ATEP news

agenda

14:00 → 16:30 **ENR ATEP Progress Meeting**

14:00	**ATEP news** **Speaker**: Philipp Lauber (IPP)	10m
14:10	**Update on beat-driven and spontaneous excitation of ZF/ Update on calculation of low frequency spectrum inclusing trapped particles** **Speakers**: Fulvio Zonca (ENEA), Matteo Valerio Falessi (ENEA)	30m
14:40	**Update on STRUPHY** **Speaker**: Stefan Possanner	20m
15:00	**Update on ATEP-3D solver** **Speaker**: Guo Meng (IPP)	10m
15:10	**Update on ORB5-ATEP PSZS comparison/ZF model in ATEP** **Speaker**: Philipp Lauber (IPP)	40m
15:50	**short reports and discussion** **Speaker**: Philipp Lauber (IPP)	30m

announcement - review meeting

Thursday, 24 October

09:00 → 12:30 **Theory & Modelling Projects**

09:00 **Operation limiting plasma instabilities in high performance tokamaks: fundamental understanding and solutions for critical problems** ¶ — 50m
ENR-MOD.01.EPFL
(25 min presentation + 15 min. discussions)
Speaker: Jonathan Graves (EPFL)

09:50 **Development of machine learning methods and integration of surrogate model predictor schemes for plasma-exhaust and PWI in fusion** — 50m
ENR-MOD.01.FZJ
(25 min presentation + 15 min. discussions)
Speaker: Dr Sven Wiesen (DIFFER)

10:40 **COFFEE BREAK** — 10m

10:50 **Energetic particle optimization of stellarator devices using near-axis magnetic fields** — 50m
ENR-MOD.01.IST
(25 min. presentation + 15 min. discussions)
Speaker: Rogerio Jorge (IST)

11:40 **Advanced energetic particle transport models (ATEP)** — 50m
ENR-MOD.01.MPG
(25 min. presentation + 15 min. discussions)
Speaker: Philipp Lauber (IPP)

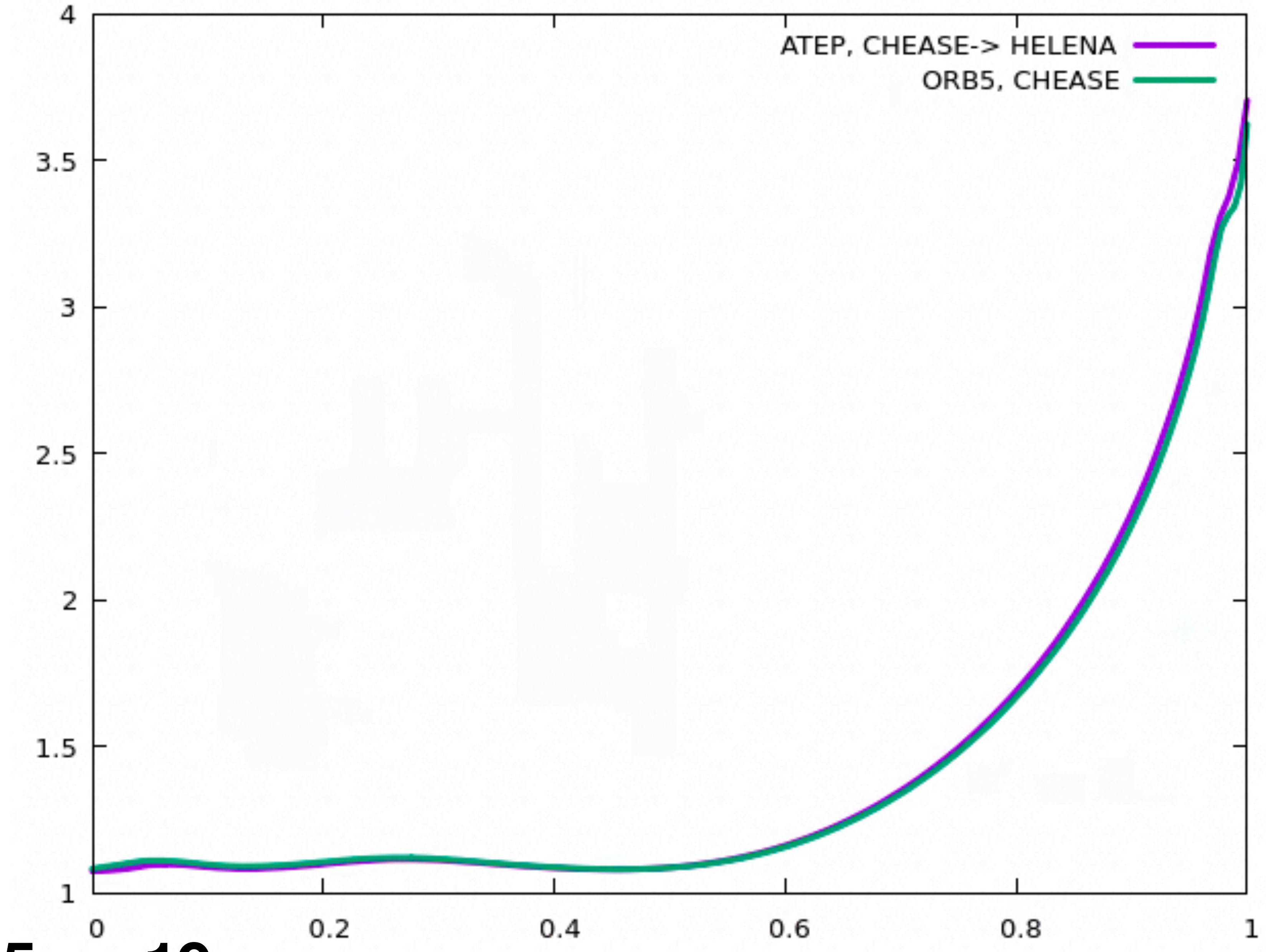
proposal: ATEP internal review meeting ˜2-3 weeks before: beginning of October, 2024

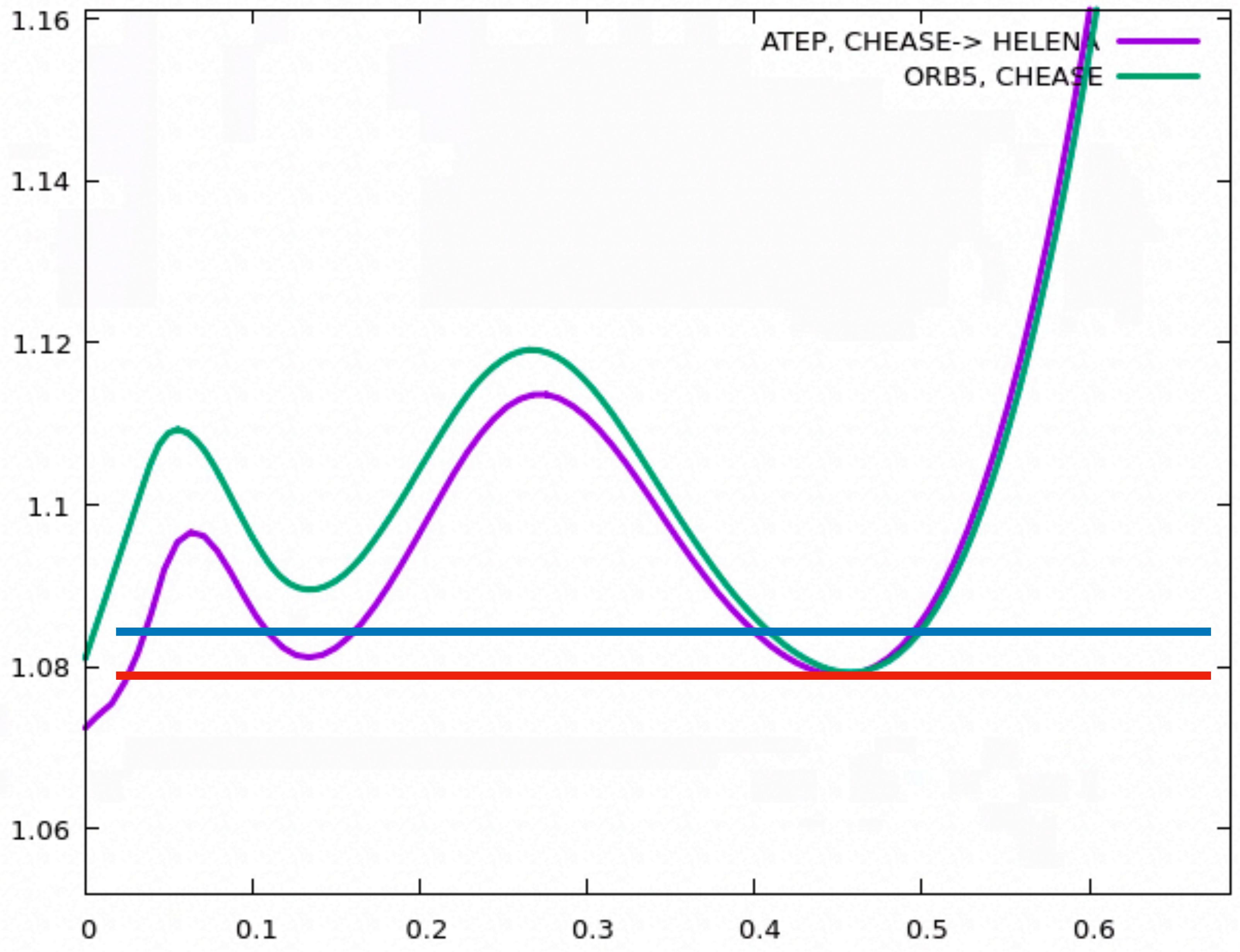
ORB5-LIGKA PSZS comparison

status and open issues

ORB5-LIGKA PSZS comparison, ITER #101006

[T Hayward-Schneider, FEC 2023]



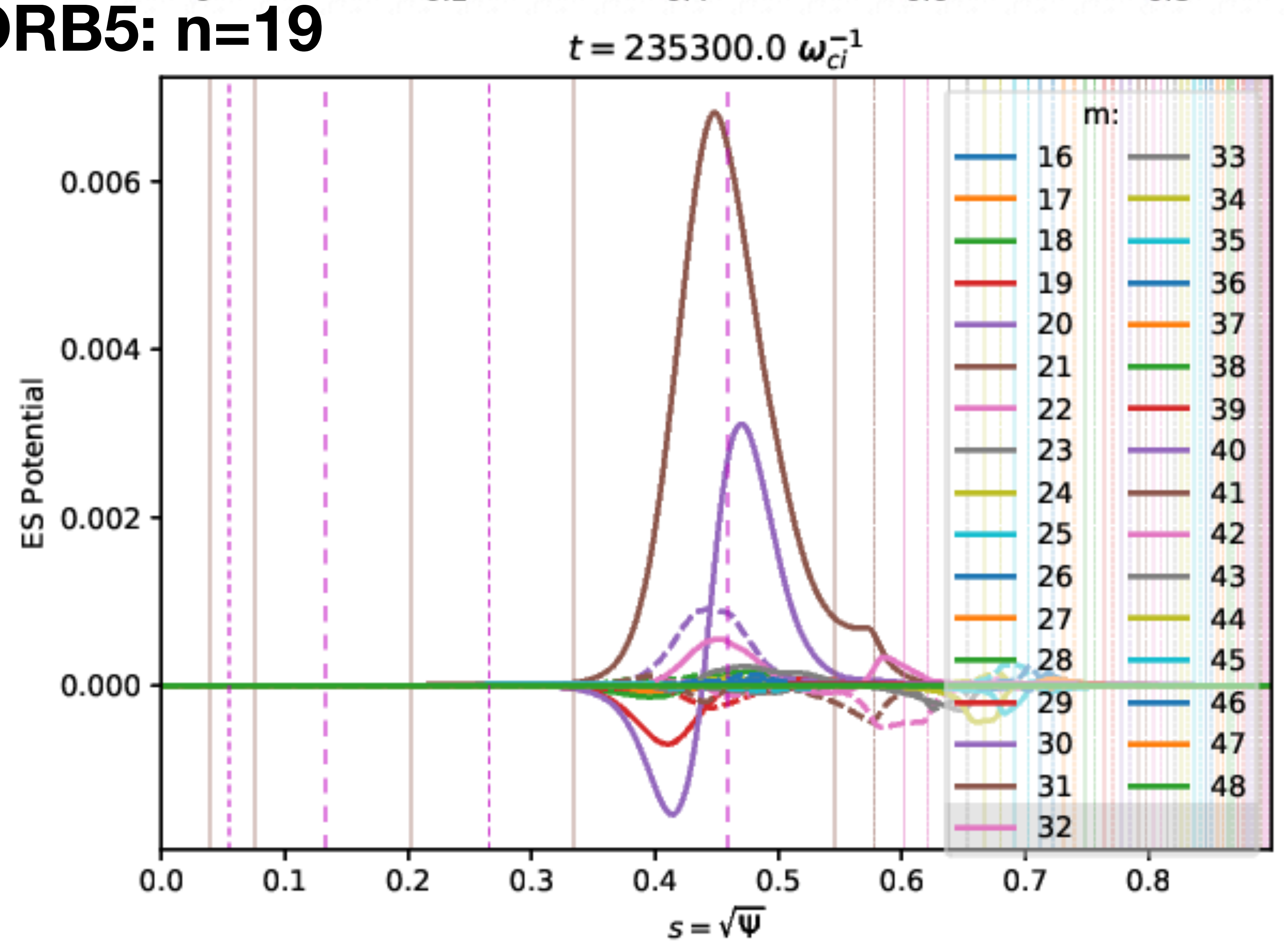


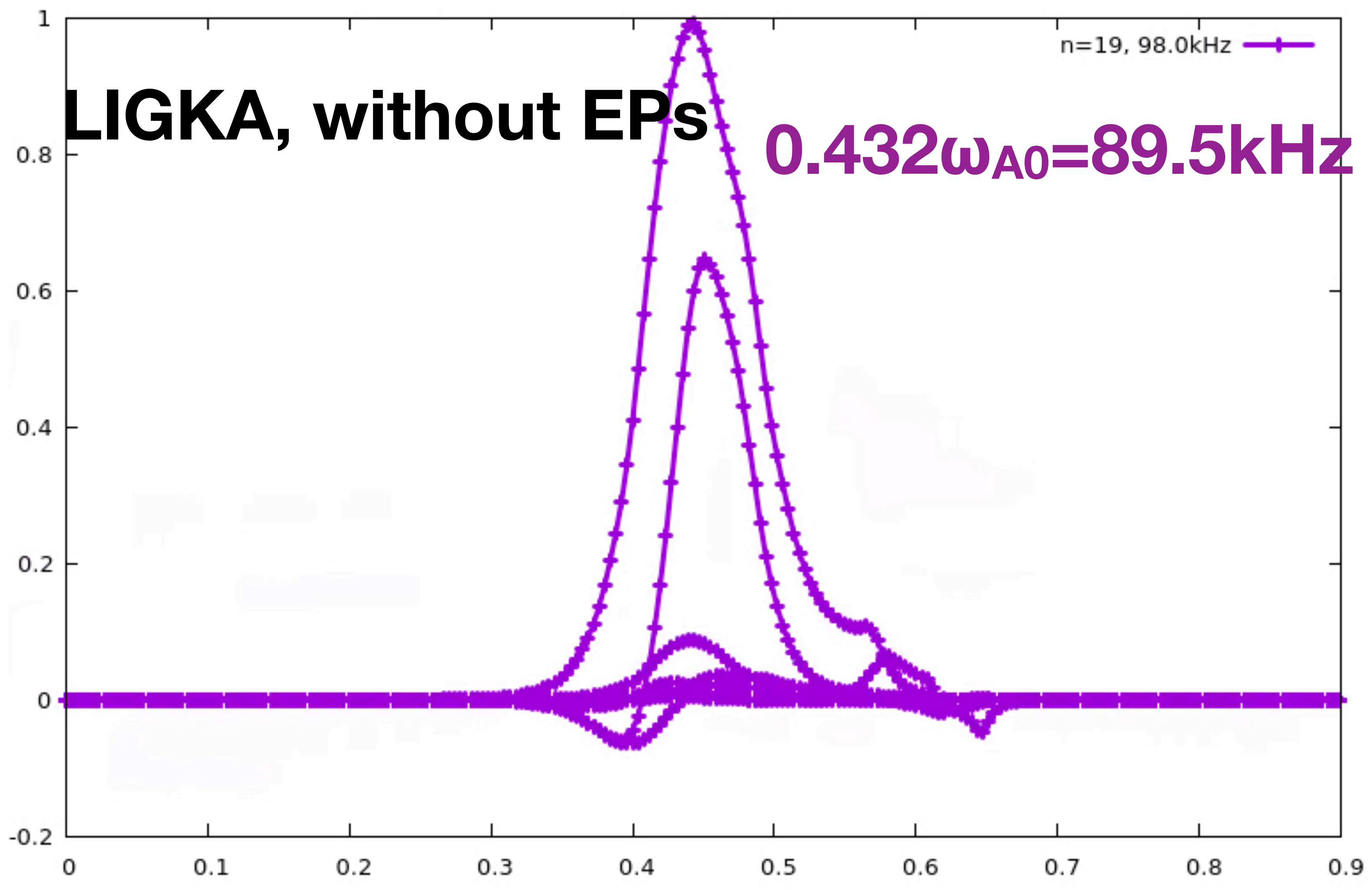
2 NBI beams: on-off

$q=q_{TAE}(n=18)=19.5/18=1.0833$

$q=q_{TAE}(n=19)=20.5/19=1.0789=q_{min}$

ORB5: n=19





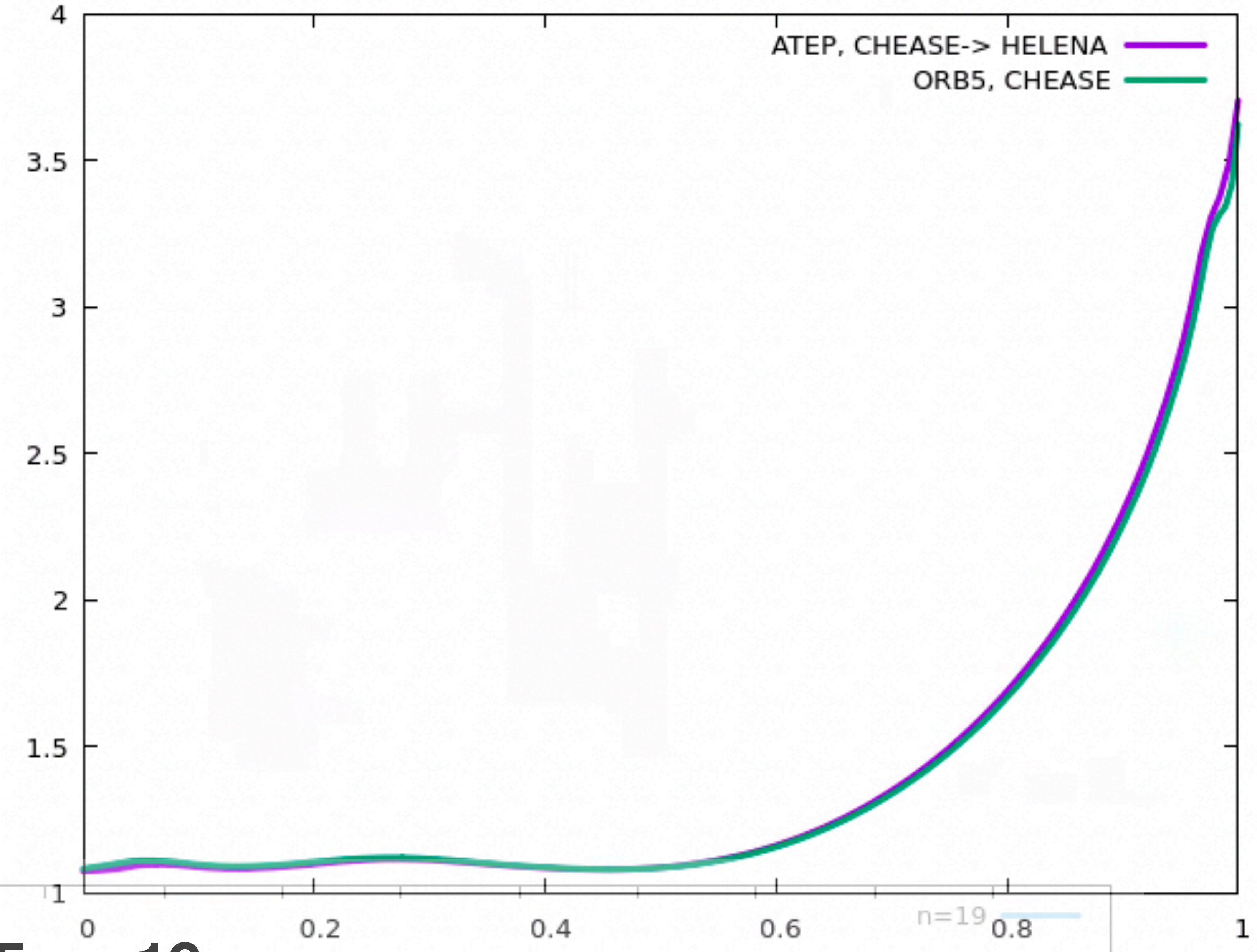
matching local q_{min}, differences in shear

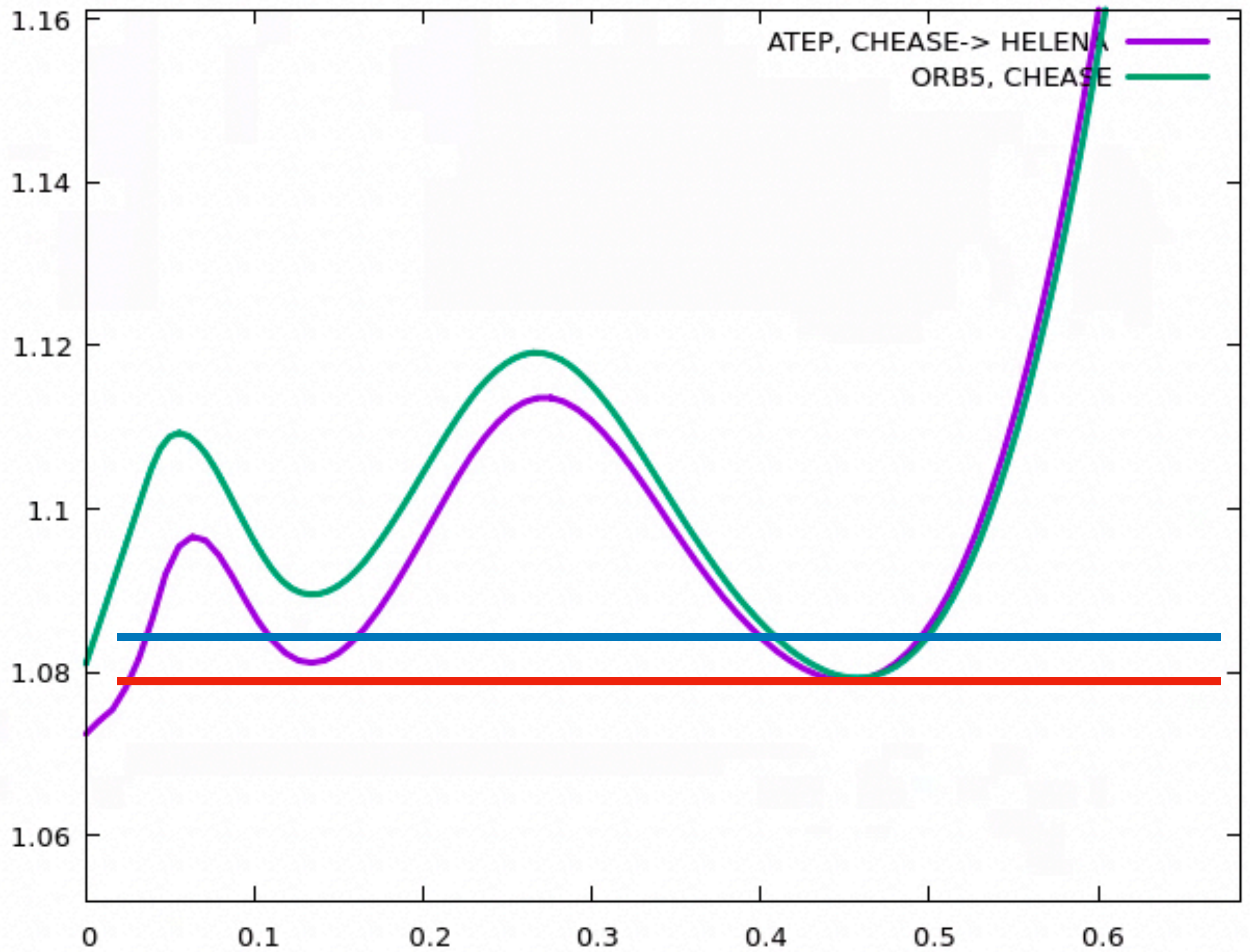
mode structures very sensitive to q

ORB5-LIGKA PSZS comparison, ITER #101006

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

[T Hayward-Schneider, FEC 2023]



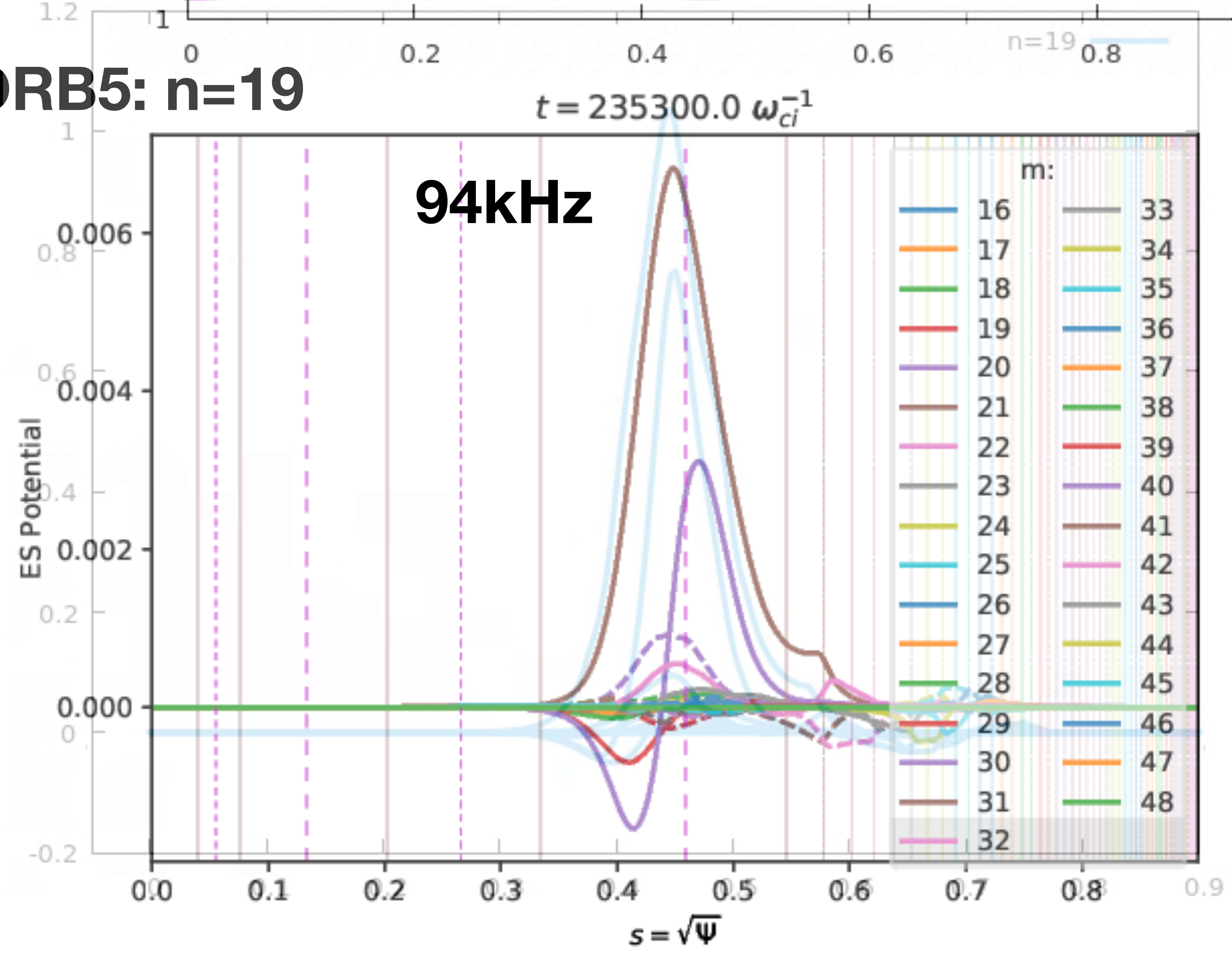


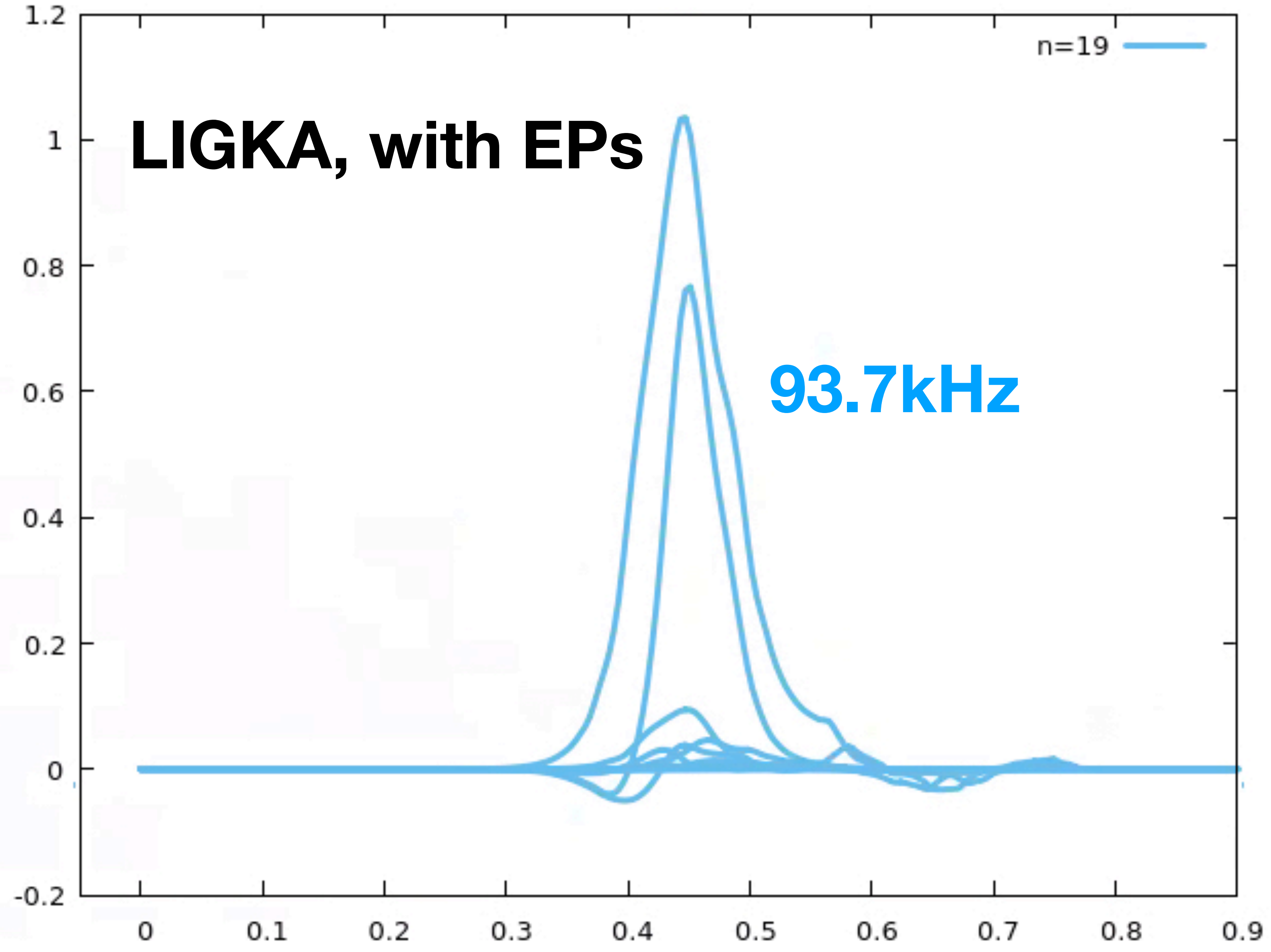
2 NBI beams: on-off

$q = q_{TAE}(n=18) = 19.5/18 = 1.0833$

$q = q_{TAE}(n=19) = 20.5/19 = 1.0789 = q_{min}$

ORB5: n=19

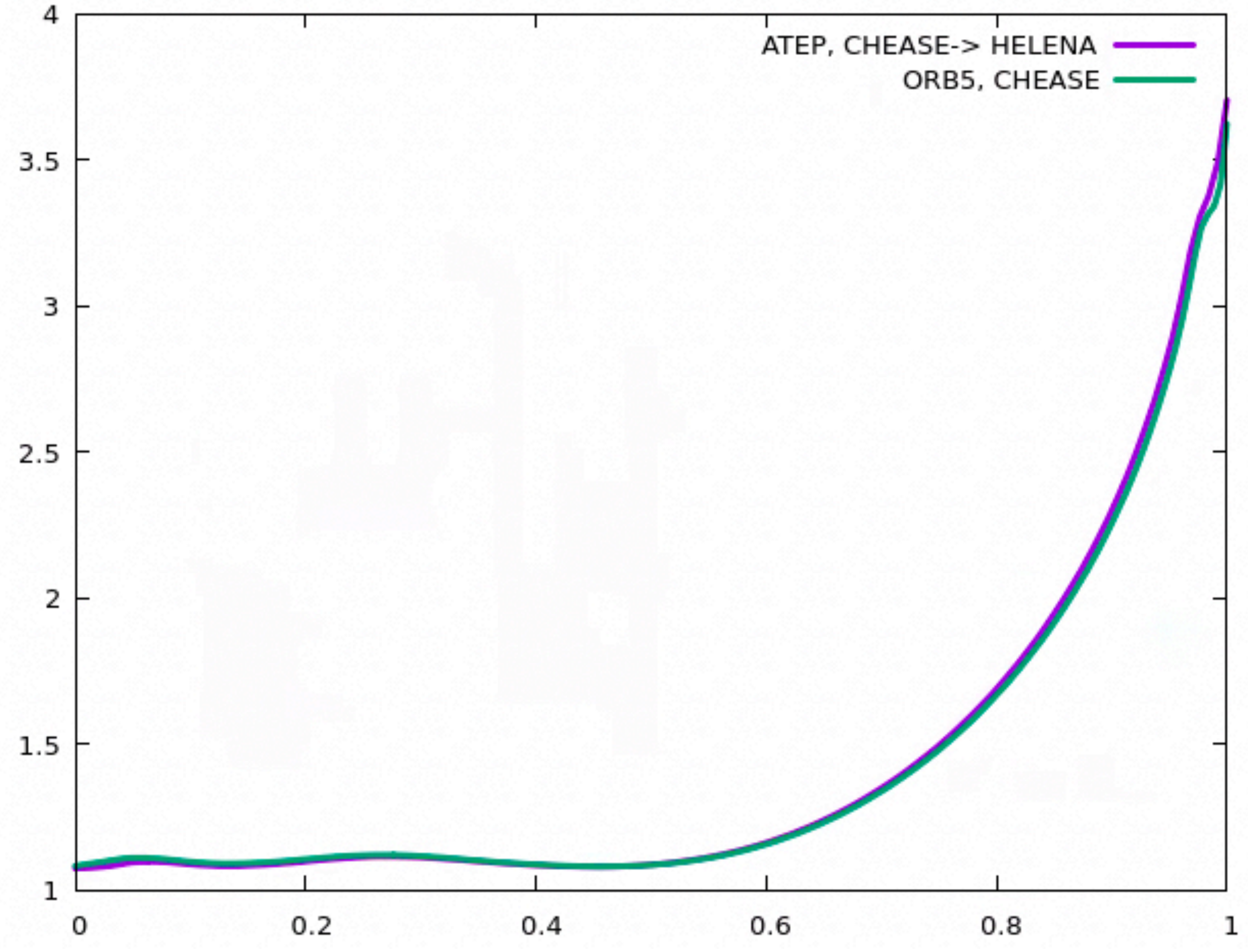


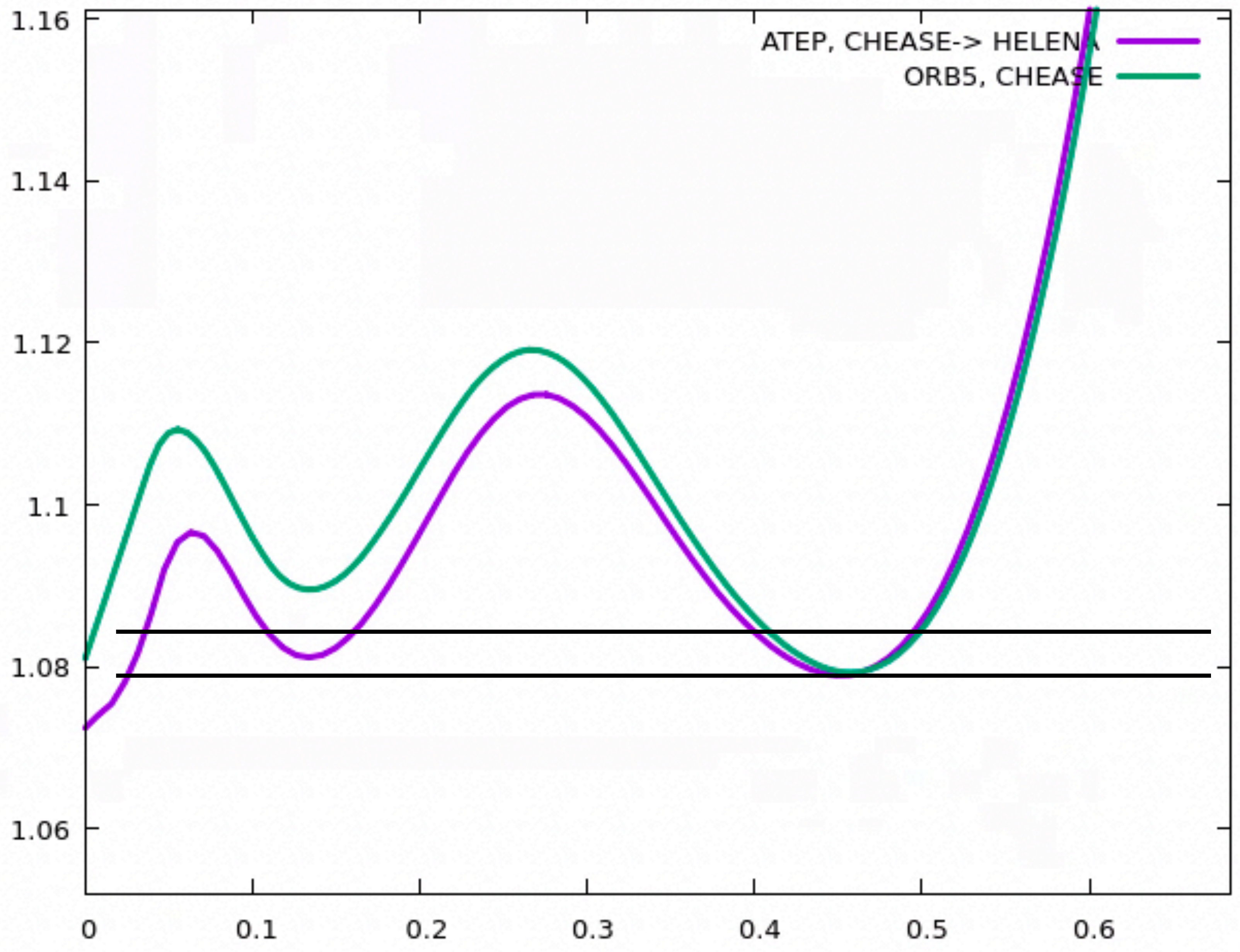


matching local q_{min}, differences in shear

mode structures very sensitive to q

ORB5-LIGKA PSZS comparison improving, ITER #101006

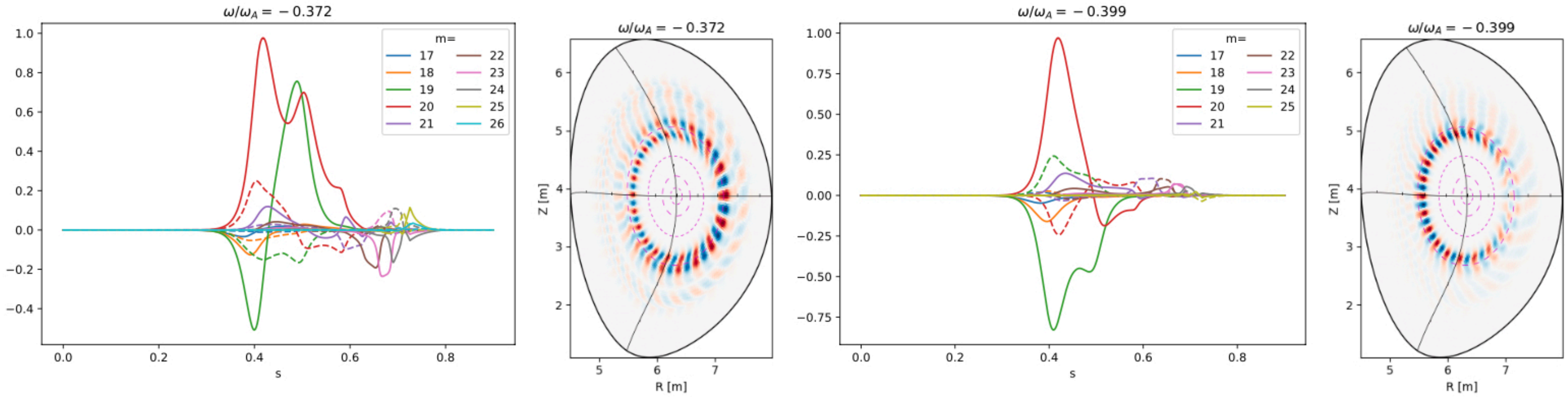




$q=q_{TAE}(n=18)=19.5/18=1.0833$

$q=q_{TAE}(n=19)=20.5/19=1.0789$

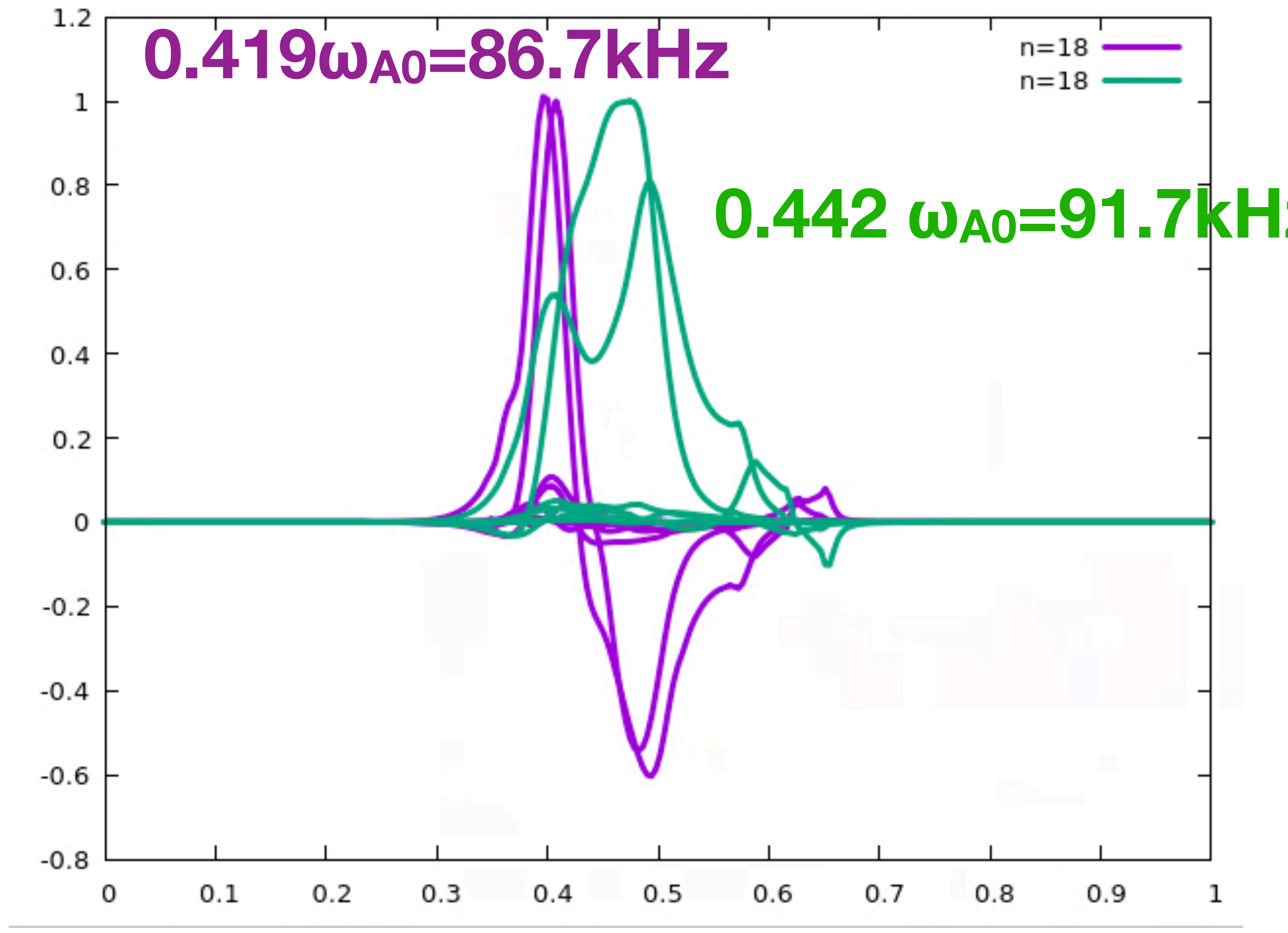
ORB5: n=18



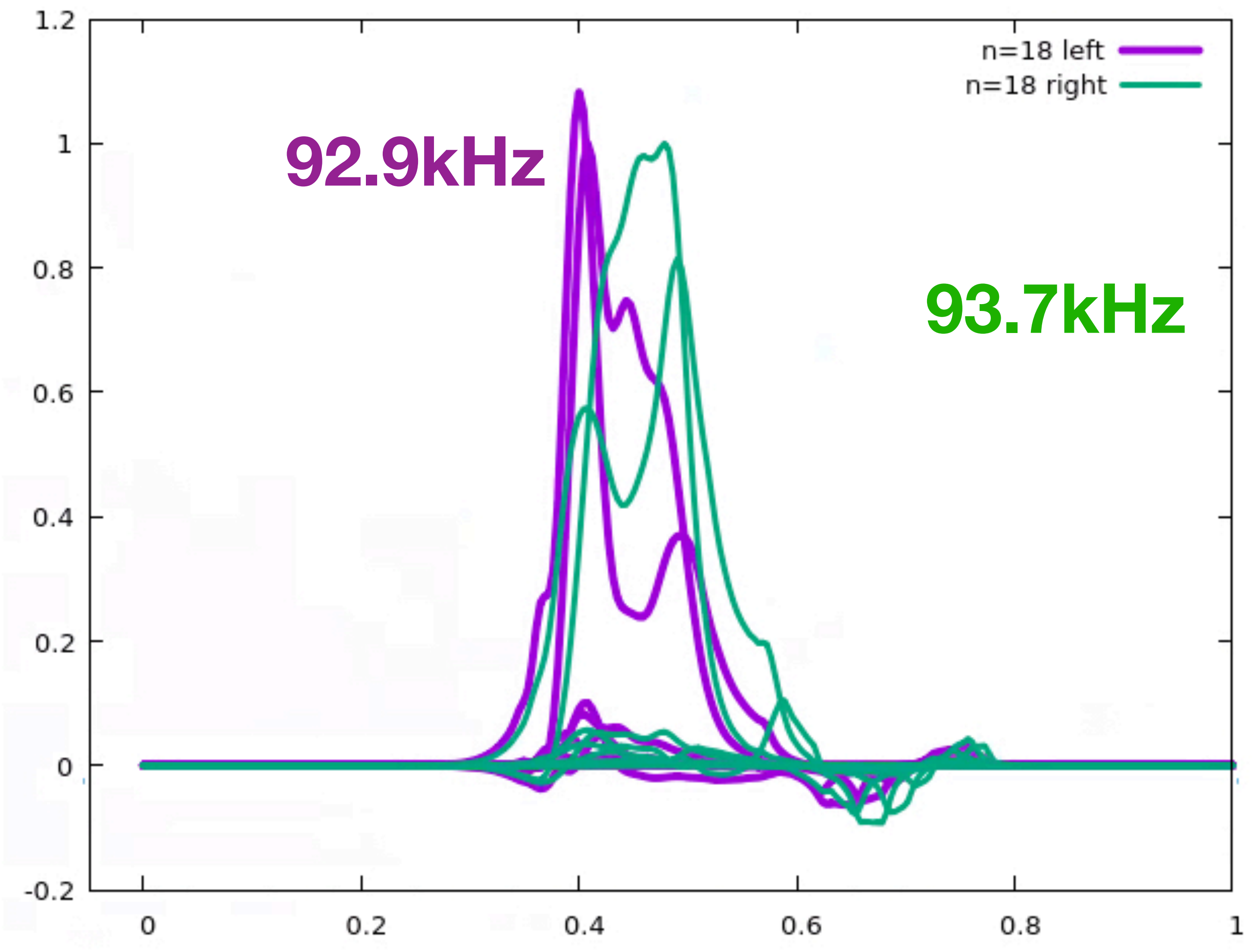
[T Hayward-Schneider FEC 2023]

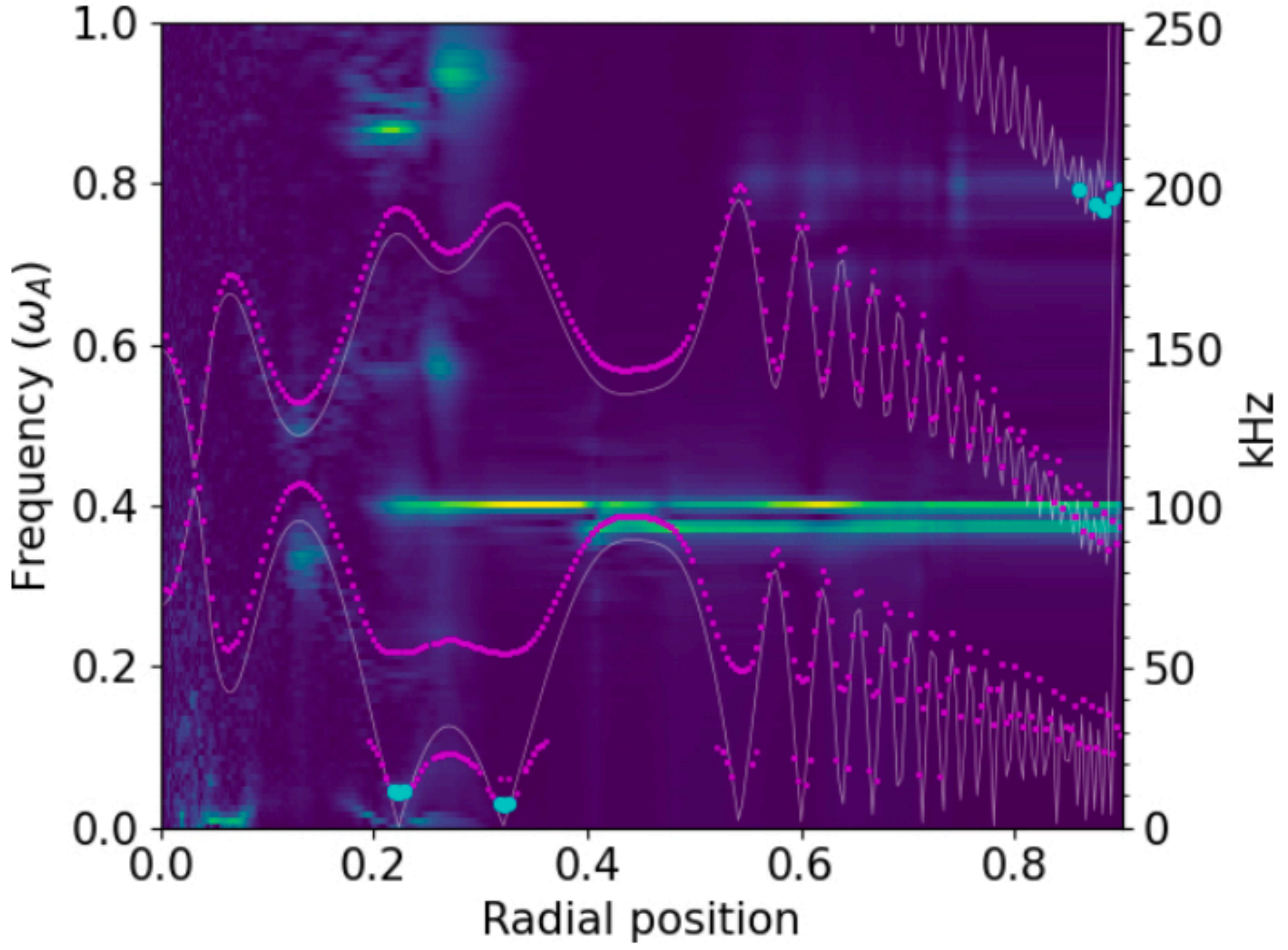
ORB5-LIGKA PSZS comparison improving, ITER #101006

LIGKA: n=18, no EPs

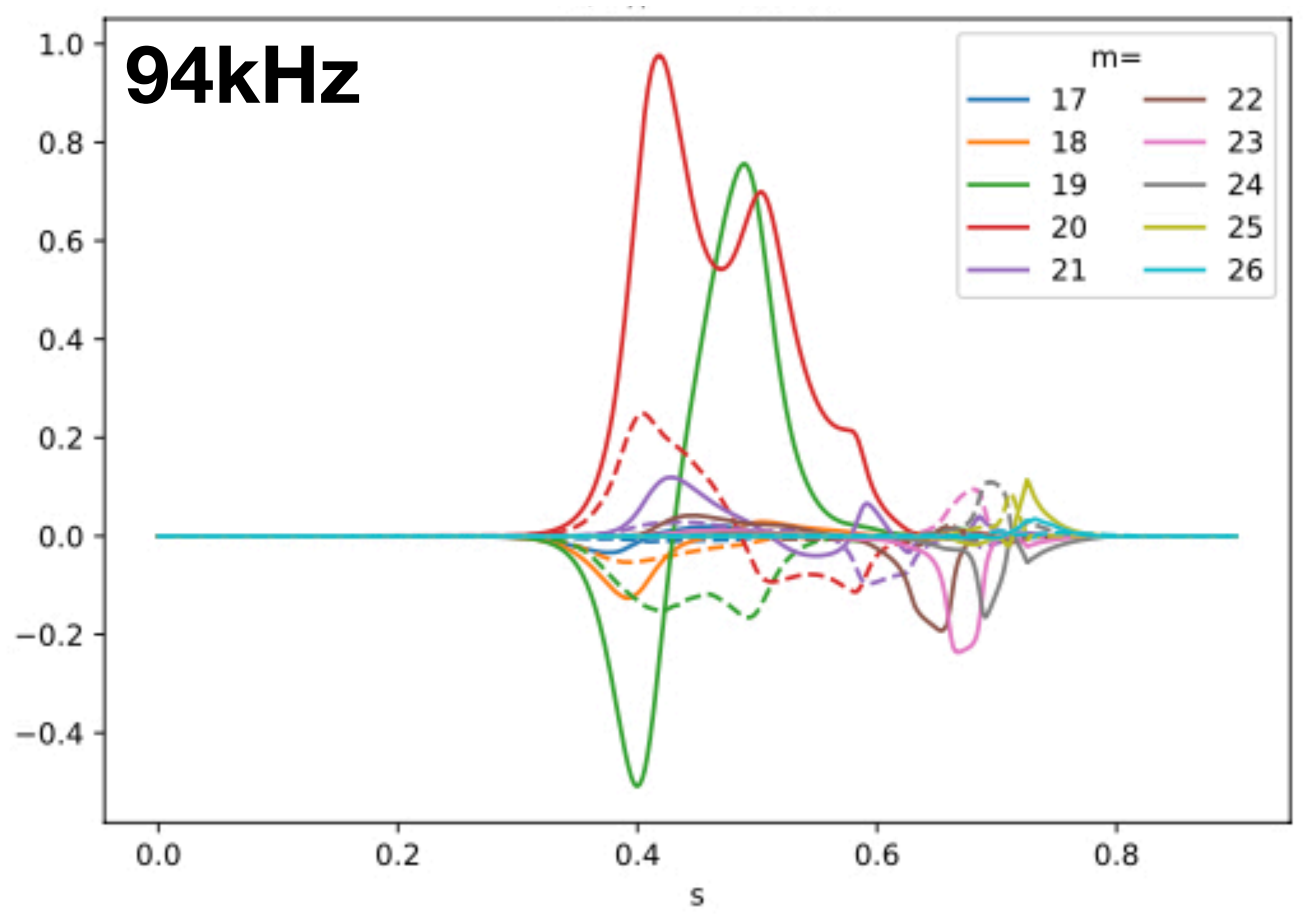


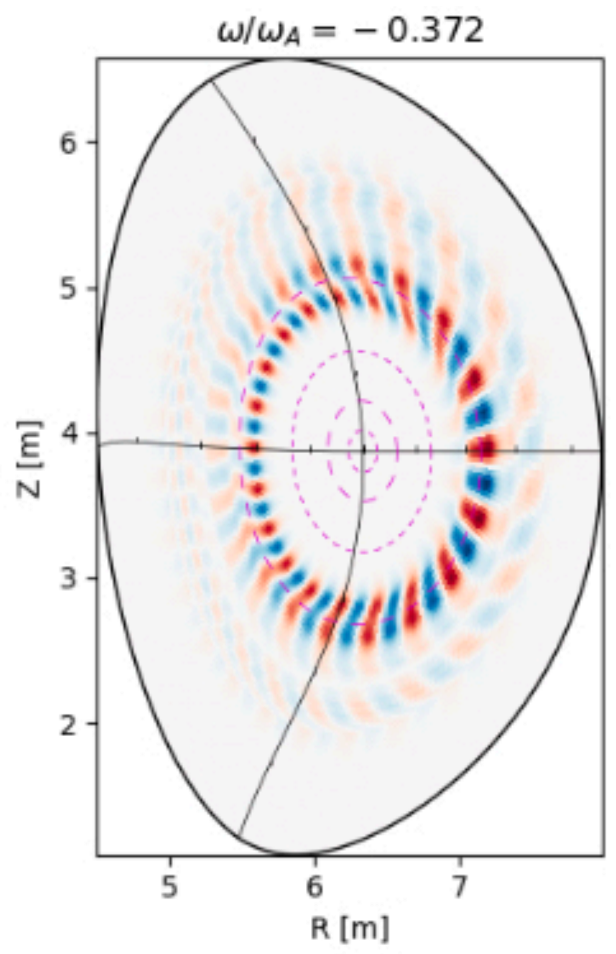
LIGKA, n=18 with EPs

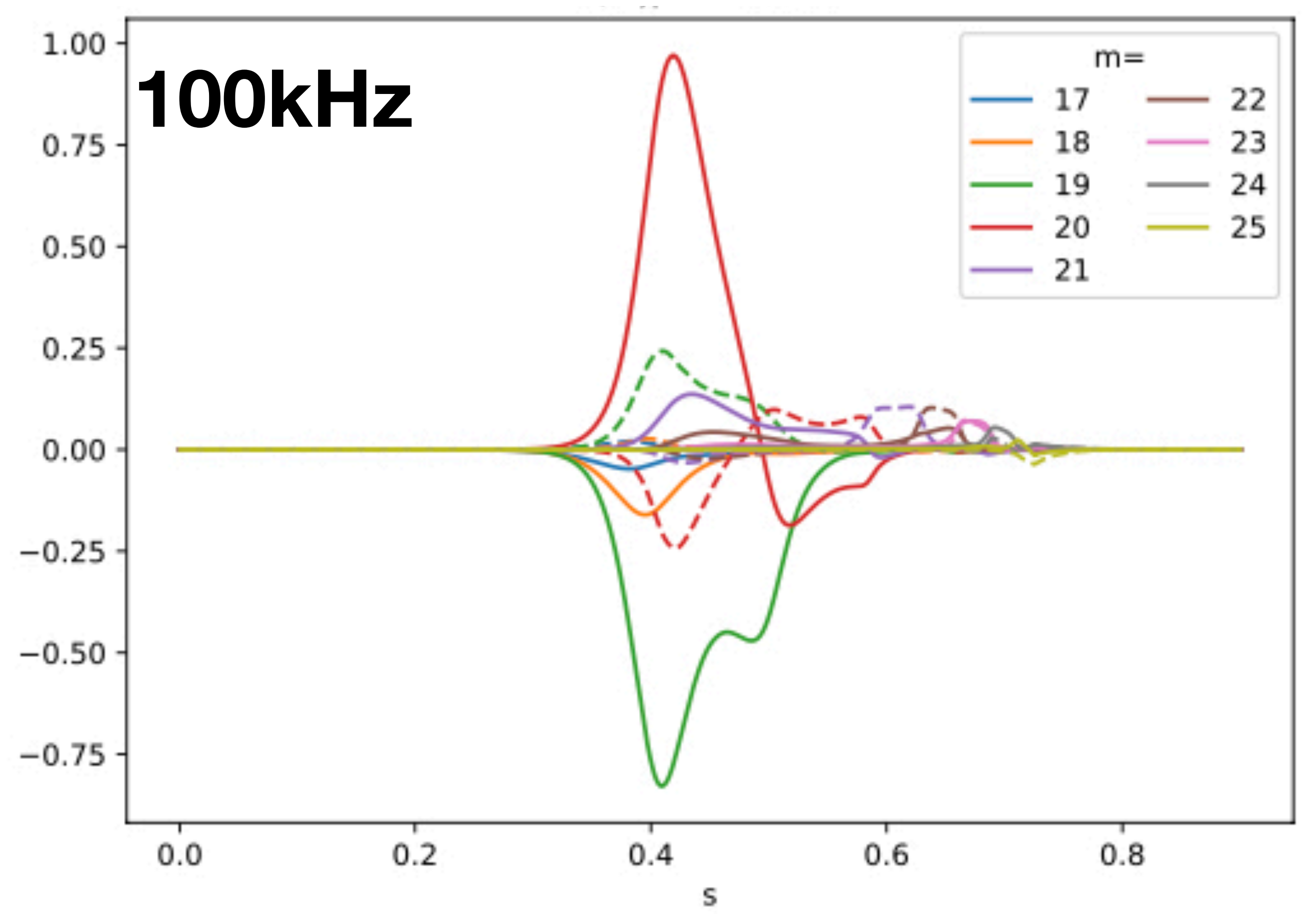


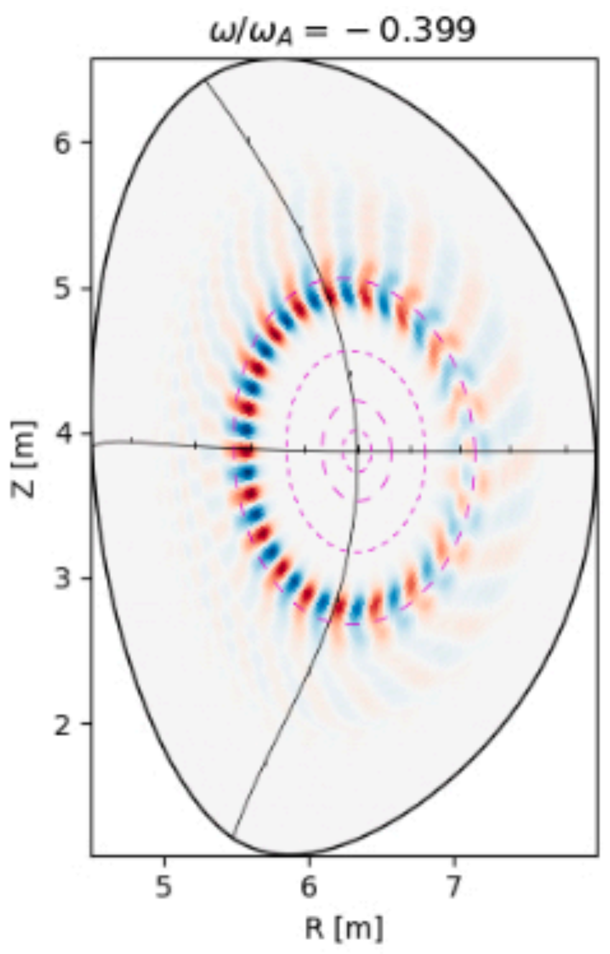


ORB5 (with EPs): n=18

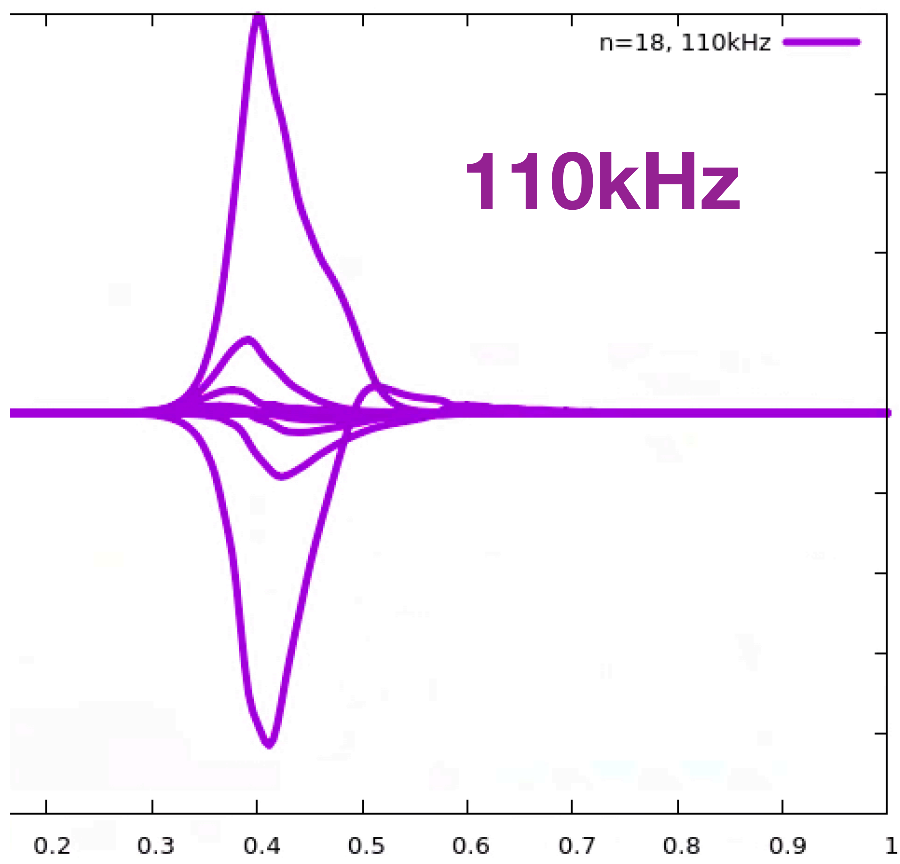






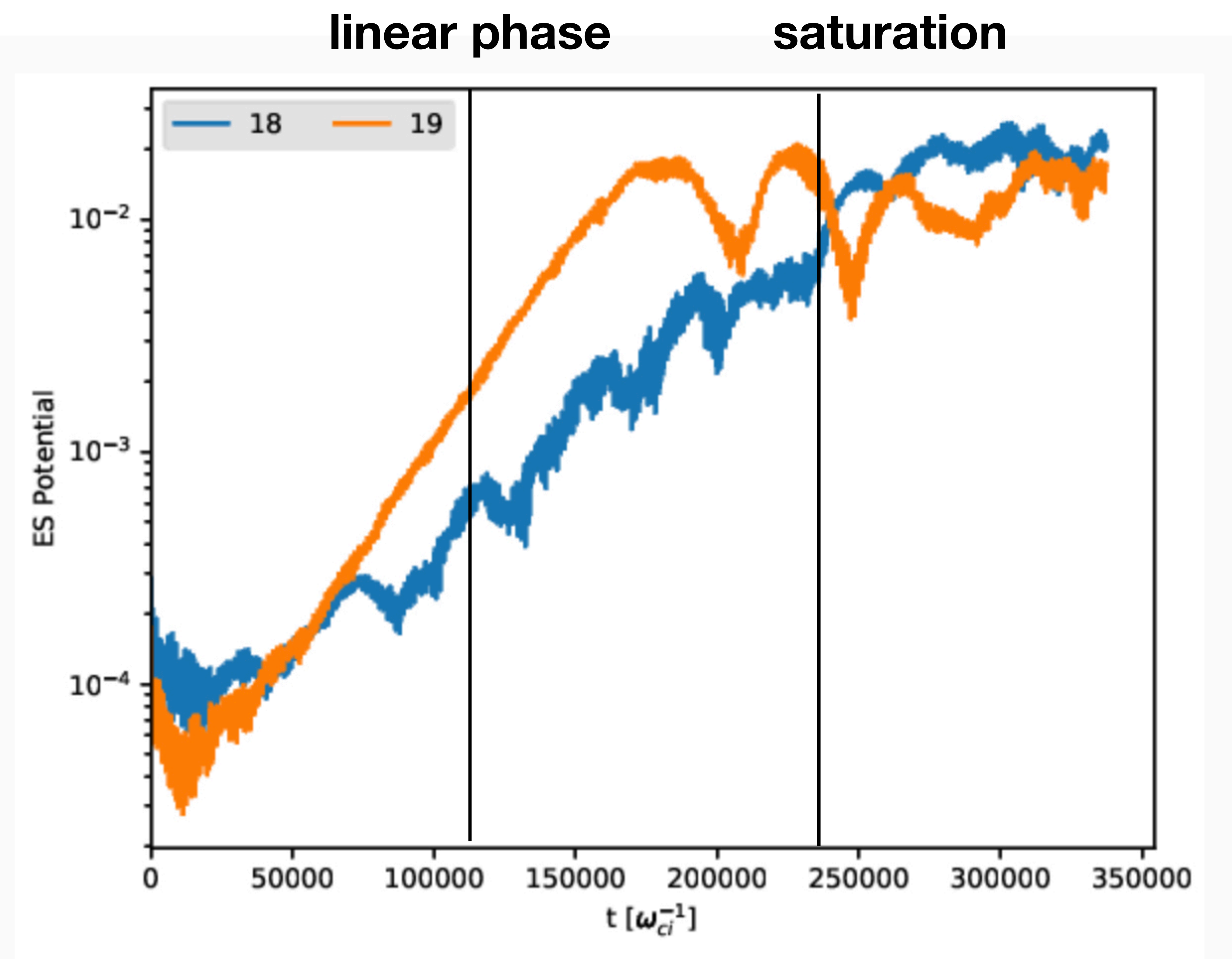


odd, n=18 with EPs



odd, n=18 without EPs

118kHz



growth rates:
ORB5: n=19: 2%
LIGKA: n=19: 2.3%

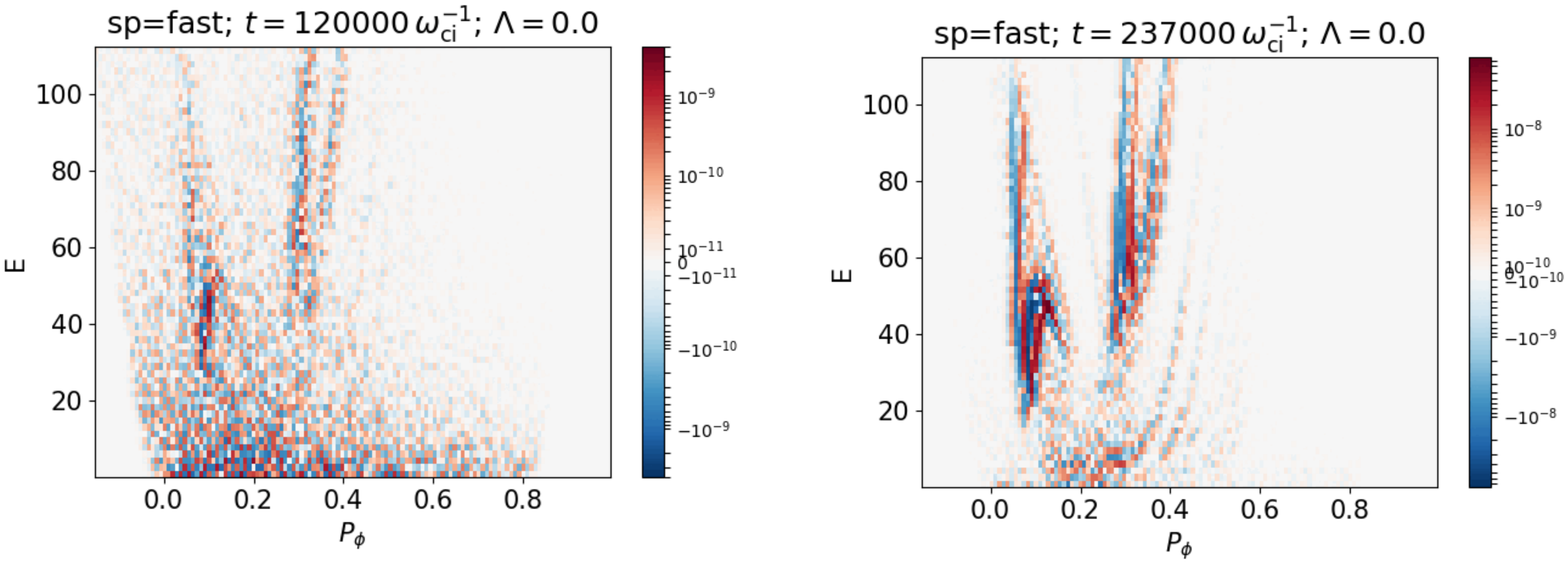
ORB5: n=18: ~2%
LIGKA: n=18 even: 0.5%
LIGKA: n=18 odd: 1.0%

ORB5: isotropic slowing down

ATEP/LIGKA: equivalent pressure Maxwellian

ORB5 PSZS [T Hayward Schneider, using diagnostics described in Bottino JPC 2022]

[keV/10]

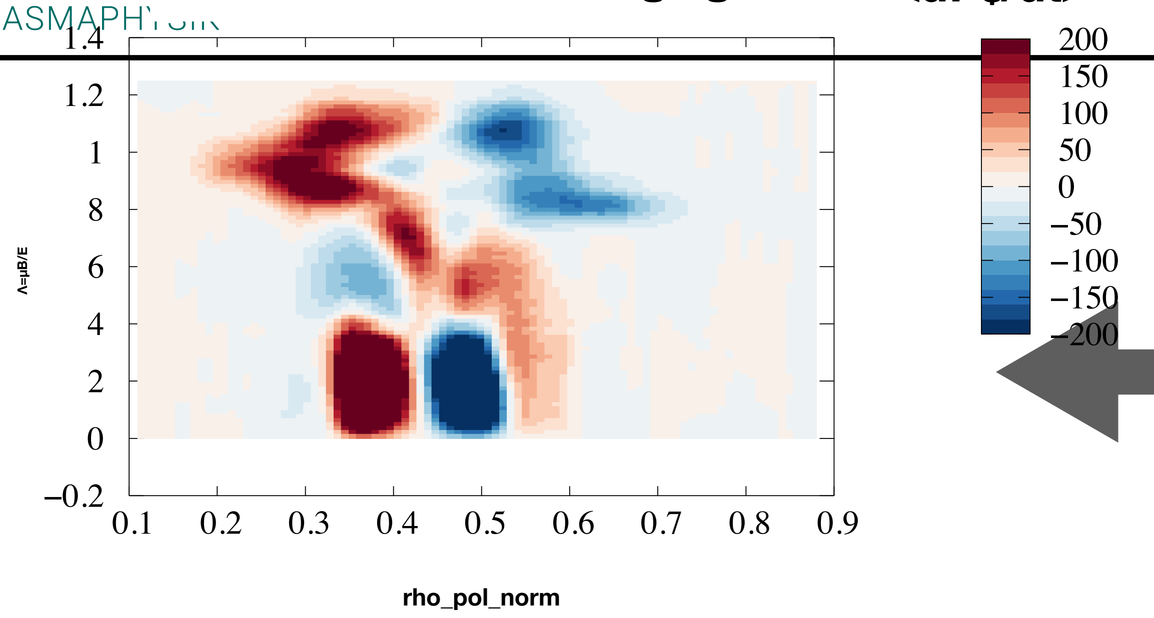


radially outwards

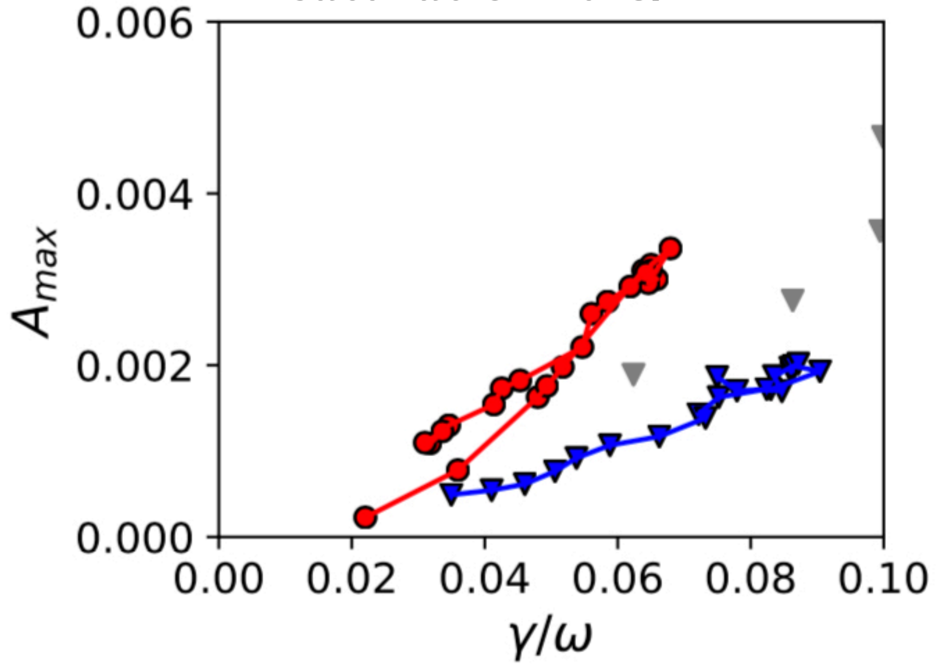
isotropic slowing down

ATEP code: physics and structure

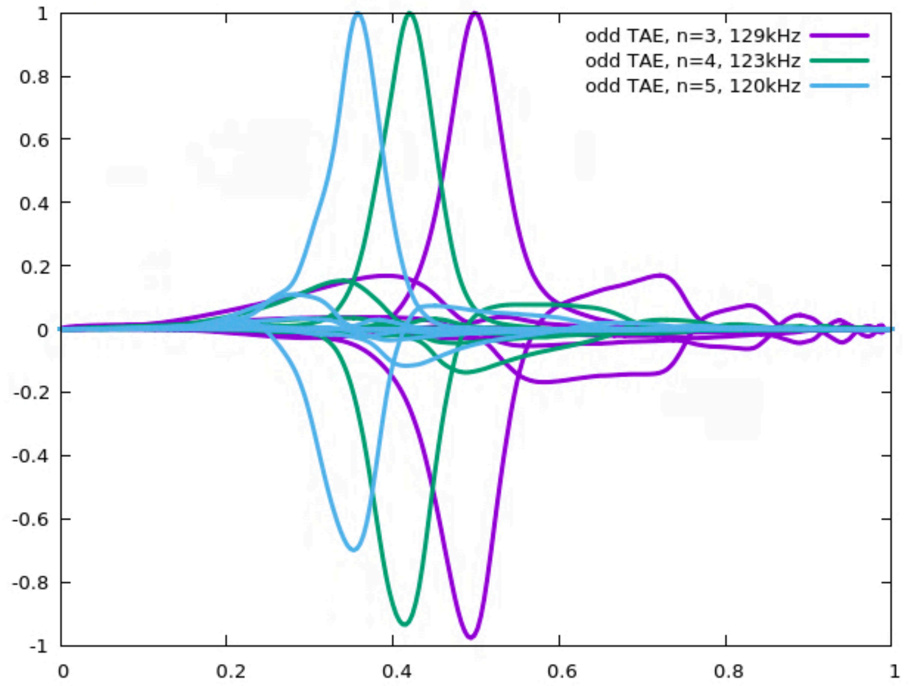
orbit+zonal averaging



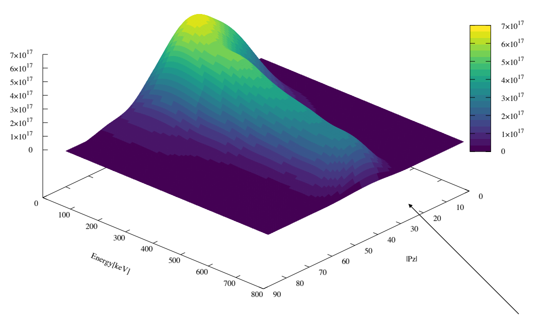
saturation rule/E



EP WF: LIGKA [20]



F_{EP} (CoM)



transport code

calculate PSZS

use NL code/model for intensity closure

or kick model

calculate linear mode spectrum

calculate D(r,E)

or

advance F_{EP} and return updated distribution IDS, or its moments

t

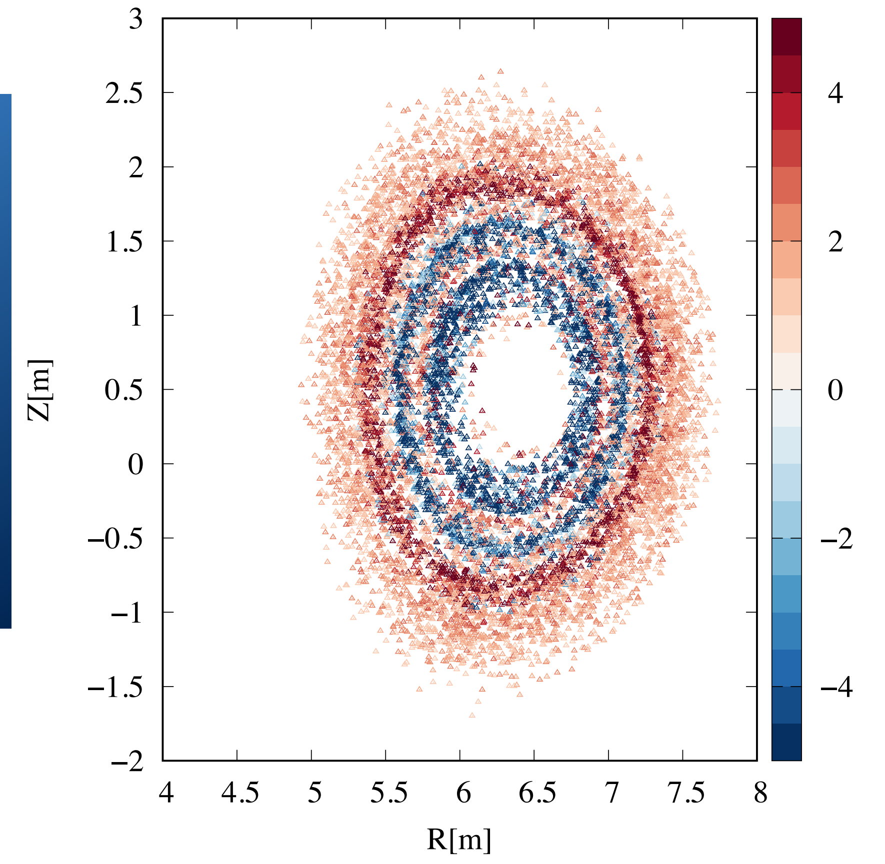
t+1

mhd_linear
distributions
core profiles
equilibrium

time

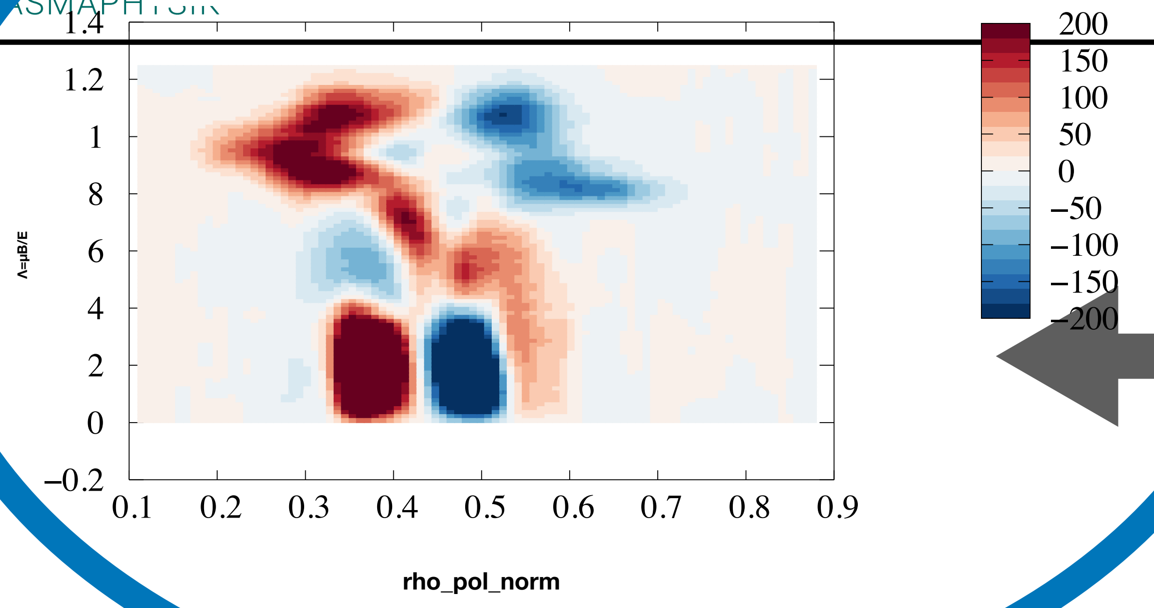
PSZS transport theory [M. Falessi et al, 2017-23]

$$\frac{\partial}{\partial t}\overline{F_{z0}} + \frac{1}{\tau_b}\left[\frac{\partial}{\partial P_\phi}\overline{\left(\tau_b \delta\dot{P}_\phi \delta F\right)_z} + \frac{\partial}{\partial \mathcal{E}}\overline{\left(\tau_b \delta\dot{\mathcal{E}} \delta F\right)_z}\right]_S = \overline{\left(\sum_b C_b^g\left[F, F_b\right] + \mathcal{S}\right)_{zS}}$$

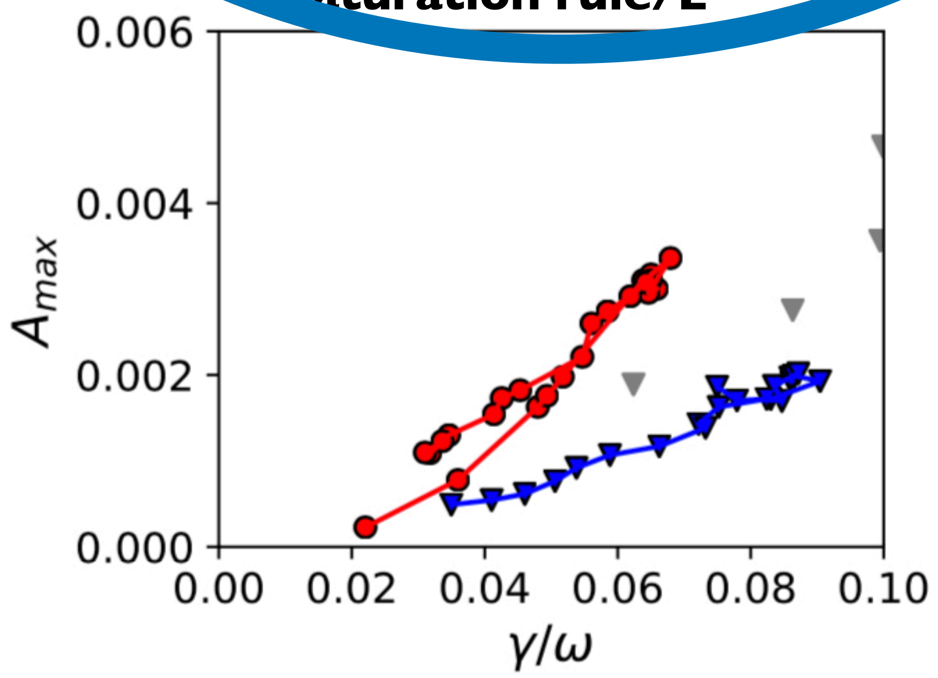


ATEP code
[Ph. Lauber, G. Meng, 2022]

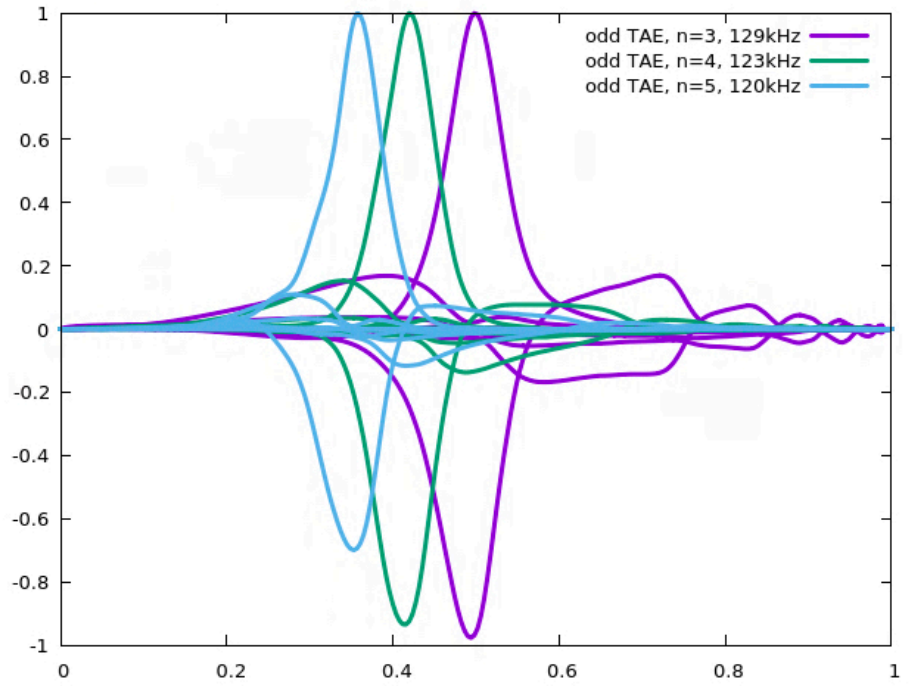
orbit+zonal averaging



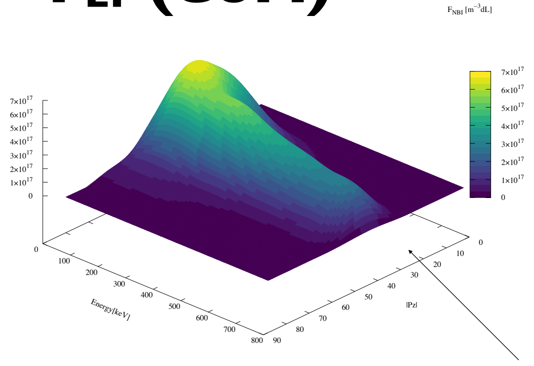
saturation rule/E



EP WF: LIGKA [20]



F_{EP} (CoM)



in the following:

- use EP-Stability WF to create HAGIS perturbations,
- follow test particles in prescribed perturbations
- 256 radial/P_Φ, 96 energy, 96 Lambda,
- 5 complete orbits of all test particles will be followed
- zonal average: 8 particles per wave period
- construct $\langle dP_\Phi/dt\rangle z$ and $\langle dE/dt\rangle z$
- calculate PSZS from single TAEs, and combinations of n=18,19 TAEs (3 different modes, with and without EPs)

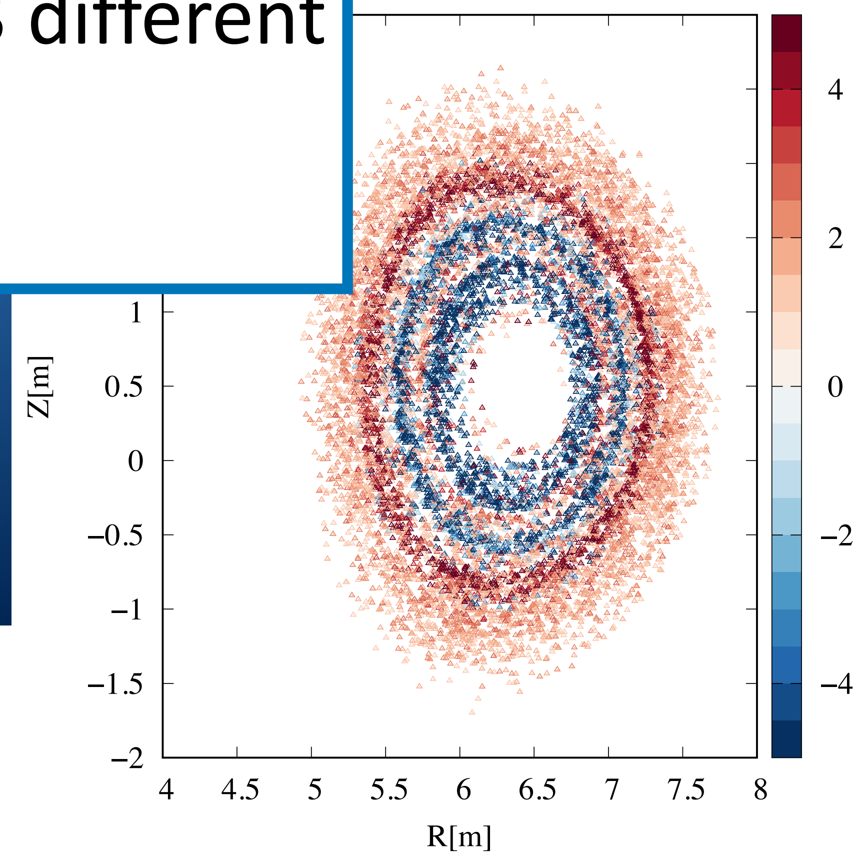
or kick model

calculate D(r,E)

or

and return updated distribution IDS, or its moments

calculate linear mode spectrum



ATEP code [Ph. Lauber, G. Meng,2022]

t

t+1

mhd_linear
distributions
core profiles
equilibrium

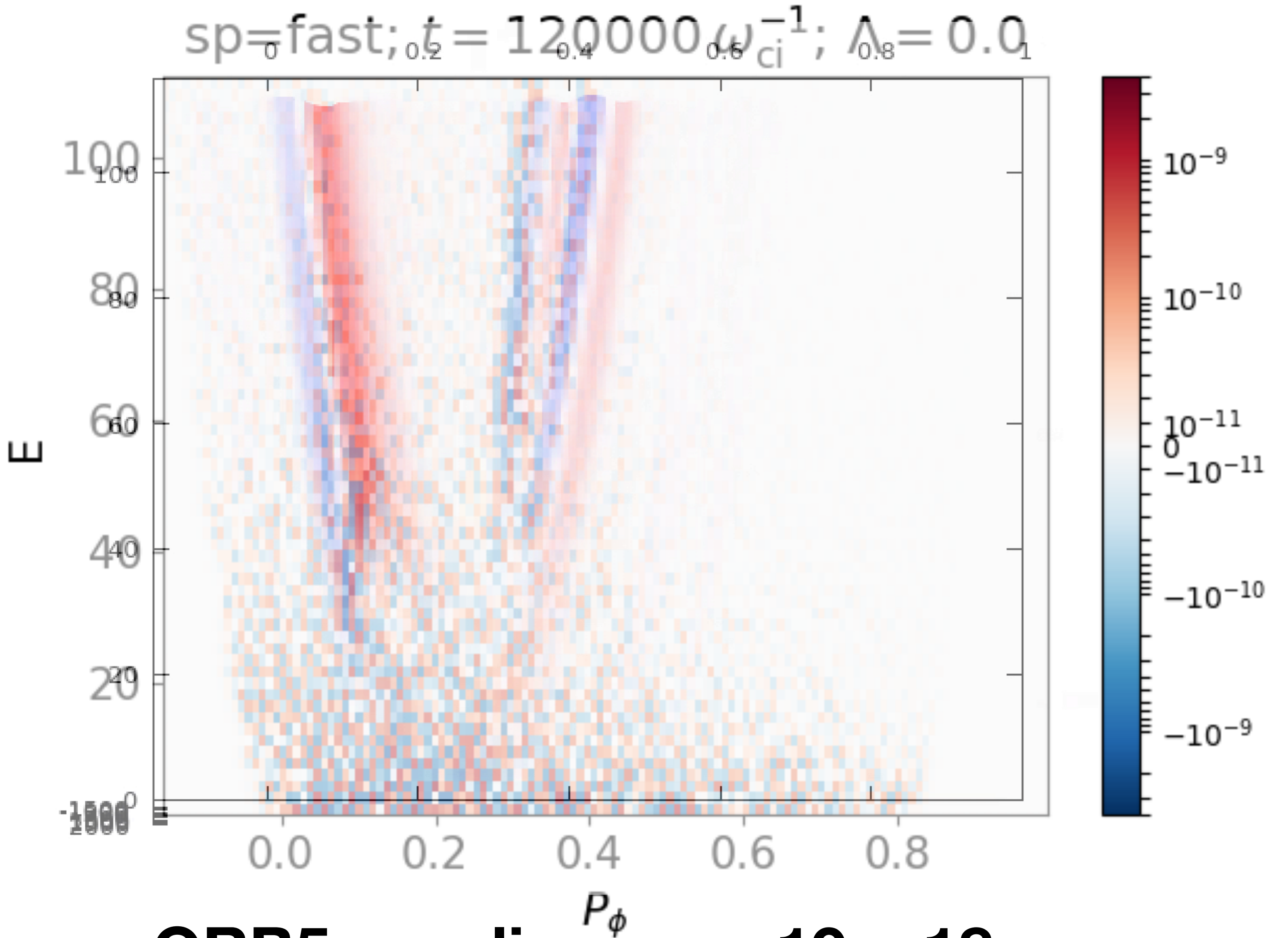
time

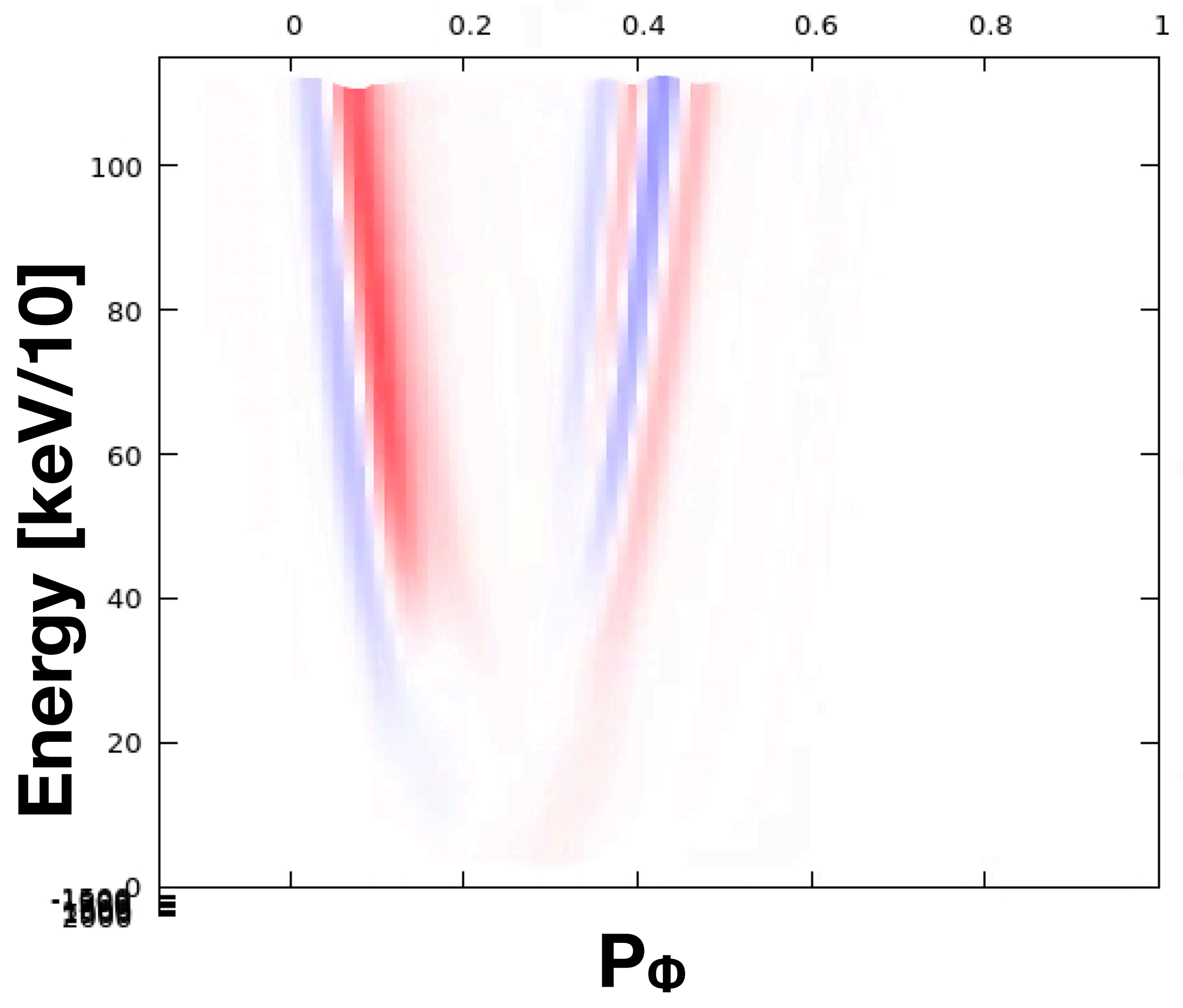
transport code

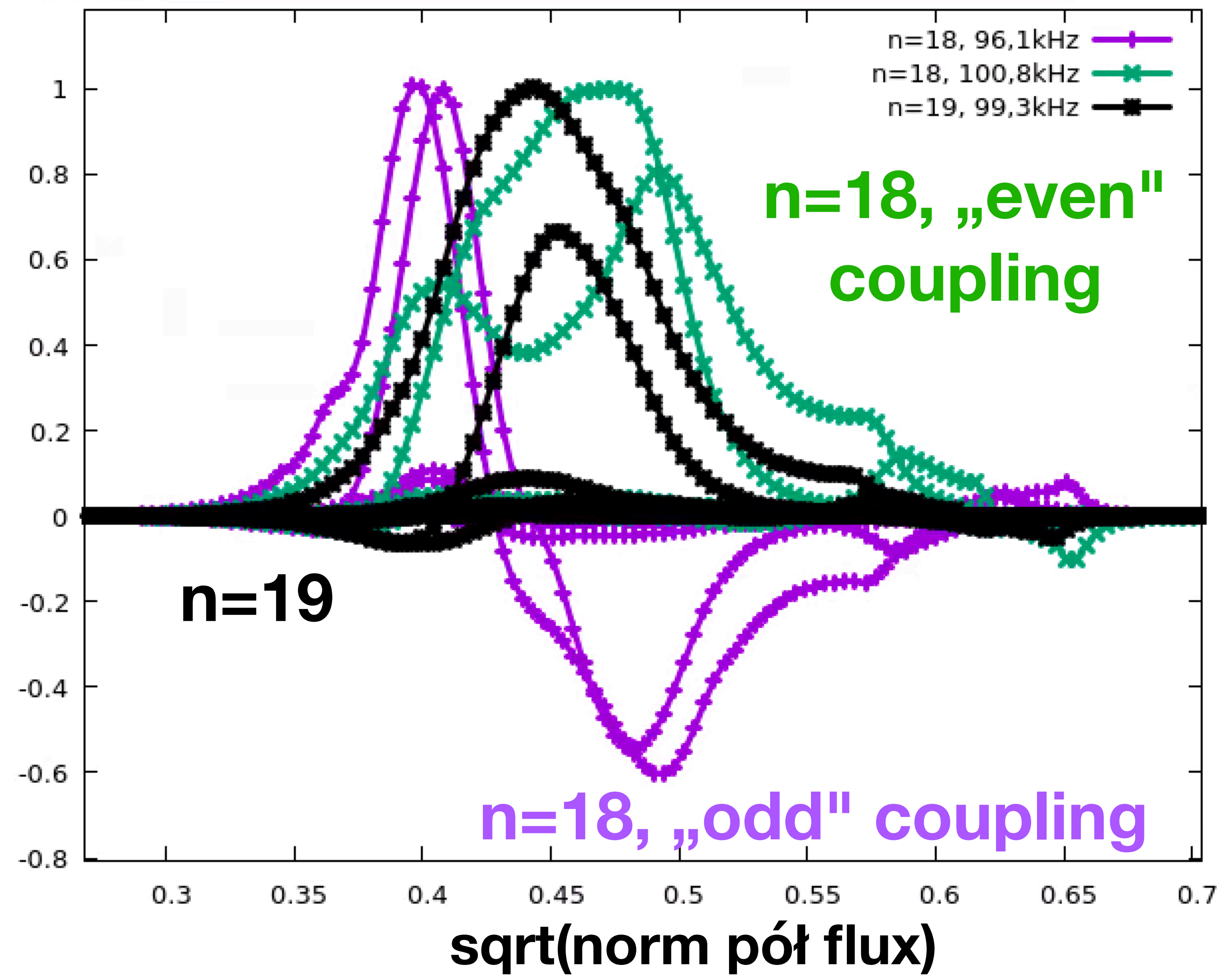
MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

Λ=μB/E=0.0 — only n=19 — no EPs - mode structures

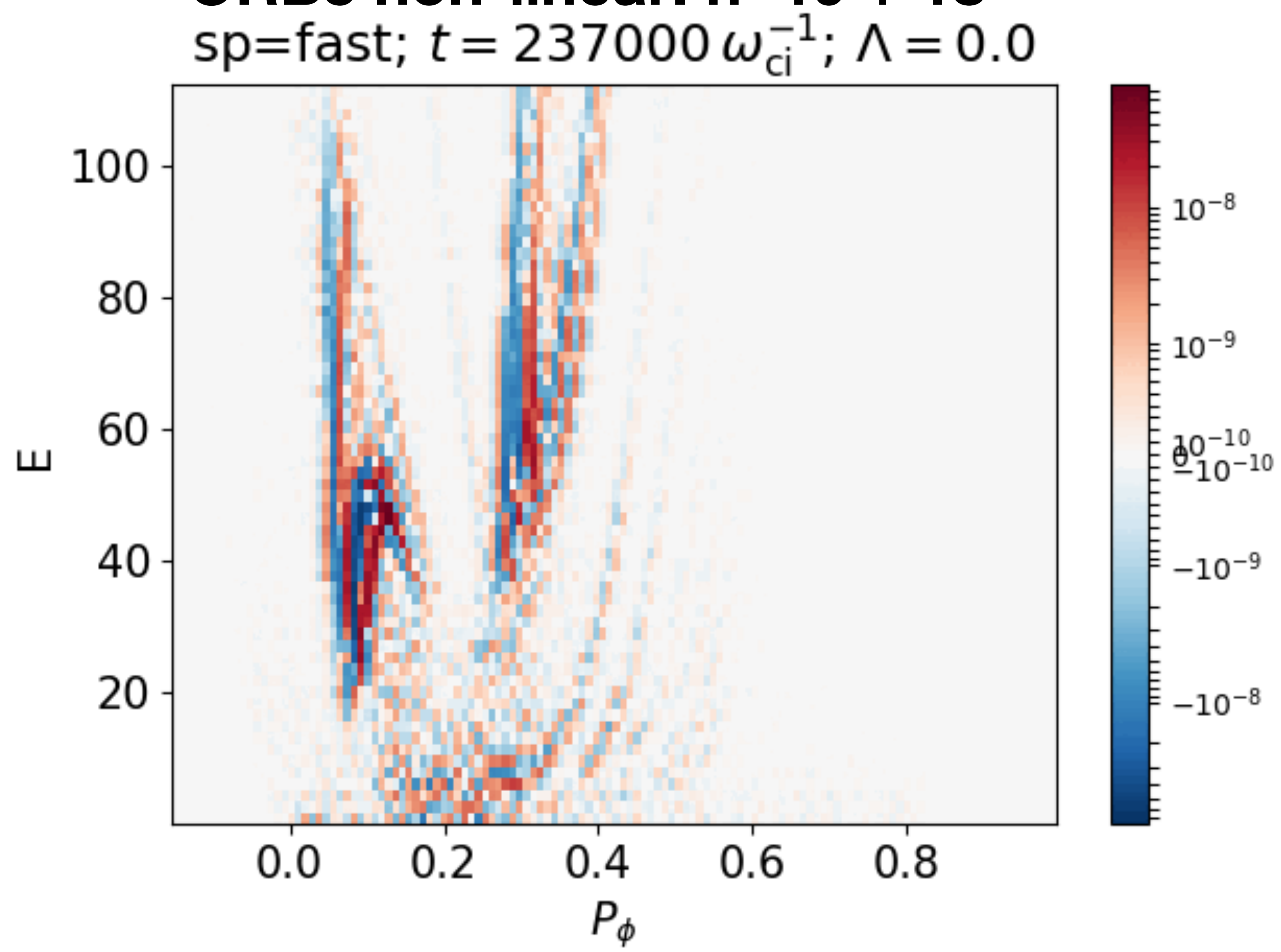
ORB5 linear - n=19 dominant



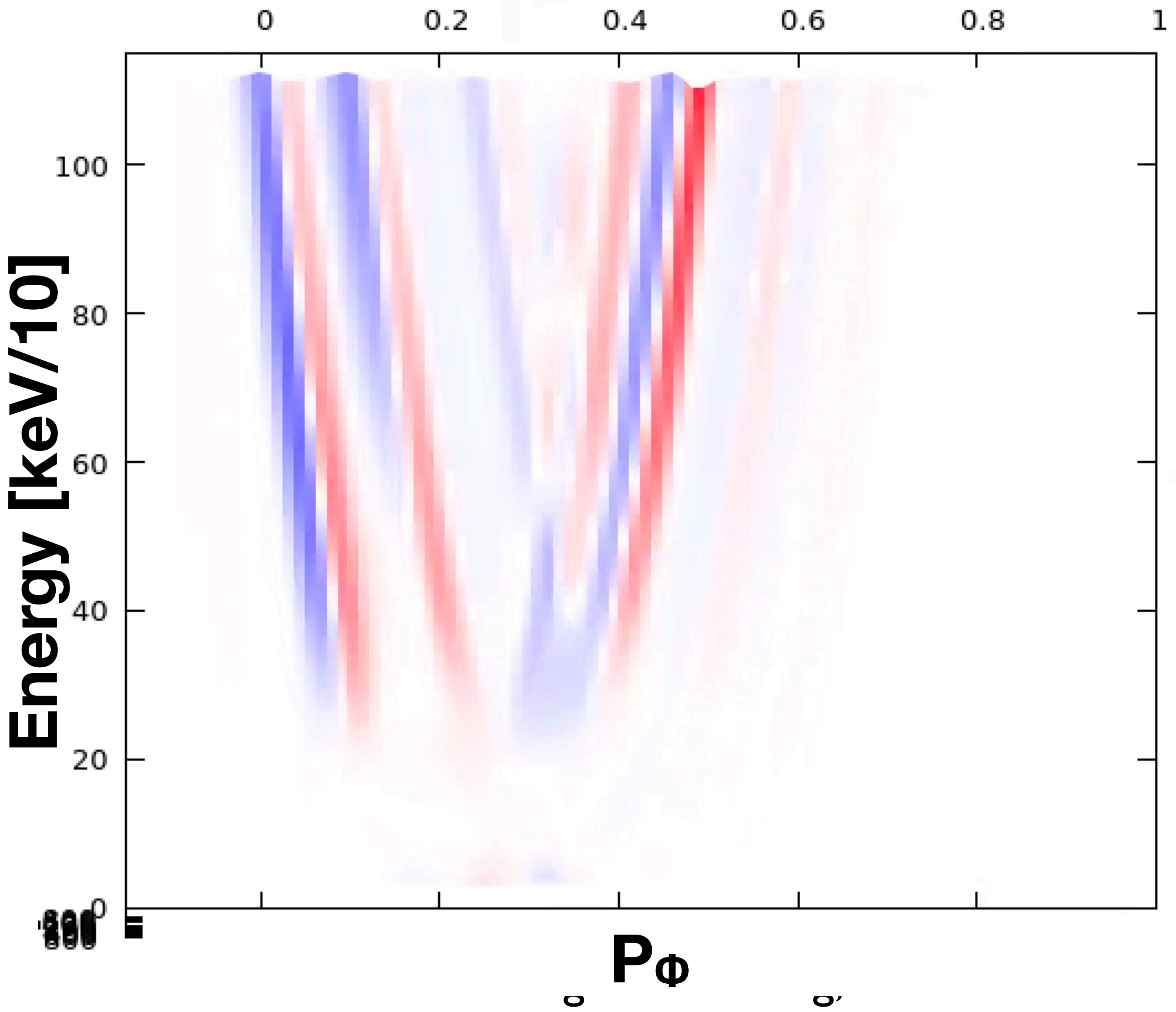




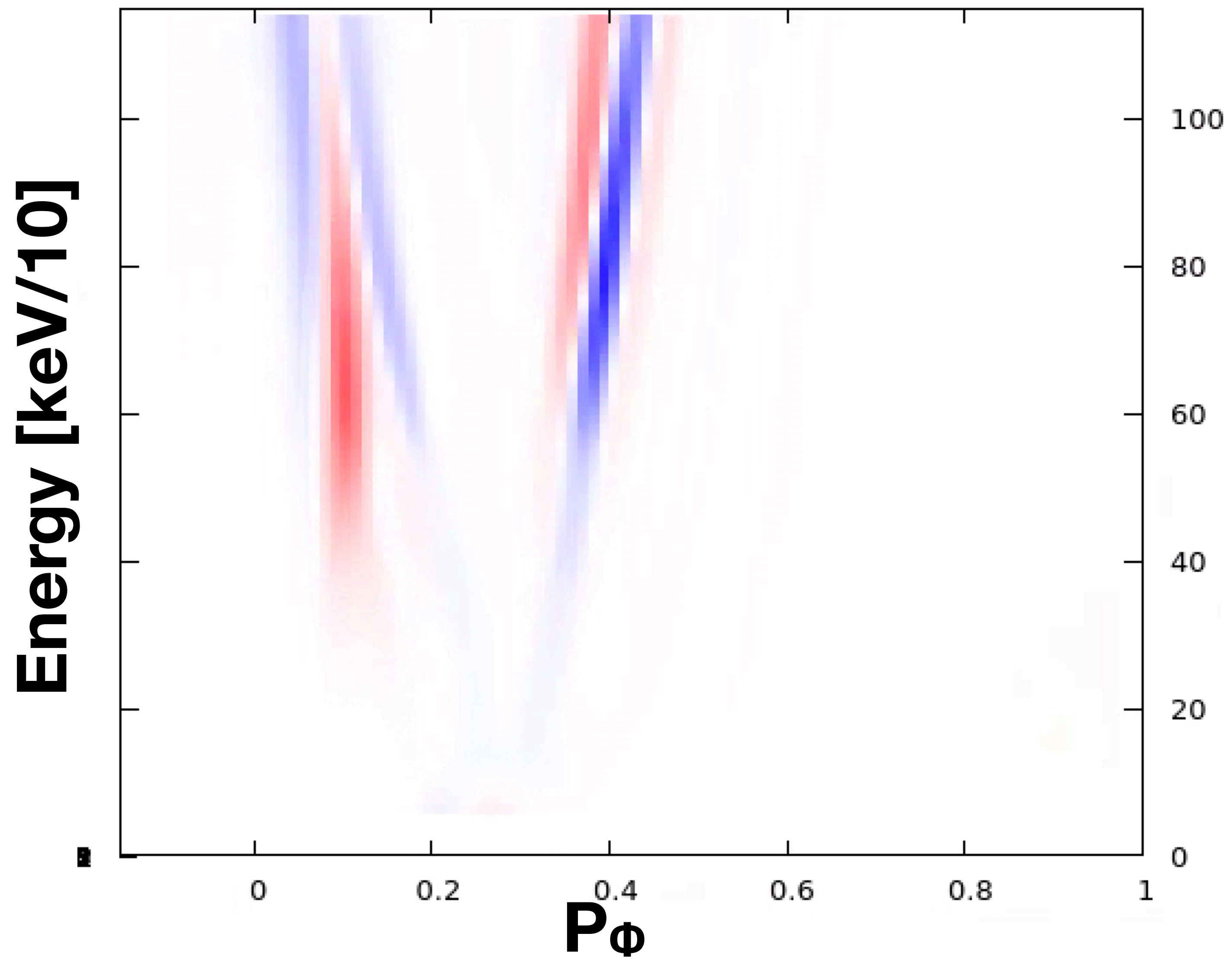
ORB5 non-linear: n=19 + 18



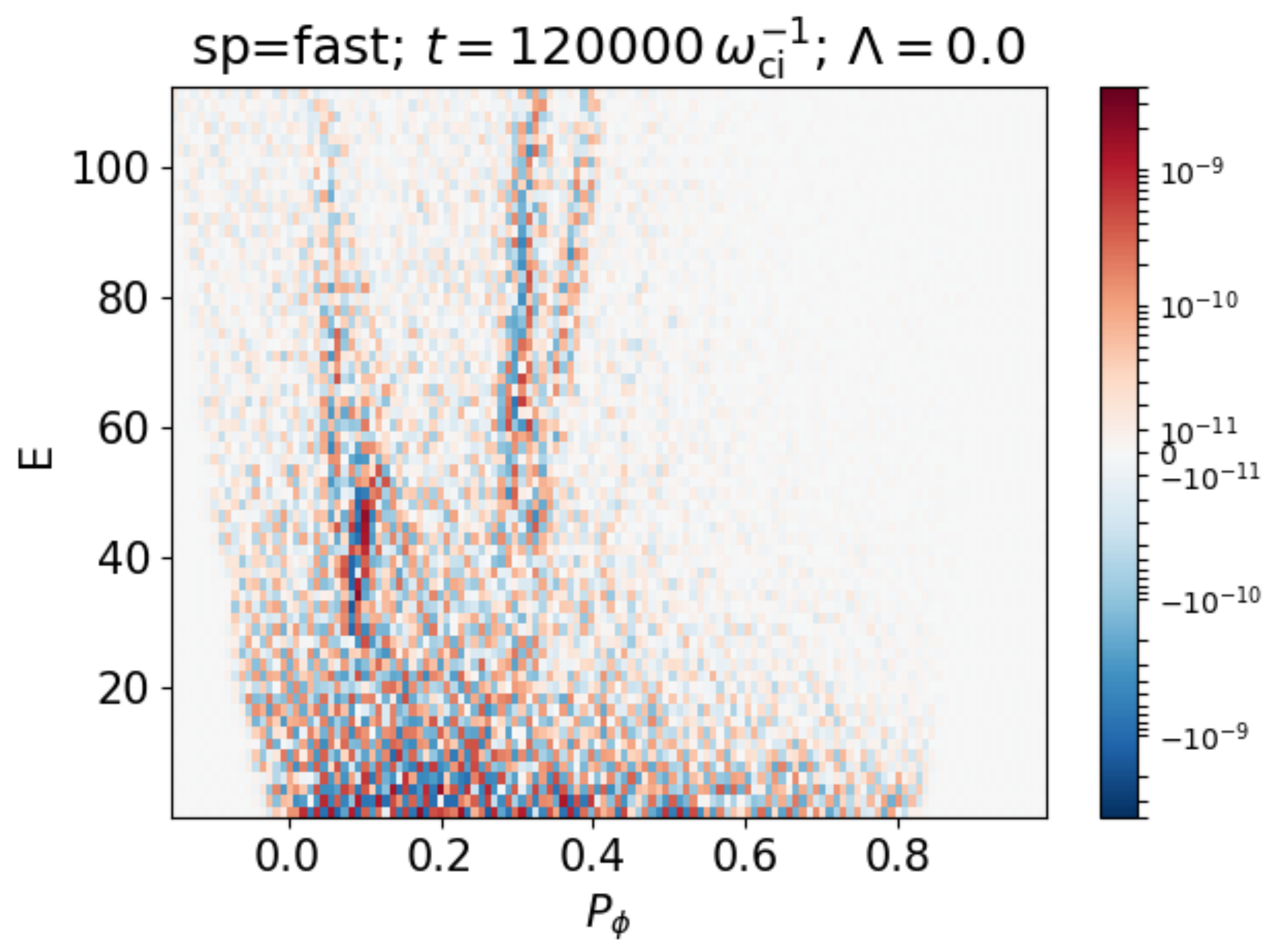
only n=18, even coupling



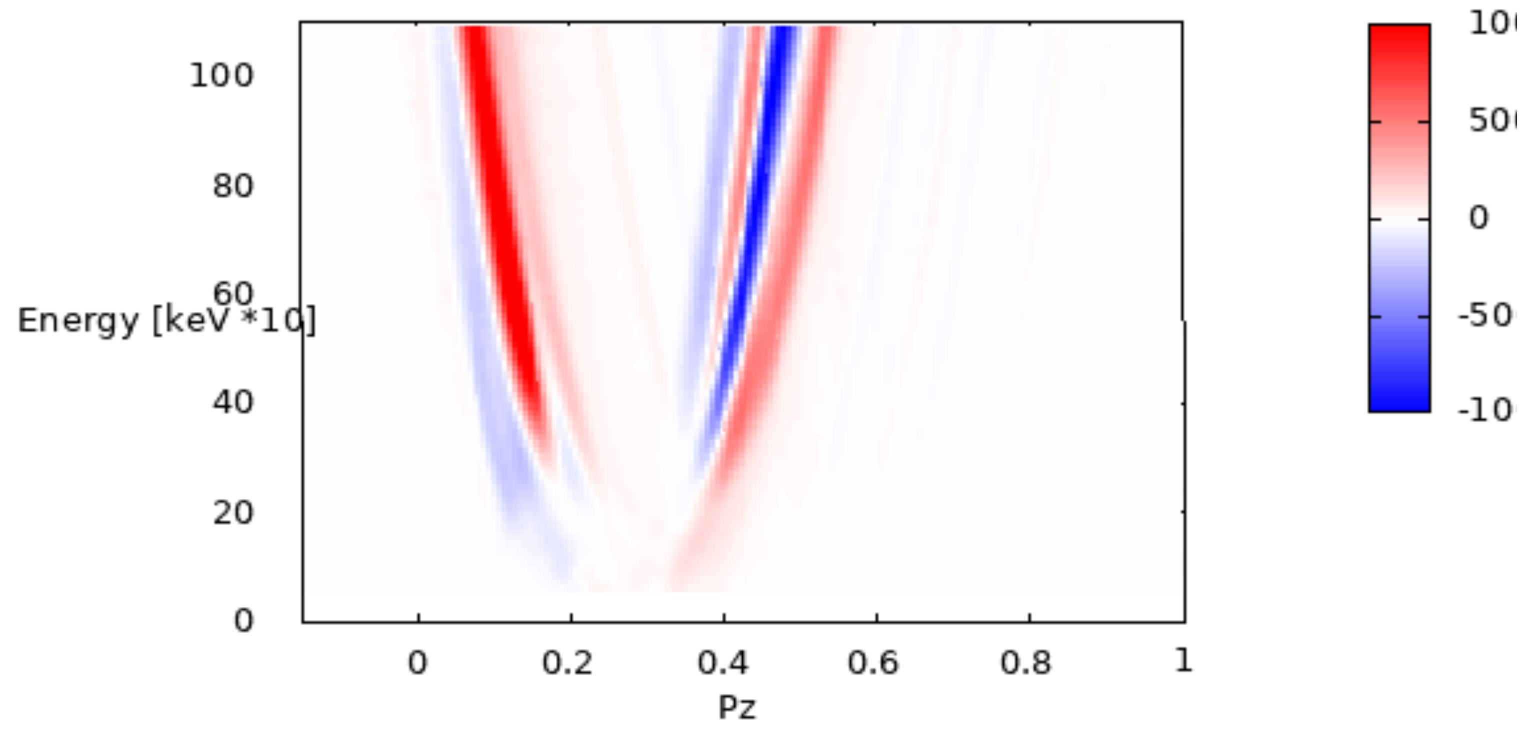
only n=18, odd coupling



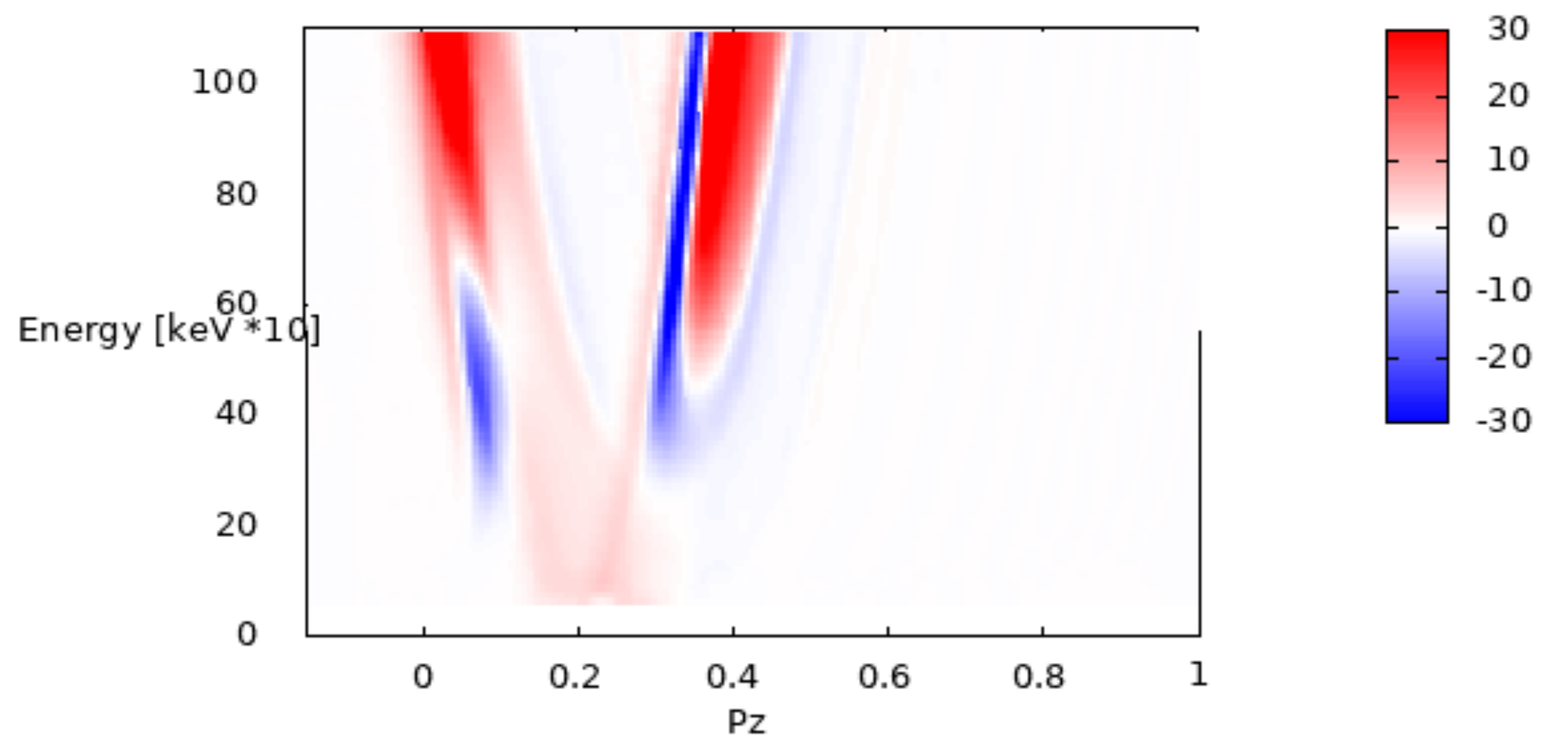
with EPs Λ=μB/E=0.0

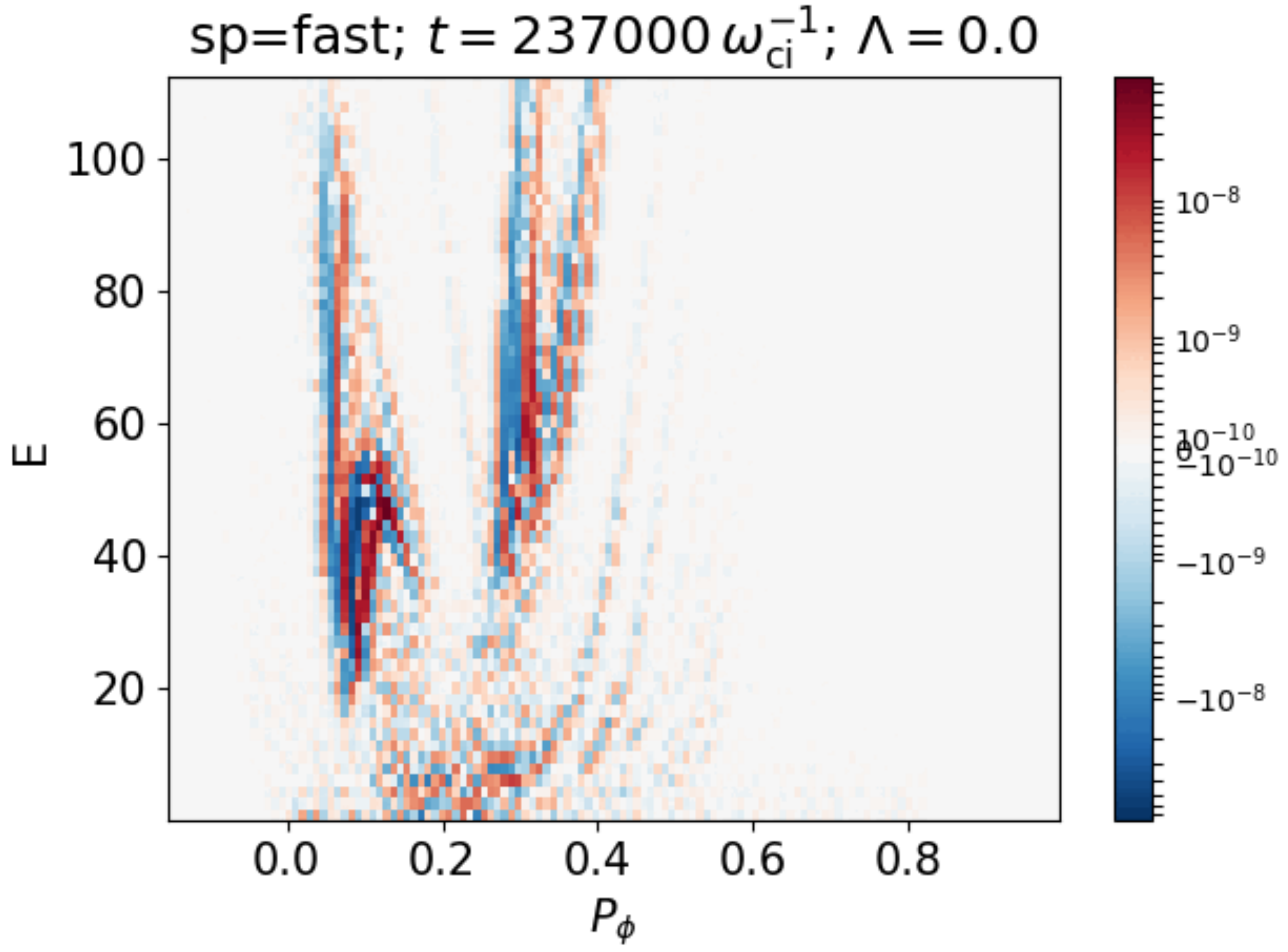


only n=19

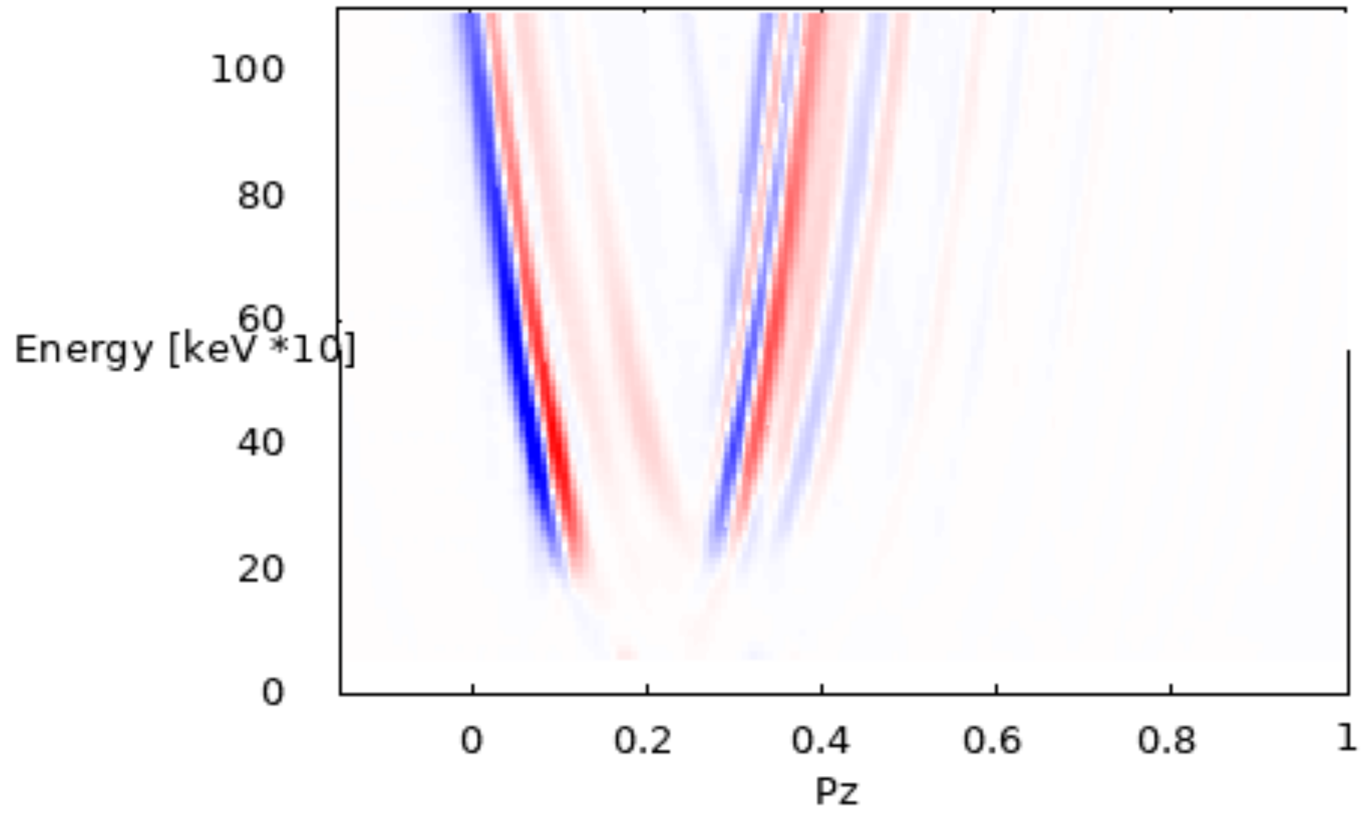


only n=18, odd TAE

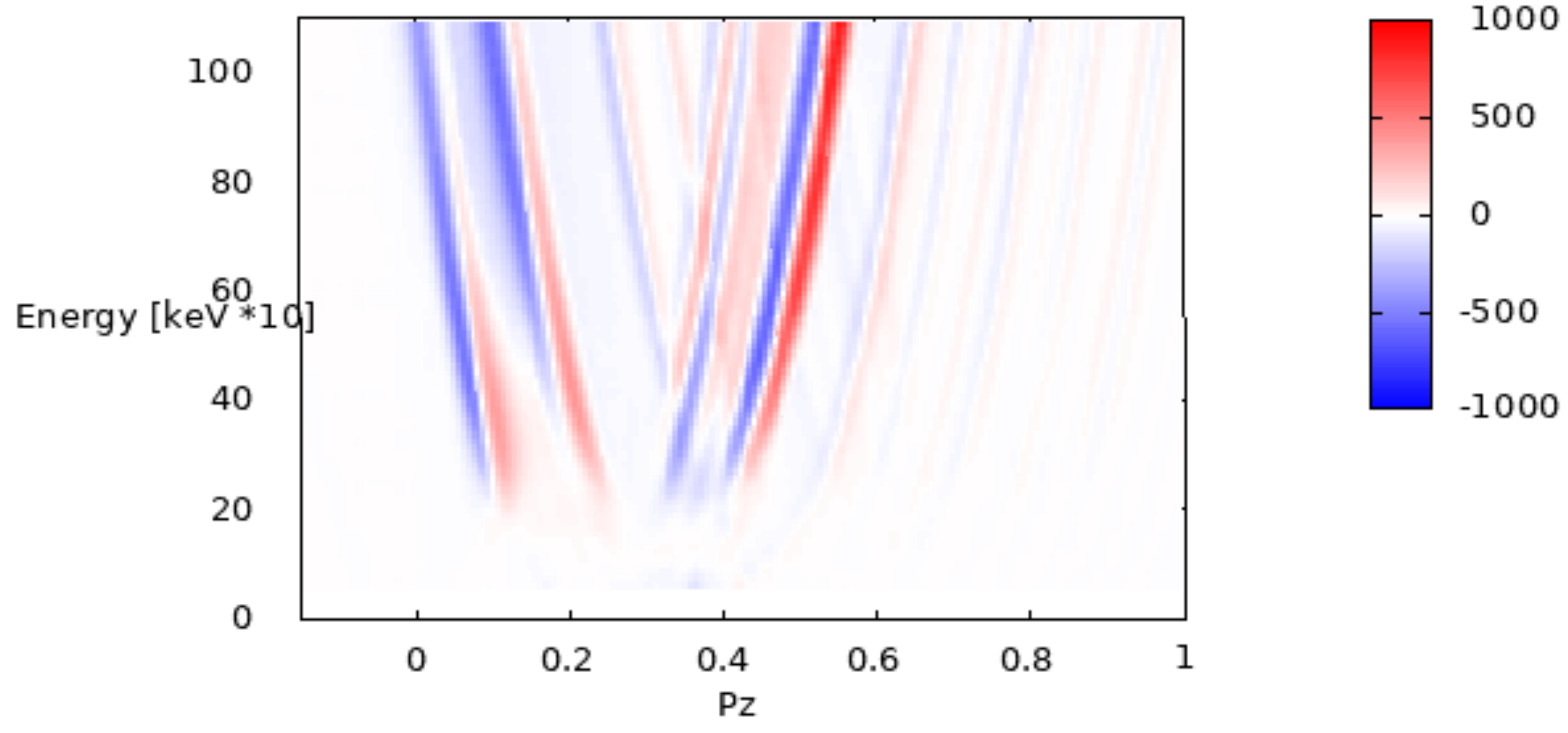




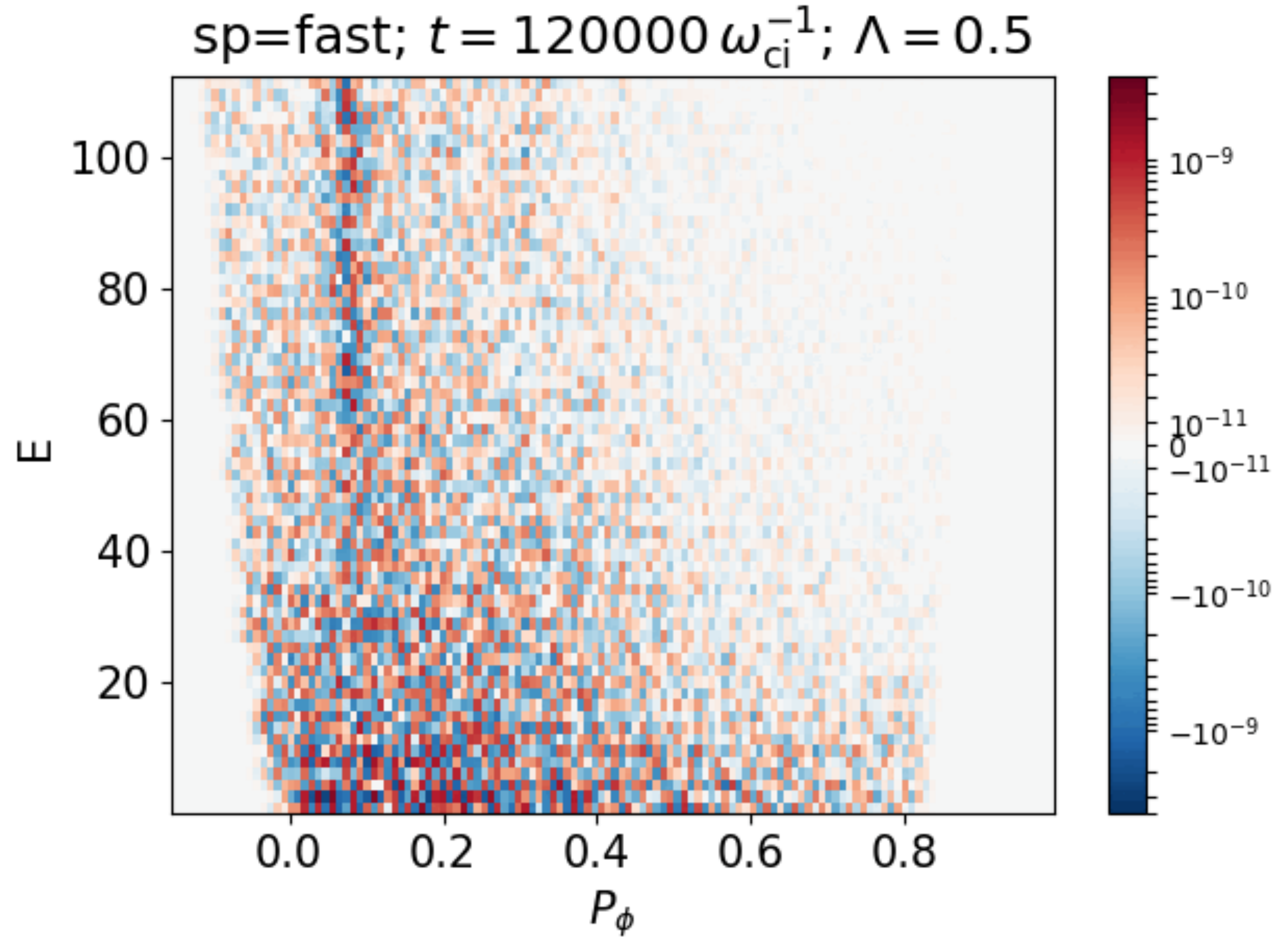
only n=18, even, inner



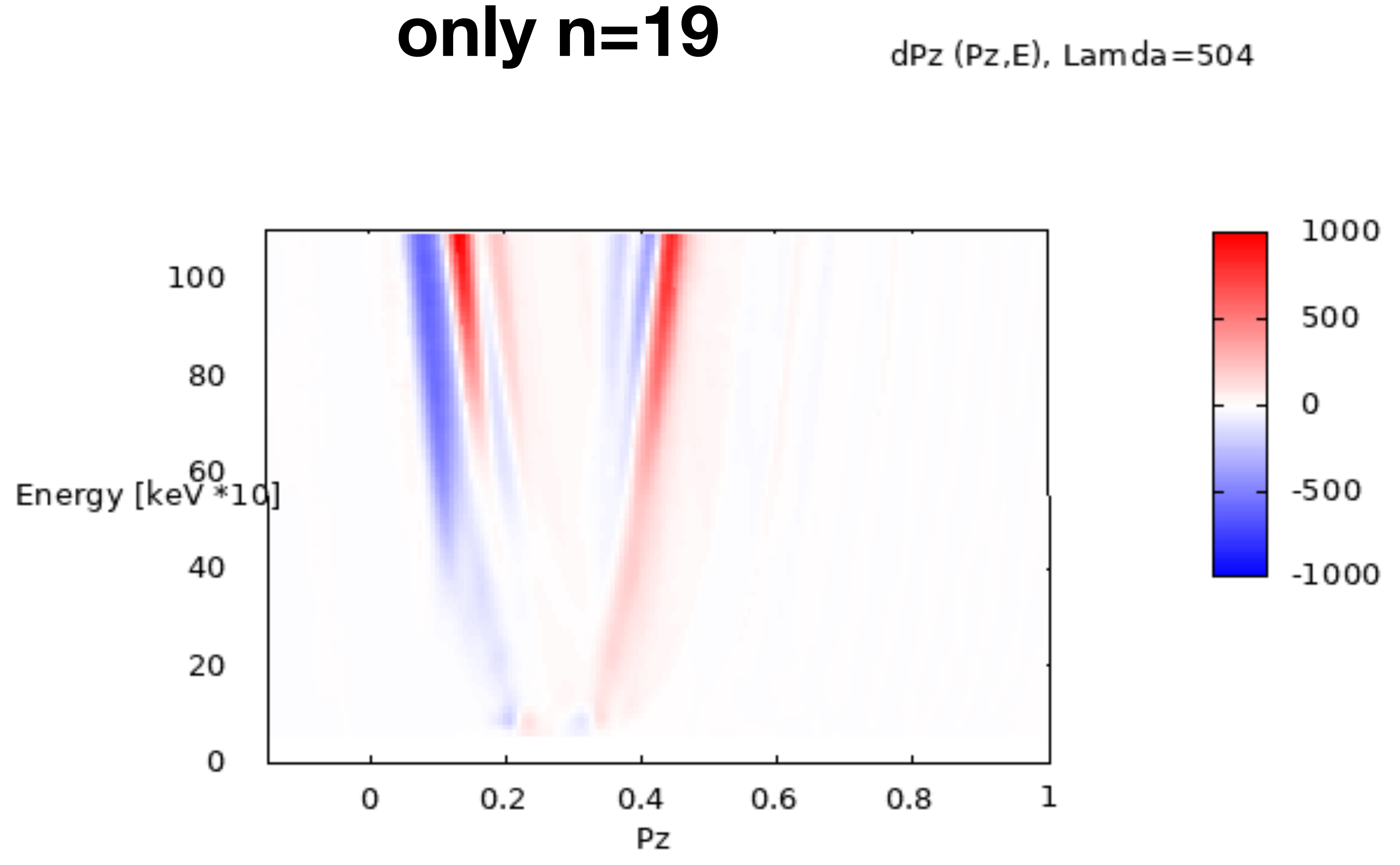
only n=18, even, outer



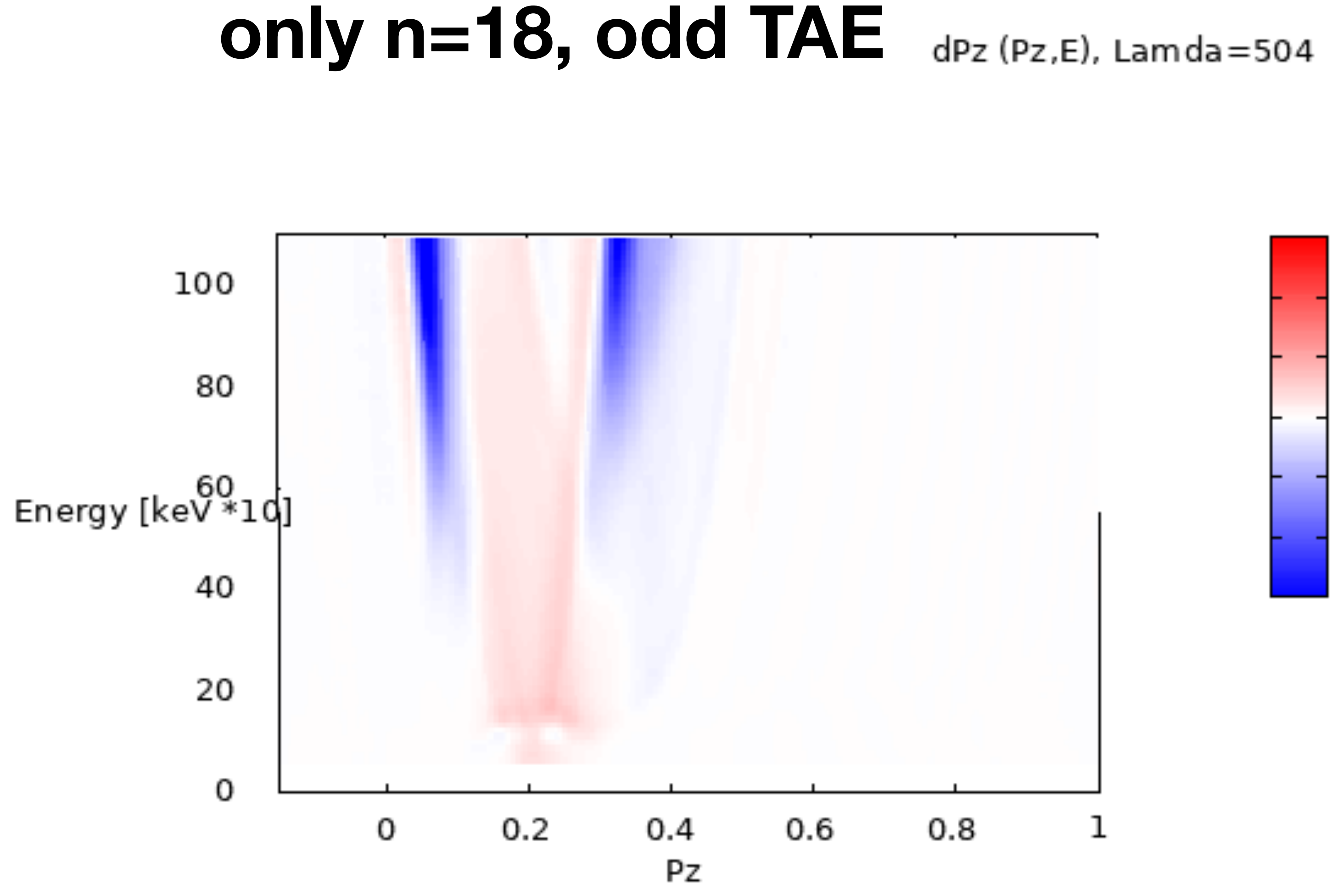
with EPs   Λ=μB/E=0.5

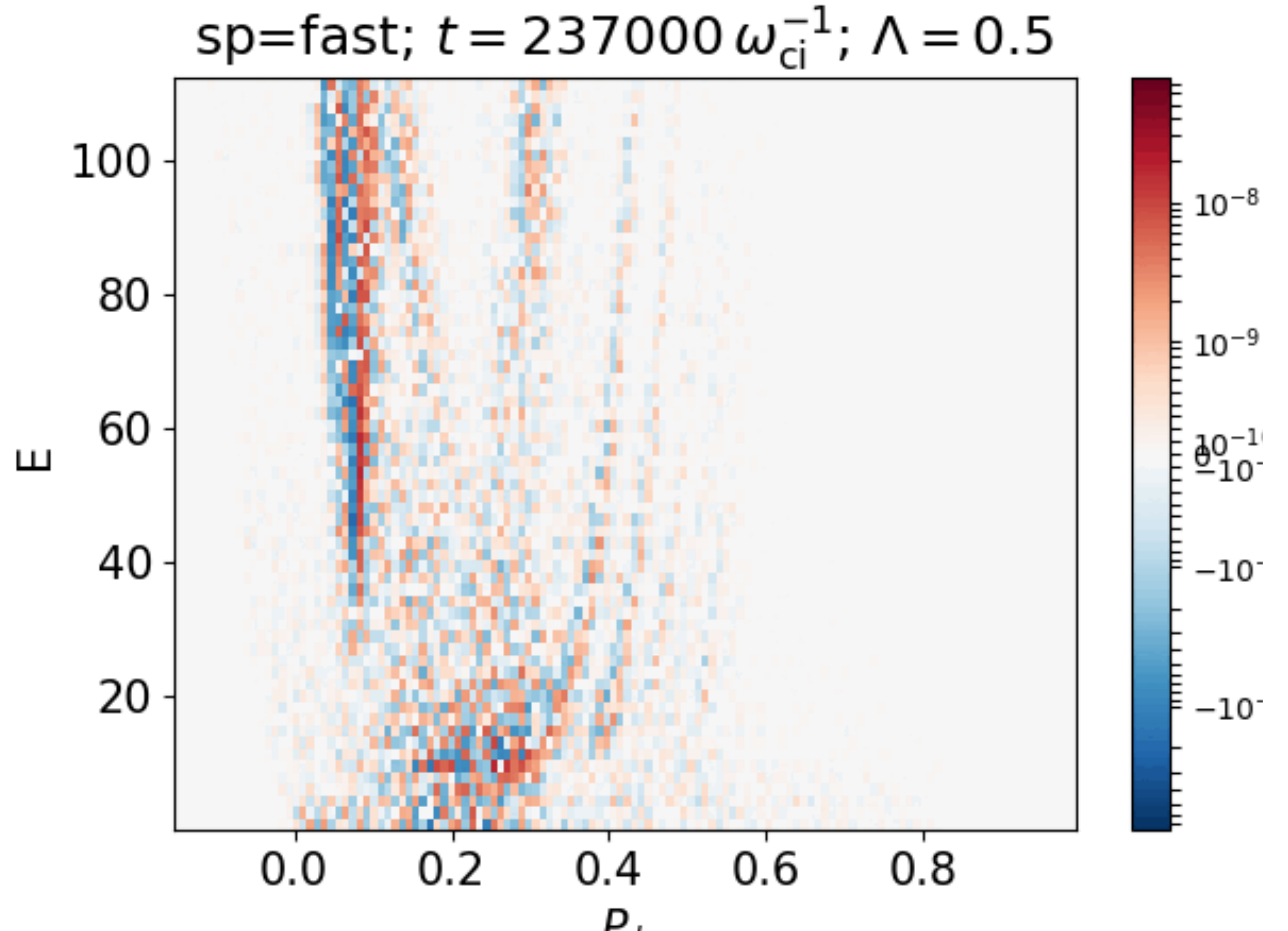


only n=19

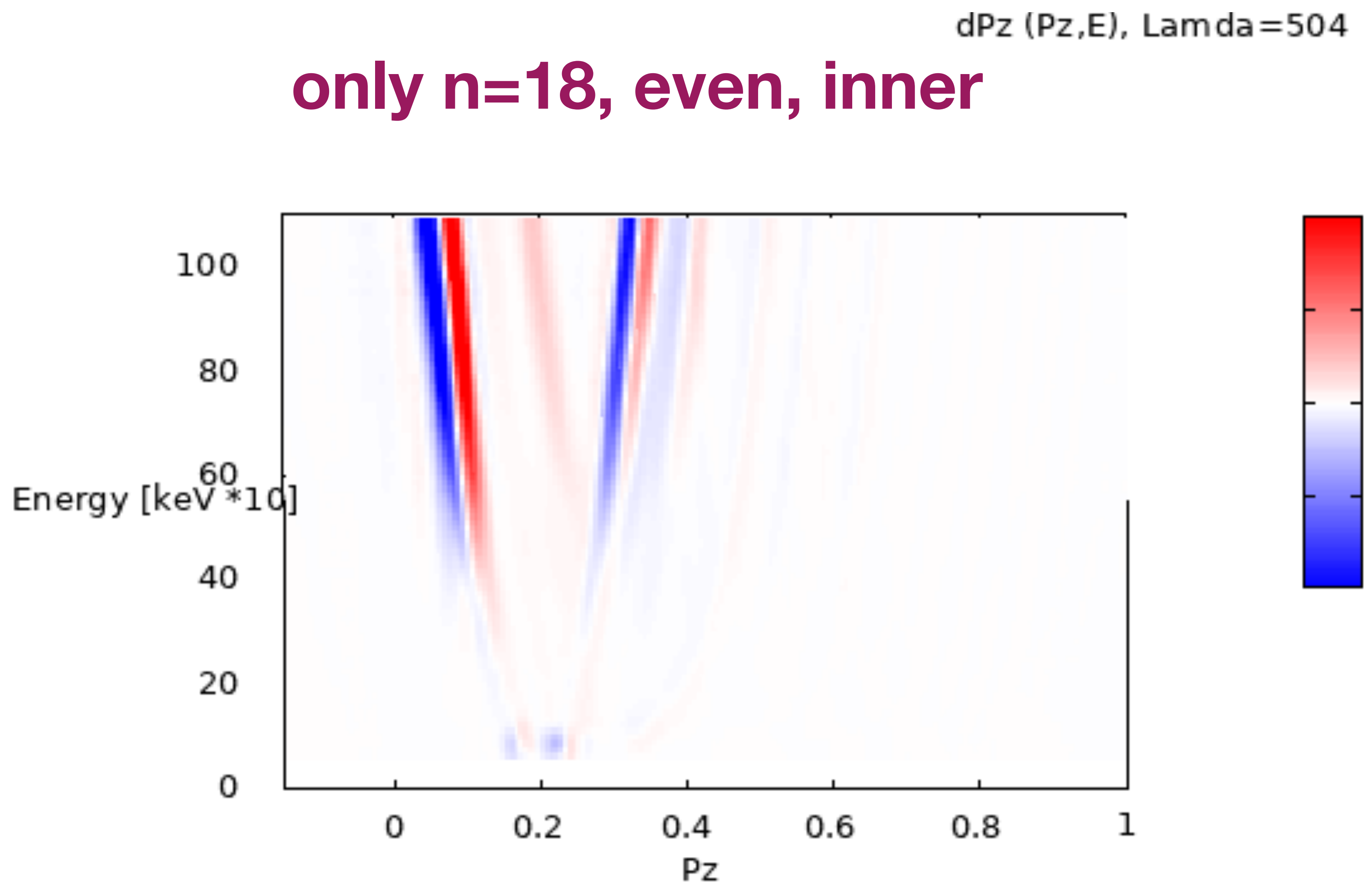


only n=18, odd TAE

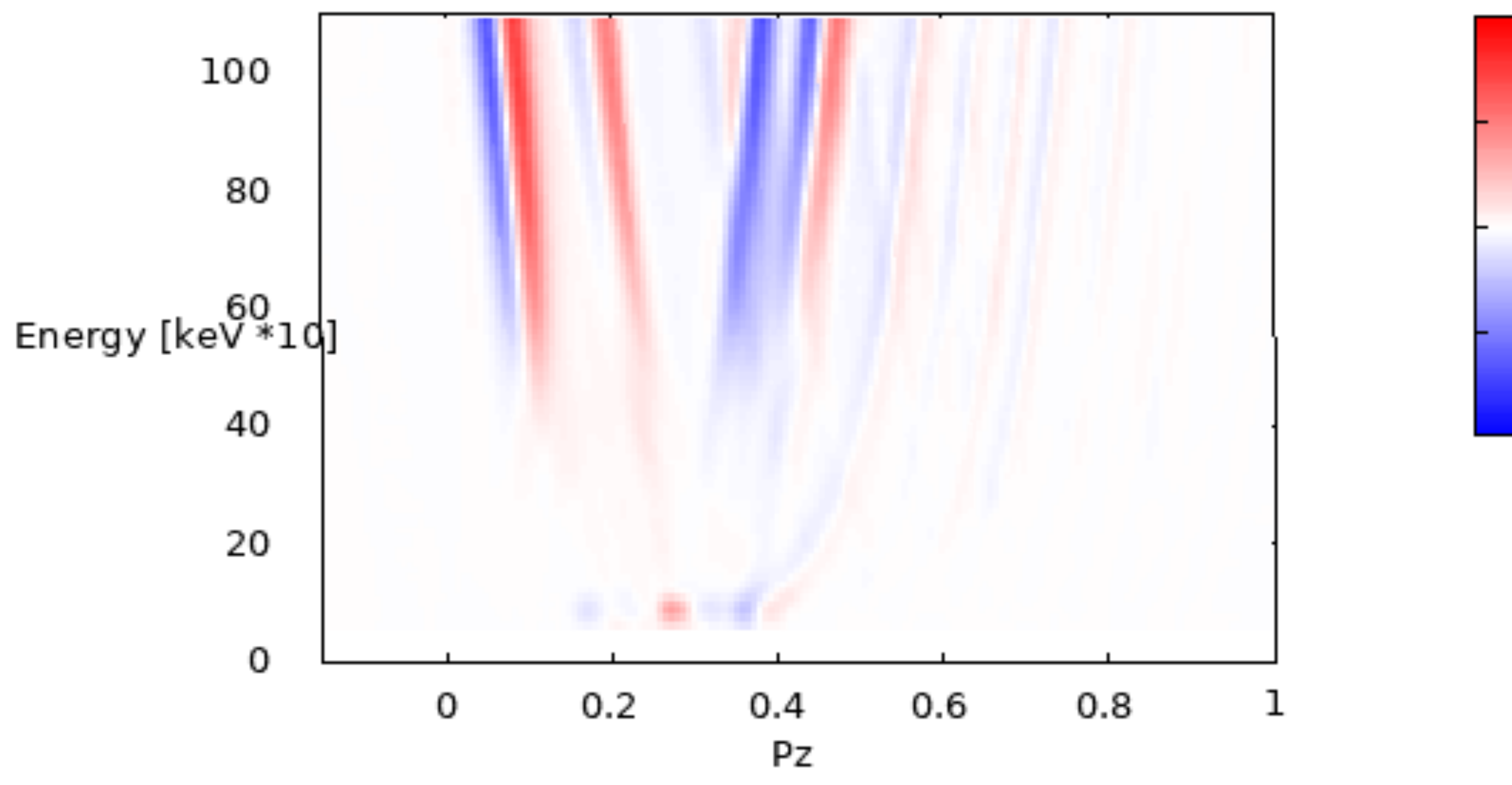




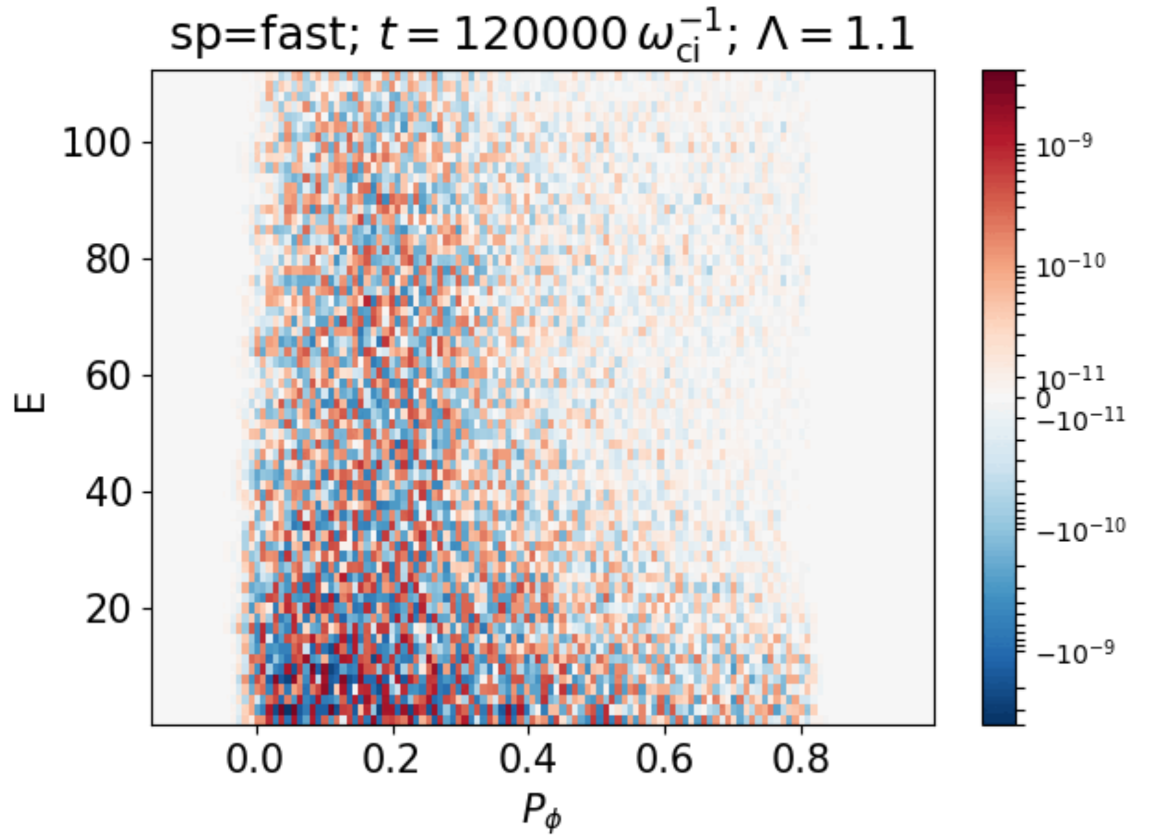
only n=18, even, inner



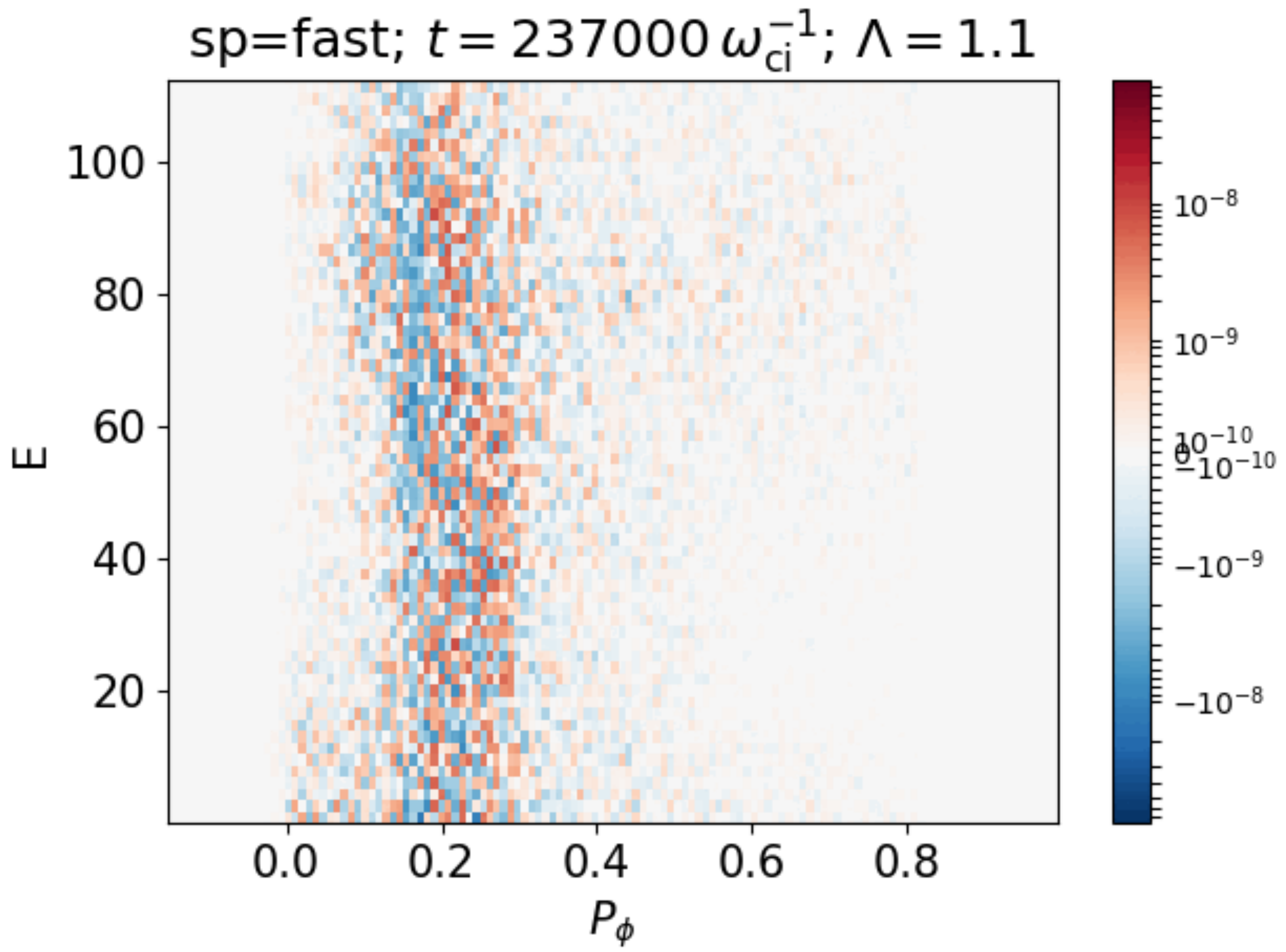
only n=18, even, outer



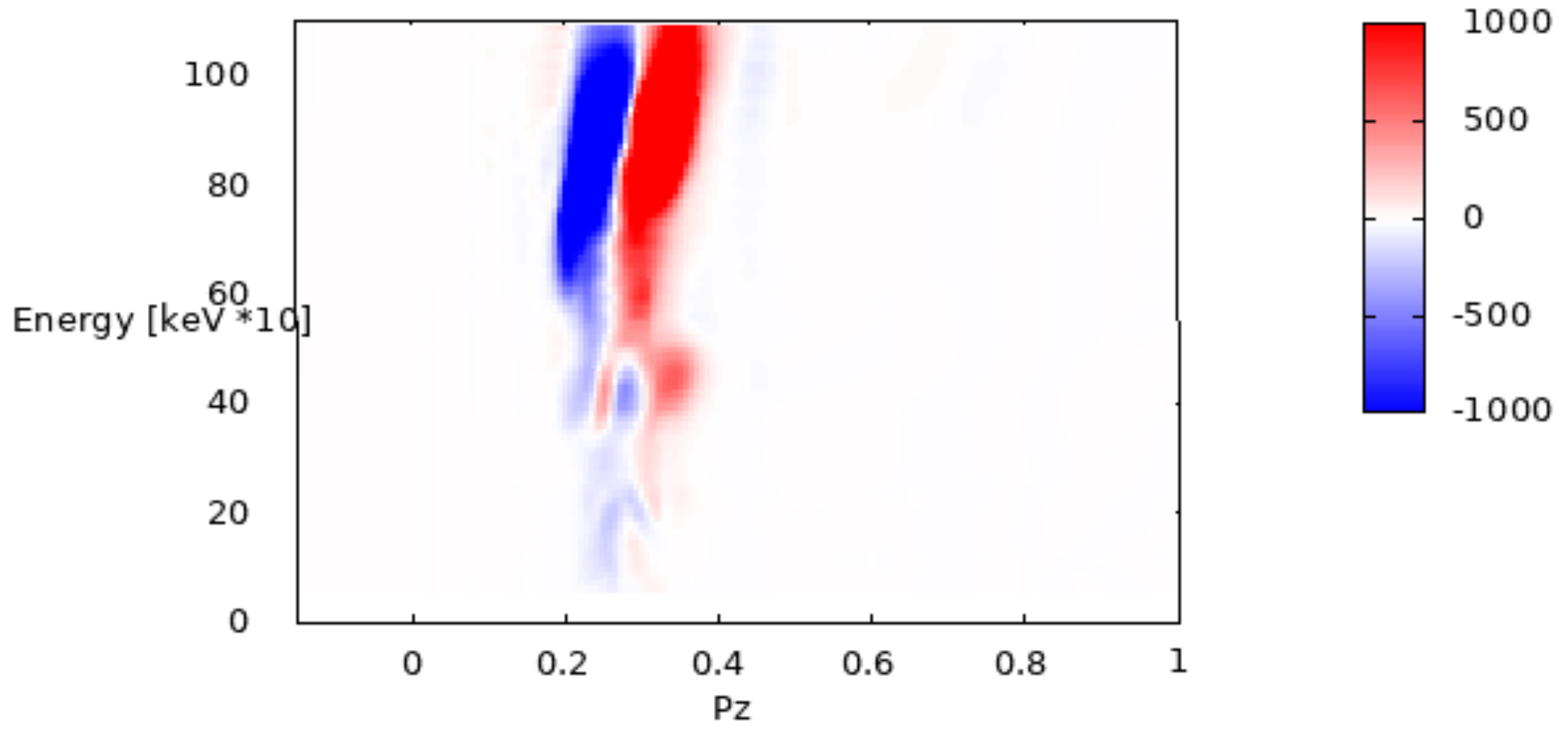
with EPs $\Lambda=\mu B/E=1.1$



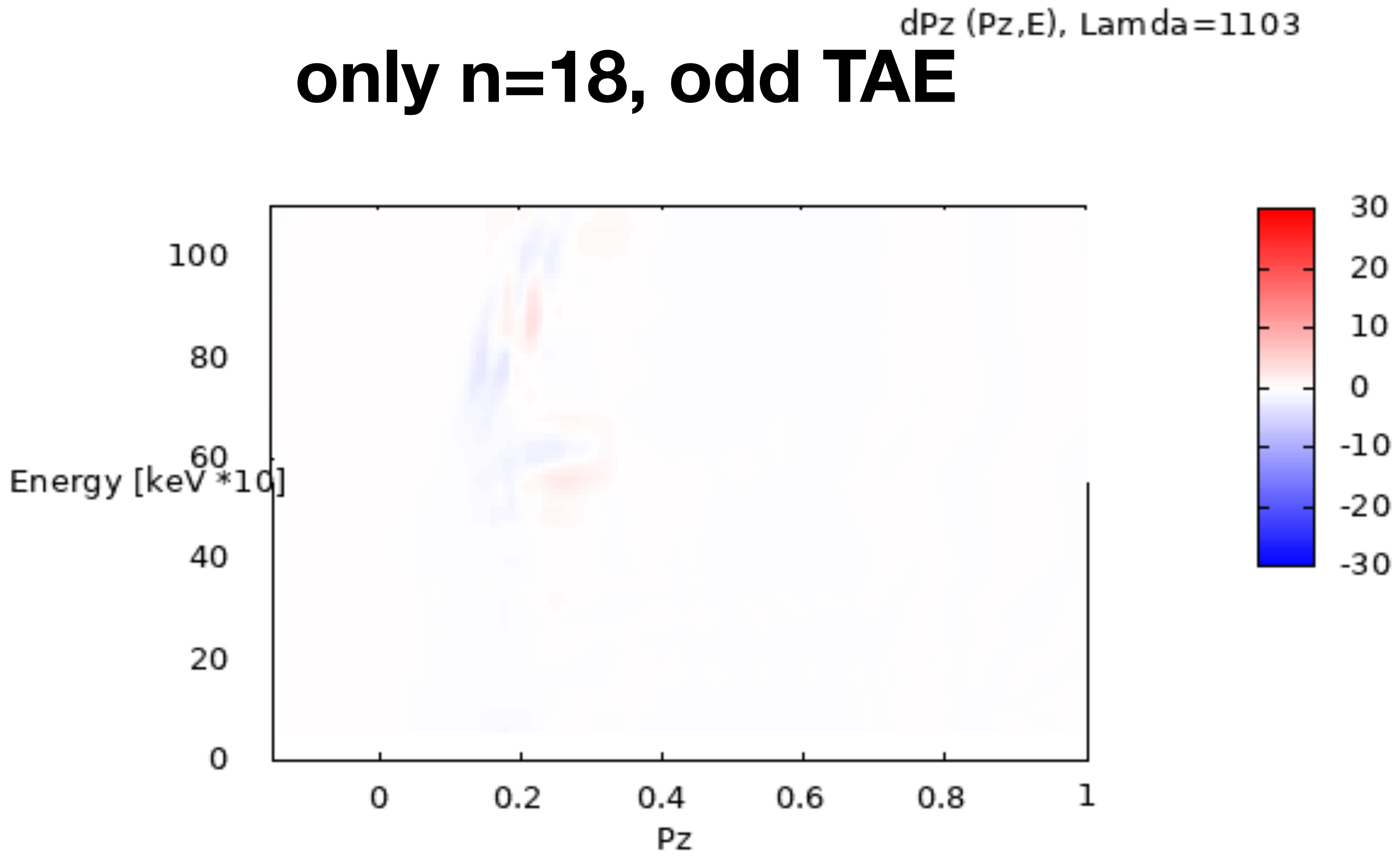
note that local aspect ratio is ˜10, very few trapped particles



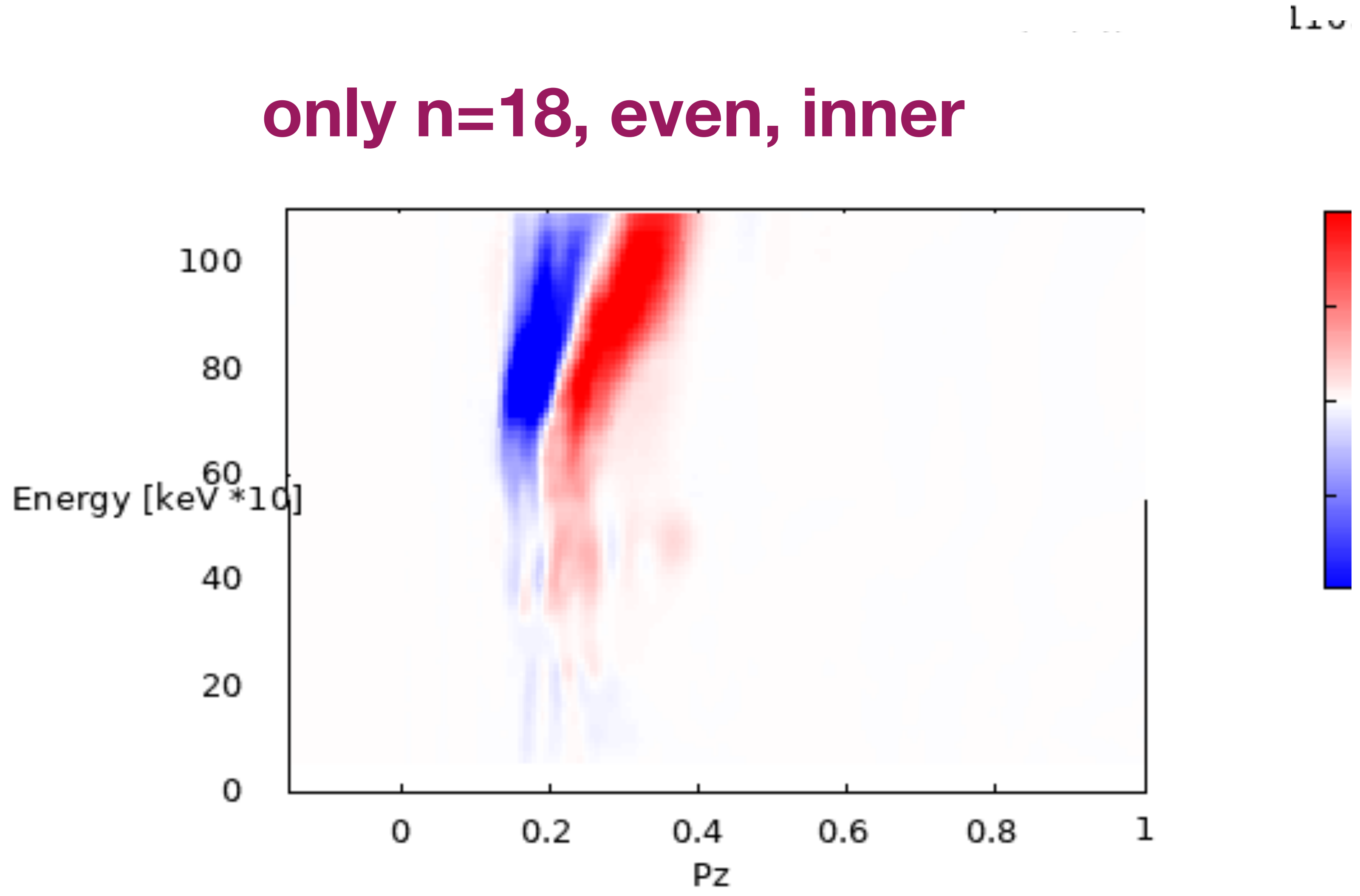
only n=19



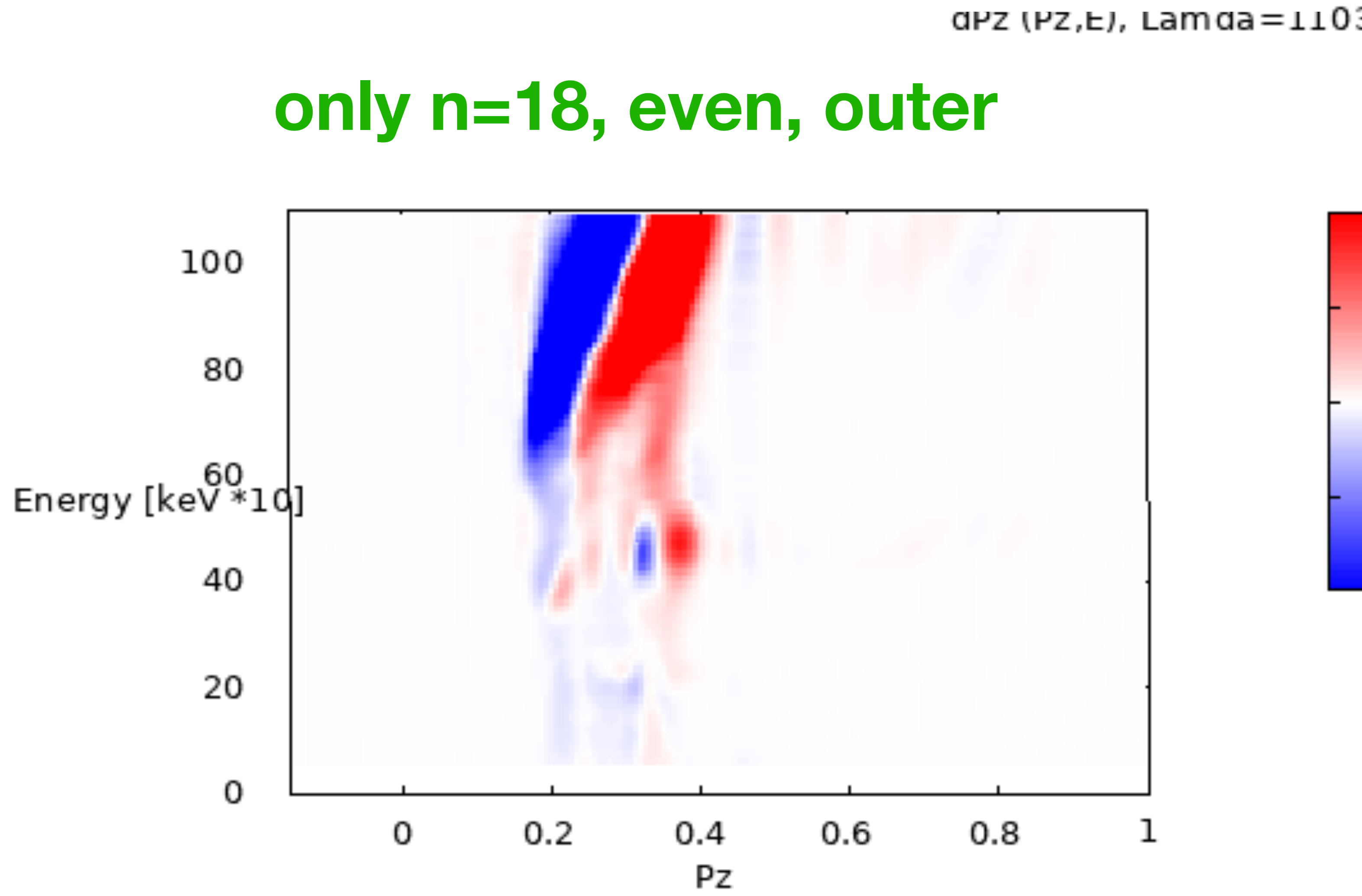
only n=18, odd TAE



only n=18, even, inner



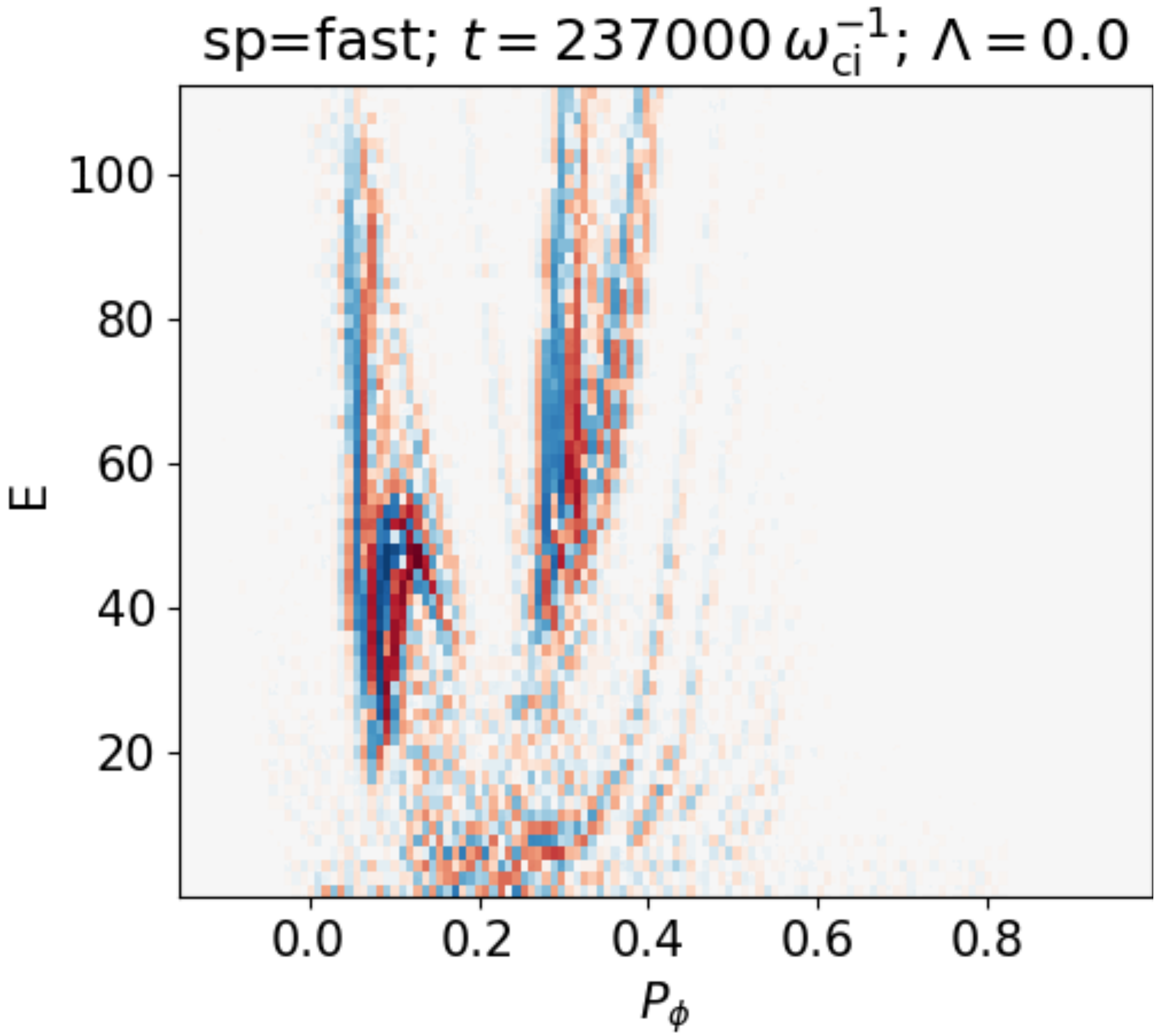
only n=18, even, outer

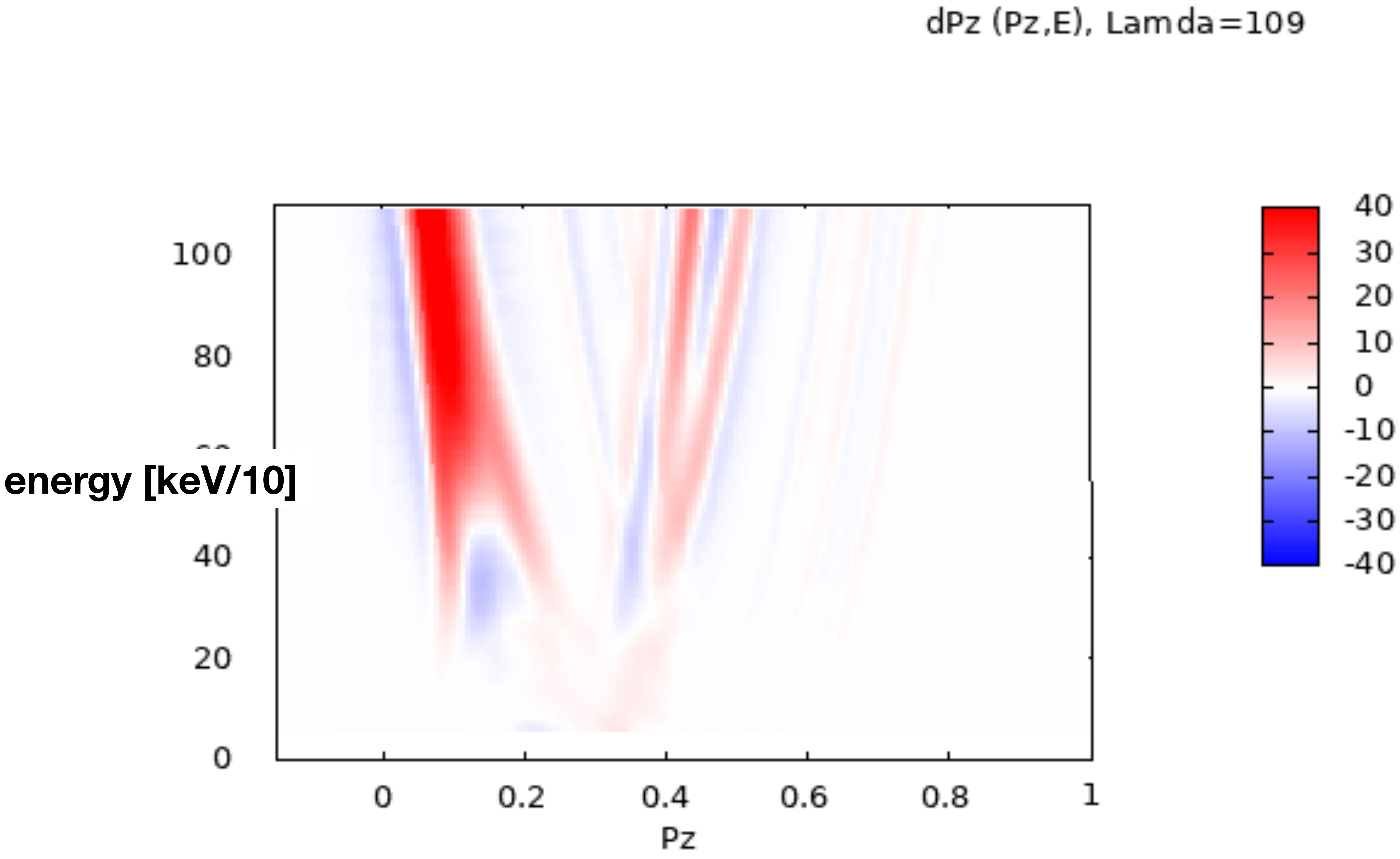


ORB5- ATEP PSZS comparison: ‚no-EP‘ eigenfunctions, combination of n=18,n=19 modes

n=18(even 1) $\delta B/B$=1.0e-5
n=18 (even 2) $\delta B/B$=4.0e-5
n=19 $\delta B/B$=5.0e-5

scale A ~ $(\gamma_L-\gamma_{damp})^2$

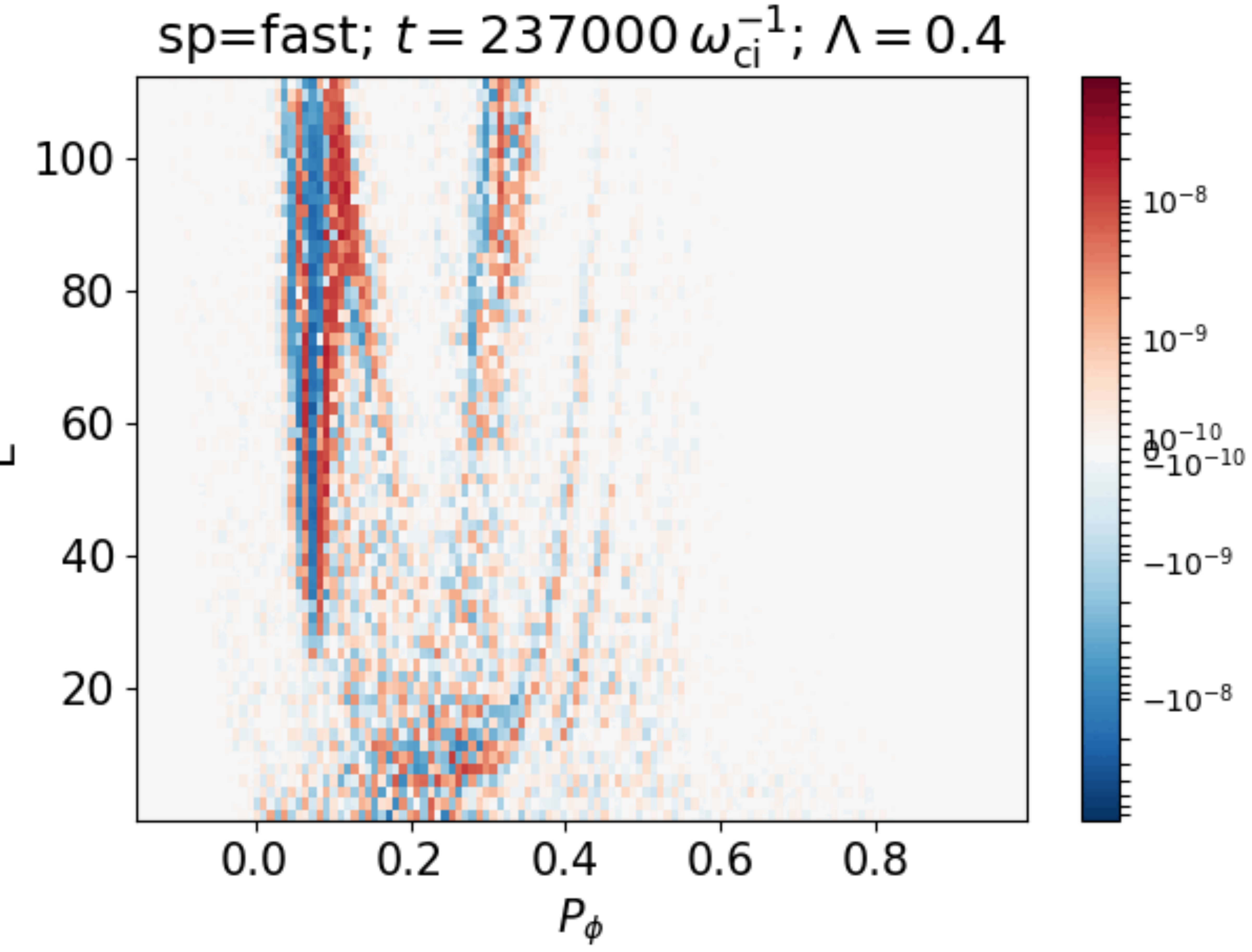


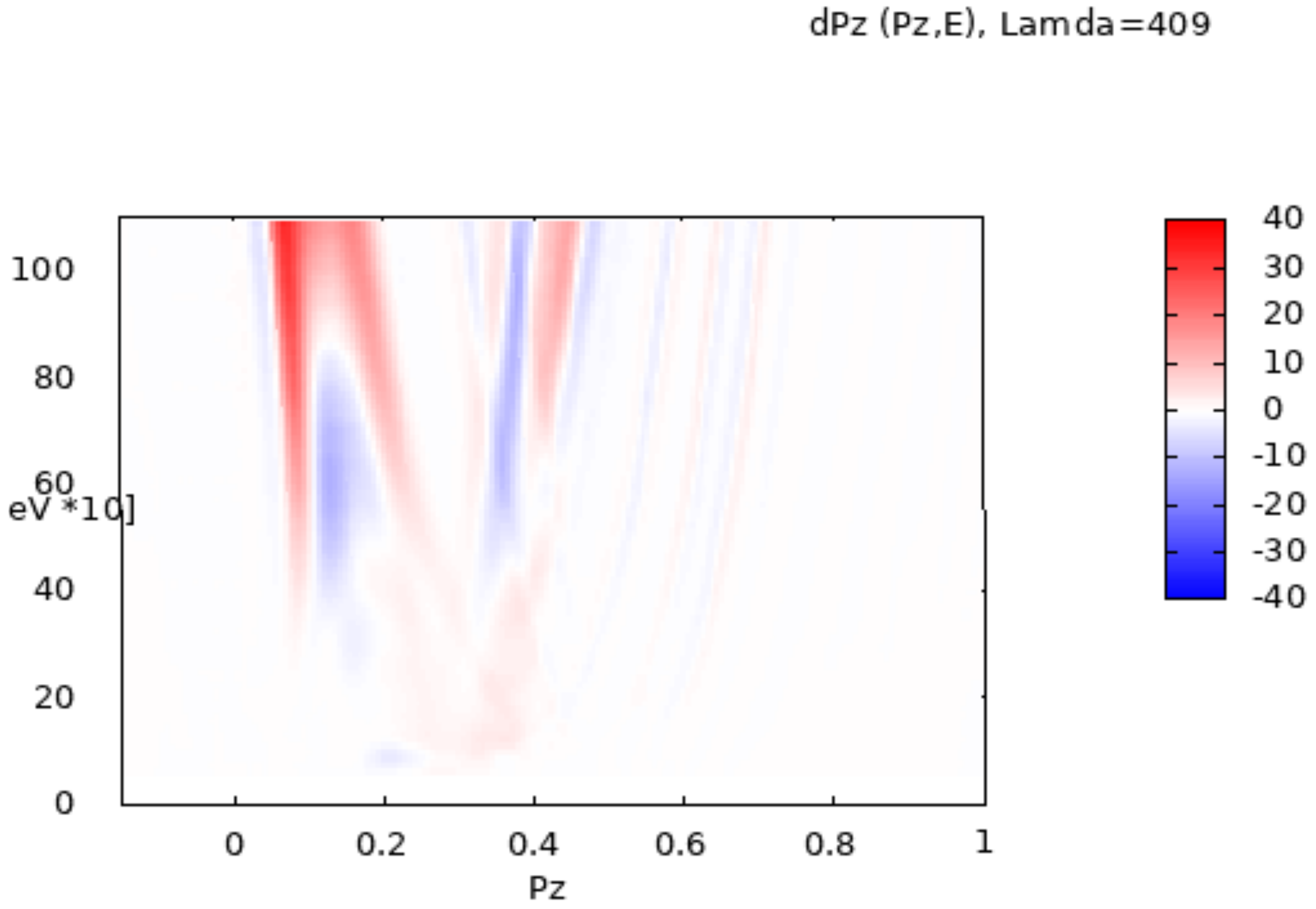


ORB5- ATEP PSZS comparison: ‚no-EP‘ eigenfunctions, combination of n=18,n=19 modes

n=18(even 1) δB/B=1.0e-5
n=18 (even 2) δB/B=4.0e-5
n=19 δB/B=5.0e-5

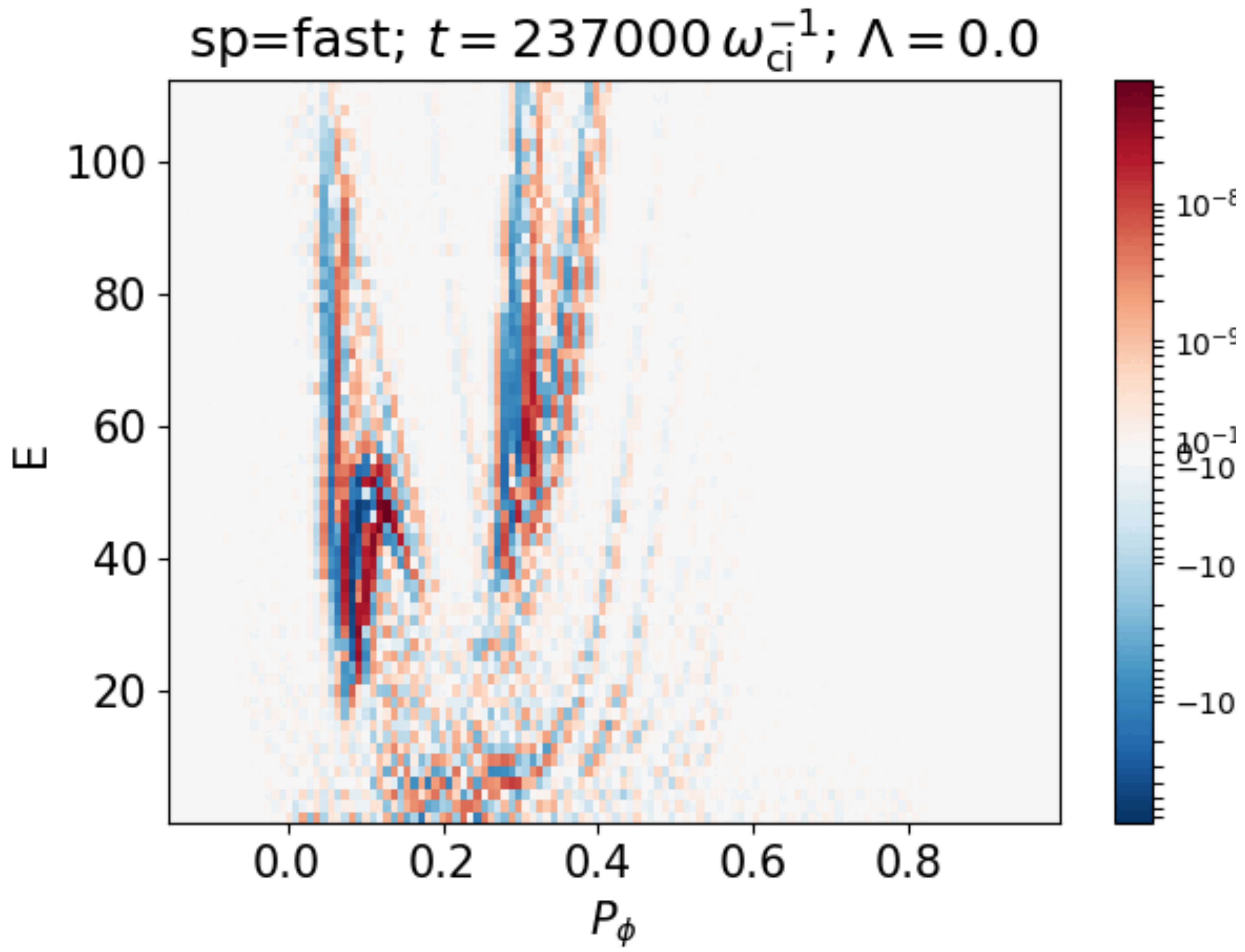
scale A ~ $(\gamma_L-\gamma_{damp})^2$

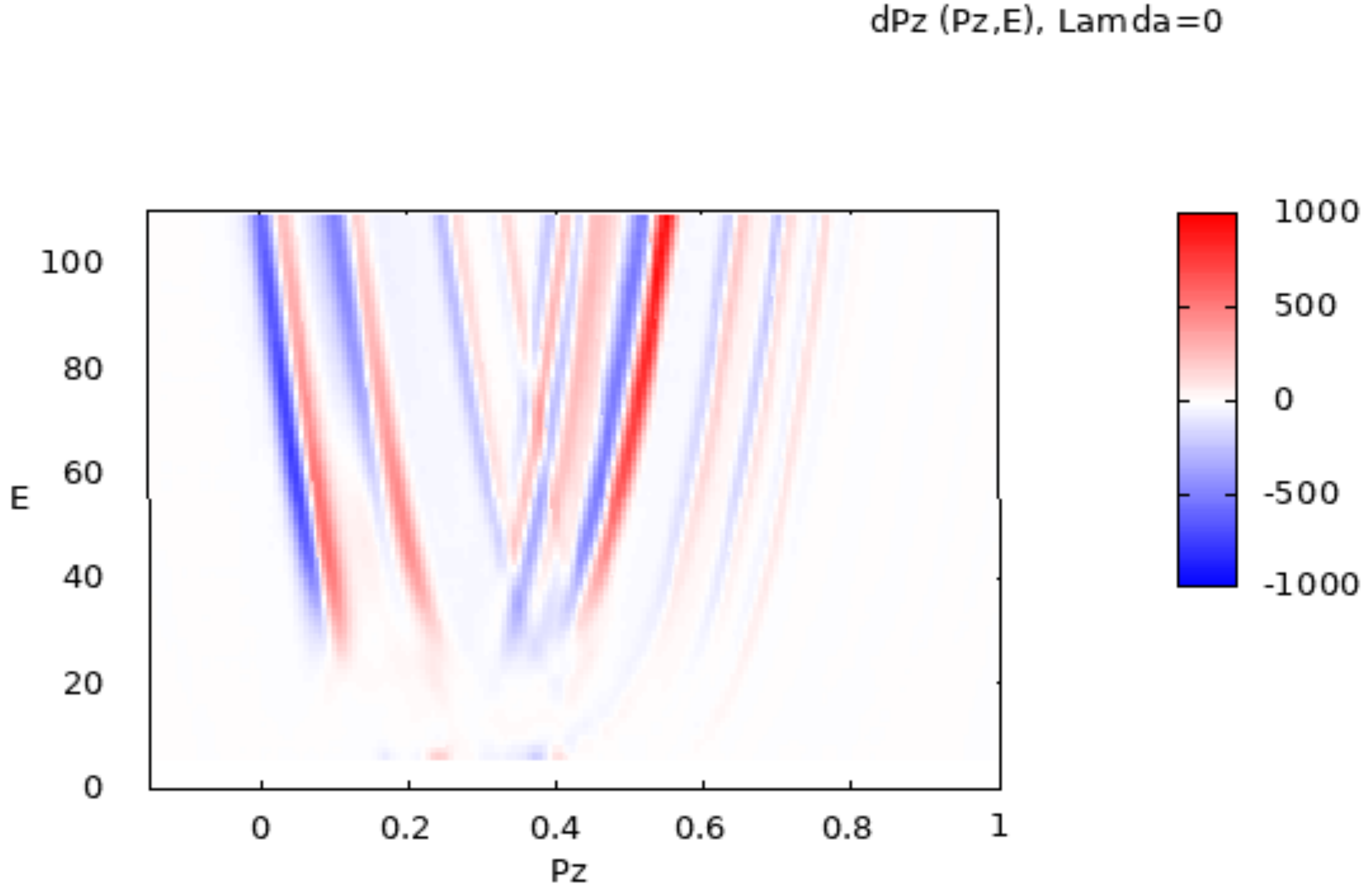




ORB5- ATEP PSZS comparison: ‚EP‘ eigenfunctions, combination of n=18,n=19 modes

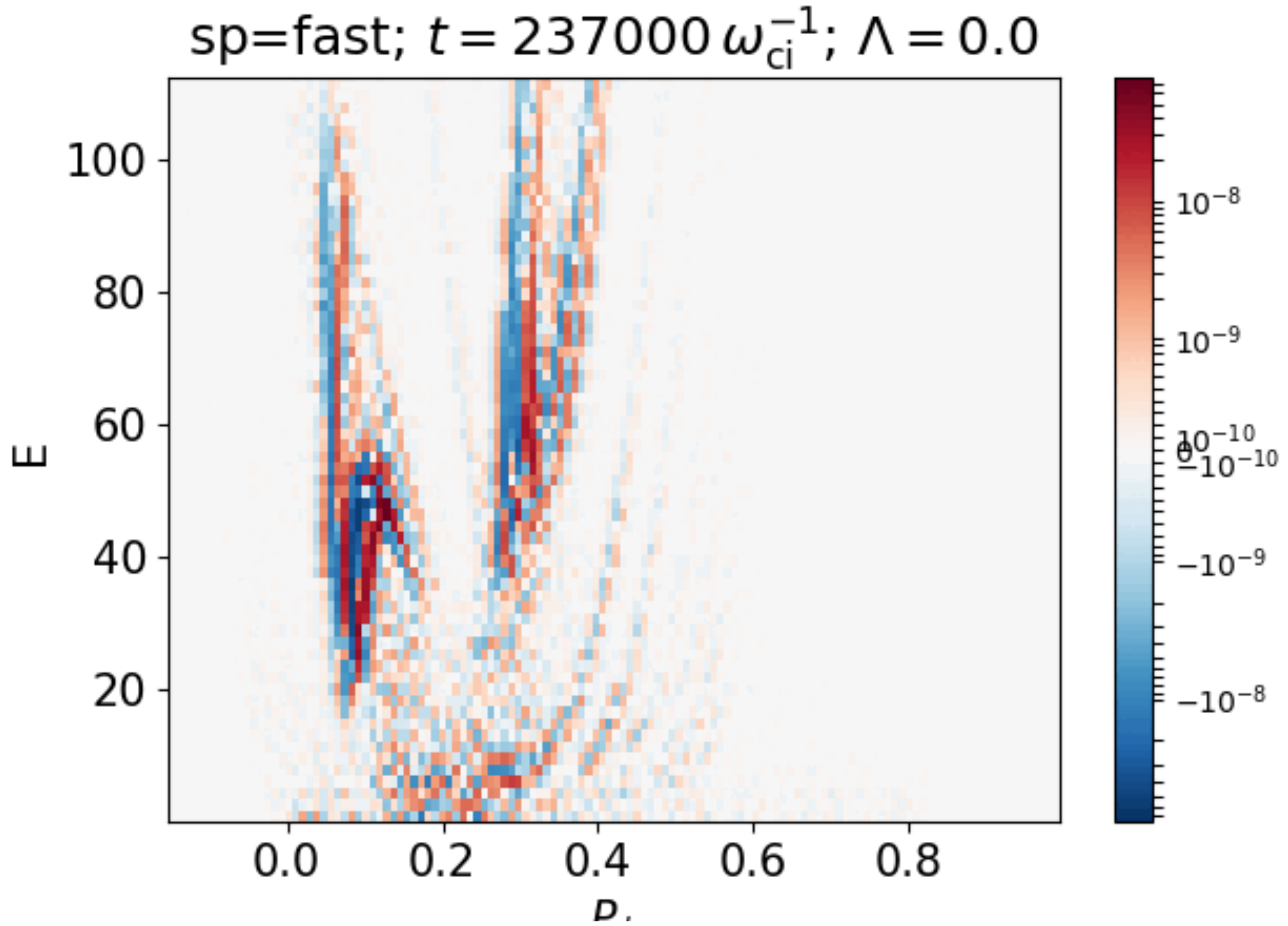
n=18(even inner) δB/B=1.0e-4
n=18 (even outer) δB/B=1.0e-3
n=19 δB/B=1.0e-4



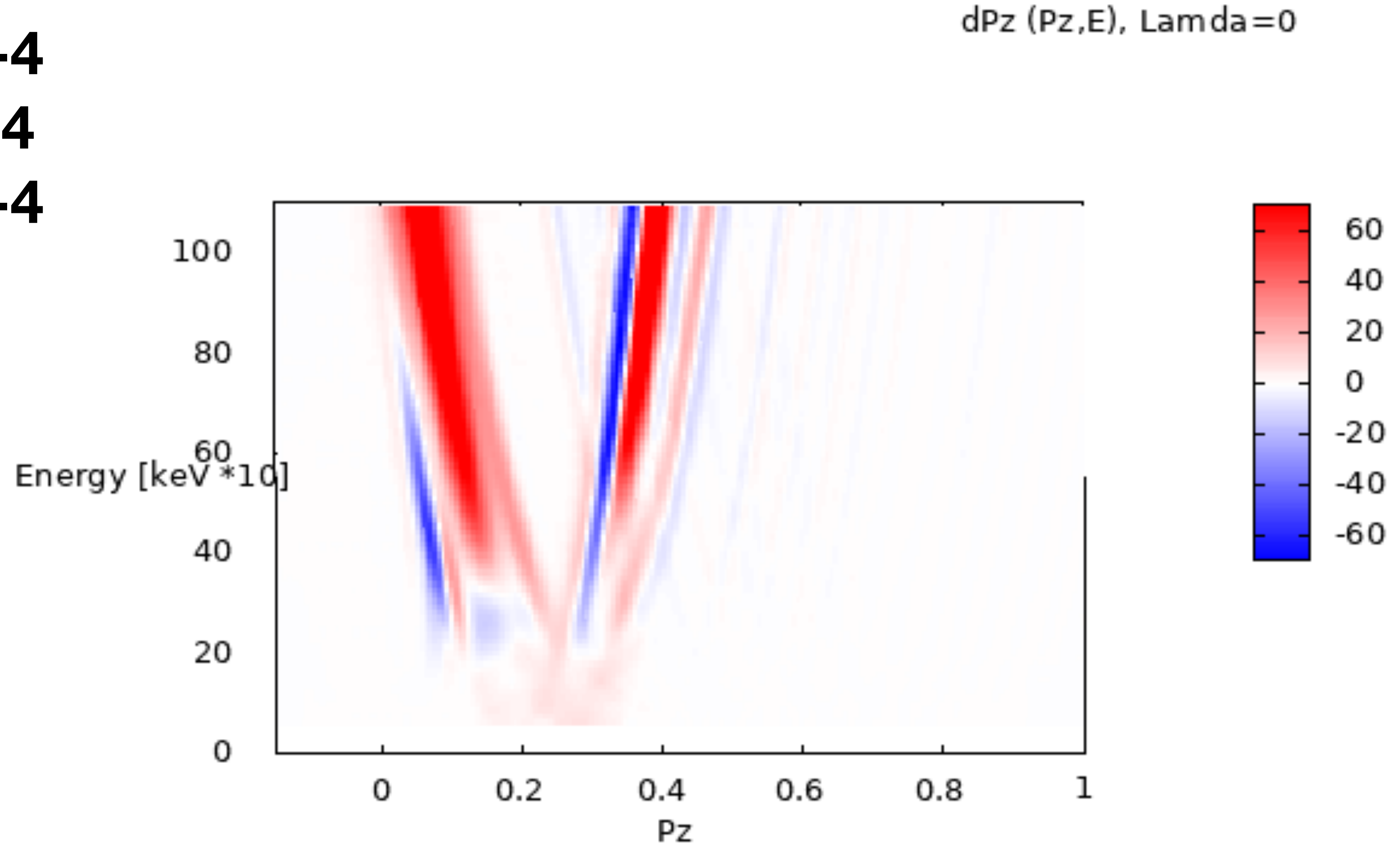


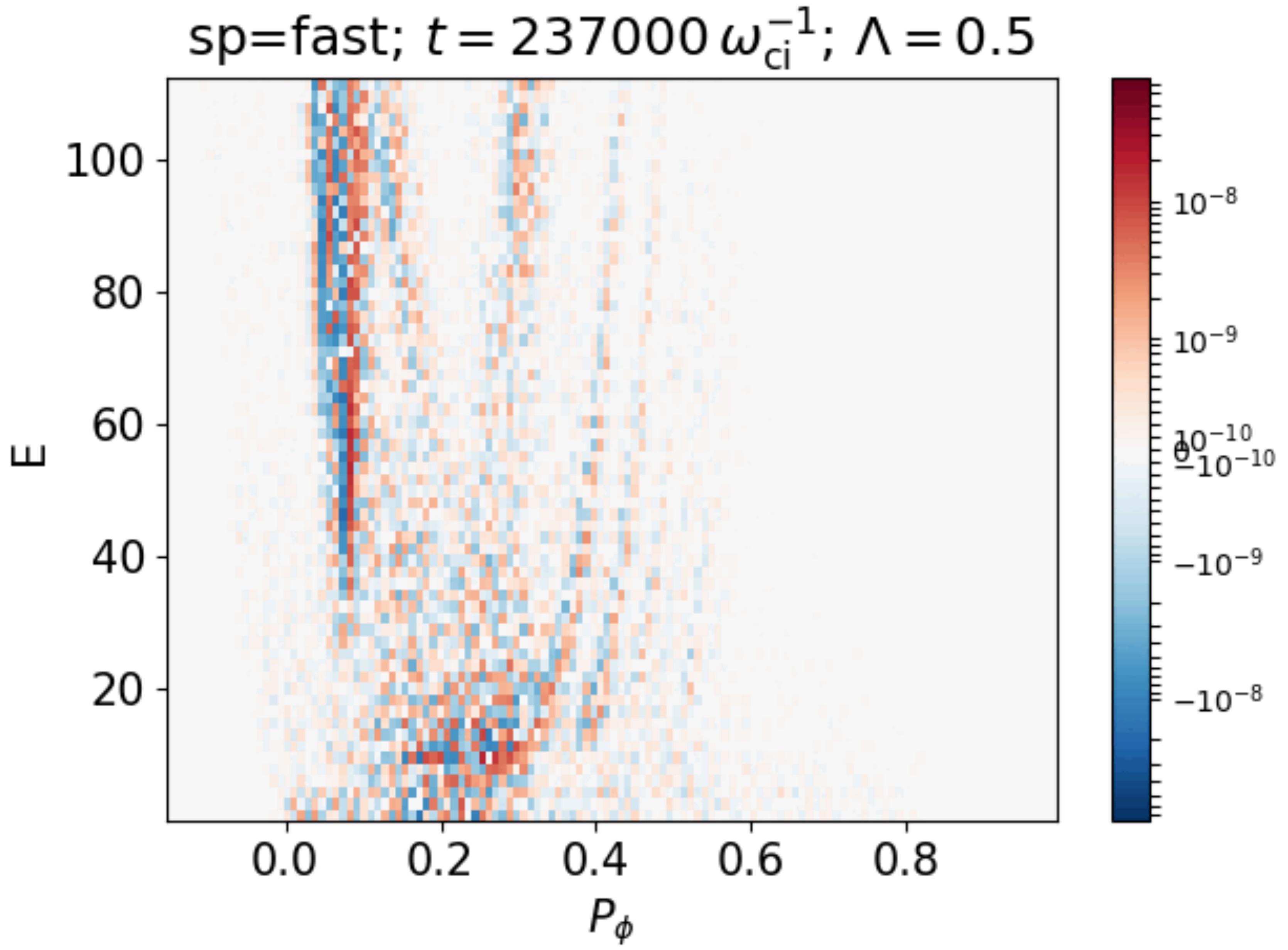
dominating n=18 ‚even outer‘ does not compare as well as other combinations- in agreement with linear growth rates!

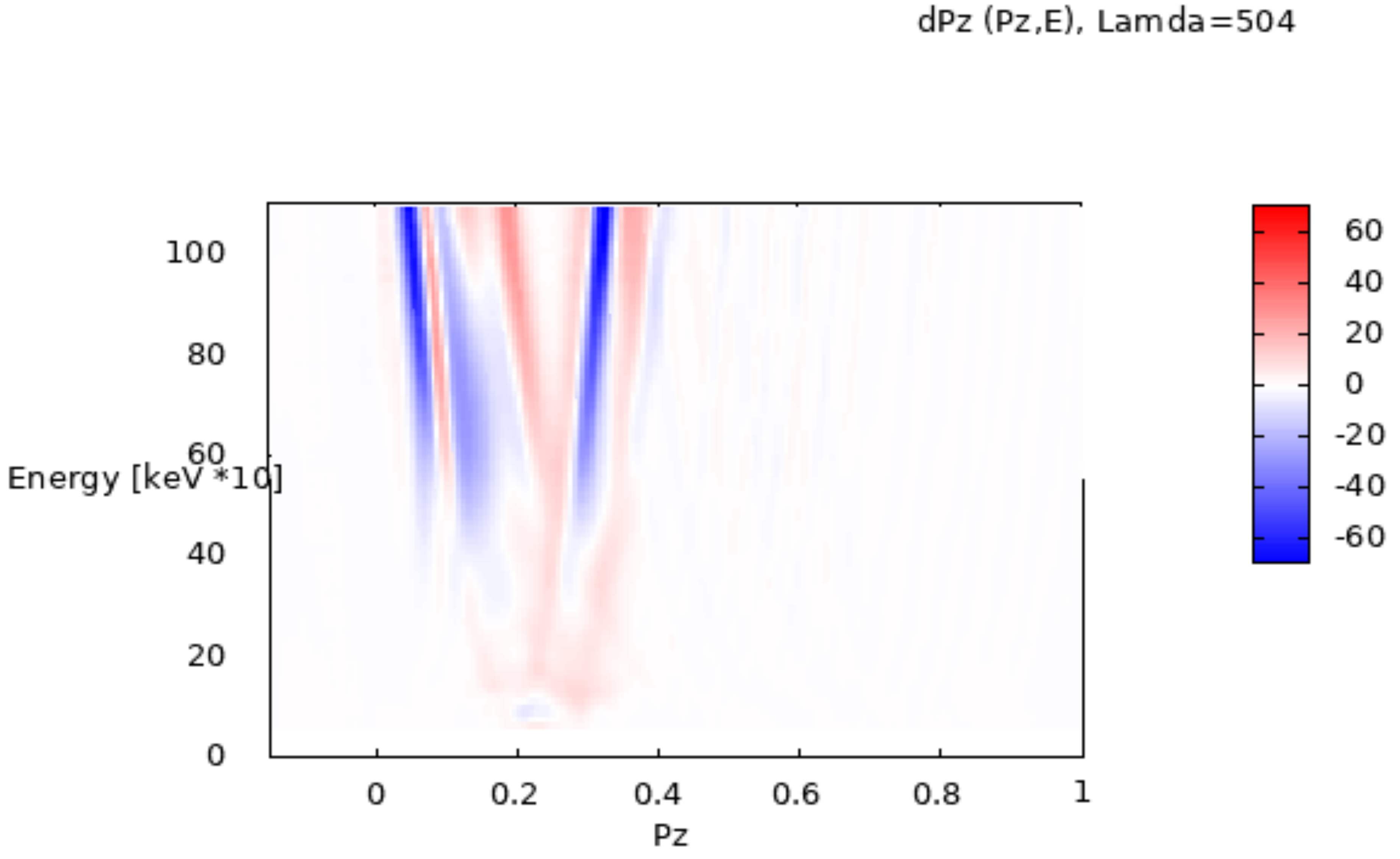
ORB5- ATEP PSZS comparison: ‚EP‘ eigenfunctions, combination of n=18 even and odd ‚n=19 modes



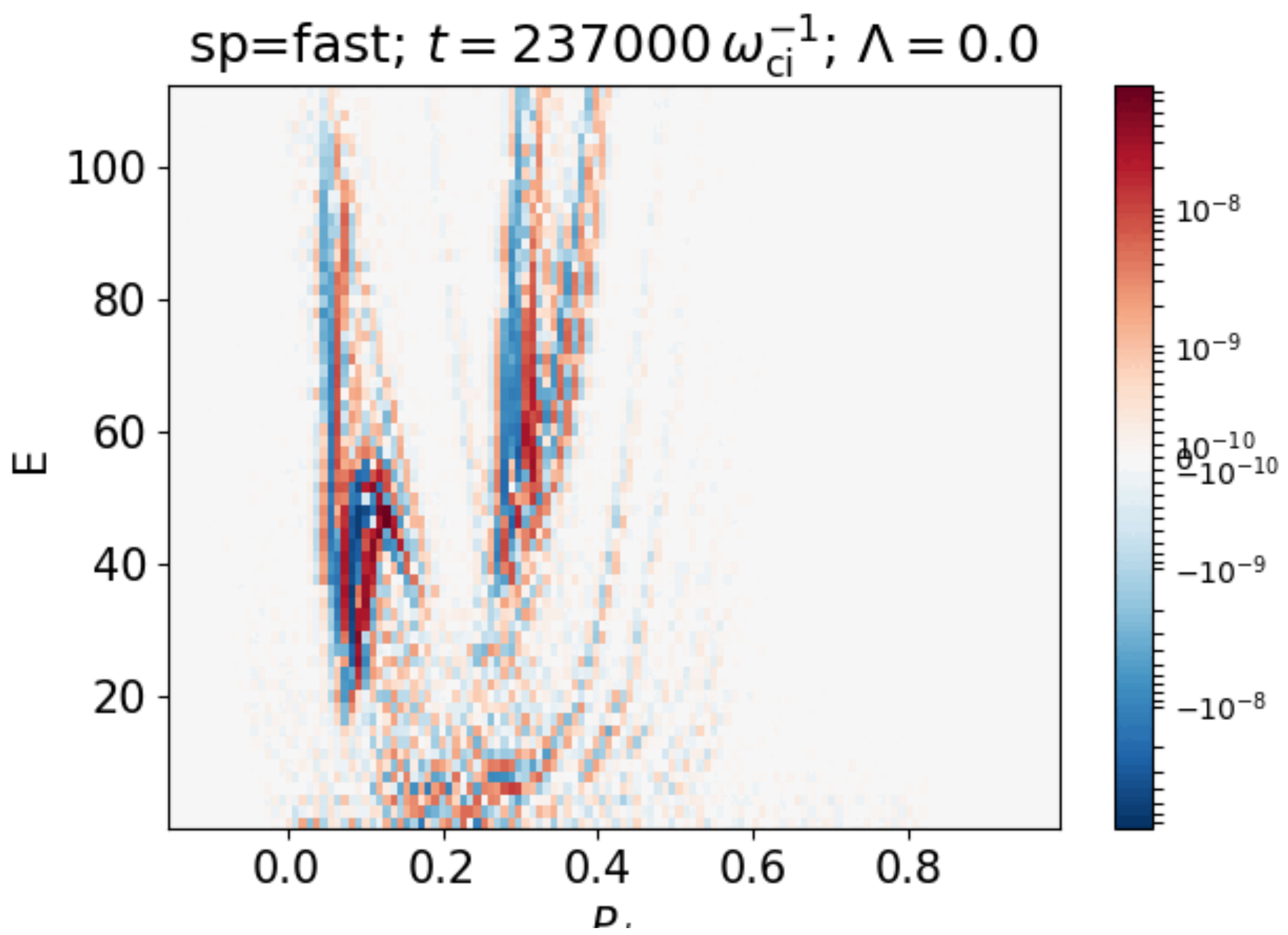
n=18(even) δB/B=1.0e-4
n=18 (odd) δB/B=1.0e-4
n=19 (even) δB/B=1.0e-4



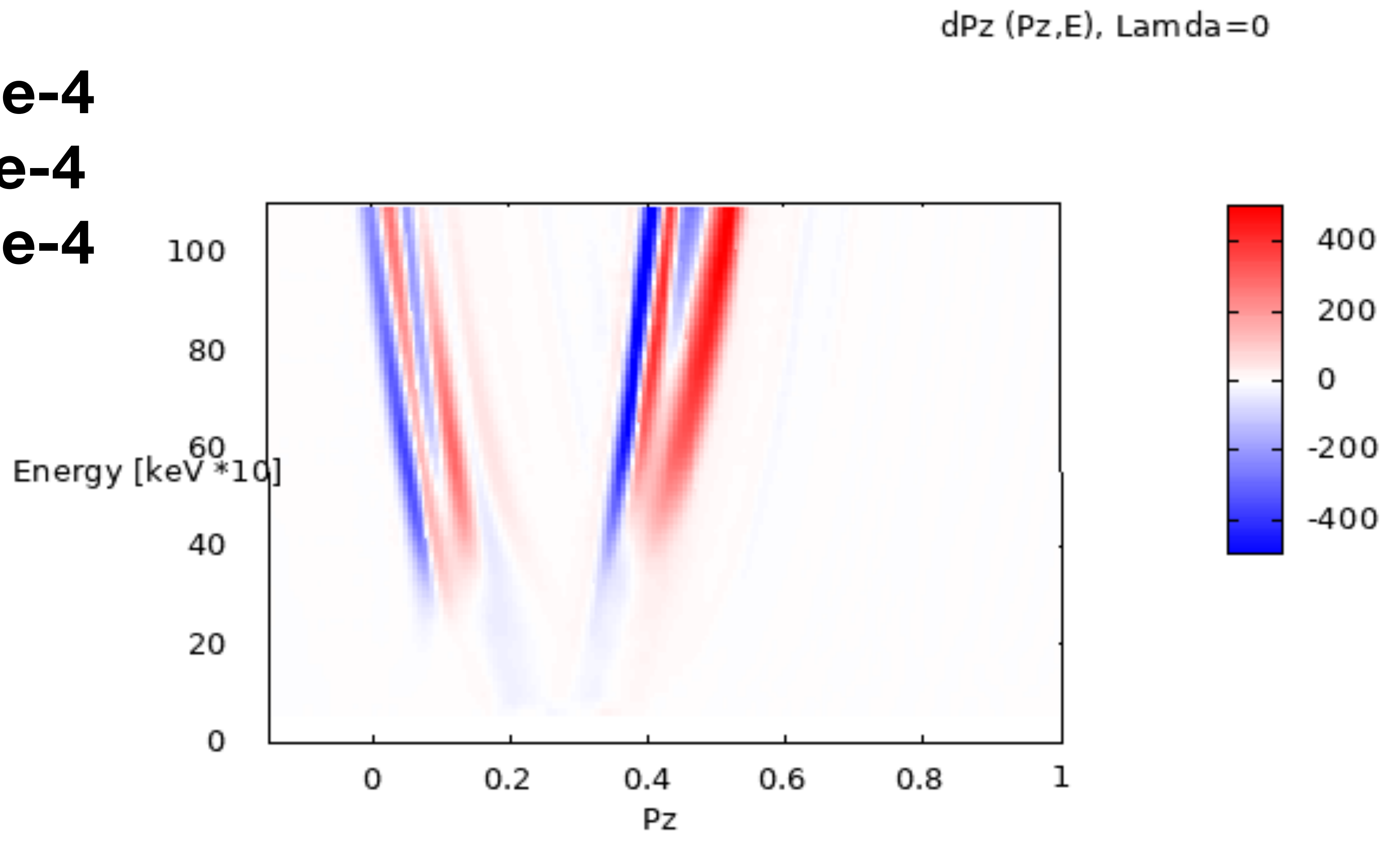


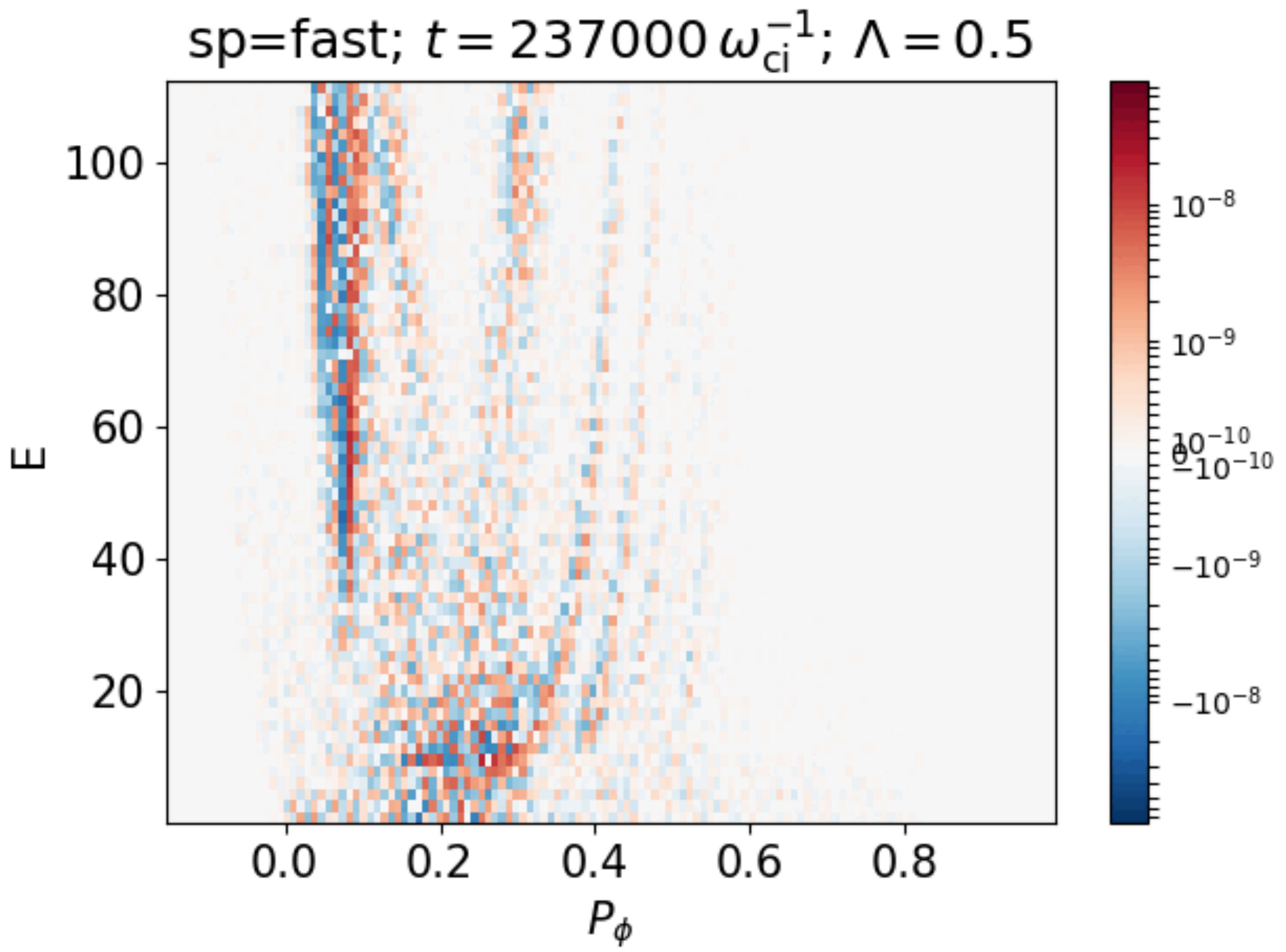


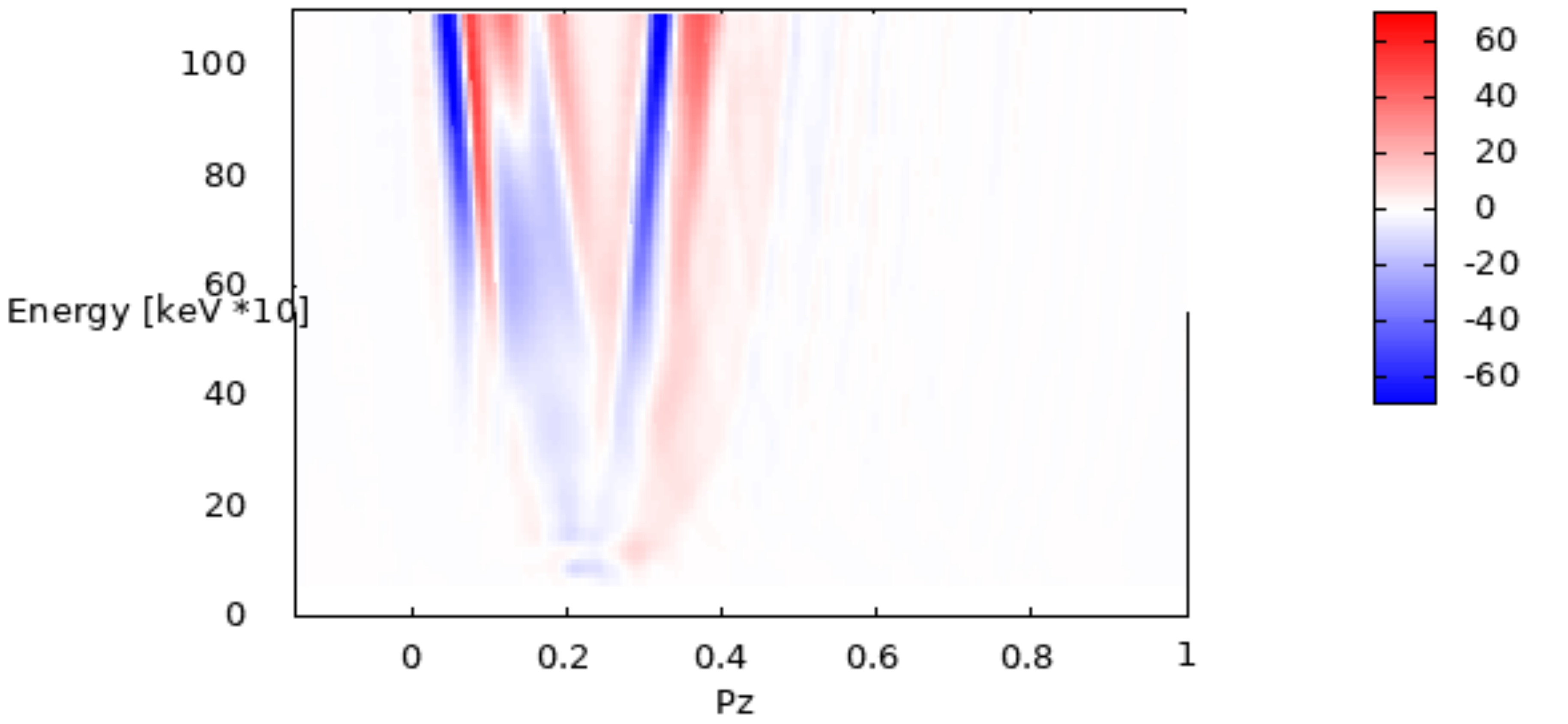
ORB5- ATEP PSZS comparison: ‚EP' eigenfunctions, combination of n=18 even and odd ‚n=19 modes



n=18(even) δB/B=1.0e-4
n=18 (odd) δB/B=5.0e-4
n=19 (even) δB/B=1.0e-4

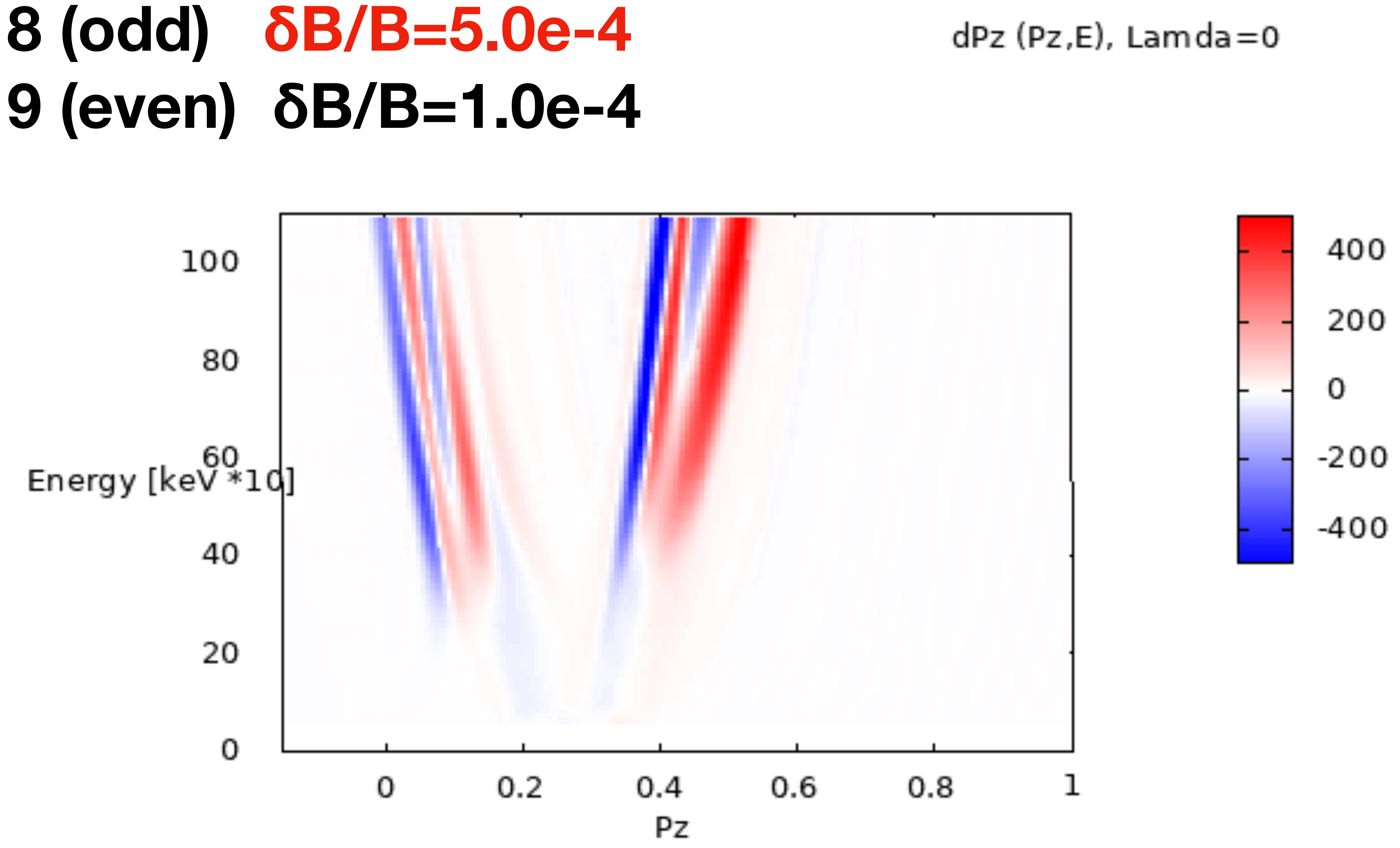


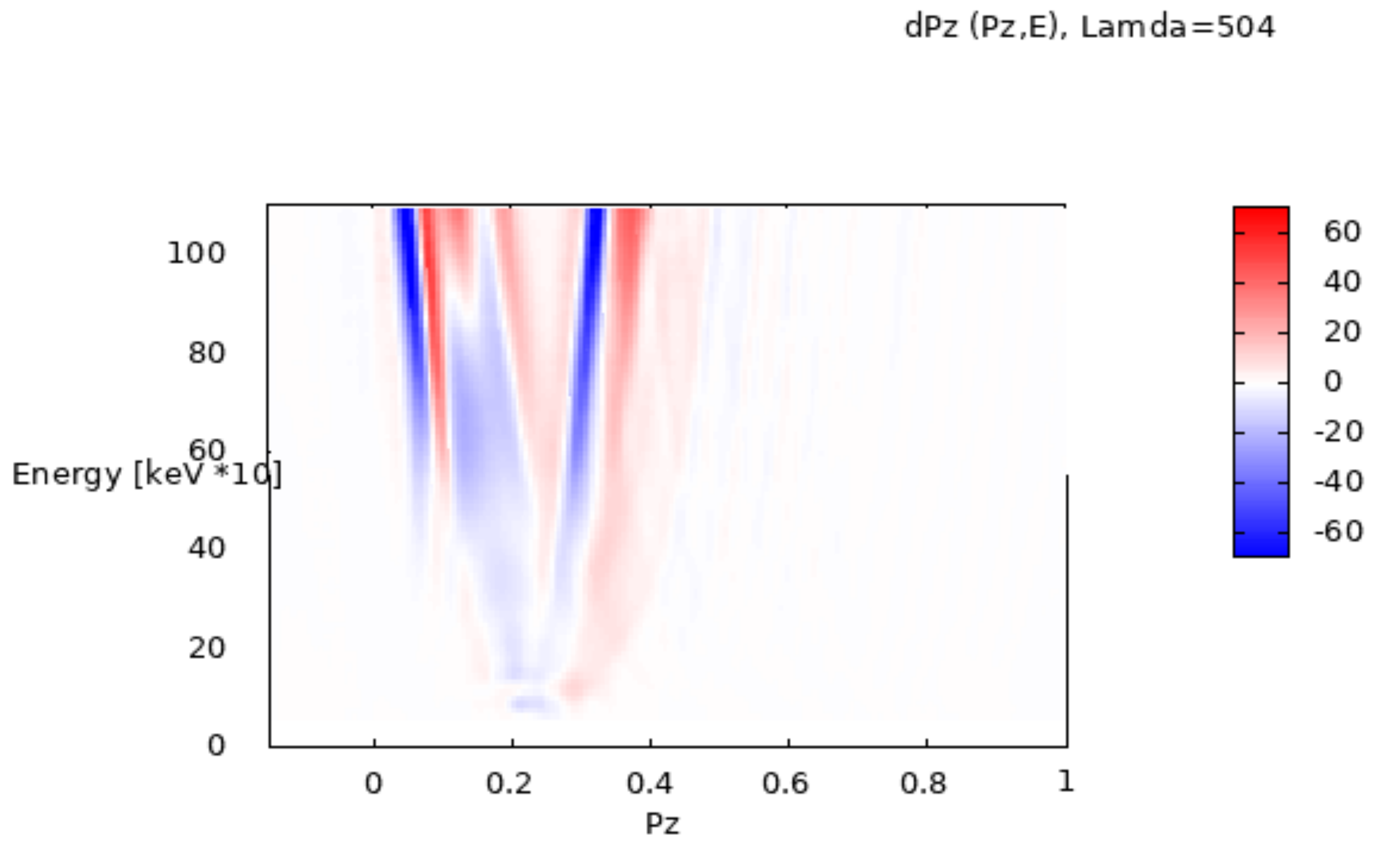




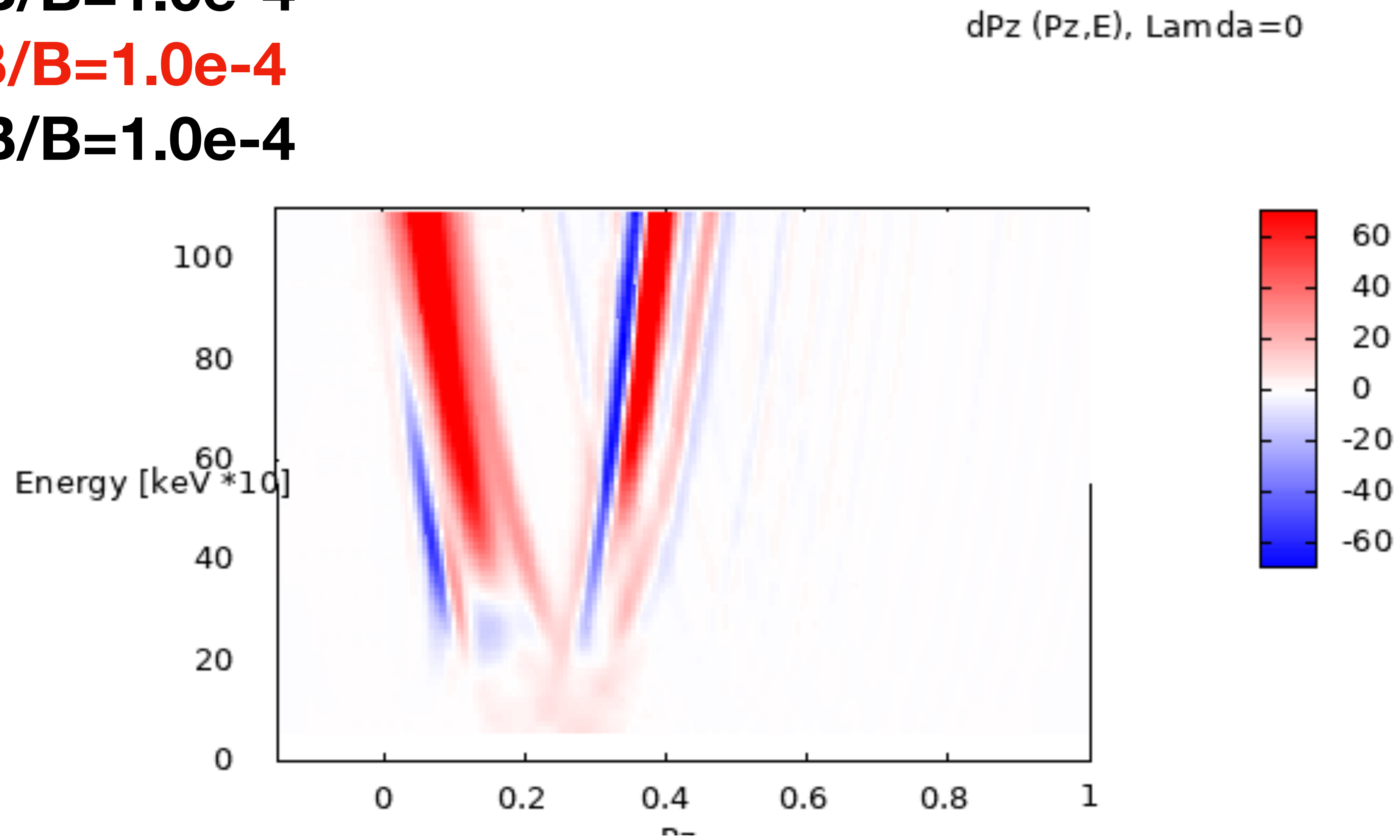
ORB5- ATEP PSZS comparison: ‚EP‘ eigenfunctions, combination of n=18 even and odd ,n=19 modes

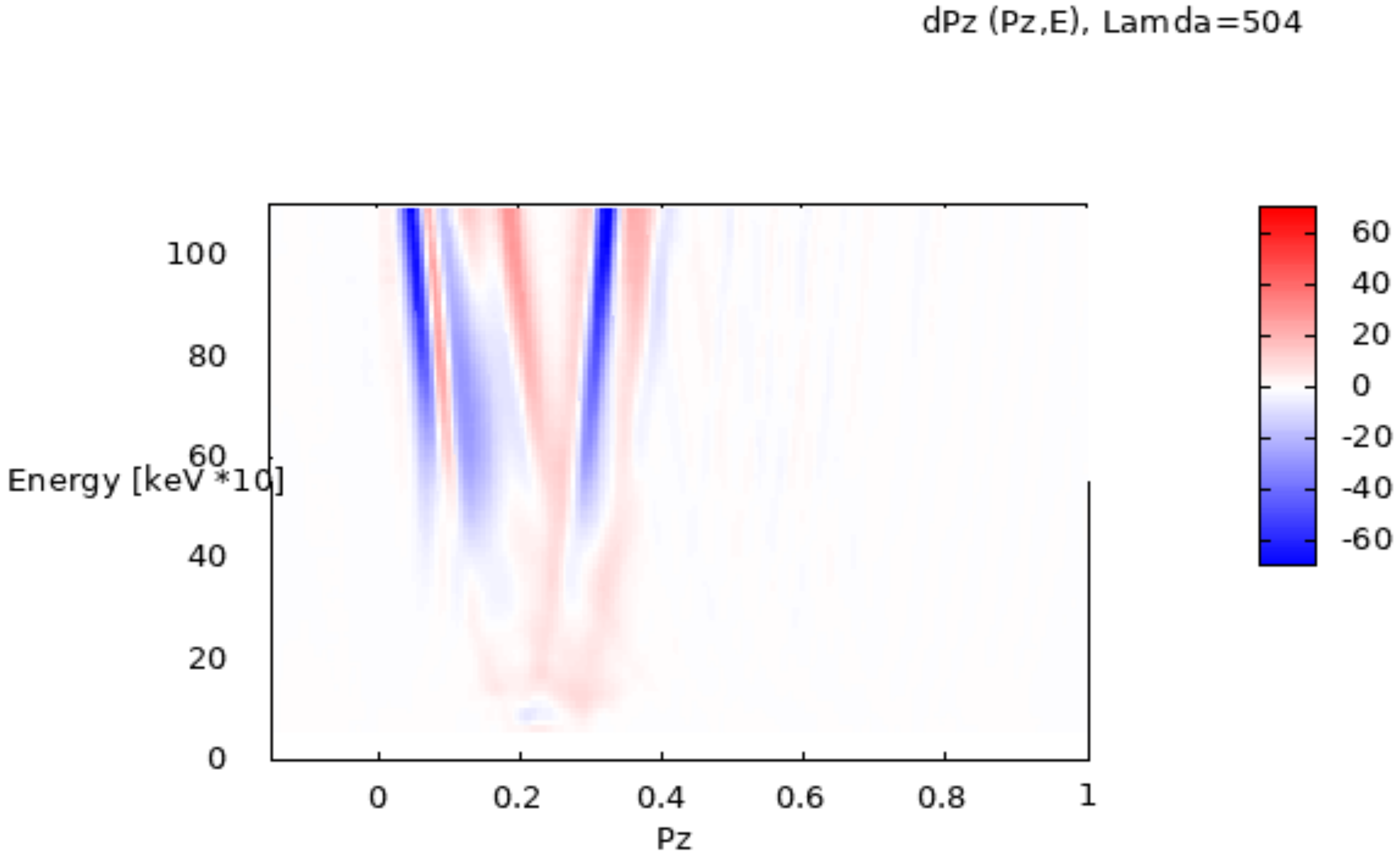
n=18(even) δB/B=1.0e-4
n=18 (odd) δB/B=5.0e-4
n=19 (even) δB/B=1.0e-4





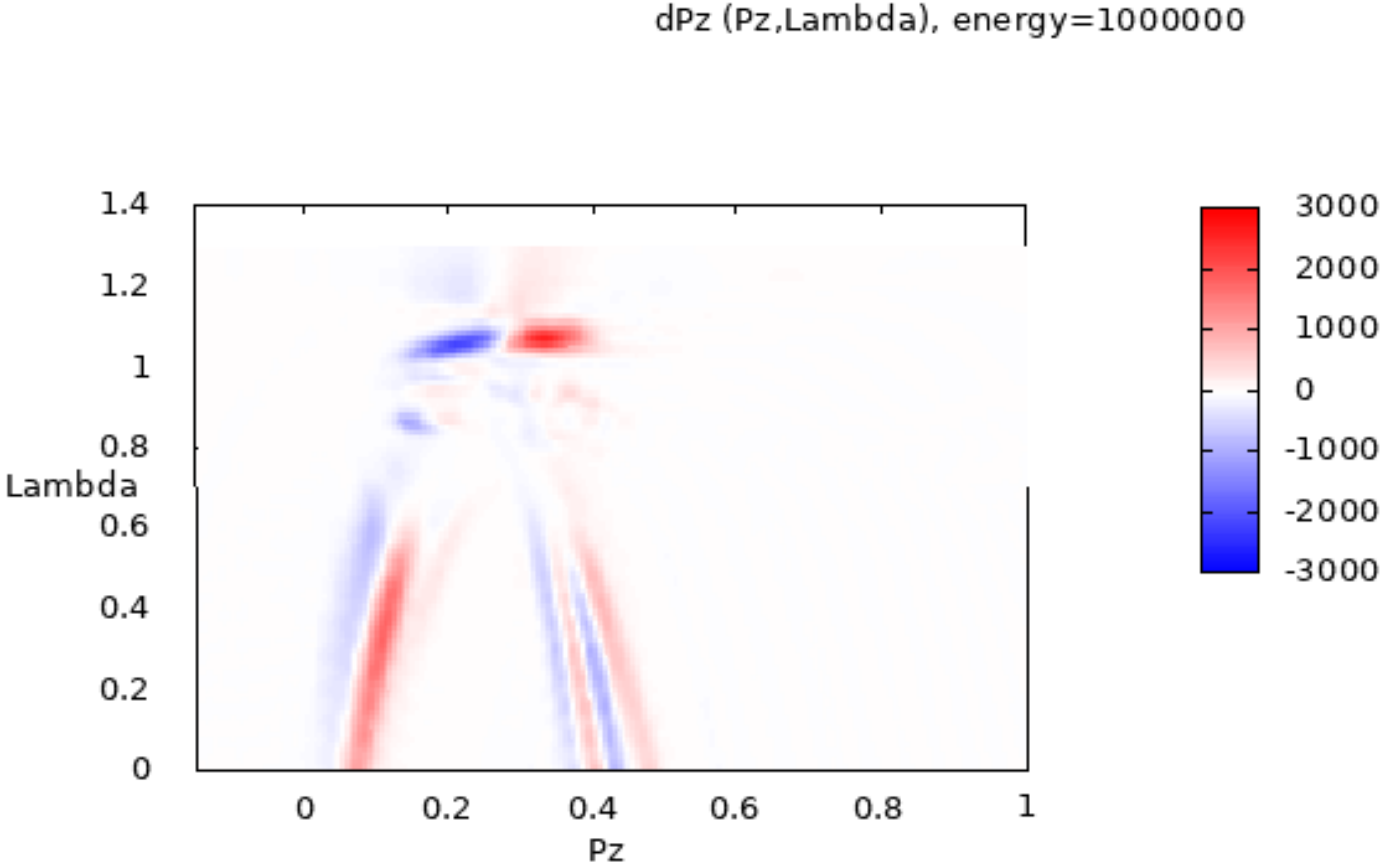
n=18(even) δB/B=1.0e-4
n=18 (odd) δB/B=1.0e-4
n=19 (even) δB/B=1.0e-4





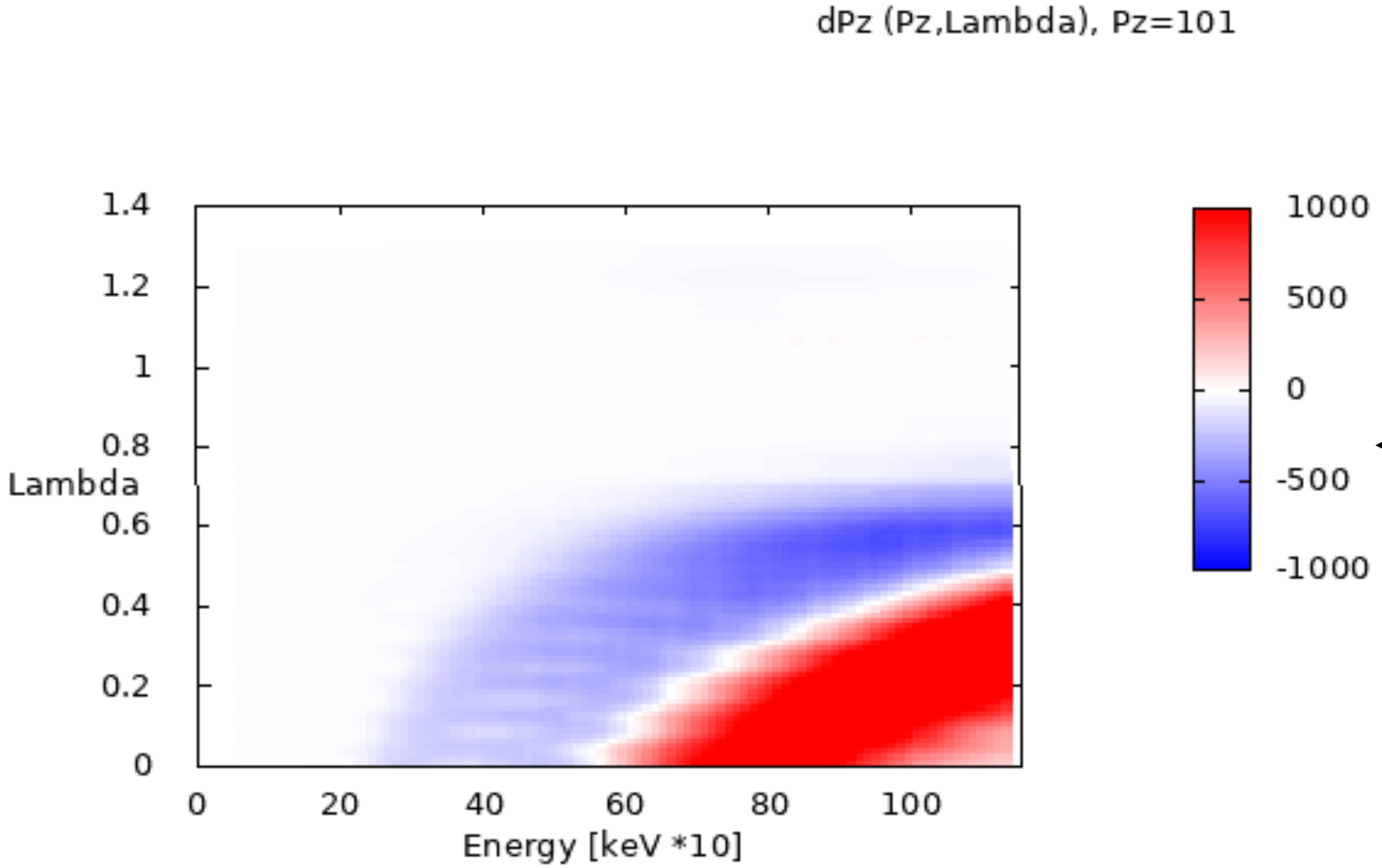
ORB5- ATEP PSZS comparison: ‚EP' eigenfunctions, combination of n=18,n=19 modes
Pz-Λ slices

n=18(even inner)   δB/B=2.0e-4
n=18 (even outer)   δB/B=2.0e-4
n=19   δB/B=1.0e-3

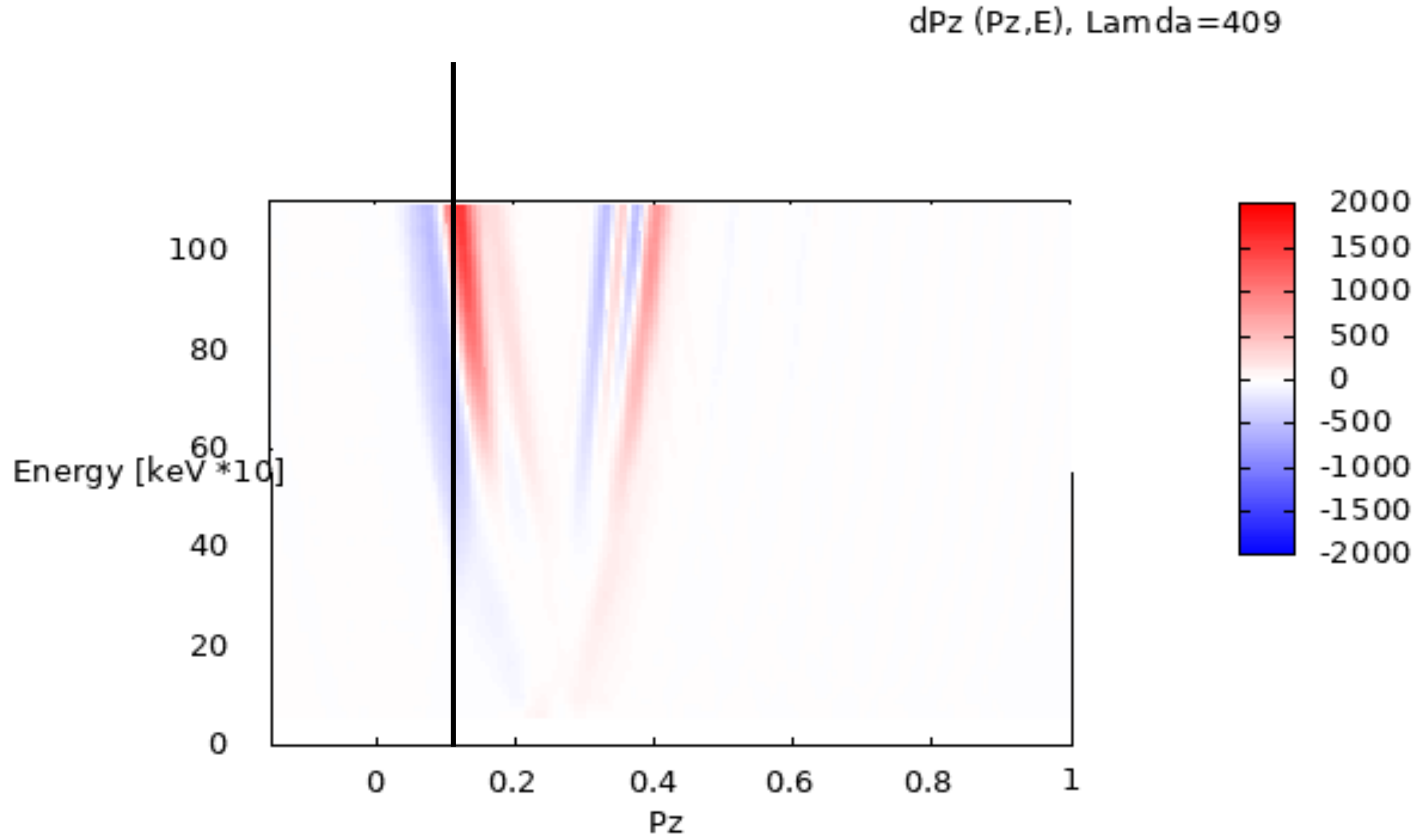


ORB5- ATEP PSZS comparison: ‚EP' eigenfunctions, combination of n=18,n=19 modes
E-Λ slices, co-passing

n=18(odd) δB/B=2.0e-4
n=18 (even) δB/B=2.0e-4
n=19 δB/B=1.0e-3



cut



as expected: PSZS structures differ at different amplitudes, especially at large amplitudes, when stochasticity limit is crossed ˜ δB/B=1.0e-3

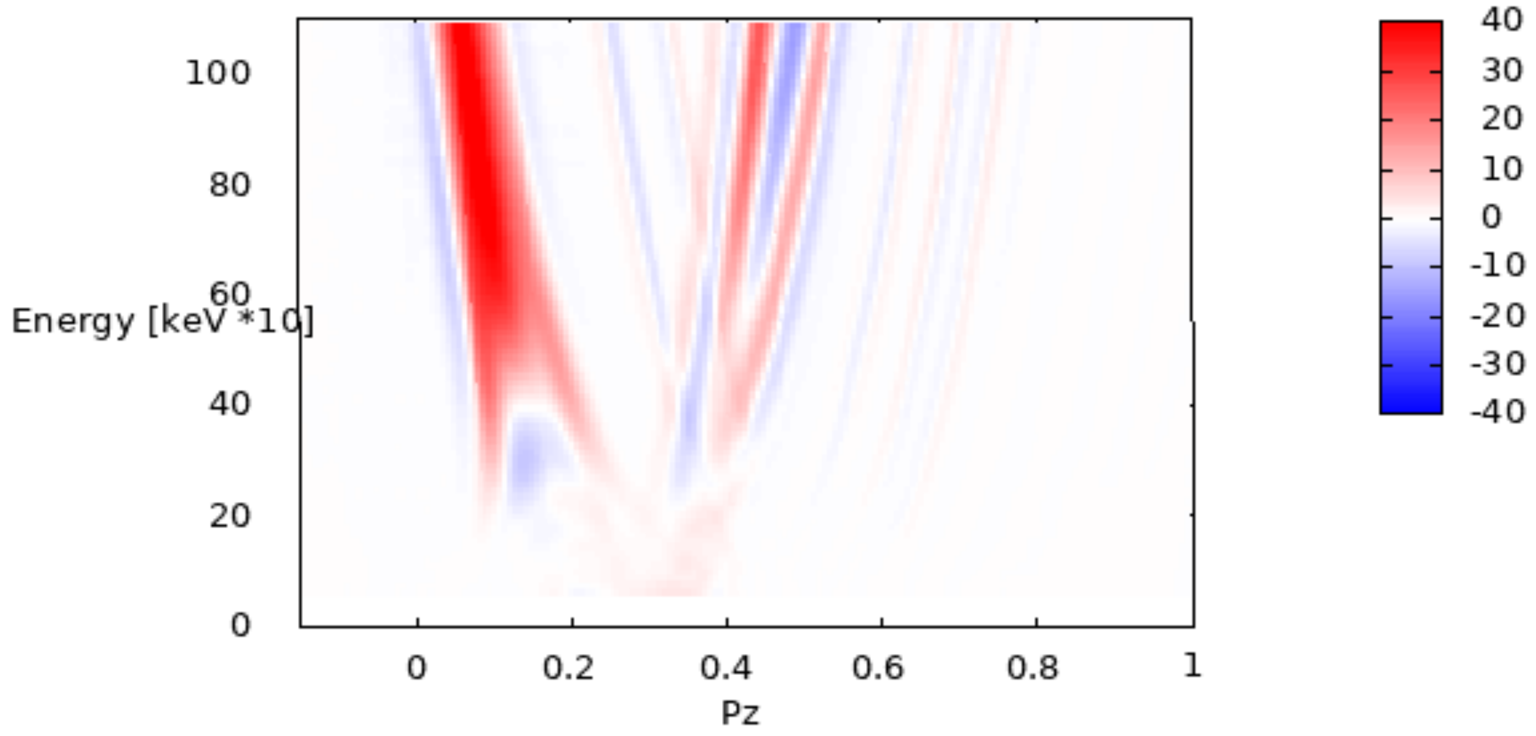
n=18(odd) δB/B=1.0e-5
n=18 (even) δB/B=4.0e-5
n=19 δB/B=5.0e-5

n=18(odd) δB/B=1.0e-4
n=18 (even) δB/B=4.0e-4
n=19 δB/B=5.0e-4

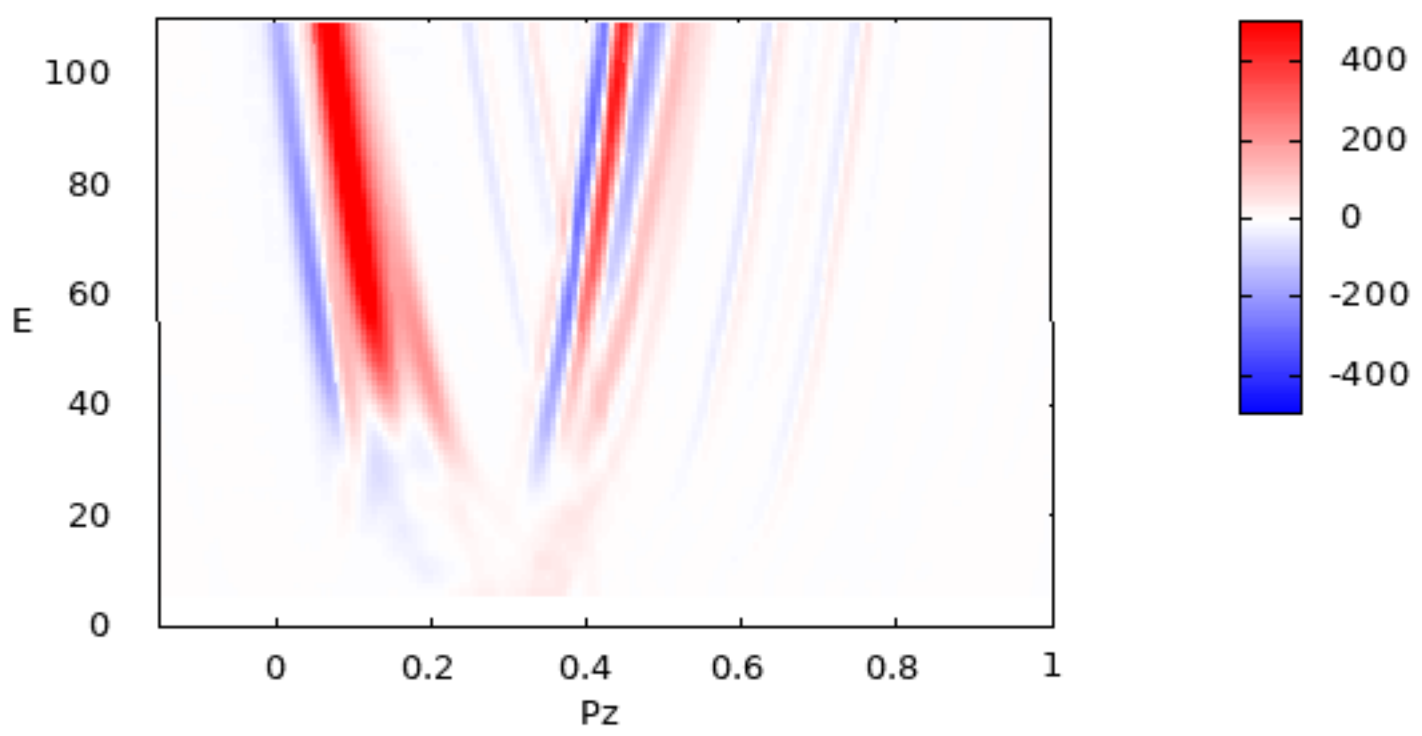
n=18(odd) δB/B=1.0e-3
n=18 (even) δB/B=4.0e-3
n=19 δB/B=5.0e-3

Λ=μB/E=0.0

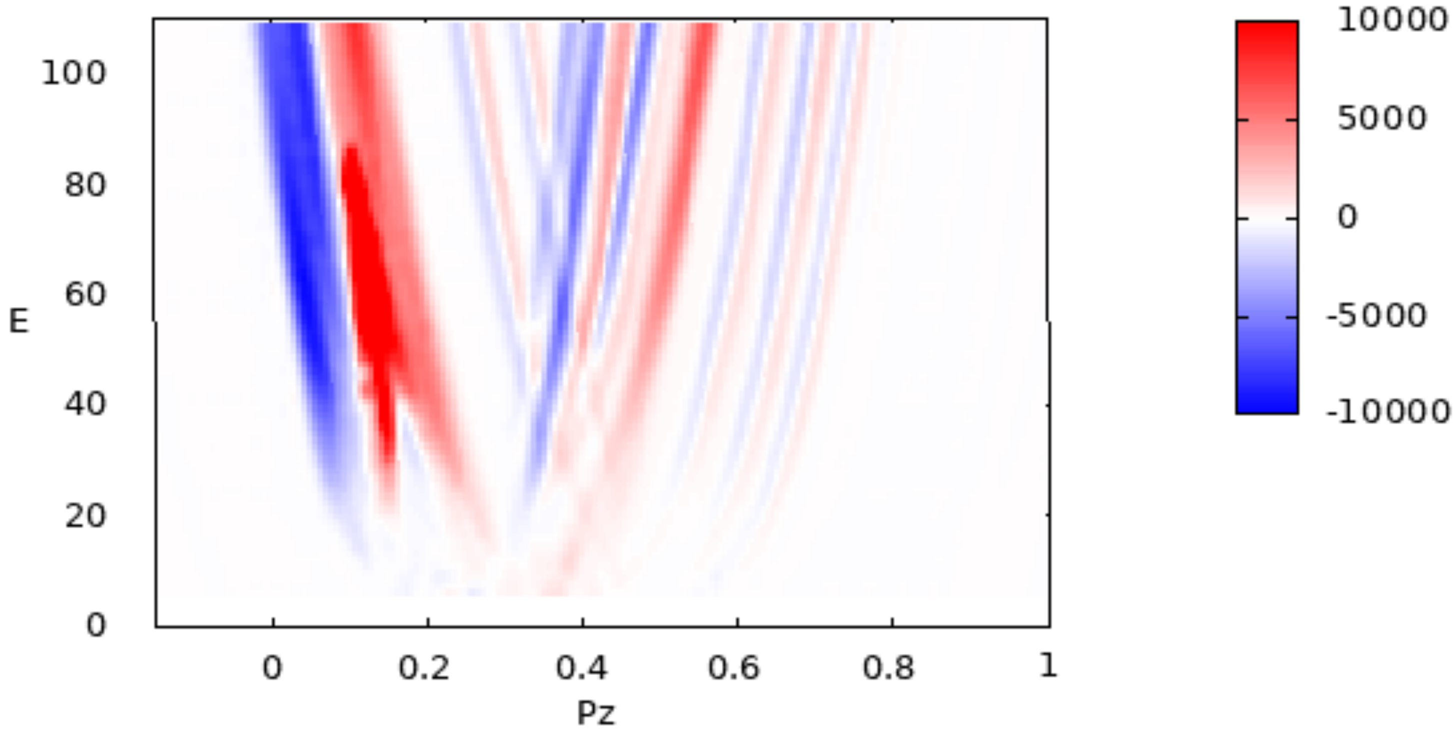
dPz (Pz,E), Lamda=0



dPz (Pz,E), Lamda=0

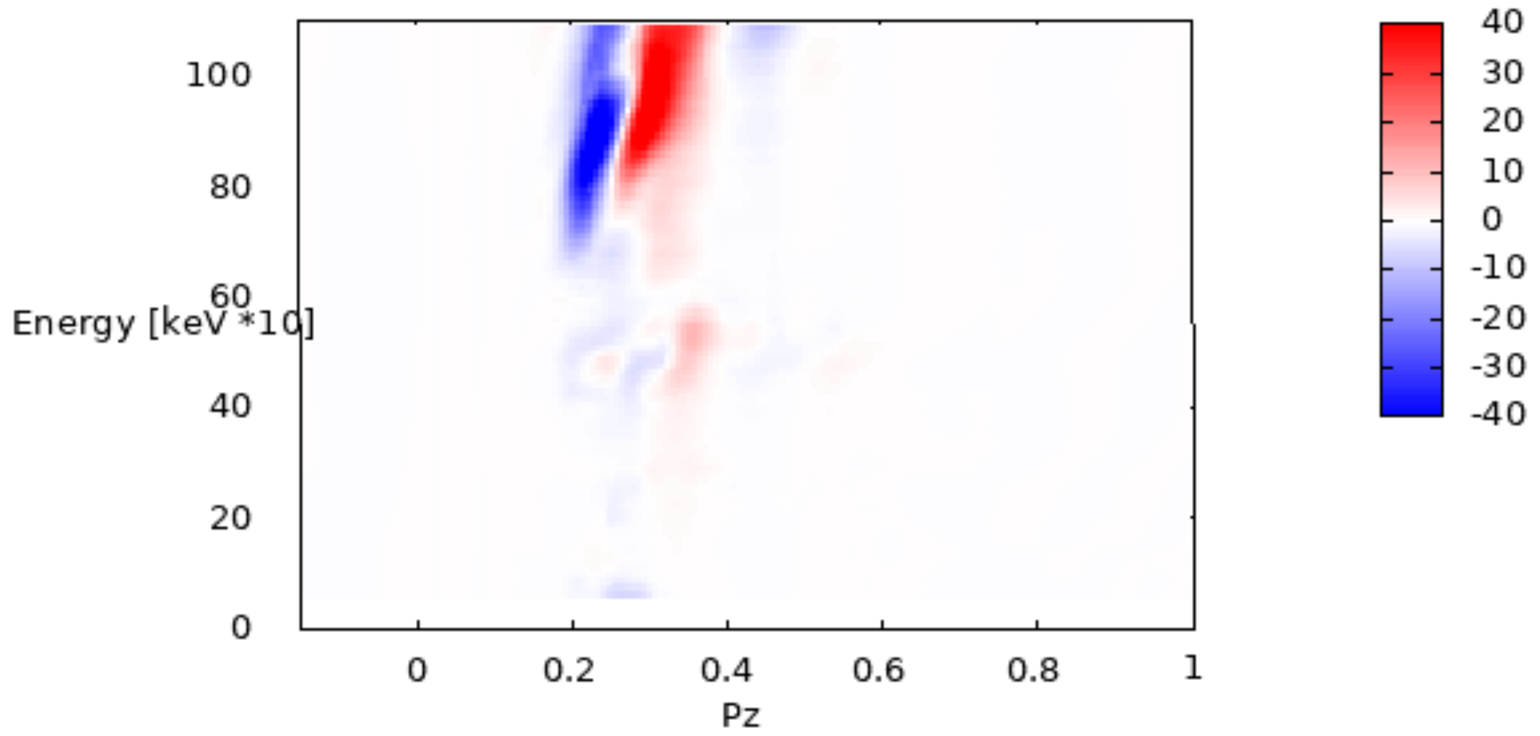


dPz (Pz,E), Lamda=0

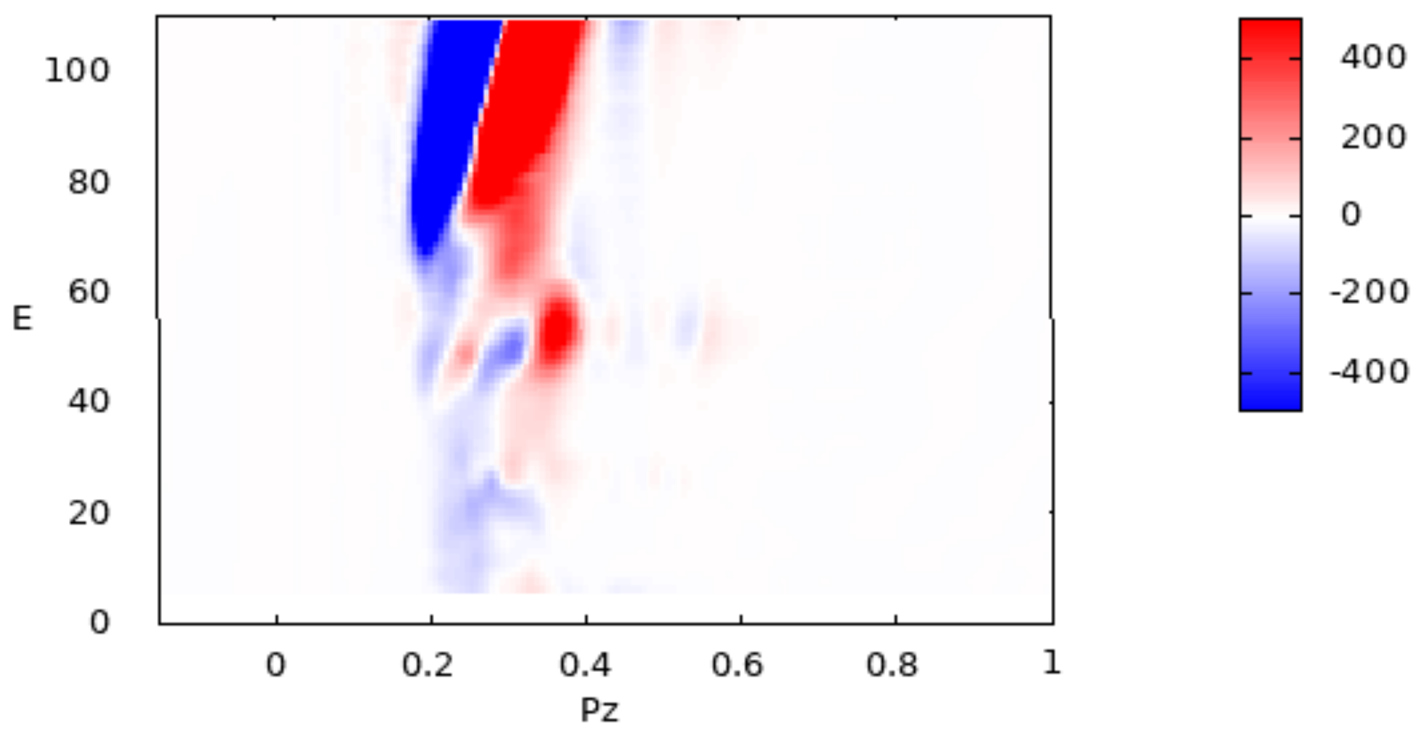


Λ=μB/E=1.1 - trapped

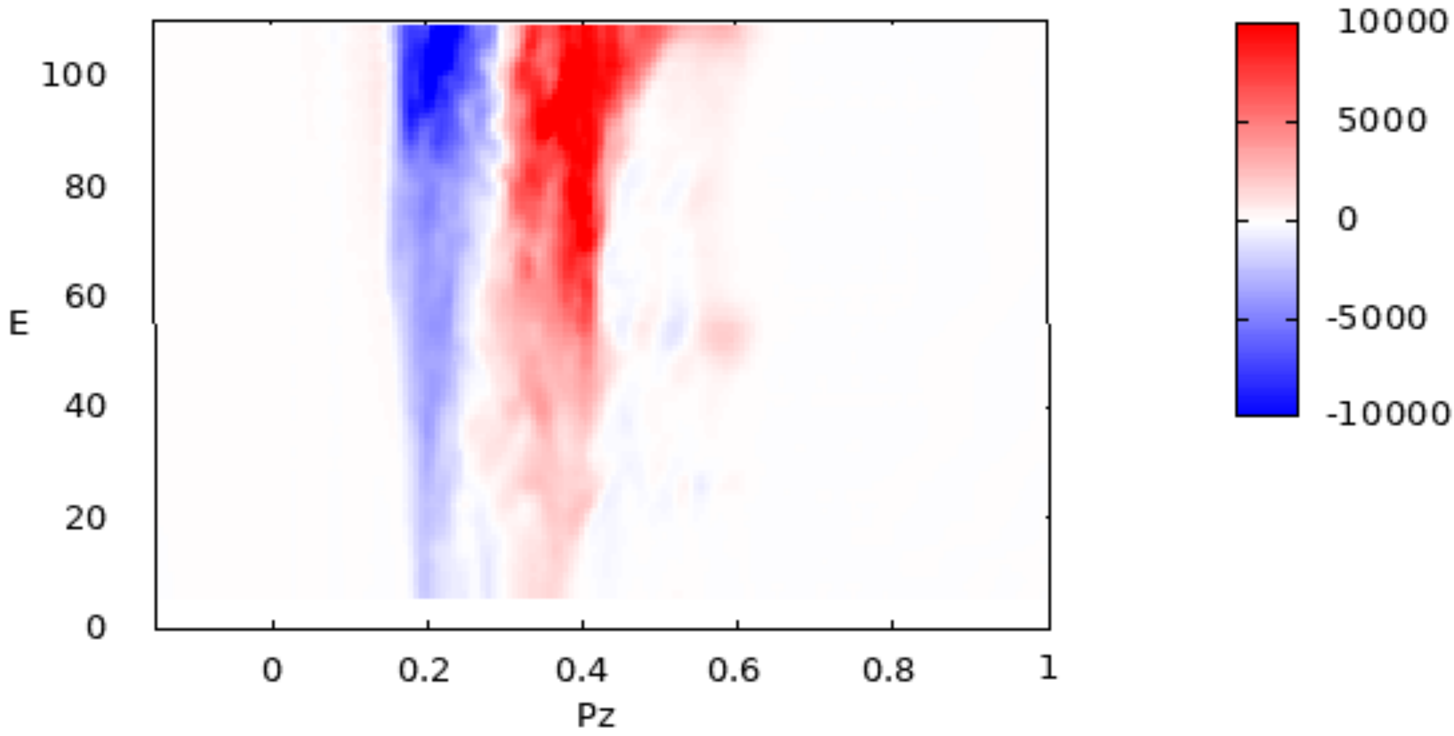
dPz (Pz,E), Lamda=1103



dPz (Pz,E), Lamda=1103



dPz (Pz,E), Lamda=1103



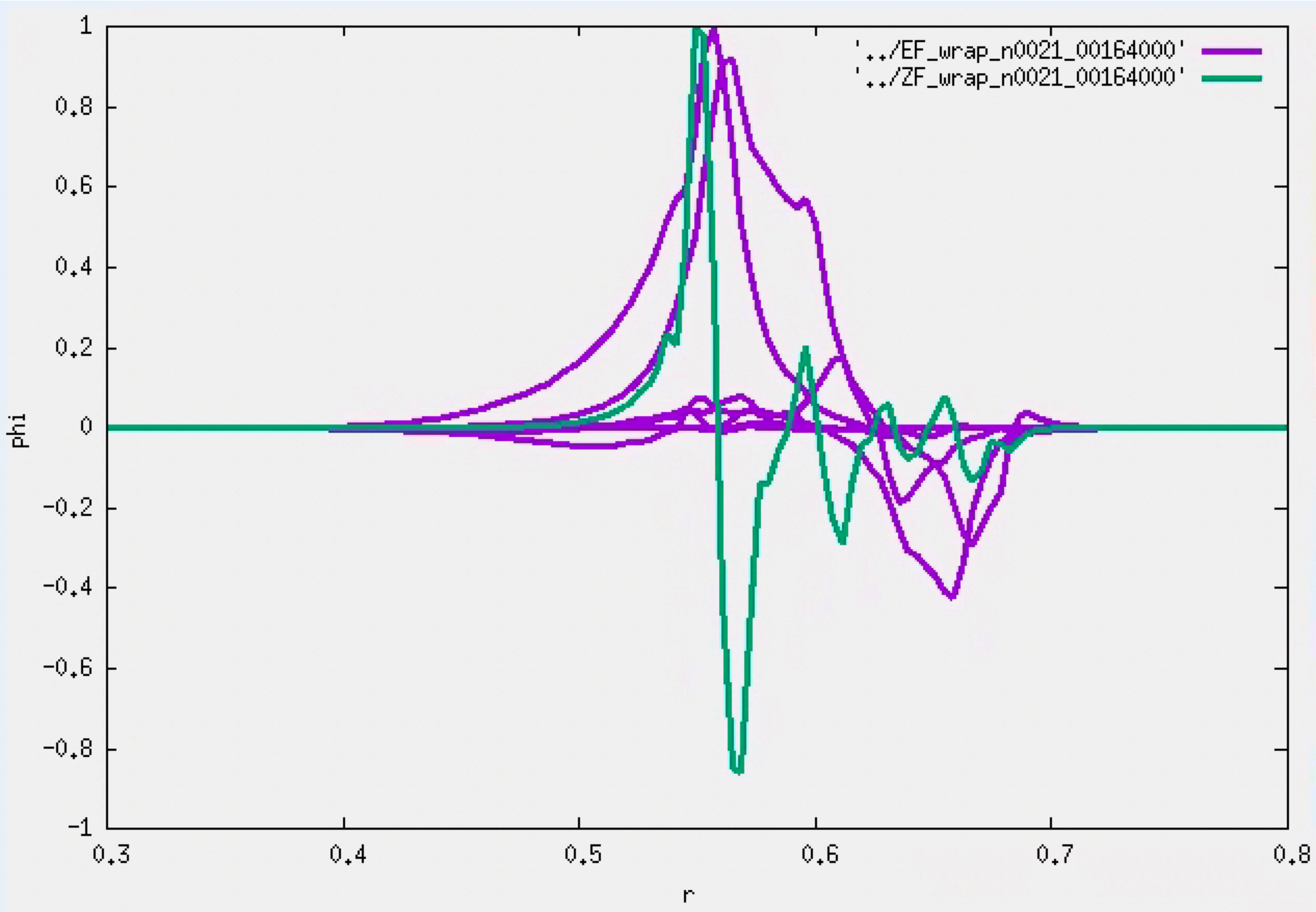
discussion:

- **comparison of ORB5 and ATEP PSZS starts to be satisfying - most differences understood in detail**
- **multi-mode cases create complex PSZS structures that are not additive - difficult to imagine a simpler model that would capture these effects…**
- **amplitude dependence of PSZS with fixed amplitude ratios found**
- **simple resonances are well represented by ATEP- resolution: 128-256 radial points are necessary**
- **higher order resonances are reliably found - confirmation of zonal and orbit averaging procedures**
- **IMAS framework is now robust for handling PSZS data (HDF5)**
- **runtime for (256x96x96): about 30mins with 64 processes - speed up easily possible; parallel collect of IDSs is demanding part**

started to implement analytical distribution functions - C. di Troia [NF 2021]

quantitative benchmark will be possible then

ZFZS model has been developed in EP-Stability workflow, orbit-finder and ATEP!



101006 TAE, n=21 and related ZFZS (model)

Z. Qiu [NF 2017]

$$\delta\psi_Z = -\frac{1}{B_0}\frac{k_{\theta,0}}{\omega_0}\frac{\partial}{\partial r}\left(|\hat{A}_0|^2\sum_m|\Phi_0|^2\right). \qquad (23)$$

to be improved, benchmarked with ORB5 and use force/beat-driven scalings (or spontaneously generated) for saturation [Juvert]

[Zonca, FEC 2023]

propagator $(\omega_G + i\partial_t - l\omega_b - \Delta_1 - \Delta_2)^{-1}$

$$\Delta_1 = -ie^{-il\vartheta_c}\overline{\left[e^{iQ_z}\left(\delta\dot{\theta}_z\partial_\theta + \delta\dot{\mathcal{E}}_z\partial_{\mathcal{E}}\right)\right]e^{il\vartheta_c}}$$

shearing

$$\Delta_2 = -\sum_{l'}\overline{e^{-il\vartheta_c}\left[e^{iQ_G}\left(\delta\dot{\theta}_G\partial_\theta + \delta\dot{\mathcal{E}}_G\partial_{\mathcal{E}}\right)^*\right]e^{il'\vartheta_c}}\frac{1}{(\omega_{GII} - l'\omega_b)} \times \overline{e^{-il'\vartheta_c}\left[e^{iQ_G}\left(\delta\dot{\theta}_G\partial_\theta + \delta\dot{\mathcal{E}}_G\partial_{\mathcal{E}}\right)\right]e^{il\vartheta_c}}.$$

resonance broadening
& frequency shift

for calculating PSZS response including ZFZS:
using implementation of neoclassical radial E-field in HAGIS by A. Bergman [PoP 2001]
next slides: ad-hoc scaling of Φ_z (note 1kV peak value for Φ_z gives for this ITER case peak E_r ˜ 25kV/m)

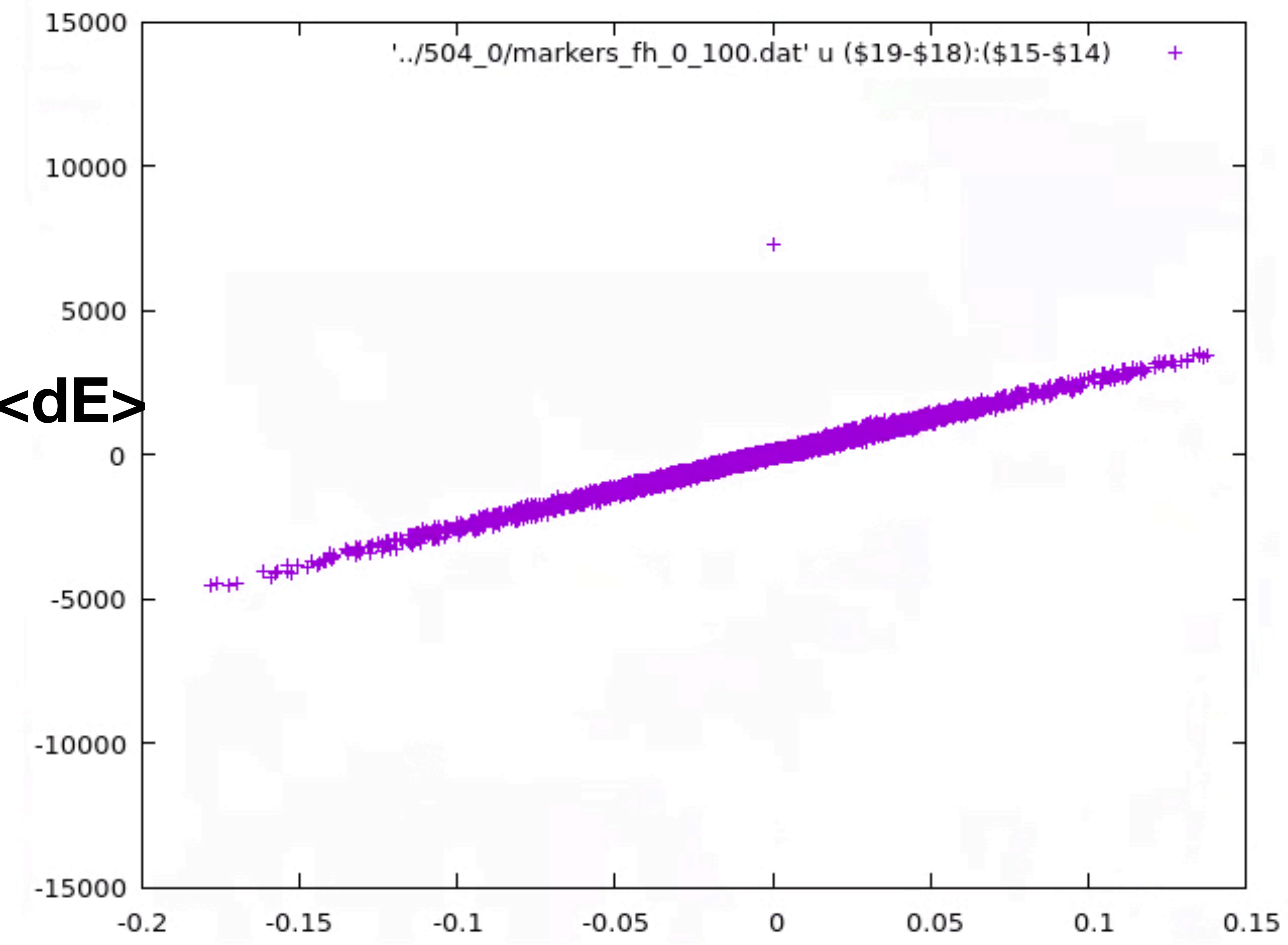
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

orbit-finder+HAGIS: snapshot of all markers in CoM space

single wave conservation: n dE - ω dP$_\Phi$ =0

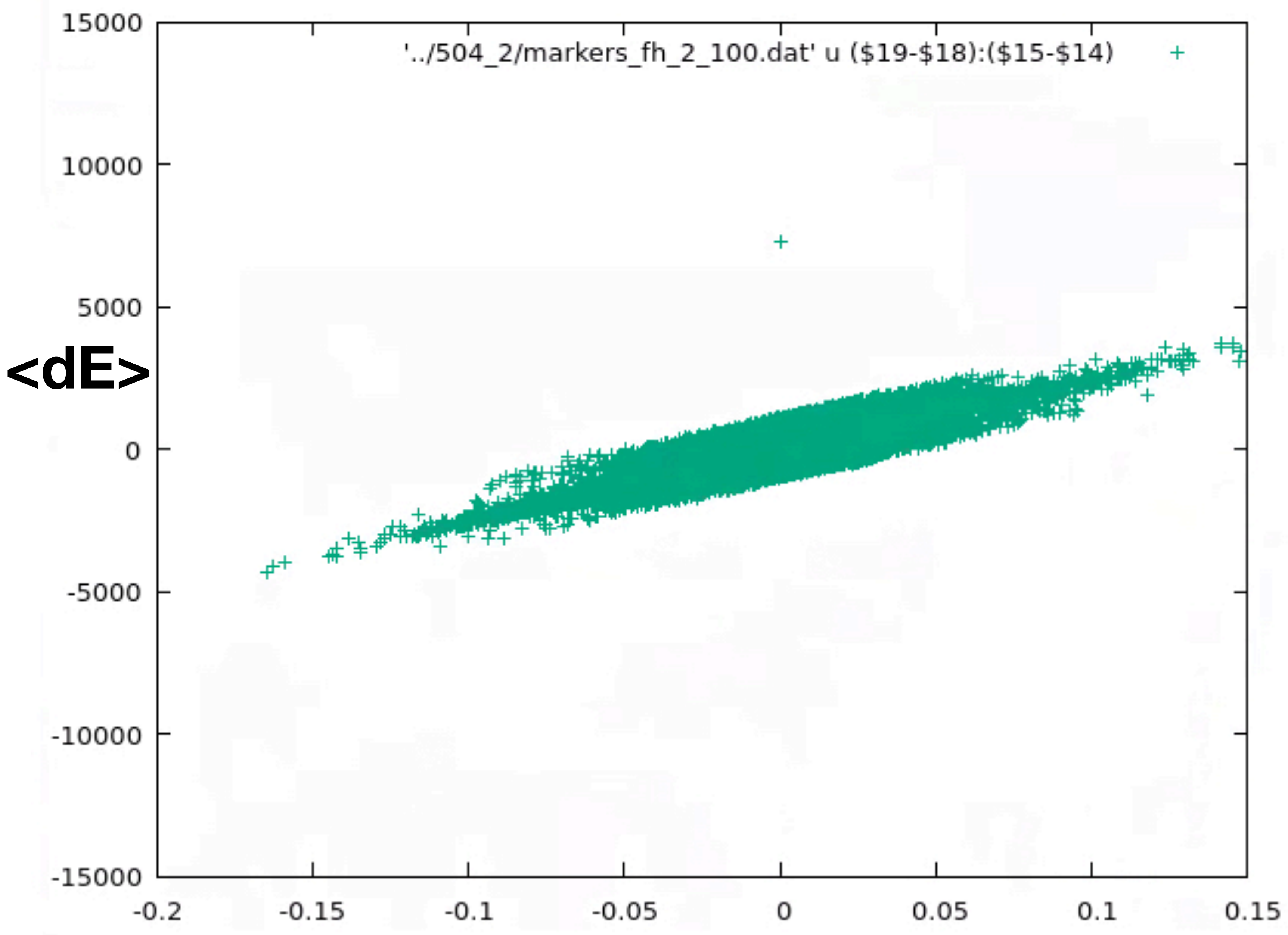
broken in presence of E-field - transport matrix is not strictly diagonal

Φ=0V



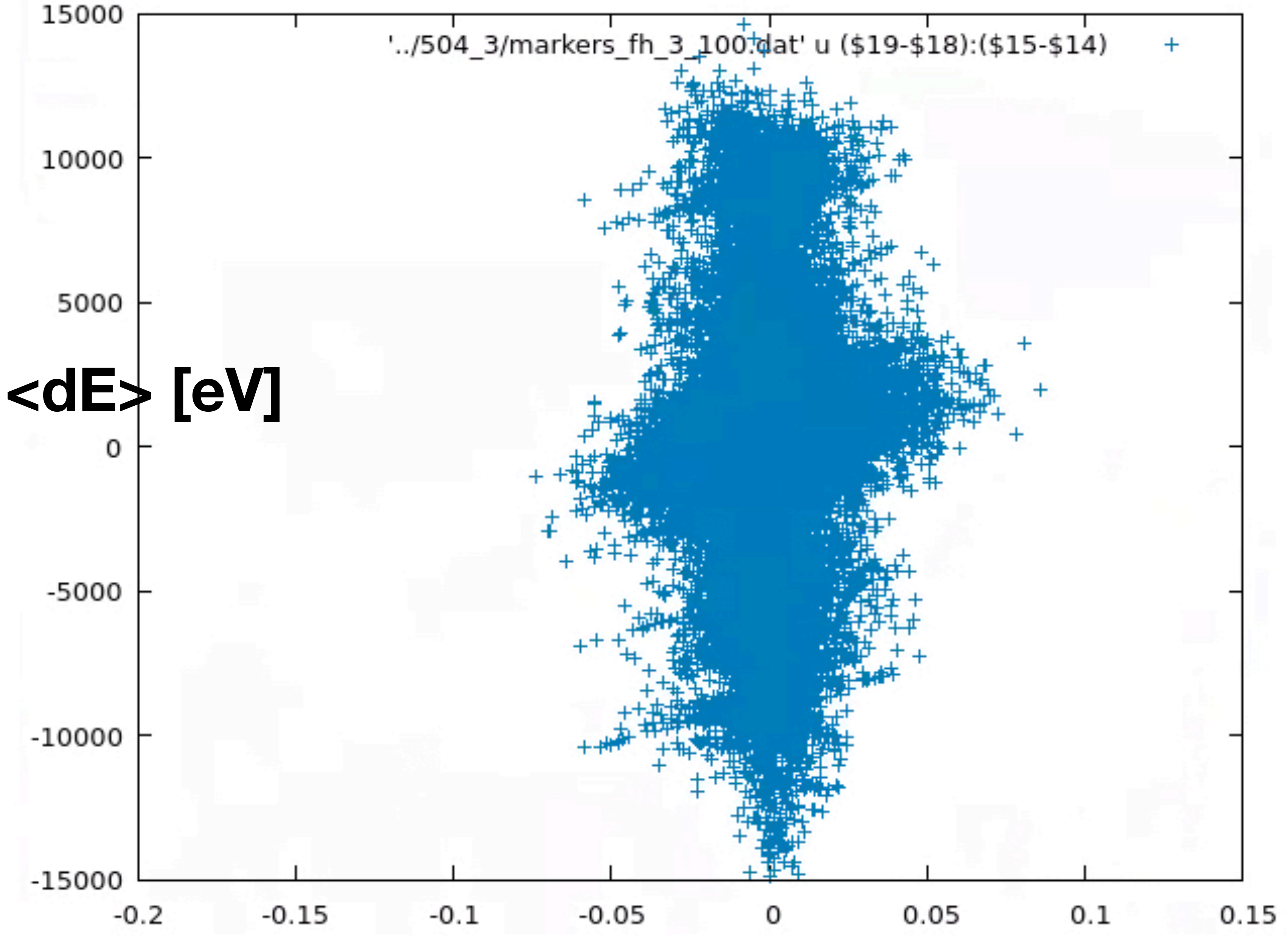
<dP$_\Phi$>

Φ=1kV



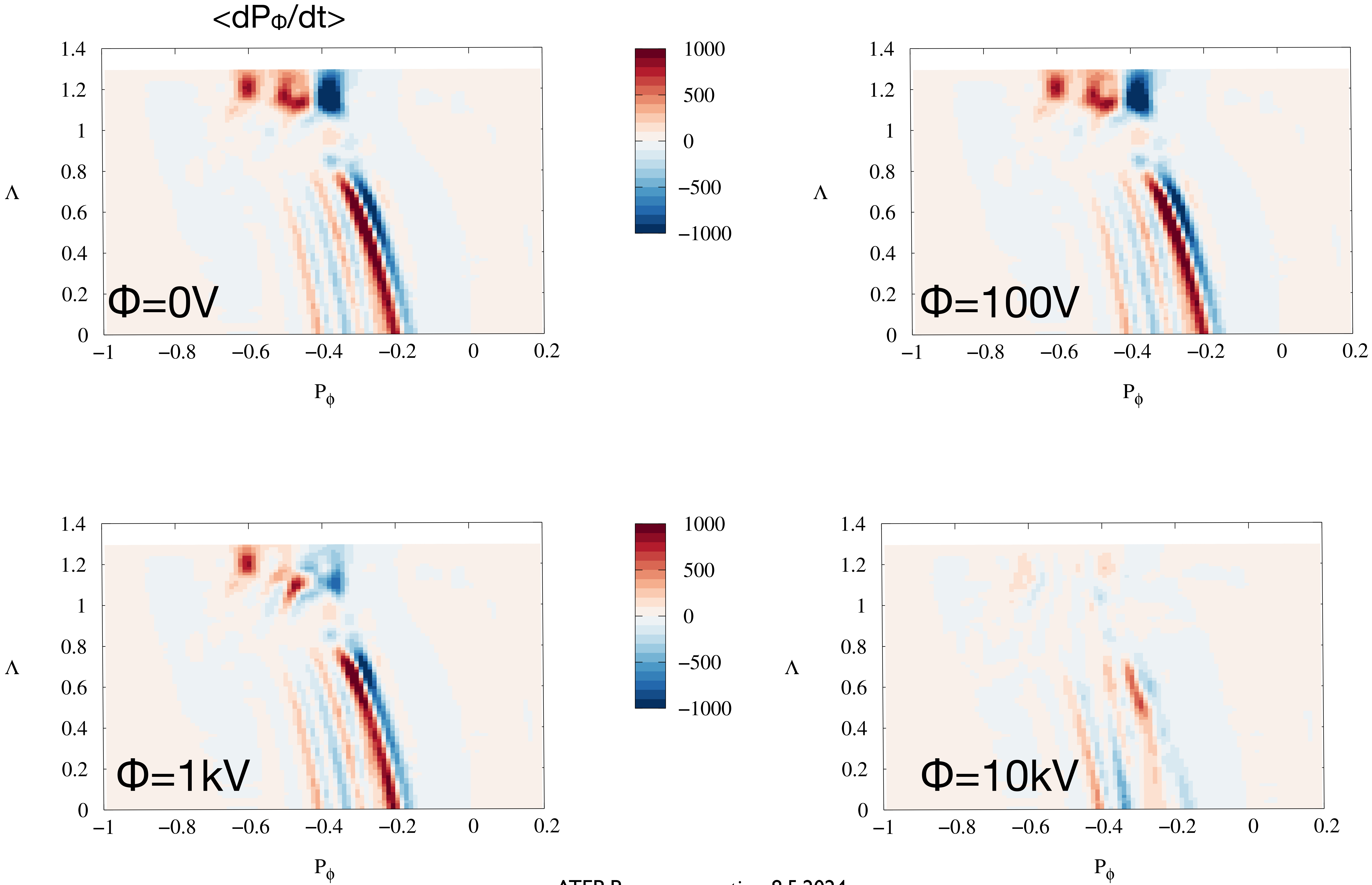
<dP$_\Phi$>

Φ=10kV

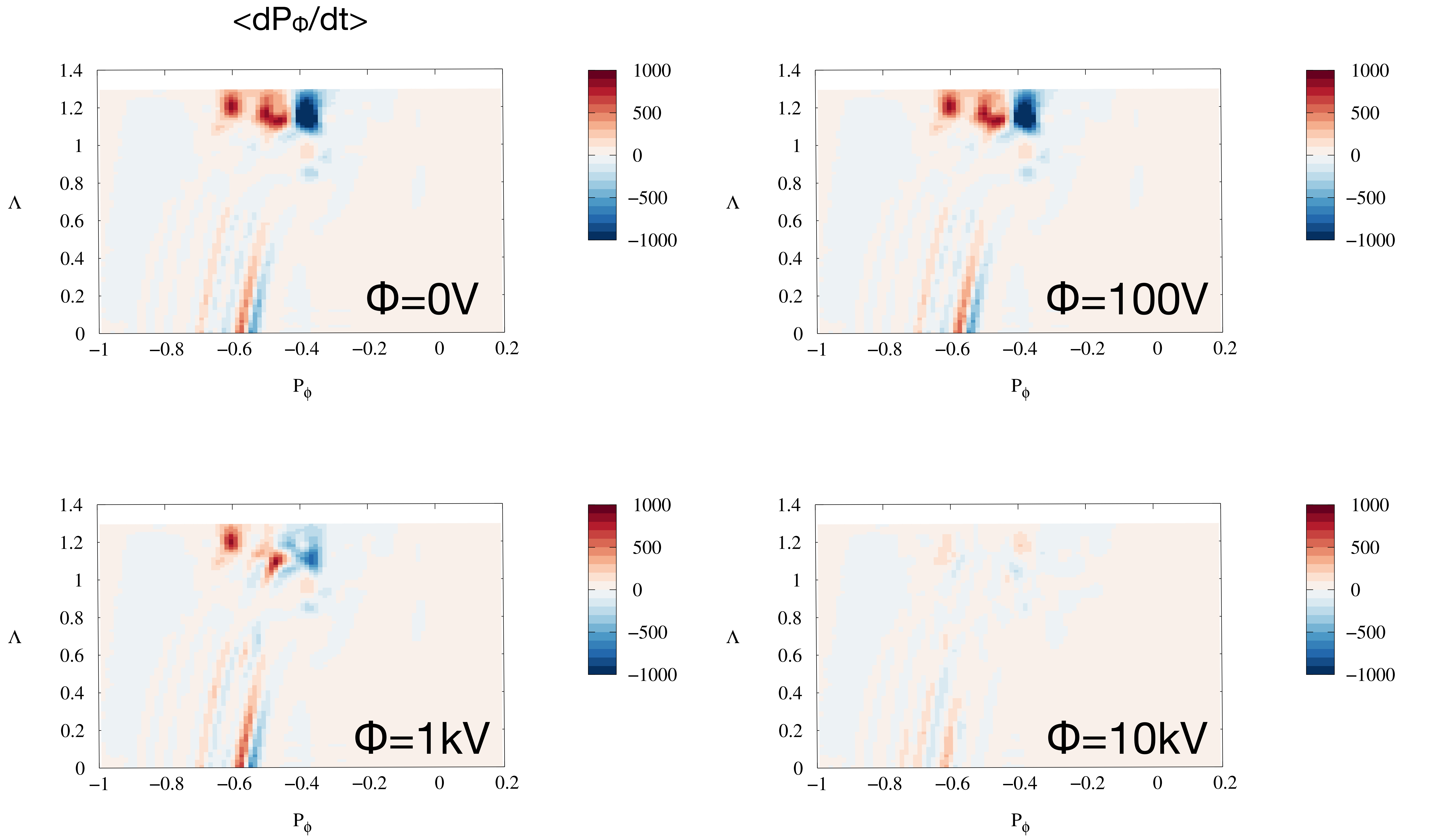


<dP$_\Phi$>

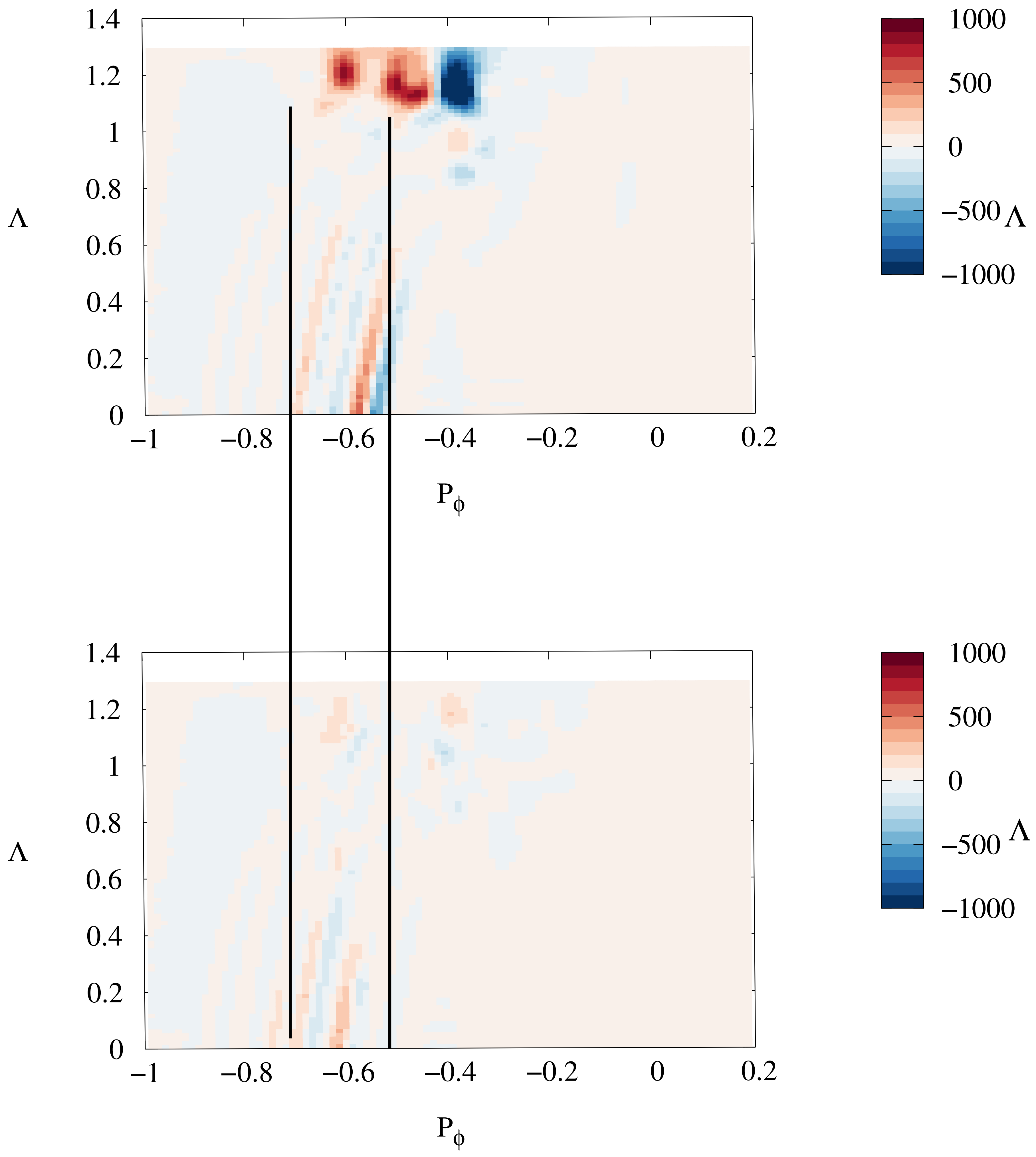
750keV co-passing+trapped ions (dB/B_{TAE}=1.0e-3)



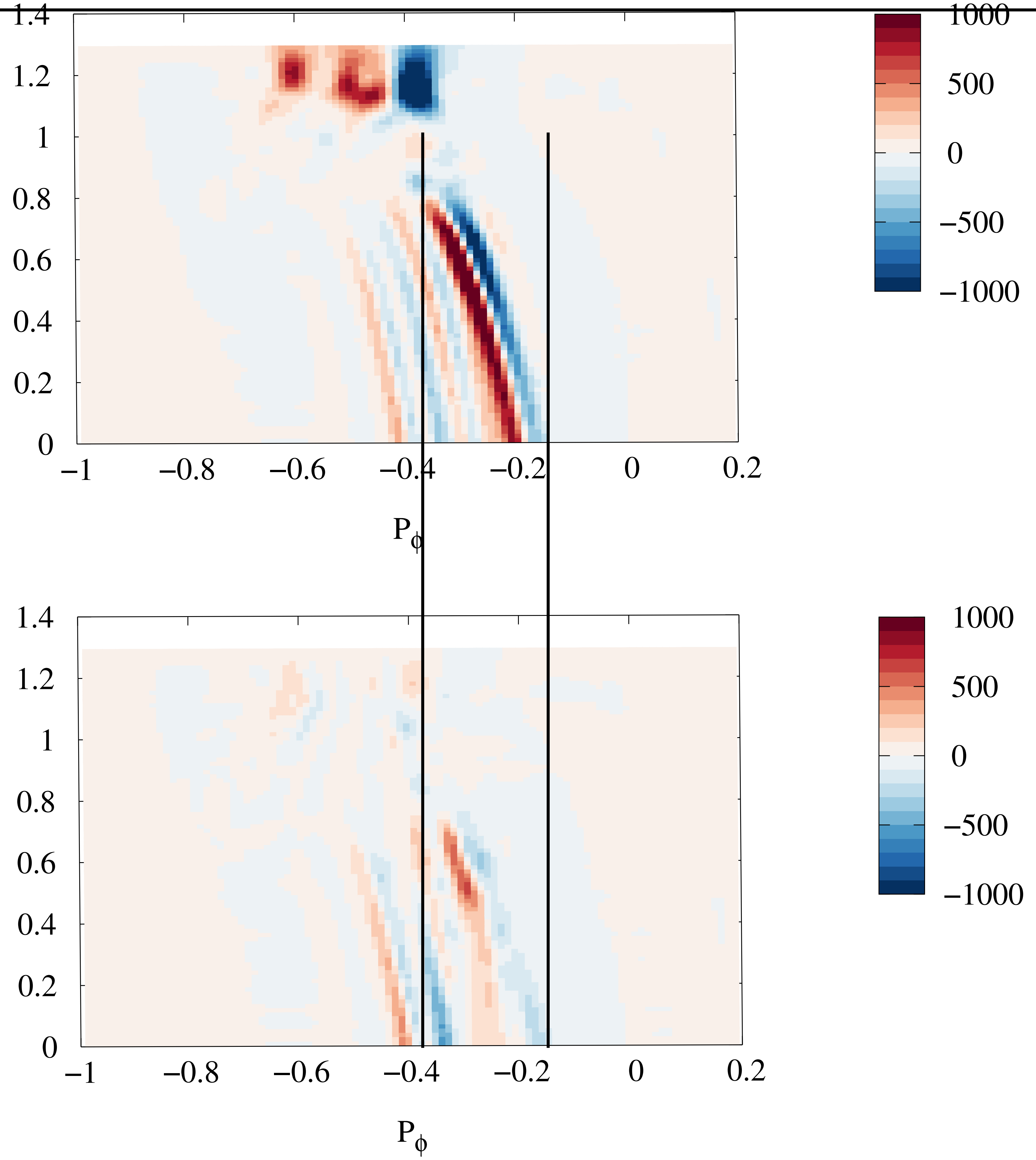
750keV counter-passing+trapped ions



0 vs 10kV: counter passing



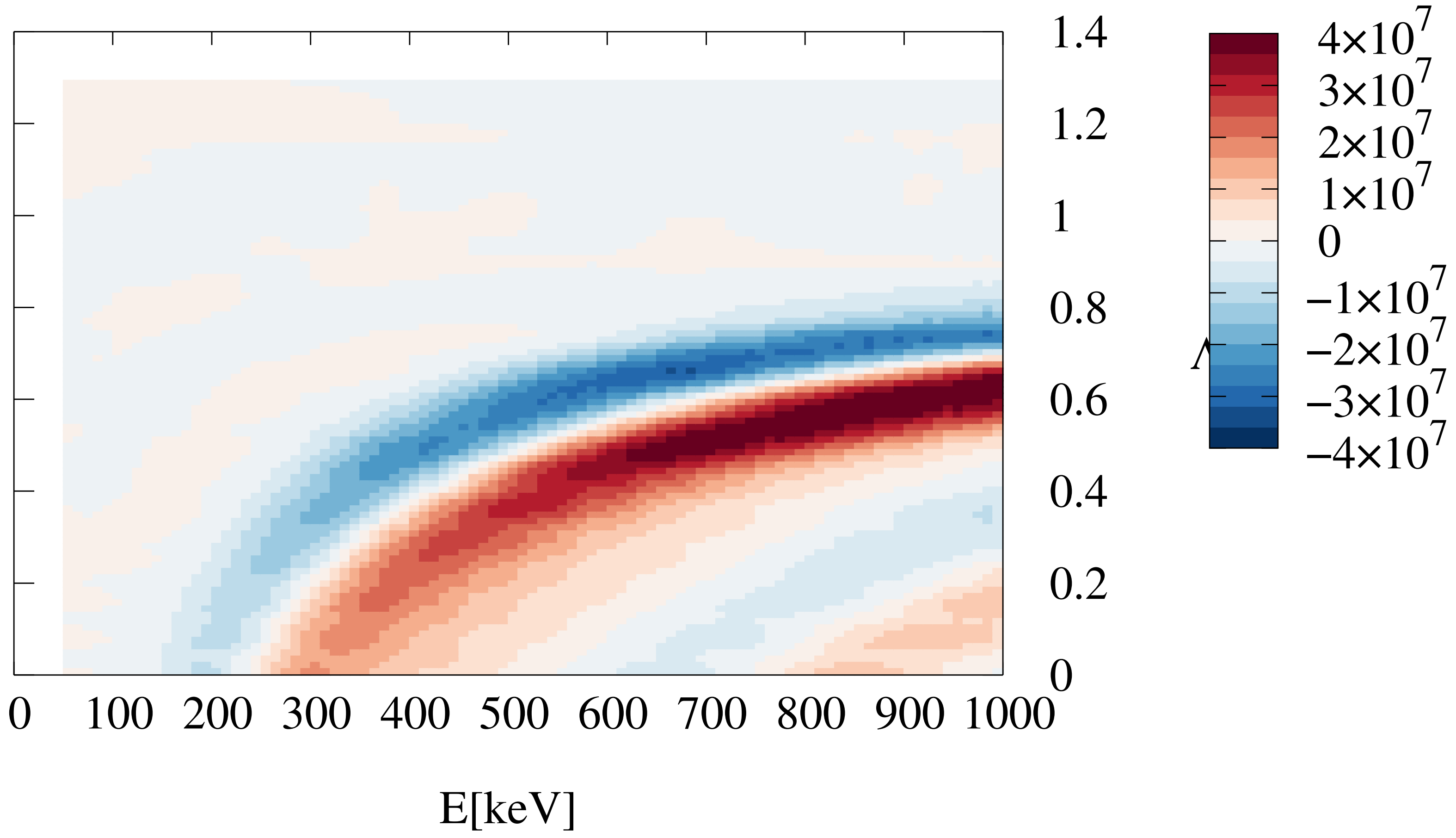
0 vs 10kV co-passing



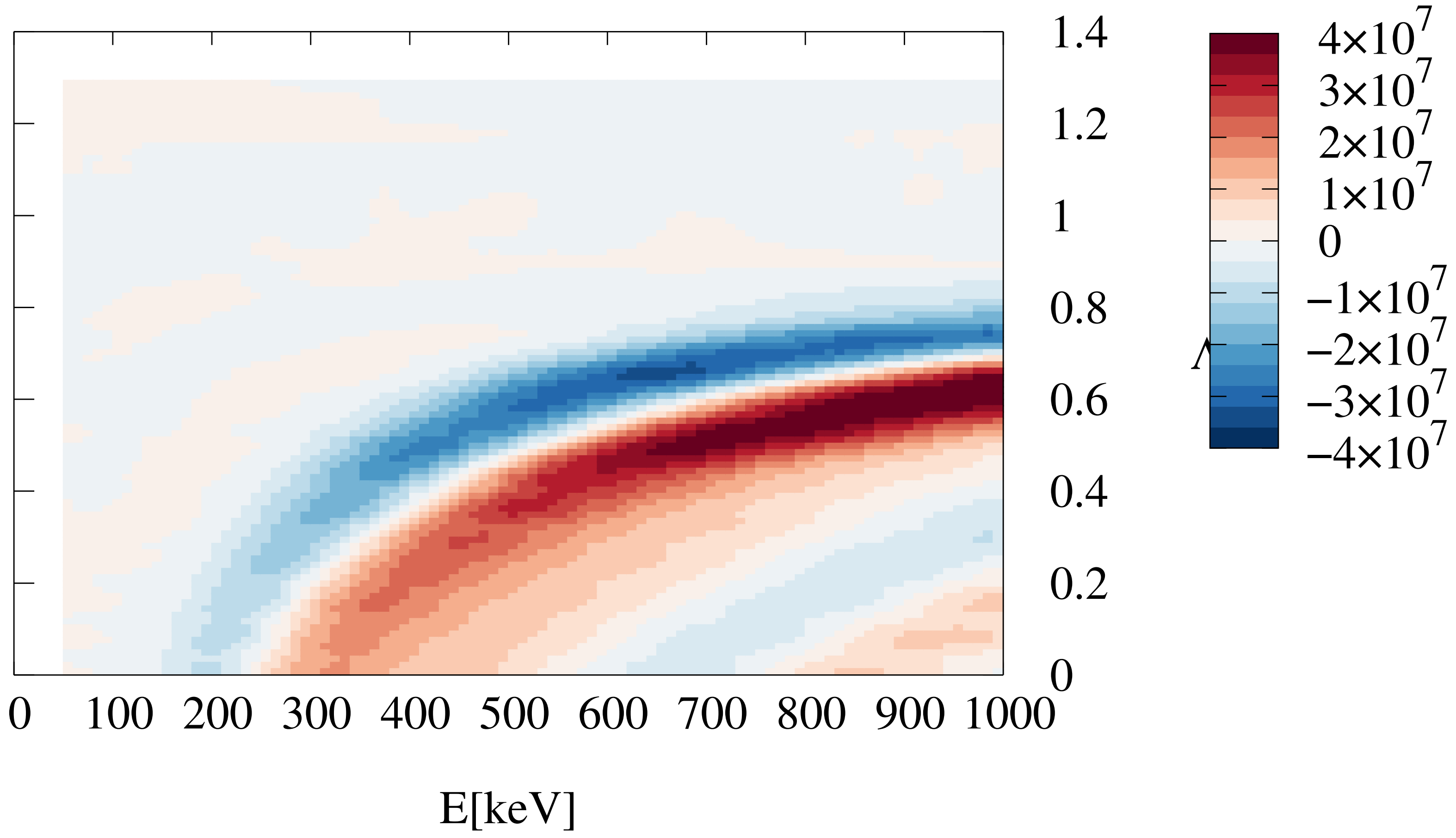
shift and broadening of resonances observed

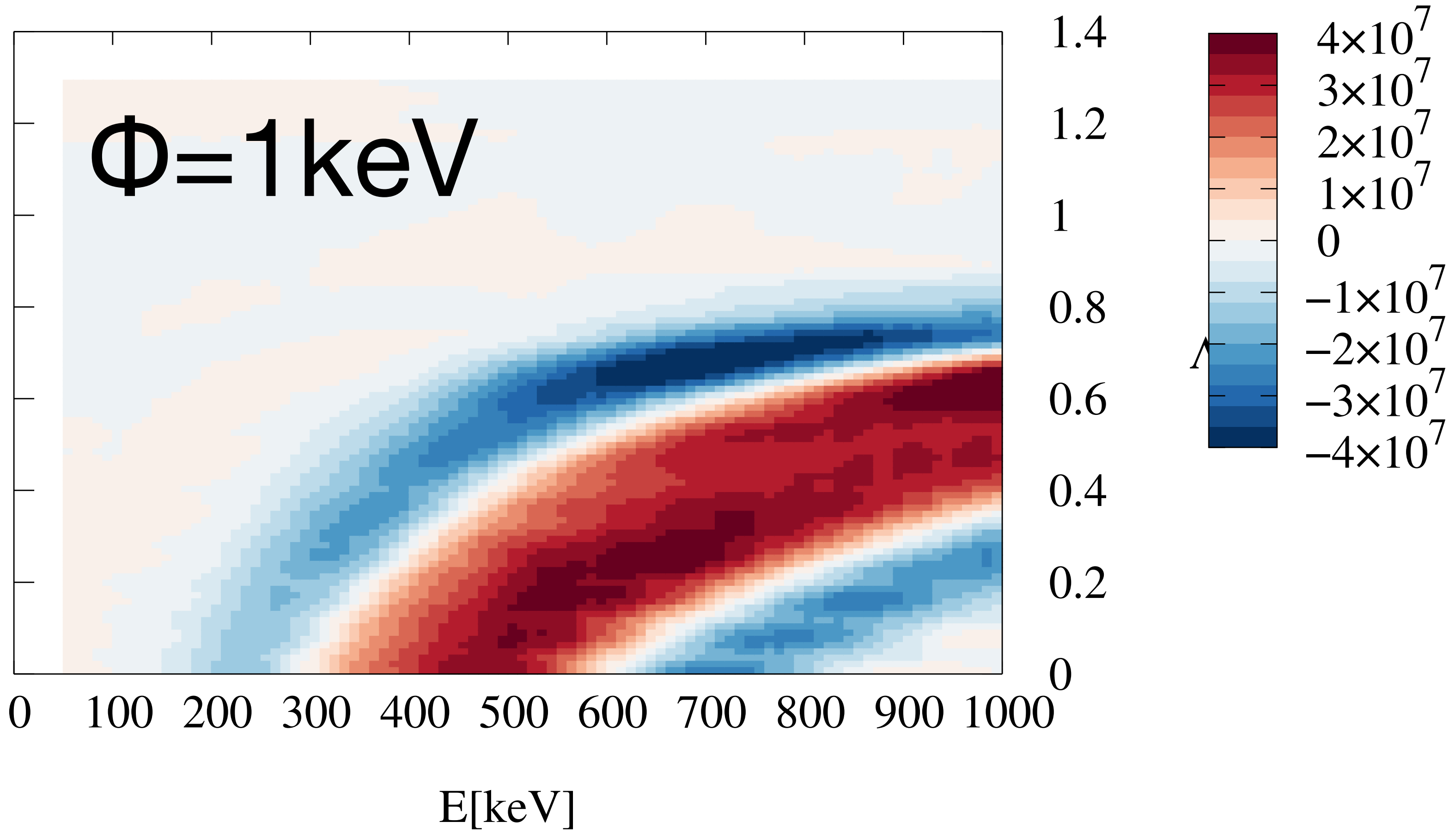
co-passing+trapped ions, Pz=-0.29

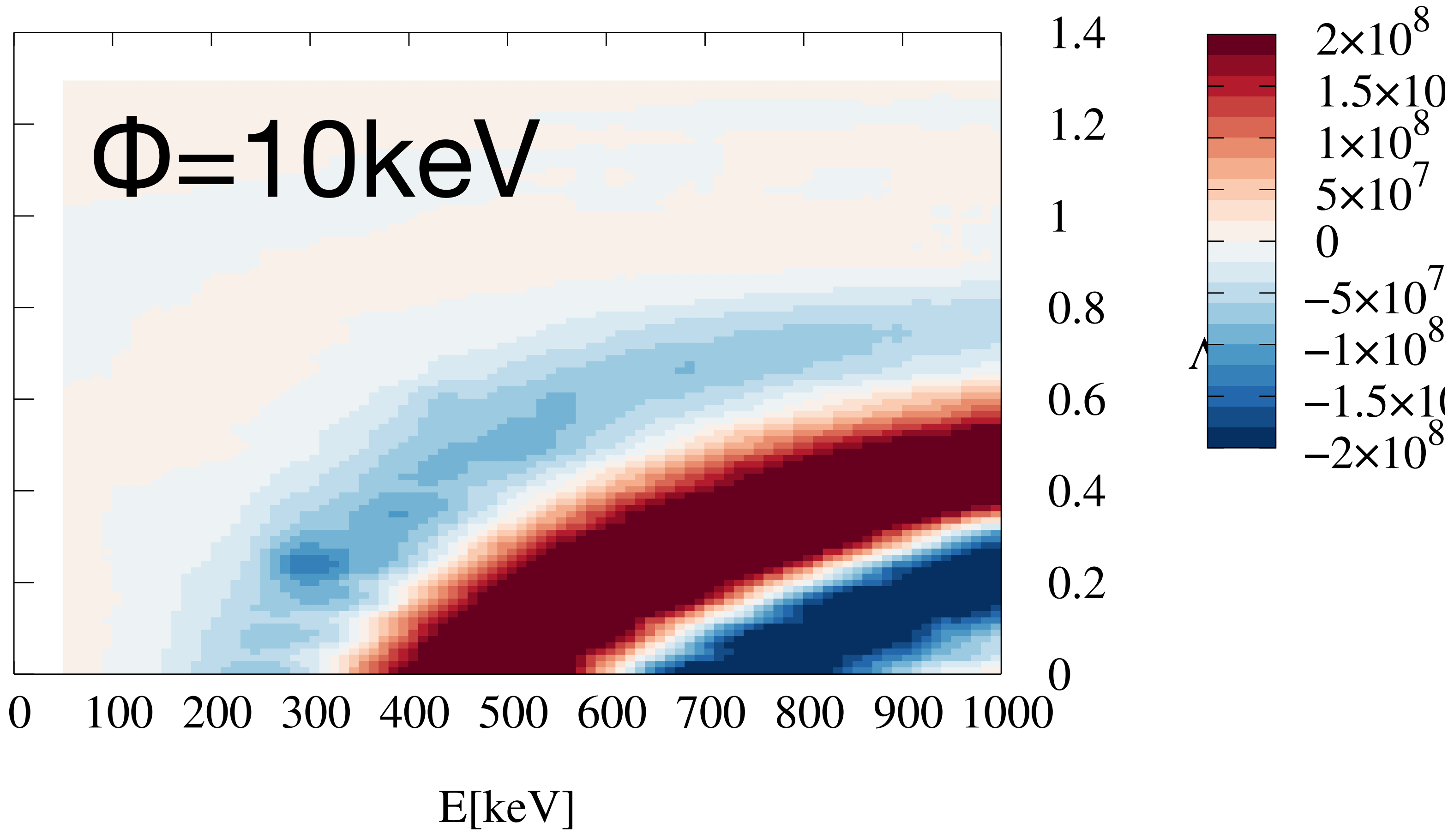
Φ=0V <dE/dt>



Φ=100V







discussion/outlook

- PSZS formulation gives detail insight into non-linear saturation physics - and can be used to set up a practical reduced model
- ready to add ZF evolution to QL model - extend energy balance equation
- quantitative studies needed for qualification of reduced model: radial mode structures and saturation amplitude ORB5 scans [Juvert, yesterday]
- including higher non-linear harmonics (2*n) has been technically prepared
- investigate other ZF generation processes (spontaneous excitation)
- investigate compatibility with existing transport models: modification of TGLF quenching rule?