Influence on ion cyclotron emission from PIC simulations of aneutronic D-He3 plasmas and 14.68 MeV protons

Tobias Slade-Harajda

Prof. R Dendy and Prof. S Chapman

WARWICK
THE UNIVERSITY OF WARWICK

Engineering and Physical Sciences Research Council

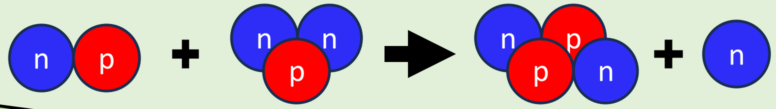
EUROfusion

Contents

- Motivation
- Ion cyclotron emission (ICE)
- Magnetoacoustic cyclotron instability (MCI)
- Simulating the fusion plasma (PIC code)
- Results
- Summary & Future work

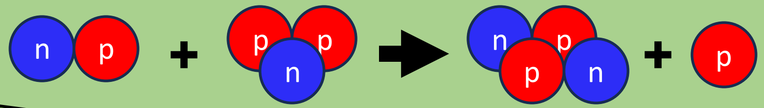
Motivation

D-T



Neutrons irradiate tokamak wall (expensive, dangerous, inefficient)

D-^{3}He




```
if neutrons==None:
        count=None
```

Need measurement which scales with reactivity, but doesn’t require neutrons

Introducing… ICE

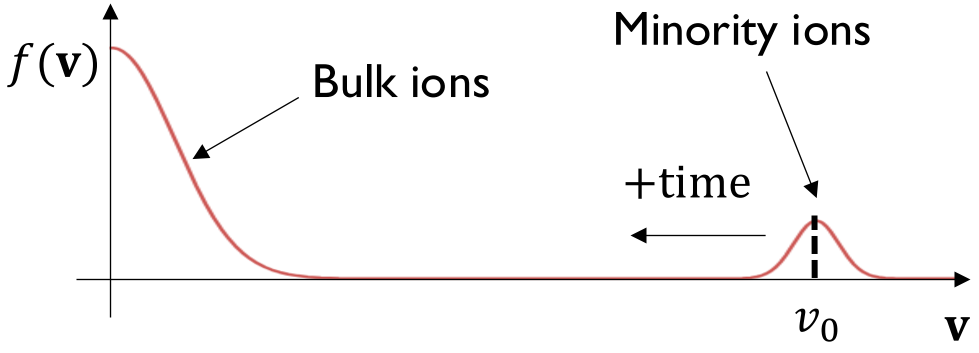
Ion cyclotron emission (ICE)

- Suprathermal emission visible at multiple ion harmonics
- Driven by the MCI, caused by strong gradients in an energetic minority's velocity-space distribution
- Measurement is passive, non-intrusive and multi-angled

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

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

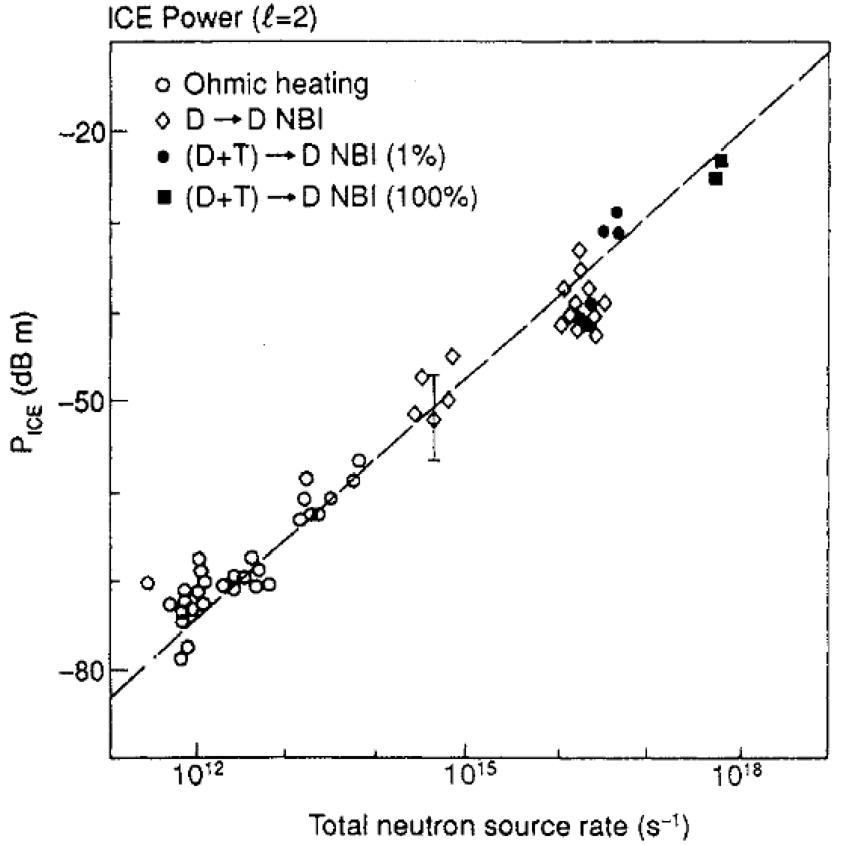
$$\frac{\partial f_\alpha(v_\parallel, v_\perp)}{\partial \mathbf{v}} > 0$$



Ion cyclotron emission (ICE)

Scales with:

- Minority concentration (ξ_{min})
- Fusion reactivity
- $v_{0\perp}/v_A$ ratio
- Pitch-angle (ϕ)
- Fuel ratio (ξ_2/ξ_1)**
- 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 $P_{ICE} \propto R_{NT}^{0.9\pm0.1}$.

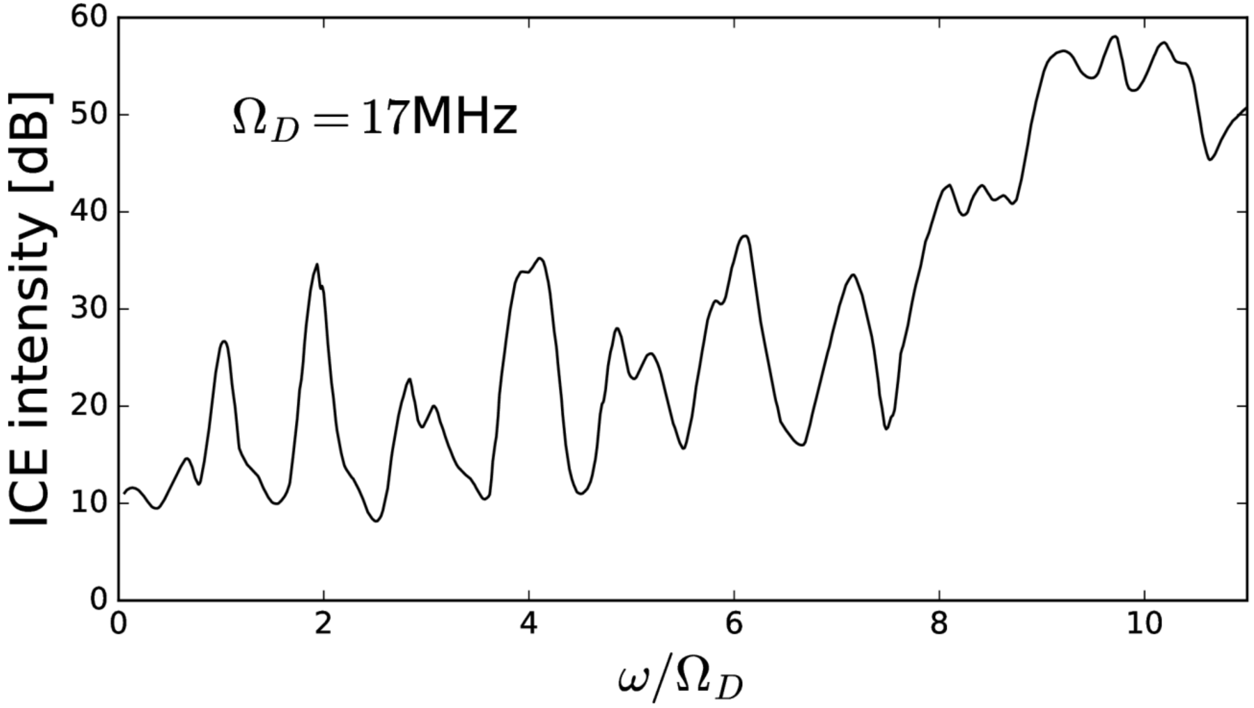
* G. A. Cottrell *et al.*, 1993 *Nuclear Fusion*, vol. 33, pp. 1365–1387
** T.W. Slade-Harajda *et al.*, 2024 *Nucl. Fusion*

Ion cyclotron emission (ICE)

Location of ICE in tokamak inferred from spacing between peaks

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

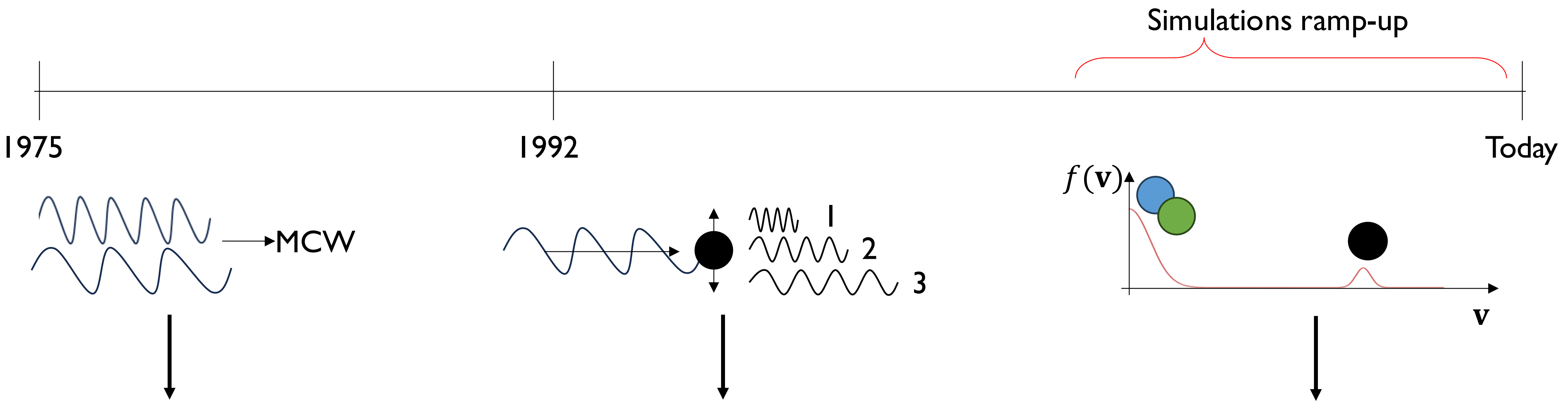
$$B_\theta^{(0)}(r) = \frac{\mu_0 I_P}{2\pi r}\left(1 - \left[1 - \left(\frac{r}{a}\right)^2\right]^\gamma \Theta(a-r)\right) *$$



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

* Caldas I L *et al.* 1996 *Chaos Solitons and Fractals* **7** 991–1010
* * G. A. Cottrell *et al.*, 1993 *Nuclear Fusion*, vol. 33, pp. 1365–1387

Magnetoacoustic Cyclotron Instability (MCI)



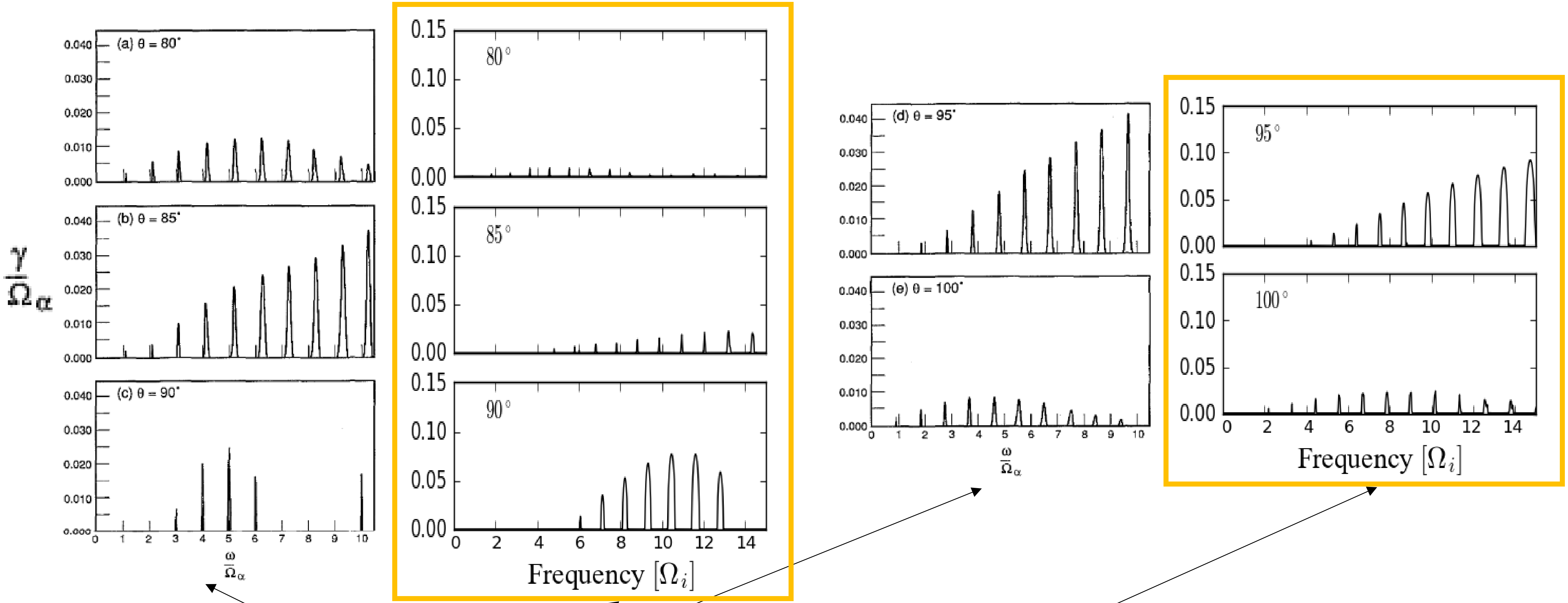
Brought on by "*a small quantity of thermonuclear reaction products in a plasma*" which are "*sufficient to excite magnetoacoustic cyclotron waves*" *

"*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)

* V. S. Belikov and Y. I. Kolesnichenko, 1975 *Sov. Phys. - Tech. Phys.*, vol. 20:9
* * R. O. Dendy *et al.* 1992 *Physics of Fluids B: Plasma Physics*, vol. 4, pp. 3996–4006

Magnetoacoustic Cyclotron Instability (MCI)



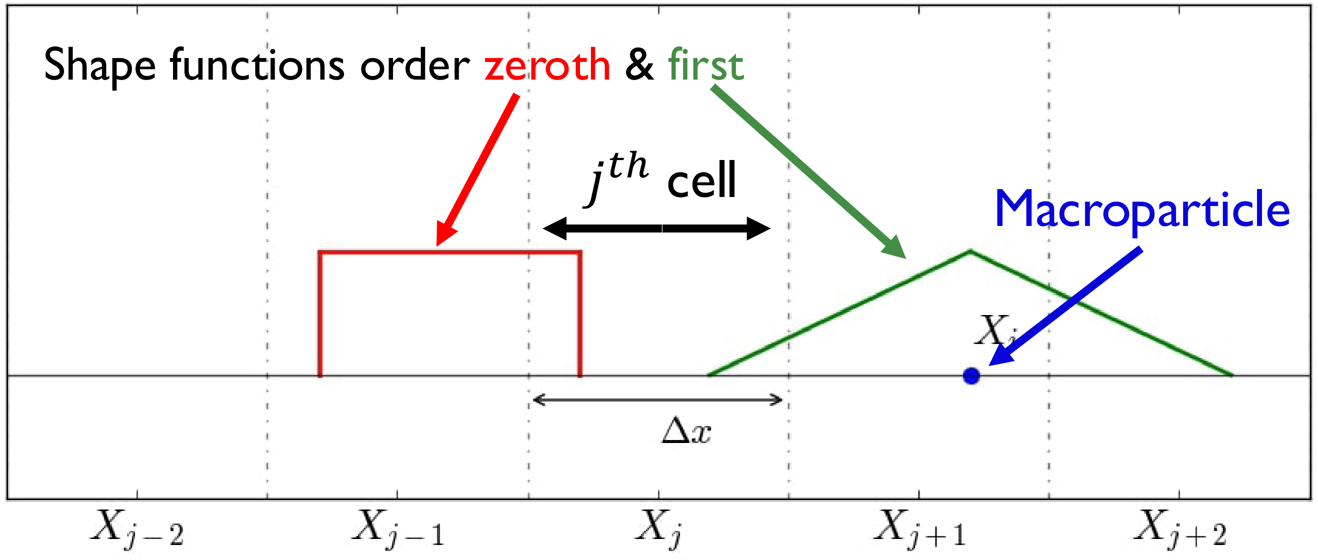
Linear theory *

New LMV solver **

* McClements K G *et al.*, 1996 *Physics of Plasmas* **3** 543–53
** J W S Cook 2022 *Plasma Phys. Control. Fusion* **64** 115002

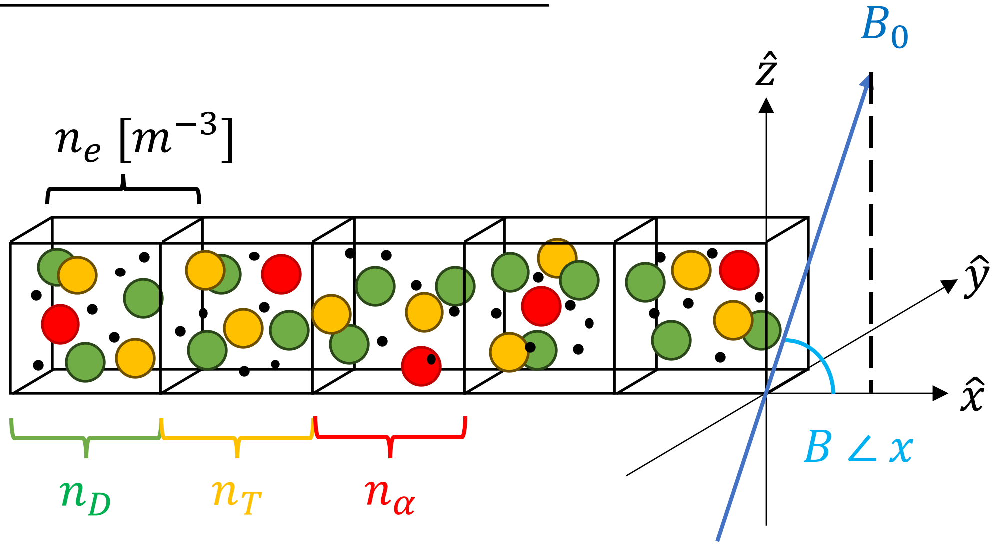
Simulations (PIC)

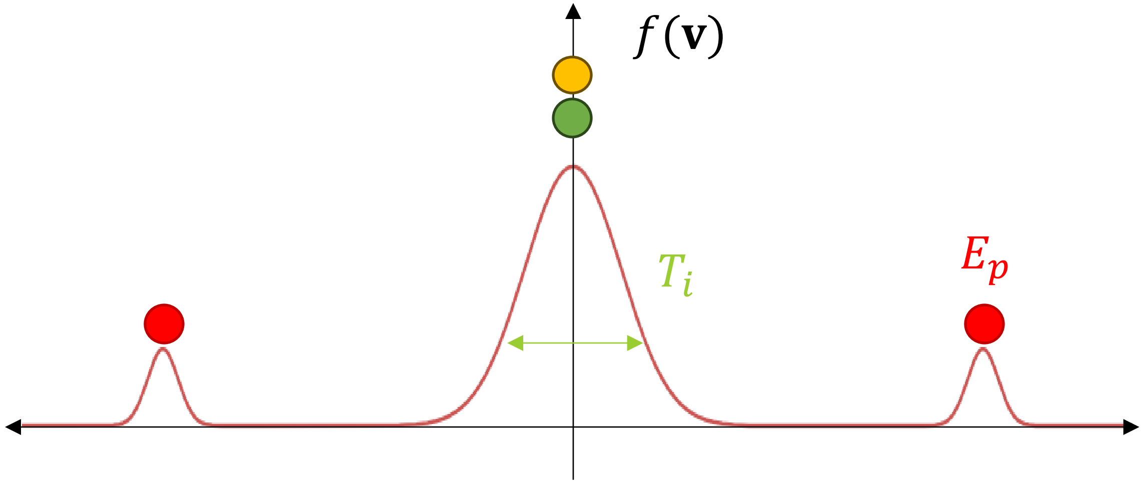
Use of the particle-in-cell (PIC) code EPOCH *



- Distribute particles with quasi-neutral densities n_σ
- Angle magnetic field θ to simulation domain
- Shape functions infer fields to the particles
- Push particles, update velocities and fields
- Rinse and repeat

2d representation





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

Simulations (PIC)

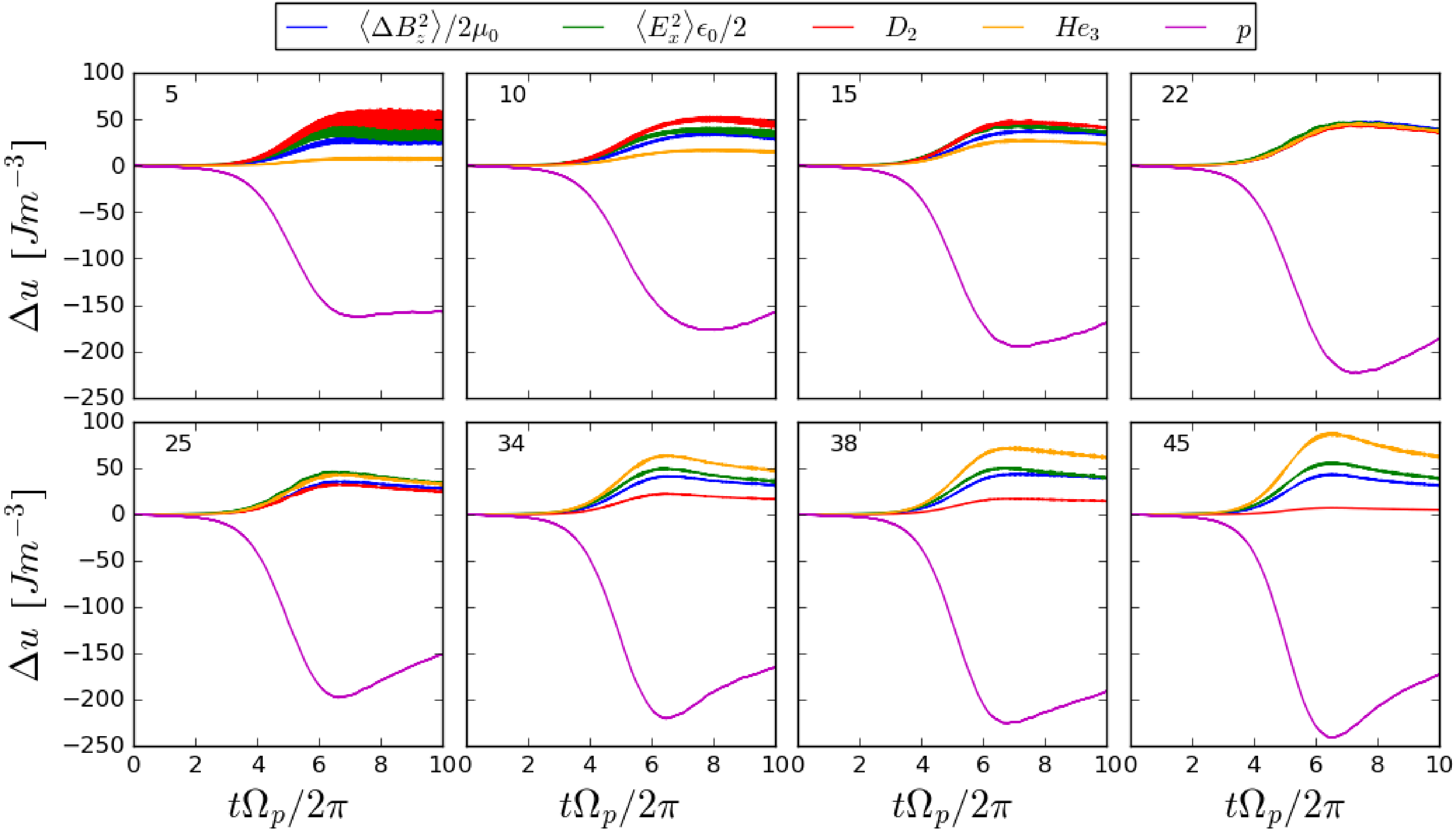
- Inclusion of tertiary ion (e.g. tritium, ***helium-3***, boron-11)
- Number density weighting (NDW) conserved

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

- Ran for simulations using $0 < \xi_{He3} \leq 0.45$
- Using JET like initial conditions for protons *
- Pure deuterium (0%), "realistic" case (22%)* and limit (45%)

* Kiptily V G *et al.*, 2022 *Plasma Phys. Control. Fusion* **64** 064001

Results : Energy



- Exponential growth of energies (MCI characteristic)
- As $\xi_{He3} \uparrow$, energy gained increases
- Deepening of energy lost by protons as $\xi_{He3} \uparrow$
- E_x grows faster than B_z (ES rather than EM?)

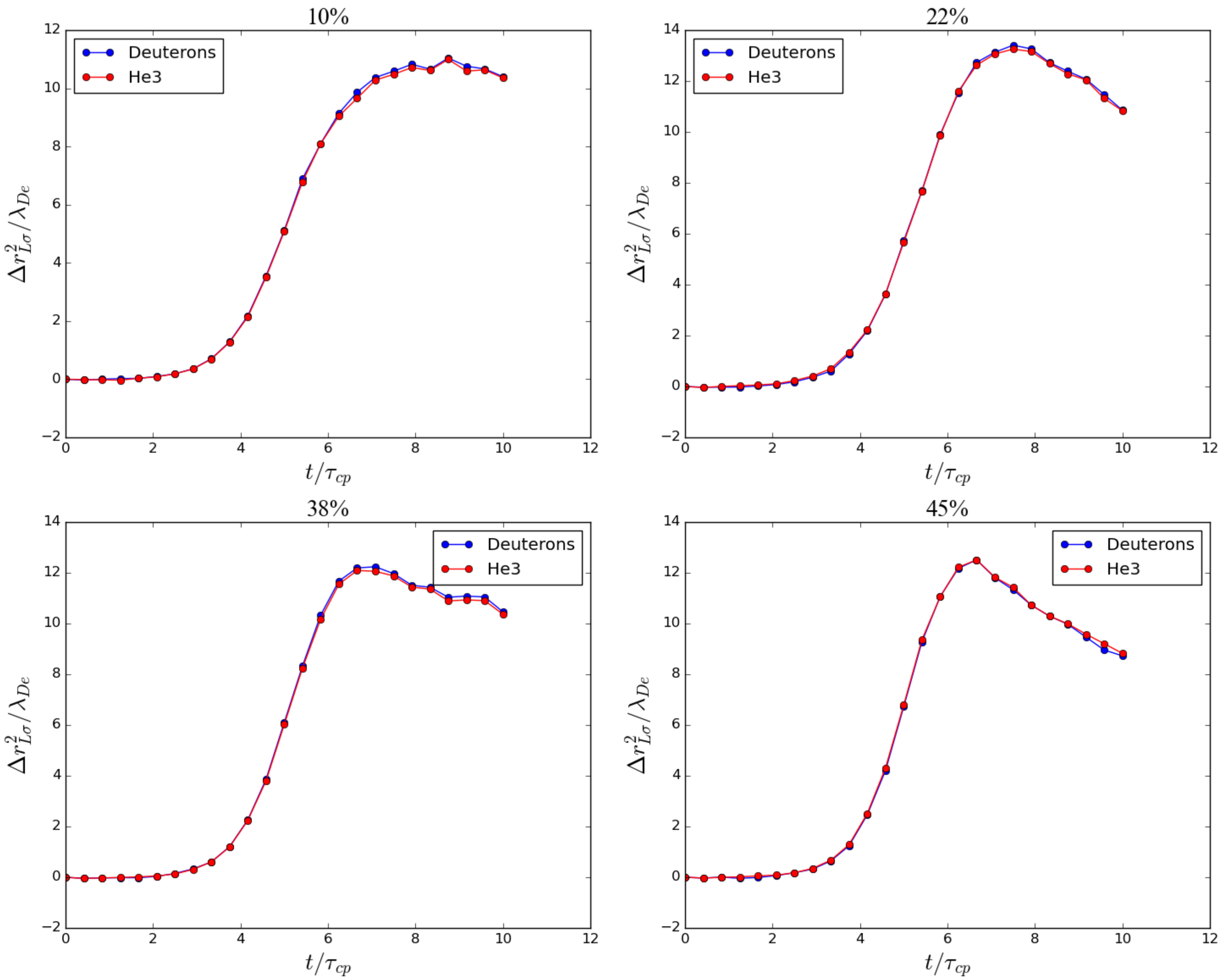
Results : Gyro-resonance. I

Derived from first principles

$$\frac{\Delta u_1}{\Delta u_2} = \frac{n_1 \Delta E_1}{n_2 \Delta E_2}$$

$$\Rightarrow \frac{n_1 m_1}{n_2 m_2}\left(\frac{\Delta v_{\perp 1}^2 + \Delta v_{\parallel 1}^2}{\Delta v_{\perp 2}^2 + \Delta v_{\parallel 2}^2}\right)$$

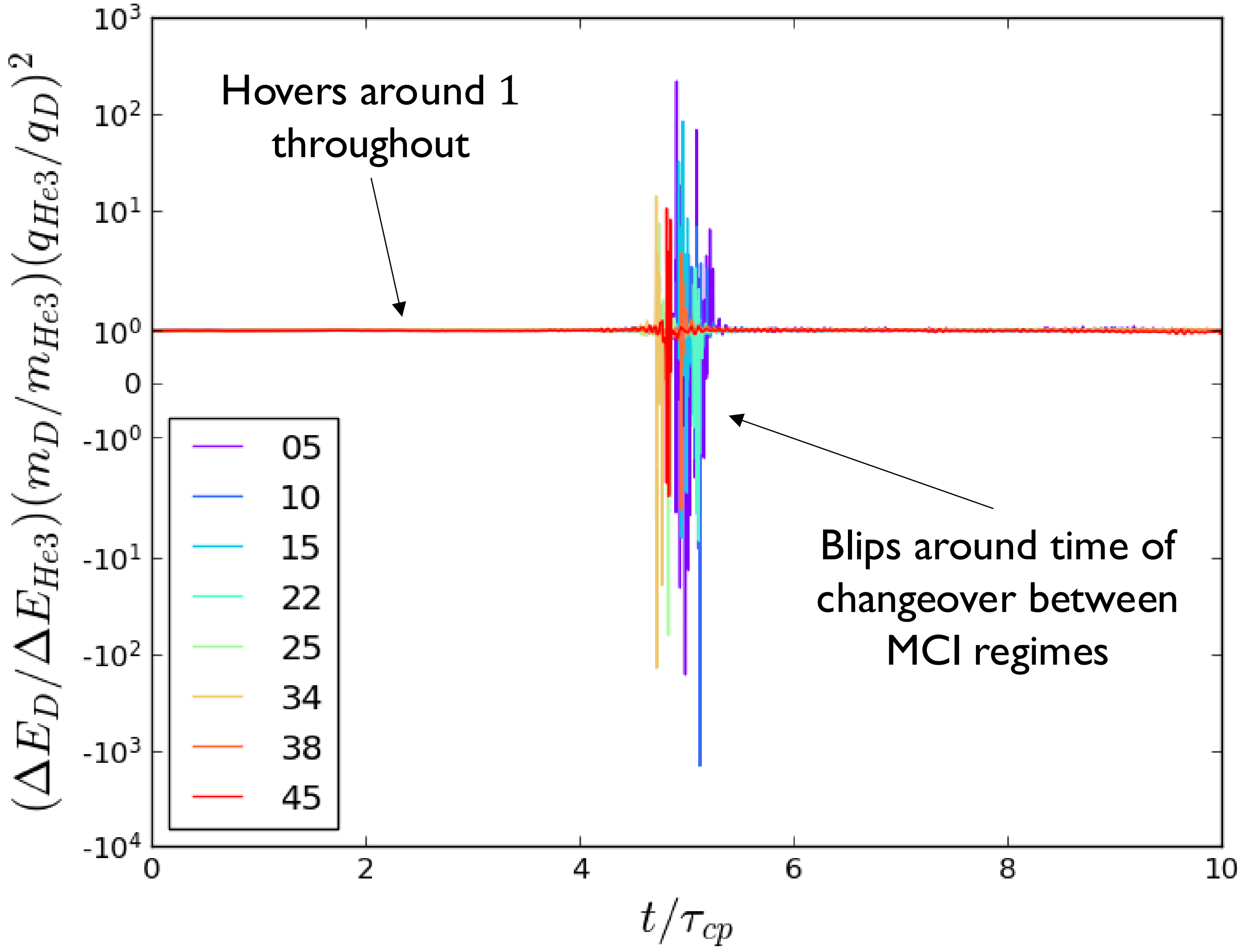
$$\Rightarrow \frac{n_1 m_2}{n_2 m_1}\left(\frac{q_1}{q_2}\right)^2 \left(\frac{\Delta r_{L1}^2}{\Delta r_{L2}^2}\right)$$



Results : Gyro-resonance.11

$$\left(\frac{\Delta r_{L1}^2}{\Delta r_{L2}^2}\right) = \frac{\Delta u_1}{\Delta u_2} \cdot \frac{n_2 m_1}{n_1 m_2}\left(\frac{q_2}{q_1}\right)^2$$

Rearranged expression to plot vs. time



- Used two methods to determine $(\Delta r_{L1}^2/\Delta r_{L2}^2)$ ratio
- Change in enclosed magnetic flux is equal for both species

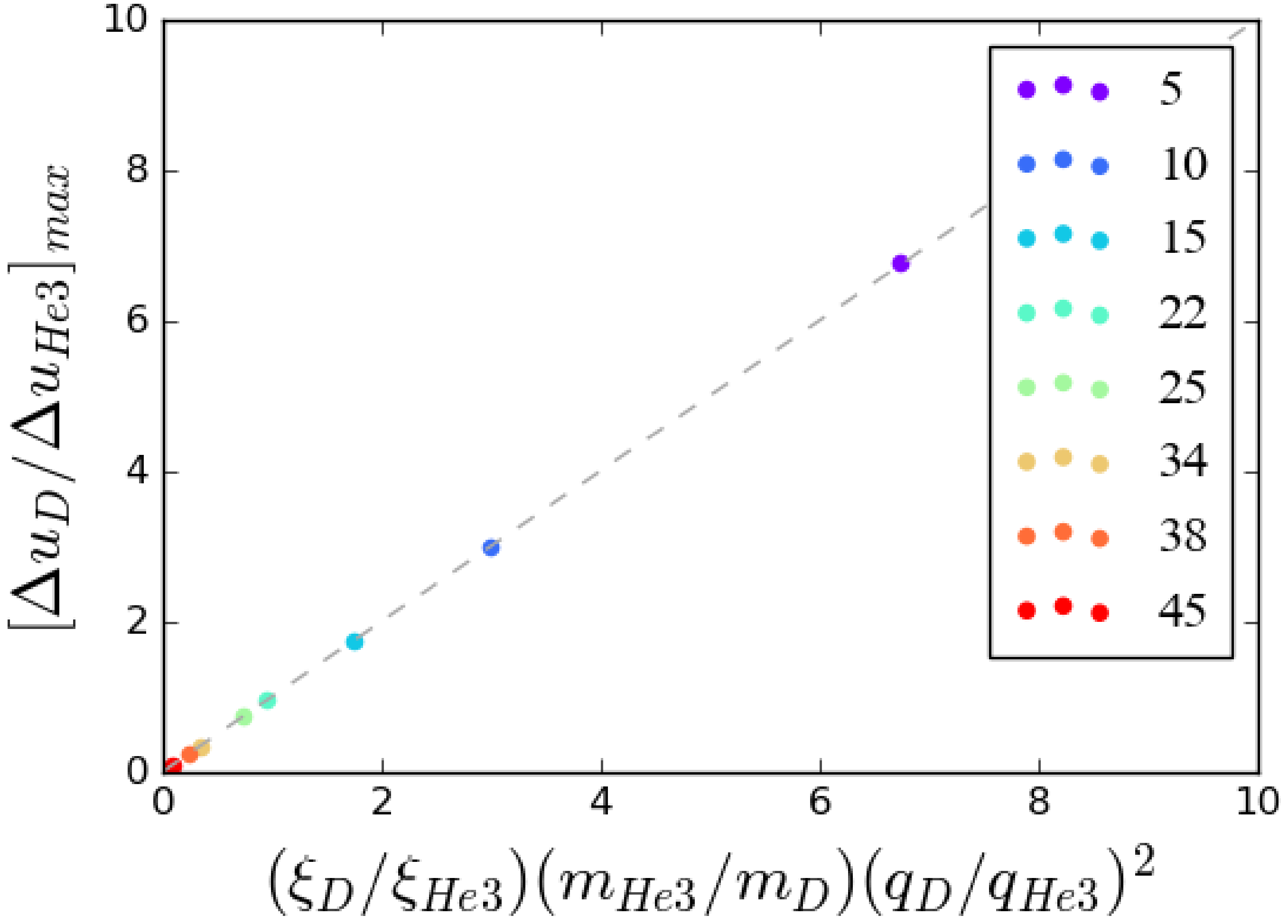
Results : Gyro-resonance.III

Removing flux enclosed term, we can plot

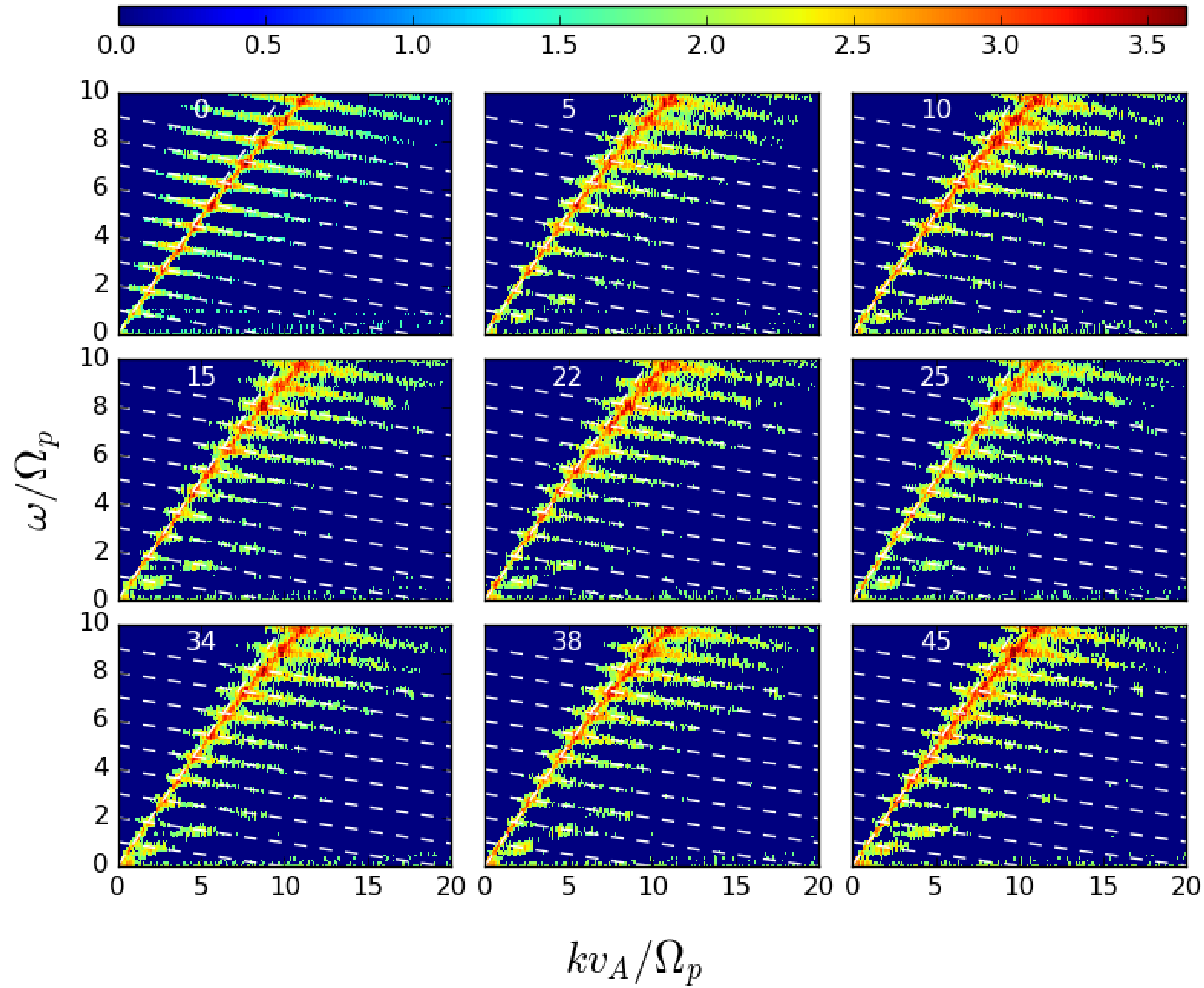
$$\frac{\Delta u_D}{\Delta u_{He3}}$$

vs.

$$\frac{\xi_D m_{He3}}{\xi_{He3} m_D}\left(\frac{q_D}{q_{He3}}\right)^2$$



Results : Fourier transforms



- ICE grows strongly for $\omega < 10\Omega_p$
- Spatiotemporal Fourier transforms in 2d (k, ω) space reveal Doppler shift
- Can predict Doppler shift using

$$\omega'_n = n\Omega_p - ku_p \cos\theta \cos\phi$$

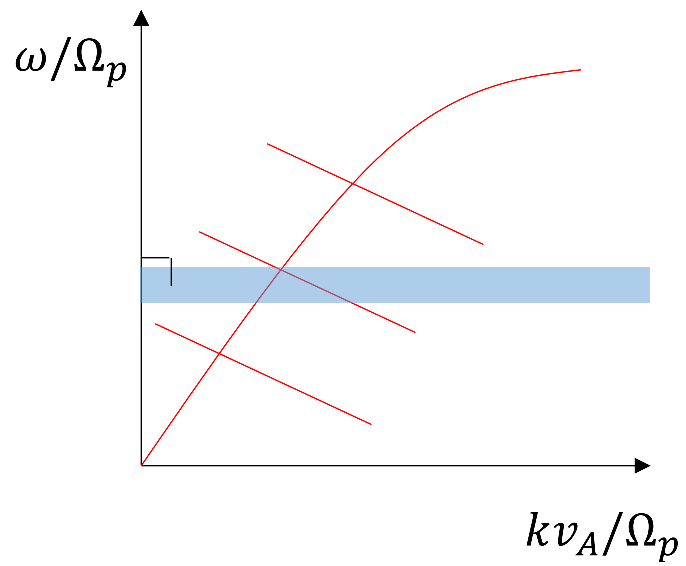
θ = Magnetic field angle

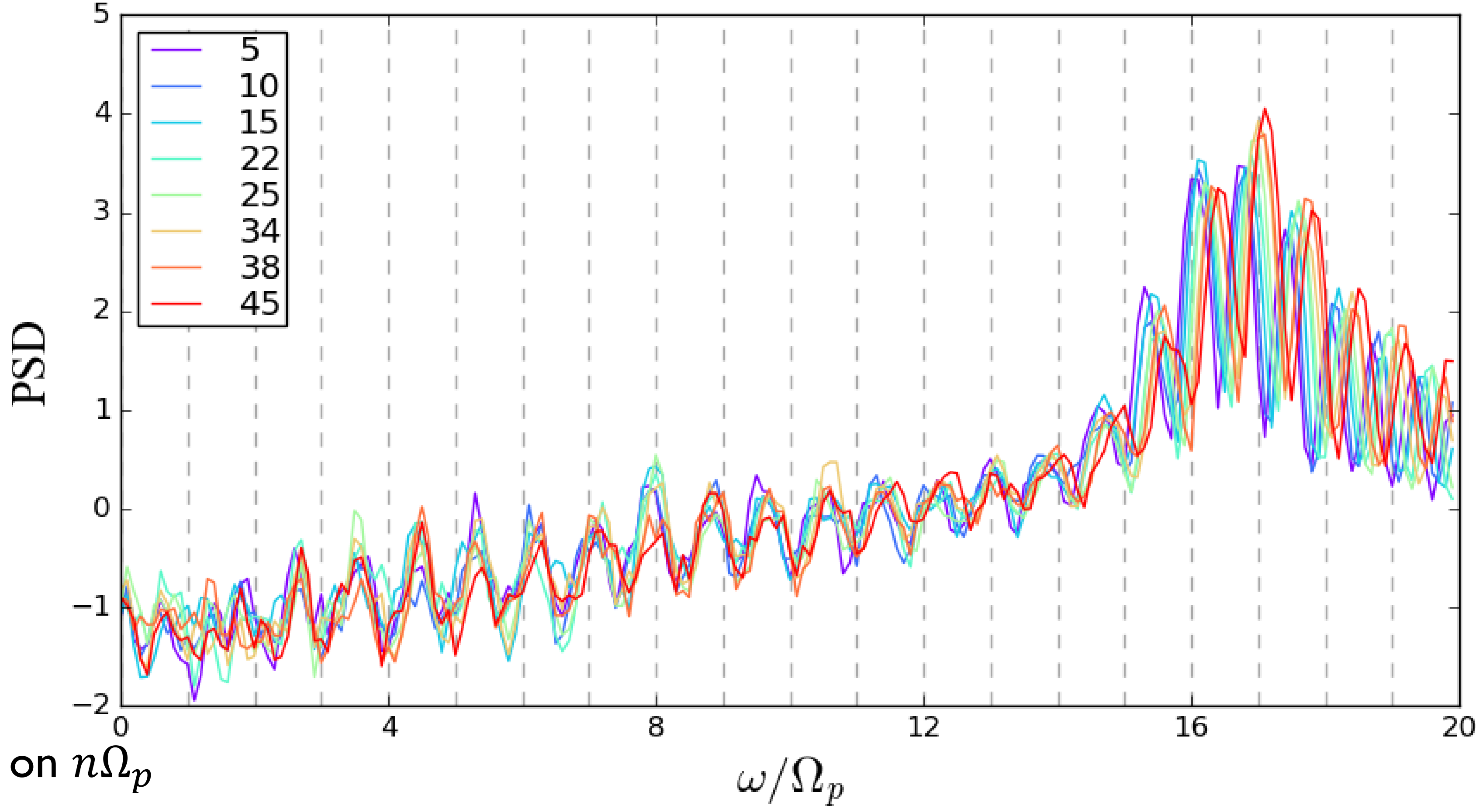
ϕ = Proton pitch-angle $\left[\tan\phi = \frac{u_{\perp 0}}{u_{\parallel 0}}\right]$

u_p = Proton birth velocity

Results : Power spectra (ω)

Traditional power – "Horizontal" scan

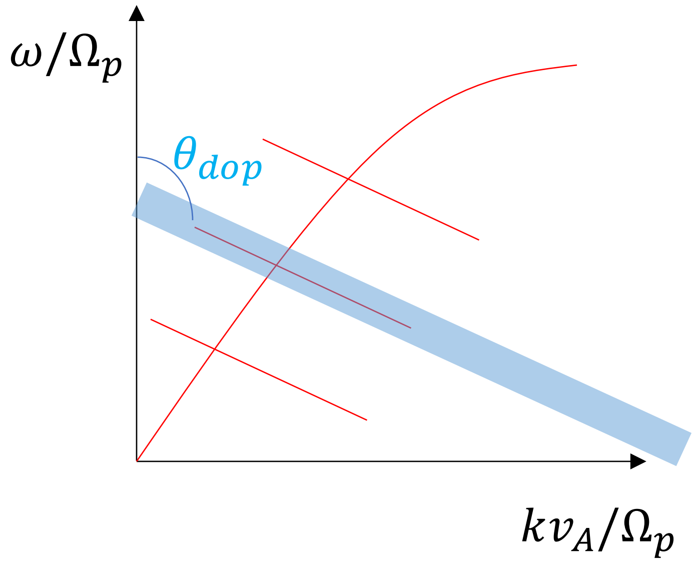


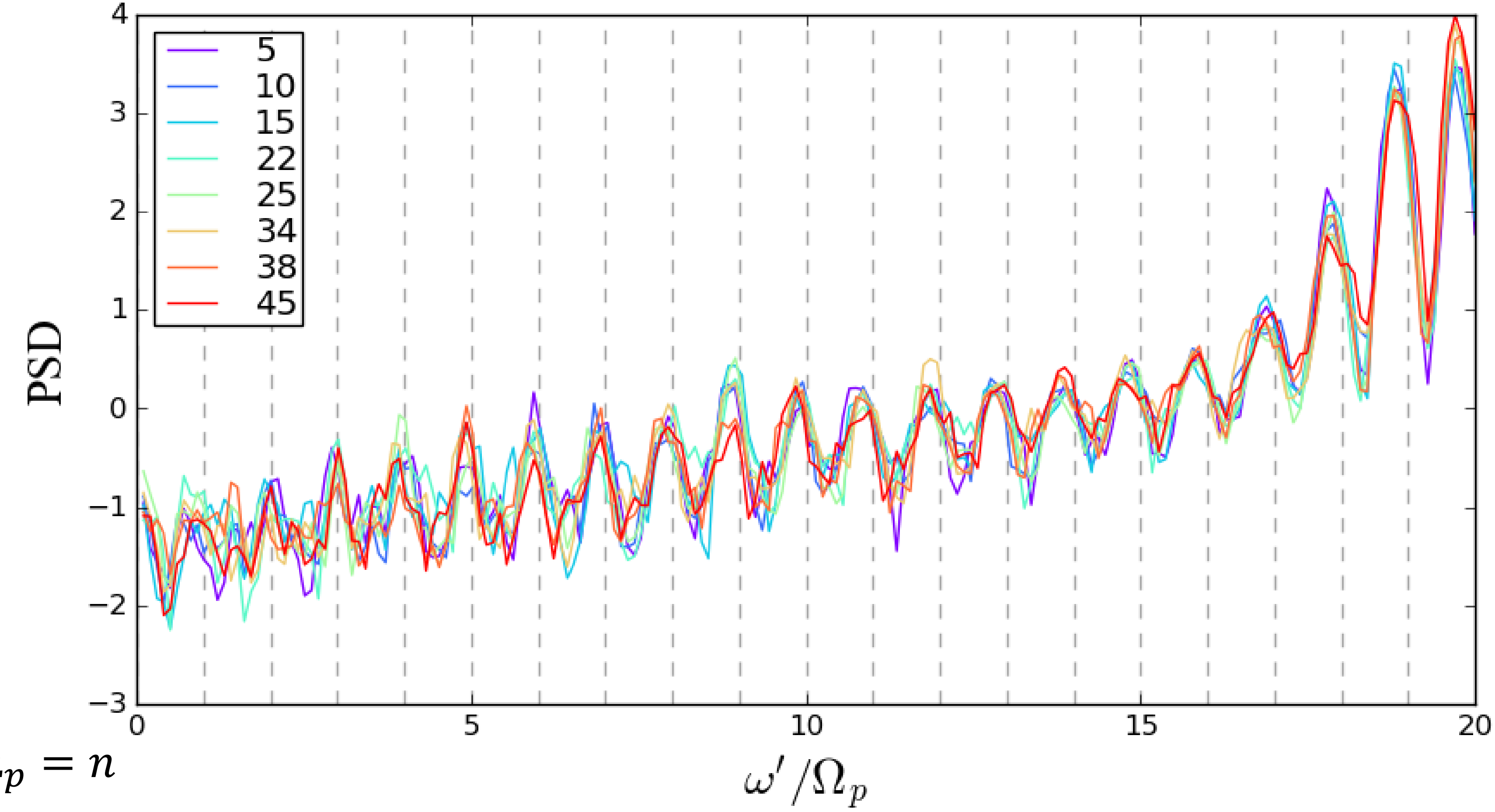


- Messy peaks, no clear excitation on $n\Omega_p$
- Most excited MCI region peaks around $17\Omega_p$
- Shift in frequencies following $\uparrow \xi_{He3}$

Results : Power spectra (ω')

Doppler power – "Diagonal" scan





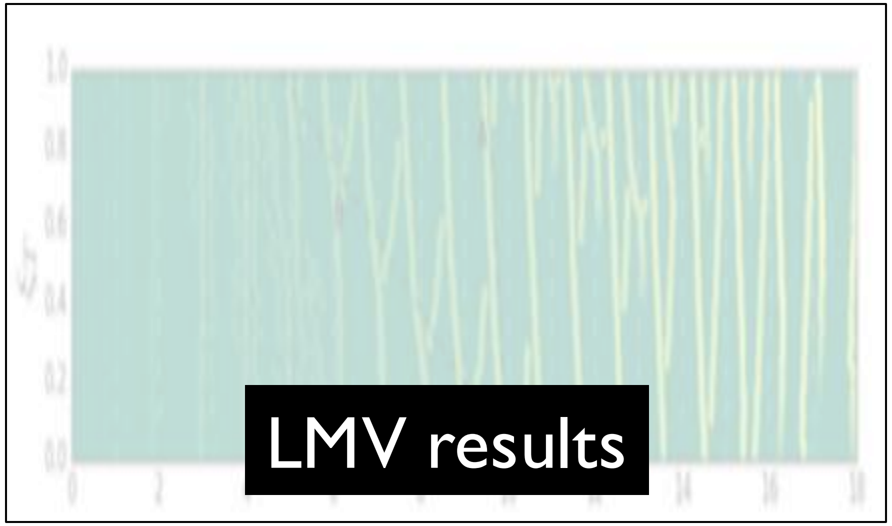
- Emissions peak neatly on $\omega_n'/\Omega_p = n$
- Frequency shift dependency on ξ_{He3} removed
- Most excited modes seen at higher relative frequency

Summary

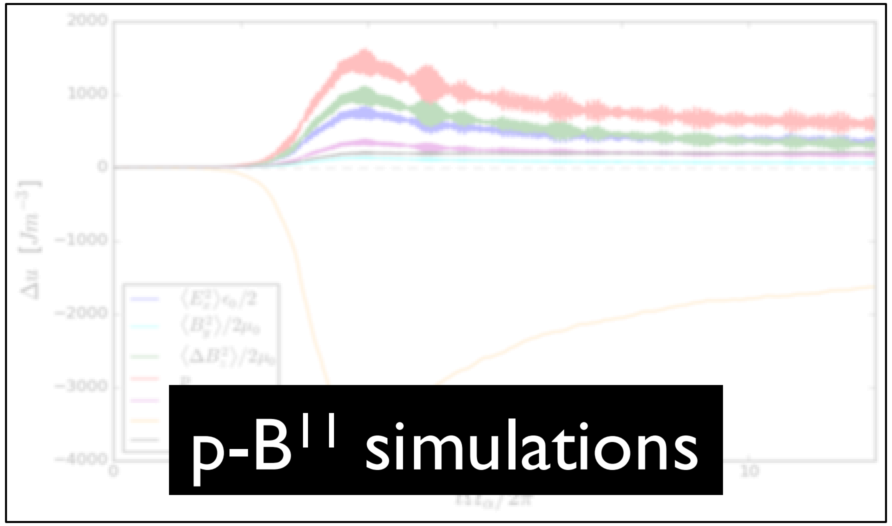
- ICE is generated in D-He3 fusion plasmas
- Concentration of He3 effects total energisation, according to gyro-resonant condition
- Change in flux enclosed by both majority ions Larmor radii is equal
- Power spectra can be computed relative to particle frequency ω'
- Doppler power spectra necessary for high energy particles

Future work

Development of LMV



LMV results



p-B^{11} simulations

Effective ions?

Future work

Thank you for listening

Many thanks to:
Prof. Richard Dendy,
Prof. Sandra Chapman,
Dr. James Cook
& Omstavan Samant