Feeling the Fusion Burn

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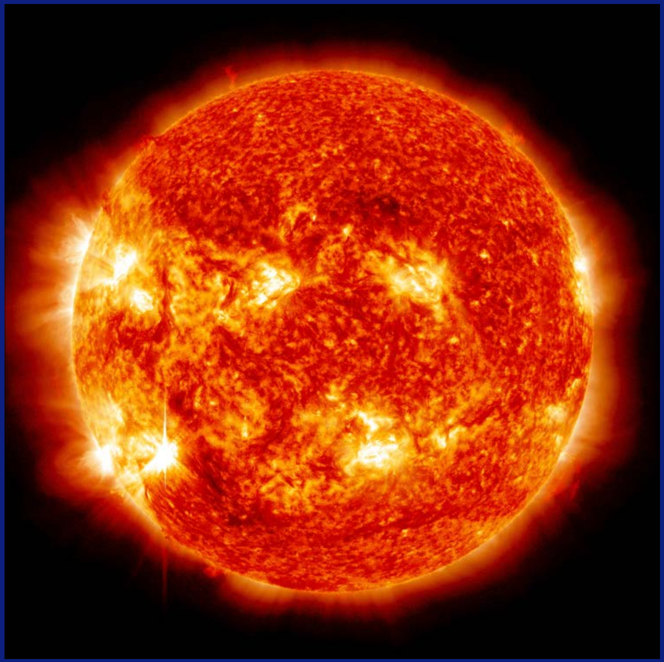
Fusion – Beating the sun

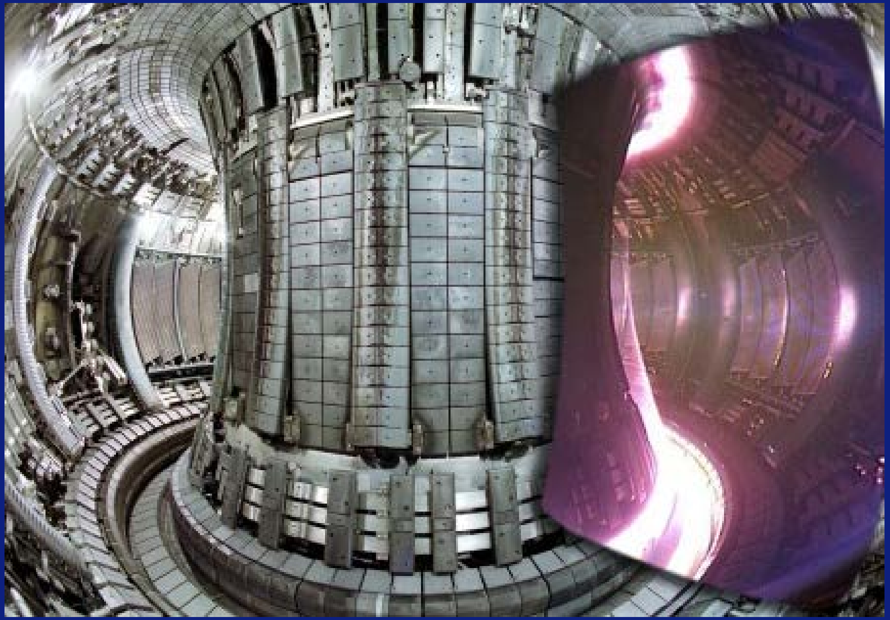


Sun – Working fusion reactor –

$T \sim 7{,}000{,}000K$ - $\rho \sim 1500 kg/m^3$- $\tau_E \sim 1{,}000{,}000\ years$ - only $500W/m^3$

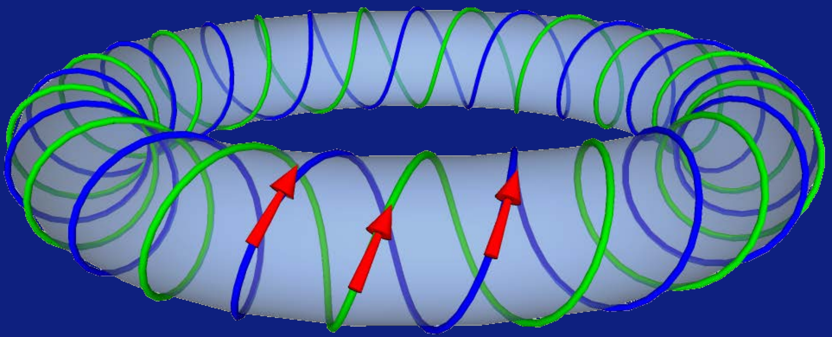
Man made fusion - in Culham

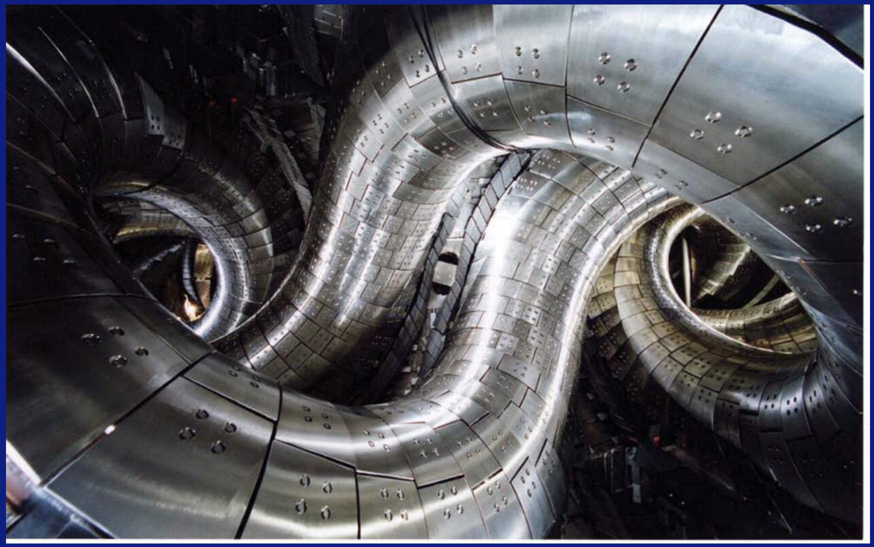
$T \sim 150{,}000{,}000K$ - $\rho \sim 10^{-7} kg/m^3$- $\tau_E \sim 1\ s$ $0.2MW/m^3$

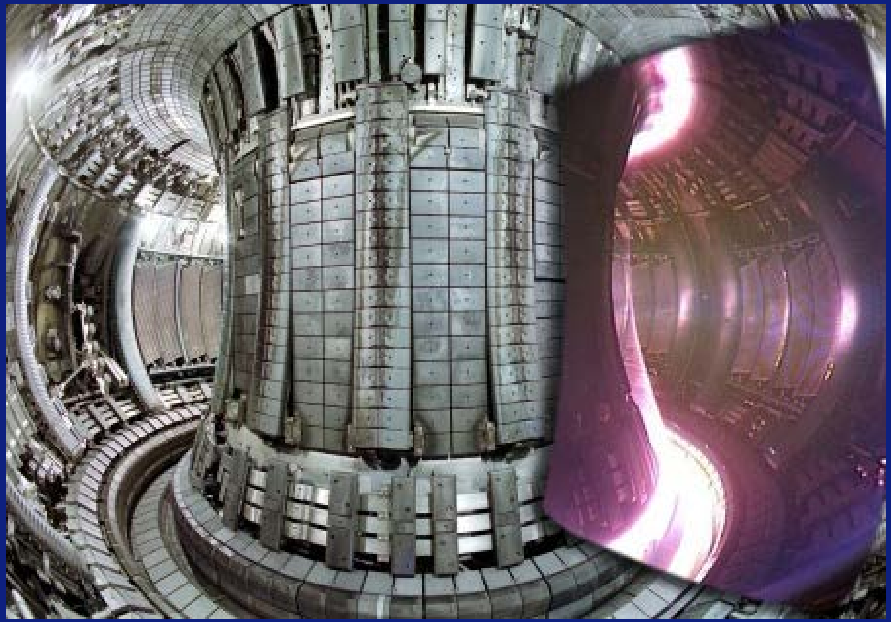


Fusion – The magnetic bottle

Restrict charged particle motion by magnetic fields, $B \sim 1T$,





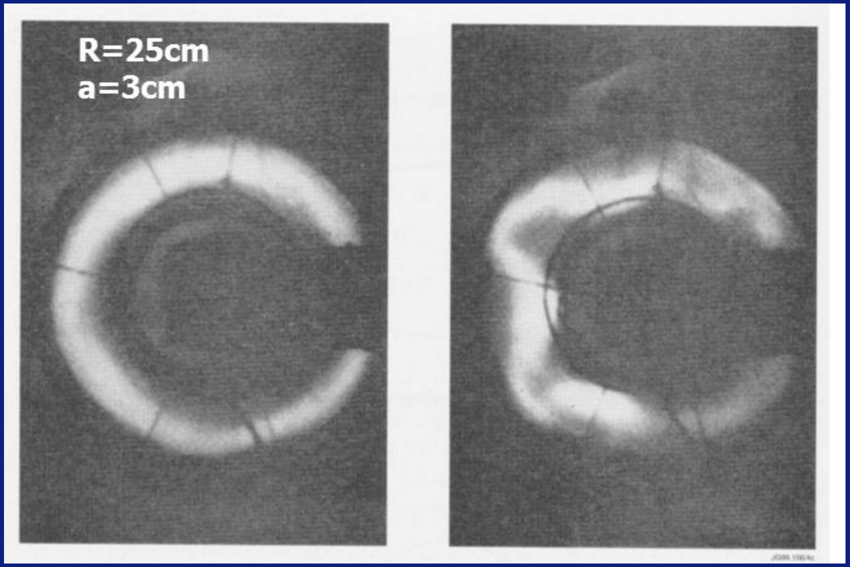


Twisted magnetic fields required → need complicated coils (Stellarator) or plasma current (Tokamak)

Fusion – The Instability problem

Confined neutral plasma not in thermodynamic equilibrium → free energy

Macroscopic (fluid like) instabilities driven by current and pressure plagued early days of fusion→ μs plasmas



Microscopic instabilities limited us to ms. Decades of research to minimise their effect → s

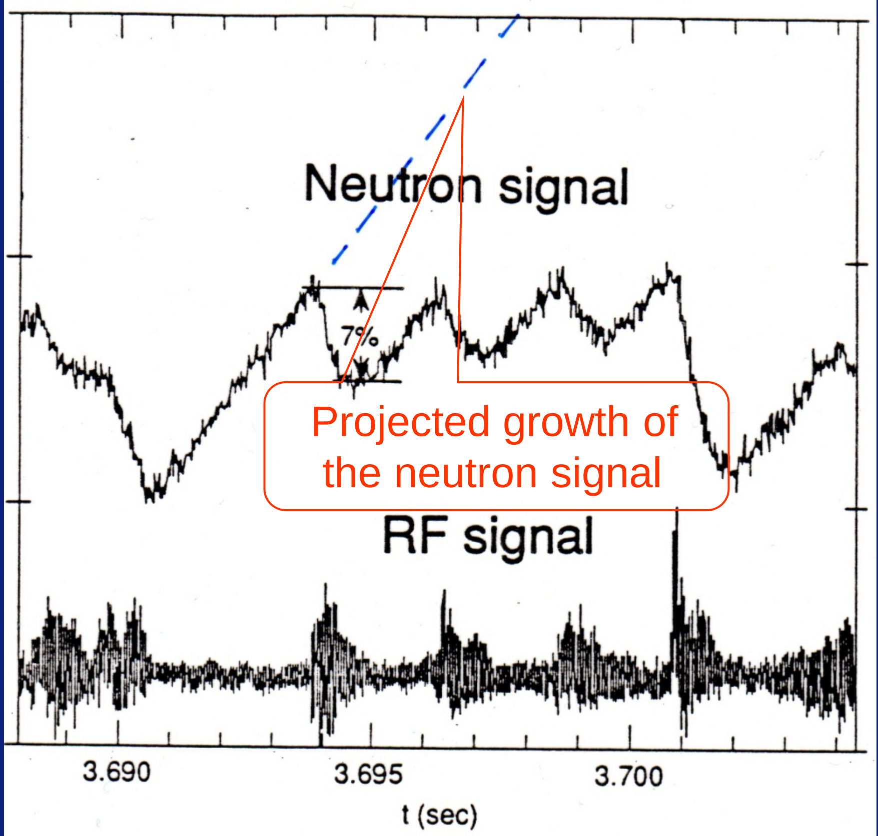
Fast particles – Heating and current drive

100's keV beams needed to reach fusion temperatures and provide current.

Fusion born alpha particles (3.5 MeV) needed for self heating

Non thermal distribution can drive instabilities/waves

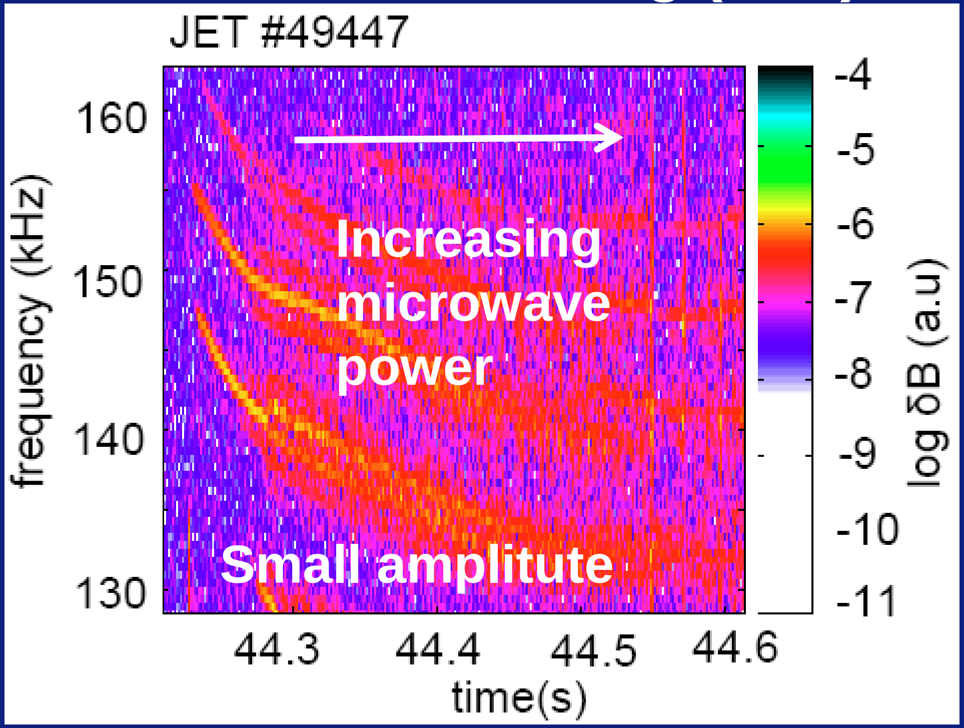
Redistribution and ejection can result in loss of heating or current or worse vessel damage



Fast particles – Fundamental physics

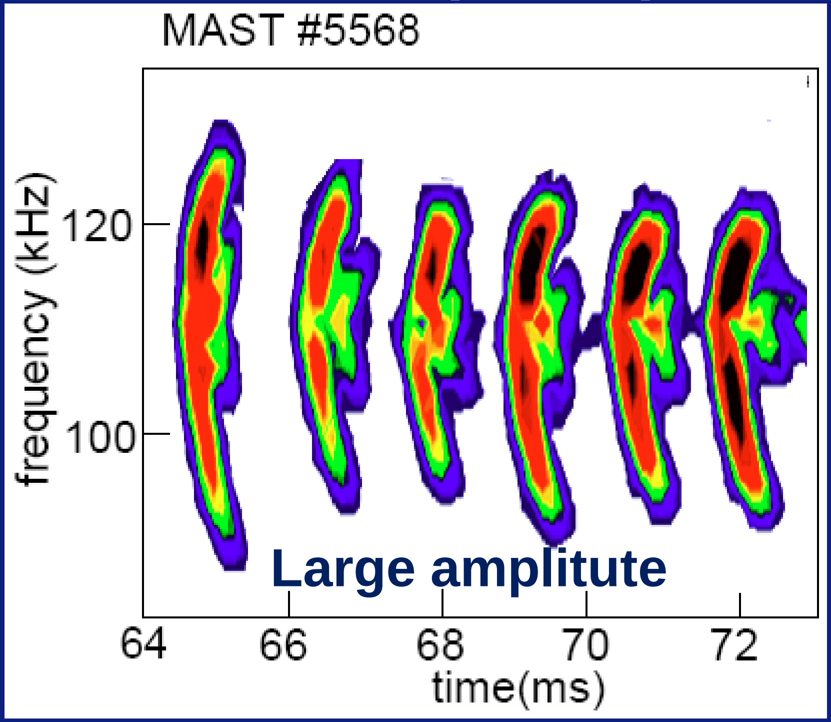
Low density but such large effect? Rich nonlinear behaviour? Disparity between same instabilities on different machines?

Microwave heating (JET)



Heeter et.al PRL 85, 3177 (2000)

Beams (MAST)



Pinches et.al PPCF, 46, S47 (2004)

Resonance – Strong wave particle interaction

Special group of particles that strongly interact with a wave

$$\text{force} \sim e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)} \xrightarrow{1D} e^{i(k(x_0+\mathrm{v}_0 t)-\omega t)}$$

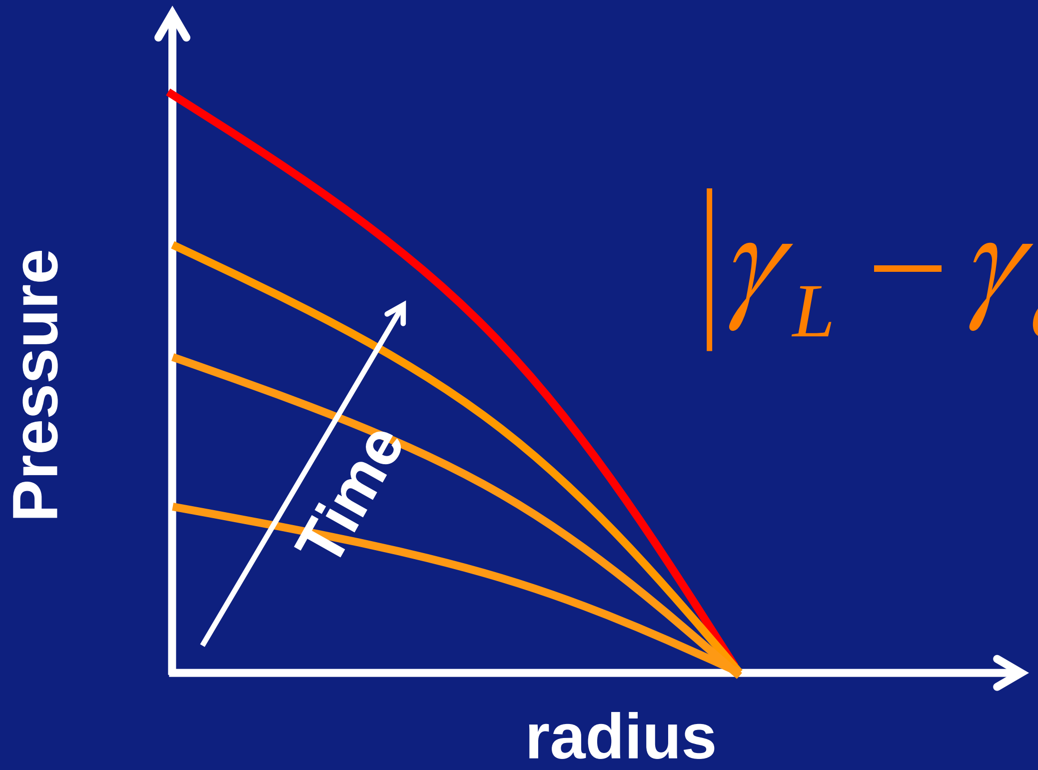
$v_0=\omega/k$ gives non oscillating force on particle

Provides a channel for energy to go from the source into the coherent motion of background not thermal motion

Allows low density fast particles to pump/drive the wave/instability

Marginal stability - Wave and collisions compete

System evolves through a threshold

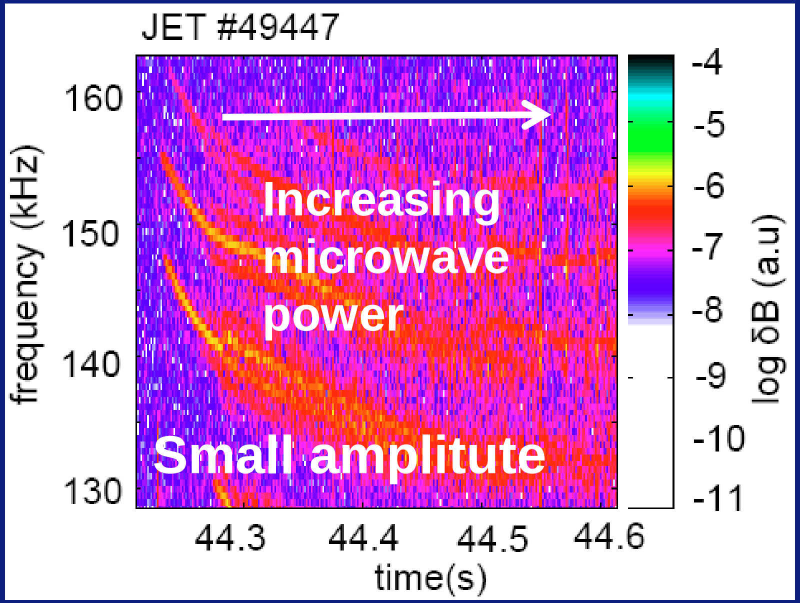


$$\left|\gamma_L - \gamma_d\right| << \gamma_L, \gamma_d$$

Collision times are comparable to growth times

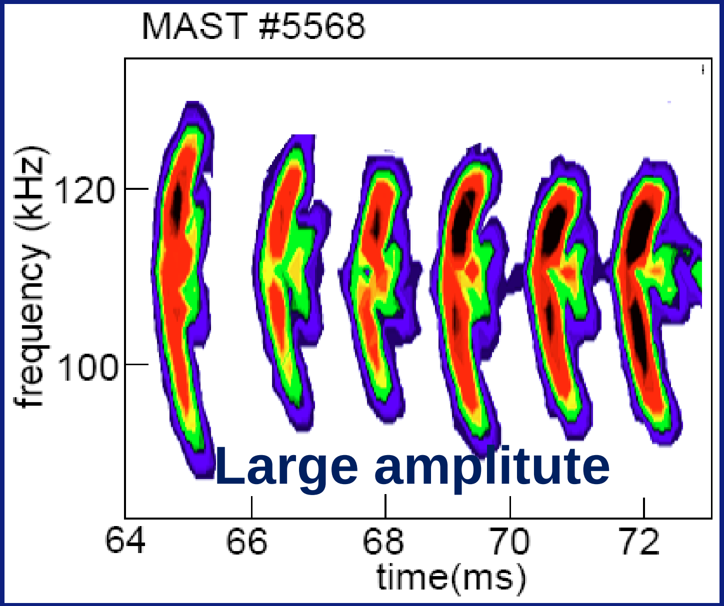
Disparity between beams and microwaves?

Microwave heating (JET)



Heeter et.al PRL 85, 3177 (2000)

Beams (MAST)



Pinches et.al PPCF, 46, S47 (2004)

Near threshold behaviour: $\gamma_L - \gamma_d << \gamma_L, \gamma_d$

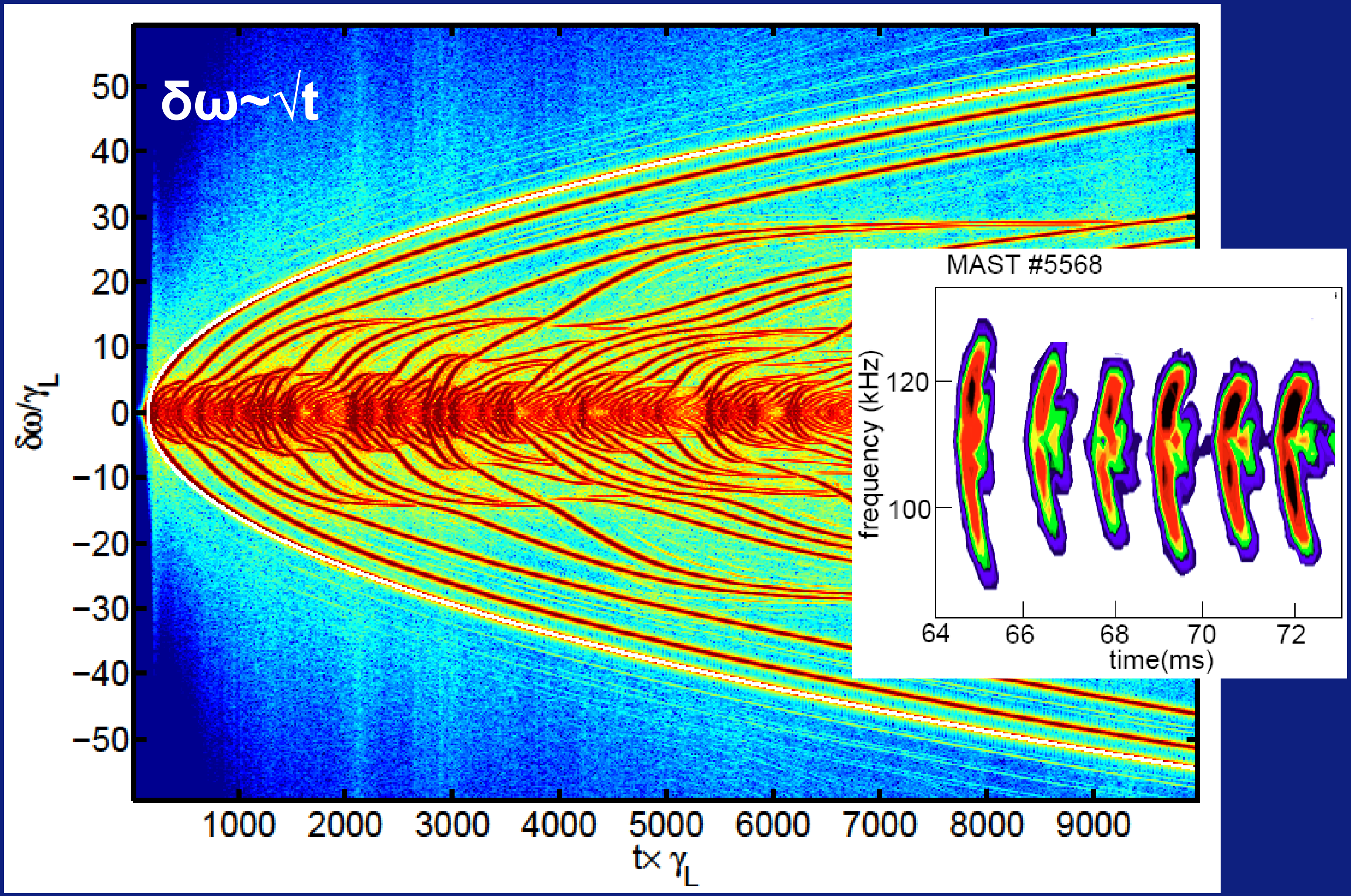
DIFFUSION (benign)

DRAG (losses)

Berk et.al PRL, 76, 1256 (1996)
Breizman et.al PoP, 4 1559 (1997)
Berk et.al Phys Lett. A 234 213 (1997)

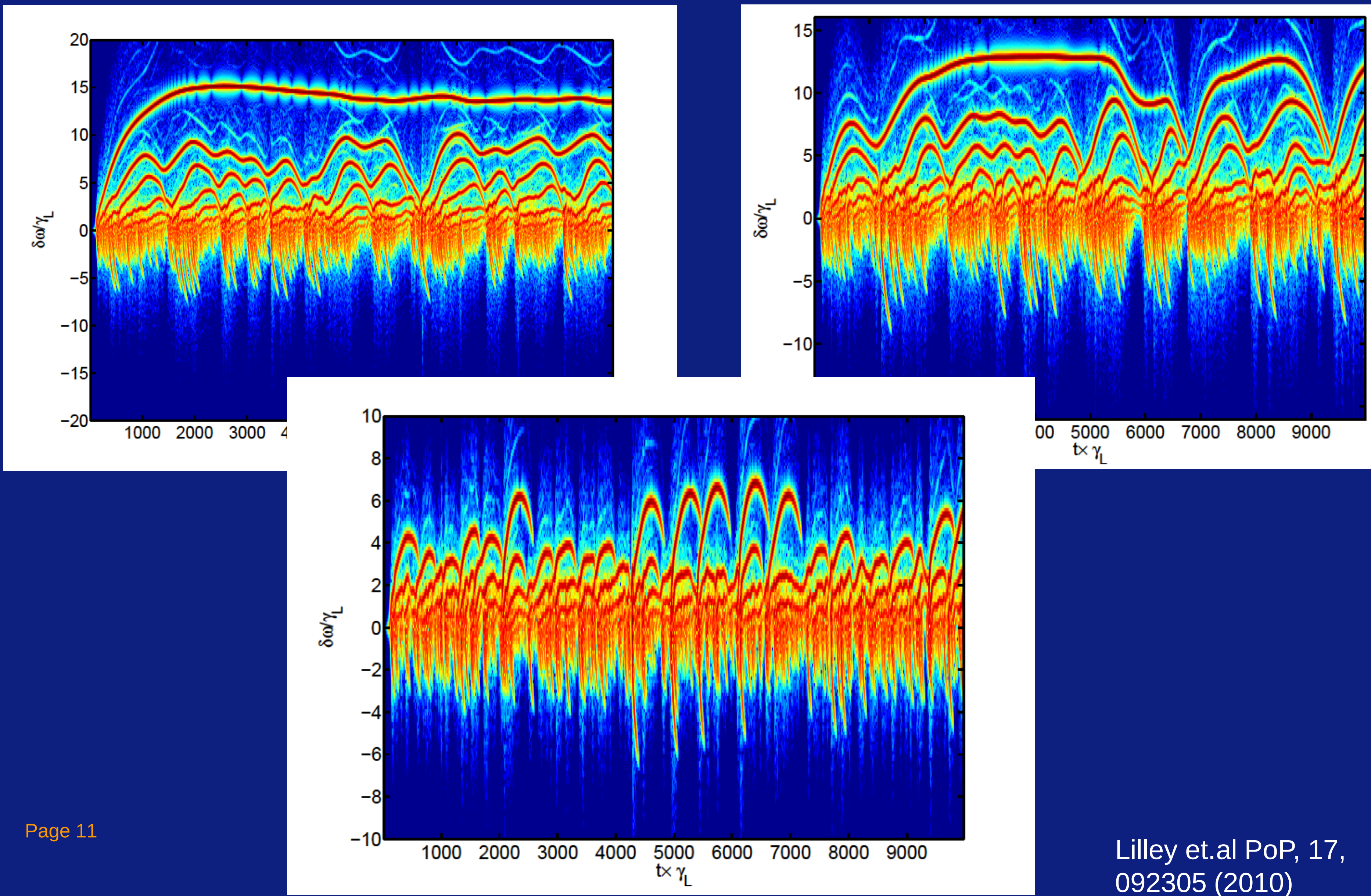
Lilley et.al PRL, 102, 195003 (2009)
Lilley et.al PoP, 17, 092305 (2010)

Chirping with dissipation - Collisionless



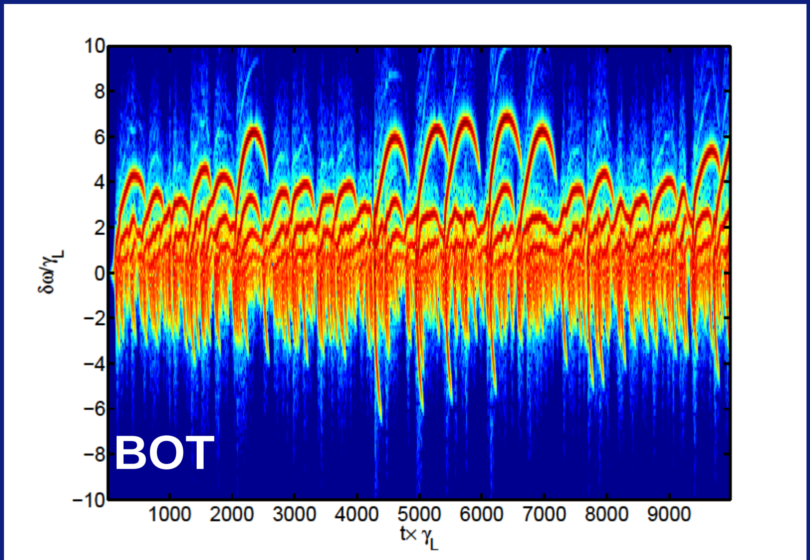
Lilley et.al PoP, 17, 092305 (2010)

Collisional asymmetry

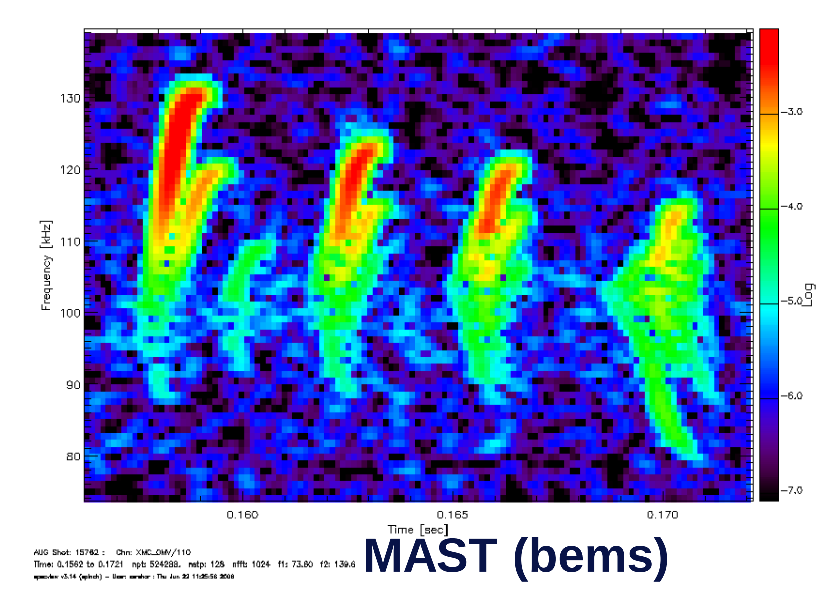


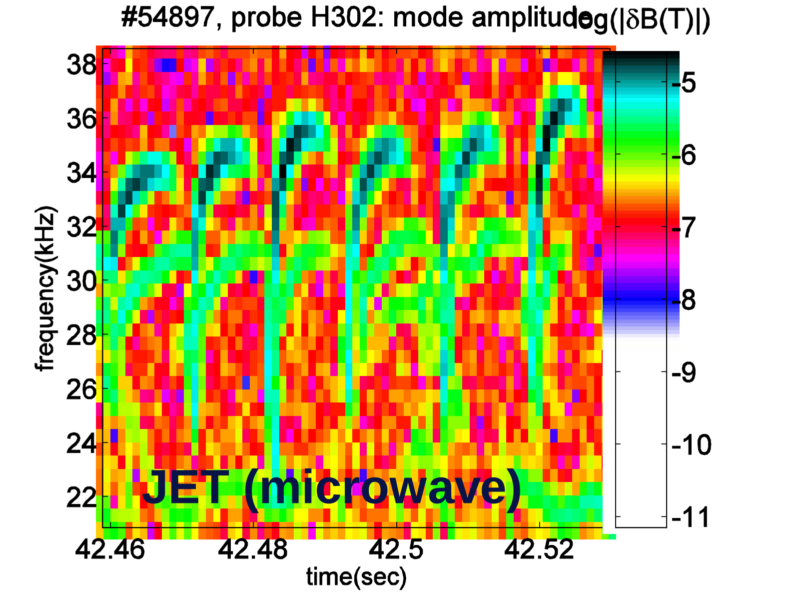
Lilley et.al PoP, 17, 092305 (2010)

Bursting modes - Experimental asymmetry

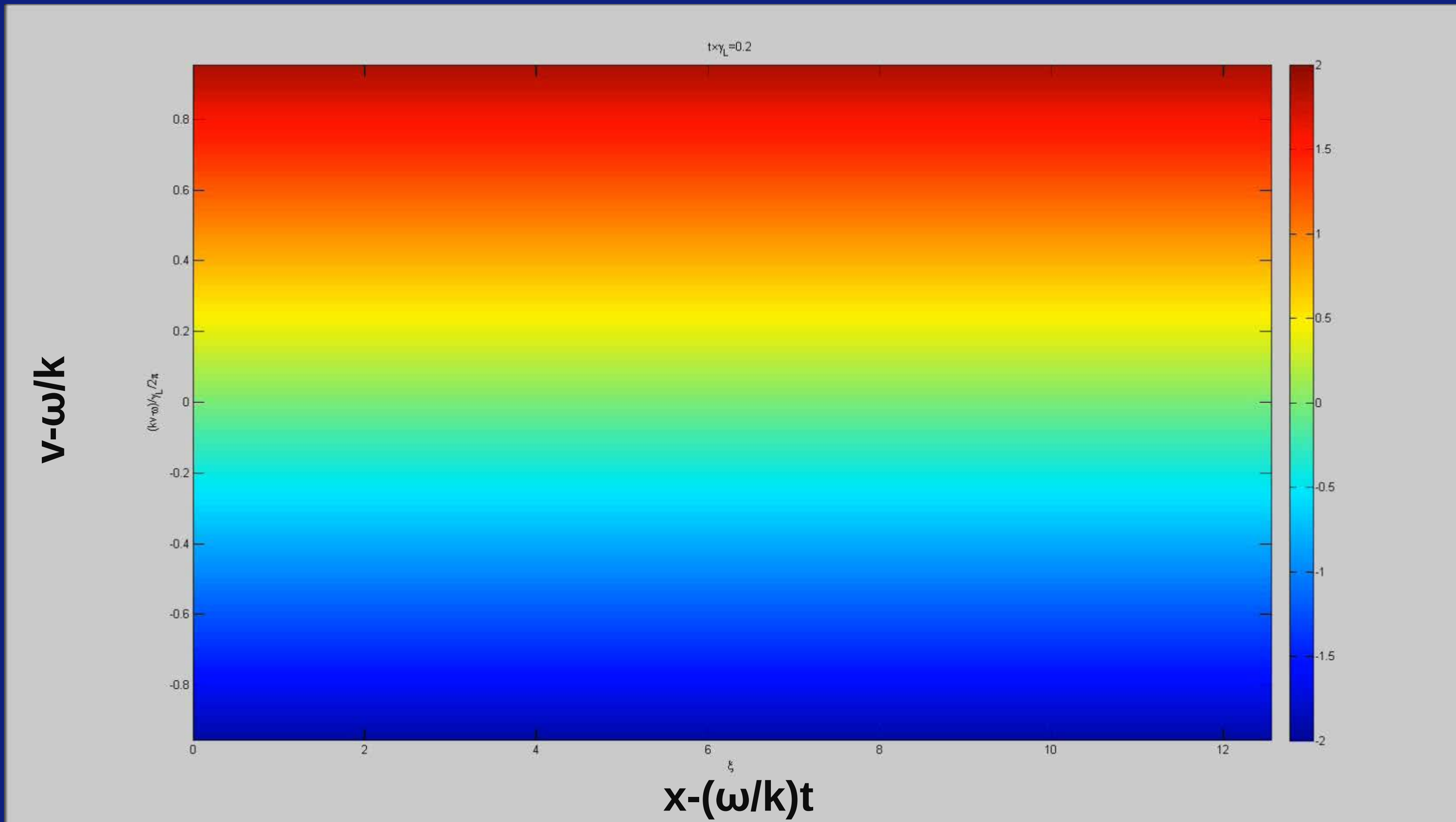


- Hooked frequency chirp seen in BOT
- Also seen in MAST (beams) and JET (microwave)



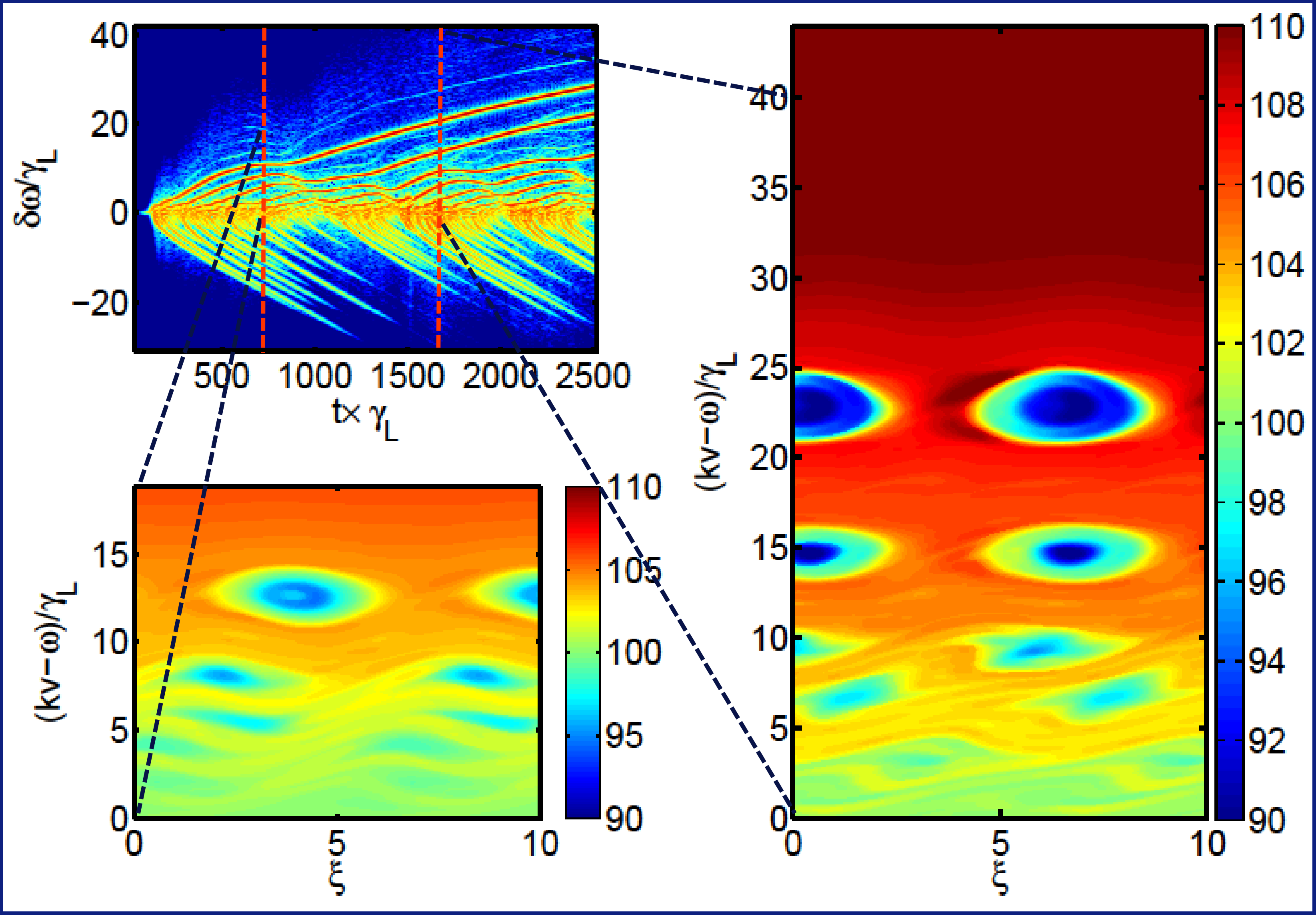


Bursting modes – What are they?



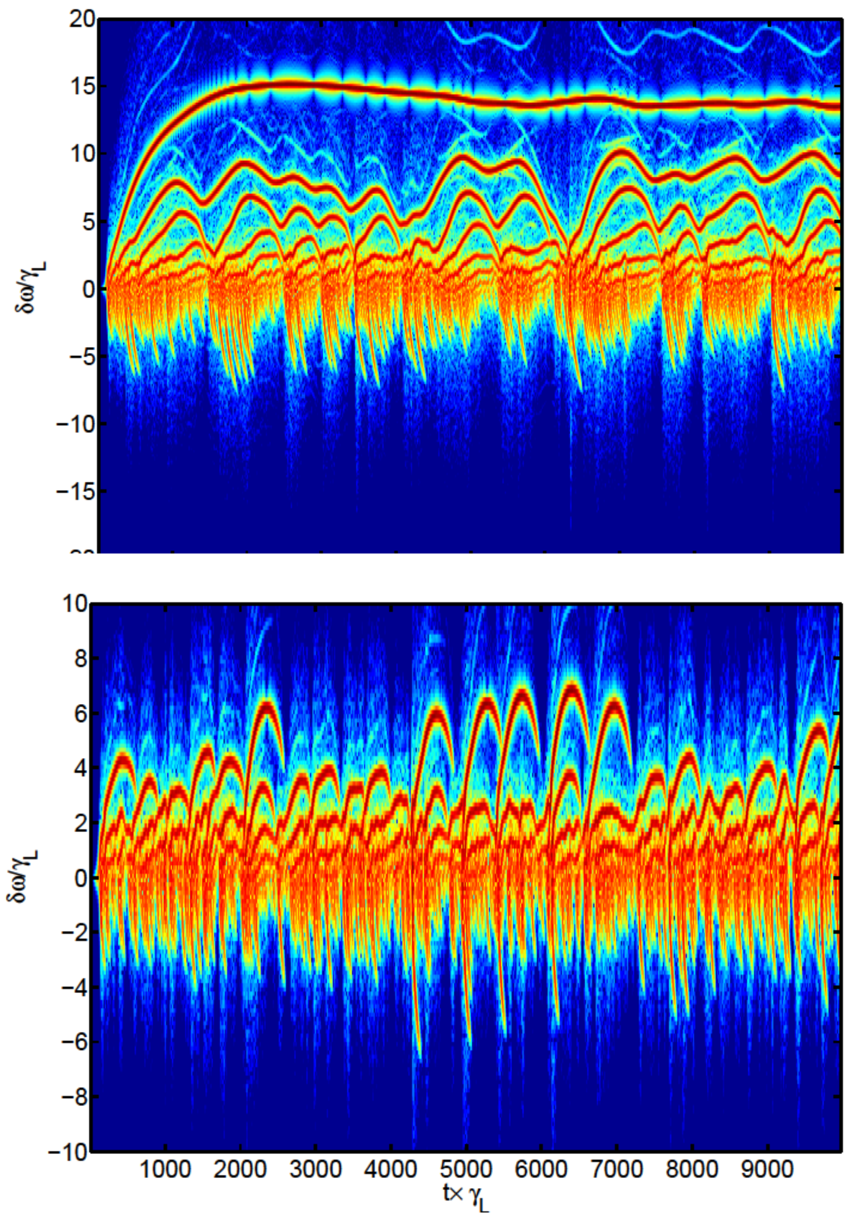
Phase space holes and clumps created.
Dissipation is essential

Spectral lines are holes and clumps



Lilley et.al PoP, 17, 092305 (2010)

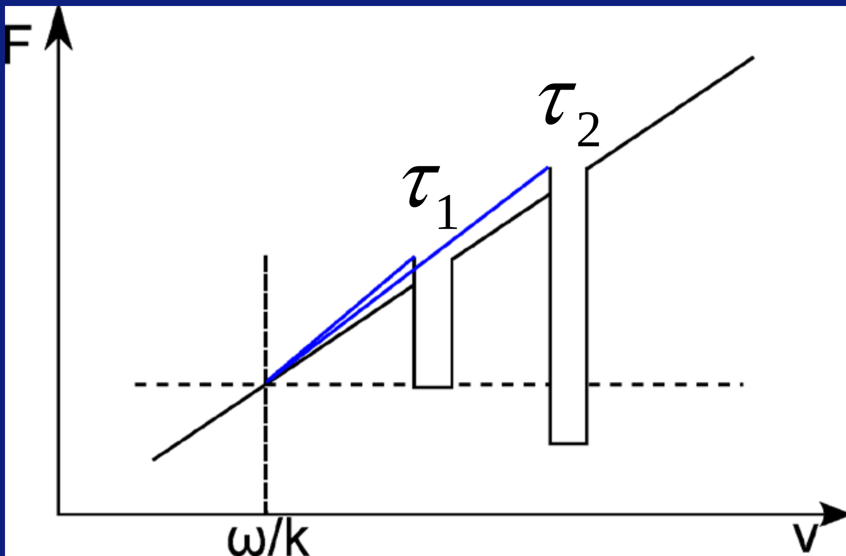
Collisions on holes and clumps



Diffusion - removes sharp features in phase space → suppresses formation / shortens lifetime of holes/clumps

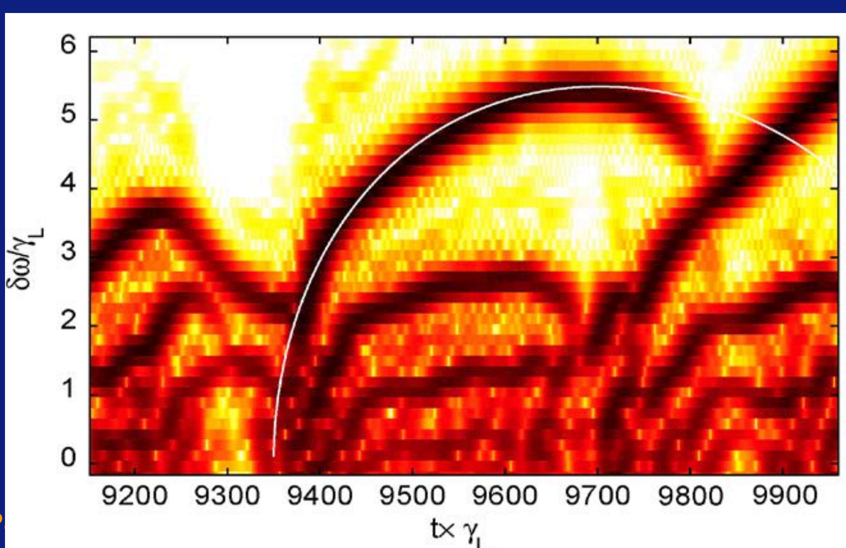
Drag more subtle - provides asymmetry because of unidirectional flow – preferentially enhances holes and suppresses clumps

Drag-Diffusion competition



$$x^2 = y\left(\frac{\partial y}{\partial \tau} + 1\right)$$

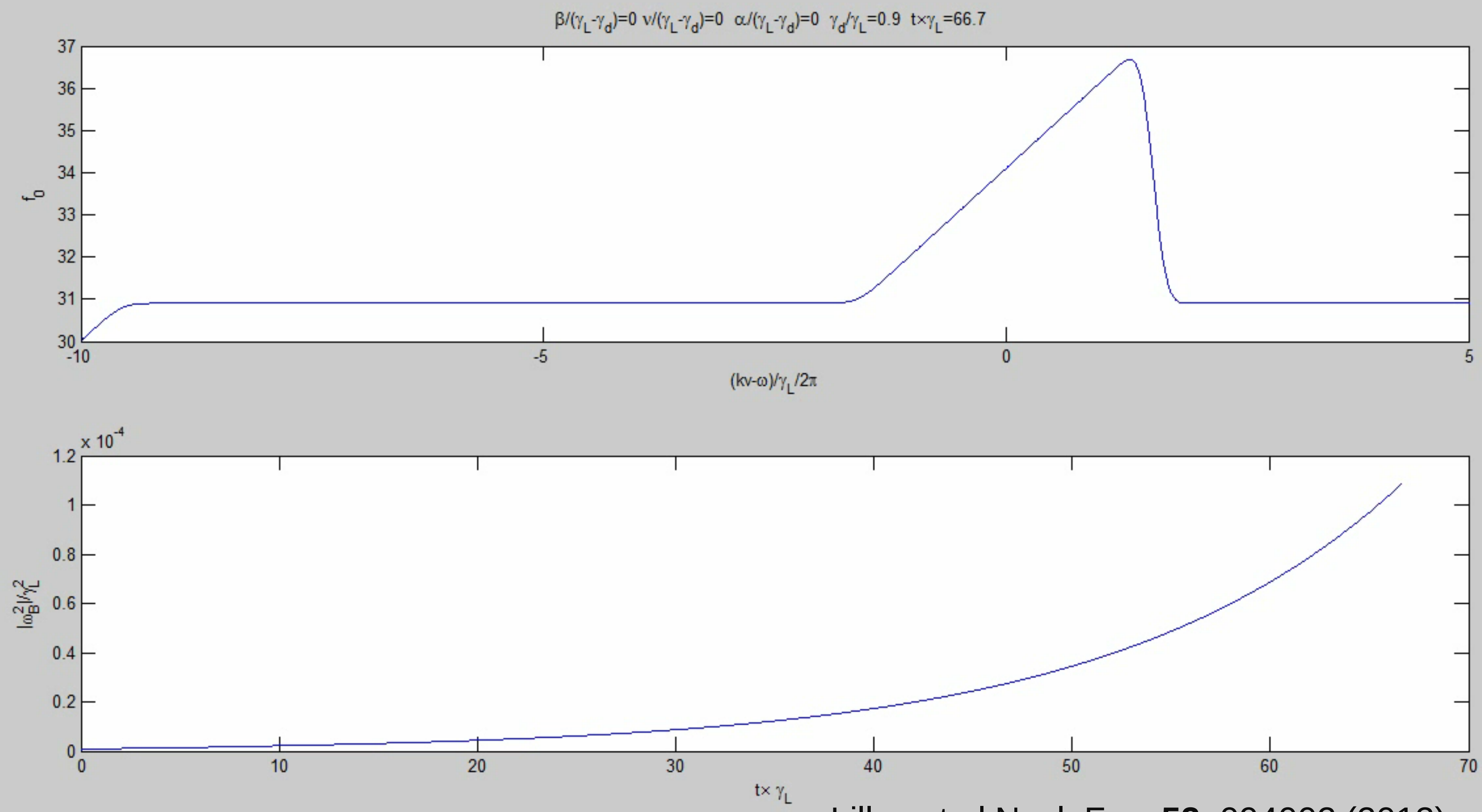
$$a\frac{\partial(xy)}{\partial \tau} + \frac{y}{x} = \left(1 + \frac{\partial y}{\partial \tau}\right)$$



- x=y=1 is steady state
- Unstable for a<1
- Stable for a>1

Lilley et.al PoP, 17, 092305 (2010)

Bursting modes - Global change in profiles



Lilley et.al Nucl. Fus. **52** 094002 (2012)

Particles convected in phase space (v→r in tokamak)

Energy release is large fraction of total energy

Summary - Fundamental physics

- Resonant particles play a key role – phase mixing is the aim of the instabilities
- Dissipation plays a non trivial role in resonant interactions
- Diffusive collisions promote benign wave saturation
- Drag acts as a seed for asymmetric frequency sweeping waves with bursting character
- Competition between drag and diffusion gives richer nonlinear environment
- Single resonance can effect global change in the fast particles

Summary - General

- Most of the plasma show stoppers have gone
- Alpha particles remain an unknown
- Early expectation was of passive behaviour
- Even when instabilities were discovered expectation was of benign behaviour
- Drag and resonance collapse from holes and clumps are causing us to rethink and recalculate
- Challenges are associated with long growth times and how to deal with multiple interacting instabilities – It's complicated enough with one…who knows what might happen with many