Impact of realistic energetic particle distributions on BAE dynamics, and validation on DIII-D experiment

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Outline

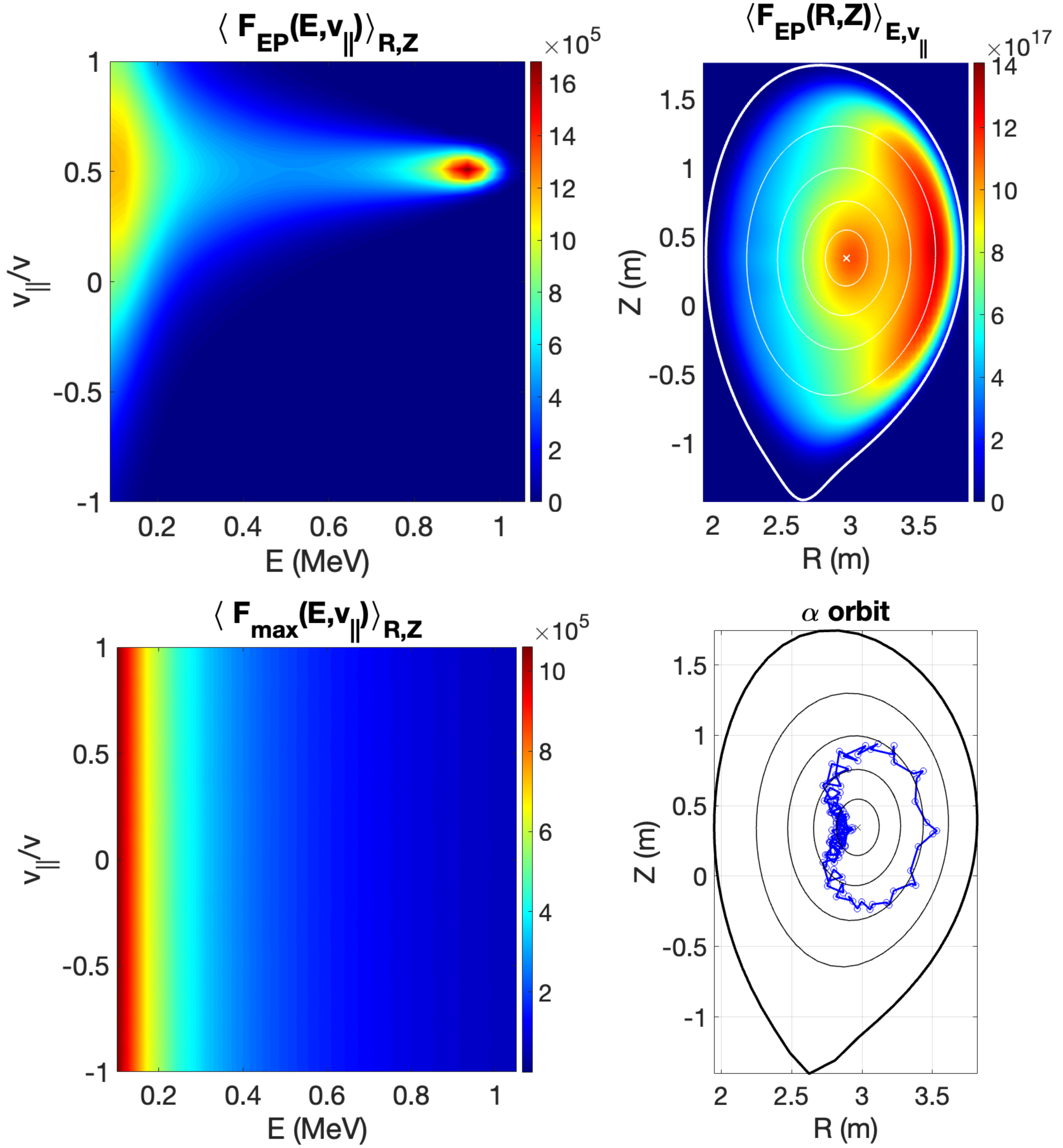
I) **Importance** of **realistic constants of motion (CoM)** space EP distribution representation for **stability** and **transport modelling**

II) **EPCoM : Numerical method** to transform **EP distributions** towards **CoM space,** and between arbitrary **representations**

III) **ITPA-EP joint activity** on realistic gyrokinetic/kinetic-MHD modelling of **BAE stability in DIII-D plasmas**

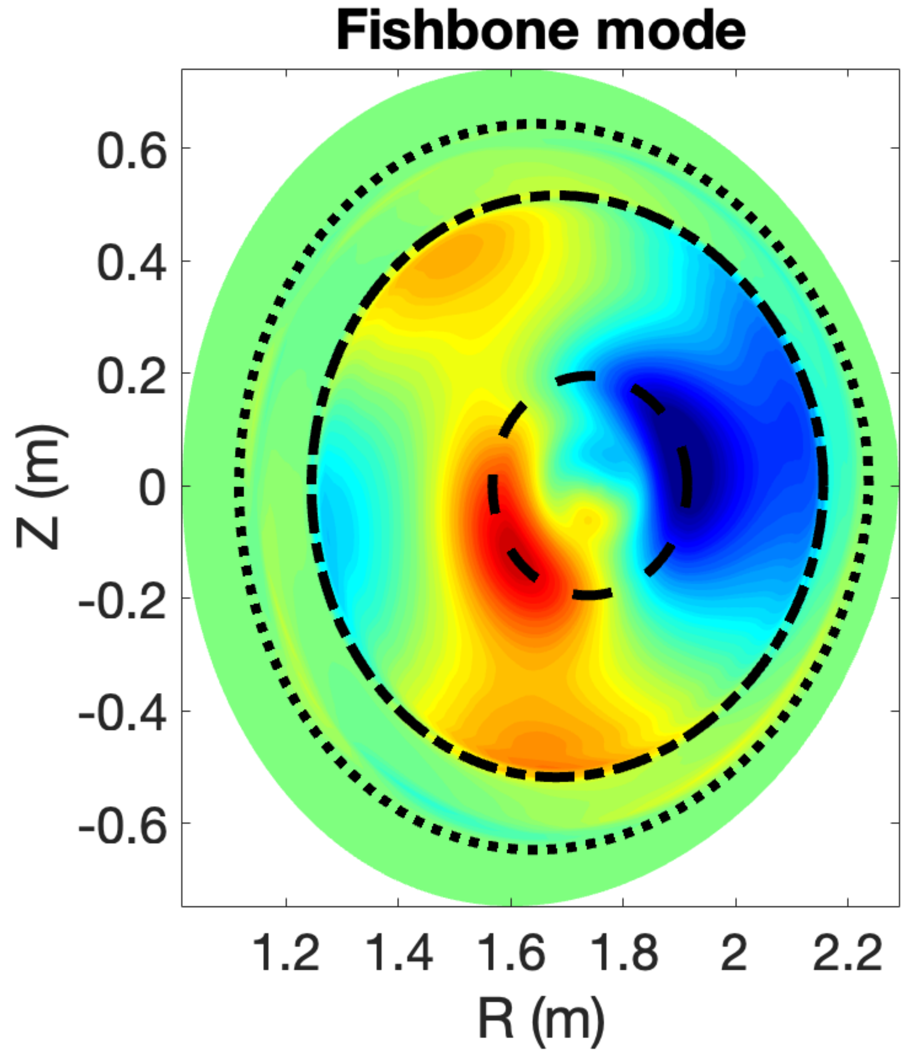
Realistic distributions differ from Maxwellians

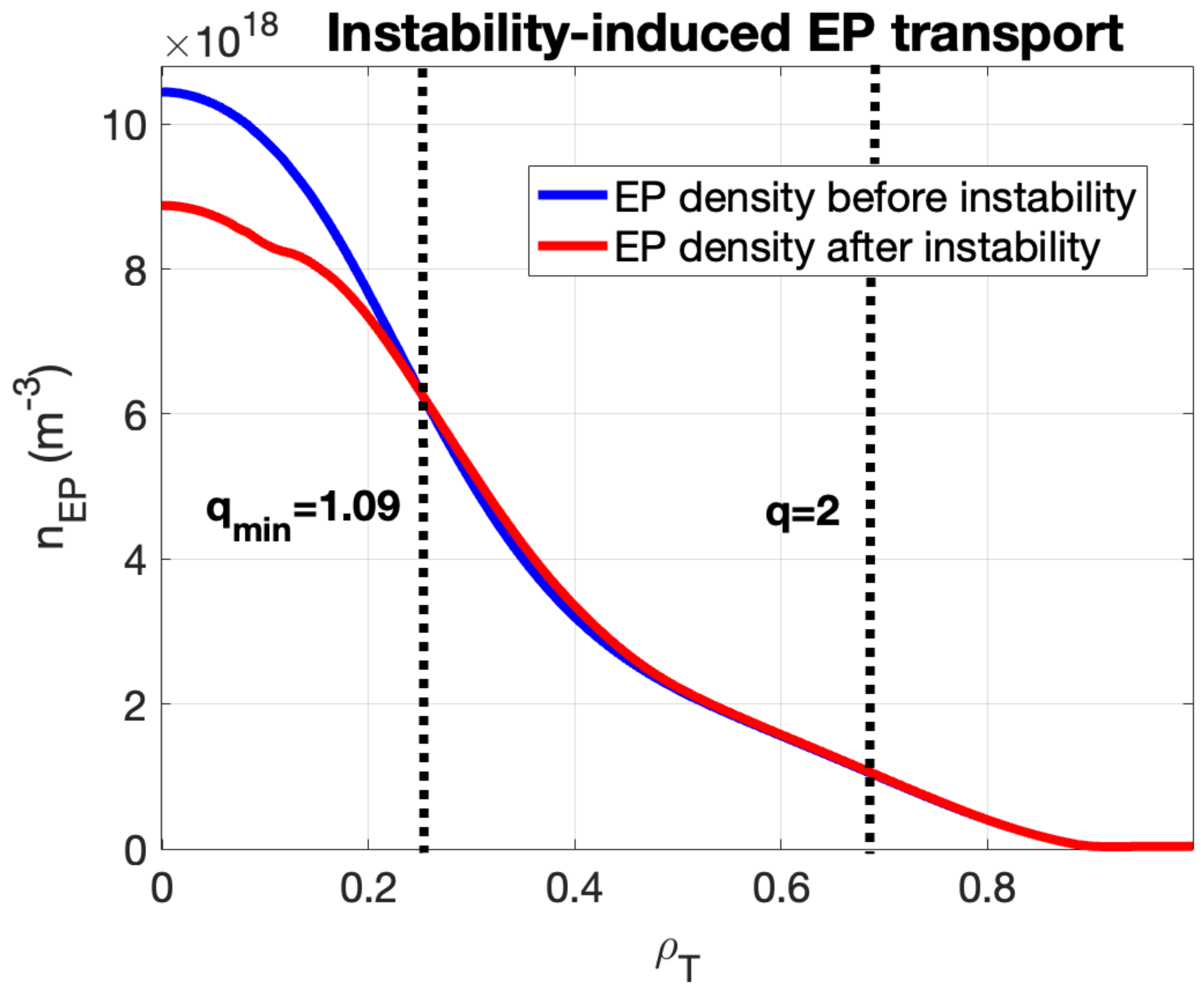
- ➢ **Energetic particles** are generated in fusion plasmas by **fusion** reactions (α) and **non-inductive heating** (NBI, ICRH)
- ➢ EPs **out of thermodynamical equilibrium,** F_{EP} **cannot** be described **analytically** as **Maxwellian** in **2D space** $F_{max}(E, r)$
- ➢ A **kinetic 6D numerical description** is required, **reduced to 4D** $(E, v_{||}, R, Z)$ under **axisymmetry** and **gyro-averaging**
- ➢ EP distributions **differ vastly** in nature **from Maxwellians** in both **velocity** and **position spaces**
- ➢ However, in most **gyrokinetic/kinetic-MHD modelling**, EP distributions are considered **Maxwellians**



EP instabilities impact confinement

Negative effect : Transport of EPs



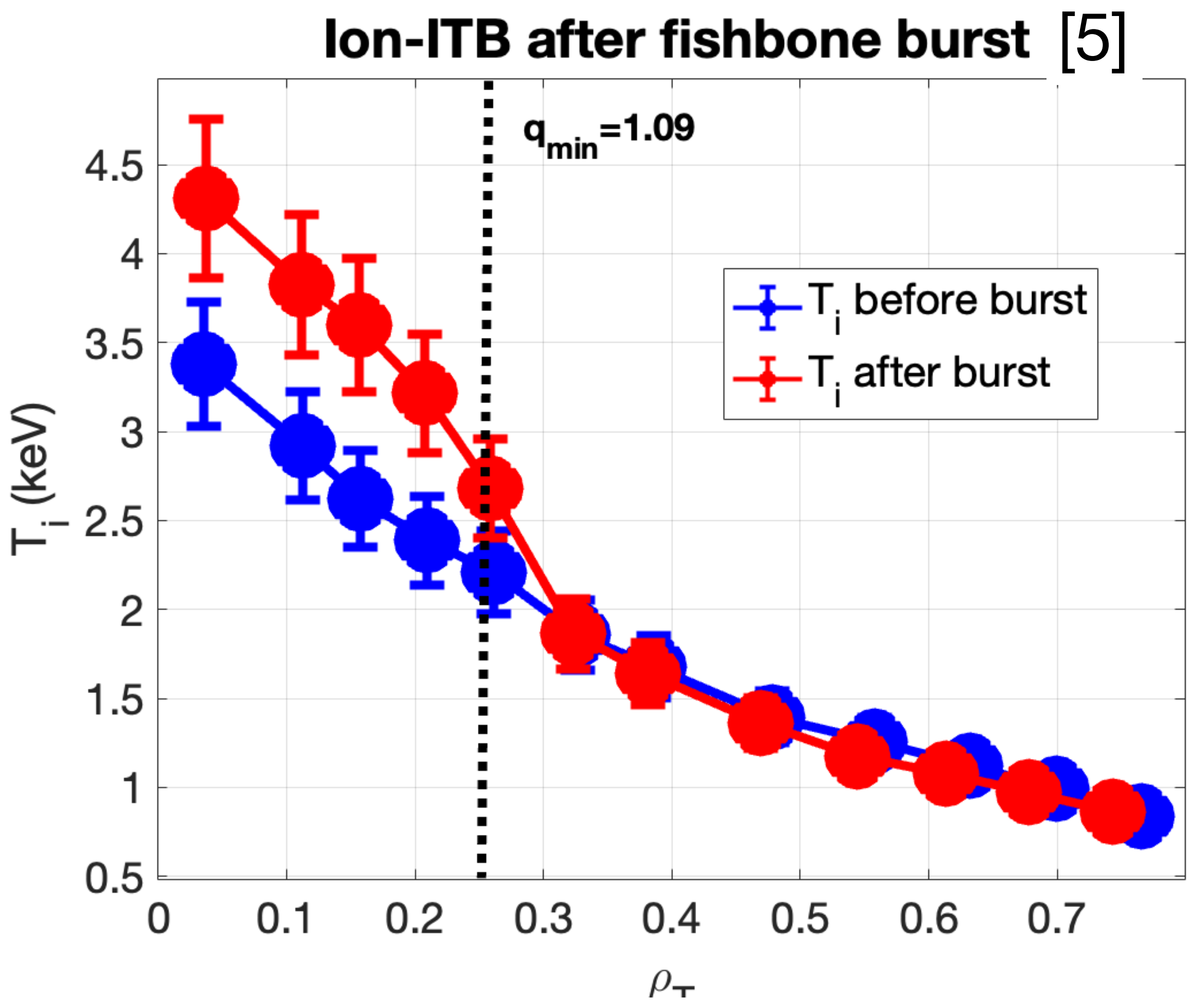


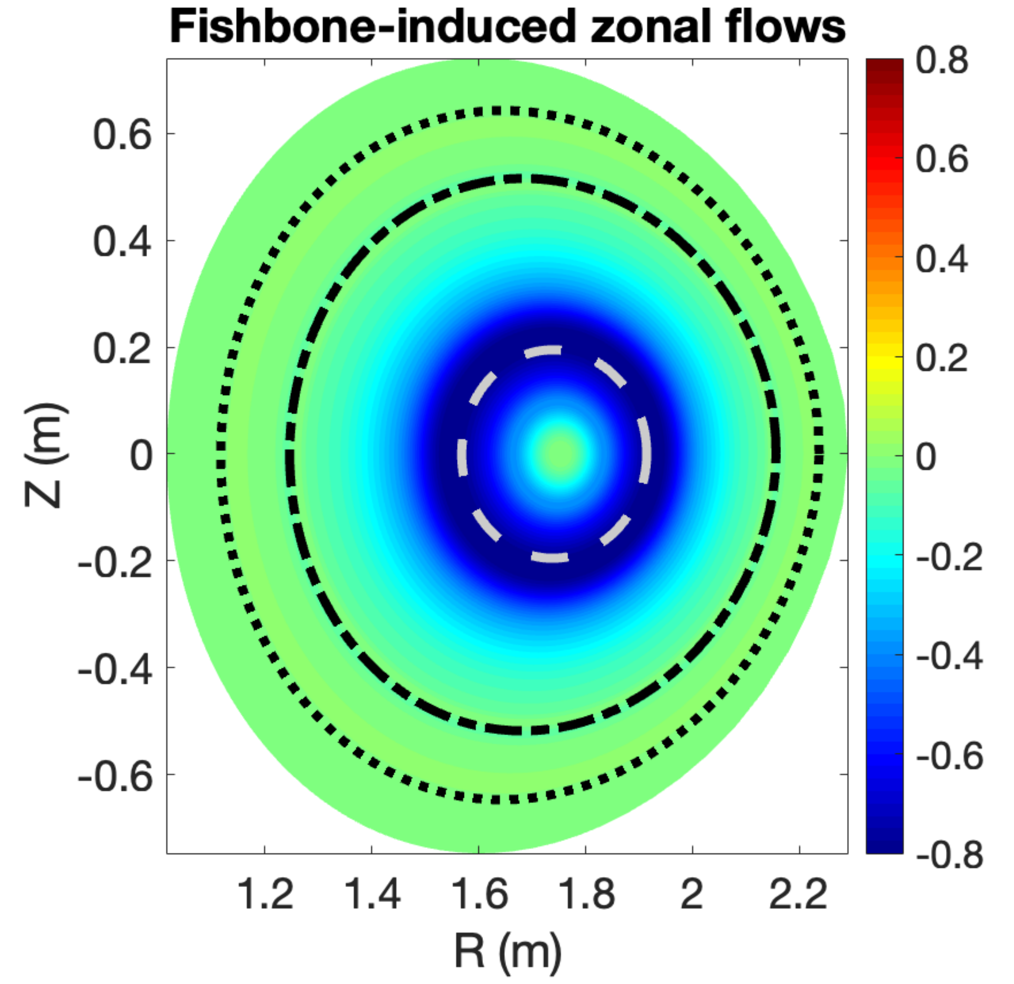
➢**EPs** can be **transported outward** by **EPMs-AEs** under **resonant** energy exchange [1,2,3]

➢**Ubiquitous phenomenon** reducing **confinement** whenever **EP-driven modes** are **unstable**

[1] K. McGuire et al. 1983, *Phys. Rev. Lett.*
[2] L. Chen et al. 1984, *Phys. Rev. Lett.*
[3] K. L. Wong et al. 1991, Phys. Rev. Lett.
[4] G. Brochard et al. 2024, *Phys. Rev. Lett.*
[5] S. Mazzi et al. 2022, *Nat. Phys.*
[6] J. Garcia et al. 2024, *Nat. Comm.*
[7] X. D. Du et al. 2025, *Phys. Rev. Lett.*
[8] A. Ishizawa et al. 2025, *Nat. Comm.*

Positive impact : turbulence mitigation



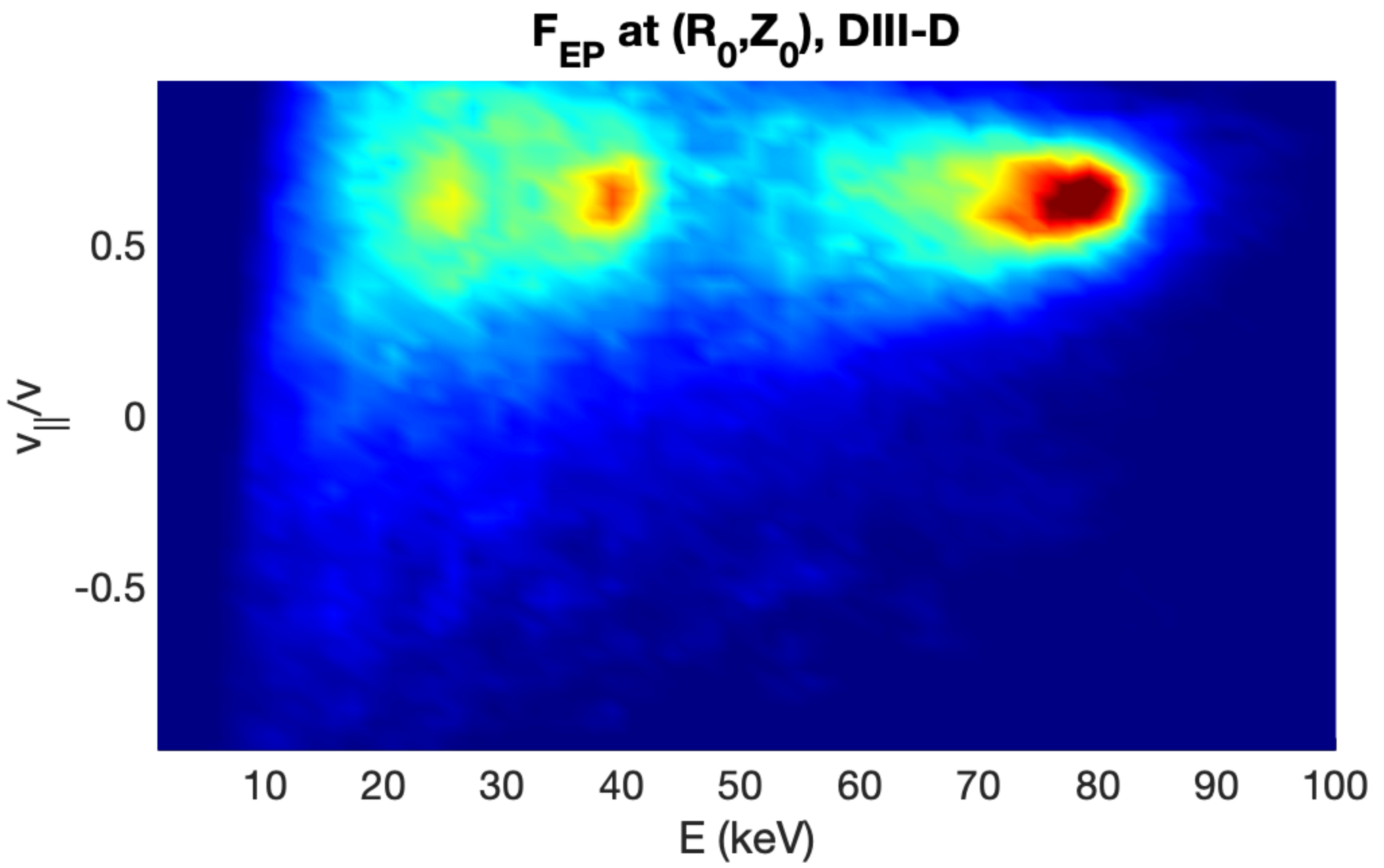


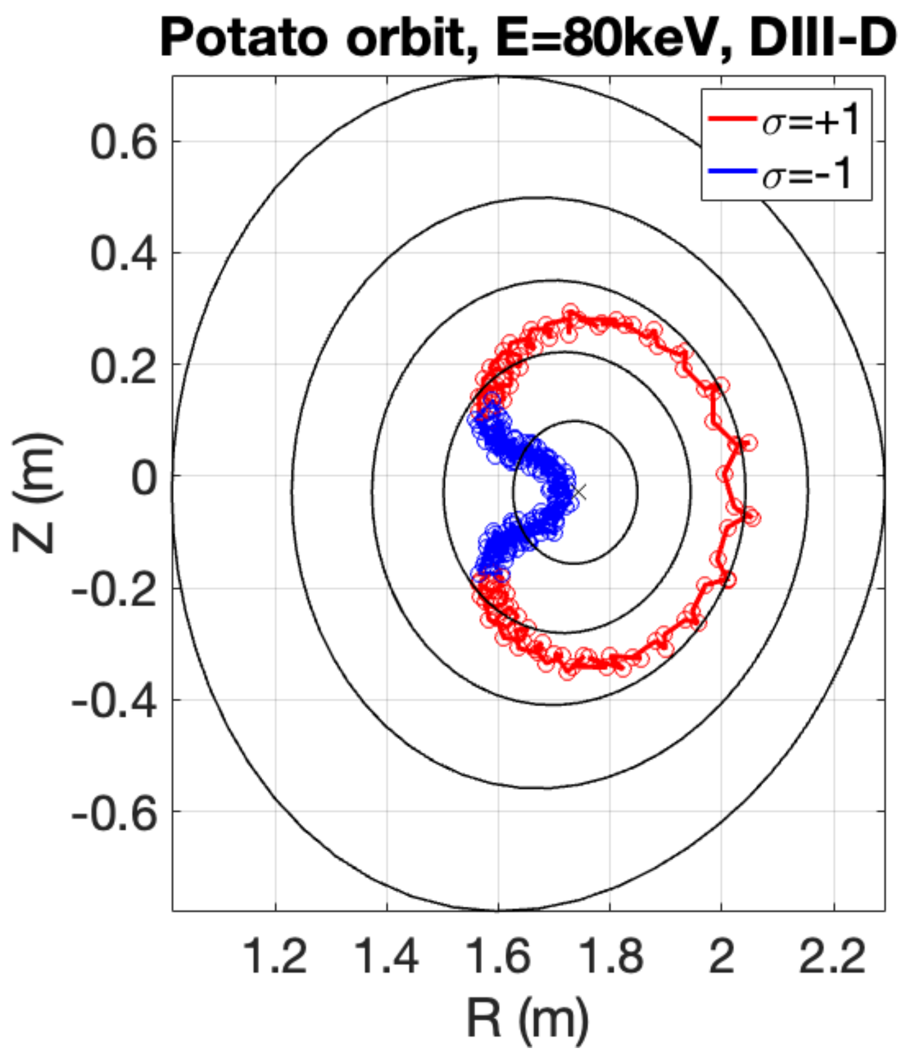
➢**EPMs** [4] **and AEs** [5,6,7,8] observed to **enhance confinement** in some **experimental configurations**

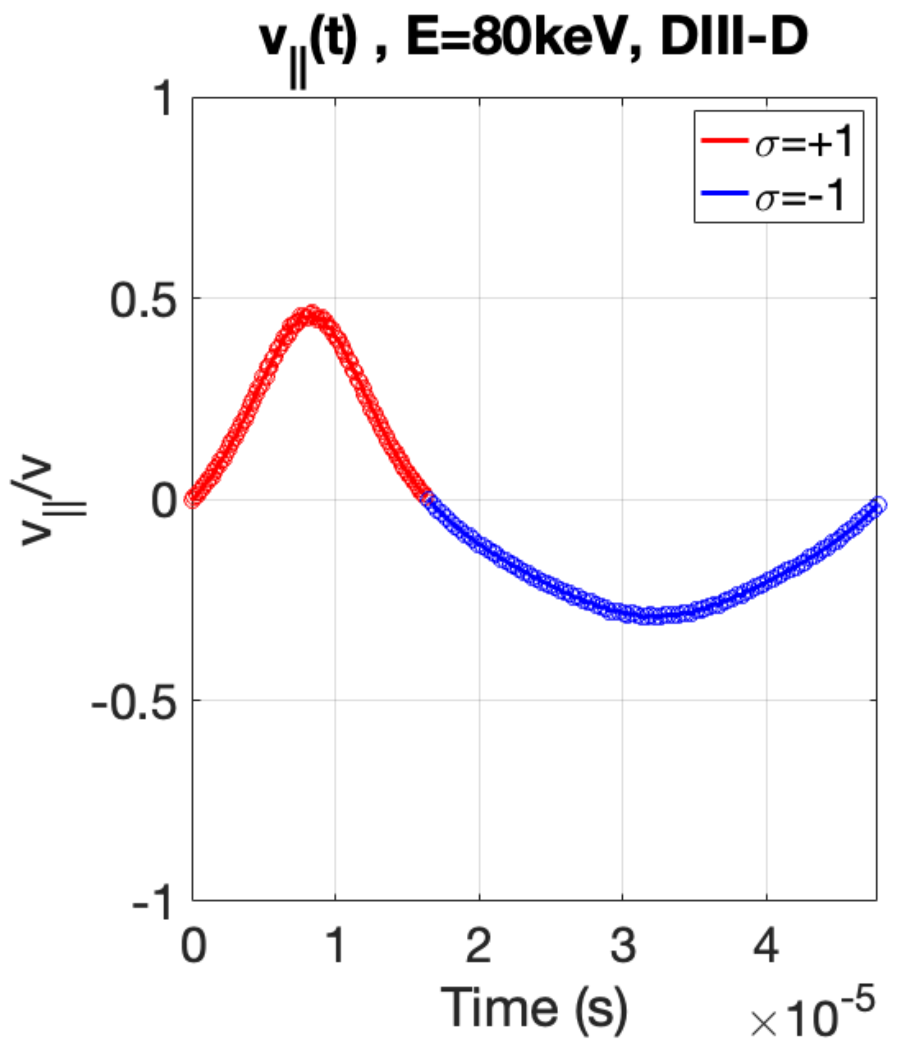
➢**Main mechanism** involved **: zonal flows generation** by the EP-driven modes [4-8]

➢Beneficial operational **domain narrow : EP drive** [8] is a **key component** of the **cross-scale interplay**

Position-velocity space inadequate for modelling







- ➢**Gyrokinetic modelling** can help **identify beneficial domain**, provided **EP distributions** are described **realistically**

- ➢**Realistic EP distributions** can be obtained, **solving numerically** [1,2] the **Fokker-Planck equation** $\frac{dF}{dt} = C(F) + S$

Not ideal for gyrokinetic modelling

- ➢**Fokker-Planck** outputs in **position-velocity** space $(E, v_{||}, R, Z)$ generally **too noisy**

- ➢EP pdf in **unmixed position-velocity spaces** are **not steady-state by design**, leading to **problematic EP drive relaxation [3,4]**

- ➢**Wave-particle resonances** driving EP-instabilities cannot be identified in $(E, v_{||}, R, Z)$ **space**

[1] A. Pankin et al. 2004, *Comp. Phys. Comm.*
[2] E. Hirvijoki et al. 2014, *Comp. Phys. Comm.*
[3] A. Könies et al. 2018, *Nucl. Fusion*
[4] G. Vlad al. 2025, *Rev. Mod. Plasma Phys*

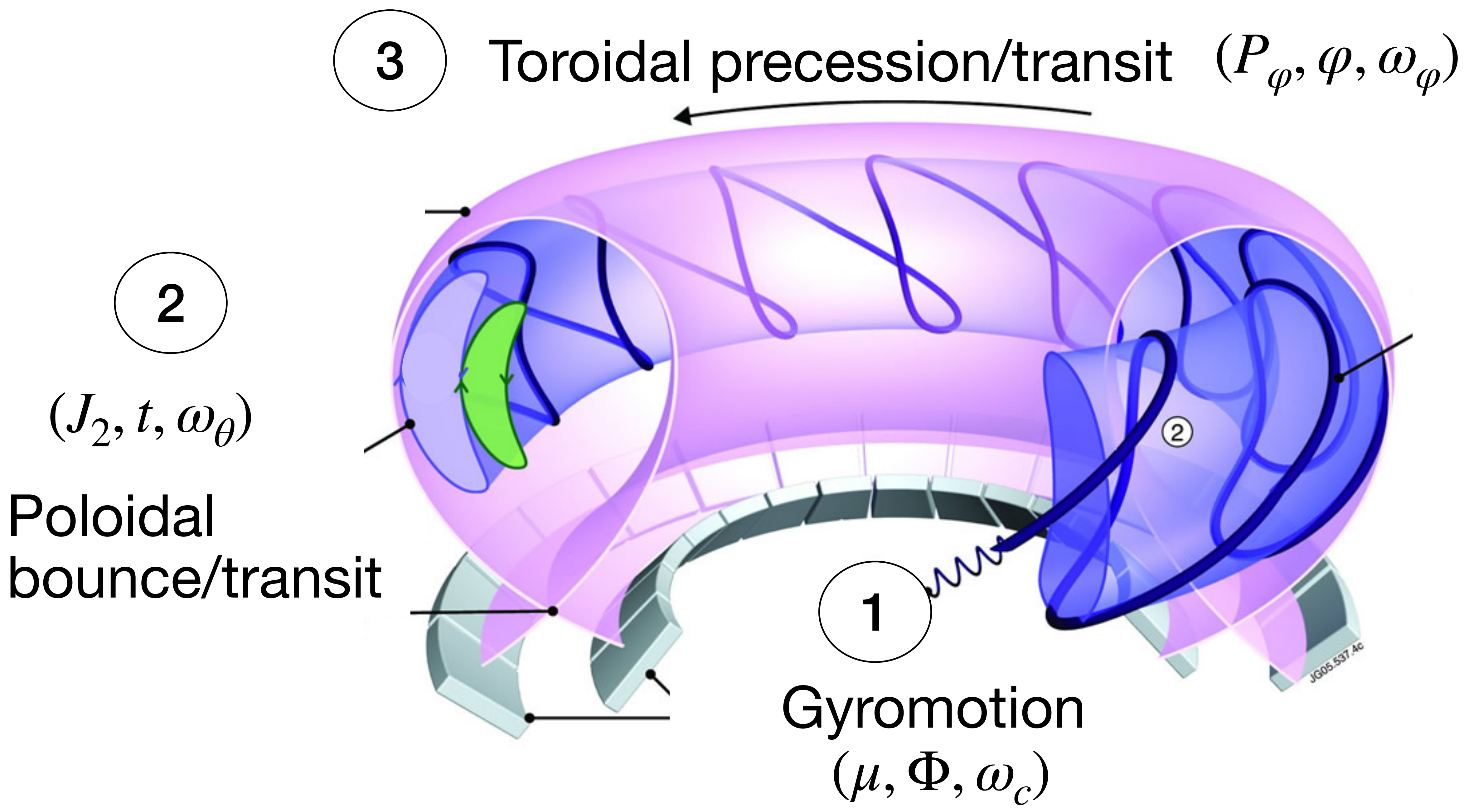
Ideal EP representation : CoM space

➢In **tokamaks,** the existence of **3 invariants reduce** the **dynamics** to a **3D constants of motion space (CoM)**

- ❖ 1st CoM : **Magnetic moment** $\mu = mv_\perp^2/2B$
- ❖ 2nd CoM : **Particle energy** $E = mv^2/2 + Ze\phi$
- ❖ 3rd CoM : **Toroidal canonical momentum**

$$P_\varphi = mv_\varphi - Ze\psi_P$$

→ **CoM** coordinates **mix position/velocity** spaces

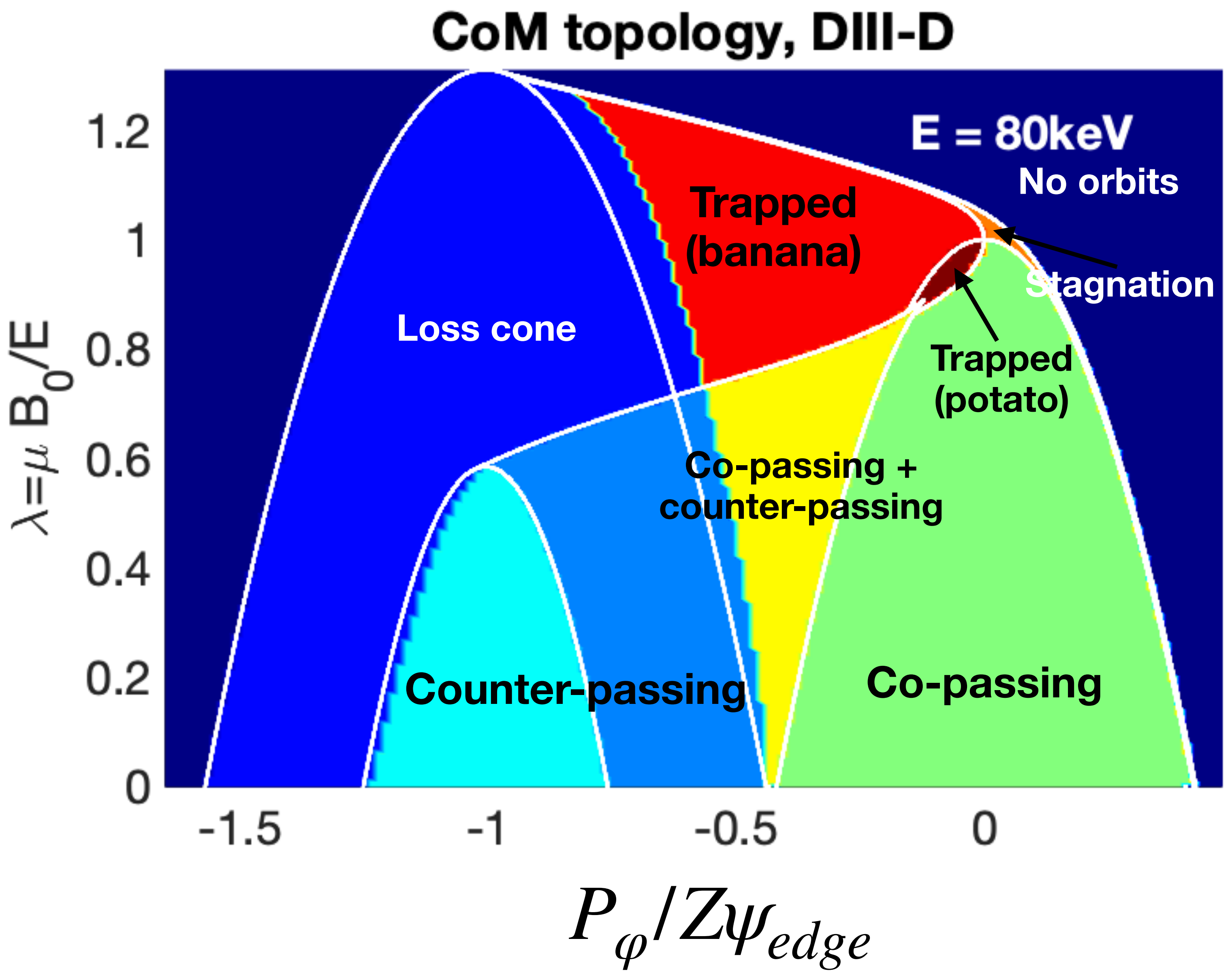


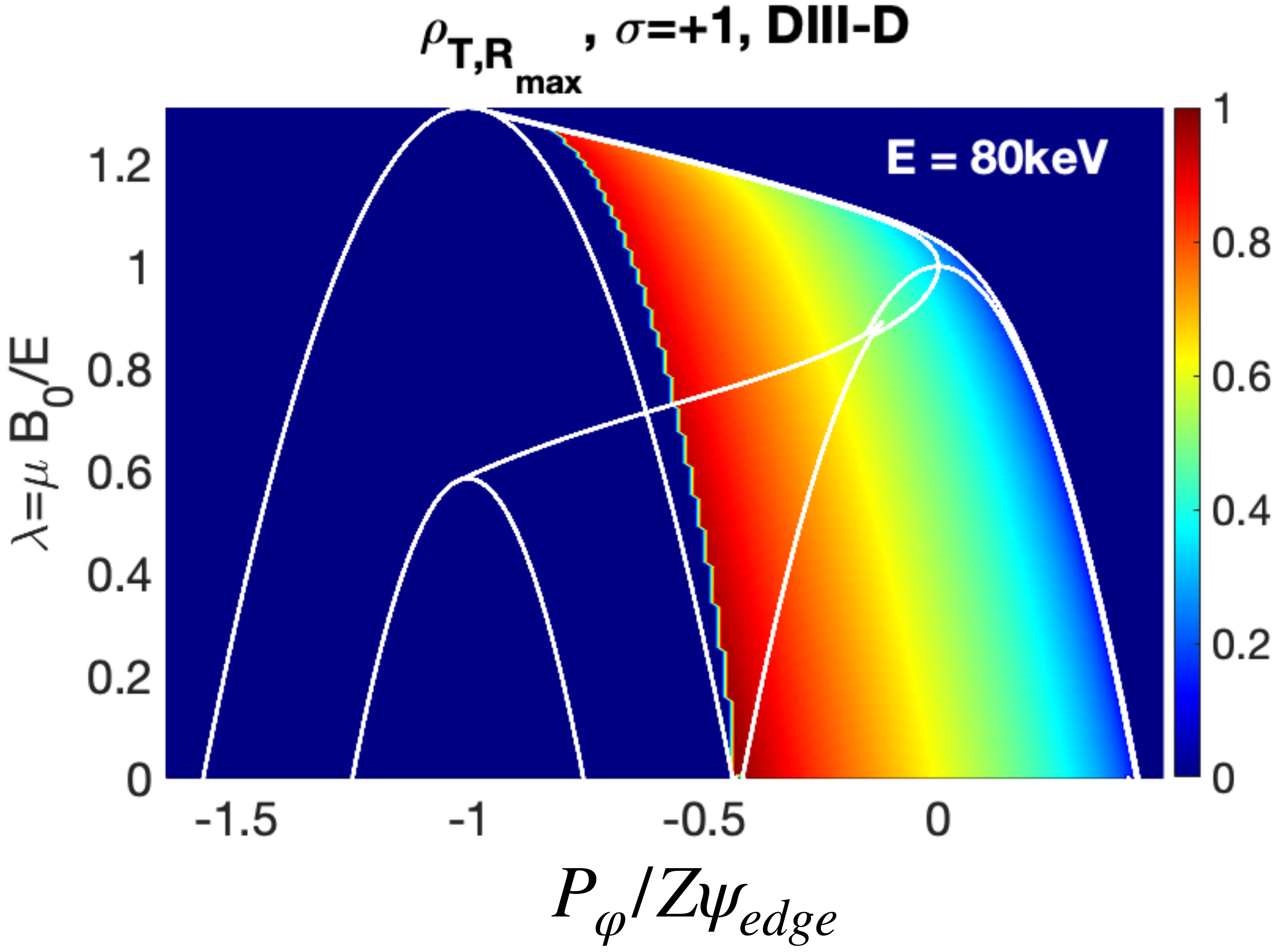
Advantages of CoM representation

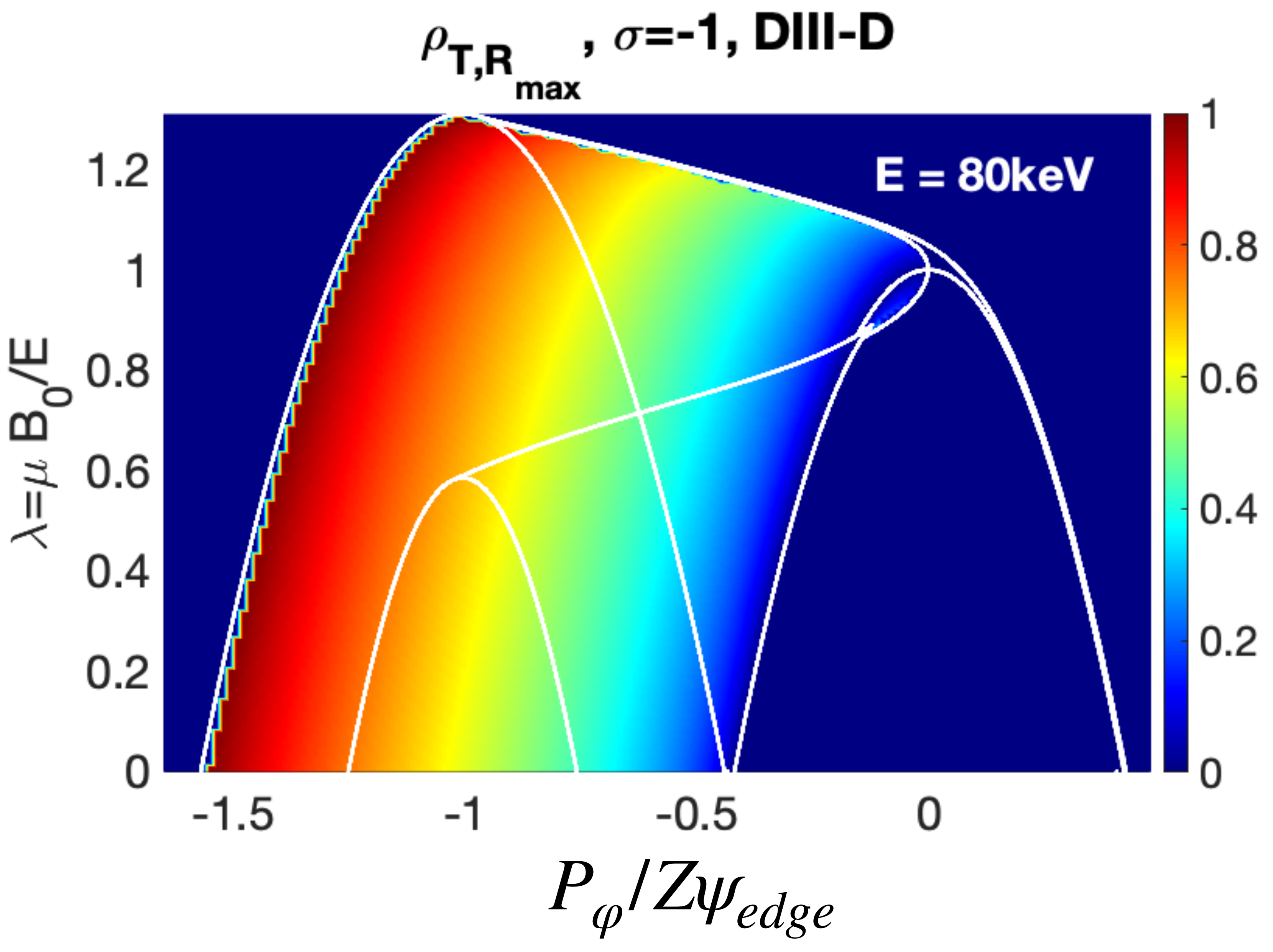
- ❖ **Dimensionality reduction** from **4D** to **3D** coordinates greatly **lower EP distribution noise**
- ❖ **EP orbits** entirely defined by **CoM coordinates, preventing EP distribution relaxation [1,2]**
- ❖ Enable **direct identification** of **driving terms** for EP-driven instabilities for **control purposes**

[1] A. Könies et al. 2018, *Nucl. Fusion*
[2] G. Vlad al. 2025, *Rev. Mod. Plasma Phys*

CoM space topology







- ➢ P_φ, E, $\lambda = \mu B_0/E$ invariants **selected** to conduct CoM analysis, following **early work** by **R. B. White** [1]
- ➢ In this CoM space, the **orbit topology** can be **clearly highlighted** for each energy slice
- ➢ **Additional « coordinate »** $\sigma = v_{||}/|v_{||}|$ to **remove orbit degeneracy** in CoM space
- ➢ **CoM orbits** can be related to **regular space** using the orbit radial coordinate ρ_T at R_{max}

EP drive and resonances explicit in CoM space

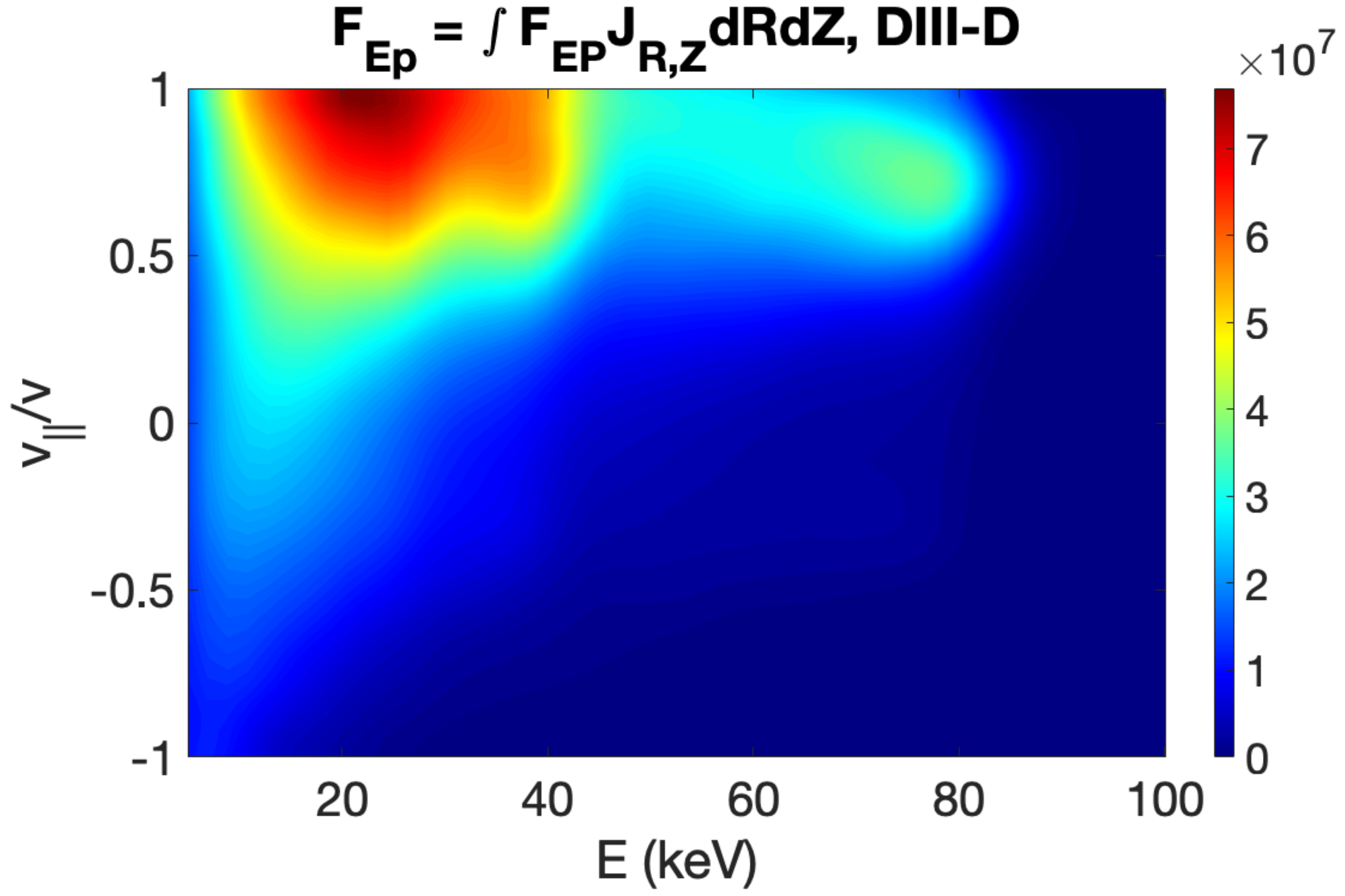
➢**EP-driven modes stability** can be described by a **general dispersion relation** [1,2]

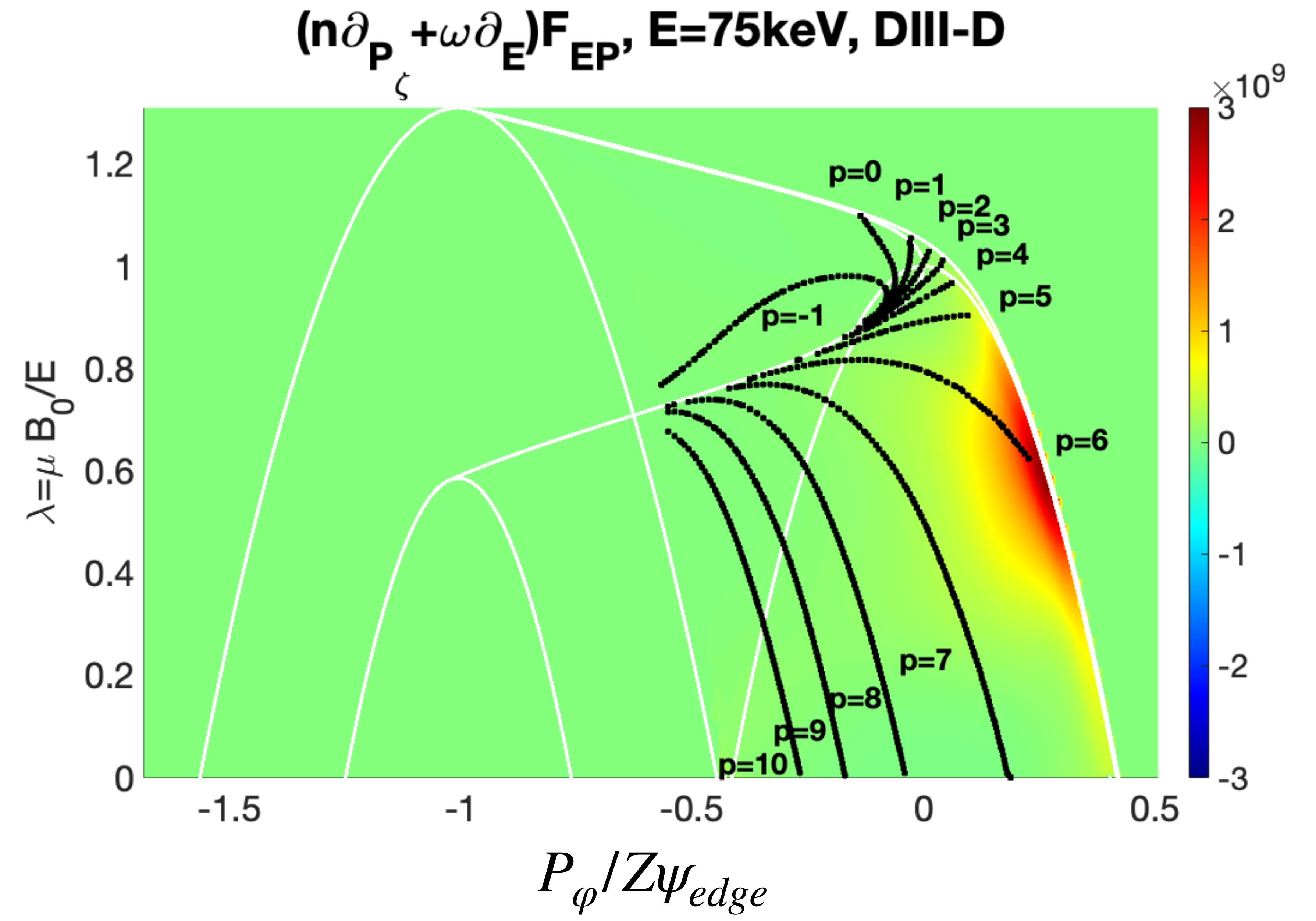
$$\omega I_R(\omega) = \delta W_{MHD} + \delta W_{EP}(\omega) \quad \delta W_{EP}(\omega) \propto \frac{n\partial_{P_\varphi} F + \omega \partial_E F}{\left(\omega + p\omega_\theta - n\omega_\varphi\right)}$$

➢The sign of $\nabla_{wp} F_0 = n\partial F_0/\partial P_\varphi + \omega \partial F_0/\partial E$ in **CoM space** determine **stability** of **EP-driven modes**

- ❖ $\nabla_{wp} F_0 > 0 \Rightarrow$ driving instabilities
- ❖ $\nabla_{wp} F_0 < 0 \Rightarrow$ damping instabilities

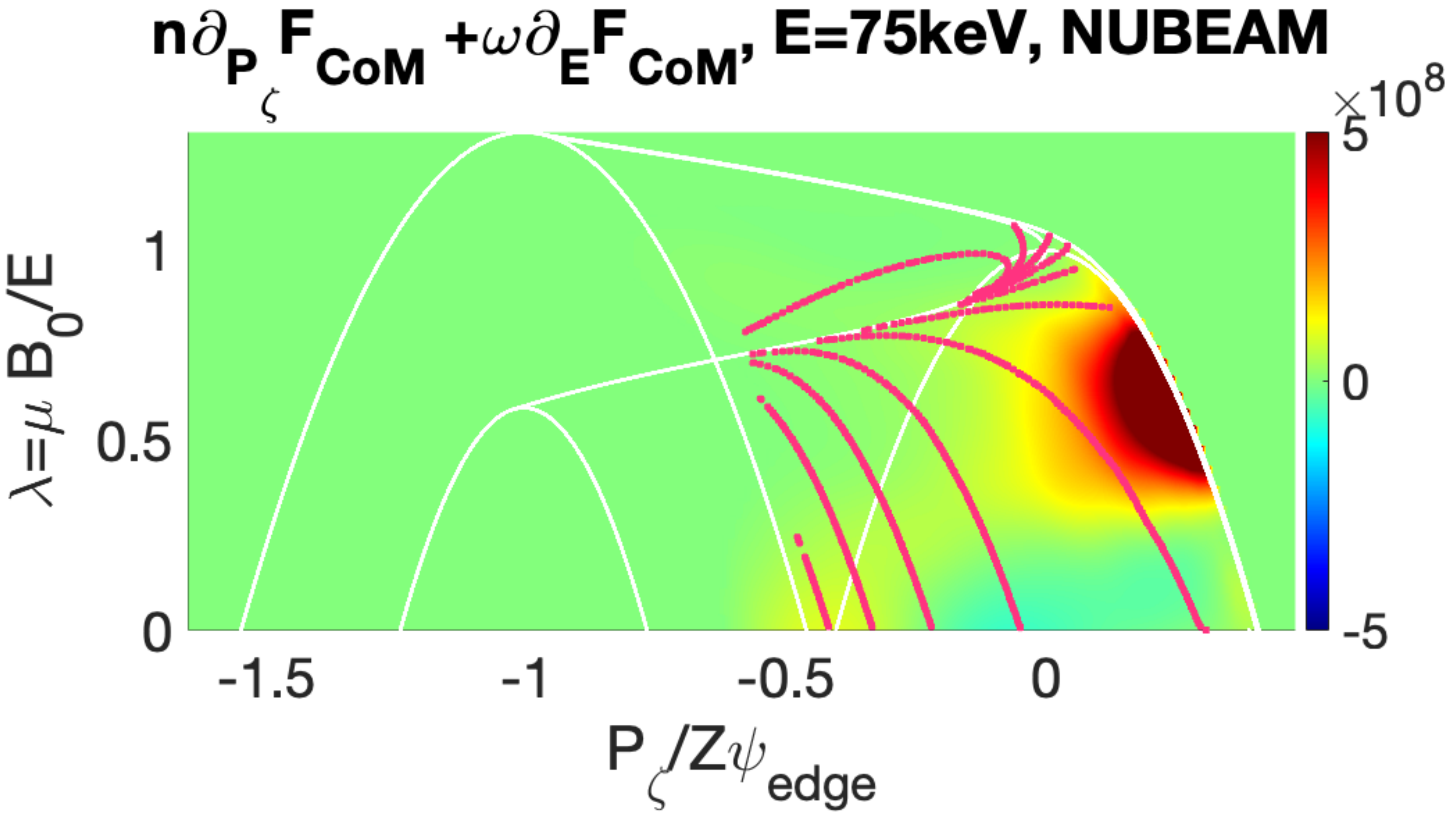
➢EP pdf gradients are **driving modes** in the vicinity of **resonances locations** $\omega = n\omega_\varphi - p\omega_\theta, \quad p \in \mathbb{Z}$

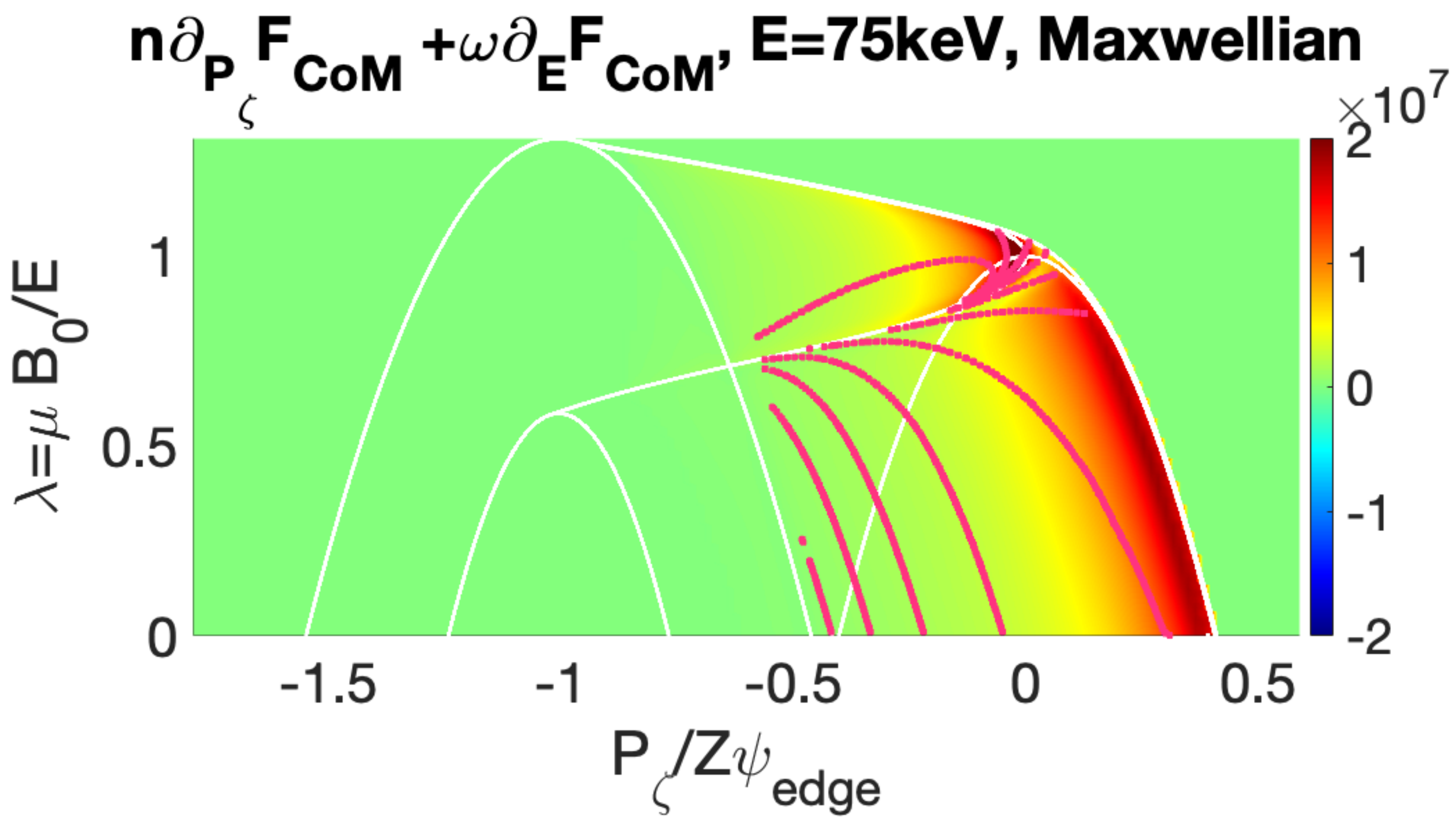




[1] L. Chen et al. 1984, *Phys. Rev. Lett.*
[2] L. Chen and F. Zonca 2016, *Review of Modern Physics*

Why realistic EP distribution matters





- **Maxwellian** approximation **can deeply affect** the **stability** and **nonlinear dynamics** of EP-driven modes
- Both **EP-driven modes** [1] and **drift-waves** [2] **linear stability** can be modified by **wave-particle resonances**
- **EP distribution**s could be **tailored** for **beneficial confinement impact :** requires **cross-scale gyrokinetic modelling** of **EP instabilities** and **microturbulence** [3,4]
- The **implementation** of **CoM distributions** in kinetic-MHD/ gyrokinetic codes and a **V&V against experiments** is an **essential first step** towards achieving confinement enhancement

[1] L. Chen et al. 1984, *Phys. Rev. Lett.*
[2] A. Di Siena et al. 2018, *Nucl. Fusion*
[3] P. F. Liu et al. 2022, *Phys. Rev. Lett.*
[4] A. Di Siena et al. 2025, *Nucl. Fusion*

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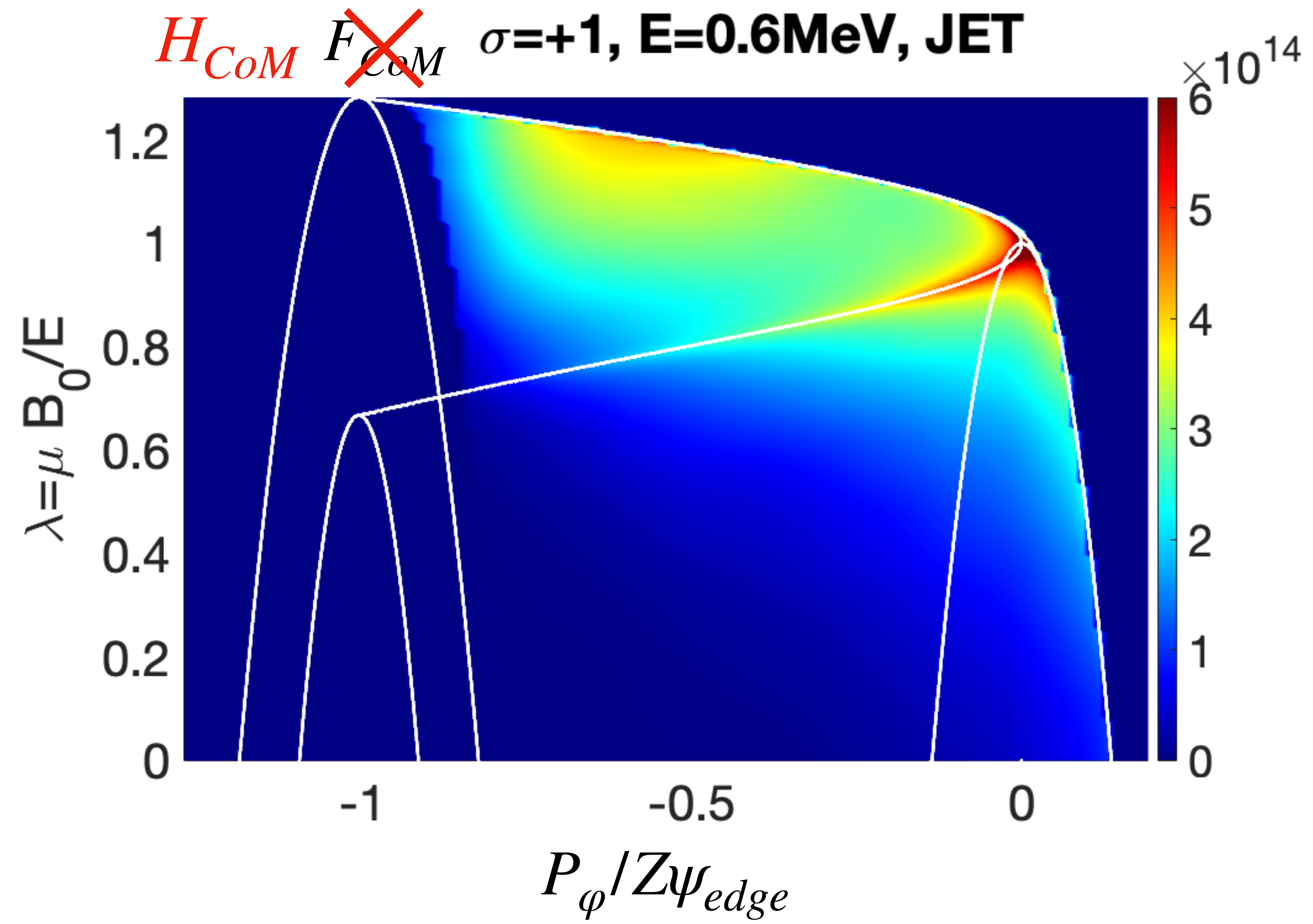
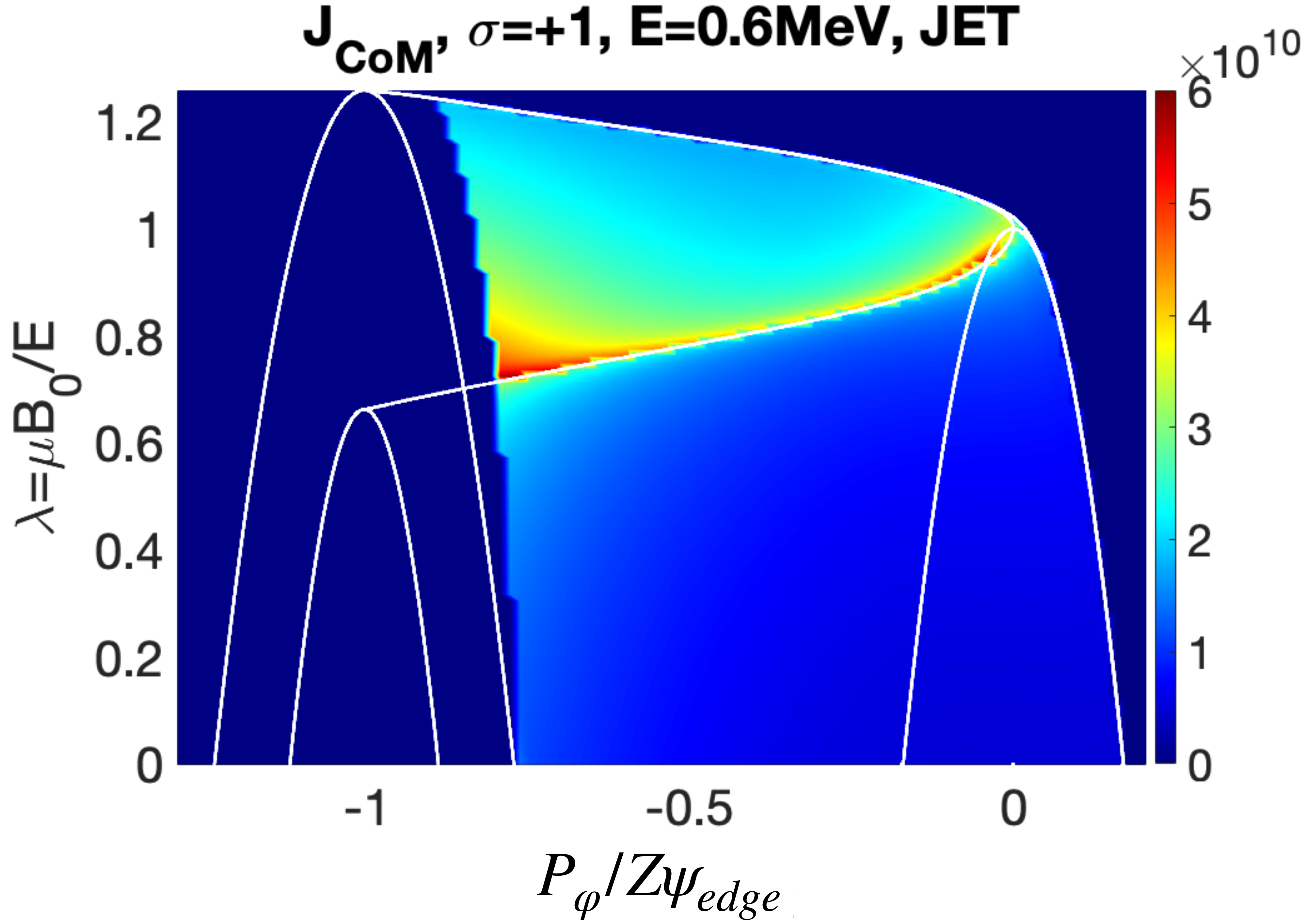
CoM projection is not trivial





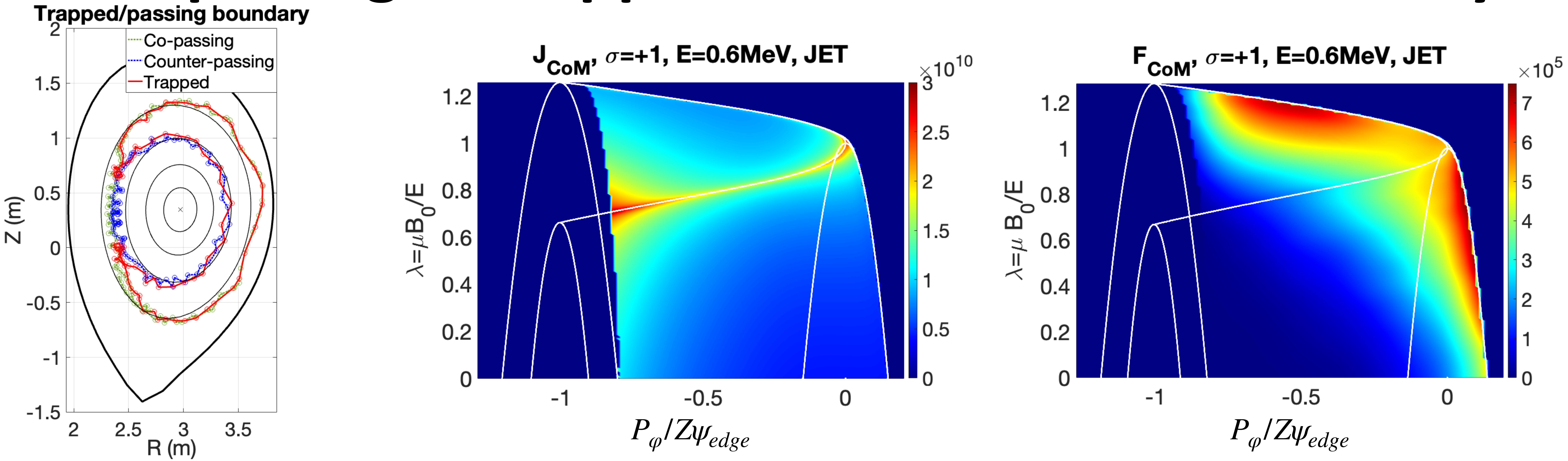
- ➢ At first sight, **one could be tempted** to simply **compute CoM distribution from markers** as

$$H_{CoM} \quad \cancel{F_{CoM}} = \sum_i^N w_i \, S(\mathbf{Z}_i - \mathbf{Z}_{CoM\ grid})/\Delta V_{CoM} \qquad F_{CoM} = \sum_i^N w_i \, S(\mathbf{Z}_i - \mathbf{Z}_{CoM\ grid})/\Delta\Upsilon_{CoM}$$

- ➢ $\Delta\Upsilon_{CoM} = J_{CoM}\Delta V_{CoM} \rightarrow$ **distortion** of cartesian volume element **under CoM transformation**

- ➢ **CoM jacobian** can be obtained from EP orbits computed locally in CoM space $\quad J_{CoM} = \frac{4\pi^2 E}{ZemB_0}\tau_b(E, \lambda, P_\varphi, \sigma)$

Splitting of trapped orbits for CoM continuity



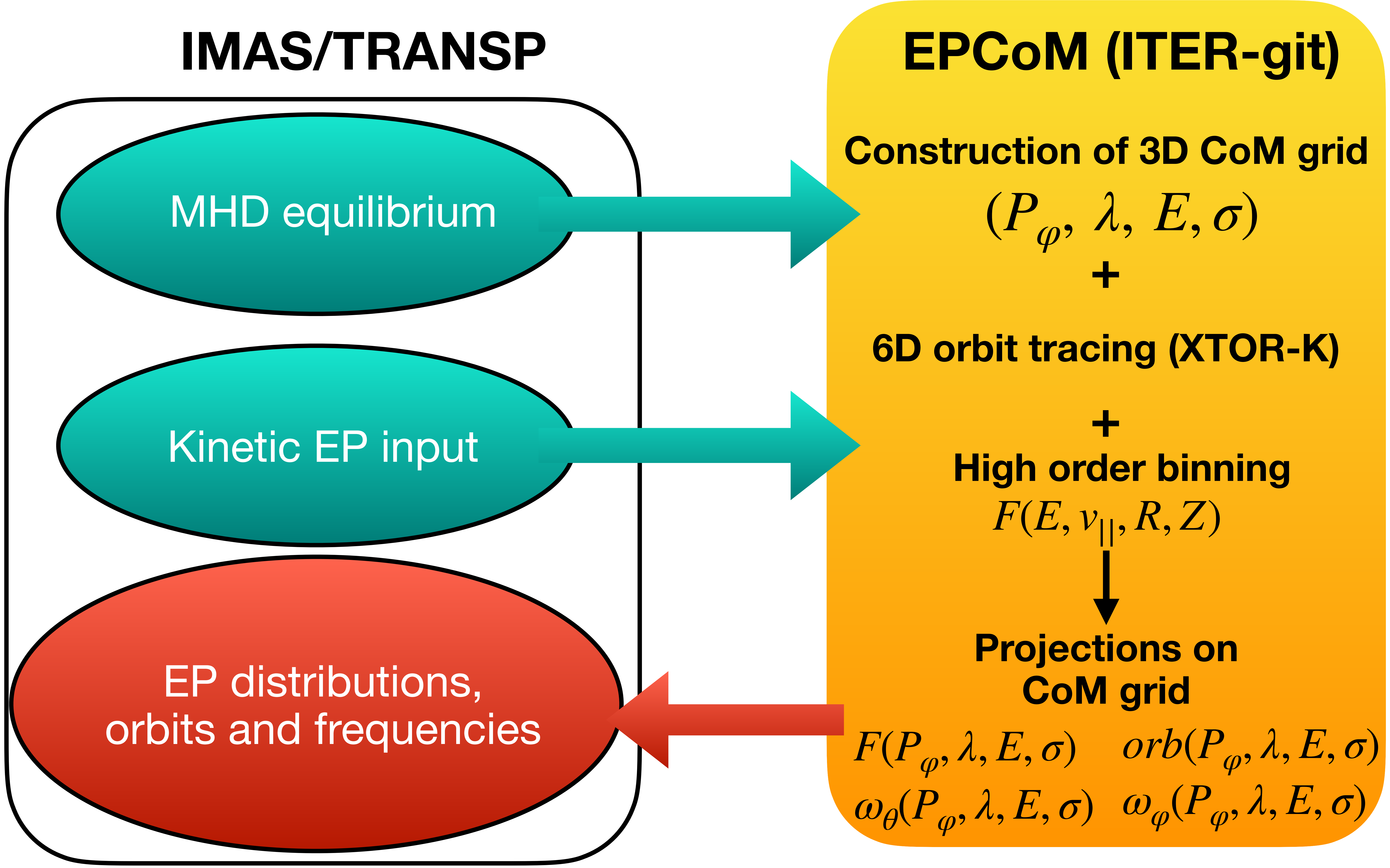
➢**Discontinuity** of J_{CoM} accross trapped-passing boundary is **mathematically artificial**

➢**Splitting** the trapped orbits $\pm$ legs enable the computation of **continuous CoM jacobian**

➢Resulting **CoM distribution well defined** across CoM space, which is **required** for **gyrokinetic/kinetic-MHD** codes

➢J_{CoM} can be **obtained** by **computing numerically** the **deformation** of the **cartesian volume element**

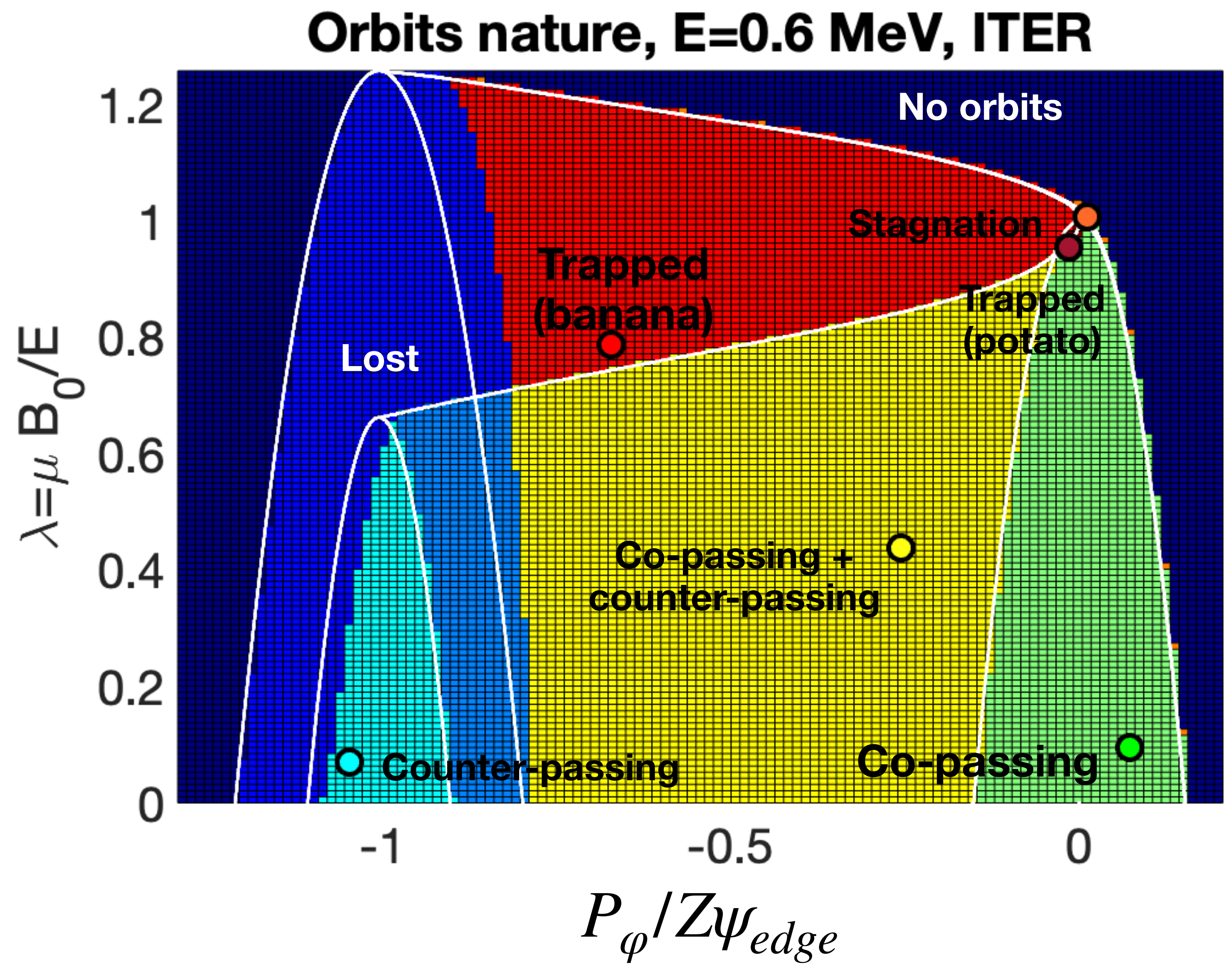
The EPCoM workflow [1]

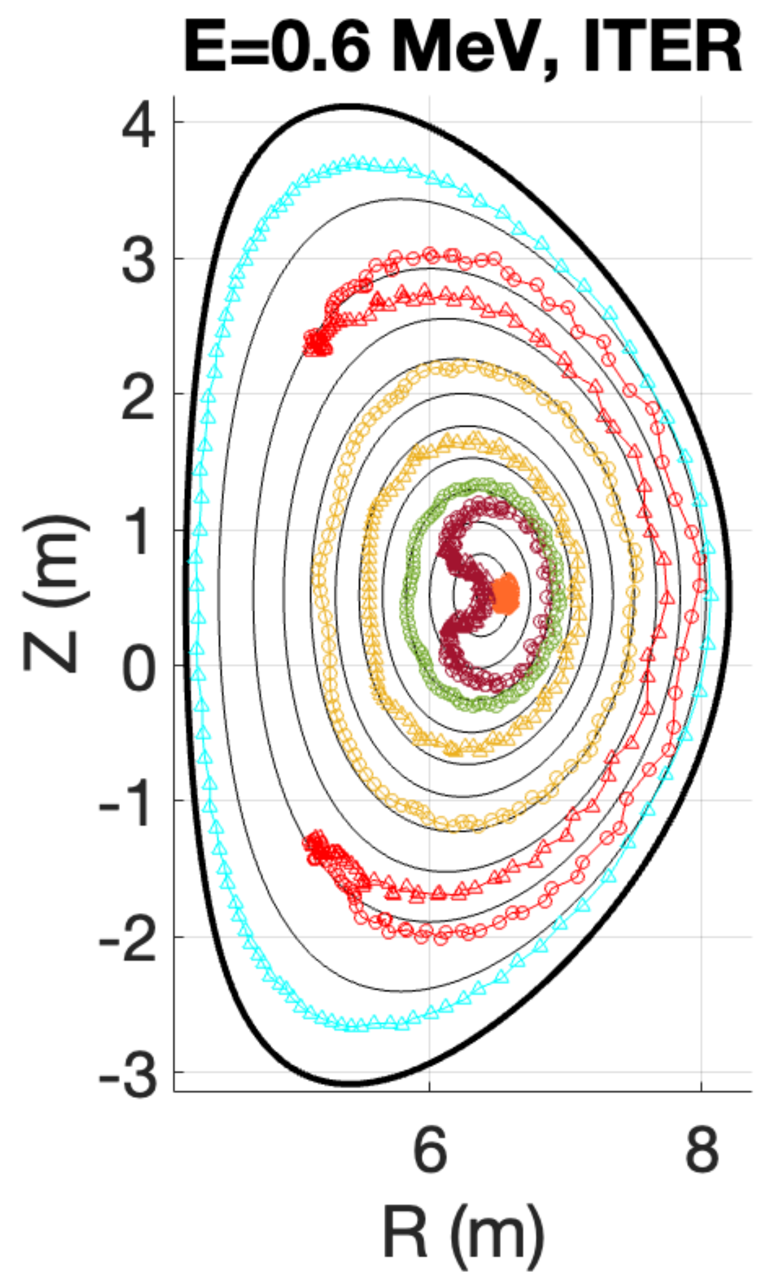


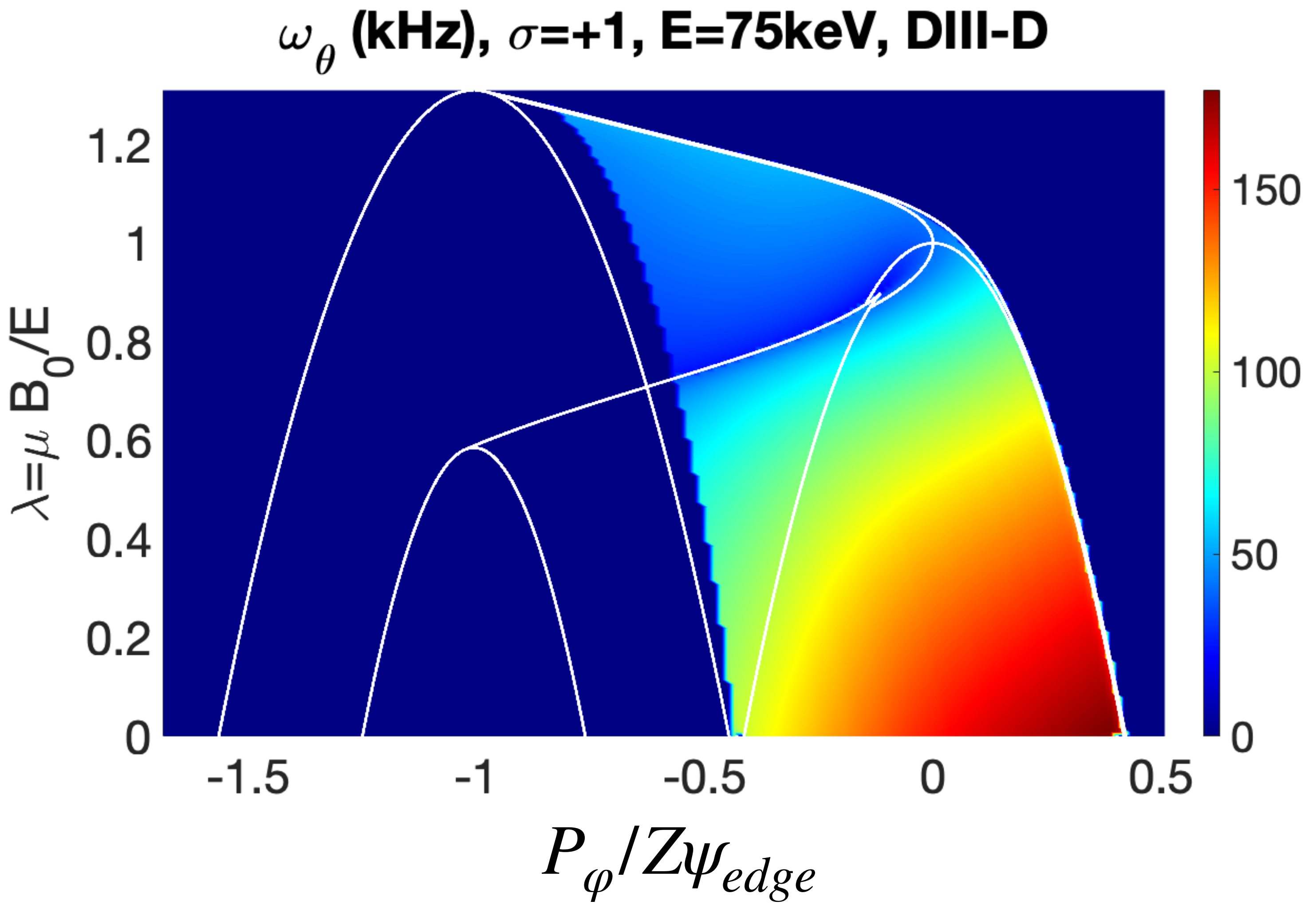
- Workflow **IMAS-compatible** and in **open-access** on ITER git server
- Also **compatible** with **TRANSP-suite outputs**
- Workflow **available** as **standard** for **the whole EP community**
- **EP distributions**, **orbits** and **frequencies** are stored on a CoM grid back into **IMAS /netcdf files**
- **EP distributions** also stored on **EpRZ grid** using orbits and CoM distributions **projection**

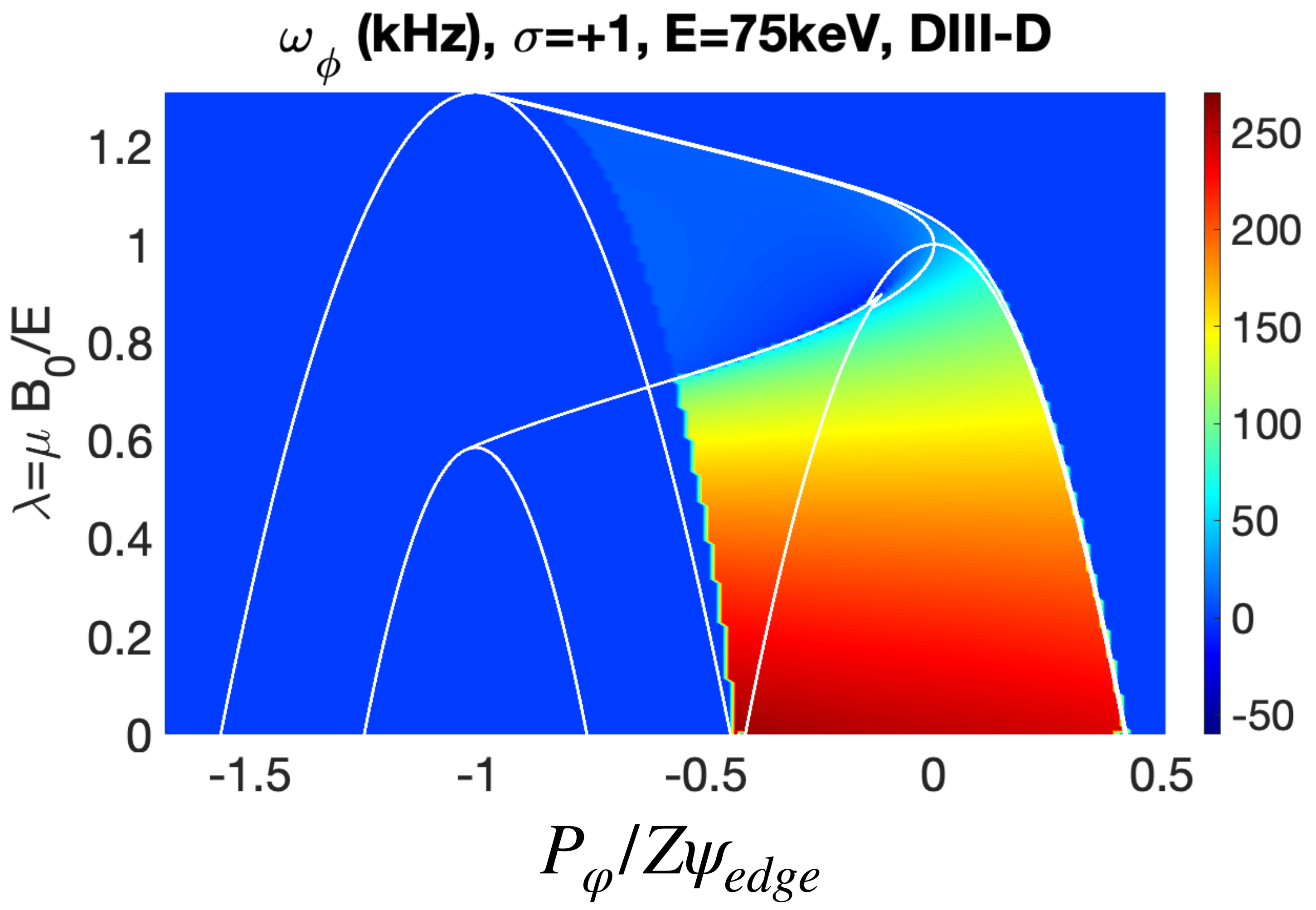
[1] G. Brochard et al. 2026, *to be submitted to Comp. Phys. Comm.*

3D CoM grid and orbits database









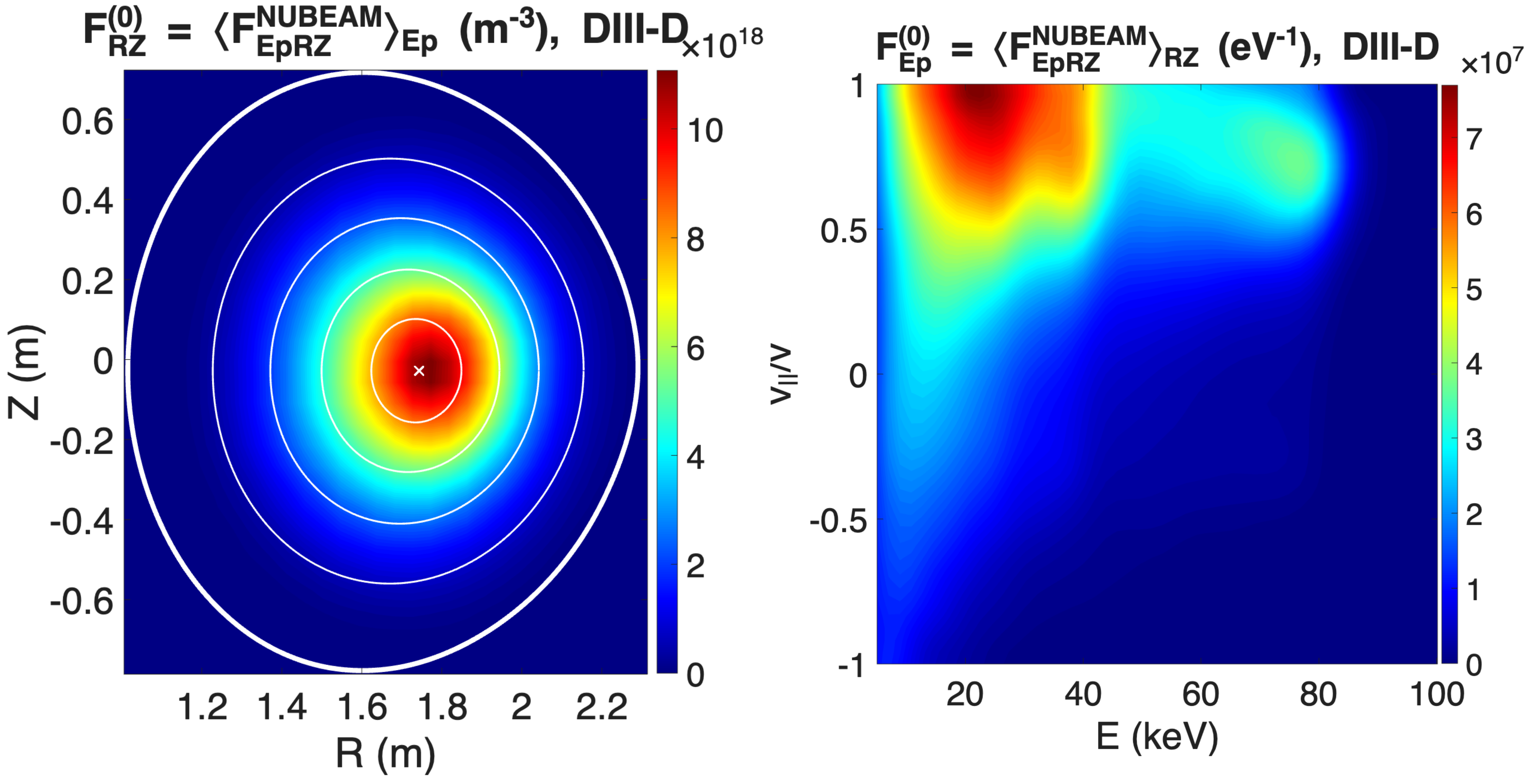
- ➢A **3D (+$\sigma = \pm 1$) cartesian grid** in CoM space is **chosen,** preventing **singularities [1]**
- ➢For **each CoM grid point**, the (p, R, Z) **orbits** are stored over 1 poloidal orbit time
- ➢Direct transformation from **CoM space** to **any coordinate systems** straightforward
- ➢ **EP frequencies** $(\omega_\theta, \omega_\varphi)$ can be obtained through **orbit analysis** ($\theta(t), \varphi(t)$ traces)
- ➢ These mappings enable **to draw 2D resonant plans** for a **given** (ω, n)

$$\omega = n\omega_\varphi(P_\varphi, \lambda, E) - p\omega_\theta(P_\varphi, \lambda, E) \quad p \in \mathbb{Z}$$

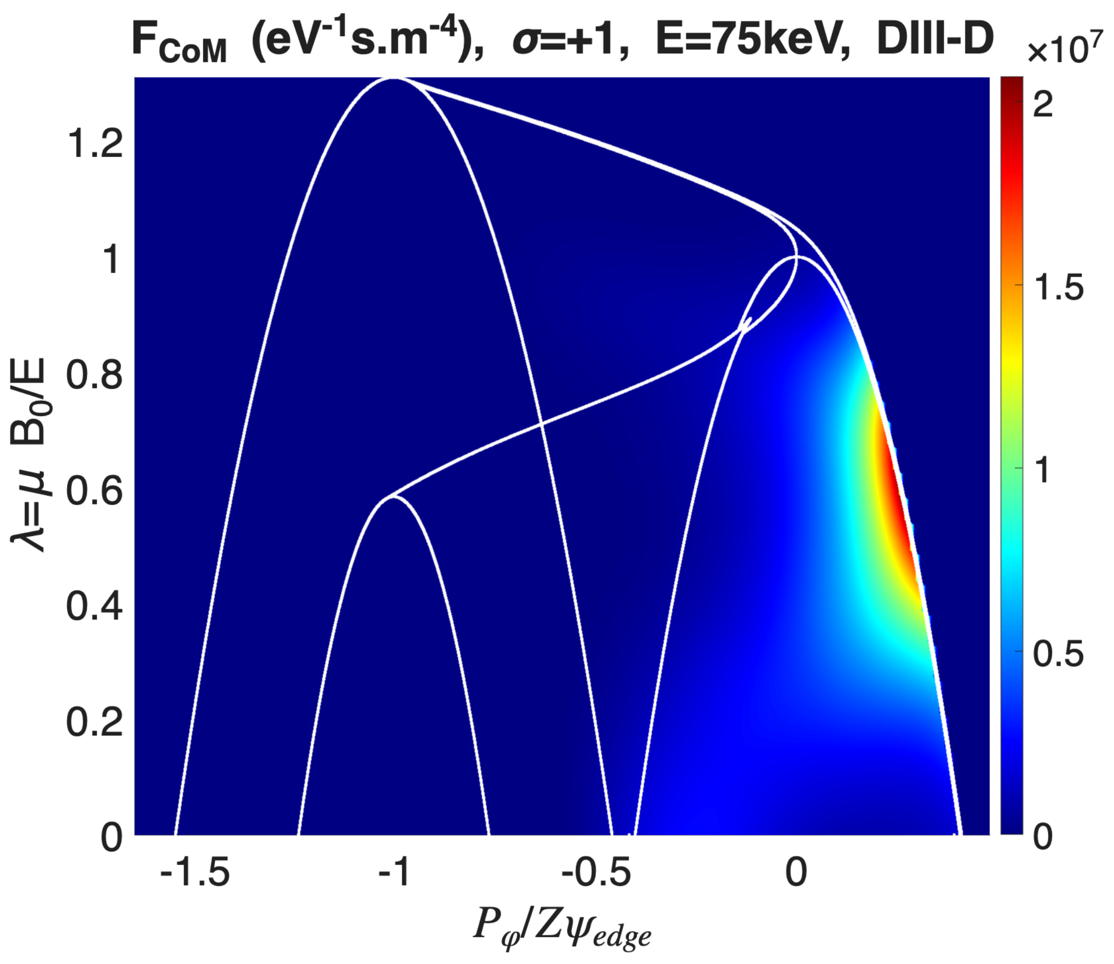
- ➢ **EPCoM output** can be used by **any code** to perform **detailed CoM space analysis**

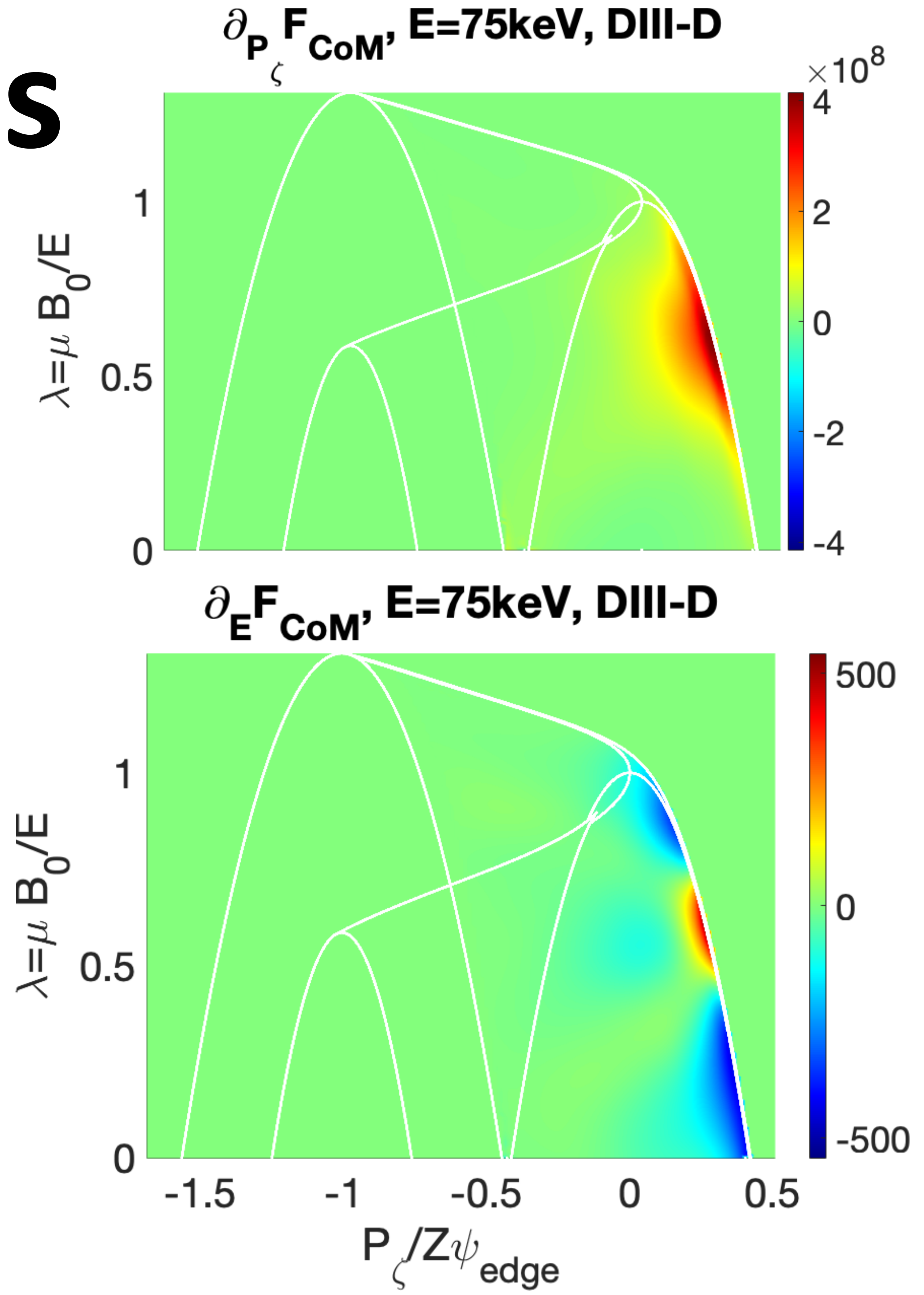
[1] A. Bierwage et al. 2022, *Comp. Phys. Comm.*

Initialisation of F_{CoM} in δF codes



EPCoM

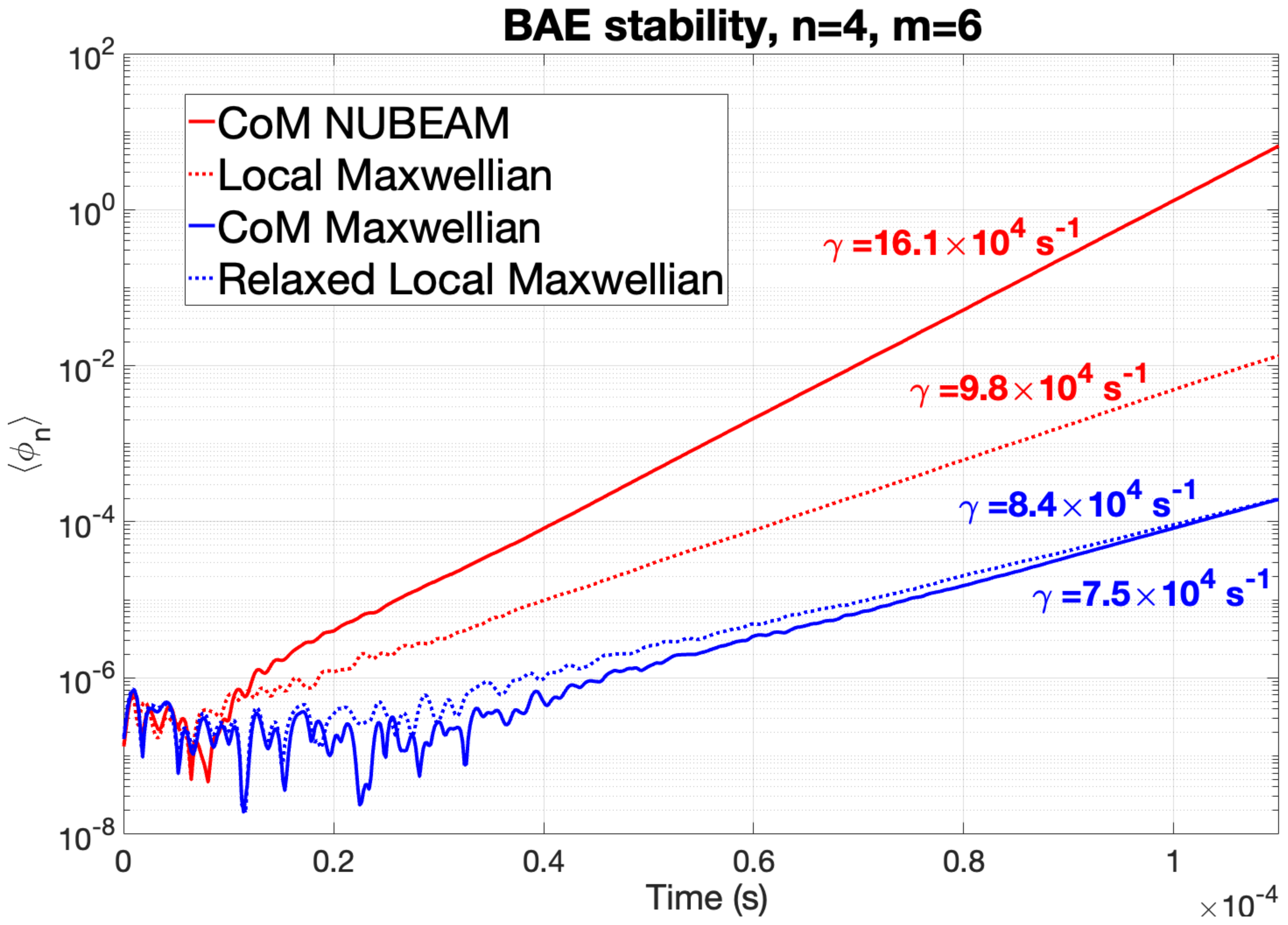


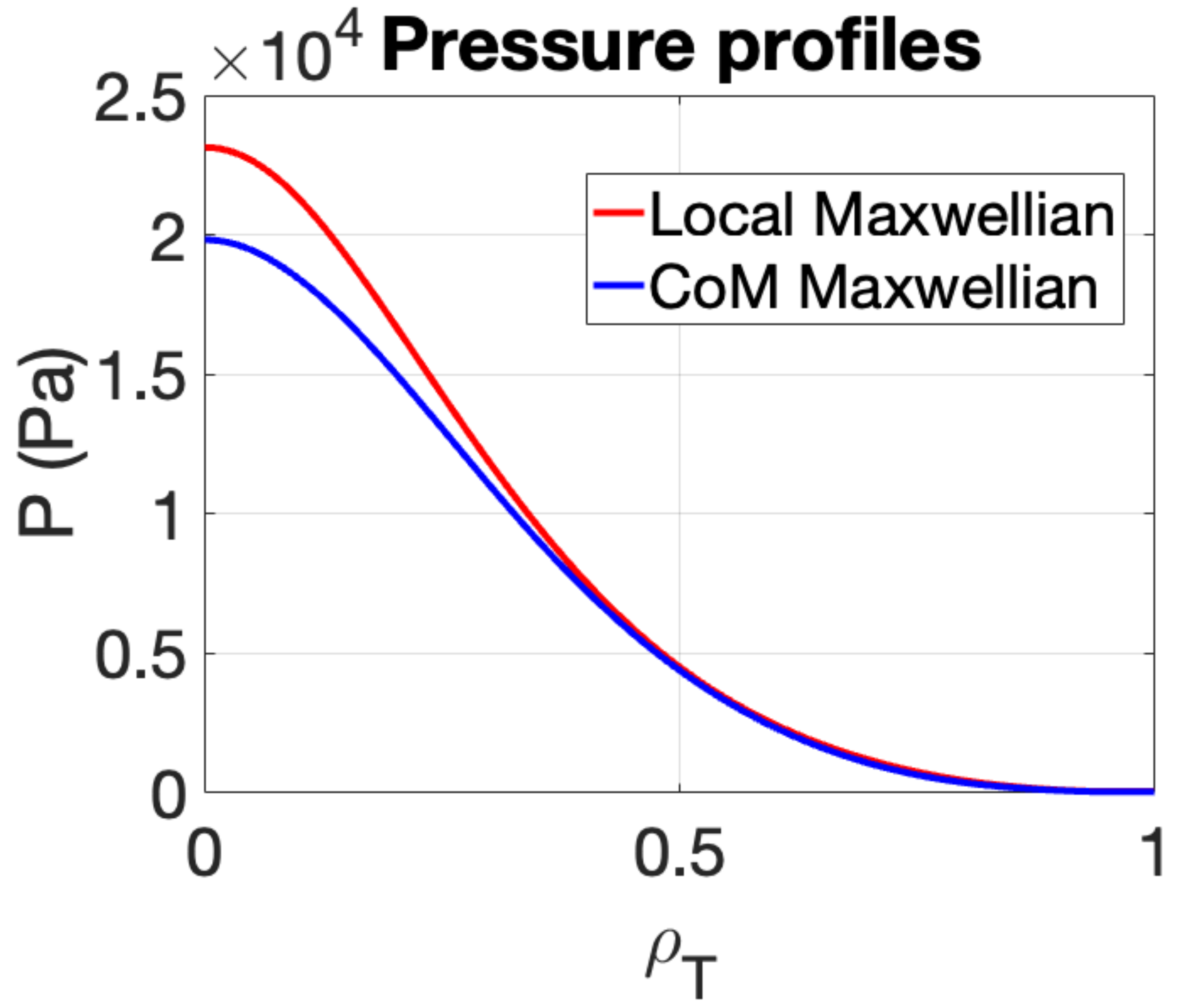


- A **3D $\mathscr{C}^2$ B-spline** is created to compute F_{CoM} **and $\partial_i F_{CoM}$ anywhere in CoM space**
- In δF **codes**, only the **EP gradients** $\nabla \ln(F_{EP}|_{\mu,v_{||}}), \partial_{v_{||}} \ln(F_{EP}|_{\mu,\mathbf{X}})$ are required in the weight equation (**Vlasov**)
- They can be locally computed in **any position-velocity space** from CoM distributions, through **chain rule operation**
- The **chain rule gradients** are **analytical**, and the **CoM derivatives** are obtained from a $\mathscr{C}^2$ spline

$$\nabla F_{\mu,v_{||}} = \nabla P_\varphi|_{\mu,v_{||}} \frac{\partial F}{\partial P_\varphi} + \nabla \lambda|_{\mu,v_{||}} \frac{\partial F}{\partial \lambda} + \nabla E|_{\mu,v_{||}} \frac{\partial F}{\partial E}$$

CoM capability successfully tested in GTC

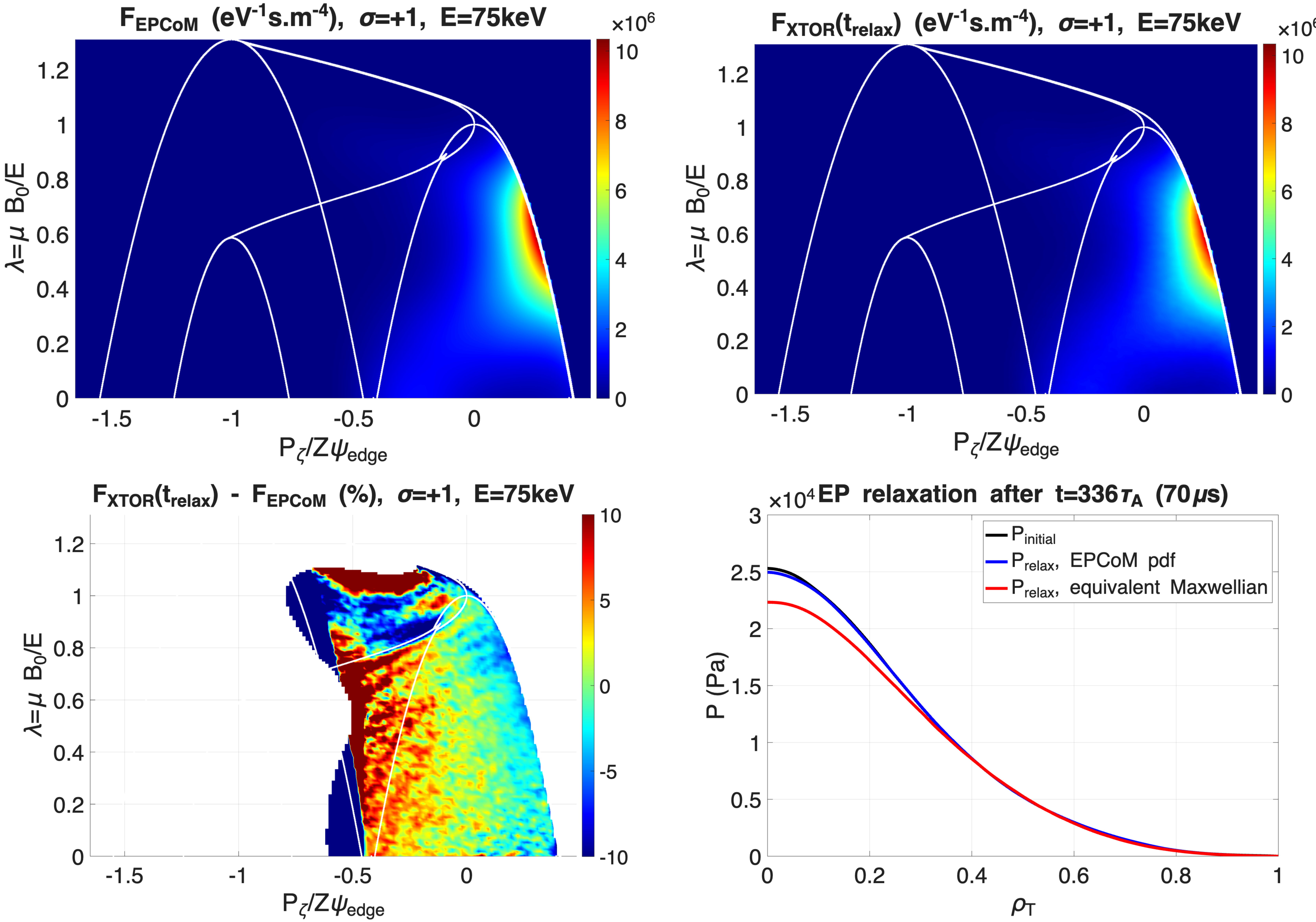




- **Chain rule test** conducted with **CoM NUBEAM, local Maxwellians and CoM maxwellian** for **BAEs** with **GTC [1]**
- **NUBEAM distribution** and its equivalent **local Maxwellian yield quite different BAE stability**, as expected
- **Stability results** are however **very similar** between the **CoM** and **relaxed local Maxwellians** → **CoM chain rule successfully tested in GTC**
- Even in this limit, results are **not identical** due to the **inclusion of EP drifts** (neoclassical effects)

[1] Z. Lin et al. 1998 , *Science*

Initialisation of F_{CoM} in full-F codes



- ➢**Full-F codes** using **Eulerian/semi-Lagrangian methods** can **directly** read F_{CoM} for **grid initialisation,** while a **Monte-Carlo approach** is required to load marker for **PIC codes**
- ➢Using 256M markers in **XTOR-K** [1], **EP loading is successful**
- ➢After $t_{relax} = 334\tau_A = 70\mu s$, **the EP pdf remains stationery,** as expected
- ➢**Comparatively**, the **equivalent Maxwellian** undergoes **significant relaxation**

[1] G. Brochard et al. 2020a, *Nucl. Fusion*

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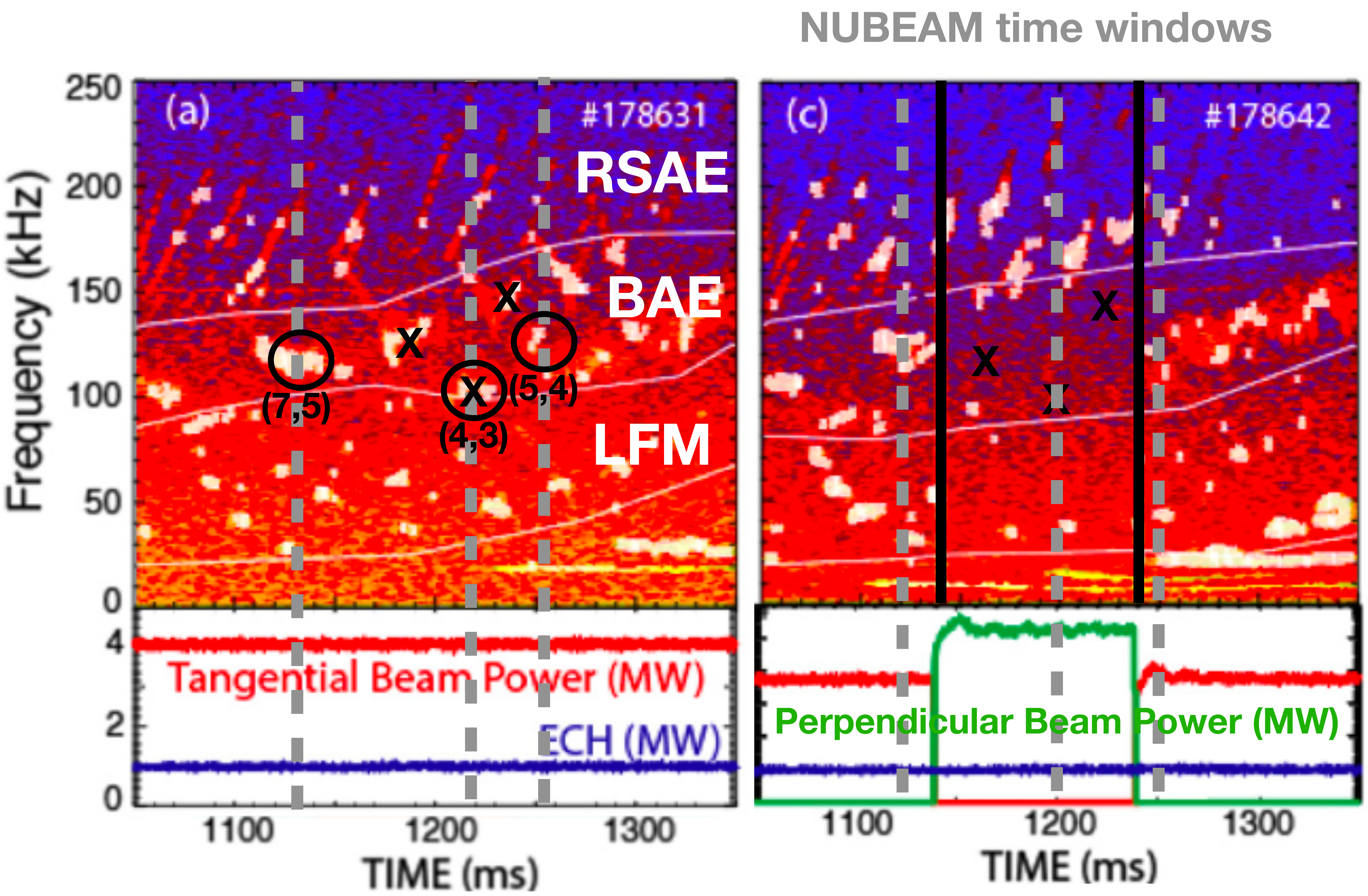
Variation of BAE stability in DIII-D discharges



➢**DIII-D shot #178642** [1,2] has been selected to conduct a **new ITPA-EP cross-code V&V** with **realistic EP distributions**

➢In **#178642**, **tangential** beams briefly swapped by **perpendicular** ones, providing a stable window for BAEs

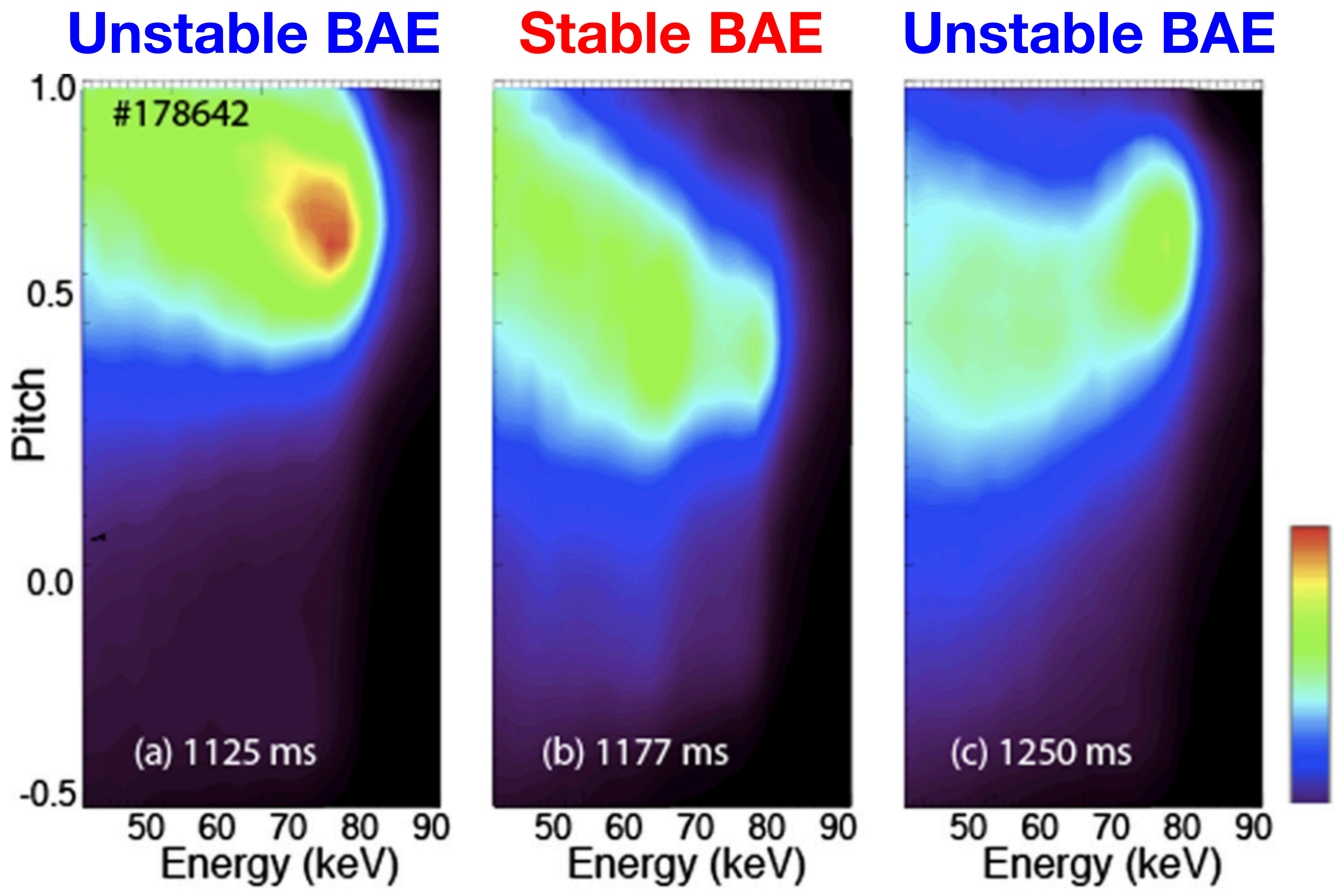
➢**NUBEAM/EPCoM tandem** used to reproduce **CoM distributions** on **three time windows**

➢**Experimental validation** on DIII-D plasmas → **basis** for **realistic evaluation** of EP-driven mode stability in **ITER**

➢Four **gyrokinetic** (GTC, ORB5, LIGKA, GENE) and five **kinetic-MHD** (XTOR-K, M3D-C1, M3D-K, MEGA, JOREK) codes currently participate to this **benchmark activity**

[1] W. W. Heidbrink et al. 2020, *Nucl. Fusion*
[2] W. W. Heidbrink et al. 2021, *Nucl. Fusion*

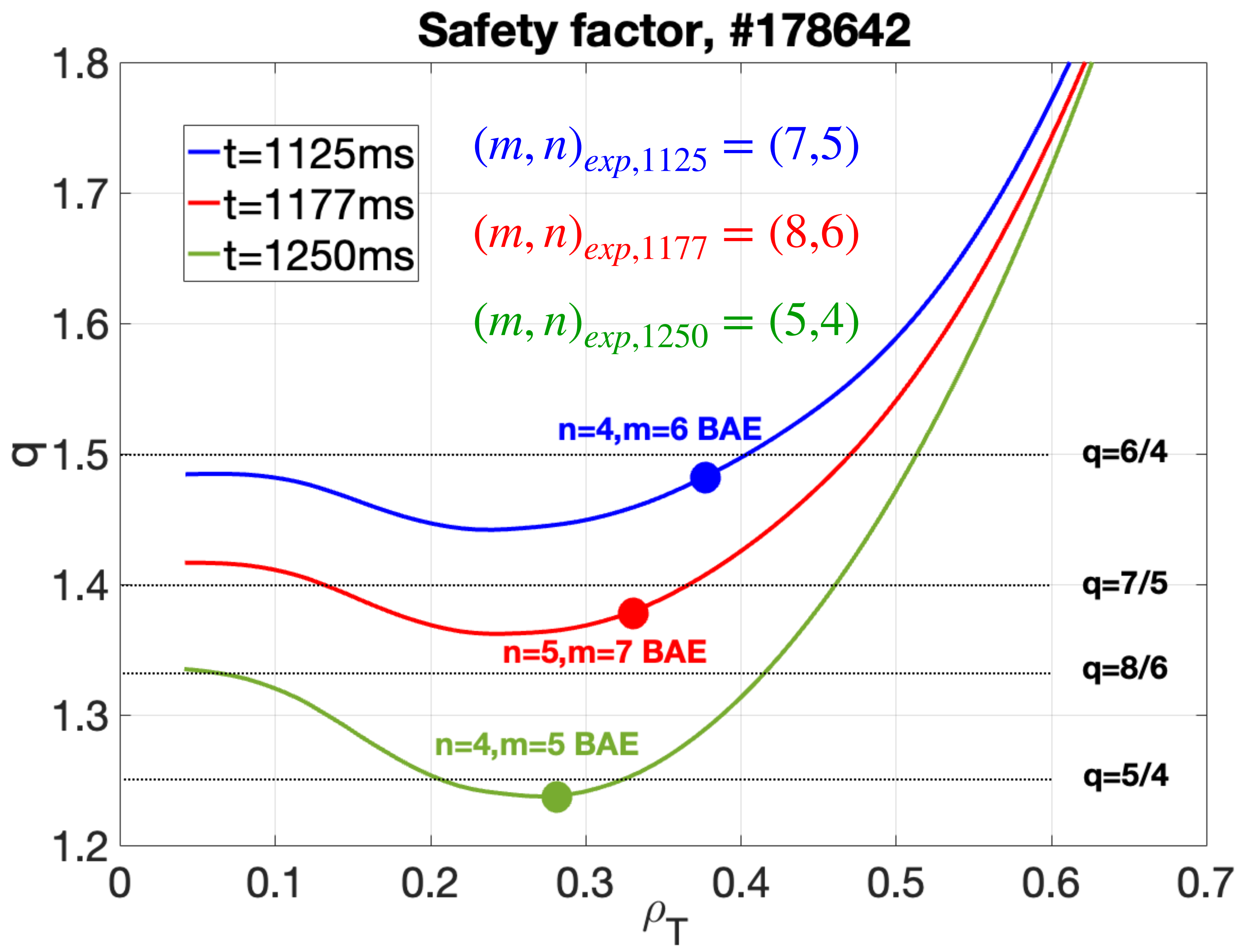
Change in BAE stability due to high-energy EP ?

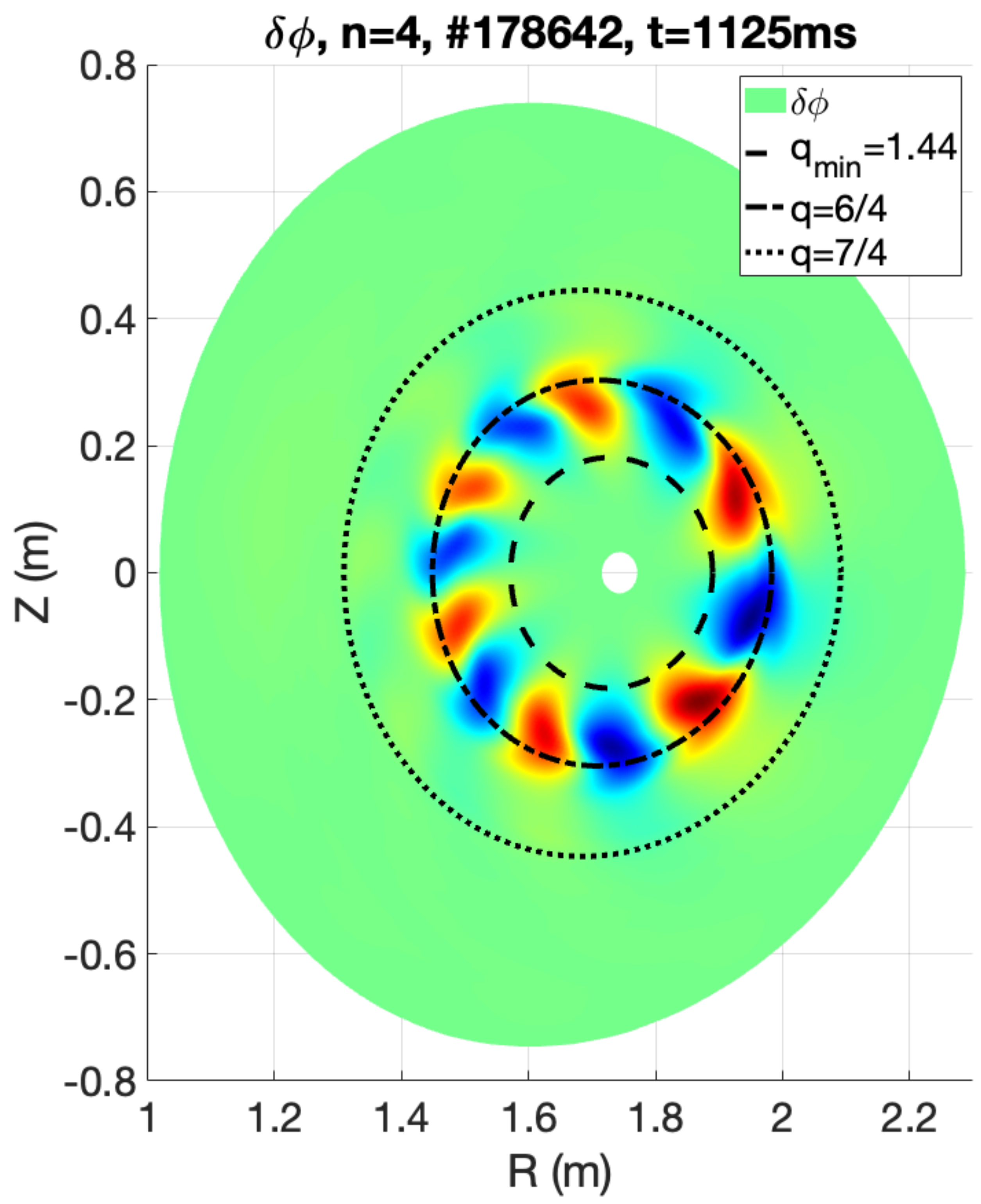


- ➢BAEs become almost **immediately stable** at **beam substitution**, while $\tau_{SD} = 150ms > \tau_{swap} = 100ms$
- ➢Changes in **high energy EPs** content could explain **change in** BAE stability [1]
- ➢**NUBEAM** simulations do show a **modification of EP distribution at injection energy** $E_0 \sim 75$keV [1]
- ➢**GTC** and **XTOR** confirms that the **wave-particle energy exchange** is **maximal** at $E \sim 75$keV

[1] W. W. Heidbrink et al. 2021, *Nucl. Fusion*

Initial BAE simulations with GTC



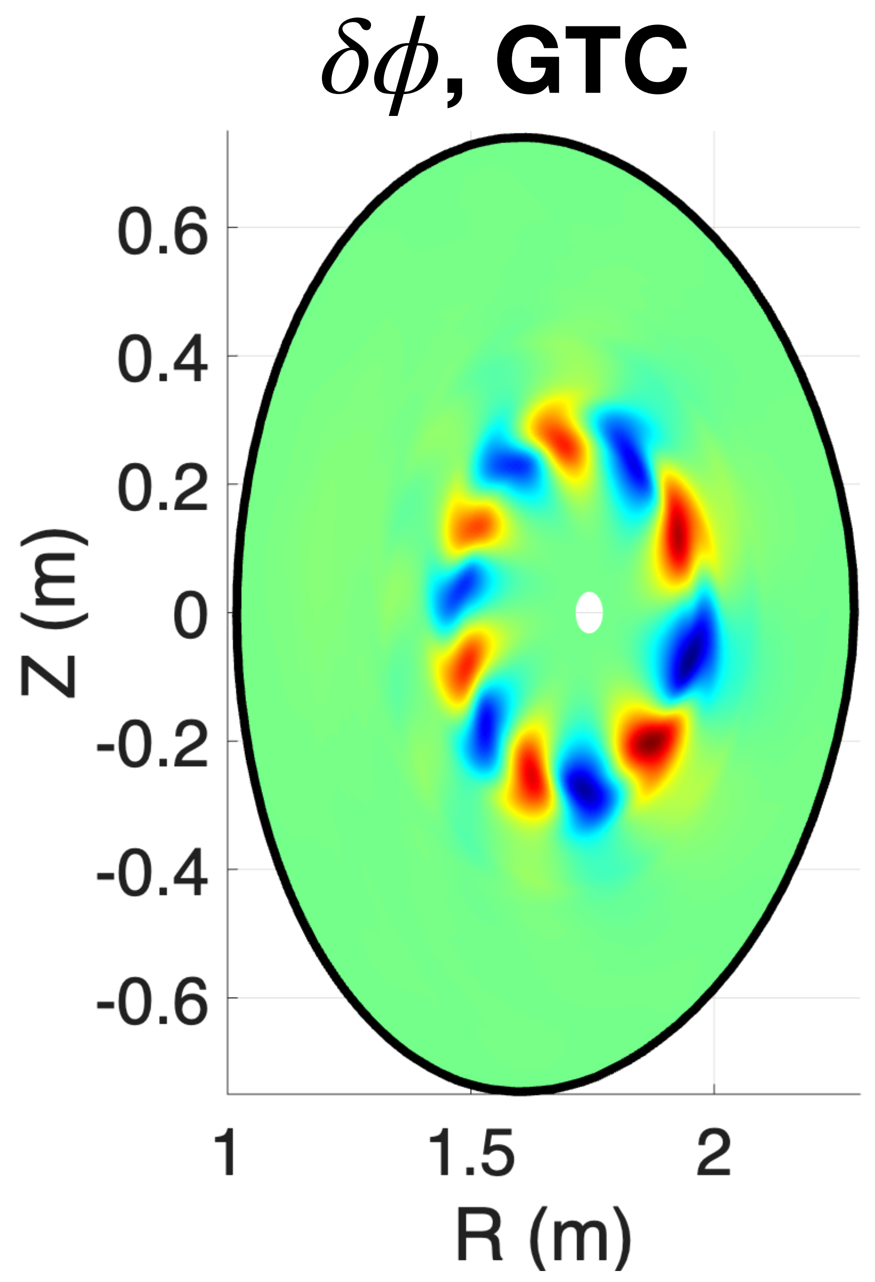


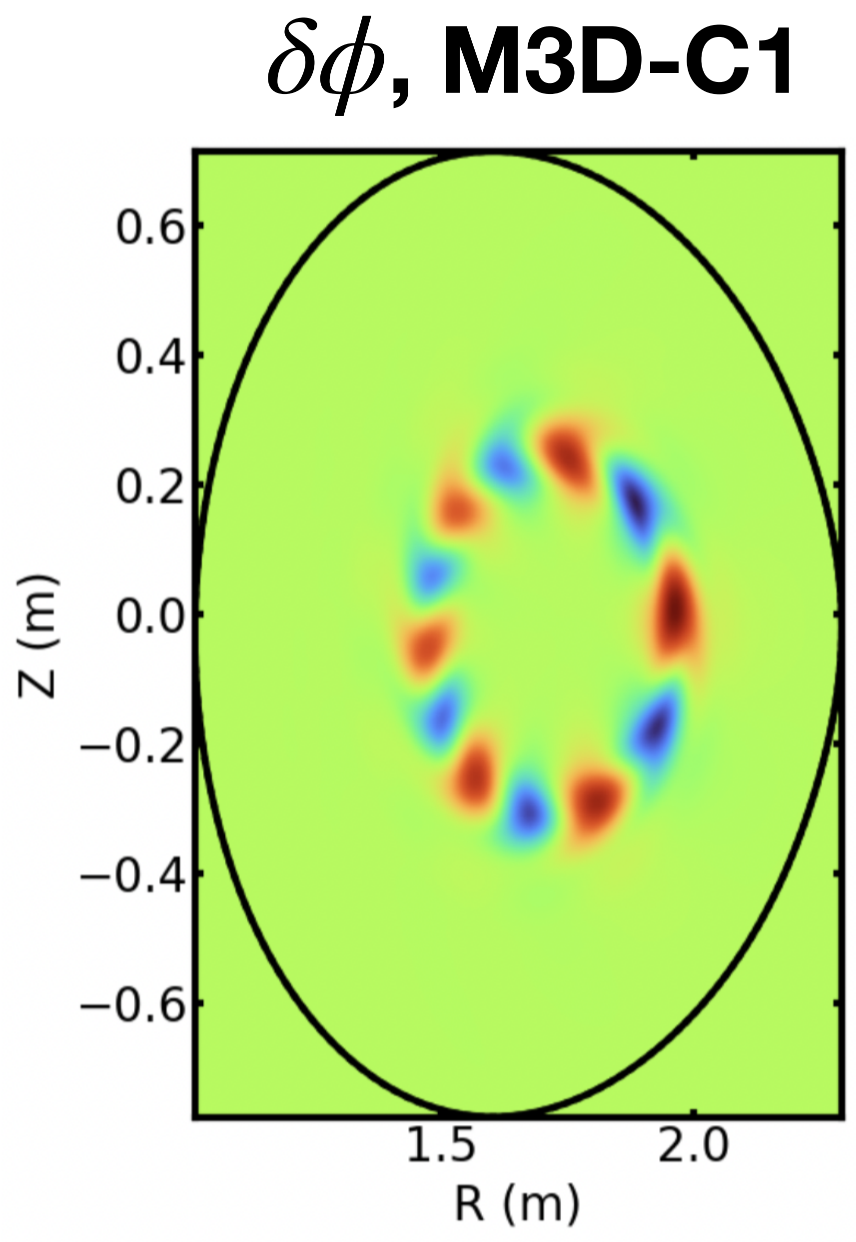
➢**GTC simulations** with EPCoM distributions performed on the **three time slices of #178642,** using neoclassical NUBEAM distributions and original EFIT equilibria

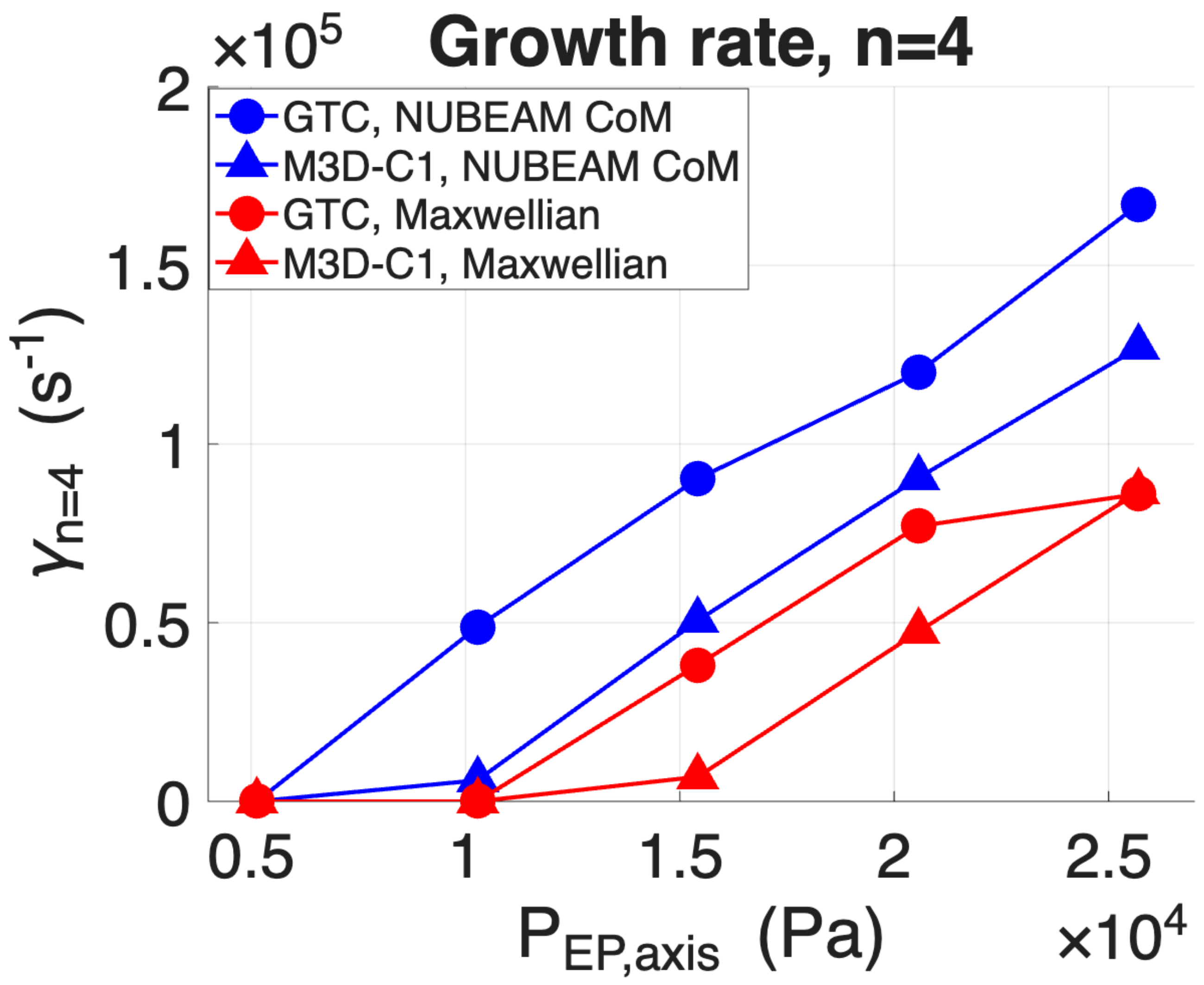
➢ **m/n** ratio **slightly differ** between GTC and #178642 **due to** ± 0.05 **variations on** q_{min} (within uncertainty)

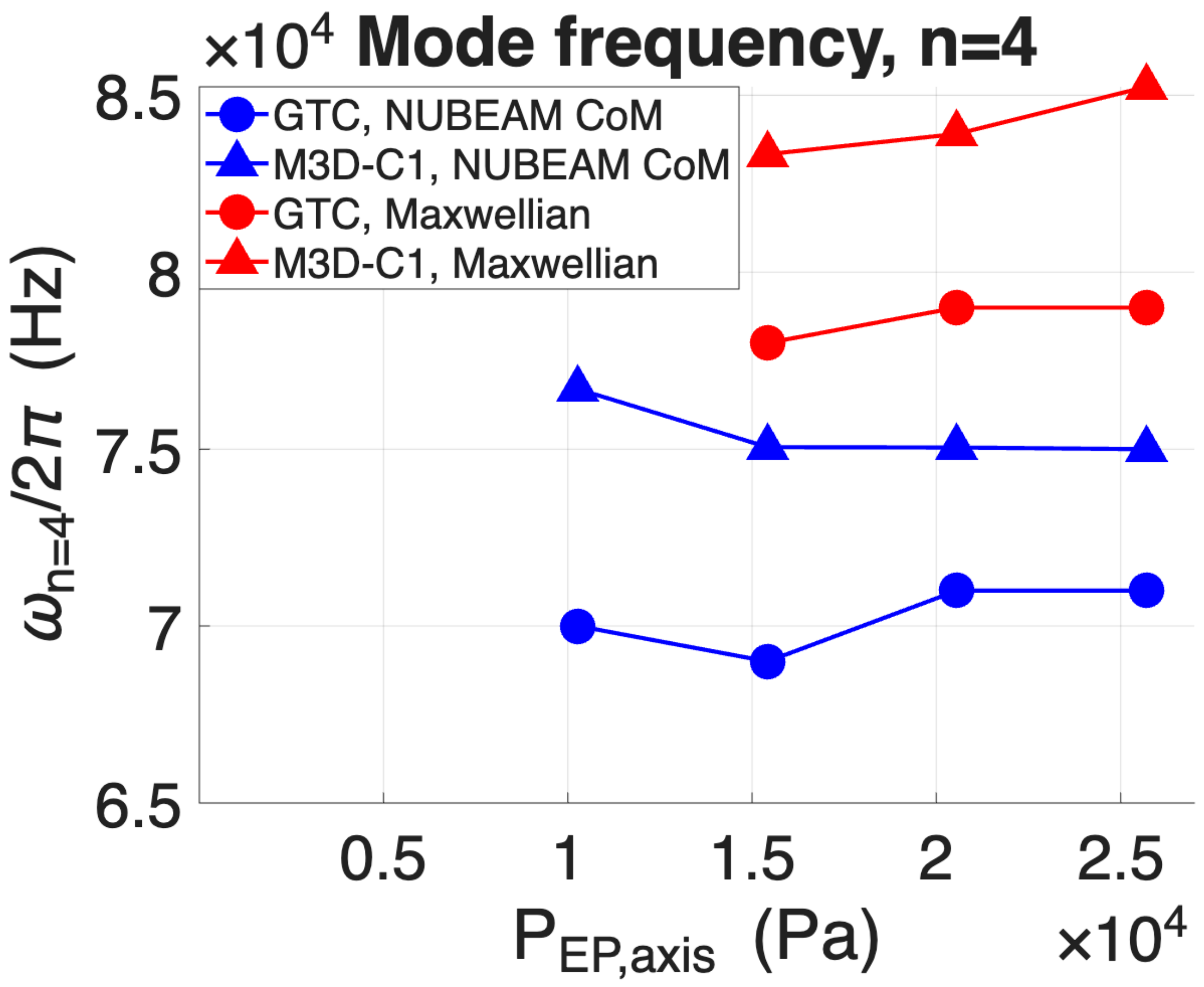
➢A q_{min} **scan** is required for **validation** → **numerical test** to emphasise **importance** of using **realistic distributions**

Maxwellian approximation strongly impacts BAE stability



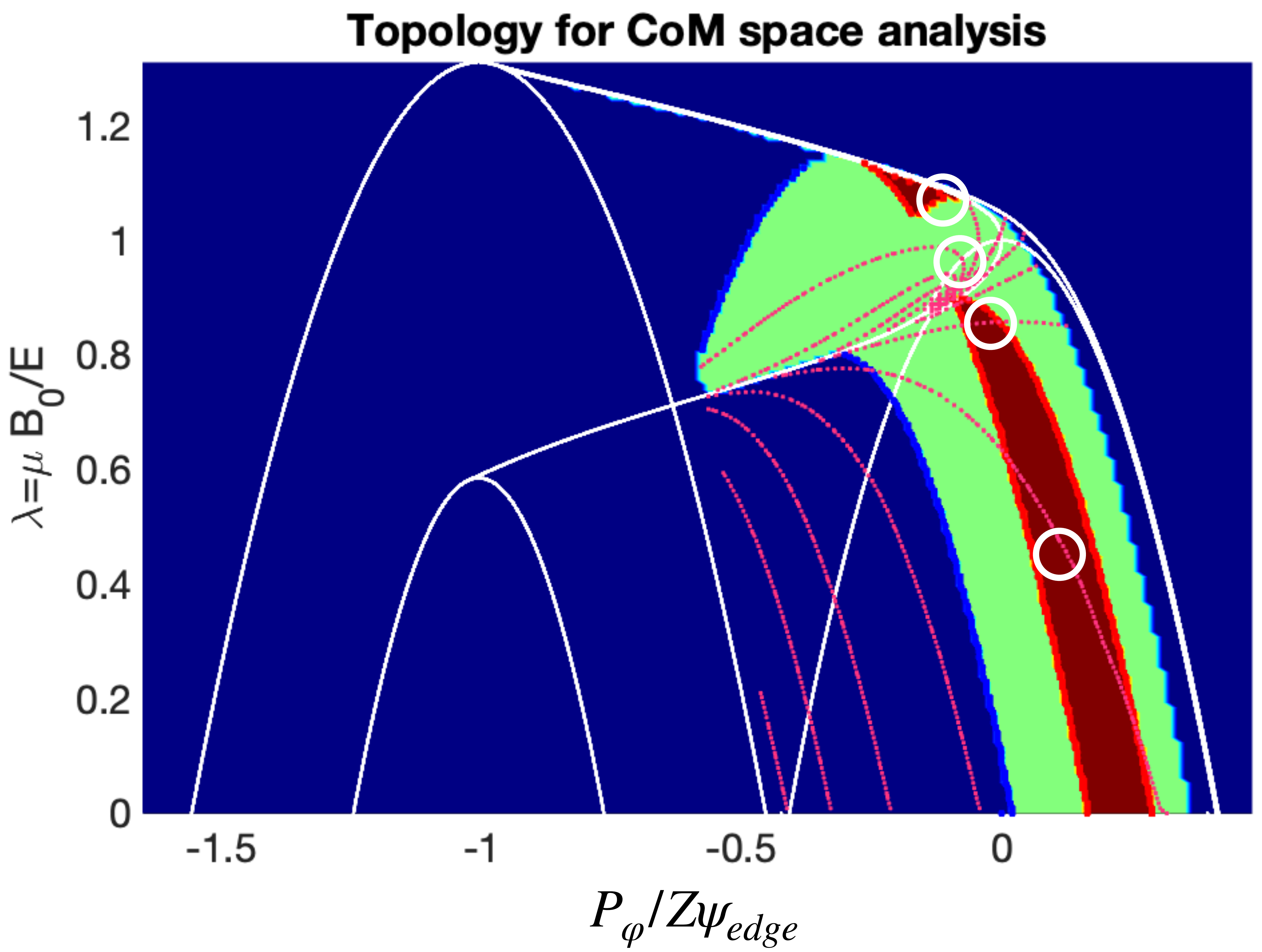


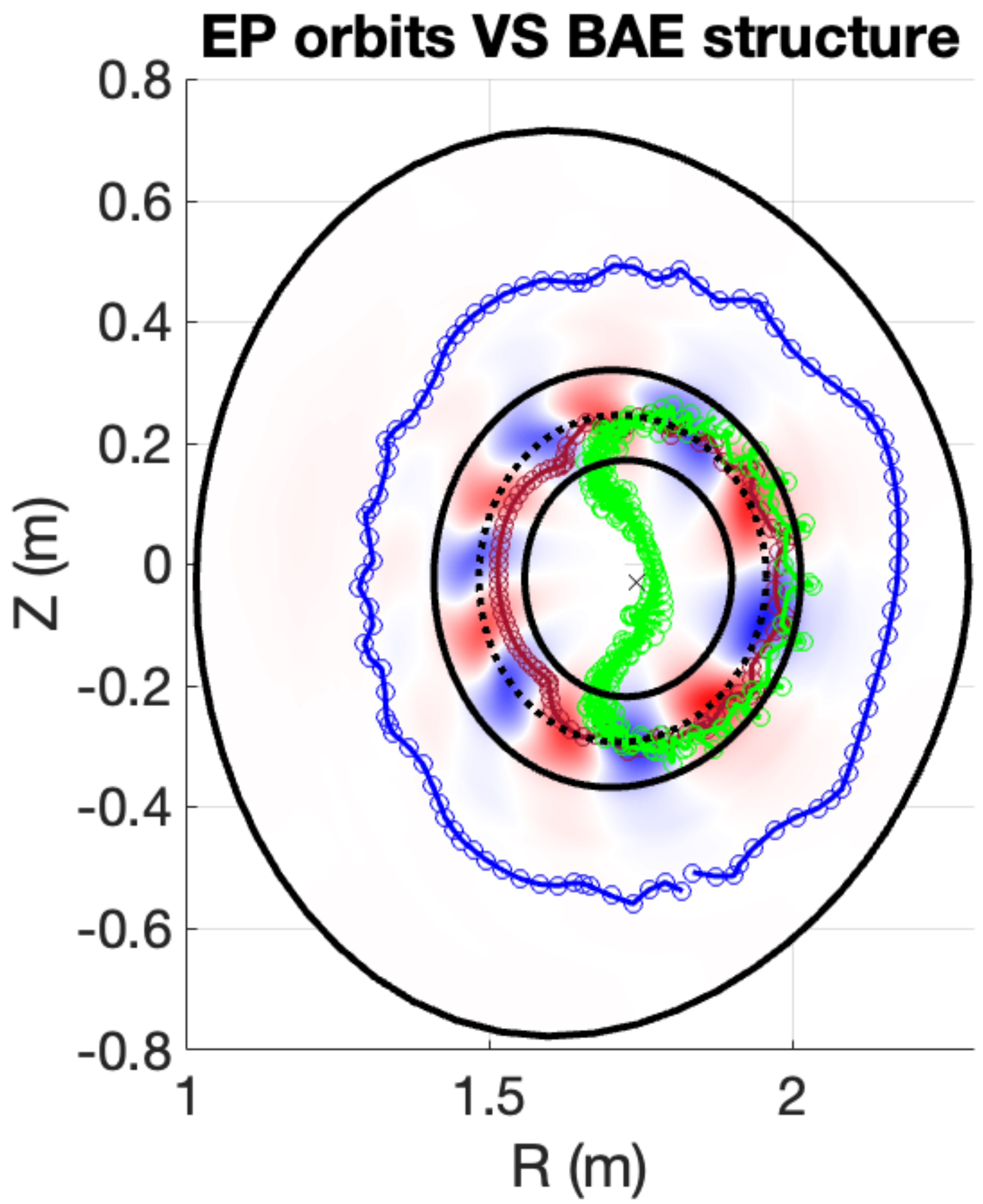




- ➢Linear **GTC** and **M3D-C1** simulations are performed for **t=1125ms** (1st unstable BAE window)
- ➢Over this **numerical test, GTC** and **M3D-C1 linear results are very similar**
- ➢**Both codes** shows that the **Maxwellian approximation lowers by a factor of 2** the BAE growth rate
- ➢The mode frequency is **weakly affected,** as expected from a **gap mode**
- ➢**Stronger EP drive** with **NUBEAM** distribution can be **explained** with **CoM space analysis**

Methodology for CoM space analysis





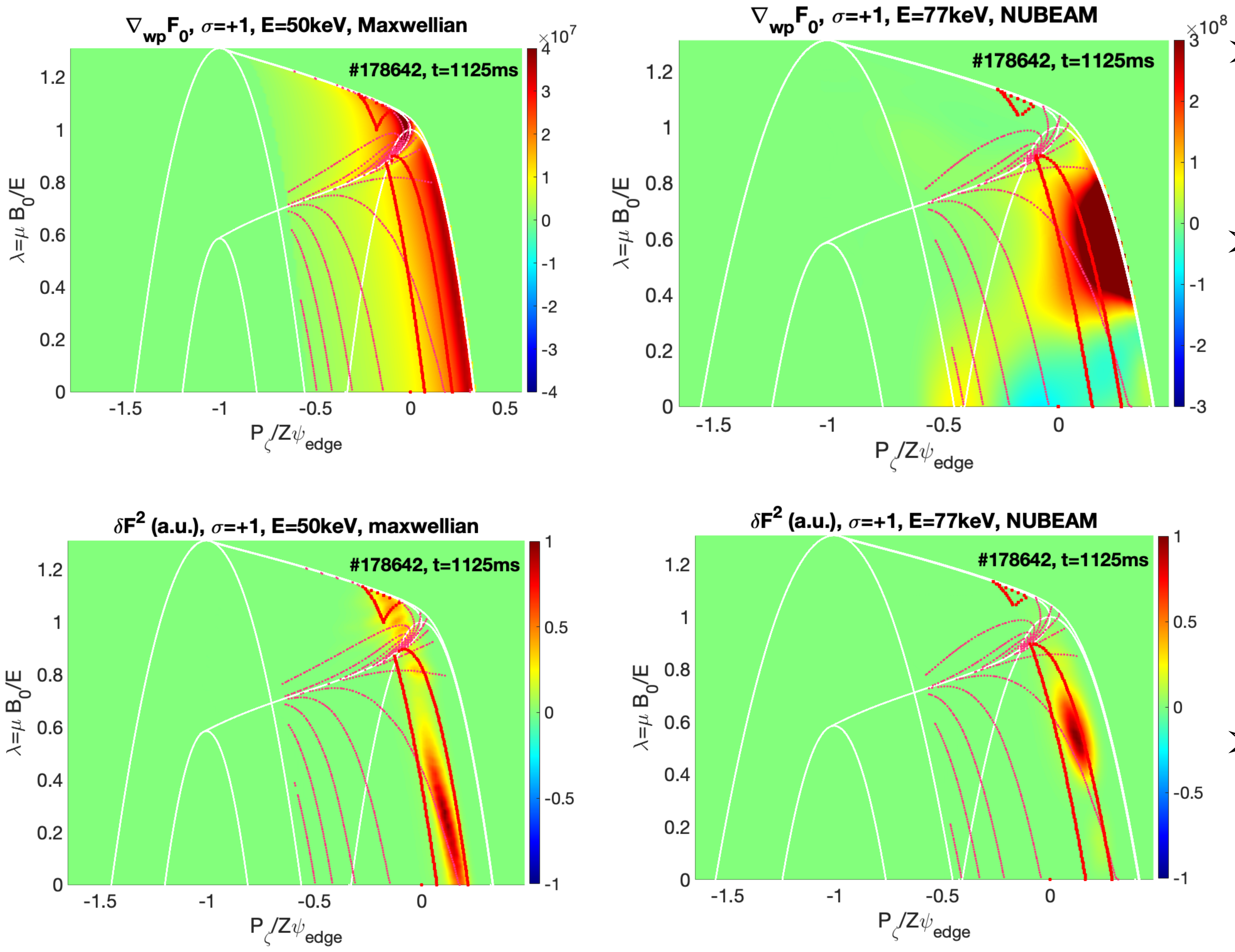
➢Phase space analysis facilitated by **highlighting** the **BAE mode structure** and **resonances positions** in CoM space

➢Based on the **CoM orbits extent, three zones** can be isolated **: orbits fully, partly** and **not confined** in the mode

➢The p **resonances** $\omega = n\omega_\varphi - p\omega_\theta$ are computed for **each BAE** (ω, n) **values**

➢**Wave-particle interactions** most likely to **occur along resonances within the fully confined domain**

Maxwellian drive significantly lower at high energy



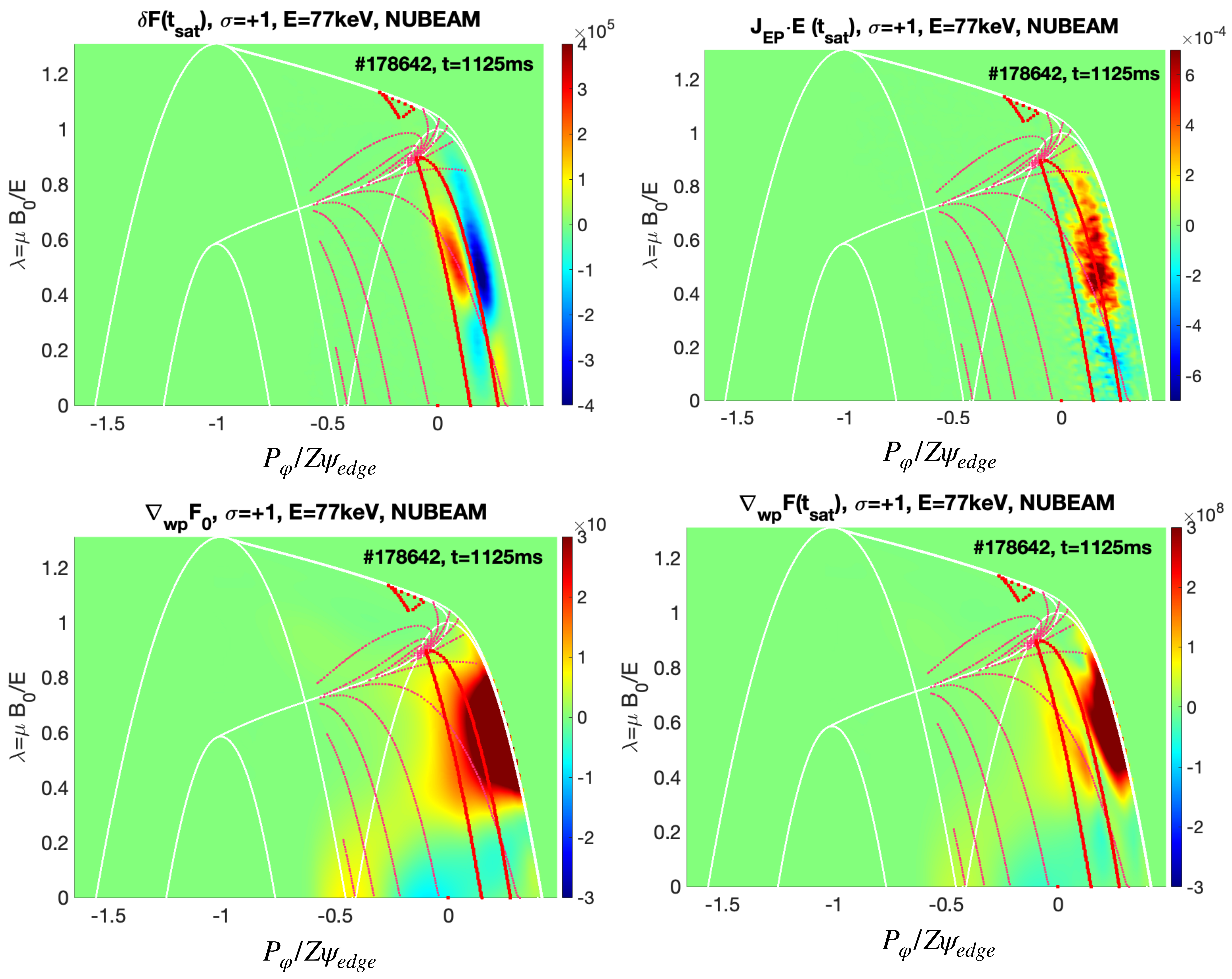
➢**The beam drive** is much **stronger** than its **Maxwellian counterpart**

➢**Less resonances** are available for the beam case, due to its **anisotropy**

➢**Resonant structures** obtained with **GTC align exactly** with expected resonances for n=4 and f=75kHz

➢The **strength of the beam** $\nabla_{wp} F_0$ explains the **stronger BAE drive**, despite less resonances available

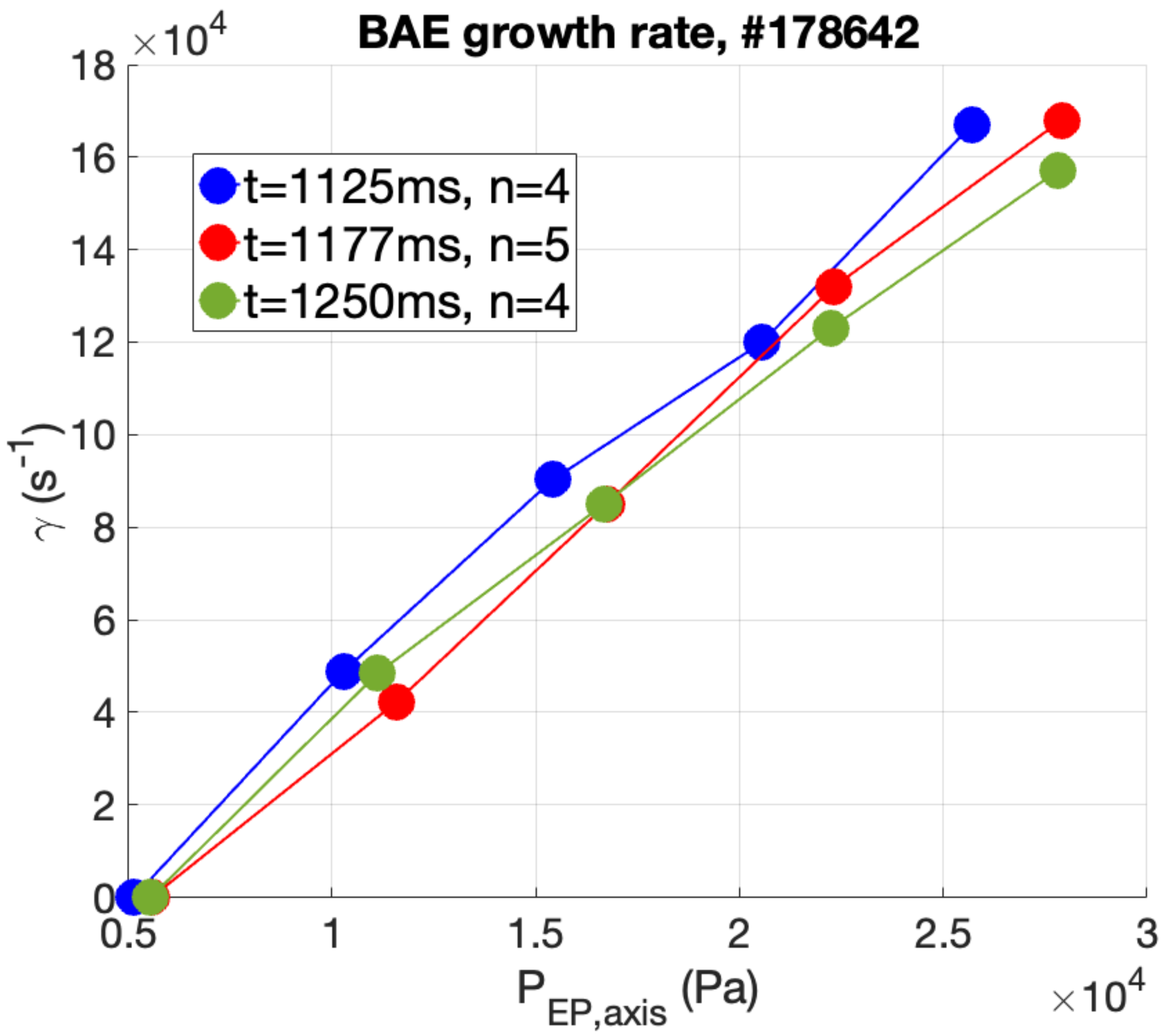
Nonlinear CoM saturation validated by theory

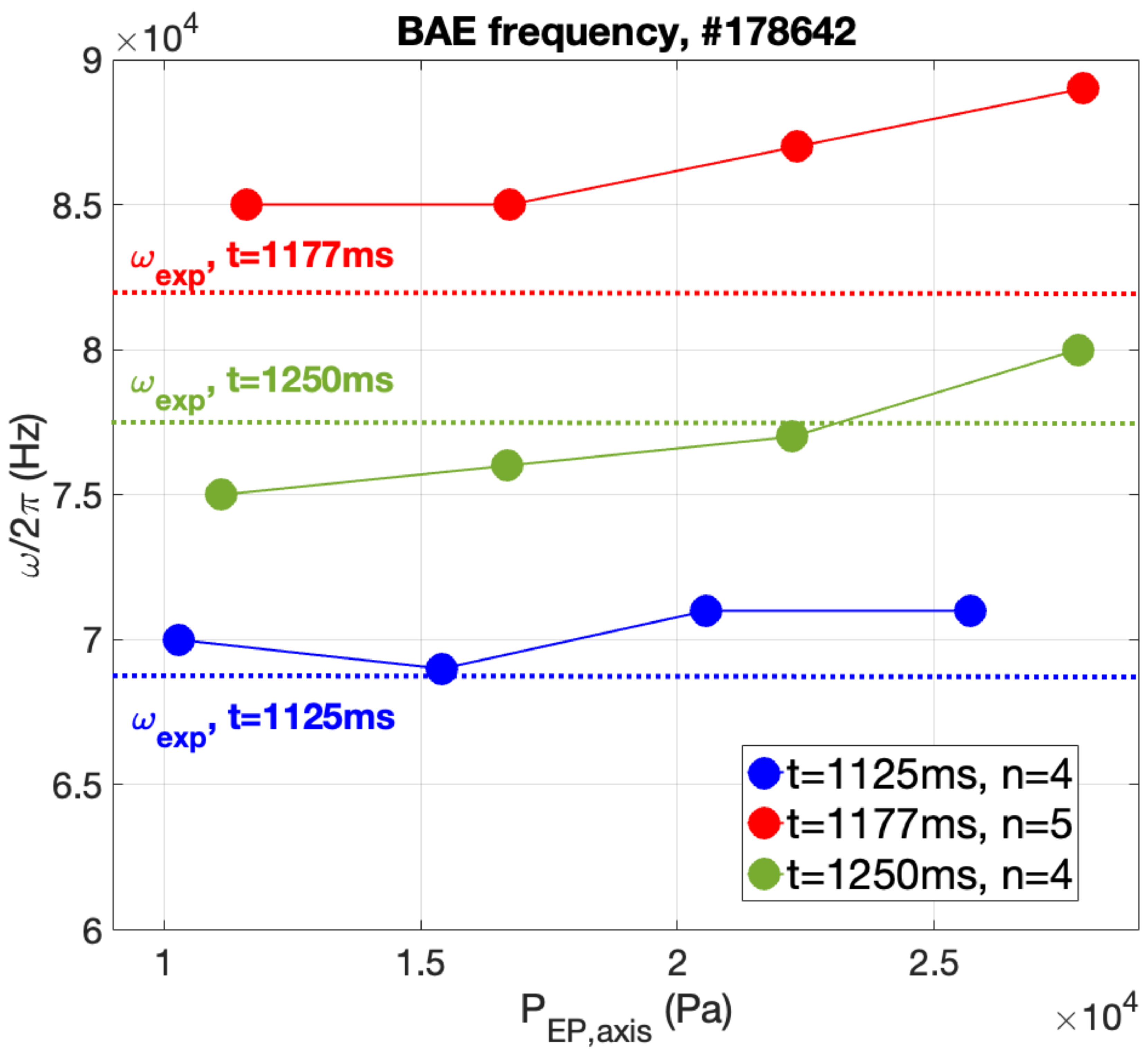


- ➢ δF_{EP} phase space zonal structures **(PSZS [1]) are plotted at BAE saturation**
- ➢ F_{EP} **flattening** develops around **resonances**
- ➢ **Outward/inward EP transport** in GTC **consistent** with $J_{EP} \cdot E$ and $\nabla_{wp} F_0$ **signs**
  - → **GTC CoM** version **verified theoretically**
- ➢ **GTC** can be **restarted** with **updated EP distributions,** accounting for EP flattening
- ➢ It provides a **direct connection** between **GTC** and the **reduced EP transport model ATEP** [2]

[1] M. V. Falessi et al., 2023, *New J. Phys.*
[2] Ph. Lauber et al., 2024, *Nucl. Fusion.*

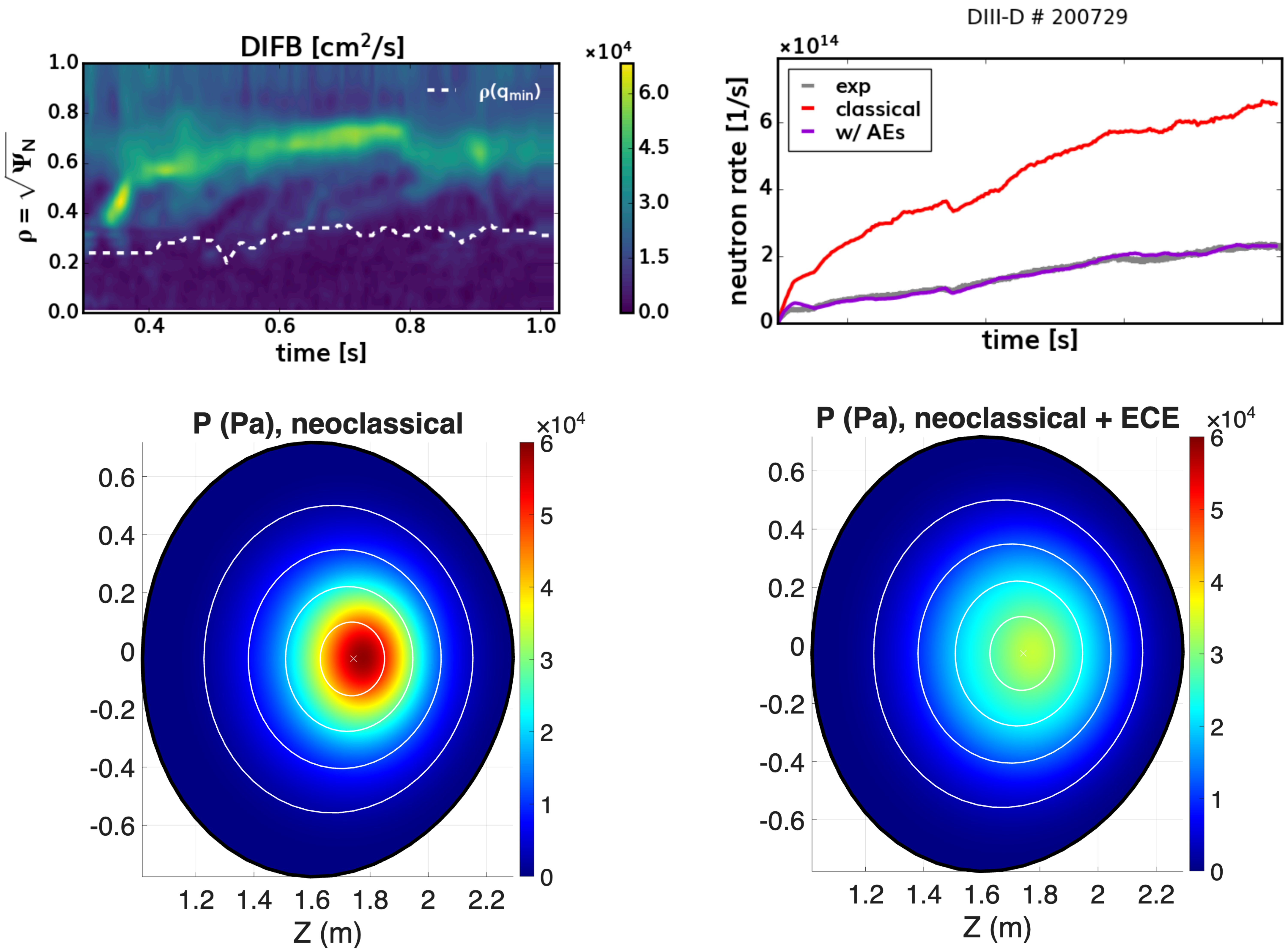
BAE stability across time slices





- ➢BAE stability is **marginally affected** over the **different times slices** in GTC **simulations**
- ➢**Contradictory** with **experiment**, where BAEs are stable at t=1177ms
- ➢ Not having the **correct n modes** and considering the **overestimated EP drive** from the **neoclassical NUBEAM** distribution are **presumably preventing** the experimental validation

More realistic beam reconstruction



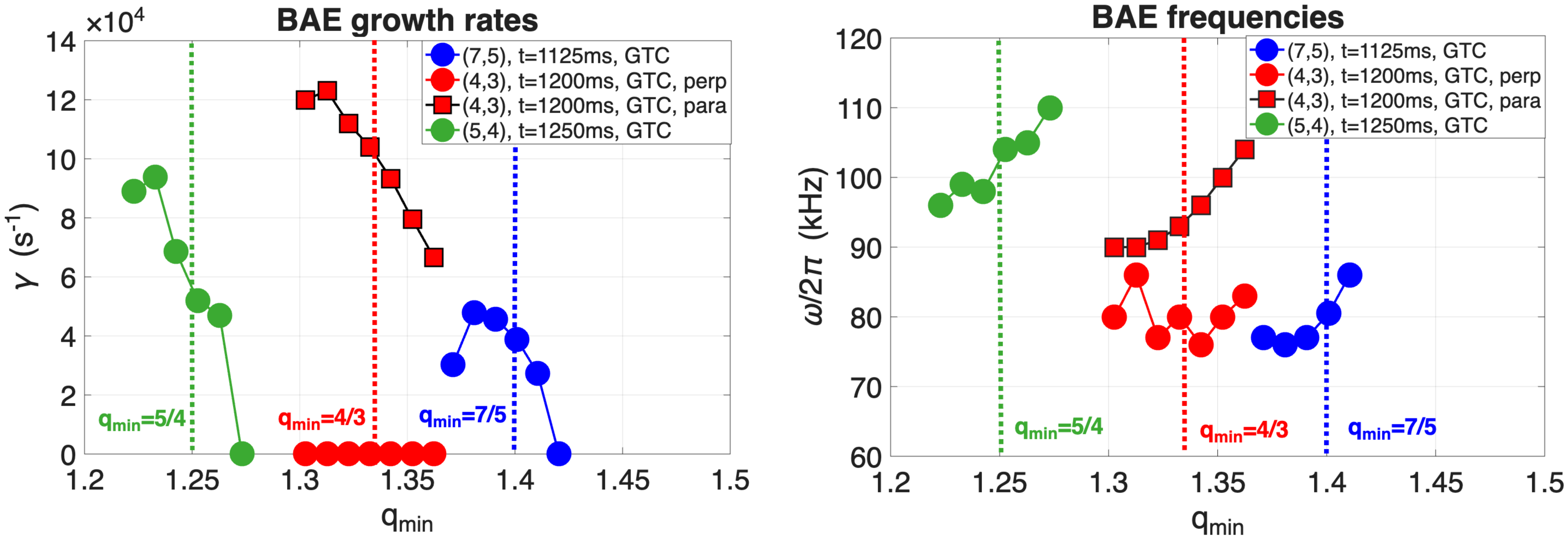
➢A **new module** has been developed in TRANSP-NUBEAM (**K. Callahan**) to **account for EP transport** due to **instabilities**

➢**ECE** measurements of the **mode amplitudes** in (t, ψ_T) used to **infer a diffusivity profile** on NUBEAM markers

➢**Method applied successfully** on DIII-D discharge **#200729**, **match** between **predicted** and **experimental** neutron rate

➢The resulting EP beam **has significantly flatter gradients** in phase space for DIII-D #178642

Validation obtained on BAE stabilisation



- **Relaxed NUBEAM** distributions including **ECE-based diffusivity now used ,** over a q_{min} **scan** enabled by the CHEASE equilibrium code
- The **same BAE** (m, n) **modes,** and the **BAE stabilisation** under **perpendicular beam** injection are **recovered by GTC**

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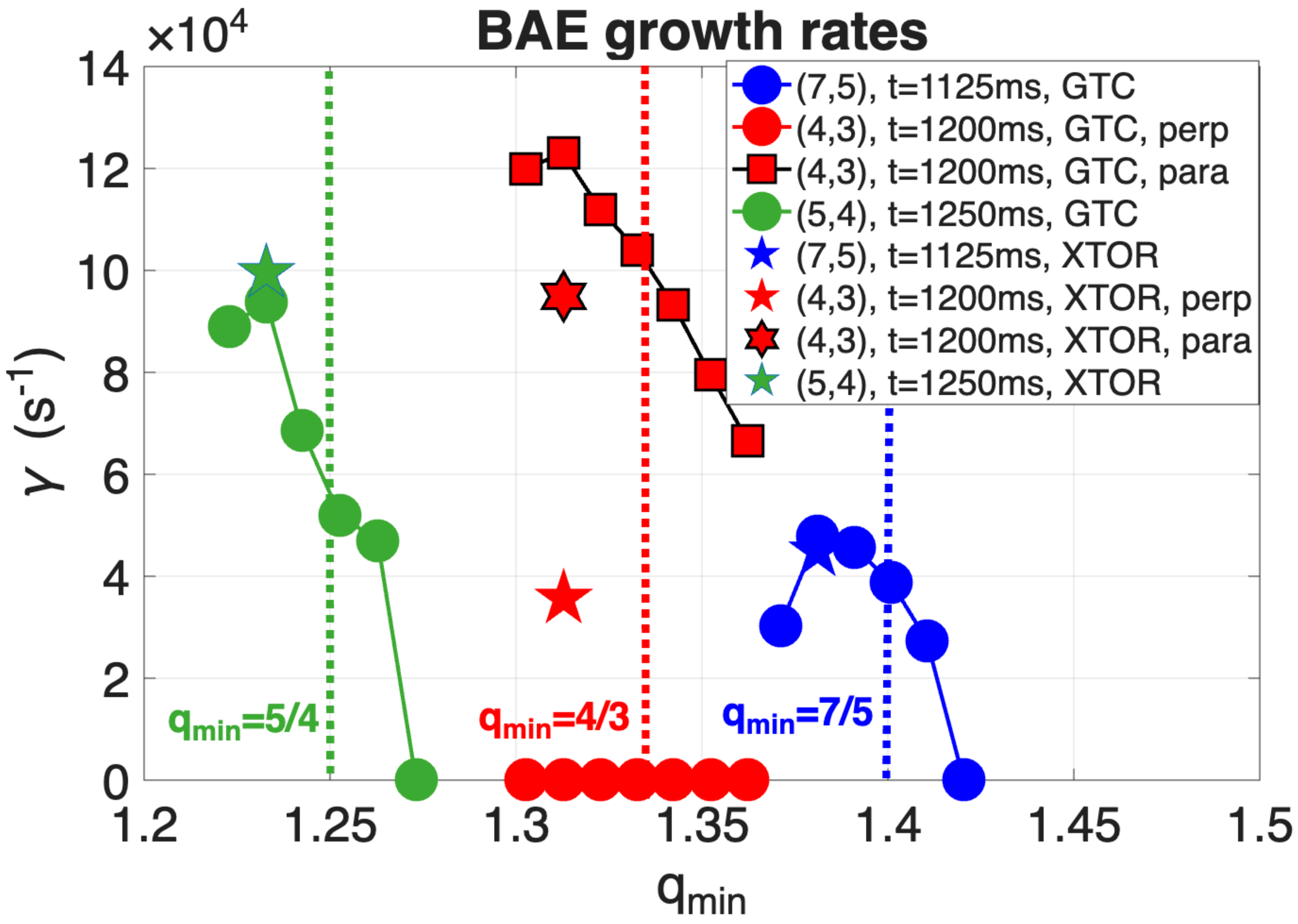

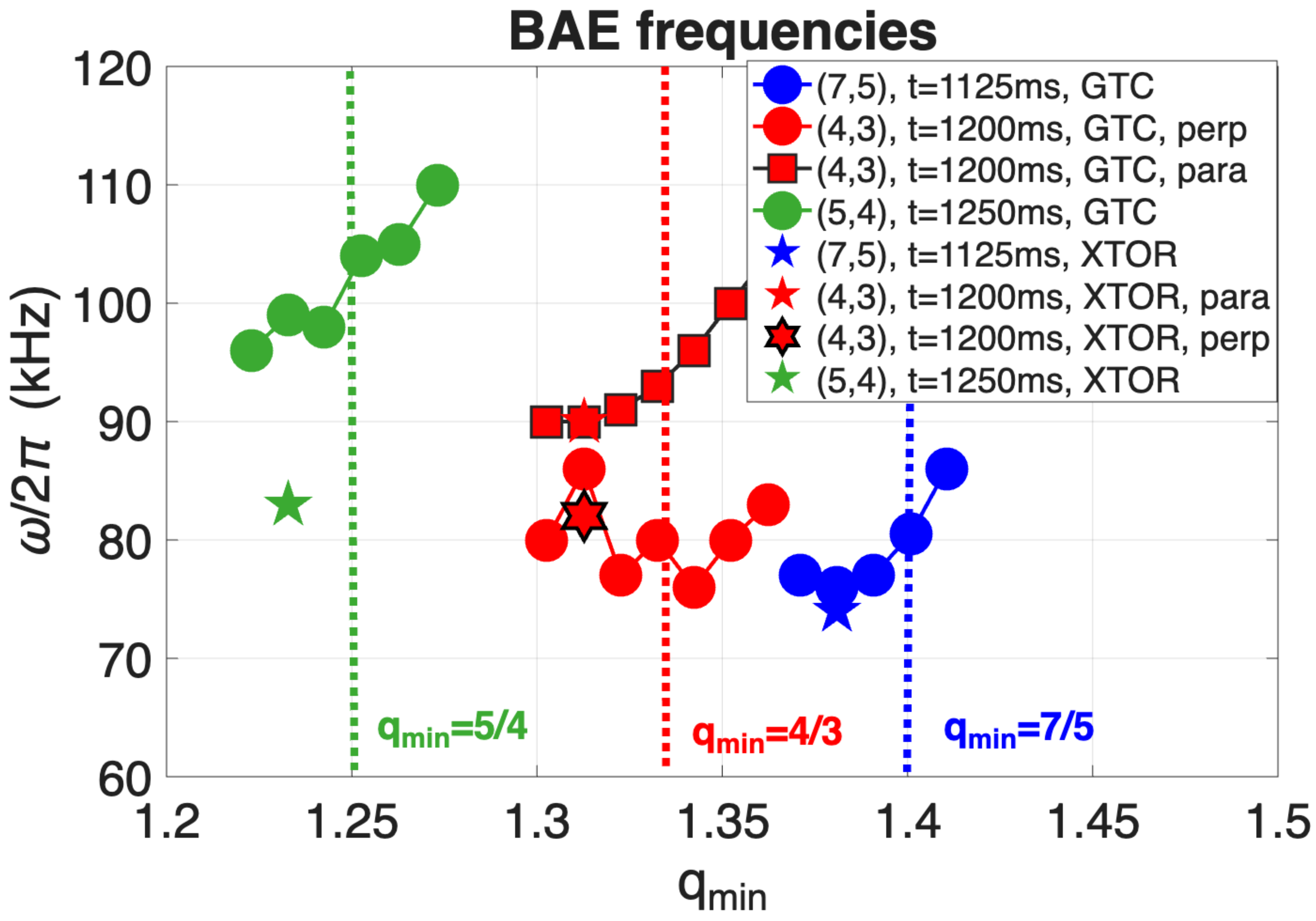

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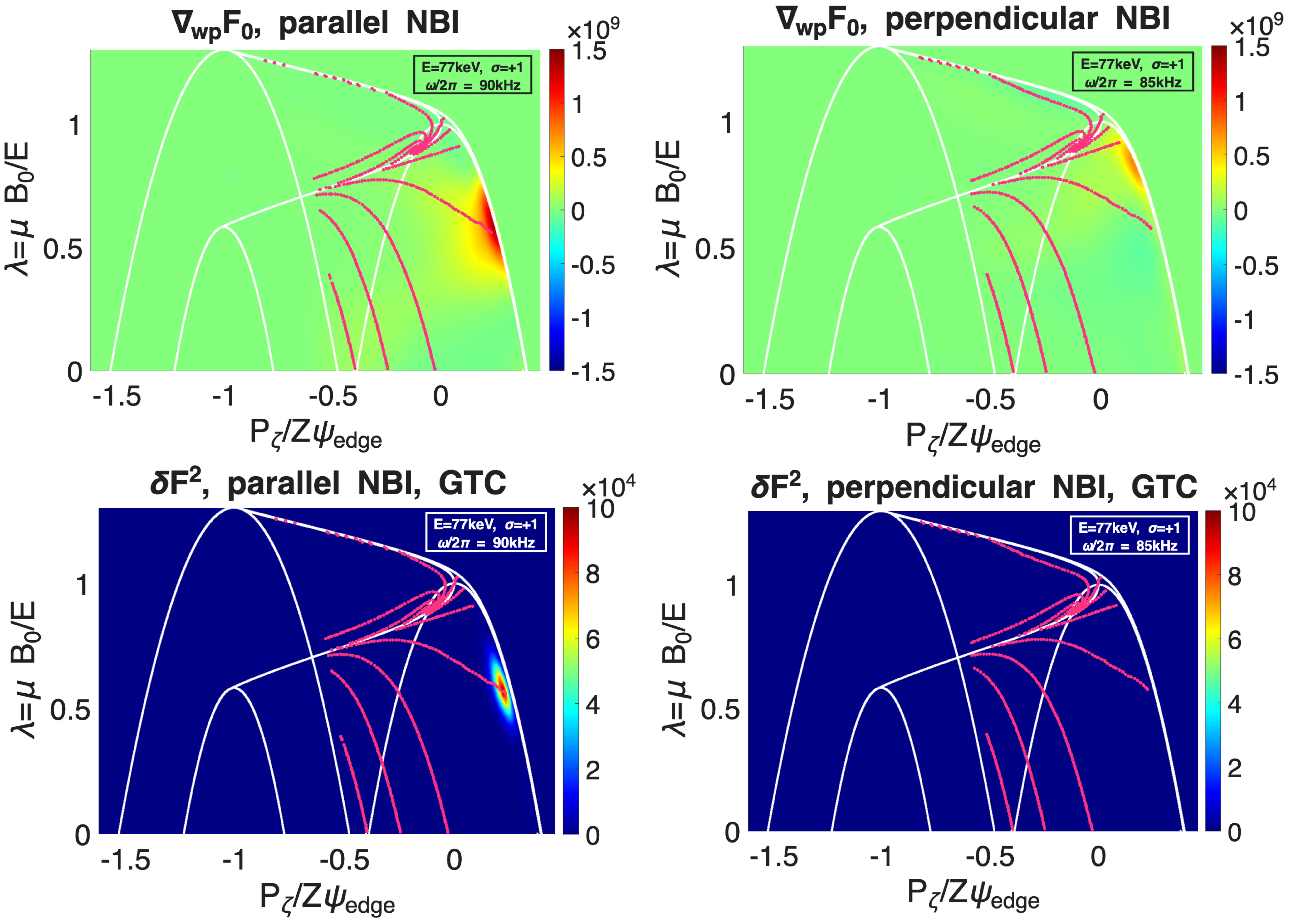
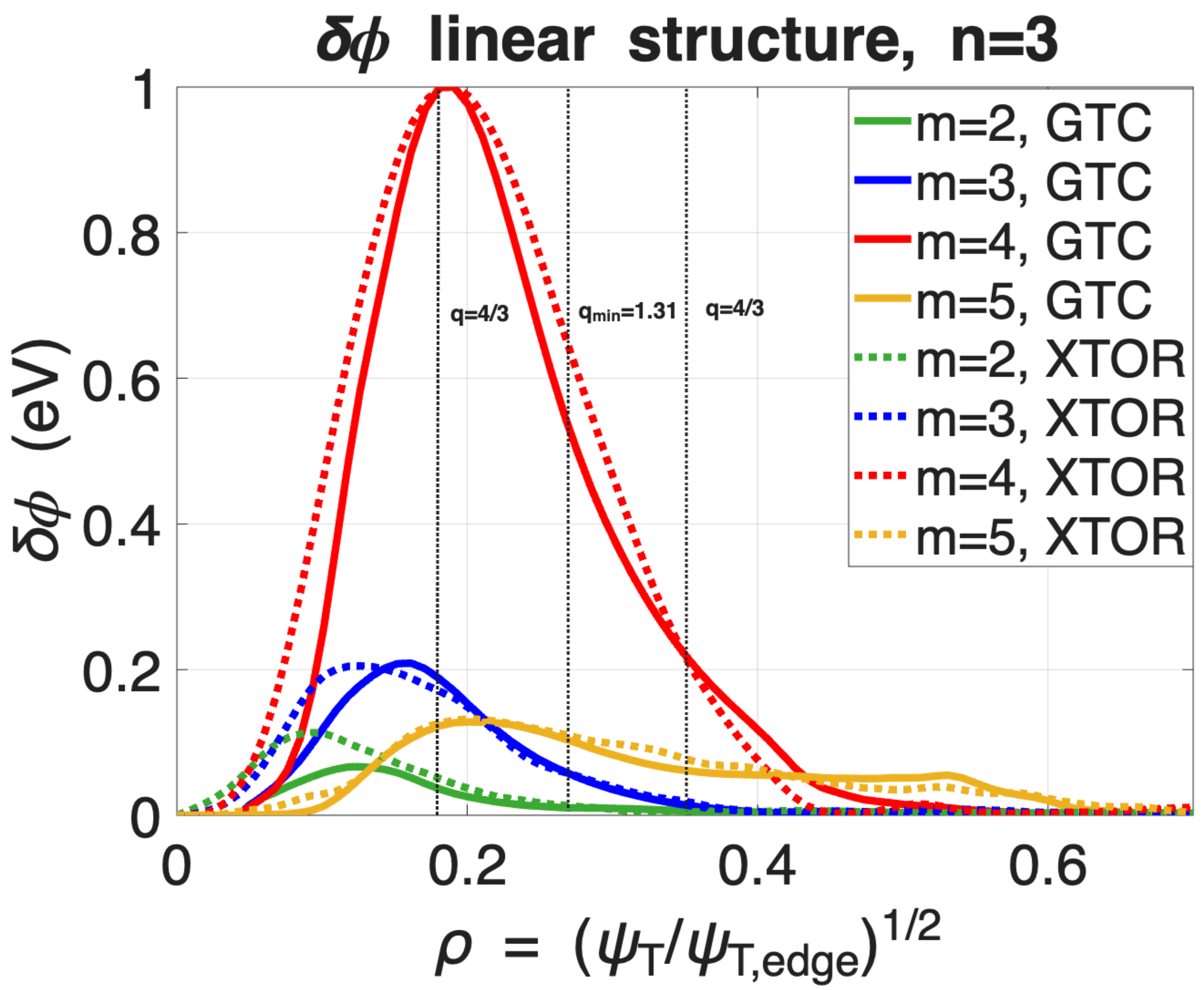
- The **same BAE** (m, n) **modes,** and the **BAE stabilisation** under **perpendicular beam** injection are **recovered by GTC**
- **XTOR** recovers **very similar stability results,** but with **marginally unstable BAE** at t=1200 under the **perpendicular** NBI, potentially due to the code **full-f nature**

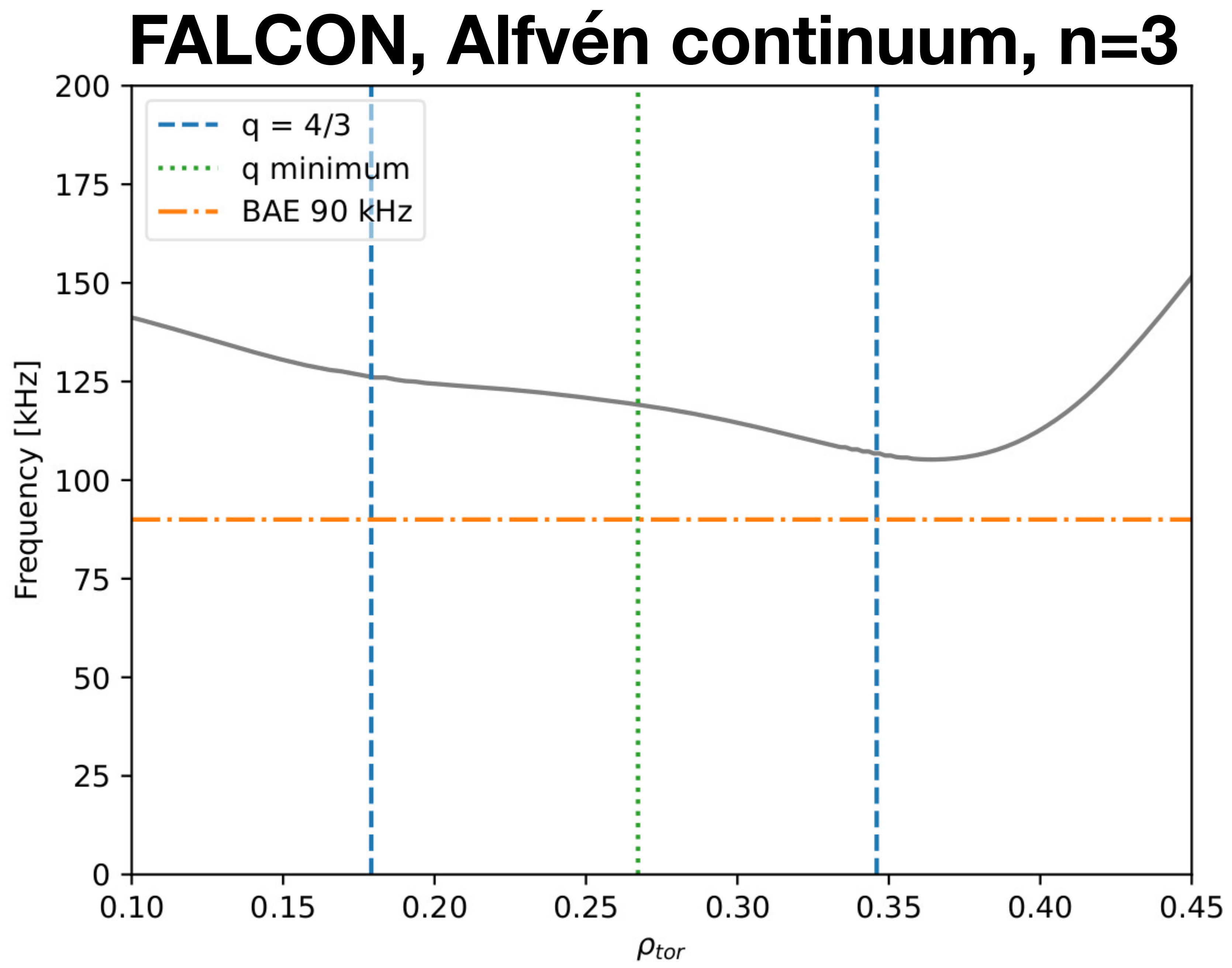
BAE stabilisation due to absent drive at resonances



- ➢Under **perpendicular** beam injection**,** the **EP drive** move towards **larger** $\lambda = \mu B_0/E$ **values**
- ➢**The perpendicular EP drive sits** right **in-between** wave-particle **resonances**
- ➢It **kills the BAE drive** compared to the parallel injection case**,** since **no resonances are excited**
- ➢The **BAE stabilisation** in **DIII-D in** indeed due to **modifications** of the **EP phase space distribution**

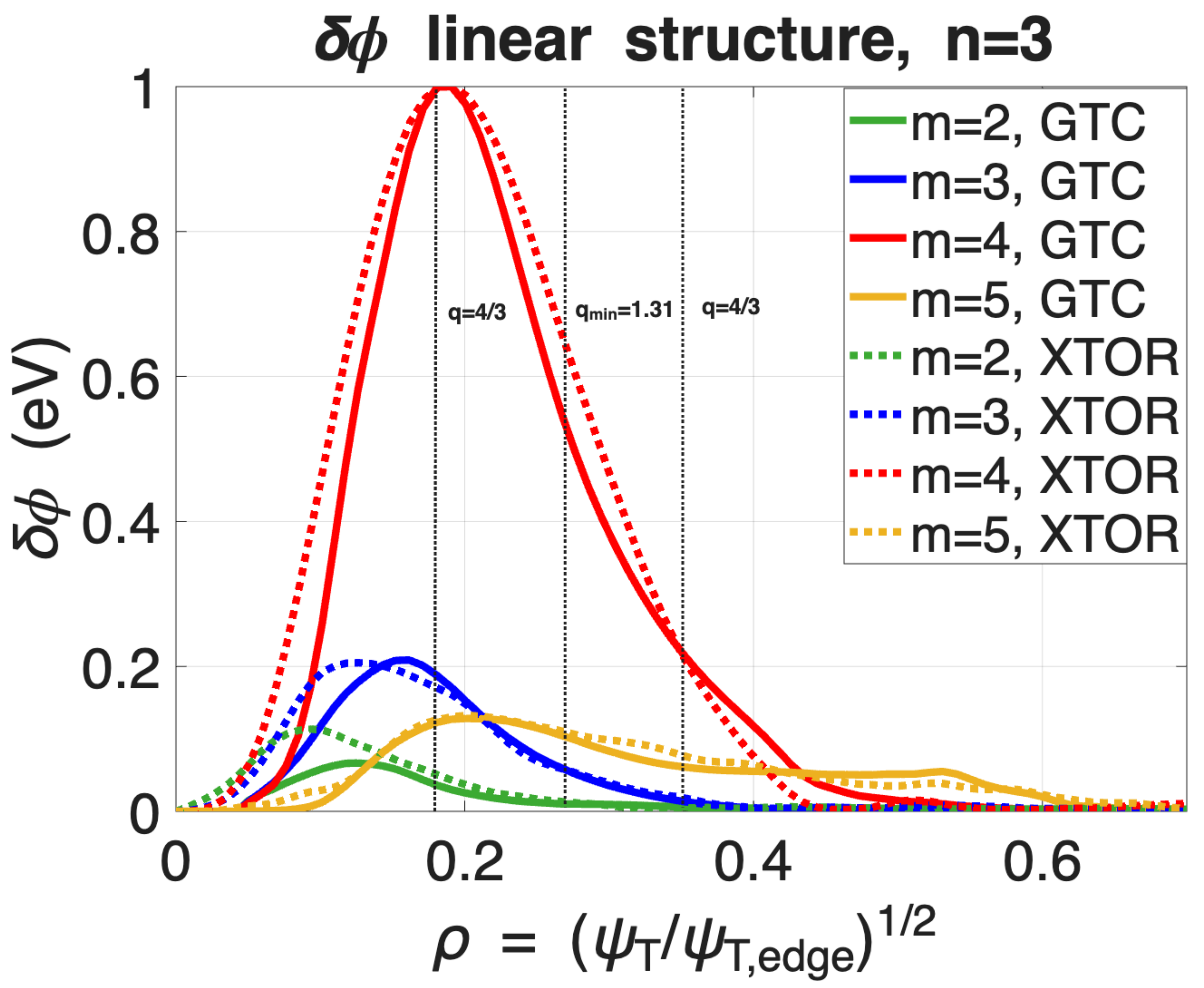
Linear and nonlinear XTOR-GTC verification

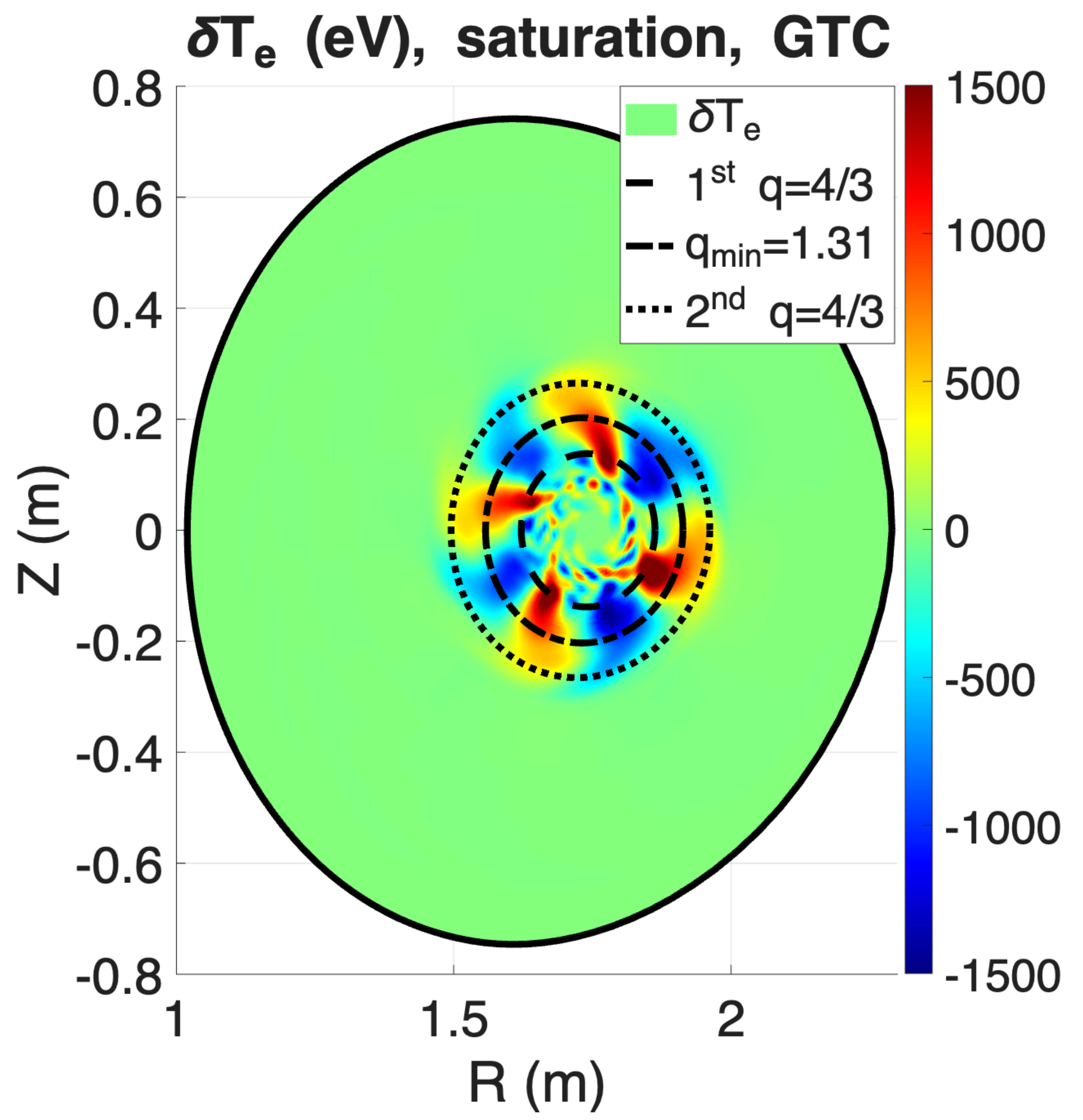


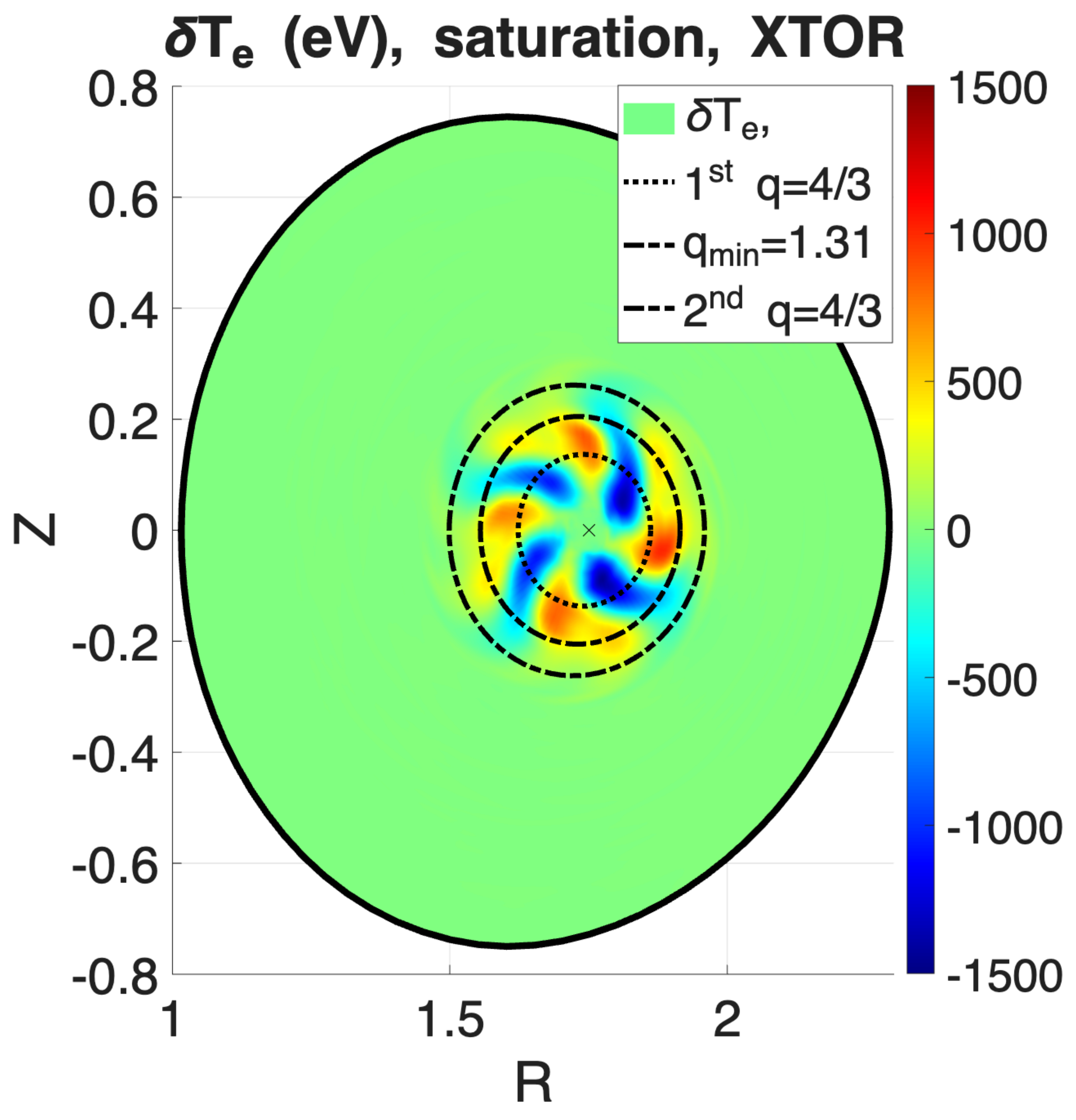


- ➢**XTOR** and **GTC linear/nonlinear results** are compared for **t=1200ms with parallel NBI**
- ➢The **linear BAE mode structures** are in **quantitative agreement** between the codes
- ➢The mode frequency lies **below the continuum** at inner $q = 4/3$, **confirming** its **BAE nature**

Linear and nonlinear XTOR-GTC verification







➢**XTOR** and **GTC linear/nonlinear results** are compared for **t=1200ms with parallel NBI**

➢The **linear BAE mode structures** are in **quantitative agreement** between the codes

➢The mode frequency lies **below the continuum** at inner $q = 4/3$, **confirming** its **BAE nature**

➢In both codes, the **BAE saturates (overshoot) at similar amplitudes** $\delta T_E \sim 1.5$ **keV**

Phase space transport GTC-XTOR verification

➢The **perturbed distributions** in **CoM** space**,** or **phase space zonal structures [1],** are in **quantitative agreement** in both **shape** and **amplitude** at **BAE saturation**

➢These results provide a **detailed V&V** of **BAE simulations** for these two codes **against DIII-D experiments**

[1] M.V. Falessi et al. 2023, *New J. Phys.*

Coupling to the ATEP transport model

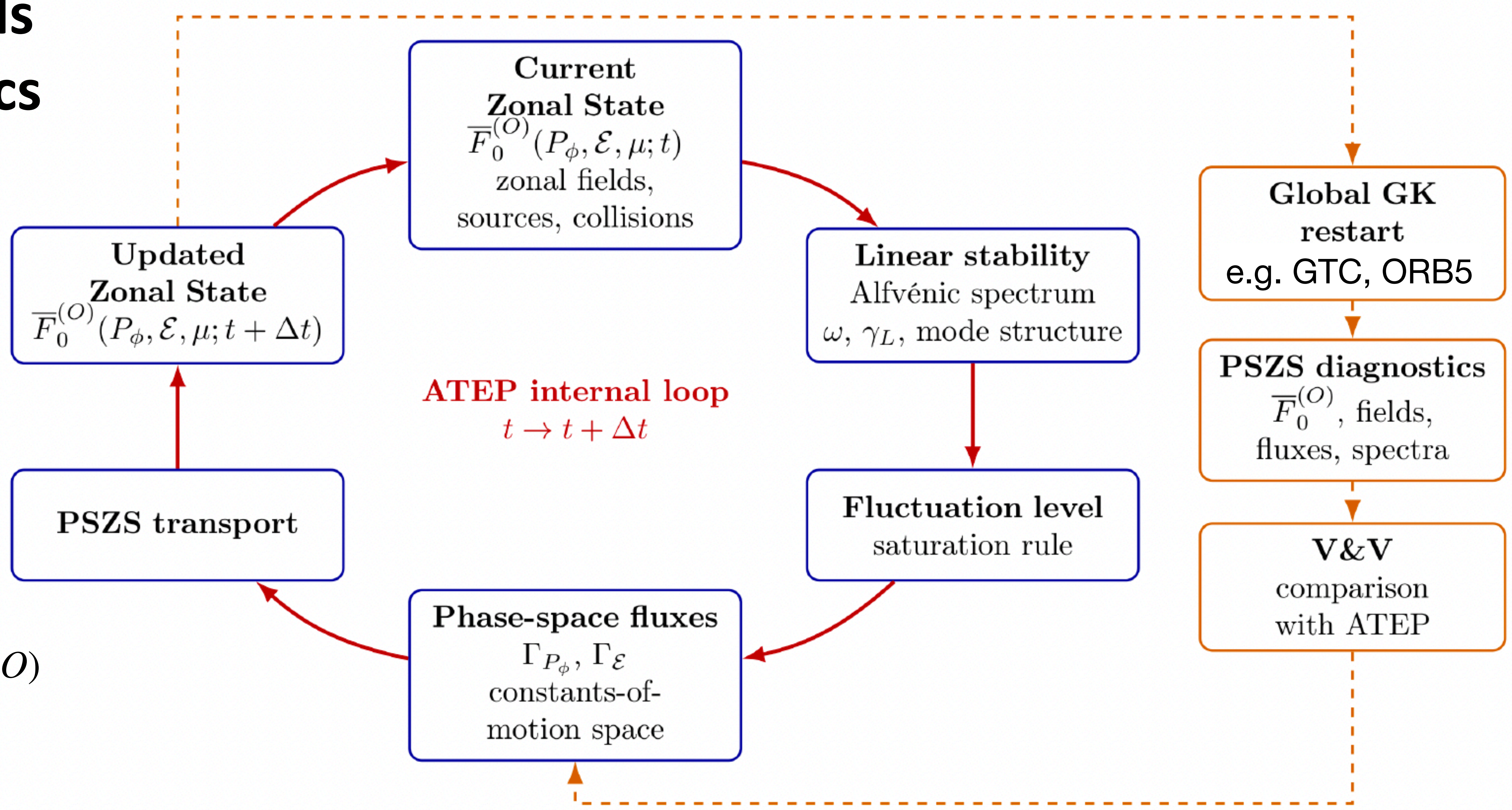
➢**GTC** and **XTOR** can connect to **realistic transport models** such as **ATEP** [1,2] through their **verified PSZS diagnostics**

$$\partial_t F_0^{(O)} + \frac{1}{\tau_B}\left[\frac{\partial}{\partial P_\varphi}\left(\tau_B \Gamma_\varphi\right) + \frac{\partial}{\partial E}\left(\tau_B \Gamma_E\right)\right] = C_0^{(O)} + S_0^{(O)}$$

$$[A]^{(O)} = \tau_B^{-1}\int A d\theta/\dot{\theta} \equiv A(P_{\varphi_i}, \mu_j, E_k) \equiv \sum_{n=1}^{N} S_{i,j,k}(P_{\varphi_n}, \mu_n, E_n)$$

$$\Gamma_{P_\varphi} = [\delta\dot{\mathbf{X}} \cdot \nabla P_\varphi \delta F]^{(O)} \qquad \Gamma_E = \left[\mathbf{X}_0 \cdot \nabla(\delta\phi - v_\parallel \delta A_\parallel + \mu B_0/Z)\delta F\right]^{(O)}$$

Global GK - ATEP transport workflow



➢Γ_{P_φ} and Γ_E are currently **being implemented** in **GTC**, following the **same scheme** as $\delta F^{(O)}$

➢**Restart** in **GTC** from an **ATEP-updated** $F^{(0)}$ is now possible due to the **new CoM space initialisation**

➢**Long term EP transport** simulations using **GTC** and **ATEP** will **soon be performed**

[1] M.V. Falessi et al. 2023, *New J. Phys.*
[2] P. Lauber et al. 2024, *Nucl. Fusion*

Conclusions

- ➢A **DIII-D discharge** with **BAEs** sensitive to **beam injection angle** have been chosen as a **V&V case to verify the use of realistic EP distributions** within the ITPA-EP community

- ➢The **NUBEAM** and **EPCoM codes** are used to **model realistically** EP distributions in **CoM space,** where the **EP drive and resonances** can be explicitly shown

- ➢**Realistic** EP distributions have a **strong impact on BAE stability** compared to equivalent **Maxwellians,** due to **stronger drive** at **injection energy**

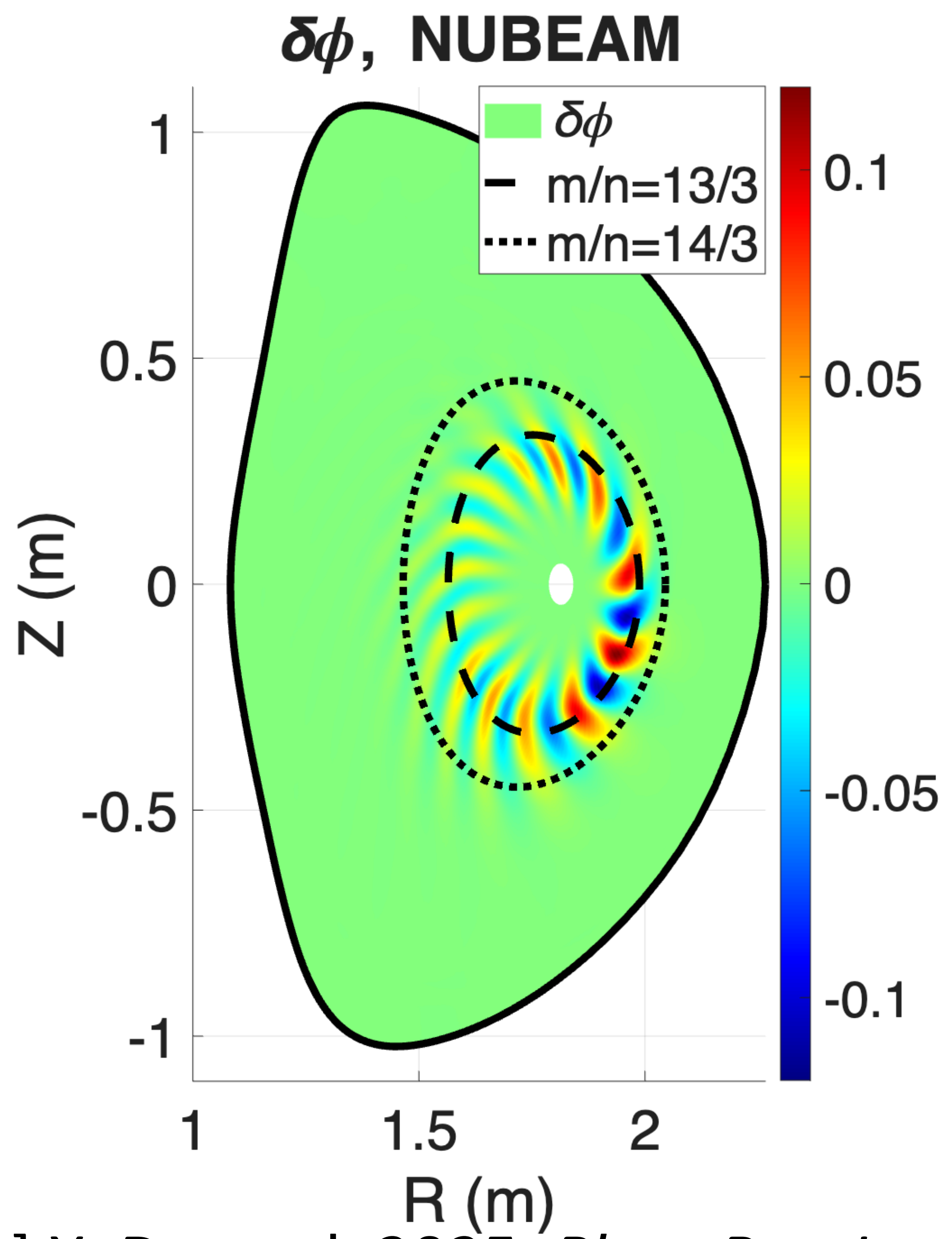
- ➢The **BAE stabilization** under perpendicular NBI **is reproduced** in **GTC** and **XTOR simulations,** and due to **misalignment** between **EP drive** and **wave-particles resonances**

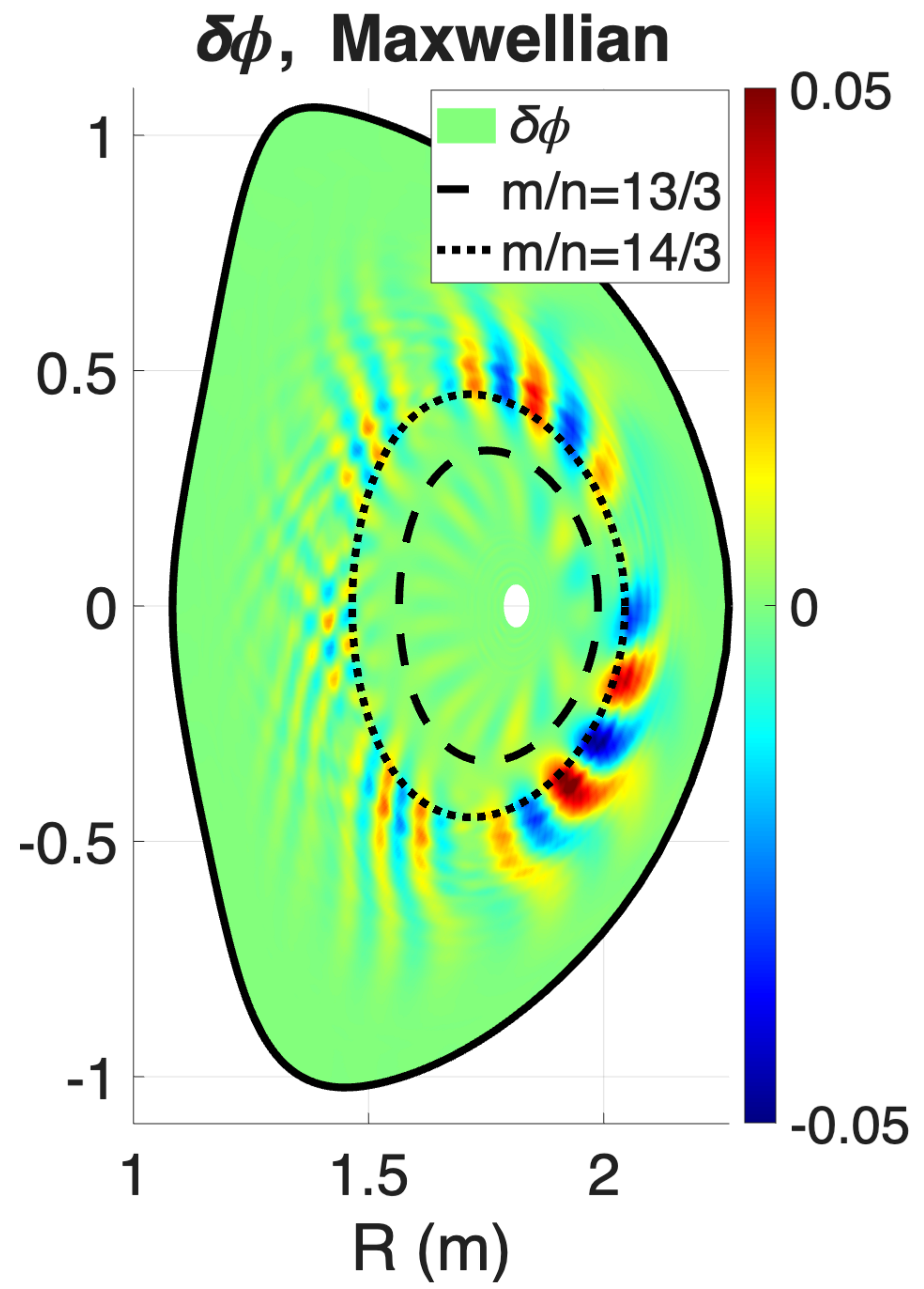
- ➢**Quantitative** linear and nonlinear **agreements obtained** for **GTC** and **XTOR** BAE simulations

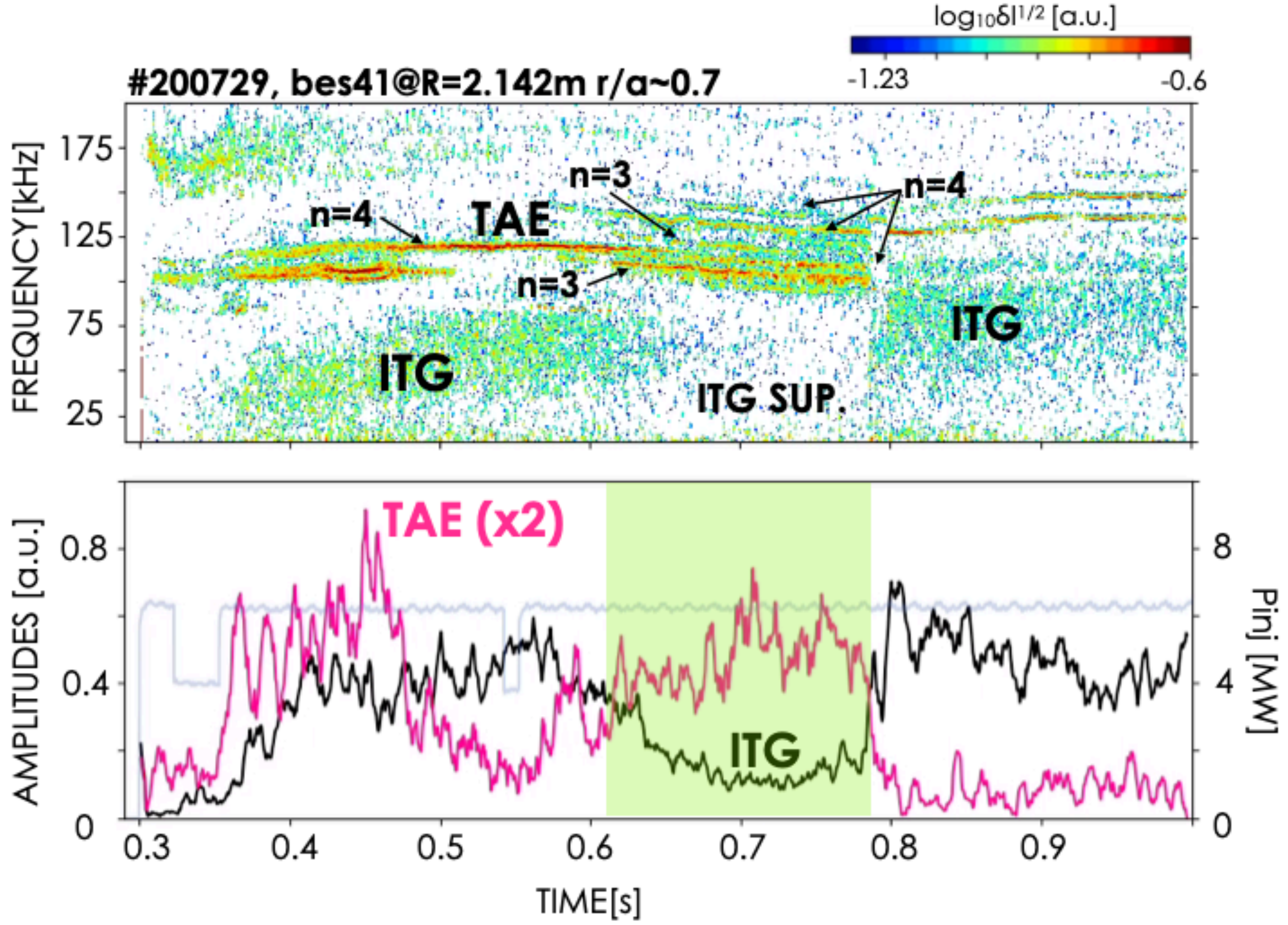
Perspectives

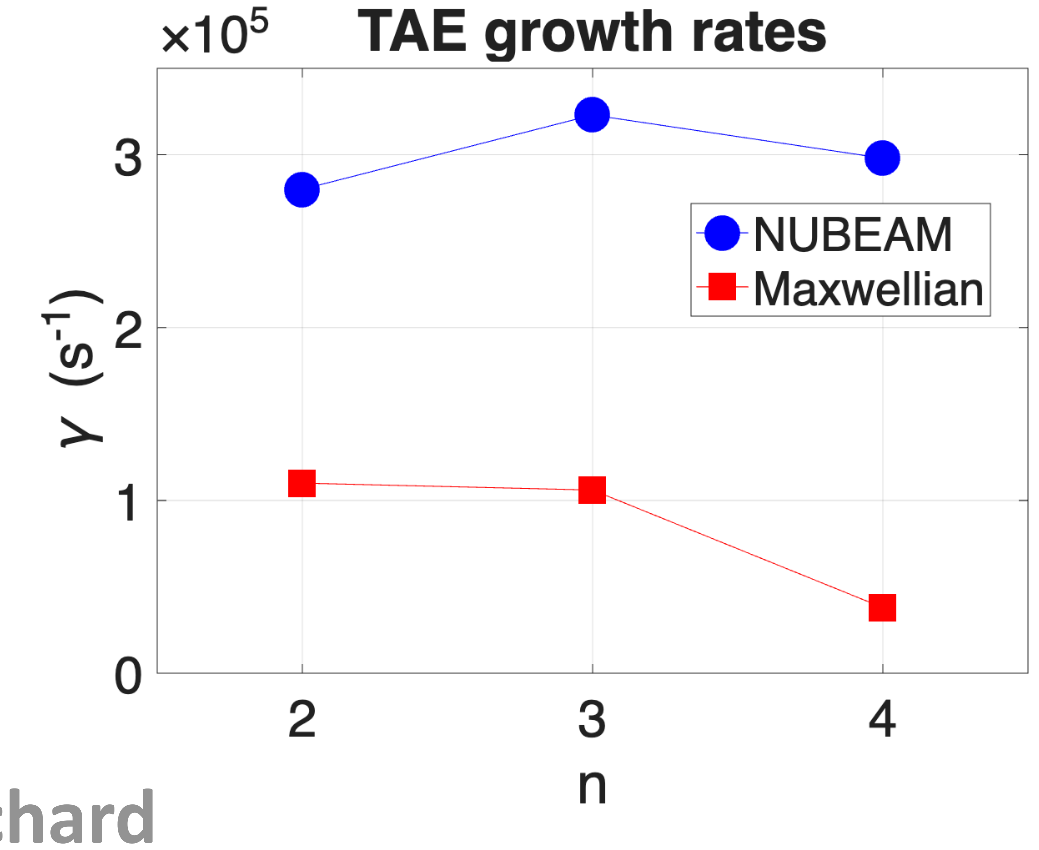
➢**Cross-scale** gyrokinetic simulations will be performed with **realistic EP distributions** to understand **confinement improvement** in **DIII-D [1]** and **JET-DT [2]** plasmas

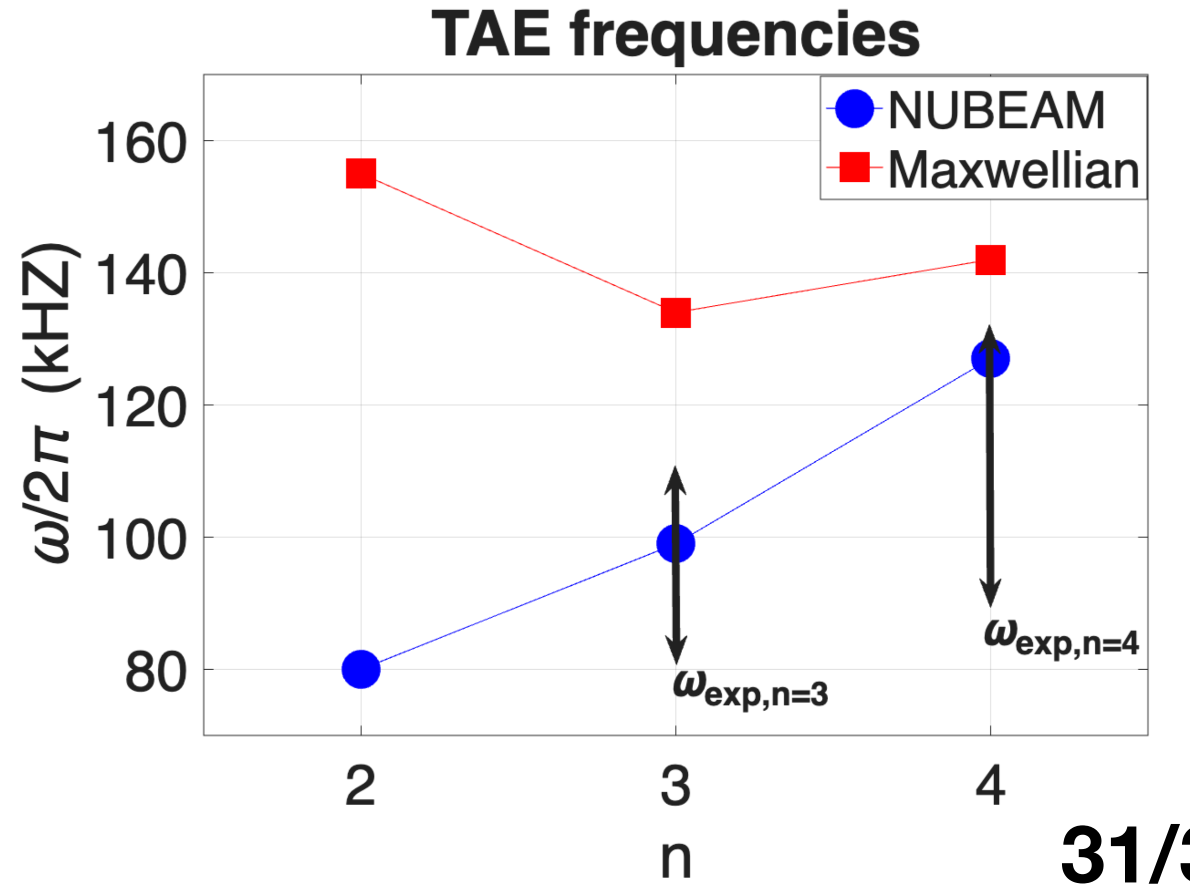
➢**Initial results** for the **DIII-D case** shows the **importance** of **realistic EP input** for modelling the **TAEs**







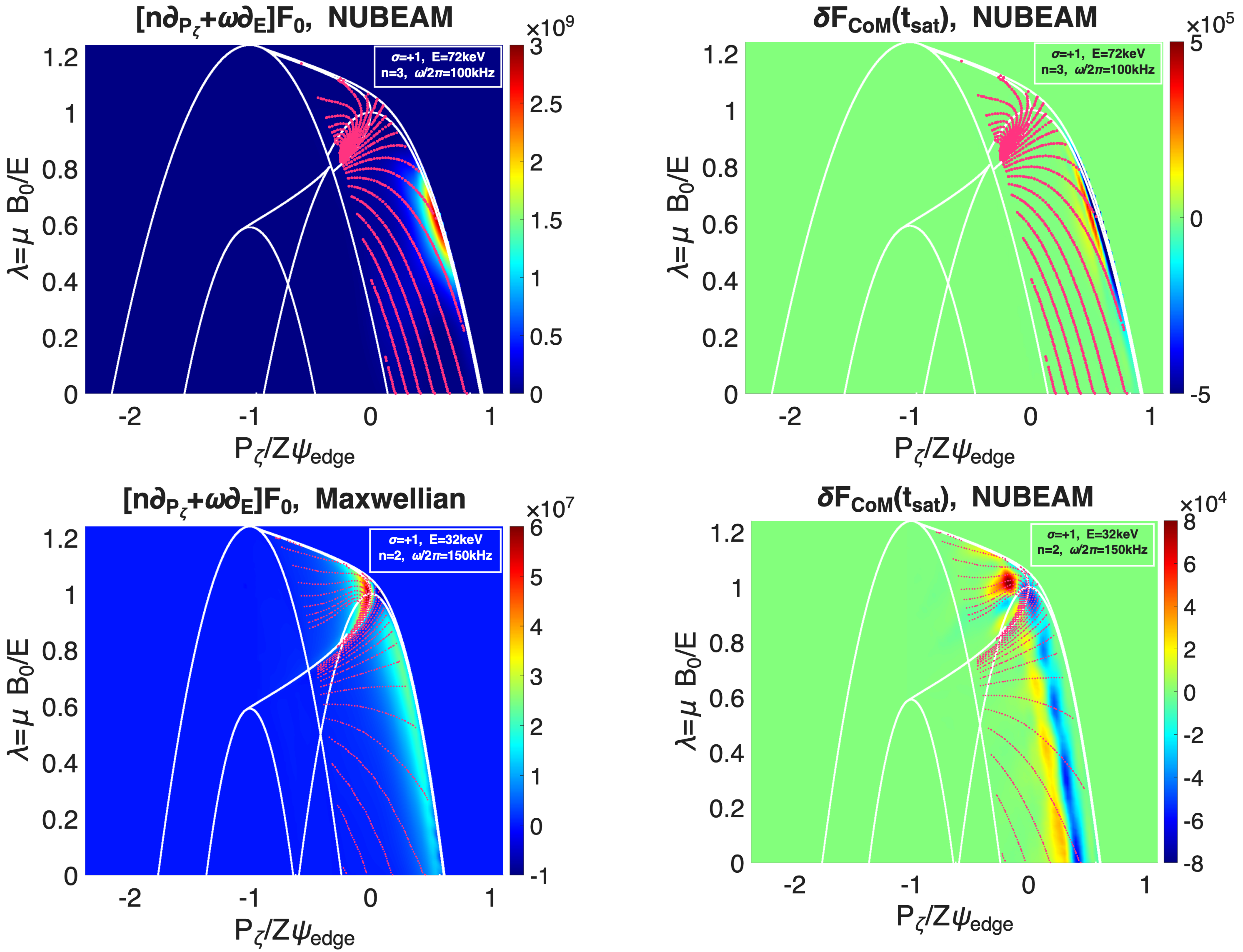




[1] X. Du et al. 2025, *Phys. Rev. Lett.*

[2] J. Garcia et al. 2024, *Nat. Comm.*

Perspectives



➢The differences in **TAE radial locations** and **strength explained by** the **significant differences** in EP drive

➢**Considering realistic EP input** is therefore **essential** to analyse even **qualitatively confinement improvement** due to cross-scale simulations