NON-CONFORMAL OBSTRUCTIONS TO BUBBLE EXPANSION

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BIG MEETING (BARCELONA)

30/10/2026

In collaboration with: David Mateos and Mikel Sanchez-Garitaonandia
Arxiv: 2607.27874

UNIVERSITAT DE BARCELONA

ICCUB

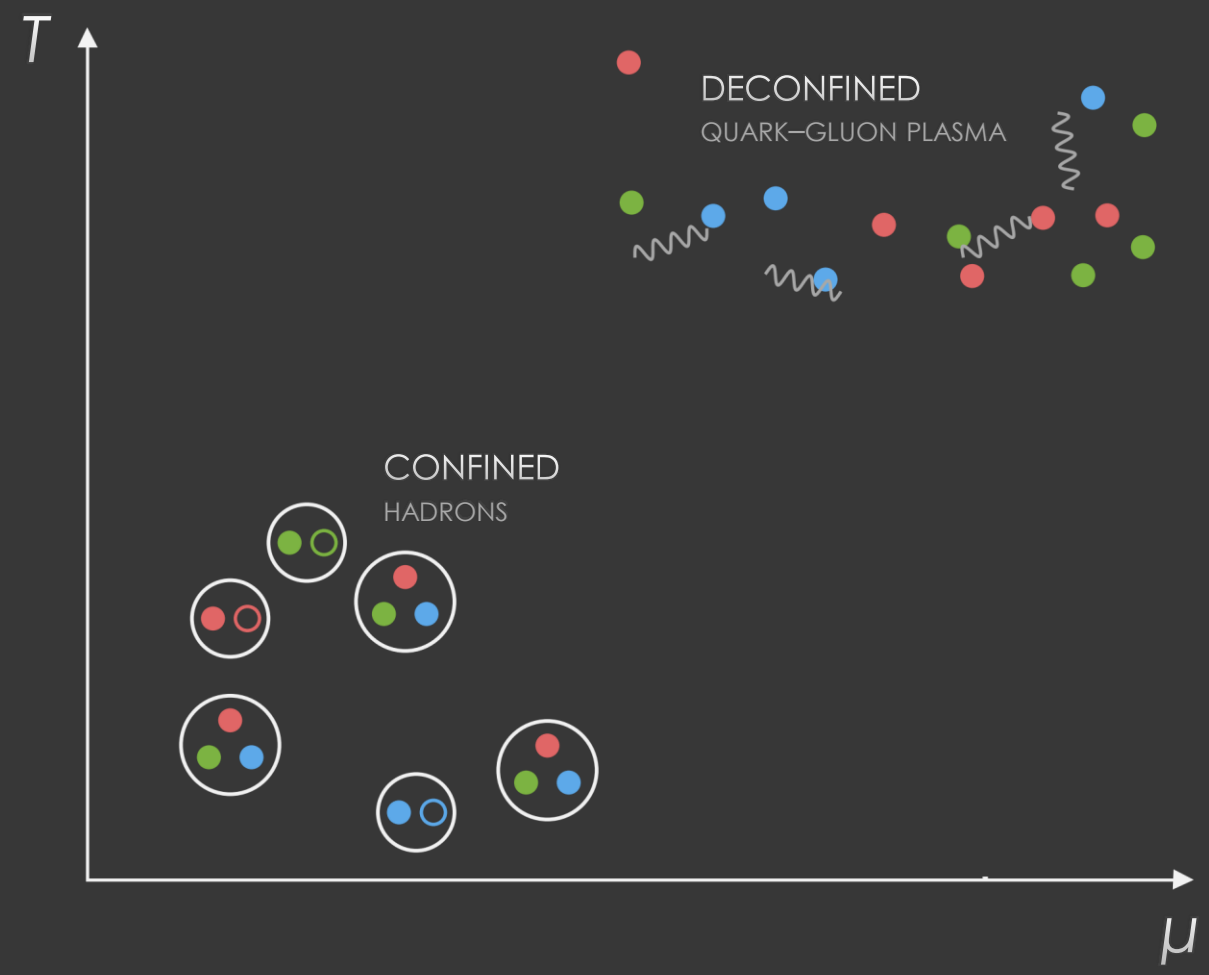
Institut de Ciències del Cosmos
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EXCELENCIA MARÍA DE MAEZTU 2020–2024

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

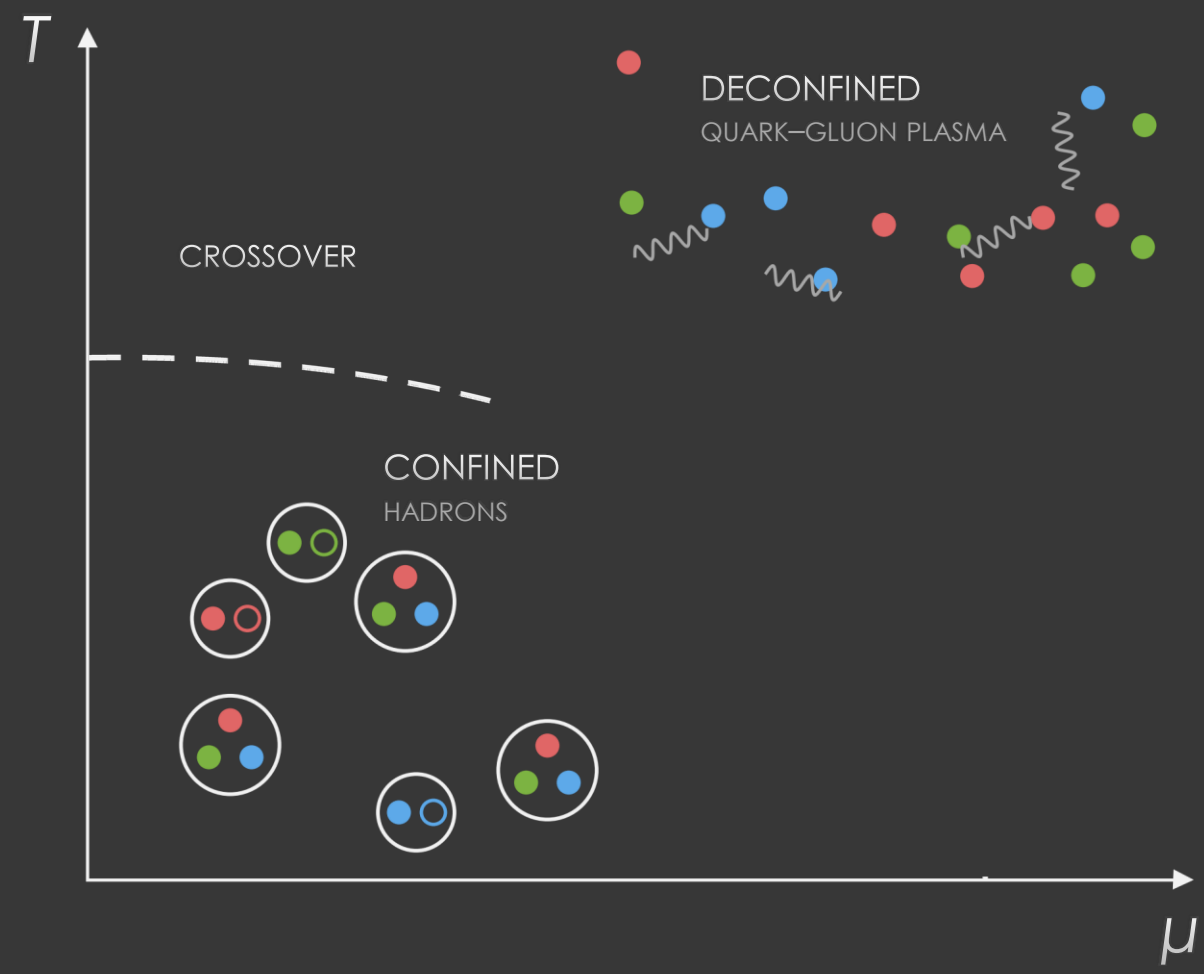
AGENCIA ESTATAL DE INVESTIGACIÓN

FIRST ORDER PHASE TRANSITIONS



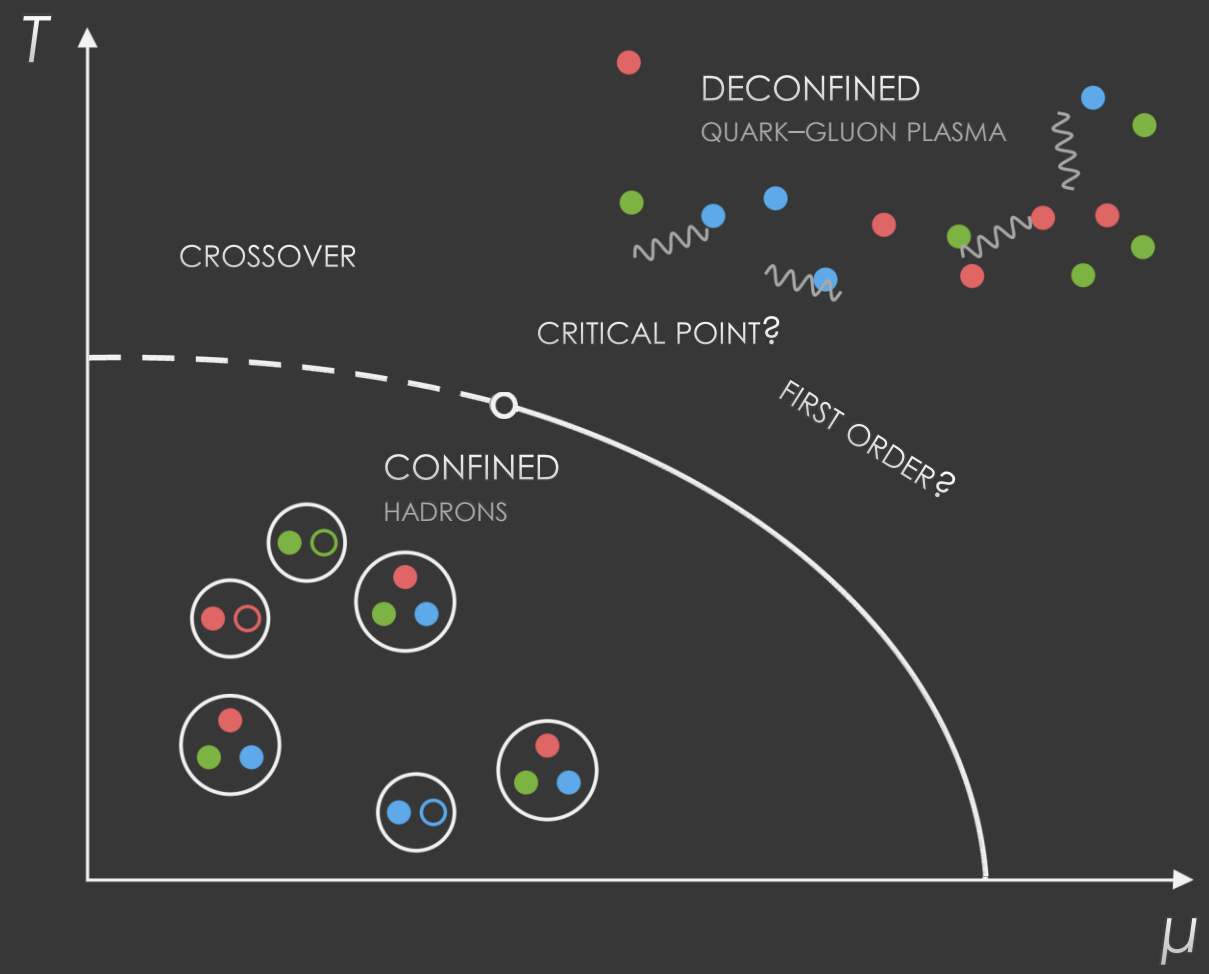
[Aoki et al., Nature 443 (2006) 675]
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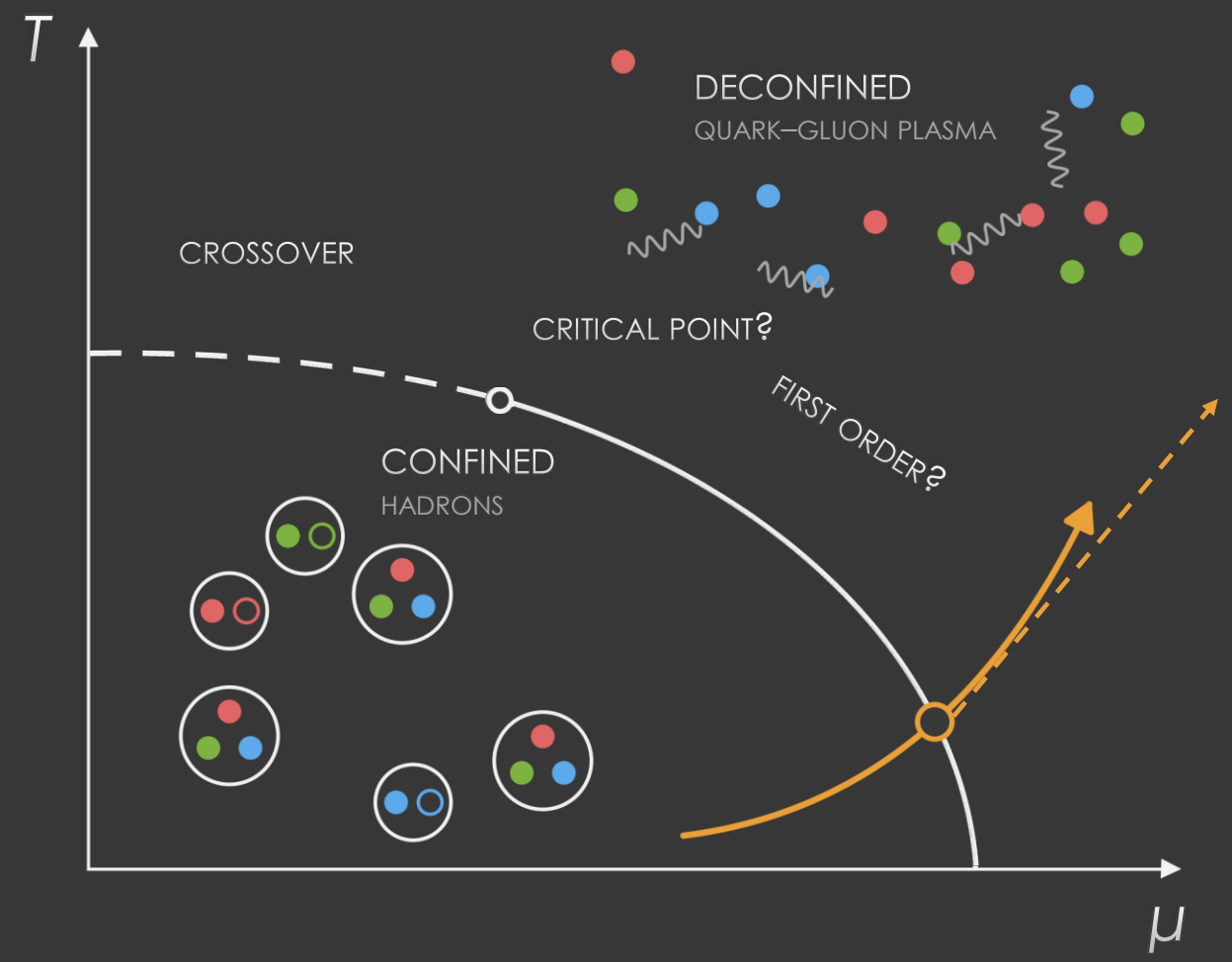
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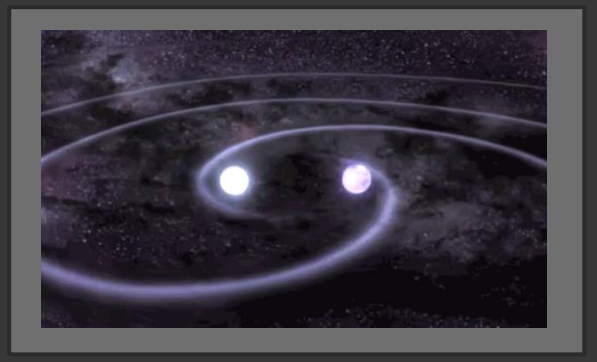
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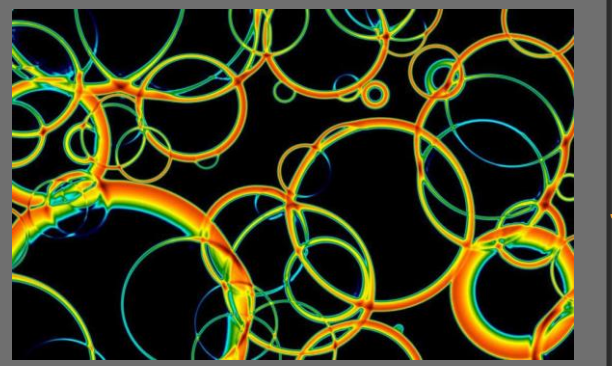
[NASA's Goddard Space Flight Center]

NEUTRON-STAR MERGERS

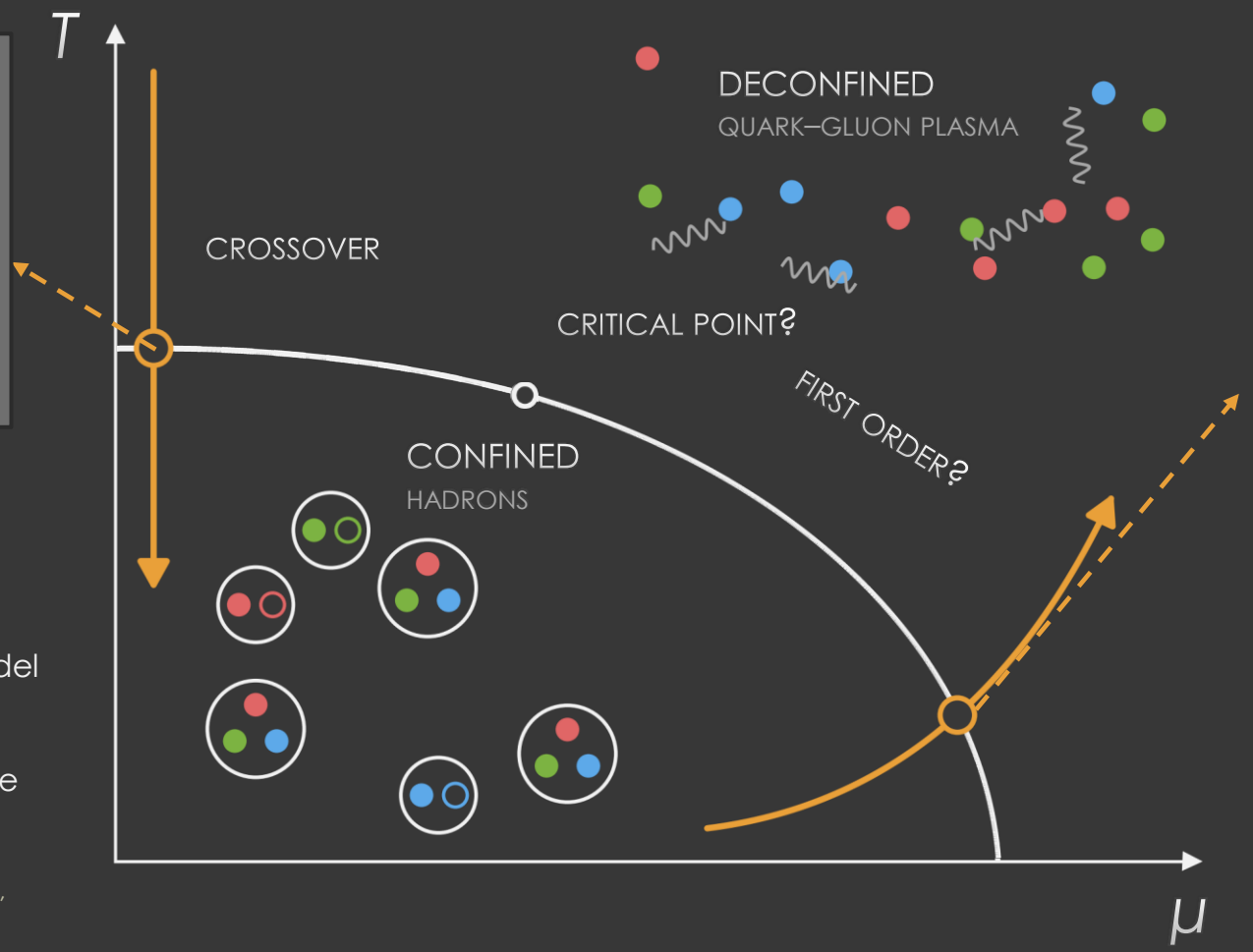
- Probe QCD at high density
- Constrain the QCD EoS at finite μ
  [Most et al., PRL 122 (2019) 061101; Bauswein et al., PRL 122 (2019) 061102; Blas et al., PRL 136 (2026) 101401; Bea et al., PRD 112 (2025) 114041, JHEP 04 (2026) 013]
- Core-collapse supernovae
  [Sagert et al., PRL 102 (2009) 081101;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

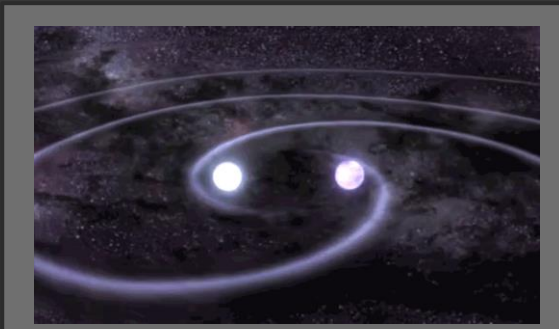
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[D. Weir, University of Helsinki]





[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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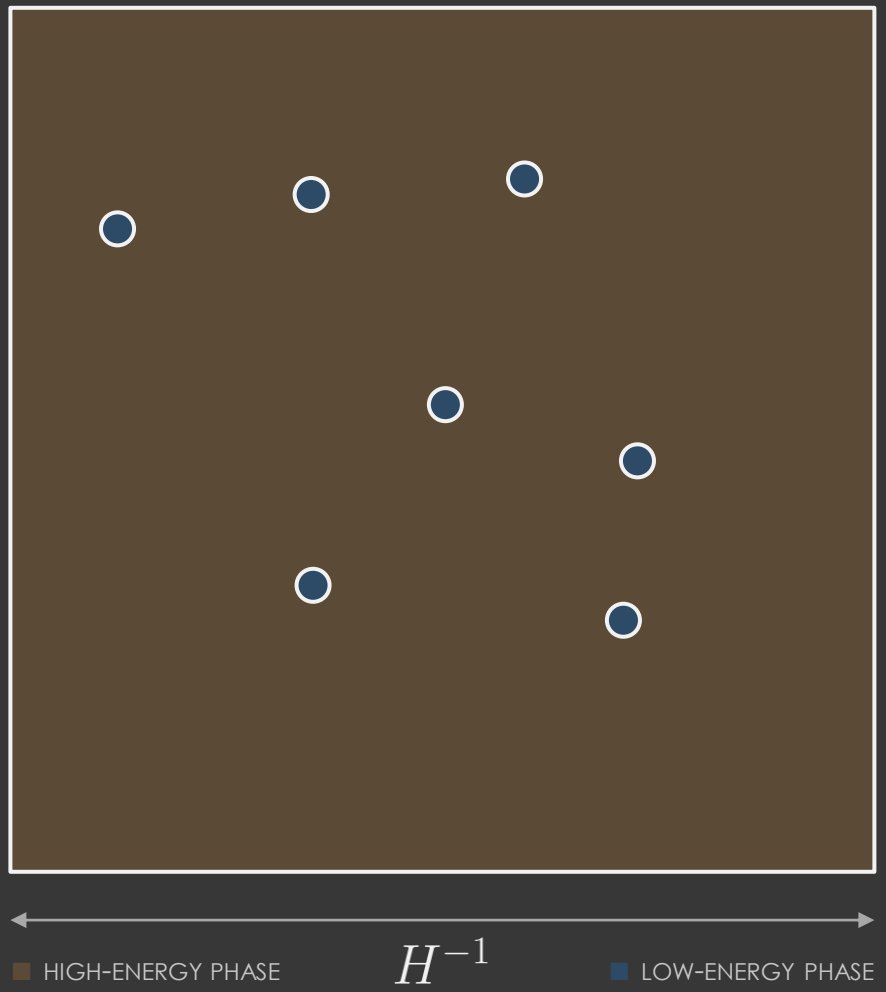
HUBBLE PATCH



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NUCLEATION



EQUATION OF STATE

T_n TEMPERATURE

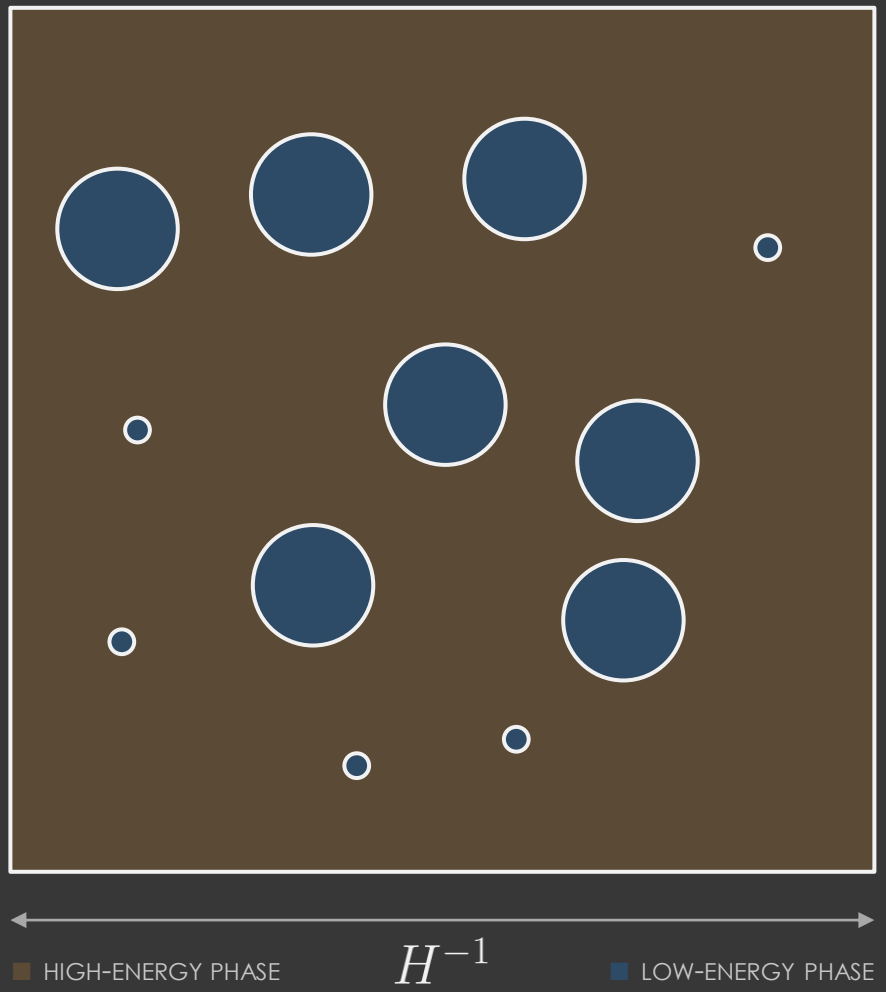
MICROSCOPIC

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

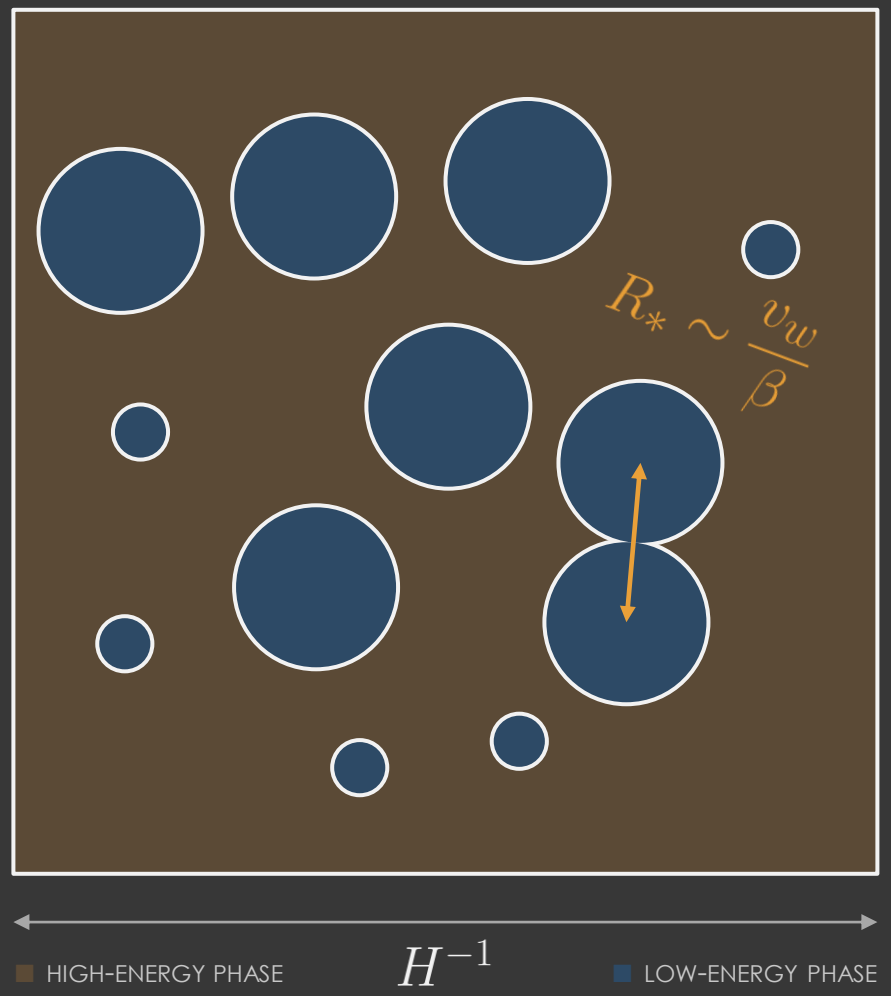
MICROSCOPIC

- β/H TRANSITION RATE
- v_w WALL SPEED

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COLLISION



EQUATION OF STATE

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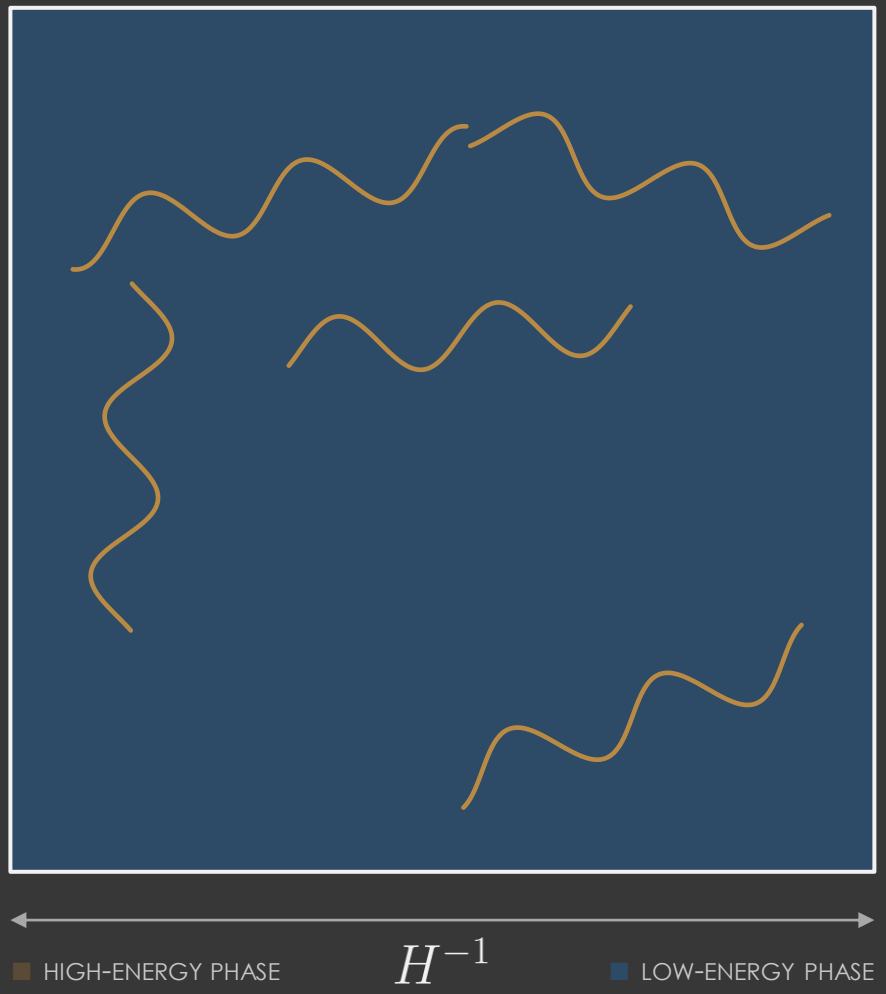
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GW EMISSION



EQUATION OF STATE

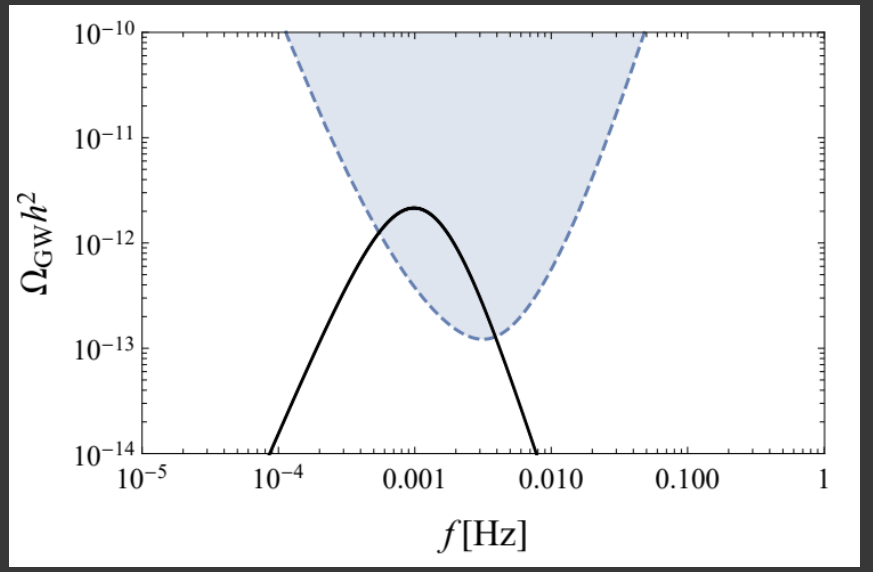
- T_n TEMPERATURE
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MICROSCOPIC

- β/H TRANSITION RATE
- v_w WALL SPEED

BUBBLE COLLISIONS

- K KINETIC ENERGY

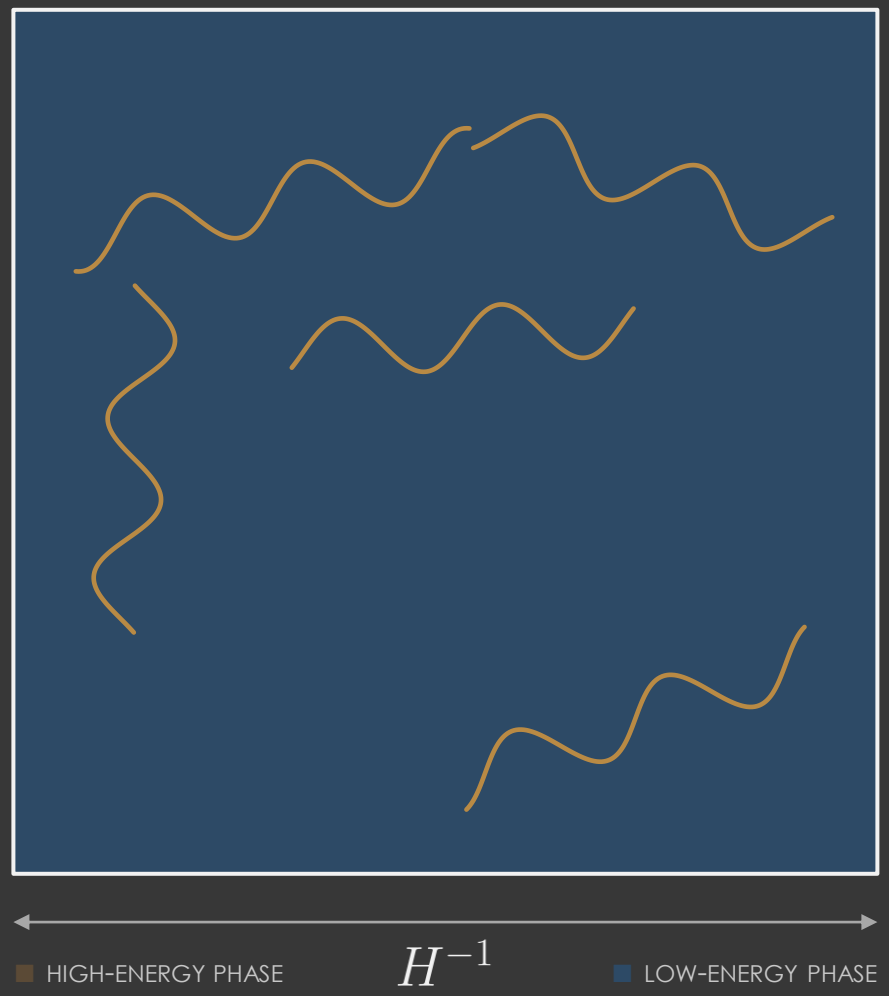


[Auclair et al., Living Rev. Rel. 26 (2023) 5]

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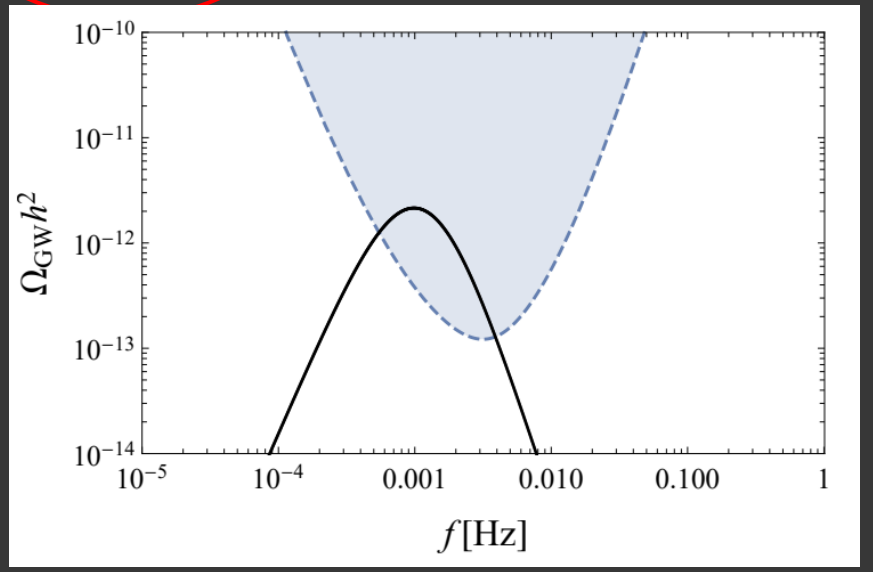
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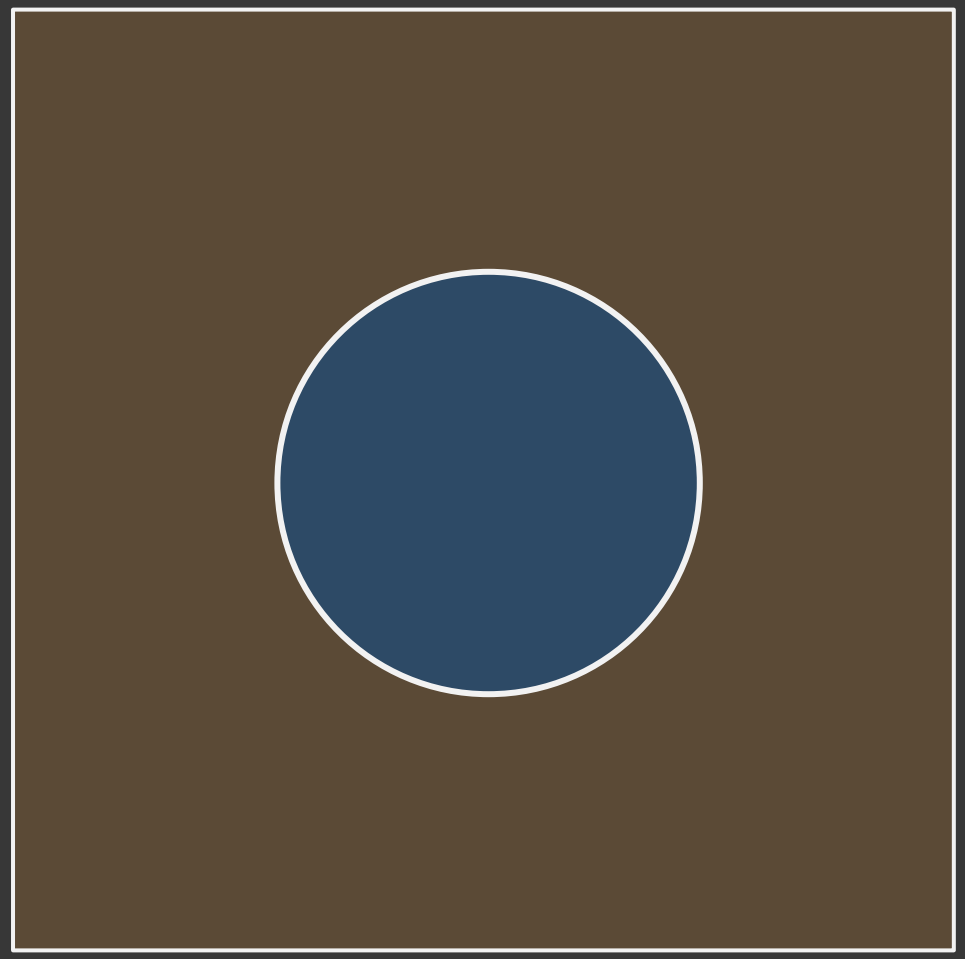


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OUTLOOK

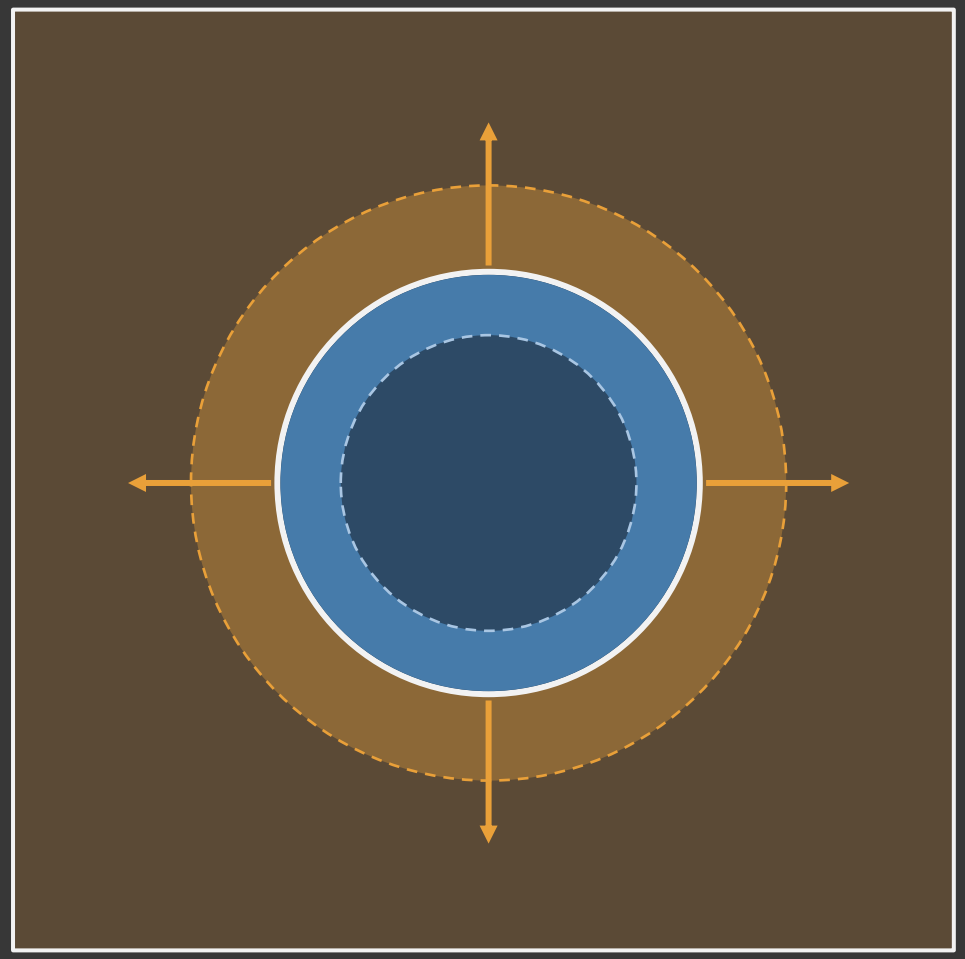
1. **Hydrodynamics of expanding bubbles**
   bubbles in a conformal EoS
2. **Non-conformal equations of state**
   from bag model to QCD-like
3. **Non-conformal obstructions**
   at the wall and along the flow
4. **Conclusions**

EXPANSION OF A SINGLE BUBBLE



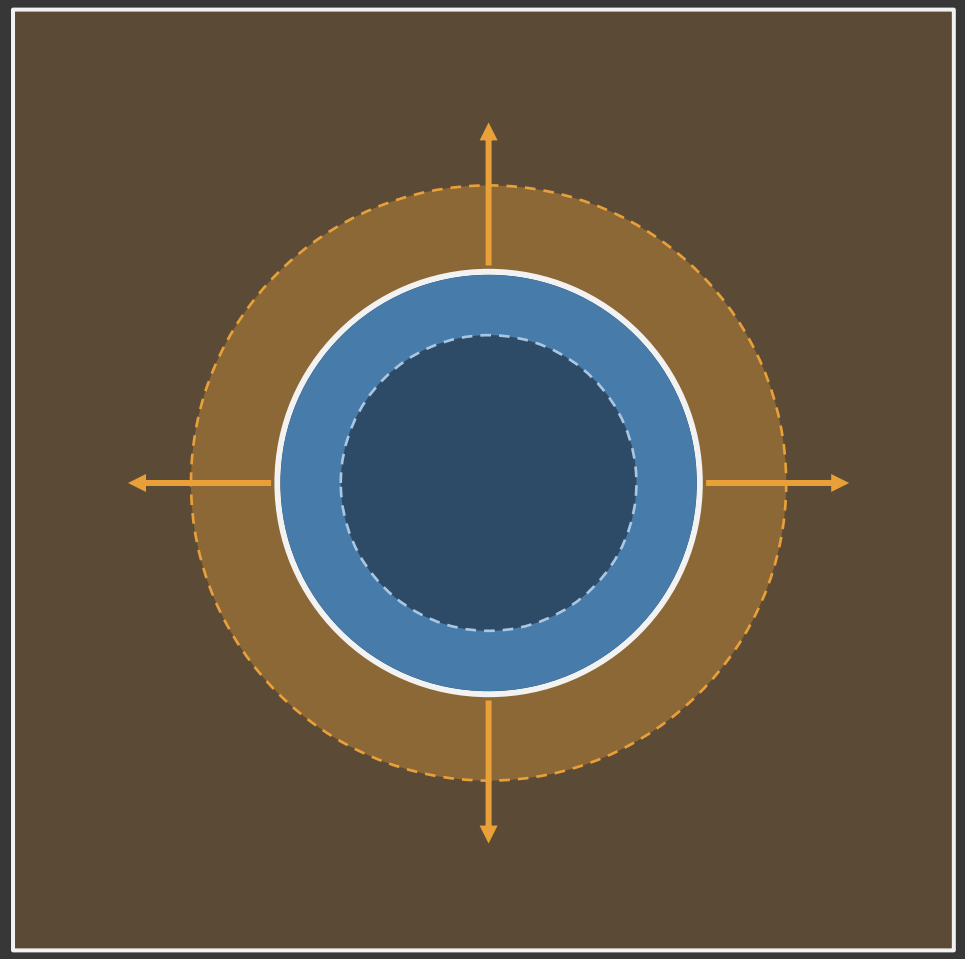
EXPANSION OF A SINGLE BUBBLE

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



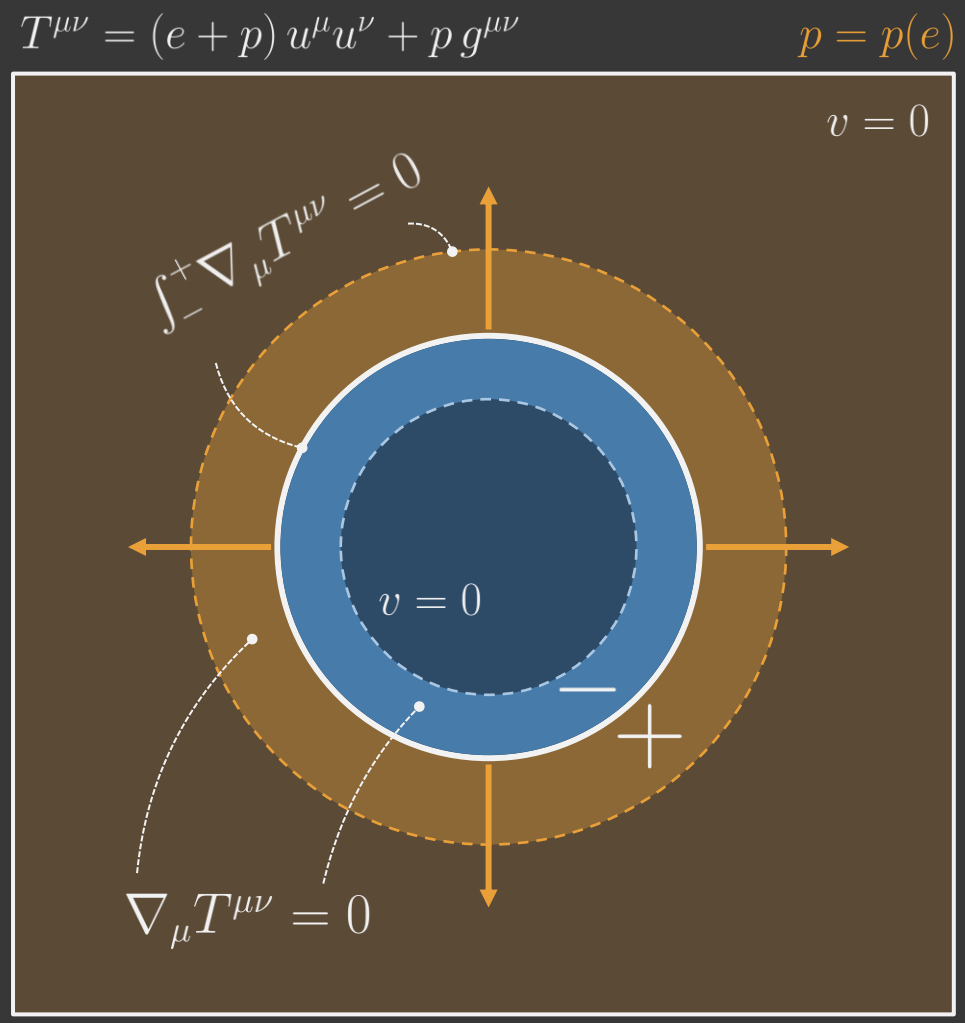
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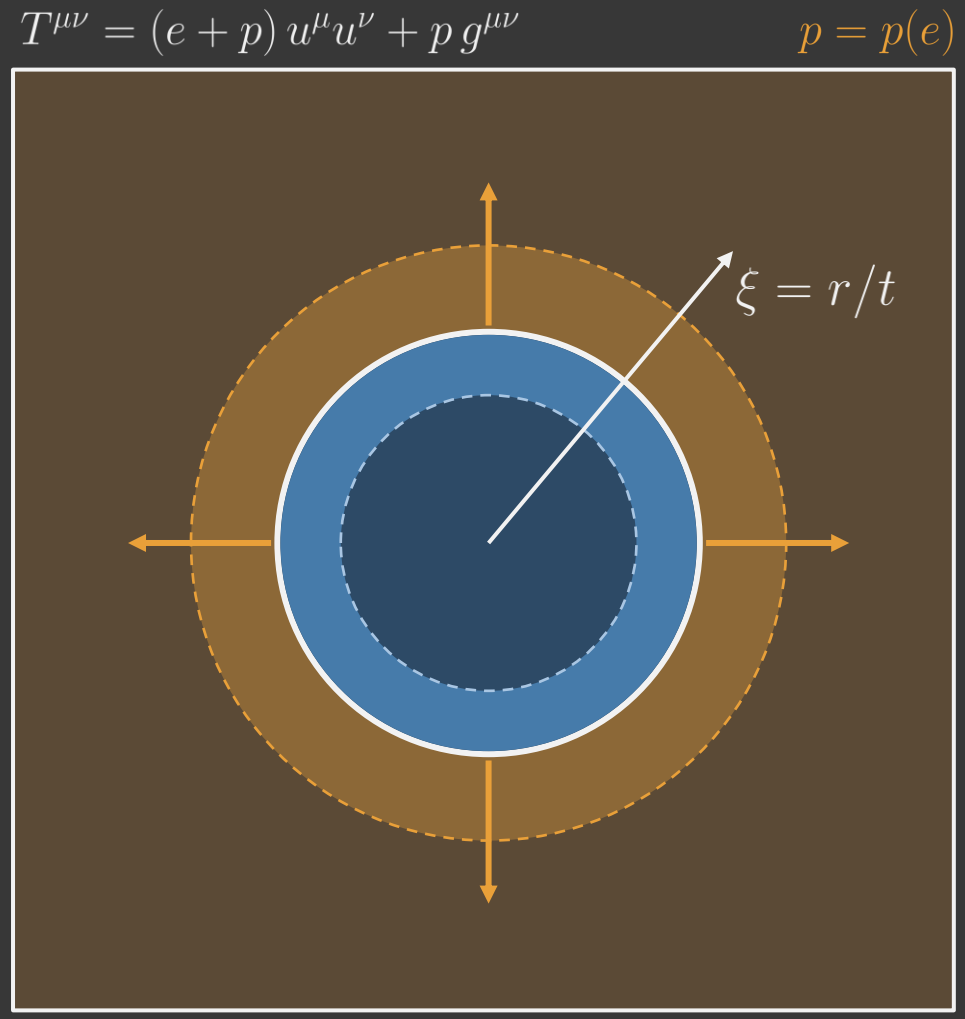
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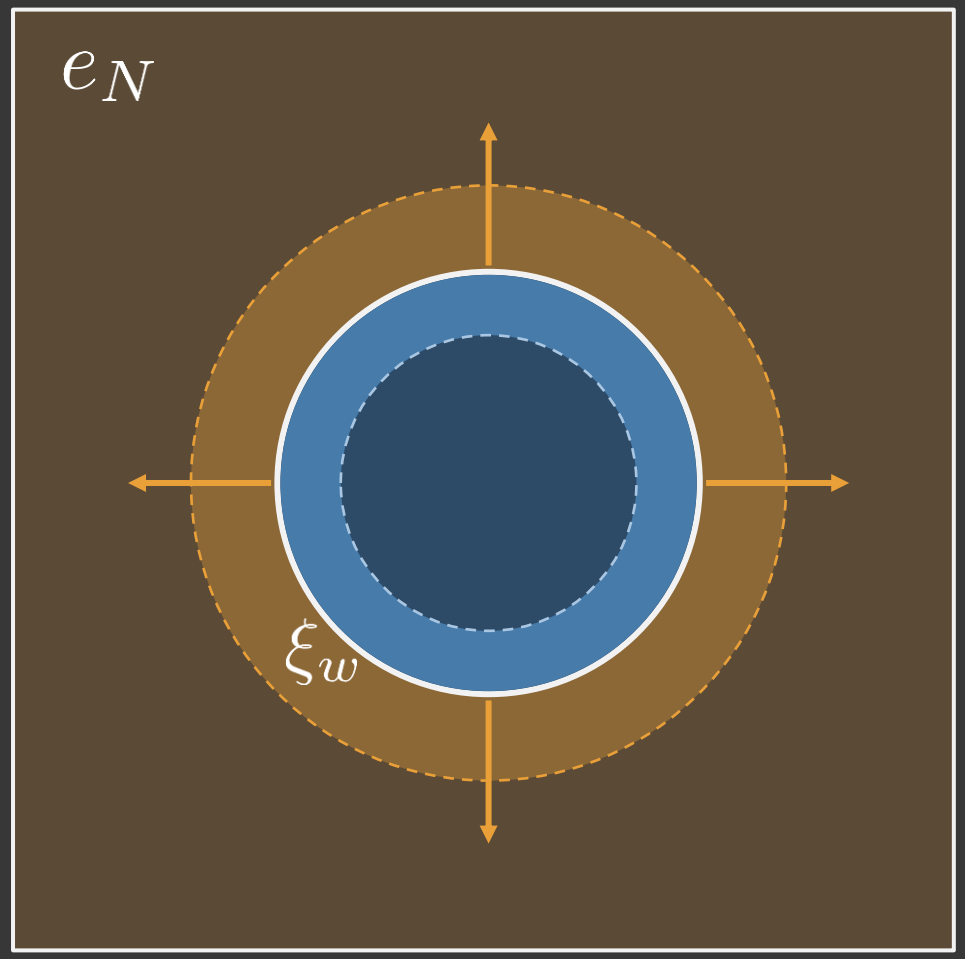
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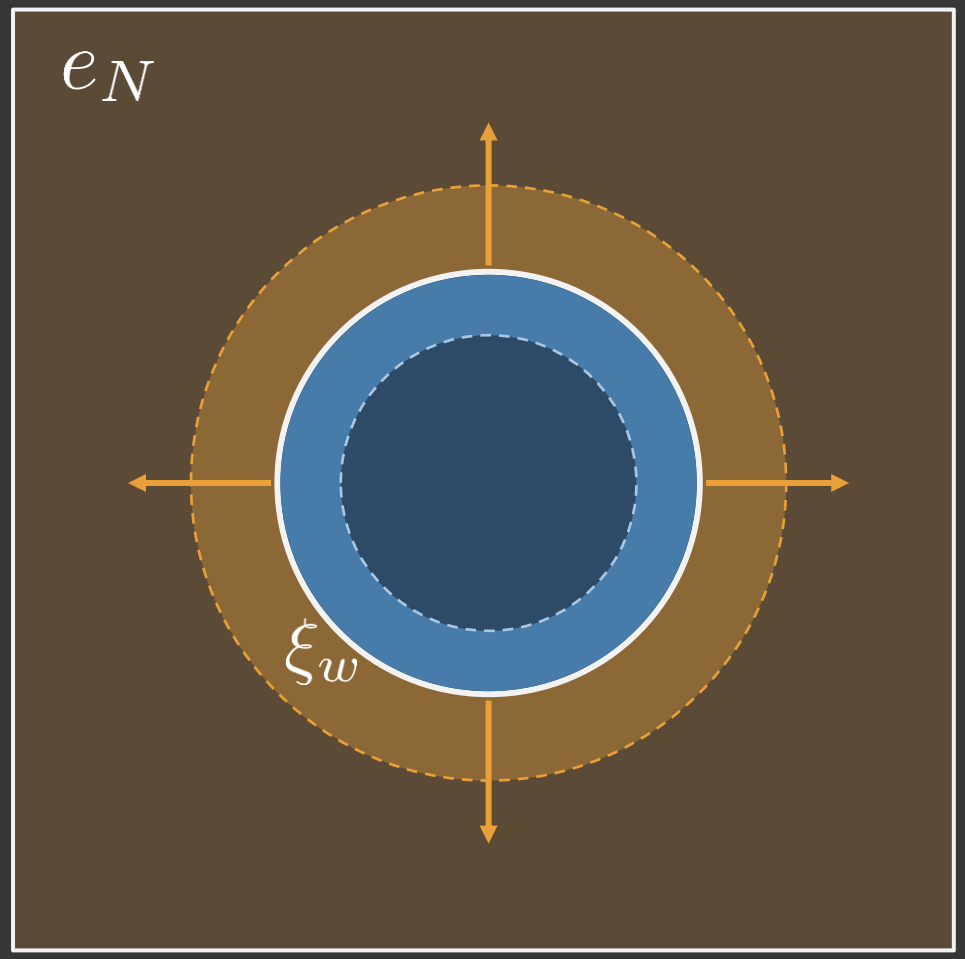
$T^{\mu\nu} = (e+p)\,u^\mu u^\nu + p\,g^{\mu\nu}$ $\quad p = p(e)$



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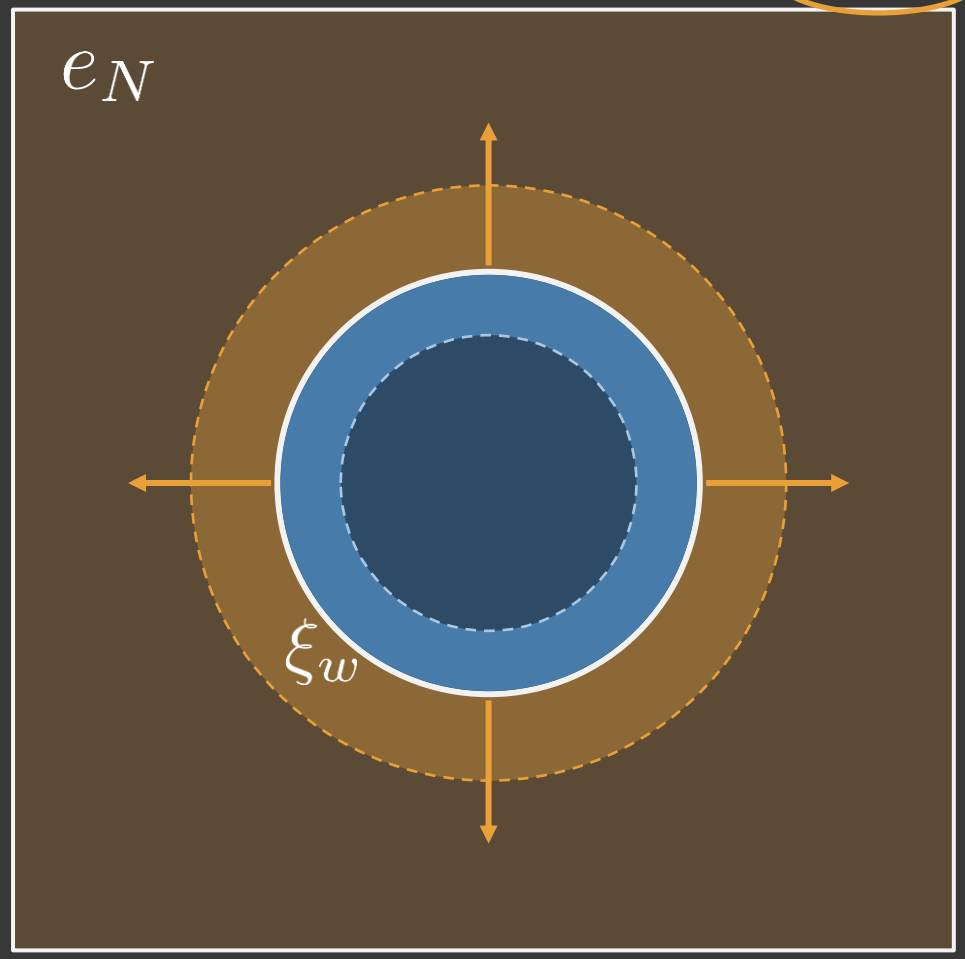
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- Key input: the EoS, which encodes the microphysics

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



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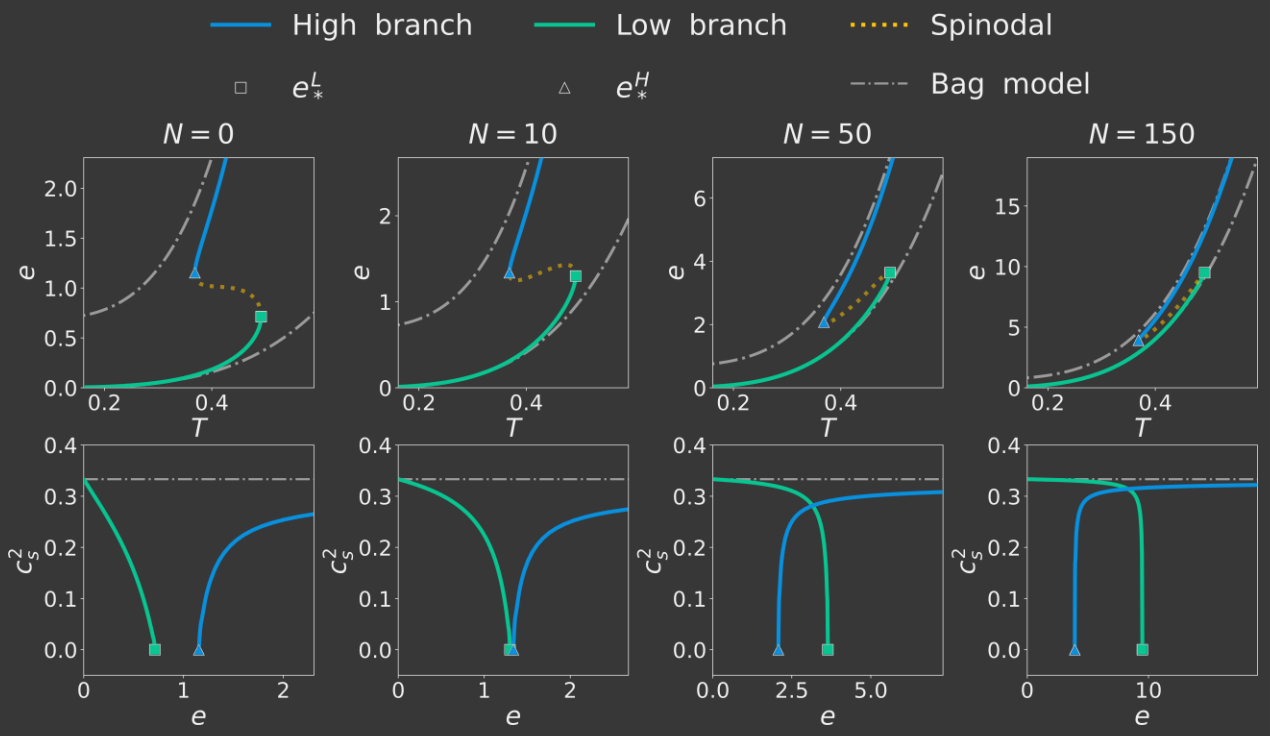
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- FOPT coupled to a N>>1 (effectively) massless particle at the critical temperature

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



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

EXPANSION MODES IN THE BAG MODEL

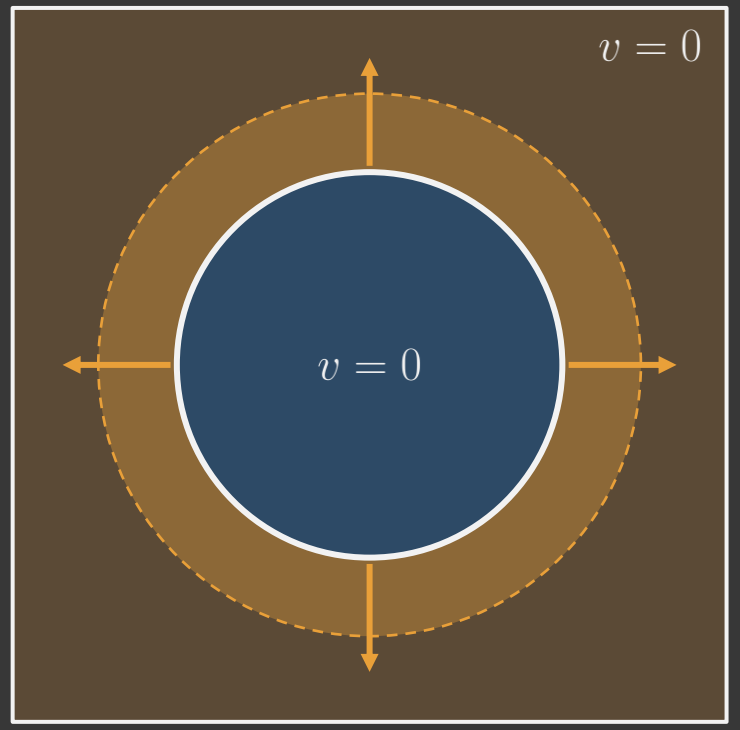
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EXPANSION MODES IN THE BAG MODEL

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Deflagration

$$\xi_w < c_s$$

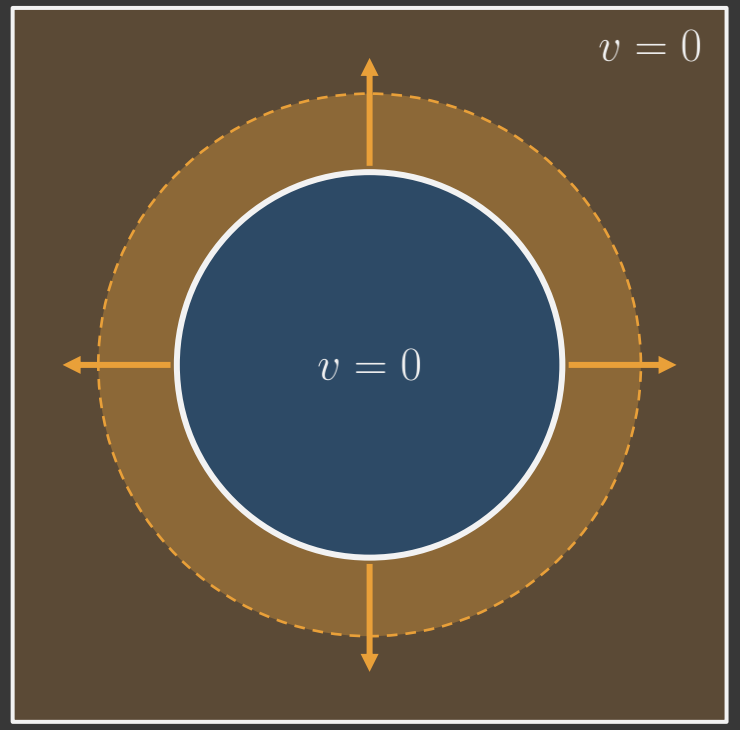


EXPANSION MODES IN THE BAG MODEL

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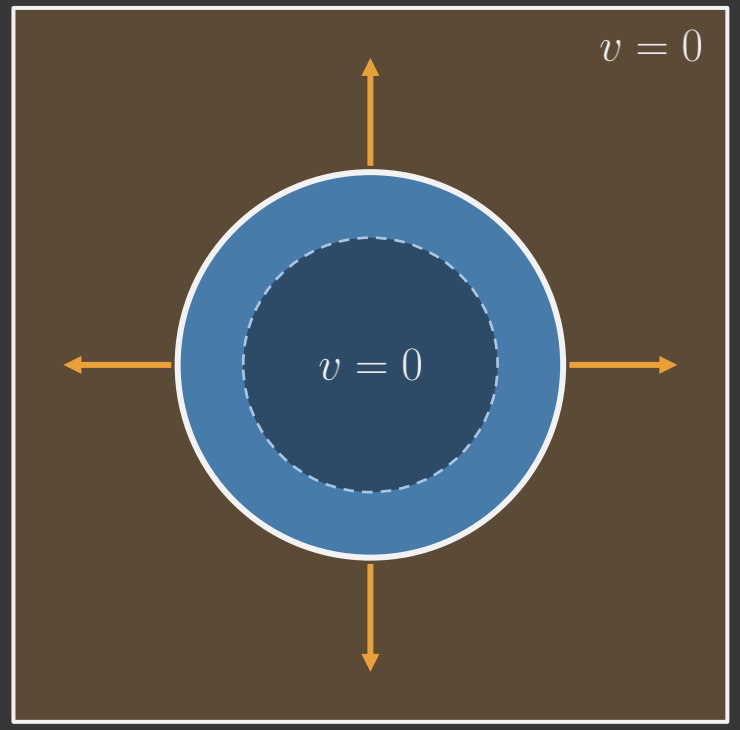
Deflagration

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Detonation

$\xi_w > \xi_J$

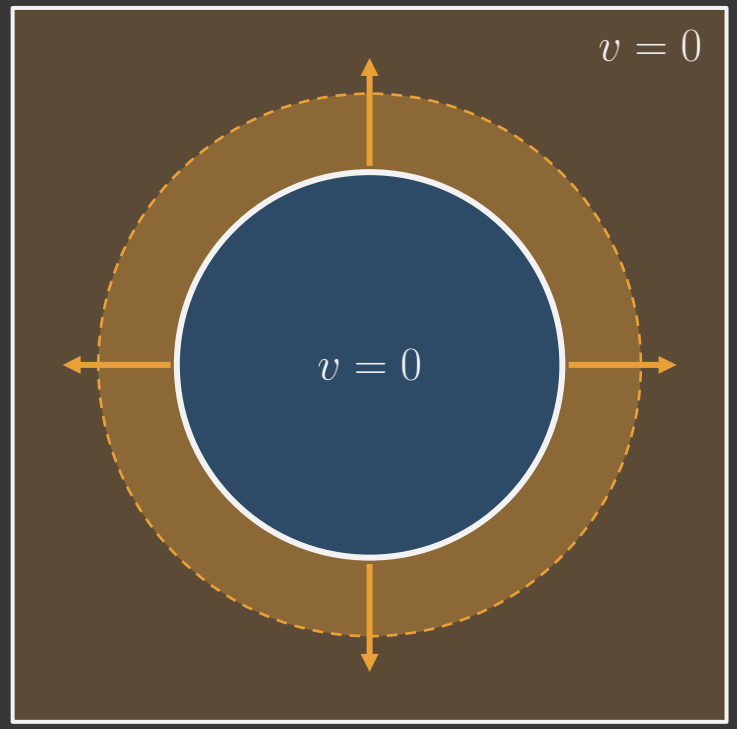


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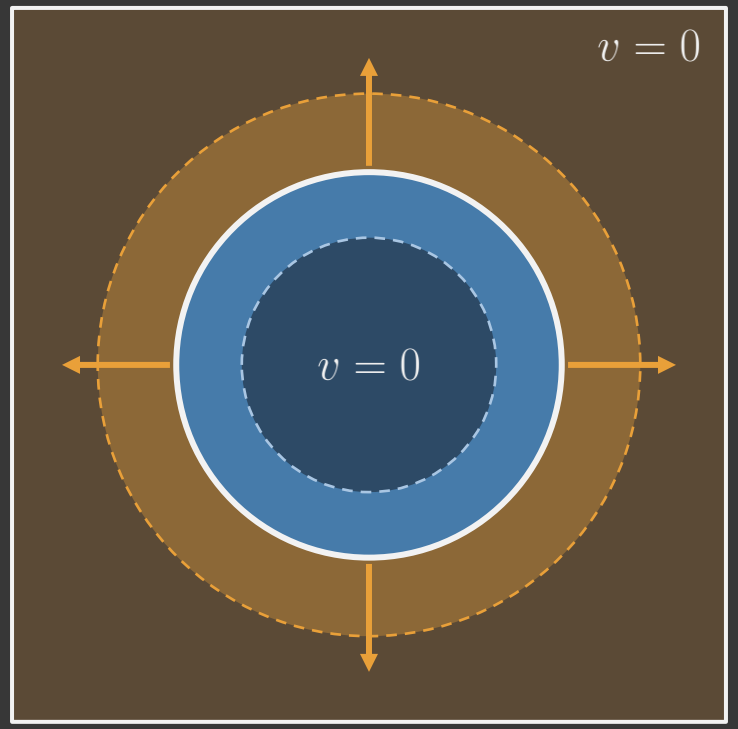
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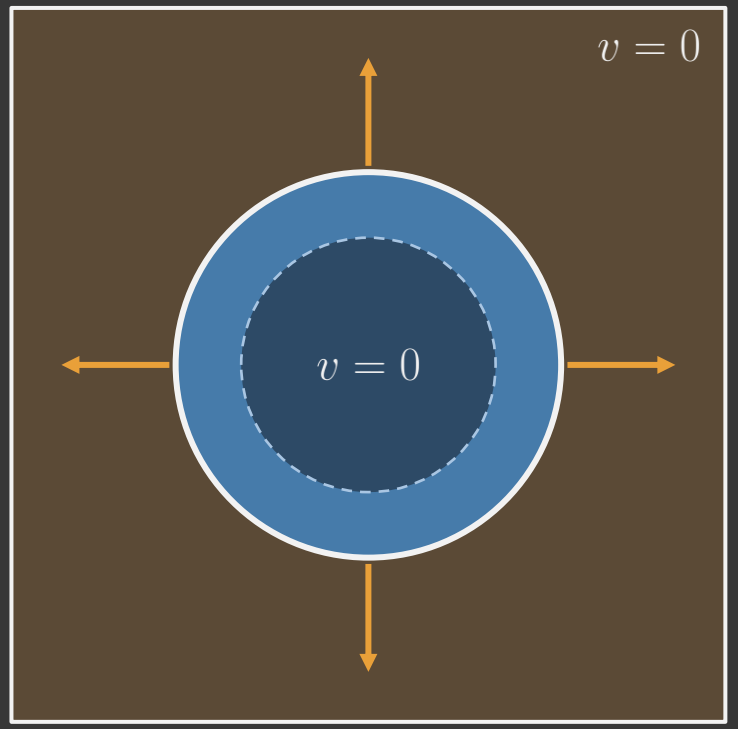
Hybrid

$c_s < \xi_w < \xi_J$



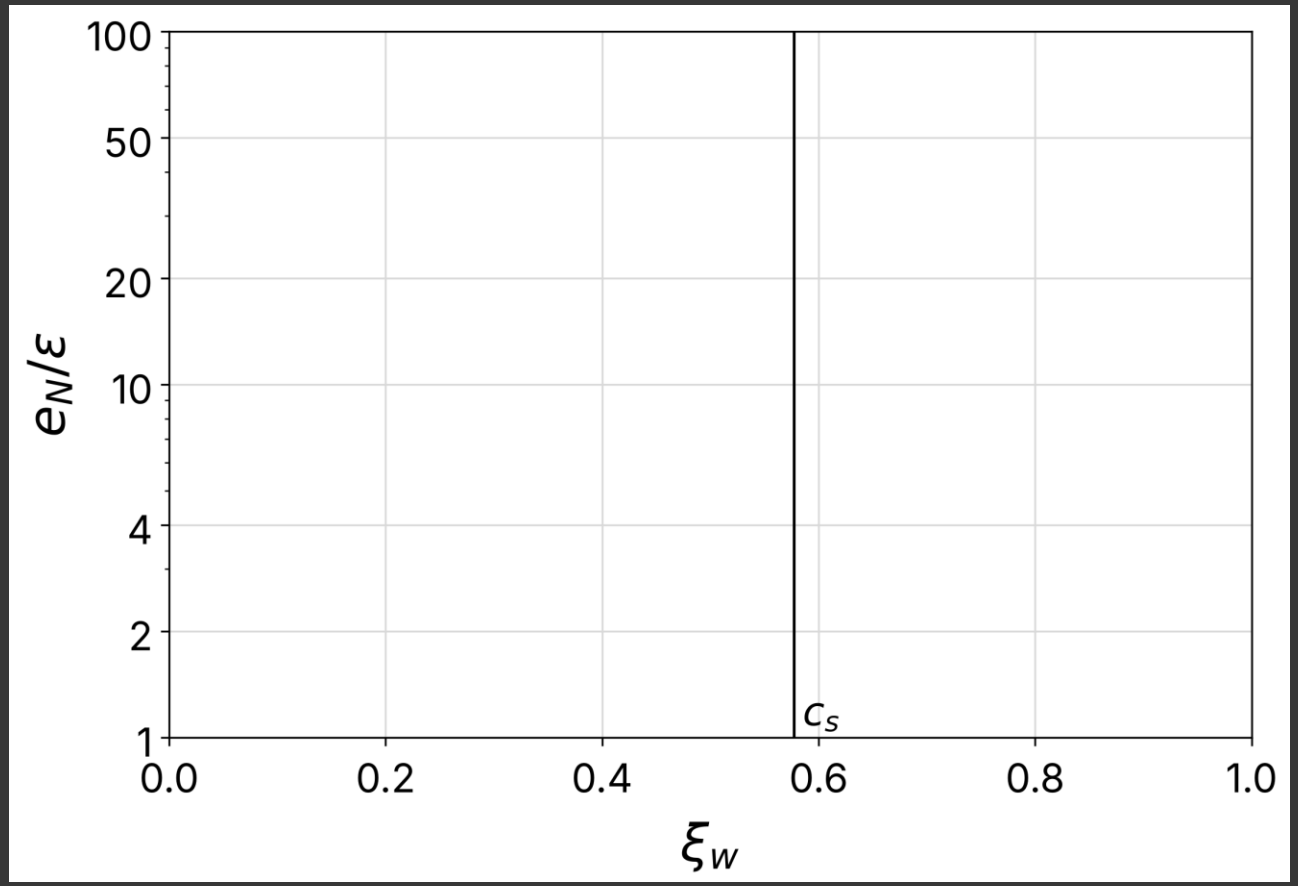
Detonation

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SPACE OF ALLOWED SOLUTIONS

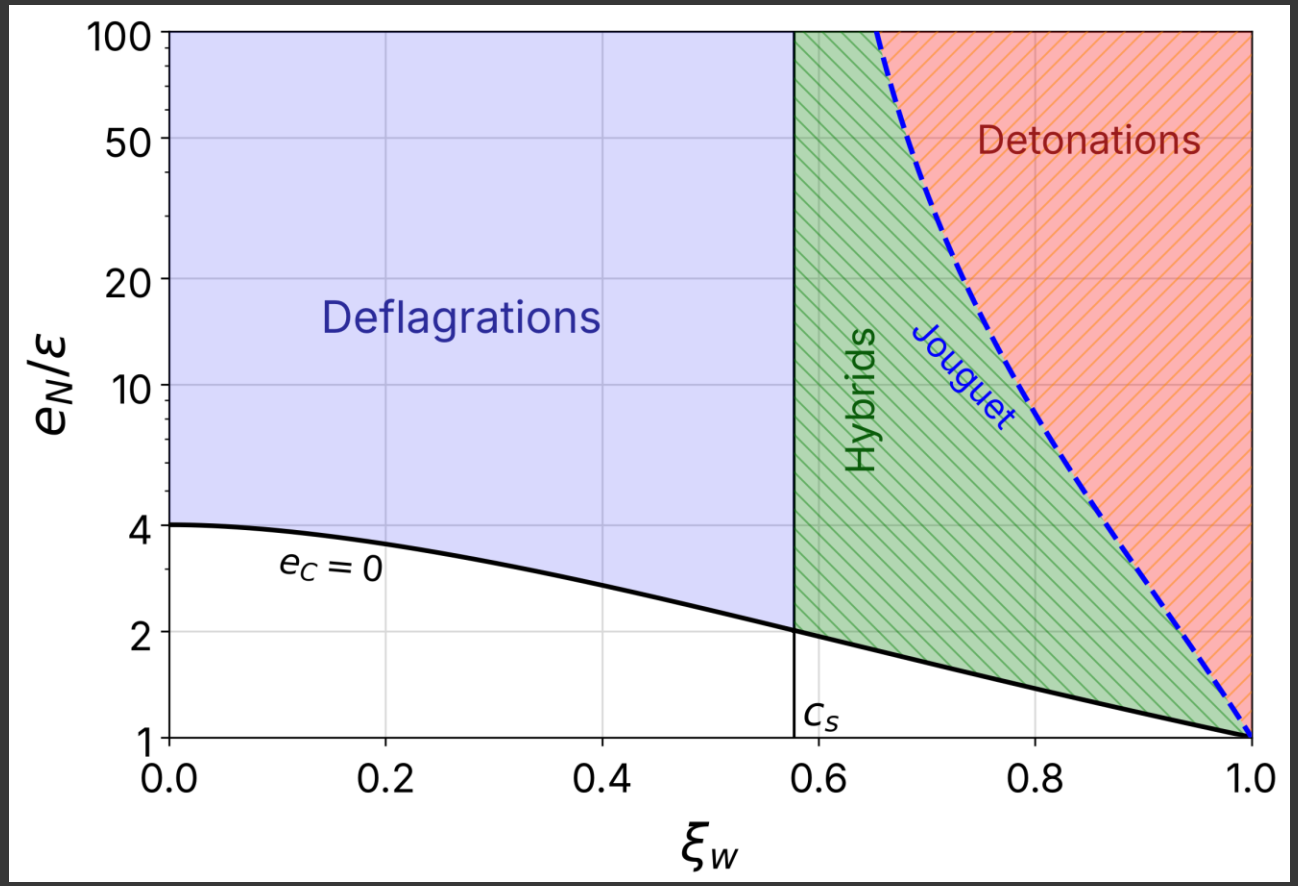
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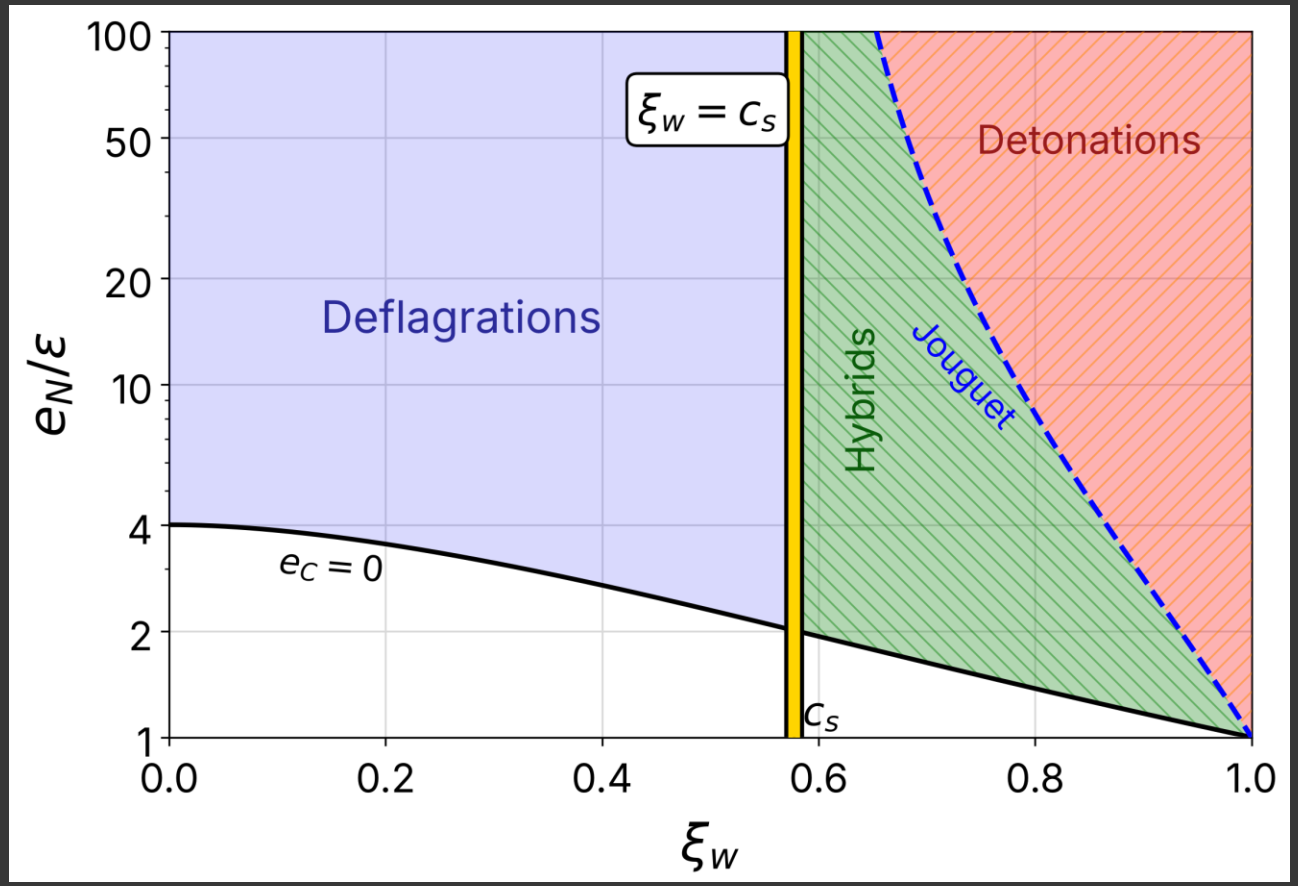
- Solutions are continuously connected: there are solutions for every ξ_w



SPACE OF ALLOWED SOLUTIONS

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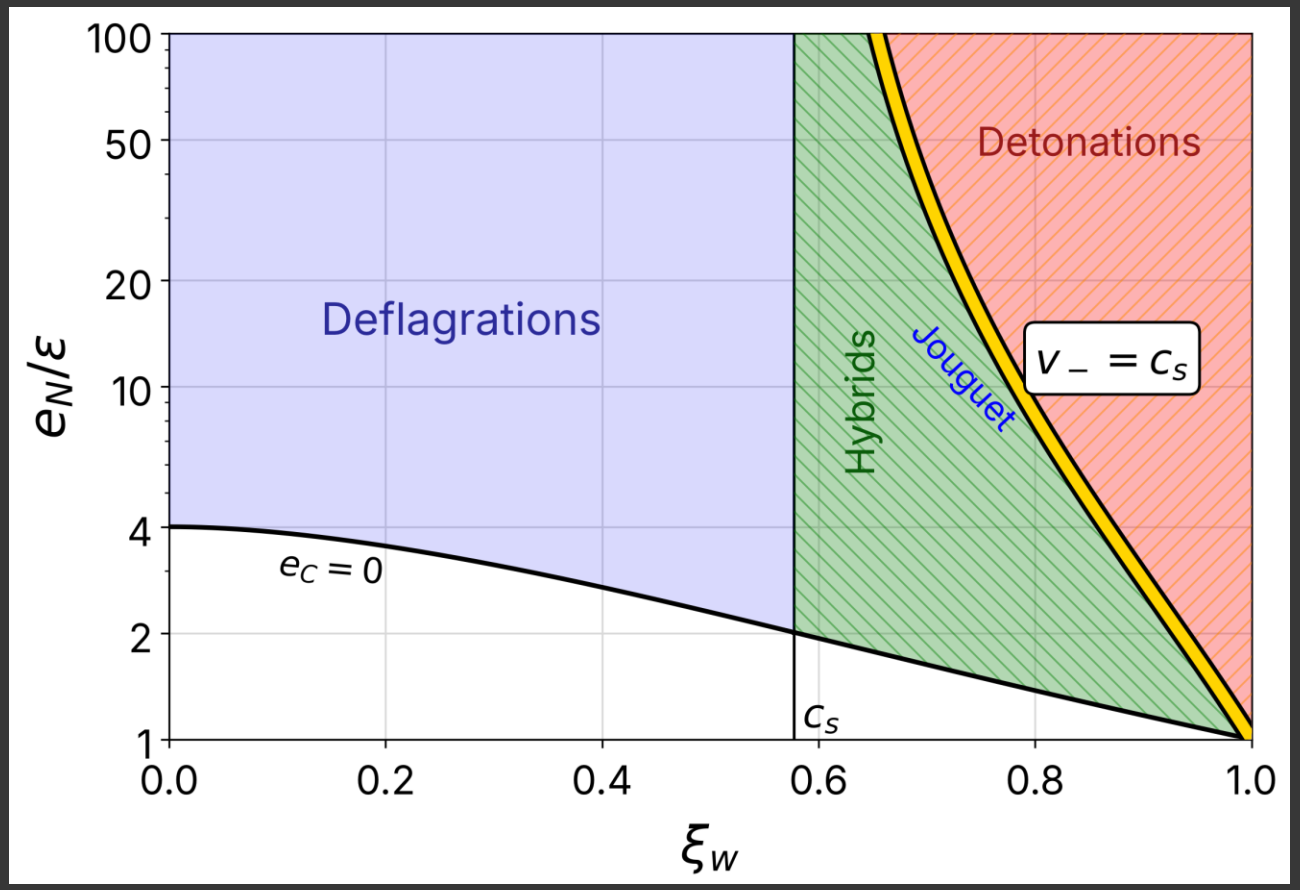
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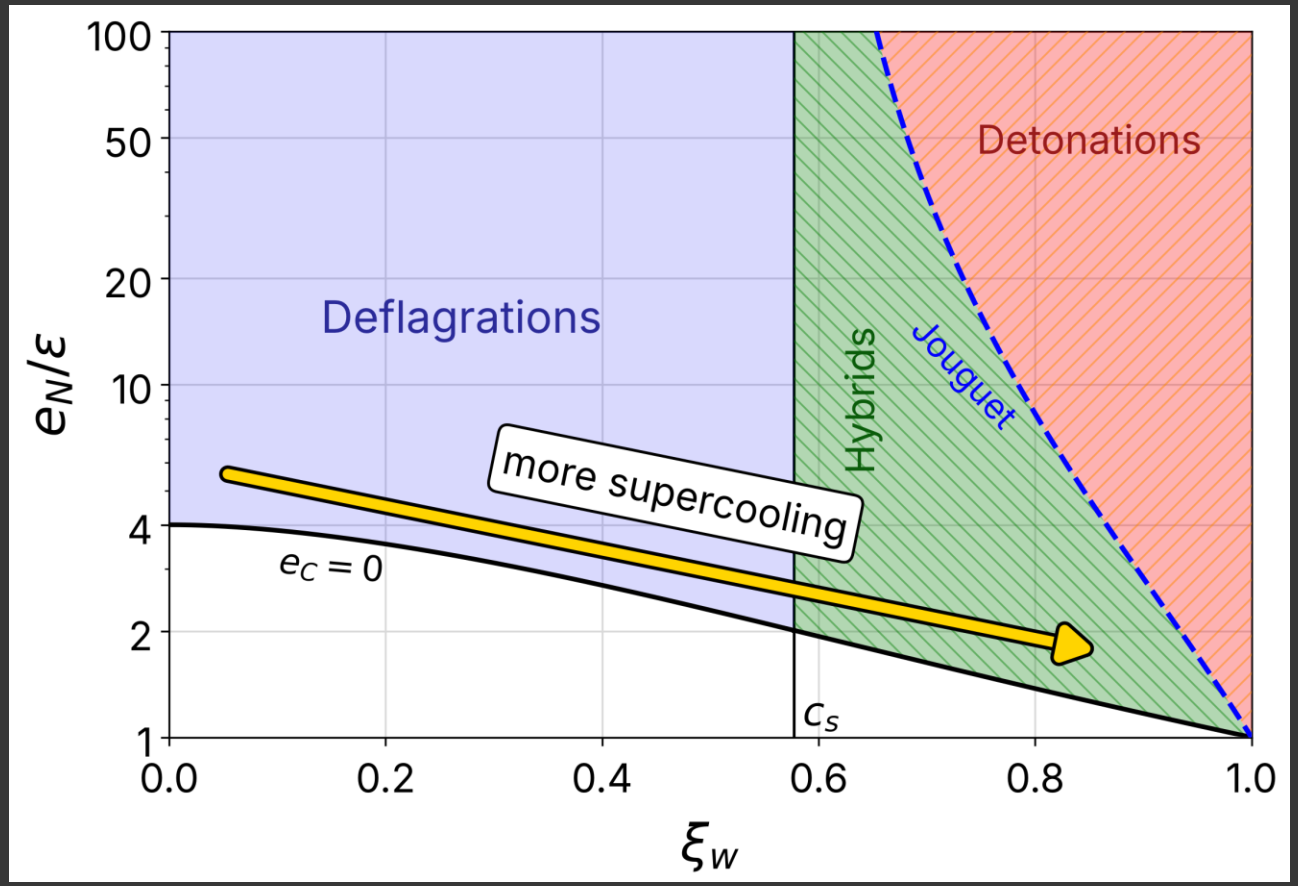
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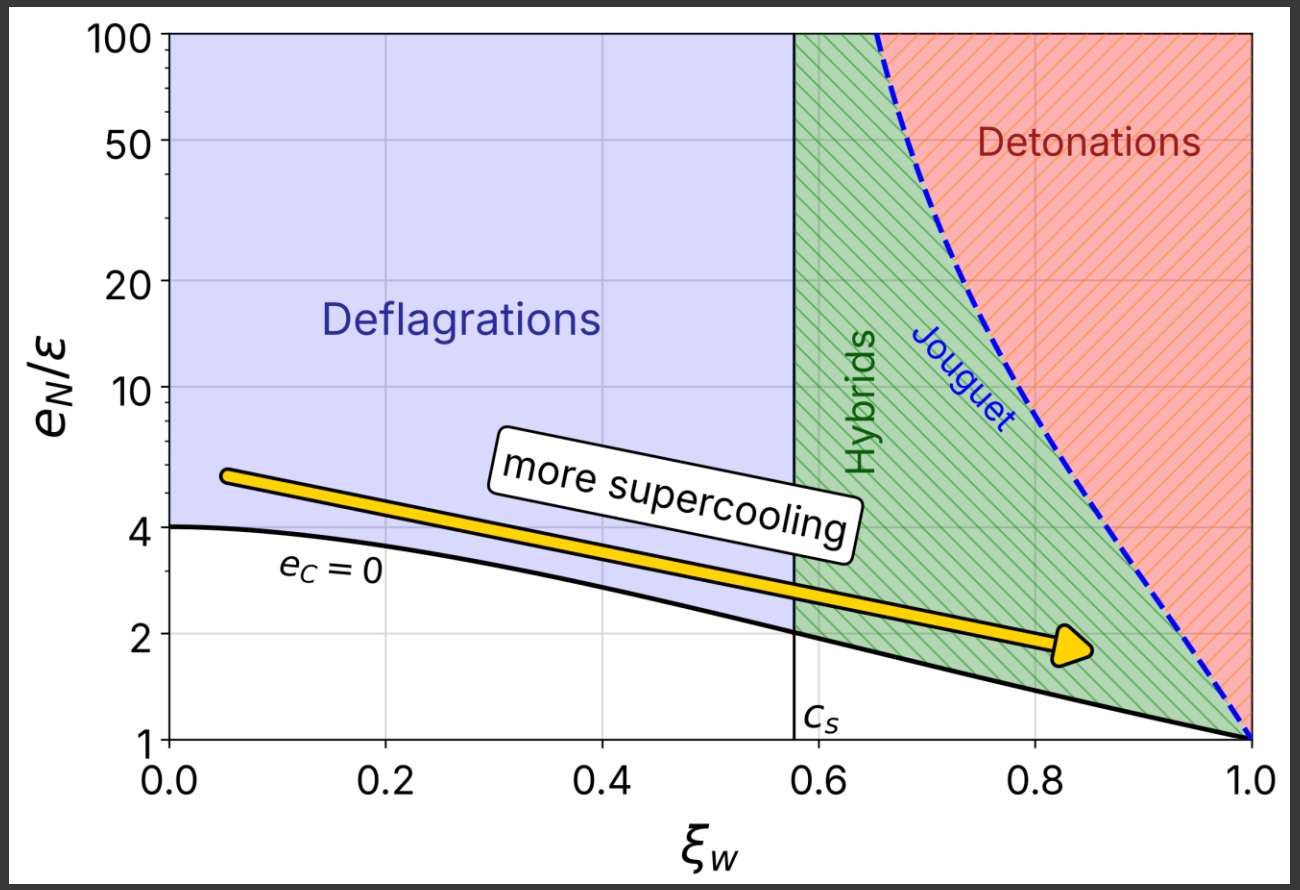
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- How does this change for a non-conformal EoS?



OUTLOOK

1 HYDRODYNAMICS OF EXPANDING BUBBLES
BUBBLES IN A CONFORMAL EOS

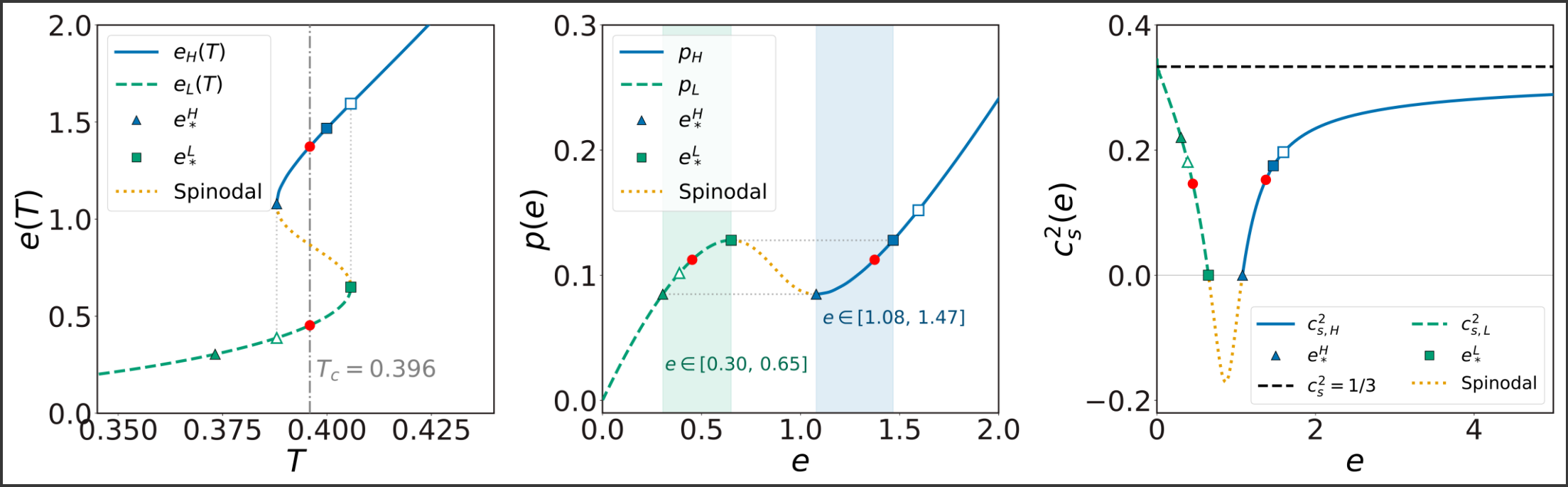
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FROM BAG MODEL TO QCD-LIKE

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

4 CONCLUSIONS

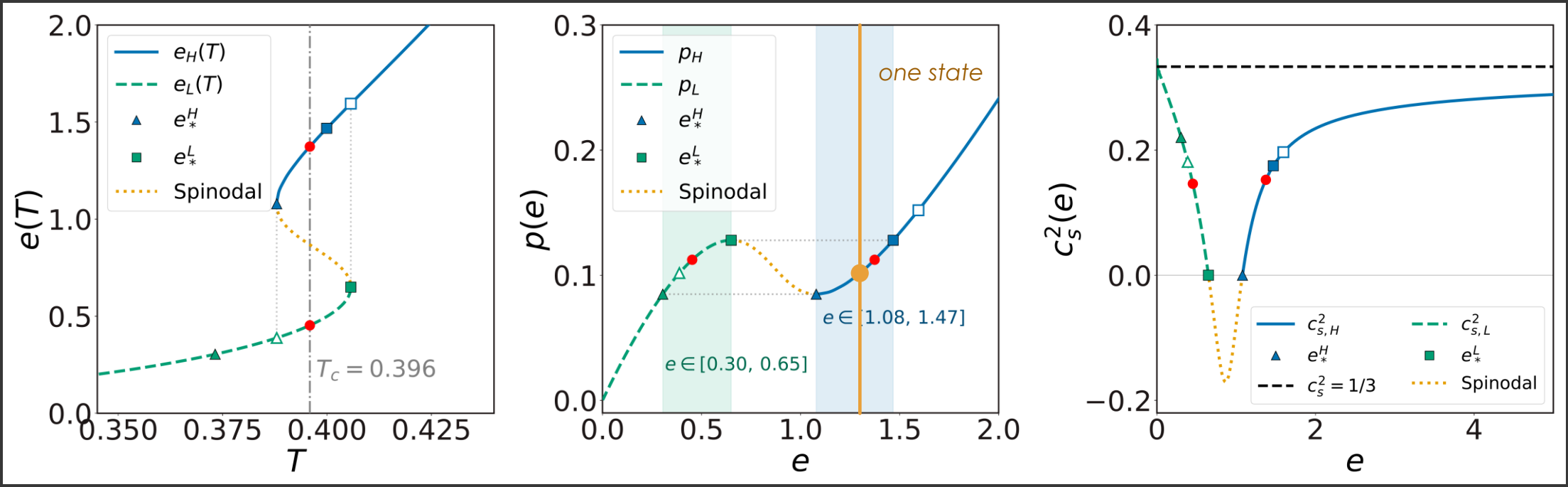
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"QCD-LIKE" EQUATIONS OF STATE



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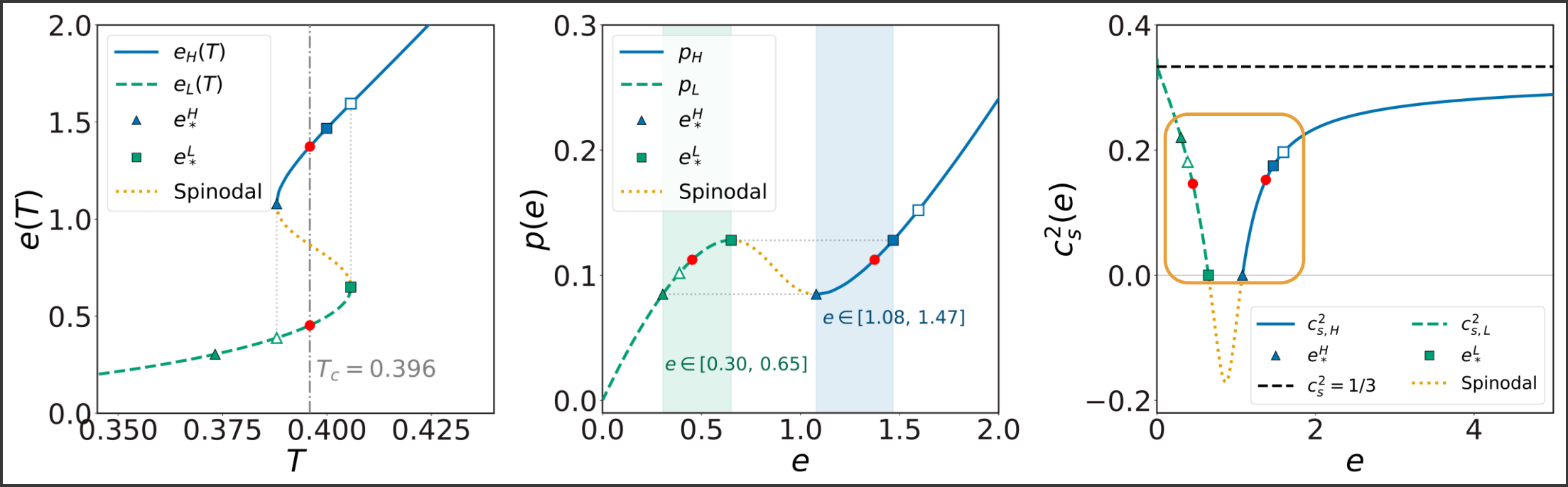
"QCD-LIKE" EQUATIONS OF STATE



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

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

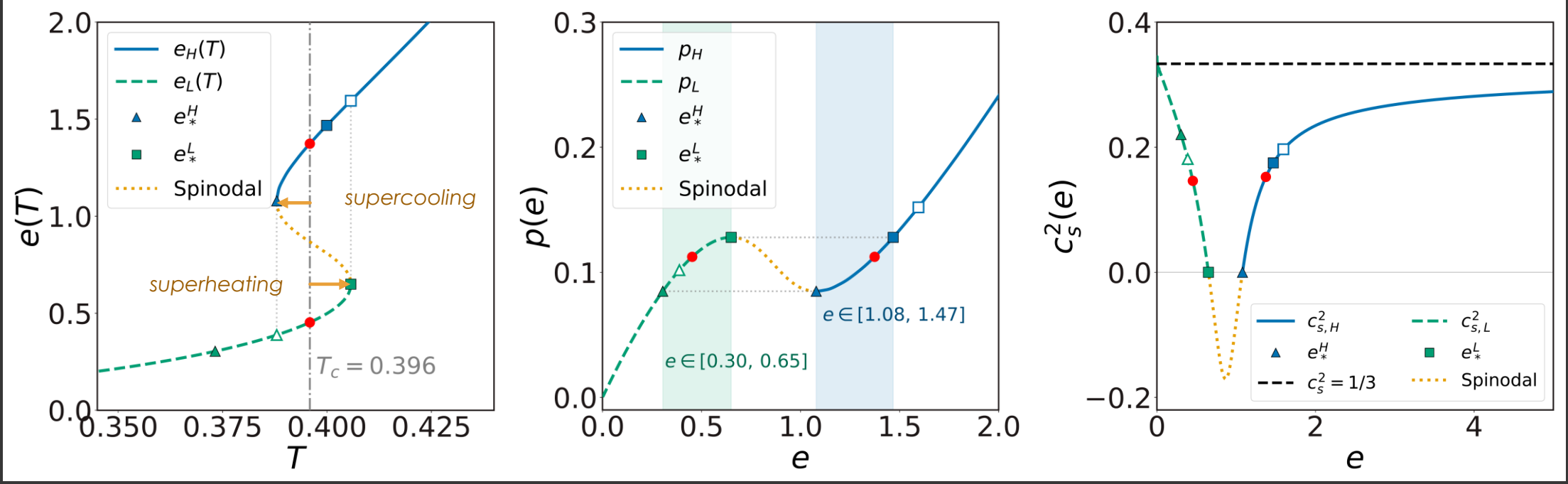
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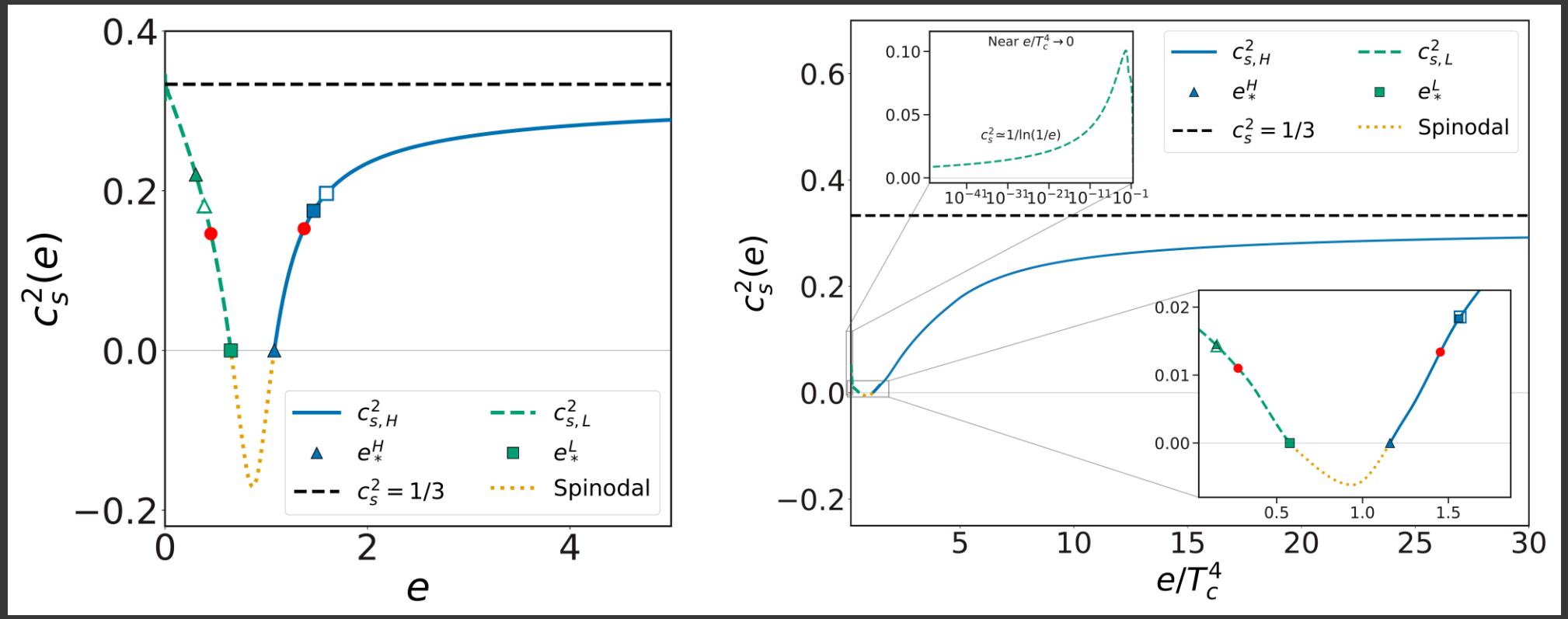
- Single valued in the energy density: one state per energy density
- Strong dependence of the speed of sound on the temperature
- Finite amount of supercooling and superheating

[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

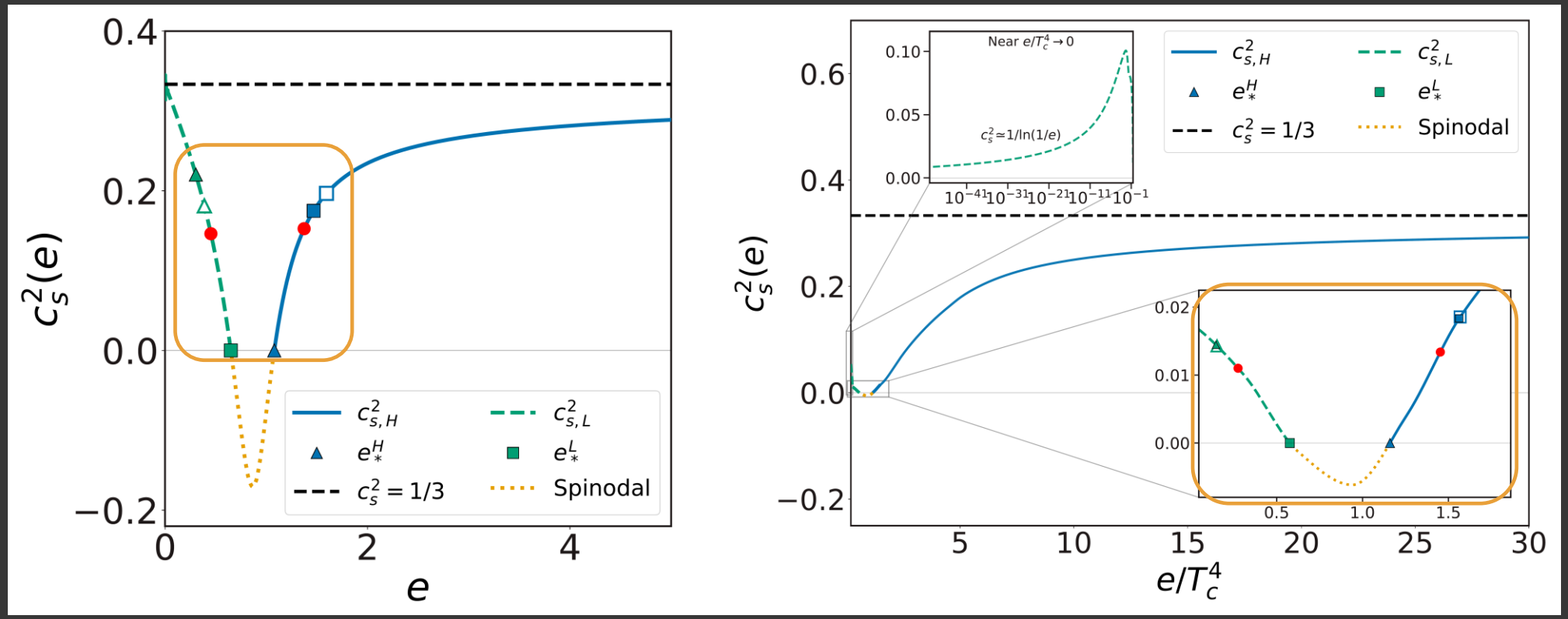


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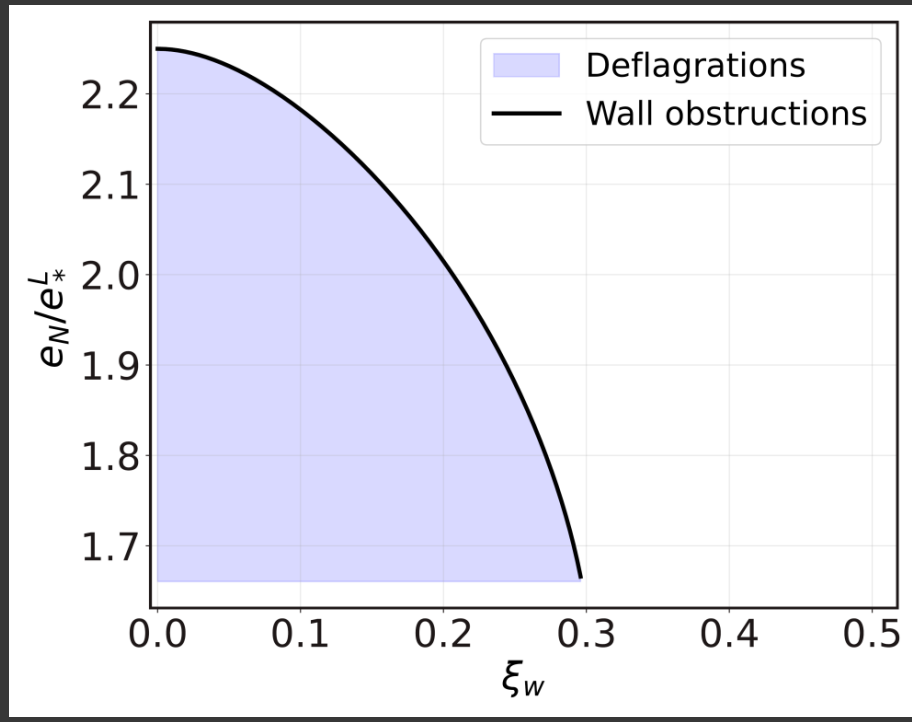


- In the range relevant for the transition, both are qualitatively similar

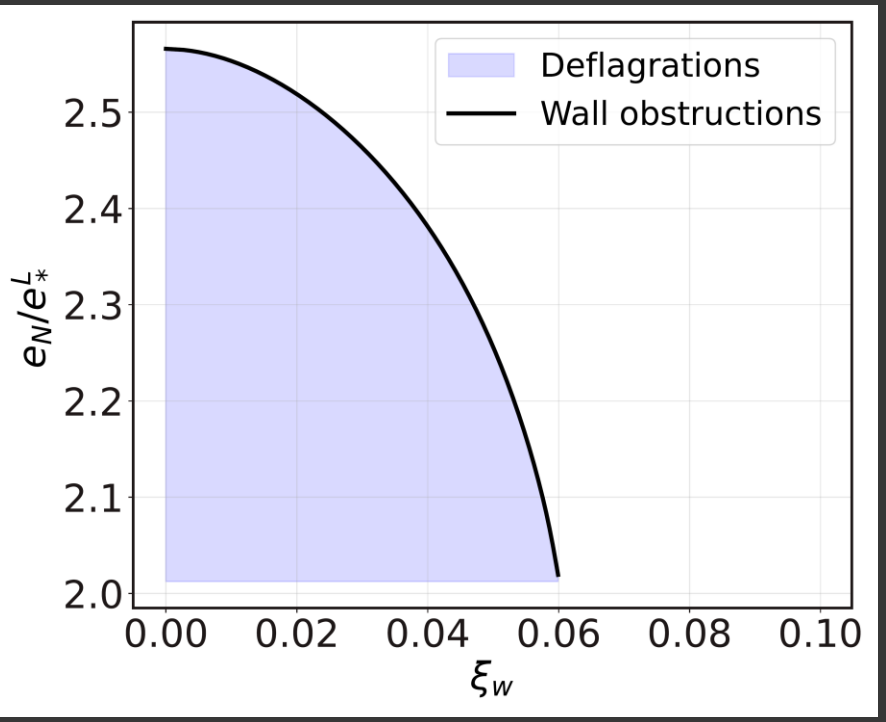
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BUBBLES IN QCD-LIKE THEORIES

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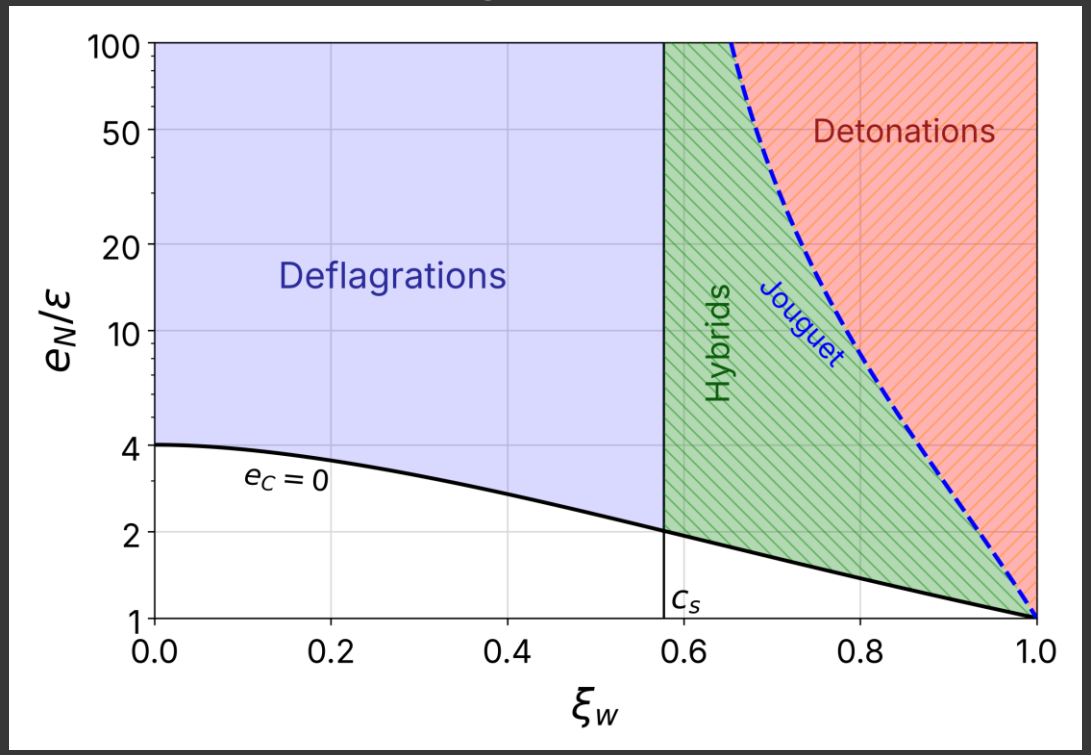
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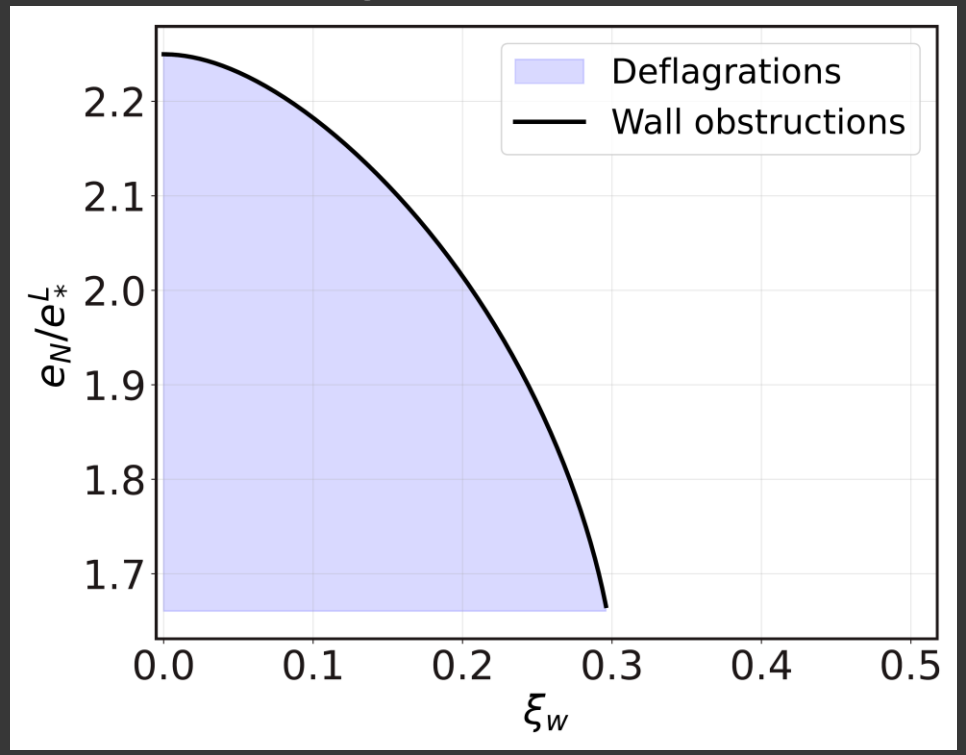
FROM THE BAG MODEL TO QCD-LIKE

Bag model



?

Holographic model



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

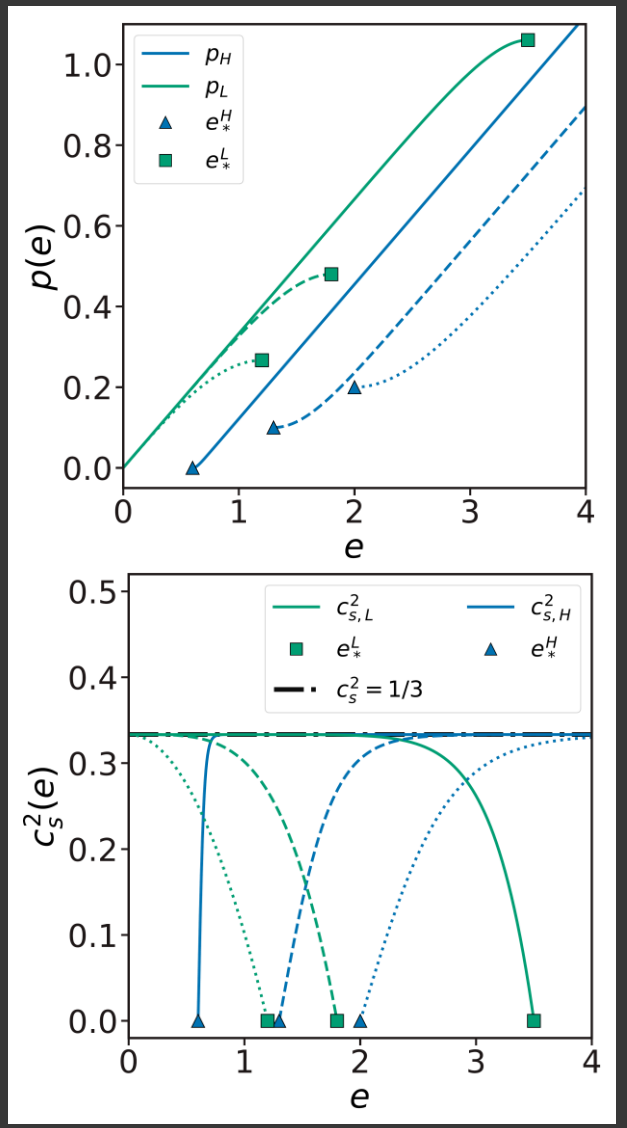
EQUATION OF STATE ANSATZ

— 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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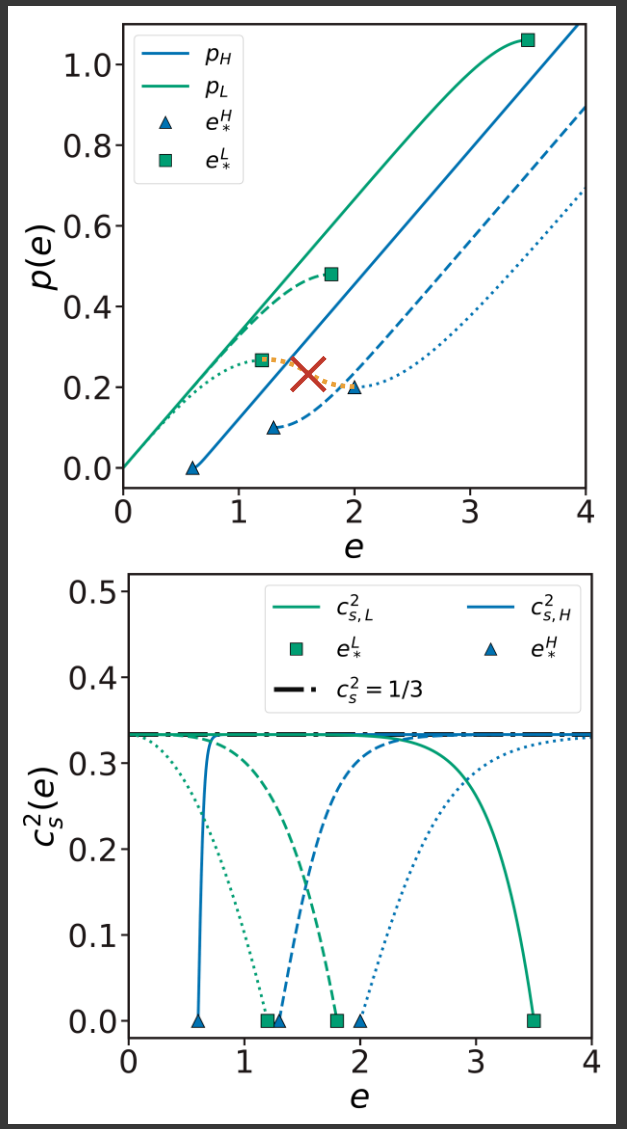
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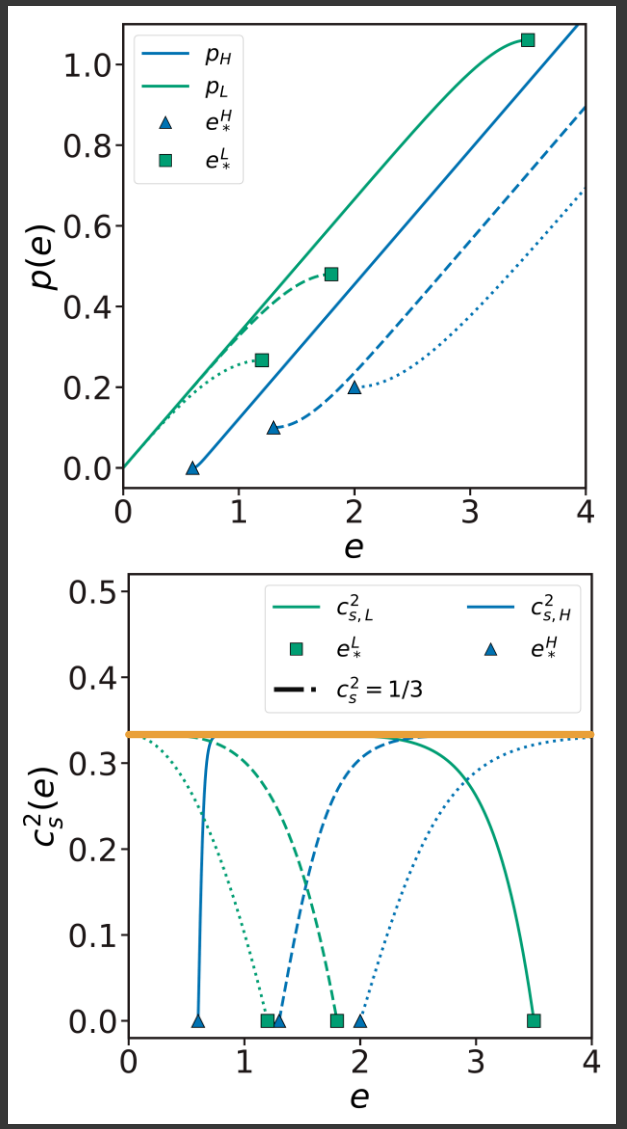
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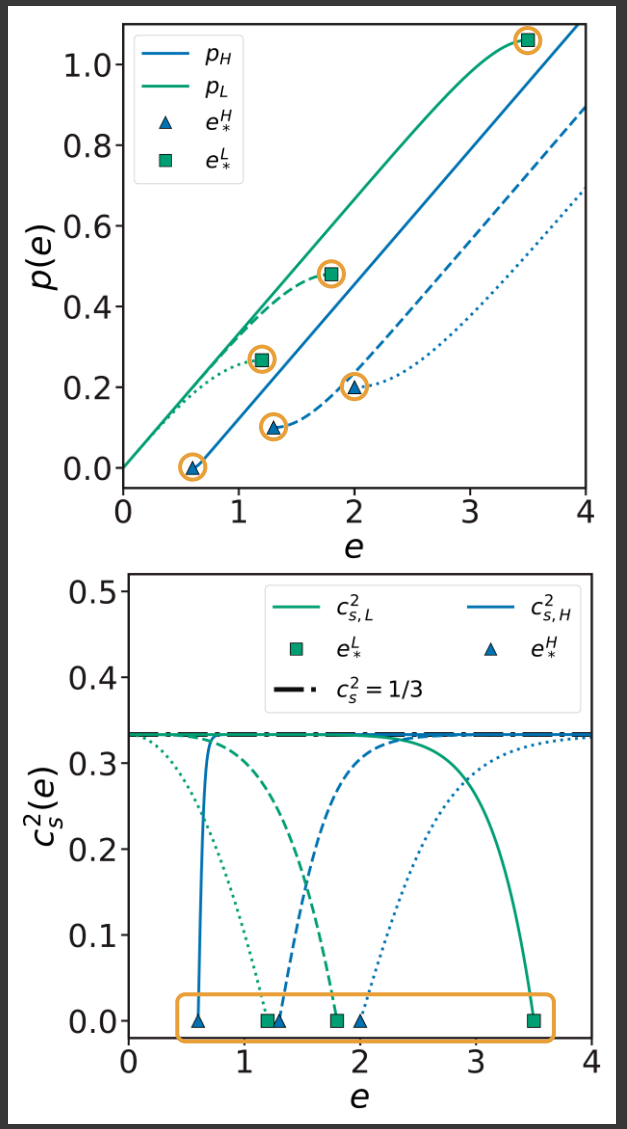
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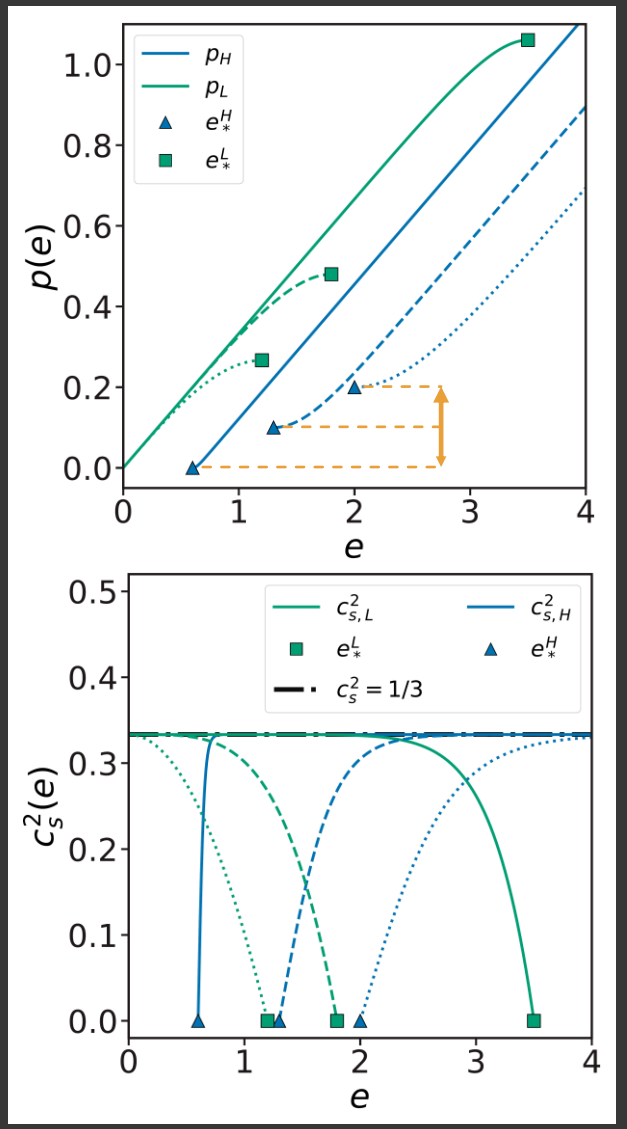
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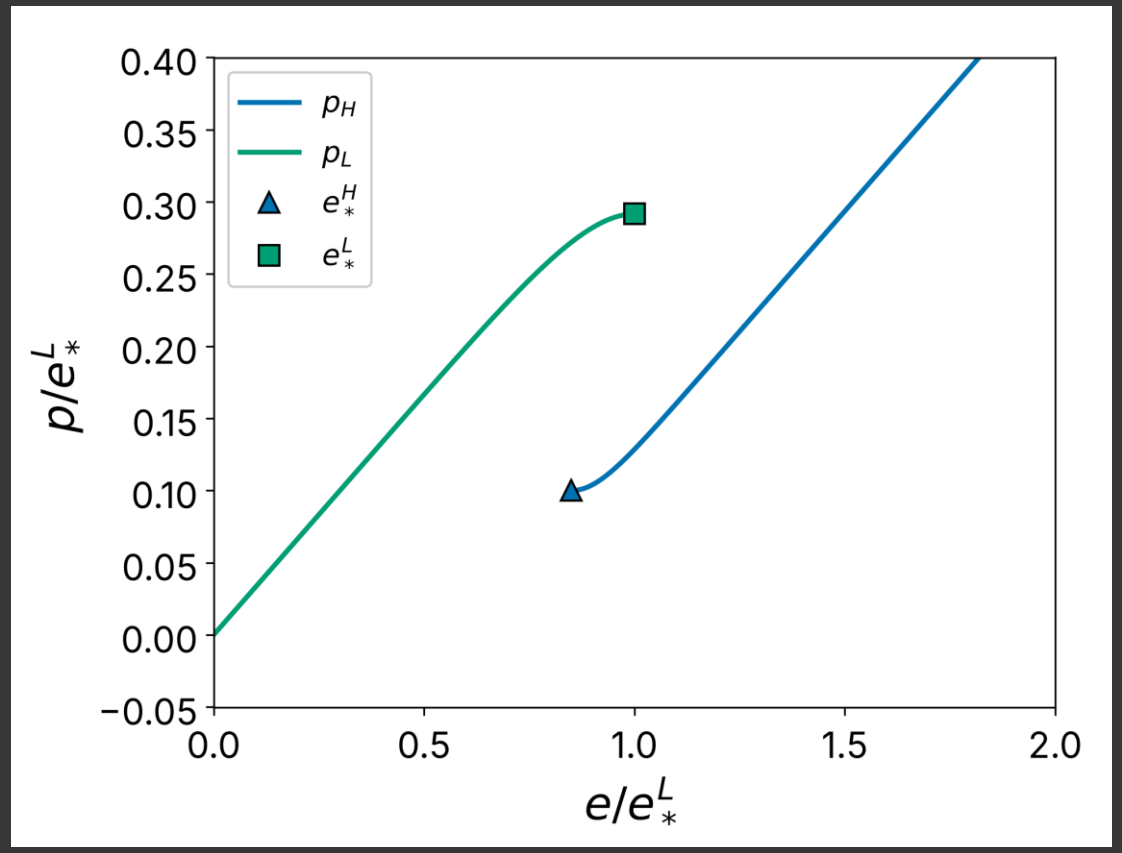
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  - δ and n control how fast c_s varies
  - p_1 plays the role of the "bag constant"



ENTROPY

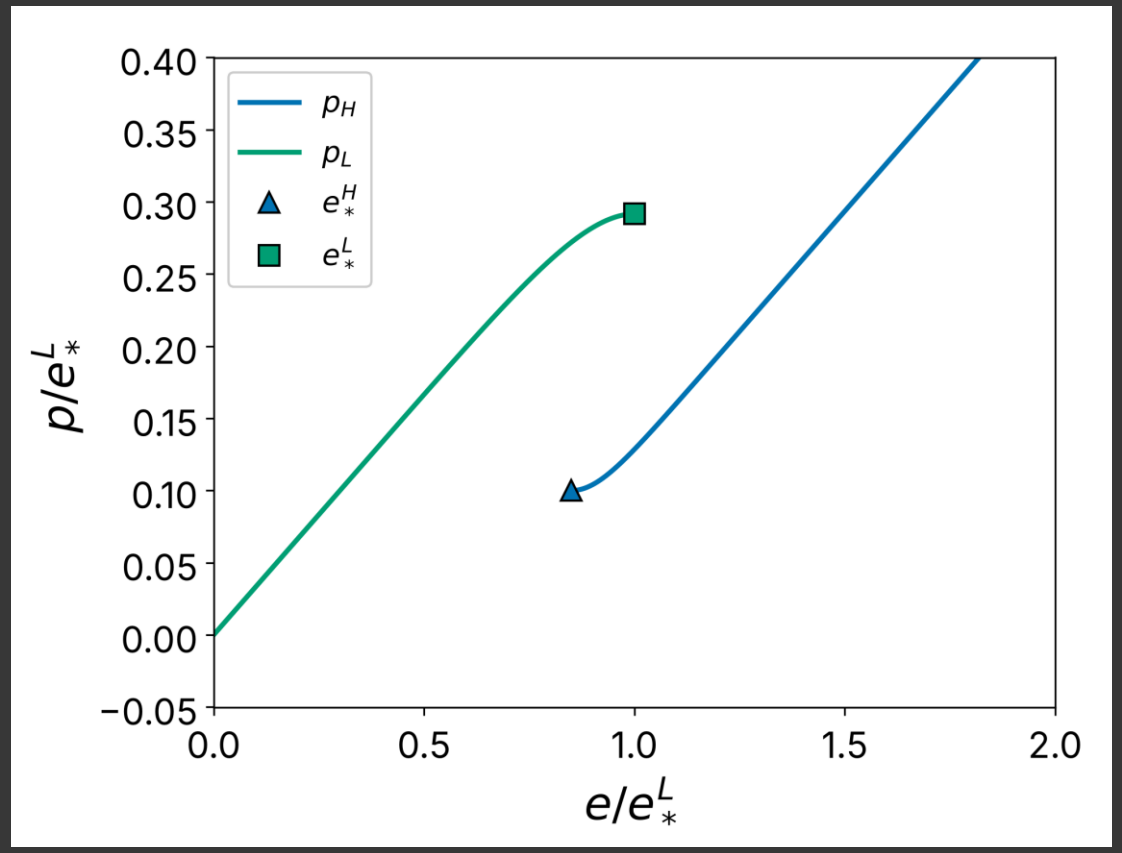
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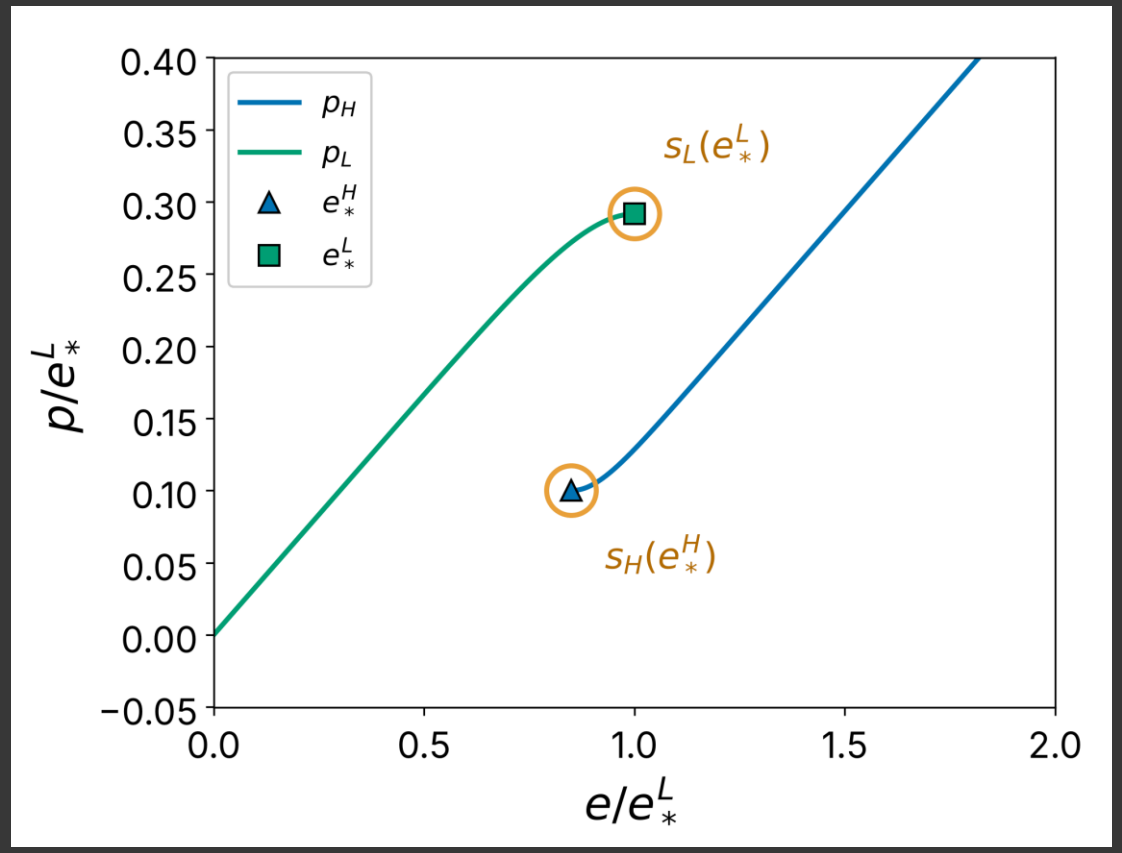


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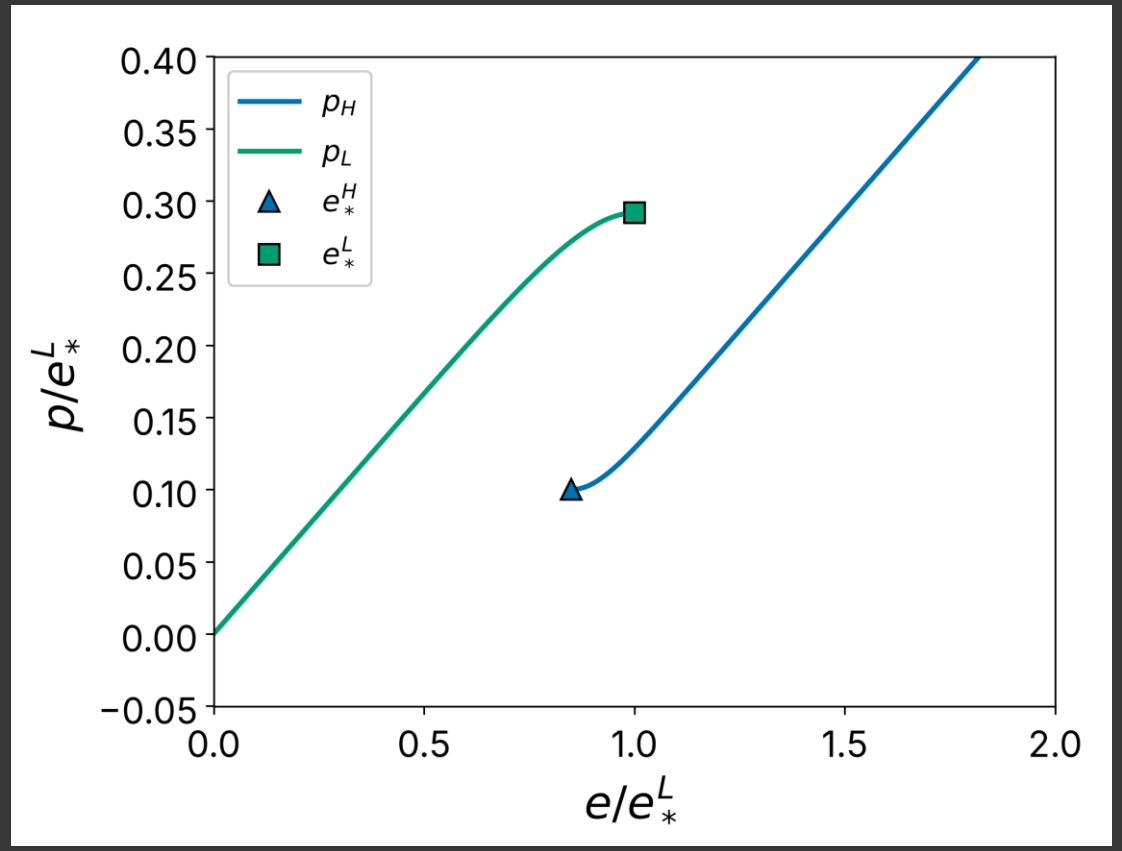


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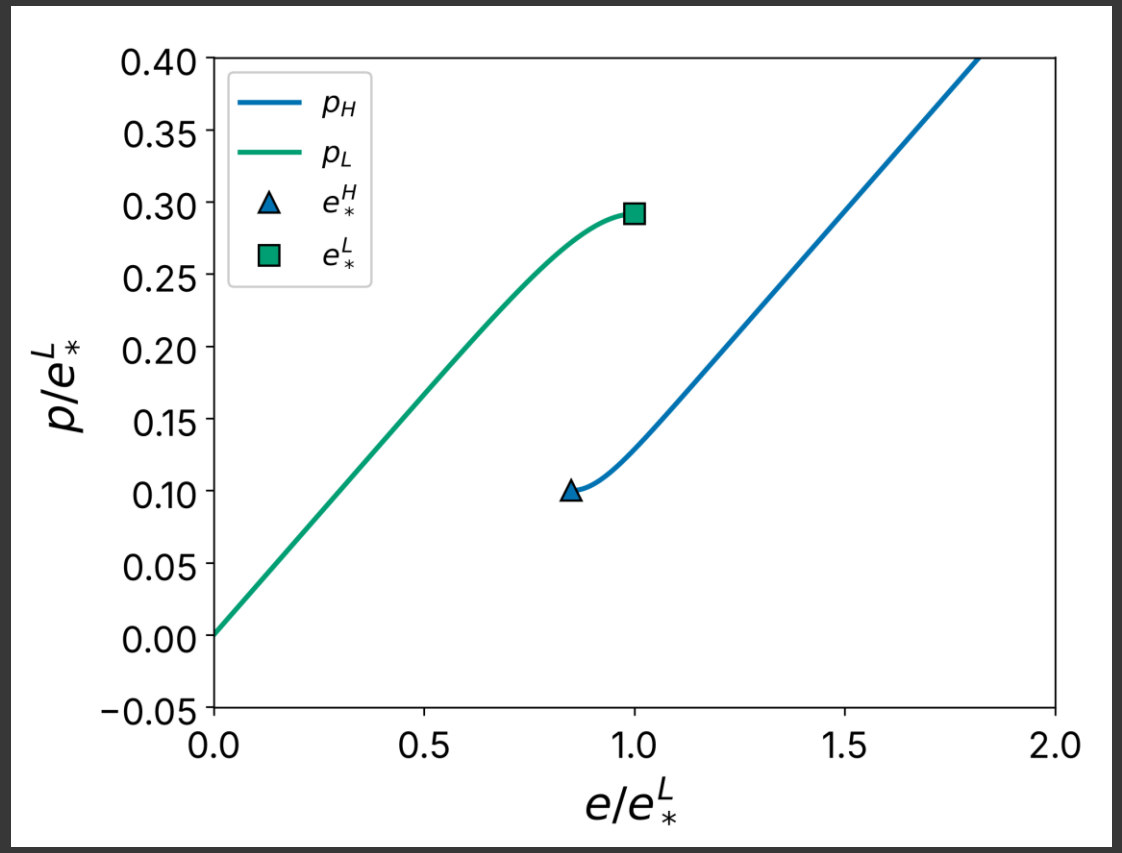
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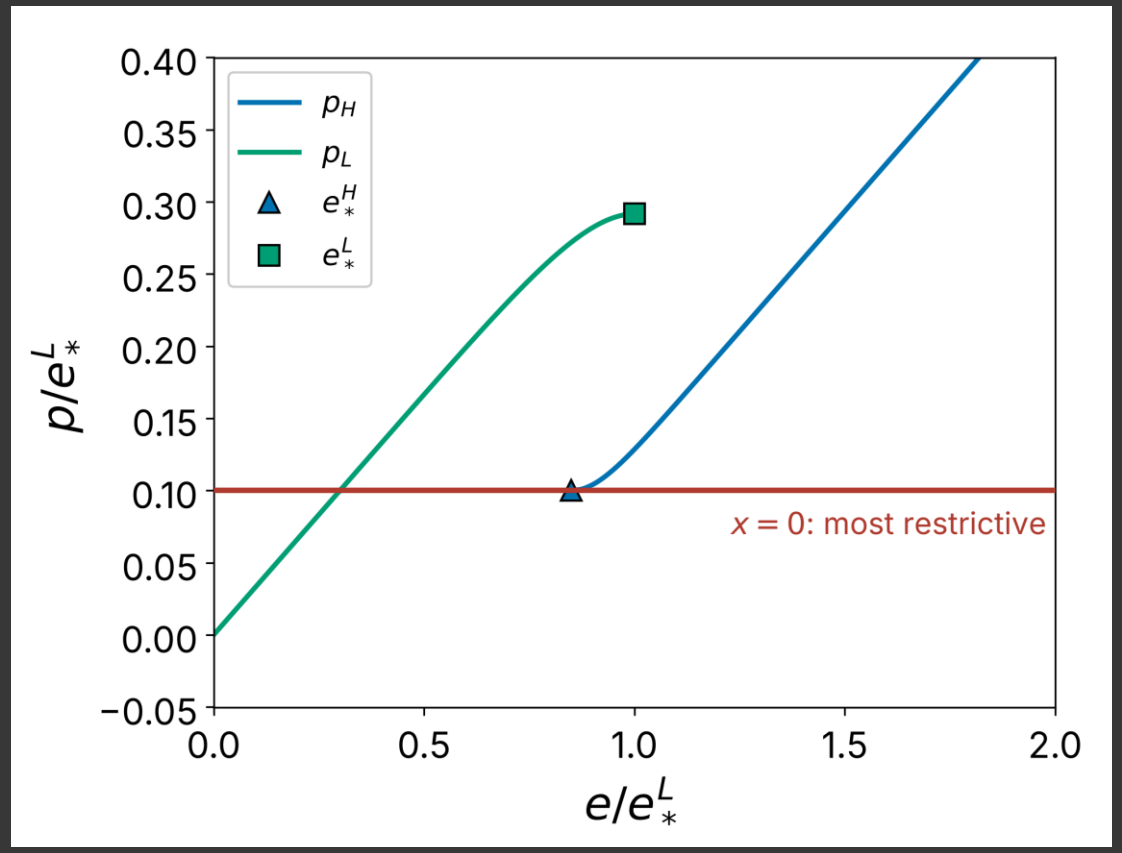
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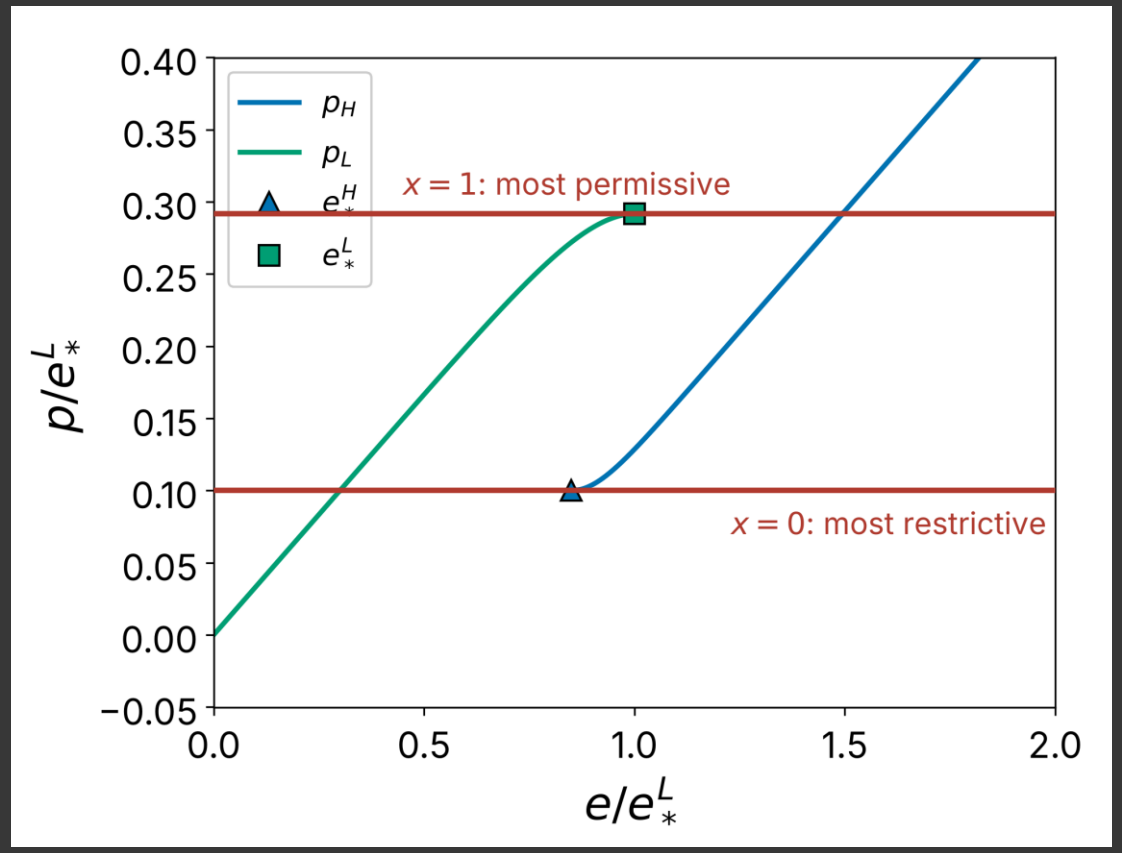
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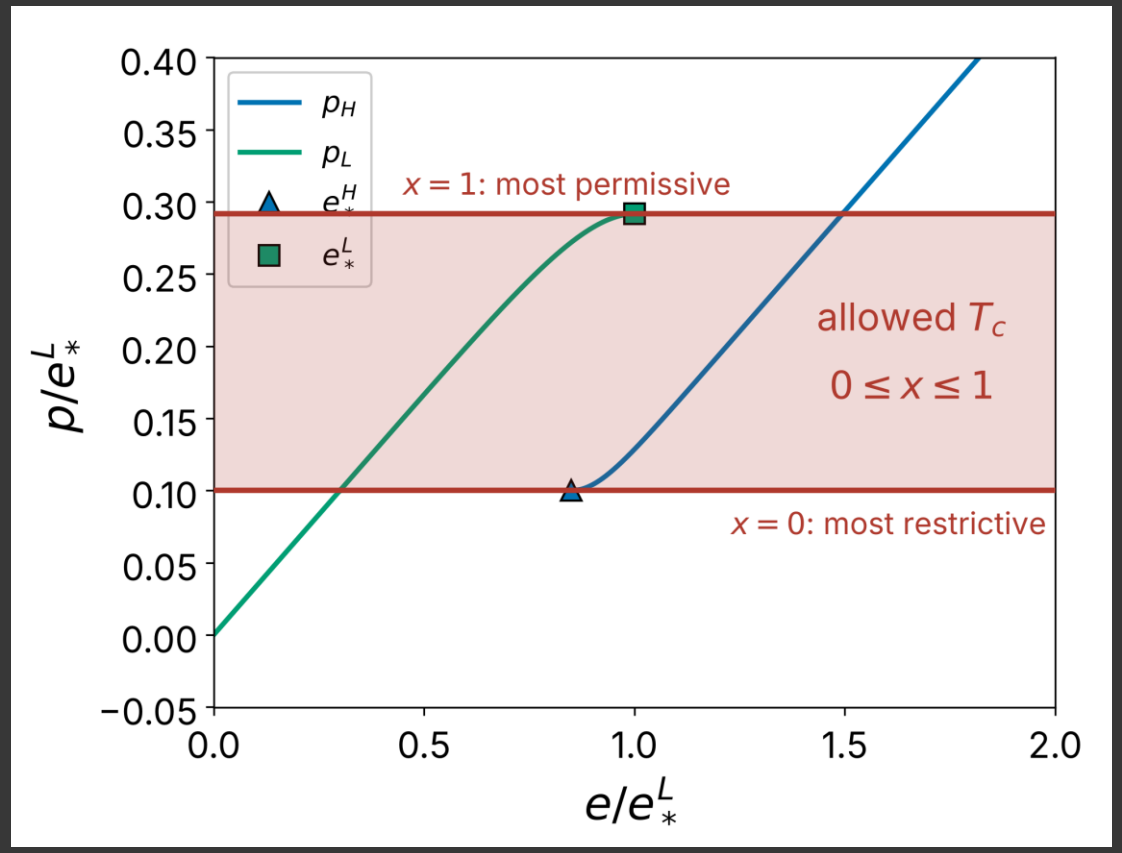
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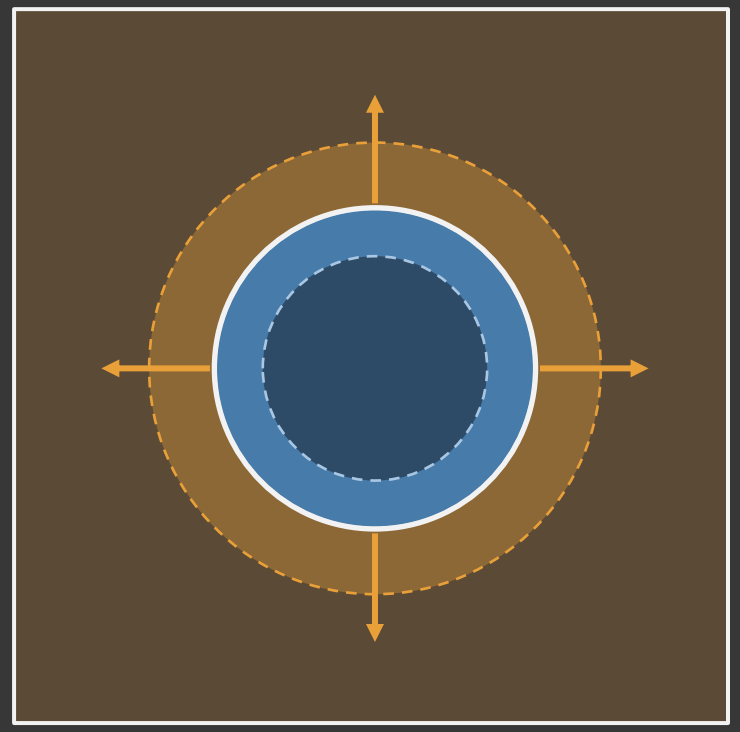
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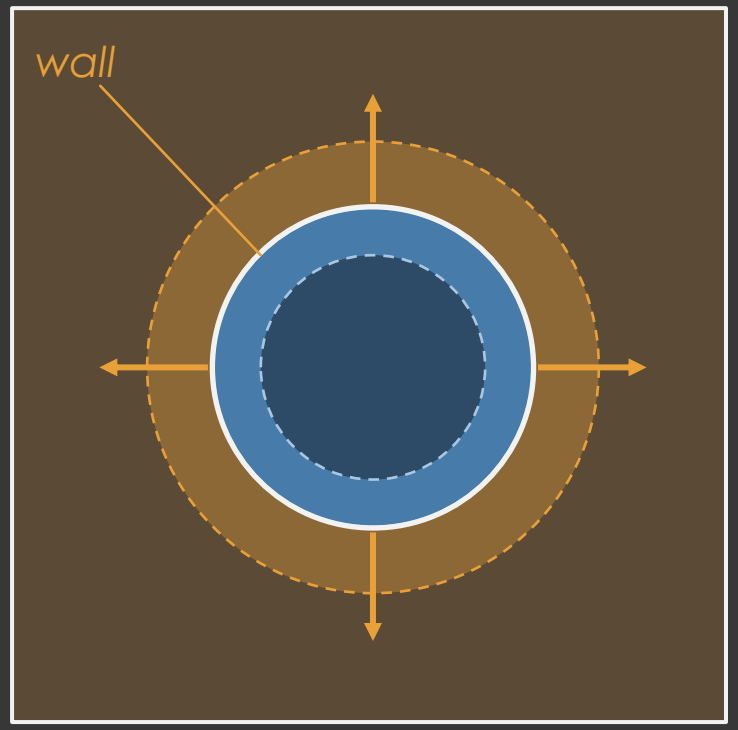
NON-CONFORMAL OBSTRUCTIONS



NON-CONFORMAL OBSTRUCTIONS

WALL OBSTRUCTIONS

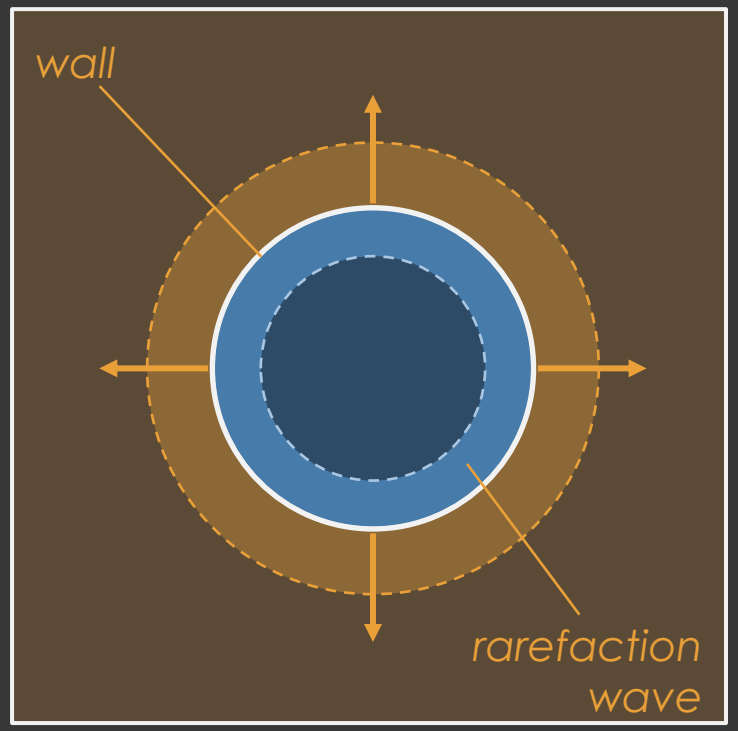
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- Affect deflagrations and detonations



NON-CONFORMAL OBSTRUCTIONS

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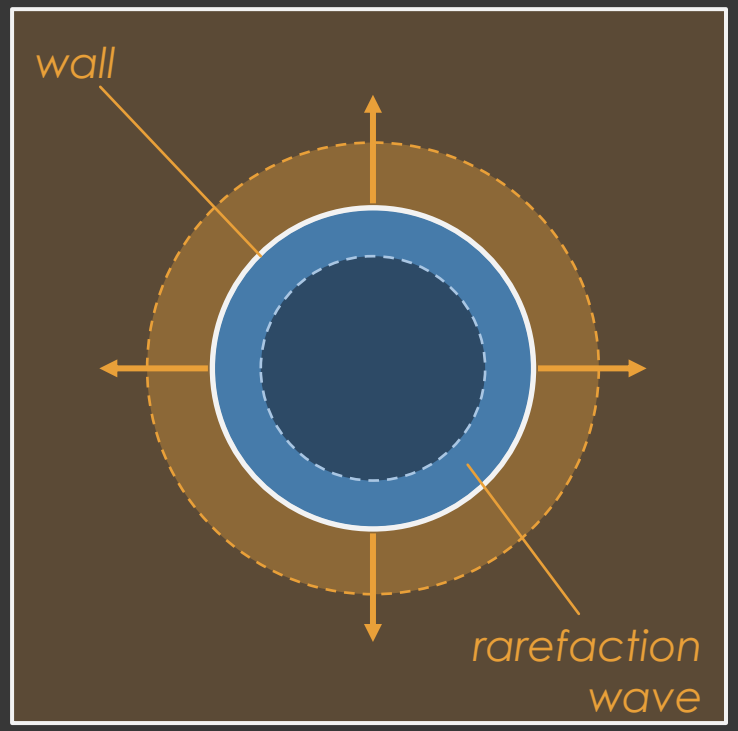
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- No continuous flow can be built along the rarefaction wave
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NON-CONFORMAL OBSTRUCTIONS

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- New solution: shocked-detonations

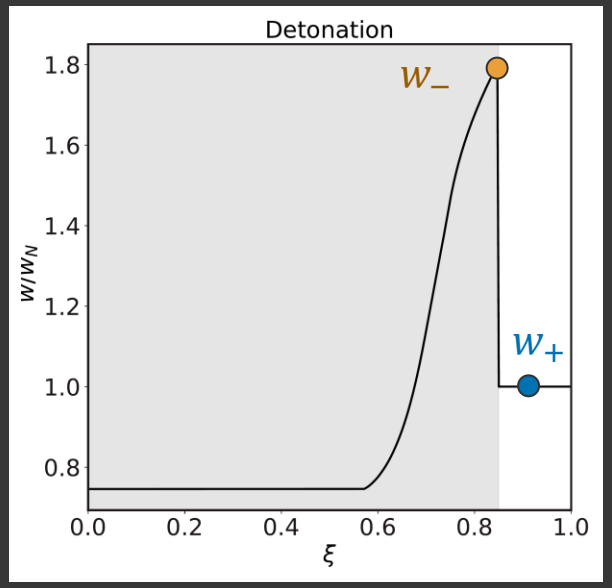
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WALL OBSTRUCTIONS: DETONATIONS

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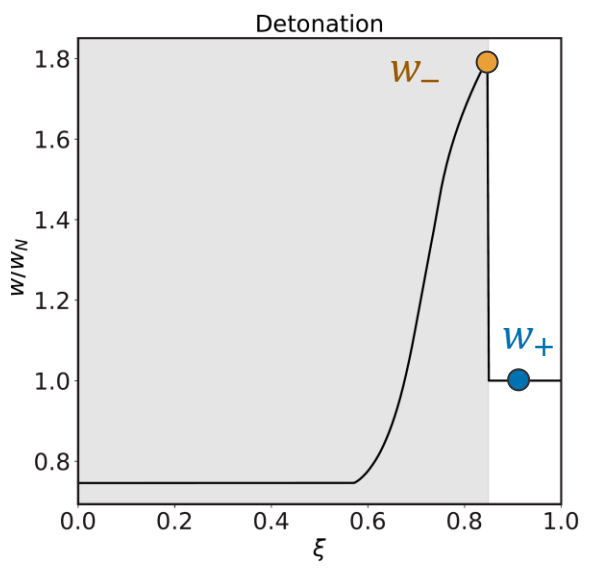
Single detonation



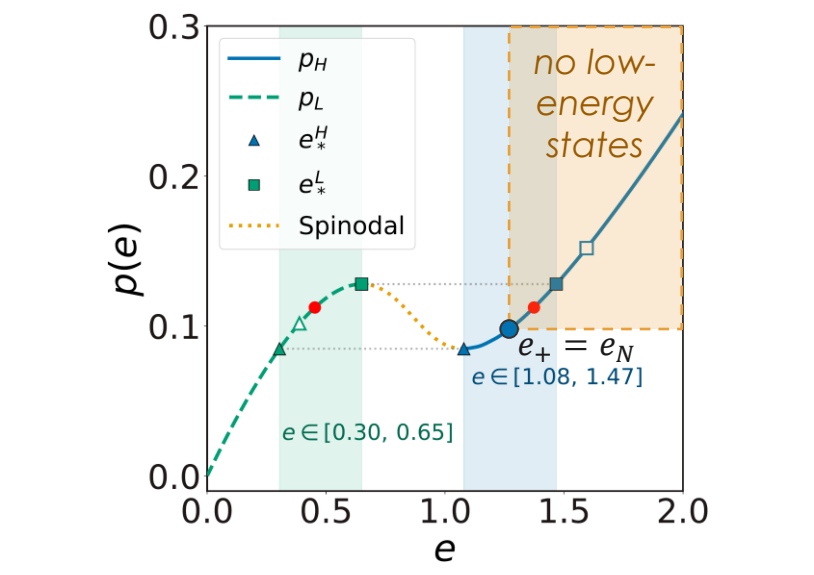
- Detonation: fluid at rest ahead of a supersonic wall, $v_+ > v_- \Rightarrow w_- > w_+$ (and $p_- > p_+$, $e_- > e_+$)

WALL OBSTRUCTIONS: DETONATIONS

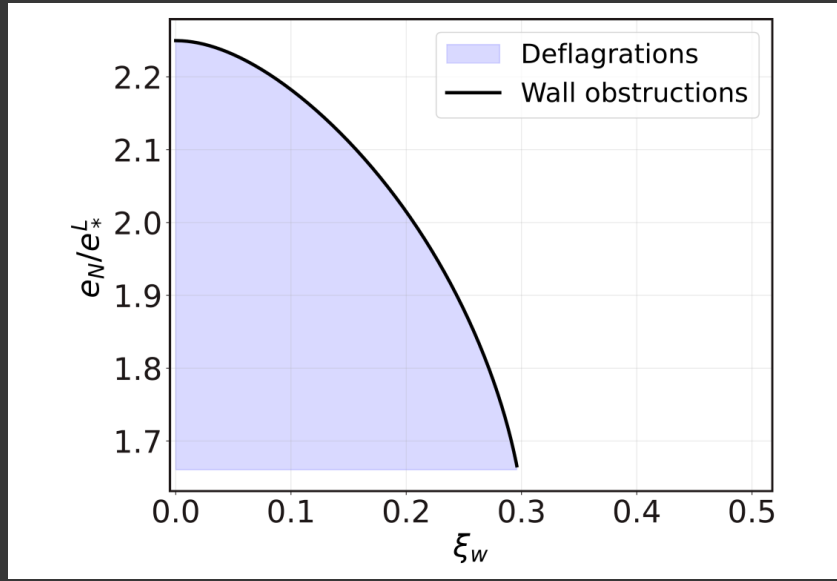
Single detonation



Holographic model: EoS



Holographic model: solutions

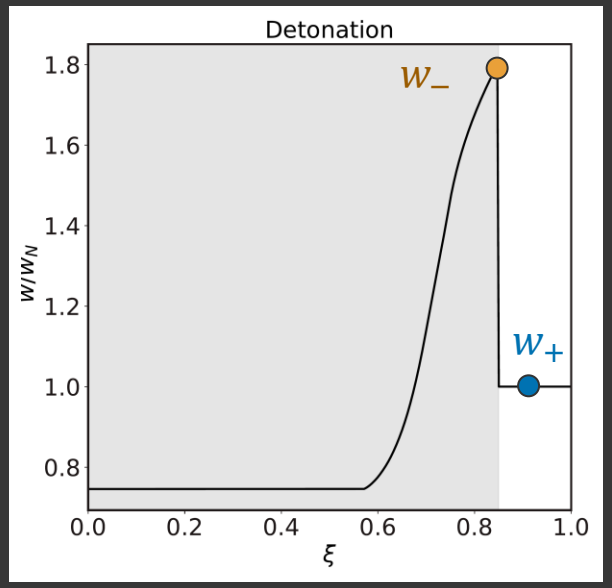


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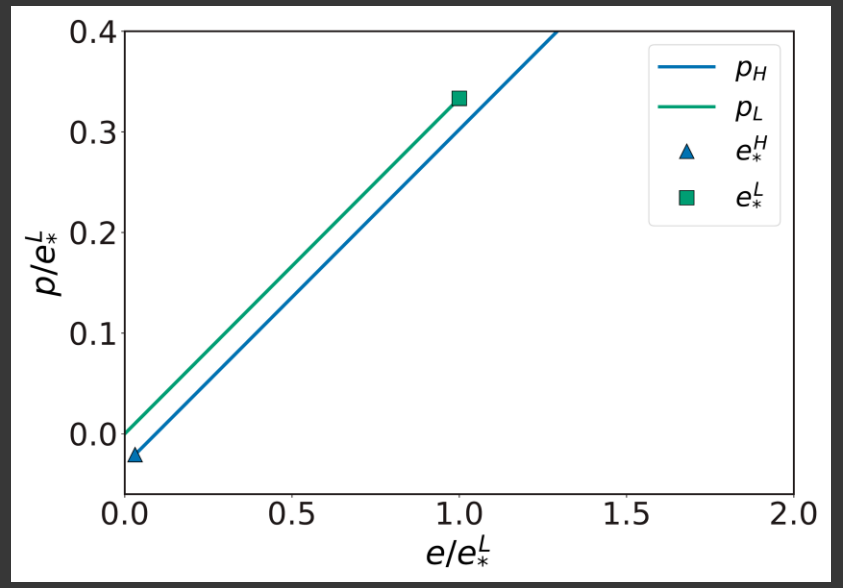
[Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

WALL OBSTRUCTIONS: DETONATIONS

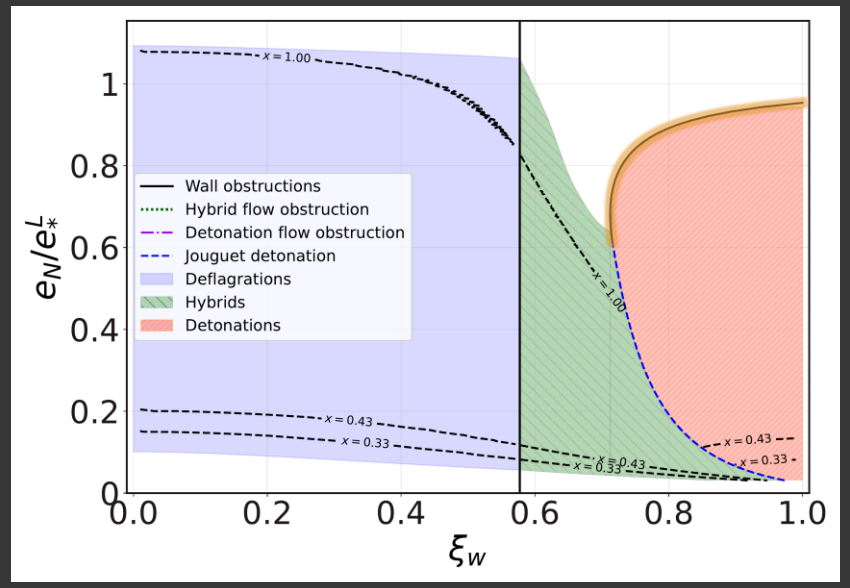
Single detonation



Bag EoS, finite ranges



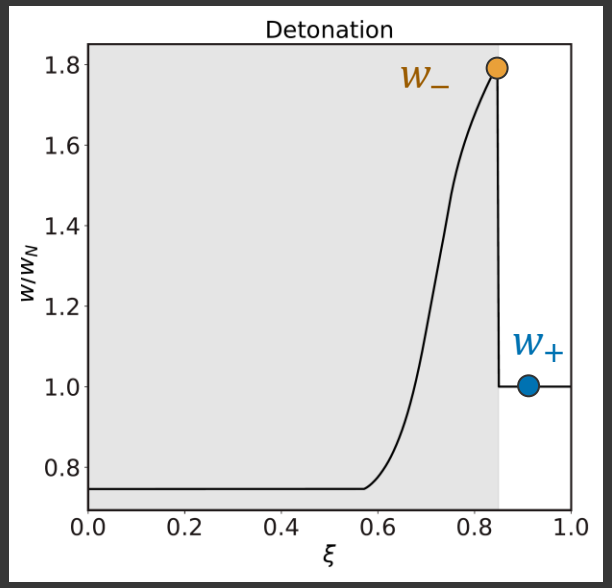
Bag model, finite ranges



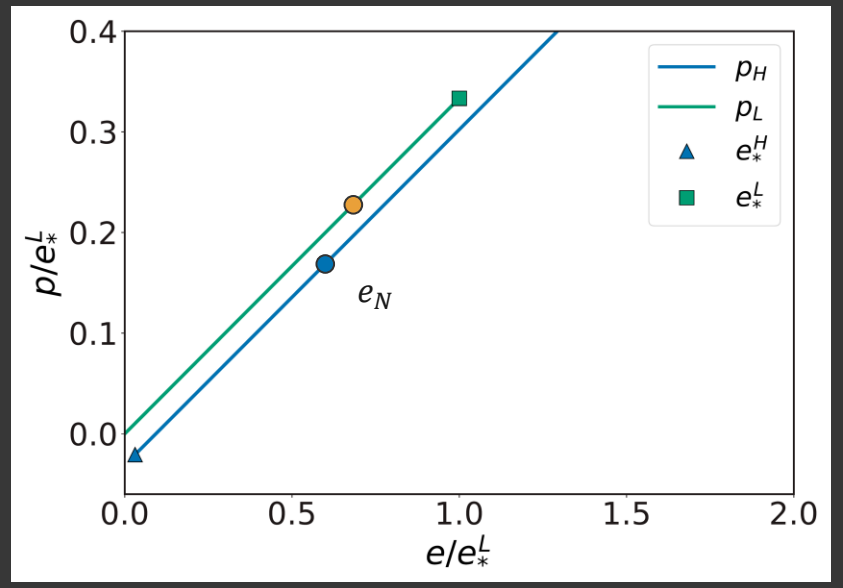
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WALL OBSTRUCTIONS: DETONATIONS

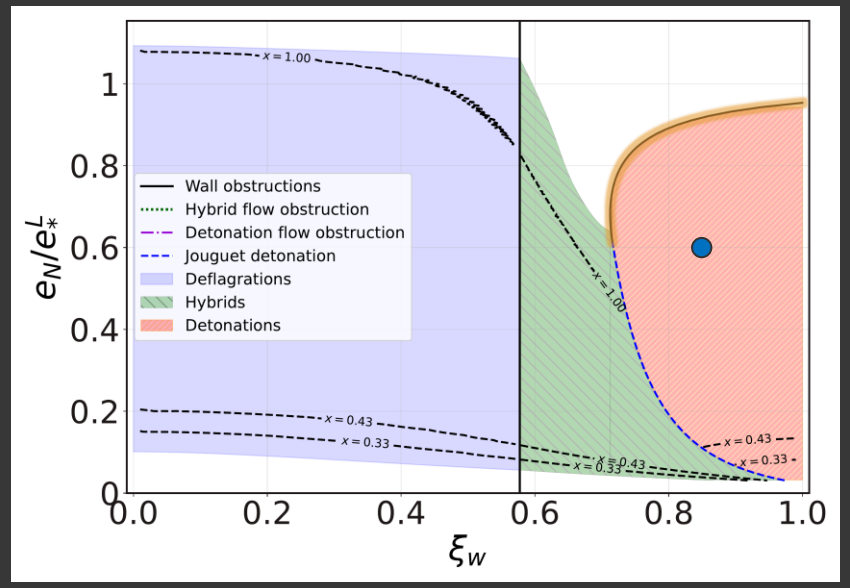
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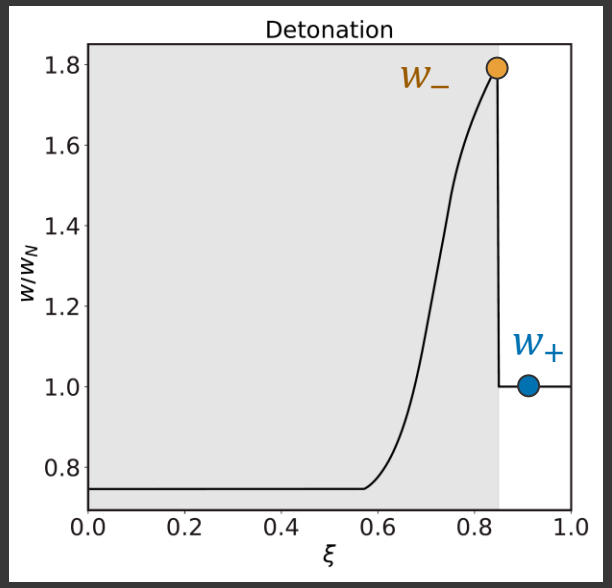
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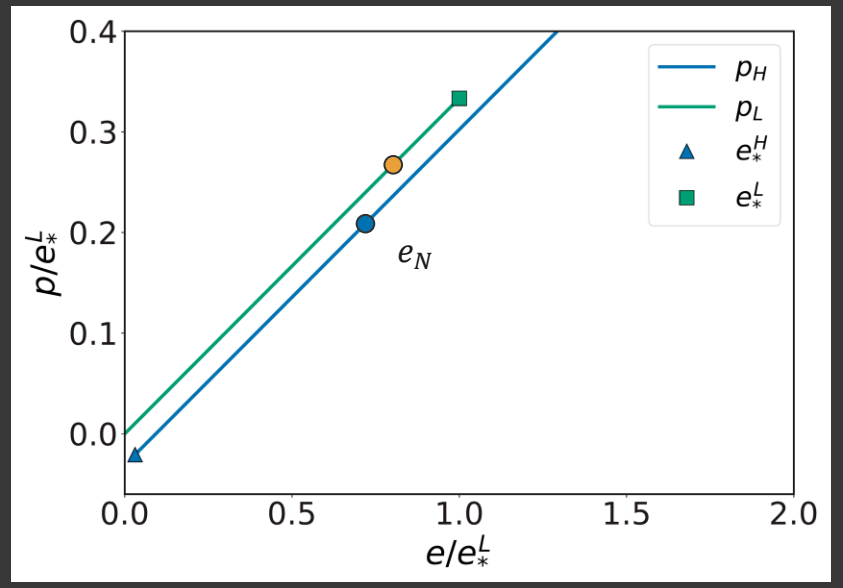
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WALL OBSTRUCTIONS: DETONATIONS

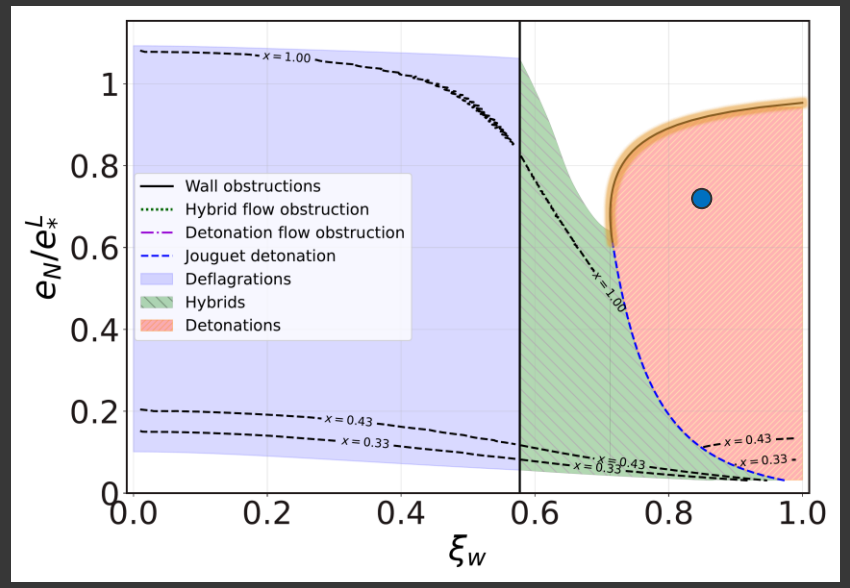
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Bag EoS, finite ranges



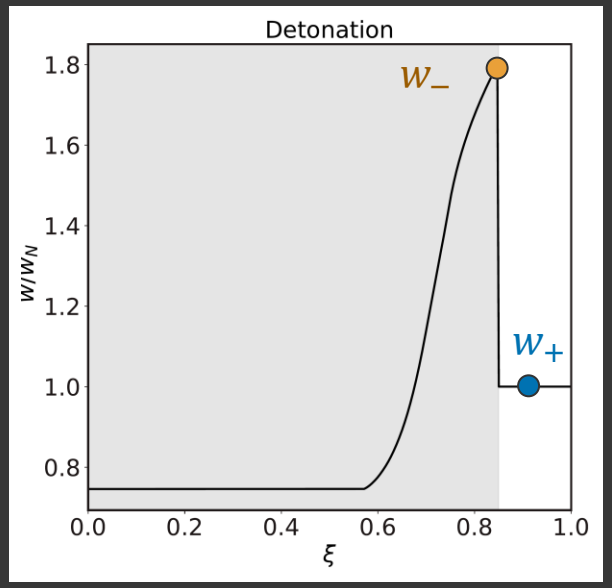
Bag model, finite ranges



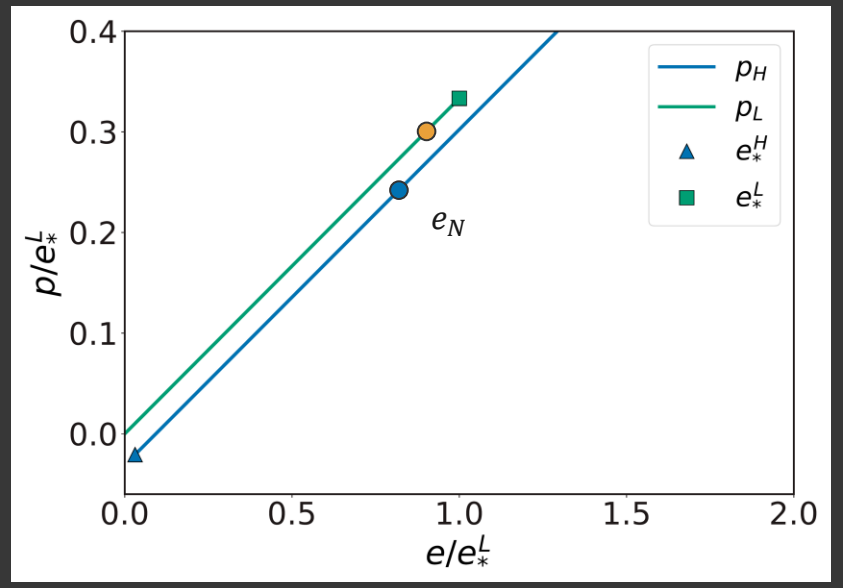
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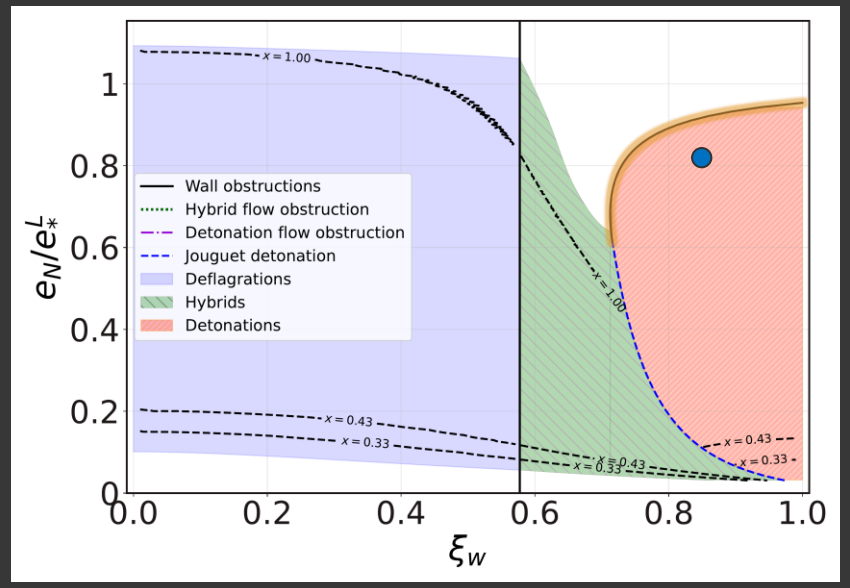
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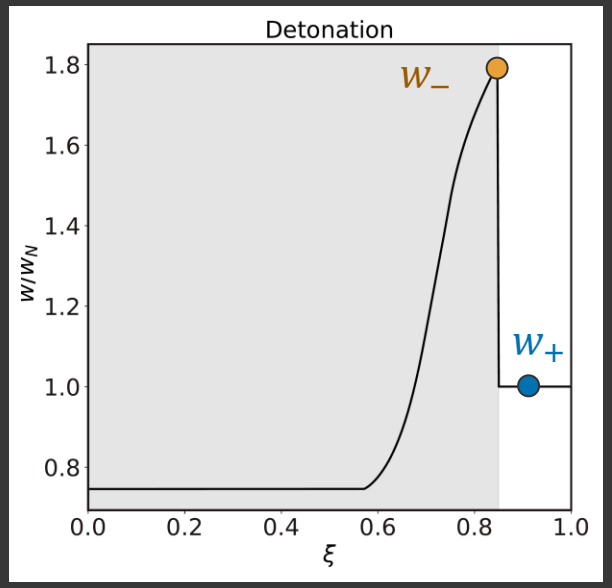
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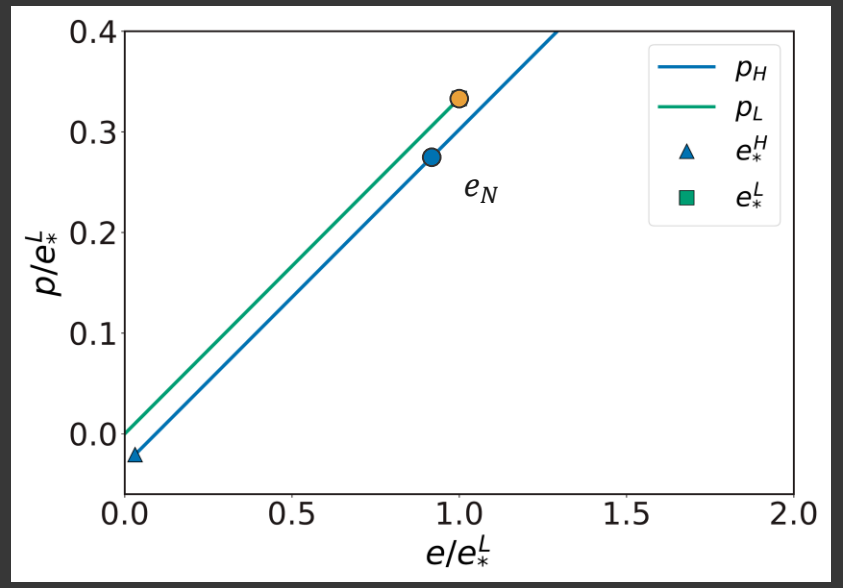
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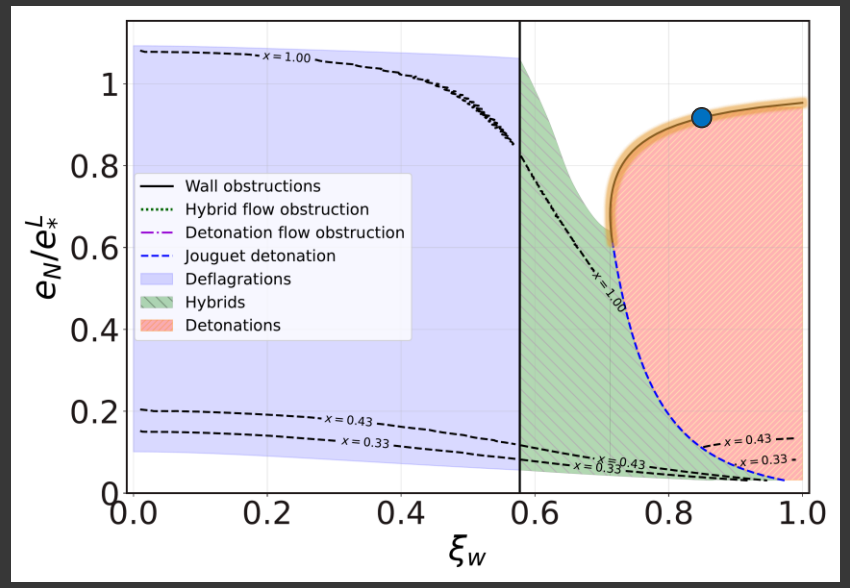
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Bag EoS, finite ranges



Bag model, finite ranges



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

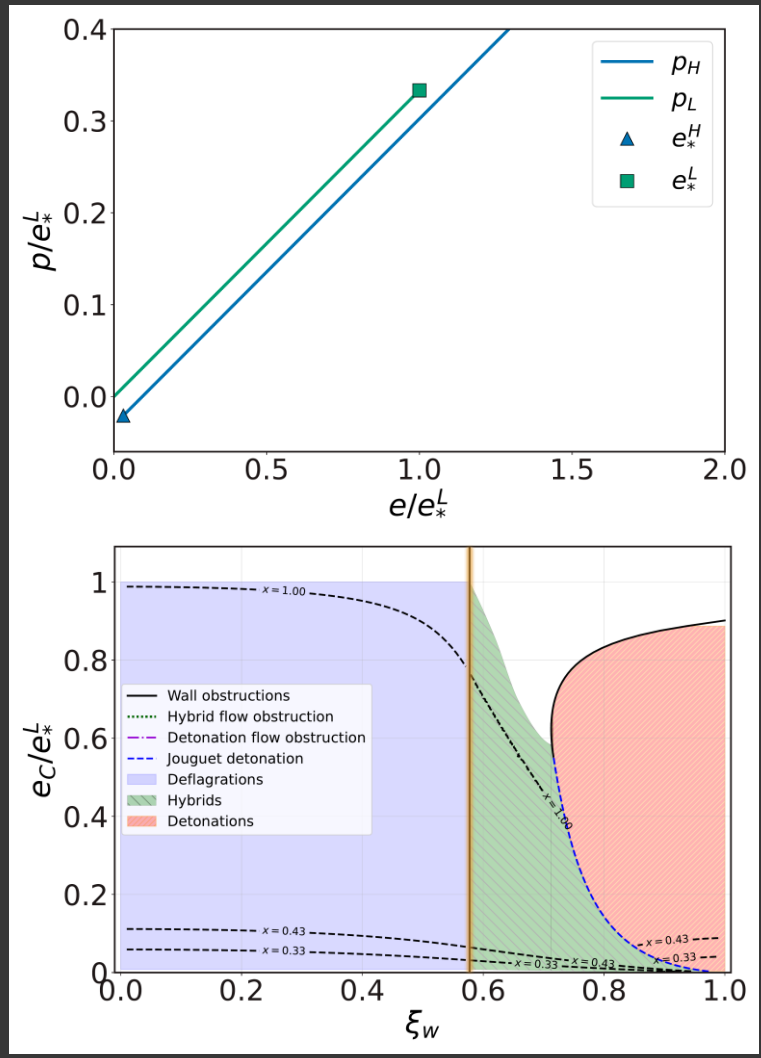
WALL OBSTRUCTIONS: DEFLAGRATIONS

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

WALL OBSTRUCTIONS: DEFLAGRATIONS

- Bag model:
  - Deflagrations and hybrids are continuously joined across the boundary $\xi_w = c_s$

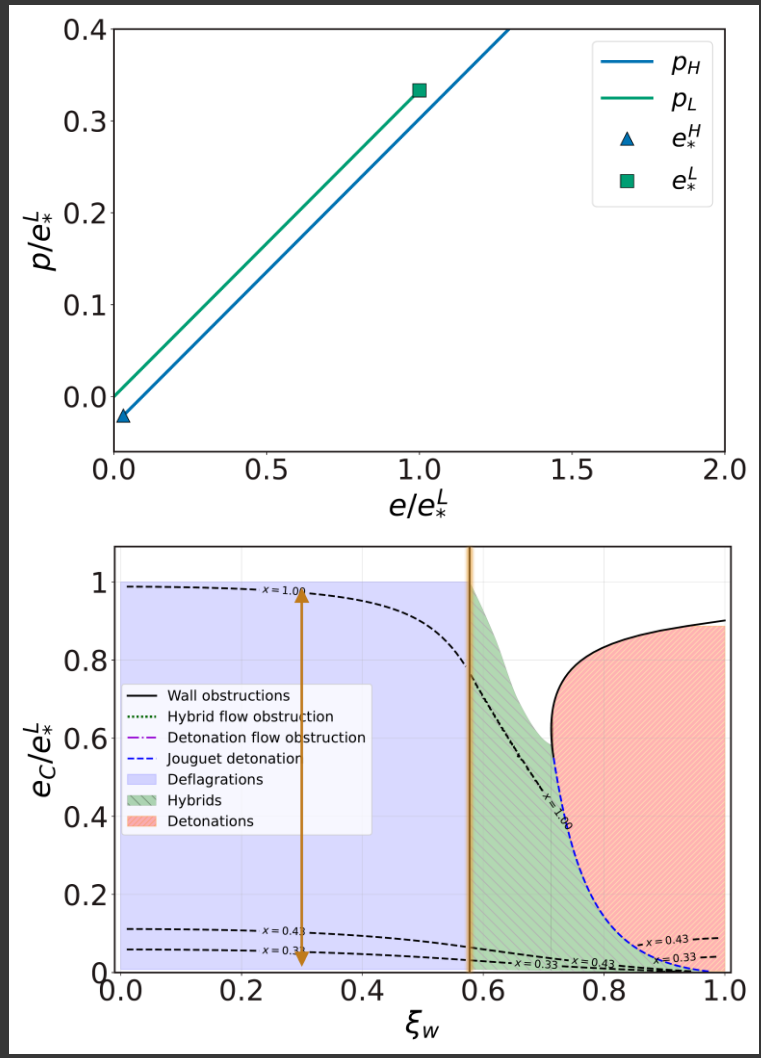
Bag model, finite ranges



WALL OBSTRUCTIONS: DEFLAGRATIONS

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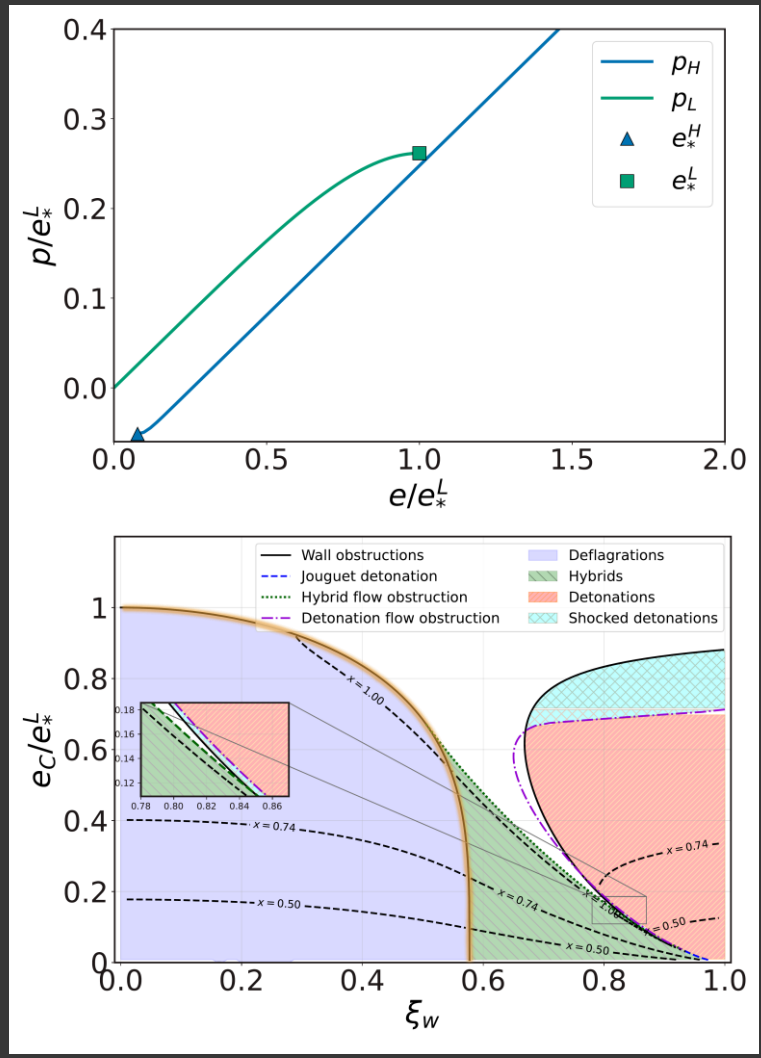
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WALL OBSTRUCTIONS: DEFLAGRATIONS

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Non-conformal EoS

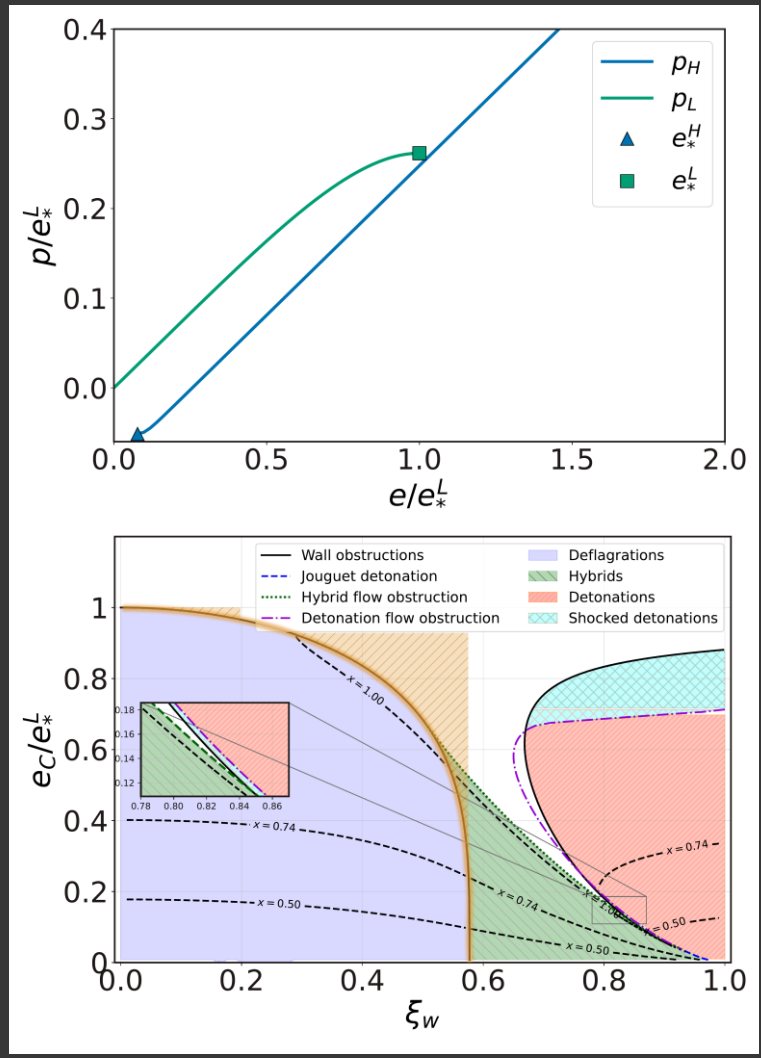


[Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

WALL OBSTRUCTIONS: DEFLAGRATIONS

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  - Deflagrations and hybrids are continuously joined across the boundary $\xi_w = c_s$
  - Deflagrations span all possible energies, $0 \leq e_C \leq e_*^L$
- Non-conformal EoS:
  - The boundary becomes $\xi_w = c_s(e_C)$
  - 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]

FLOW OBSTRUCTIONS

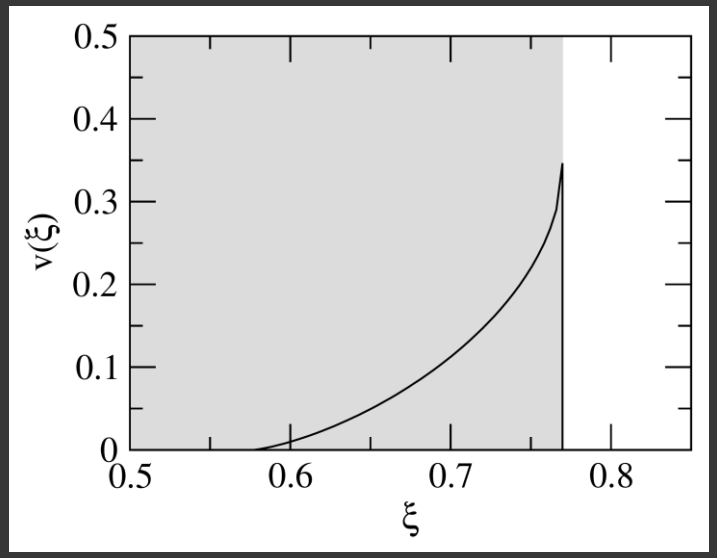
- Associated to rarefaction waves: detonations and hybrids

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

FLOW OBSTRUCTIONS

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Bag model detonation

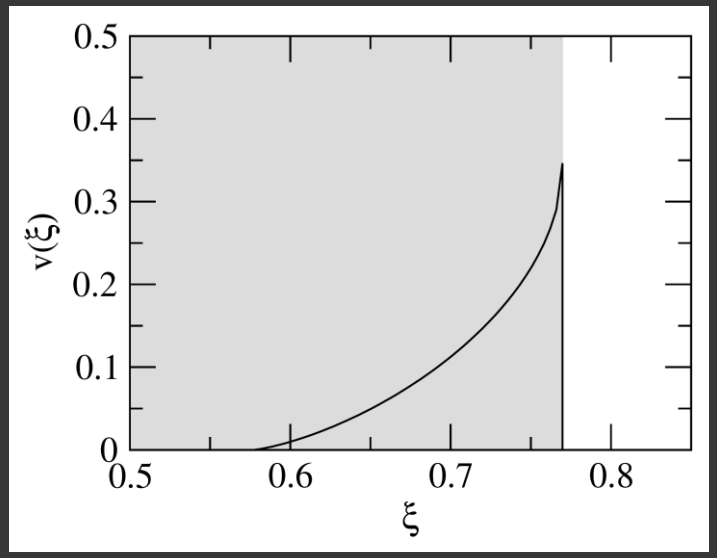


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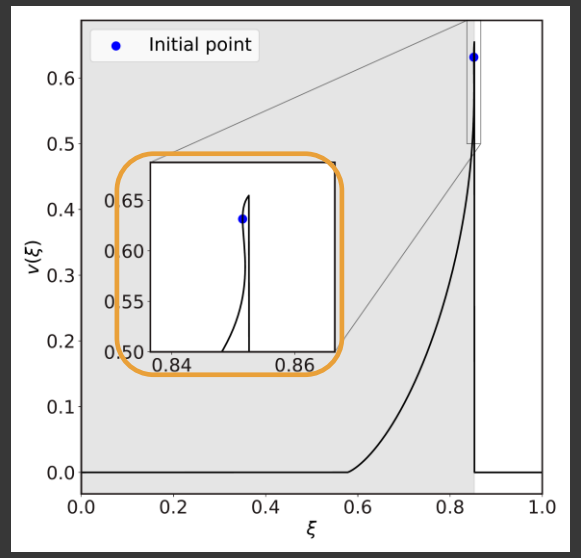
FLOW OBSTRUCTIONS

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Bag model detonation



Detonation beyond the DCP: not allowed



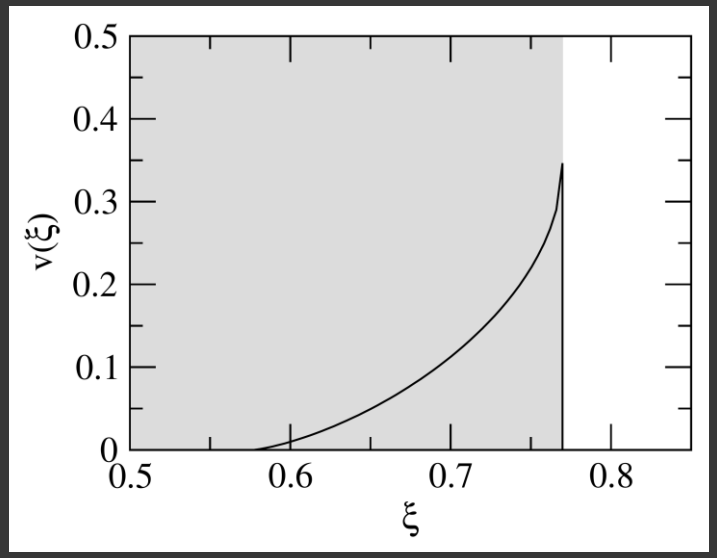
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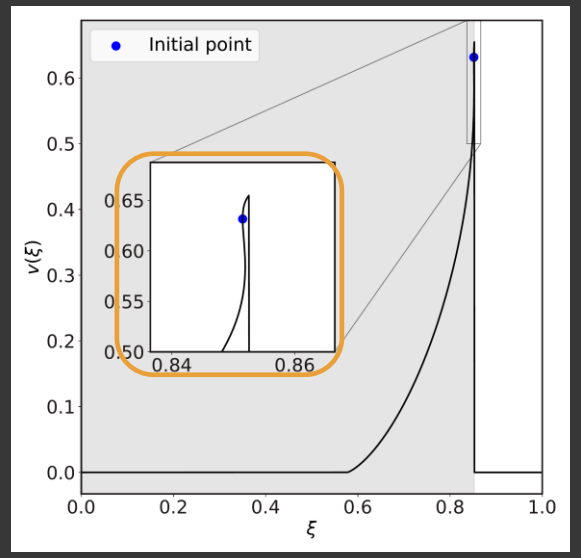
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- Constant c_s: the rarefaction wave continiously joins the fluid at rest, $v = 0$
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- They appear when the EoS has a degenerate critical point (DCP), a condition on the EoS only:

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

Bag model detonation

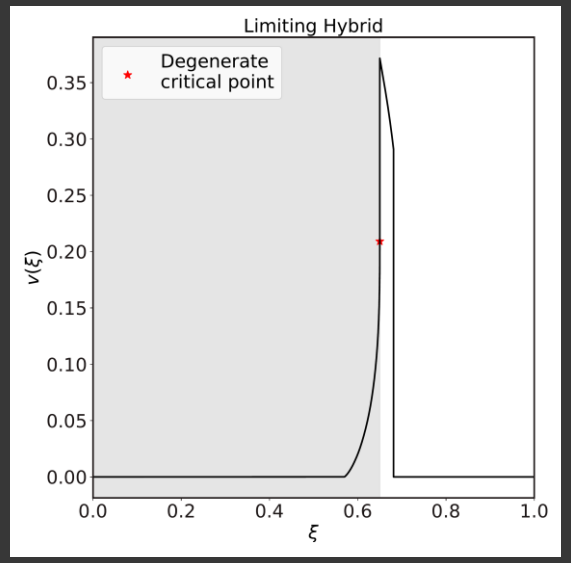


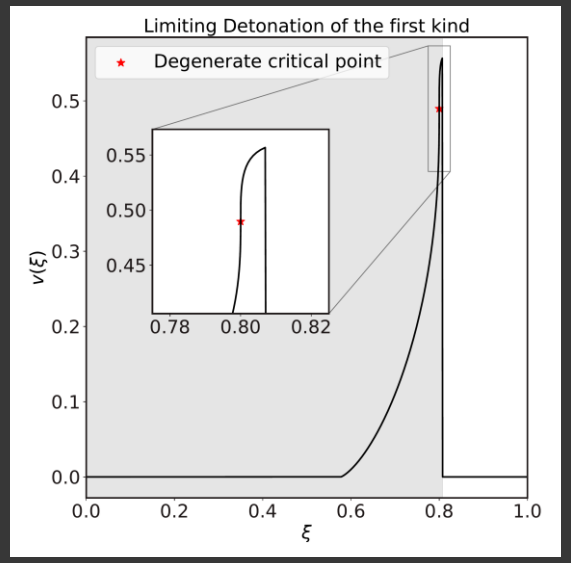
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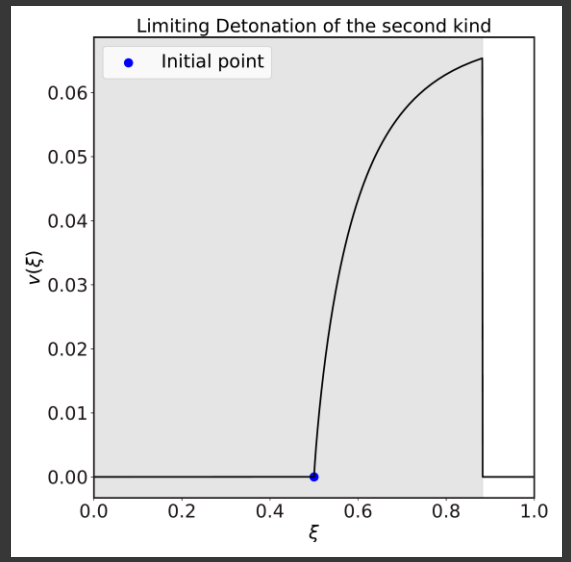


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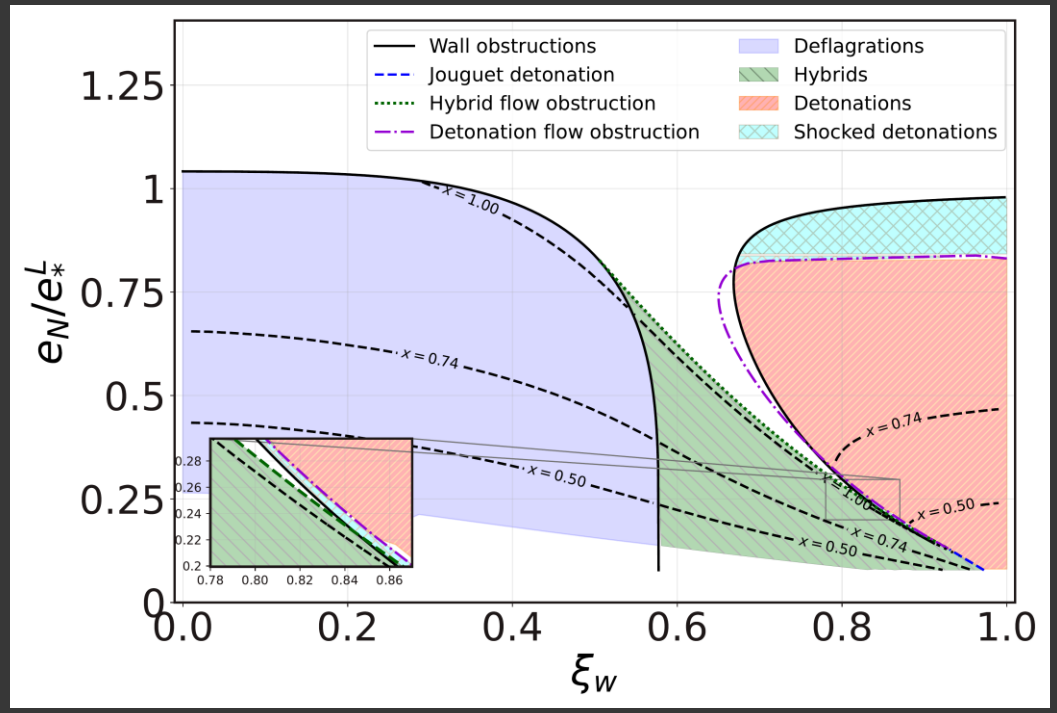
FLOW OBSTRUCTIONS





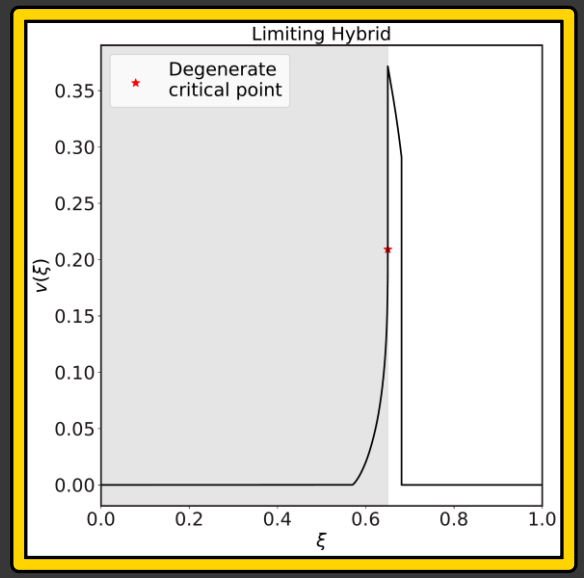


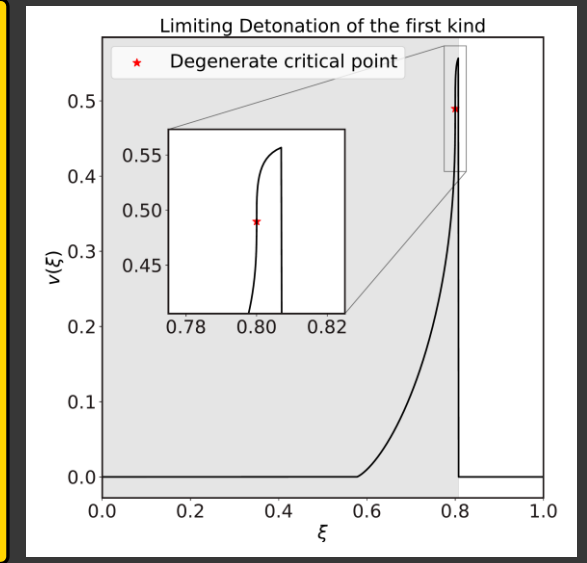
- Limiting cases give the flow obstruction lines in the space of allowed solutions

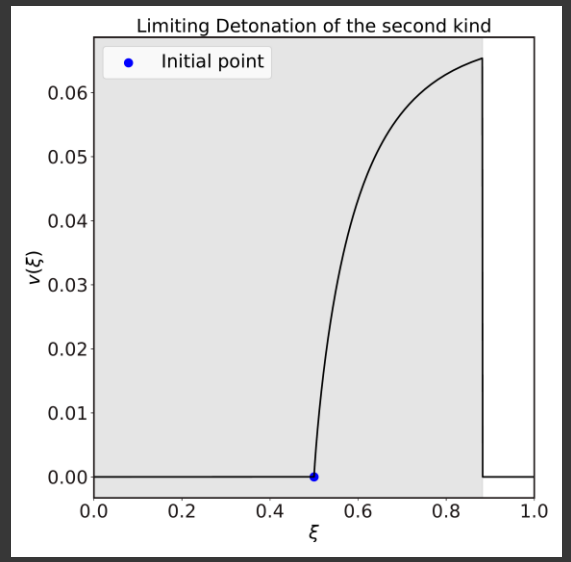


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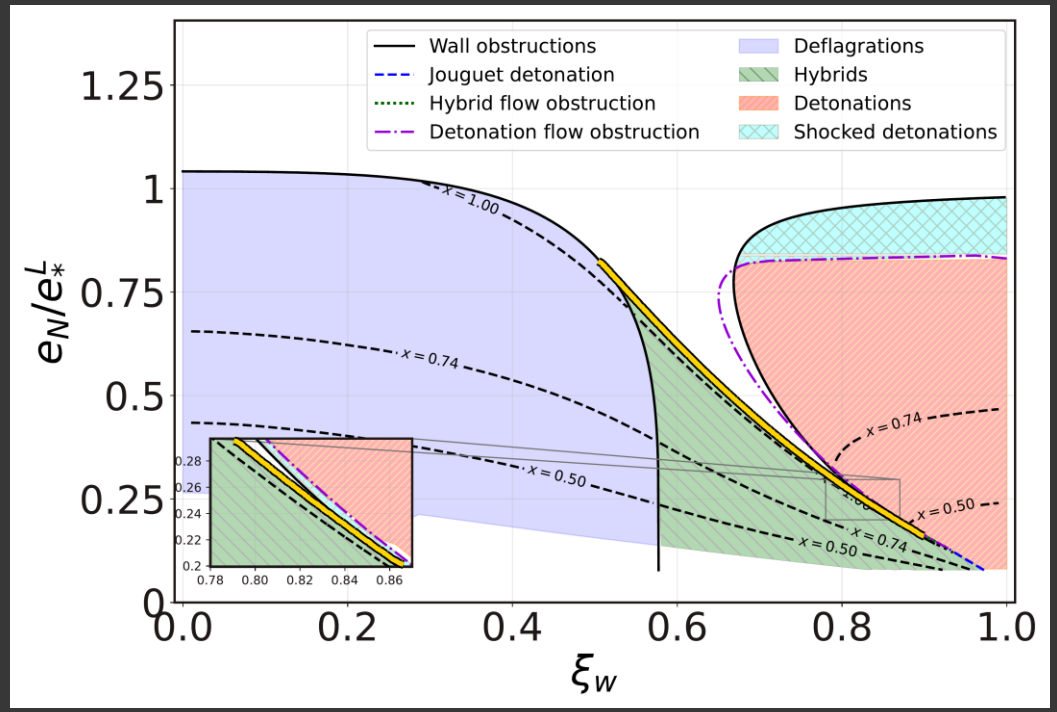
FLOW OBSTRUCTIONS





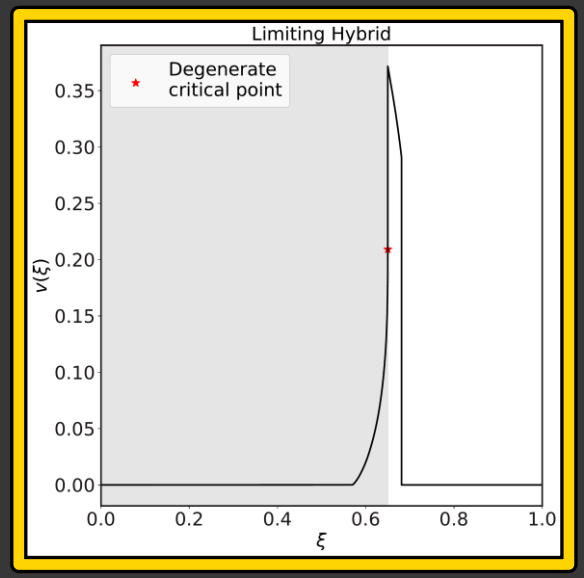


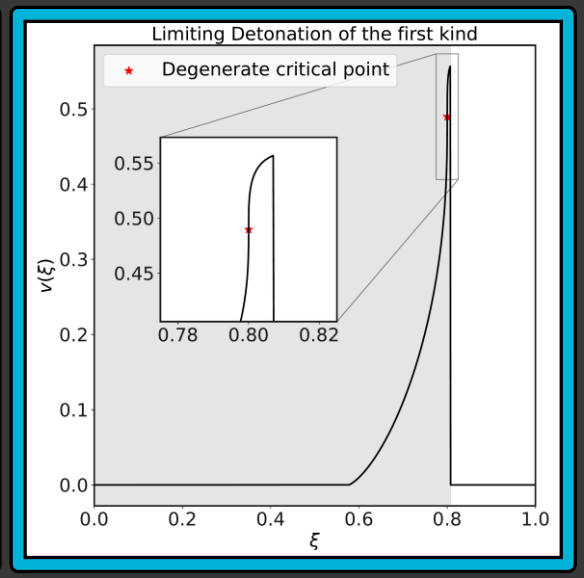
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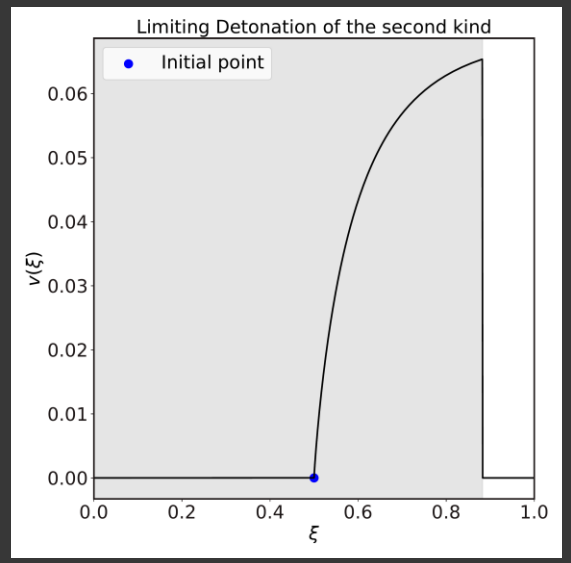


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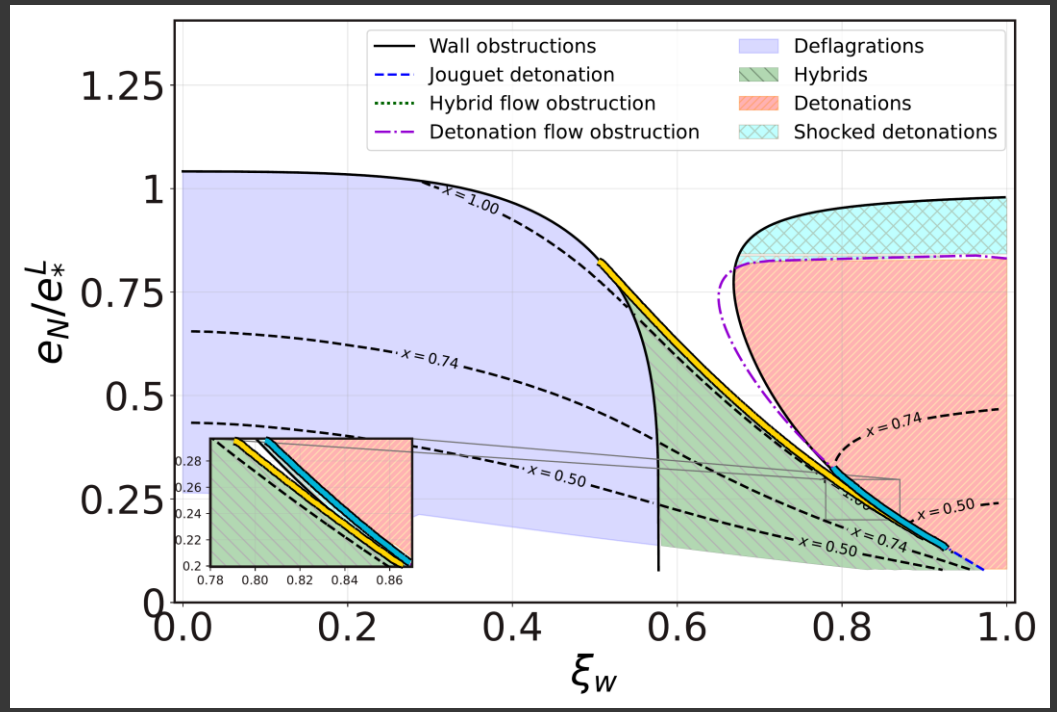
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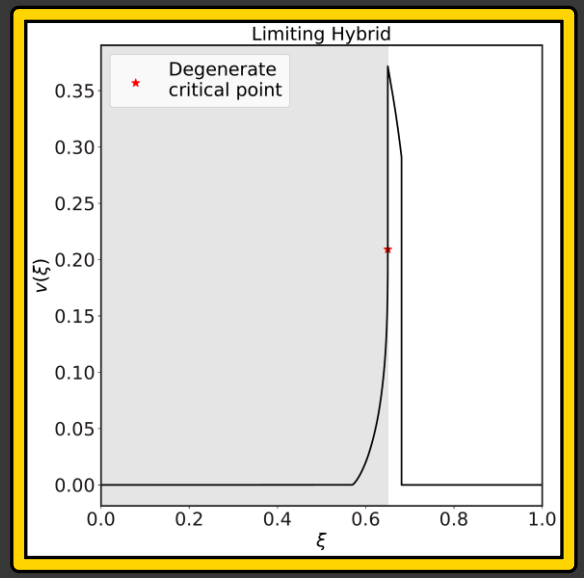


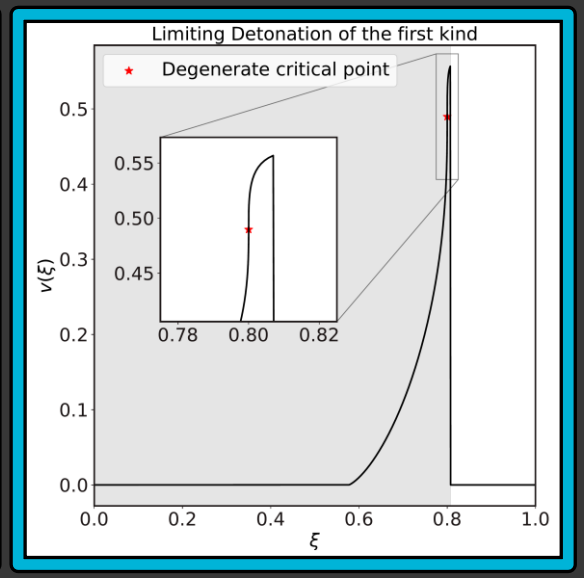
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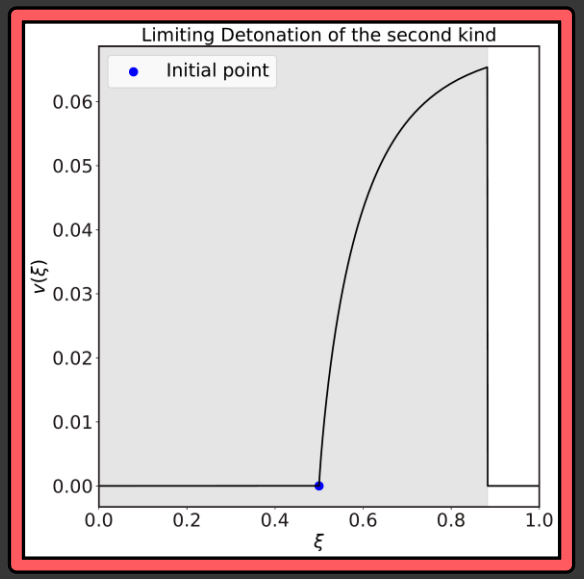


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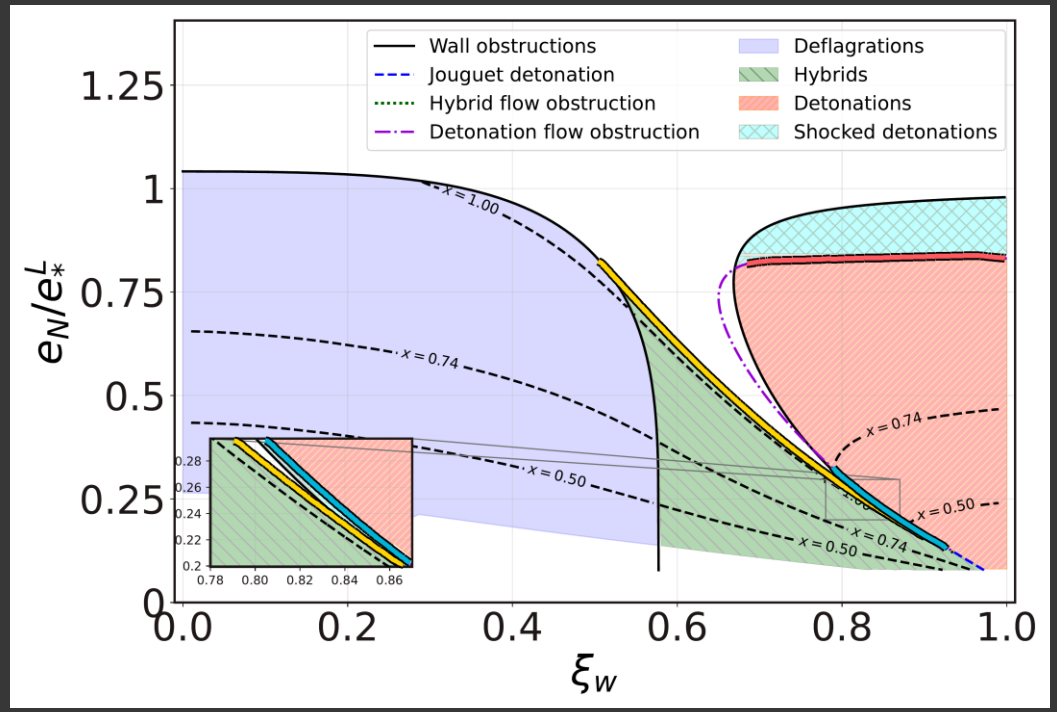
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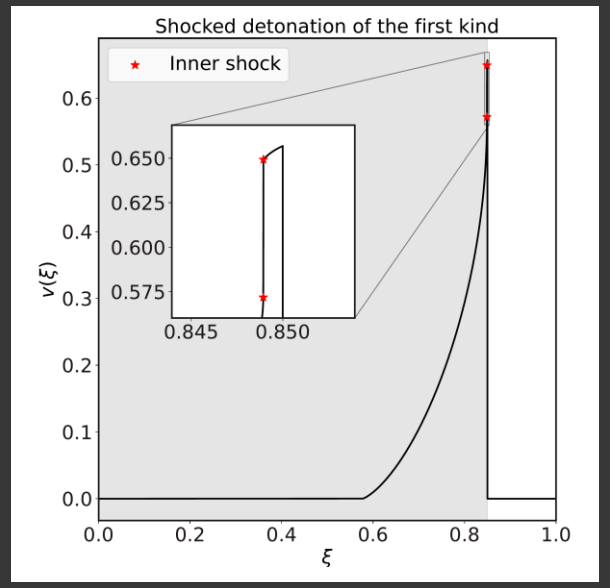
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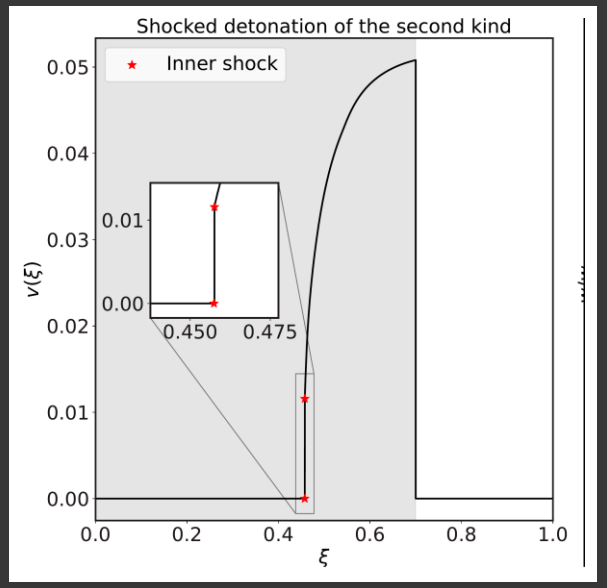


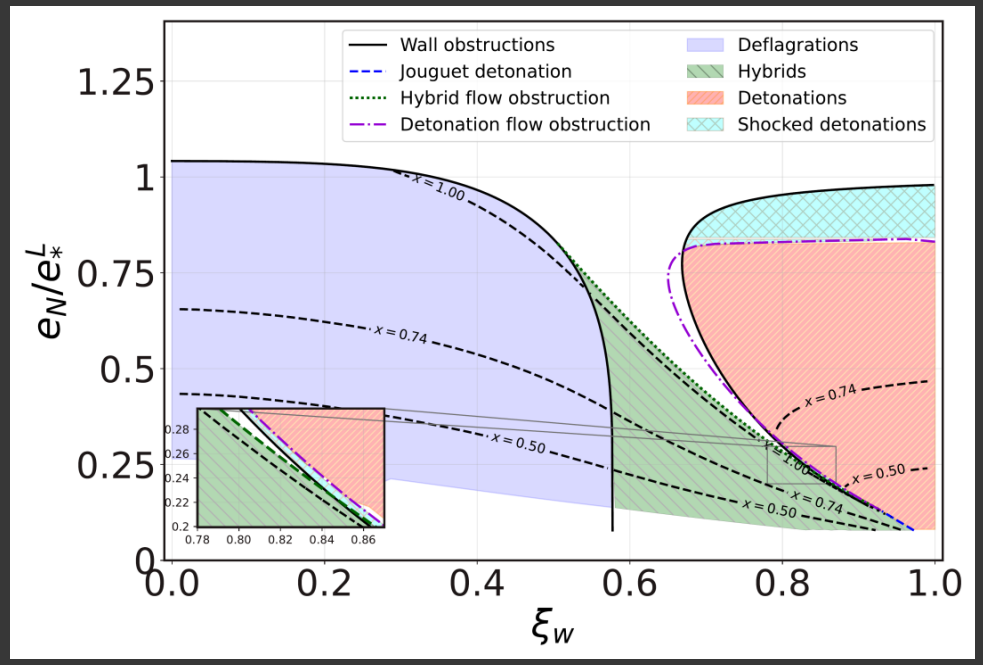
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NEW SOLUTIONS: SHOCKED DETONATIONS

- Rarefaction waves cannot be continued beyond the flow obstruction
- However, new solutions are found by introducing a shock inside the rarefaction wave ⇒ shocked detonations



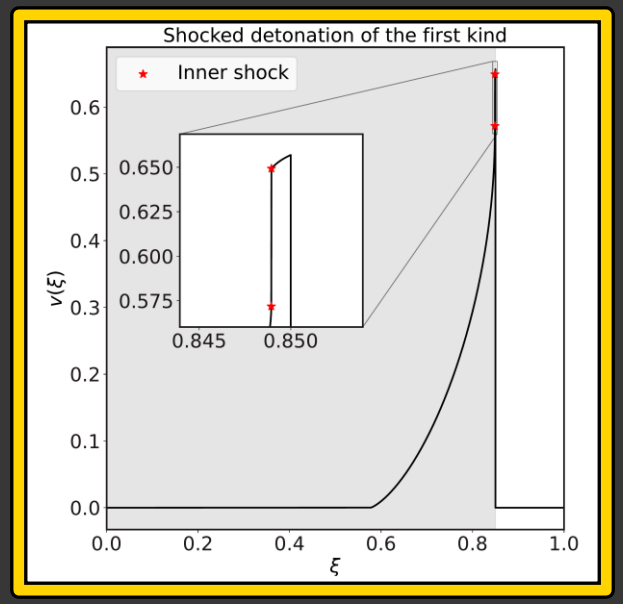


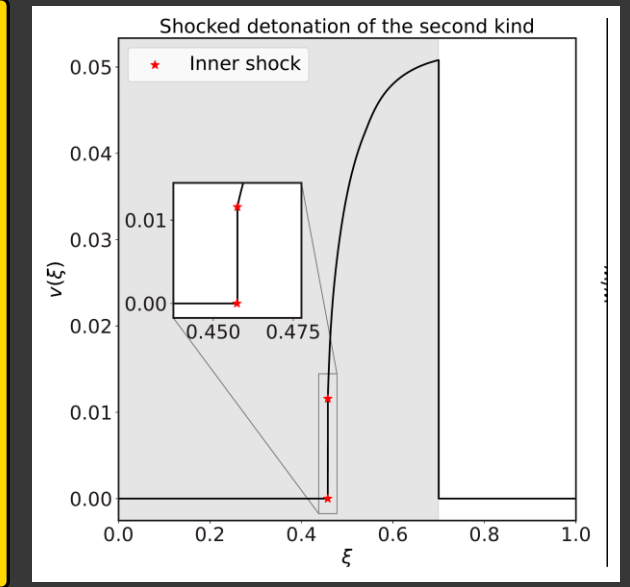


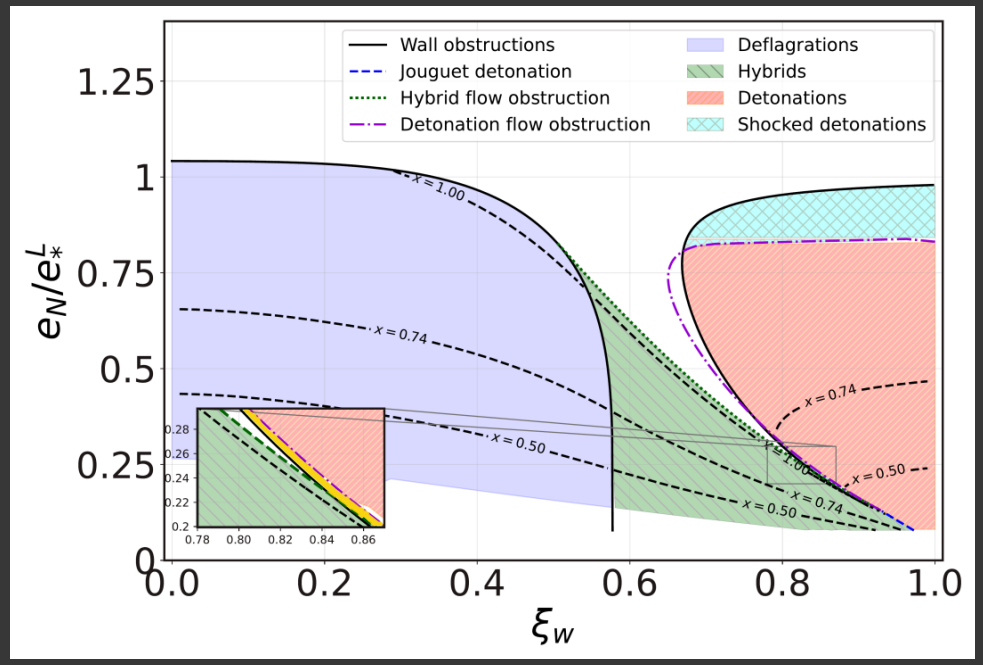
[Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

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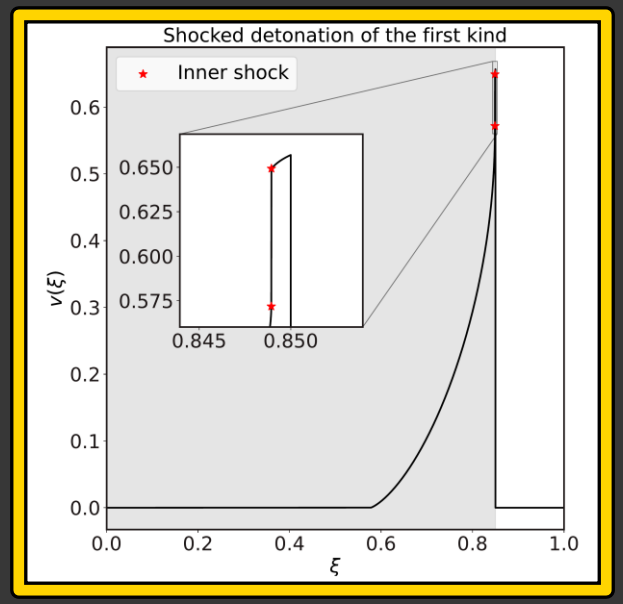


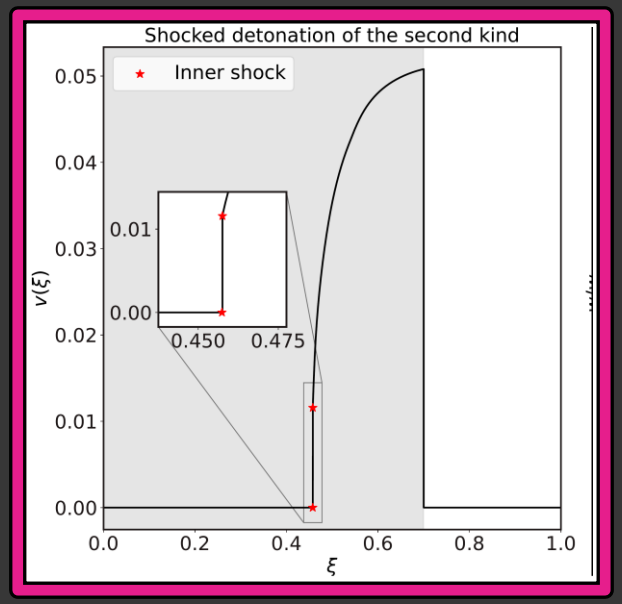


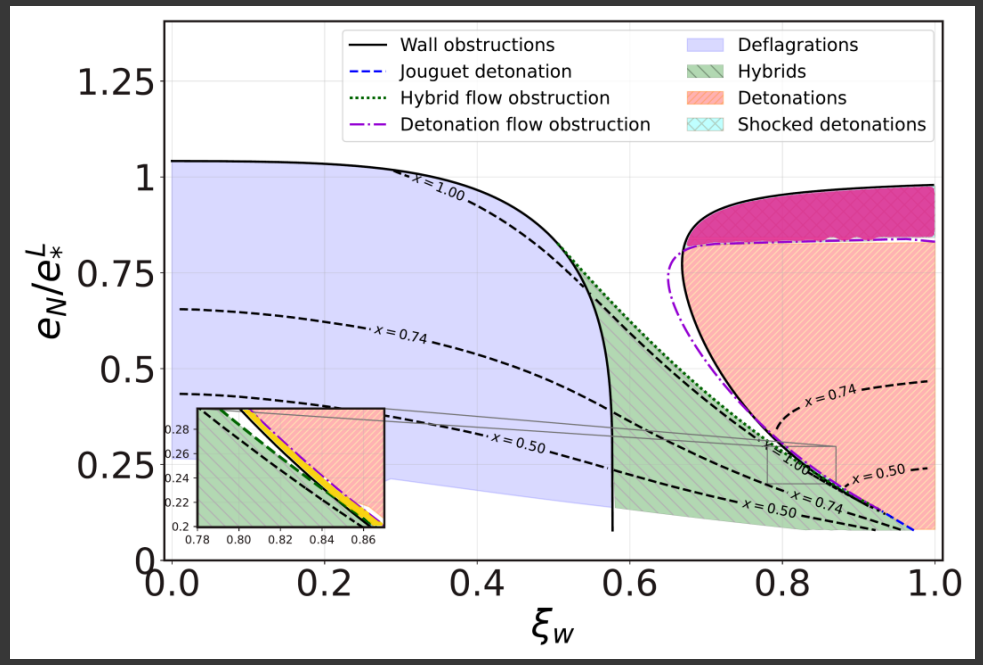
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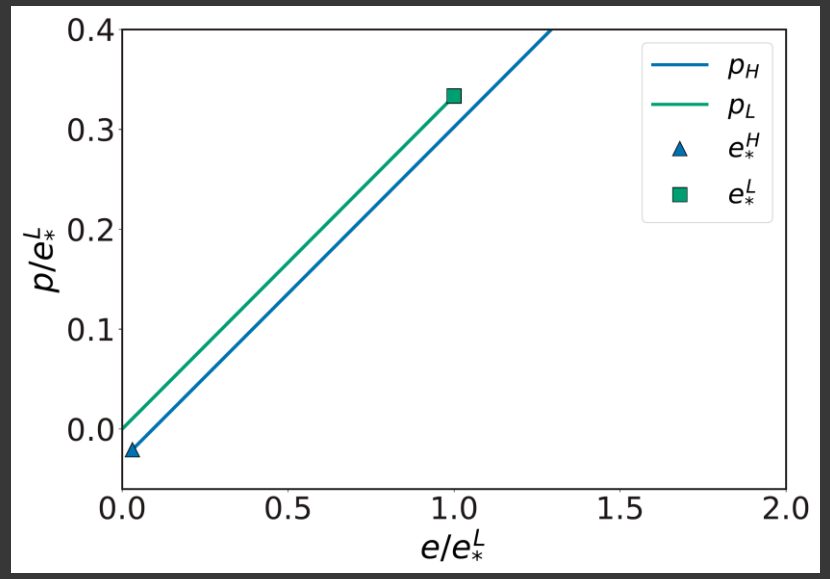




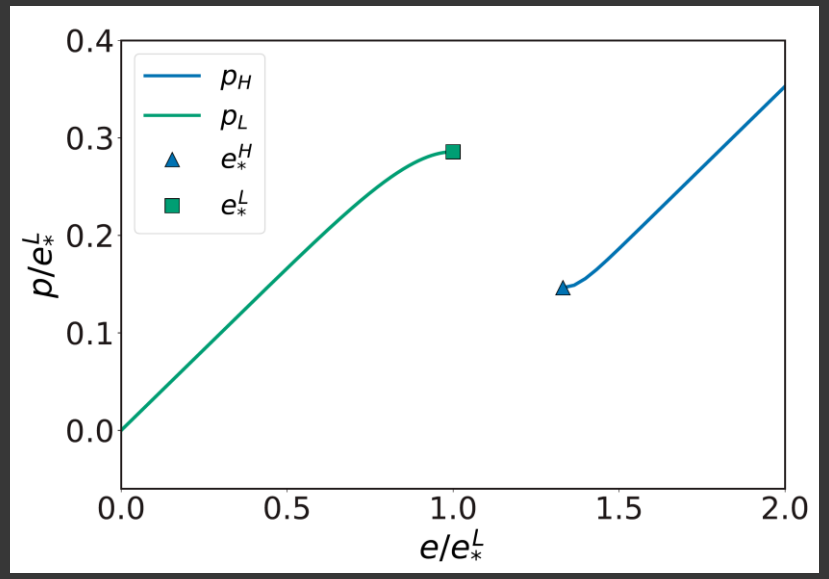
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SPACE OF SOLUTIONS

Bag-model-like EoS

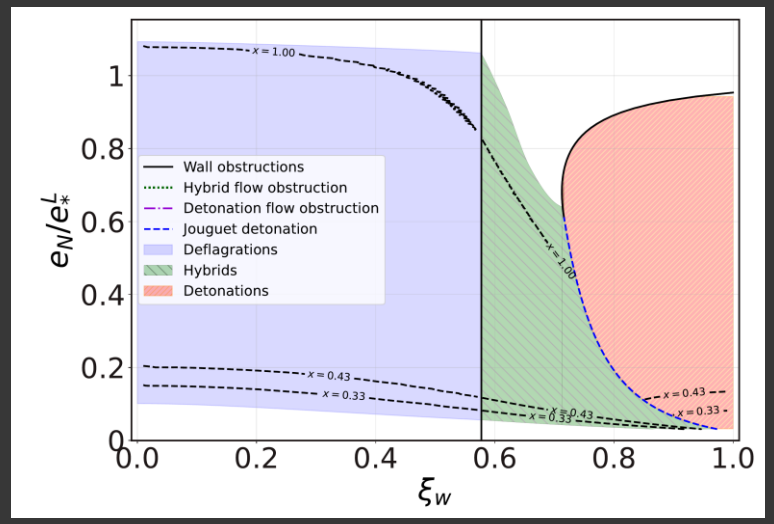


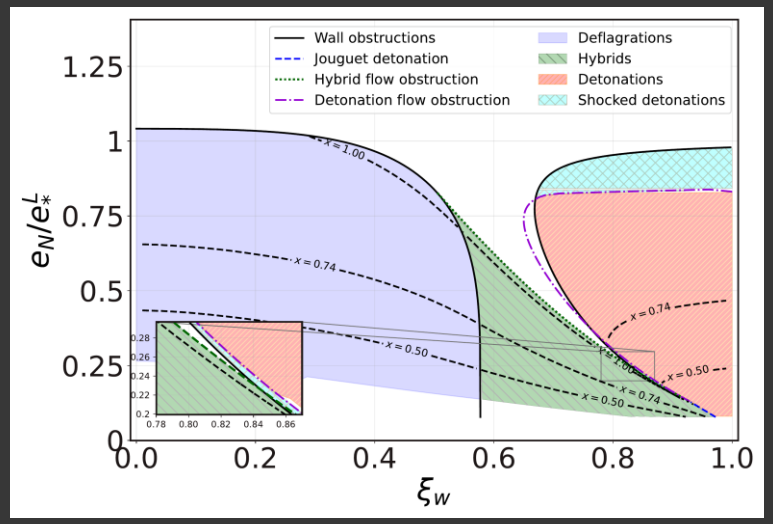
QCD-like EoS

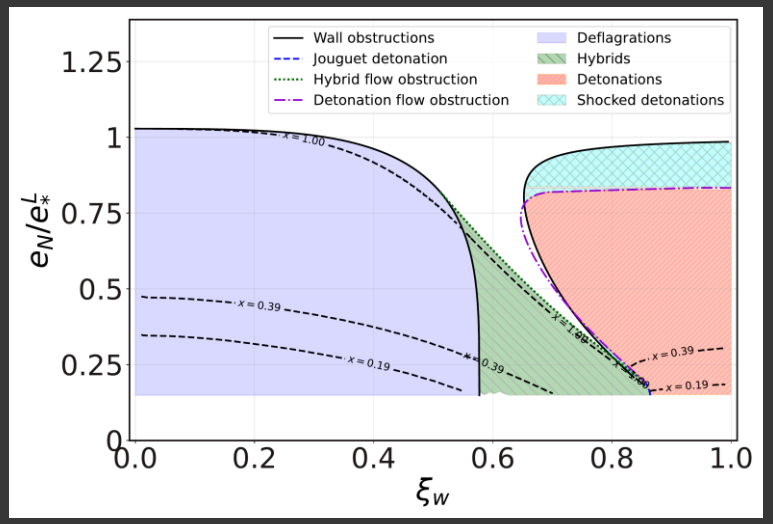


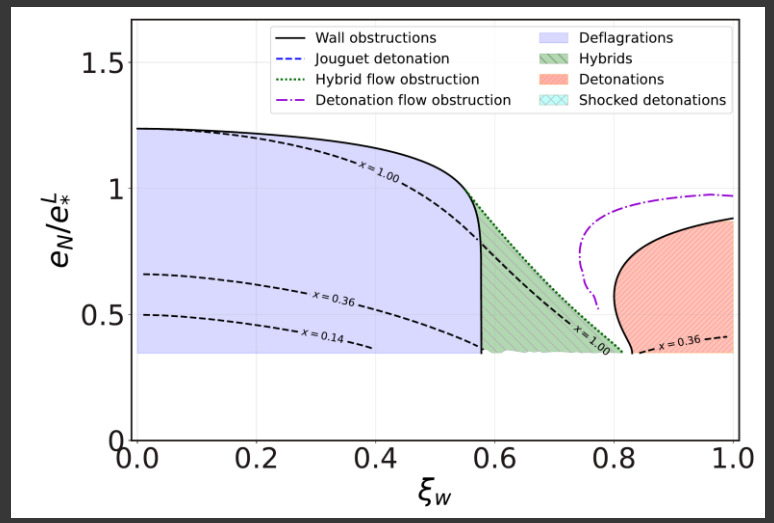
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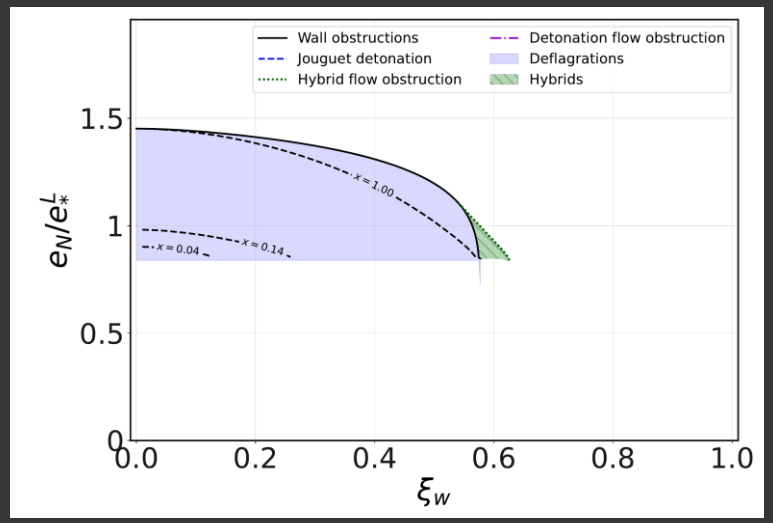
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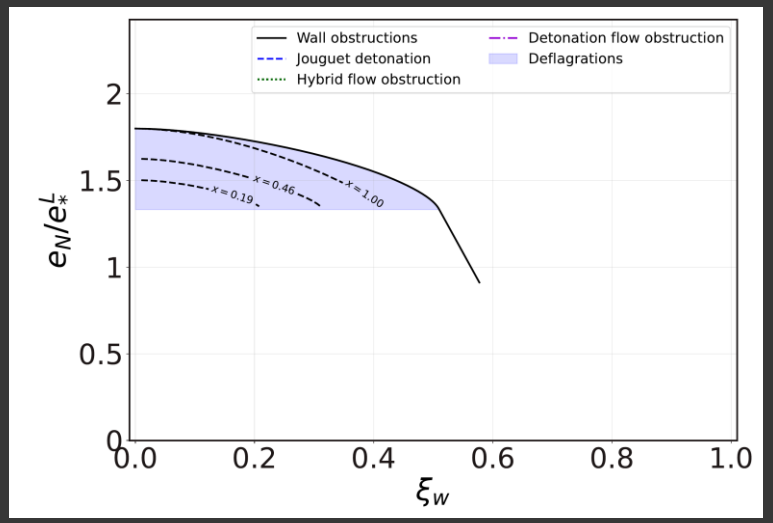












[Mateos, Sanchez-Garitaonandia, **PTA**, arXiv:2607.27874]

KINETIC ENERGY FRACTION

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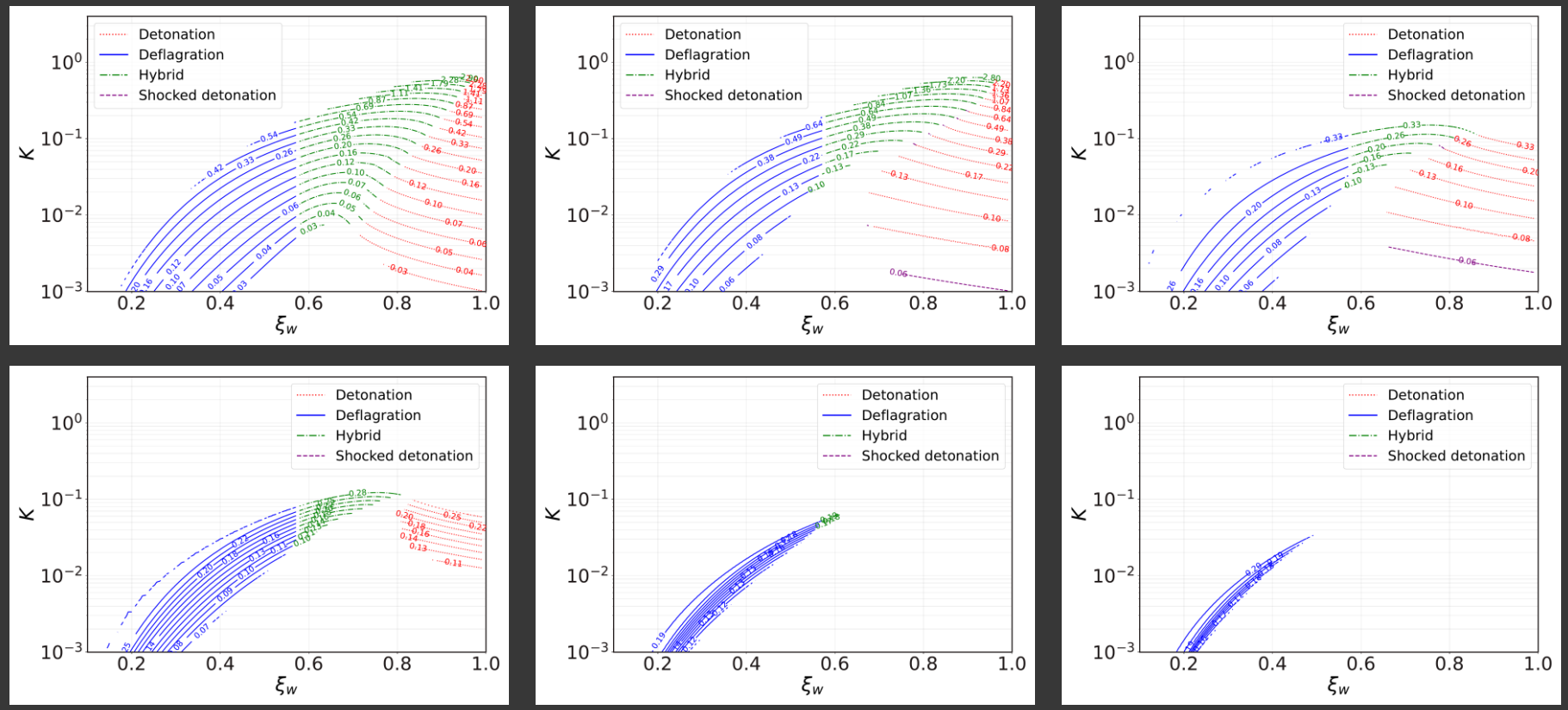
$$K = \frac{\int_{V_{\rm bubble}} d^3x\, w\gamma^2 v^2}{\int_{V_{\rm bubble}} d^3x\, \left(w\gamma^2 - p\right)}$$

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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

THANK YOU!