Can Supercooled Phase Transitions Explain the Gravitional Wave Background Observed by Pulsar Timing Arrarys?

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References: *Phys.Rev.Lett.* 132 (2024) 22, 221001

2024.09.12

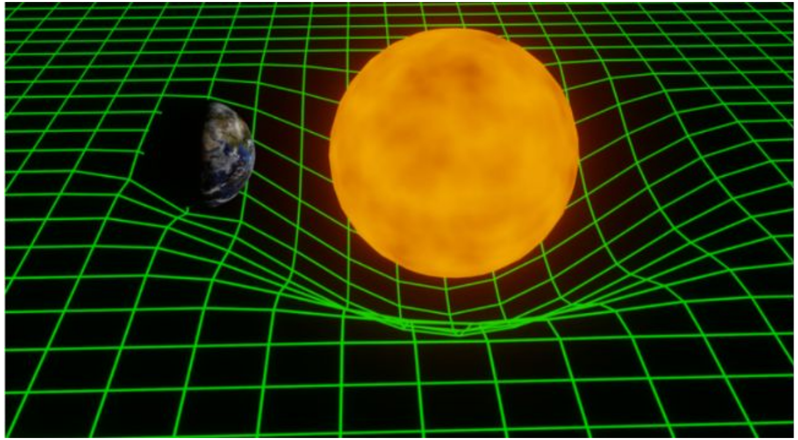
Contents

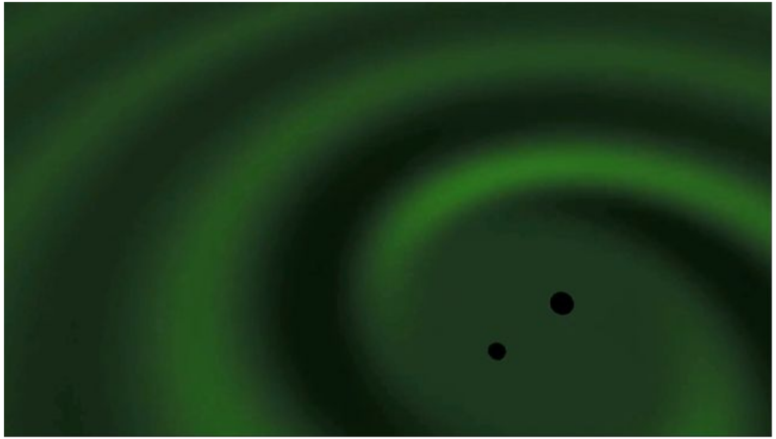
Contents

Gravitational Wave ABC

1. How to generate grvational wave (GW)?

Massive objects in the universe undergoing violent motion will generate gravitational wave signals.

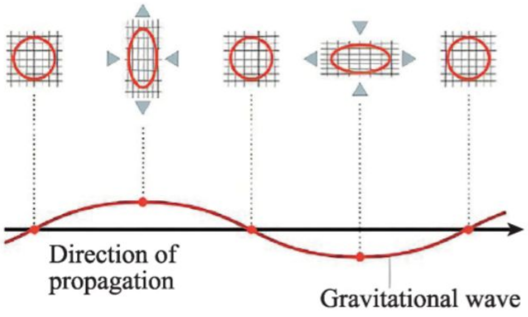


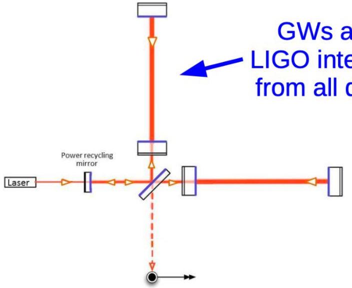


Gravitational Wave ABC

2. Detection principle:

The regions through which GWs pass will experience periodic stretching of space. By detecting these deformations, GW signals can be detected.

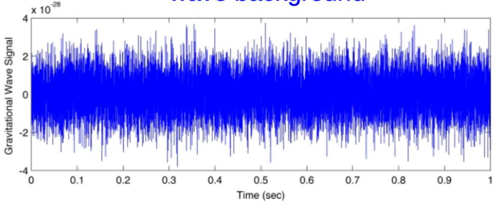




https://www.ligo.caltech.edu/page/ligos-ifo

GWs arrive at LIGO inteferometer from all directions

Stochastic gravitational wave background



https://www.ligo.org/science/GW-Stochastic.php

Different astrophysical processes generate GWs of different frequencies.

LIGO	$10 \sim 10^3$ Hz	Produced by the merger of stellar-mass binary BHs and binary neutron stars	The wave source is relatively close to the Earth
LISA, Taiji, TianQin	***mHz*** 10^{-3} Hz	Produced by the orbiting of binary stars and the capture of compact stars by massive BHs	Satellites form an interferometer network to conduct long-distance interferometric measurements
PTAs: NANOGrav, CPTA EPTA, PPTA	***nHz*** $10^{-5} \sim 10^{-9}$ Hz		Large radio telescopes observe pulsars in the universe
BICEP2, Ali	10^{-16} Hz	Triggered by supermassive binary BHs and cosmic strings	Utilize the cosmic microwave background radiation

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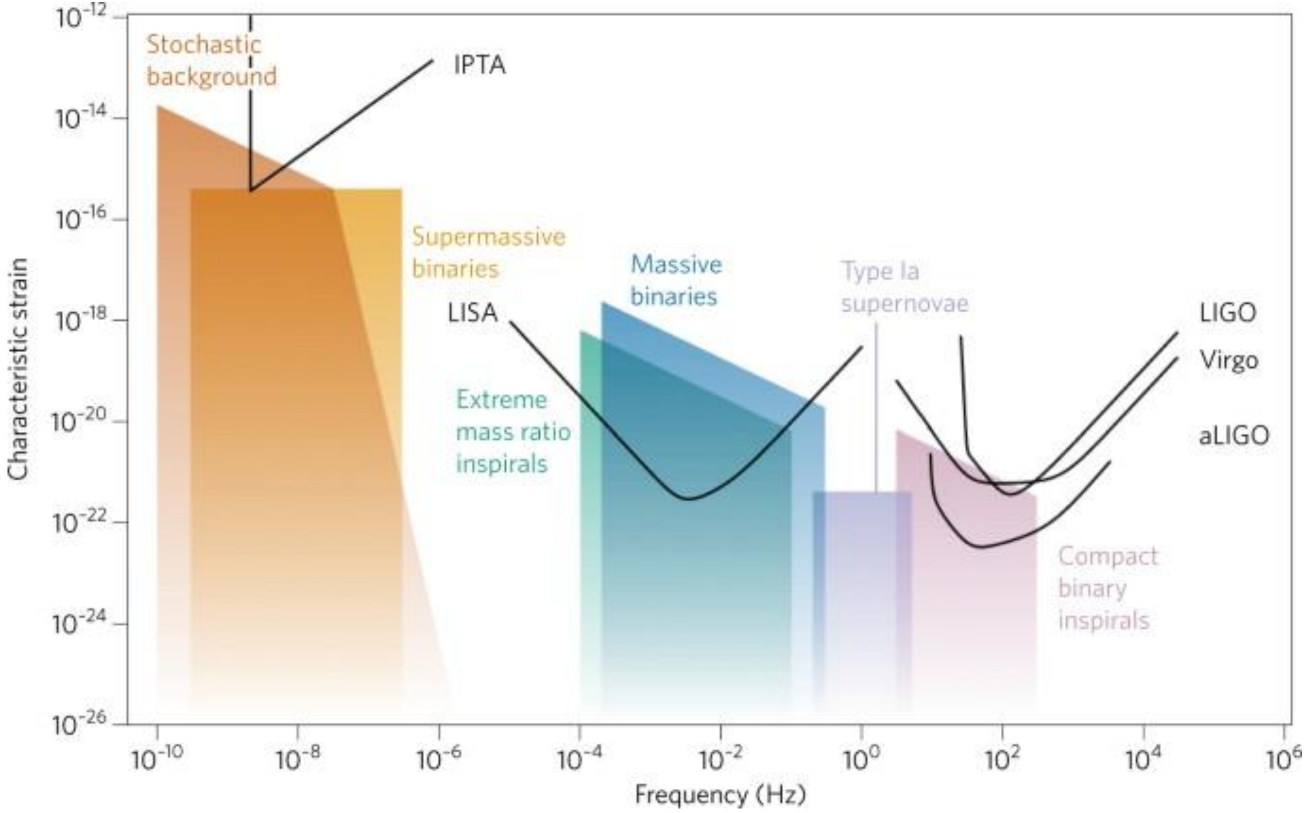
Lommen, A. Pulsar timing for gravitational wave detection. *Nat Astron* **1**, 809–811 (2017).



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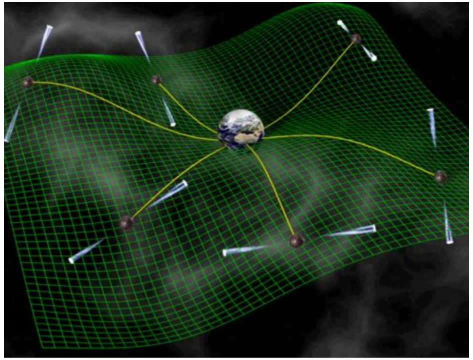
Gravitational Wave ABC

3. Detect stochastic GWs using a pulsar timing array:

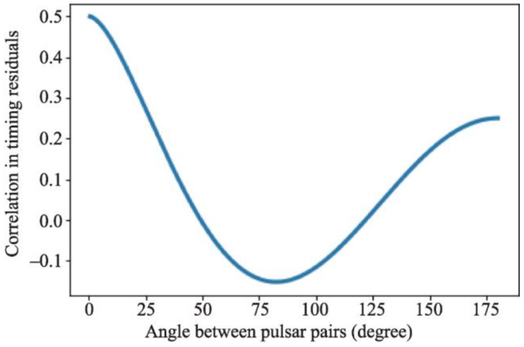
   Pulsars are a type of NS with strong magnetic fields and rapid rotation. Their rotation is very stable, emitting a pulse signal at regular intervals. If unaffected by other factors, we can stably receive these signals on Earth.



Gravitational Wave ABC

3. Detect stochastic GWs using a pulsar timing array:

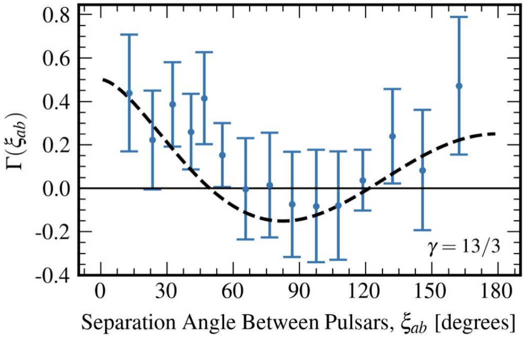
If gravitational waves pass through the region between the Earth and the pulsars, the arrival times of the pulsar signals will slight change. Observing such regular minute changes in multiple pulsars simultaneously is an important method for detecting nanohertz stochastic GWs.



Hellings-Downs curve

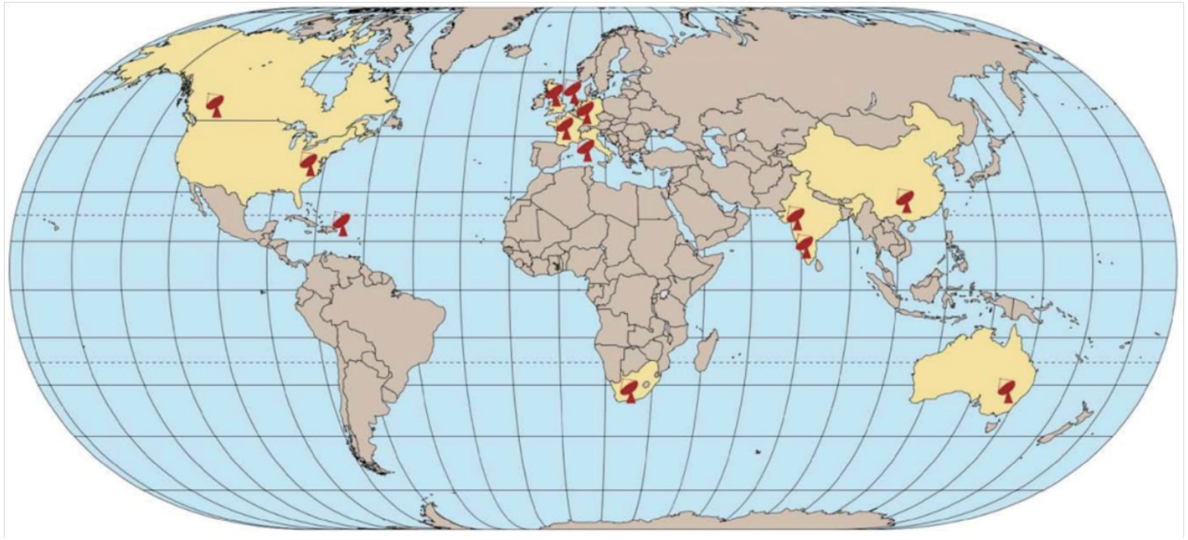
NANOGrav 15 yr Data Set

Astrophys.J.Lett. 951 (2023) 1, L8



International PTA Collaborations

EPTA monitors 18 millisecond pulsars; NANOGrav monitors 47 millisecond pulsars; PPTA monitors 27 millisecond pulsars. These three projects have also formed the International Pulsar Timing Array (IPTA) to jointly analyze and share data, enhancing detection sensitivity.



NANOGrav in the USA and Canada
EPTA in Europe
PPTA in Australia
INPTA in India
SAPTA in South Africa
CPTA in China

Gravitational Wave ABC

3. The signal from stochastic GWs

(1) Definition: When a large number of indistinguishable low frequency GWs overlap, they form a stochastic GW background signal.

(2) Possible origins:

- The overlapping GWs radiated by numerous orbiting supermassive binary BHs.
- GW remnants from the cosmic inflation period.
- Collisions of cosmic strings.
- Dark sector phase transition around 100 MeV.
- Supercooled phase transitions.

Gravitational Wave ABC

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- GW remnants from the cosmic inflation period.
- Collisions of cosmic strings.
- Dark sector phase transition around 100 MeV.
- **Supercooled phase transitions.**

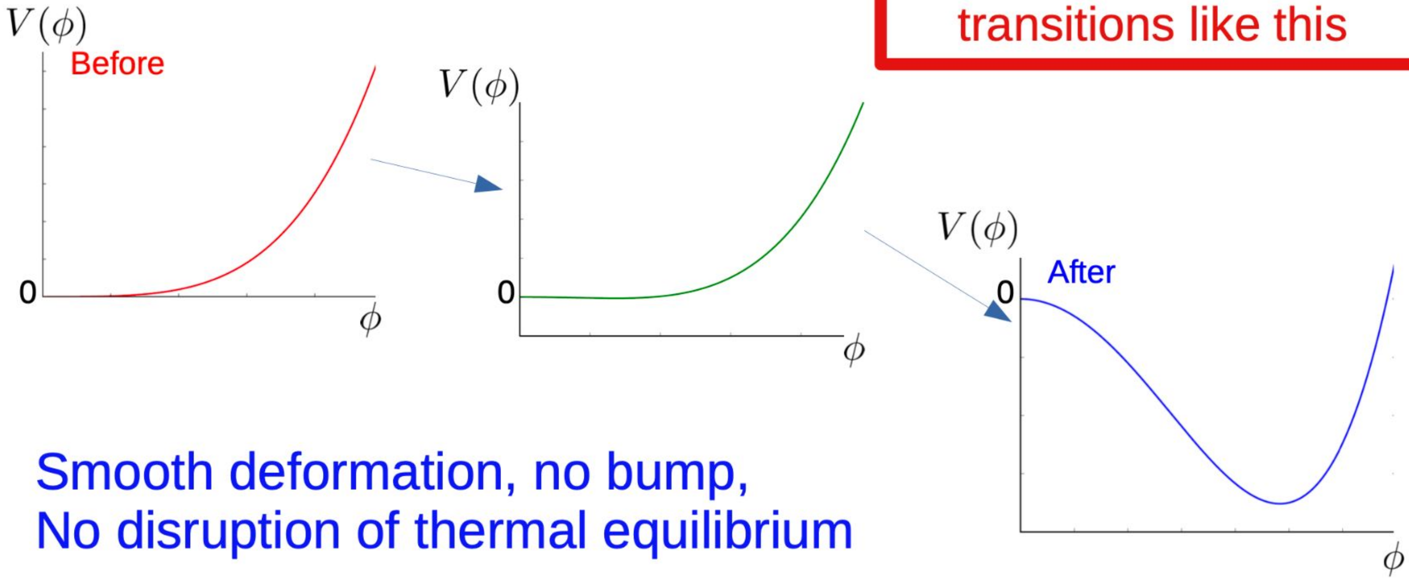
Contents

Electroweak Phase Transitions

Finite temperature potential: $\mathrm{V} = \mathrm{V}(\phi, T)$

If $V = \mu^2(T)\phi^2 + \lambda\phi^4$

We could only have phase transitions like this

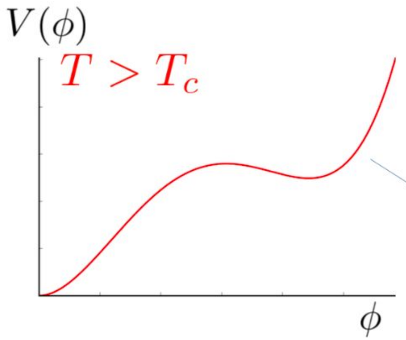


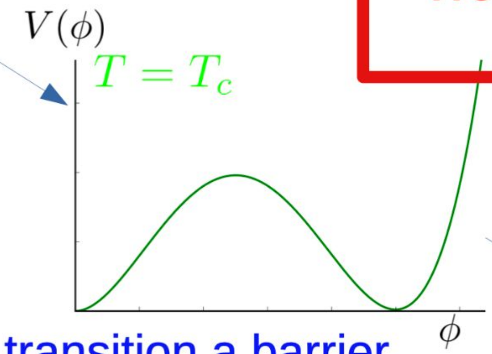
Smooth deformation, no bump,
No disruption of thermal equilibrium

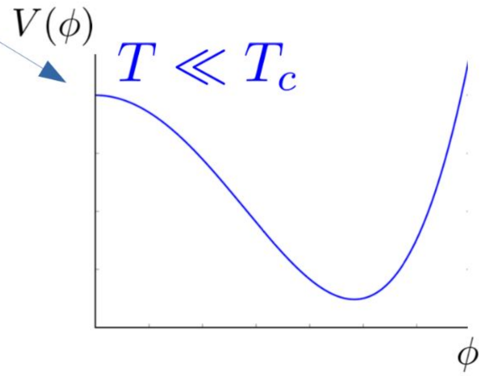
First Order Phase Transitions

If $V = \mu^2(T)\phi^2 + c(T)\phi^3 + \lambda\phi^4$

We may have phase transitions like this





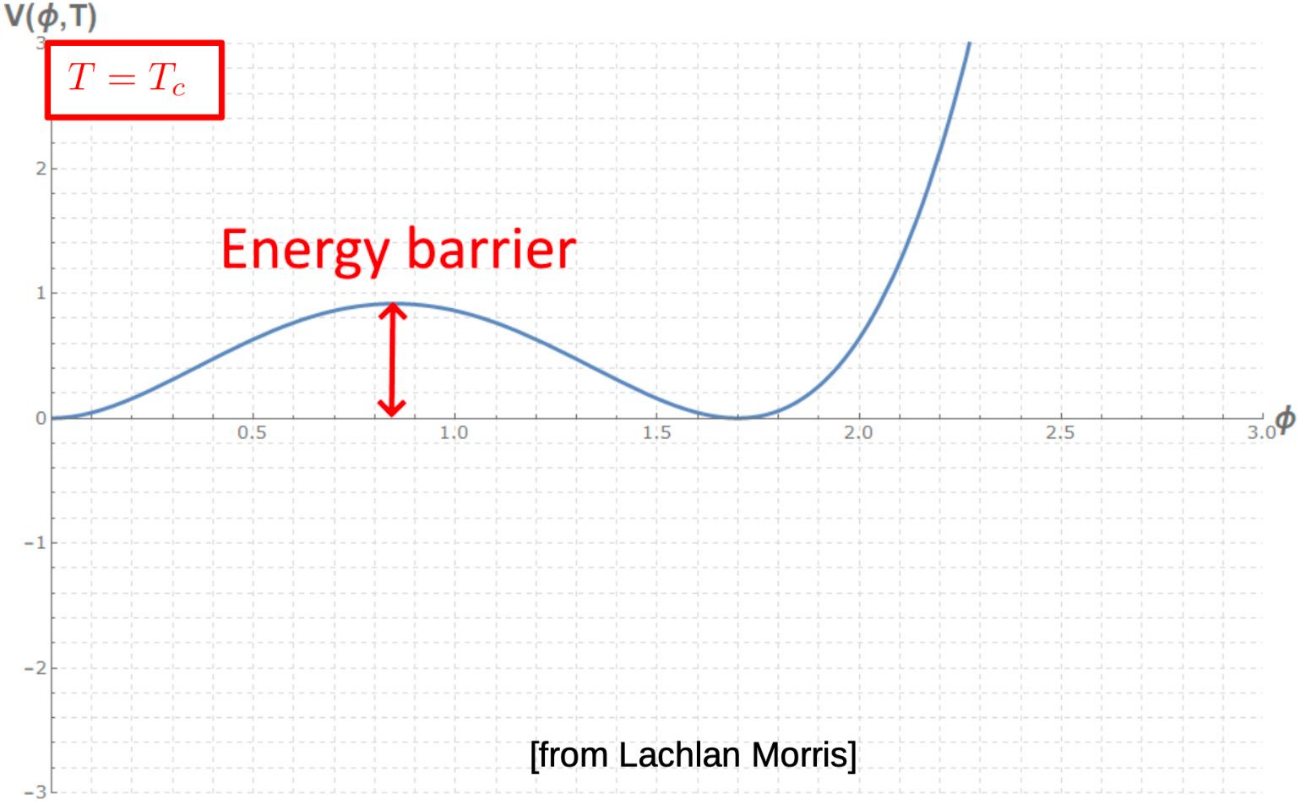


In a first order phase transition a barrier seperates the two phases during the phase transition

$$T_c = \text{critical temperature}$$
$$\equiv \text{Temperature where } V \text{ at minima are degenate}$$

Critical Temperature

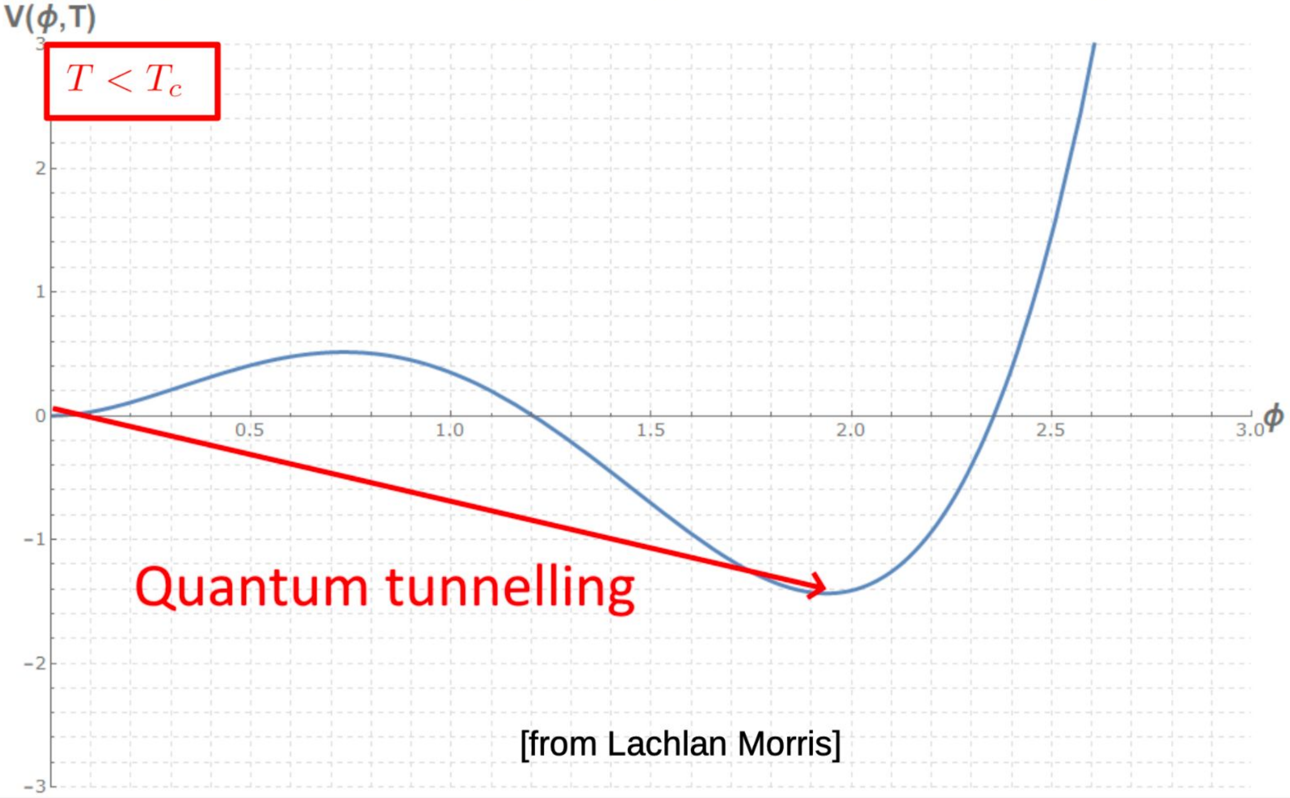
An energy barrier separates the two minima in a first order phase transition



[from Lachlan Morris]

Quantum tunnelling

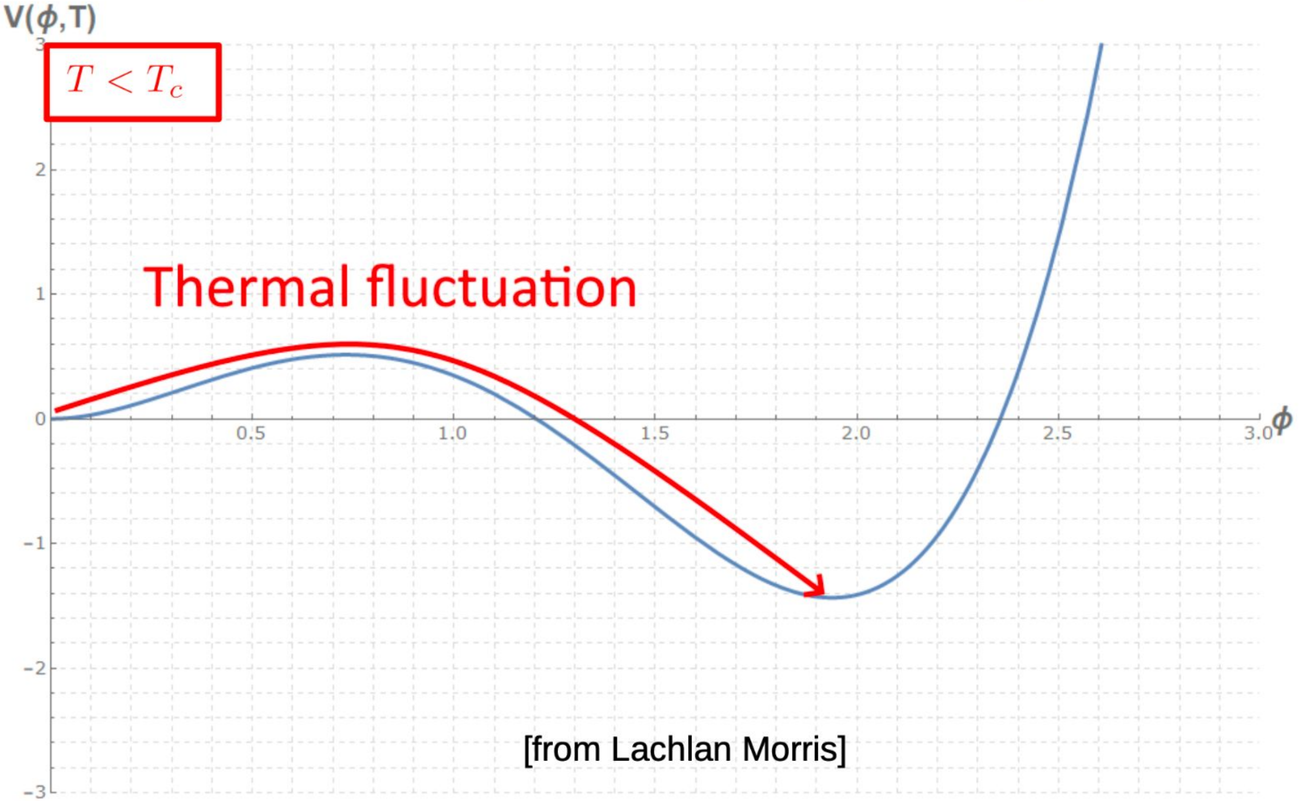
Quantum tunneling through the barrier is now possible



[from Lachlan Morris]

Thermal fluctuation

Thermal fluctuations over the barrier are also possible



[from Lachlan Morris]

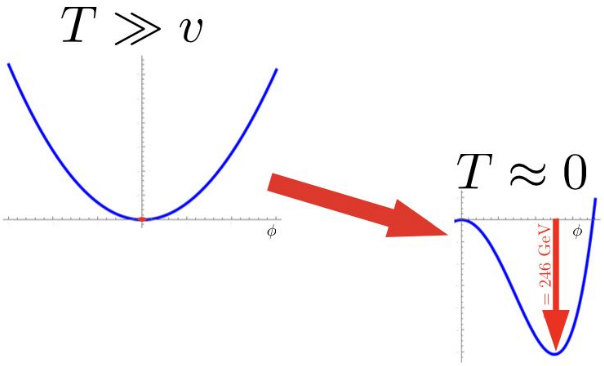
矿泉水瓶在东北室外一摇就结冰：过冷现象

一名辽宁鞍山男子在室外拿矿泉水瓶碰撞栏杆，瓶里的水瞬间结冰，引网友热议。这实际上是，温度低于凝固点但未凝固的液体不稳定，通过摇晃碰撞迅速凝固。

材料来源：澎湃新闻

Idea:

Take the EW phase transition



$$T_{EW} \sim \mathcal{O}(100\mathrm{GeV}) \longleftrightarrow f^{\mathrm{peak}} \sim 10^{-5}\ \mathrm{Hz}$$

But supercool down to

$$\mathcal{O}(100\mathrm{MeV}) \longleftrightarrow f^{\mathrm{peak}} \sim 10^{-9}\ \mathrm{Hz}$$

Archetypical example: A. Kobakhidze, C. Lagger, A. Manning and J. Yue, EPJ.C 77 (2017) 570 [1703.06552] cited by NANOGRAV.

Searching for Gravitational Waves from Cosmological Phase Transitions with the NANOGrav 12.5-Year Dataset

NANOGrav Collaboration • Zaven Arzoumanian (CRESST, Greenbelt and NASA, Goddard) et al.

Phys.Rev.Lett. 127 (2021) 25, 25 • e-Print: 2104.13930 • DOI: 10.1103/PhysRevLett.127.251302

fusion background. However, other more speculative GW sources in the PTA frequency range include cosmic strings [14, 15], a primordial GWB produced by quantum fluctuations of the gravitational field in the early universe, amplified by inflation [16–18], and cosmological phase transitions [19–23], the latter of which is the subject this study.

The NANOGrav 15 yr Data Set: Search for Signals from New Physics

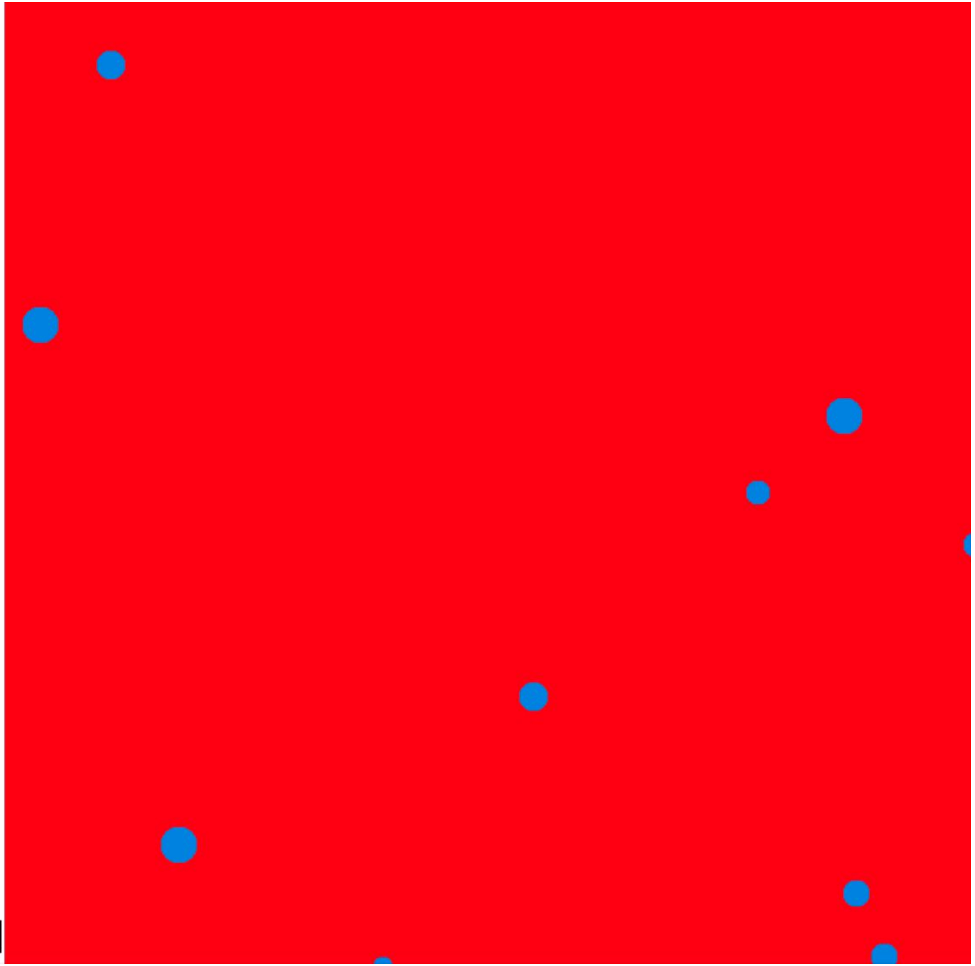
NANOGrav Collaboration • Adeela Afzal (Munster U. and Quaid-i-Azam U.) et al.

Astrophys.J.Lett. 951 (2023) 1, L11 • e-Print: 2306.16219 • DOI: 10.3847/2041-8213/acdc91

Instead, we conclude that the reconstructed posterior distribution of T_* is compatible with phase transition scenarios that have been discussed in the literature as a possible source of GWs in the PTA band: (i) BSM models in which the chiral-symmetry-breaking phase transition in quantum chromodynamics (QCD) is a strong first-order phase transition (see, e.g., Li et al. 2021; Neronov et al. 2021), and (ii) strong first-order phase transitions in a dark sector composed of new BSM degrees of freedom (see, e.g., Nakai et al. 2021; Ratzinger & Schwaller 2021). In view of the NG15 data, both of these options for the particle physics origin of the phase transition signal remain viable. A third option may consist in a strongly supercooled first-order electroweak phase transition (Kobakhidze et al. 2017).

Bubble nucleation

Bubbles of the new phase form at random locations



[image: from Lachlan Morris]

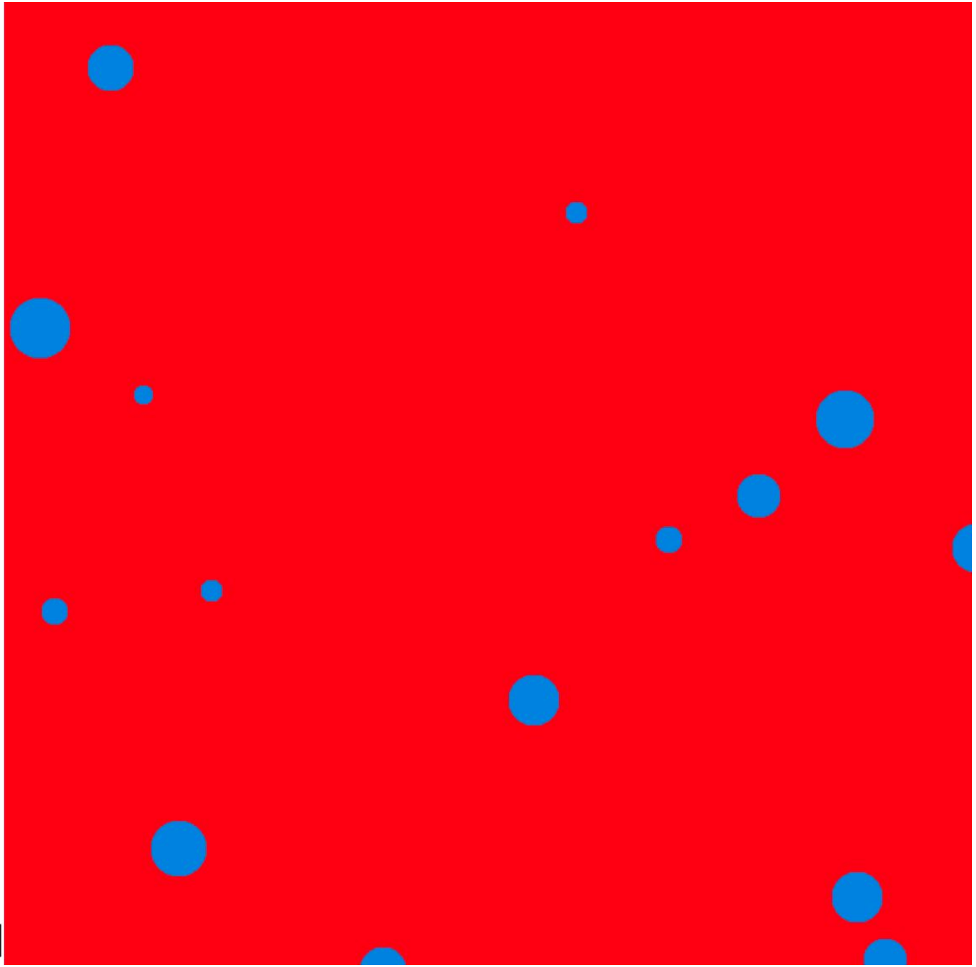
Bubble nucleation

Bubbles of the new phase form at random locations

The bubbles that already formed grow in size

while more bubbles nucleate

[image: from Lachlan Morris]



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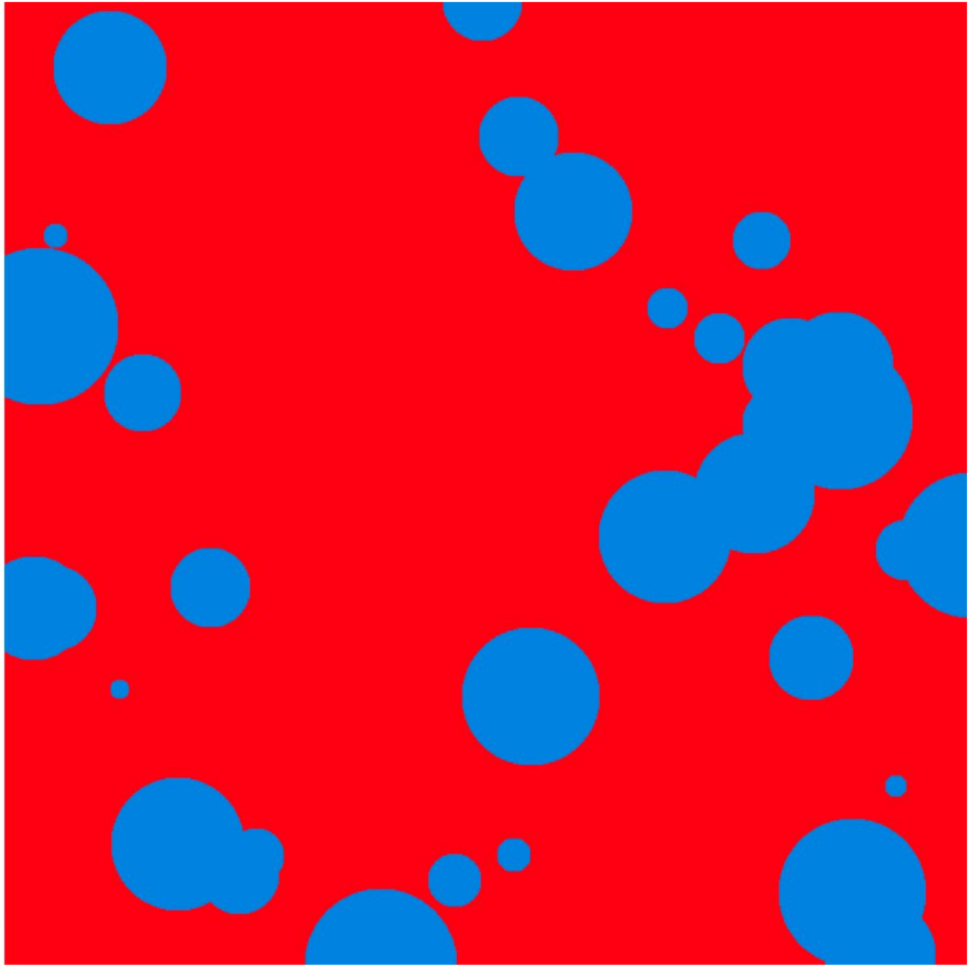
As the bubbles grow, and the number increases, collisions become more likely

[image: from Lachlan Morris]



Bubble nucleation

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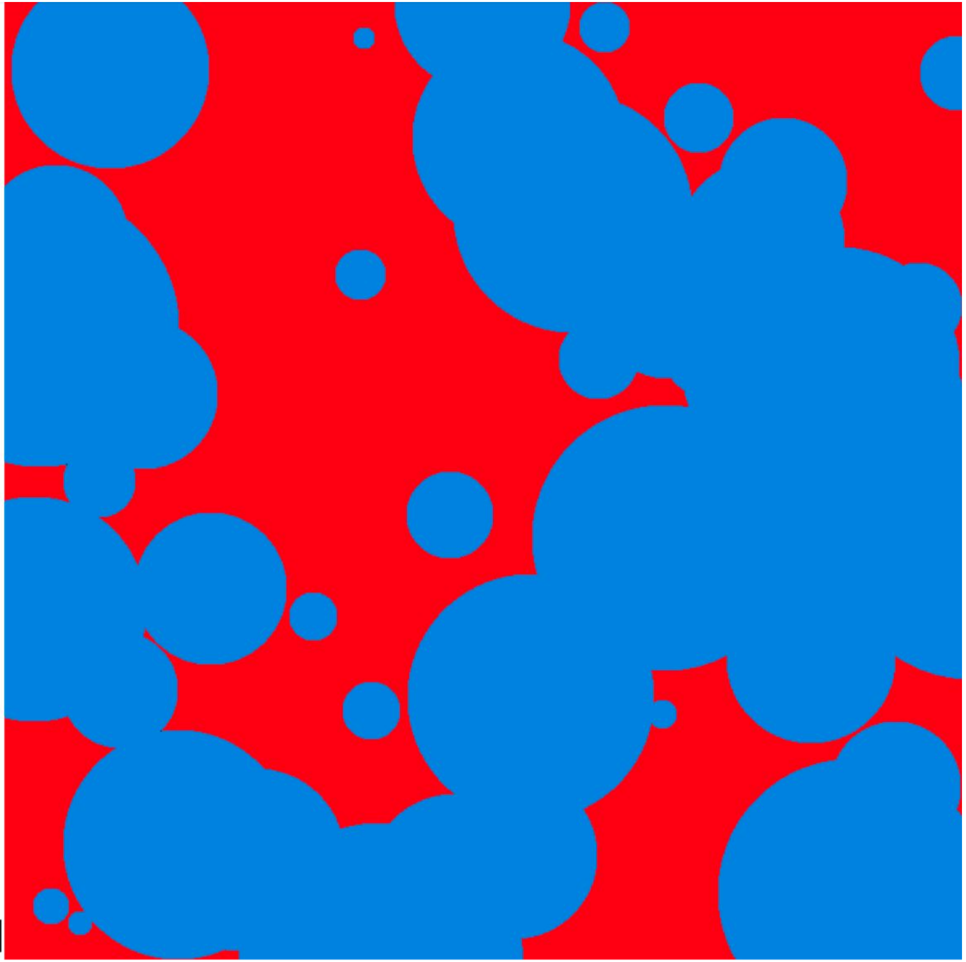
As the bubbles grow,
and the number increases,
collisions become more likely

And more and more of the space is
converted to the true vacuum

[image: from Lachlan Morris]



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The bubbles that already formed
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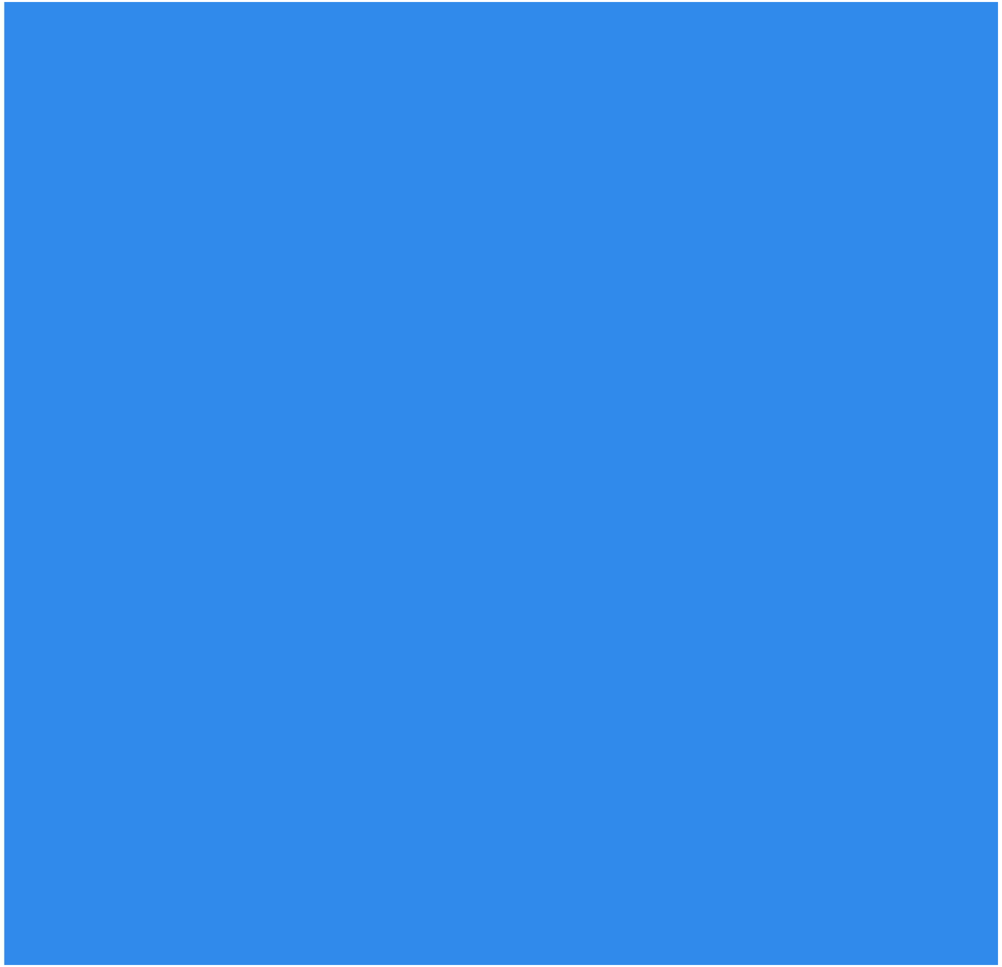
And more and more of the space is
converted to the true vacuum

Until almost all the space is in the
true vacuum



Nucleation temperature

- According to the above pictures, if the decay probability is high enough, bubbles of true vacuum nucleate and expand in the surrounding symmetric phase.
- The nucleation temperature is defined as the temperature at which most of the bubbles are produced.

Nucl.Phys.B 216 (1983) 421

- Quantitatively, the nucleation temperature is given by $N(T_n) = 1$

$$N(T) = \int_T^{T_c} dT' \, \frac{\Gamma(T')}{T' H^4(T')}$$

Bubble nucleation rate

Hubble parameter

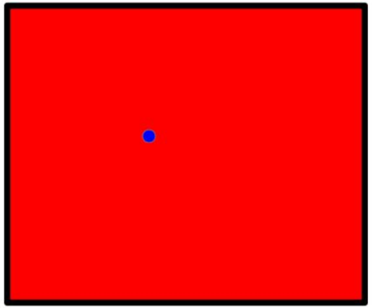
- The nucleation temperature is frequently used for evaluating GW signals but it may not exist …

  and for slow transitions it decouples from the other temperatures

Does the Phase transiton complete?

Many studies only check nucleation

Nucleation: one bubble per Hubble volume



Hubble volume

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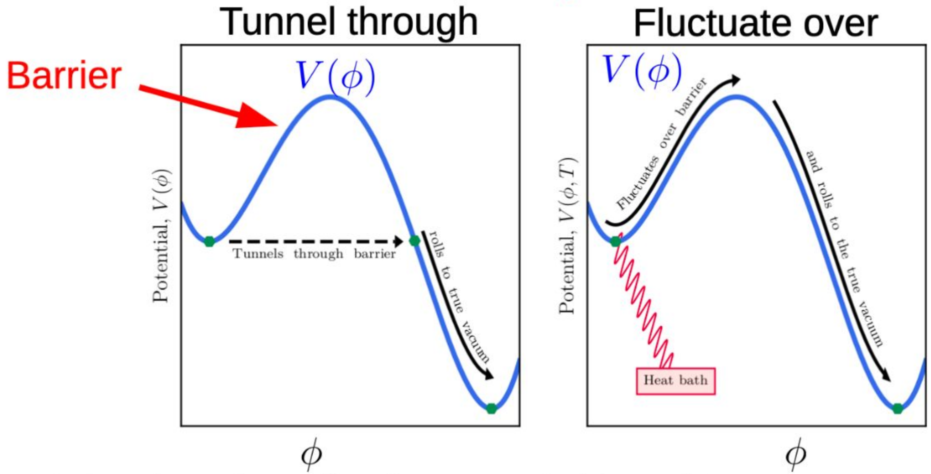
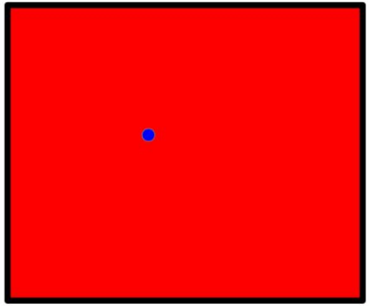




Hubble volume

If the barrier disolves quickly with temperature

→ Exponential nucleation rate → Bubbles rapidly fill space

"Fast transition" or "low supercooling"

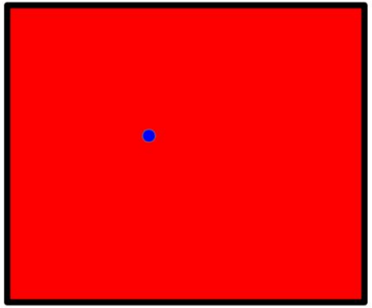
Does the Phase transiton complete?

Many studies only check nucleation

Nucleation: one bubble per Hubble volume

Not sufficient for scenarios with a lot of supercooling,

If the barrier persists to low temperatures,
→ nucleation rate can reach a maximum



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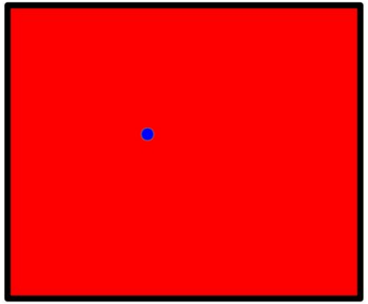

Hubble volume

Nucleation: one bubble per Hubble volume

Not sufficient for scenarios with a lot of supercooling,

If the barrier persists to low temperatures,
$\longrightarrow$ nucleation rate can reach a maximum

For such slow transitions we need the false vacuum fraction $P_f \to 0$

$$P_f(T) = \exp\left[-\frac{4\pi}{3}\int_T^{T_c}\frac{dT'}{T'^4}\frac{\Gamma(T')}{H(T')}\left(\int_T^{T'} dT''\frac{v_w(T'')}{H(T'')}\right)^3\right]$$

Stochastic so actually check:
$P_f < \epsilon$

bubble wall velocity

TransitionSolver *JCAP* 03 (2023) 006

Does the Phase transiton complete?

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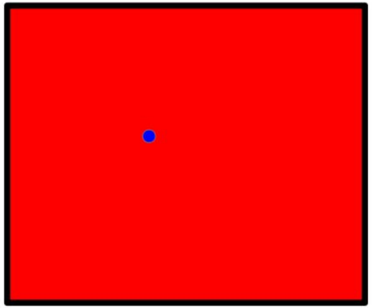
Nucleation: one bubble per Hubble volume



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Stochastic so actually check:
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Warning: even this is not enough because space is expanding

Does the Phase transiton complete?

Many studies only check nucleation

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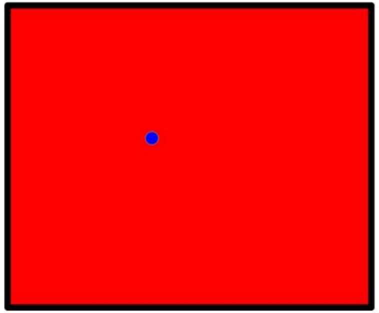
If the barrier persists to low temperatures,
$\longrightarrow$ nucleation rate can reach a maximum



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Stochastic so actually check:
$P_f < \epsilon$

Account for expansion of space-time and check $\frac{\mathrm{d}\mathcal{V}_f^{\mathrm{phys}}}{\mathrm{d}T} < 0$ *JCAP* 03 (2023) 006

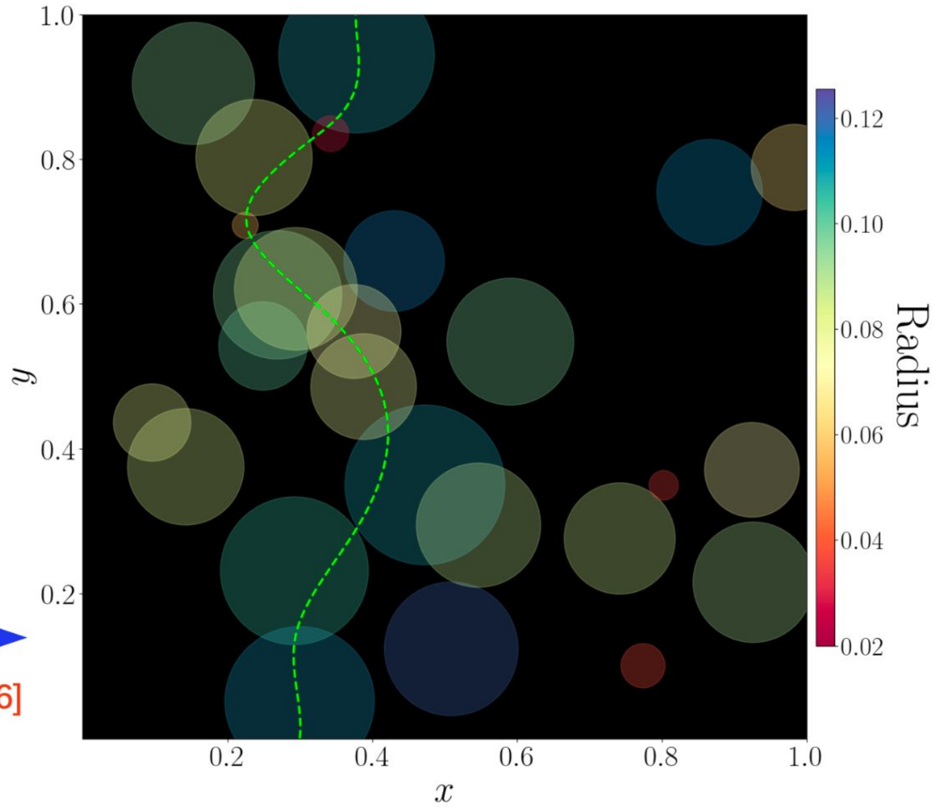
Percolation tempearture

$T_p\colon\ P_f(T_p) = 0.71$

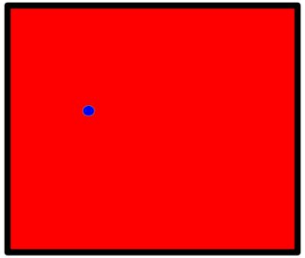
- Percolation is when there is a connected path between bubbles across the space
- Strongly linked to bubble collisions
- Good choice for a temperature at which to evaluate the GWs spectrum

Example from simple simulation

[PA, C. Balázs, L. Morris, JCAP 03 (2023), 006]



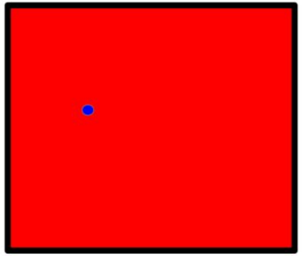
Temperature dependence



Nucleation temperature is a bad temperature to use

- not connceted to bubble collisions

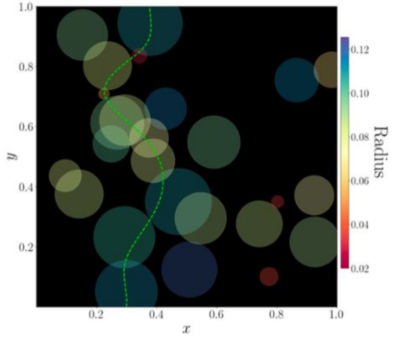
Temperature dependence



Nucleation temperature is a bad temperature to use

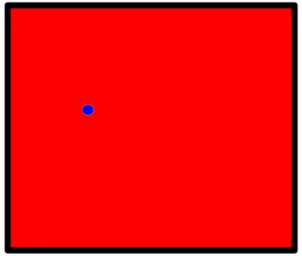
- not connceted to bubble collisions

Percolation is directly defined in terms of contact between bubbles



Percolation temperature is much better, but…

Temperature dependence



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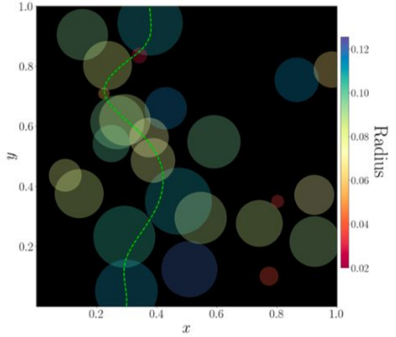
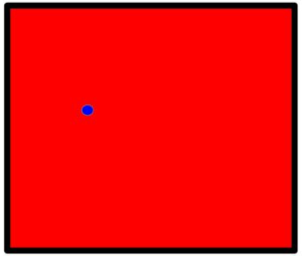


Percolation temperature is much better, but…

We still don’t know exactly correct temperature and...

Temperature dependence



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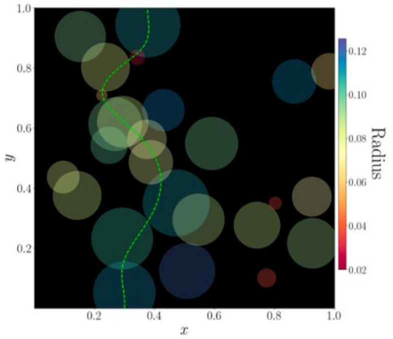


Percolation temperature is much better, but…

We still don't know exactly correct temperature and...

Percolation criteria $P_f(T_p) = 0.71$ does not account for expanding space time

→ Temperature dependence represents a significant uncertainty

False vacuum fraction $\longrightarrow$ several important milestone temperatures

Completion temperature: T_f: $P_f(T_f) = 0.01$

Percolation temperature: T_p: $P_f(T_p) = 0.71$

The instant when a significant volume of the Universe has been converted from the symmetric to the broken phase.

The nucleation temperature is instead given by $N(T_n) = 1$

$$N(T) = \int_T^{T_c} dT' \, \frac{\Gamma(T')}{T' H^4(T')}$$

The nucleation temperature is frequently used for evaluating GW signals

but it may not exist…

and for slow transitions is decouples from the other the other temperatures

Contents

Challenges

- First, the phase transition does not complete for the low temperatures associated with a nHz signal.
- Second, the energy released by the phase transition reheats the Universe to about the new physics scale and this can rule out attempts to solve the completion problem.
- Two key criteria for the challenges of fitting a nHz signal with this cubic potential:
    1. Realistic percolation: Having a percolation temperature and that the physical volume of the false vacuum is decreasing at the onset of percolation;
    2. Having a completion temperature: A temperature at which the false vacuum fraction falls to bellow 1%.

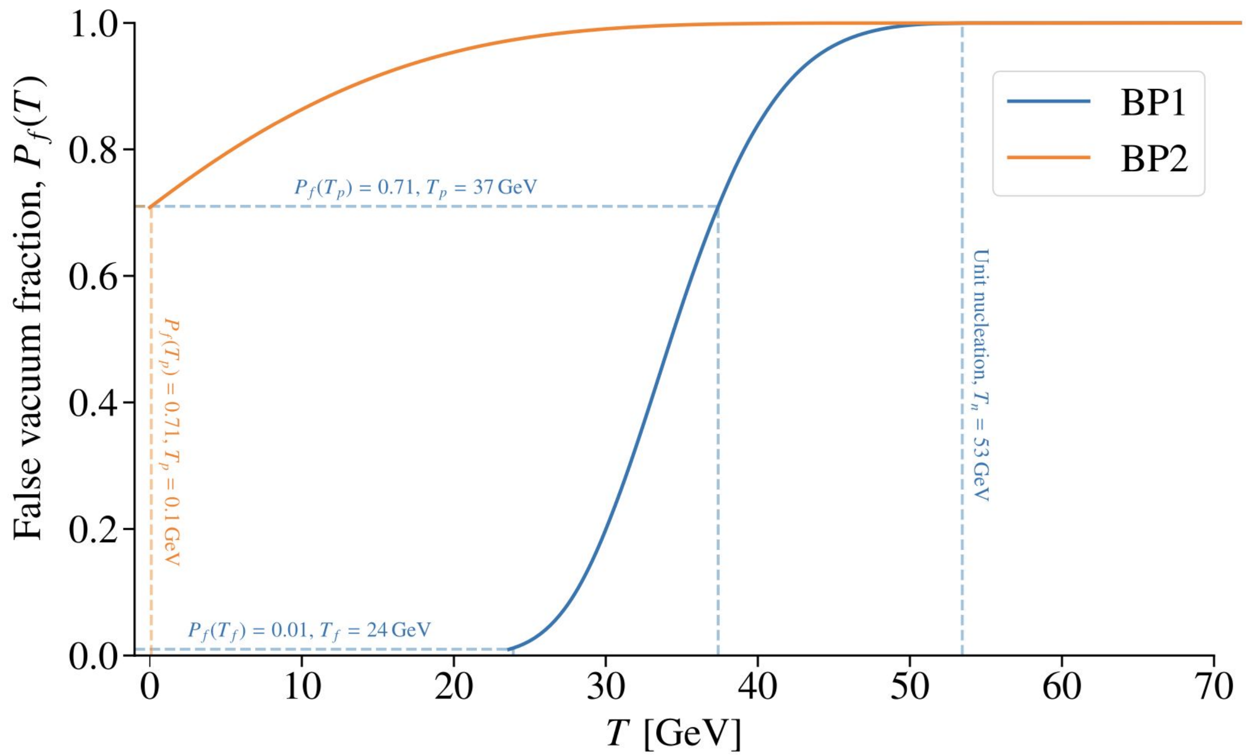
$$\mathrm{BP1}: \kappa = -117.96\,\mathrm{GeV}$$

- BP1 resulted in the most supercooling for which the transition satisfies both criteria, though it fails to supercool to sub-GeV temperatures;
- The physical volume of the false vacuum starts decreasing at exactly the percolation temperature.

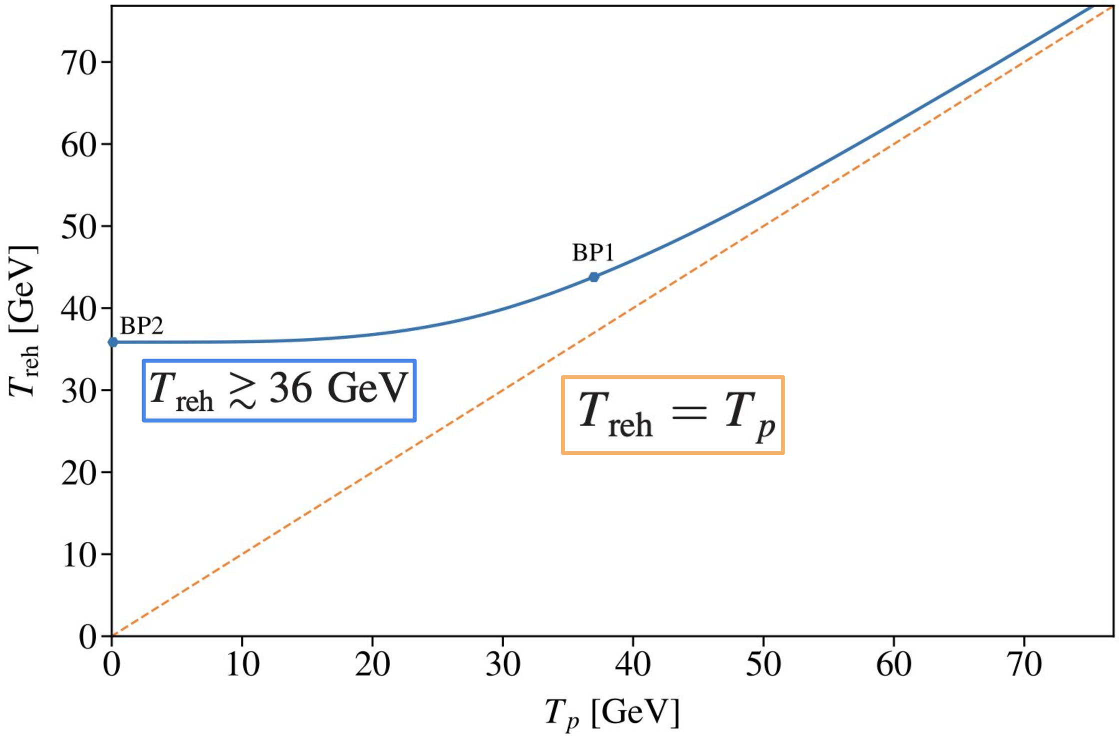
$$\mathrm{BP2}: \kappa = -118.67\,\mathrm{GeV}$$

- BP2 results in stronger supercooling with a nominal percolation temperature of 100 MeV but no completion temperature.
- Although BP2 was chosen so that percolation was estimated to begin at 100 MeV, it violates our first criteria and the space between bubbles continues to expand below 100 MeV. Thus, despite a nominal percolation temperature, percolation could be unrealistic.
- Without significant percolation of bubbles, the phase transition would not generate a SGWB.

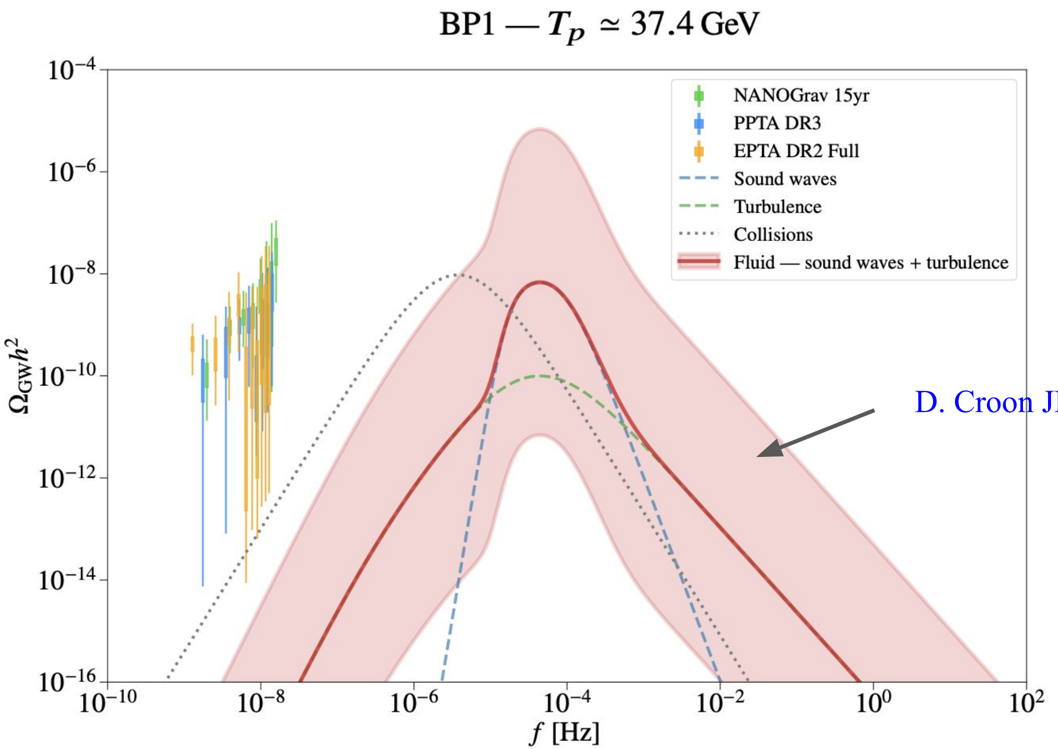
Challenge 1: Percolation and Completion



Challenge 2: Reheating

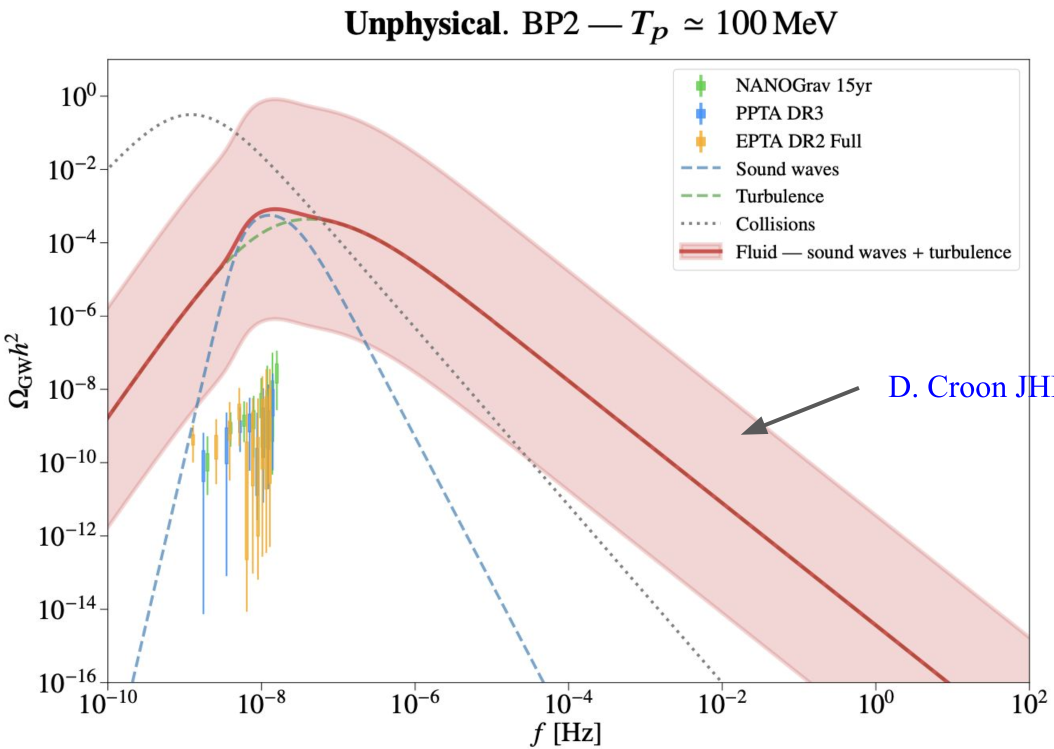


The SGWB from BP1: strongest supercooling for which the FOPT completed



D. Croon JHEP 04 (2021) 055

The SGWB from BP2: strongest supercooling for which the FOPT has a percolation temperature though it doesn't compete and percolation is questionable



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Contents

Conclusions

1. Supercooled FOPTs are an interesting explanation of the nHz SGWB recently observed by serval PTAs, as they could connect a nHz signal to the electroweak scale.
2. However, there are two major difficulties that can affect supercooled explanations:

- Percolation and Completion
- Reheating

Conclusions

3. Although the peak frequency could be reduced to nHz, supercooled phase transition don’t complete. In contrast, completing the phase transition would NOT lead to a nHz signal.

4. These issues are quite generic and they should be carefully checked in supercooled explanations.

An interview for this topic from Phys.org

Webpage: https://phys.org/news/2024-06-supercooled-phase-transitions-gravitational.html#

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JUNE 19, 2024 FEATURE Editors' notes

Supercooled phase transitions: Could they explain gravitational wave signals?

by Tejasri Gururaj , Phys.org

A new study published in *Physical Review Letters* explores the possibility that a strongly supercooled, first-order phase transition in the early universe could explain gravitational wave signals observed by pulsar timing arrays (PTAs).

Thank you
for your attention

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