CREALab

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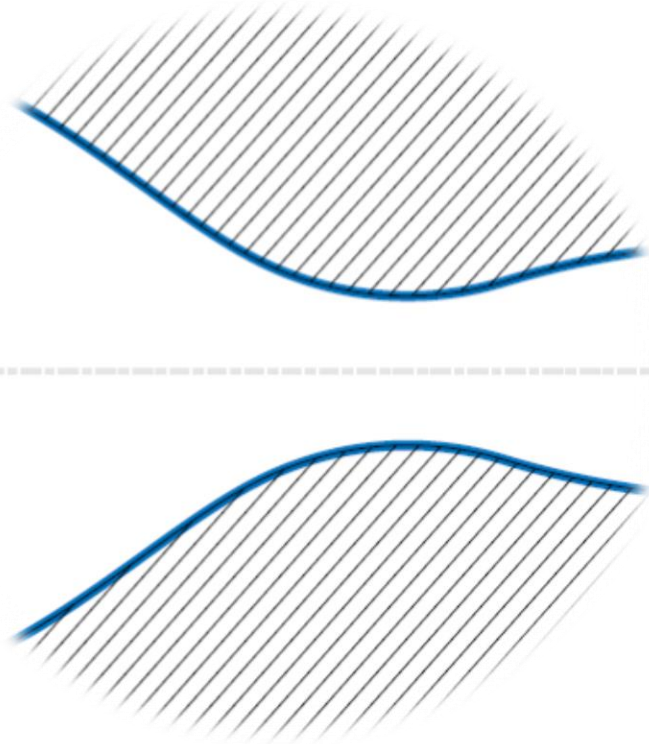
Similarity Parameters for Non-Ideal One-Dimensional Isentropic Expansions



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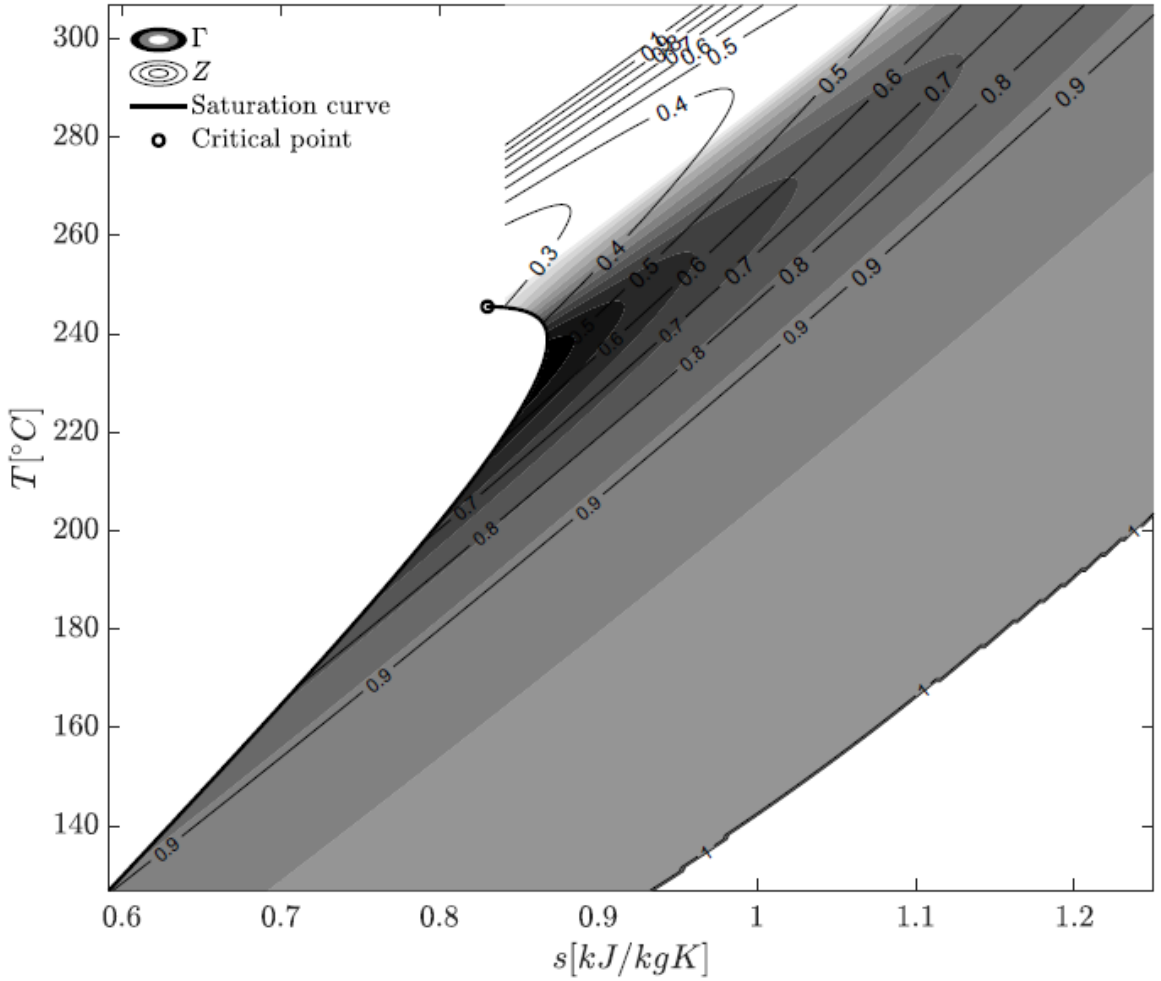
NICFD 2020 for Propulsion & Power

3rd International Seminar on Non-Ideal Compressible-Fluid Dynamics for Propulsion & Power, 29-30 Oct. 2020 – Delft

Background

*Non-Ideal Compressible Fluid Dynamics (**NICFD**)*

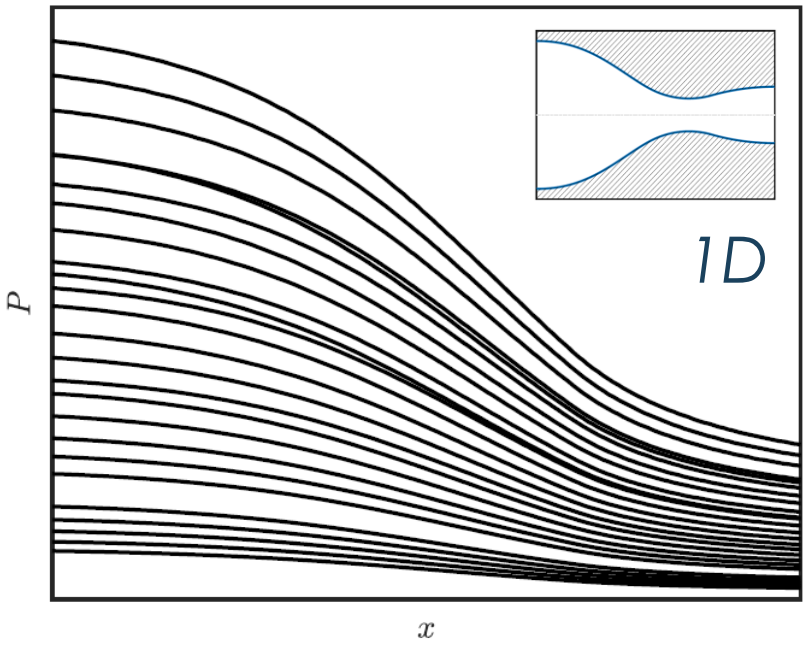


Dense vapors
Close to VLE + critical point
Two-phase

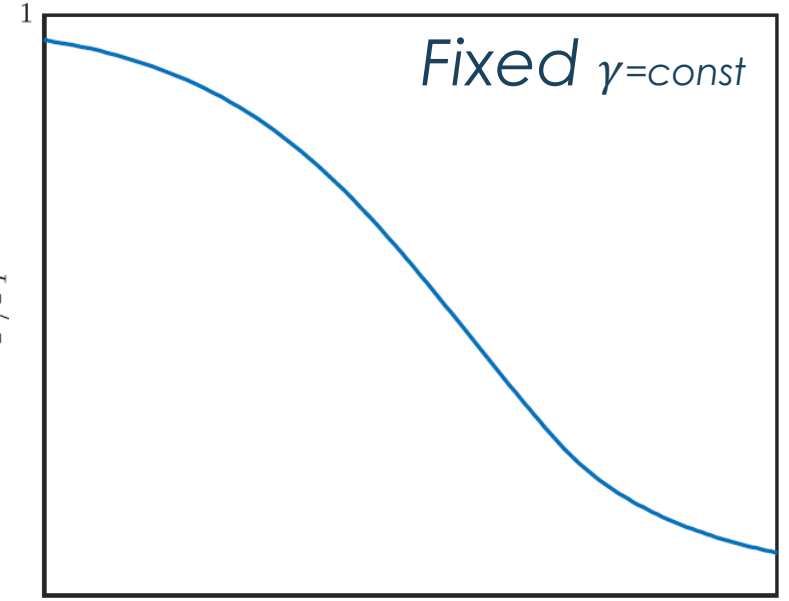
$Pv \neq RT$

Focus on: Non-Ideal Dependence of Isentropic Expansions

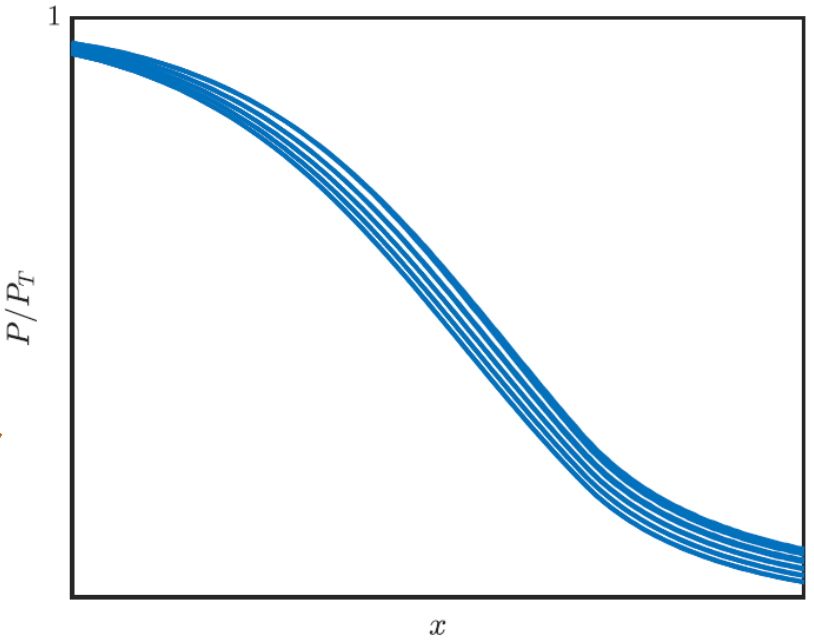
$$\frac{P}{P_T} = f(P_T, T_T)$$



pIG



~~pIG~~



Thermal and Caloric Behaviour

Thermodynamic description (pure fluid)

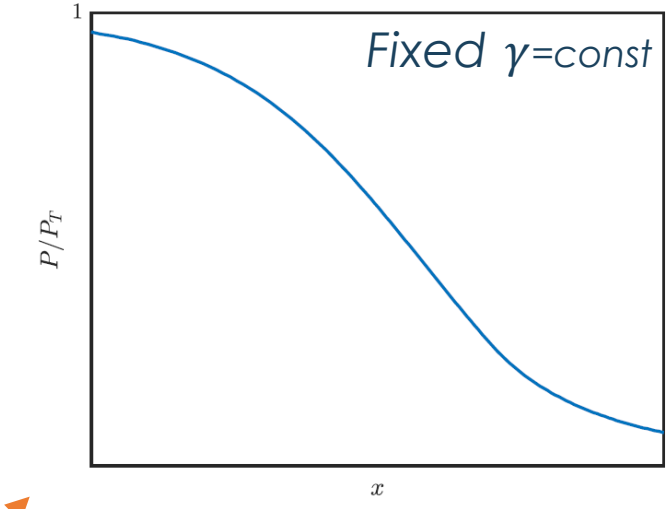
Thermal EOS
$P = P(T, v)$

$$Z = \frac{P}{R\,T\rho}$$

vs. IG at same (T, P)

IG → $Z = 1$

Same volumetric behaviour regardless of (P_T, T_T)



Caloric EOS
$e = e(T, v)$

$$\Gamma = 1 + \frac{\rho}{c}\left(\frac{\partial c}{\partial \rho}\right)_s$$

c in $iso - s$ process + molecular complexity

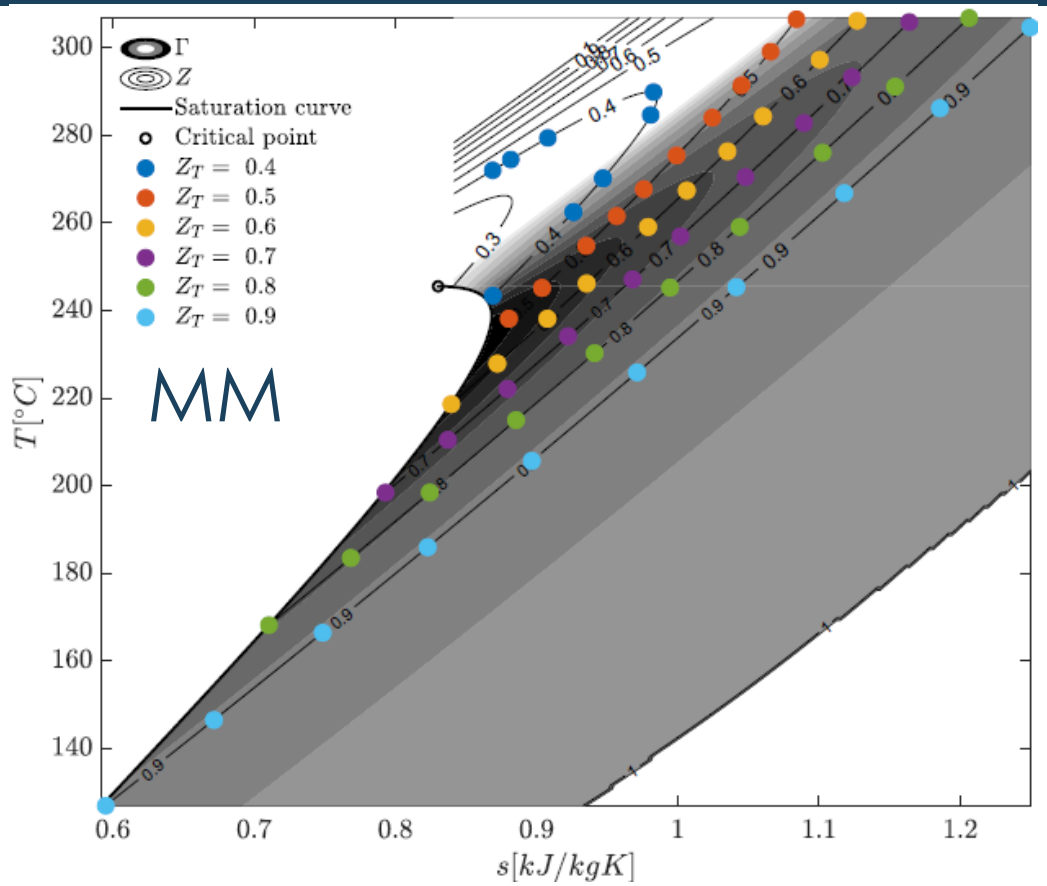
$$\Gamma = \frac{\gamma + 1}{2}$$

plG

Same caloric behaviour regardless of (P_T, T_T) for fixed fluid

Z, Γ *in* ***Non-ideal flows?***

Calculation Framework: 1D isentropic expansions

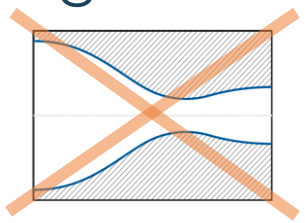


Type	Fluid
Siloxanes	MM
	MDM
	D4
	D6
Alkanes	Butane
	Pentane
	Hexane
	Octane
	Decane
Cyclic Alkanes	Cyclopentane
	Cyclohexane
Alkenes	Isobutene
	Benzene
Other Hydrocarbons	Toluene
	Acetone
Halocarbons	R1234yf
	R218
	R1233zd
	R227ea
	RC318
Other Fluids	Water
	Carbon Dioxide
	Ammonia

- 10 x (P_T, T_T) with same $Z_T = \frac{P_T}{R\, T_T\, \rho_T}$
- $0.4 \leq Z_T \leq 0.9$
- widest possible region
- $P_{max} = 3P_c$, T_{max} from TDM

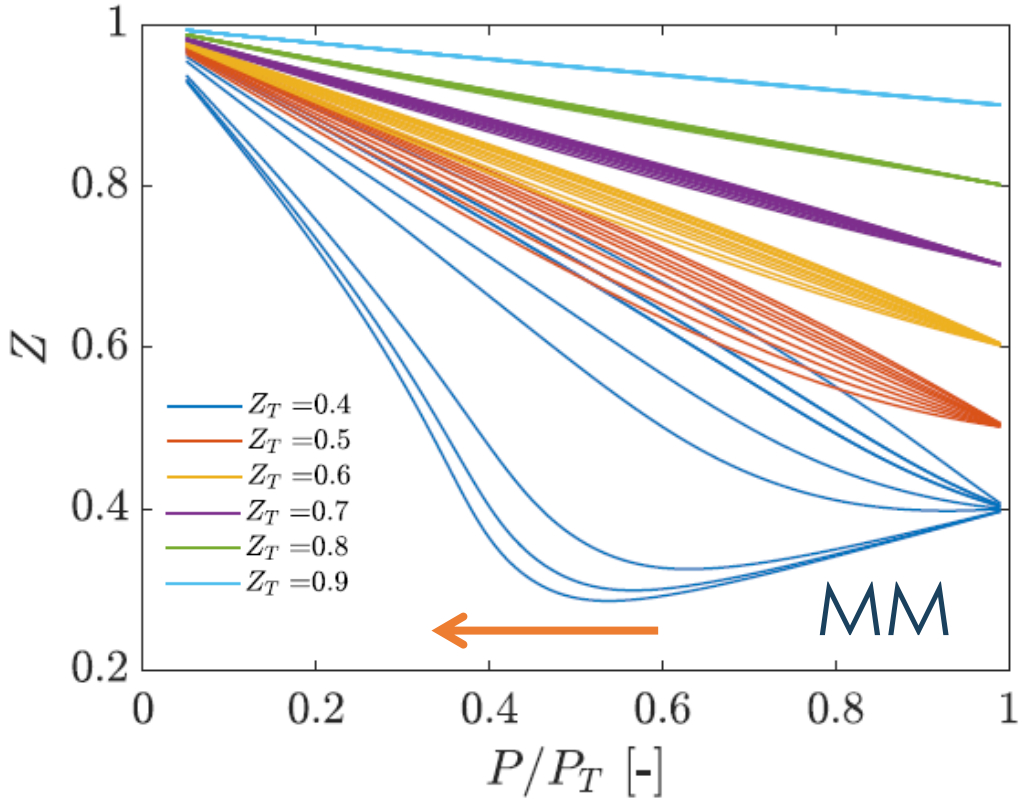
- Helmoltz energy-based TDM
- Independent of geometry:

$\frac{P}{P_T} : 1 \rightarrow 0.05$

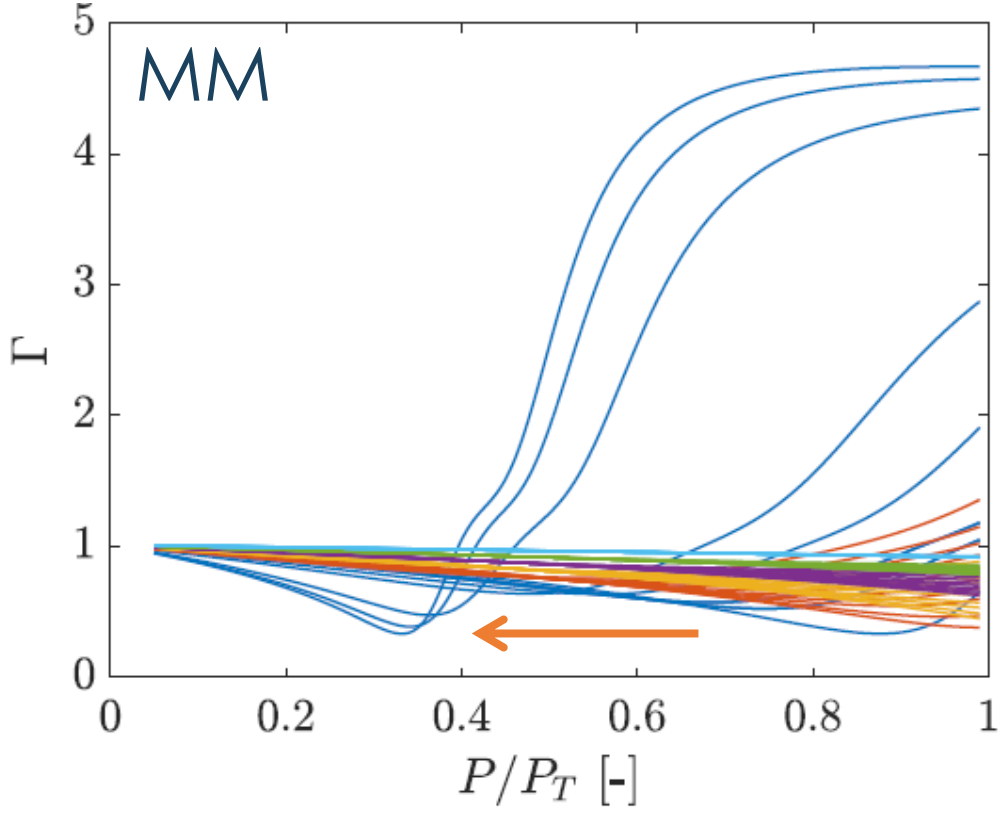


- 20 HMC fluids
- 3 LMC fluids

Results: Z and Γ Similarity



$$Z_T = \frac{P_T}{R\, T_T\, \rho_T}$$

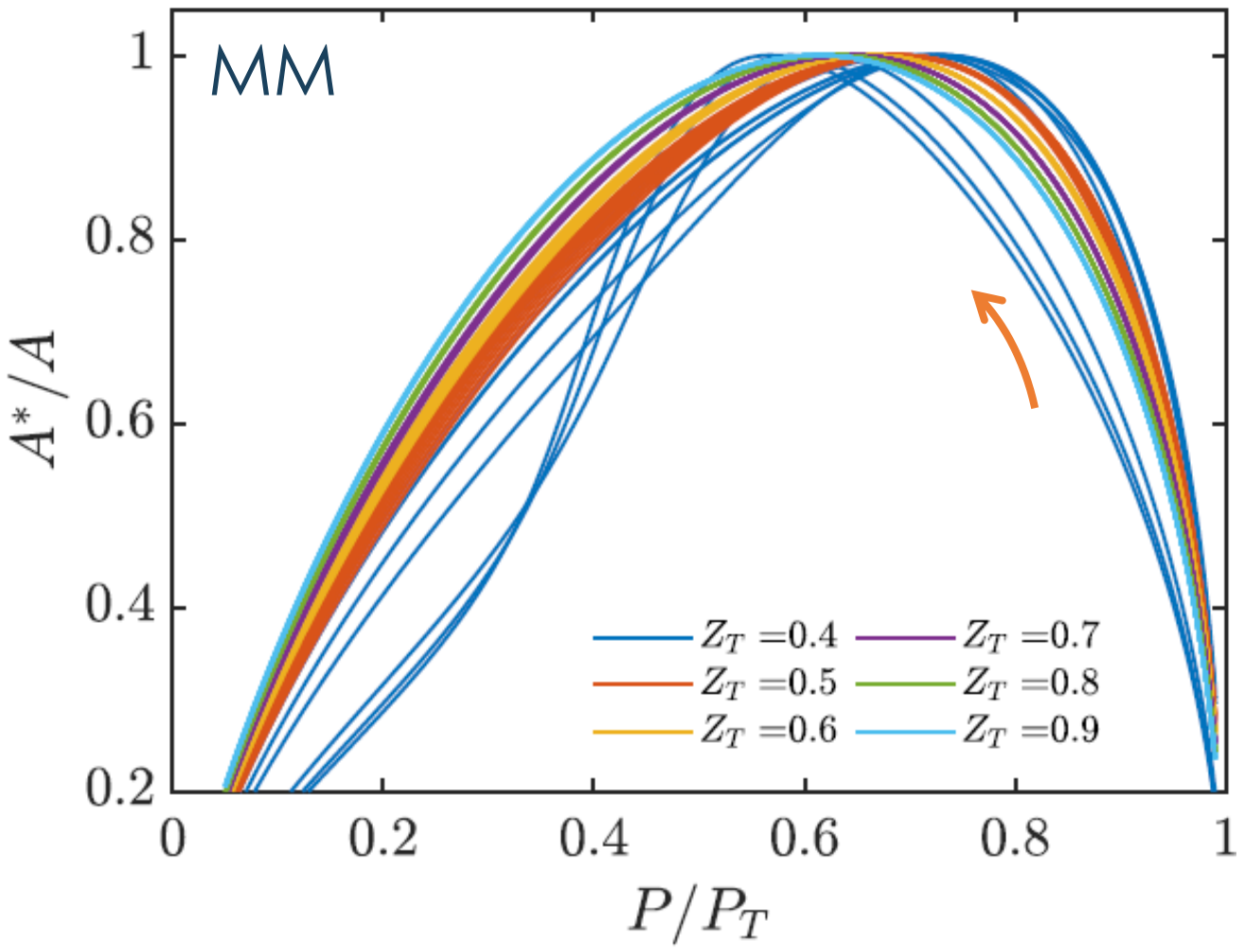


- MM (HMC)
- Same Z_T → similar Z and Γ along expansions

→ Similar **volumetric** + **caloric** behavior!

- ↓ Z_T → less similar Z and/or Γ

Results: Expansions Similarity

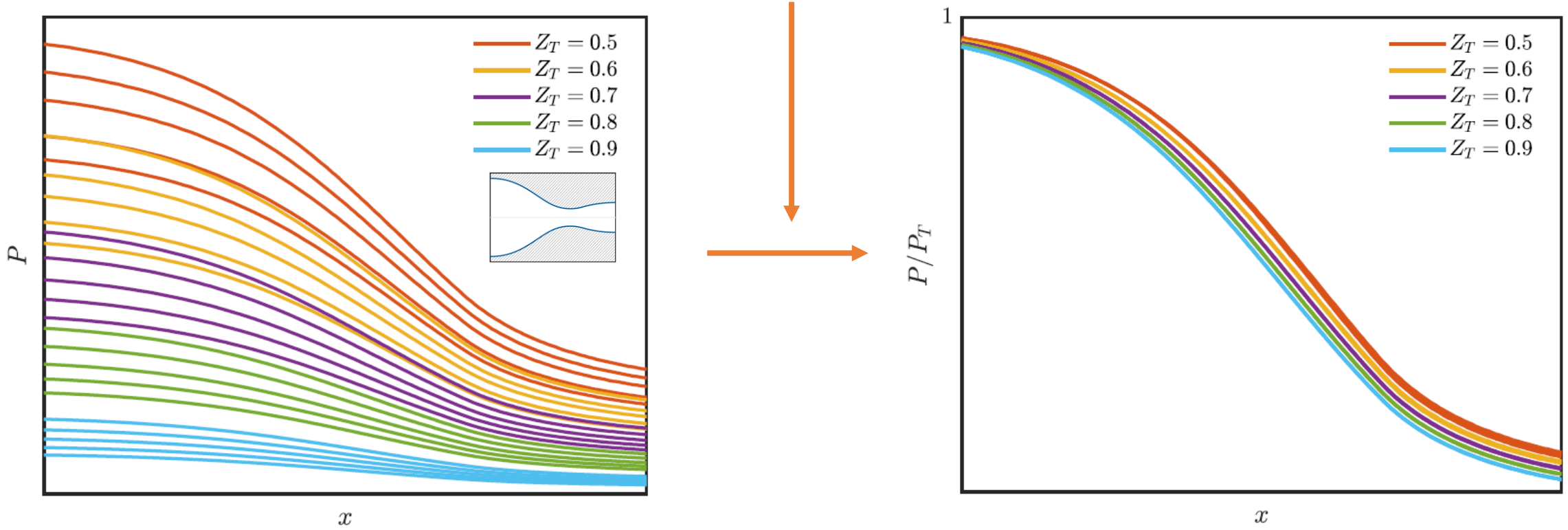


- MM (HMC)
- Expansions grouped according to Z_T (except $Z_T = 0.4$)

Results: Z_T

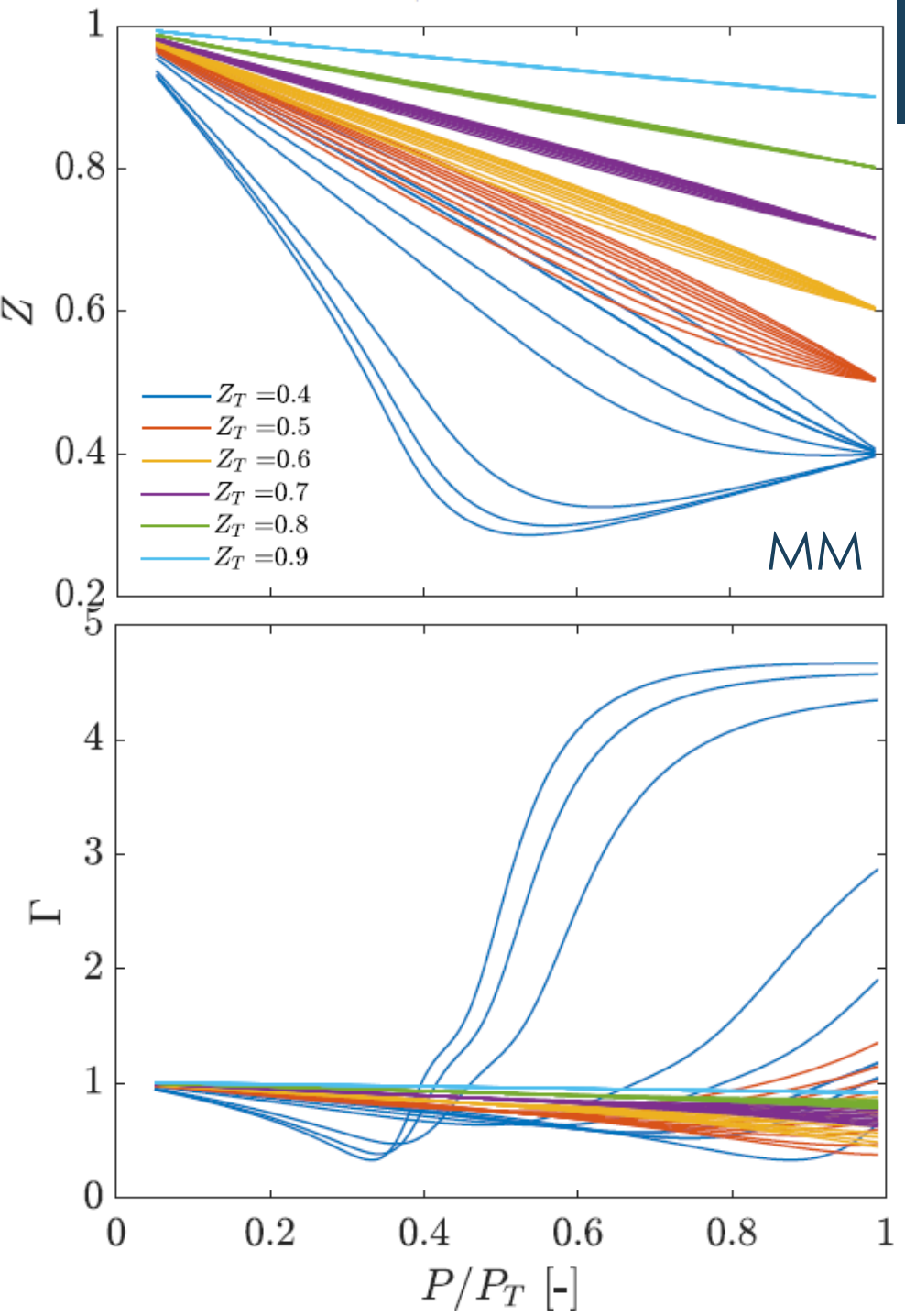
Similarity Parameter to Characterize Non-Ideal Isentropic Expansions (HMC)

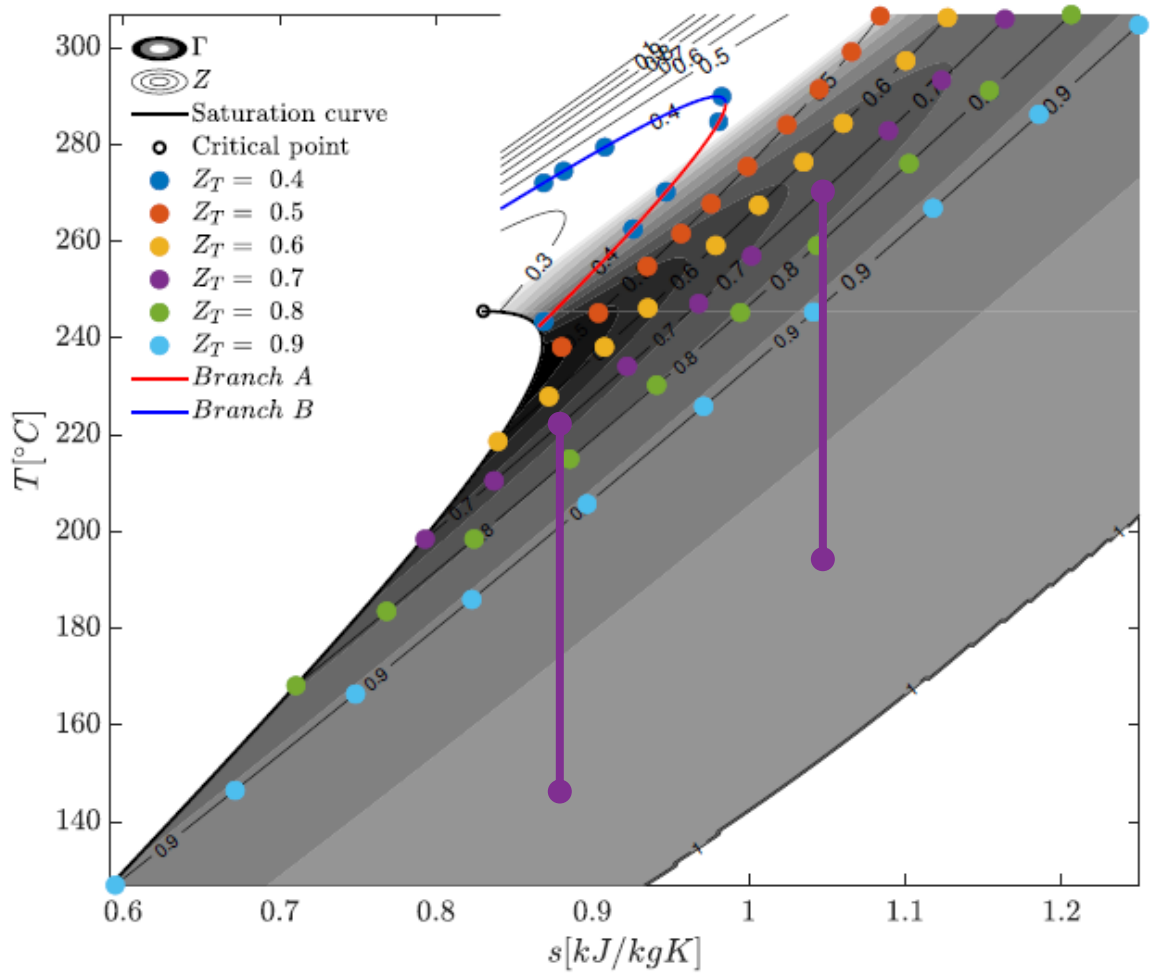
$$Z_T = \frac{P_T}{R\, T_T\, \rho_T}$$



- Experimentally verified in the TROVA!

Results: Z and Γ along expansions (HMC - MM)





Far from critical point:

$iso - Z$ // to one another

$iso - \Gamma$ // to one another

$iso - Z$ // $iso - \Gamma$

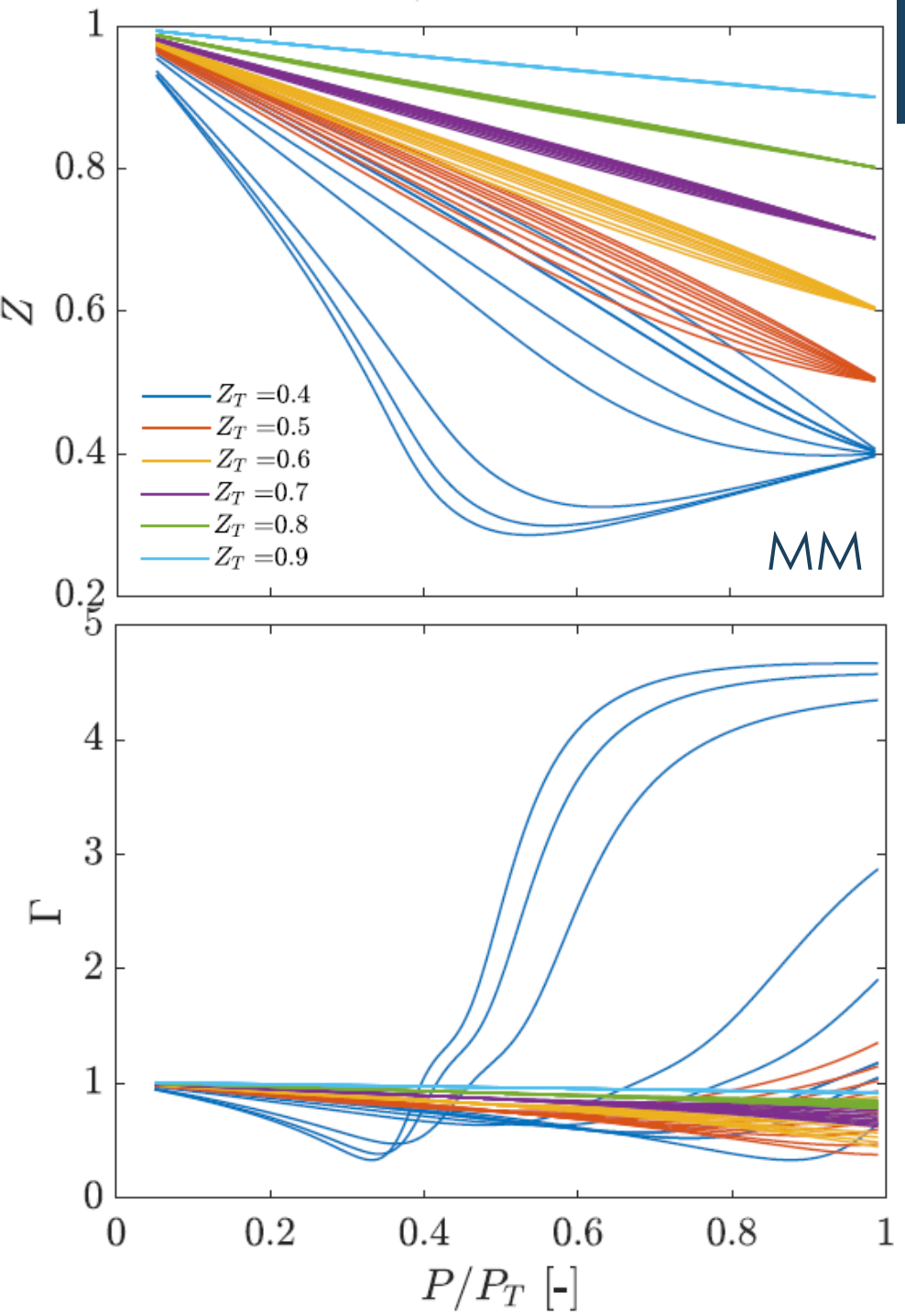
→

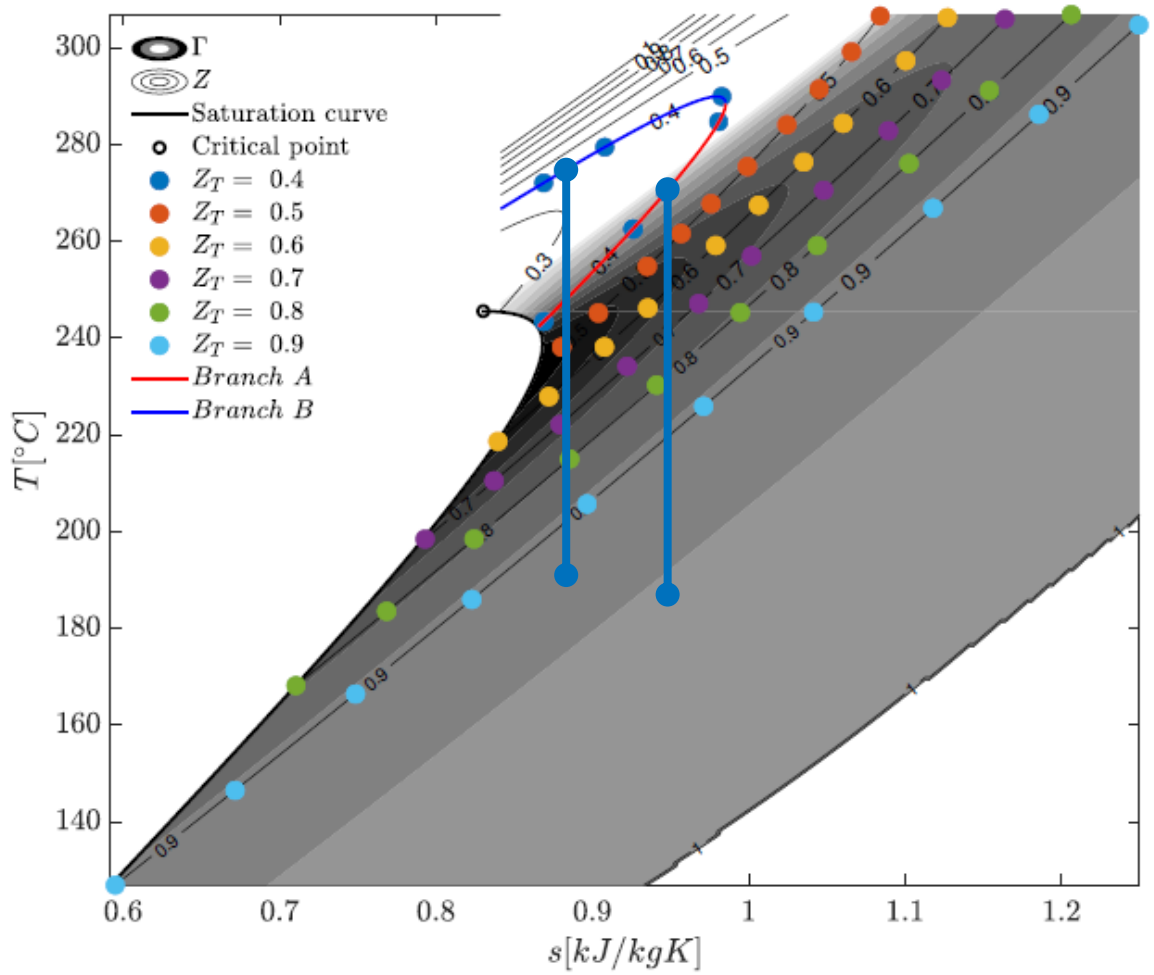
Same Z_T:

similar Z and Γ

similar expansions

Results: Z and Γ along expansions (HMC - MM)





Less ideal conditions:

Branch A

Branch B

(both *iso*−Z and *iso*−Γ)

→

Even at same Z_T:

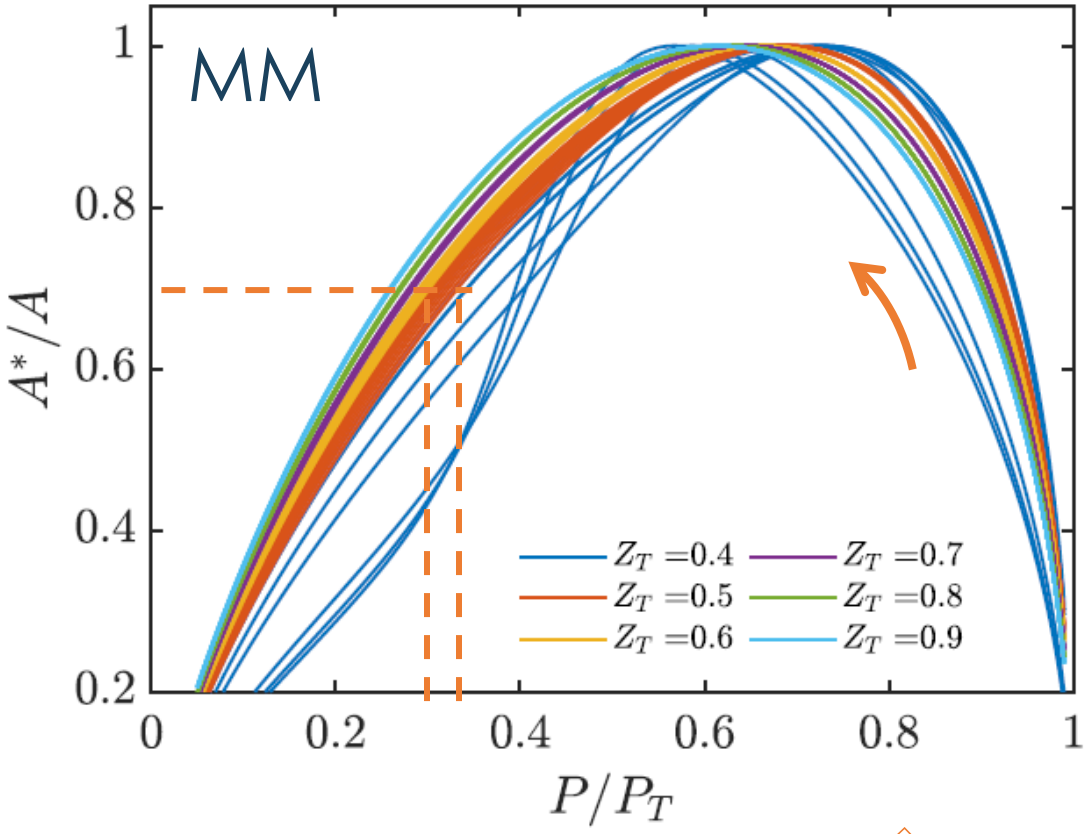
Not similar Z and Γ

Not similar expansions

Results: Z_T as a Similarity Parameter for HMC fluids

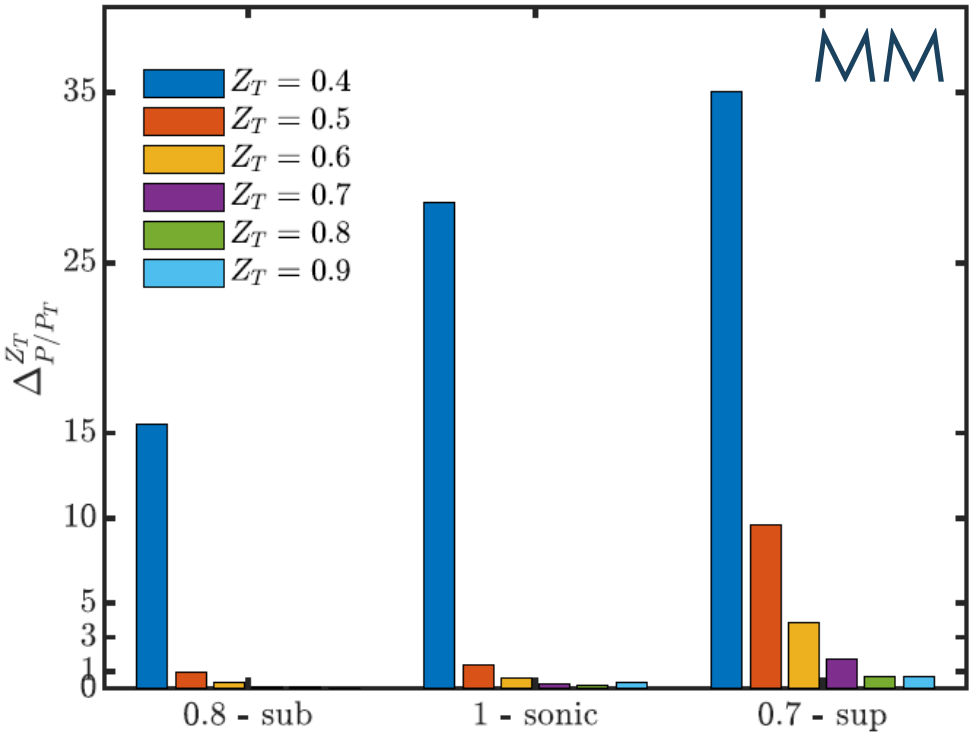
Spread in P/P_T in a 'fixed geometry' for expansions with same Z_T but different (P_T, T_T)

$$\Delta_{P/P_T}^{Z_T} = \frac{\max\ P/P_T\,(Z_T) - \min\ P/P_T(Z_T)}{\min\ P/P_T\,(Z_T)} \cdot 100$$



Z_T as similarity parameter ✓

Well representative of HMC



- ↓ $\Delta_{P/P_T}^{Z_T}$ if ↑ ideality
- ↑ $\Delta_{P/P_T}^{Z_T}$ if M ↑ (↓ denominator)

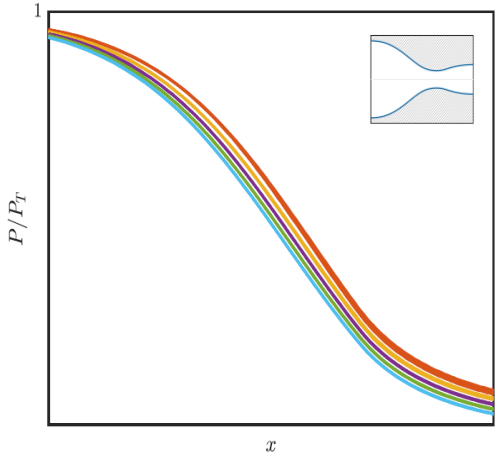
Conclusions & Future Outlook

Non-ideal 1D isentropic expansions → **Similarity Parameter**?

- HMC fluids + $Z_T \geq 0.5$

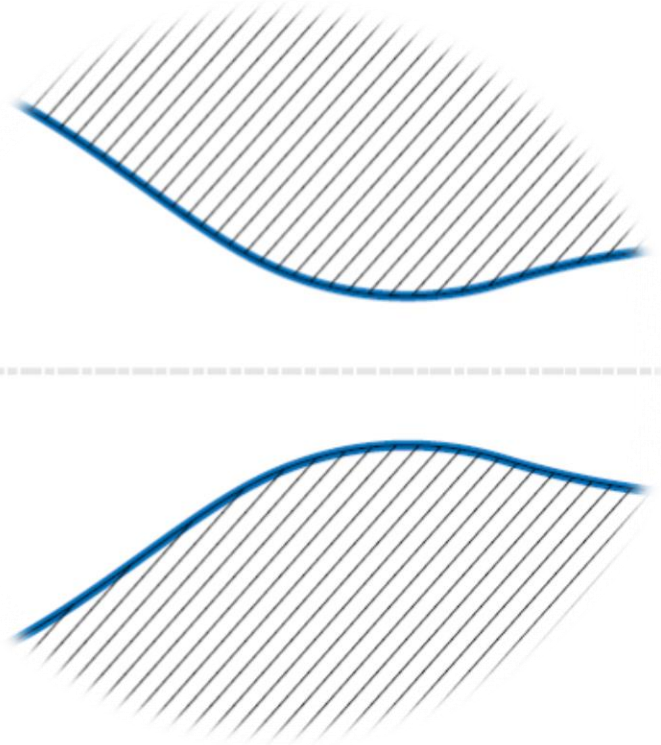
  → similar Z and Γ ($iso-Z$, $iso-\Gamma$ shape)

  → similar $\frac{P}{P_T}$



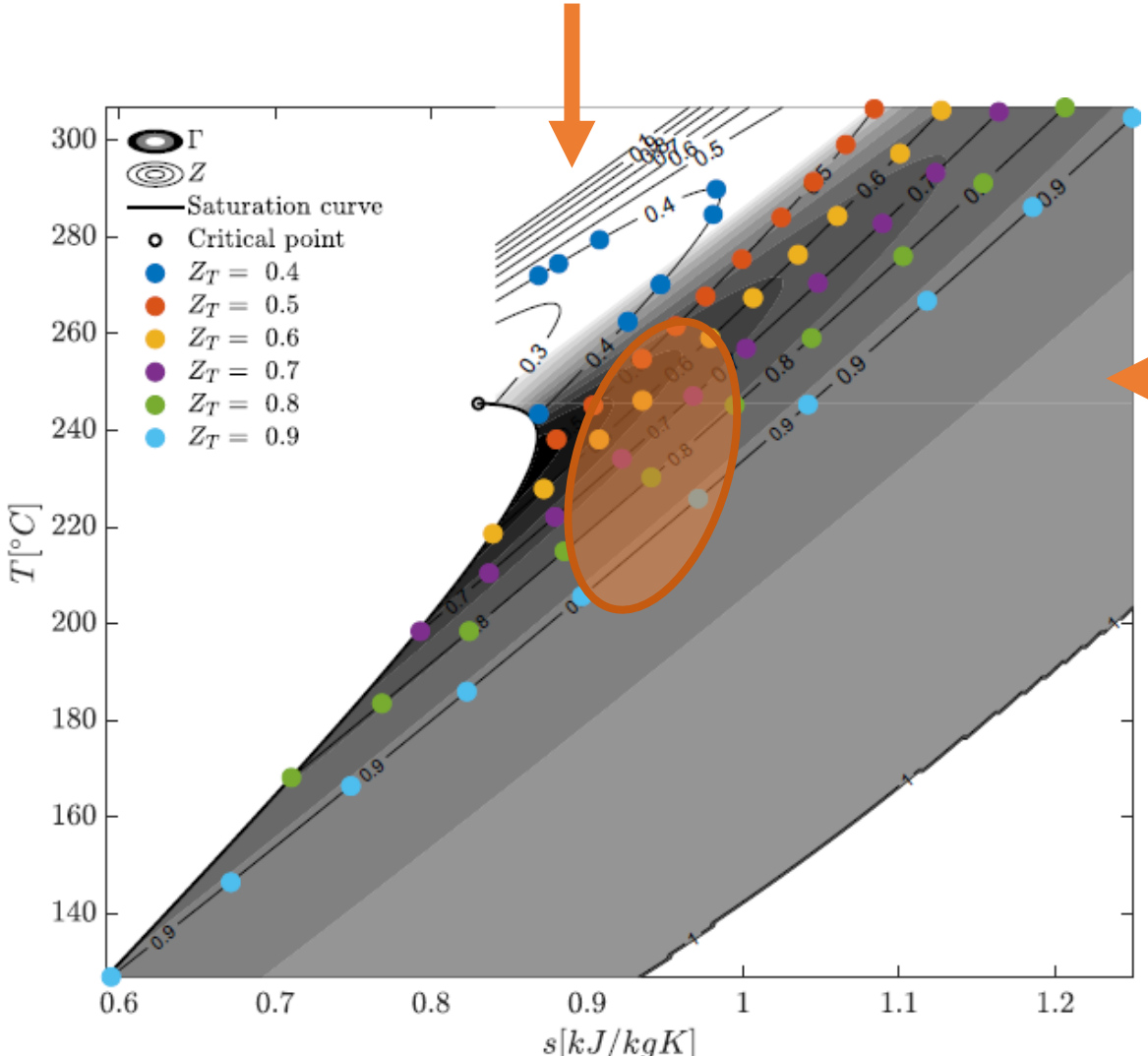
Similar thermal + caloric behaviour ⟷ Similar expansions

- VdW calculation
- Molecular interpretation



Objective

- Experimentally observed (TROVA): expansions within errorbars for $Z_T > 0.6$
  Siloxane MM + limited region

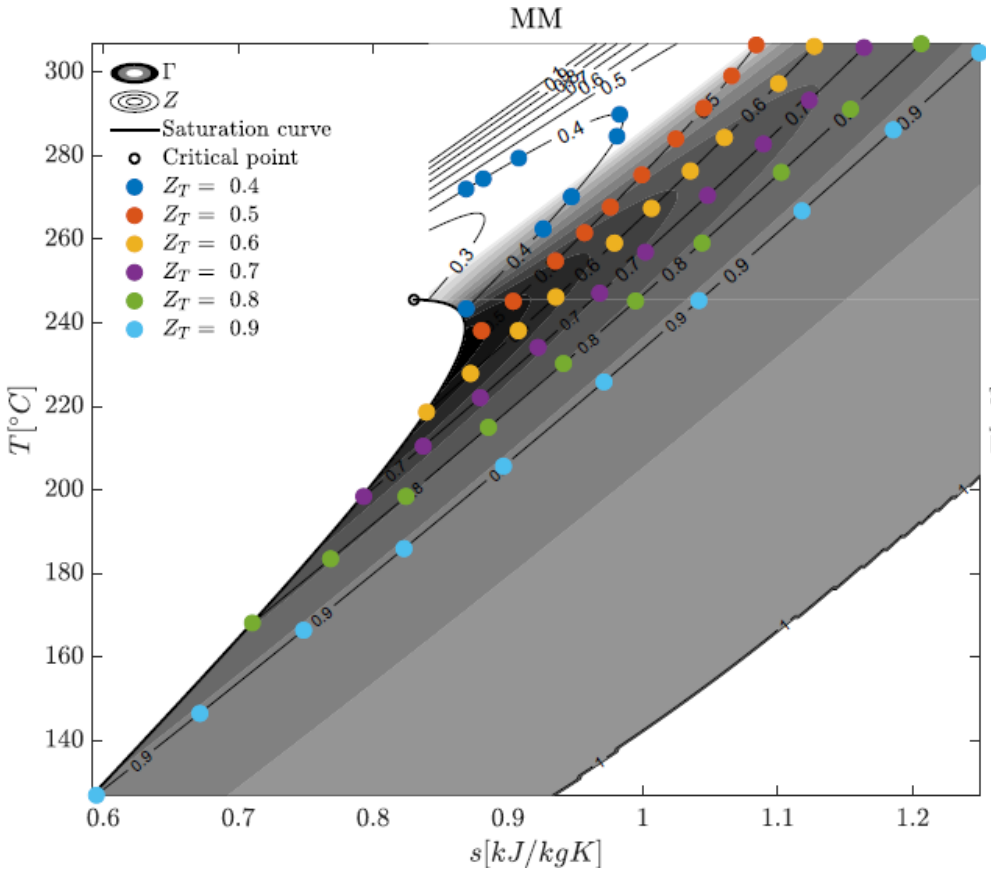


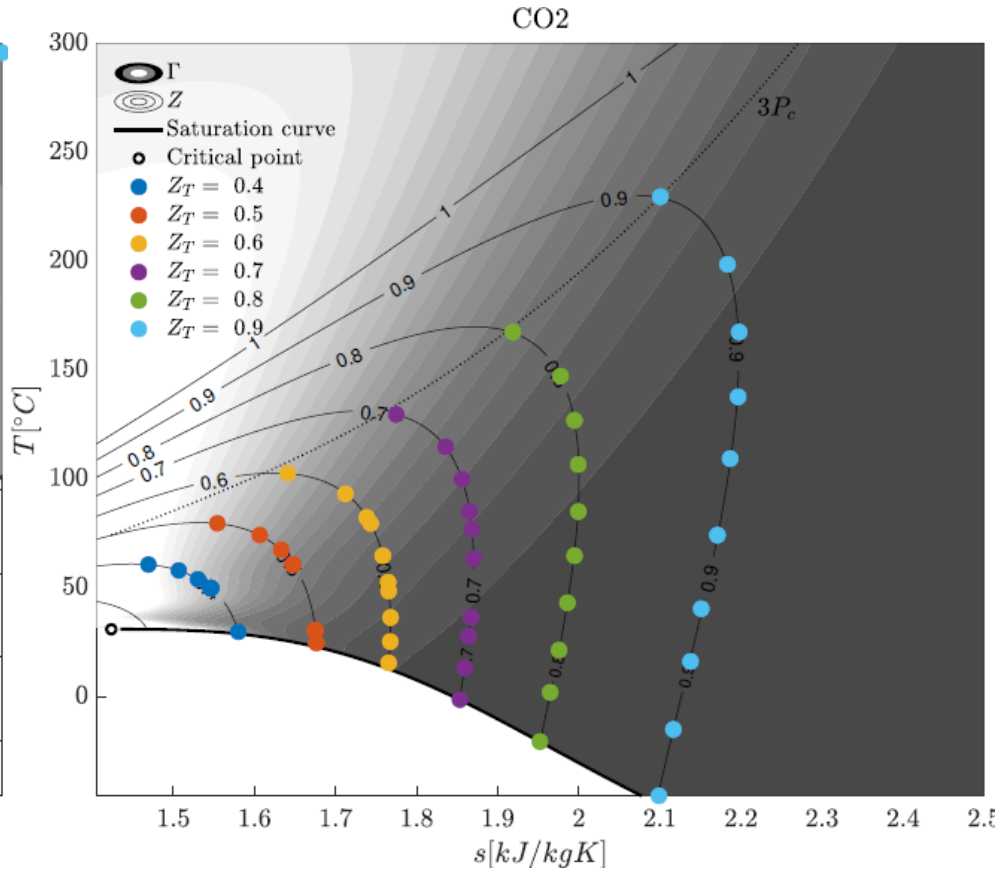
Suitability of Z_T as similarity parameter

- Wider region
- Other fluids

1D Isentropic Expansions

Calculation Framework: 1D isentropic expansions





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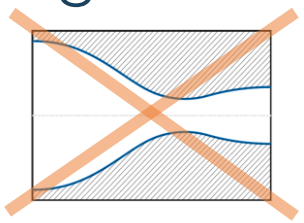
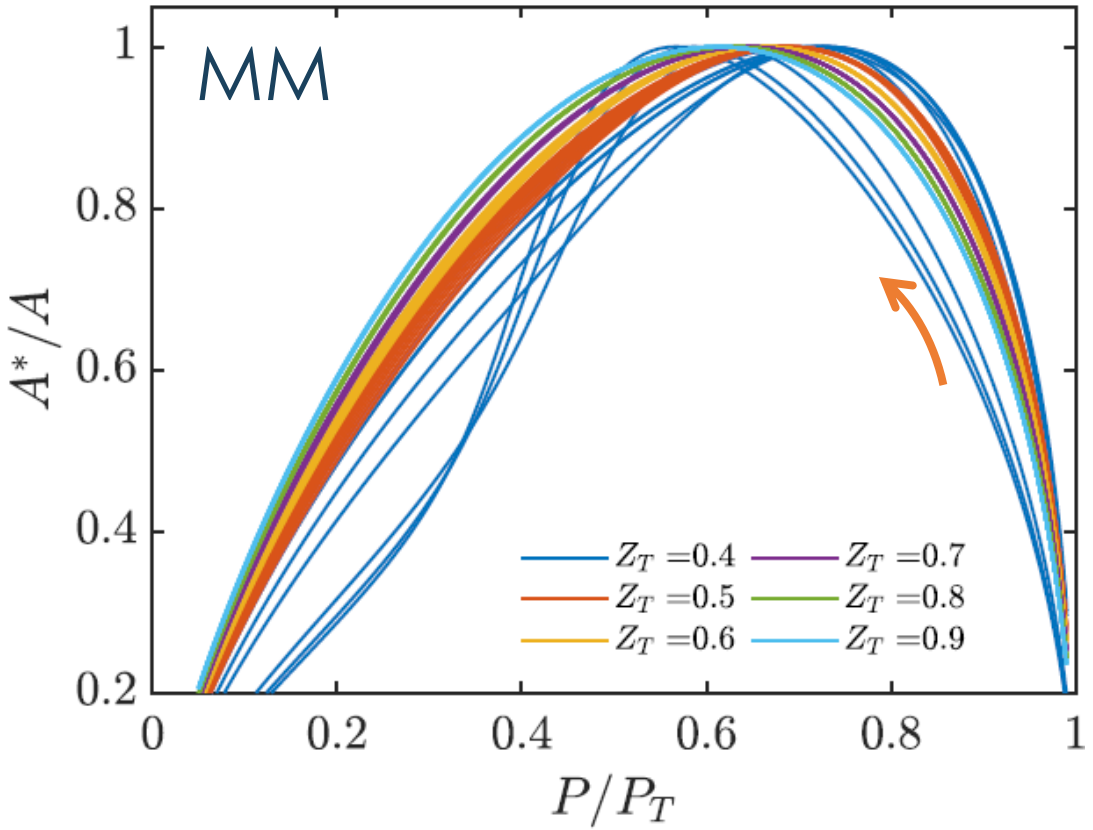
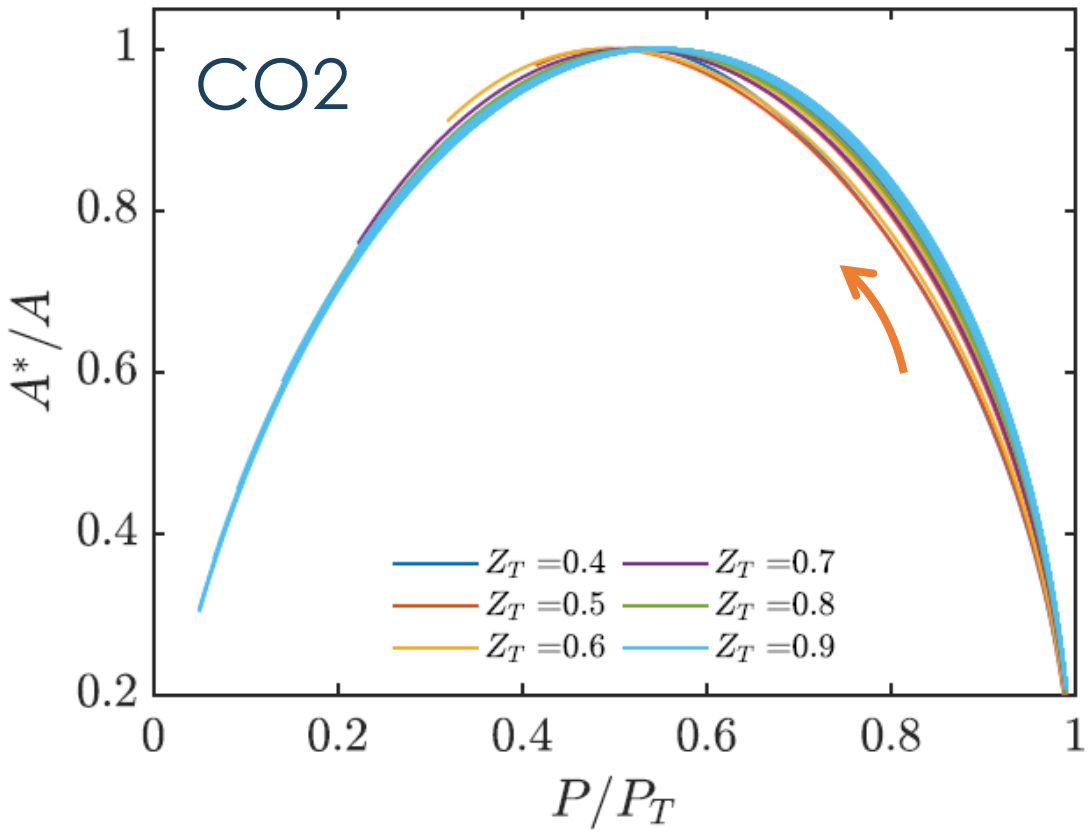


- 20 HMC fluids
- 3 LMC fluids

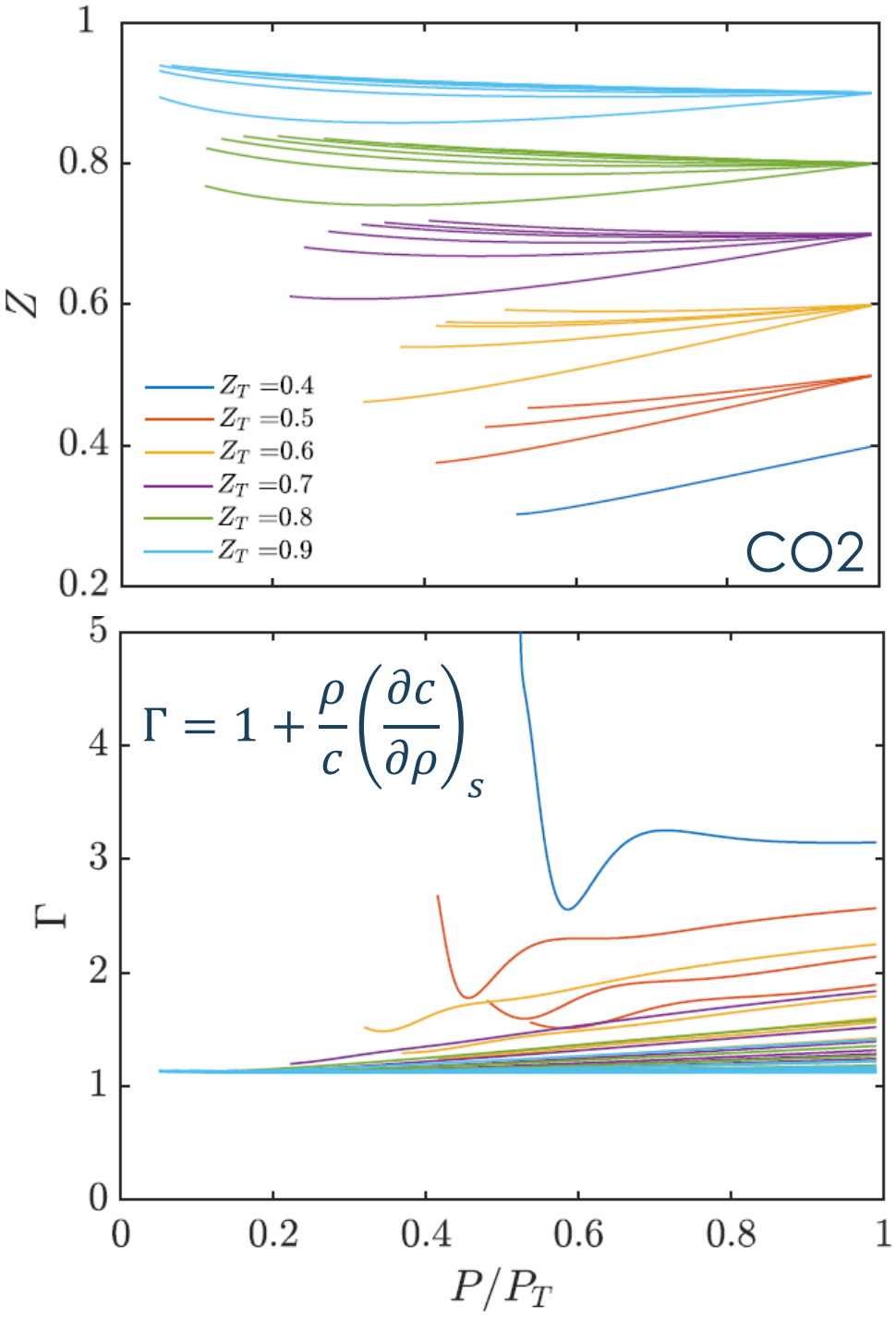
Results: P/P_T Similarity

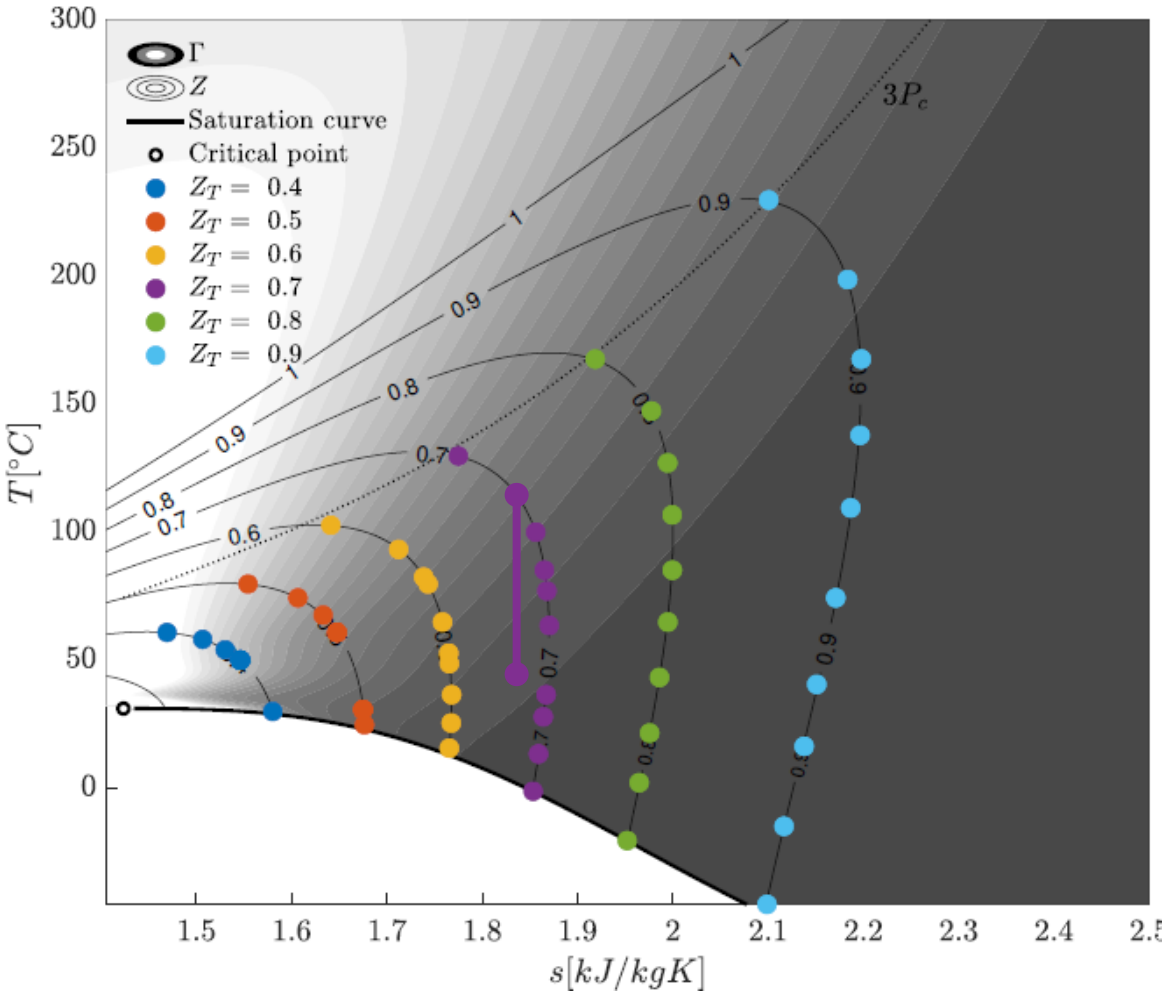
- MM (HMC) and CO2 (LMC)
- Confirmed $\frac{P}{P_T} = f(P_T, T_T)$
- Expansions grouped according to Z_T for HMC (except $Z_T = 0.4$)





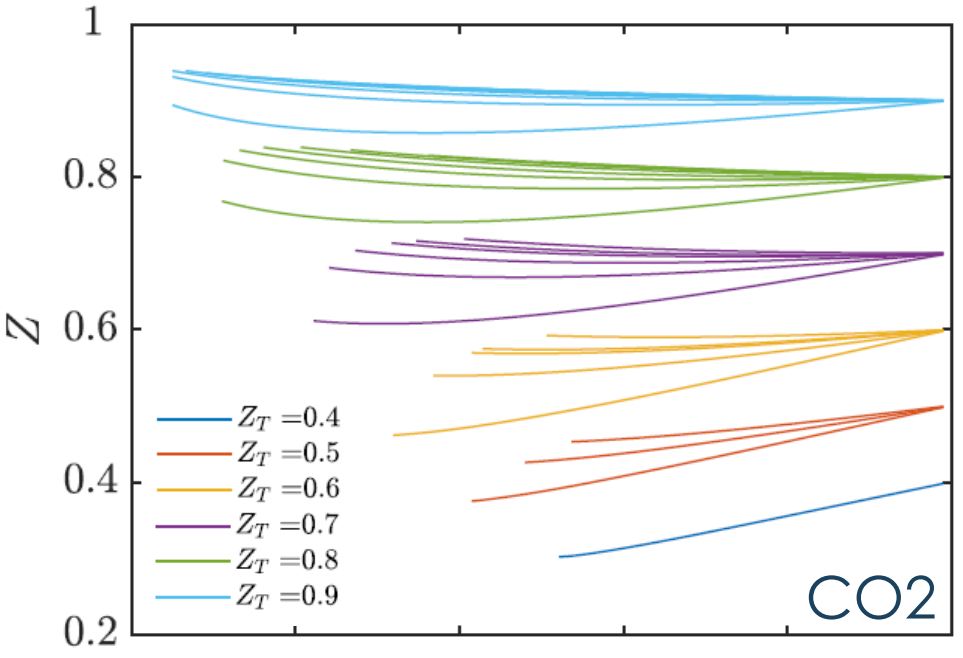
Results: Z and Γ along expansions (LMC – CO2)

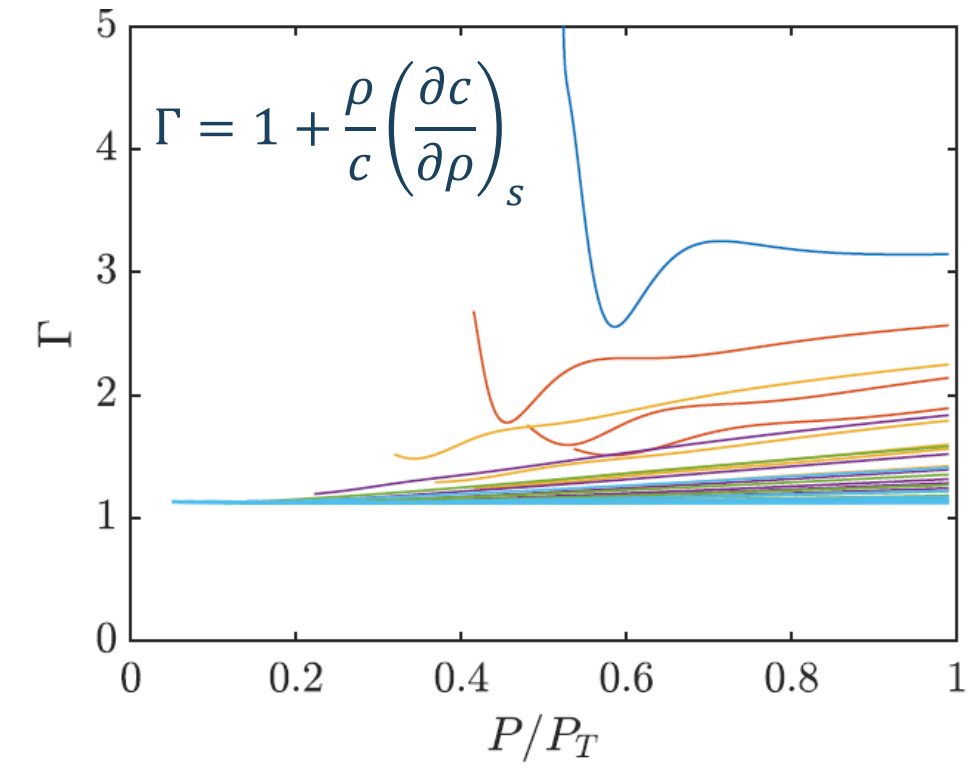


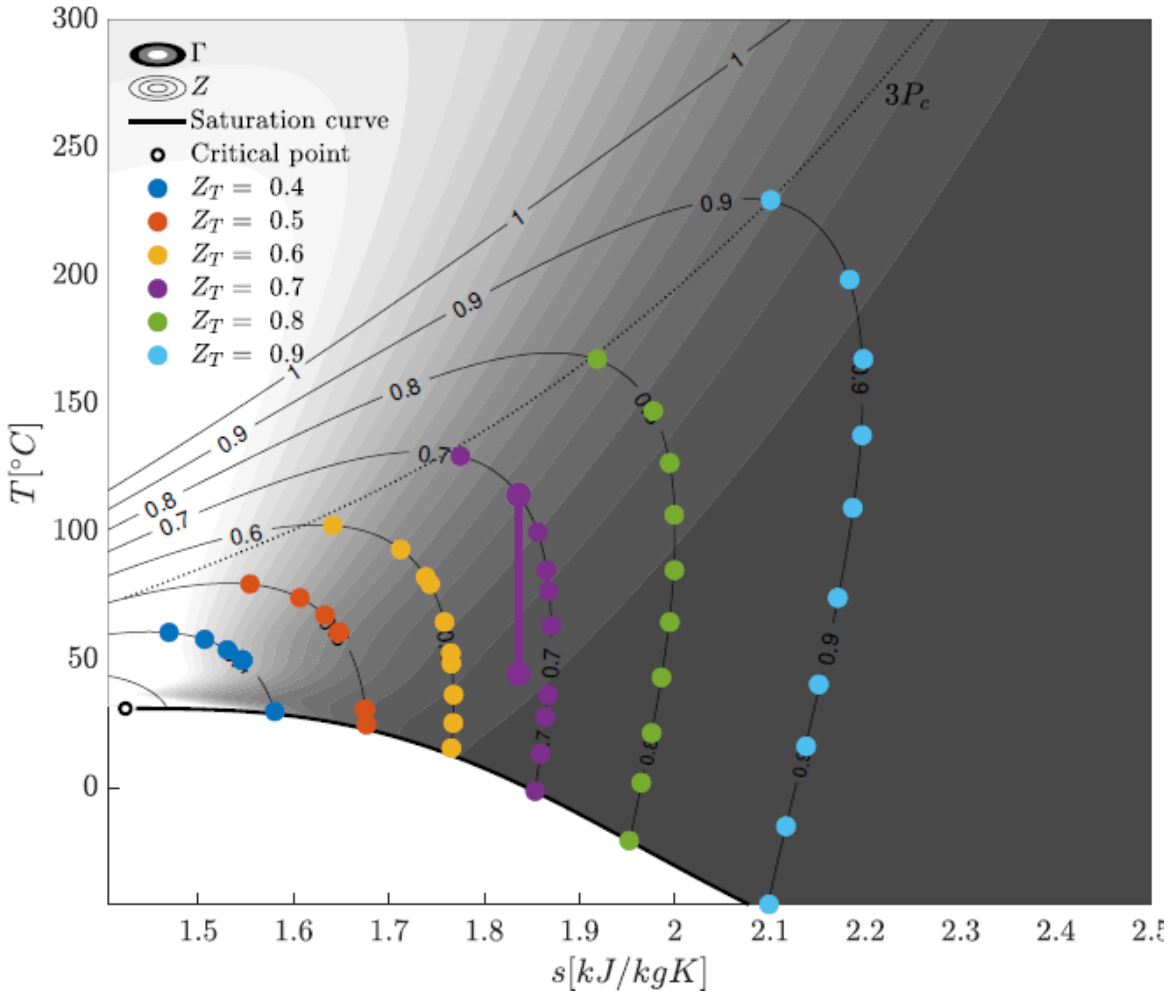


- Same Z_T → **NOT** similar expansions
  → similar Z, **NOT** similar Γ

Results: Z and Γ along expansions (LMC – CO2)







$iso - Z$ // and vertical on Branch A → same Z_T, similar $Z \approx const$

$iso - Z$ ***NOT*** // $iso - \Gamma$ → same Z_T, **NOT** similar Γ along expansions