Turbulent Dynamics of Tokamak Plasmas (TDoTP)
www.tdotp.ac.uk

Microstability and transport in high-β spherical tokamaks

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Outline

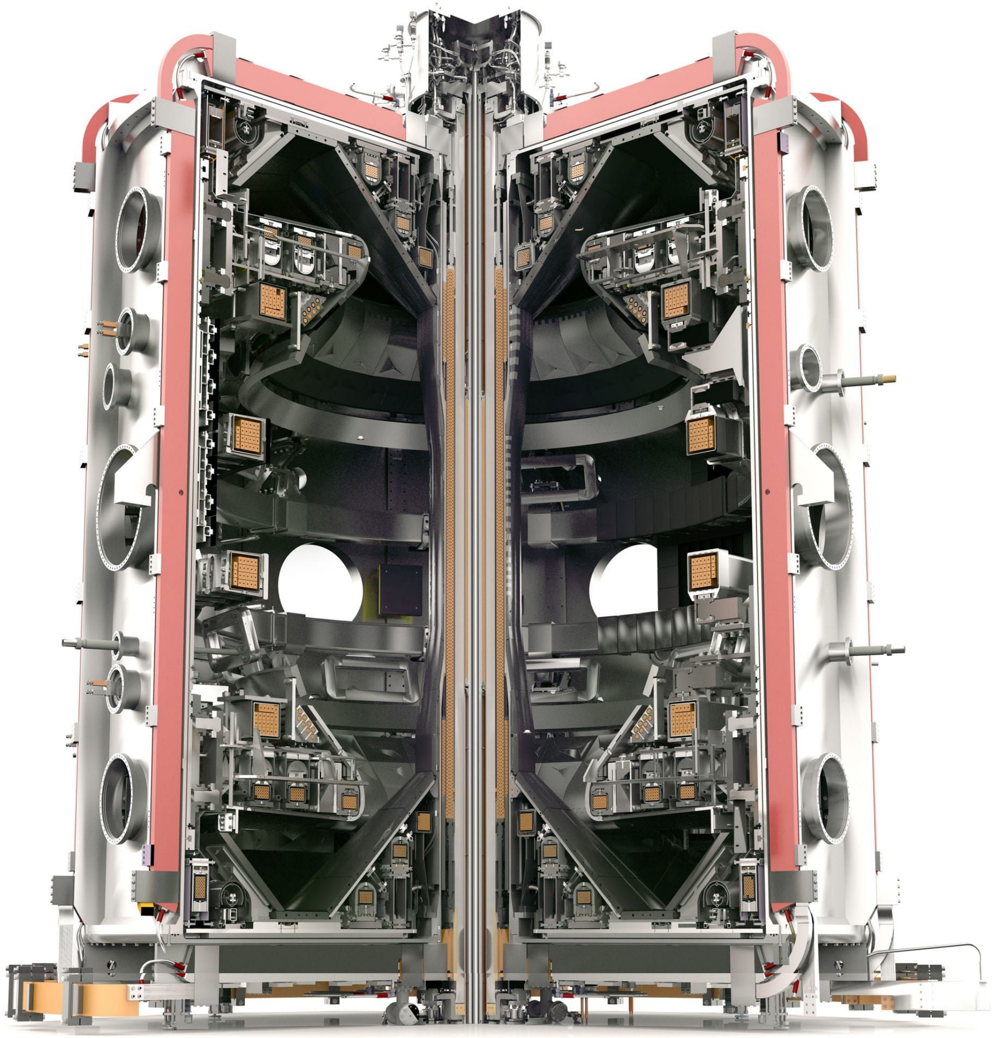
- Why high beta Spherical Tokamaks?
- Accessing large β'.
- An introduction to the TDoTP high-q_0 equilibrium.
- Linear microstability analysis.
- Nonlinear local gyrokinetic calculations.
- Future directions.

Outline

- Why high beta Spherical Tokamaks? **Brief reminder of F. Casson's talk**
- Accessing large β'. **Brief reminder of B. Davies' poster**
- An introduction to the TDoTP high-q_0 equilibrium.
- Linear microstability analysis. **Brief reminder of B. Patel's poster**
- Nonlinear local gyrokinetic calculations.
- Future directions.

Why High-β Spherical Tokamaks?

- Compact reactors can offer benefits
  - → Cheaper and quicker to build.
  - → Not without challenge.
- Fusion performance dependent on pressure
  - → Aiming for high core pressure.
  - → Either large radius, shallow gradient or small radius, high gradient.
- Spherical tokamaks good candidate, more efficient use of magnetic field.
  - → High elongation
  - → Relatively low field, high pressure.
  - → **High beta.**



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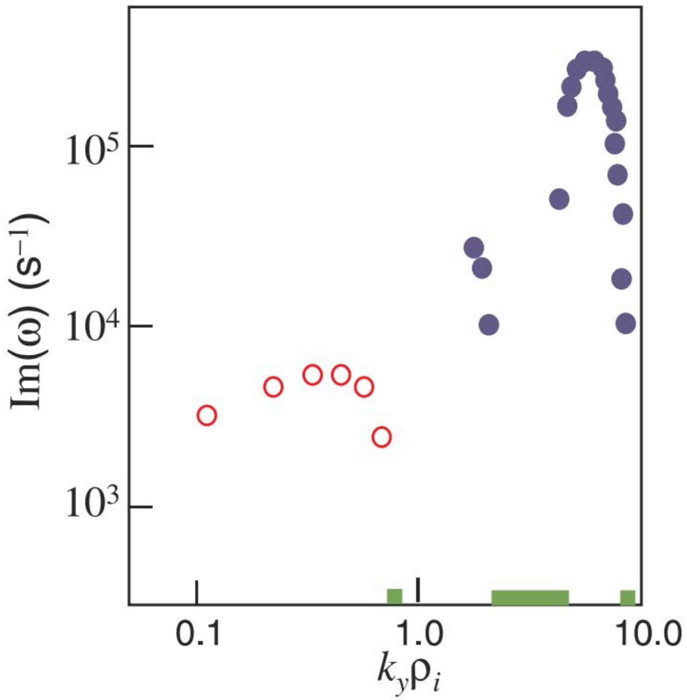
Why High-β Spherical Tokamaks?



GS2 simulations from ST power plant study find **all** electrostatic modes stable, different classes of microtearing modes (MTM) at all scales.

[H R Wilson et al, Nuclear Fusion, 44, 917 (2004)]

- Clearly not as simple as just deciding to have steep gradients!
- Achievable gradients depends on sources and transport processes.
  → Feasibility of compact ST reactor depends crucially on turbulence and confinement.
- Know β and β' can modify electrostatic instabilities as well as driving new ones.
  → What does micro-stability and turbulence look like in such a device?
  → Step change from current devices?

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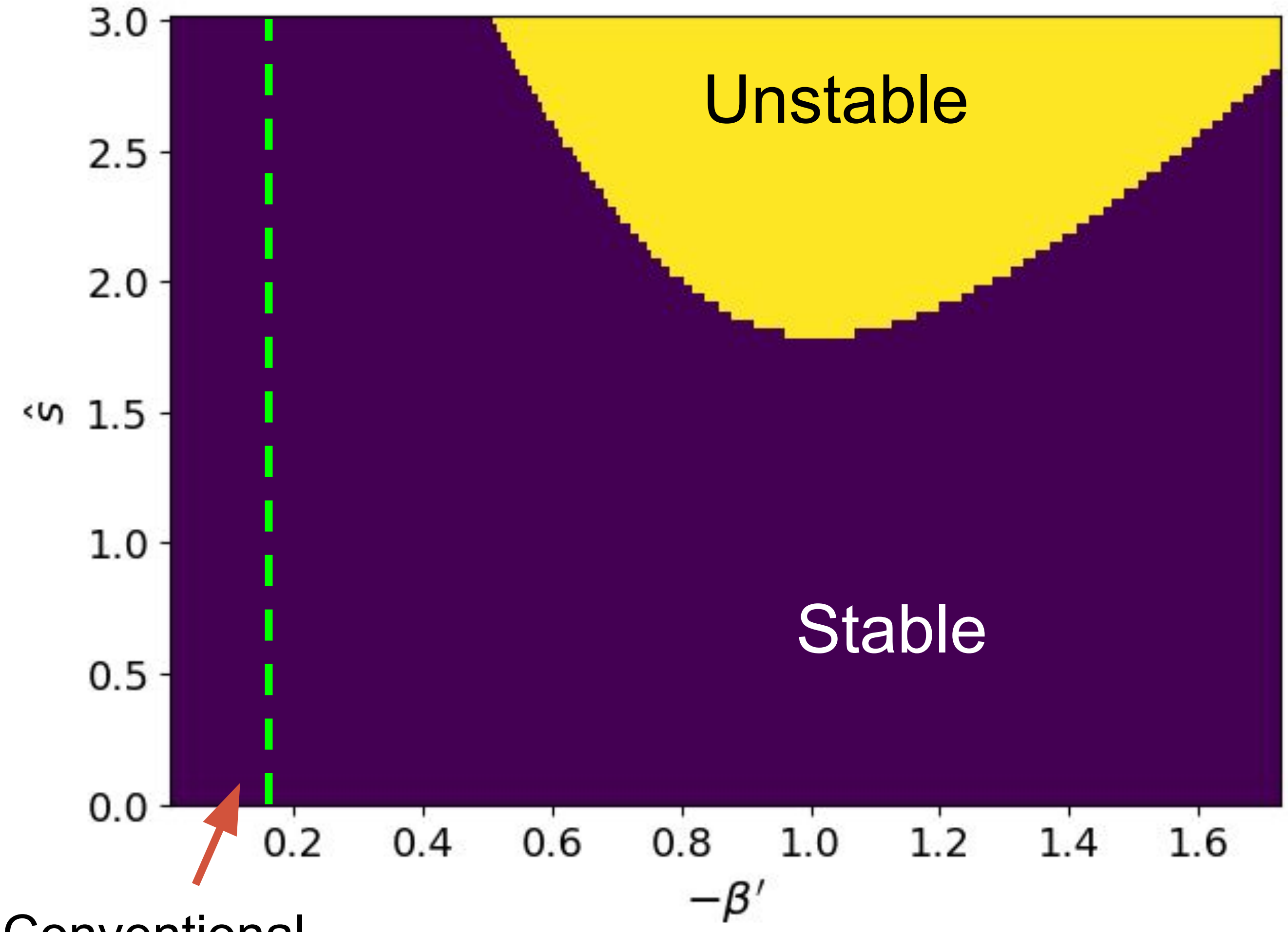
Compact High β => High β’

- Steeper gradients in compact devices to reach same volume averaged β as conventional.
- High β ST reactor needs both high β and β’
  → Similar to pedestal conditions.
  → Pressure gradient limits from KBM?
- Can use to help guide equilibrium design to optimise against KBM stability.



Conventional requirement.

Compact High β => High β’

- Steeper gradients in compact devices to reach same volume averaged β as conventional.
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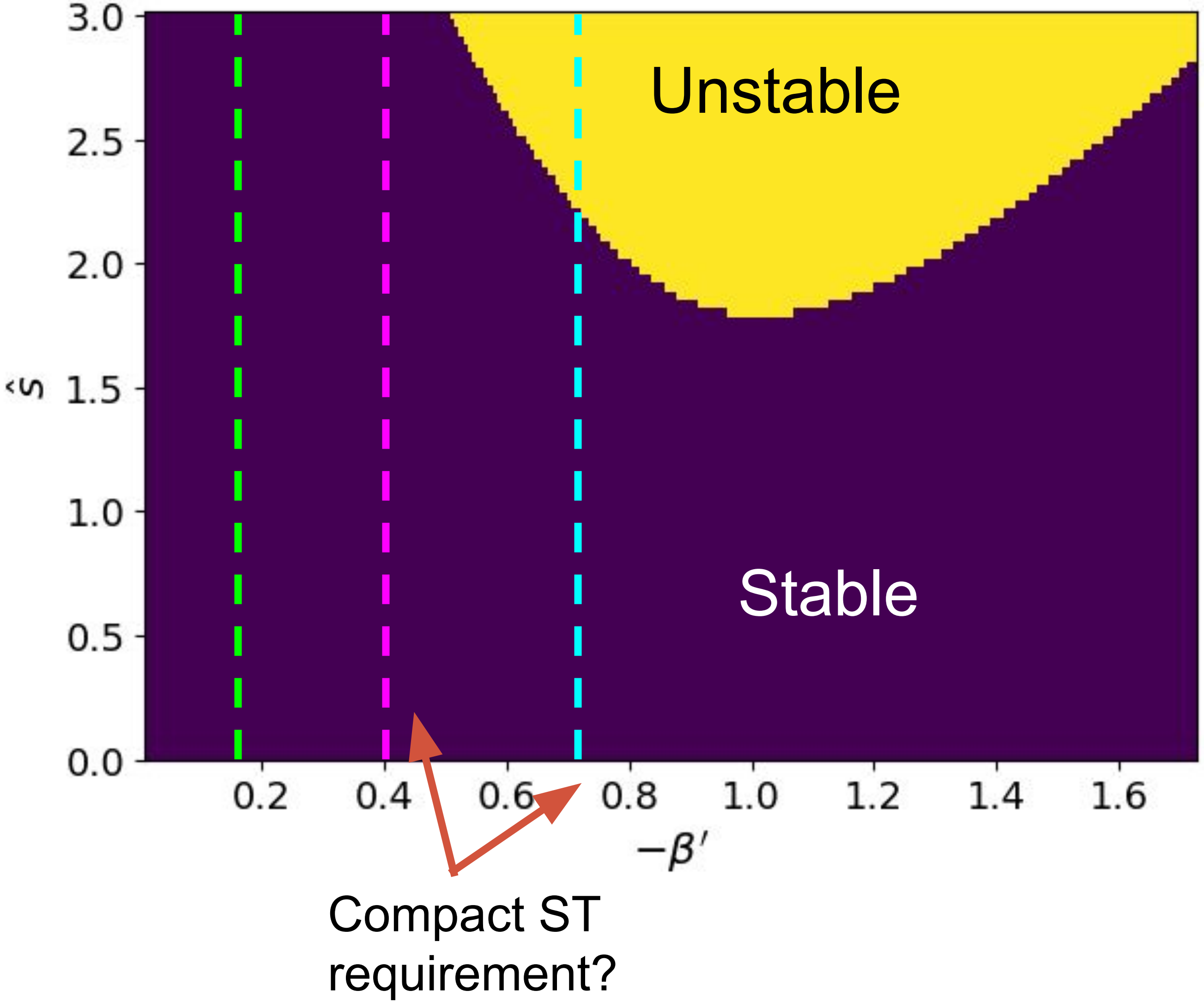
  → Pressure gradient limits from KBM?
- Can use to help guide equilibrium design to optimise against KBM stability.
  → **Maximise 2nd stability access**



[R. Davies *et. al* Plasma Phys. Control. Fusion **64** 105001 (2022) and Poster here]

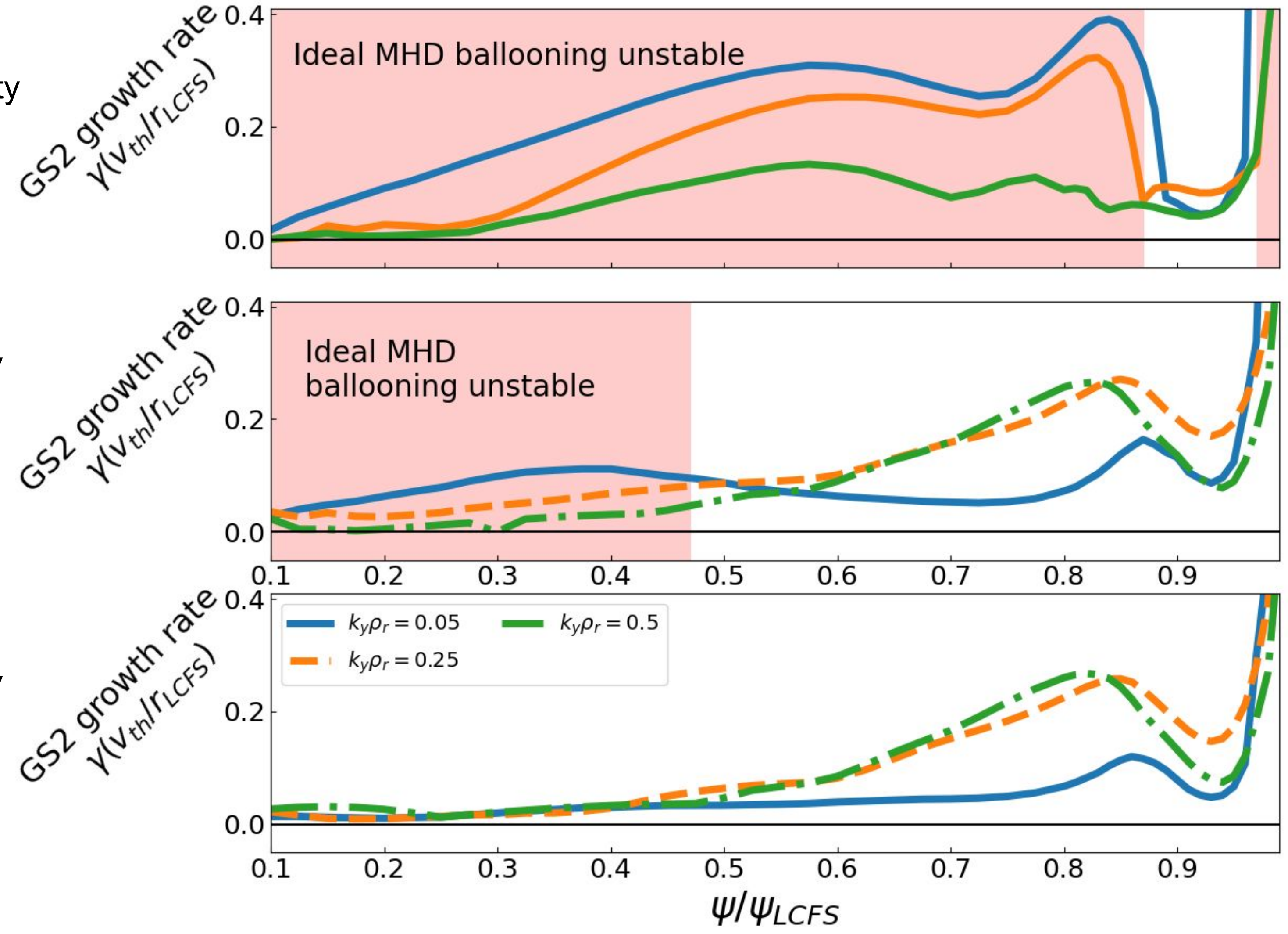
KBMs as a shaping constraint

Improving KBM stability and second stability access.

-ve triangularity
(tri_{LCFS} = -0.3)
(q_0 = 2.58)

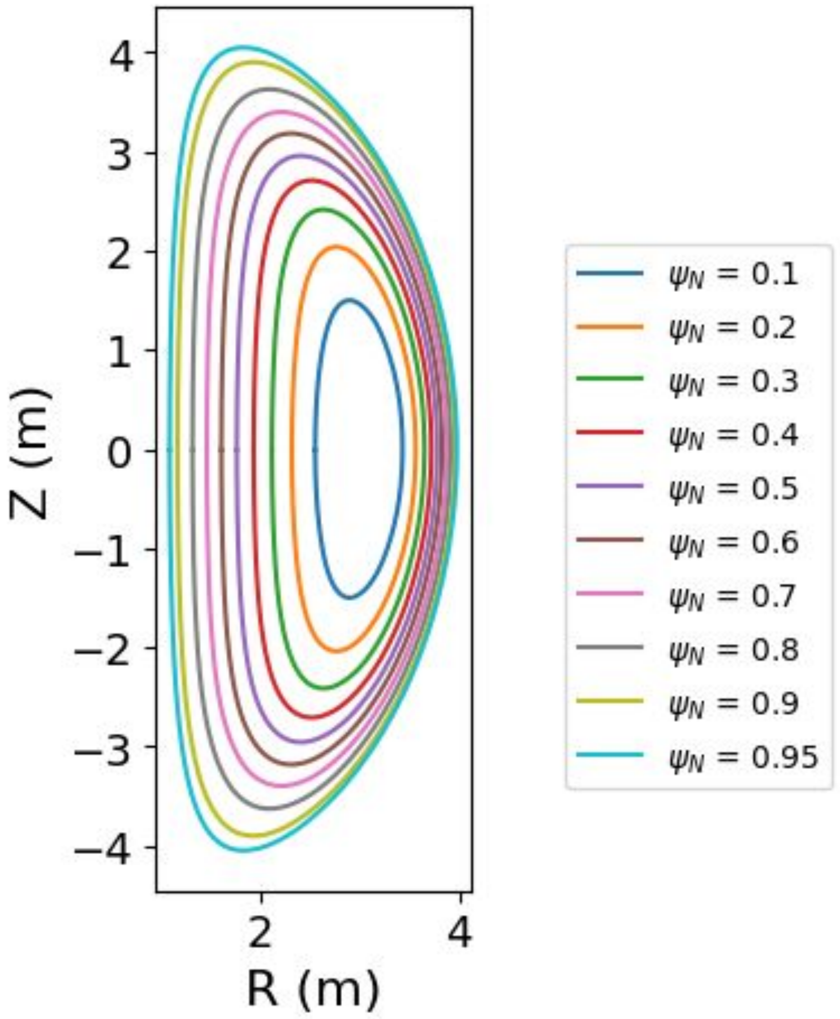
+ve triangularity
(tri_{LCFS} = 0.54)
(q_0 = 1.38)

+ve triangularity
(tri_{LCFS} = 0.54)
(q_0 = 2.71)



[R. Davies *et. al* Plasma Phys. Control. Fusion **64** 105001 (2022) and Poster here]

The high q_0 TDoTP baseline equilibrium



- High q_0=2.71 TDoTP baseline equilibrium
  → ideal MHD stable
  → β=18.6%
  → β_N=5.47
  → κ_{LCFS}=2.8
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  → P_{fus}= 808 MW
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  → **P_{heat}= 220 MW**
  → J = 16.5 MA
  → J_{BS}=11 MA (67%)

[H. Wilson et al, Zenodo 10.5281/zenodo.4641183]

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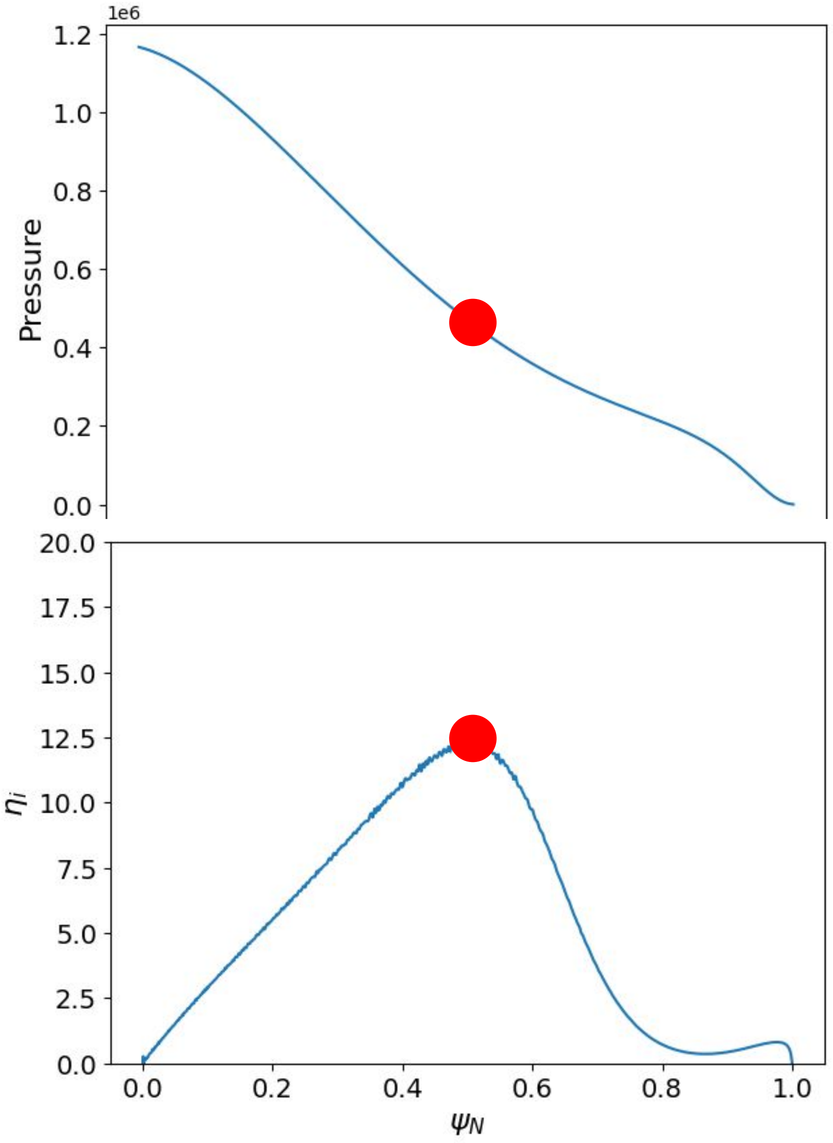


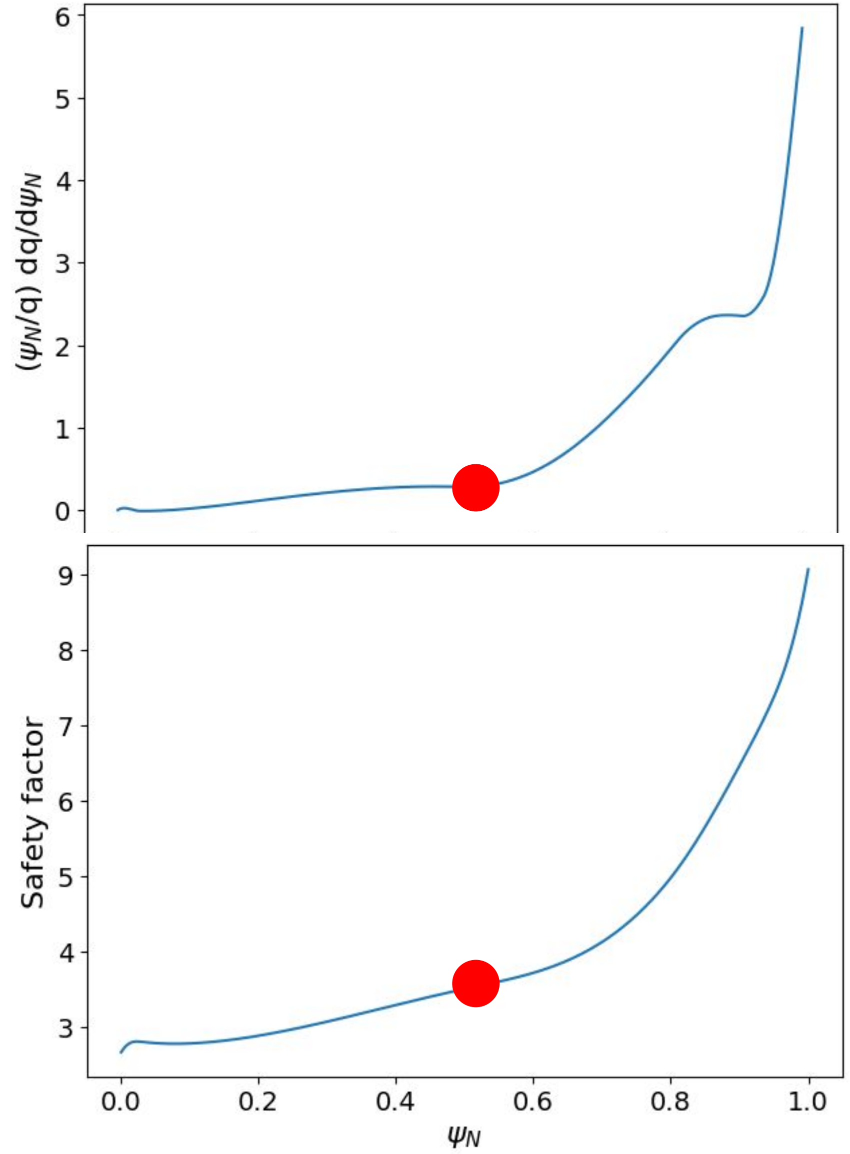
Roughly constant pressure length scale

Relatively low shear across core

Peaked η near mid-radius

High q_0

Analyse q=3.5, ψ_N~0.5 surface



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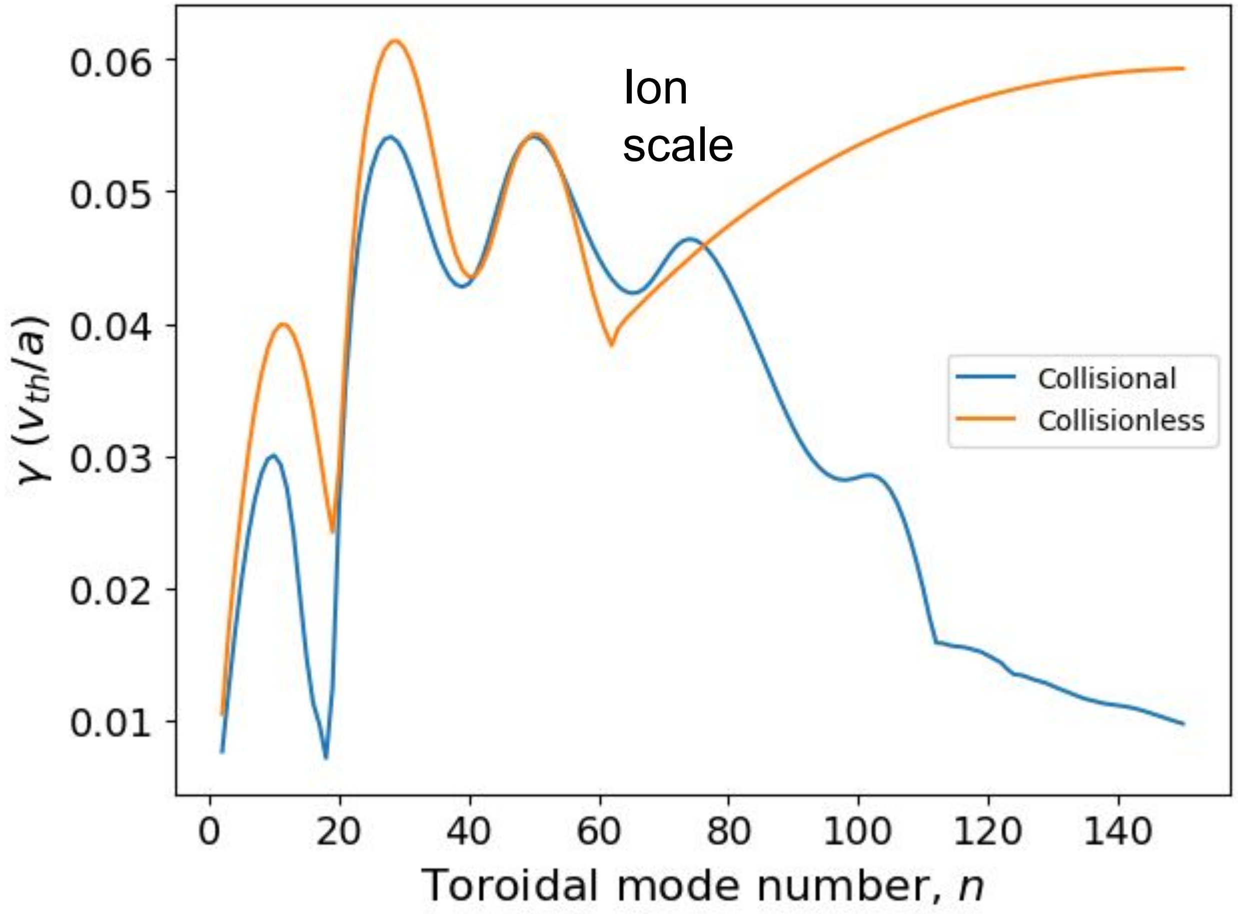
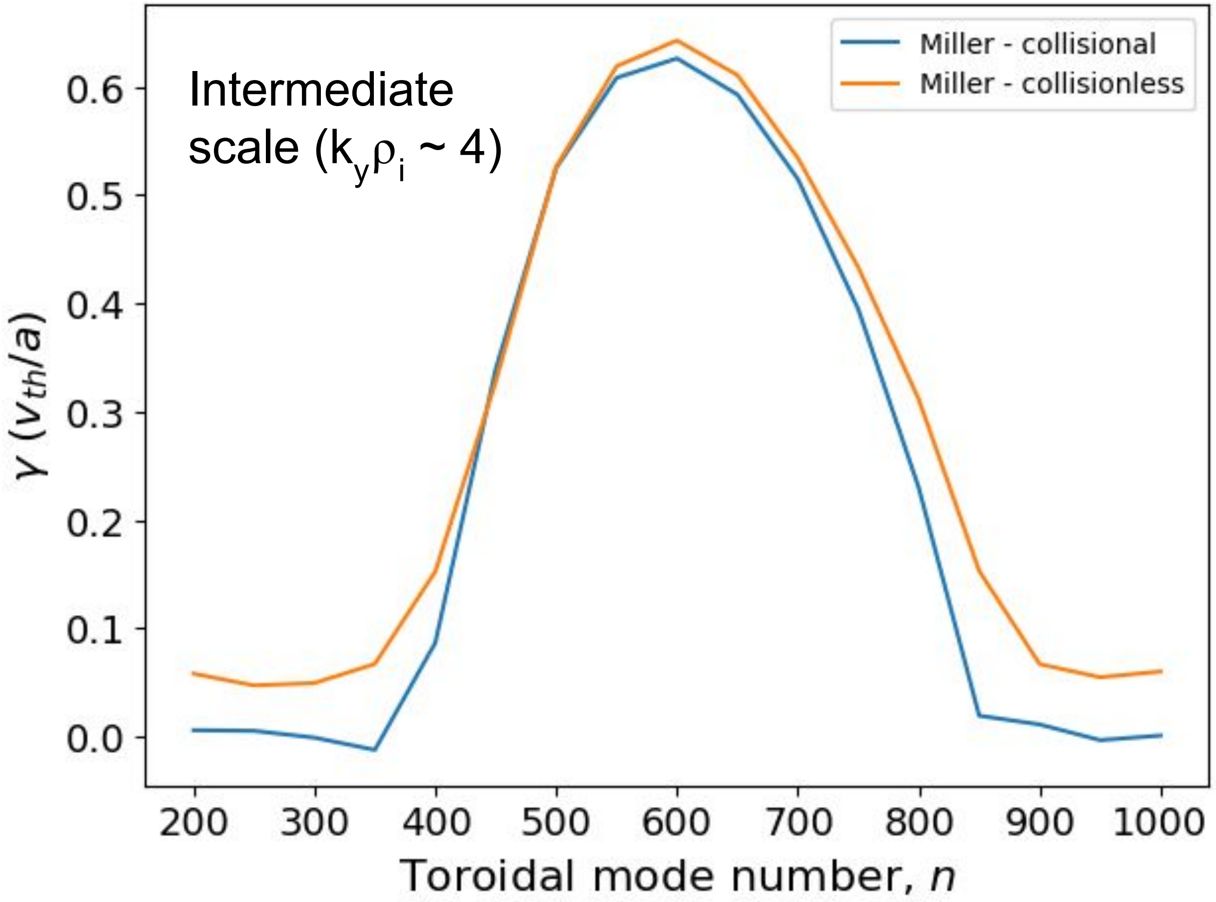
Linear stability analysis - dominant modes

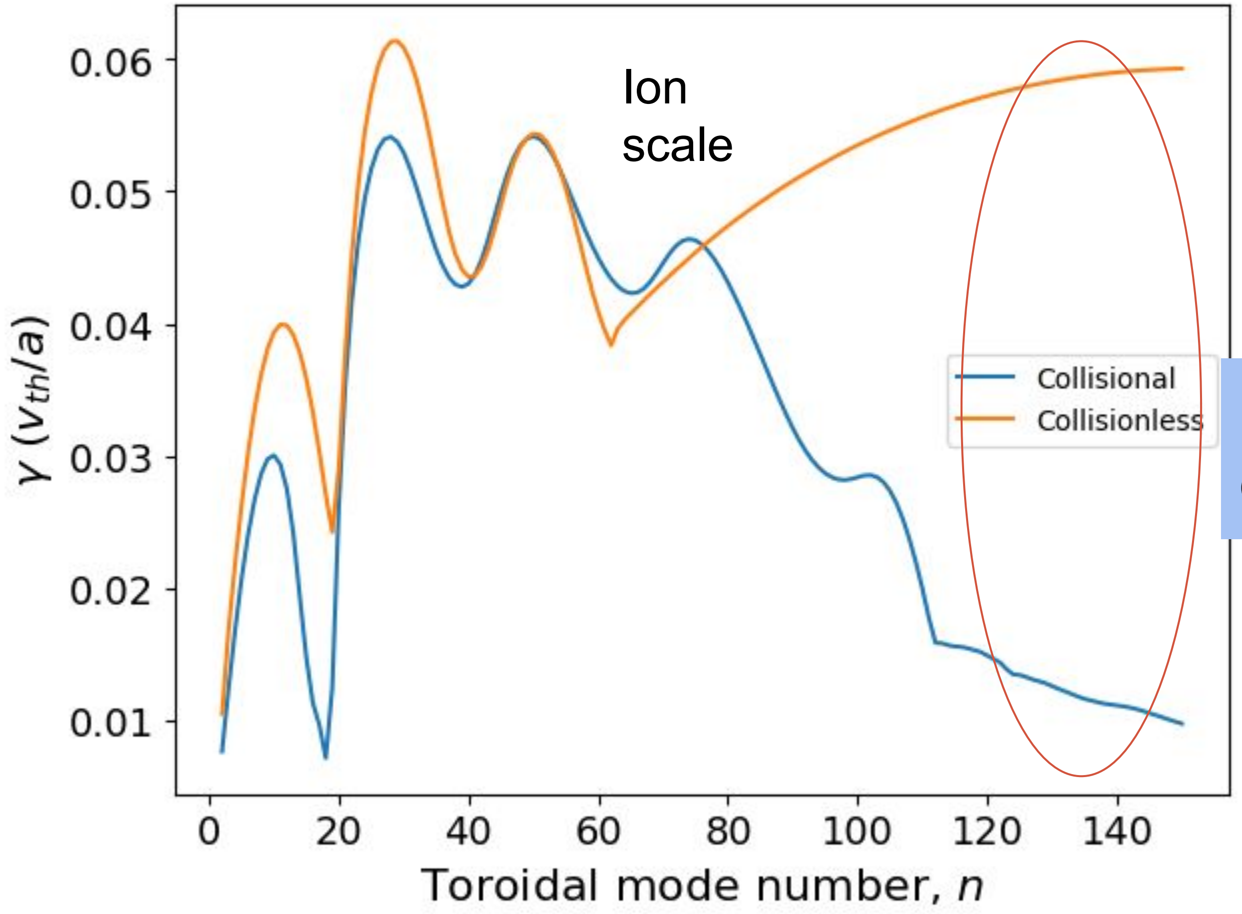


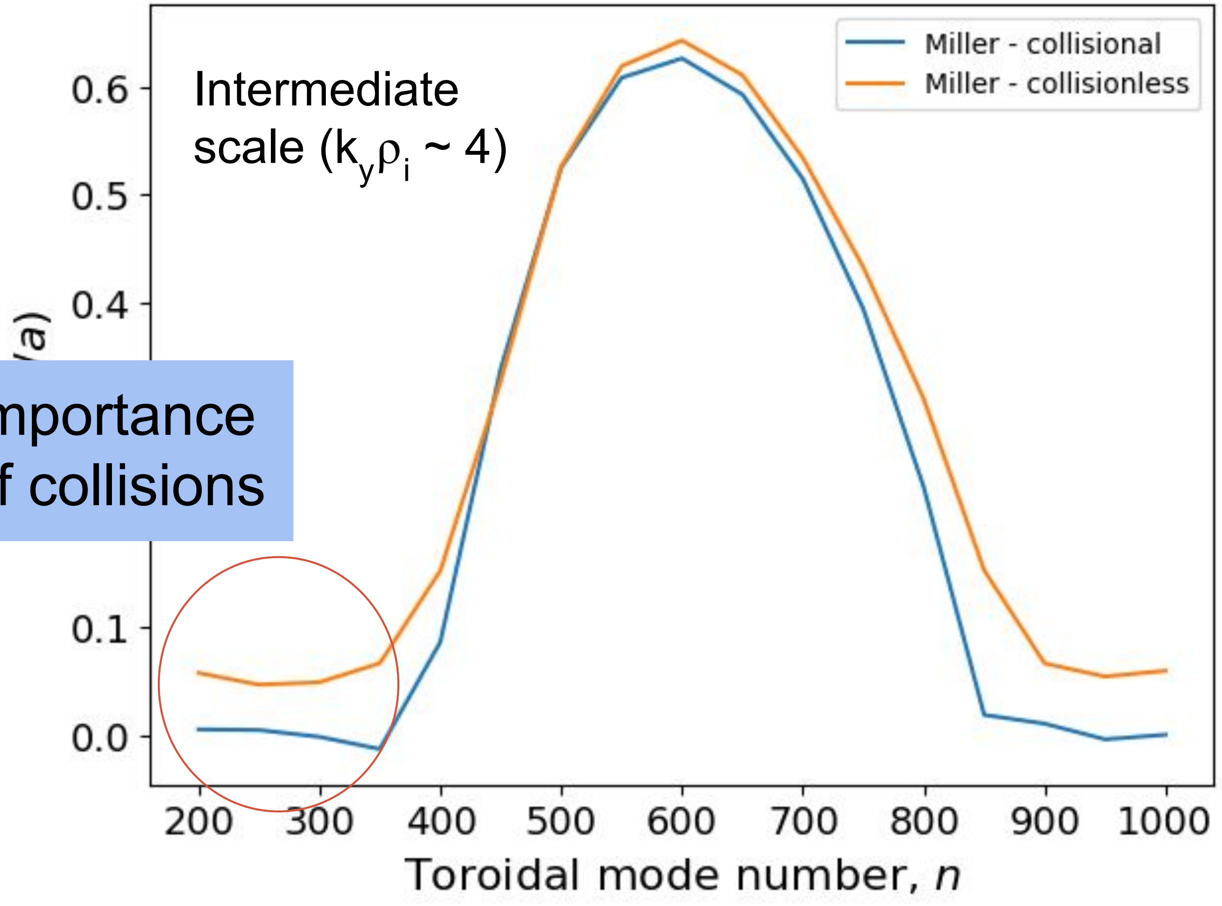


- At **ion scale dominated by KBM** like mode (more on this later).

- At **intermediate scale** find dominated by **collisionless MTM**.
- **No electron scale** modes unstable.

Linear stability analysis - dominant modes





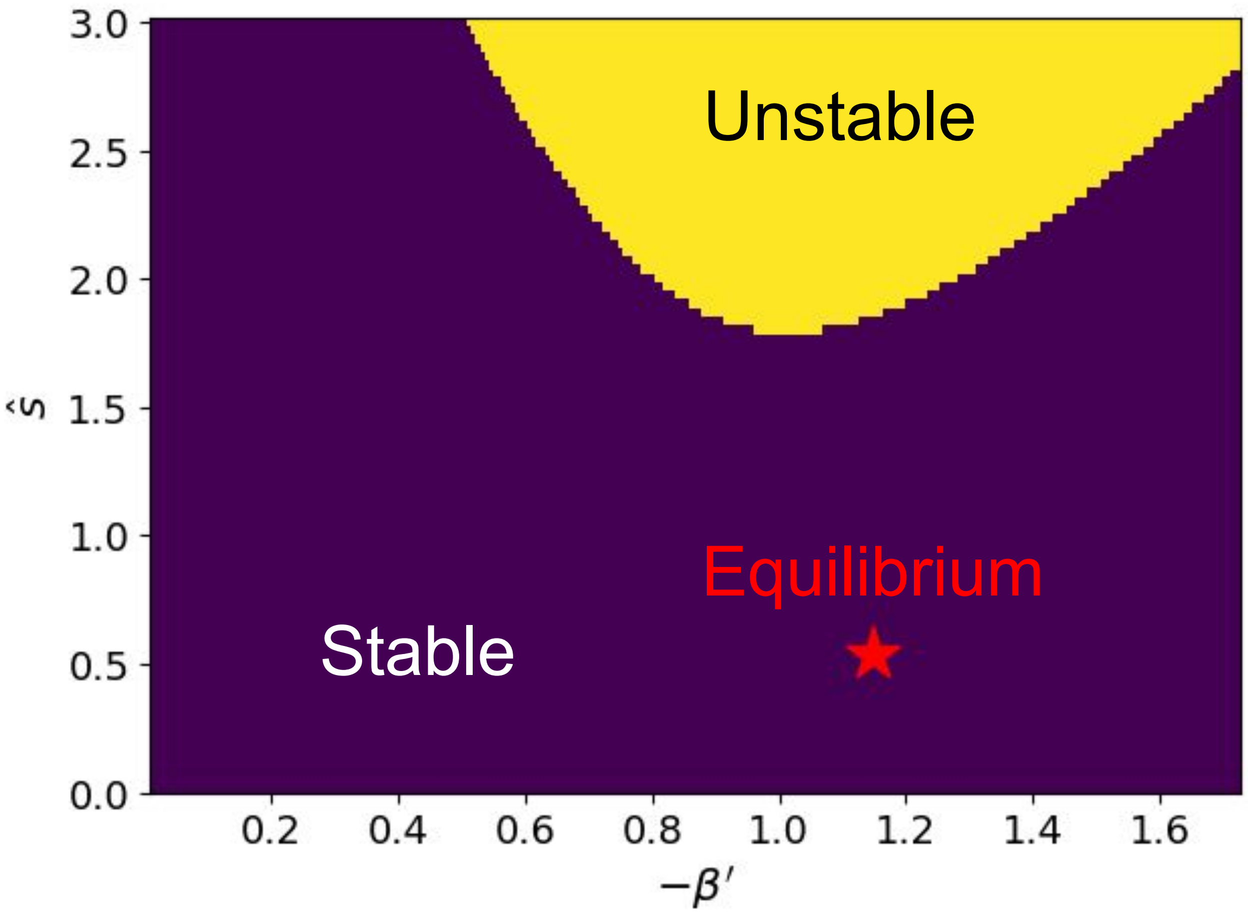
Importance of collisions

- At **ion scale dominated by KBM** like mode (more on this later).

- At **intermediate scale** find dominated by **collisionless MTM**.
- **No electron scale** modes unstable.

Linear stability analysis - what is ion scale mode?

- Called the low *n* mode KBM, but equilibrium supposed to be optimised against this!
- Ideal ballooning calculation confirms surface is far away from ideal stability boundary.
- So what is the mode?



Linear stability analysis - what is ion scale mode?

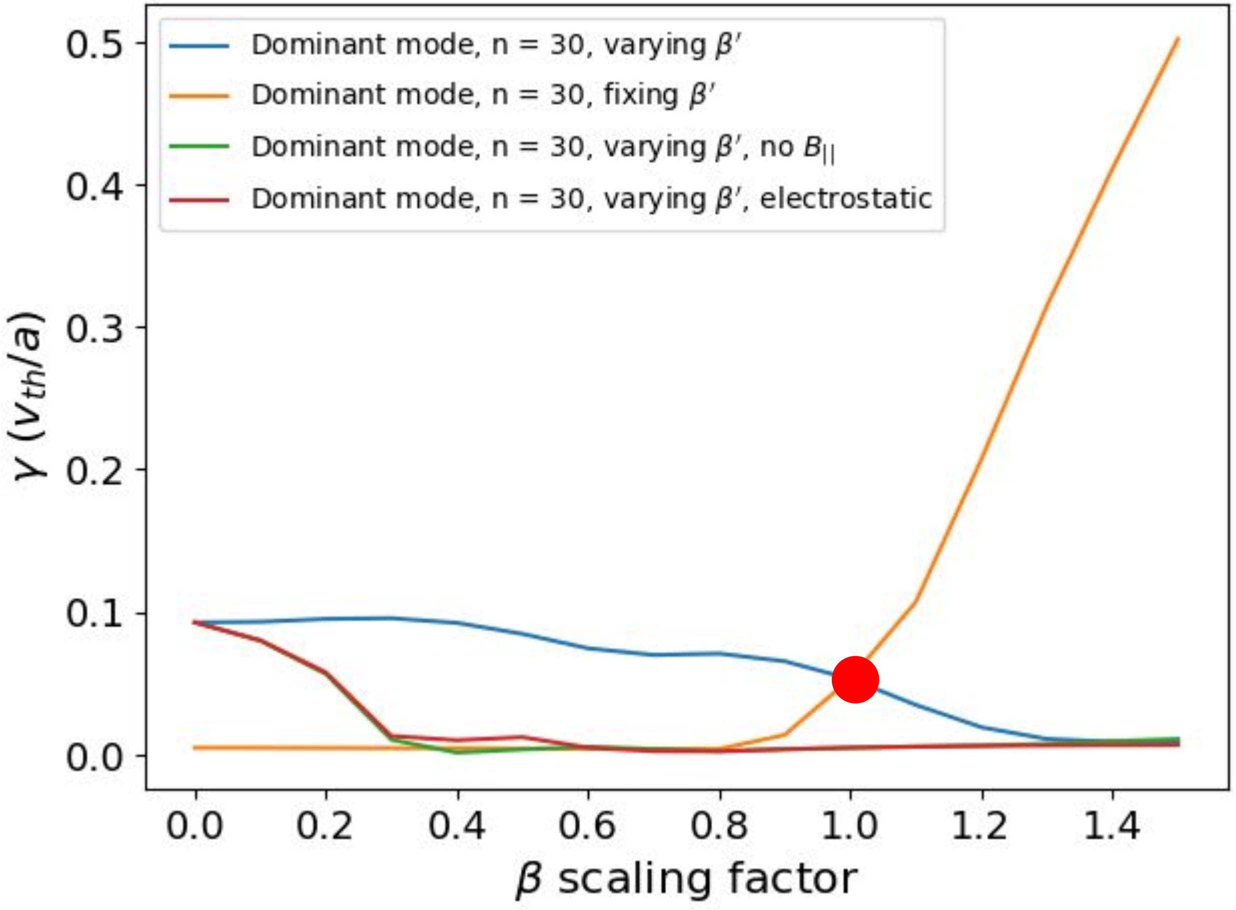
- Try scaling β and look at response.

- When done consistently, mode continuously tracked back to electrostatic limit → **Not purely EM**.

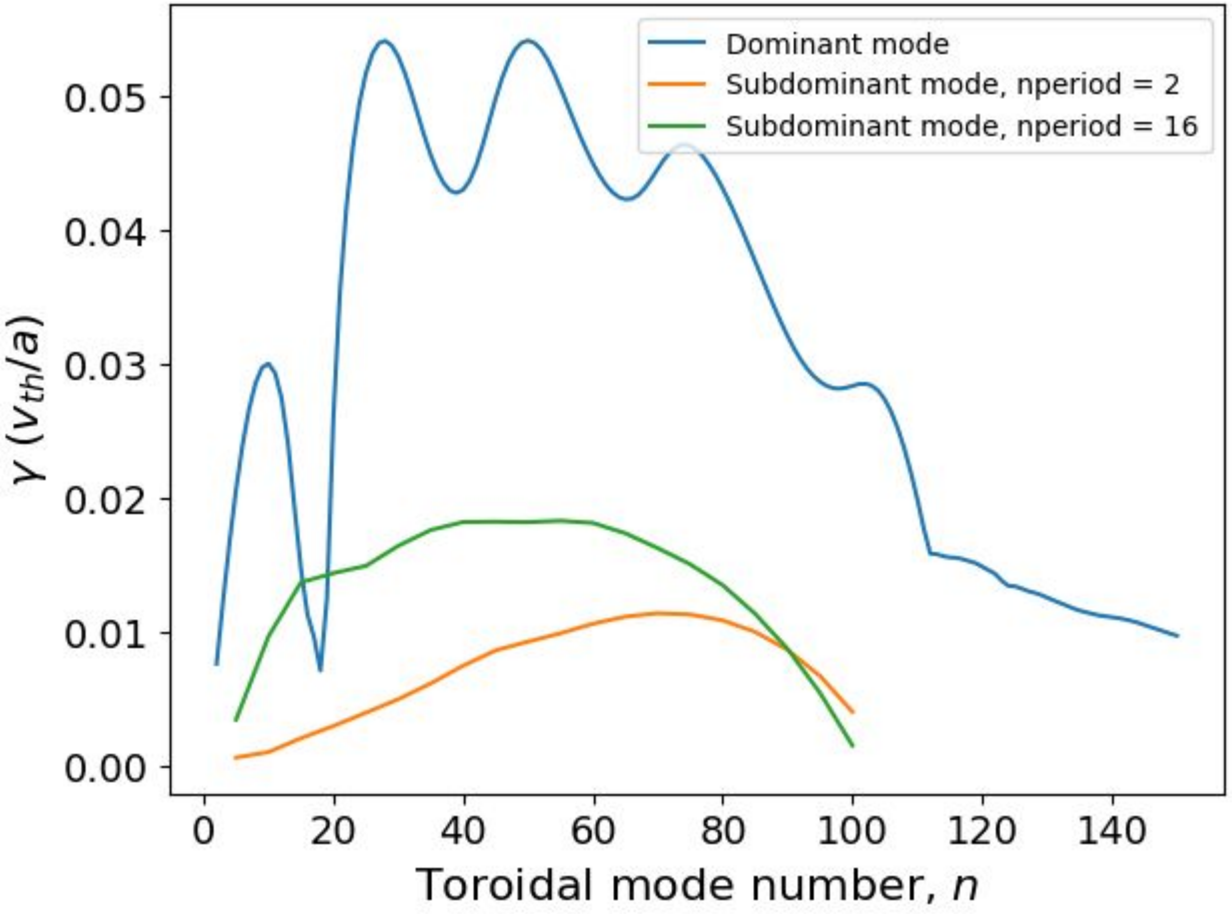
- Purely electrostatic simulation (with β’≠0) stabilised as β increased.
- When β’ held fixed mode stabilised as β dropped → **Accessing EM drive**.

- **Requires $B_{||}$** to access EM drive.

- Consistent with coupled KBM-ITG, similar behaviour seen in JET [C. Bowman et al 2018 Nucl. Fusion 58 016021]

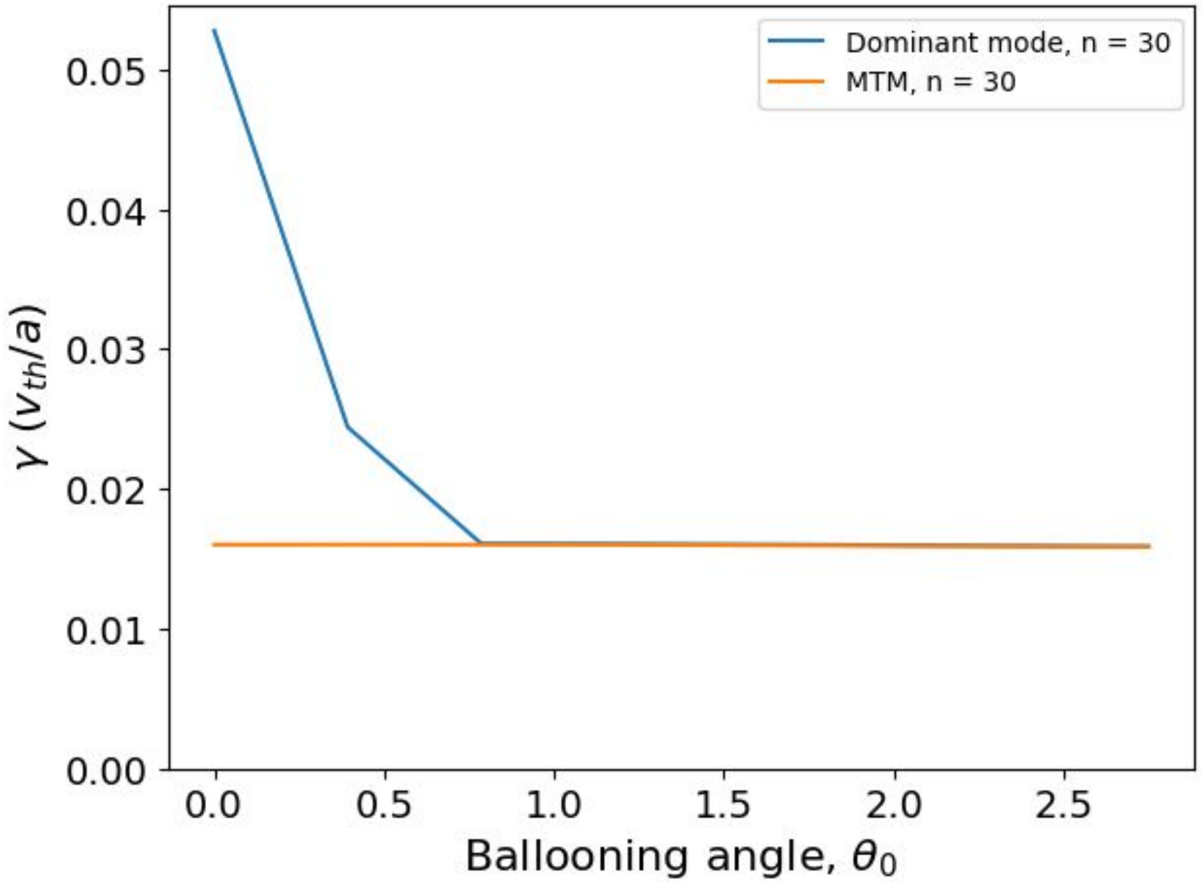


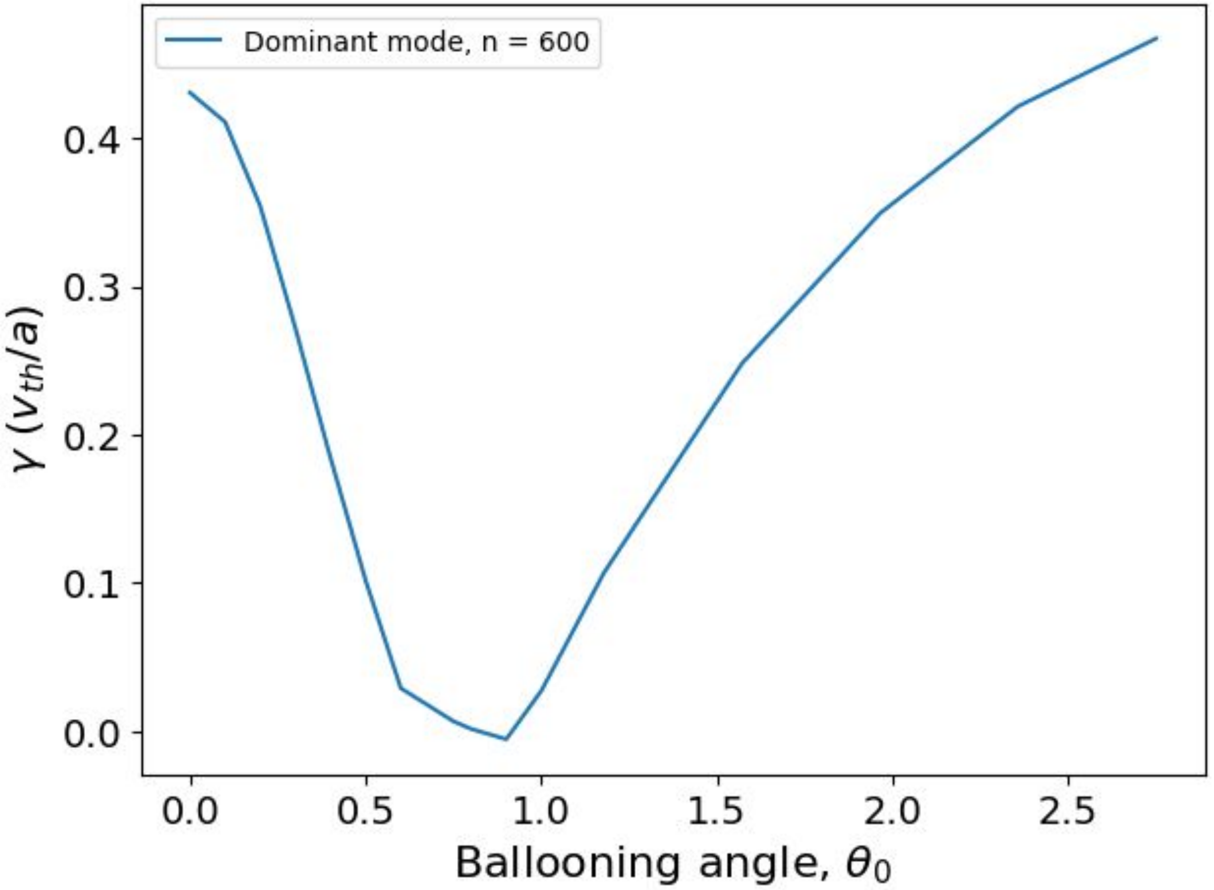
Linear stability analysis - subdominant modes



- Find highly extended $k_x\rho_e$~1, **collisional MTM** subdominant at ion scales.
- Nothing subdominant at intermediate scales.
- Similar picture across most of core surfaces. Changes in pedestal.
- Very similar to [B.S. Patel et al Nucl. Fusion 62 016009 (2022)].
- Low q_0 case broadly similar but KBM stability worse at low *n*.

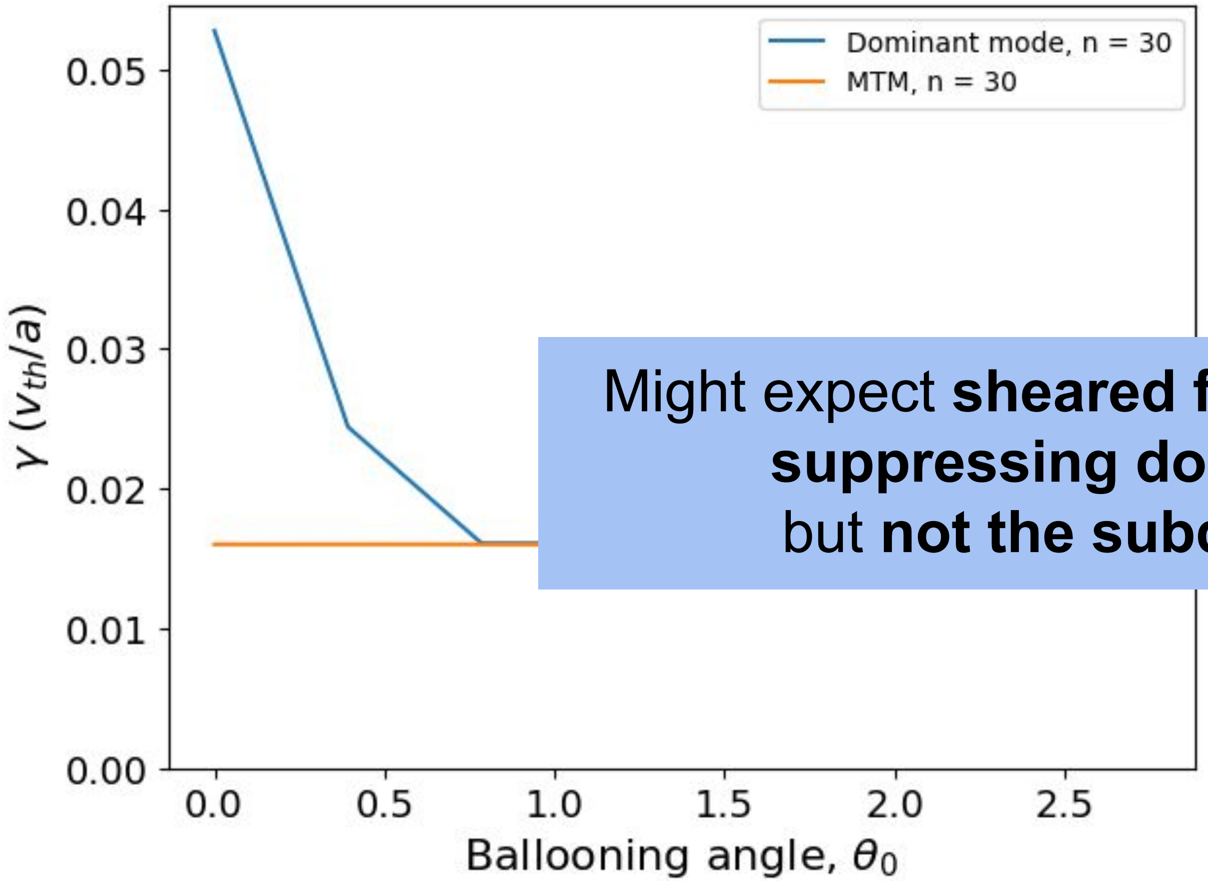
Linear stability analysis - sheared flows

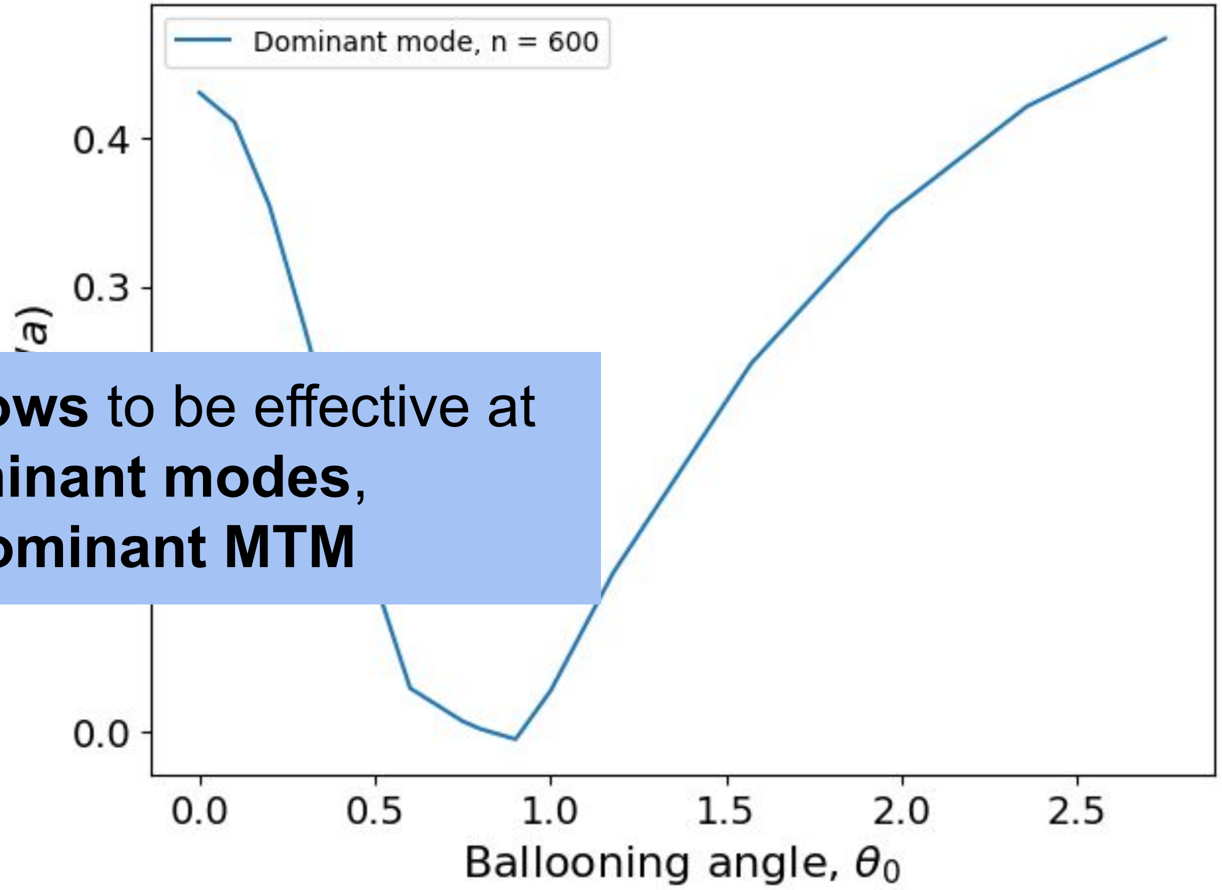




- At ion scale find KBM very sensitive to θ_0, MTM insensitive → **KBM likely suppressed by sheared flows**.
- At **intermediate scale MTM sensitive to θ_0** and also find growth rate peaks inboard. [B.S. Patel et al Nucl. Fusion 62 016009 (2022) + poster]

Linear stability analysis - sheared flows





Might expect **sheared flows** to be effective at **suppressing dominant modes**, but **not the subdominant MTM**

- At ion scale find KBM very sensitive to θ_0, MTM insensitive → **KBM likely suppressed by sheared flows**.
- At **intermediate scale MTM sensitive to θ_0** and also find growth rate peaks inboard. [B.S. Patel et al Nucl. Fusion 62 016009 (2022) + poster]

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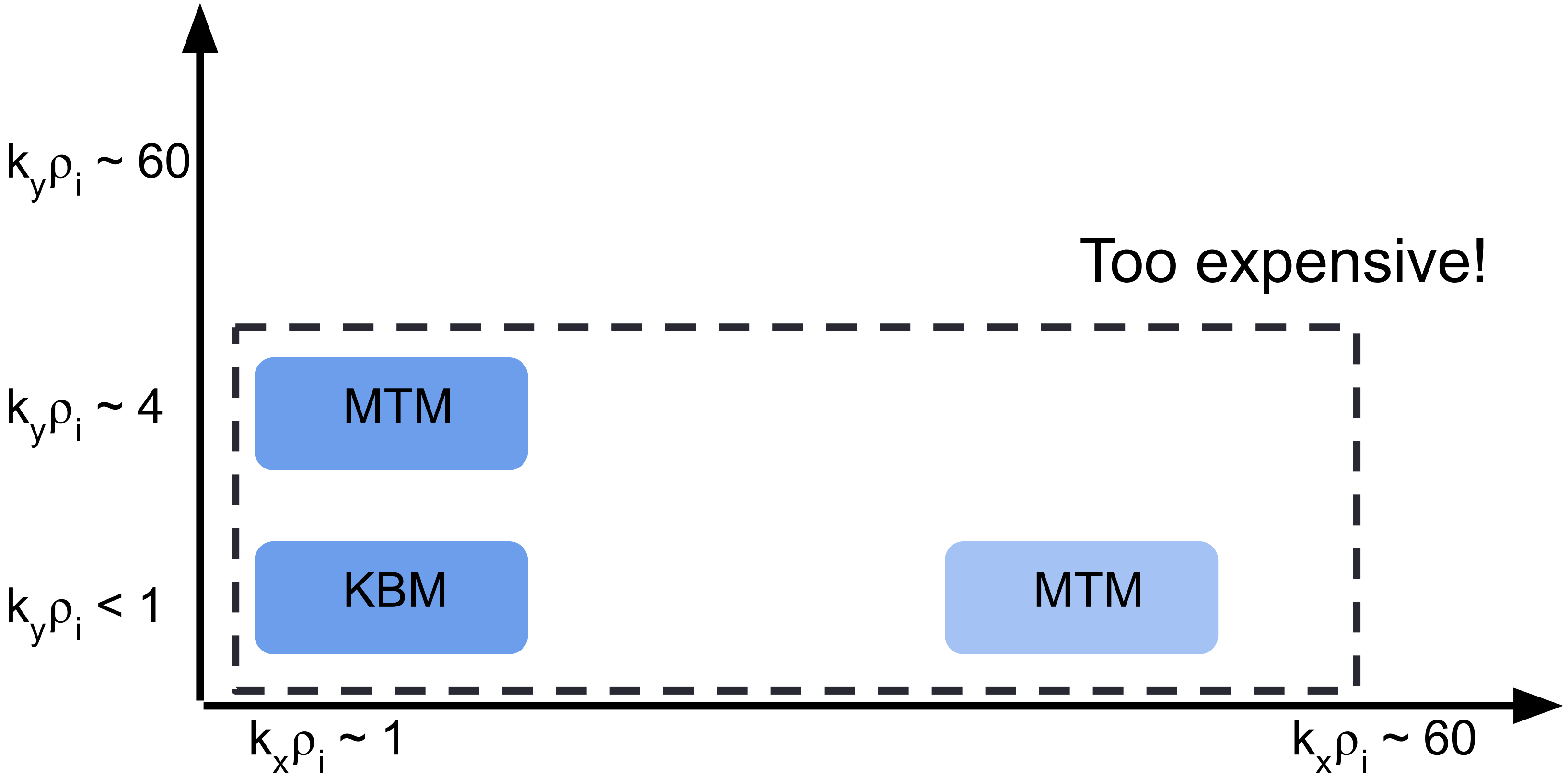
- **Nonlinear local gyrokinetic calculations.**
- Future directions.

Nonlinear simulations – Flux tube setup

- Subdominant MTM pose extreme resolution requirements
  → Define two types of simulation.



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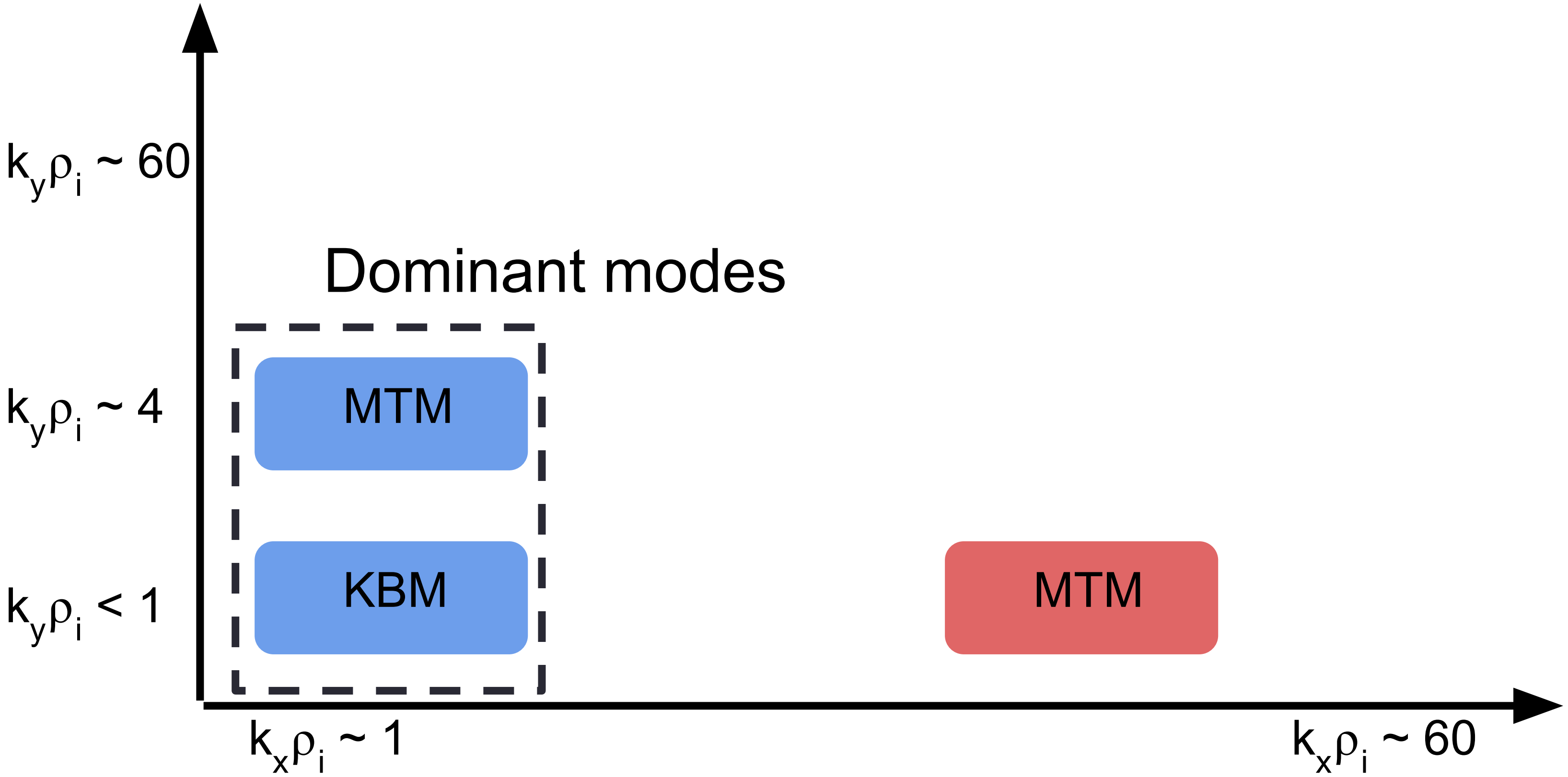

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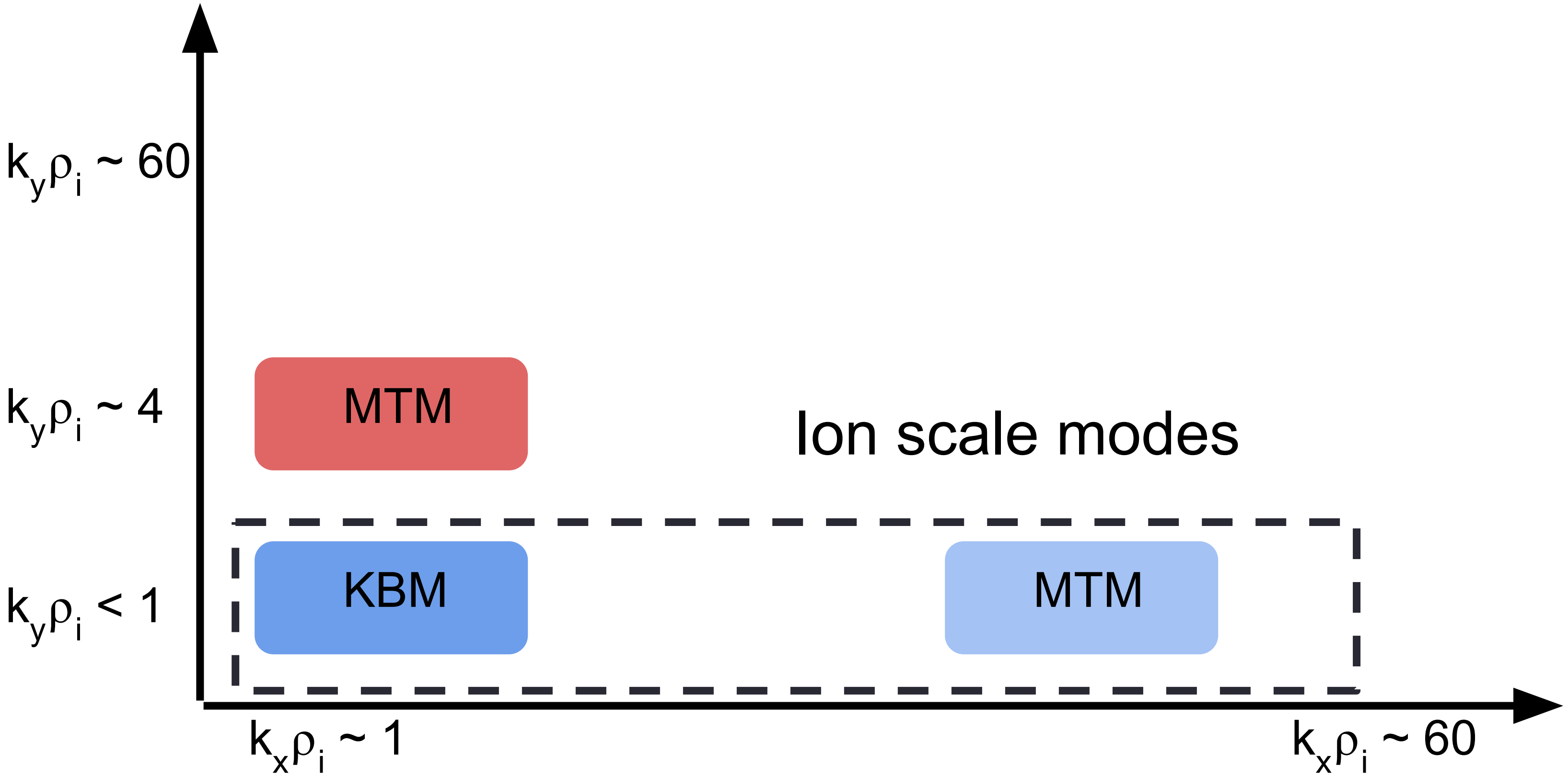
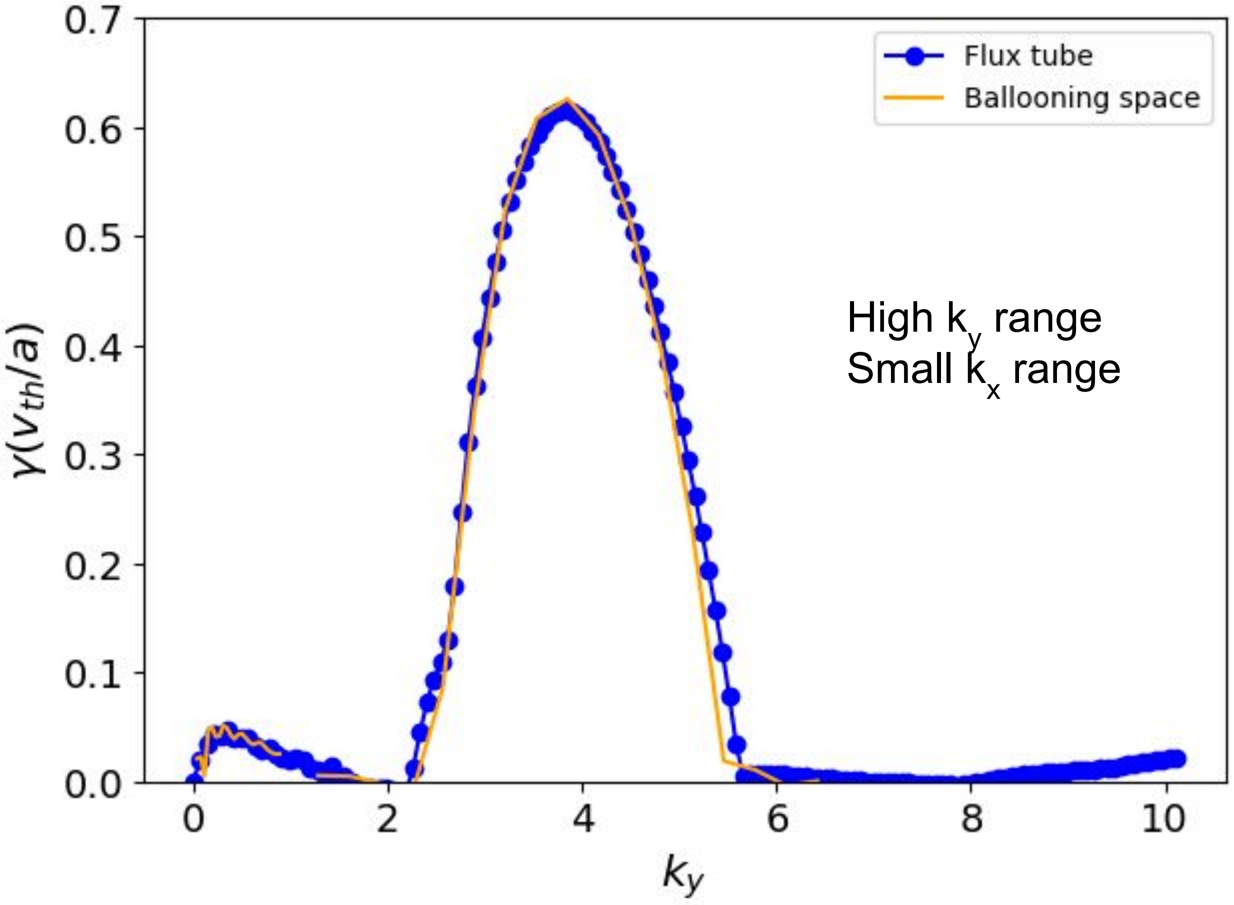


Nonlinear simulations – Flux tube setup

- Subdominant MTM pose extreme resolution requirements
  → Define two types of simulation.

- Dominant modes – which treats the full range in k_y but do not attempt to resolve high k_x ion-scale MTM.

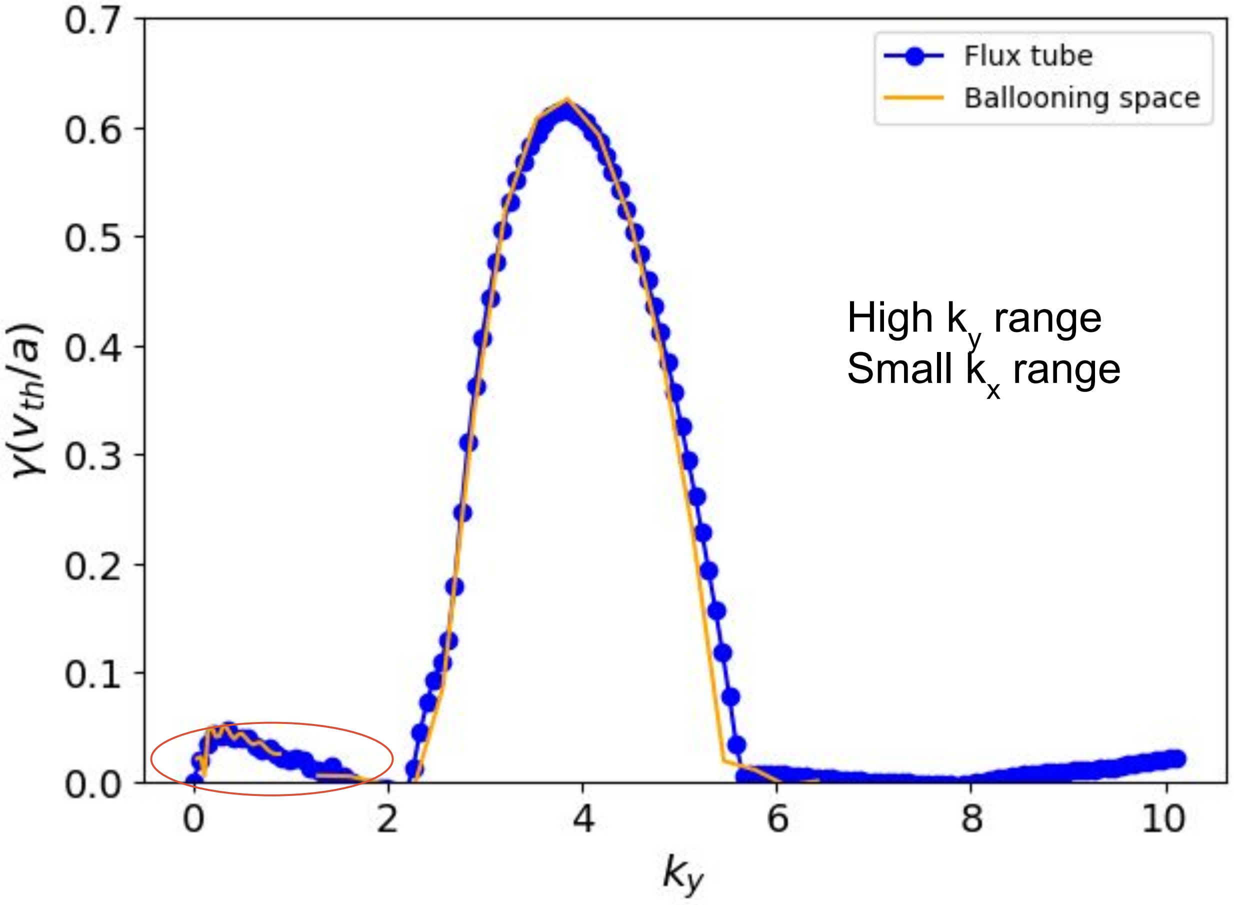


Nonlinear simulations – Flux tube setup

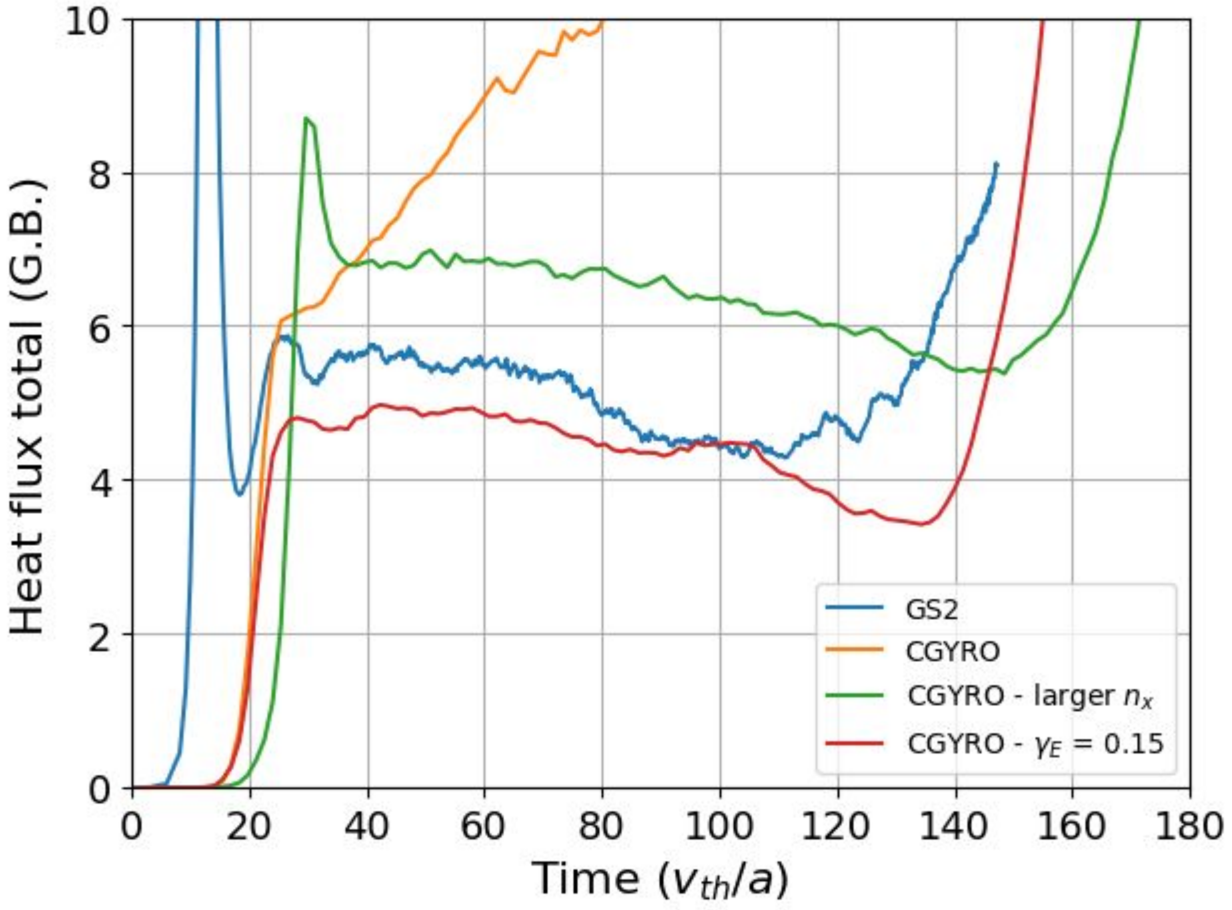
- Subdominant MTM pose extreme resolution requirements
  → Define two types of simulation.

- Dominant modes – which treats the full range in k_y but do not attempt to resolve high k_x ion-scale MTM.

- Ion scale – which only treat the ion scale k_y but attempt to resolve subdominant MTM – Come back to this one later.

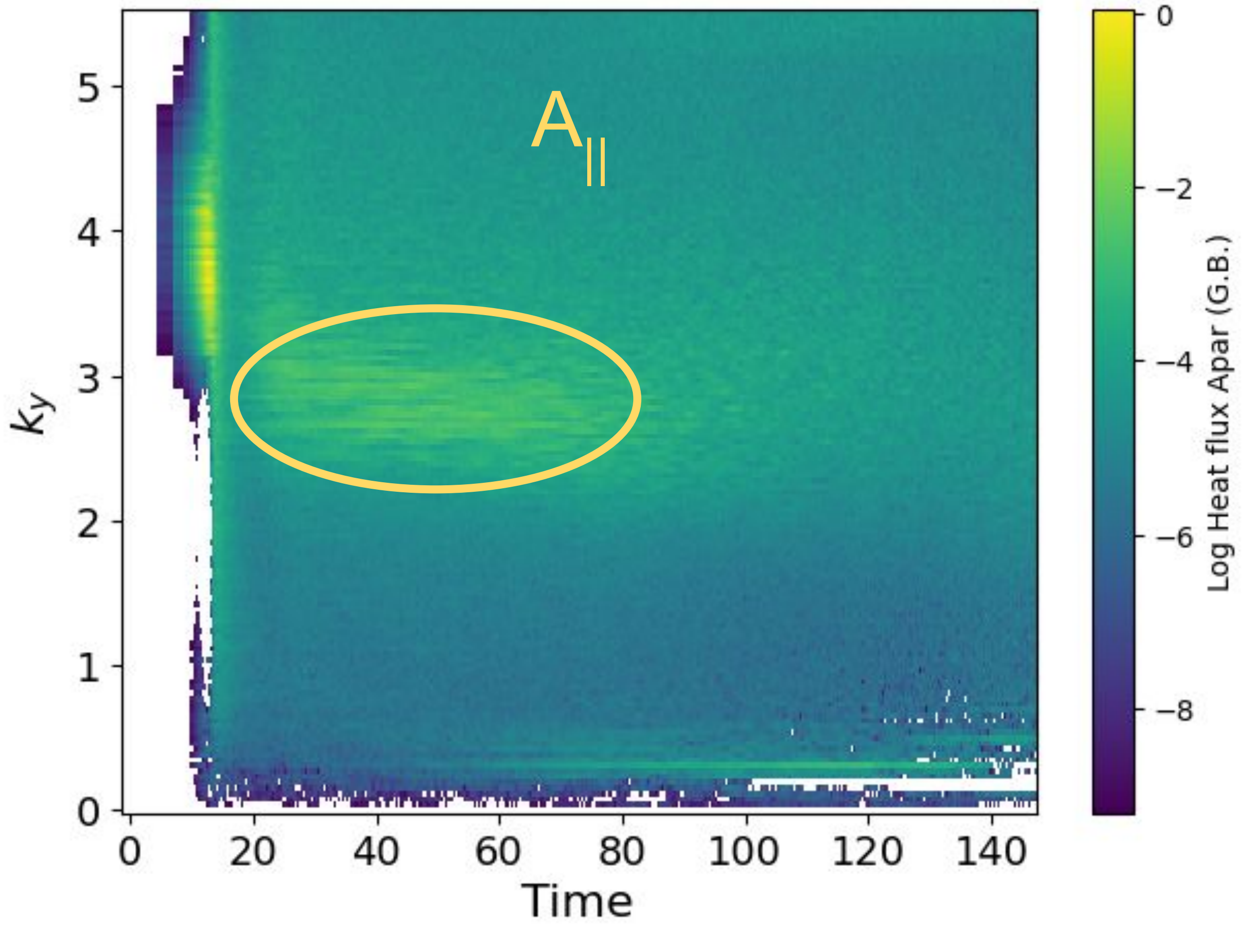


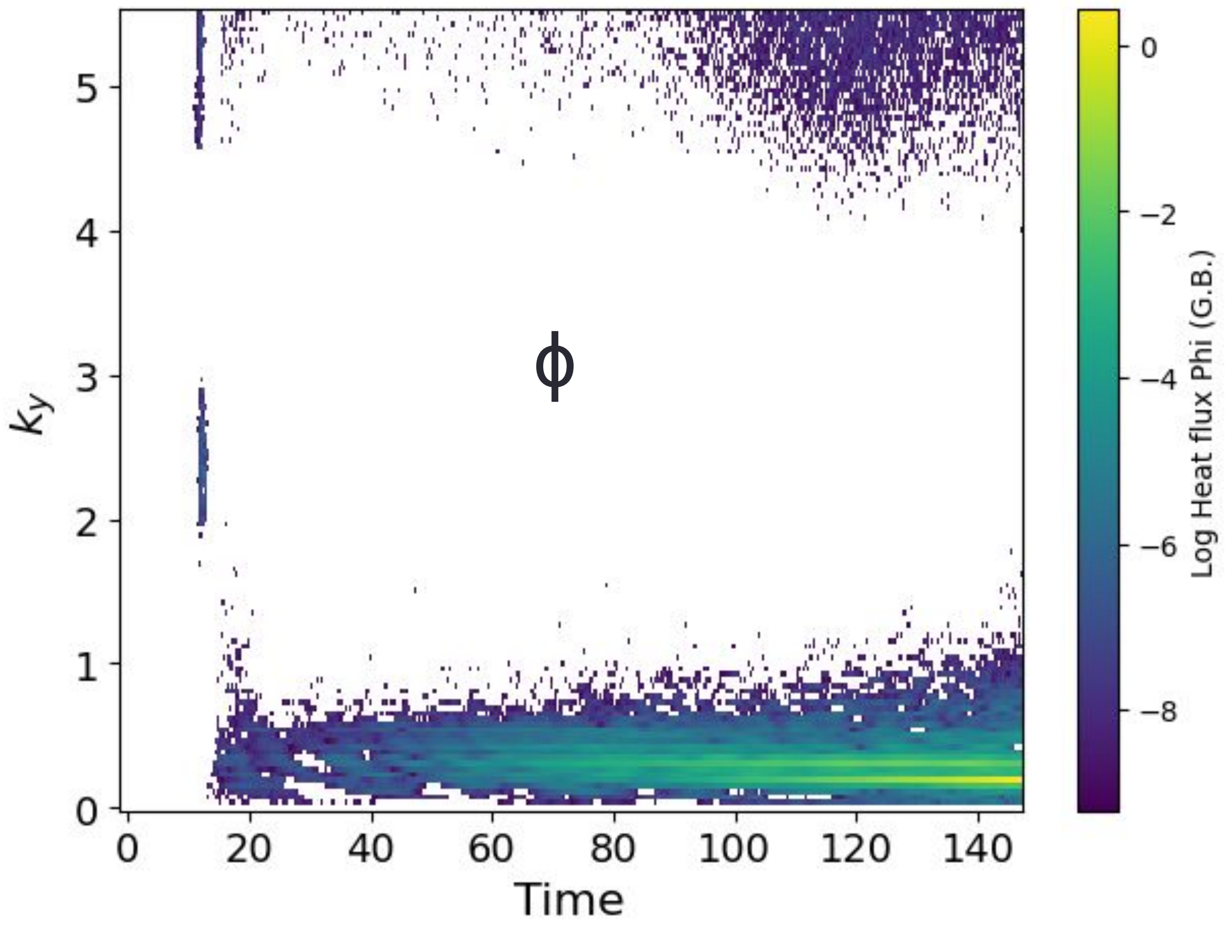
Nonlinear simulations - Dominant modes



- Simulate dominant modes case with both GS2 and CGYRO.
- Find early phase pseudo-saturation but this is lost after a short time and heat fluxes increase rapidly.
- Fairly good quantitative agreement between codes and very good qualitative agreement, including loss of saturation.
- **Suggests not purely numerical in origin**.

Nonlinear simulations - Dominant modes



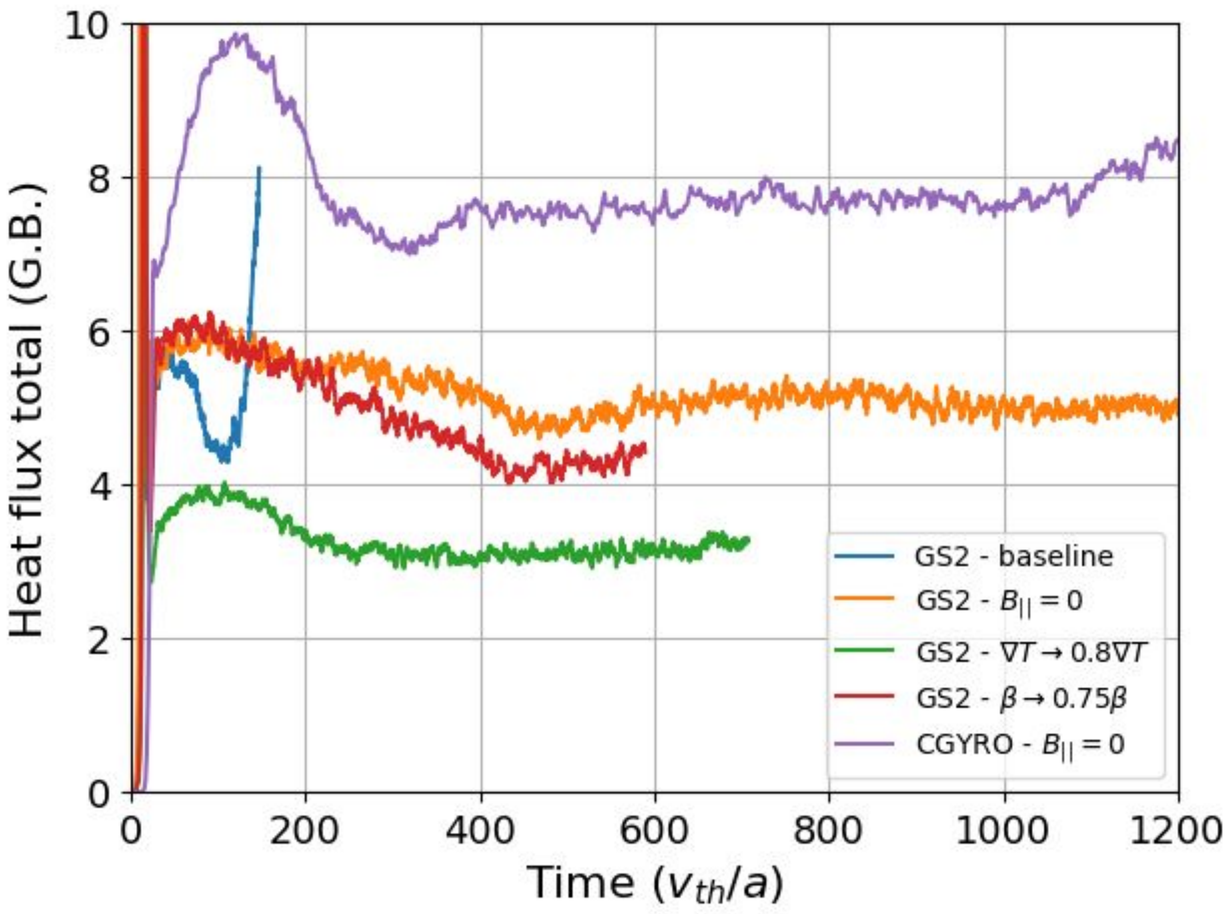


- See early growth coming from intermediate scale MTM (largest growth rate). Initially dominates.

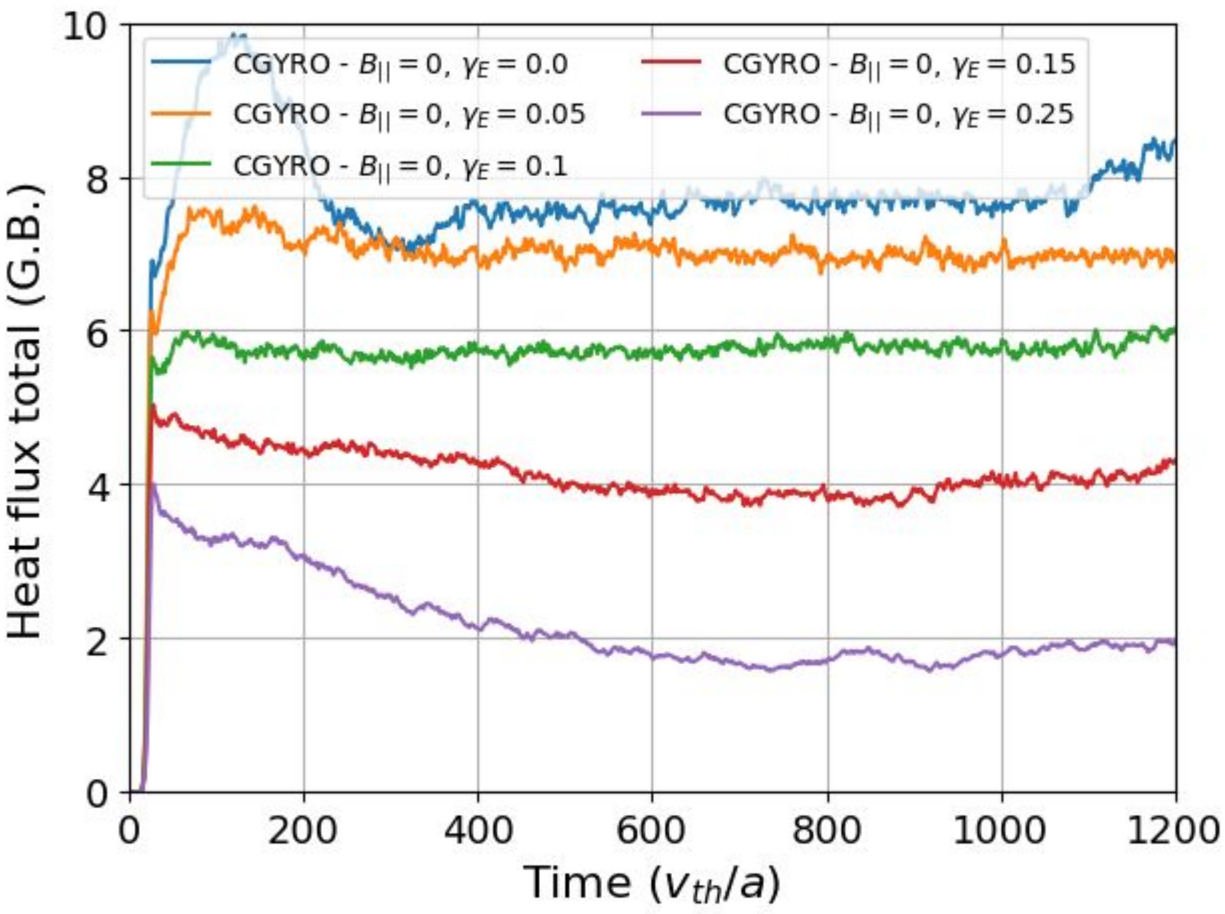
- **Ion scale modes growing up and associated with loss of saturation.**

Nonlinear simulations - Suppressing KBM

- Loss of saturation thought to be linked to KBM. Try removing this.
- Can remove $B_{||}$, reduced driving gradient or β (all β' fixed).
- Find these **all avoid loss of saturation** (or at least delay it).
- **Qualitative agreement** between codes but ~33% difference.
- Q_{GB}~ 2 MW/m^{-2}, A ~ 220 m^2.
  Q/Q_{GB} = 5
  → **Power crossing surface ~ 2.2GW, c.f. 220 MW heating**.



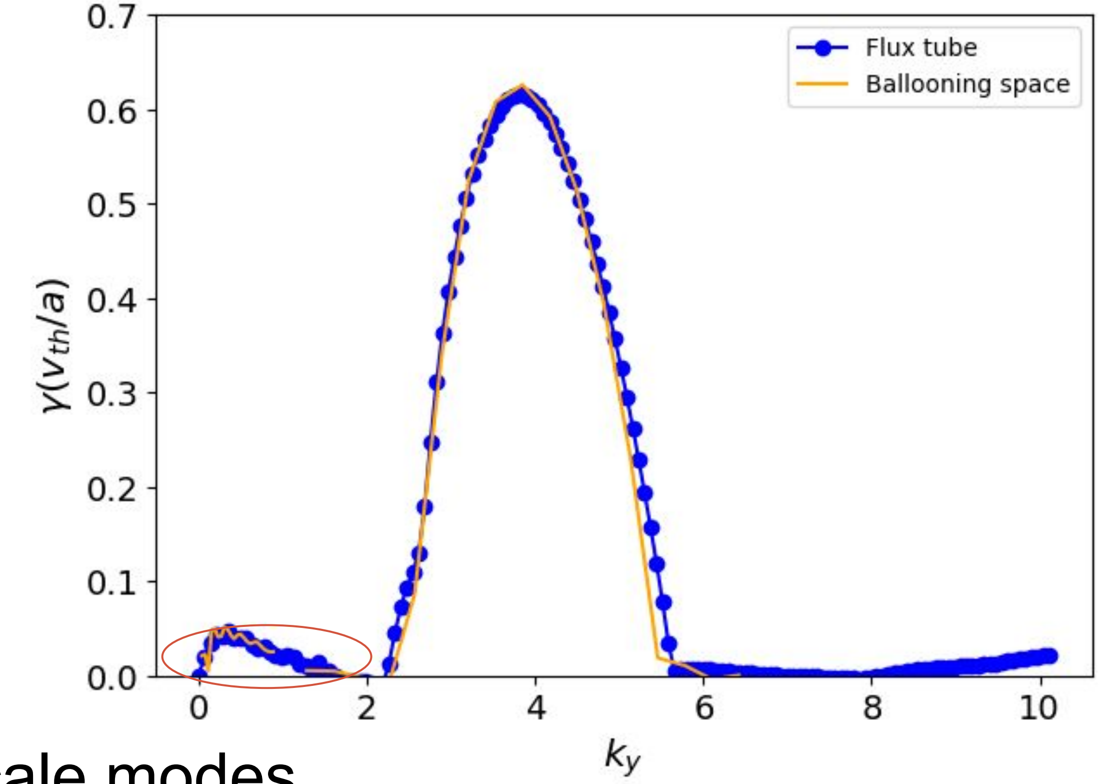
Nonlinear simulations - Impact of sheared flow

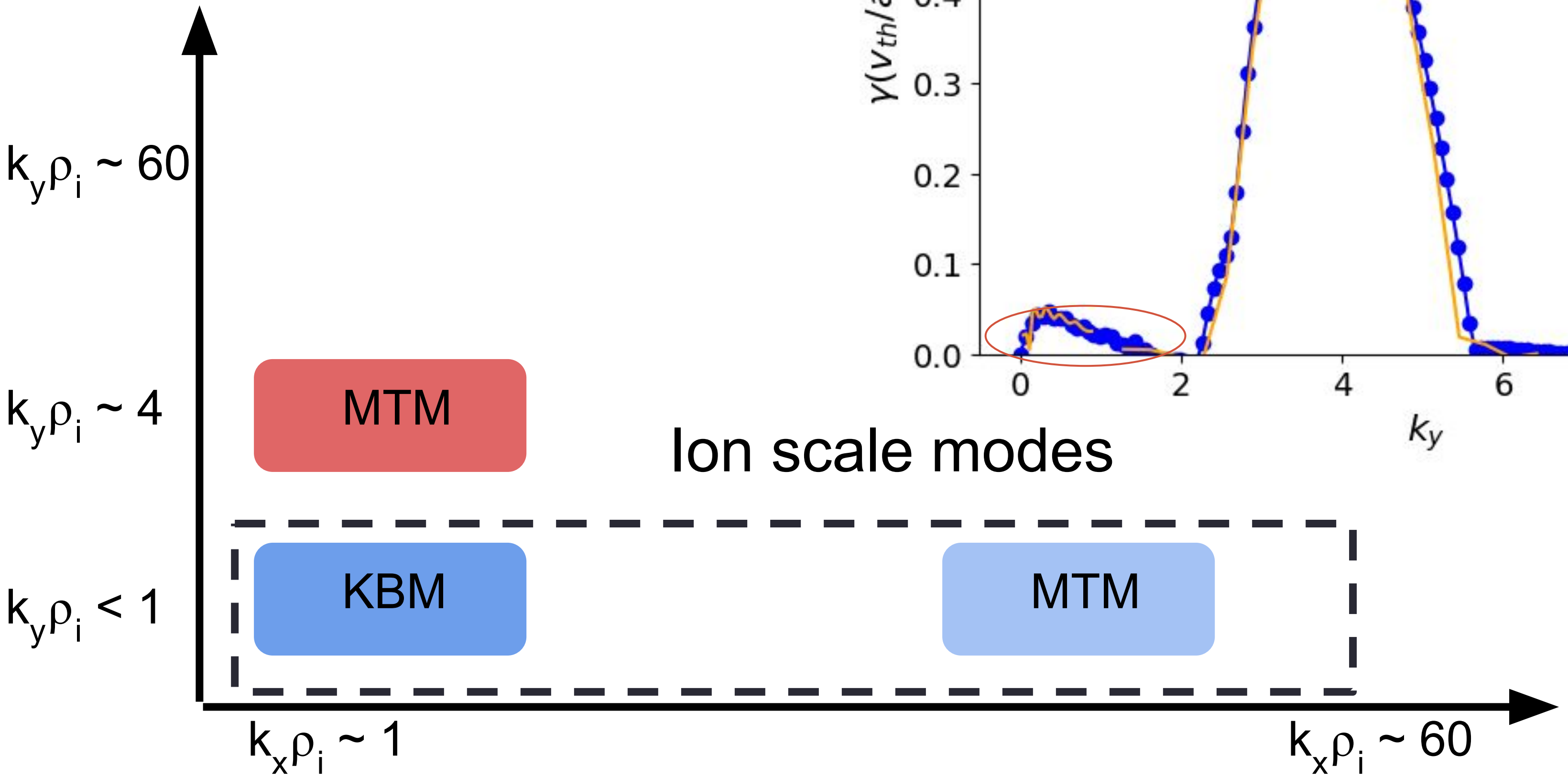


- Sheared flows expected to linearly impact **intermediate scale MTM**.
- Find **substantial reduction in Q/Q_{GB}** as shearing rate increases.
- Still ~ **4x heating power** for maximum shearing rate considered (above diamagnetic level, ~0.05 - 0.1).
- **Prediction of flow profiles in such equilibria important** to narrow down predictions.

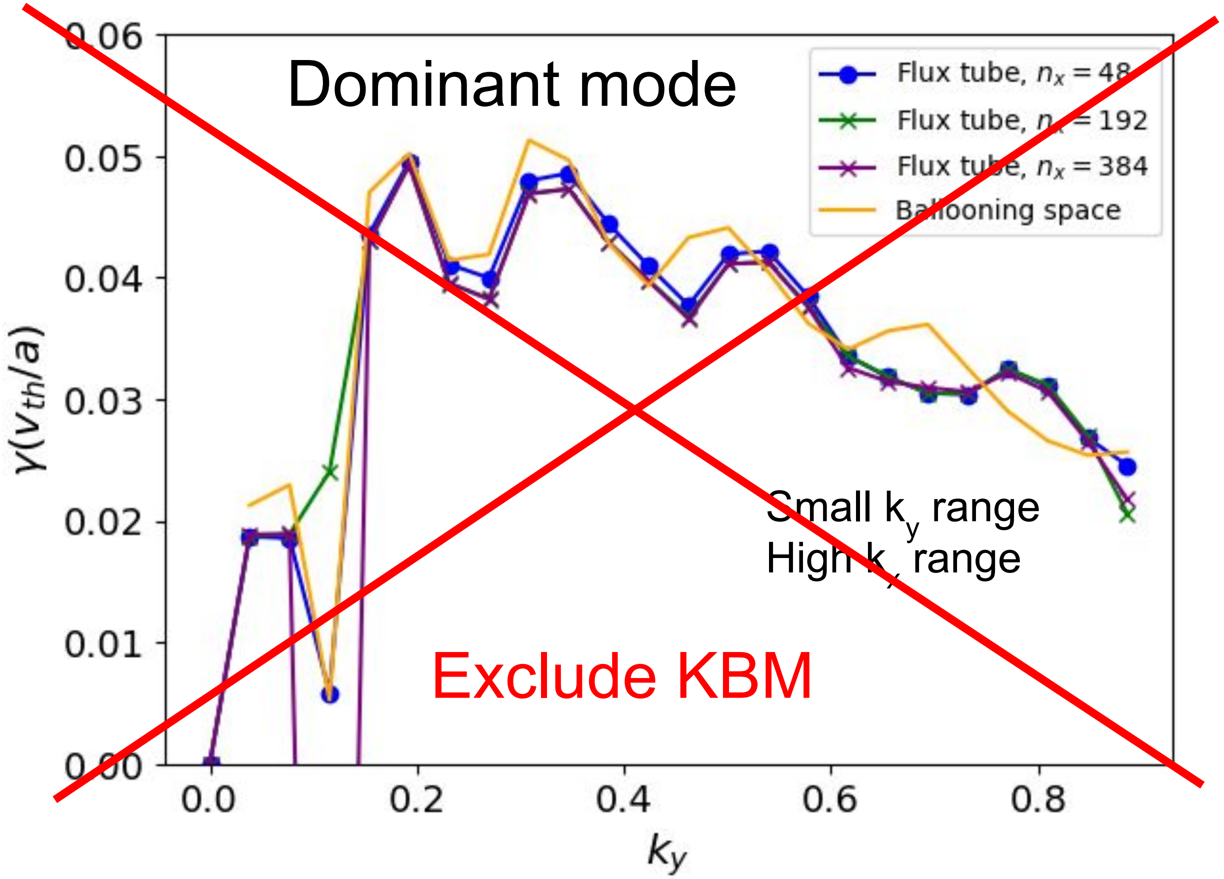
Nonlinear simulations – Flux tube setup

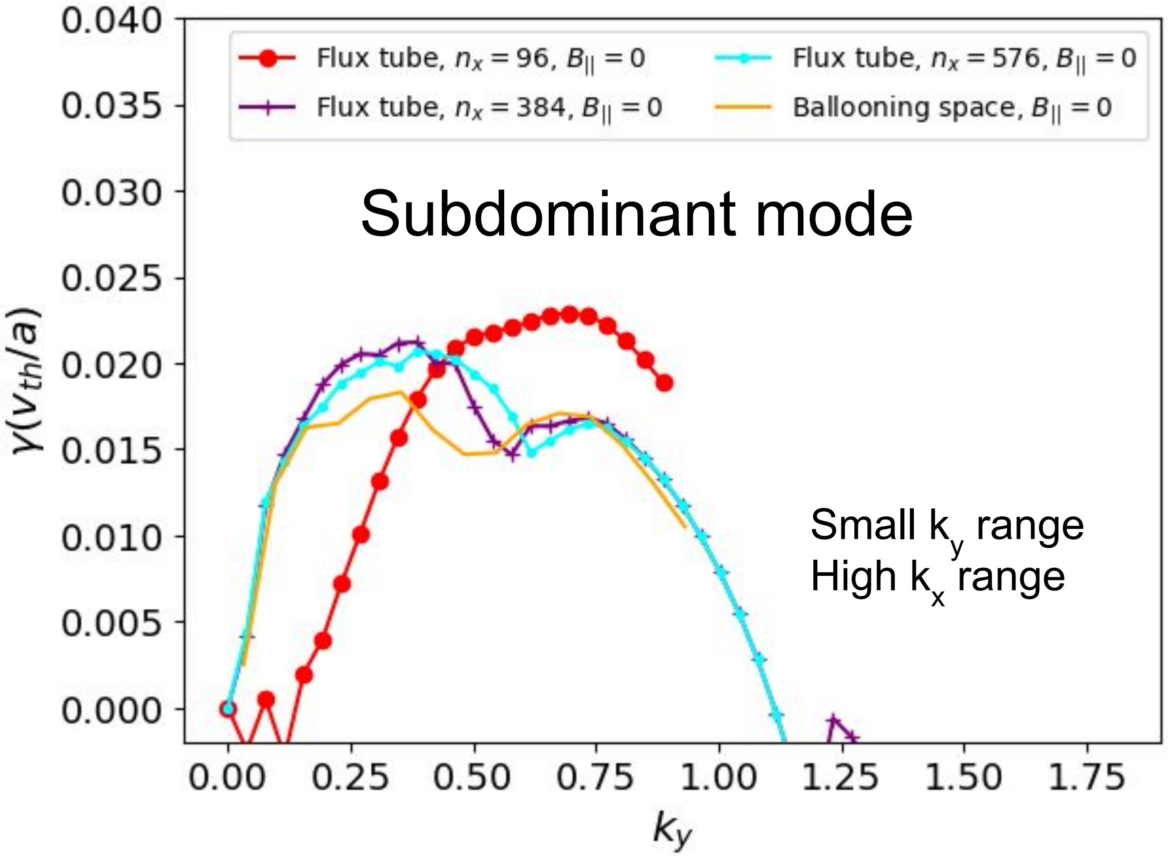
- Subdominant MTM pose extreme resolution requirements
  → Define two types of simulation.





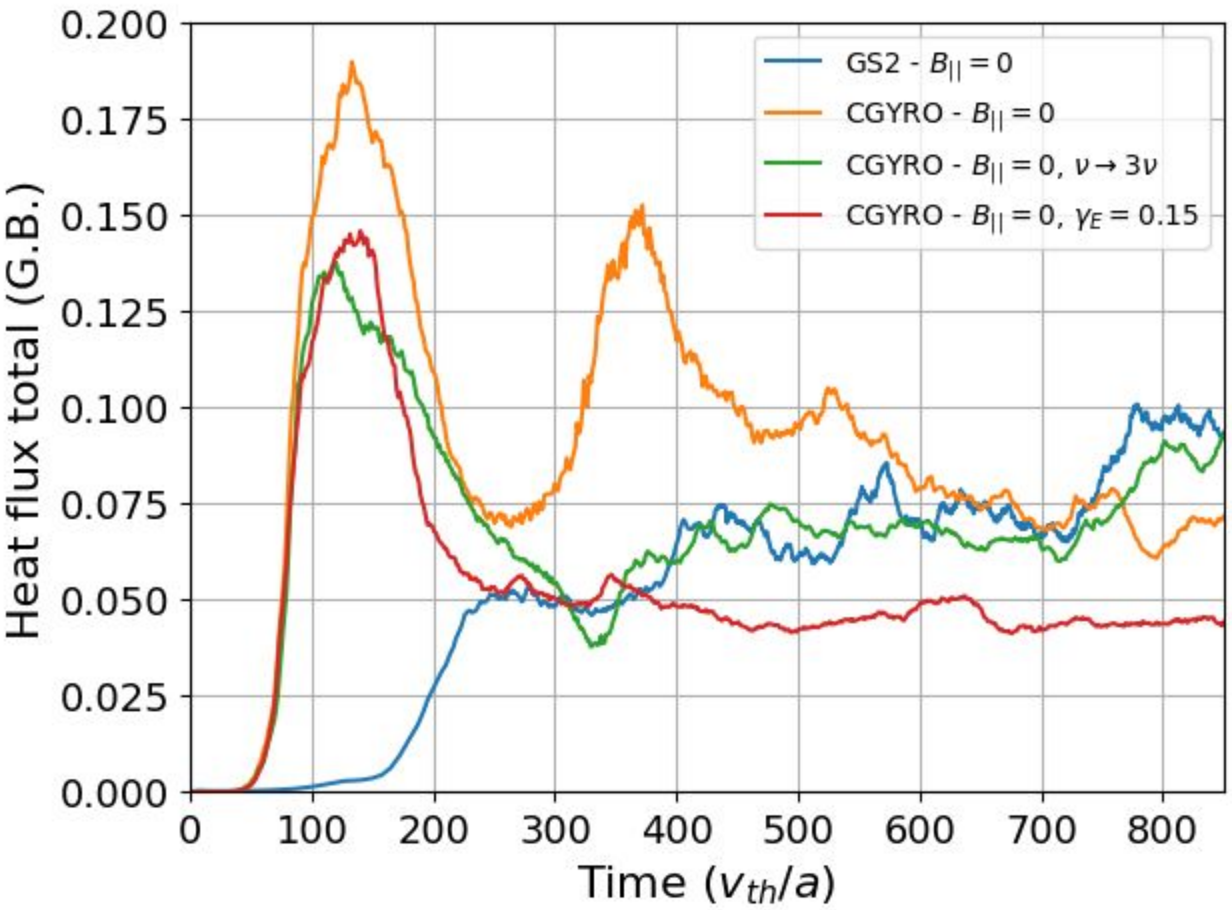
Nonlinear simulations - Flux tube setup - ion scale





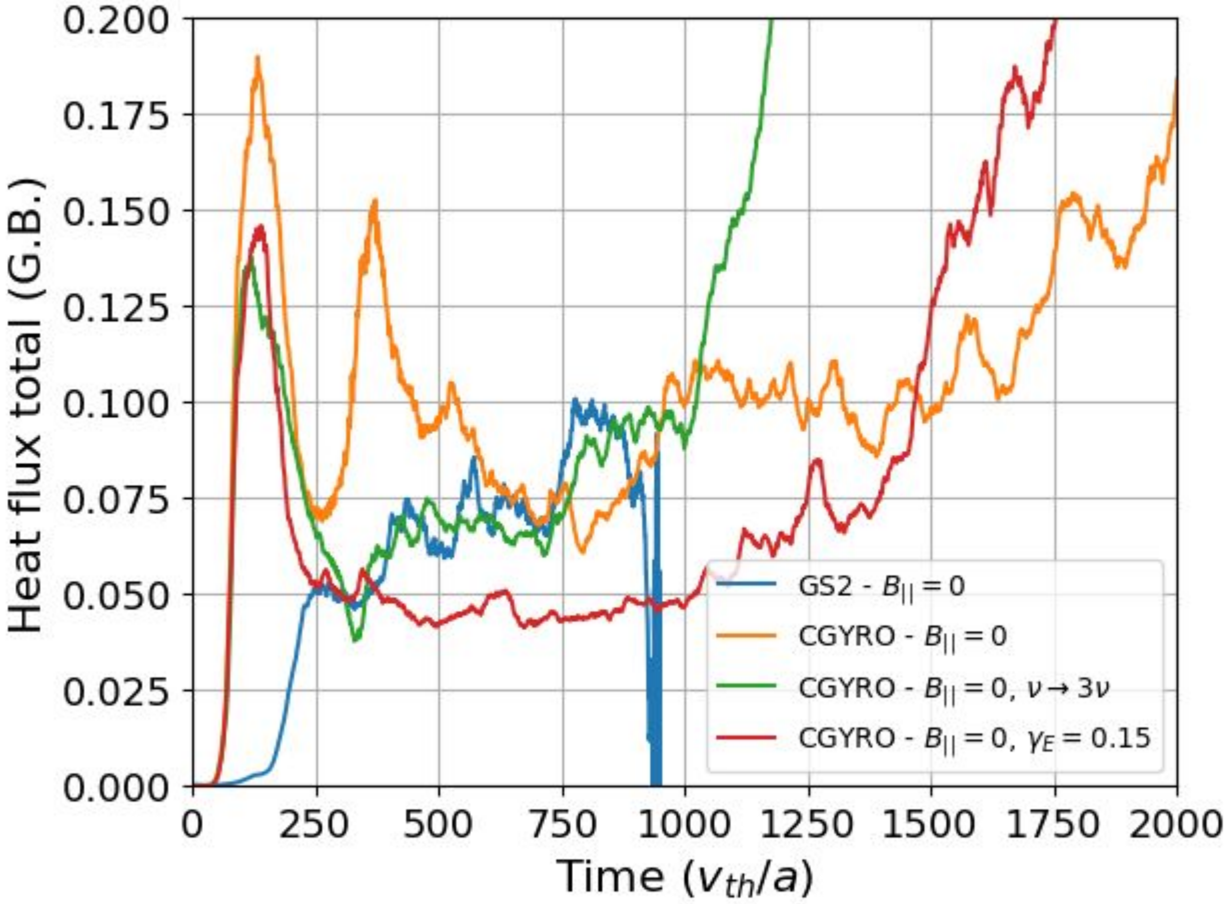
- Dominant mode easy to resolve, subdominant much more challenging! Exclude KBM here.

Nonlinear simulations - ion scale



- Focus on ion scale only. Find saturation at ~50x lower level.
- Corresponds to **~ 40 MW crossing**!
- Good agreement between codes.
- Less agreement in particle flux (but very sensitive to sheared flow).

Nonlinear simulations - ion scale



- If we run for longer **find saturation lost**.
- GS2 suffers numerical issue
- CGYRO more physical? Sees $Q/Q_{GB} > 30$
- More work required to diagnose loss of initial saturation in CGYRO. Q remains dominated by $A_{||}$ → Still MTM related?

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Summary and next steps

- High β concept ST (high q_0 TDoTP) studied with local gyrokinetics.

- Linearly find:
  → Dominated by KBM (hybrid) at ion scale k_y, collisionless MTM at intermediate scale.
  → Subdominant collisional MTM with ion scale k_y but electron scale k_x.
  → No purely electron scale instability.

- Nonlinear simulations resolving only dominant modes:
  → Pseudo-saturates at early time, dominated by intermediate MTM.
  → Saturation quickly lost due to KBM.
  → If KBM removed saturation persists for a long time, but ~10x heating power.
  → Saturation sensitive to sheared flows - role for integrated modelling, momentum transport, higher order GK (see H Wilson poster) to make predictions of shearing rate.

- Nonlinear simulations resolving only ion scale MTM:
  → Saturates with power less than/equivalent to heating power but saturation lost at late t.

Summary and next steps

- Attempted to optimise for IBM/KBM stability in equilibrium design
  → KBM less unstable, but still present (hybridises) and drives large heat flux.
  → Can we further optimise KBM and do we have all required physics (global)?

- Intermediate scale MTM drives significant flux. How do we optimise against this?
  → Peaking density gradient should help [B.S. Patel et al Nucl. Fusion 62 016009 (2022)] but what about wider impact?

- Looks like high β ST reactor designs *could* have consistent transport at high gradient. Even if these targets points are consistent can we get there? Integration [F. Casson talk]

- Power plant and scenario development need reliable reduced models for rapid design iteration but new parameter regimes naturally poses challenges for existing models
  → Pursue first principles approaches - guide development of appropriate reduced models.

- Much more to do!

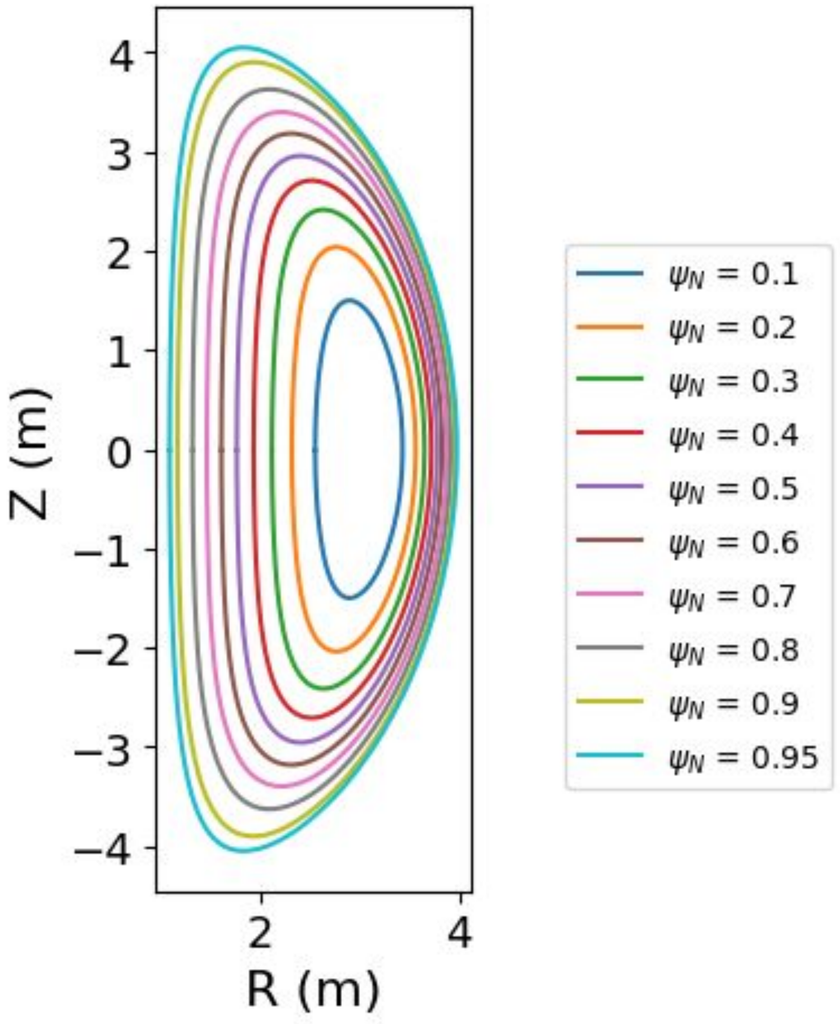
Thank you for your attention

Backup slides

Code comparisons and pyrokinetics

- Predictions from turbulence simulations must be reliable
- It helps to identify numerical issues (is this a physical or numerical instability?)
- Different numerical methods: strengths and bottlenecks
- Codes considered here: CGYRO and GS2 (local linear and nonlinear simulations)
- Use of *pyrokinetics* python library to facilitate input file conversion between codes (https://github.com/pyro-kinetics/pyrokinetics)

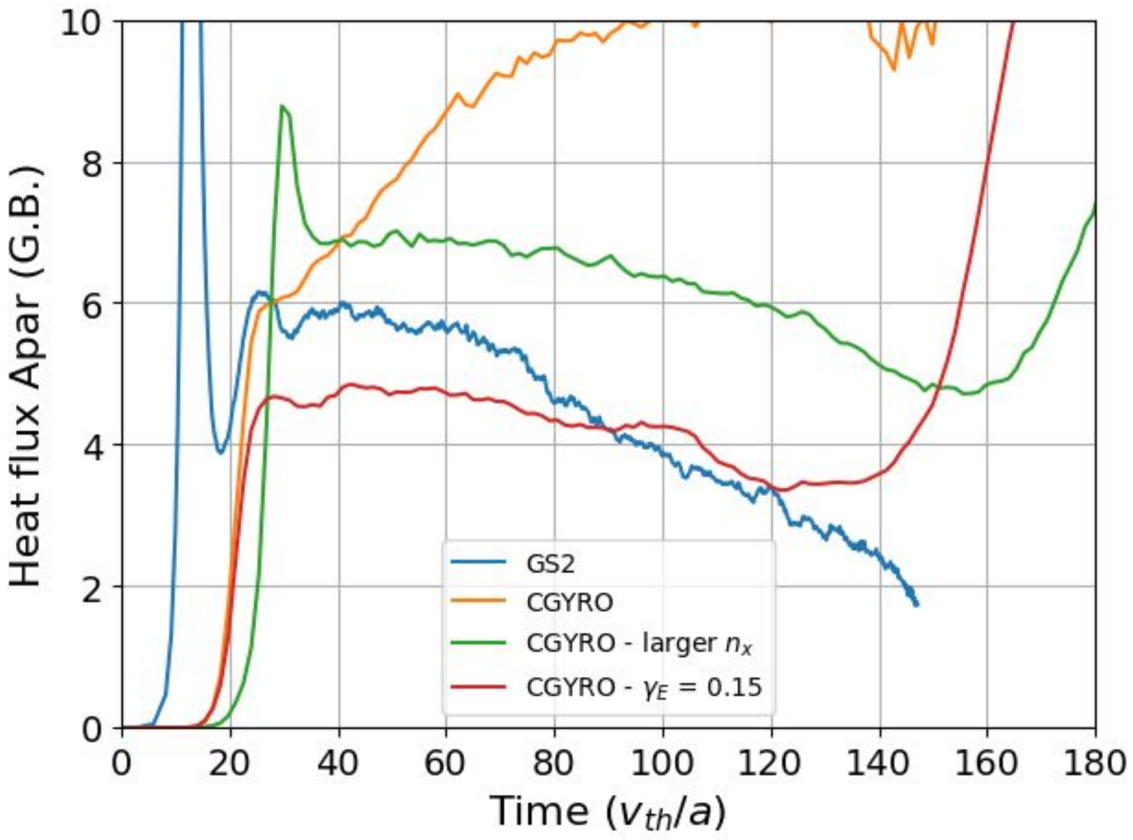
The high q_0 TDoTP baseline equilibrium

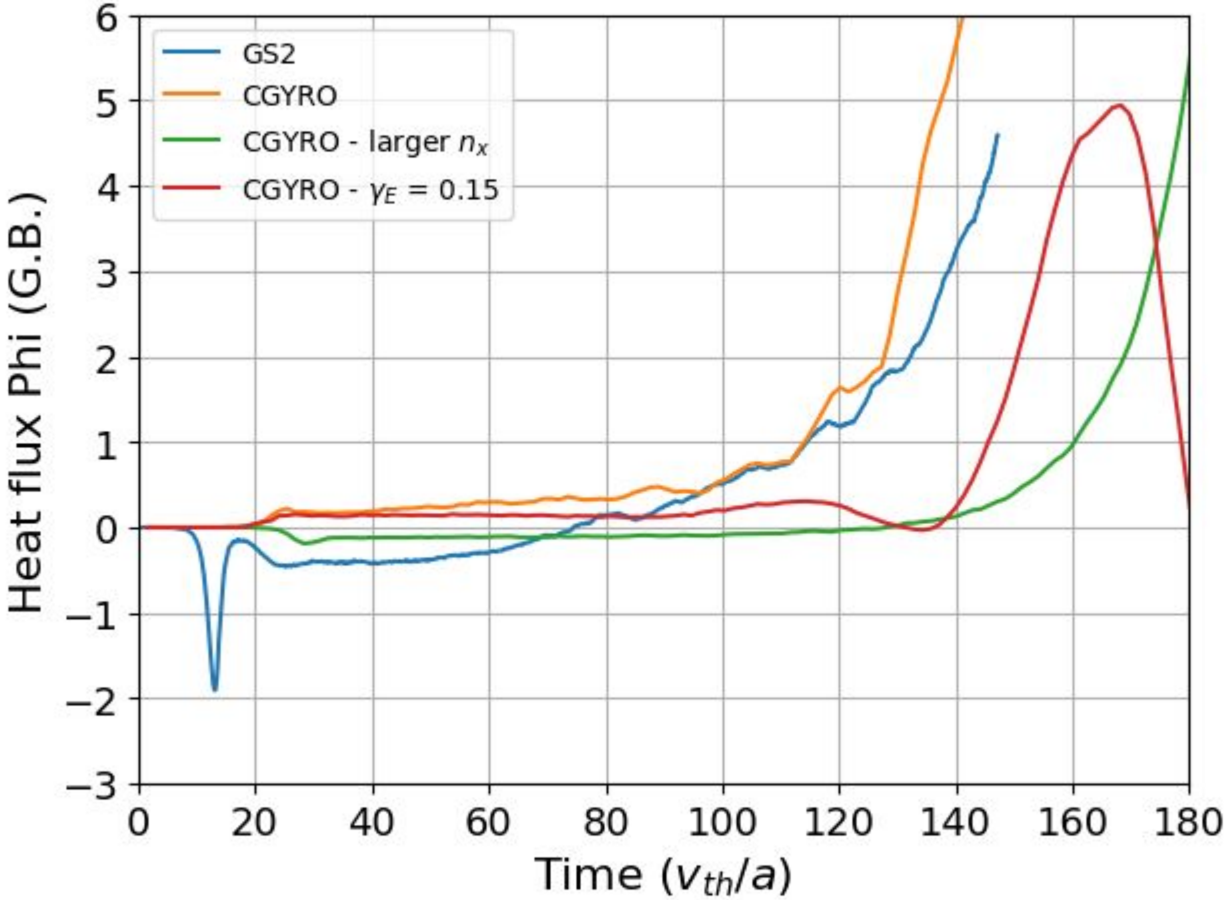


- High q_0=2.71 TDoTP baseline equilibrium (STEP SPR 46 - from F Casson talk)
  → ideal MHD stable
  → β=18.6%
  → β_N=5.47 (4.1)
  → κ_{LCFS}=2.8
  → δ_{LCFS}=0.3
  → P_{fus}= 808 MW (1.77 GW)
  → P_{aux}= 60 MW (154 MW)
  → **P_{heat}= 220 MW (508 MW)**
  → J = 16.5 MA (22 MA)
  → J_{BS}=11 MA (67%) (78%)

[H. Wilson et al, Zenodo 10.5281/zenodo.4641183]

Nonlinear simulations - Dominant modes

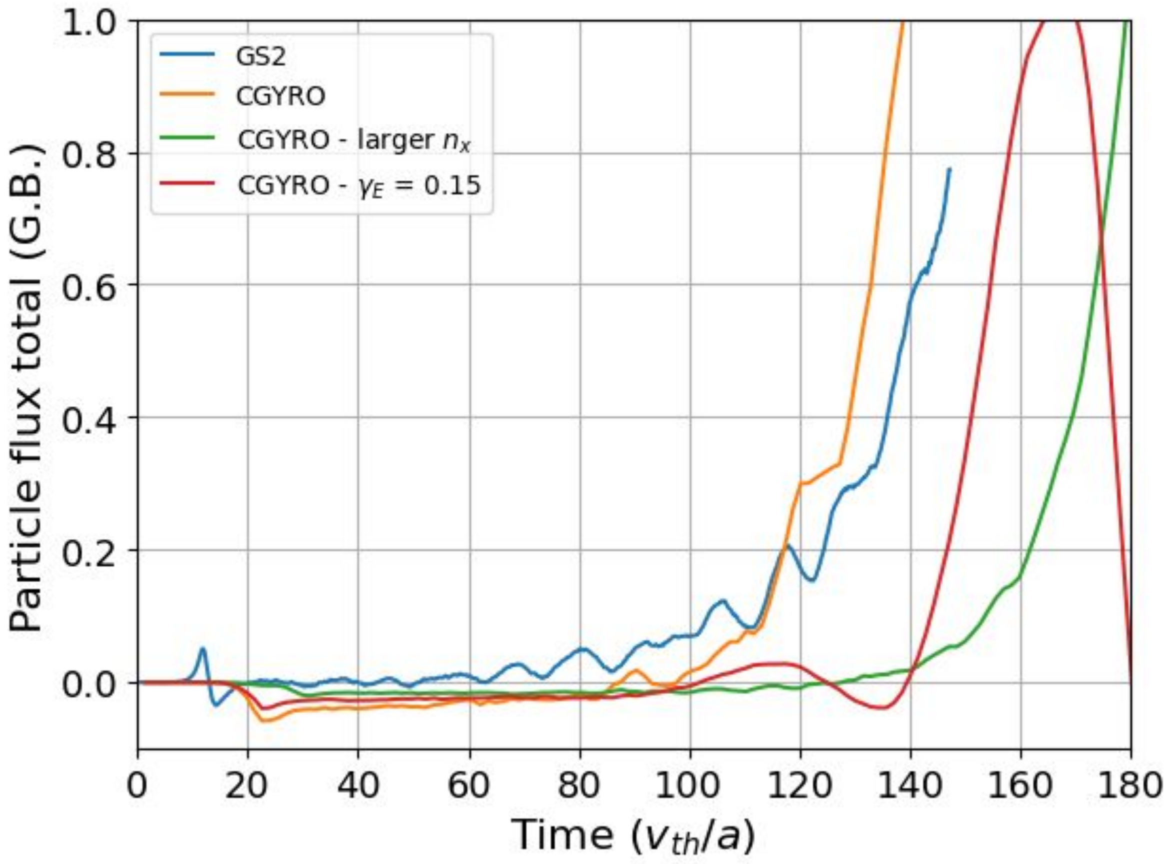


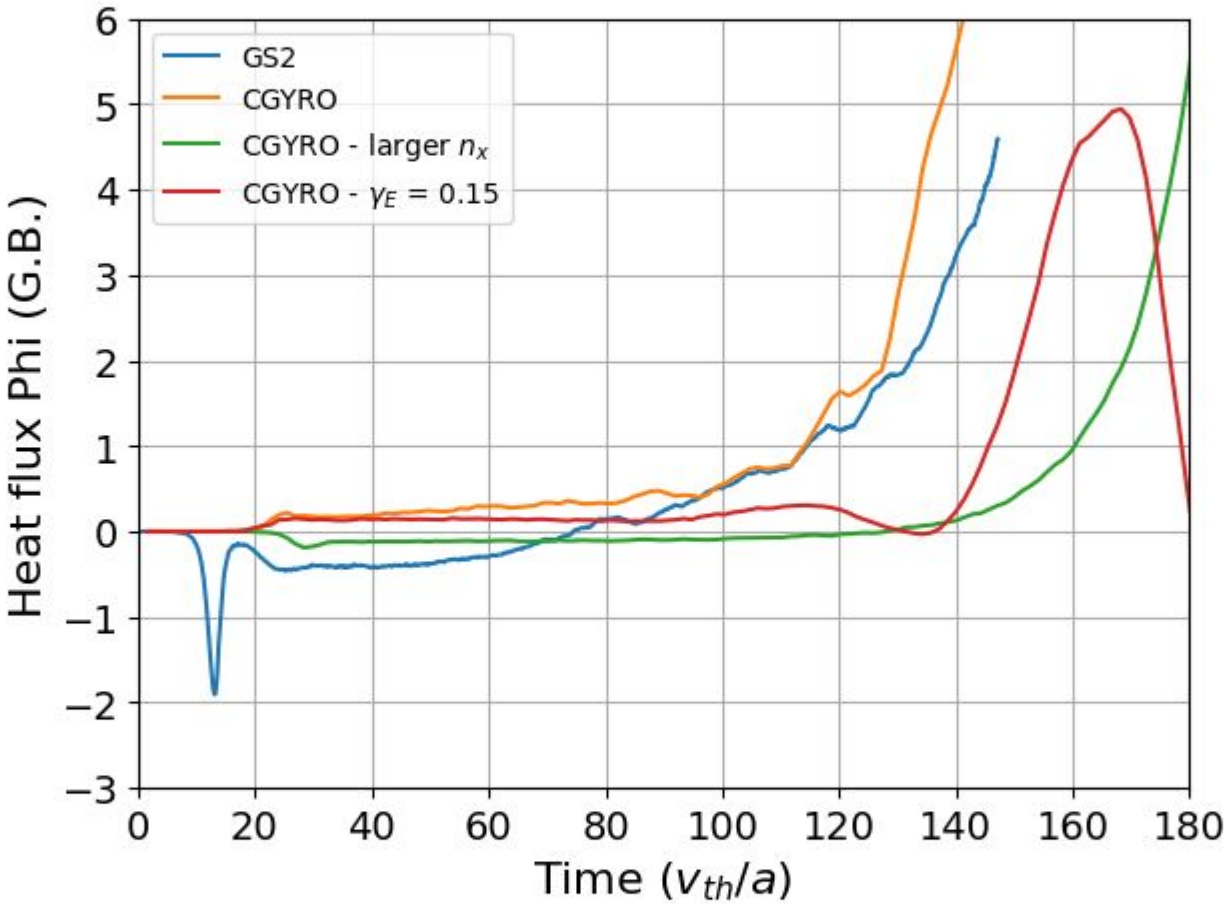


- Dominated by $A_{||}$ channel → MTM?
- Breakdown of transport channels perhaps in less good agreement.

- See **loss of saturation** coincident with **increase in electrostatic** contribution.

Nonlinear simulations - Dominant modes





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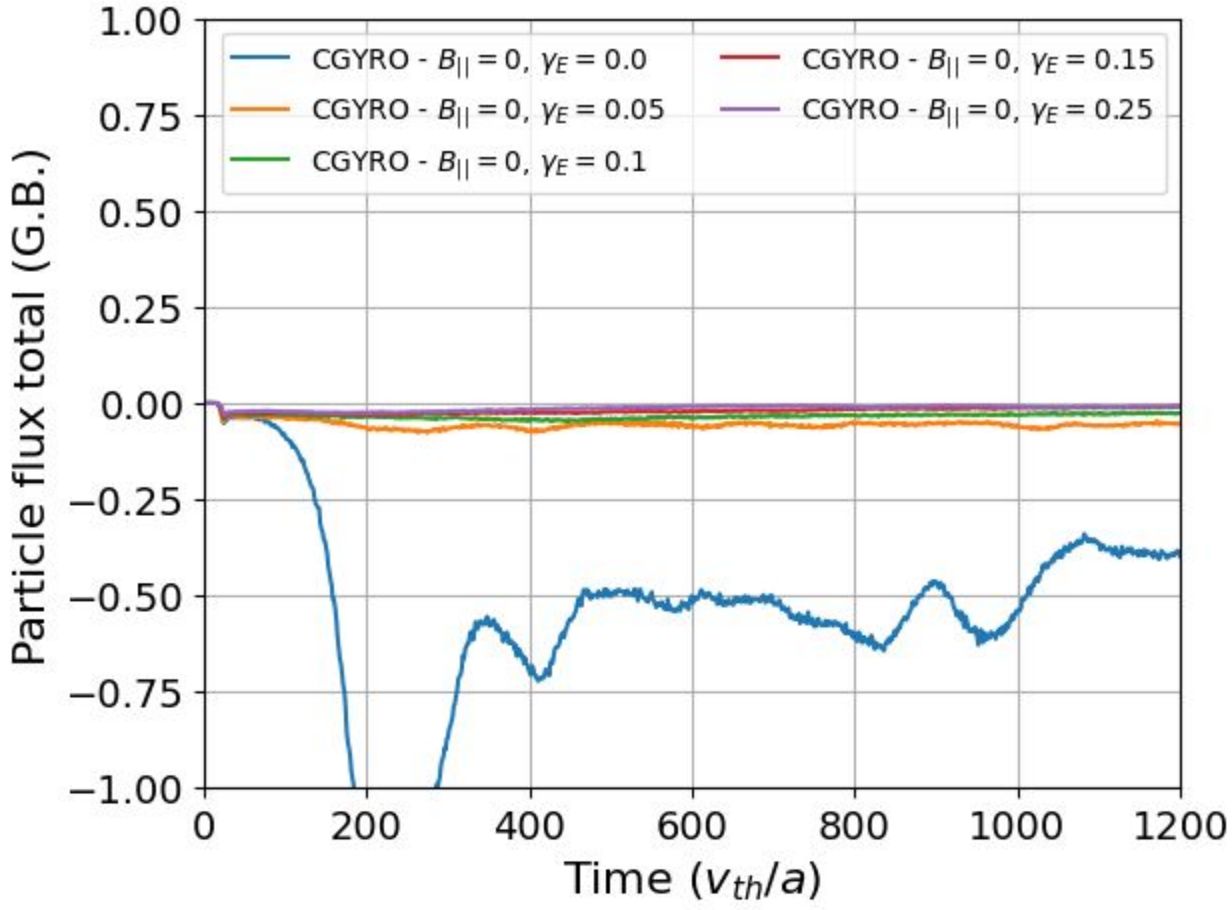
- Breakdown of transport channels perhaps in less good agreement.

- See **loss of saturation** coincident with **increase in electrostatic** contribution.
- Particle flux also increases → KBM?

Nonlinear simulations - Sheared flow



- Sheared flows expected to linearly impact **intermediate scale MTM**.
- Find substantial reduction in Q/Q_{GB} as shearing rate increases.
- Still ~4x heating power for maximum shearing rate considered.
- **Prediction of flow profiles in such equilibria important** to narrow down predictions.
- Sheared flow strongly reduces particle transport observed.