LIGKA/HAGIS - a kinetic hierarchical model for investigating energetic particle stability and transport

Ph. Lauber, V.-A. Popa, T. Hayward-Schneider

and ENR NLED, NAT, MET teams

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and ITPA EP group

motivation

- EP transport due to AEs (Alfven eigenmodes) is challenging task: global, electromagnetic, non-linear, multi-scale, resonant

- AEs are exponentially sensitive to background plasma profile shapes and EP distribution function(s): large parameter space can only be covered by simpler/faster tools

- develop linear global GK tool for:

    - connecting analytical/local/semi-local/global models in a consistent framework
    - automated scans for determining linear AE spectra
    - deliver input for all types of EP transport models: critical gradient, kick-model, RBQ, PSZS,…
    - provide possibility to deliver non-linear transport calculations to validate reduced models on large set of parameters and experiments (HAGIS)
    - use IMAS framework for transparent management of inputs and results
    - speed up models by analytically advance the models, or create databases/train AI tools
    - advance physics capabilities (e.g. wave-wave coupling, ZS models) by comparing with more complete models

references and resources

- Lauber PhD Thesis 2003: http://nbn-resolving.de/urn/resolver.pl?urn:nbn:de:bvb:91-diss2003111814131
- Lauber JCP 2007: 10.1016/j.jcp.2007.04.019
- Lauber PPCF 2009: http://stacks.iop.org/0741-3335/51/i=12/a=124009
- Lauber PREP 2013: https://doi.org/10.1016/j.physrep.2013.07.001
- Bierwage NF 2017: https://doi.org/10.1088/1741-4326/aa80fe
- Lauber JPC 2018 https://doi.org/10.1088/1742-6596/1125/1/012015
- ITPA EP: https://sharepoint.iter.org/departments/POP/ITPA/EP/Pages/default.aspx
- more information: http://www2.ipp.mpg.de/~pwl/

- and git ITER repository: git clone ssh://git@git.iter.org/stab/ligka.git ; git checkout develop

technical description (install, compile, run):
https://confluence.iter.org/pages/viewpage.action?pageId=289069024

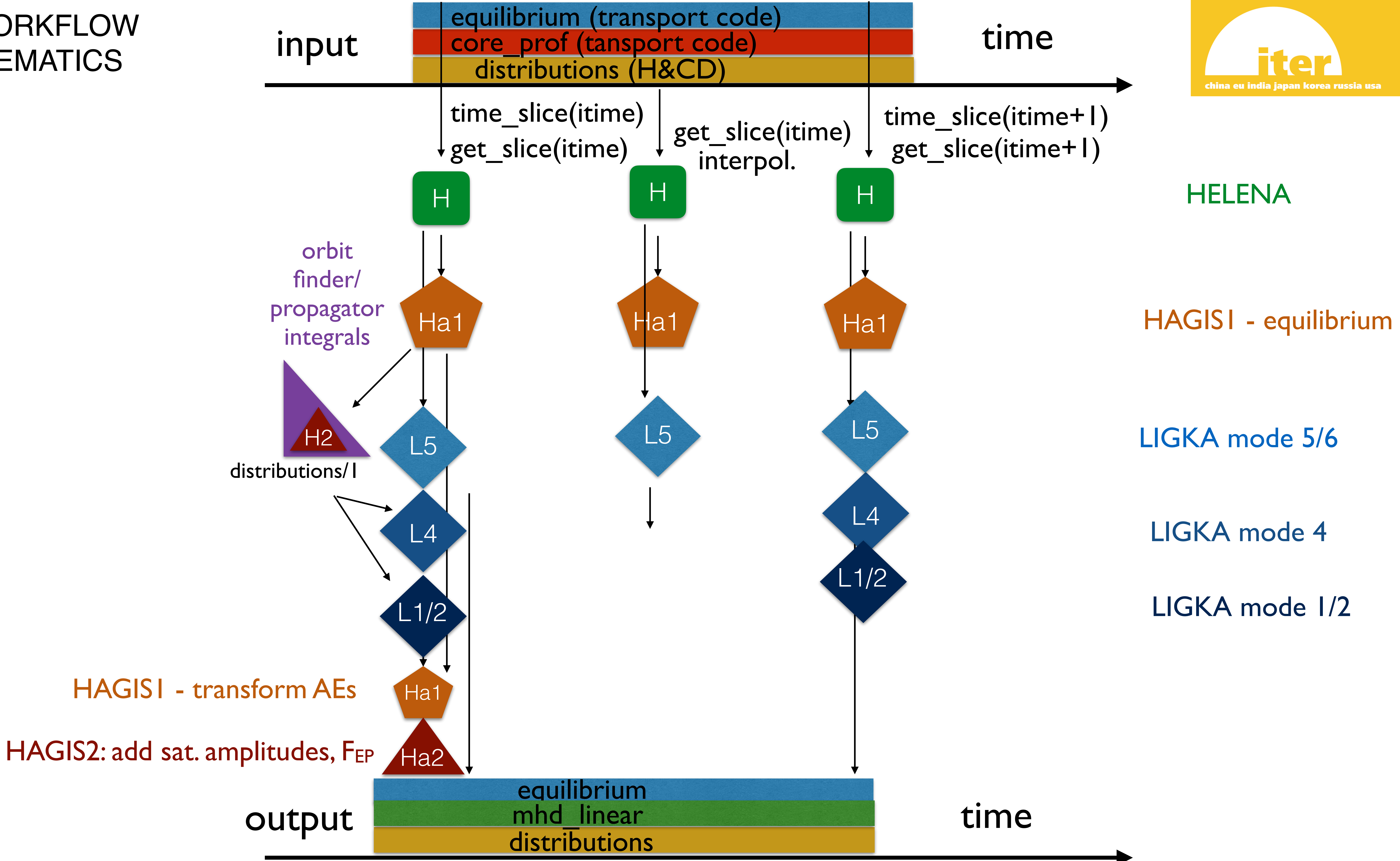
LIGKA_lib hierarchy/ HAGIS

- local, analytical estimates [mode 5]
- local reduced MHD - shear Alfvén spectra [mode 6]
- global reduced MHD - MHD eigenfunction [mode 6]
- local kinetic (w/o numerical coefficients) [mode 3/4]
- local kinetic with FLR/FOW (w/o numerical coefficients) [mode 3/4]
- global kinetic (w/o numerical coefficients): two different solvers [mode 1]
- global kinetic track mode (w/o numerical coefficients) [mode 2]

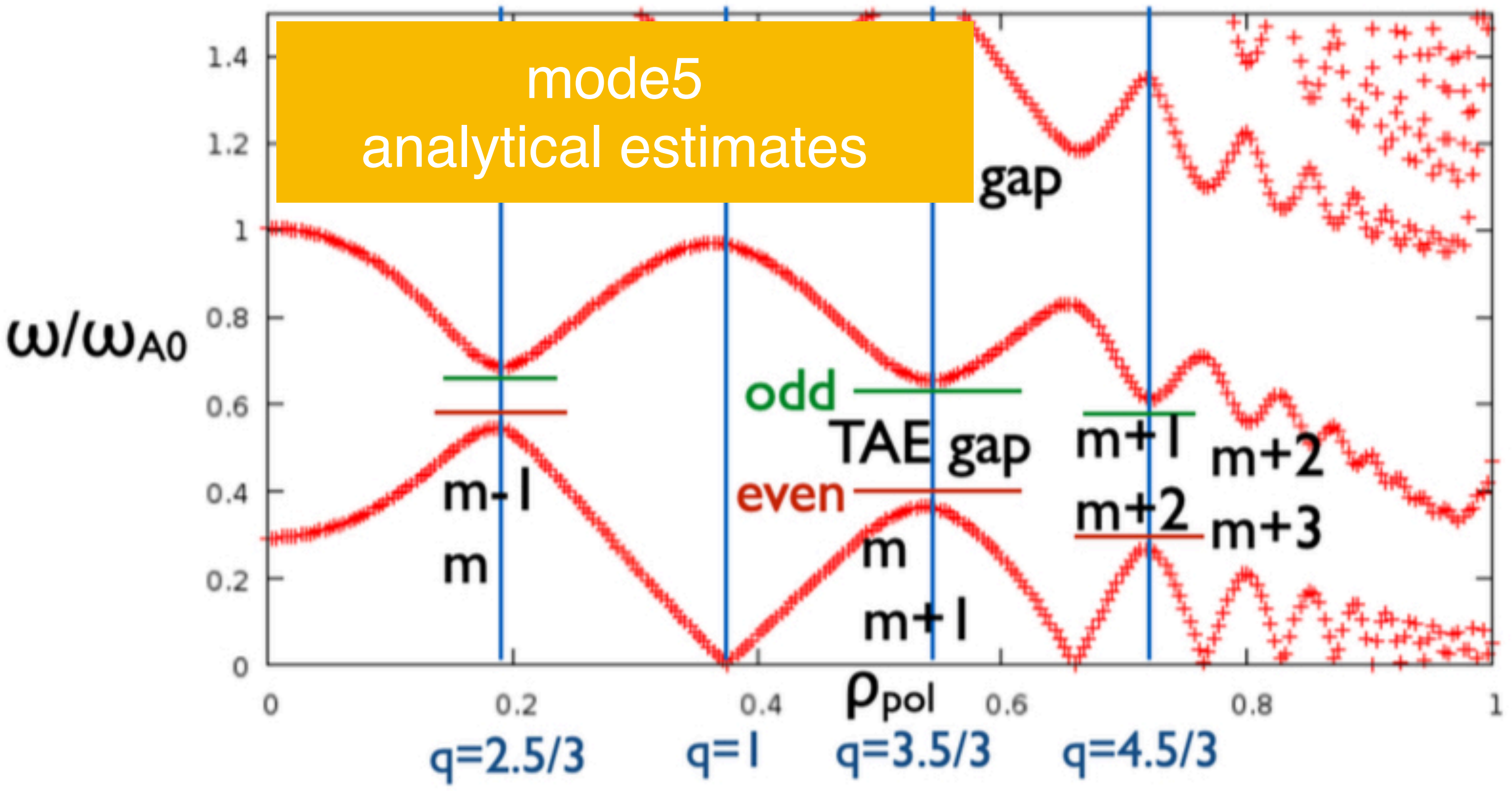
typically modes are called in sequence;
results are stored in unique structure keeping results from various calls in the same format - adoption to IMAS finished, first version of documentation available

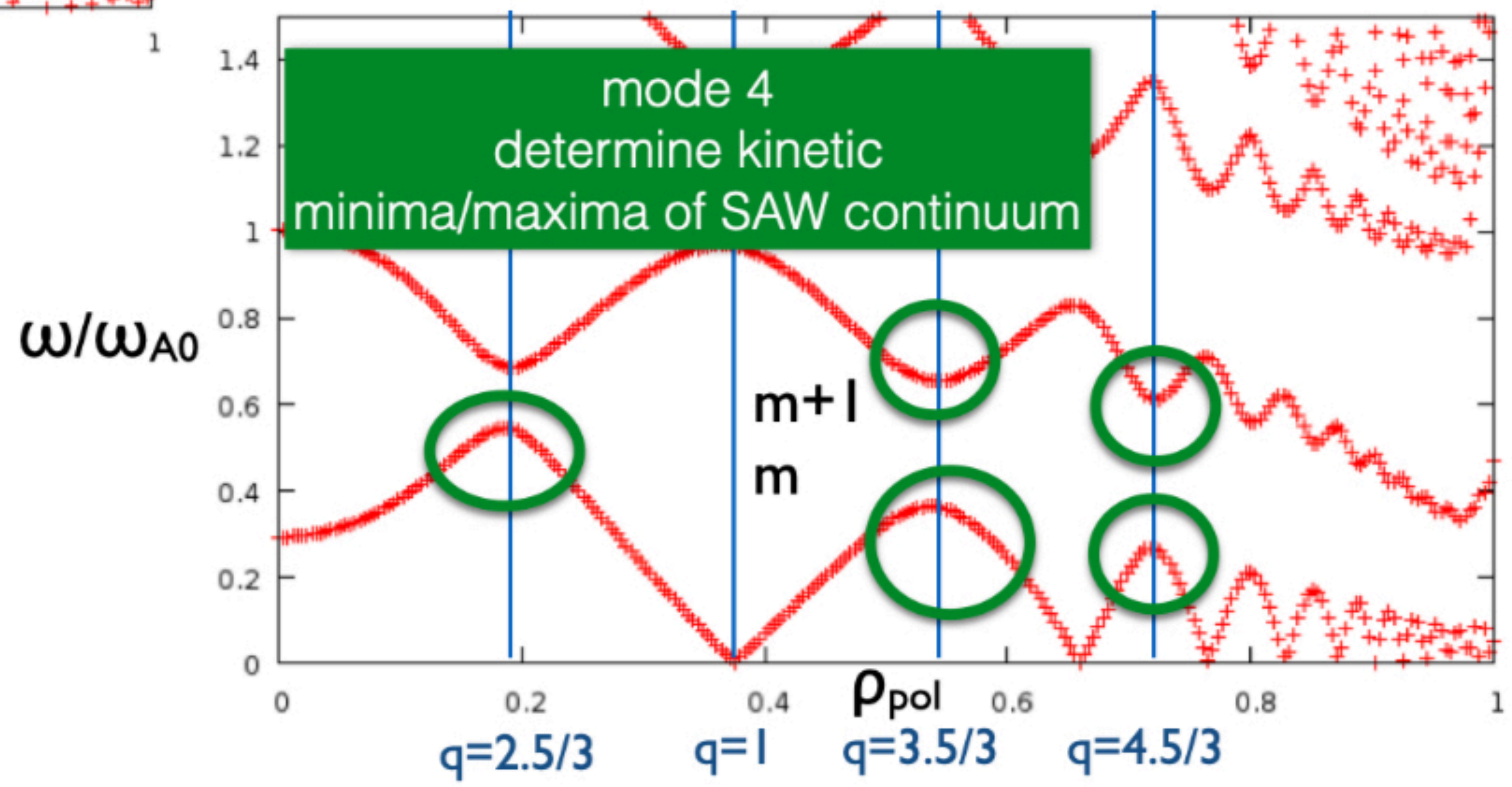
use LIGKA output (perturbation data) to run non-linear/quasi-linear HAGIS simulations

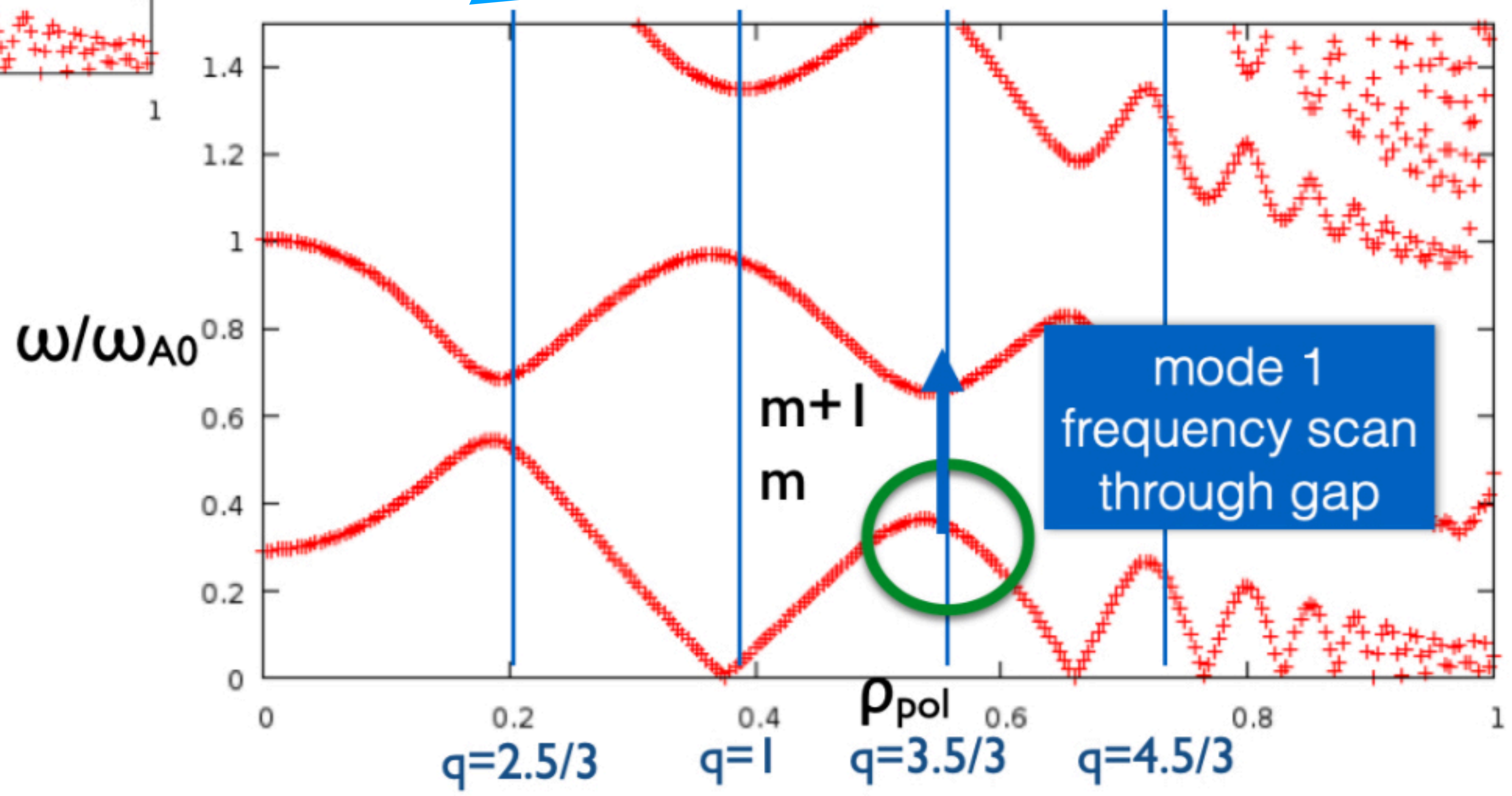
EP WORKFLOW SCHEMATICS



combination of models lead to a staged approach for automated analysis





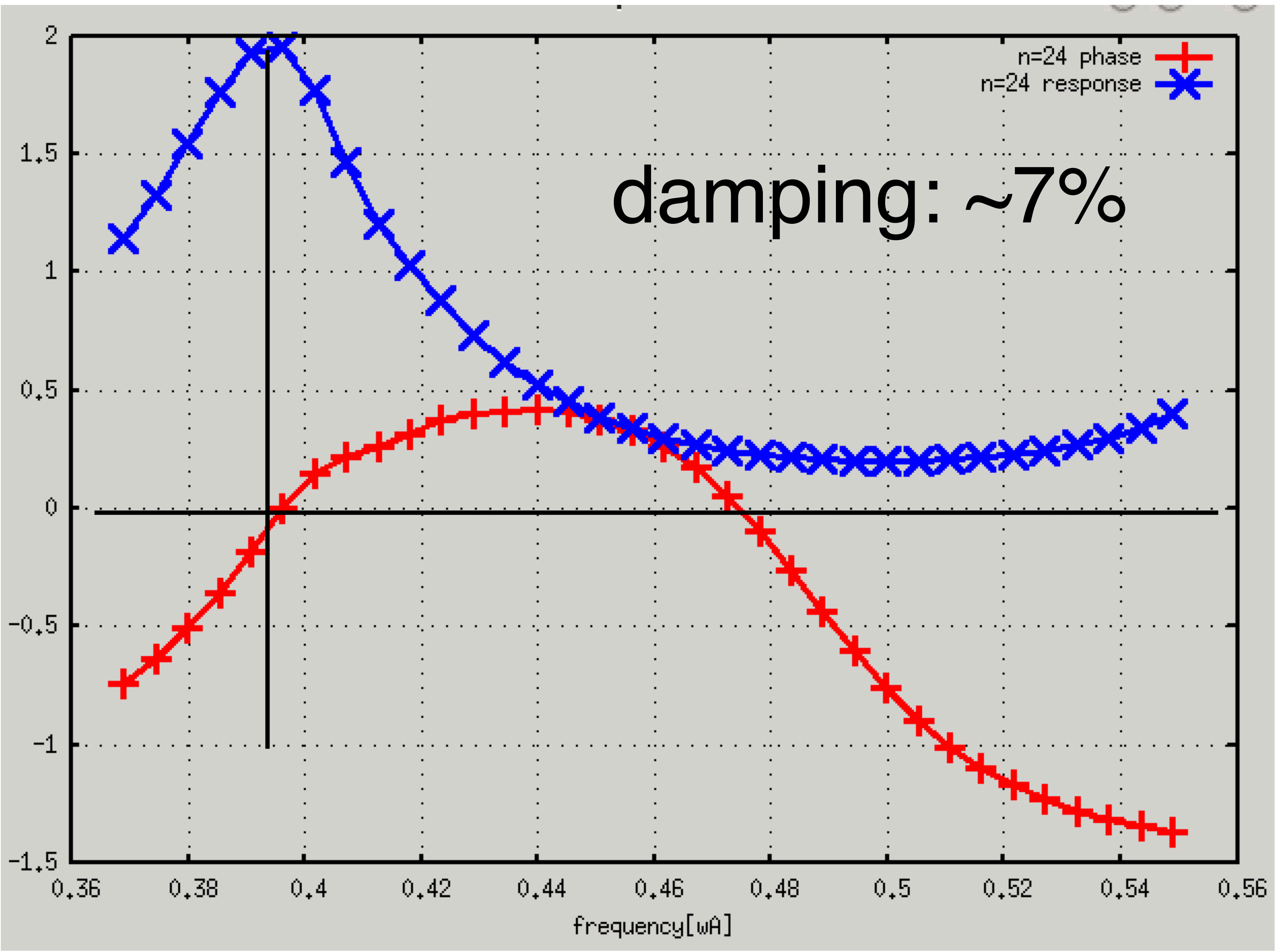


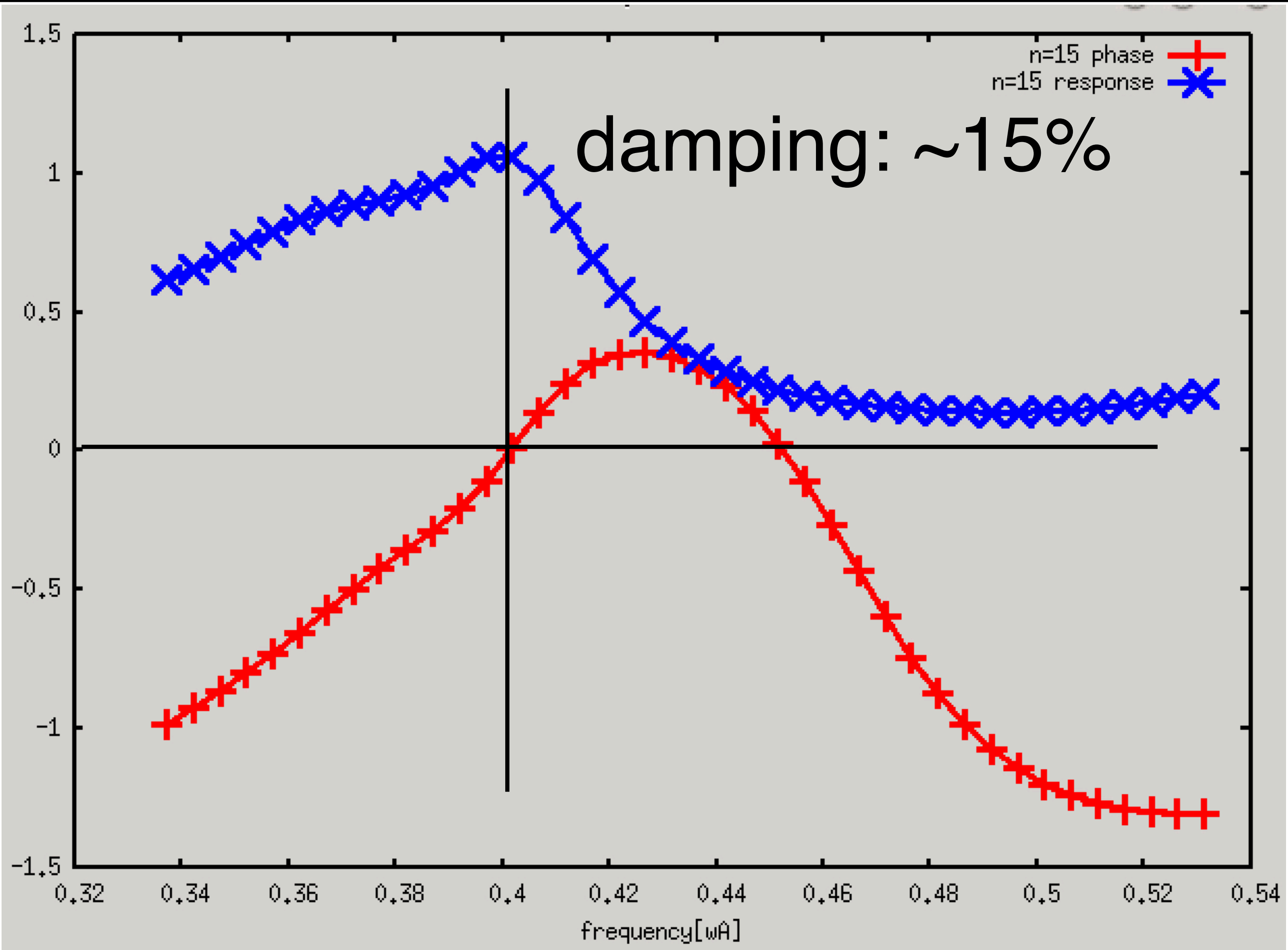
mode5:
- [Fesenyuk 2014]
- [S.D. Pinches et al PPCF 2015)]
- suggestions for useful formulae can be easily implemented (LIGKA: sub_mode5.F)

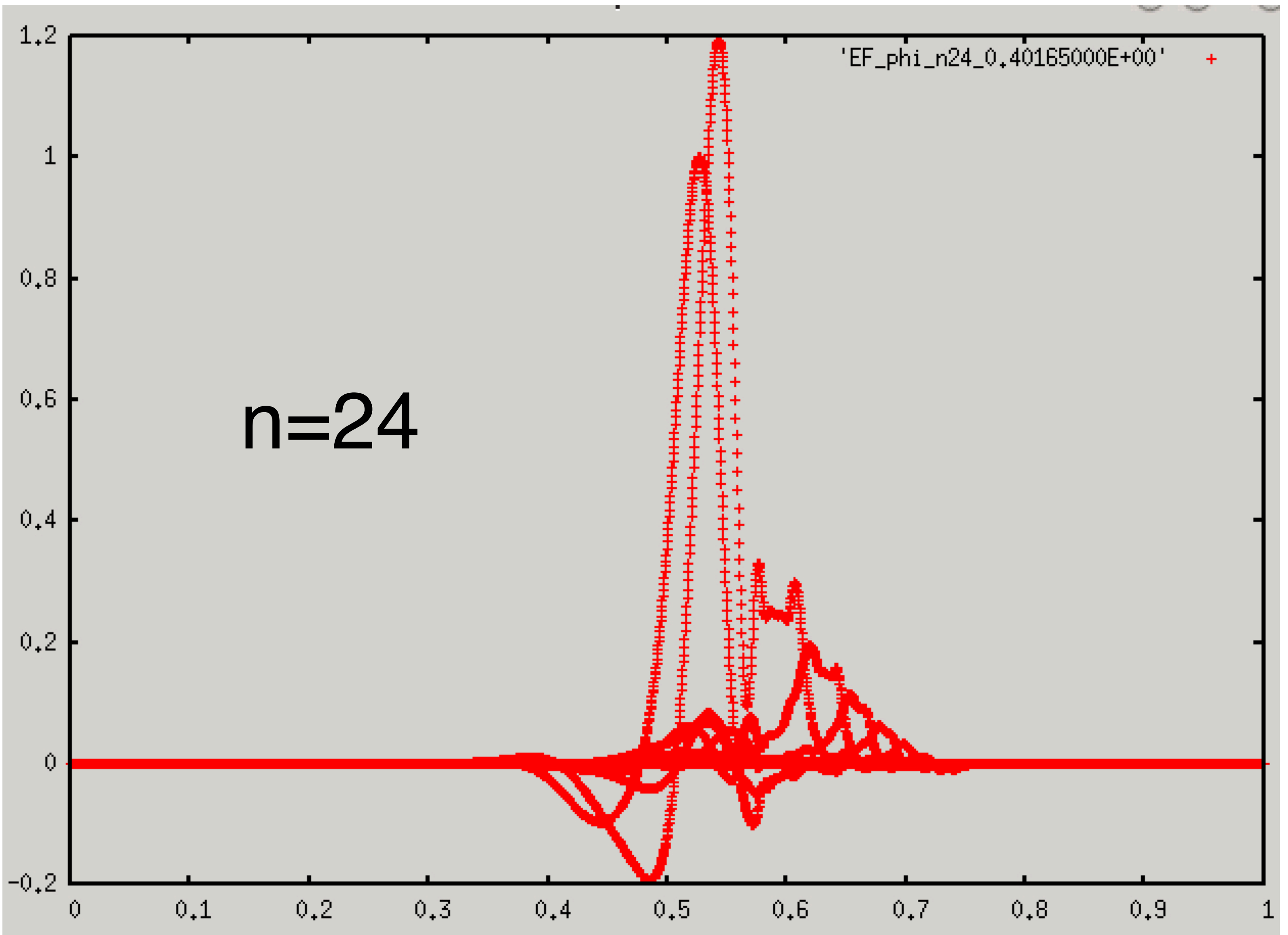
global solver (example antenna solver, LIGKA mode 1)

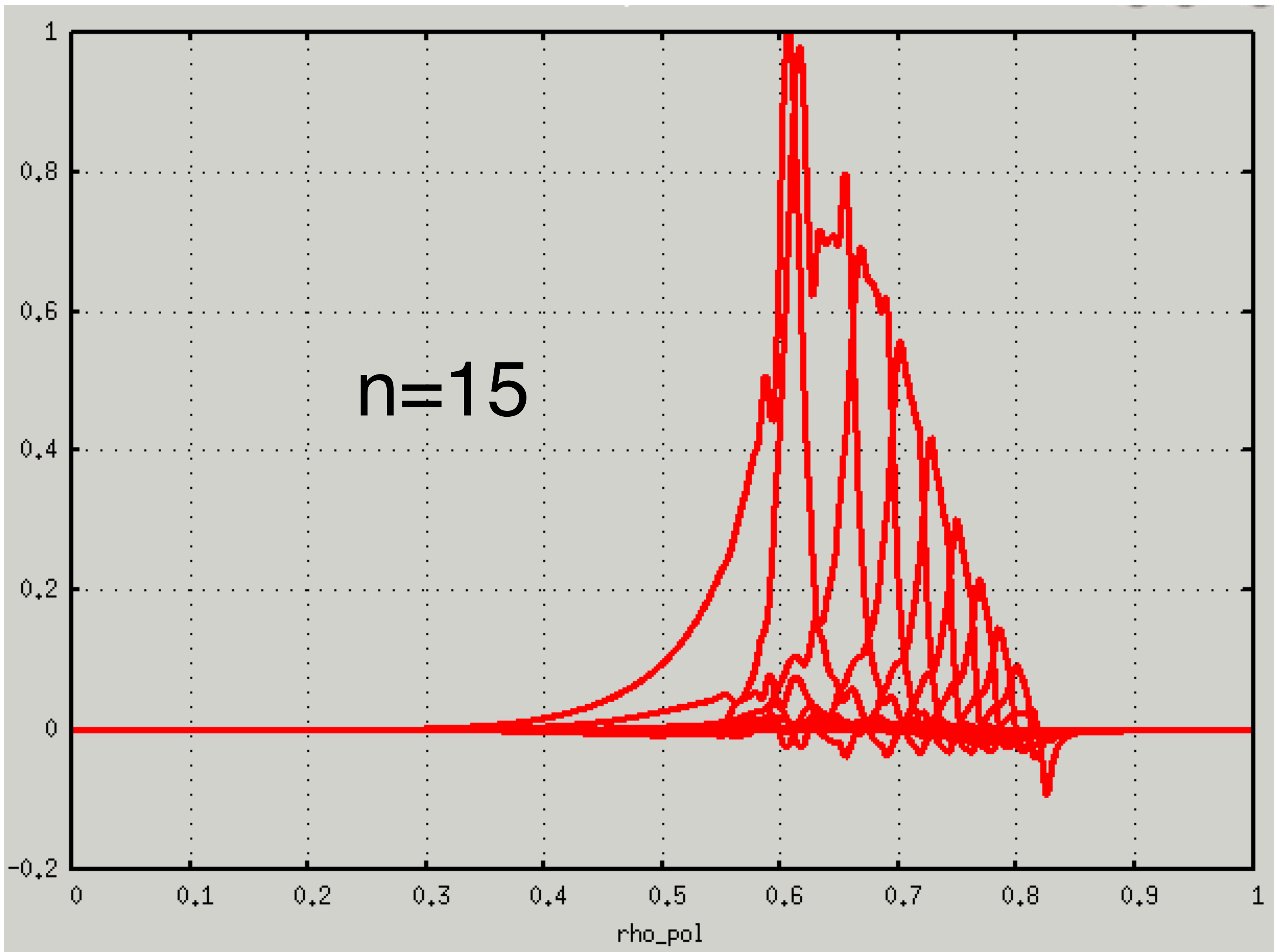
$$M(\omega)\begin{pmatrix}\phi\\ \psi\end{pmatrix} = \mathbf{d}$$

$$\mathcal{R} = \sum_m \int_0^a \phi_m \phi_m^* dr .$$







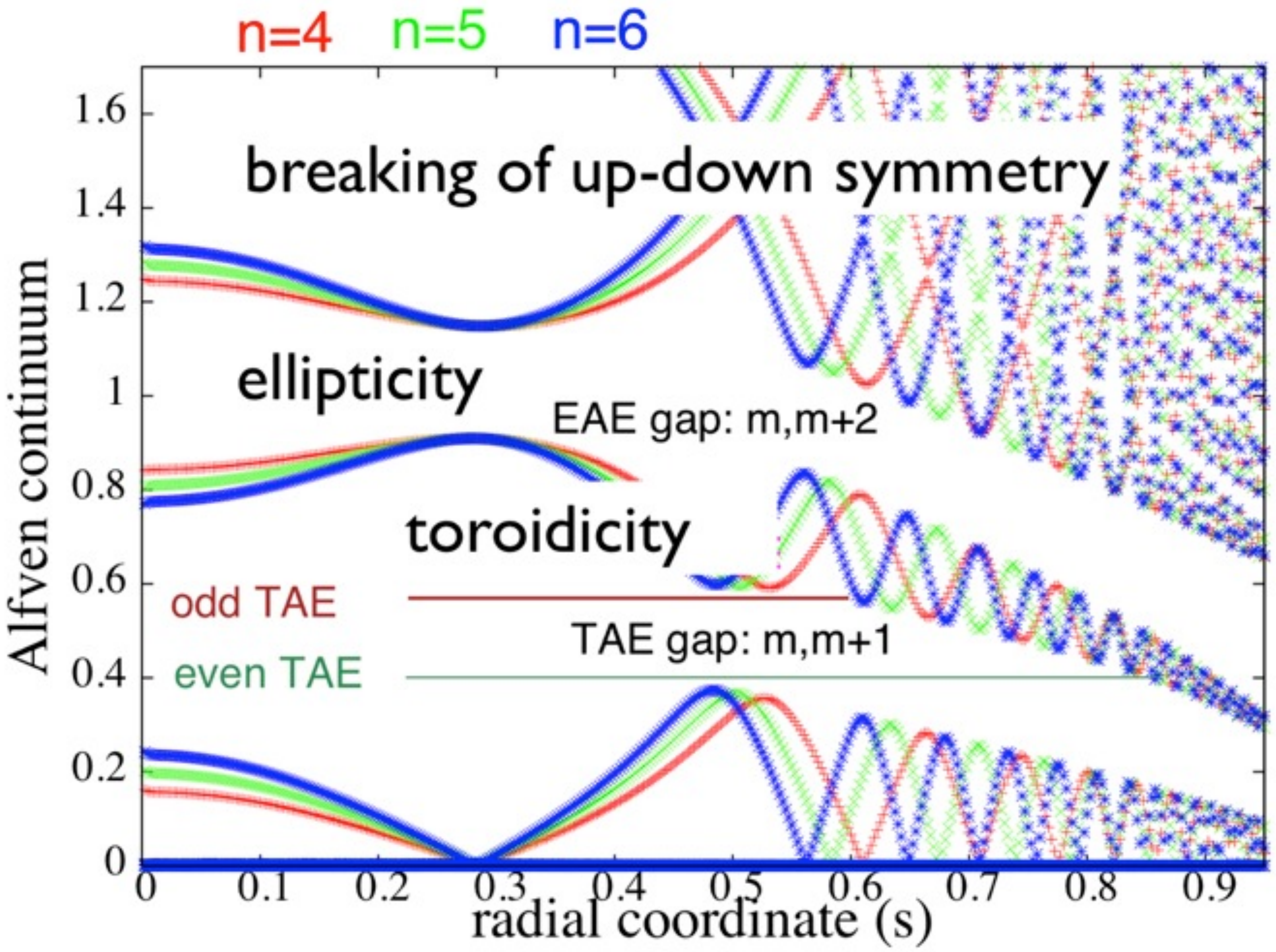


LIGKA mode1 scans entire gap

LIGKA mode 2 can be used to ‘follow’ just one mode as given by mode 1

reduced MHD limit, no compressibility

LIGKA ideal MHD spectra **(LIGKA MODE 6)**: choose equilibrium, and provide density profiles
presently only HELENA [G. Huijsmans]: git clone ssh://git@git.iter.org/eq/helena.git; git checkout /feature/EP_LIGKA



ASDEX Upgrade Alfvén continuum

$$k_{\parallel,m,n} = -k_{\parallel,(m+\delta_m),(n+\delta_n N_{fp})}$$

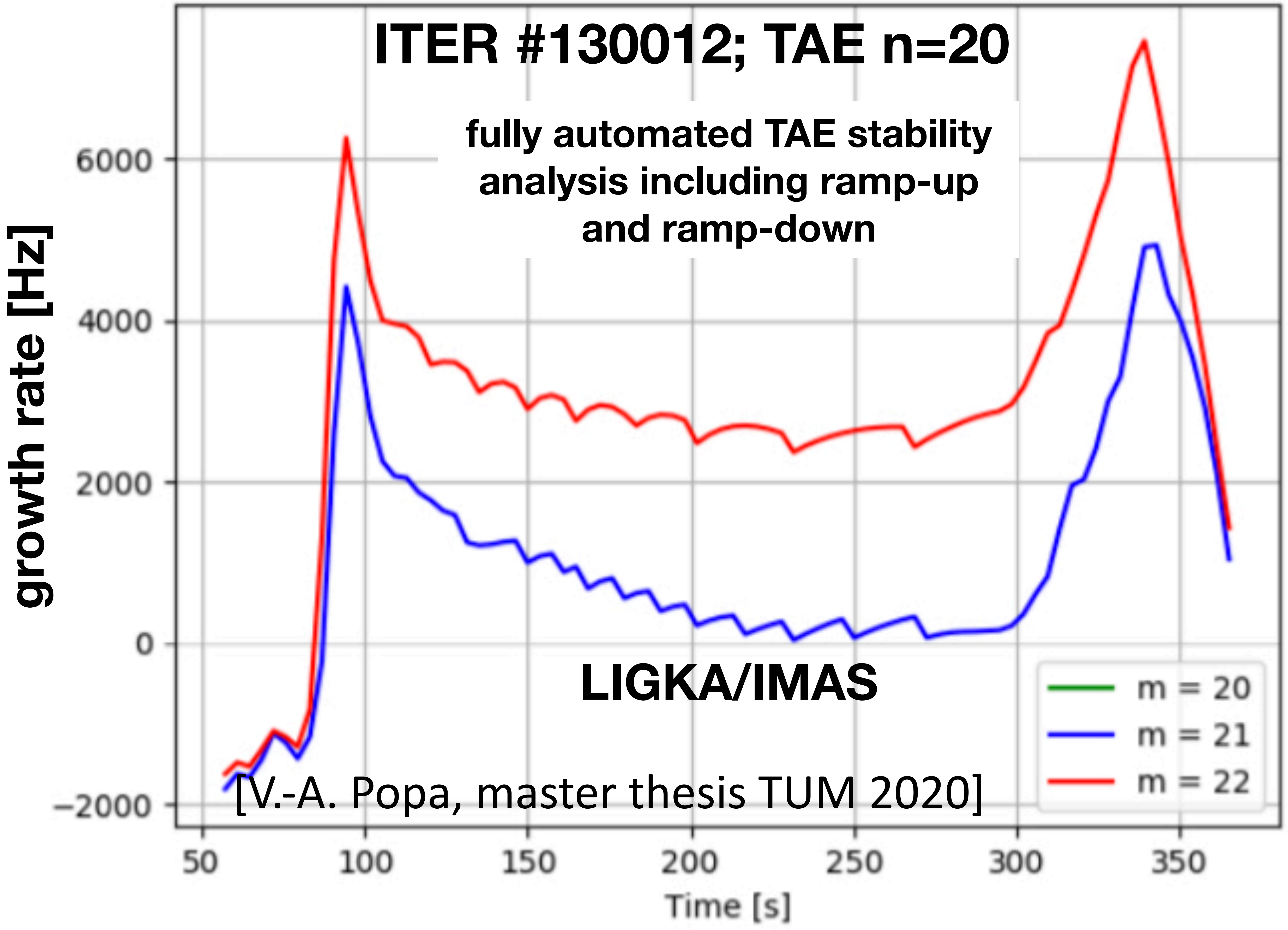
δ_m , δ_n = integer mode displacements

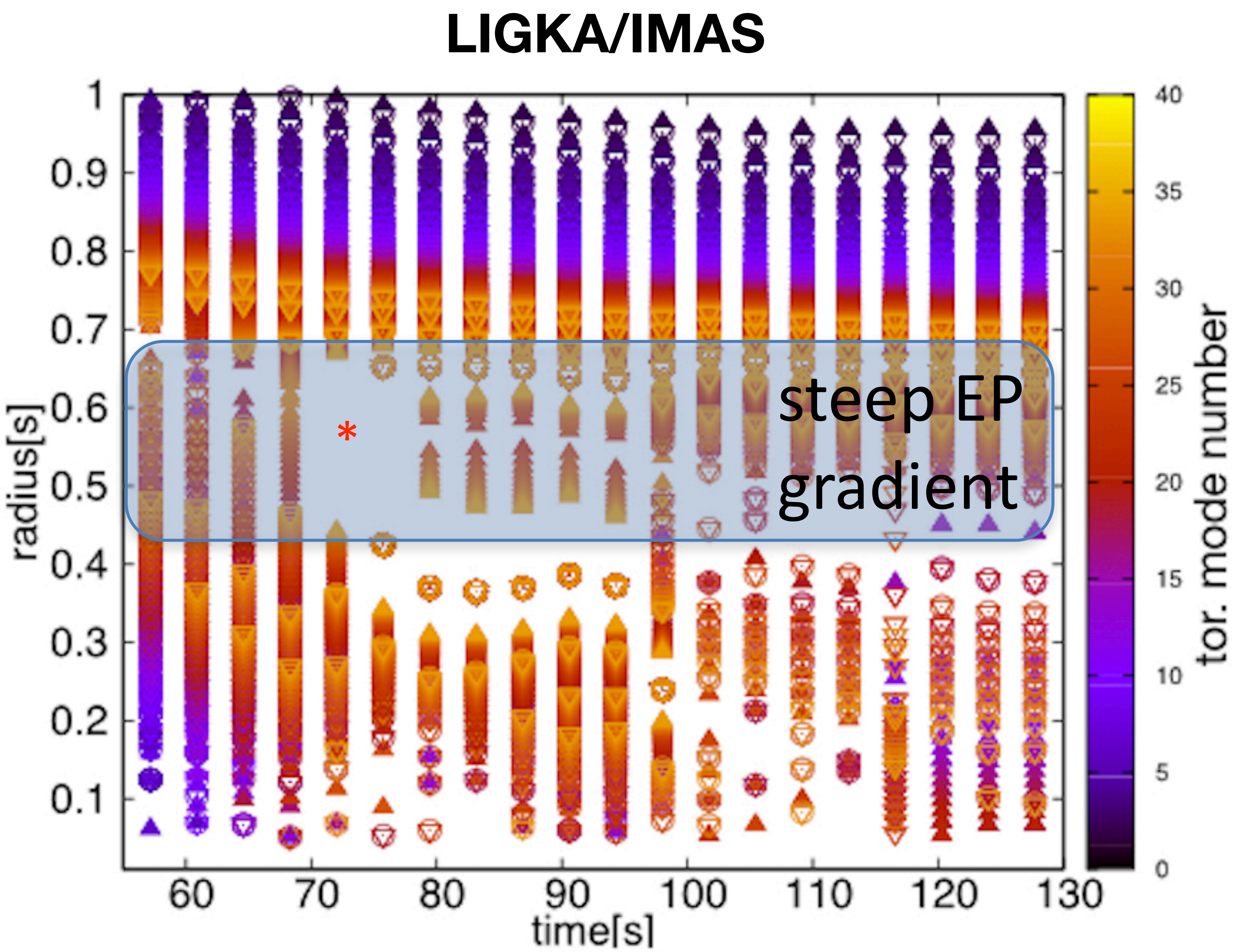
Abbreviated name	Name	δ_m	δ_n
GAE	Global Alfvén eigenmode	0	0
TAE	Toroidal Alfvén eigenmode	± 1	0
EAE	Elliptical Alfvén eigenmode	± 2	0
NAE	Noncircular Alfvén eigenmode	$\lvert\delta_m\rvert \geqslant 3$	0
MAE	Mirror Alfvén eigenmode	0	$\pm 1, \pm 2, \ldots$
HAE	Helical Alfvén eigenmode	$\lvert\delta_m\rvert \geqslant 1$	$\pm 1, \pm 2, \ldots$

[D.Spong,2003]

time-dependent, automated runs possible based on experimental/transport code output

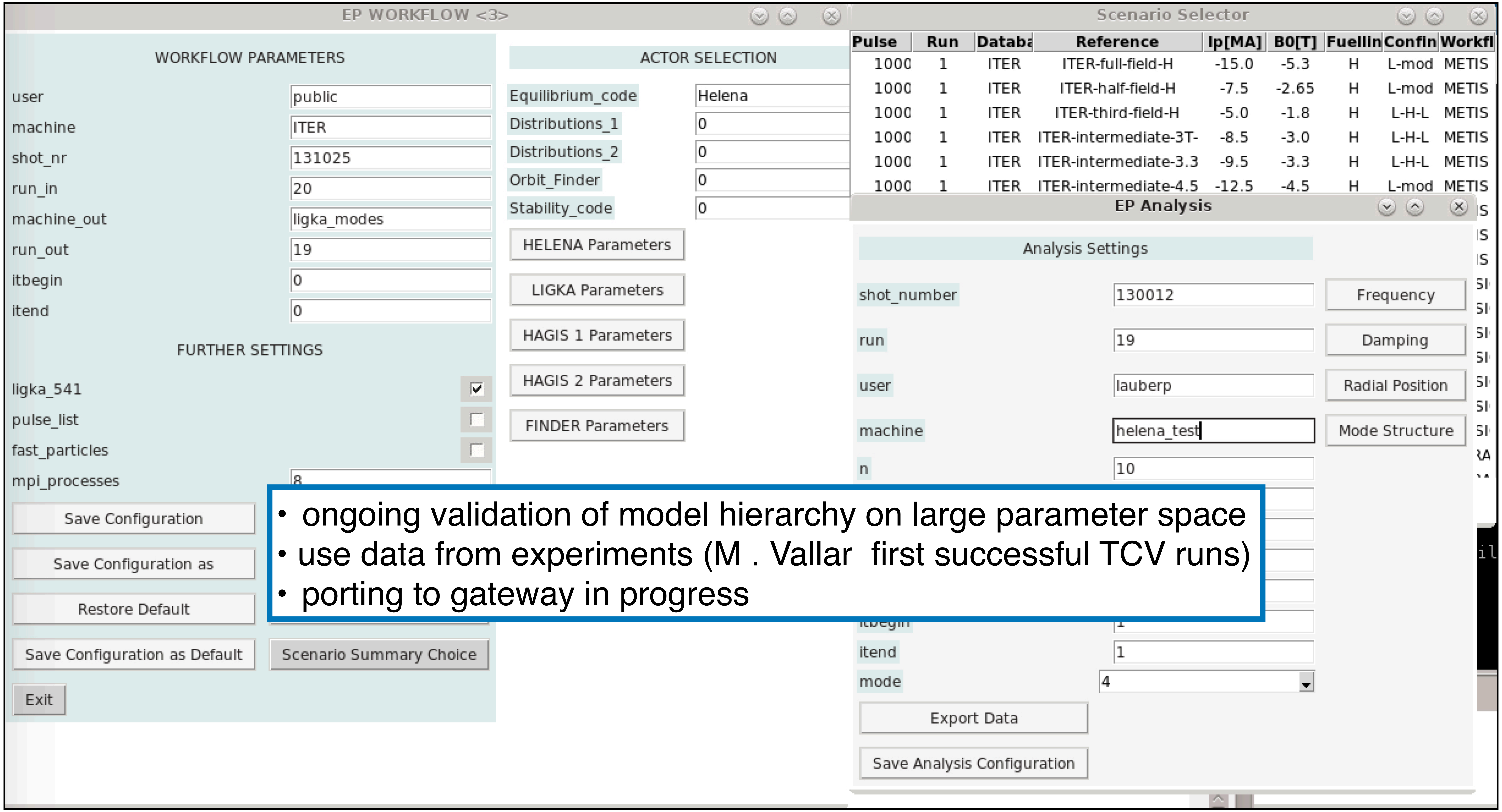
(here: ITER DT plasma based on METIS transport run)





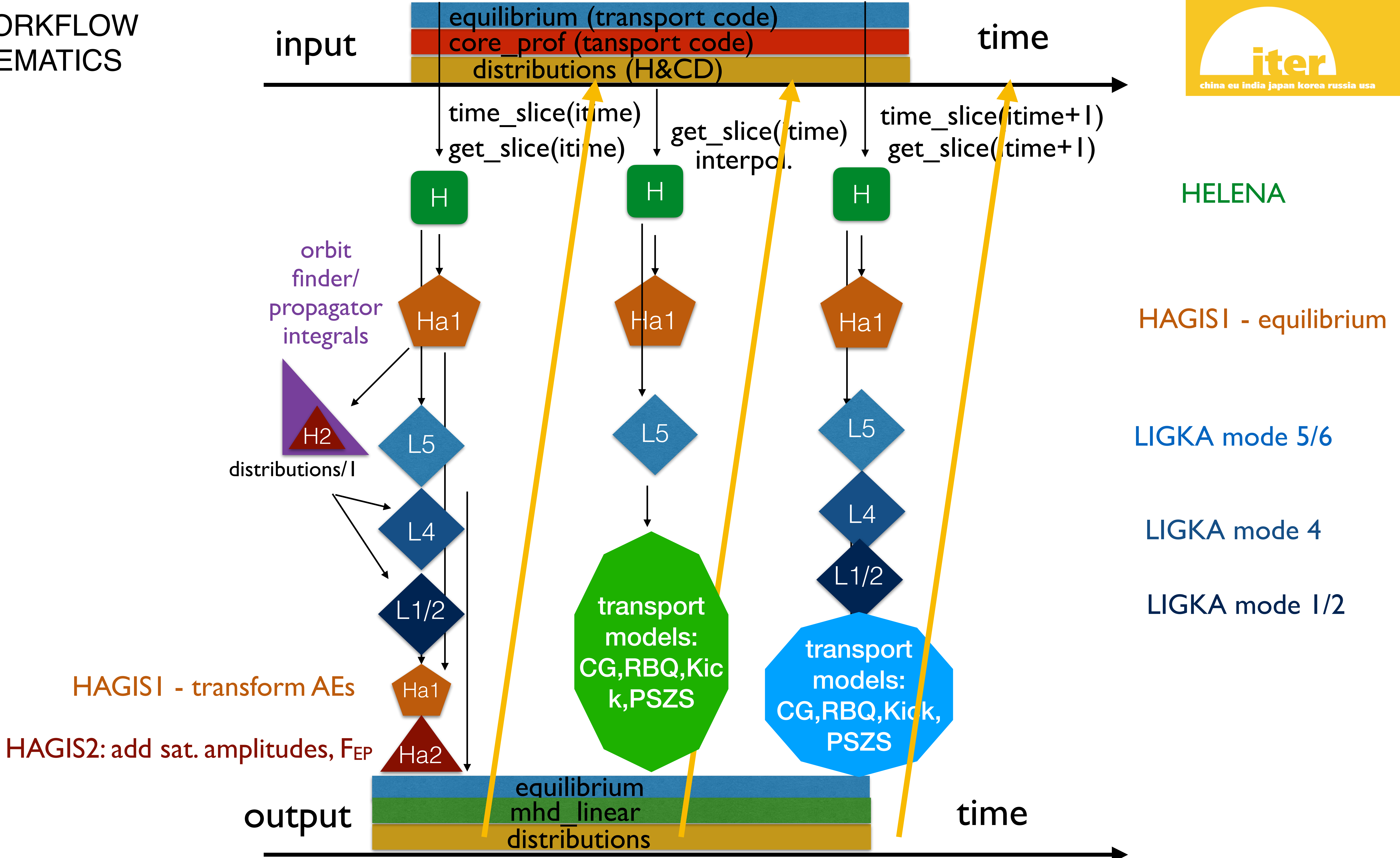
- ready for various automated **reduced EP transport models**
- identification of optimal scenarios with respect to AE locations and EP gradients: e.g. hybrid scenario with flat q≳1 has no AE resonances in steep EP gradient region *

interactive, gui, no-gui versions available [V.-A. Popa]



- ongoing validation of model hierarchy on large parameter space
- use data from experiments (M . Vallar first successful TCV runs)
- porting to gateway in progress

EP WORKFLOW SCHEMATICS



coupling with ETS:

- start with critical gradient model:
  - determine unstable spectrum
  - set diffusion coefficient for EPs in ETS at mode position (with certain shape corresponding to mode structure) to large value to force instantaneous relaxation (~5-10m^2/s)
  - update stability in next time step: faster iterations in ramp-up (current evolution, NB,α pressure build-up)

- next: use HAGIS with estimated fixed mode amplitudes to calculate phase space resolved P_Φ transport (kick-model like, not decided if probability matrices will be used like in [Podesta, 2016-2021])
  - calculate modified F_{EP} and pass back to ETS
  - use separate moments models for different regions of phase space

- advanced EP transport models (to be implemented and tested in ENR ATEP [M Falessi et al])

- compare to non-linear multi-mode HAGIS and ORB5

validation: AUG cases with modified background Ti (and possibly current?) found in scenarios with strong EP-driven mode activity