



Aspects of energetic particle physics in future tokamak devices

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burning fusion plasma physics

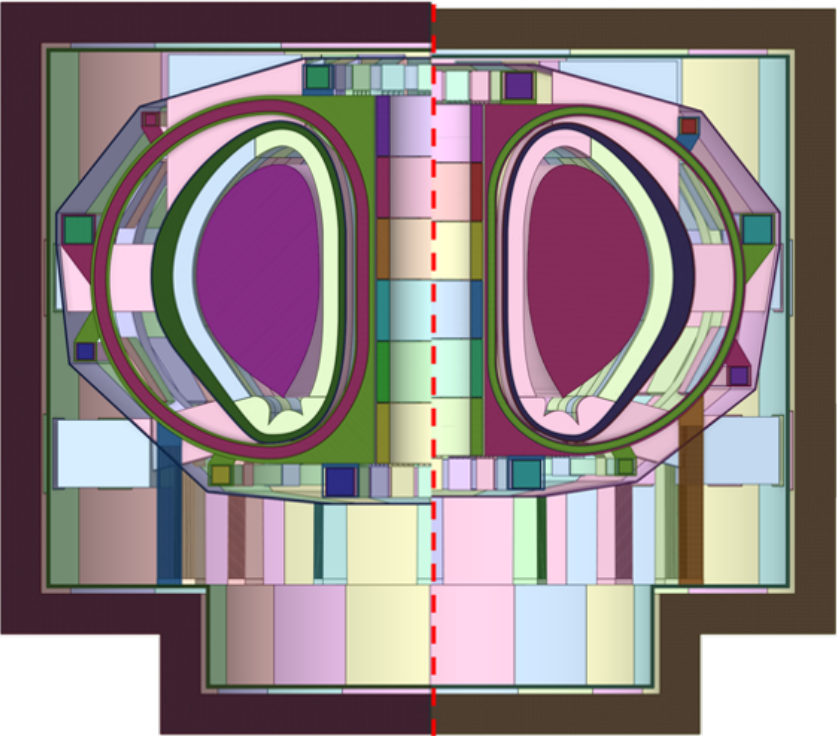
- self organisation: fusion power prediction in the presence of multi-scale physics: profiles, non-linear equilibria, phase space zonal state *[Chen&Zonca 2016, Falessi 2023]*
- long-time behaviour: influence on flux consumption in tokamaks *[Kim, NF 2024]*
- resilience to transient events
- control possibilities: ECRH+ fuelling (DT ratio/ admixed impurities)
- exhaust compatible with available technology/ materials

neutron source for addressing technology challenges

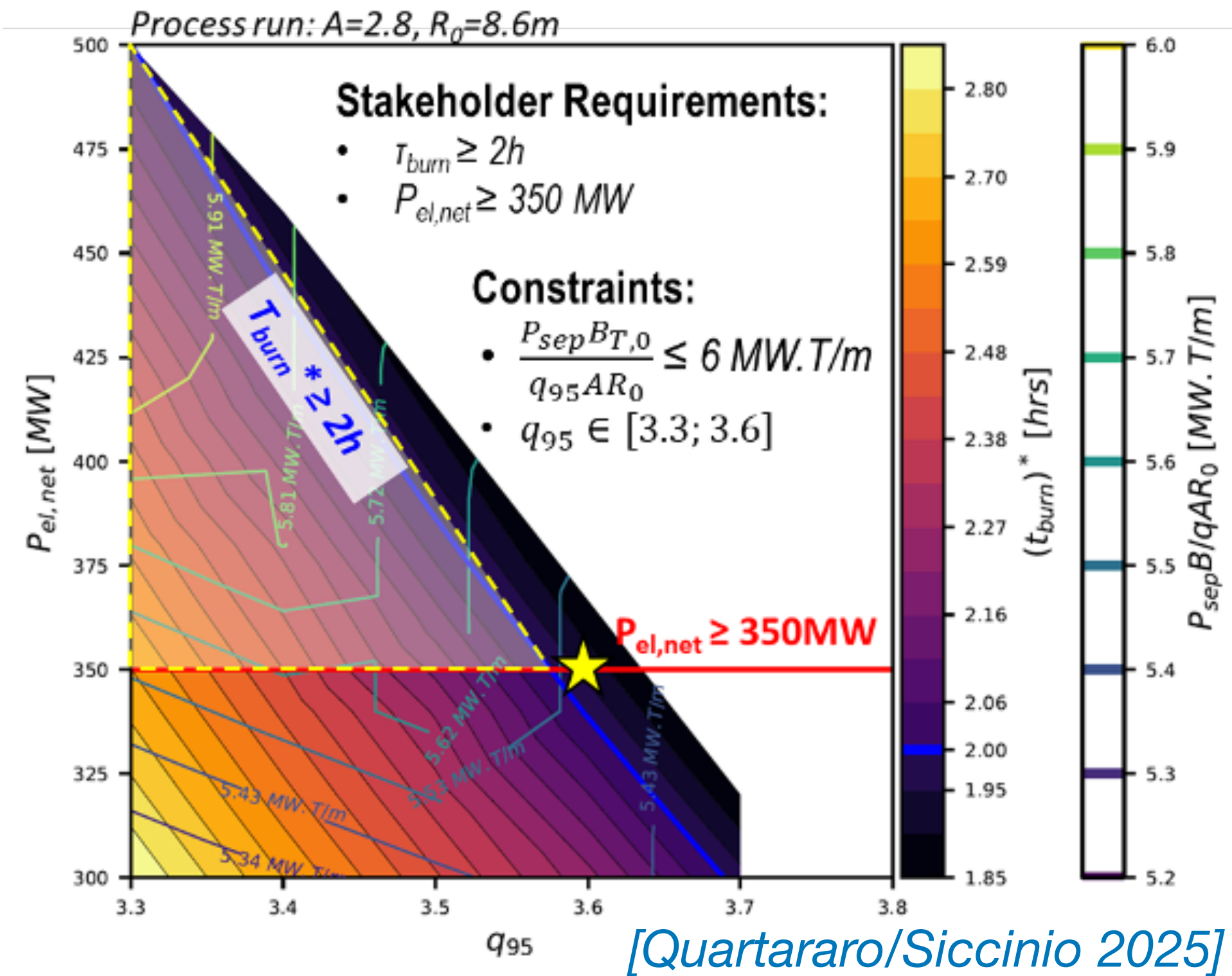
- strongly driven system using beam-target concept: **maximise neutron flux AND fluence for tritium breeding technology** and material qualification *[Frederici et al NF 2023]*
- for minimising costs: system needs to be as close as possible at the limit of operational boundaries
- needs to operate as much as possible (significant fraction of a year)
- long-time behaviour: influence on flux consumption - small central solenoid!
- exhaust compatible with available technology/ materials

EU DEMO

[Coleman NF 2025, Bourdelle Soft 2026, Luda, EPS 2026]

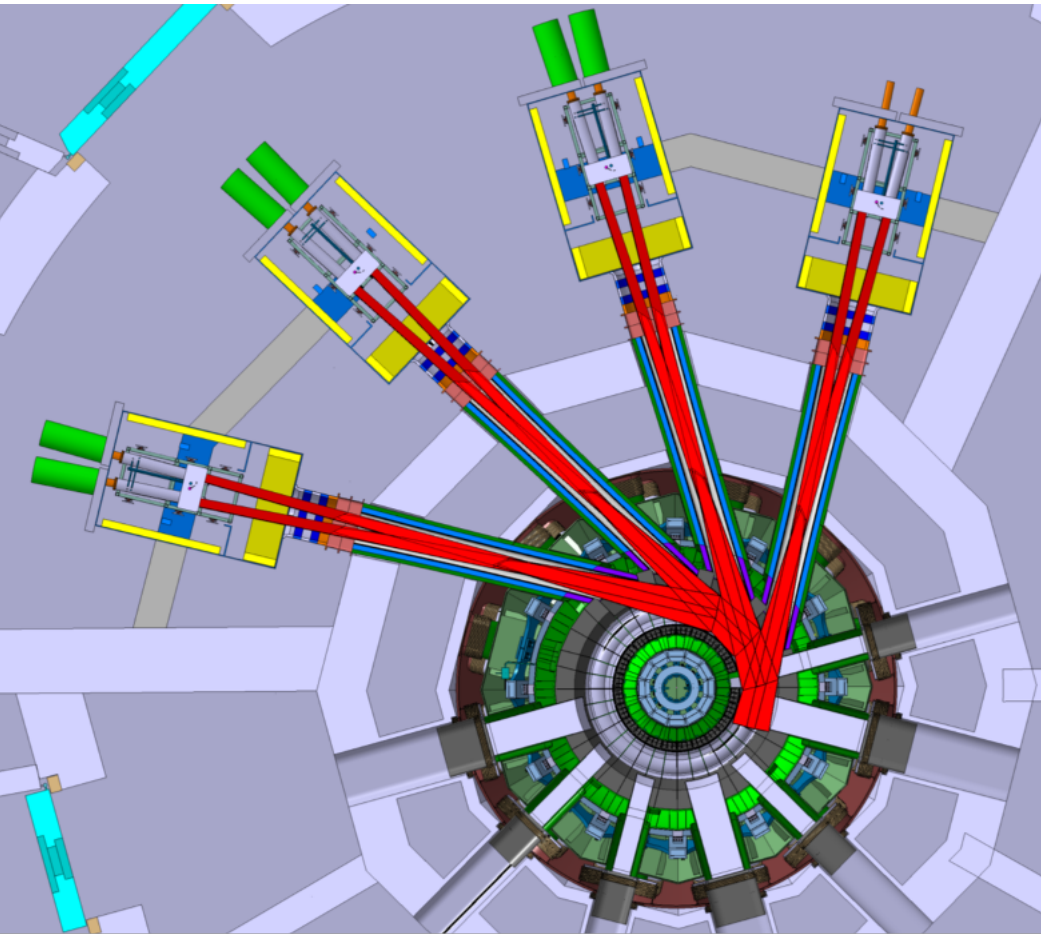


$P_{el,net}$ [MW]	350
P_{fus} [GW]	1.6
τ_{pulse} [hr]	2
divertor flux if accidental reattachment [MW/m ²]	44.3<50
A	2.8
R_0 [m]	8.6
$B_{T,0}$ [T] LTCS	4.39
lifetime dpa (blanket)	20-40



VNS (Volumetric Neutron Source)

[M.Siccinio et al EPS 2026; PPCF 2026, A. Quartararo, SOFT 2026]



NBI/ECRH[MW]	45/15 (30/30)
P_{fus} [MW]/beam target	42/36
τ_{pulse} [hr]	∞
T consumption	2.38 kg/full power year
A	4.25
R_0 [m]	2.67
$B_{T,0}$ [T] /Ip [MA]	5.6 / 2.54

- peak neutron wall load $\geq 0.5 MW/m^2$ [Frederici NF 2023]
- aiming for 30-50 dpa during lifetime
- $\beta_N < 3.5 \%$
- fully non-inductive plasma scenario
- minimize tritium consumption (below 3 kg per full power year)

EP physics: overview experiments

	AUG	VNS	JET	JT-60SA	ITER	EU DEMO	
Vol [m ³]	13	28	90	160	830	2800	
P NBI [MW]/total heating	20/34	45/60 or 30/60	10-20/34	34/41	33/83	-	
(NBI+ICRH+α)/volume	<2	1.8	~0.4	0.25	0.65	0.6	similar ratio of ion heating/volume for AUG-VNS, but:
fusion power [MW]	-	42/36	12.5	-	500	1600	
β _{EP,0} /β _{thi,0}	1*	1	0.5-2 (ICRH)	<2.5	0.5-0.7	0.7	
R ₀ ∇β _α /β _{thi}	6*	6-10	3-6	5	2	1.8	• higher beam energy • lower ICRH vs α energy
B ₀ [T]/I _p [MA]	3/1.2-1.6	5.6/2.54	3.9/3	2.25/5	6/15	4.4/19	
T _{i0} /T _{e0} [keV]	8/10	11/14	10/9	8/8	~20	~22	

* off-axis heating scenarios for maximising beam beta
beam target fusion

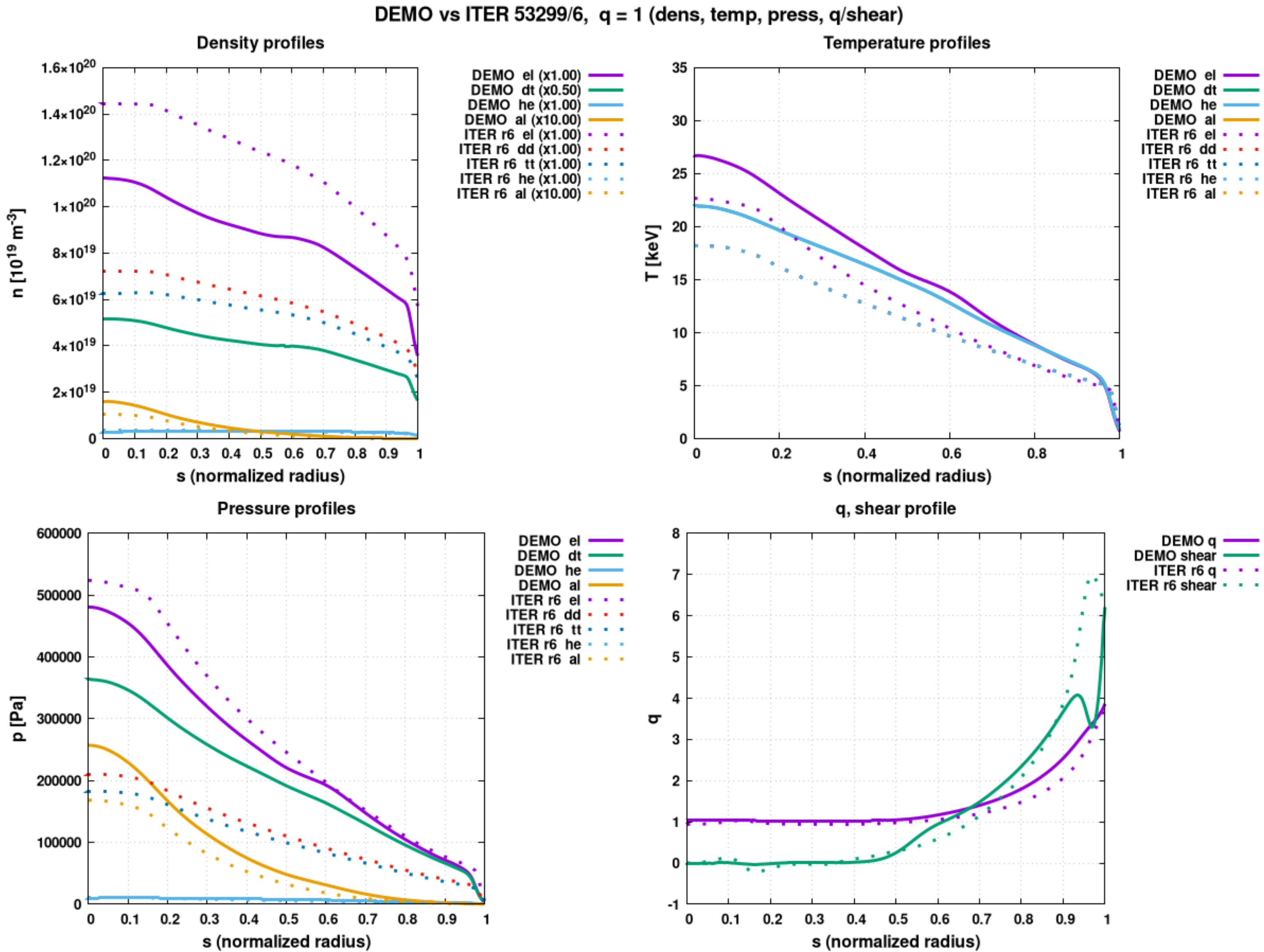
VNS/AUG: EP gradients are above energetic particle mode threshold- however dominated by sub-Alfvénic beam ions

- **alpha particle-driven mode stability** can be roughly described by β_{EP}/β_{back}
caveat: complex nonlocal dependencies of kinetic drive and damping mechanisms and gradients
[Fu, VanDam, 1989 Betti&Freidberg 1992]

• in reactor - density cancels: $\frac{\beta_{\alpha}}{\beta_{back}} \sim \frac{n^2 T_i^2 \cdot T_i^{3/2}}{n^2 T_i} \sim T_i^{5/2}$

self-organising

- large non-linearity in Ti:
 - can lead to overshoots and/or limit cycle oscillations in ramp-up/ flat top
 - beta-stabilisation and EP transport effects lead to multi-length and time-scale dynamics *[Chen&Zonca RMP 2016, Citrin, Garcia, Mantica et al]*
 - collisionless regime of alphas particles leads to long-lasting structures in phase space *[Falessi et al, PoP 2018, NJP 2023][experiments at KSTAR: Kim NF 2024]*
 - controllability? direct impact on overall design? optimisation?

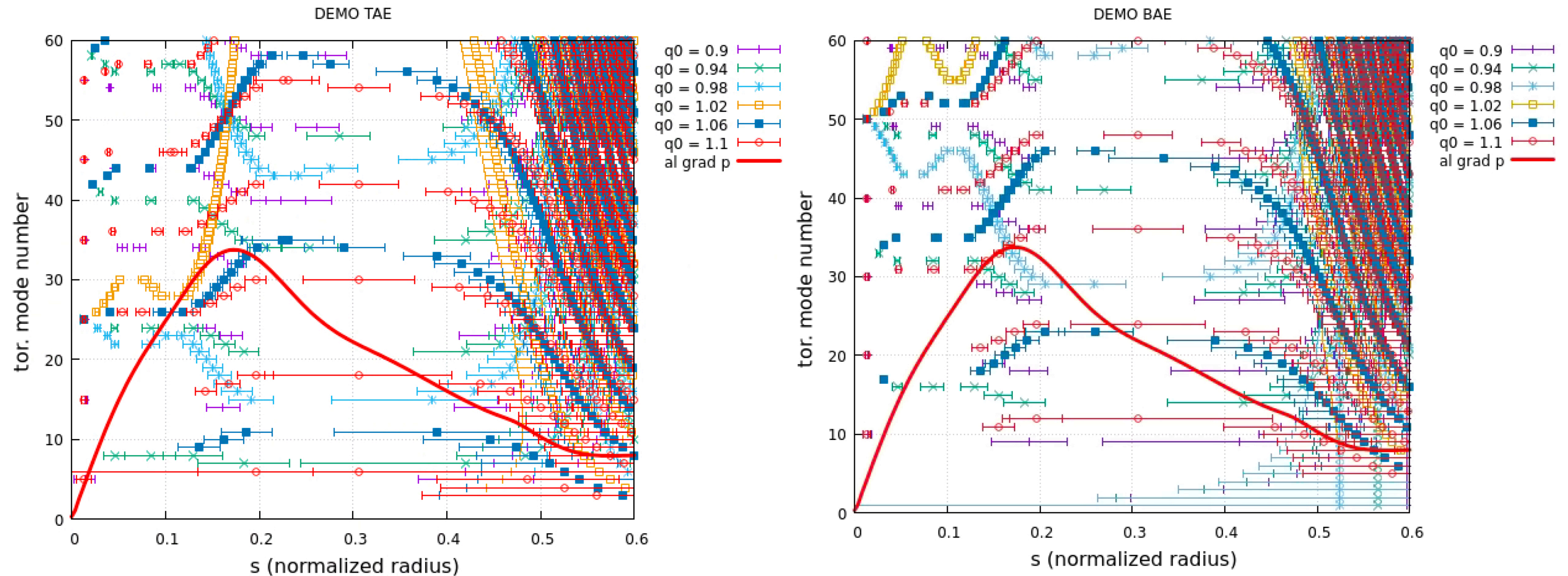


[¹ DEMO:T Luda, EPS 2026; C. Bourdelle in prep.]
[² ITER: new ITPEA TG 15MA baseline, C. Bourdelle]

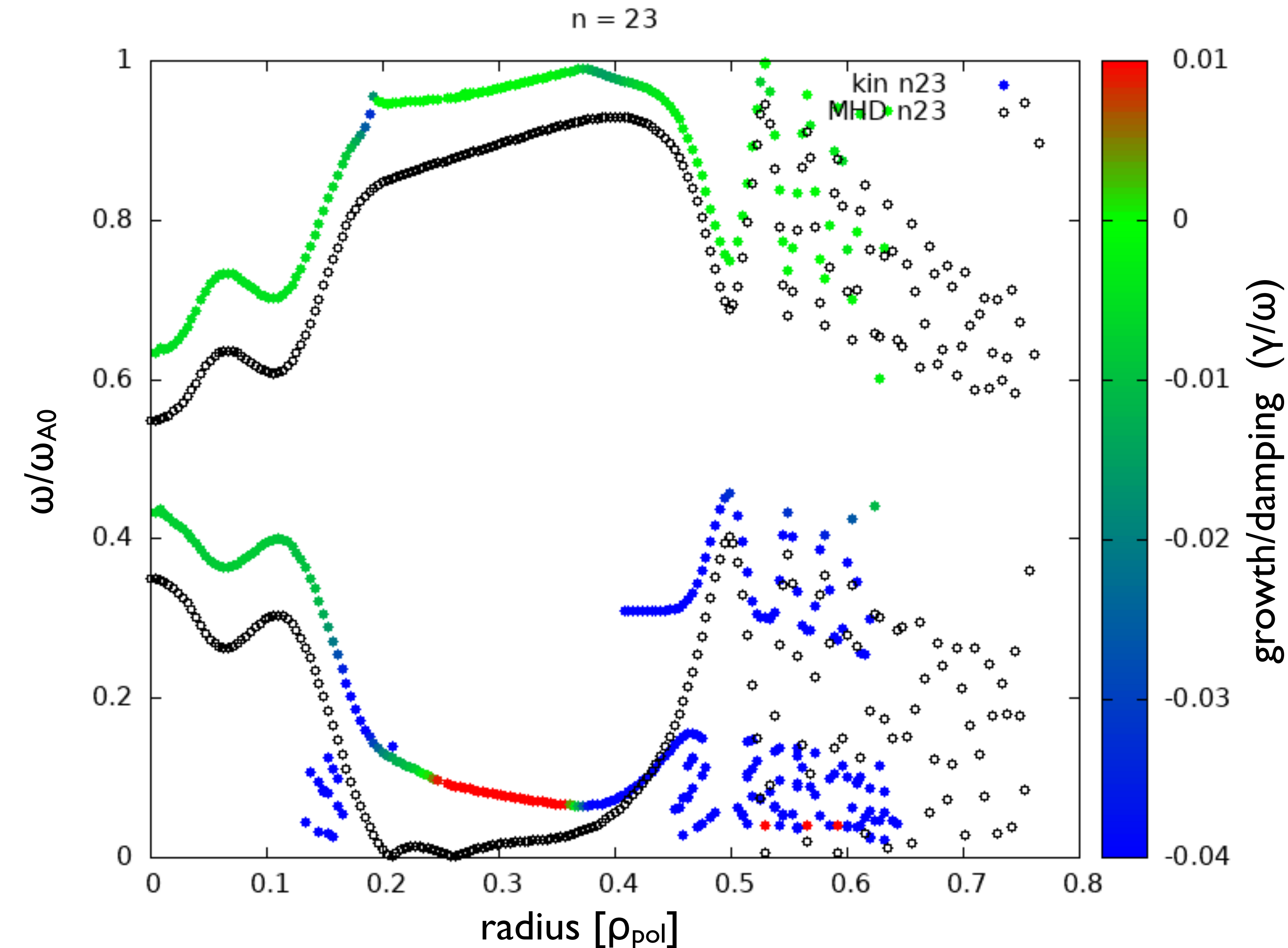
- $B_{0,ITER}=5.1T$ vs $B_{0,DEMO}=4.39T$
DEMO has higher beta despite similar $n \cdot T$
- $v_{\alpha}/v_{Alfvén} \gtrsim 1$ for alpha particles $\gtrsim 1MeV$: effective resonant drive
- most effectively driven Alfvén eigenmodes: tor. mode number $n \sim 30$

	ITER 53299/r6	DEMO
β_{0el}	4.8%	6.6%
β_{0DT}	3.6%	5.0%
$\beta_{0\alpha}$	1.7%	3.5%
$v_{\alpha}(1MeV)/v_{A0}$	1.1	1.2

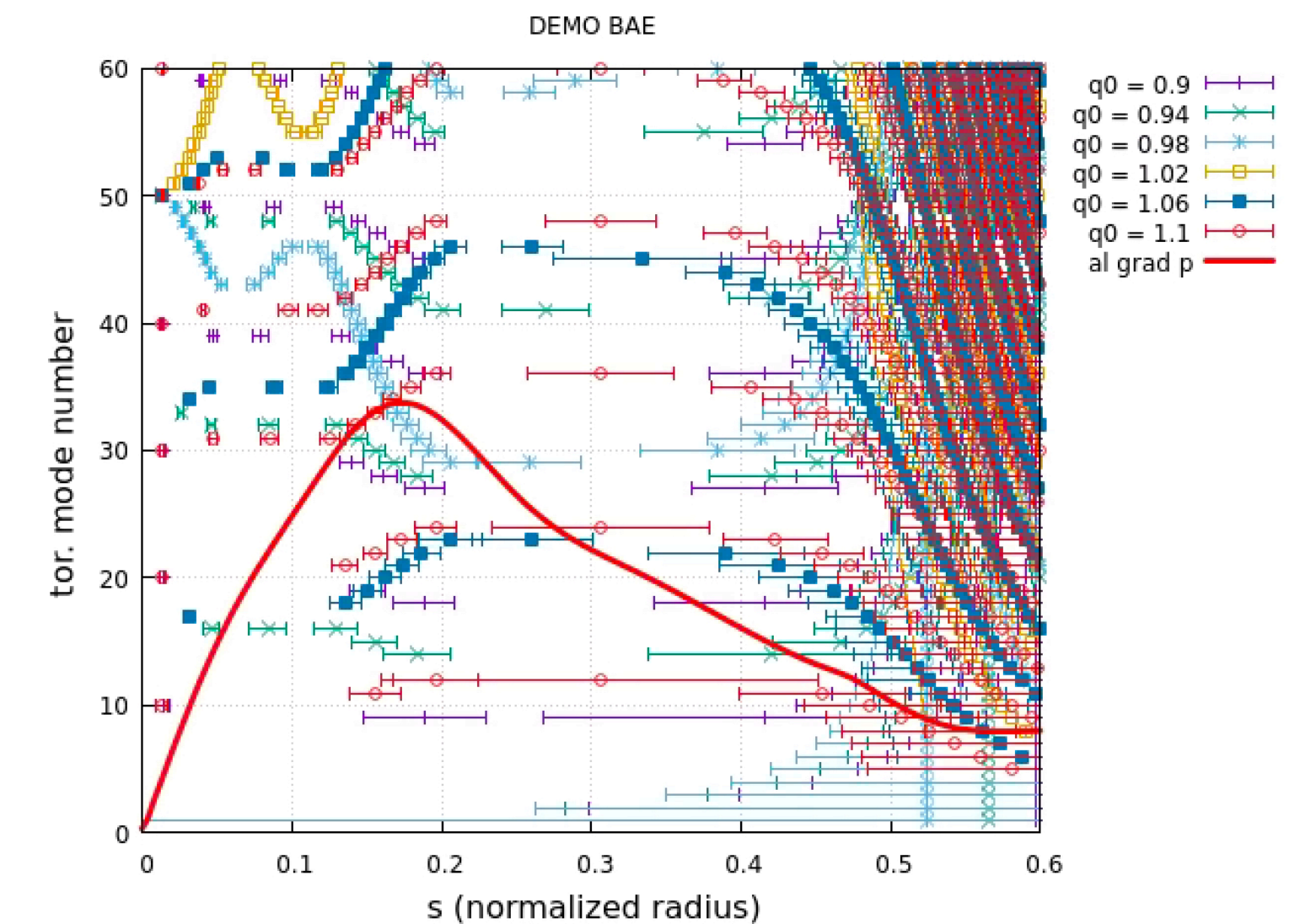
sensitivity analysis with respect to q_0



in the following: use $q=1.06$ (assuming hybrid scenario/flux pumping, no $q=1$)



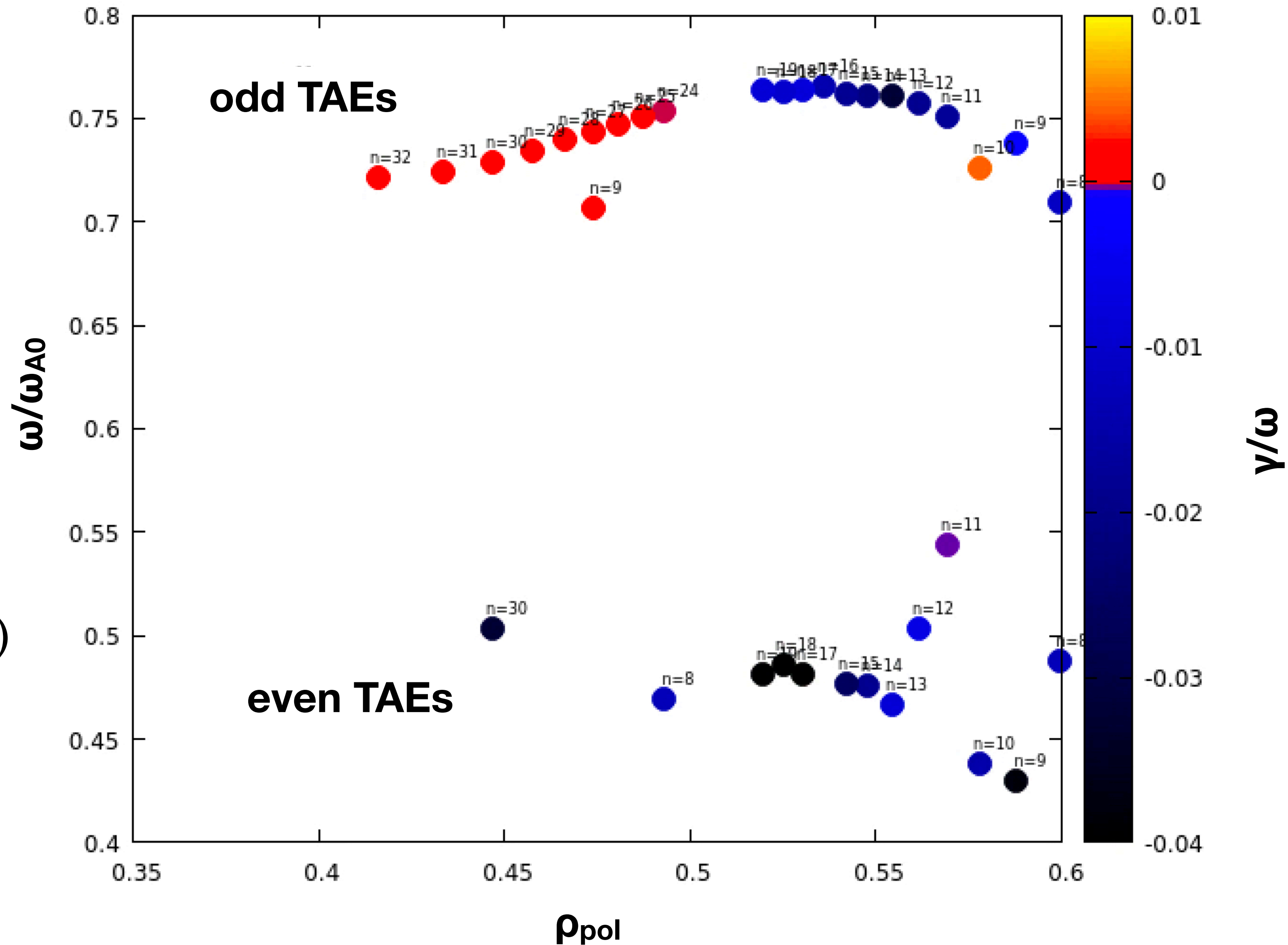
solution of local kinetic dispersion relation, including α -particles in ZOW limit



global analysis of odd and even TAE branches

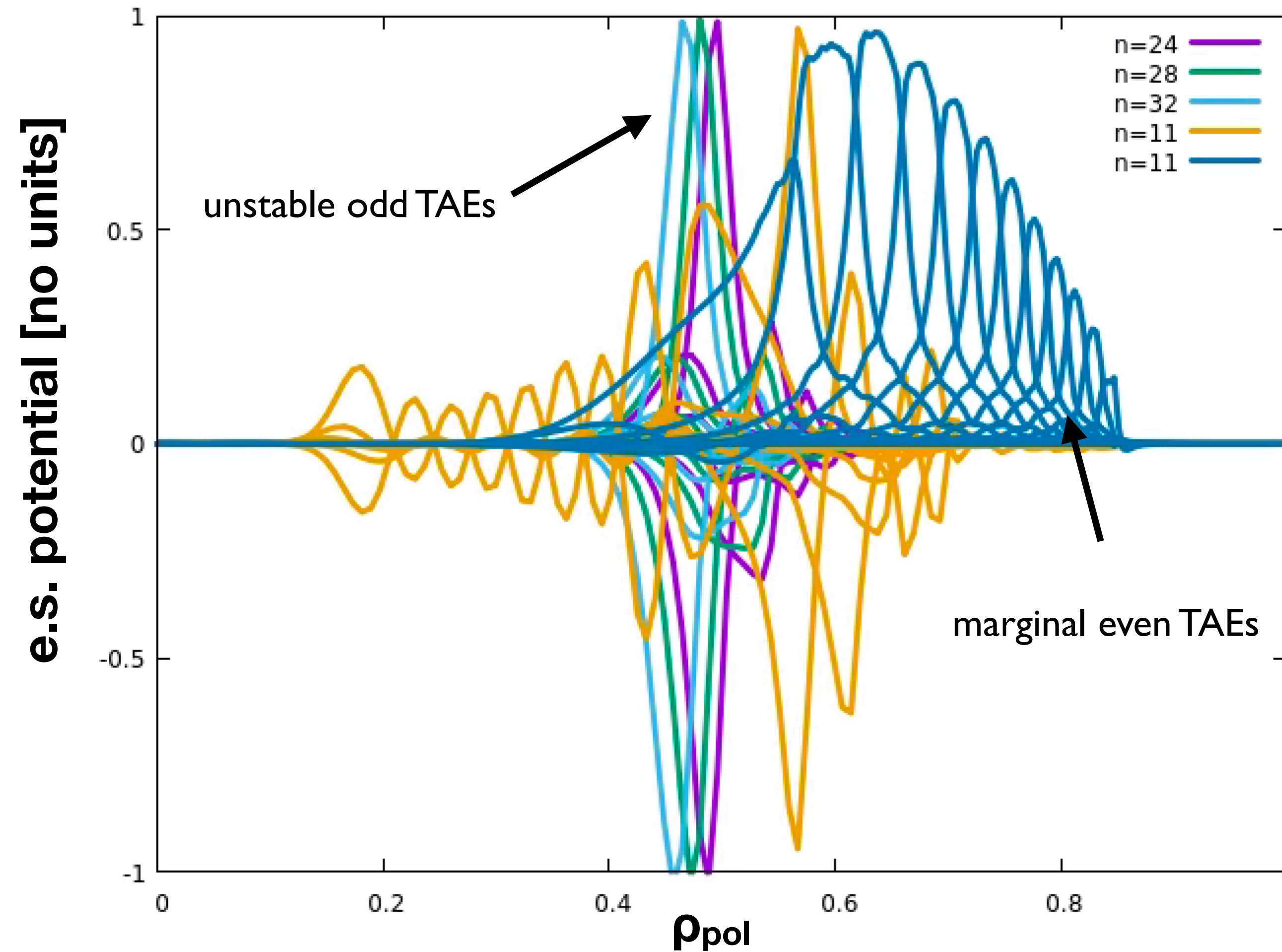
TAEs marginal for
nominal profiles
(1 MeV equ. Maxwellian)

weakly unstable
TAE spectrum for
 $n_a = 1.1 \cdot n_{a,nom}$



global analysis of odd and even TAE branches

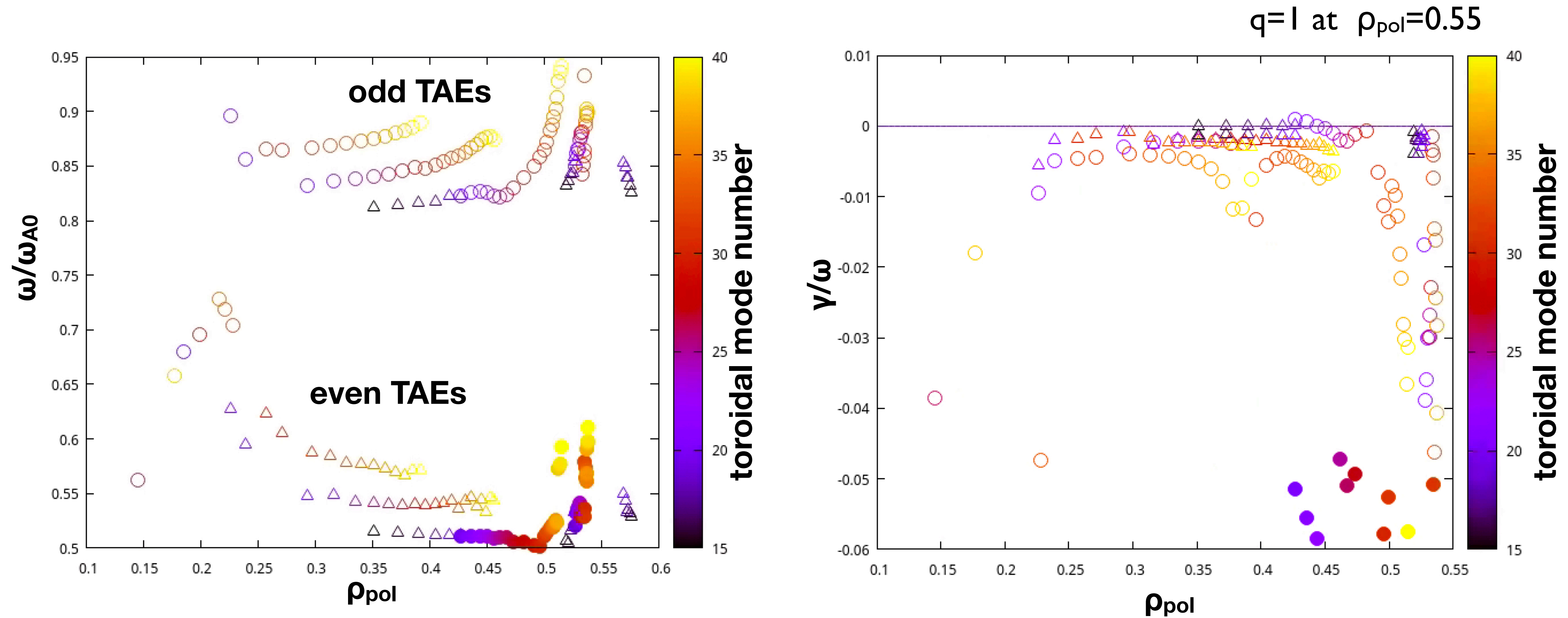
$q=1.06$



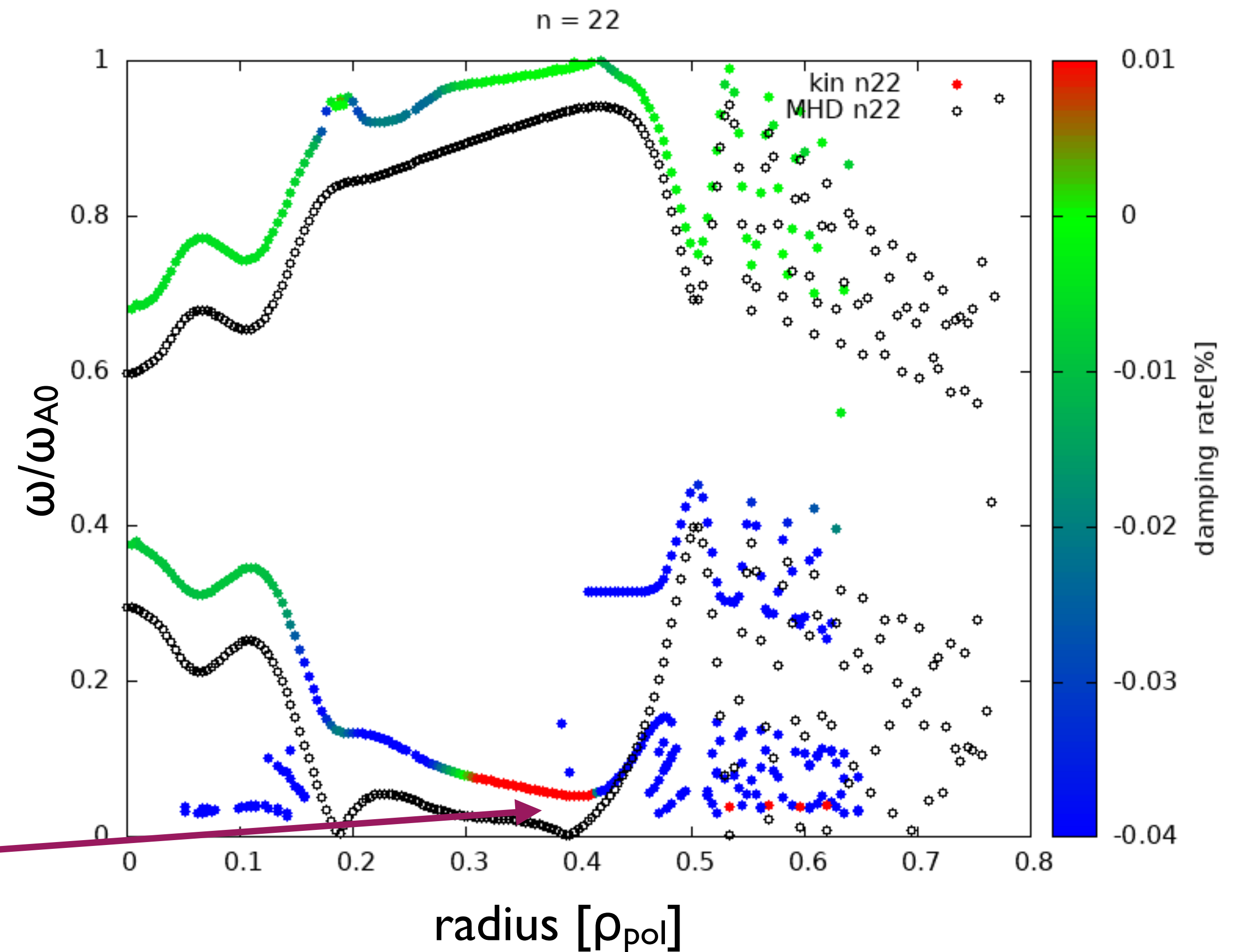
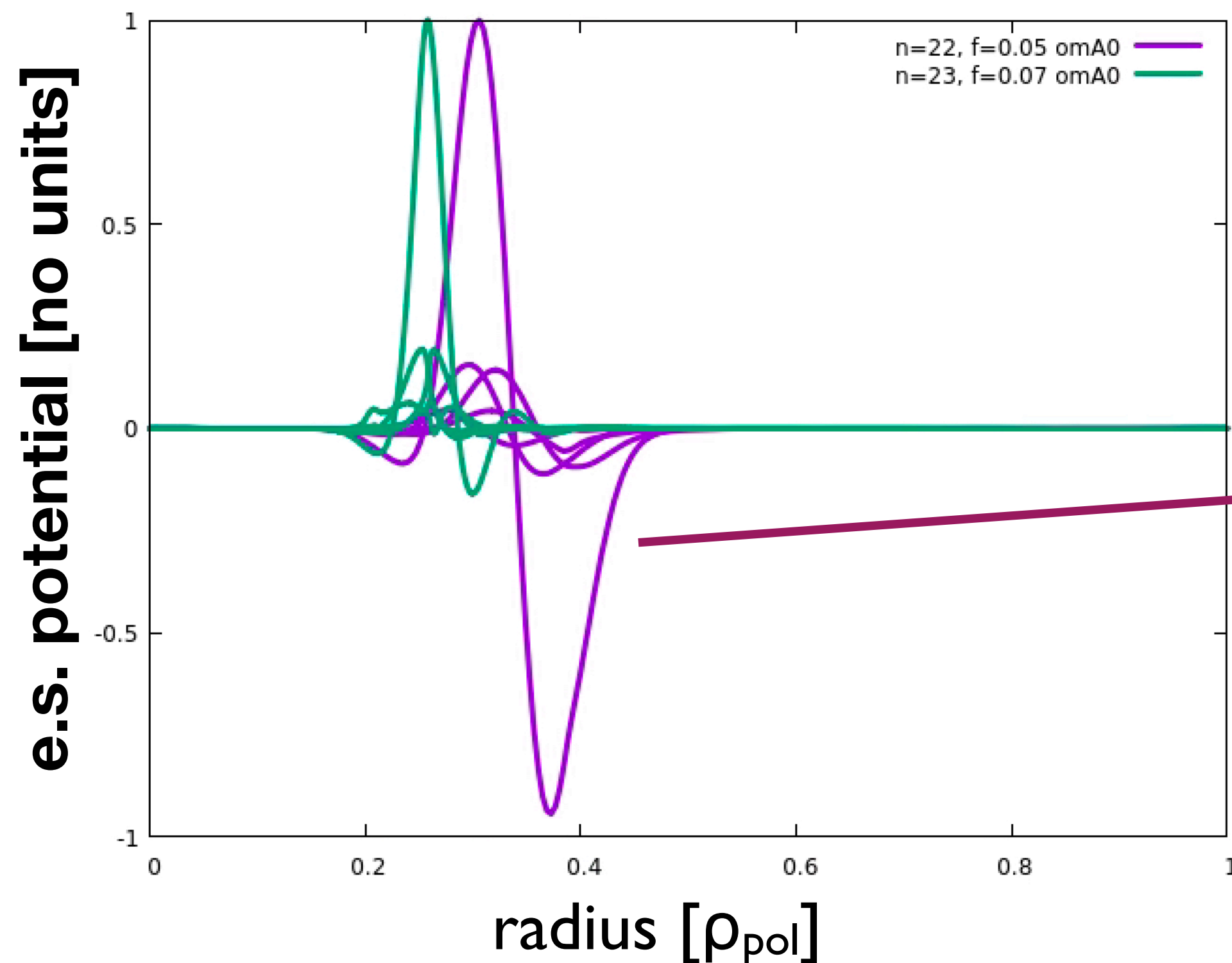
TAEs marginal for
nominal profiles

weakly unstable
TAE spectrum for
 $n_q=1.1$ $n_{q,nom}$

similar picture for $q < 1$: TAEs at mid radius weakly unstable



no unstable BAEs found in core
however high-n ALTG expected, as in ITER
[T Hayward-Schneider, NF 2023]
but: unstable low-frequency Alfvénic modes
in diamagnetic gap ($f=5-10\text{kHz}$, $\gamma/\omega=10,20\%$)



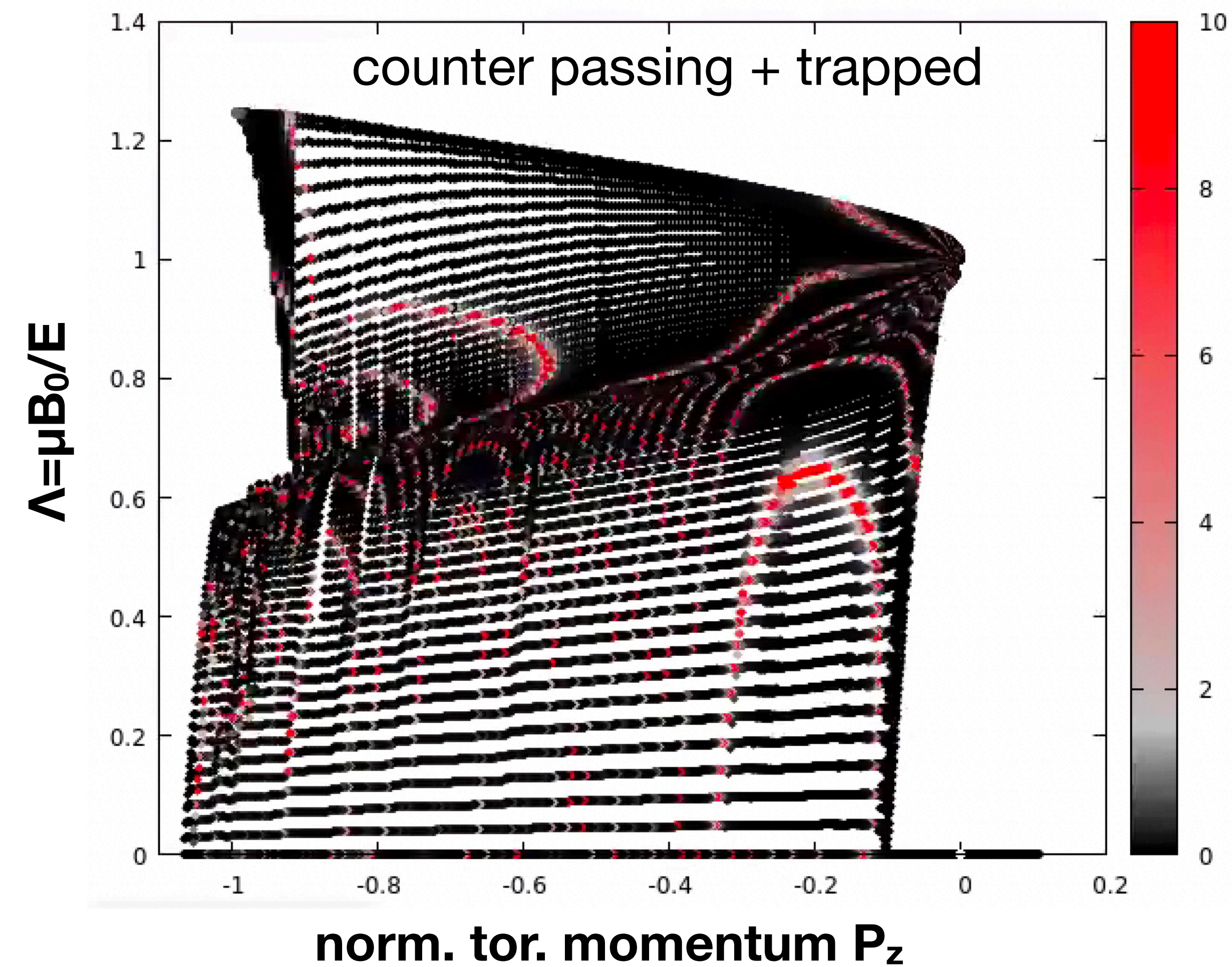
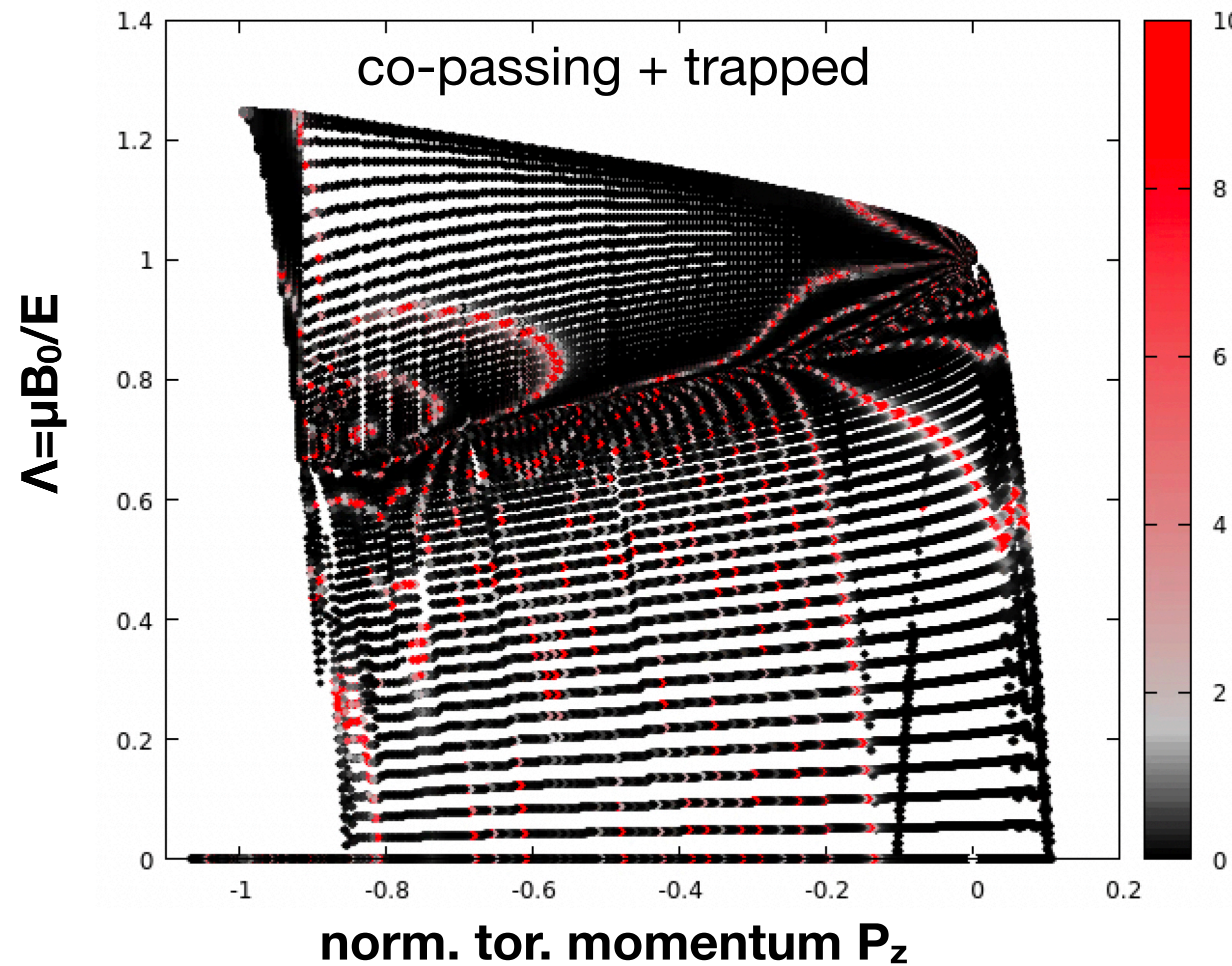


- first versions of PSZS transport code ATEP and ATEP-3D [\[Lauber, Meng NF 2023\]](#) based on PSZS transport theory [\[M.-V. Falessi & F. Zonca, 2017-2025\]](#) are presently extended and coupled to transport workflows [\[thanks M. Marin TSVV-H support, F. Koechl, F. Casson\]](#)
- embed EP Stability Workflow [\[V.-A. Popa, NF 2023\]](#) into ATEP framework [\[V.-A. Popa, T. Hayward-Schneider\]](#)
- design MUSCLE3 actor for different ATEP operational modes [\[V.-A. Popa, T. Hayward-Schneider\]](#)
- new neoclassical ATEP-3D solver including sources and sinks (python); particle/momentum/energy transport profiles as output to transport codes [\[see poster T. Sterkl at this conference\]](#)
- formulated different implementations of convection/diffusion coefficient calculations [\[T. Sterkl, Master Thesis TU Wien 2025; see poster T. Sterkl at this conference\]](#)
- use nl-theory to calculate consistent zonal response [\[R. Stucchi, talk at this conference\]](#) and compare saturation levels and radial structures with nl-GK codes [\[N. Chen, X. Wang, T. Hayward-Schneider, ORB5 team - posters at this conference\]](#)
- include fishbone model [\[poster at this conference E. Eidsvig; Brochard, PRL 2025\]](#)
- use DAS formulation [\[G Wei, 2024, Li 2023, Falessi 2025\]](#) to set up Dyson-Schrödinger envelope equations

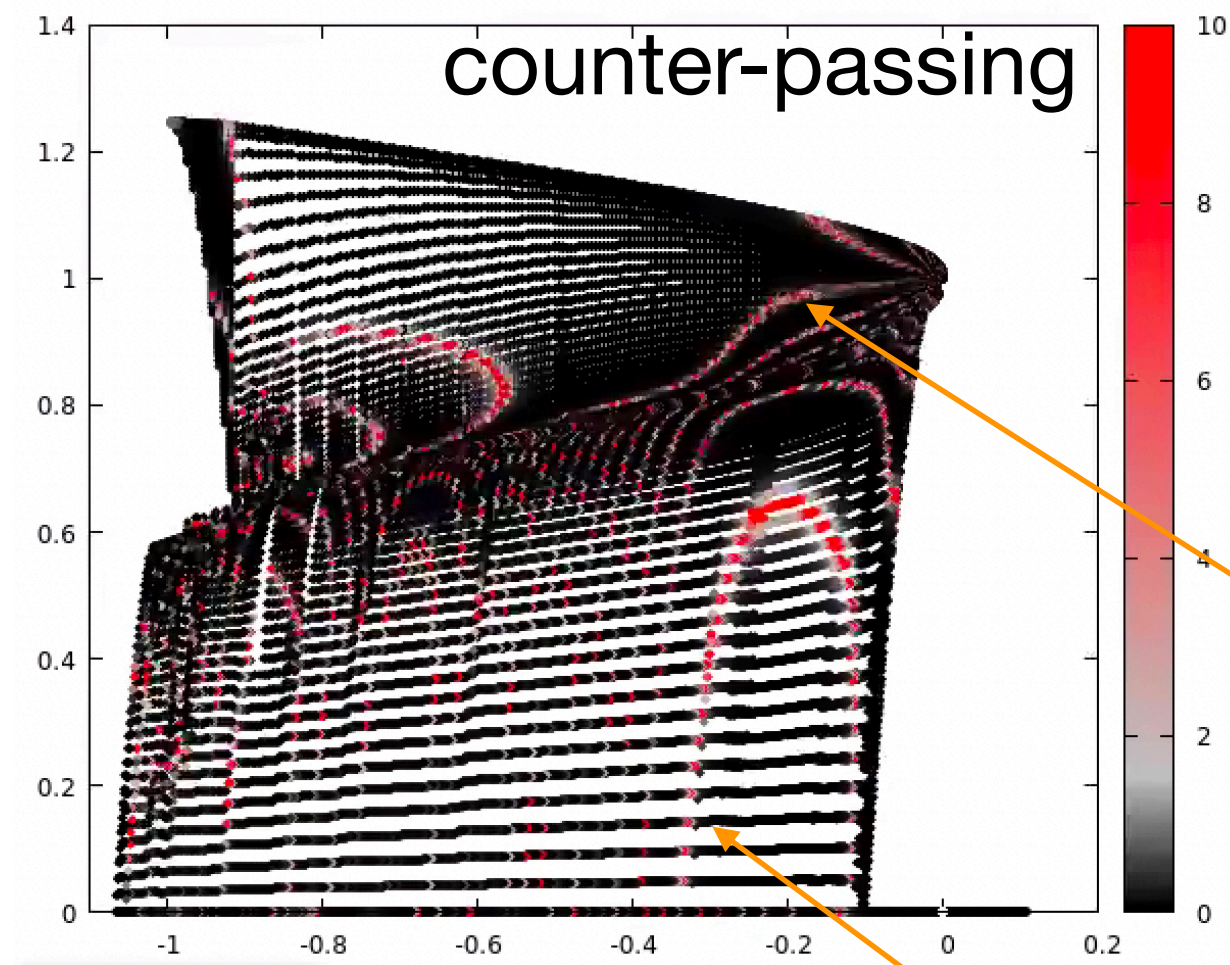
TAE resonances with α particles - here $n=24$ TAE



high energies $E=[3.0-3.5 \text{ MeV}]$

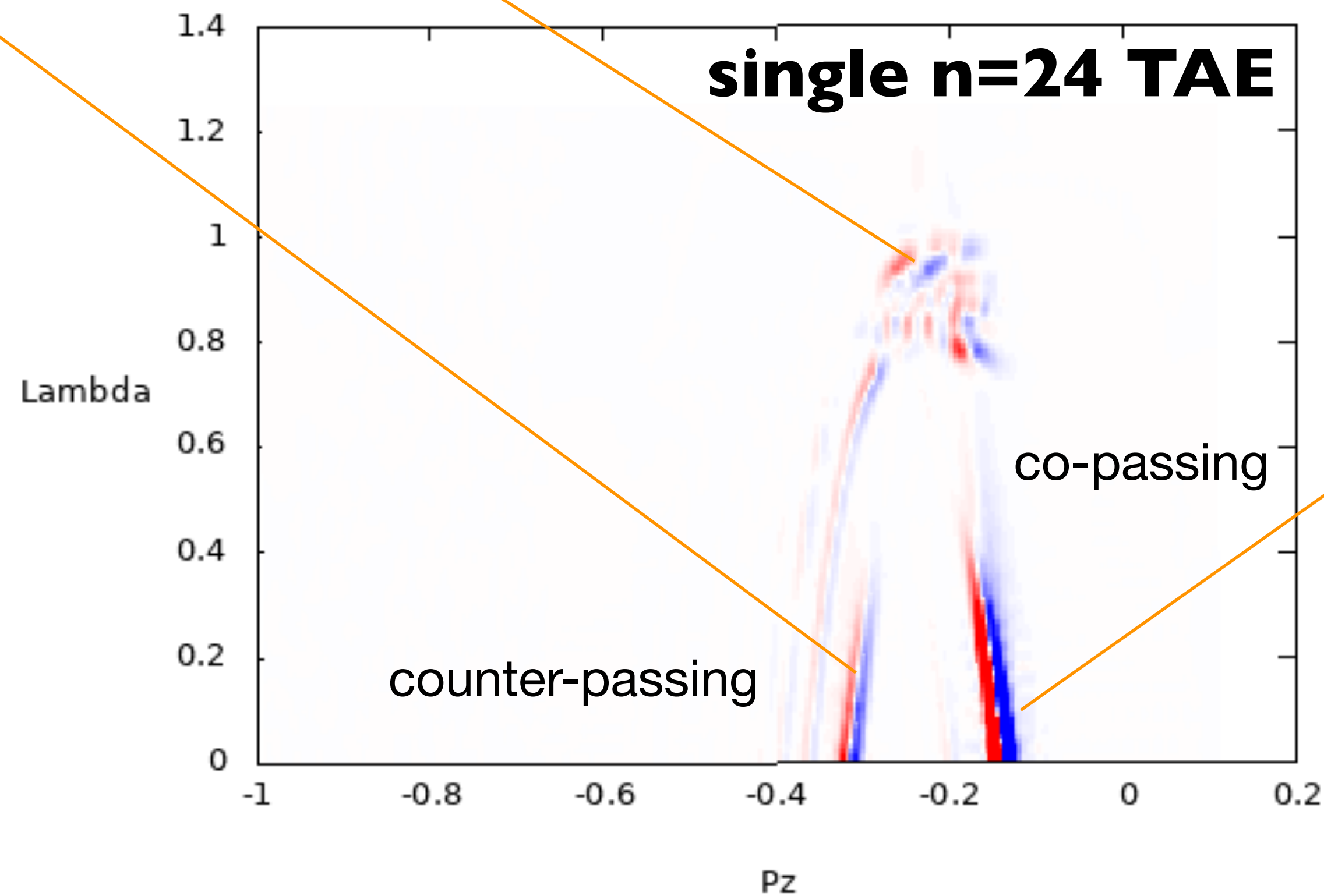
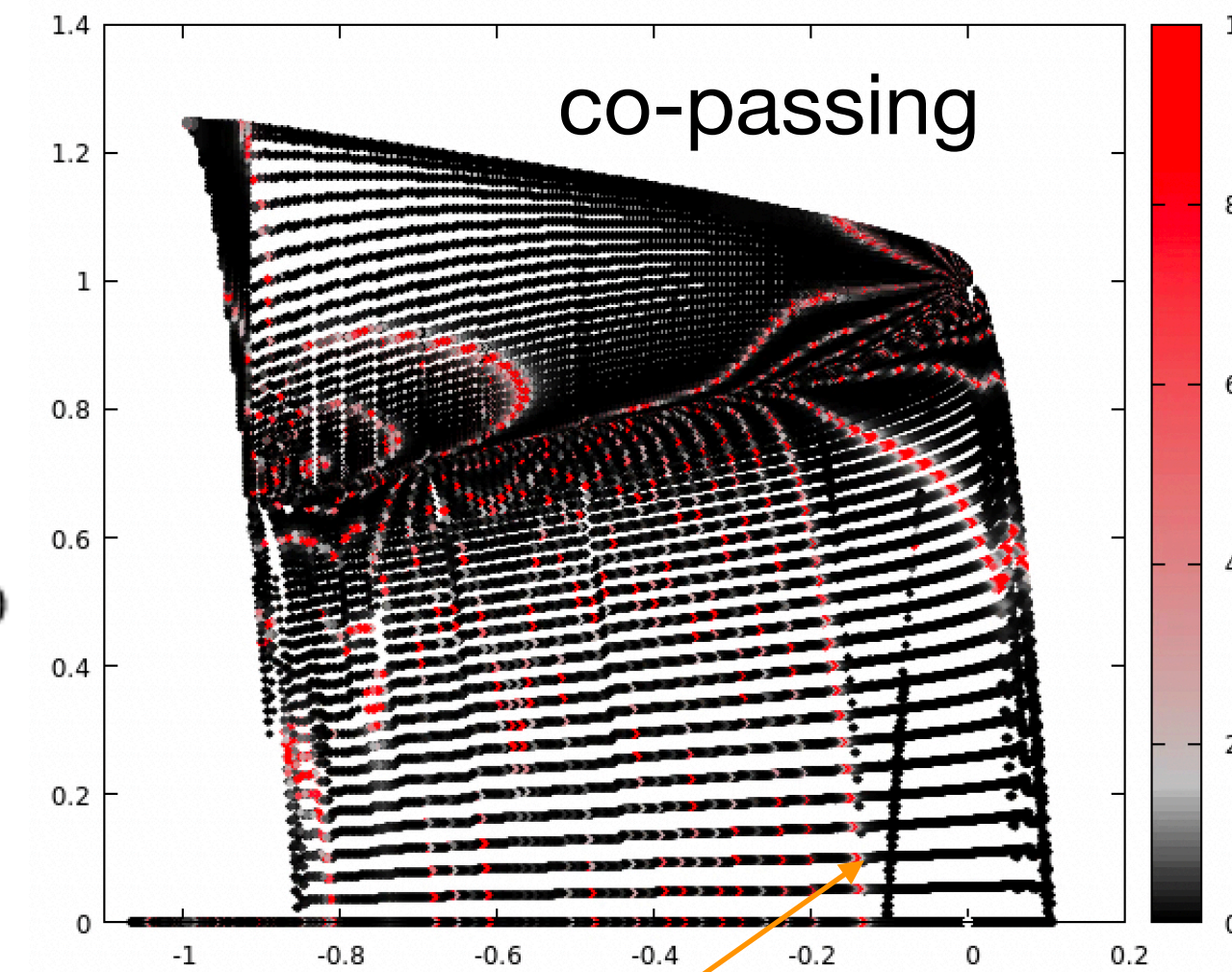


phase space zonally averages fluxes: resonant PSZS fluxes



high energies $E=[3.0-3.5 \text{ MeV}]$

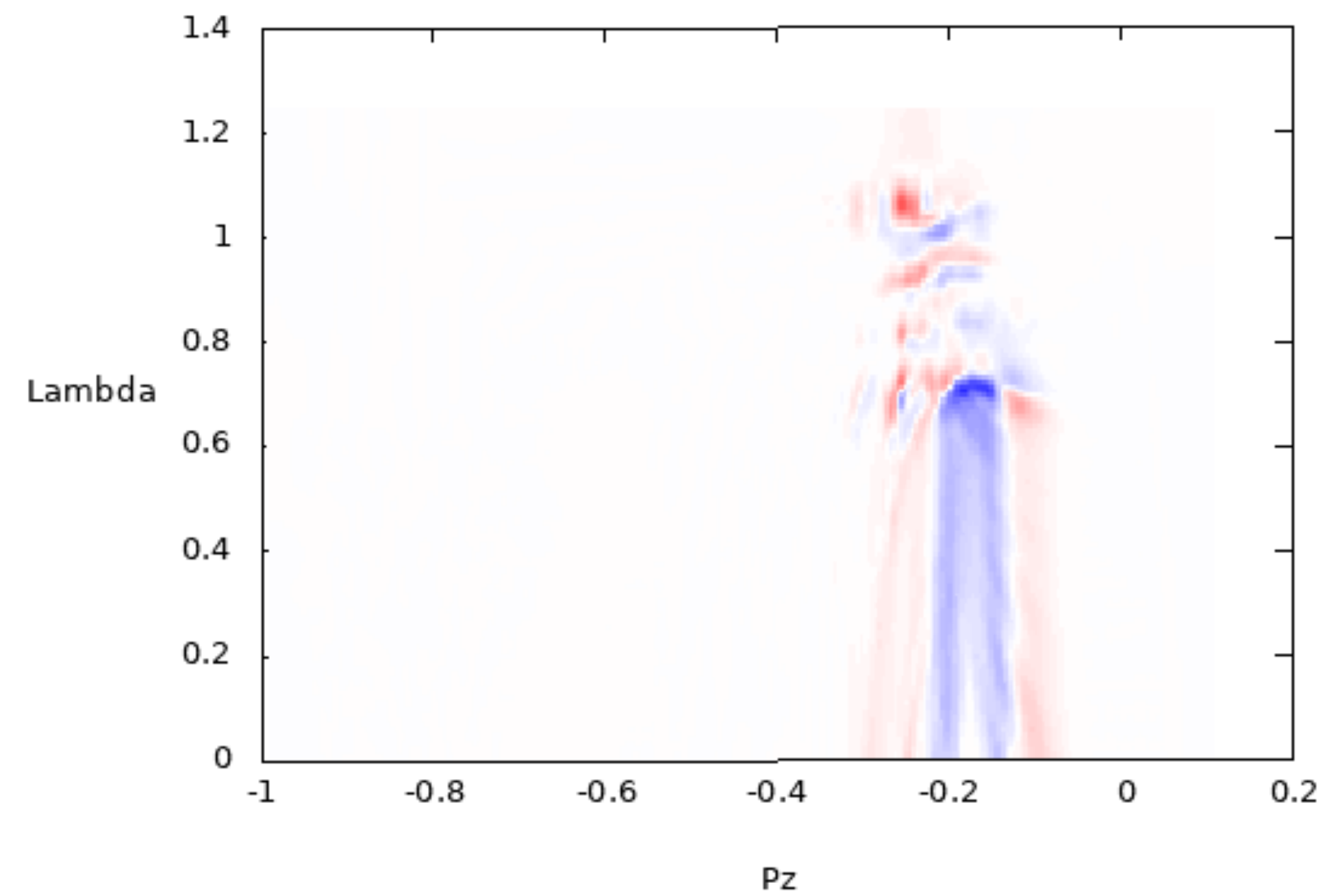
flux (Pz,Lambda), Energy=3144000



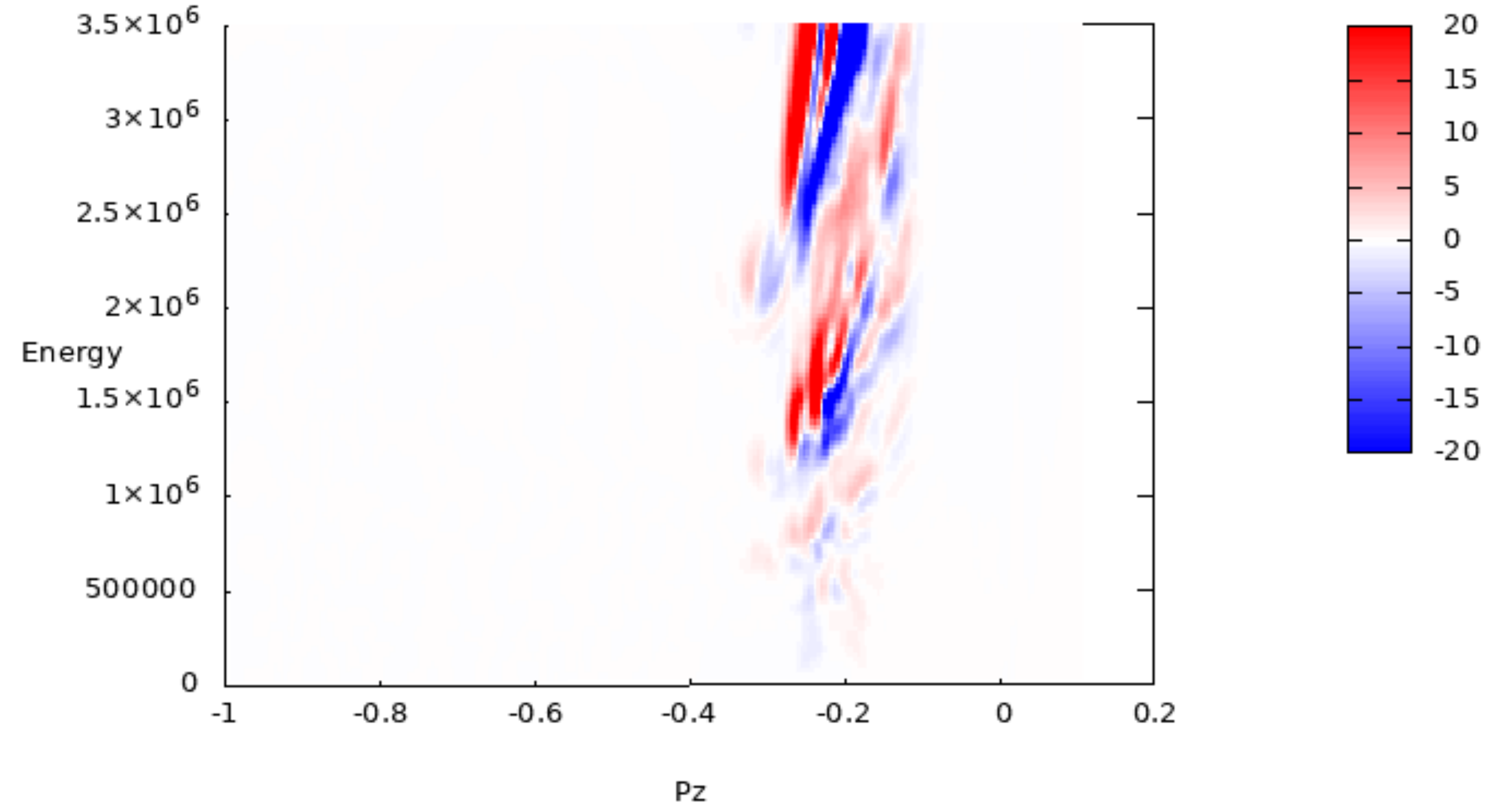
$Pz \times E \times \Lambda \times \sigma = 256 \times 64 \times 64 \times 2$

cluster of n=24-32 TAEs

flux (Pz,Lambda), Energy=900000



flux (Pz,Energy), Lambda=941

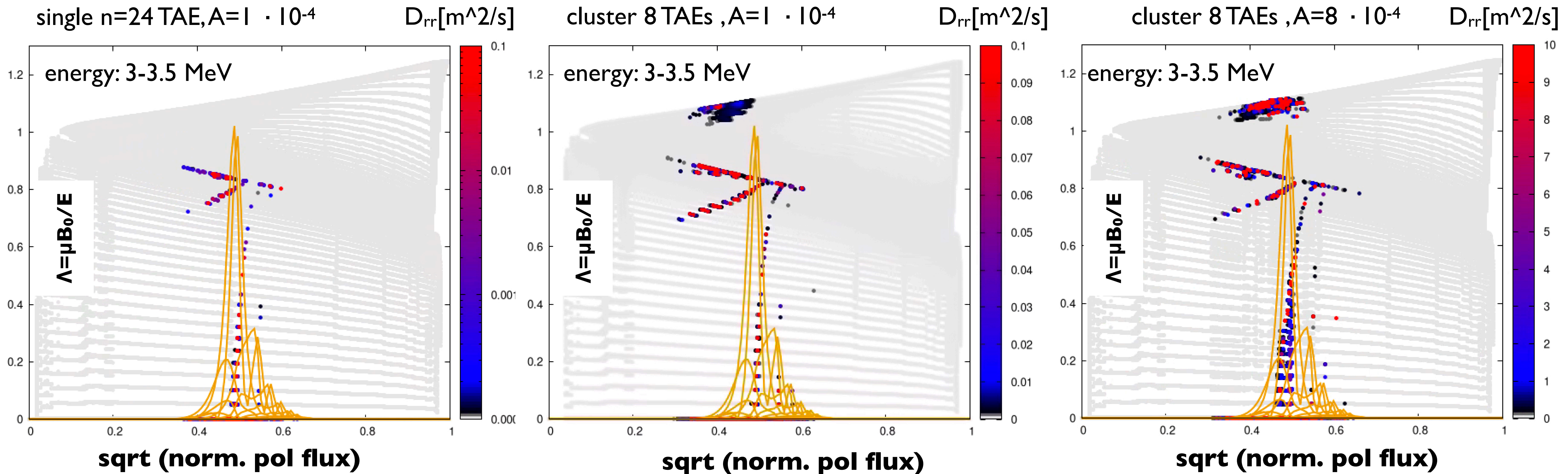


from fluxes to radial diffusion coefficients

$$D_{P,P} = \langle dP_\phi/dt \rangle^2 \cdot \tau_{ac} \quad [L\ Chen, JGR\ 104, 1999]$$

then use orbit database to map diffusion coefficient $D_{PP} \rightarrow D_{rr}[m^2/s]$

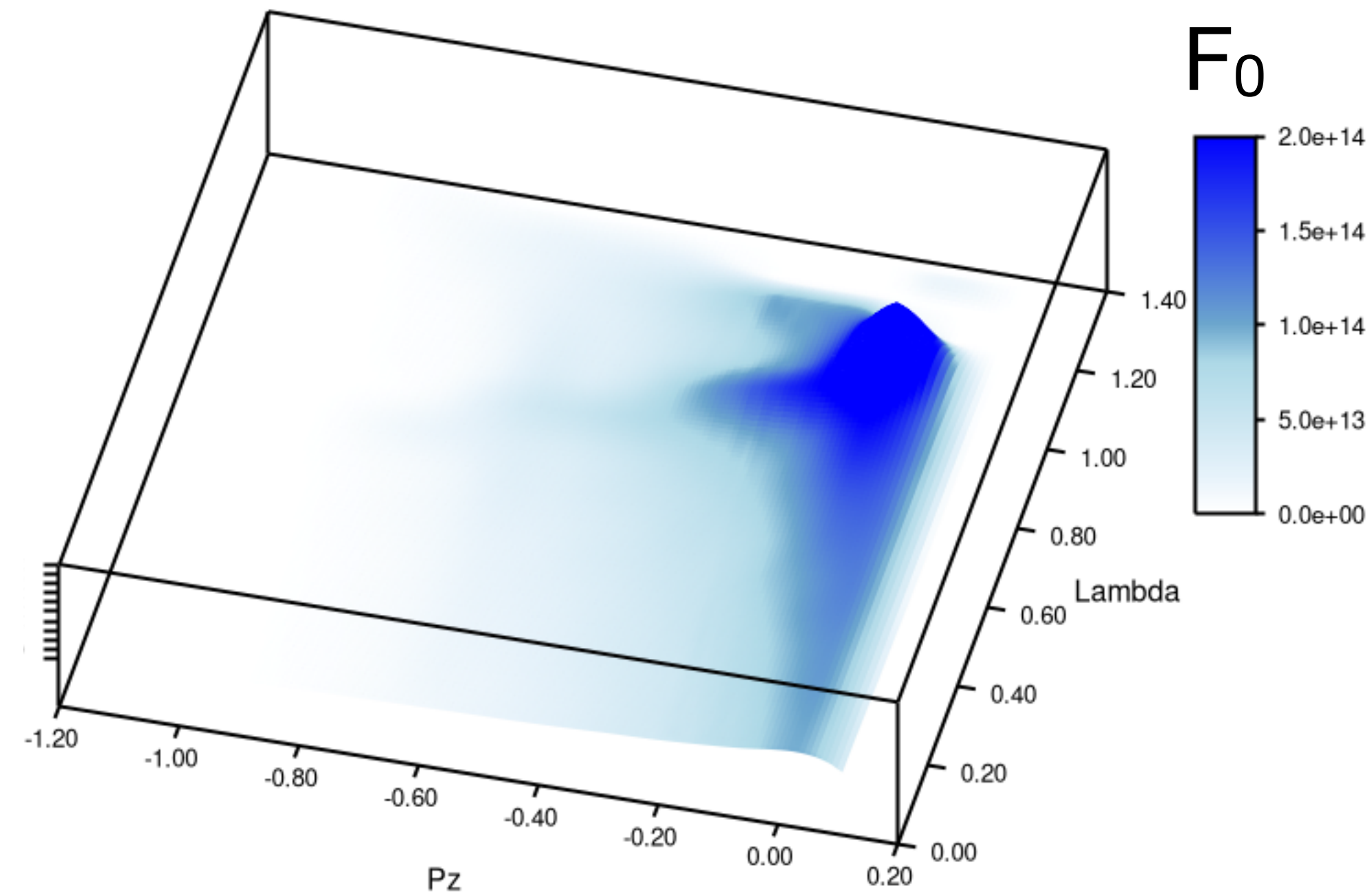
$$\tau_{ac} = \frac{\gamma}{[\omega_{TAE} - \omega_{prec} - p\omega_{t,b}]^2 + \gamma^2}$$



non-locality phase space dependent of transport of α particles

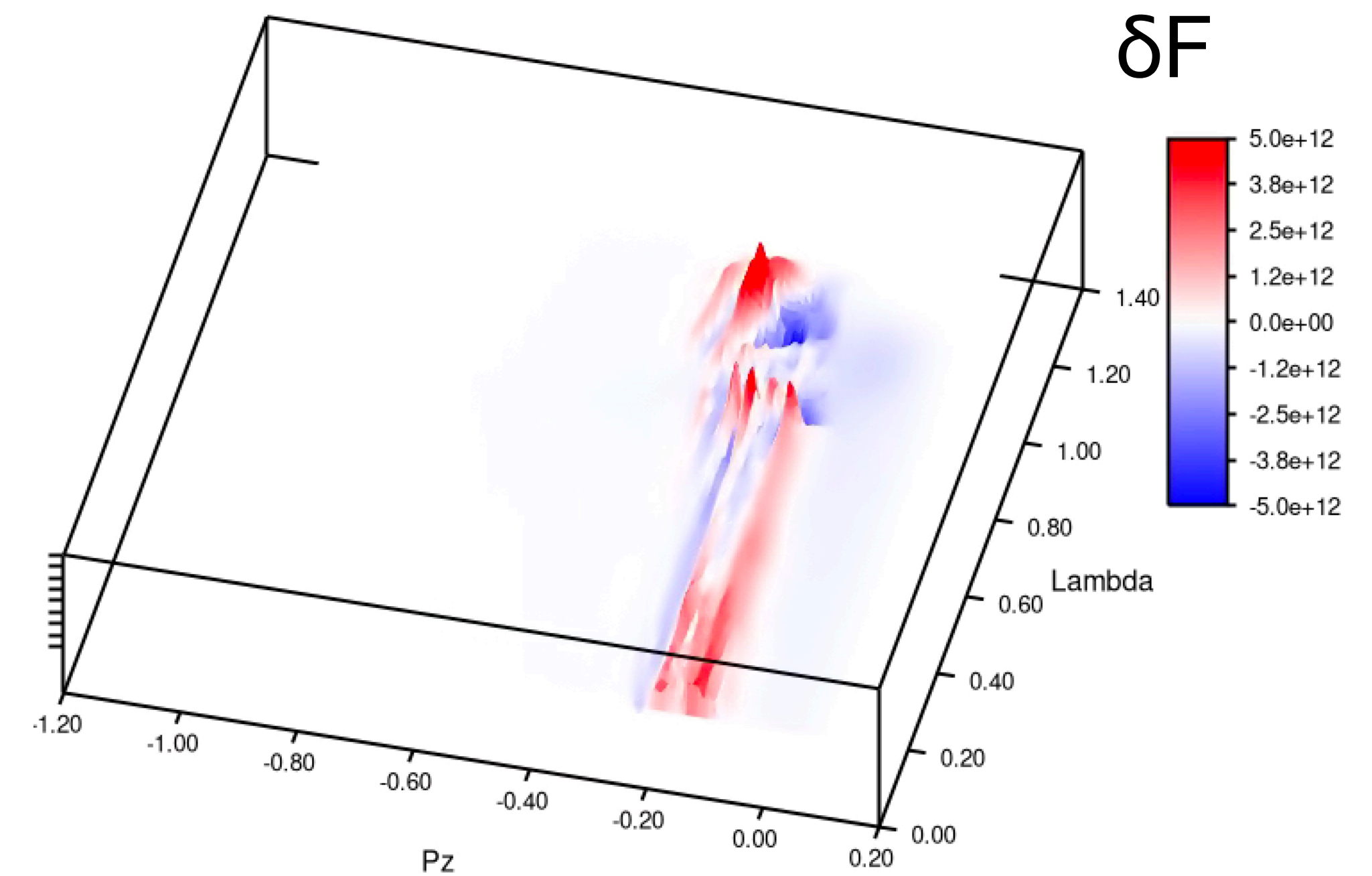
PSZS transport: cluster of $n=24-32$ TAEs

initial α - slowing down distribution



constant amplitude limit : $4 \cdot 10^{-4}$ dB/B

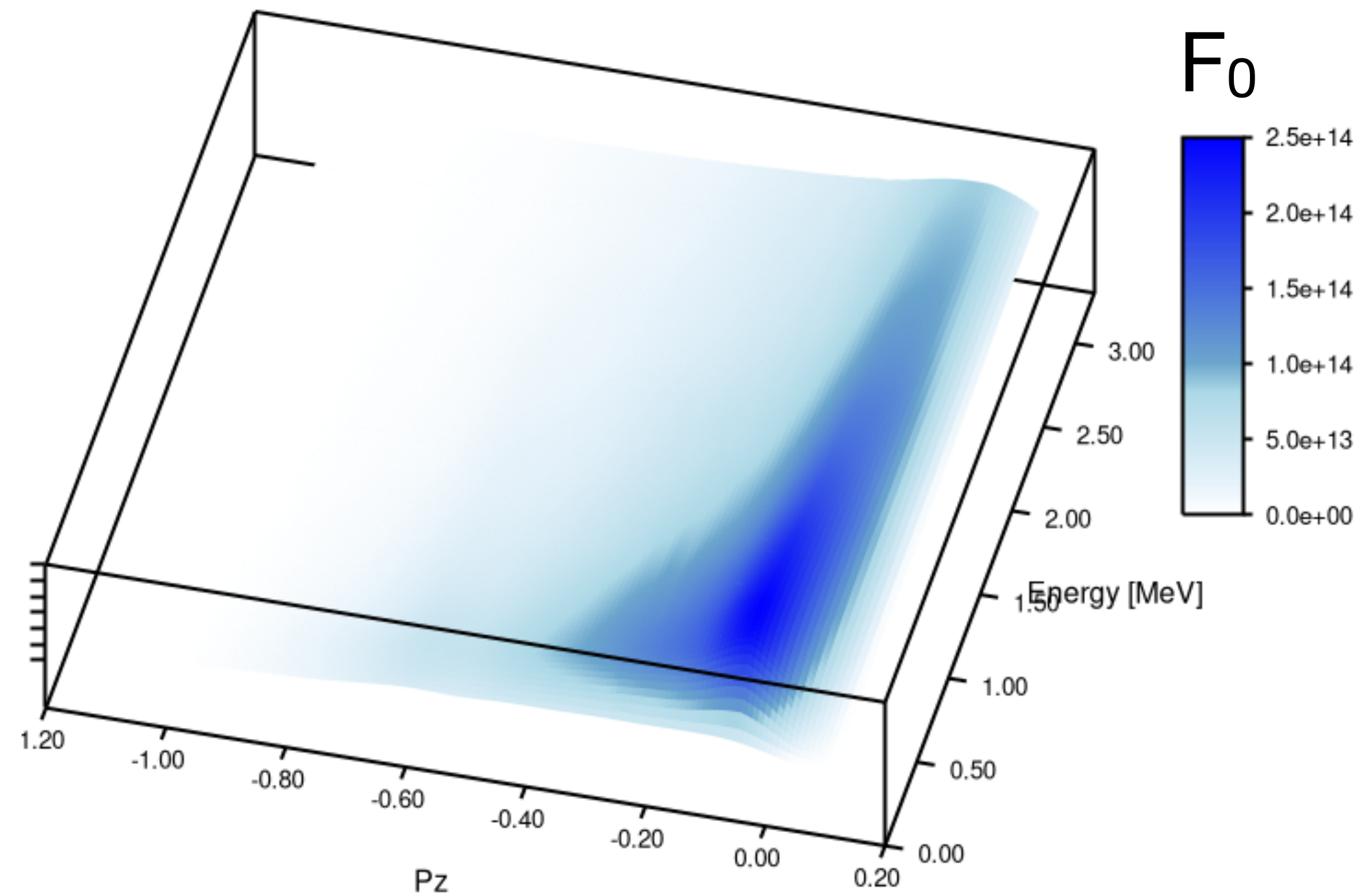
after ~ 1 ms (100 Alfvén times)



integrated over all energies

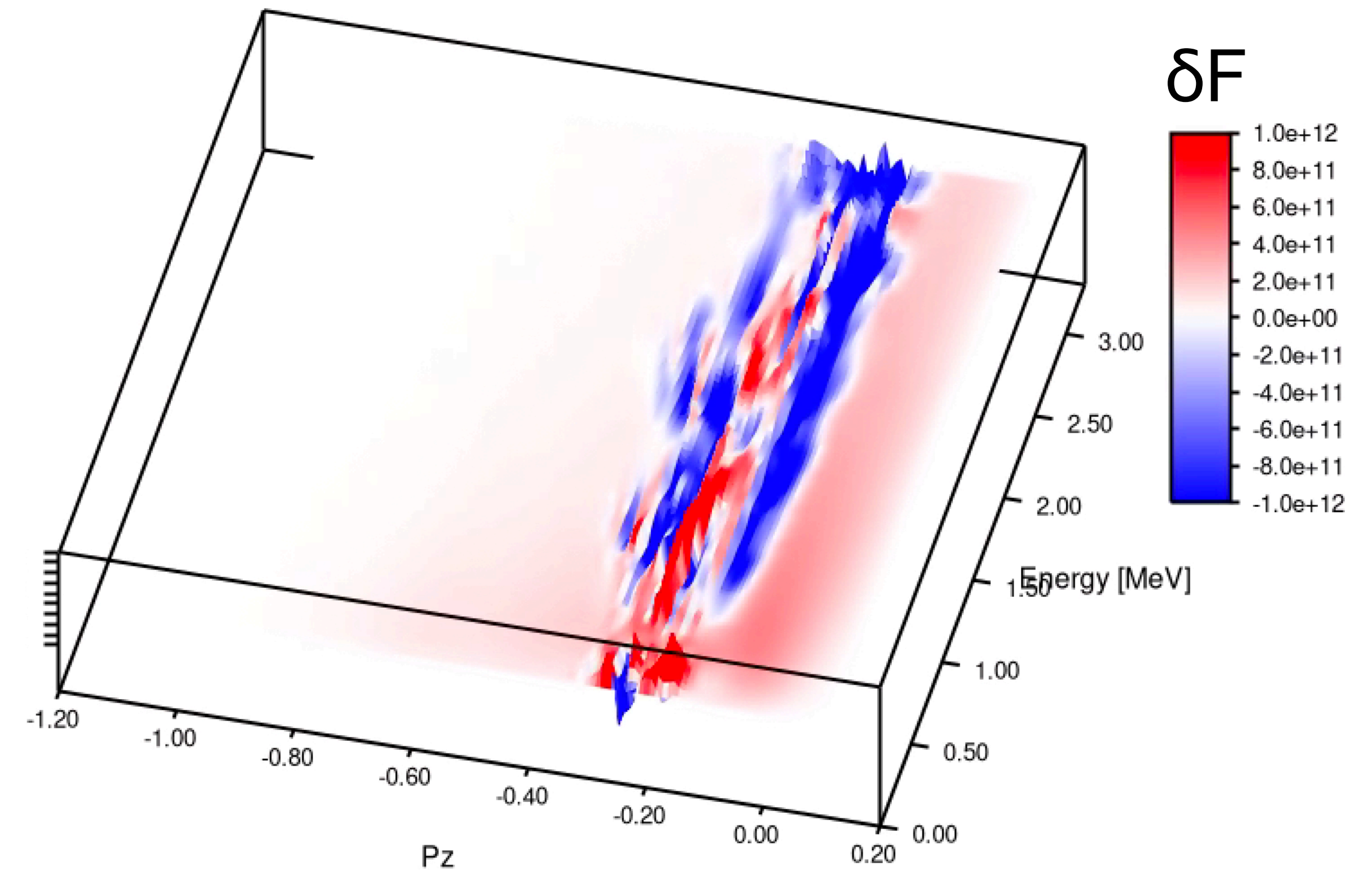
PSZS transport: cluster of n=24-32 TAEs

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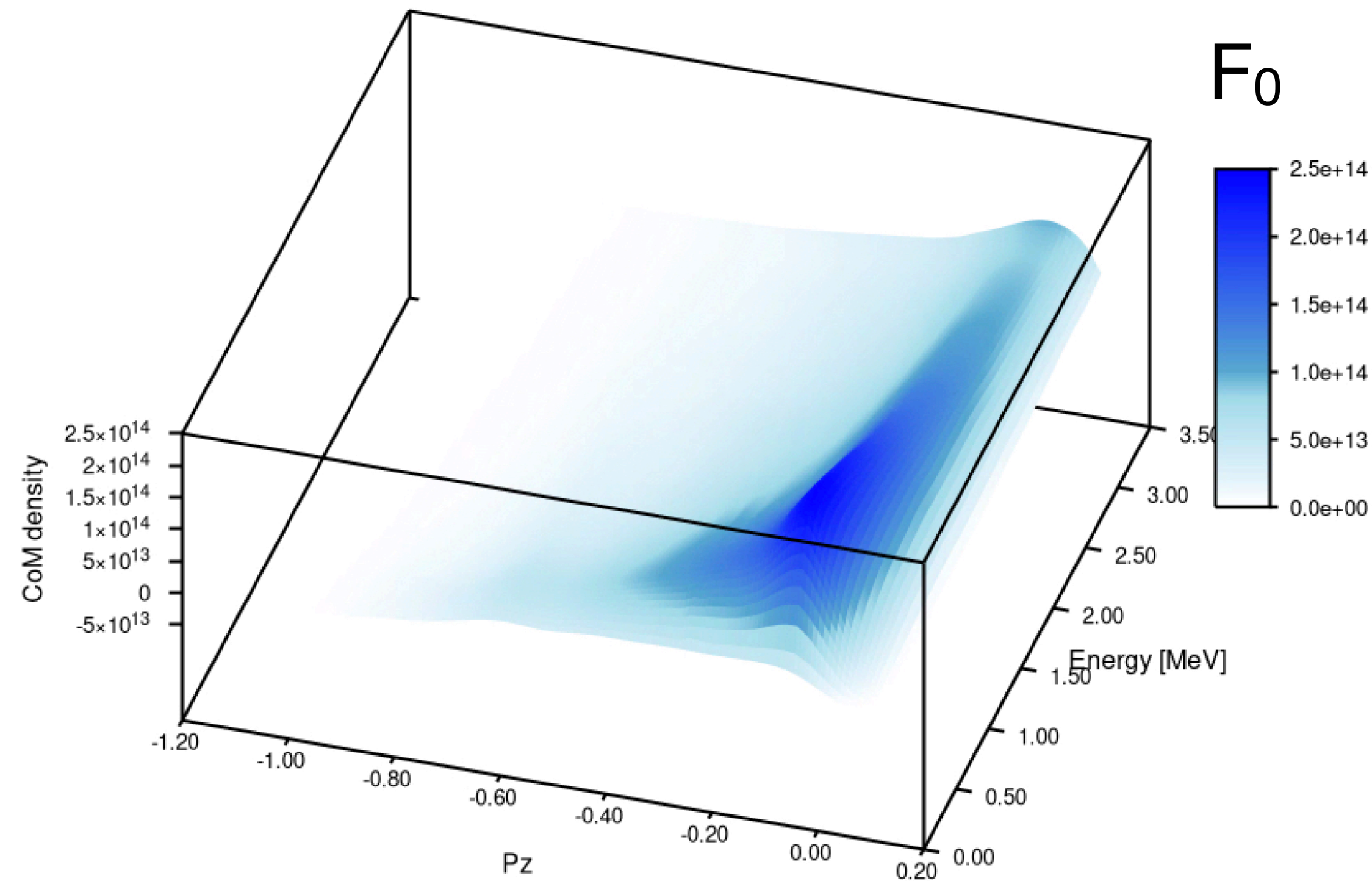
after ~ 1 ms (100 Alfvén times)



integrated over all Λ

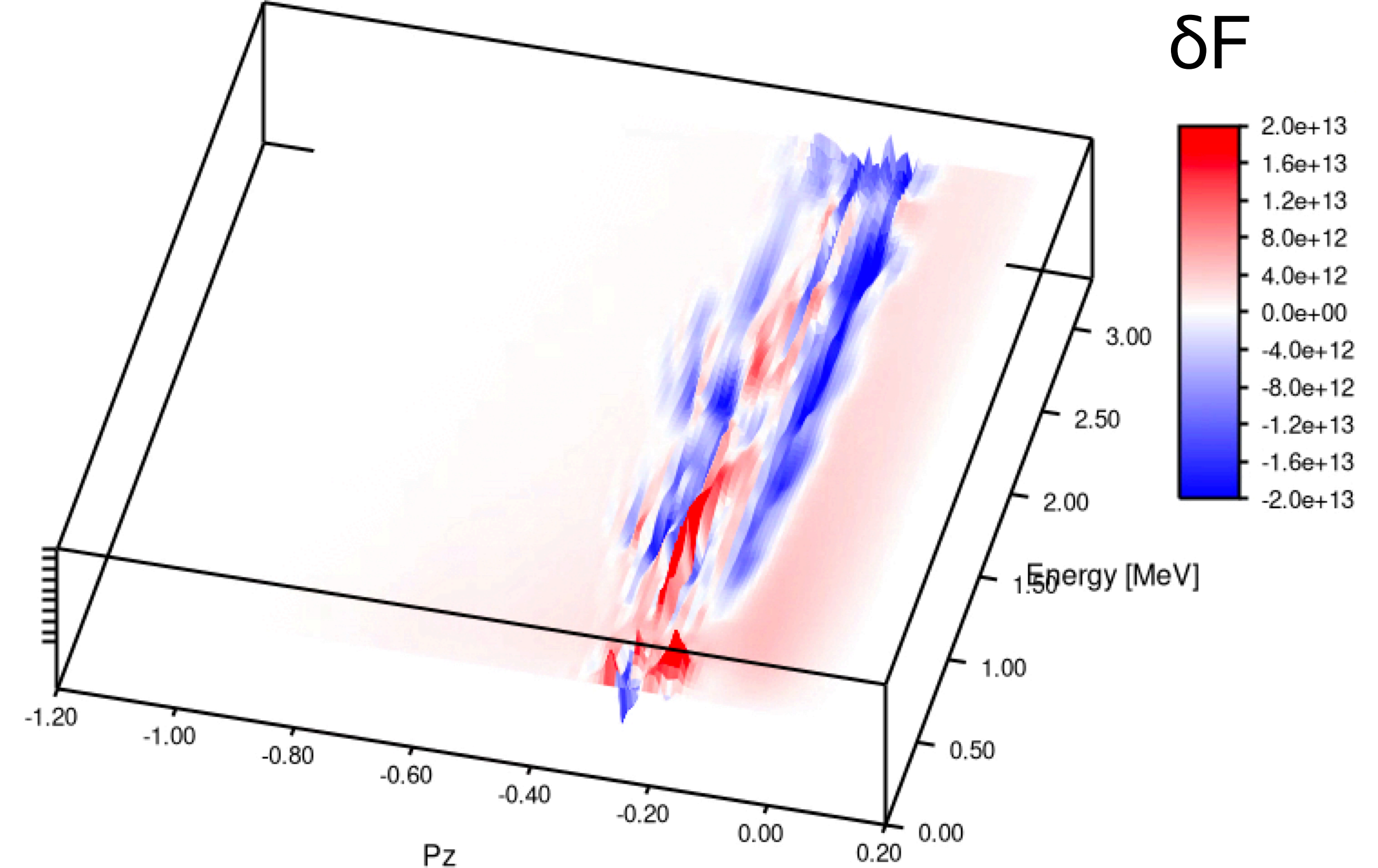
PSZS transport: cluster of n=24-32 TAEs

initial α - slowing down distribution



constant amplitude limit : $4 \cdot 10^{-4}$ dB/B

after ~ 100 ms (10000 Alfvén times)



1-10% changes in 100ms time scale - comparable to slowing down time scales
to be included in next step, together with unstable LFAMs, and marginally stable TAEs

VNS: strongly driven system, large EP fraction

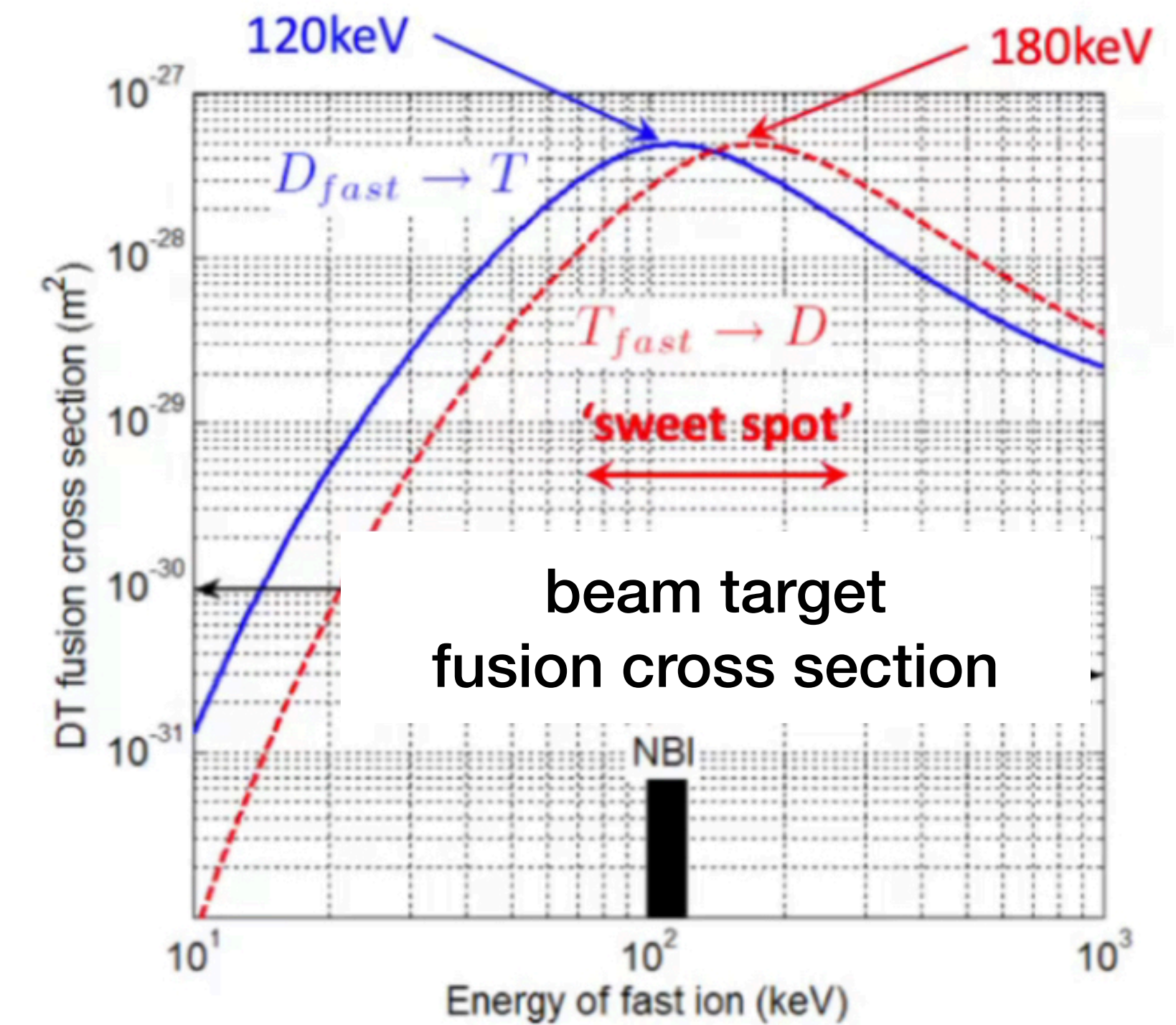
- physics principle well known, e.g. recent JET experiments, 12.5MW record [M Maslov, 2025]
- VNS: D beam in T plasma; slow down of beam ions on thermal T ions - maximise D-T reactions
- ~120 keV is sweet spot, accessible with PNBI technology
- $T_e(0)$ needs to be $\geq 10\text{keV}$: $E_{\text{crit}} \sim 220\text{keV}$

$$P_{\text{beam-target}} = f_T n_{D\text{-beam}} n_e \langle \sigma v \rangle_{\text{beam}} E_{DT}$$

$$P_{\text{thermonuclear}} = f_T(1 - f_T) n_e^2 \langle \sigma v \rangle_{\text{therm}} E_{DT}$$

in VNS: $\frac{\beta_{EP}}{\beta_{\text{back}}} \sim \frac{n^{-1} T_i^{3/2}}{n T_i} \sim T_i^{1/2} n^{-2}$ slowing down/background beta

externally driven

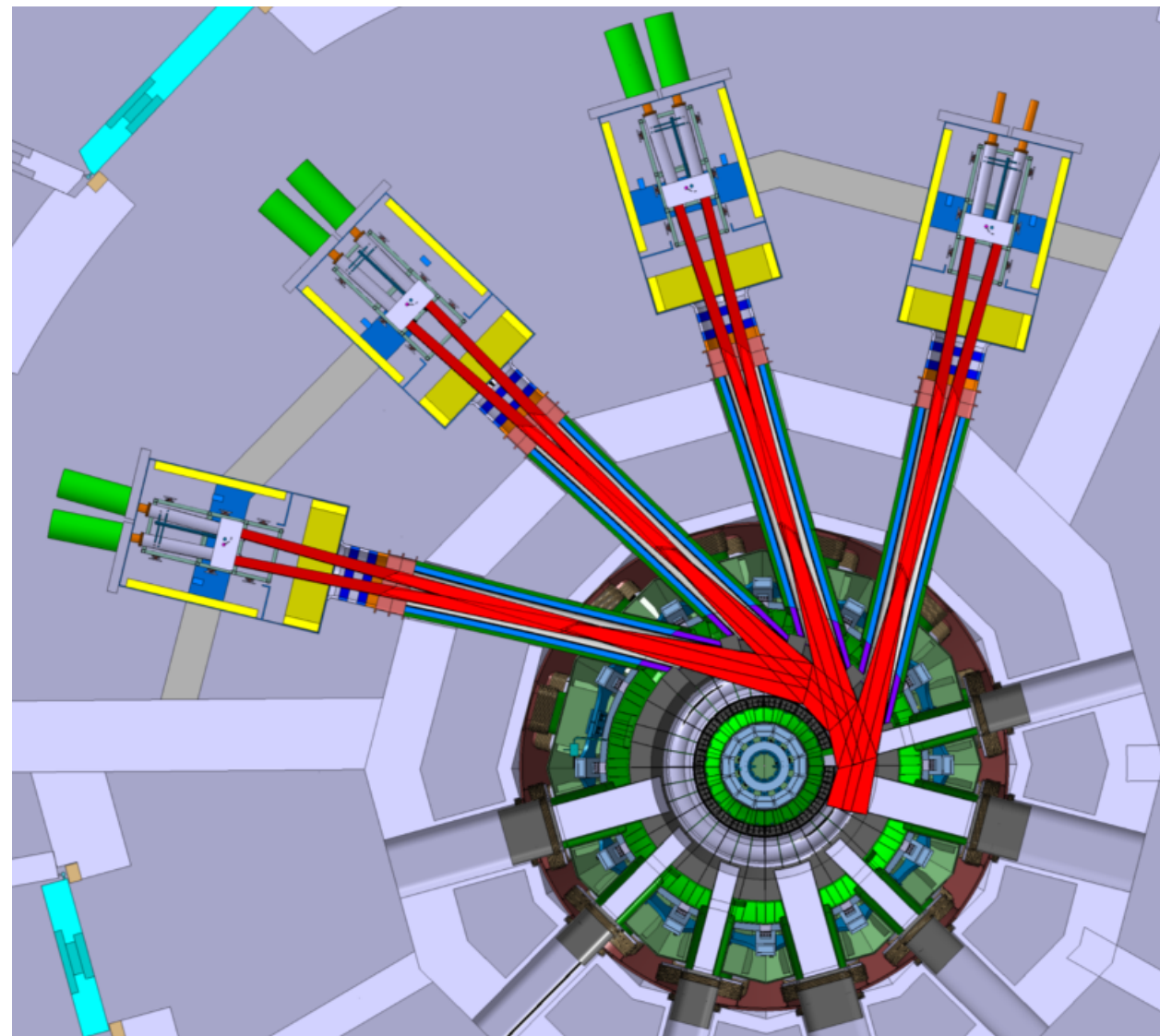


challenge: minimise dilution of T plasma with D beam;
control n, T, EP, impurity, rotation profiles to maximise neutron wall load, while protecting divertor
→ integrated modelling; challenge: outside well tested parameter range

VNS: optimisation of neutron wall load

VNS (Volumetric Neutron Source)

[M.Siccinio et al EPS 2026; PPCF 2026, A. Quartararo, SOFT 2026]



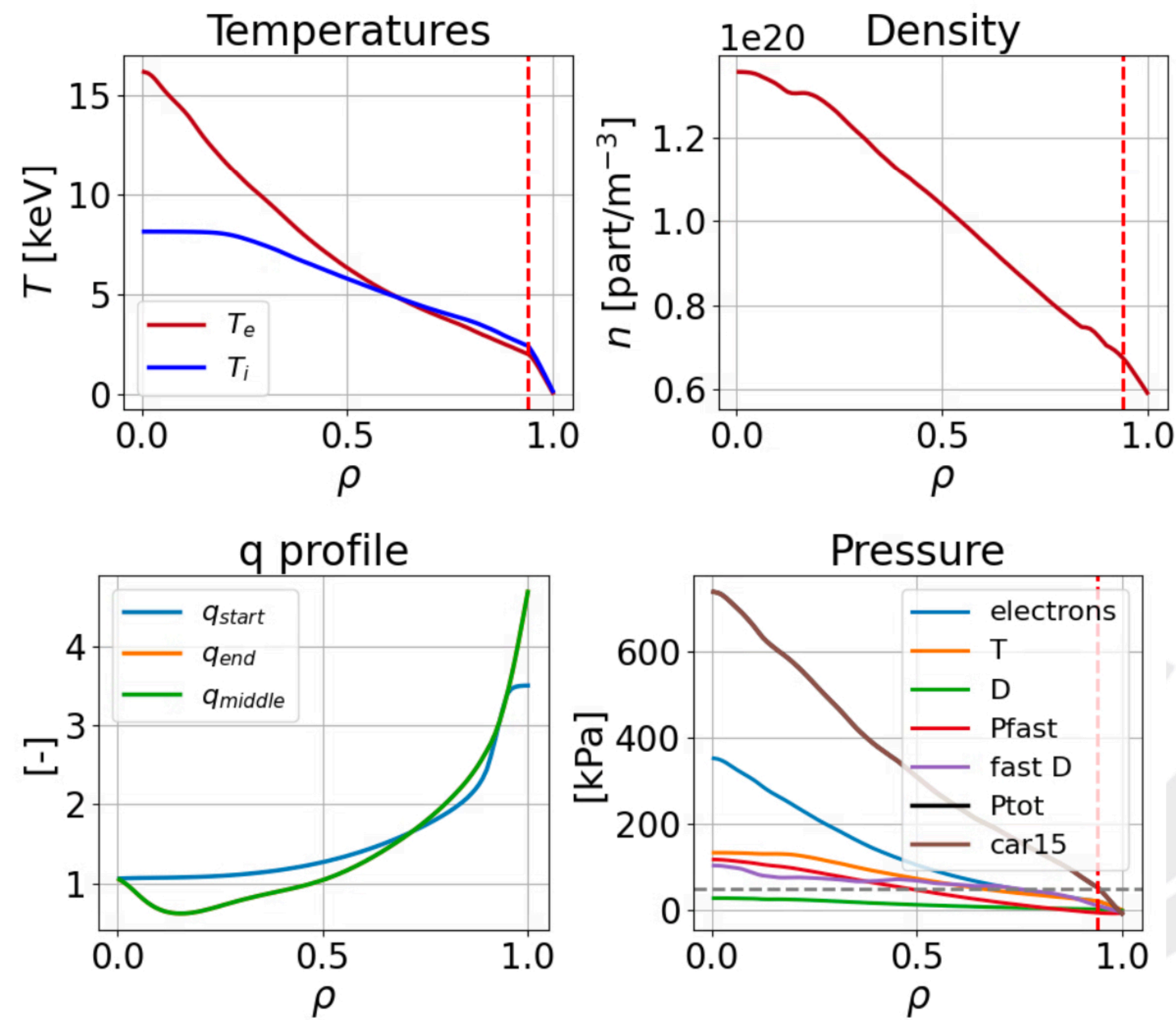
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P_{fus} [MW]/beam target	42/36
τ_{pulse} [hr]	∞
T consumption	2.38 kg/full power y
A	4.25
R_0 [m]	2.67
$B_{T,0}$ [T] / I_p [MA]	5.6 / 2.54

optimisation/trade-off problems (selection):

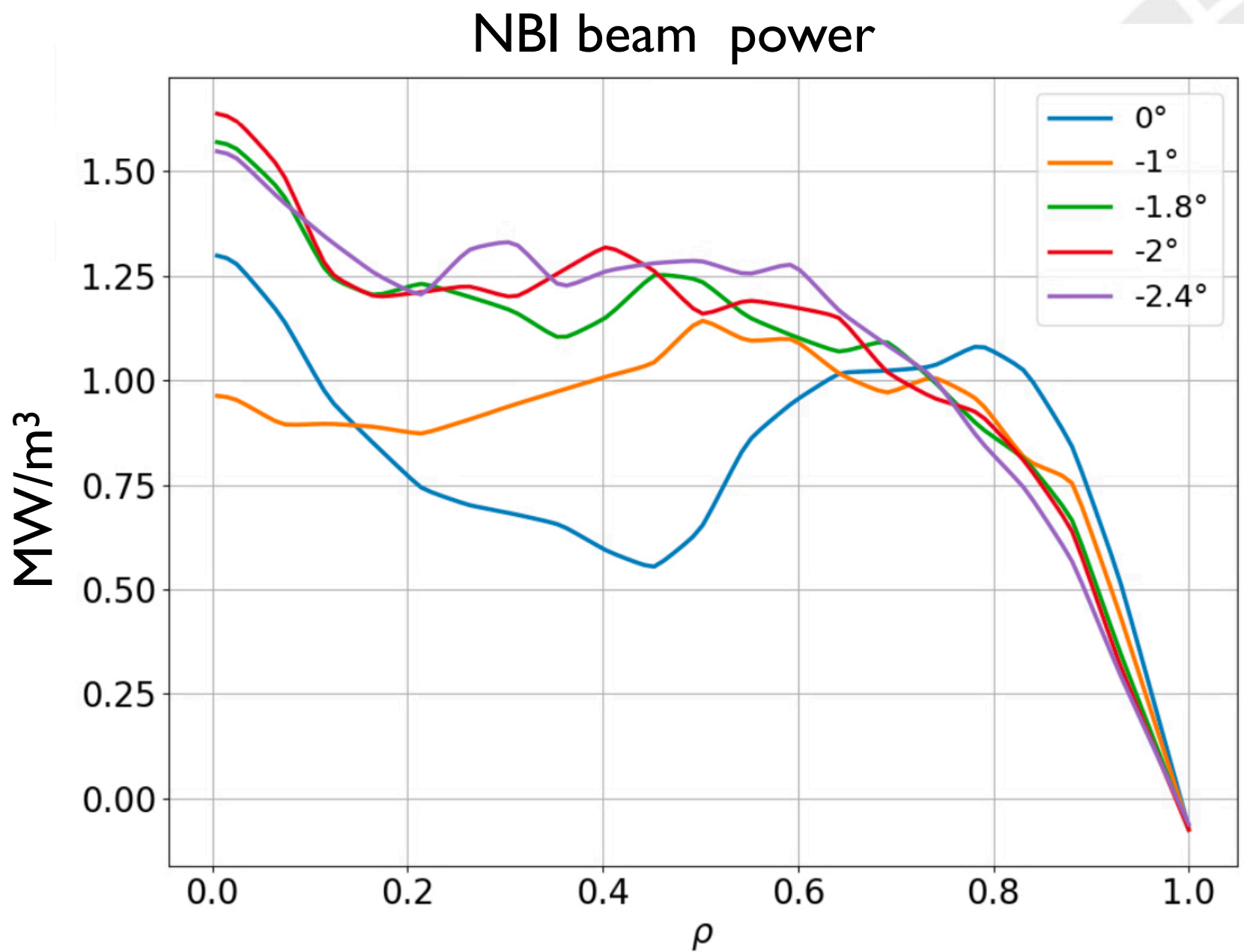
- high heating power/max. NWL **vs** exhaust: compactness of machine - small surface for high flux
- impurity seeding/high pedestal density/tritium throughput for exhaust **vs** beam penetration
- beam angle inclination **vs** NBI current drive (very little flux from central solenoid)
- PNBI limited to ~ 150 keV **vs** NNBI steady state technology needs more time to develop
- tangential injection **vs** rotation leads to decrease in beam-target cross section ('Doppler shift')
- and **vs** W transport in strongly rotating plasmas
- and **vs** MHD and EP stability/transport
- and **vs** current profile control: NBI/ECCD

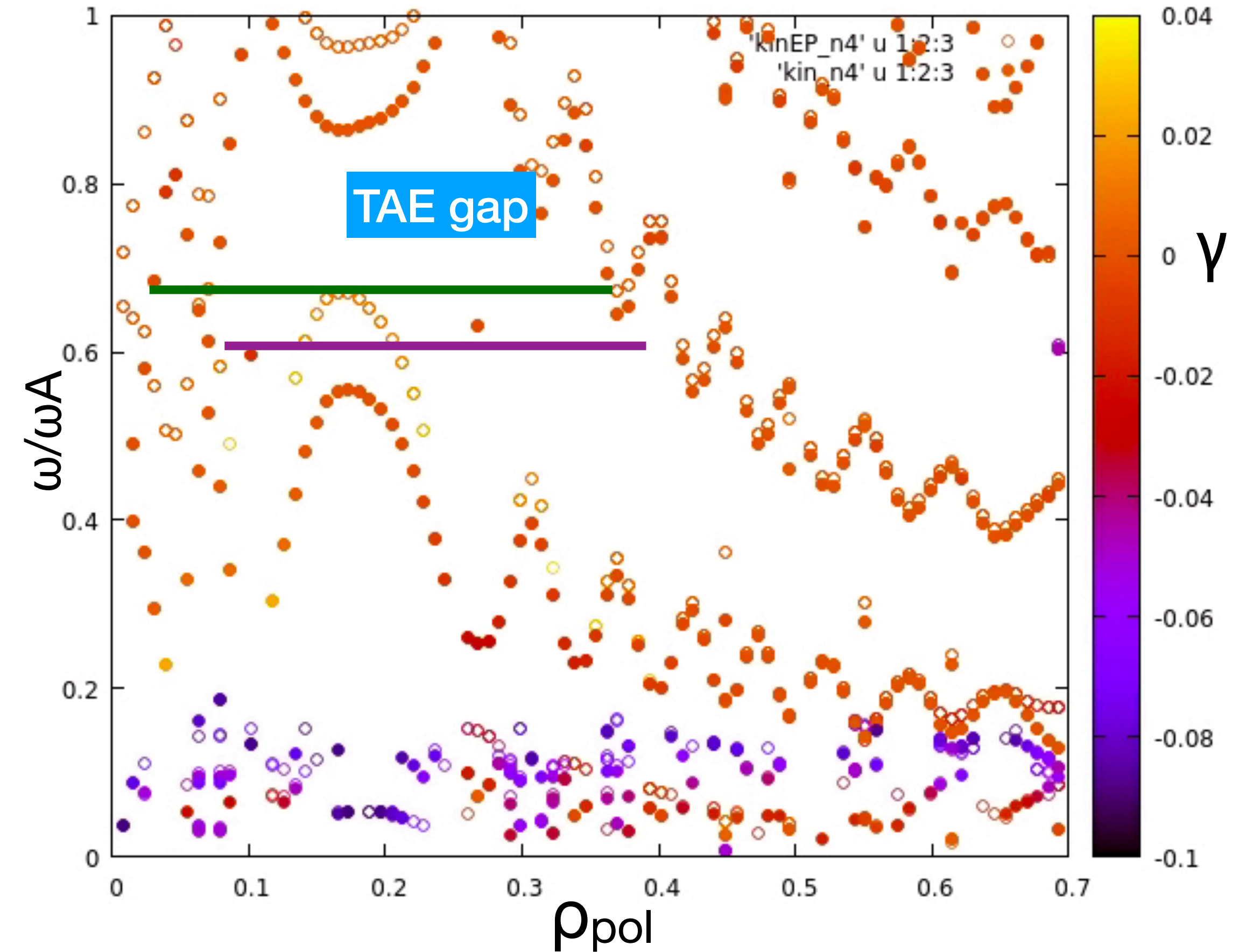
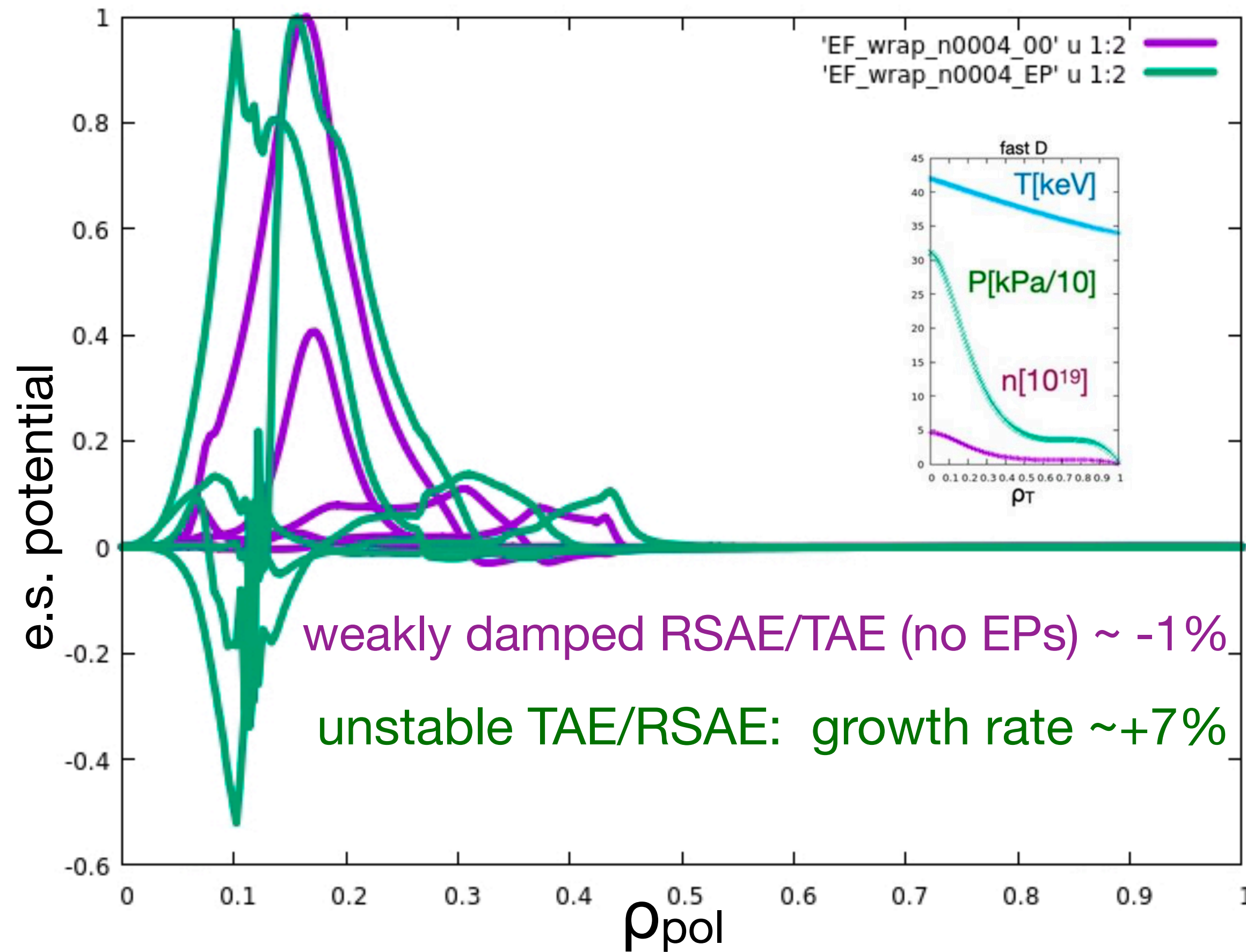


- successful validation on JET beam-target, high rotation cases
- new VNS reference scenario established (Sept 2026)



$\langle n_e \rangle$	9
beam energy	150 keV
inj. angle	2.0°
heating power	45(NBI)/15 (ECRH) MW
fusion power	27.1 MW
NWL	0.35 MW/m ²
loop volt.	4mV



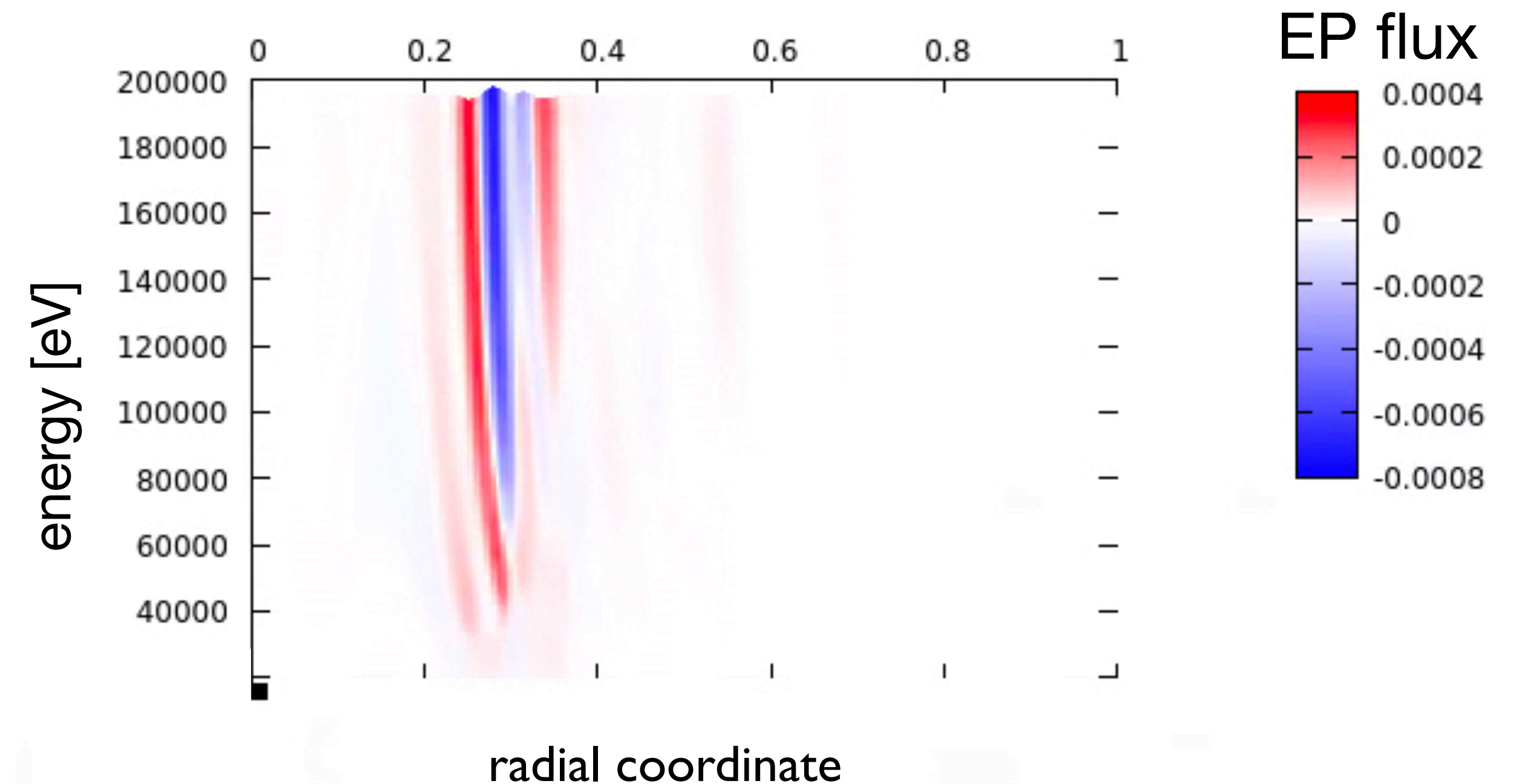
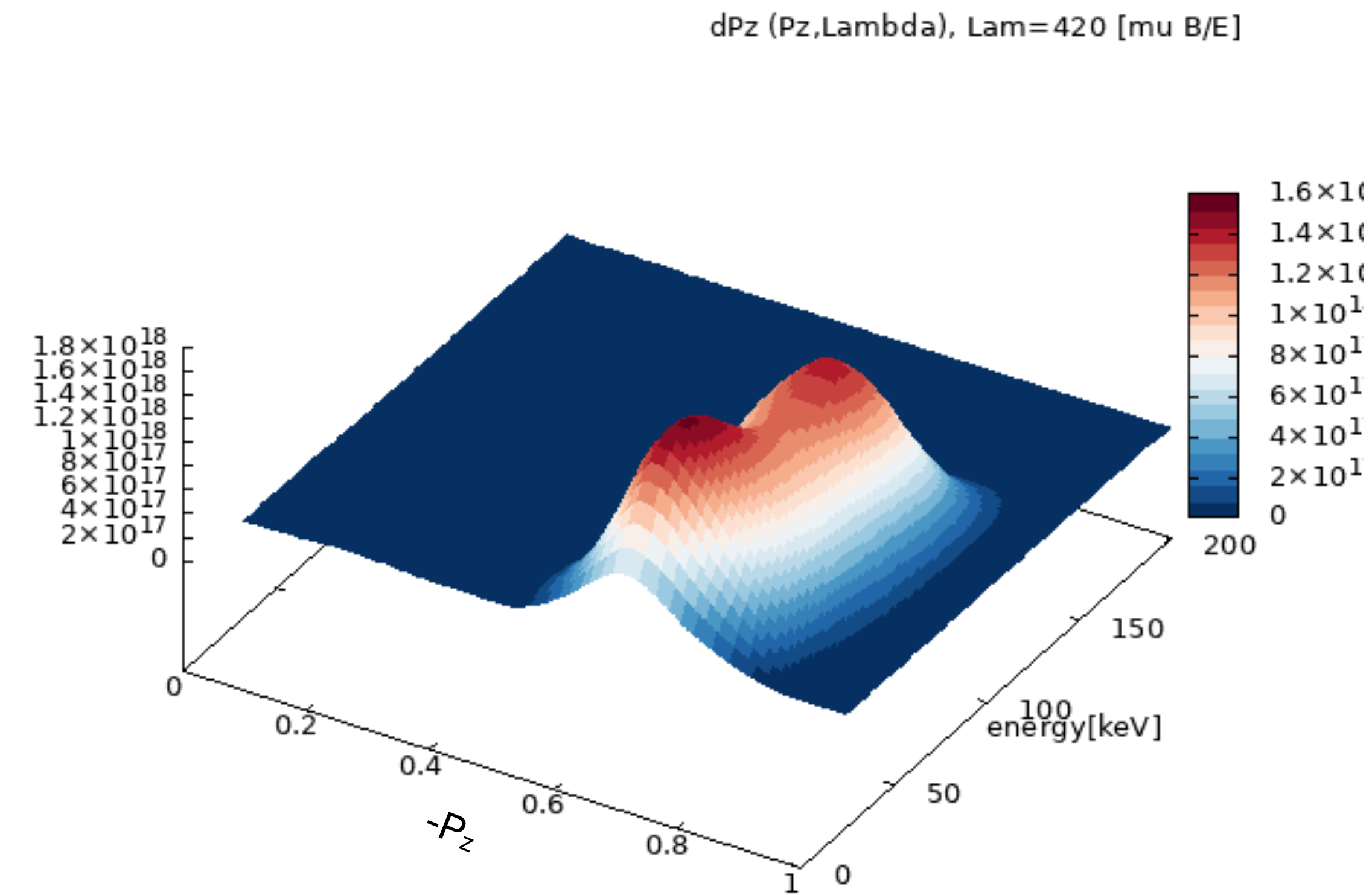


- with 1d-radial eq. Maxwellian EP profile nominal beam power profile:
- core localised Alfvénic modes found to be unstable
- TAEs driven by $v_A/3$ resonance ~60 keV circulating particles
- mode spectrum similar to AUG/JET: $n=3\dots 8$
- expected radial transport and relaxation of beam deposition profile - can cause significant reduction of fusion power

- for most unstable modes:
 $\rho_{\text{drift},\alpha} \cdot k_\theta \sim 1$, and $\rho_{\text{drift},\alpha}$
independent of B, $k_\theta \sim nq/r$;
 $\rightarrow n \sim r$ ($a=0.62\text{m}$)

CoM F_{NBI} as given ASCOT

ATEP PSZS fluxes for TAE modes:



- test case: here beam does not penetrate in core - no overlap with modes - update ASCOT runs for beam distribution
- to be done: multi-modes + different AE types + fishbones + ripple
- impact on current drive is of high interest as it impacts flux consumption and thus directly steady state condition [\[Kim, NF 2024\]](#)

burning plasmas of DEMO call require multi-scale EP analysis:

- EP redistribution in core by LFAM/AITG, mid-radius TAE, outer edge islands/ripple ($q=1$ would add another coupling channel);
- influence on current redistribution important - flux consumption!
- coupling to collisional effects and micro-turbulence is required - reduced models are key

beam-target plasmas as neutron source:

- principle is well known and demonstrated
- high-fidelity modelling is challenging: non-perturbative EP effects on deposition, current drive rotation and exhaust
- need to integrate reduced models in high-and low fidelity tools (/transport/process codes)