



UNIVERSITAT DE
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MegaHertz Gravitational Waves from Neutron Star Mergers

Jorge Casalderrey-Solana

based on works in collaborations with

D. Blas, Y. Bea, D. Mateos and M. Sánchez-Garitaonandia



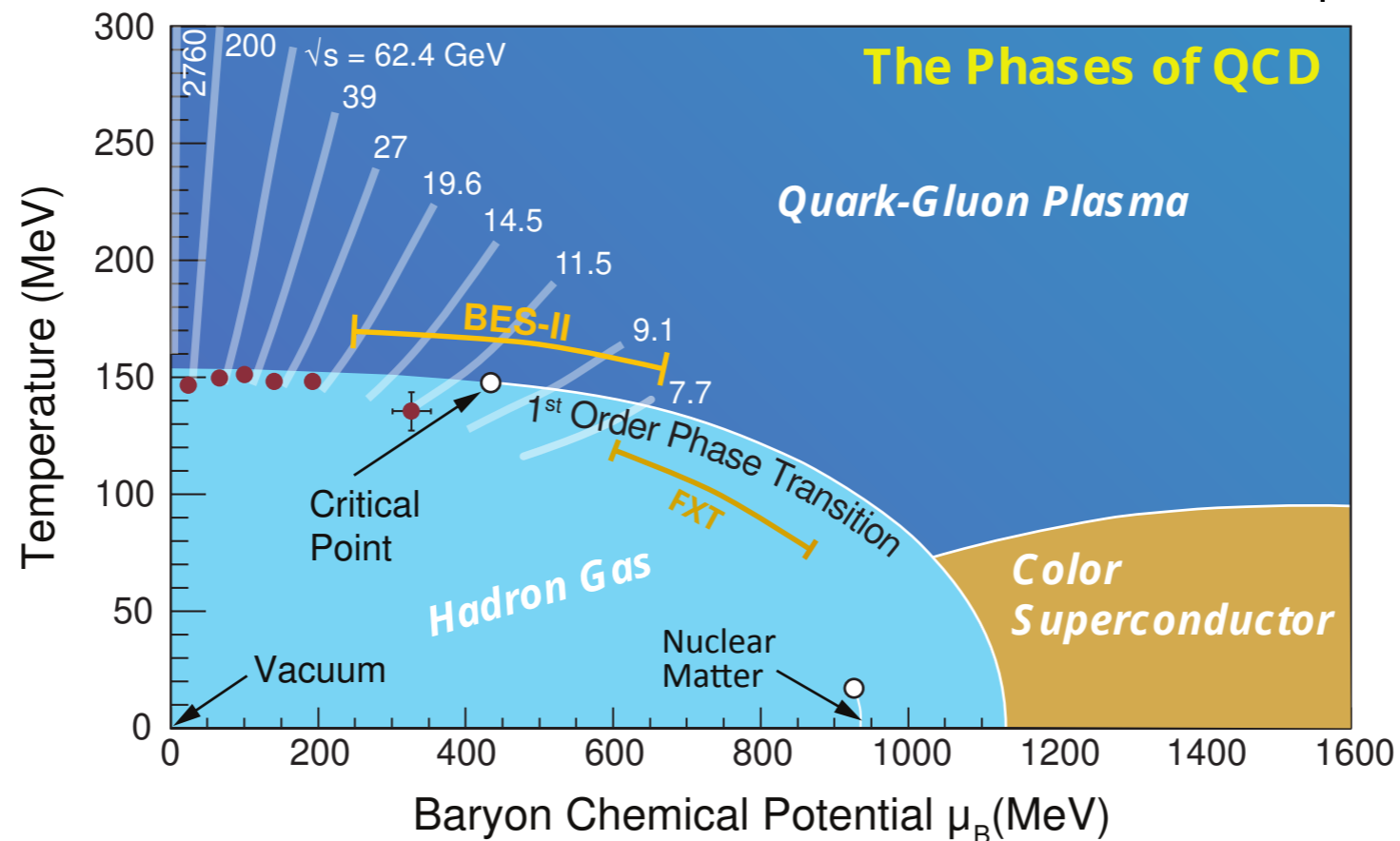
Institut de Ciències del Cosmos
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HOLOGW, GA: 101141909

QCD Phase Diagram

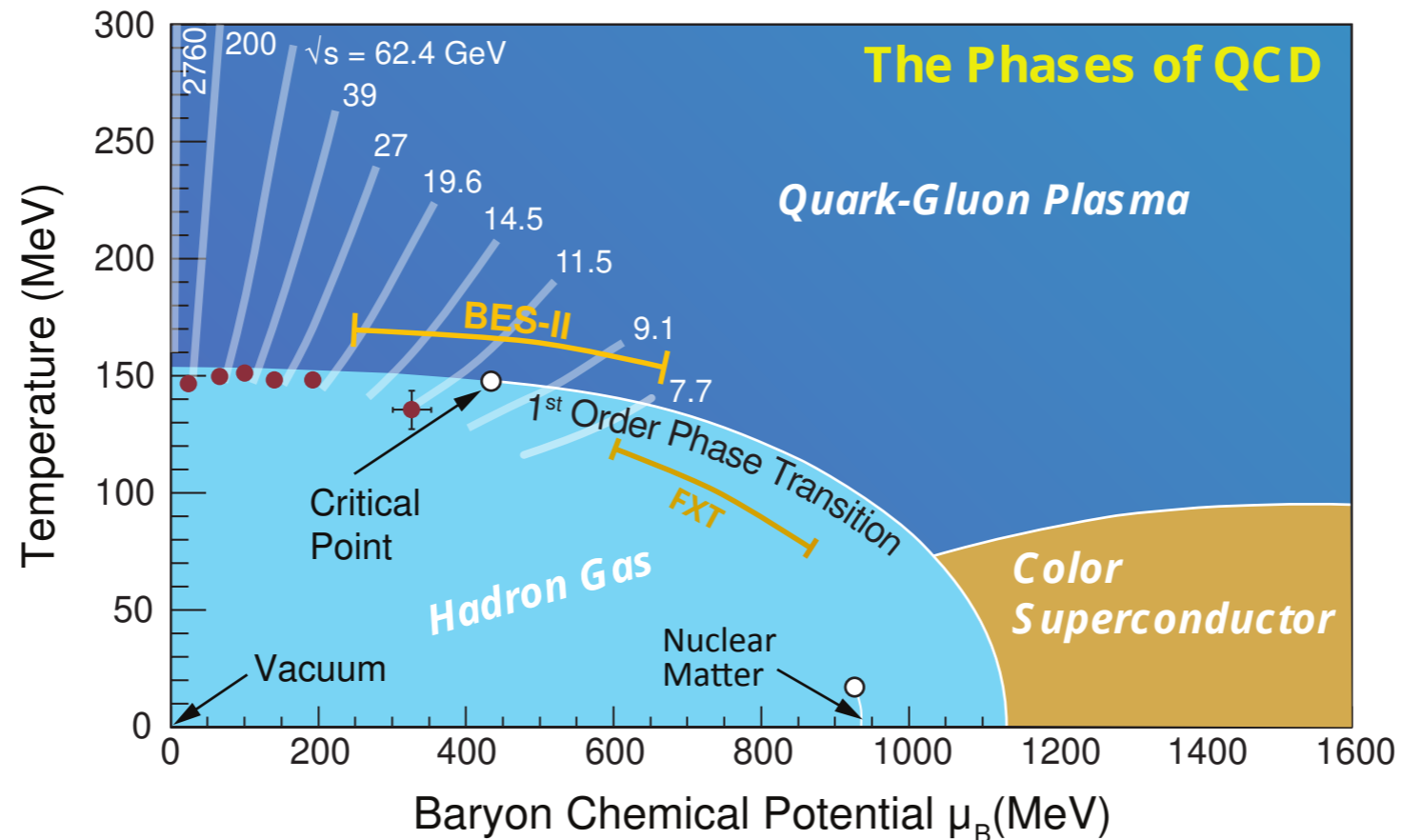
Du, Sorensen, Stephanov 2402.10183



- The QCD phase diagram is long conjectured to have a FOPT

QCD Phase Diagram

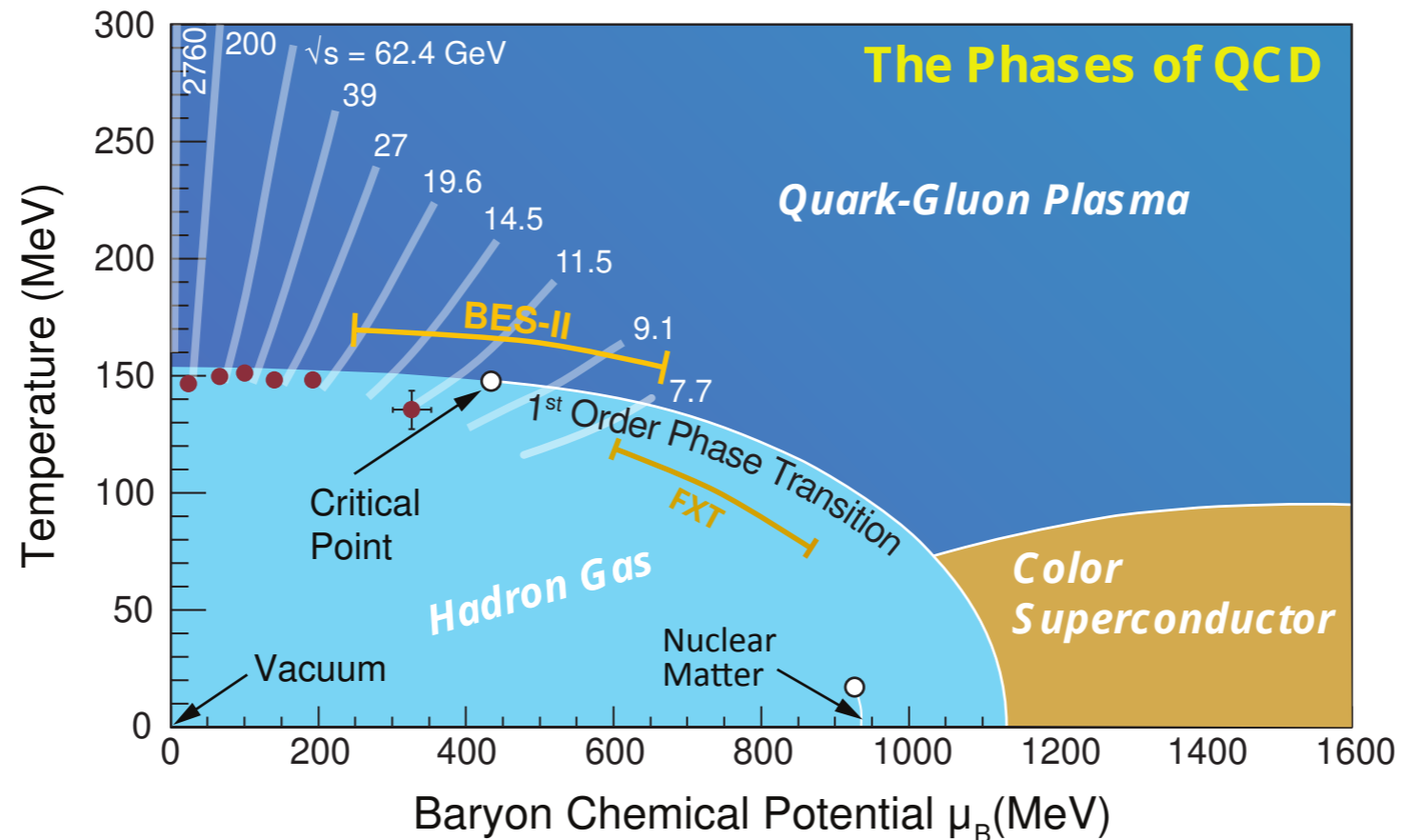
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- ⦿ Direct searches in colliders are (still) inconclusive

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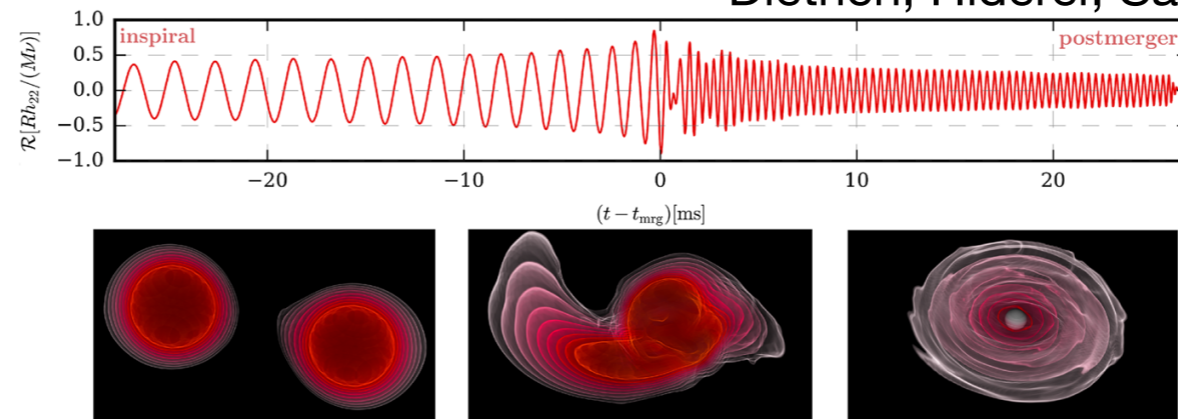
Du, Sorensen, Stephanov 2402.10183



- The QCD phase diagram is long conjectured to have a FOPT
- Direct searches in colliders are (still) inconclusive
- We may only be able to test this with Neutron Stars physics

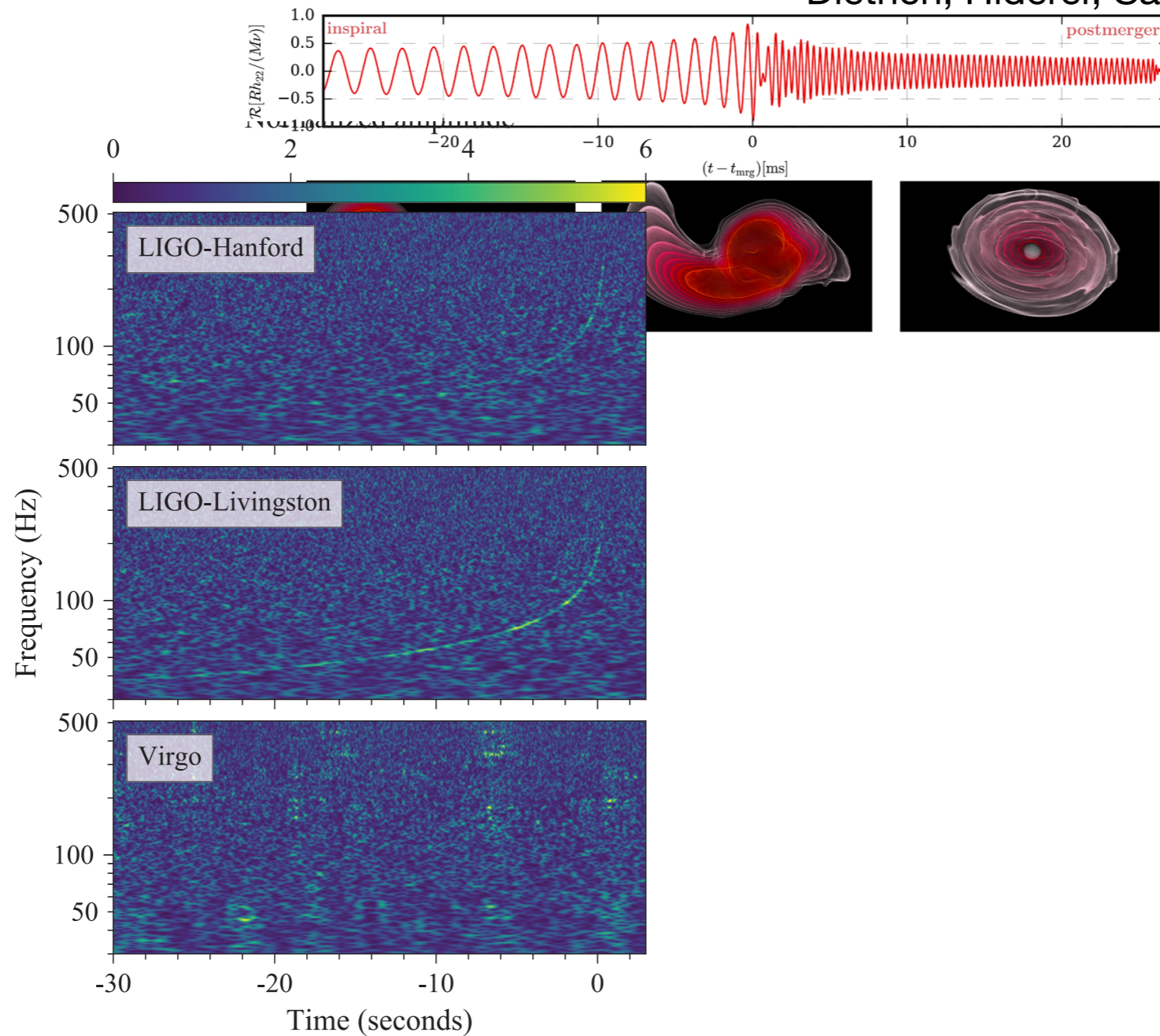
NS-NS mergers

Dietrich, Hiderer, Samajdar 2004.02527



NS-NS mergers

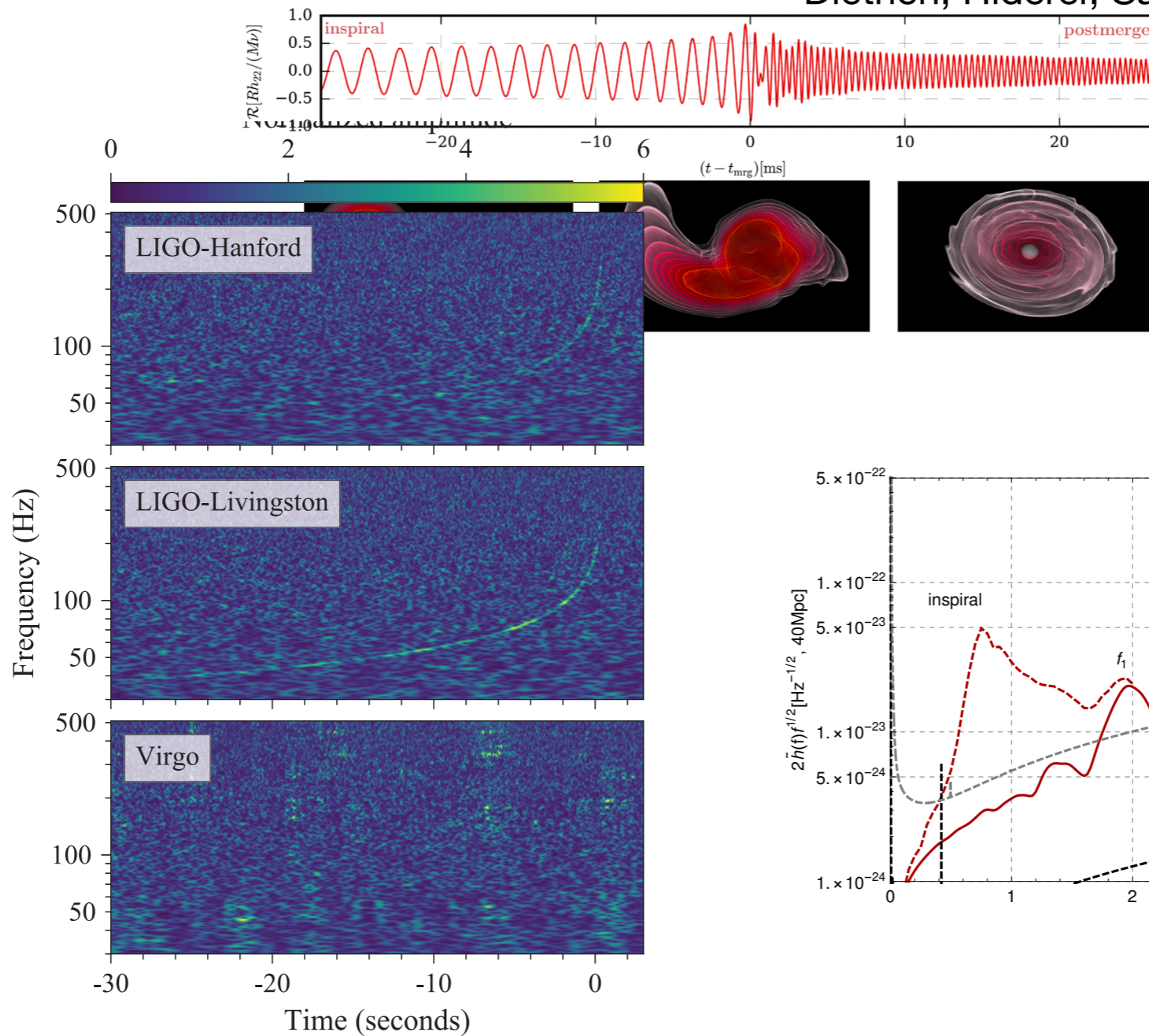
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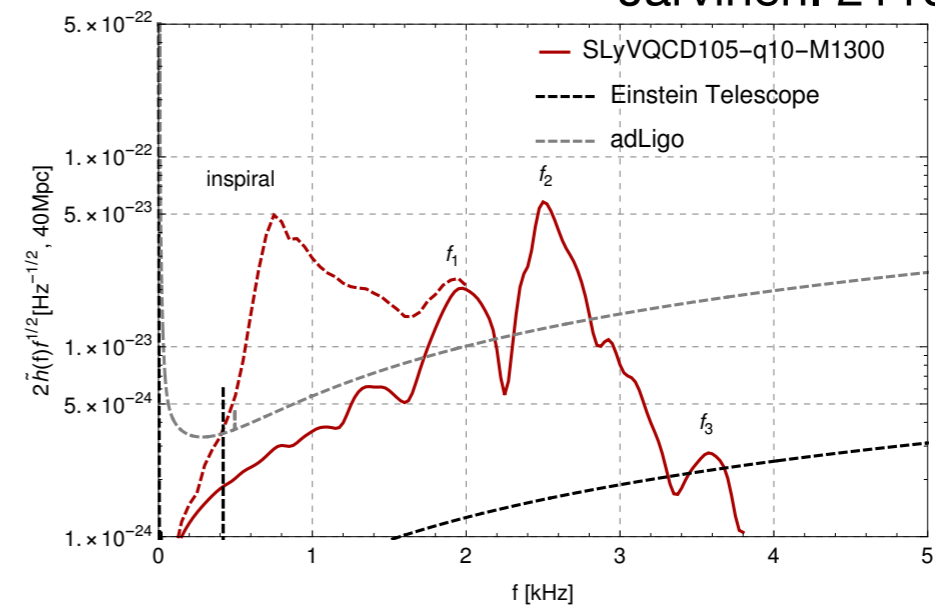
Inspiral phase
0.5-1 kHz

NS-NS mergers

Dietrich, Hiderer, Samajdar 2004.02527



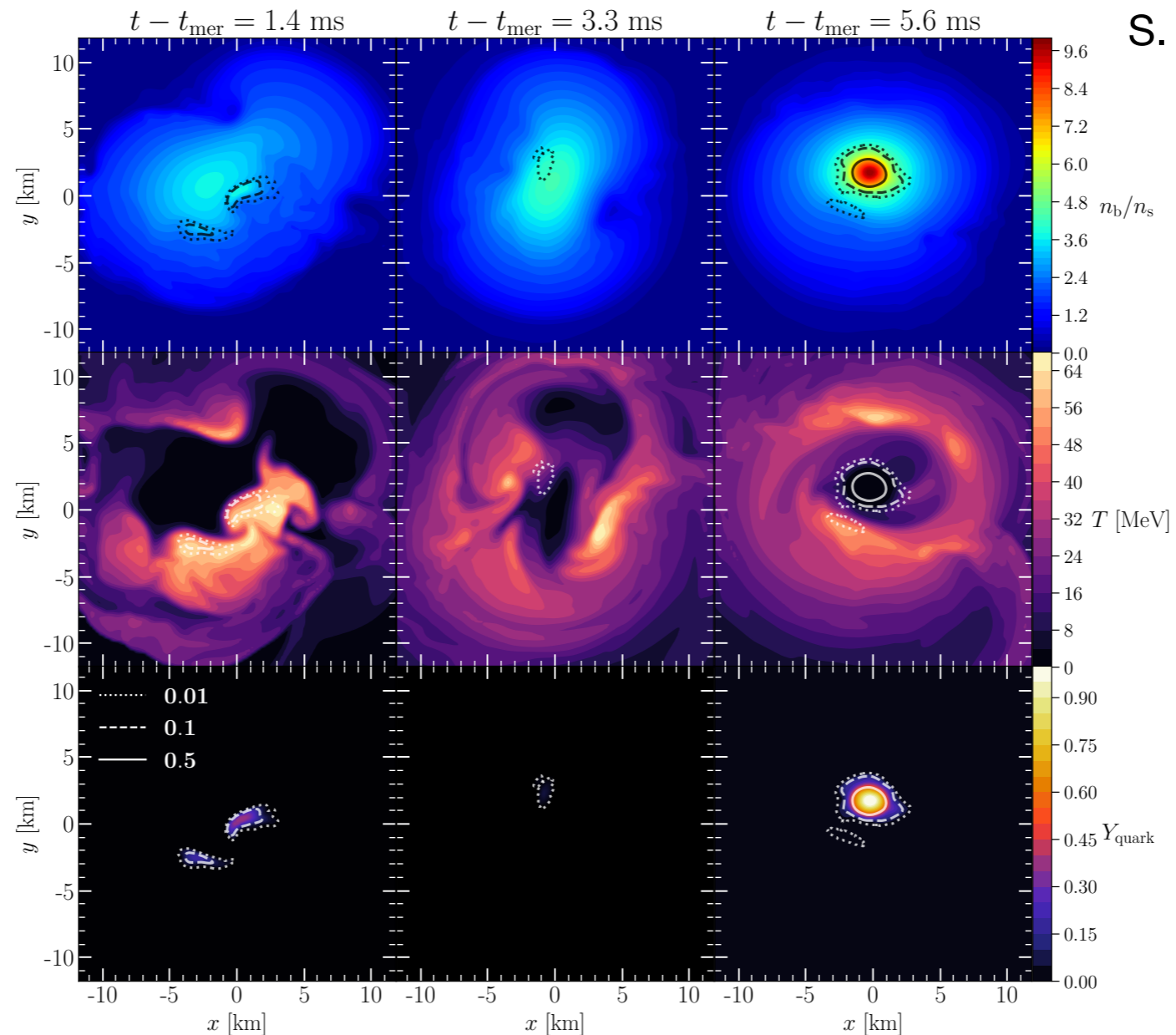
Järvinen. 2110.08281



Inspirational phase
0.5-1 kHz

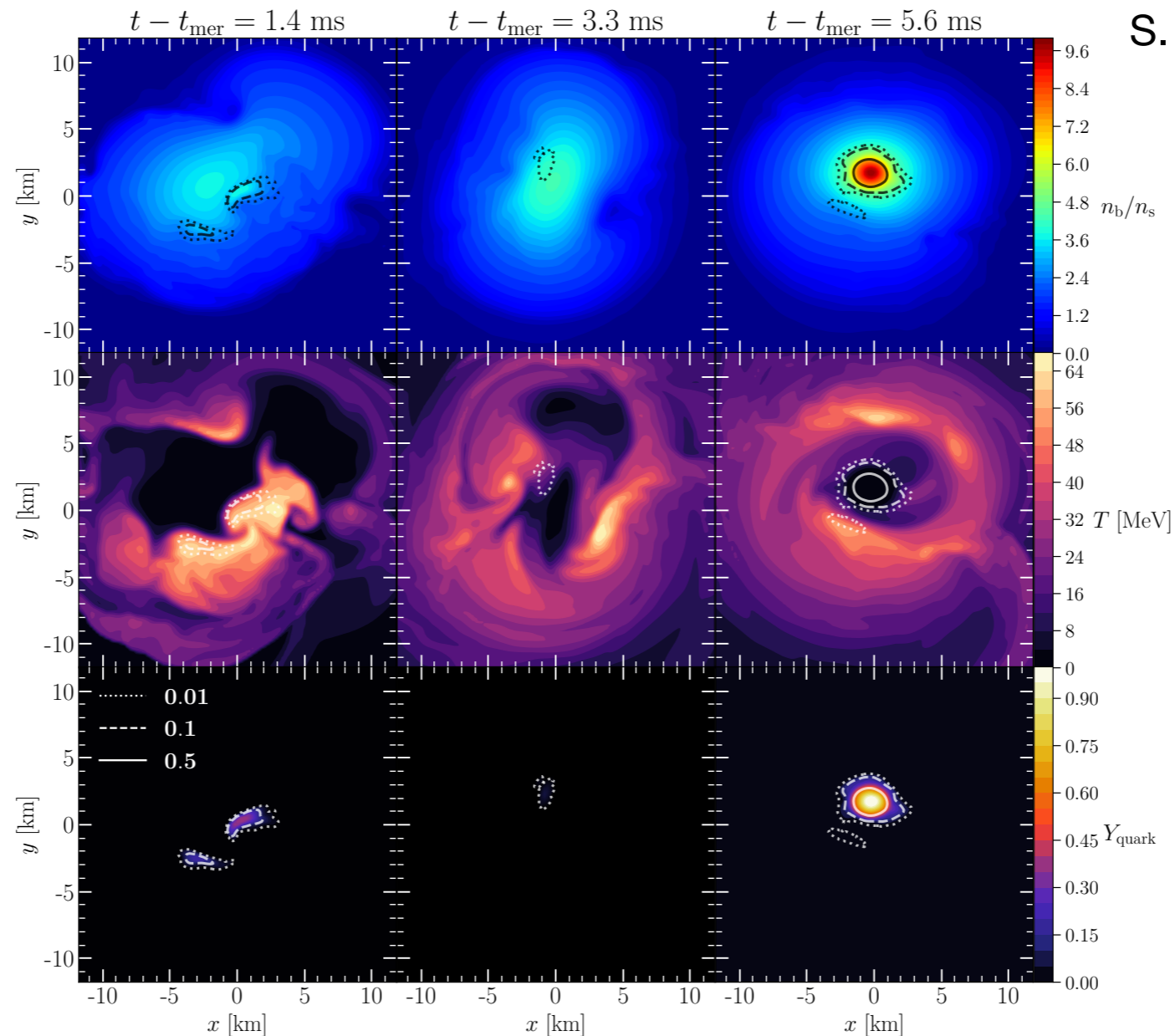
Post merger
1-4 kHz

NS-merger and First Order PT



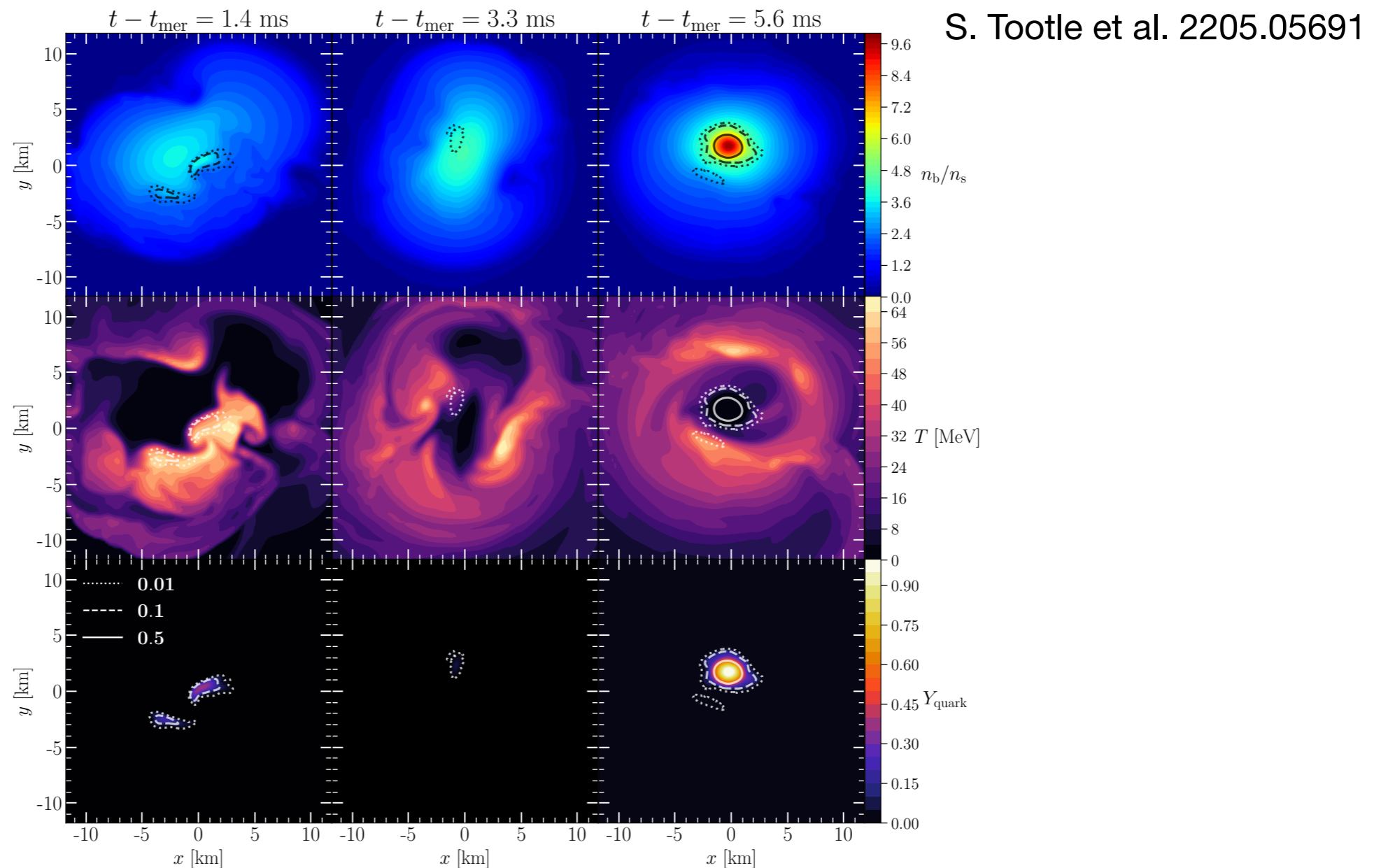
- Large regions in the quark matter phase

NS-merger and First Order PT



- Large regions in the quark matter phase
- FOPT affect the post merger dynamics

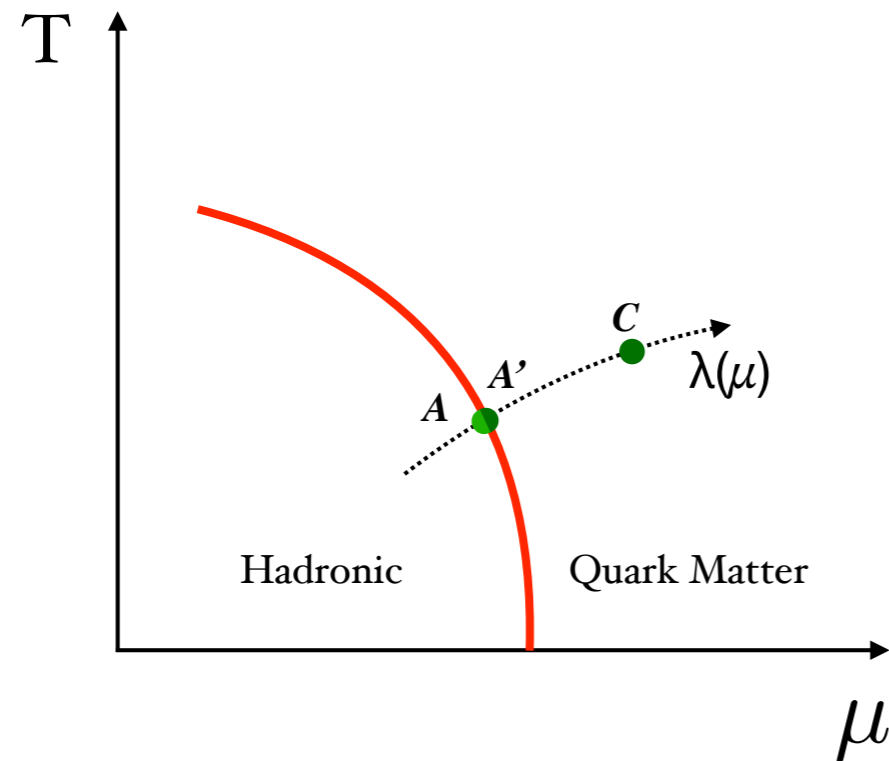
NS-merger and First Order PT



- Large regions in the quark matter phase
 - FOPT affect the post merger dynamics
- “Mild imprint of FOPT in the amplitude or frequency strain”

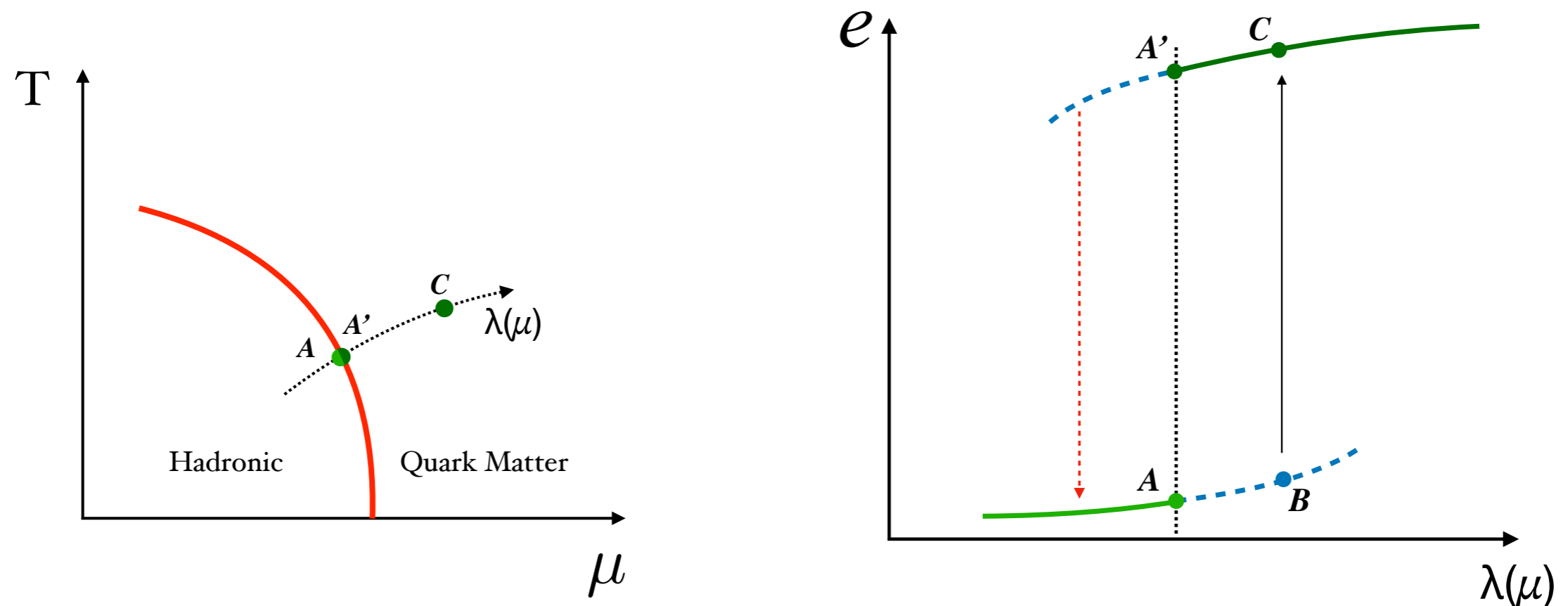
Over-Heating Nuclear Matter

- Matter compression leads to phase transition



Over-Heating Nuclear Matter

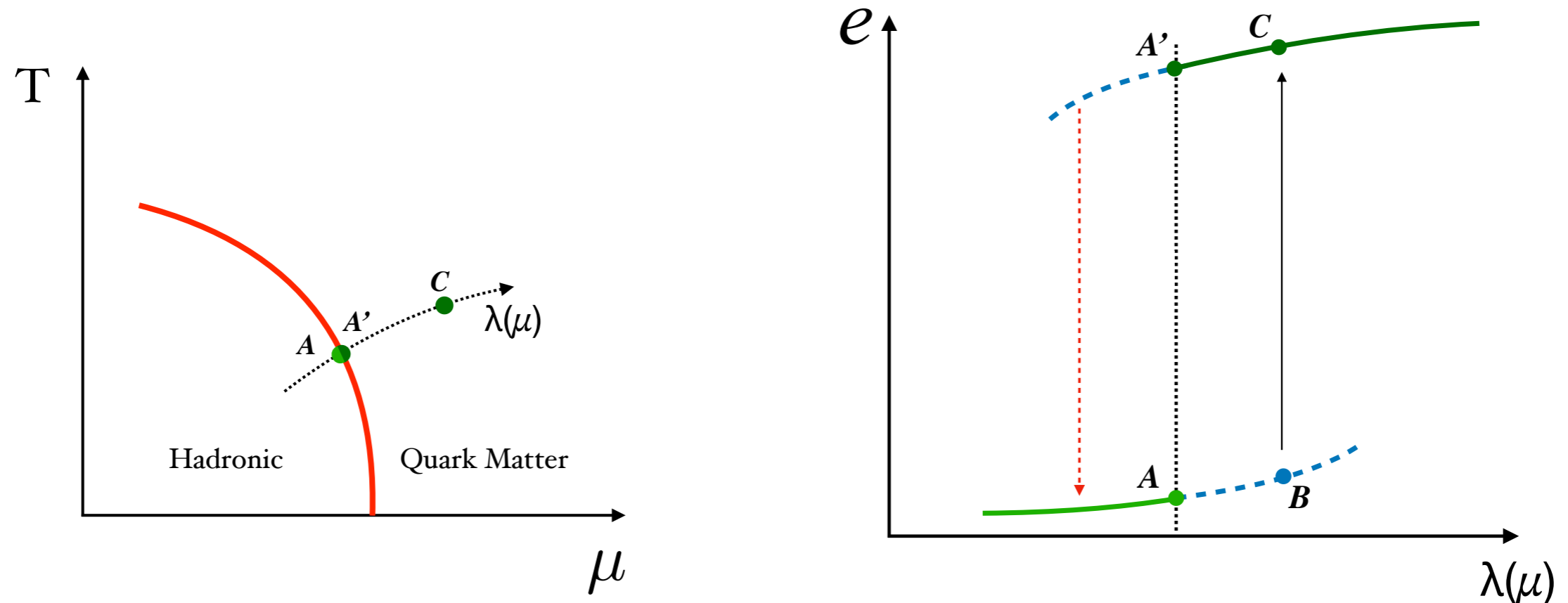
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- Over-compressed matter: locally stable, globally unstable

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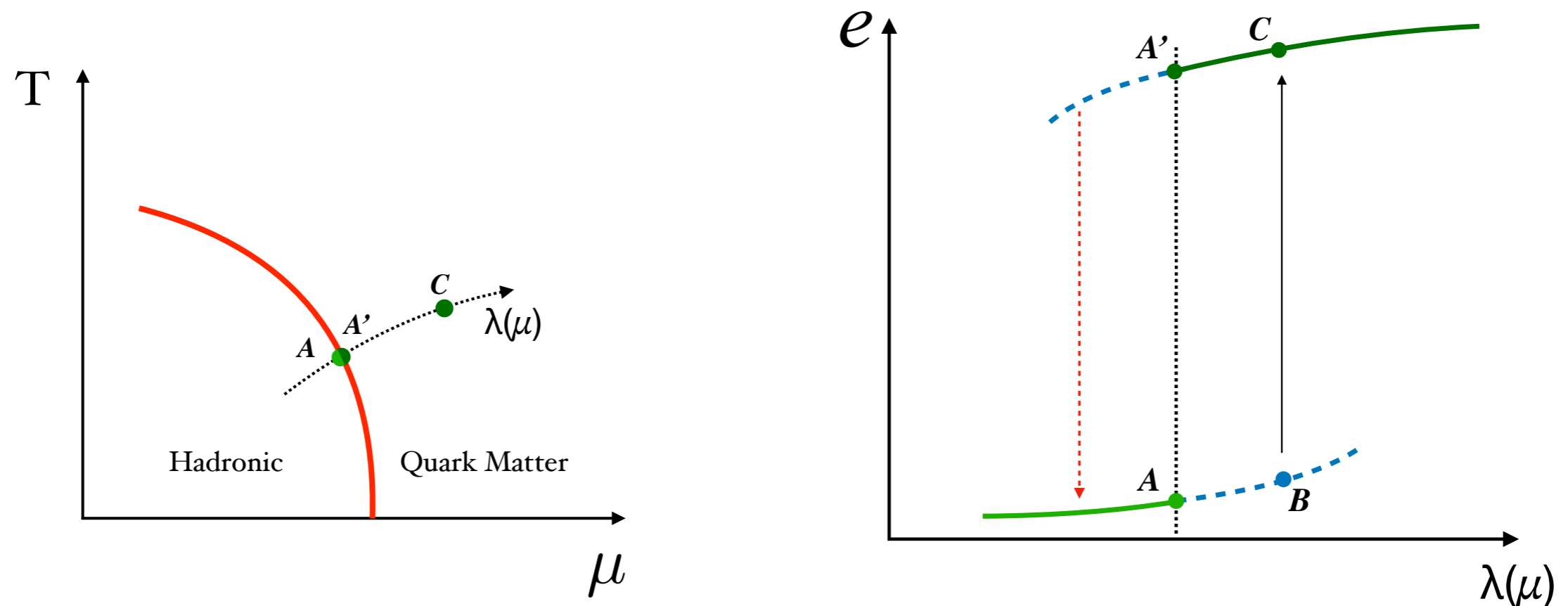
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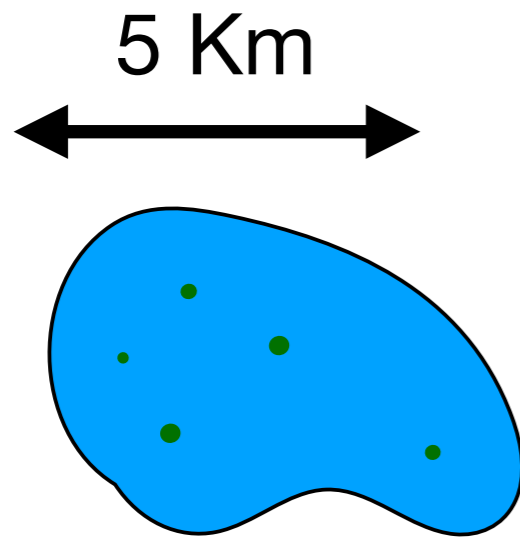
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How do bubble dynamics drive the transition?

Dynamics of the transition



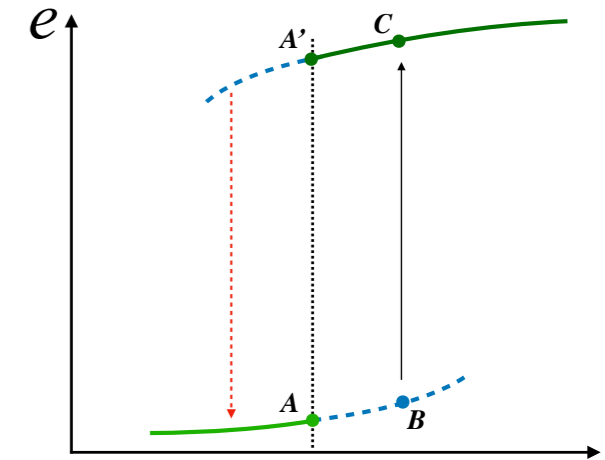
- Over Heated region

- Bubbles nucleate

$$\frac{dP}{dt d^3x} = \Lambda^4 e^{-S[\Lambda]}$$

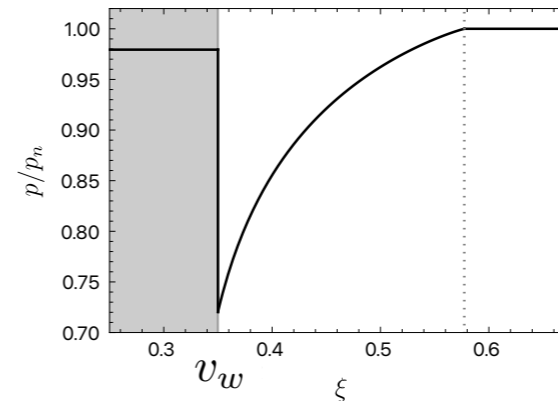
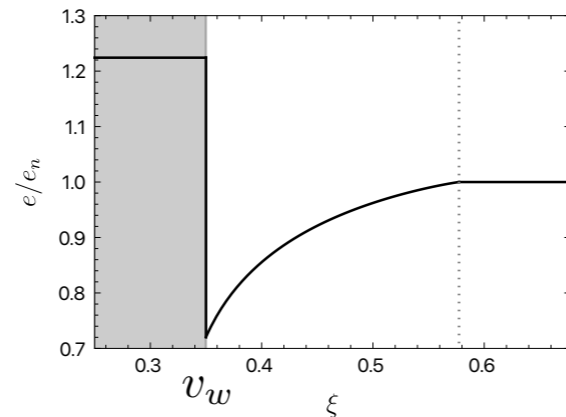
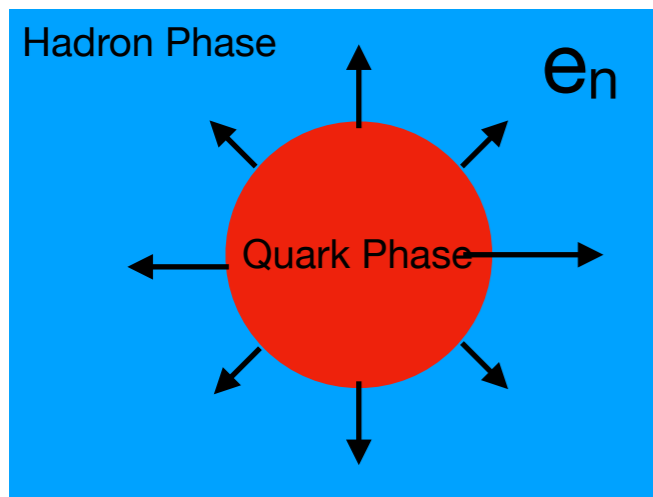
$$\mathcal{E} \simeq \mathcal{P} \simeq \Lambda^4 \simeq 0.5 \text{ GeV/fm}^3$$

- Bubbles start to expand

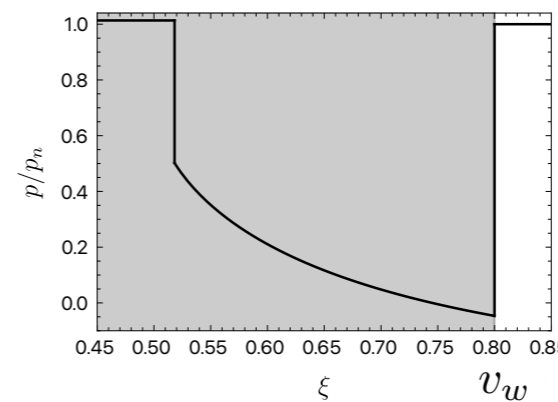
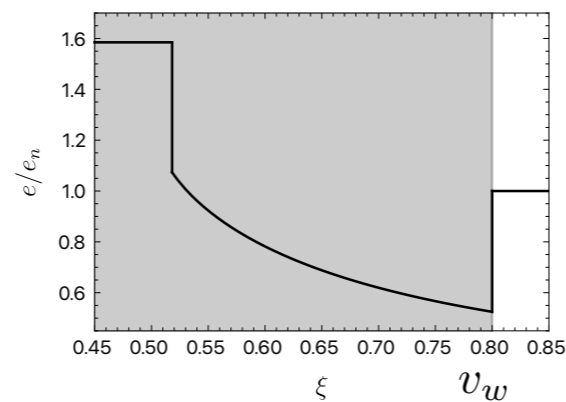


Expanding Bubbles

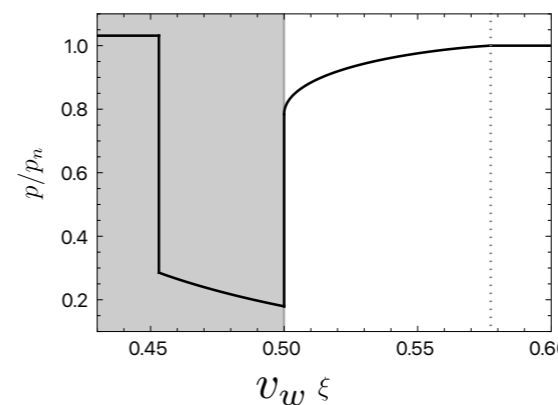
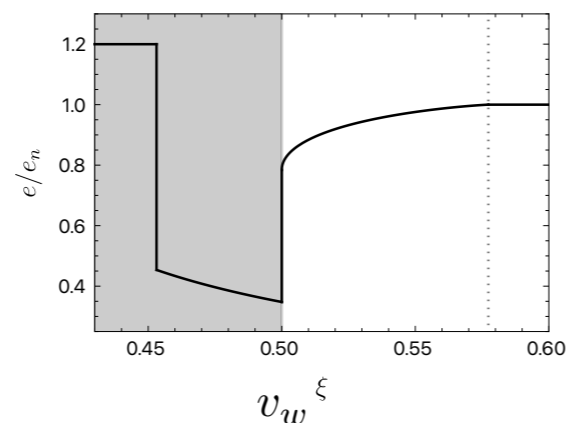
- Hydrodynamic analysis: self-similar regime with constant wall velocity



Deflagration



Detonation

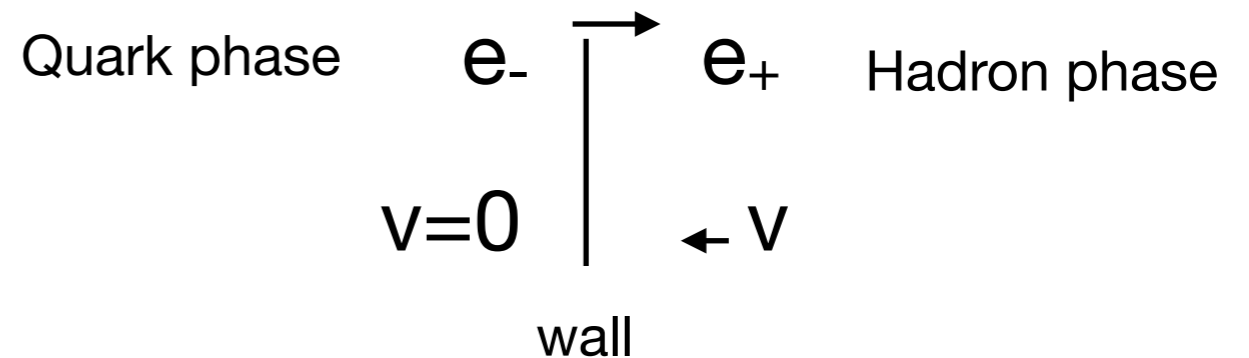
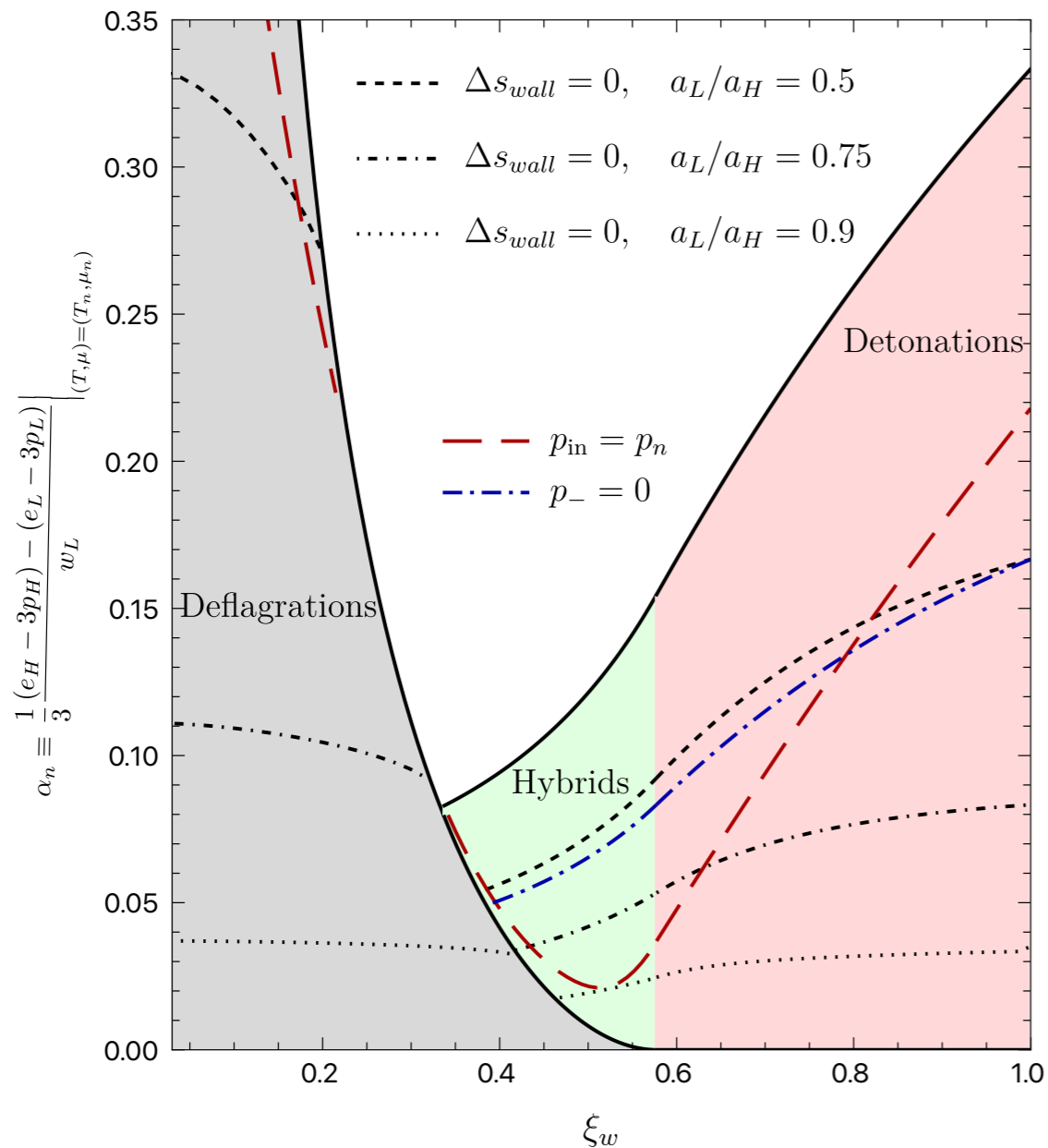


Hybrids

- Given an eos: multiple solutions allowed

Large jump of degrees of freedom

- ◉ In this limit, we can get an estimate for the wall velocity



- ◉ Large jump:

$$\frac{e_+}{e_-} \sim \frac{s_+}{s_-} \sim \frac{w_+}{w_-} \sim x \quad \Rightarrow \quad \alpha_n \sim x^{-1}$$

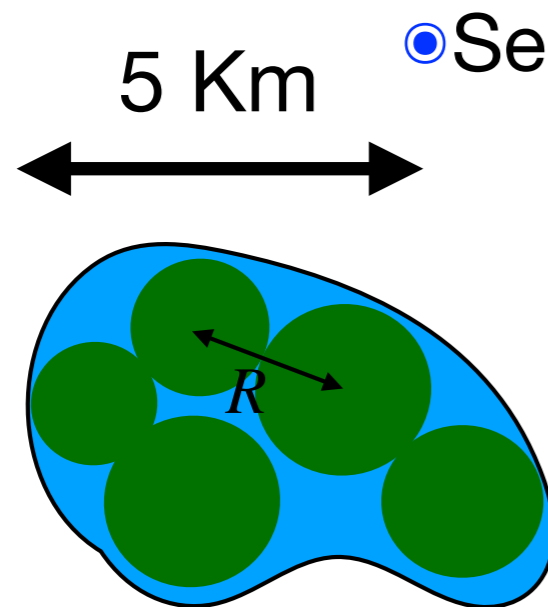
Only deflagration is possible

- ◉ Continuity across the wall implies

$$v_w \sim x$$

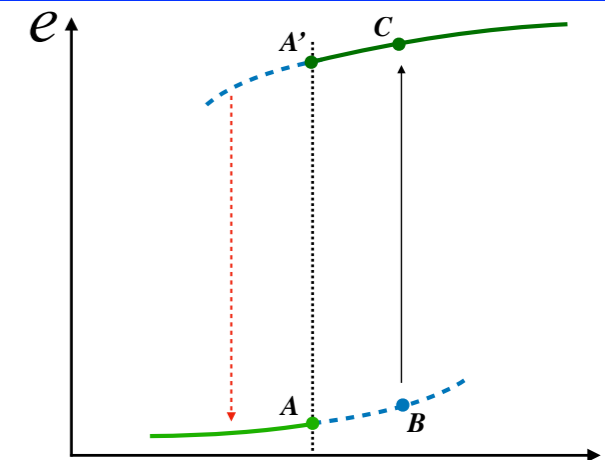
- ◉ We take $v_w \simeq 0.1$ as a representative value

Dynamics of the transition

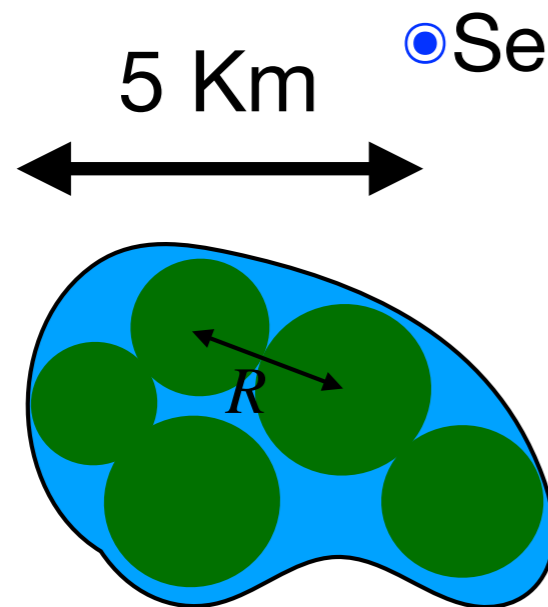


⦿ Self-similar regime:

- ⦿ Bubbles expand at constant $v_w \simeq 0.1$
- ⦿ Collide at a characteristic time $1/\beta$

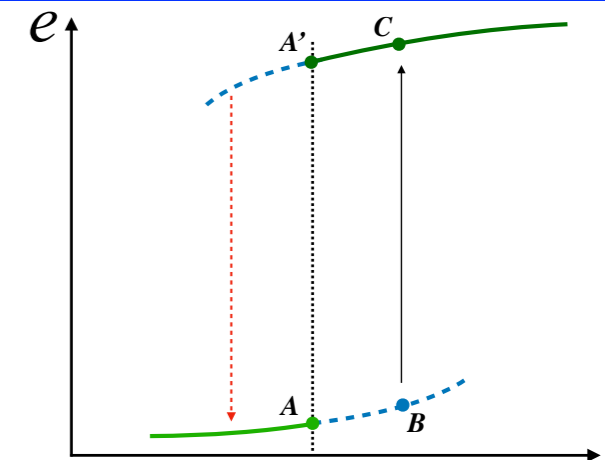


Dynamics of the transition

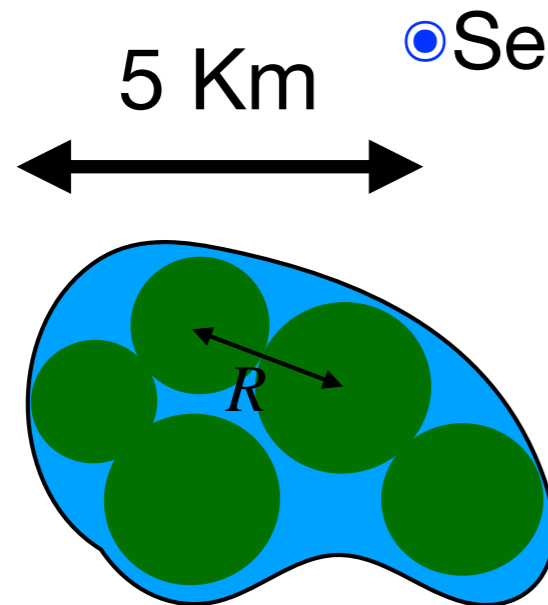


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Dynamics of the transition

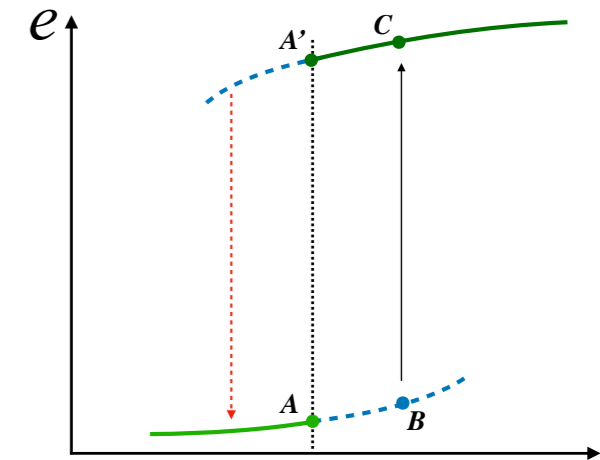


Self-similar regime:

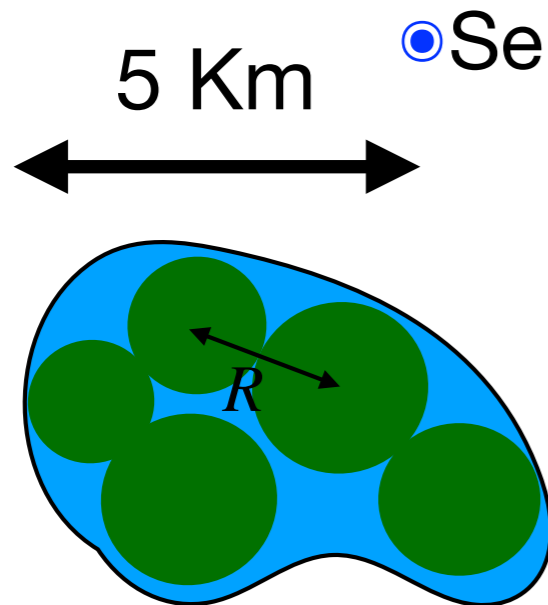
- Bubbles expand at constant $v_w \simeq 0.1$
- Collide at a characteristic time $1/\beta$
 - Prob. of a bubble within its volume ~ 1
- Exponential growth \Rightarrow

$$\beta = -\frac{dS}{dt} = \left(-\Lambda \frac{dS}{d\Lambda} \right) \left(\frac{1}{\Lambda} \frac{d\Lambda}{dt} \right)$$

$\Lambda dS/d\Lambda \sim S$
 $\frac{1}{\tau} = \frac{1}{\Lambda} \frac{d\Lambda}{dt} \quad \tau \simeq 1 \text{ ms.}$



Dynamics of the transition



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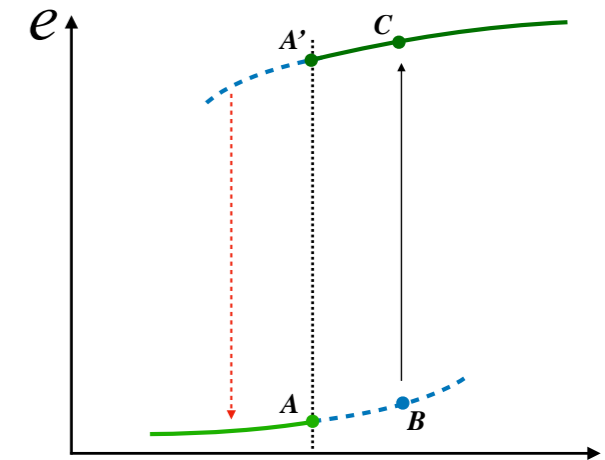
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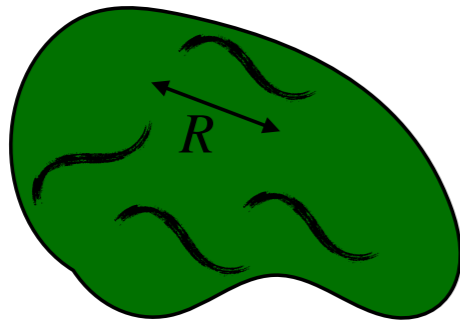

Plugging numbers: characteristic time for the transitions is

$$\beta^{-1} \simeq 5.43 \mu\text{s}$$



Dynamics of the transition

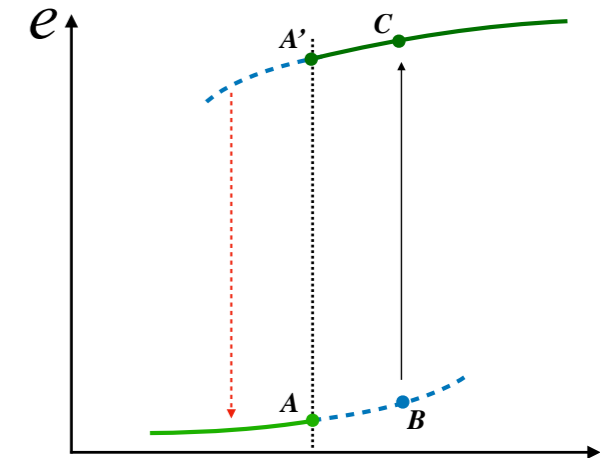
5 Km



⊙ After bubbles collide

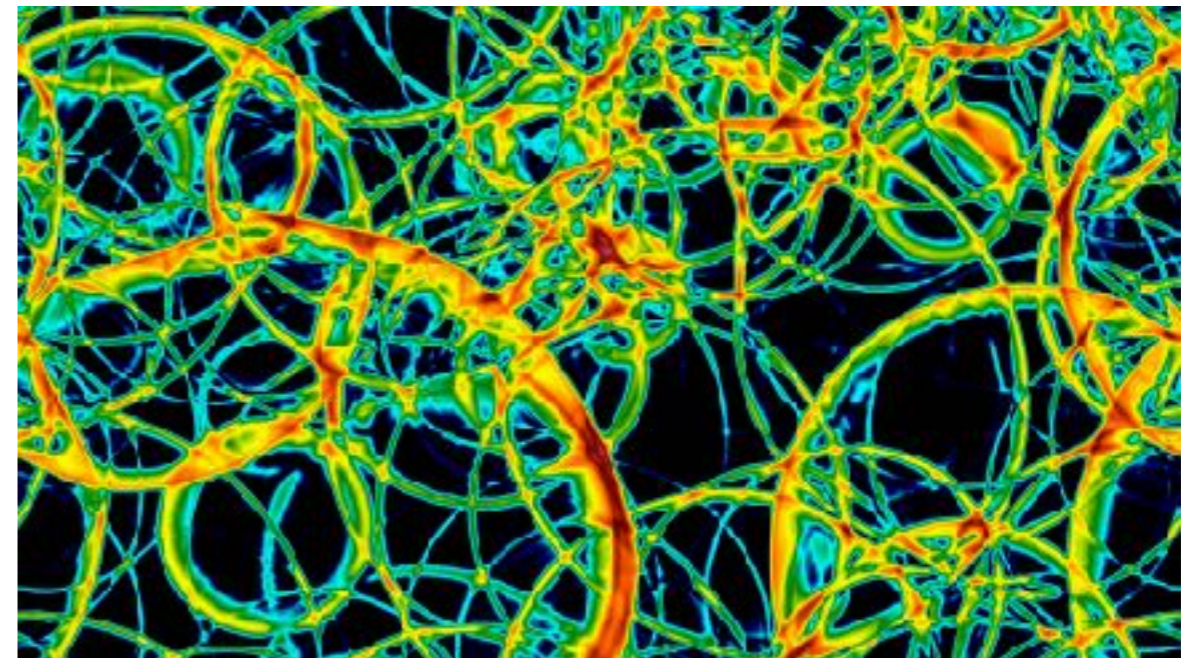
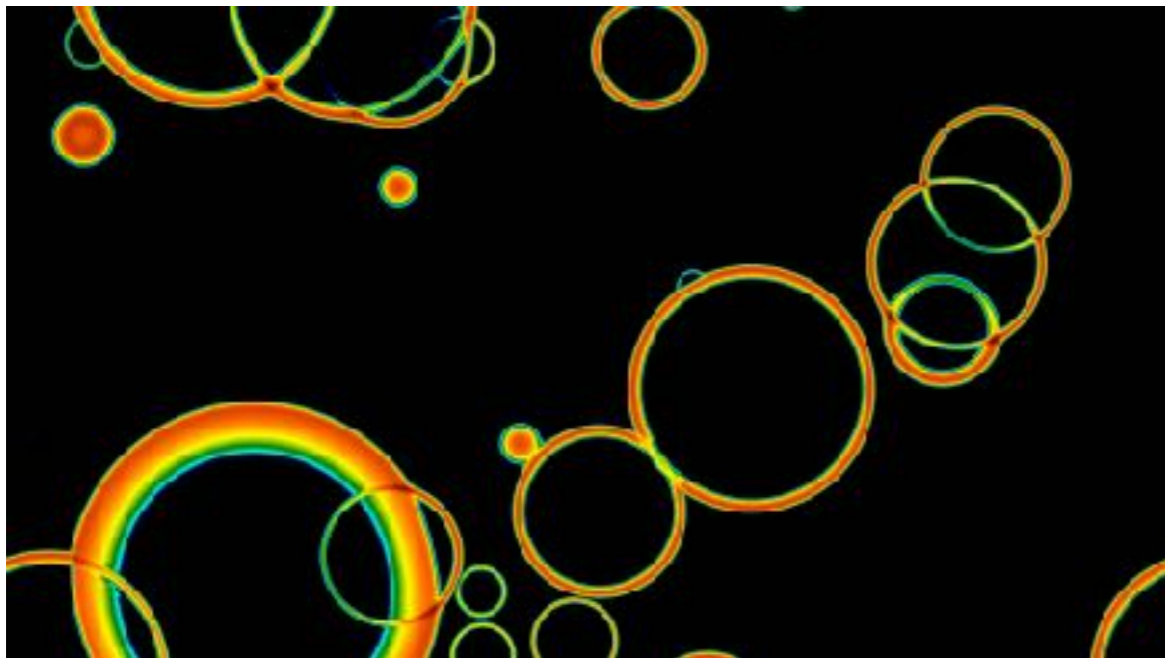
⊙ Macroscopic disturbances

$$R = (8\pi)^{1/3} \frac{v_w}{\beta} \simeq 477 \text{ m}$$



Cosmological Phase Transitions

- Physics analogous to Electro Weak cosmological transitions

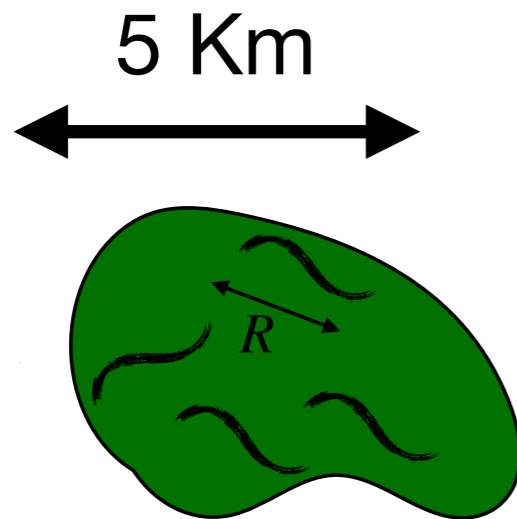


Credit: D. Weir

- Collisions of sound waves
- Turbulent flow

} \Rightarrow GW emission

Dynamics of the transition



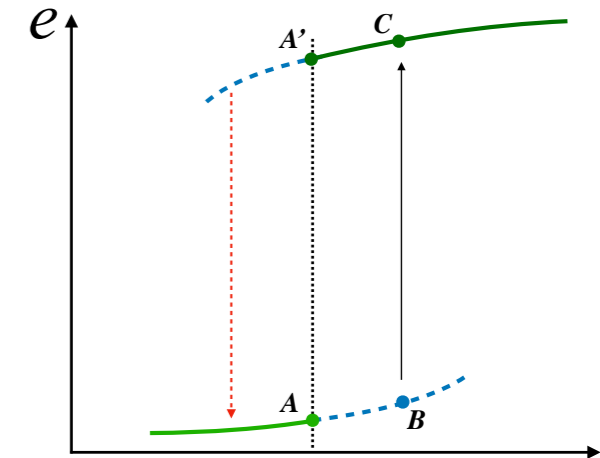
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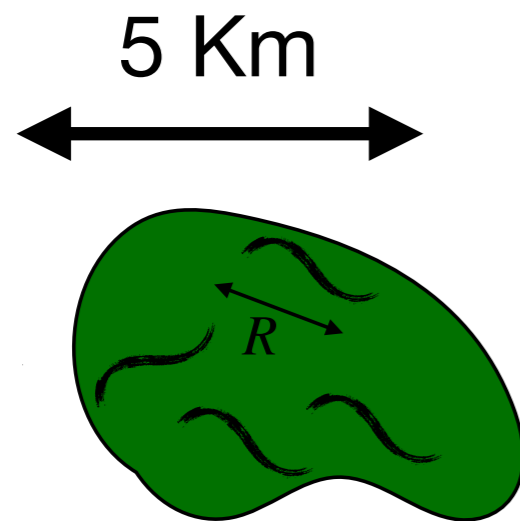
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⦿ Frequency of emitted GW from sound waves

$$f_0 \simeq \frac{0.1}{v_w} \frac{1 \text{ ms}}{\tau} \left(0.62 + 0.0034 \log \left[\left(\frac{v_w}{0.1} \right)^3 \left(\frac{\tau}{1 \text{ ms}} \right)^4 \frac{\Lambda^4}{0.5 \text{ GeV}/\text{fm}^3} \right] \right) \text{ MHz}.$$



Dynamics of the transition



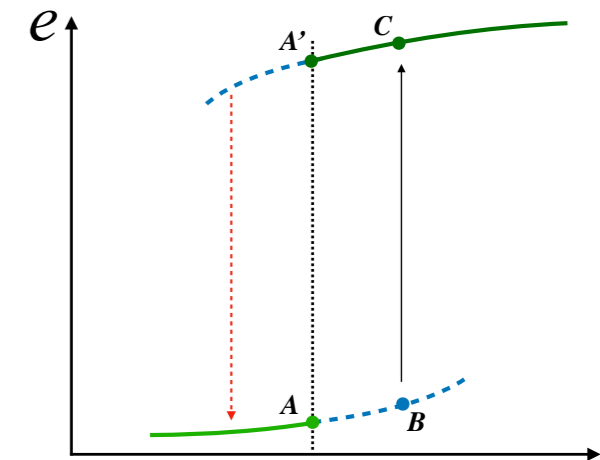
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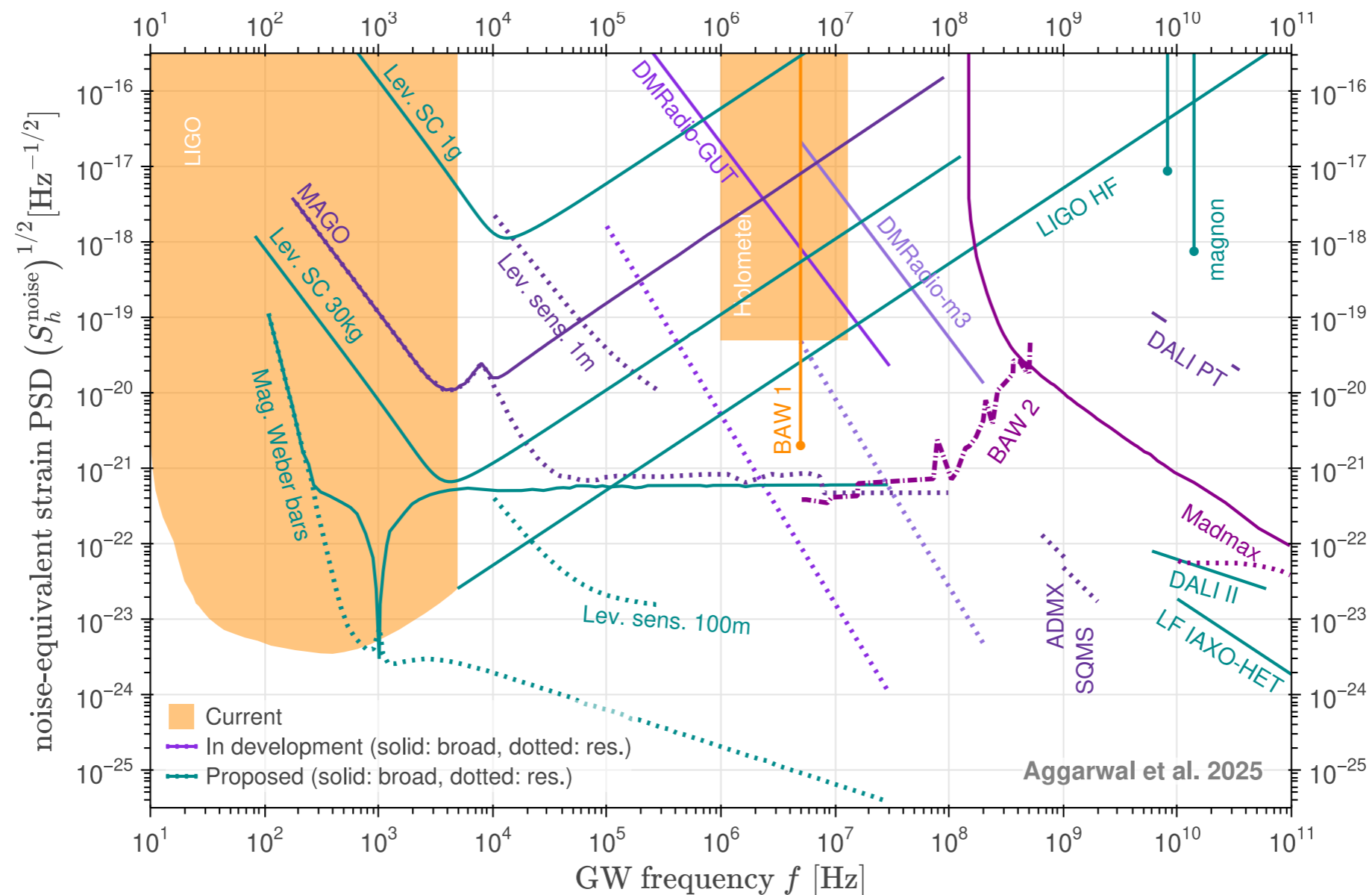
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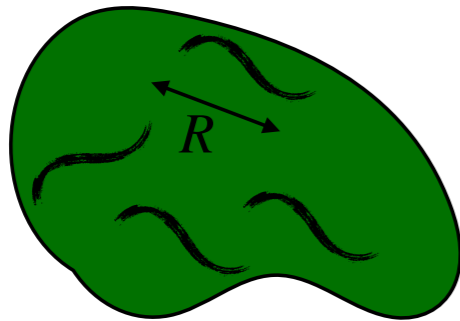
Future High Frequency Detectors



Aggarwal et al. 2501.11723

Dynamics of the transition

5 Km

Fluid velocity

$$0.01 \lesssim v_f \lesssim 0.3$$

After bubbles collide

Macroscopic disturbances

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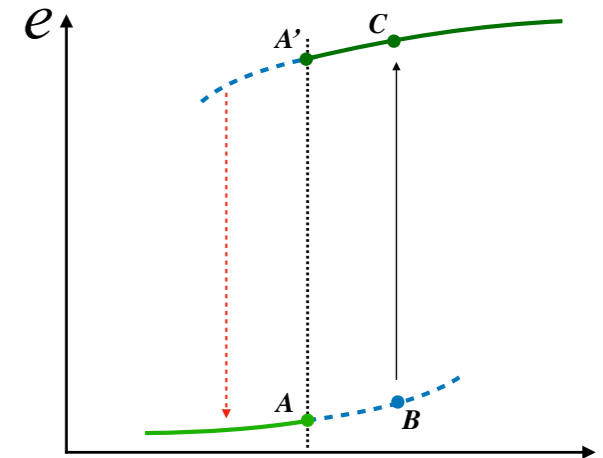
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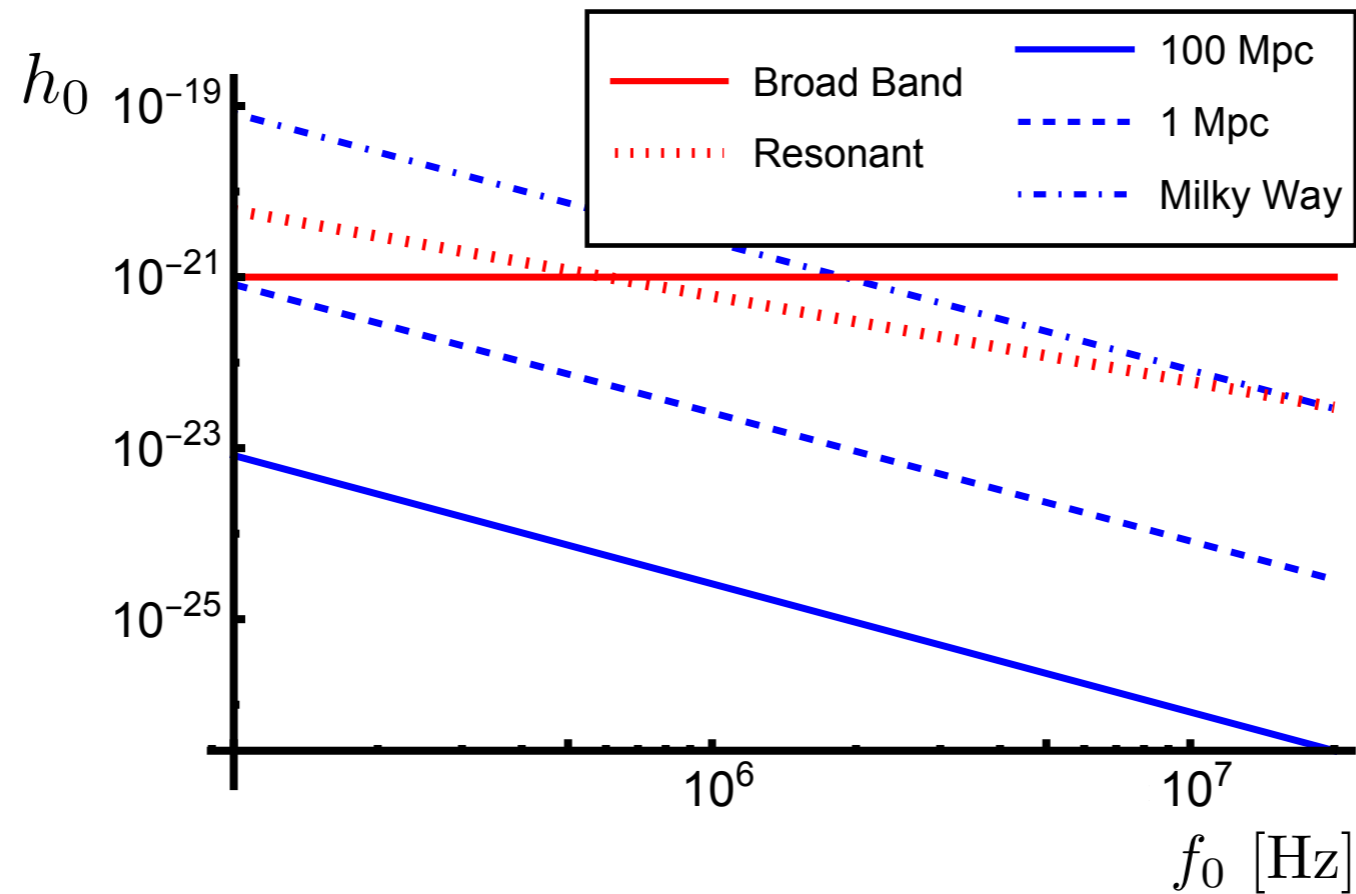
Borrowing from the analysis of cosmological transitions

Estimate of strain:

$$h_0^{\text{obs}} = h_0 \frac{L}{d} \simeq 6.2 \times 10^{-24} v_f^2 \left(\frac{\Lambda^4}{0.5 \text{ GeV/fm}^3} \right) \left(\frac{L}{5 \text{ km}} \right)^{3/2} \left(\frac{0.6 \text{ MHz}}{f} \right)^{3/2} \left(\frac{100 \text{ Mpc}}{d} \right)$$

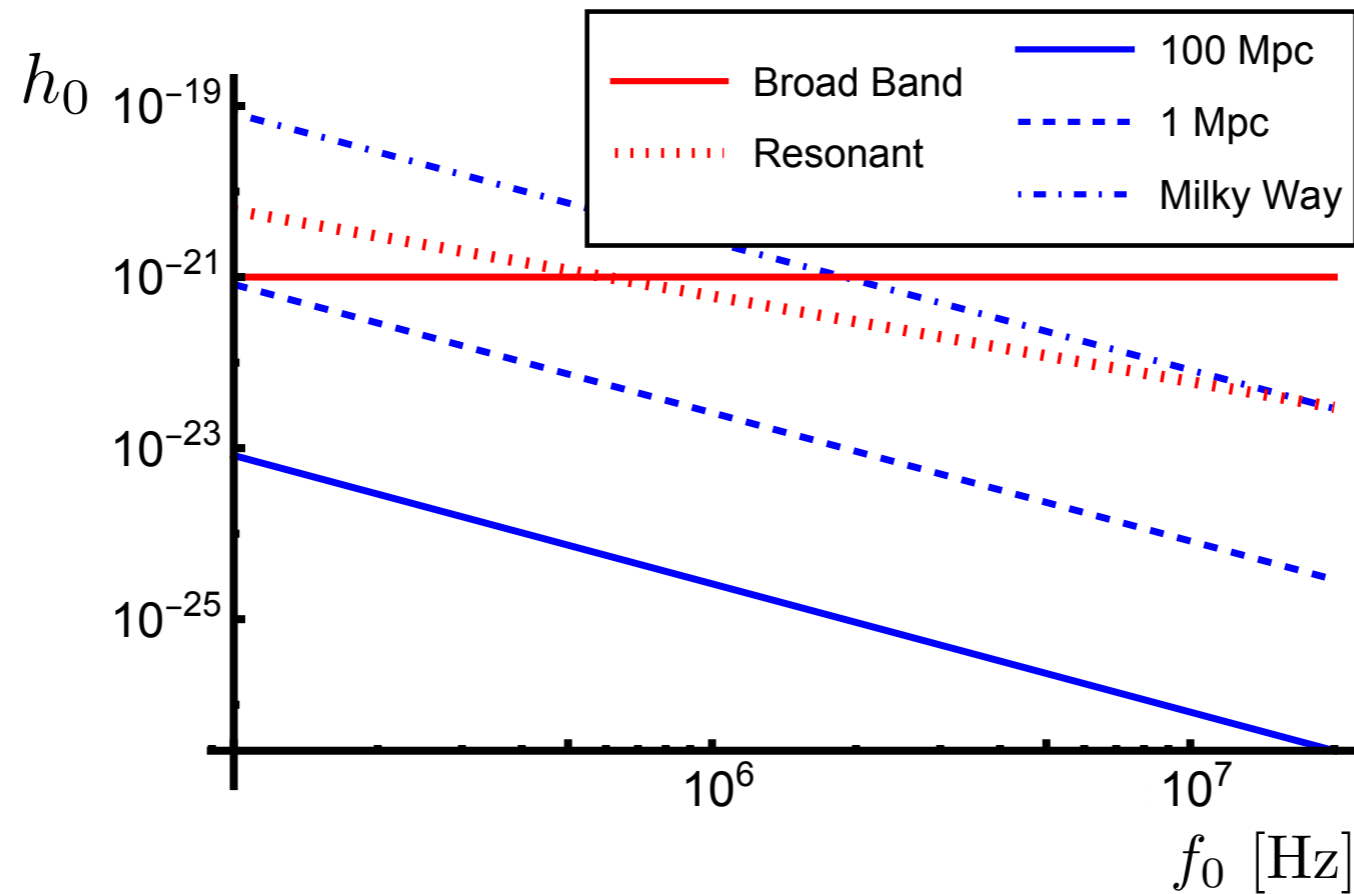


Detectability



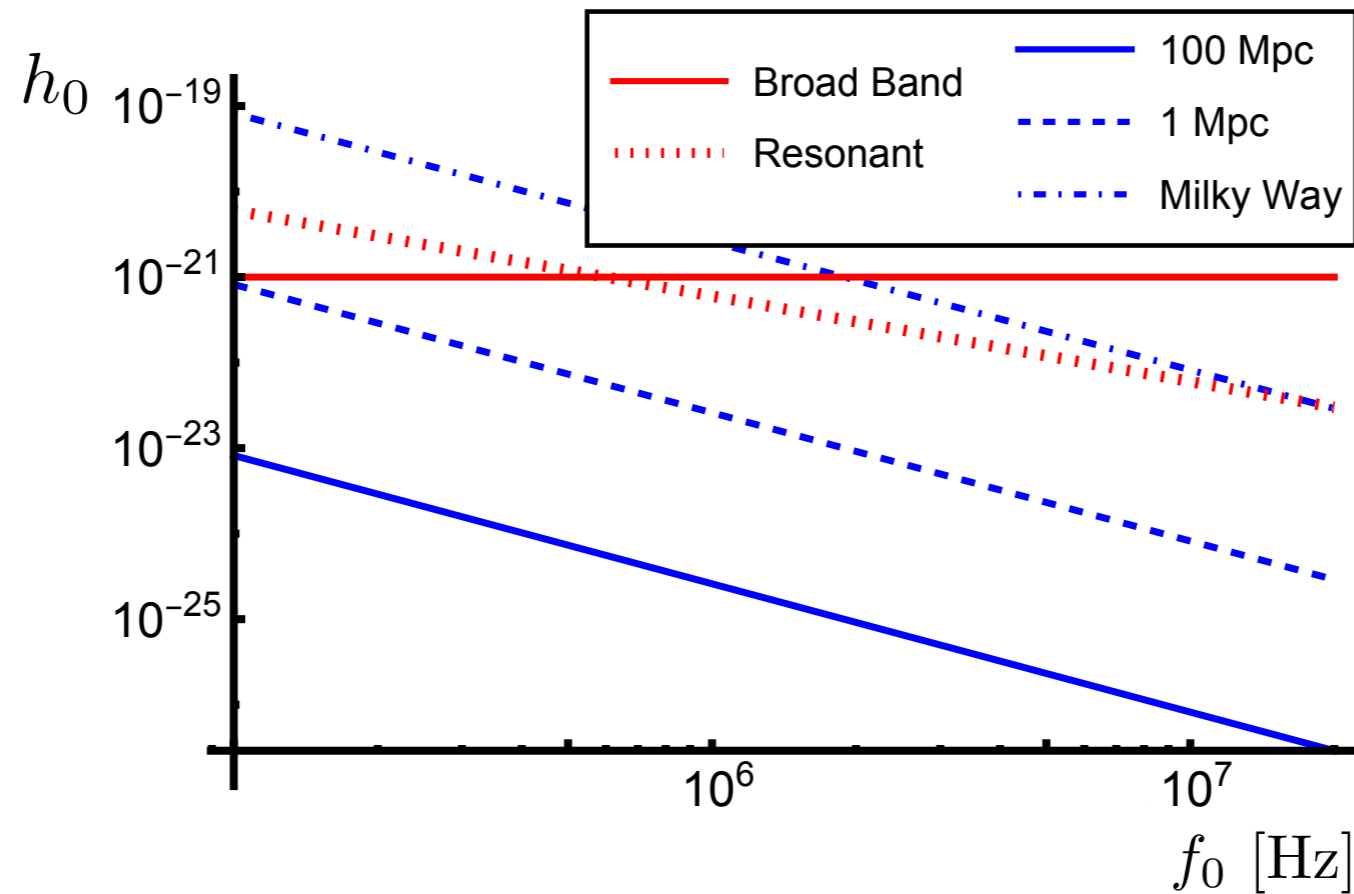
○ Close to detection but not guaranteed with current designs

Detectability



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 - Technically: Can motivate further improvements

Detectability



- Close to detection but not guaranteed with current designs
 - Technically: Can motivate further improvements
 - Theoretically: only crude estimates, addition of multiple sources...

Conclusions

- ⊙ A unique signal from phase transition;
 - ⊙ Mhz burst in coincidence with the KHz signal of the NSNS
 - ⊙ The only known signal in this band from Standar Model physics
 - ⊙ Additional motivation to push high-frequency GW detectors