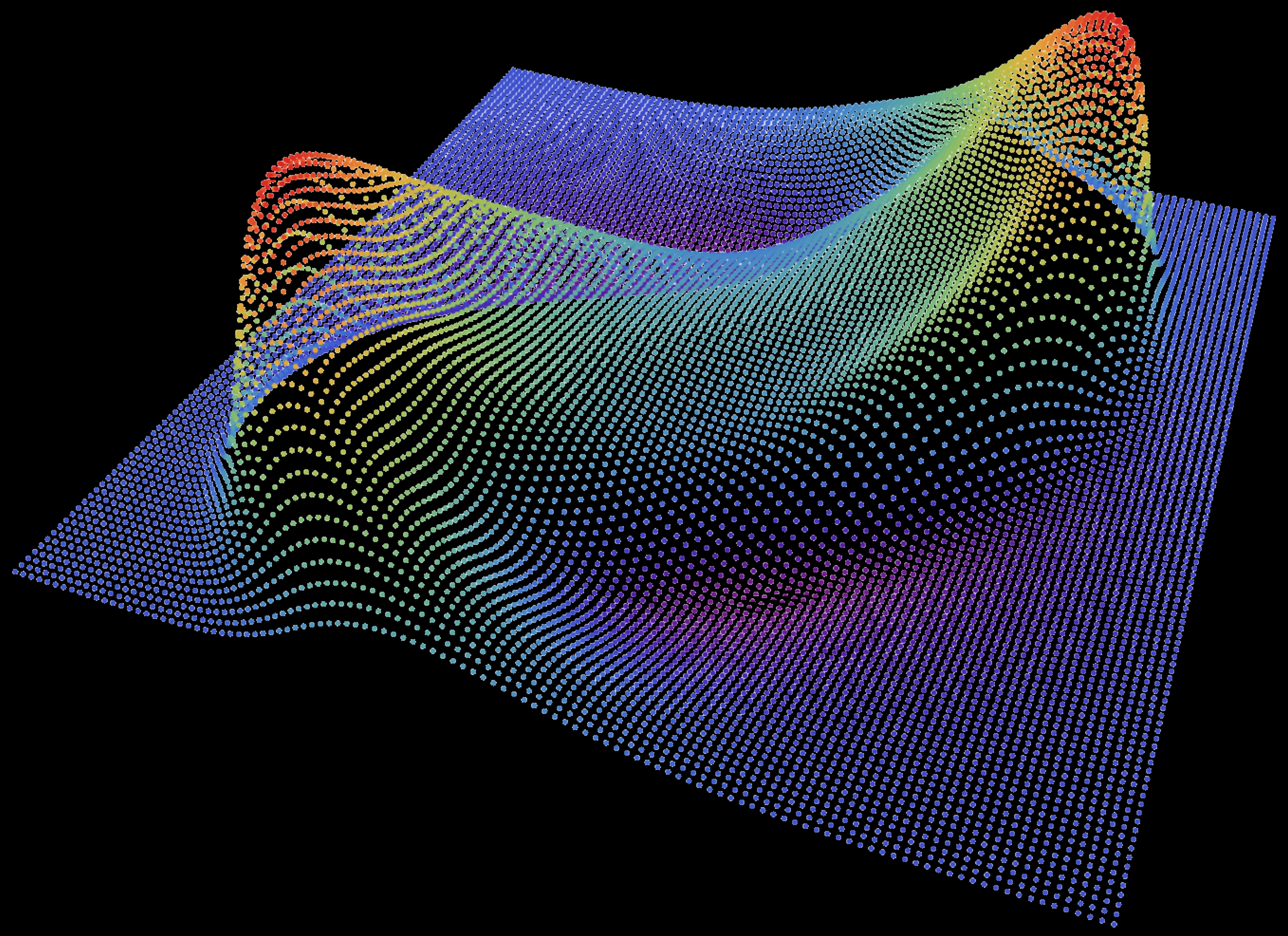
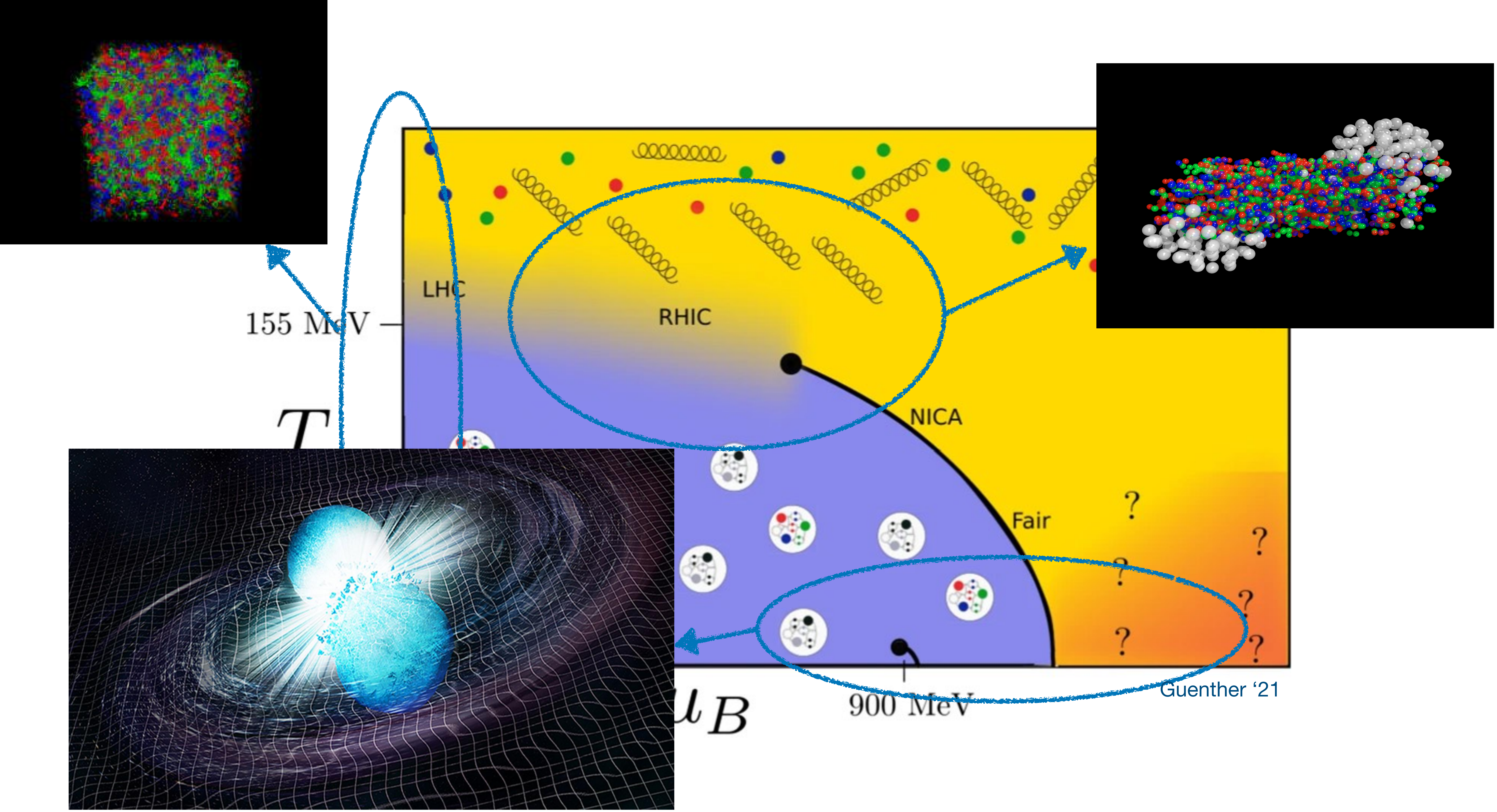
Uncovering dense matter phase transitions with gravitational waves

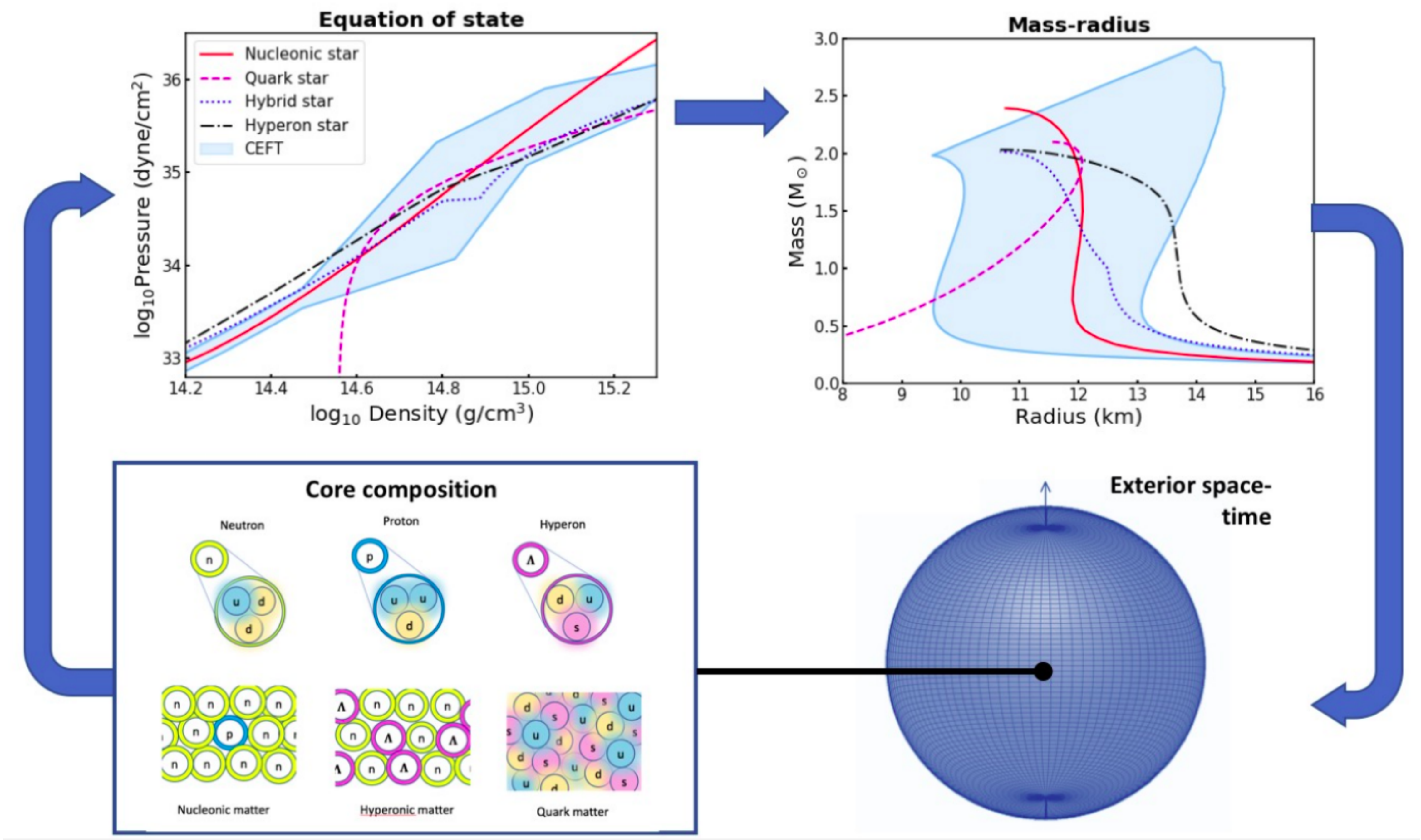


Mikel Sanchez-Garitaonandia

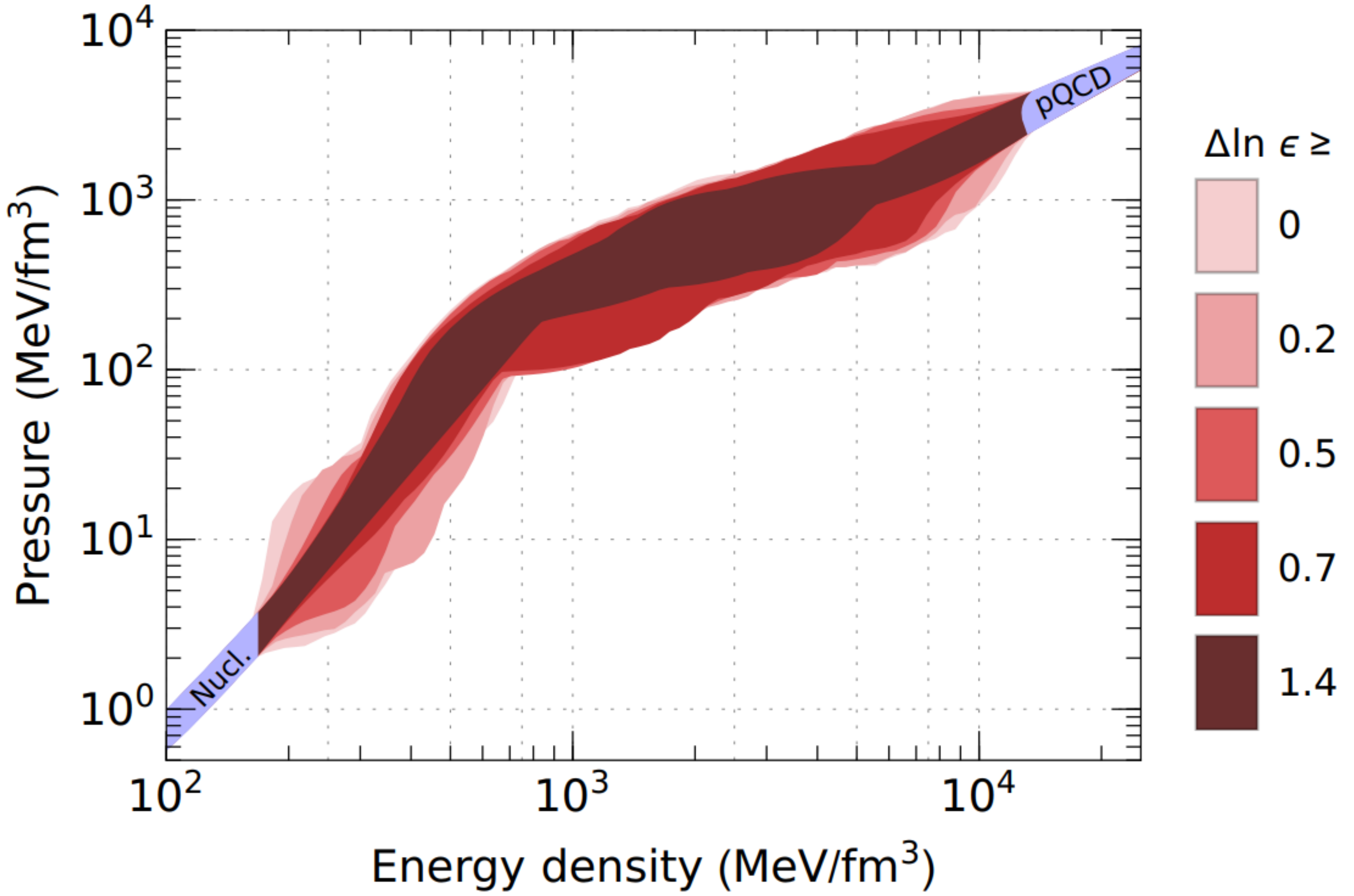
École Polytechnique

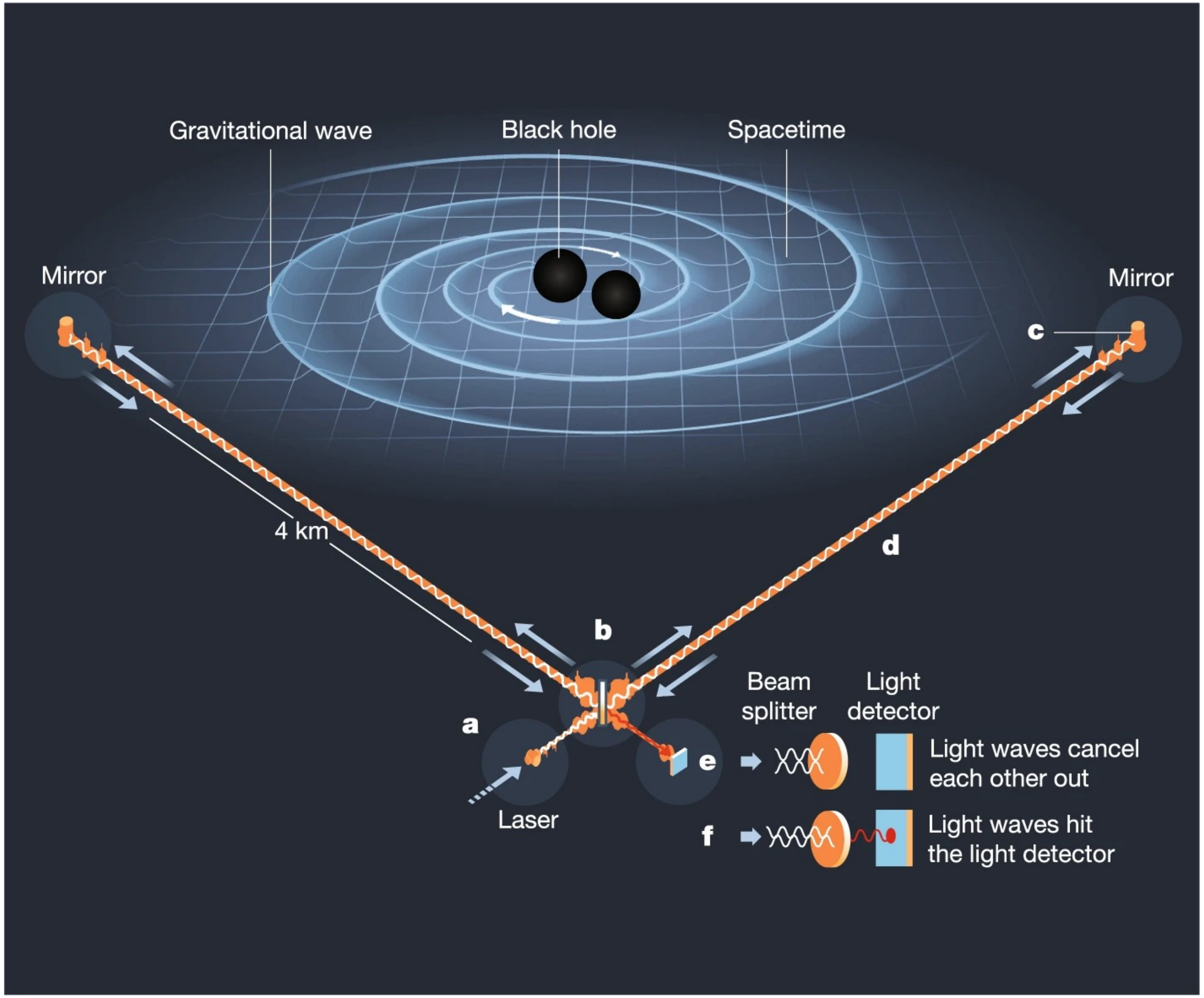

LHC
RHIC
155 MeV
NICA
Fair
T
μ_B
900 MeV
Guenther '21

Bogdanov et. al. ‘22



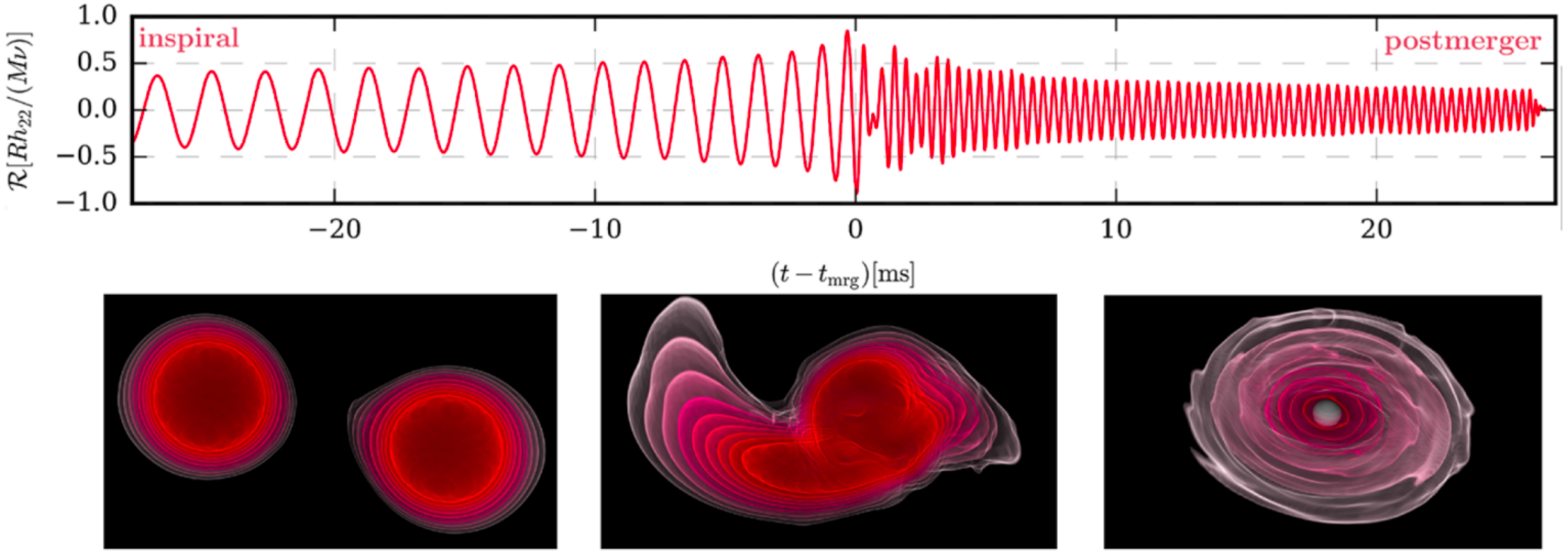
Annala, Gorda, Kurkela, Nättila, Vuorinen ‘20



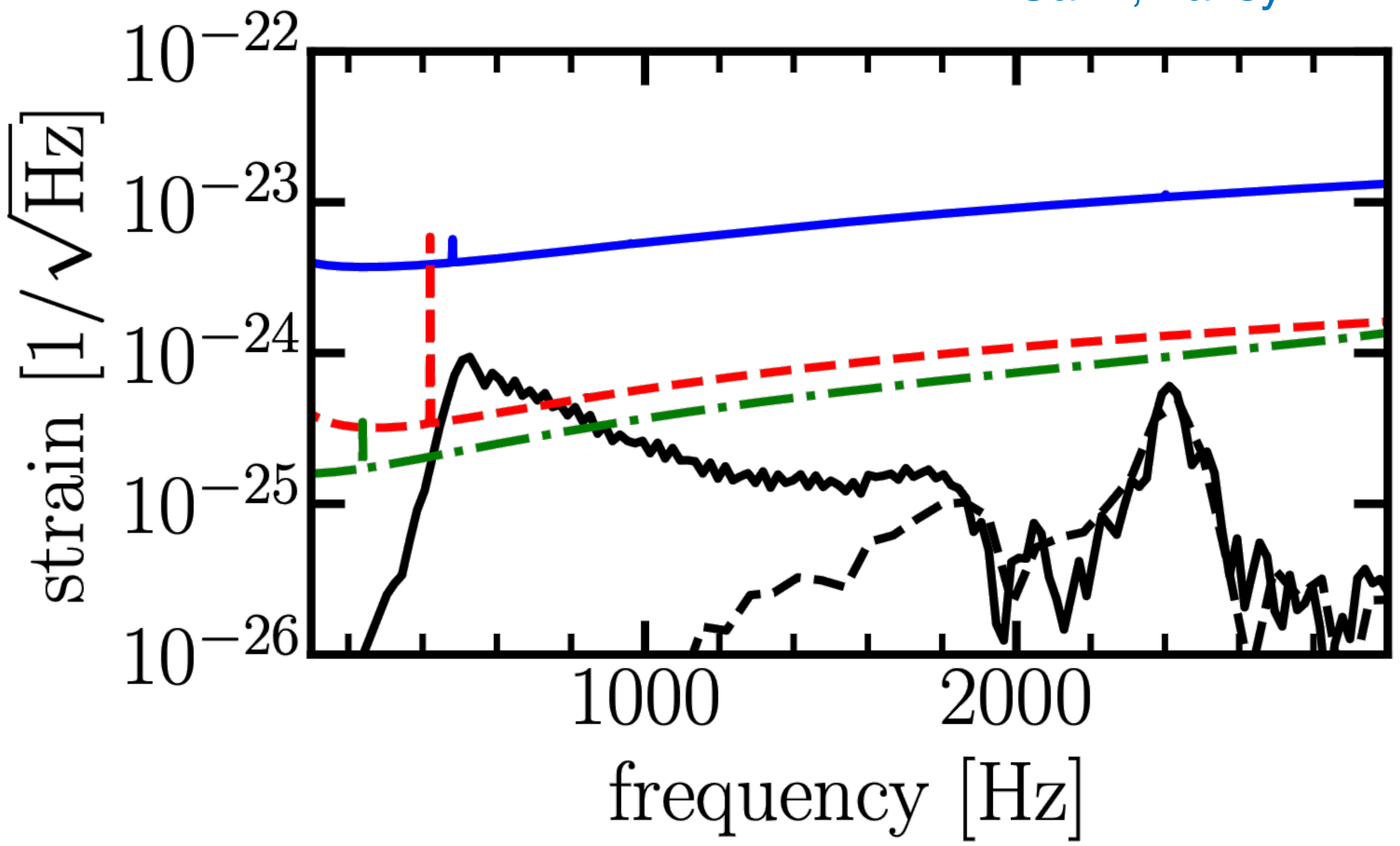


Coleman Miller, Yunes ‘19

Dietrich, Hinderer, Samajdar ‘20



Sarin, Laksy ‘22



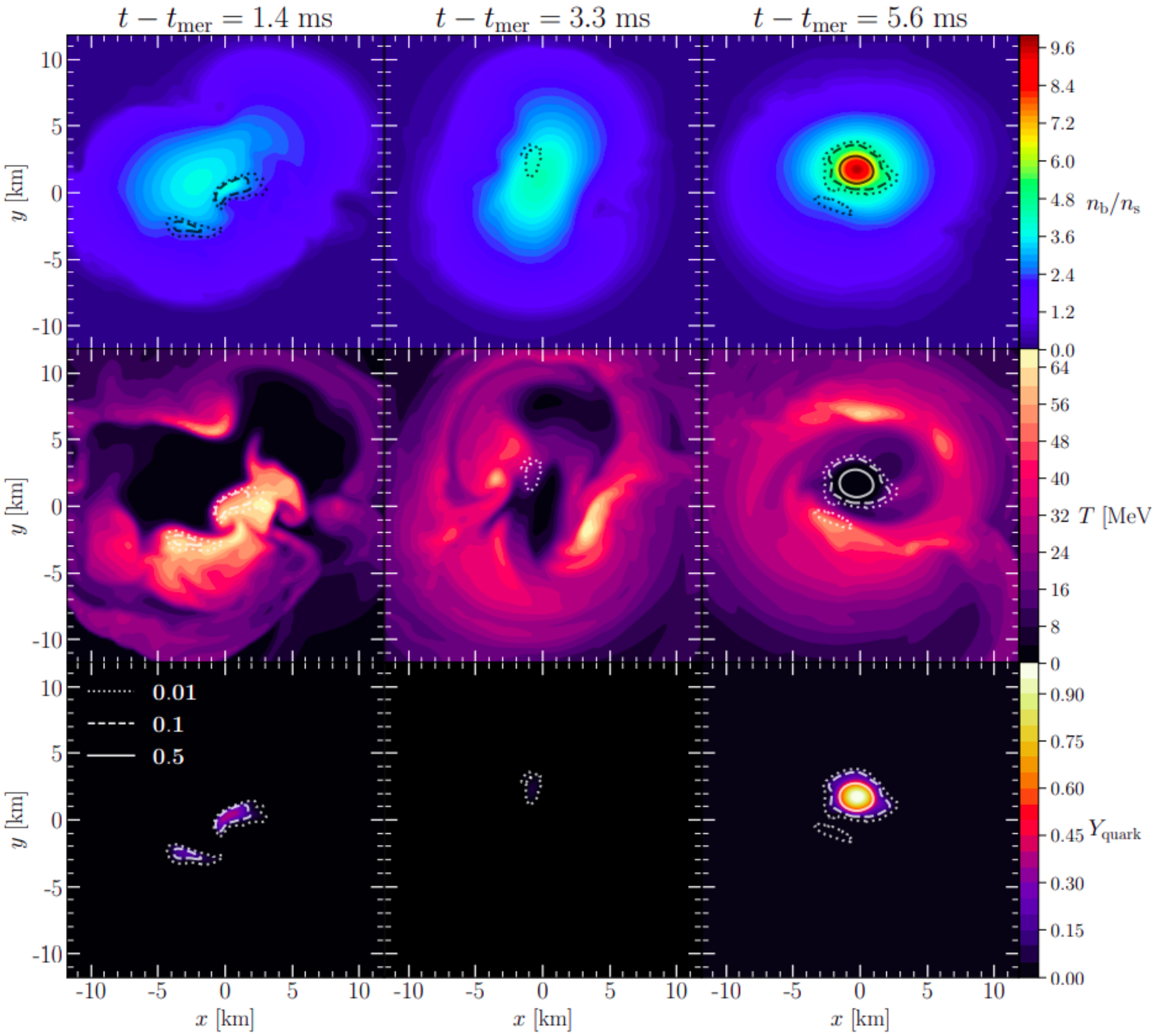
Phase Transition?

Contents

- Phase Transitions in neutron star mergers
    - MHz signal
- Superheated/Supercompressed bubble expansion
- What holography can offer
- Conclusions

Phase transitions in neutron star mergers

Casalderrey-Solana, Mateos, MSG ‘22



Tootle, Ecker, Topolski, Demircik, Järvinen, Rezolla ’22

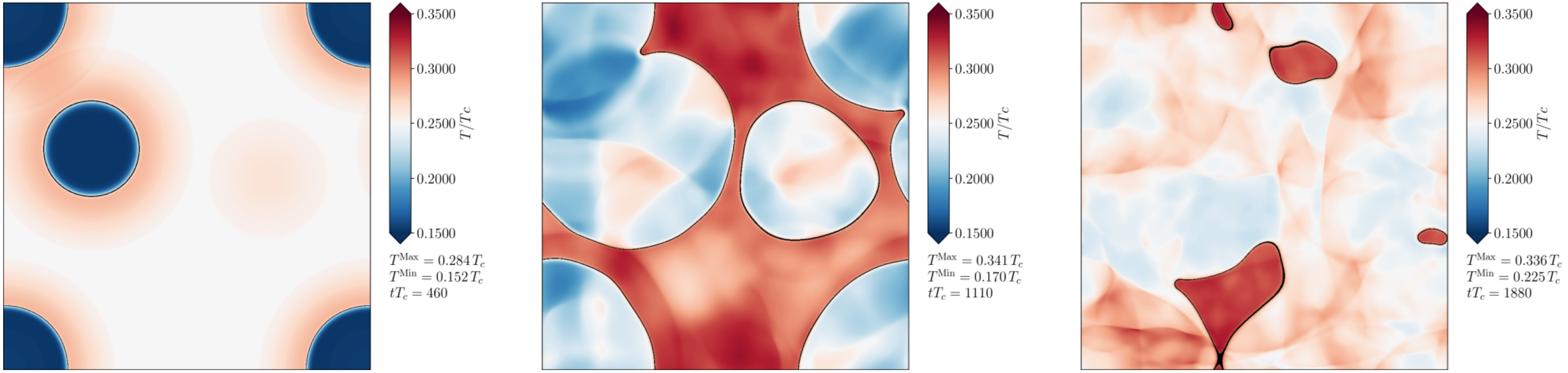
$$\tau \sim 1\text{ms}$$

$$L \sim 1\text{km}$$

~ Cosmological PT

Direct signal?

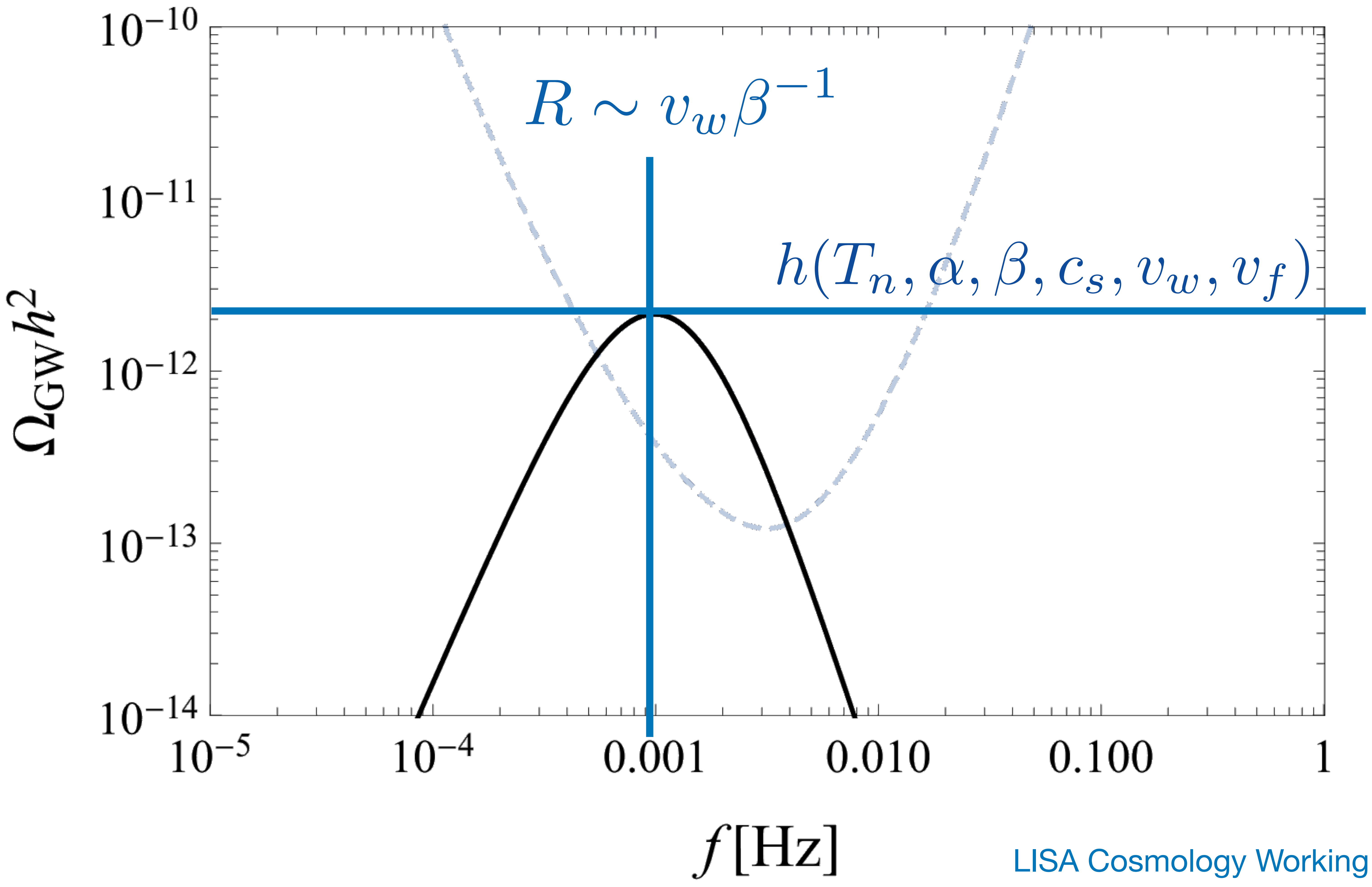
Cutting, Hindmarsh, Weir ‘19



- Effective theory of hydrodynamics + scalar field
- Microscopic input: wall velocity
- GW emission: wall collision, sound waves and vorticity
- In general sound wave contribution is the dominant one

- The spectrum can be estimated from few parameters: temperature, transition rate, speed of sound, wall speed and efficiency factor

Hindmarsh, Huber, Rummukainen, Weir ’15
Hindmarsh, Huber, Rummukainen, Weir ’17

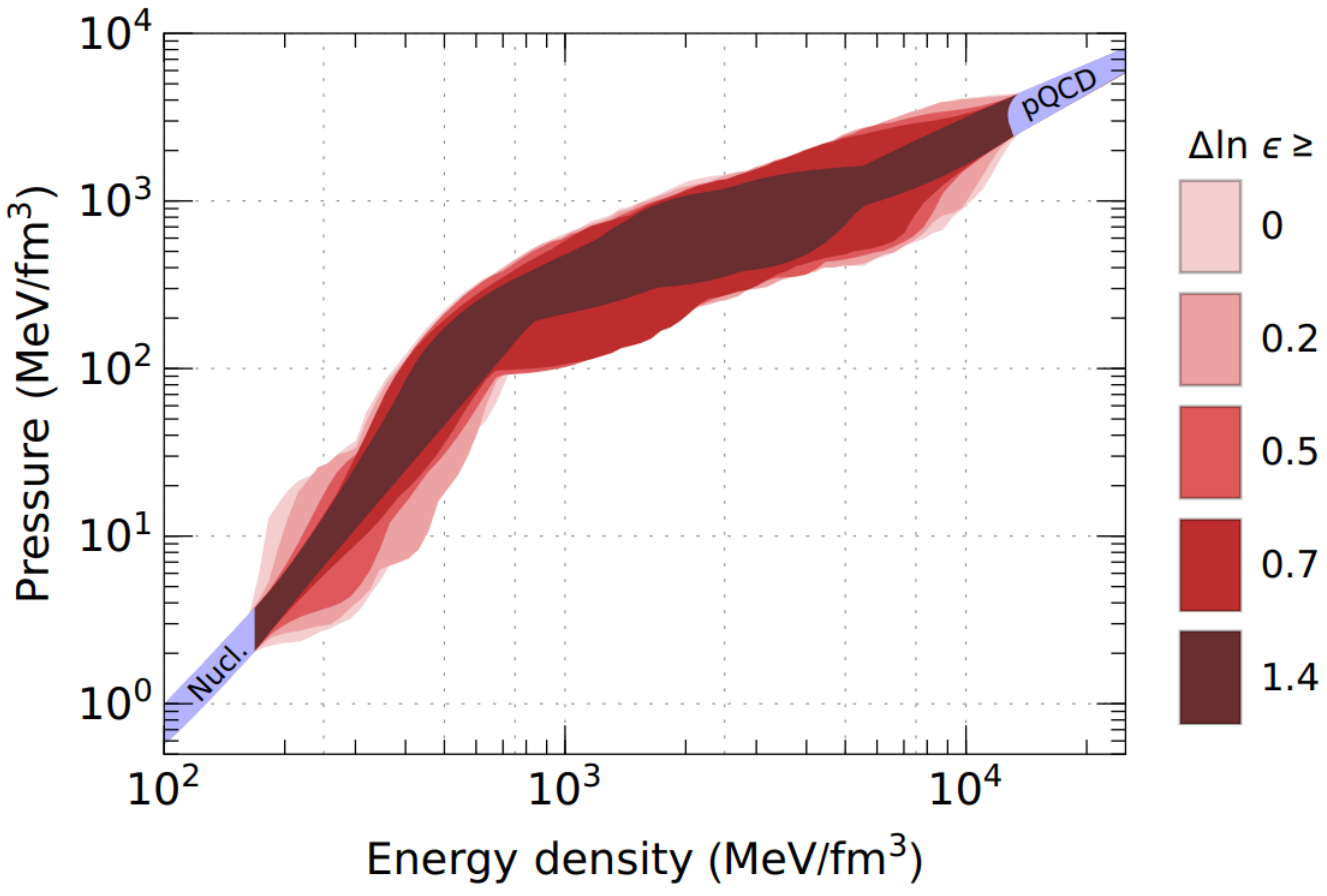


LISA Cosmology Working Group ‘22

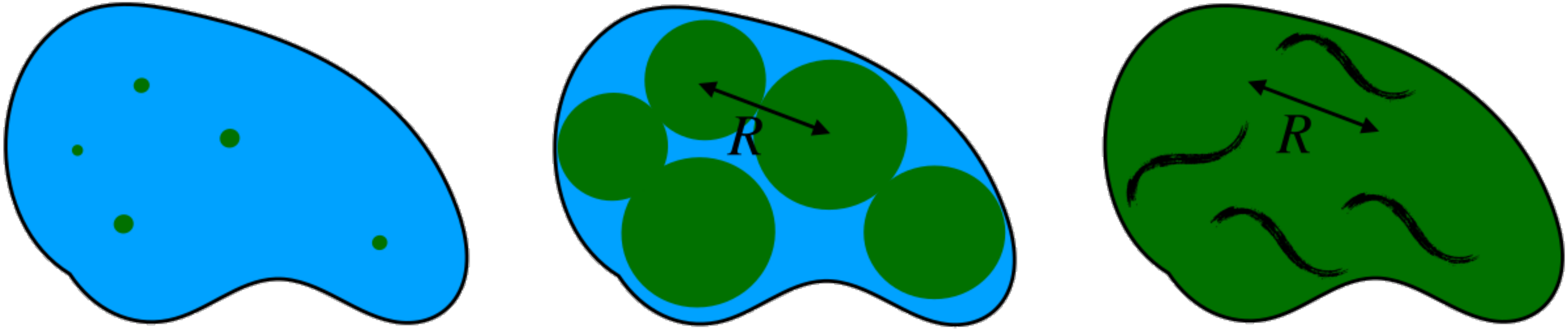
Estimating the frequency and amplitude

- Assume no specific model
- An existing FOPT is crossed

$$\Lambda \sim 1\mathrm{GeV}/\mathrm{fm}^3$$



Annala, Gorda, Kurkela, Nättila, Vuorinen '20

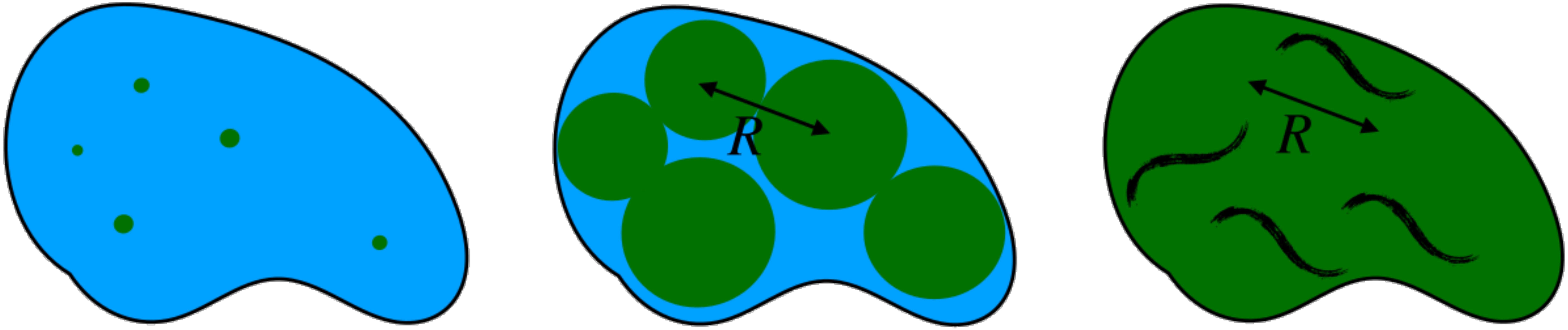


Bubbles expand and collide in ~ μs

$$R \sim v_w \beta^{-1}$$

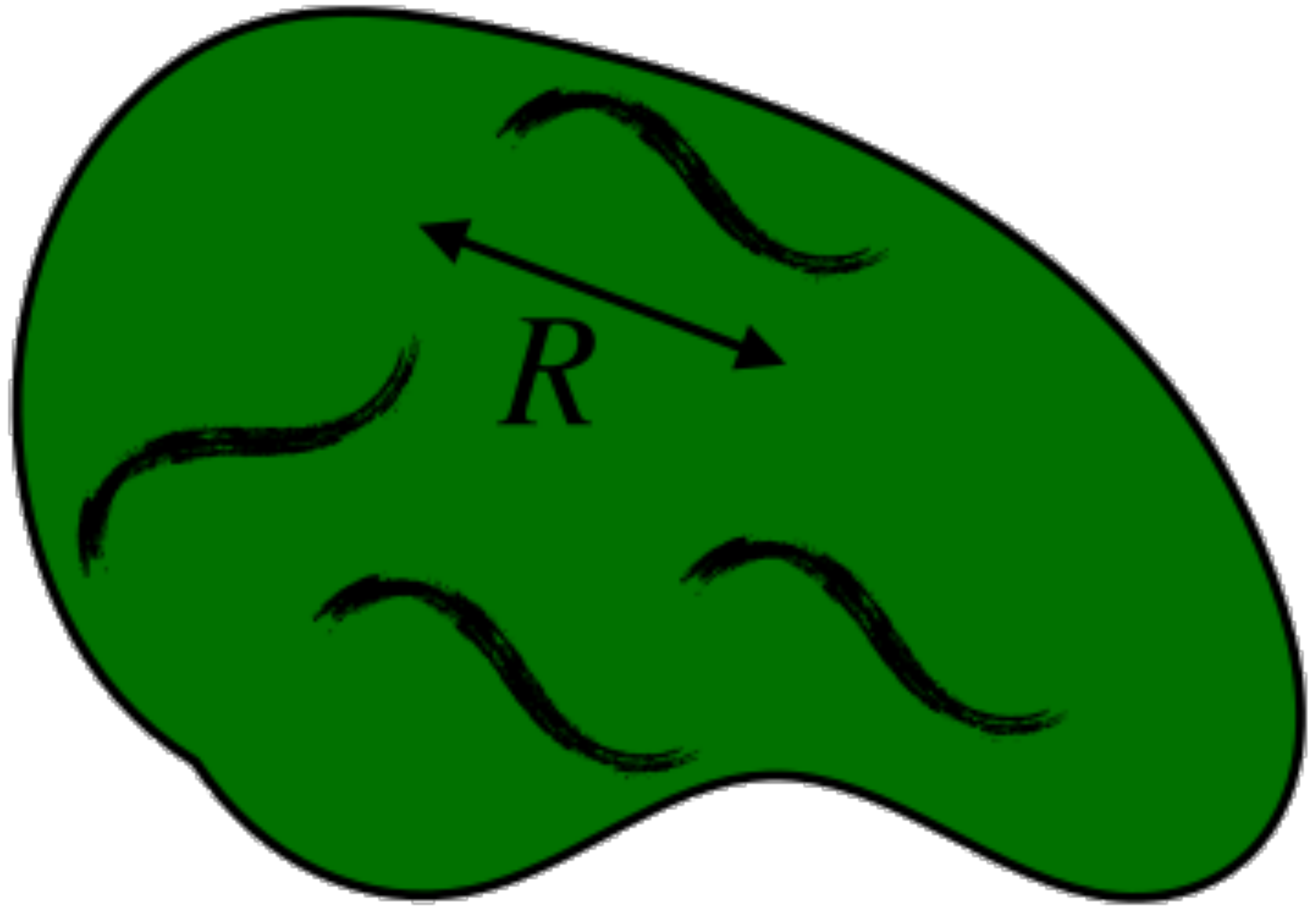
Long wavelength perturbations that live ~ ms

$$f_{peak} \sim \frac{\log(v_w^3 \tau^4 \Lambda^4)}{v_w \tau}$$



$$f_{peak} \simeq \frac{1\ \mathrm{MHz}}{v_w}\left(\frac{1\mathrm{ms}}{\tau}\right)\left[0.06502 + \frac{1}{2000\pi^{1/3}}\log\left(v_w^3\frac{\tau^4}{1\mathrm{ms}^4}\frac{\Lambda^4}{1\mathrm{GeV}/\mathrm{fm}^3}\right)\right]$$

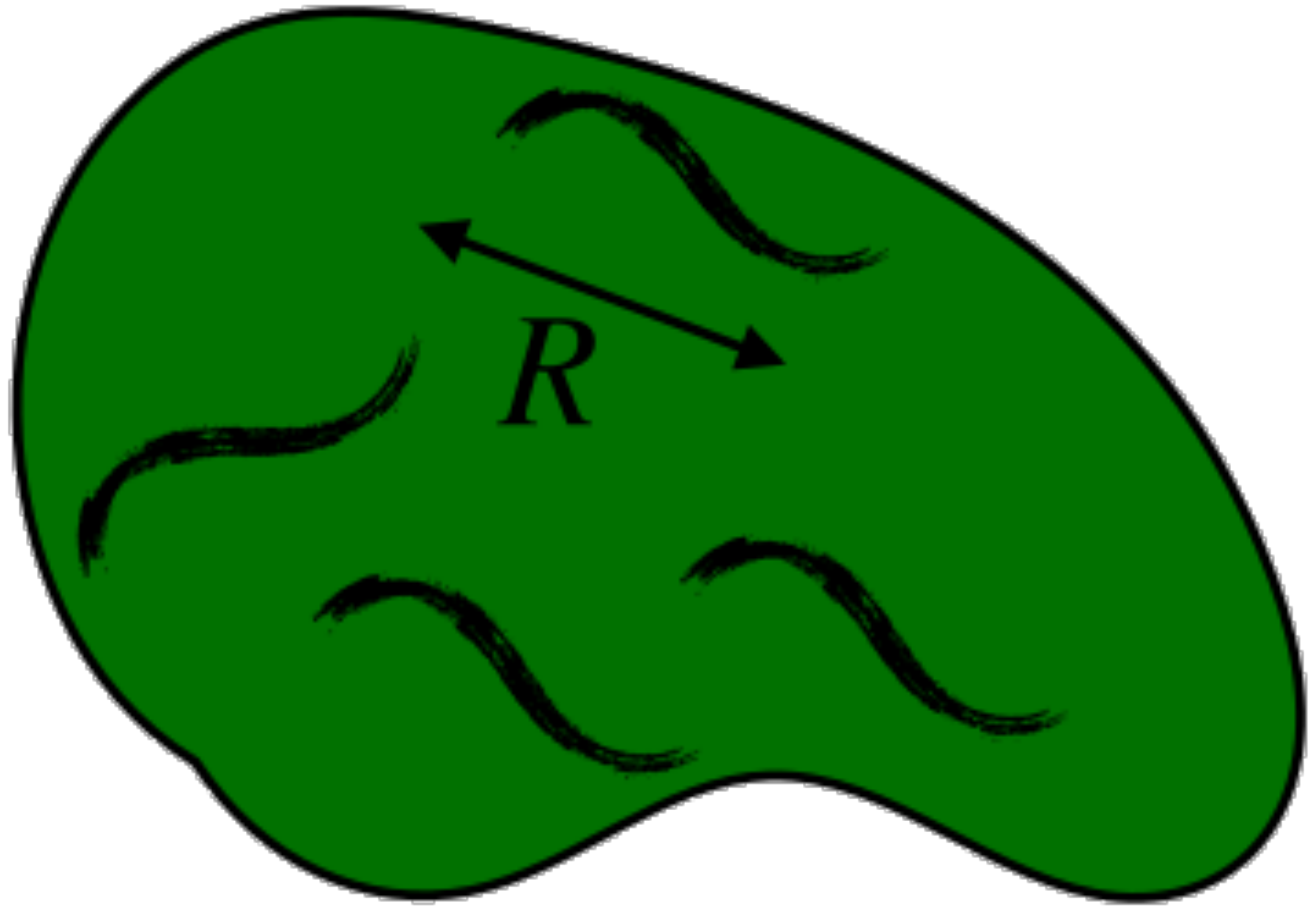
$v_w \sim 0.1$ $f_{peak} \sim 0.6\mathrm{MHz}$



Hindmarsh, Huber, Rummukainen, Weir ‘16

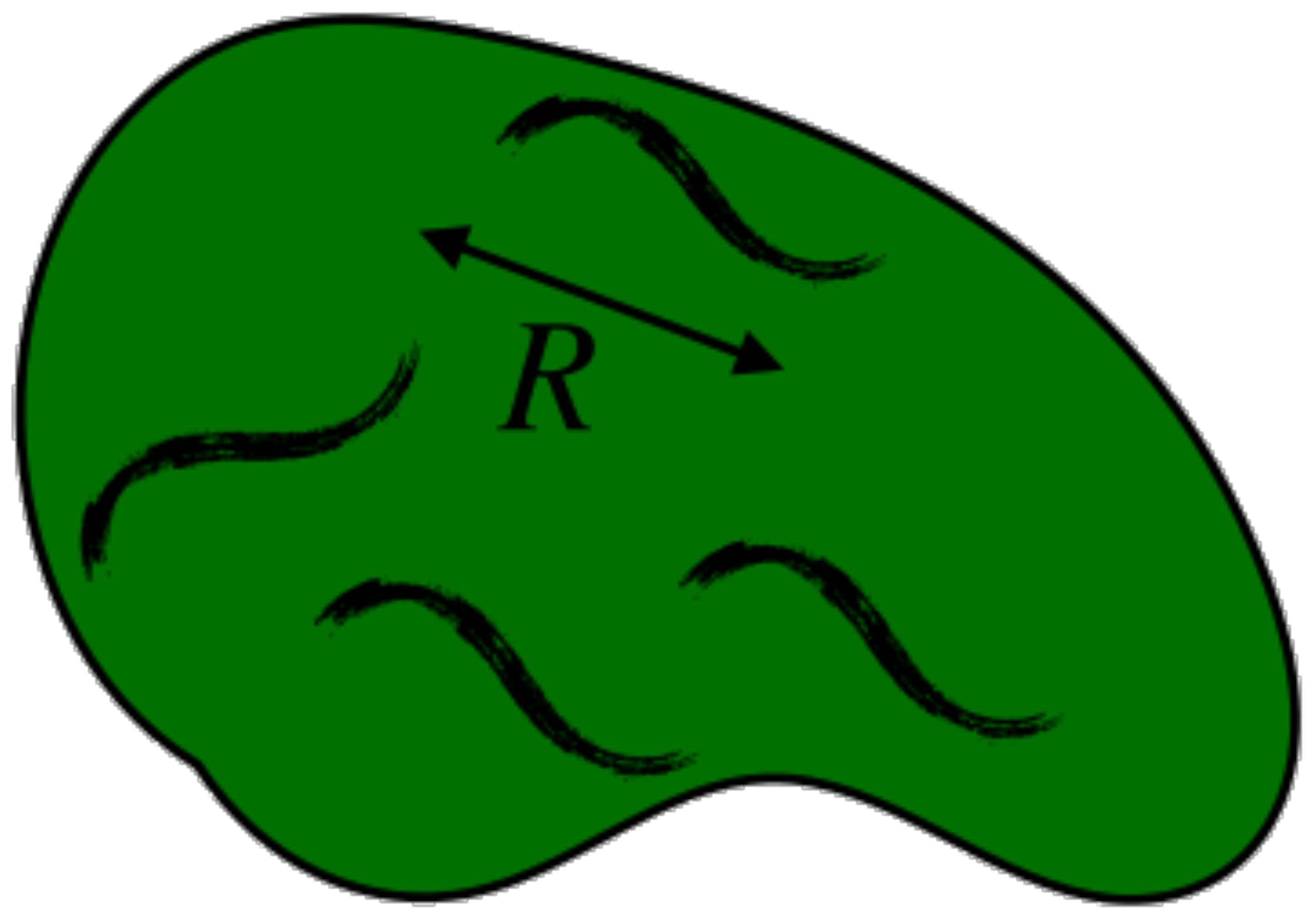
$$\rho_{GW} \sim \left((e+p)v_f^2\right)^2 R\Delta t\Omega_{GW}$$

$$\Omega_{GW} \sim 10^{-2} \qquad \Delta t \sim L/c$$



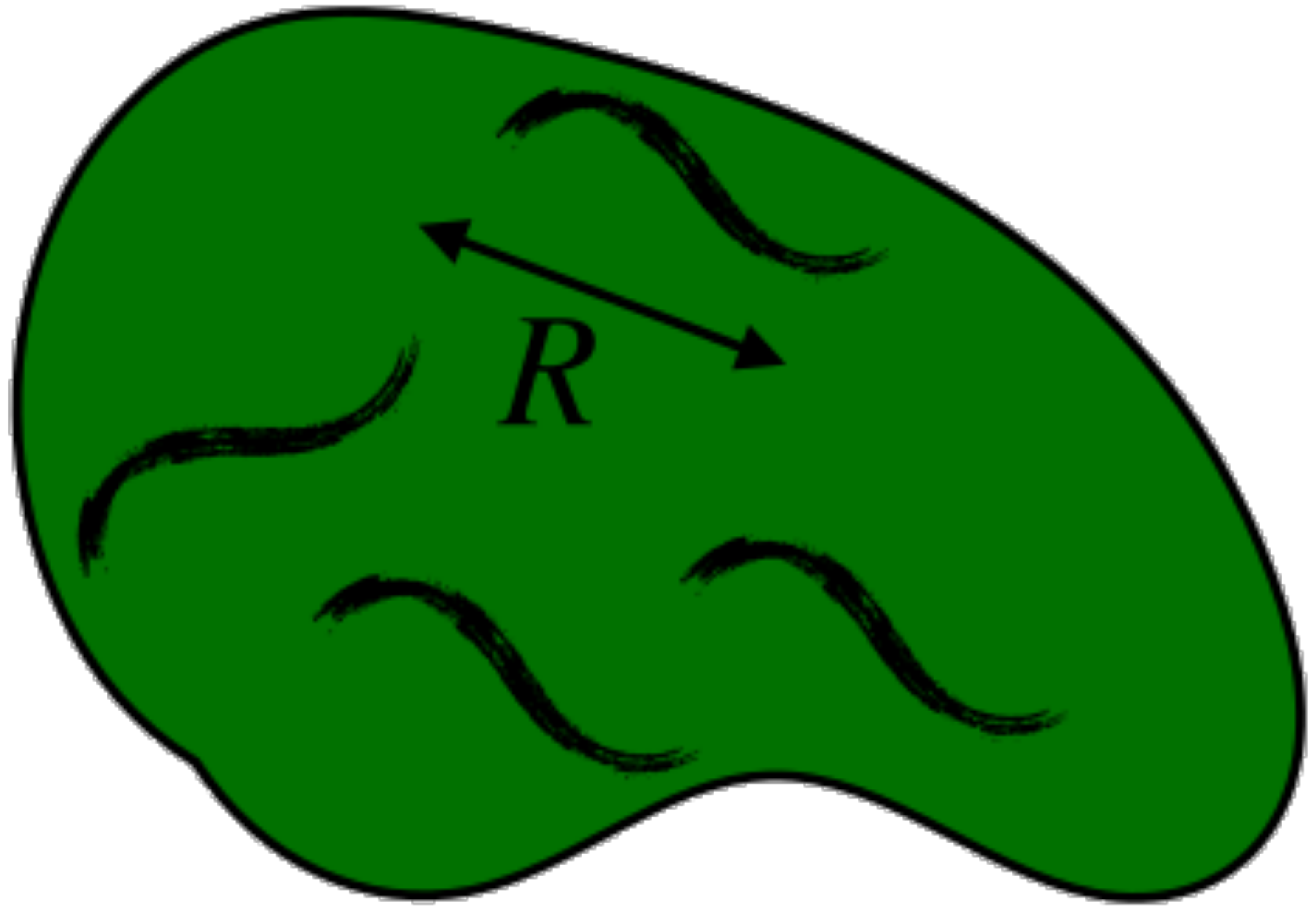
Sound contribution

$$h_c^{\text{obs}} \sim \frac{L^{3/2}\Lambda^4 v_f^2}{f^{3/2} d}$$



Sound contribution

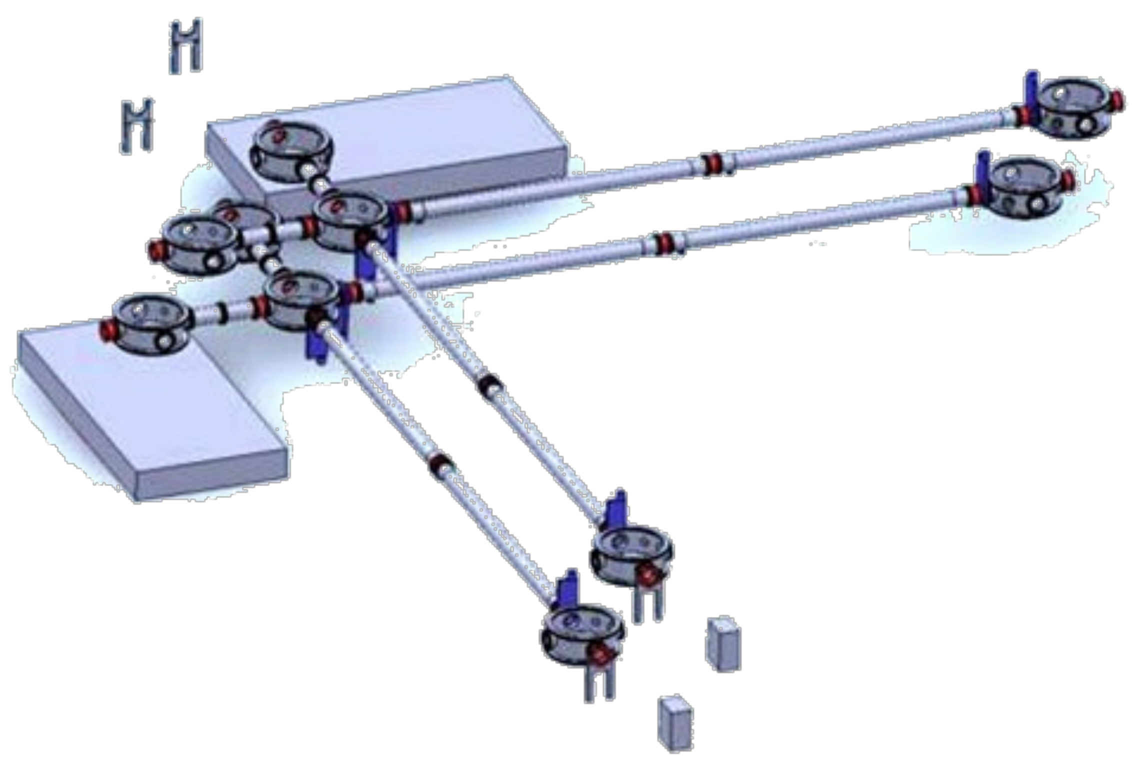
$$h_c \simeq 2.6 \times 10^{-25} v_f^2 \left(\frac{\Lambda^4}{1\ \mathrm{GeV/fm^3}}\right) \left(\frac{L}{1\ \mathrm{km}}\right)^{3/2} \left(\frac{1\ \mathrm{MHz}}{f_{\mathrm{peak}}}\right)^{3/2} \left(\frac{100\ \mathrm{Mpc}}{d}\right)$$



Sound contribution

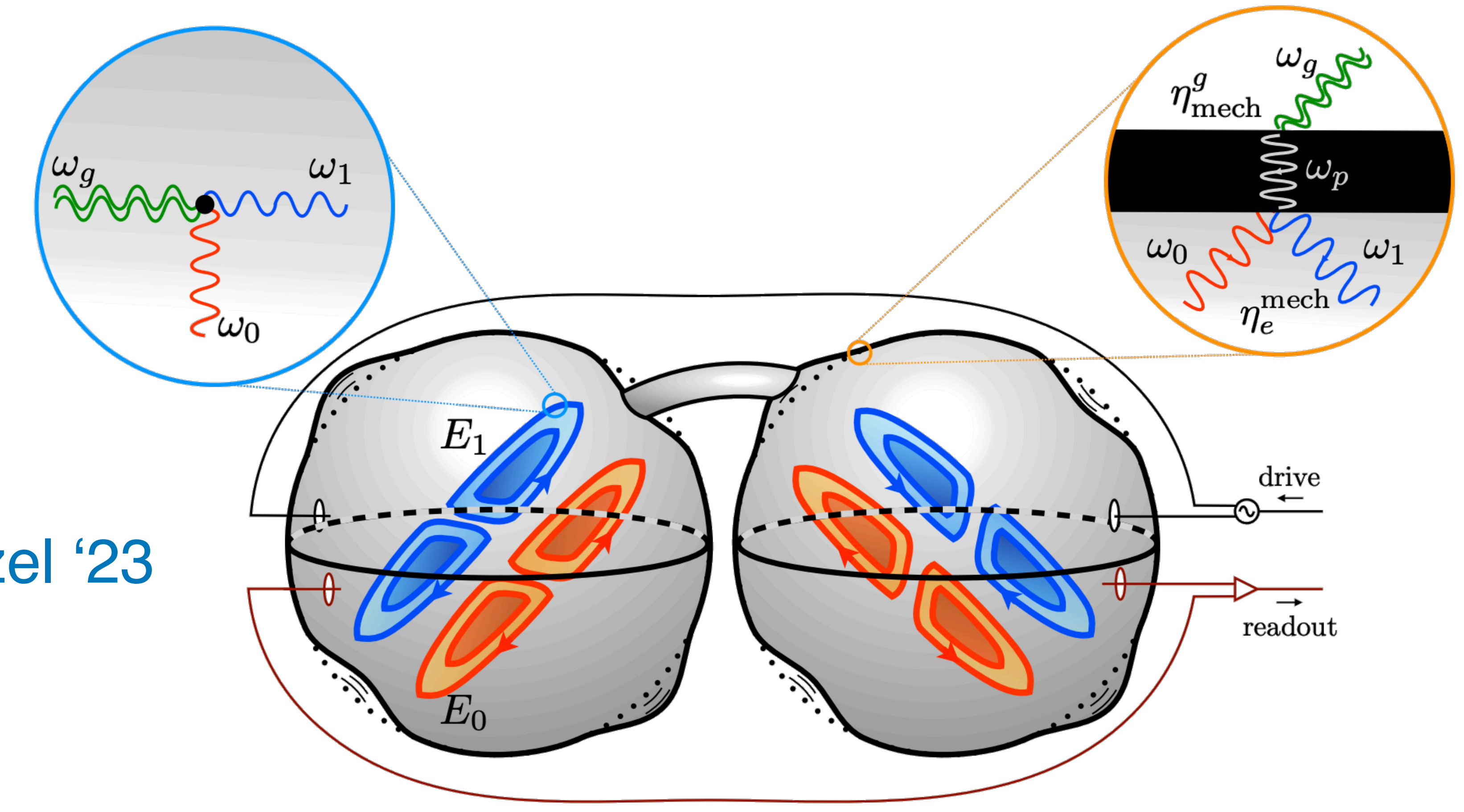
$$h_c^{\rm obs} \sim 10^{-24} v_f^2 \left(\frac{100{\rm Mpc}}{d}\right)$$

Experiments for UHFGW



Chou et al '17

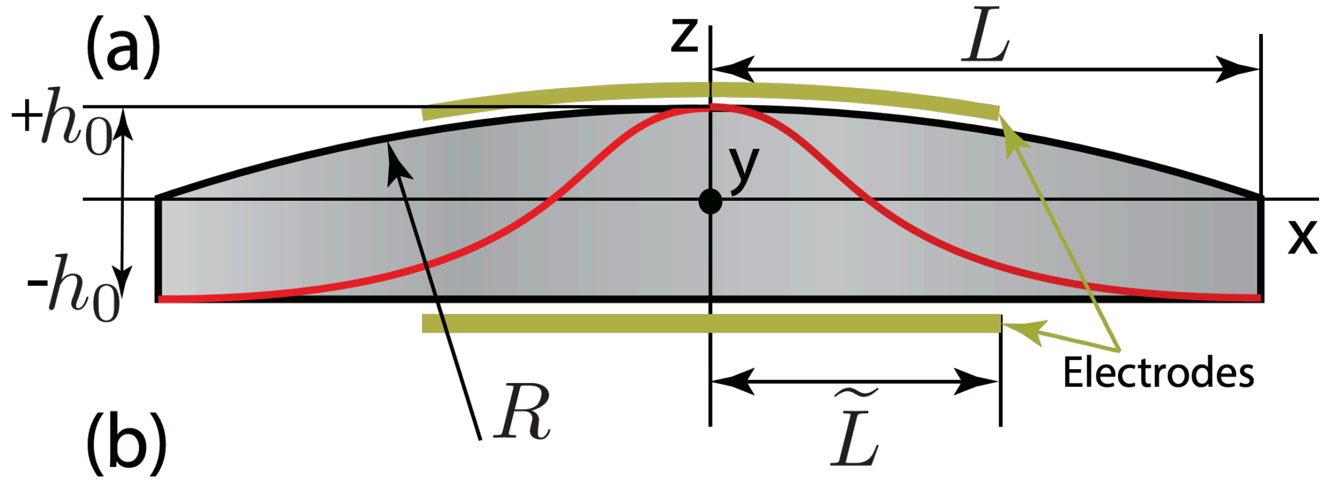
- Interferometers (holometer): $h_c \sim 10^{-19} - 10^{-18}$



- Resonant cavities: $h_c \sim 10^{-22}$

Berlin, Blas, D'Agnolo, Ellis, Harnik, Kahn, Schütte-Engel, Wentzel '23

- Bulk acoustic wave resonators: $h_c \sim 10^{-21} - 10^{-20}$



Gorbachev, Tobar '14

Gorbachev, Ivanov, van Kann, Galliou, Tobar '14

2011.12414

Other characteristics of the signal

- Signal from a single spot lasts for ~ ms
- Several spots transition back a forth during the merger
- Stochastic in nature but well localised in the sky
- Only astrophysical source (within SM) at MHz

Improvements

- Better estimate of the energy in fluid motion: v_f
- Study the collision of superheated bubbles
- Fist approximation: sound-shell model (assumes linearity)
- Expansion of isolated superheated bubbles
- Weak processes? Memory effects?

Superheated bubbles

Bea, Casalderrey-Solana, Mateos, MSG ‘24

Barni, Blasi, Vanvlasselaer ’24

Bubble expansion

$$T^{\mu\nu} = w u^\mu u^\nu - p g^{\mu\nu} \qquad j^\mu = n u^\mu$$

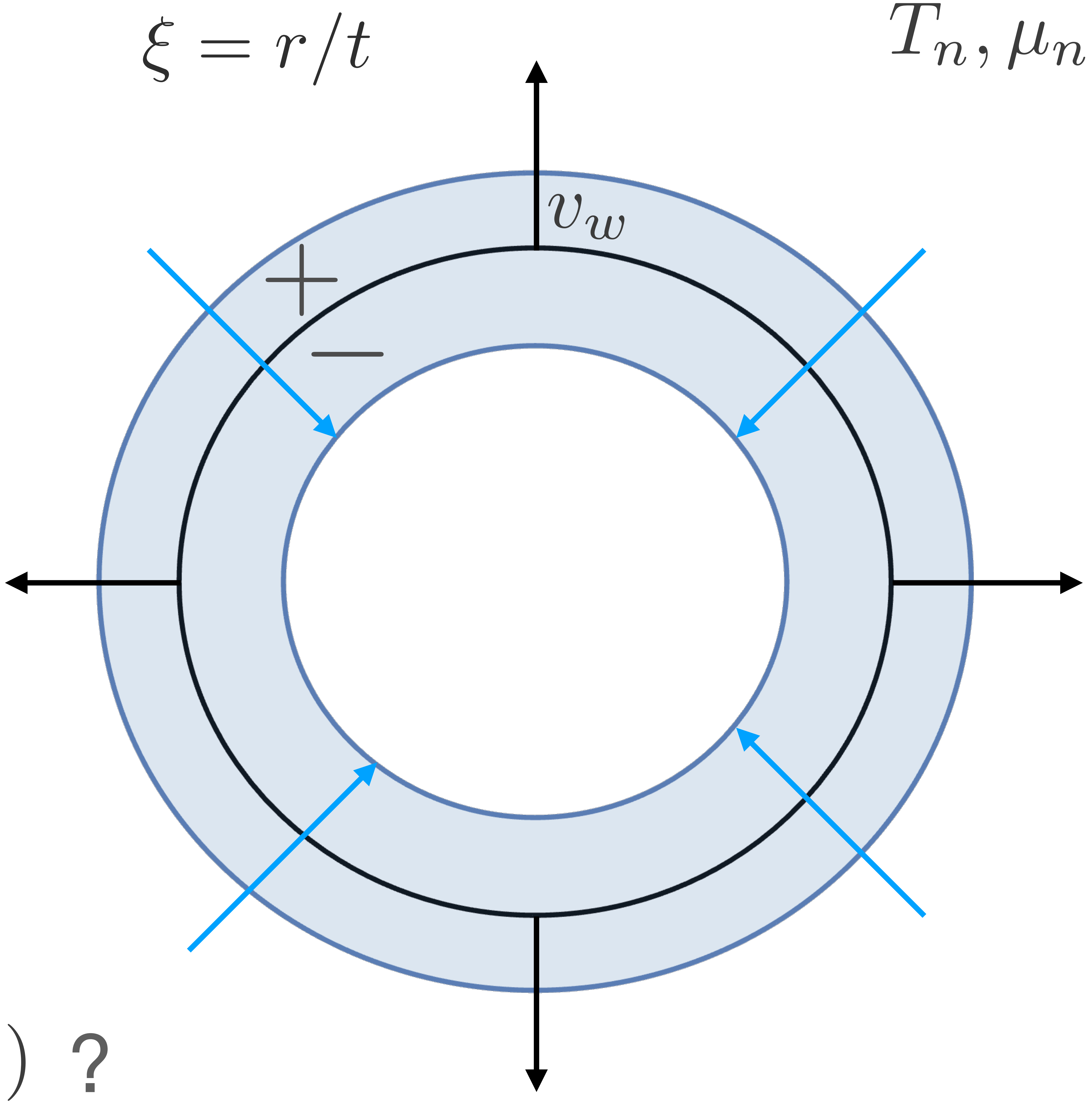
$$\partial_\mu T^{\mu\nu} = 0 \qquad \partial_\mu j^\mu = 0$$

$$p = p(e, n) \qquad c_s^2 = \frac{1}{3}$$

Matching conditions at the wall:

$$v_+ v_- = \frac{p_+ - p_-}{e_+ - e_-}, \qquad \frac{v_+}{v_-} = \frac{e_- + p_+}{e_+ - p_-}$$

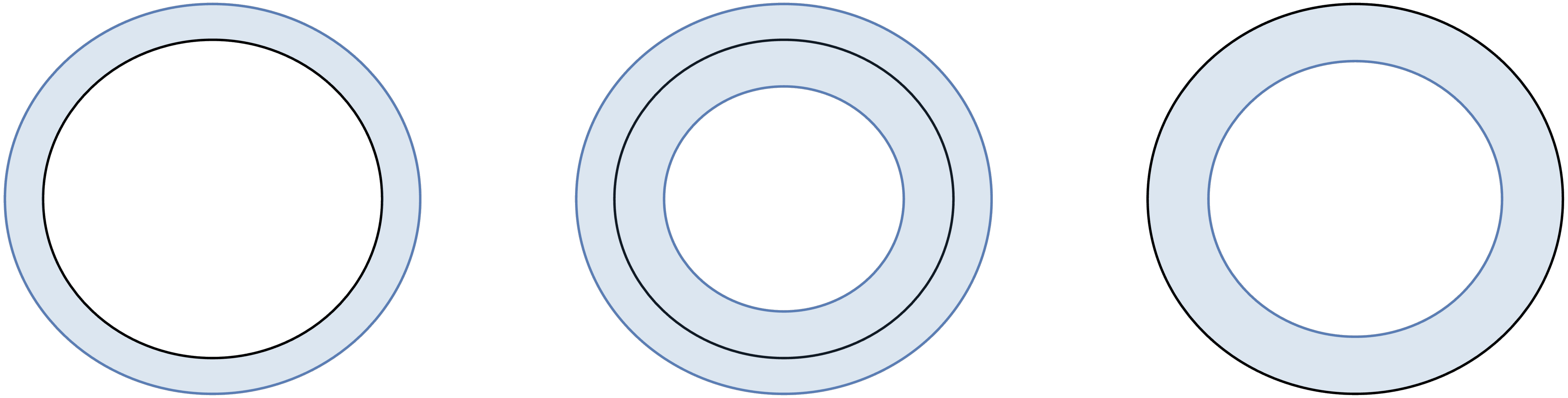
$$n_+ \gamma_+ v_+ = n_- \gamma_- v_-$$



$v_w(T_n, \mu_n)$?

Types of expansions

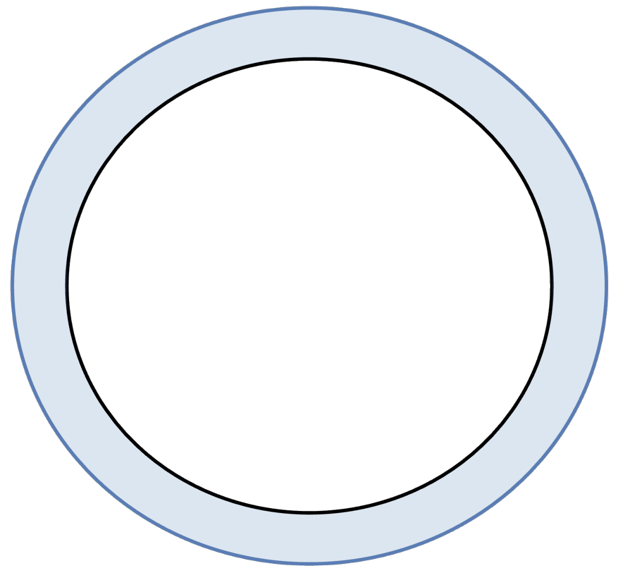
$v_w < c_s$ | $v_w \lesssim c_s$ | $v_w \geq c_s$

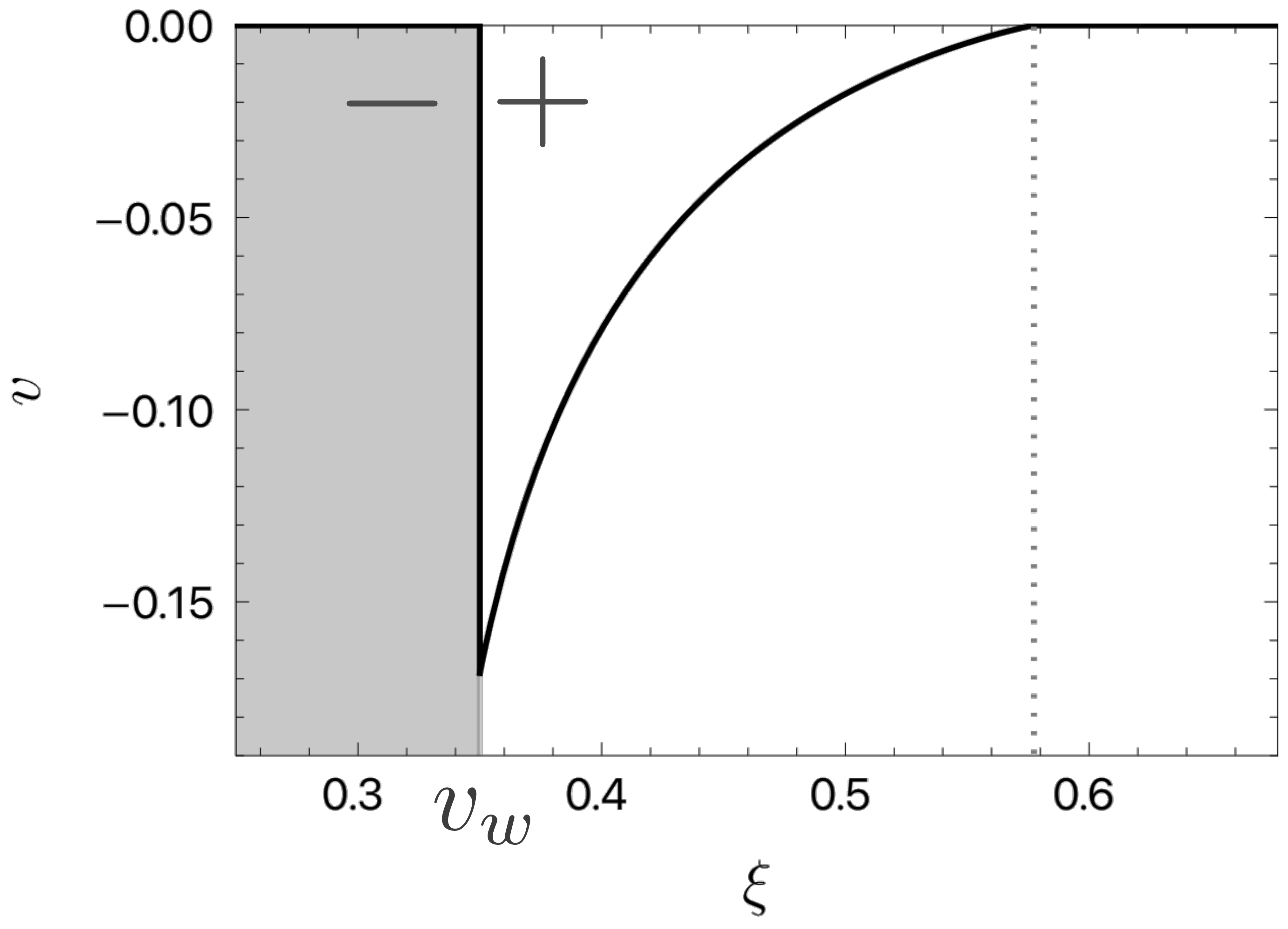


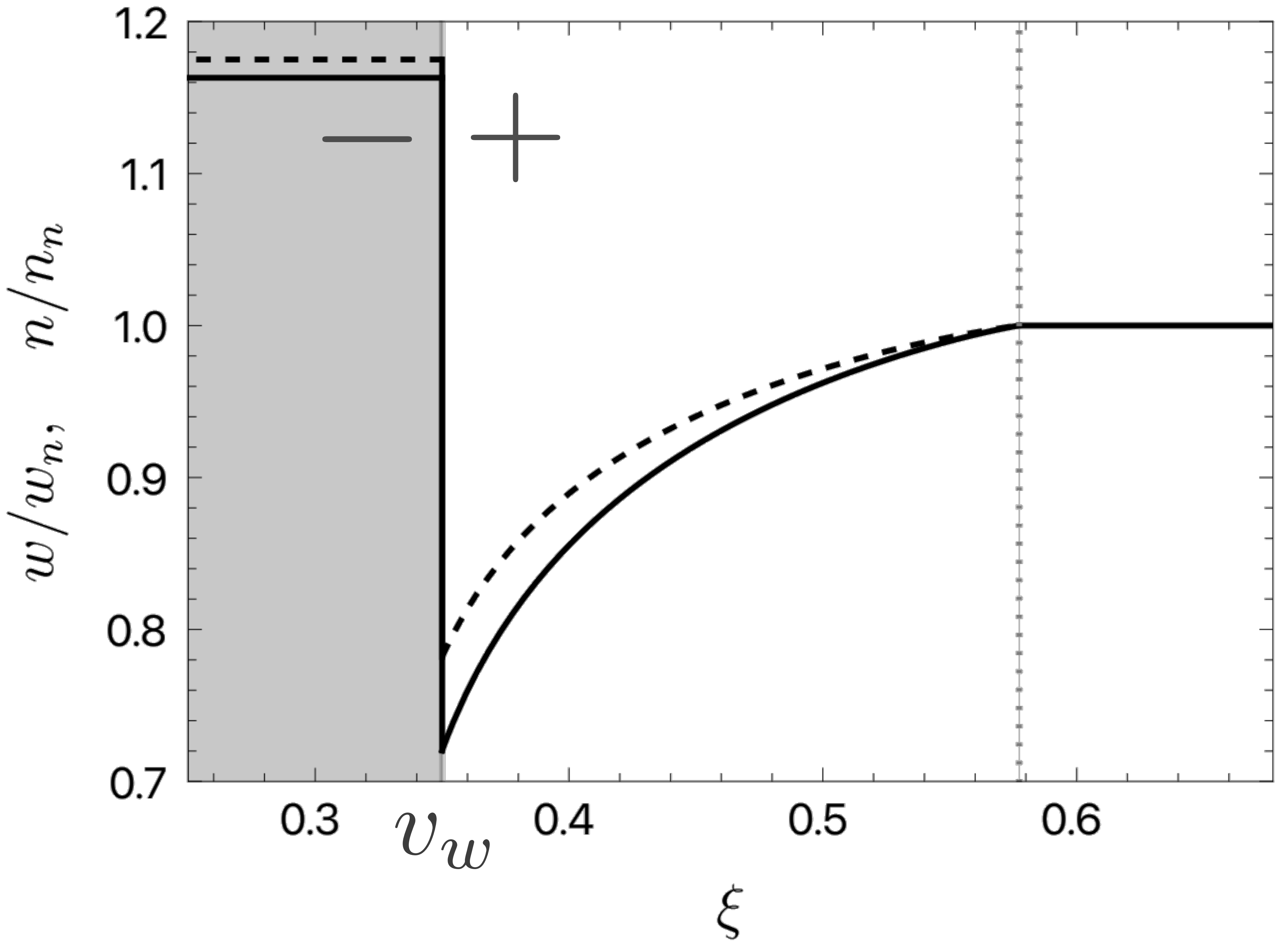
Deflagration | Hybrid | Detonation

Deflagration

$$v_w < c_s$$

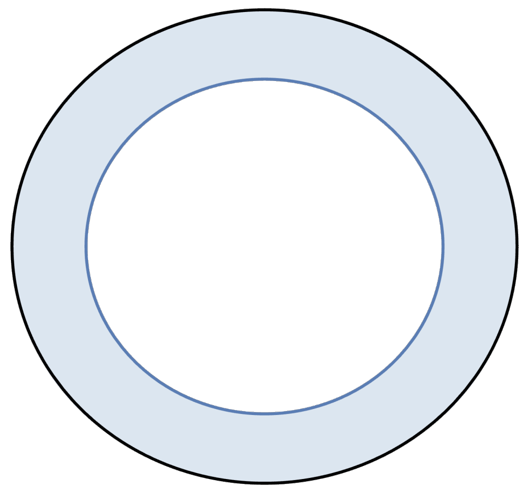


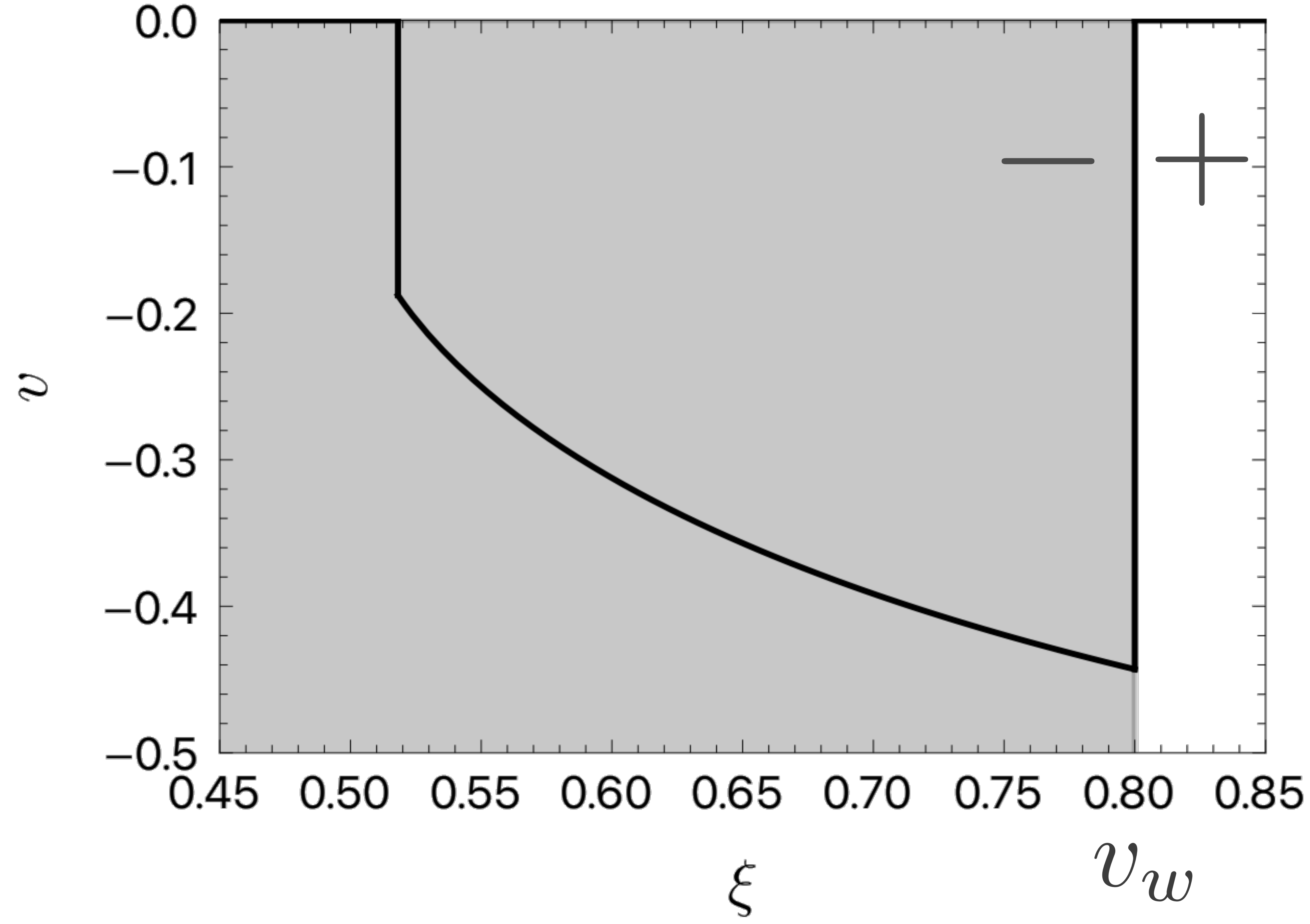


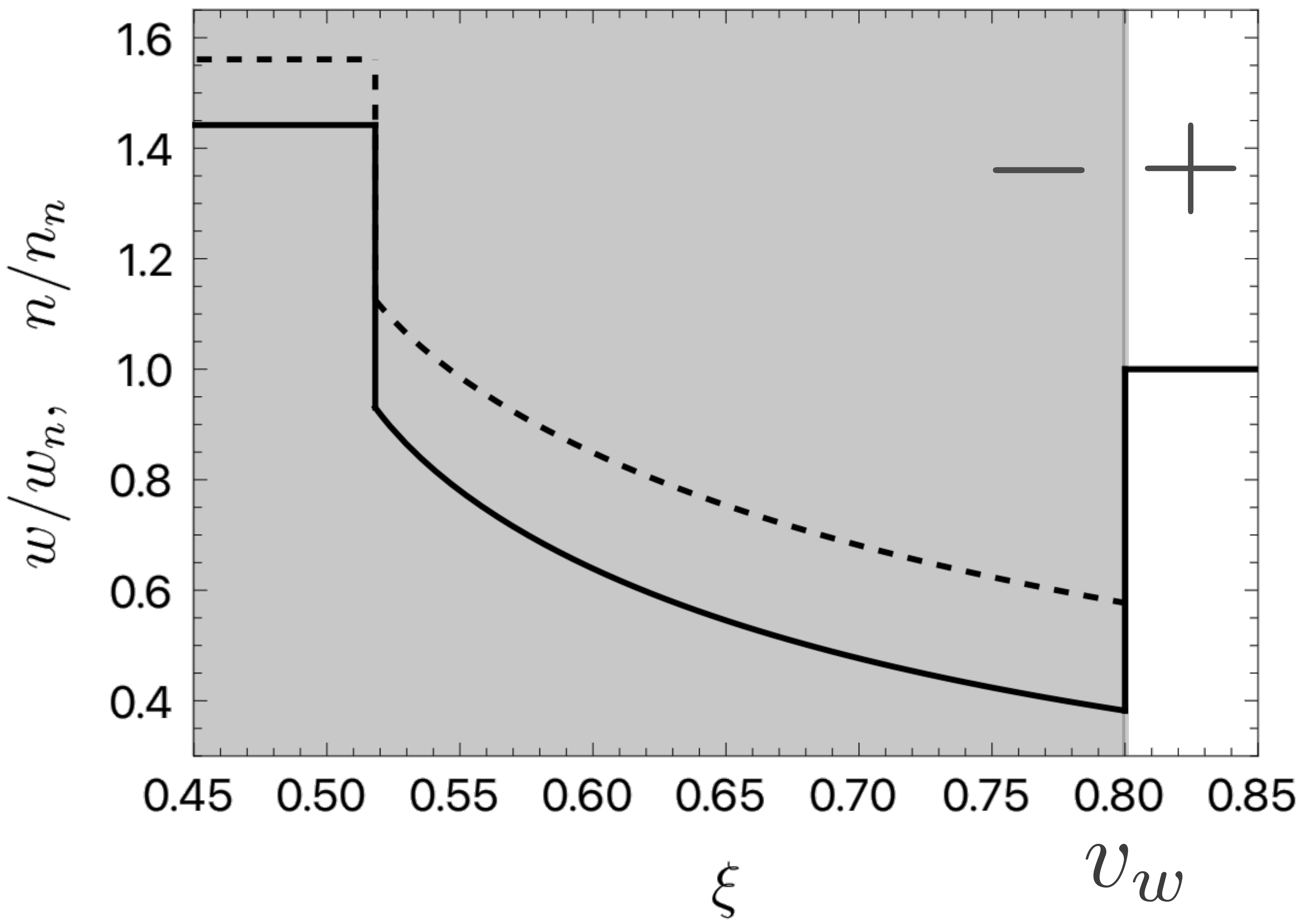


Detonation

$$v_w \geq c_s$$

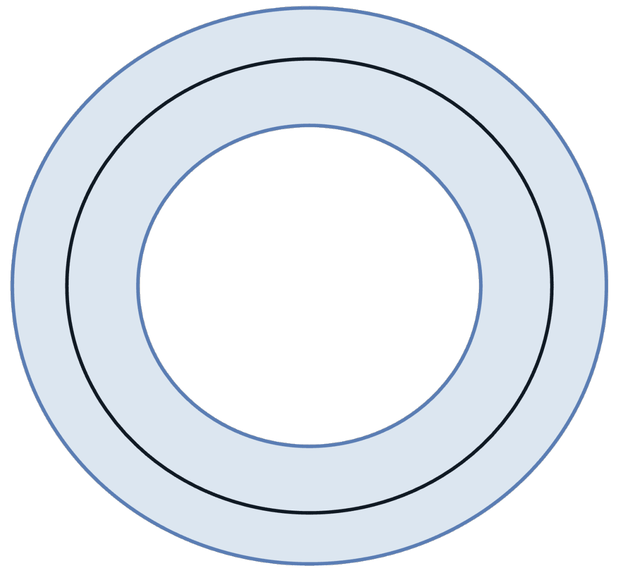


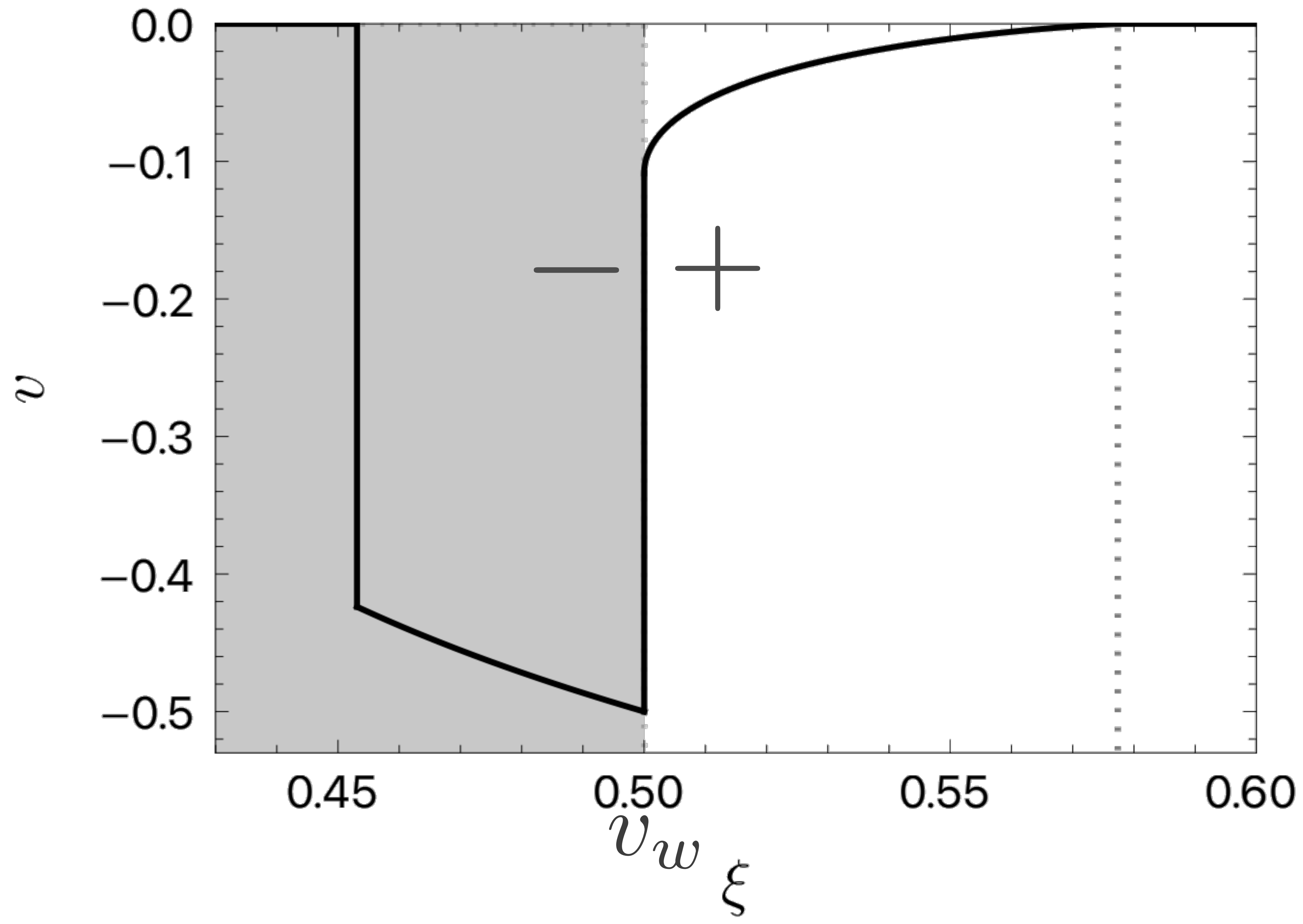


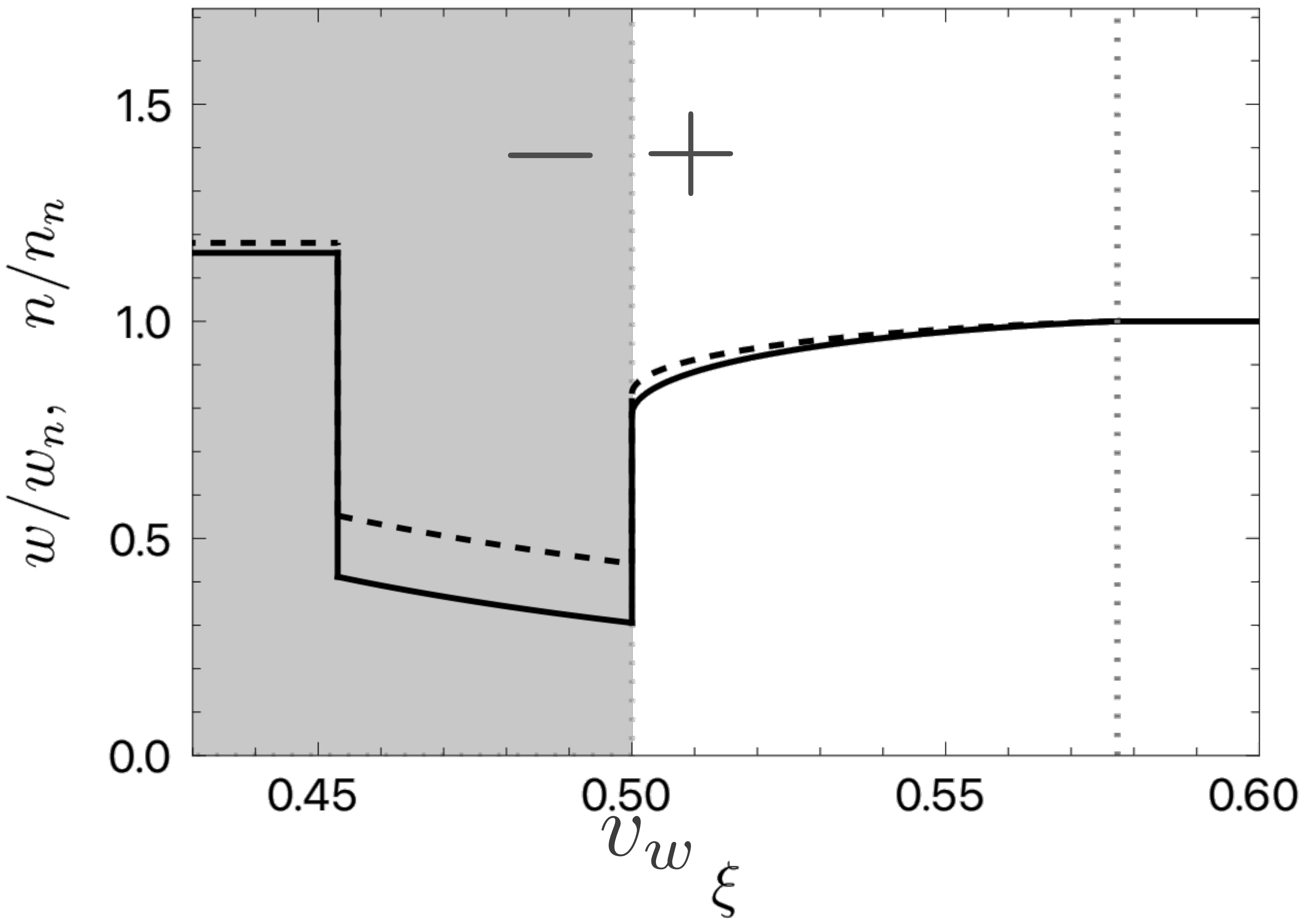


Hybrid

$v_w \lesssim c_s$

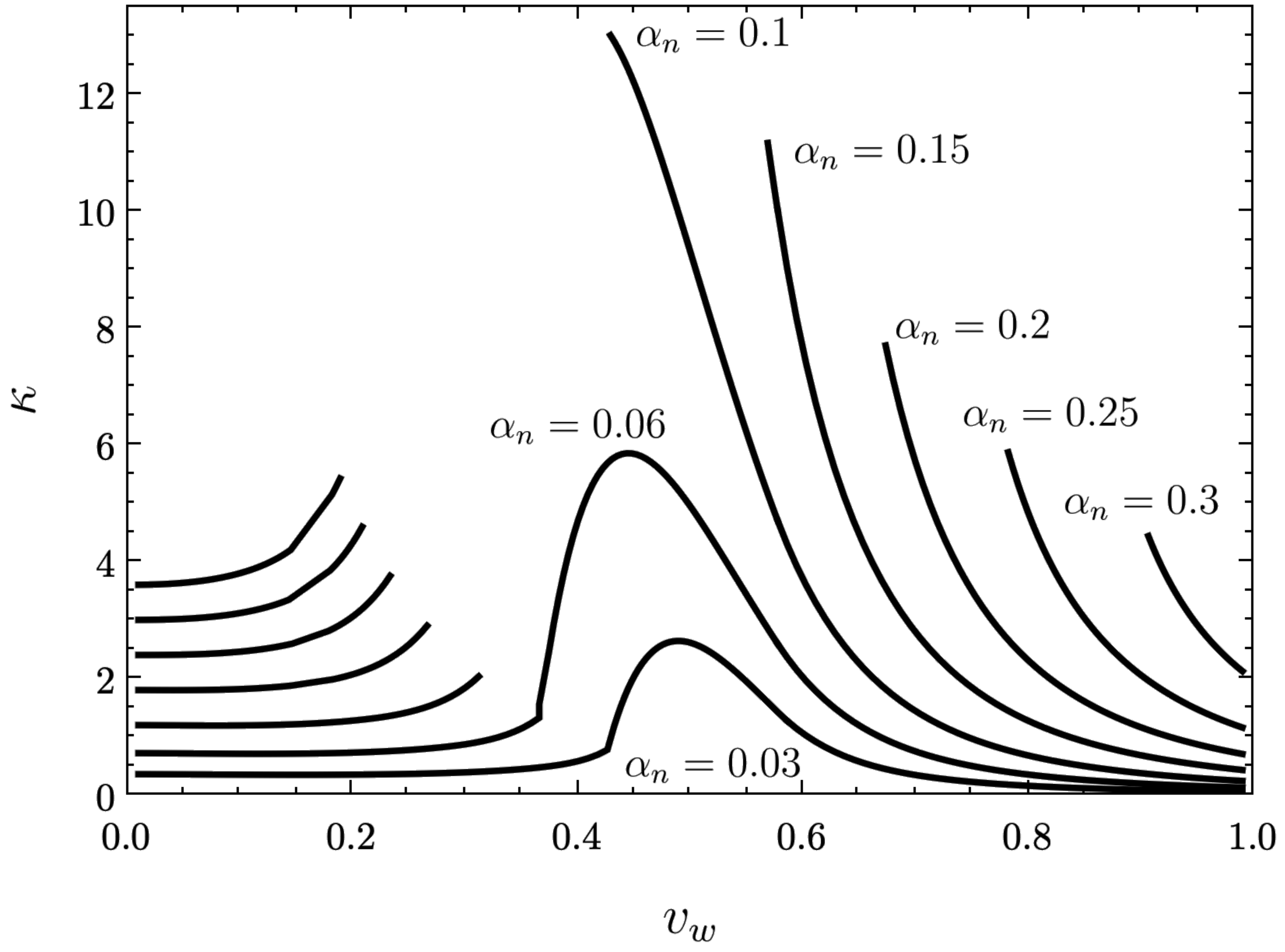






Efficiency factor

$$\kappa \sim \int w\gamma^2 v^2 \xi^2 d\xi \qquad \alpha_n \sim \frac{1}{e_n}$$



- Solutions cease to exist as strength increases
- Intermediate velocities and strengths are the most energetic
- Towards more detailed estimate of GW emission

Towards QCD

- Non-conformal EoS: relevant effect of the charge

- Understand the dynamics of bubbles in strongly coupled theories

- EoS that exhibits a QCD-like phase diagram

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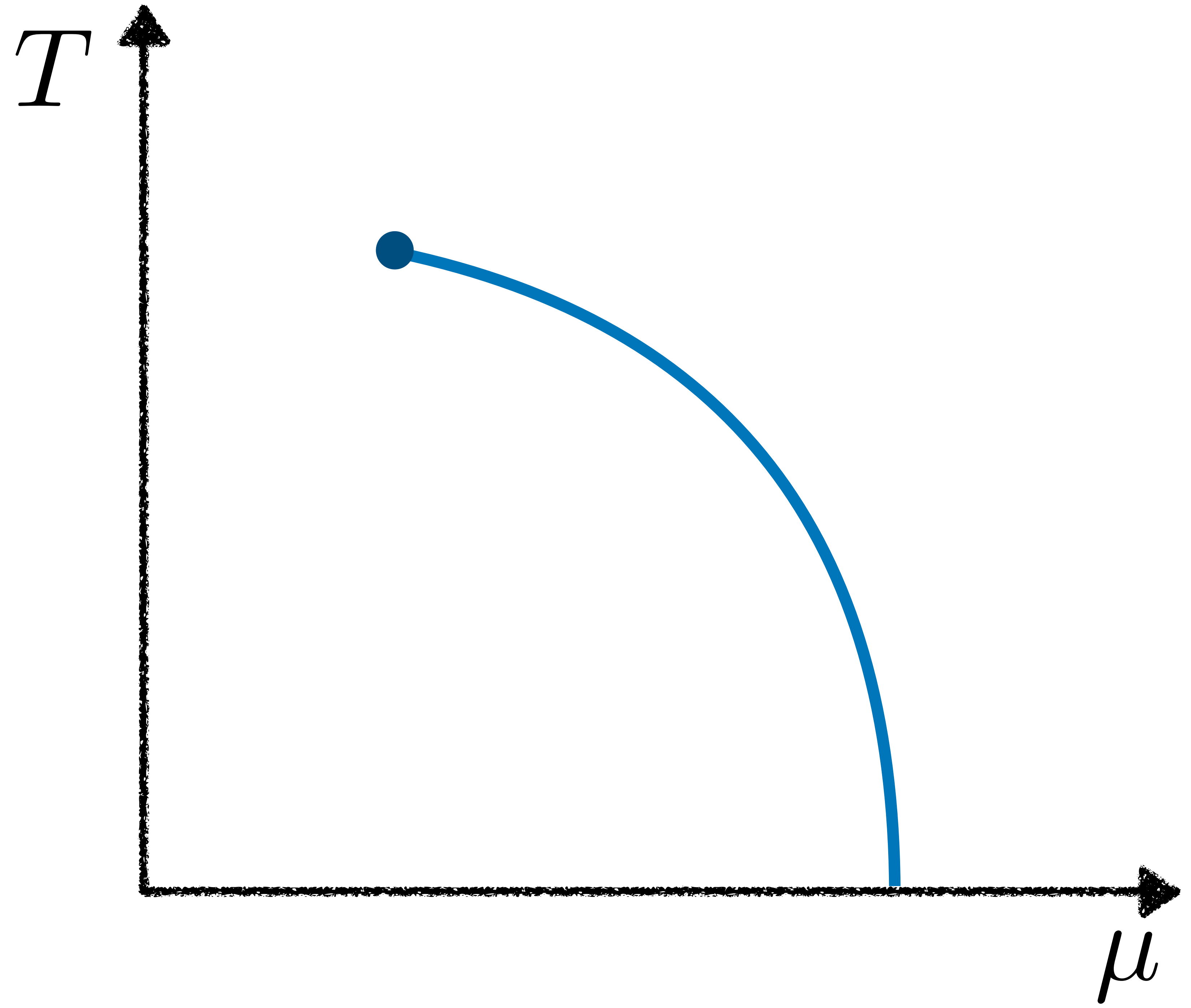
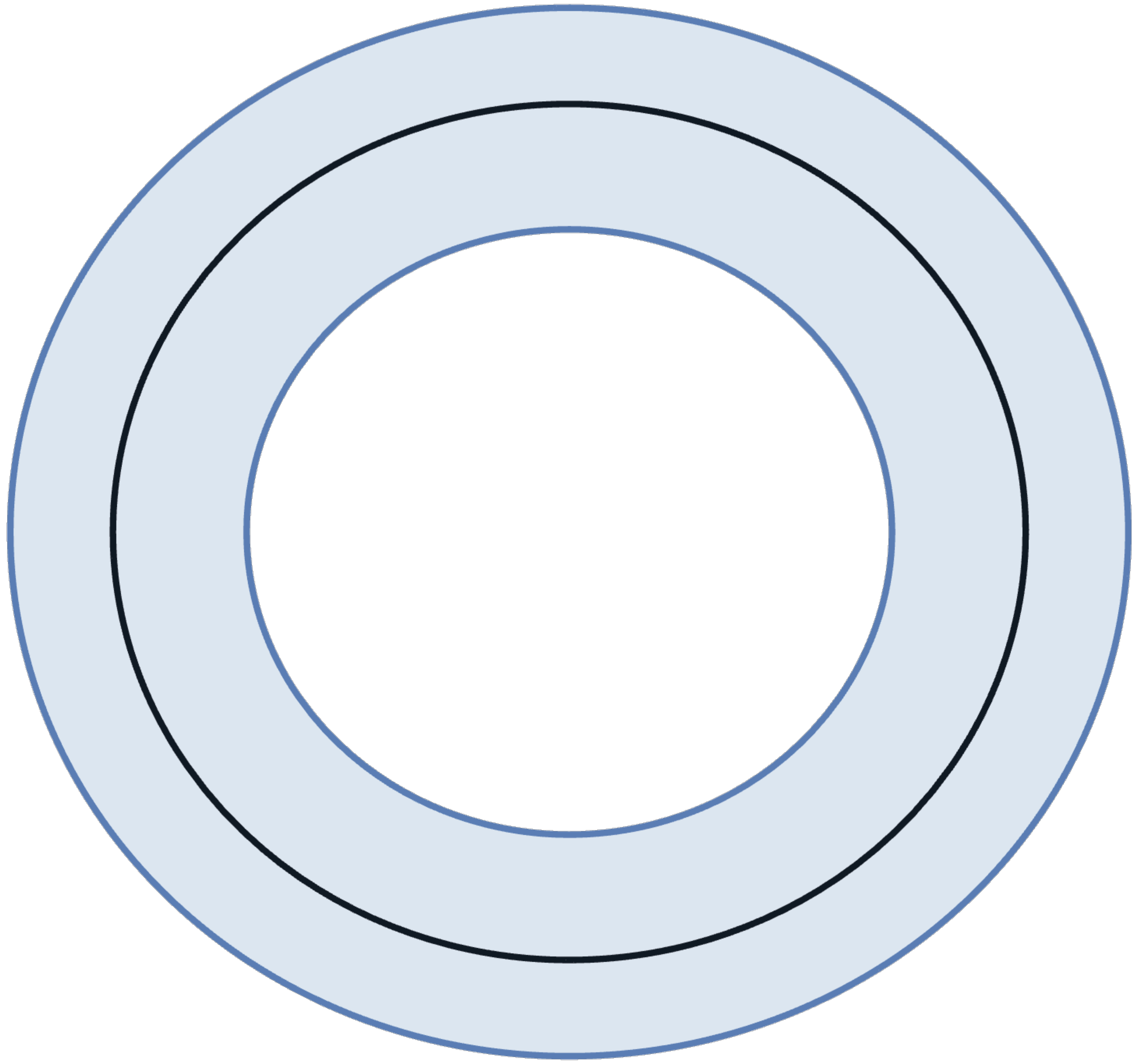


Issues at strong coupling

- Nucleation and collision intuition from EFT: hydrodynamics (plasma) + classical scalar field (wall)



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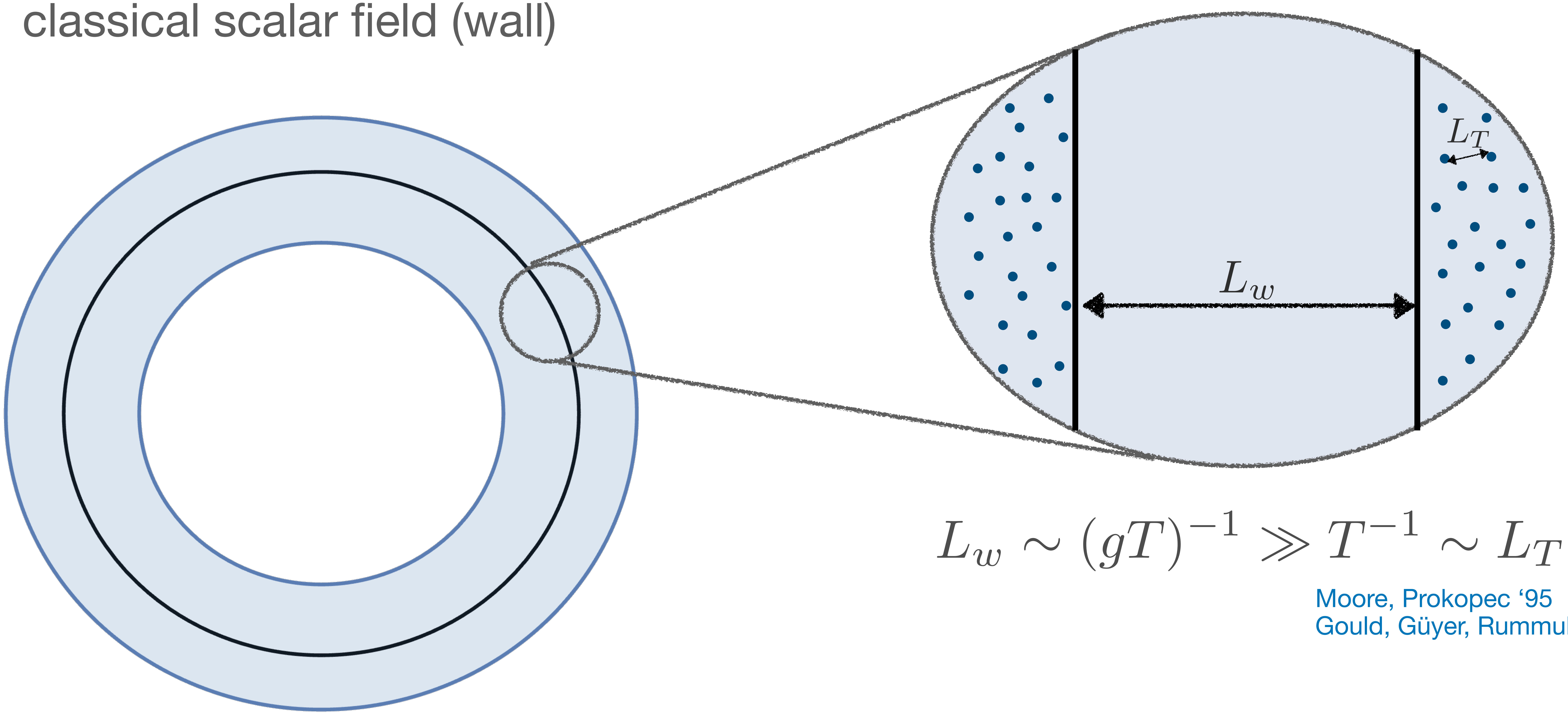
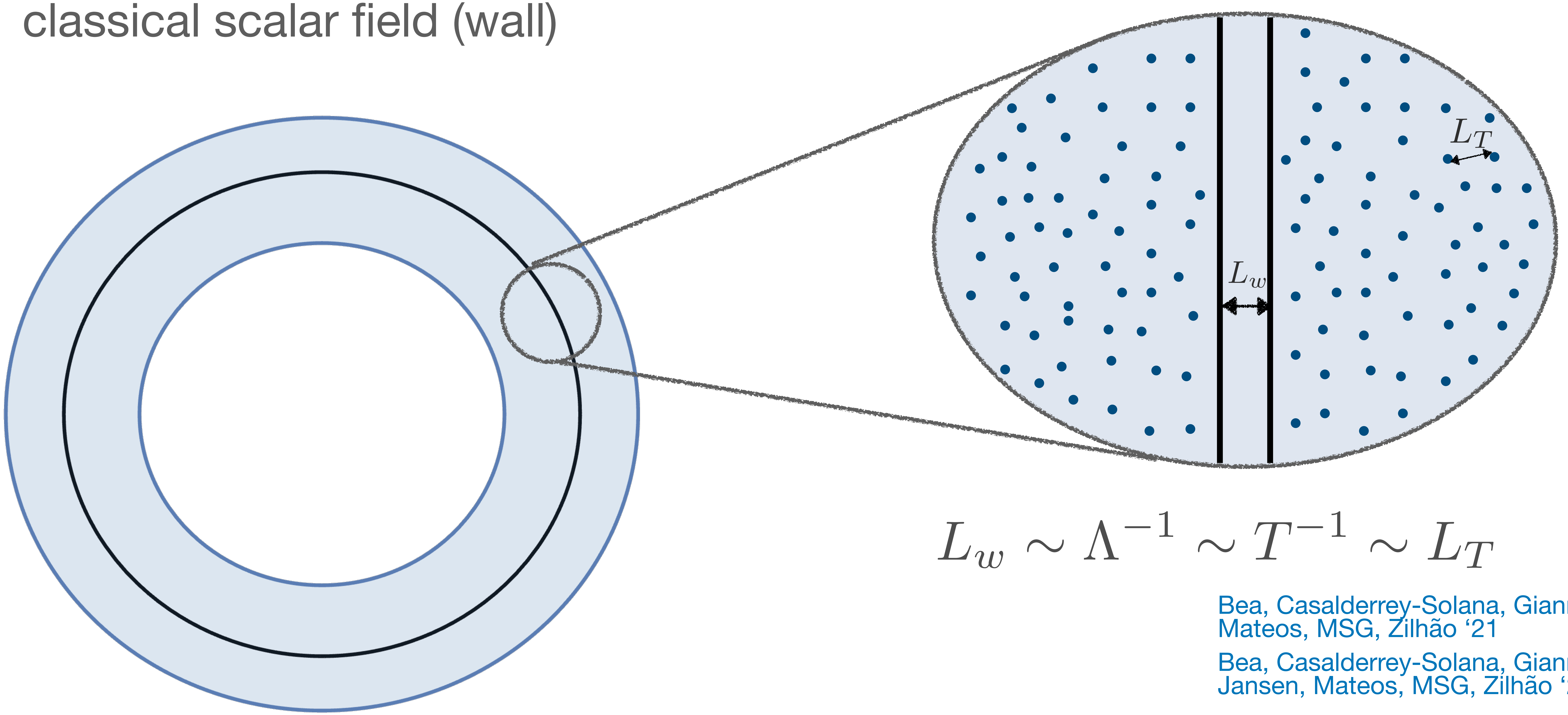


$$L_w \sim (gT)^{-1} \gg T^{-1} \sim L_T$$

Moore, Prokopec '95
Gould, Güyer, Rummukainen '23

Issues at strong coupling

- Nucleation and collision intuition from EFT: hydrodynamics (plasma) + classical scalar field (wall)



$$L_w \sim \Lambda^{-1} \sim T^{-1} \sim L_T$$

Bea, Casalderrey-Solana, Giannakopoulos, Mateos, MSG, Zilhão ‘21

Bea, Casalderrey-Solana, Giannakopoulos, Jansen, Mateos, MSG, Zilhão ‘22

Issues at strong coupling

- Hydrodynamics + scalar field is useful?
- Is there any other effective way of capturing the wall dynamics?
- Equilibrium domain walls described by 2nd order hydrodynamics

Attems, Bea, Casalderrey-Solana, Mateos, Triana ‘17
Attems, Bea, Casalderrey-Solana, Mateos, Zilhão ‘19

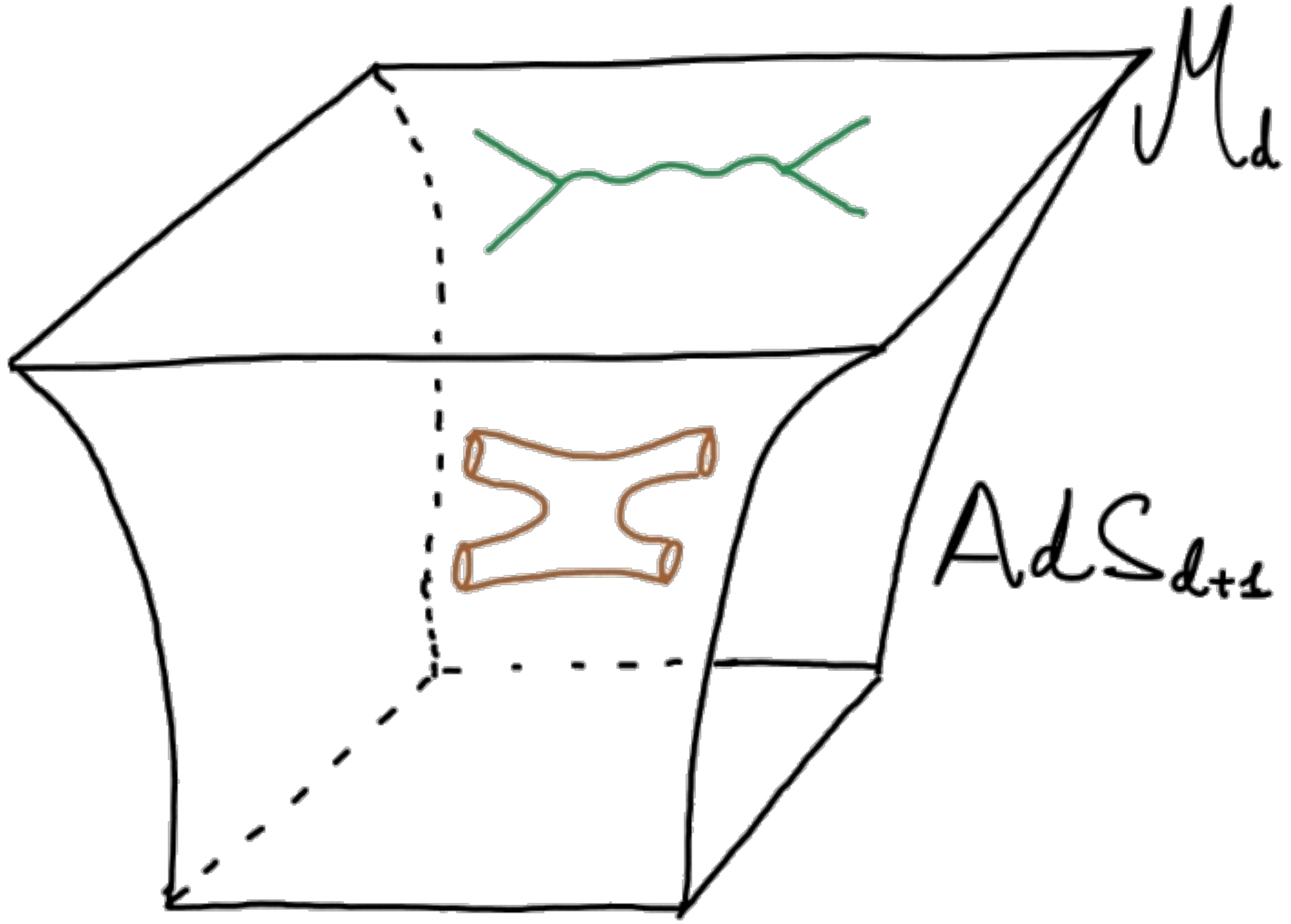
- Holography is the perfect playground to understand these questions

What holography can offer

$SU(N)\quad QFT_d$

$\Updownarrow$

$\text{Strings}\quad \text{in}\quad AdS_{d+1}$

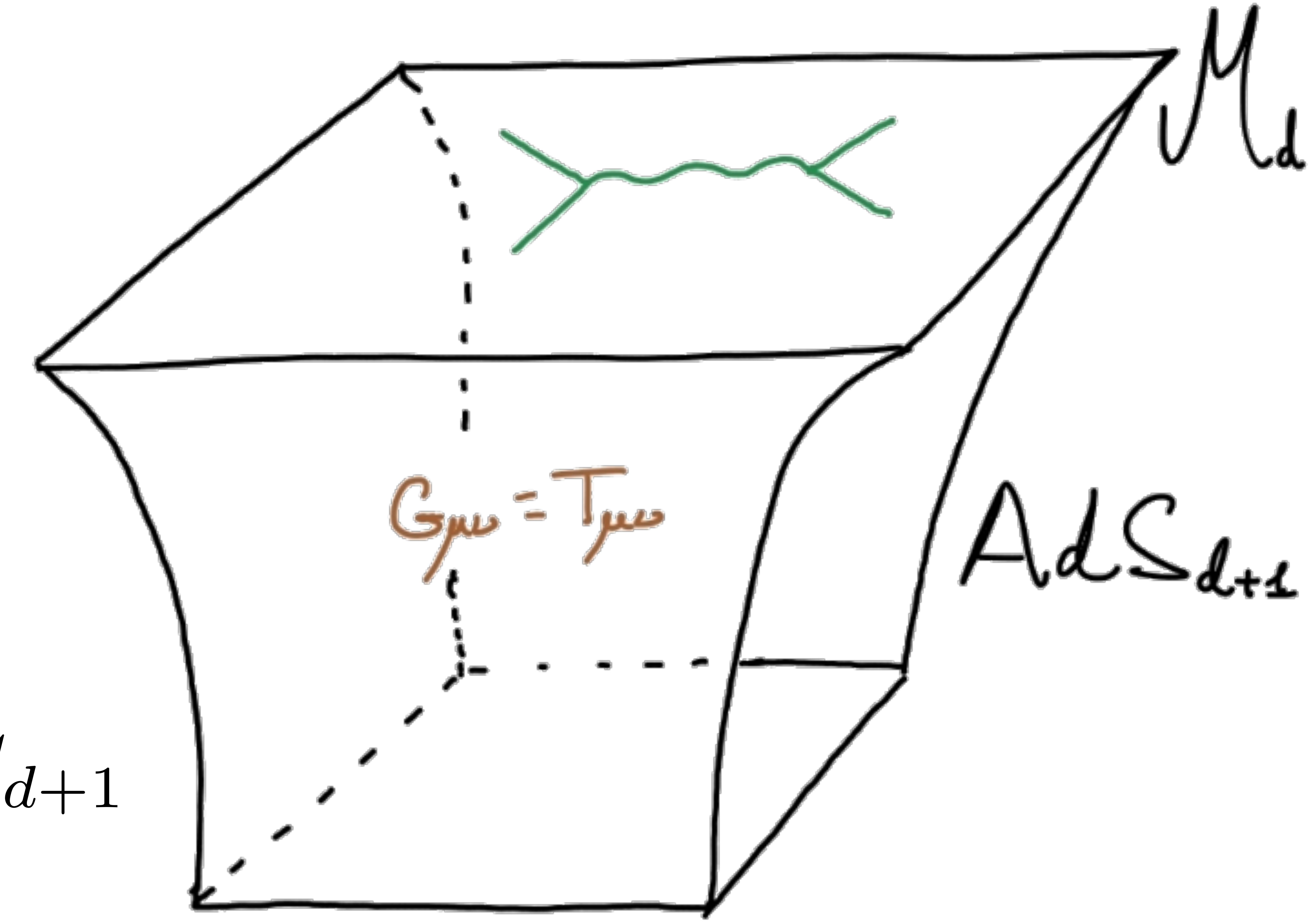


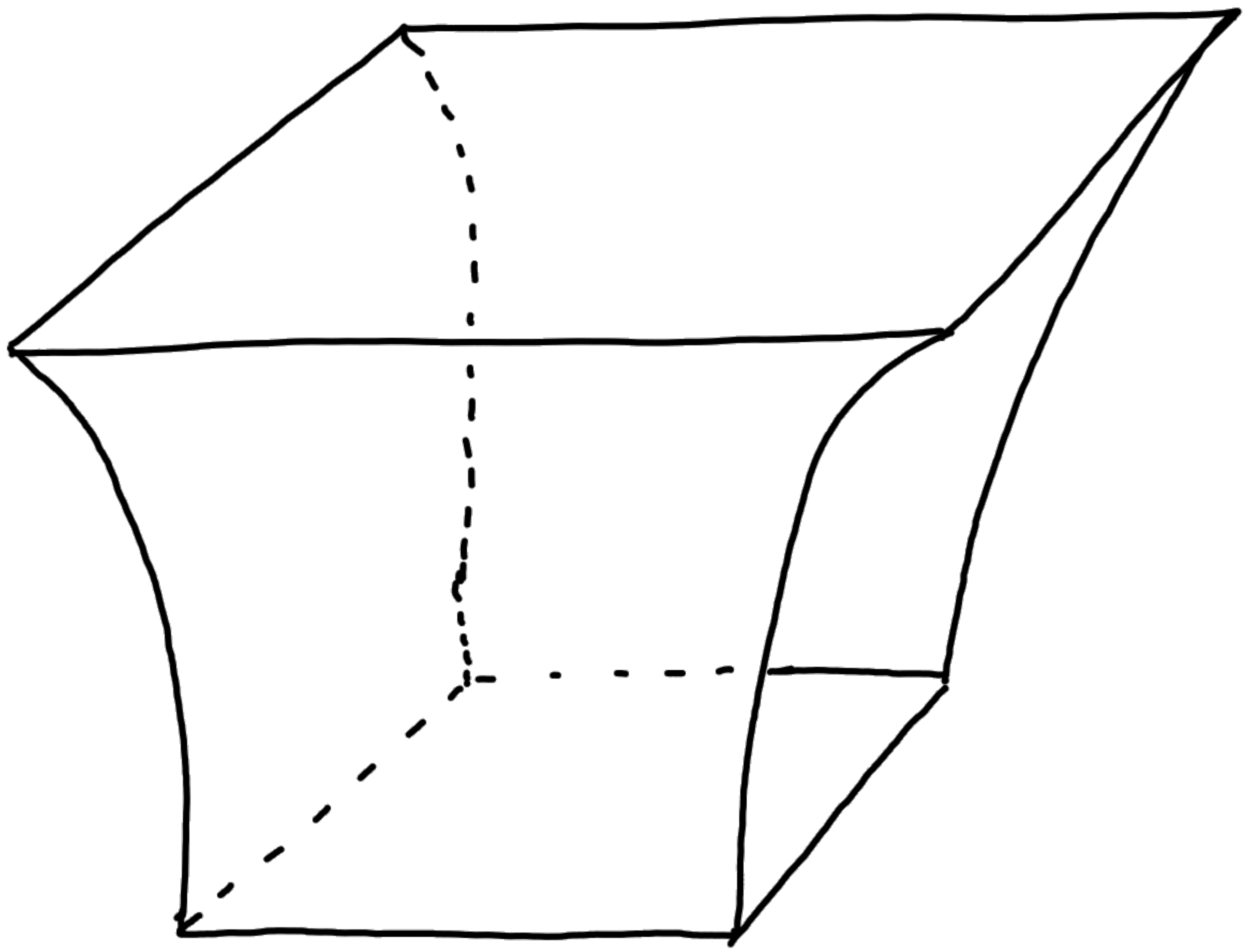
$SU(N) \quad QFT_d$

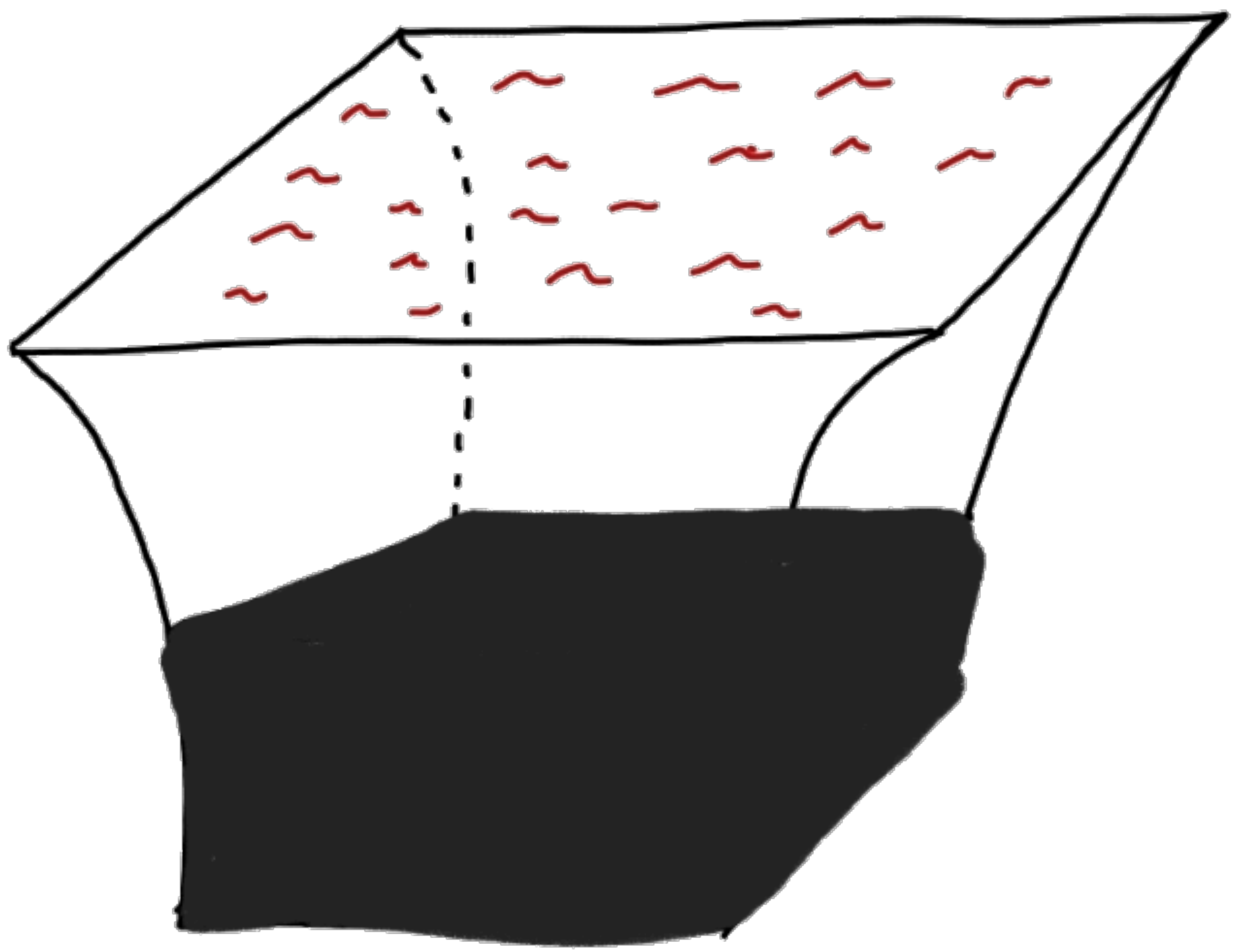
$N \gg 1 \quad \lambda \gg 1$

$\Updownarrow$

Classical Gravity in AdS_{d+1}







$$S = \mathcal{O}(N^0)$$

Confined

$$S/N^2 \sim 0$$

$$S = \mathcal{O}(N^2)$$

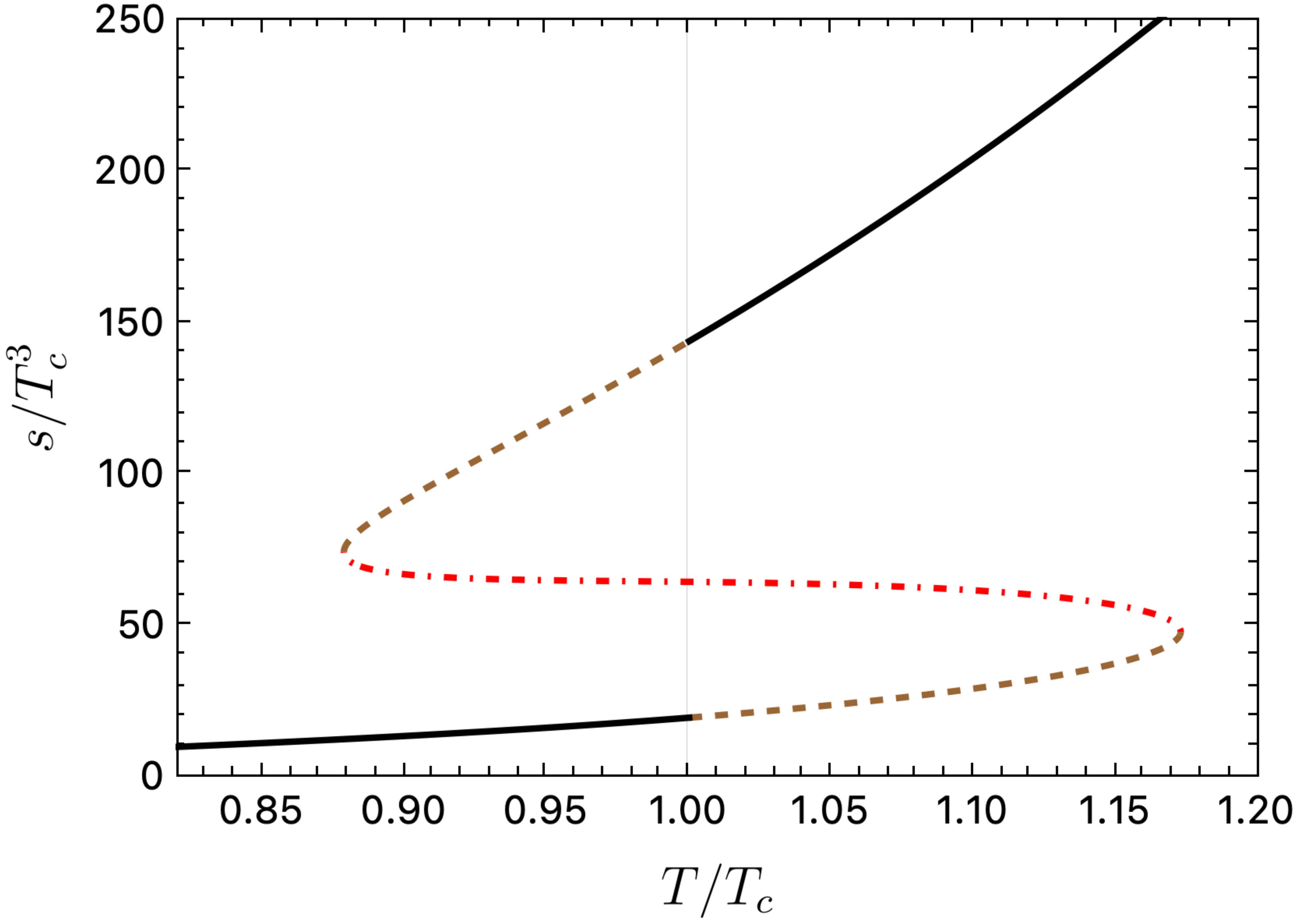
Deconfined

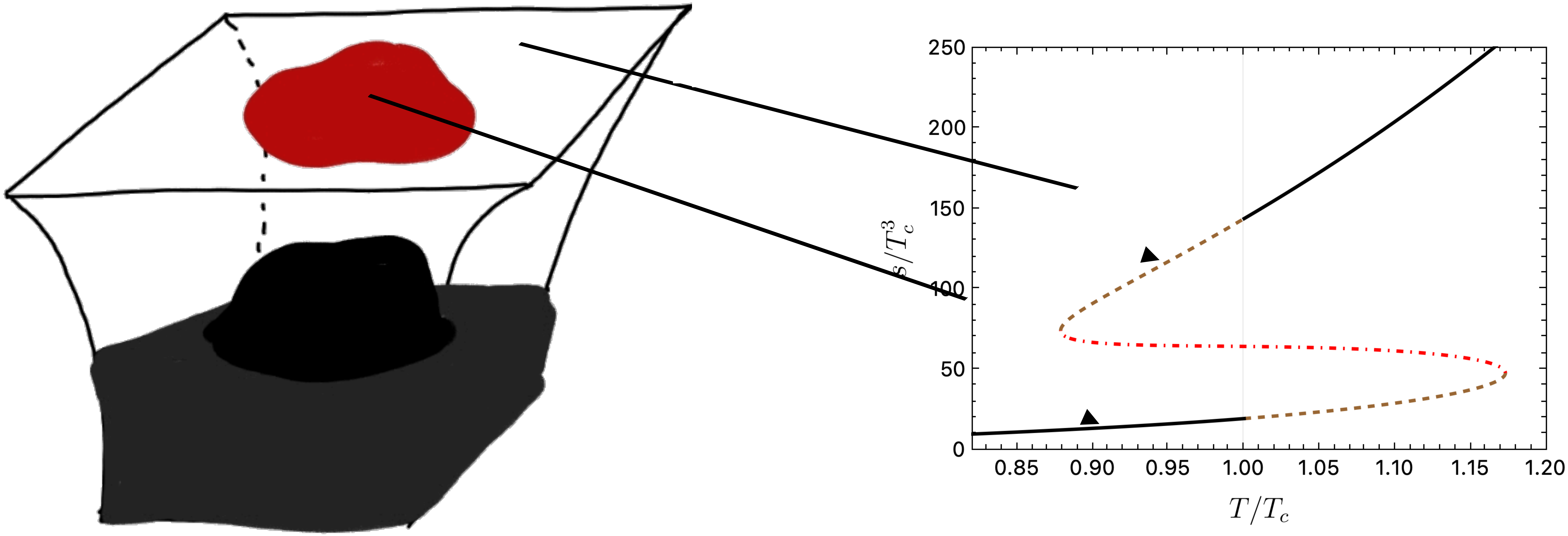
$$S/N^2 \sim 1$$

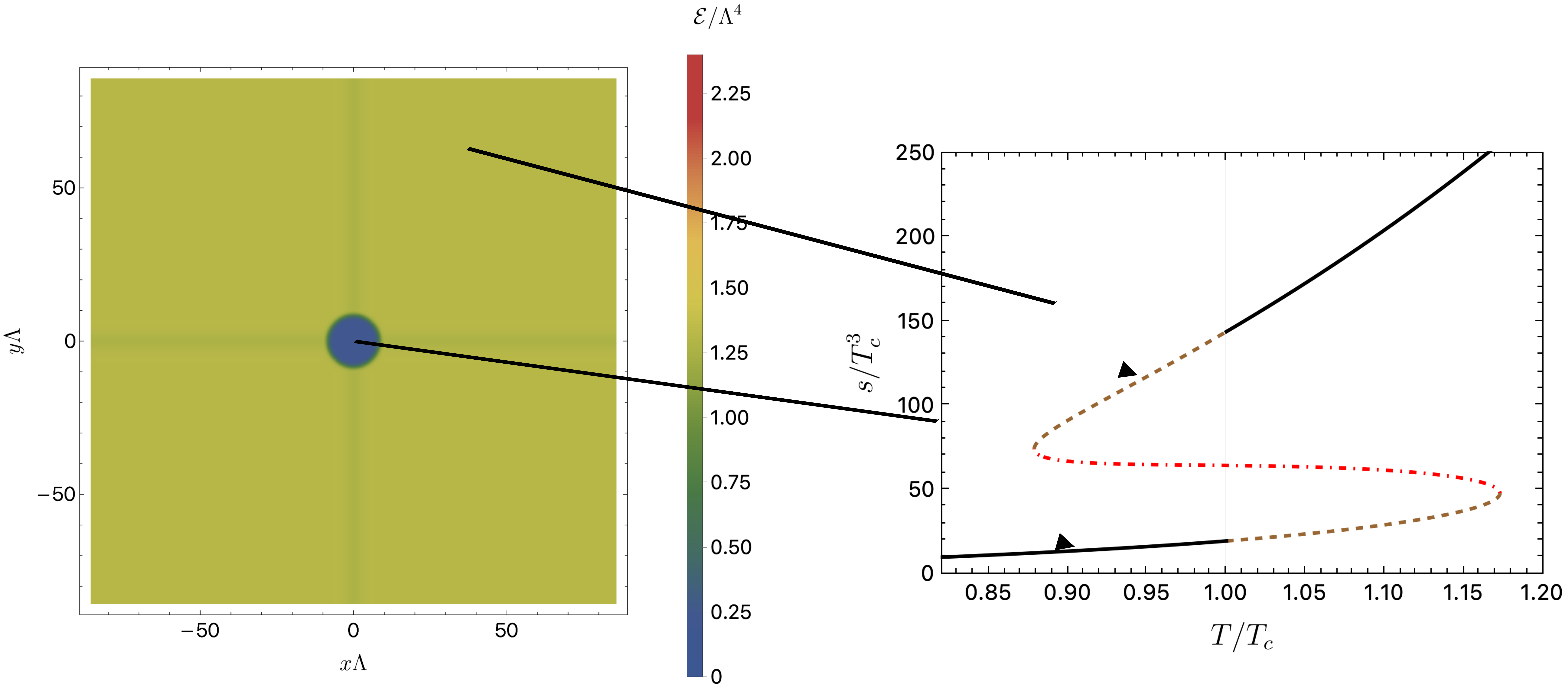
$$I = \frac{1}{\kappa_5^2} \int d^5x \left(R - \frac{1}{2} \nabla\phi^2 - V(\phi) \right)$$

Breaks conformal invariance

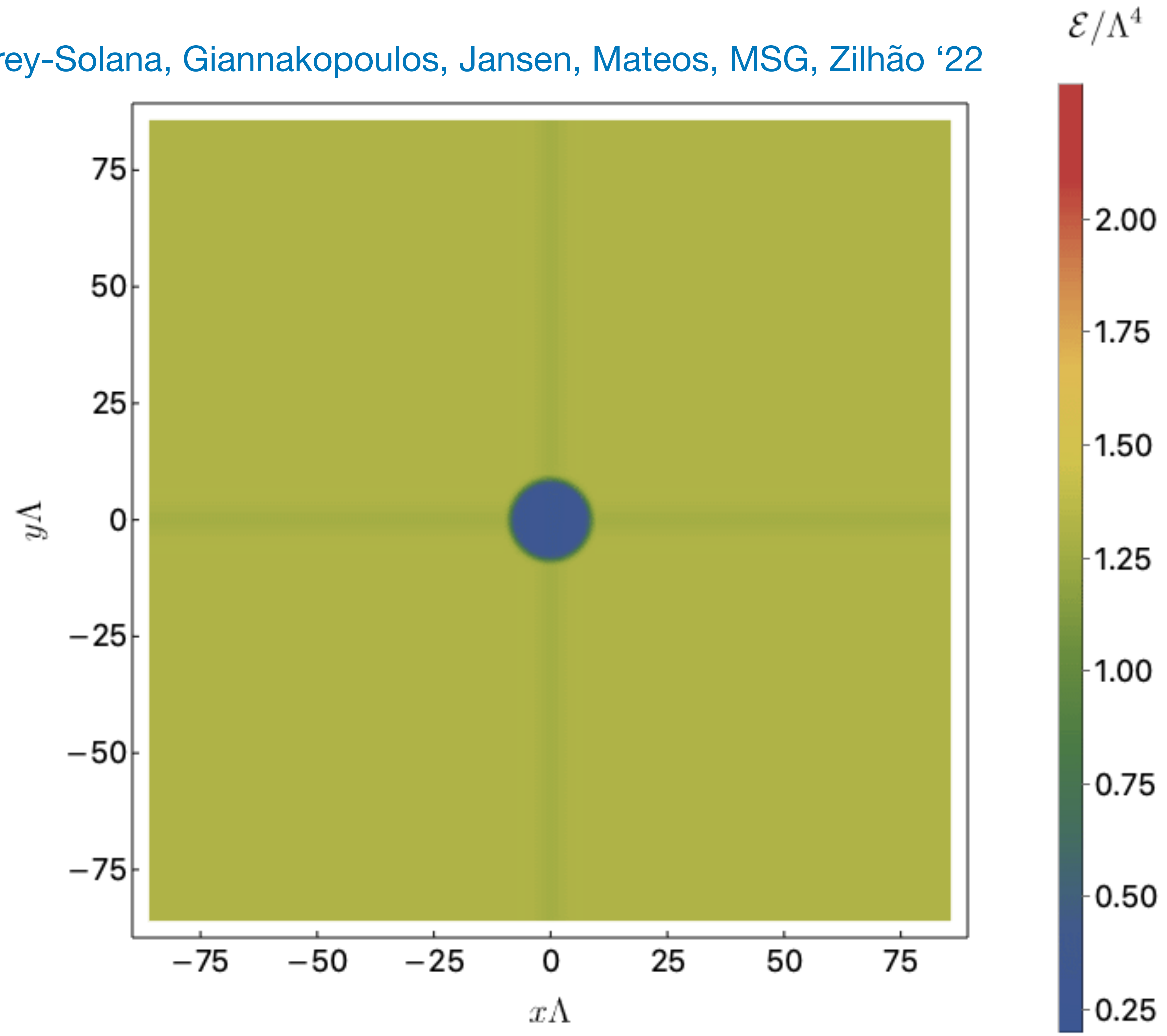
Bea, Mateos '18




250
200
150
100
50
0
s/T_c^3
0.85
0.90
0.95
1.00
1.05
1.10
1.15
1.20
T/T_c


$\mathcal{E}/\Lambda^4$
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0
$y\Lambda$
50
0
−50
−50
0
50
$x\Lambda$
s/T_c^3
250
200
150
100
50
0
0.85
0.90
0.95
1.00
1.05
1.10
1.15
1.20
T/T_c

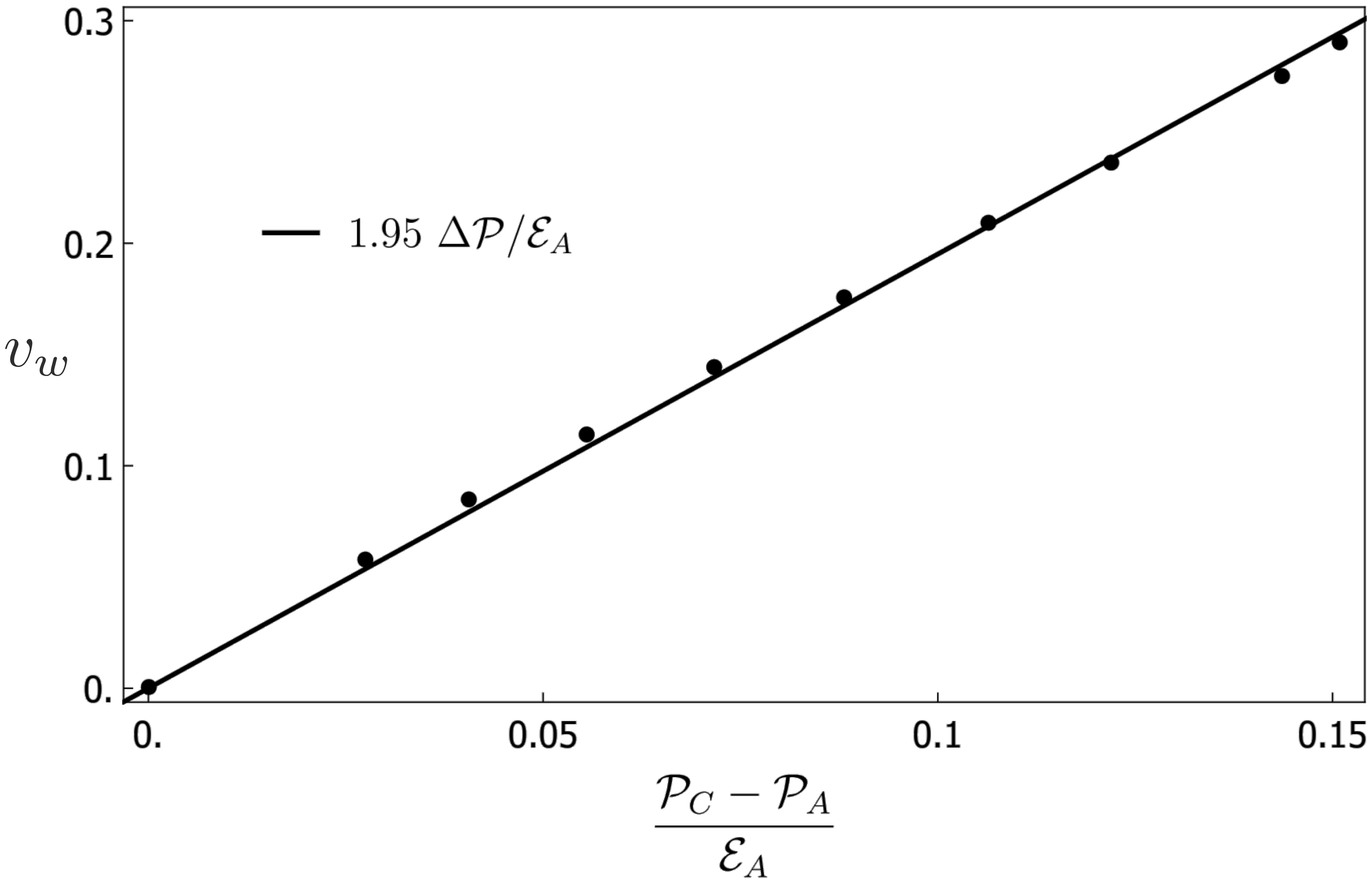
Bea, Casalderrey-Solana, Giannakopoulos, Jansen, Mateos, MSG, Zilhão ‘22



Wall velocity at strong coupling

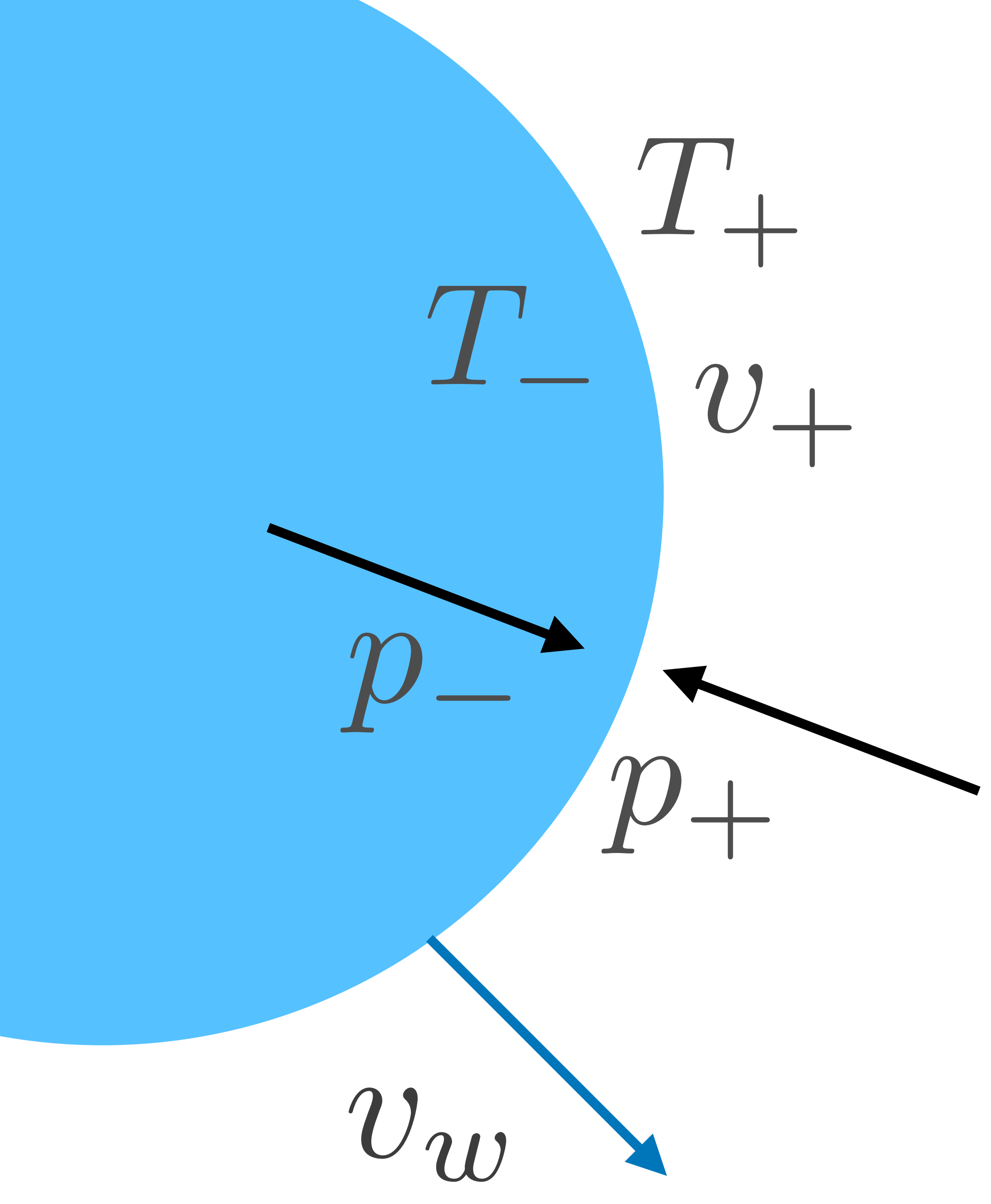
- Possible linear or simple relation?
- Why so small speeds? Strong coupling?
- Why only deflagrations (subsonic)?

Bea, Casalderrey-Solana, Giannakopoulos, Mateos, MSG, Zilhão '21



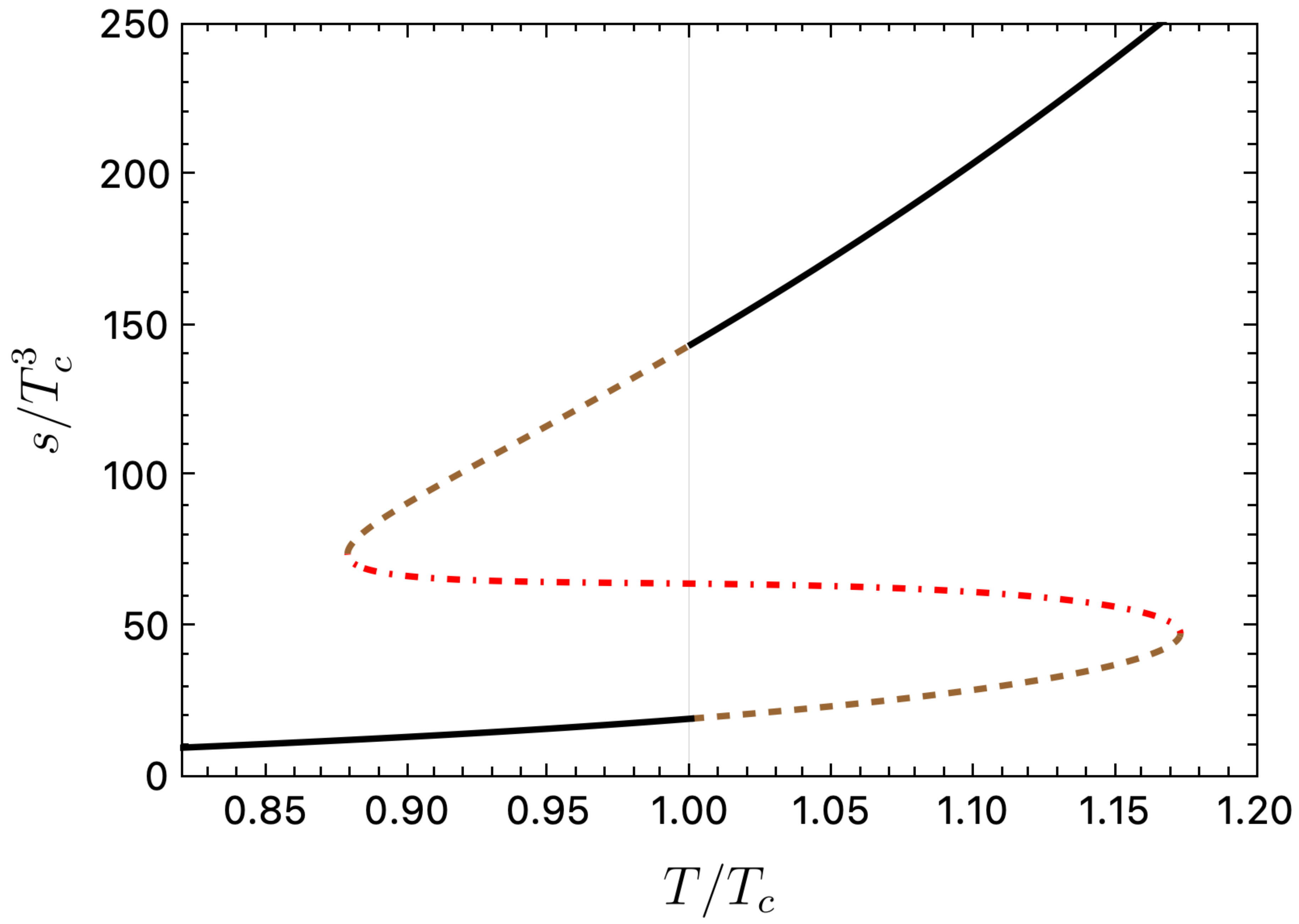
Large jump in d.o.f.

Janik, Jarvinen, Soltanpanahi, Sonnenschein ’22
MSG, van de Vis ‘23



Matching conditions at the wall

$$v_+ v_- = \frac{p_+ - p_-}{e_+ - e_-}, \qquad \frac{v_+}{v_-} = \frac{e_- + p_+}{e_+ - p_-}$$



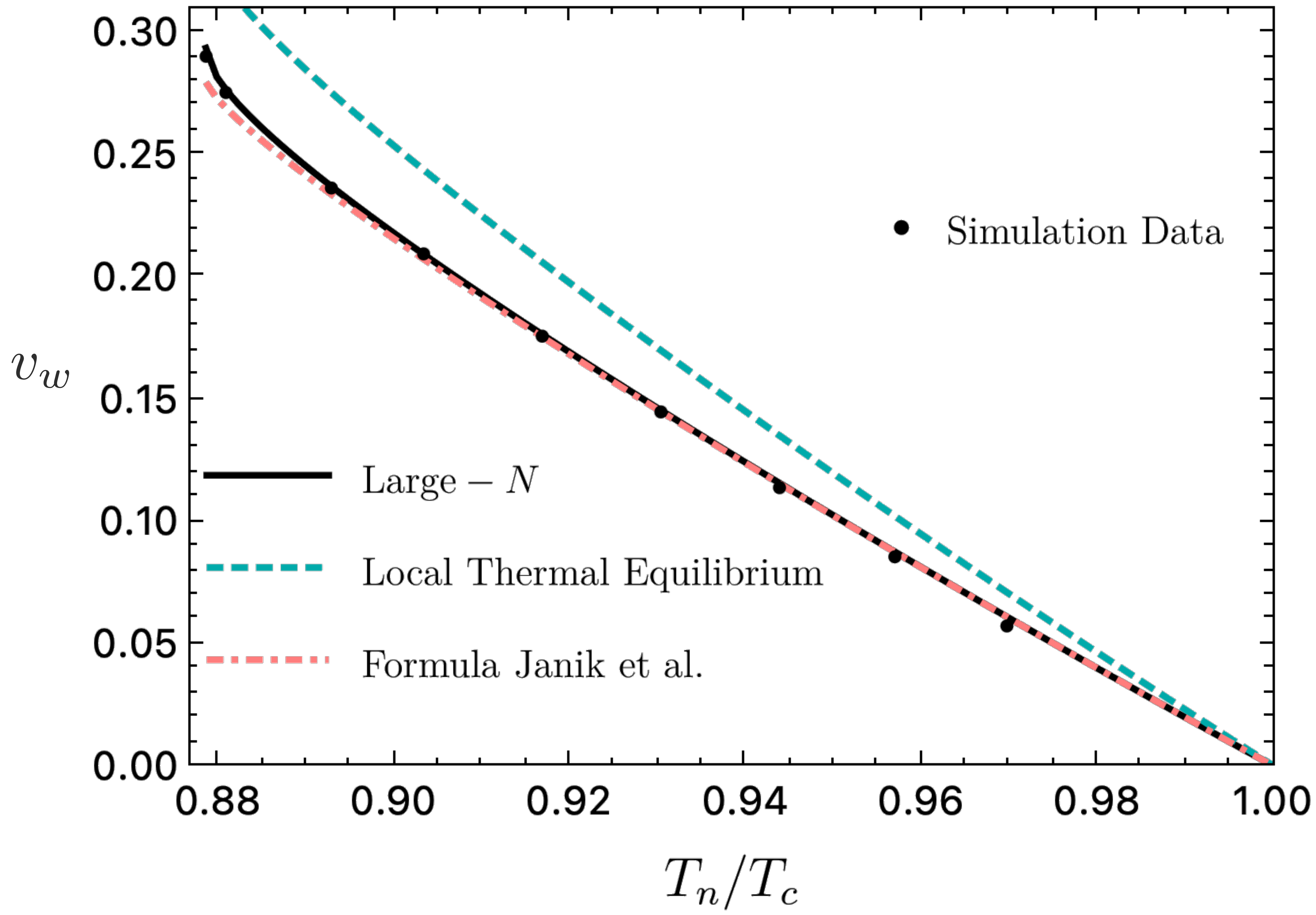
Cannot be fulfilled unless

$$T_+ = T_c, \quad v_+ = 0$$

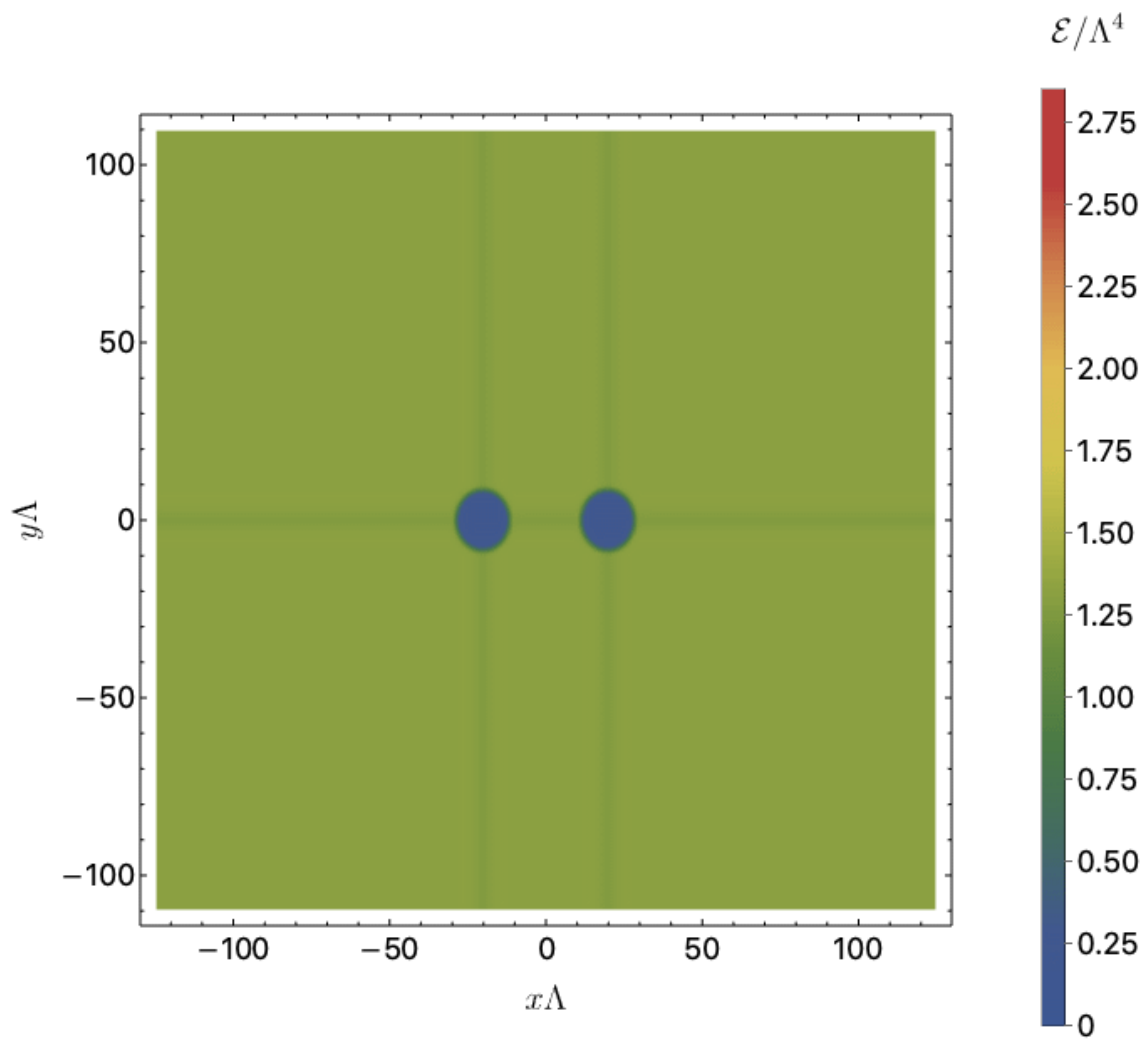
Solve hydro equations $v_w(T_n)$

Wall speed in the large jump of d.o.f

MSG, van de Vis ‘23



Very good results even if $N \sim 3$



$\mathcal{E}/\Lambda^4$
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0
100
50
0
−50
−100
$y\Lambda$
−100
−50
0
50
100
$x\Lambda$

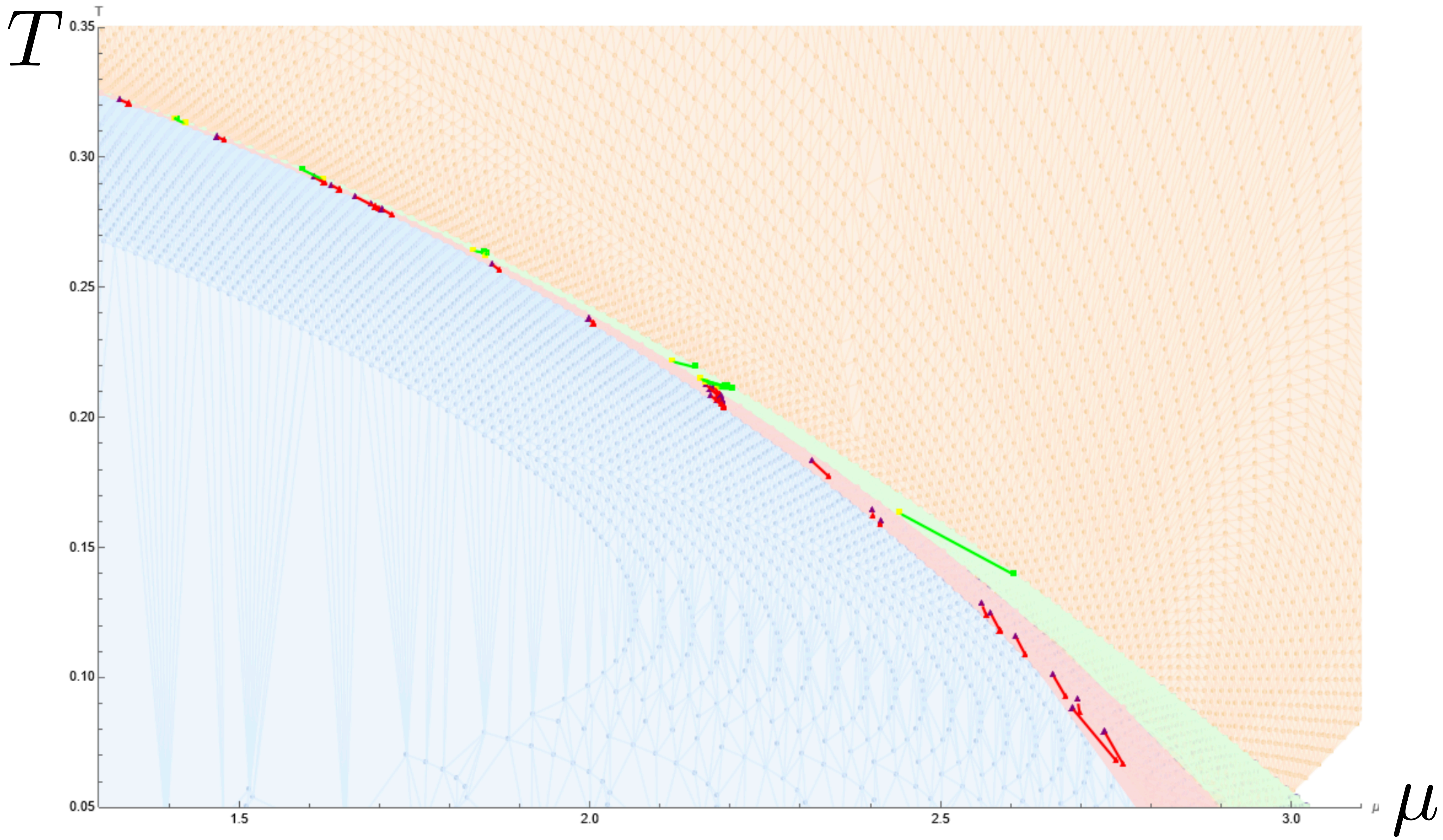
Towards Neutron Stars

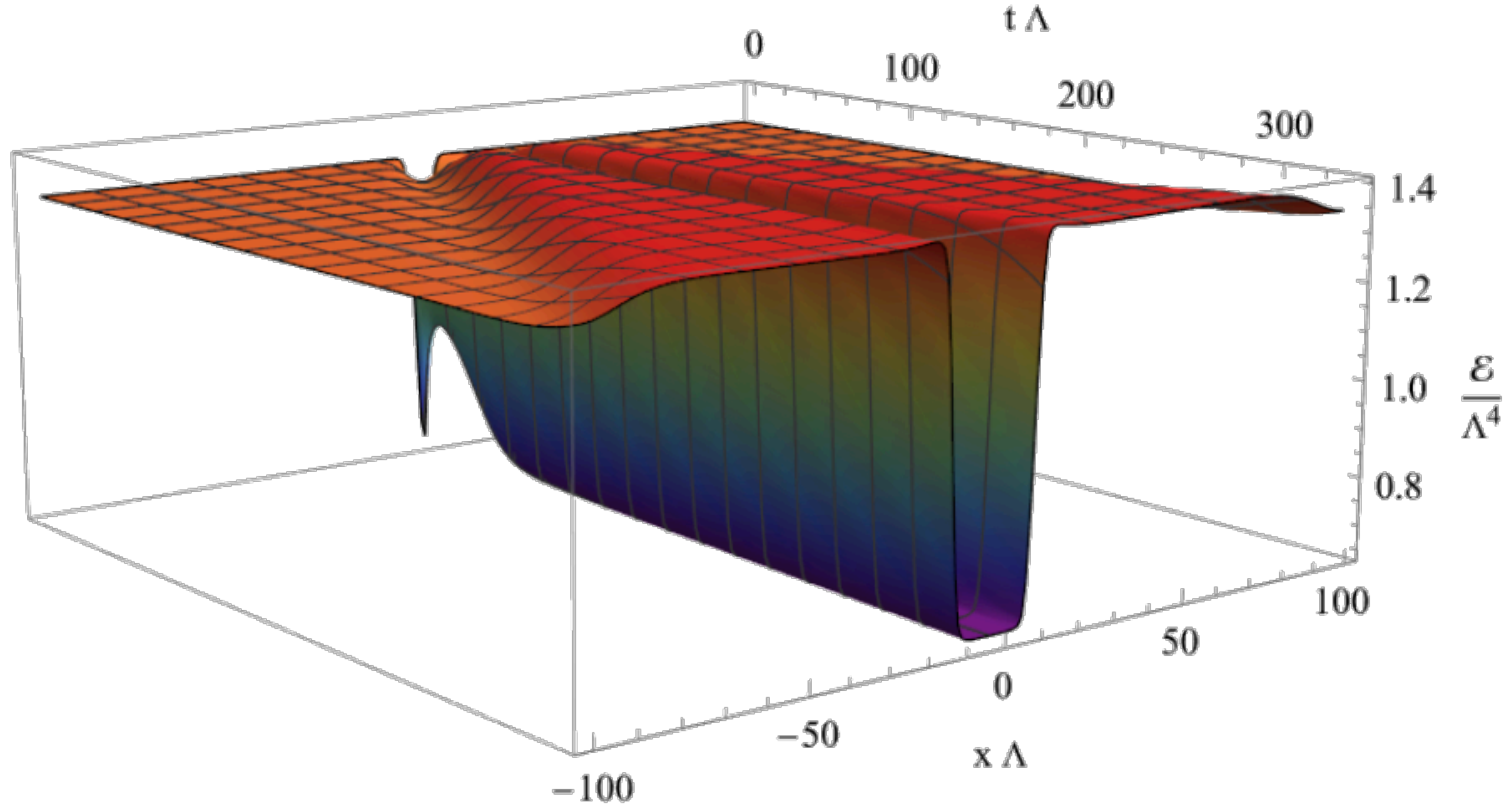
With Giliberti, Serantes

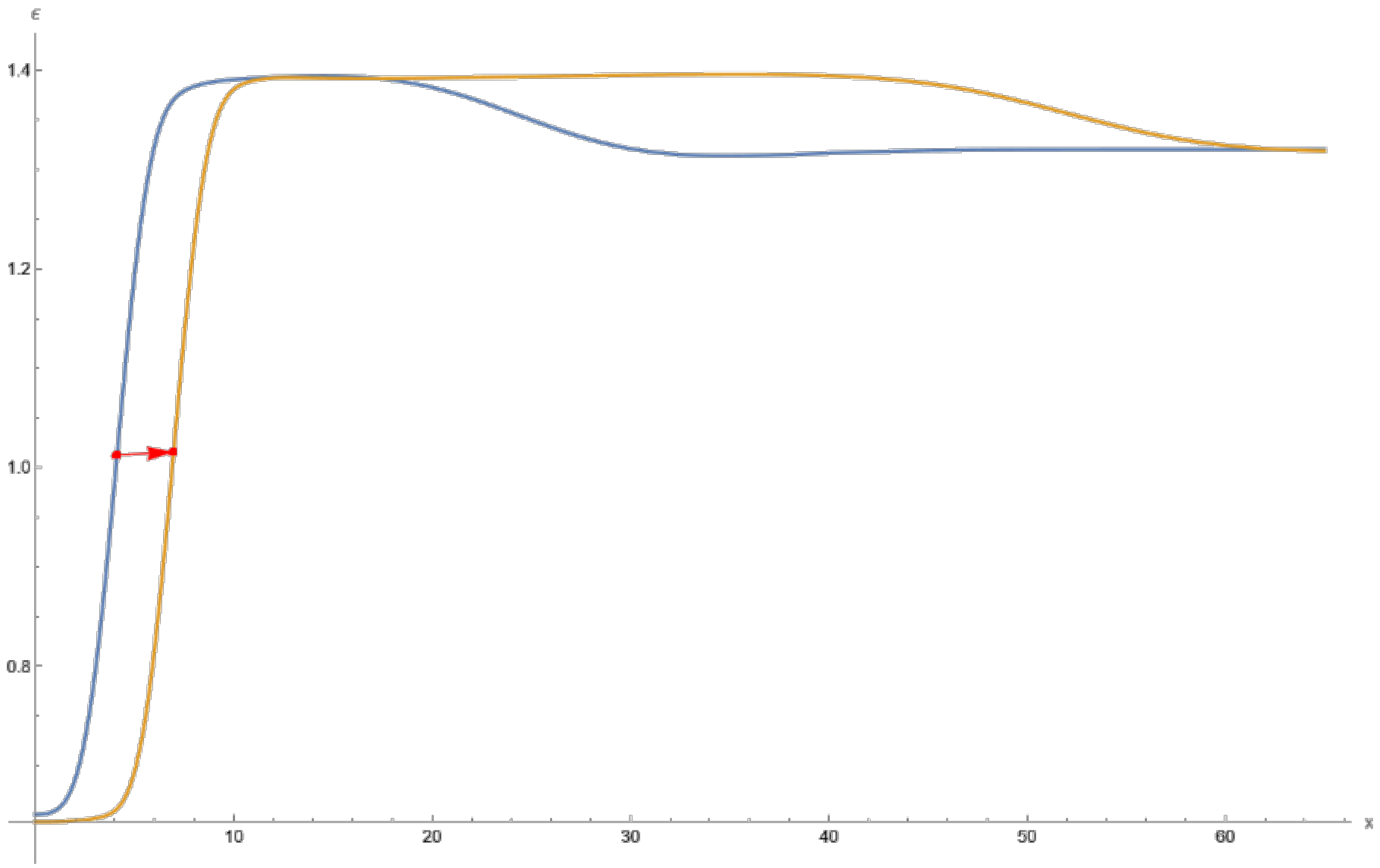
$$I = \frac{1}{\kappa_5^2}\int d^5x\sqrt{-g}\left(R - \frac{1}{2}\nabla\phi^2 - V(\phi) - f(\phi)F^2\right)$$

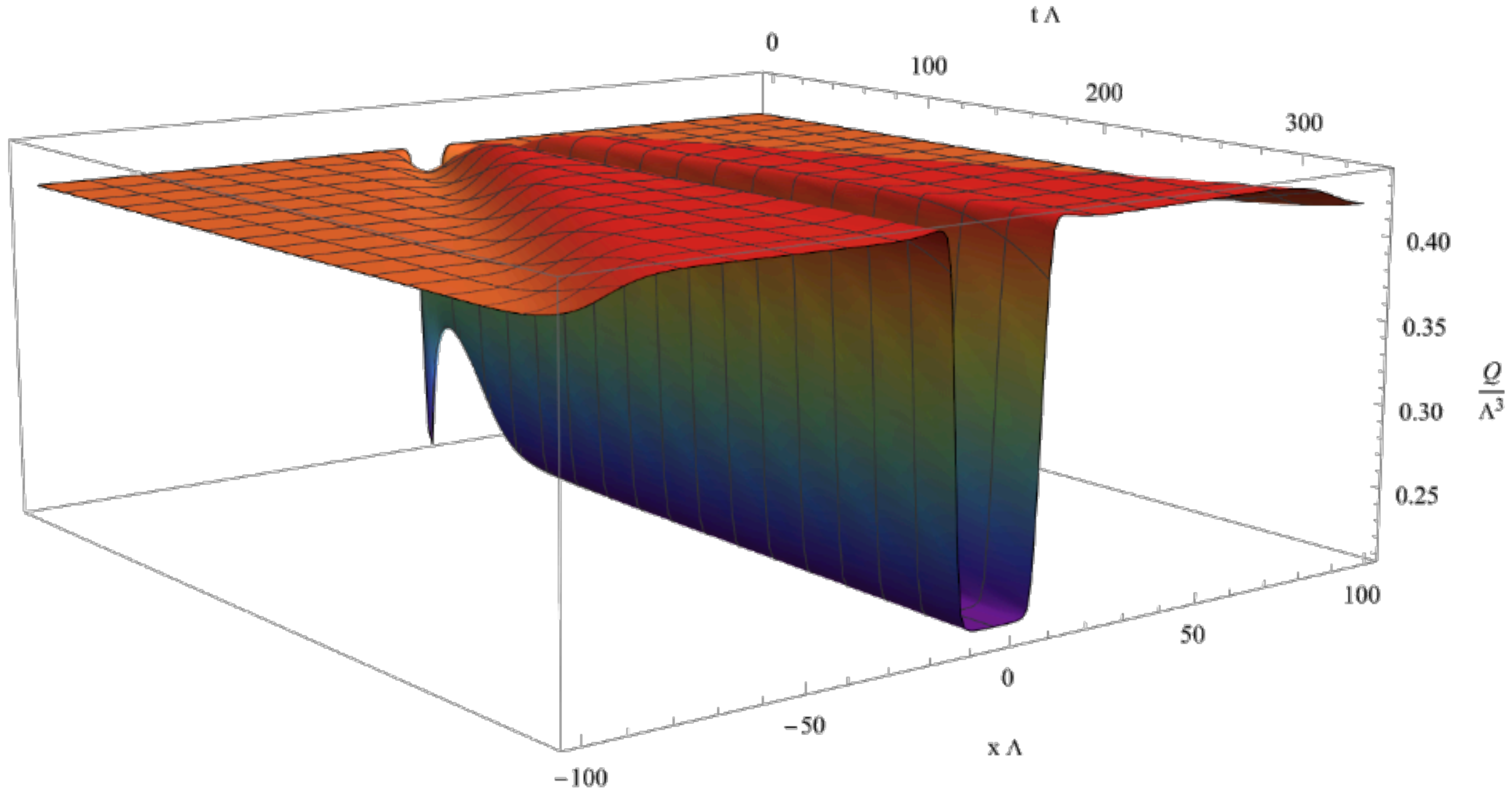
Breaks conformal invariance

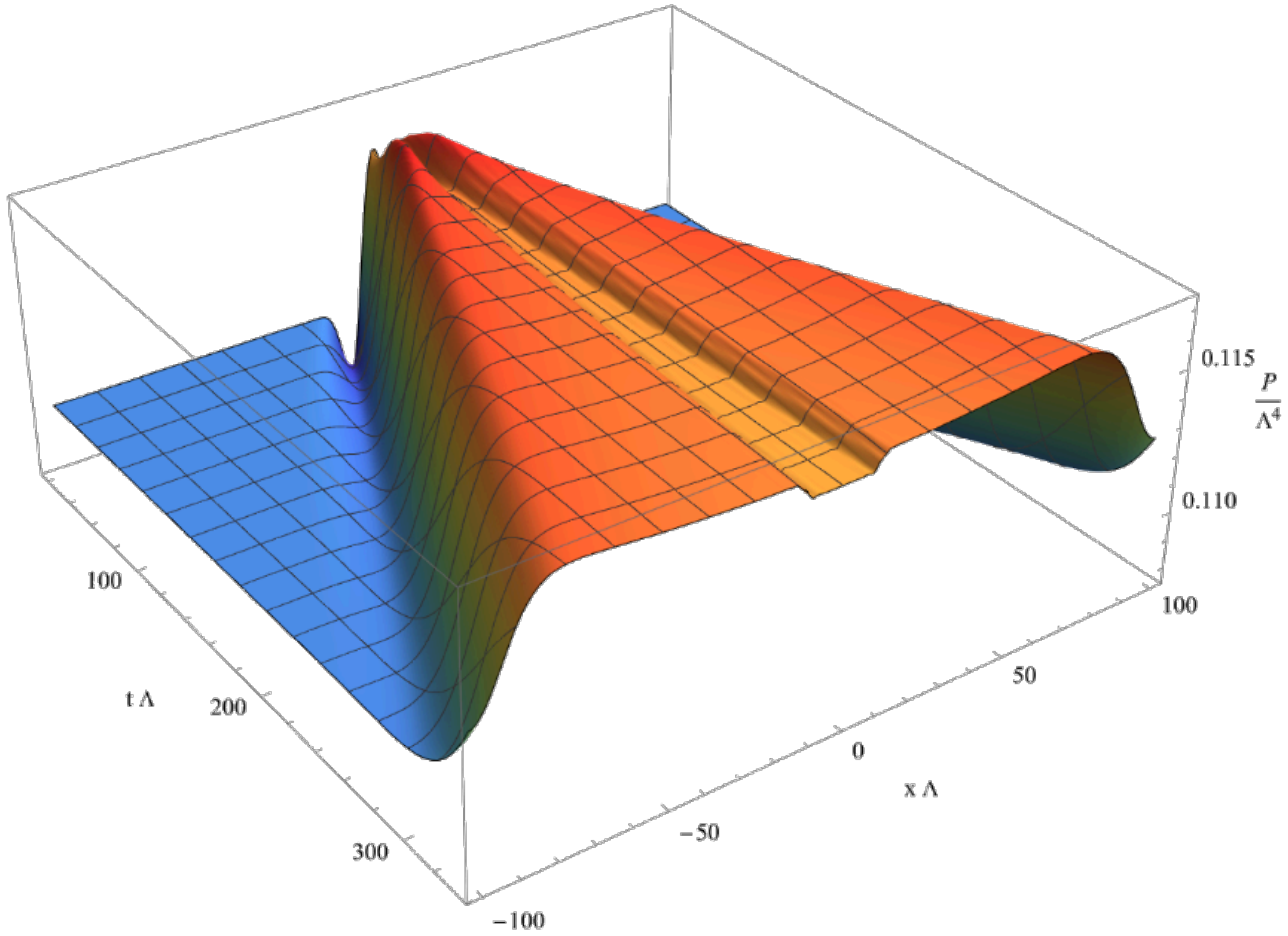
Finite density




t Λ
0
100
200
300
1.4
1.2
1.0
0.8
$\frac{\mathcal{E}}{\Lambda^4}$
100
50
0
−50
−100
x Λ


ϵ
1.4
1.2
1.0
0.8
10
20
30
40
50
60
x


t Λ
0
100
200
300
0.40
0.35
0.30
0.25
$\frac{\mathcal{Q}}{\Lambda^3}$
100
50
0
−50
−100
x Λ


0.115
0.110
$\frac{P}{\Lambda^4}$
100
t Λ
200
300
100
50
0
x Λ
−50
−100

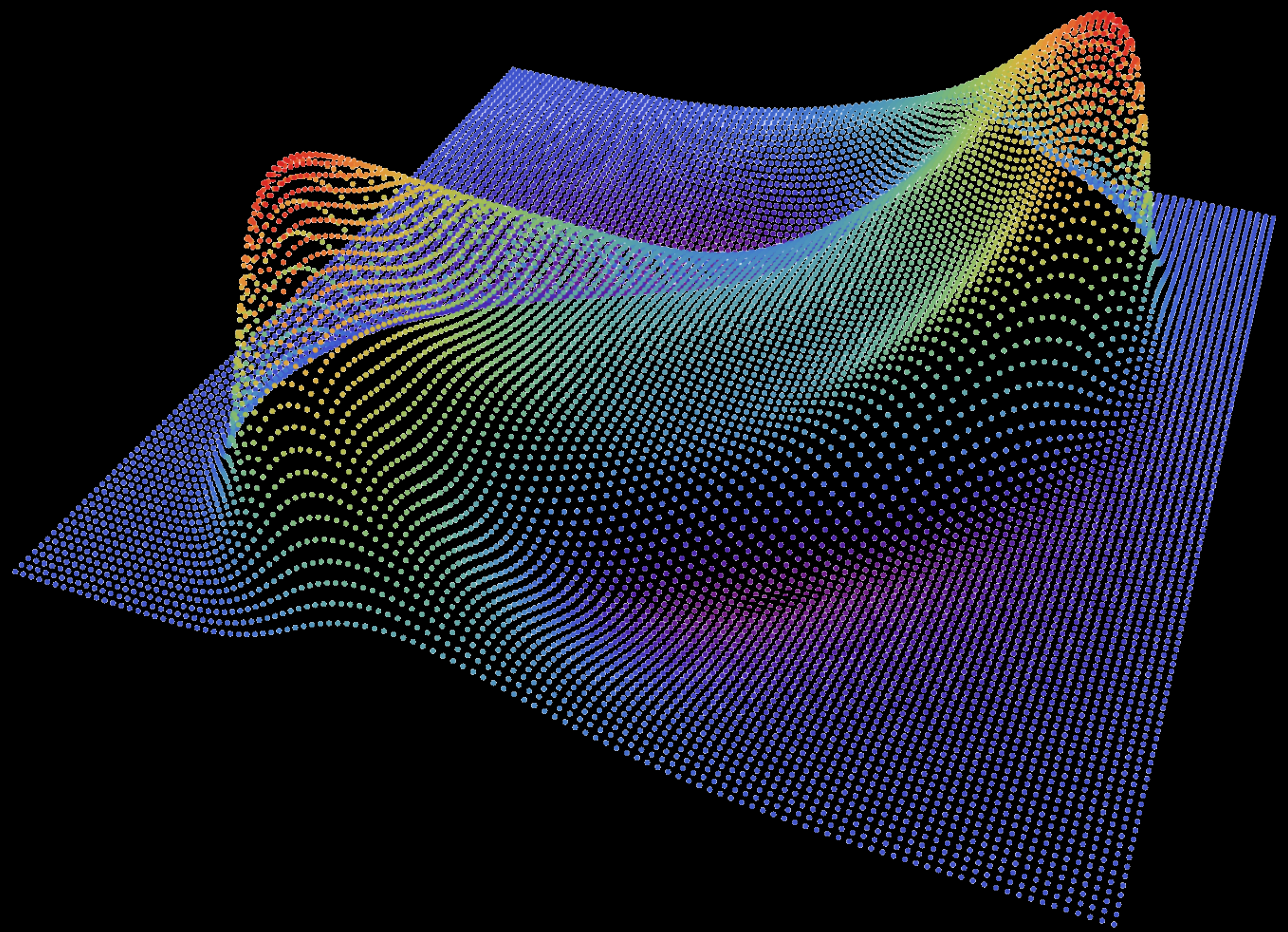
Holographic bubbles

- Wall speed at finite density
- Any approximate way of understanding the behaviour (large jump of d.o.f.)?
- Collisions of several bubbles: sources of emission and phase separation
- Check possible effective descriptions

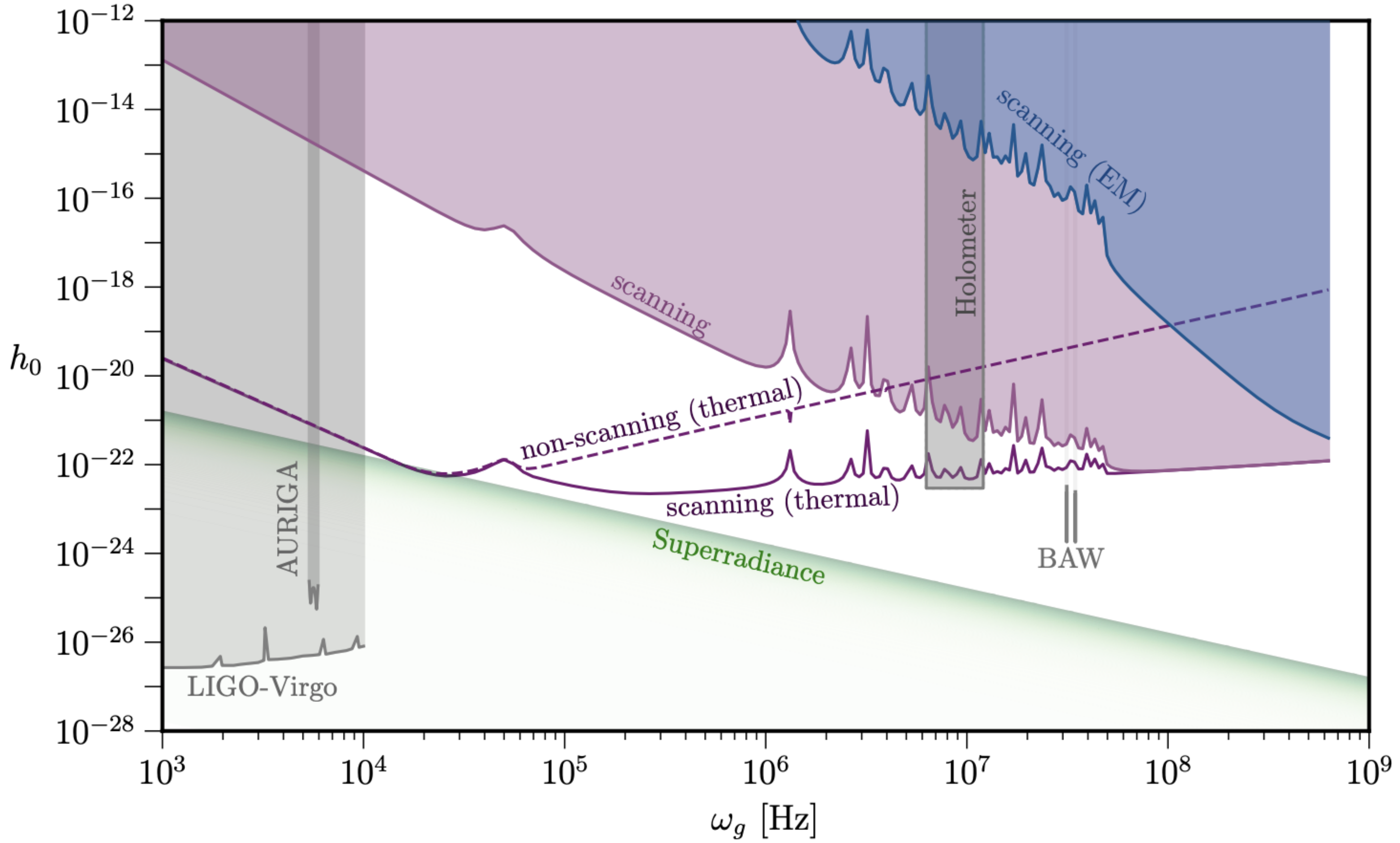
Conclusions

- FOPT in neutron star mergers implies a signal in the MHz band
- Only astrophysical source (with SM) giving rise to an emission in the MHz
- Bigger constraints from hydrodynamics on superheated bubbles
- Hydro + scalar field effective description may break down at strong coupling
- Holography to understand bubble dynamics in strongly coupled and dense mediums

Thank you!

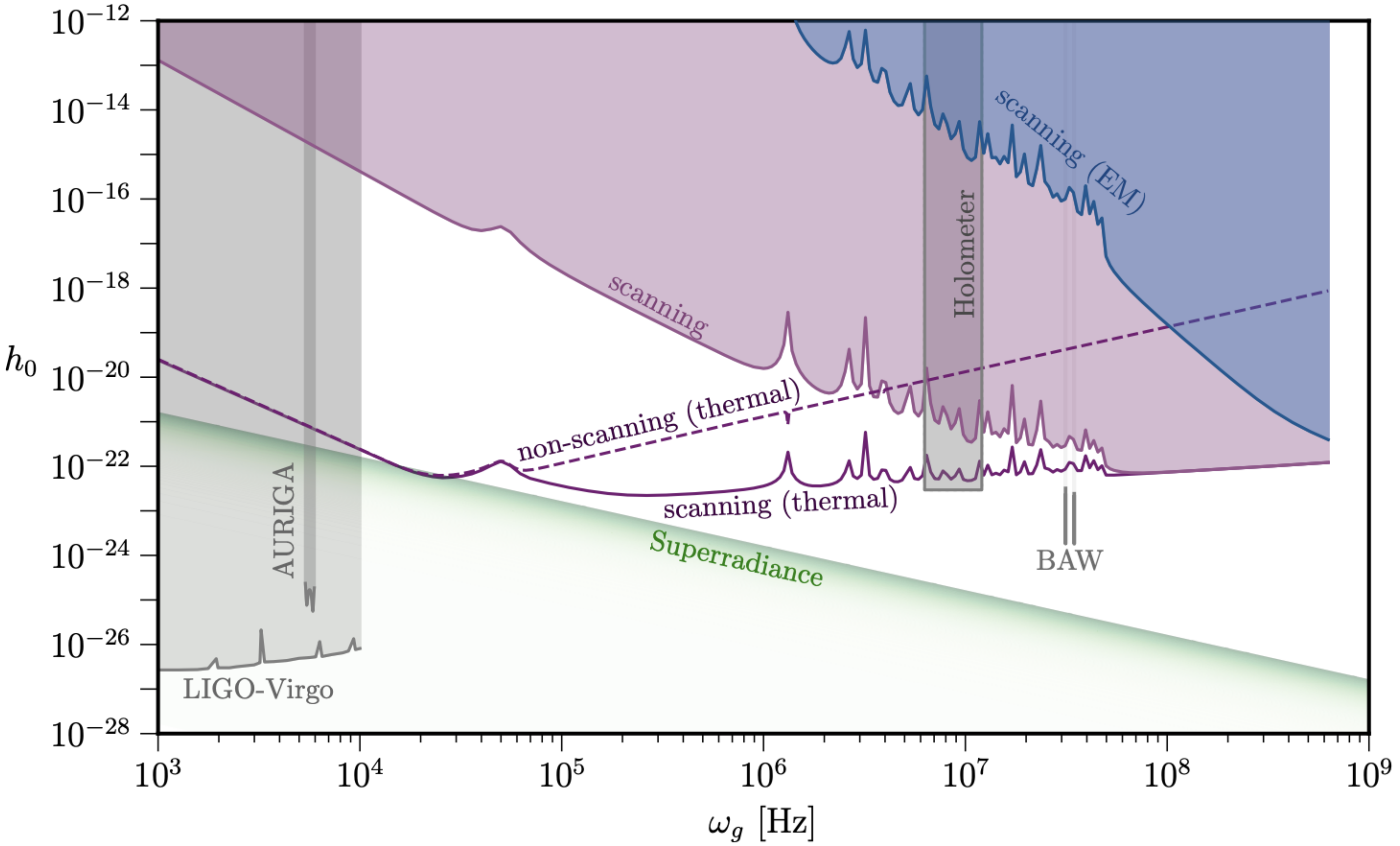


$$h_c \simeq 2.6 \times 10^{-25} v_f^2 \left(\frac{\Lambda^4}{1\ \mathrm{GeV/fm^3}}\right)\left(\frac{L}{1\ \mathrm{km}}\right)^{3/2}\left(\frac{1\ \mathrm{MHz}}{f_{\mathrm{peak}}}\right)^{3/2}\left(\frac{100\ \mathrm{Mpc}}{d}\right)$$



Berlin et al '23

$$h_c^{\text{obs}} \sim 10^{-24} v_f^2 \left(\frac{100\text{Mpc}}{d} \right)$$



Berlin et al '23

Self similar equations

$$\gamma^2(1-\xi v)\left(\frac{\nu(\xi,v)^2}{c_s^2}-1\right)\partial_\xi v=(d-1)\frac{v}{\xi}\,,$$

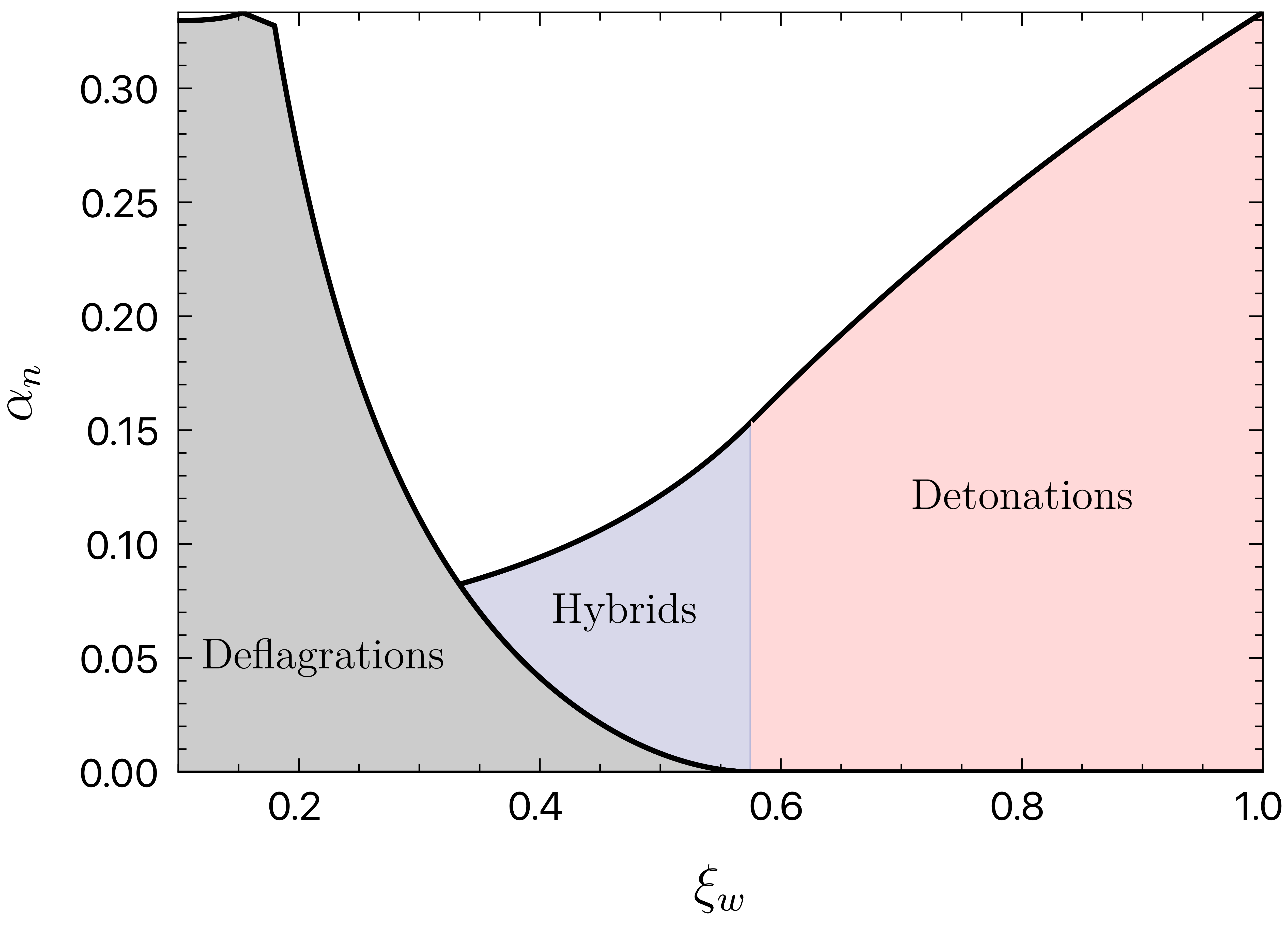
$$\xi = r/t$$

$$\frac{\partial_\xi w}{w}=\gamma^2\left(1+\frac{1}{c_s^2}\right)\nu(\xi,v)\partial_\xi v\,,$$

$$\frac{\partial_\xi n}{n}=\frac{1}{1+c_s^2}\frac{\partial_\xi w}{w}\,,$$

$$\nu(\xi,v)=\frac{\xi-v}{1-v\xi}$$

Study all possible flows for a constant c_s


Deflagrations
Hybrids
Detonations
α_n
ξ_w
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.2
0.4
0.6
0.8
1.0

$$h_c^{\mathrm{obs}} \sim \frac{L^{3/2}\Lambda^4 v_f^2}{f^{3/2} d}$$

$$h_c \simeq 2.6 \times 10^{-25} v_f^2 \left(\frac{\Lambda^4}{1\ \mathrm{GeV/fm^3}}\right)\left(\frac{L}{1\ \mathrm{km}}\right)^{3/2}\left(\frac{1\ \mathrm{MHz}}{f_{\mathrm{peak}}}\right)^{3/2}\left(\frac{100\ \mathrm{Mpc}}{d}\right)$$

$$h_c^{\mathrm{obs}} \sim 10^{-24} v_f^2 \left(\frac{100\mathrm{Mpc}}{d}\right)$$

Towards Neutron Stars

$$I = \frac{1}{\kappa_5^2} \int d^5x \sqrt{-g} \left(R - \frac{1}{2}\nabla\phi^2 - V(\phi) - f(\phi)F^2 \right)$$

Breaks conformal invariance

Finite density