

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



- 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

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

**\*\***  
PHYSICS OF PLASMAS 21, 023606 (2016)  
**Linear and nonlinear physics of the magnetoacoustic cyclotron instability of fusion-born ions in relation to ion cyclotron emission**  
L. Carbajal,<sup>1,2</sup> R. O. Dendy,<sup>1,3</sup> S. C. Chapman,<sup>1,4</sup> and J. W. S. Cook<sup>1</sup>  
<sup>1</sup>Centre for Fusion, Space and Astrophysics, Department of Physics, The University of Warwick, Coventry CV4 7AL, United Kingdom  
<sup>2</sup>ICM-1 (MCF) Fusion Association, Culham Science Centre, Abingdon OX10 0EF, Oxfordshire, United Kingdom  
<sup>3</sup>Department of Mathematics and Statistics, University of Tromsø, 9007, Tromsø, Norway  
<sup>4</sup>Max-Planck Institute for the Physics of Complex Systems, 14105, Dresden, Germany  
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The magnetoacoustic cyclotron instability (MCI) probably underlies observations of ion cyclotron emission (ICE) from energetic ion populations in tokamak plasmas, including fusion-born alpha particles in JT-6U and TFTR (Dendy et al., Nucl. Fusion 35, 1771 (1995)). ICE is a potential diagnostic for fast alpha-particles in TFTR. Furthermore, the MCI is representative of a class of collective instabilities, which may result in the partial damping of the free energy of energetic ions into radiation, and away from collisional heating of the plasma. Understanding the MCI is thus of substantial practical interest for fusion, and the hybrid approximation for a way forward. The hybrid simulations presented here focus on MCI instabilities that arise on a way forward, which the present simulations largely corroborate. Our results go further than studies by entering into the nonlinear stage of the MCI, which shows novel features. Such stronger drive at low cyclotron harmonics, the co-existence of the alpha-particle wave, self-modulation of the phase shift between the electrostatic and electromagnetic waves, and coupling between low and high frequency modes of the excited electromagnetic MHD MIP Publishing LLC. <http://dx.doi.org/10.1088/1361-6585/16010606>

**\* Particle-in-cell simulations of the magnetoacoustic cyclotron instability of fusion-born alpha-particles in tokamak plasmas**  
J. W. S. Cook,<sup>1</sup> R. O. Dendy,<sup>1,2</sup> and S. C. Chapman<sup>1,3</sup>  
<sup>1</sup>Centre for Fusion, Space and Astrophysics, Department of Physics, Warwick University, Coventry CV4 7AL, UK  
<sup>2</sup>ICM-1 (MCF) Fusion Association, Culham Science Centre, Abingdon, Oxfordshire OX10 0EF, UK  
<sup>3</sup>Department of Mathematics and Statistics, University of Tromsø, N-9007, Tromsø, Norway  
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Online at [stacks.iop.org/1361-6585/16010606](http://stacks.iop.org/1361-6585/16010606)

**Abstract**  
Ion cyclotron emission (ICE) is the only collective radiation instability driven by confined fusion-born alpha particles, observed from tokamak plasmas in both JT-6U and TFTR. Using particle-in-cell (PIC) simulations of the magnetoacoustic cyclotron instability (MCI) we describe some of the fully kinetic nonlinear processes that may underlie observations of ICE from fusion plasmas in these large tokamaks. We find that the MCI is intrinsically self-focusing on very fast timescales, which may help explain the observed correlation between linear theory and observed ICE intensity. The simulations corroborate the nature of the excited electrostatic and magnetic fluctuations, their temporal coupling, confirming the dominant role of fast Alfvénic and electromagnetic components which is assumed in earlier analytical theories.  
(Some figures may appear in colour only in the online journal)

**1. Introduction**  
Derived from injected beam ions [11–15] in tokamaks, and in magnetically confined and applied, having been discovered recently in the large tokamaks ITER [16] and ASDEX-U [17]. In ITER, ICE is thought to be associated with the MCI, which is a linear instability driven by the free energy of fusion-born alpha particles in the tokamak plasma. This heating is resonant in JT-6U and in TFTR [11] and will be central to ITER [13, 15]. It is one of the major energy channels for the fusion-born alpha particles, which can be used to pre-heat the plasma before the main deuterium-tritium (D-T) fusion reaction is initiated. The MCI is a linear instability driven by the free energy of fusion-born alpha particles, which can be used to pre-heat the plasma before the main deuterium-tritium (D-T) fusion reaction is initiated. The MCI is a linear instability driven by the free energy of fusion-born alpha particles, which can be used to pre-heat the plasma before the main deuterium-tritium (D-T) fusion reaction is initiated.

\* 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. Physics. Rev. Lett. 118 105001, 2017

**\*\***  
PHYSICAL REVIEW LETTERS  
**Stimulated Emission of Fast Alfvén Waves with Magnetically Confined Fusion Plasmas**  
J. W. S. Cook,<sup>1,2</sup> R. O. Dendy,<sup>1,3</sup> and S. C. Chapman<sup>1,4</sup>  
<sup>1</sup>Centre for Fusion, Space and Astrophysics, Department of Physics, Warwick University, Coventry CV4 7AL, United Kingdom  
<sup>2</sup>First Light Fusion Ltd., East Kilbride Industrial Park, Irvine G12 0JG, United Kingdom  
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<sup>4</sup>Max-Planck Institute for the Physics of Complex Systems, 14105, Dresden, Germany  
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As the Alfvén waves with a finite amplitude is shown to grow by a stimulated emission process that we propose for explanation in a model magnetically confined fusion plasma. Stimulated emission occurs while the wave propagates inward through the outer midplane plasma, where a population inversion of the energy distribution of fusion-born ions is observed to exist naturally. Fully nonlinear 3-D gyrokinetic simulations, which self-consistently evolve particles and fields under the Maxwell-Lorentz system, illustrate the novel ‘‘spontaneous’’ nature for the first time.  
DOI: 10.1103/PhysRevLett.118.085501

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PHYSICAL REVIEW LETTERS  
**Quantifying Fusion Born Ion Populations in Magnetically Confined Plasmas using Ion Cyclotron Emission**  
L. Carbajal,<sup>1,2</sup> R. O. Dendy,<sup>1,3</sup> S. C. Chapman,<sup>1,4</sup> and J. W. S. Cook<sup>1</sup>  
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<sup>3</sup>First Light Fusion Ltd., East Kilbride Industrial Park, Irvine G12 0JG, United Kingdom  
<sup>4</sup>Max-Planck Institute for the Physics of Complex Systems, 14105, Dresden, Germany  
(Received 8 June 2016; revised manuscript received 27 January 2017; published 1 March 2017)

Ion cyclotron emission (ICE) offers a unique promise as a diagnostic of the fusion born alpha particle population in magnetically confined plasmas. Following observations from JT-6U and TFTR that the ICE intensity  $\mathcal{I}_{\text{ICE}}$  scales approximately linearly with the measured neutron flux from fusion reactions, and with the inferred confinement,  $\tau_{\text{E}}$ , of fusion-born alpha particles confined within the plasma. We present fully nonlinear self-consistent kinetic simulations that reproduce this scaling for the first time. This involves a long-running exercise in the physics of fusion alpha-particle confinement and stability in magnetically confined fusion plasmas. In contrast to the magnetoacoustic cyclotron instability in the early stages of the experiment, we find that the ICE intensity is proportional to the fusion-born alpha particle population,  $n_{\alpha}$ , in the outer midplane region, where the ICE intensity is observed to be. This is in contrast to the linear MCI theory, which predicts a linear relationship between the intensity of fast Alfvén waves at resonant and non-resonant frequencies. We find that the ICE intensity is proportional to the fusion-born alpha particle population,  $n_{\alpha}$ , in the outer midplane region, where the ICE intensity is observed to be. This is in contrast to the linear MCI theory, which predicts a linear relationship between the intensity of fast Alfvén waves at resonant and non-resonant frequencies. We find that the ICE intensity is proportional to the fusion-born alpha particle population,  $n_{\alpha}$ , in the outer midplane region, where the ICE intensity is observed to be.

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**Nonlinear wave interactions generate high-harmonic cyclotron emission from fusion-born protons during a KSTAR ELM crash**  
B. Chapman,<sup>1,2</sup> R. O. Dendy,<sup>1,3</sup> S. C. Chapman,<sup>1,4</sup> K. K. McCliment,<sup>5</sup> G. S. Yan,<sup>6</sup> S. G. Thompson,<sup>6</sup> and M. J. Kim<sup>6</sup>  
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<sup>6</sup>Korea Research Institute of Plasma Science and Technology, P.O. Box 107, Yusong, Taejeon 305-380, Korea  
(Received 12 January 2017; revised 27 June 2017; accepted 27 July 2017)

The radio frequency detection system on the KSTAR tokamak has unexpectedly high spectral and temporal resolution. This enables measurement of previously unobserved fast plasma phenomena in the ion-cyclotron range of frequencies. Here we report and analyze a novel spectral emission from the KSTAR tokamak, which exhibits chirping on sub-microsecond timescales. This emission is identified as a nonlinear interaction between ion-cyclotron emission (ICE) waves in the range 300 MHz to 900 MHz, which exhibit chirping on sub-microsecond timescales. This emission is identified as a nonlinear interaction between ion-cyclotron emission (ICE) waves in the range 300 MHz to 900 MHz, which exhibit chirping on sub-microsecond timescales. This emission is identified as a nonlinear interaction between ion-cyclotron emission (ICE) waves in the range 300 MHz to 900 MHz, which exhibit chirping on sub-microsecond timescales.

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**Comparing theory and simulation of ion cyclotron emission from energetic ion populations with spherical shell and ring-beam distributions in velocity-space**  
B. Chapman,<sup>1,2</sup> R. O. Dendy,<sup>1,3</sup> S. C. Chapman,<sup>1,4</sup> L. A. Holland,<sup>5</sup> S. W. A. Irvine,<sup>6</sup> and B. C. Roman<sup>1,7</sup>  
<sup>1</sup>Centre for Fusion, Space and Astrophysics, University of Warwick, Coventry CV4 7AL, United Kingdom  
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<sup>6</sup>Lawrence Livermore National Laboratory, 7000, Livermore, CA 94550, USA  
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\*\* Chapman B et al. Nuclear Fusion 58 096027, 2018  
\*\*\* Chapman B et al. Plasma Phys. Control. Fusion 62 055003, 2020

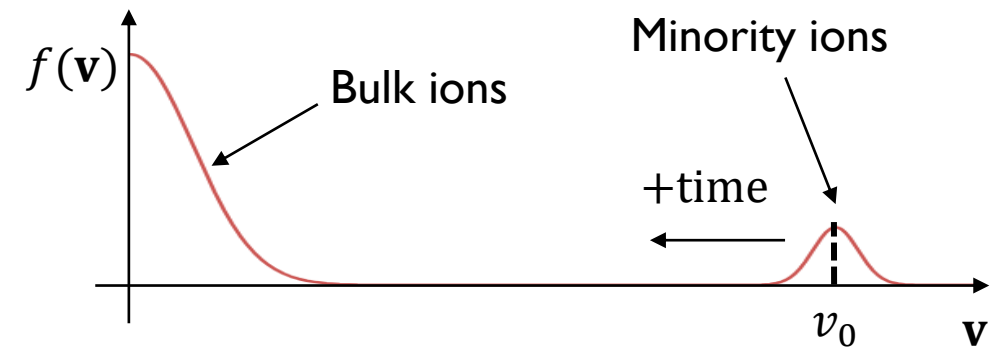
► Cook J W S Plasma Phys. Control. Fusion 64 115002, 2022

# 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

$$\Omega_{\sigma} \equiv \omega_{c\sigma} = \frac{q_{\sigma} B}{m_{\sigma}}$$
$$n\Omega_{\alpha} \quad \forall n \in \mathbb{Z}^{+}$$

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



# Ion cyclotron emission (ICE)

## Scales with:

- Minority concentration ( $\xi_\alpha$ )
- Fusion reactivity
- $v_{0\perp}/v_A$  ratio
- Pitch-angle ( $\phi$ )
- Fuel ratio ( $\xi_2/\xi_1$  ; this work)
- Magnetic field angle ( $\theta$ )

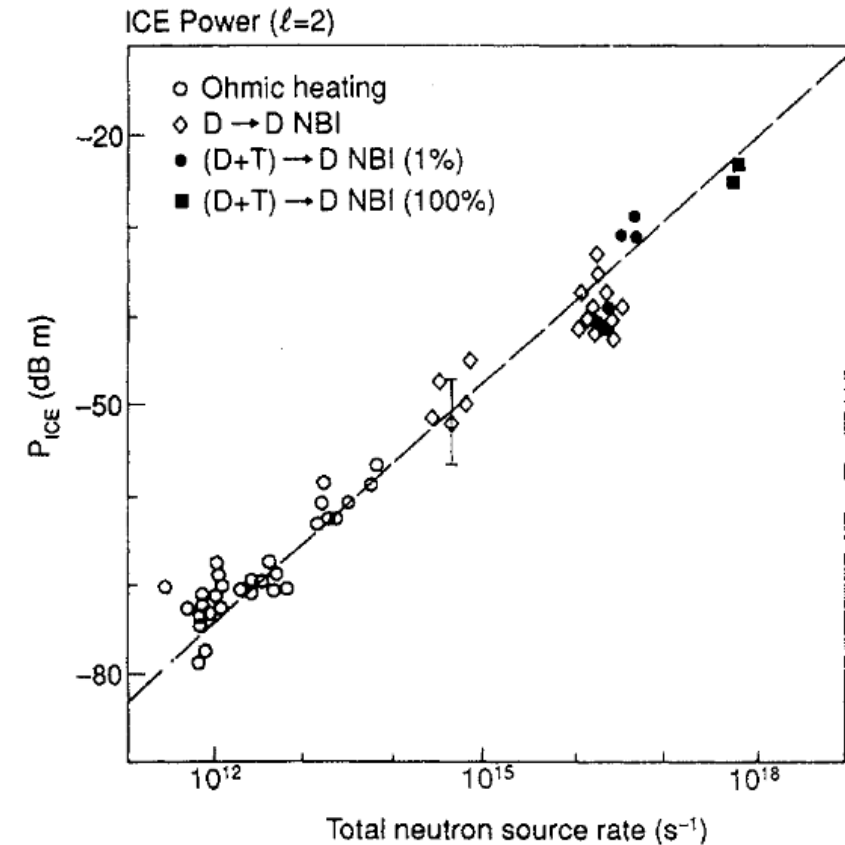


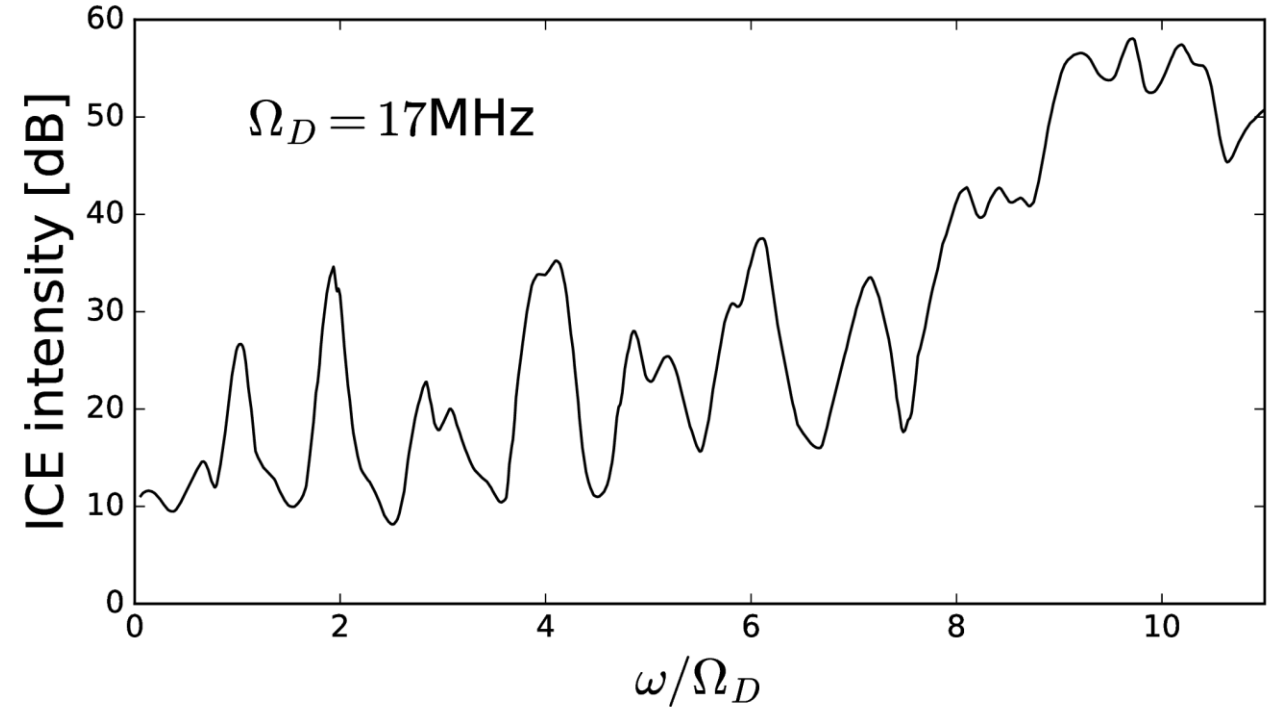
FIG. 5. Correlation between ICE intensity  $P_{ICE}$  and total neutron emission rate  $R_{NT}$  for Ohmic and NBI heated JET discharges, over six decades of signal intensity. The best fitting relation is  $P_{ICE} \propto R_{NT}^{0.9 \pm 0.1}$ .

# Ion cyclotron emission (ICE)

Location of ICE location in tokamak inferred from spacing between peaks

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

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

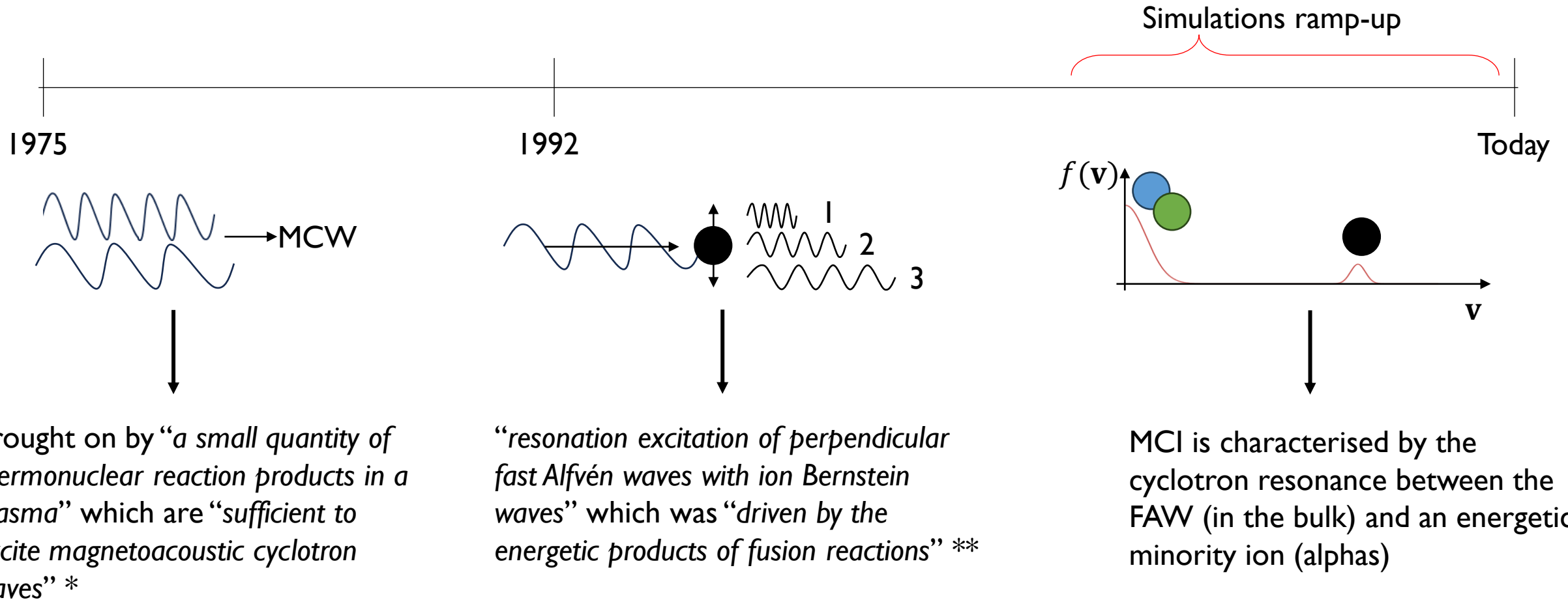


ICE spectra observed from JET plasma 26148 \*\*, spacing of 17MHz between peaks.

\* 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

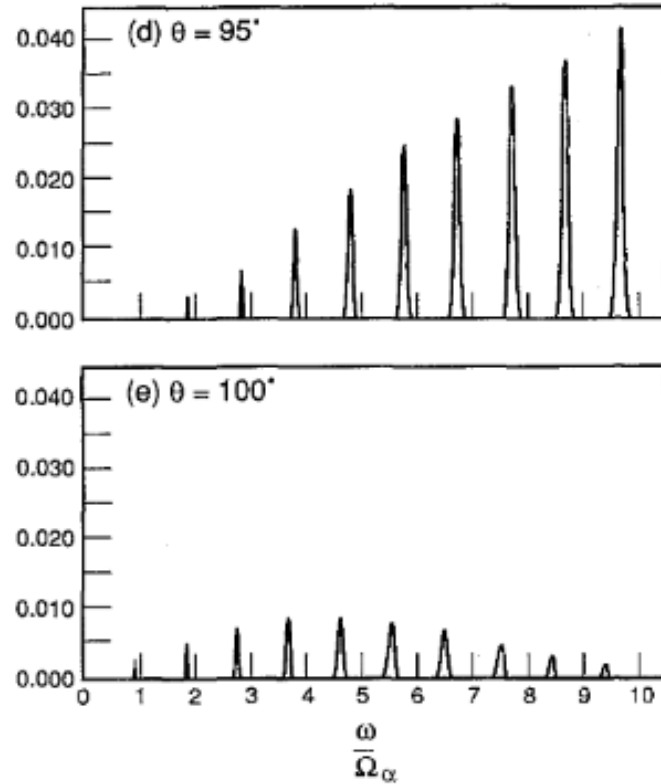
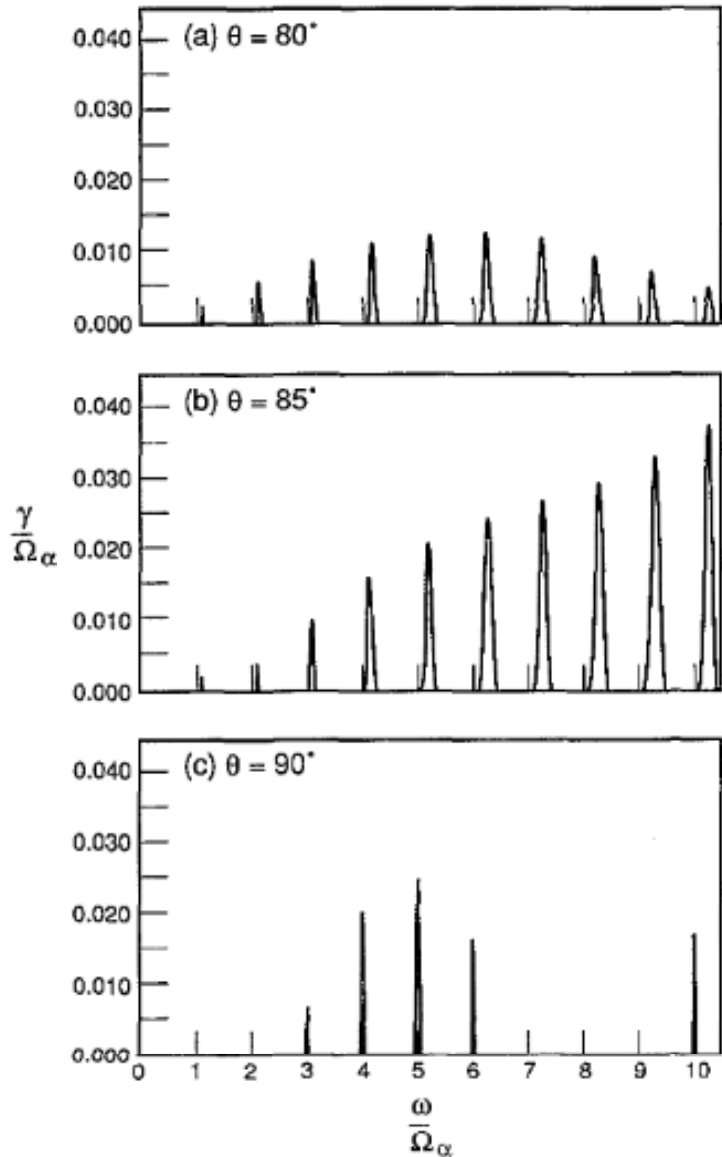
# Magnetoacoustic Cyclotron Instability (MCI)



\* 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.

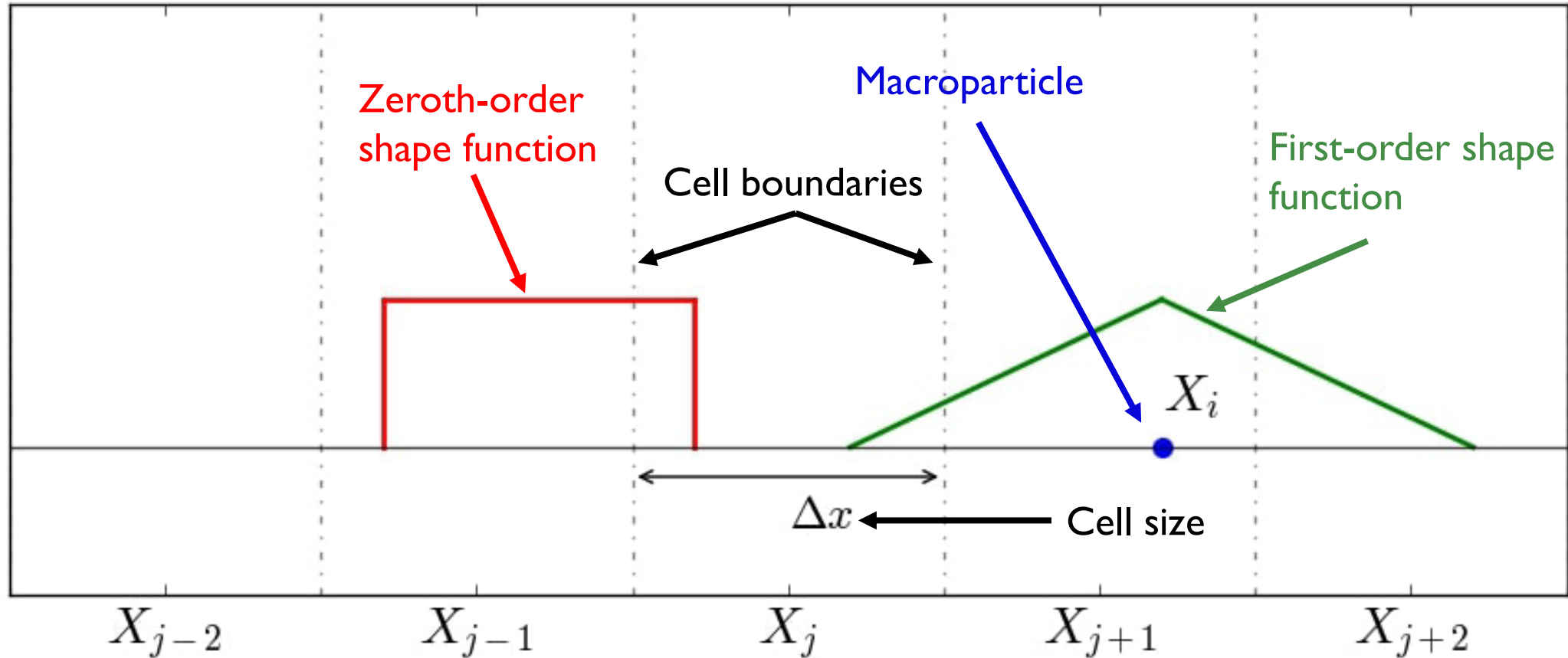
# Magnetoacoustic Cyclotron Instability (MCI)



$$\gamma = \frac{\omega_{p\alpha}^2}{\omega_{pi}^2} \frac{\Omega_i^4}{[\Omega_i + (\omega - \Omega_i)N_{\parallel}^2][\Omega_i - (\omega + \Omega_i)N_{\parallel}^2]} \times \left( \frac{l\Omega_\alpha}{k_{\parallel}v_r} M_l - \frac{2u^2}{v_r^2} \eta_l N_l \right) \frac{\sqrt{\pi}}{2\omega} e^{-\eta_l^2} \quad *$$



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



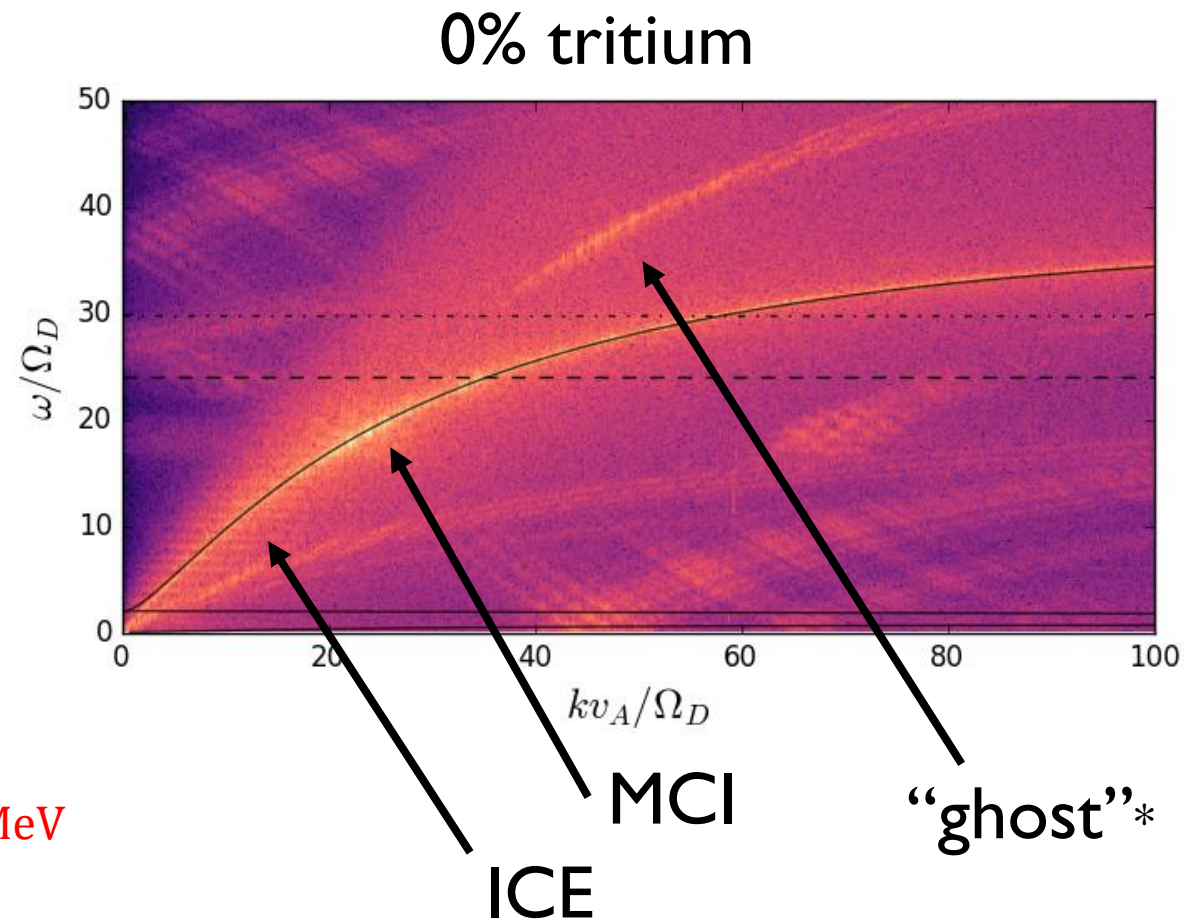
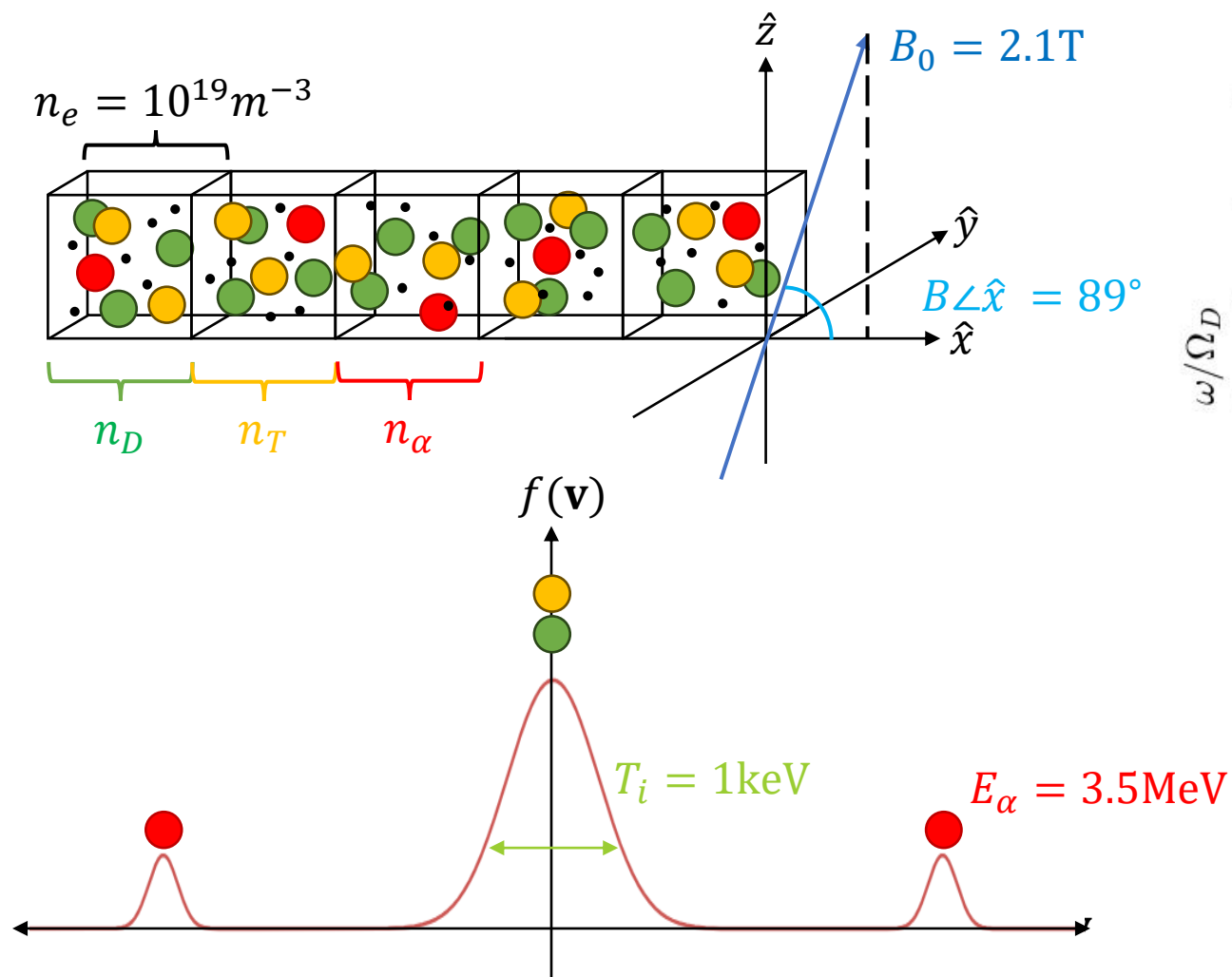
- Inclusion of tertiary ion (tritium)
- Number density weighting (NDW) conserved

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

- Introduced  $\xi_T$  (%) and fuel ratio ( $\xi_T/\xi_D$ )
- Deuteron (0%), trace tritium (1%) JET 26148 (11%) and ITER ( $\geq 50\%$ )
- Supplementary simulations

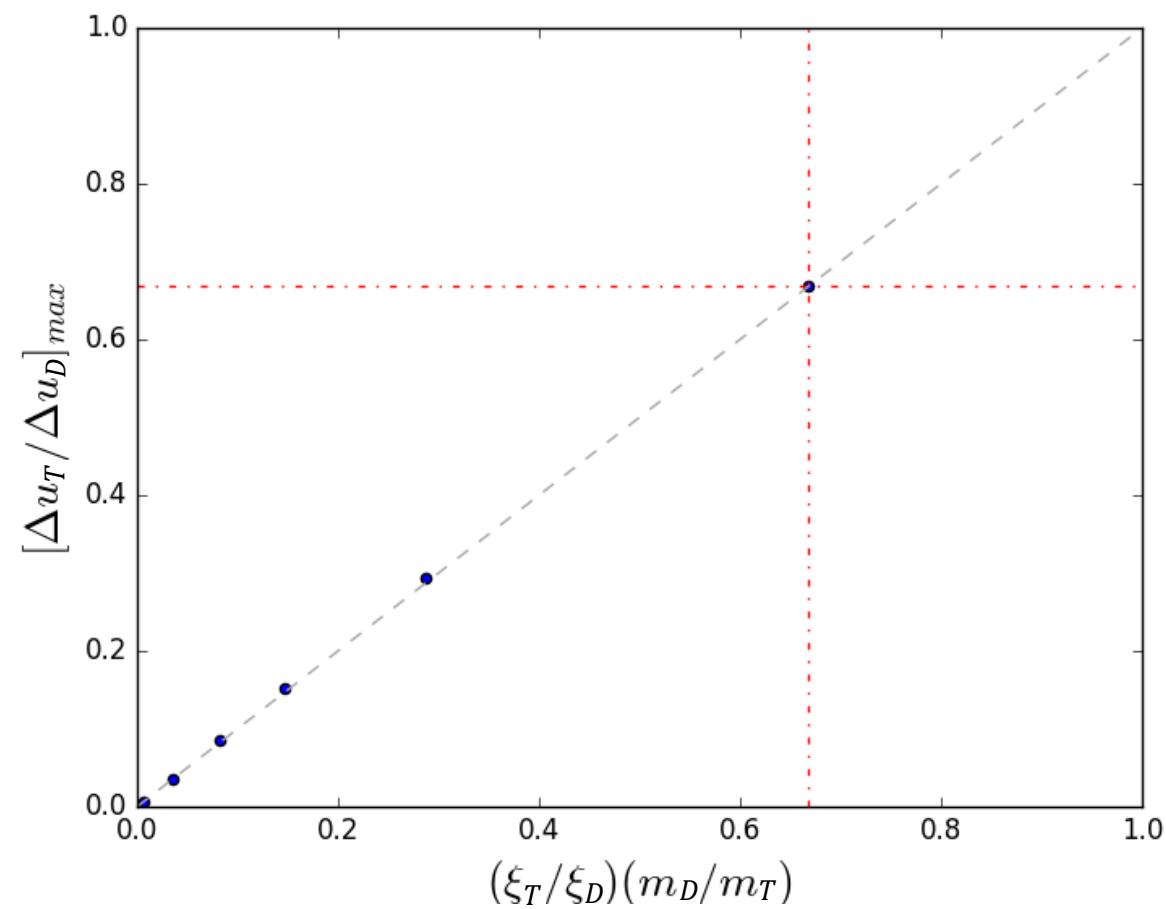
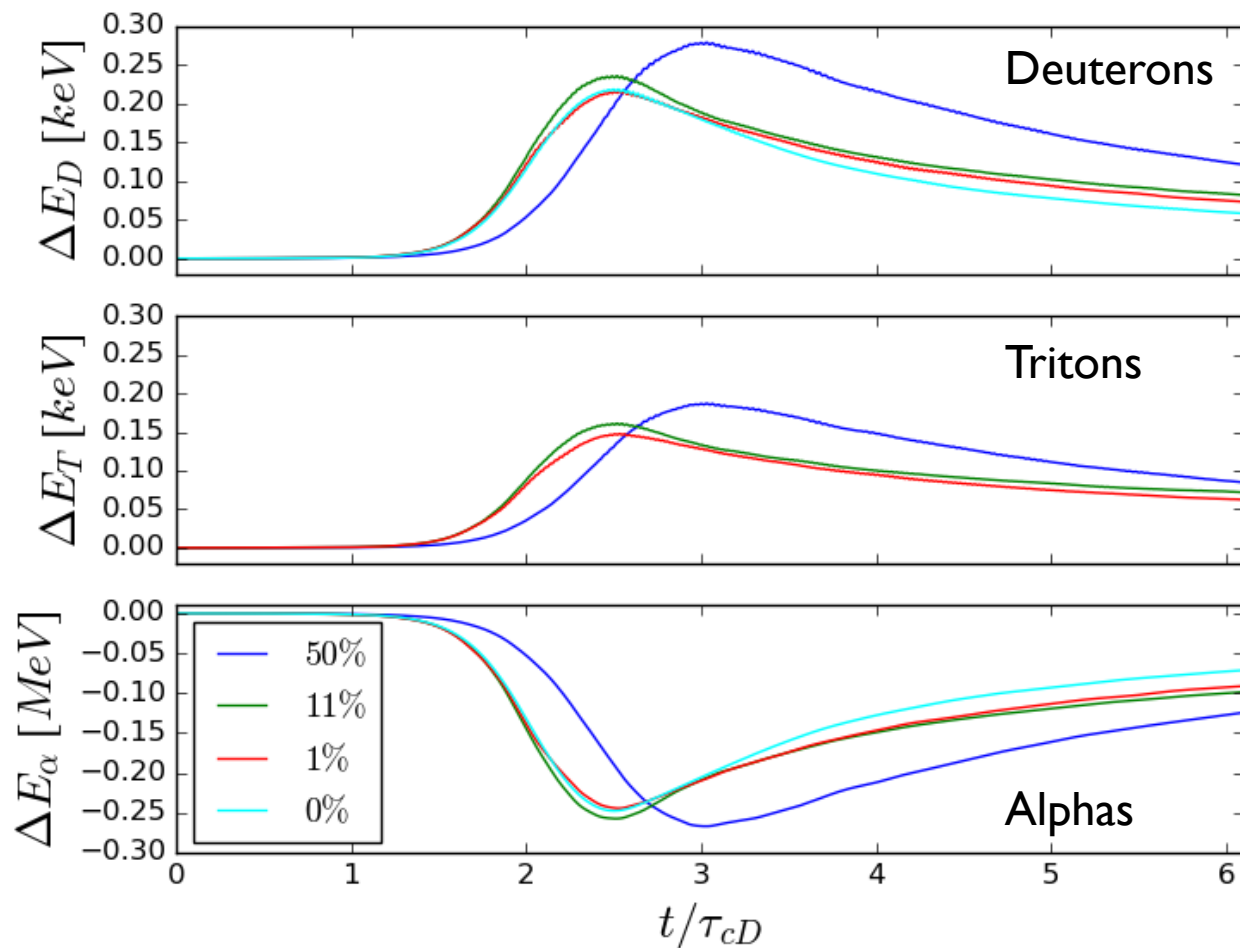
# Simulations (PIC)

## 2d representation



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

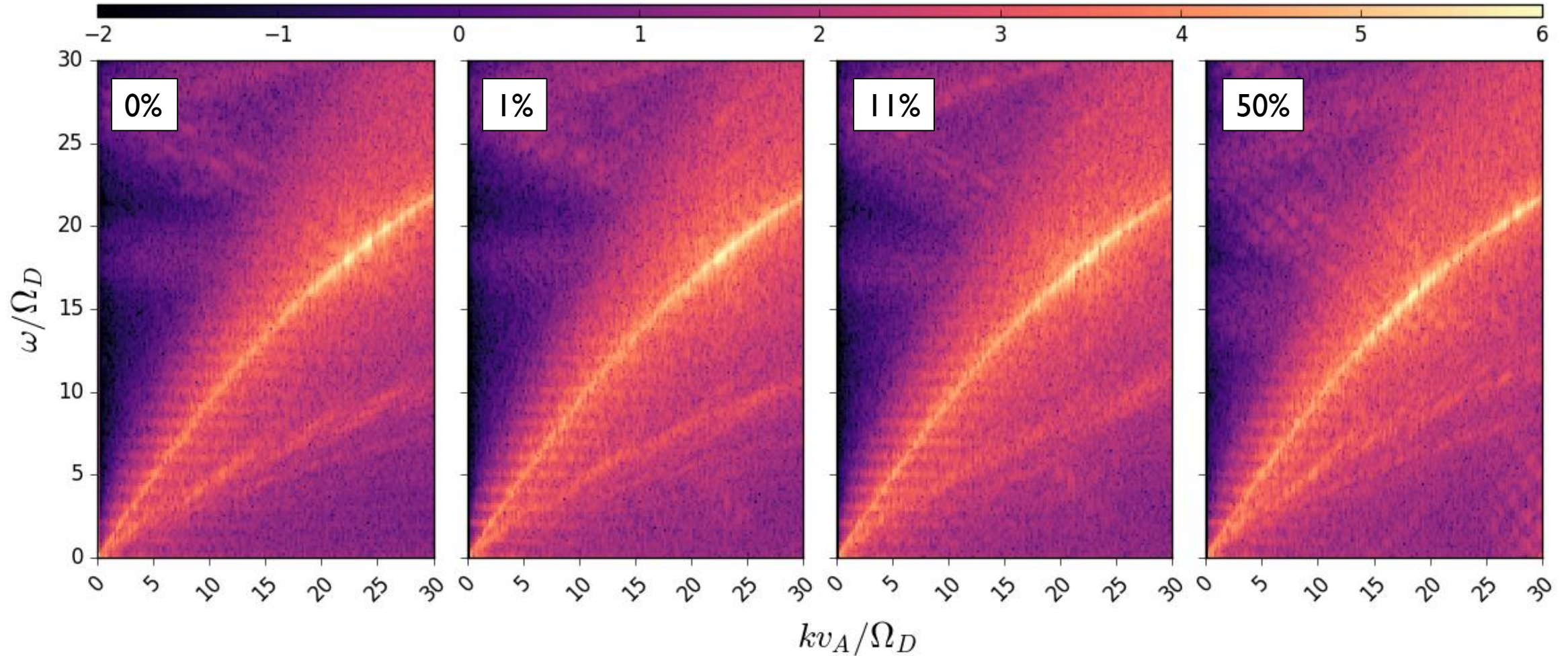
# Results : Energy



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

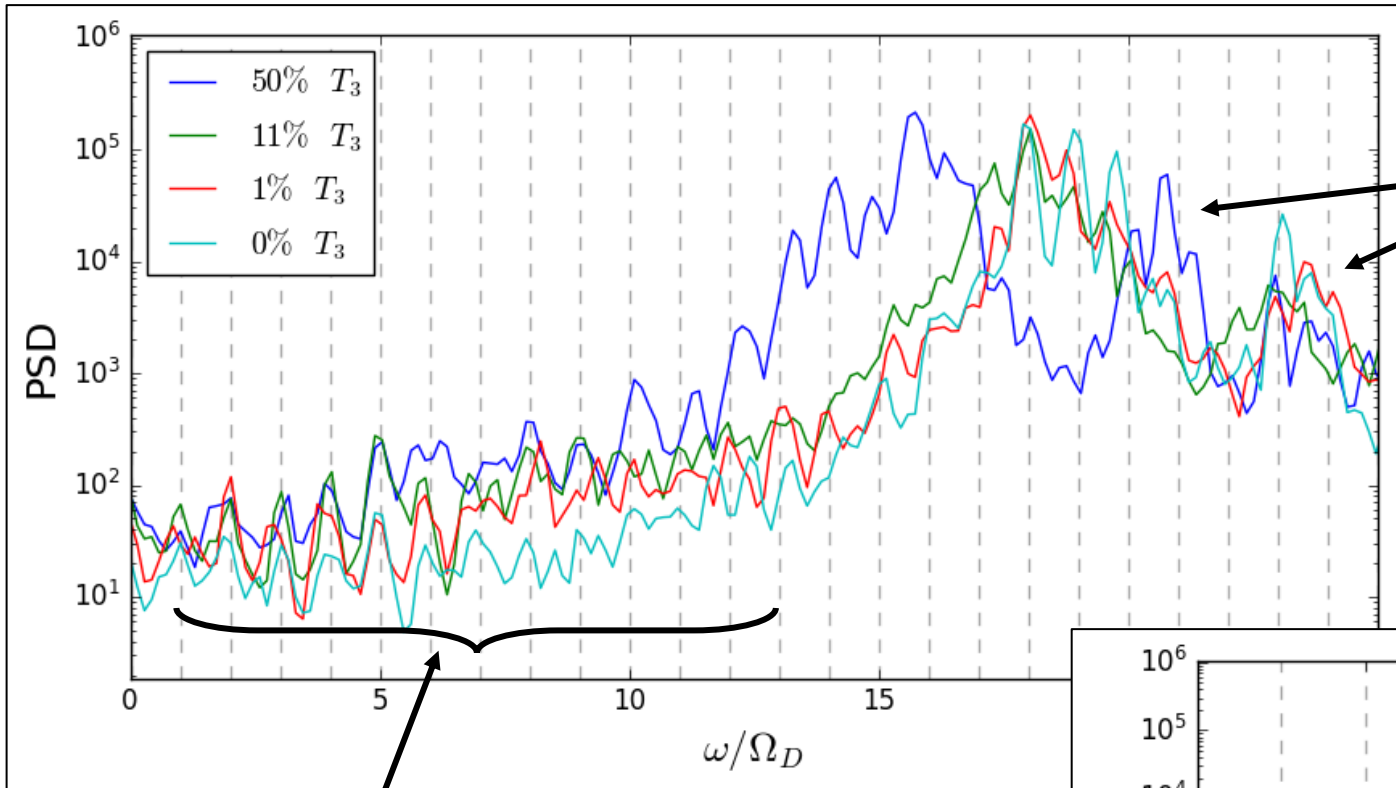
Derived from first principles :  $\Delta u_\sigma = n_\sigma \Delta E_\sigma$  : 
$$\frac{\Delta u_T}{\Delta u_D} = \frac{\xi_T m_D q_D}{\xi_D m_T q_T}$$

# Results : Fourier transforms





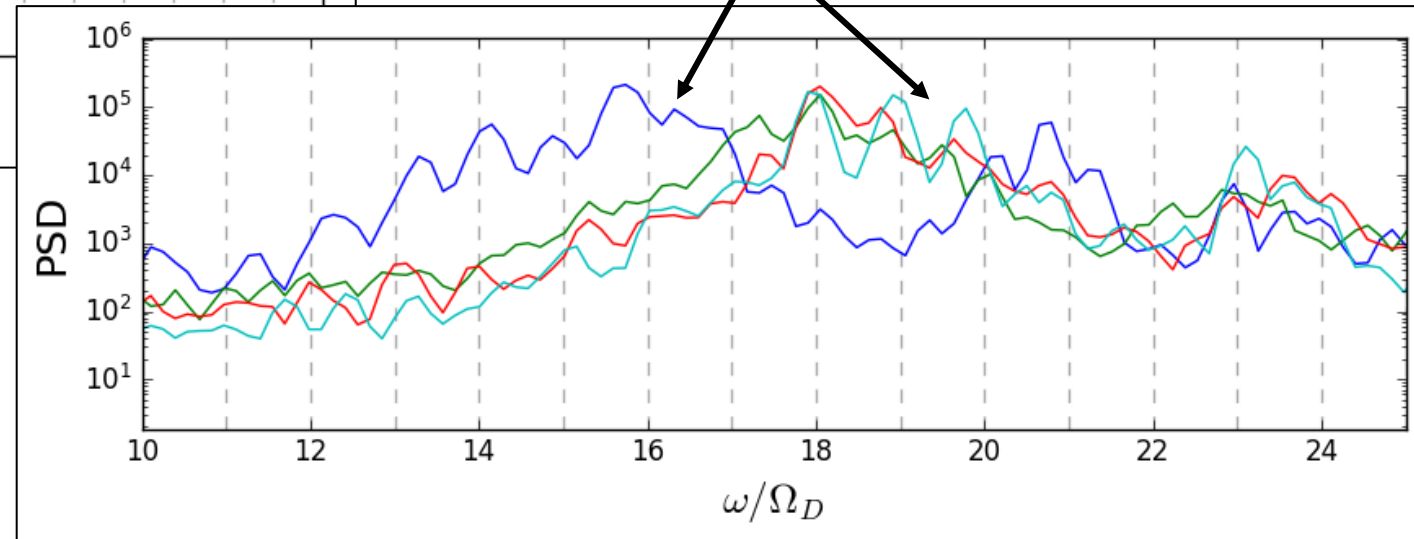
# Results : Power spectra



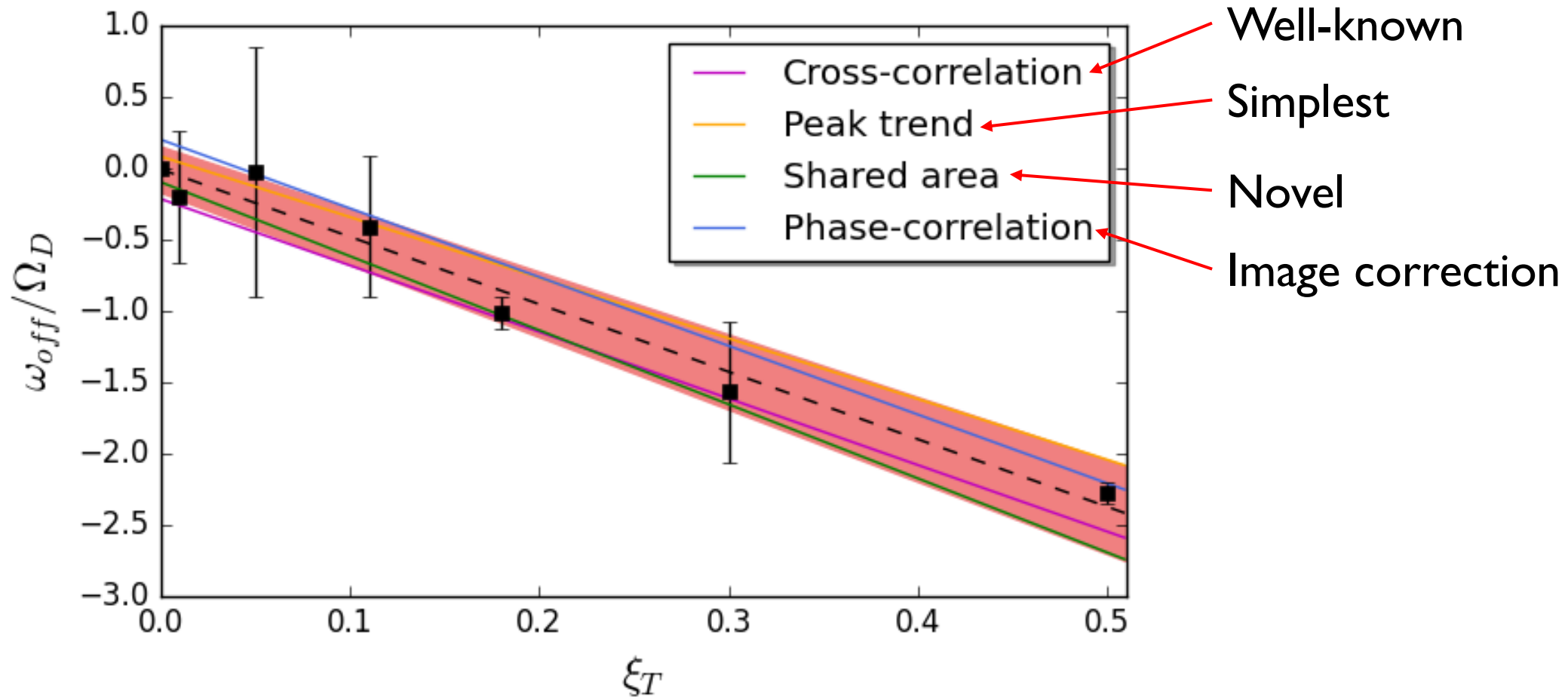
Secondary resonance on FAW branch

Increased  $\xi_T$  shifts dominant MCI region

ICE peaks at integer deuteron harmonics

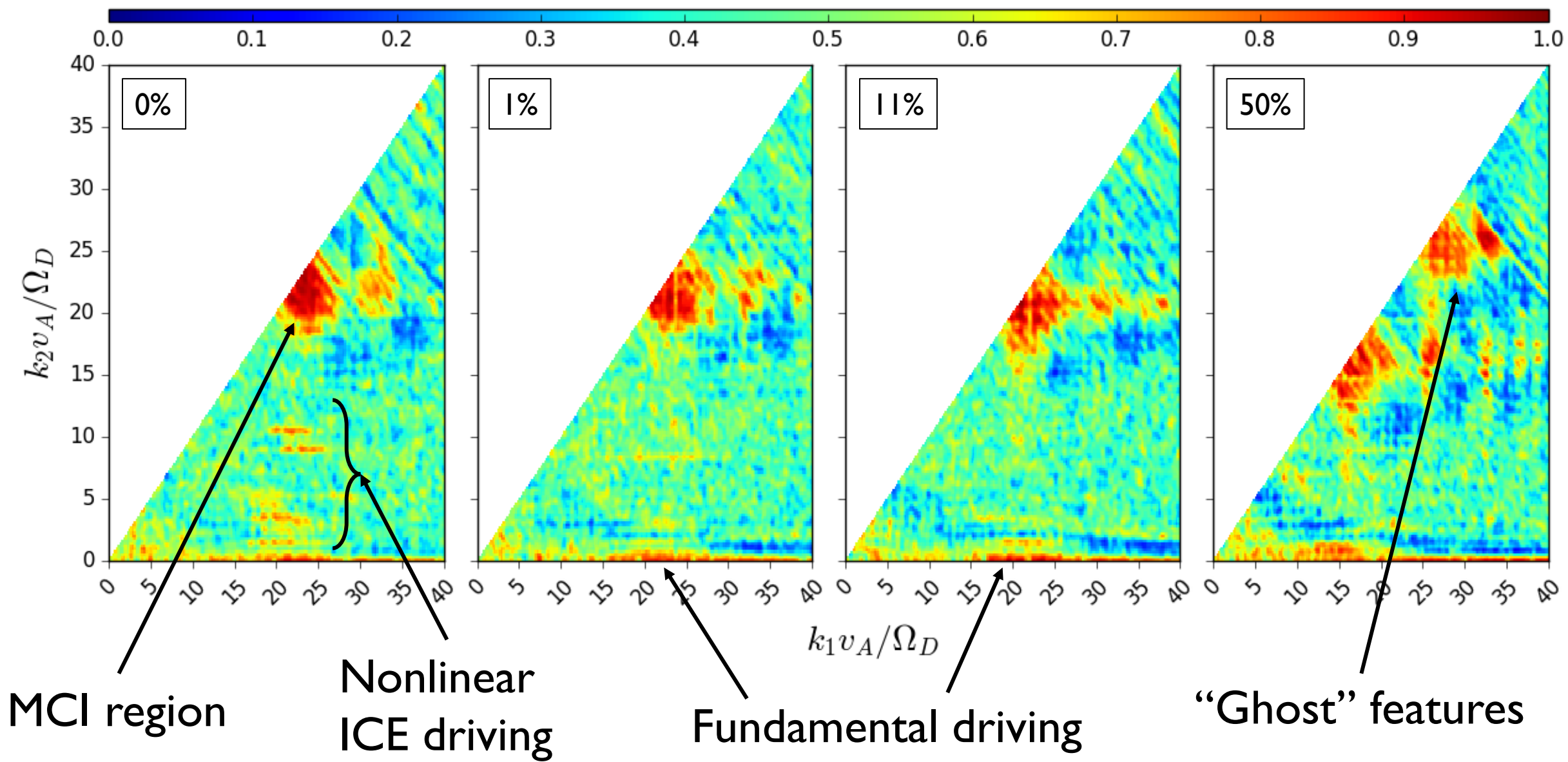


# Results : Frequency offset

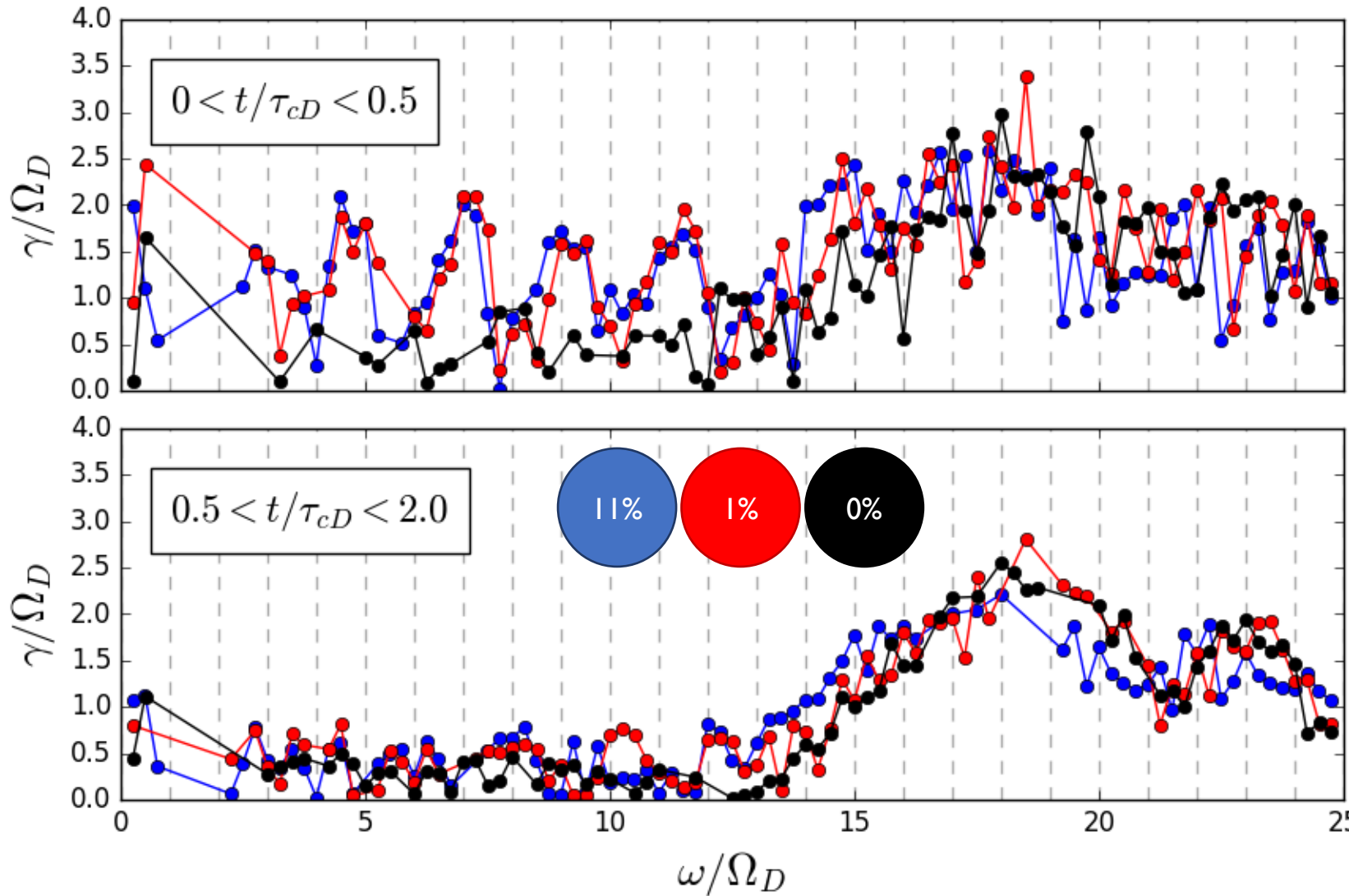


$$\omega_{off}(\xi_T)/\Omega_D = (-4.74 \pm 0.34)\xi_T + (-0.01 \pm 0.16)$$

# Results : Bicoherence



# Results : Growth rates



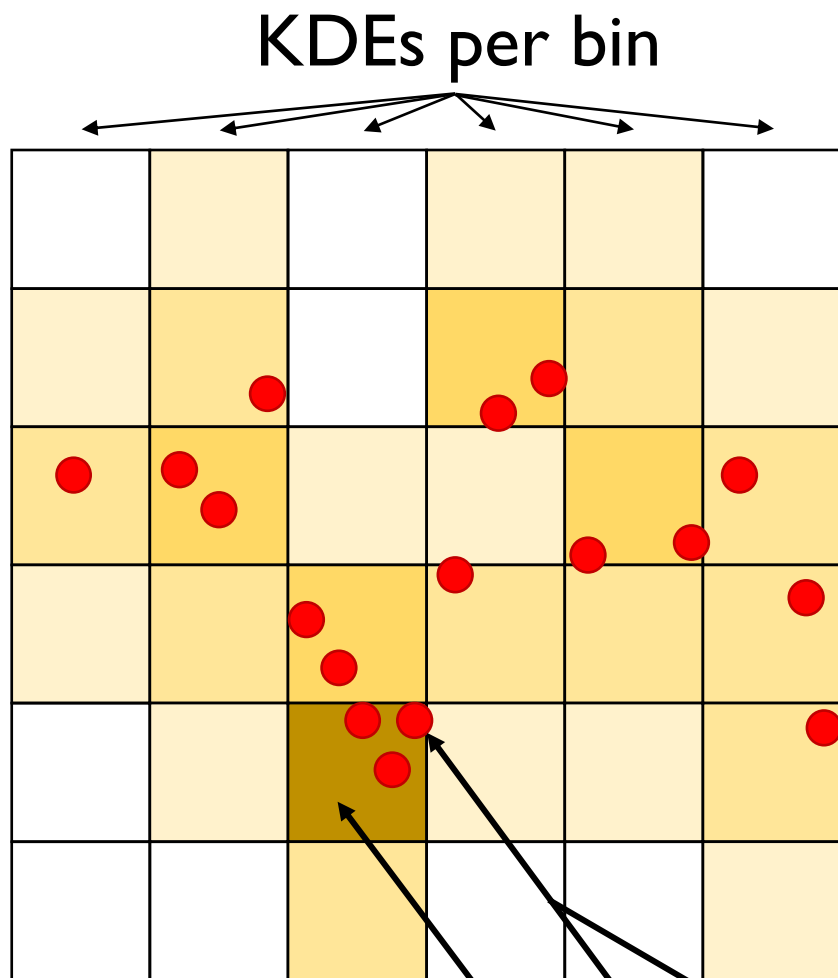
*Early:*

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

*Late:*

- No joint harmonics
- Smooth growths
- Secondary growths

# Results : Tau-squared



$\tau^2$  is minimised for best fitting data to model

Normalised to number of peaks to find  $\tau^2$  contribution minimisation

11% simulation best represents the JET 26148 data

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

JET 26148 PPR data

$\xi_T$ [%]	$\tau^2 / N_{peaks}$
0	30.0
1	28.7
5	29.8
11	27.9
18	28.7
30	29.9
50	30.0



- Bulk ions energise slower with increasing  $\xi_T$
- 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  $\xi_T$
- JET plasma 26148 is best represented by the 11% simulation
- Simulation of three ions is a necessity for  $\xi_T > 1\%$ , especially for ITER

*Thank you for listening*