To validate TGLF against GYRO, need to ensure identical model assumptions and inputs

- For comprehensive gyrokinetic analysis, we usually run GYRO with:
  - Profiles from TRANSP Plasma State files, three species (D,C,e), electron collisions (pitch angle scattering), general numerical equilibrium (from EFIT), fully EM ($A_{||}$, $B_{||}$), no MHD approximation (finite ∇P_{eq}, $\nabla B/B \neq \kappa$)
  - Typically ignore toroidal flow for linear runs ($Ma=\gamma_p=\gamma_E=0$) unless investigating quasi-linear momentum transport
- The TGLF default is slightly different:
  - Miller geometry, EM with $A_{||}$ only, MHD approximation (finite ∇P_{eq} but $\nabla B/B=\kappa$)

- To ensure identical model assumptions we have used TGLF default model for GYRO as well
  - Also need to ensure same ∇P_{eq} is used in both (typically sum of thermal species only, but can also include contribution from fast ion/beam species)

- Have double checked out.gyro.run and out.tglf.localdump to verify identical input parameters

NSTX test cases

- In NSTX H-mode discharges, any and all of the following micro-instabilities can be unstable at different regions, simultaneously: ITG, TEM, ETG, KBM, microtearing
  $\rightarrow$ challenges any reduced model

- To start, focus on cases expected to be dominated mostly by one instability
  [Ref. 1] L-mode discharge (ITG) – NSTX 141761
  I_p=0.9 MA, B_T=0.55 T, P_{NBI}=2 MW
  [Ref. 2] “Low” beta H-mode discharge (ETG) – NSTX 141031/141040
  I_p=, B_T= , P_{NBI}=3 MW
  [Ref. 3] “High” beta H-mode discharge (microtearing) – NSTX 120968/138564
  I_p=0.7 MA, B_T=0.35 T , P_{NBI}=4 MW
  [Ref. 4] NSTX-U scenario – 142301 (?)
  I_p=, B_T= , P_{NBI}=6 MW

[1] Y. Ren et al., IAEA (2012), Nucl. Fusion (2013)
[2] Y. Ren et al., Phys. Plasmas (2012)
[3] W. Guttenfelder et al., Phys. Rev. Lett. (2011)
[4] S.P. Gerhardt et al., Nucl. Fusion (2012)

NSTX L-mode at relatively low beta

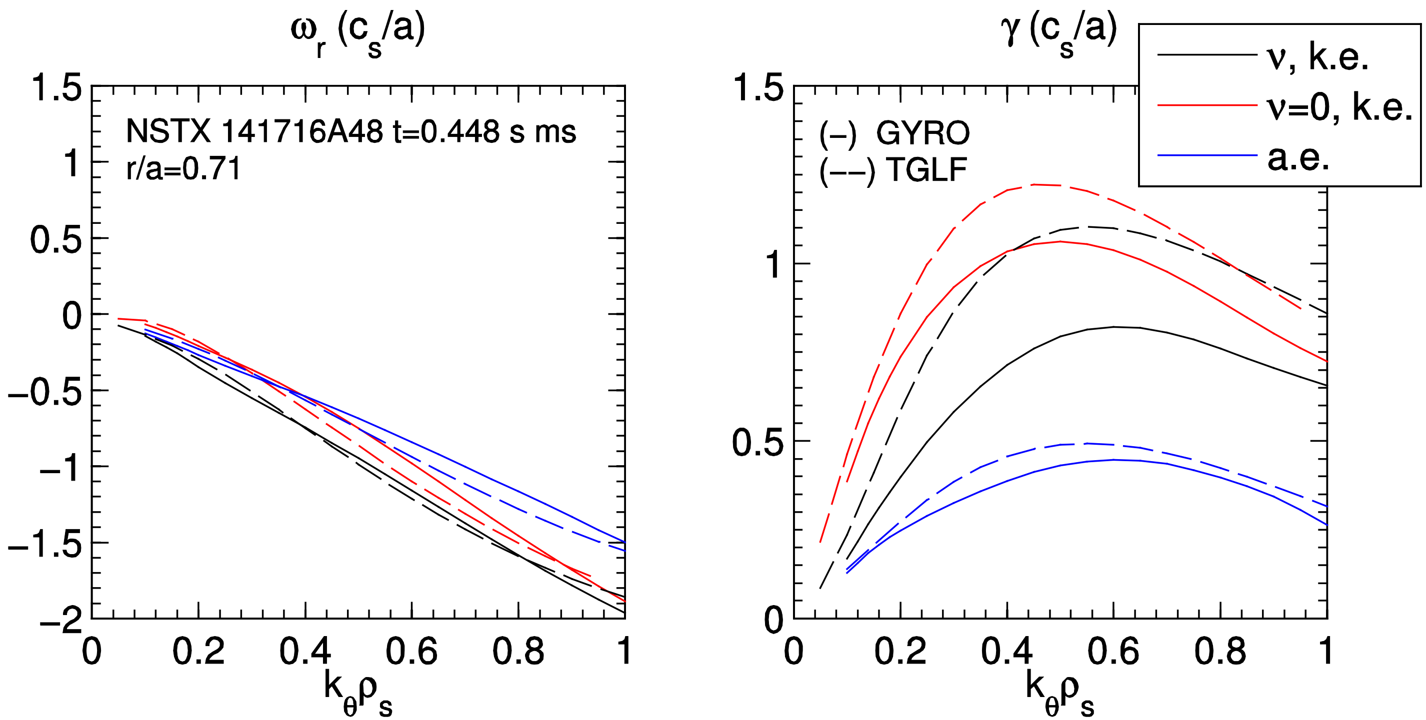
- Shaping not very extreme (local surface shape κ=1.5, δ=0.1)
- Biggest difference to DIII-D is aspect ratio (R/a<1.5) and higher $\nu_{ei} \cdot a/c_s$~0.4-2.9

r/a	q	s	T_e/T_i	a/L_{Ti}	a/L_{Te}	a/L_{ne}	Z_{eff}	ν_{ei}	β_e (%)	γ_E	γ_p	Ma	α_{MHD}
0.6	1.39	0.89	0.89	4.68	5.17	3.47	1.19	**0.39**	**0.586**	0.77	2.57	0.47	0.46
0.66	1.55	1.45	0.90	6.82	5.98	3.03	1.19	**0.61**	**0.312**	0.59	2.00	0.40	0.31
0.71	1.77	2.30	0.94	6.83	6.35	1.60	1.15	**0.99**	**0.184**	0.35	1.22	0.37	0.20
0.76	2.15	3.49	0.95	7.00	6.94	1.63	1.15	**1.75**	**0.104**	0.24	0.95	0.38	0.16
0.8	2.64	4.65	0.96	8.46	7.94	2.55	1.15	**2.86**	**0.060**	0.25	1.16	0.39	0.15

r/a	**R/a**	Z/a	κ	δ	ζ	dR/dr	dZ/dr	s_κ	s_δ	s_ζ
0.6	**1.449**	0.008	1.542	0.090	-0.013	-0.267	-0.001	-0.023	0.036	-0.027
0.66	**1.432**	0.008	1.540	0.094	-0.015	-0.286	-0.001	0.002	0.049	-0.029
0.71	**1.417**	0.008	1.542	0.099	-0.017	-0.312	-0.002	0.029	0.078	-0.025
0.76	**1.401**	0.008	1.547	0.106	-0.019	-0.351	-0.002	0.073	0.140	-0.017
0.8	**1.386**	0.008	1.555	0.115	-0.019	-0.392	-0.003	0.129	0.229	-0.002

Using identical models with collisions (ν_{ei}=0.99 c_s/a) TGLF predicts growth rates ~35% larger than GYRO

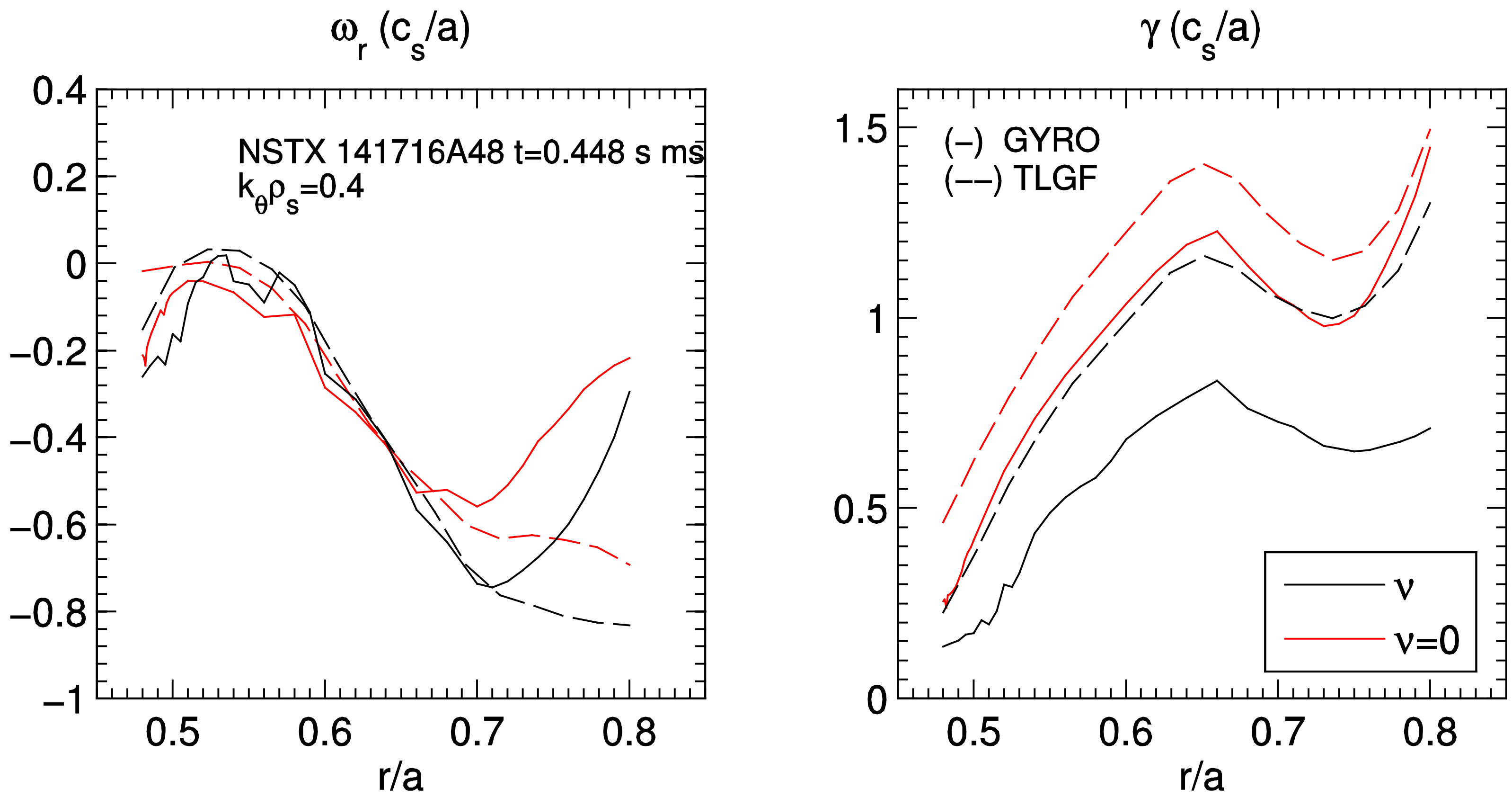
- Miller, ES (EM effects negligible in this case), MHD approx. ($\nabla B/B=\kappa$)
- Real frequencies very close
- Discrepancy is reduced to ~15% in the collisionless limit, or with adiabatic electrons



- Using GYRO eigenvalue solver [Belli]
- Have verified numerical convergence for GYRO with energy grid (8→12), radial grid (4→8), parallel grid (14→22), radial basis function order (3→5)

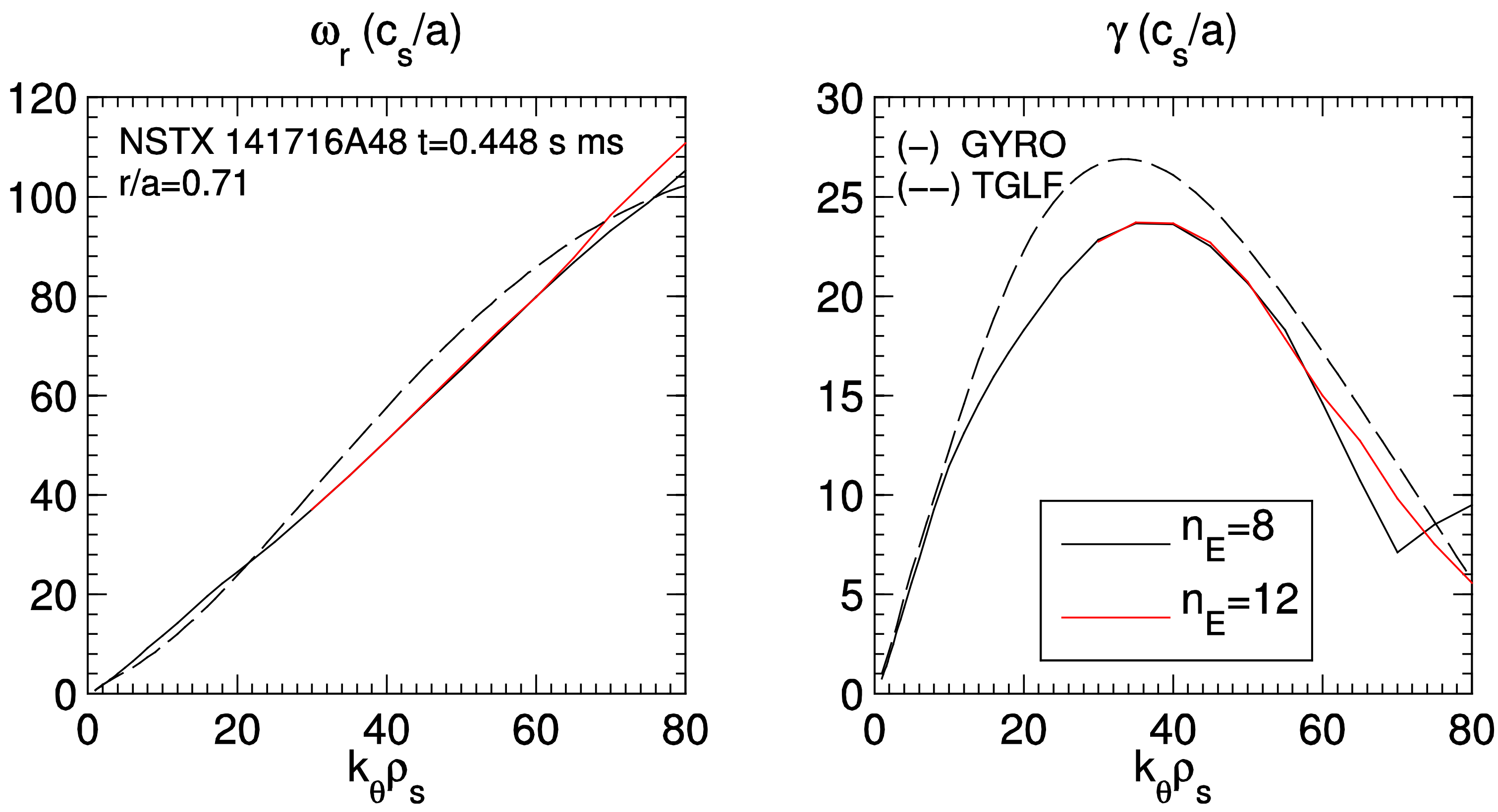
Similar agreement/discrepancy found across r/a=0.5-0.8

- Testing both with and without collisions ($k_\theta \rho_s$=0.4)



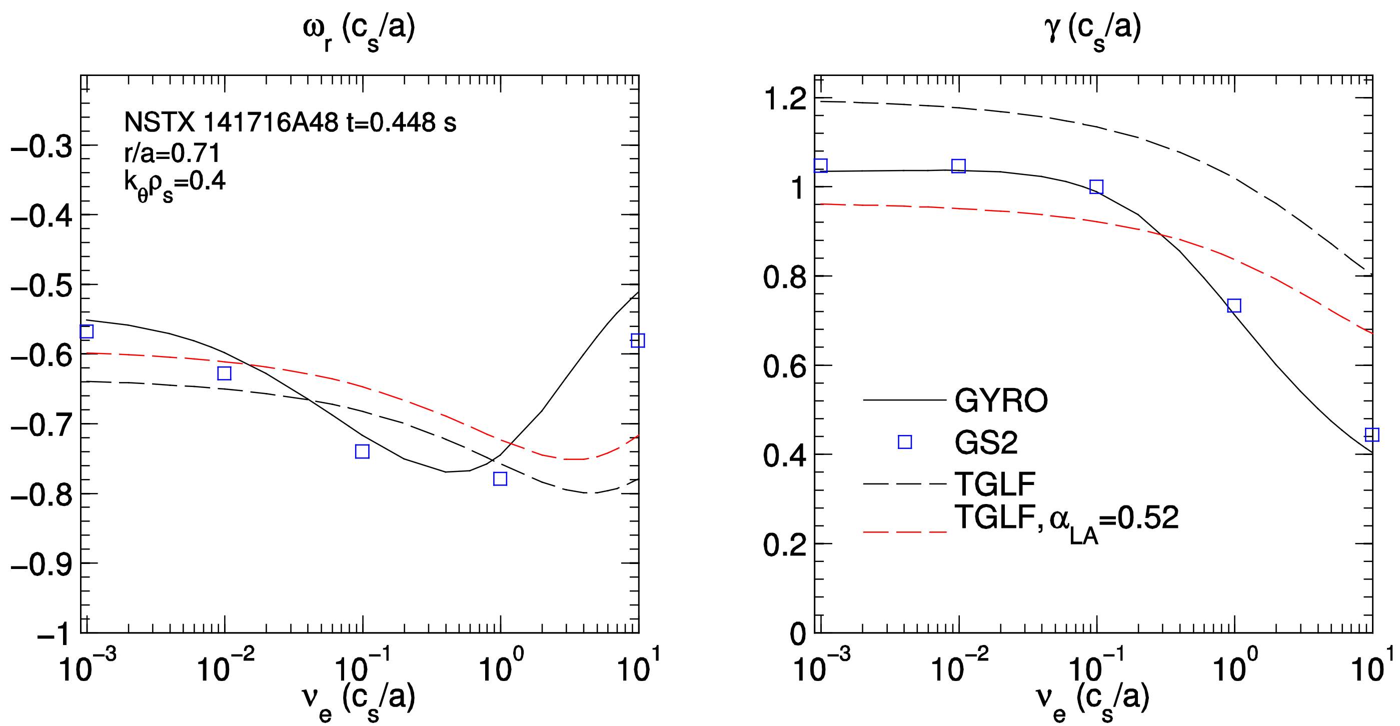
Comparable agreement for ETG growth rates

- This is collisionless, collisions make little difference
- High $k_\theta\rho_s$ GYRO simulations require more energy grid points (8→12)



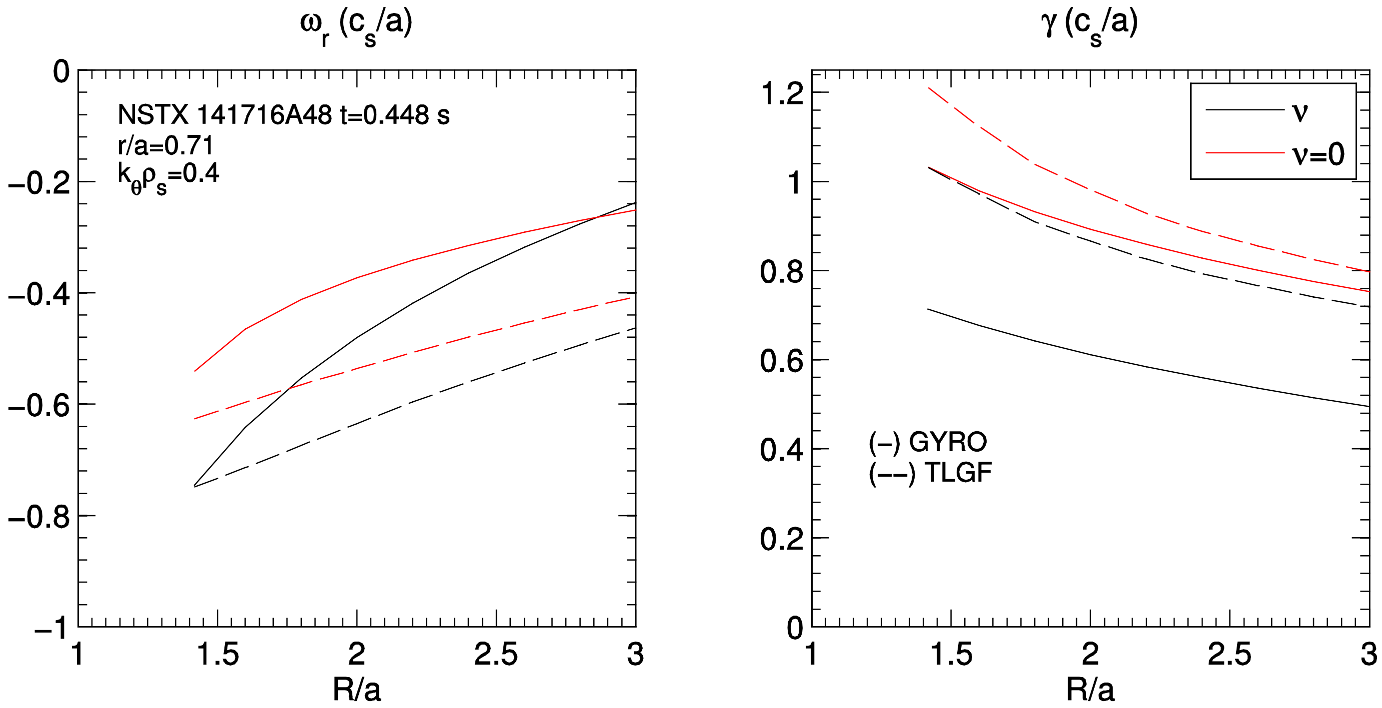
Testing sensitivity to collisionality

- GS2 agrees pretty well with GYRO (GS2 not using $\nabla B/B=\kappa$, but ~negligible effect here)
- Reducing THETA_TRAPPED (α_{LA} in the paper) from 0.7→0.52 improves agreement
- TGLF predicts a weaker tearing parity (ES) mode present over entire range



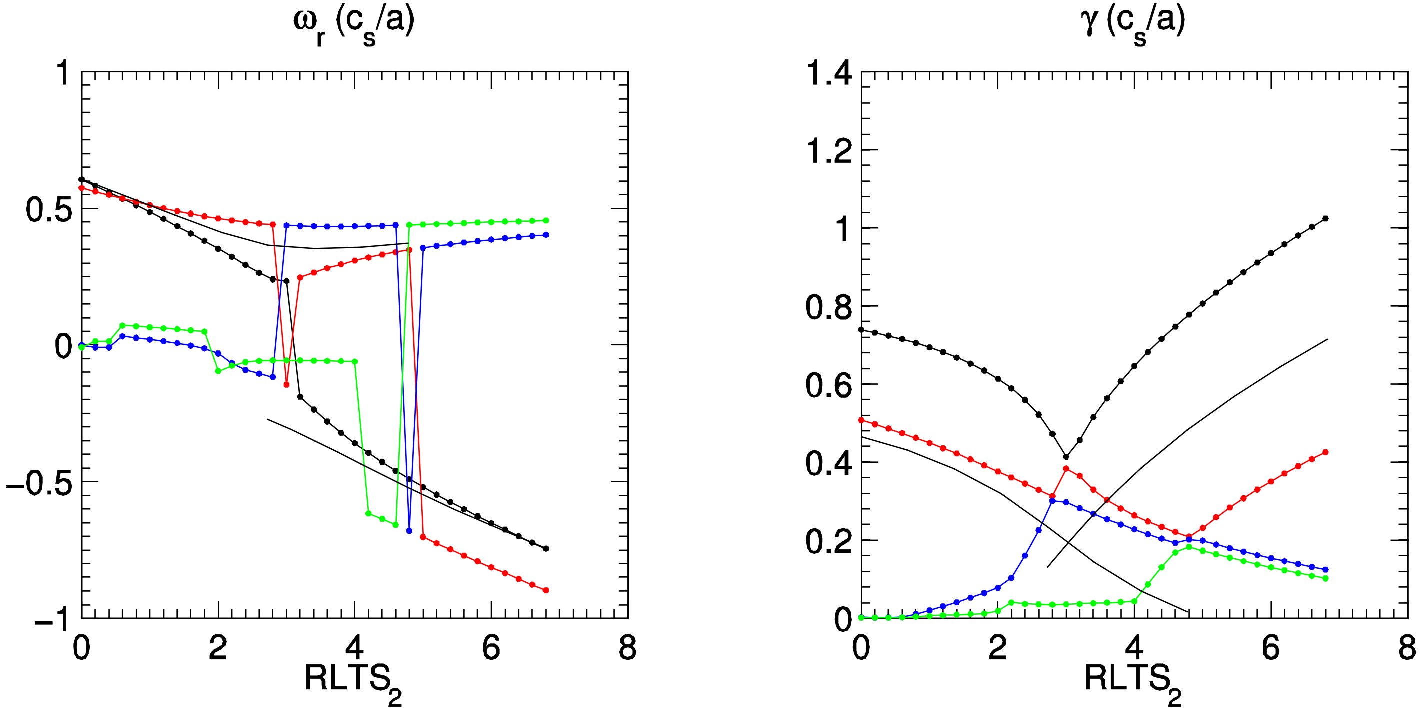
Aspect ratio doesn't matter too much

- Using Miller



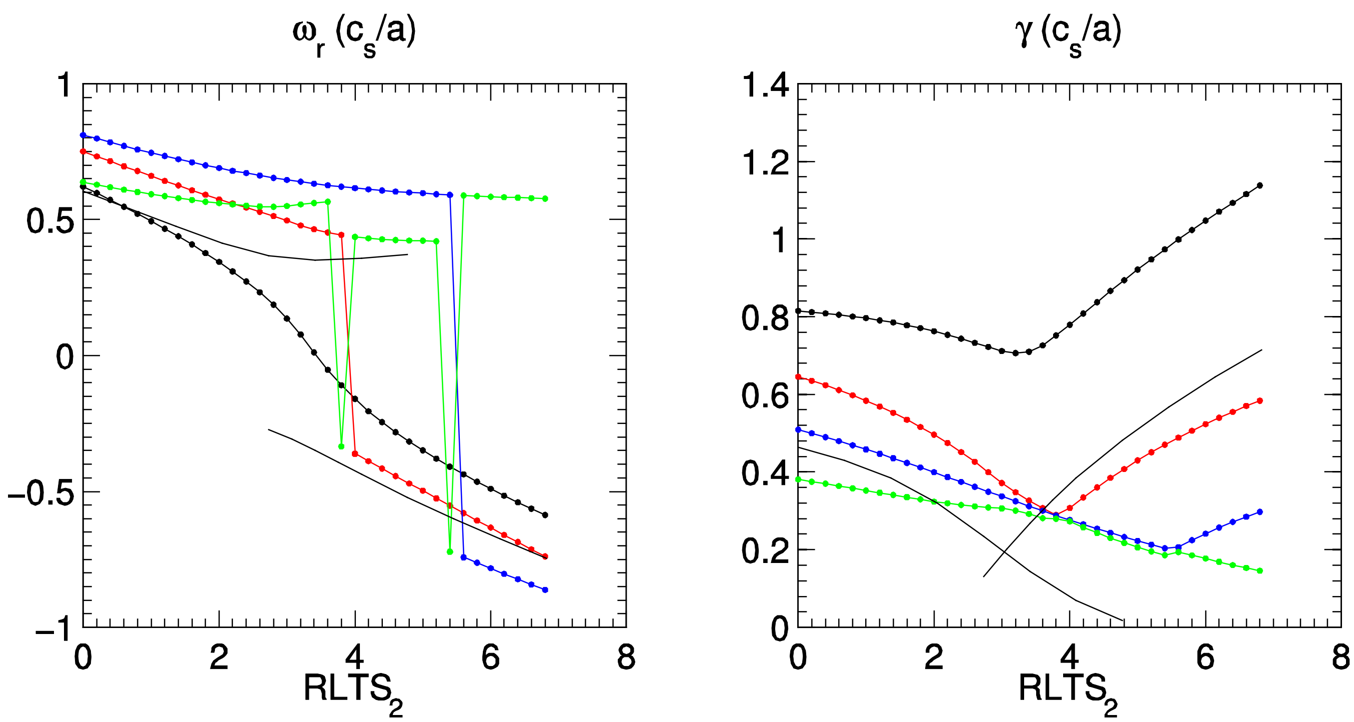
Ion temperature gradient scan ($R/L_{Td}=R/L_{Tc}$)

- Threshold for strongest mode appears to be similar
- GYRO finds second root from a/L_{Ti}>=0
- Two weaker TGLF roots are ES-tearing



Ion temperature gradient scan – nbasis = 16

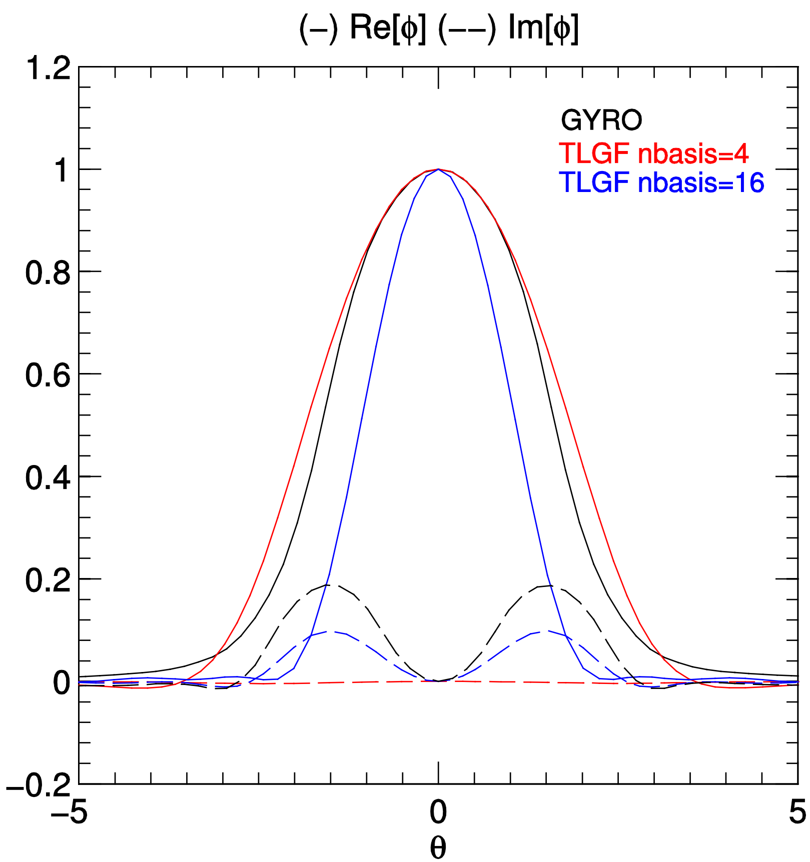
- Growth rates are larger with more basis functions
- Instead of two distinct roots, fastest growing modes at low/high a/L_{Ti} look like one smoothly varying root



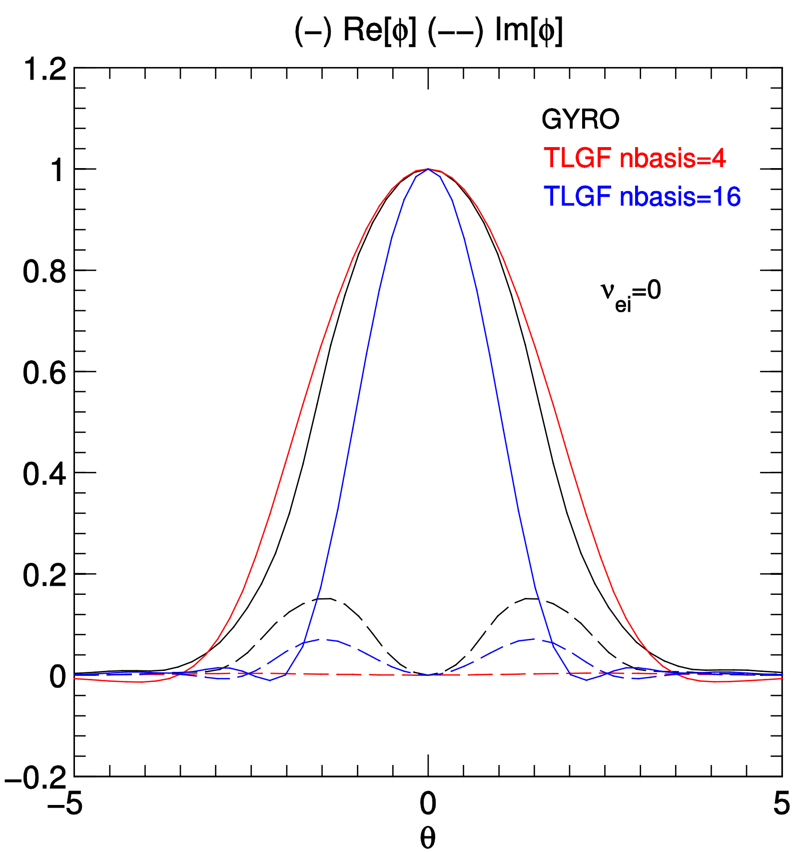
TGLF eigenfunction width is pretty close using nbasis=4

- Using nbasis=16, TGLF eigenfunctions are narrower
- Collisions make very little difference in eigenfunctions

with collisions

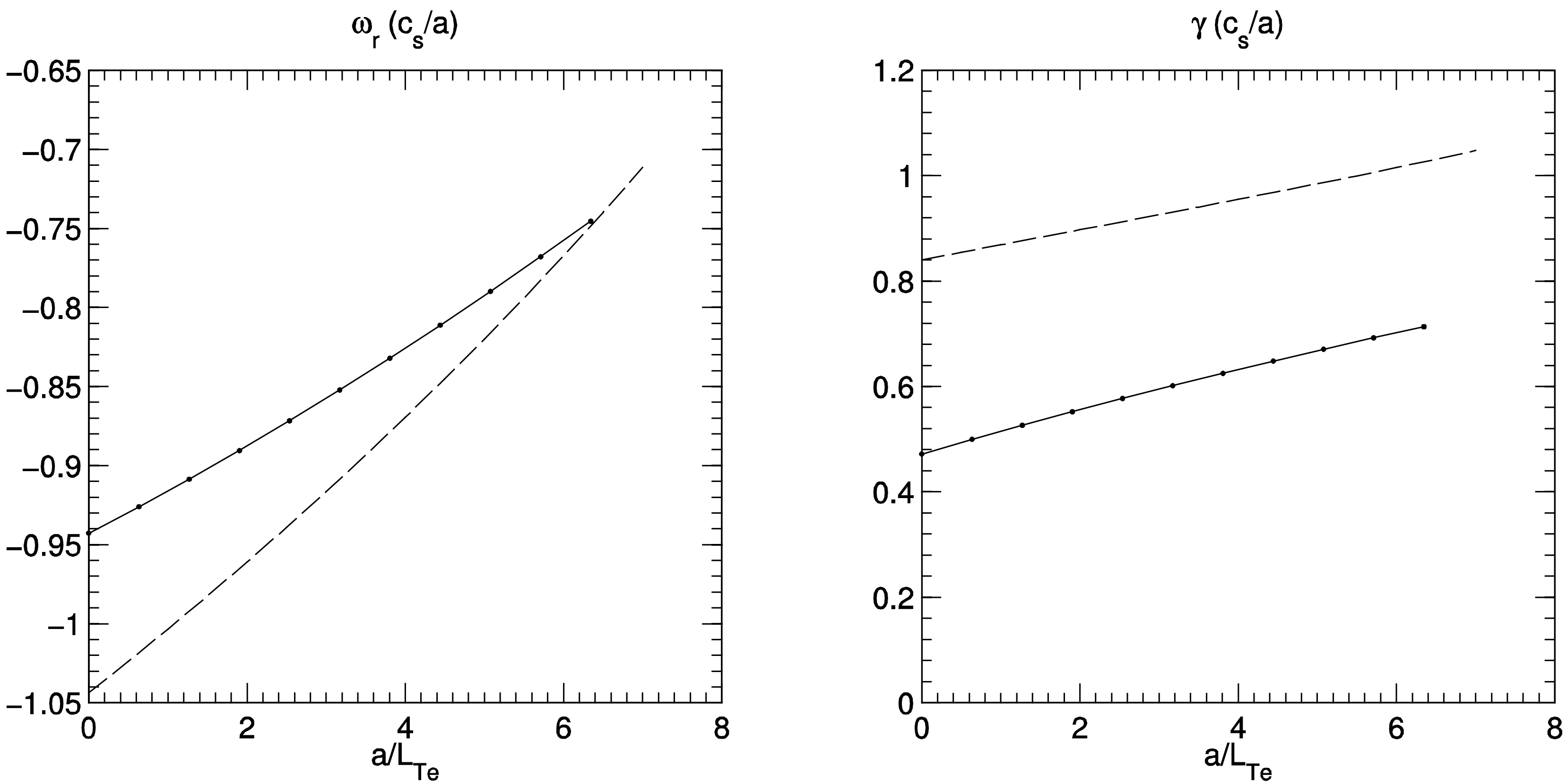


without collisions



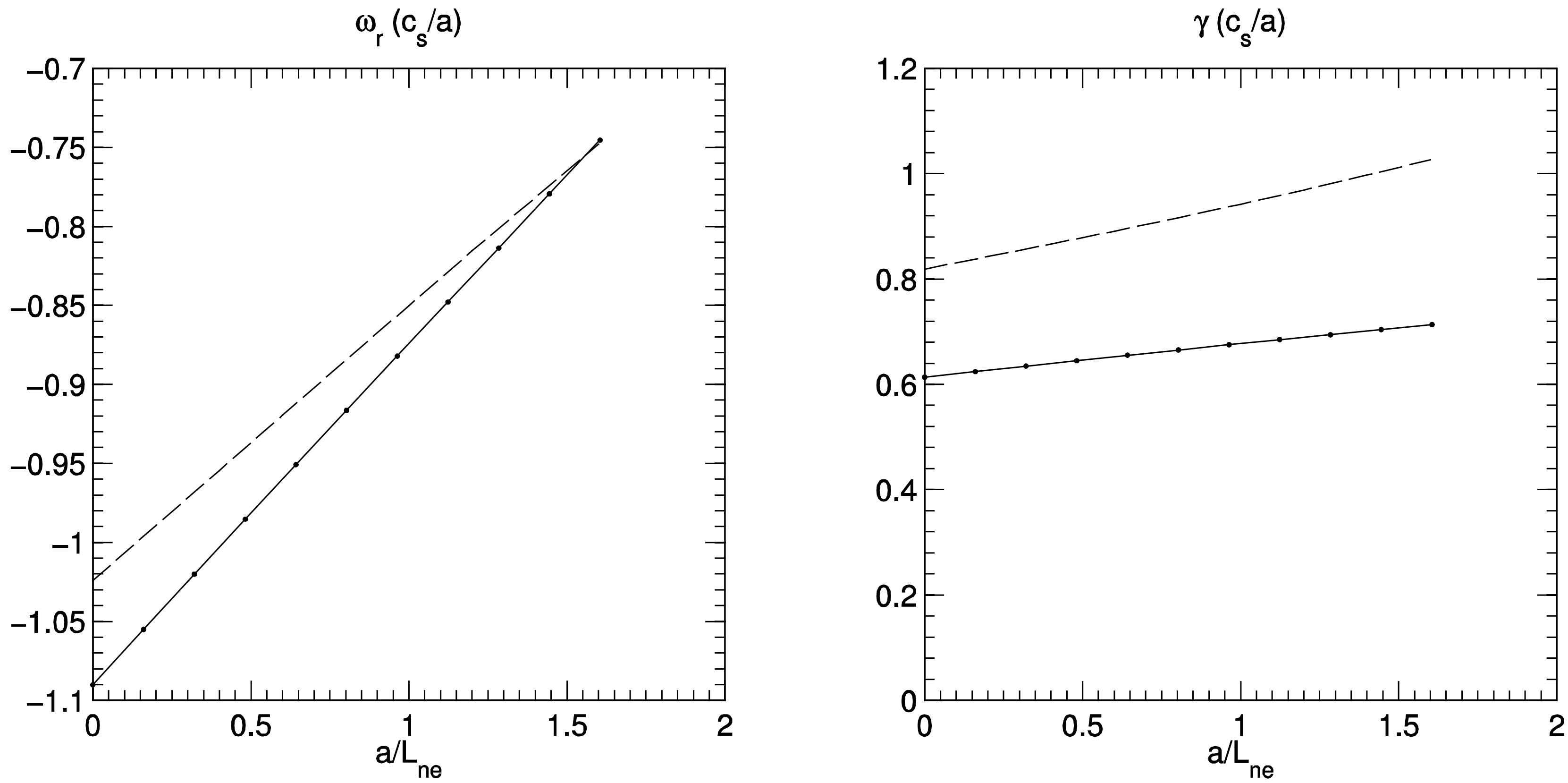
Electron temperature gradient scan

- No threshold in a/L_{Te}



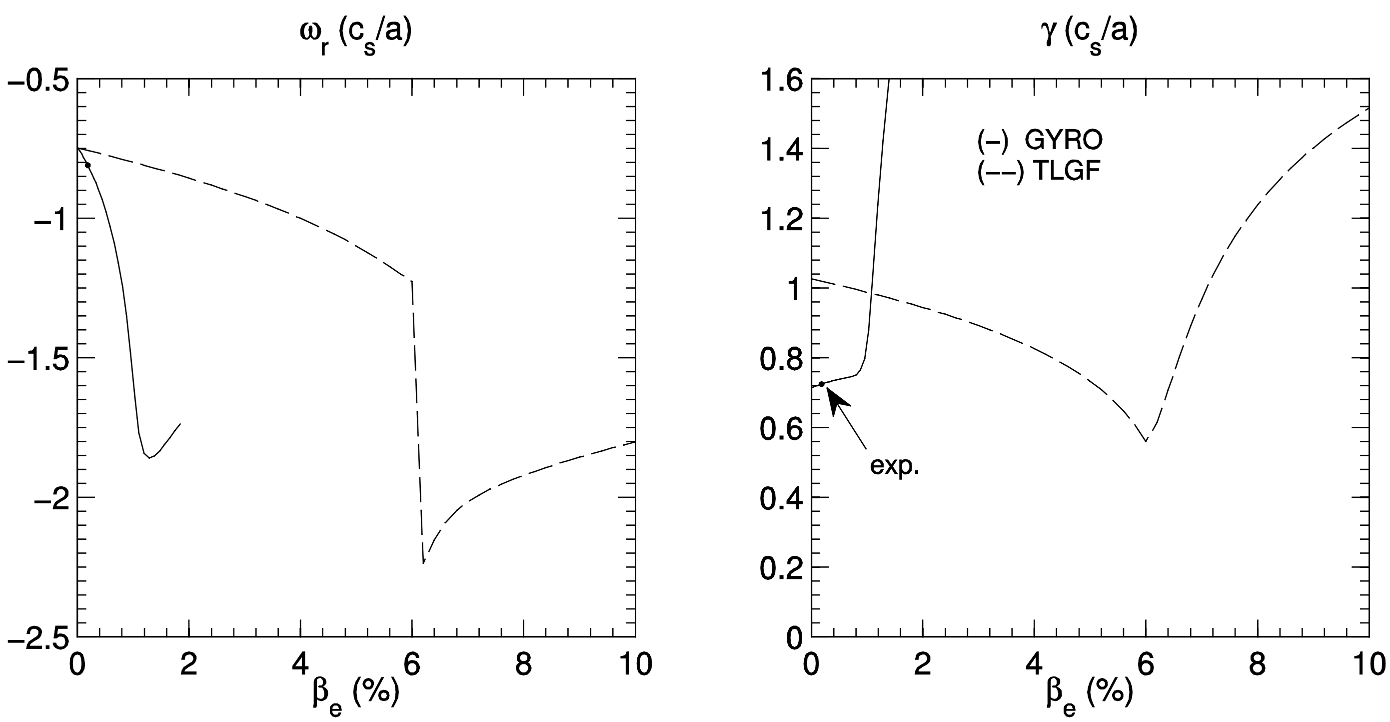
Density gradient scan

- Weak dependence ($a/L_{ne}=a/L_{nd}=a/L_{nc}$ for TGLF)



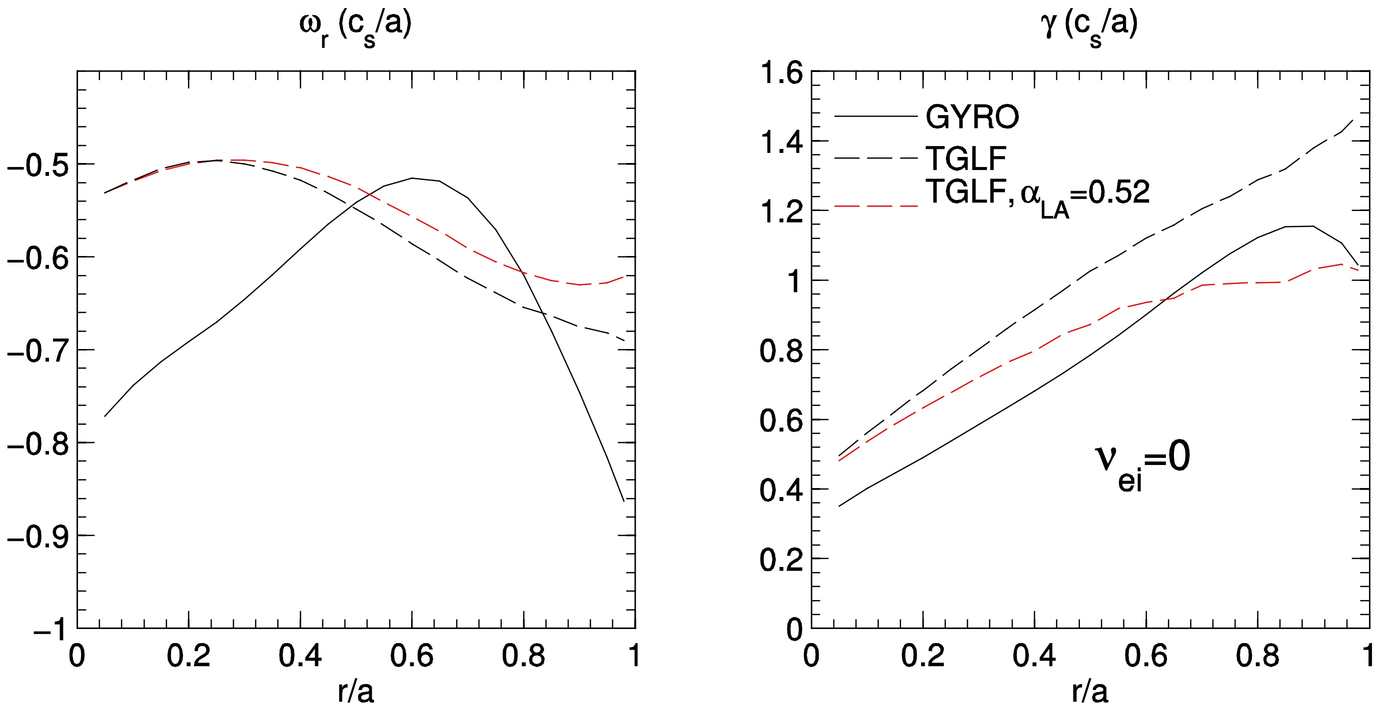
Beta scan shows negligible dependence around experimental value

- At higher β_e approaching H-mode values, GYRO shows "hybrid-KBM" behavior [Belli, PoP (2010); Guttenfelder, IAEA (2012)]
  - ITG growth rate *increases* with β_e, slowly transitions into KBM mode (not two distinct roots), phasing of Re[$A_{||}$]/Im[$A_{||}$] transitions at the same point
- TGLF shows two distinct roots, KBM threshold much higher – this seems weird
  - The GYRO transition point is around $\alpha_{MHD,unit}$=0.8, typical of what I've seen in other NSTX cases
- I think both cases are using the same fixed pressure gradient in equilibrium



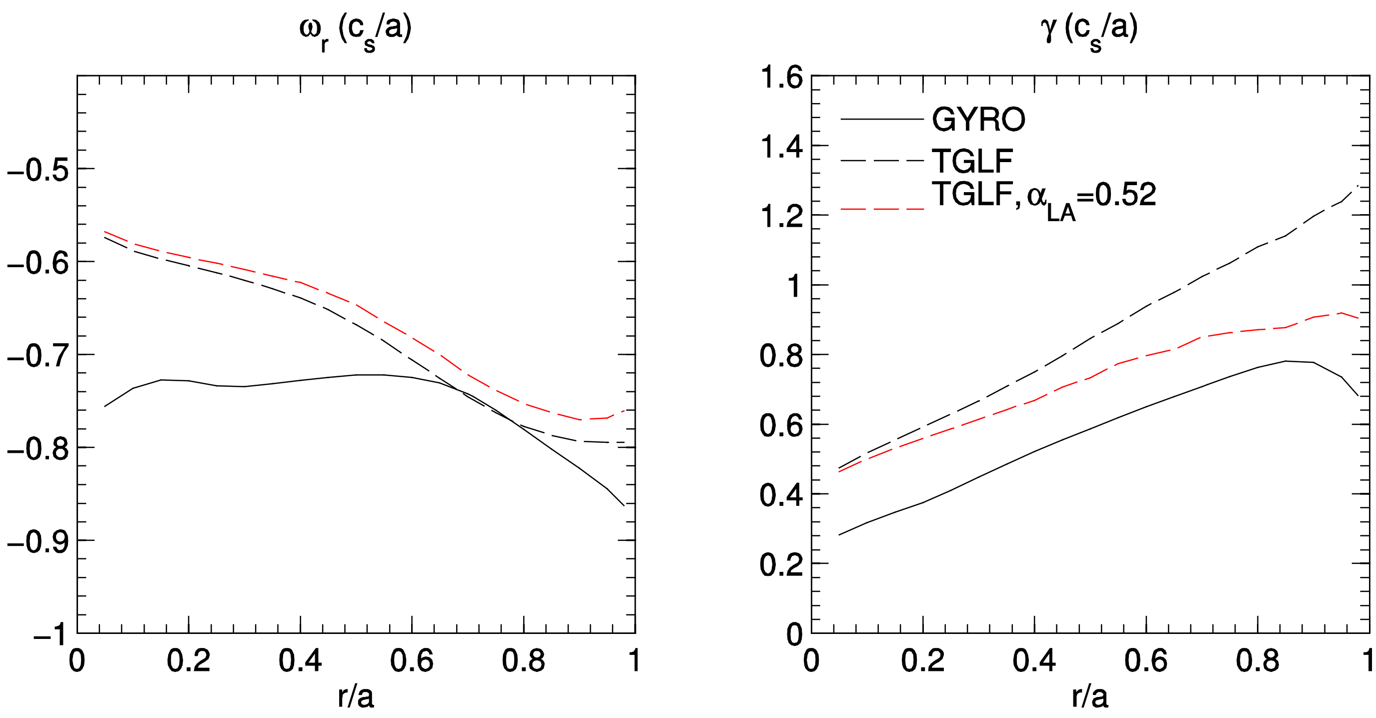
r/a scan using Miller inputs (all other parameters constant) collisionless (ν_{ei}=0)

- Reducing THETA_TRAPPED (α_{LA} in the paper) from 0.7→0.52 improves agreement for larger trapped particle fraction (r/a)



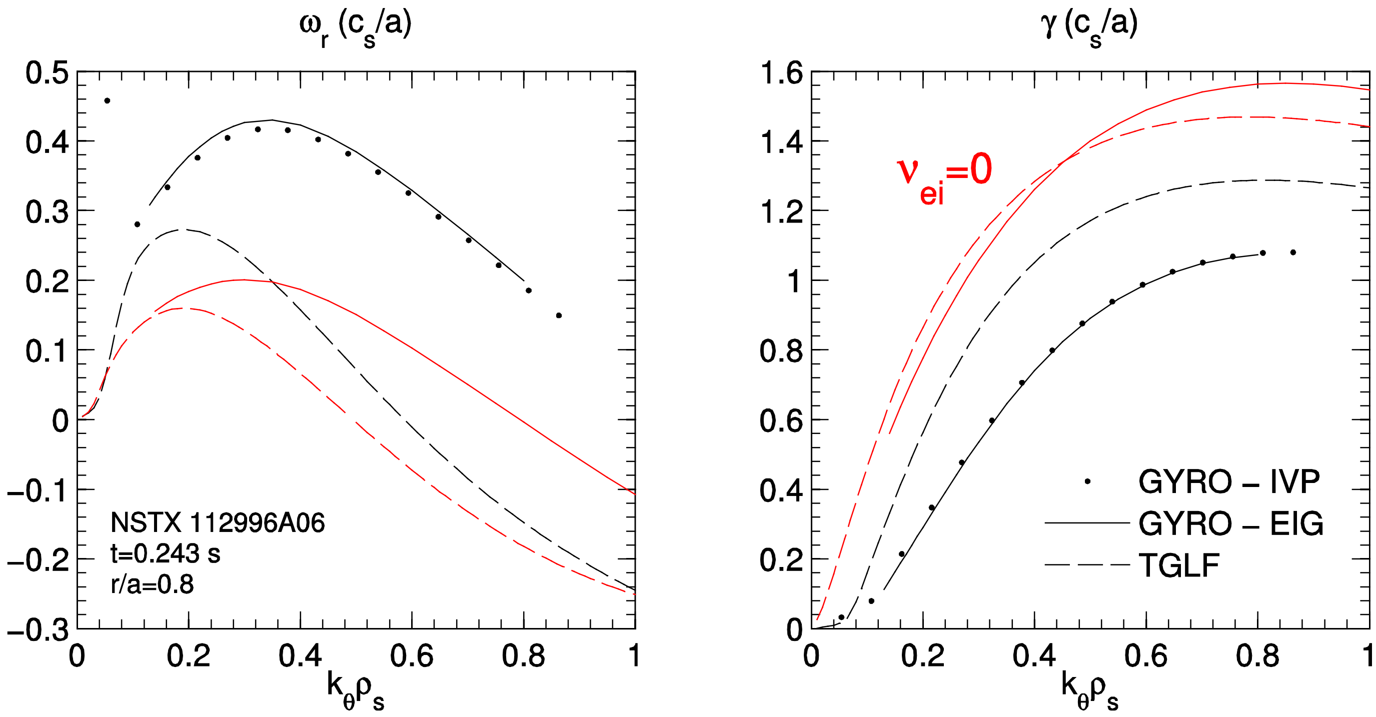
r/a scan using Miller inputs (all other parameters constant) with collisions (ν_{ei}=0.99 c_s/a)

- Reducing THETA_TRAPPED (α_{LA} in the paper) from 0.7→0.52 improves agreement for larger trapped particle fraction (r/a)



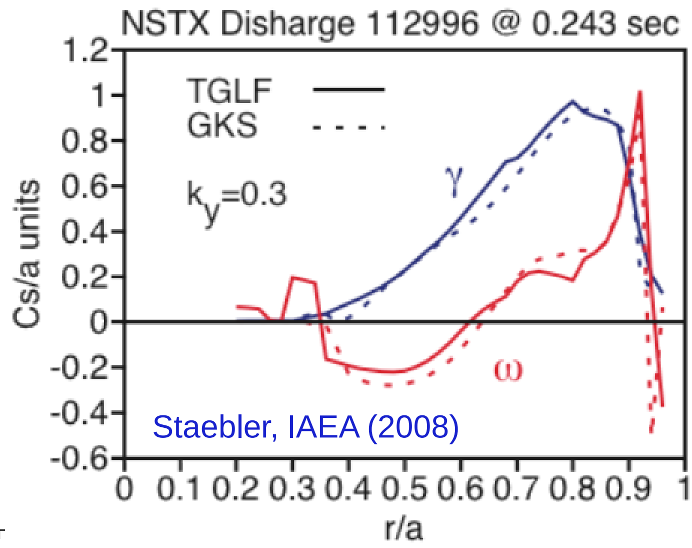
112996A06, t=0.243 s
$k_\theta\rho_s$ scan (r/a=0.8)

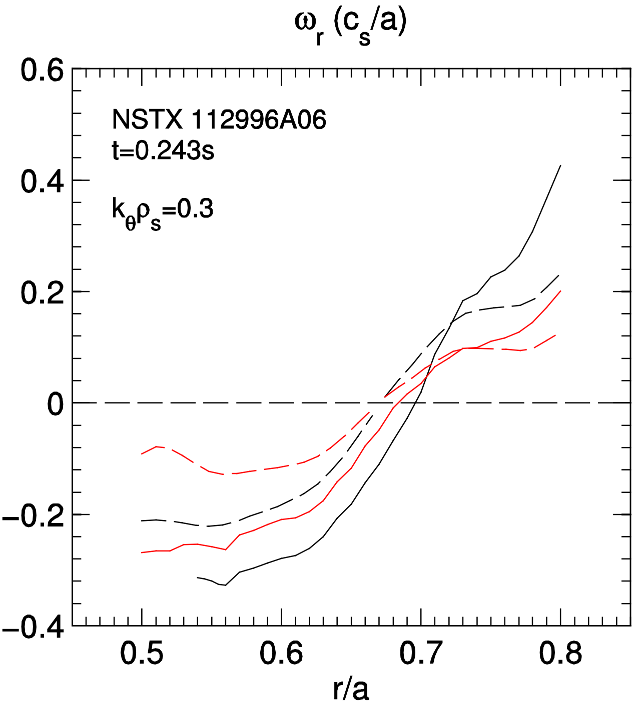
- L-mode case from Stutman, PoP (2006) & Staebler, IAEA (2008)
- Both GYRO and TGLF using Miller ($\nabla B=\kappa$), EM (φ, $A_{||}$)
- With collisions, comparable discrepancy as previous case
- Good agreement in growth rate without collisions
- (lowest $k_\theta\rho_s$ dot in GYRO-IVP run is microtearing)

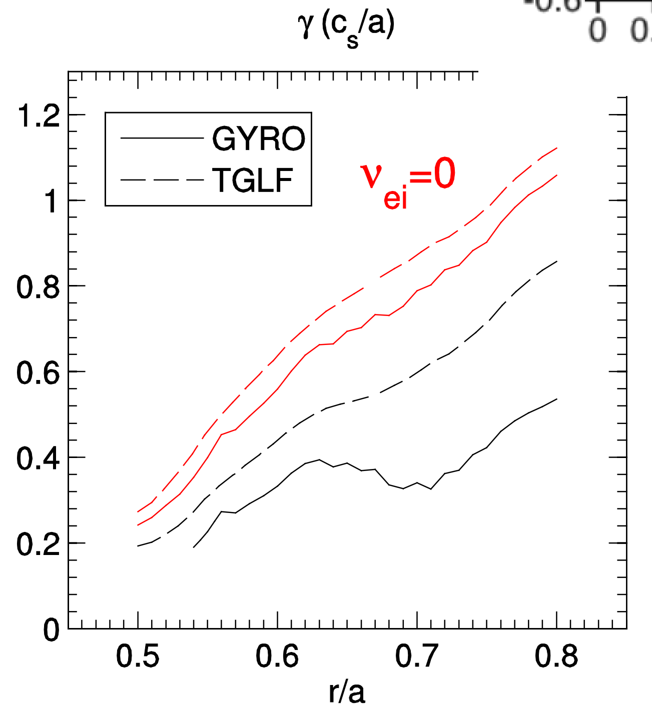


112996A06, t=0.243 s
r/a scan ($k_\theta\rho_s$=0.3)

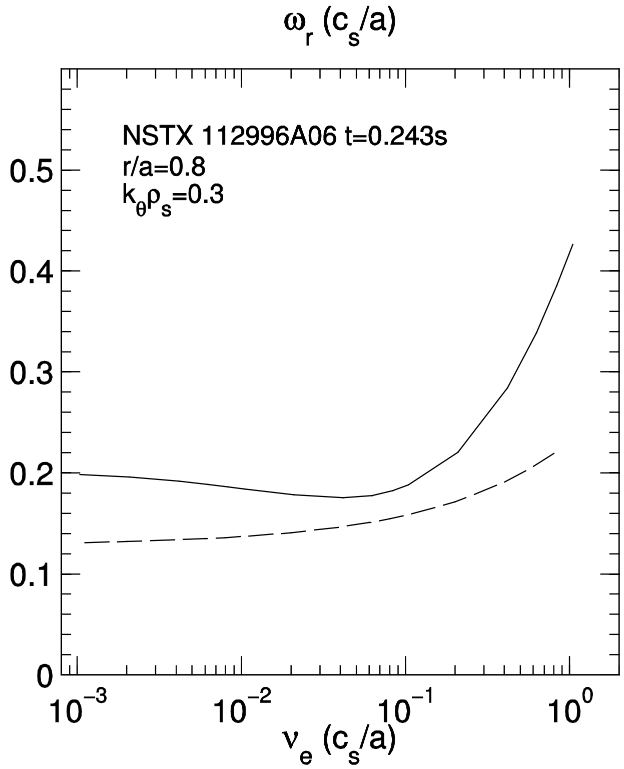
- With collisions, agreement not as good as Staebler, IAEA (2008)
- With collisions, growth rates in much better agreement
- GS2 at r/a=0.7, ky=0.3

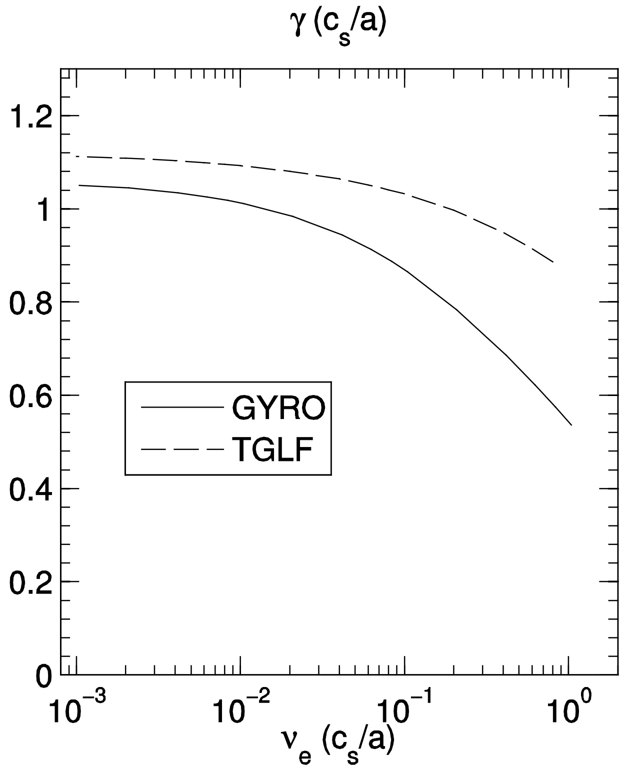






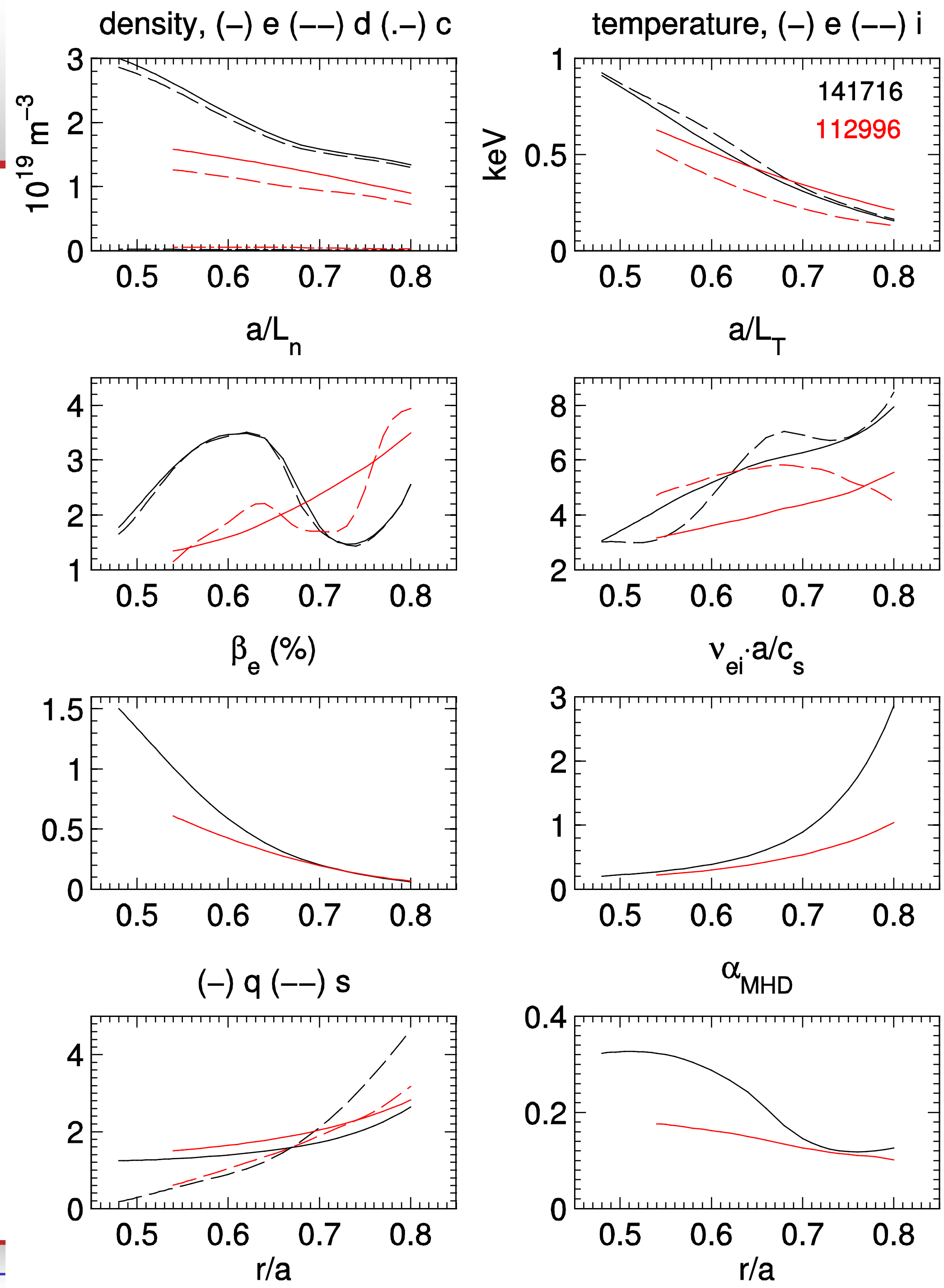
112996A06, t=0.243 s
ν_e scan (r/a=0.8, $k_\theta \rho_s$=0.3)





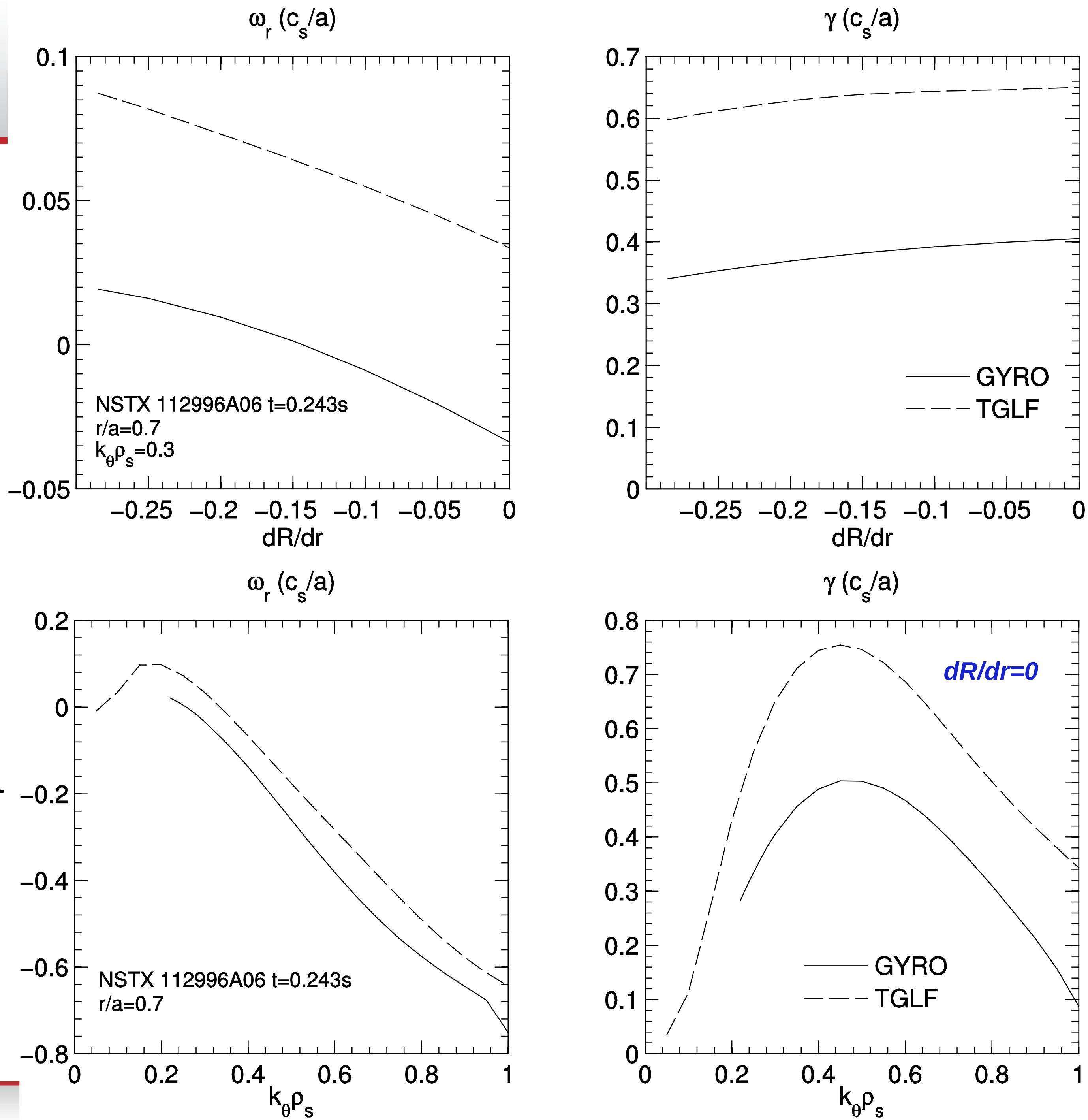
Profiles of relevant parameters for both L-mode shots (141716, 112996)

- For 112996:
  n_e , ν_e, β_e a little lower
  T_e/T_i~1.5
  weaker a/L_{Te}
  slightly higher q



dR/dr scan

- $k_\theta \rho_s$ spectra for dR/dr=0

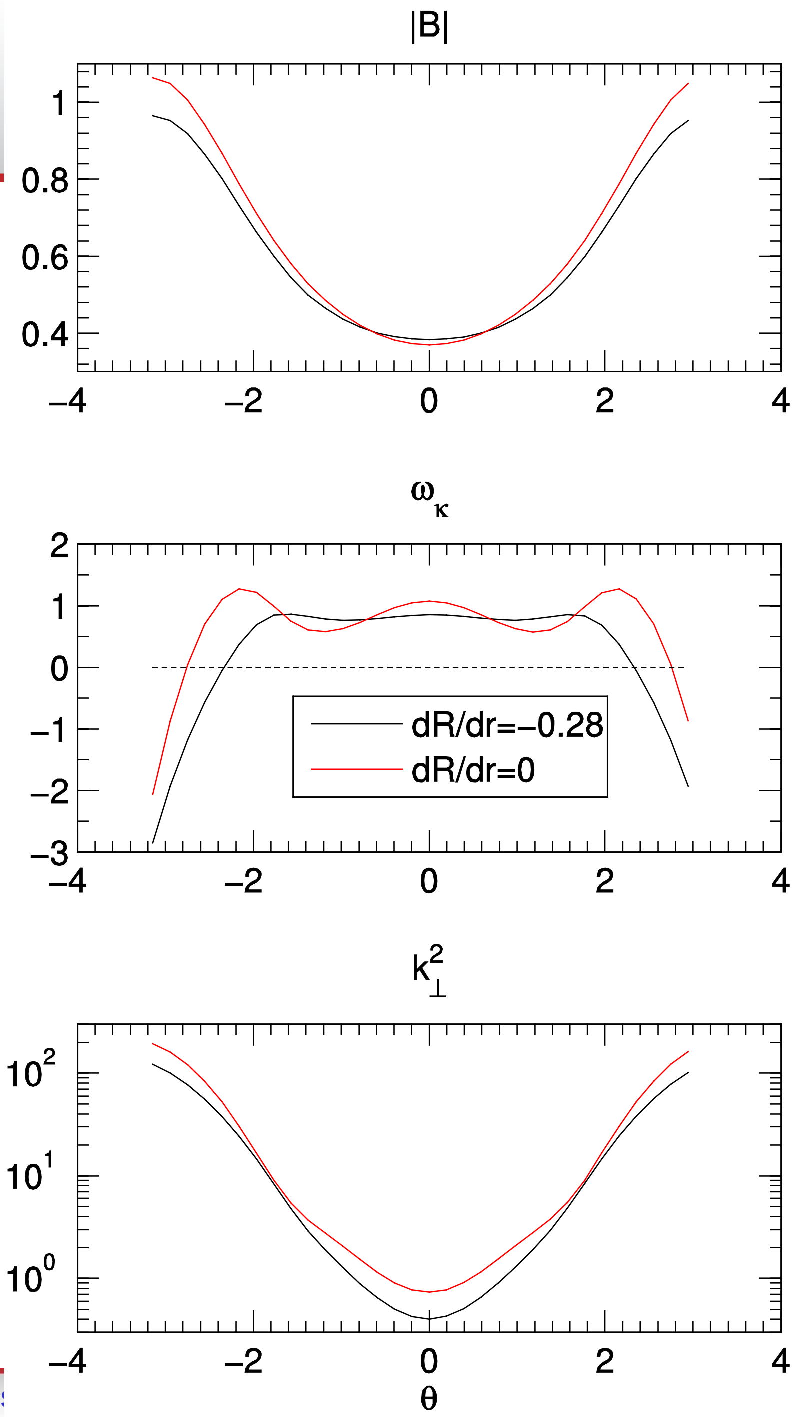


Comparing geometry metrics for dR/dr=-0.28 & 0

- Normalizing B_{unit} is different for each case

- Curvature drift coefficient is normalized in same way as GS2
  - Broader region of bad curvature with dR/dr=0

- Only showing $k_{\perp}^{2}$ (and ω_{κ} above) terms that are independent of θ_0



Overview

- Motivation
- TGLF standalone linear tests
- TGLF standalone transport tests
- TGYRO/TGLF/NEO profile predictions

Motivation

- Desire predictive capability for spherical tokamaks (STs) to help develop fully non-inductive discharges for NSTX-Upgrade and next-generation devices: CTF, FNSF, Pilot Plant, etc…
- Non-linear gyrokinetic simulations are expensive $\rightarrow$ develop reduced transport models that are much faster to evaluate in integrated simulations
- TGLF is one such <u>physics-based</u> model which is capable of including most effects expected to be important: general geometry, collisions, electromagnetic effects, flow and flow shear, multi-species
  - Does not include non-local effects at large $\rho_* = \rho_s/a$

$\Rightarrow$ Limited tests of TGLF for realistic ST parameters

TGYRO, TGLF, NEO used for modeling

TGYRO [1]

- Transport solver that takes as input TRANSP-calculated sources (P_{NBI}, dW/dt, $S_{particle}$, …) and equilibrium → predicts profiles (Ti, Te, ne, …) using choice of transport models (TGLF+NEO, TGLF+Chang-Hinton, GYRO+NEO, …)

TGLF [2]

- Fluid moments of *linear* gyrokinetic equation with closures chosen to best match a database of ~1800 linear gyrokinetic simulations
- Predicts transport using a quasi-linear + mixing length model, with coefficients tuned to best match ~100 non-linear gyrokinetic simulations (no empirical tuning, only theory based)
- Gyrokinetic simulations for validation are based on conventional aspect ratio parameters
  – Limited testing using realistic ST parameters[4]

NEO [3]

- Drift kinetic solution (…) of neoclassical transport, allowing for multiple species, toroidal flow (poloidal asymmetry), and various collision operator models
- For cases shown here, Chang-Hinton used – very close to DKE solution

[1] J. Candy et al., Phys. Plasmas **16**, 060704 (2009).
[2] G.M. Staebler et al., Phys. Plasmas **14**, 055909 (2007); Phys. Plasmas **17**, 122309 (2010).
[3] E.A. Belli & J. Candy, Plasma Phys. Control. Fusion **50**, 095010 (2008).
[4] G.M. Staebler et al., IAEA (2008).

NSTX L-mode is unstable to ~electrostatic ITG [This is older, not identical models, but basically same as new stuff]

- Linear calculations at five different radii (r/a=0.6-0.8)
- GYRO growth rates are larger than E×B shearing rates (γ_E) except for r/a=0.6
- TGLF growth rates always much larger (up to 2×)