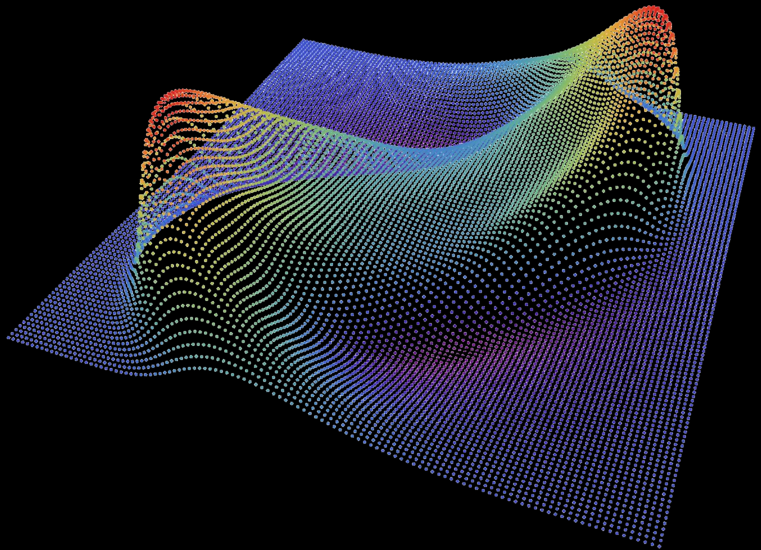
MHz GW from Neutron Star mergers



Mikel Sanchez-Garitaonandia

Jorge Casalderrey-Solana & David Mateos
2210.03171

After several years relevant QCD features remain unknown

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Strongly coupled nature at $E \sim \Lambda_{QCD}$

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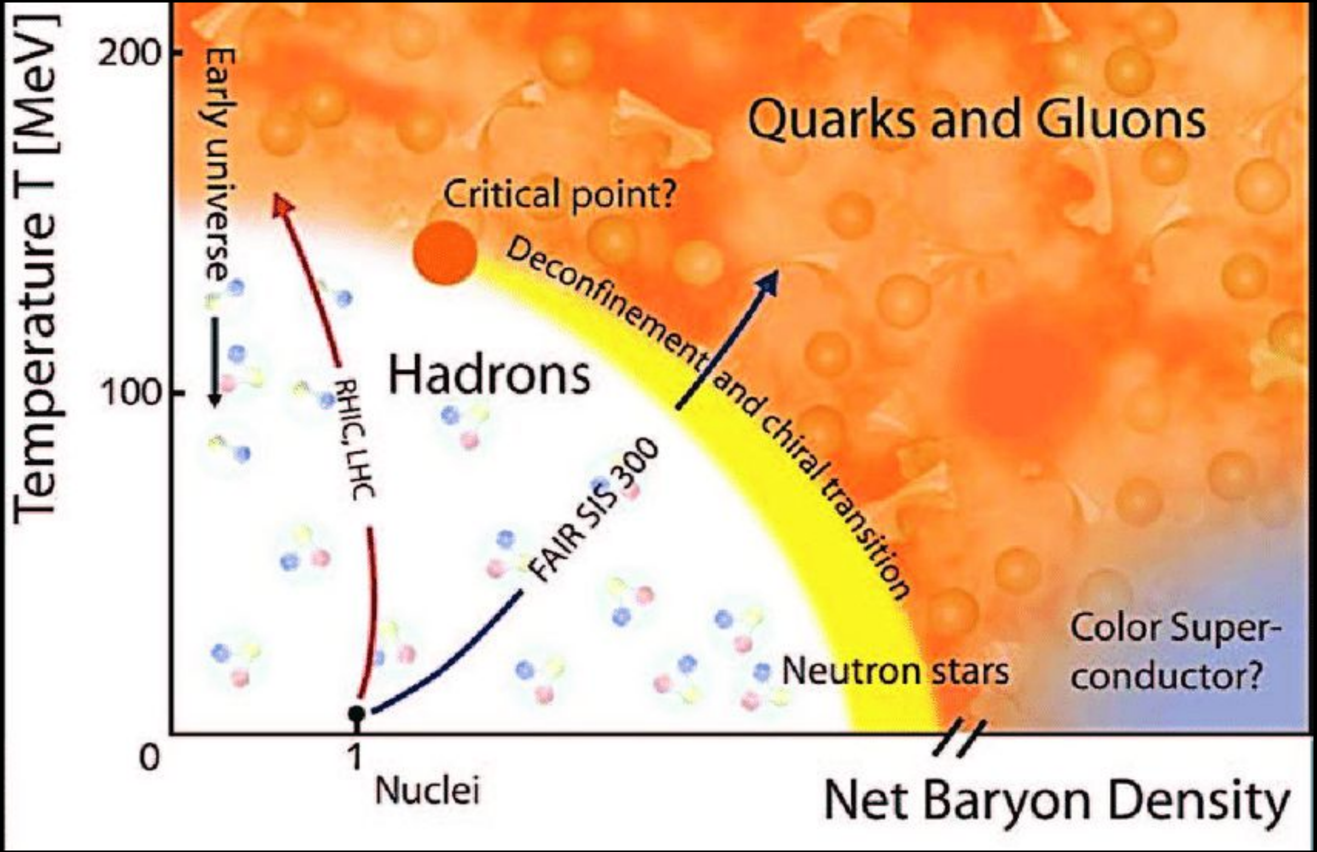
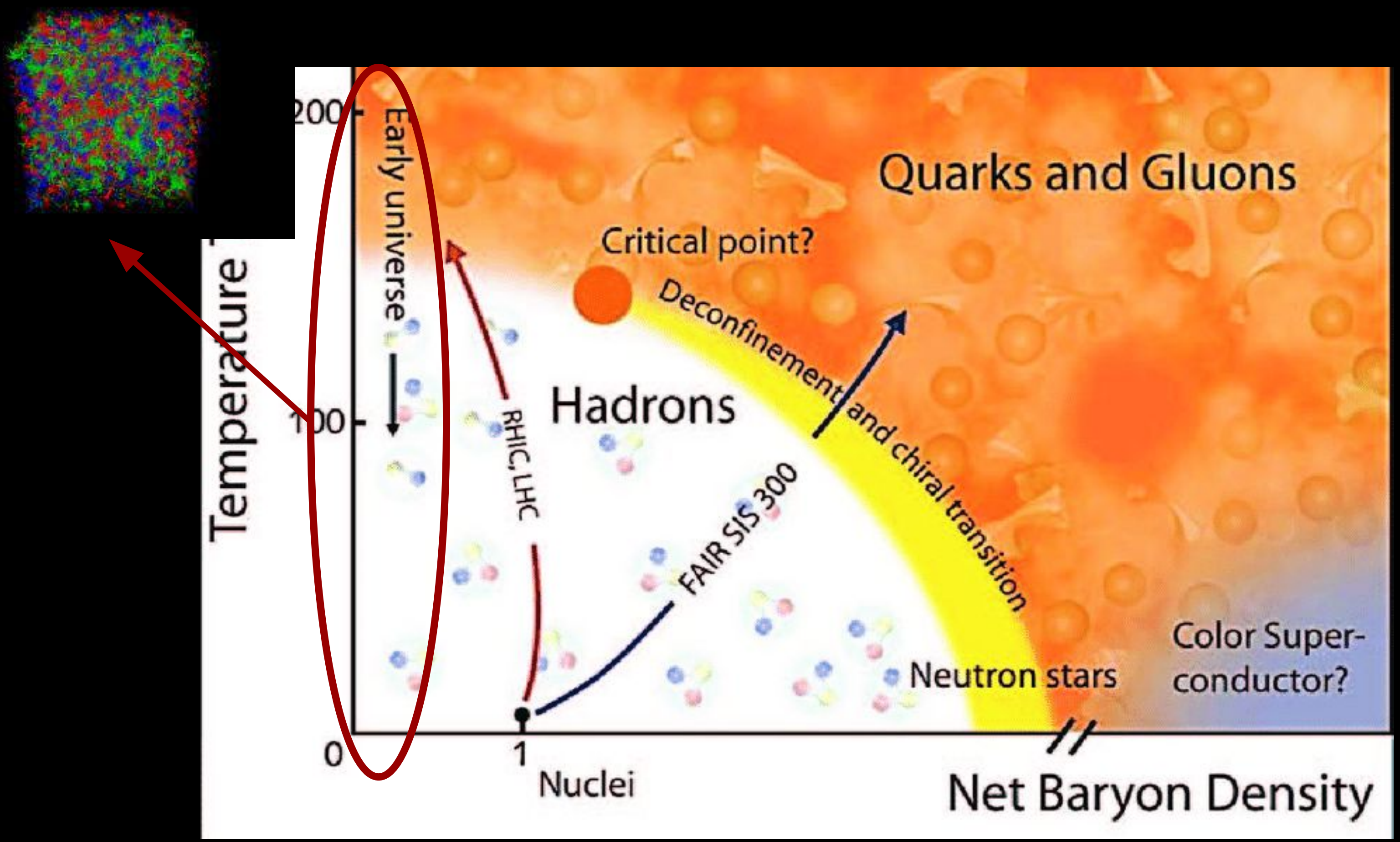
Strongly coupled nature at $E \sim \Lambda_{QCD}$

Phase diagram?



Temperature T [MeV]
200
100
0
1
Nuclei
Net Baryon Density
Early universe
RHIC,LHC
FAIR SIS 300
Hadrons
Critical point?
Quarks and Gluons
Deconfinement and chiral transition
Neutron stars
Color Super-
conductor?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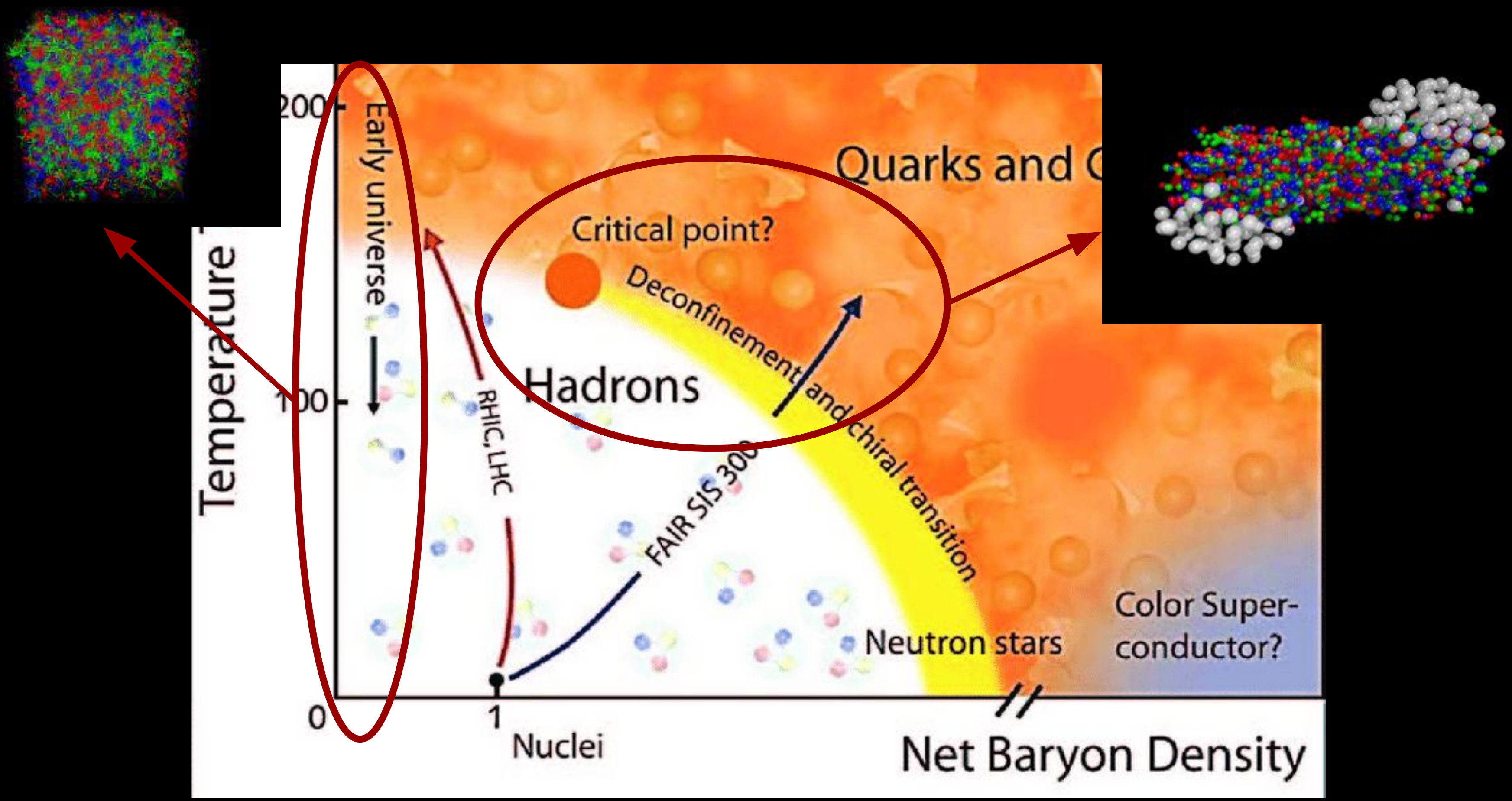

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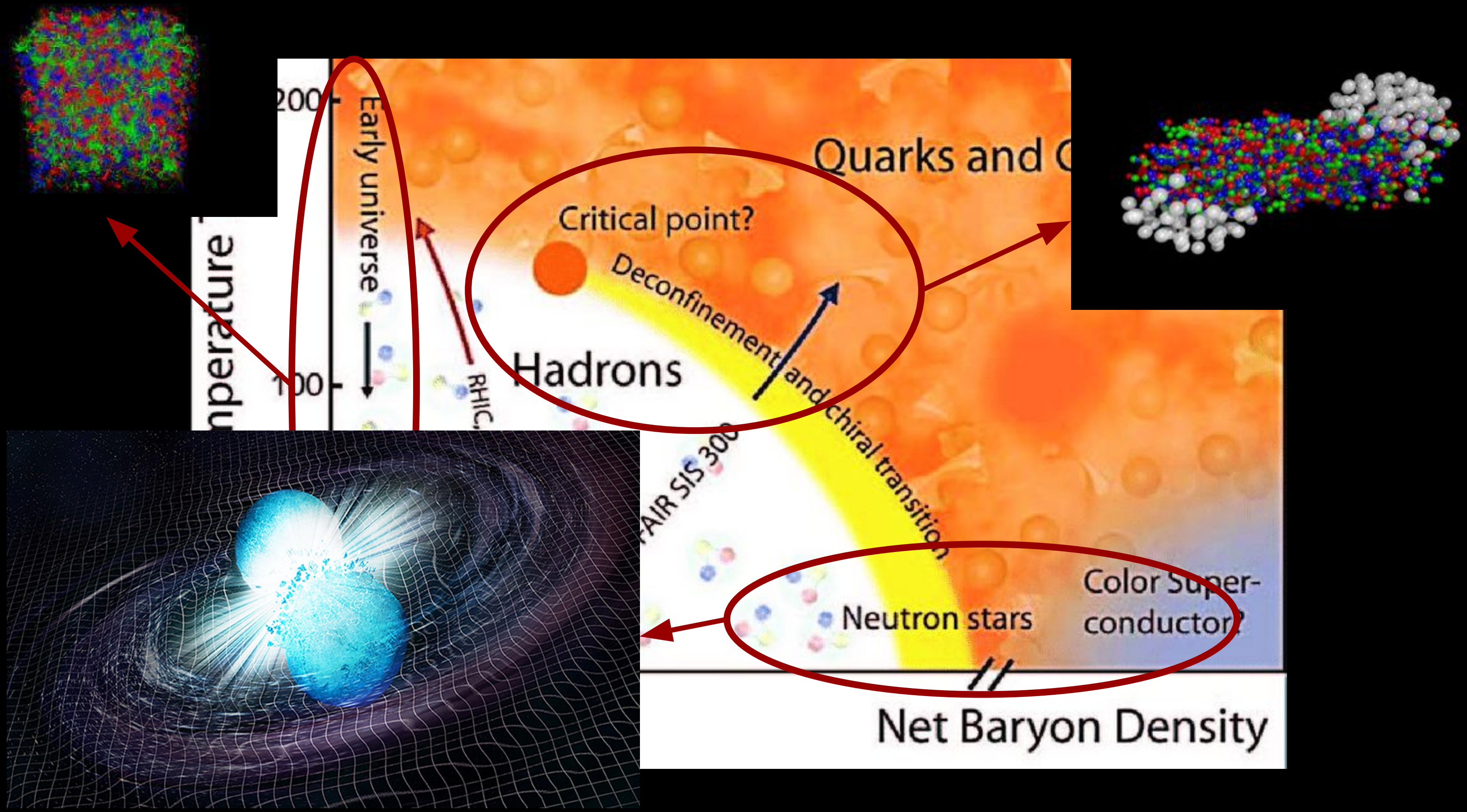
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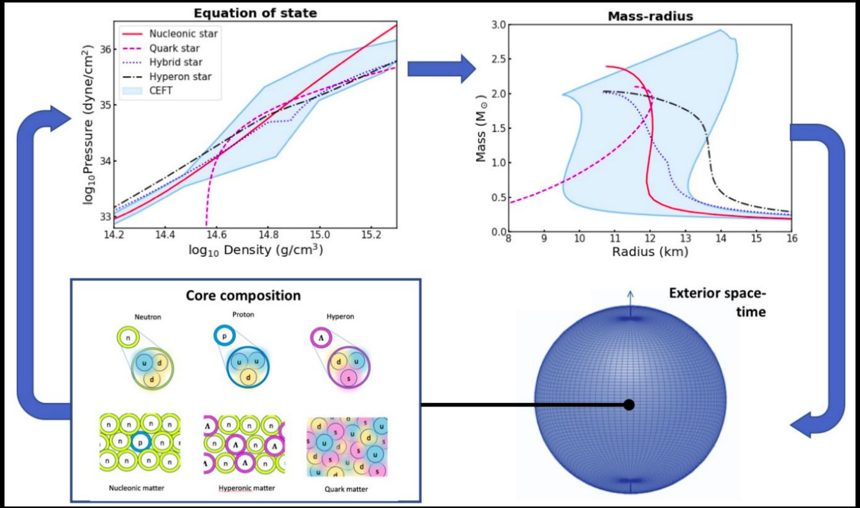
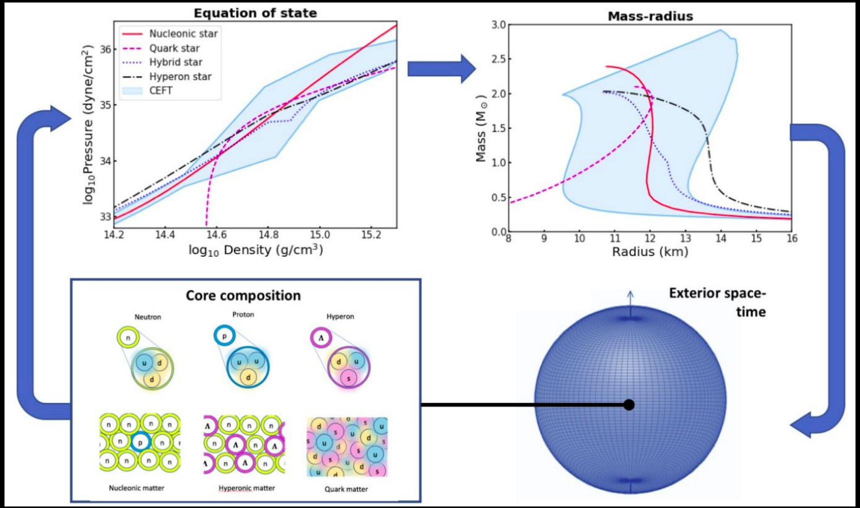
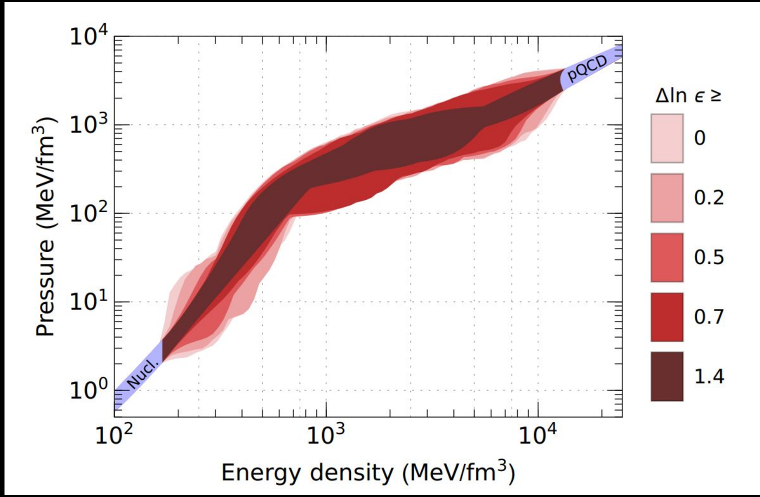
Bogdanov et. al. ‘22

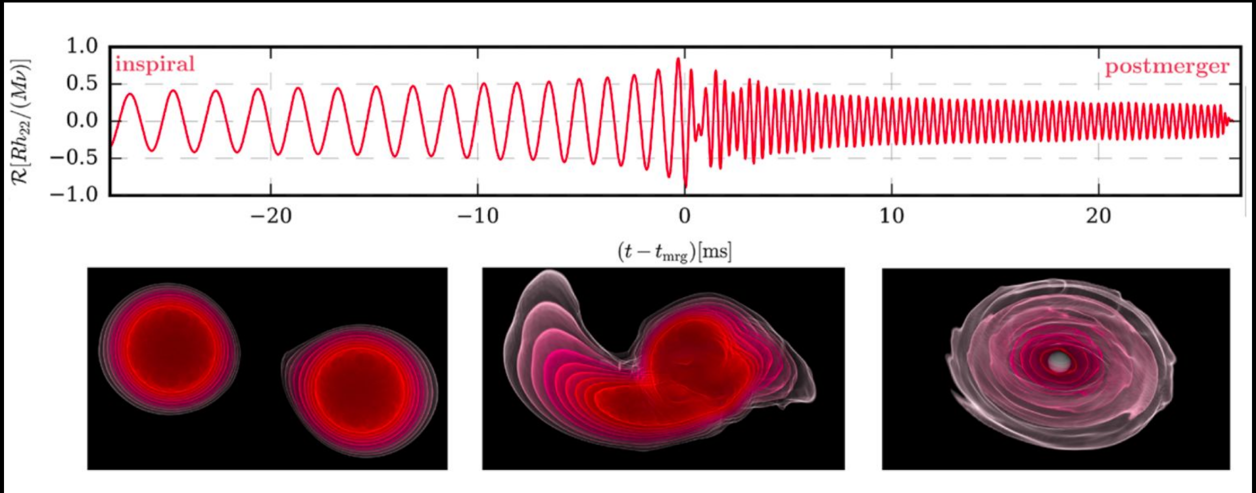


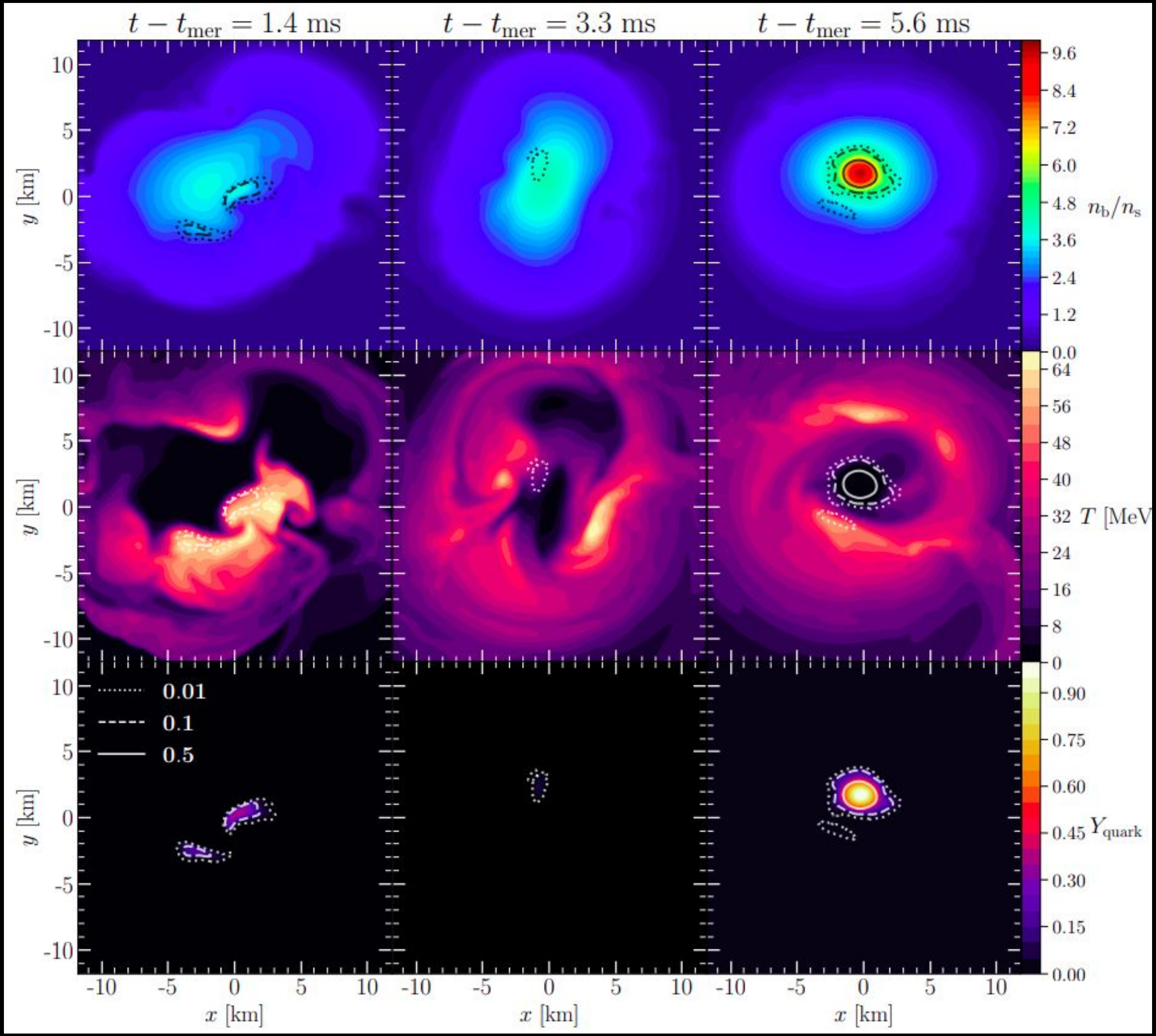
Bogdanov et. al. '22



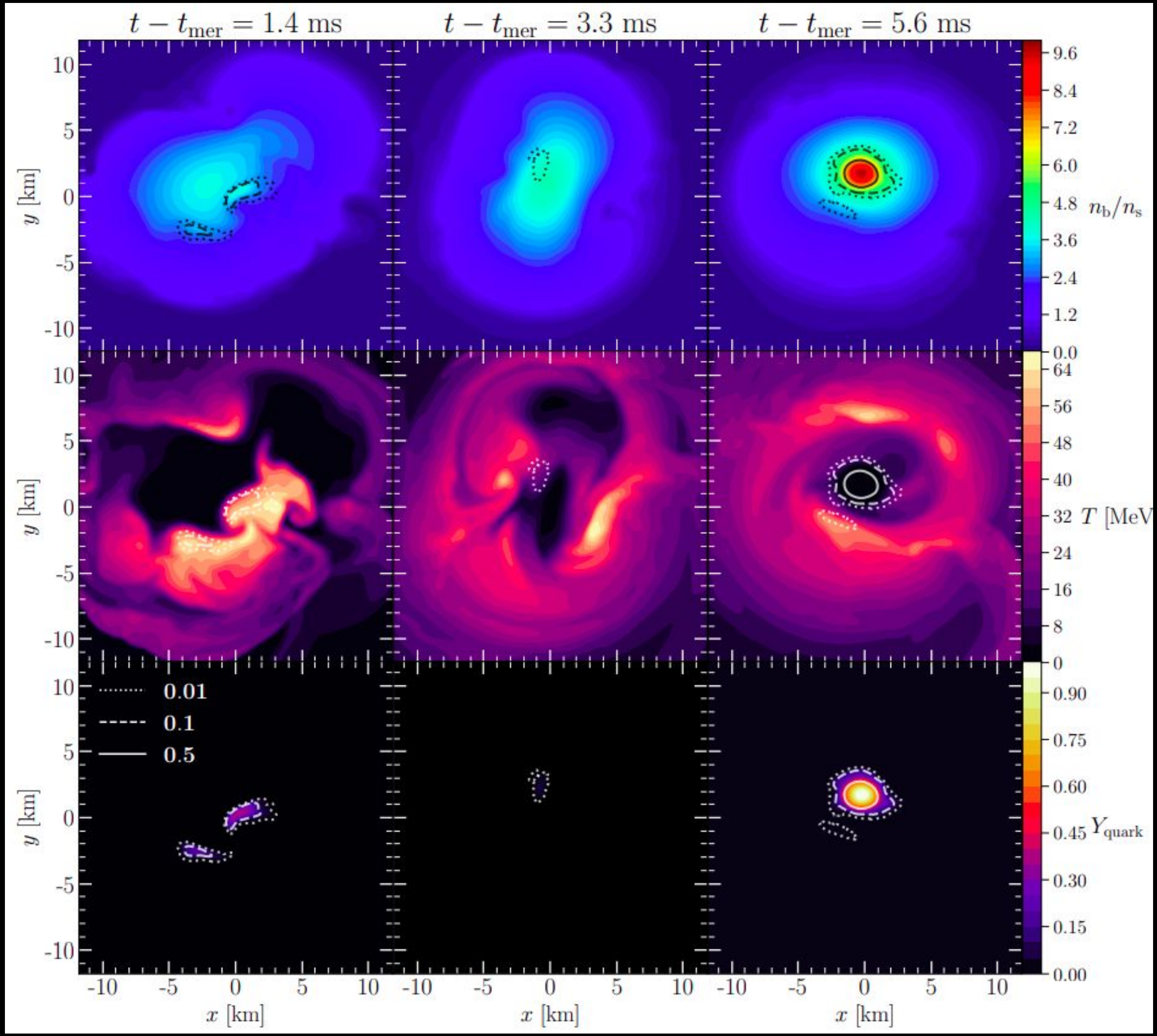
Annala, Gorda, Kurkela,
Nättila, Vuorinen '20




inspiral
postmerger
$\mathcal{R}[Rh_{22}/(M\nu)]$
1.0
0.5
0.0
−0.5
−1.0
−20
−10
0
10
20
$(t - t_{\mathrm{mrg}})$[ms]



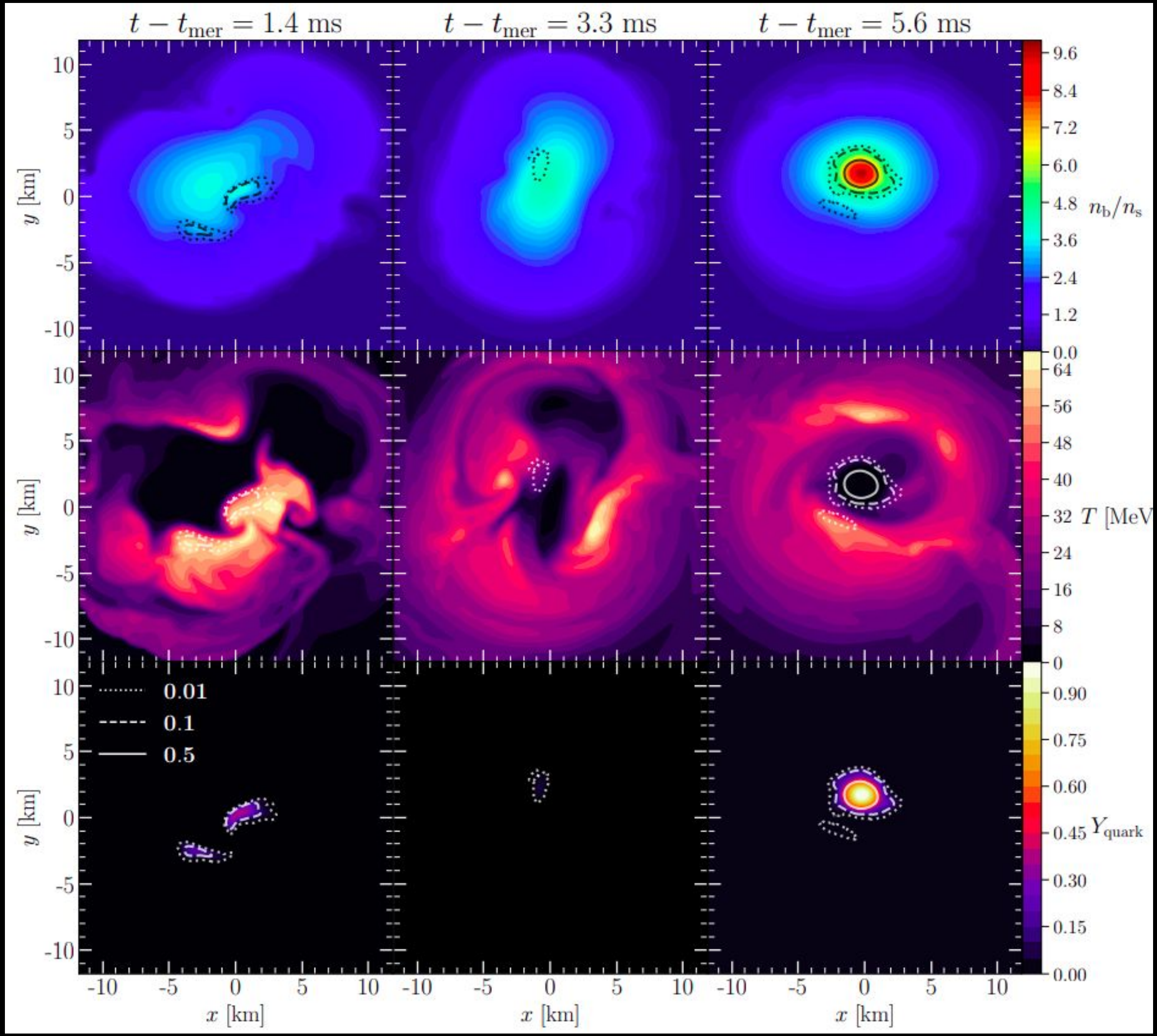
Tootle et al '22



Tootle et al '22

$\tau \sim 1$ ms >> 10^{-20} ms~ τ_{QCD}

L ~ 5 km >> 1 fm ~ L_{QCD}



Tootle et al ‘22

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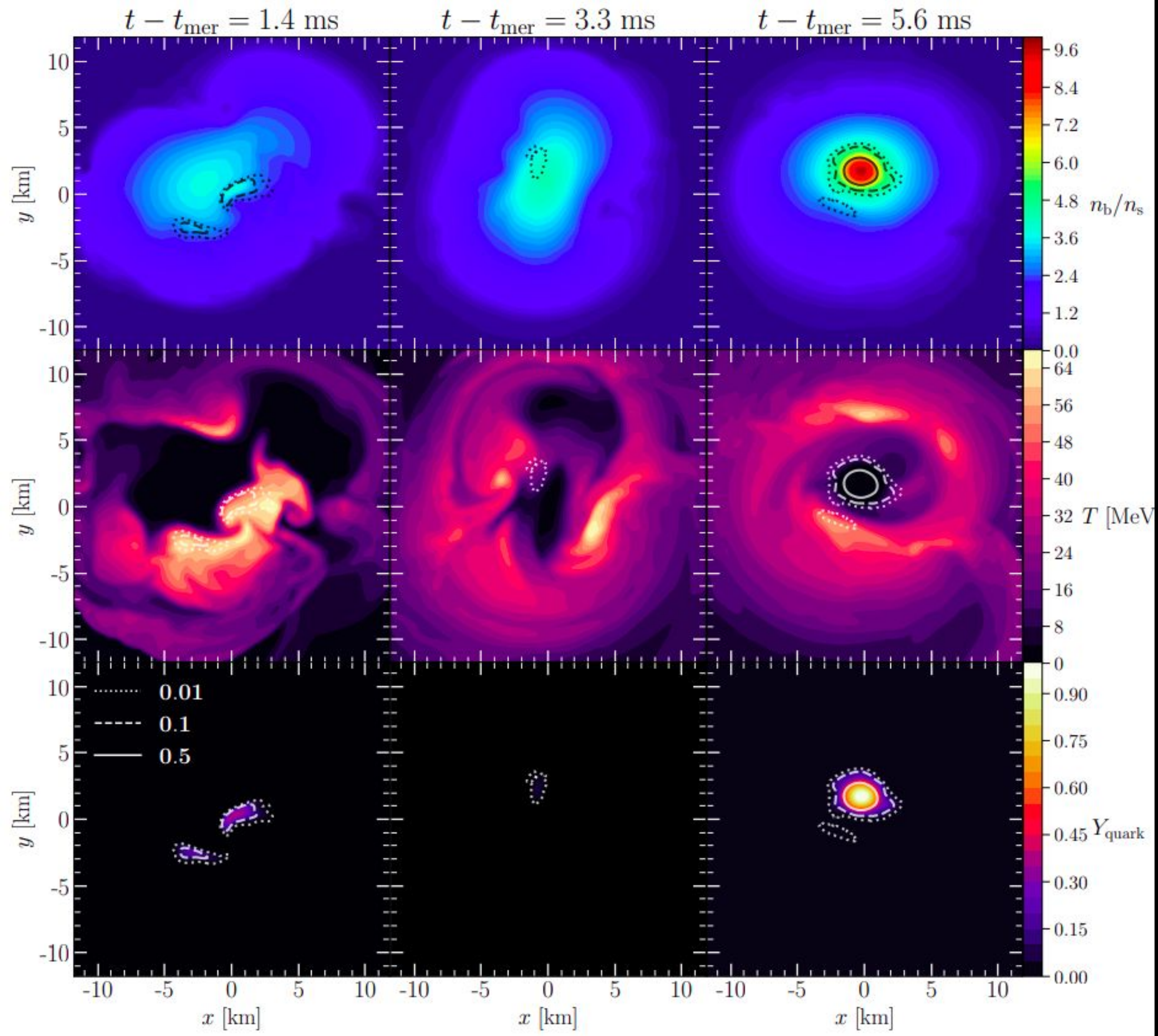
Adiabatic



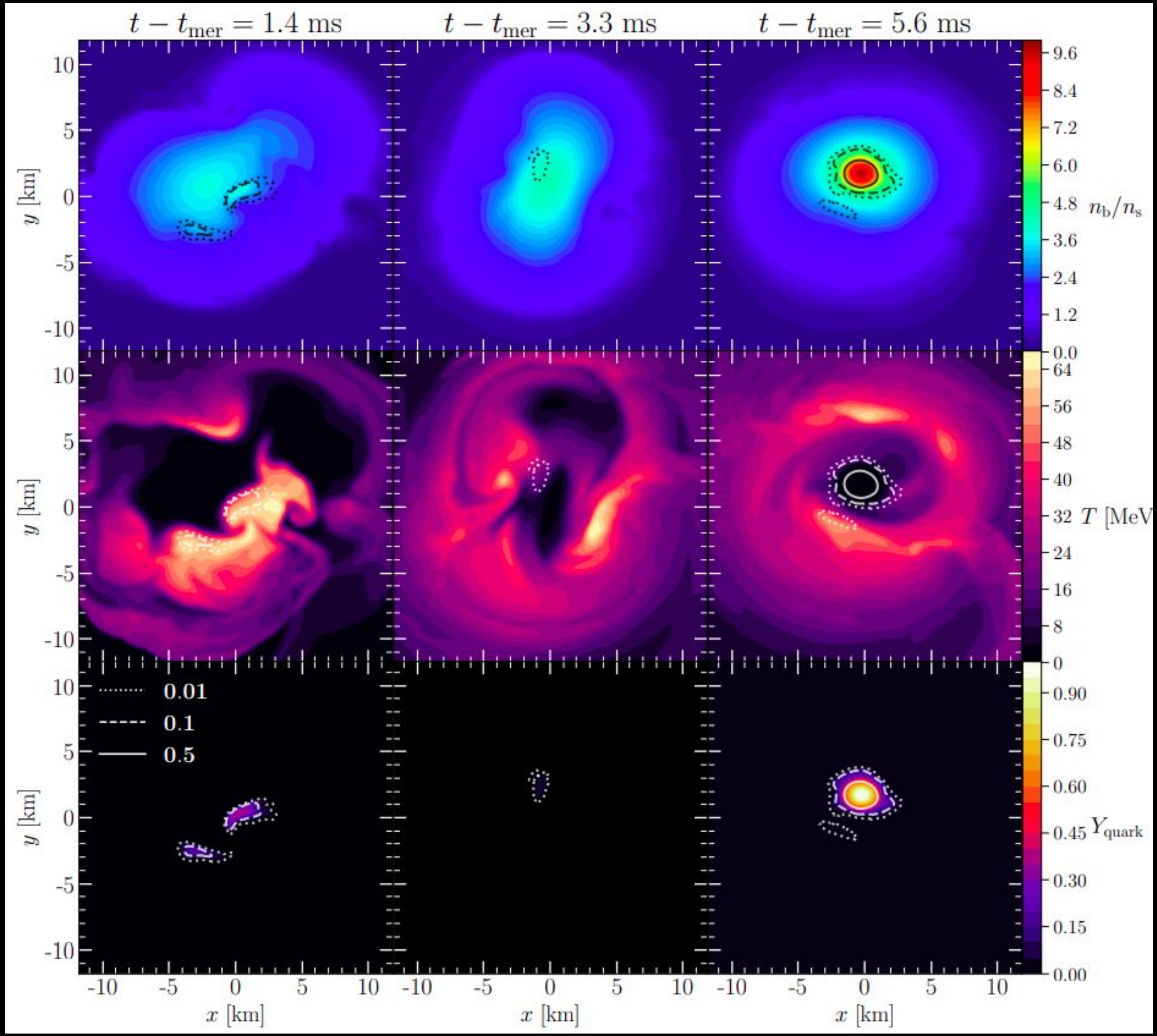
Tootle et al ‘22

$\tau \sim 1$ ms >> 10^{-20} ms~ τ_{QCD}

L ~ 5 km >> 1 fm ~ L_{QCD}

Adiabatic

Dynamics of formation?



Tootle et al '22

$\tau \sim 1$ ms >> 10^{-20} ms $\sim \tau_{QCD}$

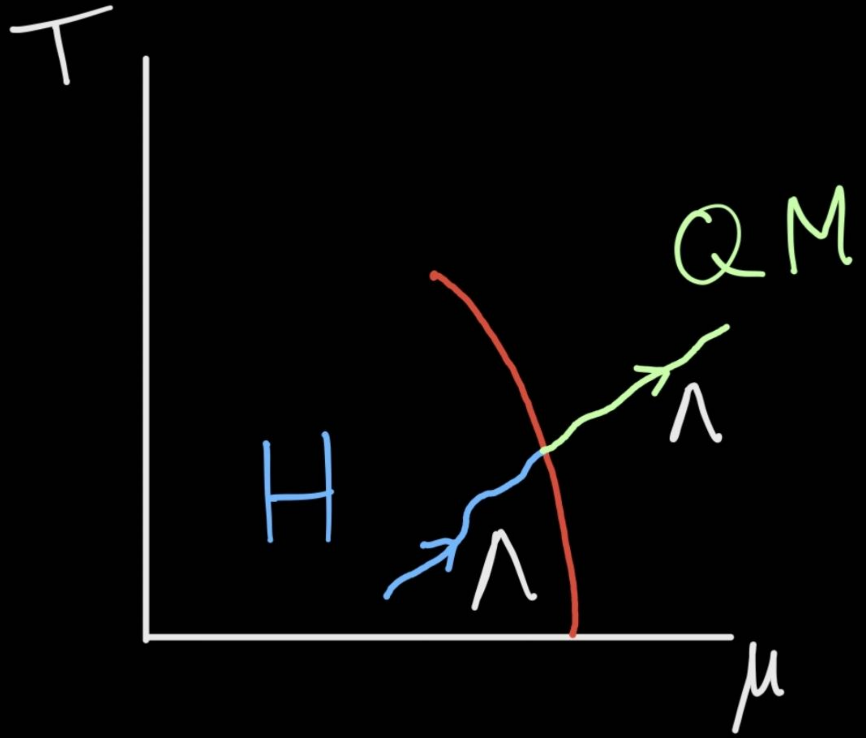
L ~ 5 km >> 1 fm ~ L_{QCD}

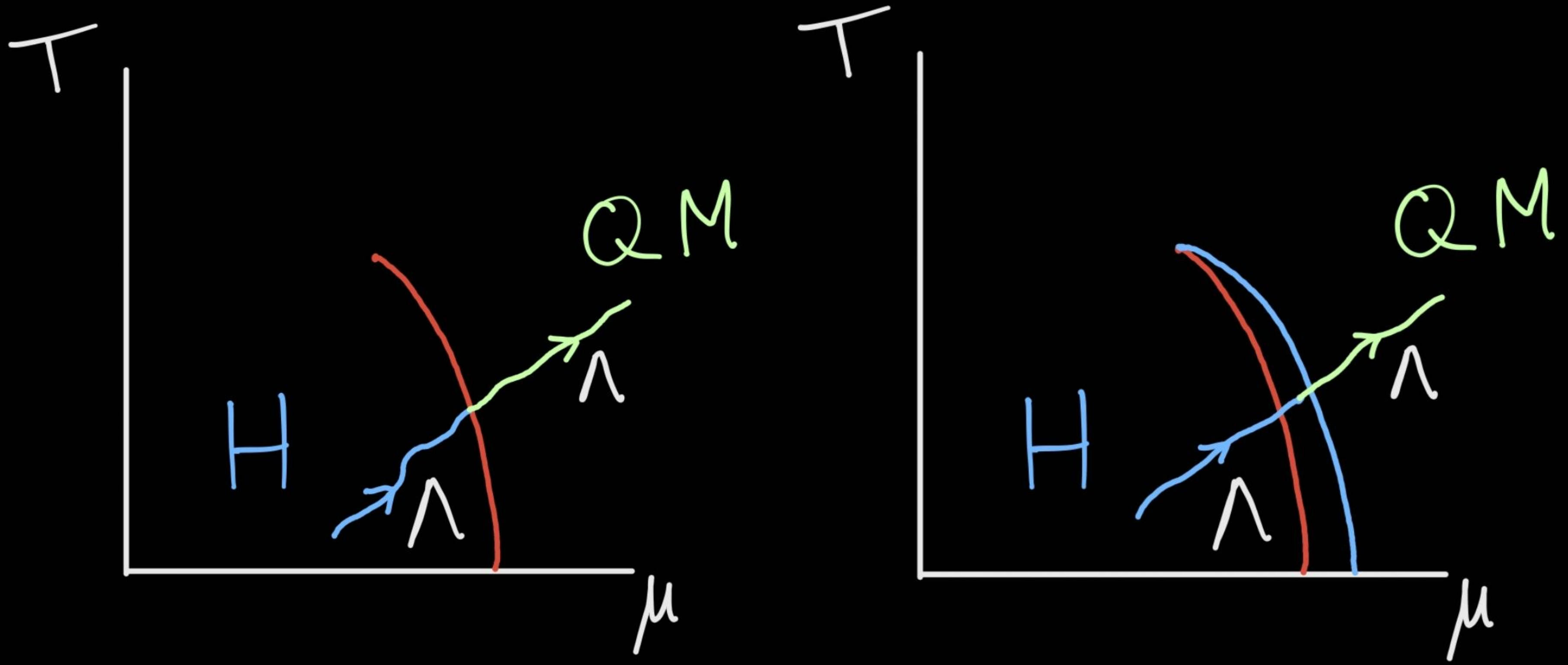
Adiabatic

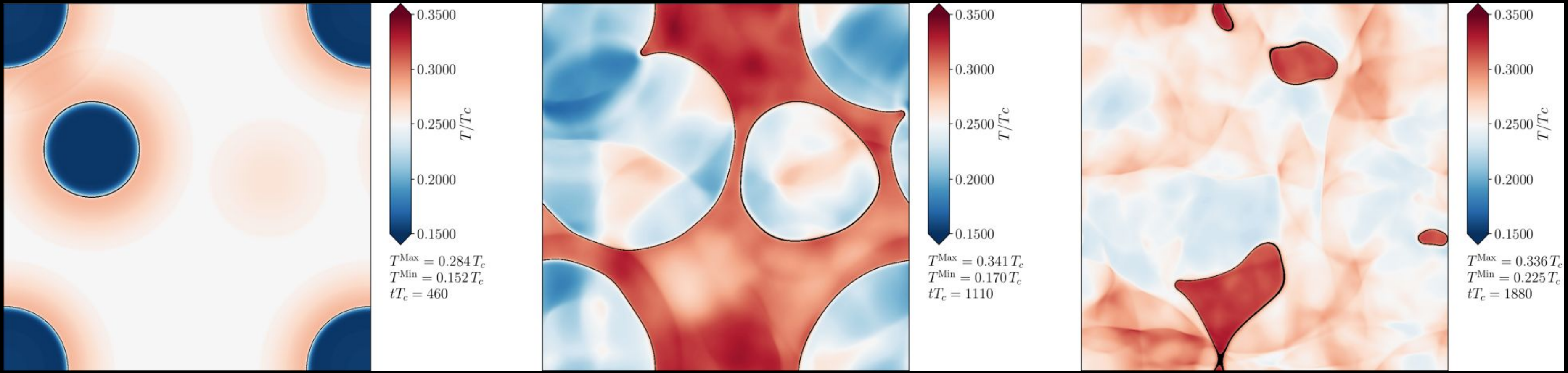
Dynamics of formation?

~ Cosmological FOPT

$\tau \sim H^{-1}$ & $\Lambda \sim T_c$


T
QM
H
Λ
Λ
μ


T
QM
H
Λ
Λ
μ
T
QM
H
Λ
Λ
μ



Cutting, Hindmarsh, Weir '19

Why?

Why?

FOPT should be short and microscopic

Why?

FOPT should be short and microscopic

Long lasting and macroscopic effects

Why?

FOPT should be short and microscopic

Long lasting and macroscopic effects

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

Assume no specific model

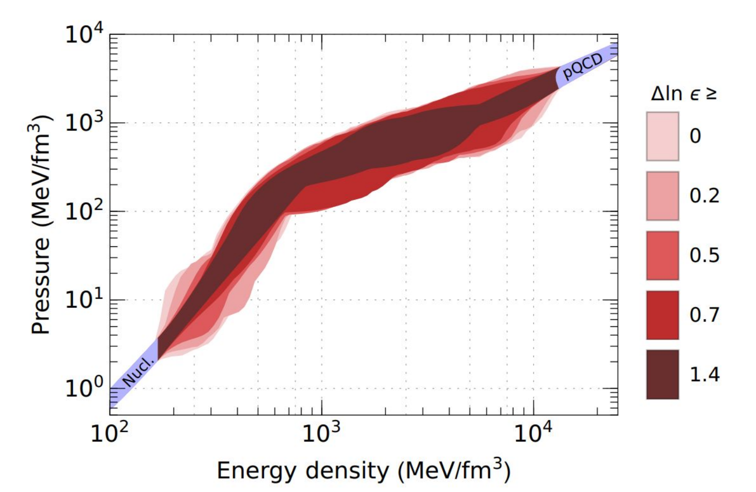
Assume no specific model

An existing FOPT is crossed

Assume no specific model

An existing FOPT is crossed

$$\Lambda^4 \sim 1 \text{ GeV/fm}^3$$



Annala, Gorda, Kurkela,
Nättila, Vuorinen ‘20

Outline

- Peak frequency

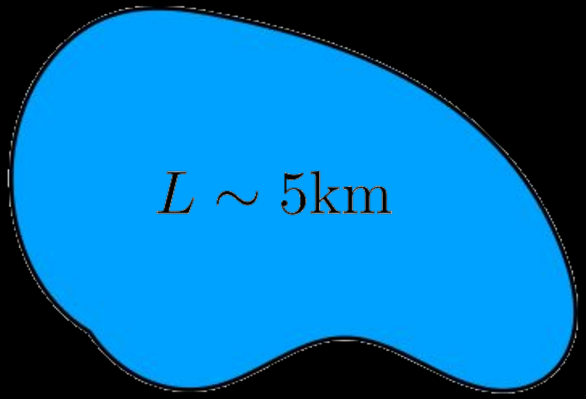
Outline

- Peak frequency
- Peak strain

Outline

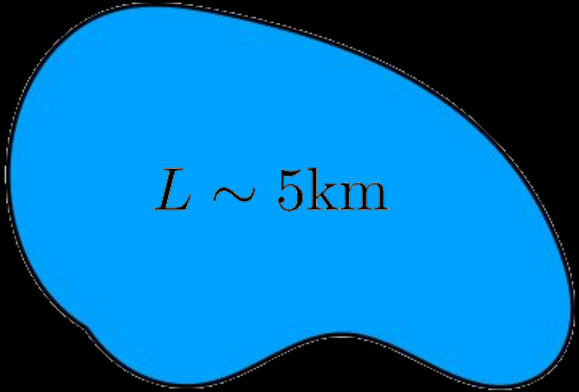
- Peak frequency
- Peak strain
- Conclusions & next steps

$$N_{bubbles} \sim \Lambda^4 e^{-S} L^3 \tau \sim 1$$



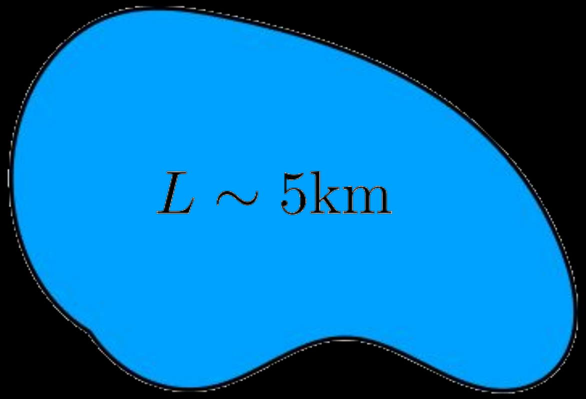
$$N_{bubbles} \sim \Lambda^4 e^{-S} L^3 \tau \sim 1$$

$$S \sim \log\left(L^3 \tau \Lambda^4\right)$$



$$N_{bubbles} \sim \Lambda^4 e^{-S} L^3 \tau \sim 1$$

$$S \sim \log\left(v_w^3 \tau^4 \Lambda^4\right)$$



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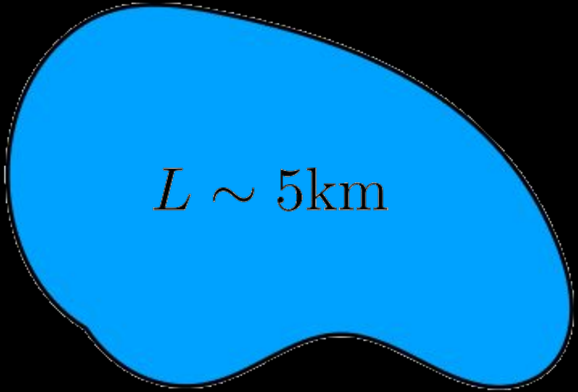
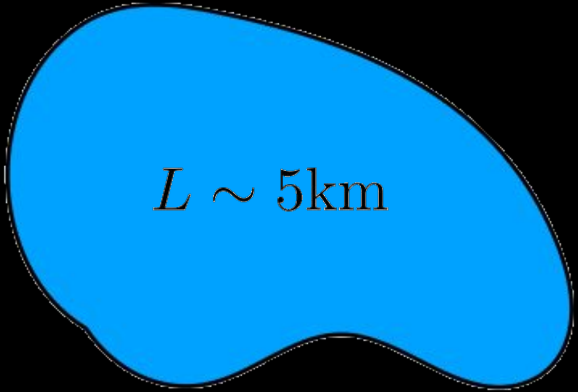


$$S \sim \log\left(v_w^3 \tau^4 \Lambda^4\right)$$

$\Lambda^4 \sim 1\ \text{GeV}/\text{fm}^3$ $v_w \sim 0.1$

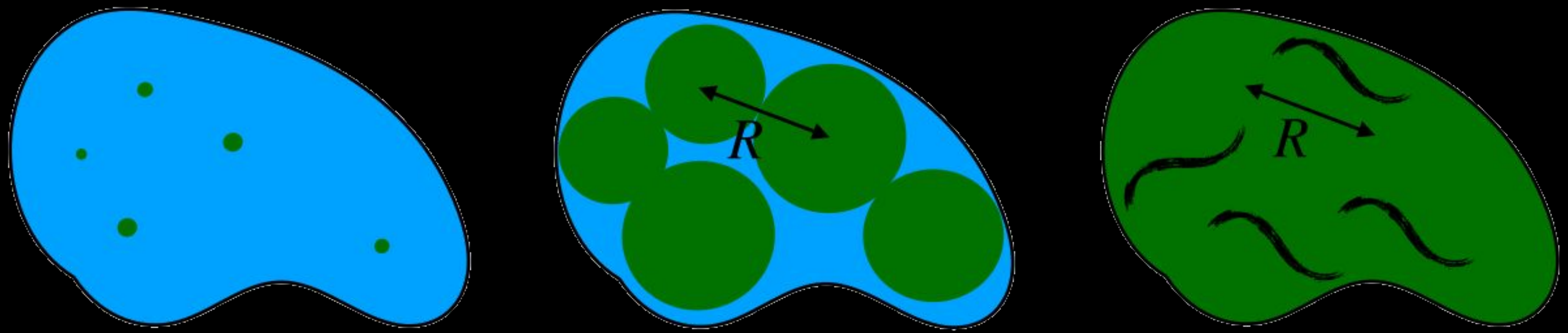
$$N_{bubbles} \sim \Lambda^4 e^{-S} L^3 \tau \sim 1$$

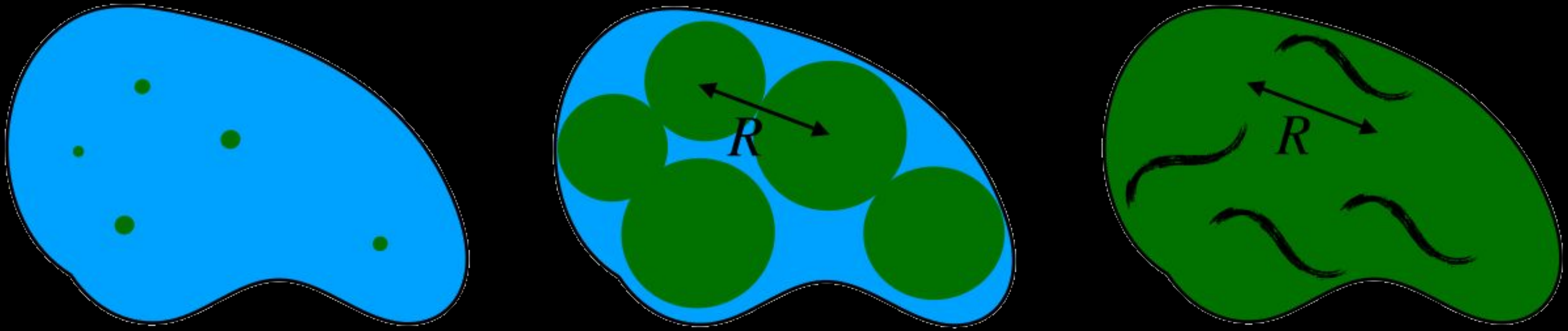


$$S \sim \log\left(v_w^3 \tau^4 \Lambda^4\right)$$

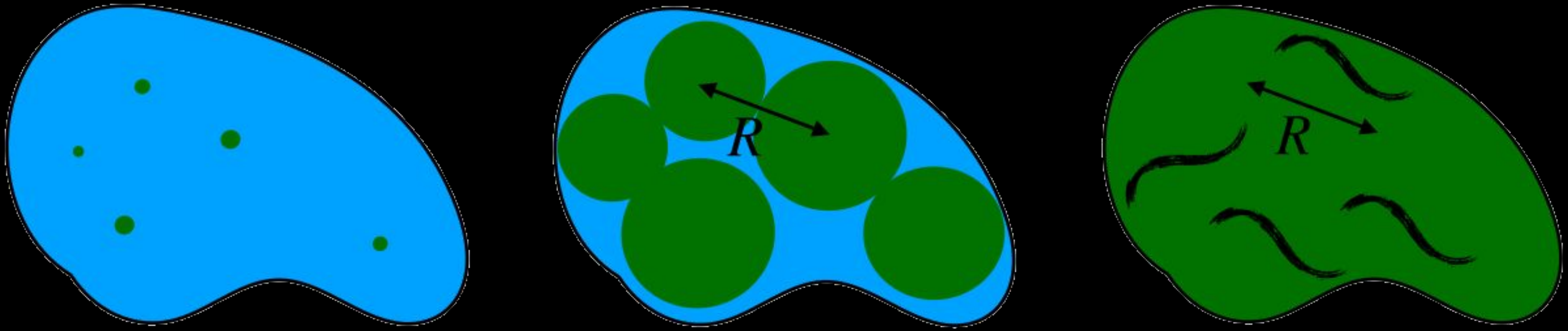
$\Lambda^4 \sim 1\ \mathrm{GeV/fm^3}$ $\quad$ $v_w \sim 0.1$

$$\beta^{-1} = \left(\frac{dS}{dt}\right)^{-1} \sim \frac{\tau}{S} \sim 6\mu s$$


R
R

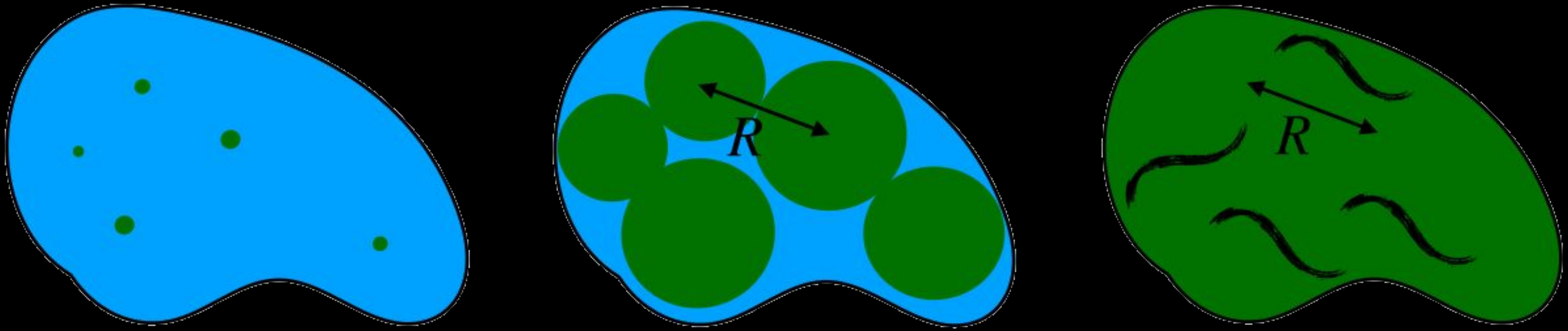


Long wavelength sound waves that are long lived ~ ms



Long wavelength sound waves that are long lived ~ ms

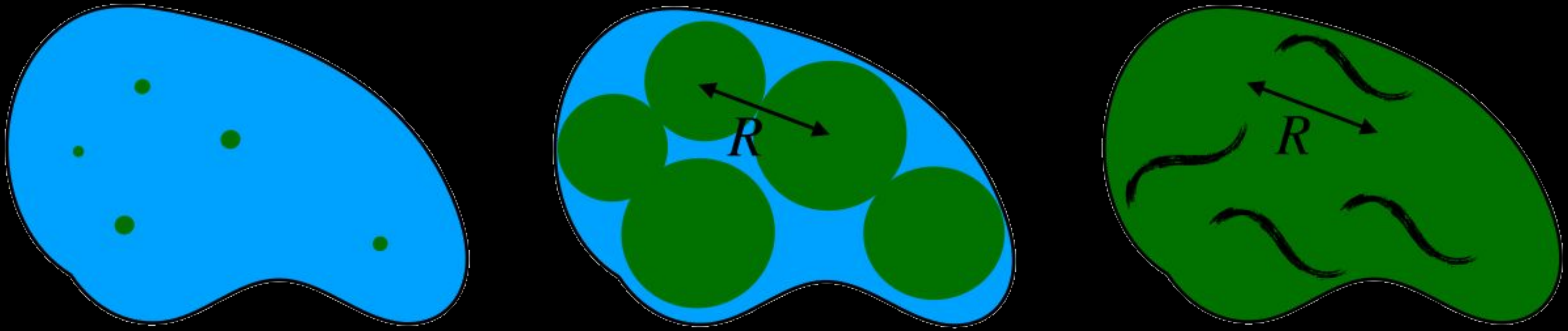
$$R = (8\pi)^{1/3}\, v_w \beta^{-1}$$



Long wavelength sound waves that are long lived ~ ms

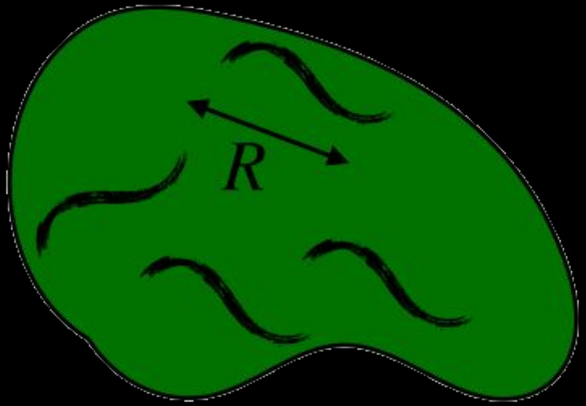
$$R = (8\pi)^{1/3}\, v_w \beta^{-1}$$

$$f \sim \frac{\log\left(v_w^3 \tau^4 \Lambda^4\right)}{(8\pi)^{1/3}\, v_w}\left(10^{-3}\mathrm{MHz}\right)$$



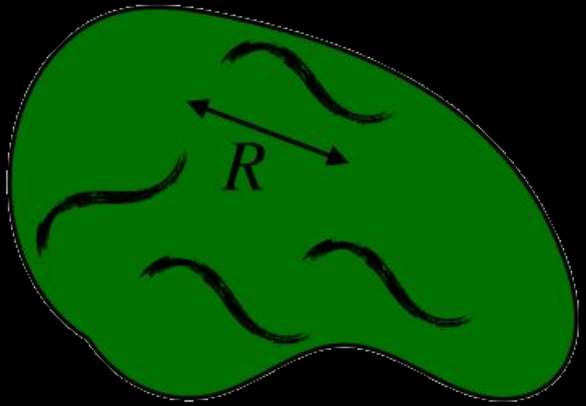
$$\Lambda^4 \sim 1\ \mathrm{GeV/fm^3} \qquad v_w \sim 0.1$$

$$f \sim \frac{\log\left(v_w^3 \tau^4 \Lambda^4\right)}{(8\pi)^{1/3}\, v_w}(10^{-3}\mathrm{MHz}) \sim 0.6\mathrm{MHz}$$



Hindmarsh, Huber,
Rummukainen, Weir ‘16

$$\rho_{GW} = \frac{1}{32\pi G}\dot{h}_{ij}^2 \simeq (8\pi G)\left[(\mathcal{E}+\mathcal{P})v_f^2\right]^2 (R\Delta t)\,\bar{\Omega}_{GW}$$



Hindmarsh, Huber,
Rummukainen, Weir ‘16

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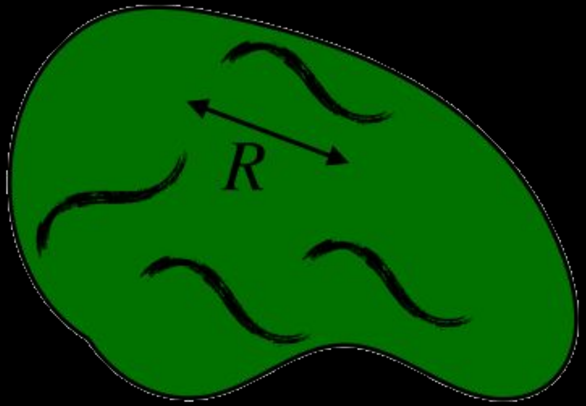
$$(\mathcal{E}+\mathcal{P})v_f^2 \sim T_f^{ij}$$



Hindmarsh, Huber,
Rummukainen, Weir '16

$$\rho_{GW} = \frac{1}{32\pi G}\dot{h}_{ij}^2 \simeq (8\pi G)\left[(\mathcal{E}+\mathcal{P})v_f^2\right]^2 (R\Delta t)\,\bar{\Omega}_{GW}$$

$$(\mathcal{E}+\mathcal{P})v_f^2 \sim T_f^{ij} \qquad\qquad \Delta t \simeq \frac{L}{c}$$

$$\bar{\Omega}_{GW} \sim 10^{-2}$$

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

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$$h_c^{obs} \sim 2.1 \times 10^{-24} v_f^2 \left(\frac{100\mathrm{Mpc}}{d}\right)$$

Conclusions

Conclusions

Signal in the MHz >> kHz

Conclusions

Signal in the MHz >> kHz

Preceded by the long inspiral in the kHz

Conclusions

Signal in the MHz >> kHz

Preceded by the long inspiral in the kHz

Signal from merger and equilibration

Conclusions

Signal in the MHz >> kHz

Preceded by the long inspiral in the kHz

Signal from merger and equilibration

Incoherent, localized in the sky and ~ ms

Conclusions

Signal in the MHz >> kHz

Preceded by the long inspiral in the kHz

Signal from merger and equilibration

Incoherent, localized in the sky and ~ ms

Several signals from mergers around the sky

Where to?

Where to?

Overheated bubbles in dense, strongly coupled systems: v_{wall}

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Overheated bubbles in dense, strongly coupled systems: v_{wall}

Better understanding of our estimation of the energy budget

Where to?

Overheated bubbles in dense, strongly coupled systems: v_{wall}

Better understanding of our estimation of the energy budget

Confirm the broken power law spectrum

Where to?

Overheated bubbles in dense, strongly coupled systems: v_{wall}

Better understanding of our estimation of the energy budget

Confirm the broken power law spectrum

Neutrino emission: change estimation & memory effects at low frequencies

Thank you!