Thermal Instability and Condensation Formation in Coronal Loops

Connecting spectral and time-dependent approaches

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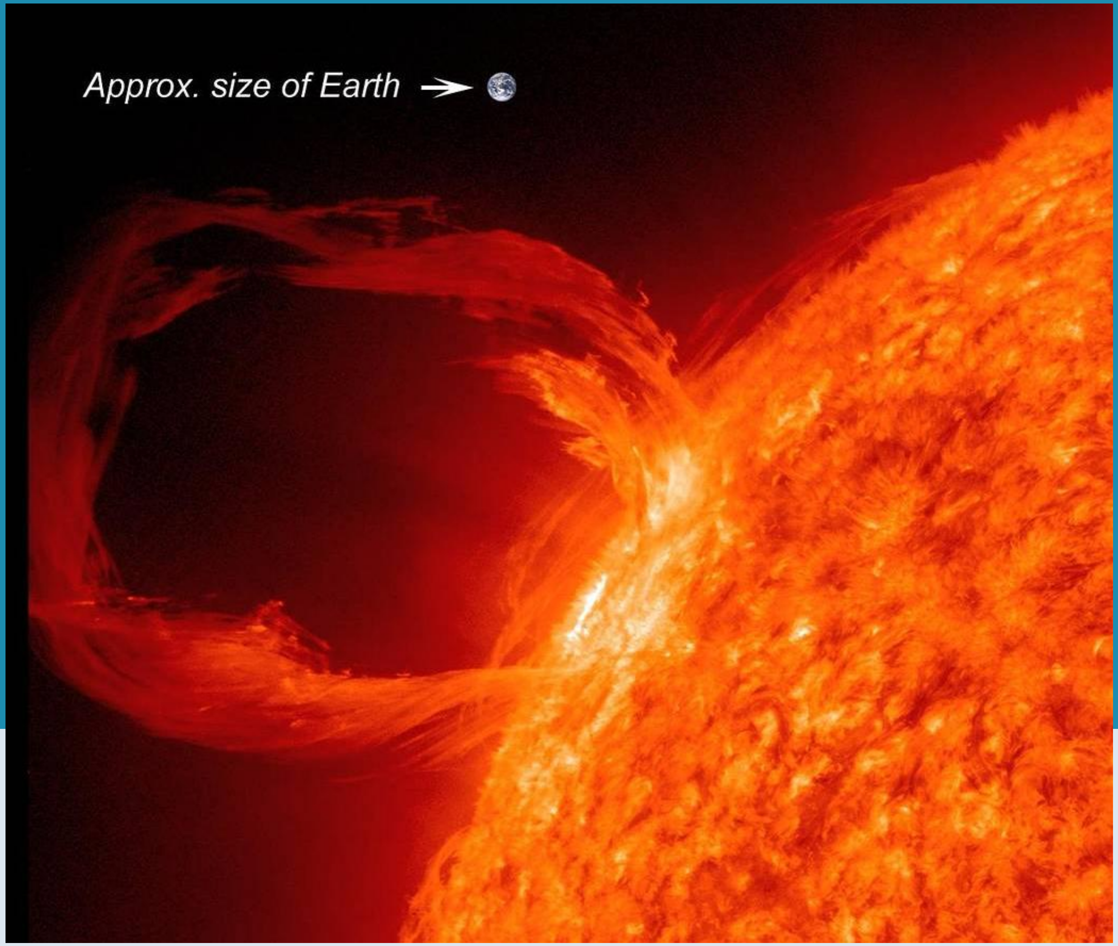

FNRS Contact Group Astronomie & Astrophysique
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Thermal instability in the solar atmosphere

How does the corona, at over 1 million K, give rise to cool, dense condensations such as prominences or coronal rain?

Plasma 10-100x cooler than their surroundings – **“snowflakes in an oven”**

- **Prominences** are large, cool ($\sim 10^4$K) plasma clouds suspended in the corona; lasting days-weeks.
- **Coronal rain is** small, short-lived condensations that form in loops and fall along field lines.

Localised cooling instability

Courtesy of NASA/SDO

Thermal instability and the heat-loss function

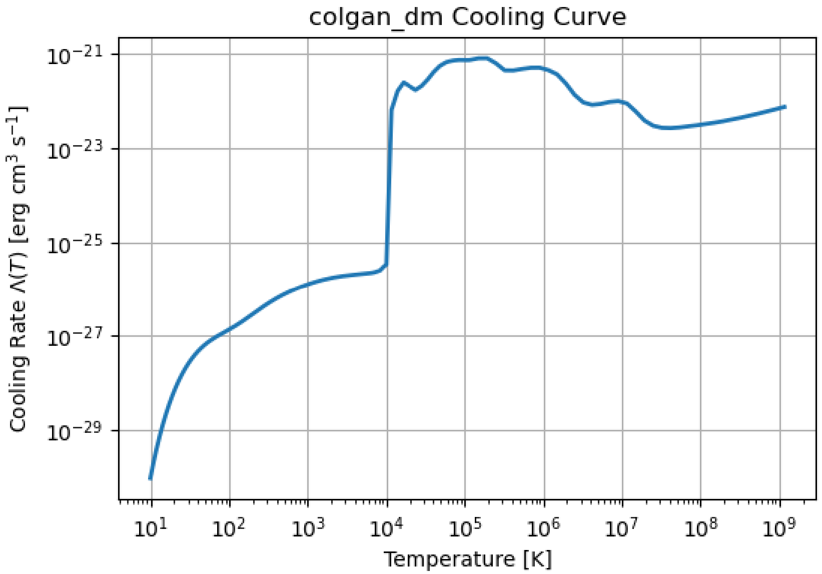
Net heat-loss function:

$$\rho \mathcal{L}(s, T) = \rho^2 \Lambda(T) - H(s)$$

- $\Lambda(T)$: optically thin radiative cooling curve (atomic emissions)
- $H(s)$: heating function (e.g. wave dissipation, reconnection)

- Small T↓ can increase losses, driving T↓ and $\rho \uparrow$.
- Leads to **runaway cooling and condensation** (Parker, 1953; Field, 1965)

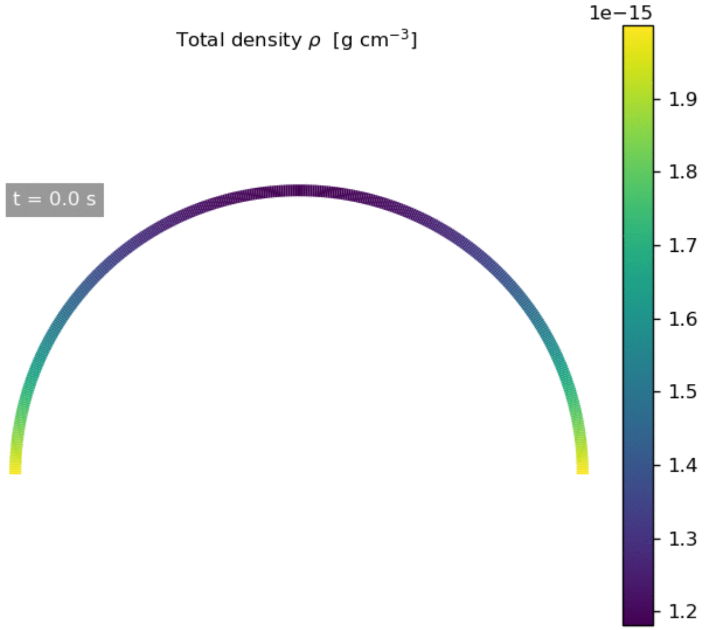
$$\boxed{\left(\frac{\partial \mathcal{L}}{\partial T}\right)_\rho < 0 \quad \Rightarrow \quad \text{unstable}}$$



Loop model

Investigate early-stage instability onset in a simple loop model.

- **1D hydrodynamic model** along a magnetic field line.
- **Semi-circular** loop geometry with line-tied footpoints.
- Subject to **gravitational stratification**
- Initially **uniform temperature**.



Loop density stratification (along magnetic field line)

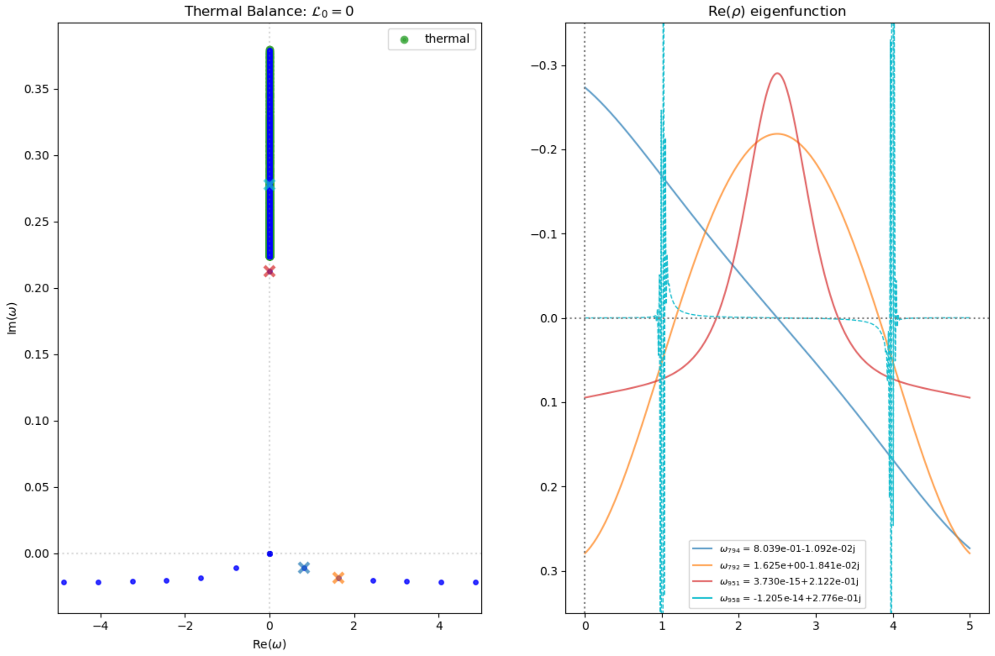
Aims

How can we apply MHD spectroscopy to understand the dynamics at play?

Claes et al., 2020, ApJS

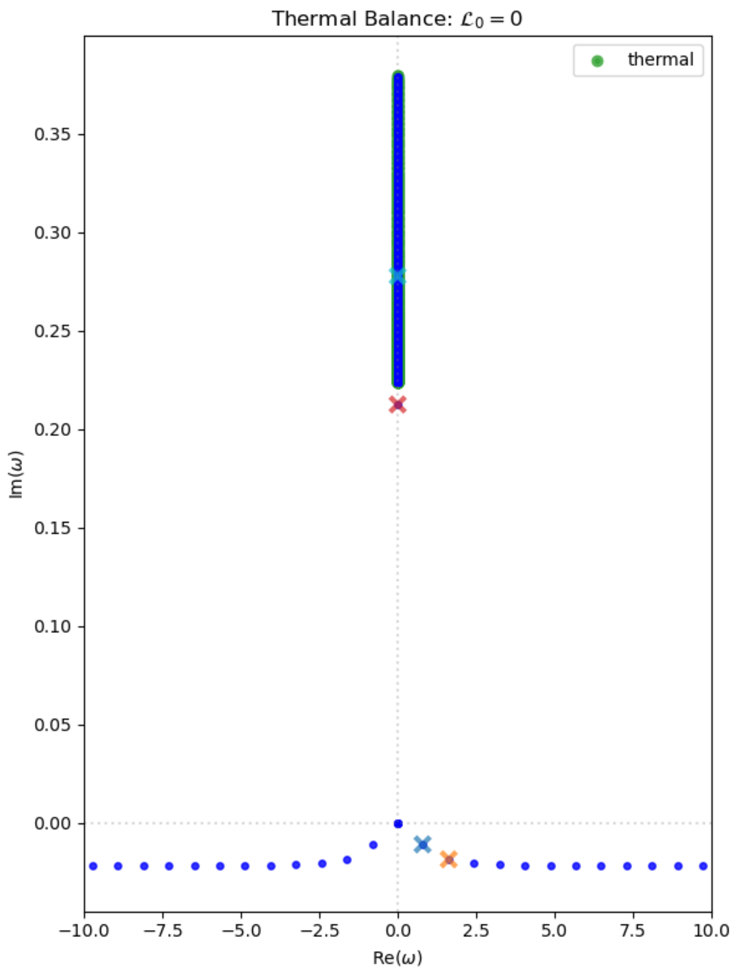
Claes and Keppens, 2023, Comput. Phys. Commun.

MHD spectroscopy: waves & instabilities



(Magneto)hydrodynamic spectroscopy

- Study all **linear waves and instabilities** supported. **How?**
- Linearised MHD equations: $\rho = \rho_0 + \rho_1$ *(equilibrium + small pert.)*
- Expand perturbations as **normal modes**: time dependence $\rho_1 \sim \exp(-i\omega t)$.
- Compute the **linear hydrodynamic spectrum** by quantifying all:
  - **Eigenvalues –** growth/decay rates
  - **Eigenfunctions –** spatial structure of modes

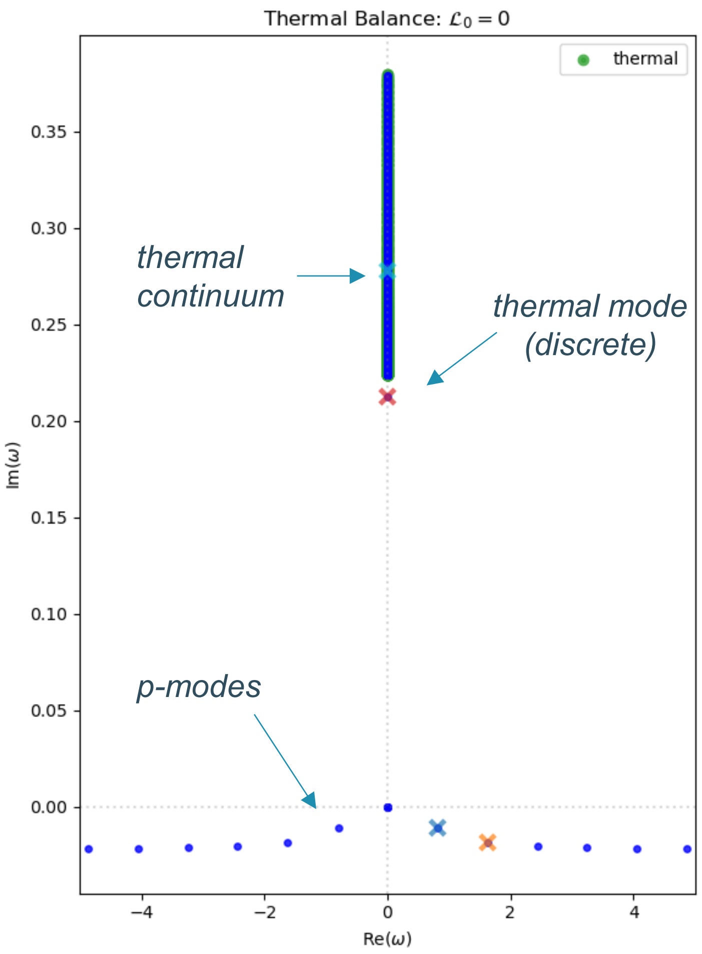


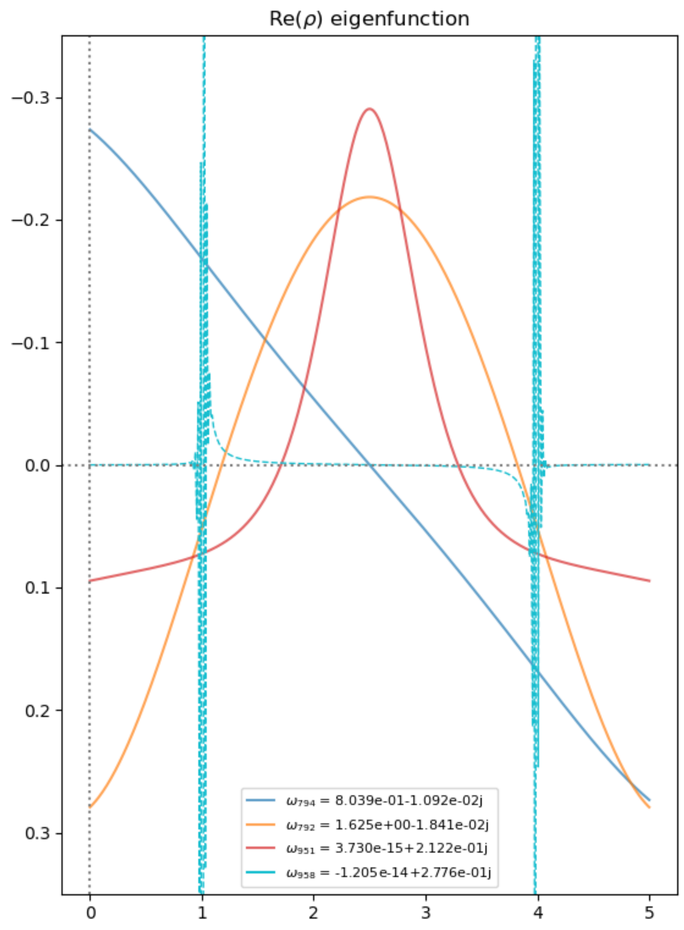
- Oscillations: $\Re(\omega)$
- Growth/damping: $\Im(\omega)$

The hydrodynamic spectrum

Spectral analysis of the loop

- 1D hydrodynamics has **3 wave modes**: $\pm$ p-modes and thermal modes
- Damped **p-modes**, stabilised by radiative losses.
- Unstable **thermal branch** along $\Re(\omega) = 0$.
- Thermal branch contains:
  - **continuum** (highly localised)
  - **discrete** global modes.





Effect of background heating on stability

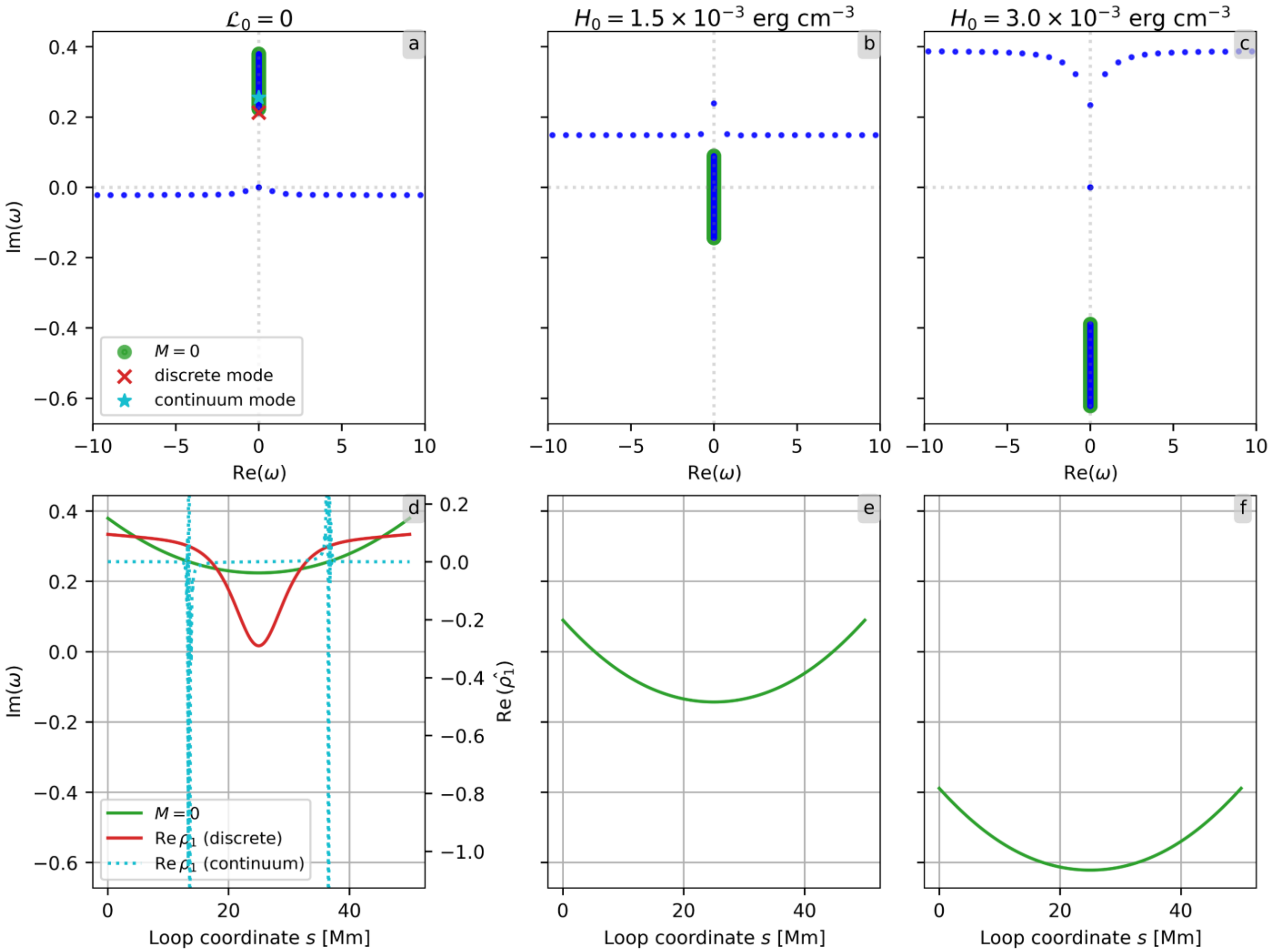
- Thermal misbalance:

$$\mathcal{L}_0(s) = \rho_0 \Lambda(T_0) - H_0(s).$$

- Three heating levels:
  - (a) thermal balance: $\mathcal{L}_0 = 0$
  - (b) mild excess heating: $H_0 = 1.5 \times 10^{-3}$ erg cm^{-3} s^{-1}
  - (c) strong excess heating: $H_0 = 3.0 \times 10^{-3}$ erg cm^{-3} s^{-1}

(Keppens et al., 2025, ApJ, 989, 51)

- Are these unstable modes **actually excited**?
- Do their **growth rates** match in time evolution?
- **Which modes are dominant**, and how important is **transient behaviour**?
- When do **nonlinear effects** take over from linear growth?



Varying background heating completely modifies the linear spectrum!

KU LEUVEN

Linking the spectrum with numerical simulation

Spectral

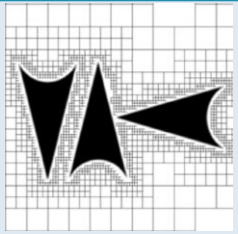
LEGOLAS
- **Eigenvalues** and **eigenfunctions**
- **Stability** and **growth rates**
- **Mode structure** along the loop

Linear

LEGOLAS-IVP
- **Evolve perturbations in time**
- Confirm dominant spectral mode
- Identify **which ICs excite which modes**
- Capture **transient behaviour**

Nonlinear

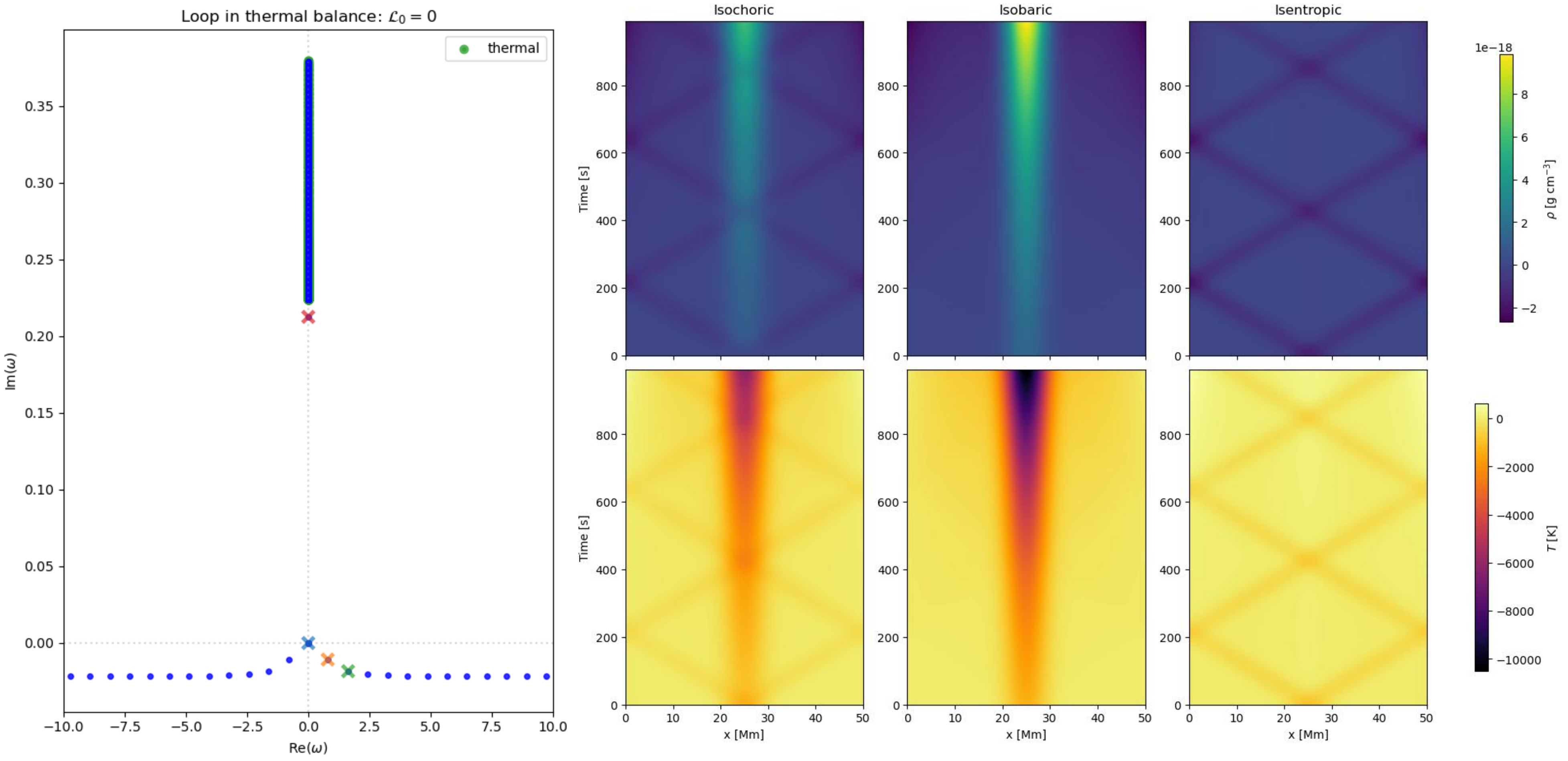
MPI-AMRVAC
- Follow onset → saturation
- Formation and evolution of condensations
- Quantify **linear → nonlinear transition**



Spectral response to initial conditions

- **Pulses in temperature and density** used to excite modes
- **Isobaric:** localised thermal instability
- **Isentropic:** acoustic p-modes
- **Isochoric:** both thermal and p-modes

TI is most closely-associated with **isobaric** conditions.



Summary and outlook

Summary:

- 1D HD loop study linking **spectral analysis**, **linear IVP evolution**, and **nonlinear simulations**.
- Time-dependent behaviour (modes + growth rates) **is consistent** with the linear spectrum.
- Demonstrated that **linear thermal modes** can **evolve nonlinearly into condensations** (not shown).

Future Outlook:

- **Effects of thermal conduction:** Assess the expected stabilising effects of $\kappa_\parallel \neq 0$.
- **Extend to MHD:** coupling with Alfvénic and slow-mode dynamics.
- **More realistic models:** add chromospheric base, localised heating prescriptions

Thank You

Thank you for your attention!

Any questions?

Appendix A: Thermal instability mechanism

Mechanism (Field 1965):

- Small parcel of gas undergoes a perturbation in T or ρ
- Thermodynamics (1st law): $T\frac{dS}{dt} = -\mathcal{L}$
- Linearised:

$$\frac{d\,\delta S}{dt} = -\frac{1}{\rho T}\left(\mathcal{L}_\rho\,\delta\rho + \mathcal{L}_T\,\delta T\right) = -\frac{1}{\rho T}\left(\delta\mathcal{L}\right)$$

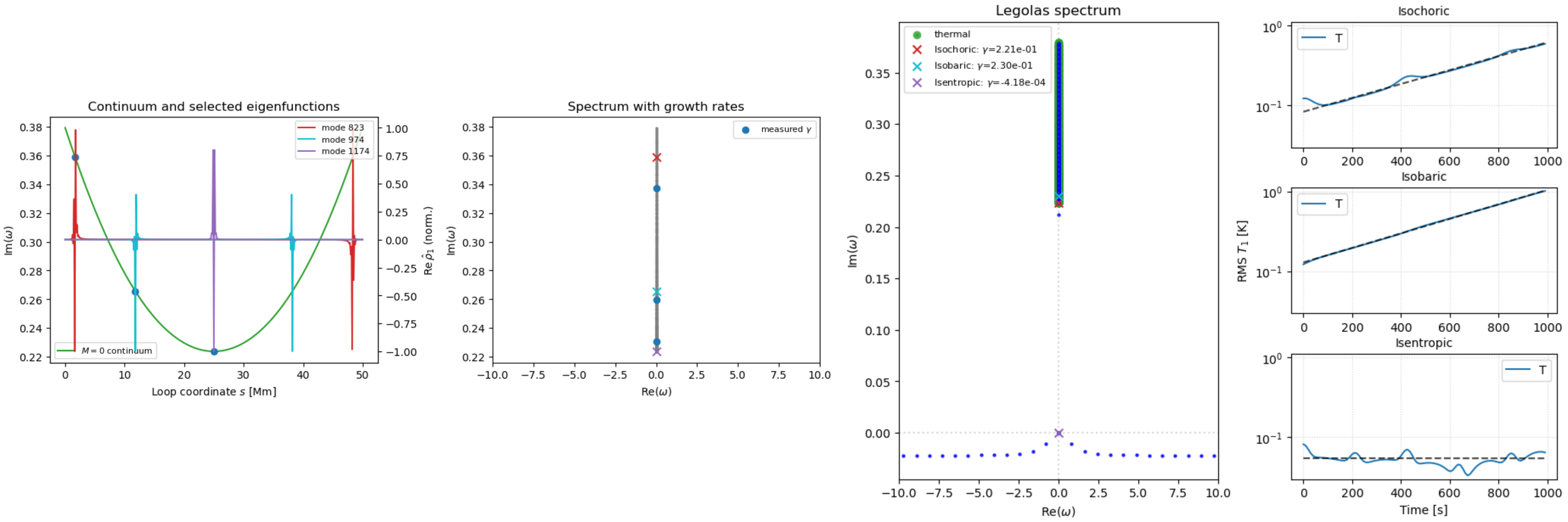
Instability condition:

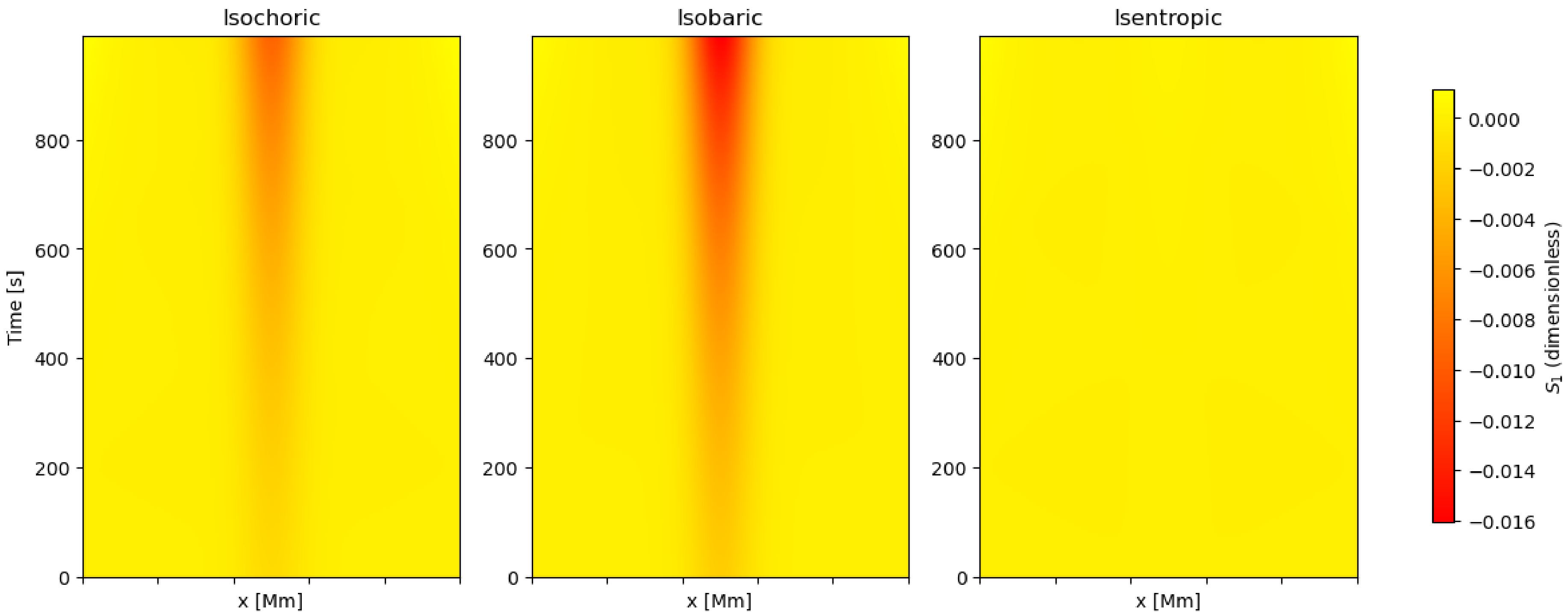
- Runaway cooling if small cooling perturbation causes drop in entropy: $\delta T < 0 \;\Rightarrow\; d\delta S/dt < 0$
- Assume isochoric ($\delta\rho = 0$). This happens if

$$\boxed{\left(\frac{\partial\mathcal{L}}{\partial T}\right)_A < 0 \quad\Rightarrow\quad \text{unstable}}$$

$A = p$ (isobaric) or $A = \rho$ (isochoric)

Appendix B: Additional figures





Isochoric
Isobaric
Isentropic
Time [s]
x [Mm]
x [Mm]
x [Mm]
0
200
400
600
800
0.000
−0.002
−0.004
−0.006
−0.008
−0.010
−0.012
−0.014
−0.016
S_1 (dimensionless)