Study of Negative Triangularity on Alfvénic modes in DTT

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ENEA C.R. Frascati, Italy

DTT 2025 Annual TSVV-02 workshop

October 16h-17th, 2025

Purpose

- **Stability analysis**: the prerequisite to allow operation of plasma fusion devices and it prevents bad plasma performances and/or plasma wall damages.

- **Alfvénic modes analysis**: constitute the preliminary step of the following investigation including energetic particles.
- Alfvén modes exist in the magnetic field configuration of tokamaks due to frequency gaps in the continuous Alfvén spectrum; these modes can be driven unstable by energetic particles, causing transport losses.
- Indeed, energetic particles are characterized by velocities of the order of the Alfvén velocity so they can resonantly transfer power to Alfvén modes, driving them unstable.

Outline

- codes flow chart: CHEASE, MARS, HYMAGYC, FALCON
- first studies on DTT **Negative Triangularity**:
  flipped boundary (from Positive Triangularity)
- updated DTT Positive Triangularity equilibrium
  - Infernal modes studies
  - Alfvén modes
- studies on DTT **Negative Triangularity**:
  from 1D transport solver (Real Geometry)
  - infernal modes studies
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1-D transport solvers
(e.g. JINTRAC or ASTRA)

General info (such as total current, magnetic field, geometric radius, magnetic radius)
Pressure p
Current density
dp/dψ
Poloidal current flux function T
TT'
ψ
q profile
Plasma boundary

ASCOT code

fast particle density
…

1-D transport solvers
(e.g. JINTRAC or ASTRA)

CHEASE
Equilibrium code

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General info (such as total current, magnetic field, geometric radius, magnetic radius)
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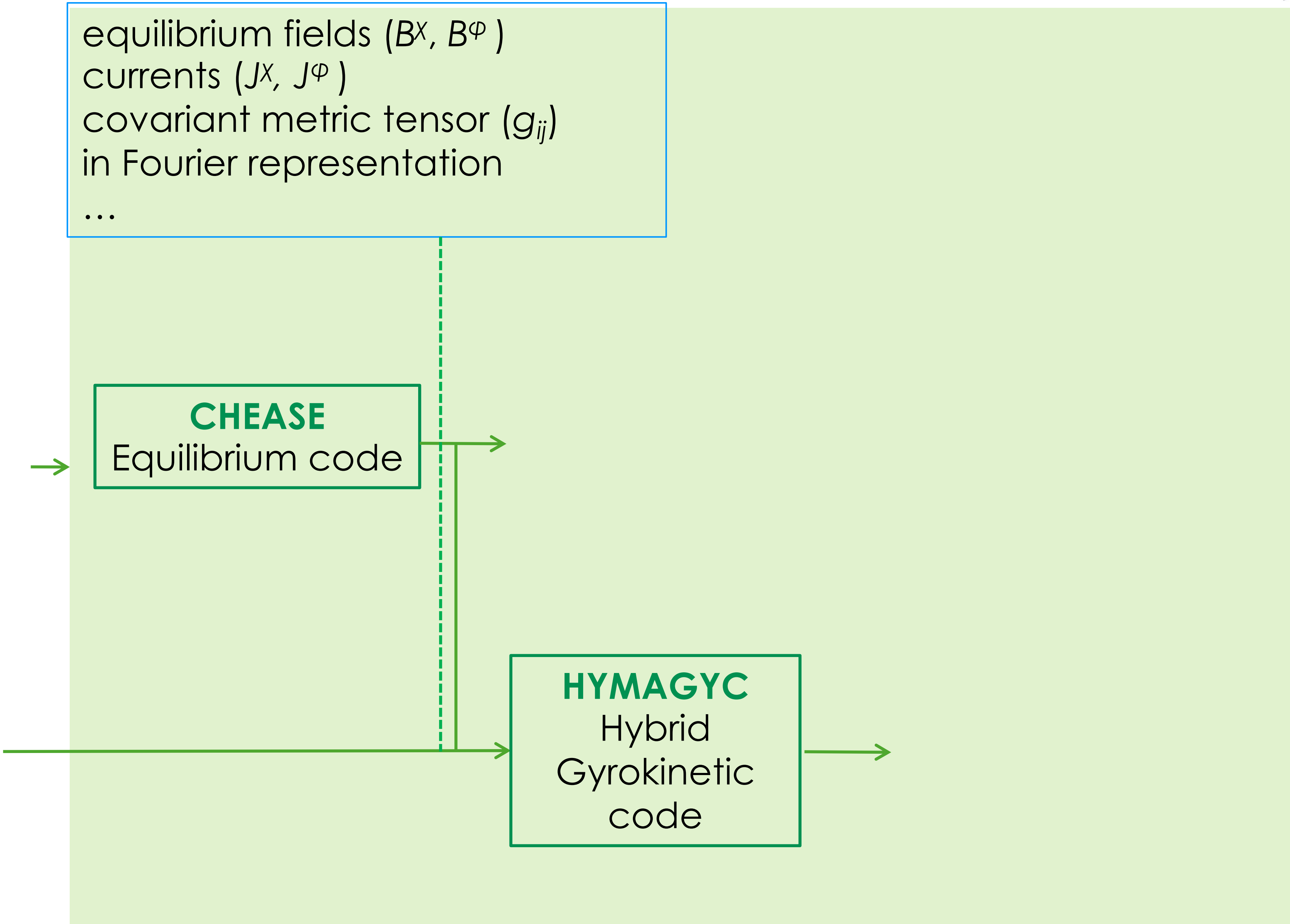
Plasma boundary

ASCOT code

HYMAGYC
Hybrid Gyrokinetic code

fast particle density
…


equilibrium fields (B^χ, B^φ)
currents (J^χ, J^φ)
covariant metric tensor (g_{ij})
in Fourier representation
...
CHEASE
Equilibrium code
HYMAGYC
Hybrid
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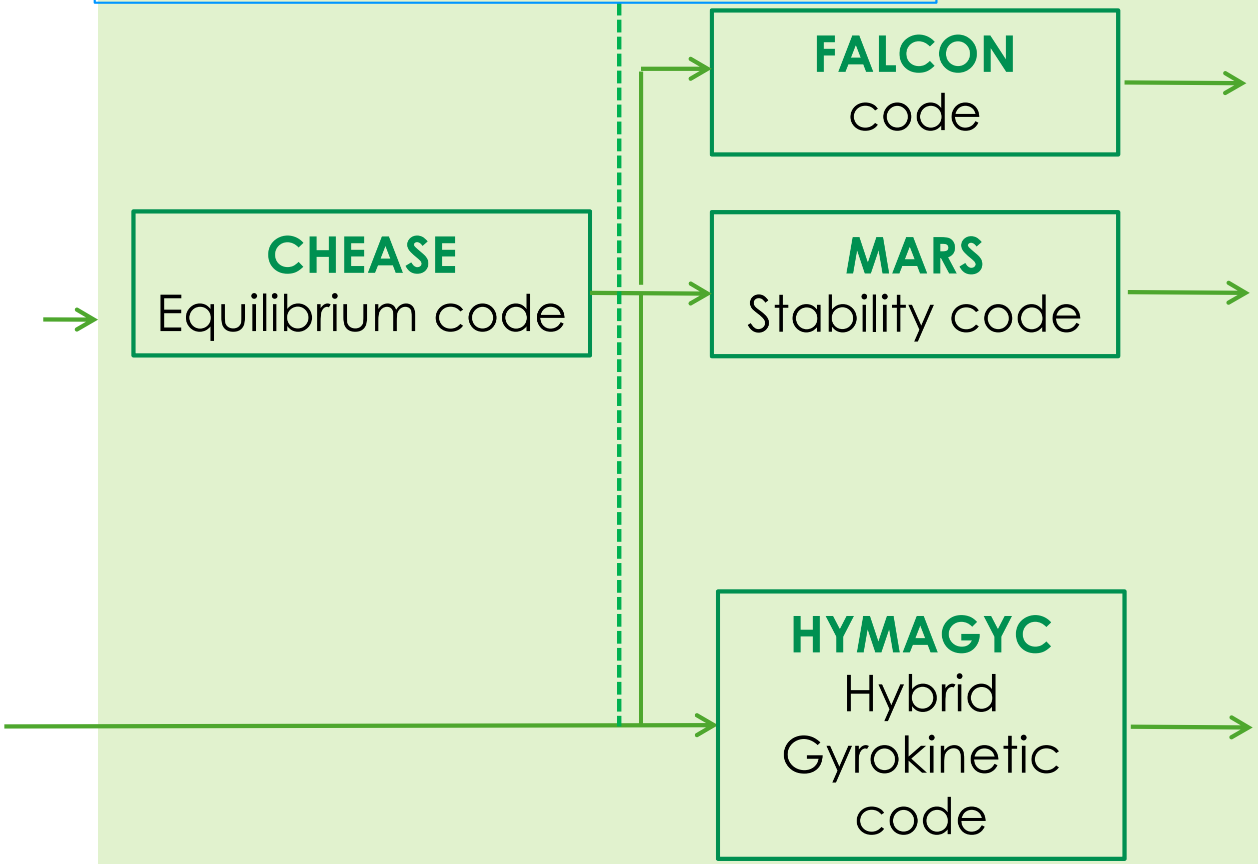

equilibrium fields (B^χ, B^φ)
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…

CHEASE
Equilibrium code

FALCON
code

MARS
Stability code

HYMAGYC
Hybrid
Gyrokinetic
code

Perturbed fields
Growth/Damping rate
and frequency of the
mode instability
…

equilibrium fields (B^{χ}, B^{φ})
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CHEASE
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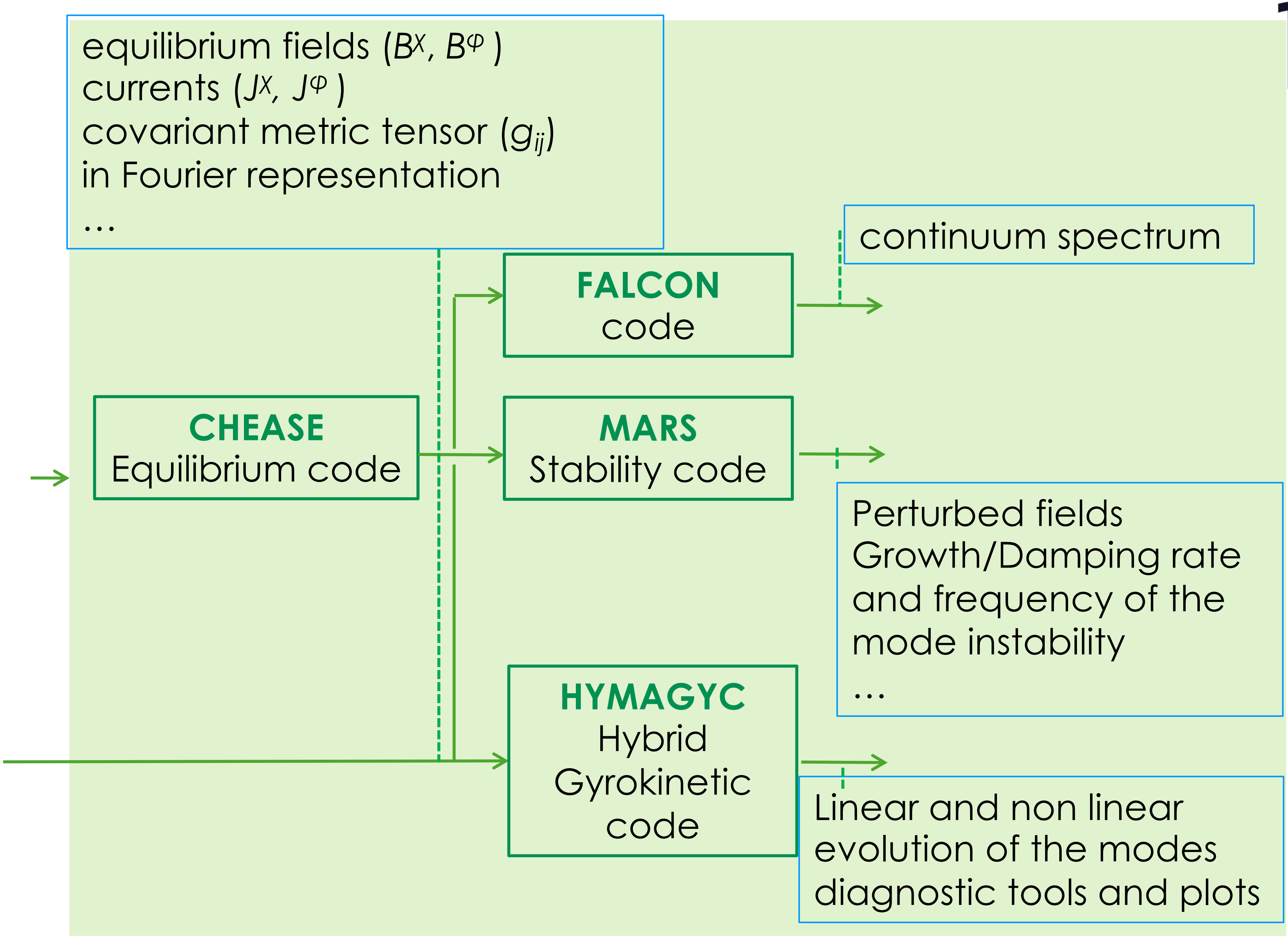
HYMAGYC
Hybrid
Gyrokinetic
code

Linear and non linear
evolution of the modes
diagnostic tools and plots


equilibrium fields (B^{χ}, B^{φ})
currents (J^{χ}, J^{φ})
covariant metric tensor (g_{ij})
in Fourier representation
…
continuum spectrum
FALCON
code
CHEASE
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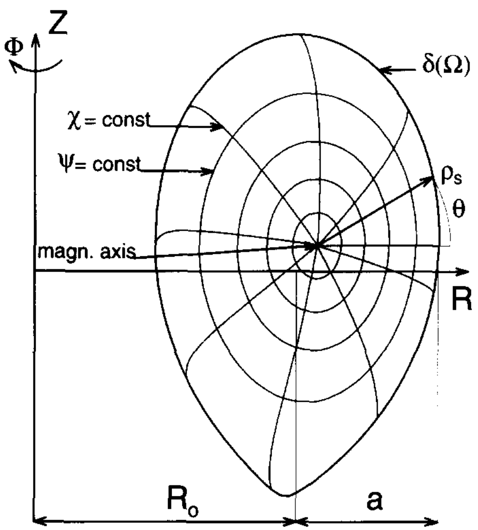
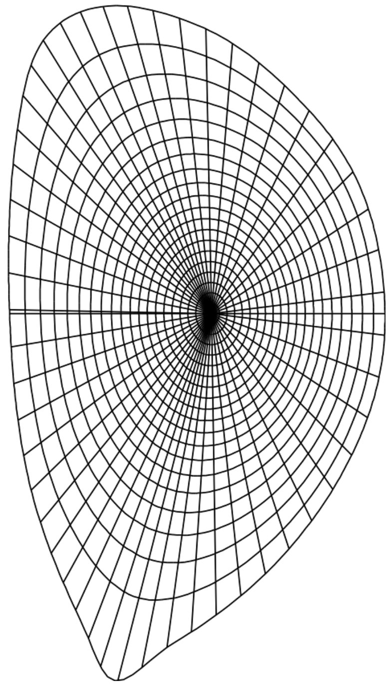
CHEASE

high resolution equilibrium code
it solves the Grad-Shafranov equation in
axisymmetric general **toroidal** geometry

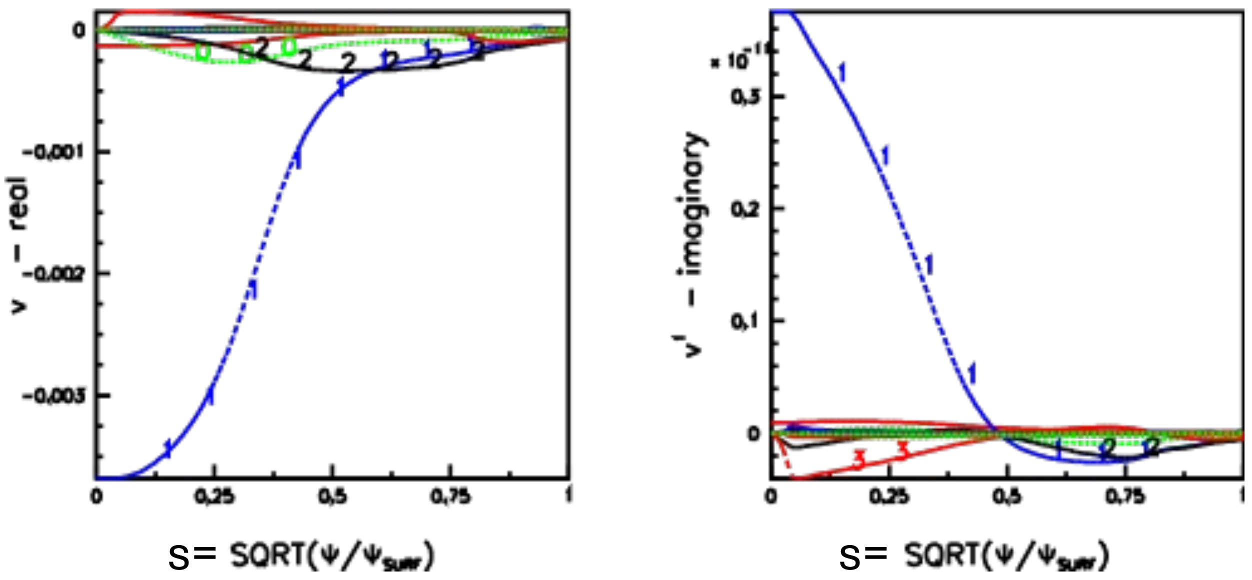




H. Lütiens et al., Computer Physics Communications 97 (1996) 219-260

MARS

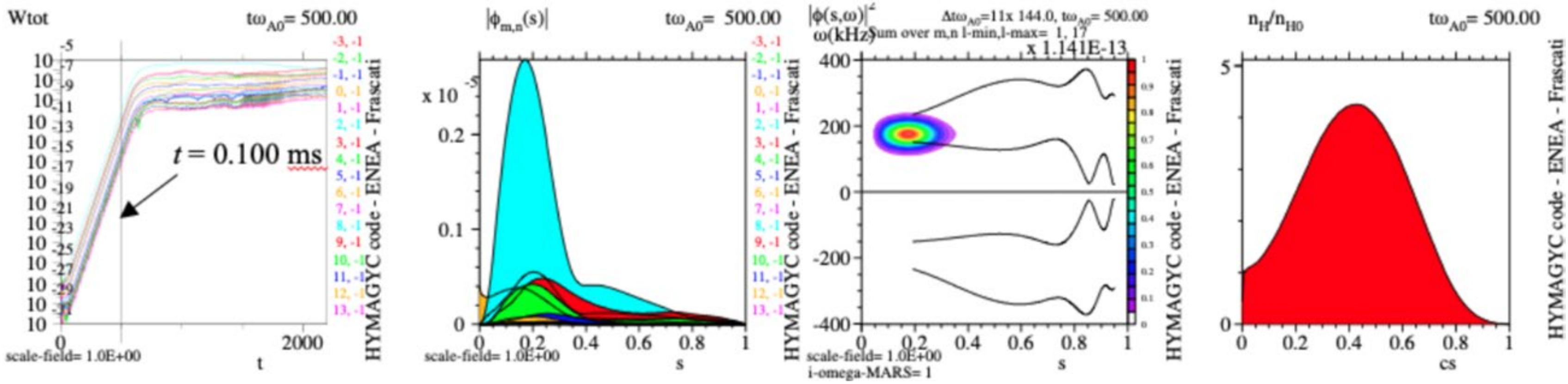
global **stability** **eigenvalue** code
it solves **full, linear, resistive** MHD equations in
axisymmetric general **toroidal geometry**



A. Bondeson et al., Physics of Fluids, B4:1889–1900, 1992

HYMAGYC

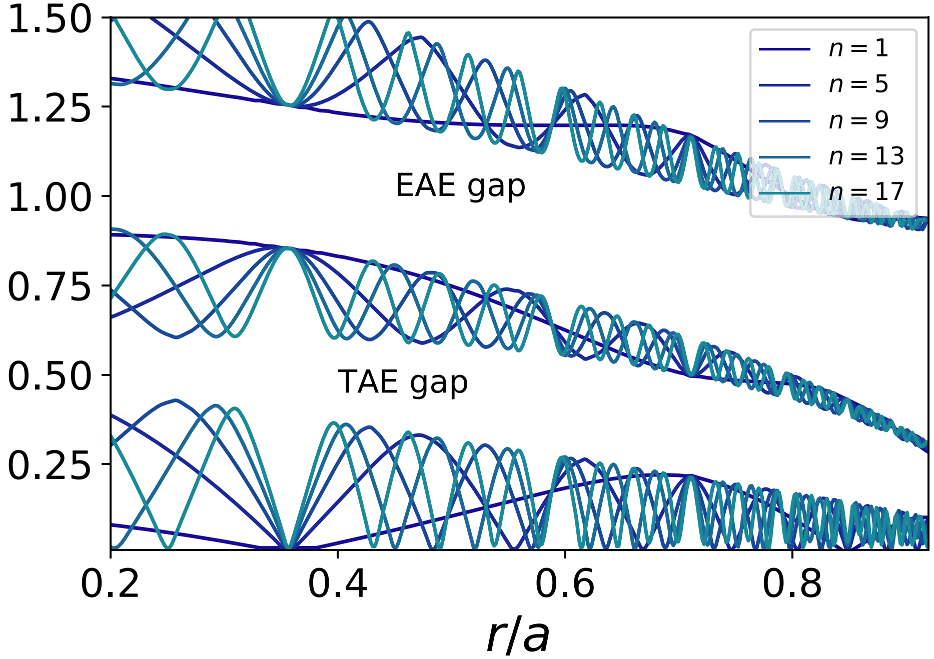
gyrokinetic hybrid initial value code
it is made of two modules: the fluid module describes the bulk plasma,
the **kinetic** module solves the Vlasov equations with a PIC (particle in cell) tecnique
Self-consistent code



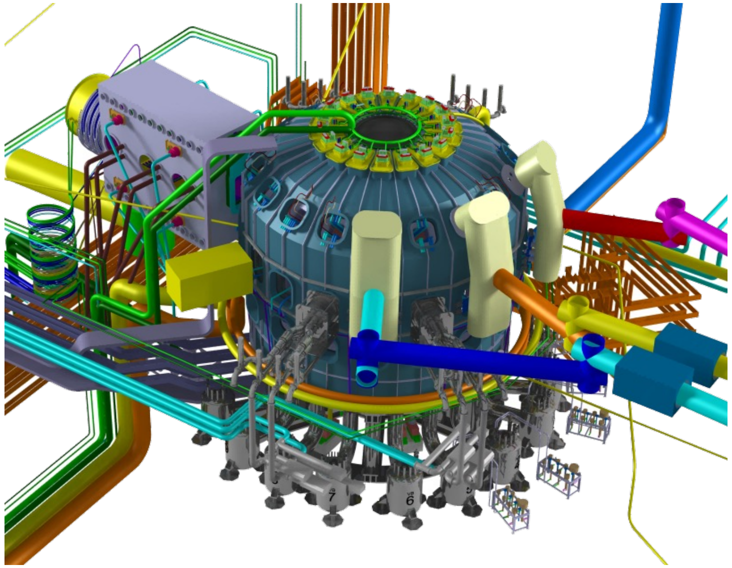
G. Vlad et al., Reviews of Modern Plasma Physics 9(27):1–31 (2025)

FALCON

Floquet Alfvén continuum local code that applies Floquet theory to handle the periodic equilibrium variation along the field lines (in poloidal angle)



M.V. Falessi et al 2019, Phys. Plasmas 26, 082502



DTT layout

major radius R (m)	**2.19**
minor radius a (m)	0.70
Volume (m^3)	35
Plasma current (MA)	5.5
Vacuum $B_{toroidal}$ at R=2.19 m	5.85
Electron density $\overline{n_e}$ (10^{20} m^3)	1.5
Auxiliary power P_{tot} (MW)	45
P_{ECRH} (MW)	29
P_{ICRH} (MW)	6
P_{NBI} (MW)	10

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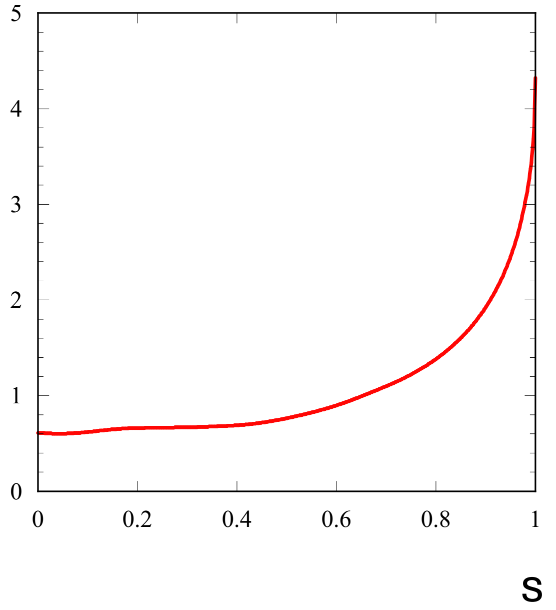
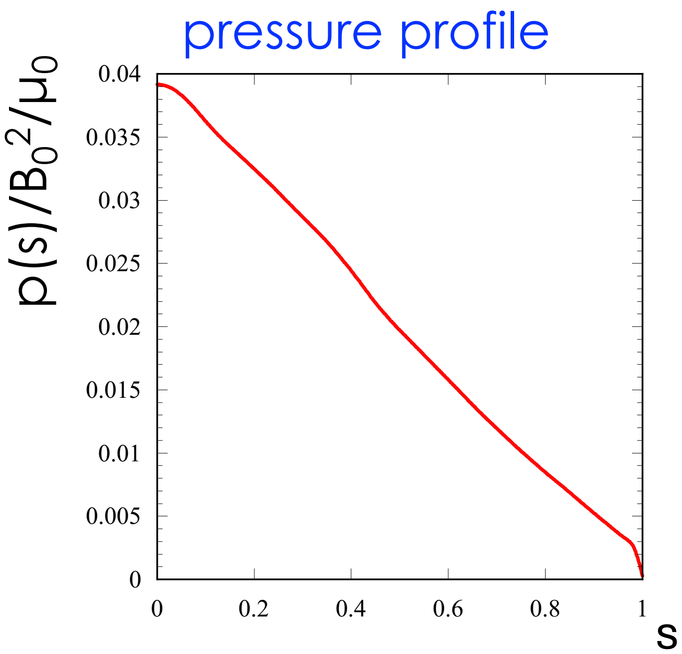
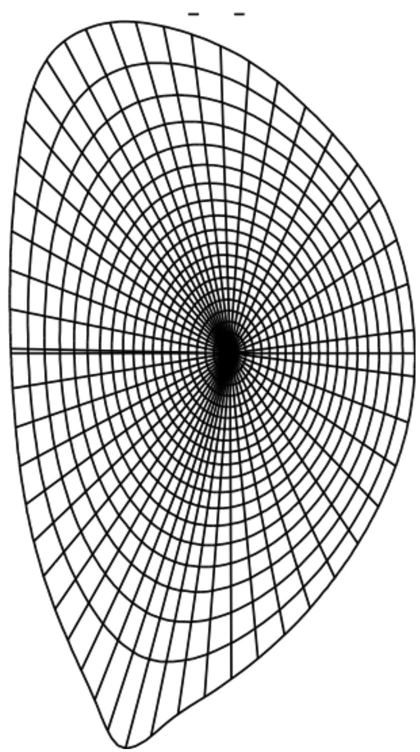
Main profiles PT:

	DTT PT_FullPower
I_{tot} [MA]	5.5
B_0[T]	5.85
q_0	0.6
q_{edge}	4.32
$q_{95\%}$	2.9
β_{tor}%	2.31
β_N%	1.70
p_0[MPa]	1.06

Alfresco_PPF3345







Negative triangularity: flipped boundary

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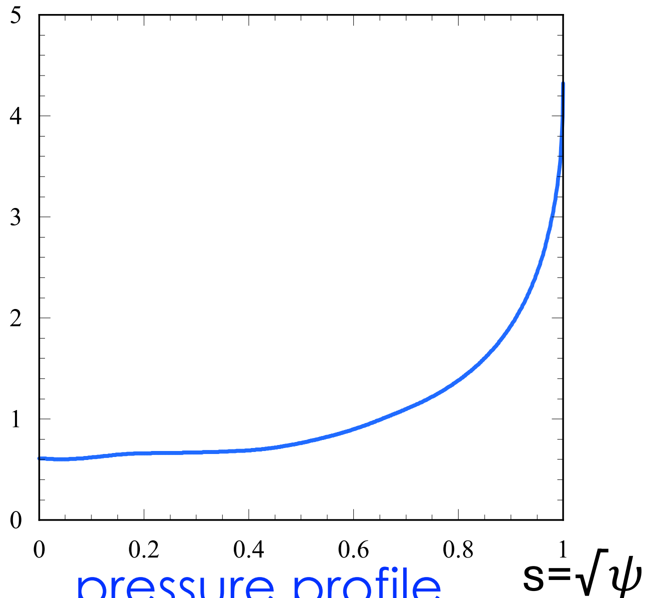
Alfresco_PPF3345

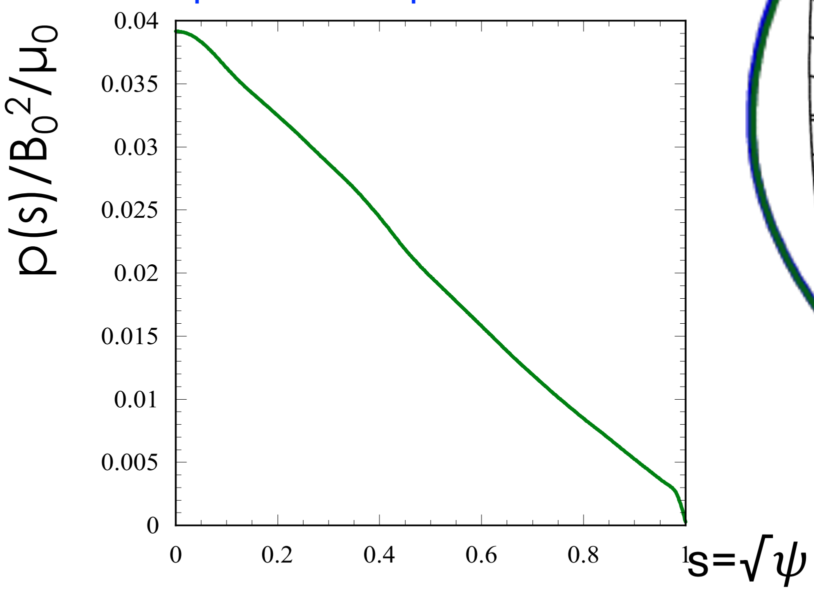
NT triangularity fixed p', I*

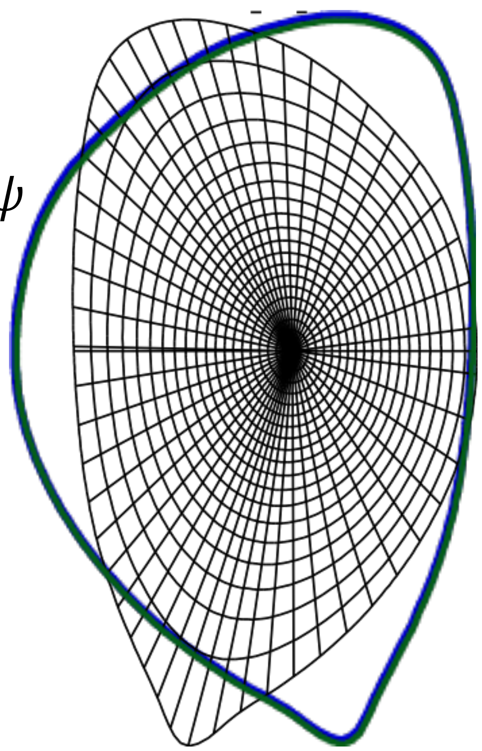
NT triangularity fixed p', q

q profile



pressure profile





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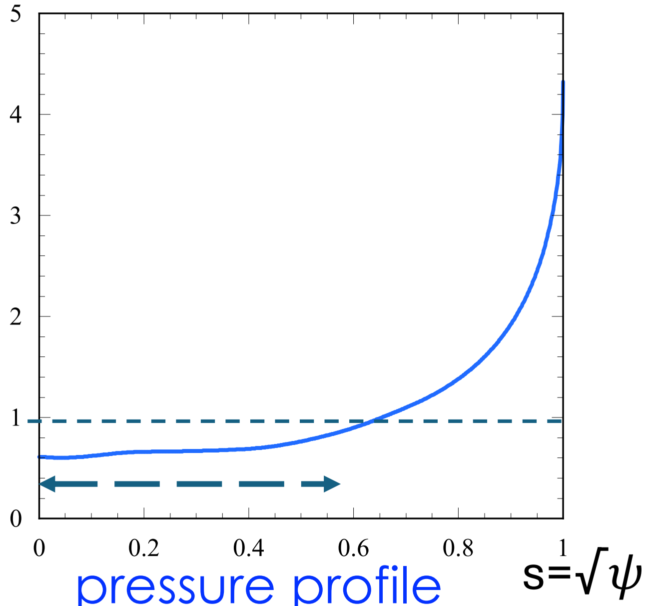
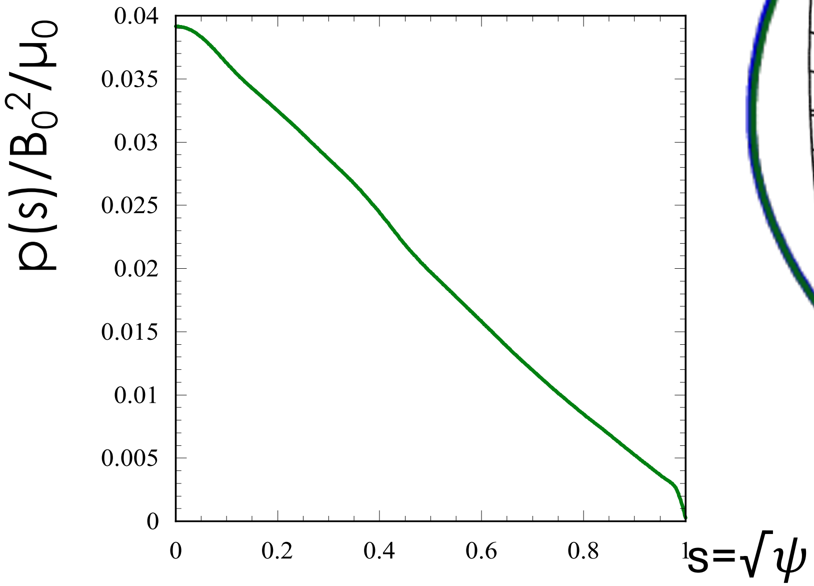
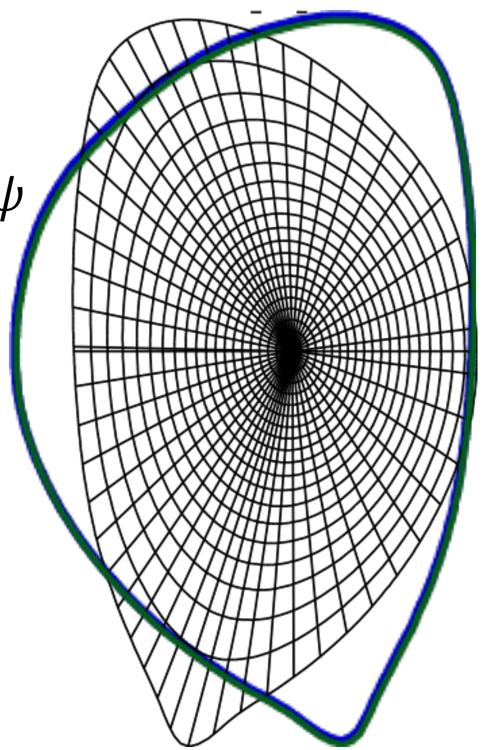
Alfresco_PPF3345

q profile



pressure profile

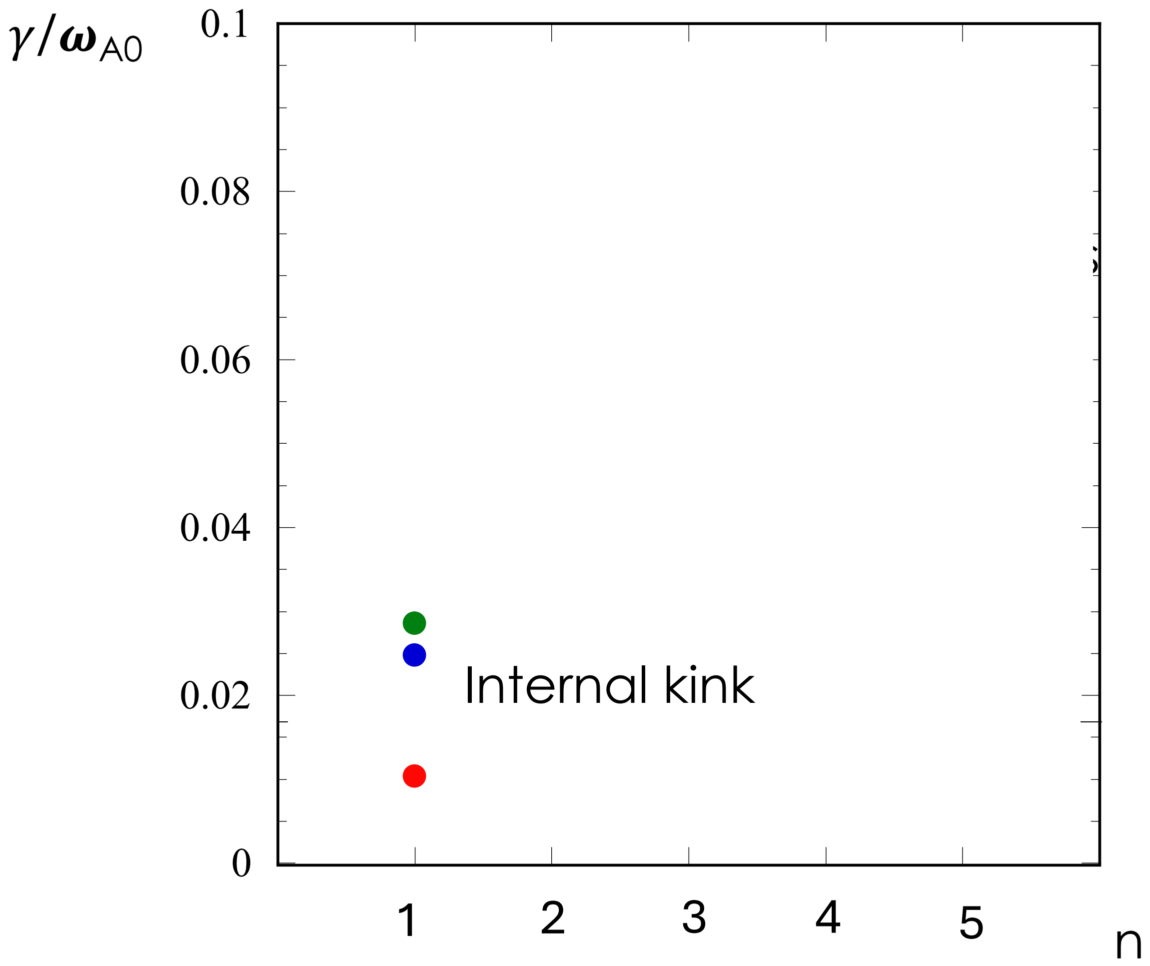




NT triangularity fixed p', I*

NT triangularity fixed p', q

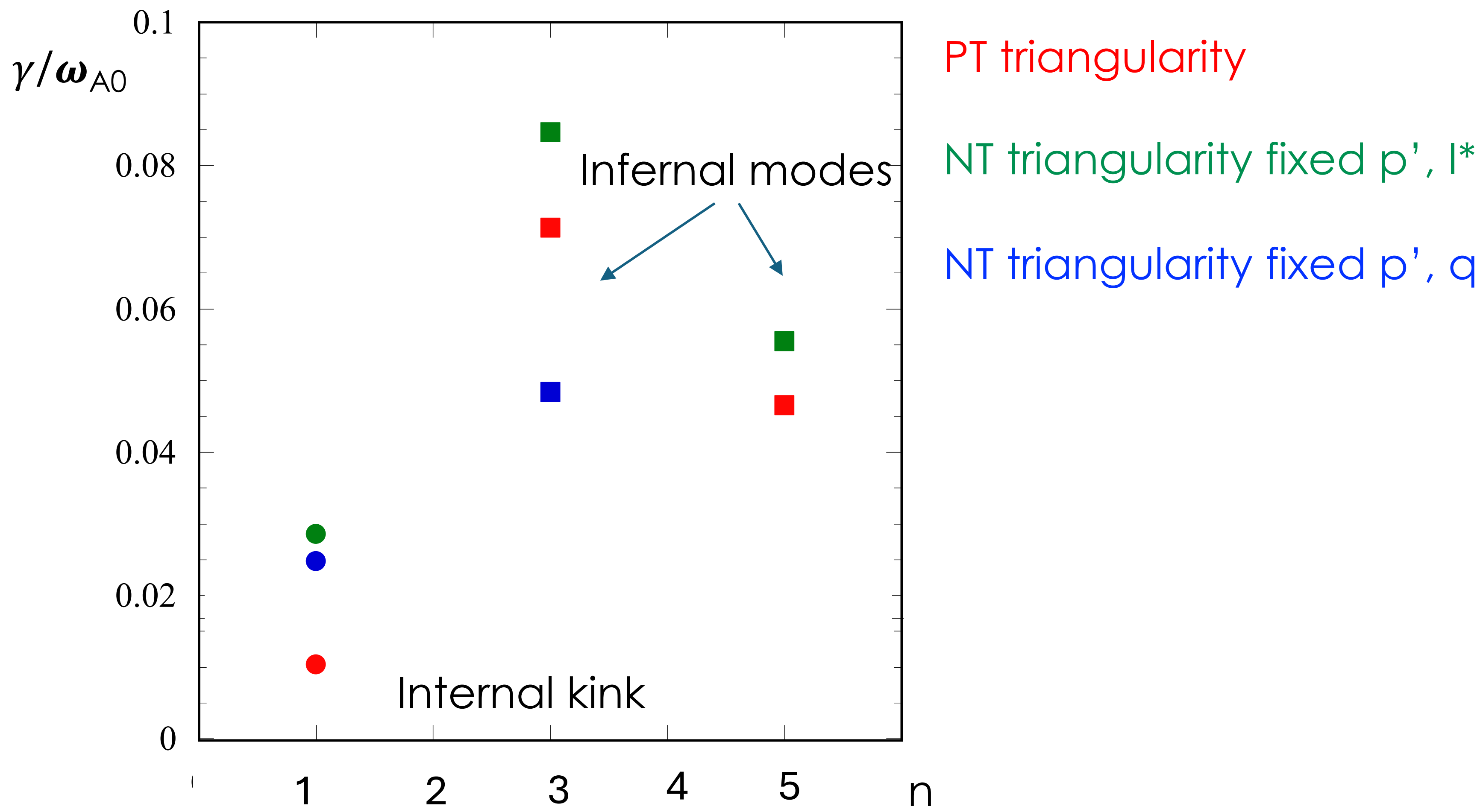
MHD analysis with MARS code



PT triangularity

NT triangularity fixed p’, I*

NT triangularity fixed p’, q



γ/ω_{A0}
0.1
0.08
0.06
0.04
0.02
0
Infernal modes
Internal kink
1
2
3
4
5
n
PT triangularity
NT triangularity fixed p', I*
NT triangularity fixed p', q

- ✓ Negative Triangularity has been investigated in a case of flipped boundary
- ✓ Nothing to be worth underlining as compared to PT as concerns MHD stability for investigated n
- ✓ PT/NT scenario is affected by ideal internal kink and infernal modes!!
- ✓ Scenario optmization regarding pressure and q profile would be required
- ✓ Broadened ECRH deposition profile goes in this direction
- ✓ Updated linear analysis is required

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Main profiles PT update:

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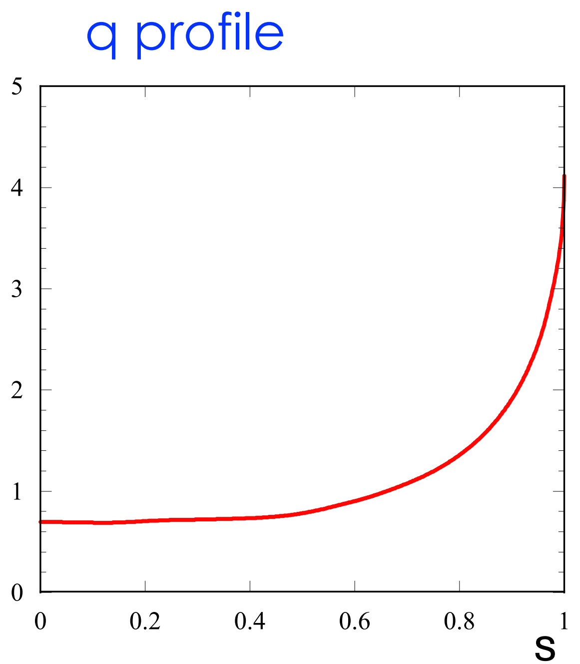
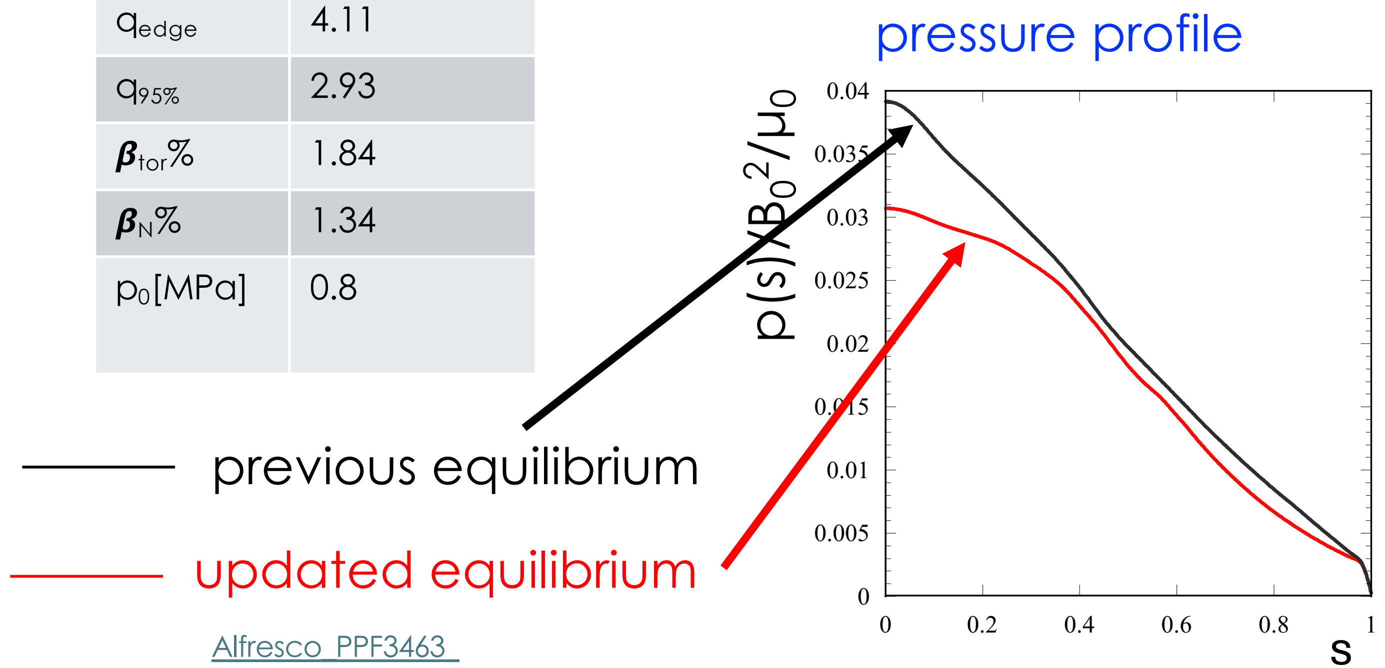
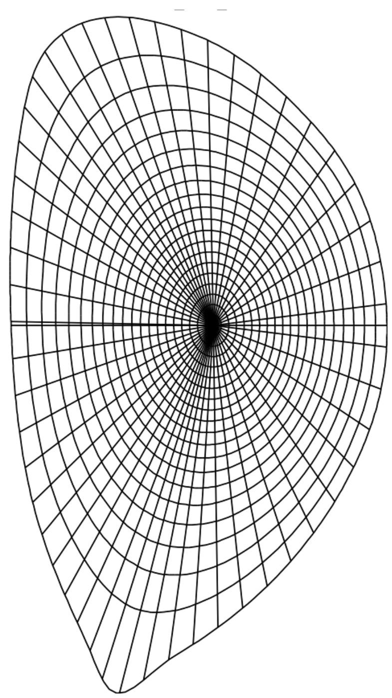
I_{tot} [MA]	5.5
B_0[T]	5.85
q_0	0.70
q_{edge}	4.11
$q_{95\%}$	2.93
β_{tor}%	1.84
β_N%	1.34
p_0[MPa]	0.8





Alfresco_PPF3463



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October 16th-17th, 2025 V. Fusco Annual TSVV-02 Meeting

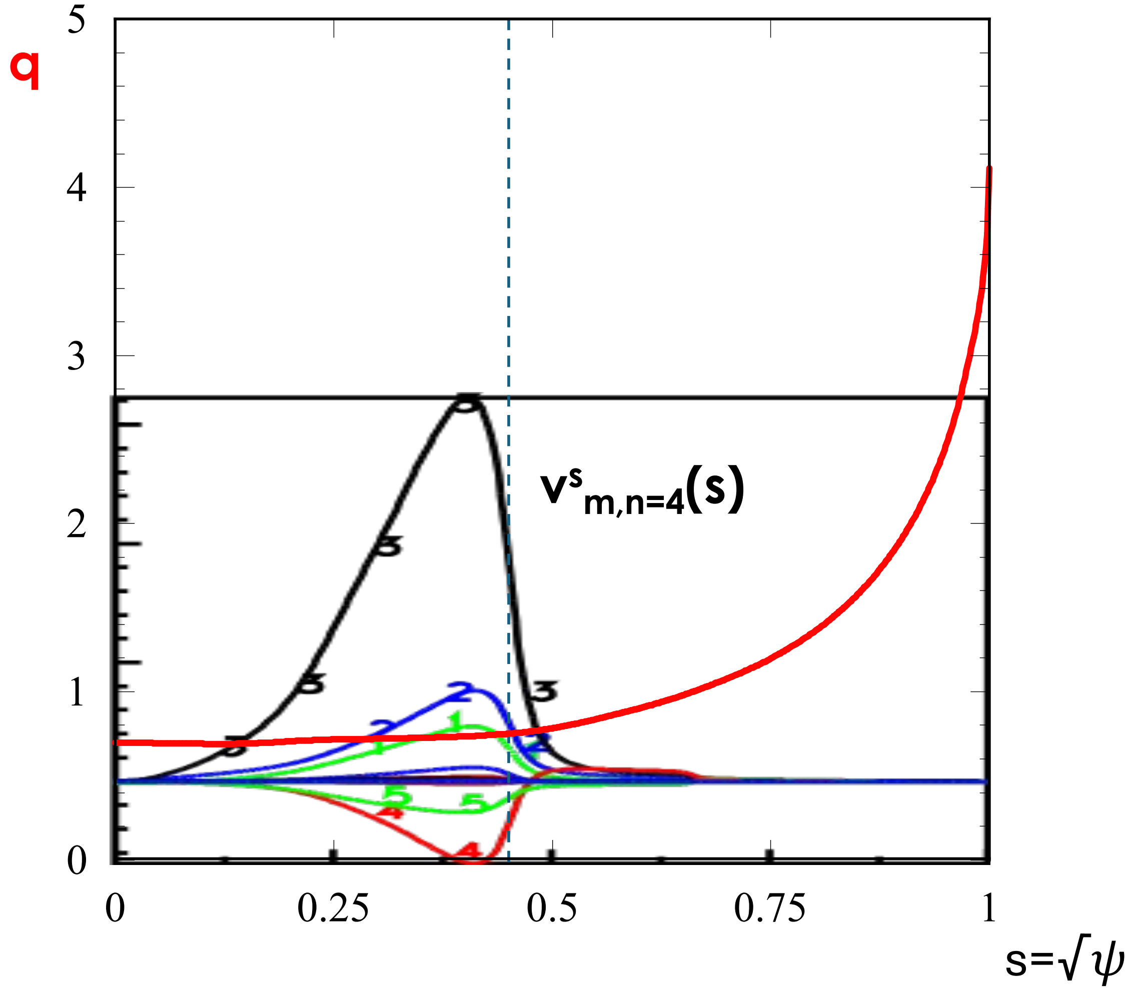
Infernal modes in PT update

Results from the MARS code

- ✓ Scan for toroidal mode numbers n=**2,… ,15** with the MARS code

Infernal modes in PT update

Results from the MARS code



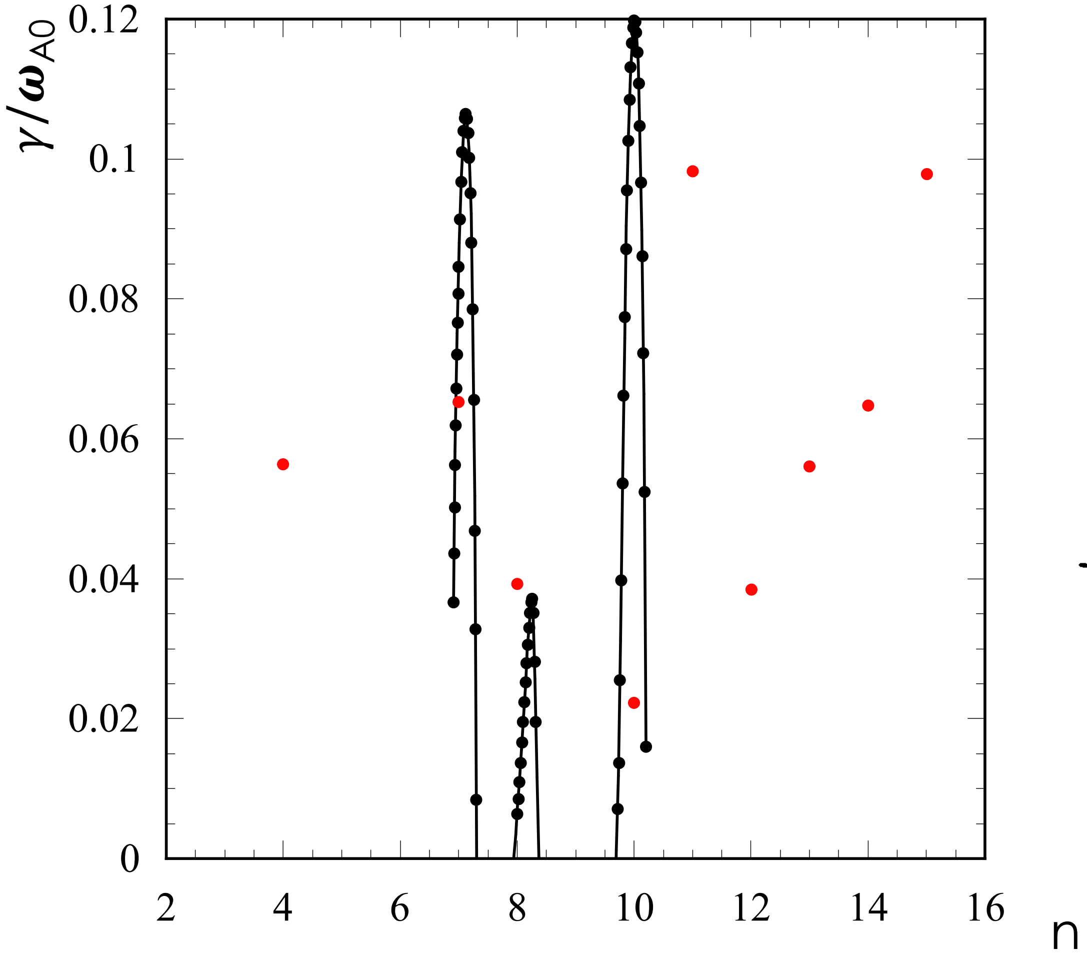
n=4

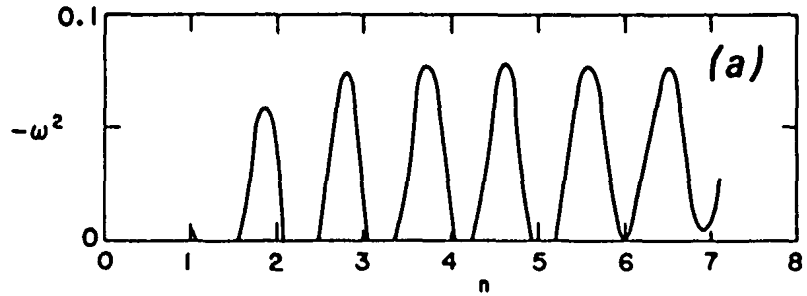
!!!!Infernal mode
q=3/**4**
s=0.45

s component $\mathbf{v^s_{m,n}(s)}$
perturbed velocity
m polidal mode number
n=4 toroidal mode number

Infernal modes in PT update: growth rates

✓ Oscillatory behaviour vs continuum n=1…15





[J. Manickam, 1987 Nucl. Fusion 27 1461]

Infernal modes

✓ High performance scenarios often have an extended region of low magnetic shear.

✓ This could cause **Infernal modes** to appear; indeed, they are **pressure driven** internal MHD instabilities that are excited in a region of **low shear.**

✓ They are **Zero frequency** modes with a **finite growing rate**

Infernal modes

✓ Concern about Infernal modes is related to:

- degradation of plasma confinement
- the onset of NTMs observed experimentally [D. Brunetti et al 2016 J. Phys.: Conf. Ser. 775 012002]
- the eventually extended radial structure [M Coste-Sarguet and J P Graves 2024 Plasma Phys. Control. Fusion 66 095004]
- the growth rate oscillatory behaviour with respect to n-toroidal mode number that makes any prediction impossible [Manickam, 1987 Nucl. Fusion 27 1461]
- overwhelming of Alfvén modes, that hinders their studies

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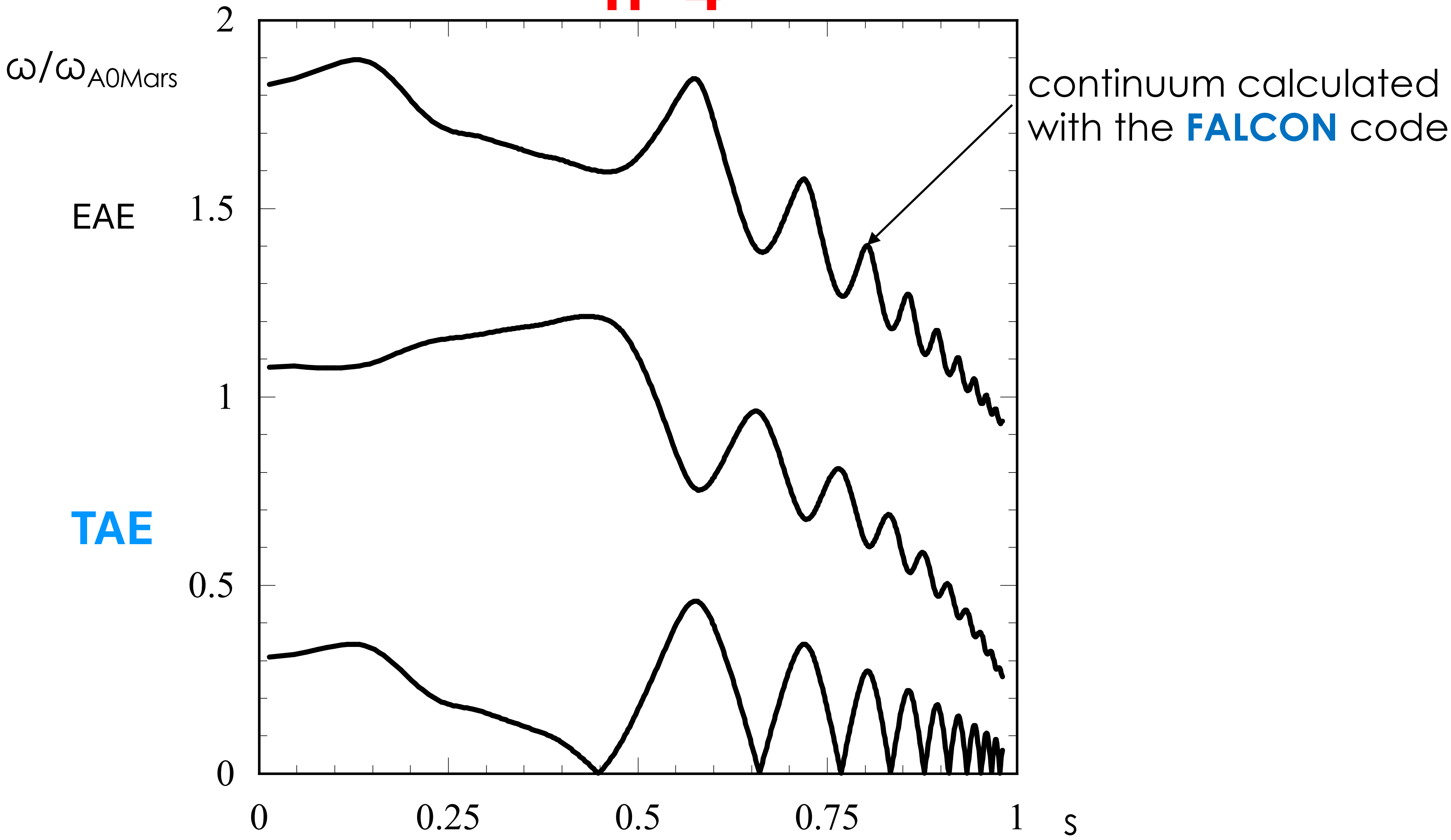
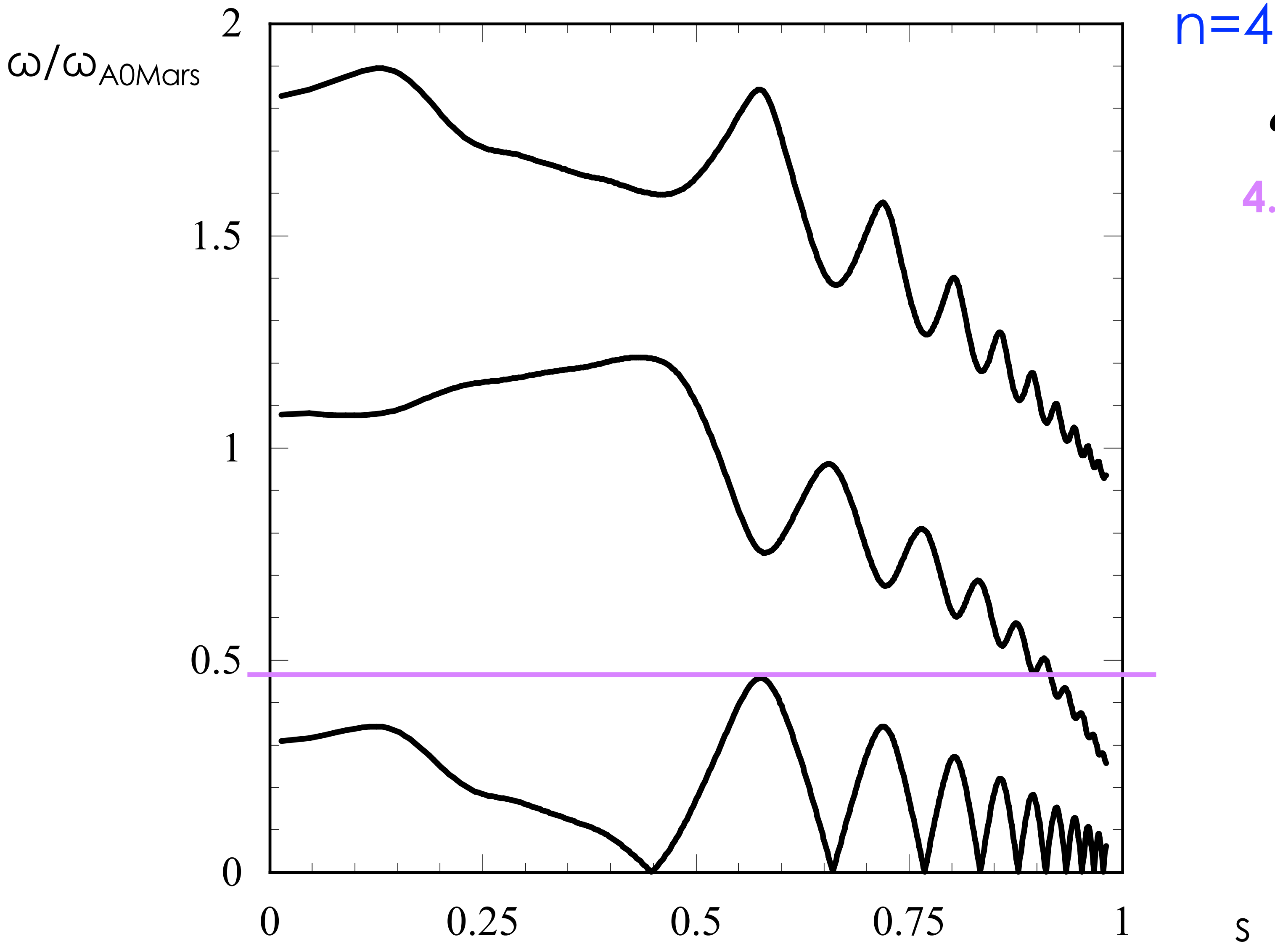
Alfvén modes
Shear Alfvén continuum spectrum
n=4



Alfvén modes

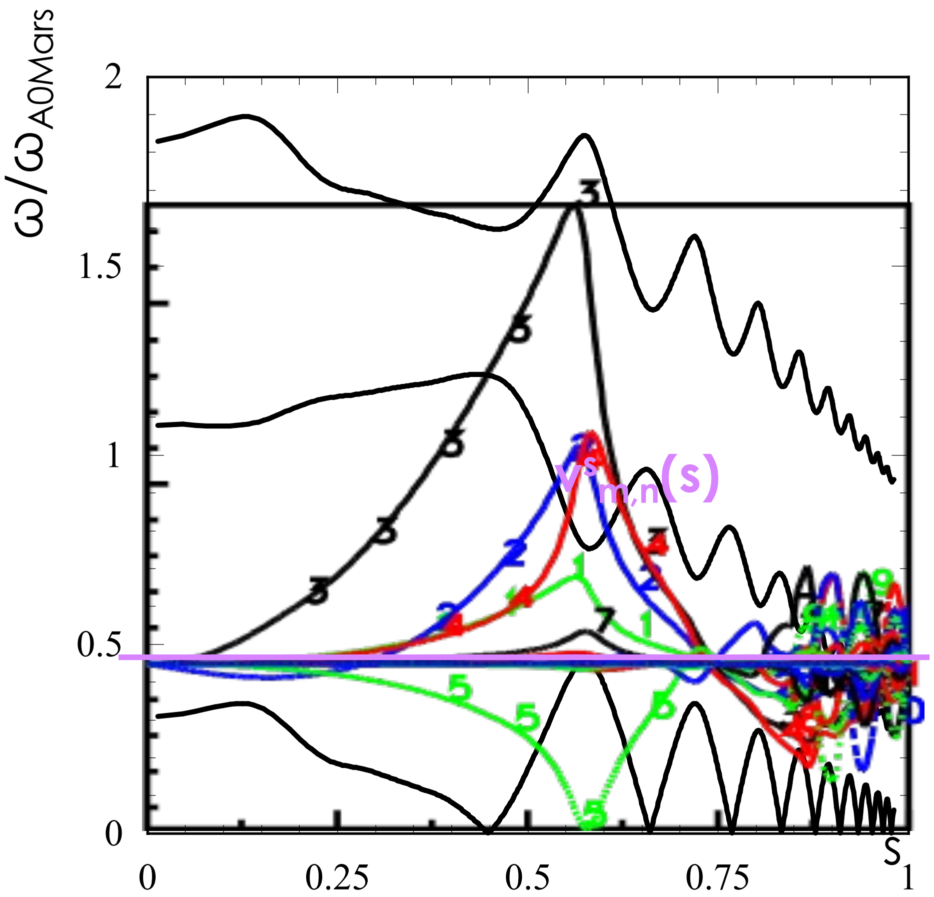


ω/ω_{A0Mars}

4.66648E-01

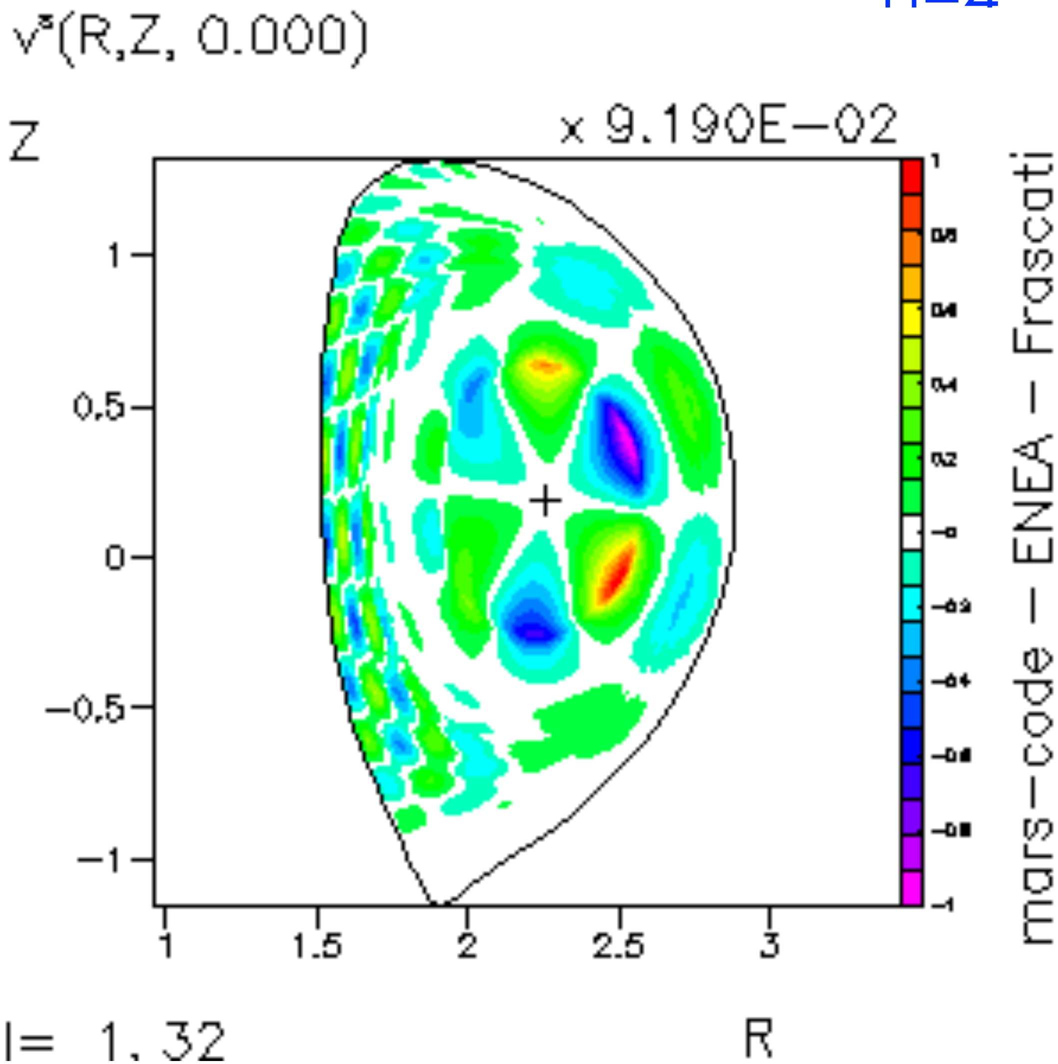
Alfvén modes

Perturbed velocity in Fourier space

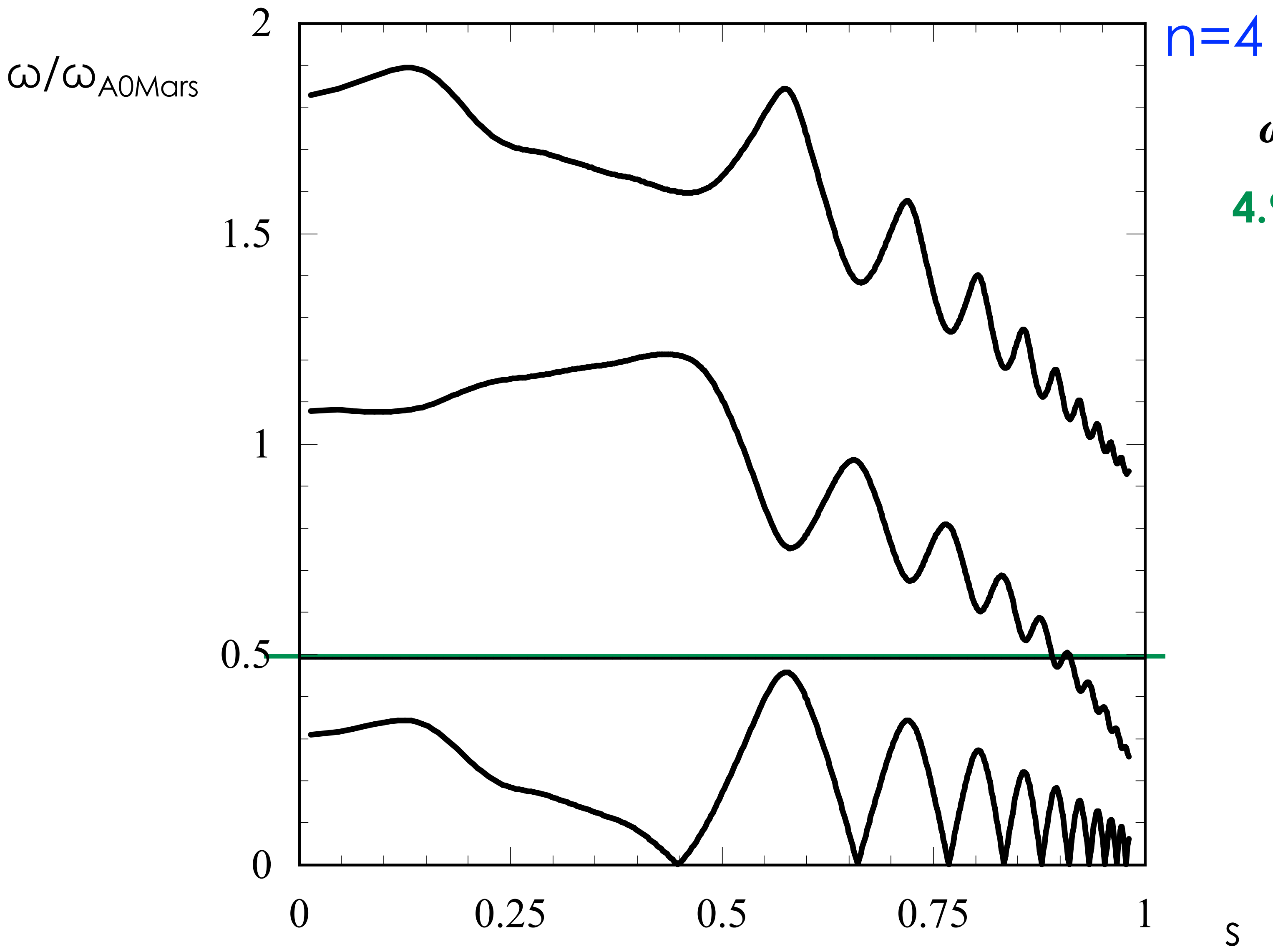


Perturbed velocity in real space

n=4



Alfvén modes



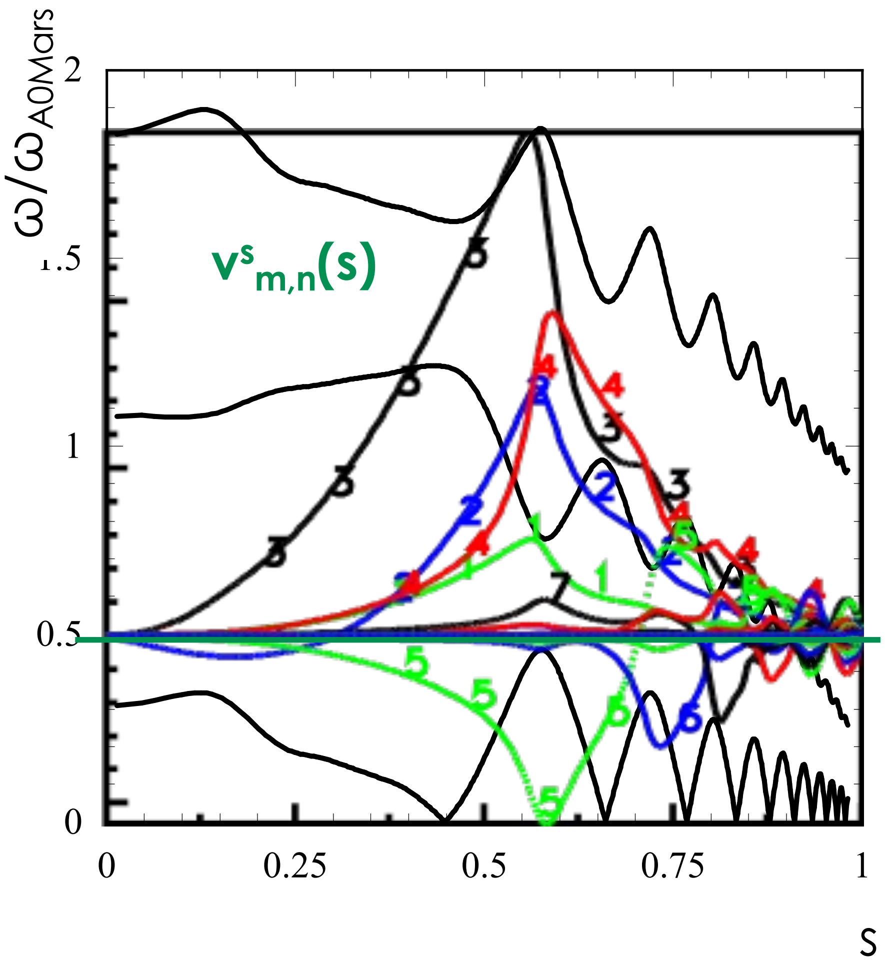
ω/ω_{A0Mars}

4.91244E-01

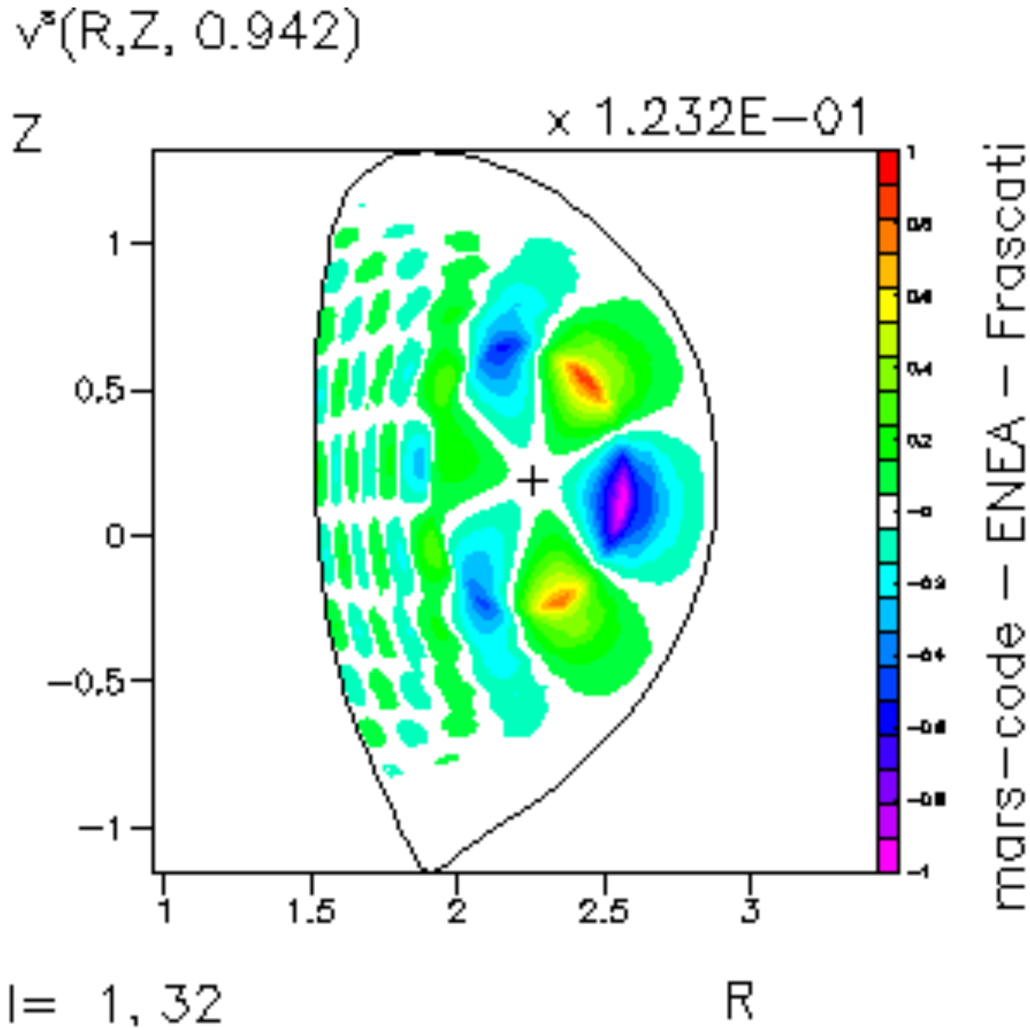
Alfvén modes

n=4

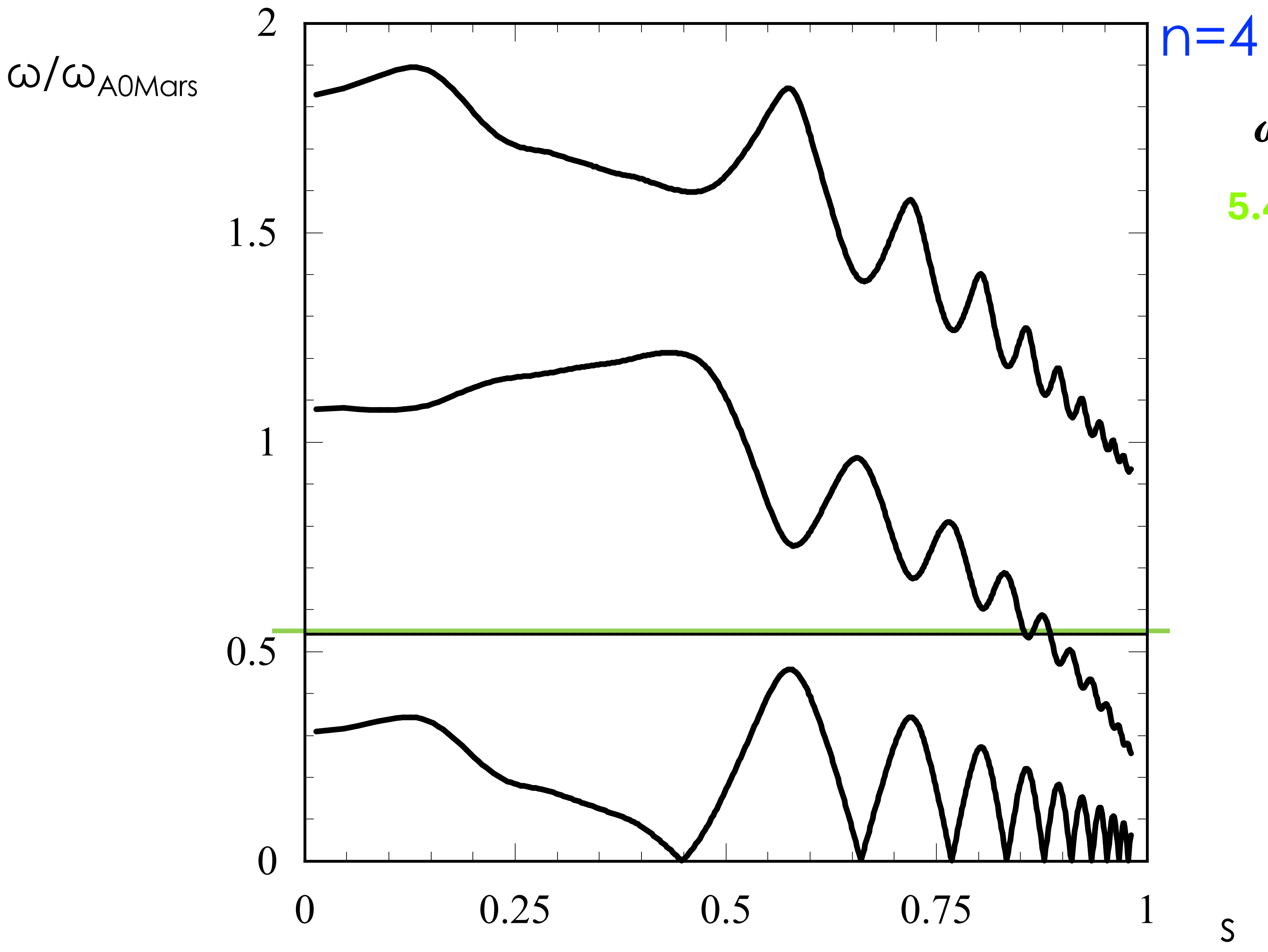
Perturbed velocity in Fourier space



Perturbed velocity in real space



Alfvén modes



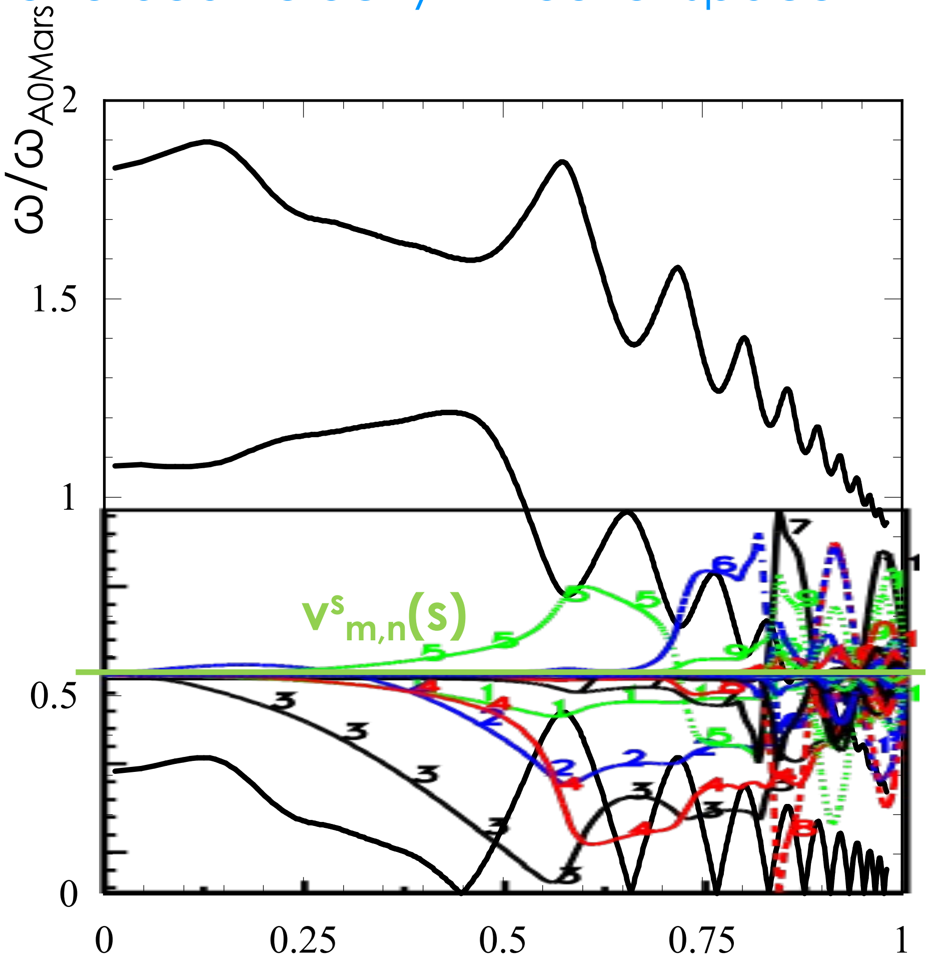
ω/ω_{A0Mars}

5.41890E-01

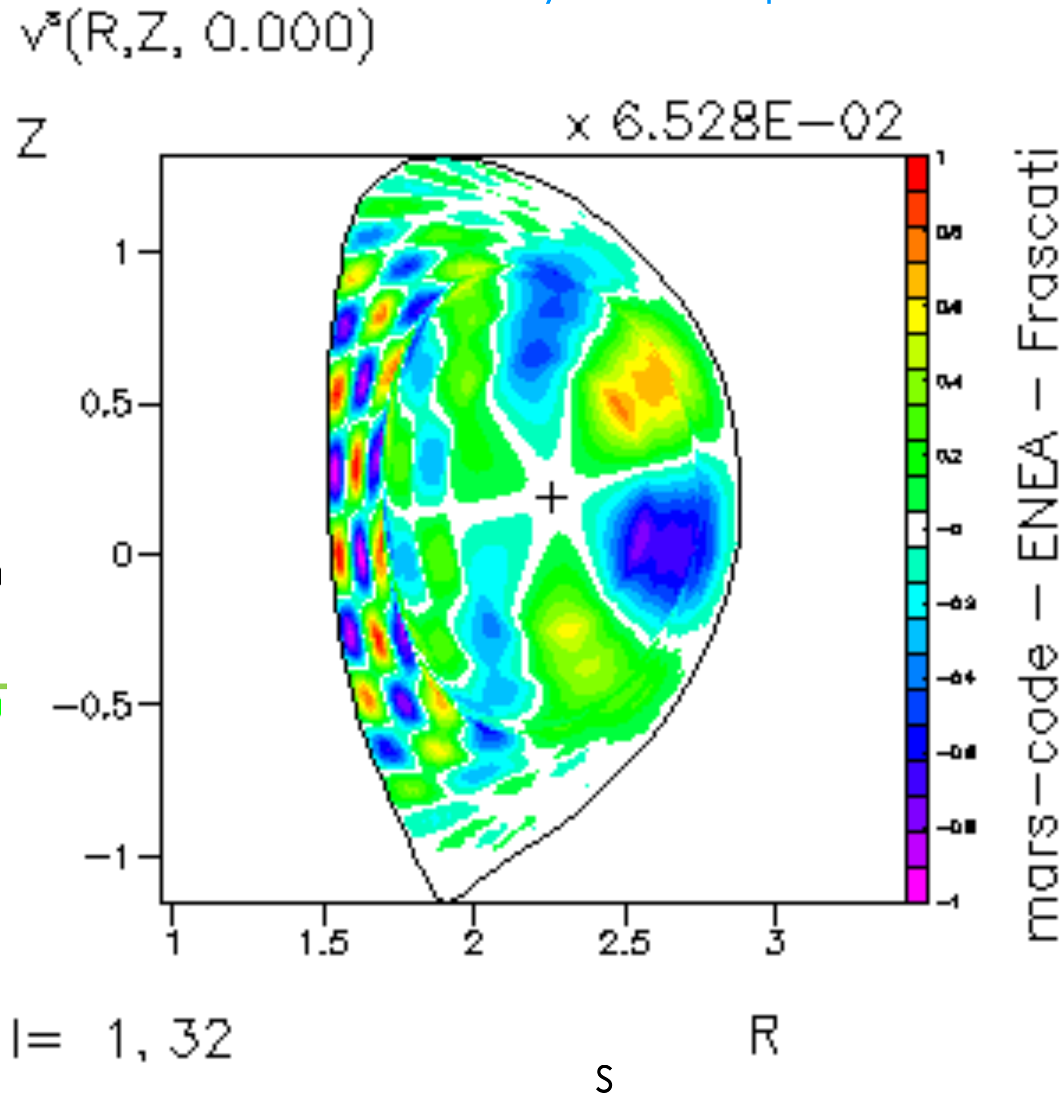
Alfvén modes

n=4

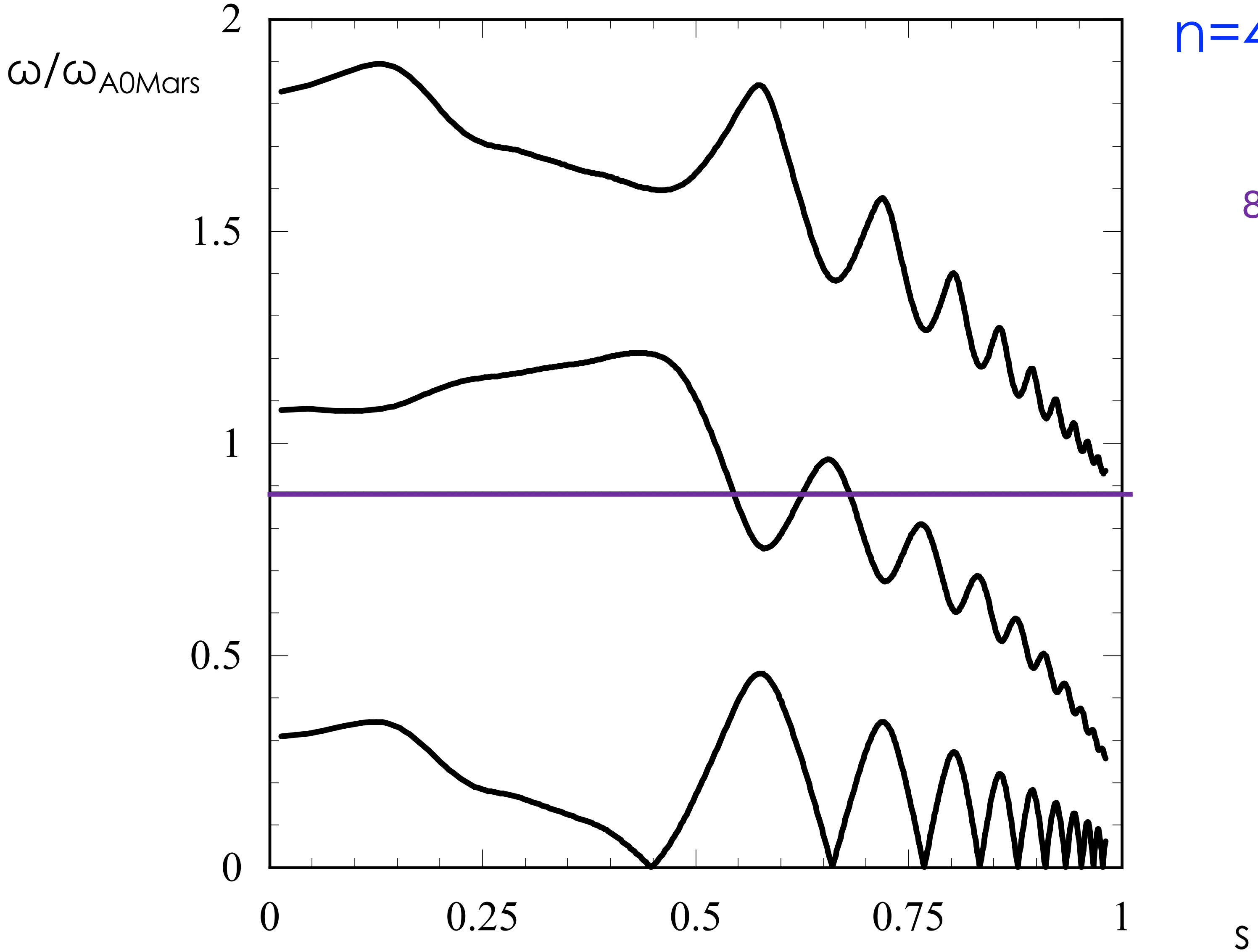
Perturbed velocity in Fourier space



Perturbed velocity in real space



Alfvén modes



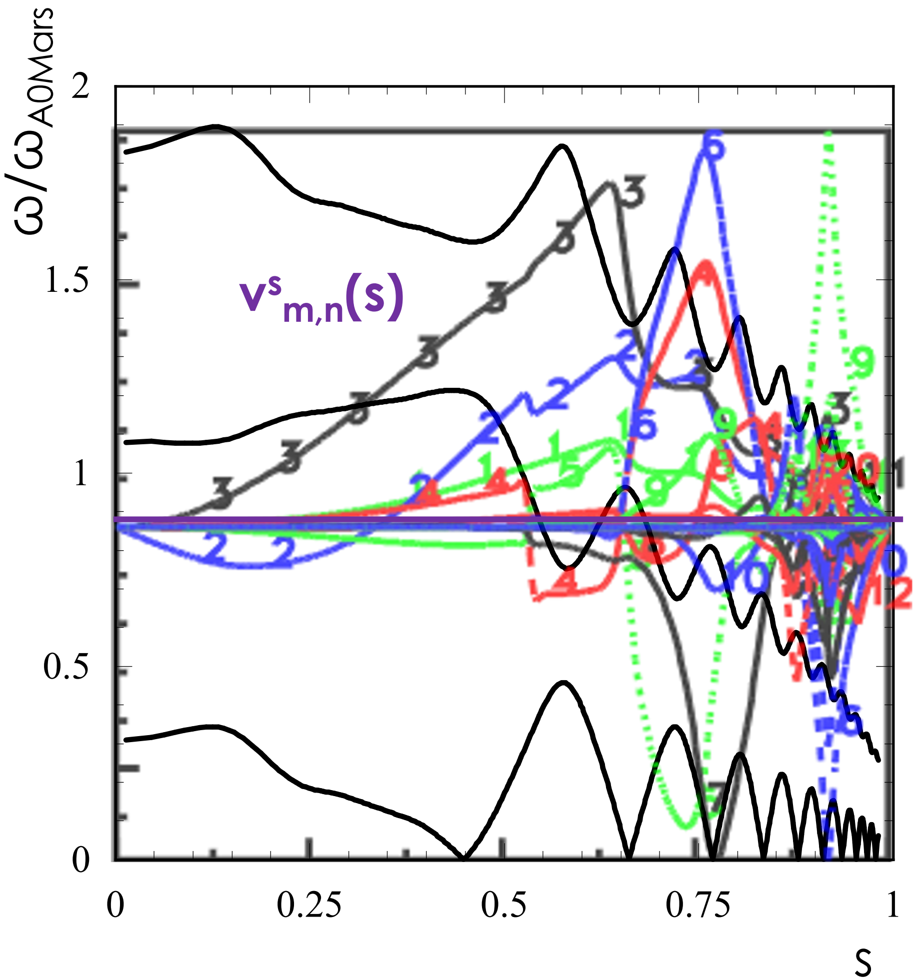
n=4

ω/ω_{A0Mars}

8.83871E-01

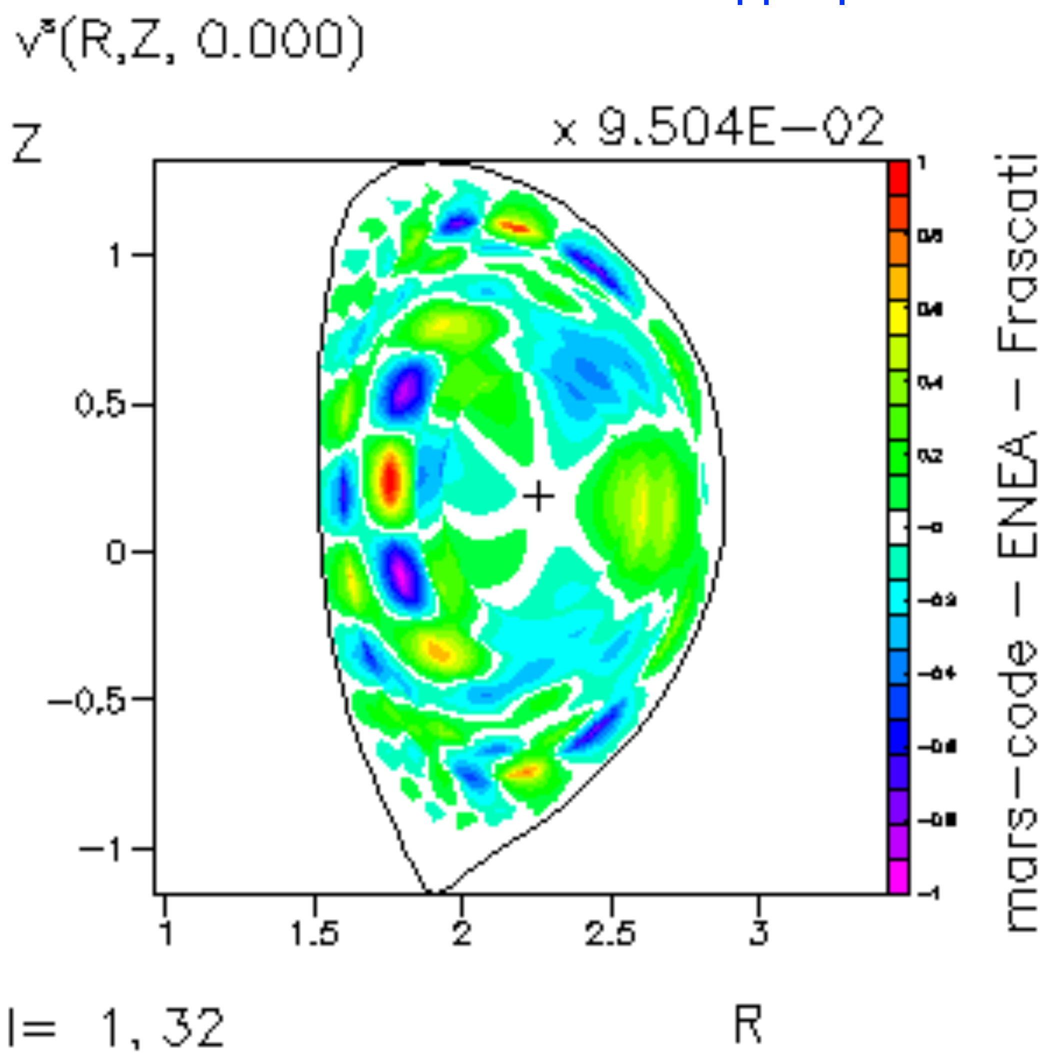
Alfvén modes

Perturbed velocity in Fourier space

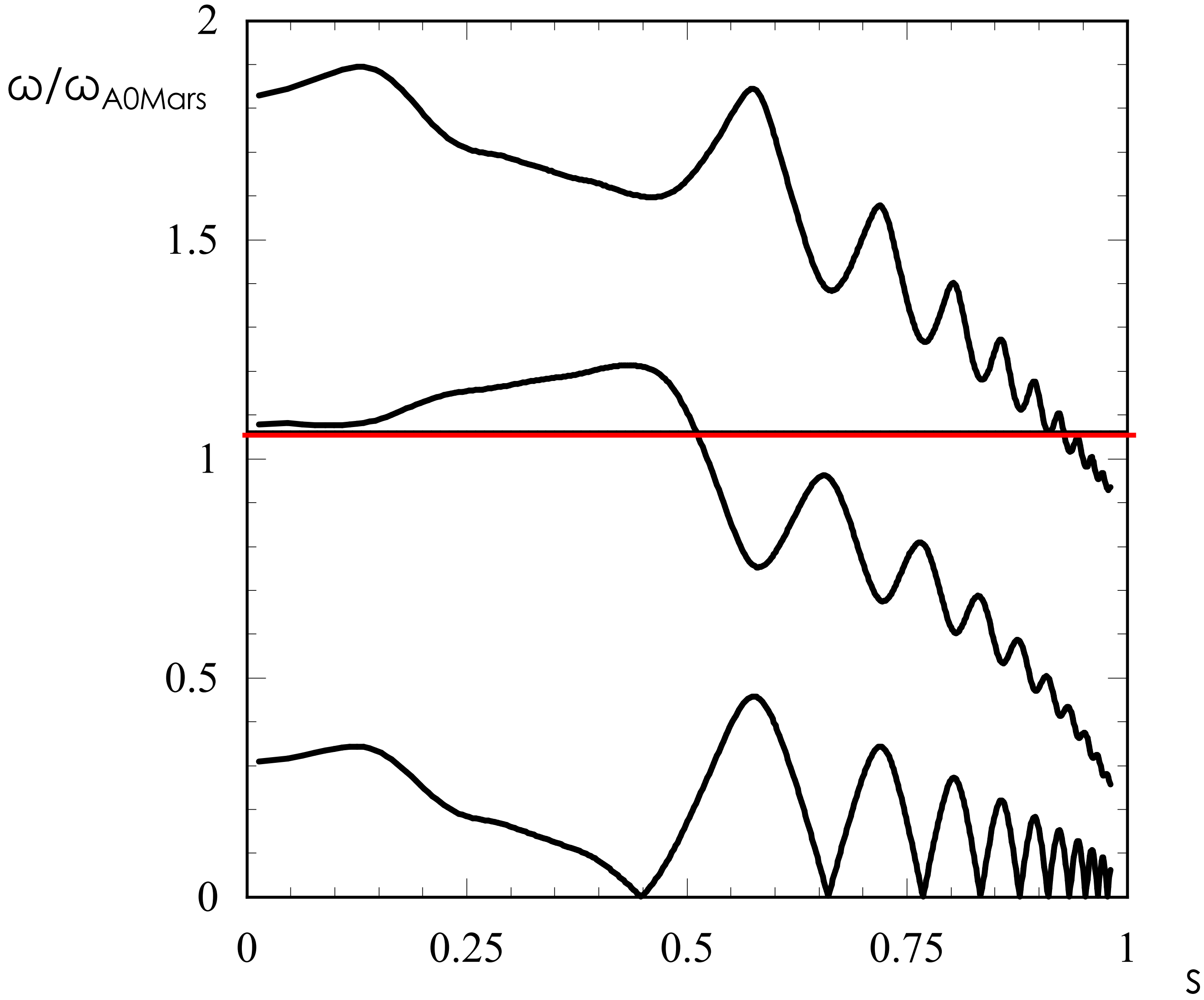


Perturbed velocity in real space

n=4



Alfvén modes

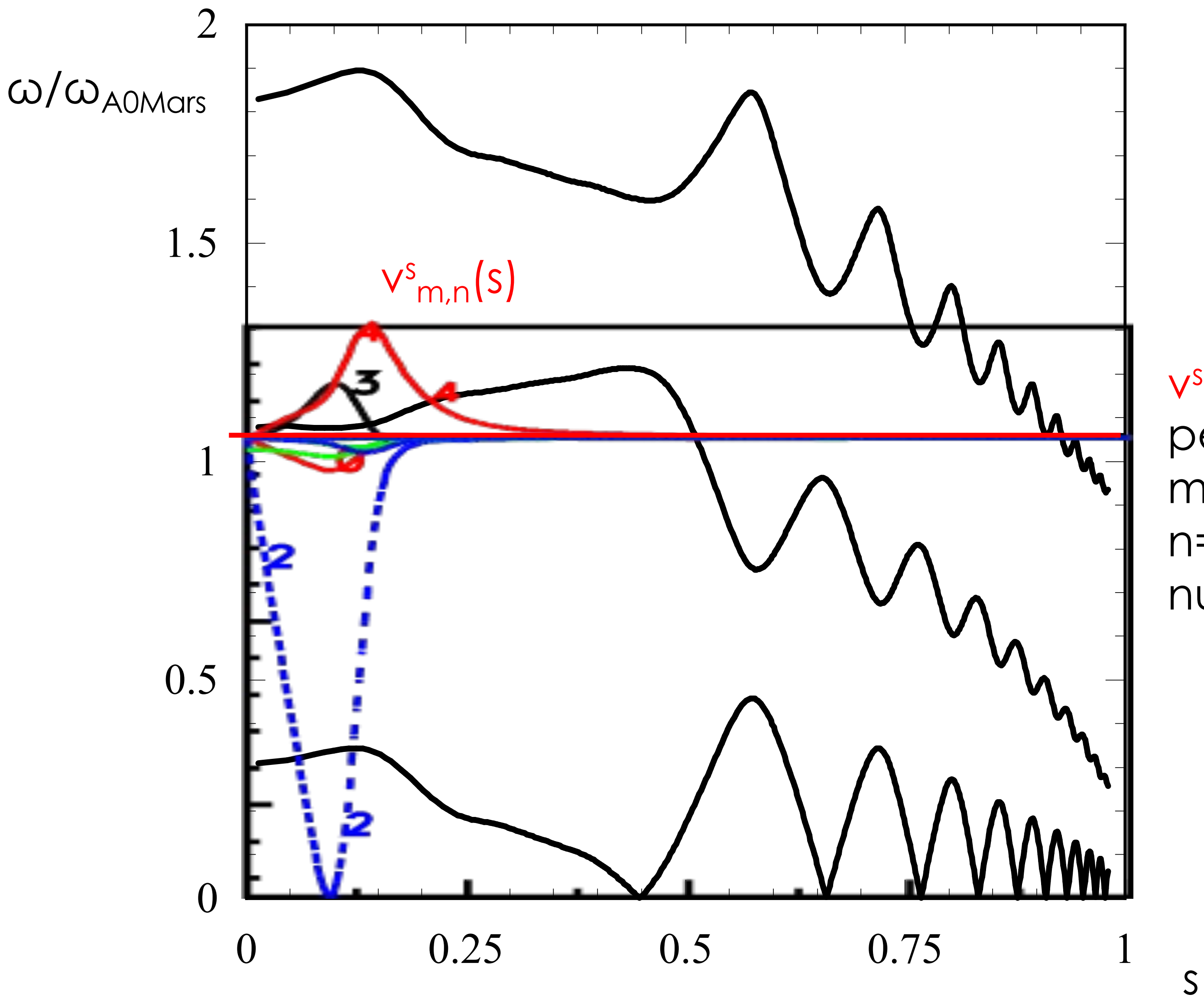


n=4

ω/ω_{A0Mars}

1.06247E+00

Alfvén modes



n=4

ω/ω_{A0Mars}

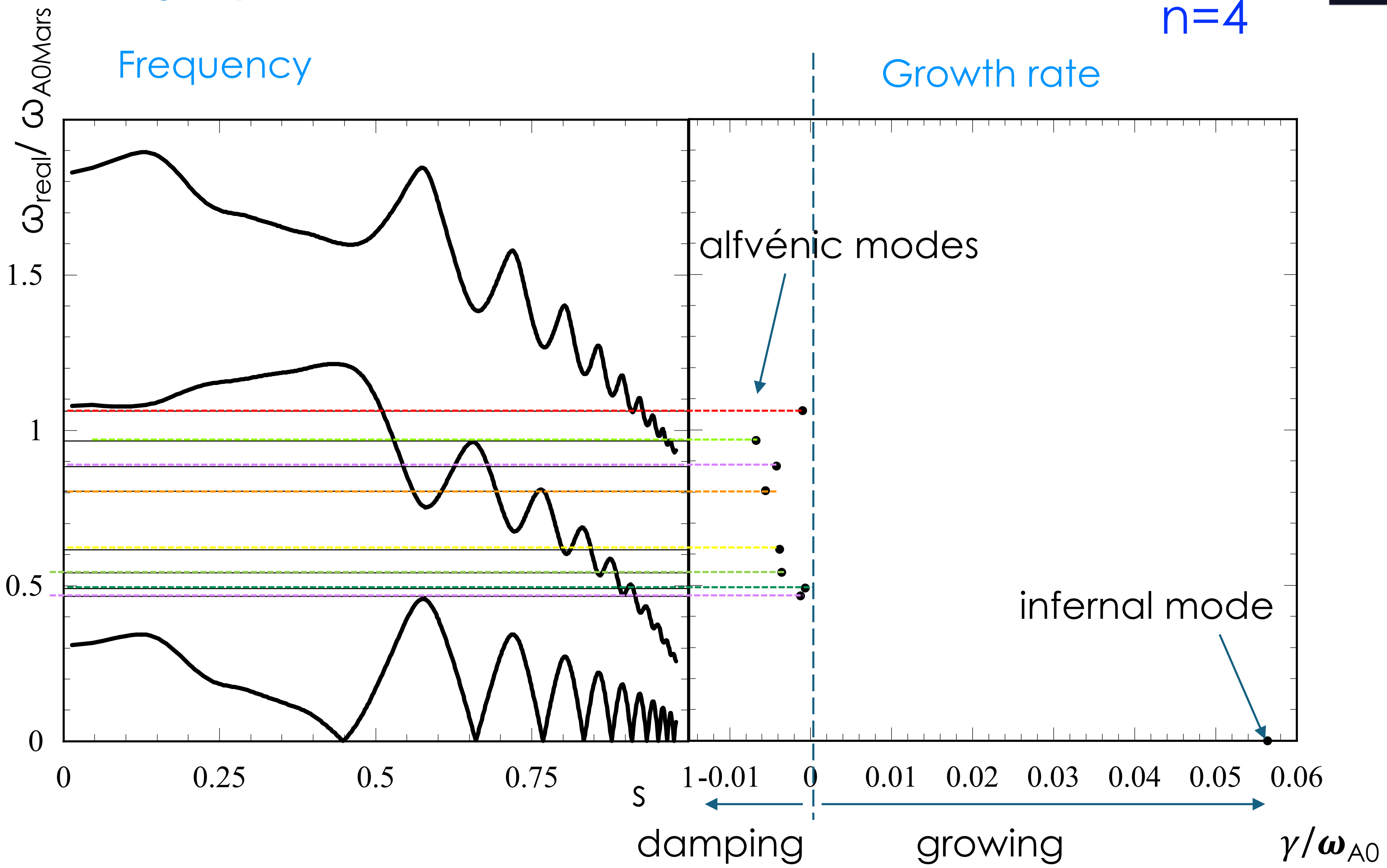
1.06247E+00

$v^{s}_{m,n}(s)$
perturbed velocity
m polidal number
n=4 toroidal mode number

Alfvén modes

- ✓ energetic particles not included

n=4



Alfvén modes studies: results from the HYMAGYC code

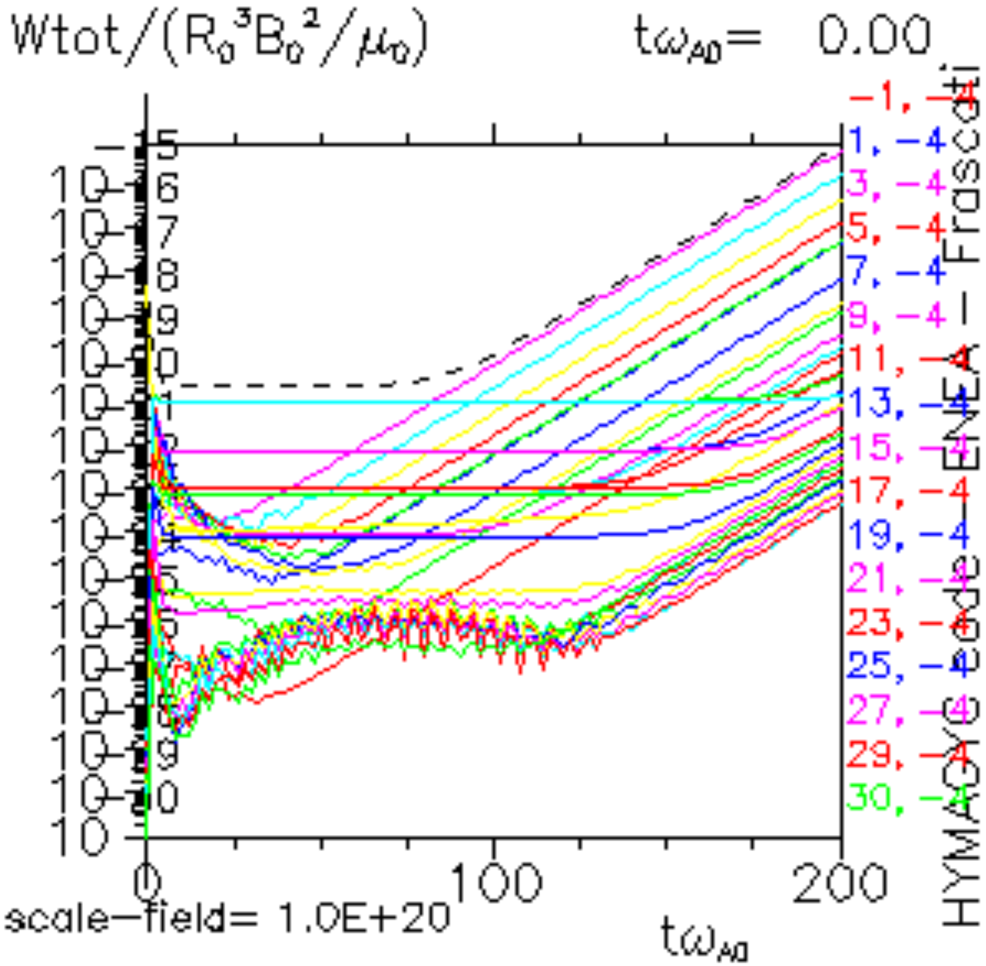
✓ energetic particles not included

n=4

Alfvén modes studies: results from the HYMAGYC code

n=4

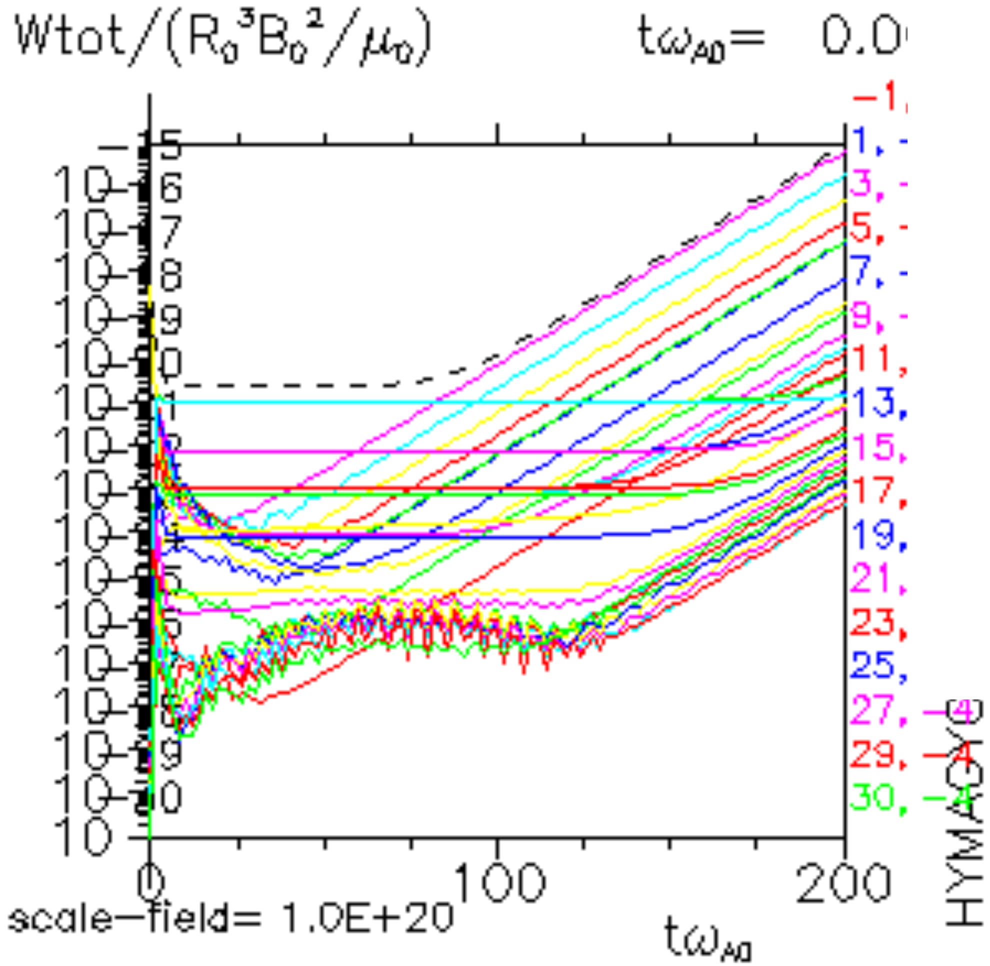
Total energy



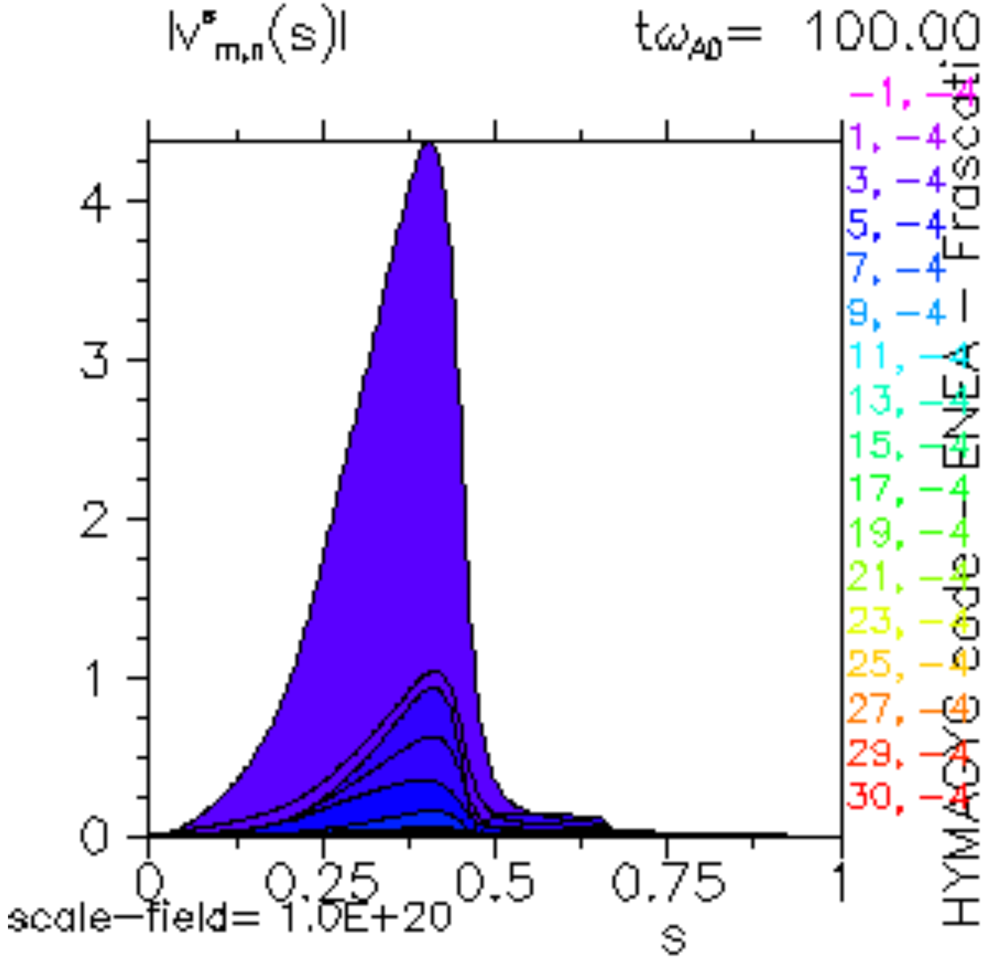
Alfvén modes studies: results from the HYMAGYC code

n=4

Total energy

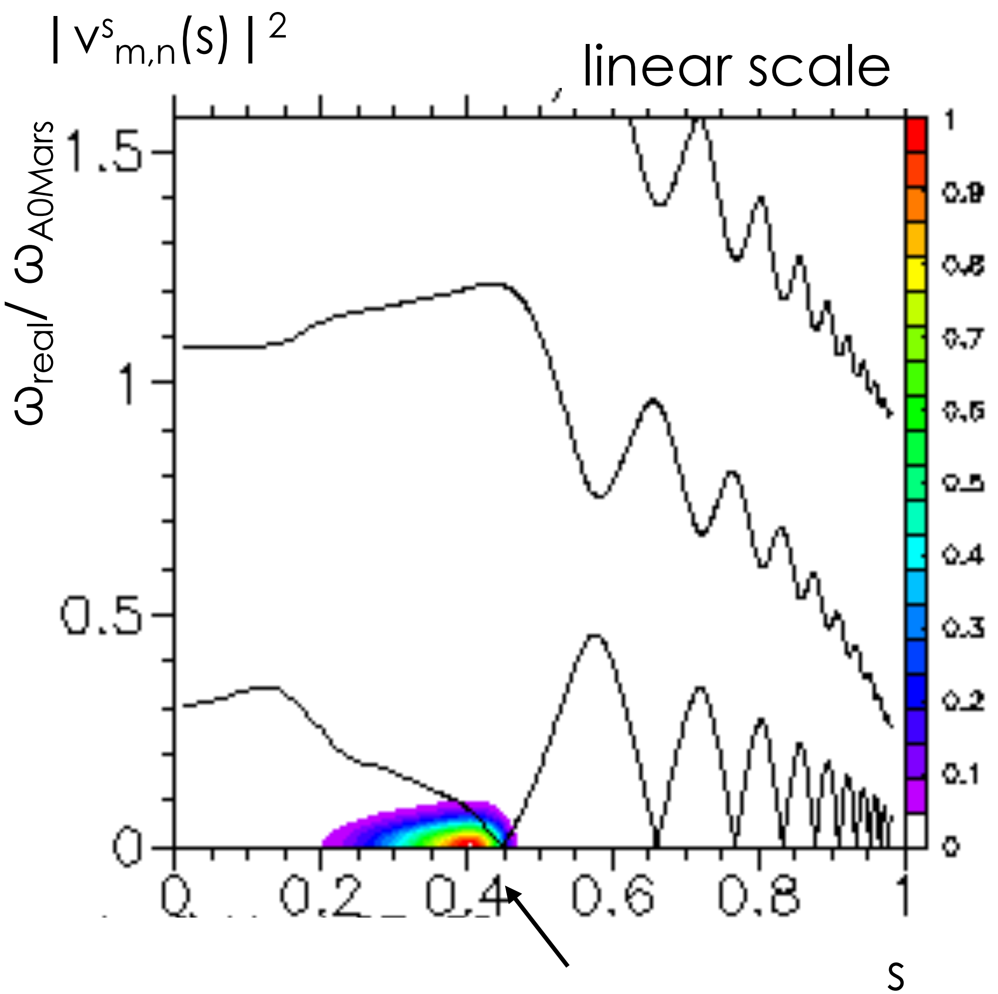


Perturbed velocity



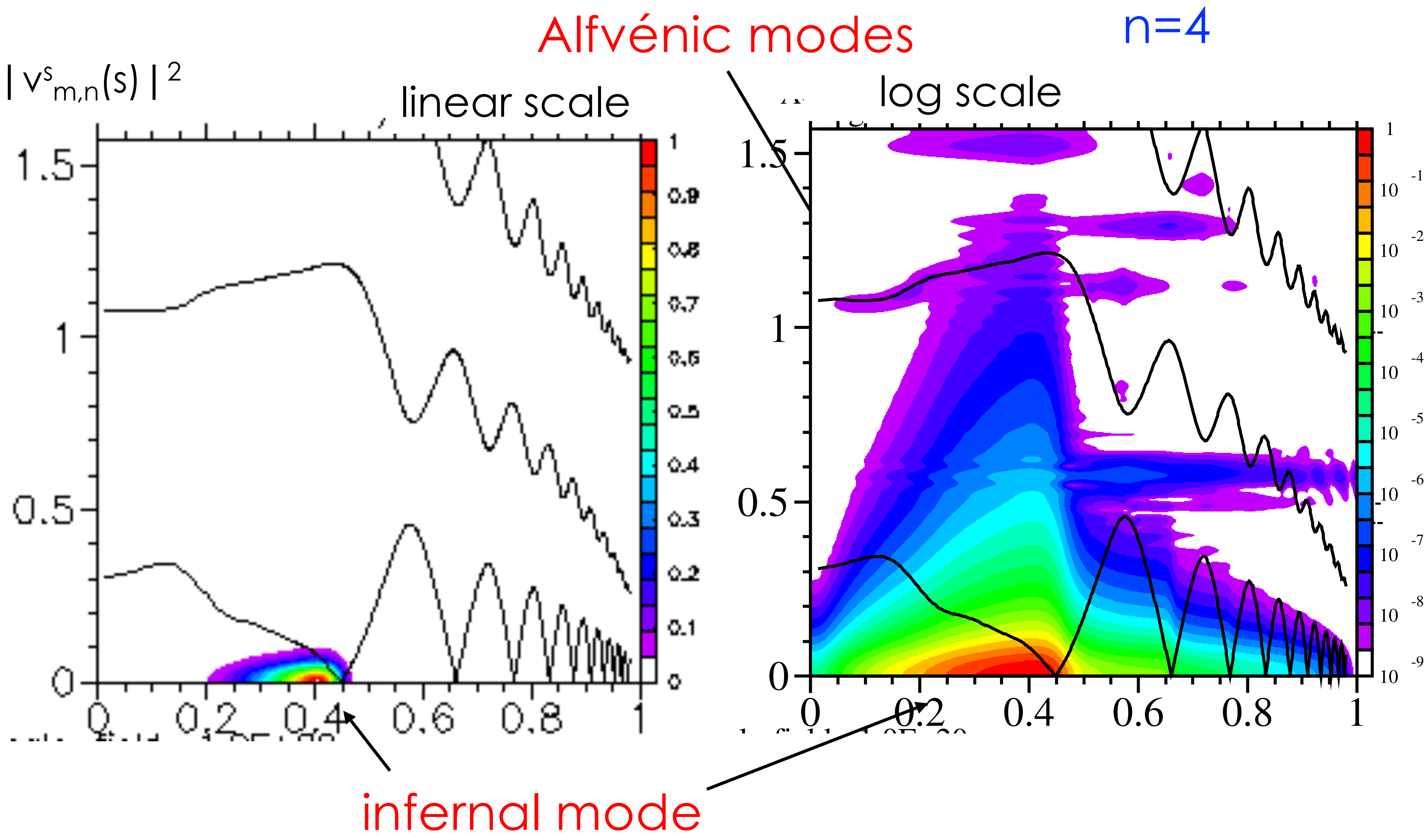
Alfvén modes studies: results from the HYMAGYC code

n=4



internal mode

Alfvén modes studies: results from the HYMAGYC code



Conclusions

- ✓ Positive triangularity has been studied from low to high toroidal mode numbers n
- ✓ Infernal modes revealed @ q rational surfaces -> *growing modes* which do overwhelm Alfven modes
- ✓ Alfvenic modes revealed within continuum spectrum gaps ->*damped modes*
- ✓ Alfvenic modes studies evolution and dynamics is hindered by the stronger unstable infernal modes

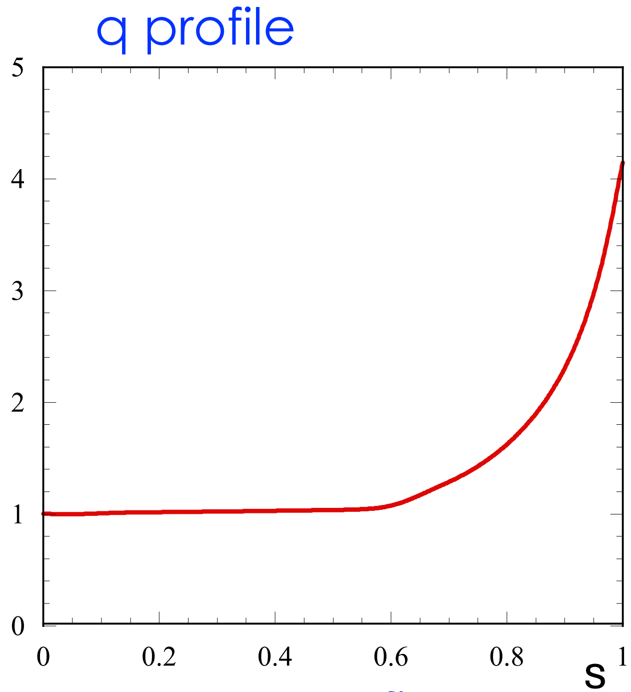
Outline

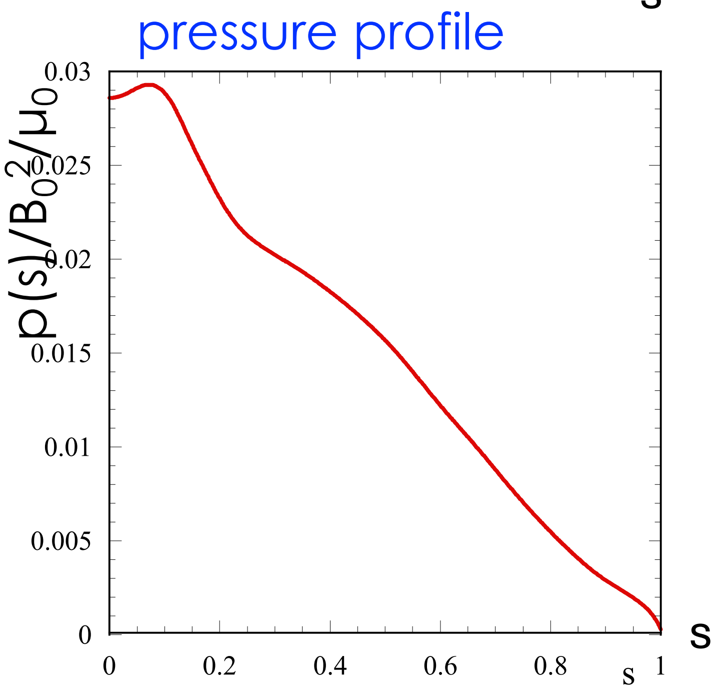
- codes flow chart: CHEASE, MARS, HYMAGYC, FALCON
- first studies on DTT **Negative Triangularity**: **flipped boundary** (from Positive Triangularity)
- updated DTT Positive Triangularity equilibrium
  - Internal modes studies
  - Alfvén modes
- studies on DTT **Negative Triangularity**: **from 1D transport solver** (Real Geometry)
  - internal modes studies
  - Alfvén modes

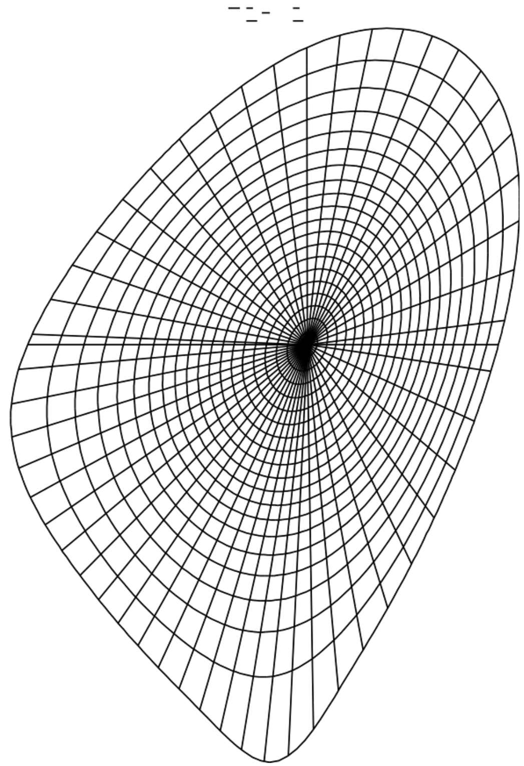
Profiles NT from transport solver

	DTT NT_FullPower
I_{tot} [MA]	3.0
B_0[T]	5.85
q_0	1.004
q_{edge}	4.15
$q_{95\%}$	3.49
β_{tor}%	1.53
β_N%	2.07
p_0[MPa]	0.78

- ✓ the equilibrium shows a higher q profile because the **model of sawtooth** has been included in the transport solver







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  - **infernal modes studies**
  - Alfvén modes

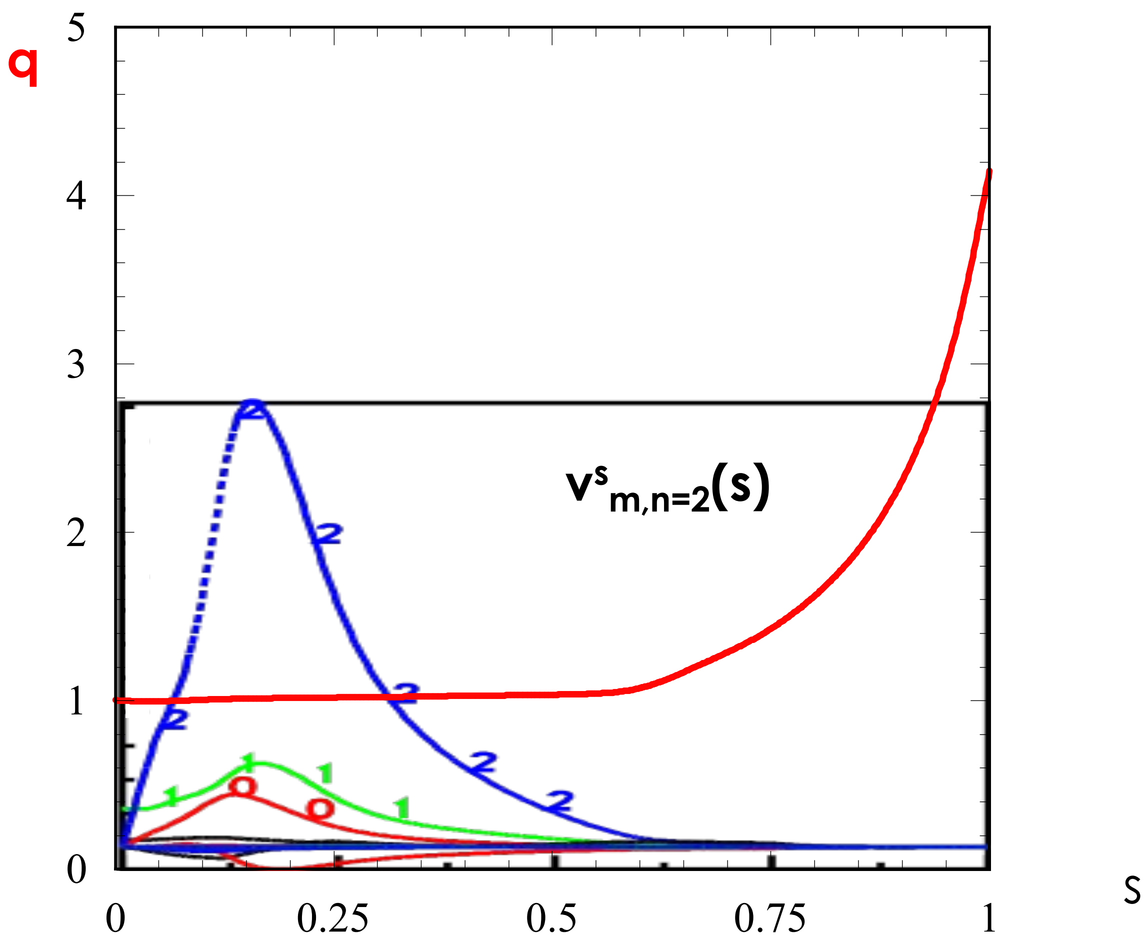
Infernal modes in NT

Results from the MARS code

- ✓ Scan for different toroidal mode numbers n=2, …,15 with the MARS code

Infernal modes in NT

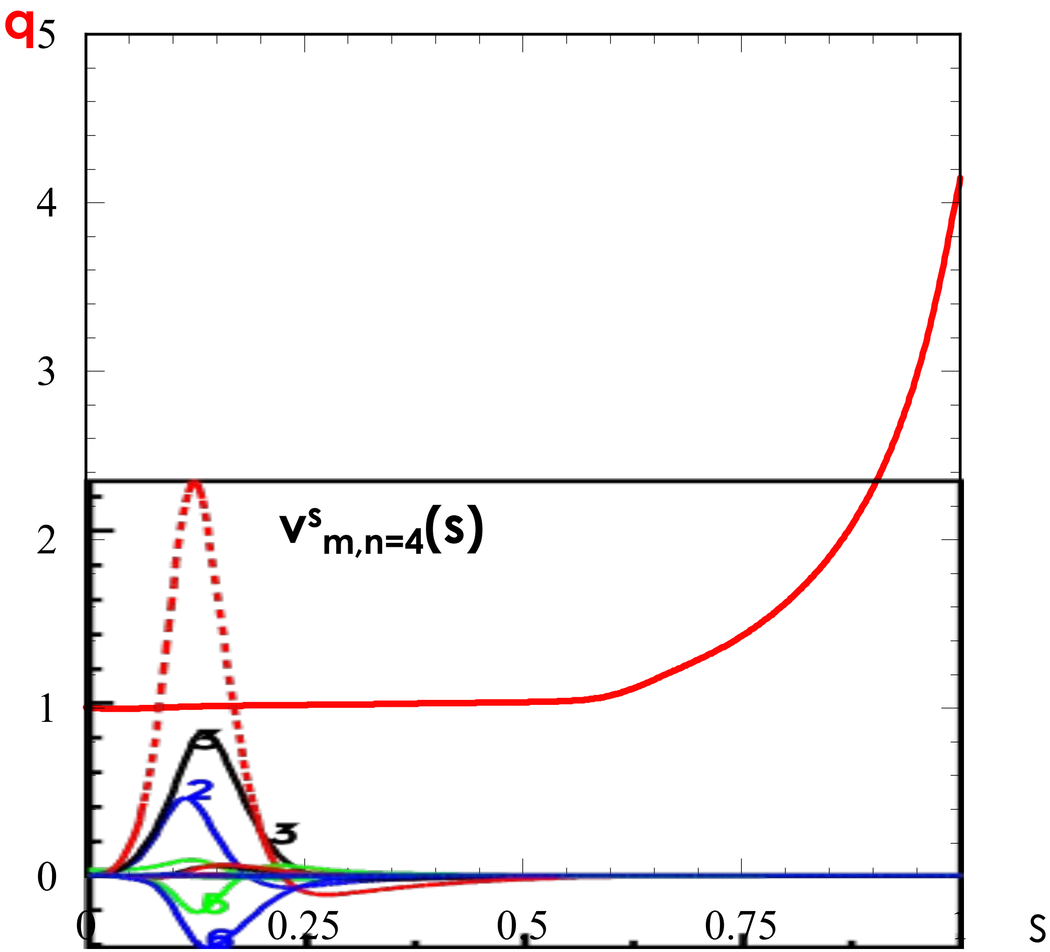
✓ Scan with the MARS code for different toroidal mode numbers n=2…15



n=2

!!!!Infernal mode

Infernal modes in NT

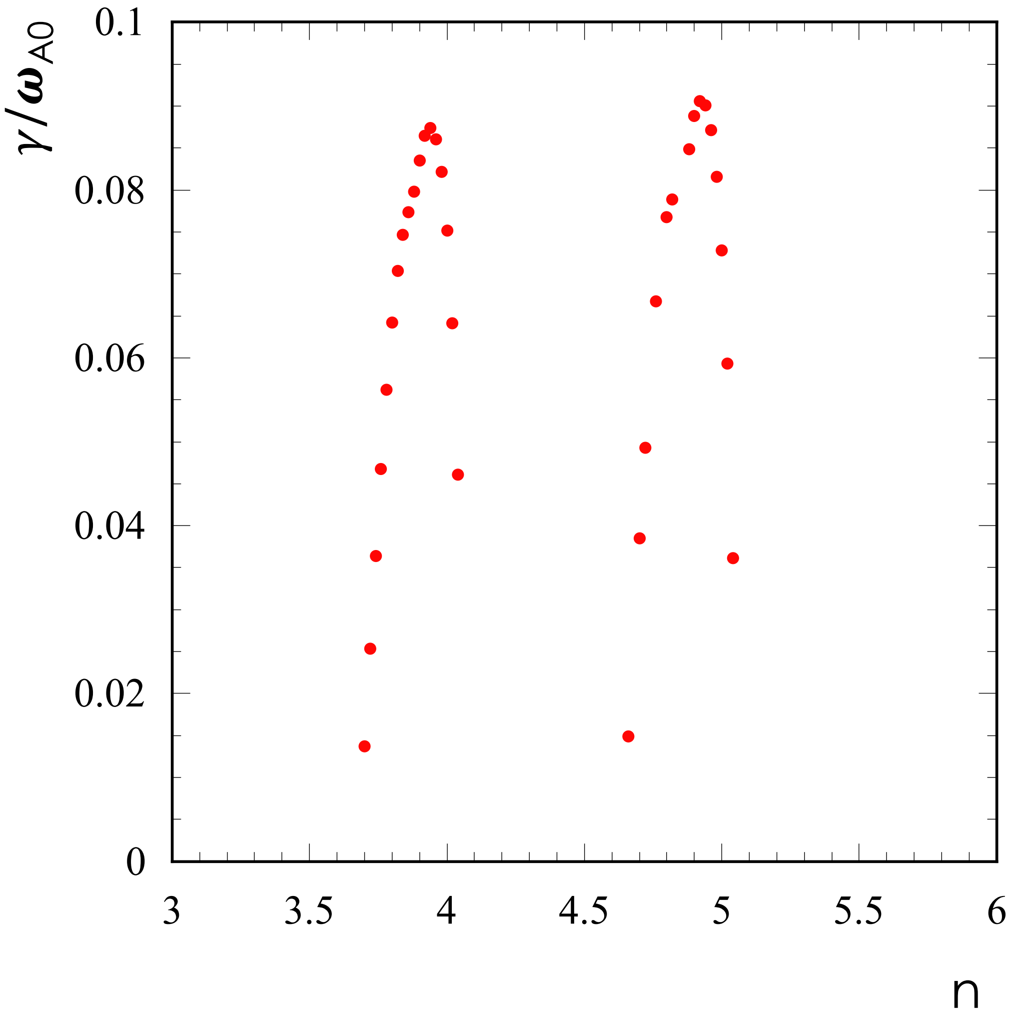


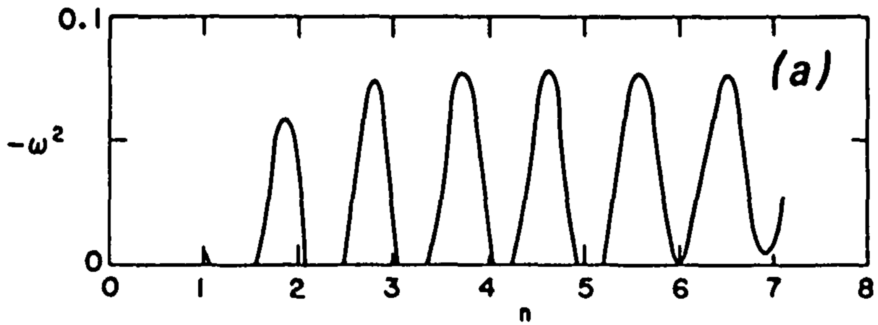
n=4

!!!!Infernal mode

Infernal modes in NT growth rates

Oscillating behaviour of infernal modes with n





J. Manickam, 1987 Nucl. Fusion 27

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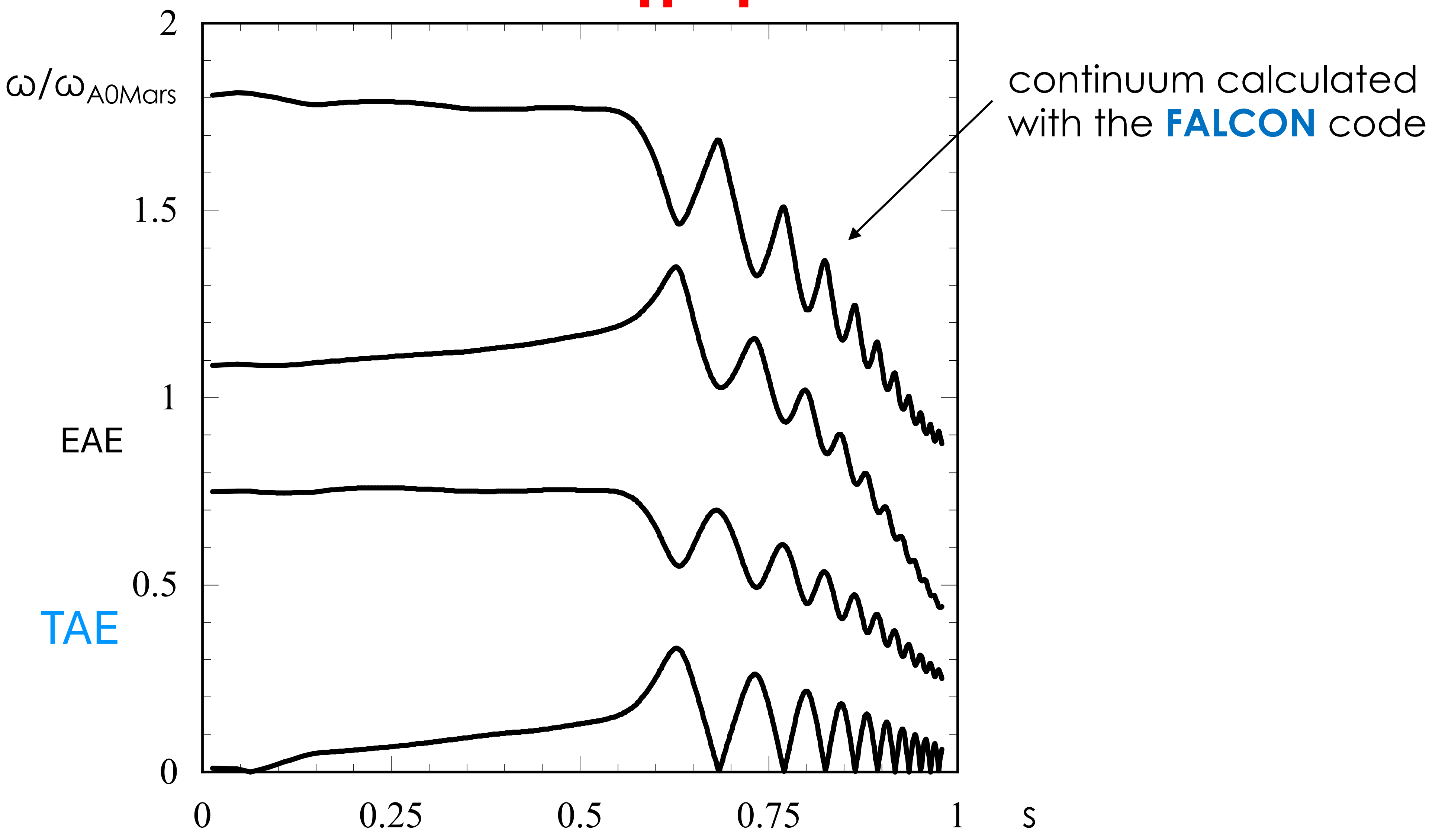
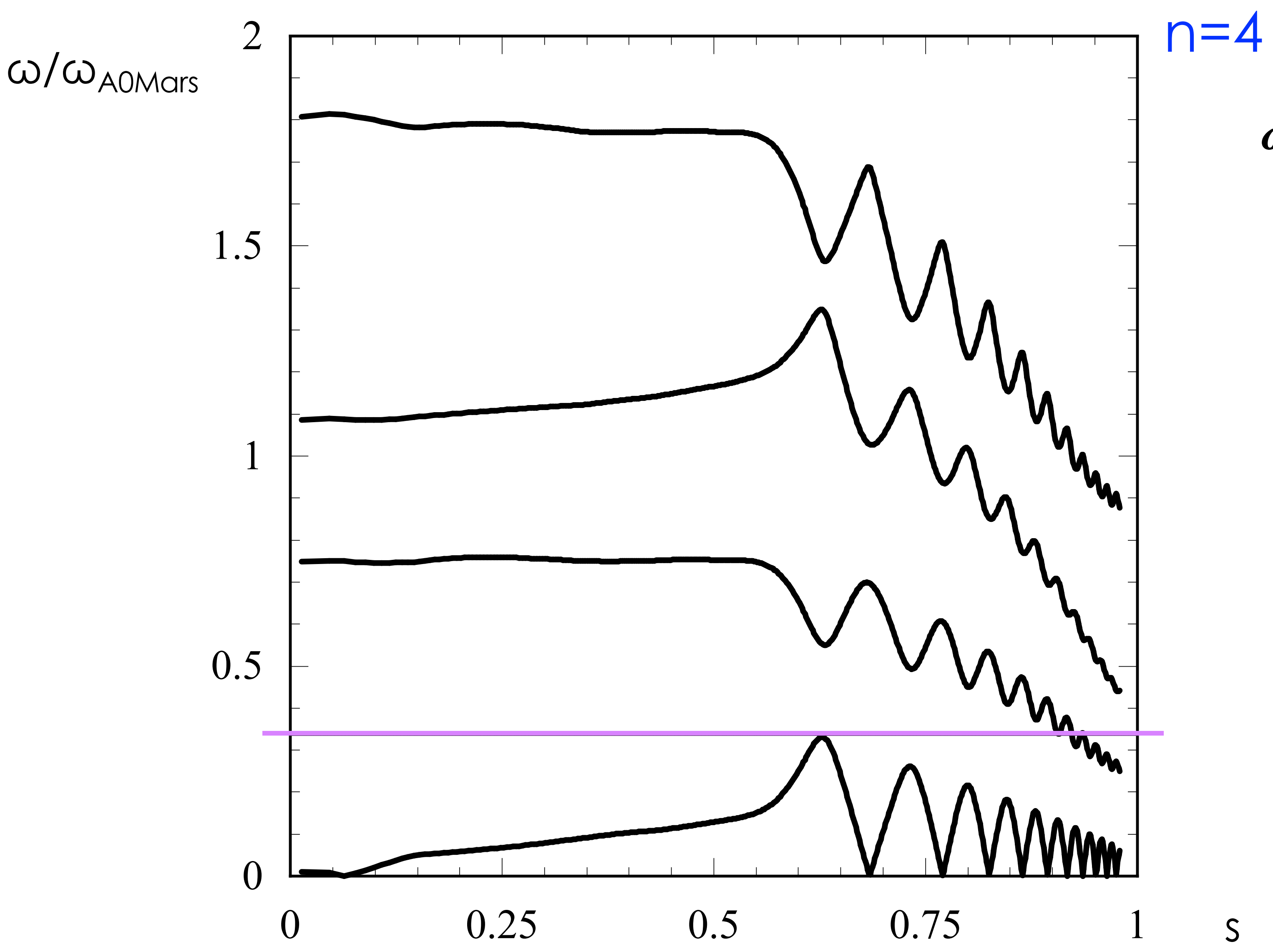
  - internal modes studies
  - **Alfvén modes**

Alfvén modes NT
Shear Alfvén continuum spectrum for n=4



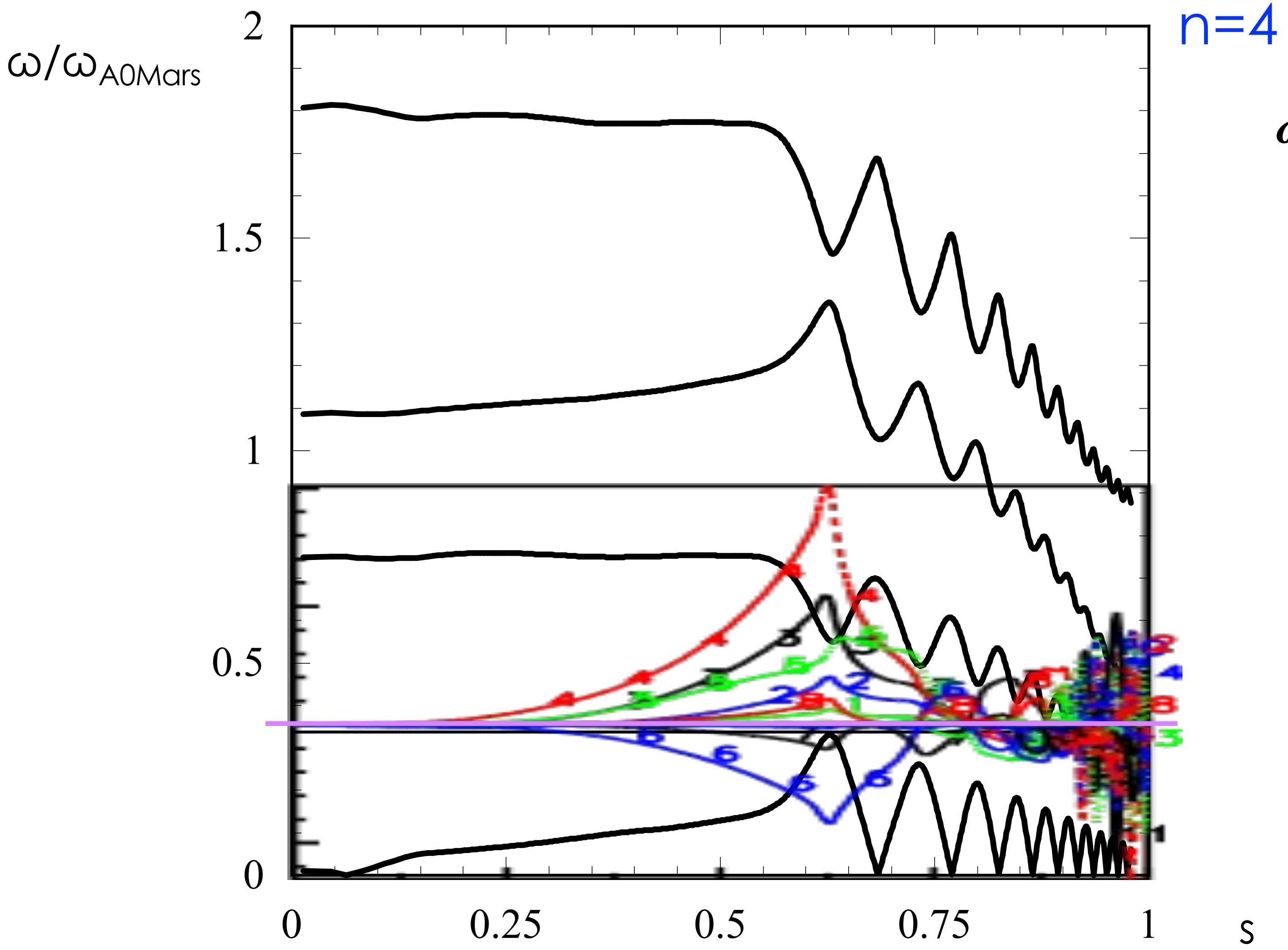
Alfvén modes NT



ω/ω_{A0Mars}

0.33823

Alfvén modes NT

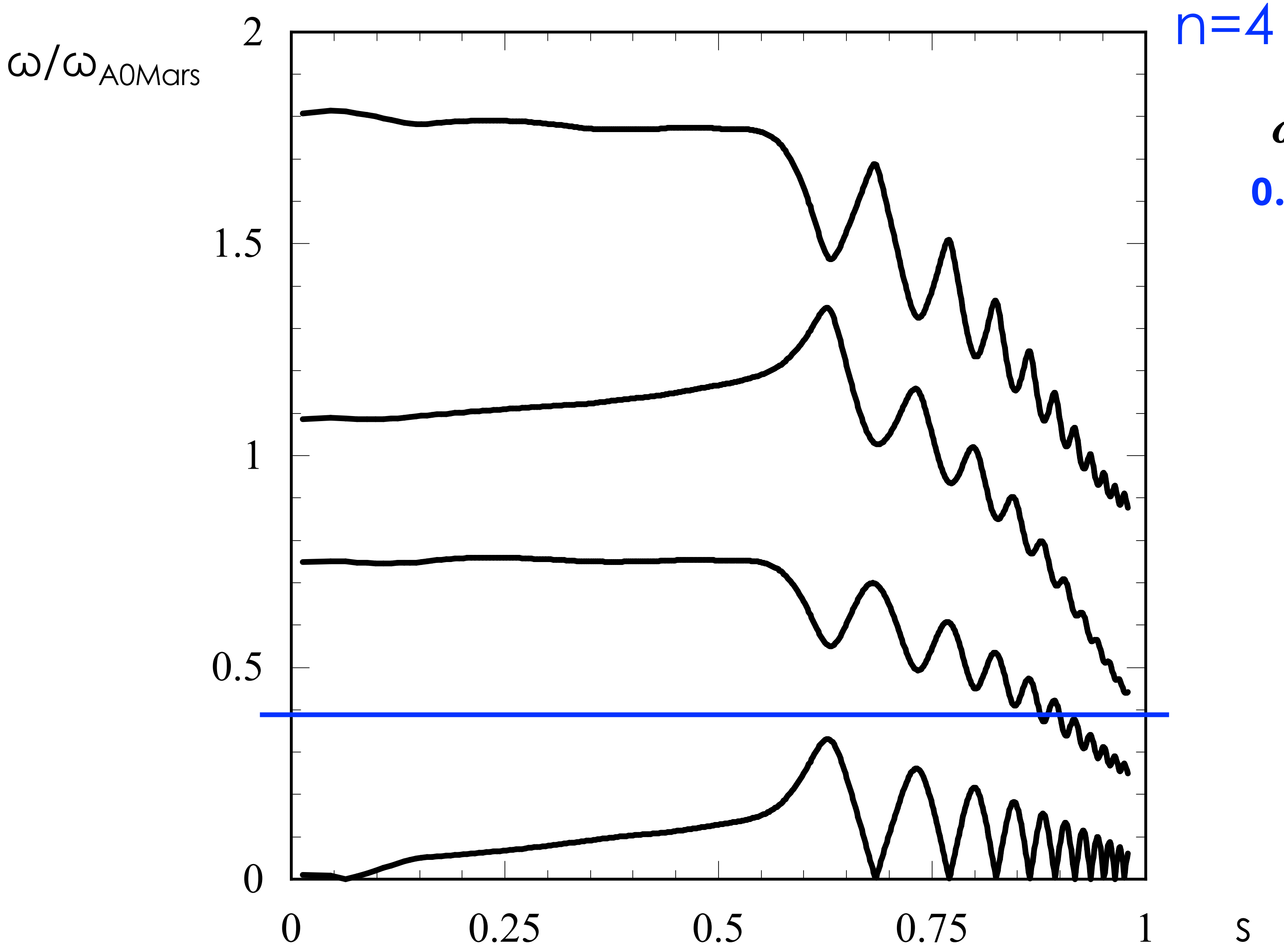


ω/ω_{A0Mars}

0.33823

$v^s_{m,n}(s)$

Alfvén modes NT

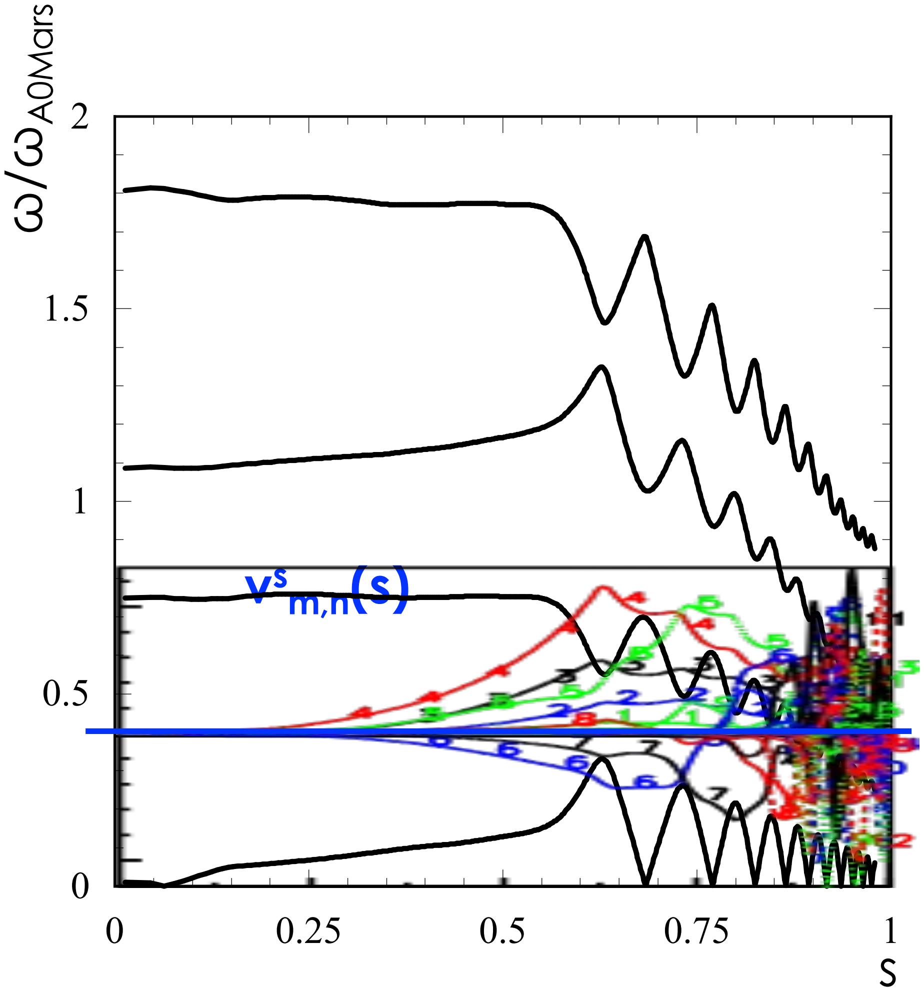


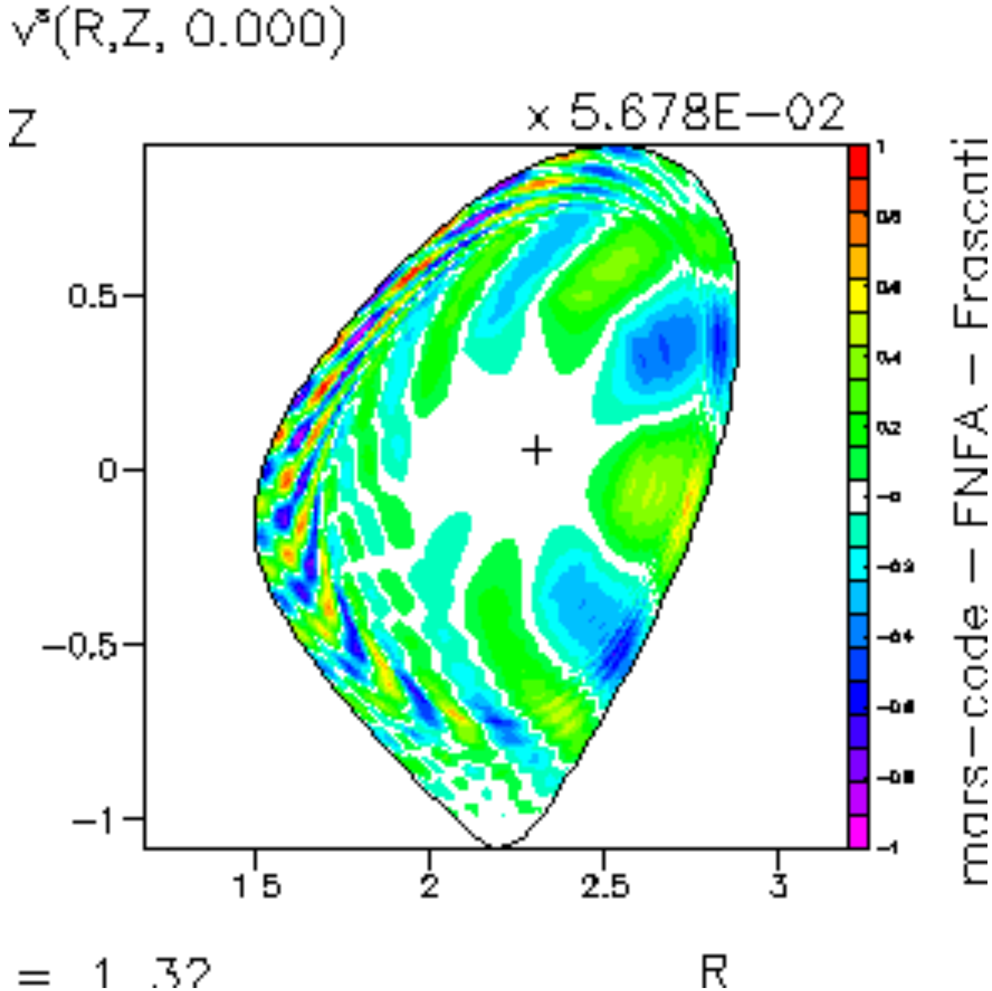
ω/ω_{A0Mars}

0.388870

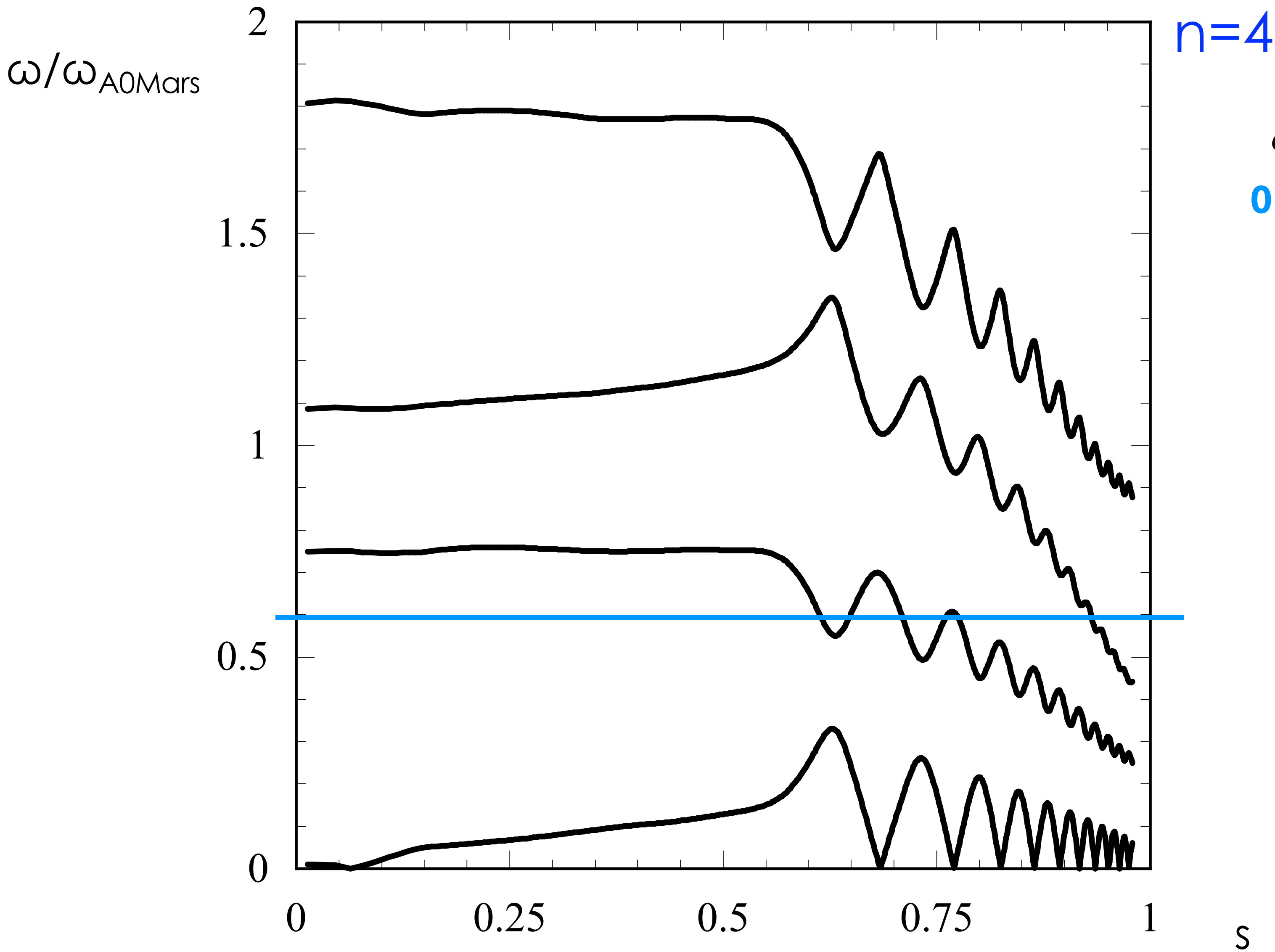
Alfvén modes NT

n=4





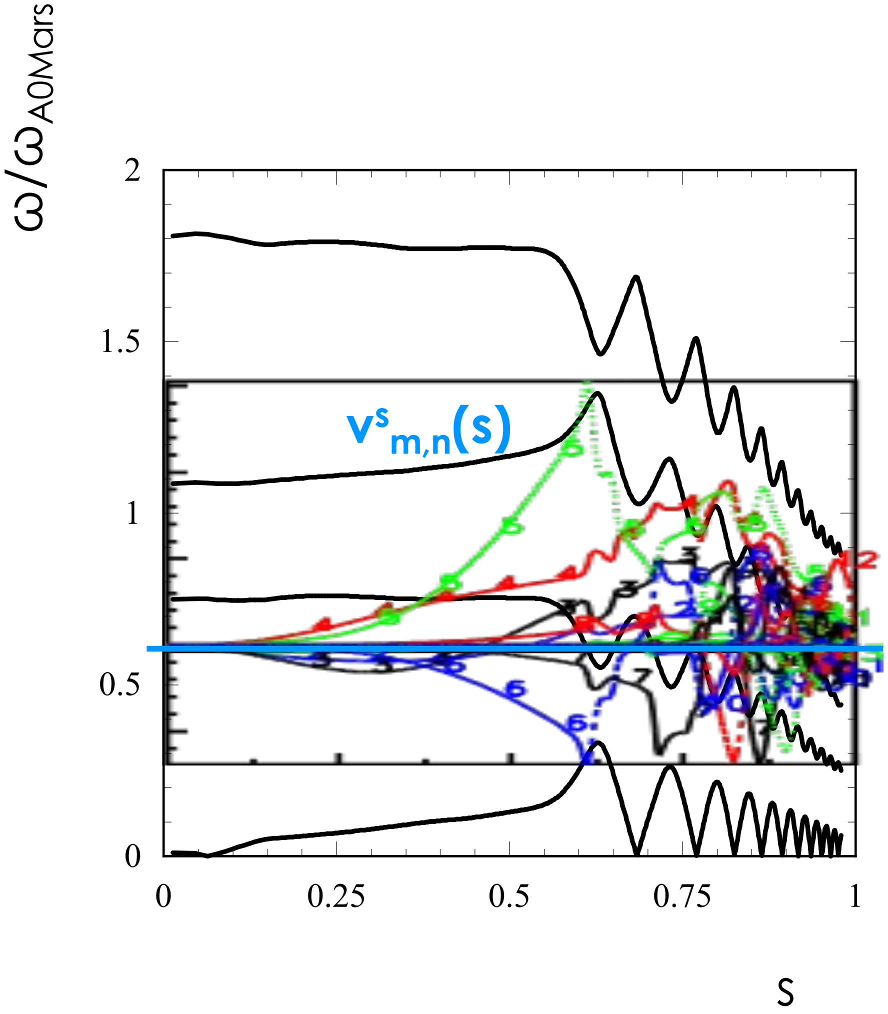
Alfvén modes NT



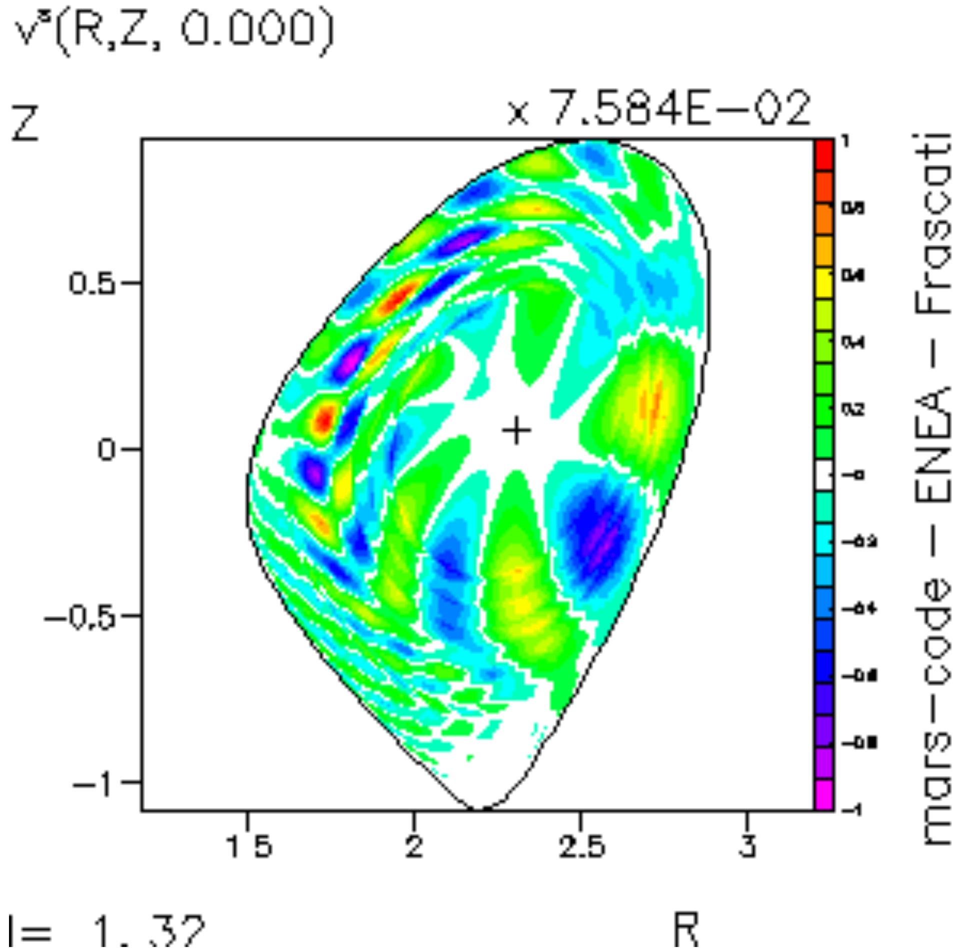
ω/ω_{A0Mars}

0.595610

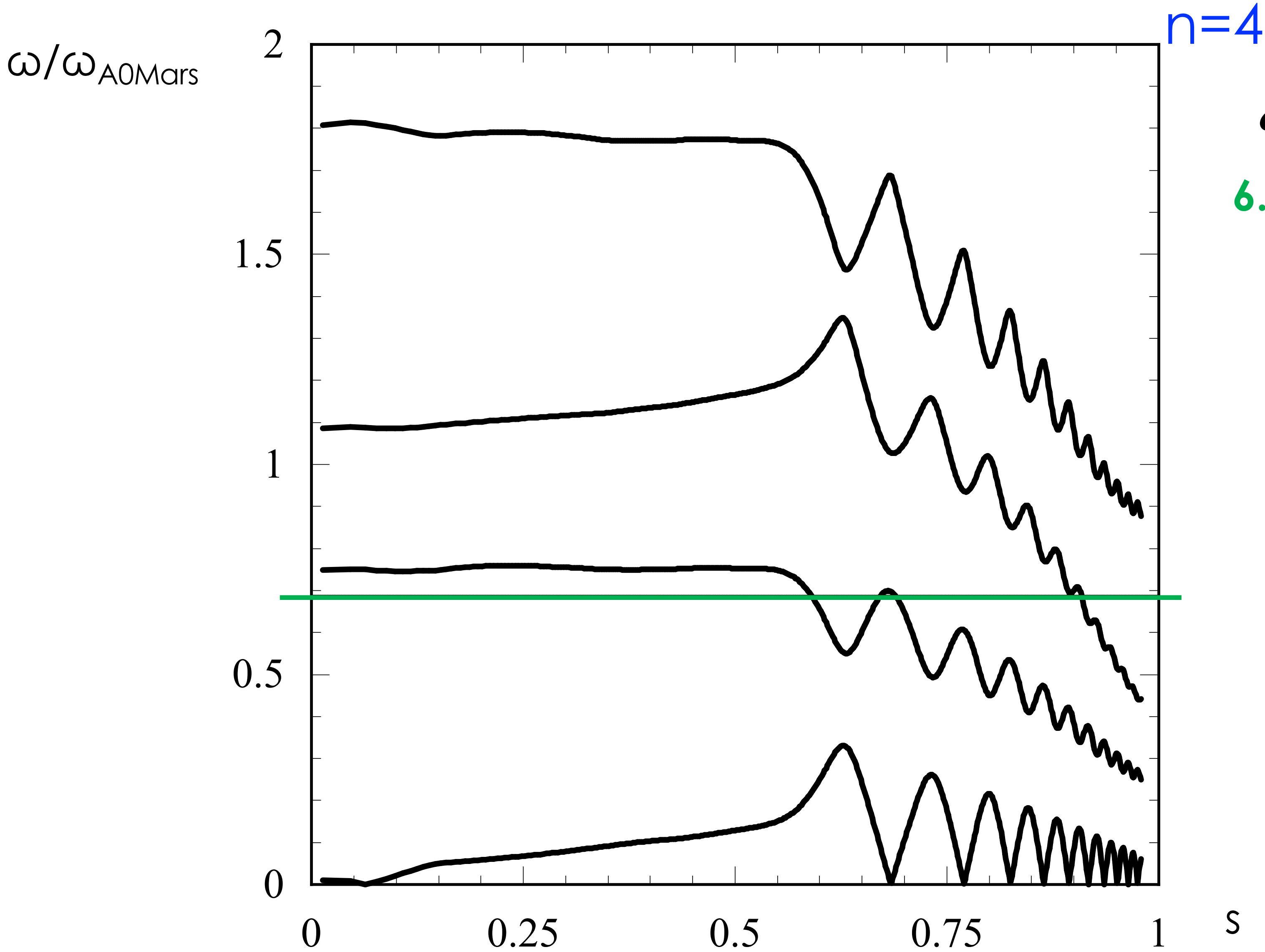
Alfvén modes NT



n=4



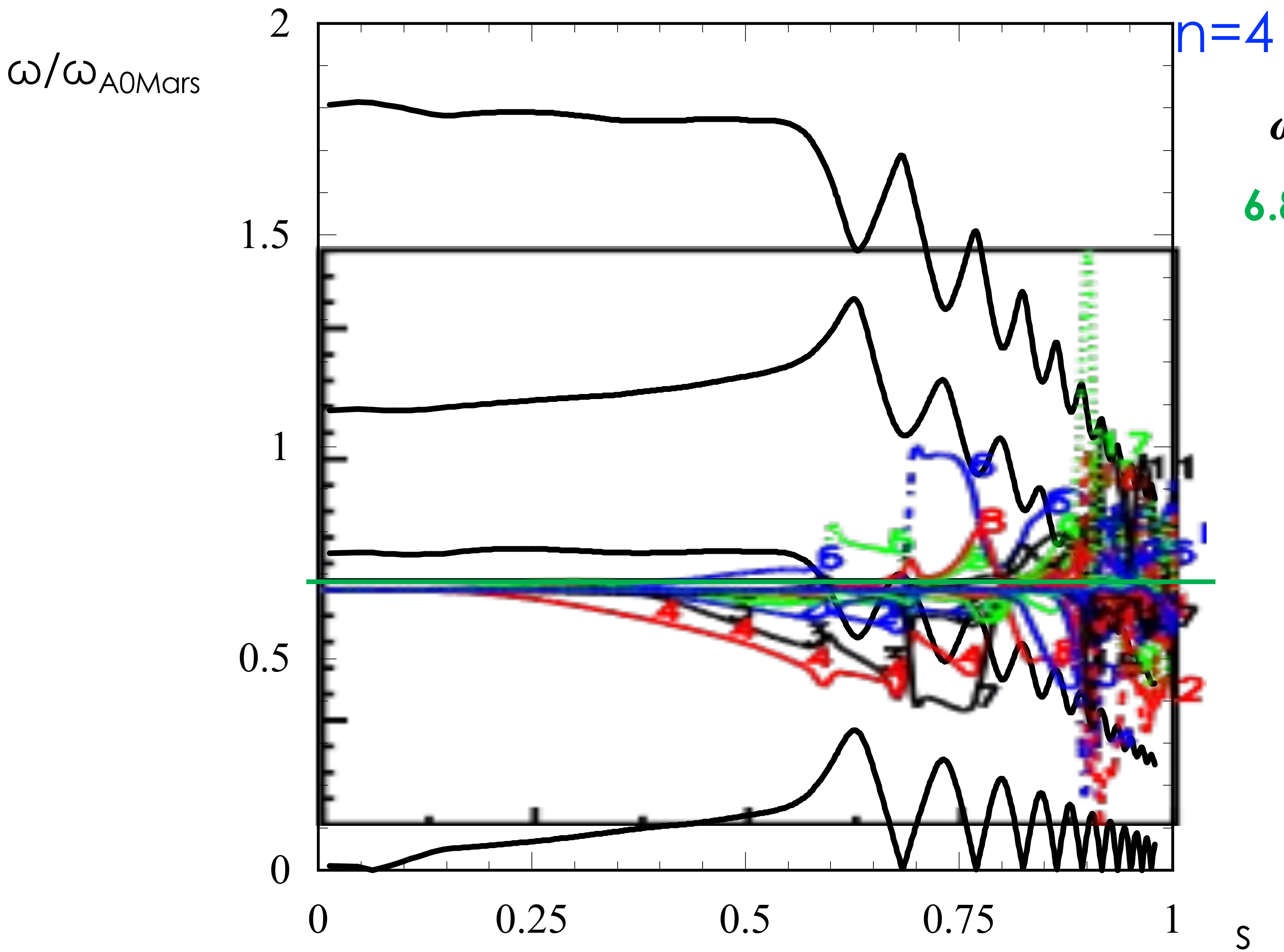
Alfvén modes NT: results from the MARS code



ω/ω_{A0Mars}

6.86268E-01

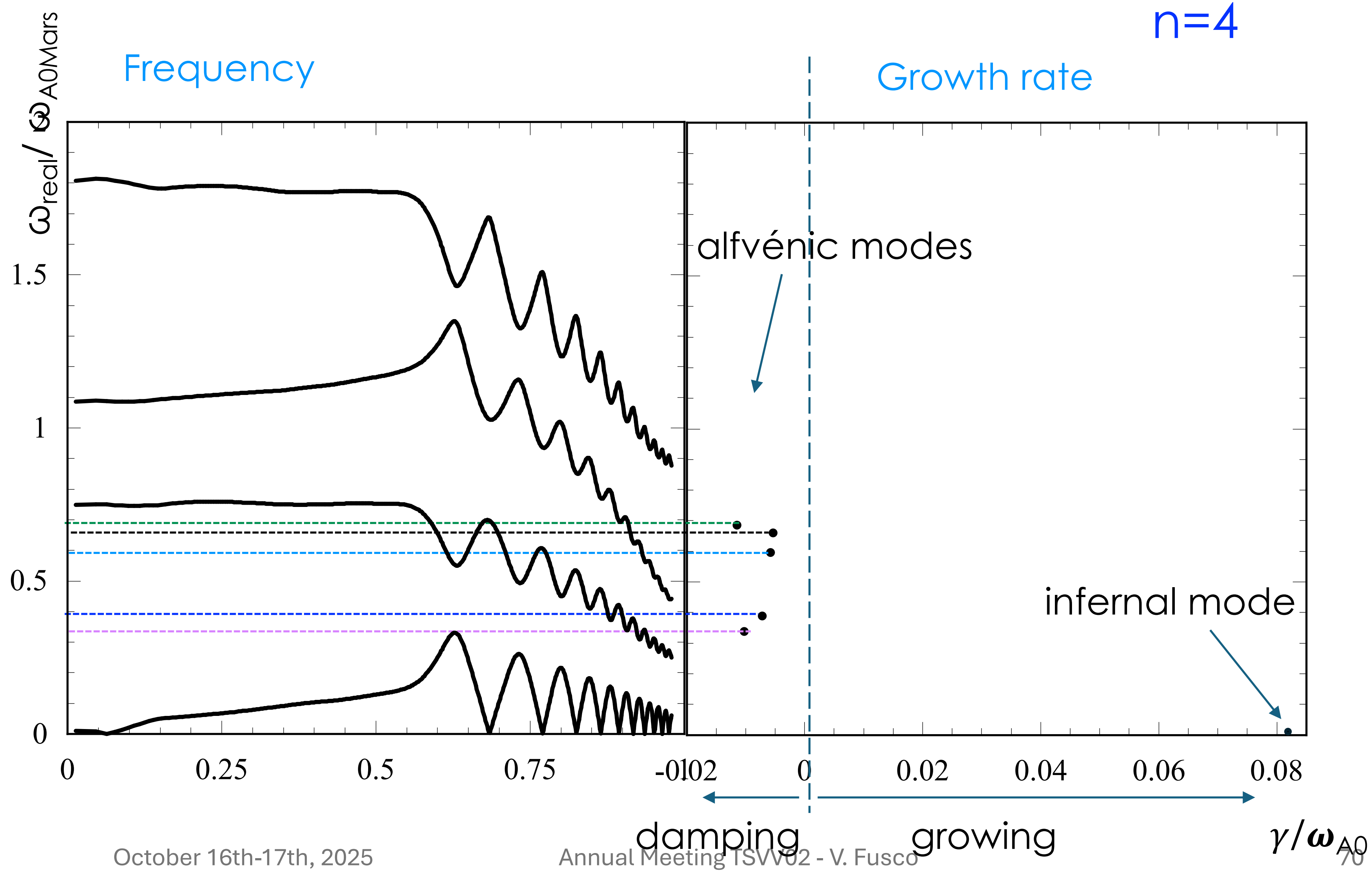
Alfvén modes NT



ω/ω_{A0Mars}

6.86268E-01

Alfvén modes NT



Alfvén modes studies NT: results from the HYMAGYC code

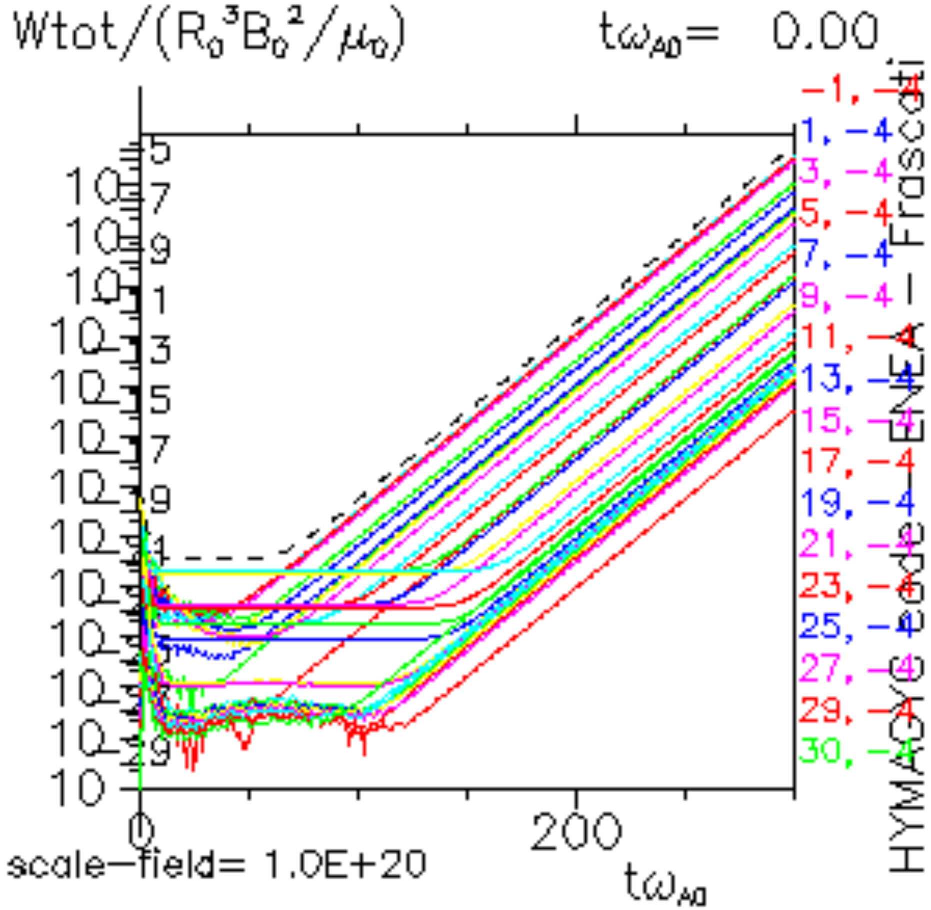
n=4

- ✓ energetic particles not included

Alfvén modes studies NT: results from the HYMAGYC code

n=4

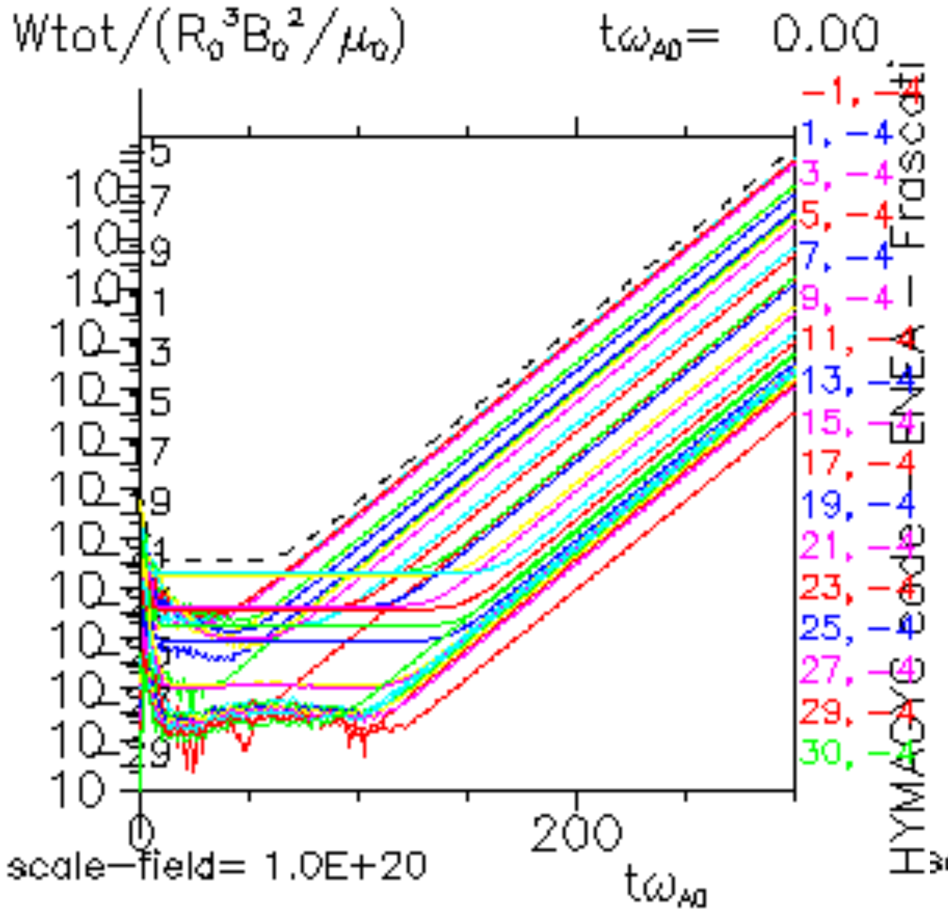
Total energy



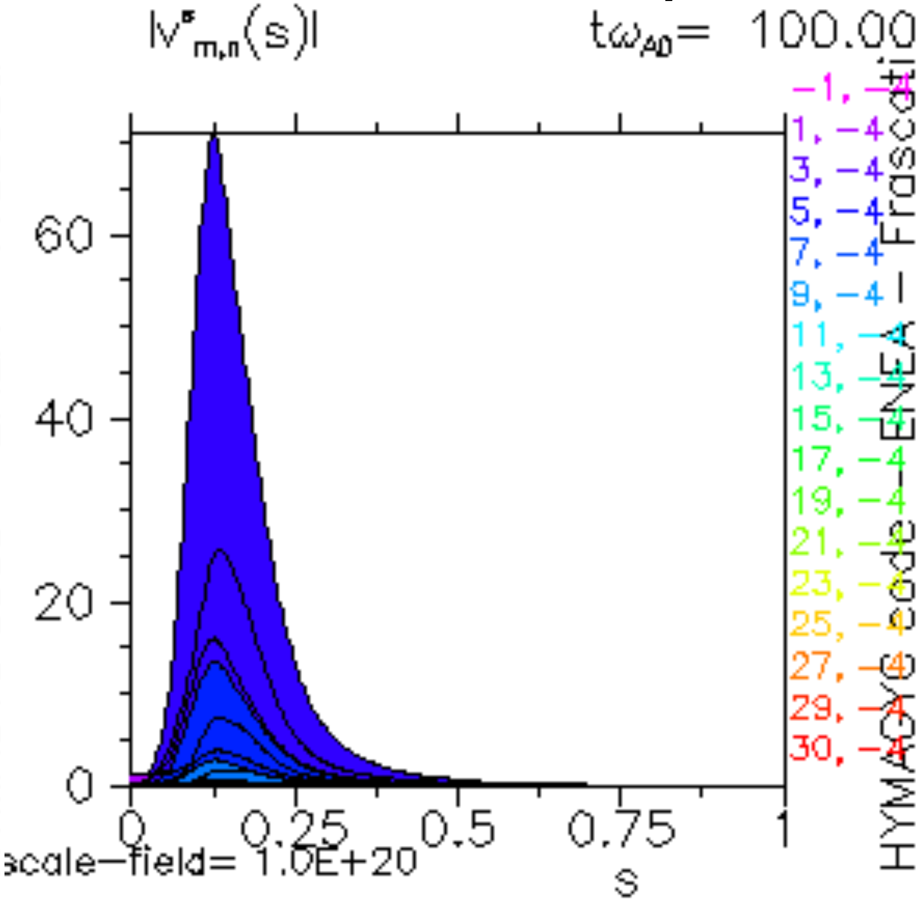
Alfvén modes studies NT: results from the HYMAGYC code

n=4

Total energy

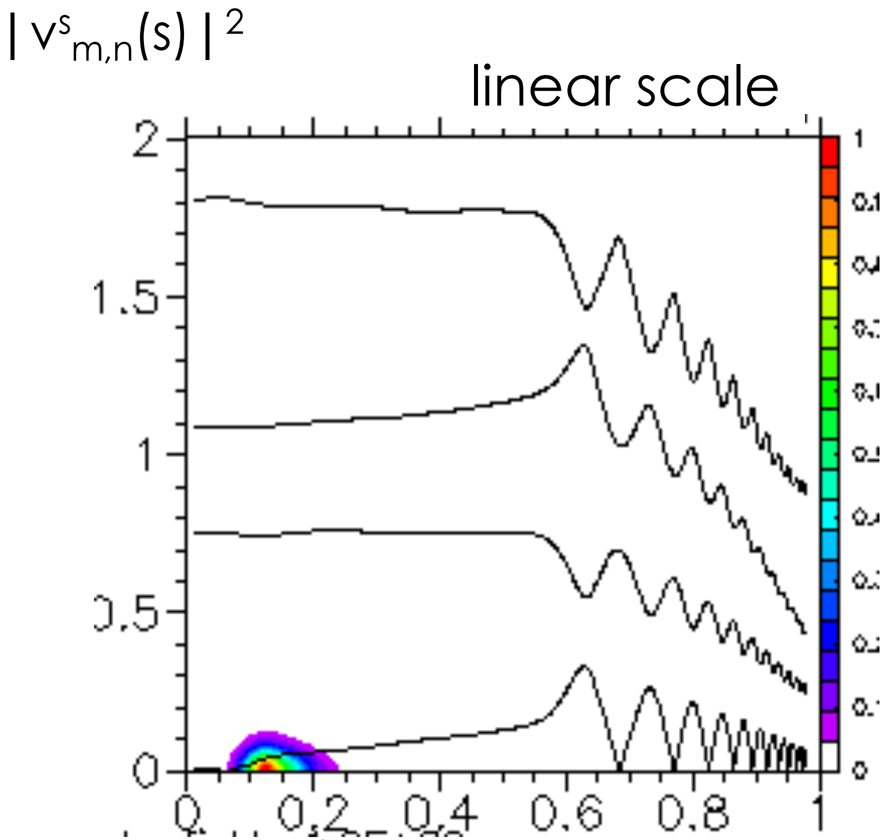


Perturbed velocity



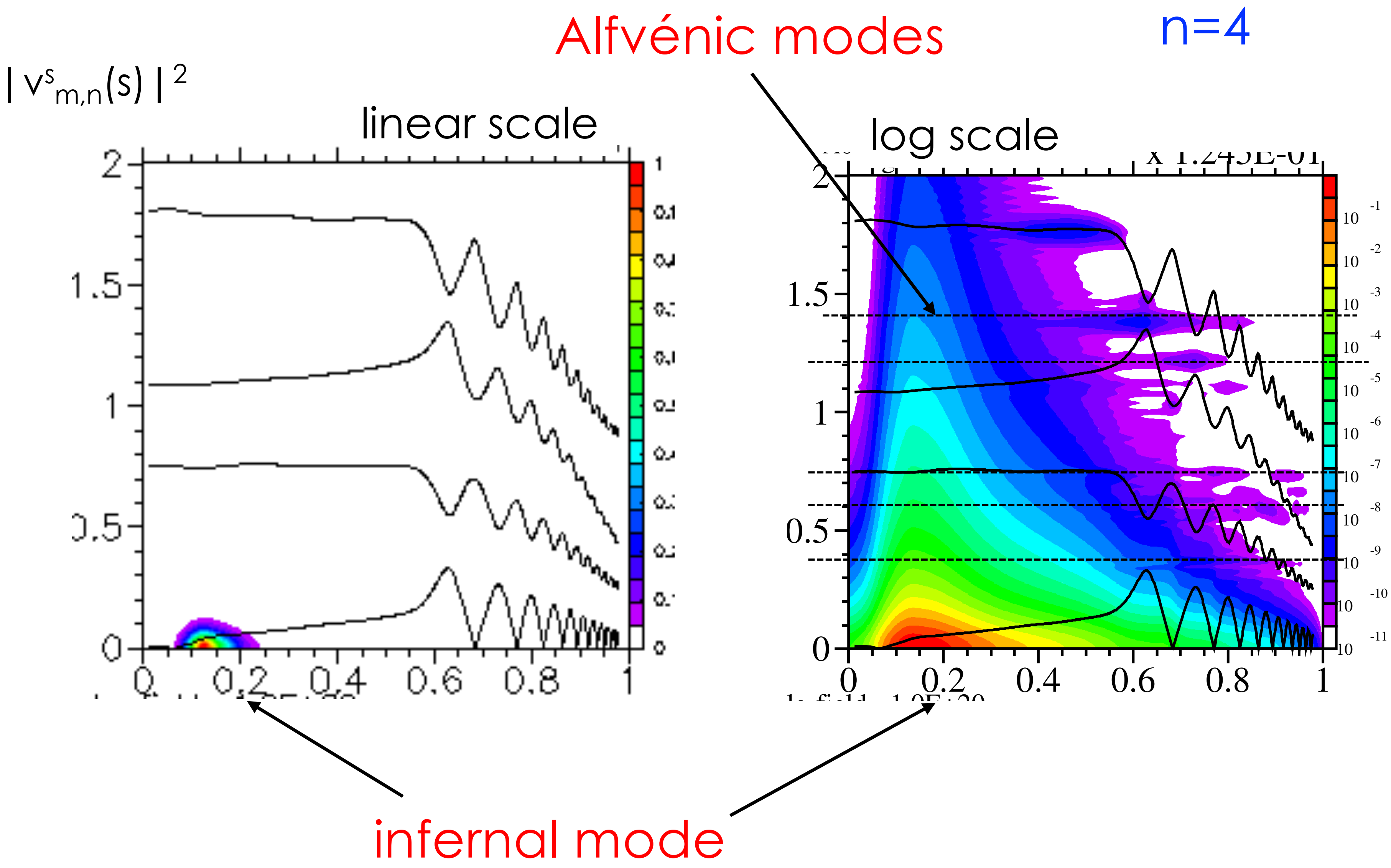
Alfvén modes studies NT: results from the HYMAGYC code

n=4



internal mode

Alfvén modes studies NT: results from the HYMAGYC code



Conclusions NT

- ✓ Negative triangularity has been studied from low to high toroidal mode numbers n
- ✓ Infernal modes revealed within q flat zone
  -> growing modes which do overwhelm Alfven modes
- ✓ Alfvenic modes revealed within continuum spectrum gaps
  ->damped modes
- ✓ Alfvenic modes studies evolution and dynamics is hindered by the stronger infernal modes

Work in progress

- ✓ Sawtooth model has been included in the transport code:
  - ✓ interesting to study evolution of the equilibrium from MHD point of view at **different time** of the sawtooth crash which changes q profiles but also pressure

- ✓ Infernal modes do change confinment and equilibrium,
  - ✓ we can think about a q profile and/or pressure profiles that avoids these modes to allow Alfvén modes evolution and dynamics studies **driven by energetic particles**

Other activities from Frascati-ENEA group

- ✓ Excitation of toroidal Alfvén eigenmode by energetic particles in DTT and effect of negative triangularity [Guangyu Wei et al 2025 Nucl. Fusion 65 106035]
- ✓ A linear gyrokinetic local code to investigate the stability of Alfven eigenmodes with **non-perturbative** treatment of EP drive and core plasma Landau damping.
  - ✓ **Built upon the theoretical foundation of GFLDR (generalized fishbone like dispertion relation)**
  - ✓ **Ballooning-mode representation** ⇒ facilitating the resolution of fine radial structure.
  - ✓ Kinetic effects such as **FLR, FOW, and wave-particle resonance** are fully retained.
  - ✓ Excitation of TAE by EPs in DTT equilibrium demonstrates distinct resonance structures of circulating and trapped particles for different particle species.

Evidence of the study

✓ Previous studies [Wei G. et al., 2024 Phys. Plasmas 31 072505] found that triangularity has little impact on TAE in the **fluid limit**; on the contrary , the introduction of **kinetic effects** makes a significant difference due to the modification of equilibrium orbits.

✓ Excitation of TAE by EPs in DTT equilibrium demonstrates distinct resonance structures of circulating and trapped particles for different particle species.

1. In NT, wave-particle coupling results in a larger TAE growth-rate (particularly evident for circulating particles and for low-moderate toroidal mode number)
2. Precession and bounce frequencies of trapped particle significantly modified by NT: this results in either stabilizing or destabilizing effects depending critically on the toroidal mode number n
3. Moreover, NT equilibria exhibit a shrunk toroidal gap resulting in a TAE with its frequency closer to the lower accumulation point and thus increasing the continuum damping

Thanks for your attention