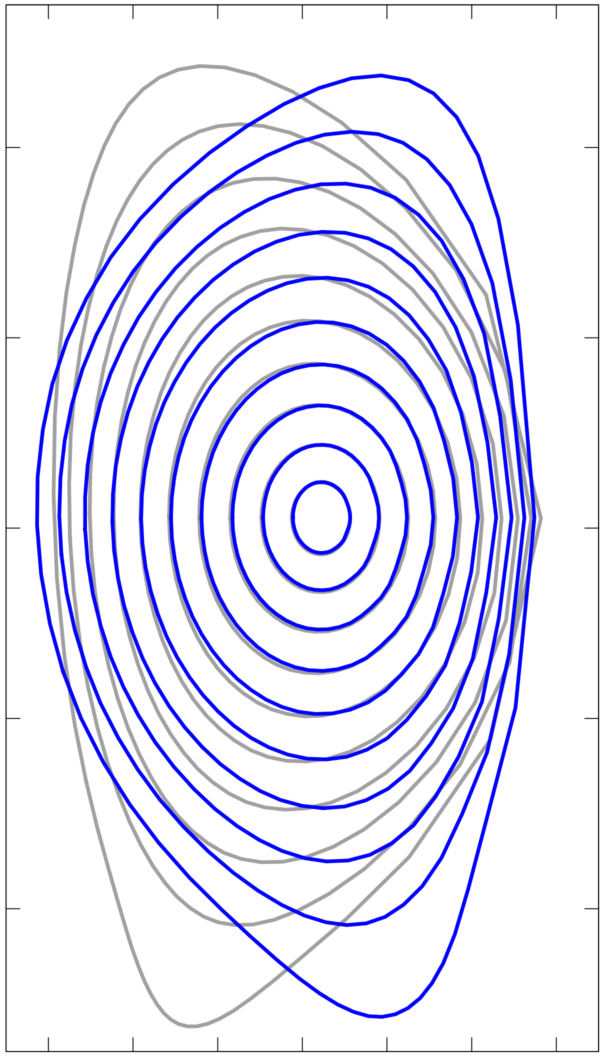
Gyrokinetic calculations for a negative triangularity DEMO



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Swiss Plasma Center, EPFL

KDII#8 Final Meeting
01 July 2020

Motivation

- Negative δ potentially has the following benefits:
  - Improves confinement
  - Increases the L-H power threshold, thereby keeping the plasma in L-mode and avoiding ELMs

Objectives

- Compare the positive and negative δ DEMO equilibria using local nonlinear GENE gyrokinetic simulations with kinetic electrons
    - Distinguish the effect of plasma profiles and magnetic geometry
    - Investigate profile stiffness
    - Do so at several minor radii (i.e. $\rho_{tor} = 0.62, 0.72, 0.82$)

Error in chease calculation of input equilibria :(

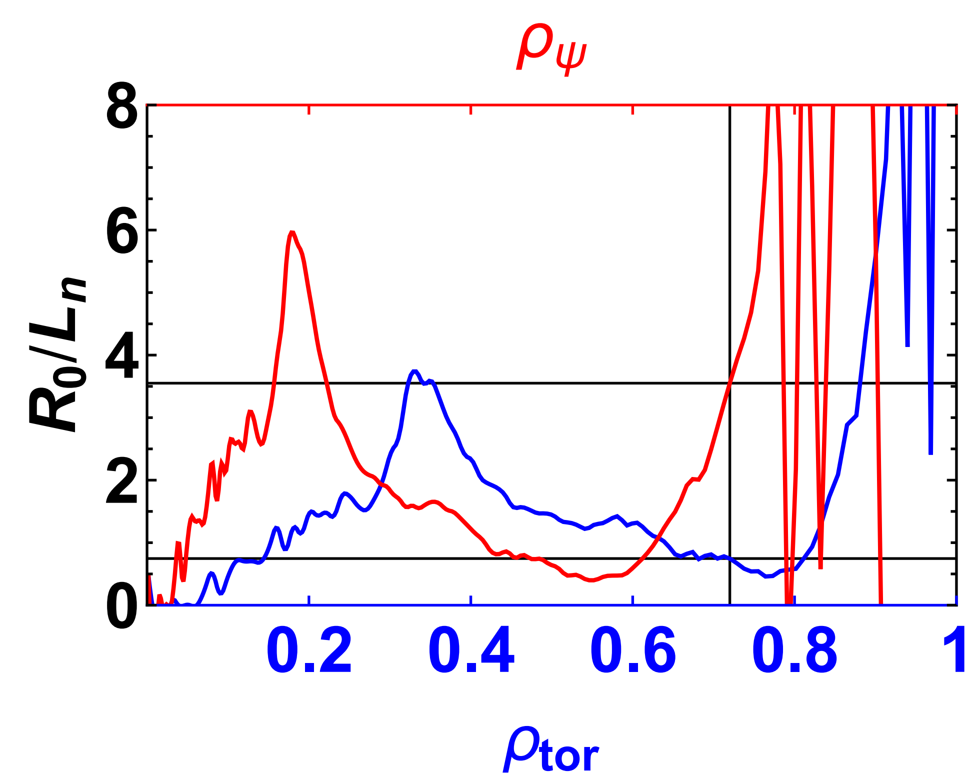
- Past simulations used the magnetic equilibria at $\rho_{tor} = 0.72$, but the plasma profiles at $\rho_{\psi} = 0.72$

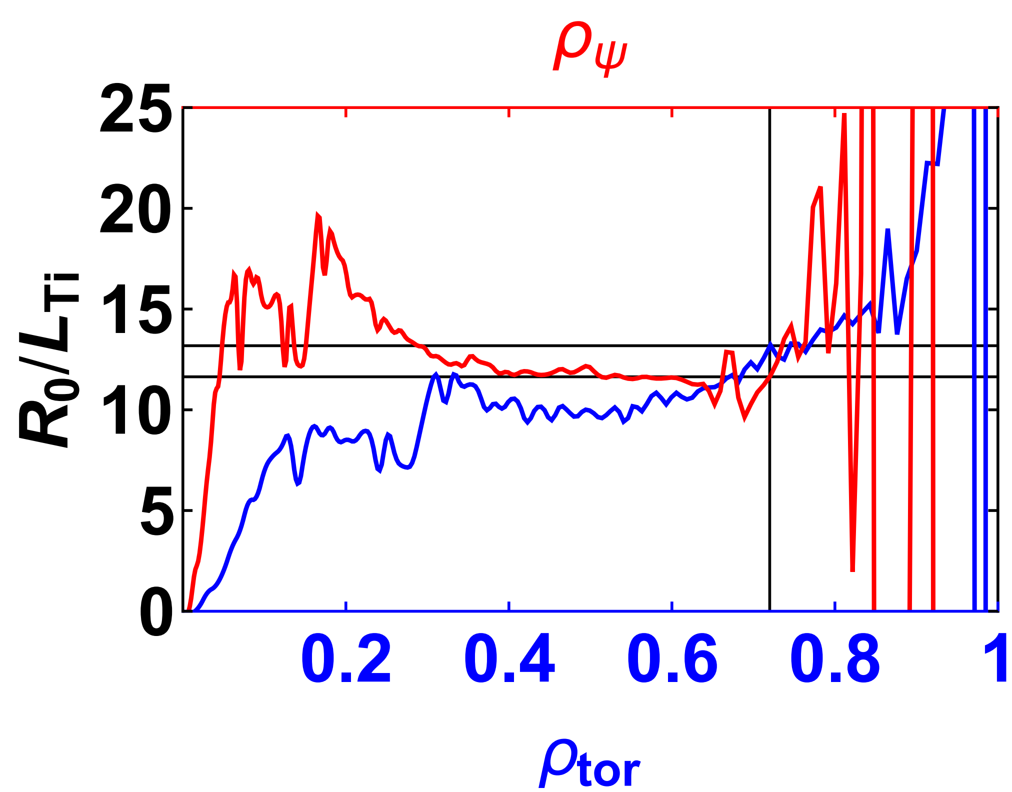
- Errors are:

  ▶ Should be $R_0/L_n \approx 0.7$, not 3.5

  - Should be $R_0/L_{Ts} \approx 13$, not 11

  - Should be $T_i/T_e \approx 1.0$, not 1.1

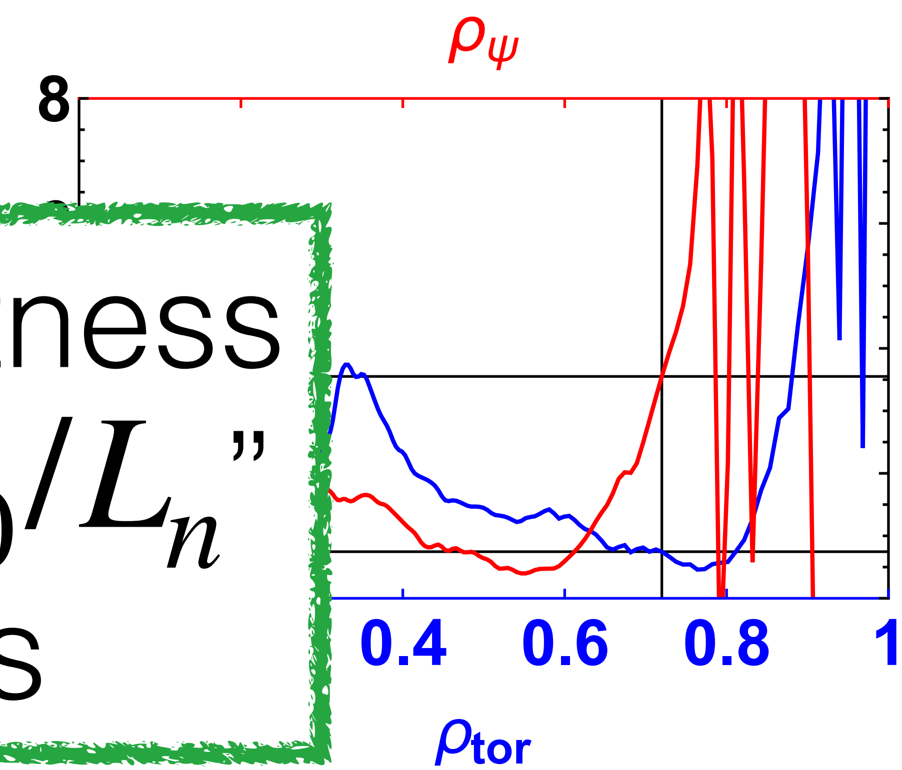




Error in chease calculation of input equilibria :(

- Past simulations used the magnetic equilibria at ρ_{to} … plasma profiles …

Explore robustness using "high R_0/L_n" simulations



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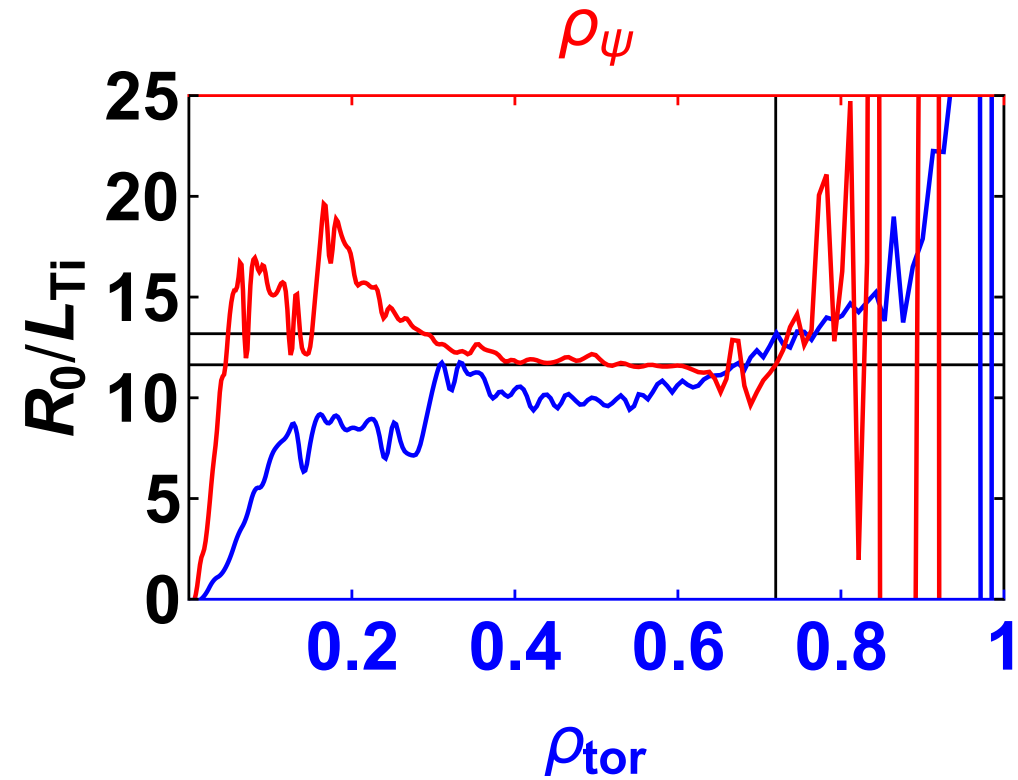

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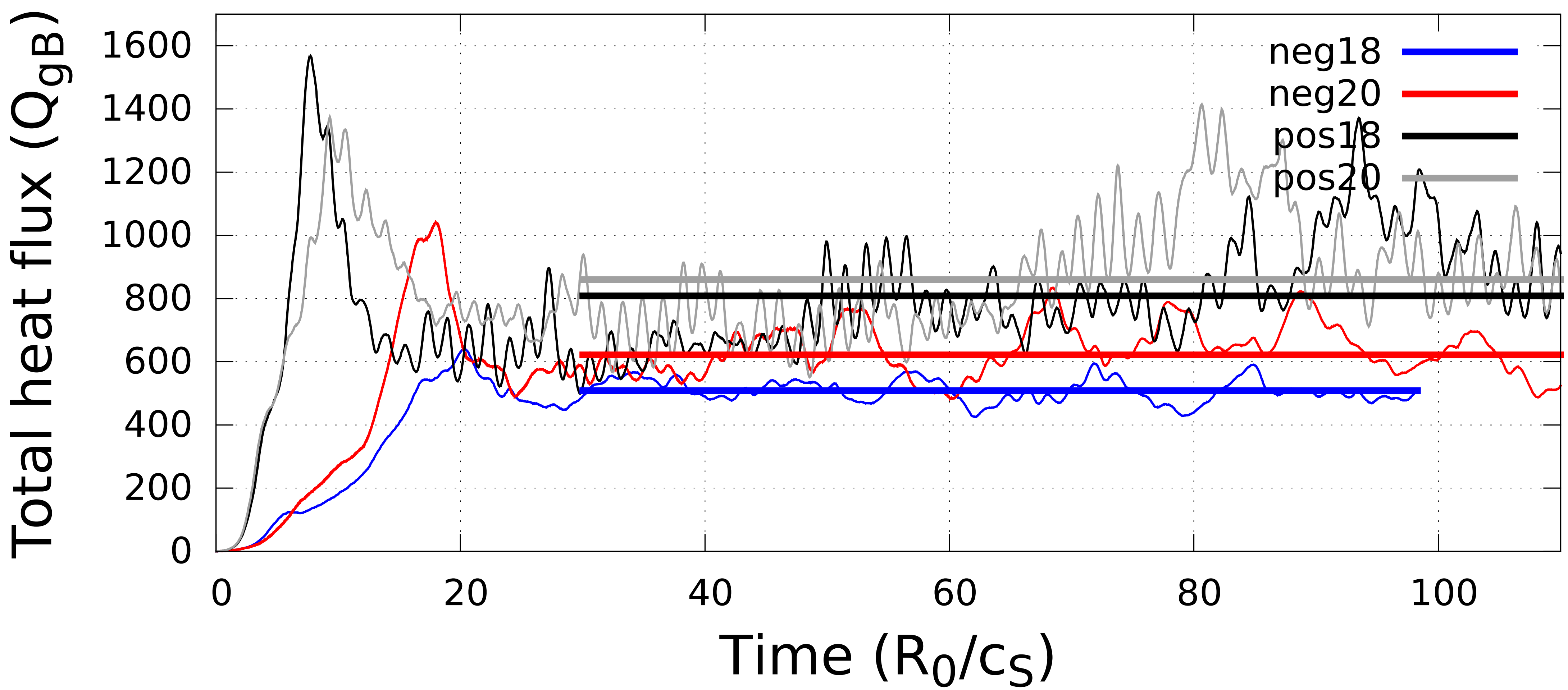
All sorts of results

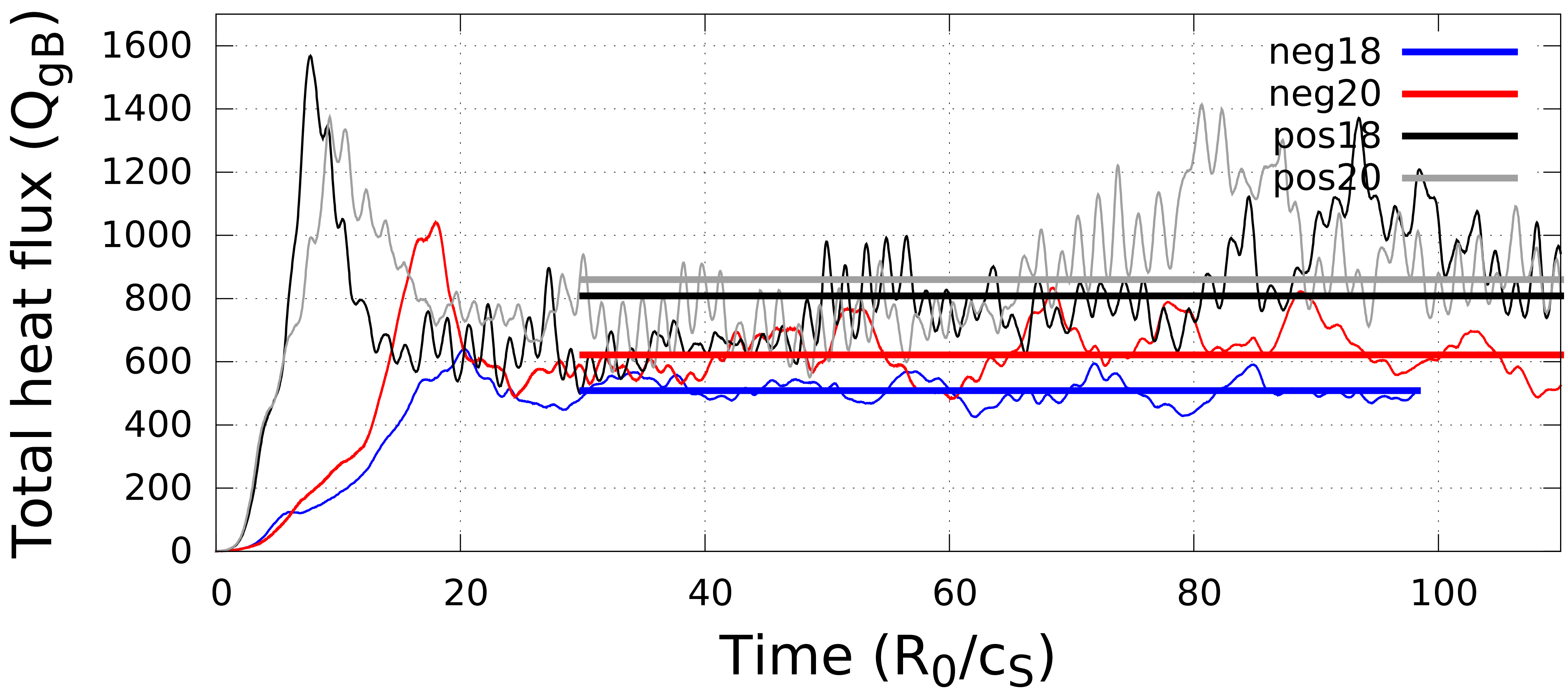
Type	**Nominal**								**High R_0/L_n**			
ρ_{tor}	**0.62**		**0.72**				**0.82**		**0.72**			
I_p	**18MA**		**18MA**		**20MA**		**18MA**		**18MA**		**20MA**	
δ	**pos**	**neg**	**pos**	**neg**	**pos**	**neg**	**pos**	**neg**	**pos**	**neg**	**pos**	**neg**

High R_0/L_n, $\rho_{tor} = .72$: examining past results



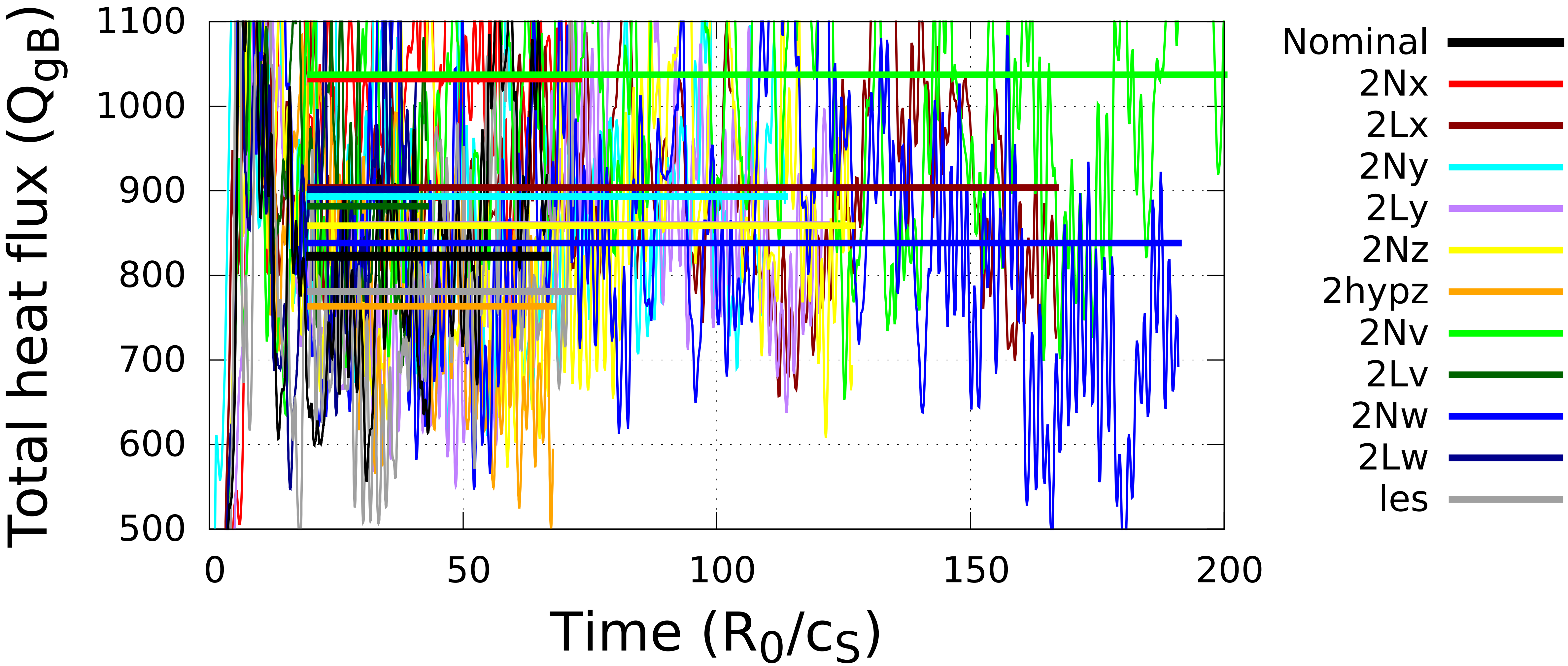
- Prior results showed a strong oscillation arising from the zonal flows

High R_0/L_n, $\rho_{tor} = .72$: examining past results



- Prior results showed a strong oscillation arising from the zonal flows
- Appears to be the GAM

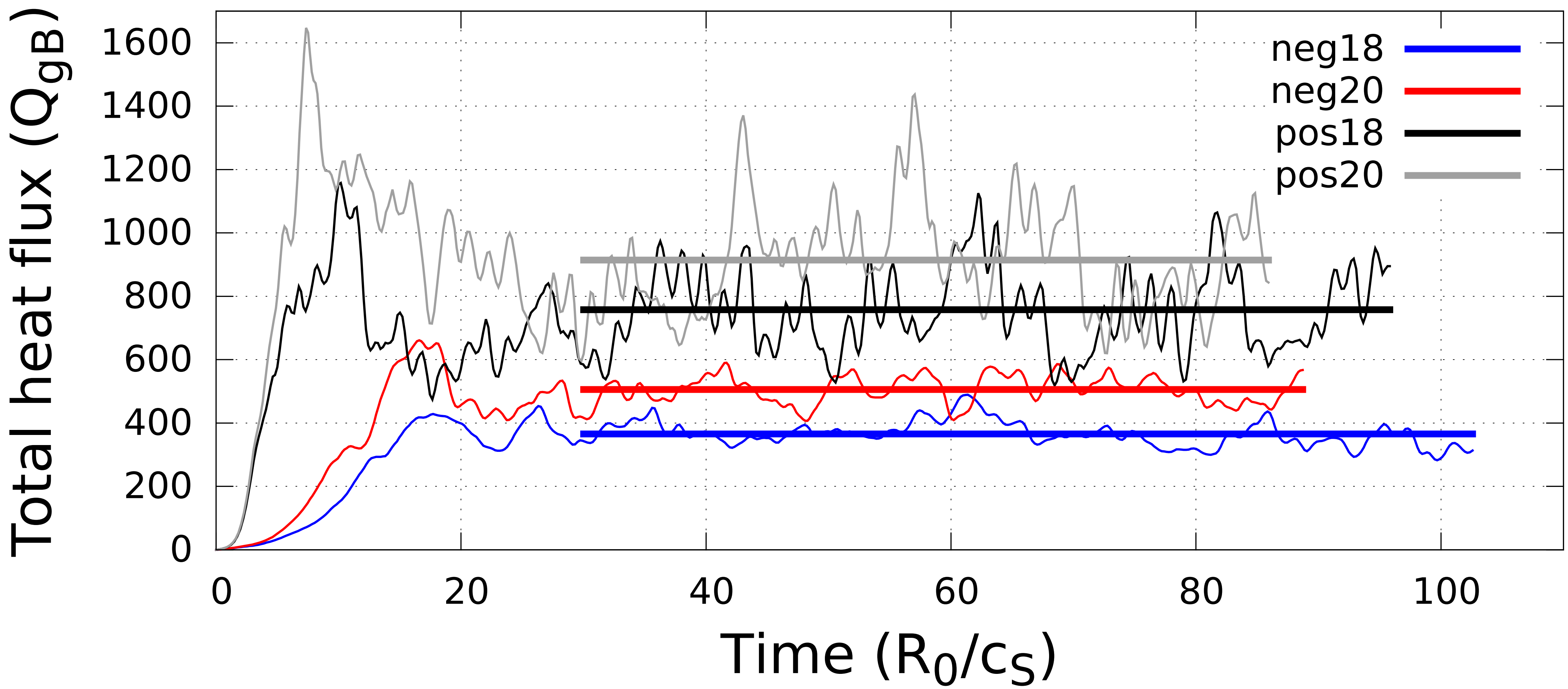
High R_0/L_n, $\rho_{tor} = .72$: resolution study



- Found two under-resolved parameters: N_x and, surprisingly, $N_{v||}$
- Increasing $N_{v||}$ reduces the amplitude of the GAM

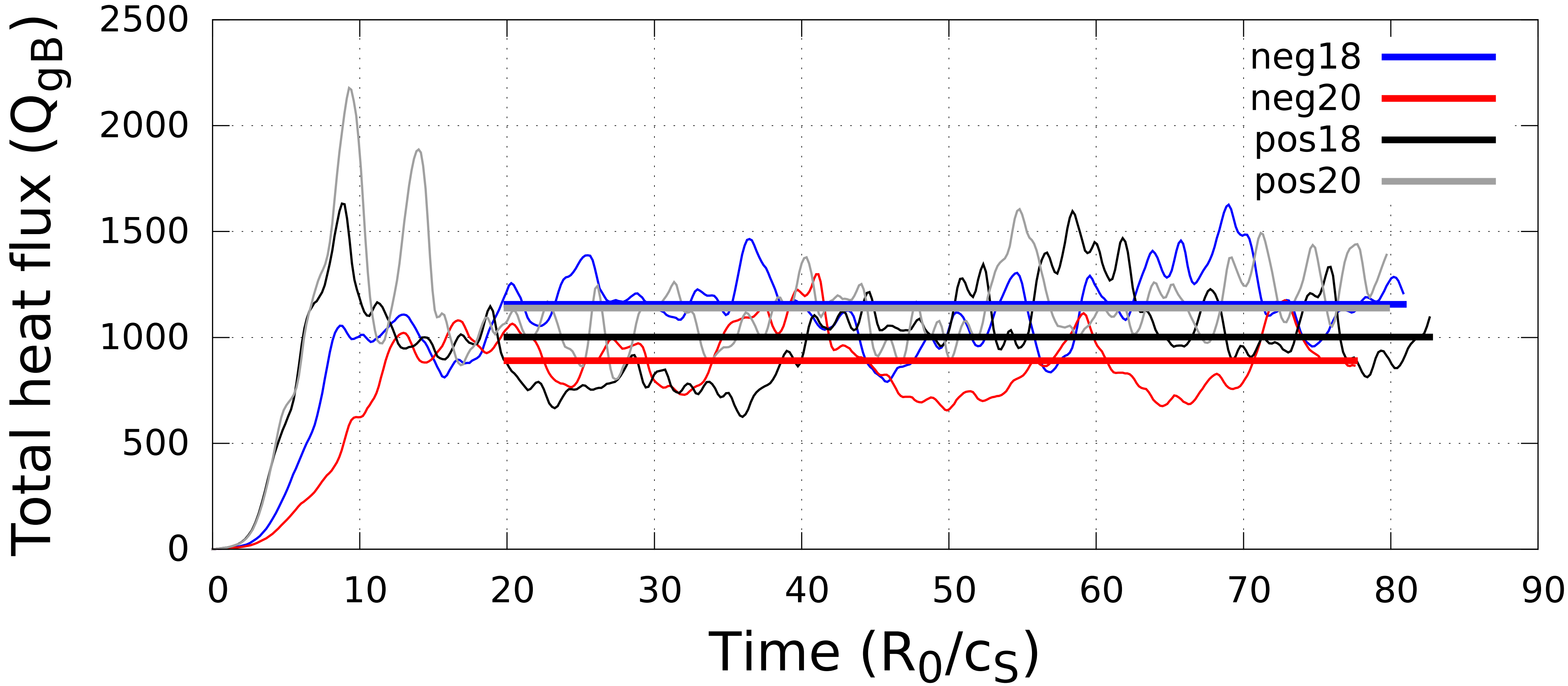
Main results

High R_0/L_n, $\rho_{tor} = .72$: final results



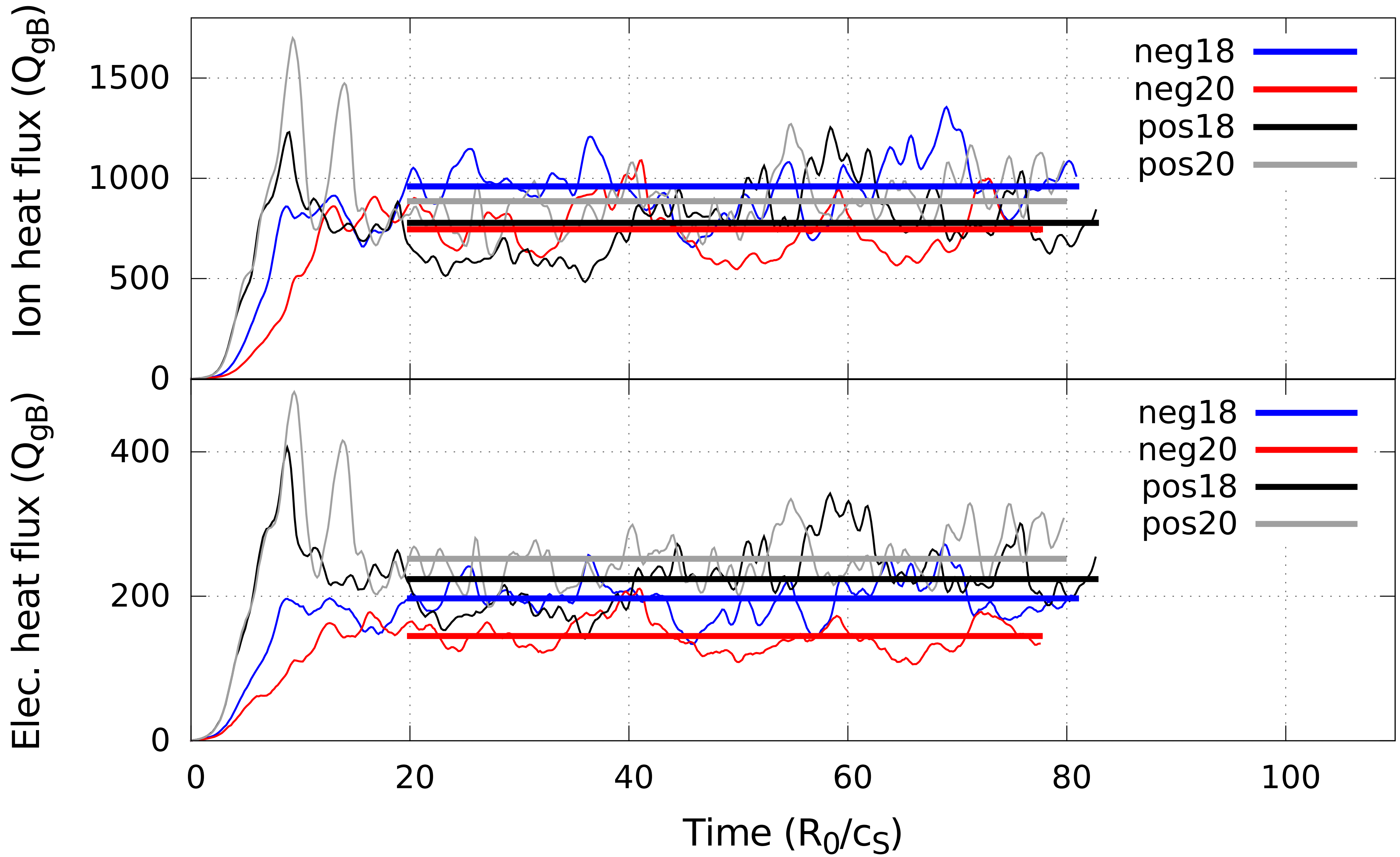
- Similar results as last year

Nominal, $\rho_{tor} = .72$: final results



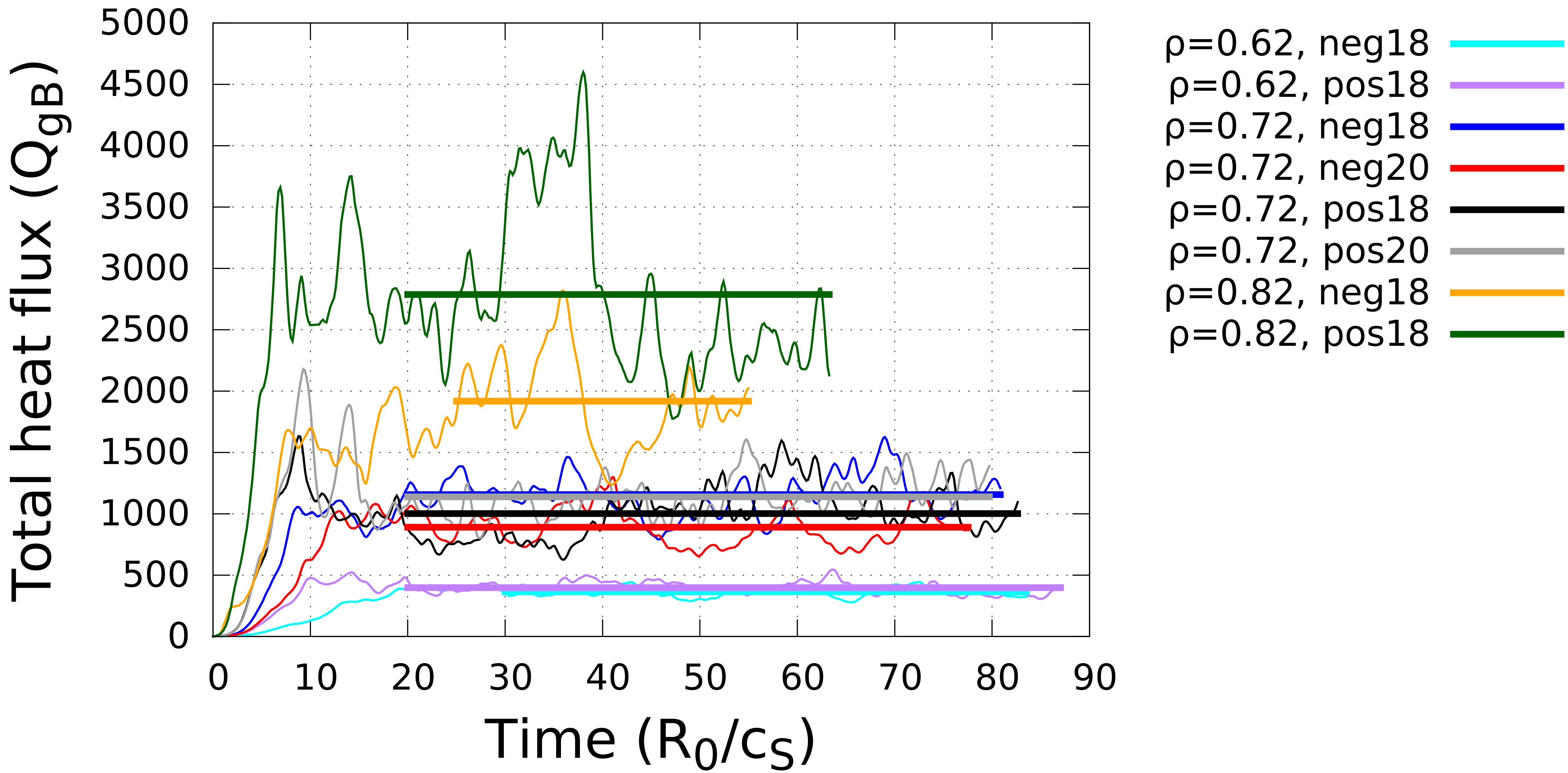
- Somewhat higher values than the high R_0/L_n cases
- Total heat fluxes are similar between all cases

Nominal, $\rho_{tor} = .72$: final results



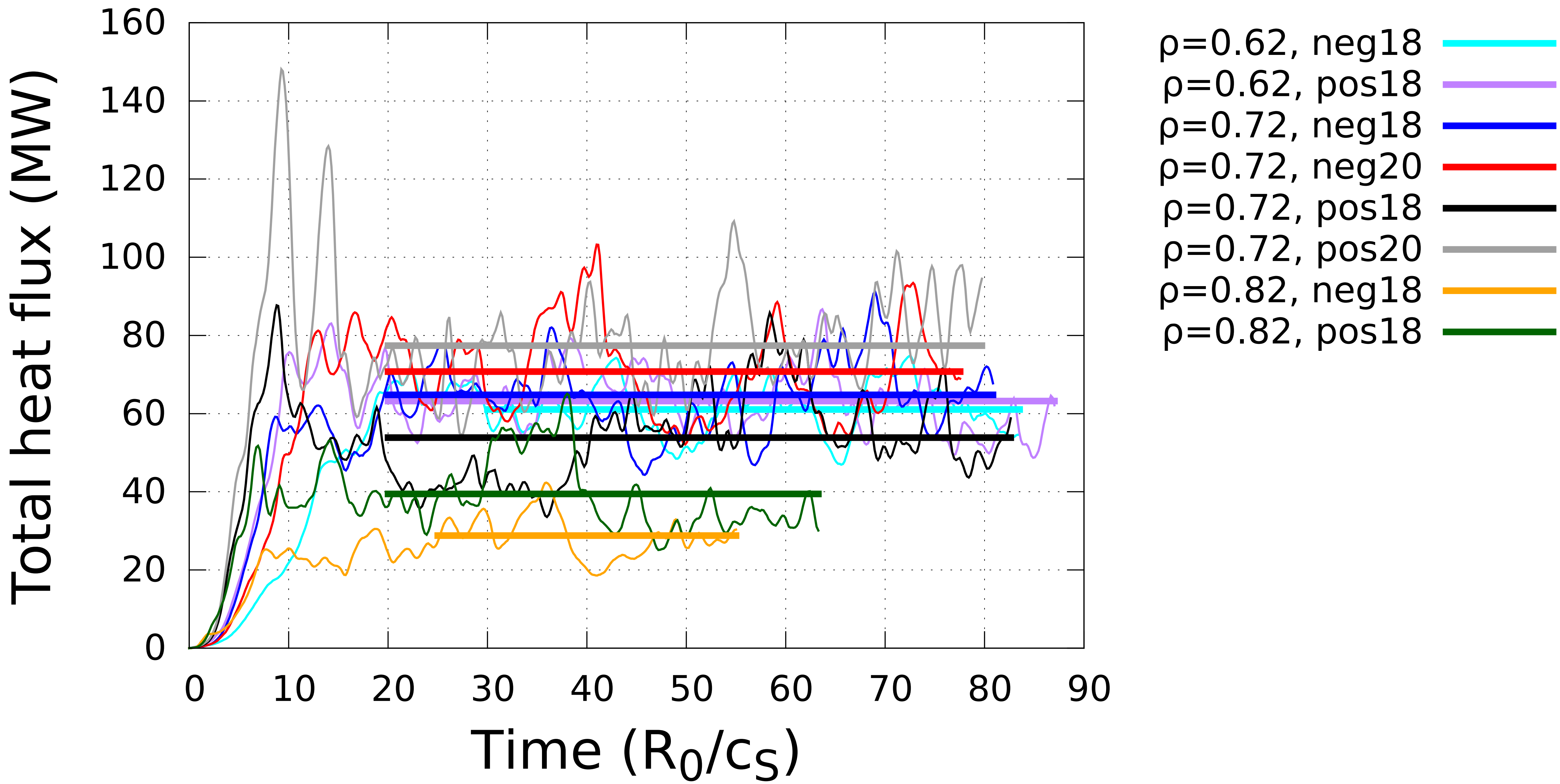
- The ion heat flux is dominant in these simulations, but **the electron heat flux is reduced by negative triangularity**

Nominal, $\rho_{tor} = .62,\ .72,\ .82$: final results



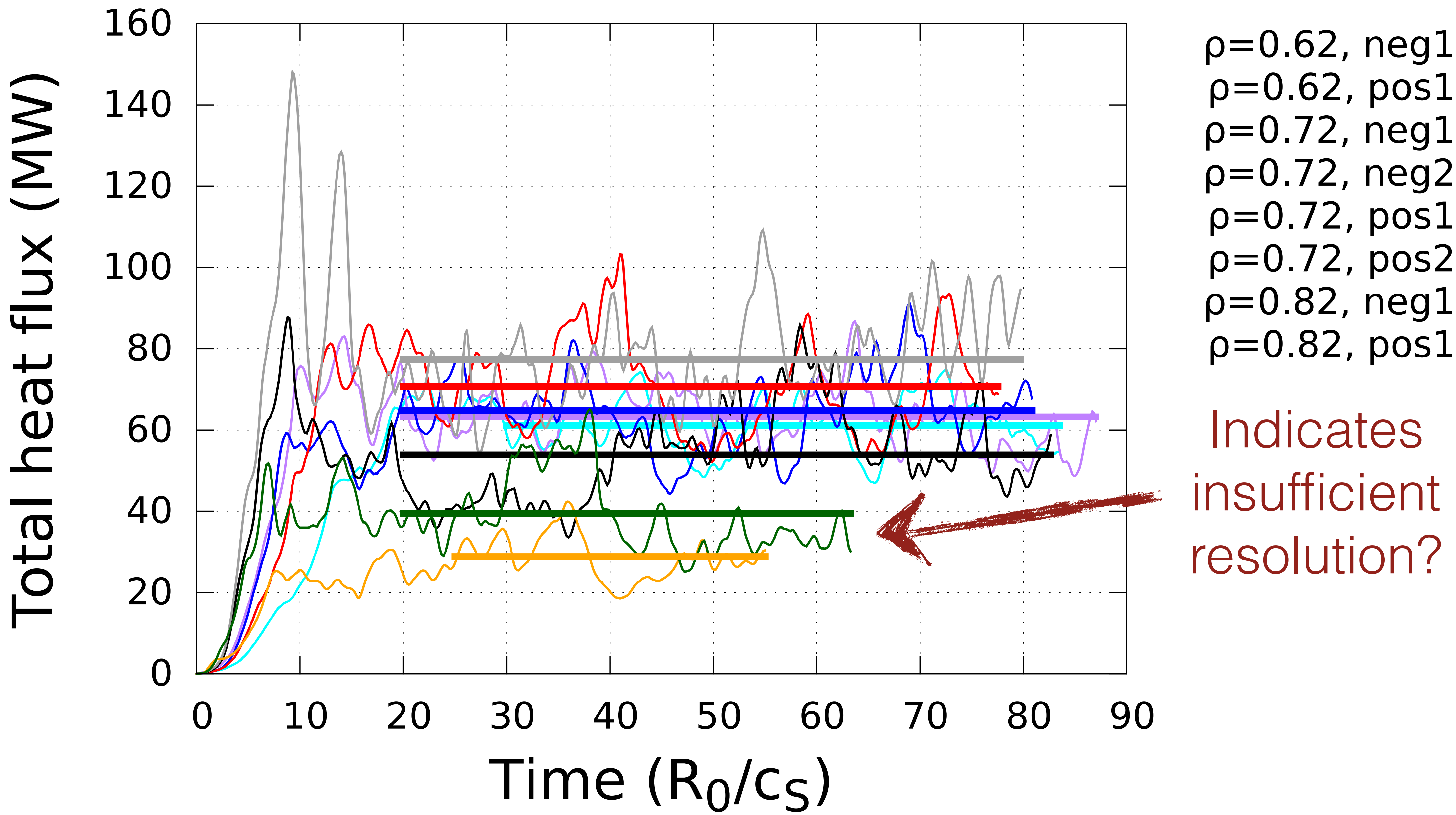
- Heat flux increases with radius in gyroBohm units

Nominal, $\rho_{tor} = .62,\ .72,\ .82$: final results



- Heat flux increases with radius in gyroBohm units, but not in MW

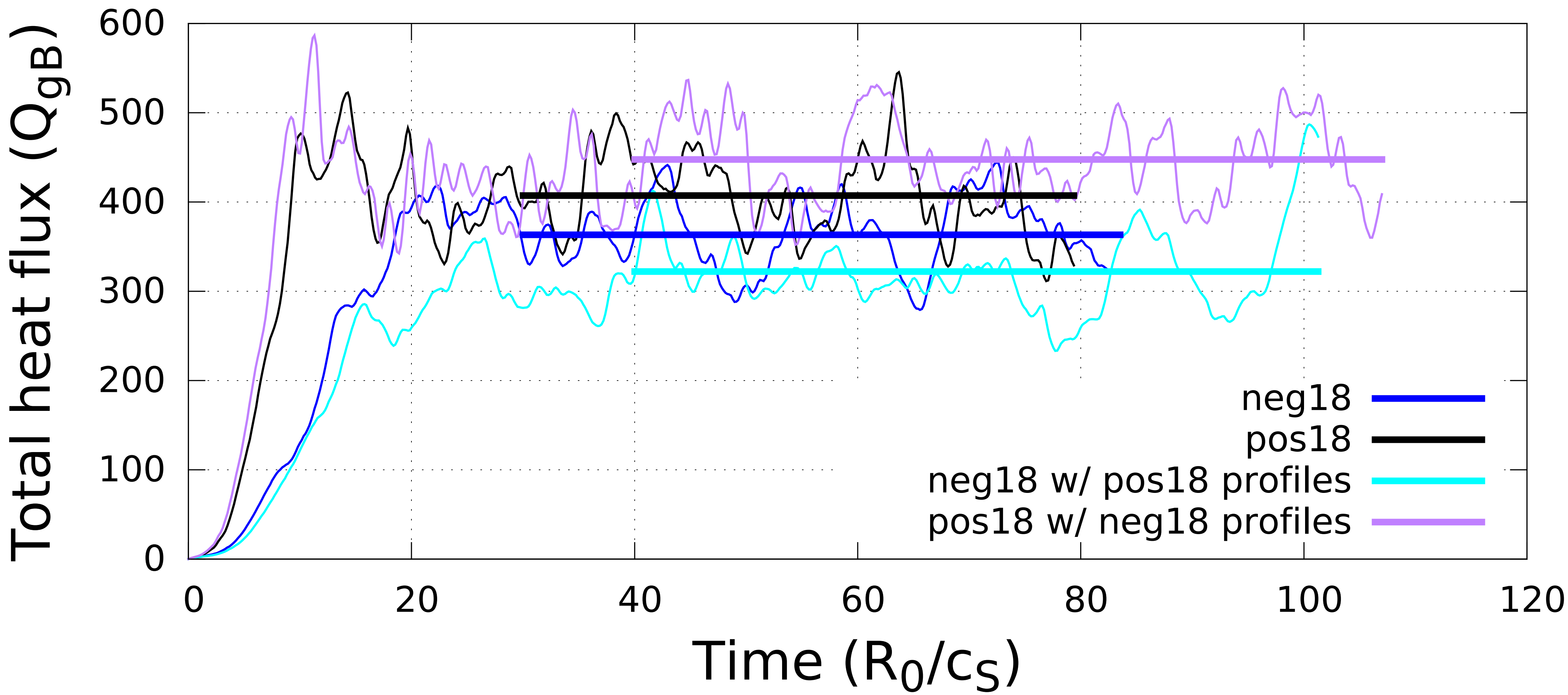
Nominal, $\rho_{tor} = .62,\ .72,\ .82$: final results



- Heat flux increases with radius in gyroBohm units, but not in MW

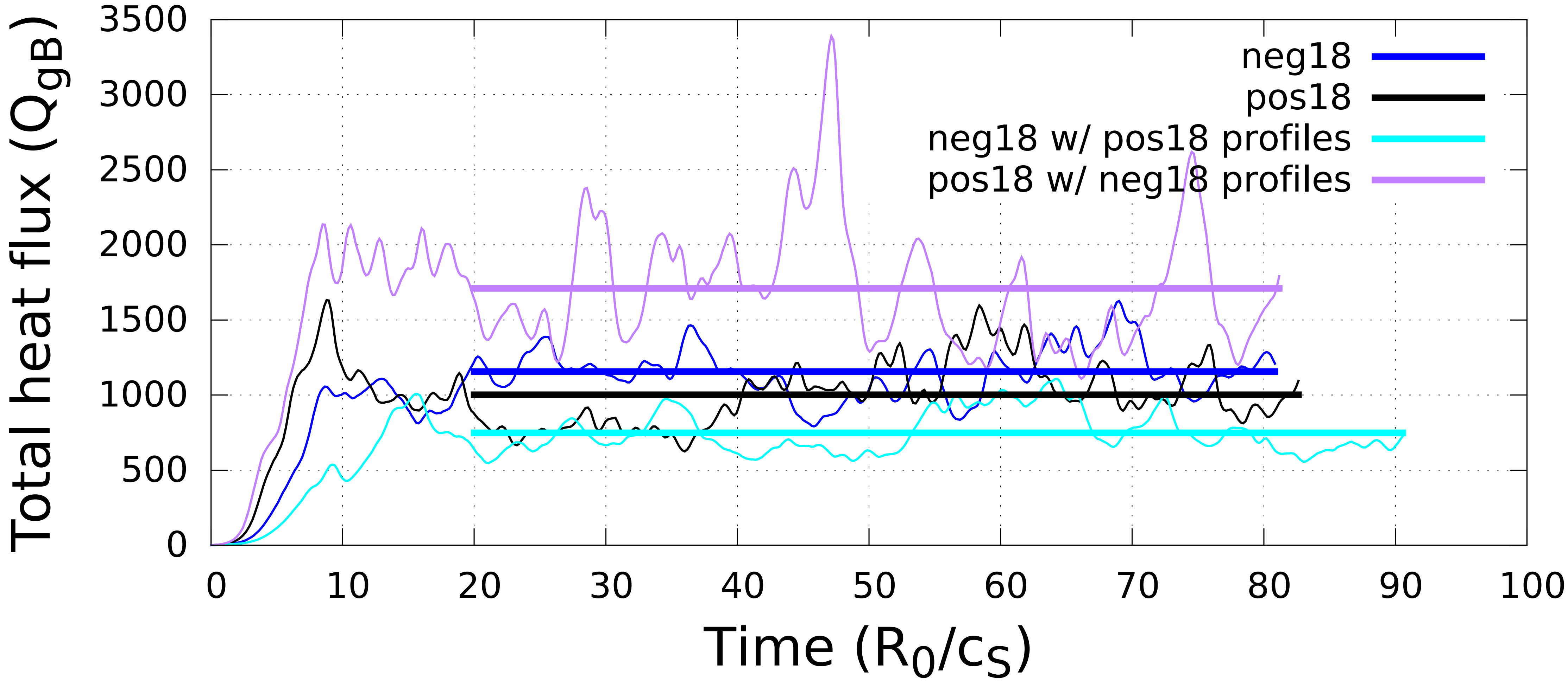
Swapping plasma profiles

Nominal, $\rho_{tor} = .62$: swapping plasma profiles



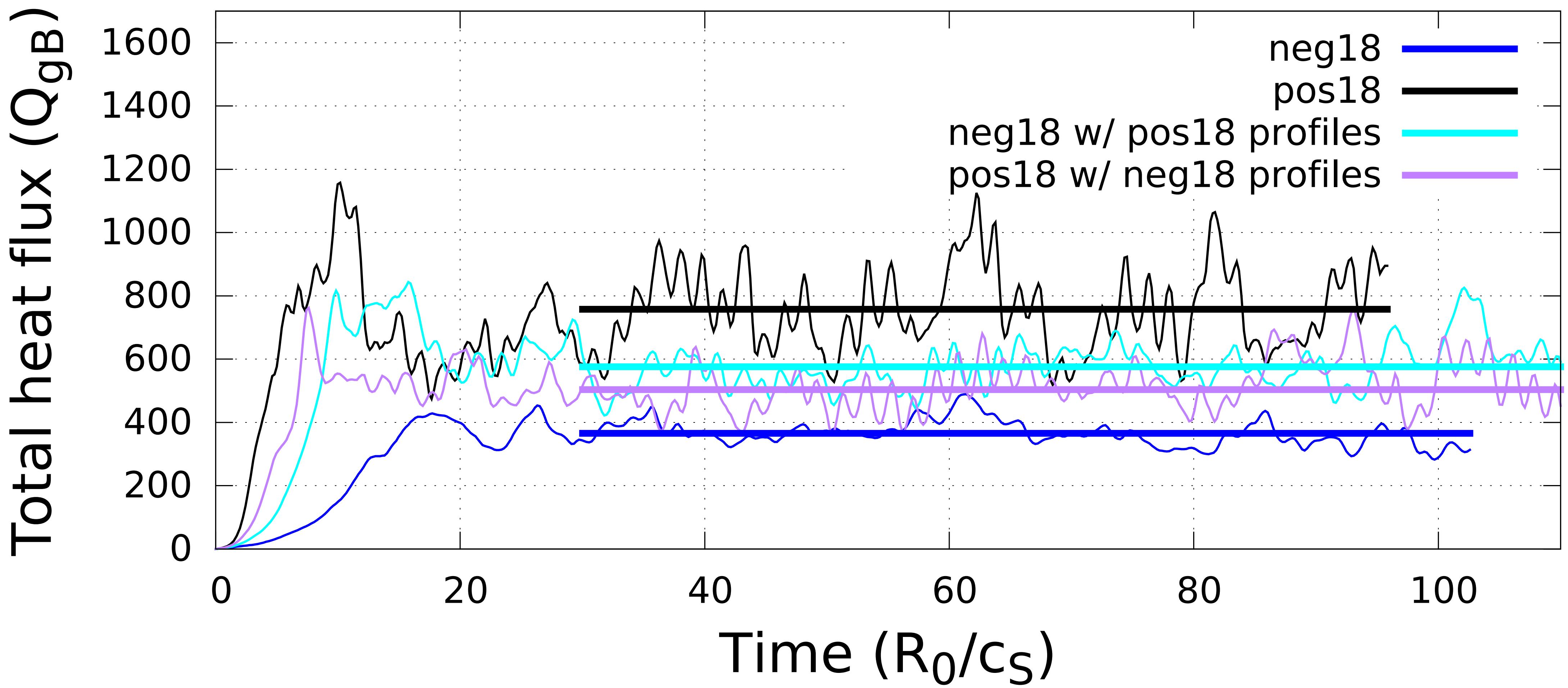
- Negative δ magnetic geometry is stabilizing (holding profiles constant)
- Changes the heat flux by roughly 20%

Nominal, $\rho_{tor} = .72$: swapping plasma profiles



- Negative δ magnetic geometry is stabilizing (holding profiles constant)
- Changes the heat flux by roughly 40%

High R_0/L_n, $\rho_{tor} = .72$: swapping plasma profiles



- Negative δ magnetic geometry is stabilizing (holding profiles constant)
- Changes the heat flux by roughly 30%

Nominal, $\rho_{tor} = .82$: swapping plasma profiles

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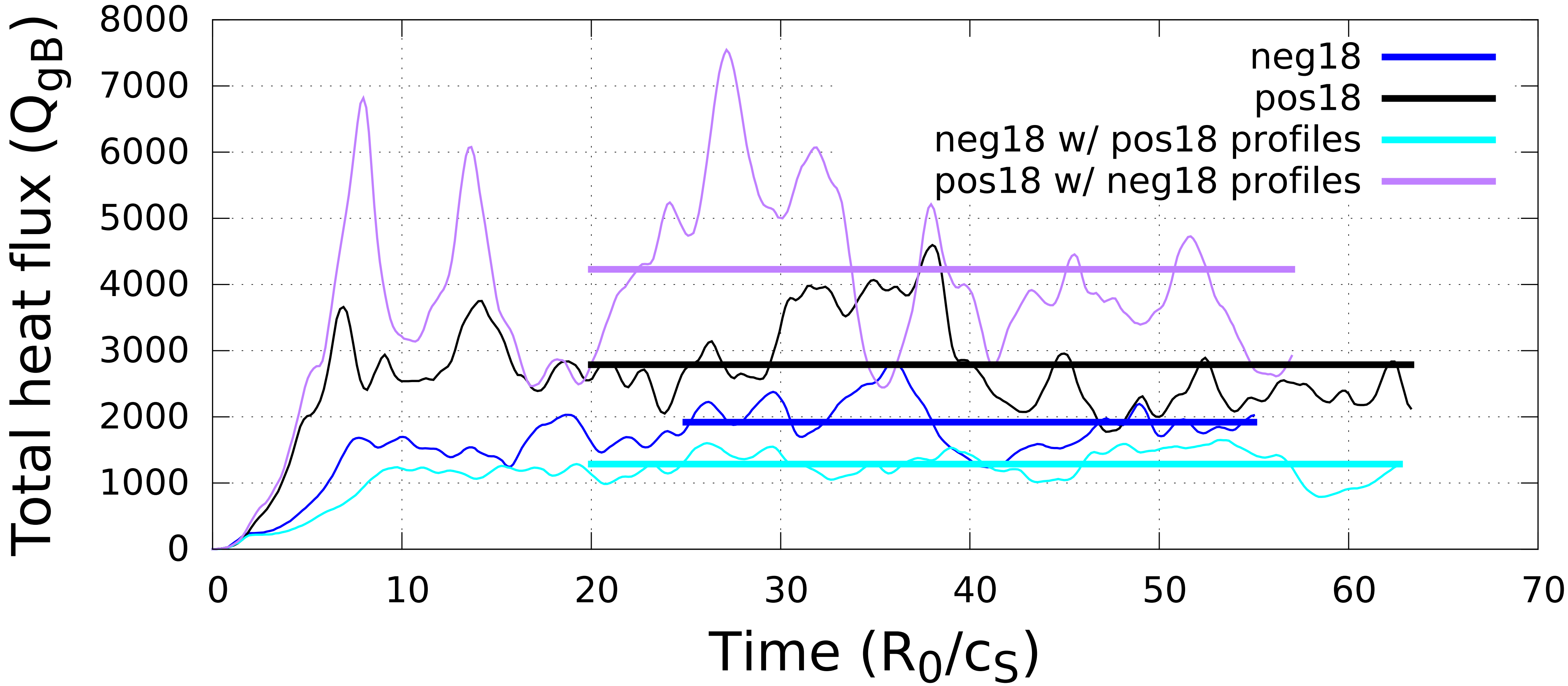
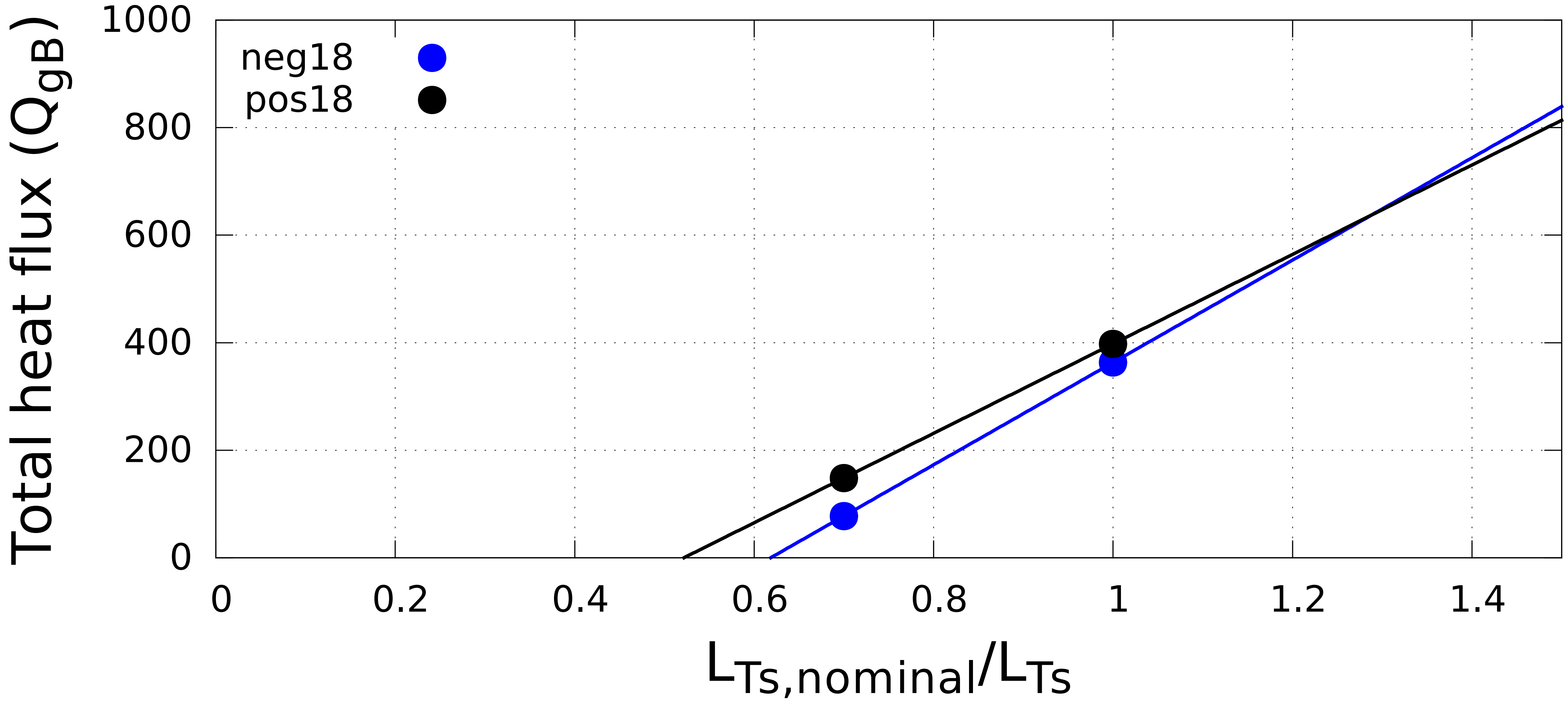


- Negative δ magnetic geometry is stabilizing (holding profiles constant)
- Changes the heat flux by roughly 65%

Investigating profile stiffness

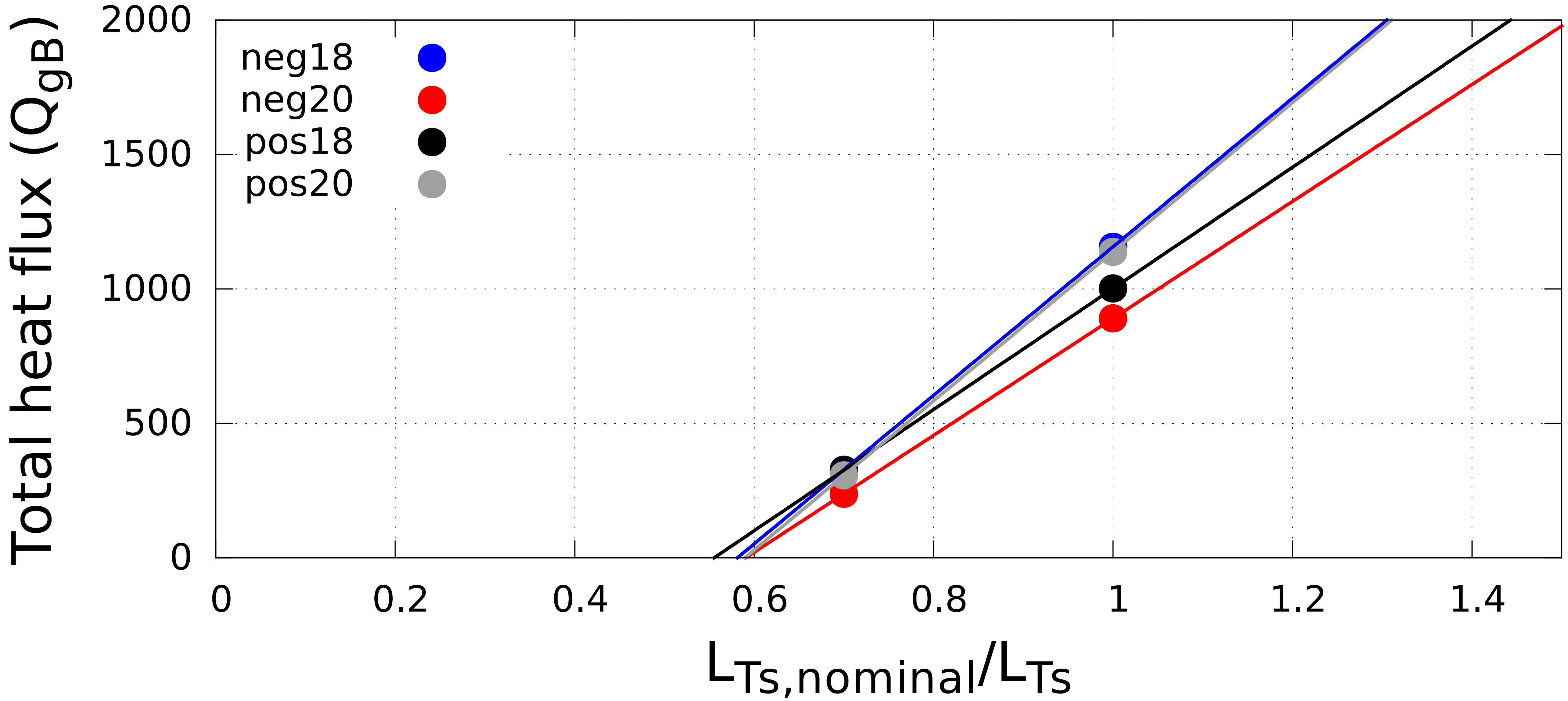
Nominal, $\rho_{tor} = .62$: profile stiffness



- Triangularity has little effect on stiffness
- Similar critical gradients

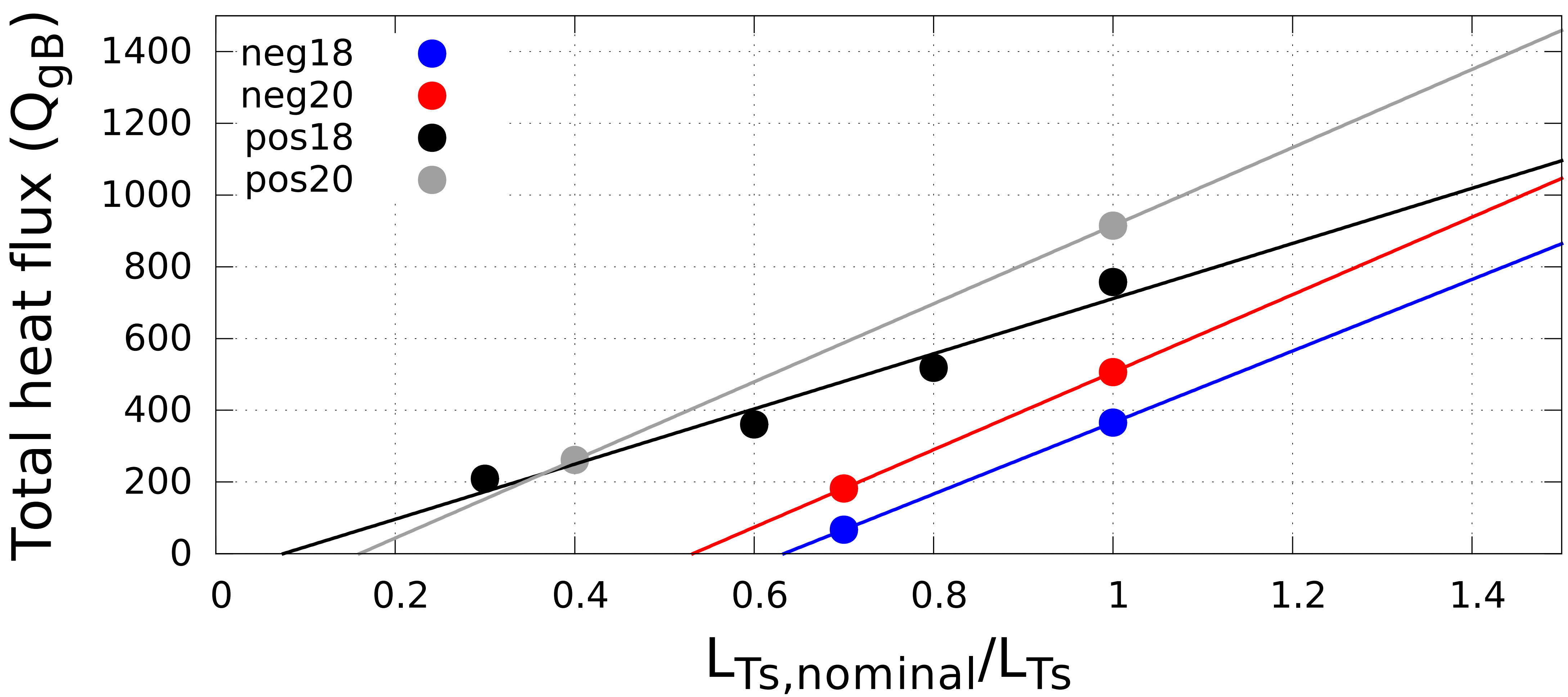
Nominal, $\rho_{tor} = .72$: profile stiffness

EPFL
Swiss Plasma Center



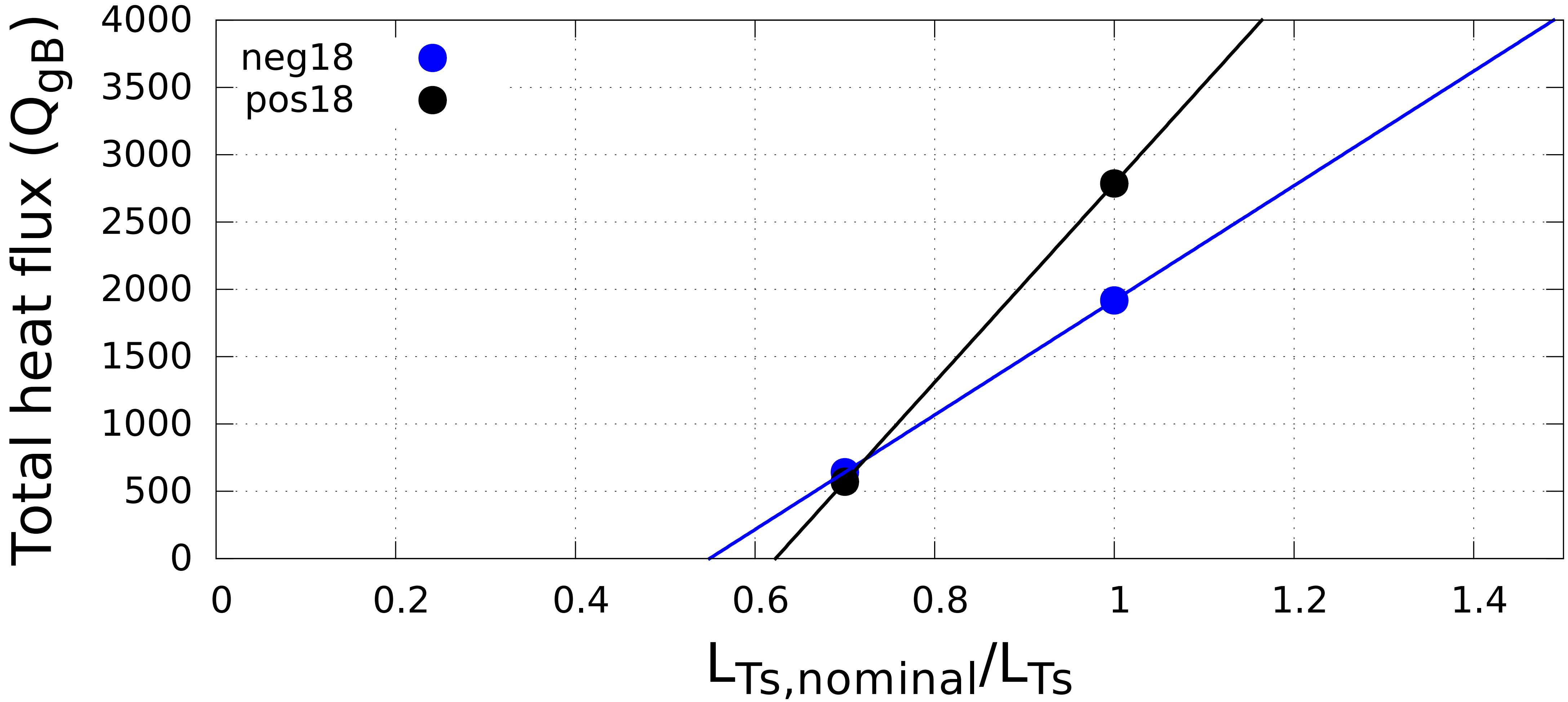
- Triangularity has little effect on stiffness
- Similar critical gradients

High R_0/L_n, $\rho_{tor} = .72$: profile stiffness



- Negative δ is slightly more stiff than positive δ
- Different critical gradient, but remember these profiles are inconsistent

Nominal, $\rho_{tor} = .82$: profile stiffness



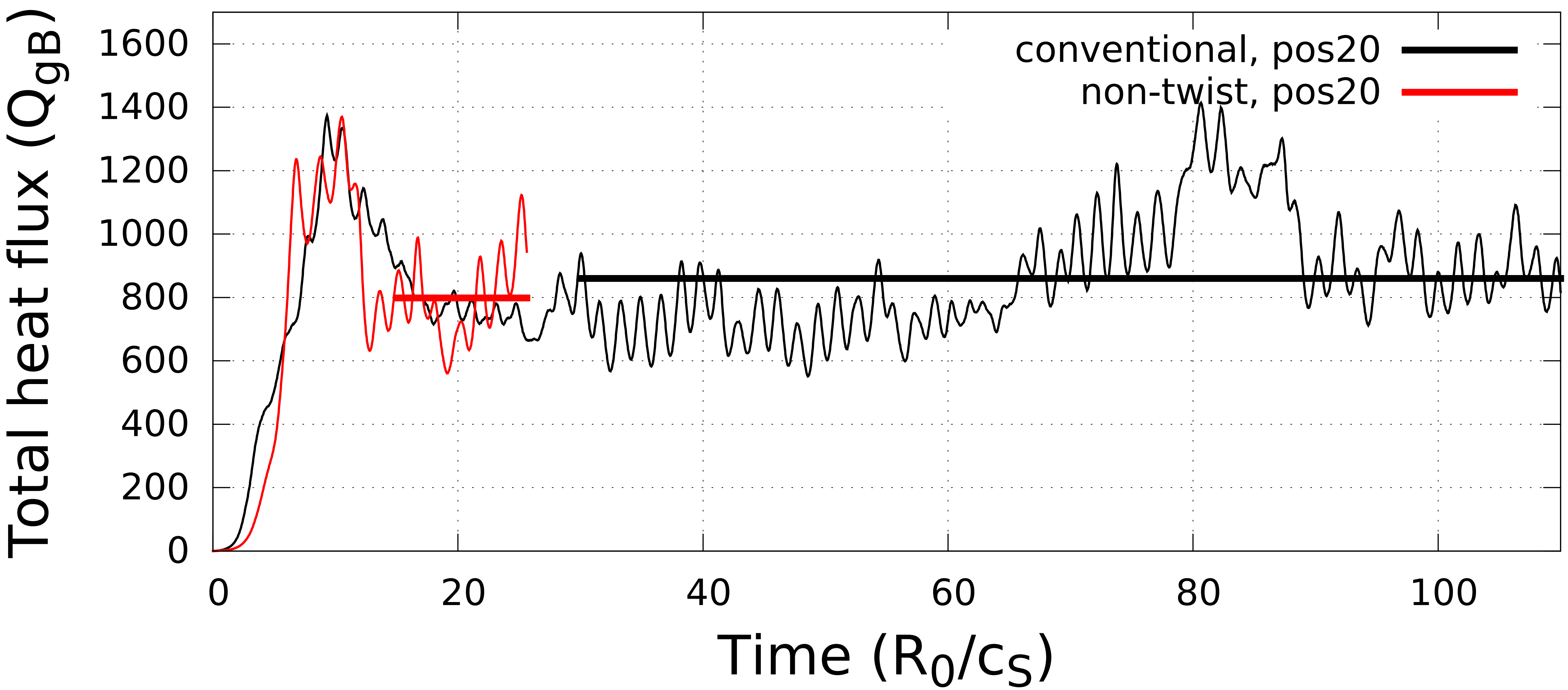
- Indicates that positive δ is somewhat more stiff
- Similar critical gradients

Takeaways

- These simulations indicate that (in order of robustness):

    1. negative δ lowers the fraction of heat transported by electrons
    2. negative δ reduces heat transport at constant plasma profiles
    3. both the plasma profiles and the magnetic geometry have a significant impact on the heat flux, which seems to increase with minor radial location
    4. positive vs. negative δ has minimal effect on profile stiffness

Future work

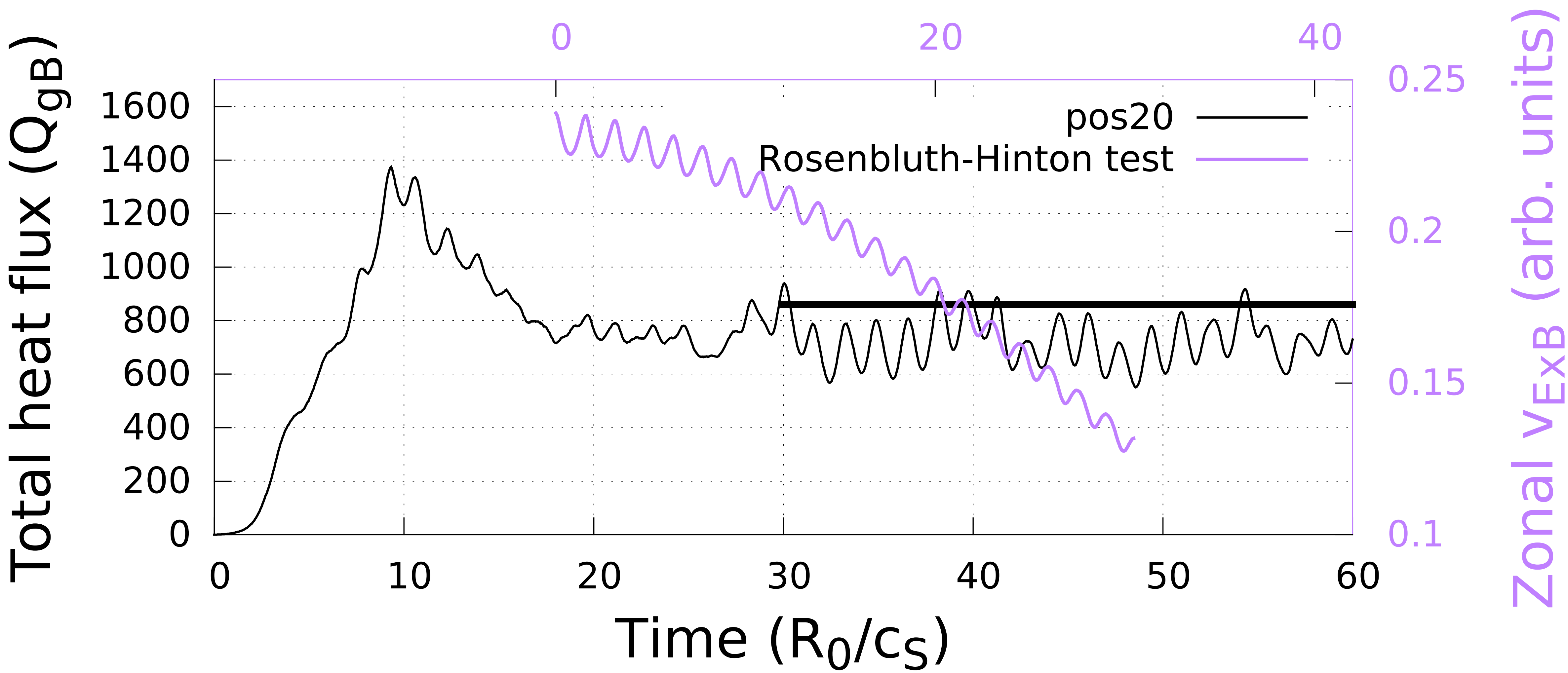


- Test if new type of simulation domain can make high $\hat{s}$ simulations cheaper
- Swap individual geometric coefficients to determine which are important

Thank you!

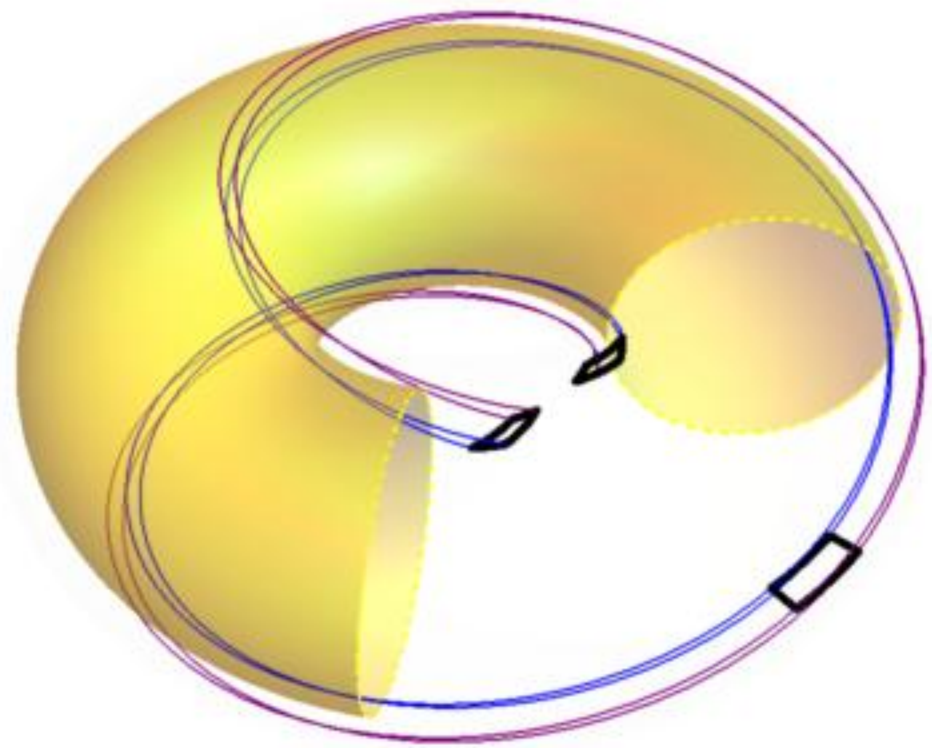
High R_0/L_n, $\rho_{tor} = .72$: examining past results

Sugama and Watanbe, *J. Plasma Phys.* ***72*** (2006).

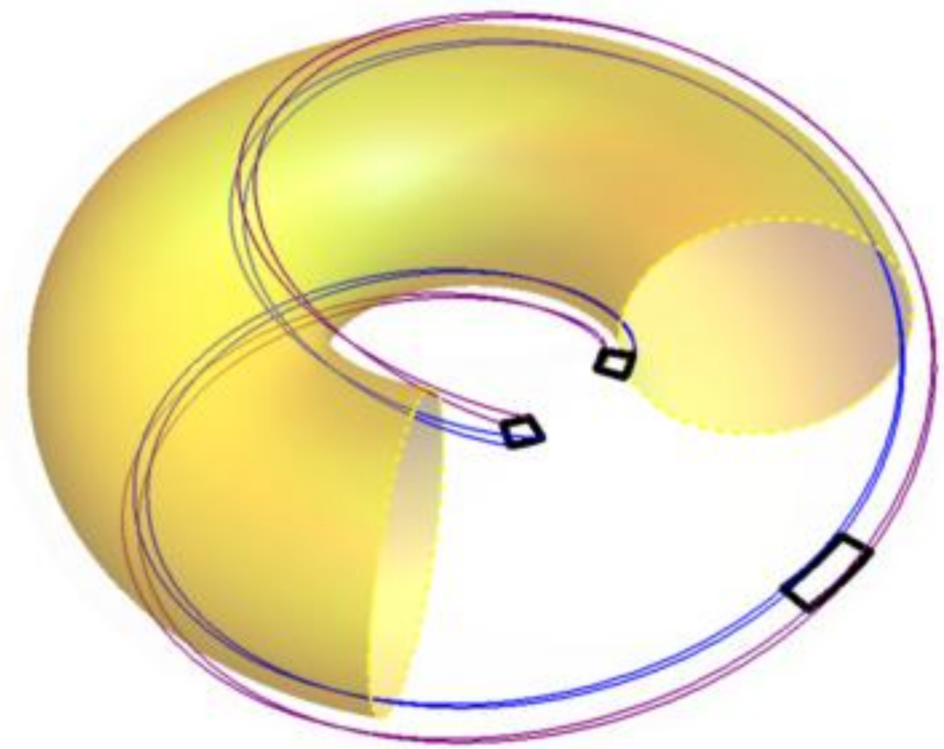


- Appears to be the GAM, as the frequency matches a Rosenbluth-Hinton test and is close to simple theoretical predictions

Non-twisting flux tube to move outwards



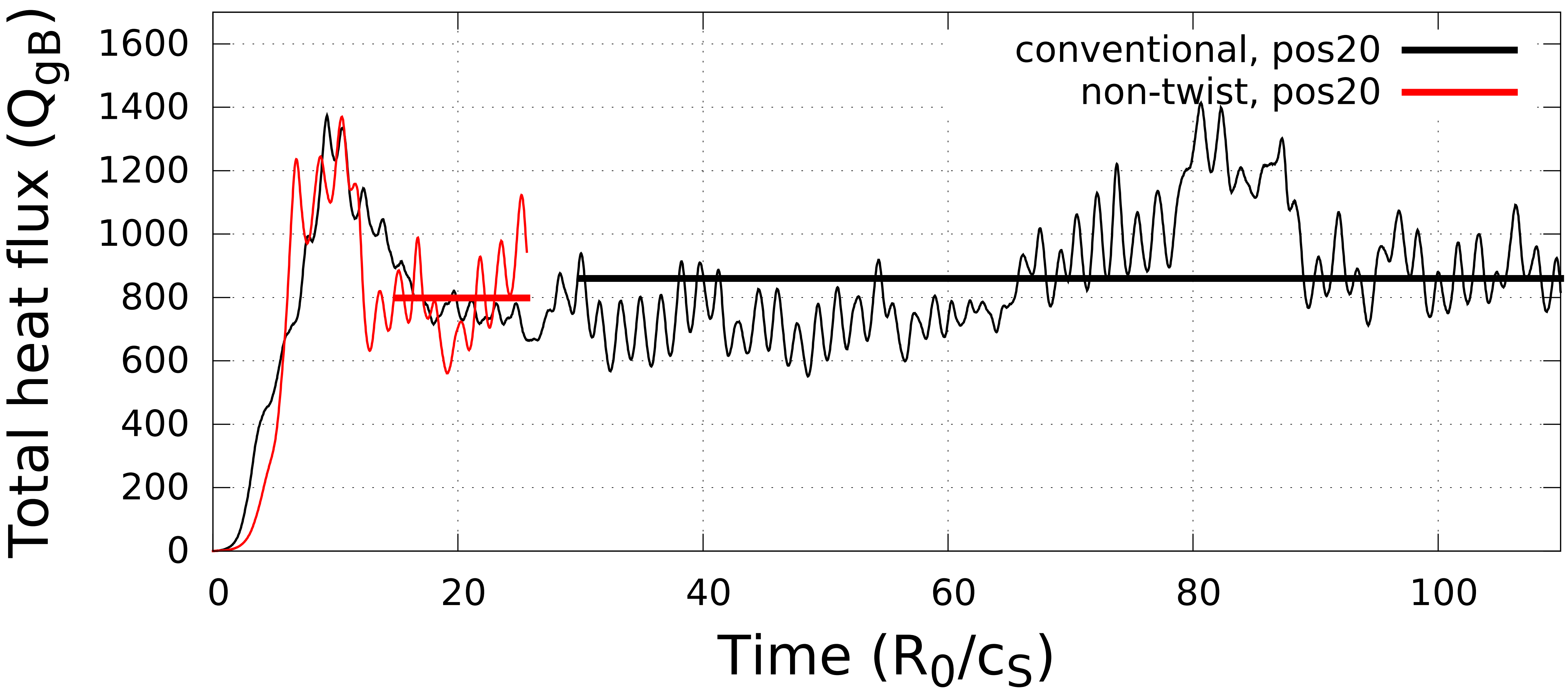
Conventional



Non-twisting

- Domain follows a central field line, but allows magnetic shear to move field lines through the periodic domain
- Should enable more efficient numerical treatment of large magnetic shear

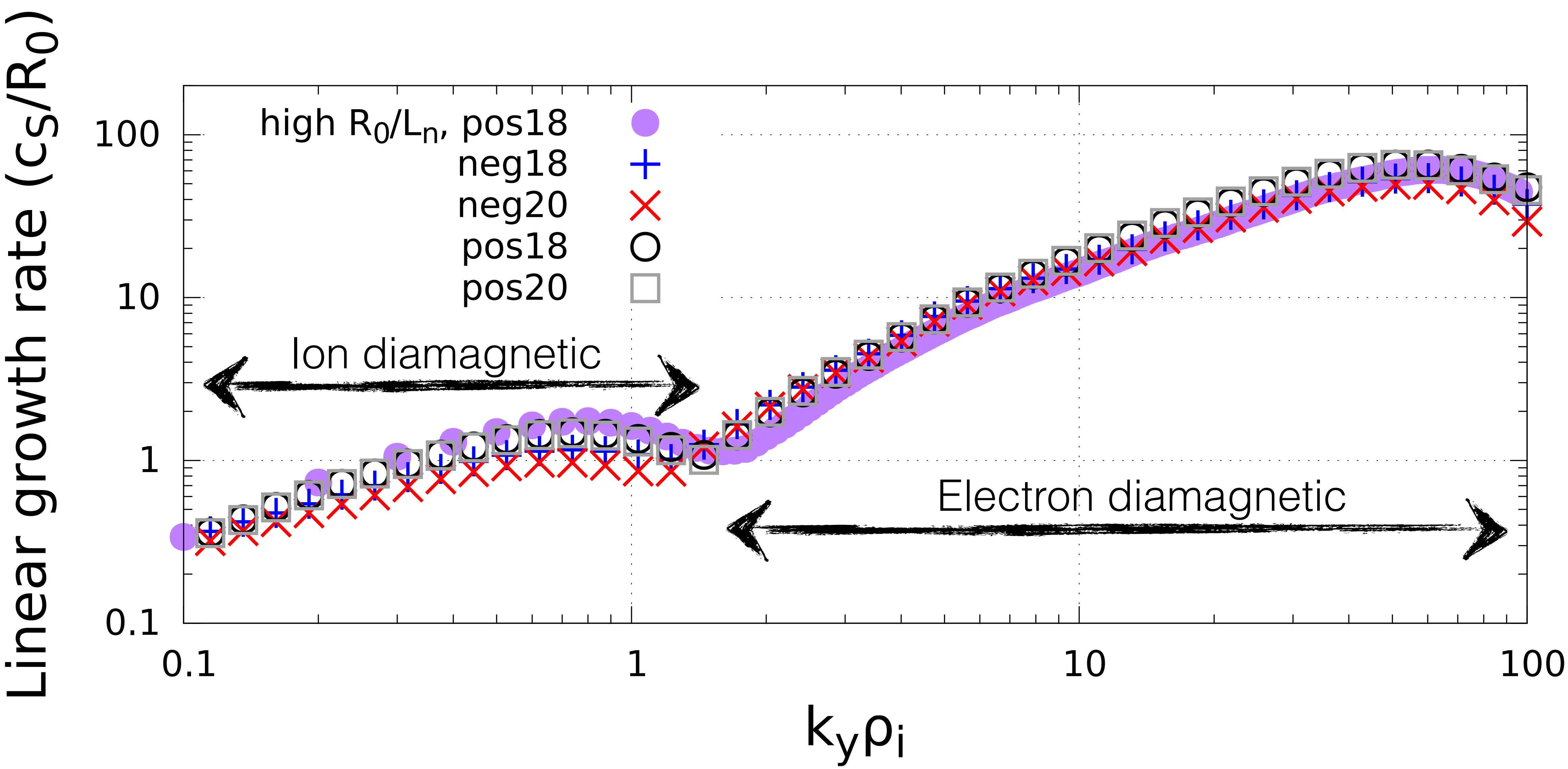
Non-twisting flux tube benchmark



- Benchmarked using full nonlinear DEMO geometry and kinetic electrons
- Next perform radial resolution study to determine computational savings

Nominal: Linear spectrum with kinetic electrons

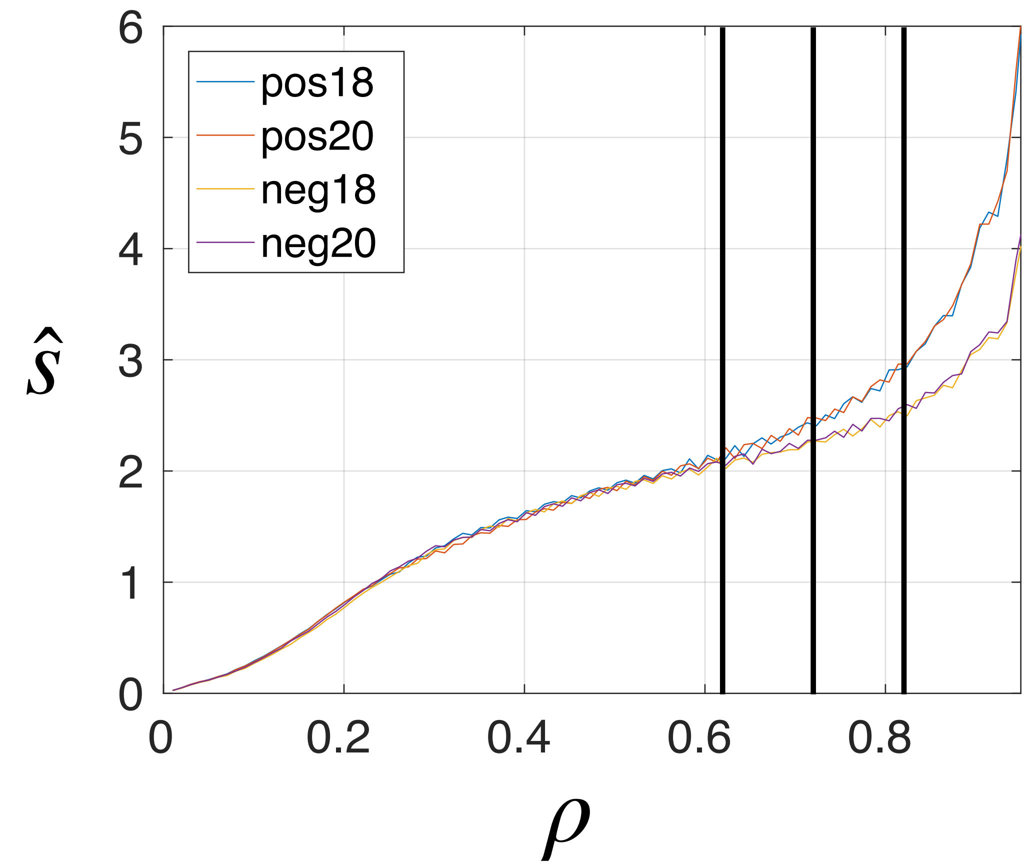
Staebler et al. *Nucl. Fusion* ***57*** (2017).



- Like the high R_0/L_n case: comparing $\gamma/k_y\Big|_{ITG} \approx 2.0$ with $\gamma/k_y\Big|_{ETG} \approx 1.3$, suggests that multi-scale interactions are marginal

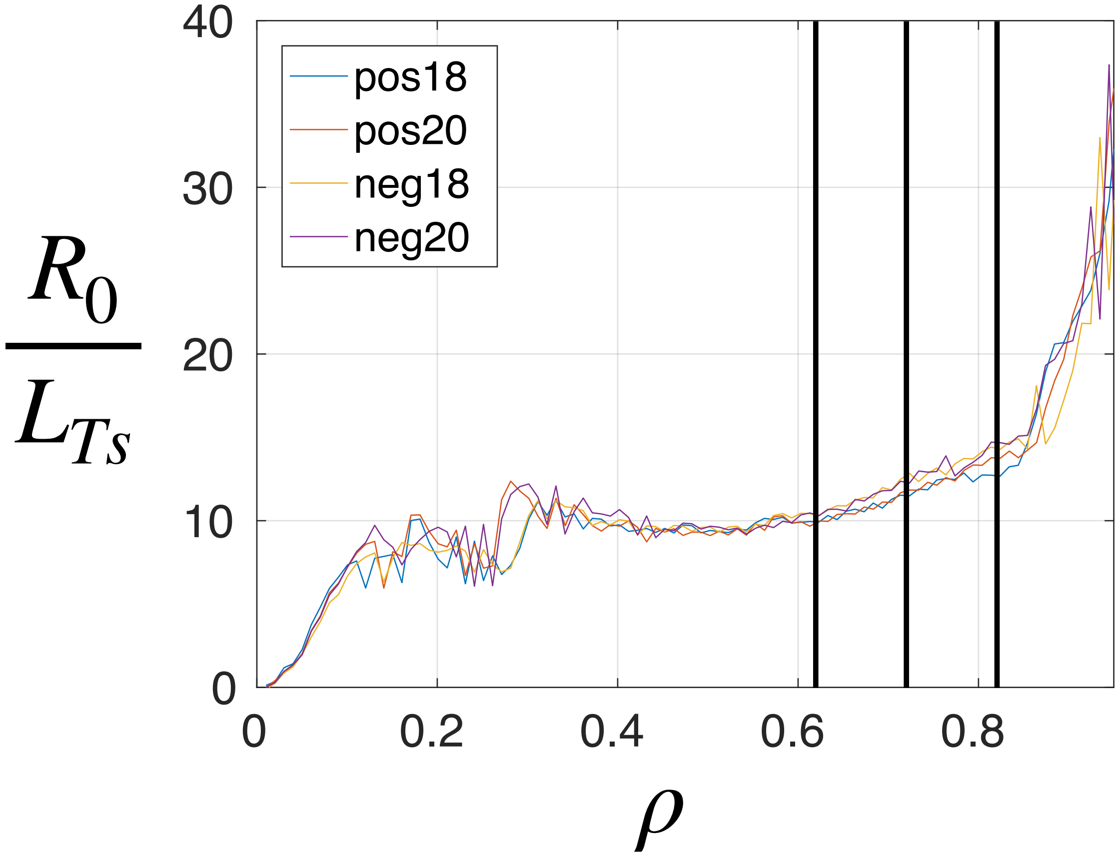
Simulate flux surfaces at $\rho = \{0.62,\ 0.72,\ 0.82\}$

- Simulations near the edge are difficult due to:
    - Large values of magnetic shear



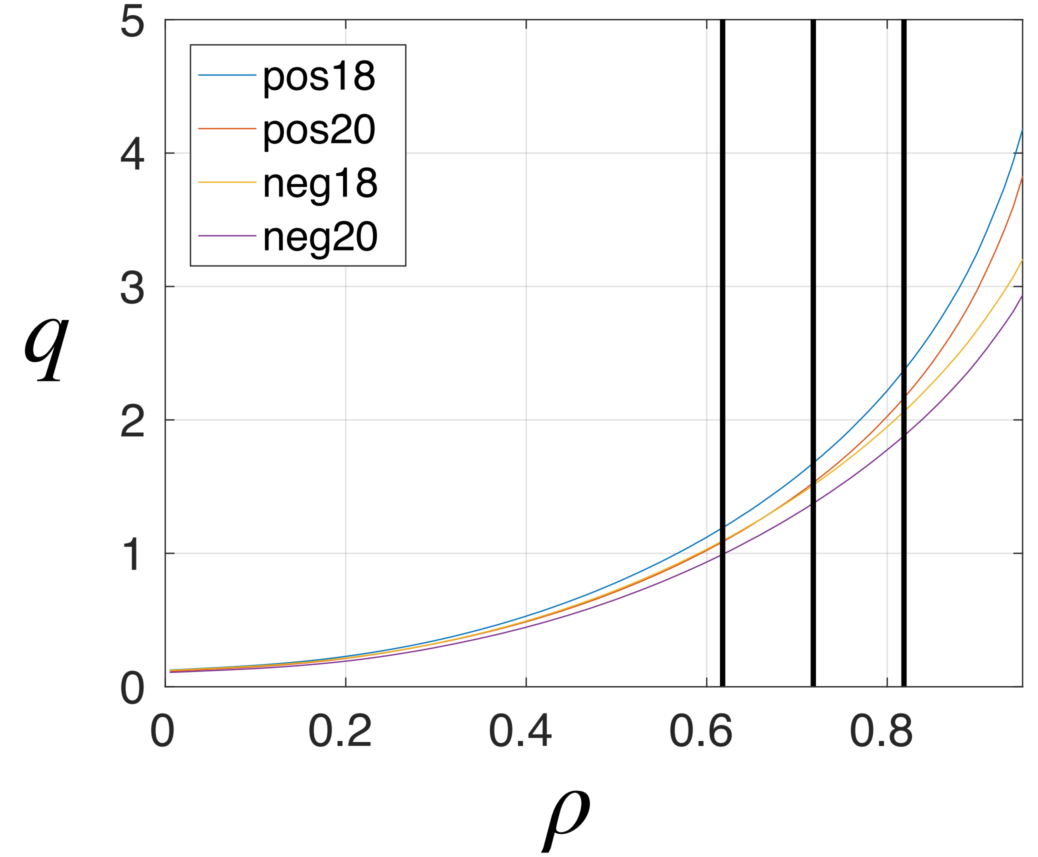
Simulate flux surfaces at $\rho = \{0.62,\ 0.72,\ 0.82\}$

- Simulations near the edge are difficult due to:
  - Large values of magnetic shear
  - Large logarithmic gradients



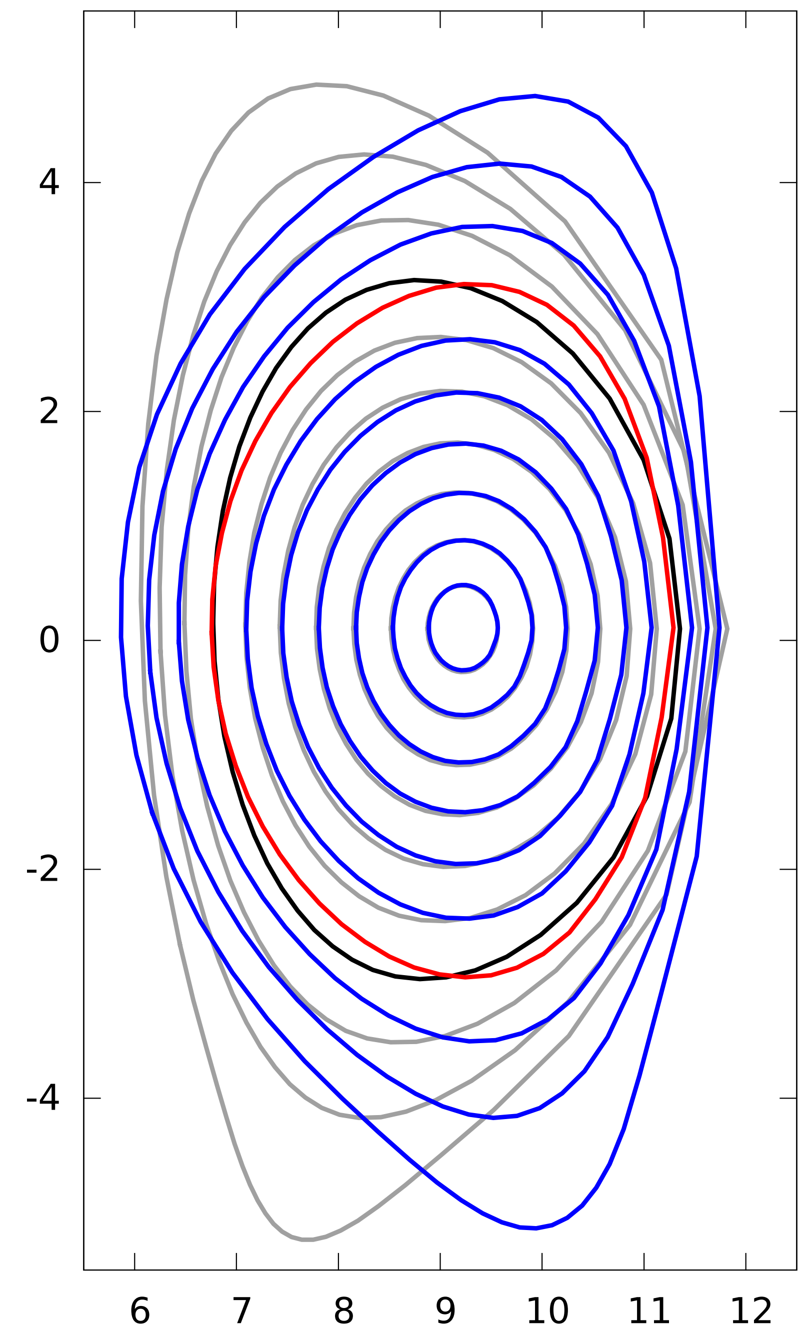
Simulate flux surfaces at $\rho = \{0.62,\ 0.72,\ 0.82\}$

- Simulations near the <u>edge</u> are difficult due to:
  - Large values of magnetic shear
  - Large logarithmic gradients
- Simulations in the <u>core</u> are problematic because:
  - Sawtooth inversion radius at $\rho \approx 0.6$



Simulate flux surfaces at $\rho = \{0.62,\ 0.72,\ 0.82\}$

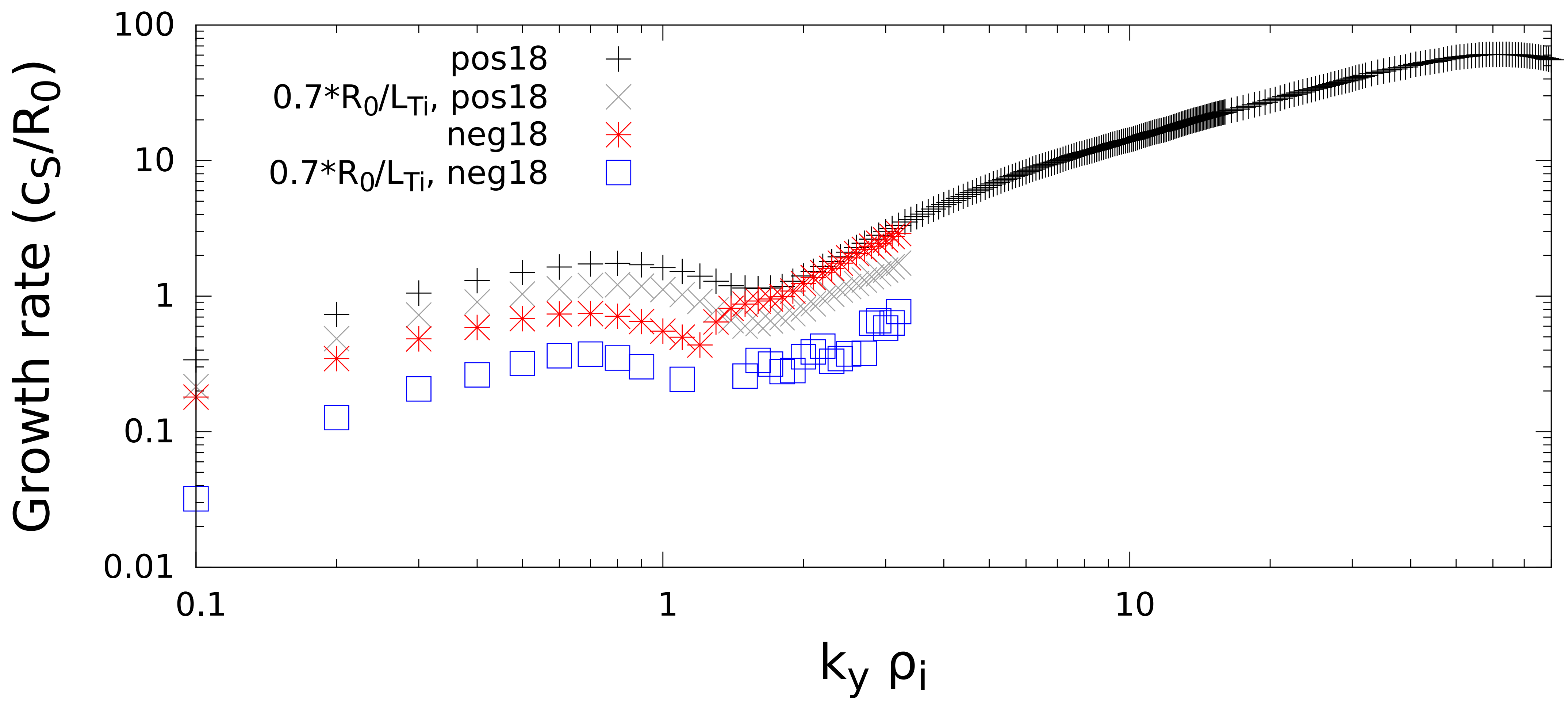
- Simulations near the edge are difficult due to:
  - Large values of magnetic shear
  - Large logarithmic gradients
- Simulations in the core are problematic because:
  - Sawtooth inversion radius at $\rho \approx 0.6$
  - Impact of triangularity is weaker



Last year: Linear results with kinetic electrons

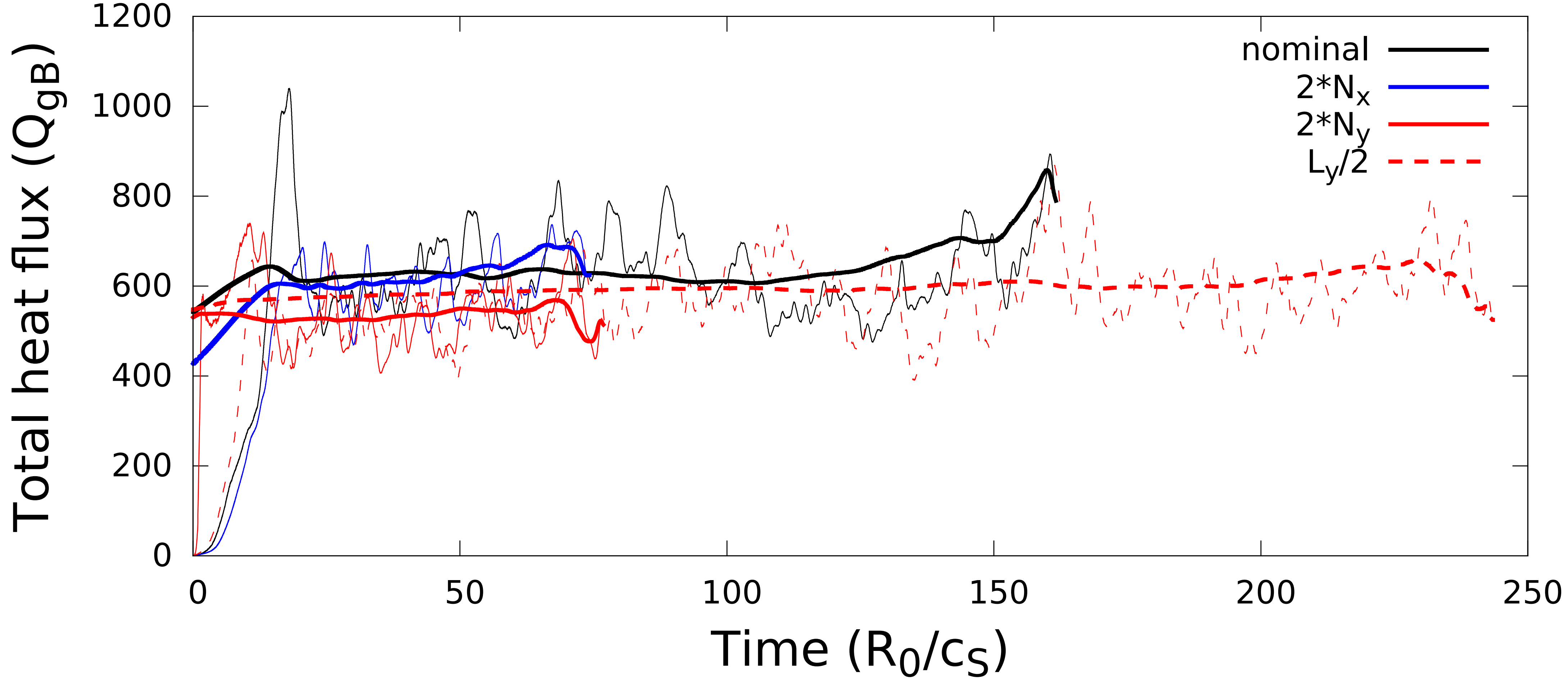
Staebler et al. *Nucl. Fusion* ***57*** (2017).

- A common rule of thumb, comparing $\gamma/k_y\Big|_{ITG} \approx 2.2$ with $\gamma/k_y\Big|_{ETG} \approx 1.0$, suggests that multi-scale interactions are fairly weak

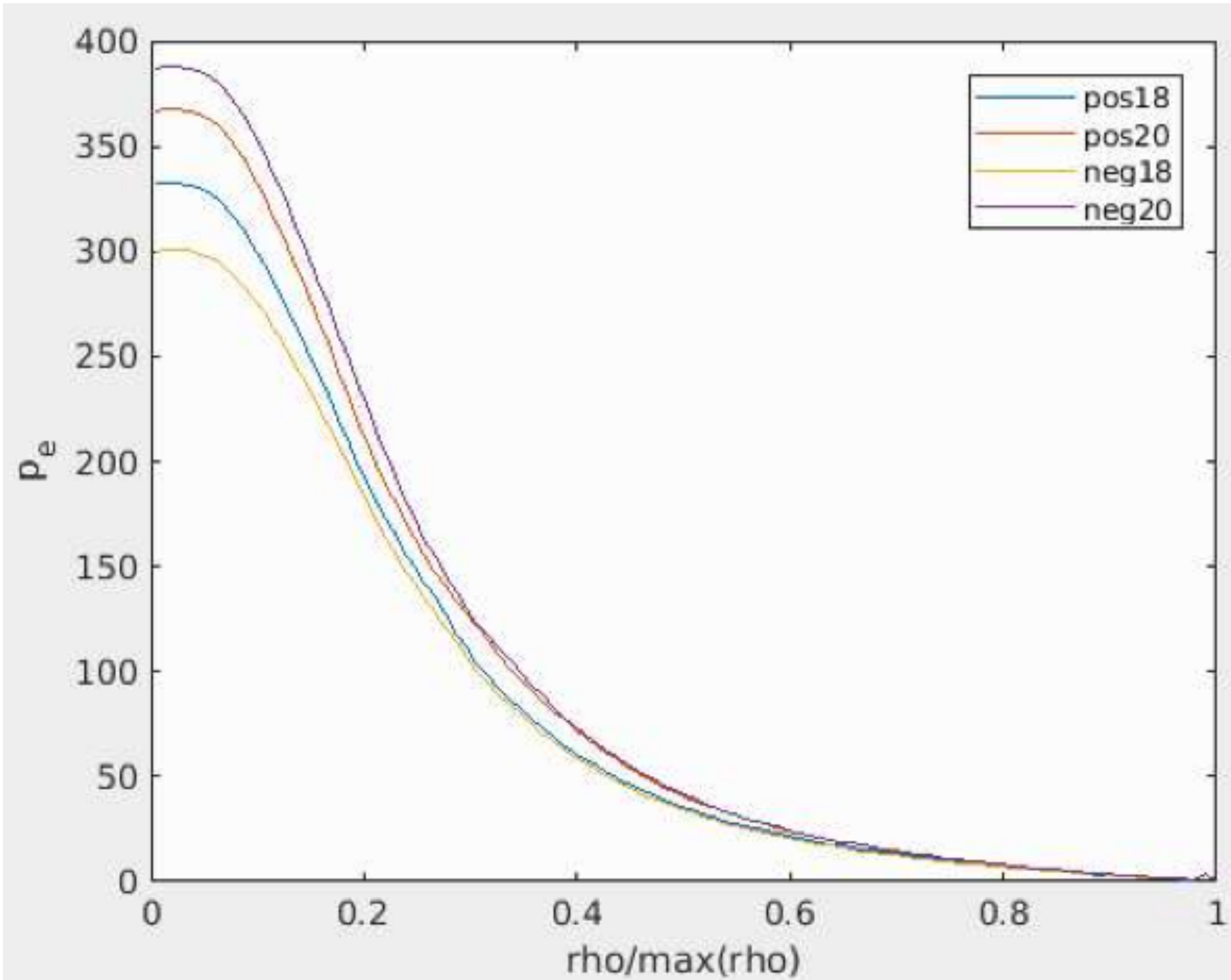


Last year: resolution study with kinetic electrons

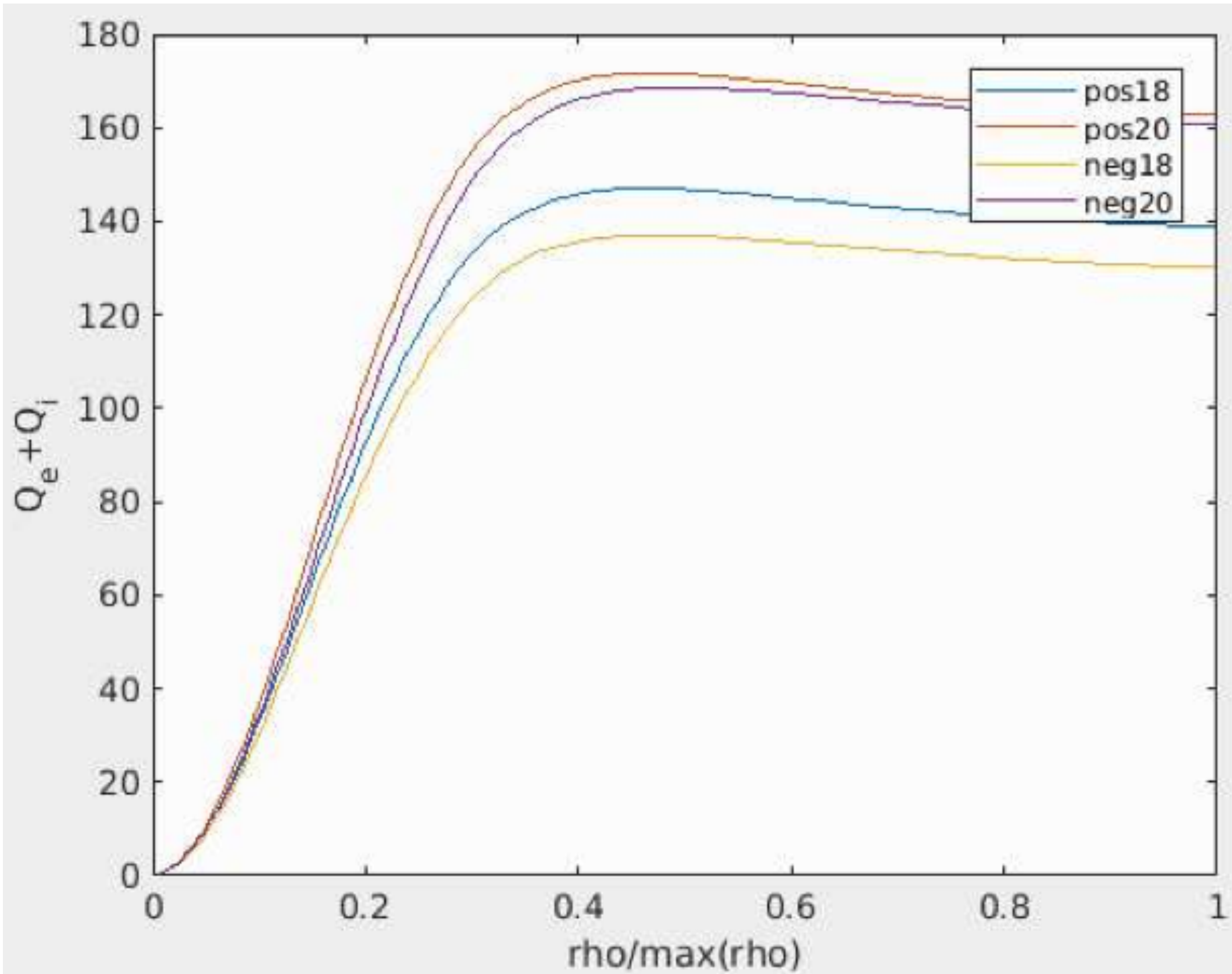
- Resolution study of the **neg20** case for the most concerning parameters seems satisfactory



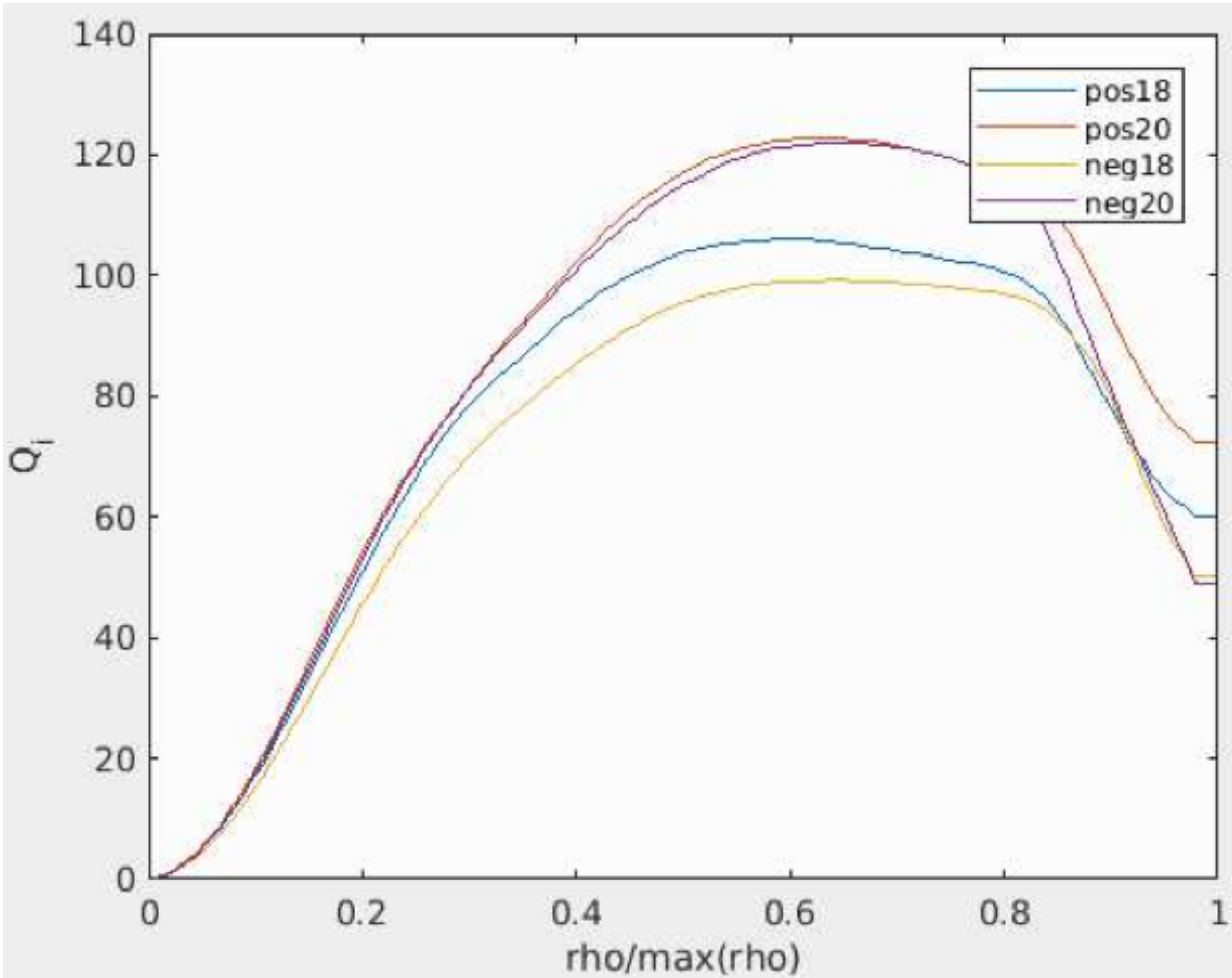
Electron pressure profile from TGLF



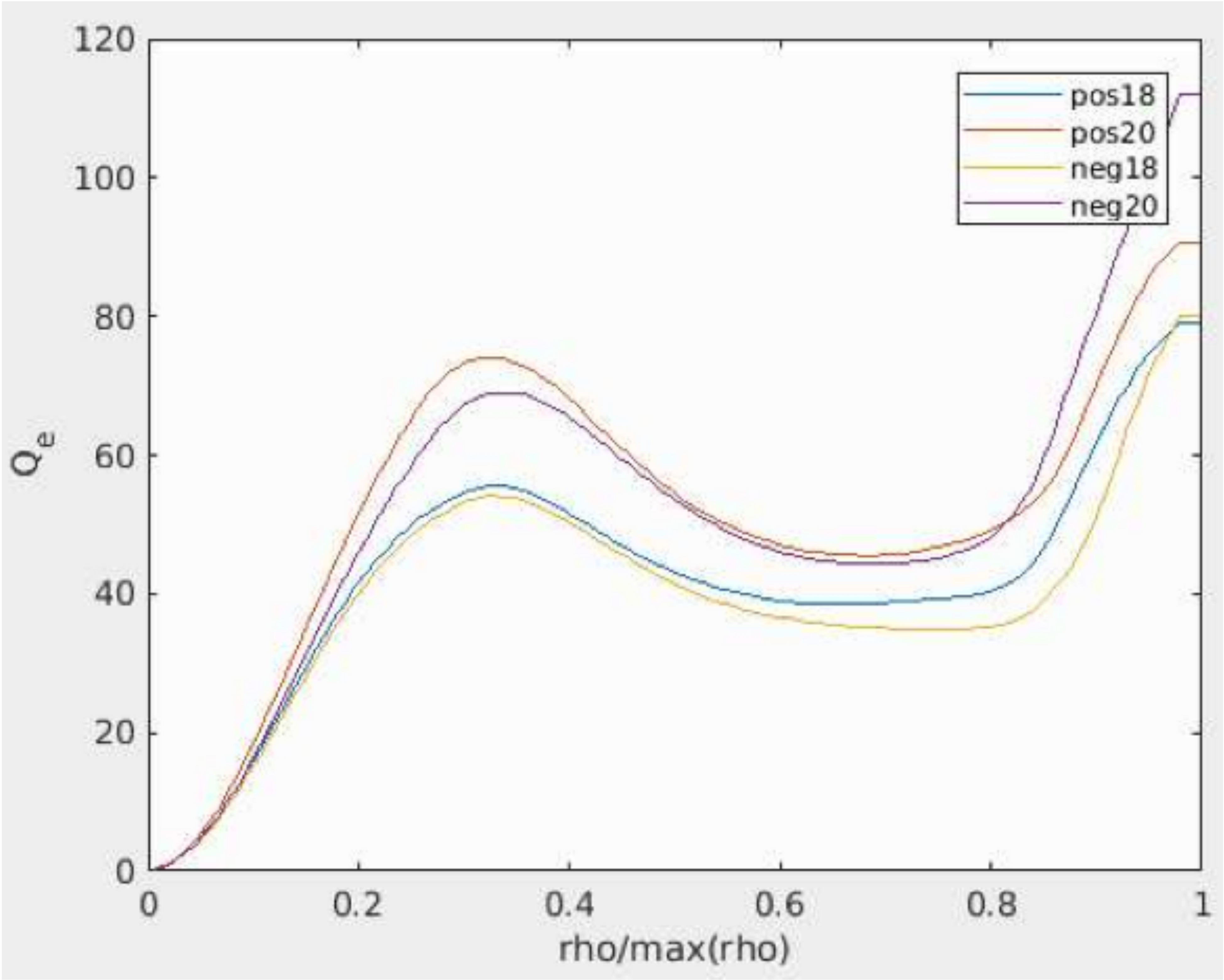
Total heat flux from TGLF in MW



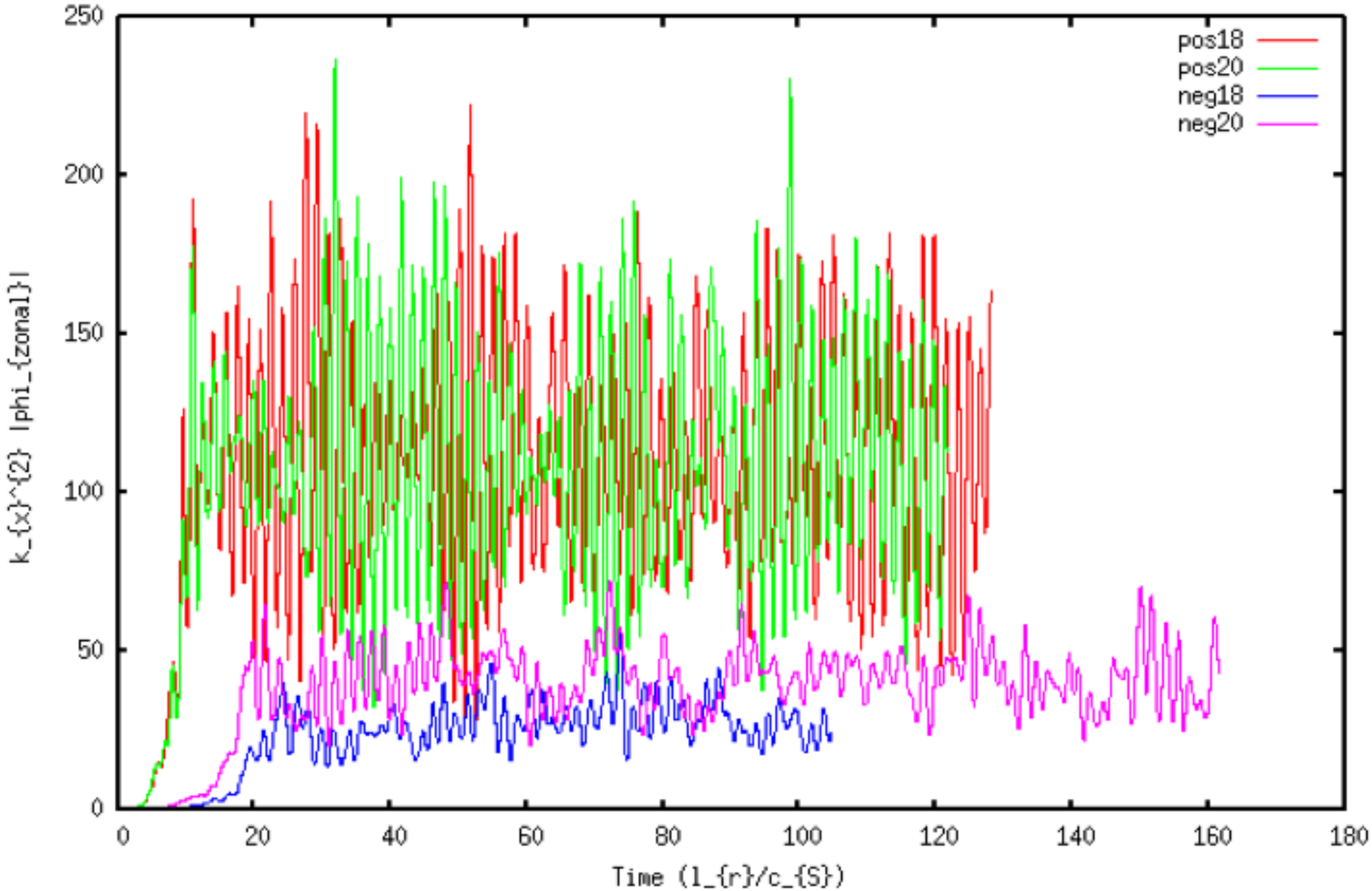
Ion heat flux from TGLF in MW



Electron heat flux from TGLF in MW



Zonal oscillations from nonlinear kinetic simulations



Input parameters for nonlinear kinetic simulations

```
! pos18
&geometry
magn_geometry = 'chease'
q0        =    1.7049163
shat      =    2.3791041
geomdir   = '.'
geomfile = 'ogyropsi.h5'
x_def = 'arho_t'
flux_pos =    0.72000000
minor_r  =    0.42802953
major_R  =    1.0000000
dpdx_term= 'gradB_eq_curv'
dpdx_pm  =    0.31365353E-01
norm_flux_projection   = F
/

&species
name    = 'ions'
omn     =    3.7726245
omt     =    10.384133

mass    =    1.0000000
temp    =    1.1012114
dens    =    1.0000000
charge =  1
/

&species
name    = 'electrons'
omn     =    3.7726245
omt     =    10.046073

mass    =   0.21785000E-03
temp    =    1.0000000
dens    =    1.0000000
charge = -1
```

omt/omn = 2.75

```
! pos20
&geometry
magn_geometry = 'chease'
q0        =    1.5550048
shat      =    2.3914969
geomdir   = '.'
geomfile = 'ogyropsi.h5'
x_def = 'arho_t'
flux_pos =    0.72000000
minor_r  =    0.42847416
major_R  =    1.0000000
dpdx_term= 'gradB_eq_curv'
dpdx_pm  =    0.33737323E-01
norm_flux_projection   = F
/

&species
name    = 'ions'
omn     =    3.9569369
omt     =    10.734664

mass    =    1.0000000
temp    =    1.1218137
dens    =    1.0000000
charge =  1
/

&species
name    = 'electrons'
omn     =    3.9569369
omt     =    10.514612

mass    =   0.21785000E-03
temp    =    1.0000000
dens    =    1.0000000
charge = -1
```

omt/omn = 2.71

```
! neg18
&geometry
magn_geometry = 'chease'
q0        =    1.5343302
shat      =    2.2000282
geomdir   = '.'
geomfile = 'ogyropsi.h5'
x_def = 'arho_t'
flux_pos =    0.72000000
minor_r  =    0.41714032
major_R  =    1.0000000
dpdx_term= 'gradB_eq_curv'
dpdx_pm  =    0.36014773E-01
norm_flux_projection   = F
/

&species
name    = 'ions'
omn     =    2.7080109
omt     =    8.5717145

mass    =    1.0000000
temp    =    1.1058137
dens    =    1.0000000
charge =  1
/

&species
name    = 'electrons'
omn     =    2.7080109
omt     =    9.9598991

mass    =   0.21785000E-03
temp    =    1.0000000
dens    =    1.0000000
charge = -1
```

omt/omn = 3.16

```
! neg20
&geometry
magn_geometry = 'chease'
q0        =    1.3988000
shat      =    2.2103327
geomdir   = '.'
geomfile = 'ogyropsi.h5'
x_def = 'arho_t'
flux_pos =    0.72000000
minor_r  =    0.41760834
major_R  =    1.0000000
dpdx_term= 'gradB_eq_curv'
dpdx_pm  =    0.39377451E-01
norm_flux_projection   = F
/

&species
name    = 'ions'
omn     =    2.9316145
omt     =    9.9035116

mass    =    1.0000000
temp    =    1.1116355
dens    =    1.0000000
charge =  1
/

&species
name    = 'electrons'
omn     =    2.9316145
omt     =    9.9796884

mass    =   0.21785000E-03
temp    =    1.0000000
dens    =    1.0000000
charge = -1
```

omt/omn = 3.38

Input parameters for nonlinear adiabatic sims.

```
pos18
&geometry
magn_geometry = 'chease'
q0        =    1.7049163
shat      =    2.3791041
geomdir   = '.'
geomfile = 'ogyropsi.h5'
x_def = 'arho_t'
flux_pos =    0.72000000
minor_r  =    0.42802953
major_R  =    1.0000000
dpdx_term= 'gradB_eq_curv'
dpdx_pm  =    0.31365353E-01
norm_flux_projection  = F
/

&species
name    = 'ions'
omn     =    5.5182257
omt     =    14.977186

mass    =    1.0000000
temp    =    1.0000000
dens    =    1.0000000
charge =  1
```

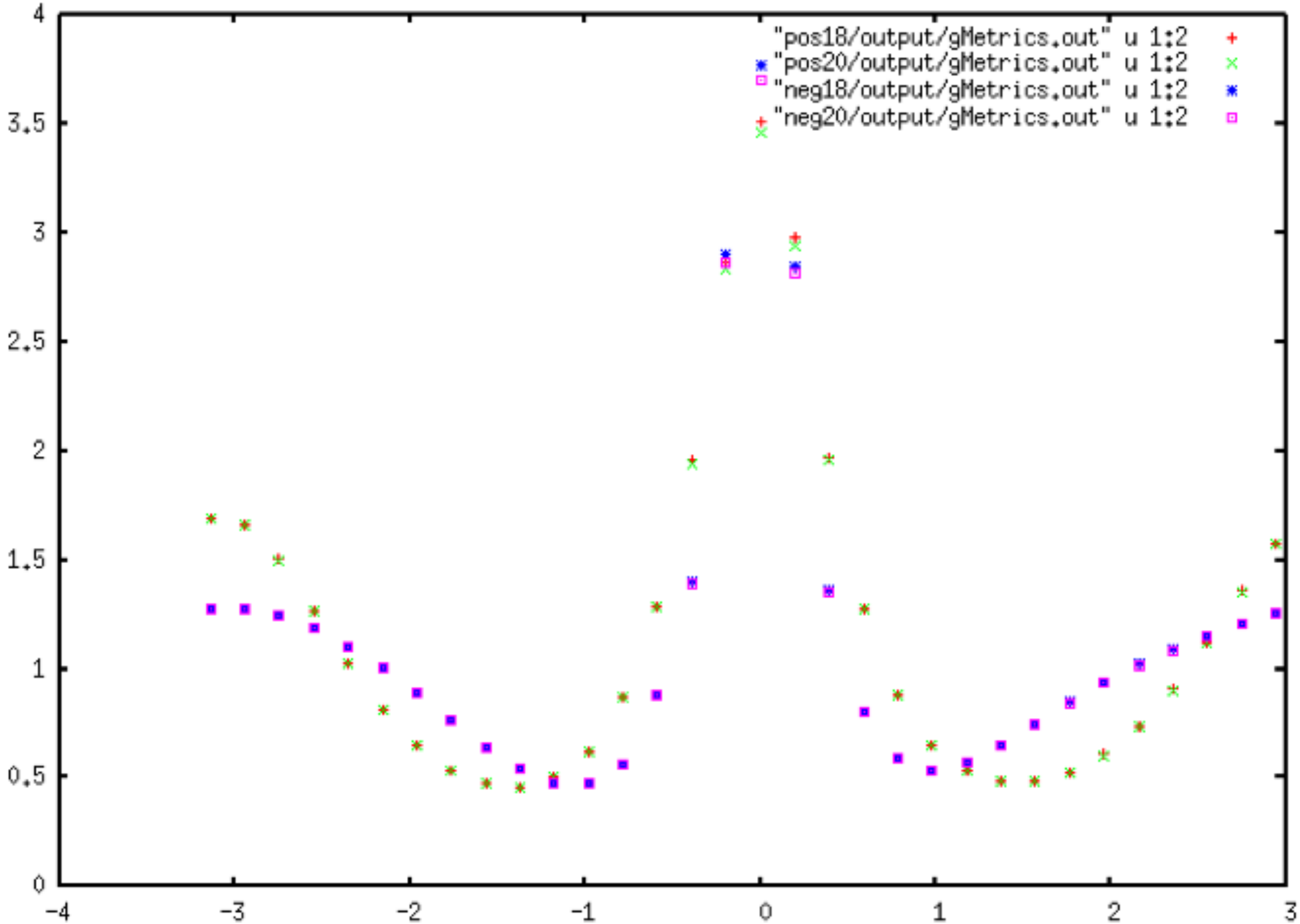
```
pos20
&geometry
magn_geometry = 'chease'
q0        =    1.5550048
shat      =    2.3914969
geomdir   = '.'
geomfile = 'ogyropsi.h5'
x_def = 'arho_t'
flux_pos =    0.72000000
minor_r  =    0.42847416
major_R  =    1.0000000
dpdx_term= 'gradB_eq_curv'
dpdx_pm  =    0.33737323E-01
norm_flux_projection  = F
/

&species
name    = 'ions'
omn     =    5.0452291
omt     =    13.214426

mass    =    1.0000000
temp    =    1.0000000
dens    =    1.0000000
charge =  1
```

```
neg18
&geometry
magn_geometry = 'chease'
q0        =    1.5343302
shat      =    2.2000282
geomdir   = '.'
geomfile = 'ogyropsi.h5'
x_def = 'arho_t'
flux_pos =    0.72000000
minor_r  =    0.41714032
major_R  =    1.0000000
dpdx_term= 'gradB_eq_curv'
dpdx_pm  =    0.36014773E-01
norm_flux_projection  = F
/

&species
name    = 'ions'
omn     =    3.4580024
omt     =    11.342345

mass    =    1.0000000
temp    =    1.0000000
dens    =    1.0000000
charge =  1
```

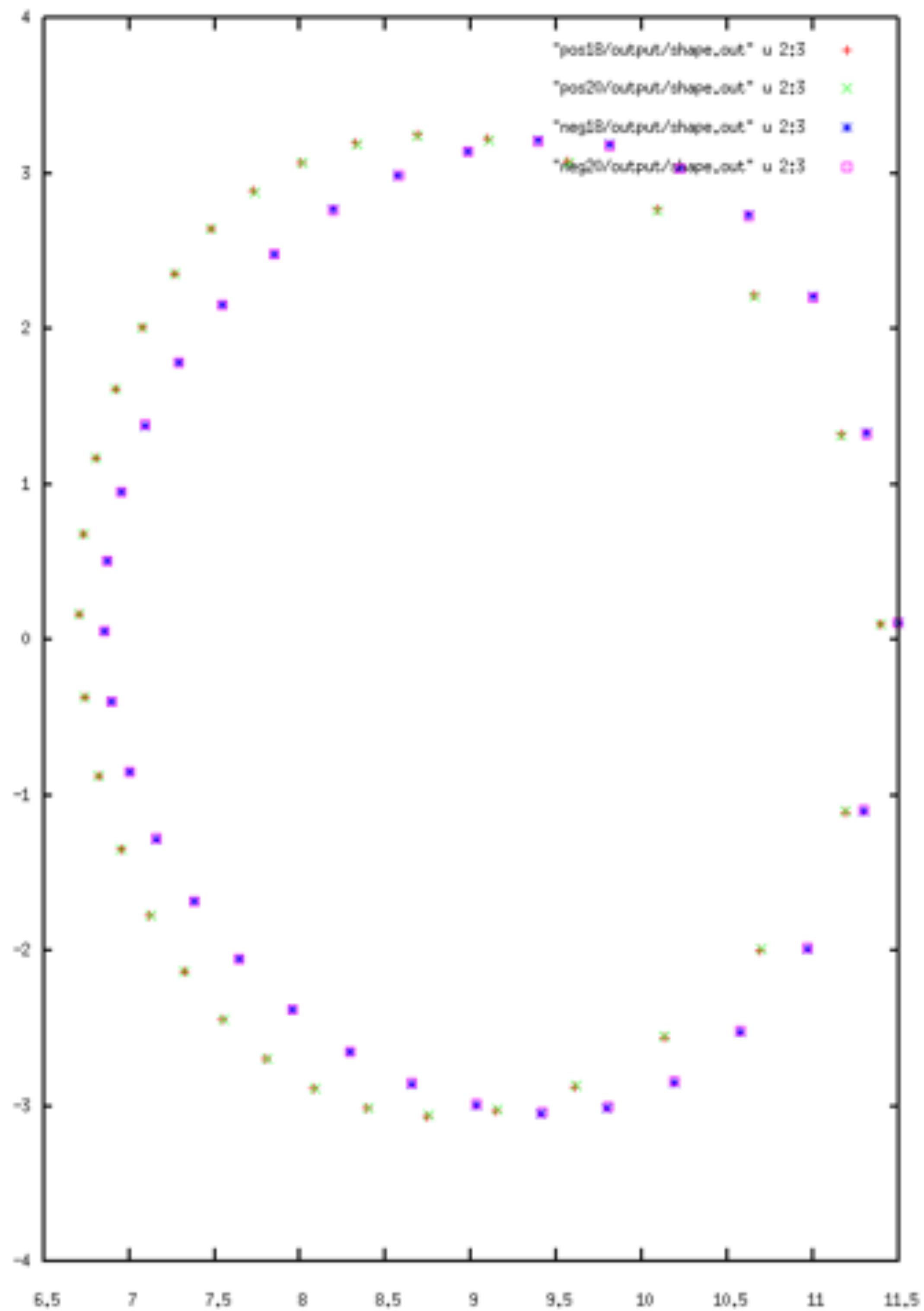
```
neg20
&geometry
magn_geometry = 'chease'
q0        =    1.3988000
shat      =    2.2103327
geomdir   = '.'
geomfile = 'ogyropsi.h5'
x_def = 'arho_t'
flux_pos =    0.72000000
minor_r  =    0.41760834
major_R  =    1.0000000
dpdx_term= 'gradB_eq_curv'
dpdx_pm  =    0.39377451E-01
norm_flux_projection  = F
/

&species
name    = 'ions'
omn     =    3.7474076
omt     =    13.374003

mass    =    1.0000000
temp    =    1.0000000
dens    =    1.0000000
charge =  1
```

omt/omn = 2.71　　omt/omn = 2.62　　omt/omn = 3.28　　omt/omn = 3.57

$\left| \vec{\nabla} \rho \right|^2$ as a function of poloidal angle

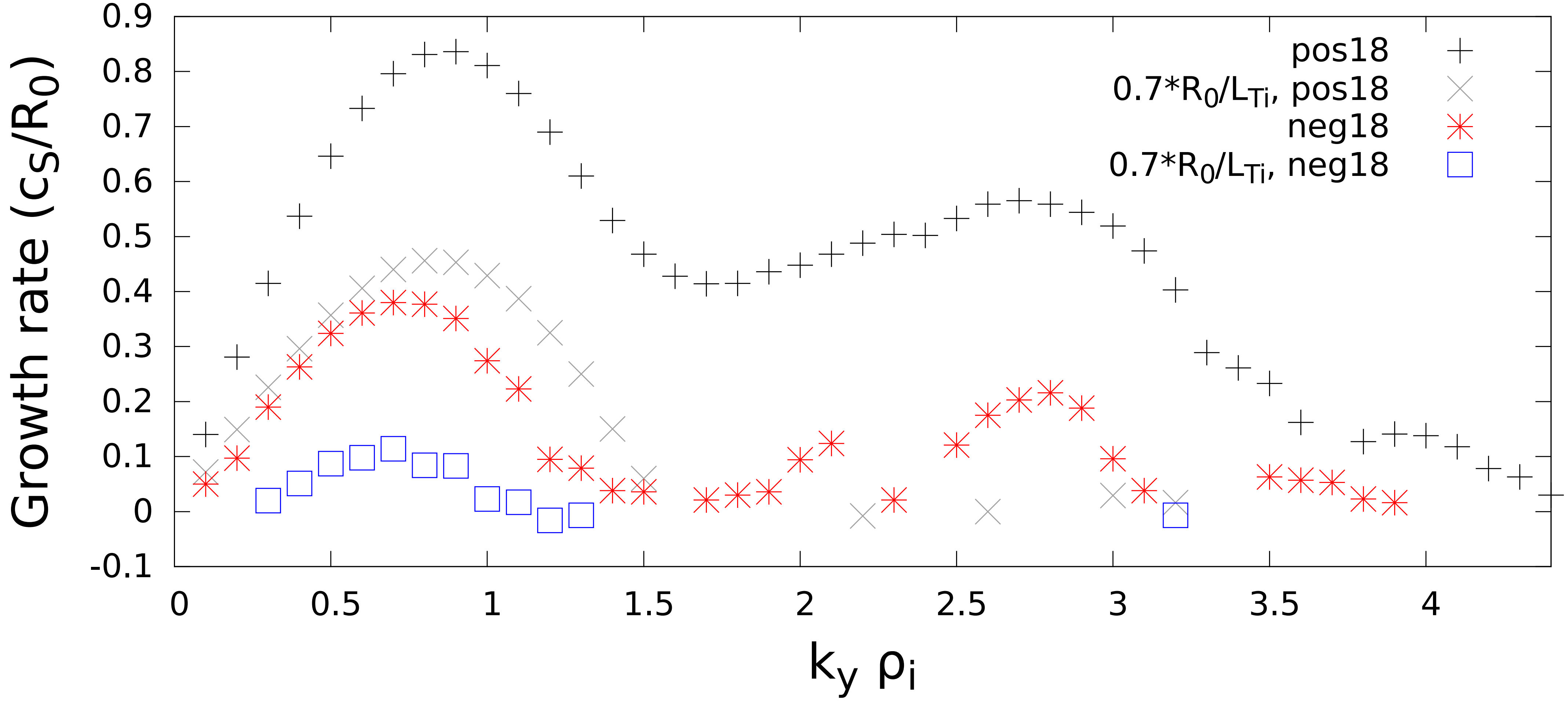


Flux surface shape in the poloidal plane



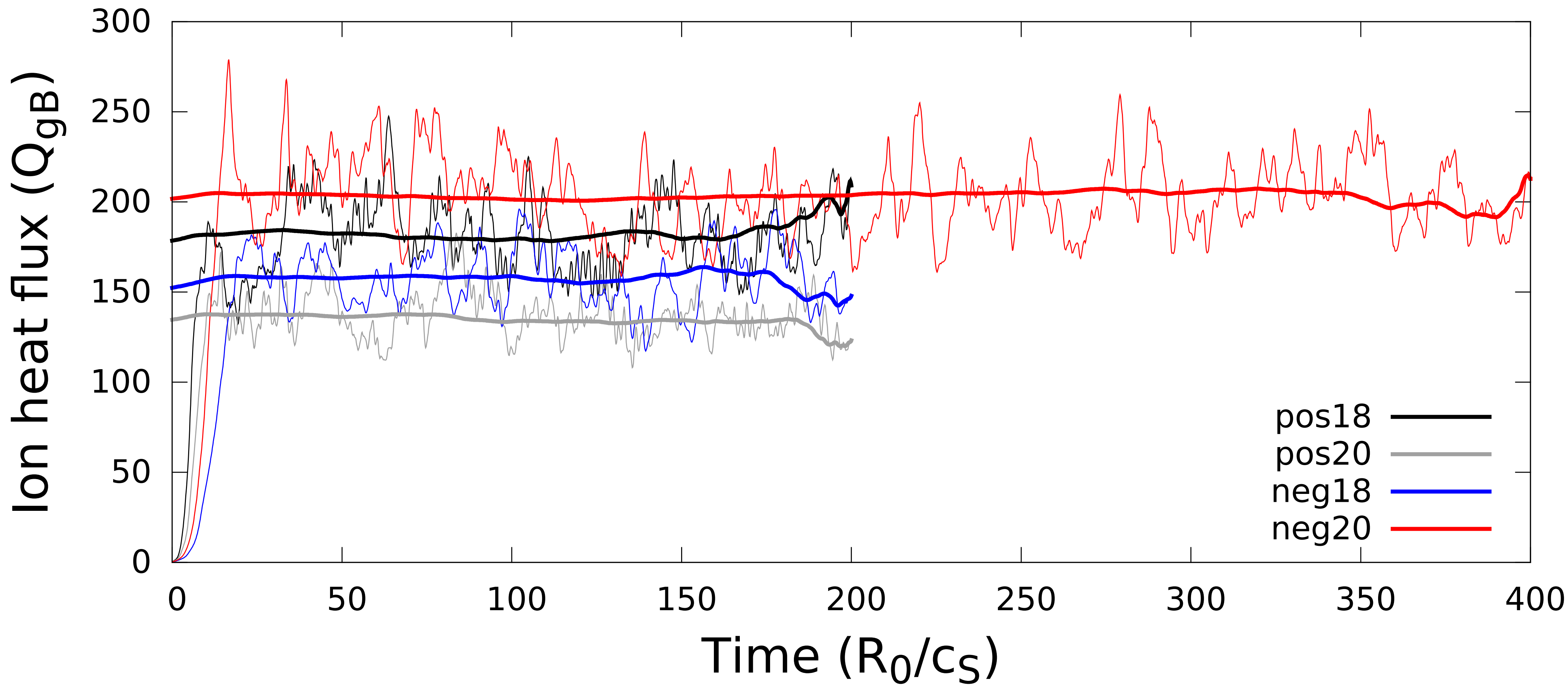
Linear results with adiabatic electrons

- Found a fairly broad spectrum of unstable modes
- Critical gradient for negative δ is maybe a bit larger



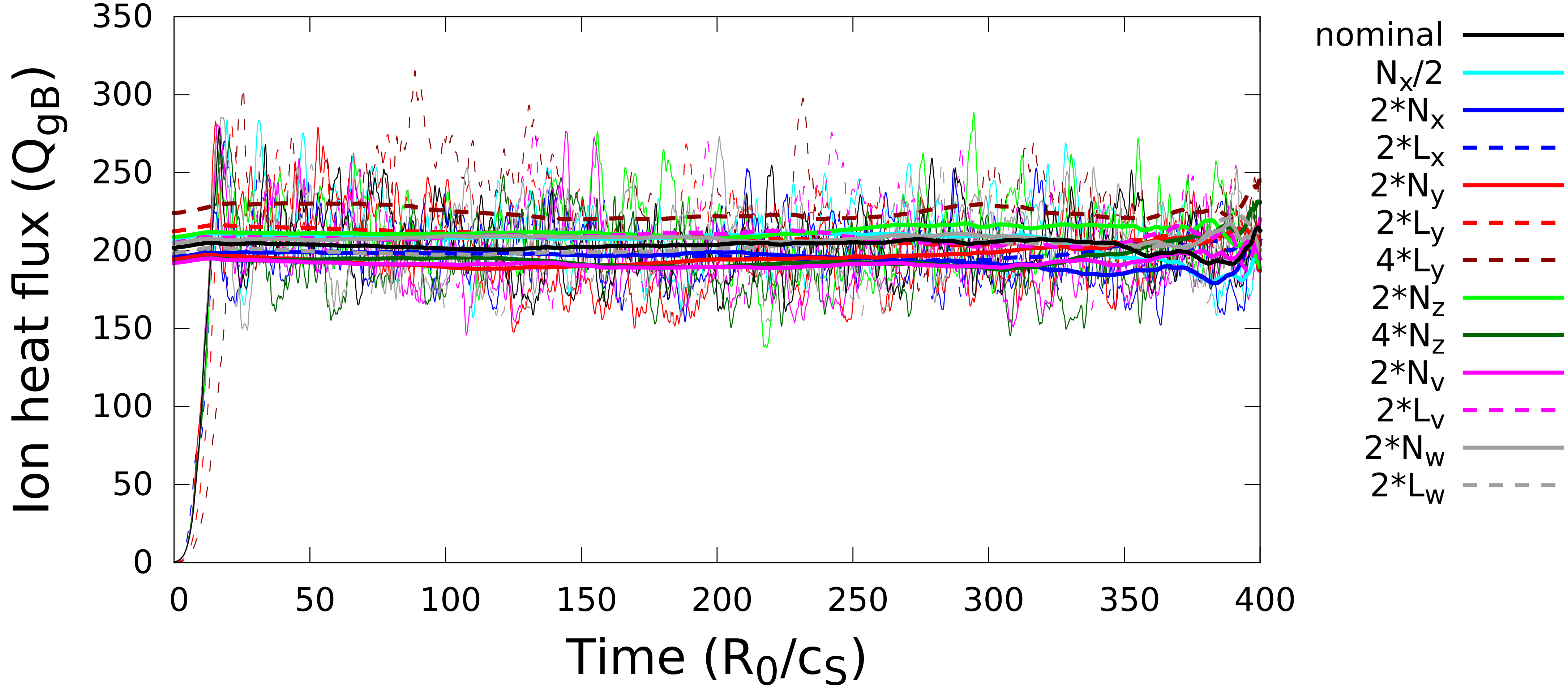
Nonlinear results with adiabatic electrons

- Results are mixed, but indicates that negative δ **increases** energy transport
- Main purpose is to find most strongly driven case for resolution study



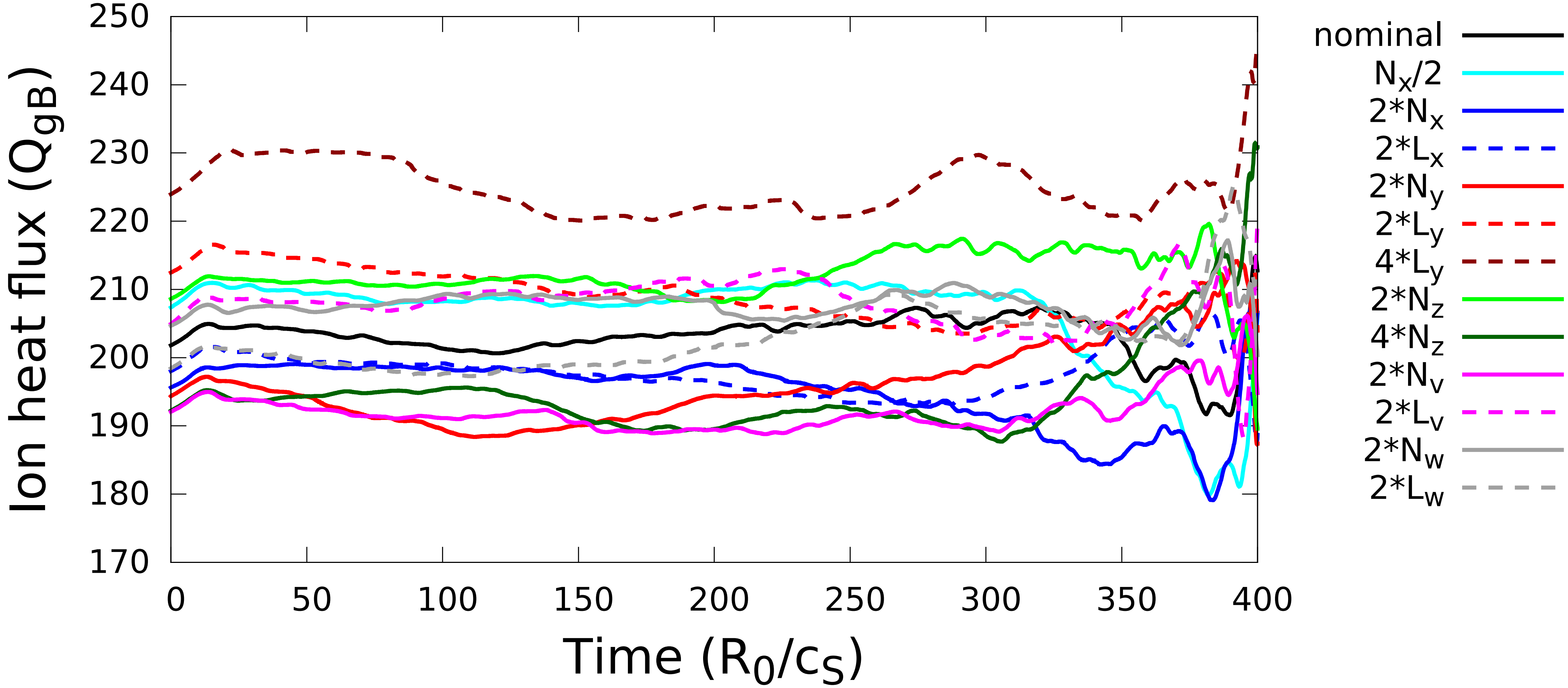
Nonlinear resolution study with adiabatic electrons

- Resolution study of the **neg20** case indicates that L_y should be doubled and N_x can be halved



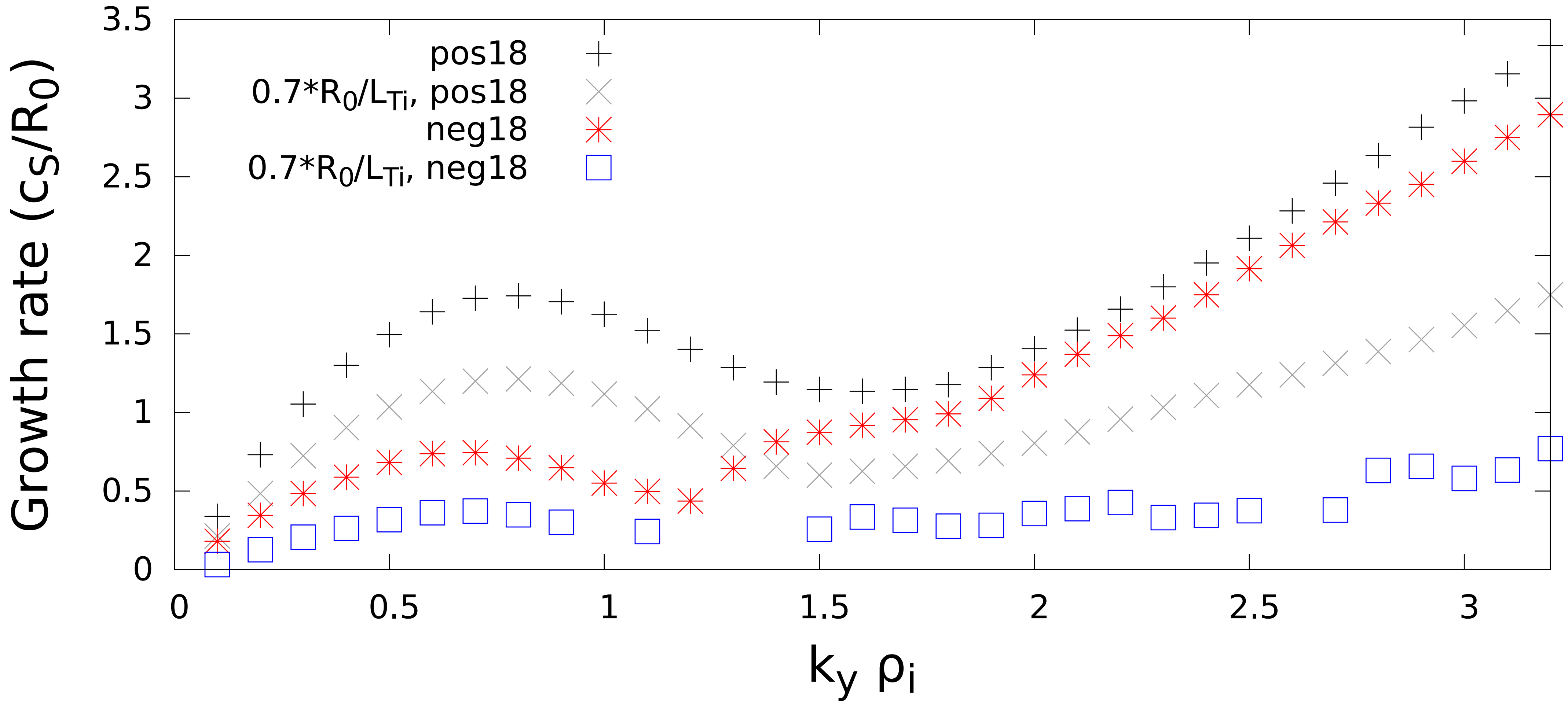
Nonlinear resolution study with adiabatic electrons

- Resolution study of the **neg20** case indicates that L_y should be doubled and N_x can be halved



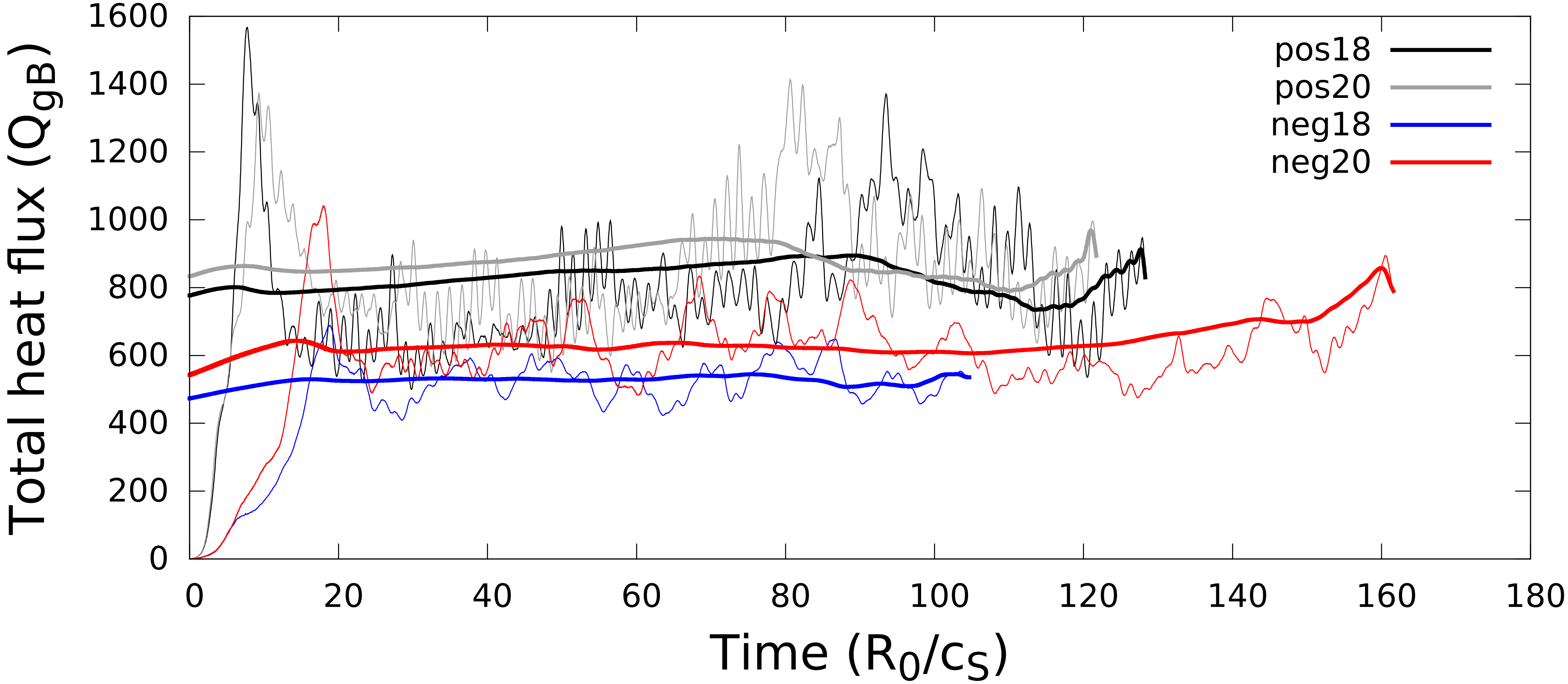
Linear results with kinetic electrons

- See surprising divergence with small scale turbulence (concerning!)
- Again, critical gradient for negative δ is maybe a bit larger



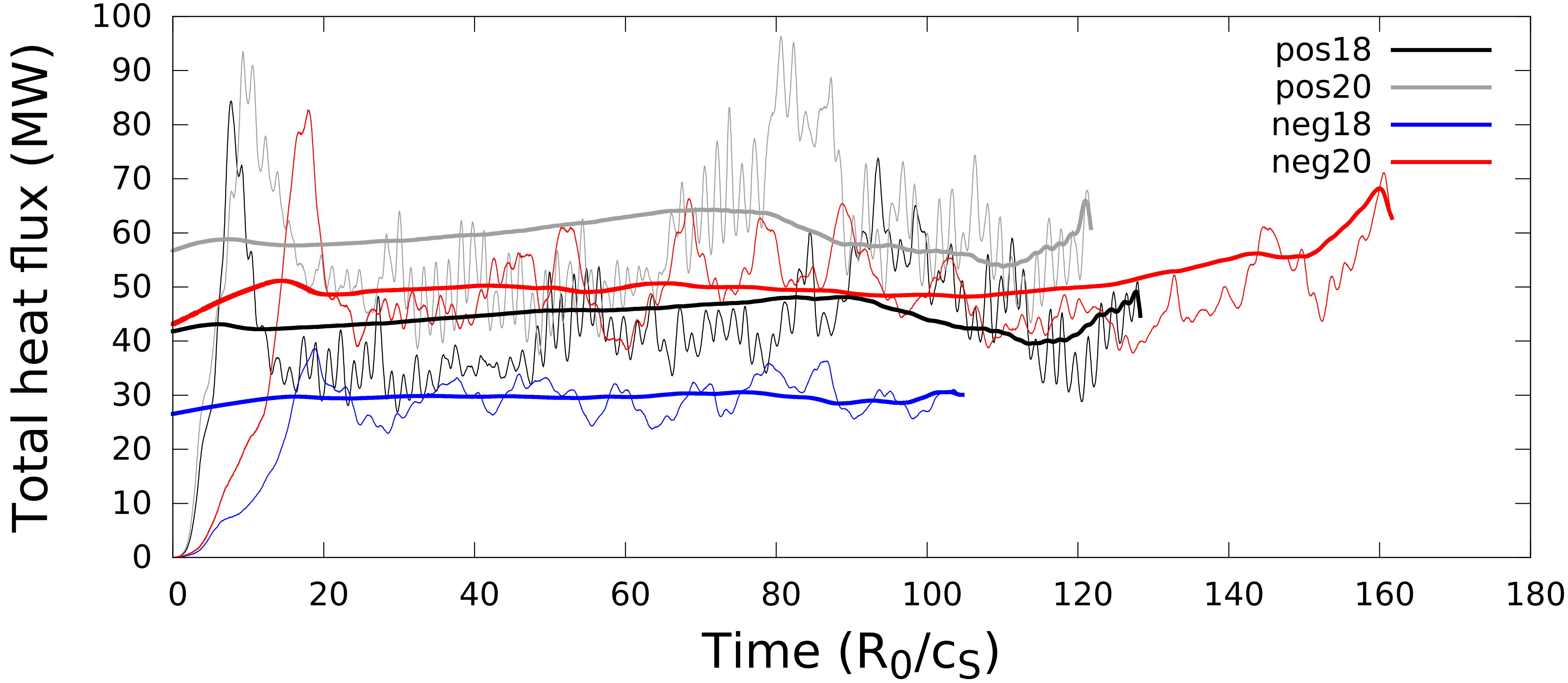
Nonlinear results with kinetic electrons

- Negative δ cases have lower total heat flux
- Positive δ cases exhibit an unusual oscillation from the zonal flows



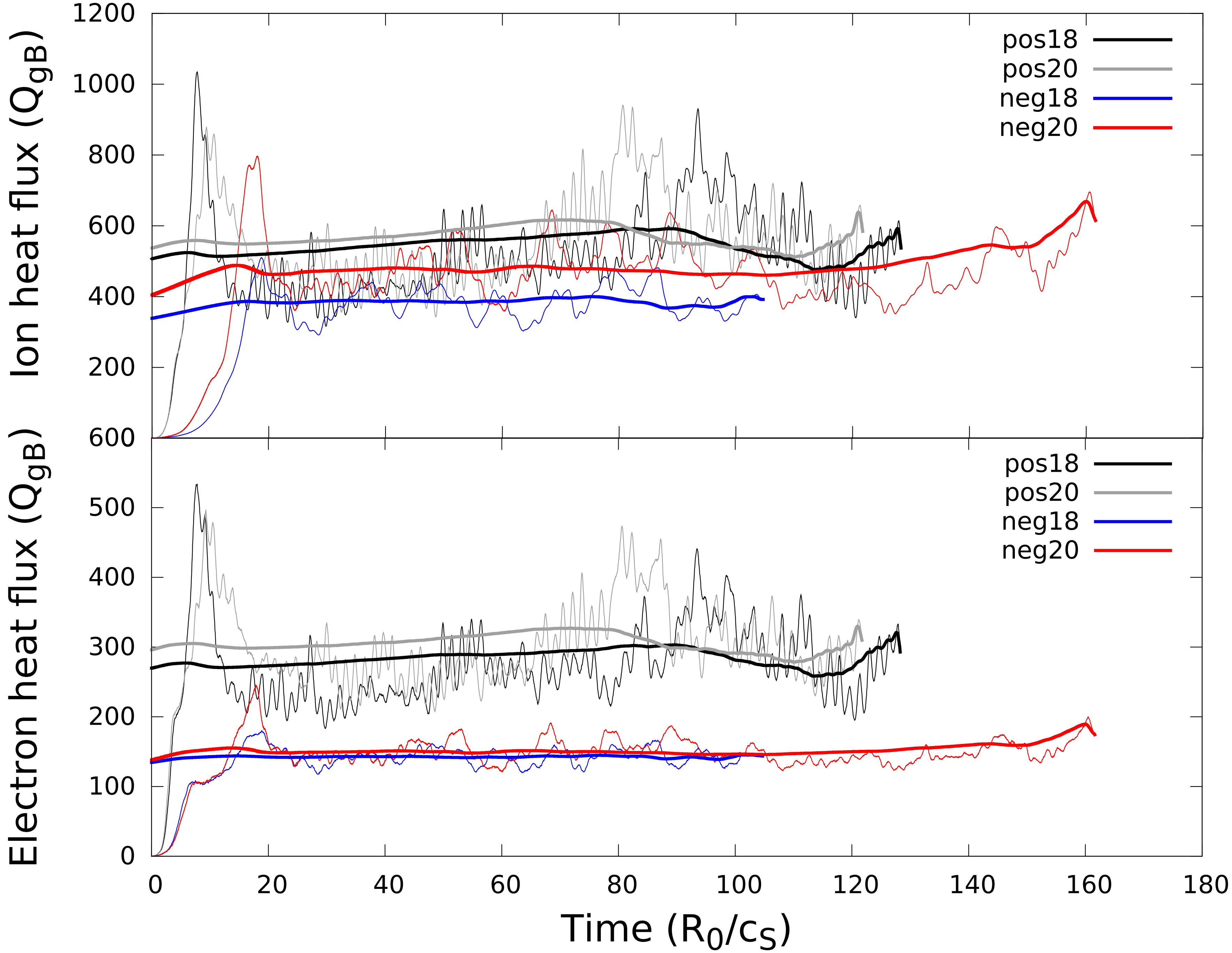
Nonlinear results with kinetic electrons

- Same trends hold true for required heating power (i.e. adjusting for differences in surface area, temperature, and density)



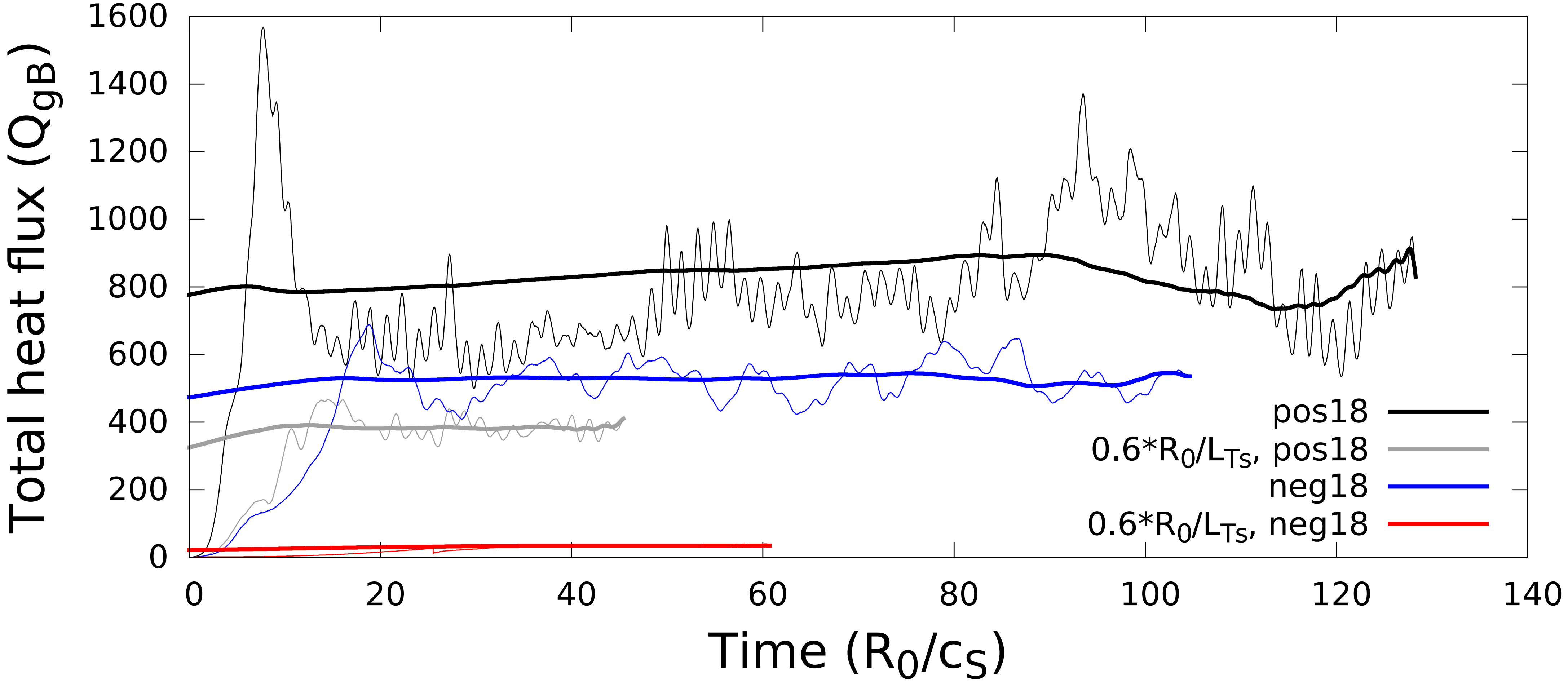
Nonlinear results with kinetic electrons

- Electron heat flux is more strongly affected by reversing δ



Nonlinear stiffness study with kinetic electrons

- Negative δ has a higher critical gradient



Nonlinear stiffness study with kinetic electrons

- Negative δ has a higher critical gradient