

High-Frequency Gravitational Waves from Phase Transitions in Nascent Neutron Stars

PPC 2026

Jorinde van de Vis



Based on [2603.18153](#) with Katarina Bleau, Joachim Kopp and Jiheon Lee

Quark matter in neutron stars?

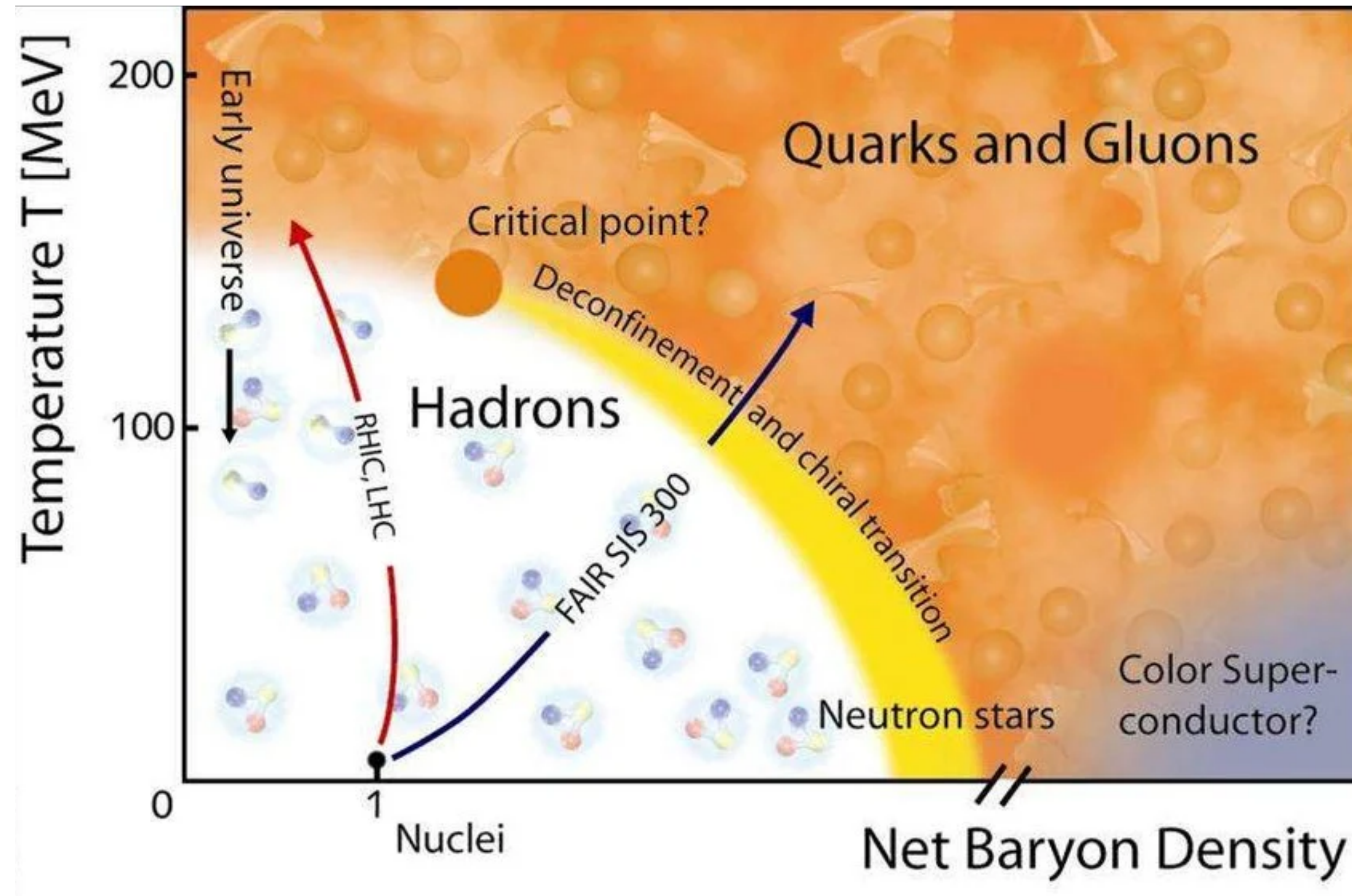


Fig: [Aarts, Attanasio, Jäger, Seiler, Sexty, Stamatescu 2014](#)

Quark matter in neutron stars?

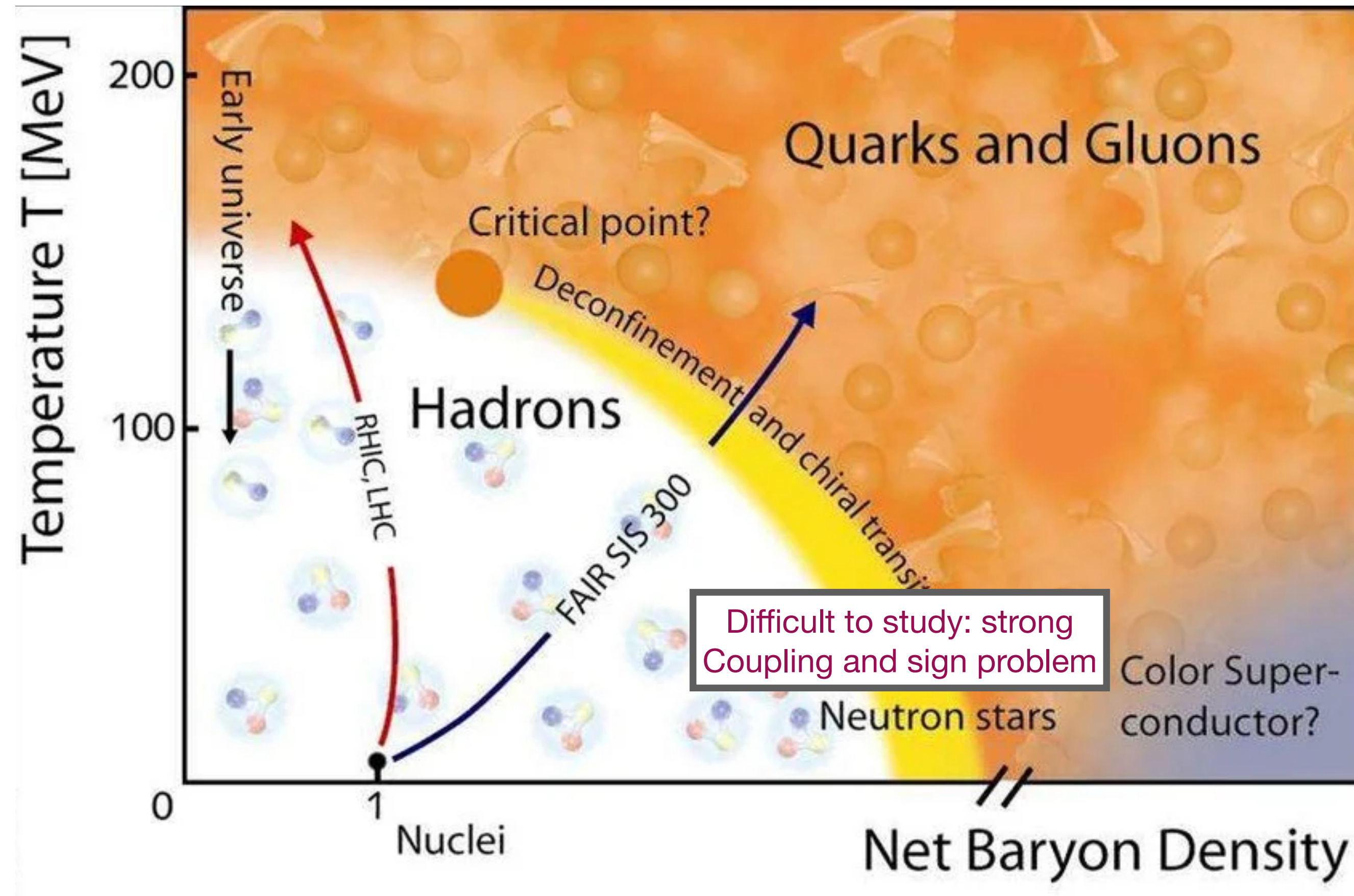


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Quark matter in neutron stars?

Evidence for quark-matter cores in massive neutron stars

Eemeli Annala¹, Tyler Gorda², Aleksi Kurkela^{3,4}, Joonas Nättilä^{5,6,7} & Aleksi Vuorinen¹

Strongly interacting matter exhibits deconfined behavior in massive neutron stars

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Bayesian inference favors quark matter in neutron star interiors

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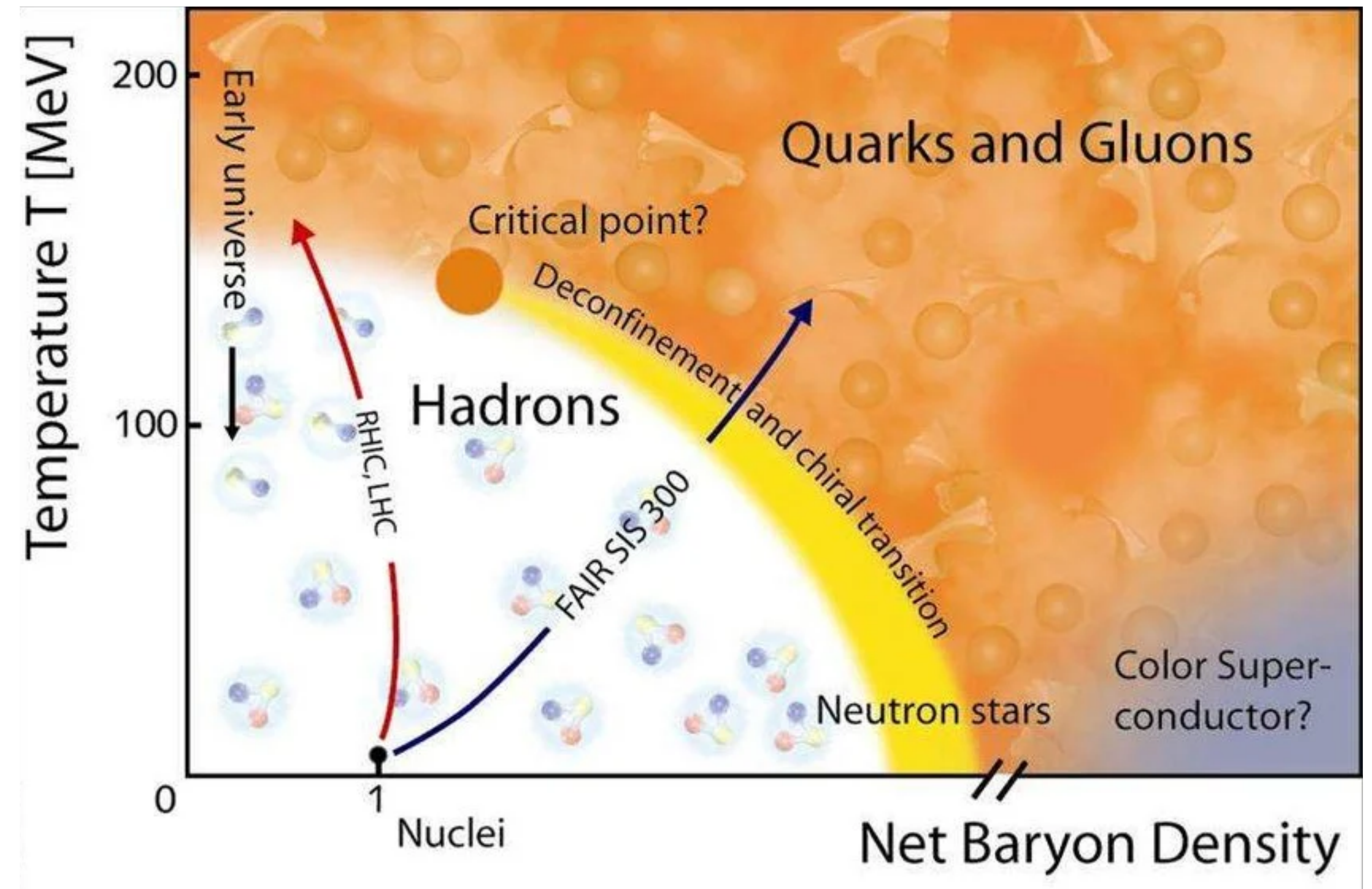


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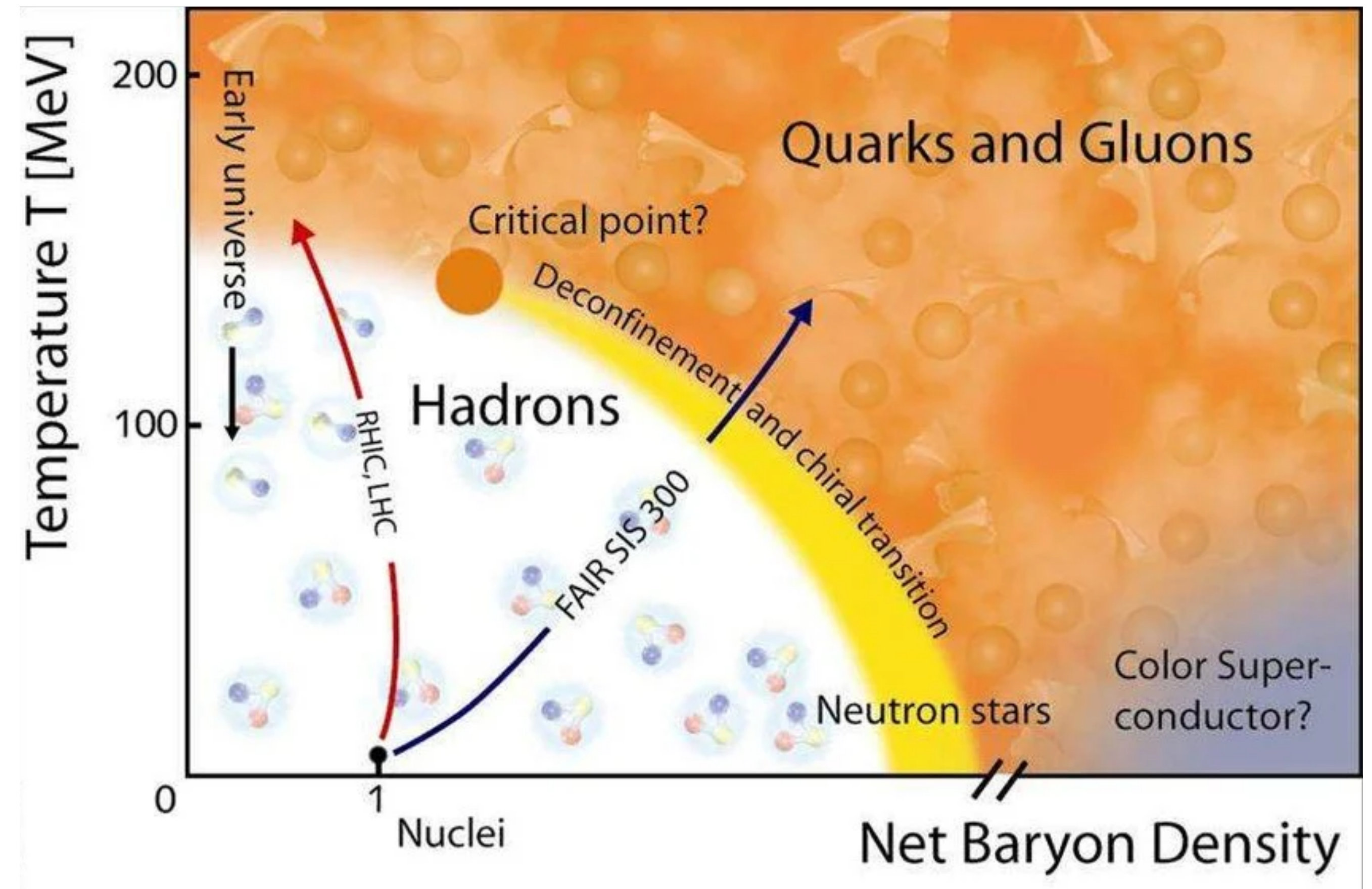
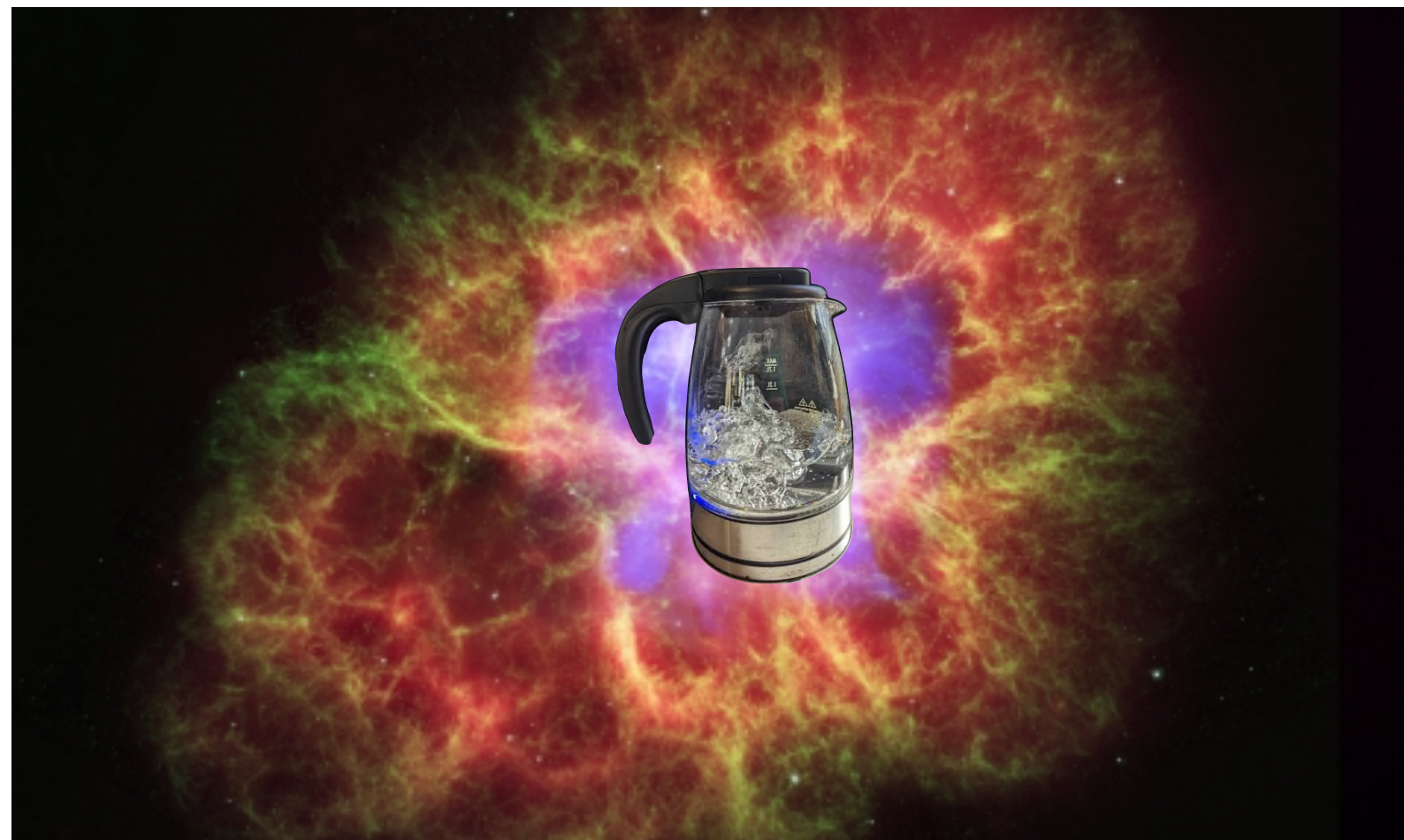
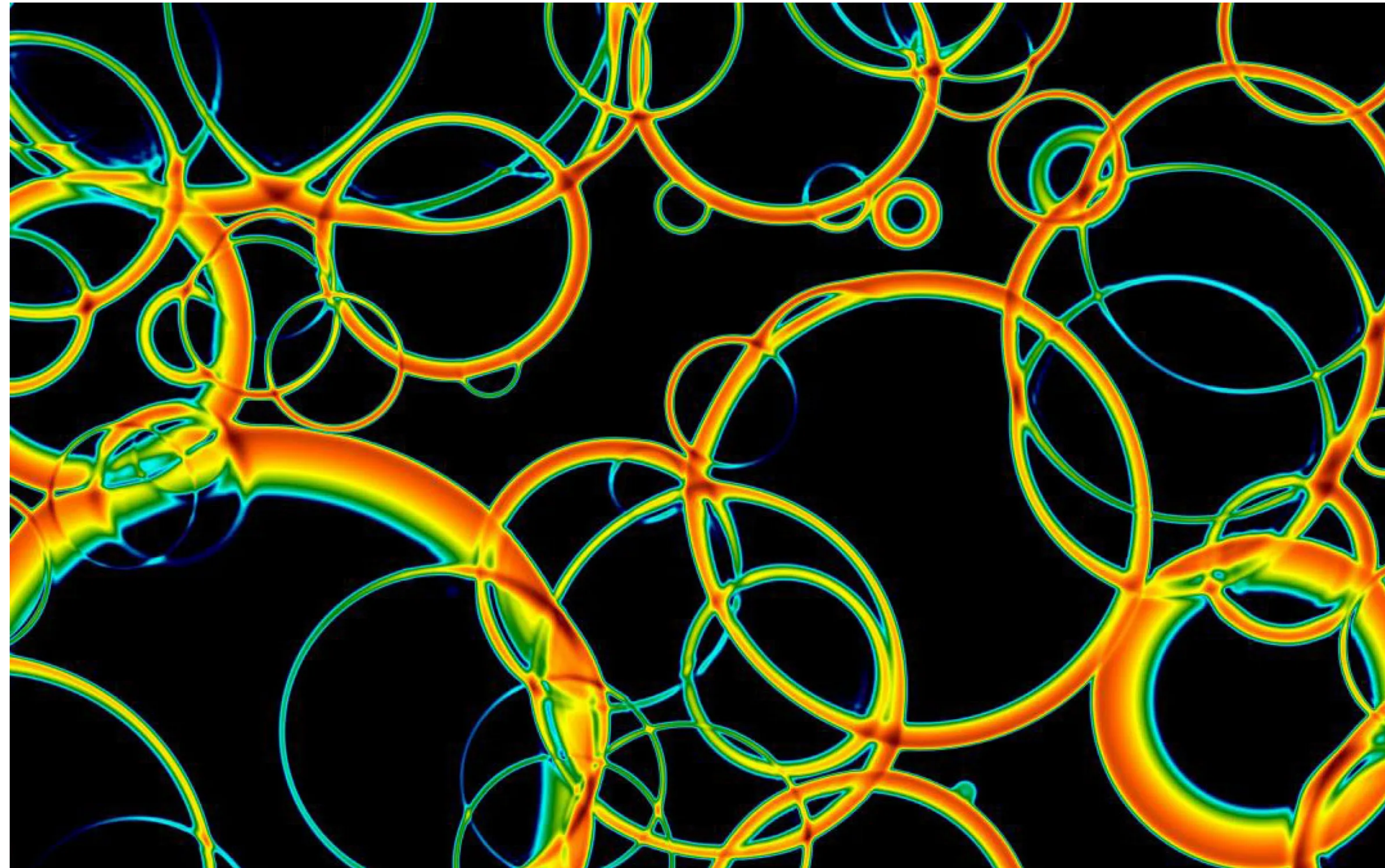


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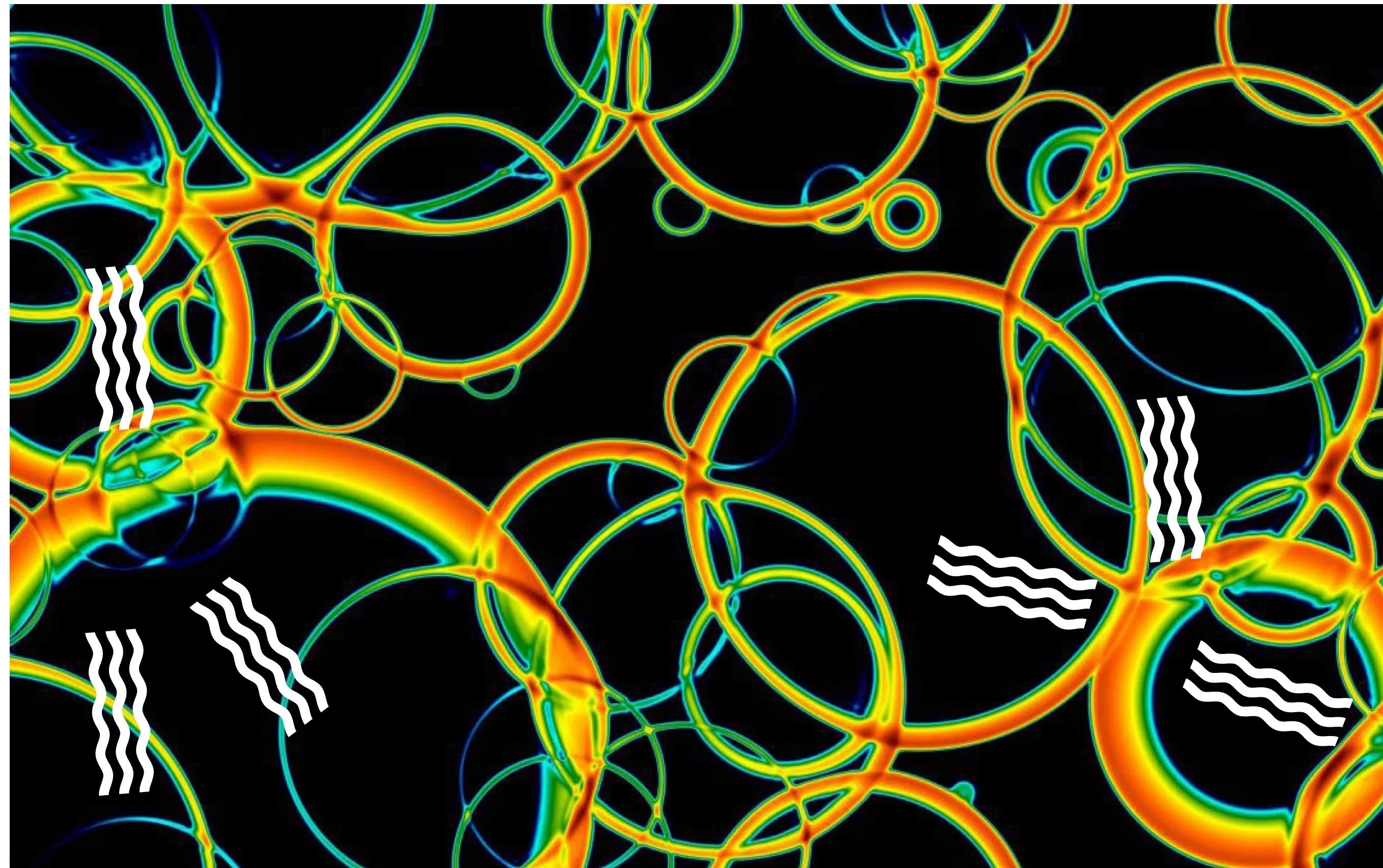
High frequency gravitational wave signal?



Simulation of a cosmological phase transition

Credit: David Weir

High frequency gravitational wave signal?

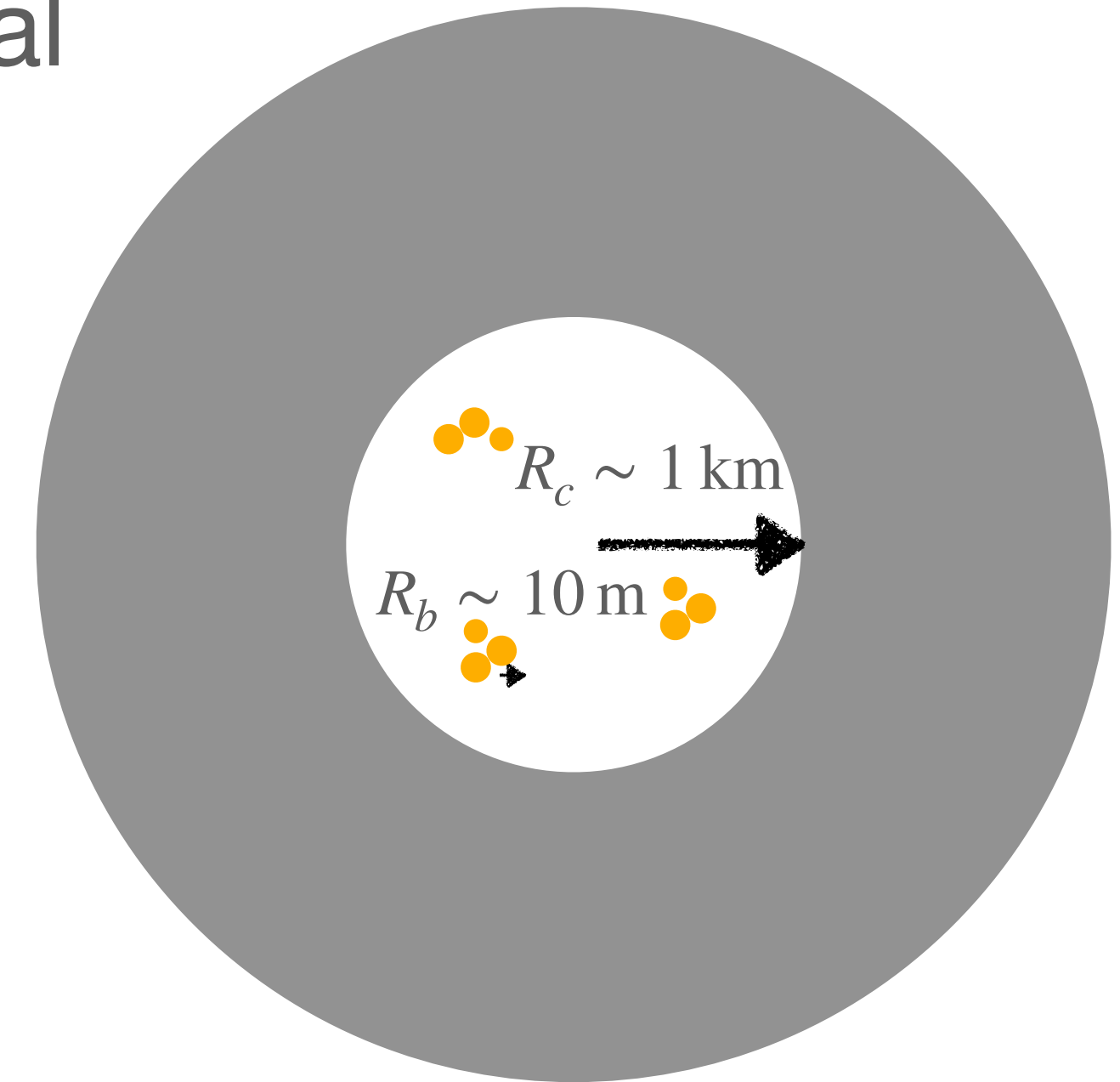


Simulation of a cosmological phase transition

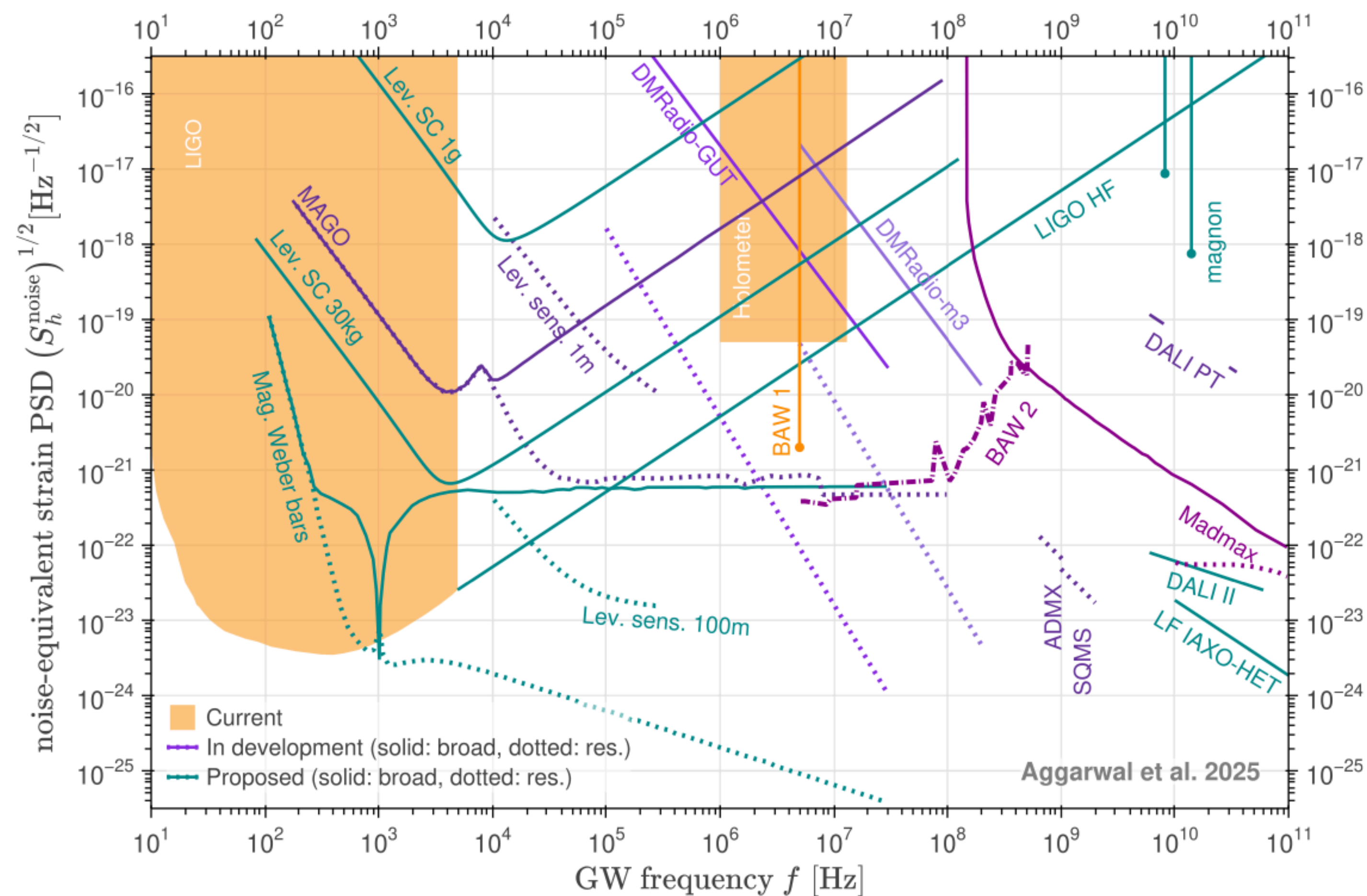
Credit: David Weir

High frequency gravitational wave signal?

- Bubbles with a radius of ~ 10 m source a GW signal with $f \sim 30$ MHz
- GW signal from hot or compressed spots in neutron star mergers with $100 \text{ kHz} \lesssim f \lesssim 10 \text{ MHz}$
[Blas, Casalderrey-Solana, Mateos, Sanchez-Garitaonandia 2022](#)

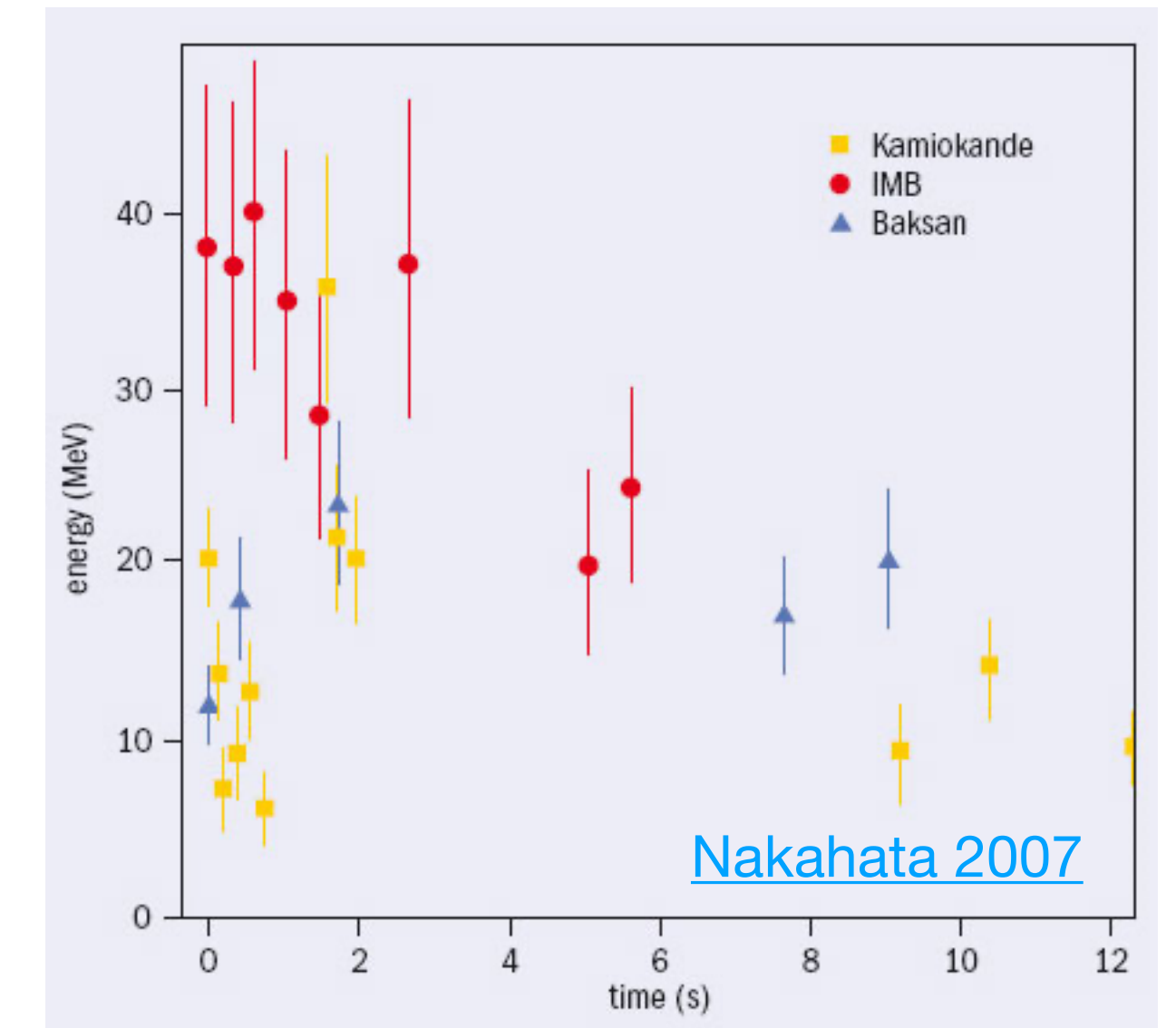


Searches for high frequency gravitational waves



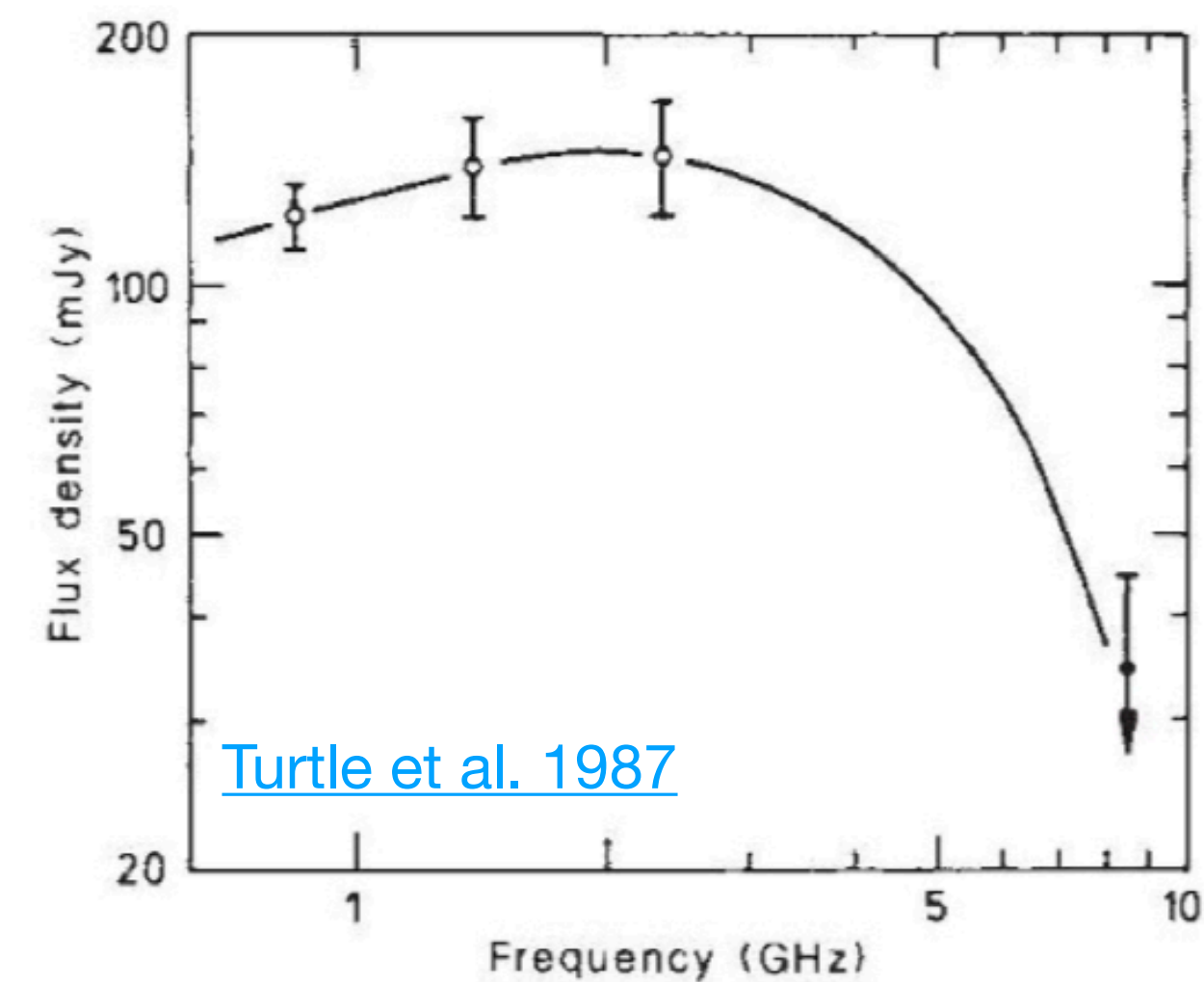
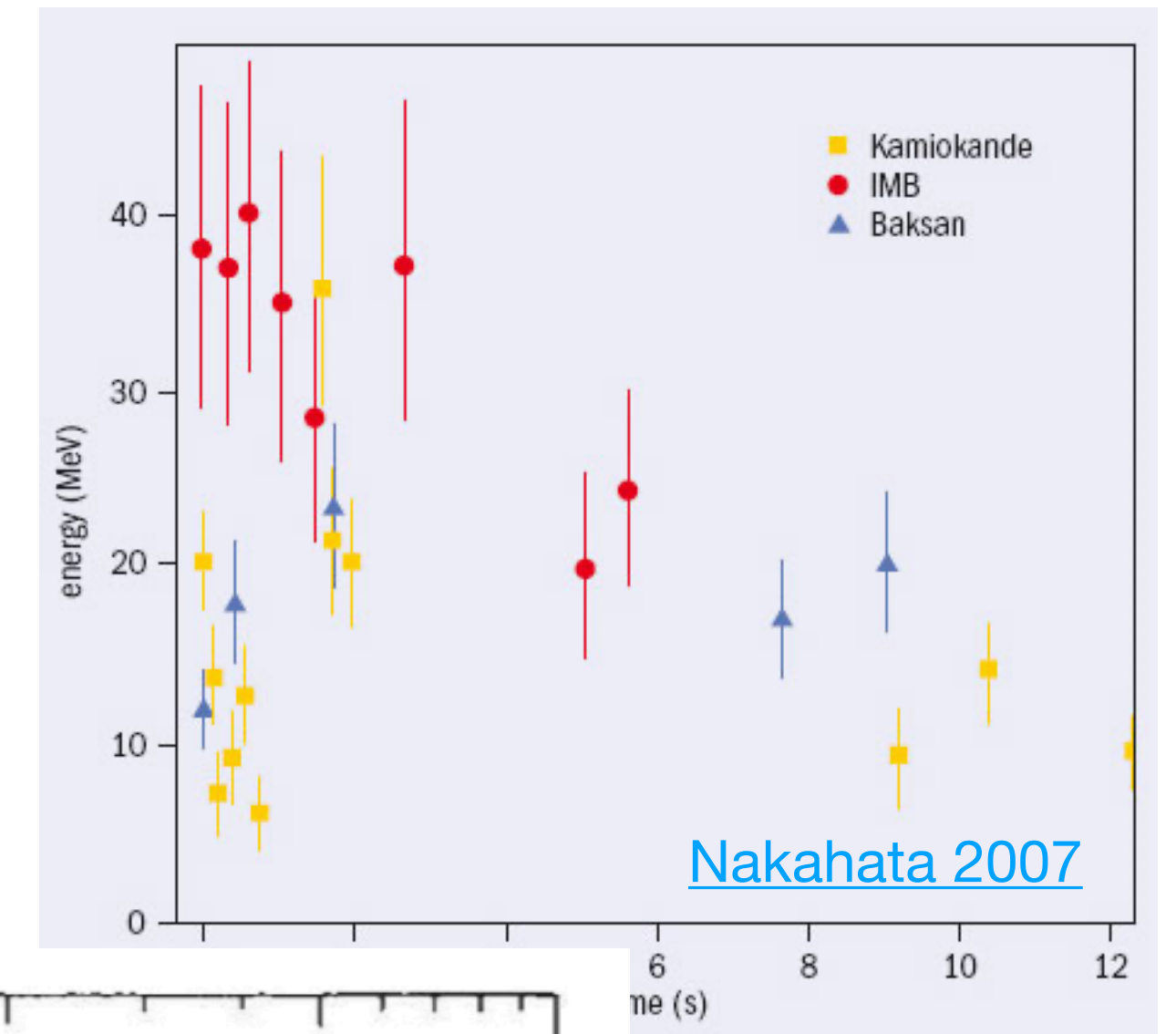
Supernovae = super-multimessenger?

- Neutrinos



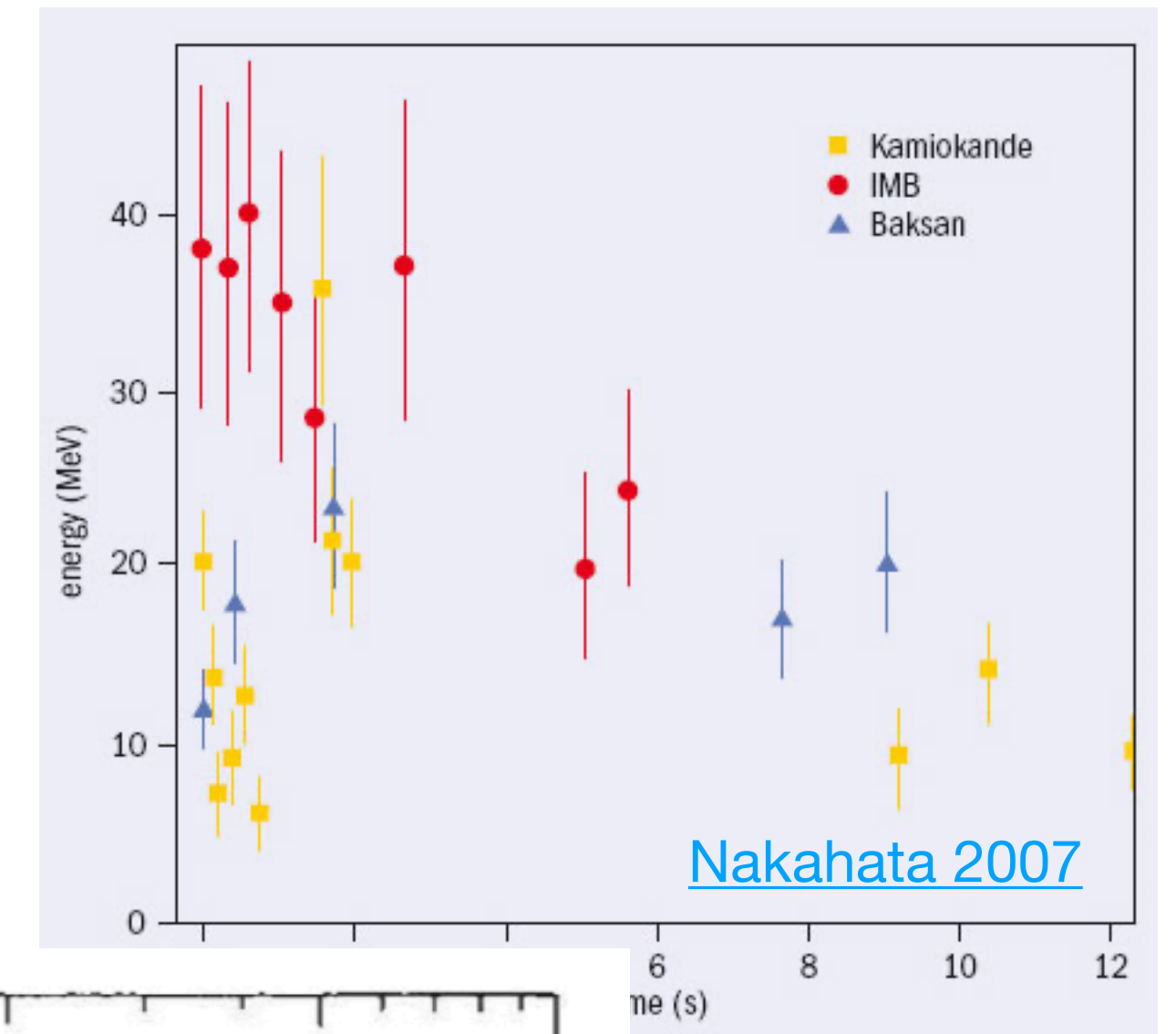
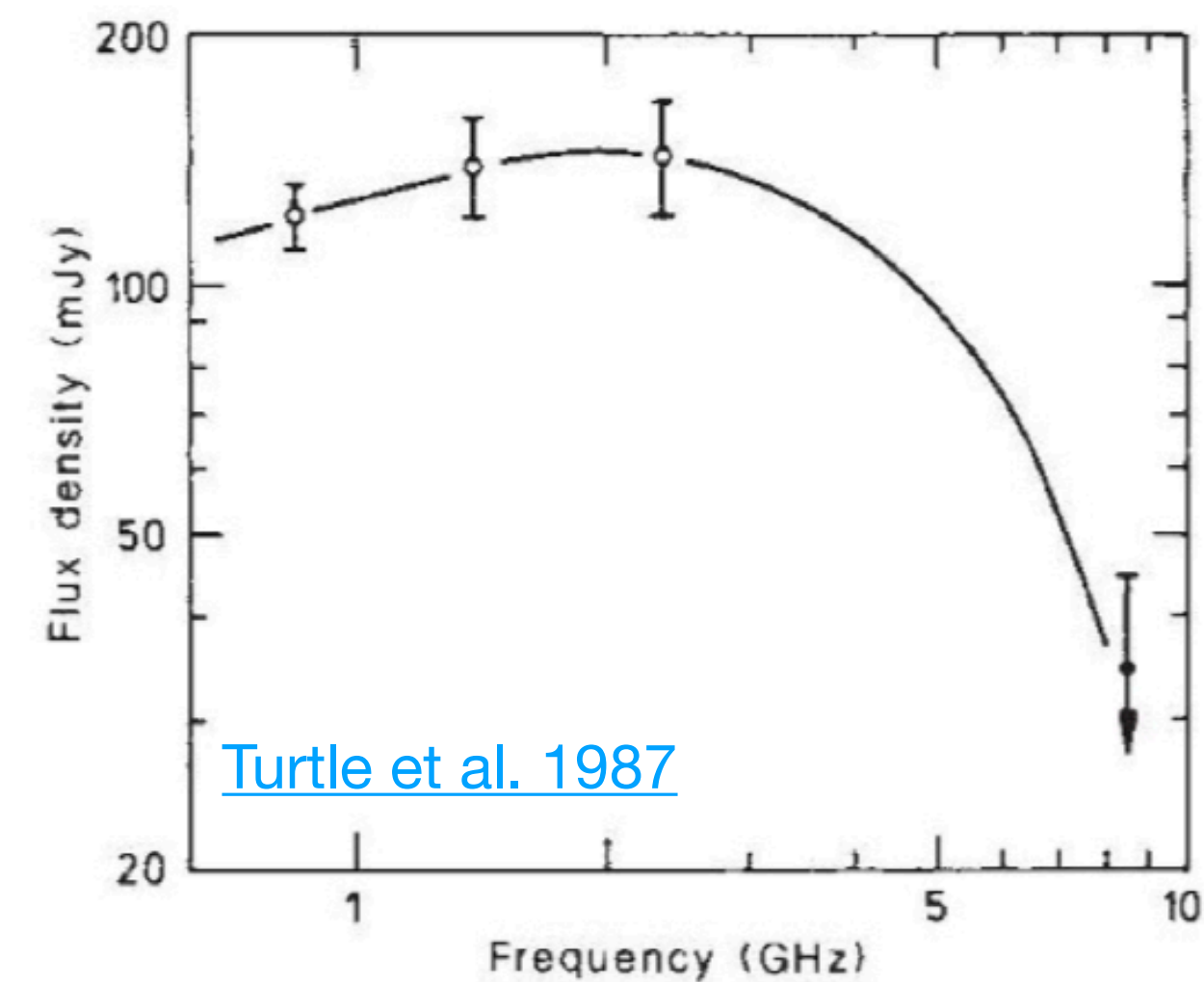
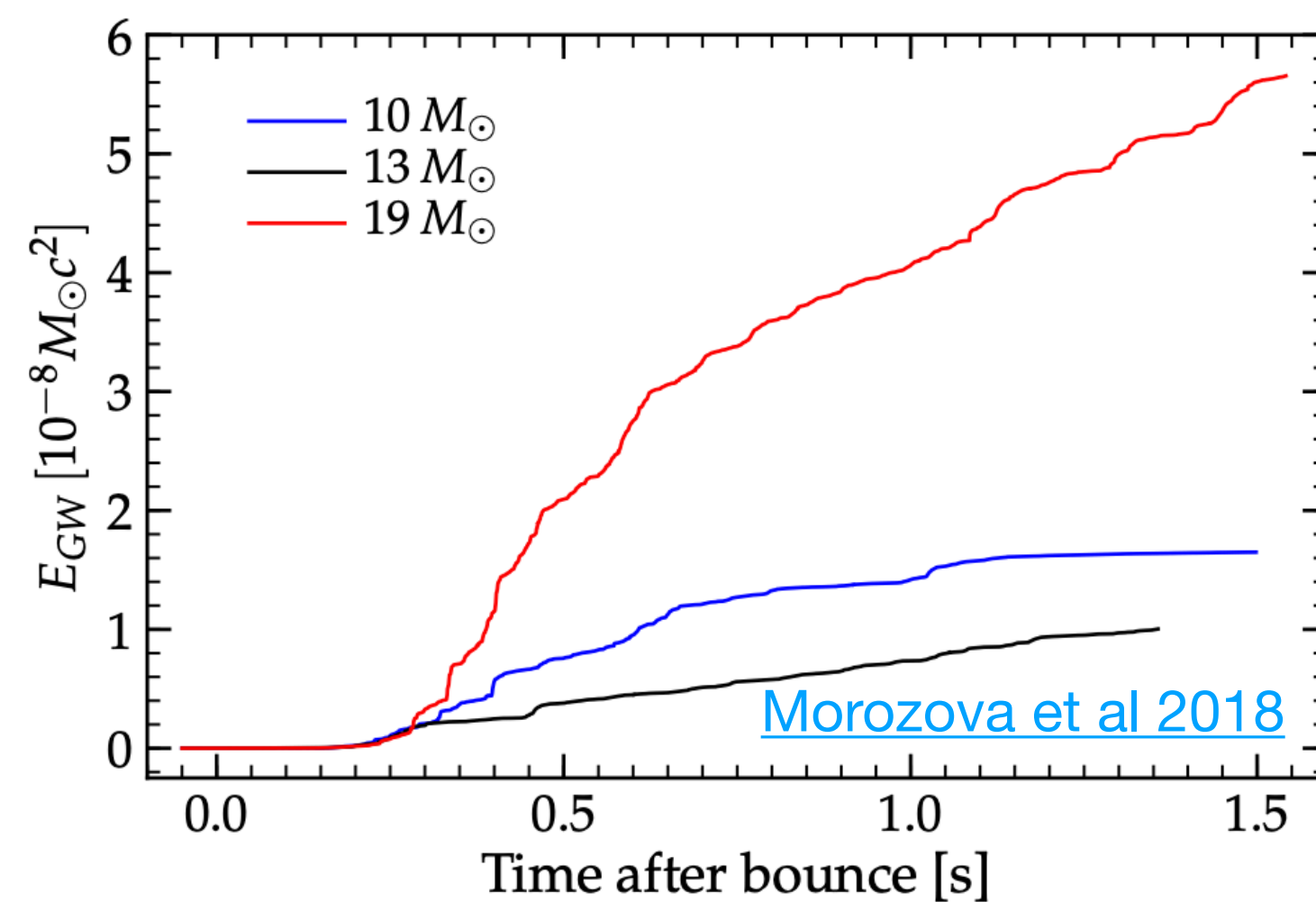
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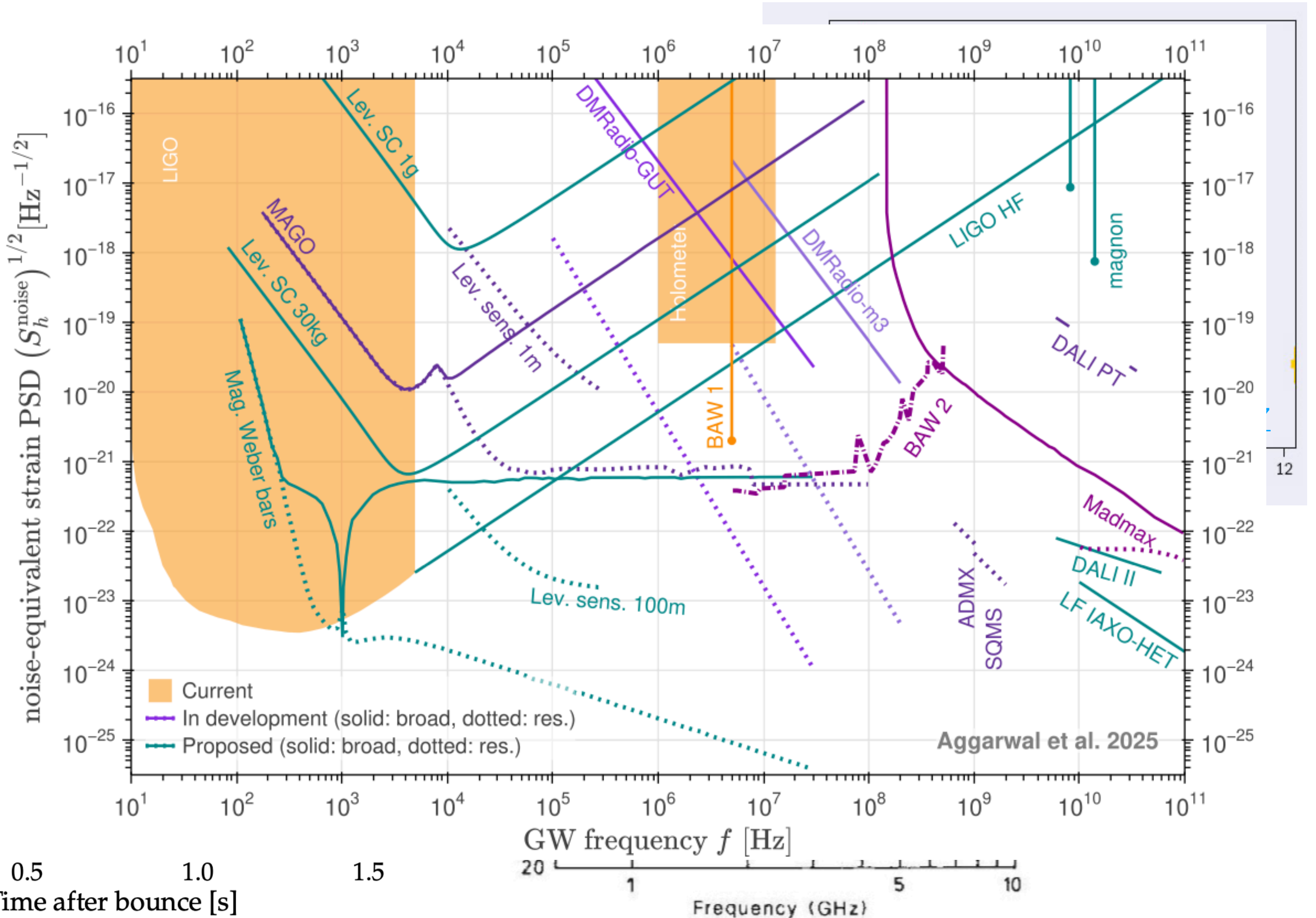
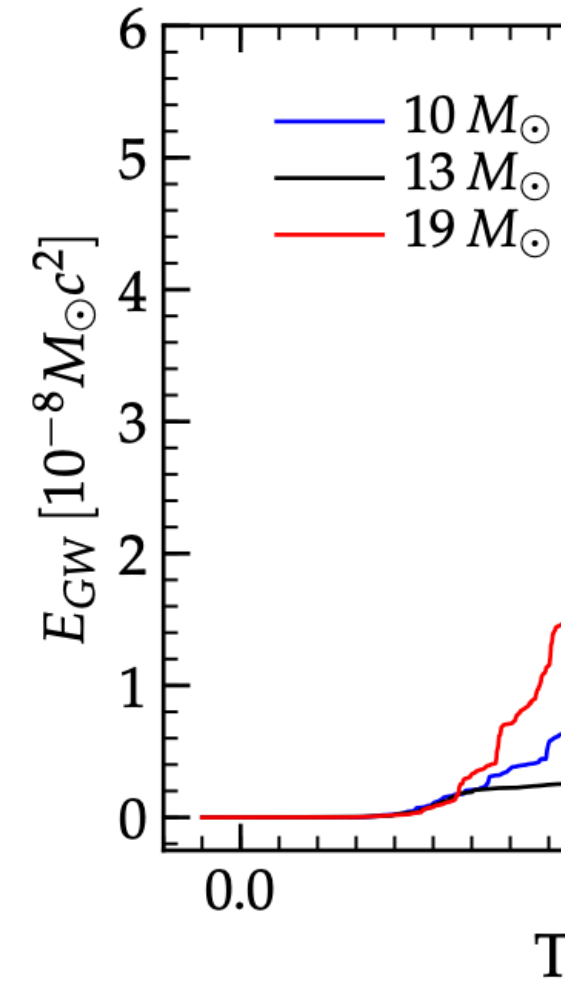
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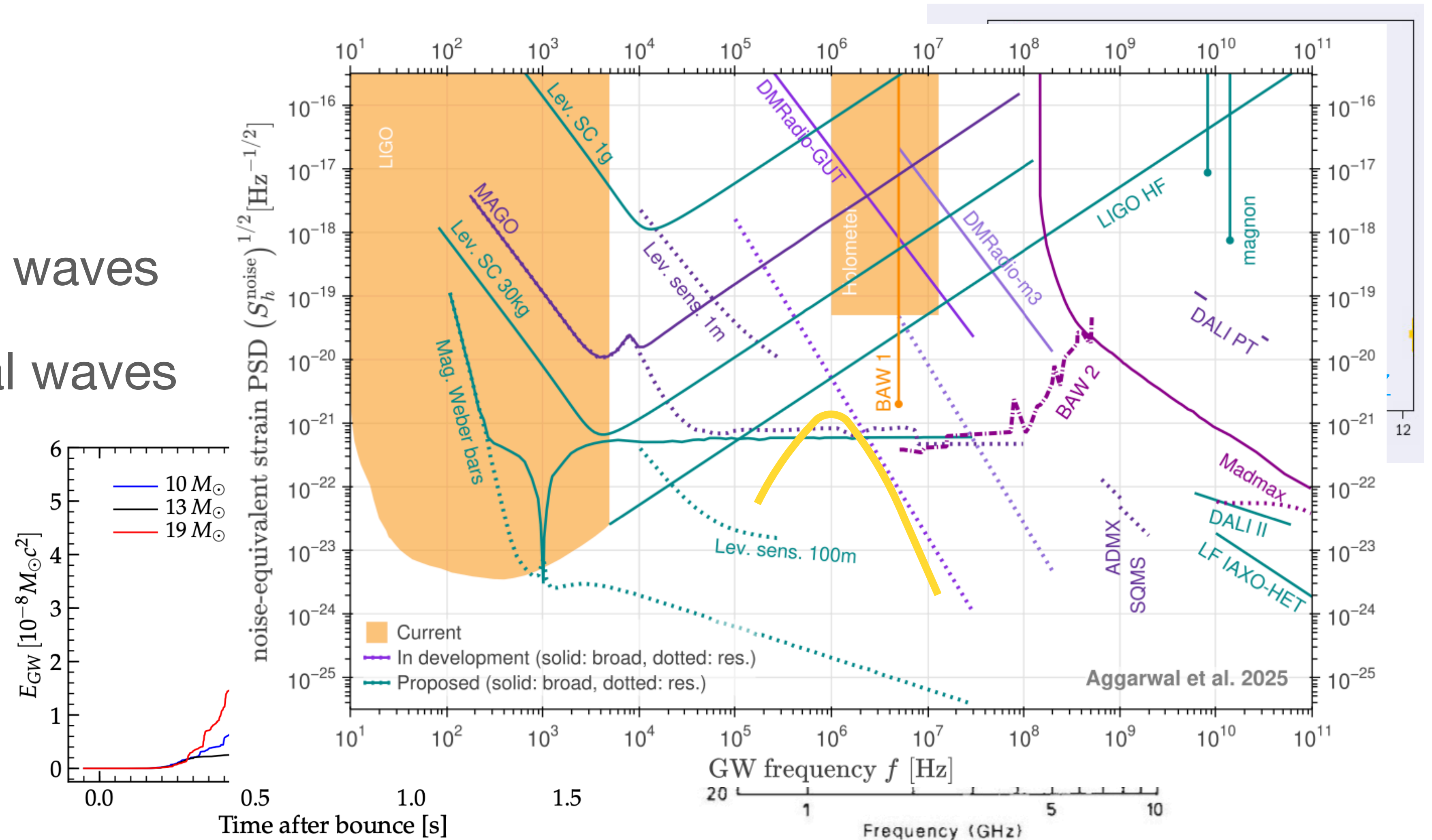
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- Neutrinos
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- kHz gravitational waves
- MHz gravitational waves



Supernovae = super-multimessenger?

- Neutrinos
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Trying to solve the sign problem

Understanding the QCD EOS with MHz GWs



Estimating the gravitational wave spectrum

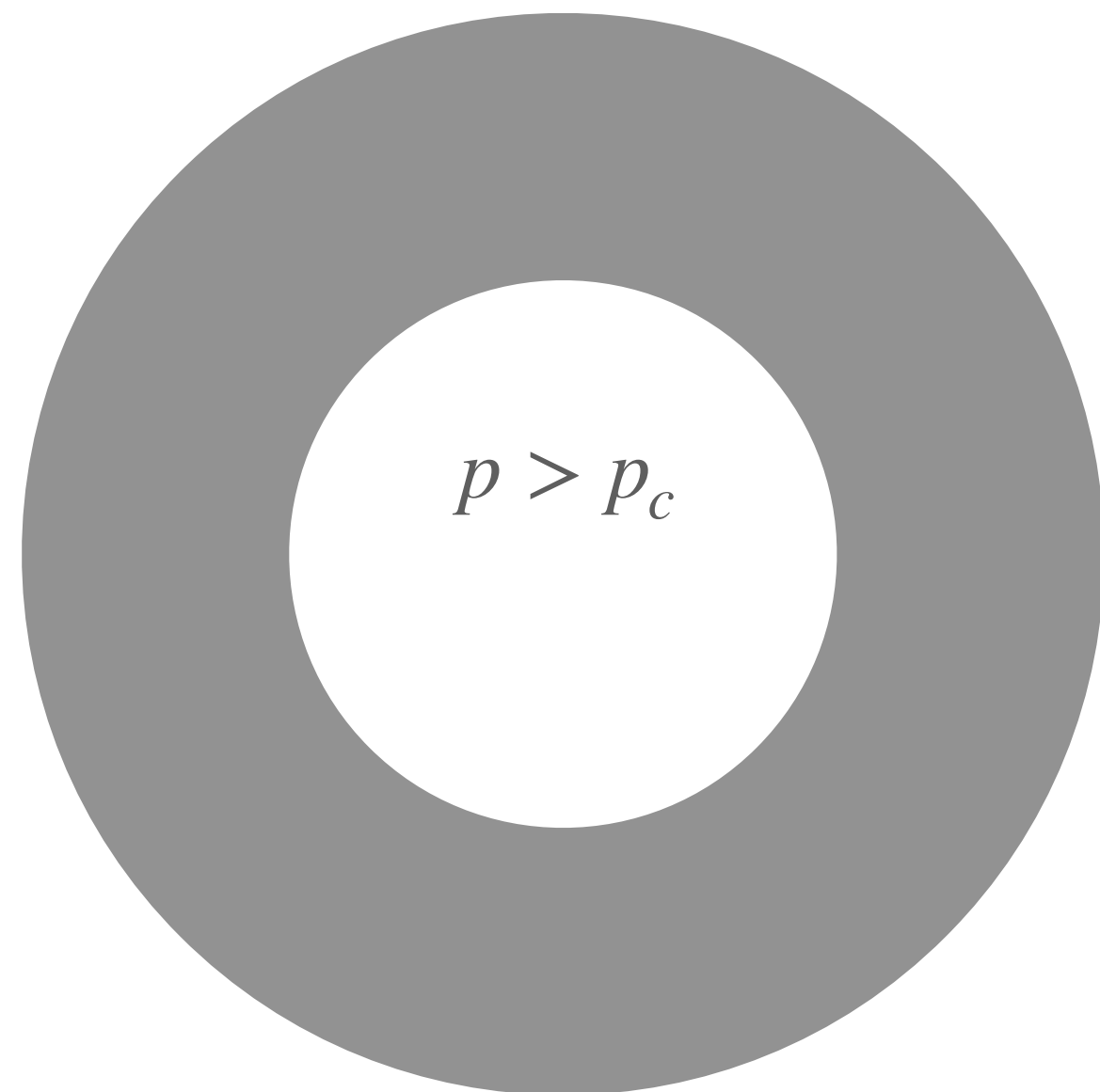
- Build on models for cosmological gravitational wave signals (Sound Shell model)
- Try out a few equations of state ($p(\mu, T)$, $e(\mu, T)$, $n(\mu, T)$)
- Neglect backreaction of the phase transition onto the evolution of the star
- A lot of things can be improved!



Model of a neutron star

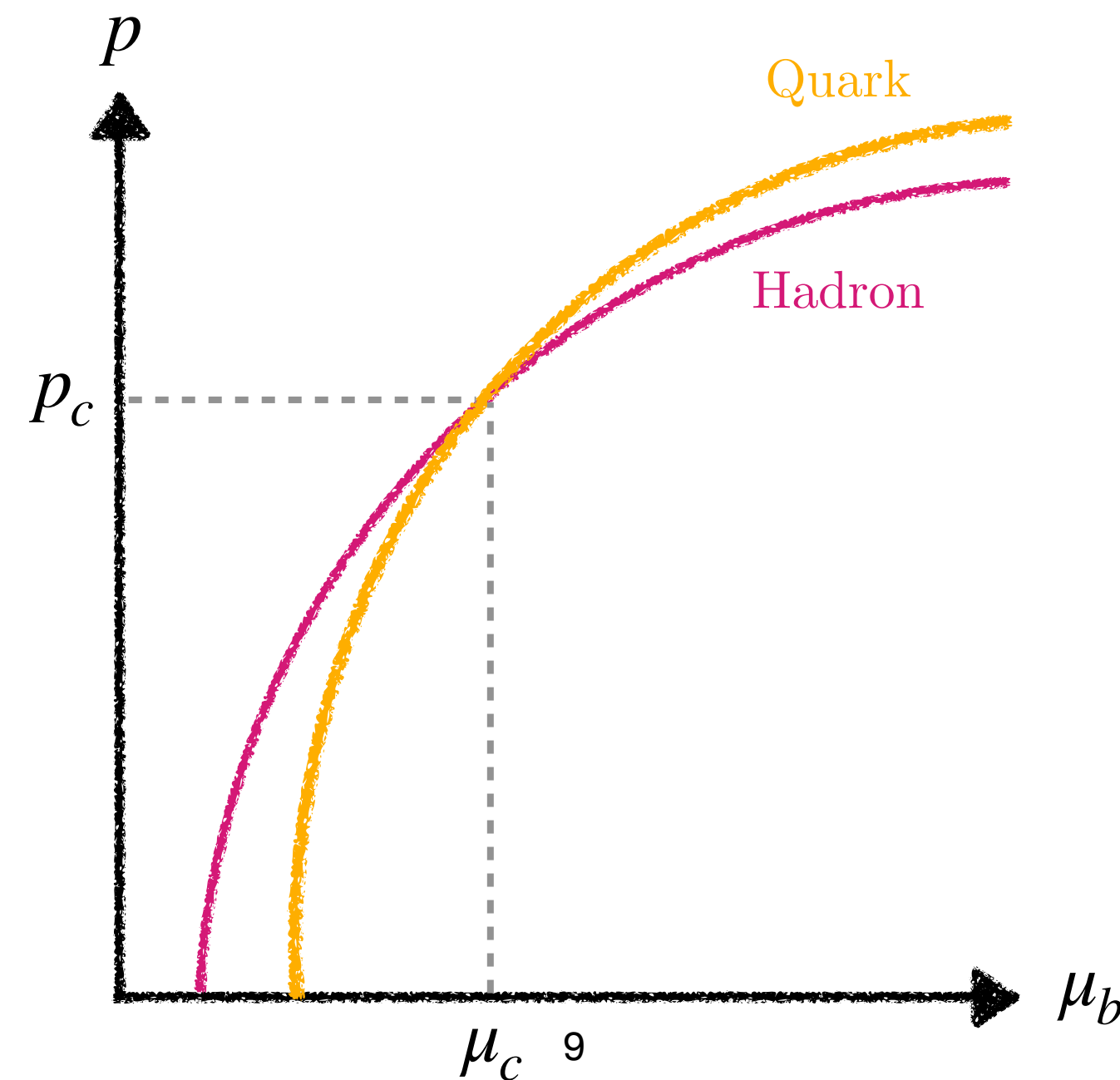
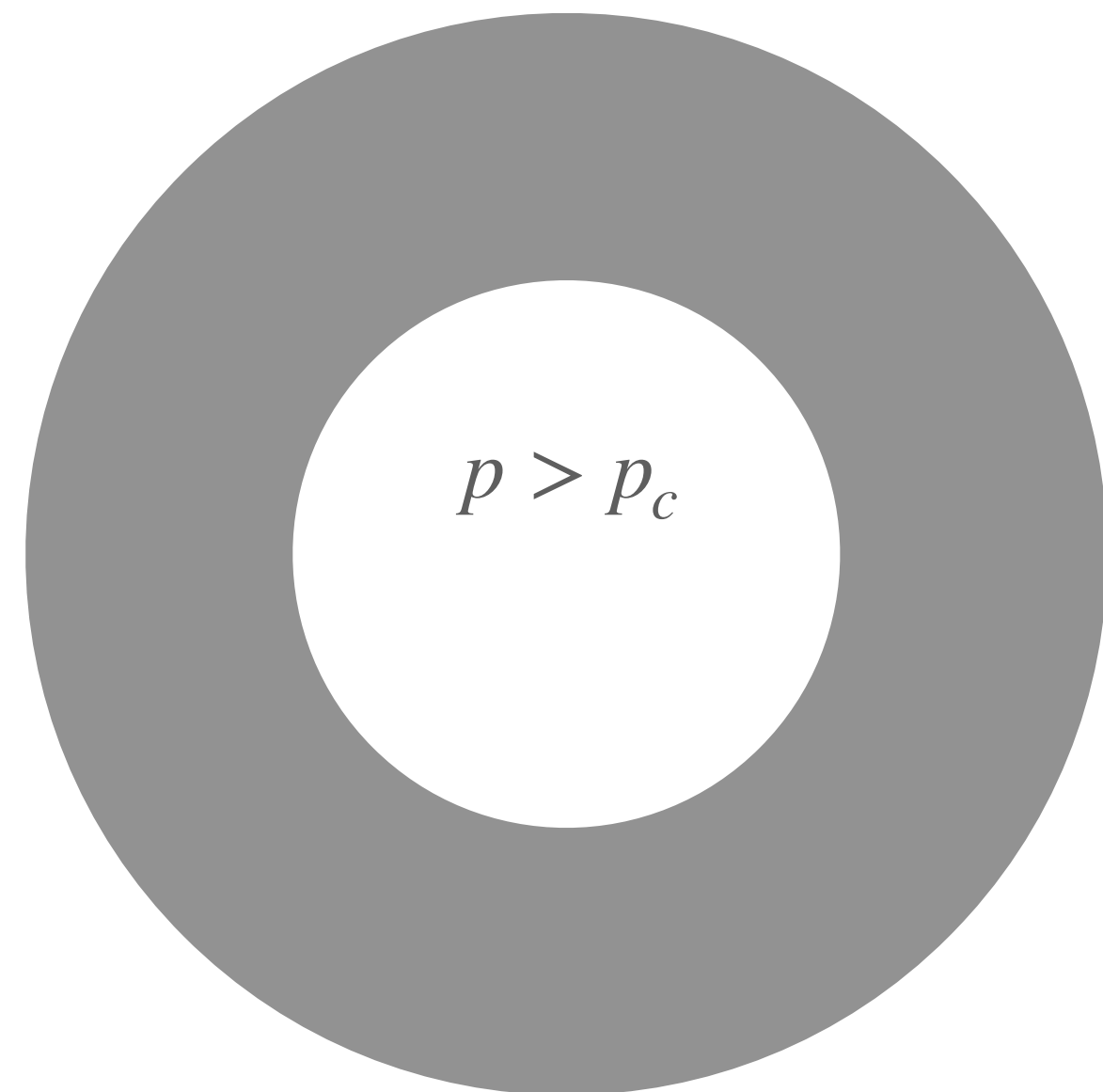
First order phase transition during core collapse

- During accretion, the pressure inside the star increases



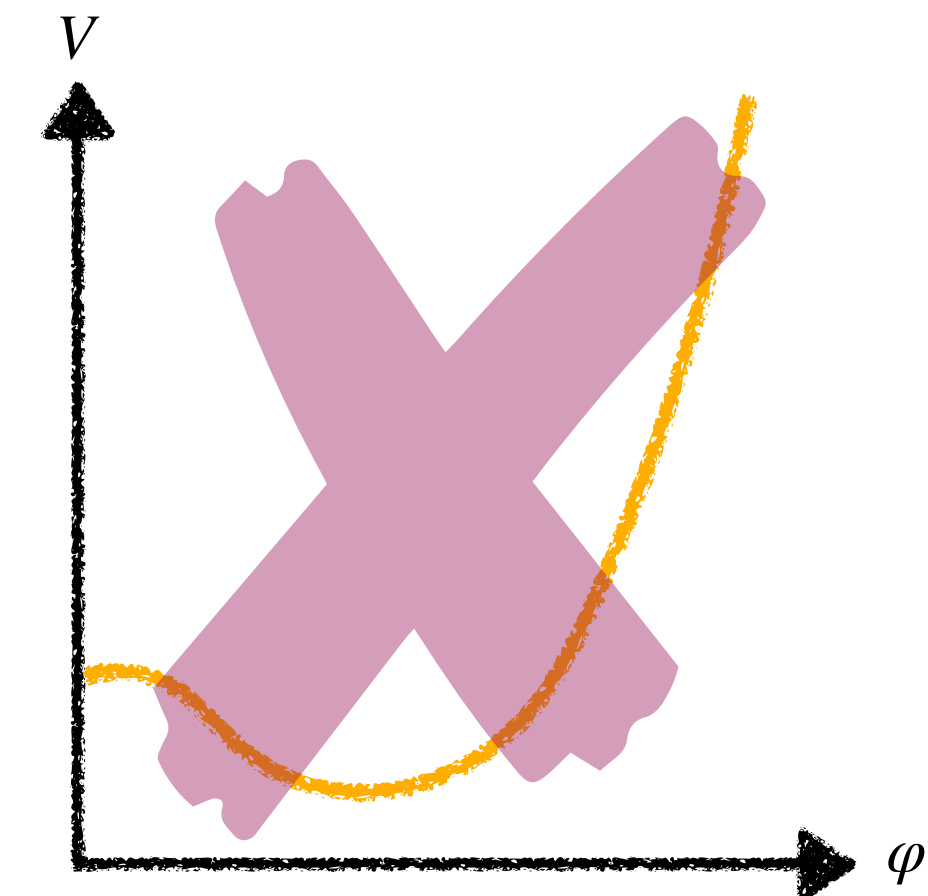
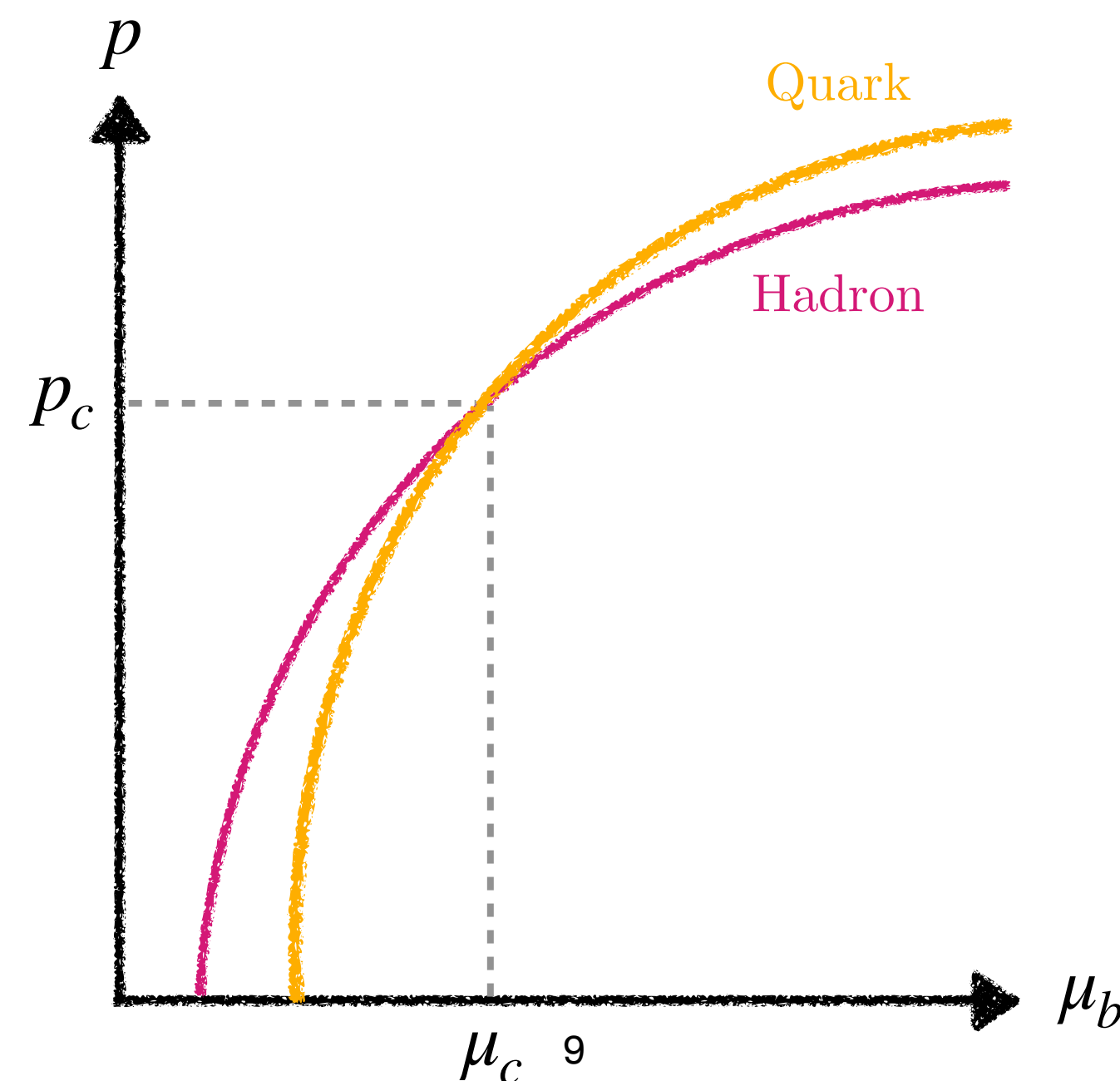
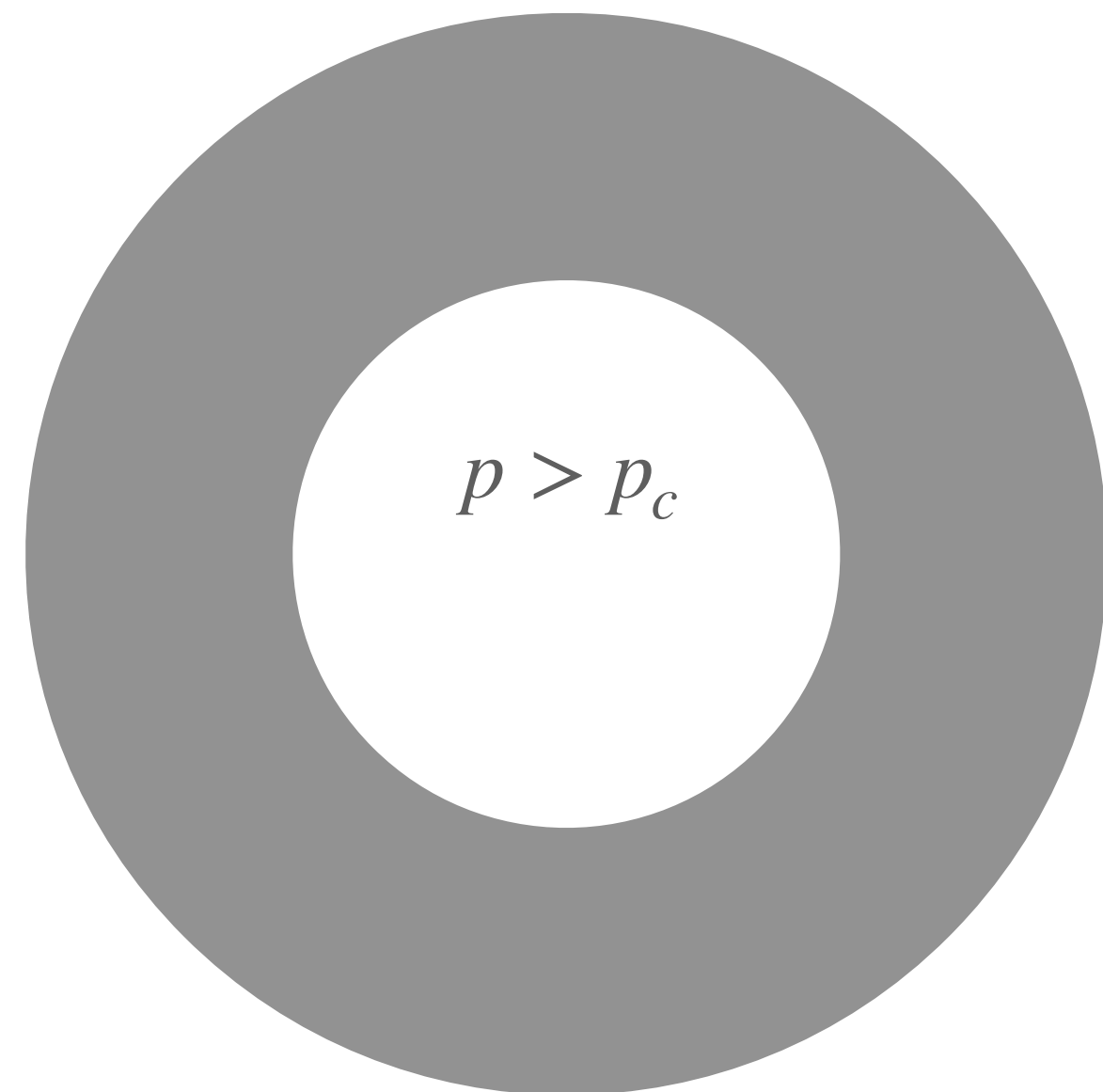
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First order phase transition during core collapse

- During accretion, the pressure inside the star increases
- For $r < R_c$, the pressure exceeds the critical pressure $p > p_c$
- Surface tension σ delays onset of transition. Larger σ : larger $\mu_n - \mu_c$

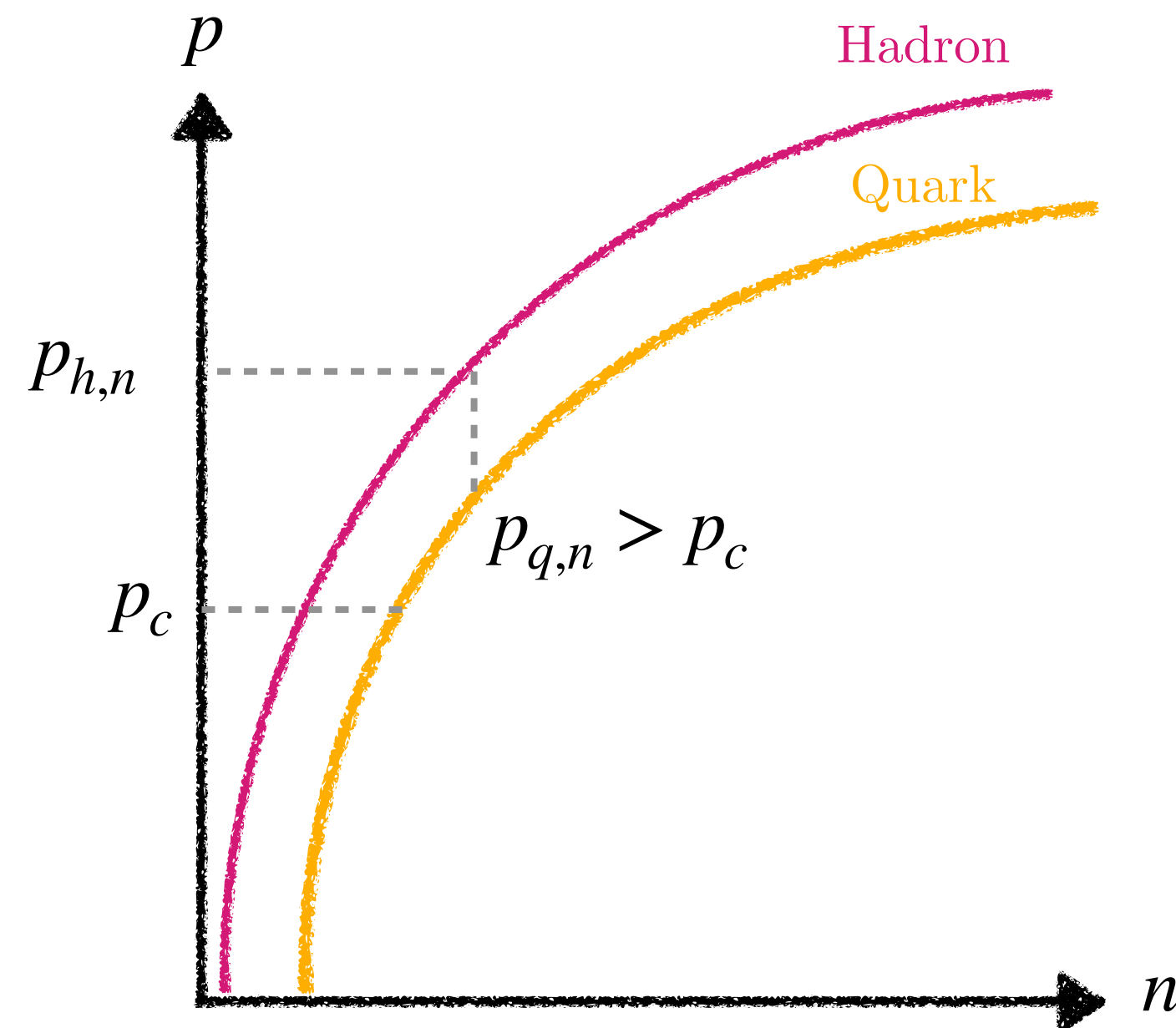


Three scenarios

Sizeable σ

Small σ

- $p_q(n_n) > p_c$: the phase transition completes

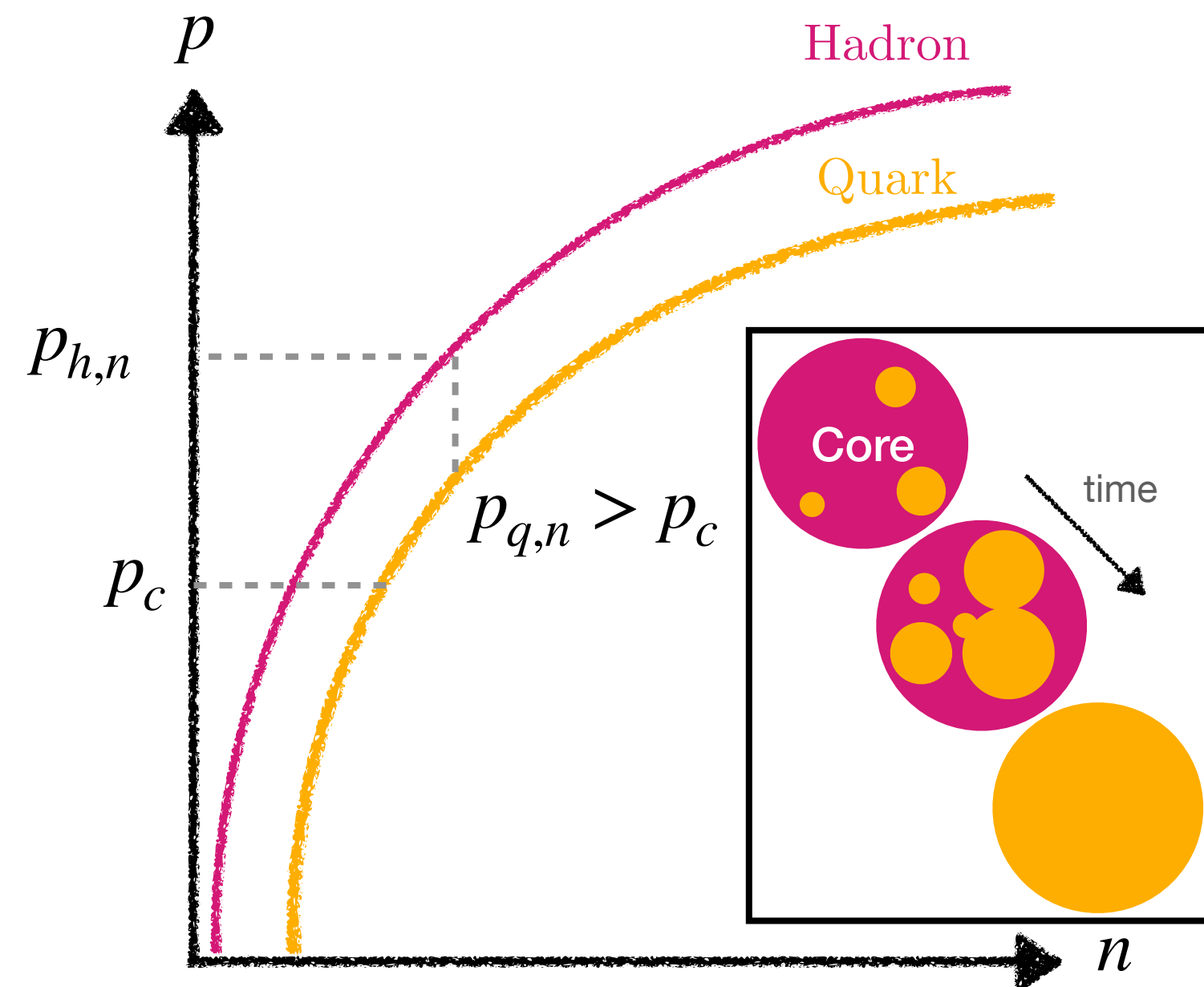


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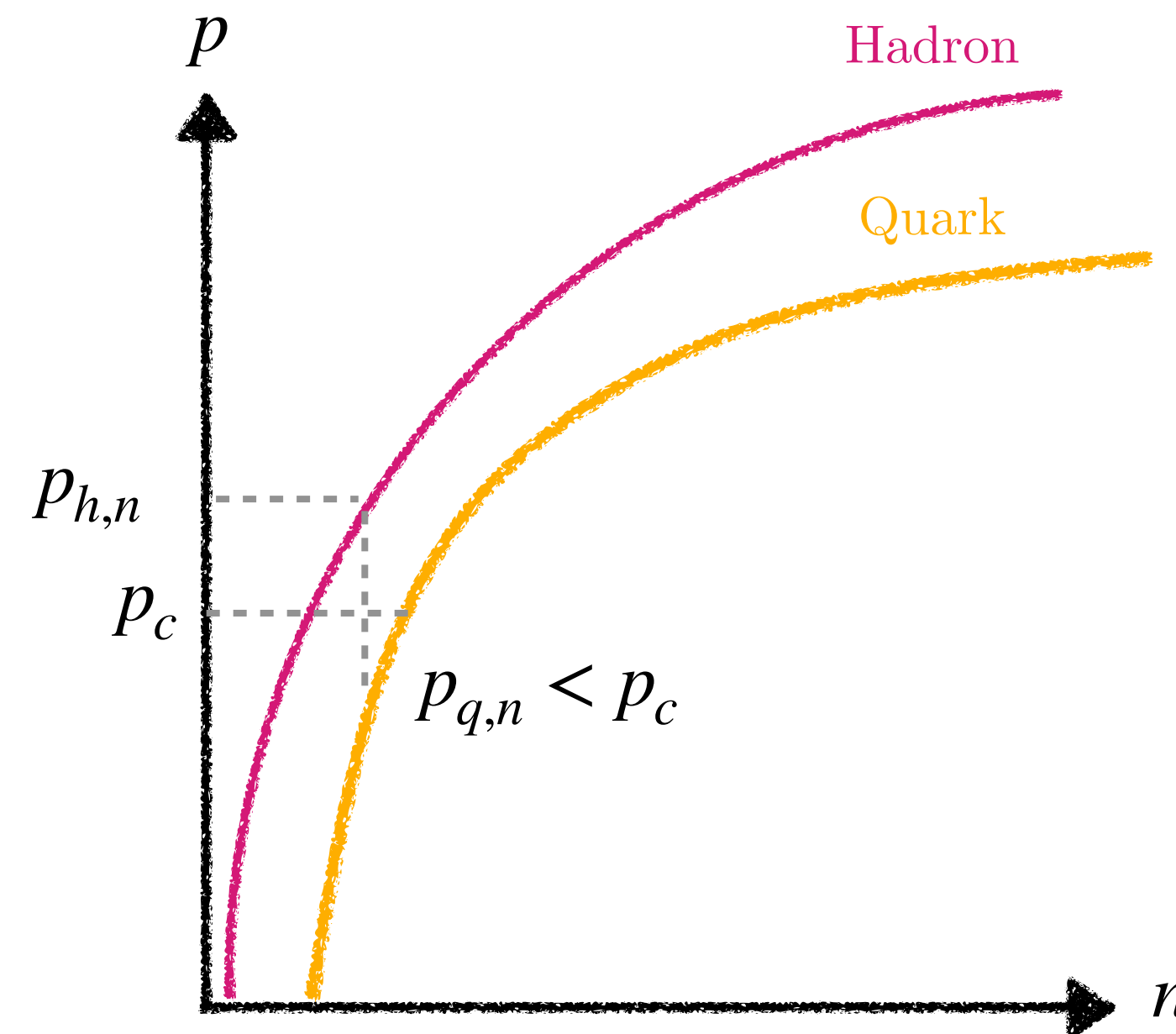
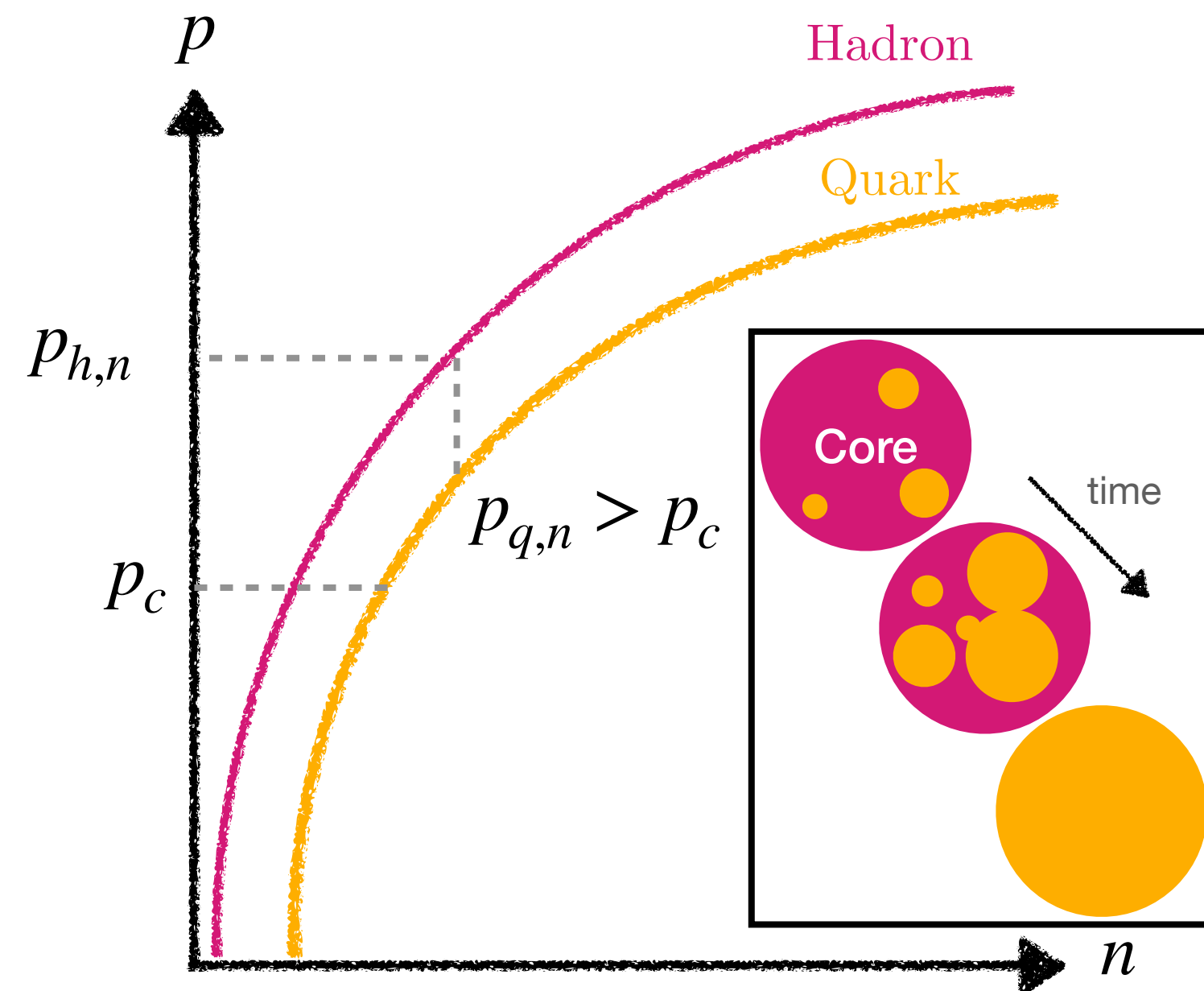


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- $p_q(n_n) > p_c$: the phase transition completes
- $p_q(n_n) < p_c$: the phase transition stalls (similar to [Witten 1984](#))

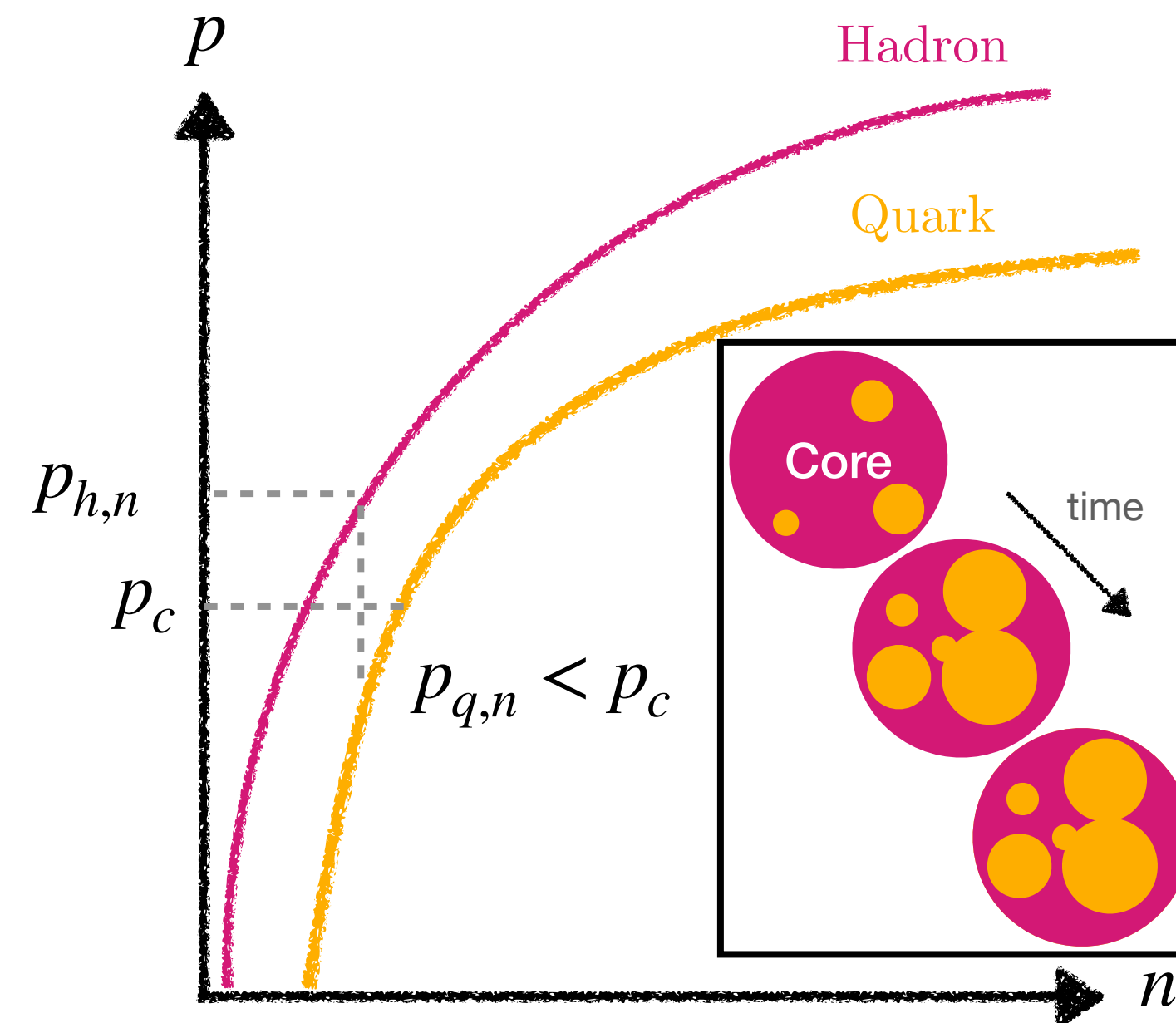
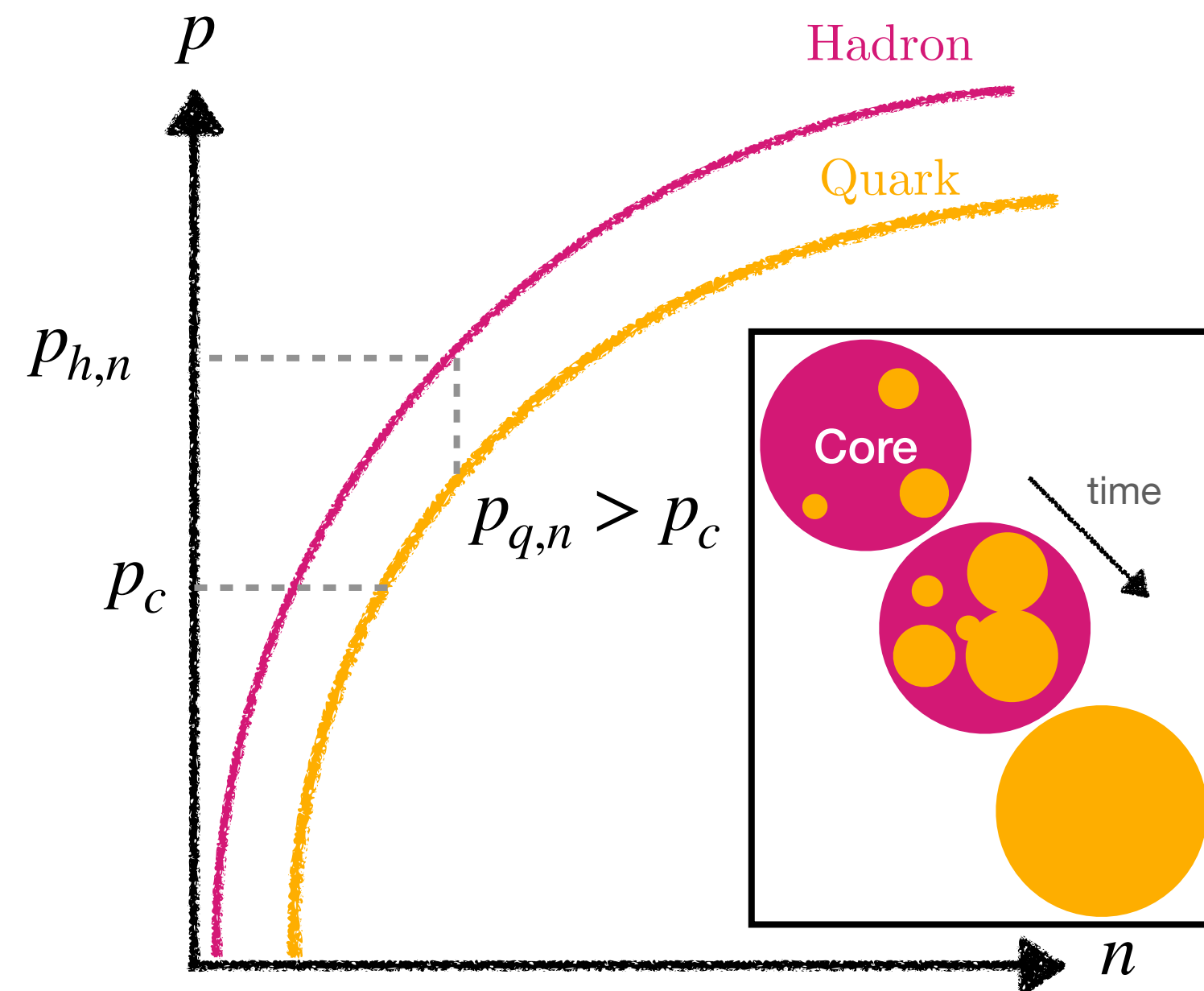


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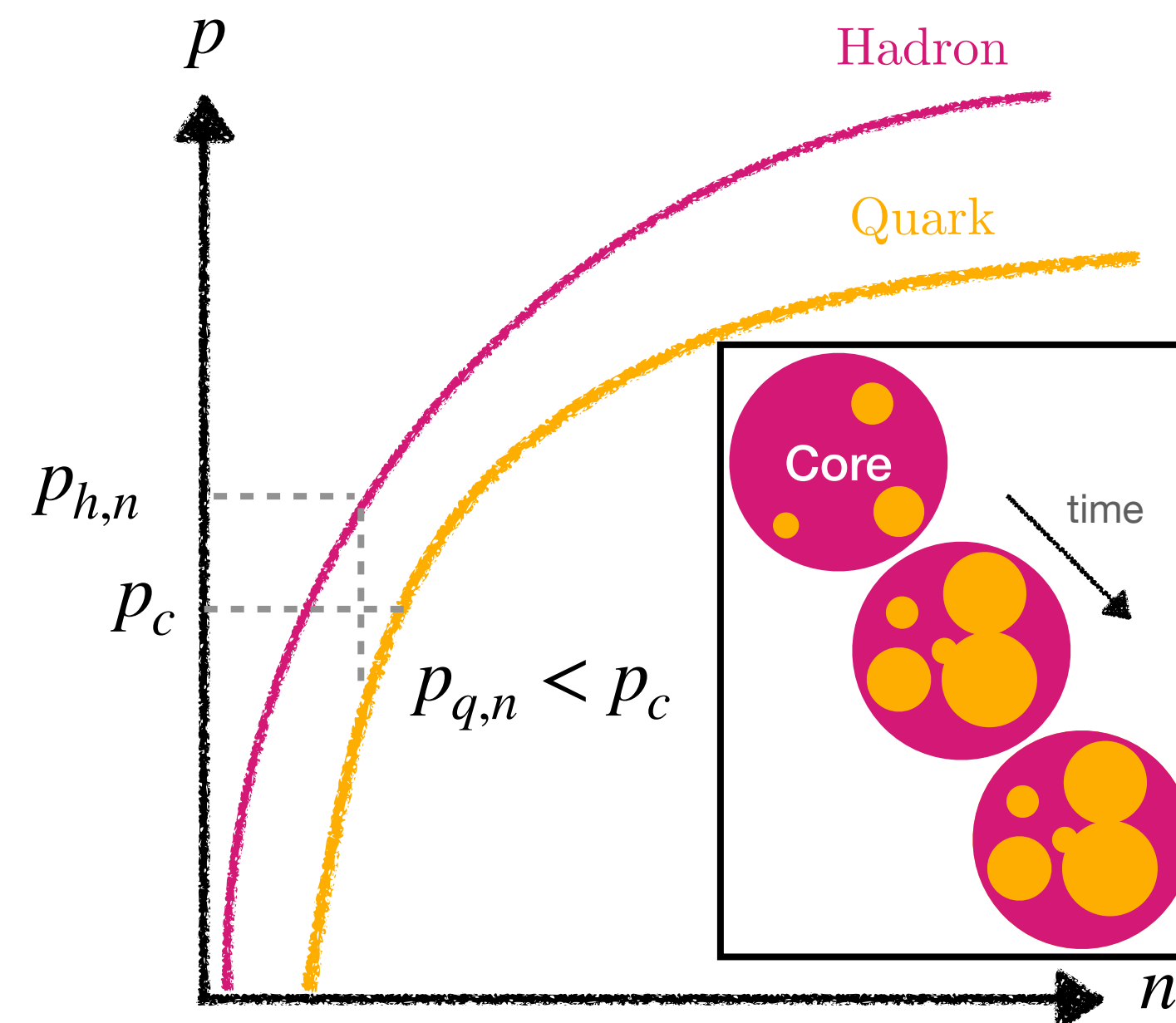
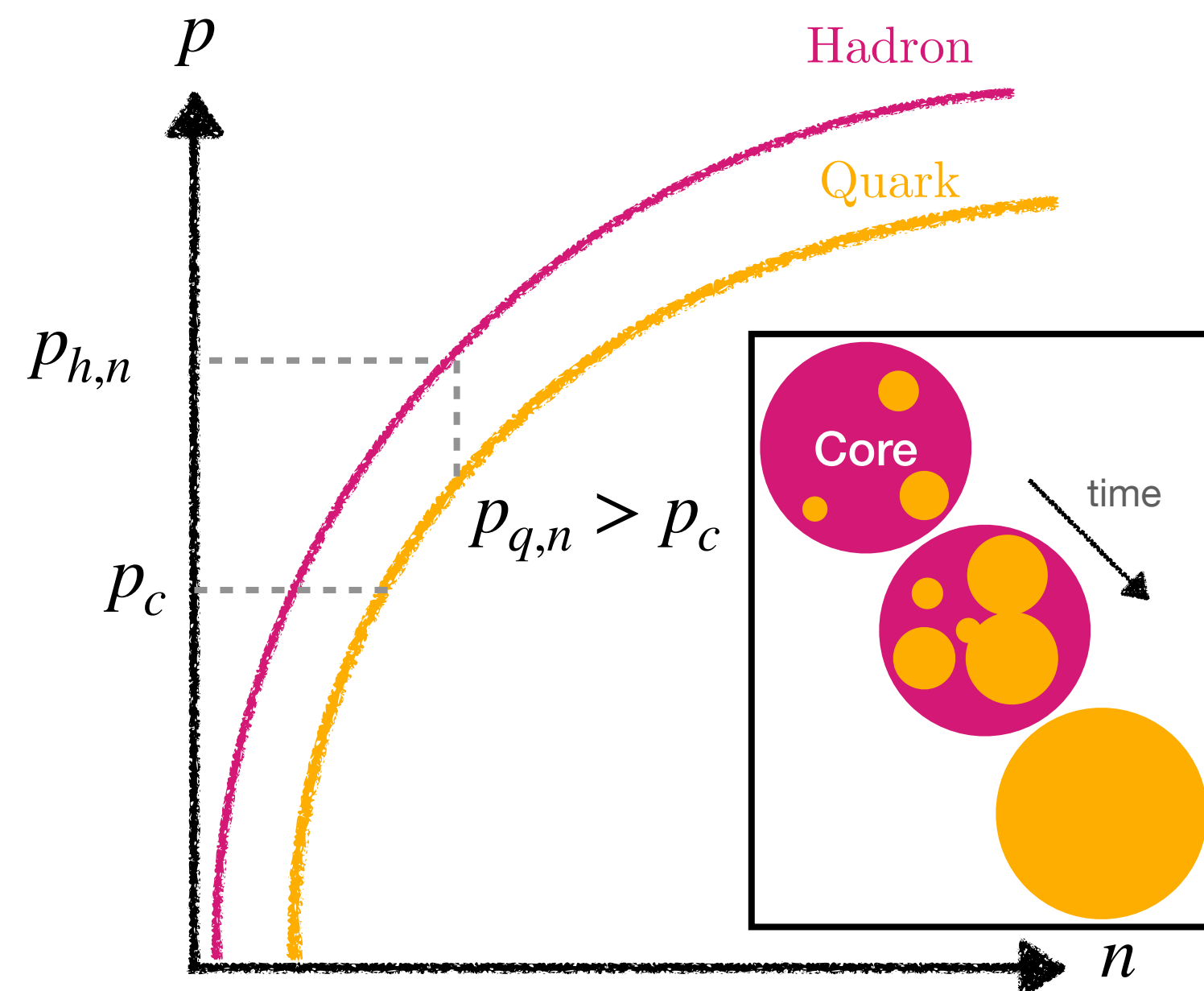
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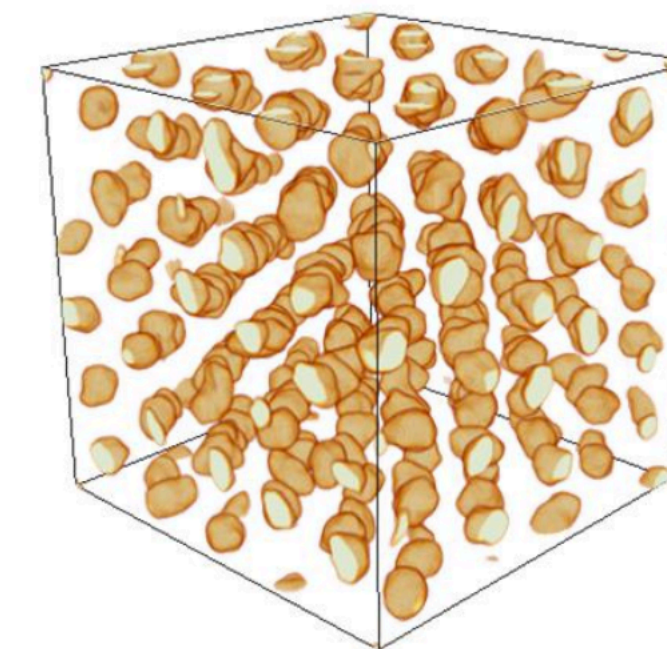
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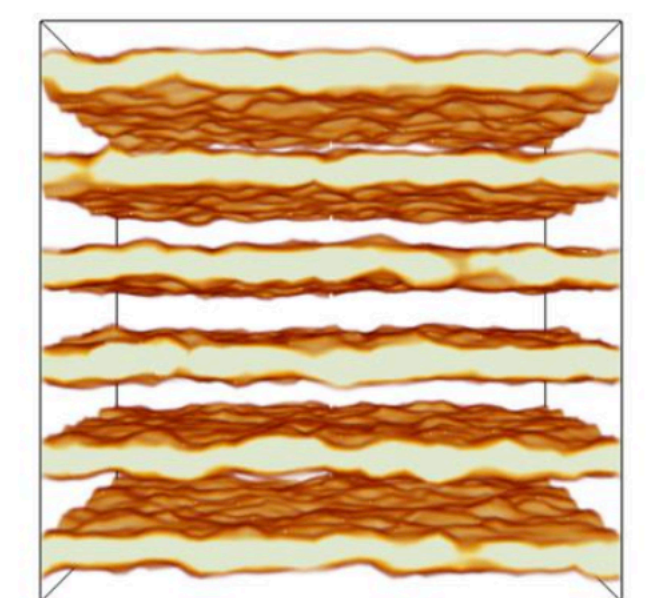
Small σ

- Microscopically mixed phase
[Caplan, Horowitz 2017](#)

(a) Gnocchi



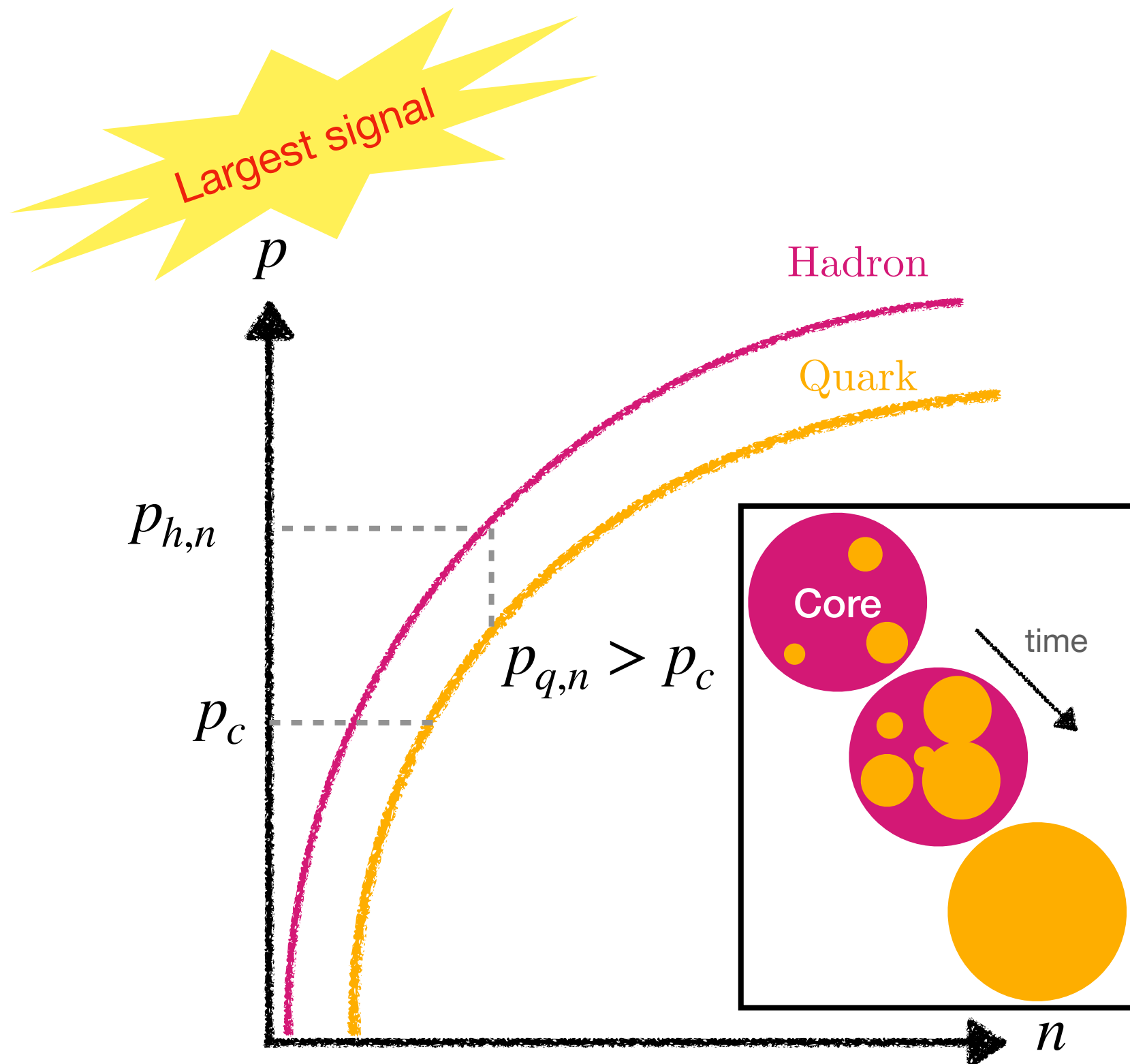
(d) Lasagna



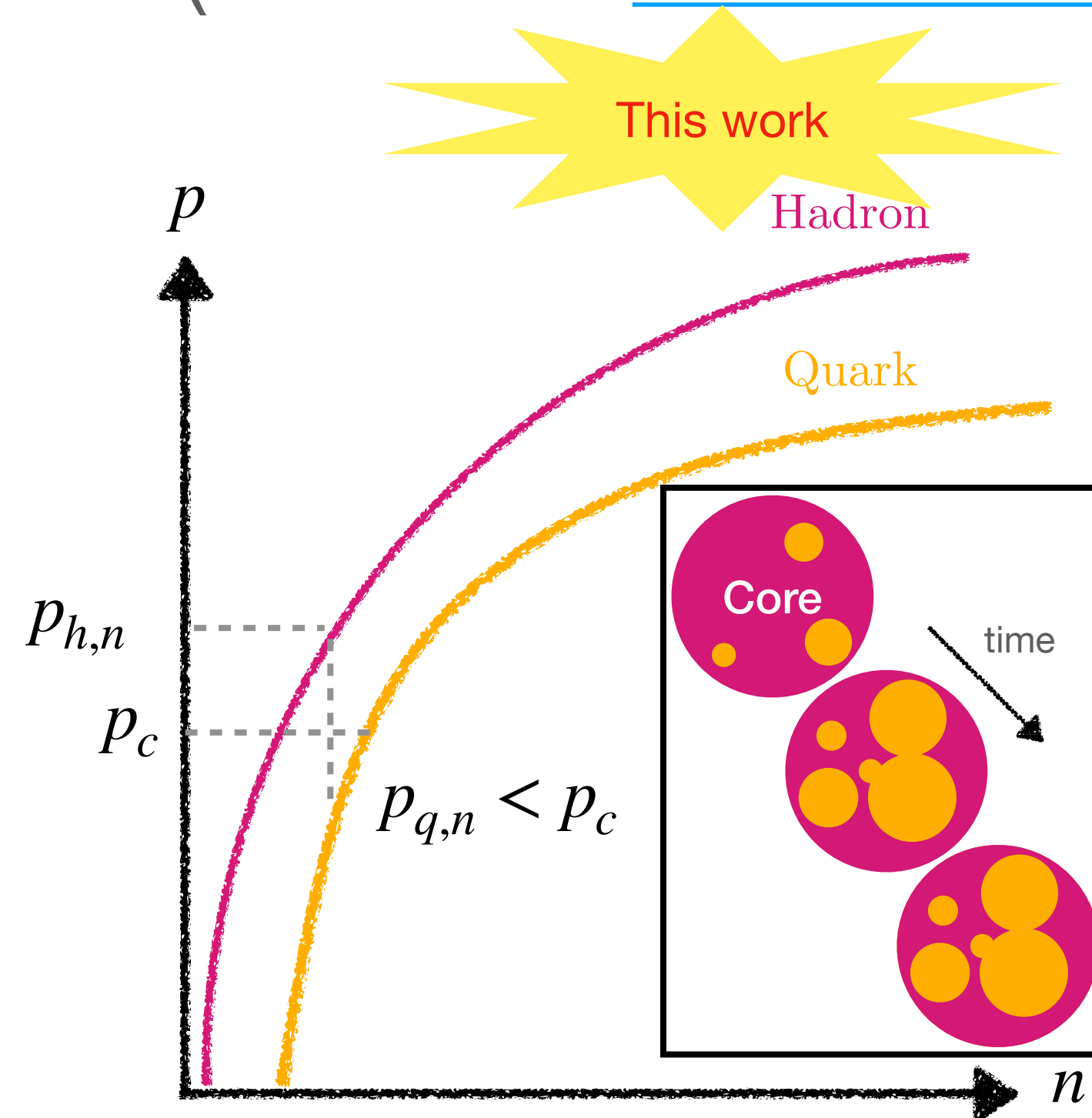
Three scenarios

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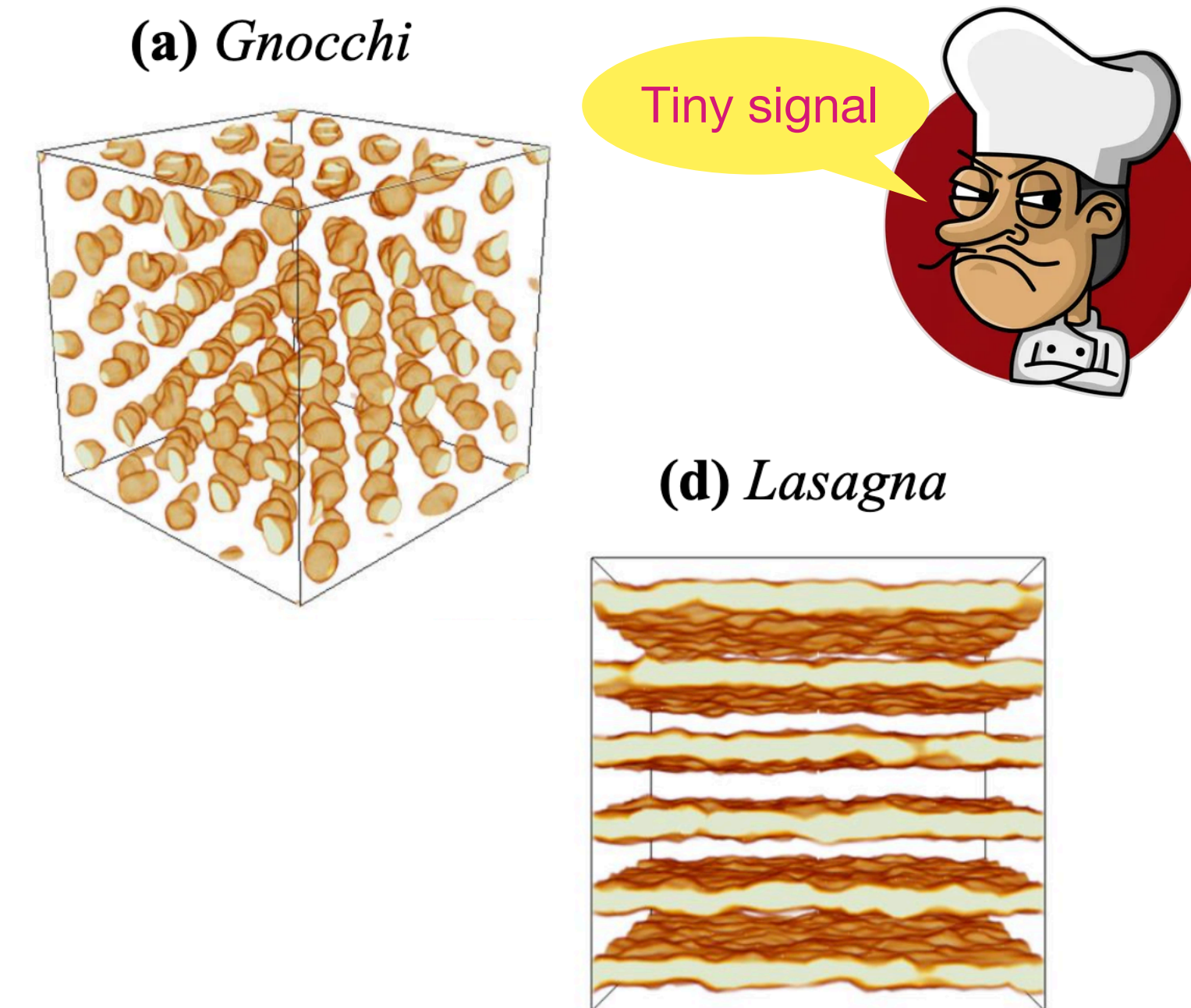


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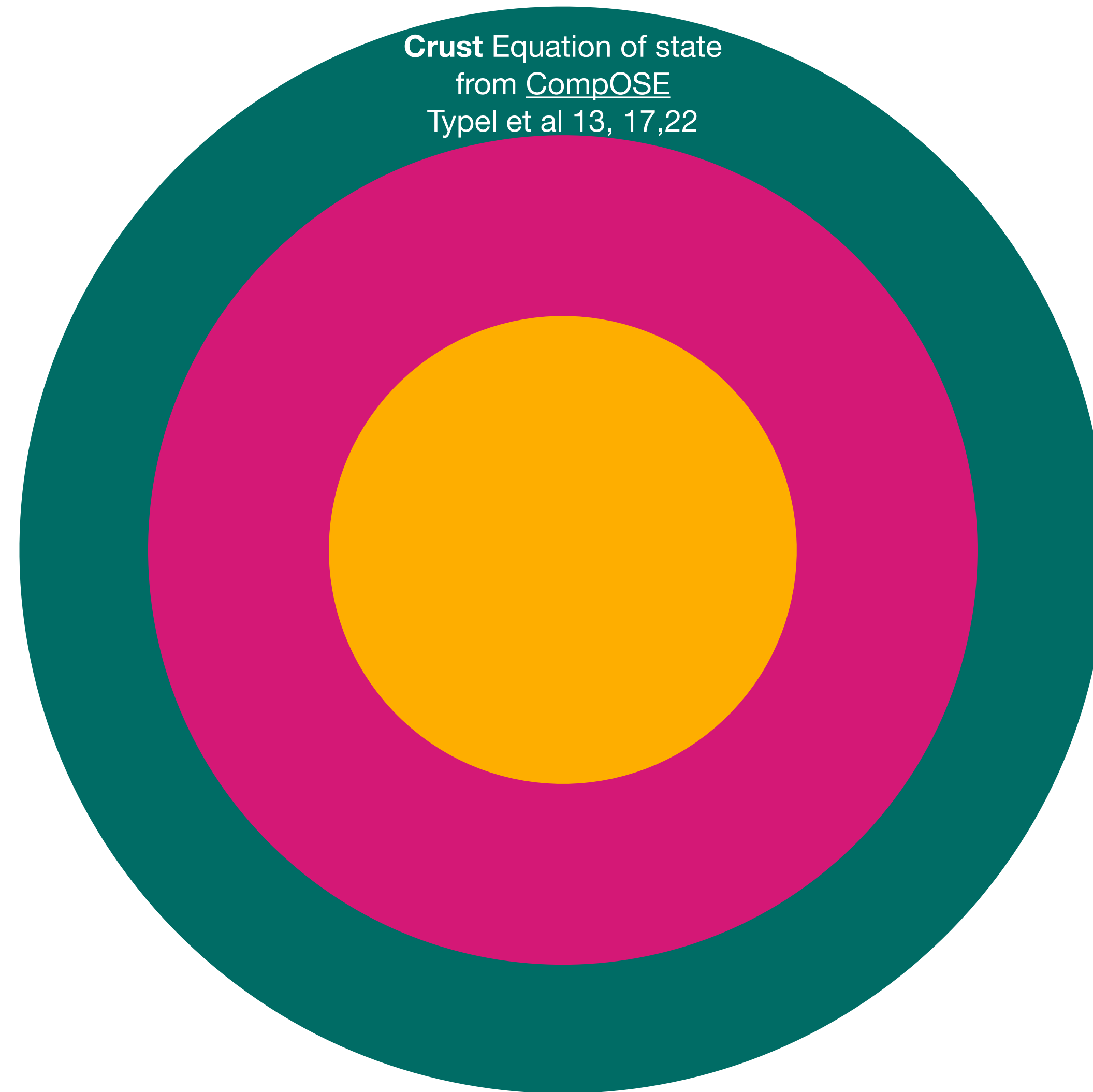


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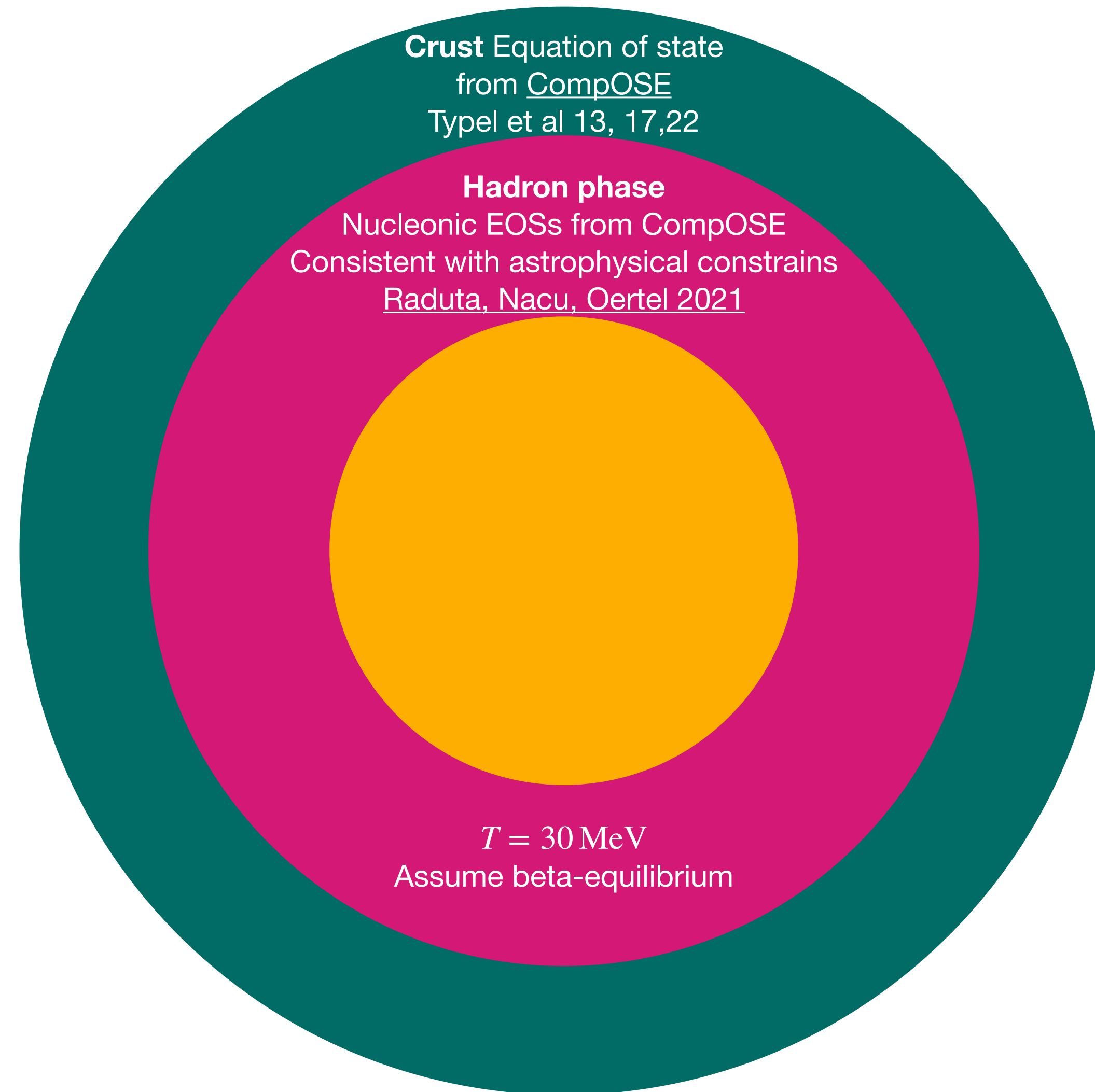
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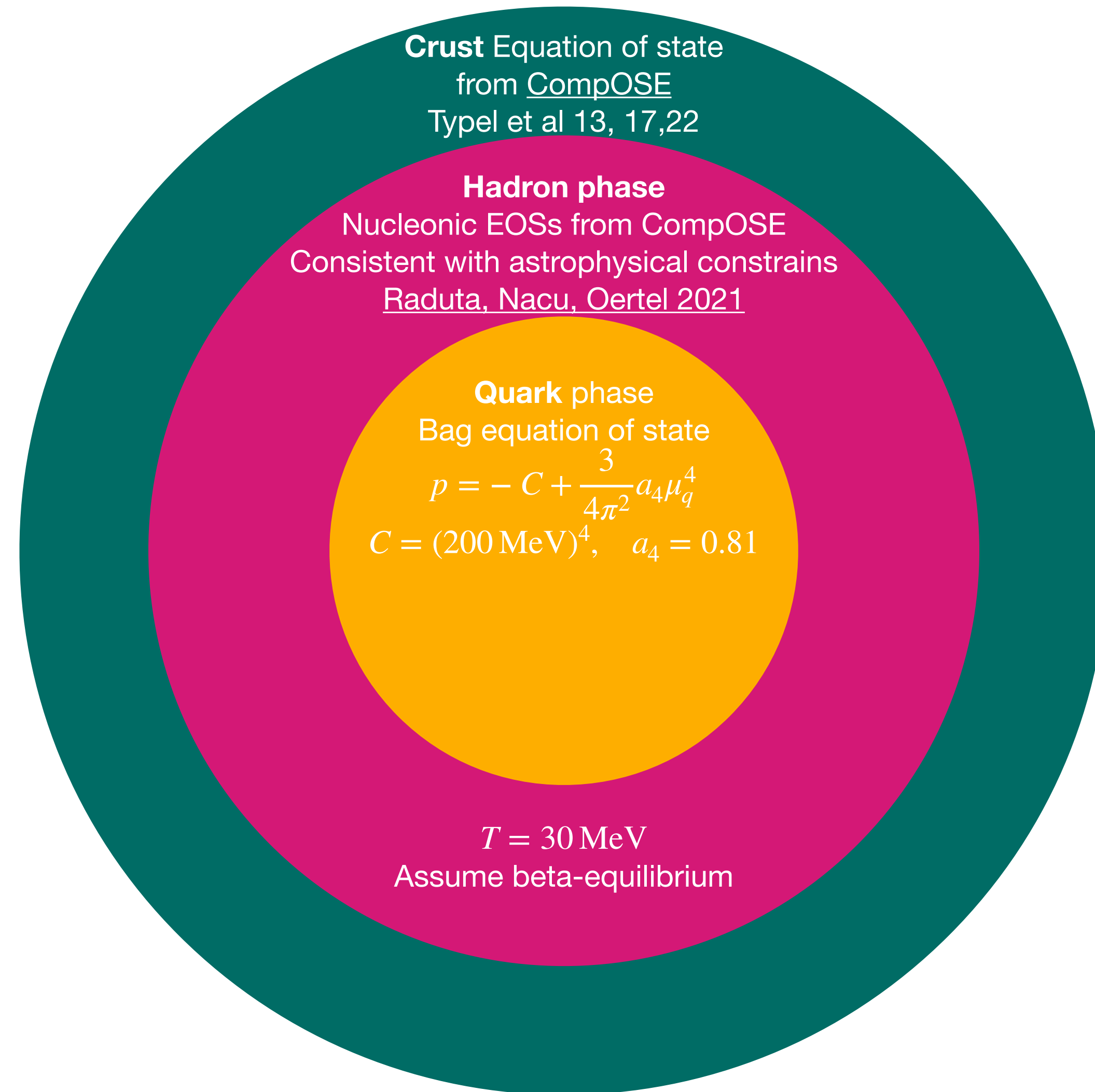
Modelling the neutron star



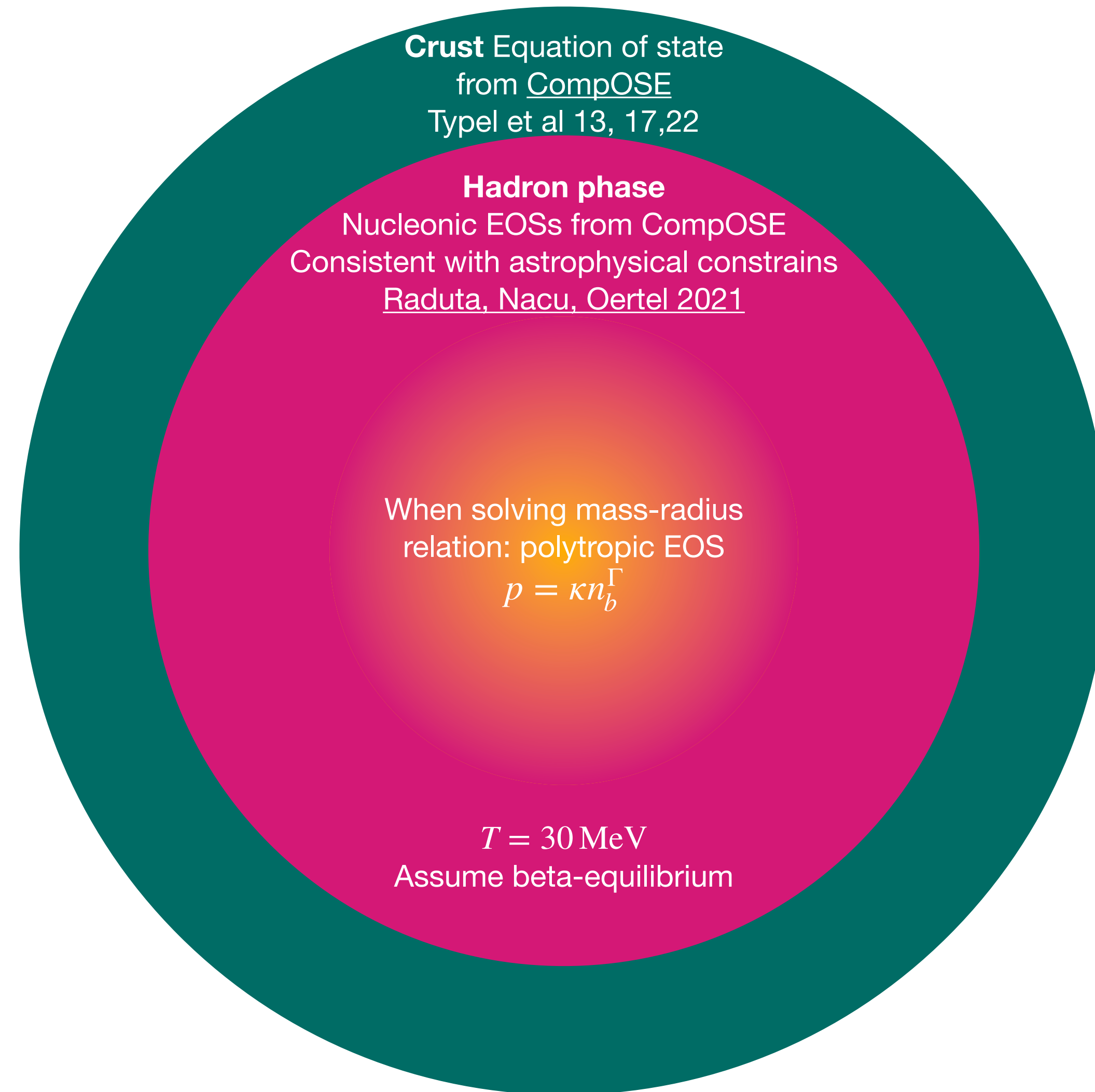
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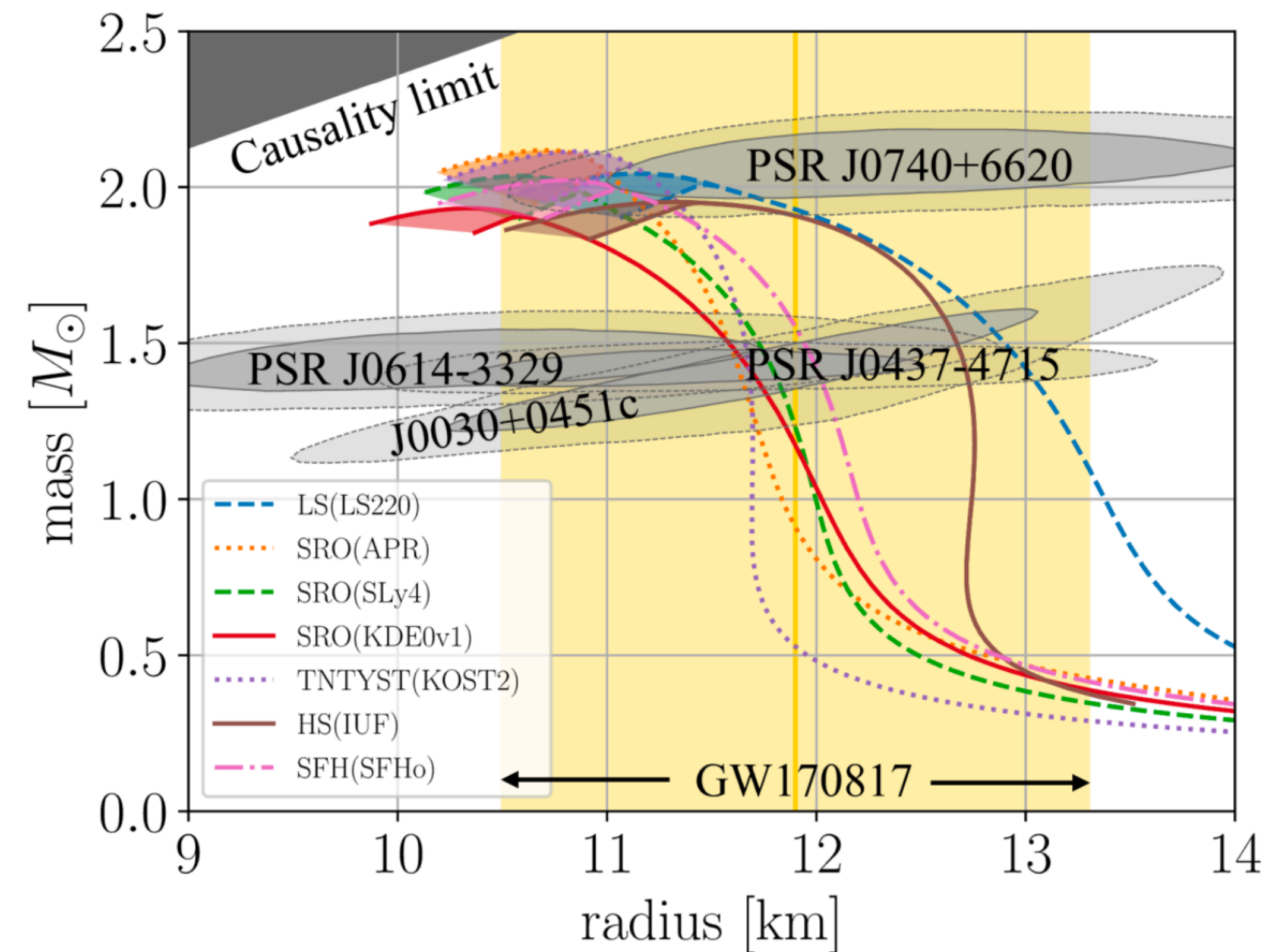


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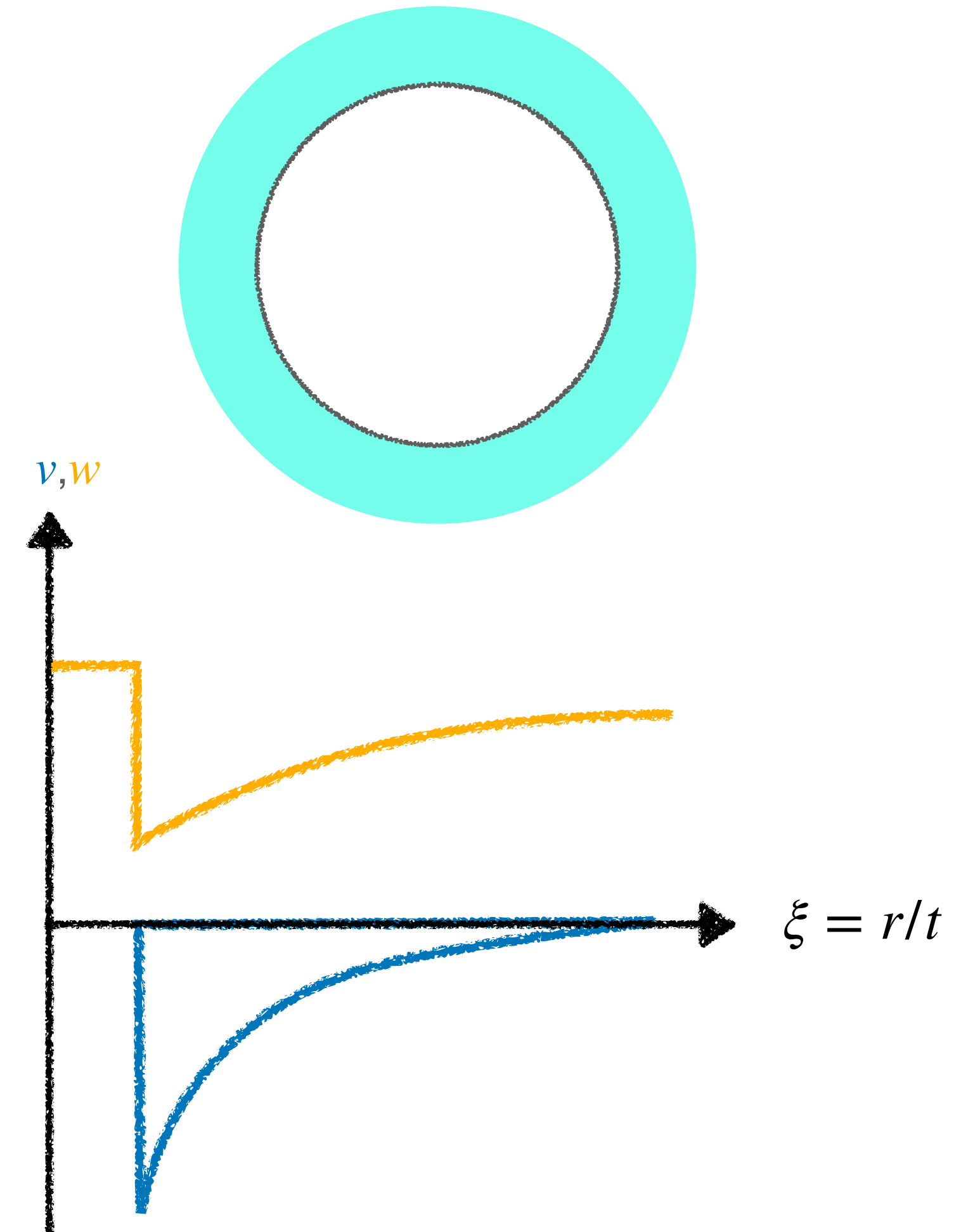
Mass-radius relation and maximum pressure

- Solve Tolman–Oppenheimer–Volkoff equation with [PYTOV](#) :
- Check that EOSs are consistent with neutron star observations
- Find the size of the core
- Maximum pressure before collapse into black hole



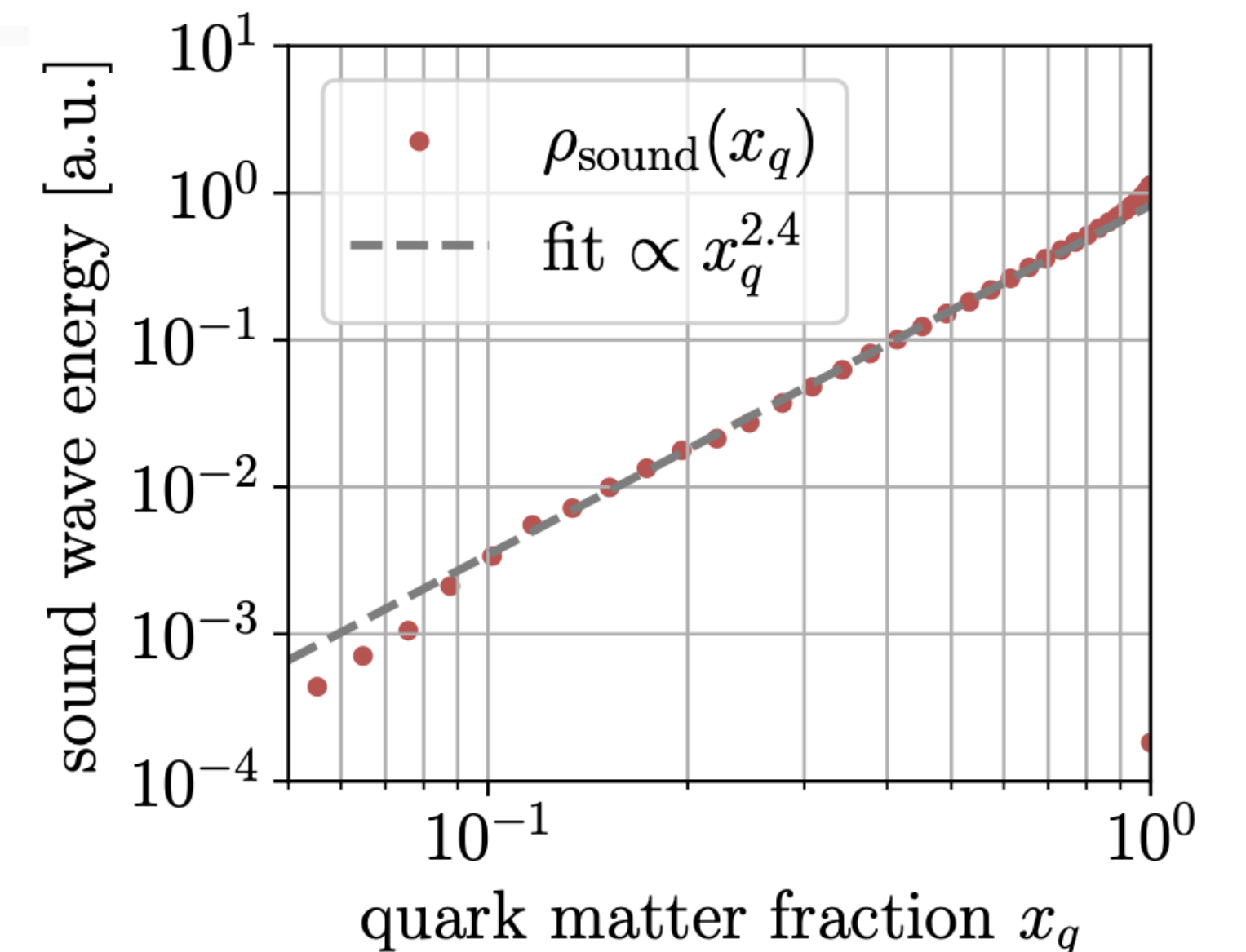
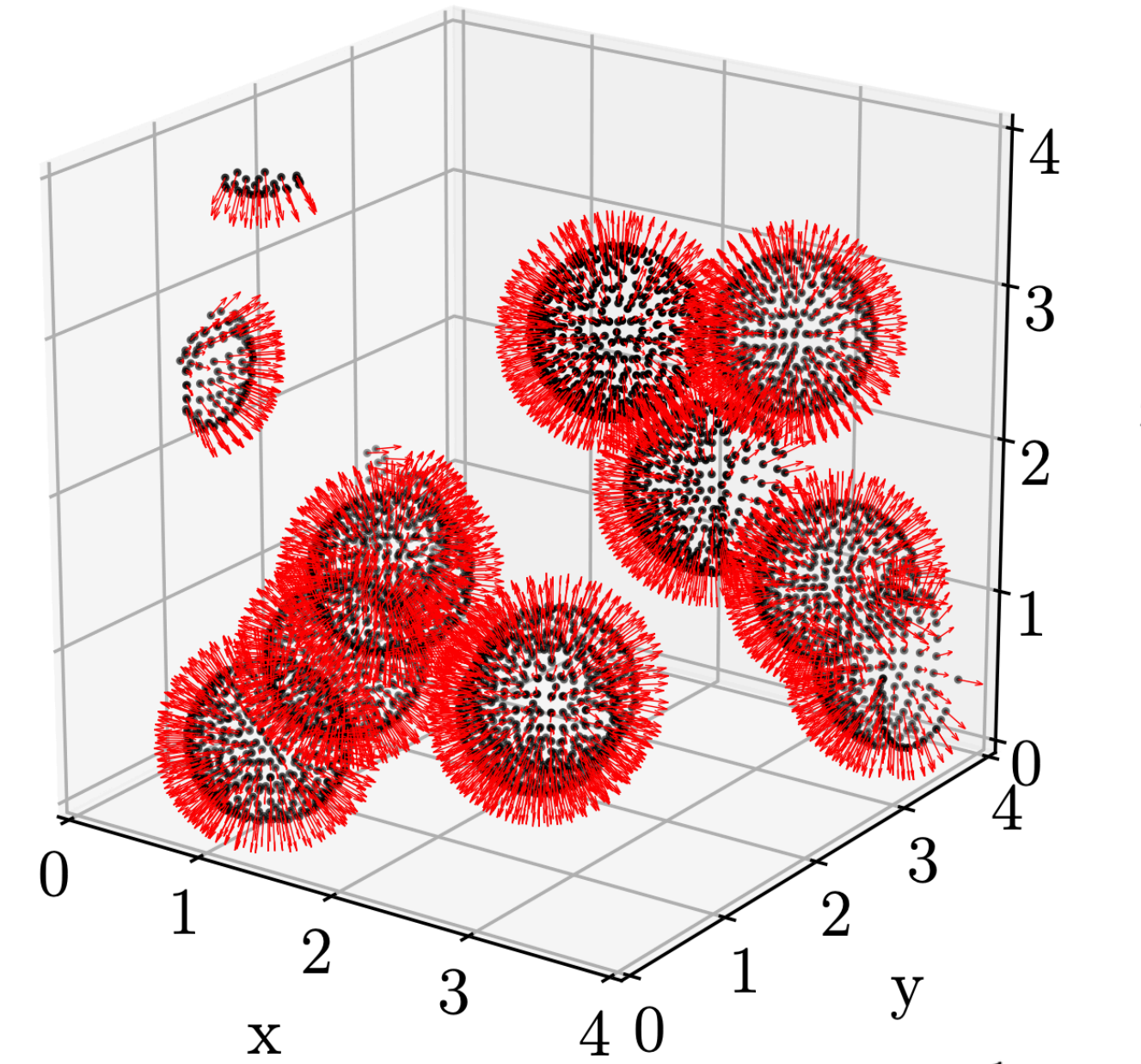
Gravitational waves from sound waves

- Fluid motion sources sound waves, sound waves source GWs
- Hydrodynamics profiles for inverse phase transition [Barni, Blasi, Vanvlasselaer 24](#), [Bea, Casalderrey-Solana, Mateos, Sanchez-Garitaonandia 24](#)
- Assume $c_s^2 = 1/3$ everywhere
- Assume local thermal equilibrium to estimate v_w [Ai, Garbrecht, Tamarit 21](#), [Ai, Laurent, JvdV 23](#)
- Use the Sound Shell model to estimate the GW spectrum [Hindmarsh 2016](#), [Hindmarsh, Hijazi 2019](#), using [PTTools](#)



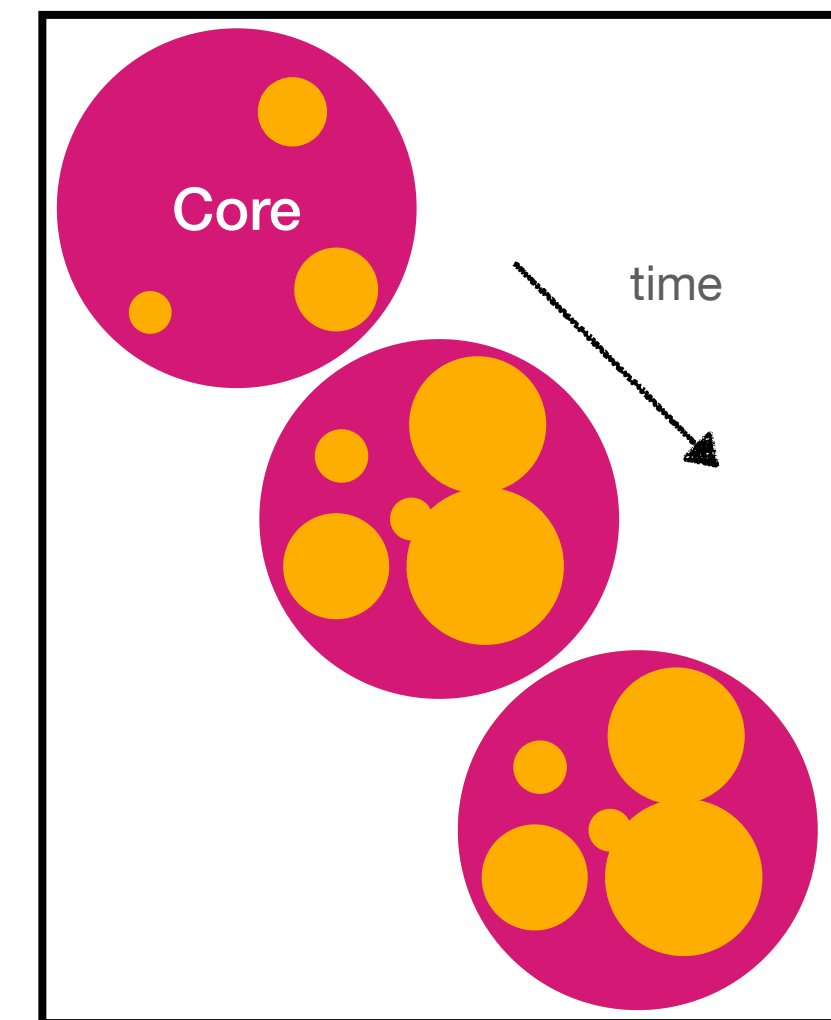
Amplitude of an incomplete phase transition

- Sound shell model assumes complete phase transition, but our transition stalls, and $x_q(p_s) < 1$
- Some bubbles never collide and therefore do not source GWs
- Extract the fraction of energy converted to sound waves in simplified simulation
- Rescale the sound shell amplitude with $x_q^{4.8}$

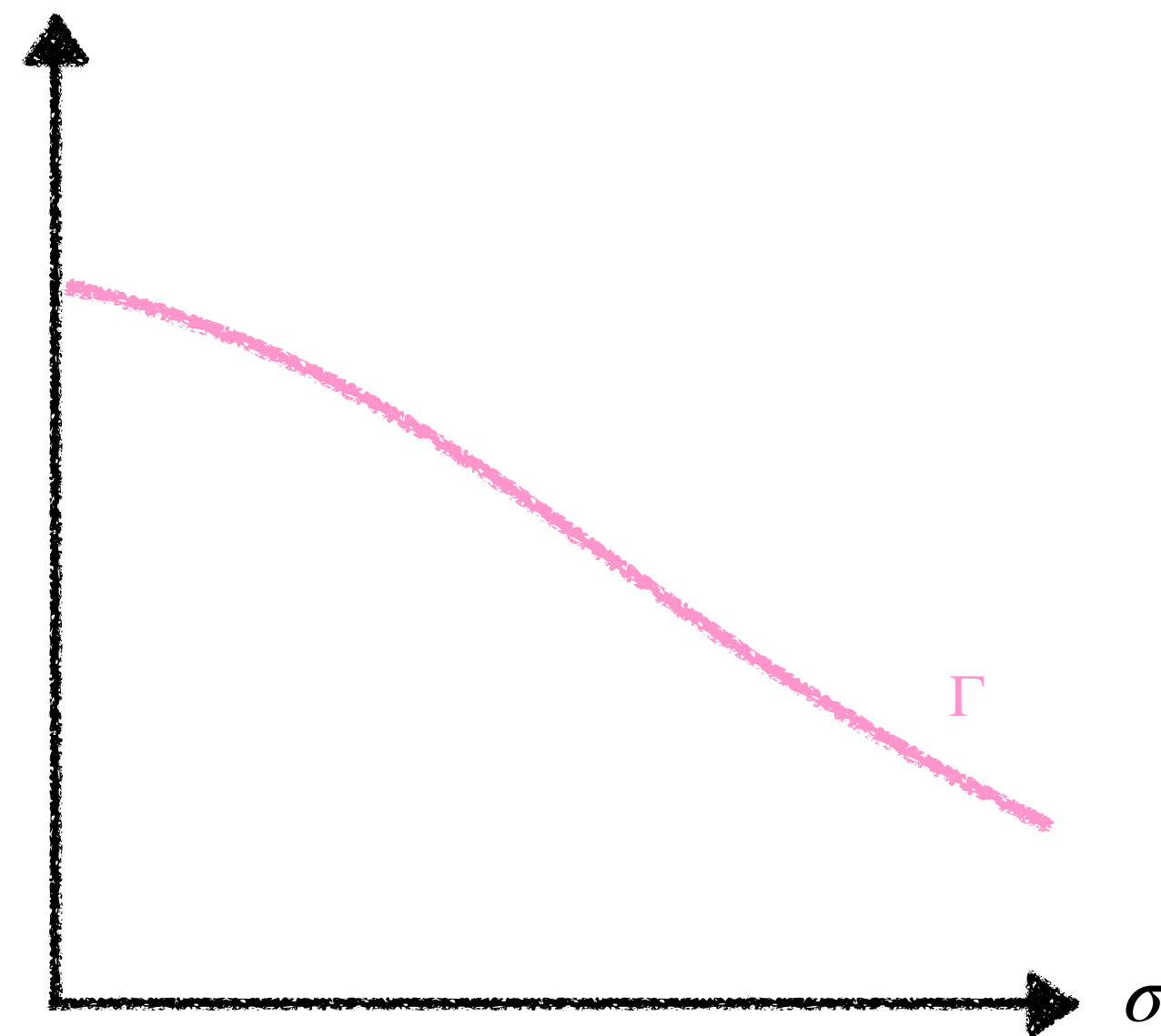


Bubble nucleation rate

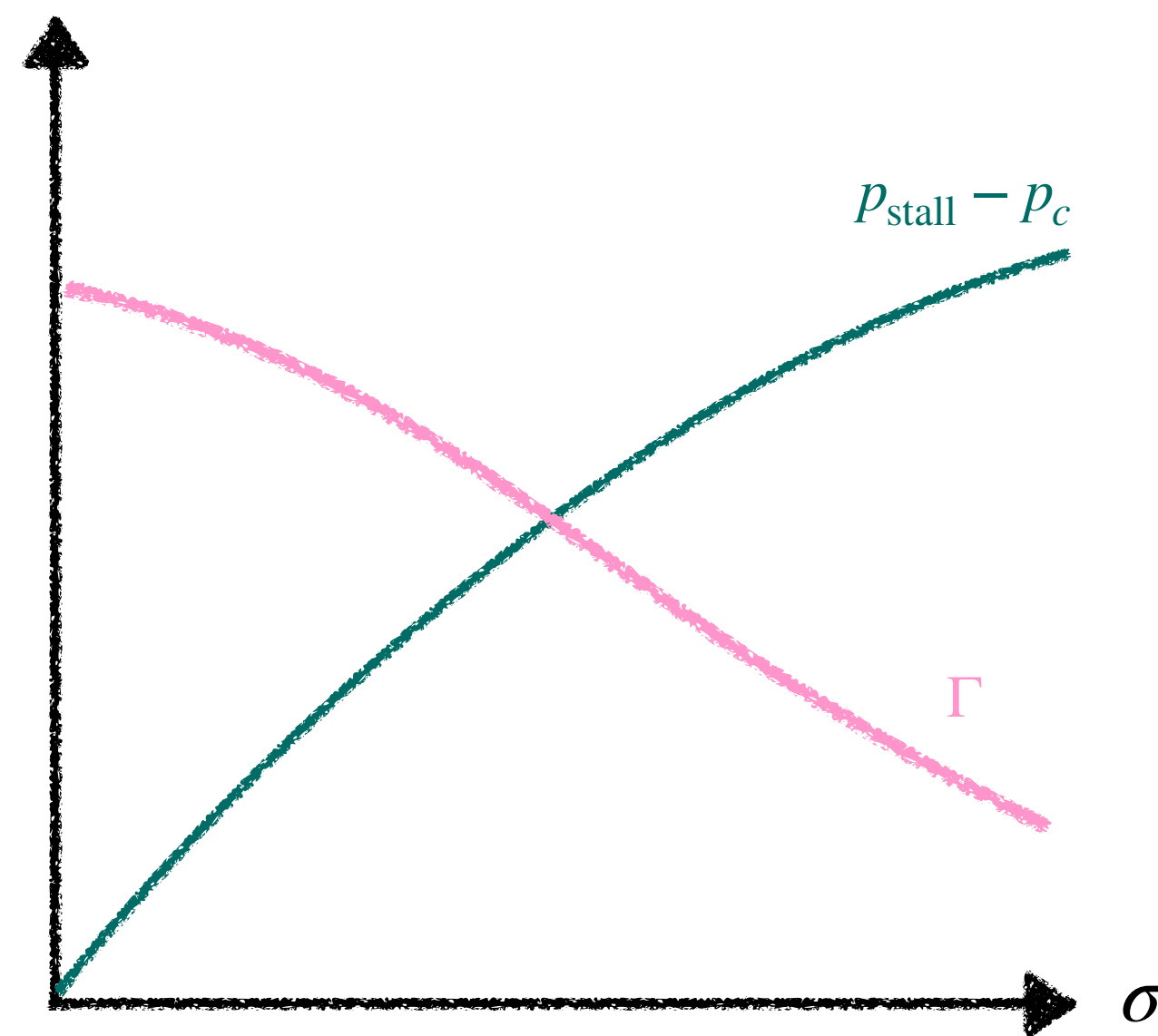
- Nucleation rate $\Gamma \sim \Lambda^4 e^{-S_{\text{eff}}}$
- Equations of state do not tell us what S_{eff} is
- Thin-wall approximation $S_{\text{eff}} = \frac{27\pi^2}{2} \frac{\sigma^4}{(\Delta V)^3}$ From EOS
- We take $\Lambda = 200 \text{ MeV}$



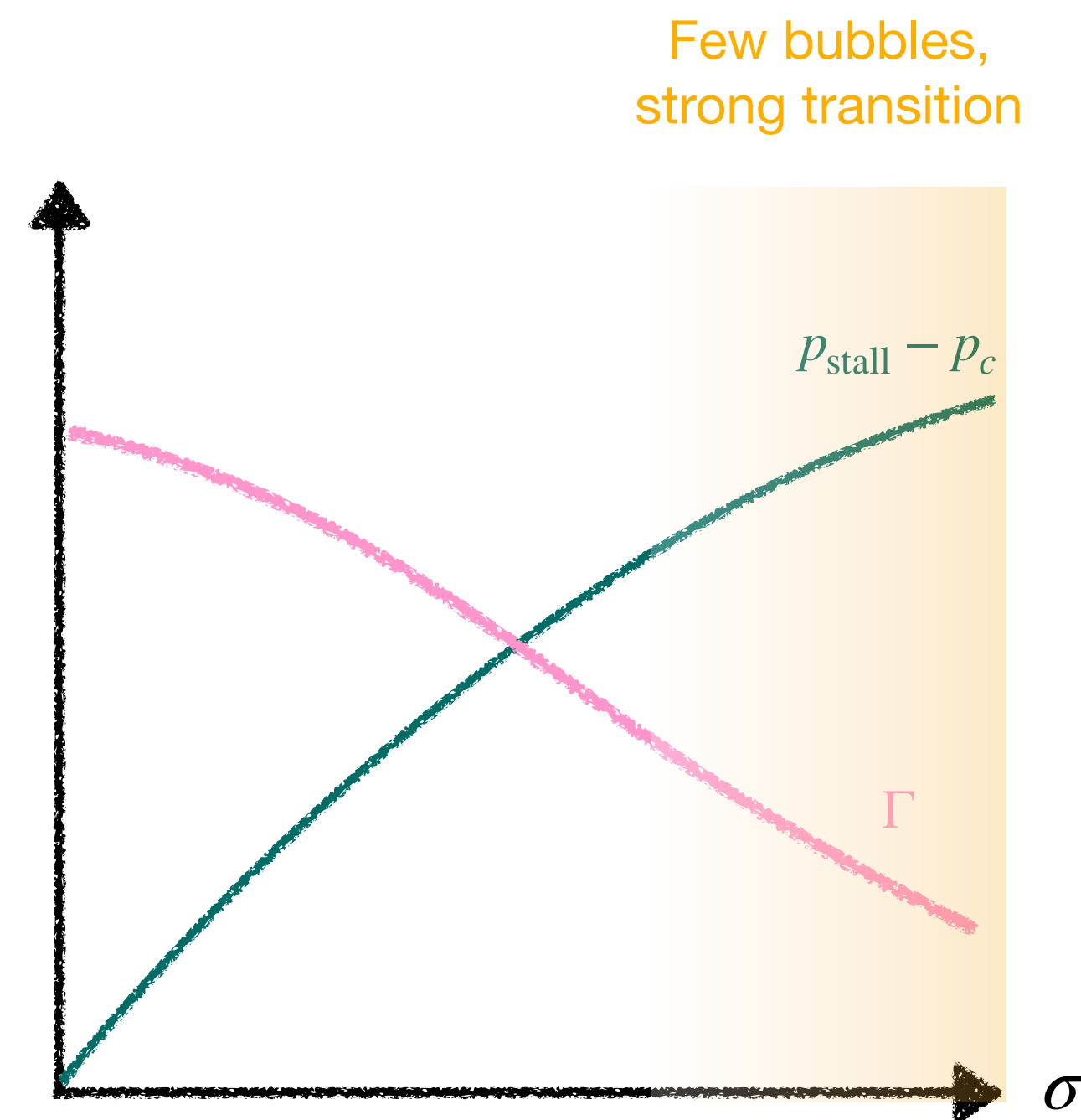
Stalling pressure versus surface tension



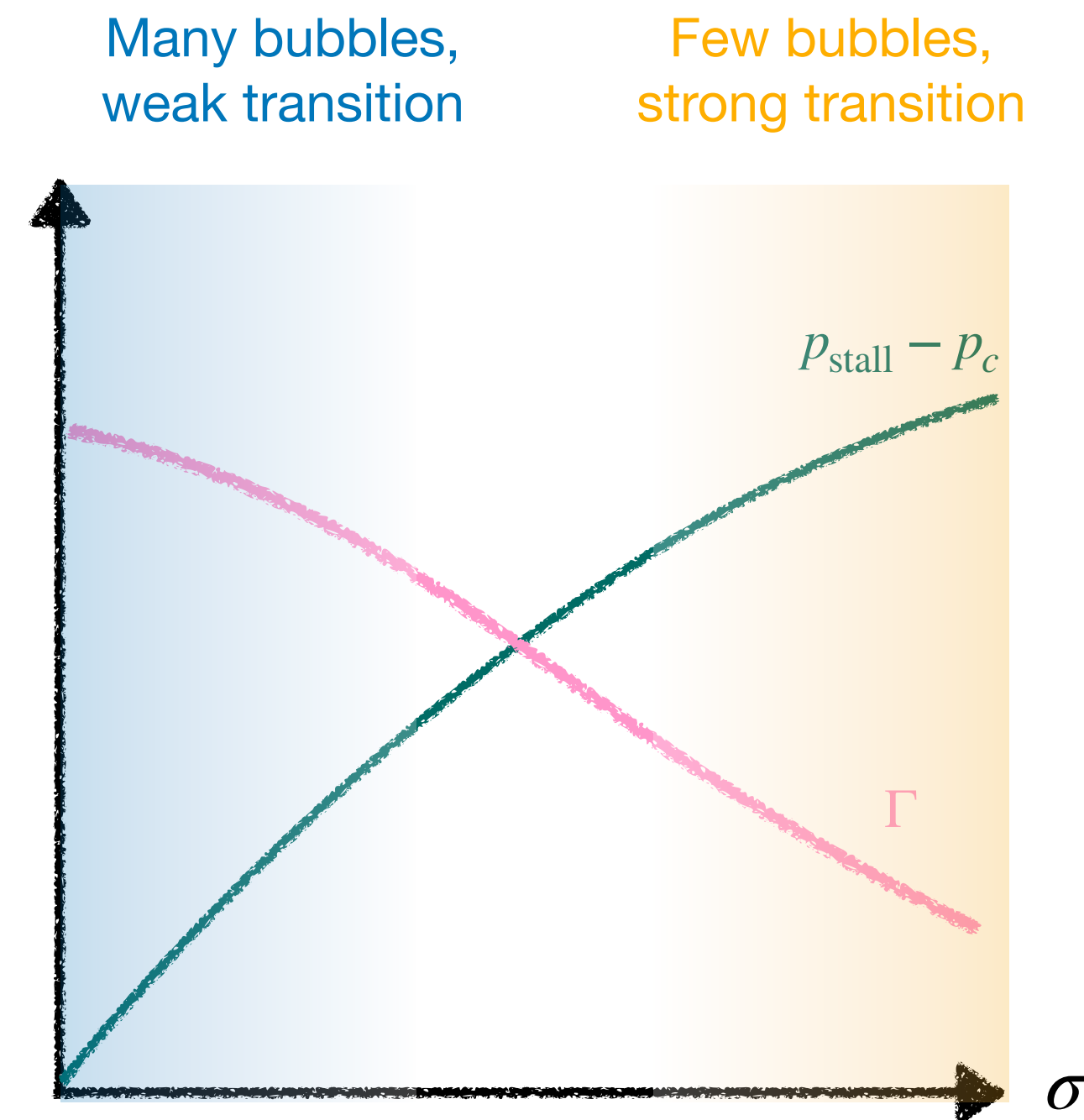
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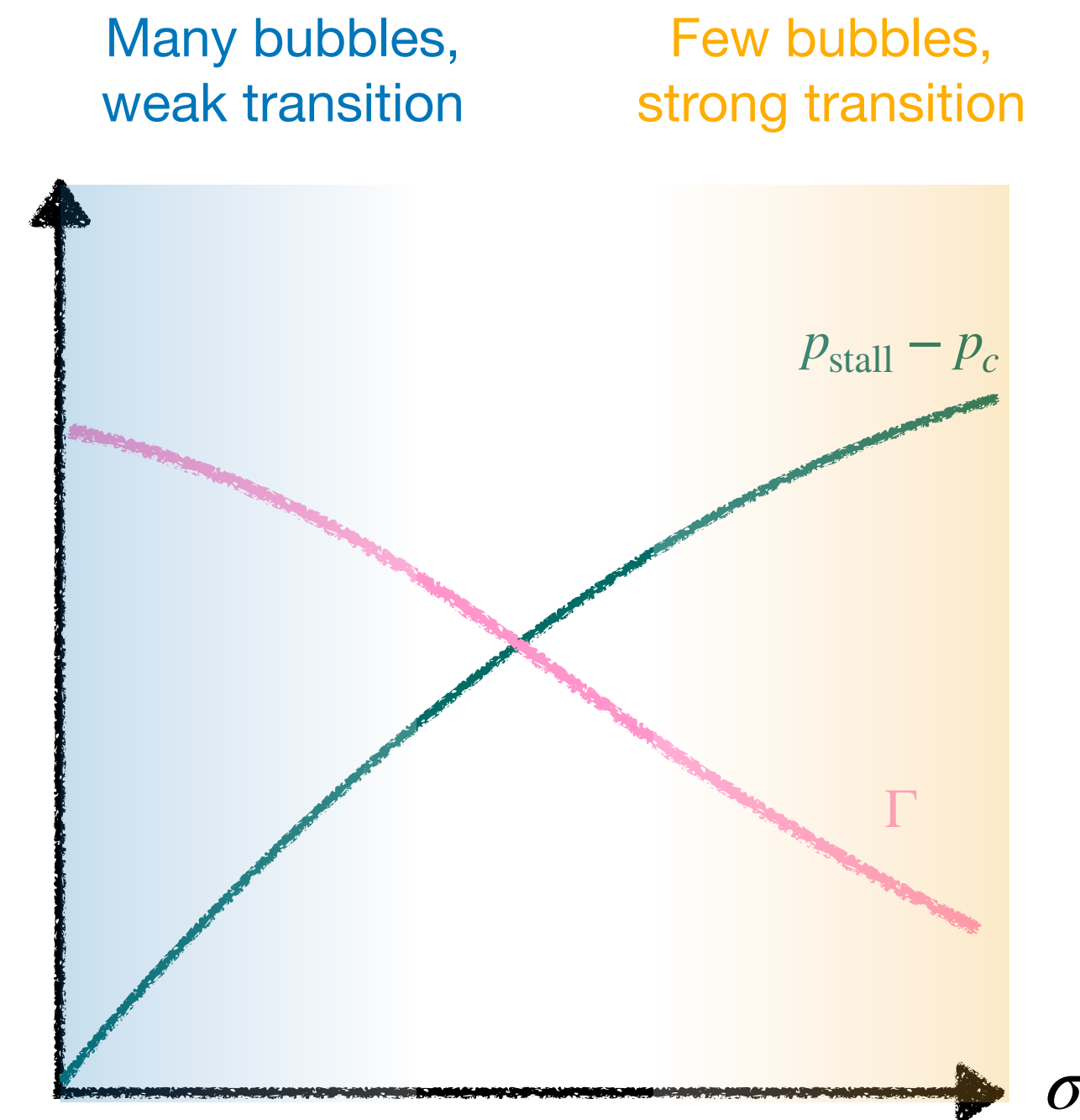
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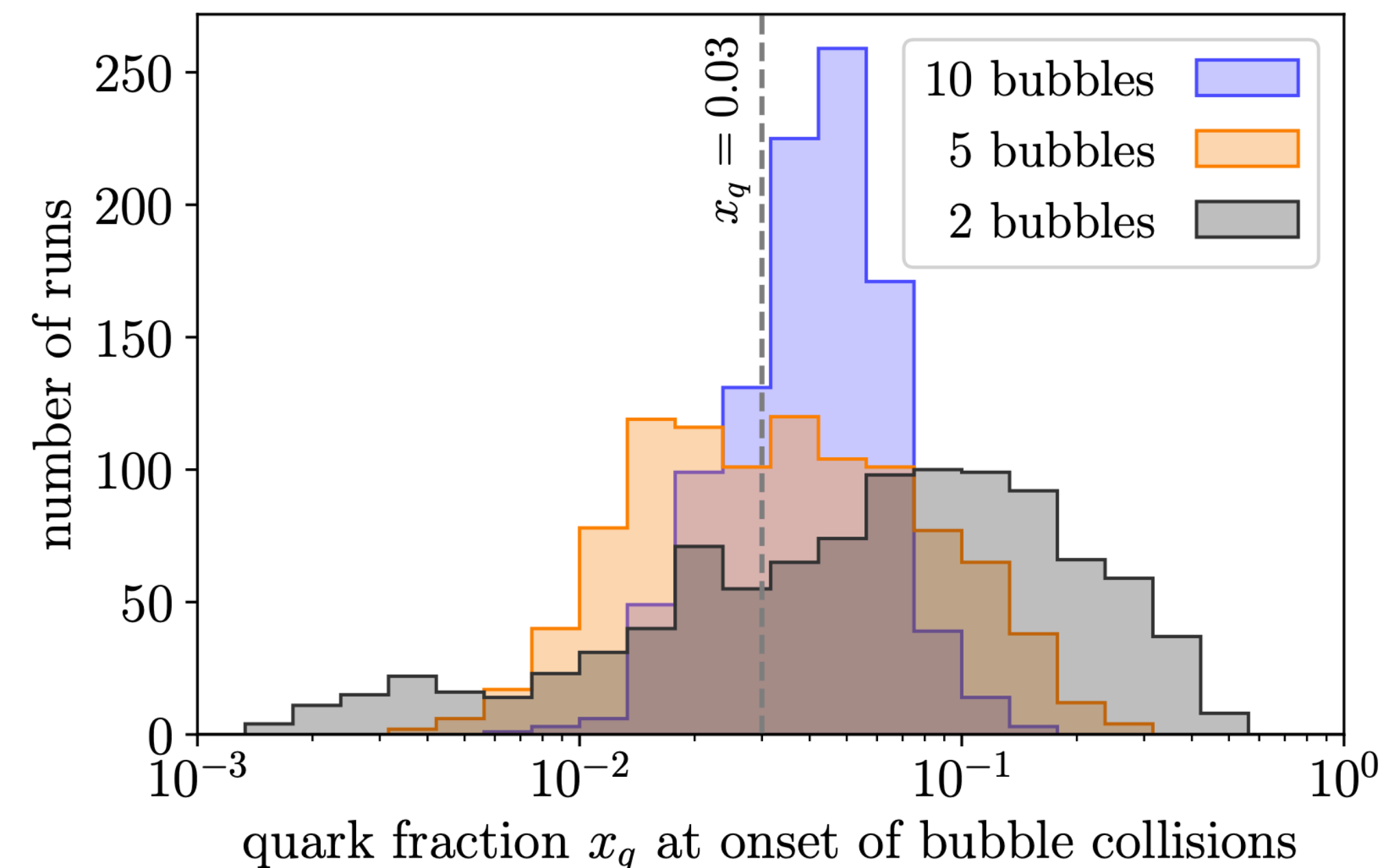
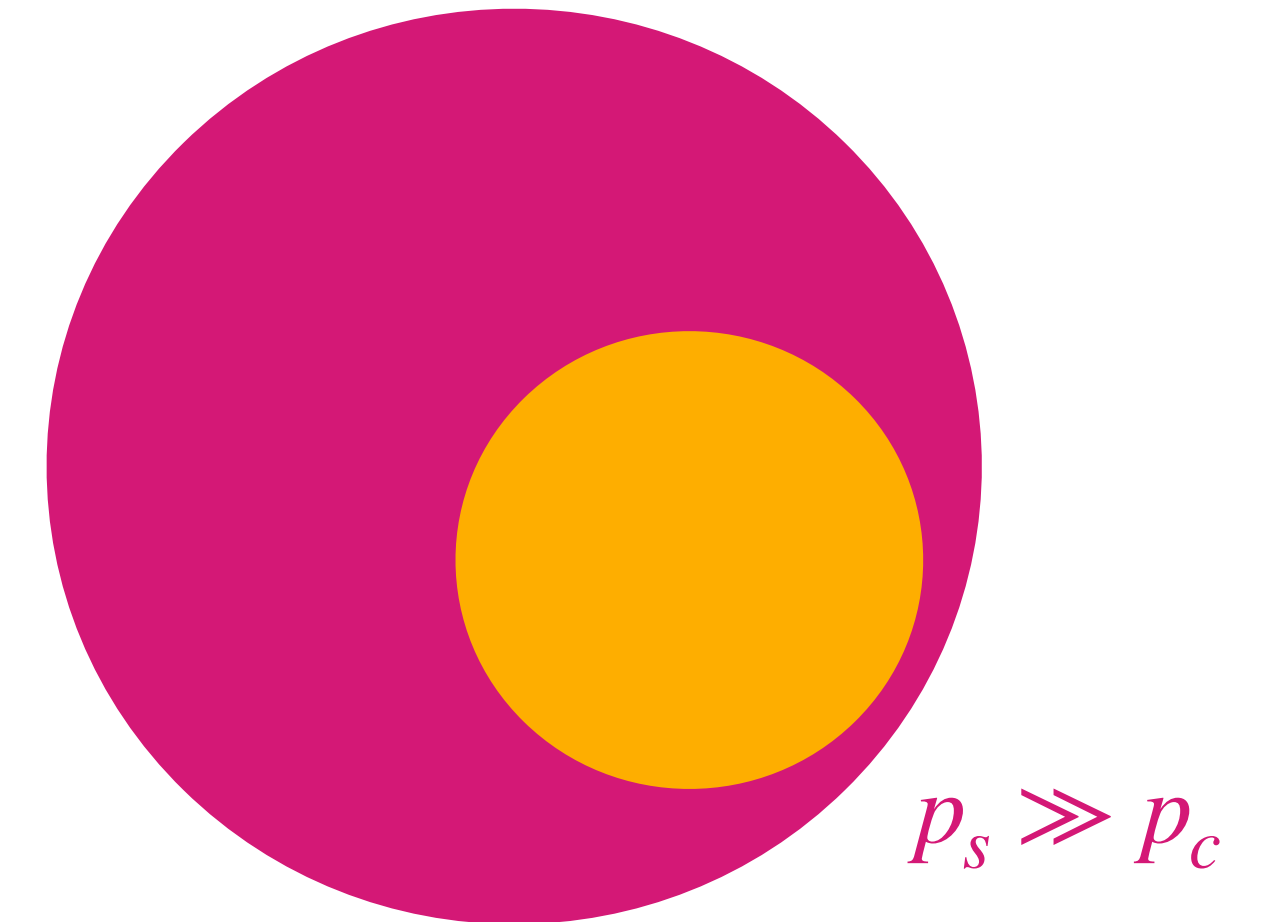
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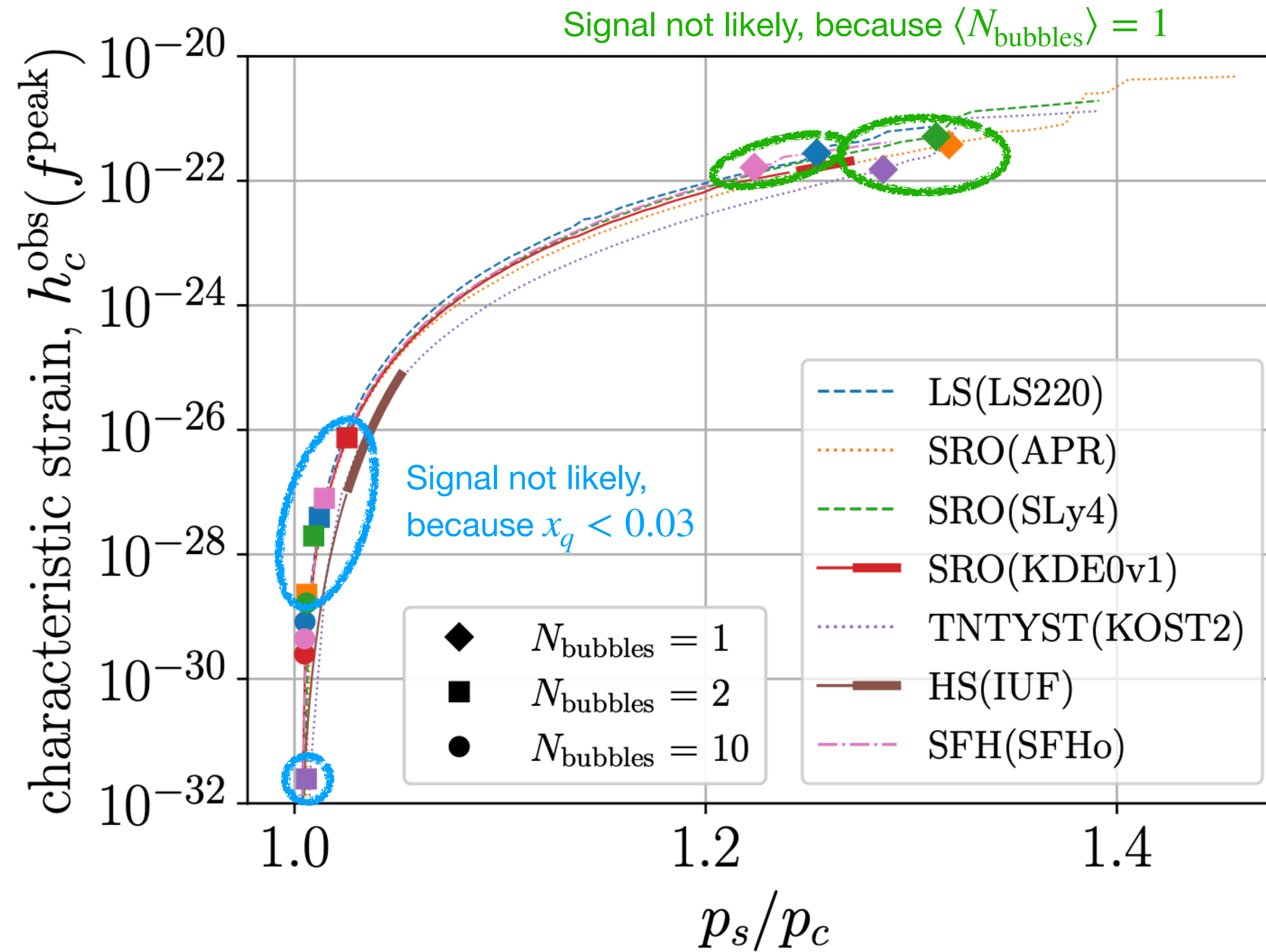
- σ is unknown, so we vary $p_{\text{stall}} < p_{\text{max}}$ and determine corresponding GW signal and σ
- Quark fraction x_q follows from baryon number conservation

Peak frequency and number of bubbles

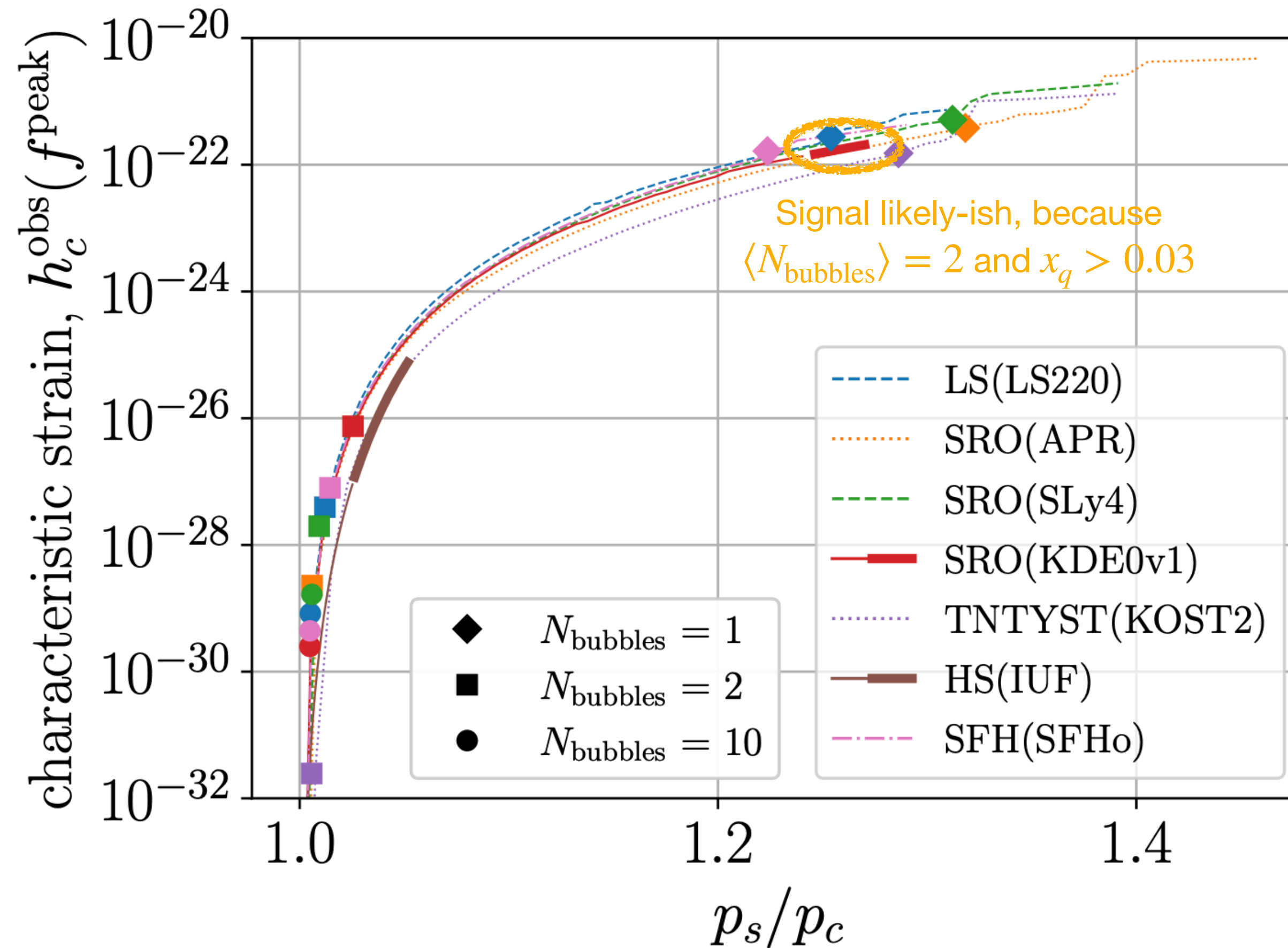
- $f^{\text{peak}} \simeq \langle r_{\text{bubble}} \rangle^{-1} = [n_{\text{bubbles}}/x_q]^{1/3}$
- We solve n_{bubbles} and x_q from p_{stall}
- The strongest transitions have very few bubbles
- A single bubble can not source a GW signal!
- $\mathcal{O}(\text{few})$ bubbles may never meet
- For $x_q > 0.03$ reasonable chance that collisions start before the transition stalls



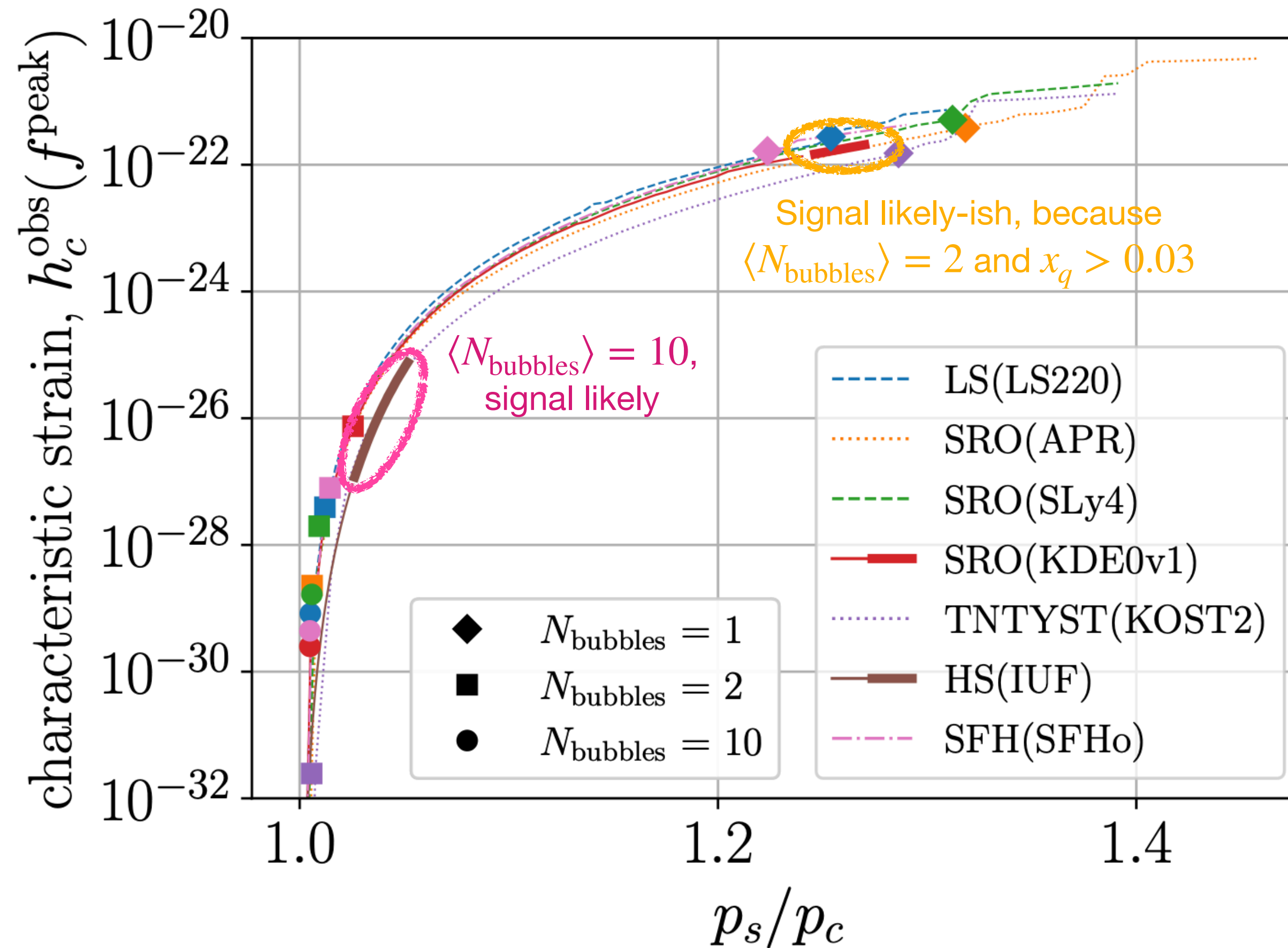
Characteristic strain for a source close to the galactic center



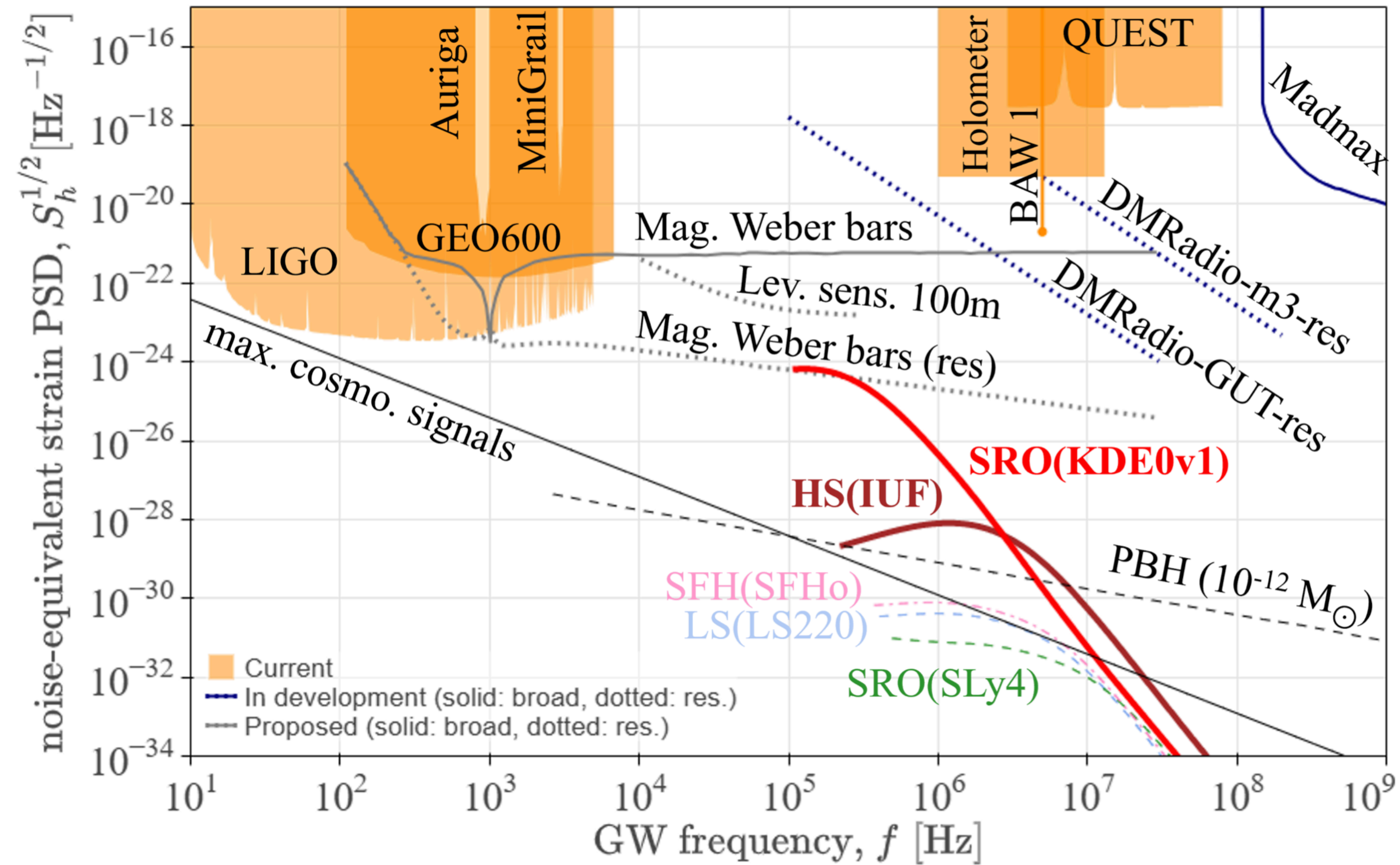
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Characteristic strain for a source close to the galactic center



Signals and experimental prospects



Outlook

- Dropping the assumption of β -equilibrium? Better prospects for observability!
- Use model-agnostic EOSs
- Solve hydrodynamics with the exact equation of state
- Simulate incomplete phase transitions to extract GW signal
- Include the interplay with large-scale evolution of the collapse

Trying to solve the sign
problem

Understanding the QCD
EOS with MHz GWs



Back-up

Quark fraction and peak frequency

- Baryon number conservation: $x_q n_{b,q}(\mu_{b,c}) + (1 - x_q) n_{b,h}(\mu_{b,c}) = n_{b,h}(\mu_{b,s})$ (1)

- Number of bubbles at time $t > t_c$:

$$n_{\text{bubbles}}(t) = \int_{t_c}^t dt' [1 - x_q(t')] \Gamma \quad (2)$$

- Fraction of core that has transitioned at $t > t_c$:

$$x_q(t) = 1 - \exp \left[- \int_{t_c}^t dt' \Gamma \frac{4}{3} \pi \min [x_q(t_s) R_c^3, v_w^3 (t_s - t')^3] \right] \quad (3)$$

x_q is determined from eq.(1), and $\Delta V(t)$ from the mass growth rate of [Shankar, Mösta, Haas, Schnetter 2025](#)

- $f^{\text{peak}} \simeq \langle r_{\text{bubble}} \rangle^{-1} = [n_{\text{bubbles}}/x_q]^{1/3}$

PT properties for our equations of state

Hadron EoS	R_c [km]	v_w	x_q	σ [MeV/fm ²]	f^{peak} [MHz]
LS(LS220) [51, 52]	0.75	0.066	0.0075	8.01	1.6
SRO(APR) [36, 37, 53]	0.46	0.038	0.0025	5.24	583
SRO(SLy4) [37, 51, 54]	0.62	0.052	0.0050	6.38	2.3
SRO(KDE0v1) [37, 51, 55]	2.82	0.23	0.15	96.1	0.16
TNTYST(KOST2) [38]	0.061	0.031	0.0020	3.96	498
HS(IUF) [39, 40, 56–58]	1.36	0.15	0.061	17.9	1.5
SFH(SFHo) [39, 40, 58, 59]	0.81	0.066	0.0082	8.86	1.5

TABLE I. Phase transition parameters underlying the characteristic strain calculation in Figs. 3 and 4 for the different hadron EoS considered in this paper. The columns from left to right are the radius of the quark matter core (the region where $p > p_c$), the bubble wall velocity, the final quark matter fraction (see Eq. (3)), the bubble surface tension, and the peak GW frequency. Every quantity is calculated at the stalling pressure where the expected bubble number decreases to 2 for the first time. For HS(IUF) and SRO(KDE0v1), we use instead the maximum pressure before the star becomes unstable as ≥ 2 bubbles are expected even at that pressure. This choice corresponds to the largest likely GW signal.