

MHz gravitational waves from neutron star mergers

$t = 500.0$

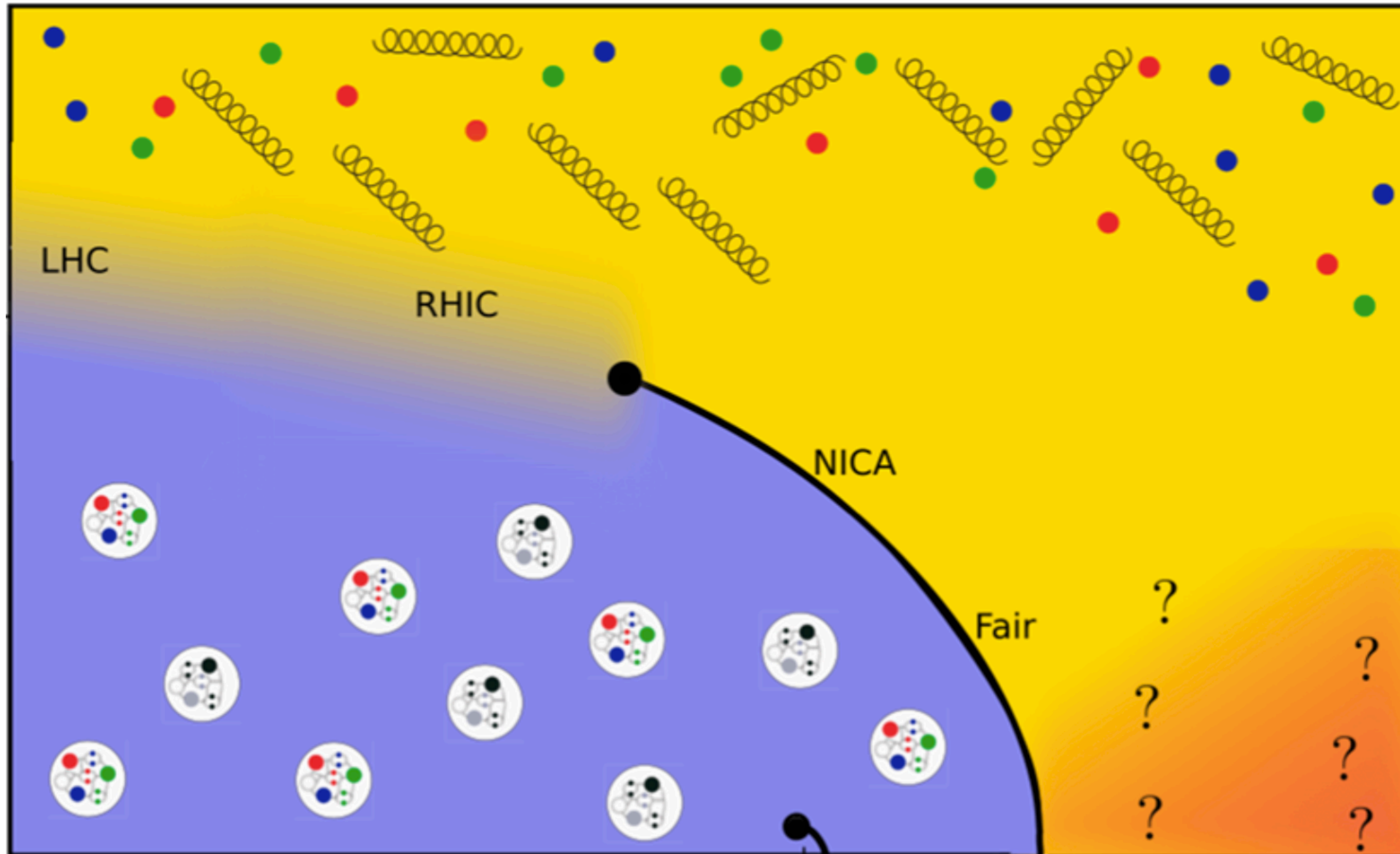
$t = 562.5$

$t = 1000.0$

Mikel Sanchez Garitaonandia

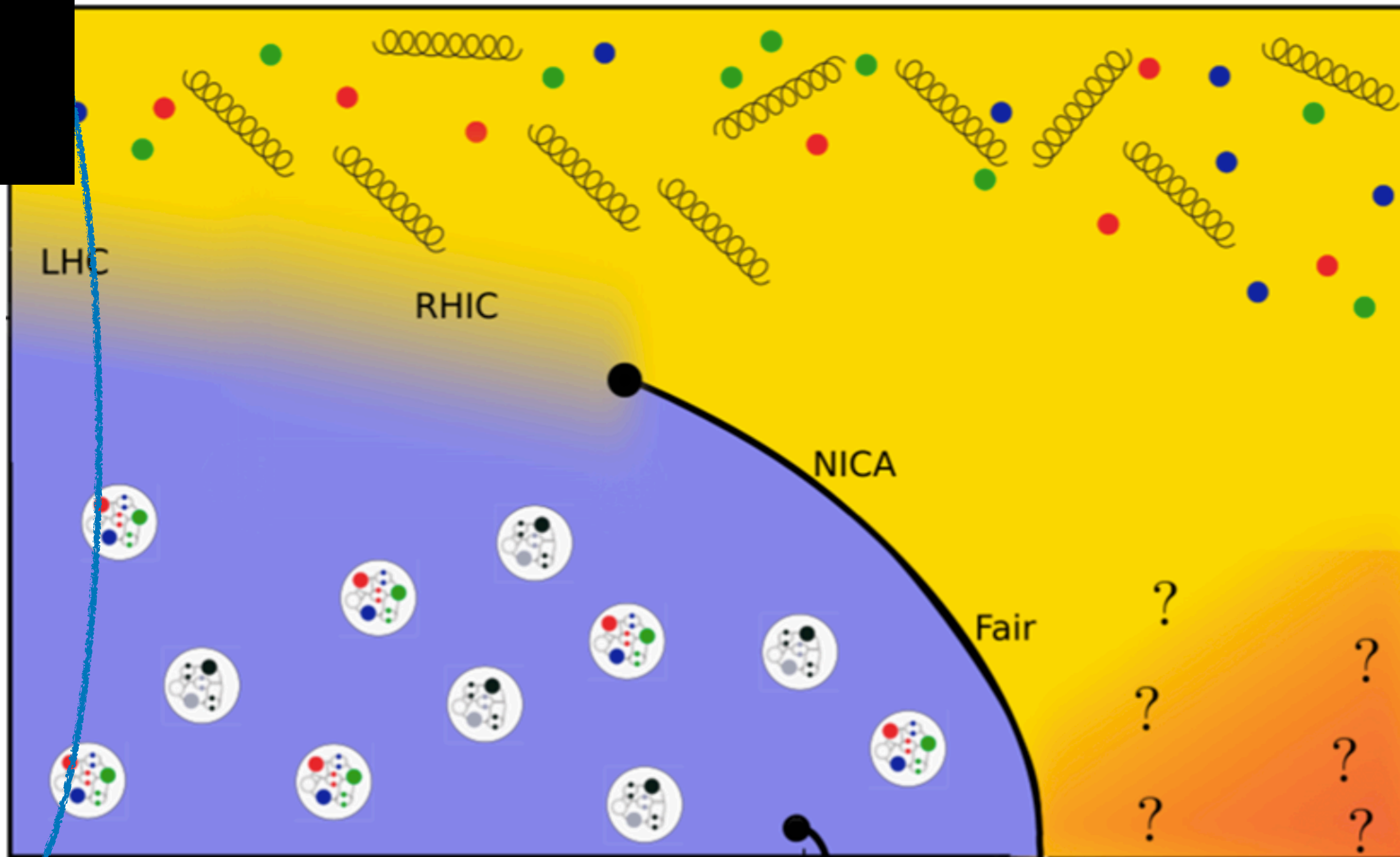
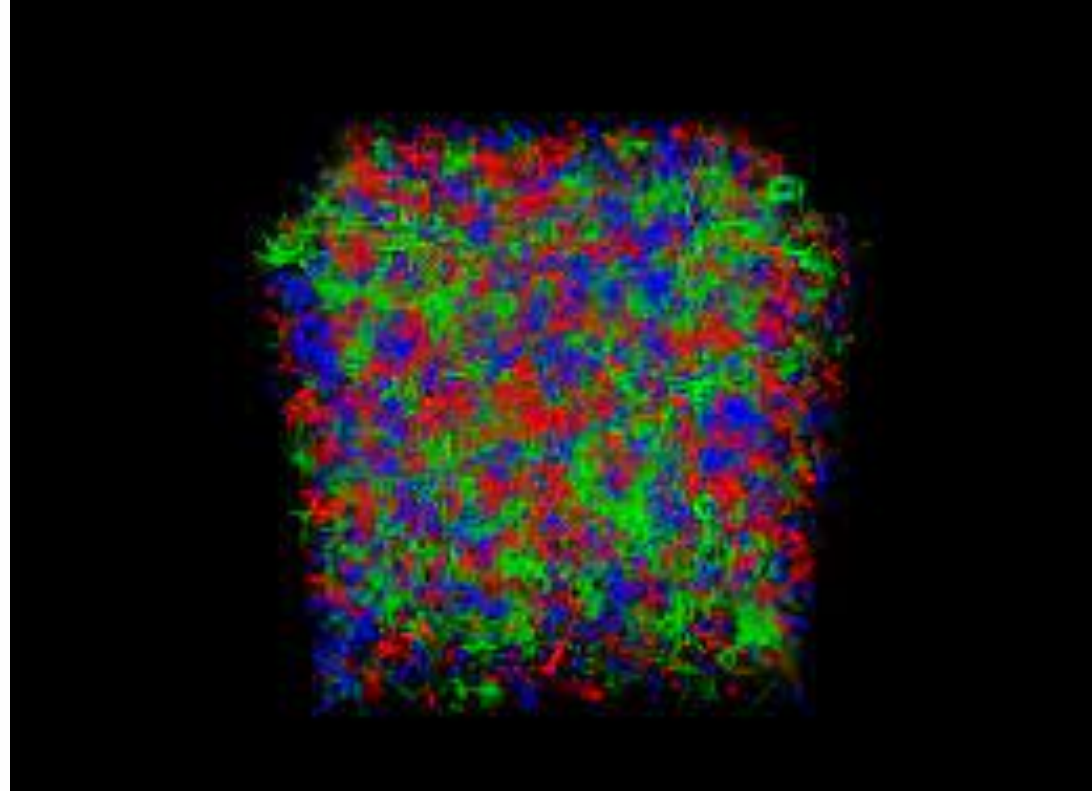


QCD phase diagram



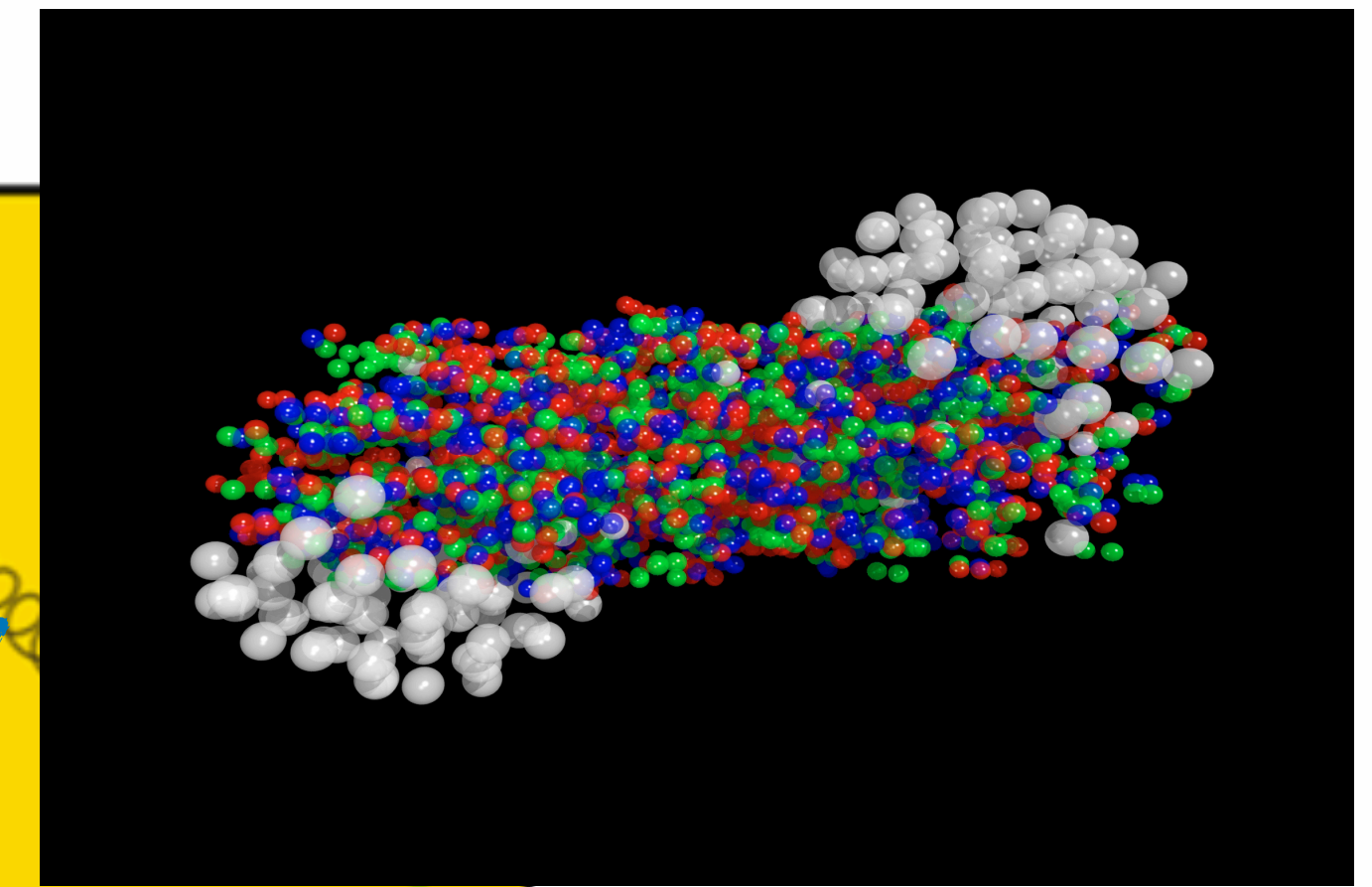
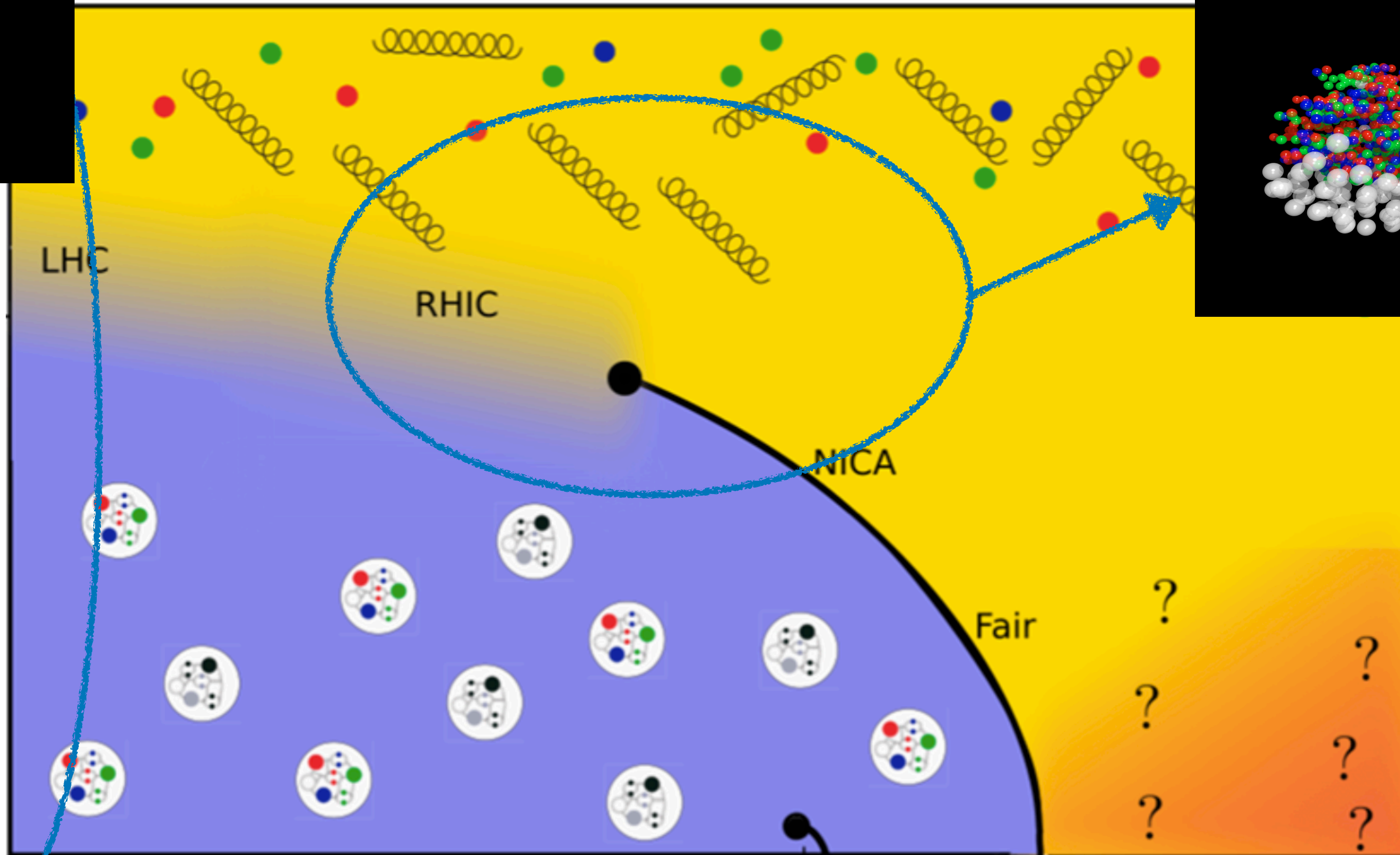
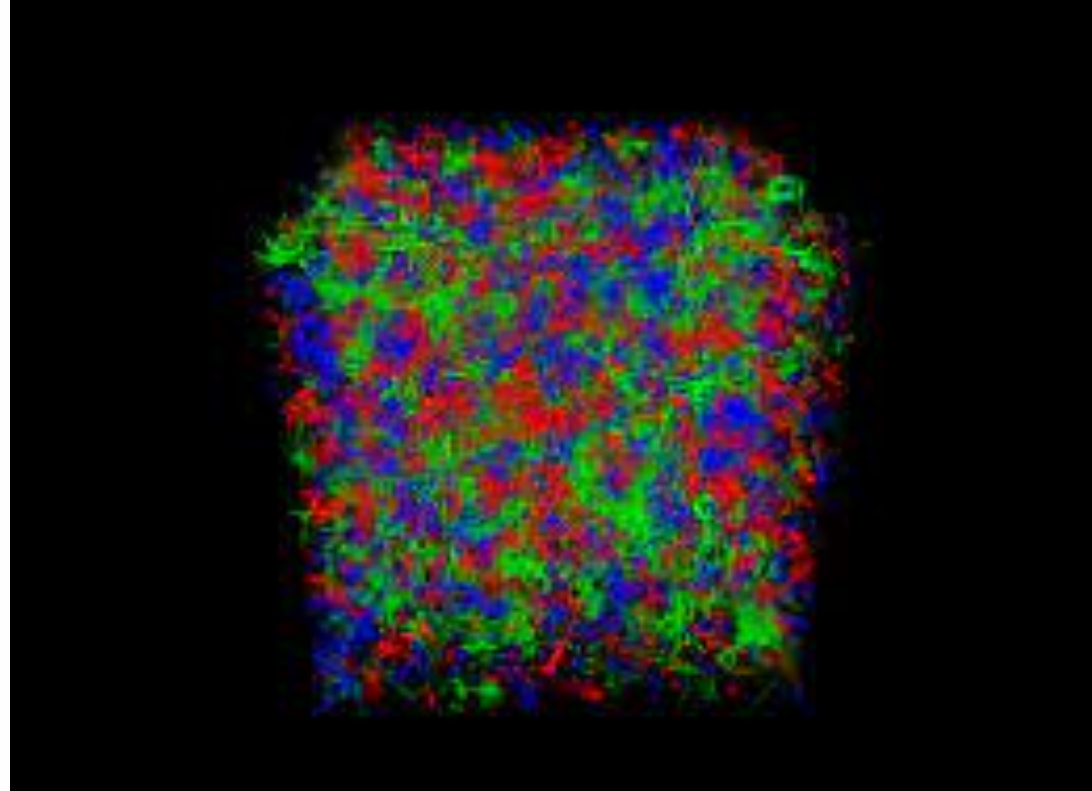
Guenther '21

QCD phase diagram



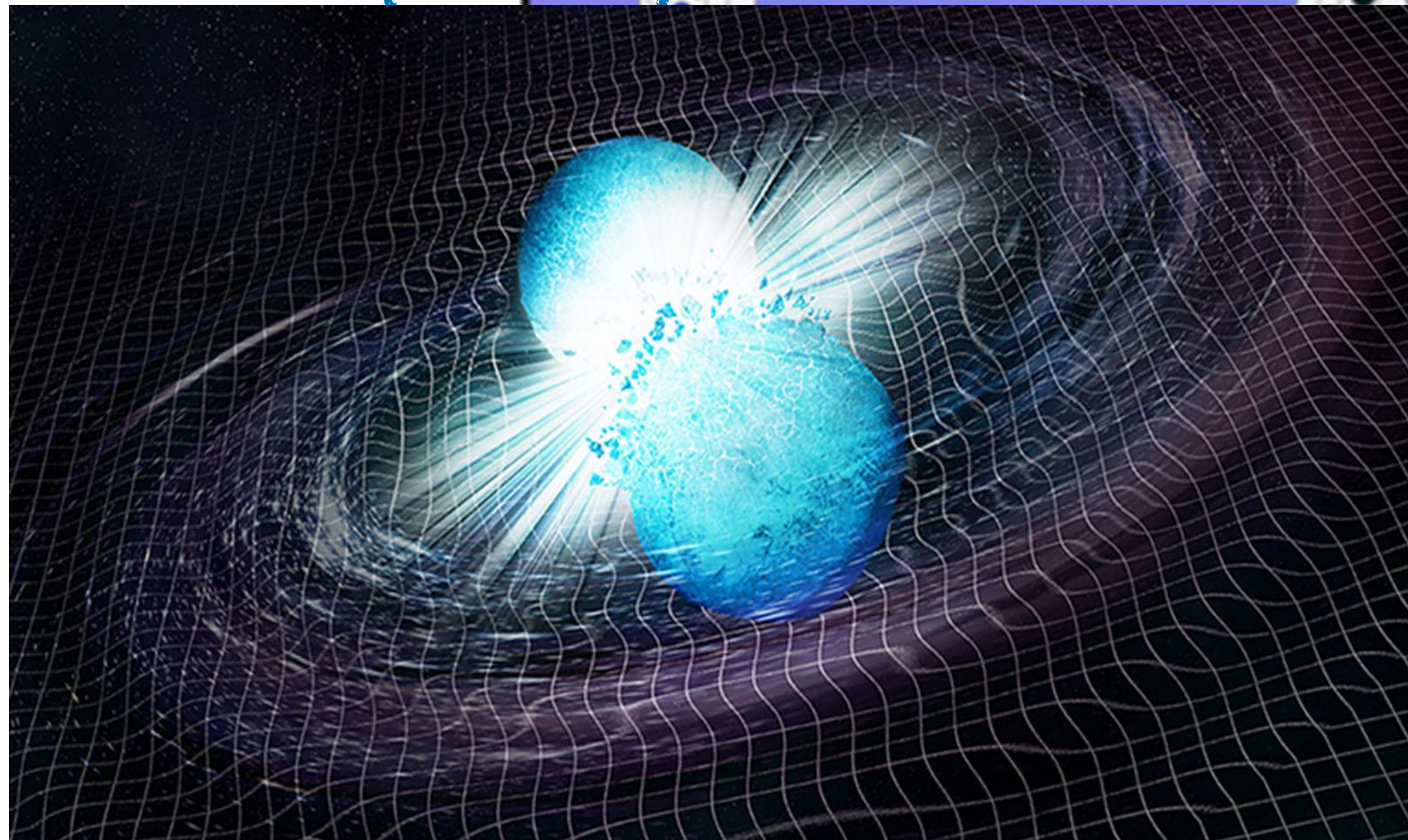
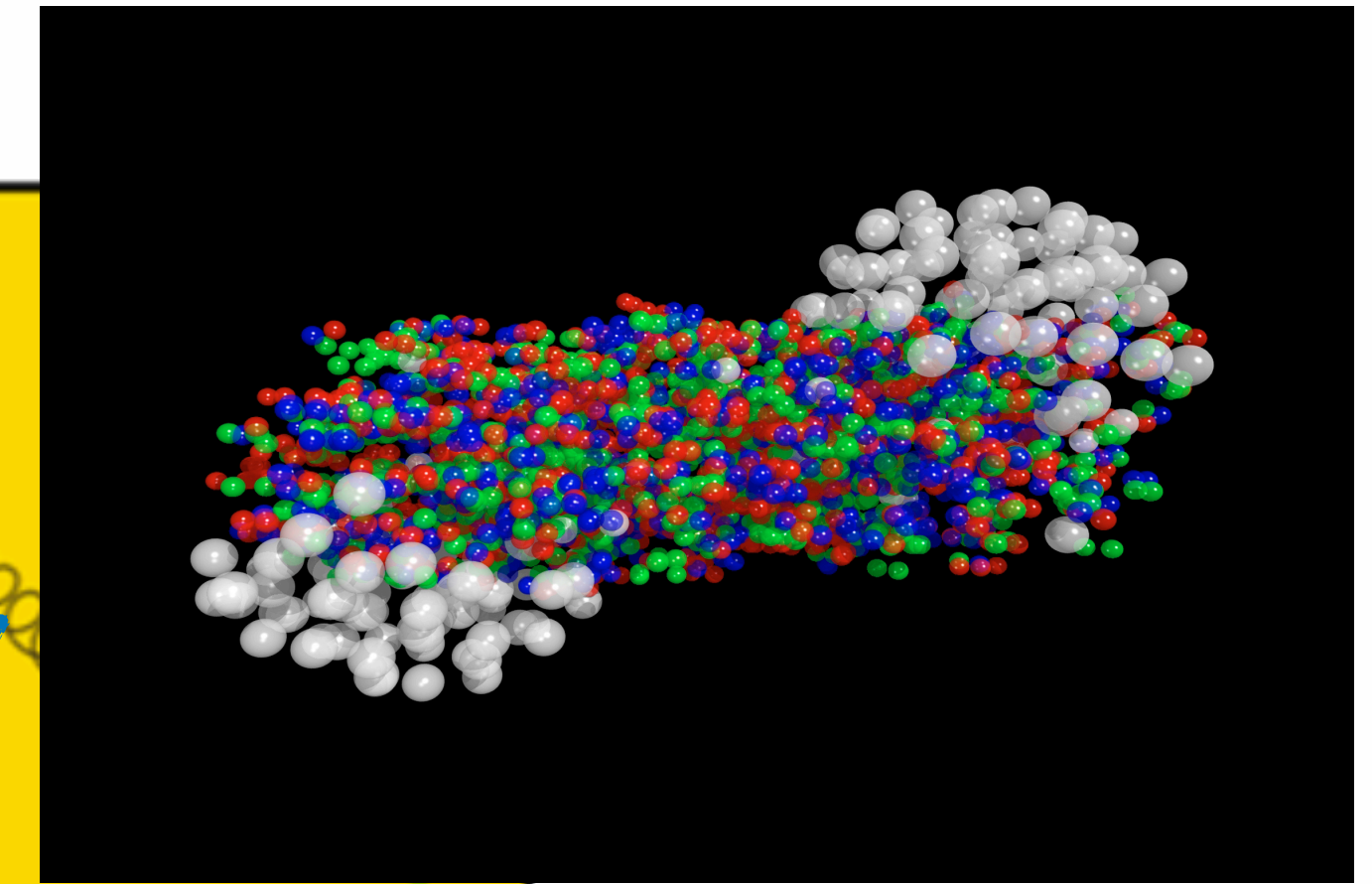
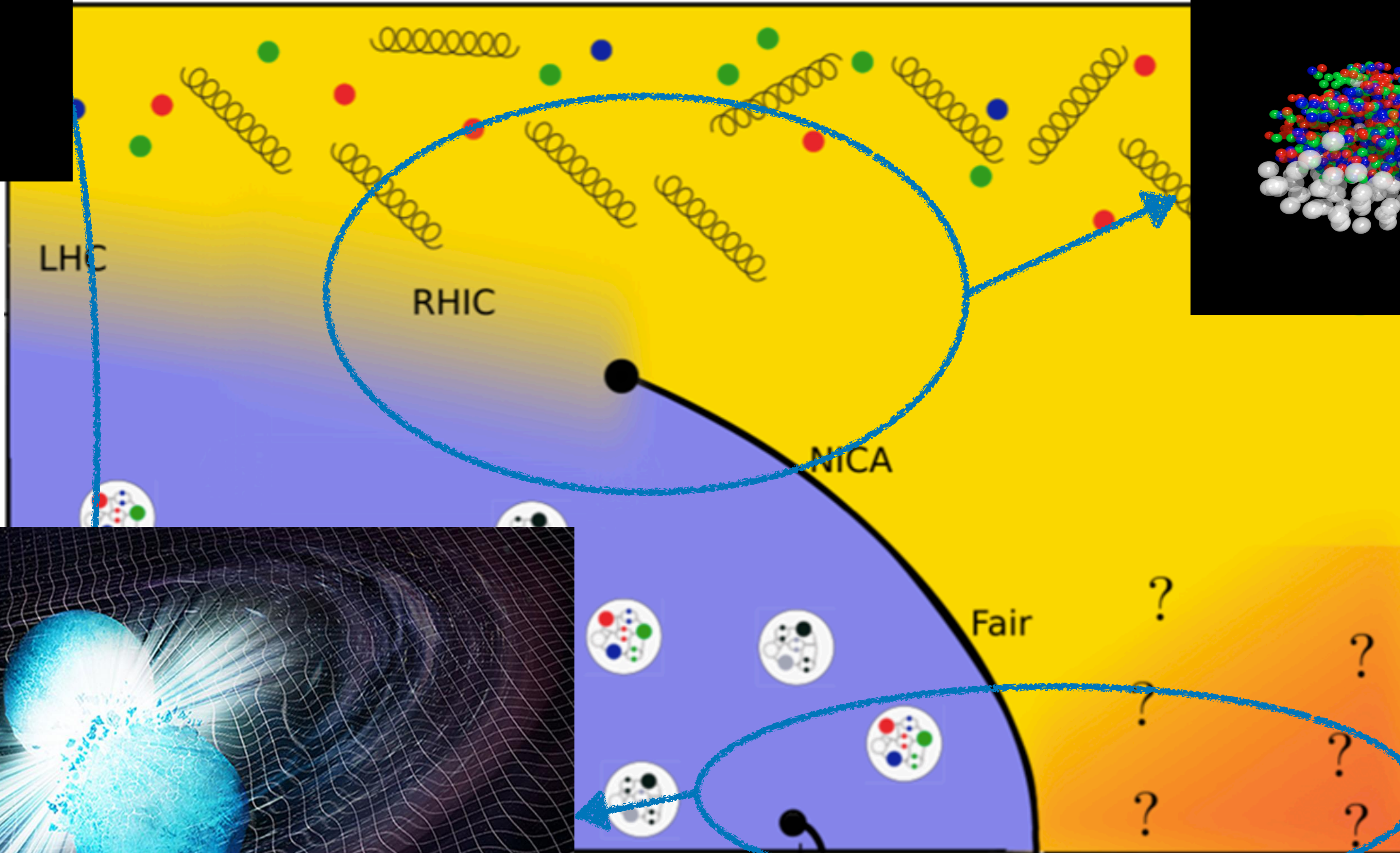
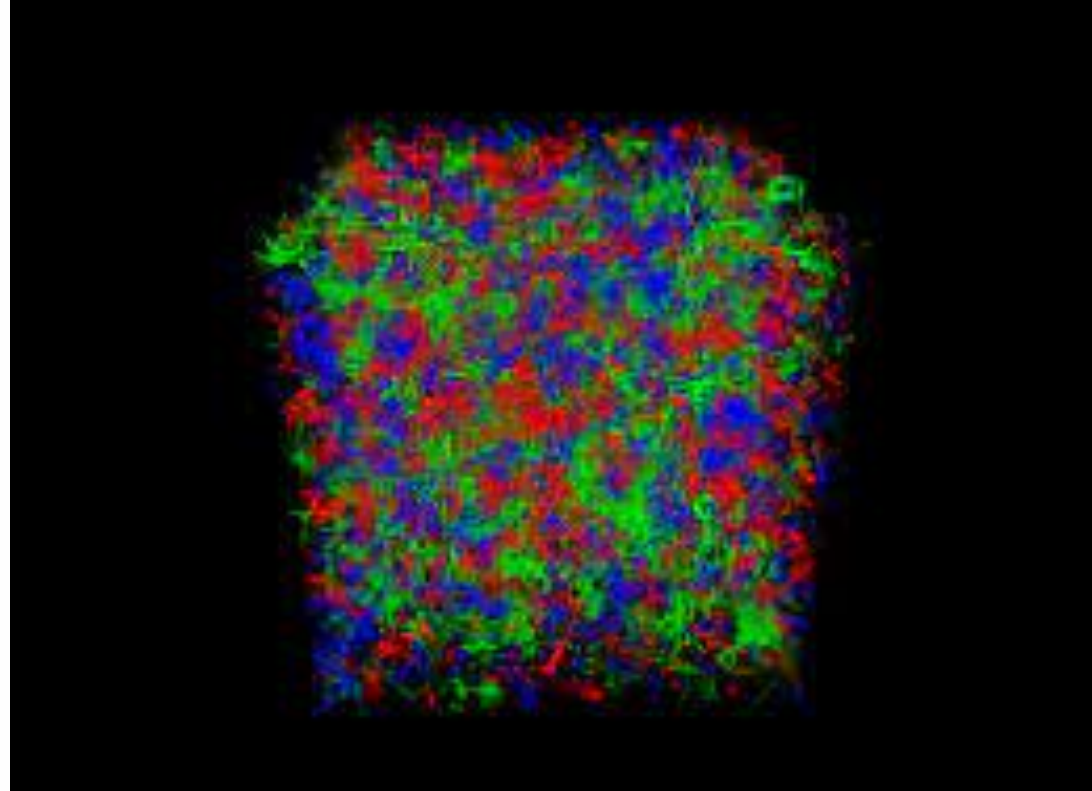
Guenther '21

QCD phase diagram



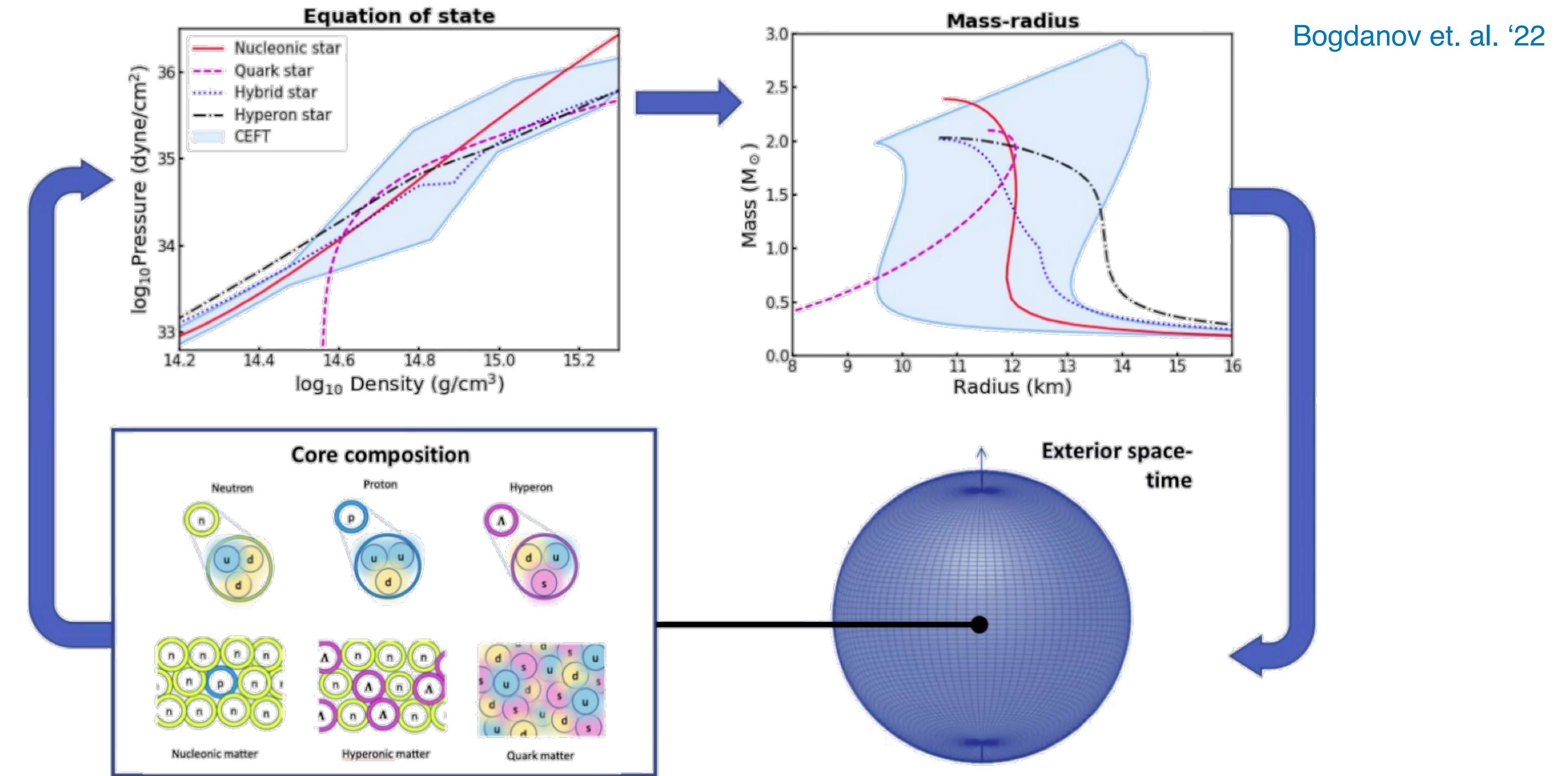
Guenther '21

QCD phase diagram



Guenther '21

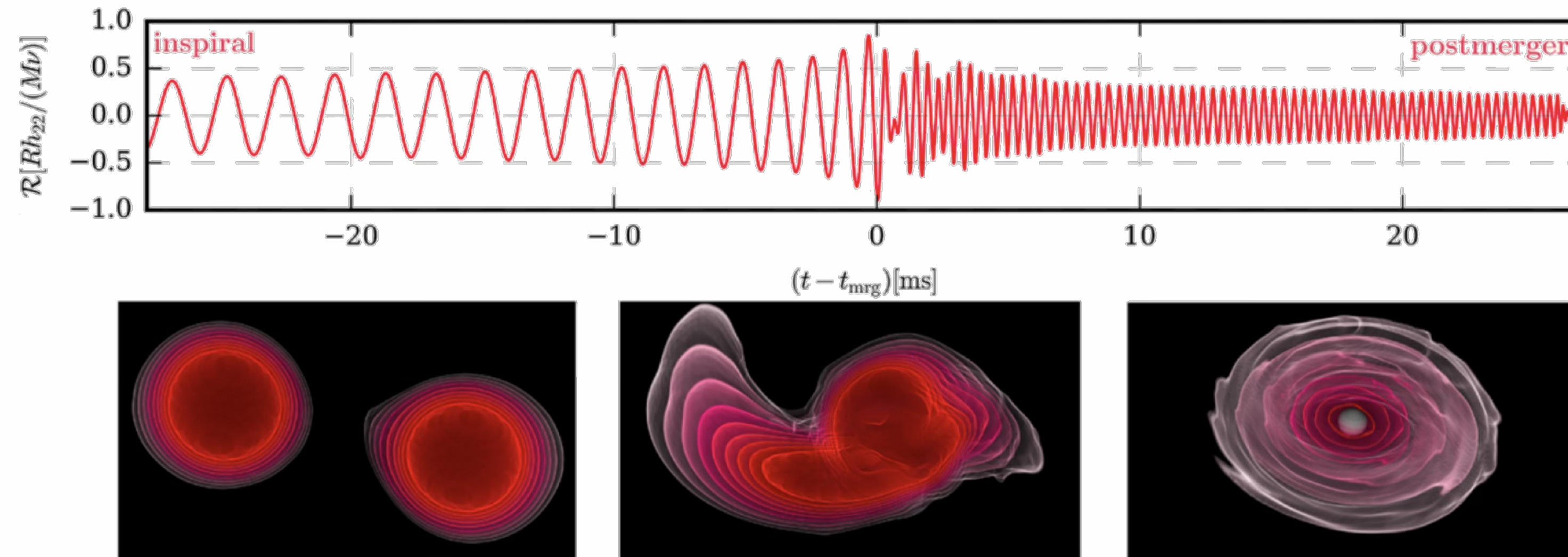
QCD EoS



Astrophysical data restricts the “cold” equations of state (EoS)

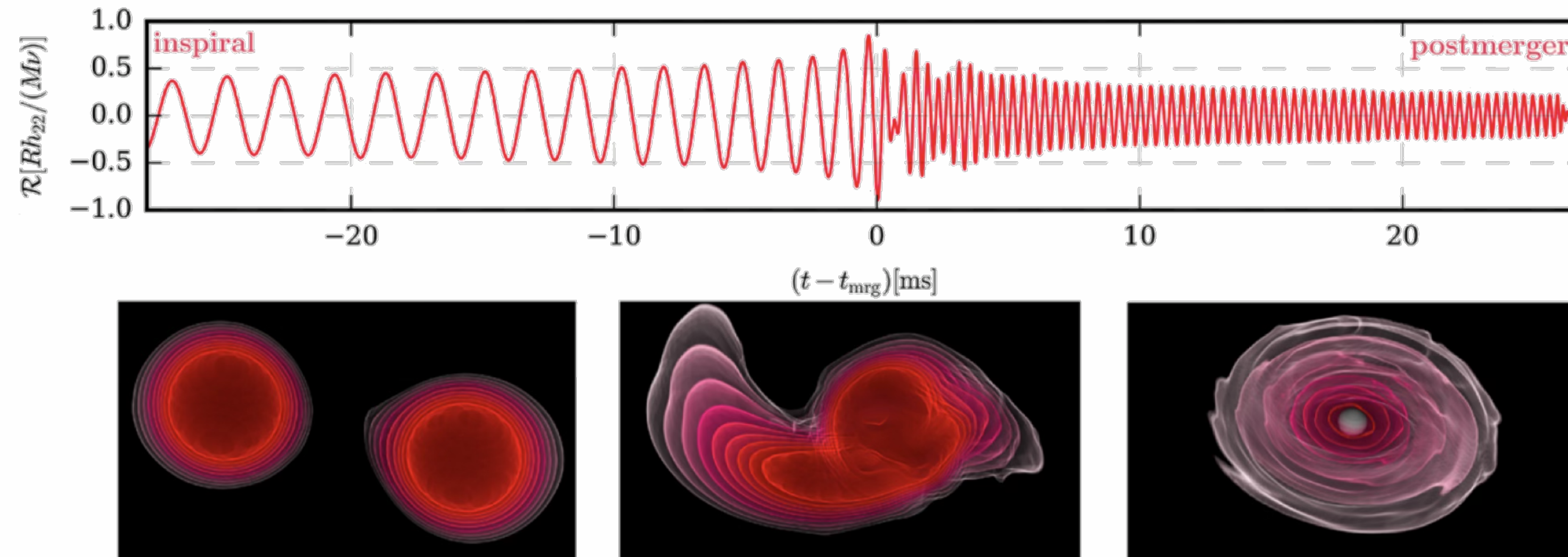
QCD EoS

Dietrich, Hinderer, Samajdar '20



QCD EoS

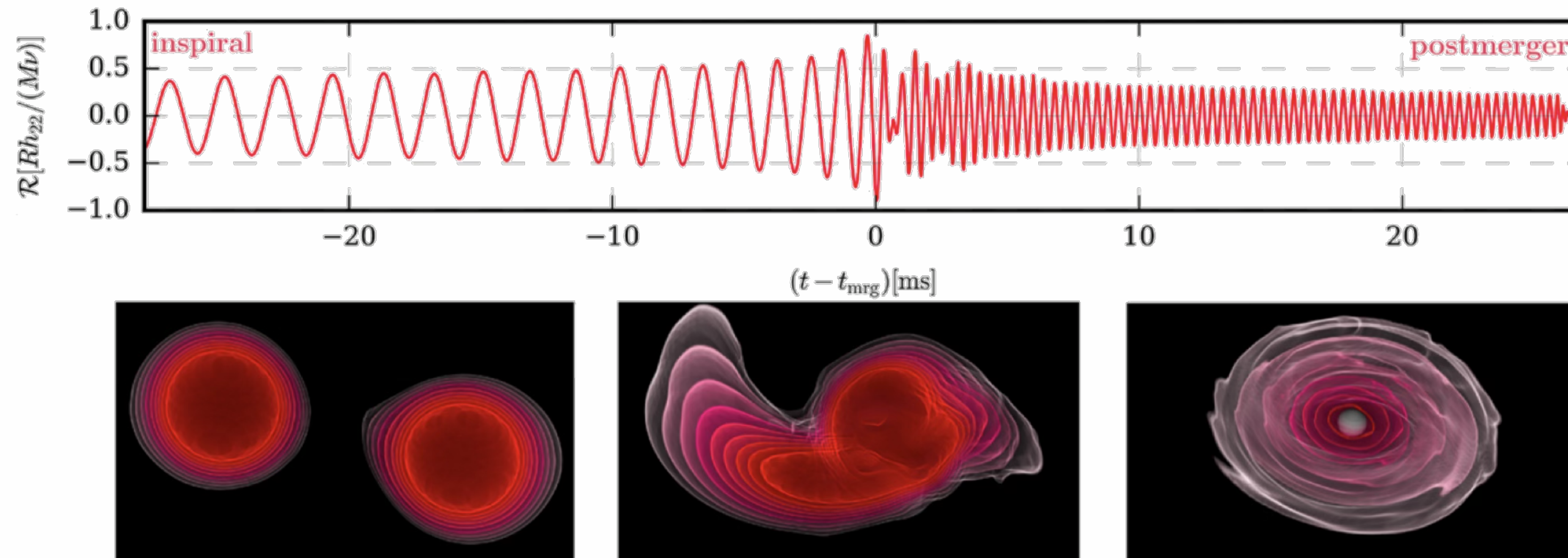
Dietrich, Hinderer, Samajdar '20



- Gravitational waves bring higher temperature EoS information

QCD EoS

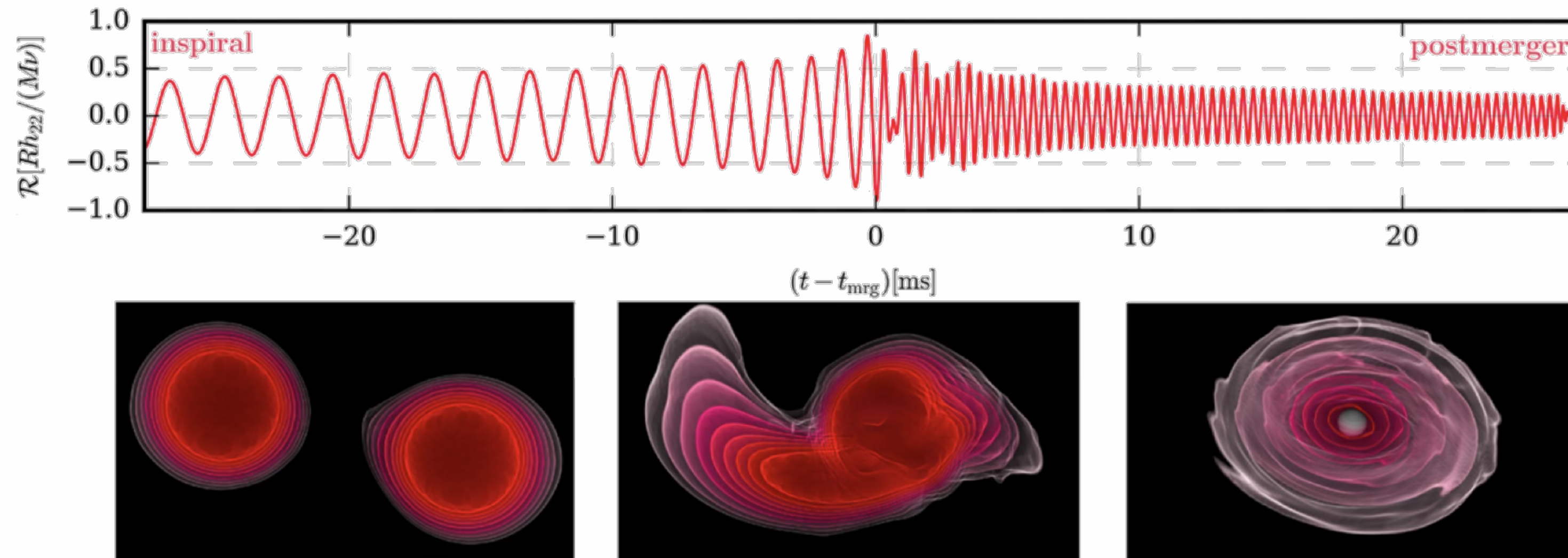
Dietrich, Hinderer, Samajdar '20



- Gravitational waves bring higher temperature EoS information
- If first-order phase transition (FOPT):

QCD EoS

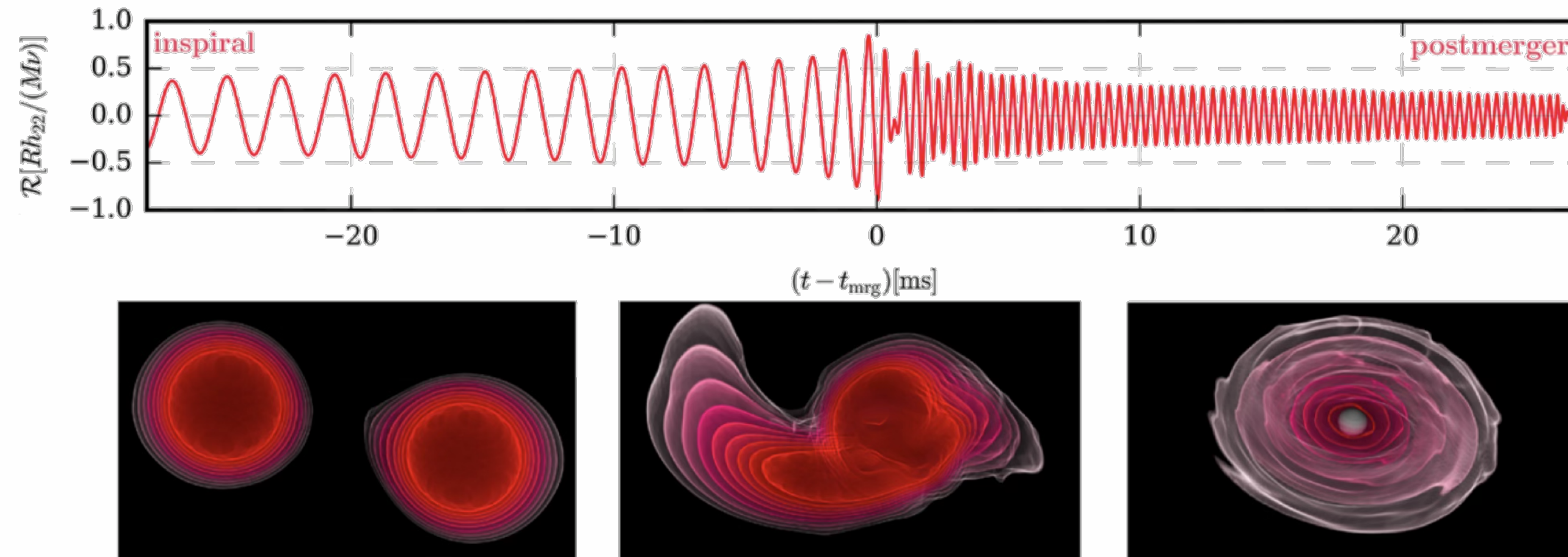
Dietrich, Hinderer, Samajdar '20



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 - Macroscopic effects: modifications in kHz signal

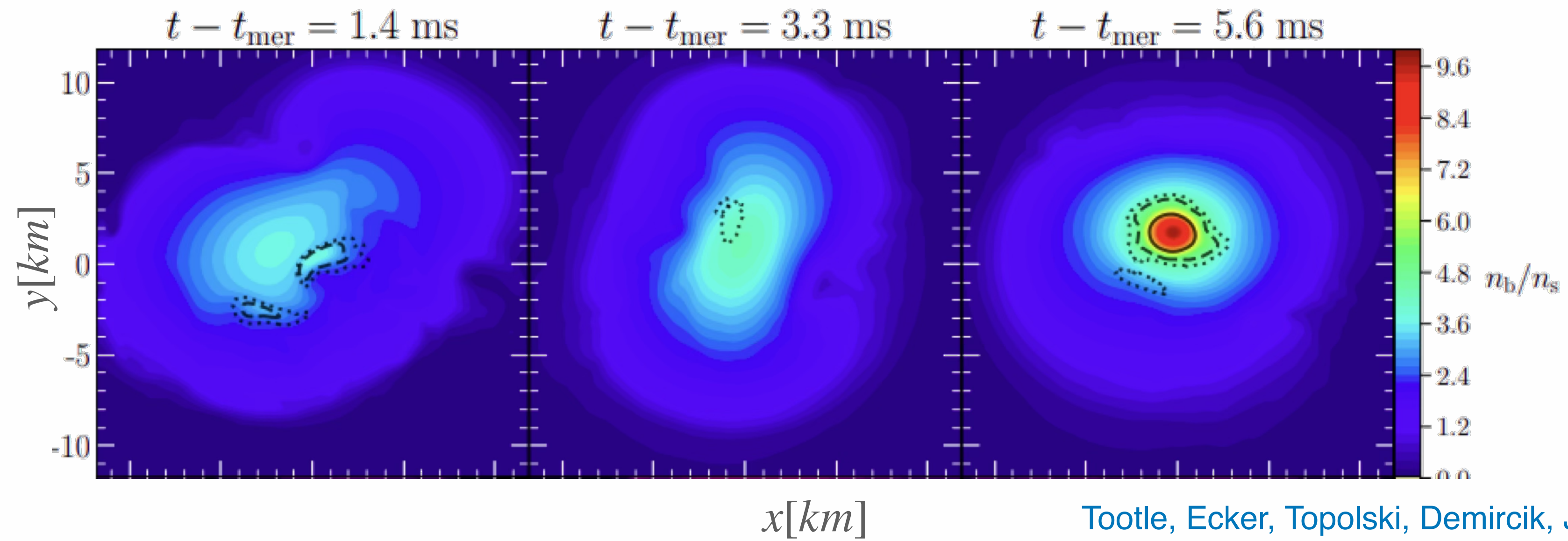
QCD EoS

Dietrich, Hinderer, Samajdar '20



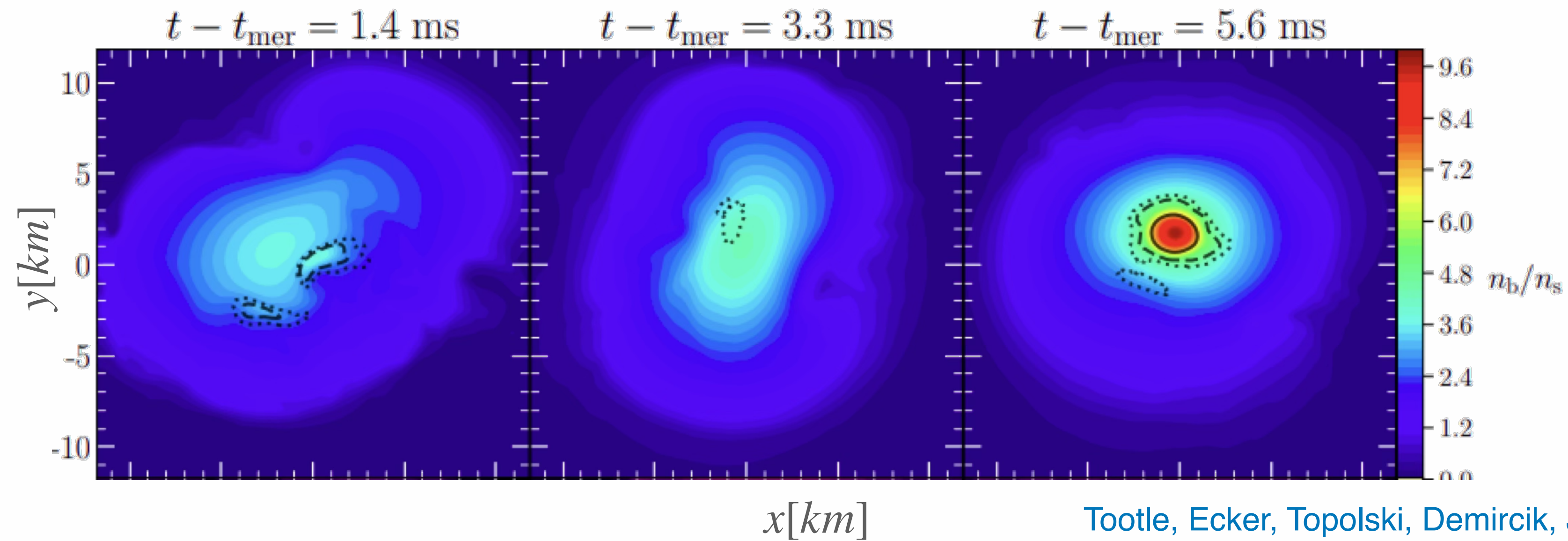
- Gravitational waves bring higher temperature EoS information
- If first-order phase transition (FOPT):
 - Macroscopic effects: modifications in kHz signal
 - Microscopic effects: direct signal

First-order phase transitions in mergers



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

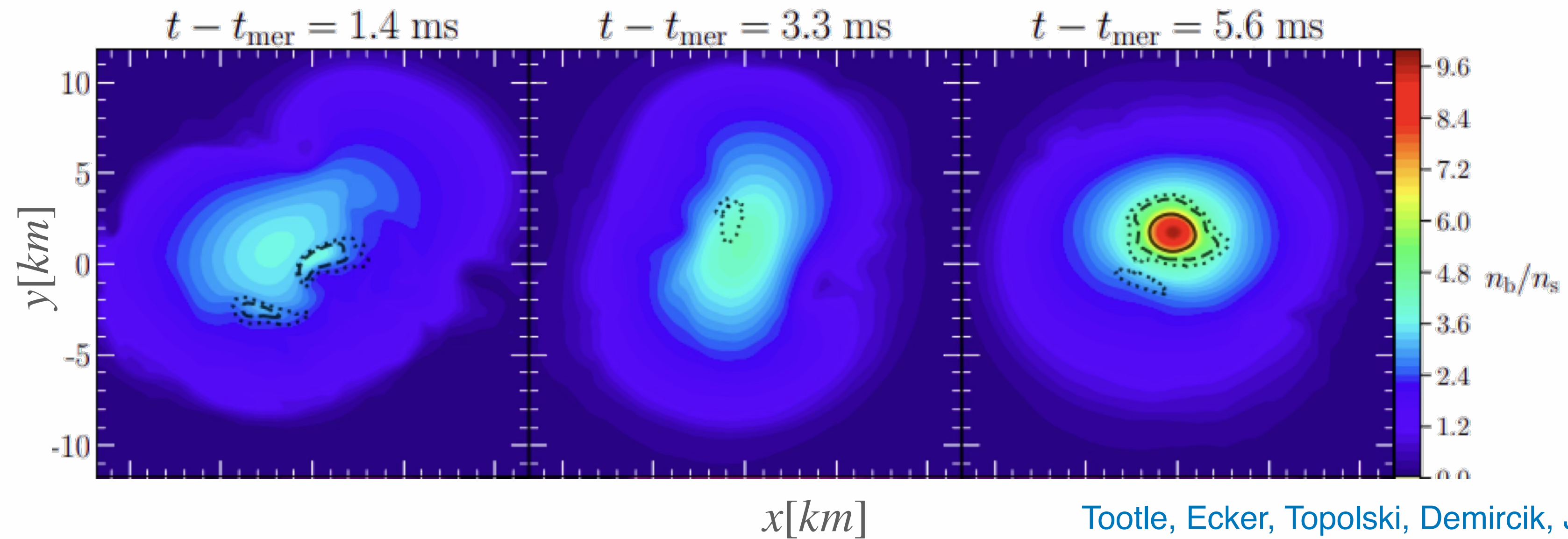
First-order phase transitions in mergers



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

- Adiabatic evolution: Characteristic time/length scales \gg QCD scale

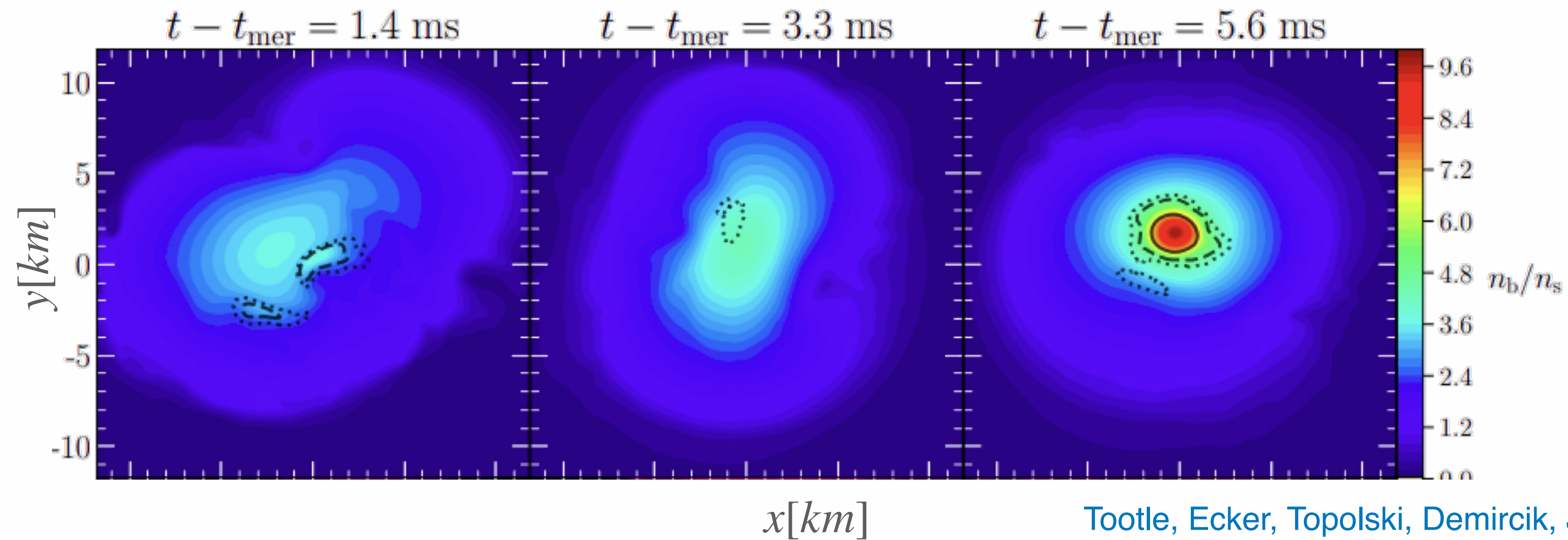
First-order phase transitions in mergers



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- FOPT proceed through the nucleation, expansion and collision of bubbles

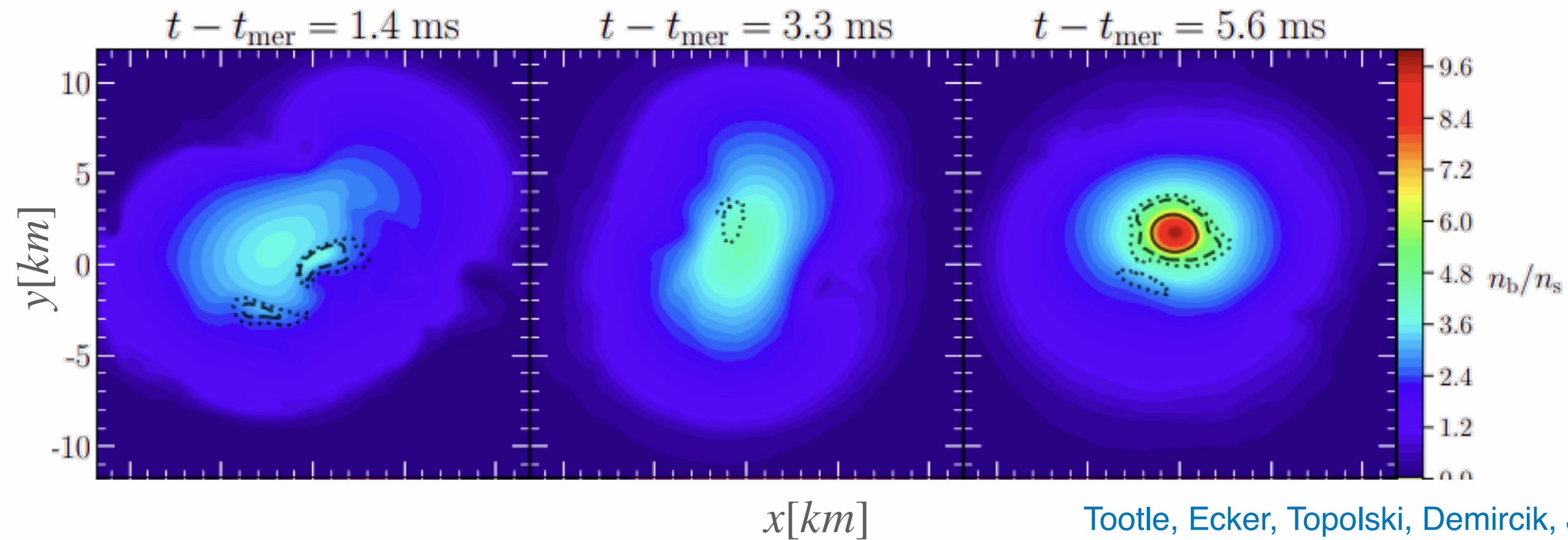
First-order phase transitions in mergers



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 - Similar to cosmological transitions ($\text{ms} \sim \tau \sim H^{-1}$)

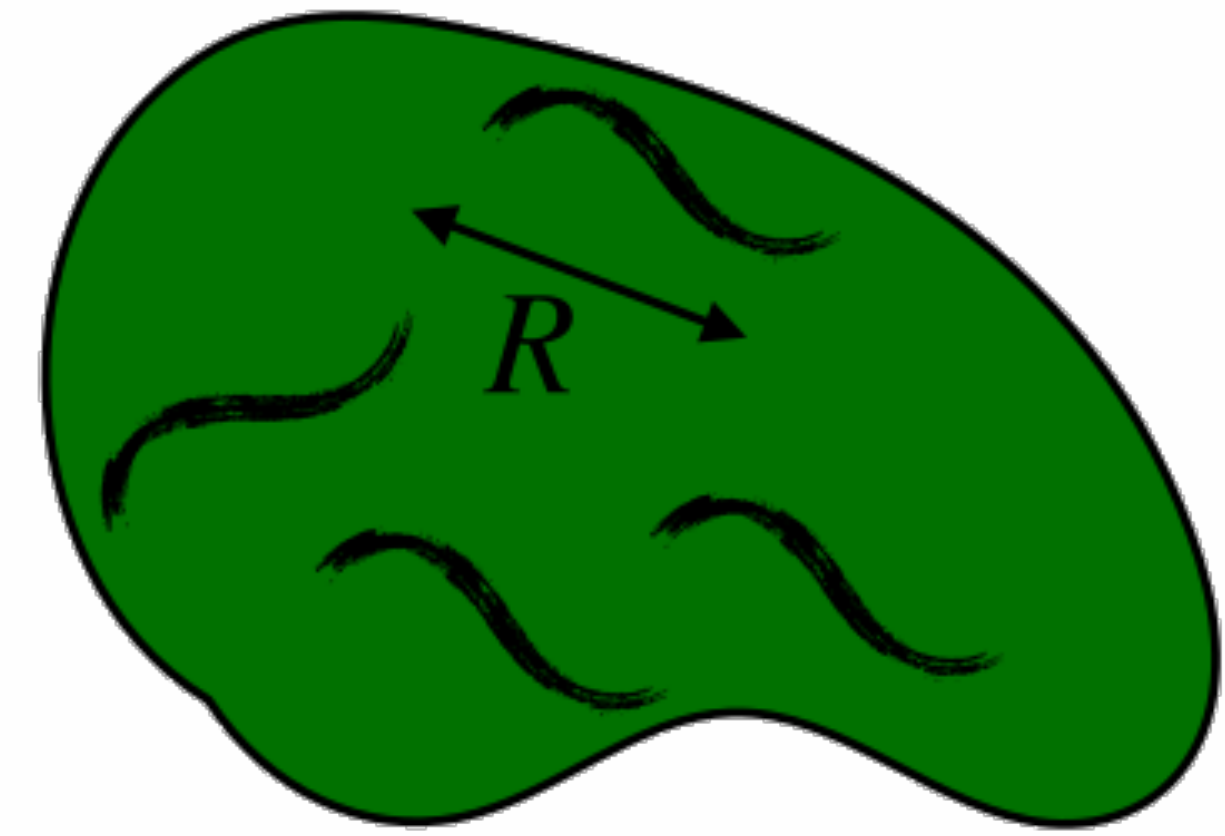
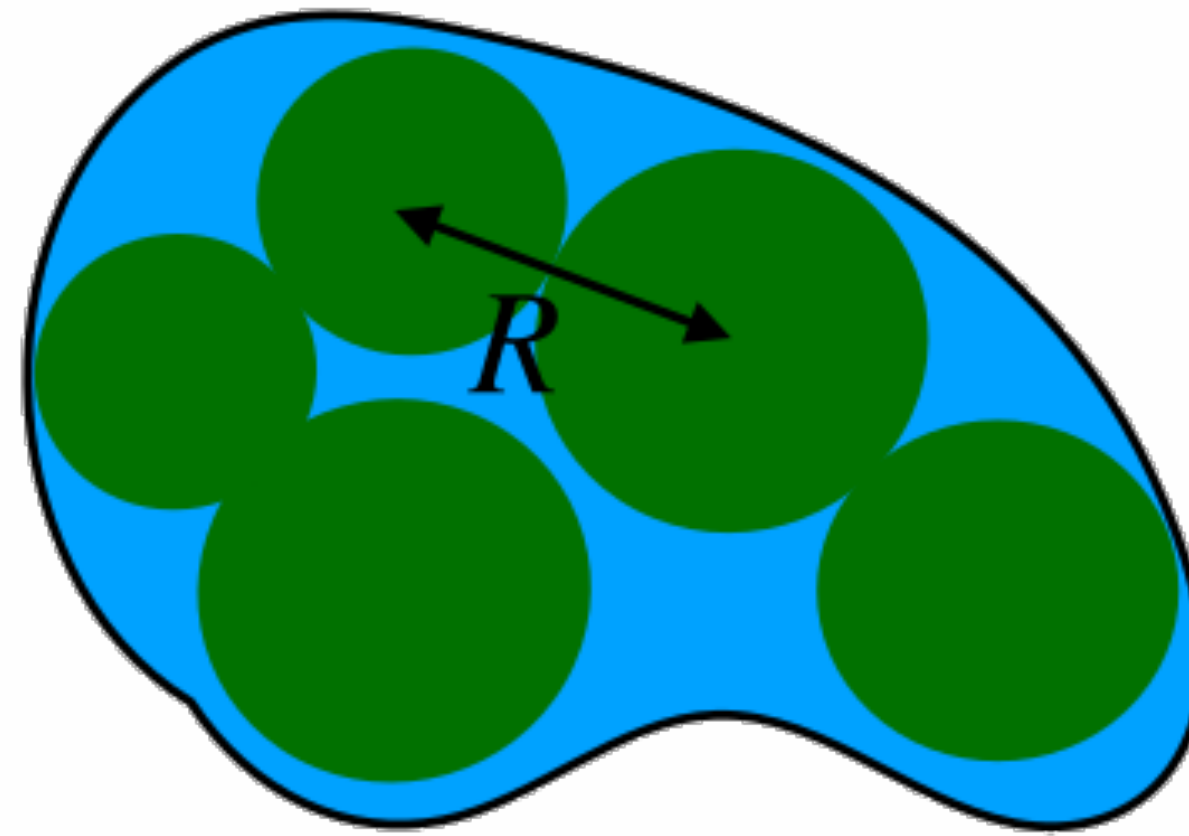
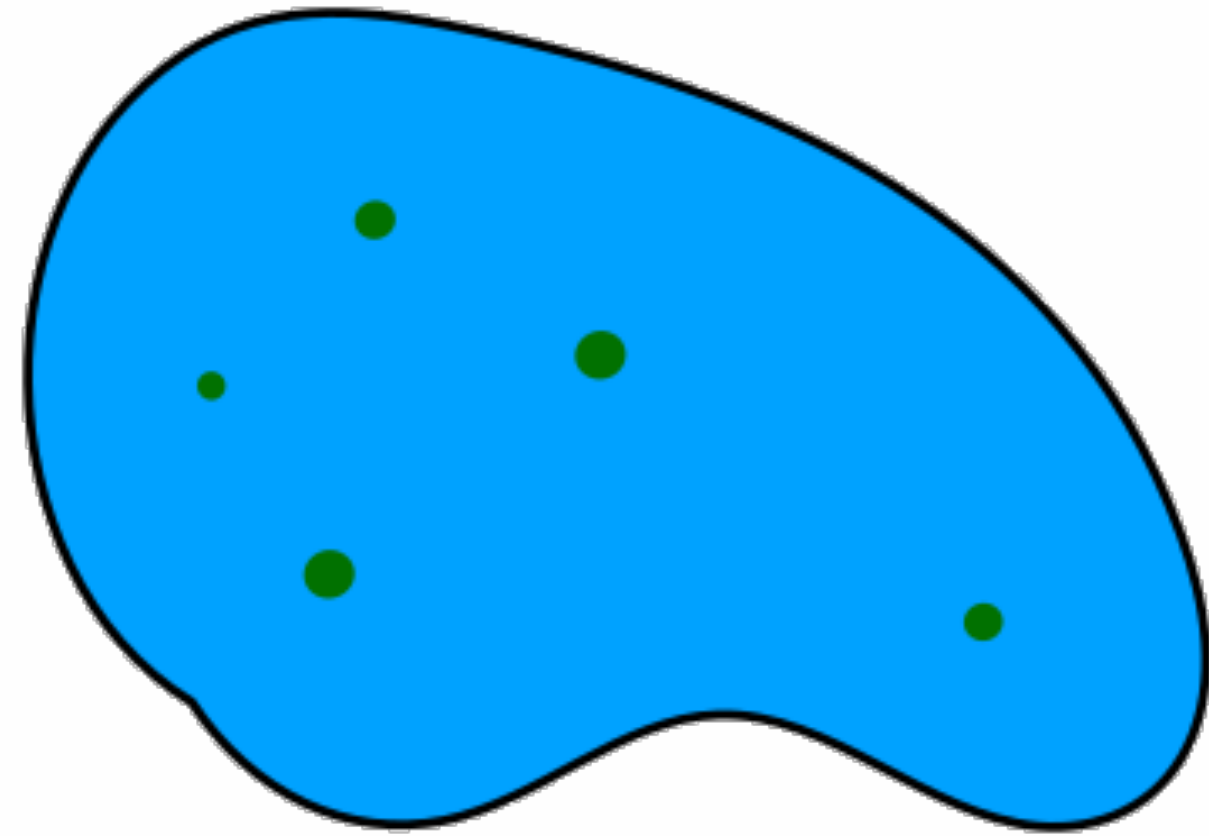
First-order phase transitions in mergers



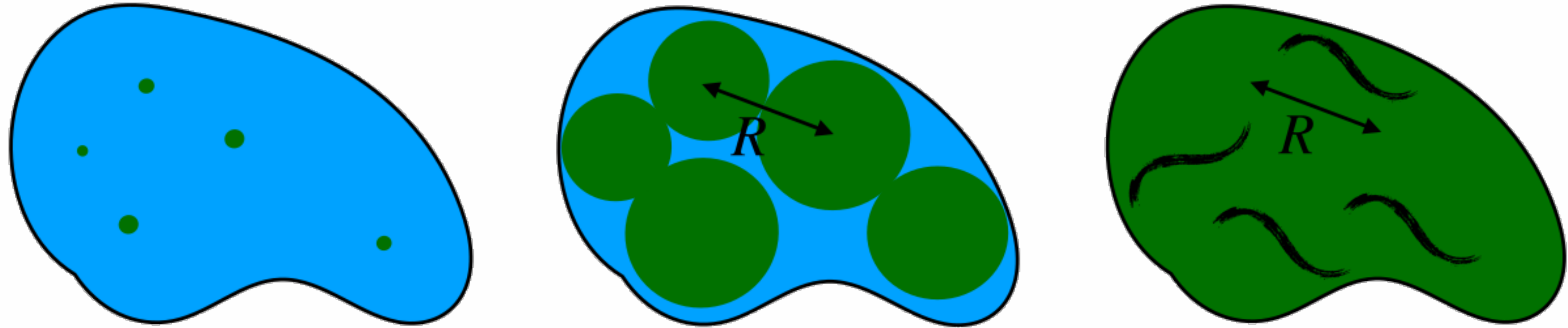
Tootle, Ecker, Topolski, Demircik, Järvinen, Rezolla '22

- Adiabatic evolution: Characteristic time/length scales \gg QCD scale
- FOPT proceed through the nucleation, expansion and collision of bubbles
 - Similar to cosmological transitions ($\text{ms} \sim \tau \sim H^{-1}$)
 - Direct signal

Gravitational waves from FOPTs

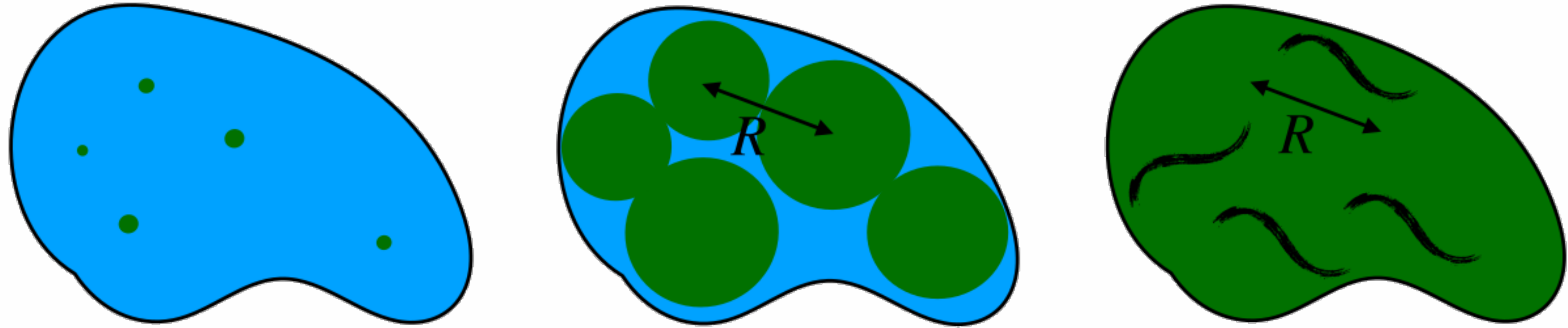


Gravitational waves from FOPTs

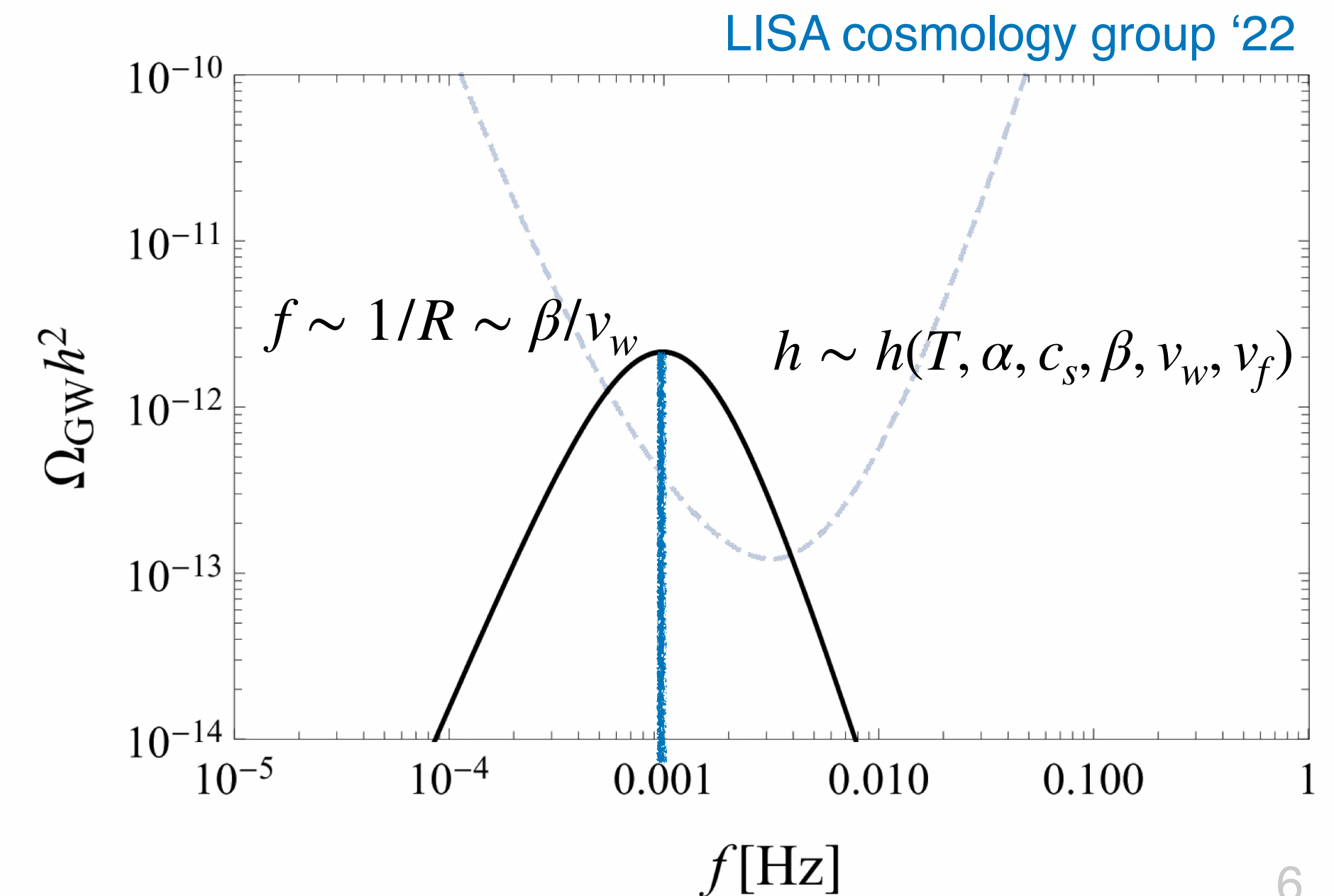


- Dominant GW emission from sound waves

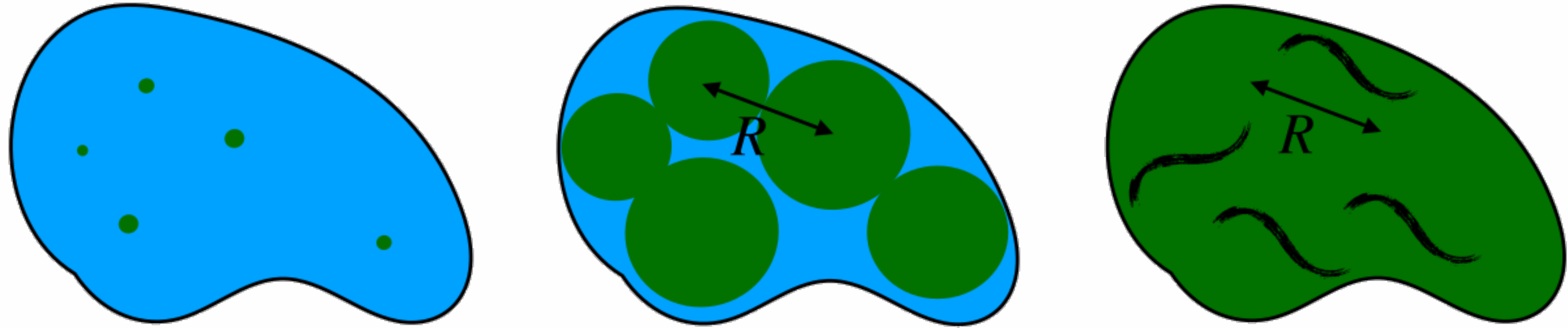
Gravitational waves from FOPTs



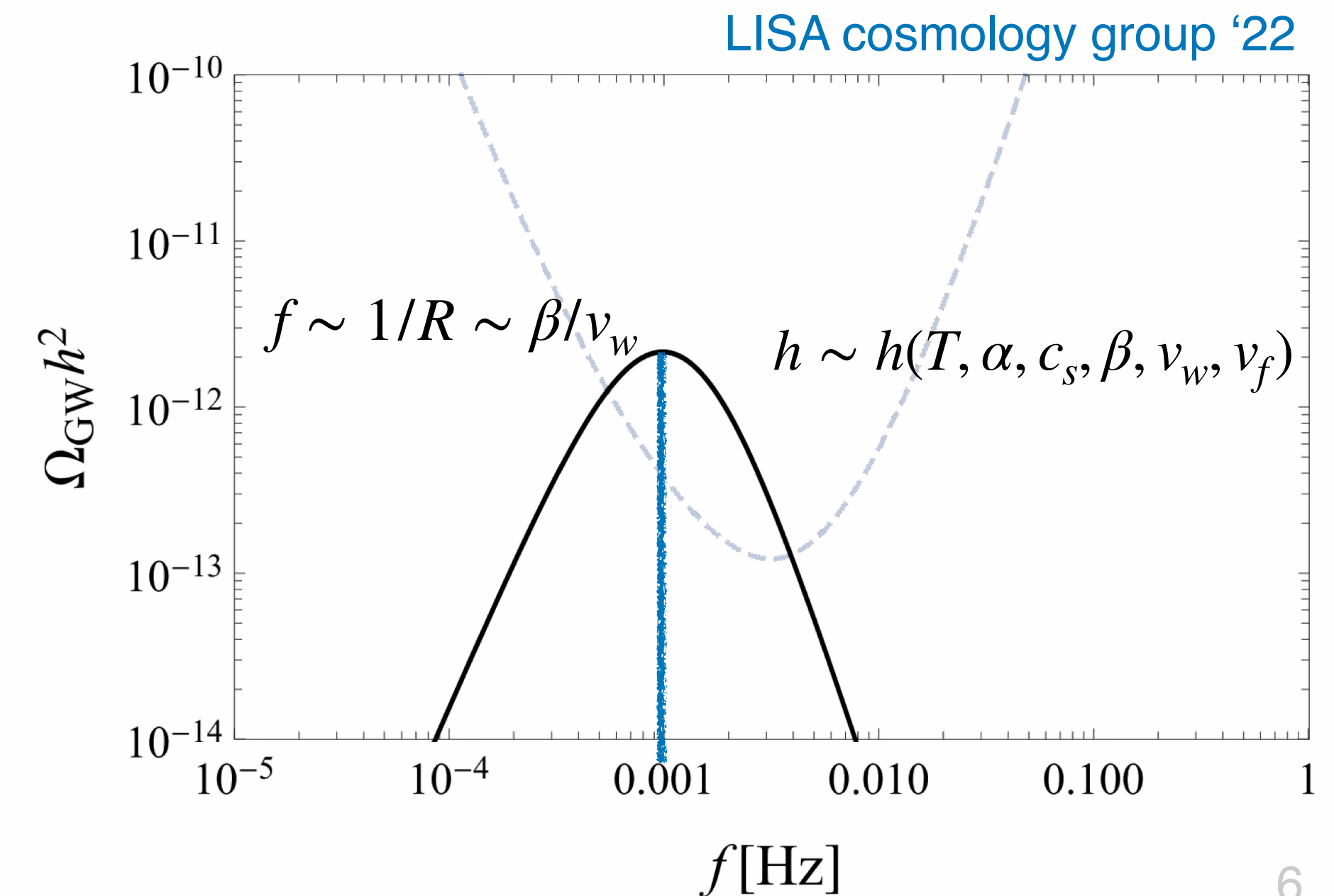
- Dominant GW emission from sound waves
- Vast amount of results for early universe transitions



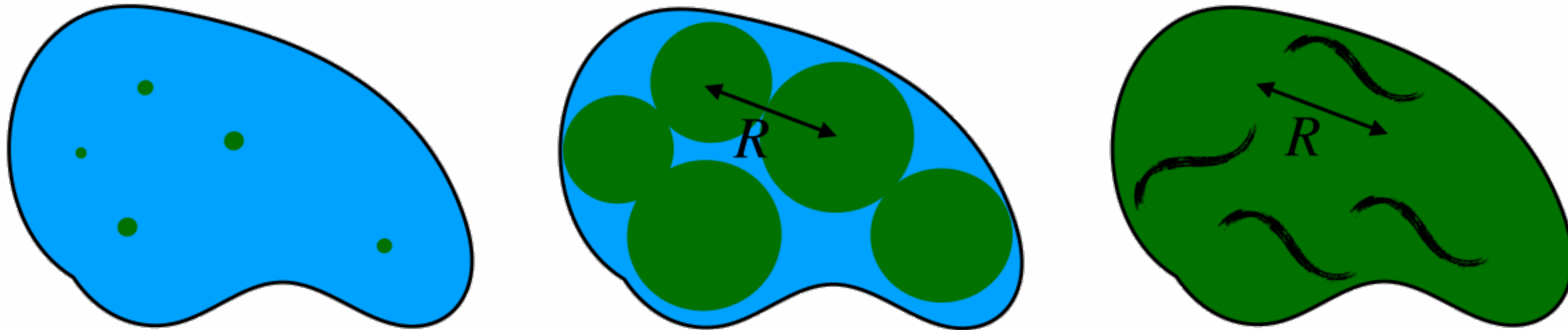
Gravitational waves from FOPTs



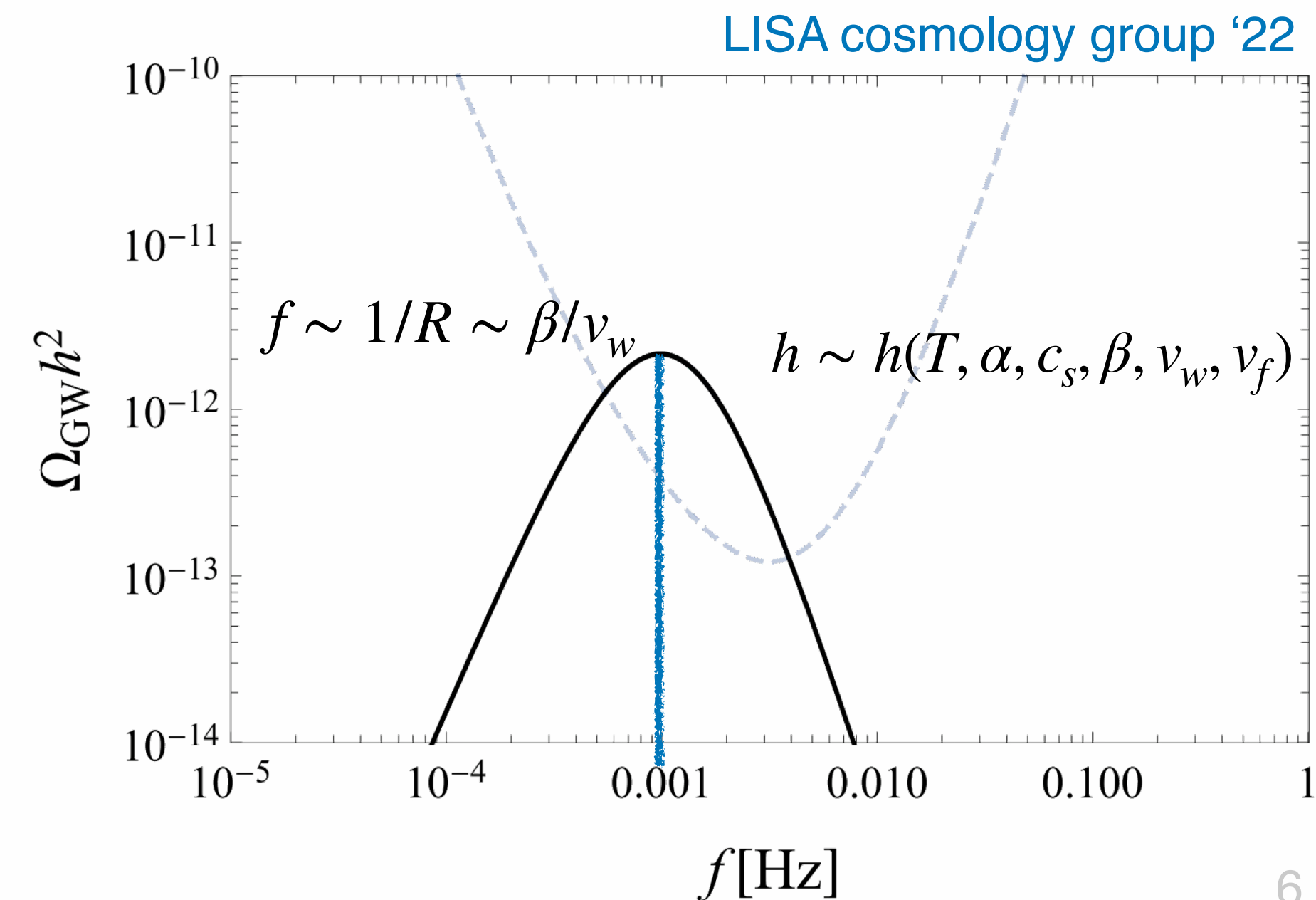
- Dominant GW emission from sound waves
- Vast amount of results for early universe transitions
- Borrow results for a first raw estimate



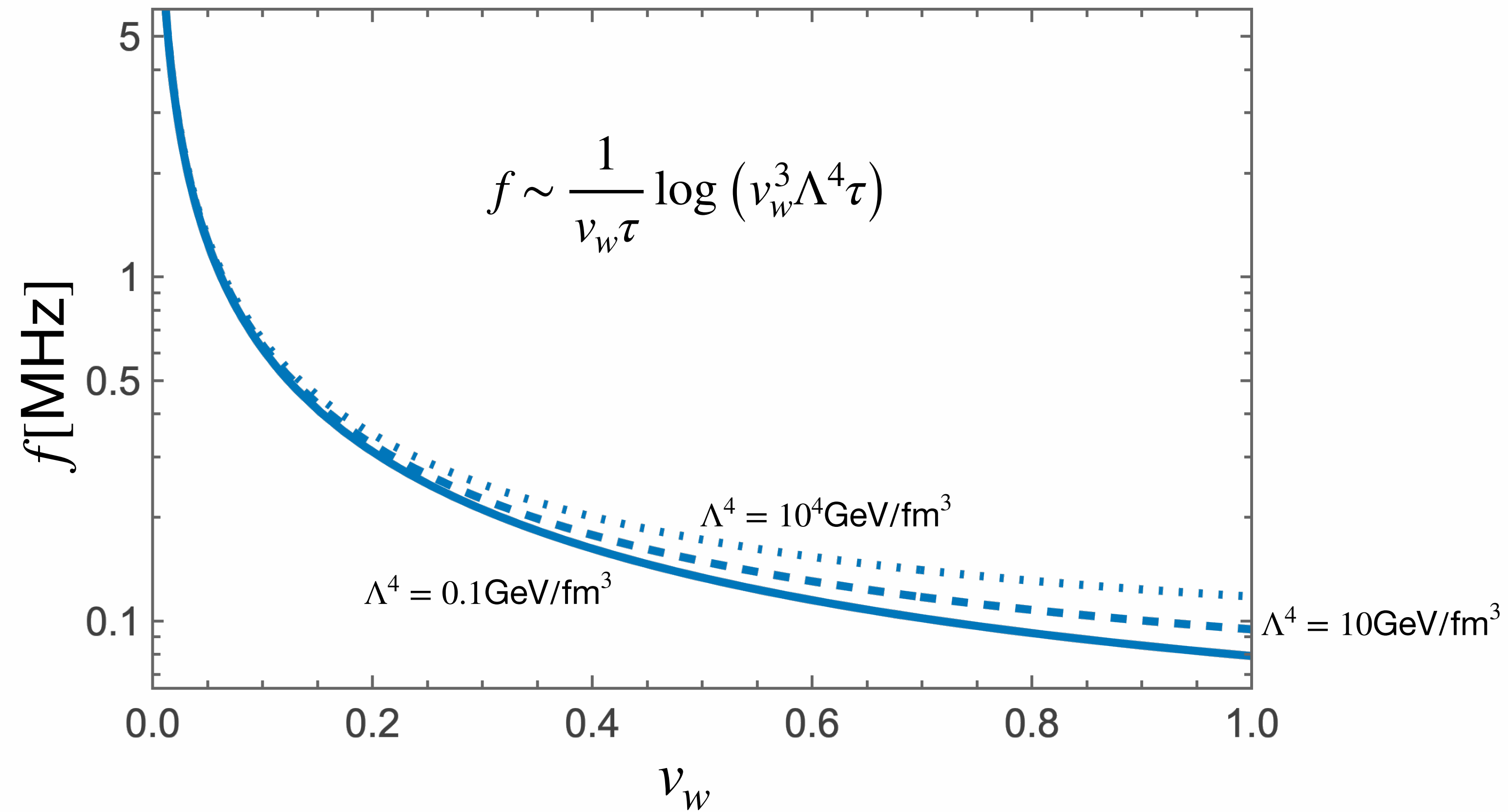
Gravitational waves from FOPTs



- Dominant GW emission from sound waves
- Vast amount of results for early universe transitions
- Borrow results for a first raw estimate
- Study dynamics of more general transitions



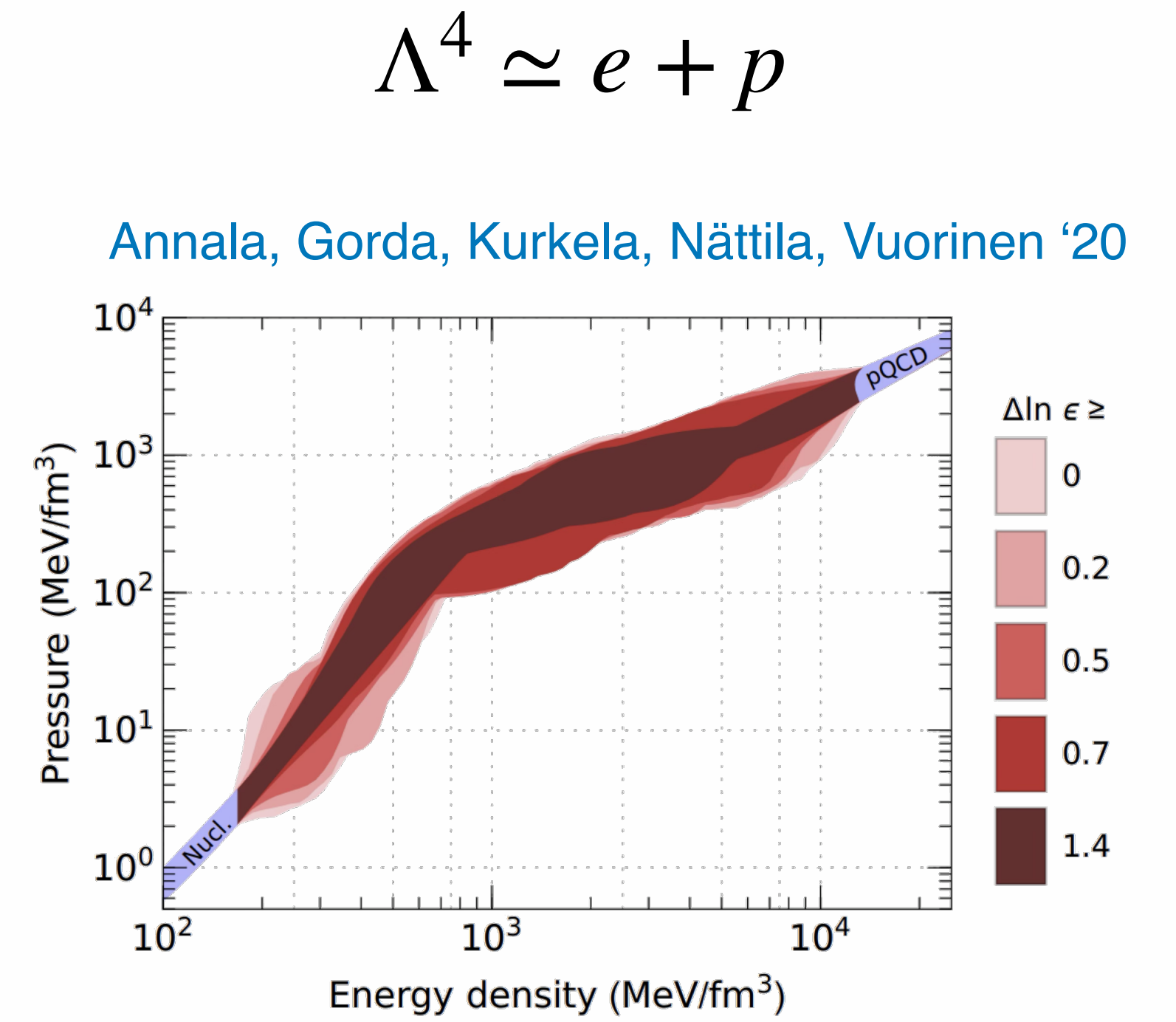
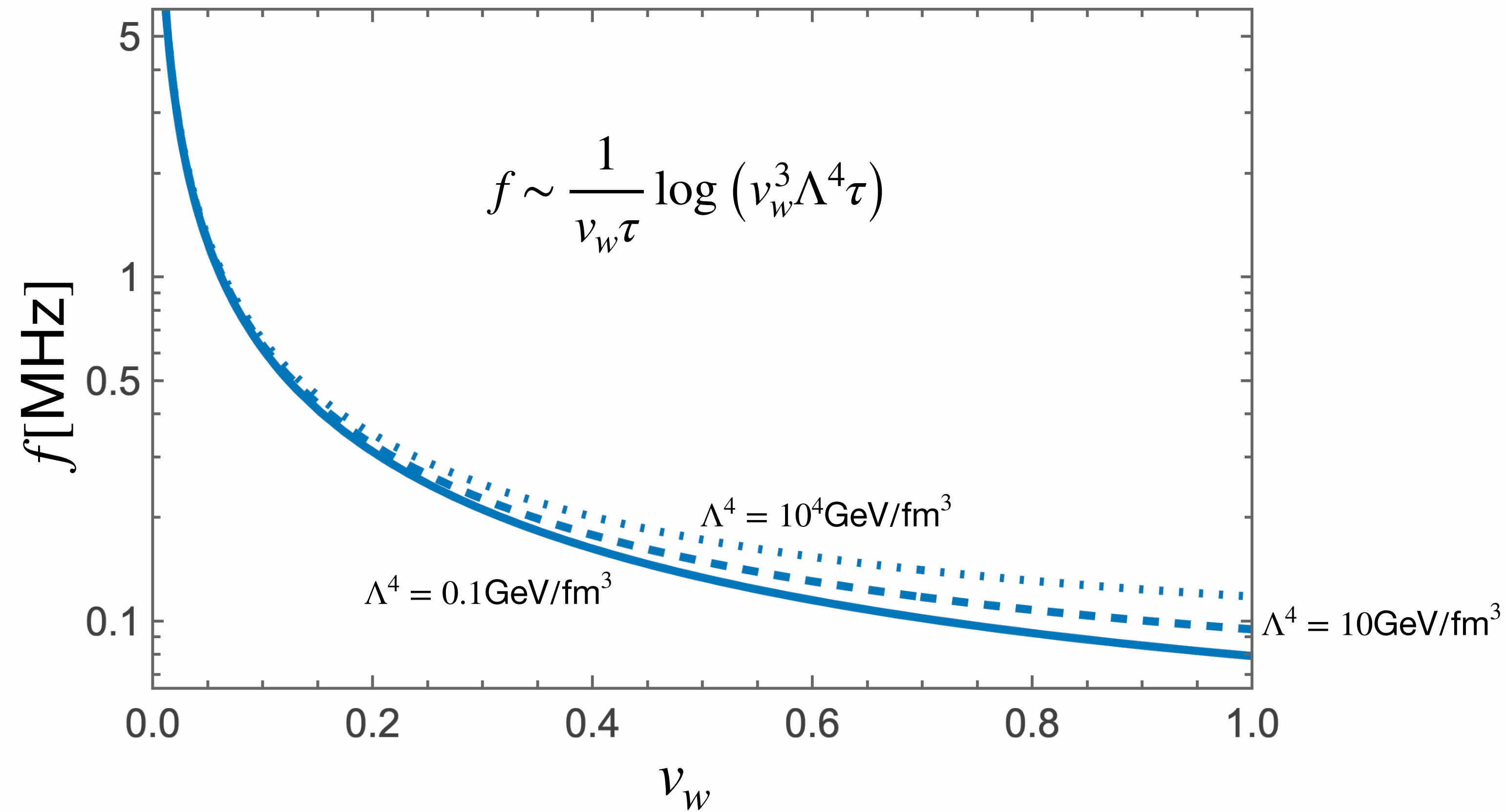
Peak frequency



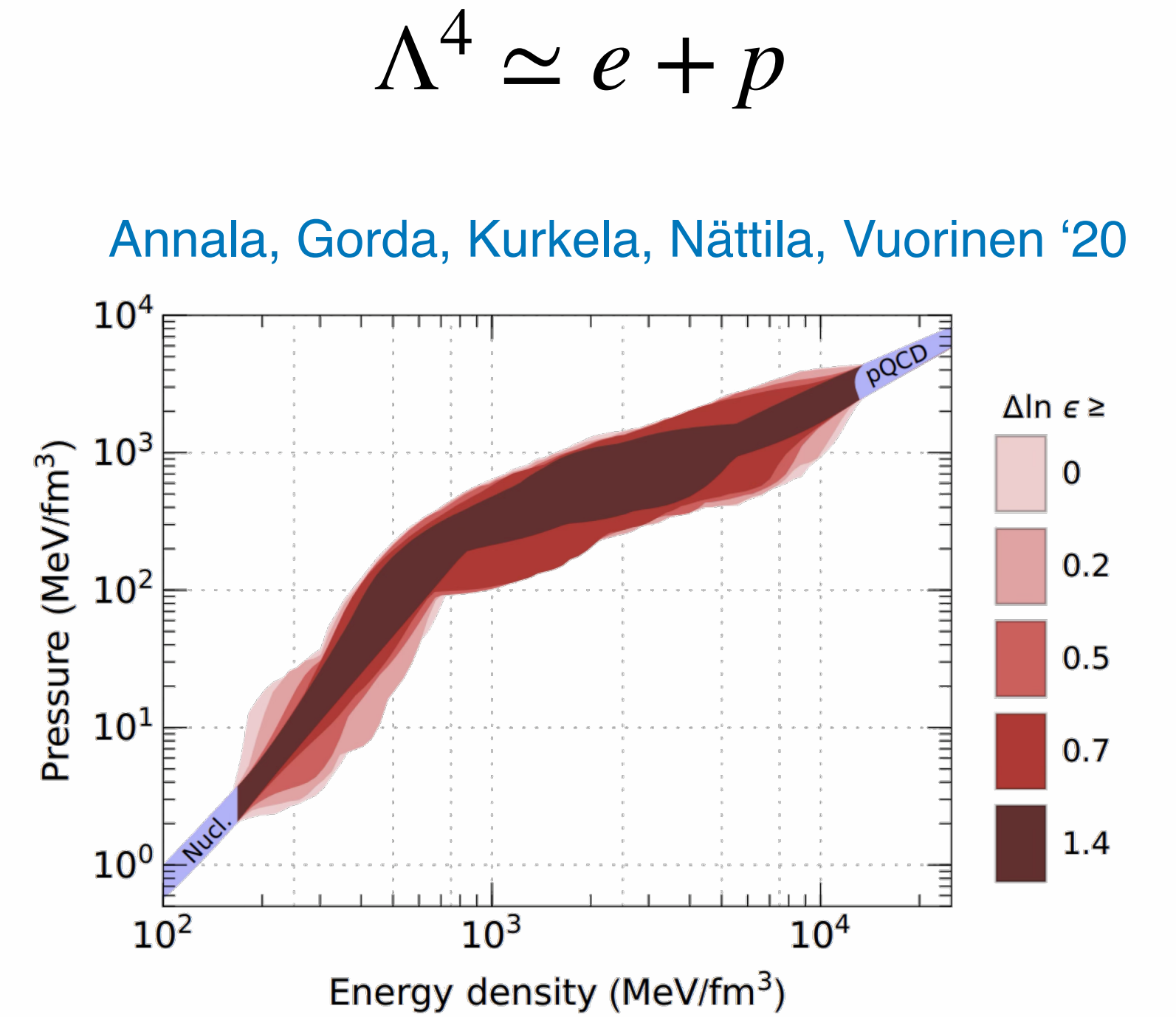
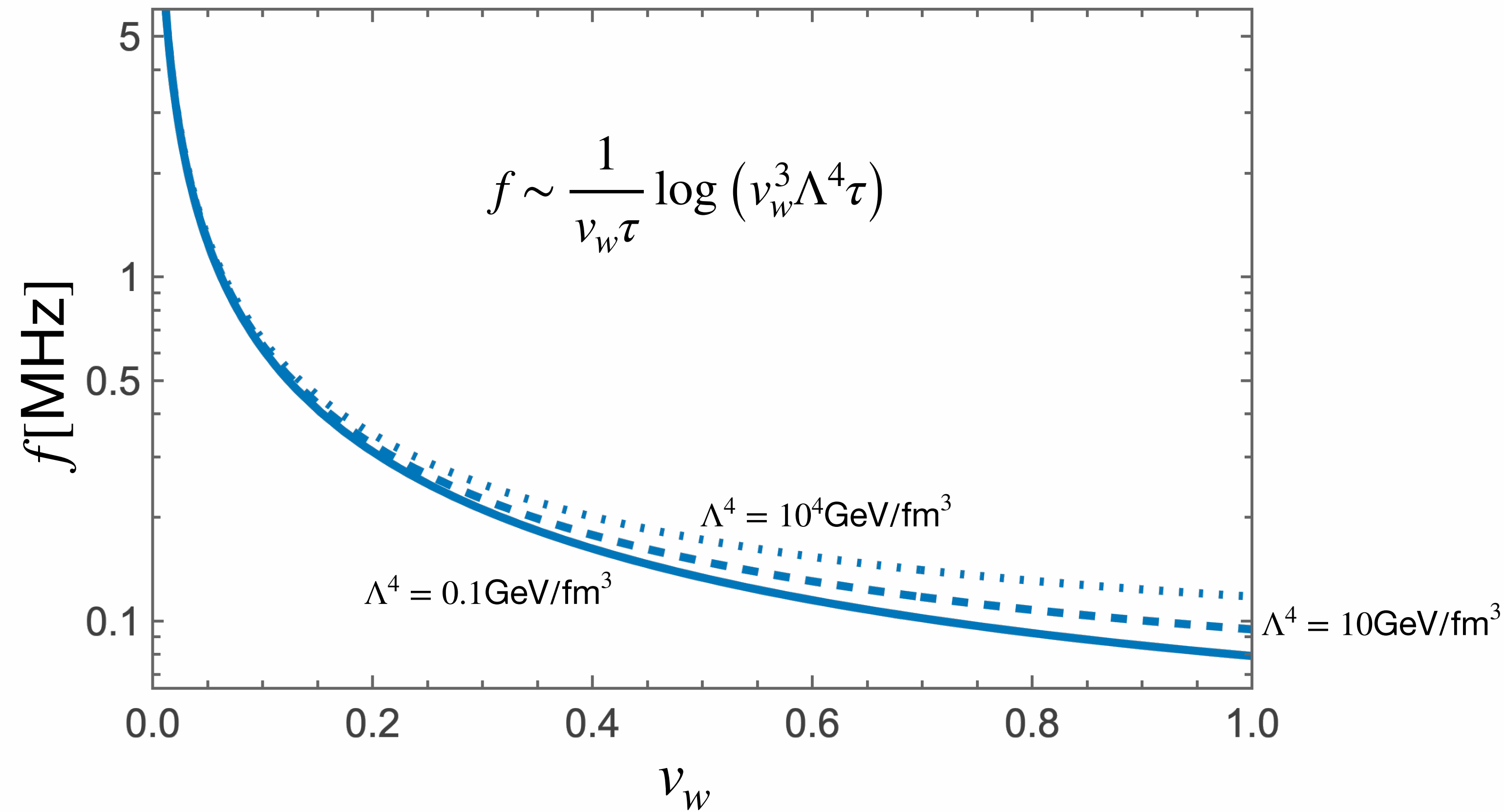
$$\Lambda^4 \simeq e + p$$

Peak frequency

Blas, Casalderrey-Solana, Mateos, MSG '22

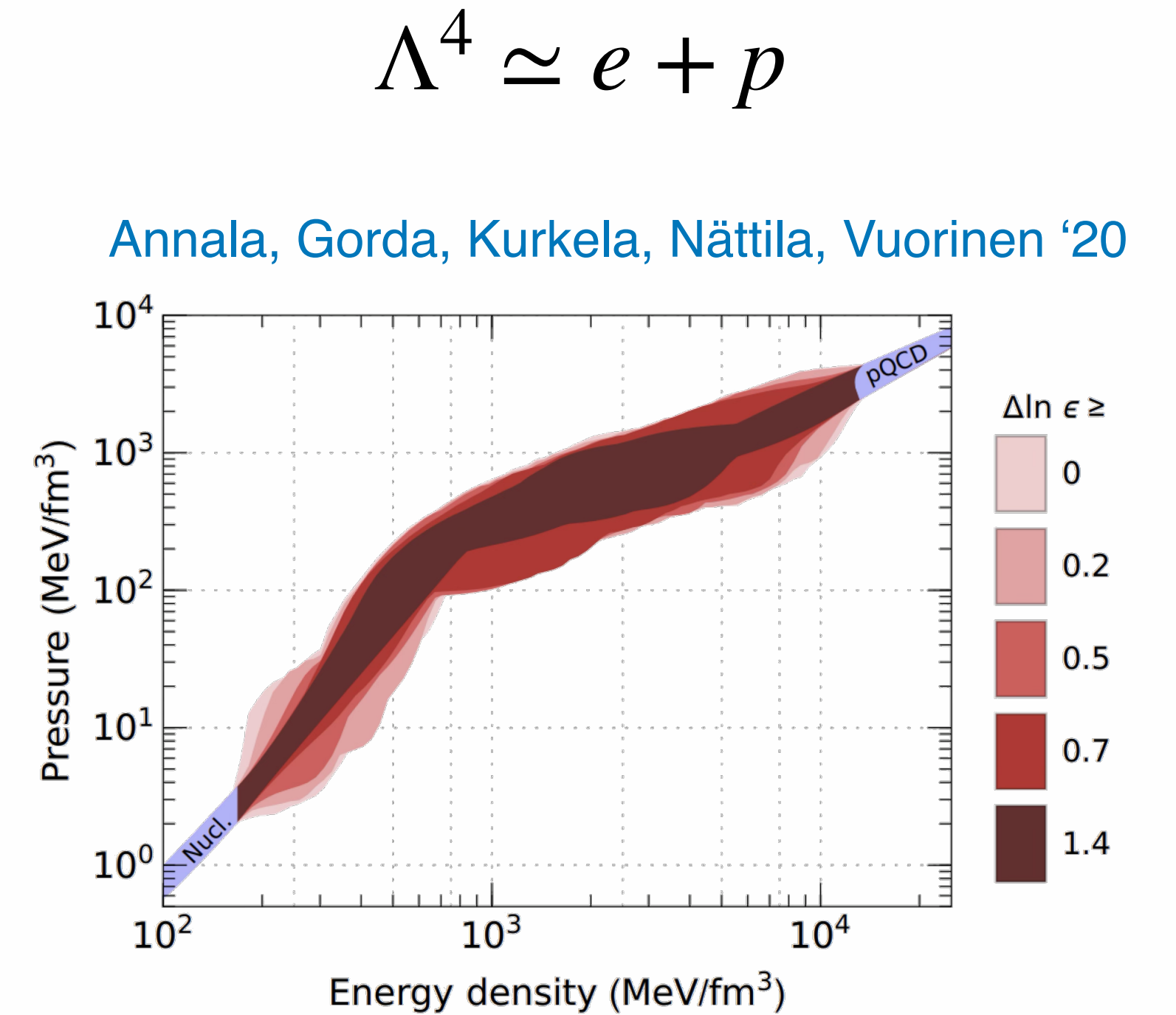
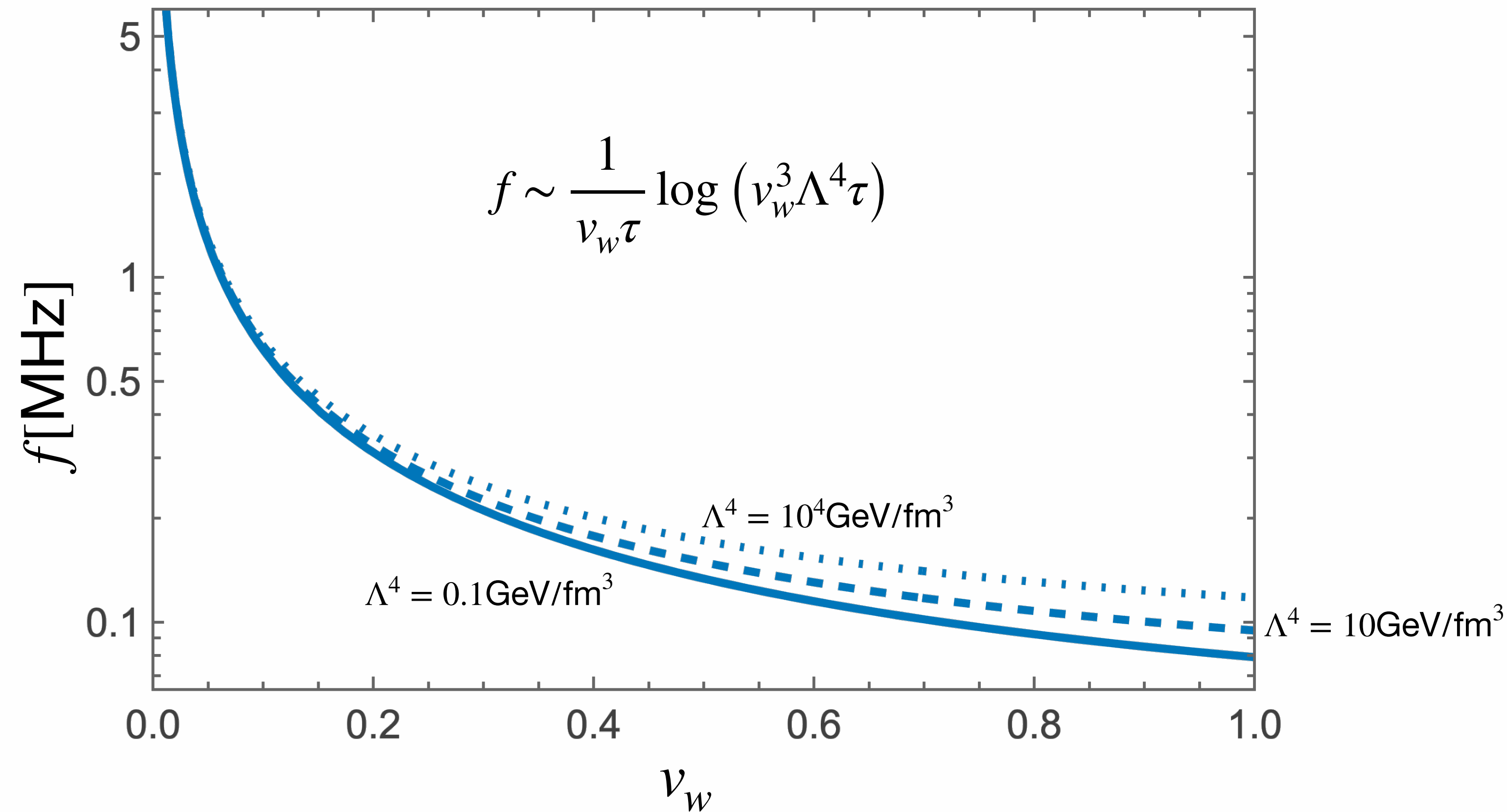


Peak frequency



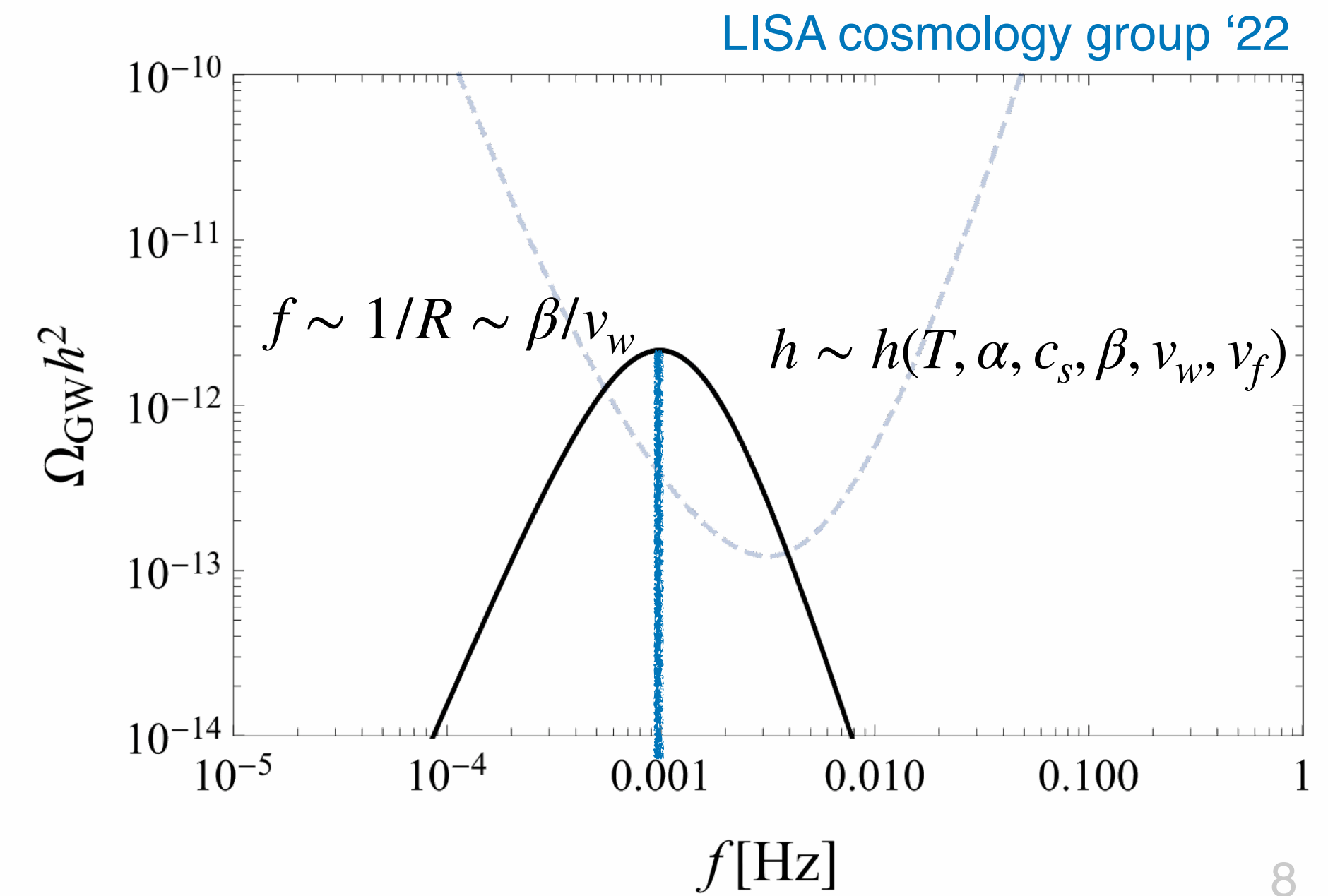
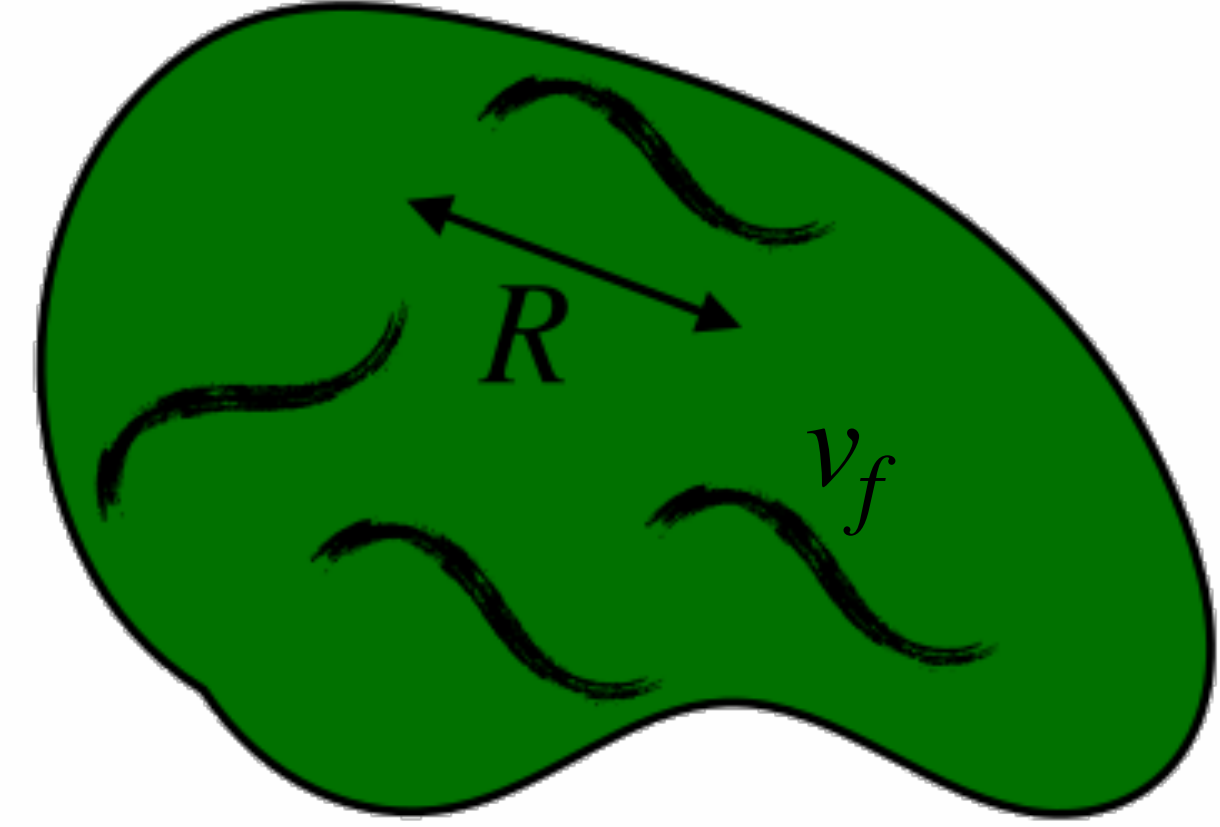
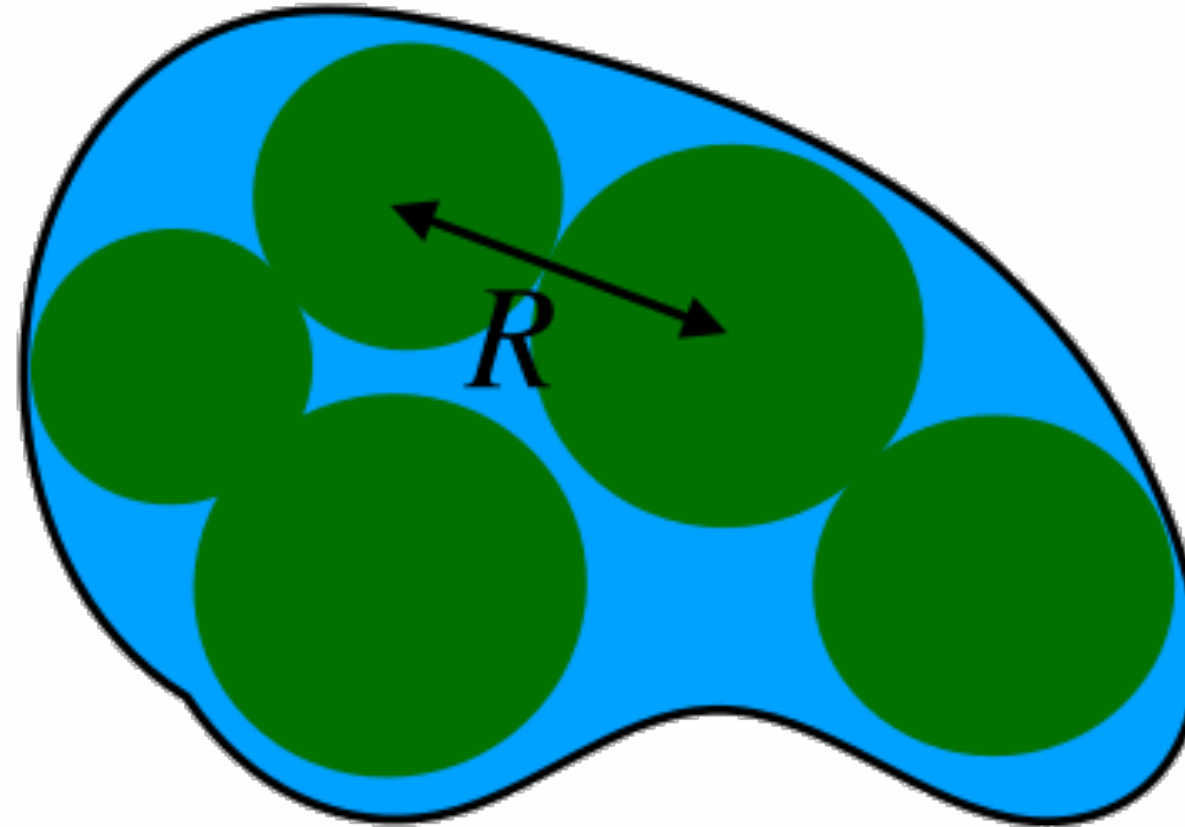
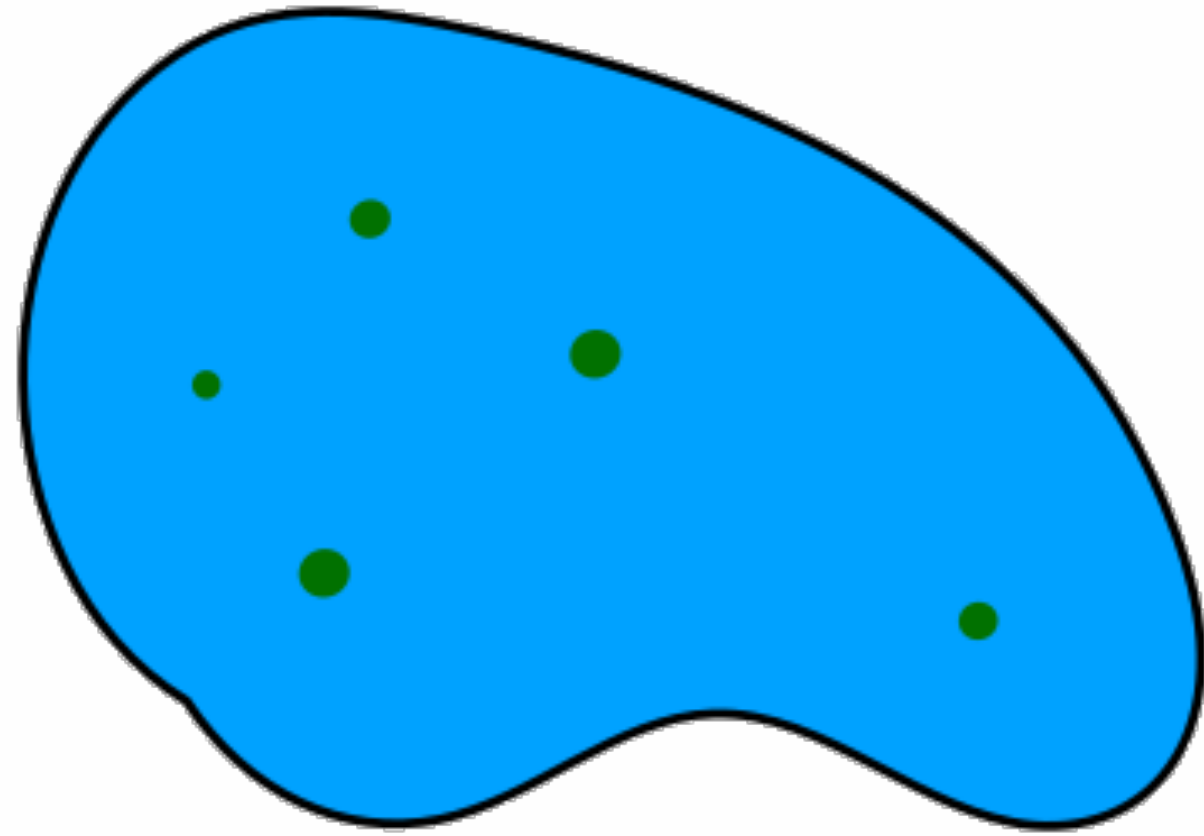
- Uncertainty in microscopic details is logarithmically suppressed

Peak frequency

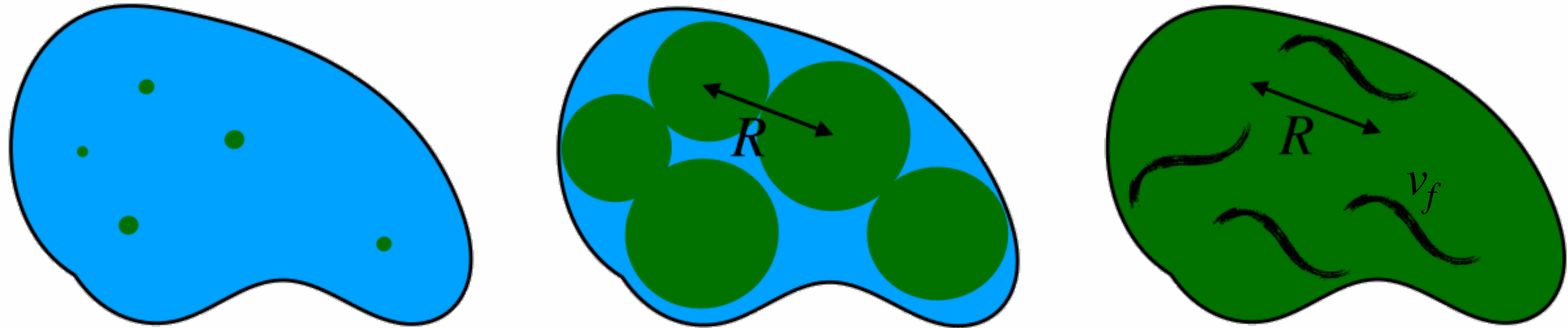


- Uncertainty in microscopic details is logarithmically suppressed
- **Frequency above few hundred kHz**

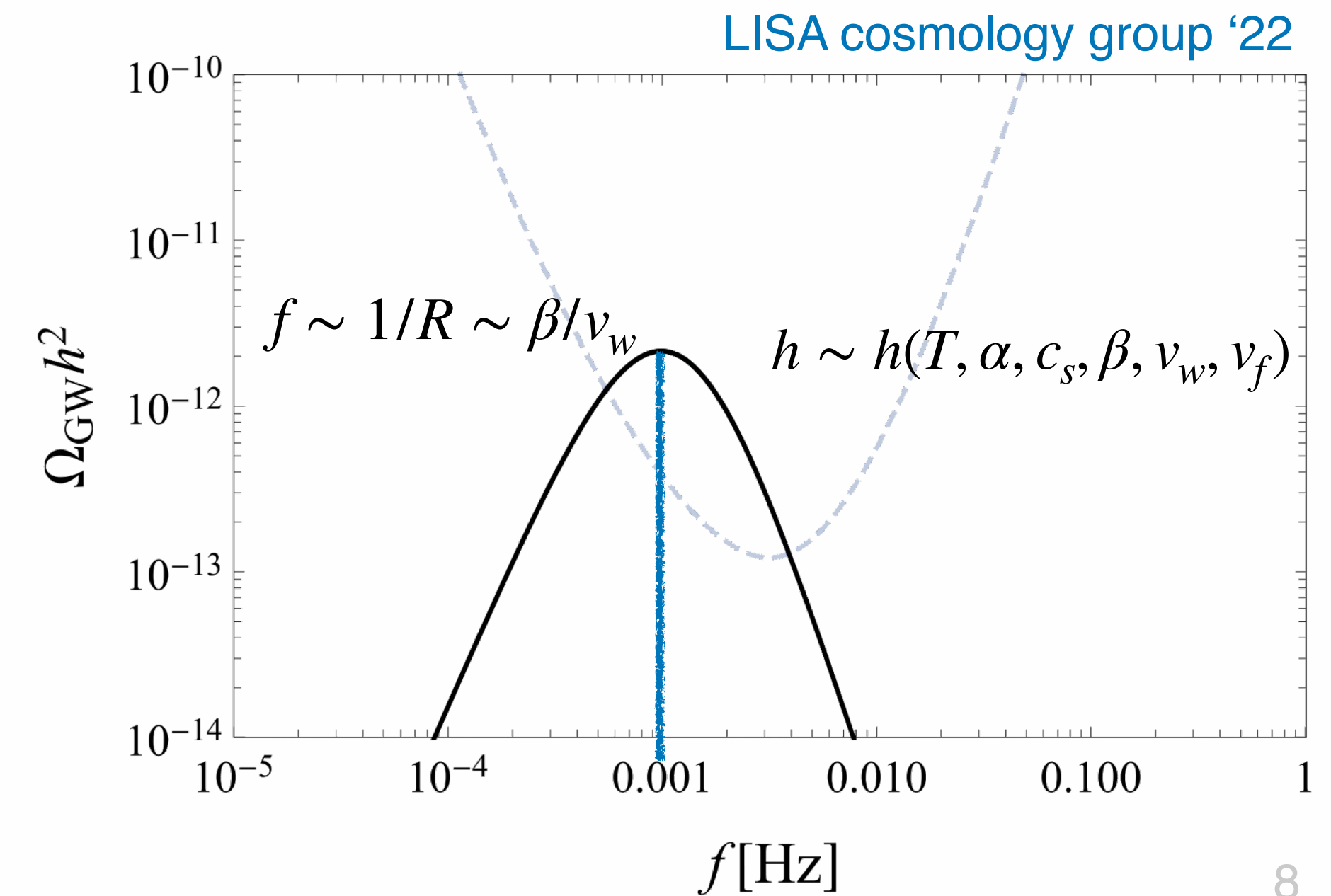
Peak amplitude



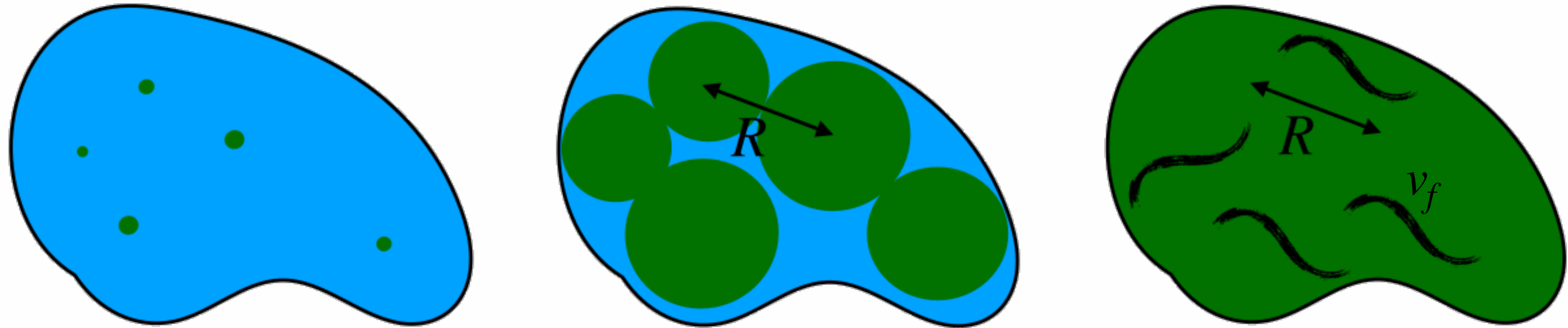
Peak amplitude



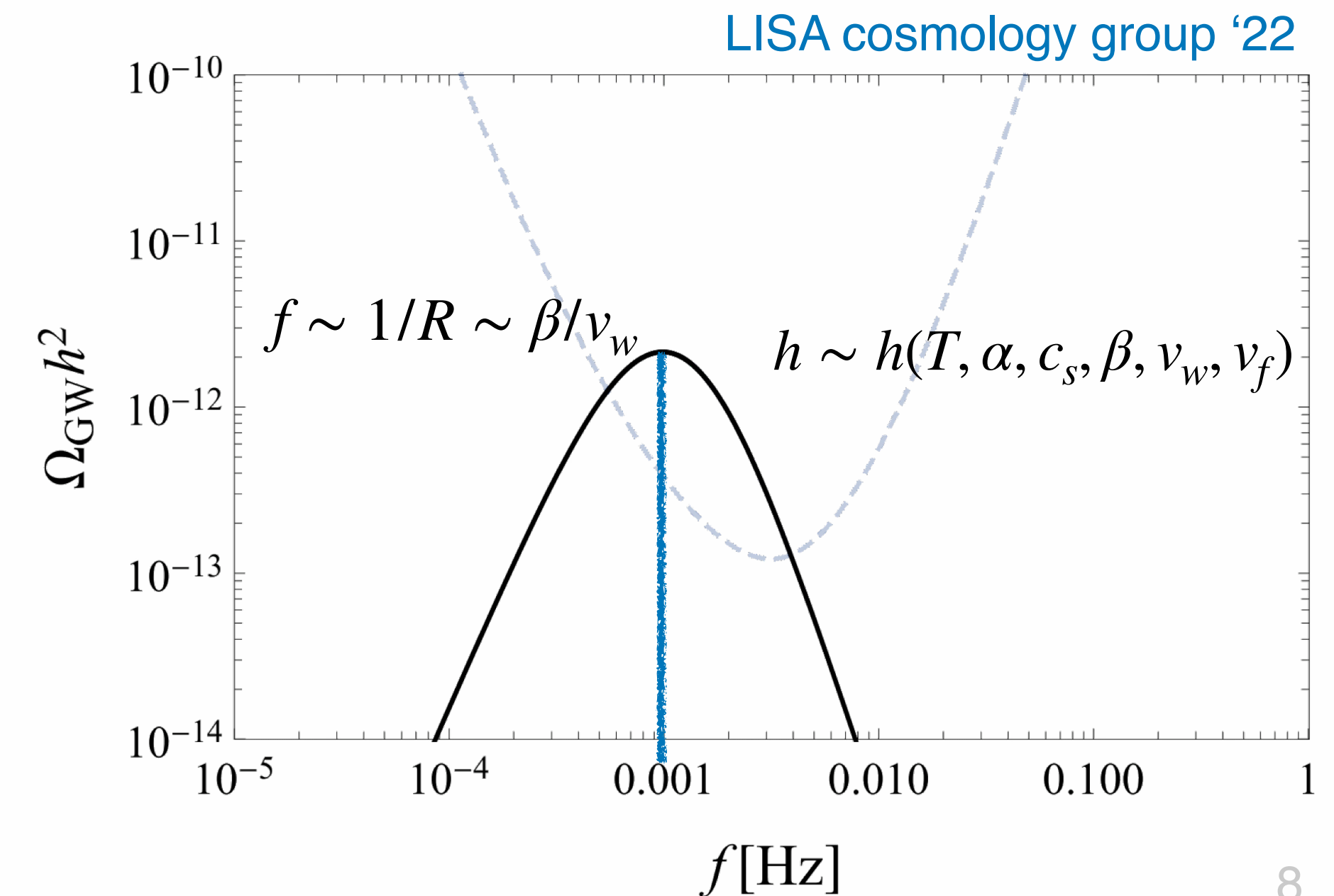
- Sensitive to dynamics of the bubbles and medium



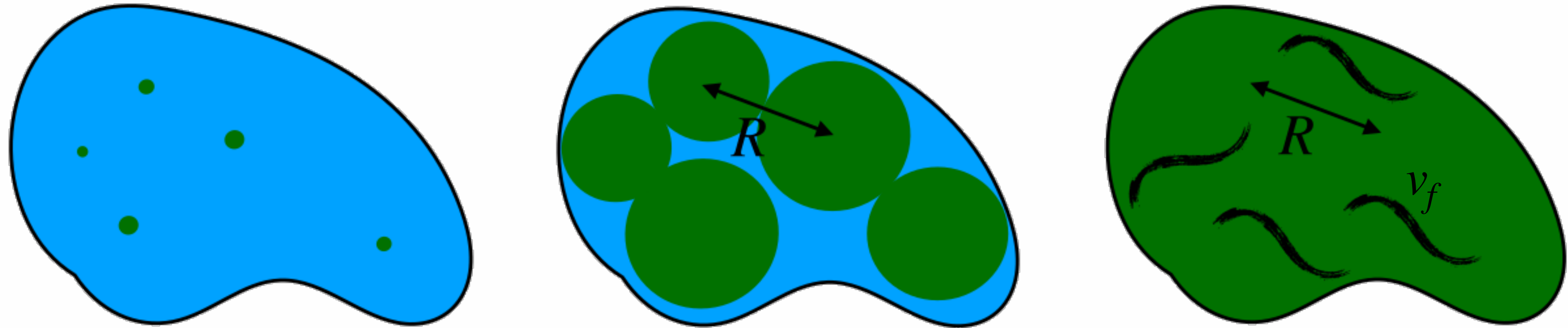
Peak amplitude



- Sensitive to dynamics of the bubbles and medium
- First approximation: use cosmological results

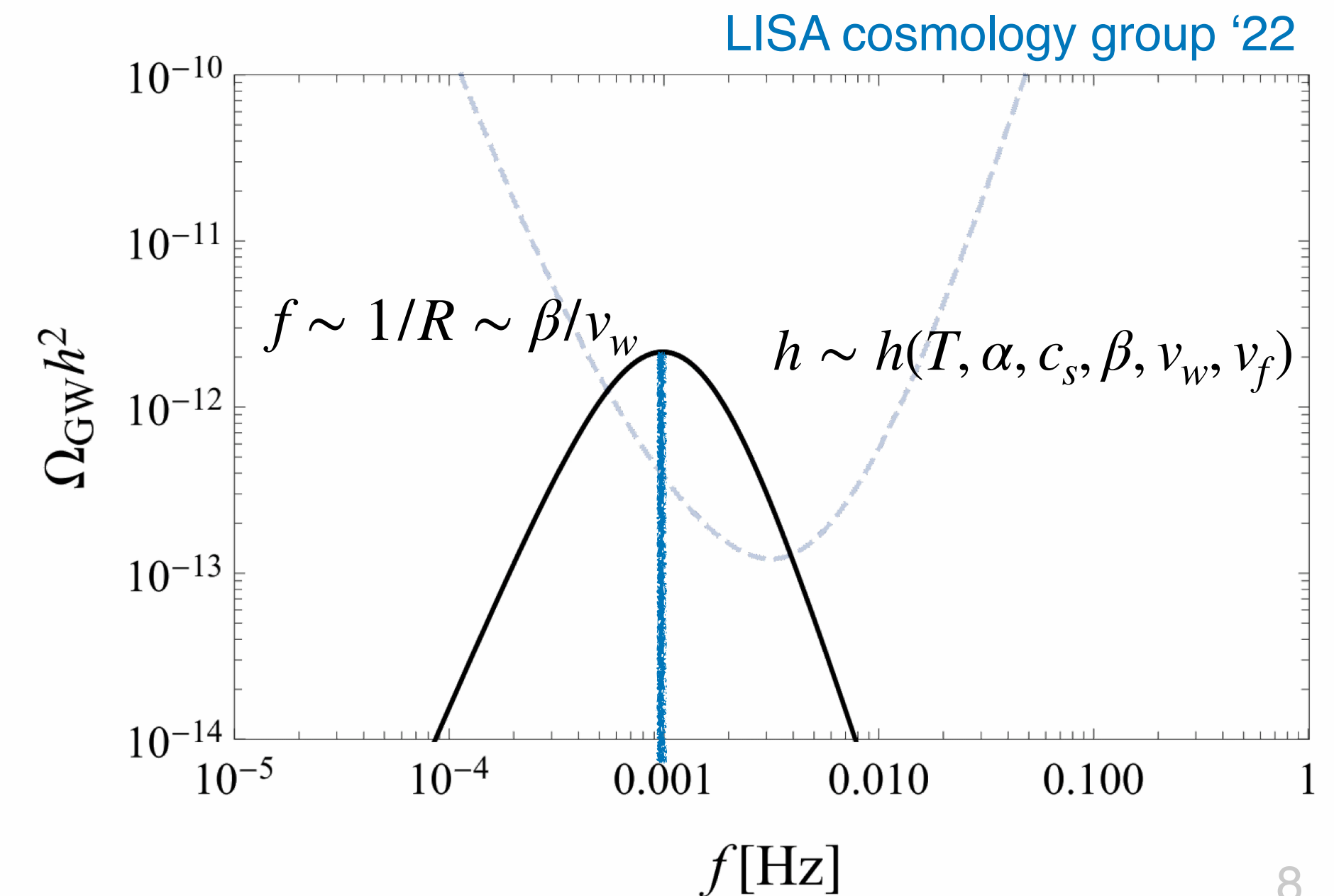


Peak amplitude

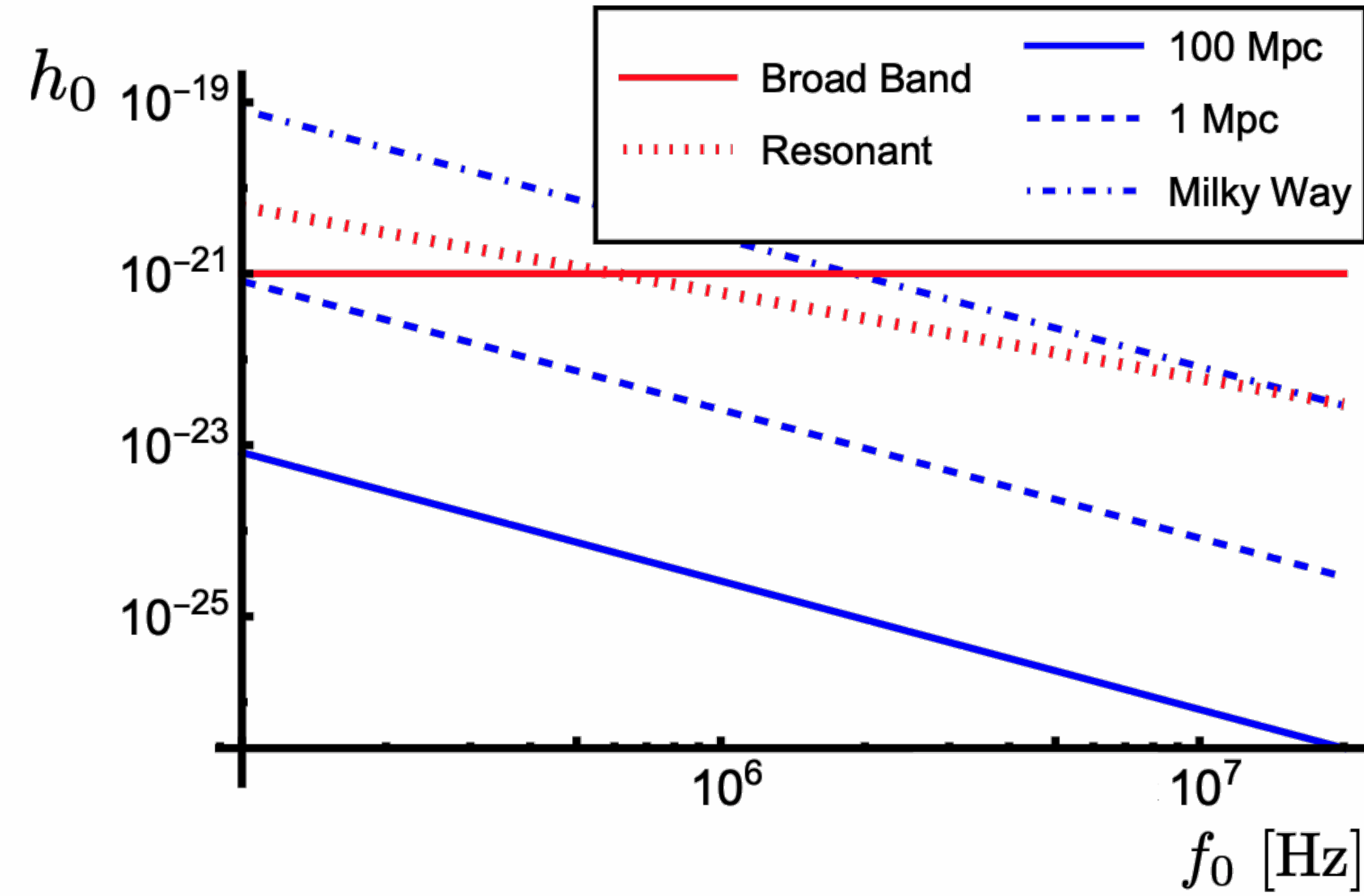


- Sensitive to dynamics of the bubbles and medium
- First approximation: use cosmological results

$$h_0 \sim v_f^2 \frac{\Lambda^4}{f^{3/2} d} \quad 0.01 \leq v_f \leq 0.3$$



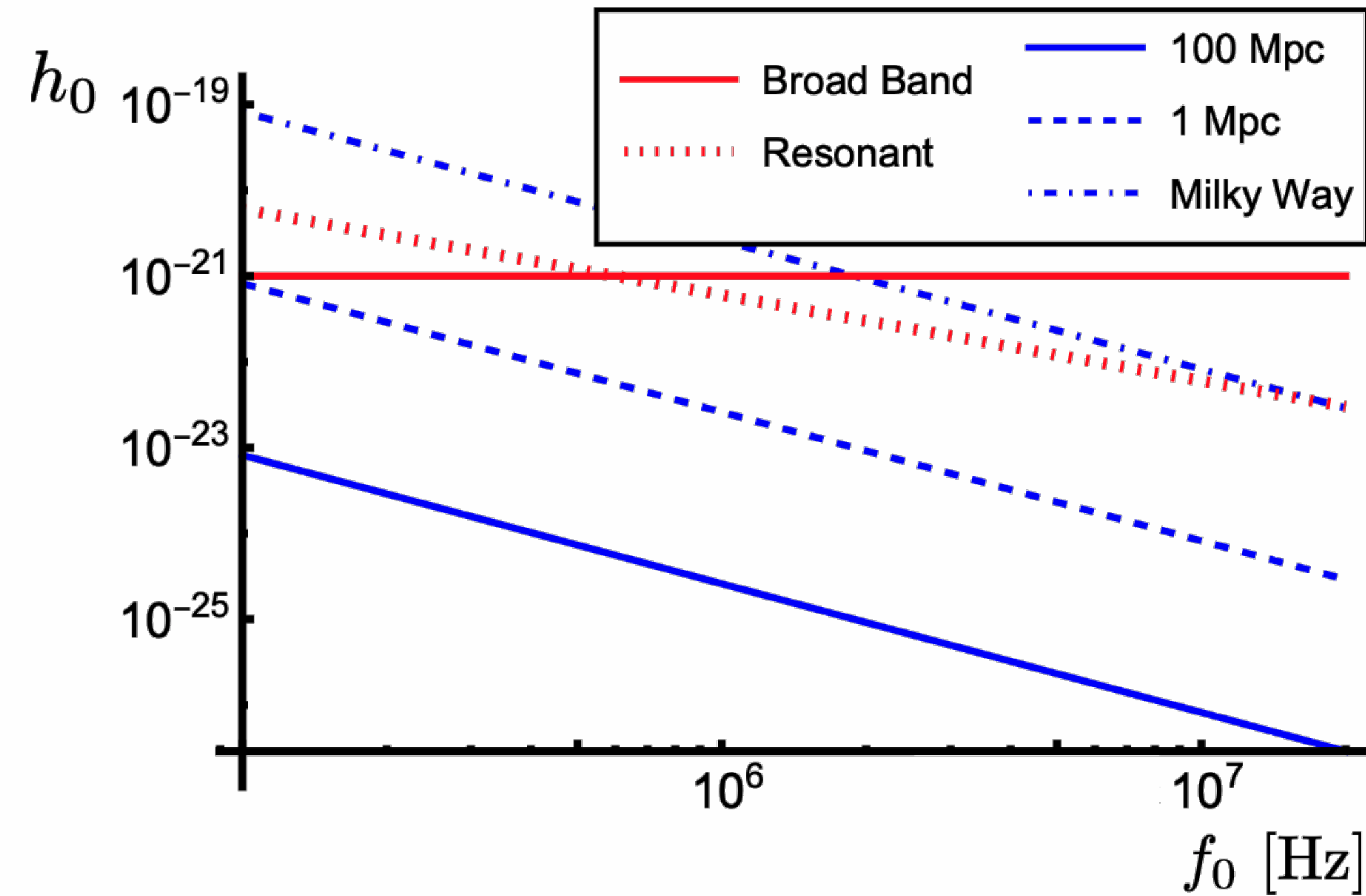
Peak amplitude



Weber bars

Domcke, Ellis, Rodd '25

Peak amplitude

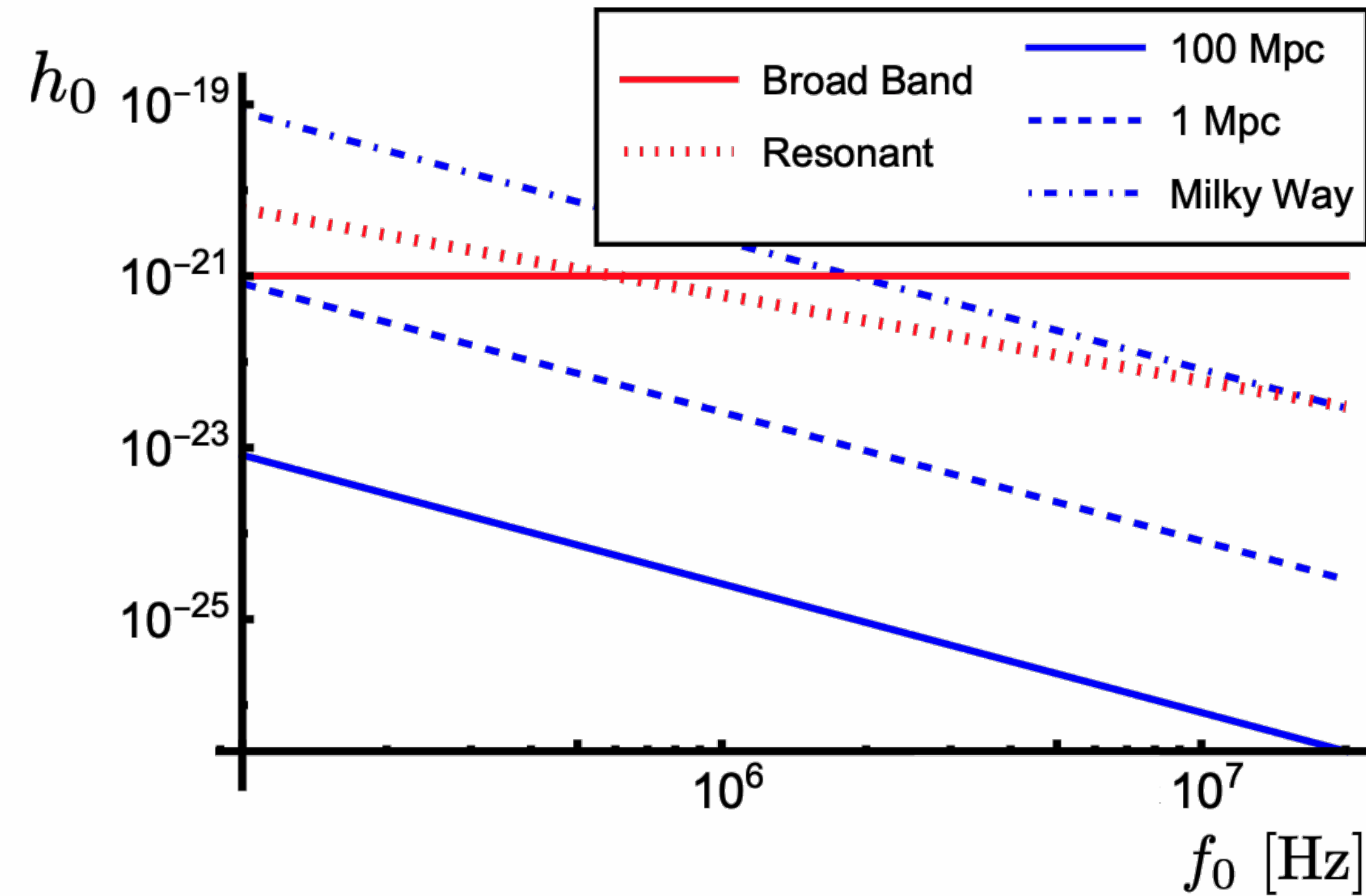


Weber bars

Domcke, Ellis, Rodd '25

- Broadband or resonant searches depending on frequency

Peak amplitude

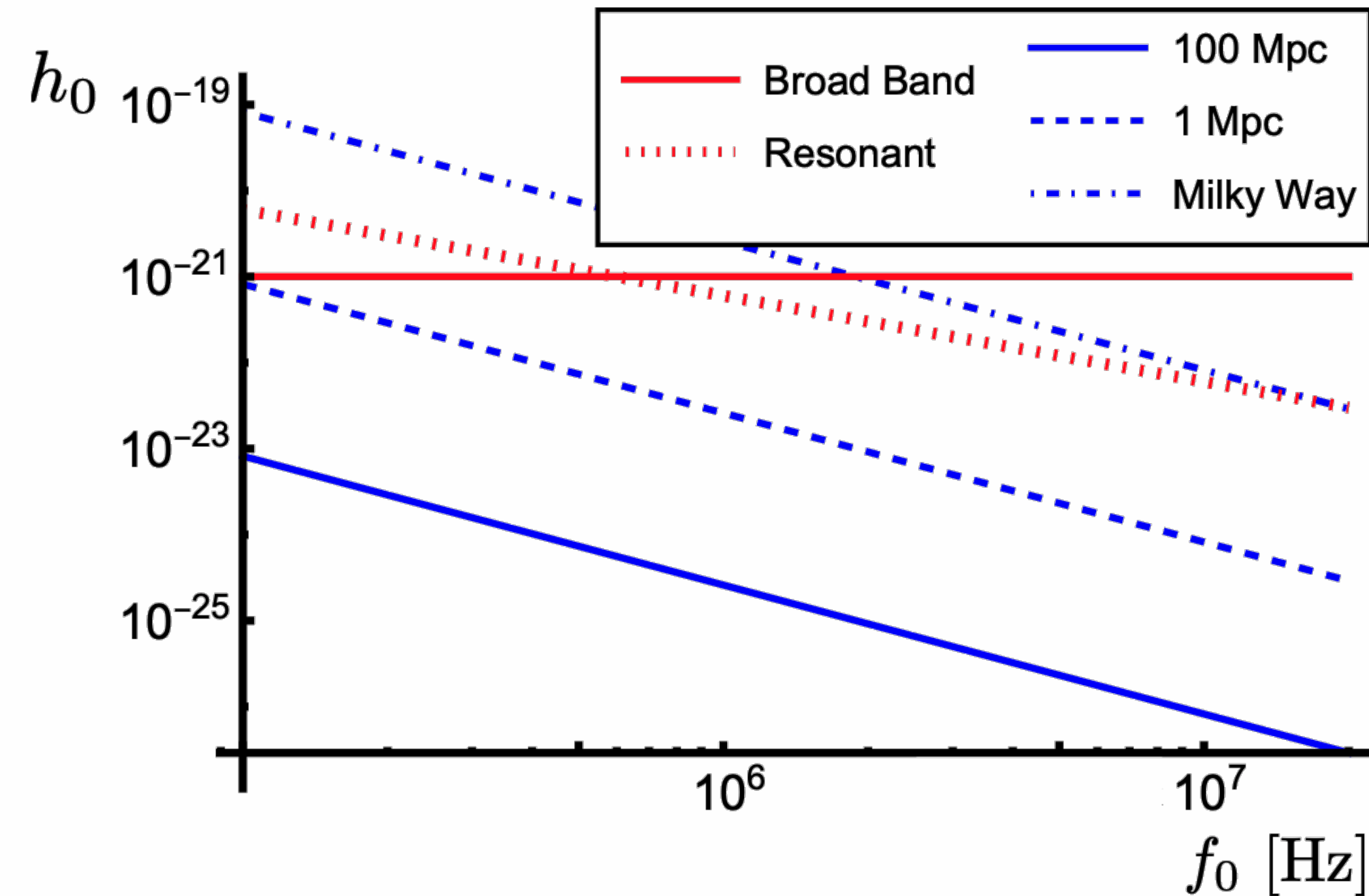


Weber bars

Domcke, Ellis, Rodd '25

- Broadband or resonant searches depending on frequency
- Short signal but inspiral signal allow for coincident methods

Peak amplitude



Weber bars

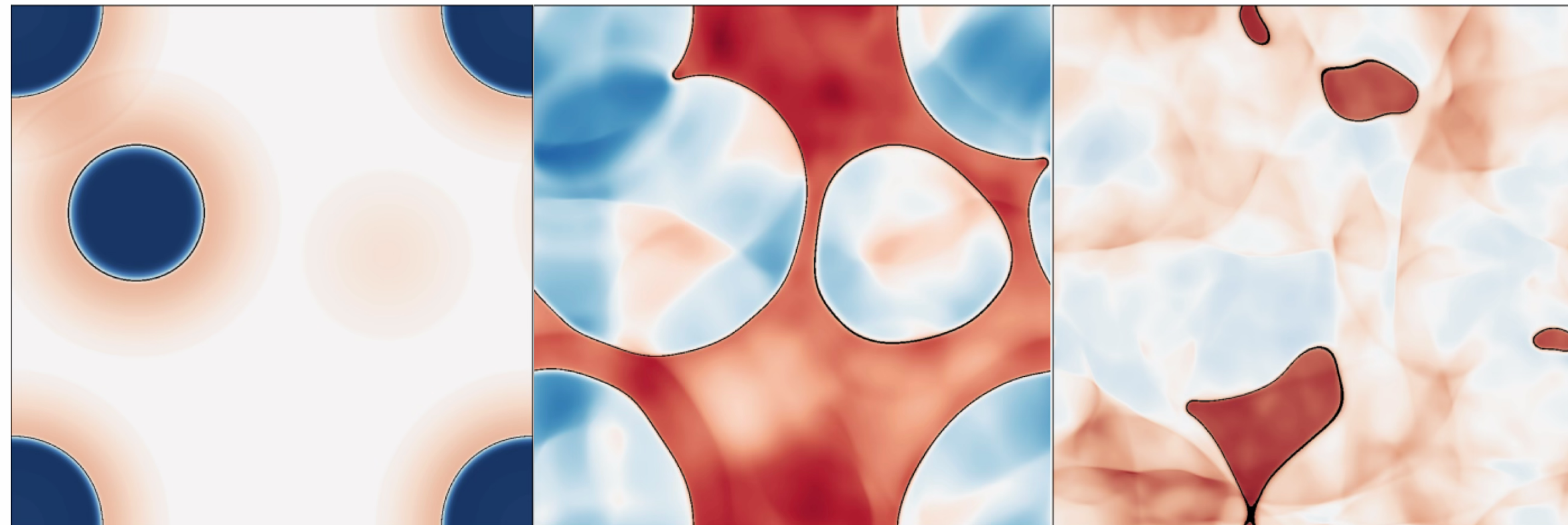
Domcke, Ellis, Rodd '25

- Broadband or resonant searches depending on frequency
- Short signal but inspiral signal allow for coincident methods
- Multiple detectors can improve sensitivity

Theoretical improvements

Theoretical improvements

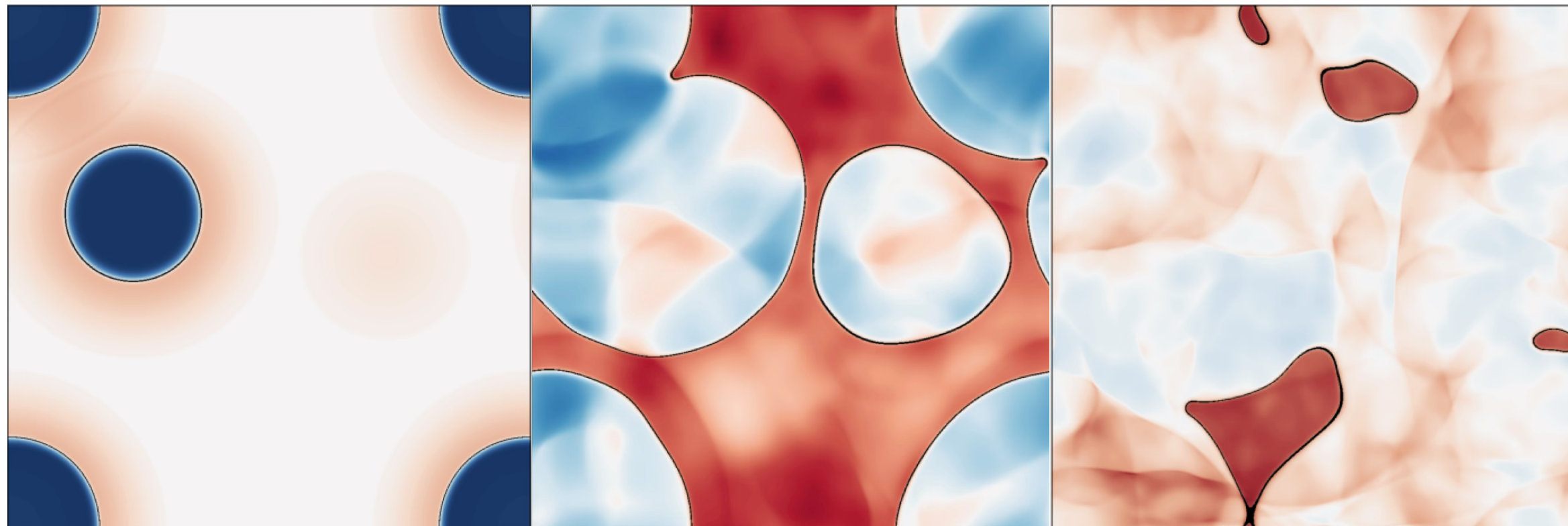
- Existing FOPTs results:



Cutting, Hindmarsh, Weir '19

Theoretical improvements

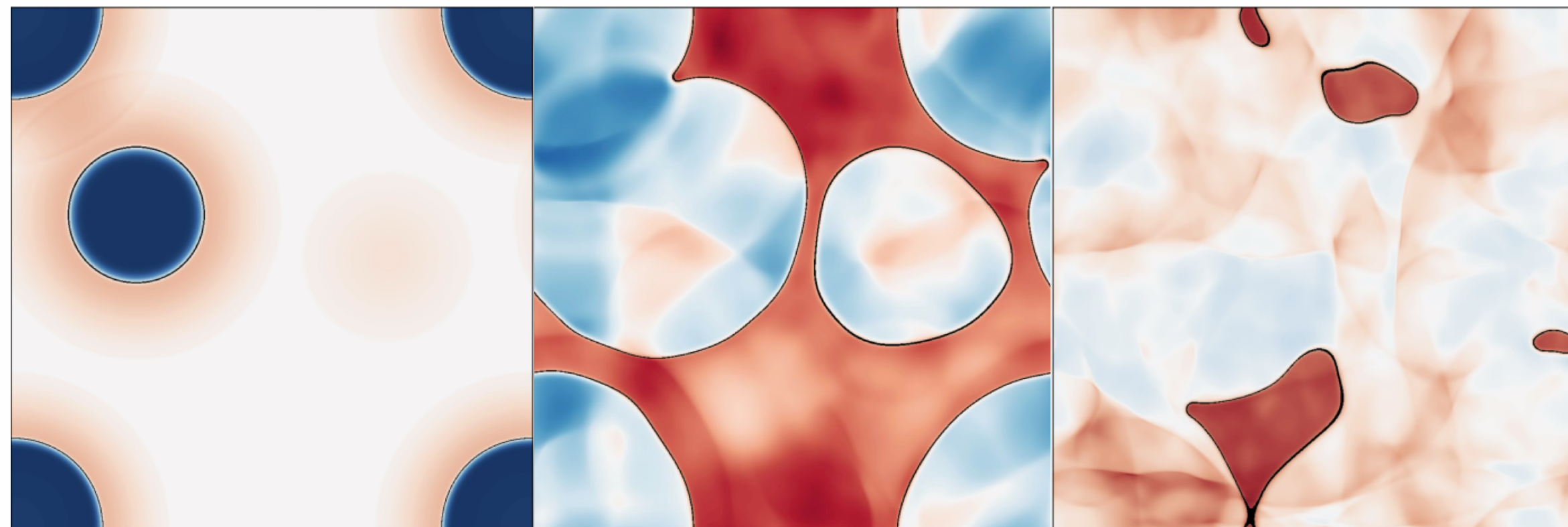
- Existing FOPTs results:
 - Electroweak-like: weak coupling



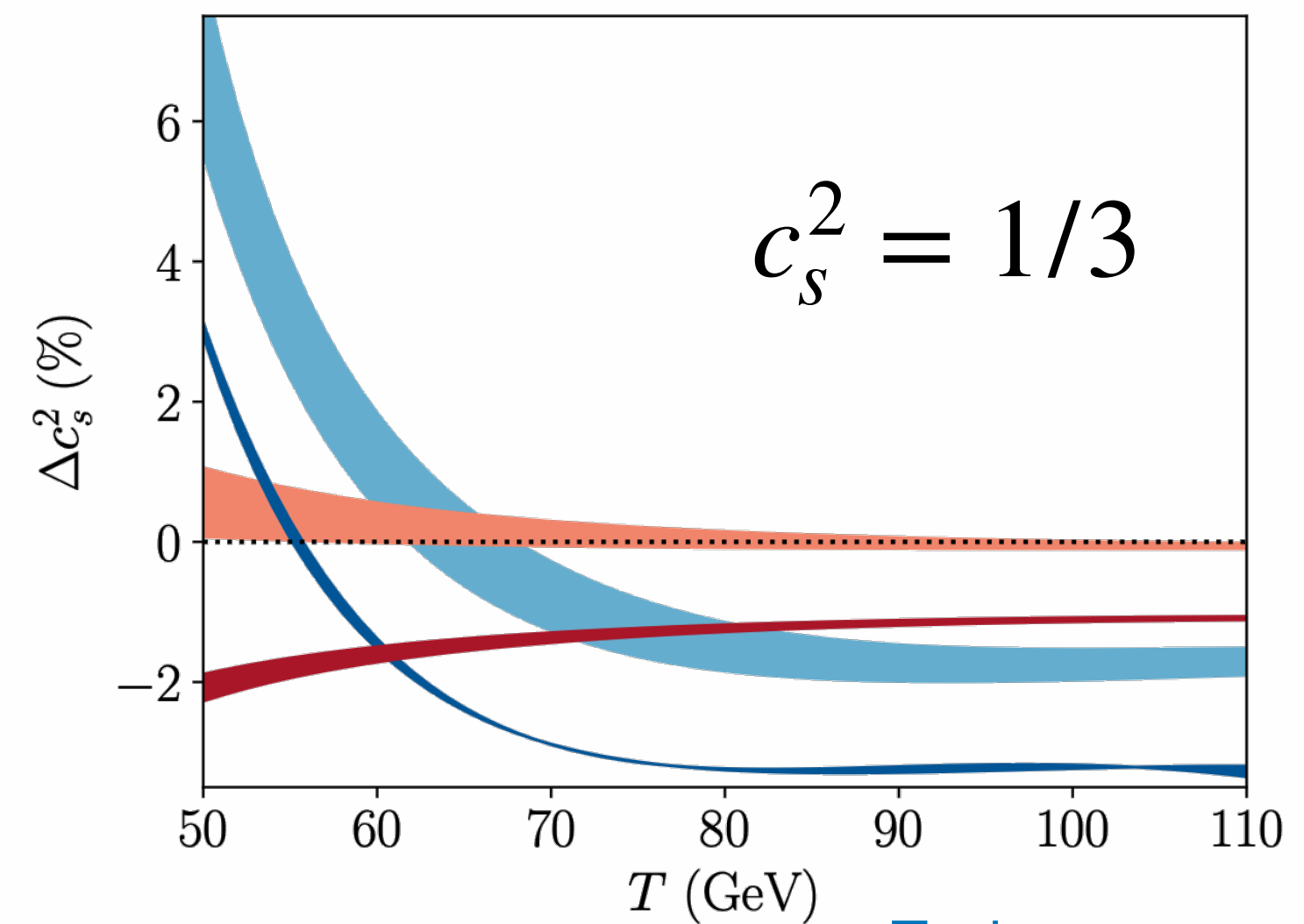
Cutting, Hindmarsh, Weir '19

Theoretical improvements

- Existing FOPTs results:
 - Electroweak-like: weak coupling
 - Constant speed of sound



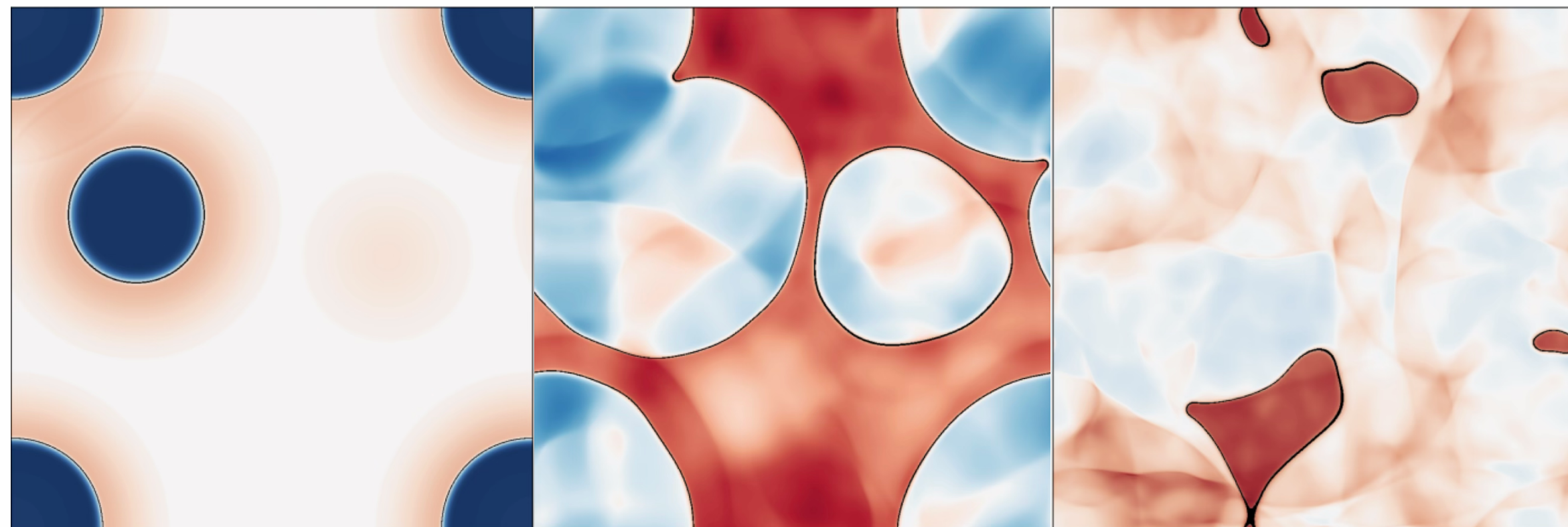
Cutting, Hindmarsh, Weir '19



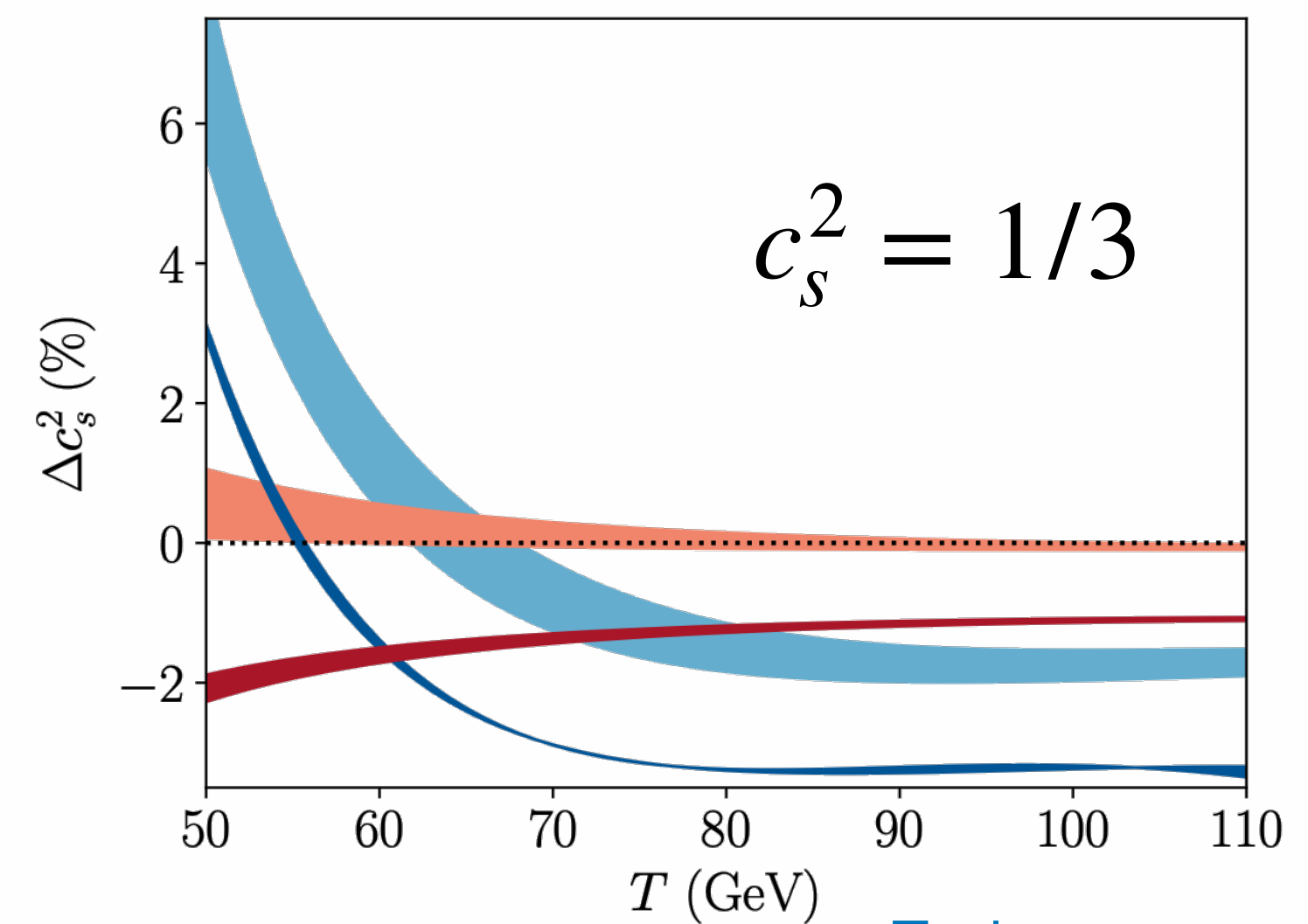
Tenkanen, van de Vis '22

Theoretical improvements

- Existing FOPTs results:
 - Electroweak-like: weak coupling
 - Constant speed of sound
 - Direct: from high to low energies



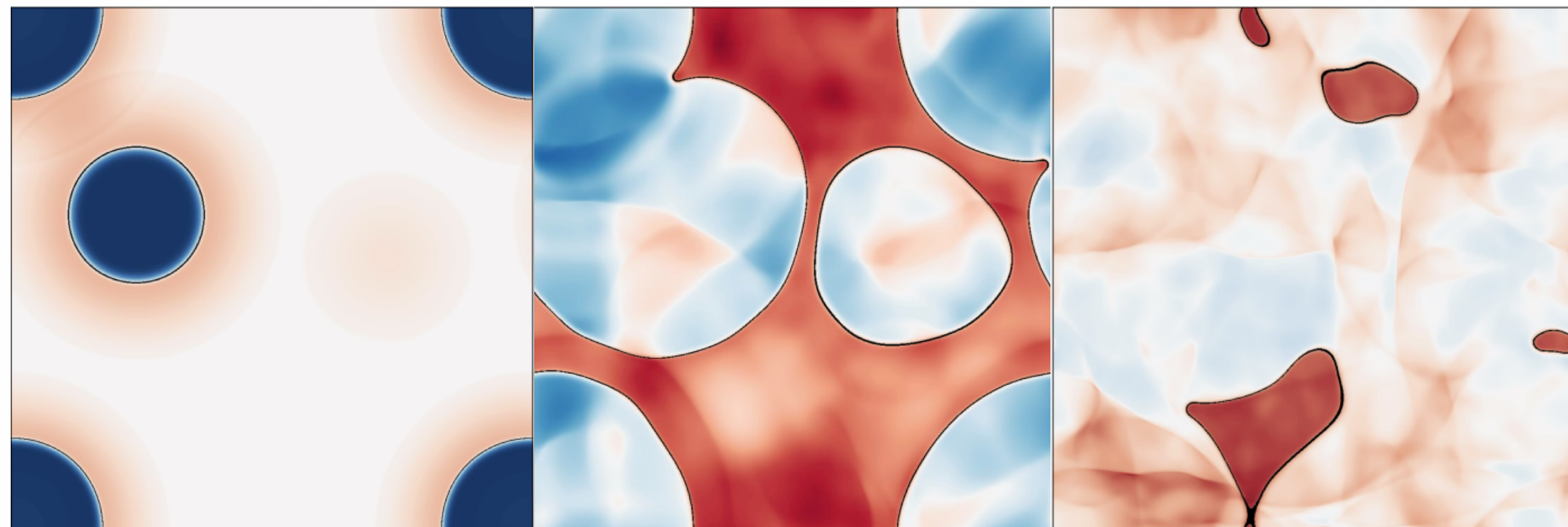
Cutting, Hindmarsh, Weir '19



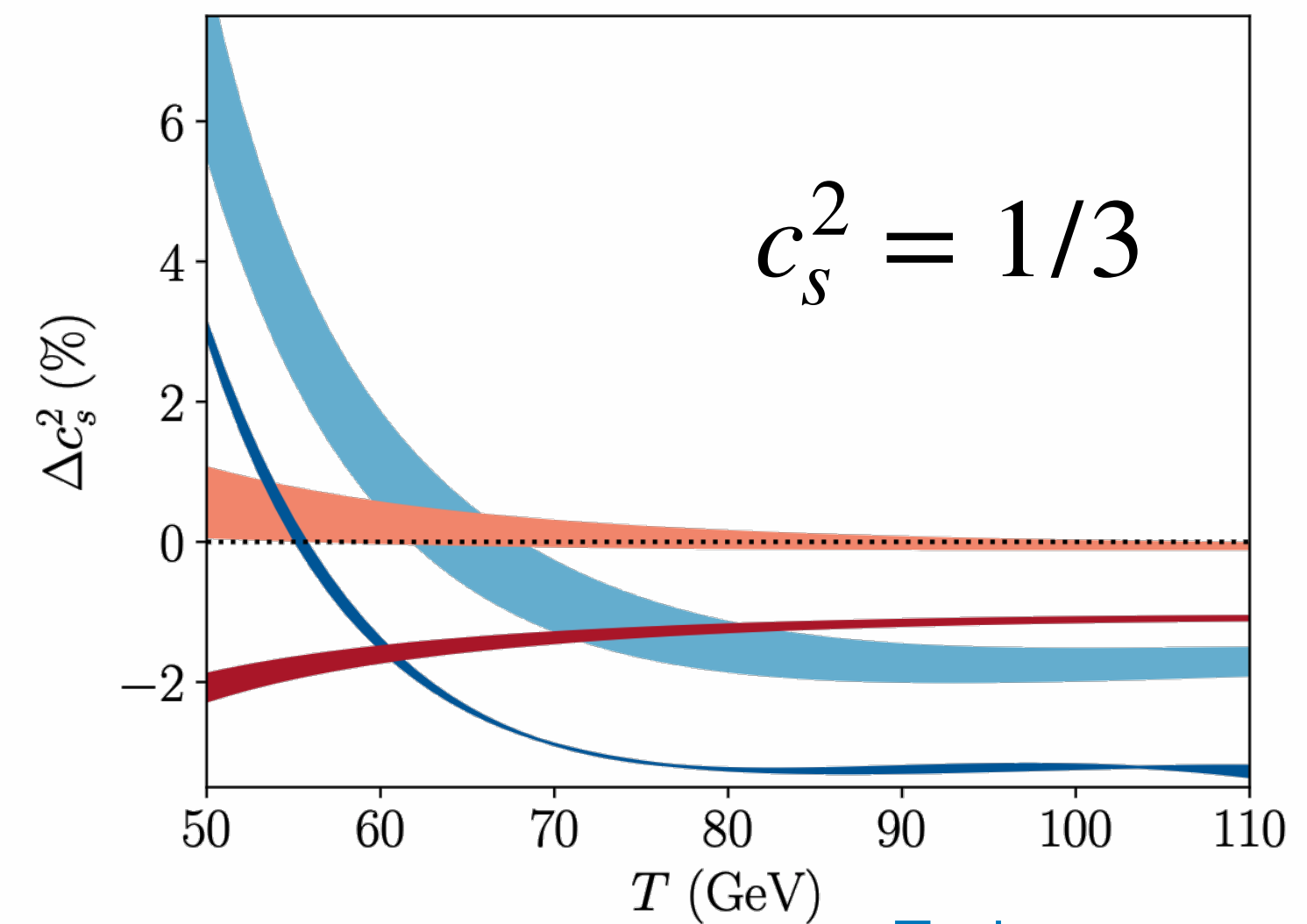
Tenkanen, van de Vis '22

Theoretical improvements

- Existing FOPTs results:
 - Electroweak-like: weak coupling
 - Constant speed of sound
 - Direct: from high to low energies
 - Final homogeneous state



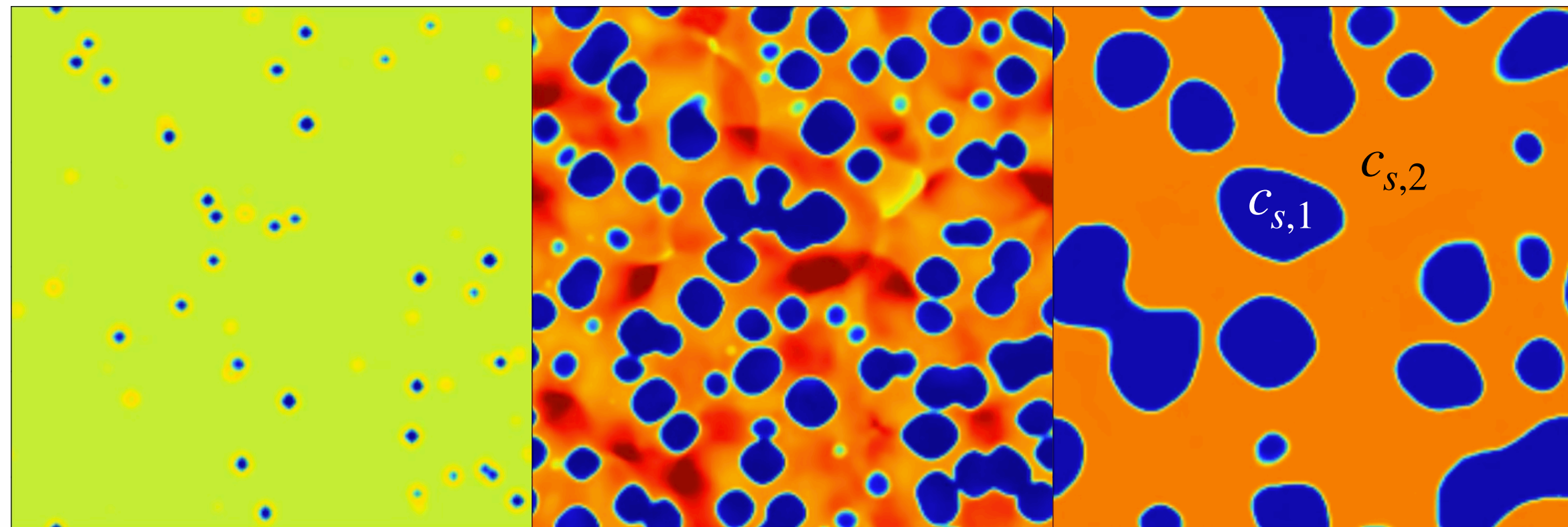
Cutting, Hindmarsh, Weir '19



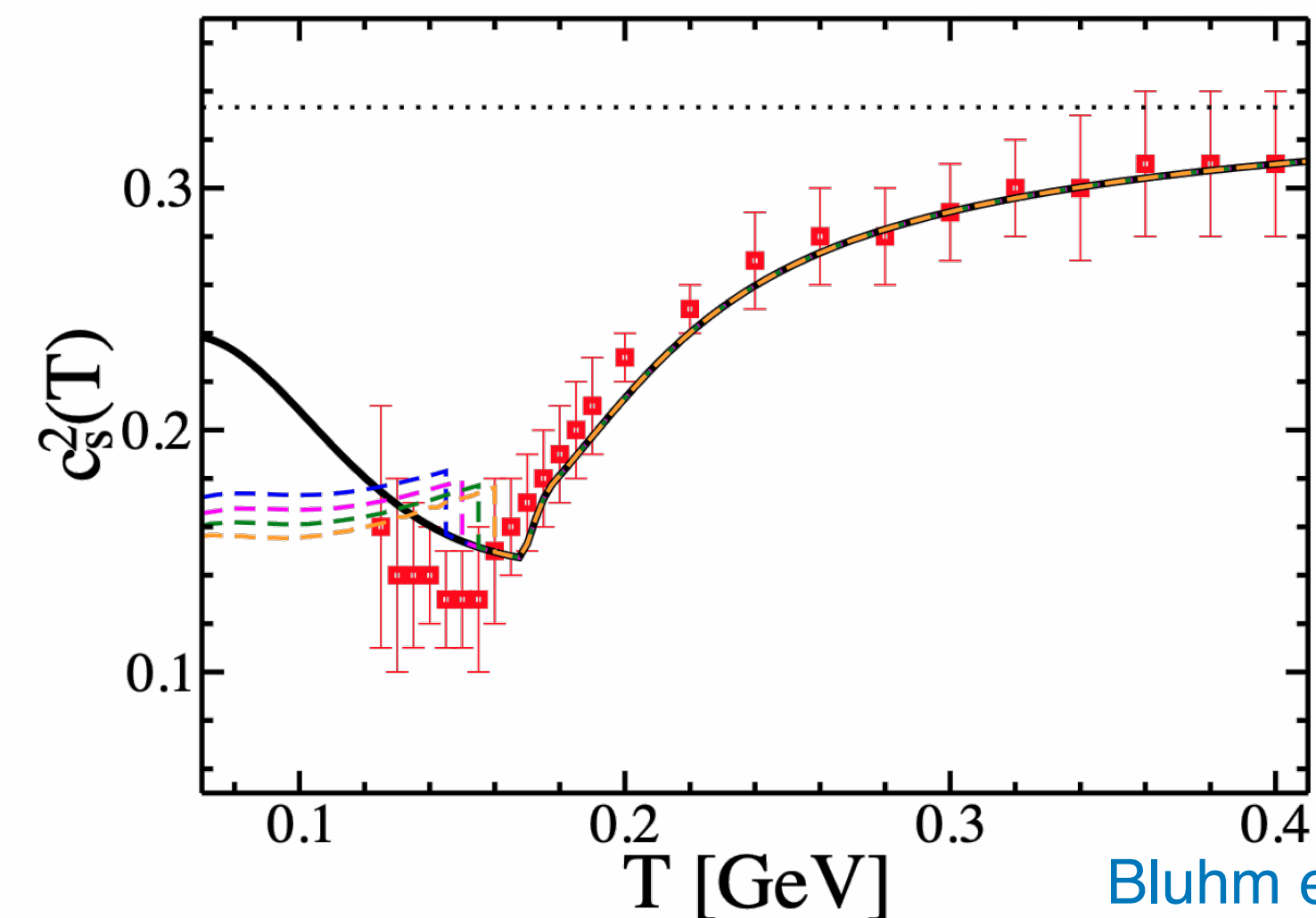
Tenkanen, van de Vis '22

Theoretical improvements

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- Neutron star FOPTs:



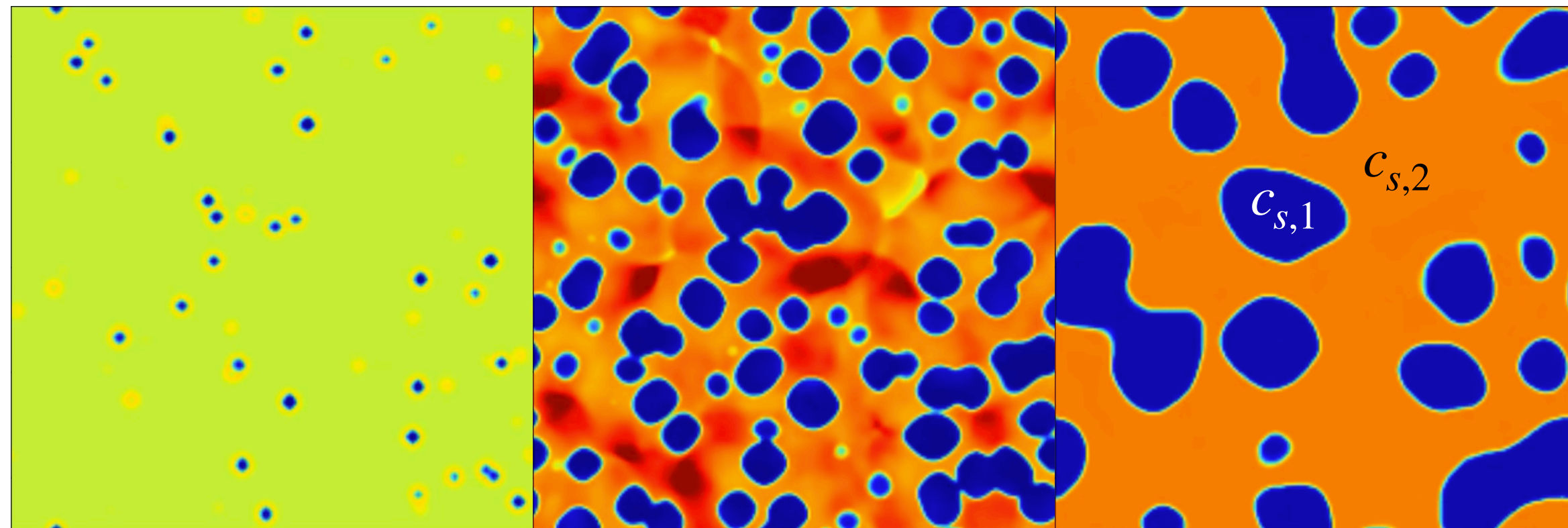
Bea, Luna, Mateos, MSG, Tarancon-Alvarez, van de Vis in progress



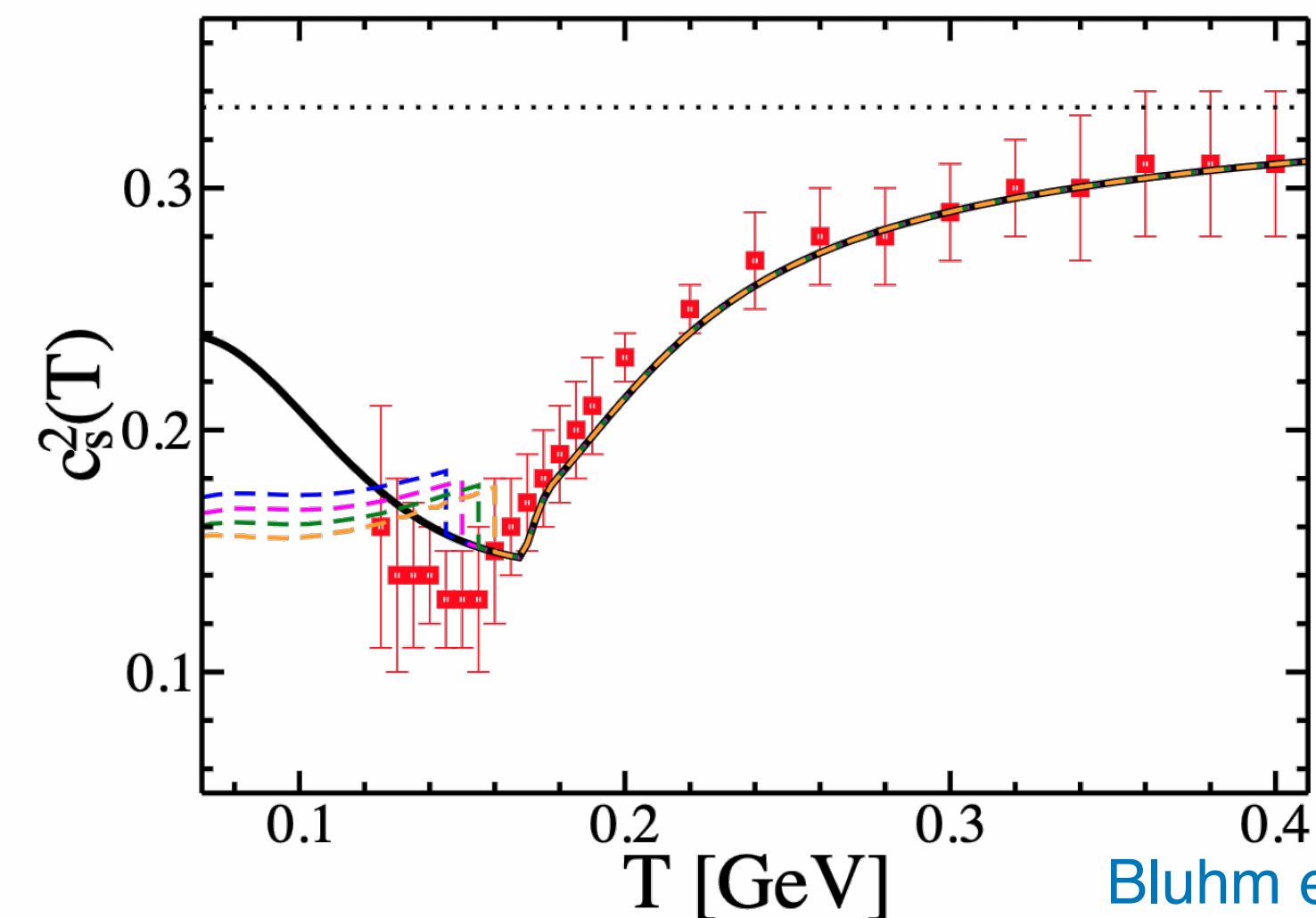
Bluhm et al '13

Theoretical improvements

- Existing FOPTs results:
 - Electroweak-like: weak coupling
 - Constant speed of sound
 - Direct: from high to low energies
 - Final homogeneous state
- Neutron star FOPTs:
 - Strong coupling & finite density



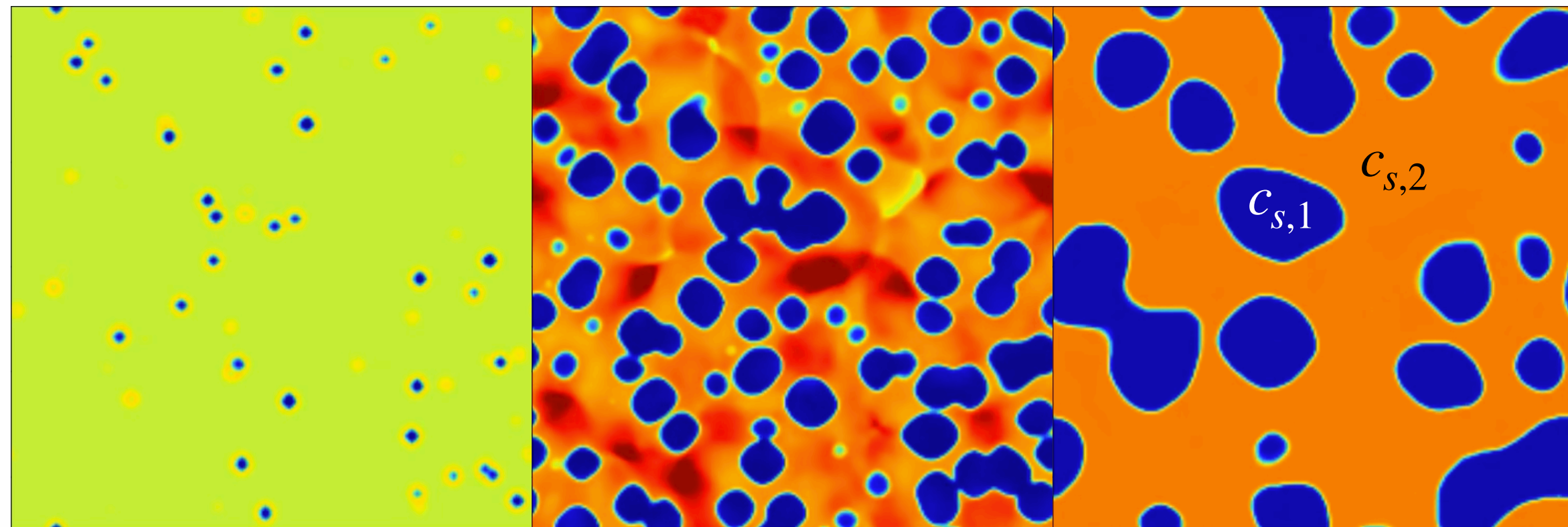
Bea, Luna, Mateos, MSG, Tarancon-Alvarez, van de Vis in progress



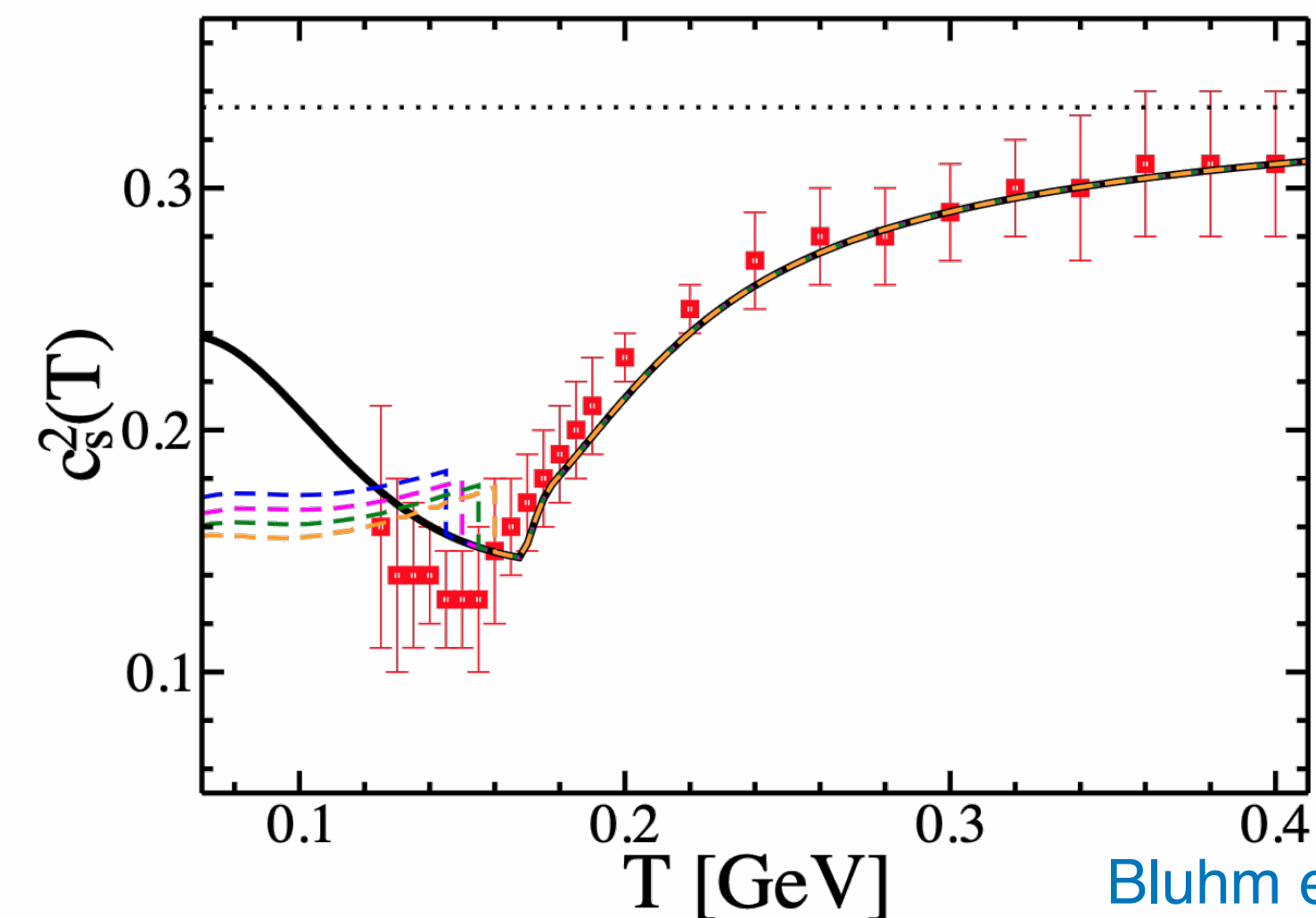
Bluhm et al '13

Theoretical improvements

- Existing FOPTs results:
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 - Constant speed of sound
 - Direct: from high to low energies
 - Final homogeneous state
- Neutron star FOPTs:
 - Strong coupling & finite density
 - Non-constant speed of sound



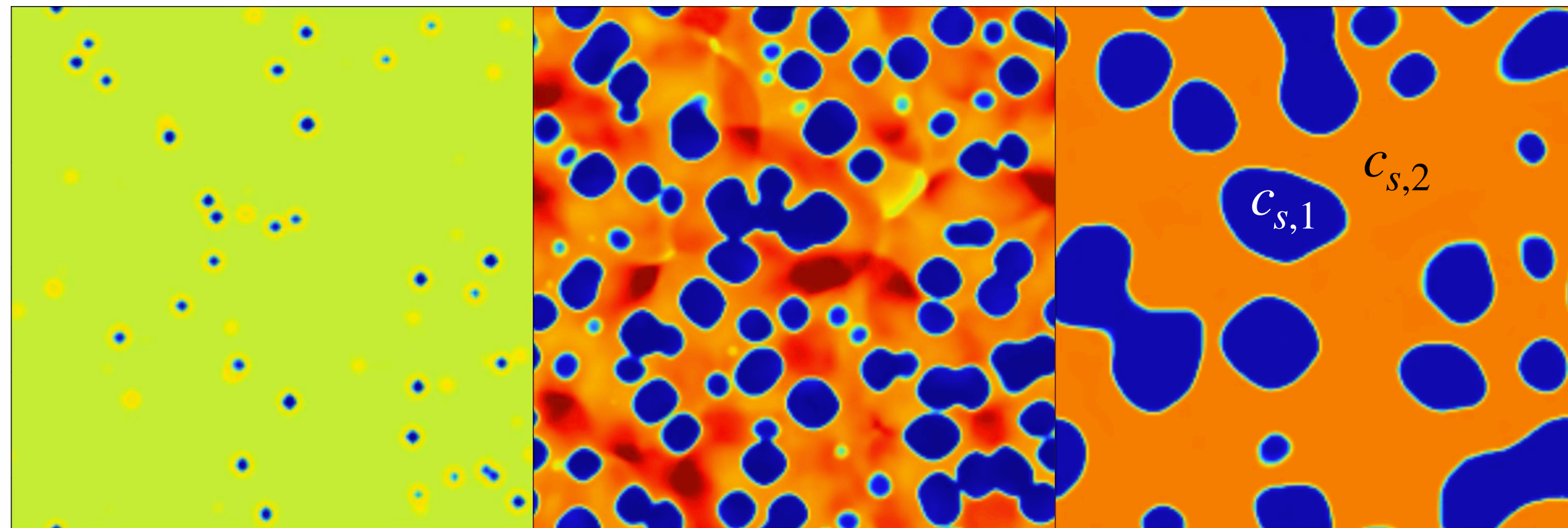
Bea, Luna, Mateos, MSG, Tarancon-Alvarez, van de Vis in progress



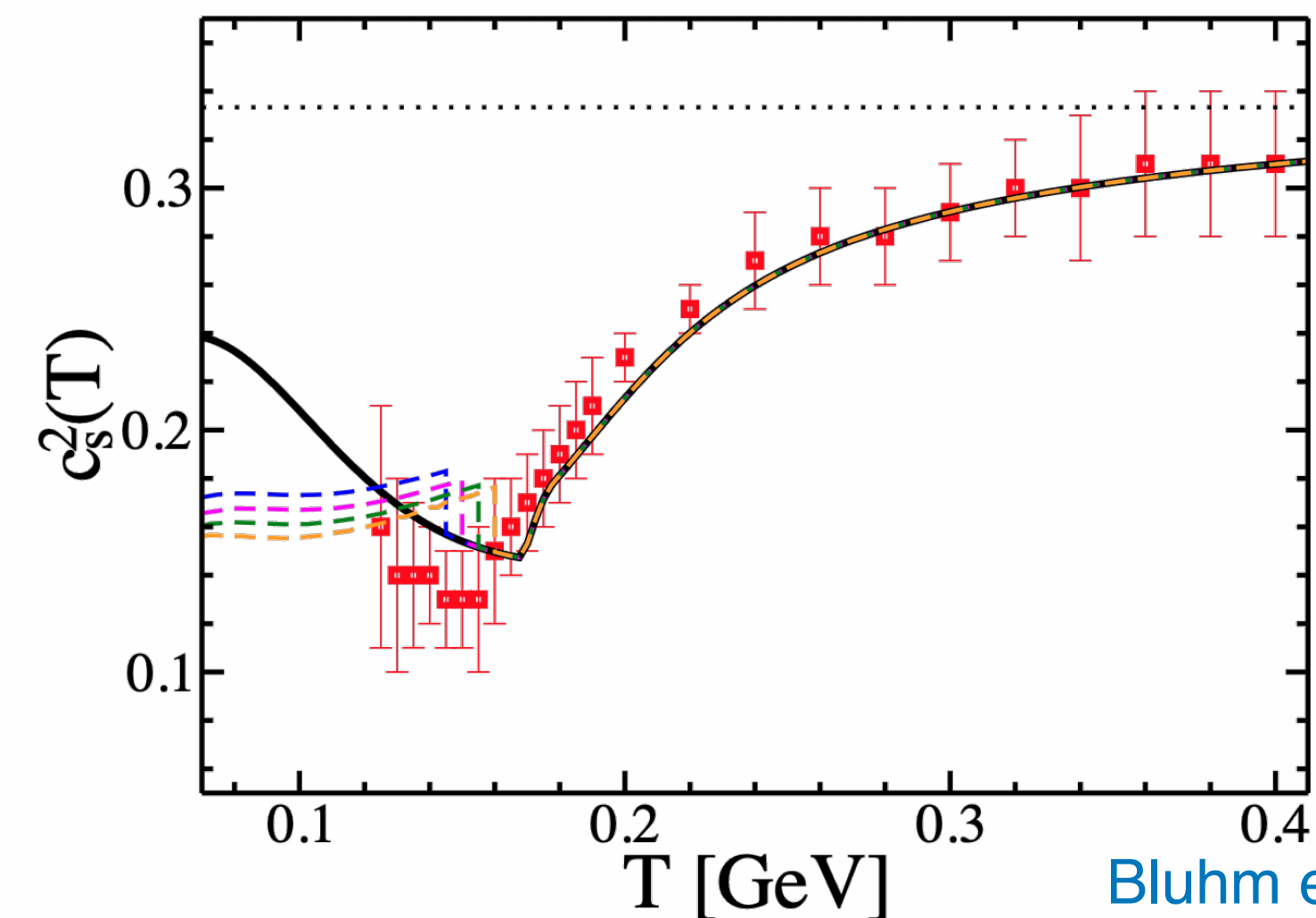
Bluhm et al '13

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 - Electroweak-like: weak coupling
 - Constant speed of sound
 - Direct: from high to low energies
 - Final homogeneous state
- Neutron star FOPTs:
 - Strong coupling & finite density
 - Non-constant speed of sound
 - Inverse: from low to high energies



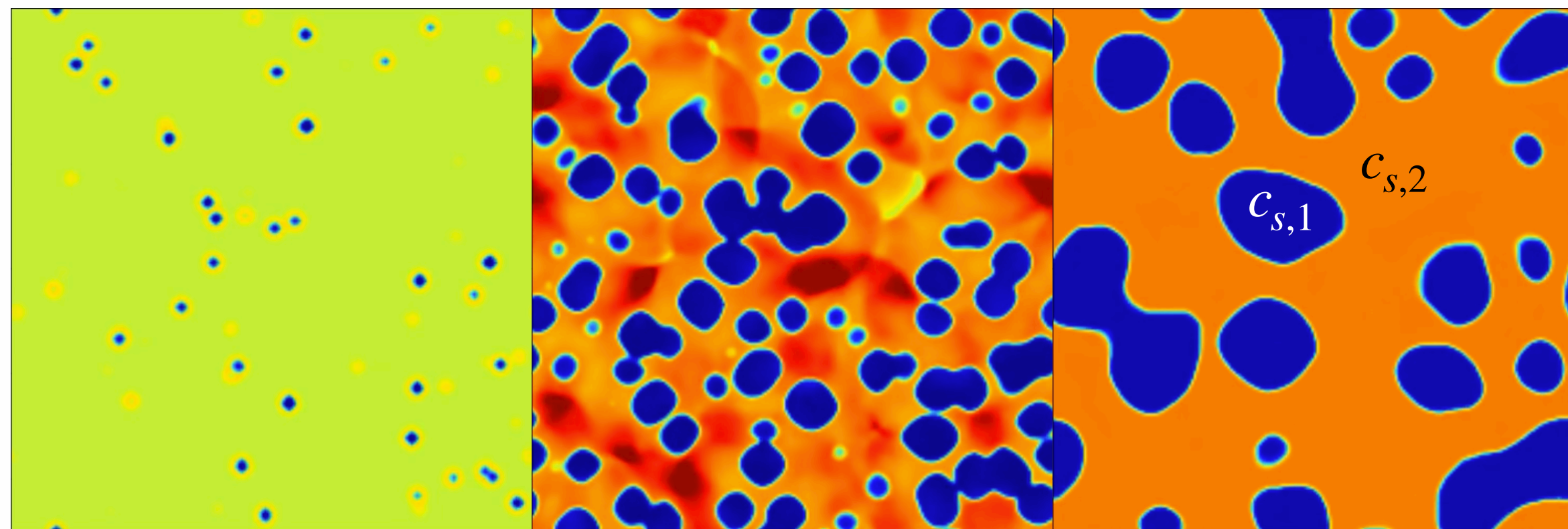
Bea, Luna, Mateos, MSG, Tarancon-Alvarez, van de Vis in progress



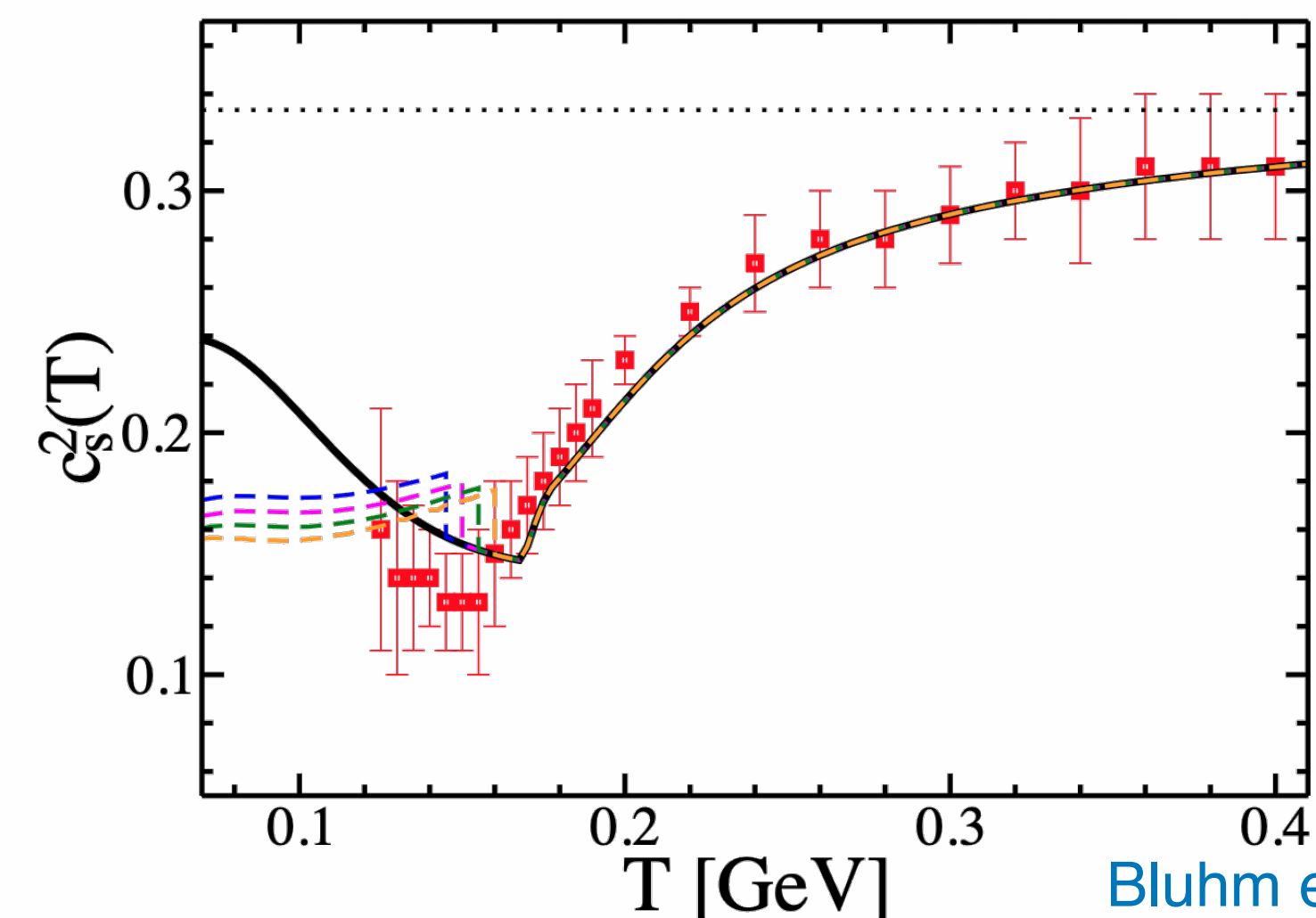
Bluhm et al '13

Theoretical improvements

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 - Electroweak-like: weak coupling
 - Constant speed of sound
 - Direct: from high to low energies
 - Final homogeneous state
- Neutron star FOPTs:
 - Strong coupling & finite density
 - Non-constant speed of sound
 - Inverse: from low to high energies
 - Final phase coexistence ($c_{s,1}$, $c_{s,2}$)



Bea, Luna, Mateos, MSG, Tarancon-Alvarez, van de Vis in progress



Bluhm et al '13

Inverse/Superheated transitions

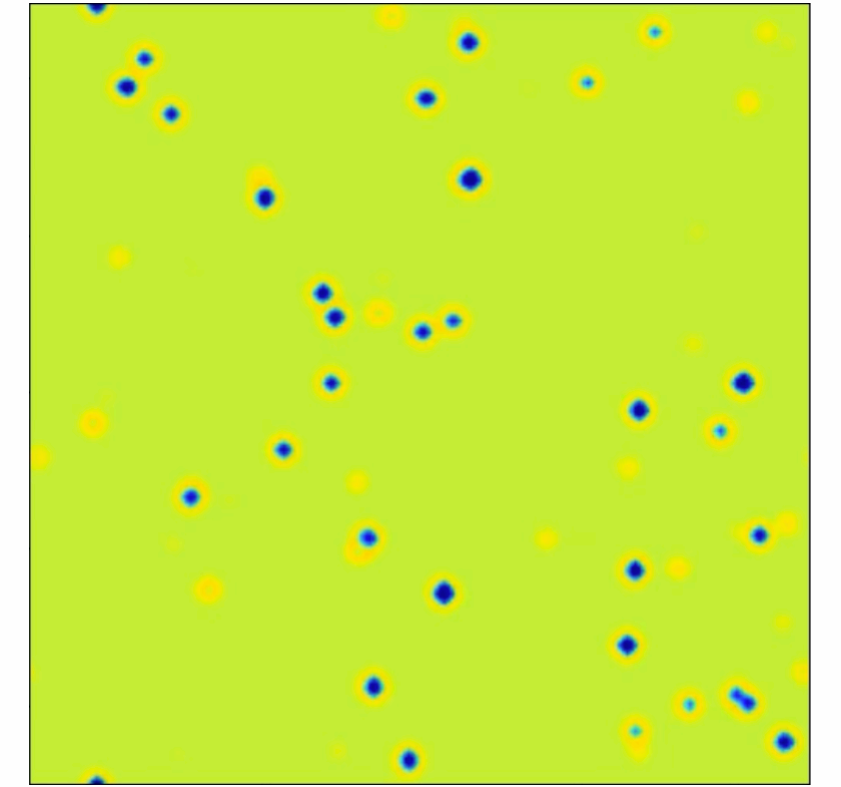
Barni, Blasi, Vanvlasselaer '24
Bea, Casalderrey-Solana, Mateos, MSG '24

Inverse/Superheated transitions

Barni, Blasi, Vanvlasselaer '24

Bea, Casalderrey-Solana, Mateos, MSG '24

- Hydrodynamics of isolated inverse bubbles:

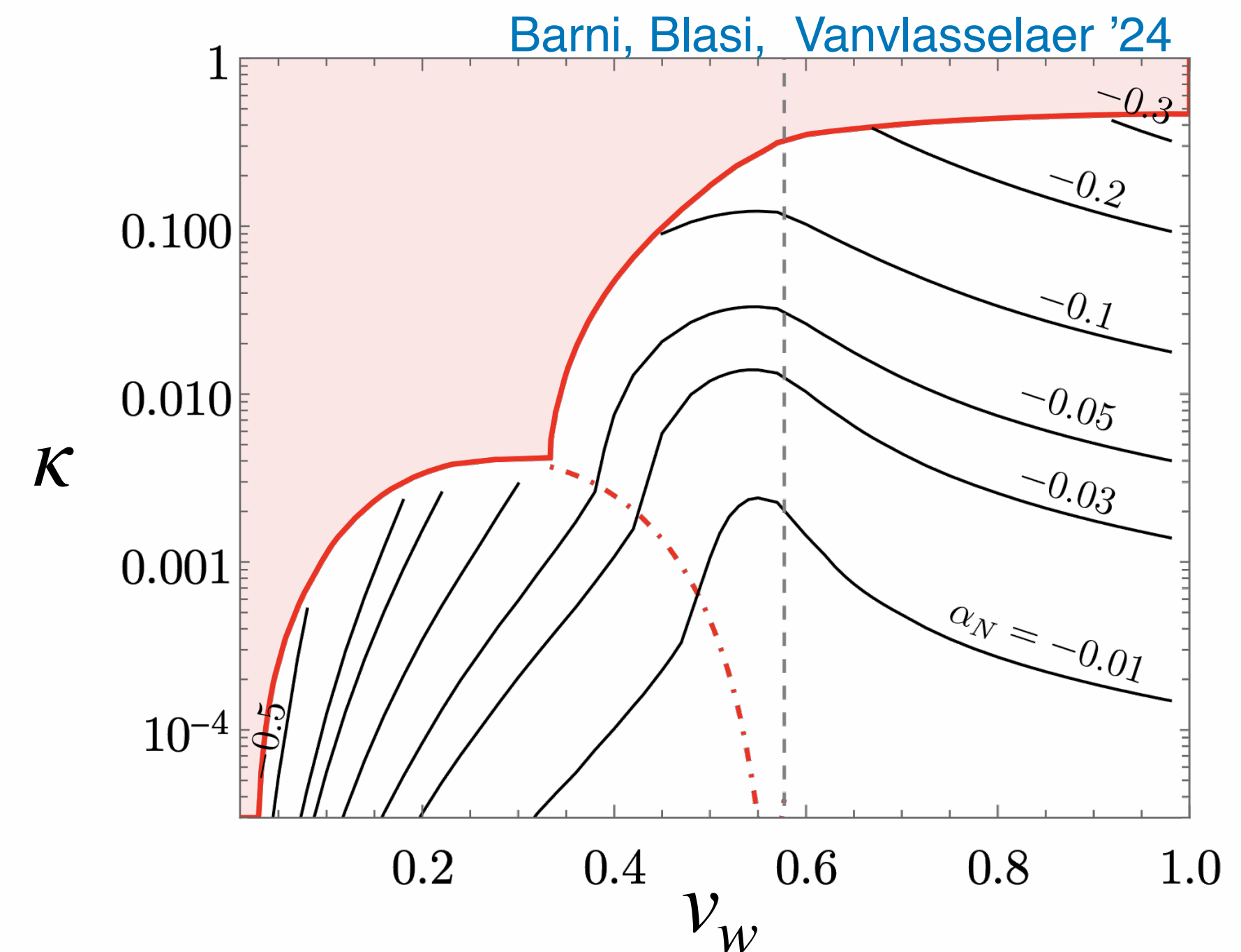
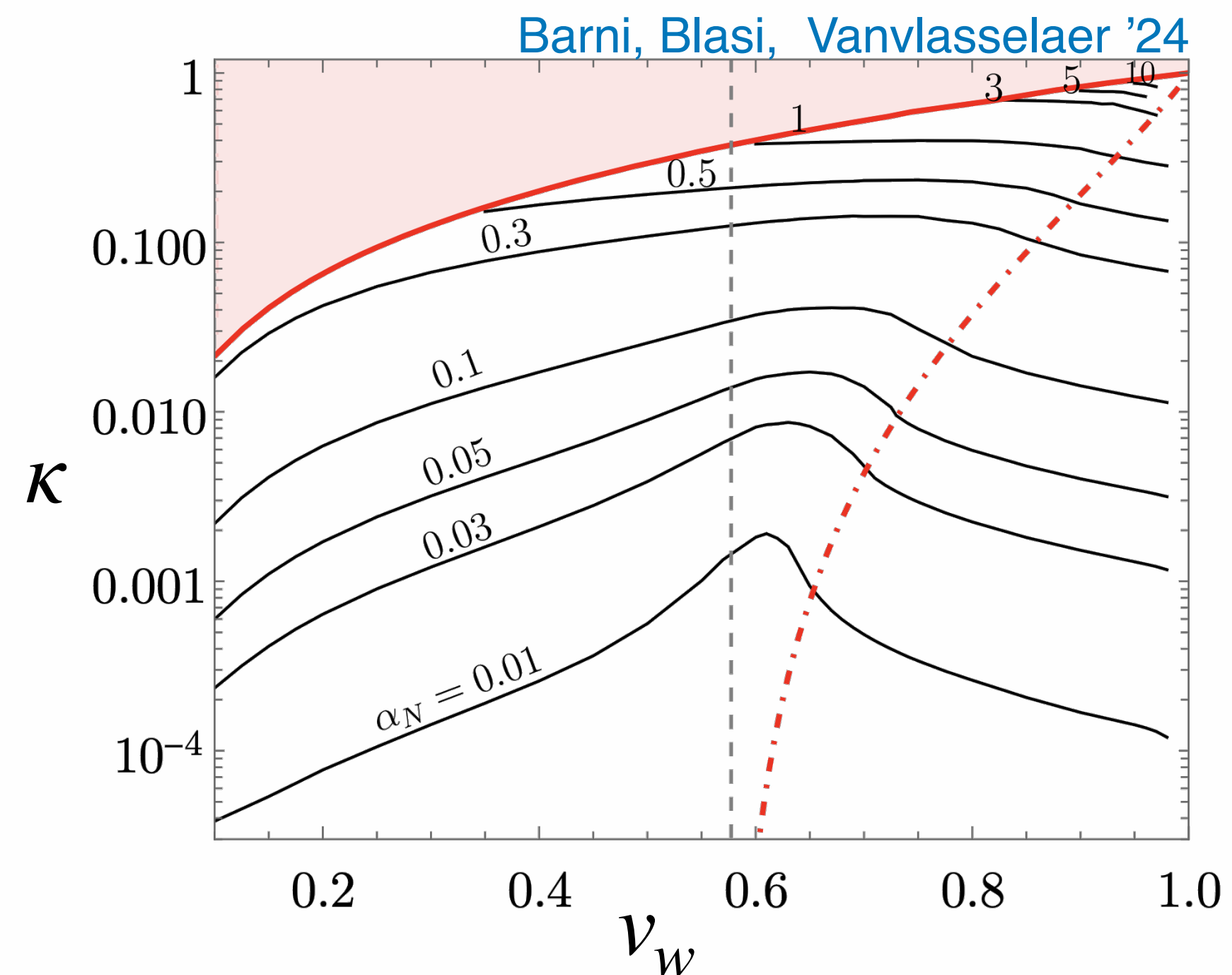
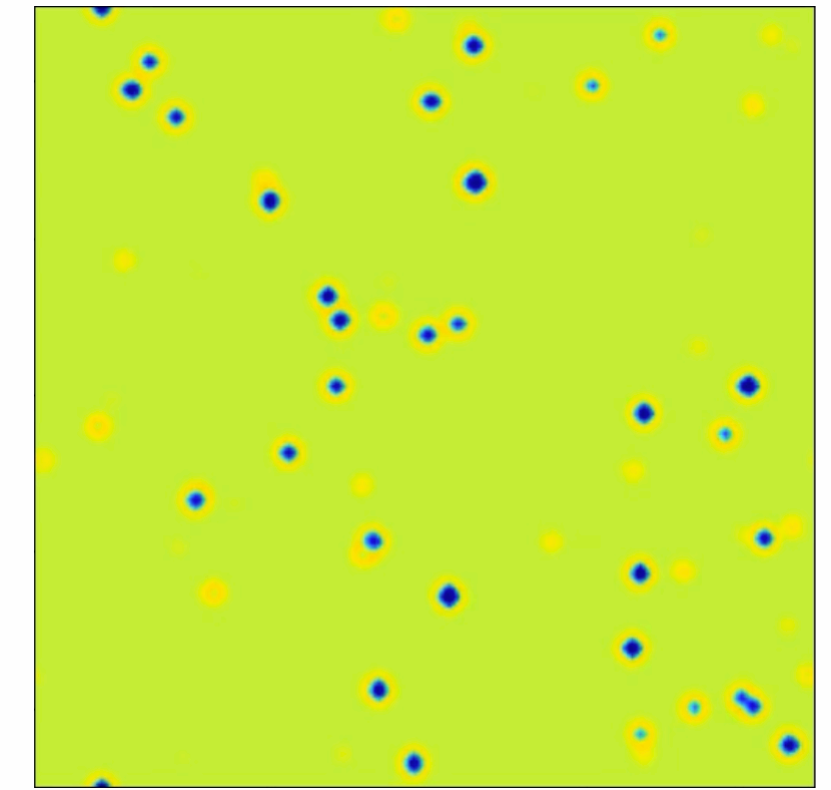


Inverse/Superheated transitions

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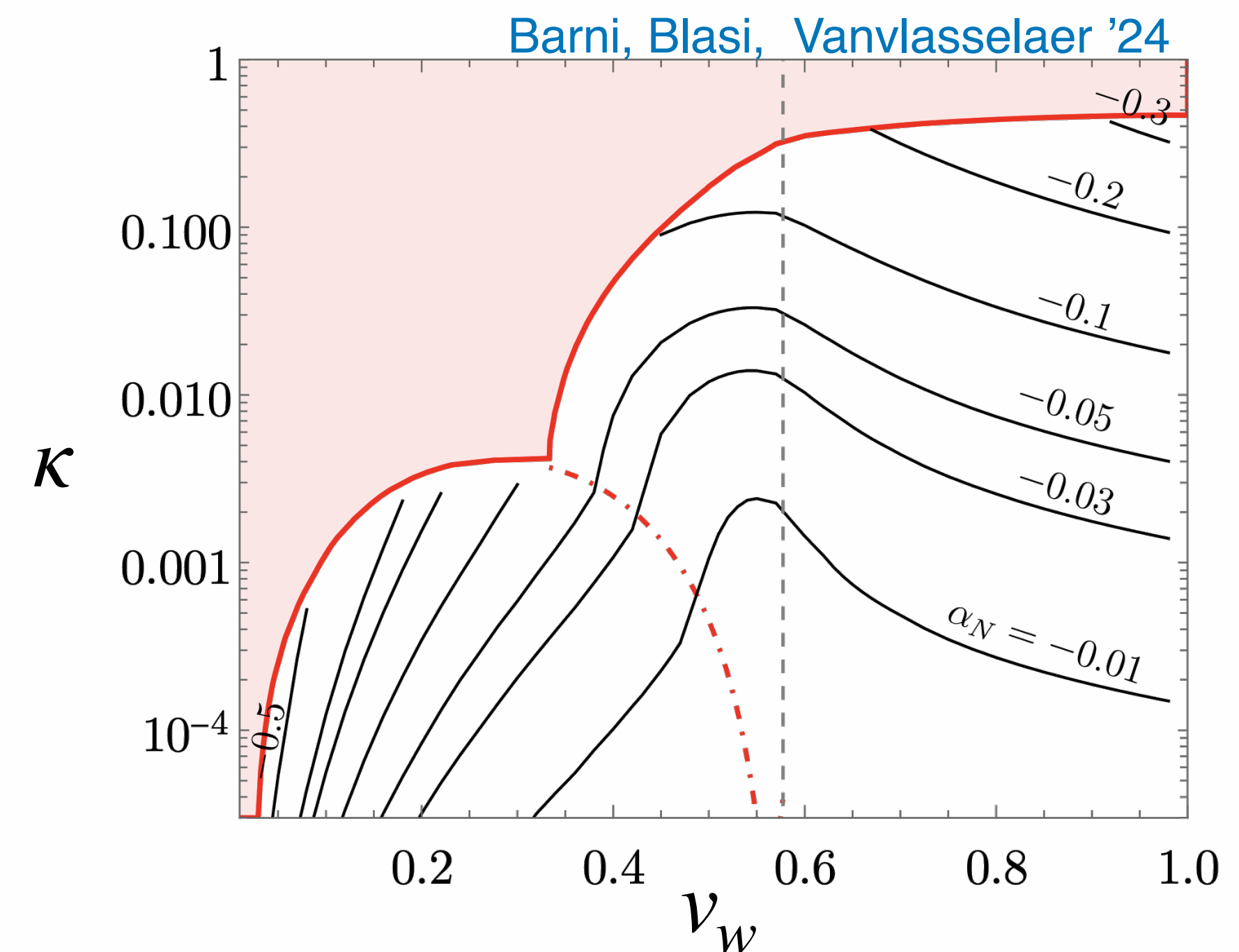
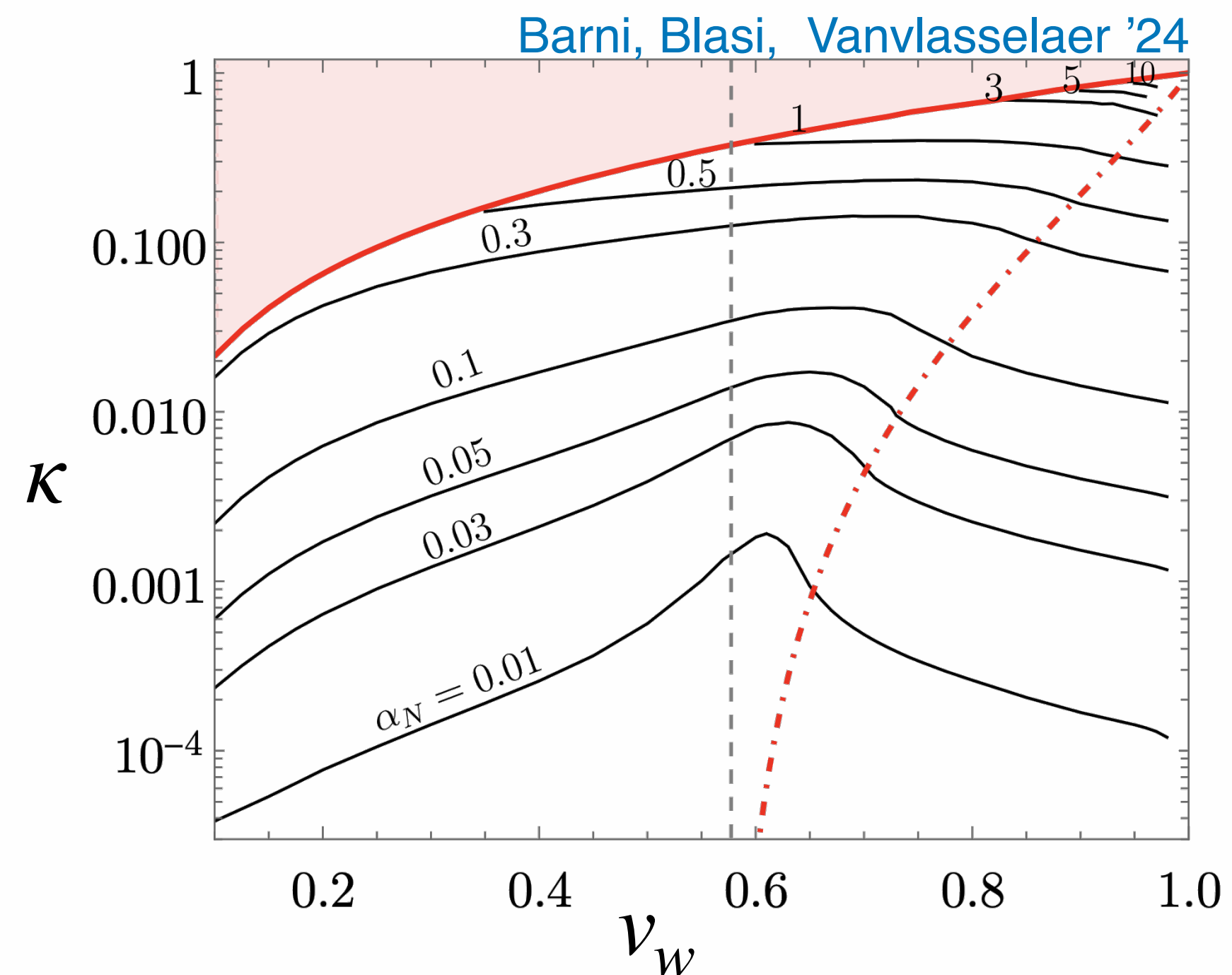
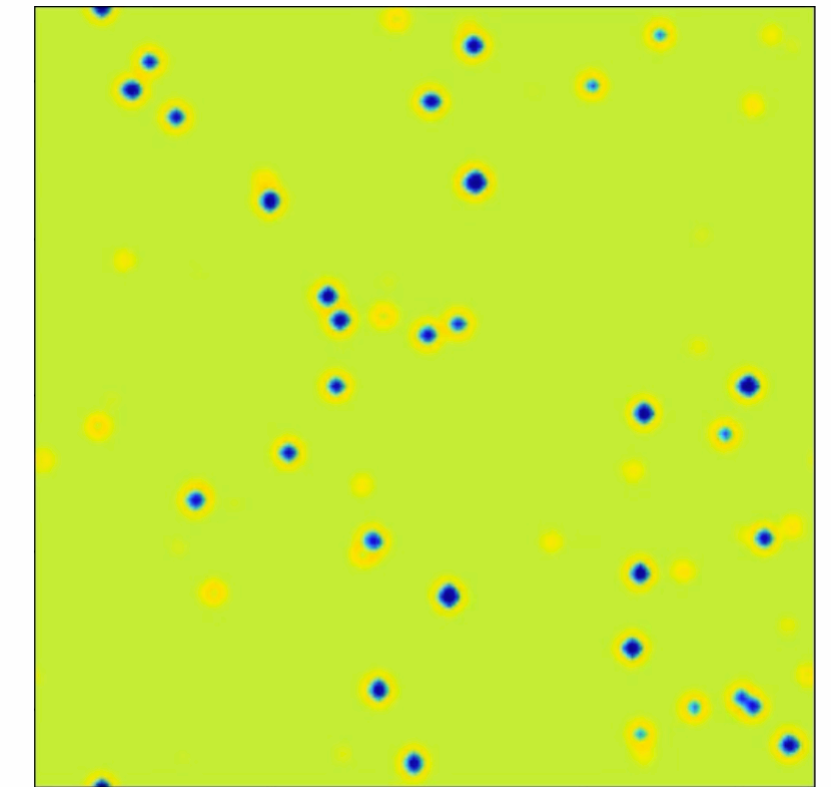


Inverse/Superheated transitions

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 - Expansion speed constraint by hydrodynamics alone

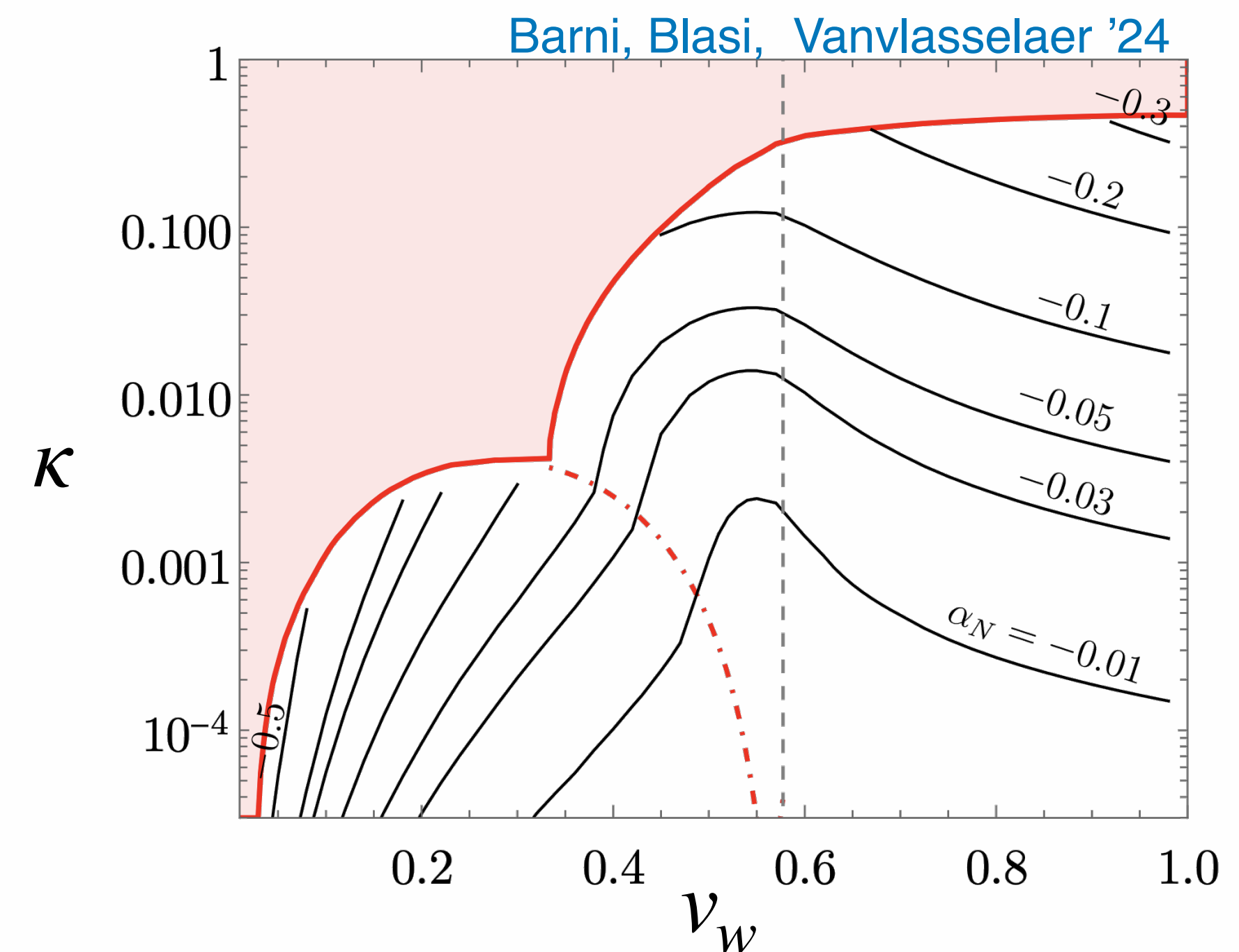
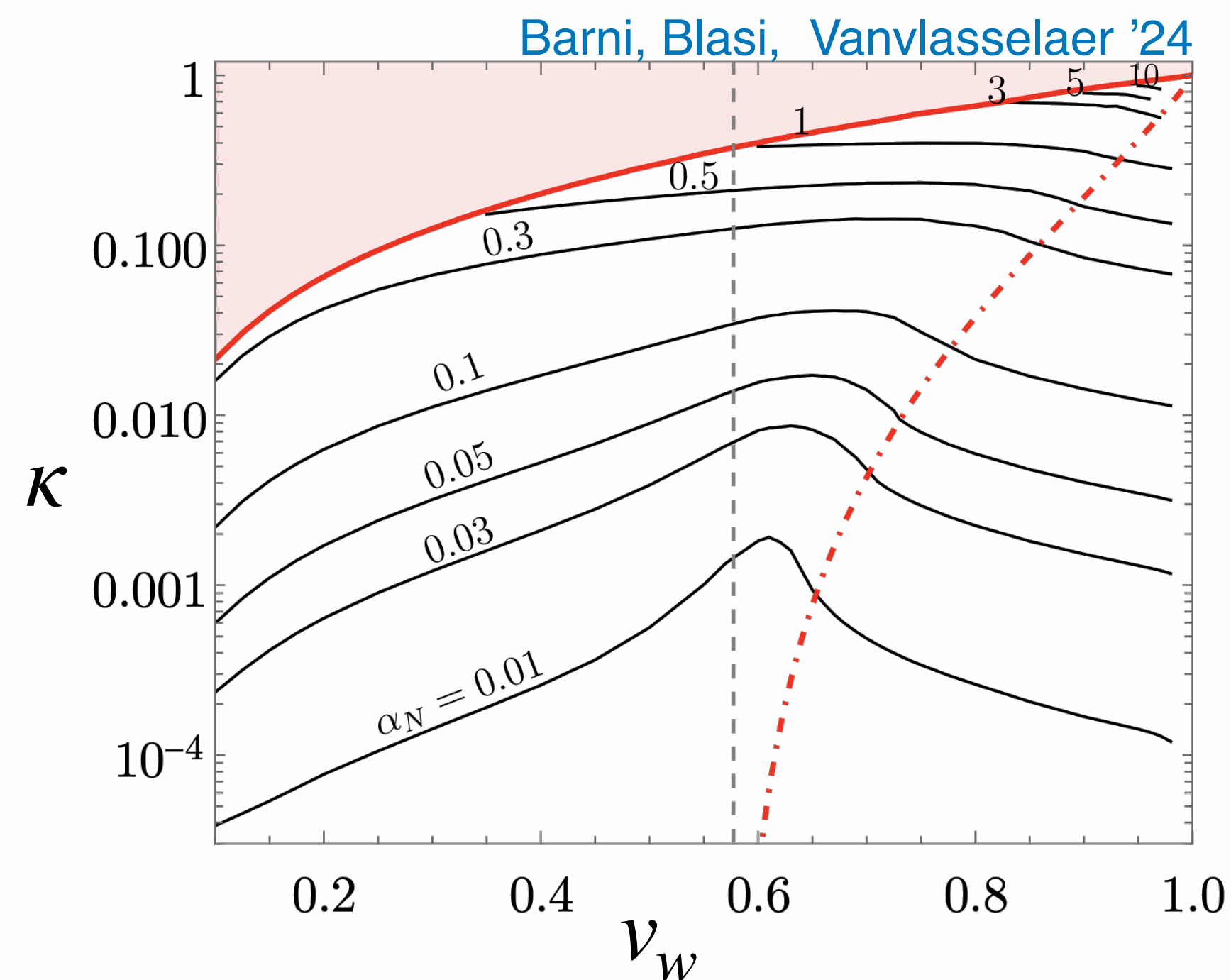
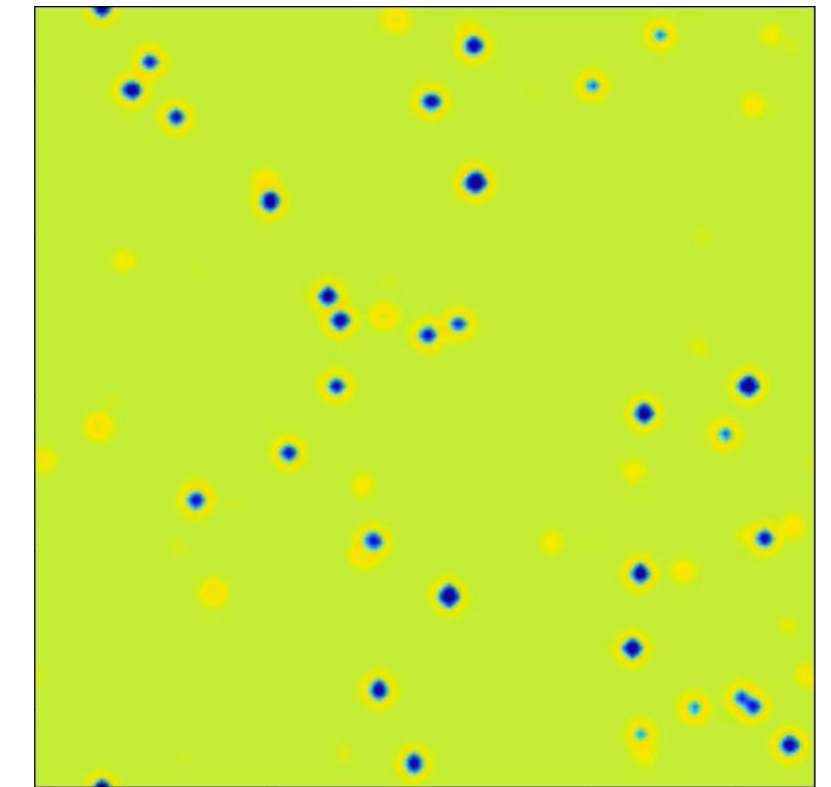


Inverse/Superheated transitions

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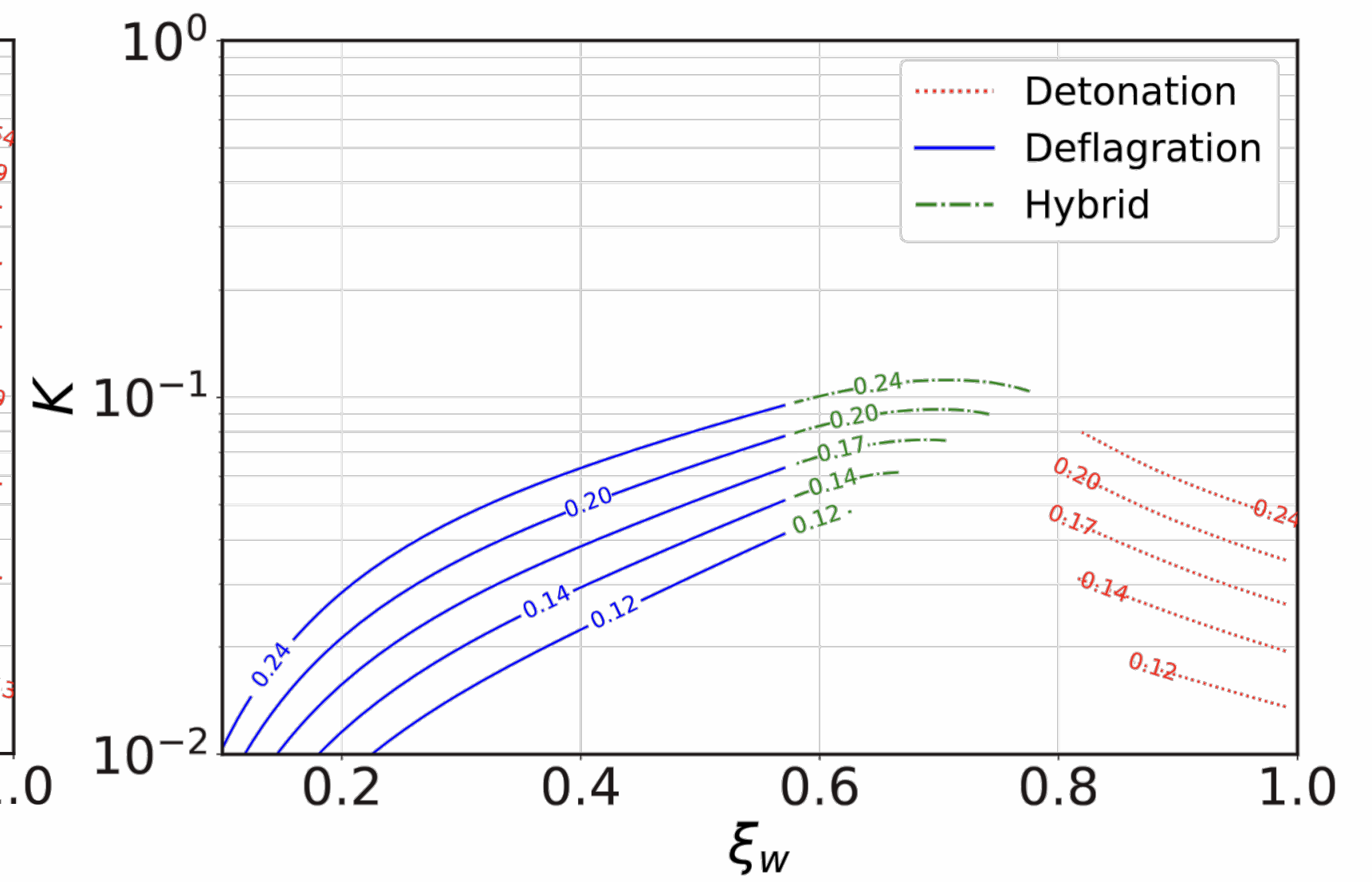
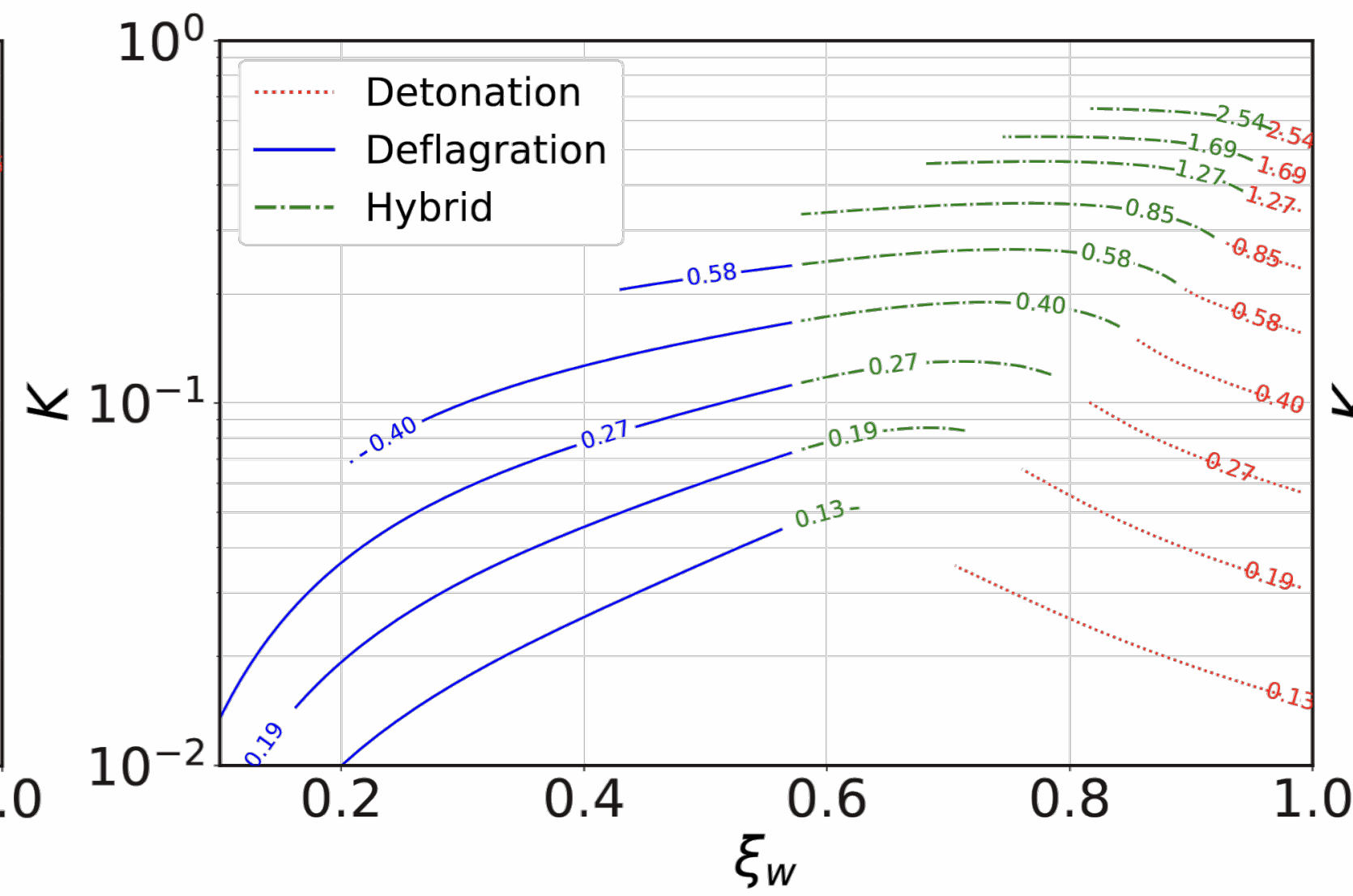
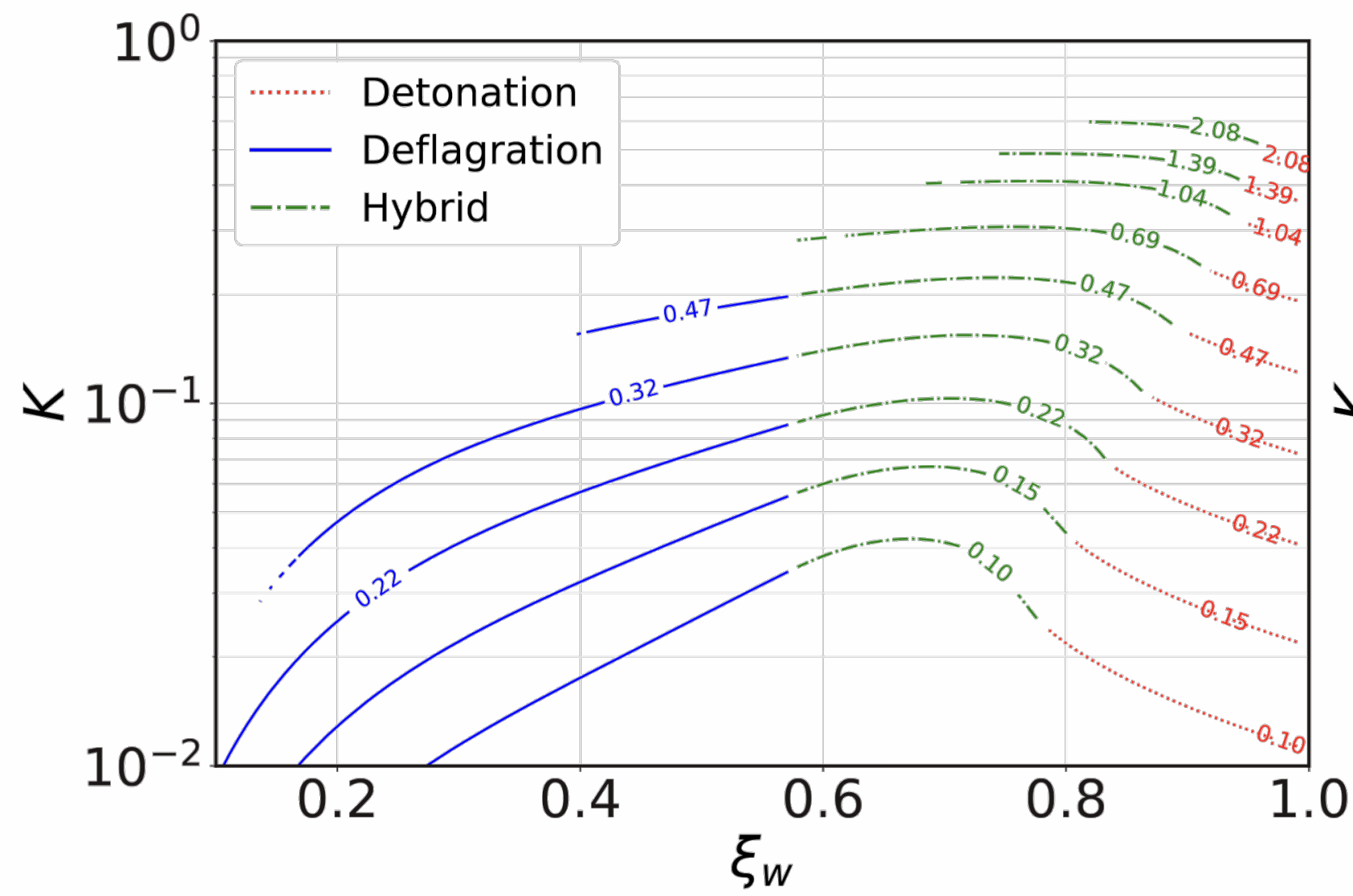
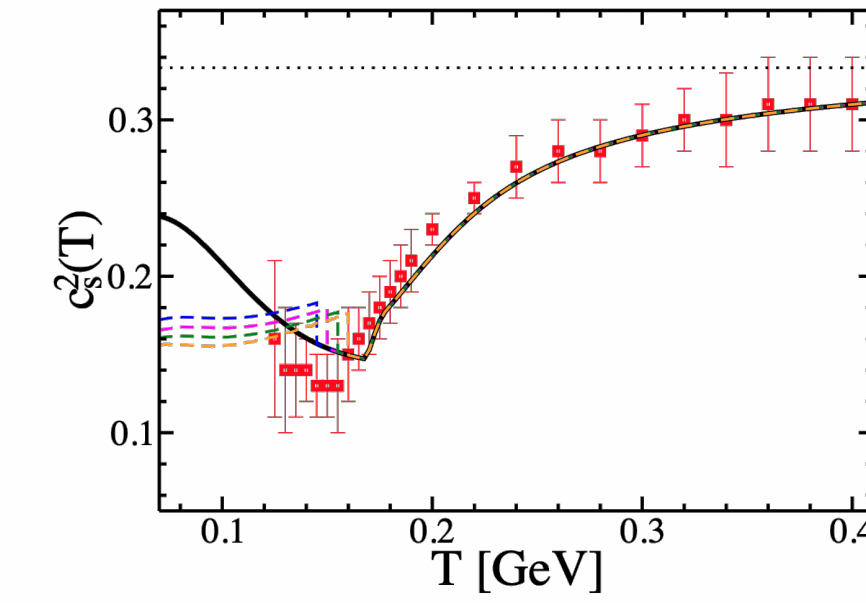
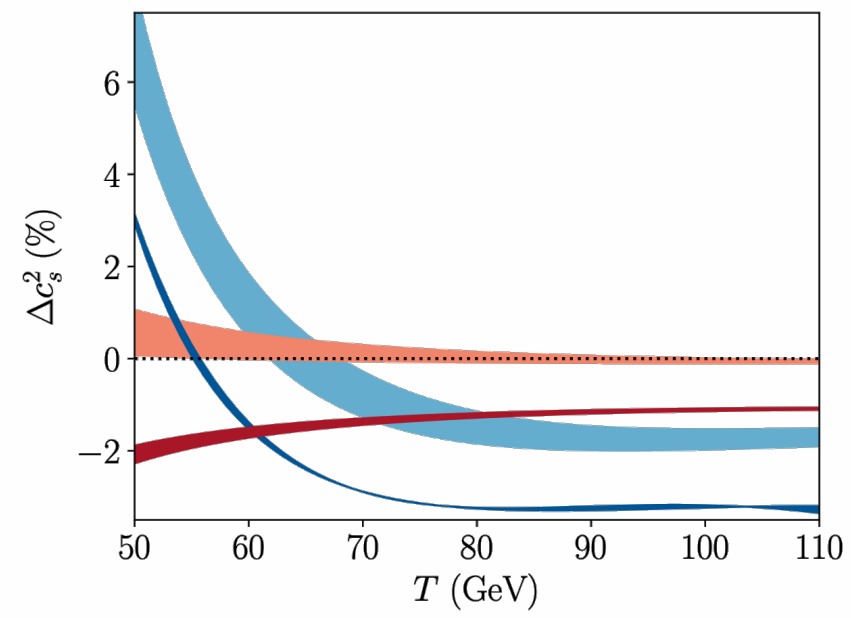
Bea, Casalderrey-Solana, Mateos, MSG '24

- Hydrodynamics of isolated inverse bubbles:
 - Simple self-similar problem gives energy budget
 - Expansion speed constraint by hydrodynamics alone
 - Intermediate velocities are energetically most efficient



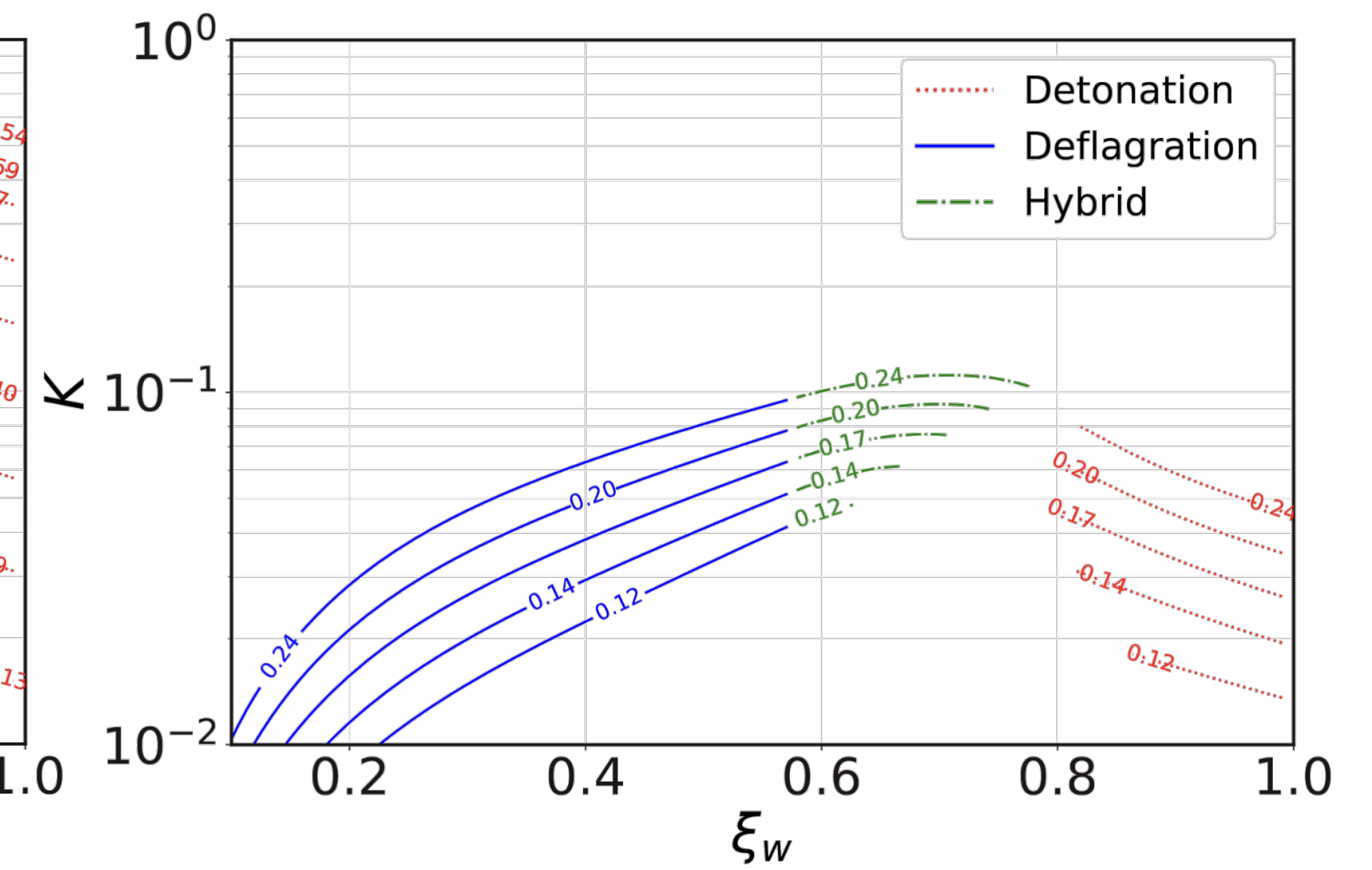
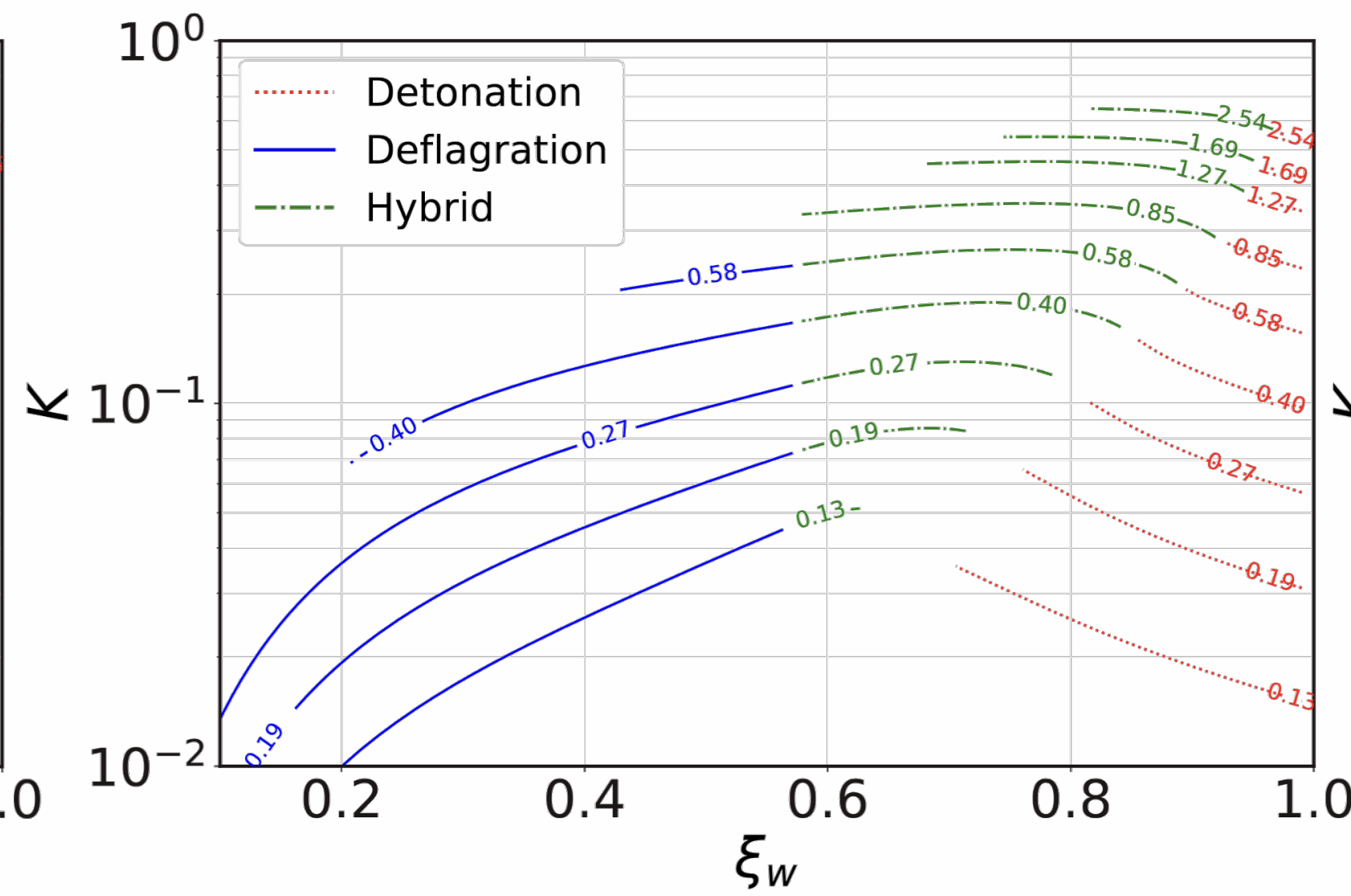
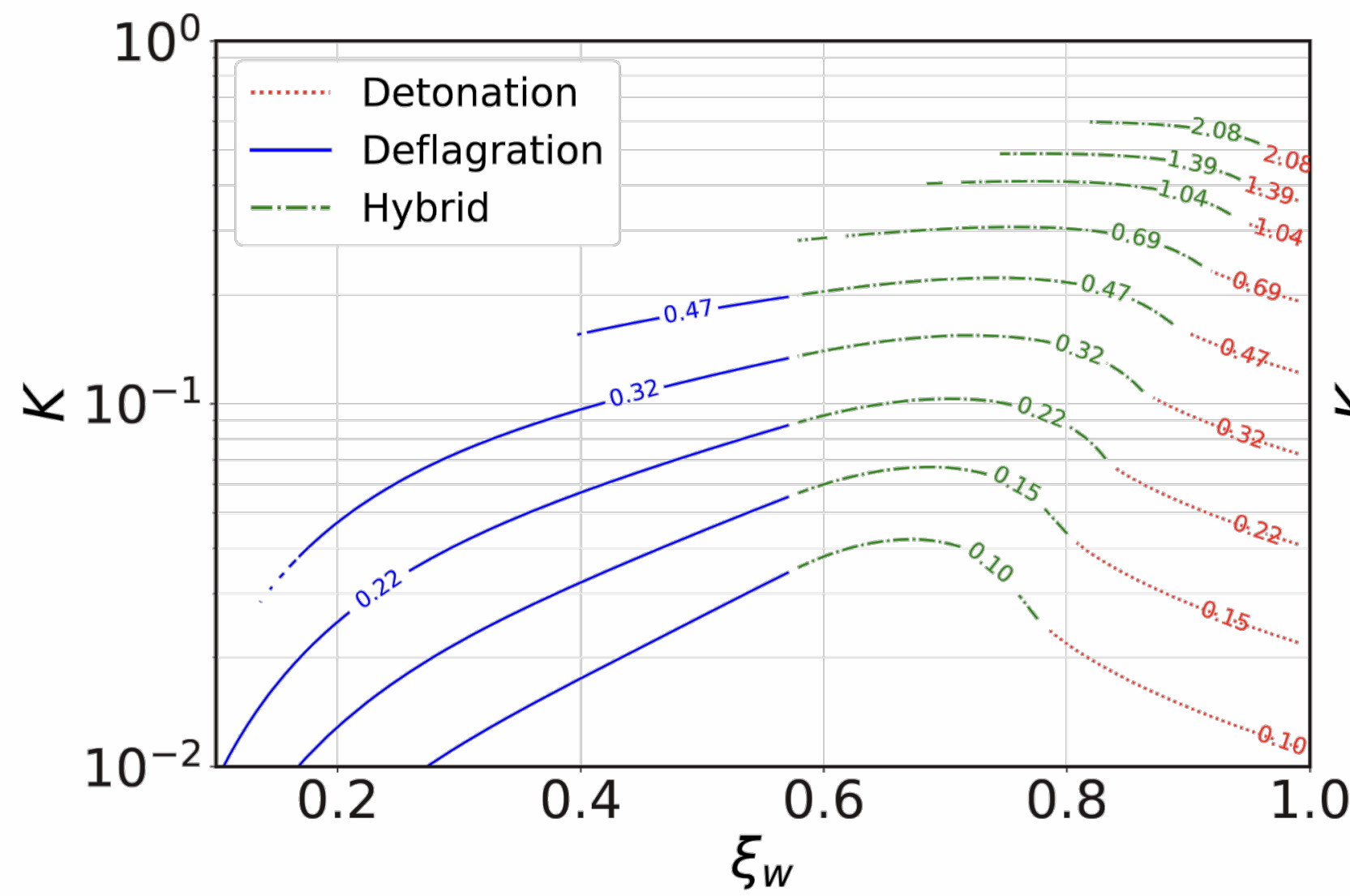
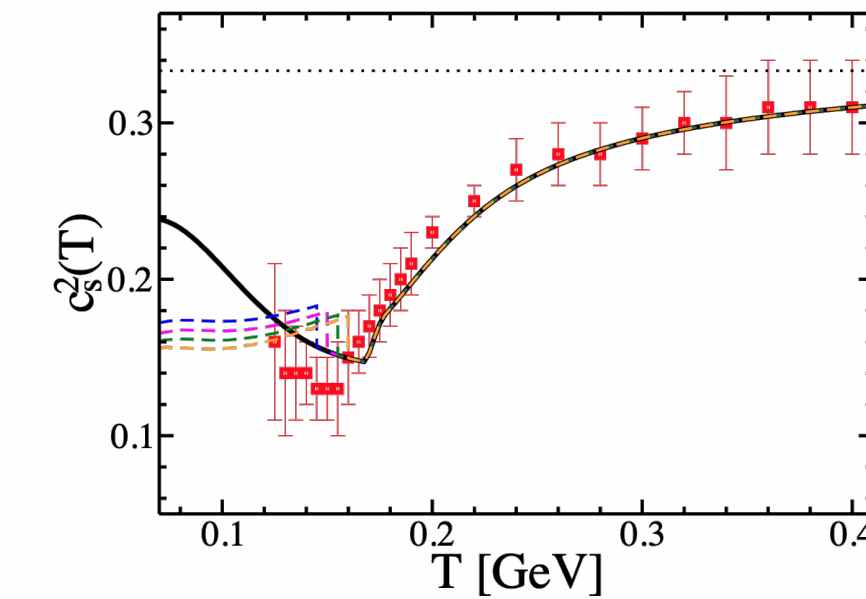
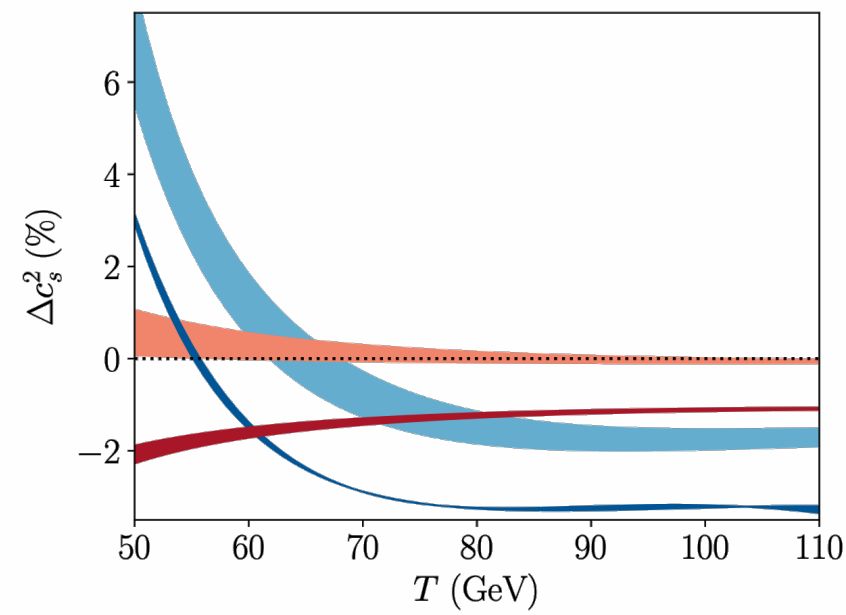
Non-constant speed of sound

Mateos, MSG, Tarancon-Alvarez to appear



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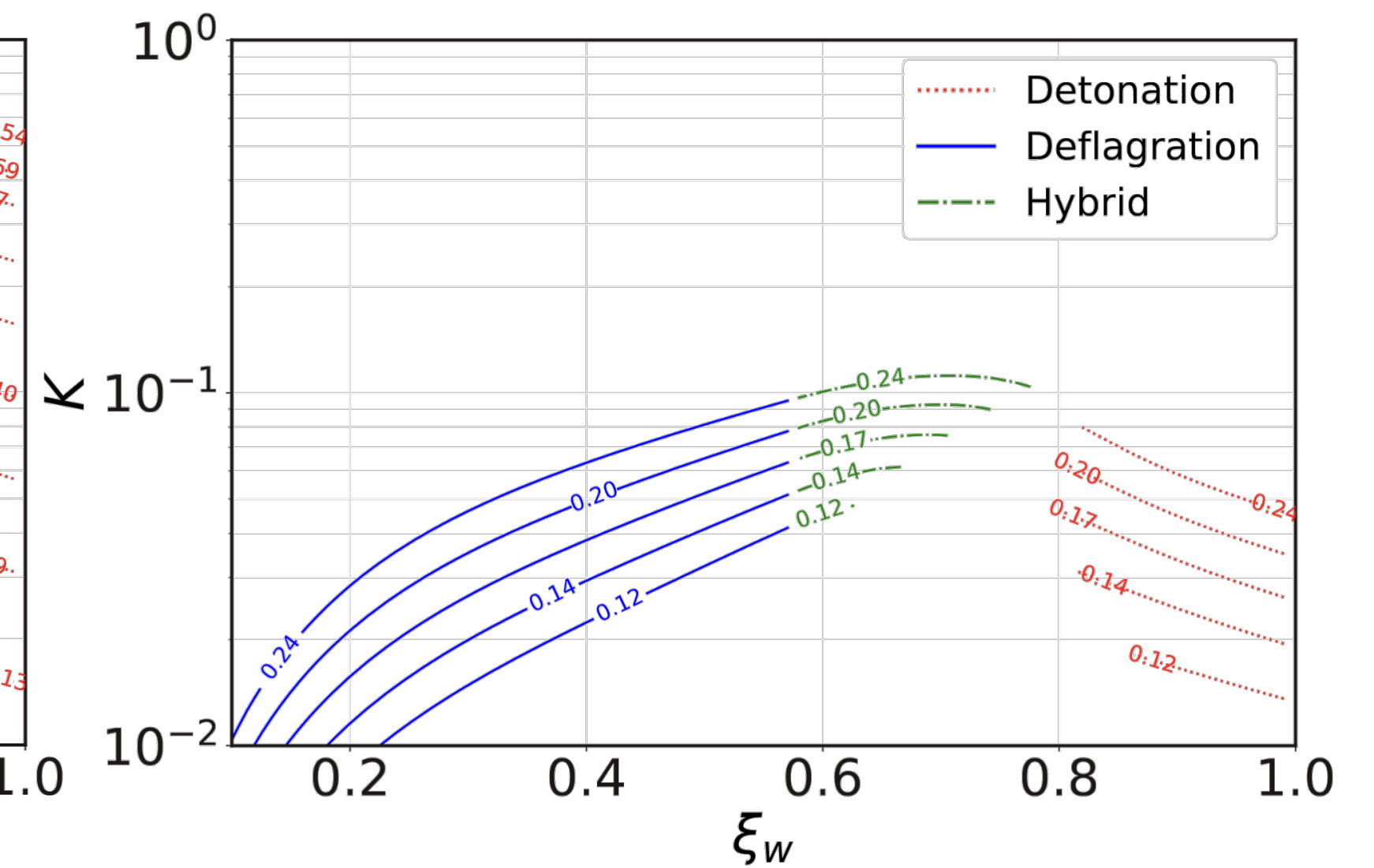
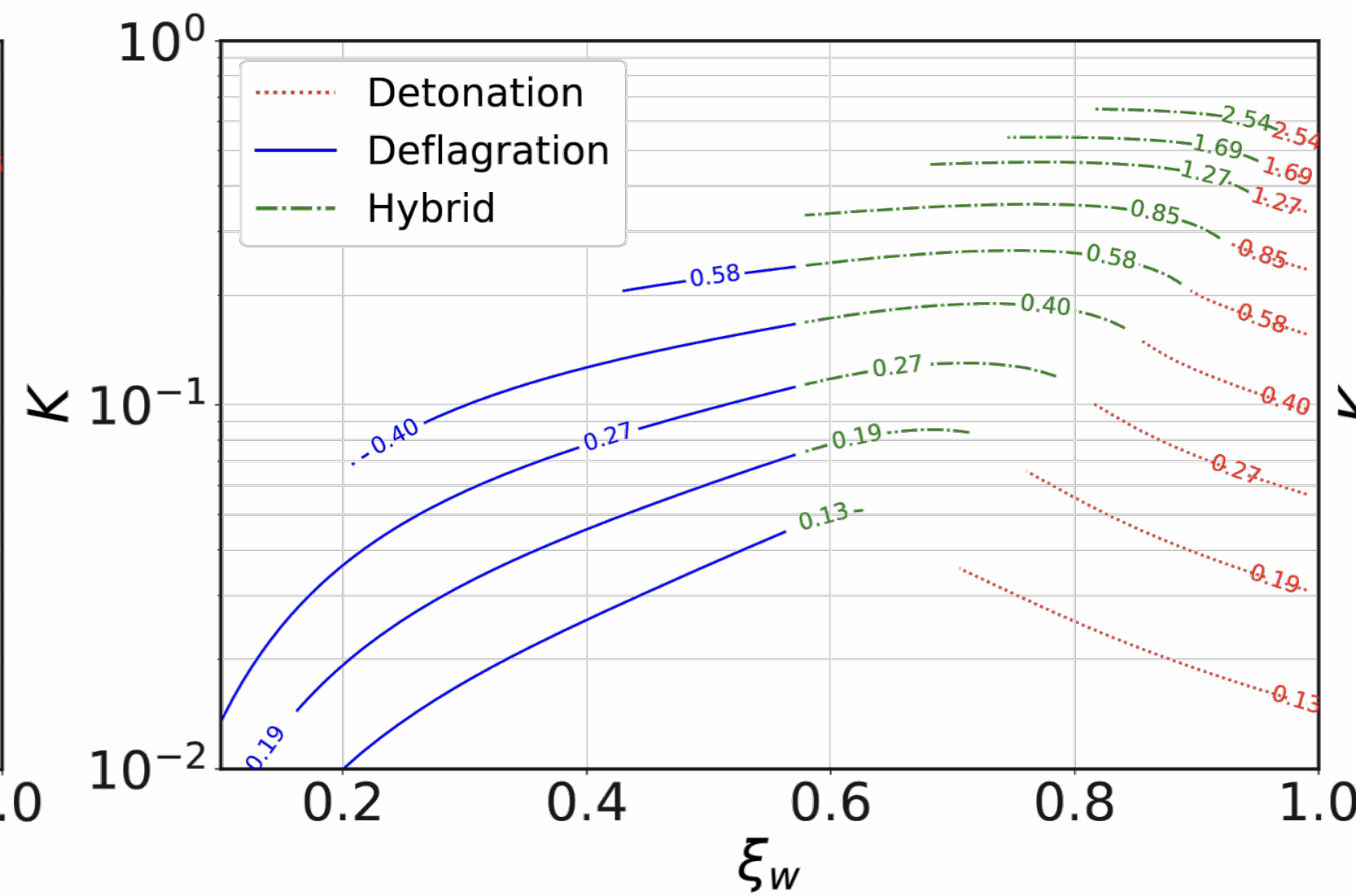
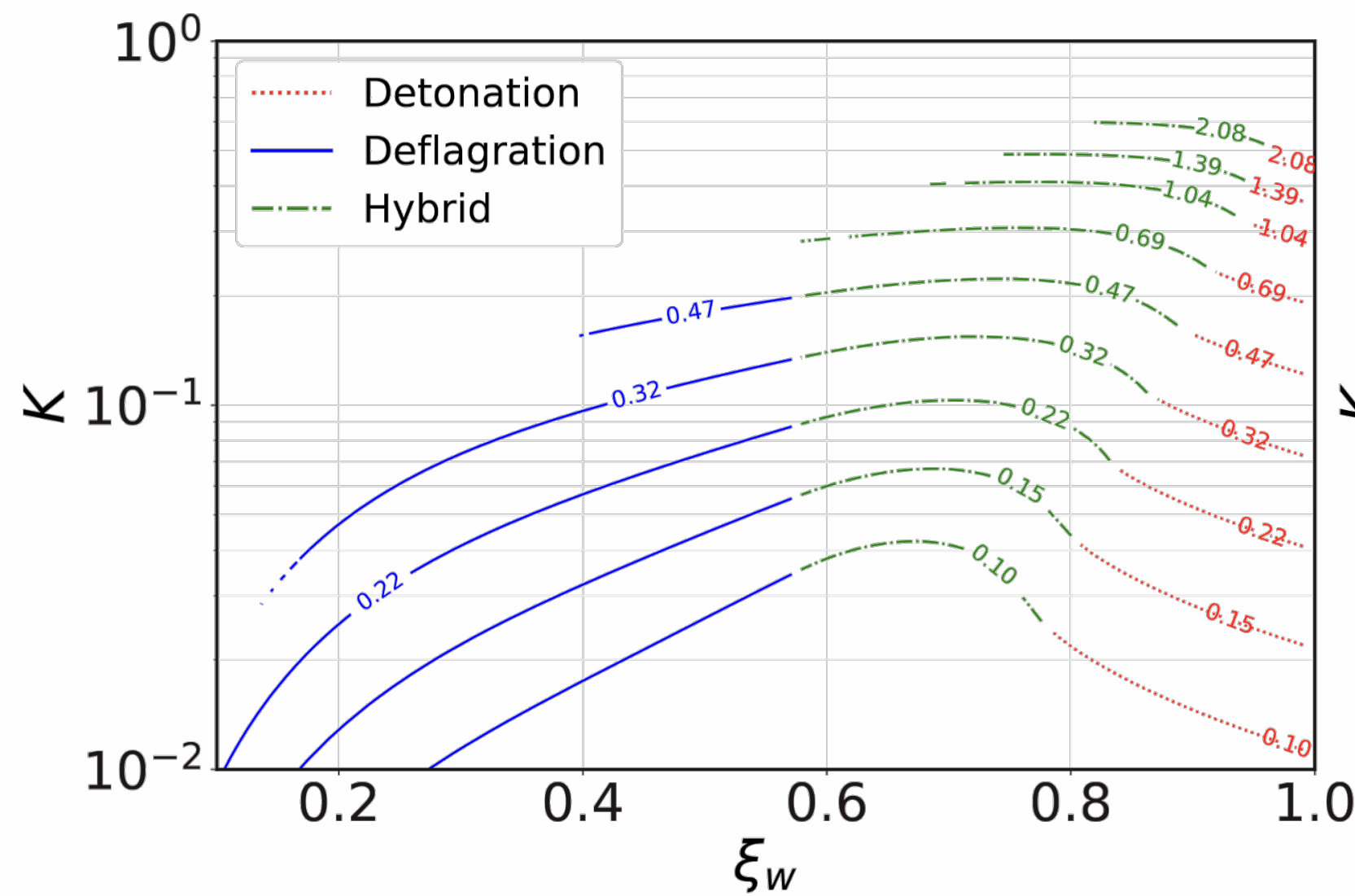
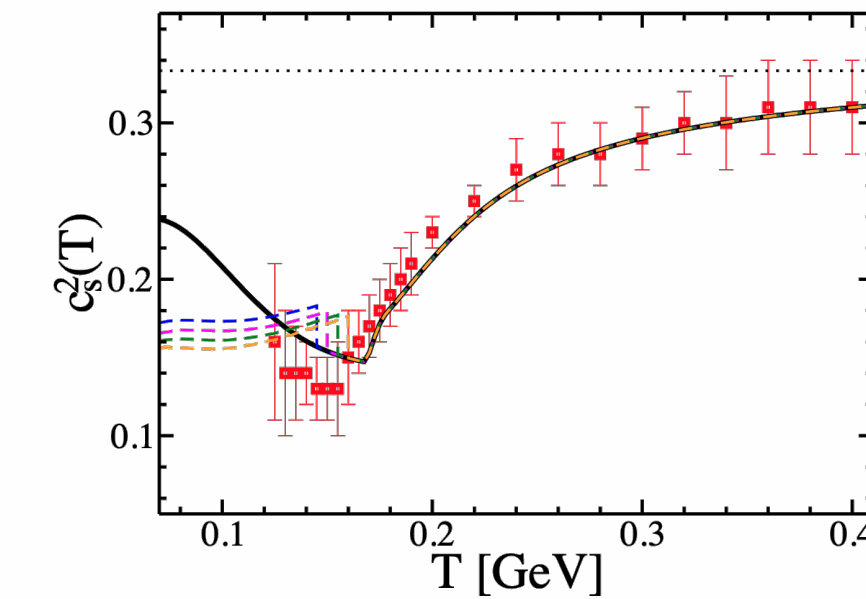
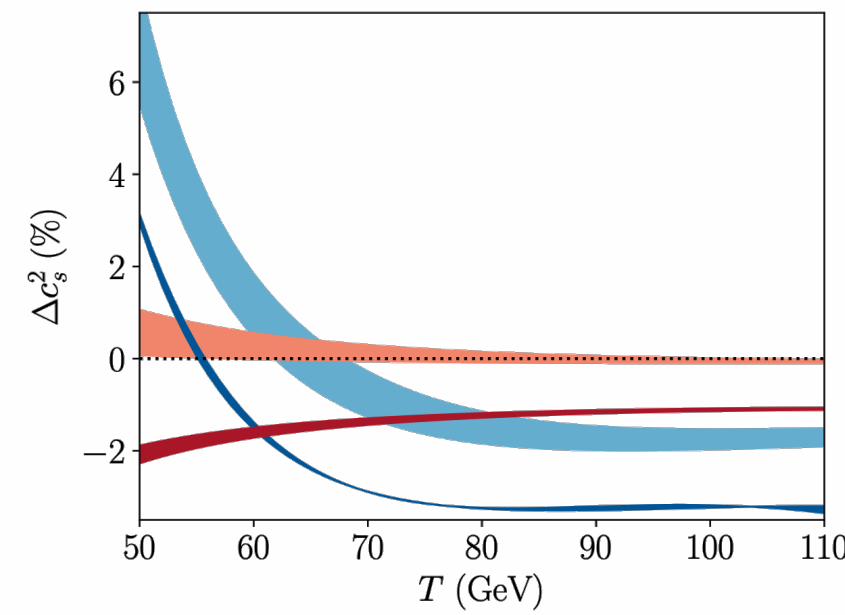
Mateos, MSG, Tarancon-Alvarez to appear



- Varying speed of sound constraints at intermediate wall speeds

Non-constant speed of sound

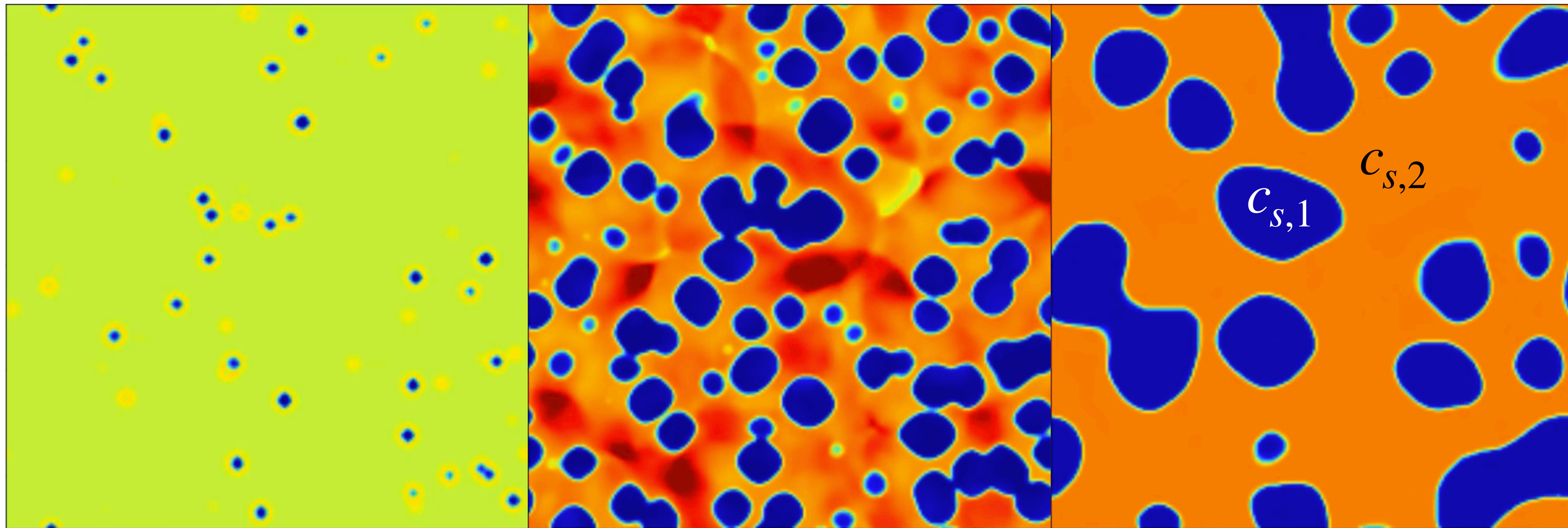
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- Varying speed of sound constraints at intermediate wall speeds
- Finite supercooling/superheating effects constraint the high speed regime

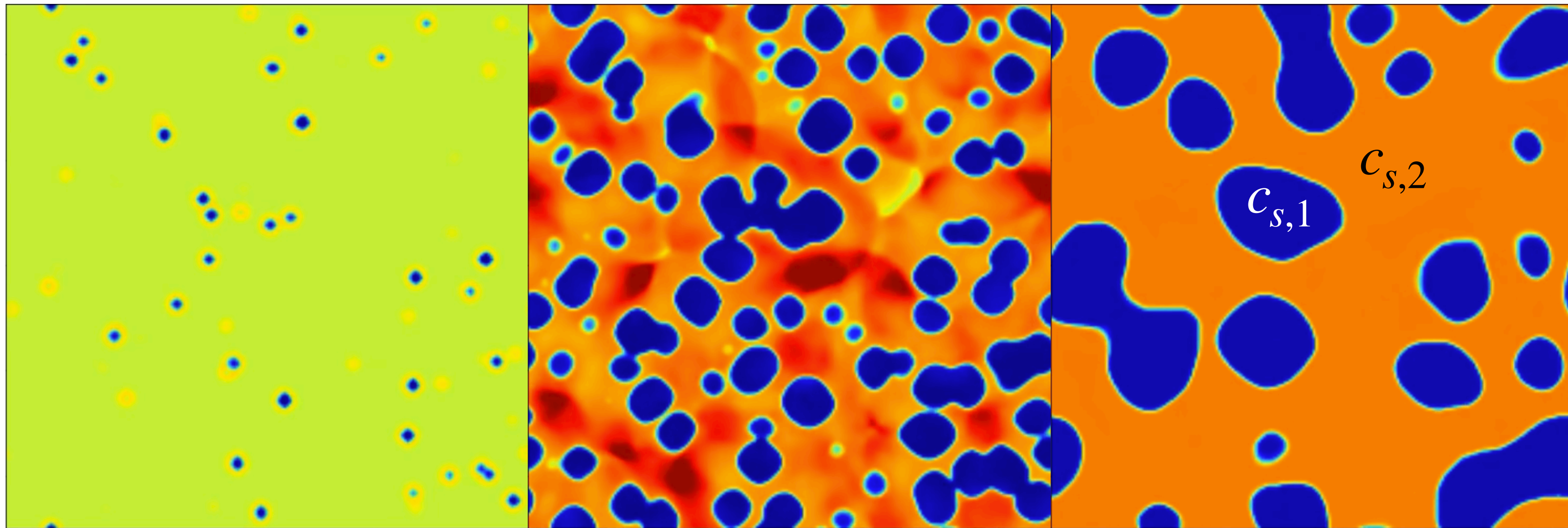
Spectrum from bubble collisions

Bea, Luna, Mateos, MSG, Tarancon-Alvarez, van de Vis in progress



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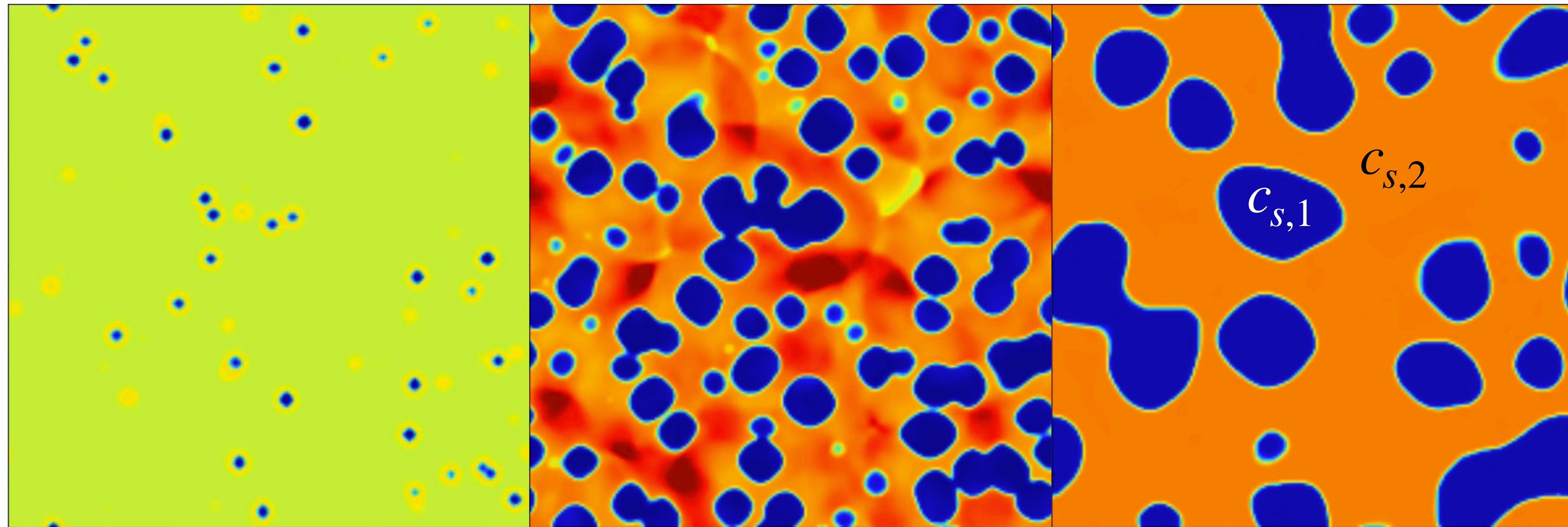
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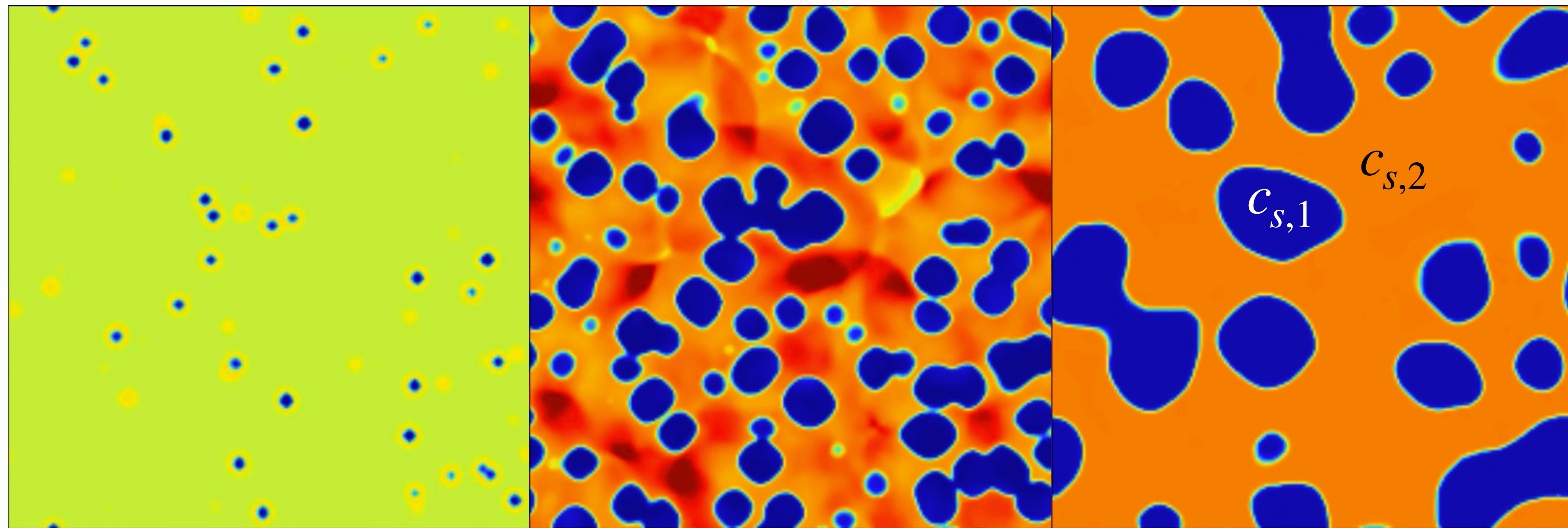
Bea, Luna, Mateos, MSG, Tarancon-Alvarez, van de Vis in progress



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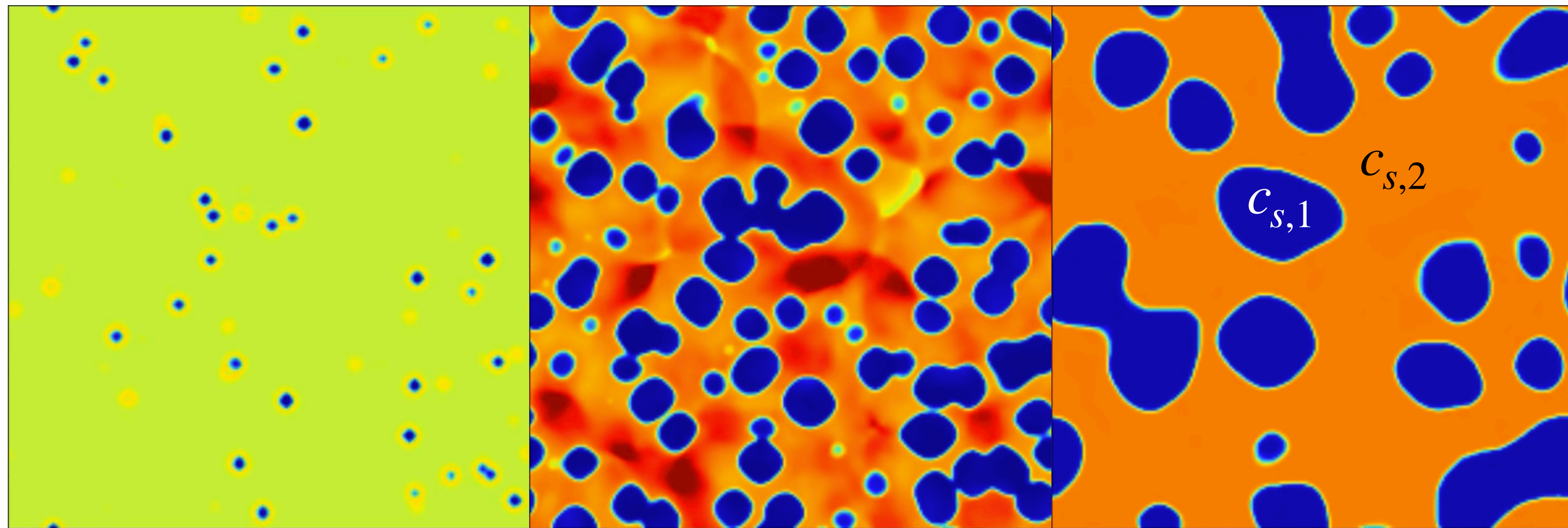
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Bea, Luna, Mateos, MSG, Tarancon-Alvarez, van de Vis in progress



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- Spectrum sensitive to the inhomogeneous nature of the medium?

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- **Learning about general FOPTs and their spectrum**

Thank you!