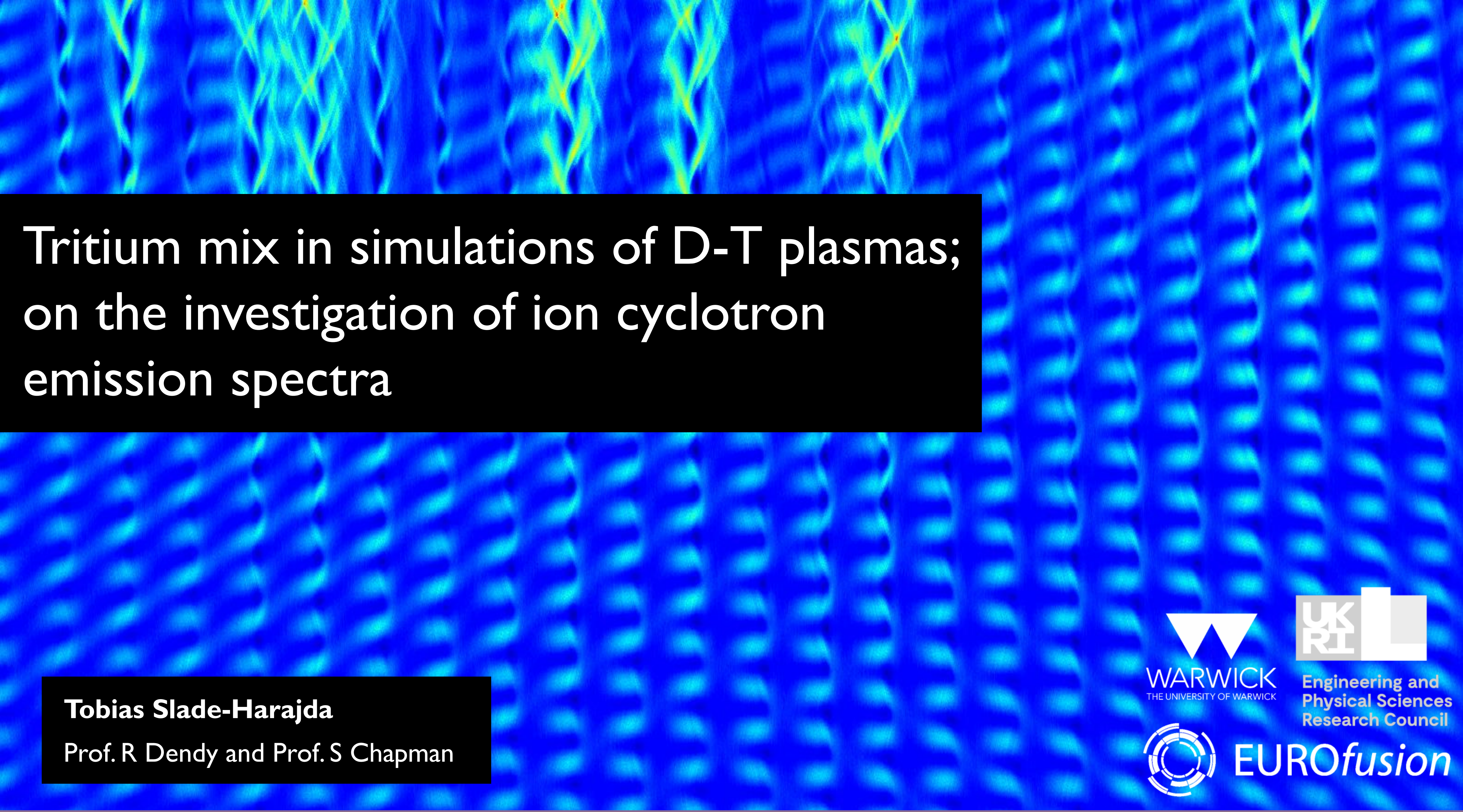


Tritium mix in simulations of D-T plasmas; on the investigation of ion cyclotron emission spectra

Tobias Slade-Harajda

Prof. R Dendy and Prof. S Chapman

Contents

- Motivation
- Ion cyclotron emission (ICE)
- Magnetoacoustic cyclotron instability (MCI)
- Simulating the fusion plasma (PIC code)
- Results; power spectra, energy, Fourier transforms…
- Summary & Future work

Motivation

$$D + T \to \alpha(3.5\text{MeV}) + n$$

** Linear and nonlinear physics of the magnetoacoustic cyclotron instability of fusion-born ions in relation to ion cyclotron emission

L. Carbajal, R. O. Dendy, S. C. Chapman, and J. W. S. Cook

★ Stimulated Emission of Fast Alfvén Waves within Magnetically Confined Fusion Plasmas

J. W. S. Cook, R. O. Dendy, and S. C. Chapman

★★★ Comparing theory and simulation of ion cyclotron emission from energetic ion populations with spherical shell and ring-beam distributions in velocity-space

B Chapman, R O Dendy, S C Chapman, L A Holland, S W A Irvine and B C G Reman

* Particle-in-cell simulations of the magnetoacoustic cyclotron instability of fusion-born alpha-particles in tokamak plasmas

J W S Cook, R O Dendy and S C Chapman

*** Quantifying Fusion Born Ion Populations in Magnetically Confined Plasmas using Ion Cyclotron Emission

L. Carbajal, R. O. Dendy, S. C. Chapman, and J. W. S. Cook

★★ Nonlinear wave interactions generate high-harmonic cyclotron emission from fusion-born protons during a KSTAR ELM crash

B. Chapman, R.O. Dendy, S.C. Chapman, K.G. McClements, G.S. Yun, S.G. Thatipamula and M.H. Kim

⅄ Doublet splitting of fusion alpha particle driven ion cyclotron emission

J W S Cook

* Cook J W S *et al. Plasma Phys. Control. Fusion* **55** 065003, 2013
* * Carbajal L *et al. Physics of Plasmas* **21**, 2014
* * * Carbajal L *et al. Phys. Rev. Lett.* **118** 105001, 2017

★ Cook J W S *et al. Phys. Rev. Lett.* **118** 18500, 2017
★★ Chapman B *et al. Nuclear Fusion* **58** 096027, 2018
★★★ Chapman B *et al. Plasma Phys. Control. Fusion* **62** 055003, 2020

⅄ Cook J W S *Plasma Phys. Control. Fusion* **64** 115002, 2022

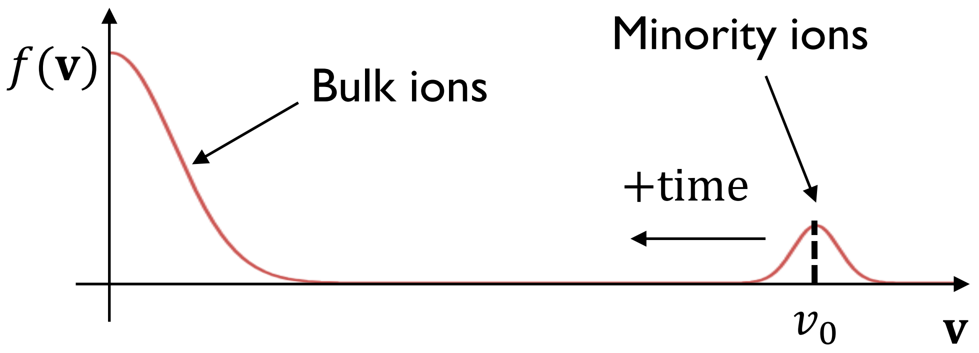
Ion cyclotron emission (ICE)

- Suprathermal emission visible at multiple ion harmonics
- Driven by the MCI, driven by strong gradients in energetic minority (alpha-particles) velocity-space distribution
- Measurement is passive, non-intrusive and multi-angled

$$\Omega_\sigma \equiv \omega_{c\sigma} = \frac{q_\sigma B}{m_\sigma}$$

$$n\Omega_\alpha \; \forall \; n \in \mathbb{Z}^+$$

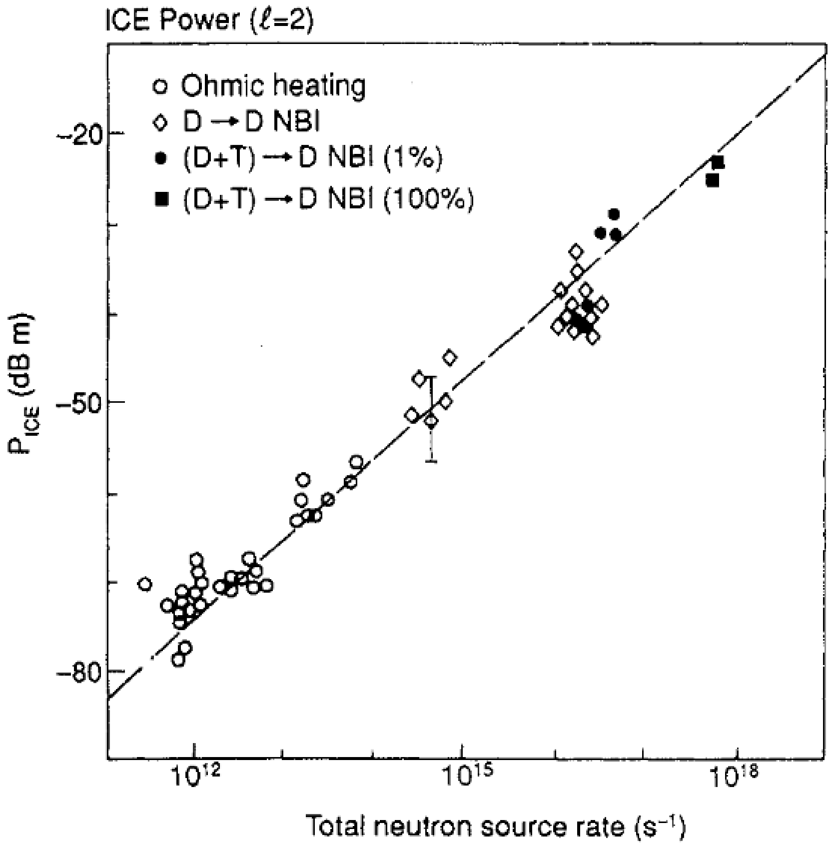
$$\frac{\partial f_\alpha(v_\parallel, v_\perp)}{\partial \mathbf{v}} > 0$$



Ion cyclotron emission (ICE)

Scales with:

- Minority concentration (ξ_α)
- Fusion reactivity
- $v_{0\perp}/v_A$ ratio
- Pitch-angle (ϕ)
- Fuel ratio (ξ_2/ξ_1 ; this work)
- Magnetic field angle (θ)



*

FIG. 5. Correlation between ICE intensity P_{ICE} *and total neutron emission rate* R_{NT} *for Ohmic and NBI heated JET discharges, over six decades of signal intensity. The best fitting relation is* $P_{ICE} \propto R_{NT}^{0.9\pm0.1}$.

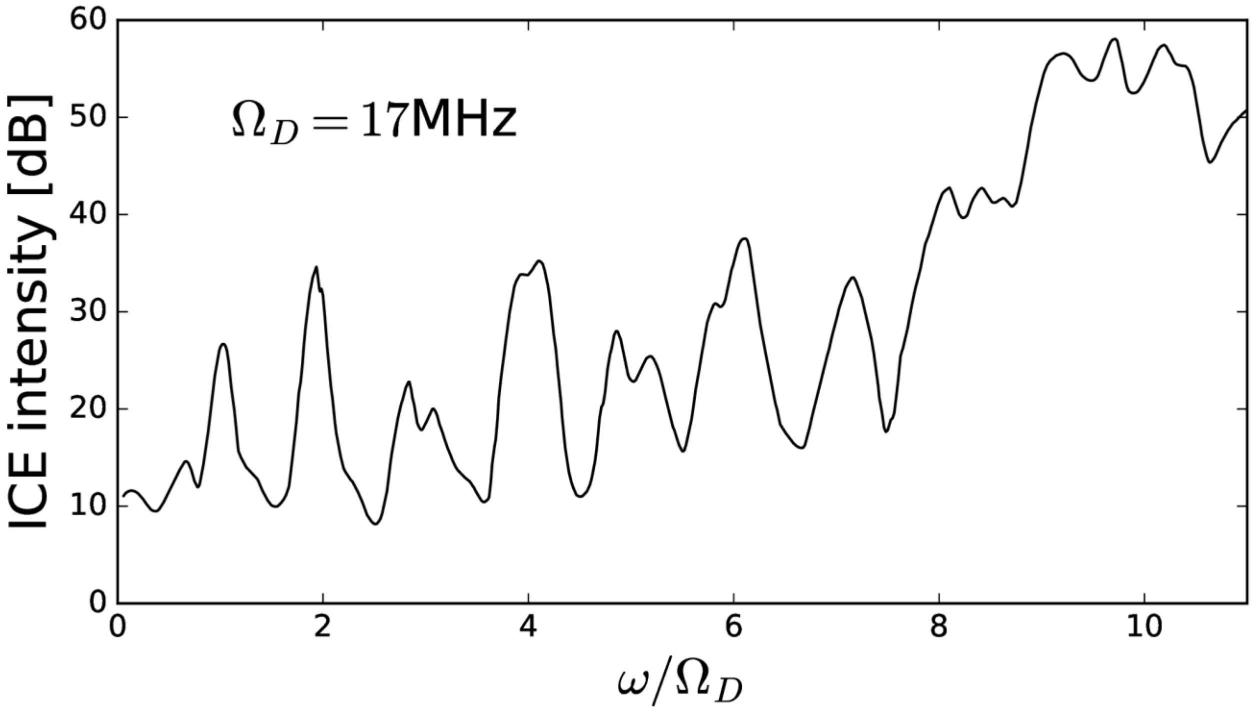
* G. A. Cottrell *et al.*, *Nuclear Fusion*, vol. 33, pp. 1365–1387, Sept. 1993

Ion cyclotron emission (ICE)

Location of ICE location in tokamak inferred from spacing between peaks

$$B(r) = \frac{\Omega m}{Ze}$$

$$B_\theta^{(0)}(r) = \frac{\mu_0 I_P}{2\pi r}\left(1 - \left[1 - \left(\frac{r}{a}\right)^2\right]^\gamma \Theta(a - r)\right) *$$



ICE spectra observed from JET plasma 26148 **, spacing of 17MHz between peaks.

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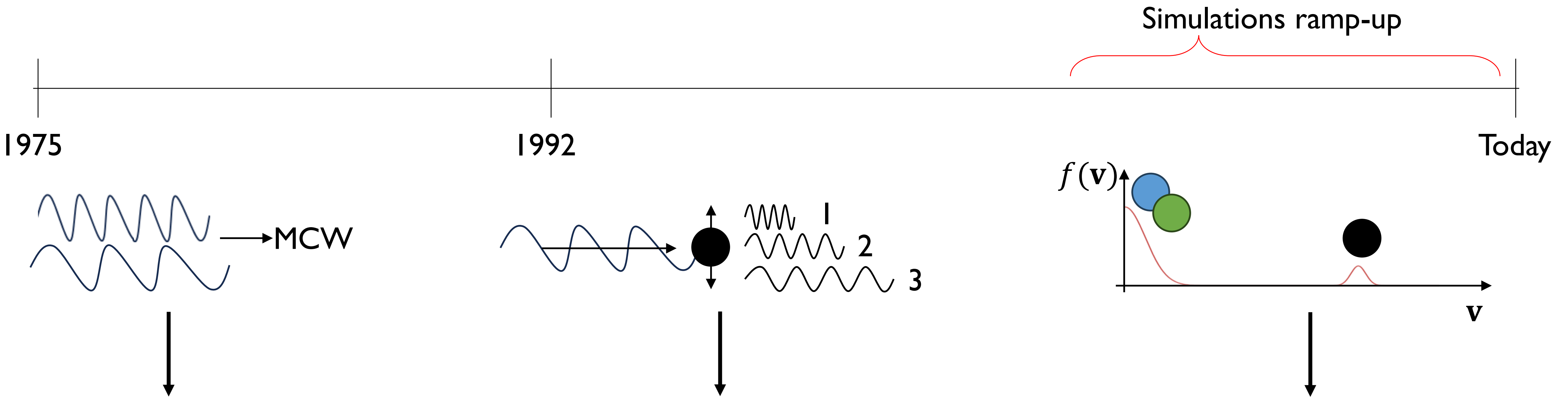
* Caldas I L *et al. Chaos Solitons and Fractals* **7** 991–1010, Jul. 1996

** G. A. Cottrell *et al.*, *Nuclear Fusion*, vol. 33, pp. 1365–1387, Sept. 1993

Magnetoacoustic Cyclotron Instability (MCI)



Brought on by "*a small quantity of thermonuclear reaction products in a plasma*" which are "*sufficient to excite magnetoacoustic cyclotron waves*" *

"*resonation excitation of perpendicular fast Alfvén waves with ion Bernstein waves*" which was "*driven by the energetic products of fusion reactions*" **

MCI is characterised by the cyclotron resonance between the FAW (in the bulk) and an energetic minority ion (alphas)

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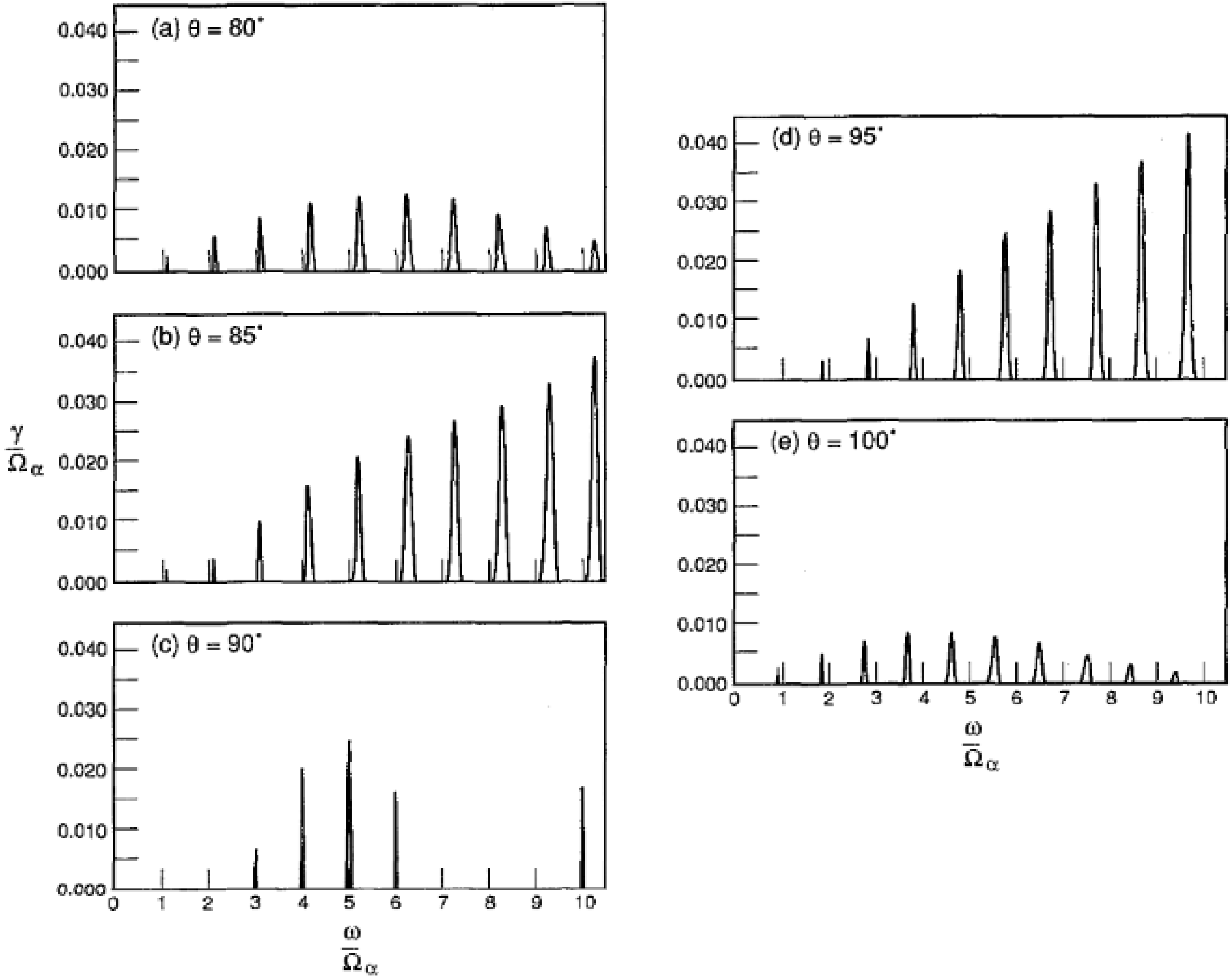
* V. S. Belikov and Y. I. Kolesnichenko, *Sov. Phys. - Tech. Phys.*, vol. 20:9, 9 1975.

* * R. O. Dendy *et al. Physics of Fluids B: Plasma Physics*, vol. 4, pp. 3996–4006, Dec. 1992.

Magnetoacoustic Cyclotron Instability (MCI)



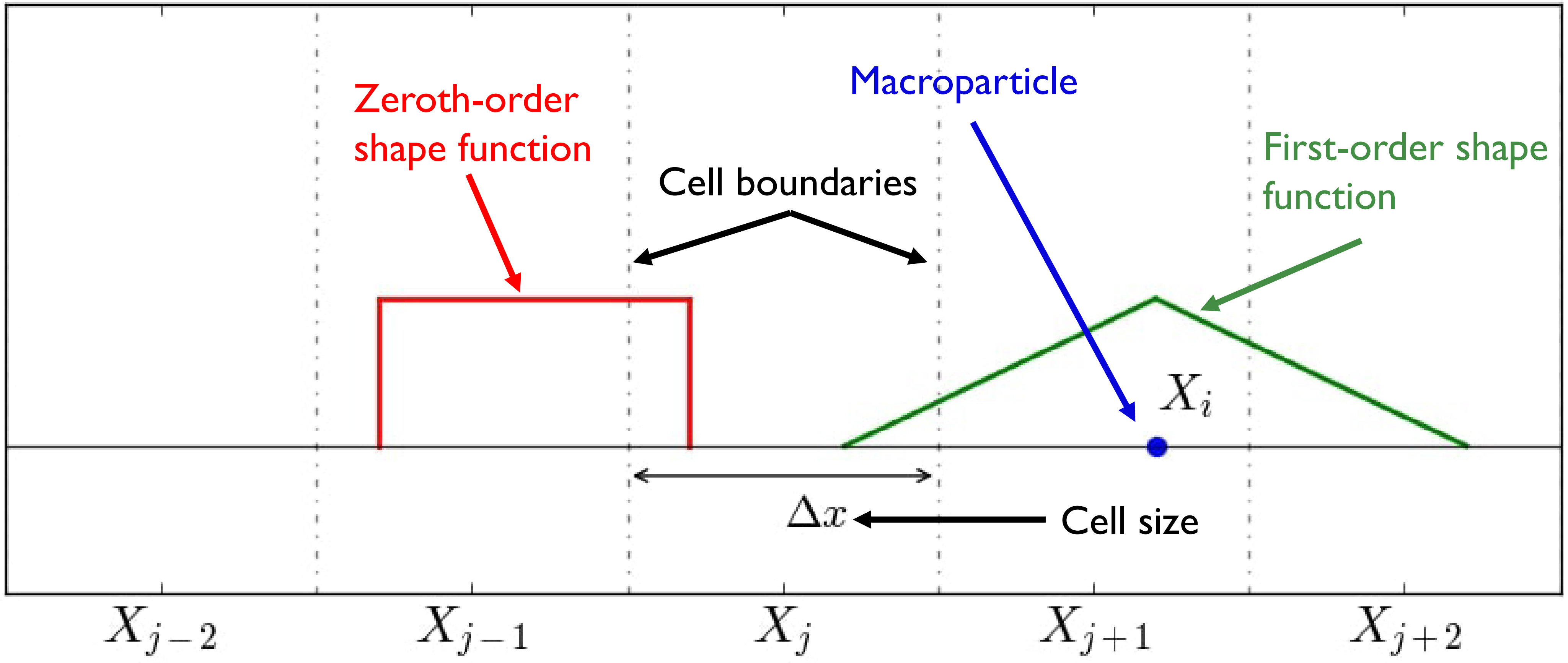
$$\gamma = \frac{\omega_{p\alpha}^2}{\omega_{pi}^2}\frac{\Omega_i^4}{[\Omega_i + (\omega - \Omega_i)N_\parallel^2][\Omega_i - (\omega + \Omega_i)N_\parallel^2]}$$

$$\times\left(\frac{l\Omega_\alpha}{k_\parallel v_r}M_l - \frac{2u^2}{v_r^2}\eta_l N_l\right)\frac{\sqrt{\pi}}{2\omega}e^{-\eta_l^2} \quad *$$

* McClements K G *et al. Physics of Plasmas* **3** 543–53, Feb 1996

Simulations (PIC)

Use of the particle-in-cell (PIC) code EPOCH *



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* T. D. Arber *et al. Plasma Physics and Controlled Fusion*, vol. 57, p. 113001, Nov. 2015.

Simulations (PIC)

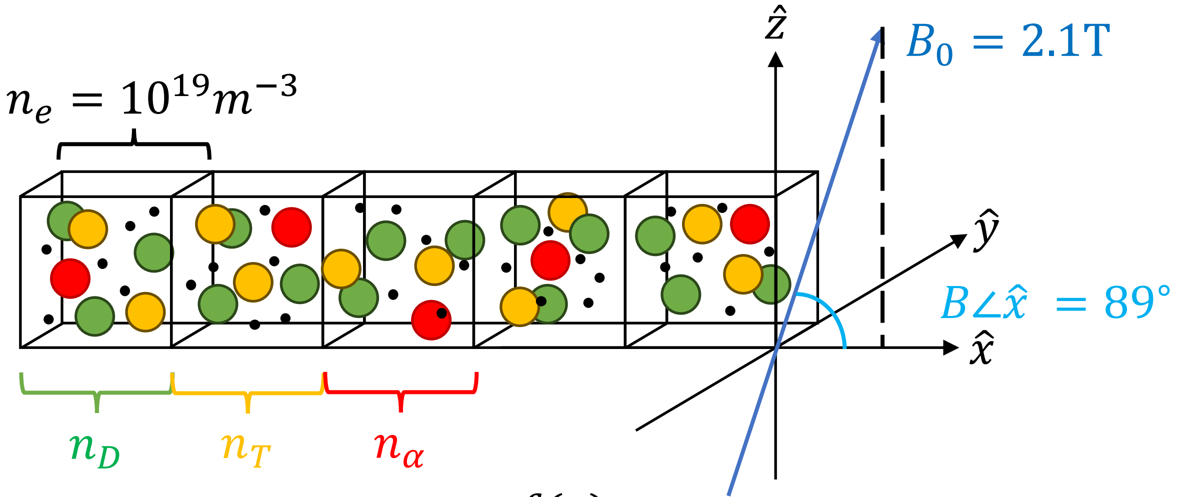
- Inclusion of tertiary ion (tritium)
- Number density weighting (NDW) conserved

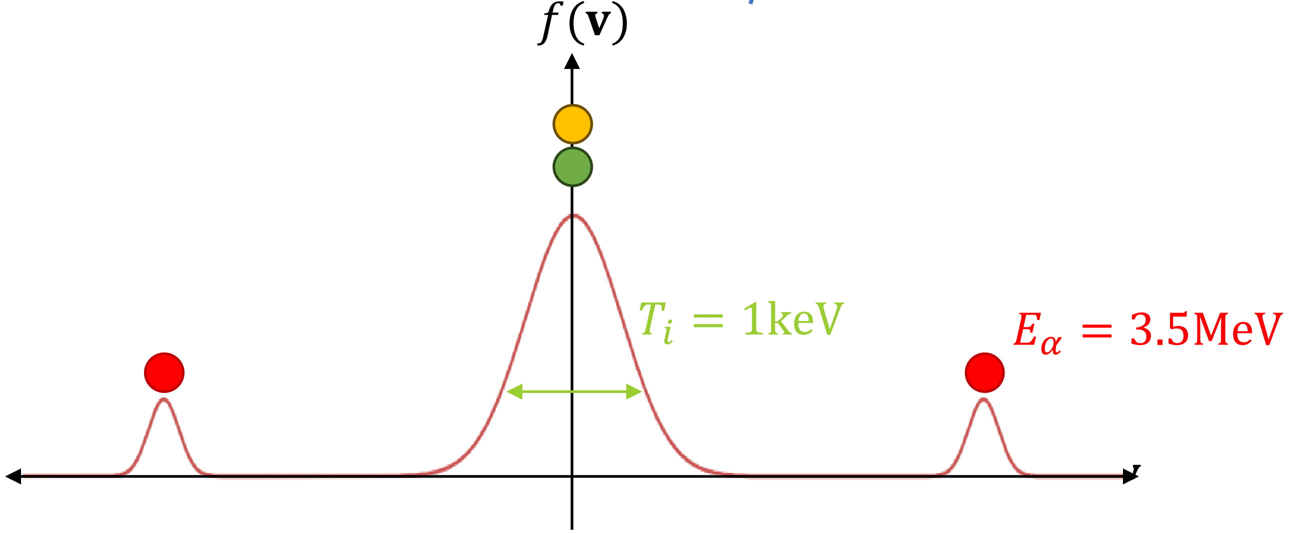
$$\boxed{\mathbf{NDW} = \frac{n_\sigma}{N_\sigma}}$$

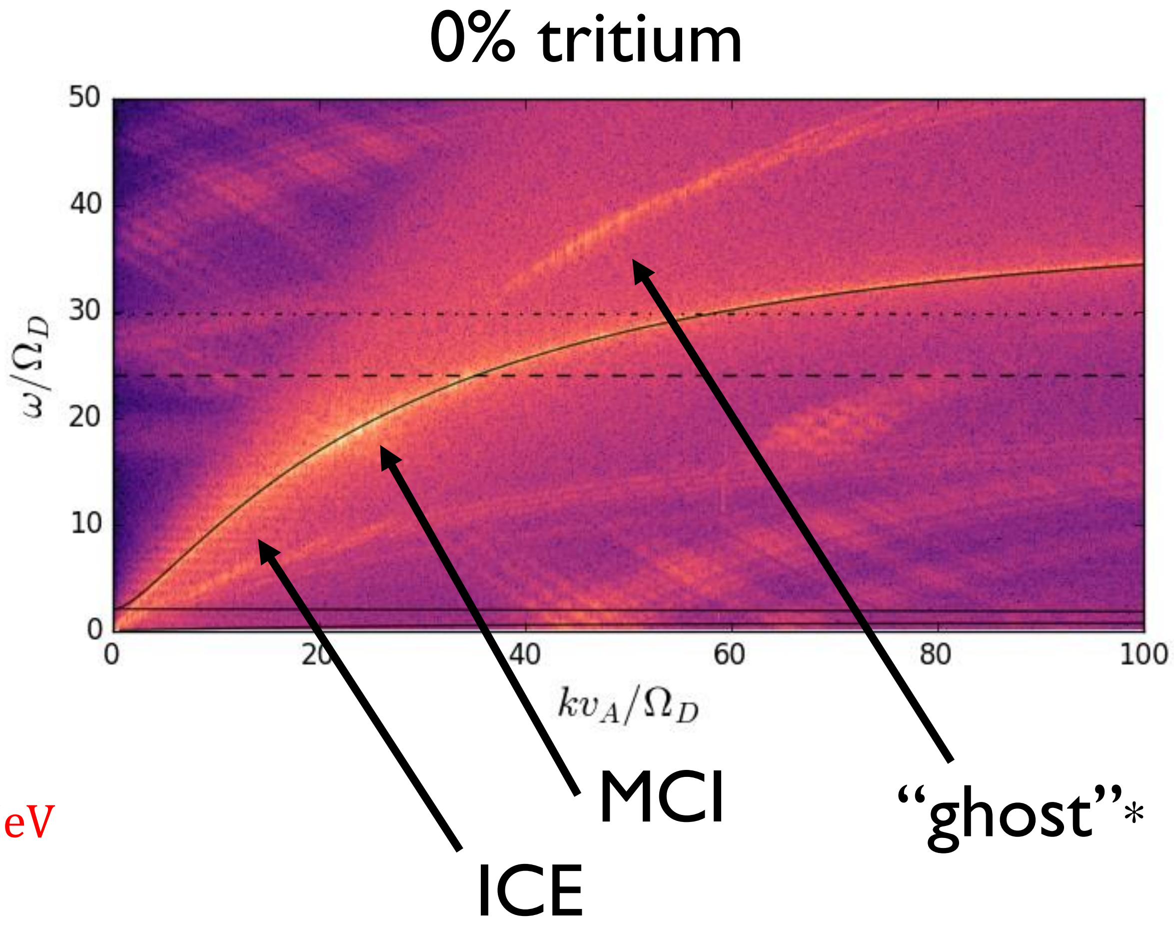
- Introduced ξ_T(%) and fuel ratio (ξ_T/ξ_D)
- Deuteron (0%), trace tritium (1%) JET 26148 (11%) and ITER (≥50%)
- Supplementary simulations

Simulations (PIC)

2d representation







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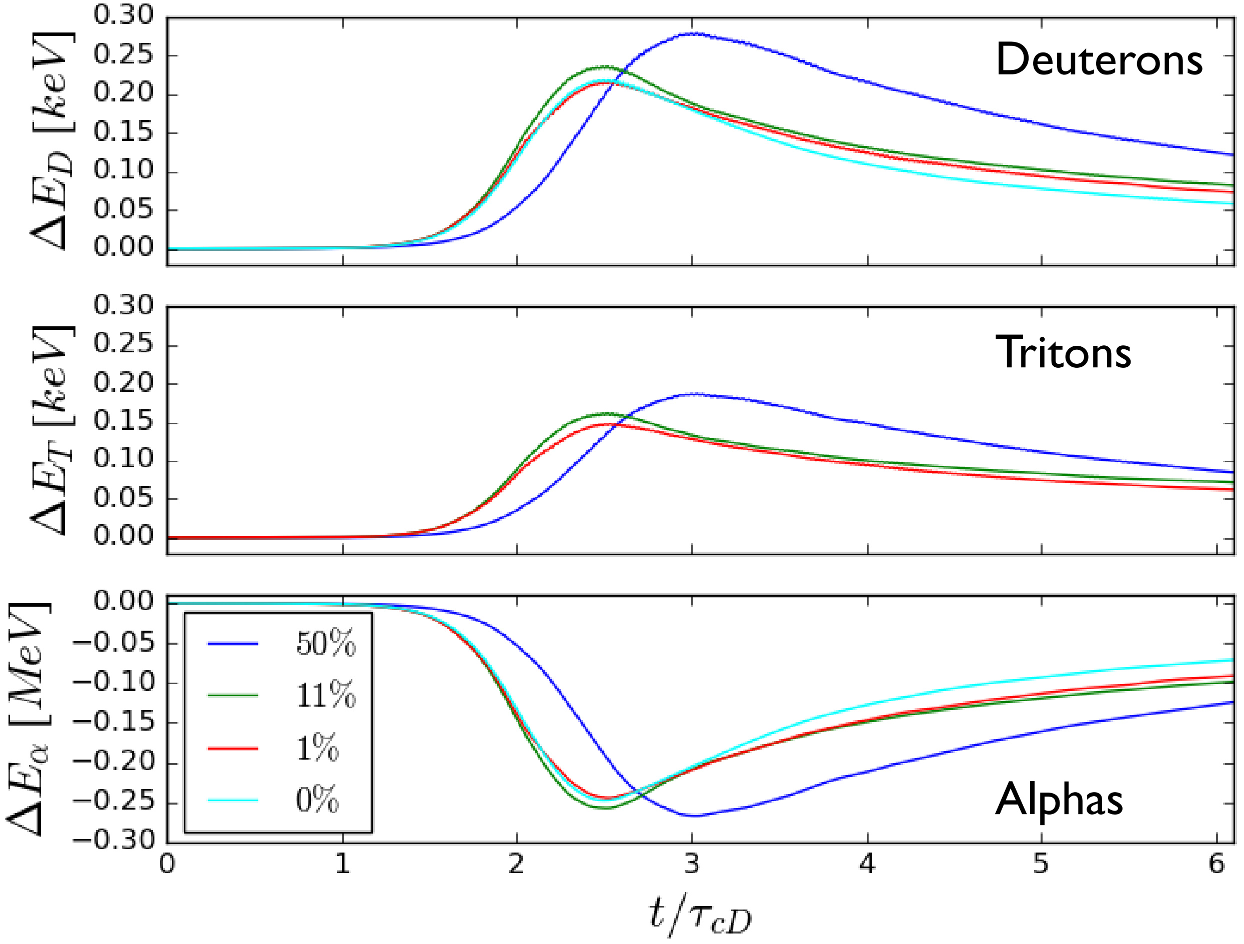
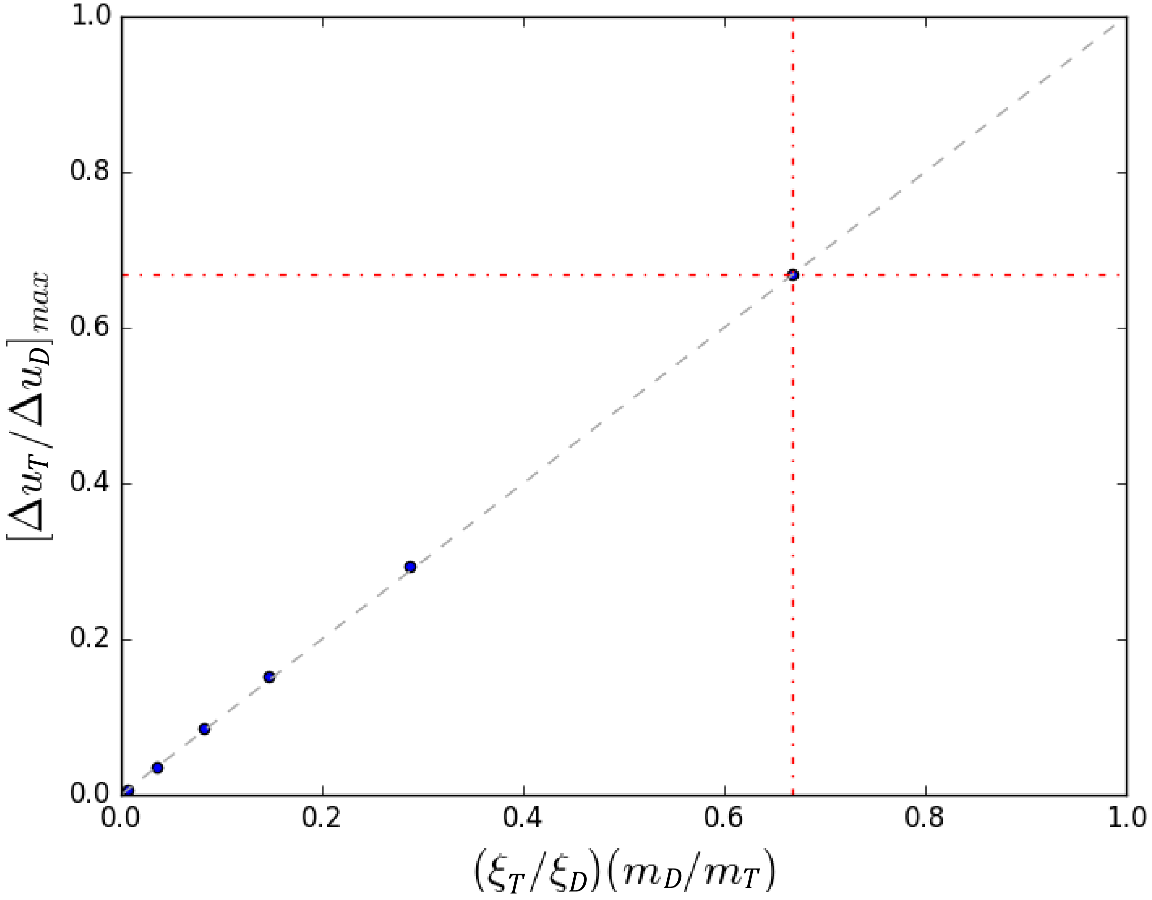
* Chapman B *et al.* *Nuclear Fusion* **58** 096027, Sep 2018

Results : Energy

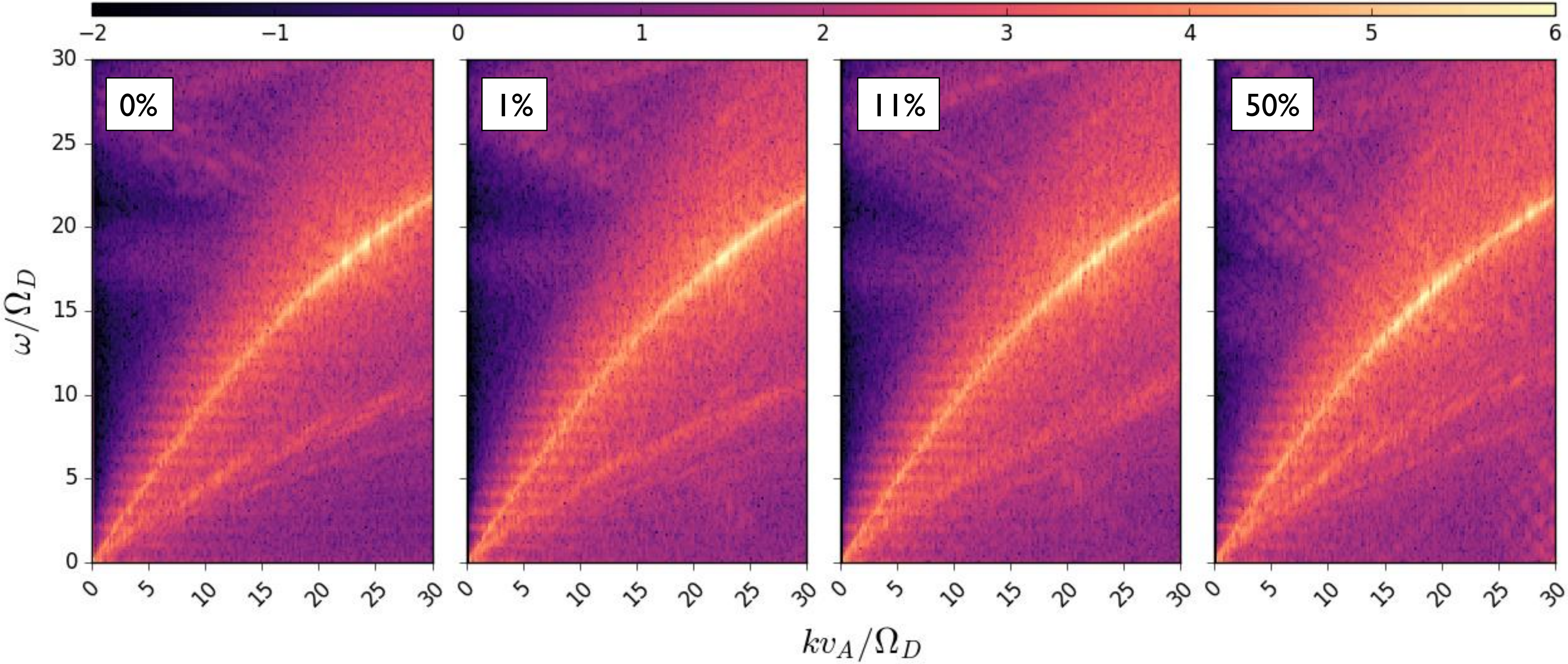




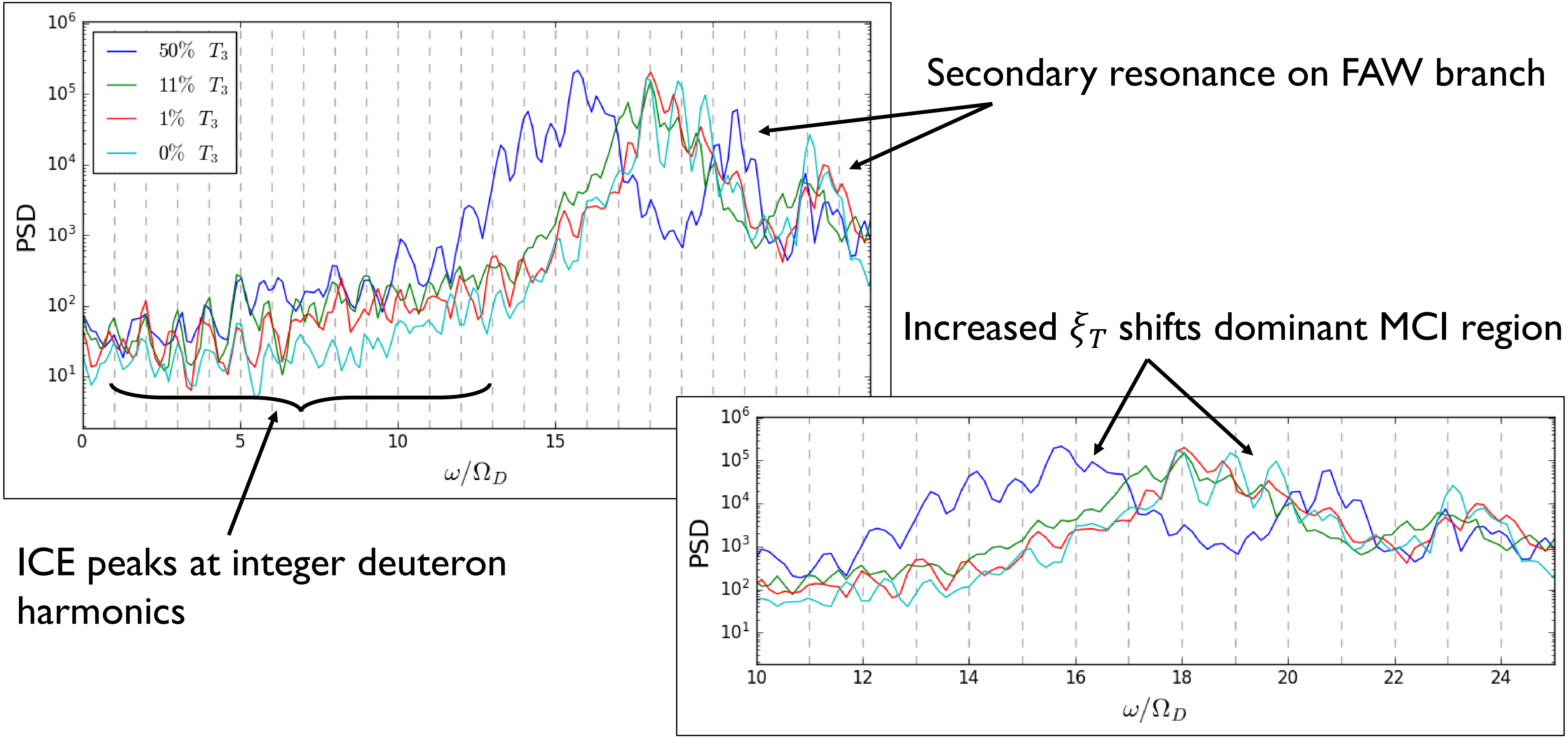
$$\Delta \mathrm{E}_\sigma = E_{0\sigma} - E(t)$$

Derived from first principles : $\Delta \mathrm{u}_\sigma = n_\sigma \Delta \mathrm{E}_\sigma$: $\dfrac{\Delta \mathrm{u}_T}{\Delta \mathrm{u}_D} = \dfrac{\xi_T m_D q_D}{\xi_D m_T q_T}$

Results : Fourier transforms



Results : Power spectra

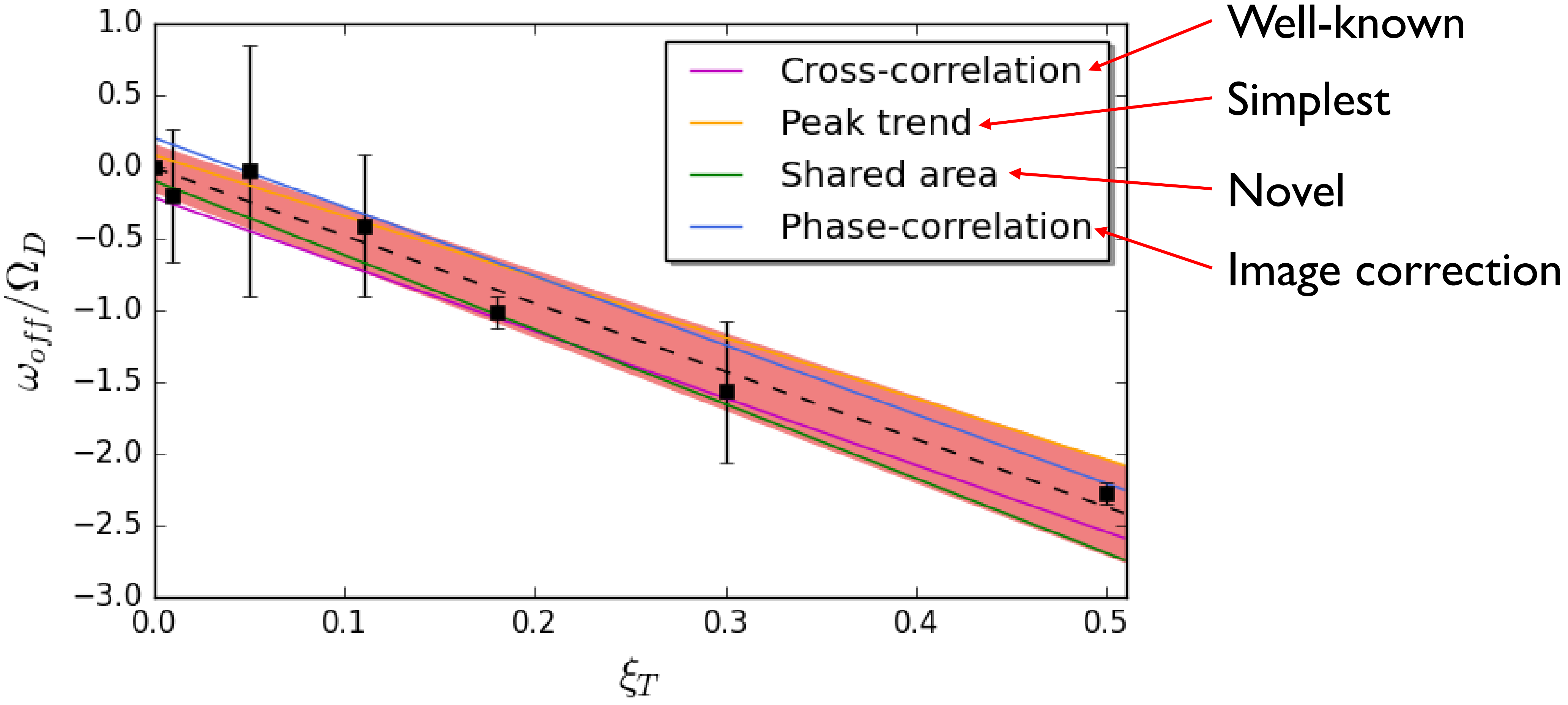


Secondary resonance on FAW branch

Increased ξ_T shifts dominant MCI region

ICE peaks at integer deuteron harmonics

Results : Frequency offset



Well-known

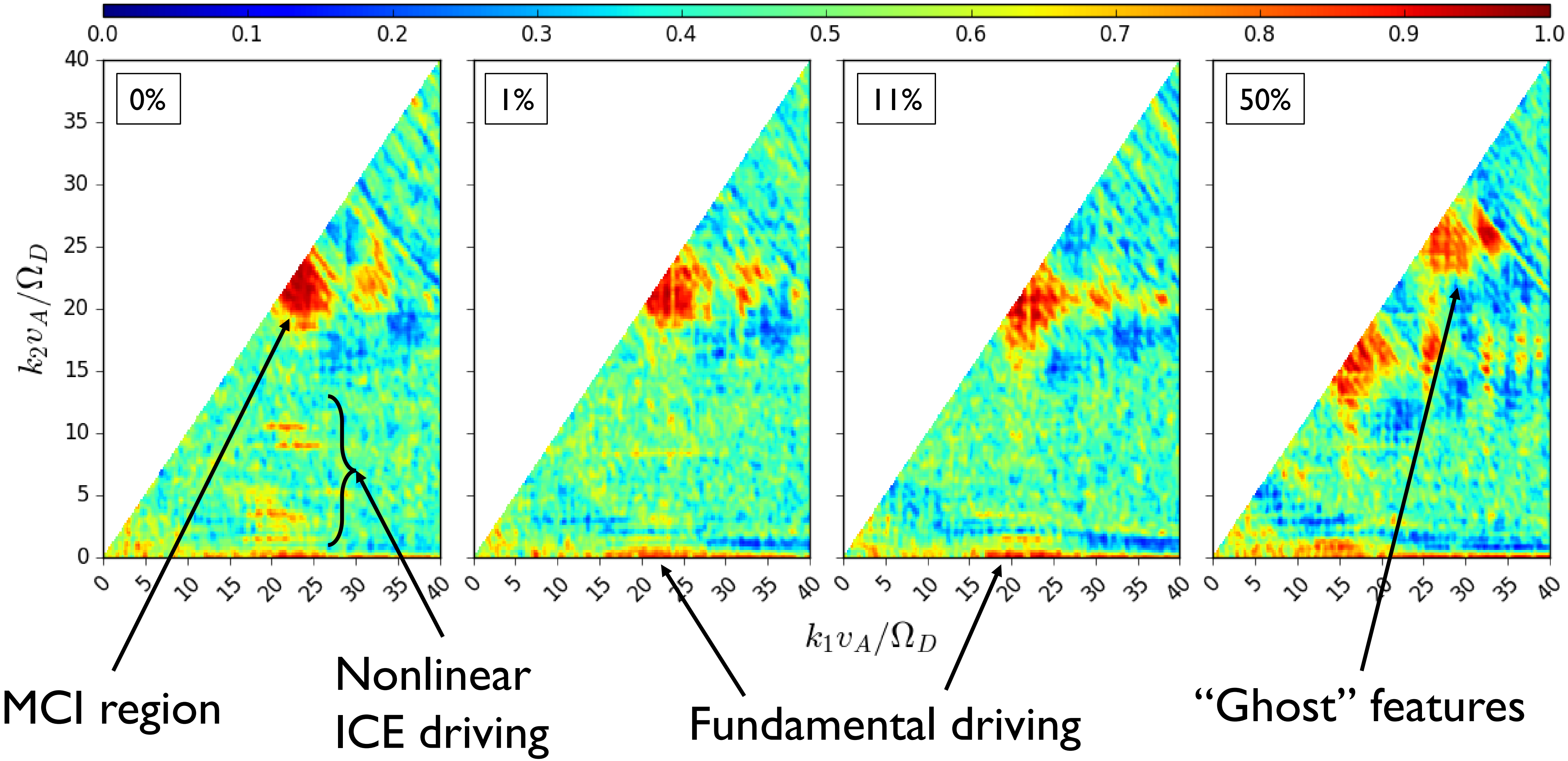
Simplest

Novel

Image correction

$$\omega_{off}(\xi_T)/\Omega_D = (-4.74 \pm 0.34)\xi_T + (-0.01 \pm 0.16)$$

Results : Bicoherence



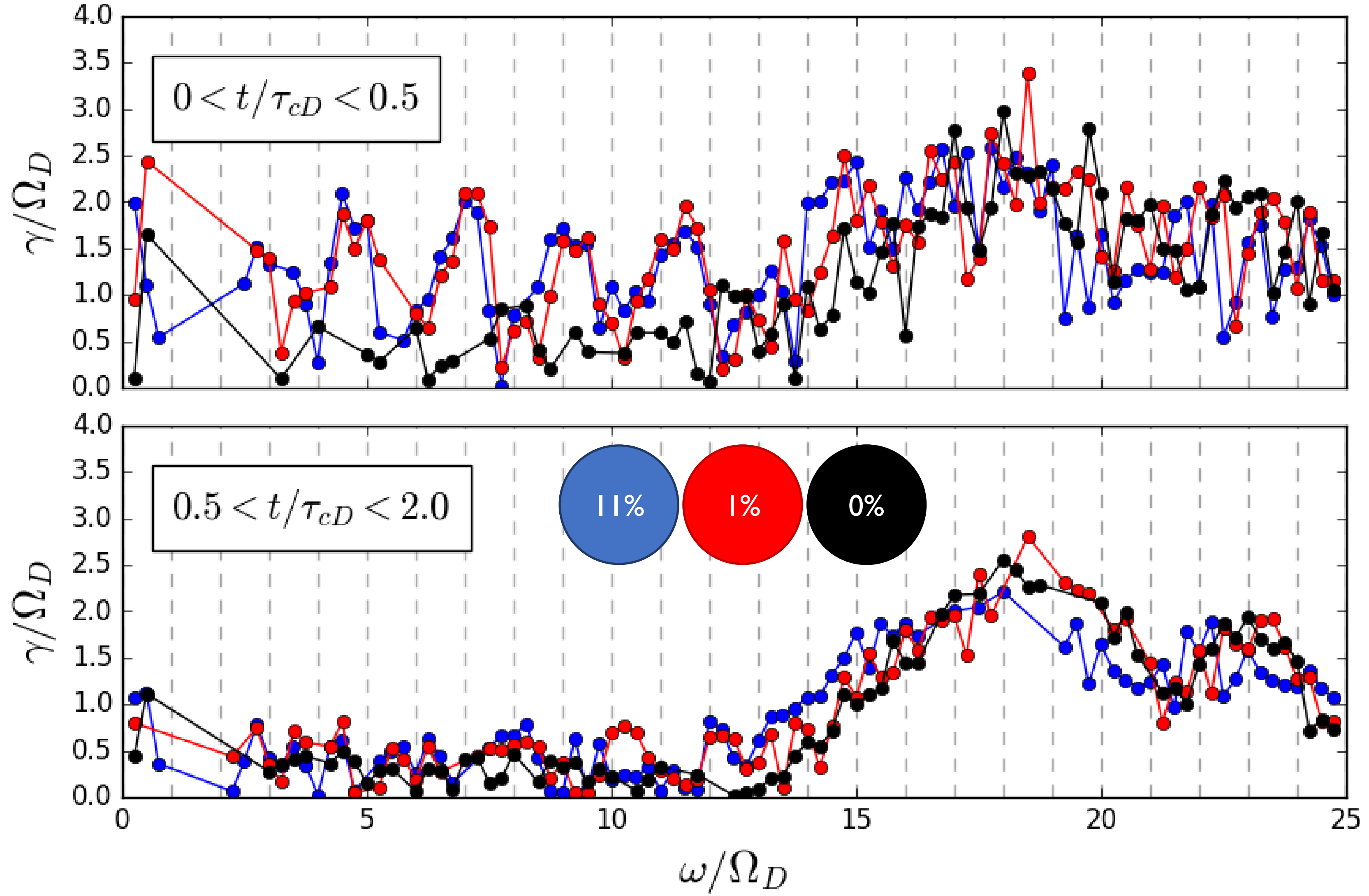
MCI region

Nonlinear ICE driving

Fundamental driving

“Ghost” features

Results : Growth rates



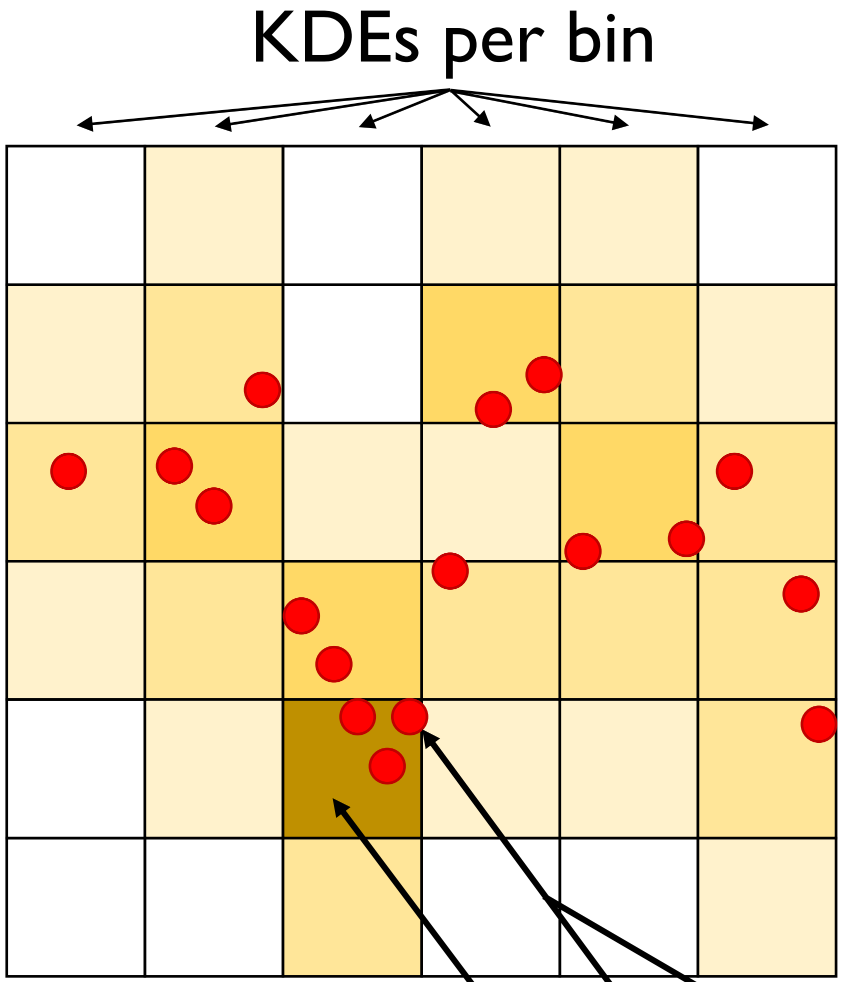
Early:

- Joint driving $p\Omega_D = q\Omega_T$
- Less defined
- Transient

Late:

- No joint harmonics
- Smooth growths
- Secondary growths

Results : Tau-squared



$$\tau^2 = -2 \sum_i \ln[\rho(x_i, y_i)]$$

JET 26148 PPR data

τ^2 is minimised for best fitting data to model

Normalised to number of peaks to find τ^2 contribution minimisation

11% simulation best represents the JET 26148 data

ξ_T [%]	τ^2/N_{peaks}
0	30.0
1	28.7
5	29.8
11	27.9
18	28.7
30	29.9
50	30.0

Summary

- Bulk ions energise slower with increasing ξ_T
- Ratio of D-T energisation equivalent to their mass ratios, Larmor radii matching/gyro-resonance
- Power spectra shifted quantified by negative linear correlation w.r.t ξ_T
- JET plasma 26148 is best represented by the 11% simulation
- Simulation of three ions is a necessity for $\xi_T > 1\%$, especially for ITER

Future work

Thank you for listening