Extension of Energetic Geodesic Acoustic Modes to Passing Particle Populations

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Overview of fusion and plasma physics

- Fusion reactions release large amounts of energy
- Advantages: Fuel ingredients are abundant in nature, safe, waste has shorter half-life
- Need to heat fuel to ~ 100 million degrees. Confine with magnetic fields - tokamak

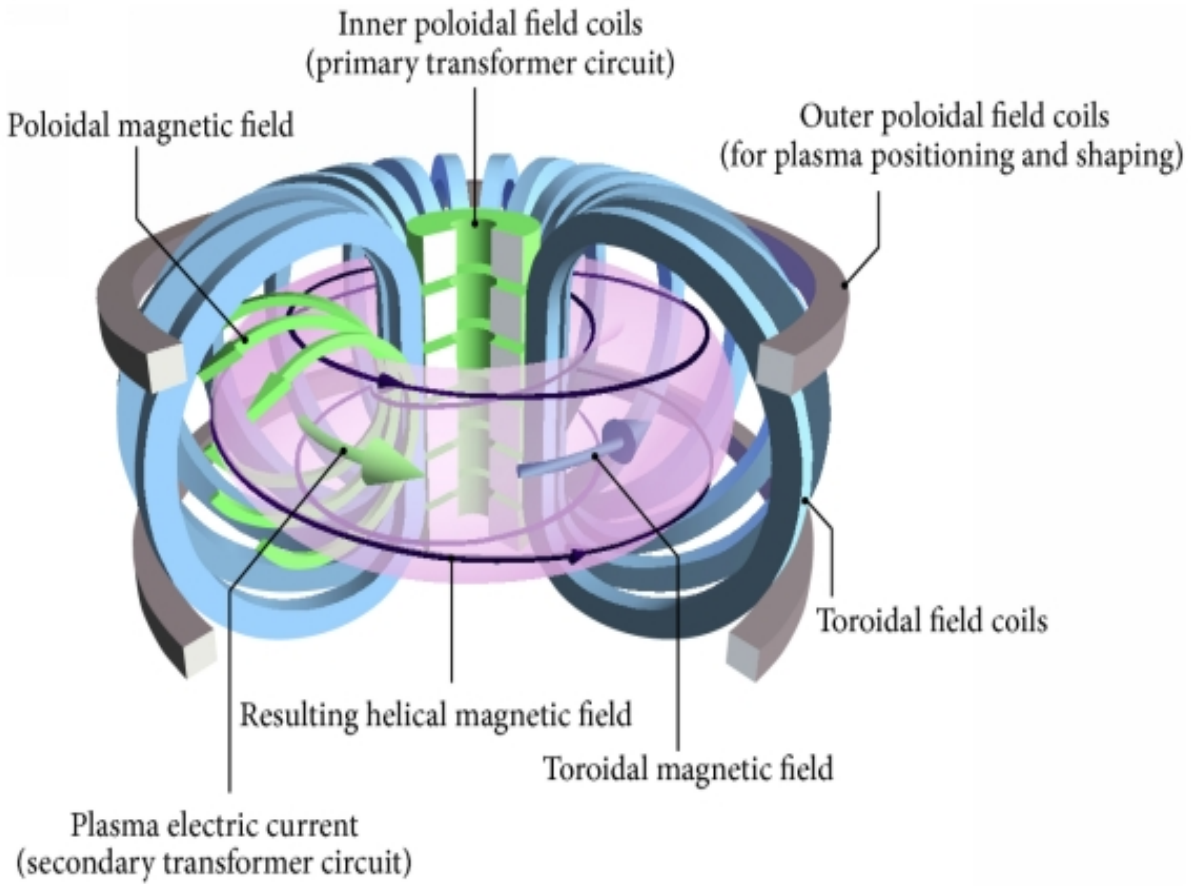


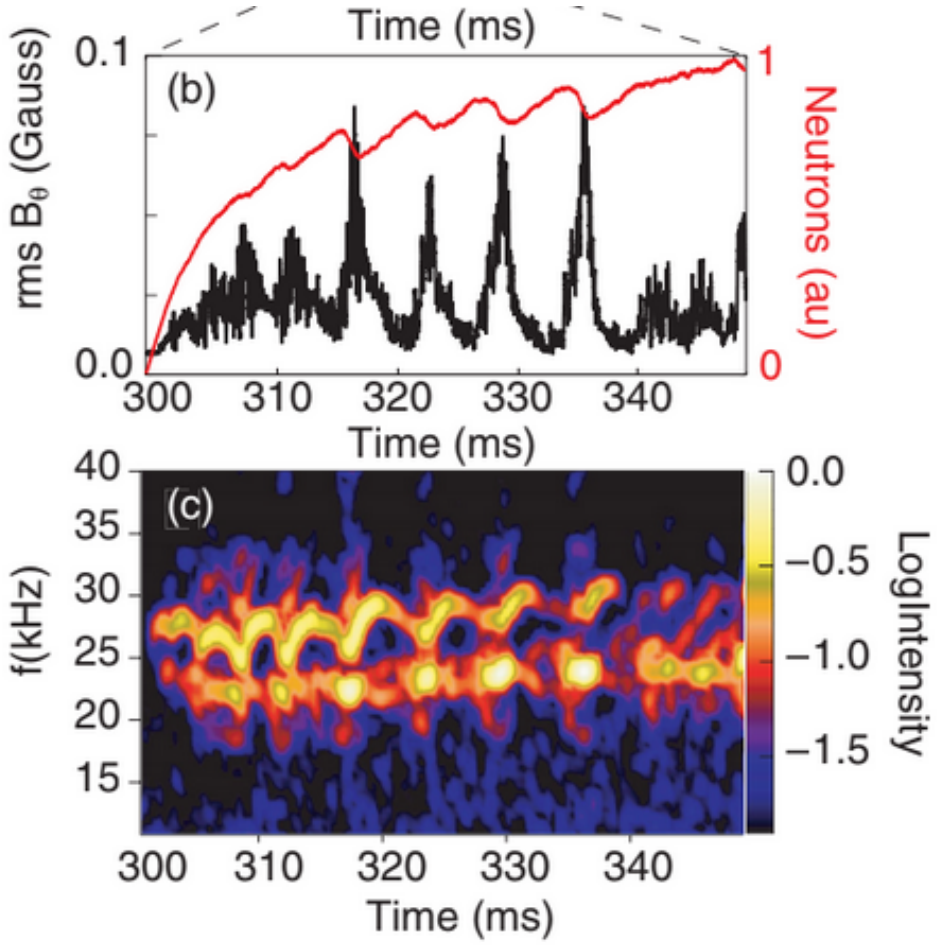
Fig: S. Li *et al*., Abstract and Applied Analysis, **Vol . 2014**, 940965 (2014)

Instabilities and heating

- Problem: need to understand/control instabilities that harm confinement
- My project: energetic particle mode driven unstable by fast ions
- Importance: common heating techniques introduce fast (energetic) particles
- E.g. neutral beam injection (NBI) – inject high energy neutral particles into plasma, transfer energy via collisions

Discovery of EGAMs

- Nazikian *et al.* experimentally found new mode
- Half the geodesic acoustic mode (GAM) frequency
- Frequency chirping correlated with drop in neutron emission → redistribution or loss of fast ions
- Electron density and temperature fluctuations inconsistent with theory for GAMs

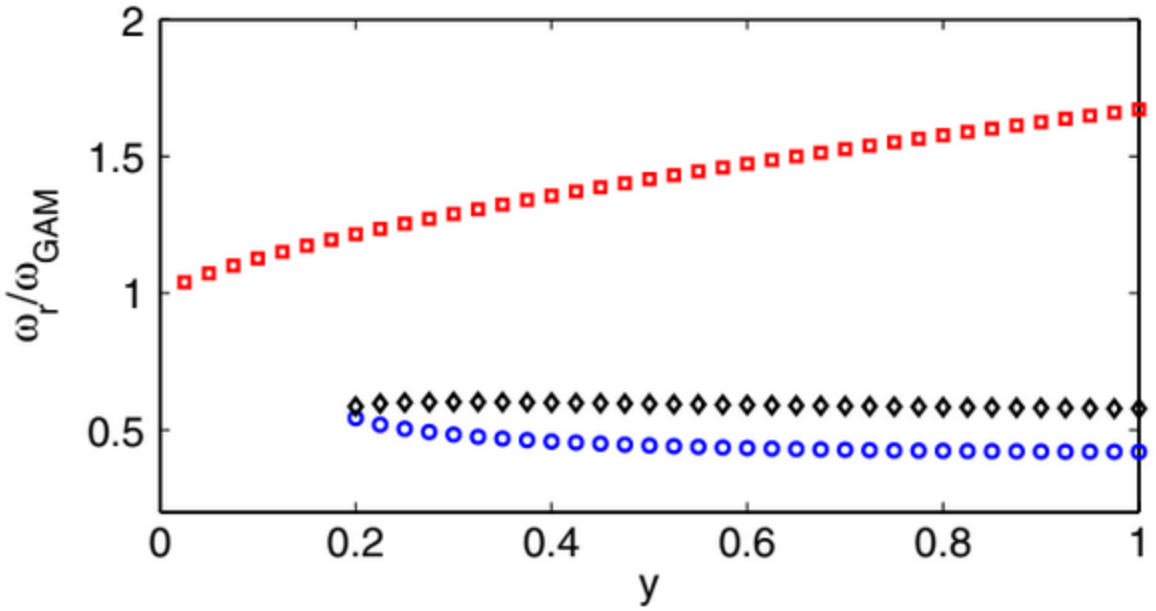


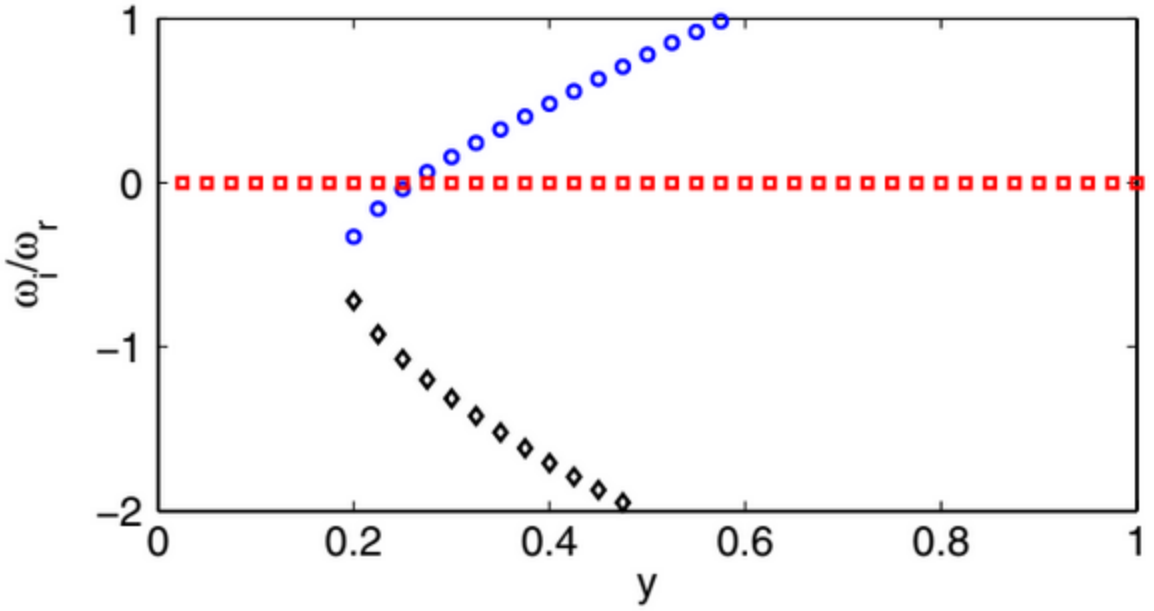
Nazikian *et al*., Physical Review Letter, **101**, 185001 (2008)

Discovery of EGAMs

- Fu developed hybrid-kinetic model to show mode is a new energetic particle mode. Used slowing-down distribution for fast ion velocities
- Solved dispersion equation → up to three modes present
- Bifurcation dependent on Y – ratio of energetic particle pressure to thermal plasma pressure
- Mode frequencies and stability dependent on Z – ratio of particle orbit frequency to GAM frequency. Only ever one unstable mode, frequency always less than GAM
- Driven unstable by wave-particle interaction, named EGAM

Fu, Physical Review Letter, **101**, 185002 (2008)


2
1.5
1
0.5
ω_r/ω_{GAM}
0
0.2
0.4
0.6
0.8
1
y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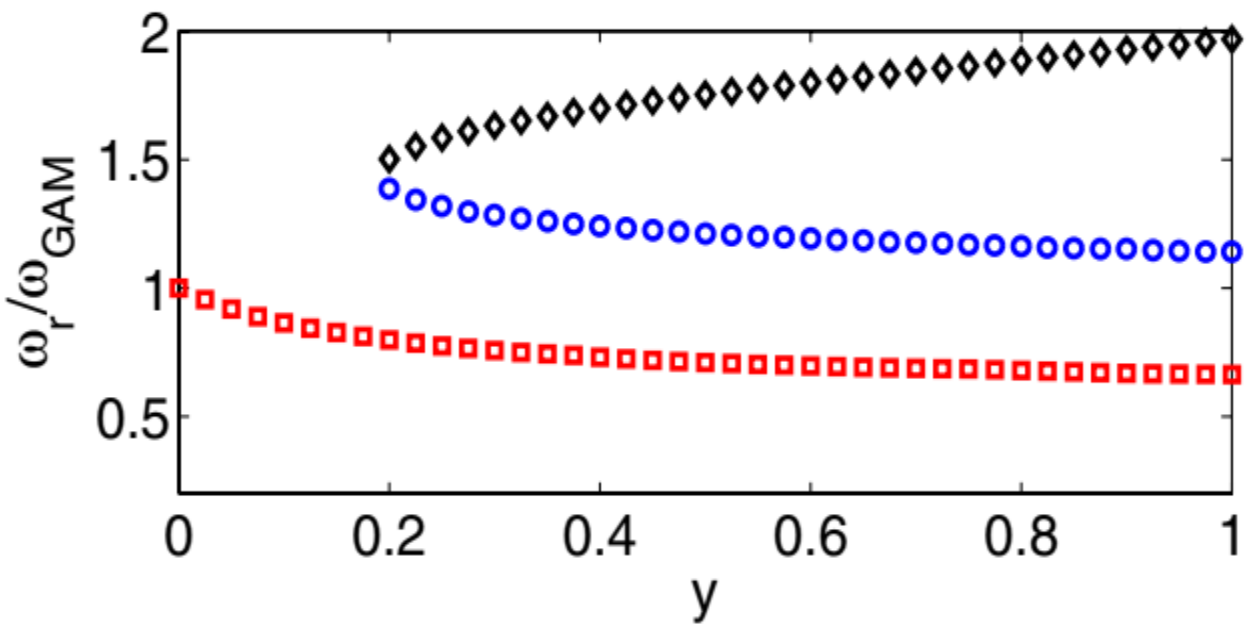
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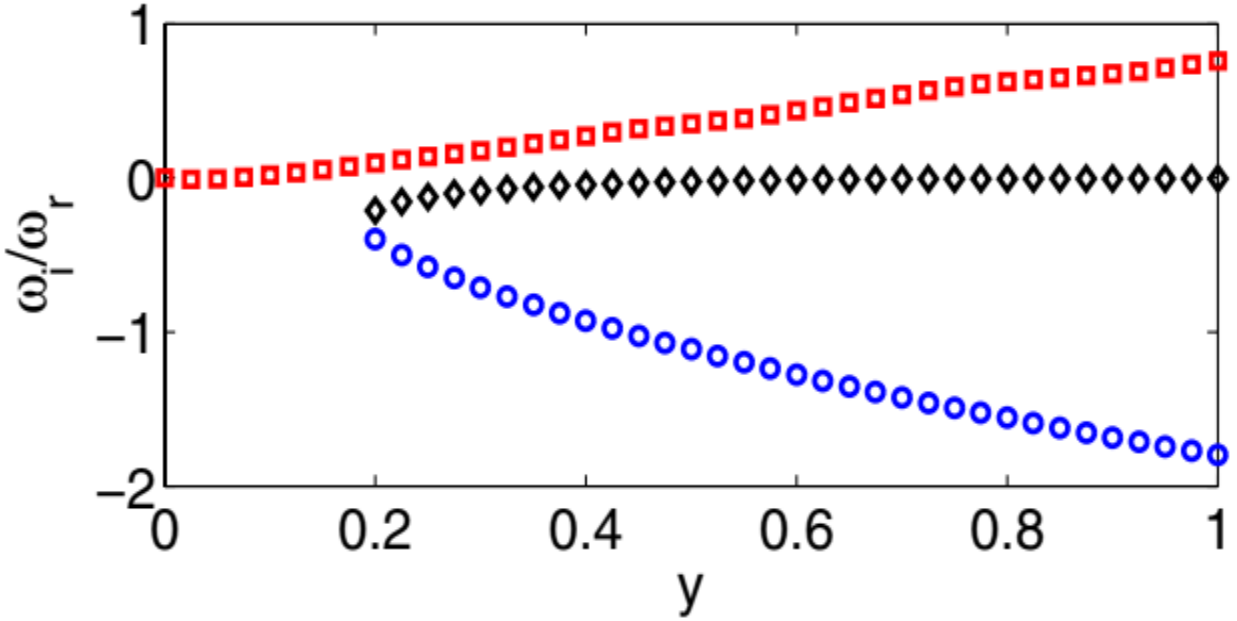
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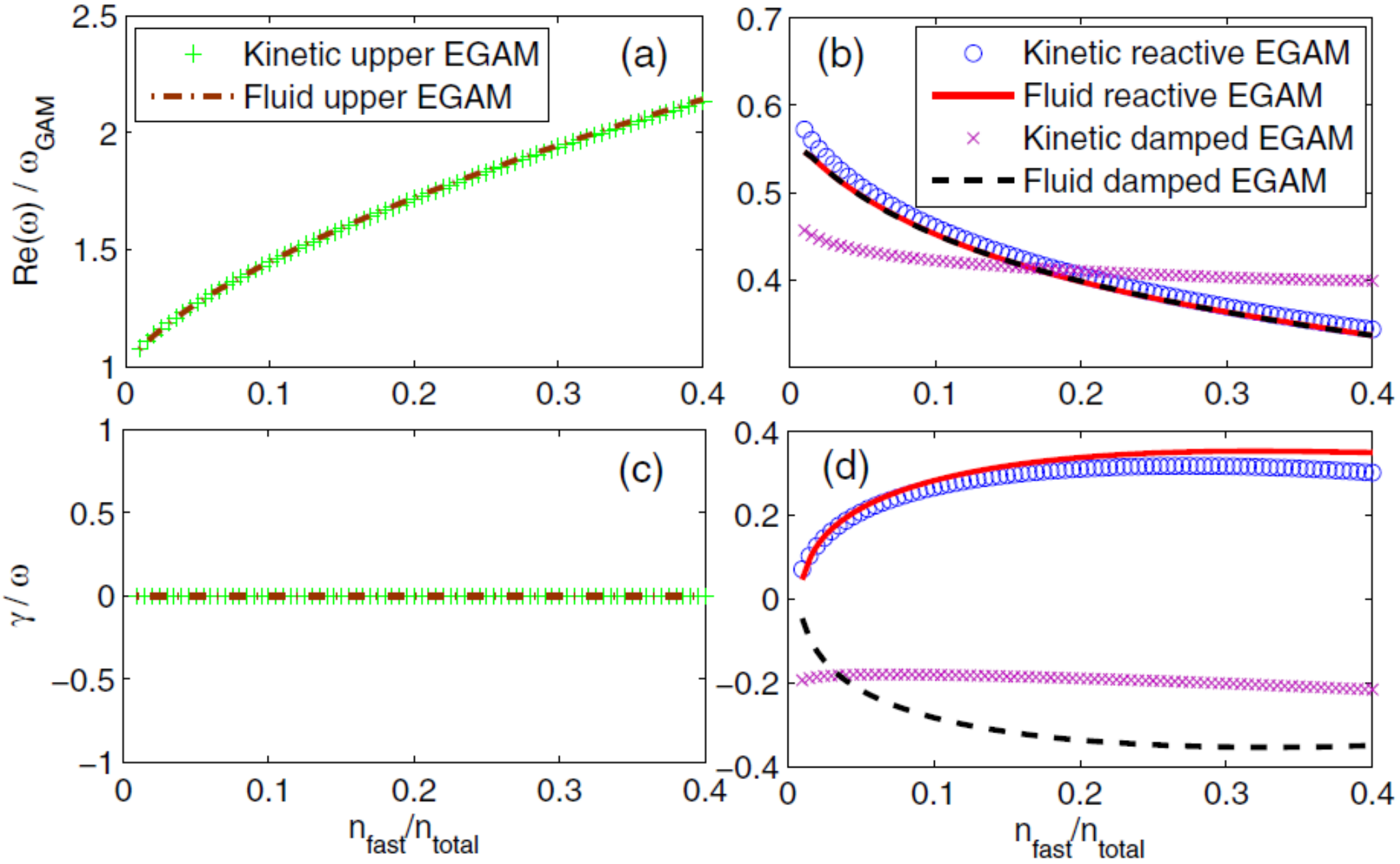
y

Reactive EGAMs

- Problem: Most EGAM studies slowing-down distribution function, but mode appears ~ 1ms after beam is turned on whereas slowing down time for ions is ~ 10ms
- Qu, Hole, Fitzgerald tried modelling fast particles using fluid theory – excludes Landau damping
- Able to predict same unstable EGAMs and their early appearance
- New class of EGAMs that aren't driven unstable by kinetic effects; reactive EGAMs
- Important for confinement, but also chance to study new Physics

Z. S. Qu, M. J. Hole, and M. Fitzgerald, Phys. Rev. Lett. **116**, 095004 (2016)


Kinetic upper EGAM
Fluid upper EGAM
(a)
Re(ω) / ω_GAM
Kinetic reactive EGAM
Fluid reactive EGAM
Kinetic damped EGAM
Fluid damped EGAM
(b)
(c)
γ / ω
(d)
n_fast/n_total
n_fast/n_total

Particle orbits

- Trapped – mirror point as B field strength increases towards inside of cross-section.
- Trapped orbits bounce back and form ‘banana’ shaped orbit
- Passing orbits – pass fully around cross-section
- Co/counter moving means moving in same/opposite toroidal direction as plasma current

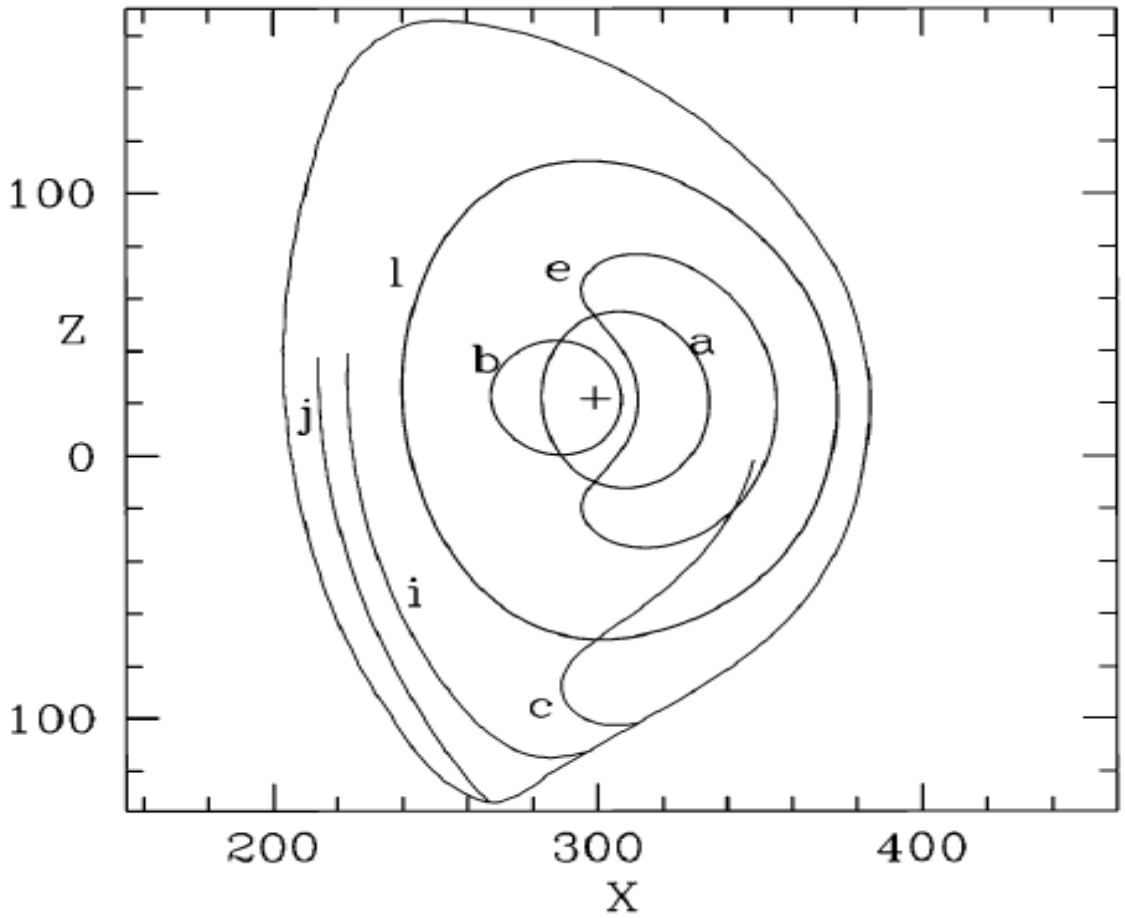


Fig: R. B. White, *The Theory of Toroidally Confined Plasmas, 3rd ed*. (Imperial College Press, London, 2001)

- Constants of motion: particle magnetic moment μ, energy W, toroidal canonical angular momentum P_ζ (like orbit radius)
- Gives diagram of orbit classifications
- Current code for reactive EGAMs (EGAMERS) includes trapped but not passing orbits
- Introduce high energy (W) cut-off to simplify boundaries

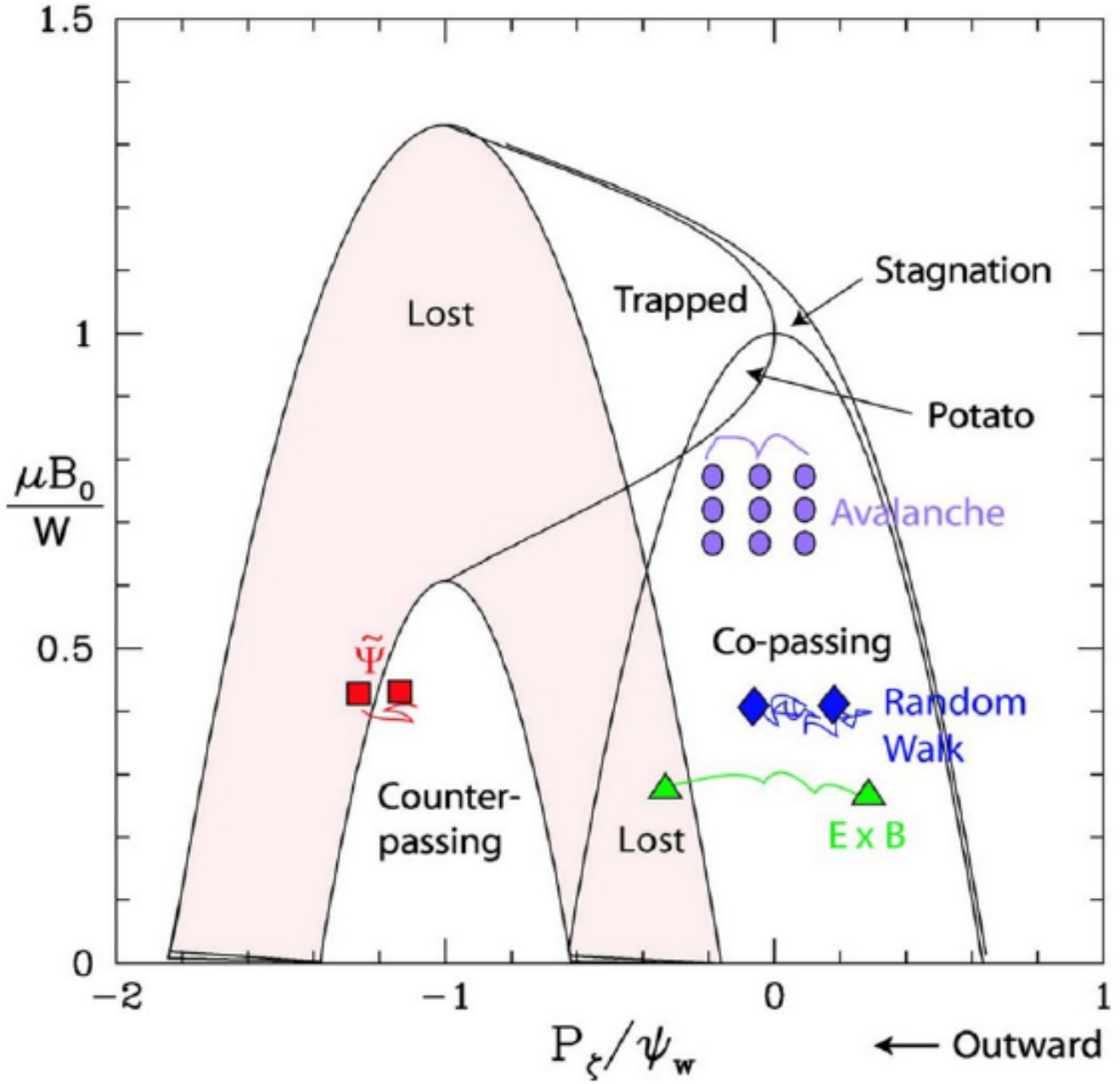


Fig: W. W. Heidbrink, Physics of Plasmas **15**, 055501 (2008)

Project goals

- Solve for passing particle orbit frequencies, paths
- Incorporate into EGAMERS code, solve for electric field of EGAMs as well as frequency, growth rate
- Investigate mode structure of different EGAM types for different equilibrium profiles
- Investigate EGAM parameter dependence on particle orbit frequency/width/direction of motion

EGAMERS

- Energetic Geodesic Acoustic ModE Radial Structure
- Eigenvalue code assuming simple tokamak geometry and using minimum amount of physics – fast results for theoretical studies

Future directions

- Relax high energy (W) cut-off to consider all orbits
- Use particle-in-cell (PIC) technique to include non-linear effects – compare results

Summary

- Background:
  - New class of modes, reactive EGAMs, that can be modelled using fluid theory and are driven unstable by fast ions from beam injection
  - Current models include trapped orbits but not passing orbits
- Project:
  - Find domain of passing orbits (using a simplification), include orbits in EGAMERS
  - Use code to analyse the mode structure of different types of EGAMs, along with frequency and growth rate for different profiles, and find dependence on orbit width/frequency.

Thanks!