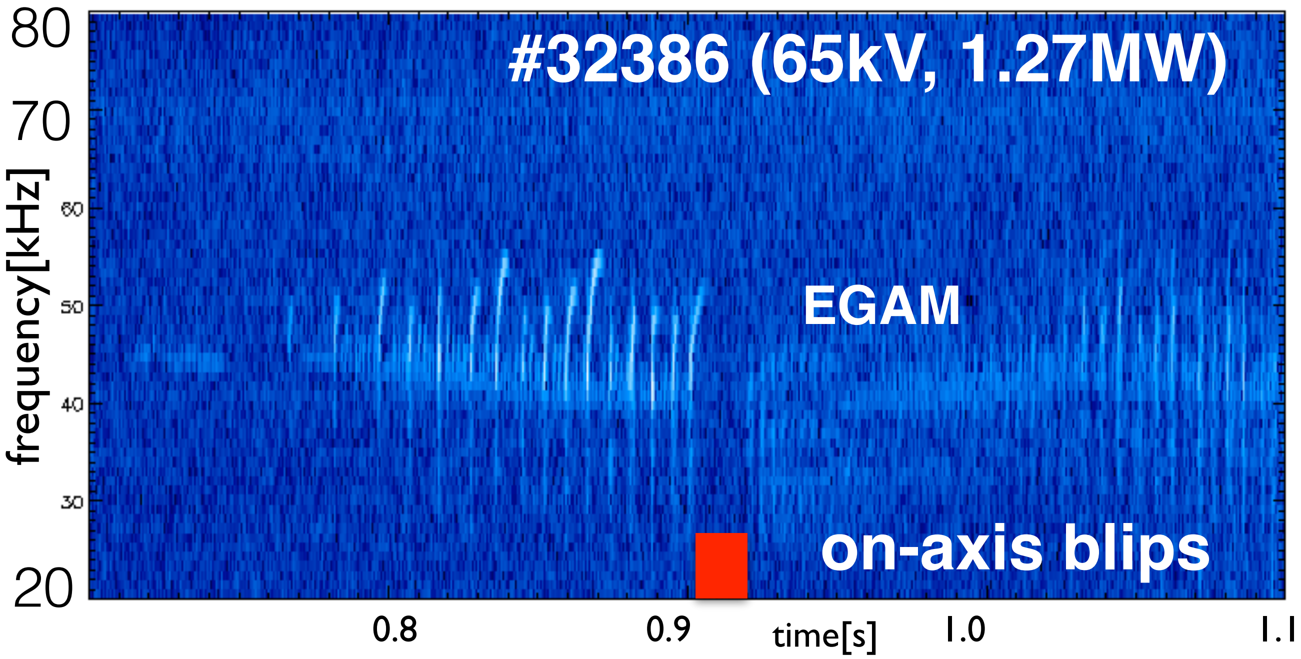


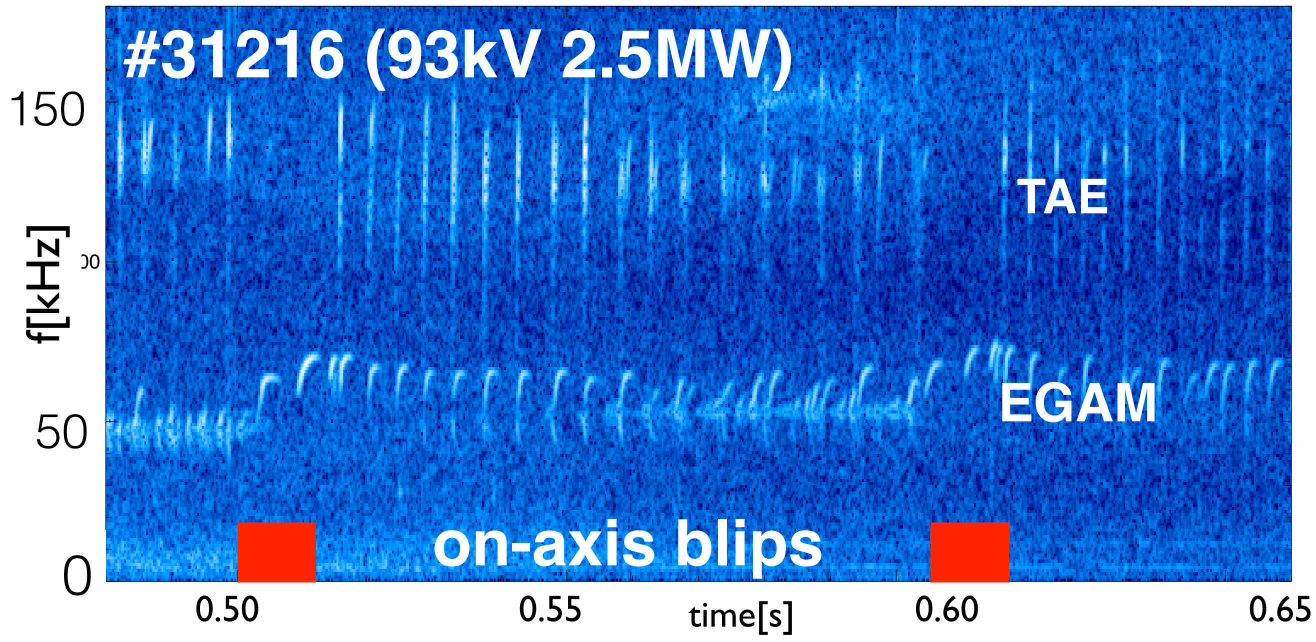
discussion (I)

- the combination of low background temperatures caused by core radiation and large EP pressure allows one to excite modes that are usually not accessible by sub-Alfvénic beam excitation: new experimental data facilitates the understanding cross scale and cross-frequency coupling mechanisms also in cases when modes are not present

- for EGAM excitation the beam anisotropy characteristics has to match the frequency range of the GAM continuum

- other regimes with lower beam energy are accessible for EGAM destabilisation and the influence of on-axis beam blips can be understood:





discussion(II)

- influence of EGAMs on turbulence *[Zarzoso 2013-18]* and presence of ‘anomalous ion heating’ *[Osakabe,Ido 2014]* could not be clarified yet: although there are clear differences in turbulent spectra between phases with and w/o EGAMs, this cannot be straightforwardly attributed to the EGAMs, since also overall plasma conditions change considerably

- co- and counter propagating AEs open possibility for non-linear wave-wave coupling studies

- scenario can be seen as complement to recent studies of ECRH influence on AE stability *[Van Zeeland 2014, Sharapov 2017]*: ECRH in NB heated discharges usually stabilises AEs - our scenario demonstrates opposite effect when ‘cooling’ the background

- scenario can be seen as a close relative to fully non-inductive scenarios *[J. Stober FEC 2016, A Bock 2017, D Rittich EX/P8-25]* with central ECCD (800kA) and current hole discharges (600keV) with *[B Geiger, EX 2-3]*

- these scenarios facilitate the physics understanding, preparation of tools and (advanced) scenarios for future devices such as JT-60SA, DTT, ITER, DEMO other slides

motivation: predicting self-organisation of burning fusion plasmas: previous exp. work

- recent DIII-D results *[Collins PRL 2016,Heidbrink 2017]* report stiff Alfvén eigenmode (AE) induced EP transport in ramp-up scenarios; confirming the applicability of quasi-linear theory *[Dupree 1966, Berk 1995, Gorelenkov 2018]*; resonance overlap of multiple AEs creates near-marginal EP profile

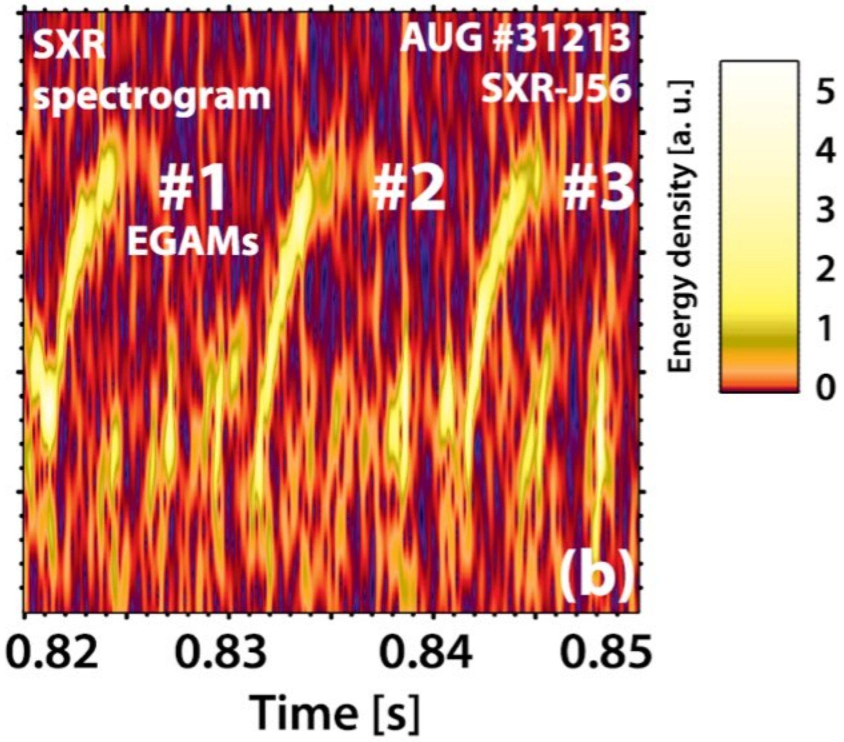
- DIII-D *[Wang 2013]*, ASDEX Upgrade *[Schneller 2013]* and JET *[Nabais, Varenna 2018]* report non-linear subdominant excitation of AEs indicating radially dependent relaxation of EP profiles

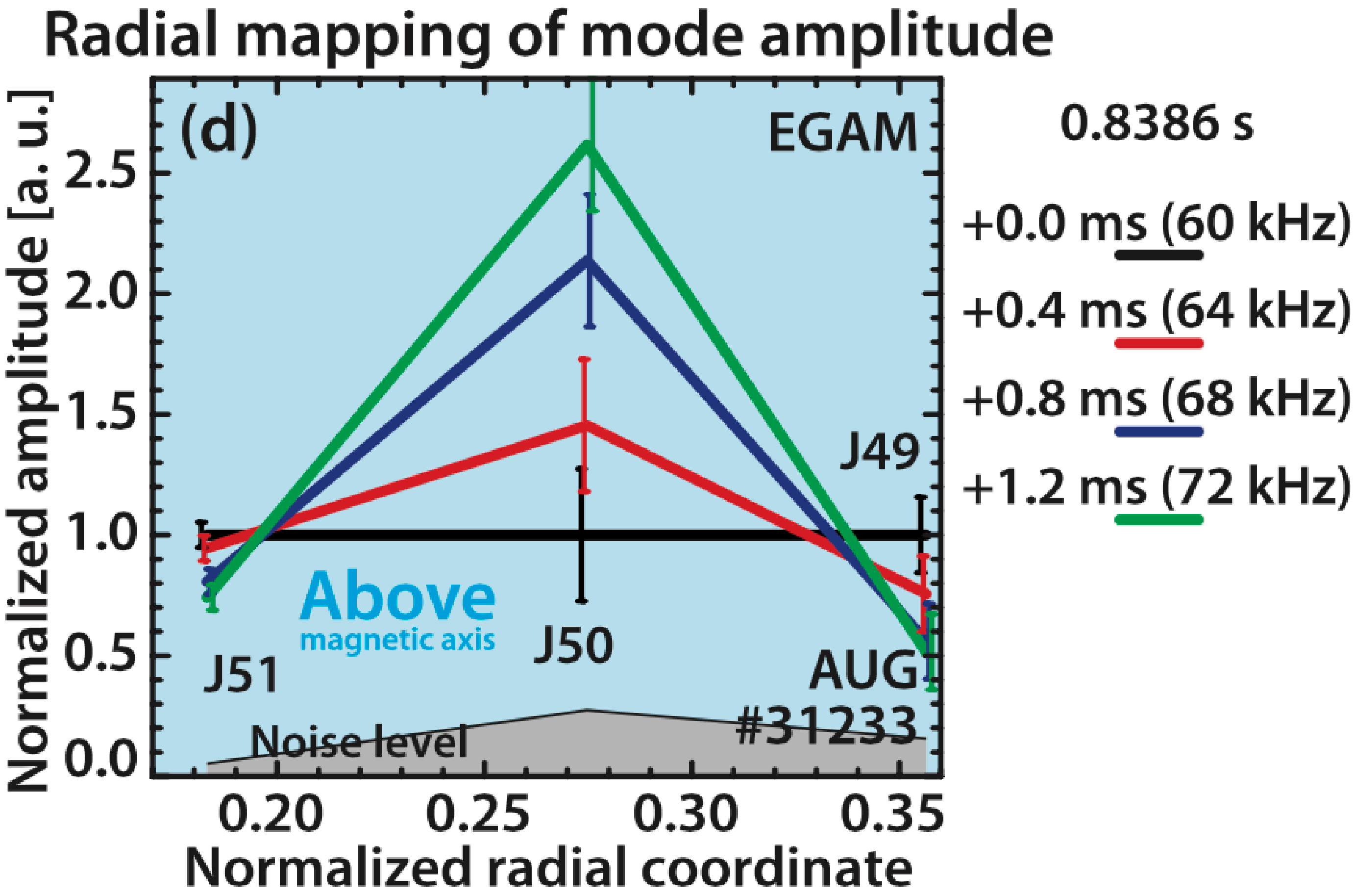
- JT-60U and spherical tokamaks (NSTX *[Fredrickson 2006, Crocker 2006, Podesta 2018]*, MAST *[Gryaznevich, 2006]*) with super-Alfvénic neutral beam injection (NBI) report typically strongly chirping modes and ALEs (abrupt large events) where besides wave-particle nonlinearities also non-linear mode-mode interaction is an important ingredient *[Todo NF 2012, 2015; Bierwage Nature 2018]*

- aim: provide experimental data to investigate the transition and onset conditions of non-linear EP dynamics for the development of model hierarchy; test various competing models for 3-wave interaction processes for AEs and ZS *[Hahm 1995, Todo 2012, Chen&Zonca 2012, Qui 2018]* and chirping onset *[Briguglio, Wang 2015; Duarte 2017]*

EGAM properties: non-linear amplitude evolution observed

- one the most prominent modes: EP-driven geodesic acoustic mode
  [other exp. observations: Boswell, Berk Nazikian, Ido, Chen, Horvath,…]
- visible in magnetics, soft-X ray: toroidal mode number **n=0**; dominant poloidal mode number **n=2** *[Wahlberg 2008]*; global mode, peaked in core ρ_{pol}~0.2-0.4

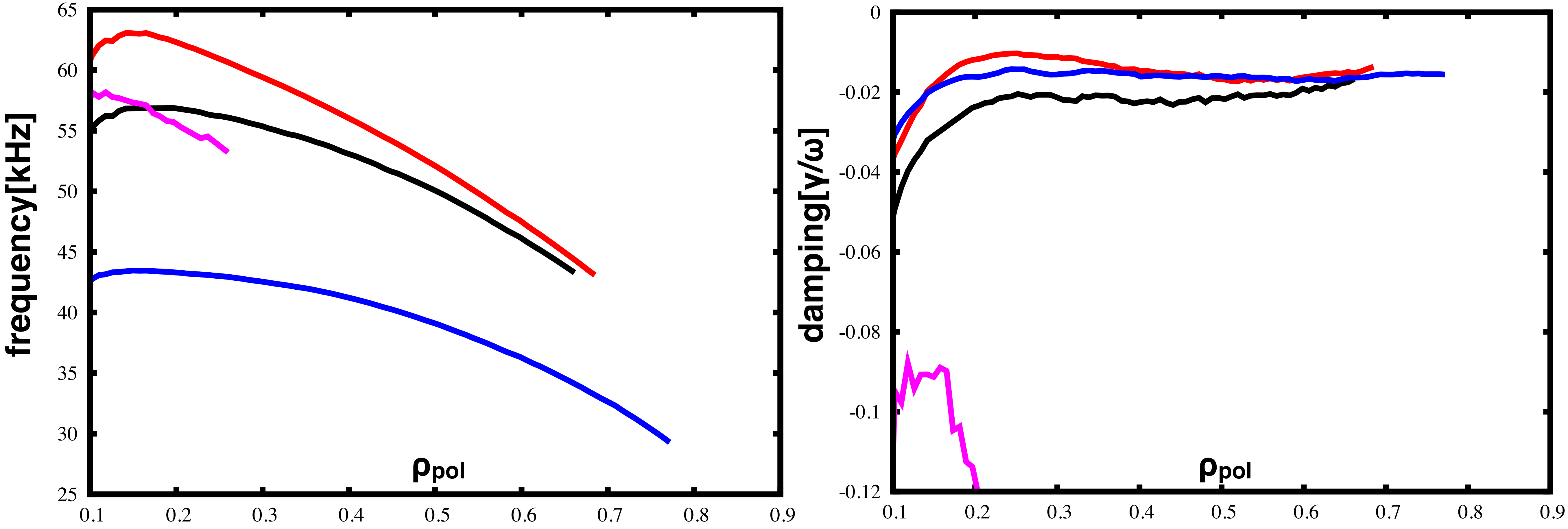




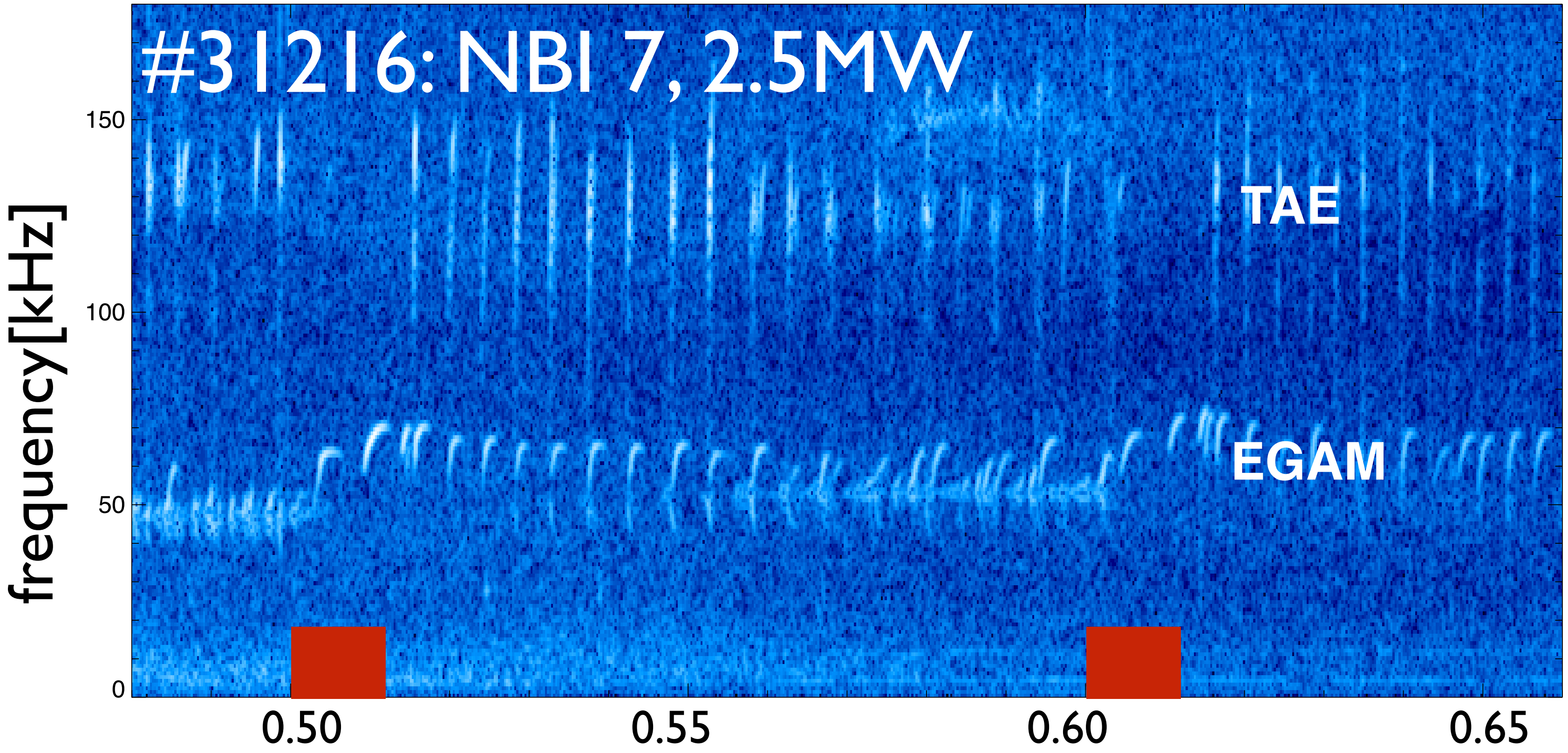
[Horvath et al,NF 2016]

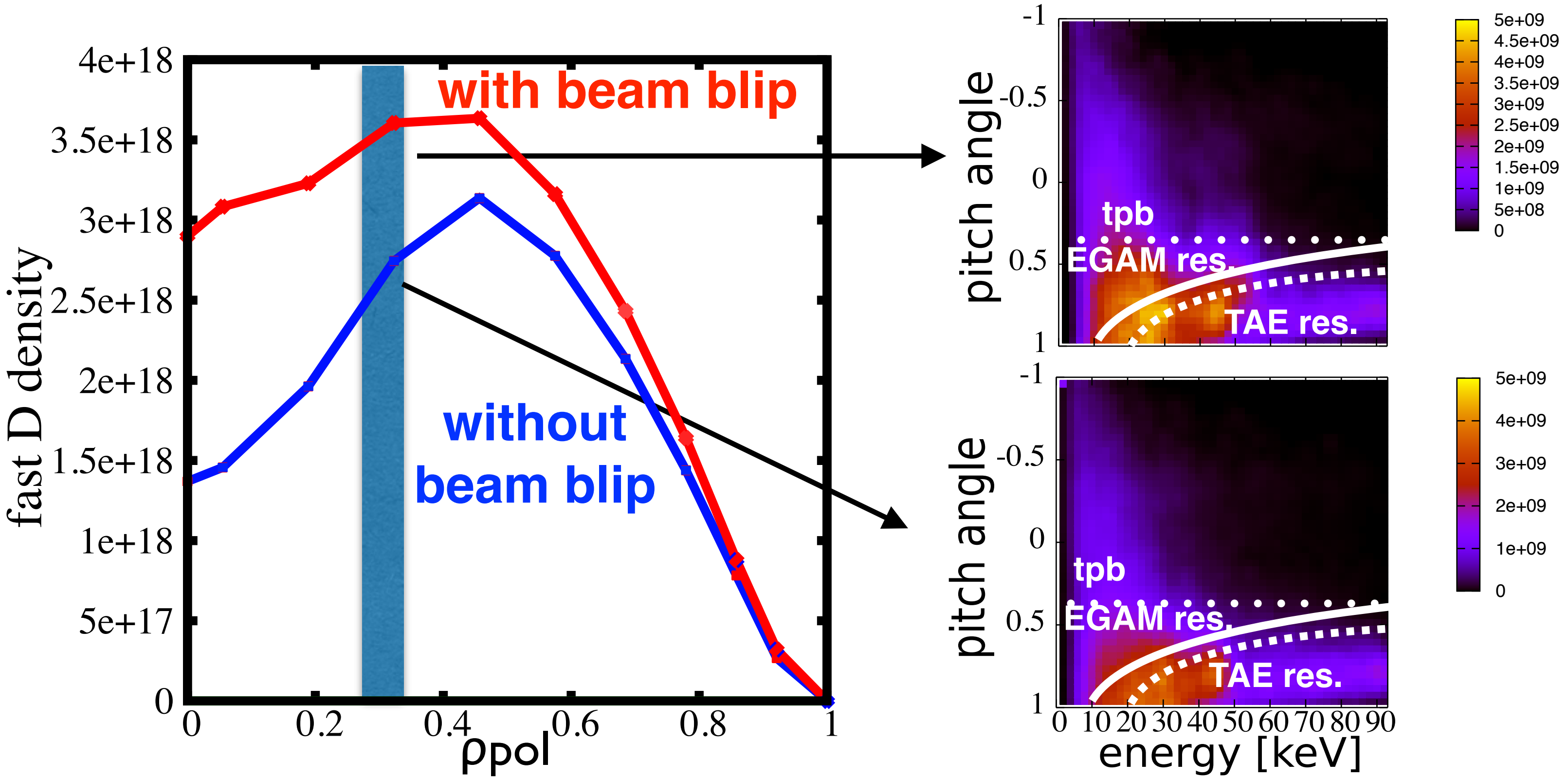
control cases: lower q ,set $T_e=T_i$,$T_i=T_i/2$

- reference parameters (last slide)
- lower q_0 from 2.4 to 1.99 (so far EGAMs were never observed for q<2)
- set $T_e=T_i$: increases f_{GAM}, reduces damping! Te inversion not a necessary ingredient for EGAM excitation (as experimentally confirmed)
- lower T_i by factor 2, $T_e=T_{e,ref}$



damping analysis does not explain alone EGAM excitation conditions


#31216: NBI 7, 2.5MW
frequency[kHz]
150
100
50
0
TAE
EGAM
0.50
0.55
0.60
0.65

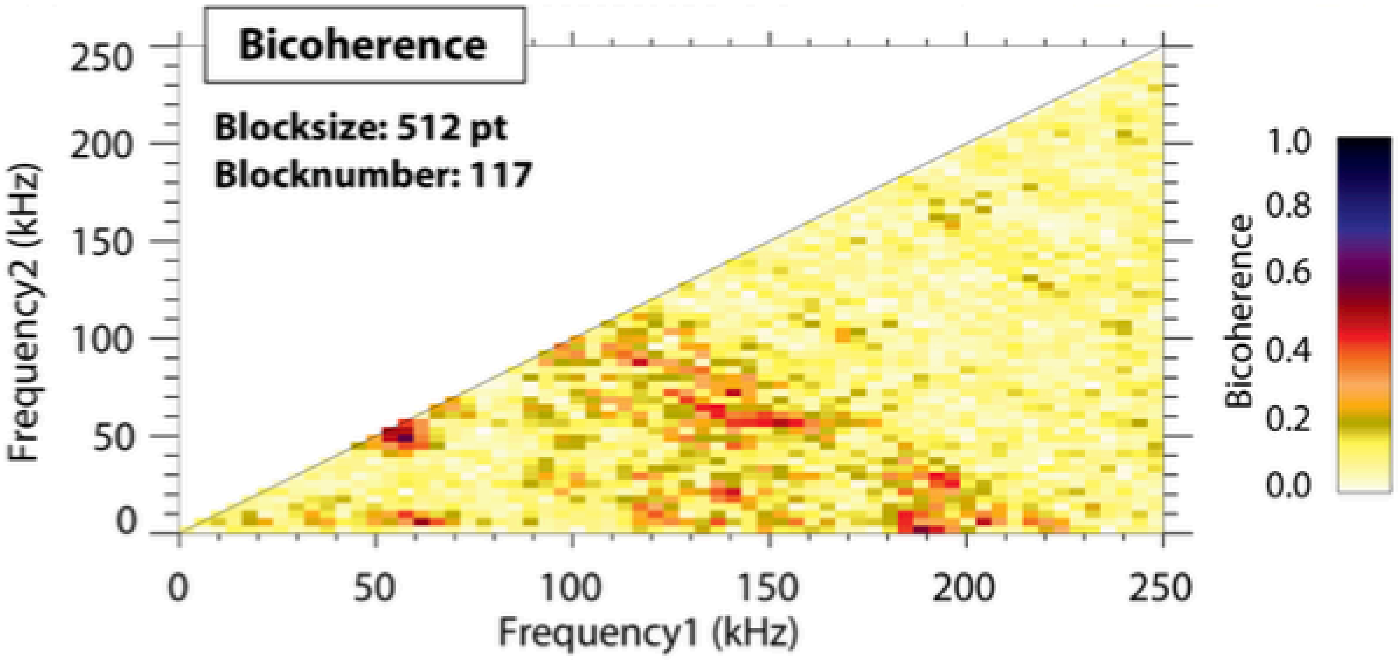

4e+18
3.5e+18
3e+18
2.5e+18
2e+18
1.5e+18
1e+18
5e+17
0
fast D density
with beam blip
without
beam blip
0
0.2
0.4
0.6
0.8
1
ρpol
pitch angle
-1
-0.5
0
0.5
1
tpb
EGAM res.
TAE res.
5e+09
4.5e+09
4e+09
3.5e+09
3e+09
2.5e+09
2e+09
1.5e+09
1e+09
5e+08
0
pitch angle
-1
-0.5
0
0.5
1
tpb
EGAM res.
TAE res.
5e+09
4e+09
3e+09
2e+09
1e+09
0
0
10
20
30
40
50
60
70
80
90
energy [keV]

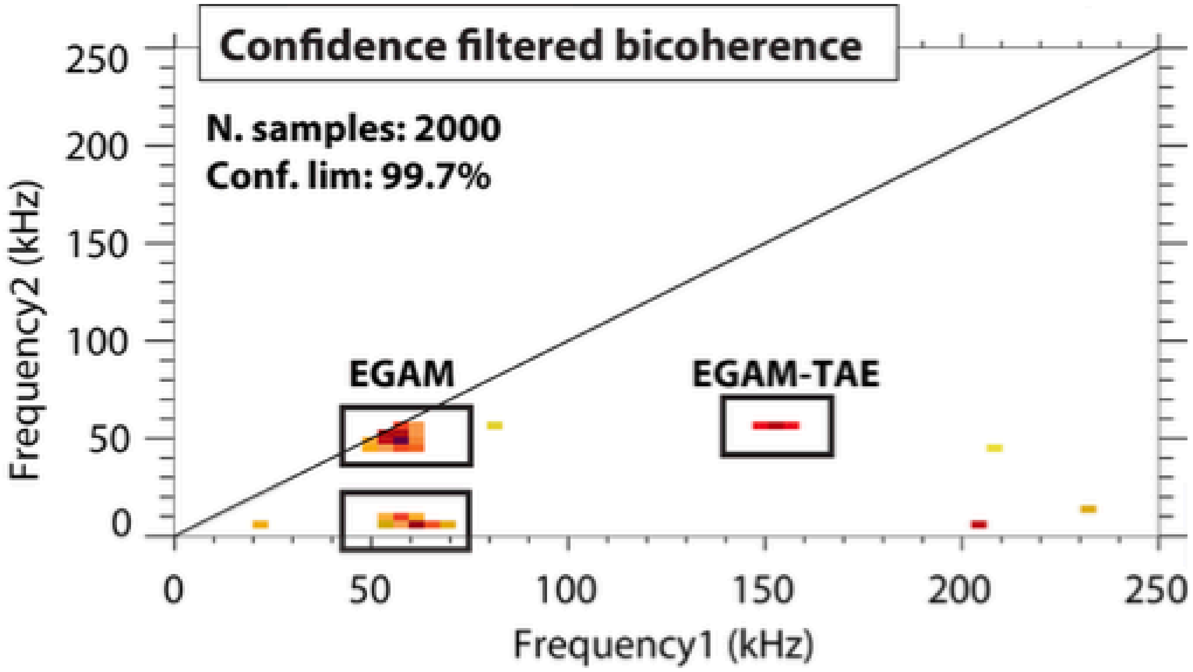
advanced bicoherence analysis [P Poloskei et al IAEA TCM 2017]

phase randomized bicoherence probability density function calculation

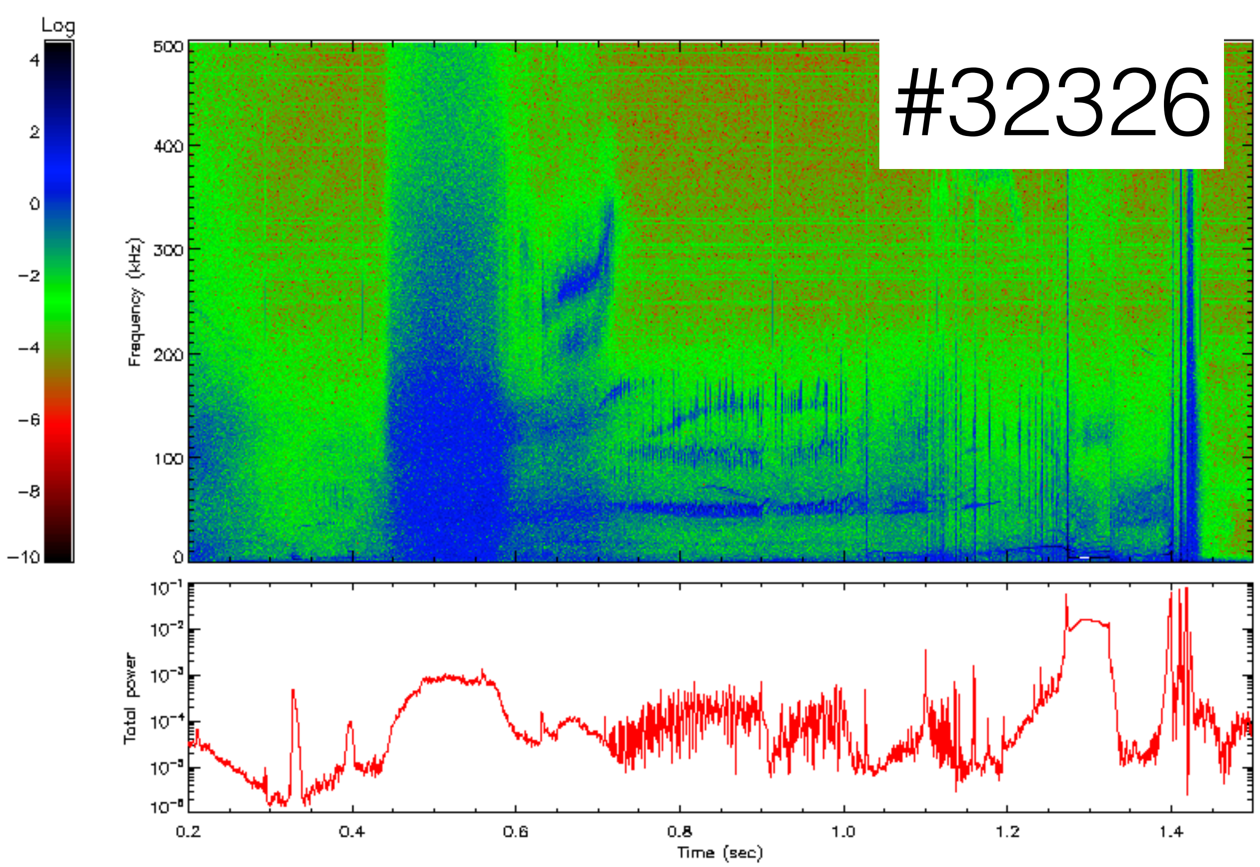
- High bicoherence around at (55, 55) kHz indicates **strongly nonlinear EGAMs.** (see spectrogram at ~110 kHz)
- **Without filtering interaction with TAEs is not clear**

- Filtering shows high, significant bicoherence around (155, 55) kHz
- Indicates the **nonlinear interaction between EGAMs and TAEs**



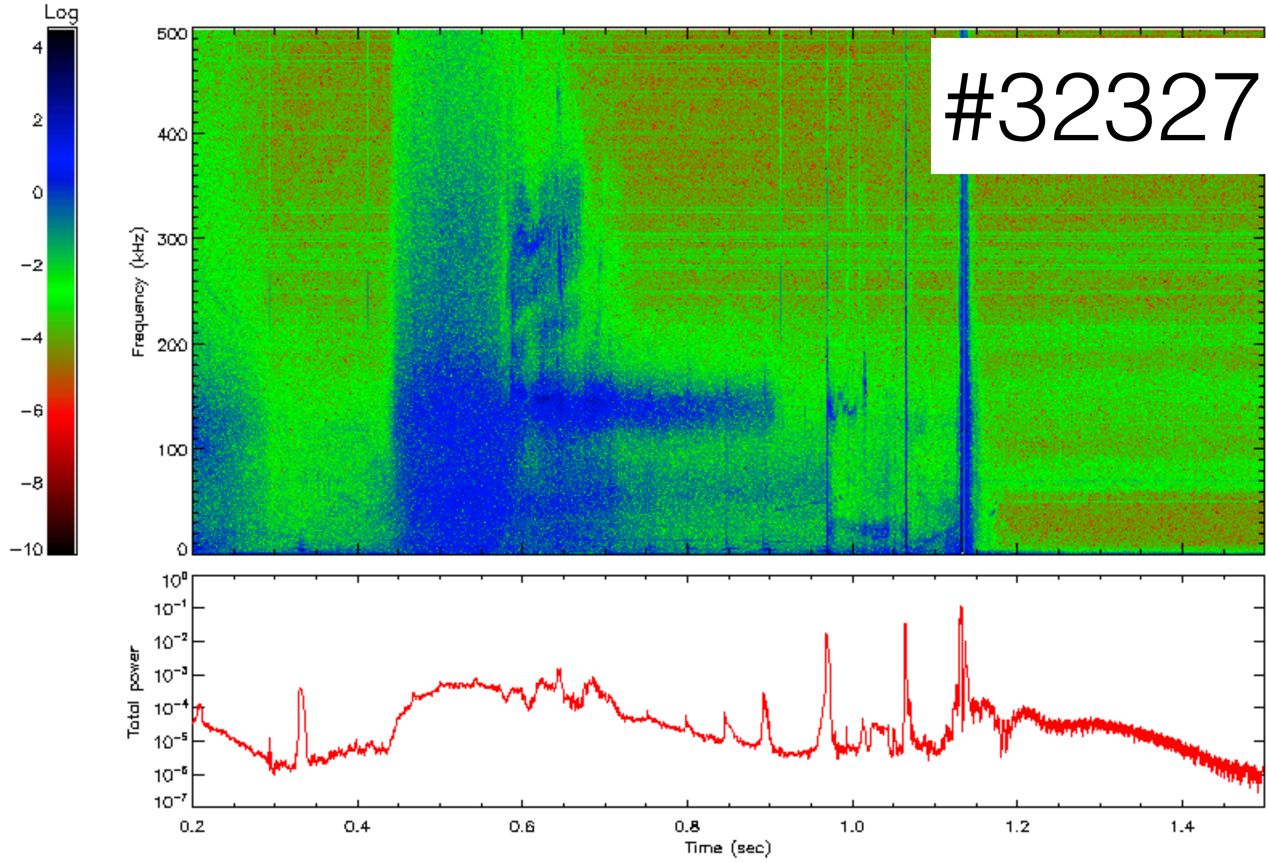


4 shots 16.10.2015   MHD C09-16 normalised spectra



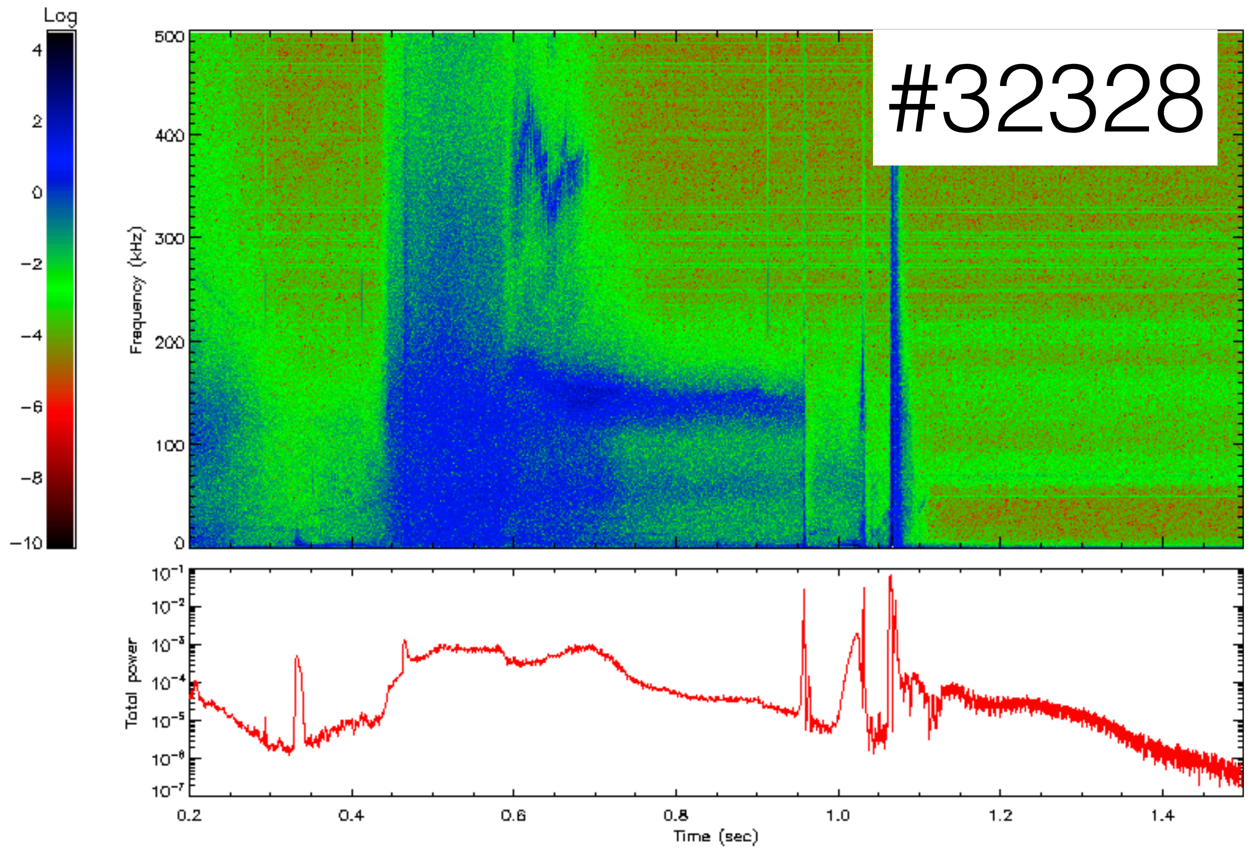
AUG Shot: 32326 : MHD : C09-16 npts: 2599999

Time: 0.200 to 1.500 frq: 0.0 to 500.0 nfft: 4096 npad: 0 nstp: 512 nme: 1000 ncor: 200



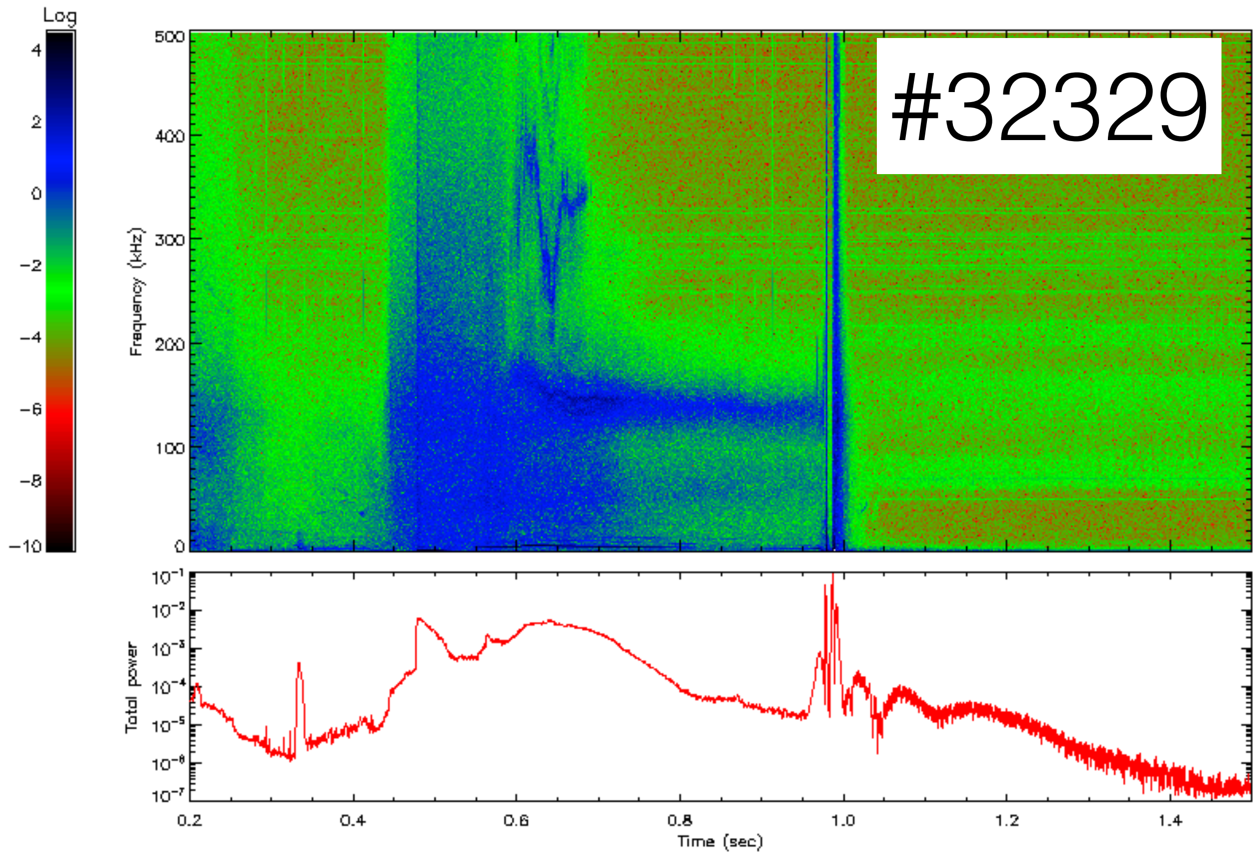
AUG Shot: 32327 : MHD : C09-16 npts: 2599999

Time: 0.200 to 1.500 frq: 0.0 to 500.0 nfft: 4096 npad: 0 nstp: 512 nme: 1000 ncor: 200



AUG Shot: 32328 : MHD : C09-16 npts: 2599999

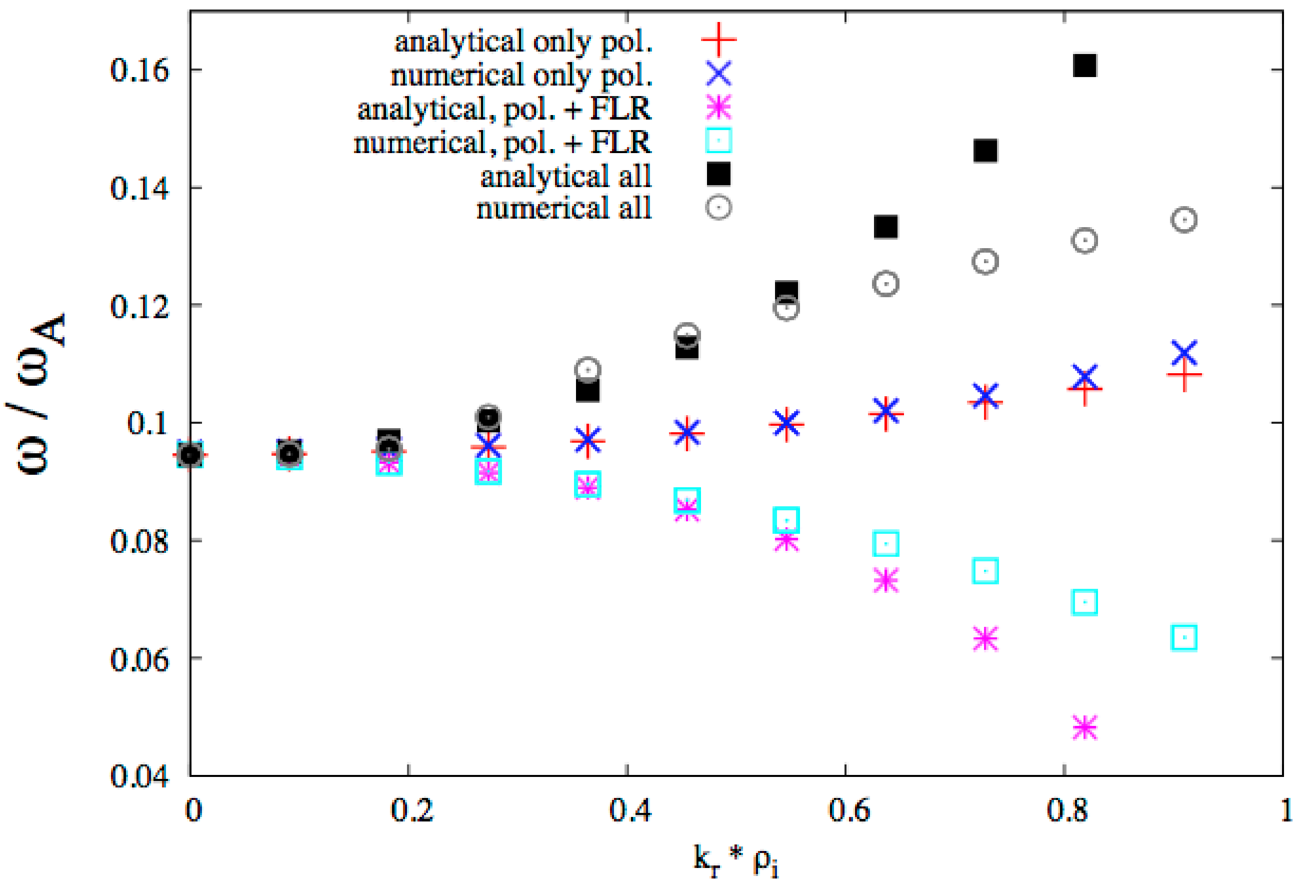
Time: 0.200 to 1.500 frq: 0.0 to 500.0 nfft: 4096 npad: 0 nstp: 512 nme: 1000 ncor: 200

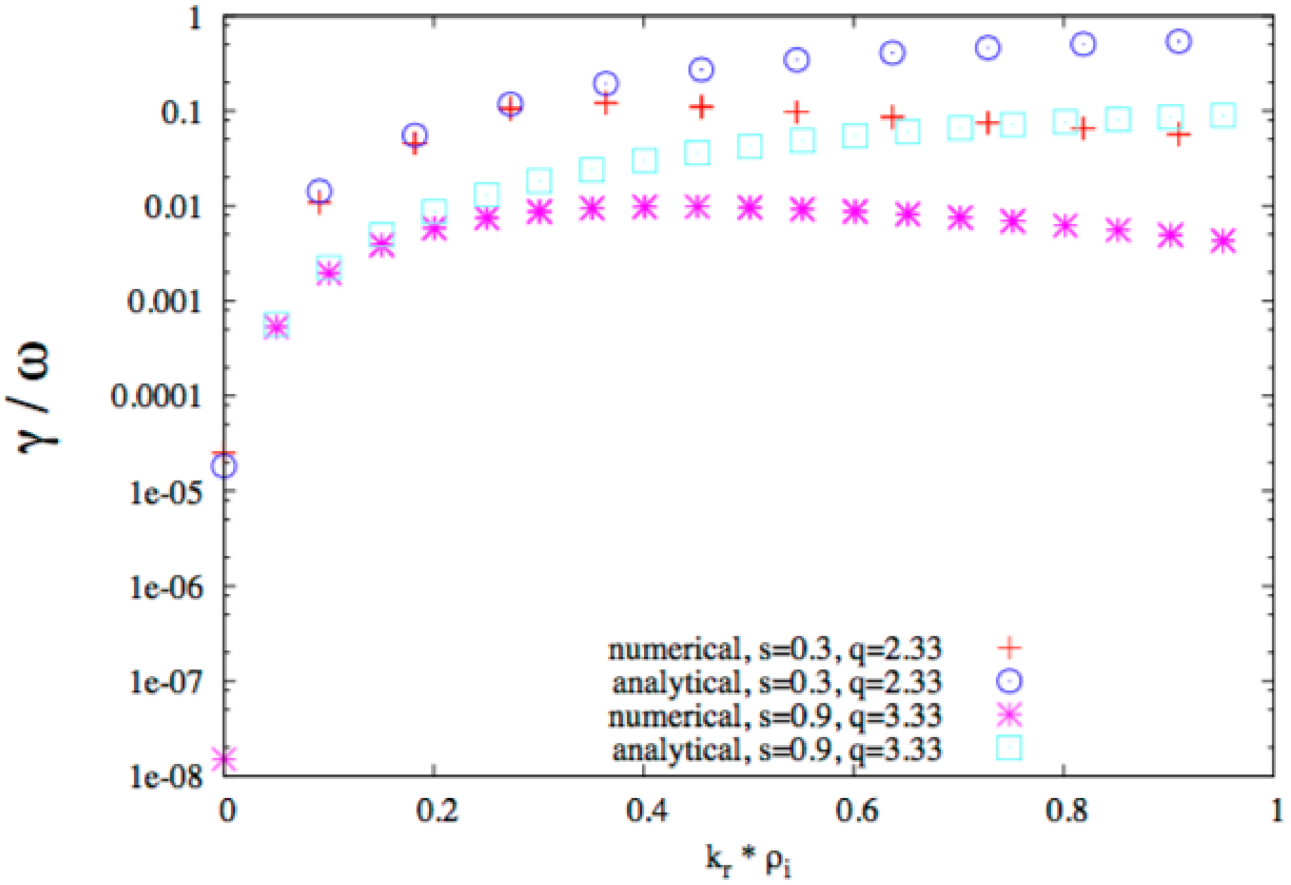


AUG Shot: 32329 : MHD : C09-16 npts: 2599999

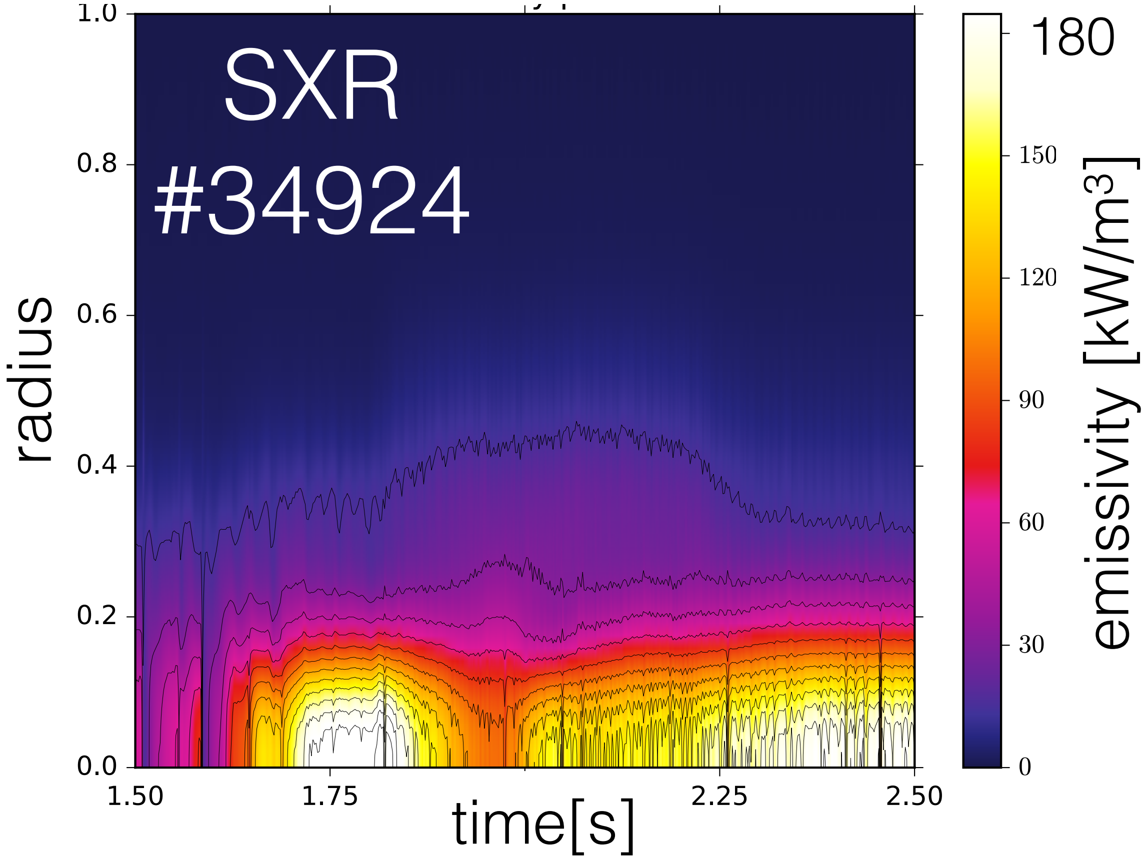
Time: 0.200 to 1.500 frq: 0.0 to 500.0 nfft: 4096 npad: 0 nstp: 512 nme: 1000 ncor: 200

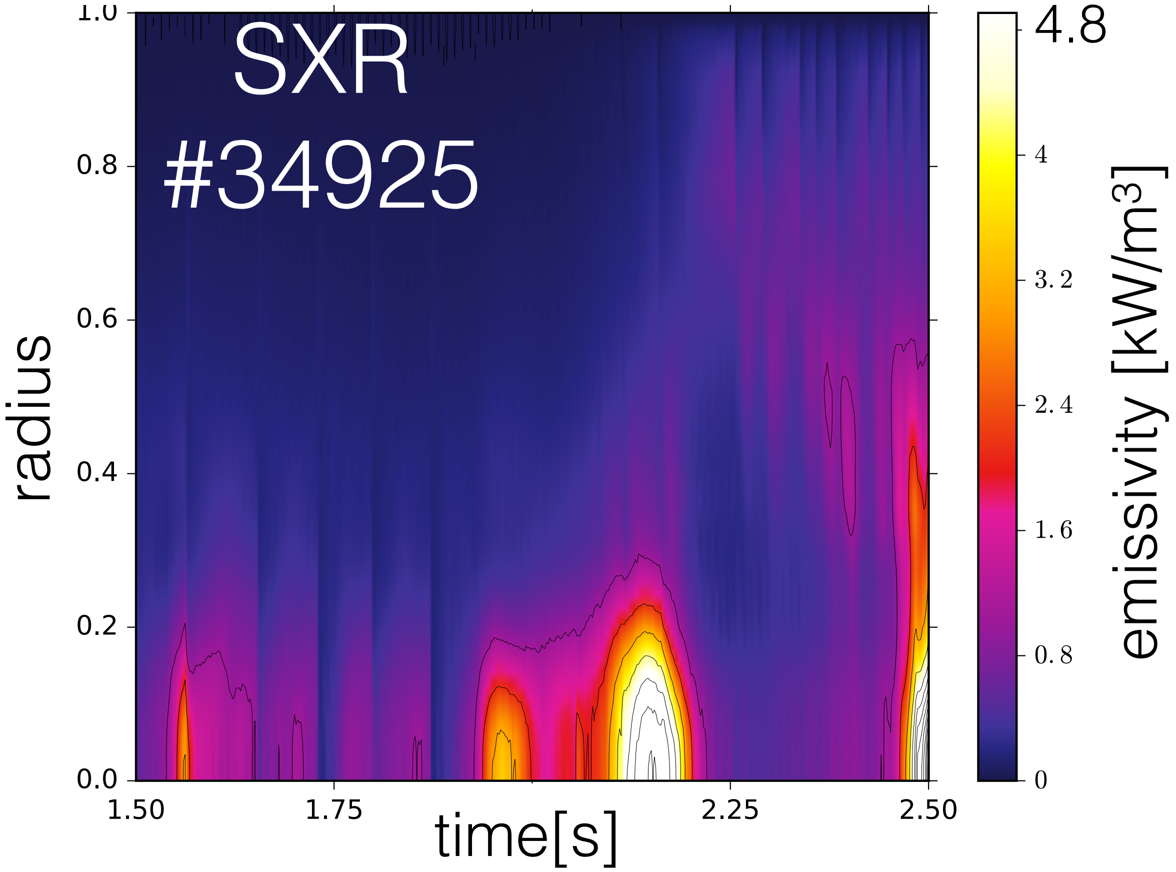
LIGKA: FLR/FOW validation with analytical theory



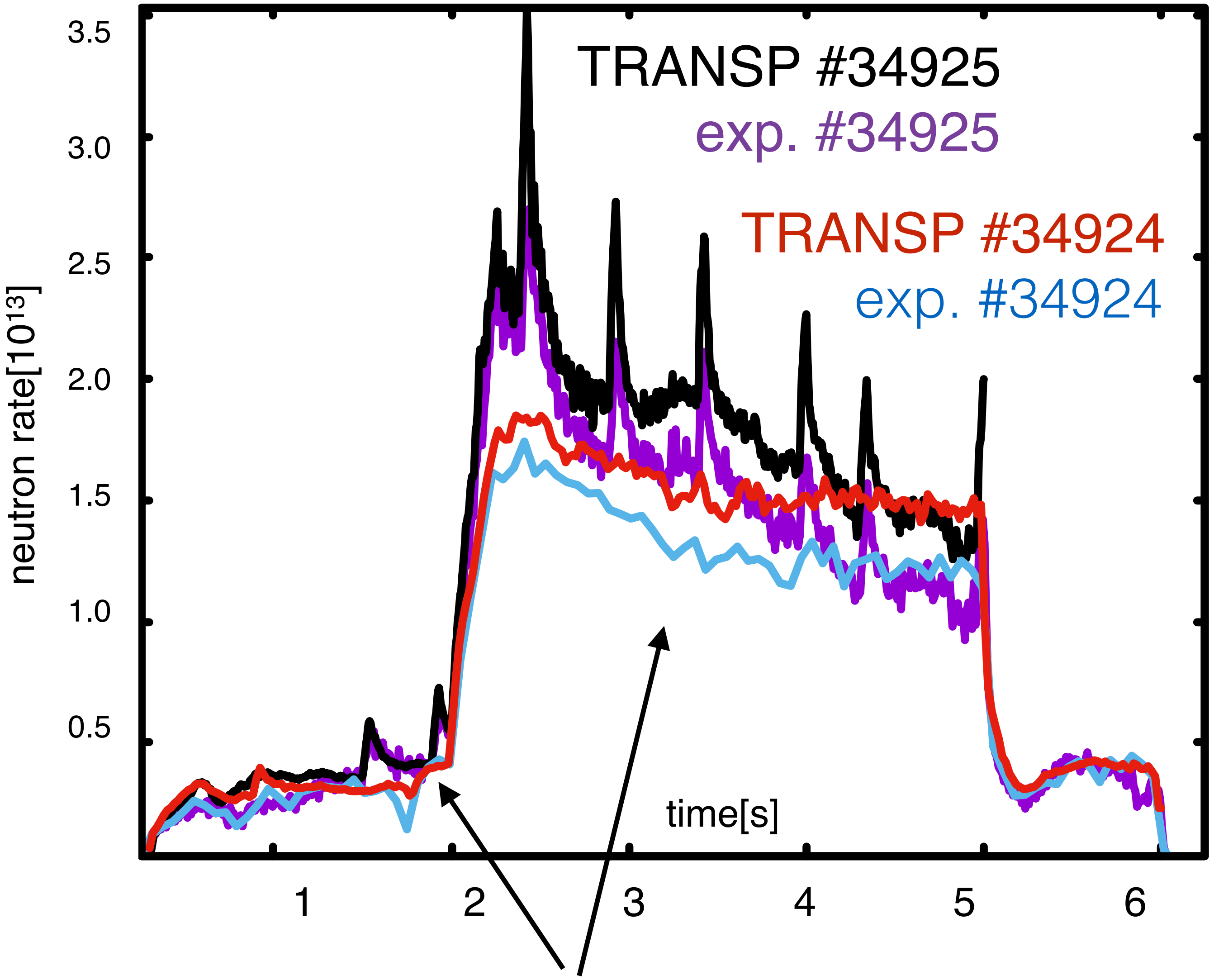


strong core radiation confirmed by SXR tomography





tungsten concentration:
$c_W = 3\times10^{-4} - 2\times10^{-3}$

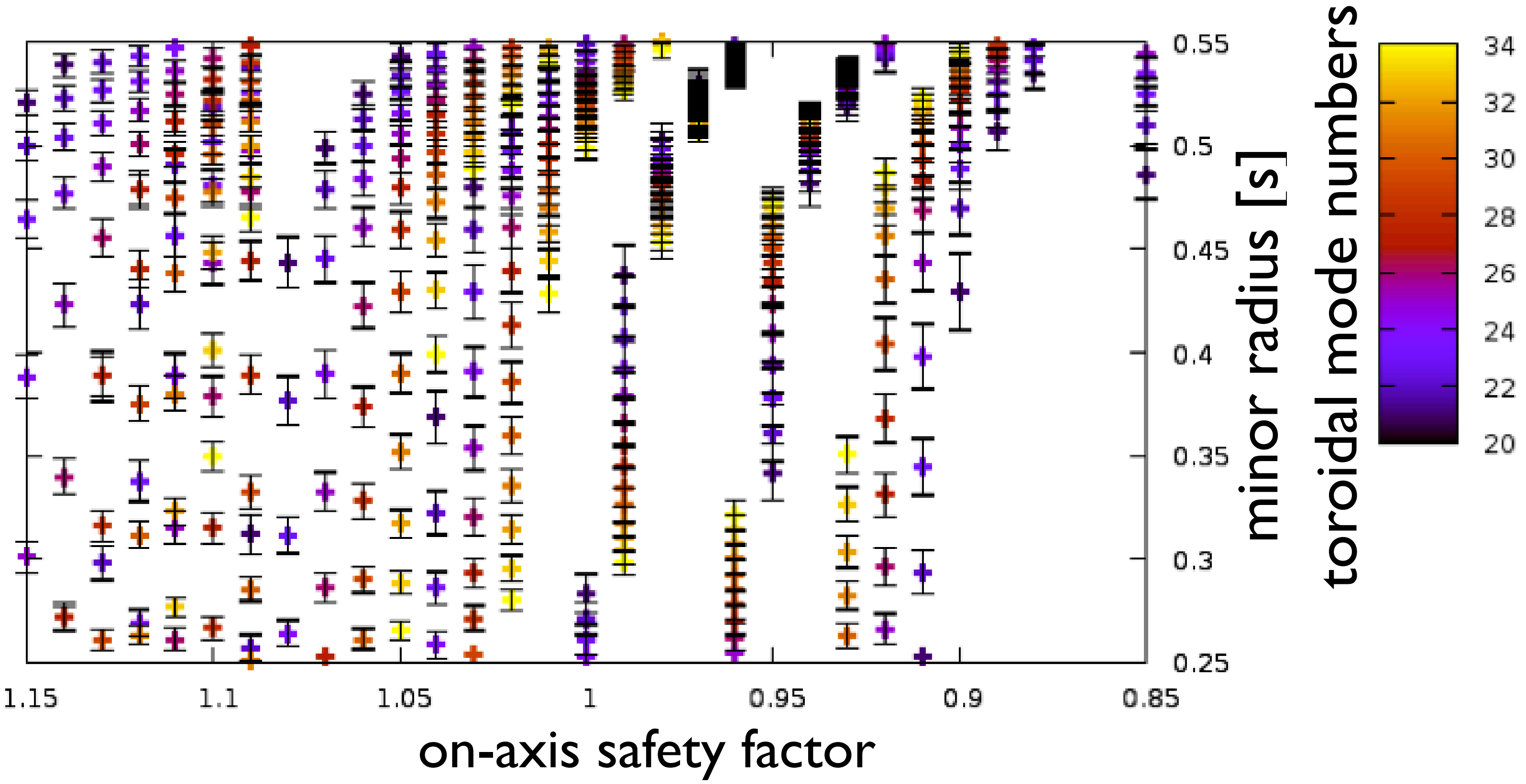


neutron deficit larger in
5MW (2 beam phase)

linear gyrokinetic eigenvalue solver LIGKA

- LIGKA library comprises several local and global models for kinetic Alfvén mode (AE) physics and low frequency global modes
- various dispersion relations in literature (e.g. BAE, GAM, KGAM dispersion relation including FLR and FOW effects *[Lauber, Varenna 2018]* were directly derived from model equations
- fully numerical (based on HAGIS particle orbit information) and analytical evaluation of resonance integrals possible
- local and global solvers using either analytical or numerical v-space integrals
- in combination with non-linear HAGIS code, fast and automated stability and non-linear saturation evaluations for AE physics possible *[Hayward-Schneider & Lauber 2017/18]*

15MA ITER scenario:
linear TAE-α driven
stability overview



linear gyrokinetic eigenvalue solver LIGKA: reduced models

Perform broad search for potentially unstable modes ($s < 0.55$)