



Aspects of energetic particle physics in future tokamak devices

Ph. Lauber

C. Bourdelle, F. Maviglia, A. Quartararo, M. Siccinio, P. Zumbolo, S. Wiesen,
C. De Piccoli, K. Särkimäki, A. Snicker, P. Vincenzi, M. Weiland, E. Bray, T. Luda, E. Fable, C. Angioni
T. Hayward-Schneider, M.-V. Falessi, V.-A. Popa, T. Sterkl, R. Stucchi, F. Zonca, and input from TSVV-G,H, DCT, WPDES teams



MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK



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burning fusion plasma physics

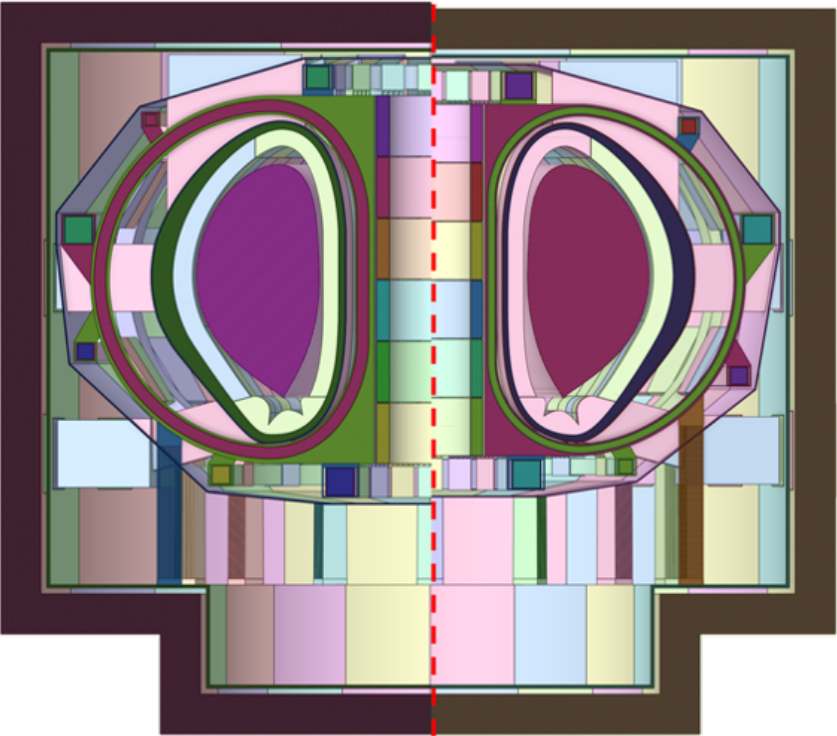
- self organisation: fusion power prediction in the presence of multi-scale physics: profiles, non-linear equilibria, phase space zonal state *[Chen&Zonca 2016, Falessi 2023]*
- long-time behaviour: performance degradation due to weak TAEs *[Kim, NF 2024]*
- resilience to transient events
- control possibilities: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

neutron source for addressing technology challenges

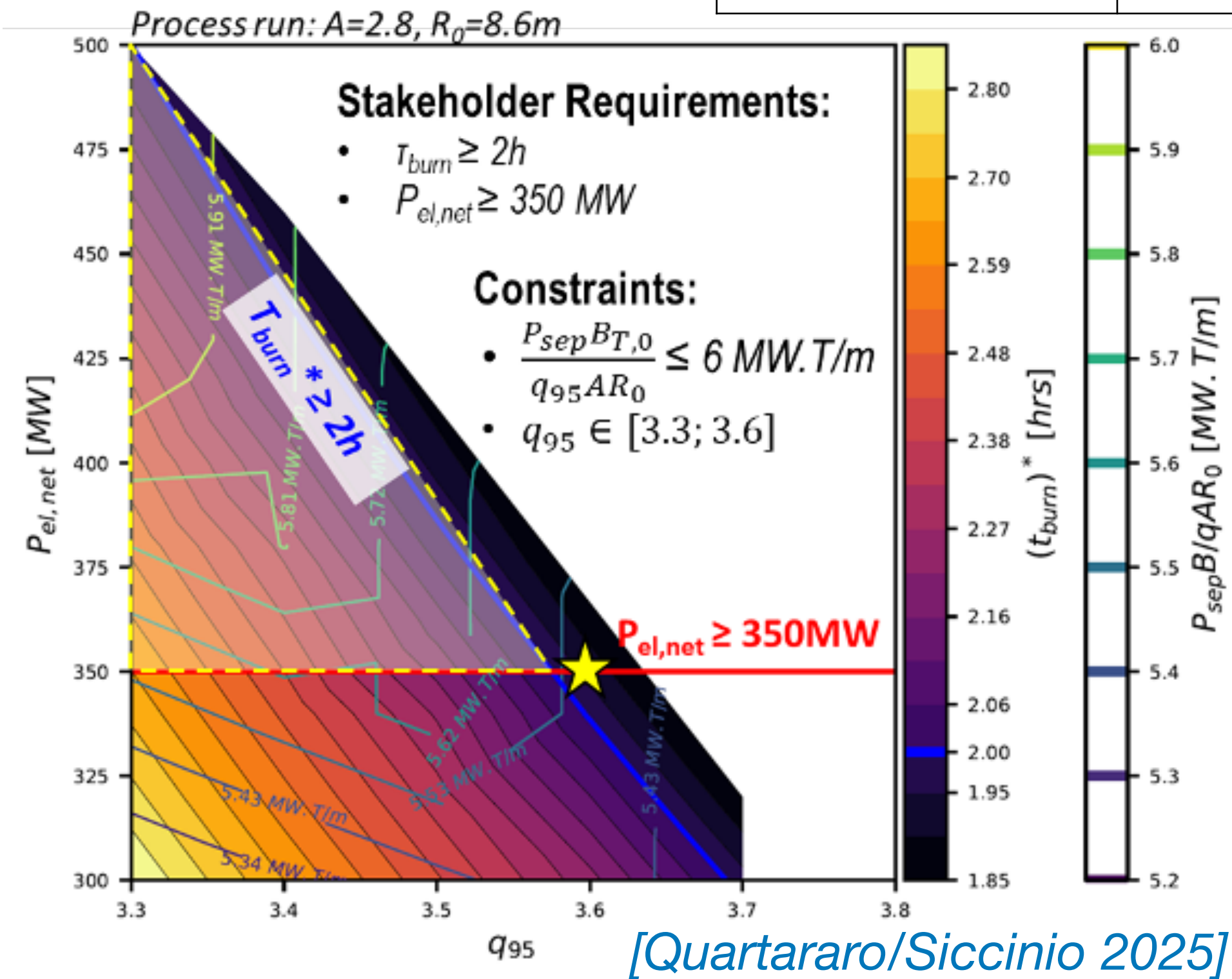
- strongly driven system using beam-target concept: **maximise neutron flux AND fluence for tritium breeding technology** and material qualification *[Frederici et al NF 2023]*
- for minimising costs: system needs to be as close as possible at the limit of operational boundaries
- needs to operate as 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]

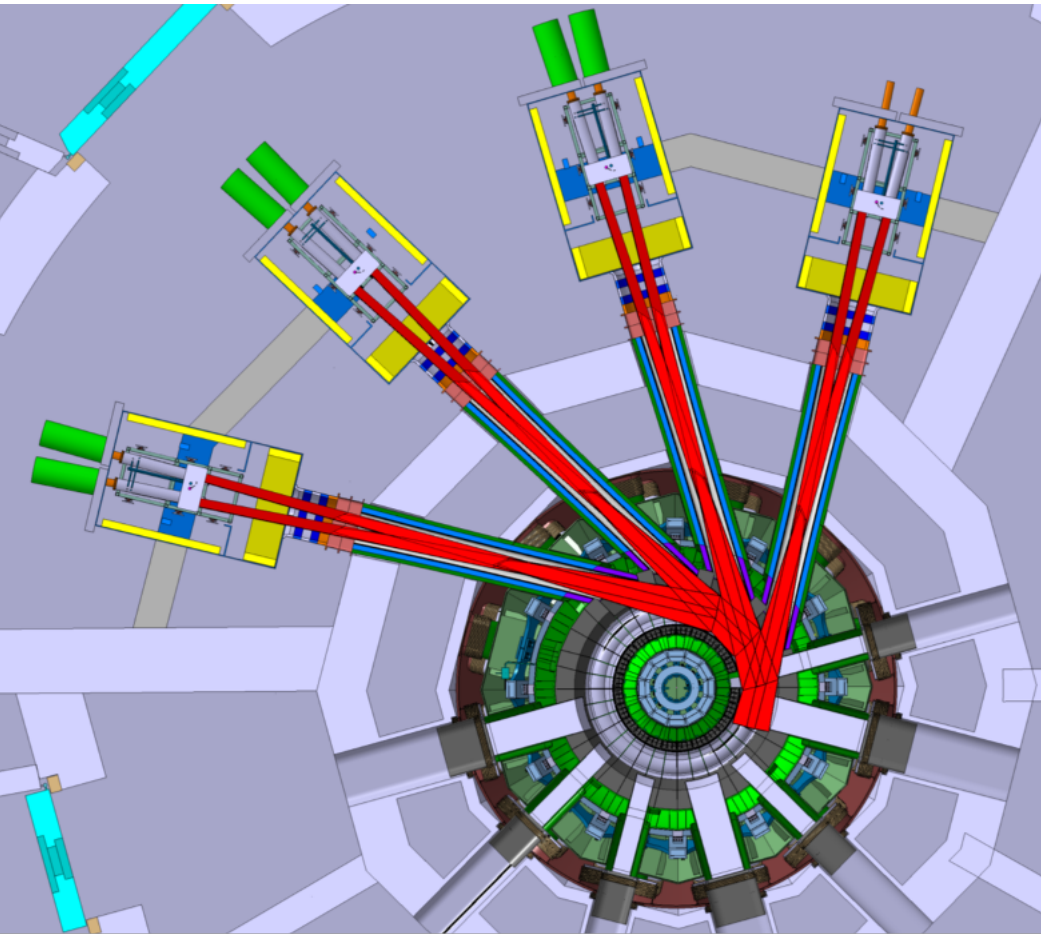


$P_{el,net}$ [MW]	350
P_{fus} [GW]	1.6
τ_{pulse} [hr]	2
divertor flux if accidental reattachment [MW/m ²]	44.3<50
A	2.8
R_0 [m]	8.6
$B_{T,0}$ [T] LTCS I_p [MA]	4.39/19
lifetime dpa (blanket)	20-40



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] / I_p [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
fusion power [MW]	-	42/36	12.5	-	500	1600
$\beta_{EP,0}/\beta_{thi,0}$	1*	1	0.5-2 (ICRH)	<2.5	0.5-0.7	0.7
$R_0 \nabla \beta_\alpha / \beta_{thi}$	6*	6-10	3-6	5	2	1.8
$B_0[T]/I_p[MA]$	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

similar ratio of ion heating/volume for AUG-VNS, but:

- higher beam energy
- lower ICRH vs α energy

* 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: $\frac{\beta_{\alpha}}{\beta_{back}} \sim \frac{n^2 T_i^2 \cdot T_i^{3/2}}{n^2 T_i} \sim T_i^{5/2}$

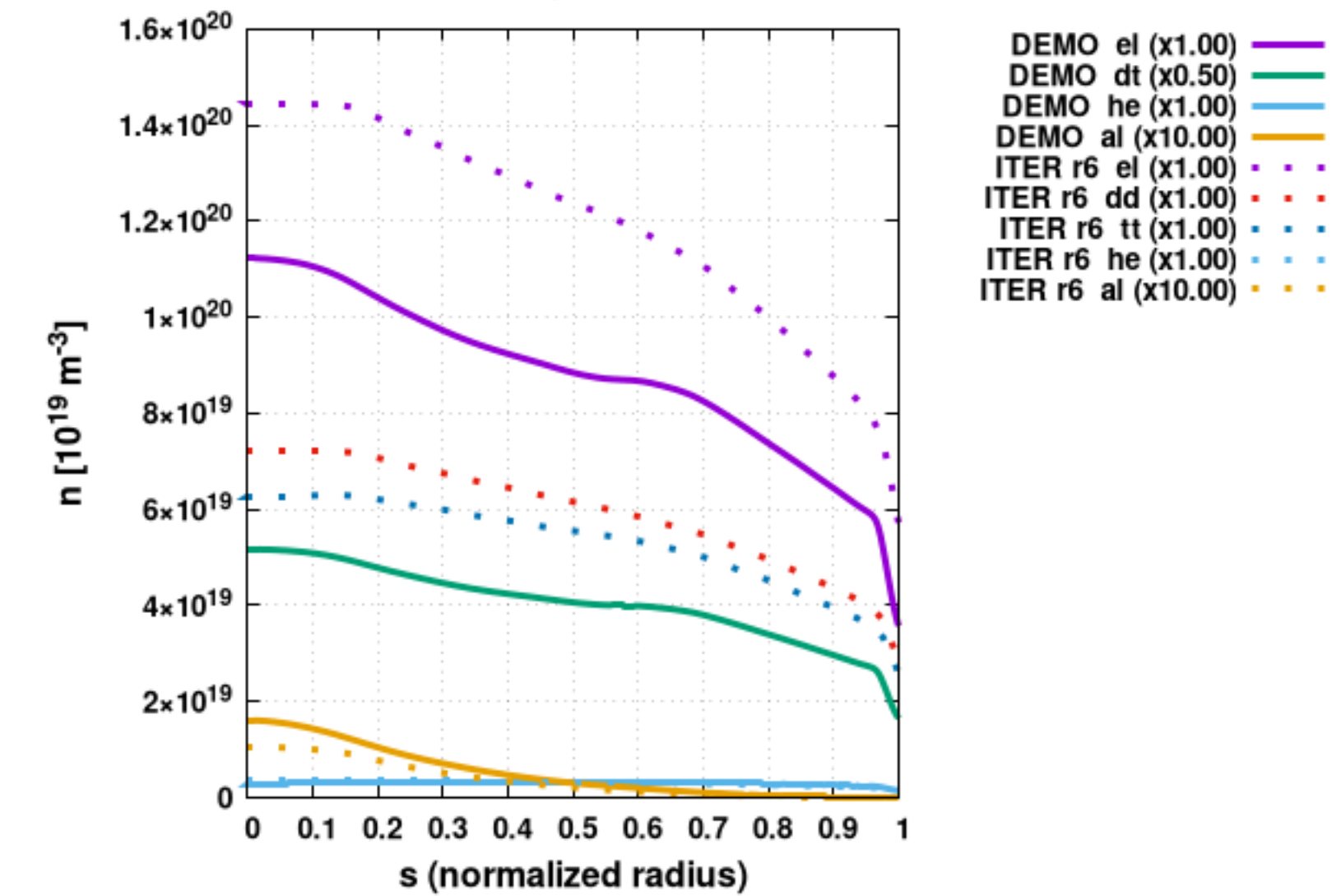
self-organising

- 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?

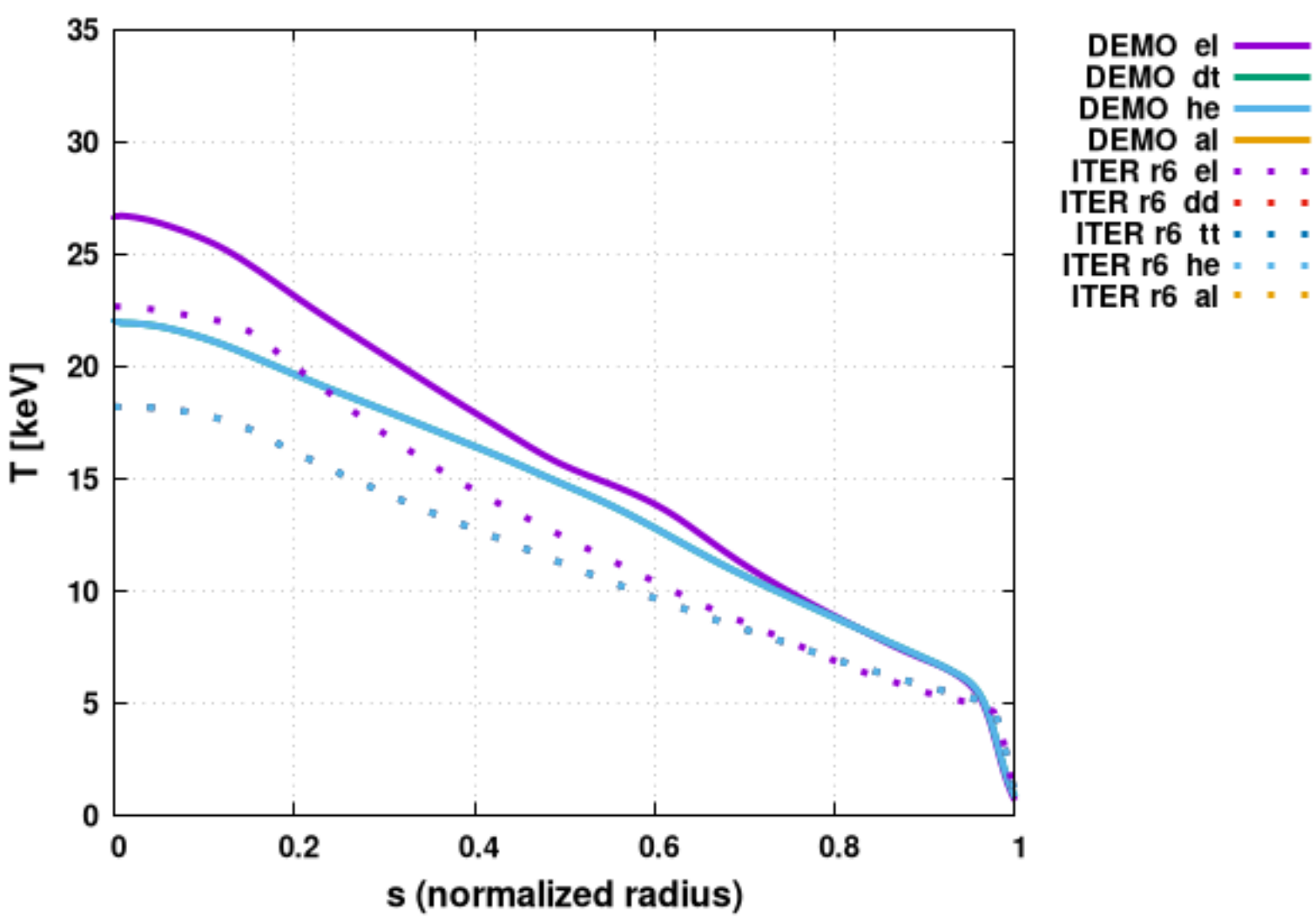
ASTRA TGLF SAT2

DEMO vs ITER 53299/6, $q = 1$ (dens, temp, press, q /shear)

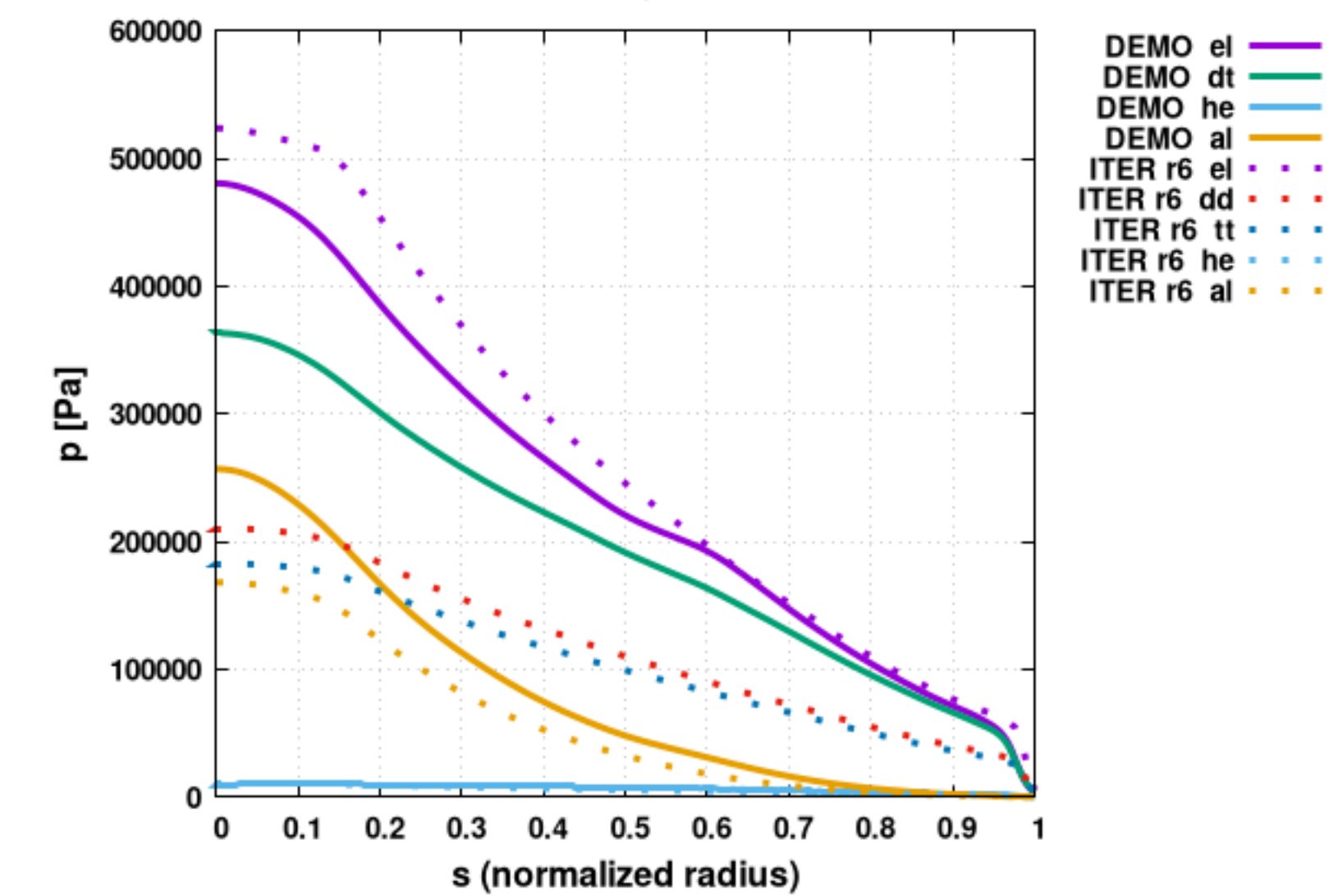
Density profiles



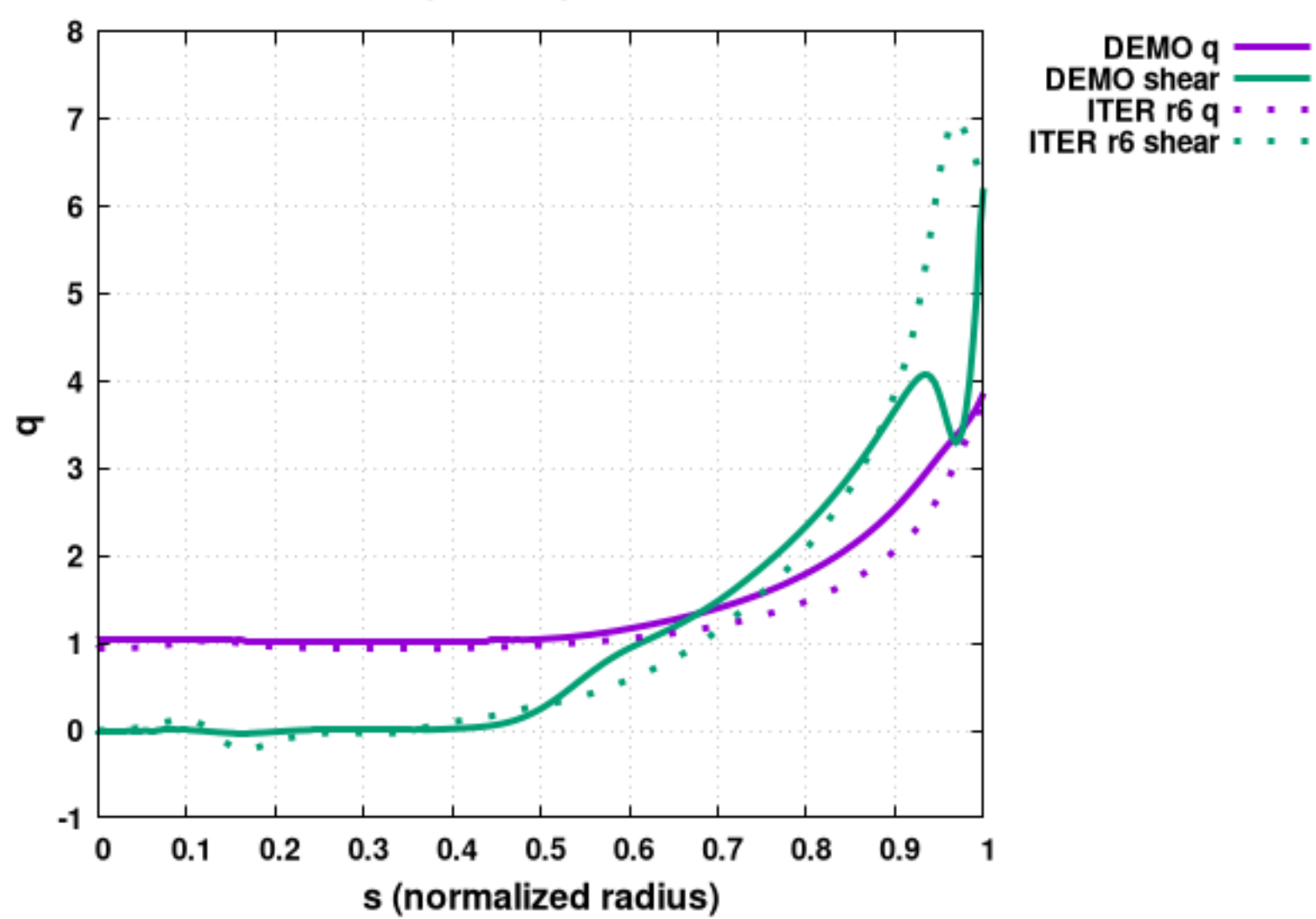
Temperature profiles



Pressure profiles



q , shear profile

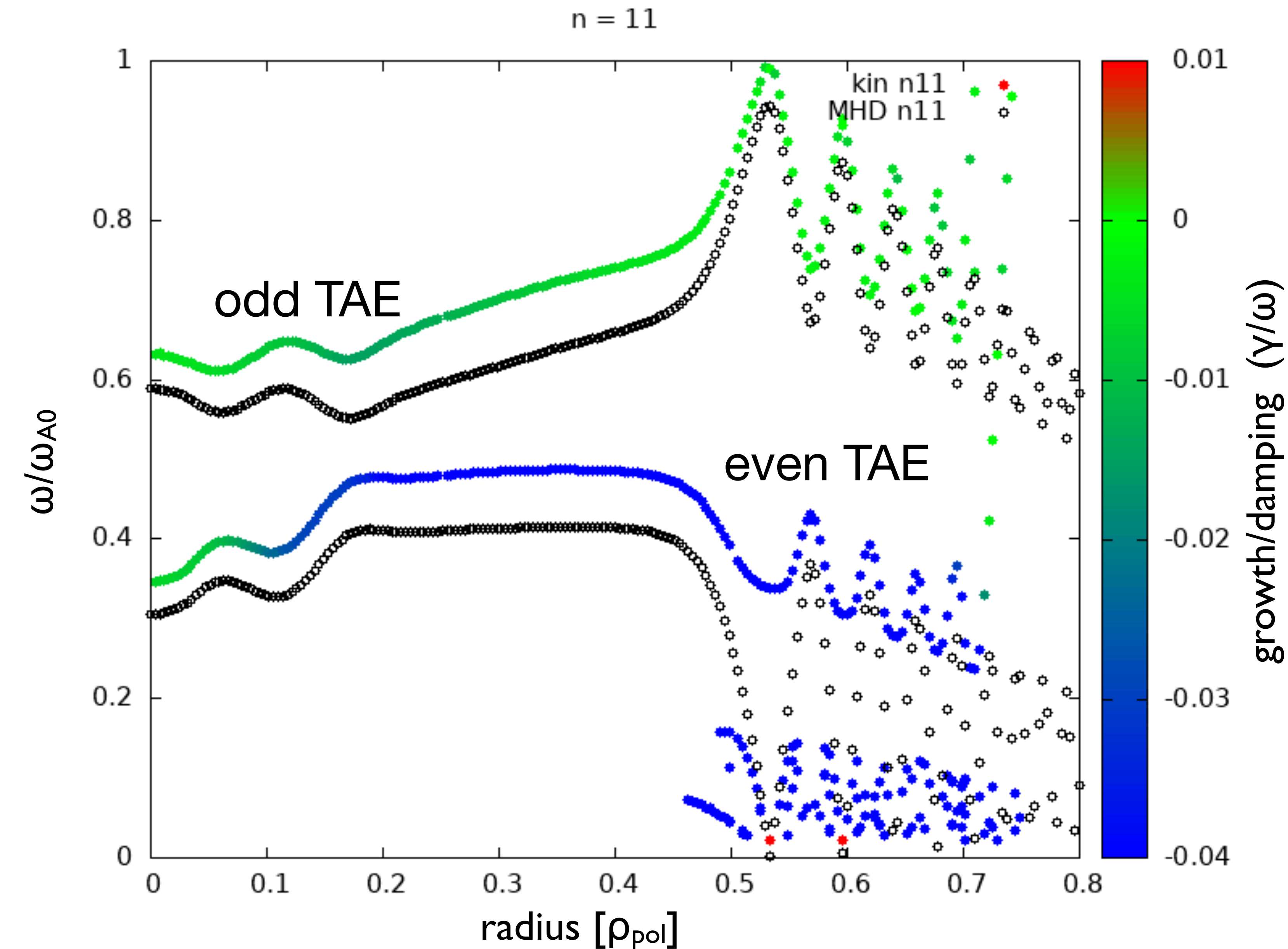


[¹ DEMO:T Luda, EPS 2026; C. Bourdelle in prep.]

[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 $n*T$
- $v_\alpha/v_{Alfvén} \gtrsim 1$ for alpha particles $\gtrsim 1MeV$: effective resonant drive
- most effectively driven Alfvén eigenmodes: tor. mode number $n \sim 20-30$

	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

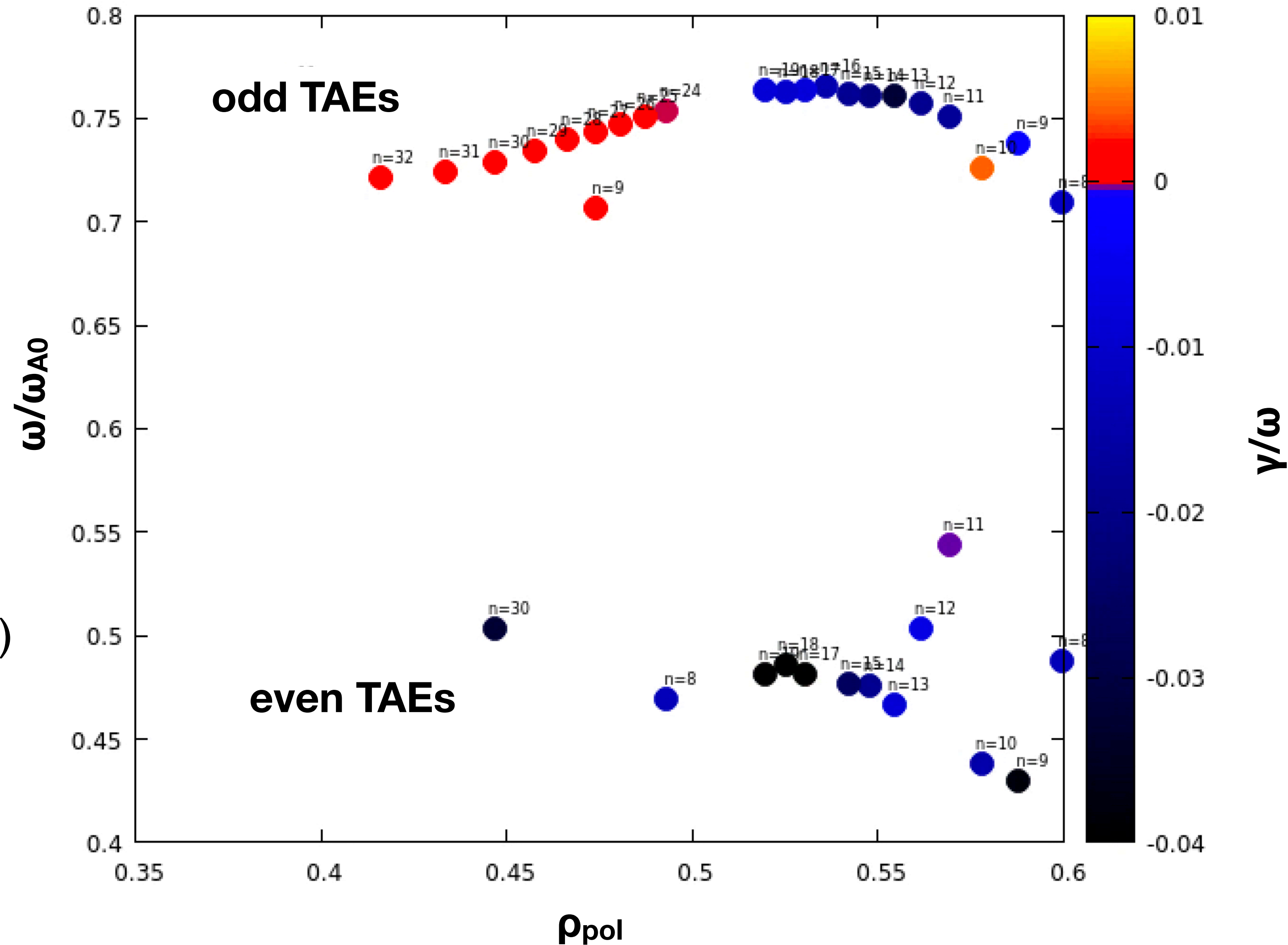


solution of local kinetic dispersion relation, including α -particles in ZOW limit

global analysis of odd and even TAE branches

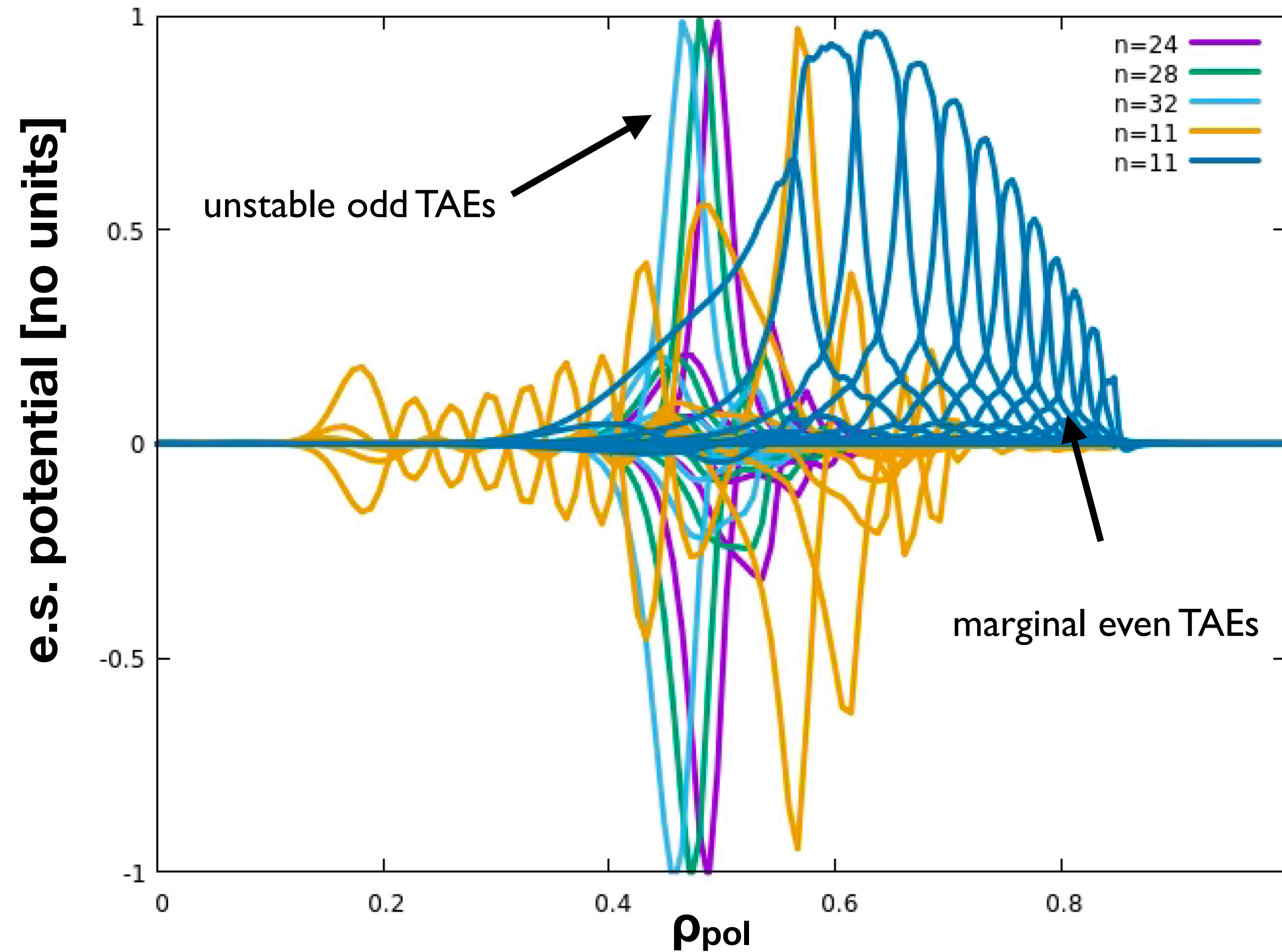
TAEs marginal for
nominal profiles
(1 MeV equ. Maxwellian)

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



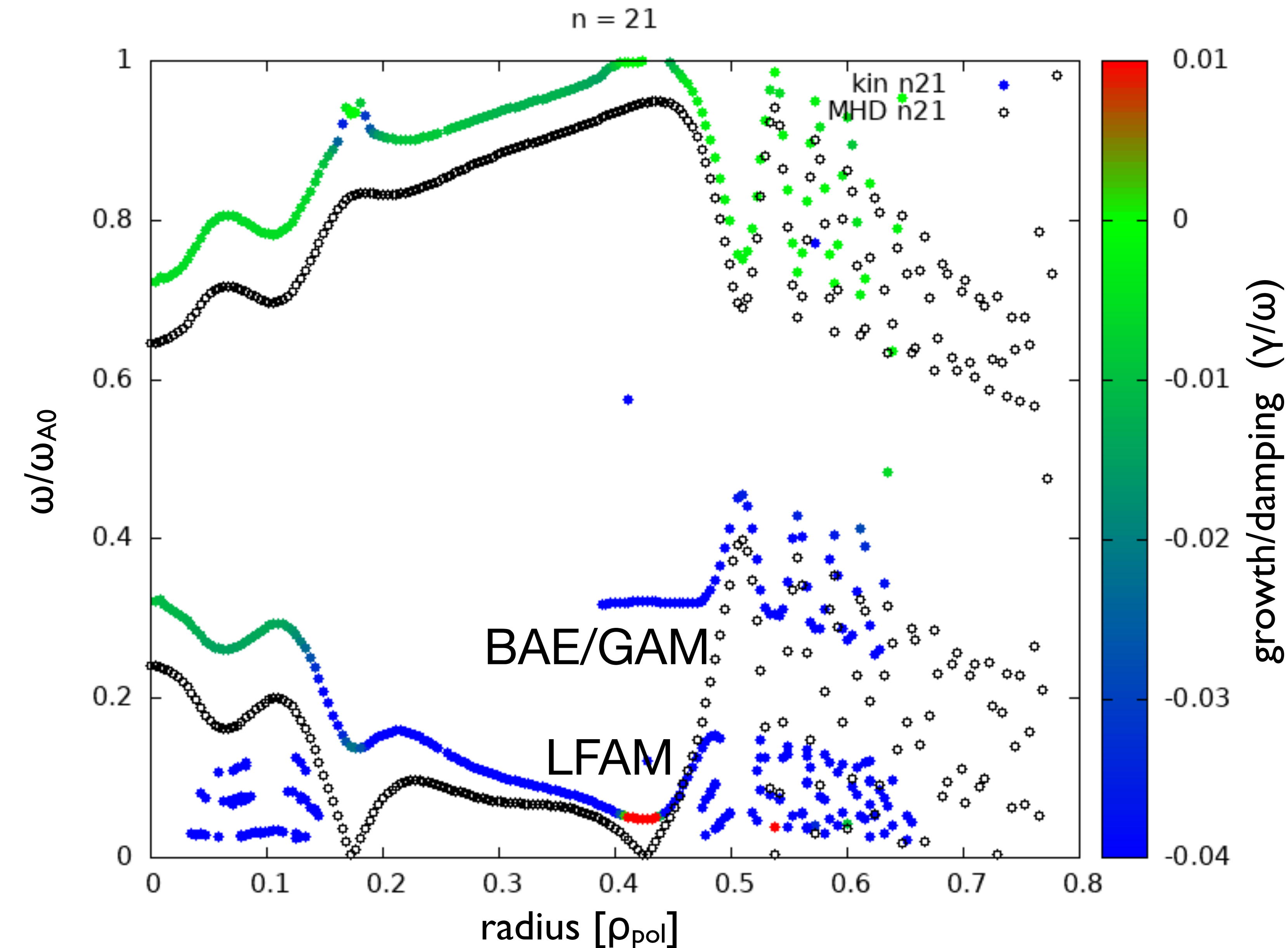
global analysis of odd and even TAE branches

$q=1.06$

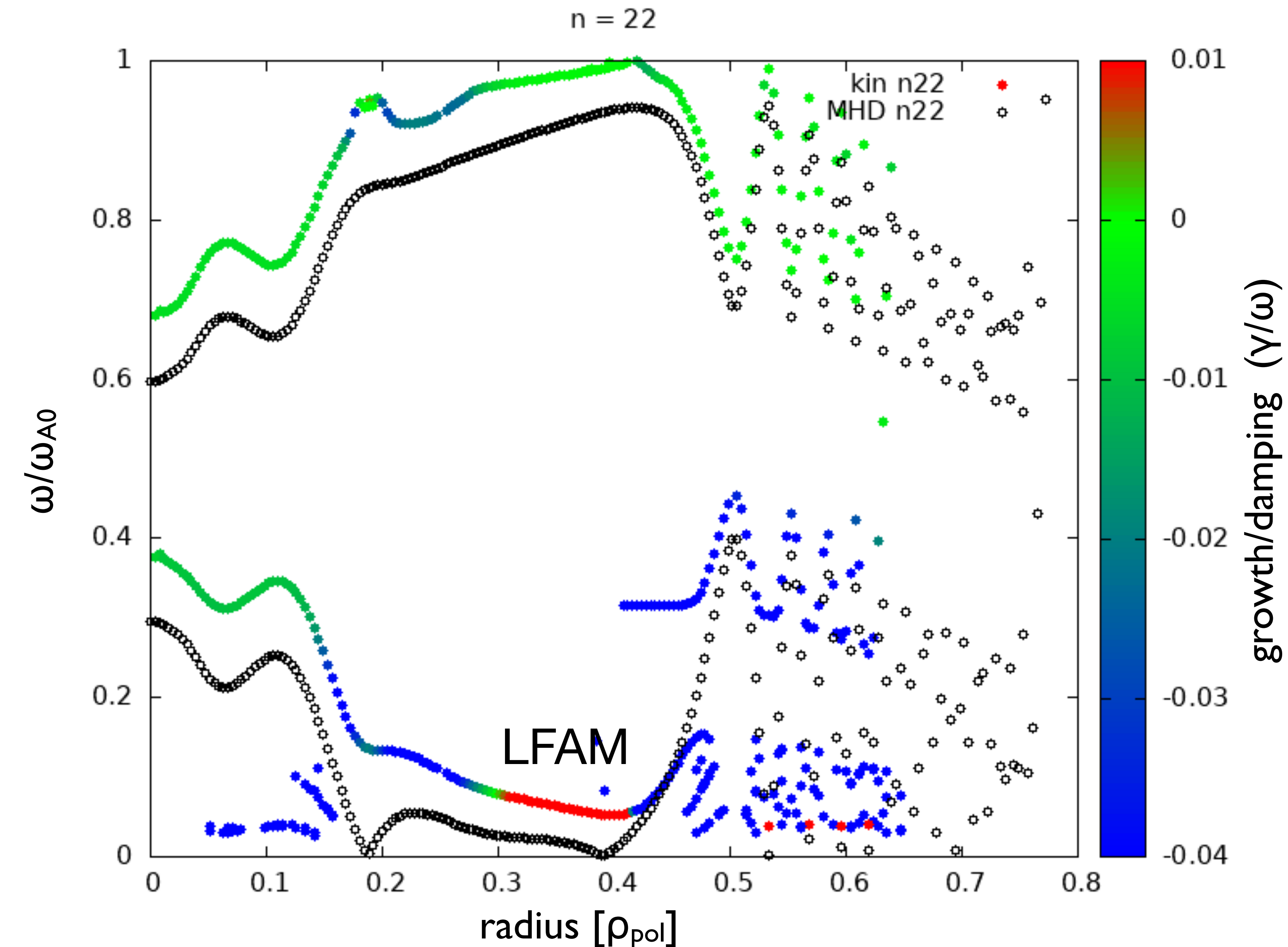


TAEs marginal for
nominal profiles

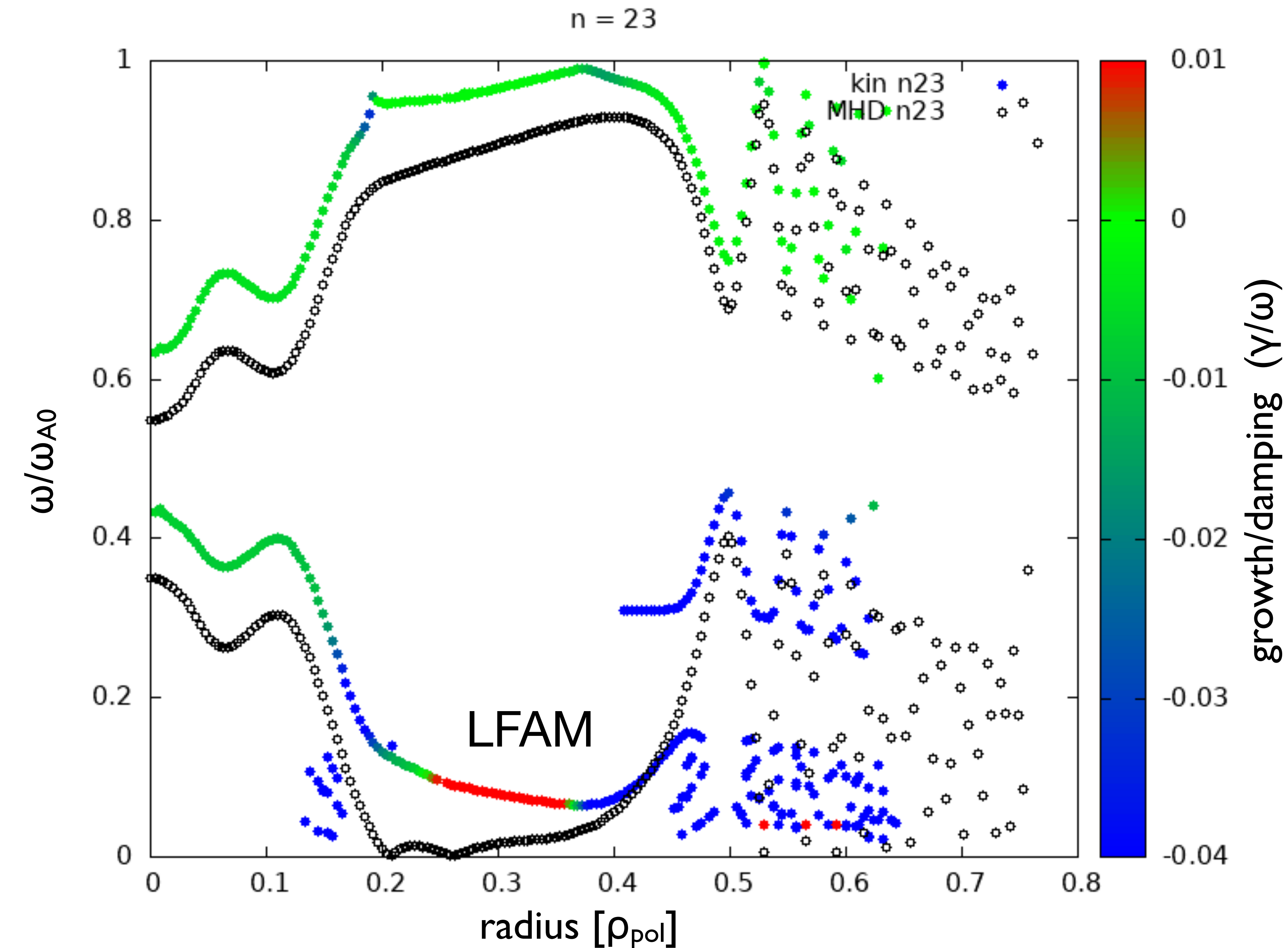
weakly unstable
TAE spectrum for
 $n_q=1.1$ $n_{q,nom}$



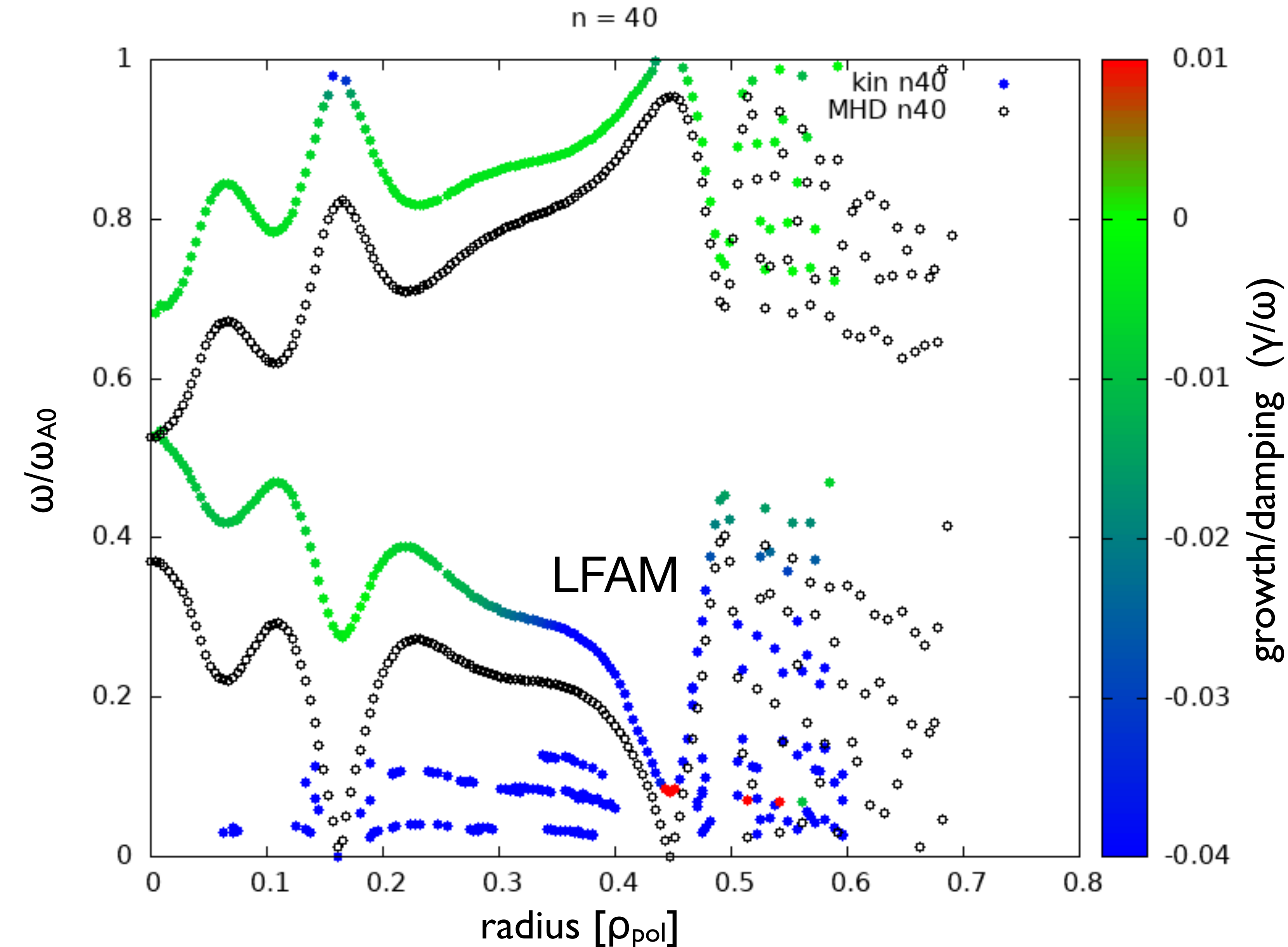
solution of local kinetic dispersion relation, including α -particles in ZOW limit



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

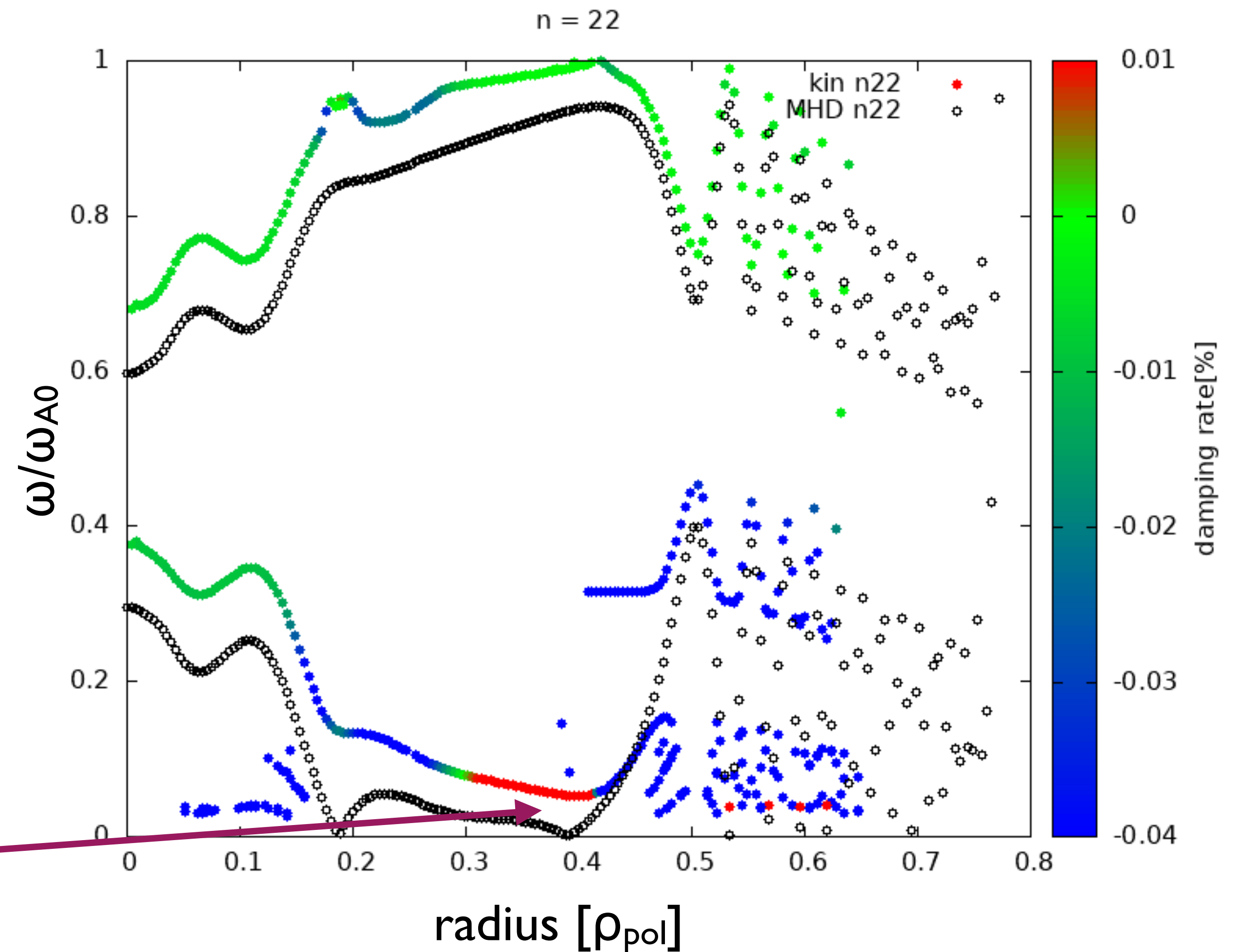
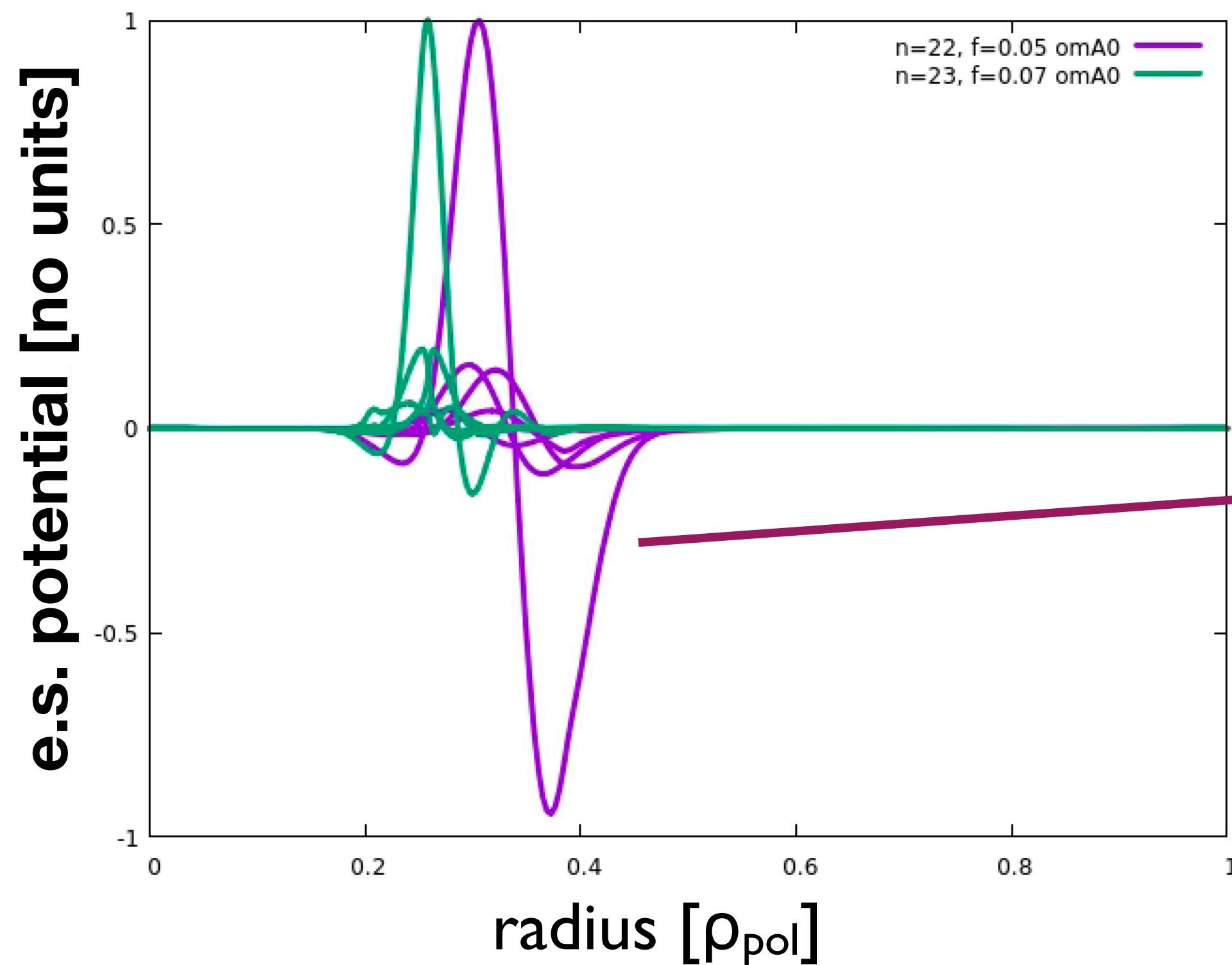


solution of local kinetic dispersion relation, including α -particles in ZOW limit



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

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 ($f=5-10\text{kHz}$, $\gamma/\omega=10,20\%$)





- PSZS transport code ATEP [\[Lauber, Meng NF 2024\]](#) based on PSZS transport theory [\[M.-V. Falessi & F. Zonca, 2017-2025\]](#) presently 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 (MUSCLE3) [\[V.-A. Popa, T. Hayward-Schneider\]](#)

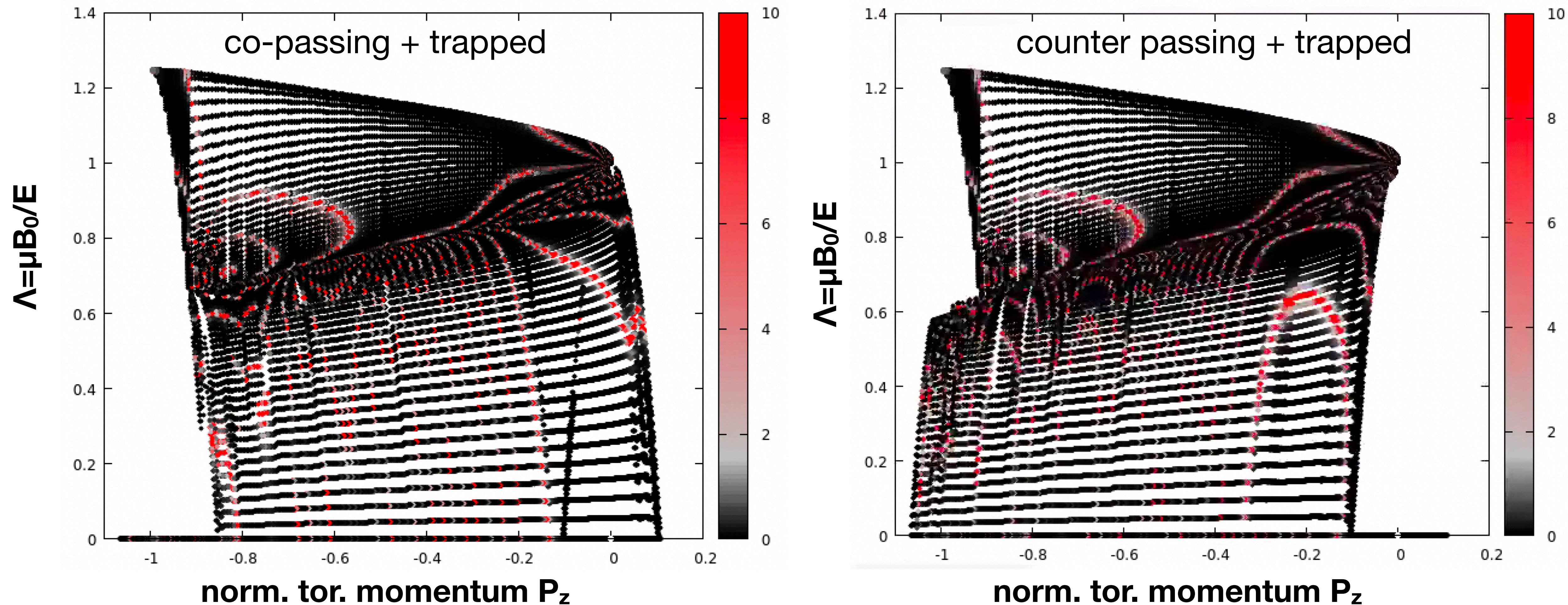
various extensions ongoing:

- new neoclassical ATEP-3D CoM 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 models [\[poster at this conference E. Eidsvig; Brochard, PRL 2025\]](#)
- use DAS formulation [\[G Wei, 2024, Li 2023, Falessi 2025\]](#) to set up Dyson-Schrödinger envelope equations

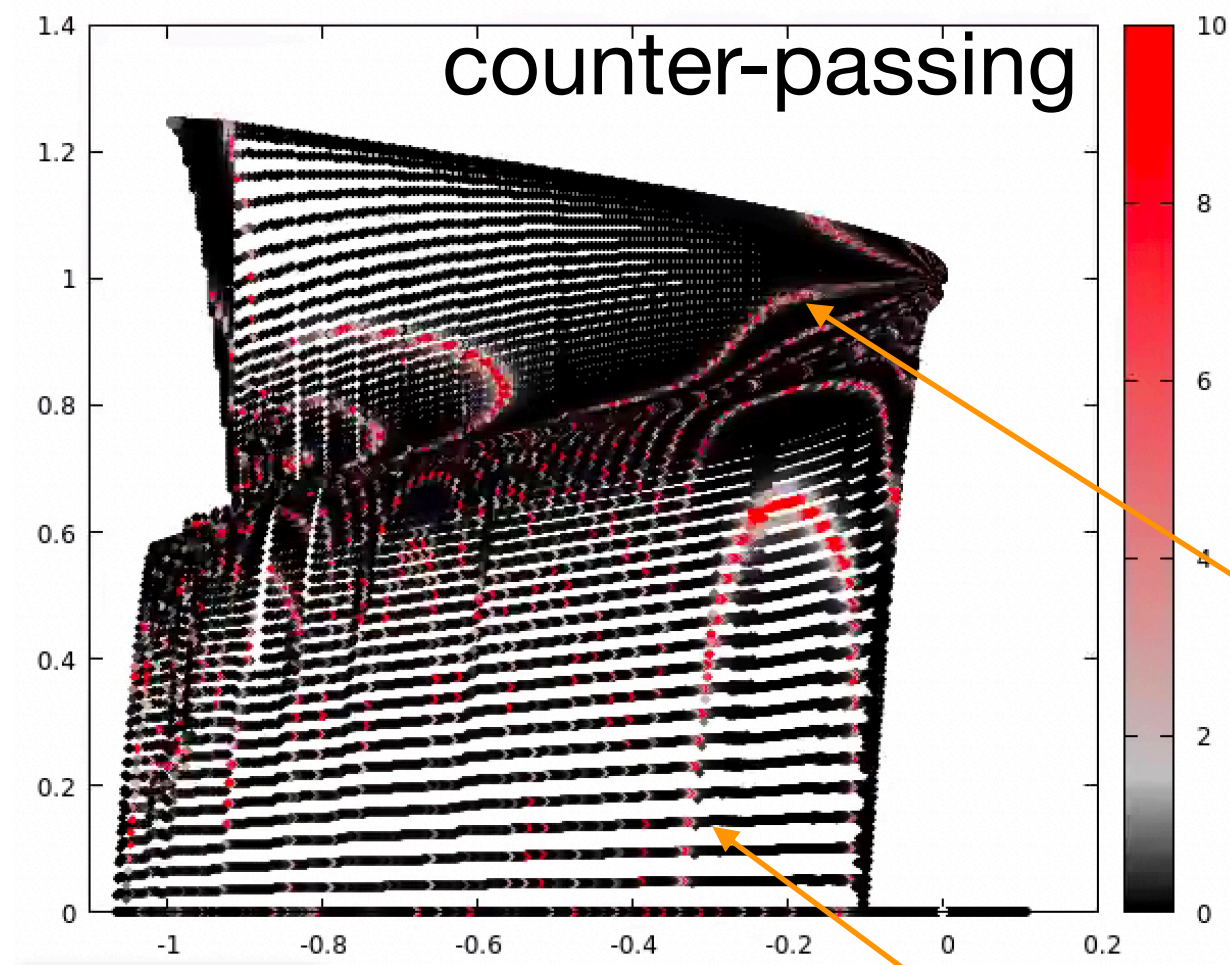
TAE transport assessment using ATEP model

assemble orbit database: TAE resonances with α particles - here $n=24$ TAE

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



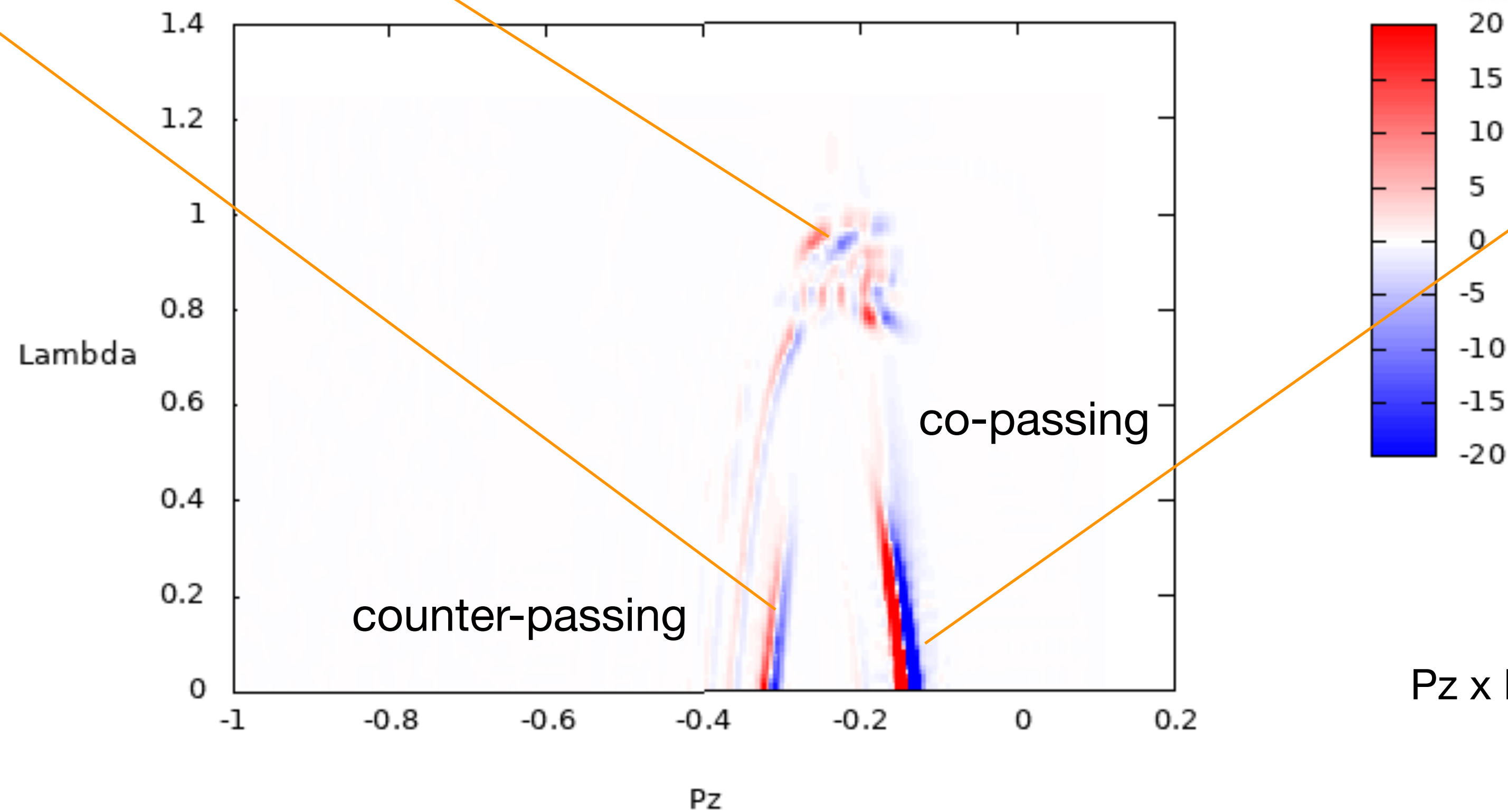
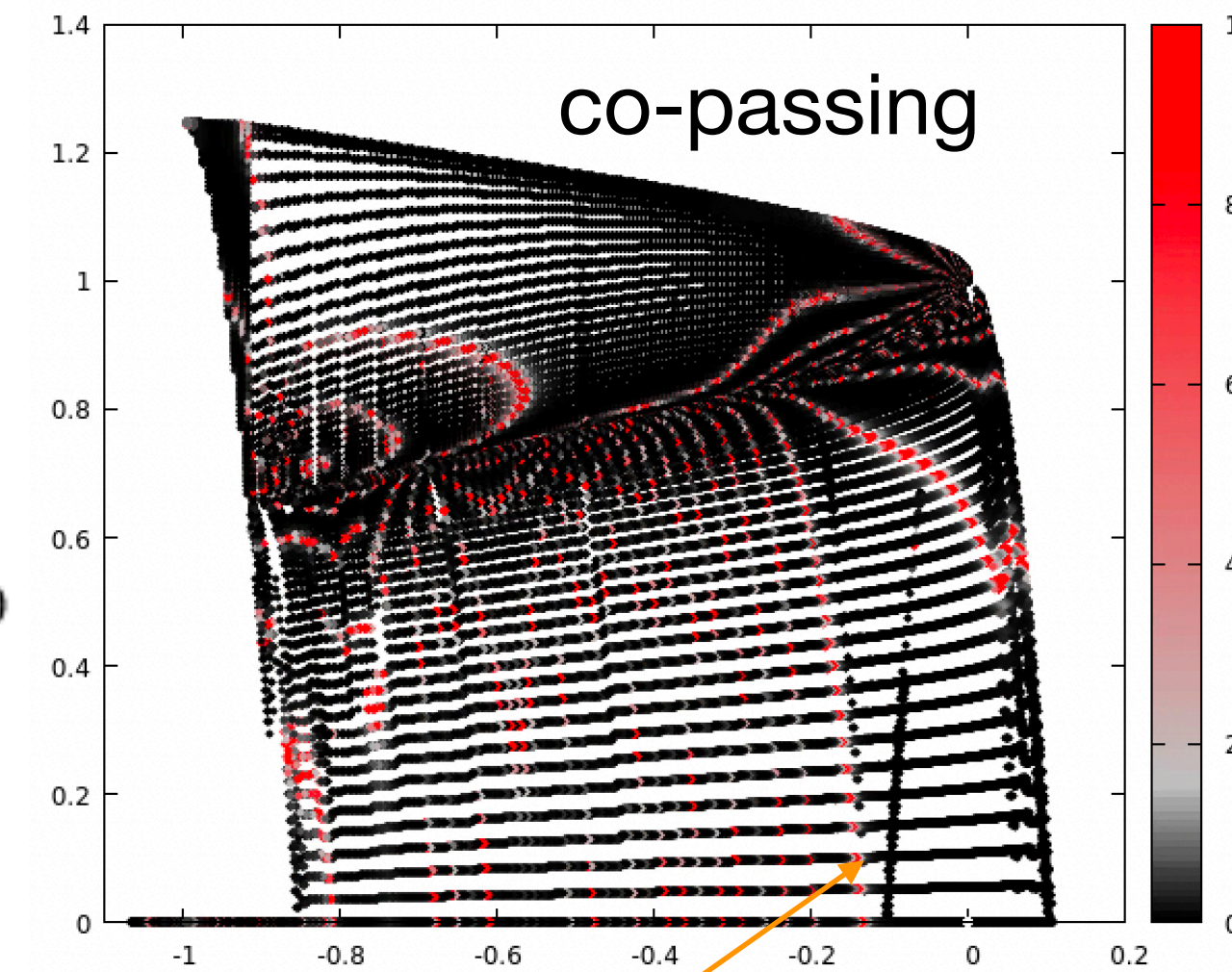
phase space zonally averages fluxes: resonant PSZS fluxes



single $n=24$ TAE, fixed ampl.

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

flux (Pz,Lambda), Energy=3144000

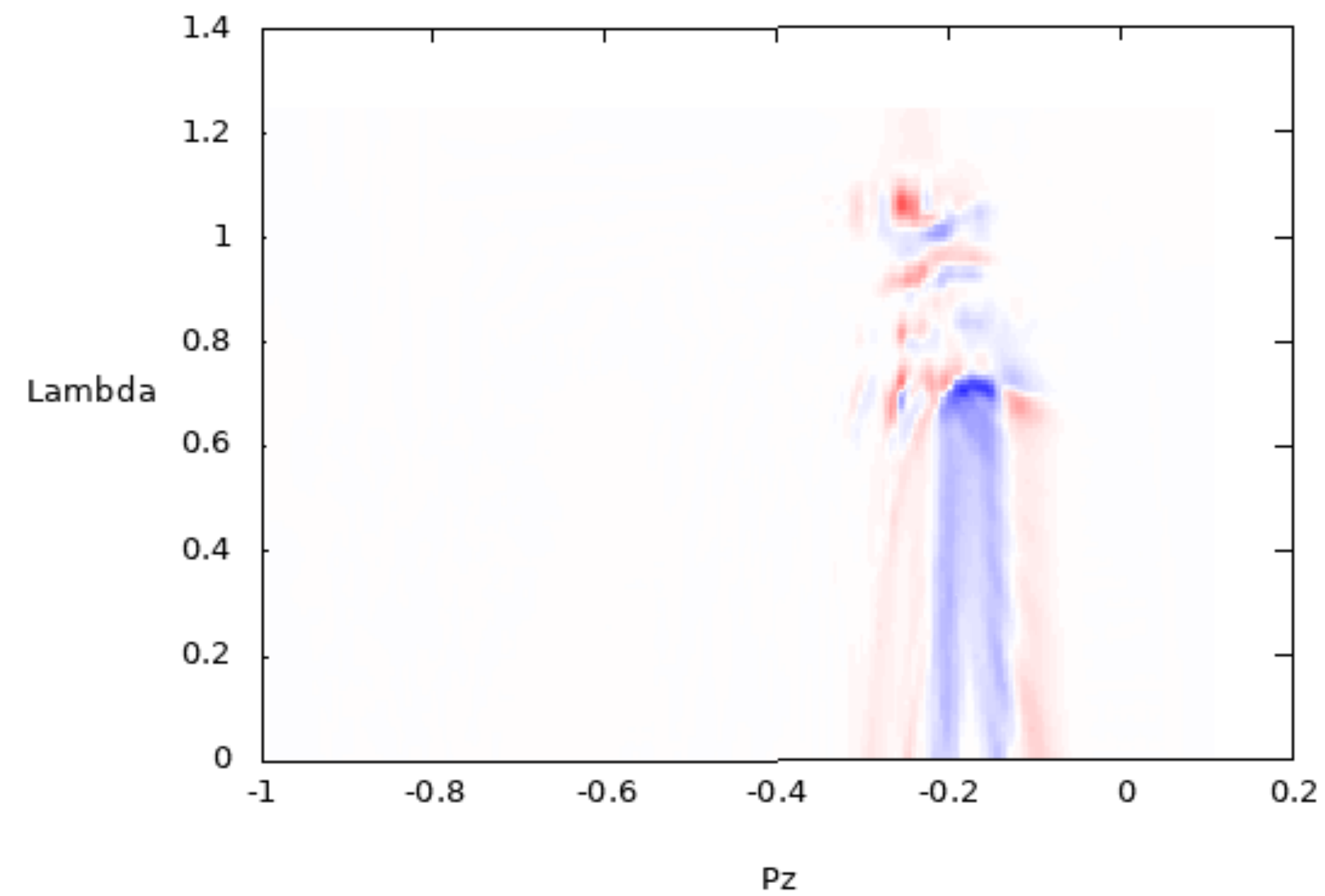


$Pz \times E \times \Lambda \times \sigma = 256 \times 64 \times 64 \times 2$

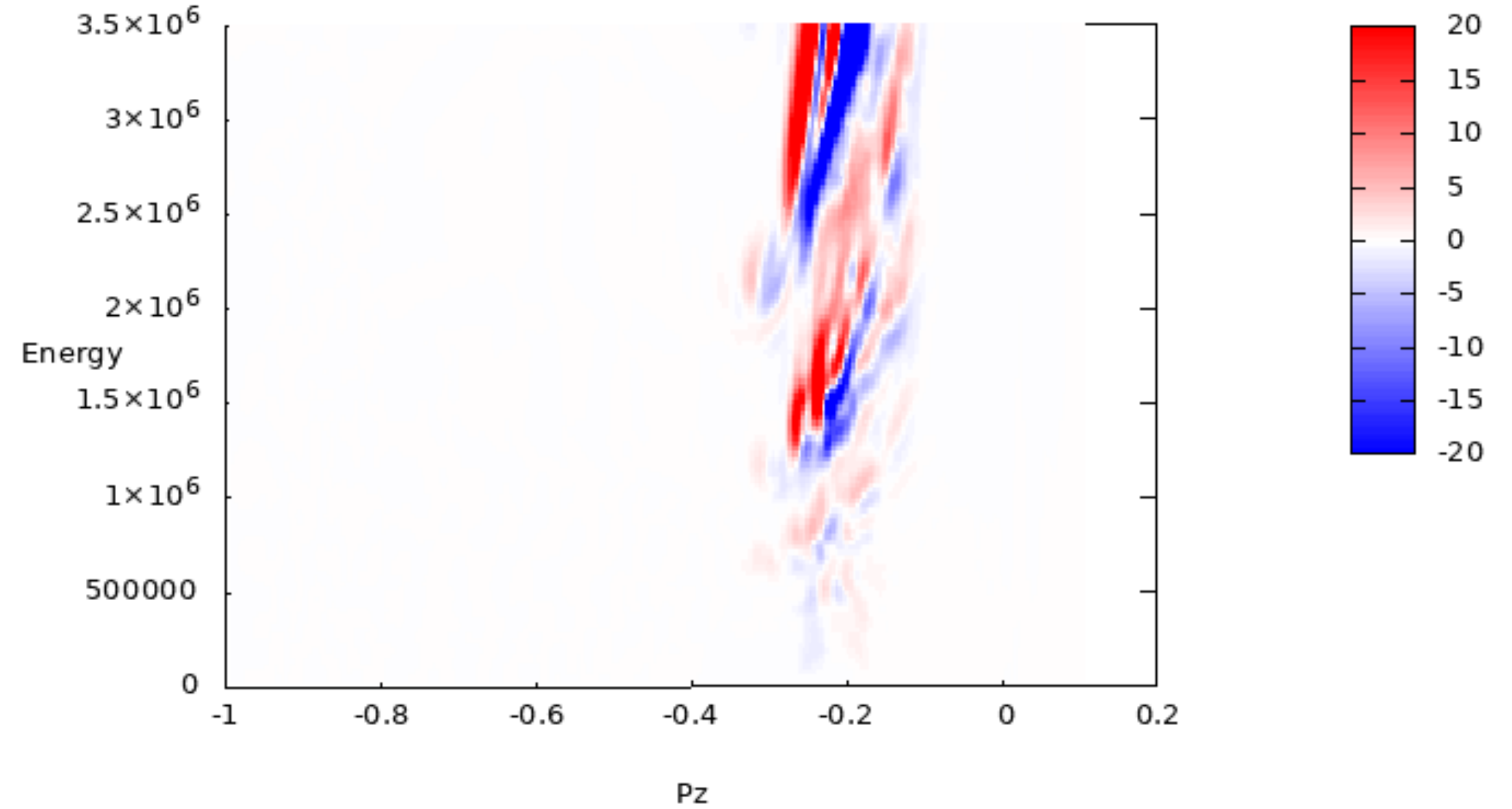
phase space zonally averages fluxes: resonant PSZS fluxes

cluster of $n=24-32$ TAEs

flux (Pz,Lambda), Energy=900000



flux (Pz,Energy), Lambda=941

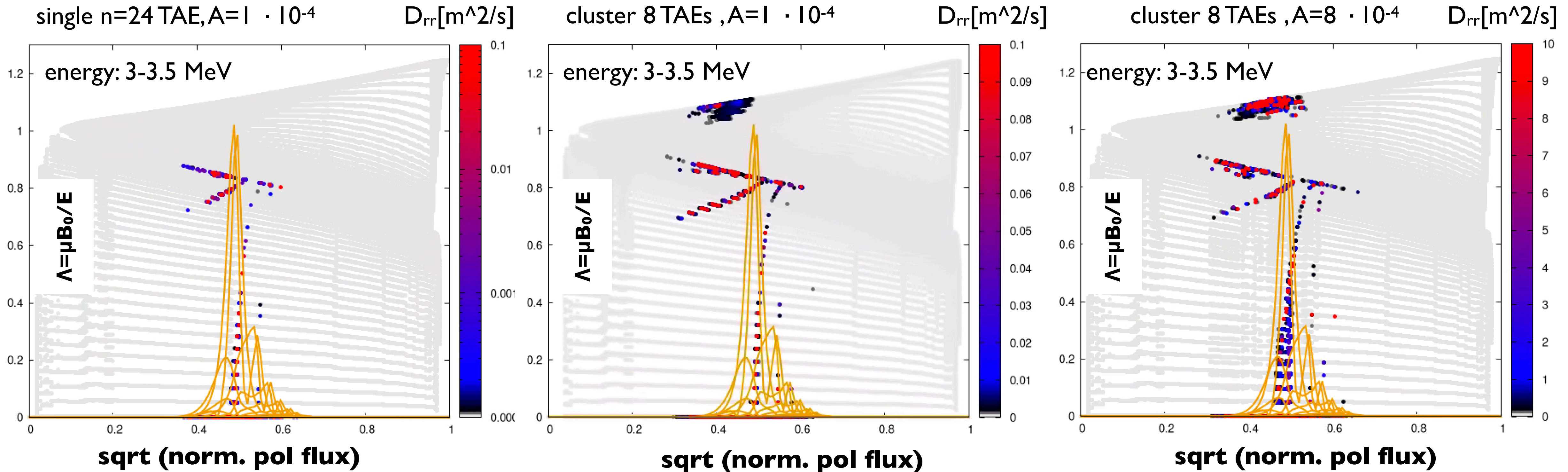


from fluxes to radial diffusion coefficients

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

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

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

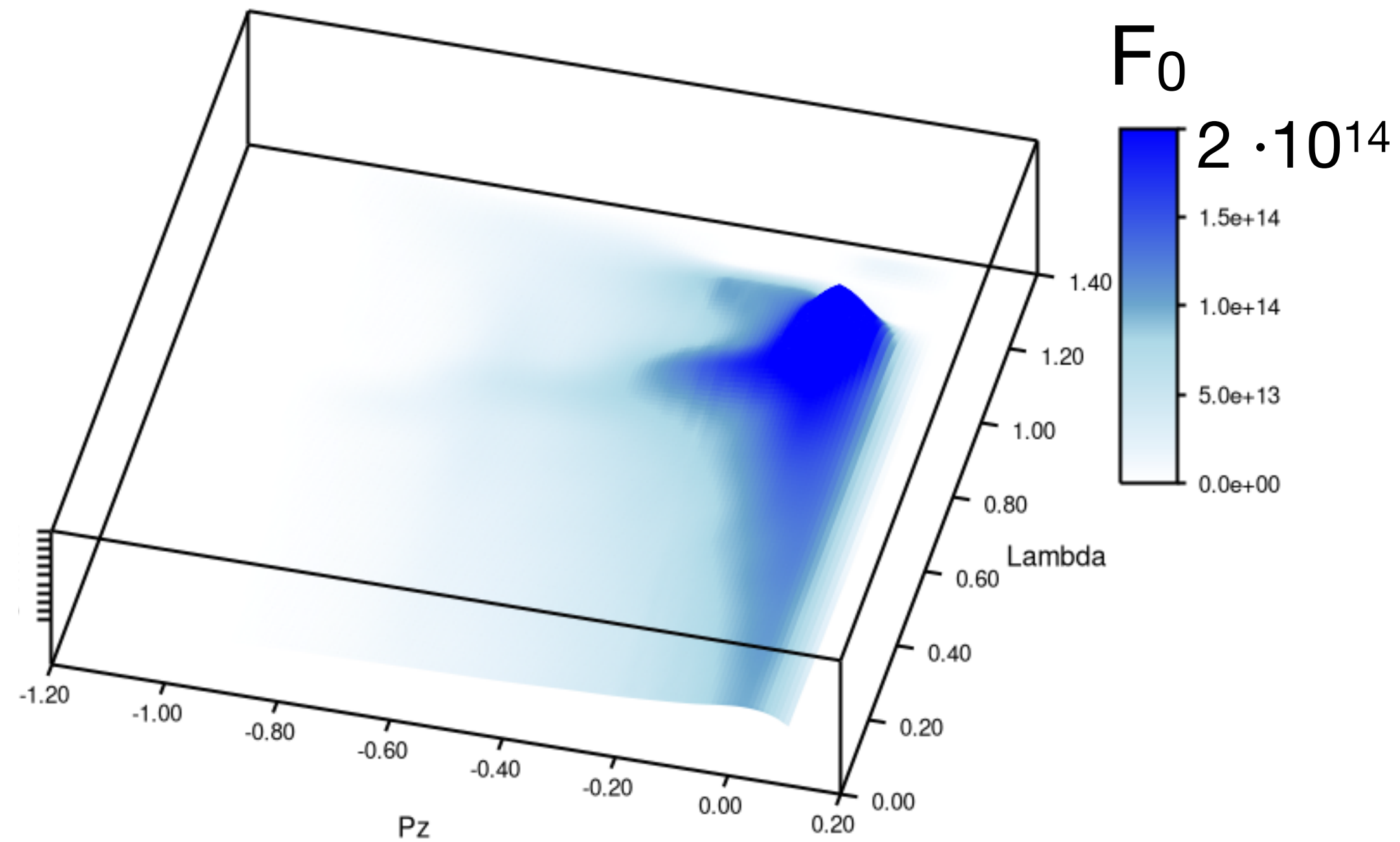


non-locality phase space dependent of transport of α particles

to be implemented for modes other than TAEs

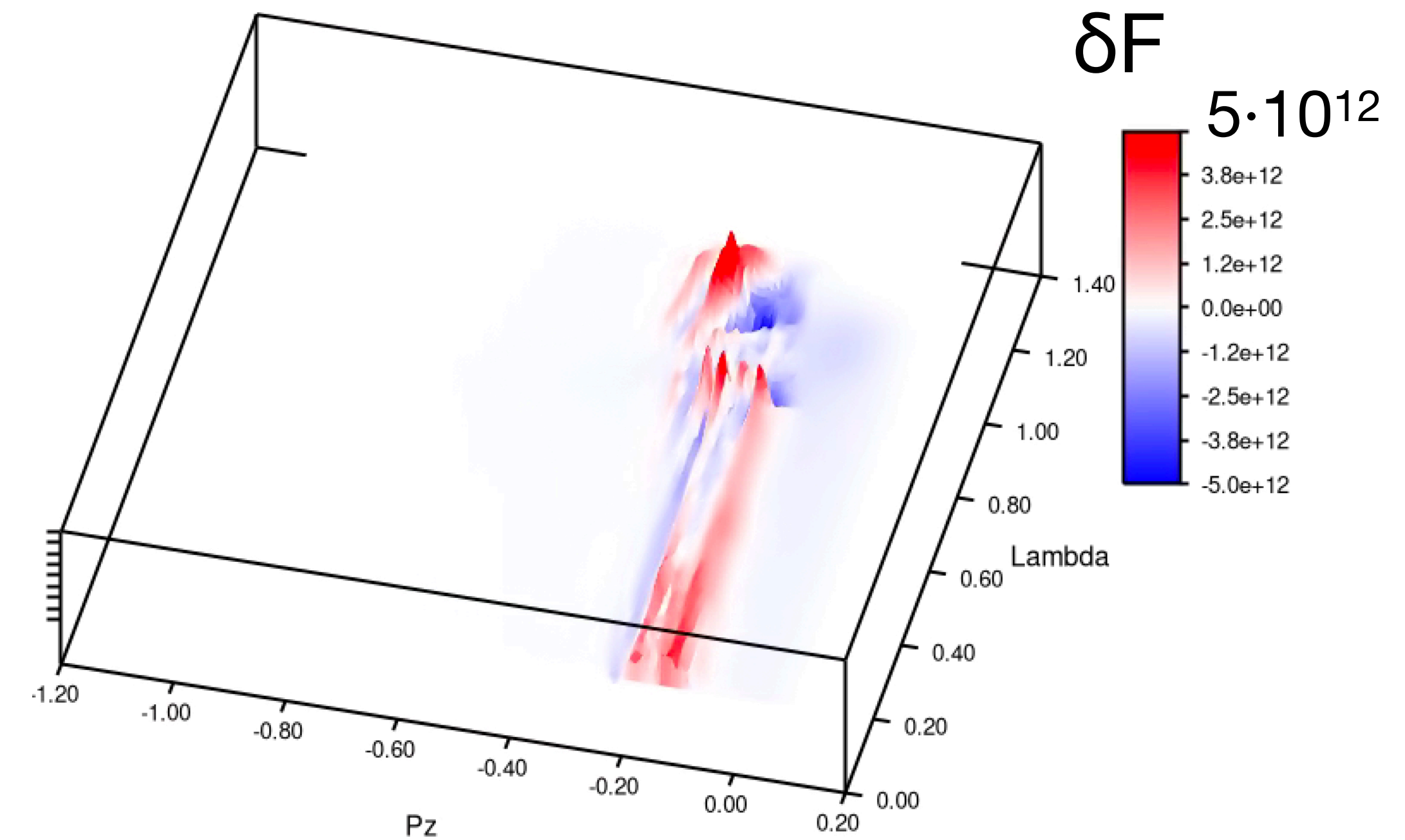
PSZS transport: n=24 TAE

initial α - slowing down distribution



constant amplitude limit : $1 \cdot 10^{-4}$ dB/B

after ~ 1 ms (100 Alfvén times)

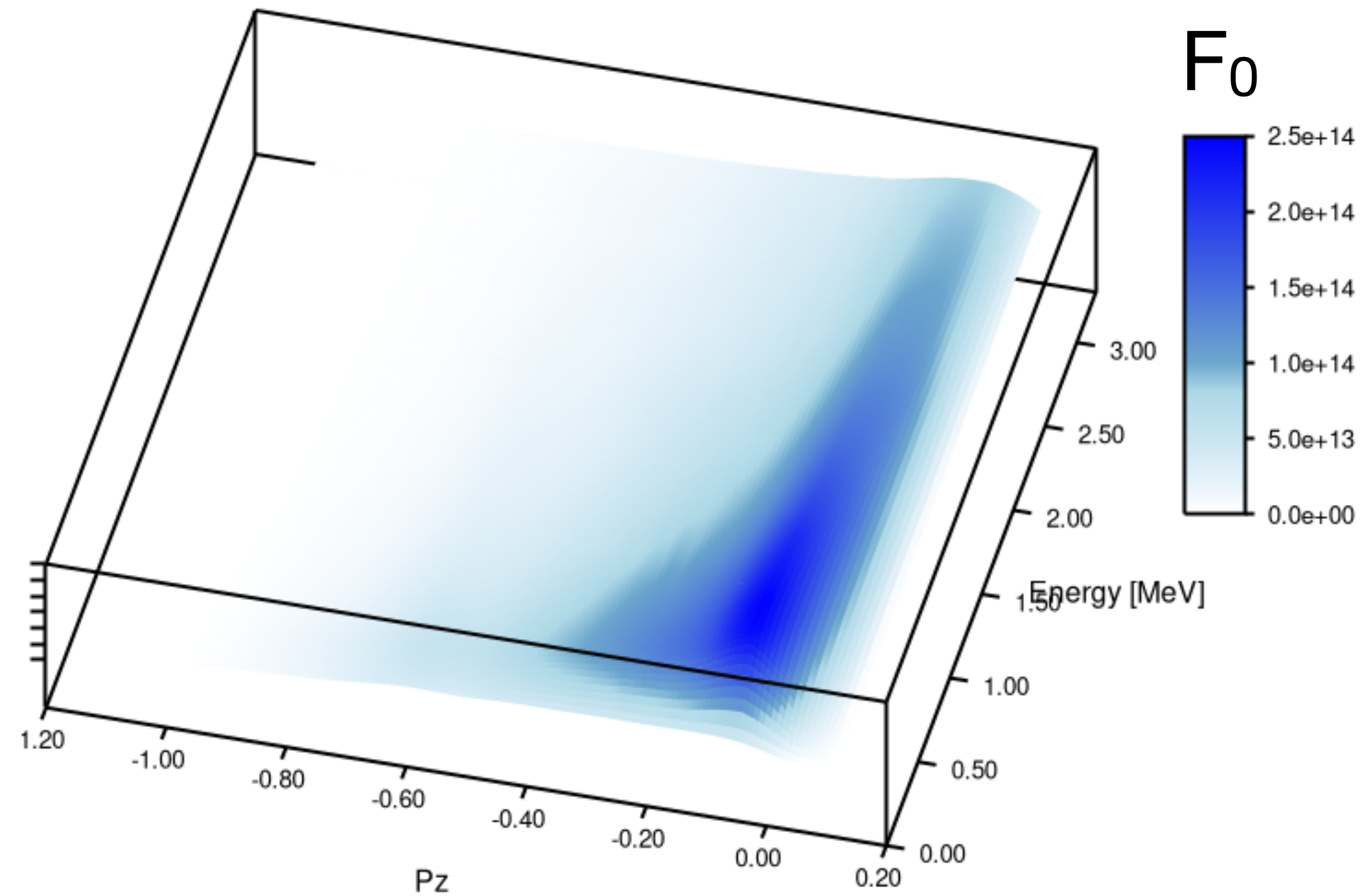


integrated over all energies

transport $(\delta F/F_0)$ 1-5 percent range

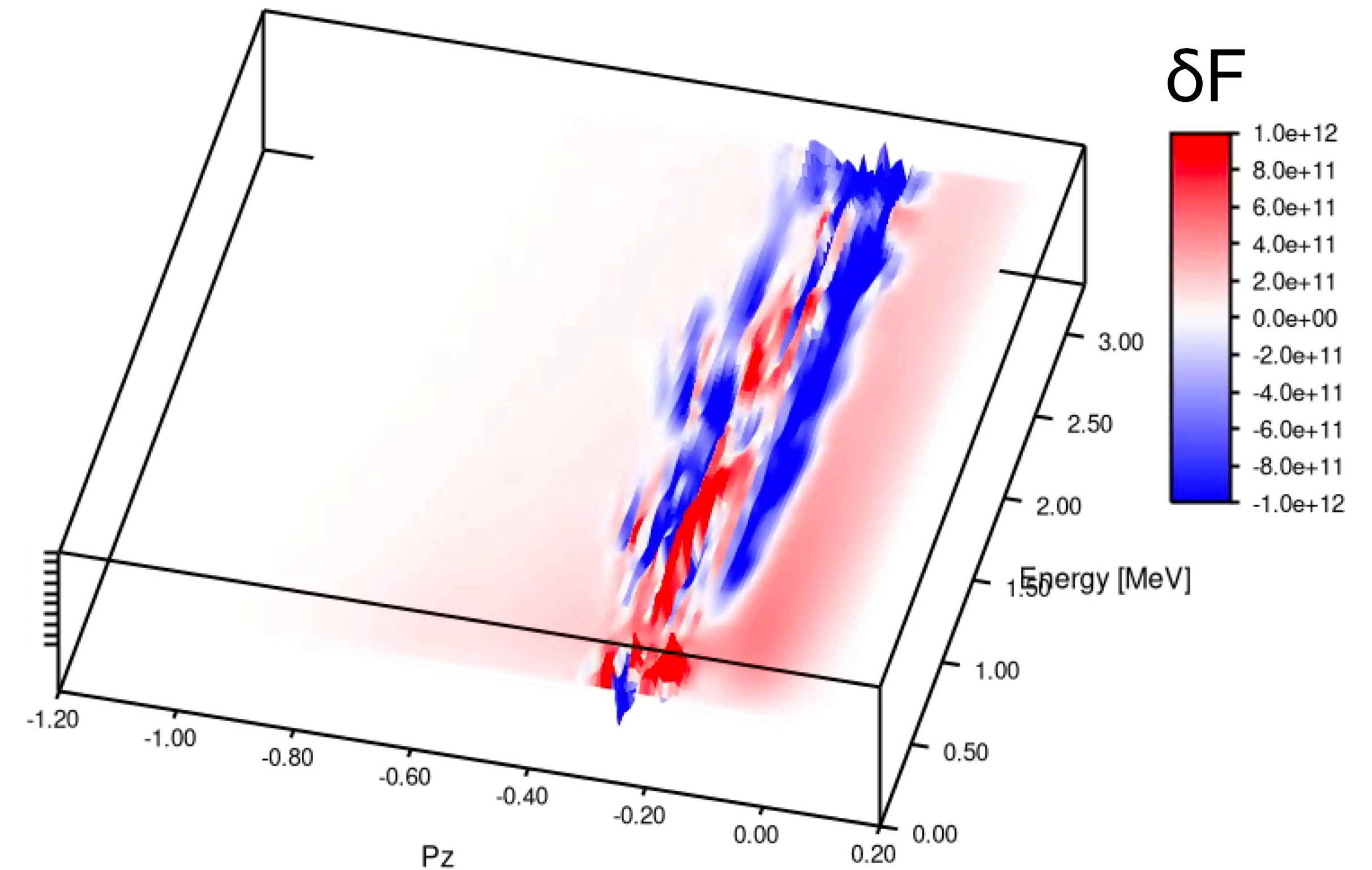
PSZS transport: n=24 TAE

initial α - slowing down distribution



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

after ~ 1 ms (100 Alfvén times)



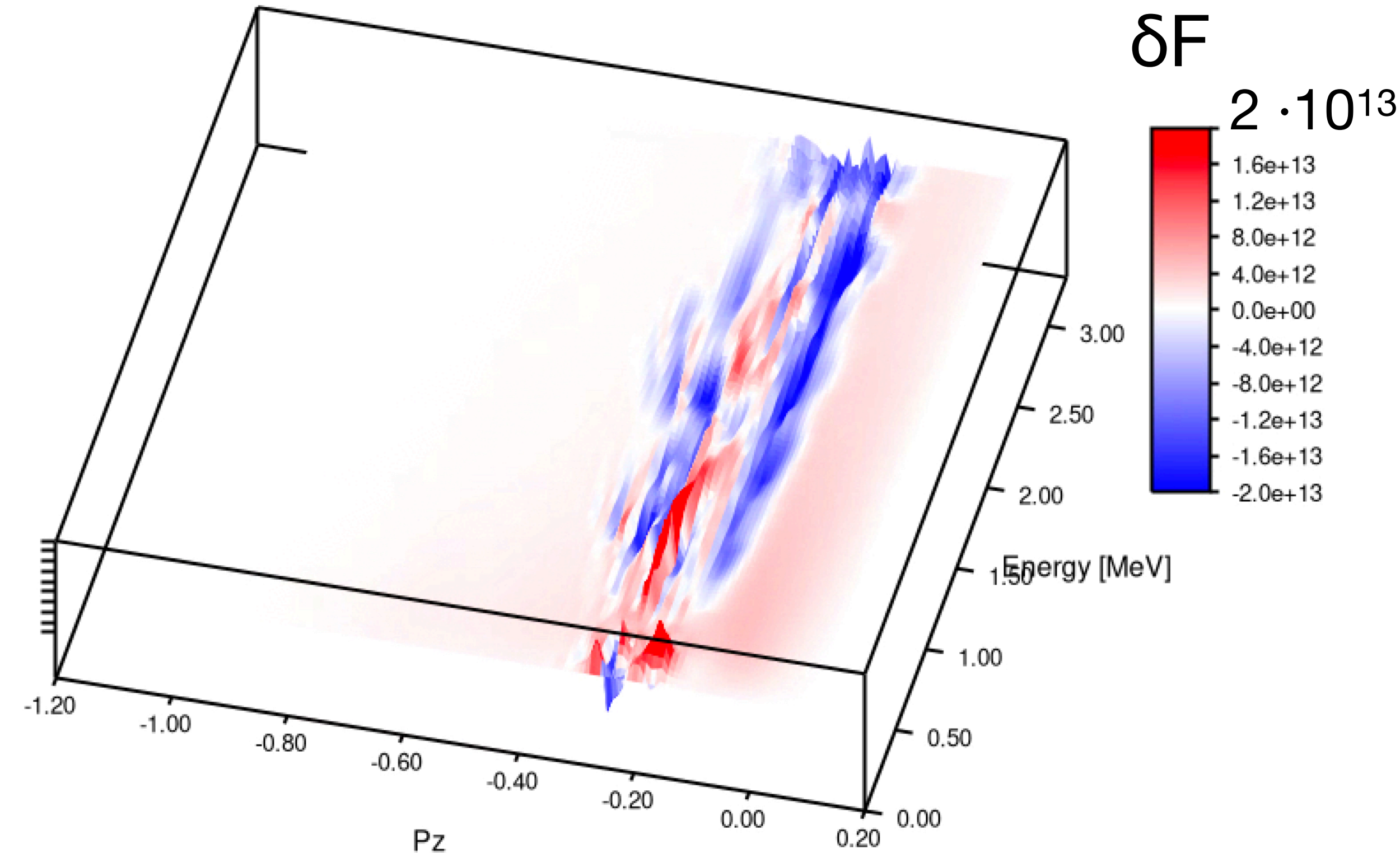
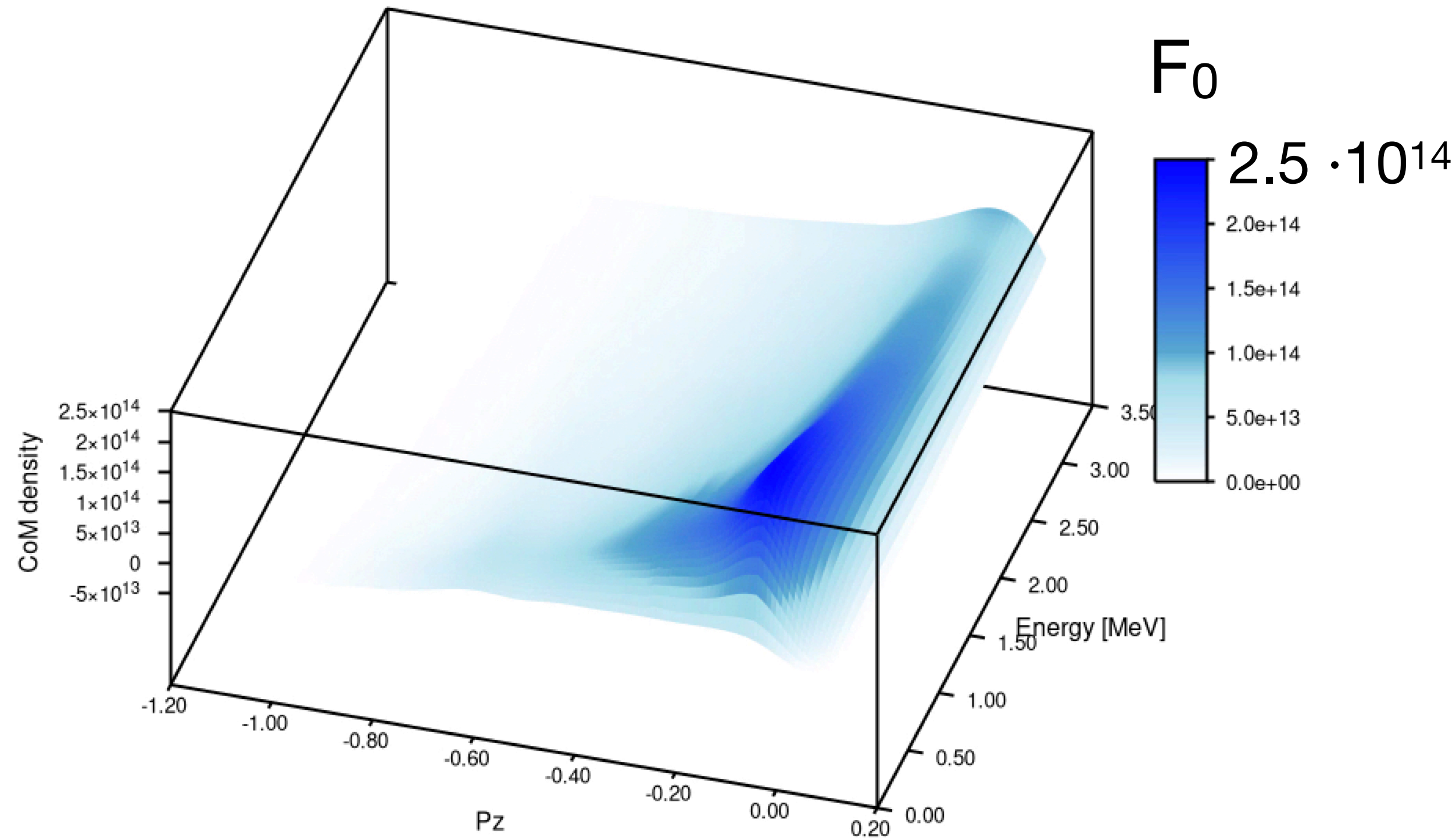
integrated over all Λ

transport ($\delta F/F_0$) 1-5 percent range

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

initial α - slowing down distribution

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

VNS: strongly driven system, large EP fraction

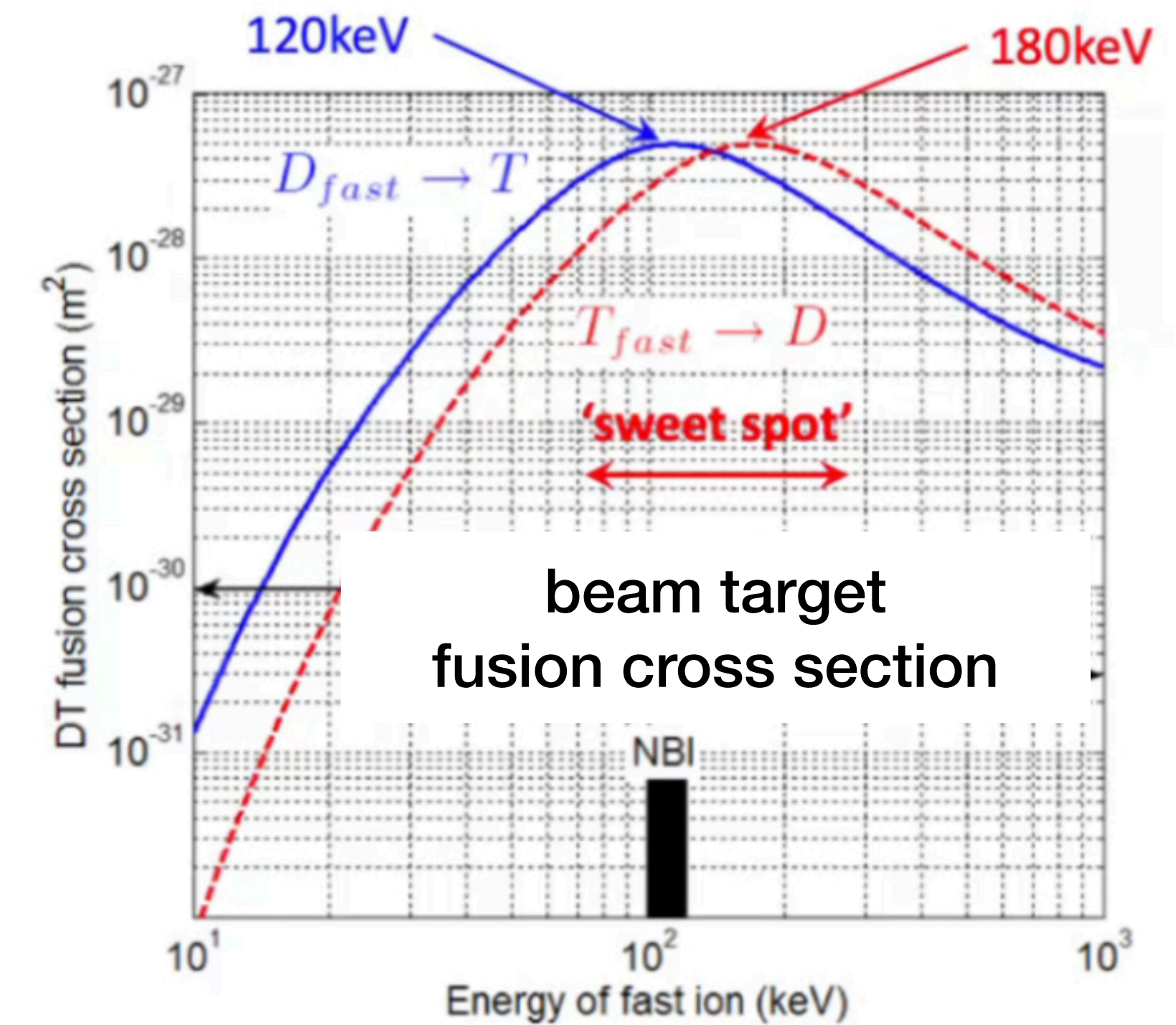
- physics principle well known, e.g. recent JET experiments, 12.5MW record [M Maslov, 2025]
- VNS: D beam in T plasma; slow down of beam ions on thermal T ions - maximise D-T reactions
- ~120 keV is sweet spot, accessible with PNBI technology
- $T_e(0)$ needs to be $\geq 10\text{keV}$: $E_{\text{crit}}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

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

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

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

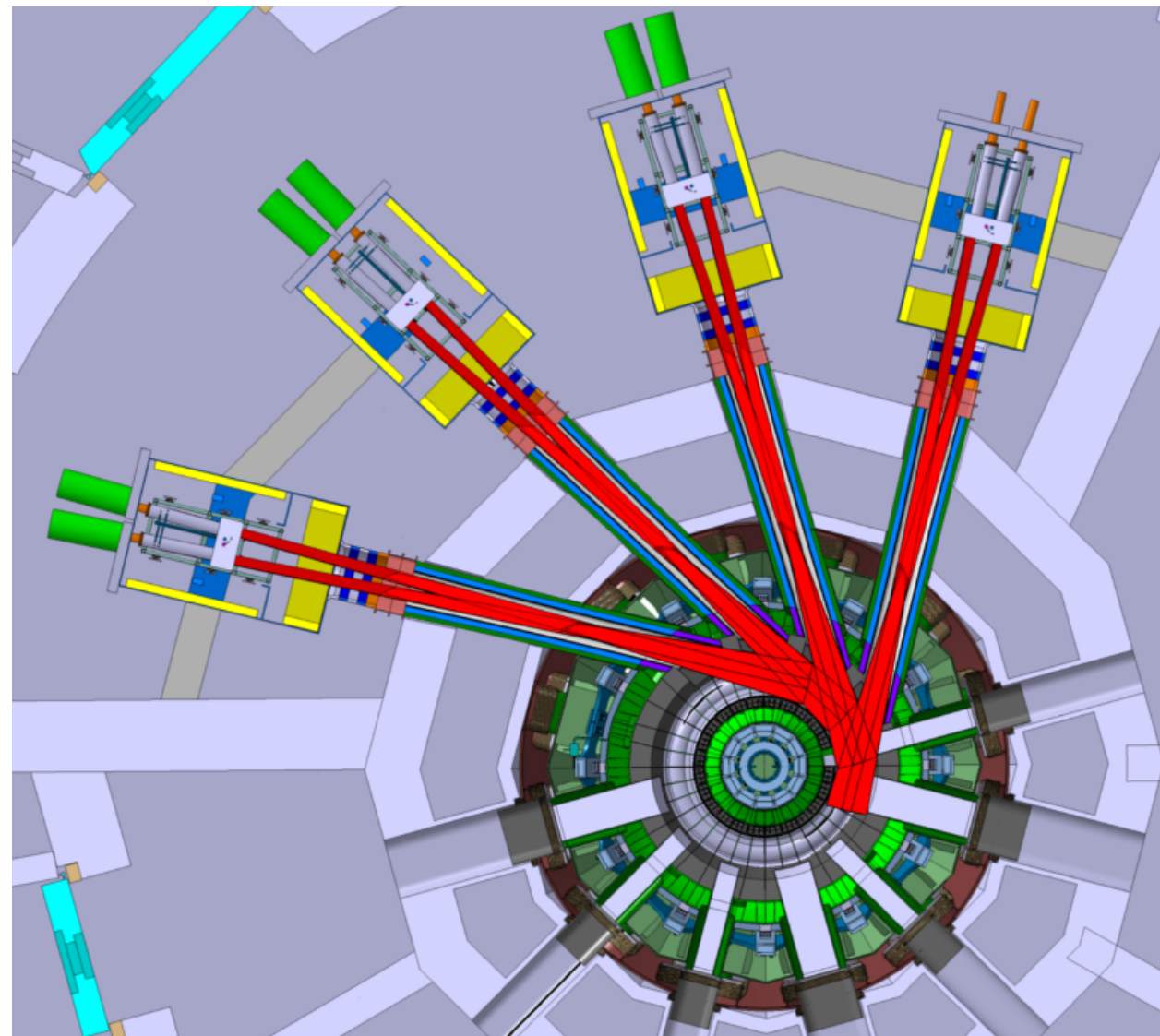


challenge: minimise dilution of T plasma with D beam;
control n, T, EP, impurity, rotation profiles to maximise neutron wall load, while protecting divertor
→ integrated modelling; challenge: outside well tested parameter range

VNS: optimisation of neutron wall load

VNS (Volumetric Neutron Source)

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

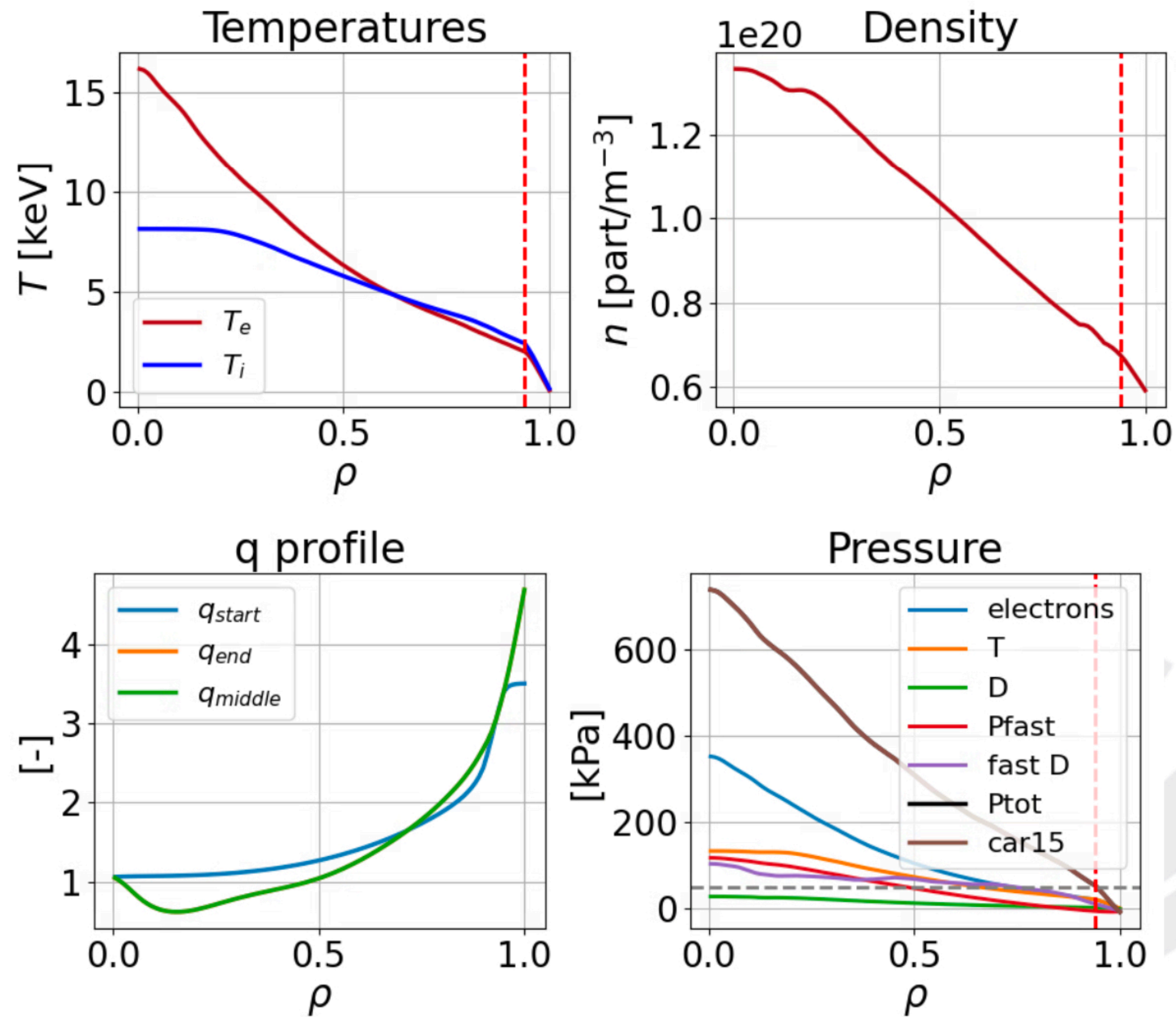


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P_{fus} [MW]/beam target	42/36
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T consumption	2.38 kg/full power y
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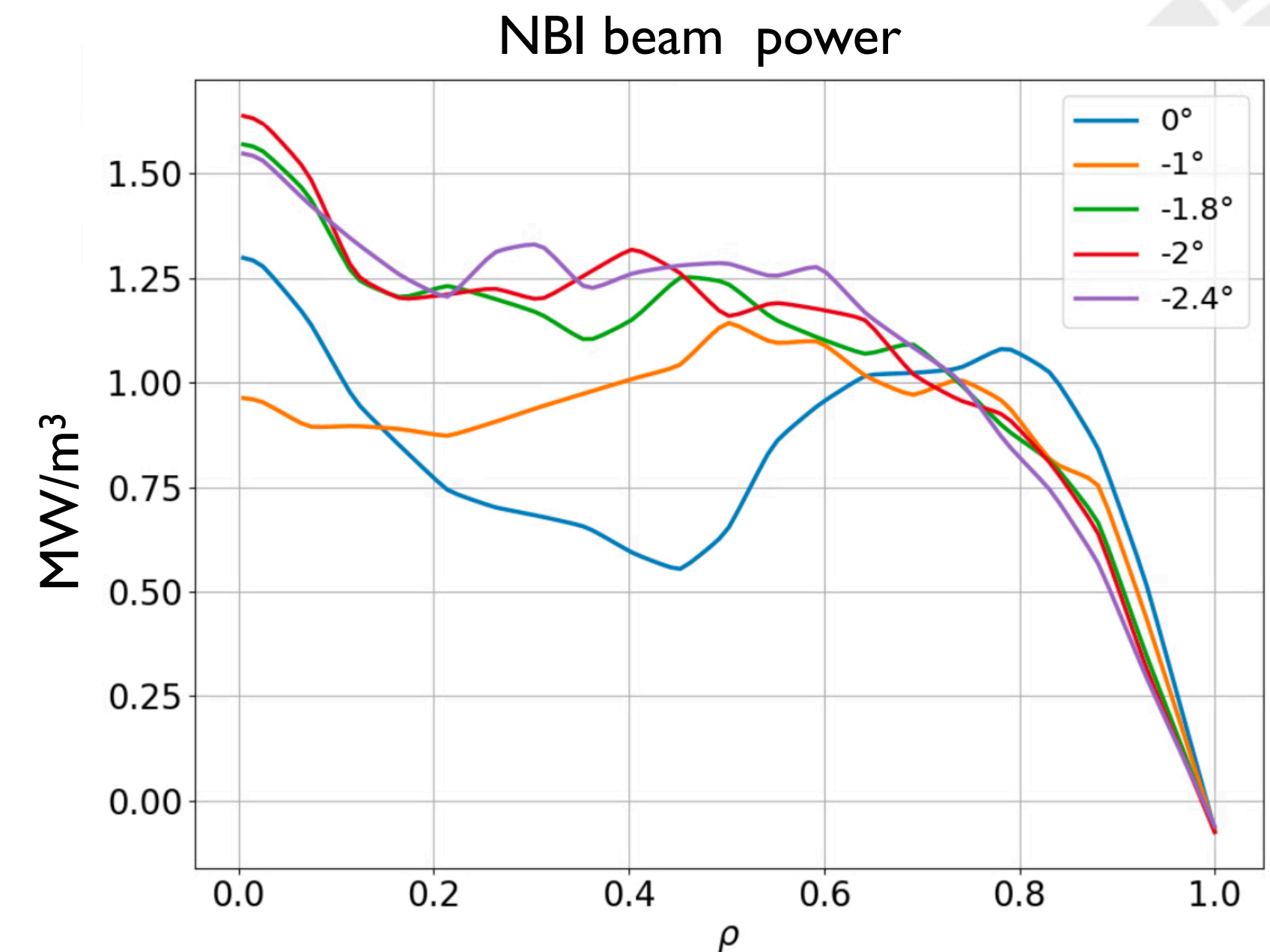
optimisation/trade-off problems (selection):

- 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

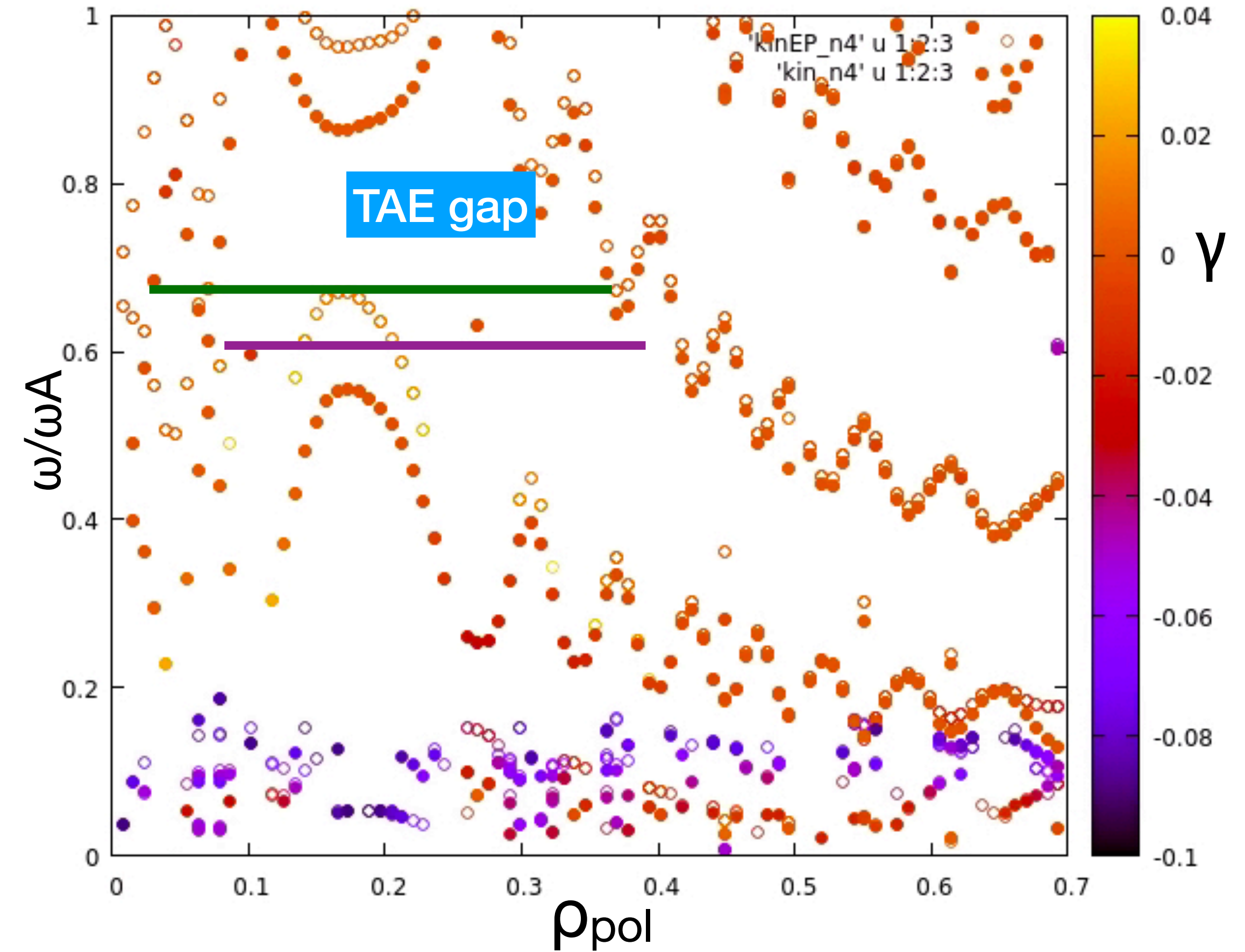
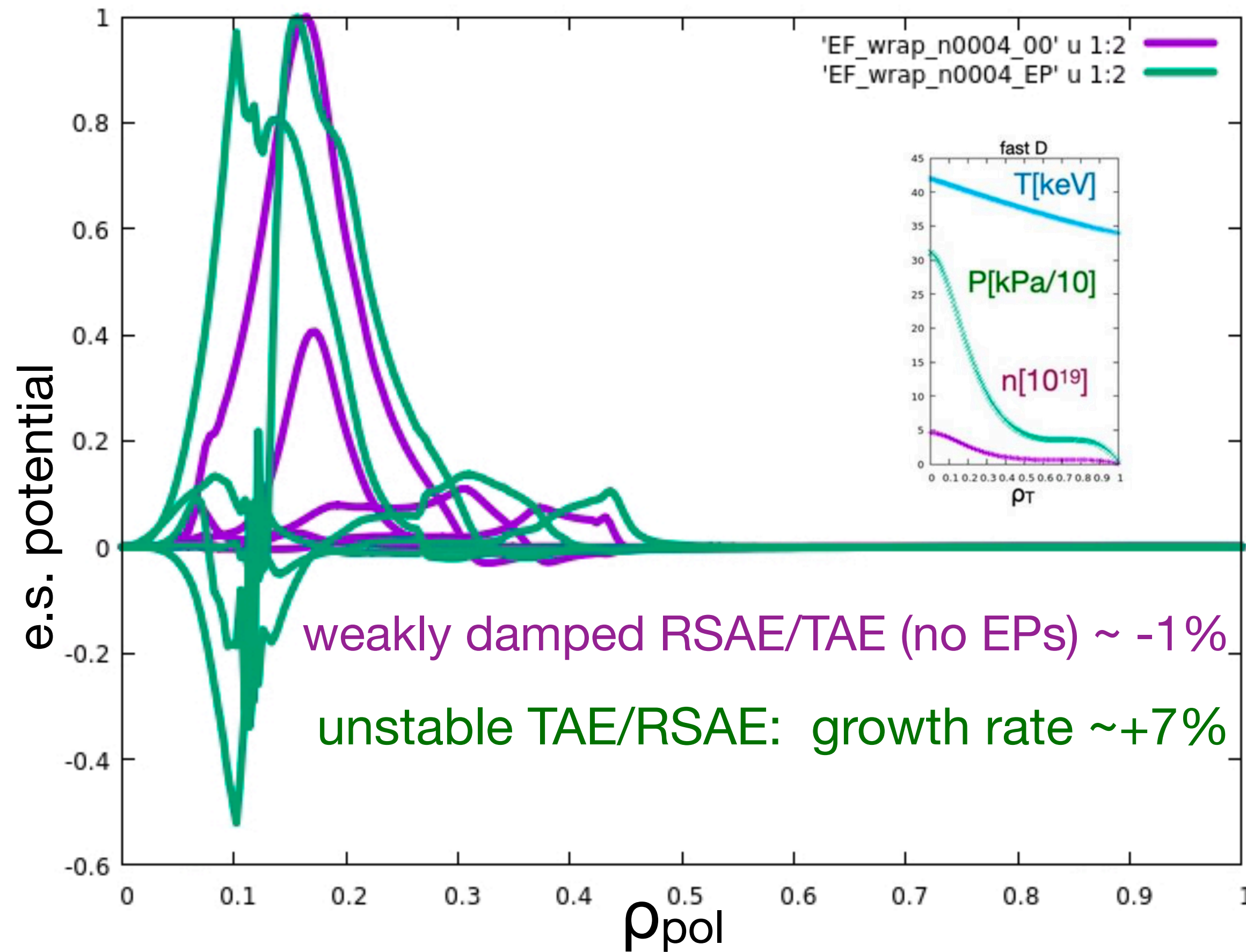
- successful validation on JET beam-target, high rotation cases
- new VNS reference scenario established (Sept 2026)



$\langle n_e \rangle$	$9 \cdot 10^{19} \text{ m}^{-3}$
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



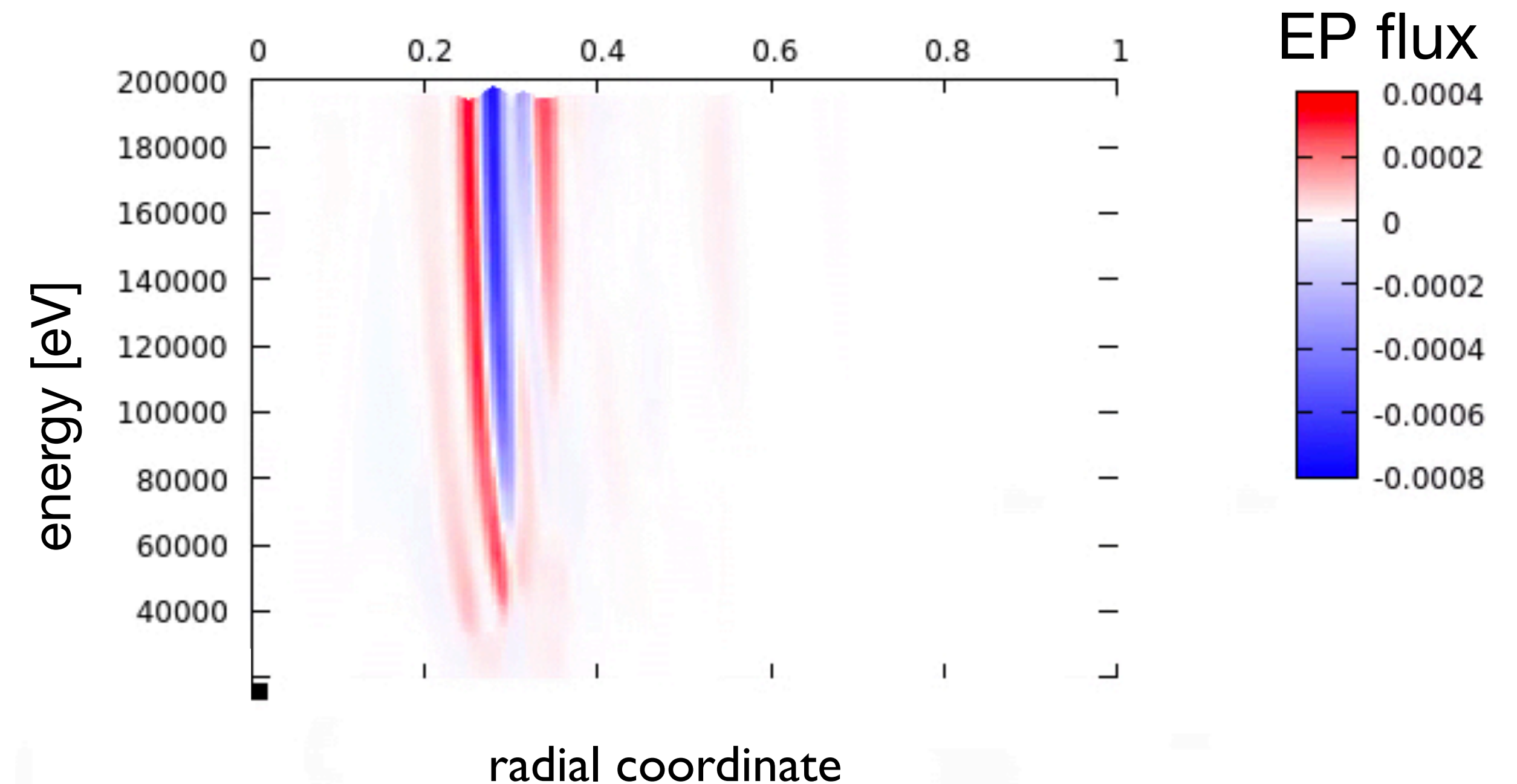
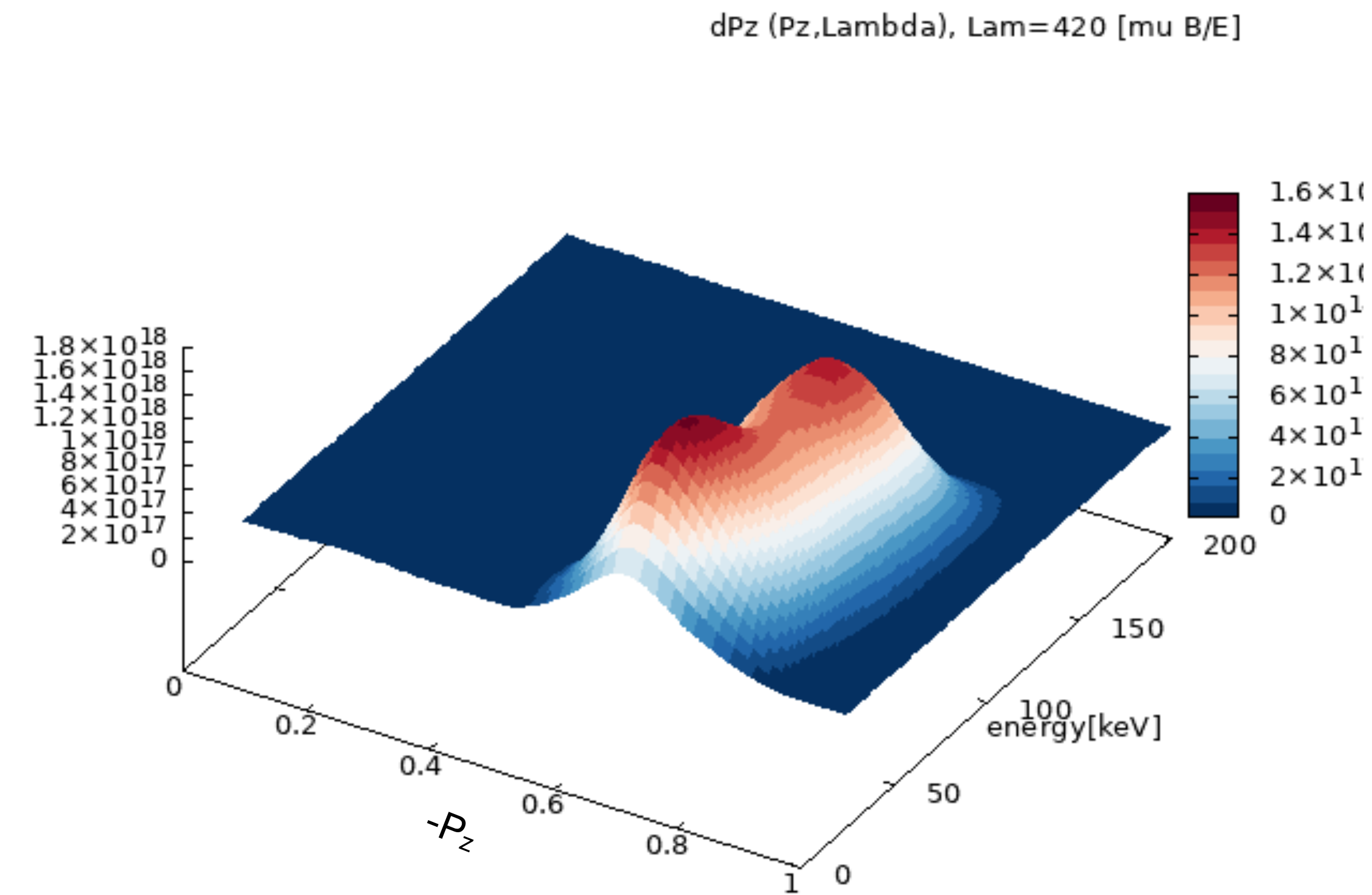
global analysis: Alfvénic modes (here n=4 TAE on previous case with full power)



- 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 and current profile modifications

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:

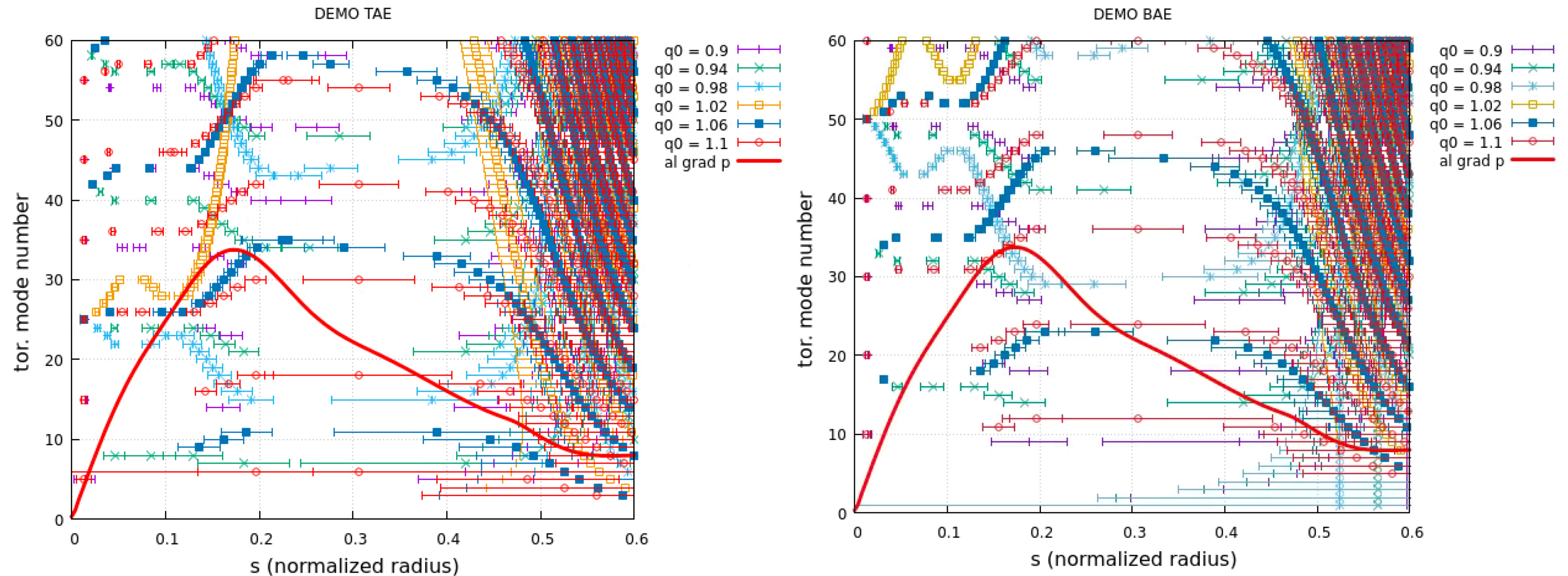
- EP redistribution in core by LFAM/AITG, mid-radius TAE, outer edge islands/ripple ($q=1$ would add another coupling channel);
- influence on current redistribution important - flux consumption!
- coupling to collisional effects and micro-turbulence is required - reduced models are key

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)

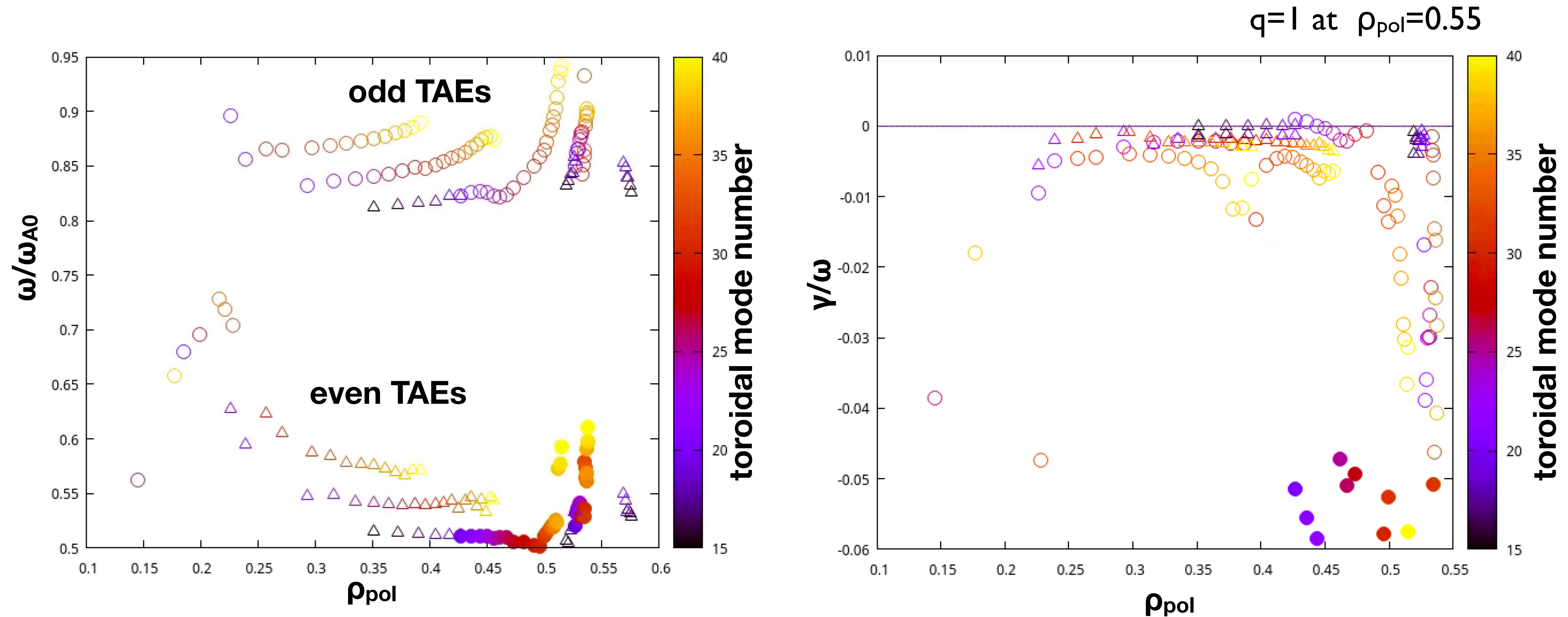


sensitivity analysis with respect to q_0



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

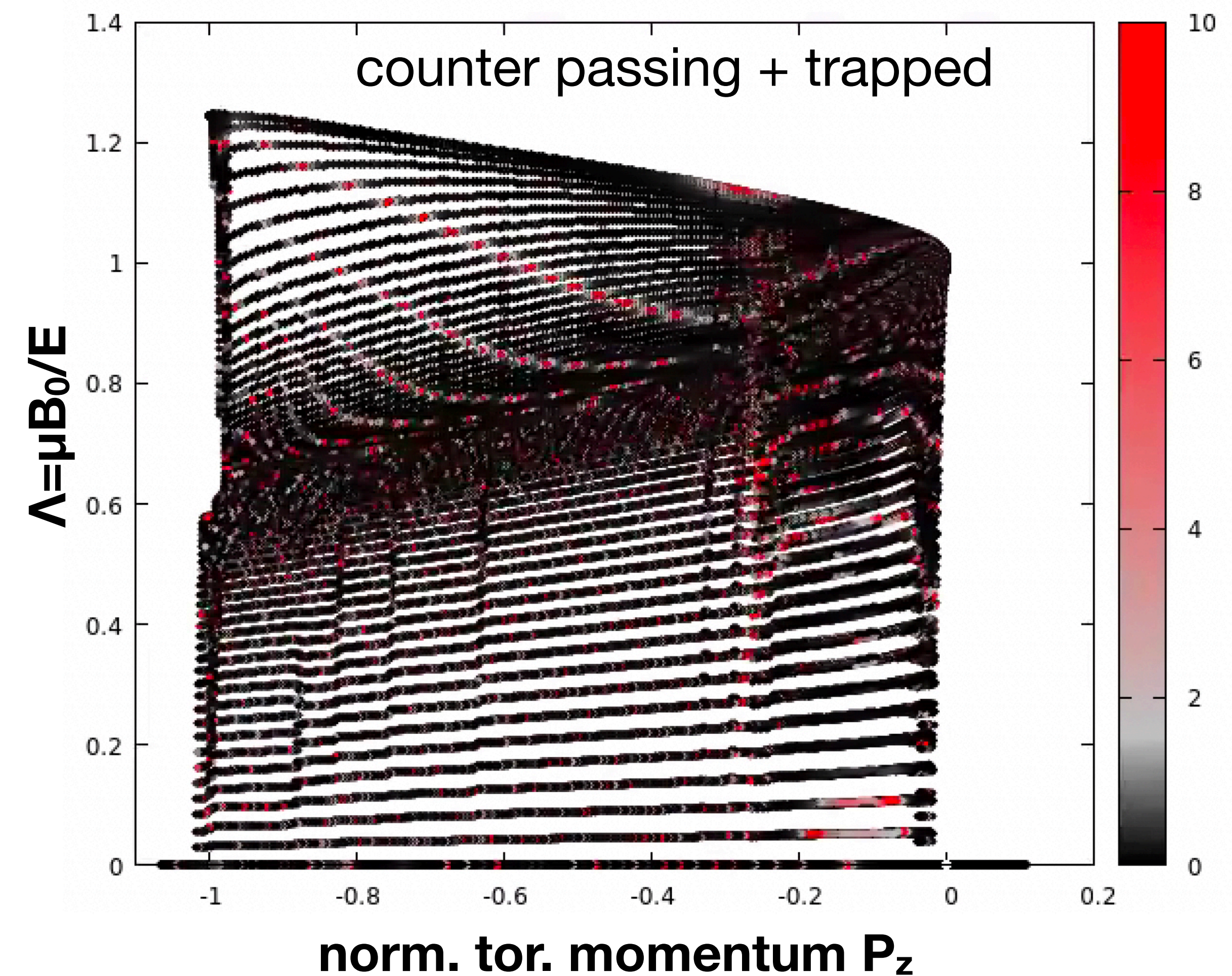
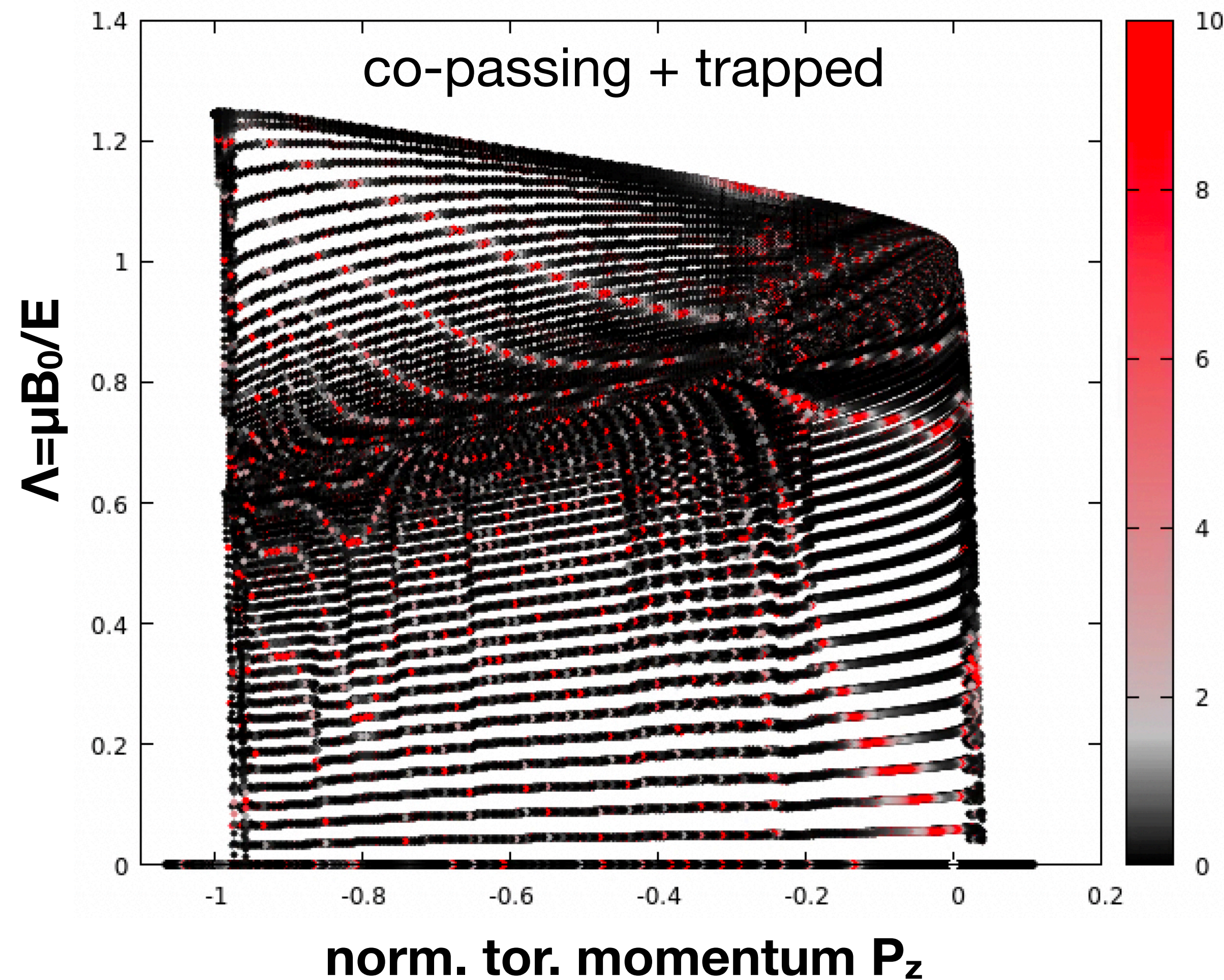
similar picture for $q < 1$: TAEs at mid radius weakly unstable

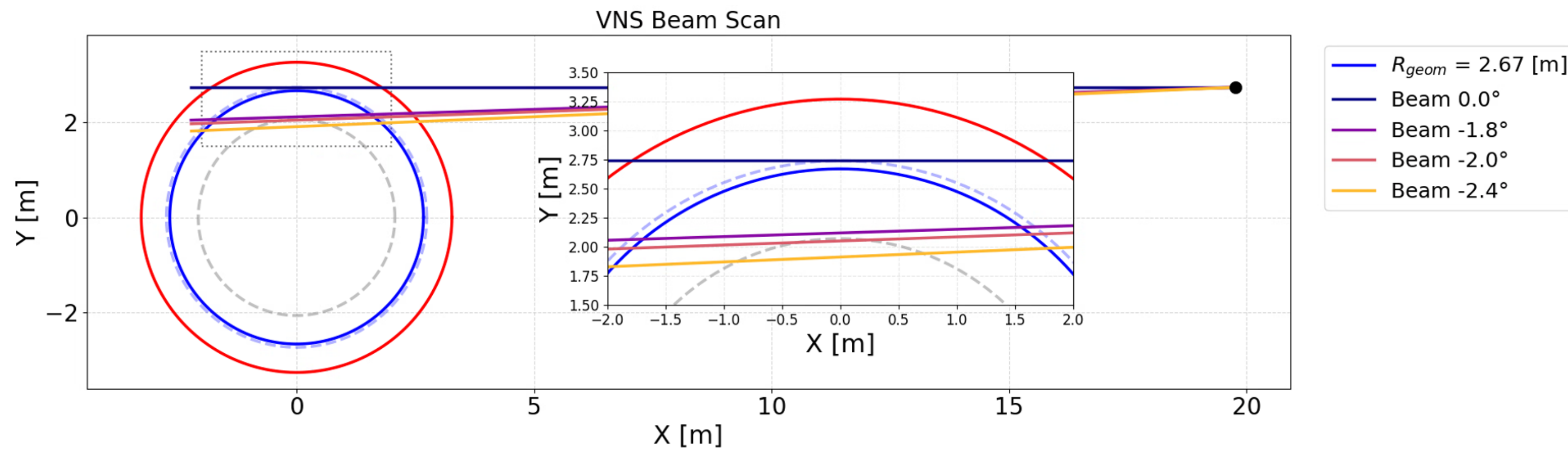


TAE resonances with α particles - here $n=24$ TAE



low energies $E=[0.1-0.5 \text{ MeV}]$







VNS current design point

Parameters (METIS):

Major Radius = 2.67 m

Toroidal Field = 5.6 T

Aspect Ratio = 4.25

Sep. Elongation = 1.6

Triangularity = 0.23

NBI Power = 42.5 MW

Beam Energy = 120 keV

EC Power = 8 MW

Safety Factor $q_{95} = 3.1602$

Line average density = $11 \times 10^{19} \text{ m}^{-3}$

Plasma Surface = 95.3809 m²

Peak NWL = 0.5114 MW/m²

Av. NWL = 0.32058 MW/m²

BetaN = 2.7209 %Tm/MA

Fusion Power = 38.2219 MW

Centr. El. Temperature = 12.9134 keV

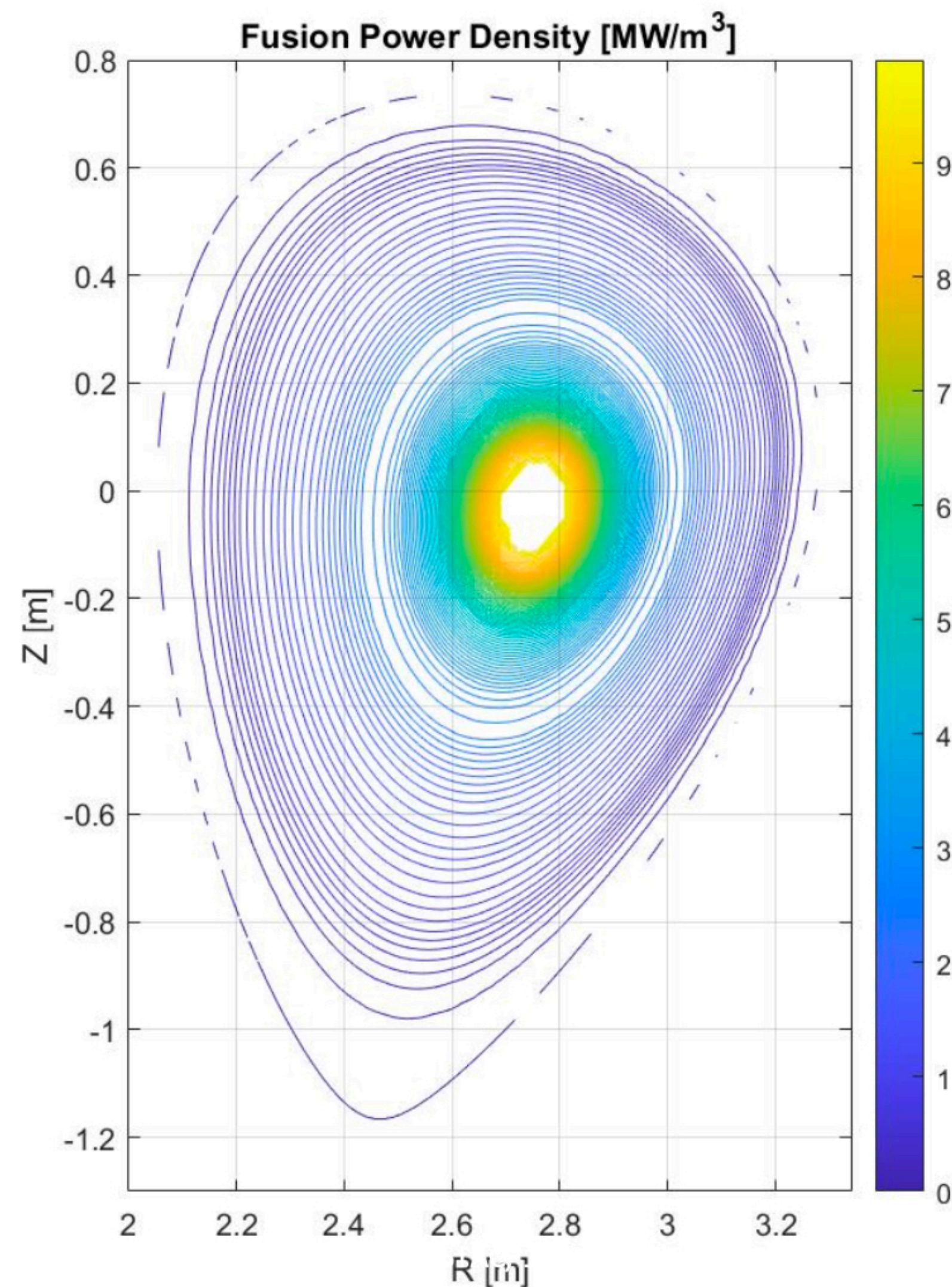
Pl. Current = 2.5401 MA

Tot. Beta Poloidal = 1.8749

D Fraction in Bulk Plasma = 0.17006

Power to Divertor = 55.6196 MW

Fully non-inductive plasma!



[Siccino, ESM Jan 2026]

Ideally, one would operate a 100% D-beam on 100% T-plasma to maximize the reaction rate.

But, since the burn-up is very low, the contribution of the beams to fueling (and thus to density) is non-negligible.

High plasma current and toroidal field are required for MHD stability (beta limit) and for fast particles confinement



A fundamental aspect – T consumption

- **T is a very scarce resource** – world availability for civil use is few kg/year, with a cost of ~30 k€/g
- **Our device cannot rely on T self-sufficiency** (a machine which tests the blanket cannot work if and only if the blanket works)

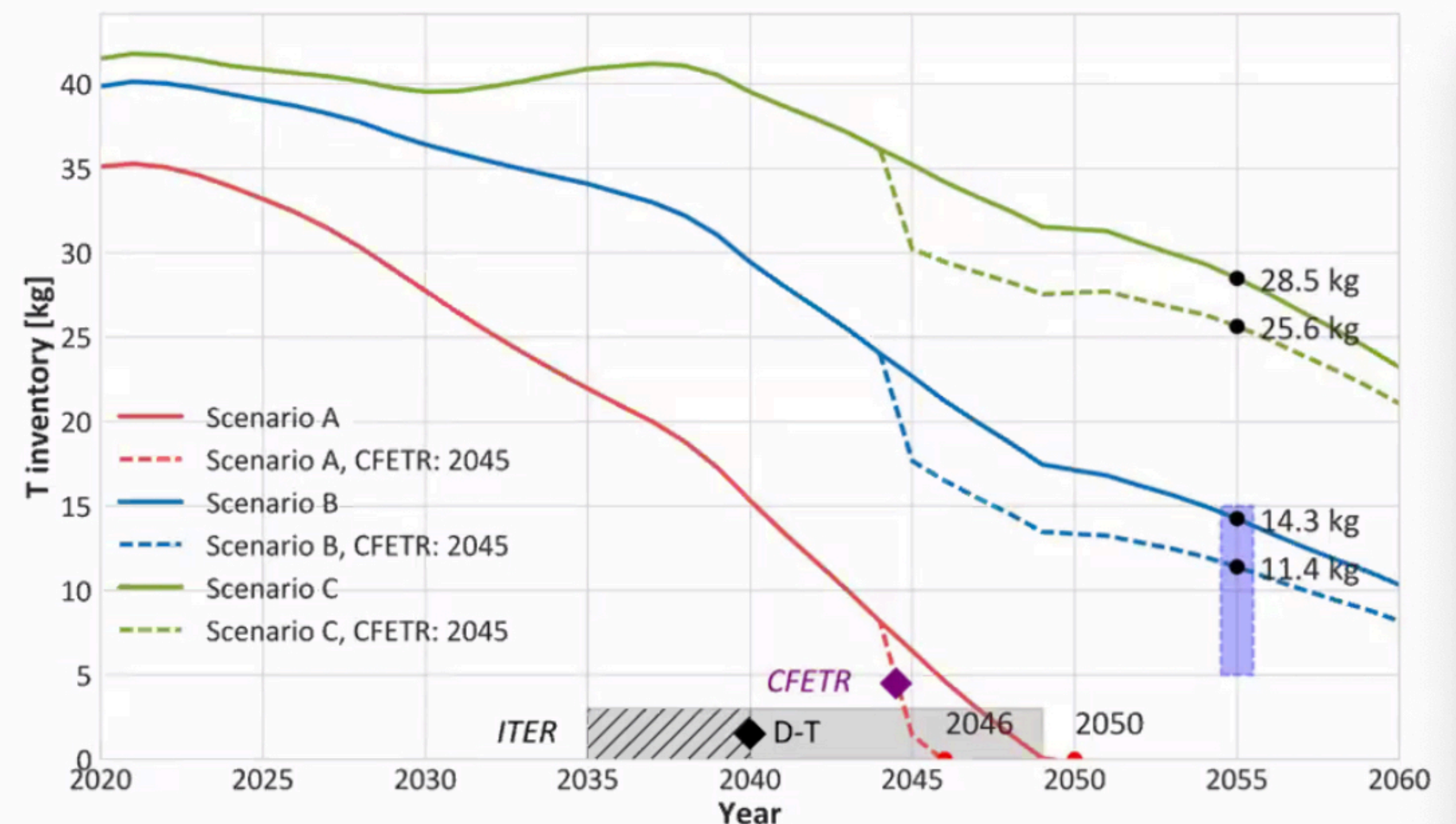
T-consumption must be low!

- **A large size device**, independently on how P_{fus} is generated, **would require high P_{fus} and thus high T consumption** (because $NWL \propto \frac{P_{fus}}{S}$ and S is large)

[Figure: M. Coleman and M. Kovari, Nucl. Fusion 2018]

The T consumption constraint *forces* the size of the device to be as small as possible.

	DEMO	VNS
P_f (MW)	2000	30
NWL (MW/m ²)	1	0.5
fpy to reach 20 dpa	2	4
T (kg) consumed to reach 20 dpa	224	6.8





VNS mission

What is VNS?

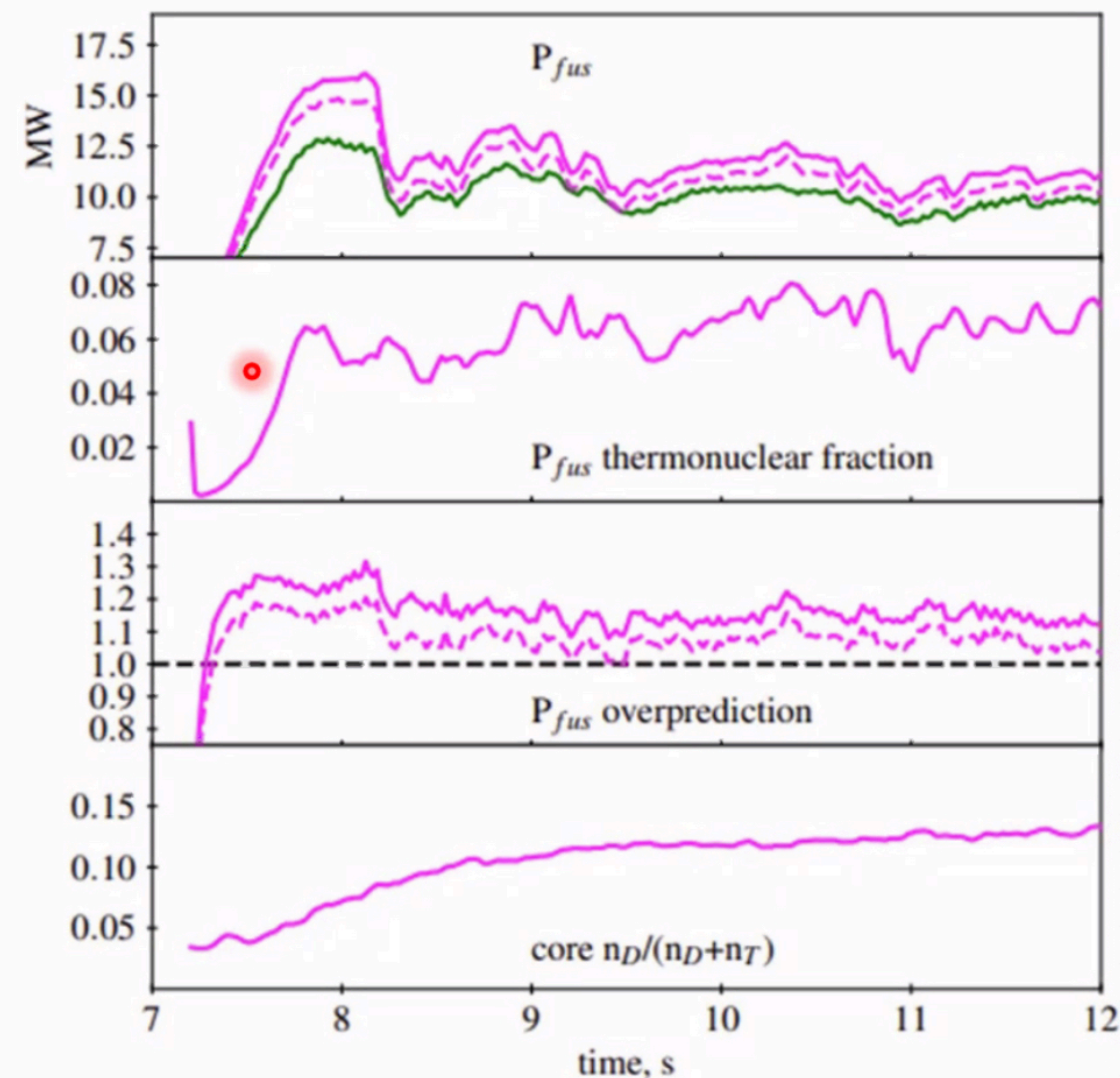
High Level Objectives

1. To be build in parallel to ITER
2. Nuclear technology mission (DT plasma)
3. Breeding blanket/in-vessel components: concept validation, testing, qualification
4. **Not relying on T self-sufficiency**
5. ...

Requirements/ Design Operation Constraints

- (from 1) it must rely on a demonstrated physics – **beam-target ($Q \leq 1$)** (e.g. JET T-rich plasmas, see figure)
- (from 2, 3) Sufficient high level of n-flux → **must achieve a relevant $NWL \geq 0.5 \text{ MW/m}^2$**
- (from 2, 3) Must achieve relatively high fluence levels $F = NWL \times \text{Irradiation time} = NWL \times \text{time} \times A_v \rightarrow (20-50 \text{ dpa})$. **Very long pulses are mandatory**
- (from 4) Operate with tritium from external supplies (non self sufficient) → **must minimize P_{fus}**

JET shot #99971, T-rich



[Figure: M. Maslov et al., Nucl. Fusion 2023]



Energy of the beam

The fusion cross section decreases quite fast for $E_b > \sim 120 \text{ keV}$.

If a proper beam deposition is granted, **higher beam energy has therefore only marginal impact on the fusion power generation**, at the price of technological complications.

High beam energy can however be beneficial for:

- Reducing rotation at given beam energy (which affects W transport)
- Improve beam deposition
- Improve NBCD

The choice of $E_b = 120 \text{ keV}$ has been made to remain in the positive ion beam realm.

