NON-CONFORMAL OBSTRUCTIONS TO BUBBLE EXPANSION

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21/10/2026

In collaboration with: David Mateos and Mikel Sanchez-Garitaonandia

Arxiv: 2607.27874

UNIVERSITAT DE BARCELONA

ICCUB

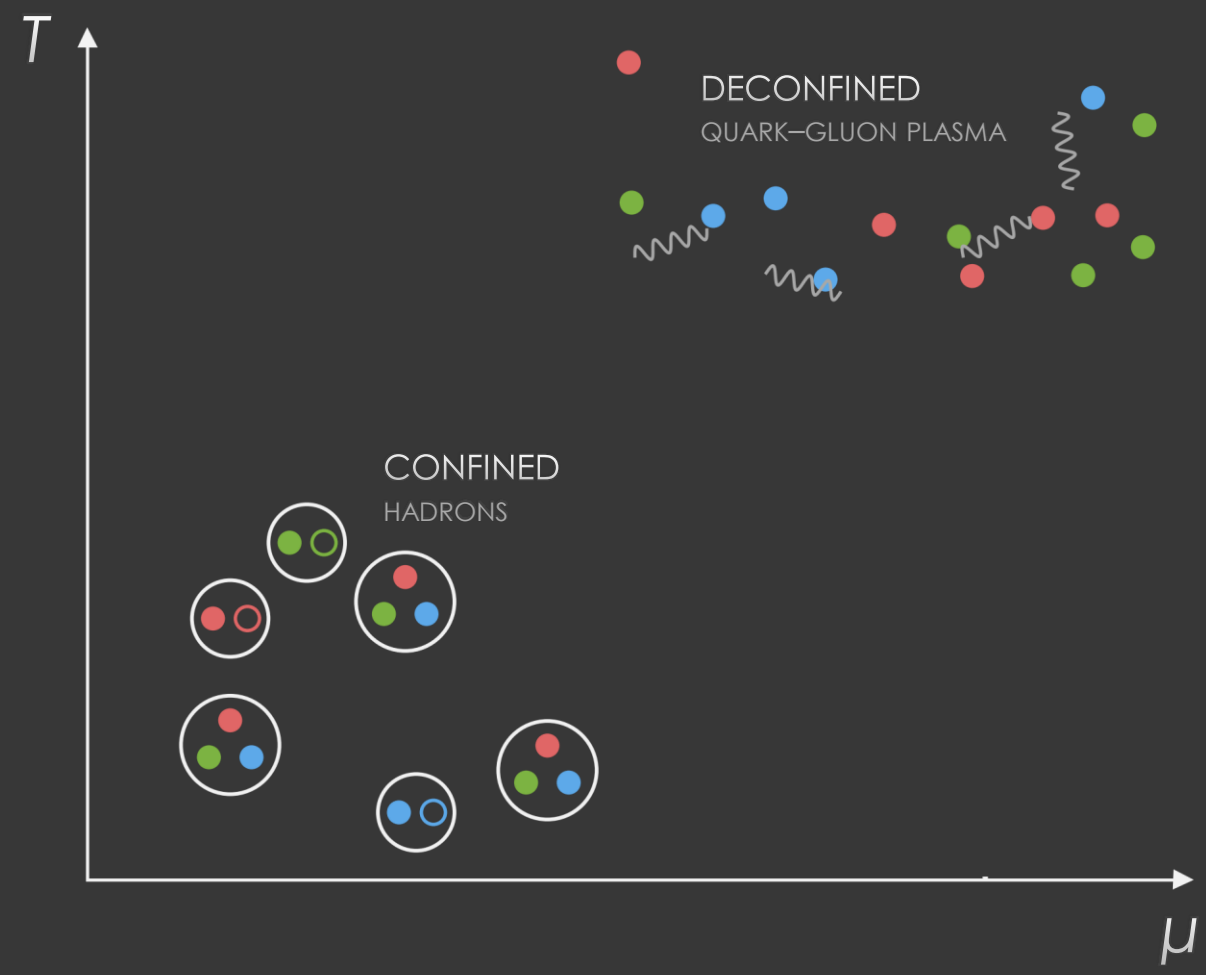
Institut de Ciències del Cosmos
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EXCELENCIA MARÍA DE MAEZTU 2020–2024

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

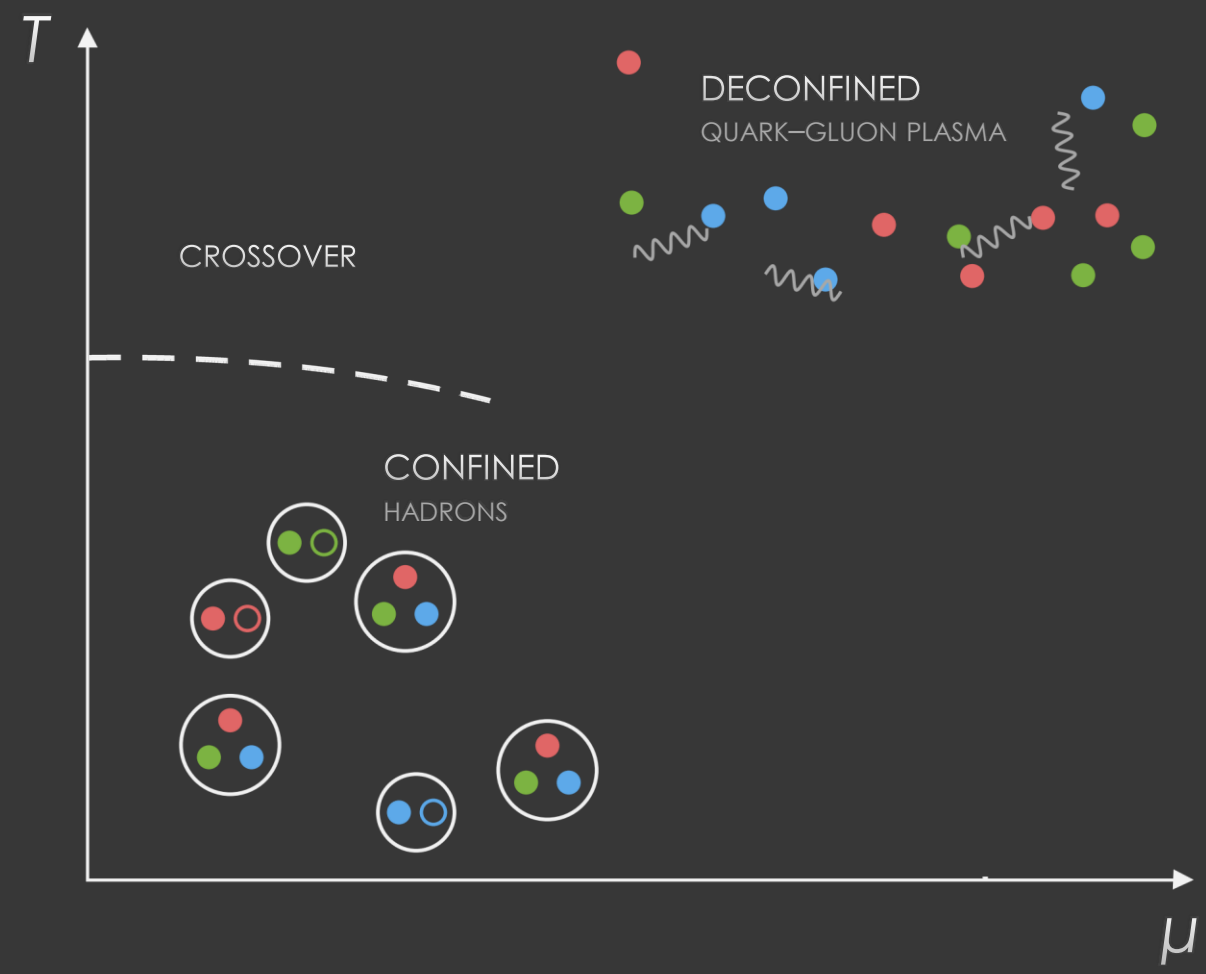
AGENCIA ESTATAL DE INVESTIGACIÓN

FIRST ORDER PHASE TRANSITIONS



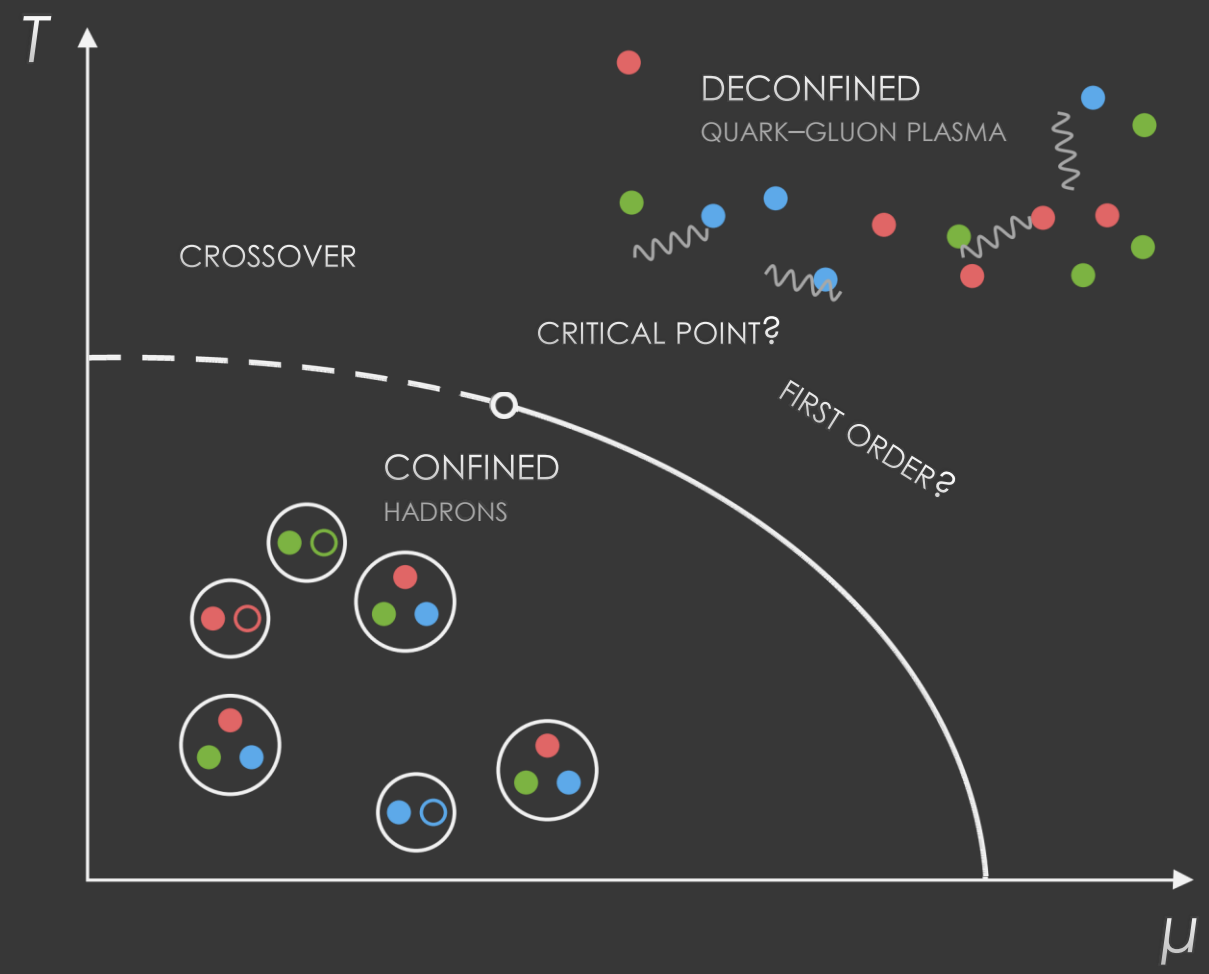
[Aoki et al., Nature 443 (2006) 675]
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FIRST ORDER PHASE TRANSITIONS



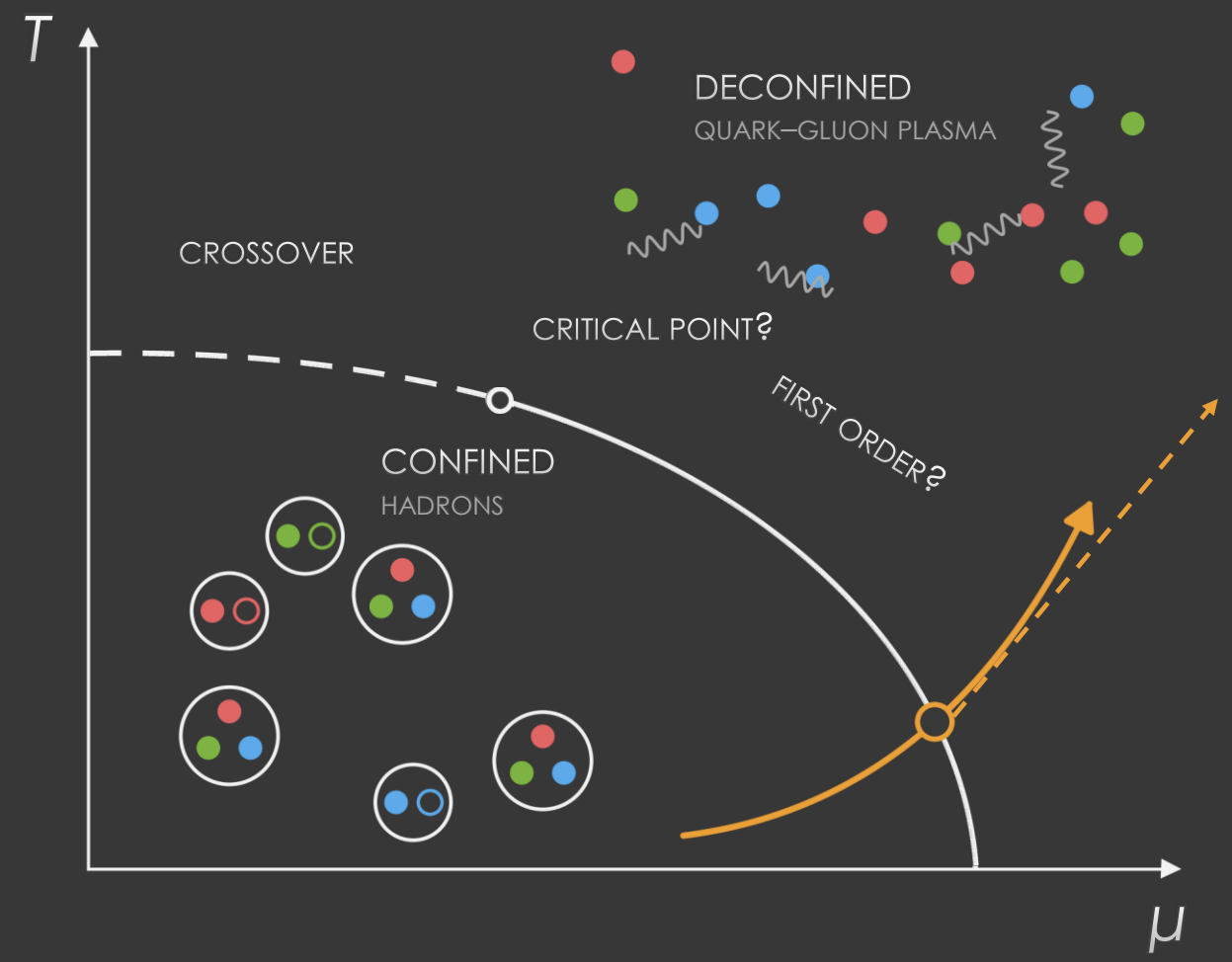
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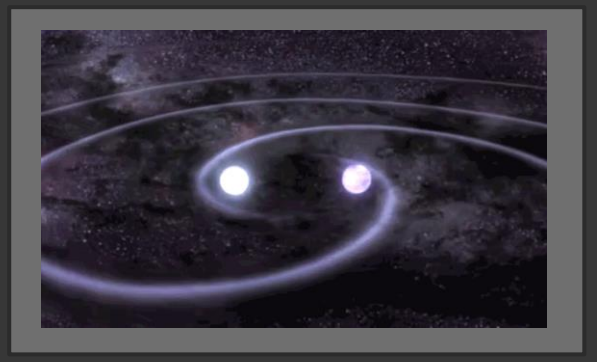
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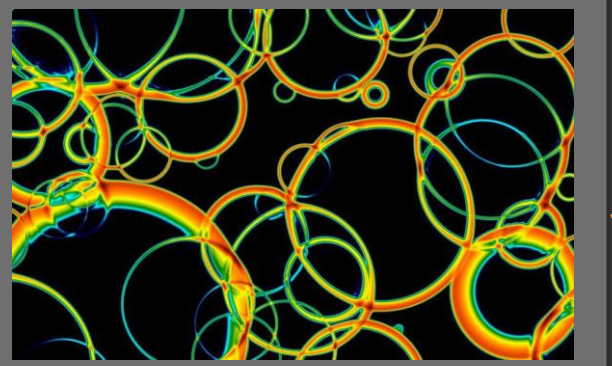
[NASA's Goddard Space Flight Center]

NEUTRON-STAR MERGERS

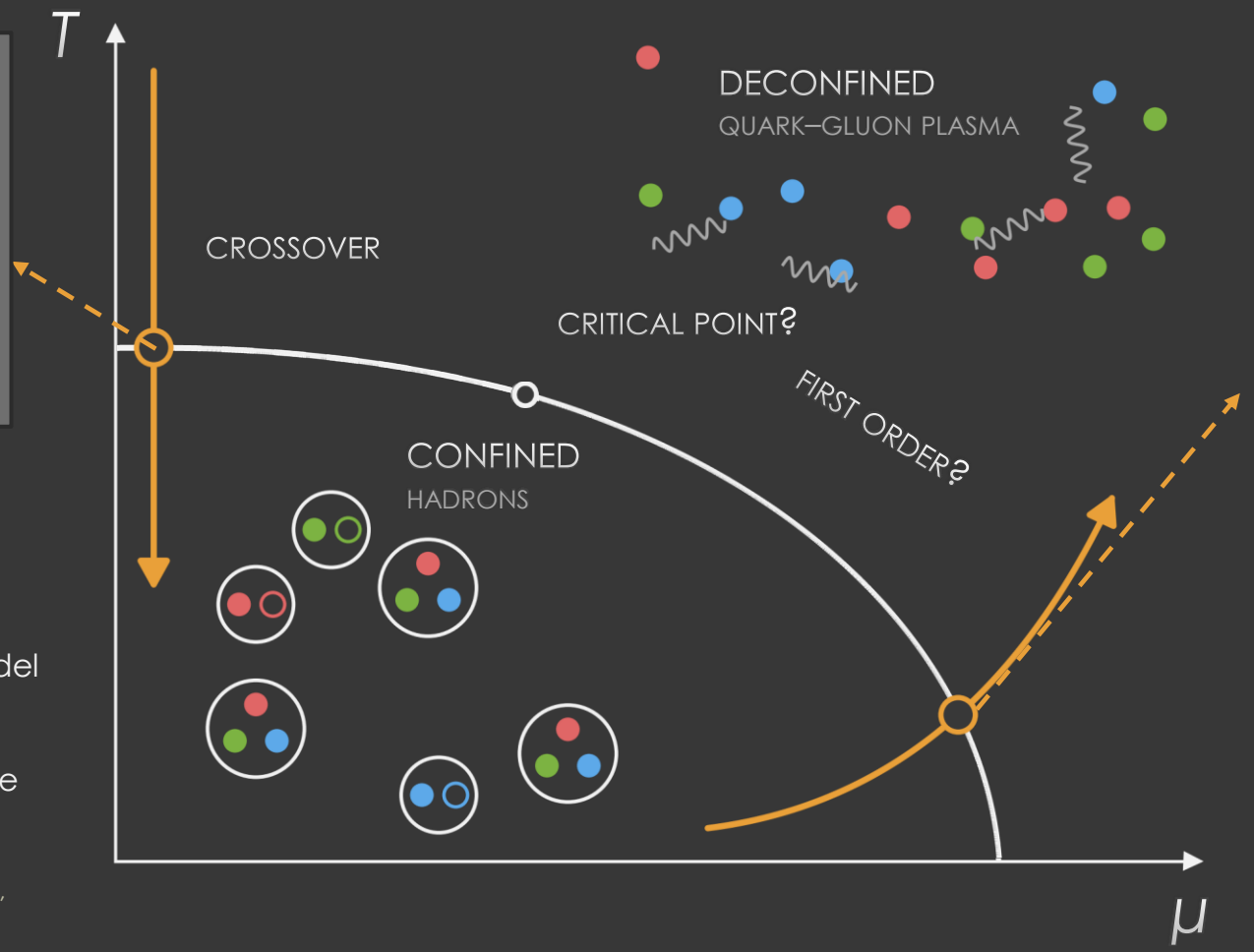
- Probe QCD at high density
- Constrain the QCD EoS at finite μ
  [Most et al., PRL 122 (2019) 061101; Bauswein et al., PRL 122 (2019) 061102; Blas et al., PRL 136 (2026) 101401; Bea et al., PRD 112 (2025) 114041, JHEP 04 (2026) 013]
- Core-collapse supernovae
  [Sagert et al., PRL 102 (2009) 081101; Fischer et al., Nat. Astron. 2 (2018) 980; Bleau et al., arXiv:2603.18153]

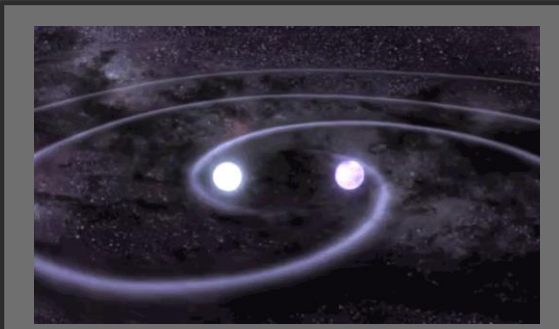
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[D. Weir, University of Helsinki]





[NASA's Goddard Space Flight Center]

EARLY UNIVERSE

- QCD is a crossover at $\mu \approx 0$: no first-order transition in the Standard Model
  [Kajantie et al., PRL 77 (1996) 2887]
- A first-order transition would be a signature of BSM physics, observable through its gravitational-wave background
  [Caprini et al., JCAP 03 (2020) 024; Athron et al., Prog. Part. Nucl. Phys. 135 (2024) 104094]

NEUTRON-STAR MERGERS

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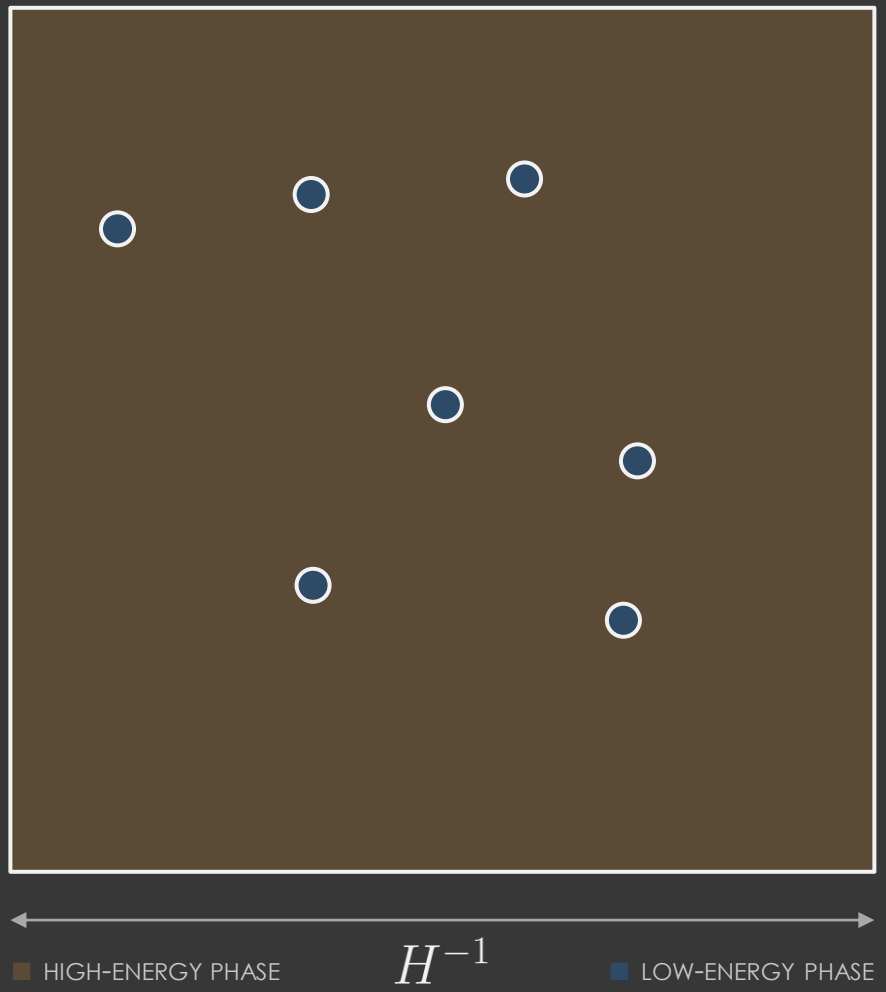
HUBBLE PATCH



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NUCLEATION



EQUATION OF STATE

T_n TEMPERATURE

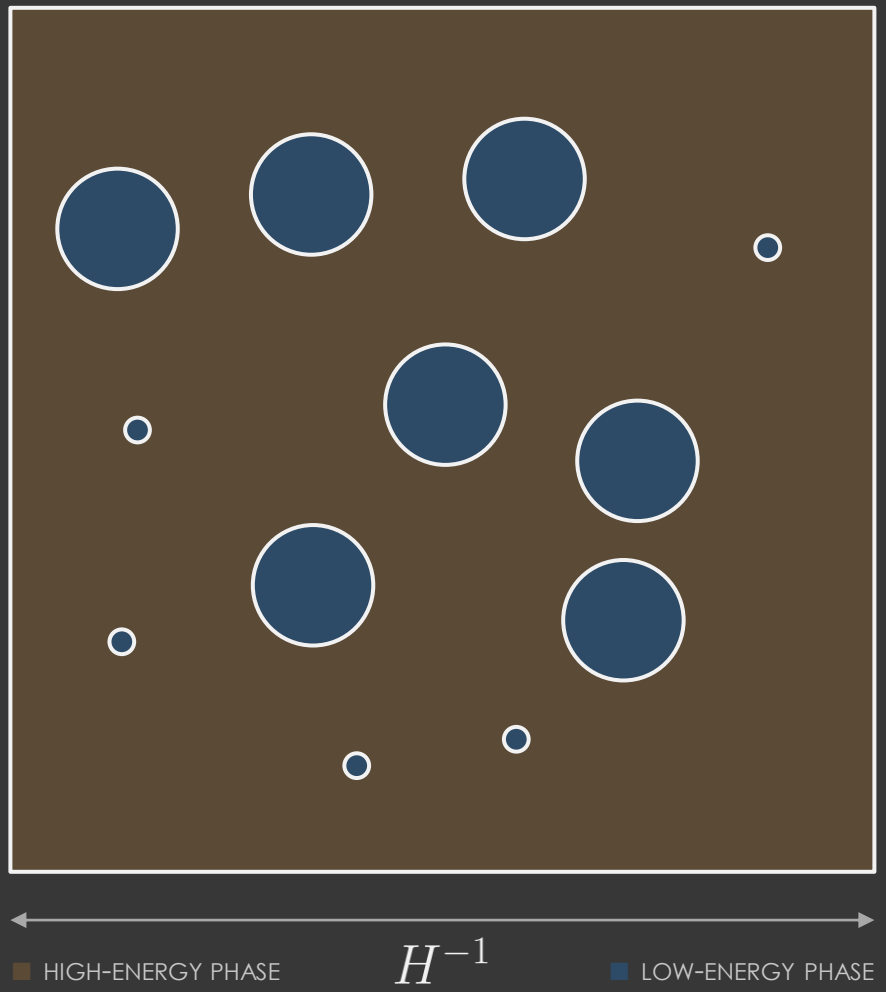
MICROSCOPIC

β/H TRANSITION RATE

FIRST ORDER PHASE TRANSITIONS

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EXPANSION



EQUATION OF STATE

- T_n TEMPERATURE
- α STRENGTH
- c_s SPEED OF SOUND

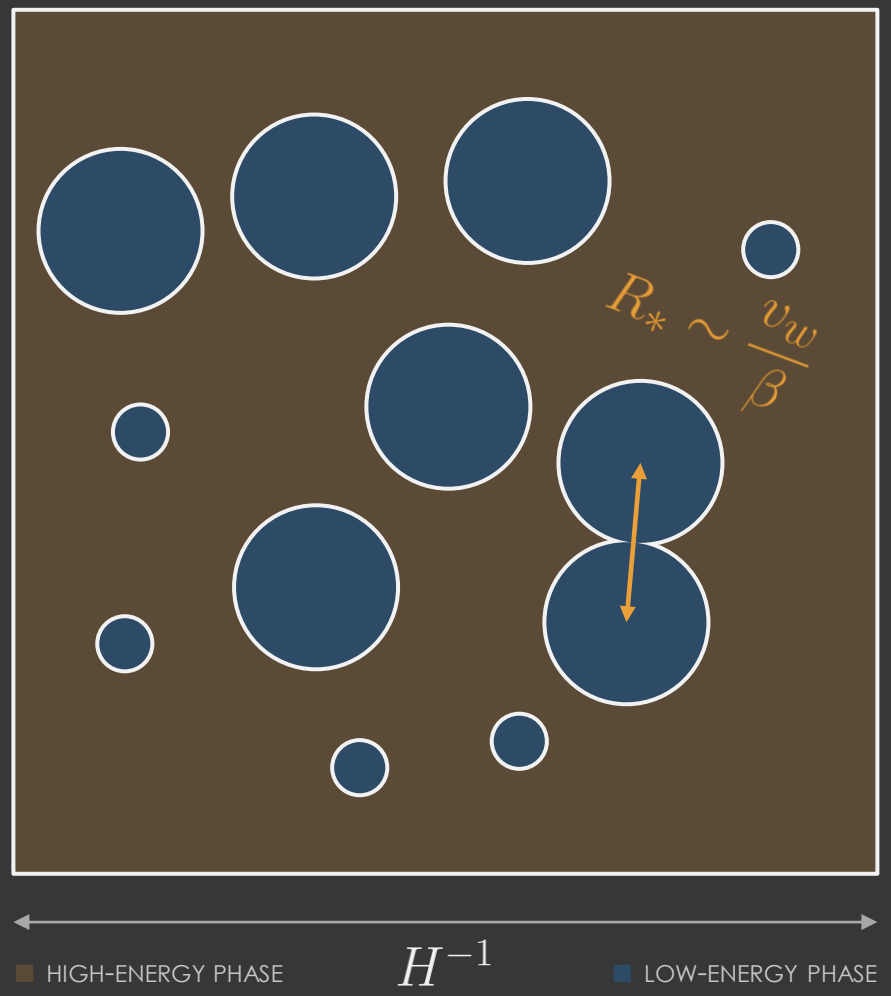
MICROSCOPIC

- β/H TRANSITION RATE
- v_w WALL SPEED

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COLLISION



EQUATION OF STATE

T_n	TEMPERATURE
α	STRENGTH
c_s	SPEED OF SOUND

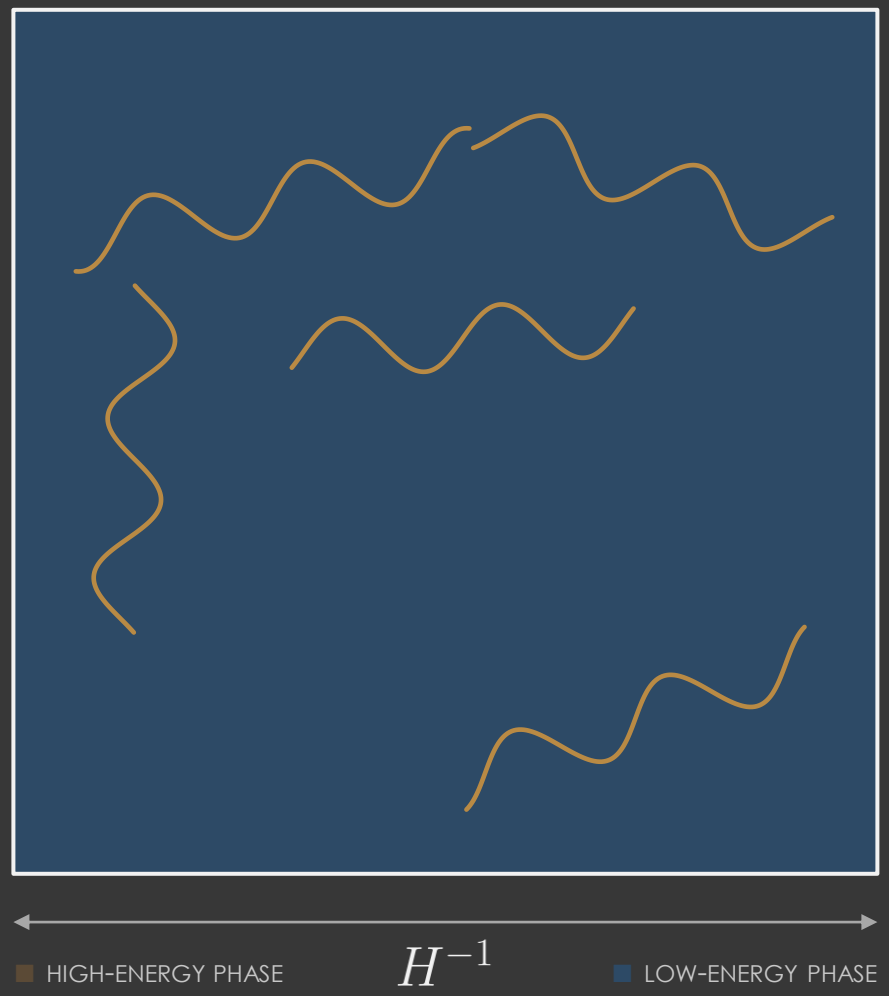
MICROSCOPIC

β/H	TRANSITION RATE
v_w	WALL SPEED

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GW EMISSION



EQUATION OF STATE

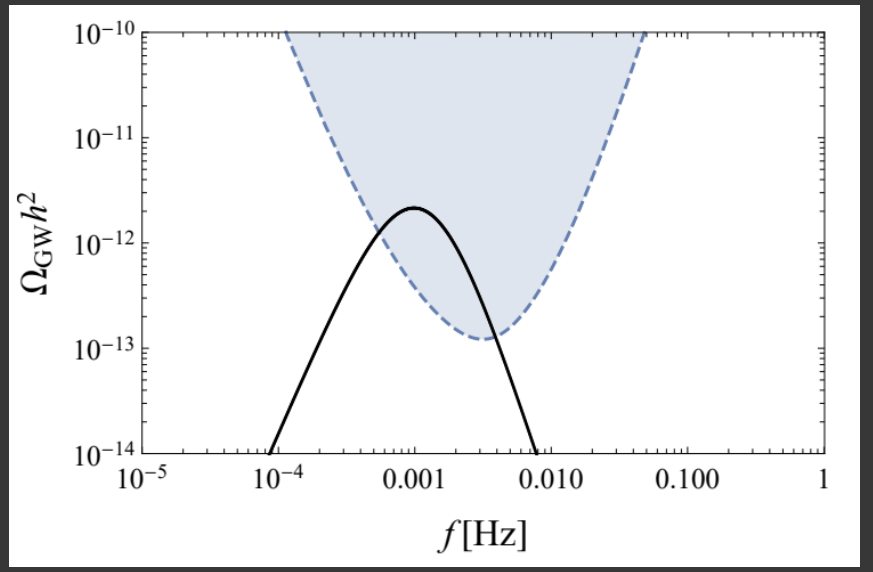
- T_n TEMPERATURE
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MICROSCOPIC

- β/H TRANSITION RATE
- v_w WALL SPEED

BUBBLE COLLISIONS

- K KINETIC ENERGY

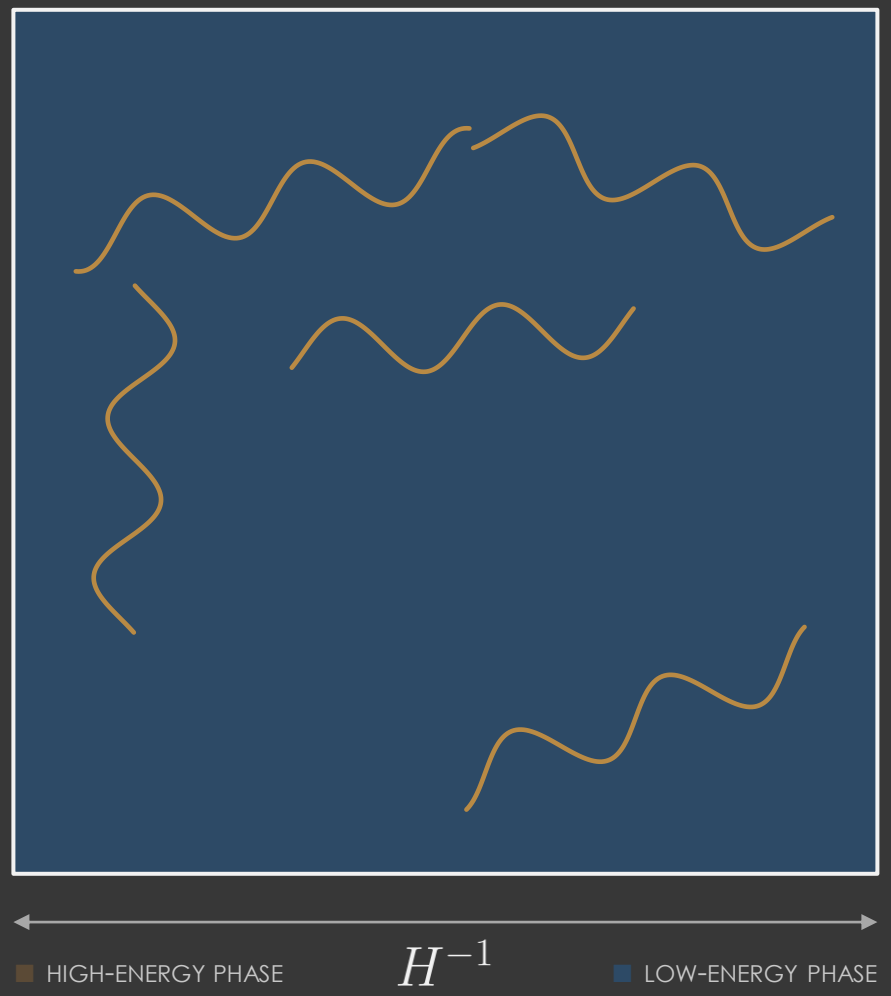


[Auclair et al., Living Rev. Rel. 26 (2023) 5]

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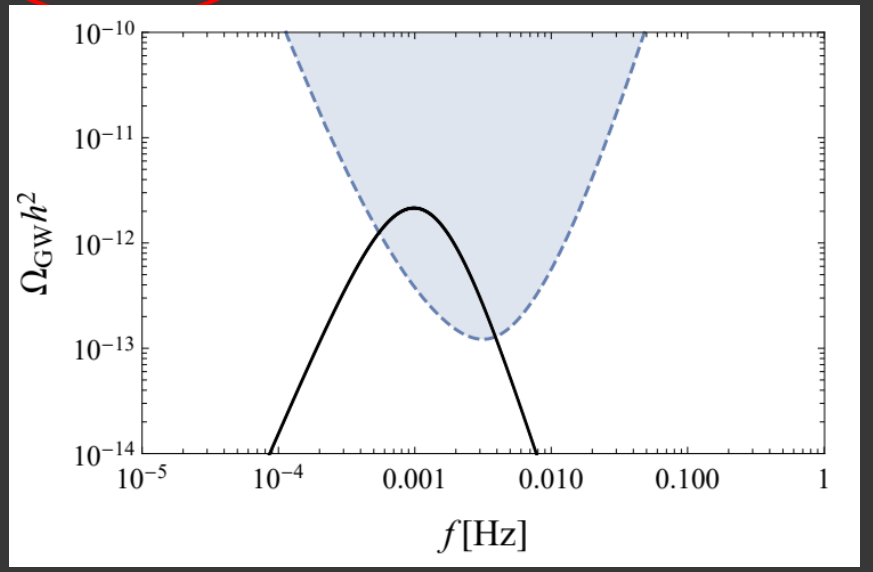
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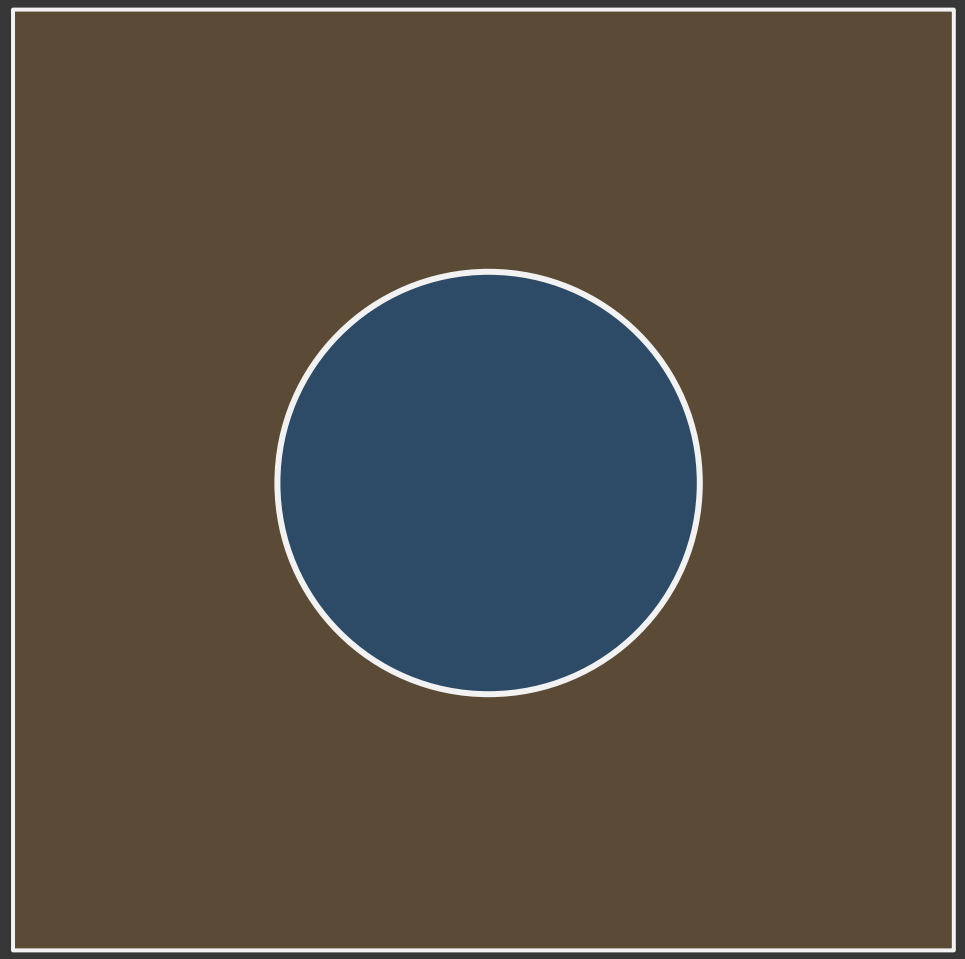


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OUTLOOK

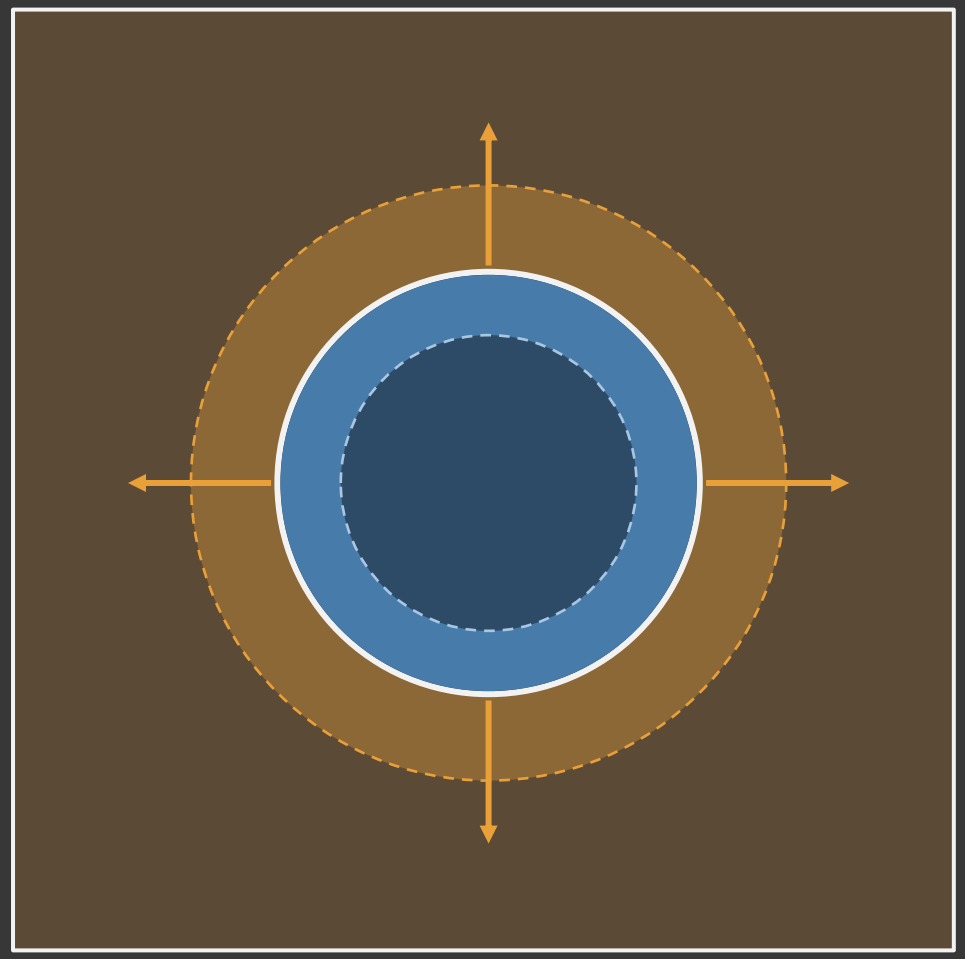
1. **Hydrodynamics of expanding bubbles**
   bubbles in a conformal EoS
2. **Non-conformal equations of state**
   from bag model to QCD-like
3. **Non-conformal obstructions**
   at the wall and along the flow
4. **Conclusions**

EXPANSION OF A SINGLE BUBBLE



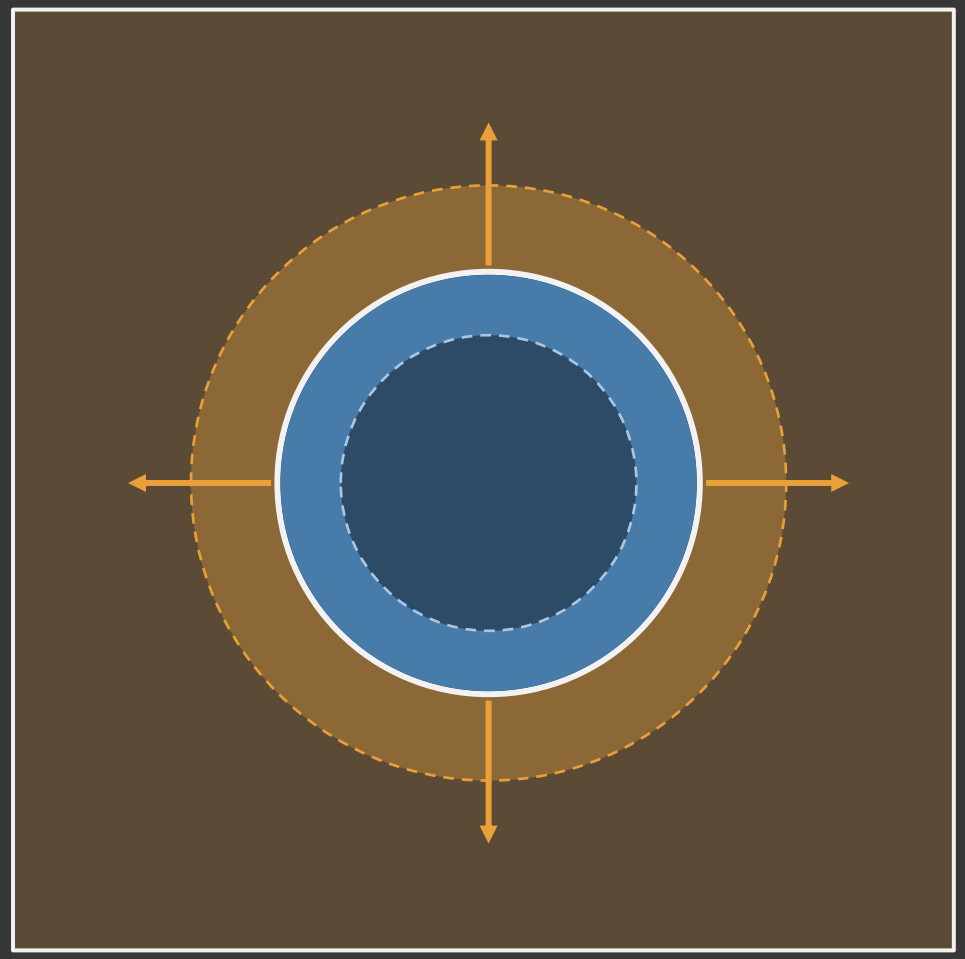
EXPANSION OF A SINGLE BUBBLE

- Determines the allowed expansion modes: already constrains the wall velocity and kin. energy fraction.



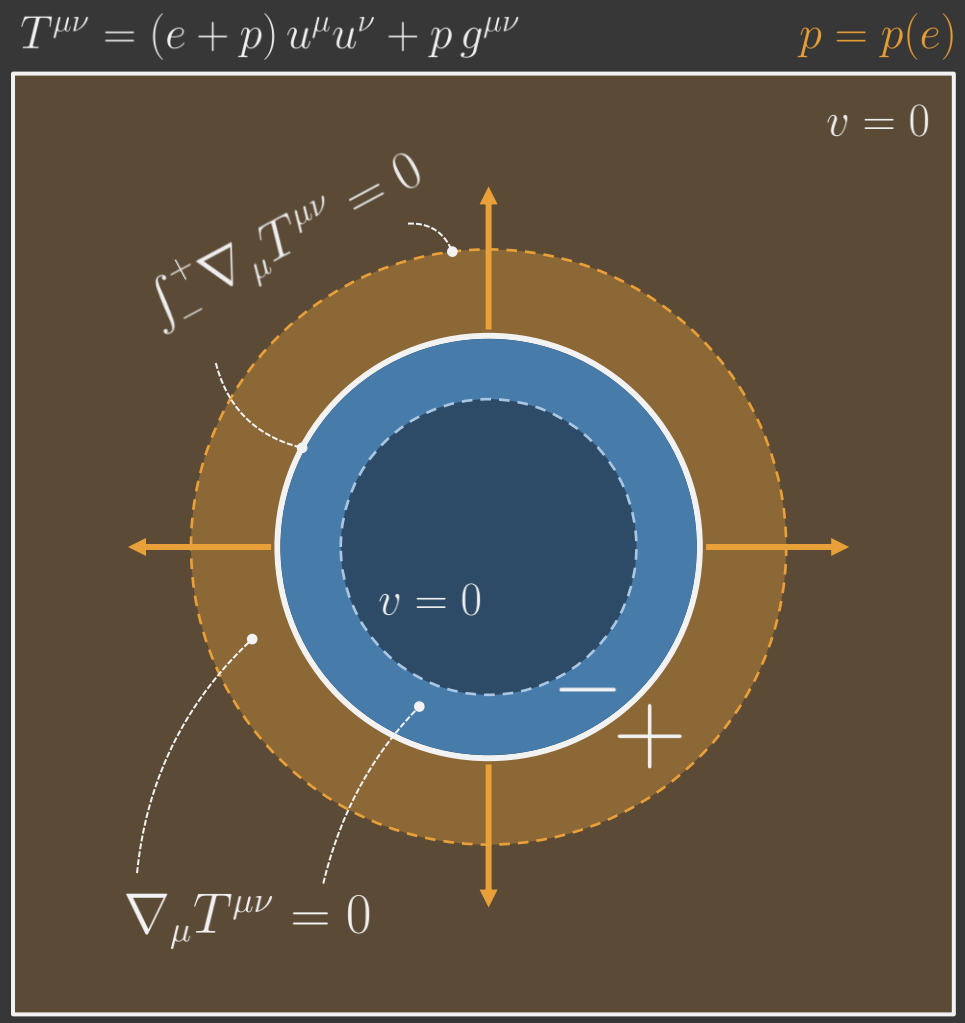
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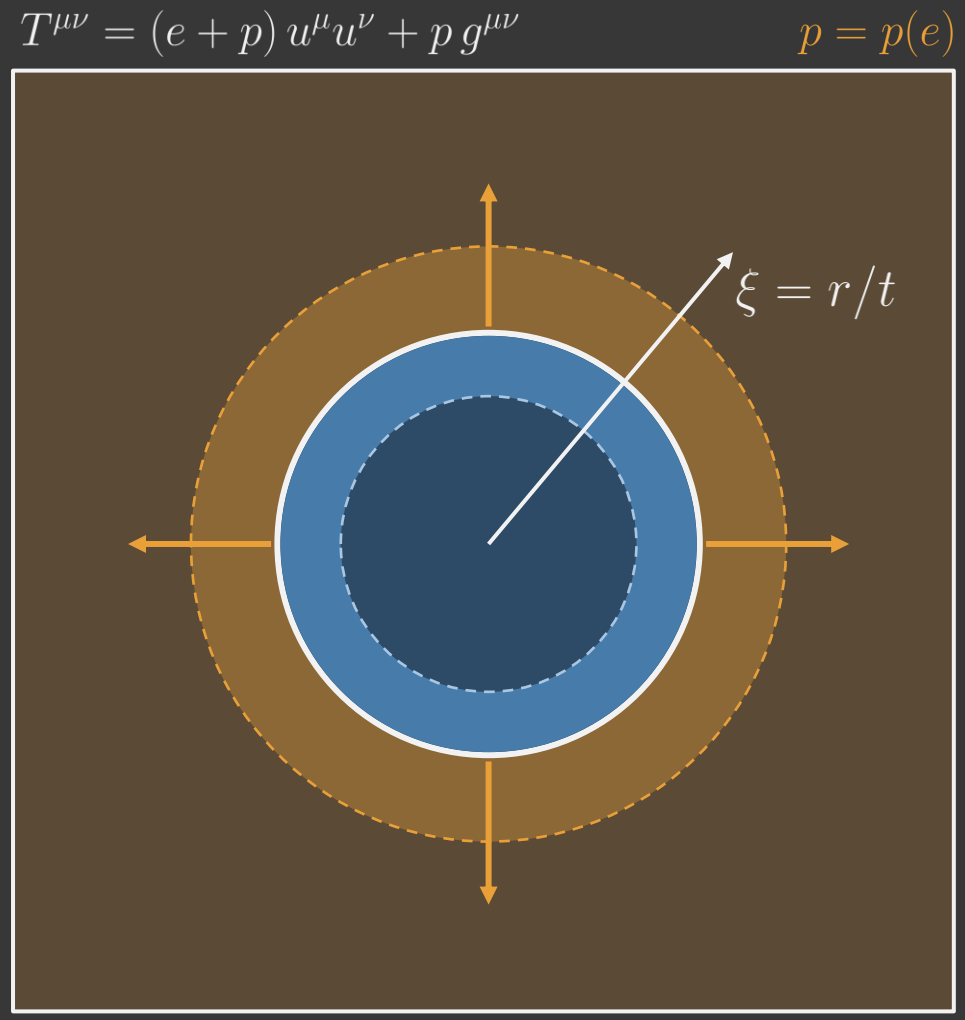
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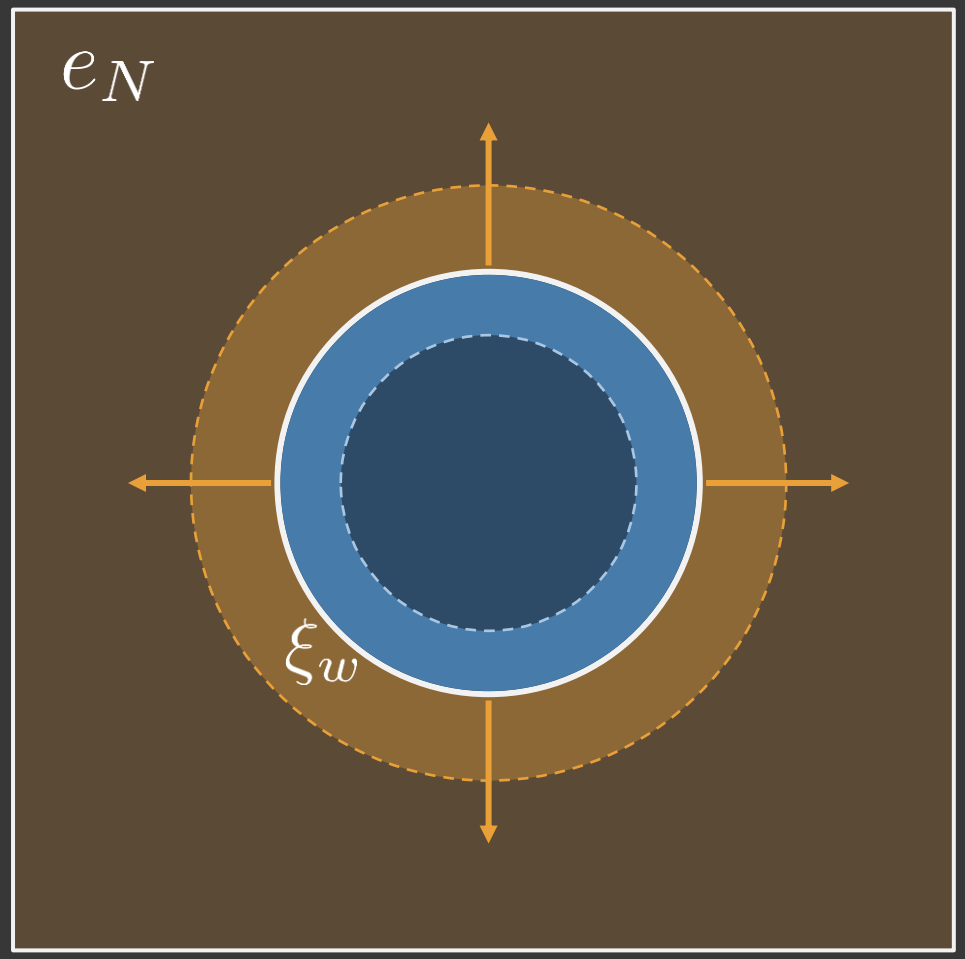
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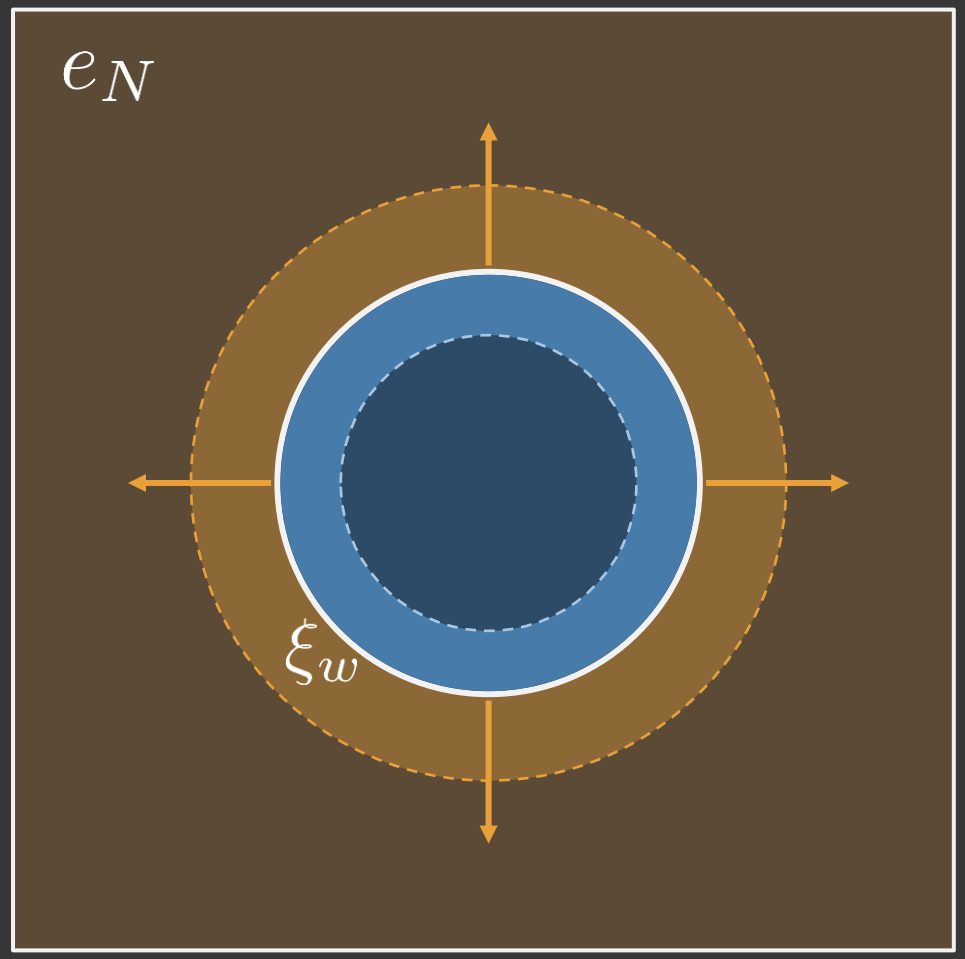
$T^{\mu\nu} = (e+p)\,u^\mu u^\nu + p\,g^{\mu\nu}$ $\quad p = p(e)$



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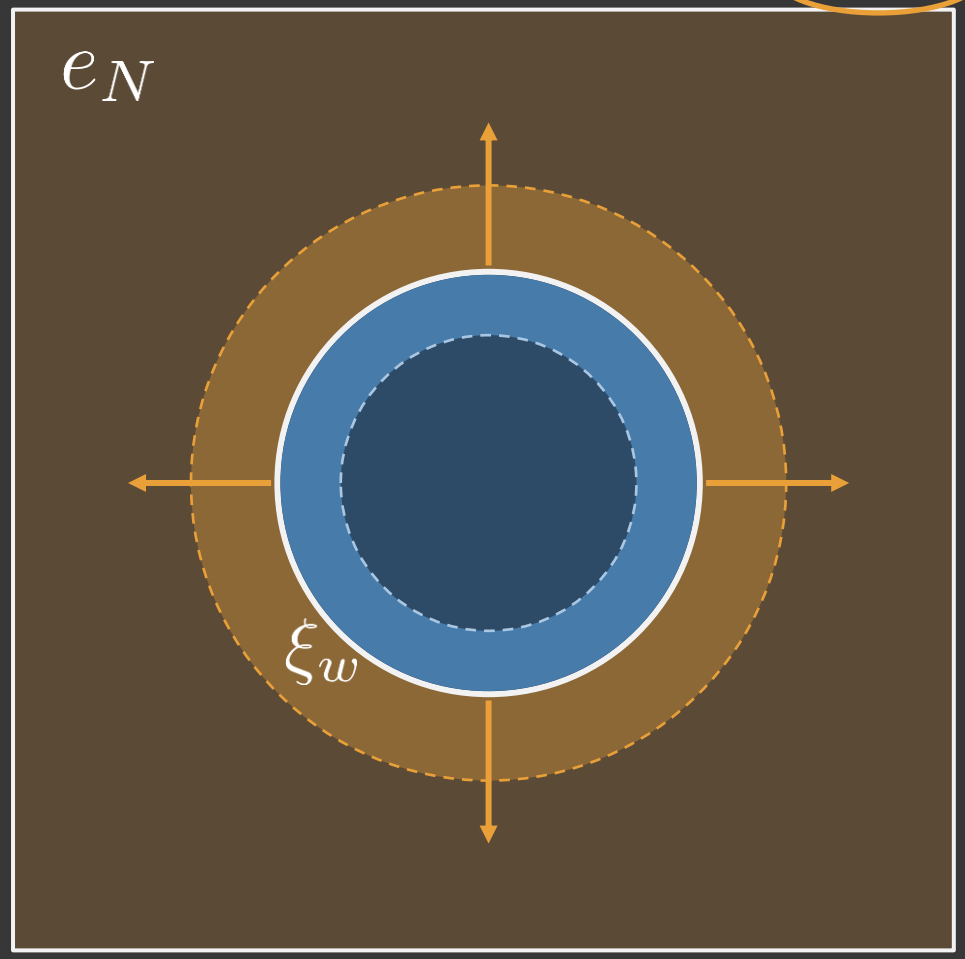
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- Key input: the EoS, which encodes the microphysics

$T^{\mu\nu} = (e+p)\,u^\mu u^\nu + p\,g^{\mu\nu}$ $\quad p = p(e)$



THE BAG-MODEL

$$p = p(e)$$

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- Simple model of FOPT with radiation-type eos

$$p_H(T) = \tfrac{1}{3} a_H T^4 - \epsilon \qquad p_L(T) = \tfrac{1}{3} a_L T^4$$

$$p_H(e) = \tfrac{1}{3} e - \tfrac{4}{3} \epsilon \qquad p_L(e) = \tfrac{1}{3} e$$

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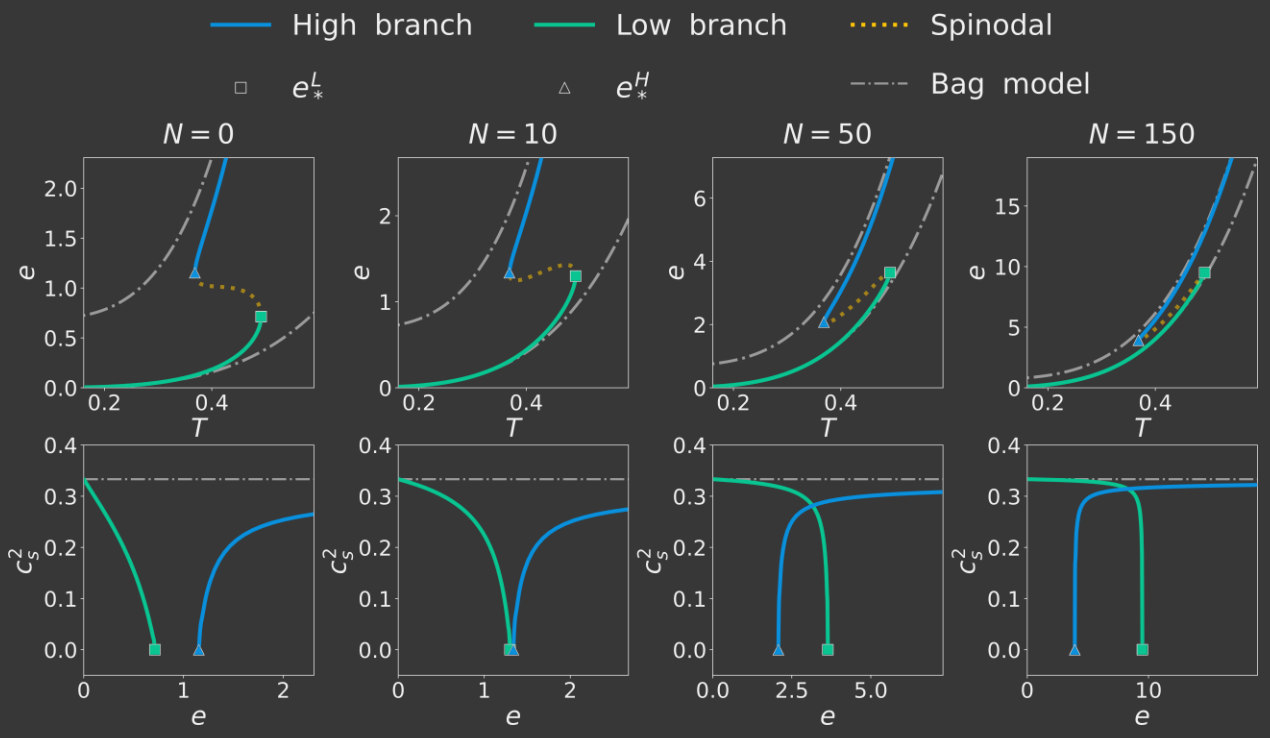
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- FOPT coupled to a N>>1 (effectively) massless particle at the critical temperature

$$p(T) = \mathcal{P}(T) + \tfrac{1}{3} N T^4$$



[Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874 (2026)]

EXPANSION MODES IN THE BAG MODEL

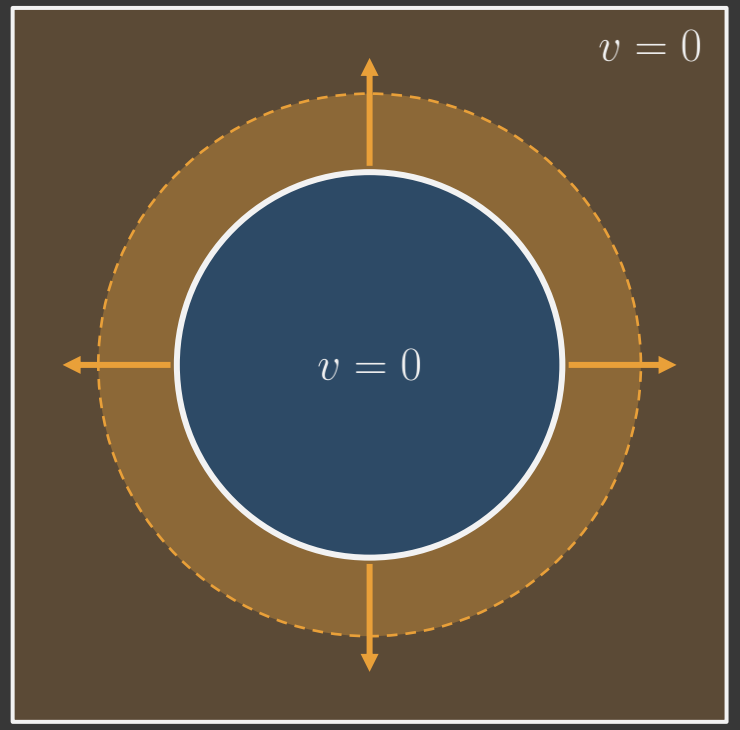
[Espinosa et al., JCAP 06 (2010) 028]

EXPANSION MODES IN THE BAG MODEL

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Deflagration

$$\xi_w < c_s$$

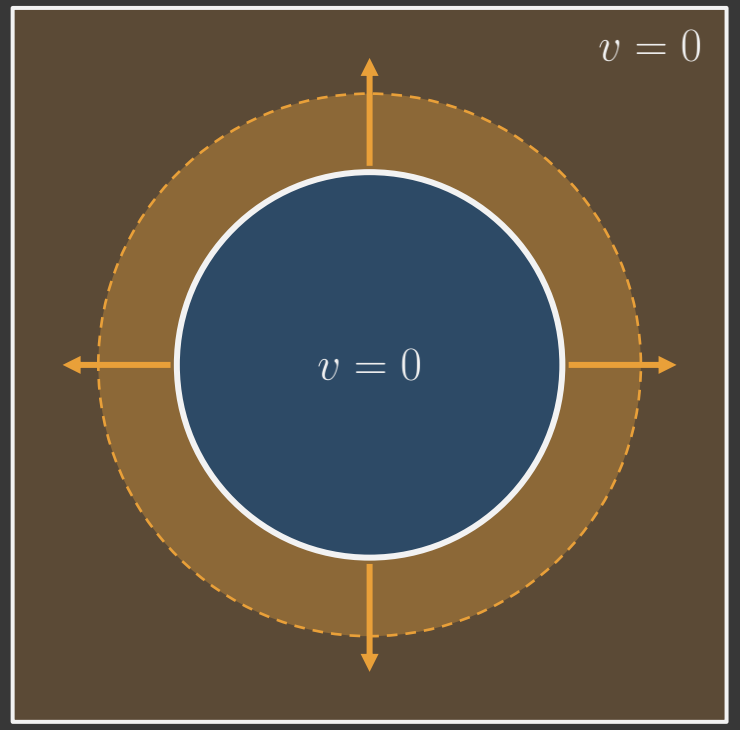


EXPANSION MODES IN THE BAG MODEL

[Espinosa et al., JCAP 06 (2010) 028]

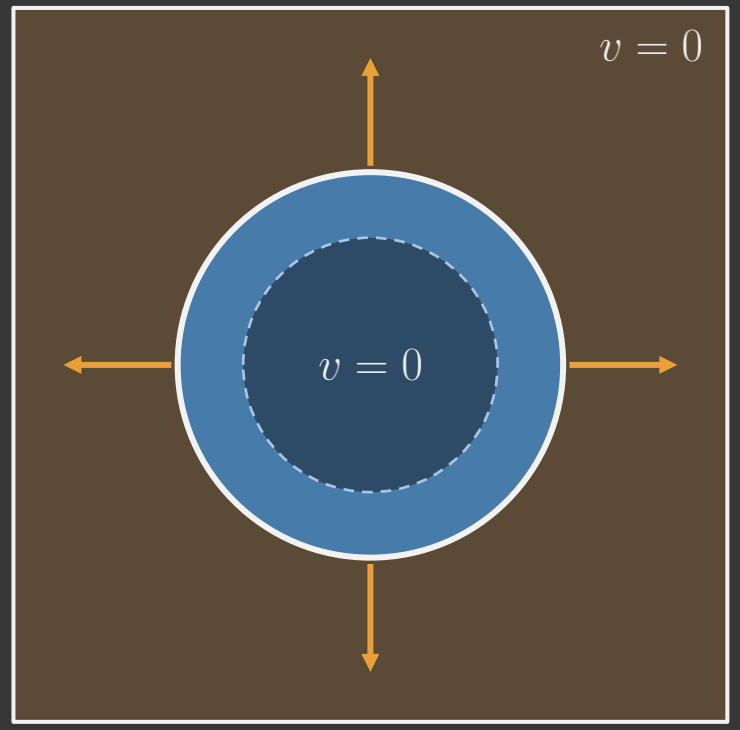
Deflagration

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Detonation

$\xi_w > \xi_J$

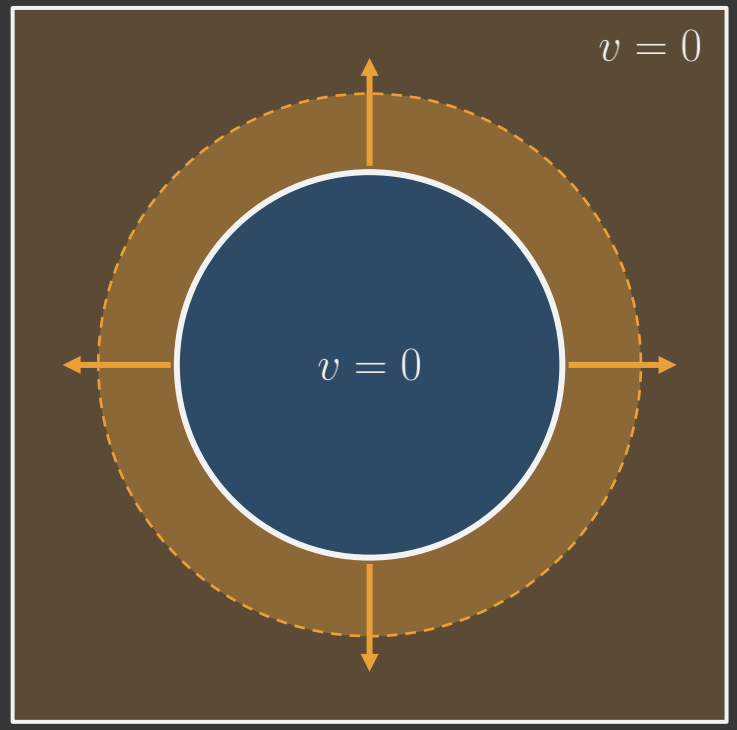


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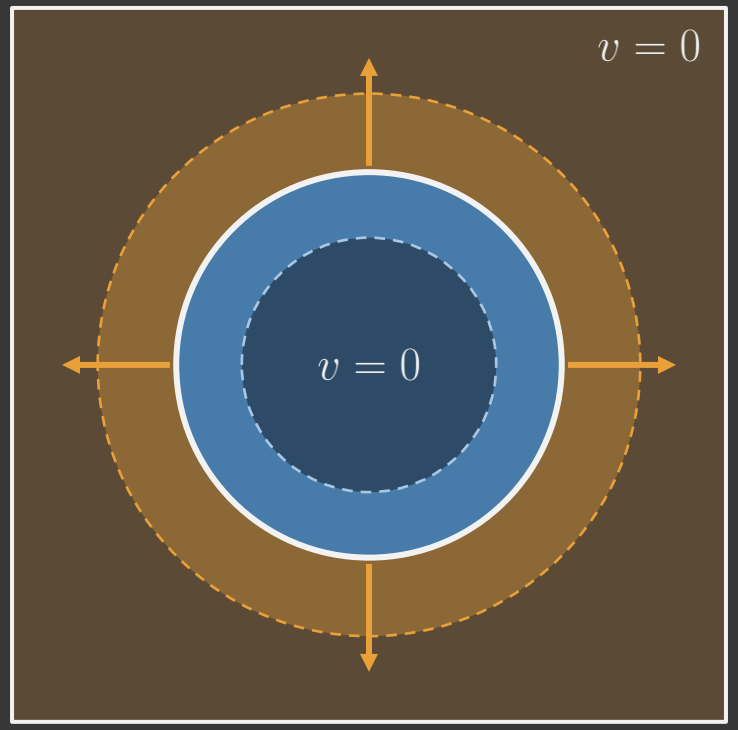
Deflagration

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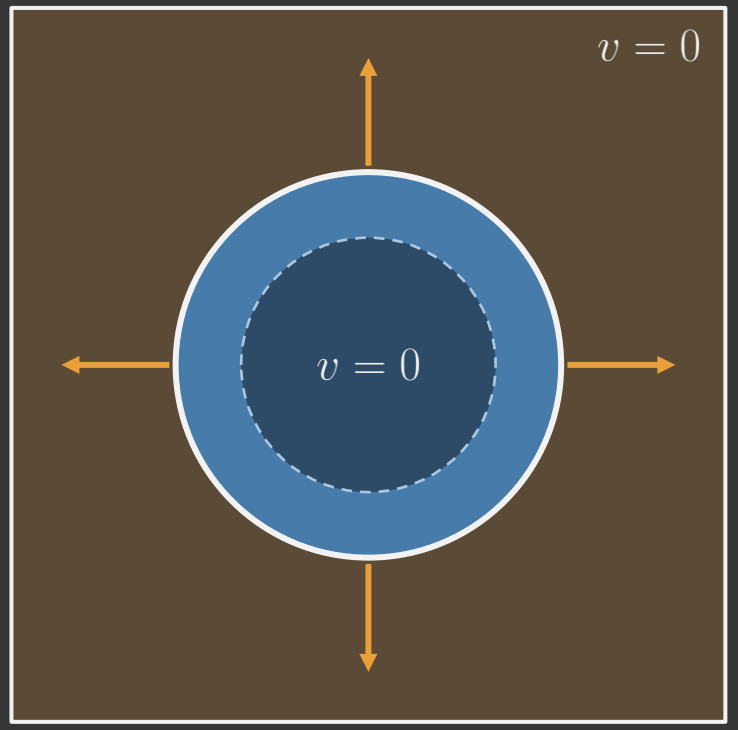
Hybrid

$c_s < \xi_w < \xi_J$



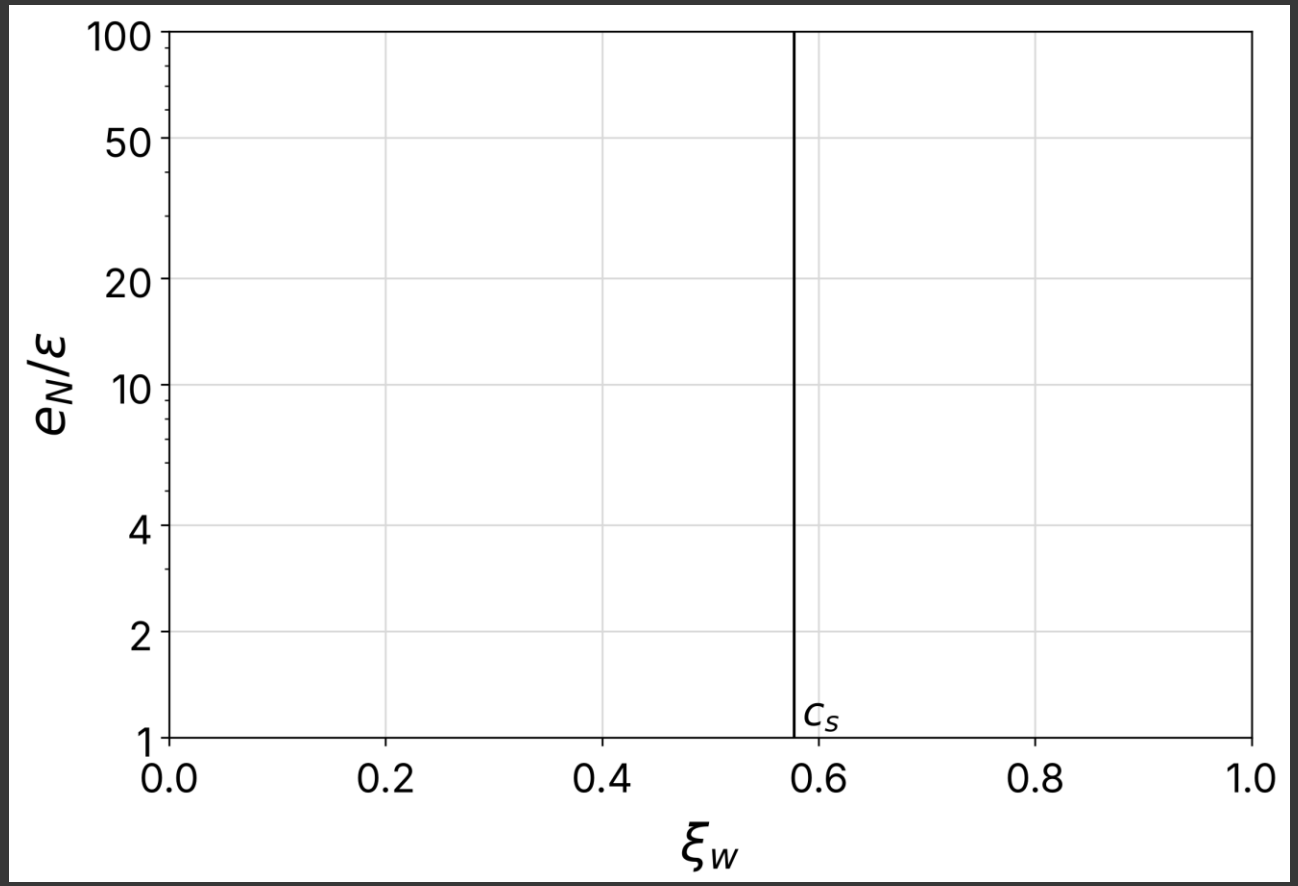
Detonation

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SPACE OF ALLOWED SOLUTIONS

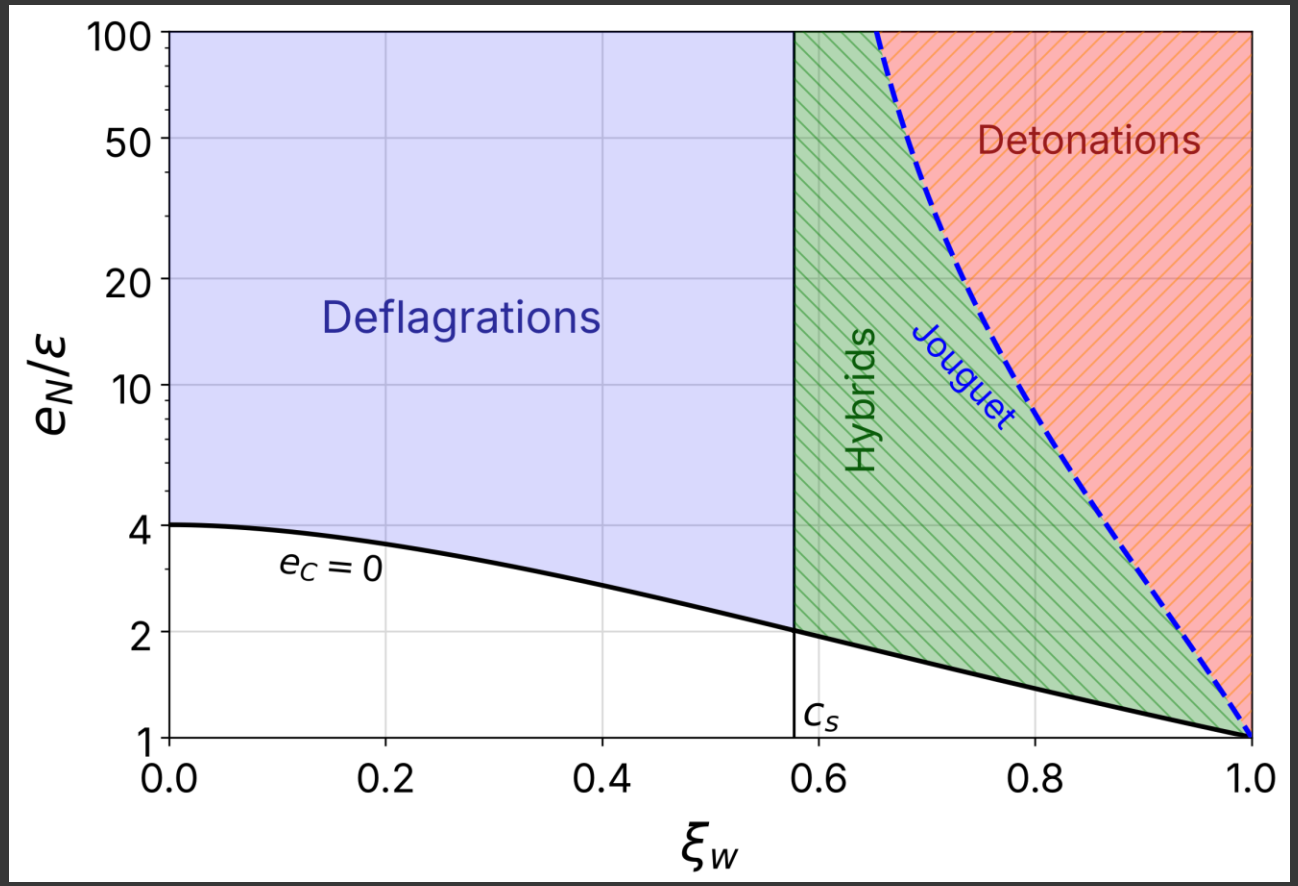
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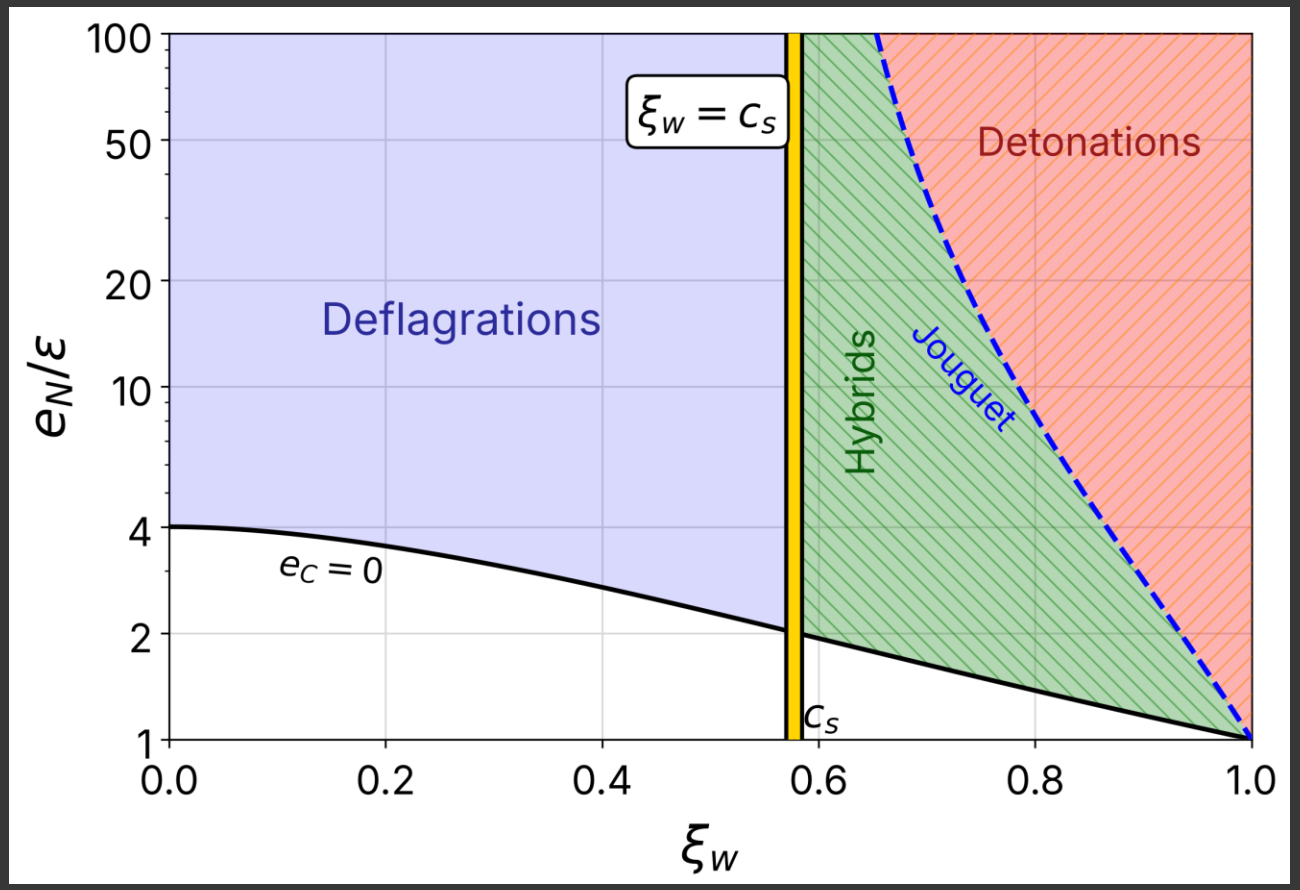
- Solutions are continuously connected: there are solutions for every ξ_w



SPACE OF ALLOWED SOLUTIONS

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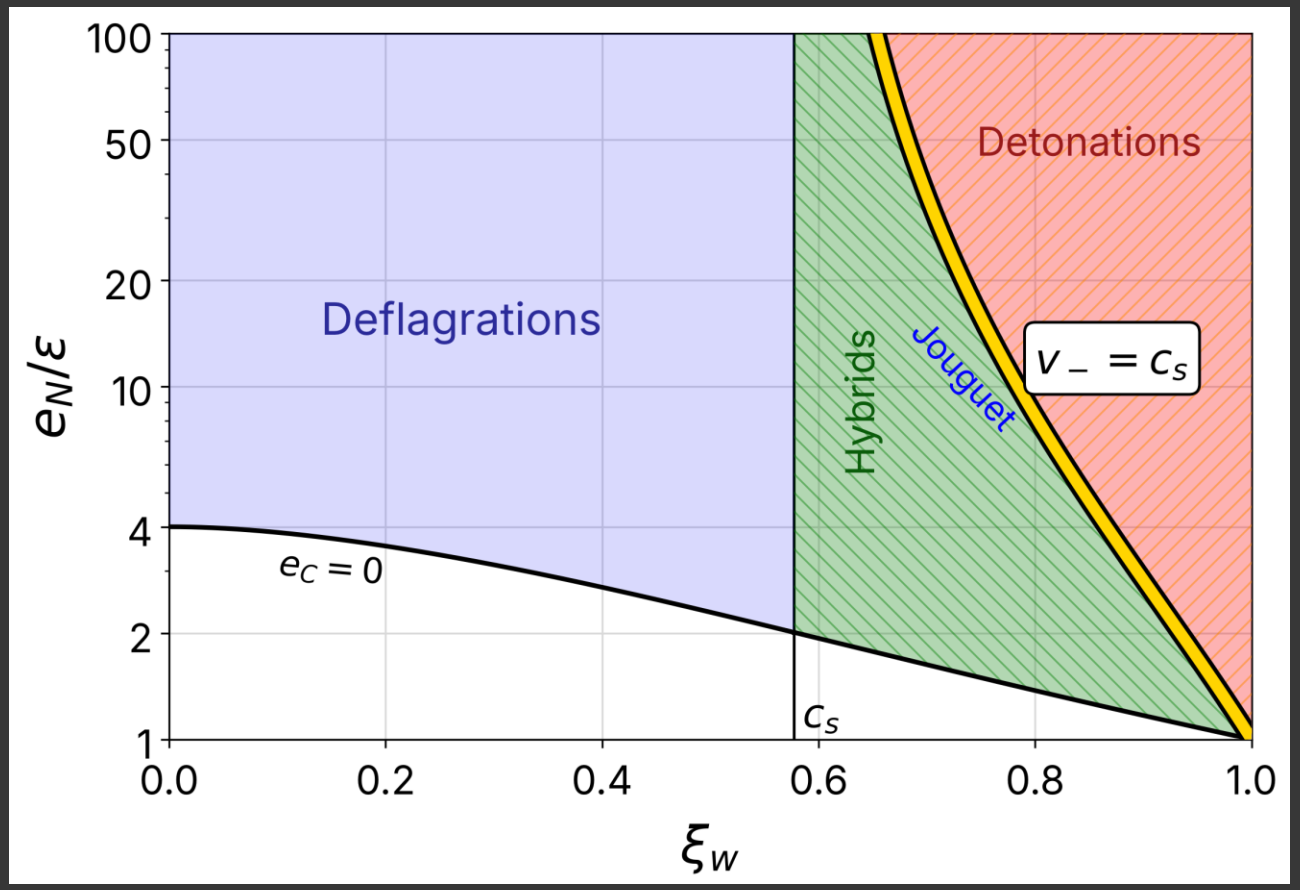
- Solutions are continuously connected: there are solutions for every ξ_w
- Deflagrations and hybrids are separated by $\xi_w = c_s$



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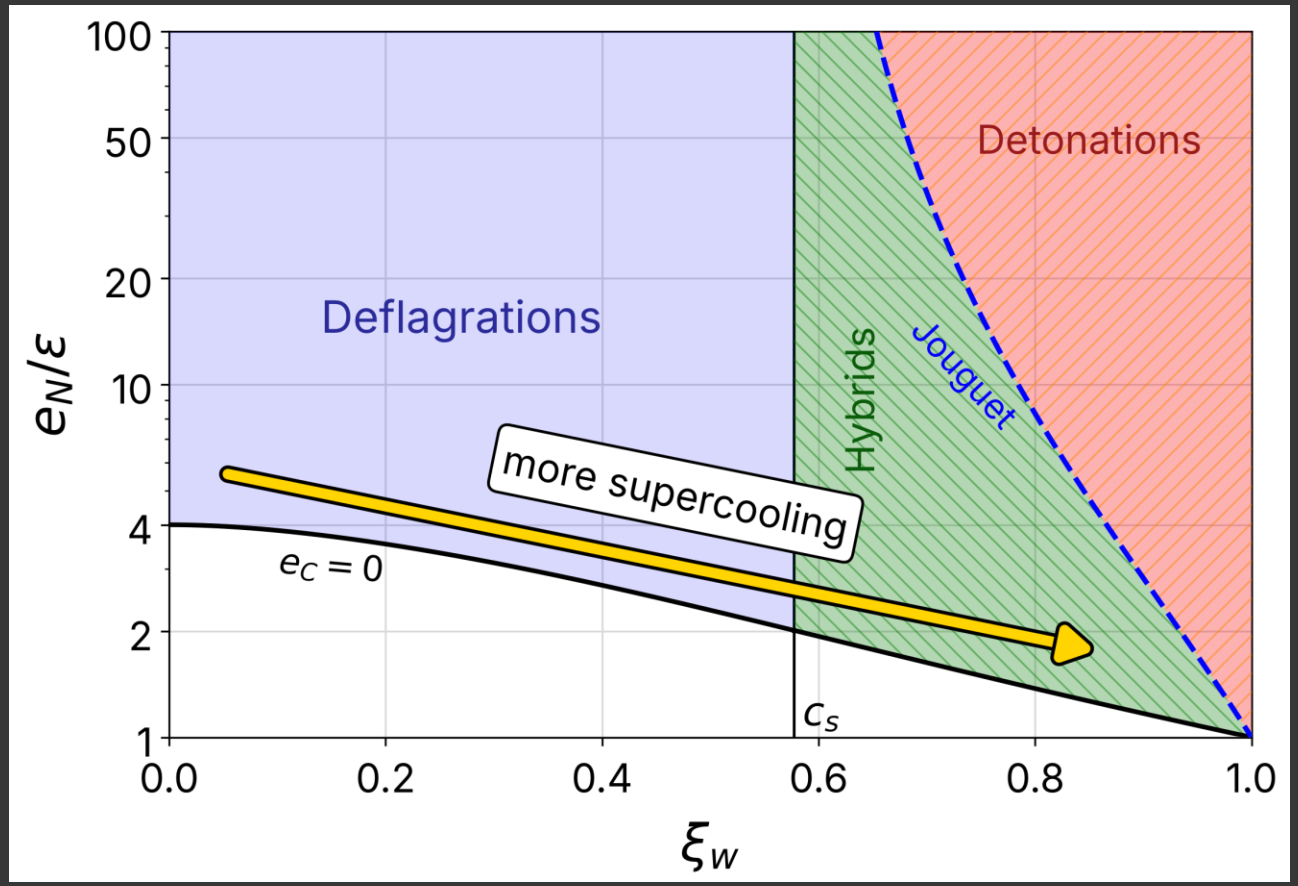
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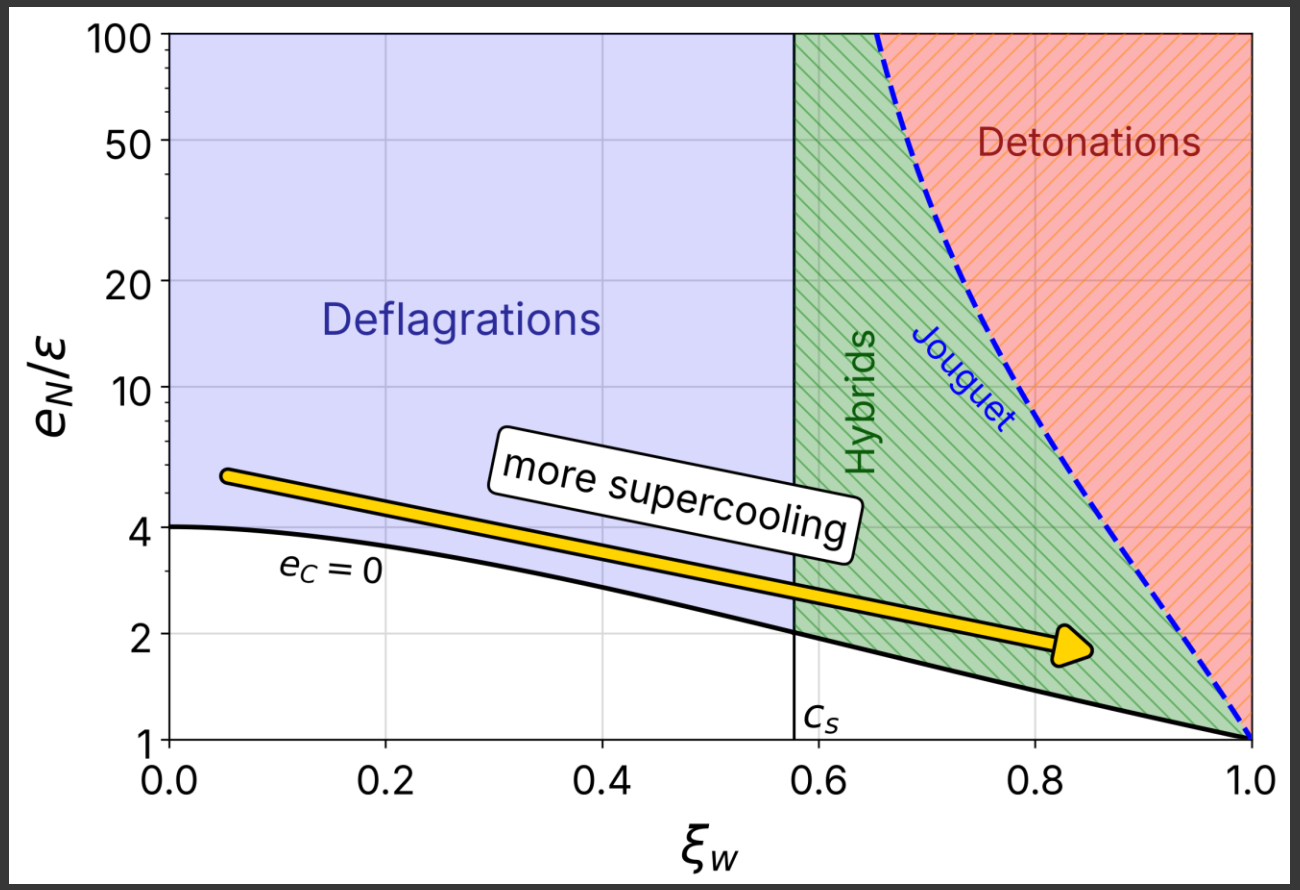
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SPACE OF ALLOWED SOLUTIONS

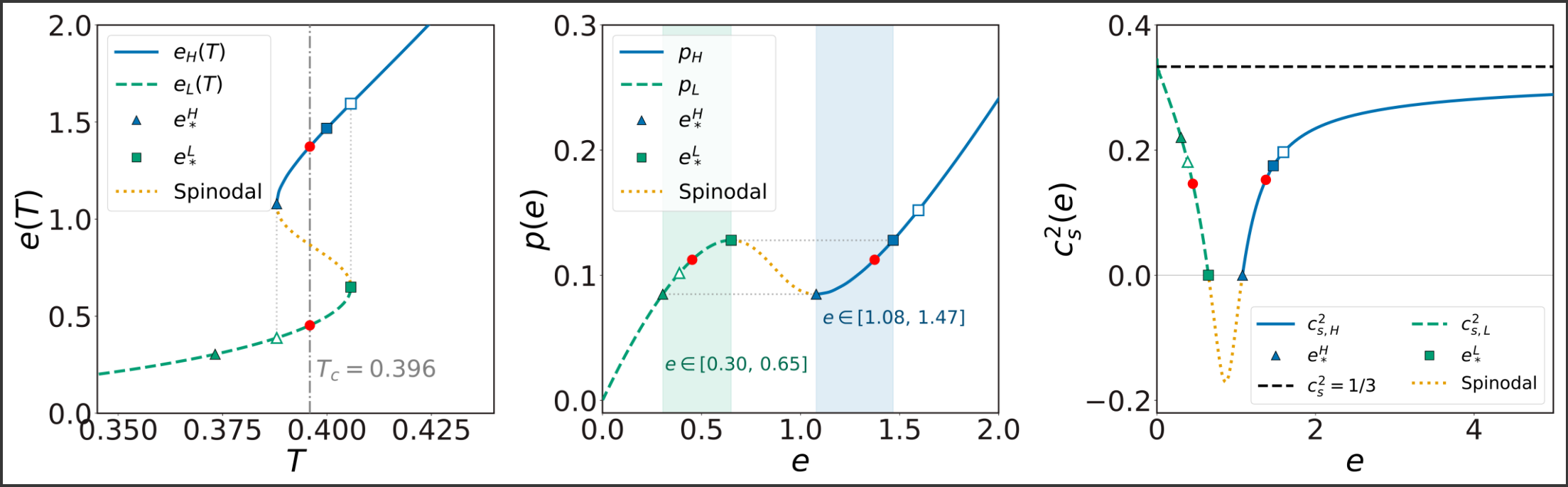
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- As the supercooling increases (lower e_N), the wall velocity increases
- How does this change for a non-conformal EoS?



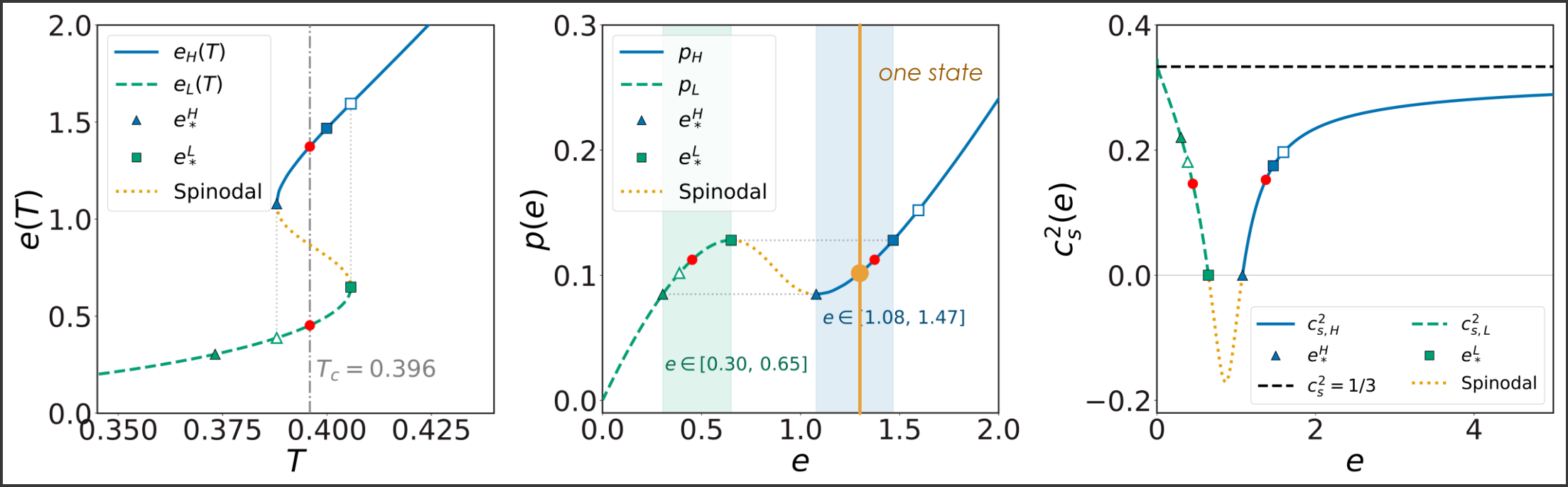
[Bea, Mateos, JHEP 08 (2018) 034; Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

"QCD-LIKE" EQUATIONS OF STATE



[Bea, Mateos, JHEP 08 (2018) 034; Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

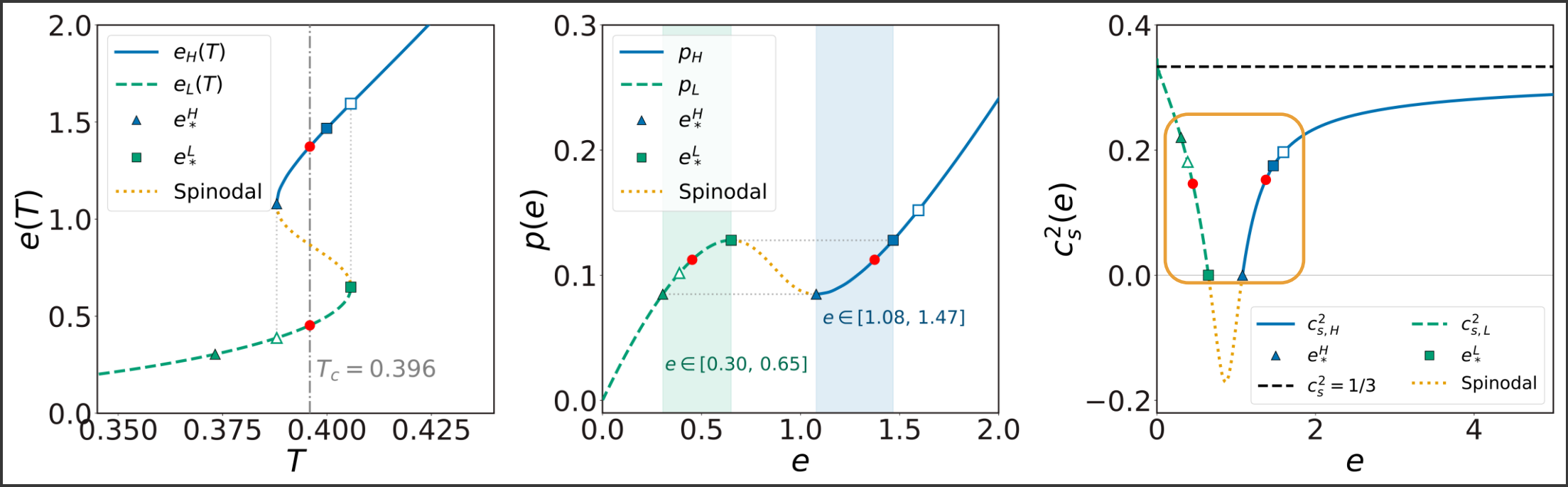
"QCD-LIKE" EQUATIONS OF STATE



- Single valued in the energy density: one state per energy density

[Bea, Mateos, JHEP 08 (2018) 034; Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

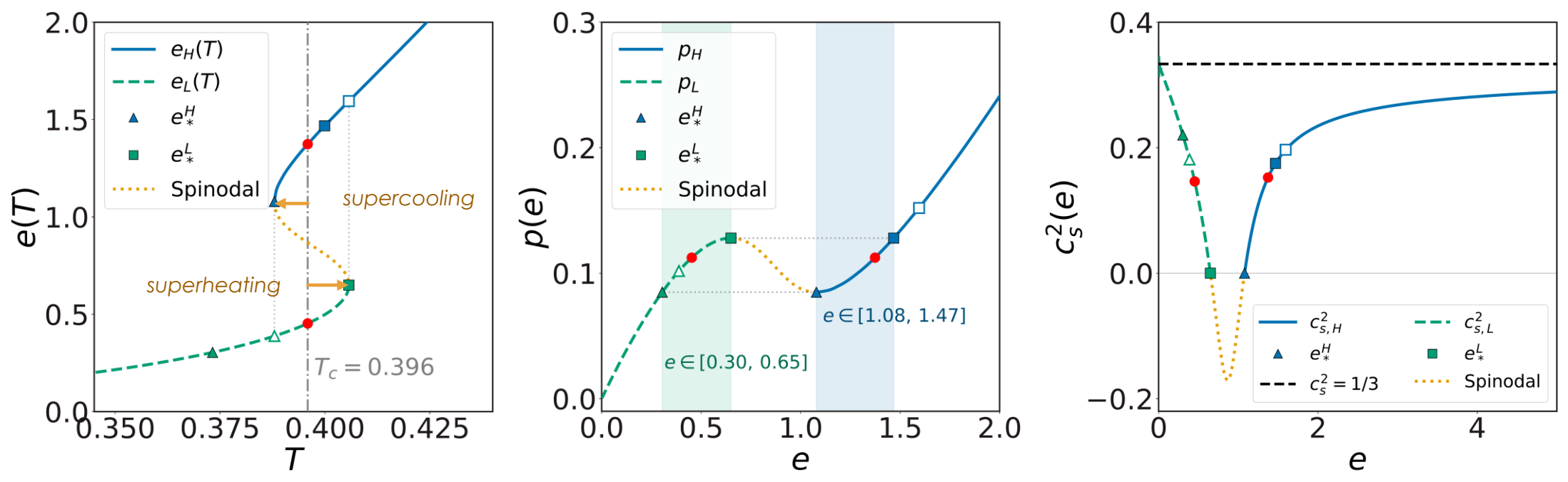
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"QCD-LIKE" EQUATIONS OF STATE



- Single valued in the energy density: one state per energy density
- Strong dependence of the speed of sound on the temperature
- Finite amount of supercooling and superheating

[Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

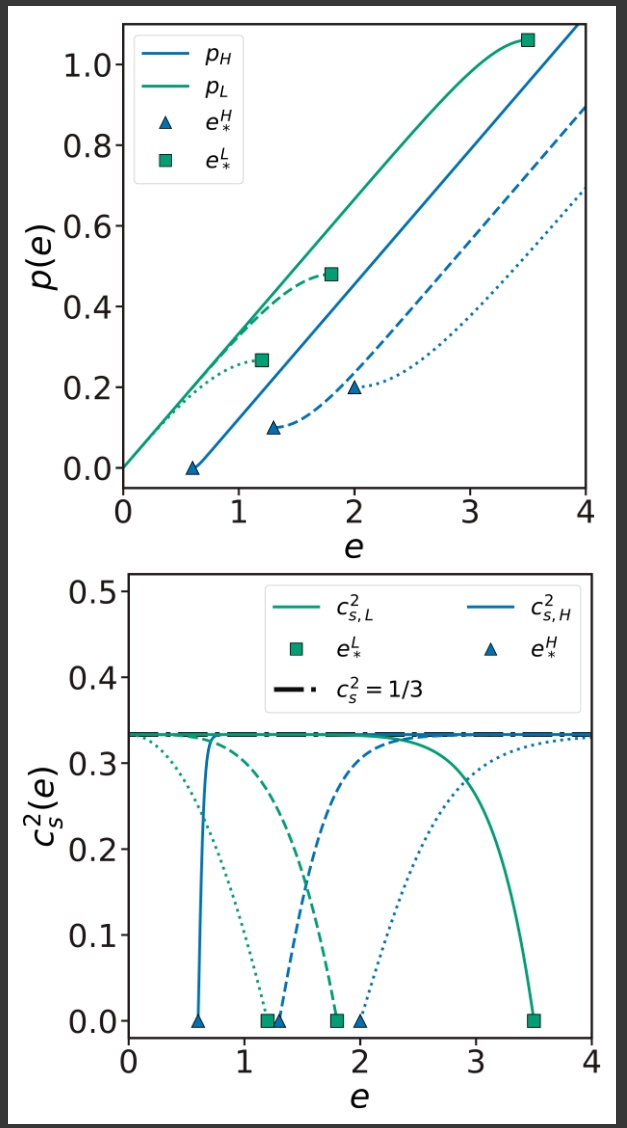
EQUATION OF STATE ANSATZ

— Bag-model-like - - Intermediate ····· Non-conformal

- Ansatz interpolating between QCD-like and bag-model-like (reduced) EoS

$$p_L(e) = \frac{1}{3}\left(e - \frac{e^{n+1}}{(n+1)\,(e_*^L)^n}\right)$$

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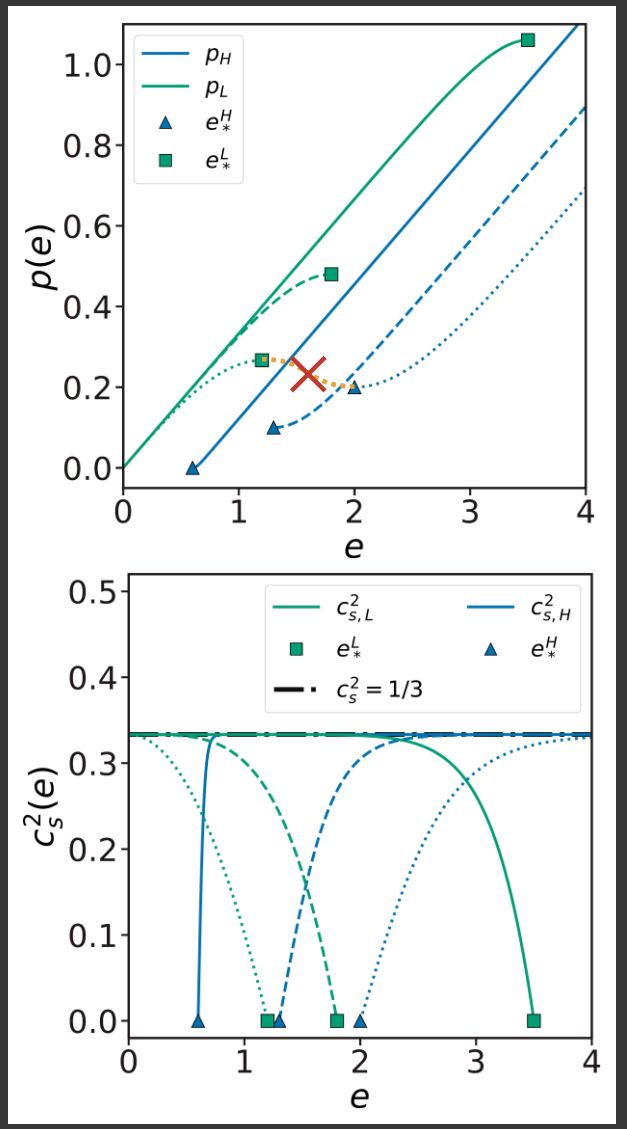
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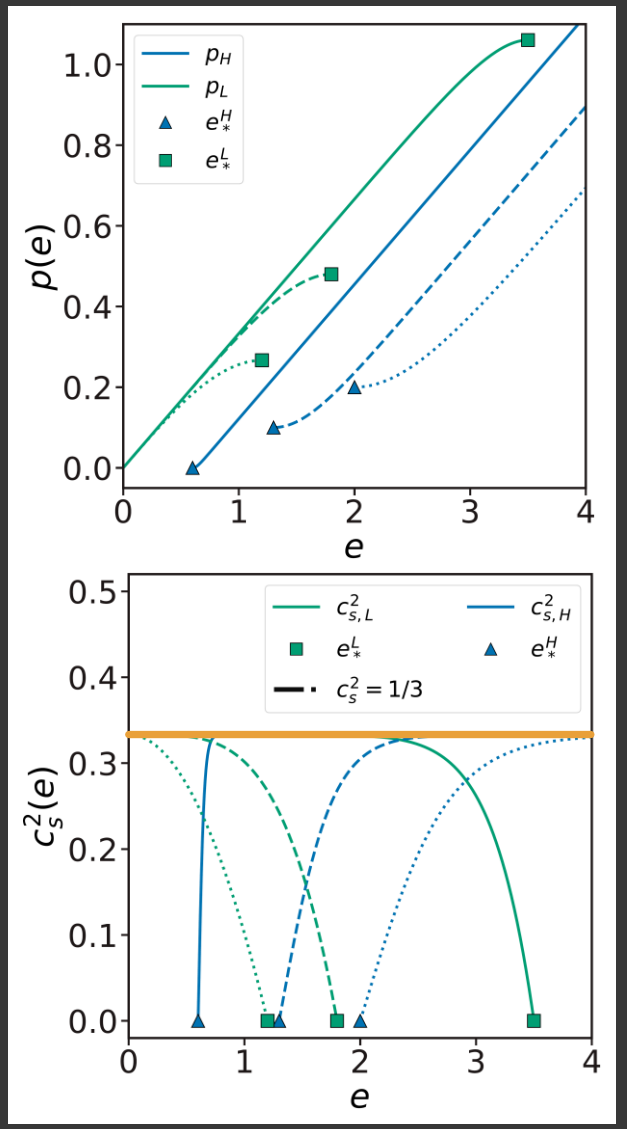
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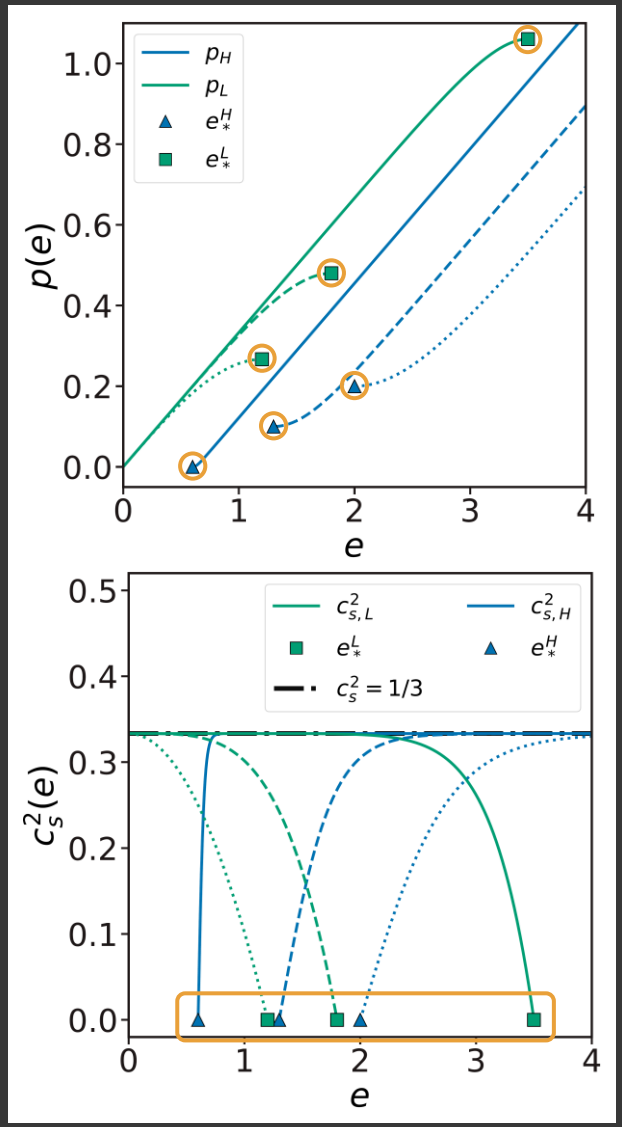
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EQUATION OF STATE ANSATZ

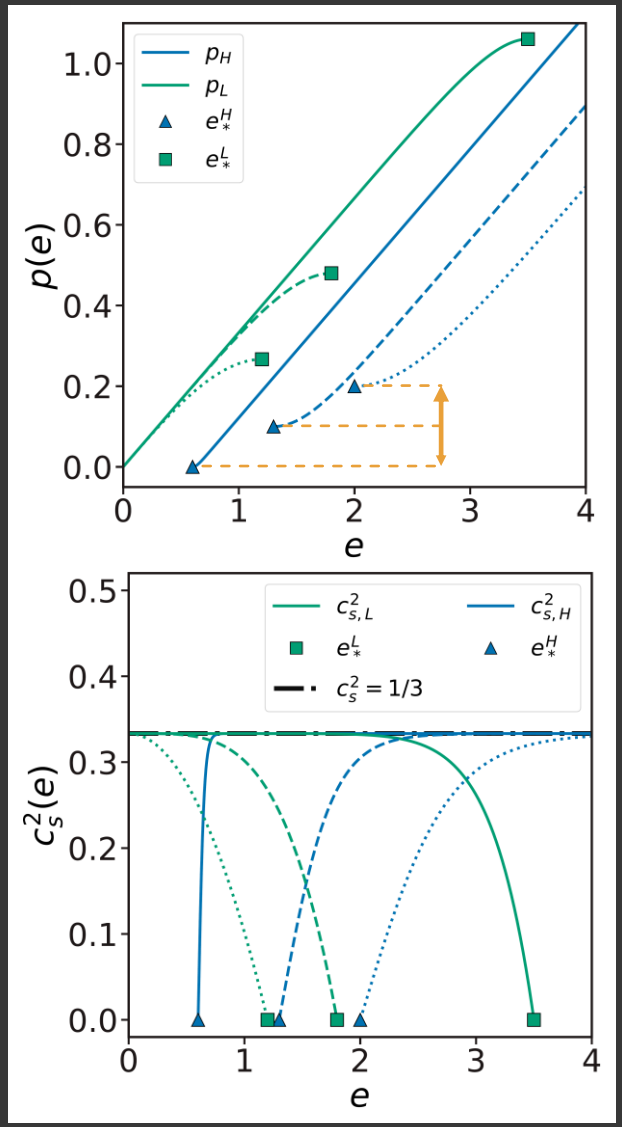
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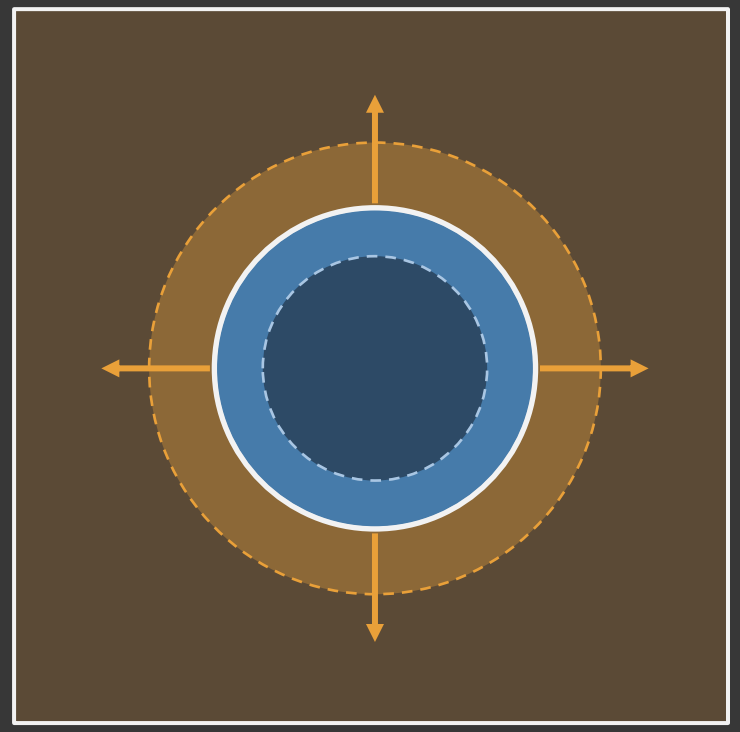
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  - $c_s^2 = 0$ at the turning points e_*^H, e_*^L
  - δ and n control how fast c_s varies
  - p_1 plays the role of the "bag constant"



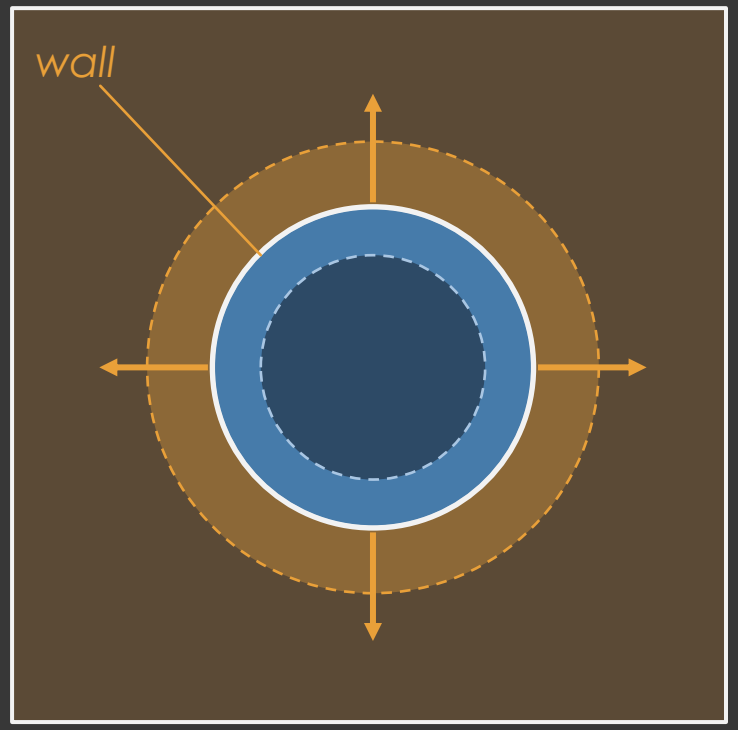
NON-CONFORMAL OBSTRUCTIONS



NON-CONFORMAL OBSTRUCTIONS

WALL OBSTRUCTIONS

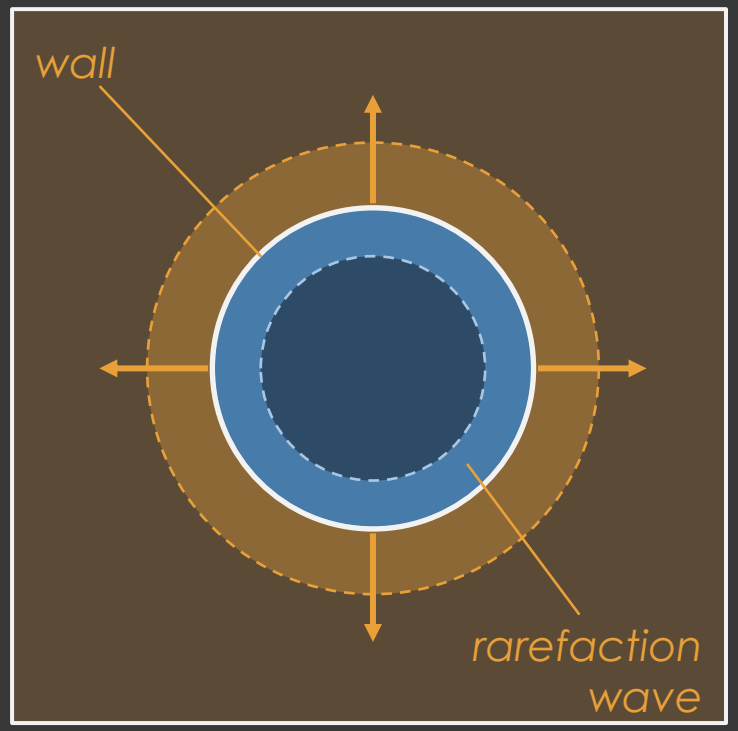
- The junction conditions at the wall cannot be solved
- Local: only $p(e)$ and $c_s(e)$ at the wall matter
- Affect deflagrations and detonations



NON-CONFORMAL OBSTRUCTIONS

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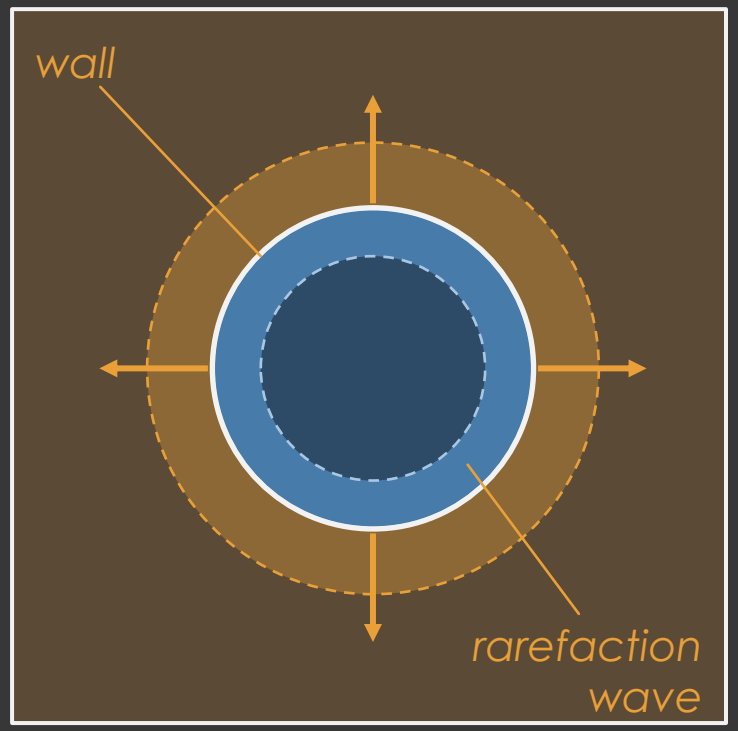
FLOW OBSTRUCTIONS

- No continuous flow can be built along the rarefaction wave
- Global: sensitive to how c_s varies with e
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FLOW OBSTRUCTIONS

- No continuous flow can be built along the rarefaction wave
- Global: sensitive to how c_s varies with e
- Affect hybrids and detonations
- New solution: shocked-detonations

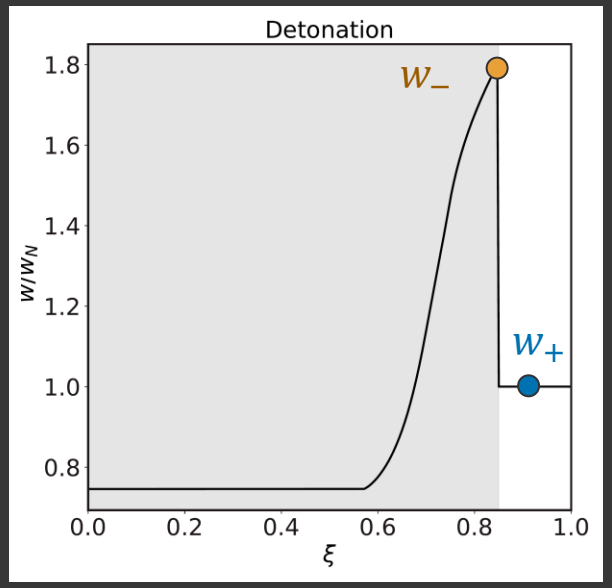
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WALL OBSTRUCTIONS: DETONATIONS

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WALL OBSTRUCTIONS: DETONATIONS

Single detonation

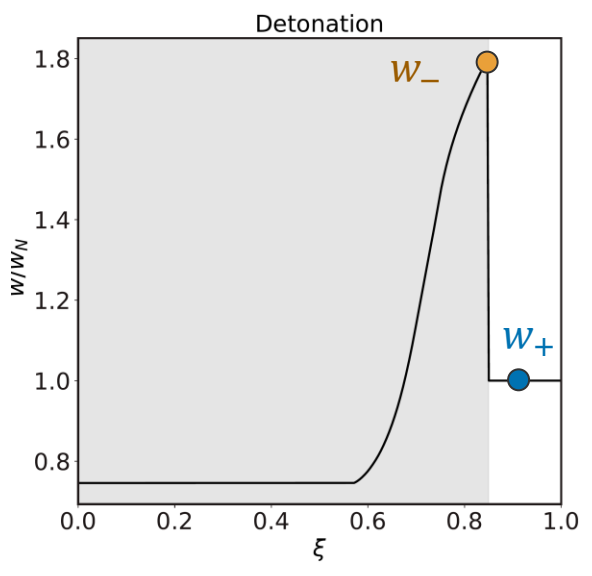


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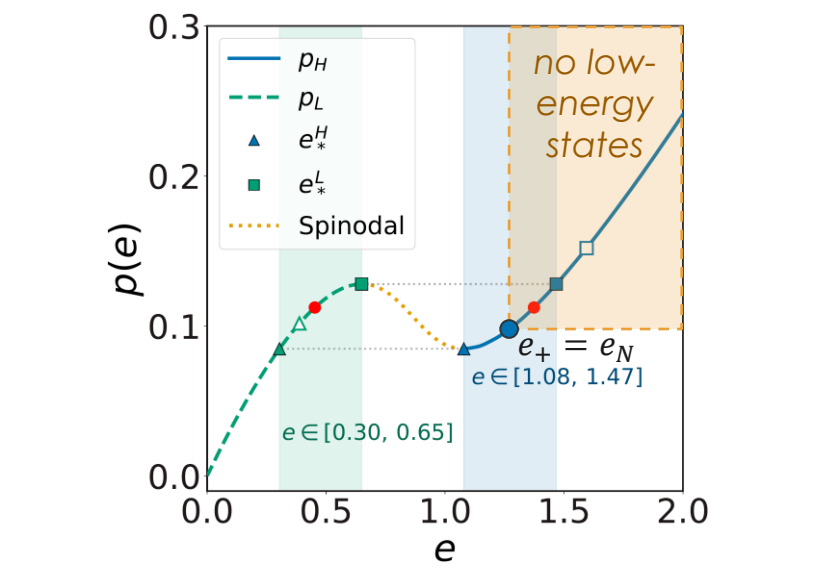
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WALL OBSTRUCTIONS: DETONATIONS

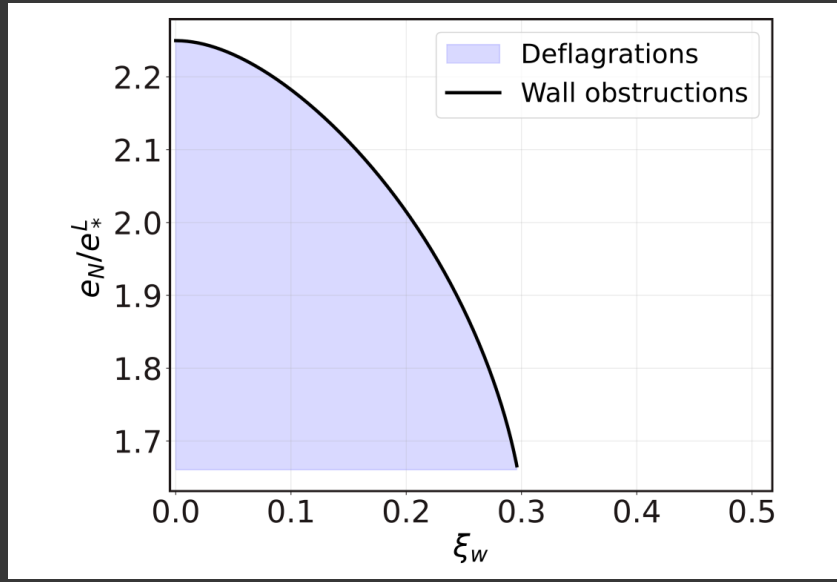
Single detonation



Holographic model: EoS



Holographic model: solutions

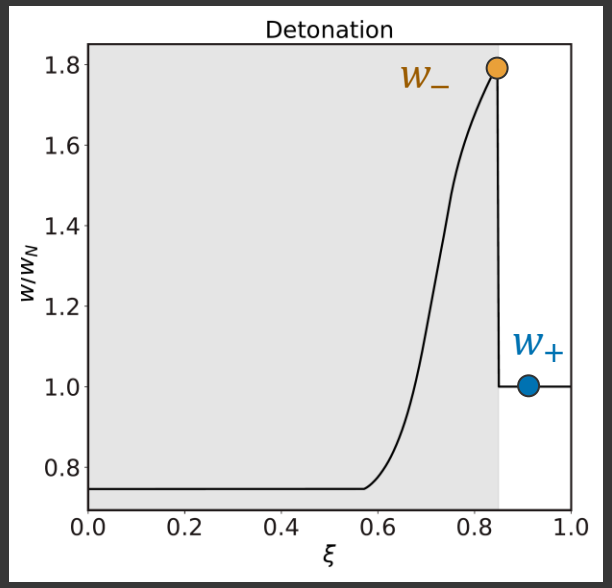


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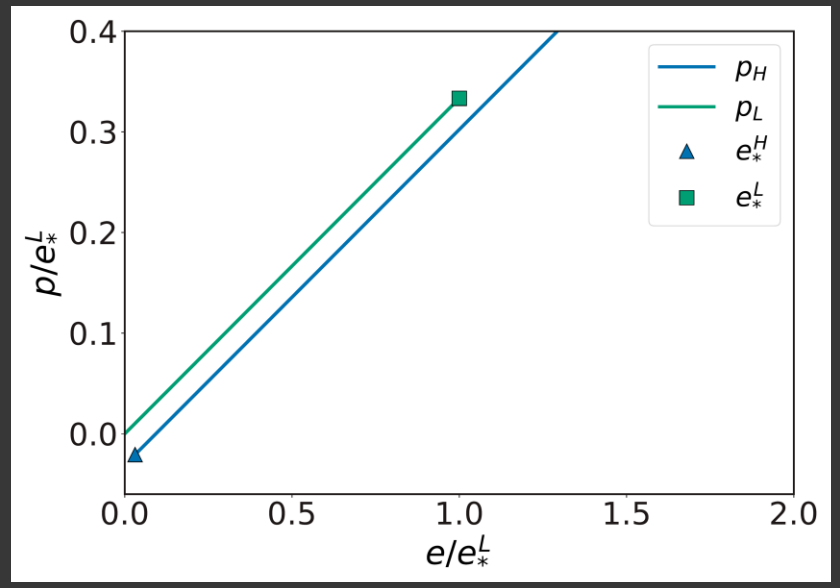
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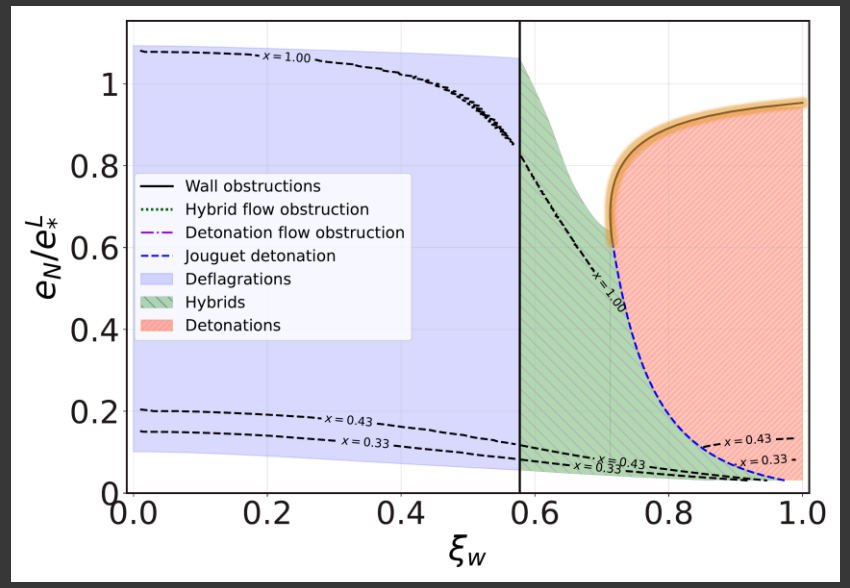
Single detonation



Bag EoS, finite ranges



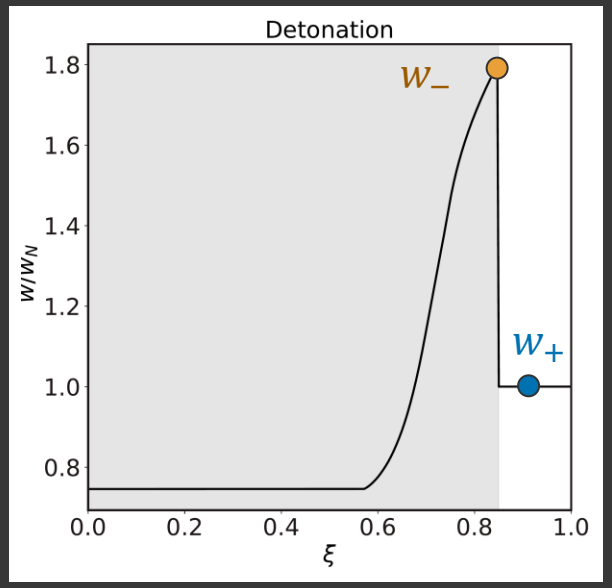
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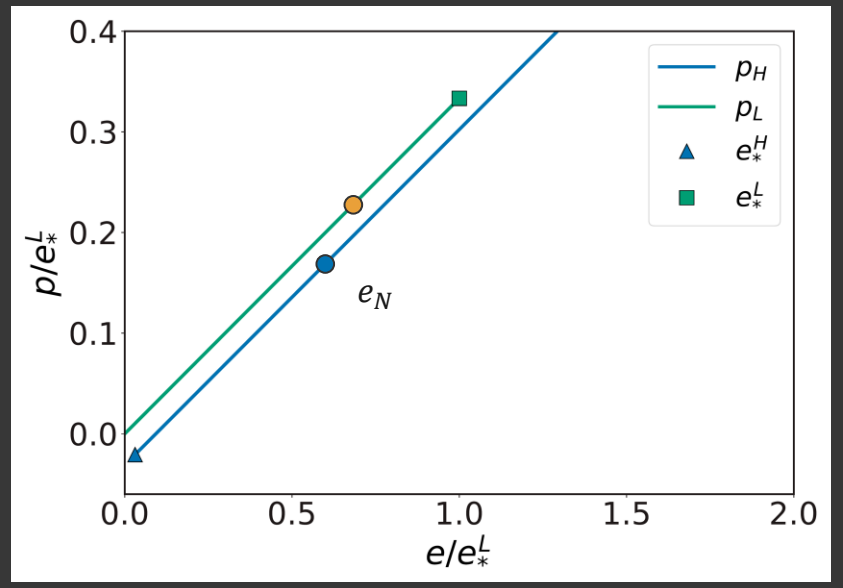
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WALL OBSTRUCTIONS: DETONATIONS

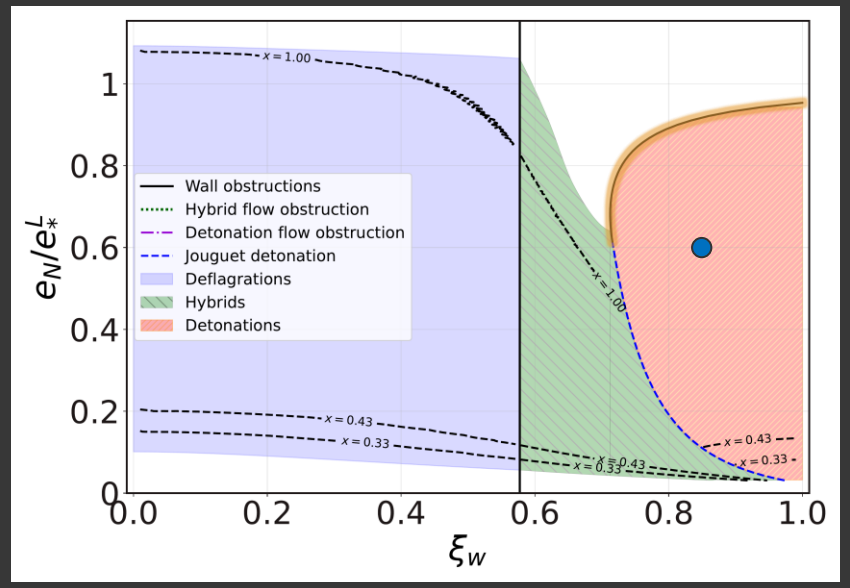
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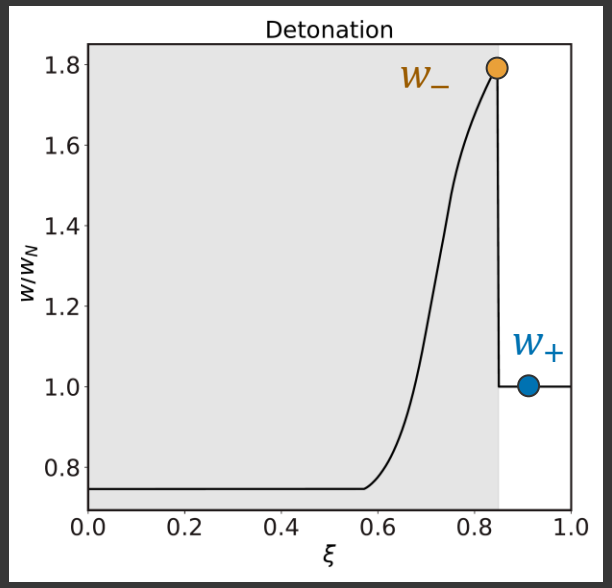
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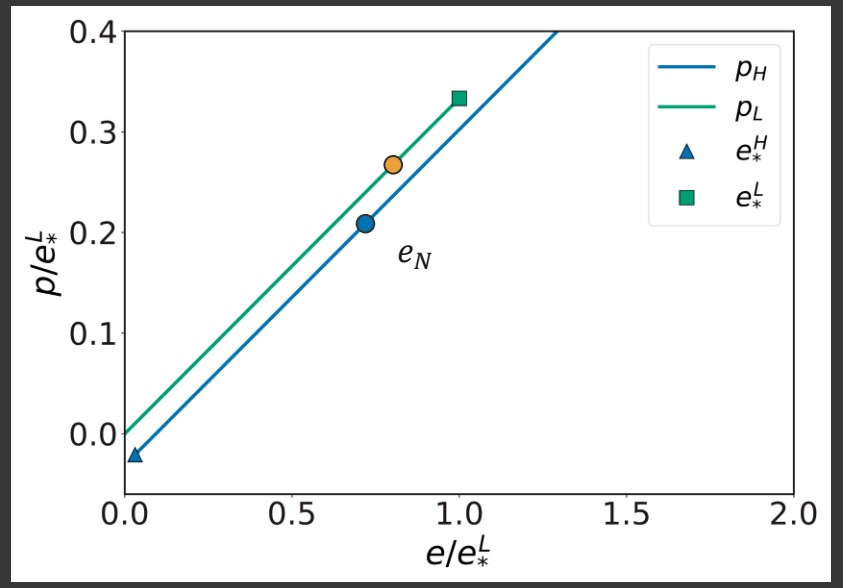
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WALL OBSTRUCTIONS: DETONATIONS

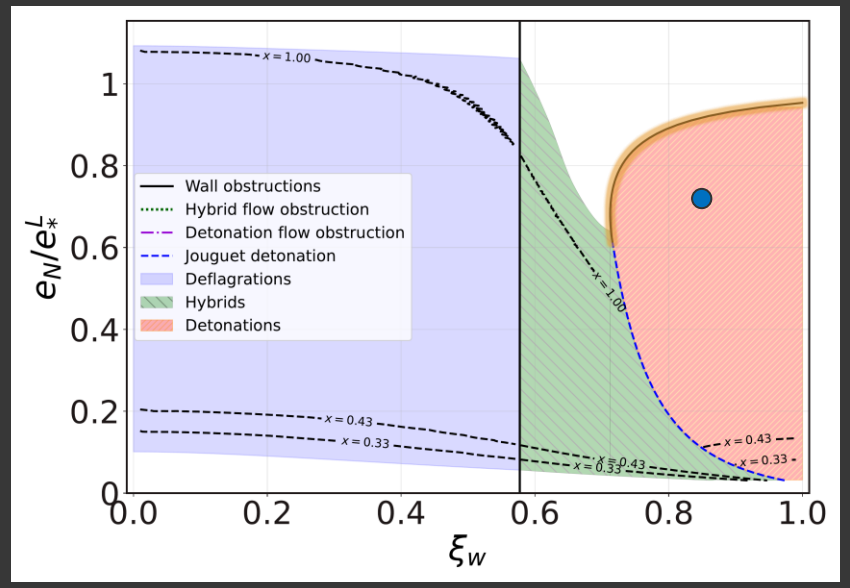
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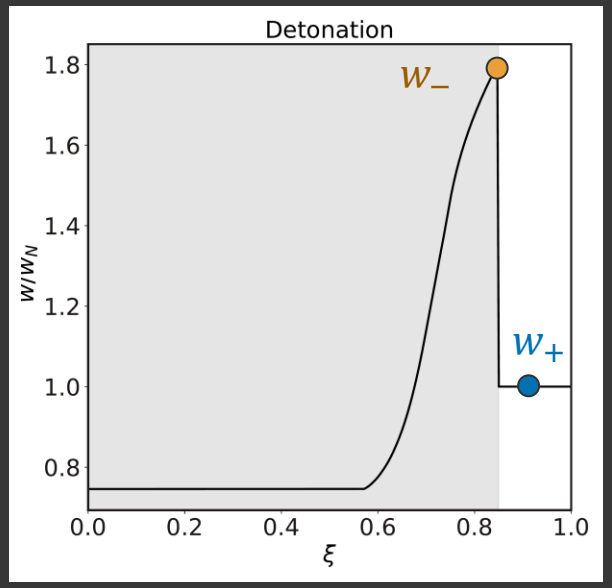
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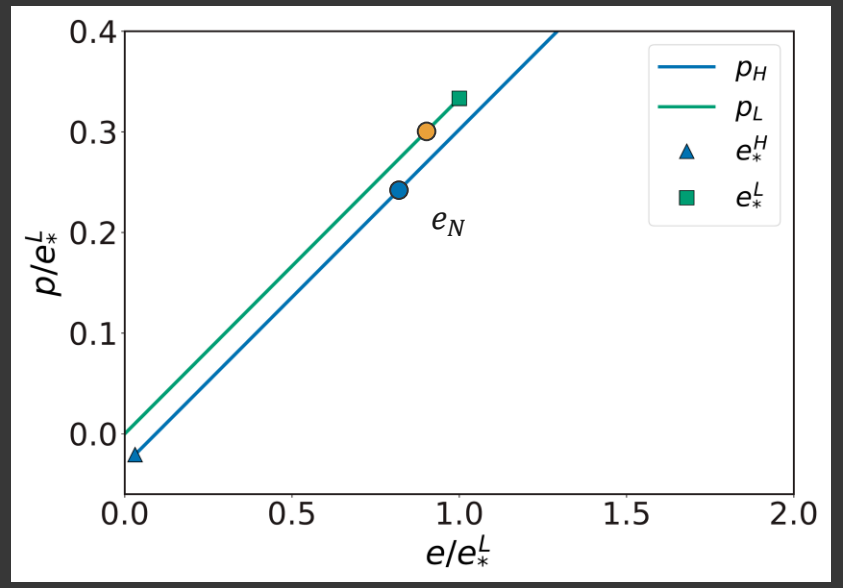
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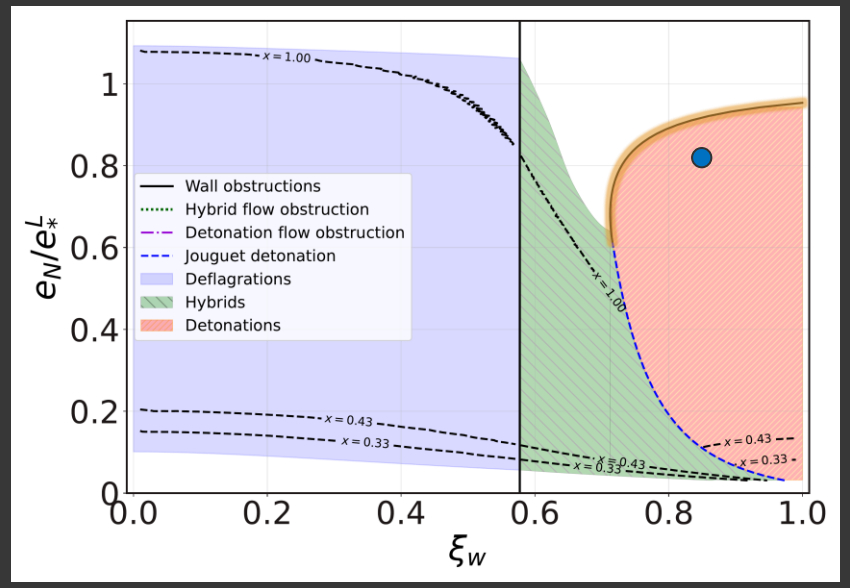
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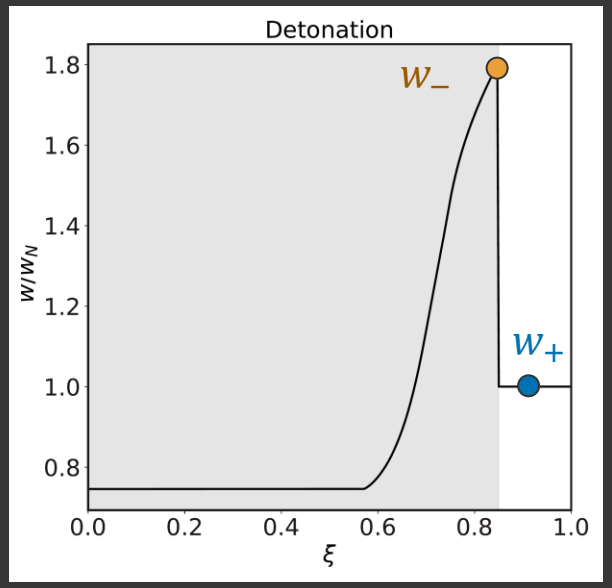


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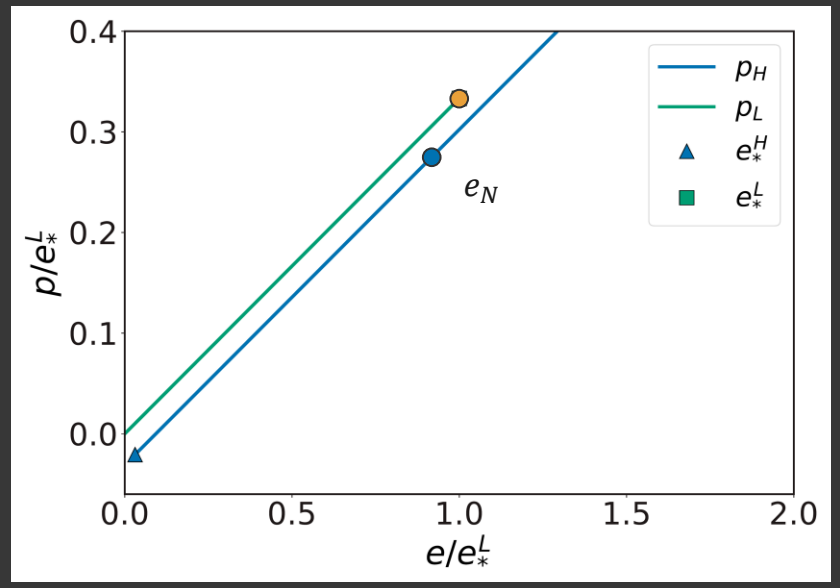
[Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

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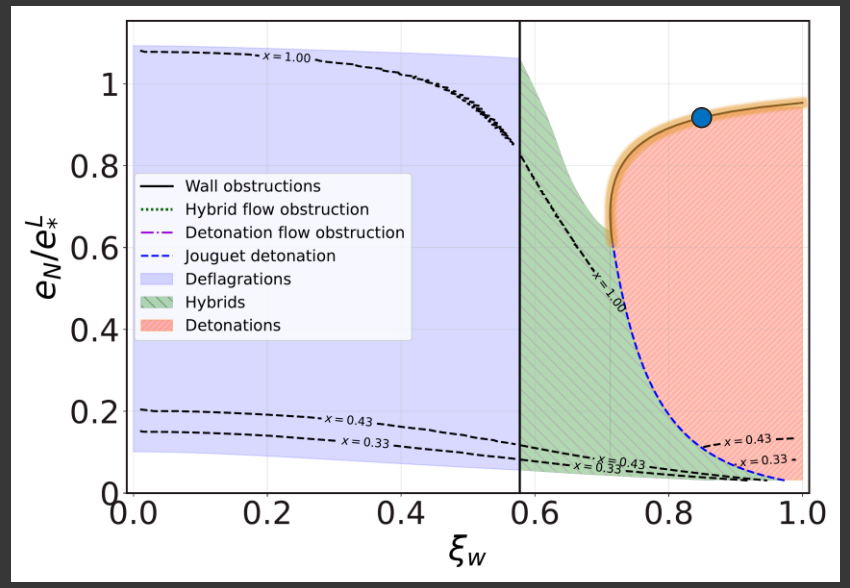
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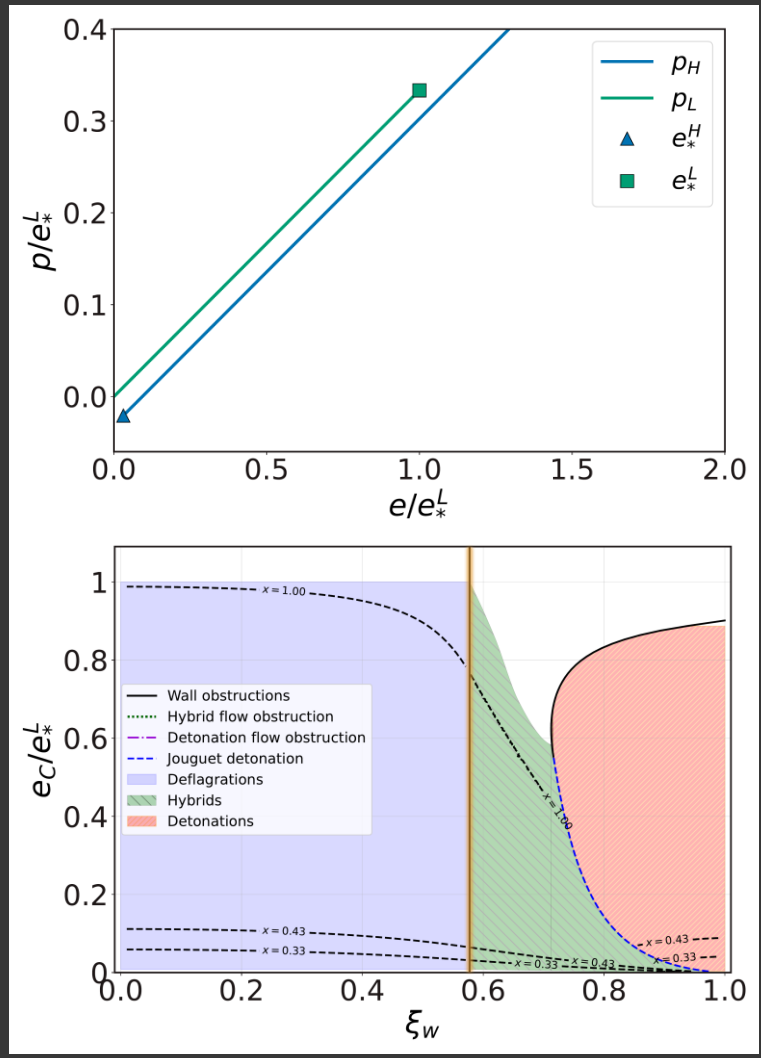
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WALL OBSTRUCTIONS: DEFLAGRATIONS

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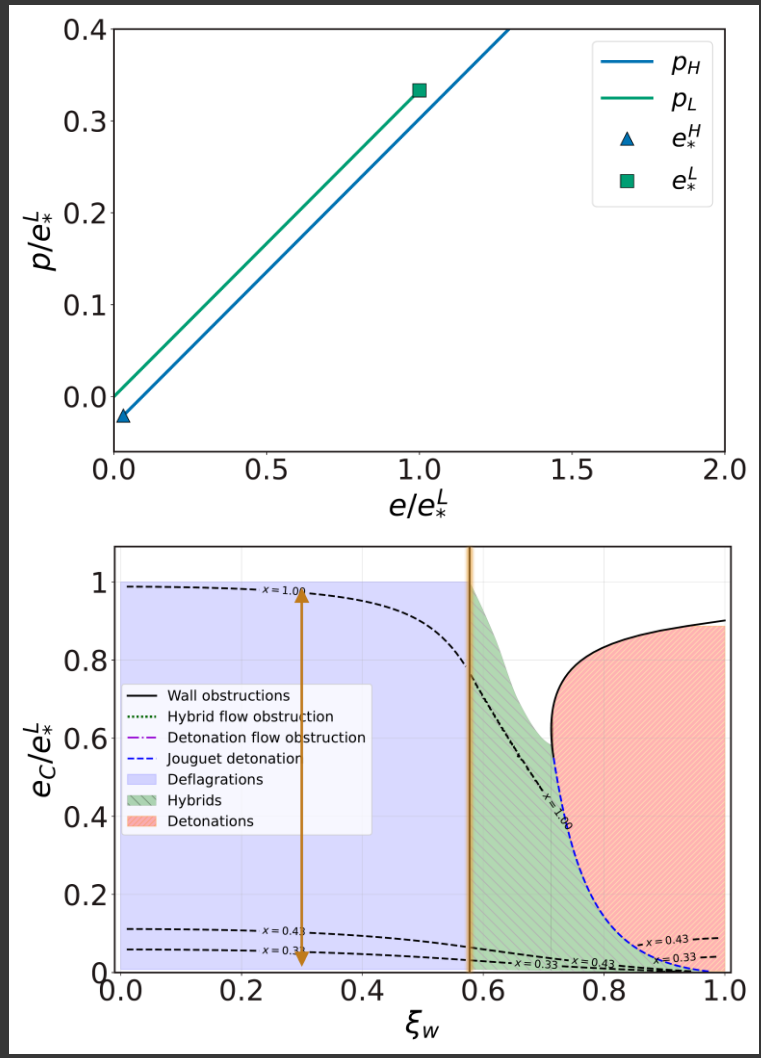
Bag model, finite ranges



WALL OBSTRUCTIONS: DEFLAGRATIONS

- Bag model:
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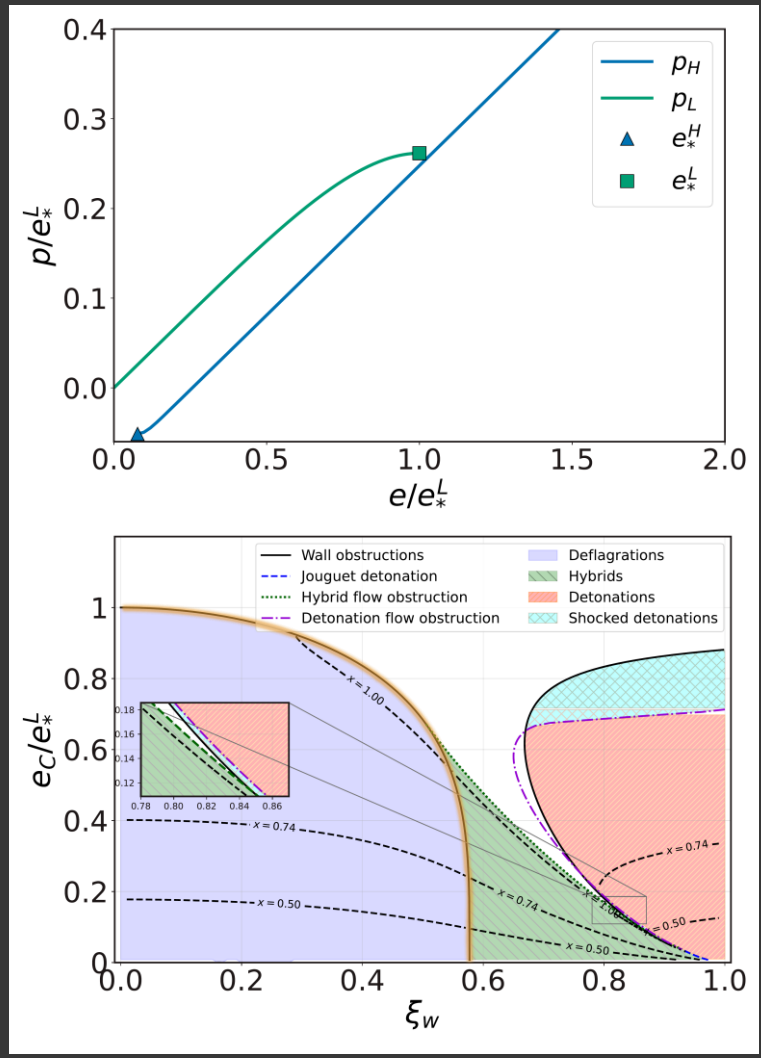
Bag model, finite ranges



WALL OBSTRUCTIONS: DEFLAGRATIONS

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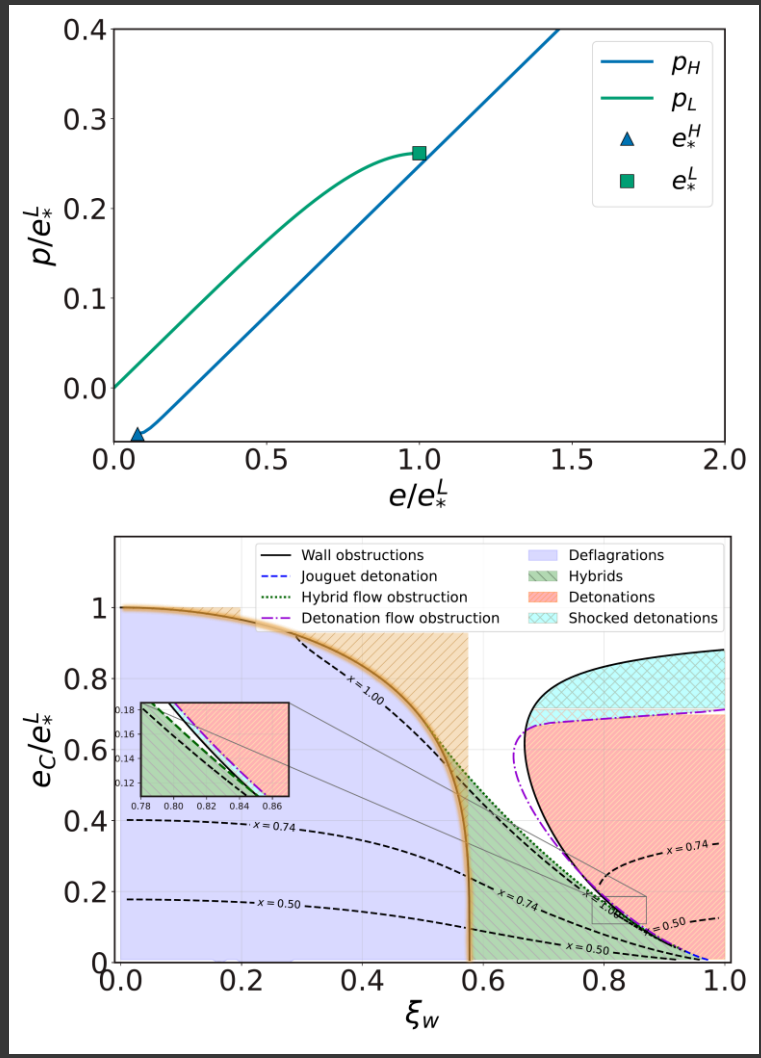
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  - Deflagrations don't cover the whole range of available energies

Non-conformal EoS



[Espinosa et al., JCAP 06 (2010) 028; Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

FLOW OBSTRUCTIONS

[Espinosa et al., JCAP 06 (2010) 028; Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

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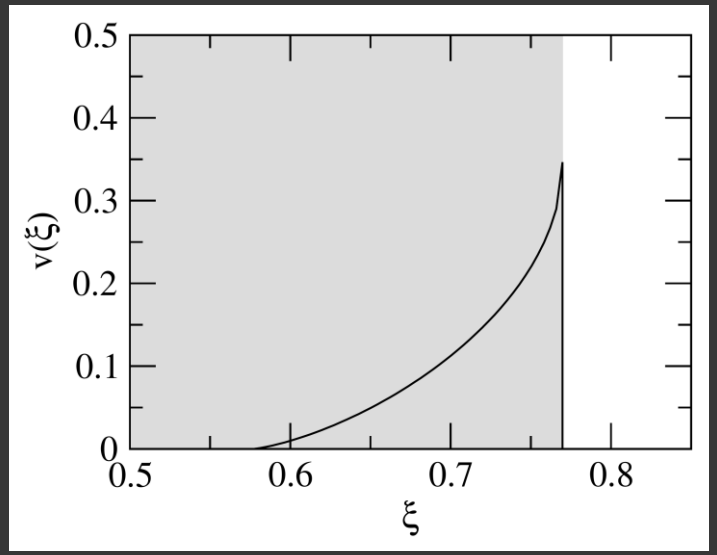
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[Espinosa et al., JCAP 06 (2010) 028; Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

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Bag model detonation

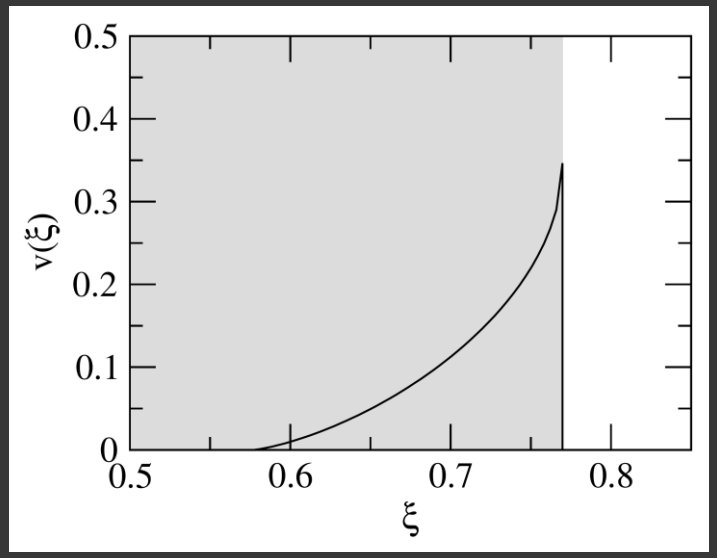


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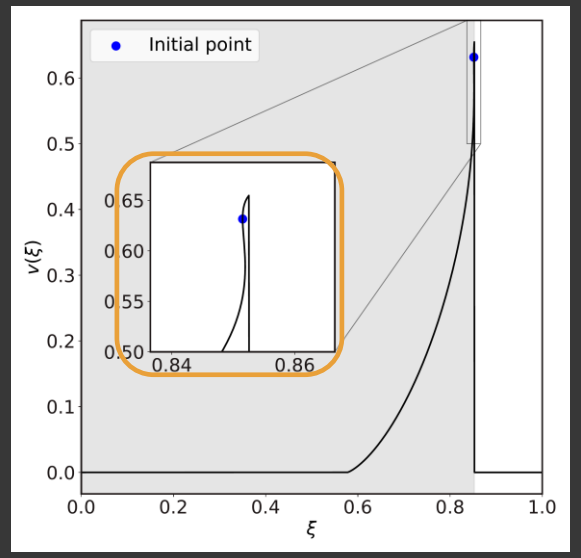
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Detonation beyond the DCP: not allowed



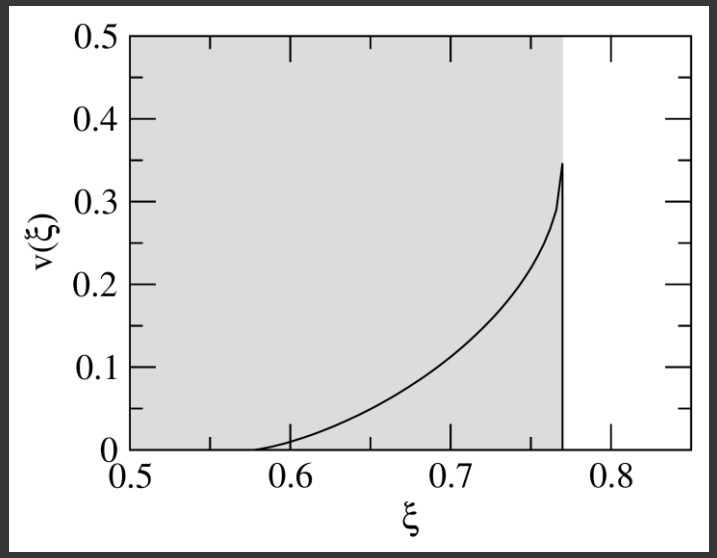
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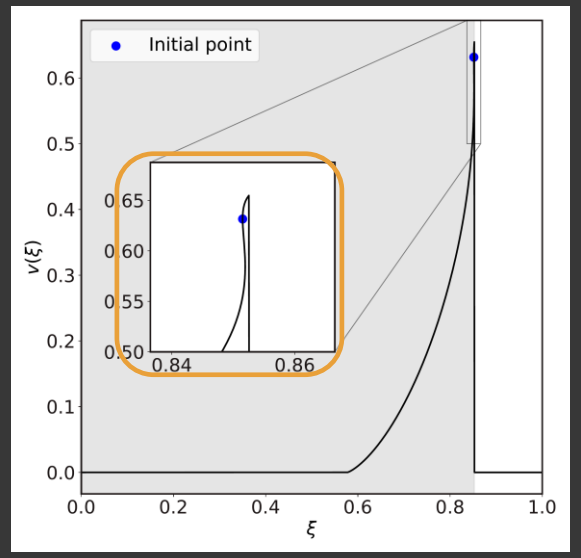
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- They appear when the EoS has a degenerate critical point (DCP), a condition on the EoS only:

$$\frac{dc_s^2}{de} = -\frac{2\left(1-c_s^2\right)c_s^2}{e+p}$$

Bag model detonation

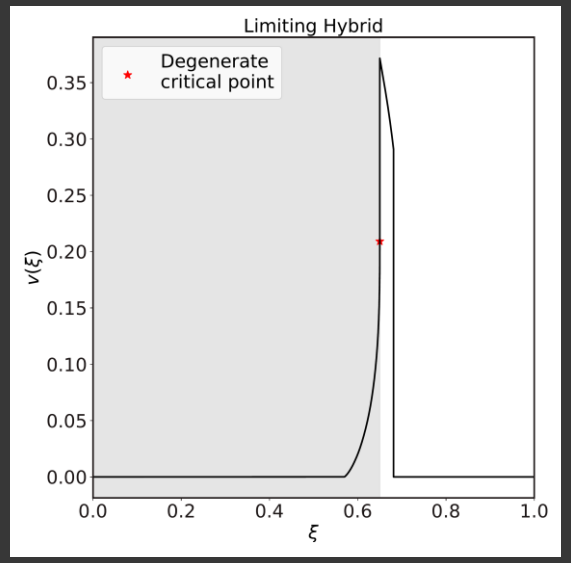


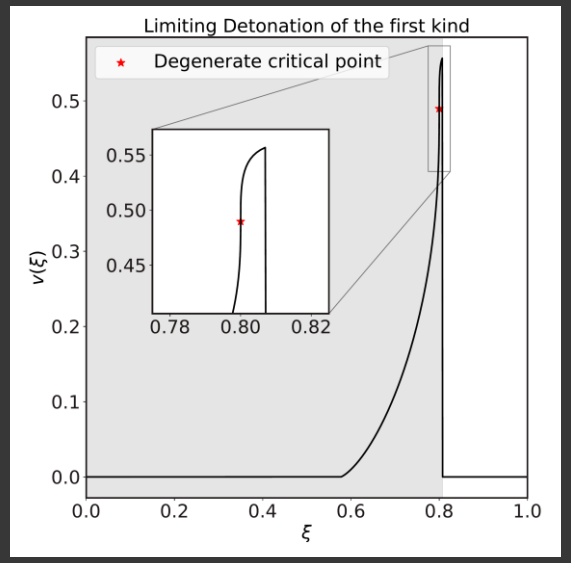
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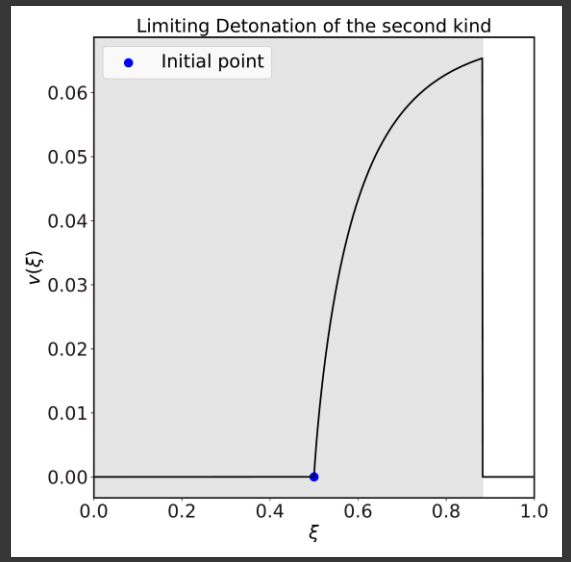


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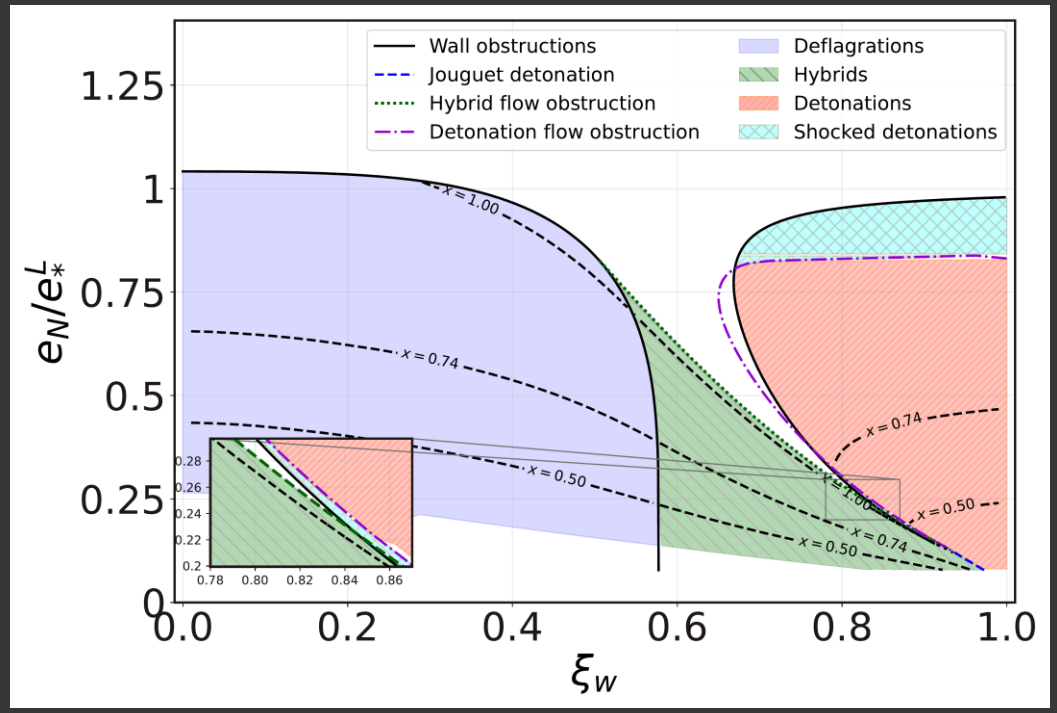
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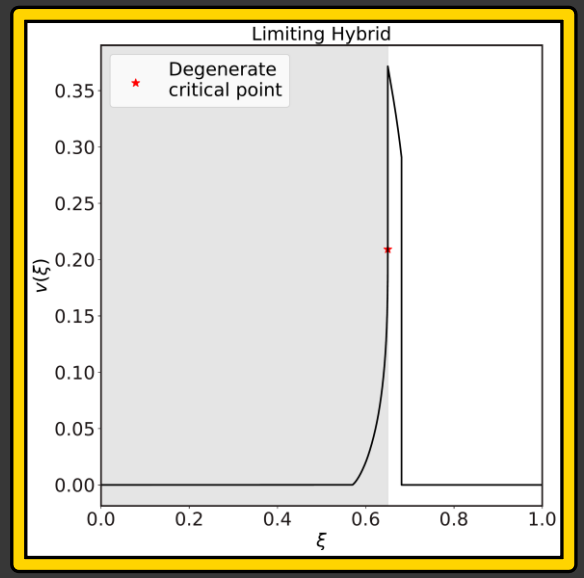


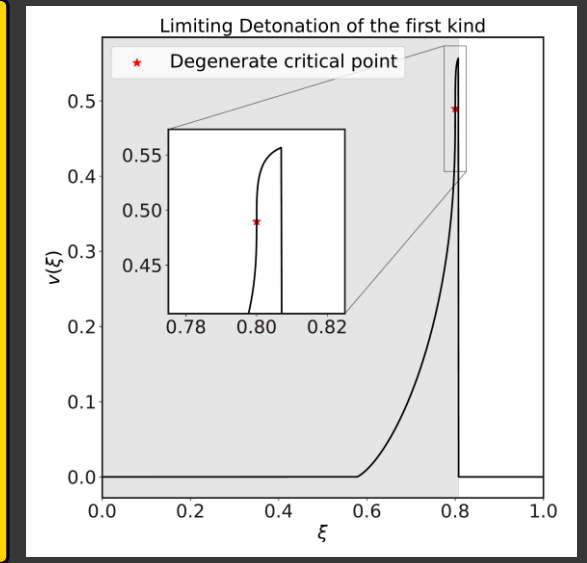
- Limiting cases give the flow obstruction lines in the space of allowed solutions

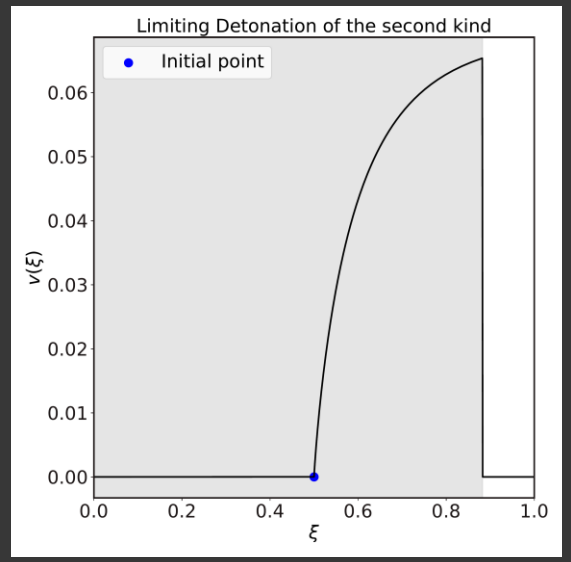


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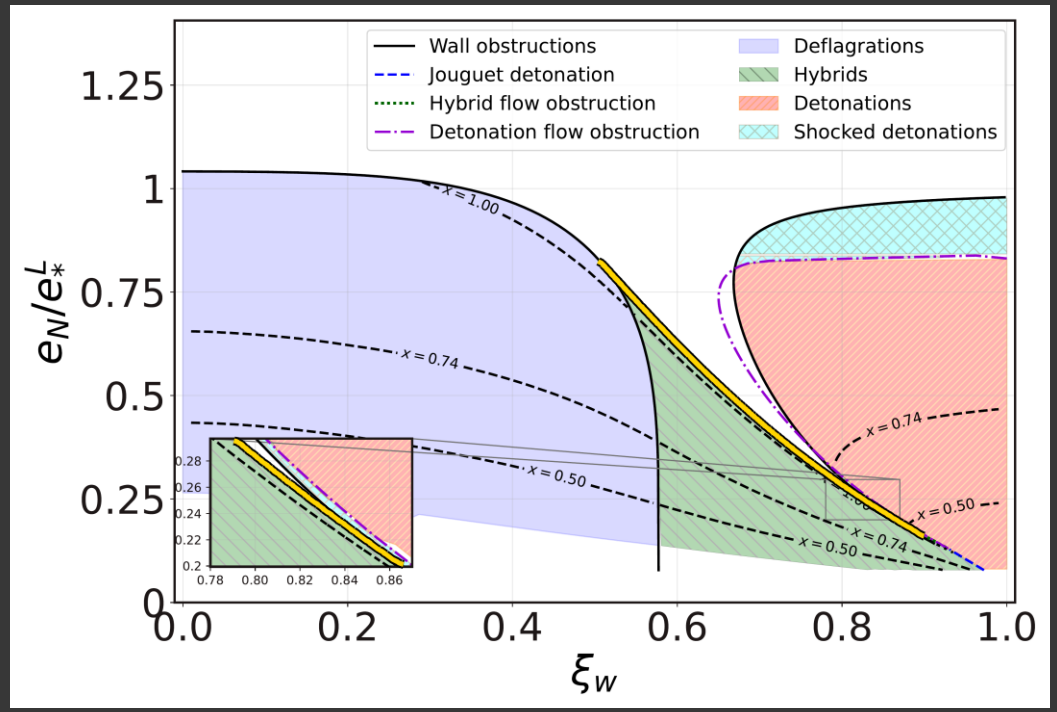
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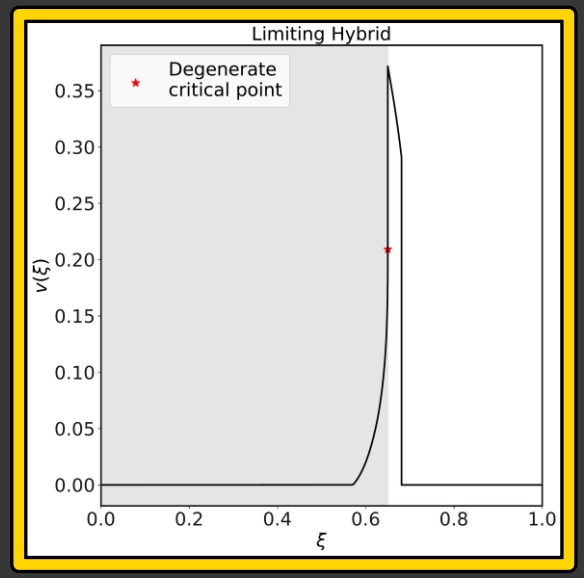


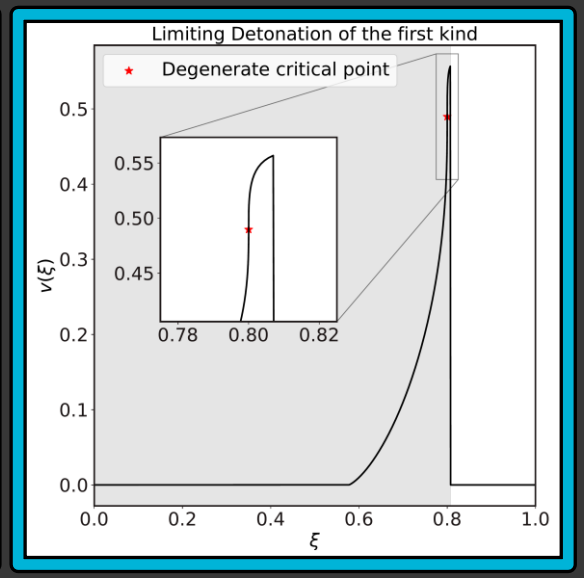
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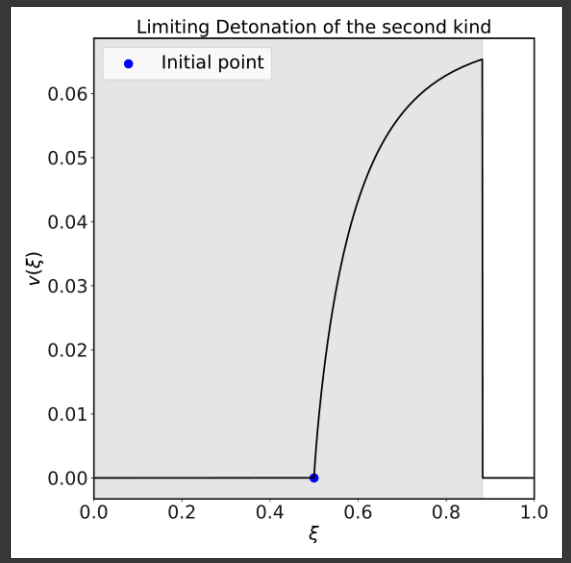


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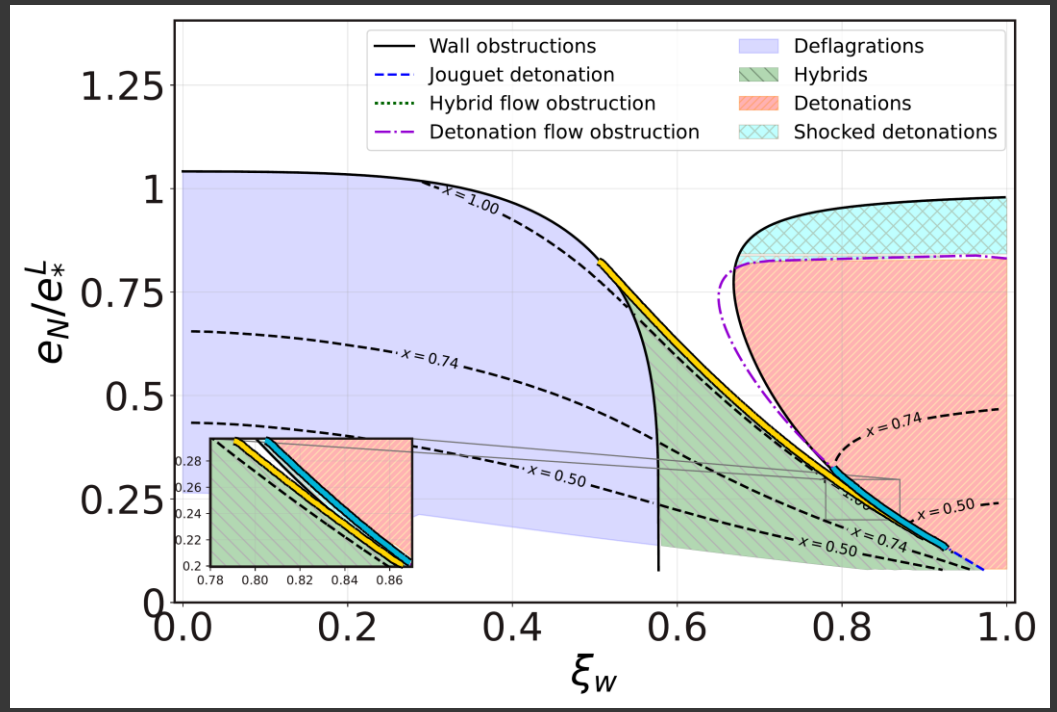
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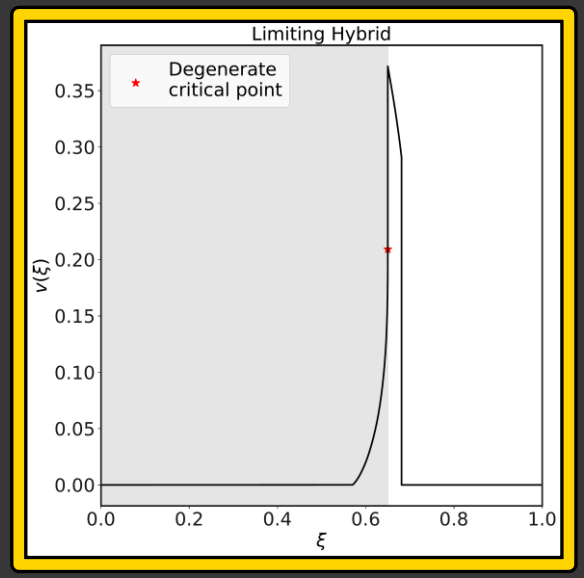


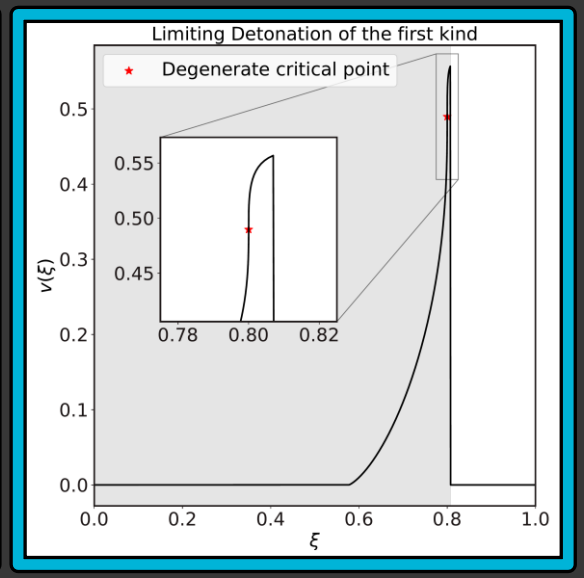
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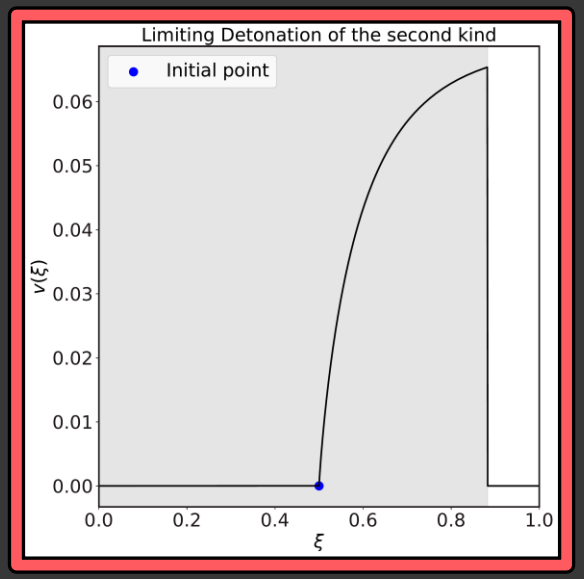


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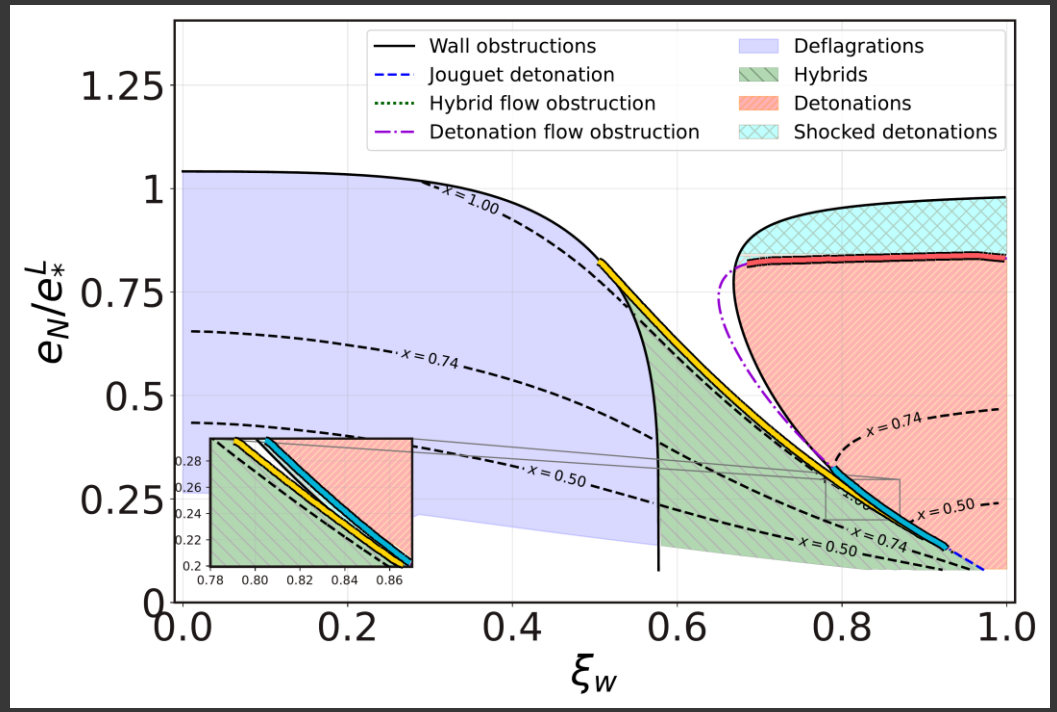
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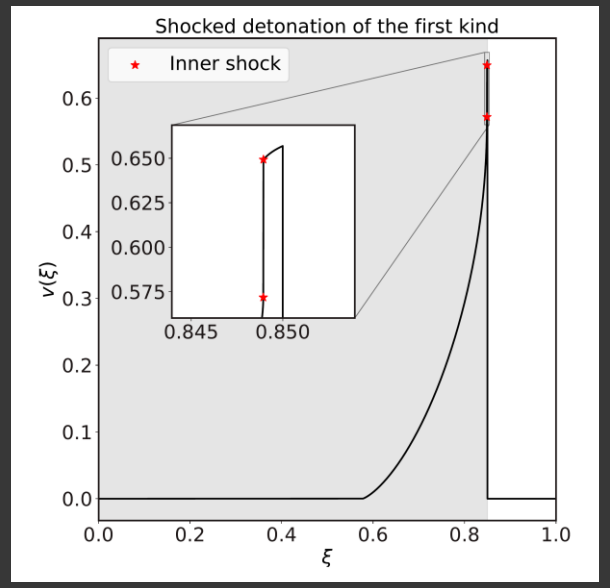
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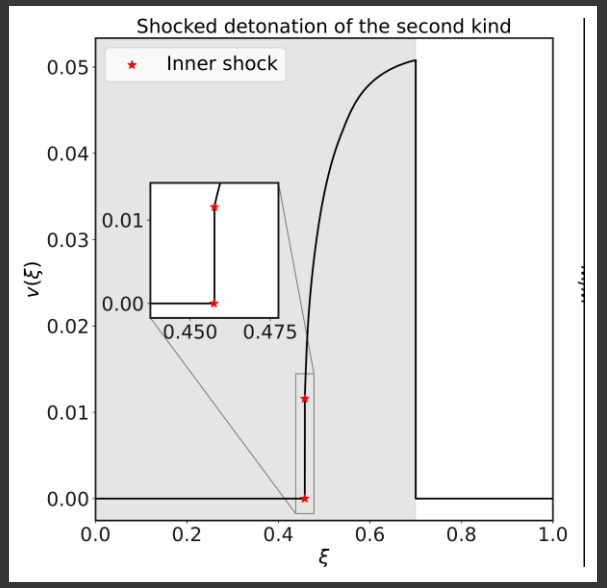


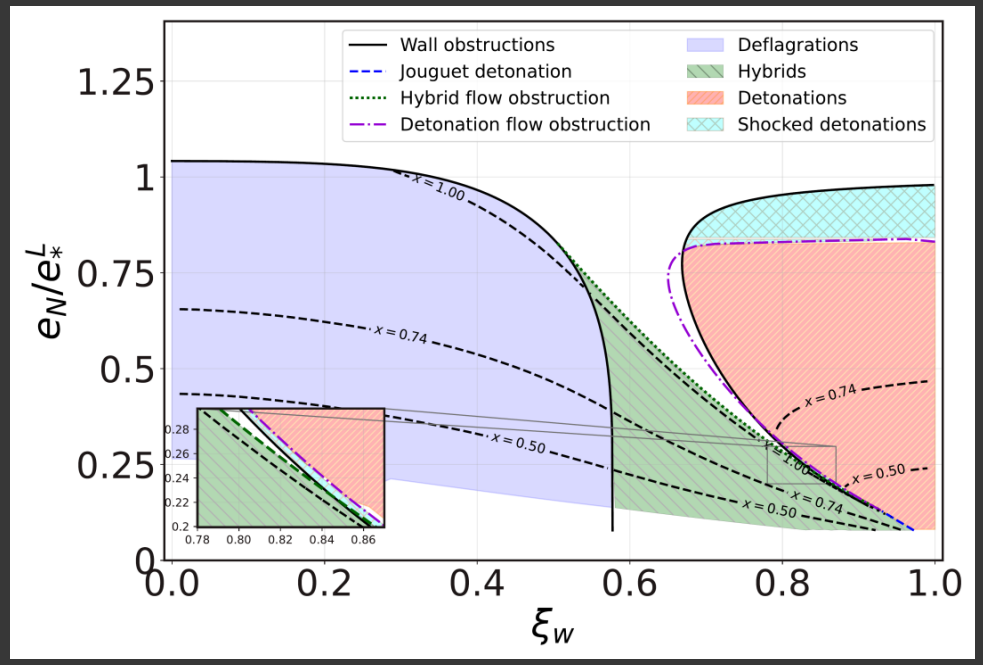
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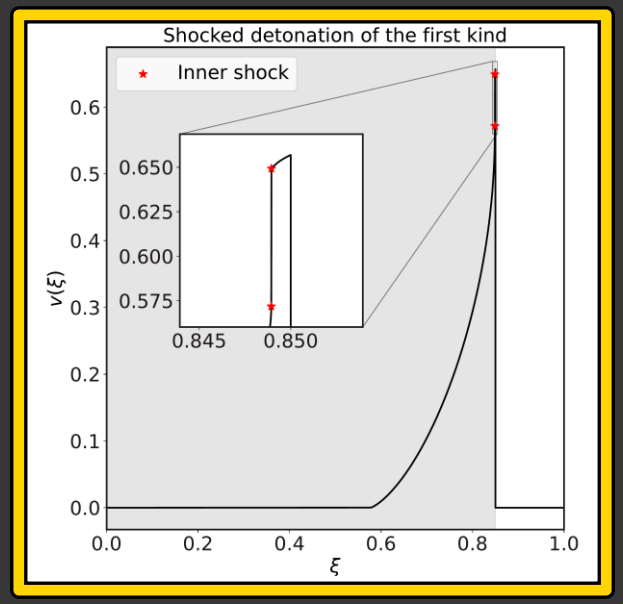


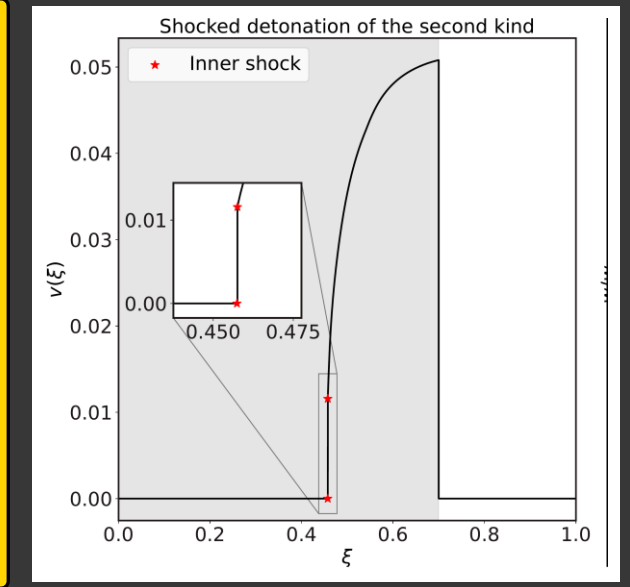


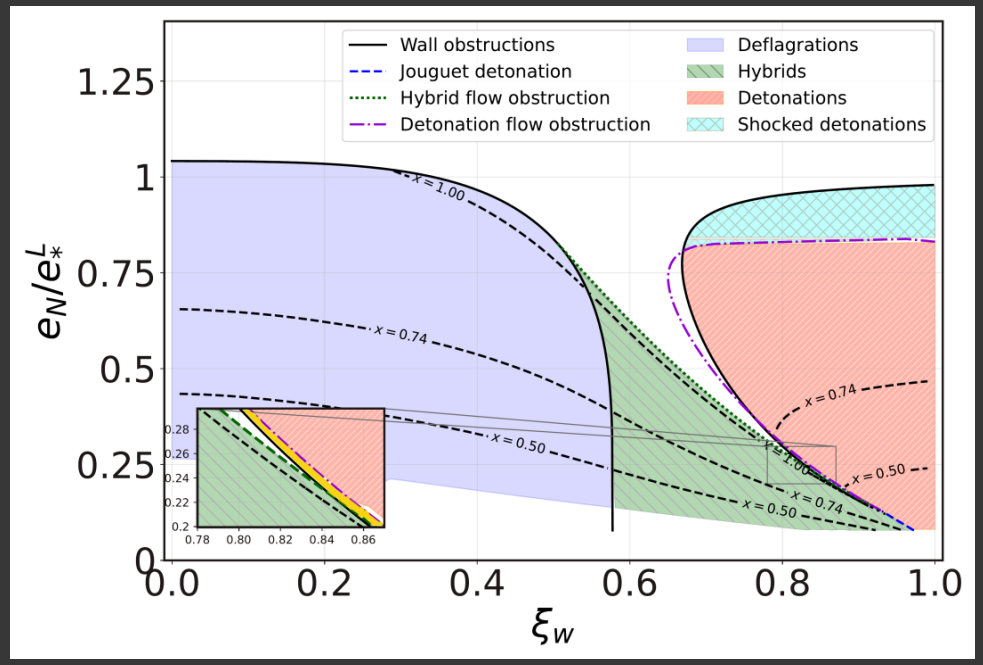
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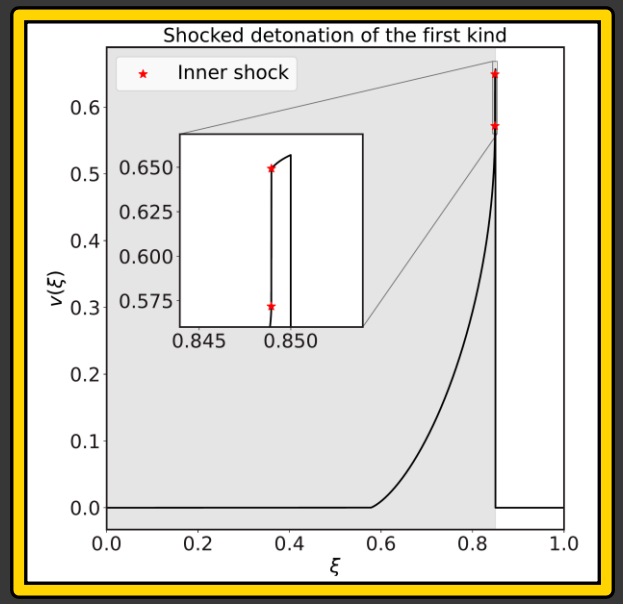


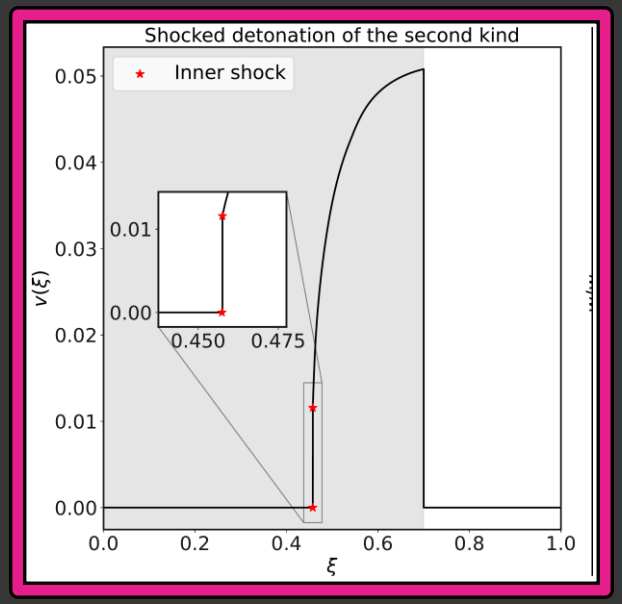


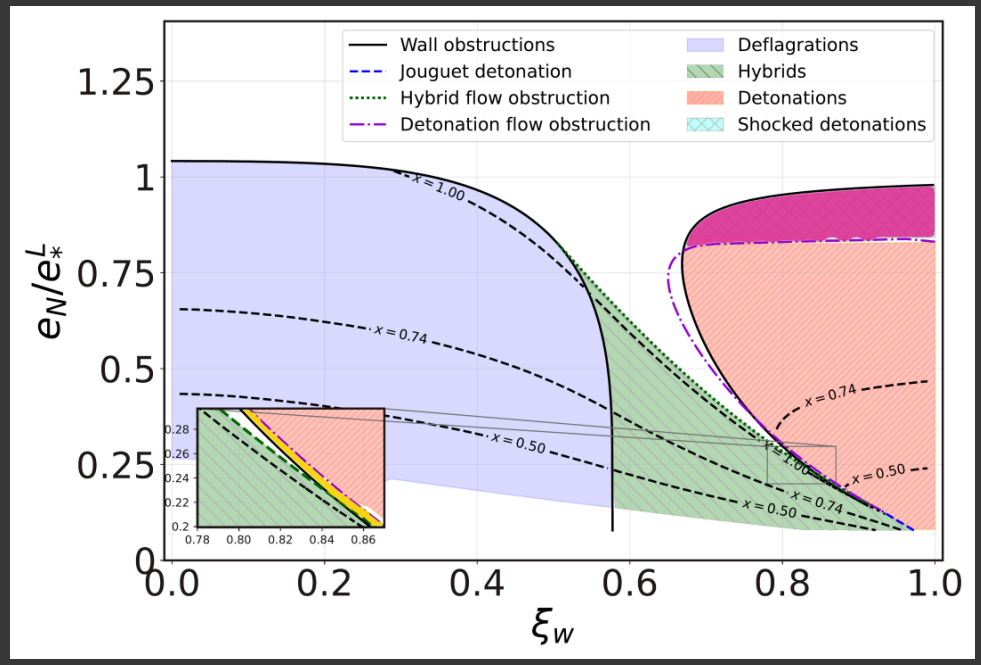
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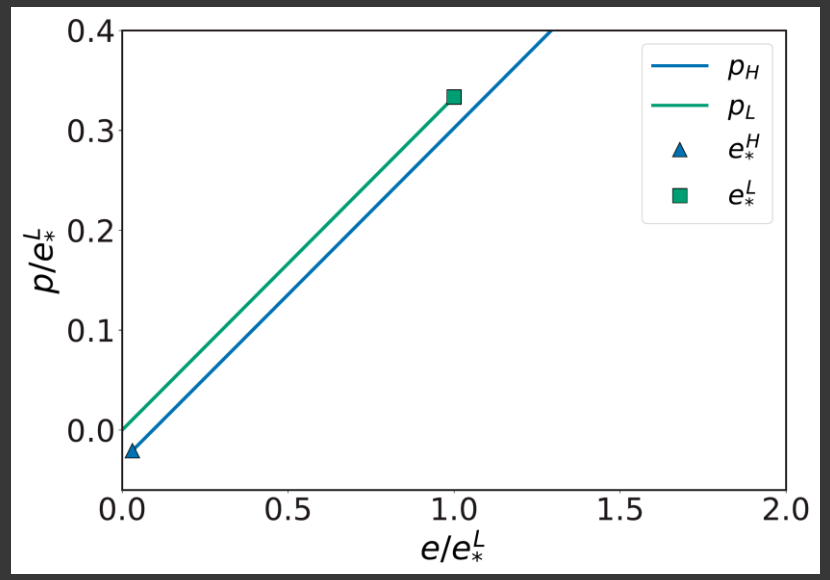




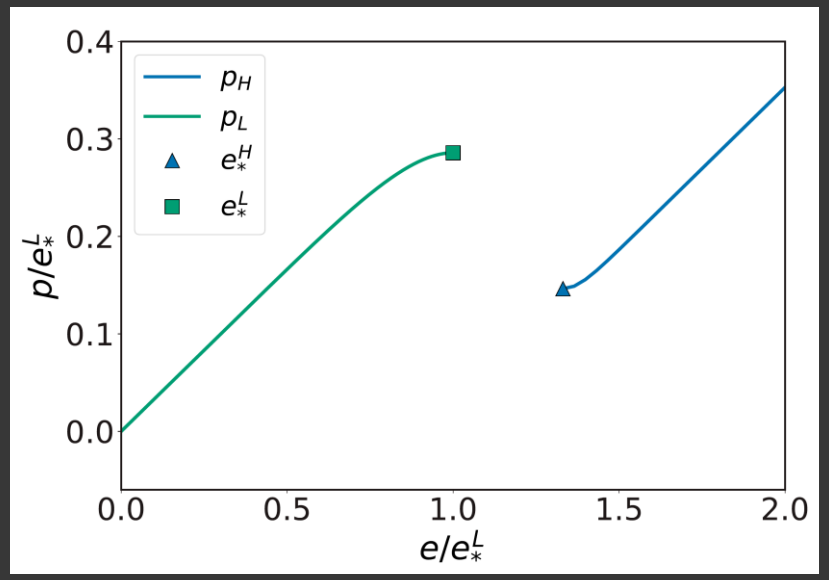
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SPACE OF SOLUTIONS

Bag-model-like EoS

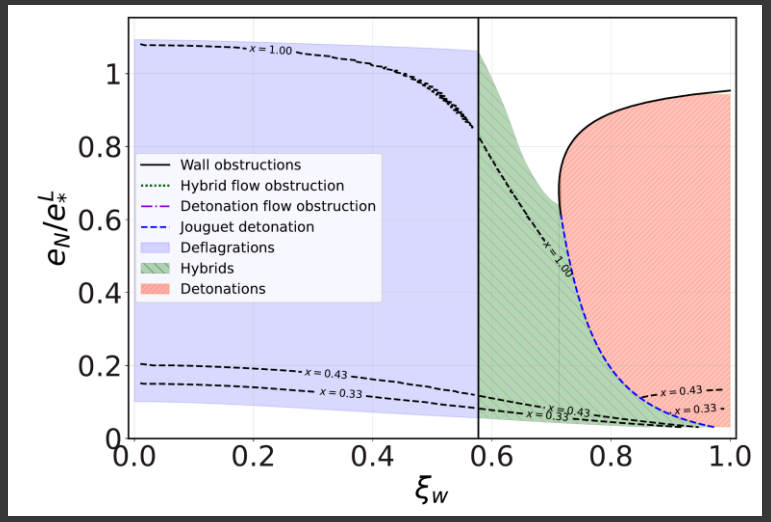


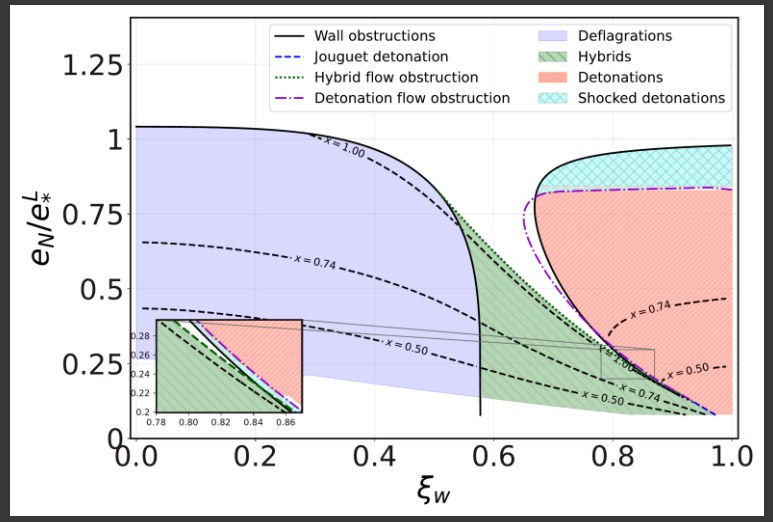
QCD-like EoS

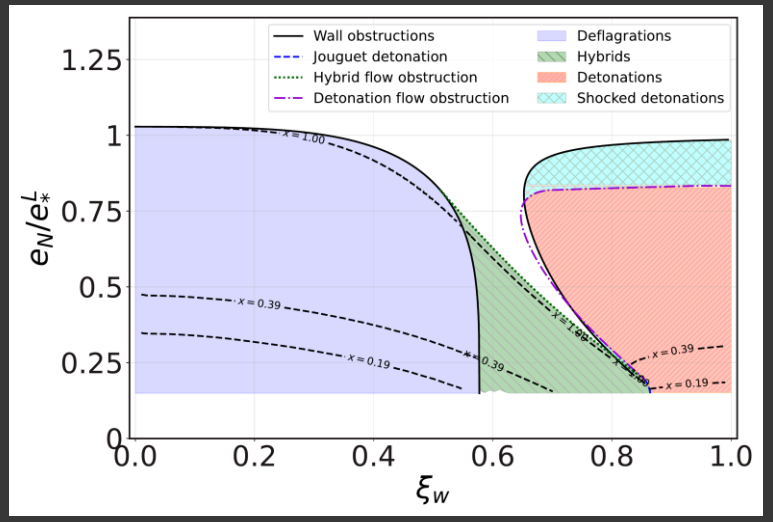


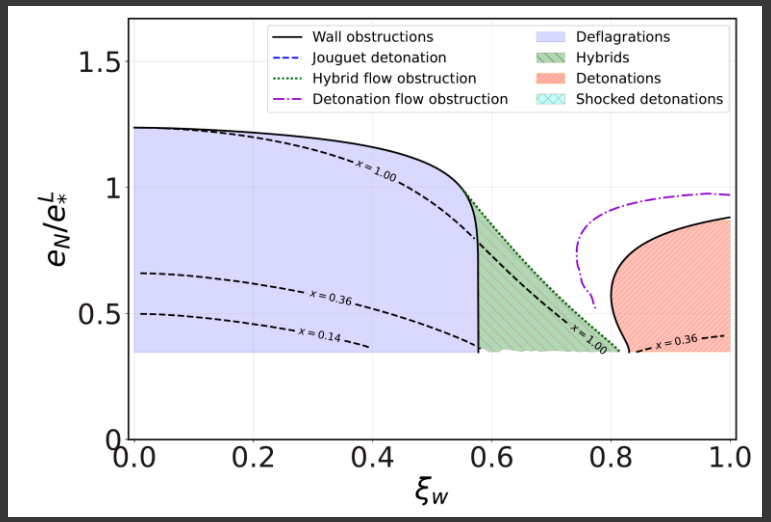
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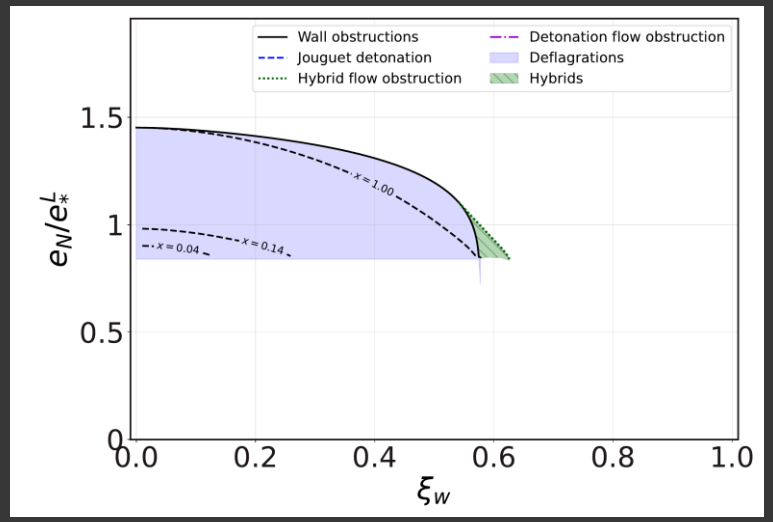
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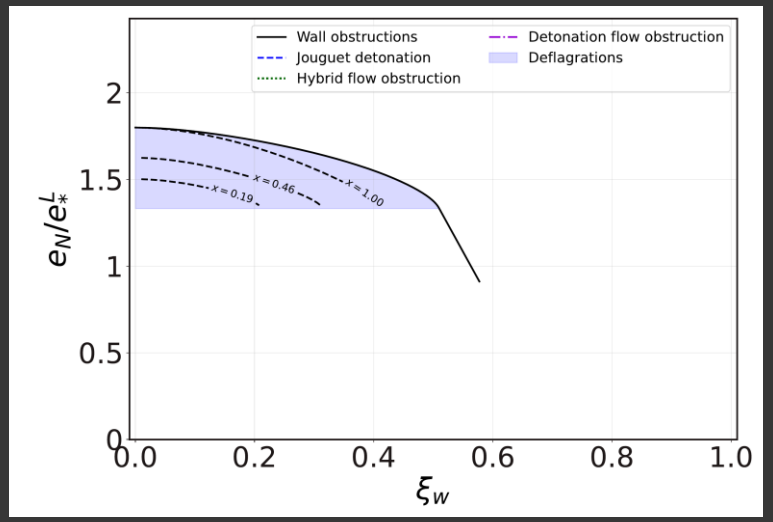












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KINETIC ENERGY FRACTION

- The kinetic energy fraction gives a proxy for the gravitational-wave emission:

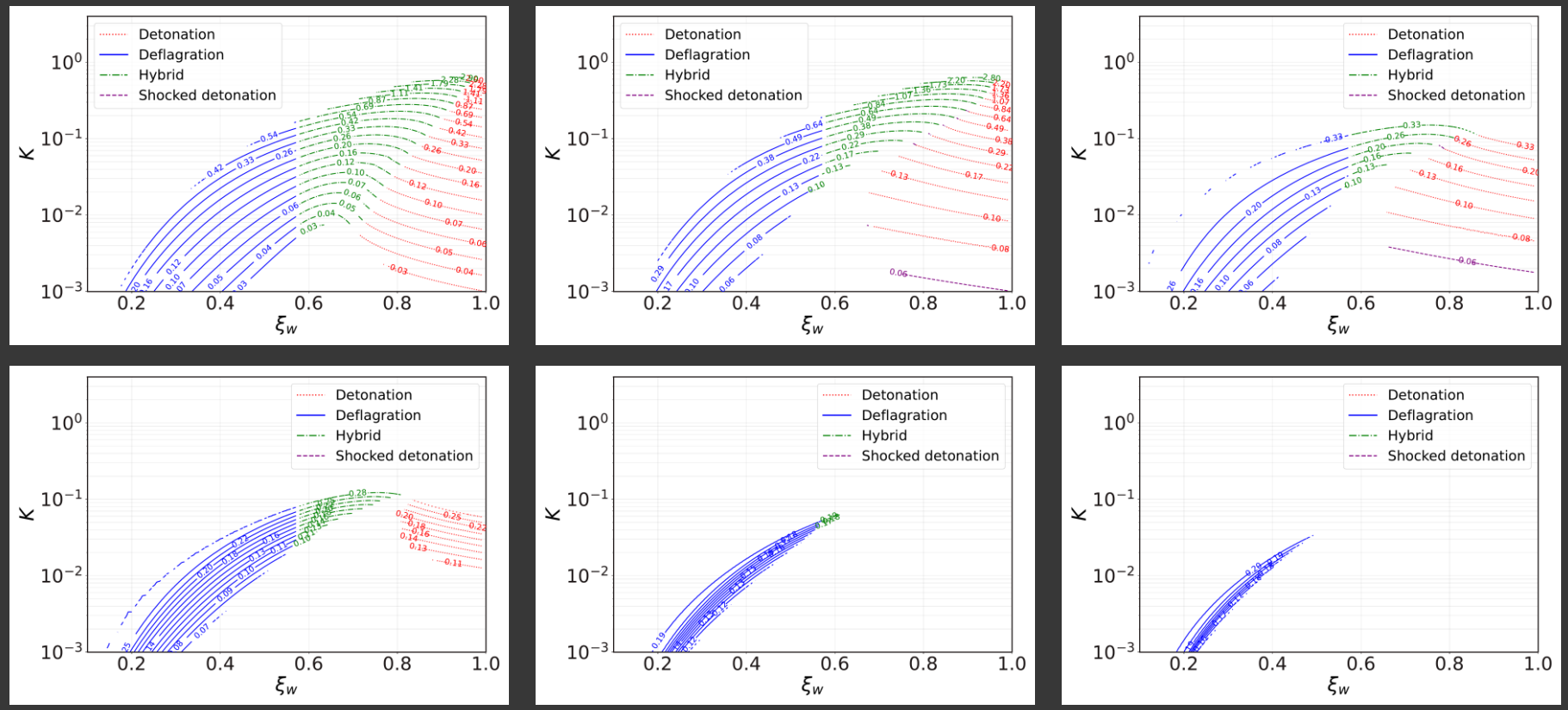
$$K = \frac{\int_{V_{\text{bubble}}} d^3x \; w\gamma^2 v^2}{\int_{V_{\text{bubble}}} d^3x \; (w\gamma^2 - p)}$$

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FUTURE WORK

- Dynamics of the transition: cosmic separation of phases
  [Aurrekoetxea, Bea, Luna, Mateos, Sanchez-Garitaonandia, **PTA**, van de Vis, in progress]
- Non-conformal effects in superheated (inverse) FOPTs
- Finite chemical potential: non-conformality fully couples the charge equation ⇒ neutron star mergers

Code: **SNOBEX** — github.com/pedrota2000/SNOBEX

CONCLUSIONS

Applying for postdocs!
pedro.tarancon@icc.ub.edu
github.com/pedrota2000

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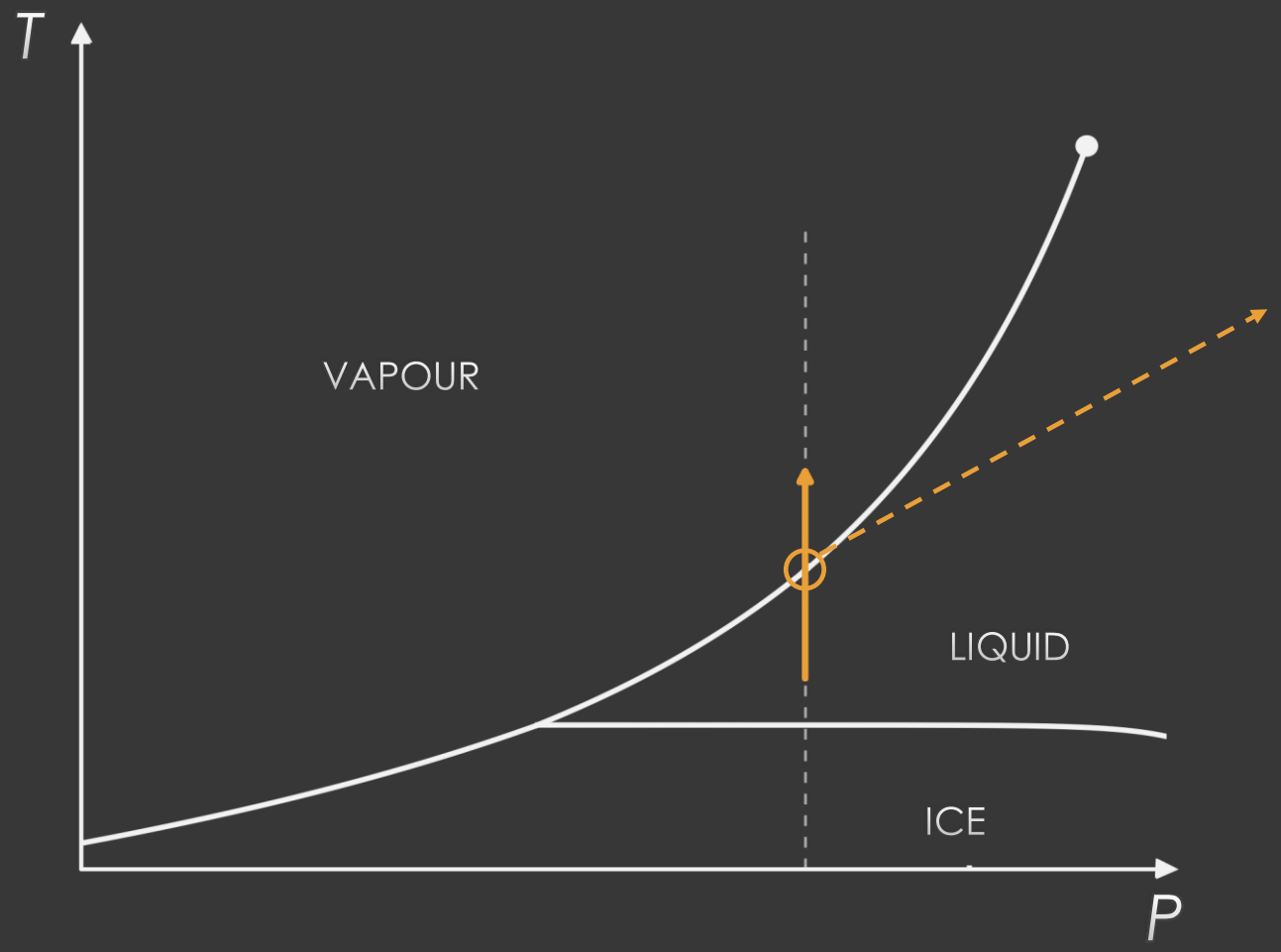
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THANK YOU!

BACKUP SLIDES

FIRST ORDER PHASE TRANSITIONS

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BOILING WATER

OUTLOOK

1 HYDRODYNAMICS OF EXPANDING BUBBLES
BUBBLES IN A CONFORMAL EOS

2 NON-CONFORMAL EQUATIONS OF STATE
FROM BAG MODEL TO QCD-LIKE

3 NON-CONFORMAL OBSTRUCTIONS
AT THE WALL AND ALONG THE FLOW

4 CONCLUSIONS

EXPANSION MODES IN THE BAG MODEL

[Espinosa et al., JCAP 06 (2010) 028]

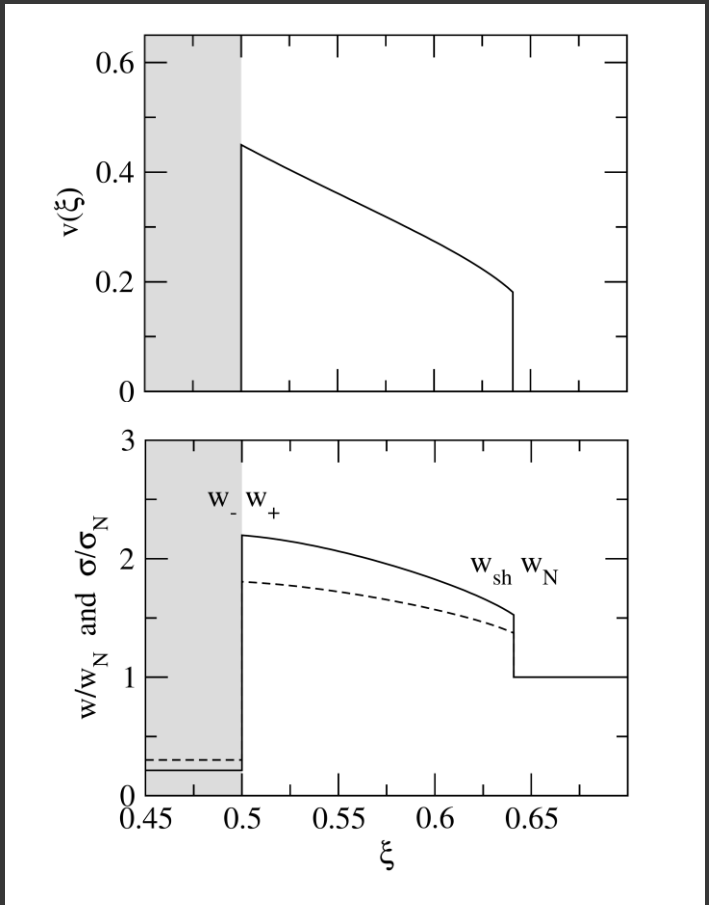
Deflagration	Hybrid	Detonation
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$c_s < \xi_w < \xi_J$

Detonation

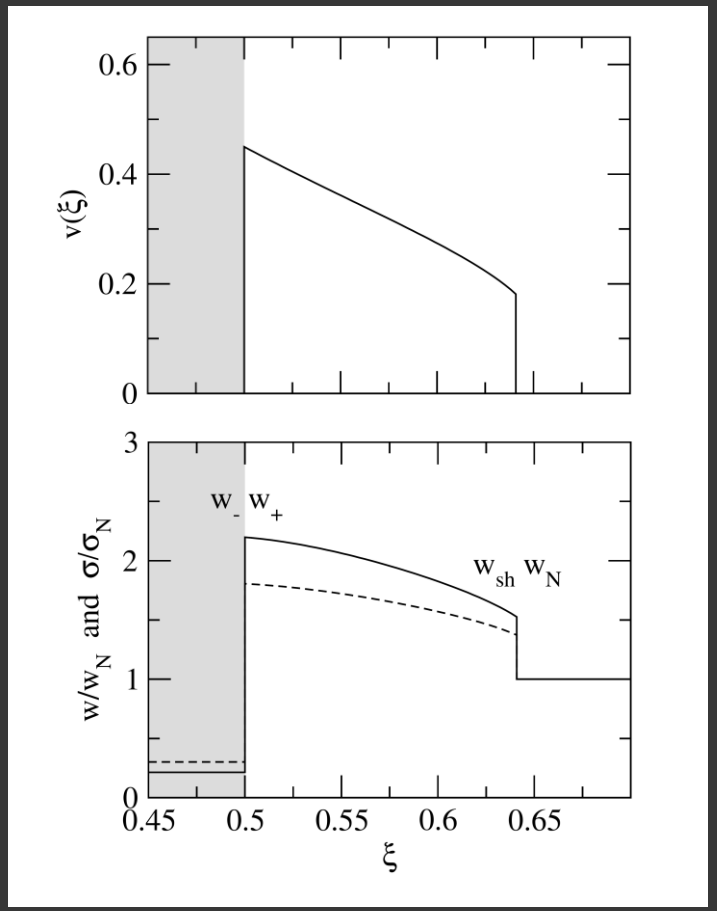
$\xi_w > \xi_J$

EXPANSION MODES IN THE BAG MODEL

[Espinosa et al., JCAP 06 (2010) 028]

Deflagration

$\xi_w < c_s$

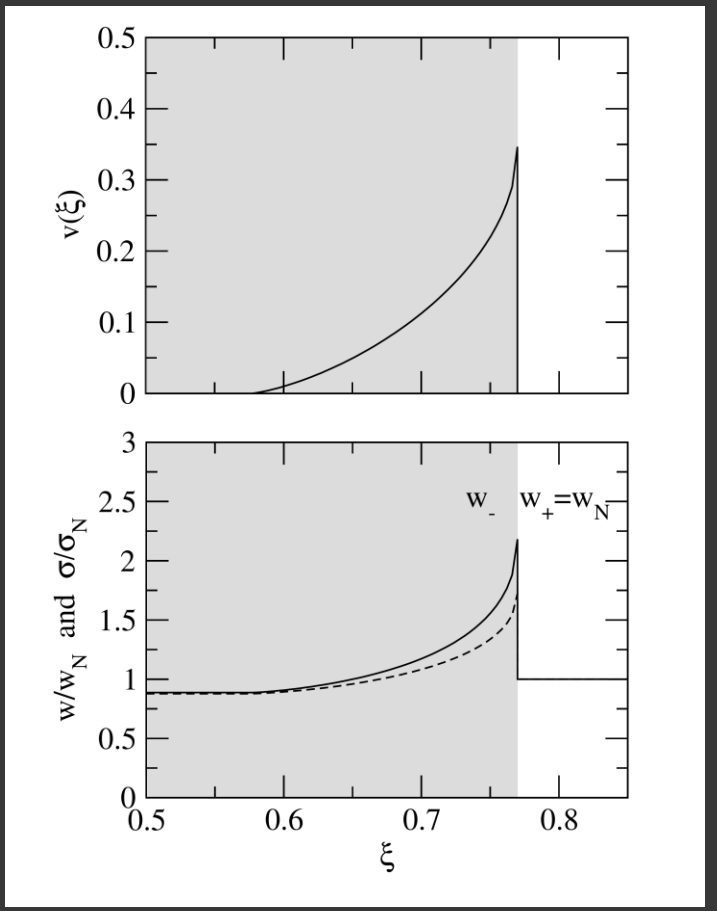


Hybrid

$c_s < \xi_w < \xi_J$

Detonation

$\xi_w > \xi_J$

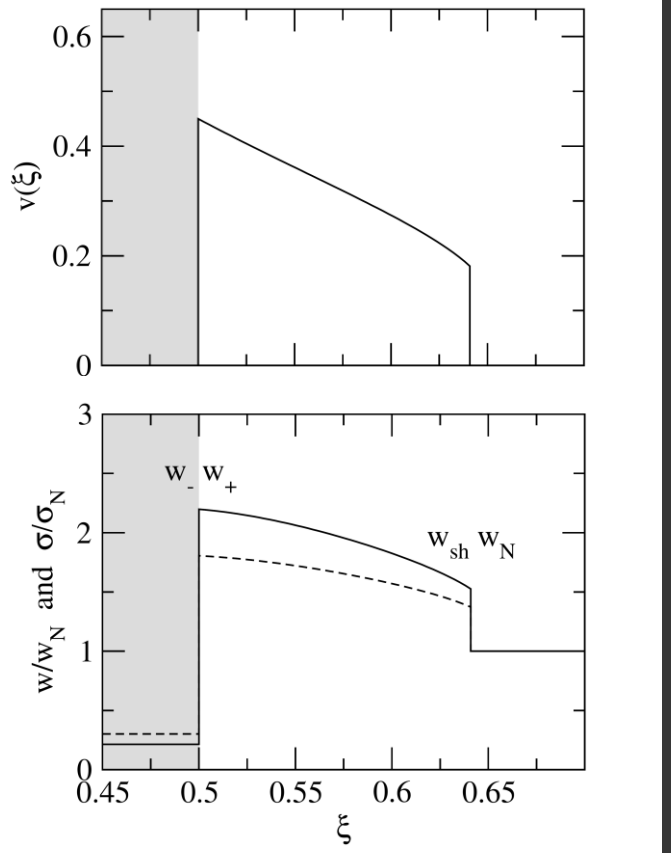


EXPANSION MODES IN THE BAG MODEL

[Espinosa et al., JCAP 06 (2010) 028]

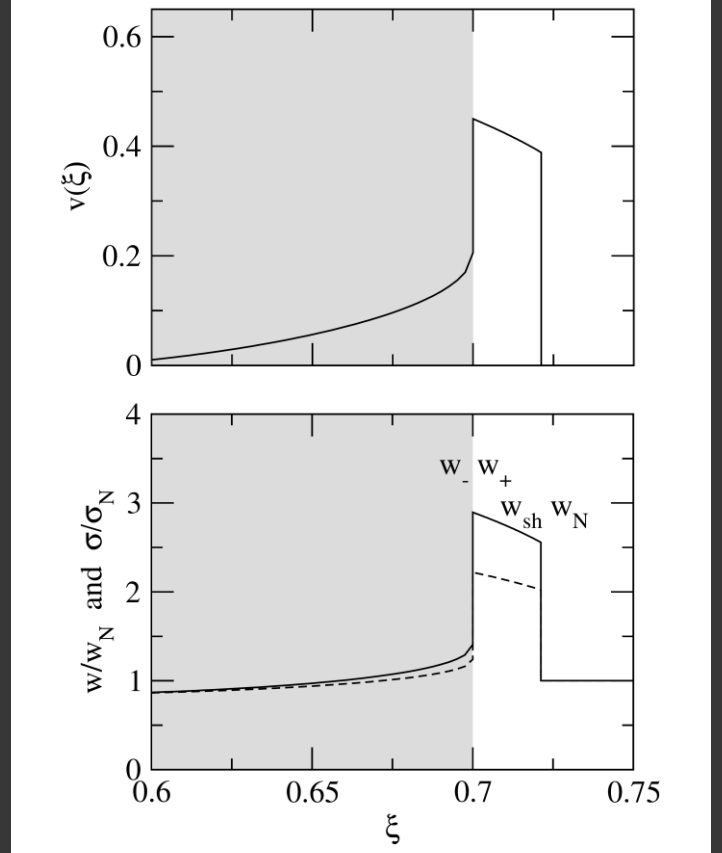
Deflagration

$\xi_w < c_s$



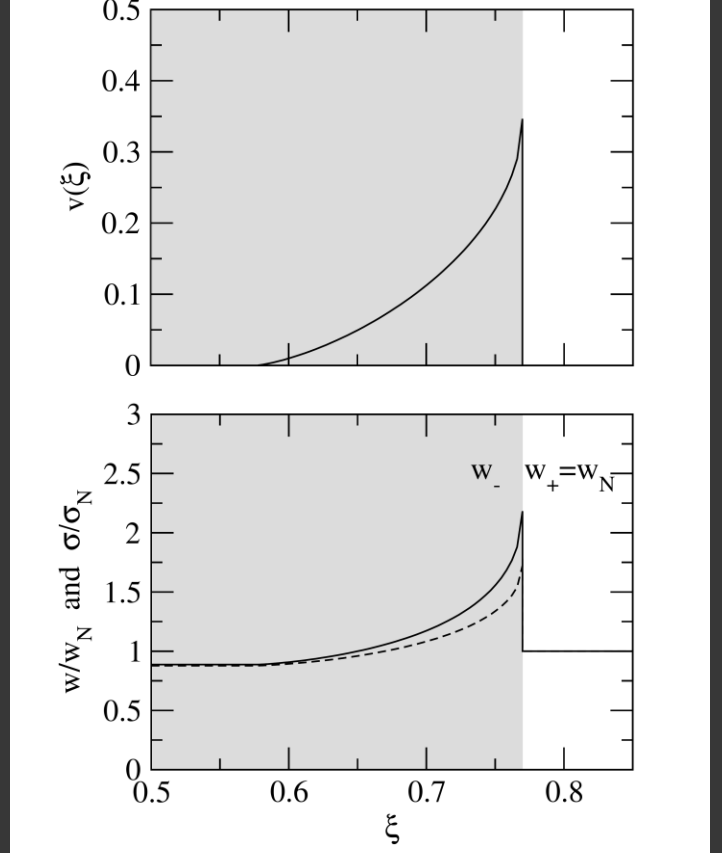
Hybrid

$c_s < \xi_w < \xi_J$



Detonation

$\xi_w > \xi_J$

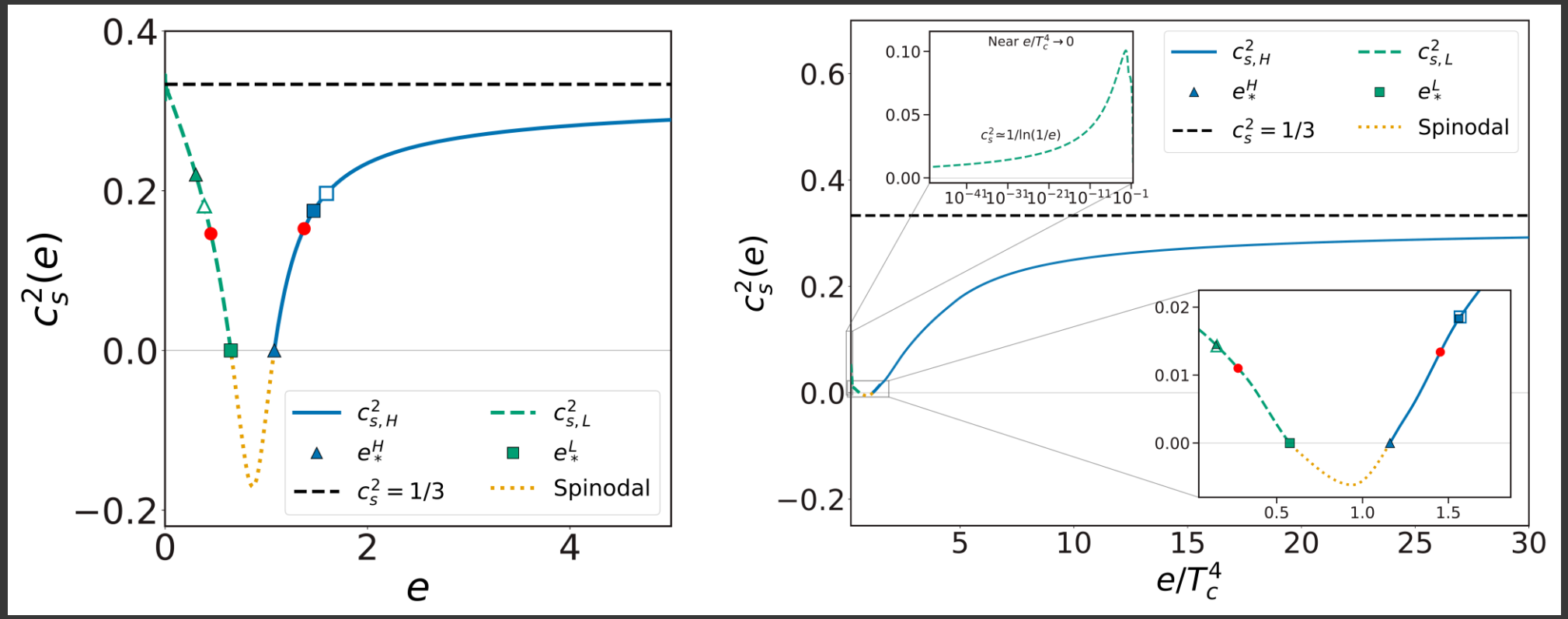


[Castorina et al., EPJC 66 (2010) 207; Vovchenko et al., PRC 91 (2015) 024905; Agasian et al., EPJA 53 (2017) 138; Khaidukov et al., PRD 98 (2018) 074031; Athenodorou, Teper, JHEP 11 (2020) 172; Mason et al., EPJ Web Conf. 274 (2022) 08007; Mason et al., PoS LATTICE2022 (2023) 216; Lucini et al., PRD 108 (2023) 074517; Giusti et al., PLB 868 (2025) 139775]

"QCD-LIKE" EQUATIONS OF STATE

Holographic model

Pure SU(3) YM

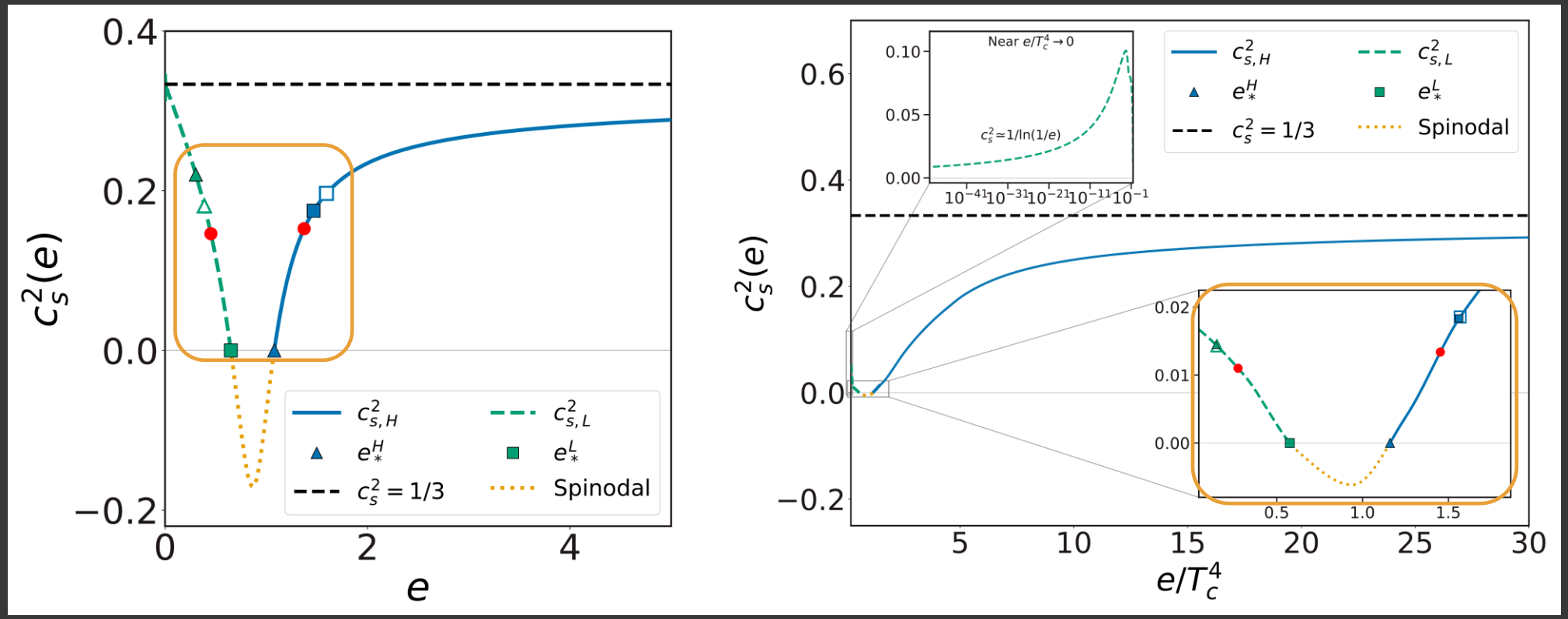


[Castorina et al., EPJC 66 (2010) 207; Vovchenko et al., PRC 91 (2015) 024905; Agasian et al., EPJA 53 (2017) 138; Khaidukov et al., PRD 98 (2018) 074031; Athenodorou, Teper, JHEP 11 (2020) 172; Mason et al., EPJ Web Conf. 274 (2022) 08007; Mason et al., PoS LATTICE2022 (2023) 216; Lucini et al., PRD 108 (2023) 074517; Giusti et al., PLB 868 (2025) 139775]

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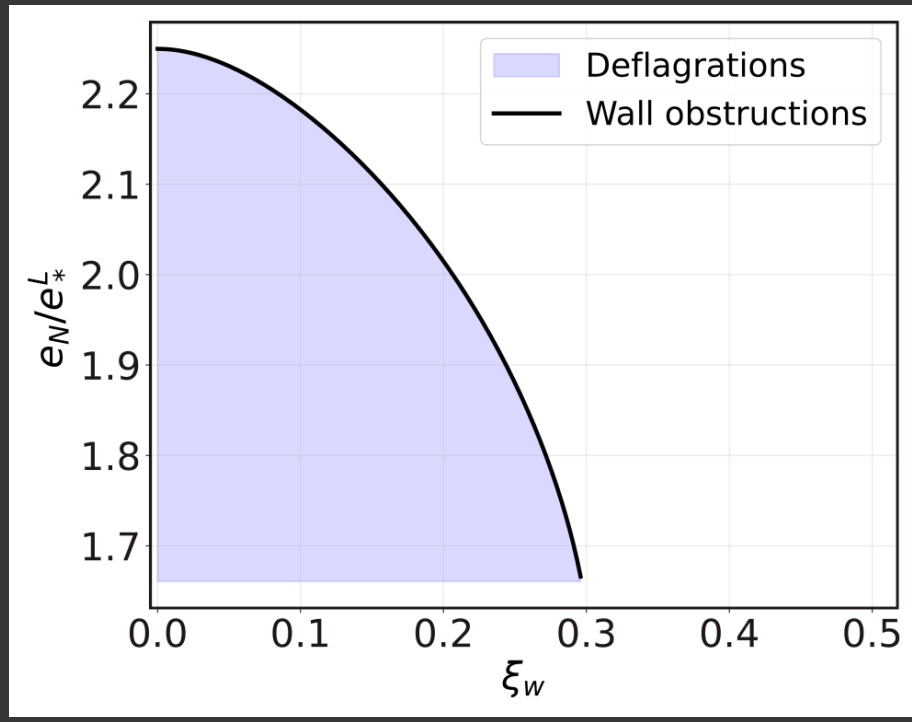


- In the range relevant for the transition, both are qualitatively similar

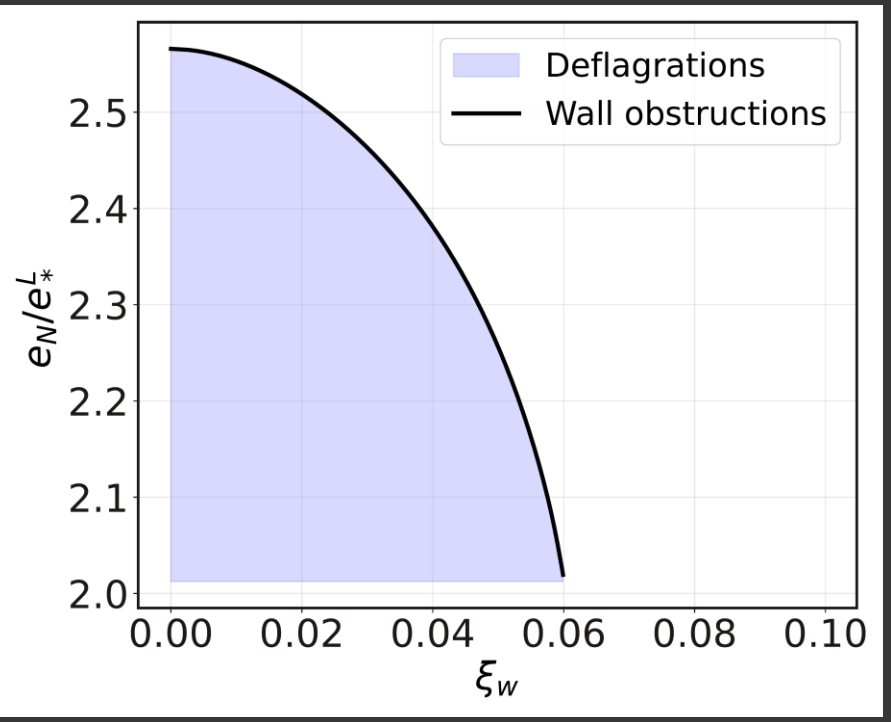
[Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

BUBBLES IN QCD-LIKE THEORIES

Holographic model



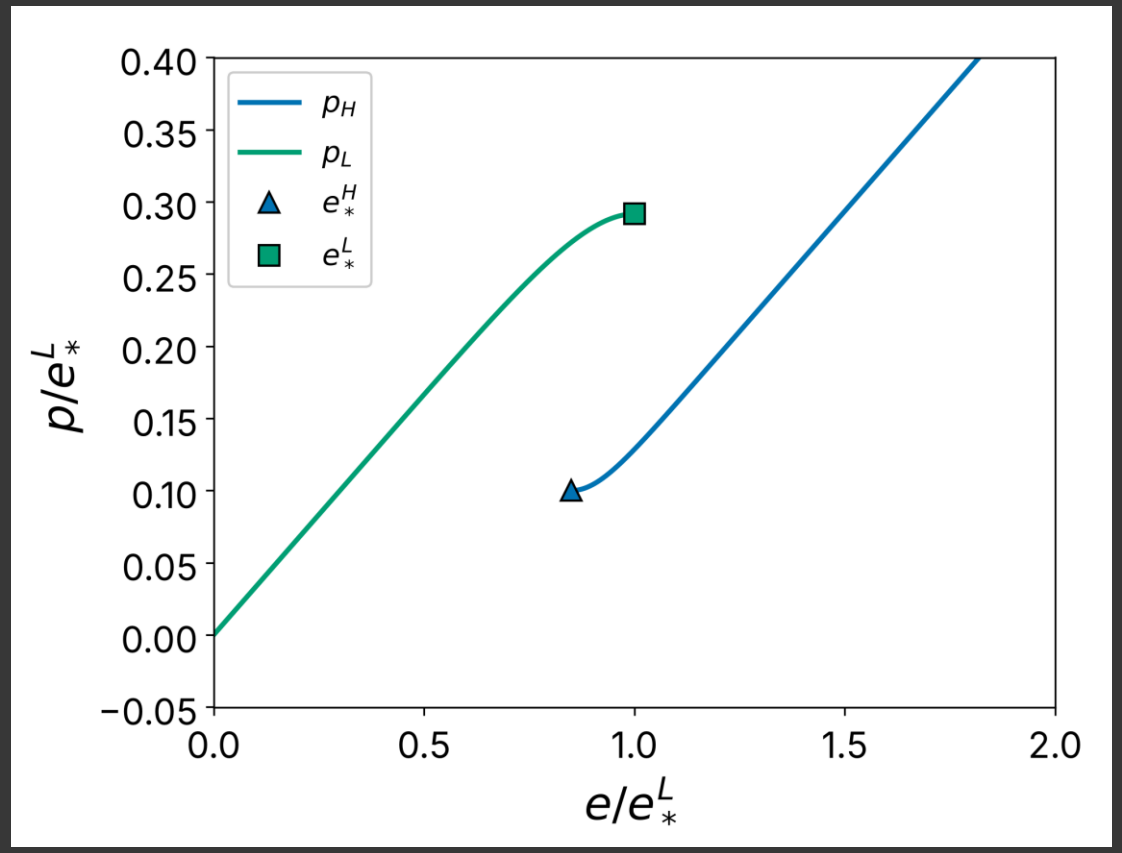
Pure SU(3) YM



[Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

ENTROPY

- Check whether the obstructions we find are more restrictive than the second law

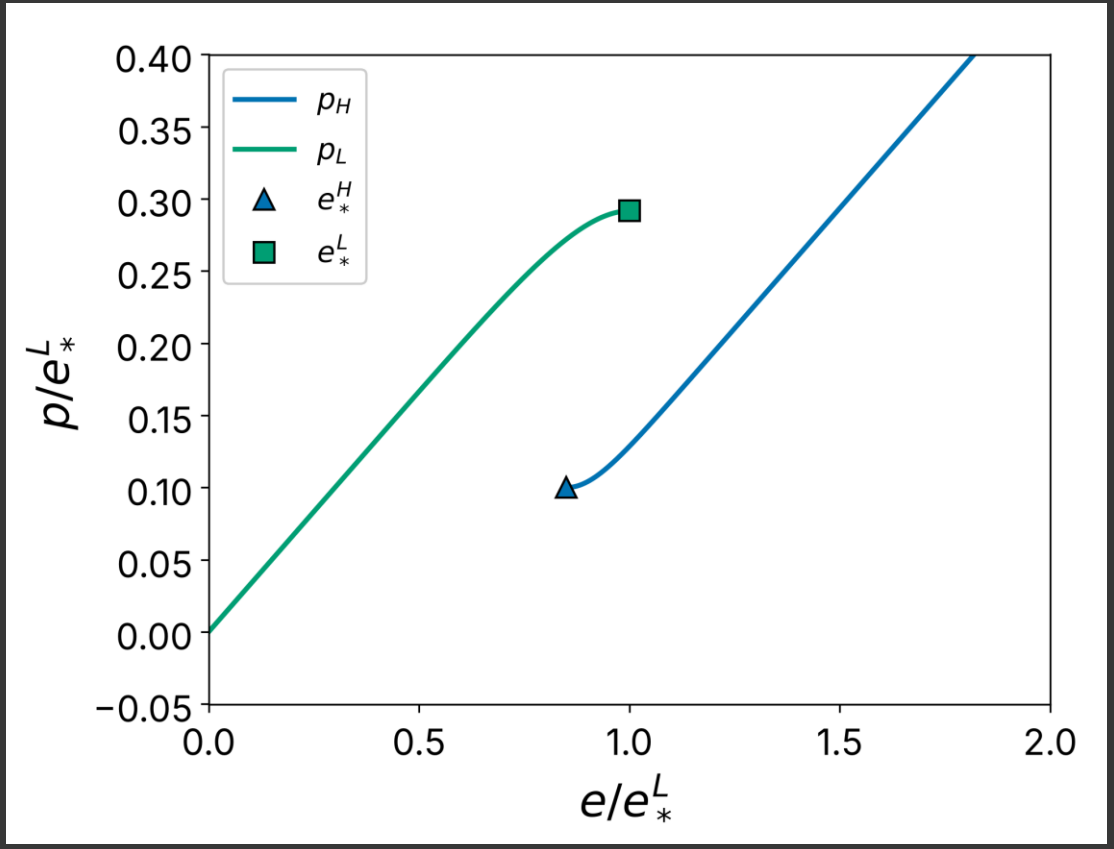


[Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

ENTROPY

- Check whether the obstructions we find are more restrictive than the second law
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$$e + p(e) = T\, s = \frac{s(e)}{s'(e)}$$



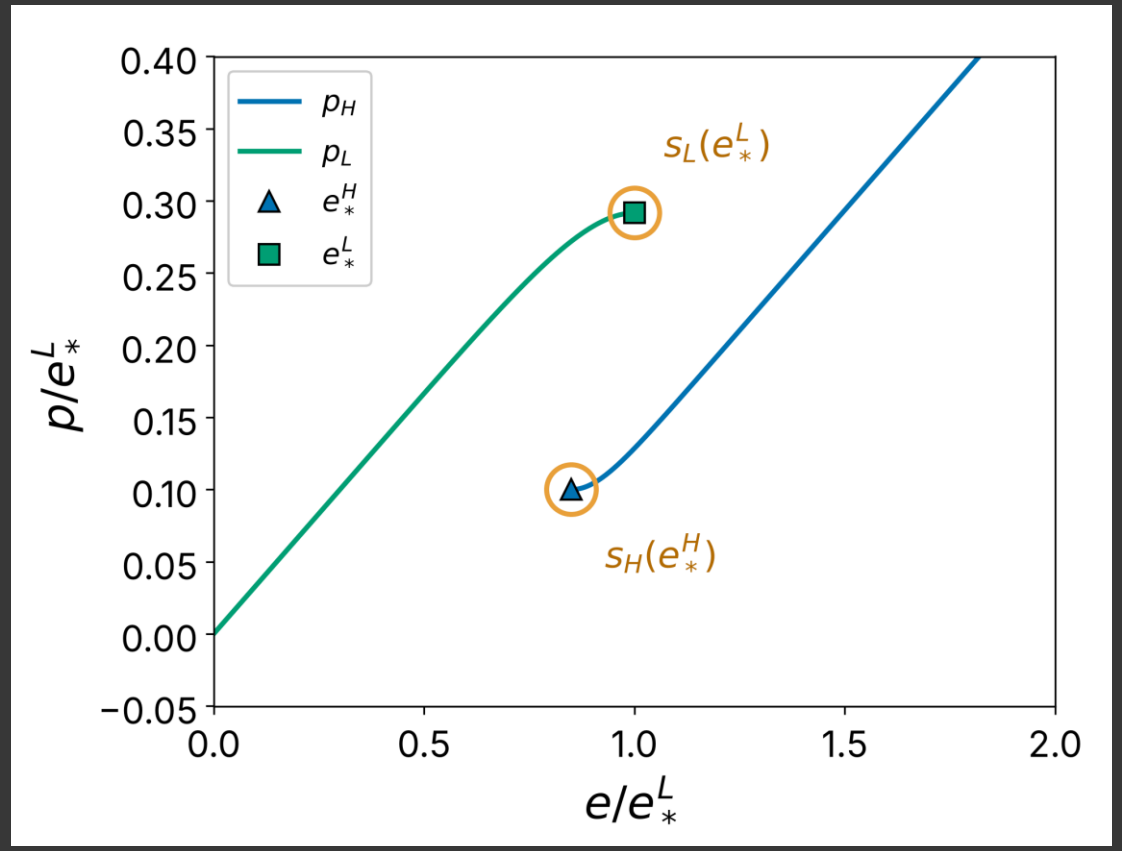
[Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

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- Check whether the obstructions we find are more restrictive than the second law
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  - Only one if the spinodal branch is included



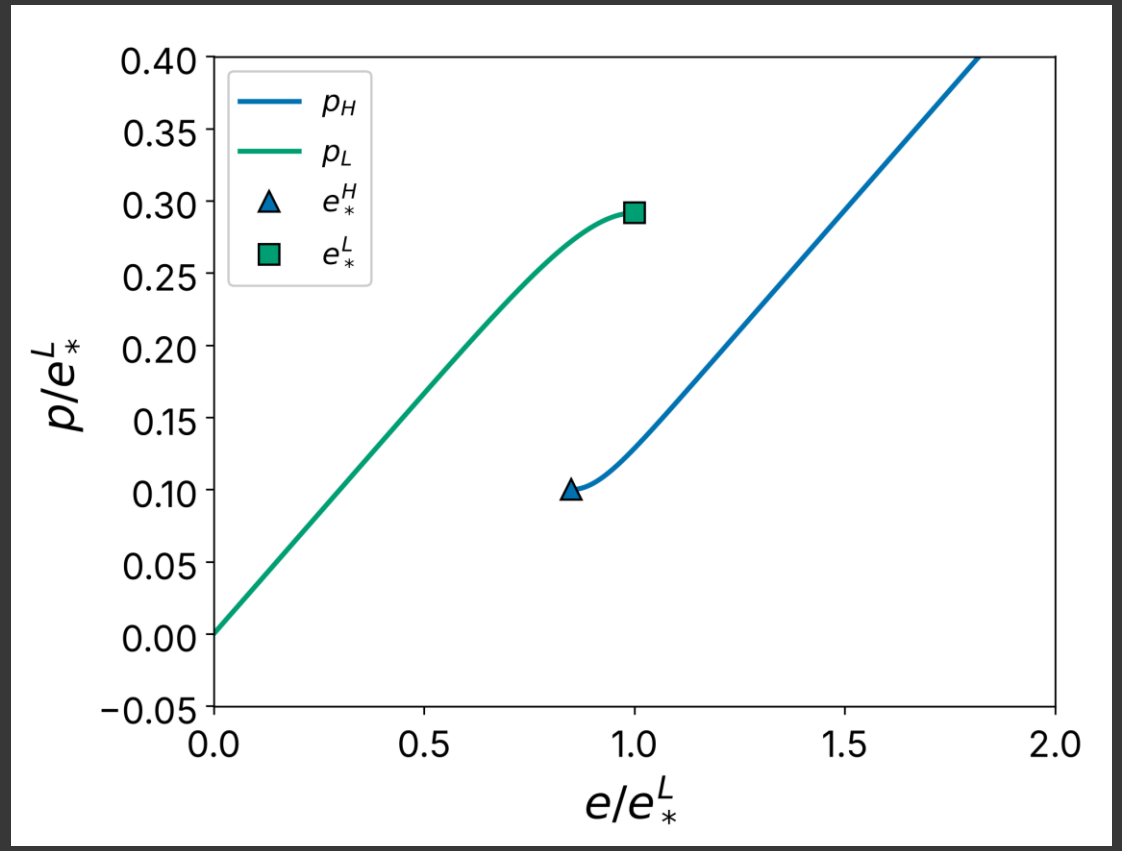
[Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

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- Equivalent to choosing $T_c \Longrightarrow p_c$



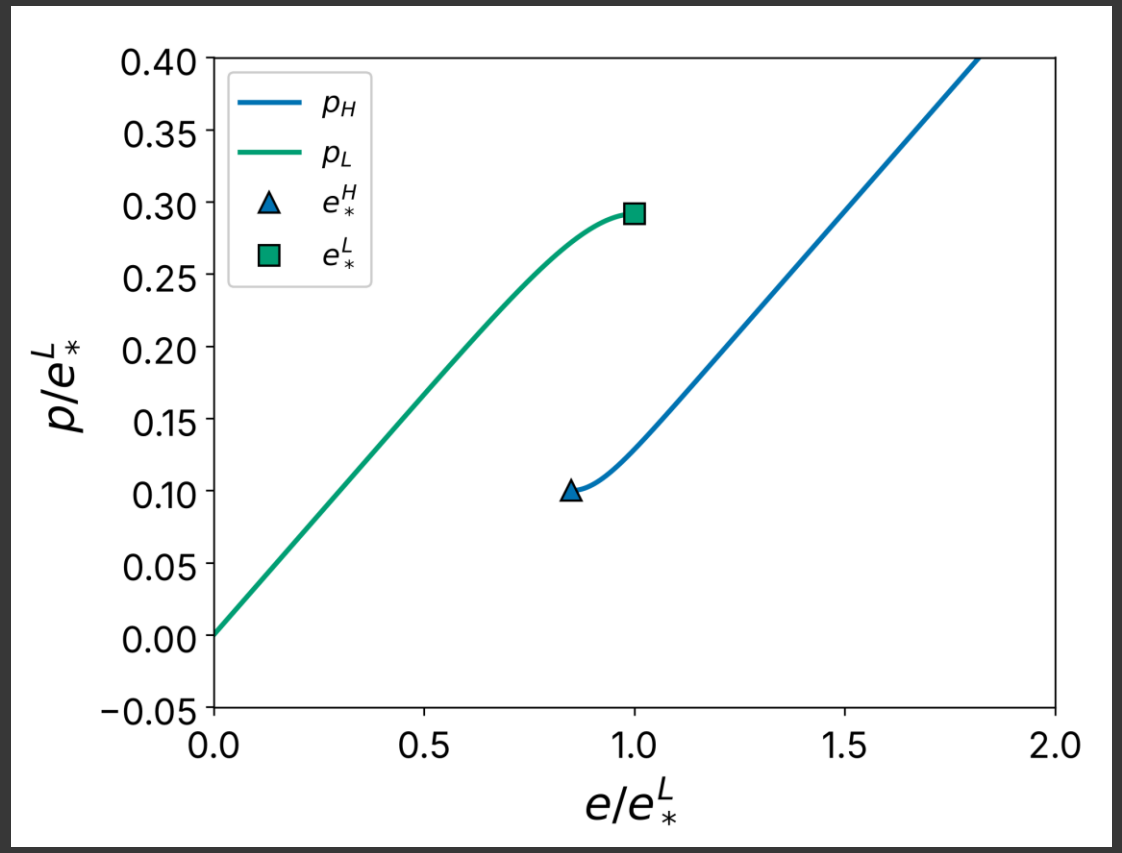
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- Label the choices by x:

$$x = \frac{T_c - T(e_*^H)}{T(e_*^L) - T(e_*^H)}$$



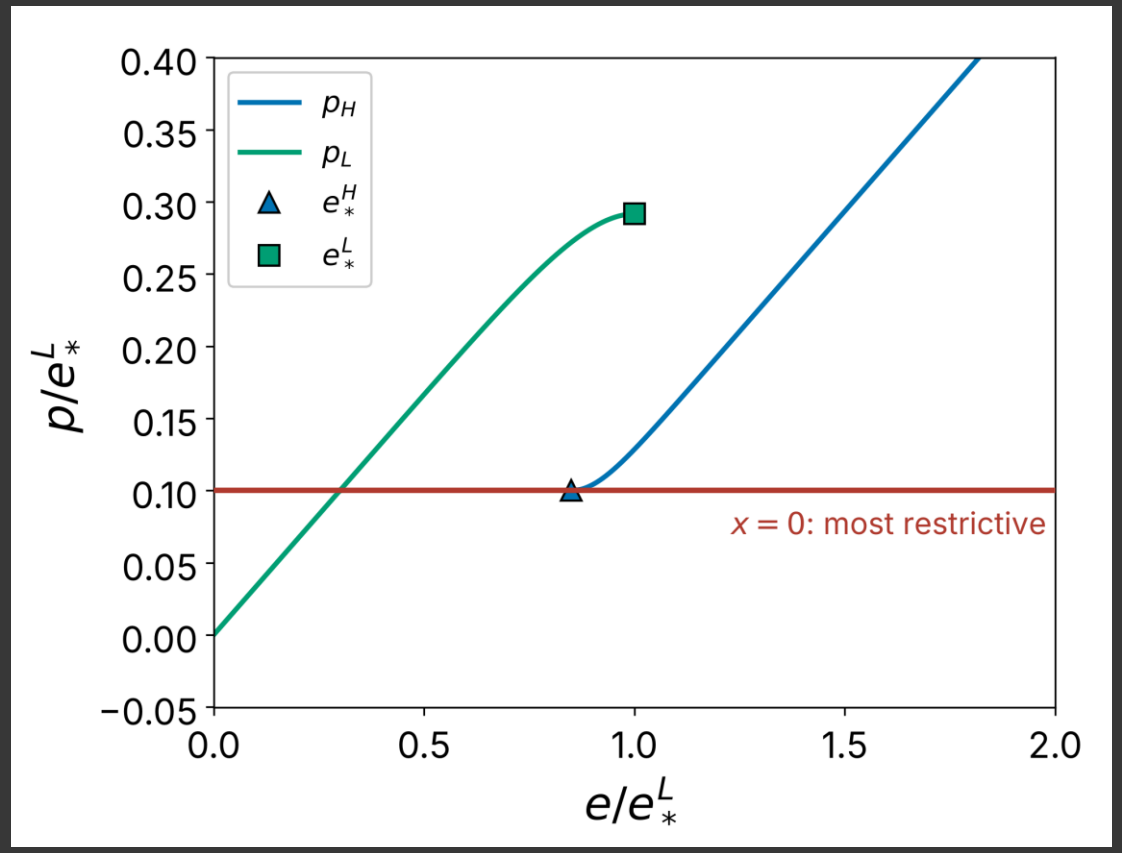
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[Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

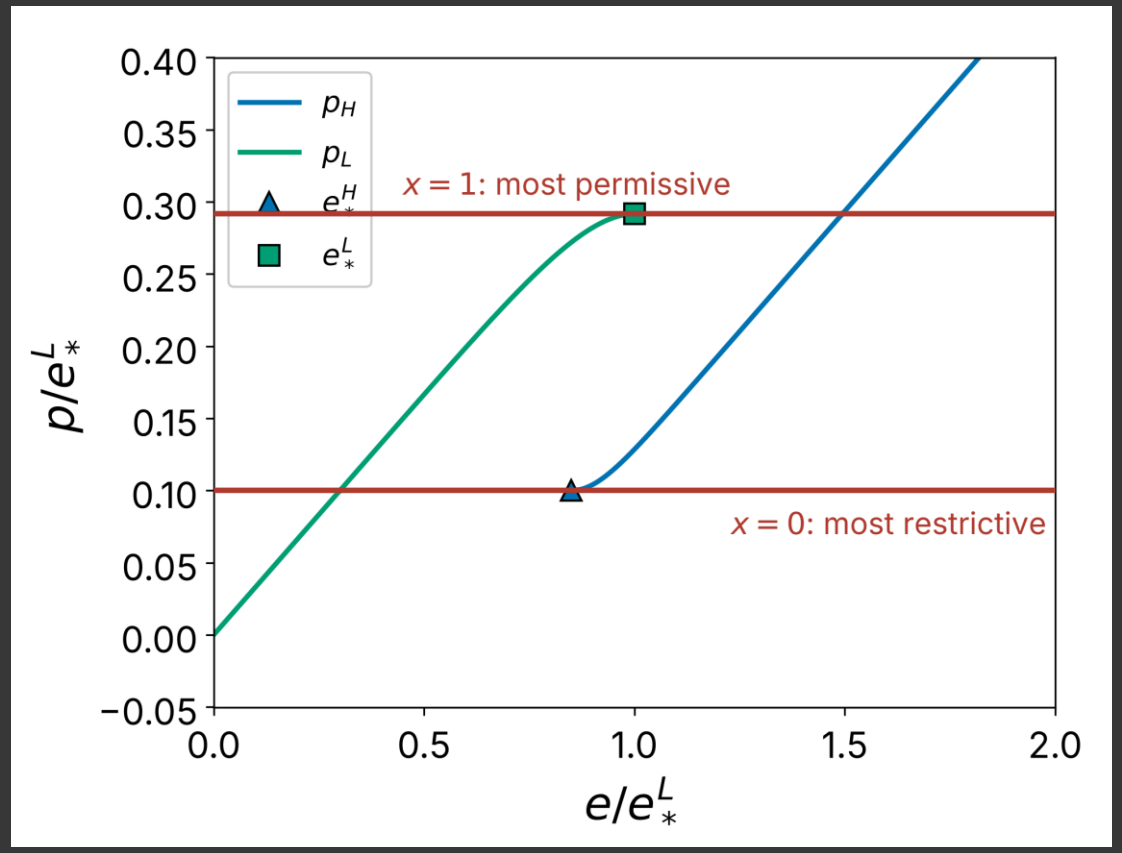
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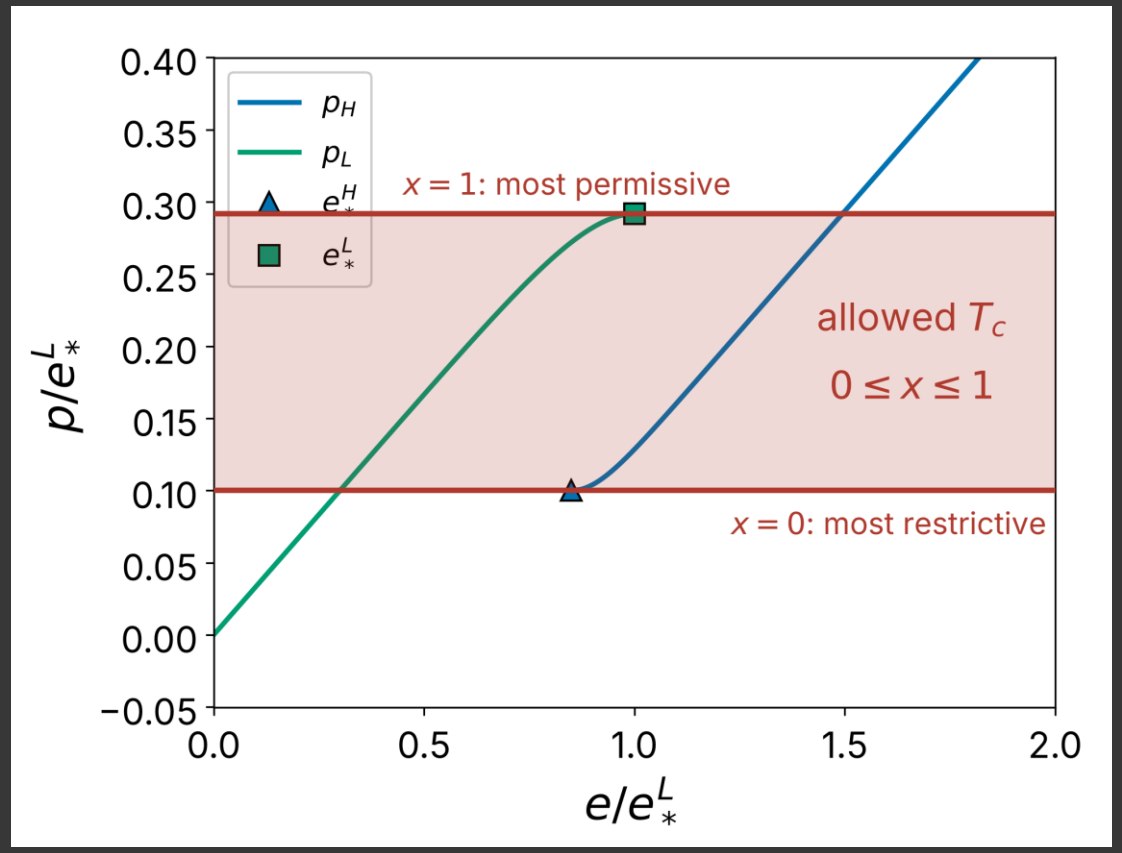
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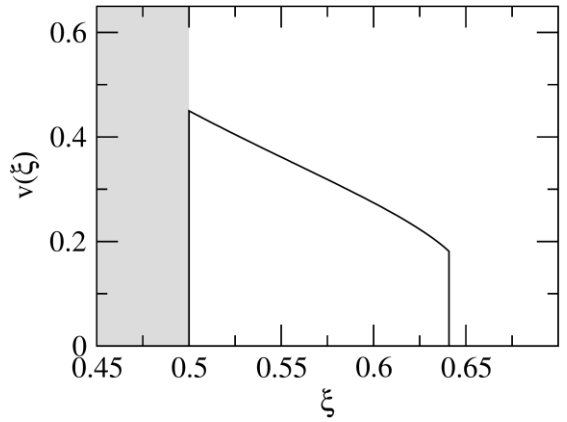


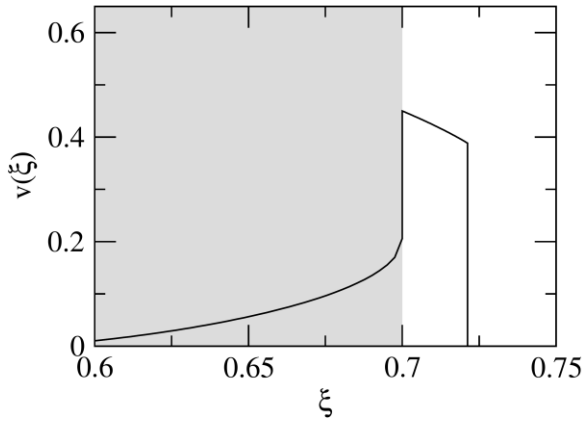
[Espinosa et al., JCAP 06 (2010) 028; Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

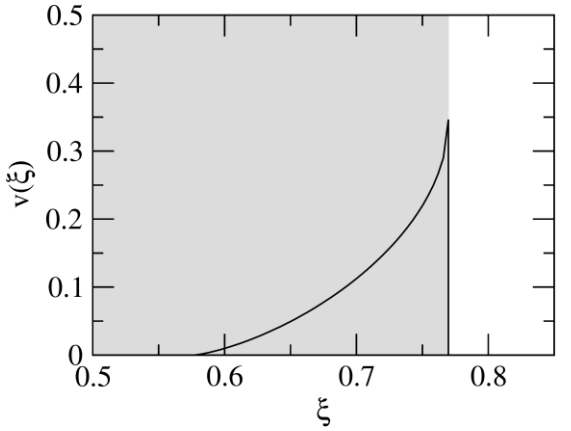
VELOCITY PROFILES: BAG MODEL VS QCD-LIKE

Deflagration | Hybrid | Detonation

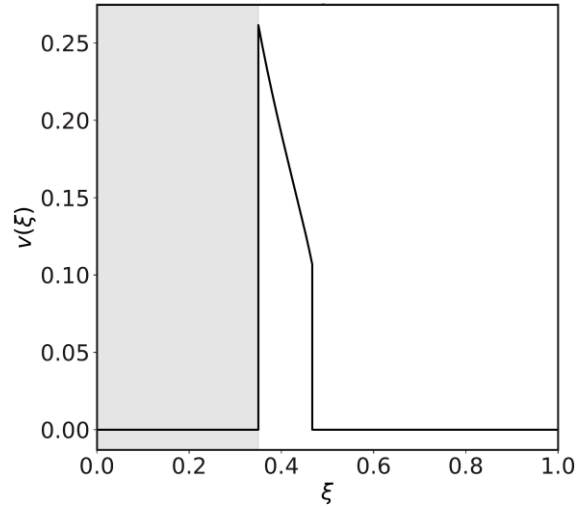
Bag model

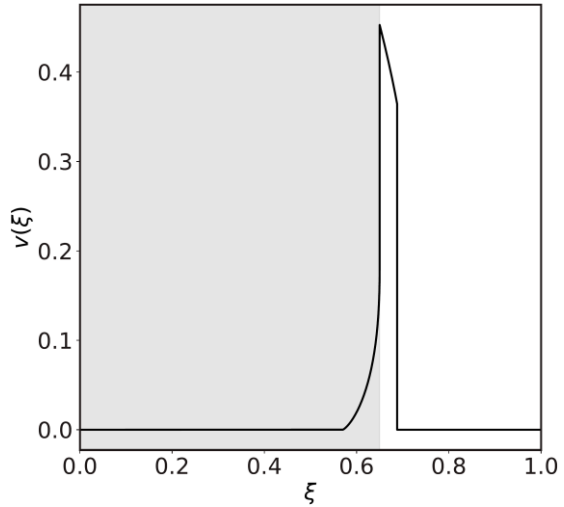


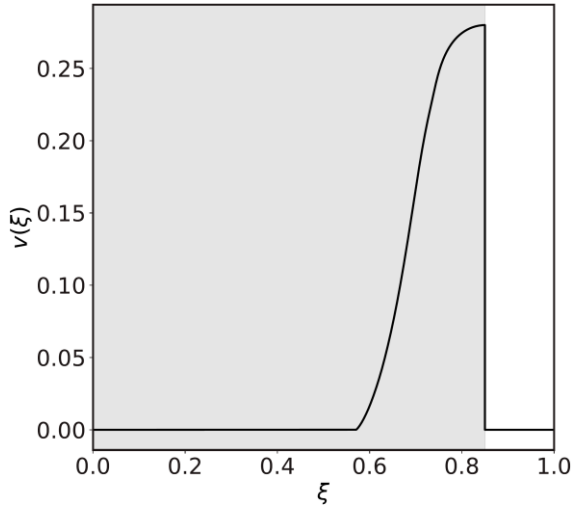




Our ansatz

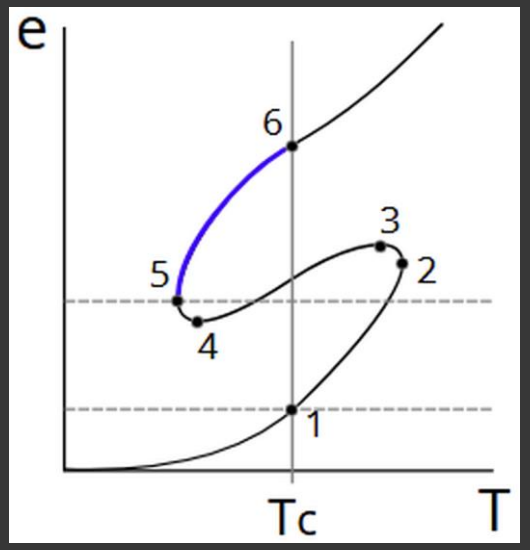


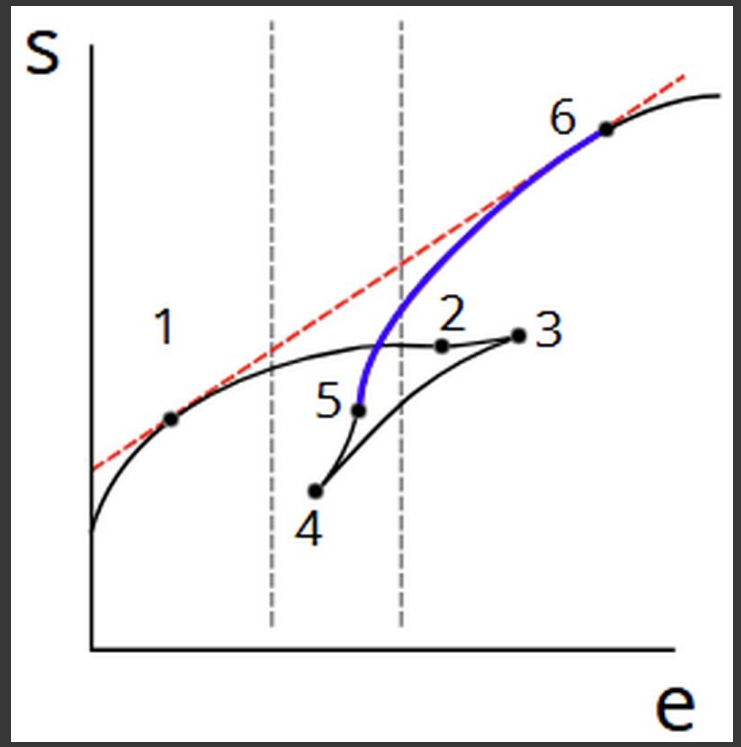


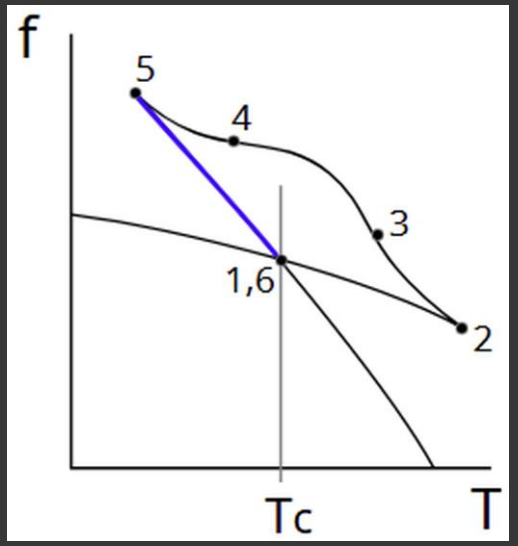


[Aurrekoetxea, Bea, Luna, Mateos, Sanchez-Garitaonandia, **PTA**, van de Vis, in progress]

SEPARATION OF PHASES



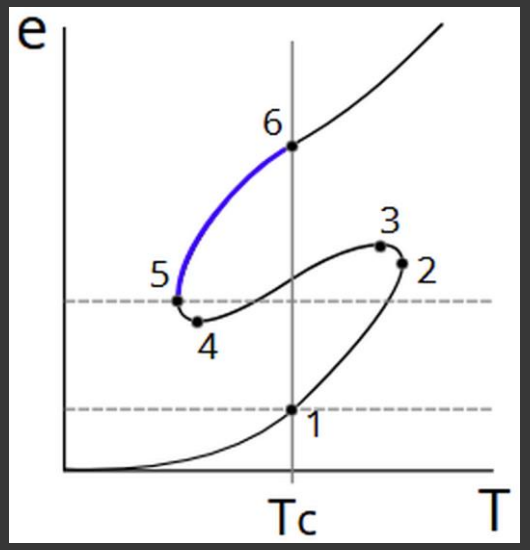


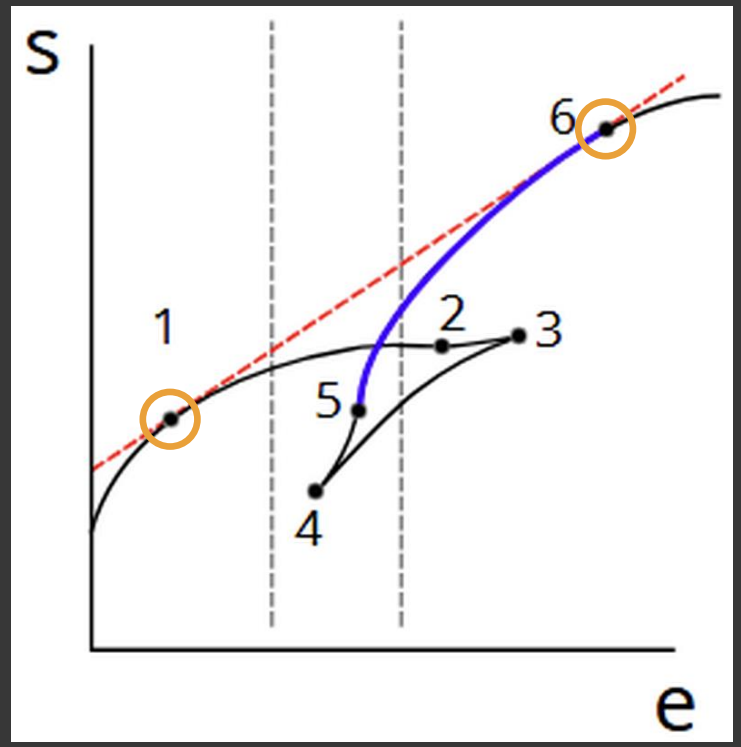


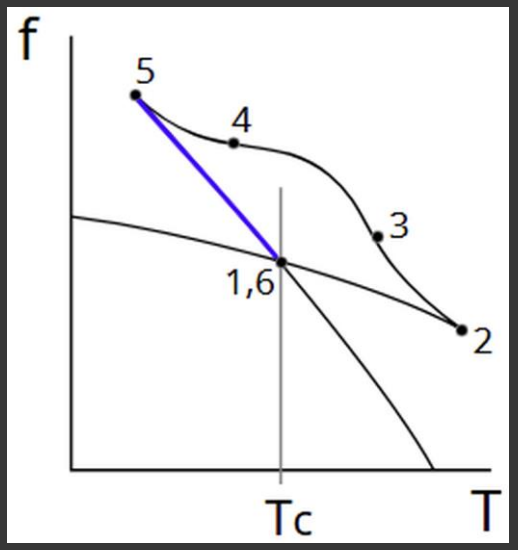
[Aurrekoetxea, Bea, Luna, Mateos, Sanchez-Garitaonandia, **PTA**, van de Vis, in progress]

SEPARATION OF PHASES

- At $T = T_c$ the two phases have the same free energy: they can coexist (points 1, 6)



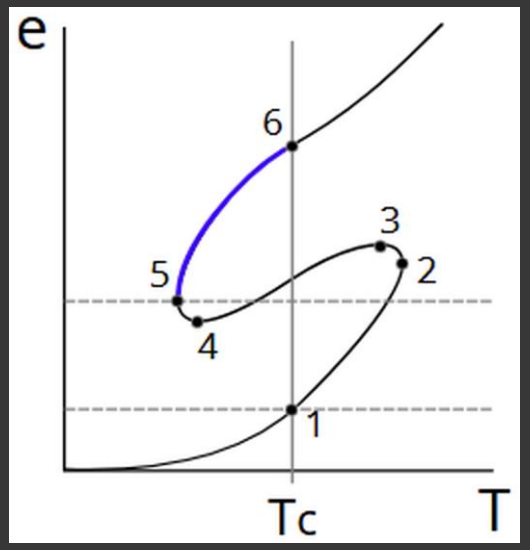


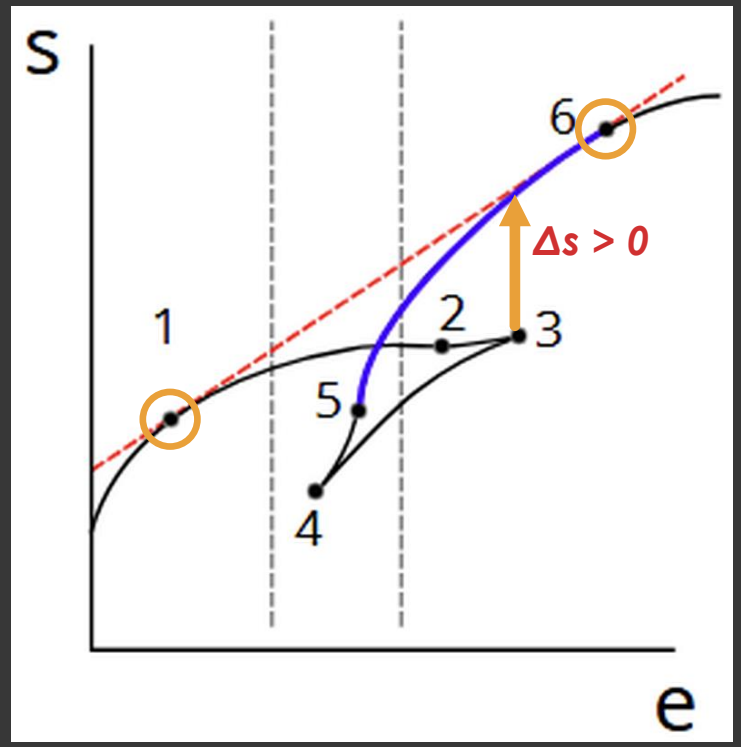


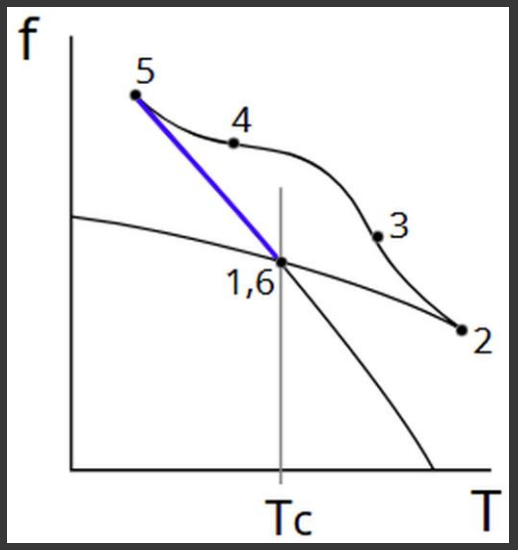
[Aurrekoetxea, Bea, Luna, Mateos, Sanchez-Garitaonandia, **PTA**, van de Vis, in progress]

SEPARATION OF PHASES

- At $T = T_c$ the two phases have the same free energy: they can coexist (points 1, 6)
- A mixture of 1 and 6 has the entropy of the red line: above any homogeneous state with the same energy



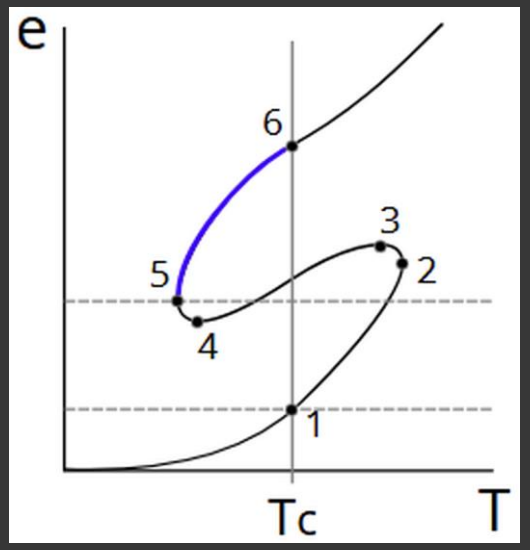


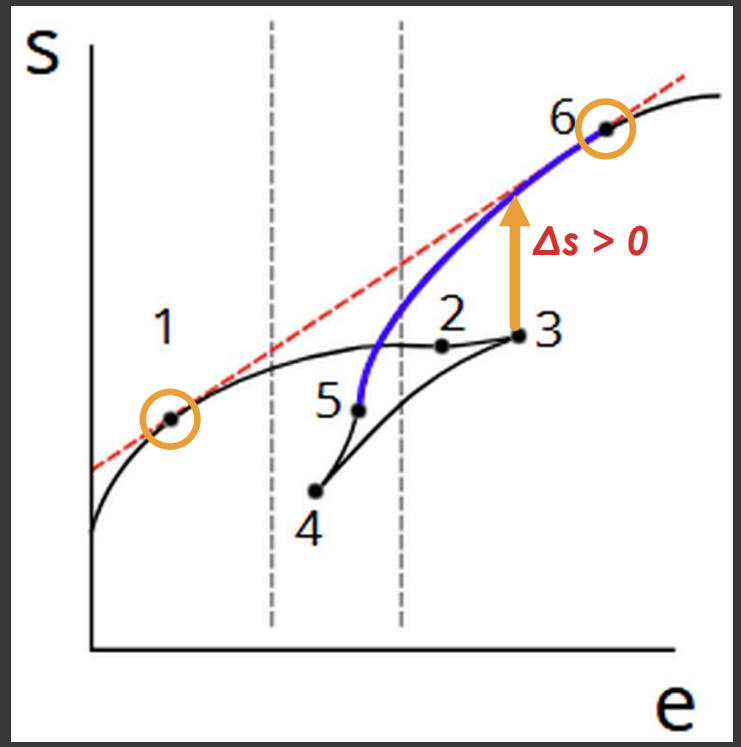


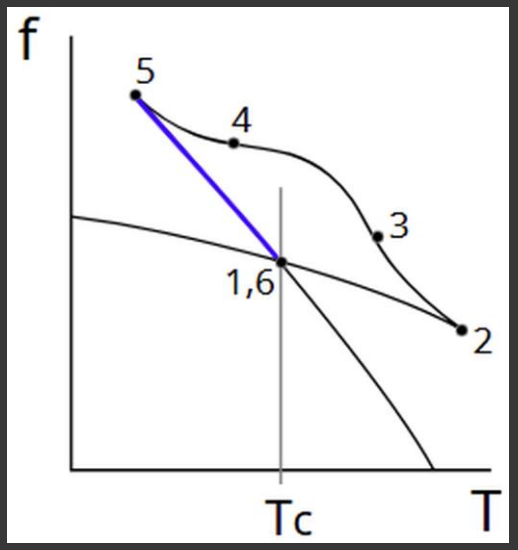
[Aurrekoetxea, Bea, Luna, Mateos, Sanchez-Garitaonandia, **PTA**, van de Vis, in progress]

SEPARATION OF PHASES

- At $T = T_c$ the two phases have the same free energy: they can coexist (points 1, 6)
- A mixture of 1 and 6 has the entropy of the red line: above any homogeneous state with the same energy
- Maximizing the entropy ⇒ the system separates into domains of the two coexisting phases



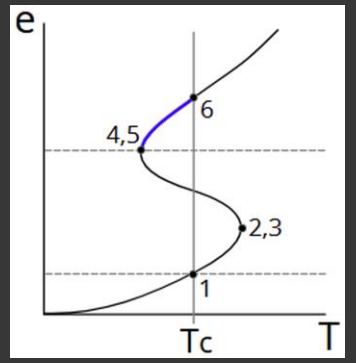


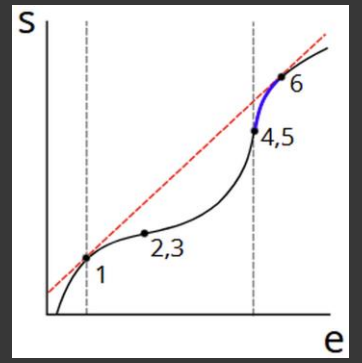


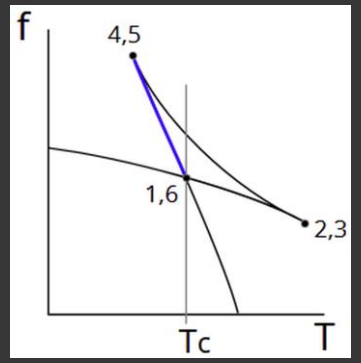
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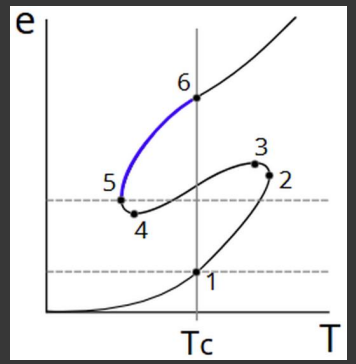
CASE 1

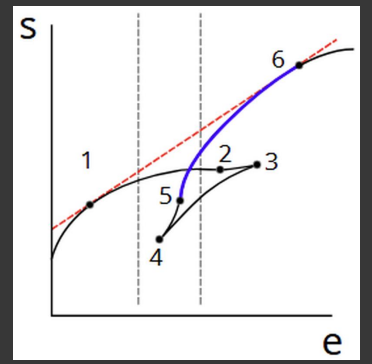


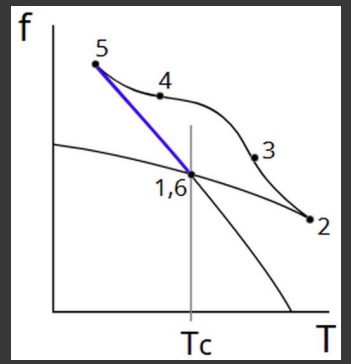




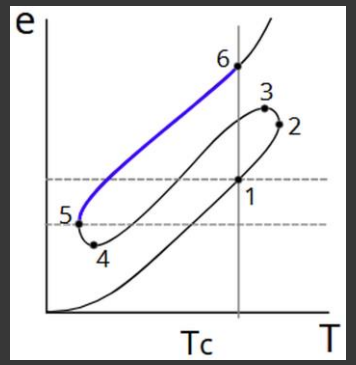
CASE 2

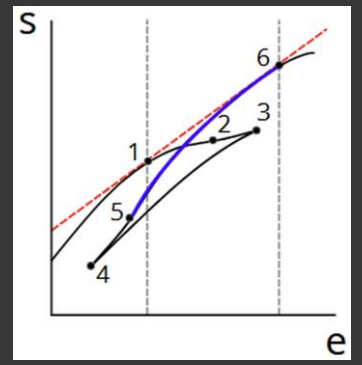


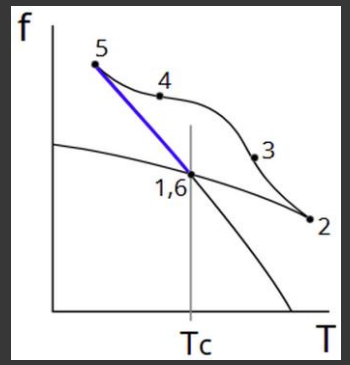




CASE 3



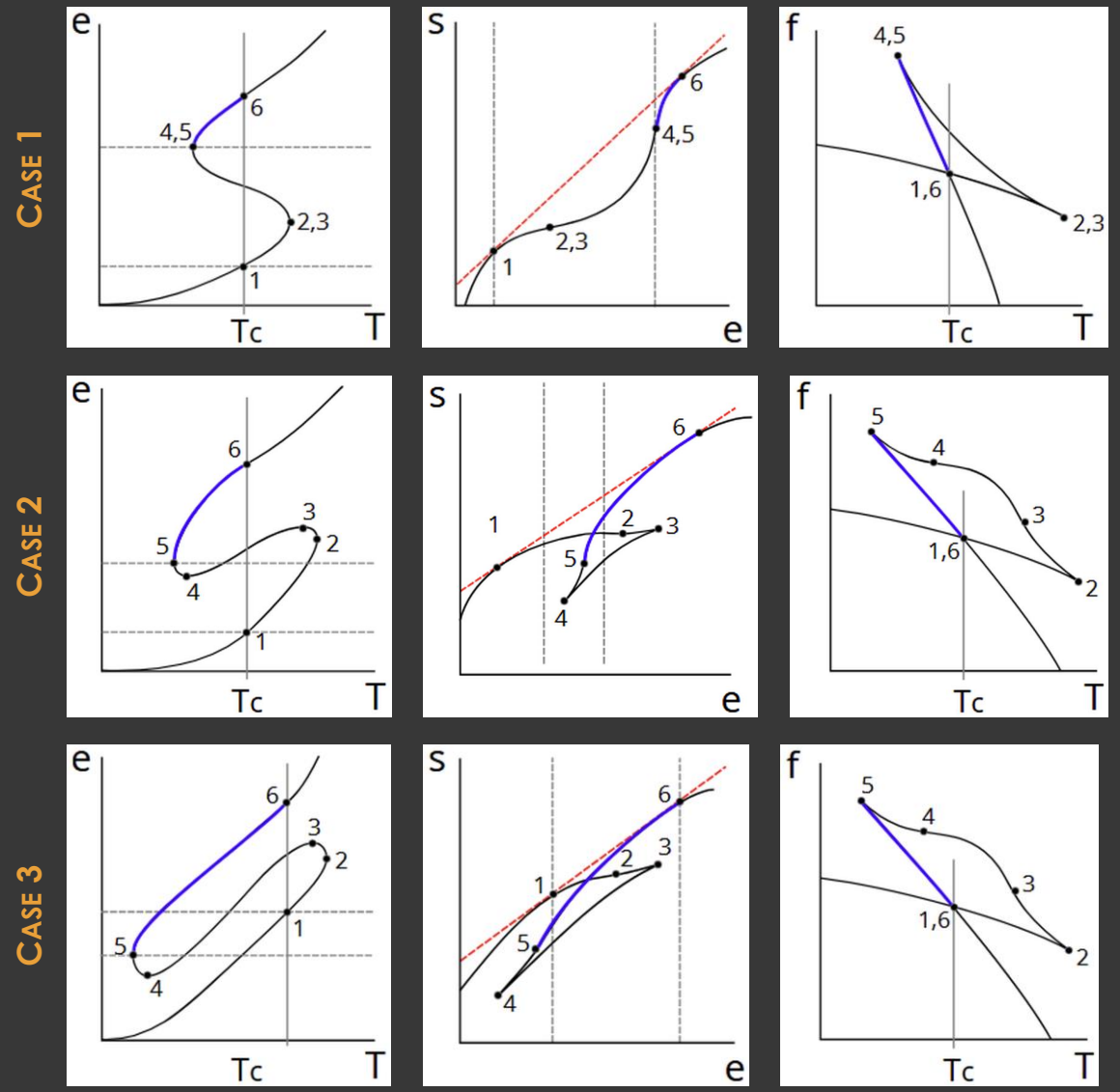




[Aurrekoetxea, Bea, Luna, Mateos, Sanchez-Garitaonandia, **PTA**, van de Vis, in progress]

SEPARATION OF PHASES

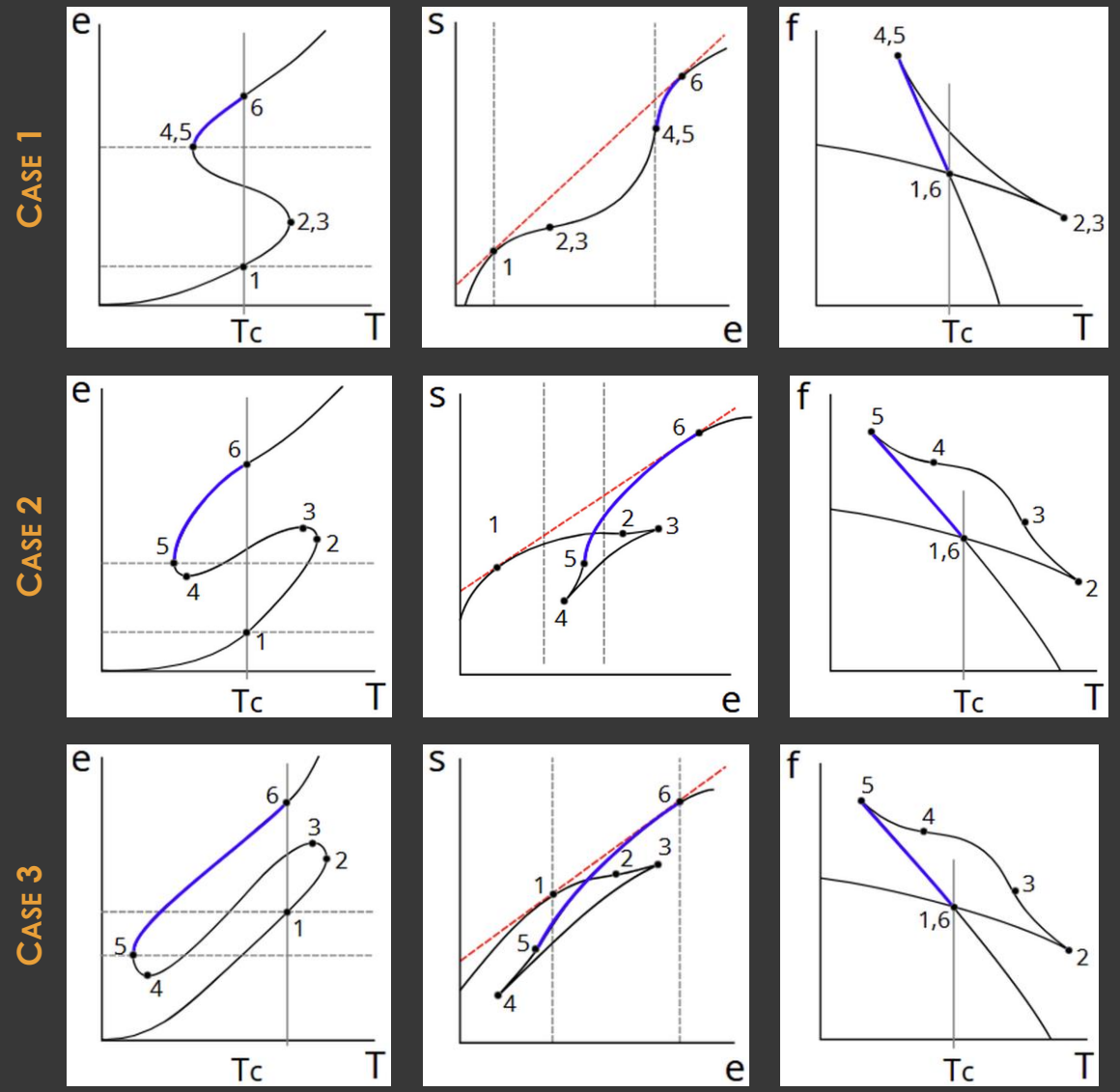
- Between the turning points, homogeneous states (blue branch) are thermodynamically unstable



[Aurrekoetxea, Bea, Luna, Mateos, Sanchez-Garitaonandia, **PTA**, van de Vis, in progress]

SEPARATION OF PHASES

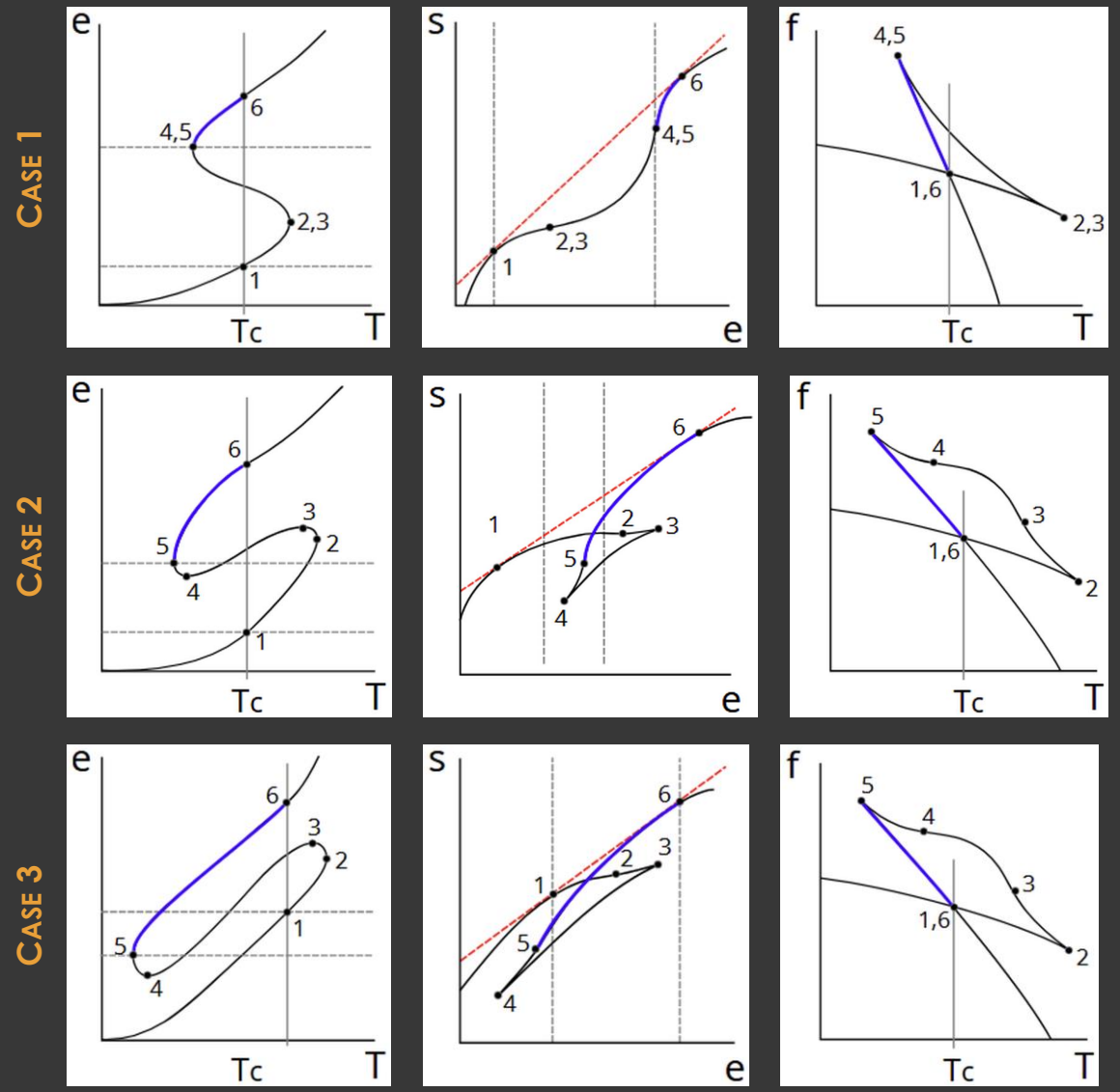
- Between the turning points, homogeneous states (blue branch) are thermodynamically unstable
- The system can separate into the two phases, which coexist at $T = T_c$ with equal free energy (points 1, 6)



[Aurrekoetxea, Bea, Luna, Mateos, Sanchez-Garitaonandia, **PTA**, van de Vis, in progress]

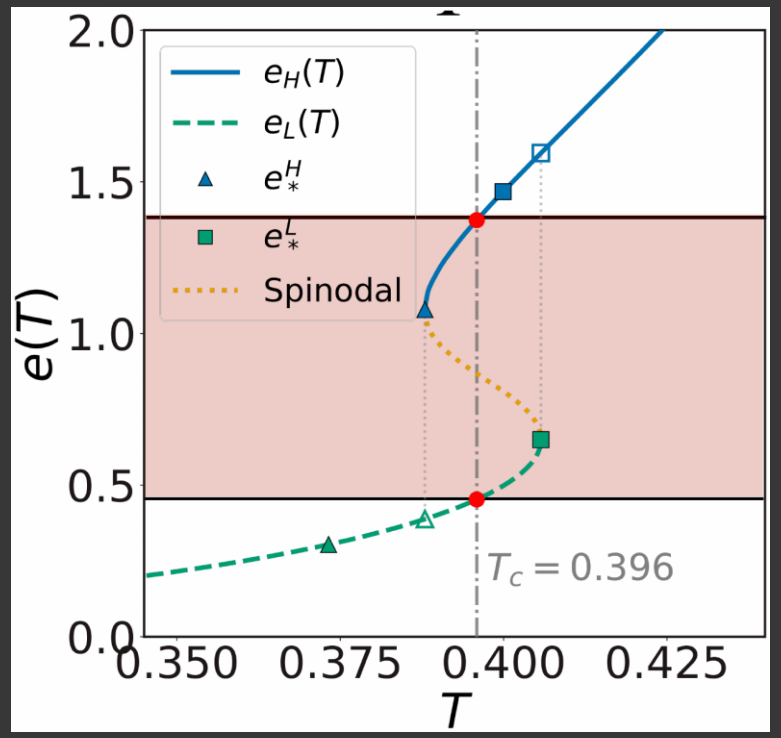
SEPARATION OF PHASES

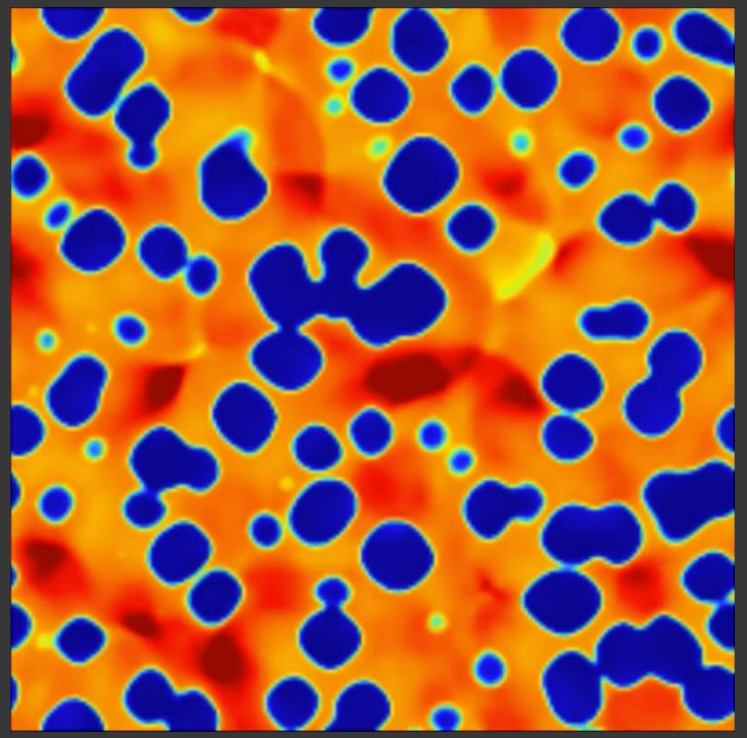
- Between the turning points, homogeneous states (blue branch) are thermodynamically unstable
- The system can separate into the two phases, which coexist at $T = T_c$ with equal free energy (points 1, 6)
- Phase separation maximizes the entropy: the mixed state (red dashed line) lies above the homogeneous branch in $s(e)$



[Aurrekoetxea, Bea, Luna, Mateos, Sanchez-Garitaonandia, **PTA**, van de Vis, in progress]

BUBBLE COLLISIONS IN QCD-LIKE MODELS

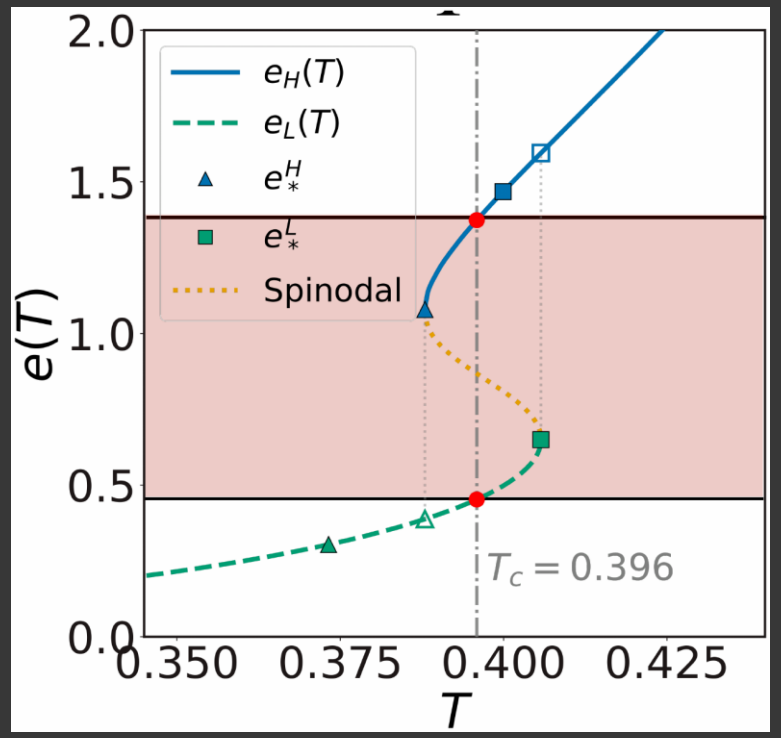


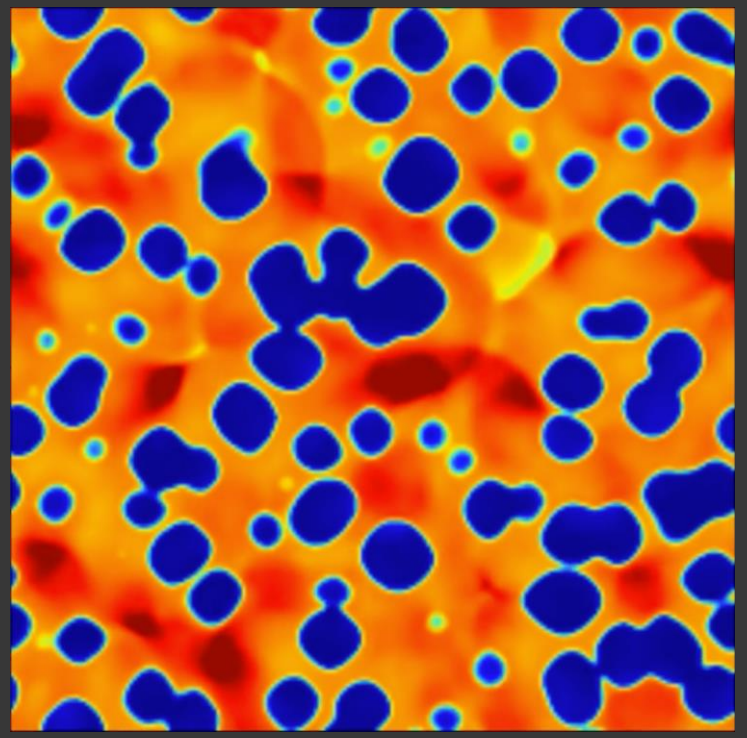


[Aurrekoetxea, Bea, Luna, Mateos, Sanchez-Garitaonandia, **PTA**, van de Vis, in progress]

BUBBLE COLLISIONS IN QCD-LIKE MODELS

- Real-time evolution of the hydrodynamic equations in a shock-capturing scheme

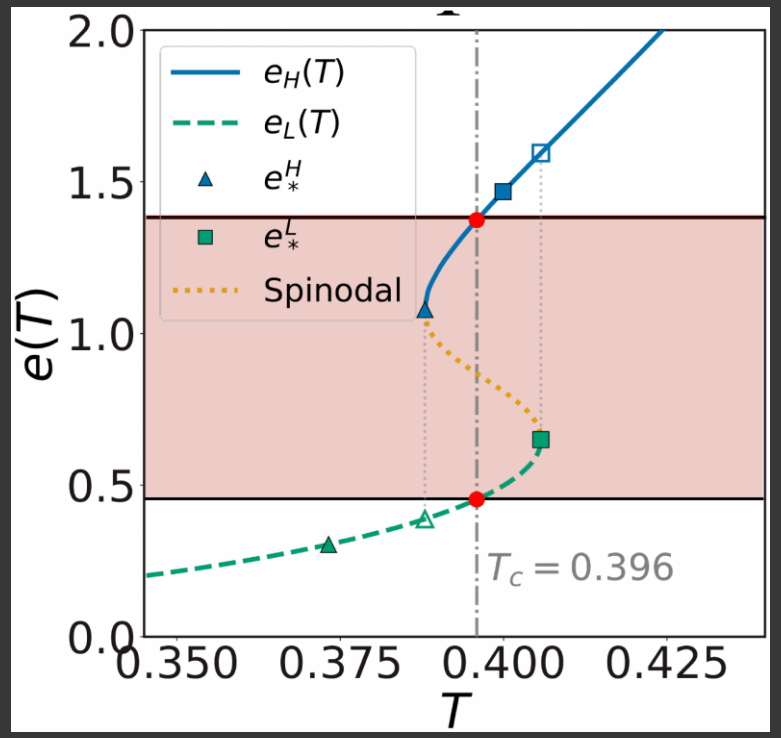


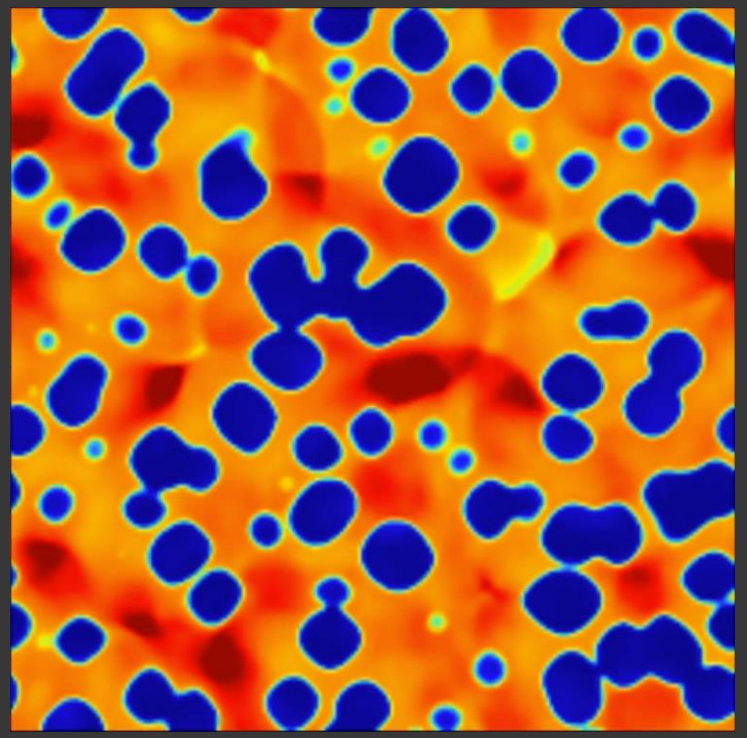


[Aurrekoetxea, Bea, Luna, Mateos, Sanchez-Garitaonandia, **PTA**, van de Vis, in progress]

BUBBLE COLLISIONS IN QCD-LIKE MODELS

- Real-time evolution of the hydrodynamic equations in a shock-capturing scheme
- For energies inside the coexistence band there is no homogeneous final state

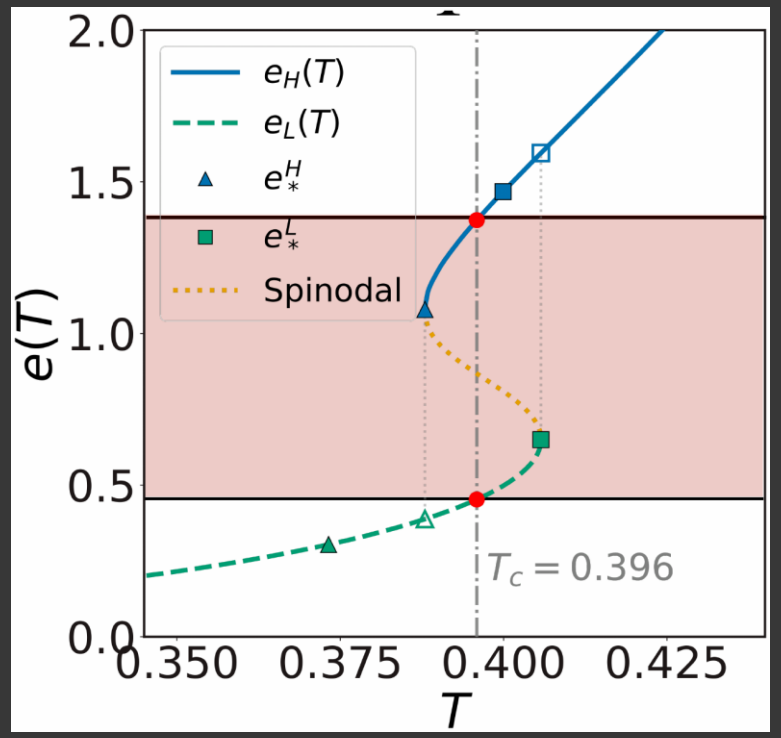


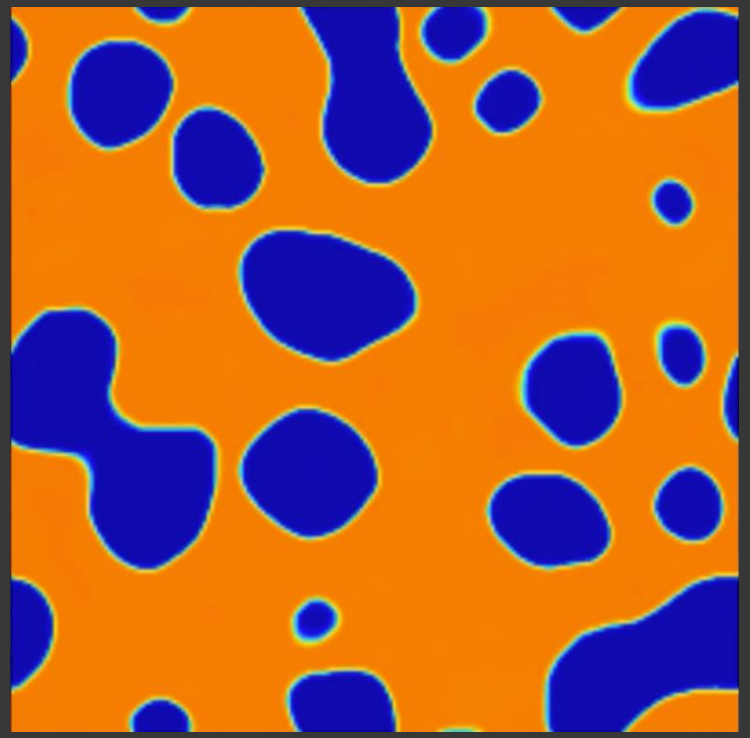


[Aurrekoetxea, Bea, Luna, Mateos, Sanchez-Garitaonandia, **PTA**, van de Vis, in progress]

BUBBLE COLLISIONS IN QCD-LIKE MODELS

- Real-time evolution of the hydrodynamic equations in a shock-capturing scheme
- For energies inside the coexistence band there is no homogeneous final state
- After the collisions the system settles into separated domains of the two phases

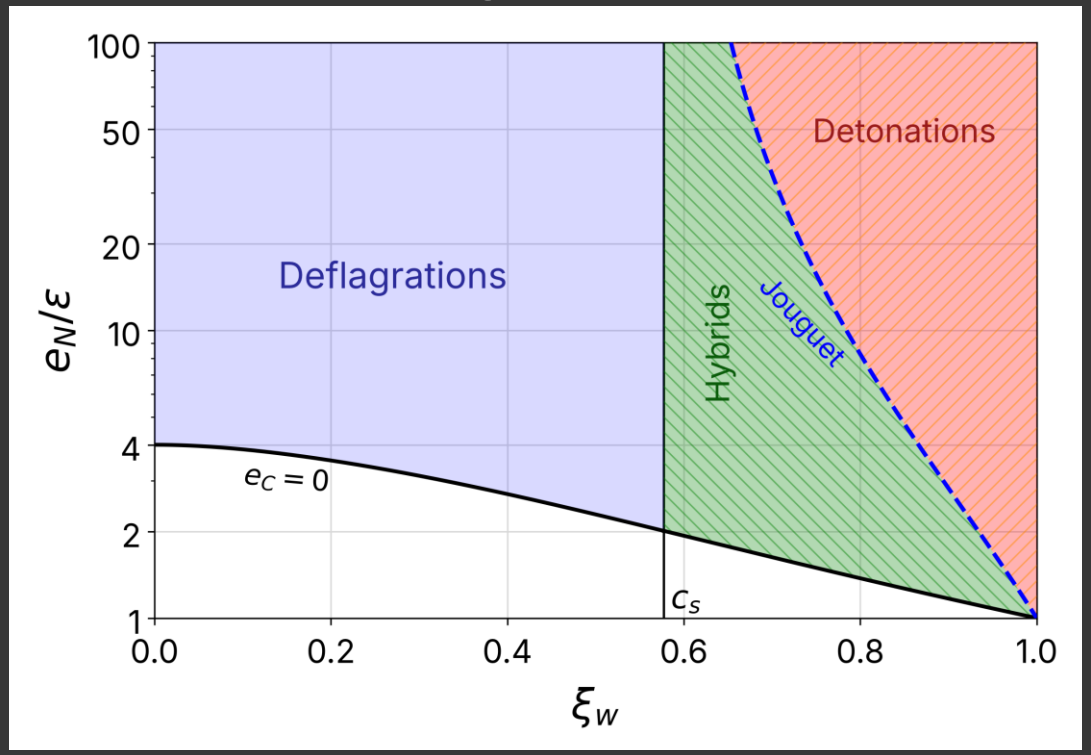




[Espinosa et al., JCAP 06 (2010) 028; Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

FROM THE BAG MODEL TO QCD-LIKE

Bag model



?

Holographic model

