DESY Cosmology Group - Journal Club

Primordial Black Holes from First-Order Cosmological Phase Transitions [2105.07481]

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

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Contents

Primordial Black Holes

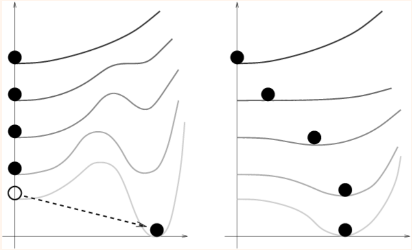
Black holes formed in the early universe, not as remnants of stars

- could constitute part or all of dark matter
- could create dark matter particles upon evaporation
- could change expansion history of the universe
- provide seeds of supermassive black holes

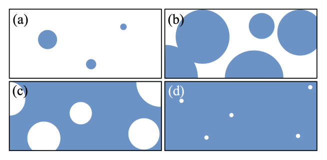
Production mechanisms involve:

- collapse of density perturbations generated during inflation
- collapse of topological defects
- collision of bubble walls during a first-order phase transition

First Order Phase Transitions (FOPT)



- right: continuous (second-order) phase transitions are happening, as the name suggests, smoothly
- left: **first order phase transitions** lead to formation of bubbles, in which the field tunnelled from the **false vacuum** to the **true vacuum**, which then expand, see below (blue/white: true/false vacuum respectively).



First Order Phase Transitions (FOPT)

Assume two local minima with $\langle\phi\rangle = 0$ and $\langle\phi\rangle = v$. At T_c, the **critical temperature**, both minima are degenerate. Below this temperature, v is the global minimum, i.e. true vacuum. The decay rate to this is given by, Linde 1983,

$$\Gamma(T) \approx T^4 e^{-S_3(T)/T}, \tag{1}$$

where $S_3(T)$ is the action of a specific, $O(3)$-symmetric solution (bounce solution) to the fields eoms. The FOPT becomes efficient when the transition probability during one Hubble time in one Hubble volume becomes of $\mathcal{O}(1)$, i.e.

$$\Gamma(T_n)H^{-4}(T_n) \approx 1, \tag{2}$$

which defines the **nucleation temperature** T_n.
It $T_n \ll T_c$, we call the FOPT **super-cooled**.

General Idea

Previous papers about **formation of PBHs during first-order phase transitions** have considered **energy density stored in the bubble wall**. New ideas focus on a **population of particles that interact with the bubble wall**.

Baker, Breitbach, et al. 2021 cite the recent paper Hong, Jung, and Xie 2020, where small pockets of false vacua are sustained by stable dark matter particles that have insufficient energy to transverse the bubble wall, leading to **Fermi-balls**, but show that the resulting density can be large enough to form **PBHs** directly.

Primordial Black Holes from First-Order Cosmological Phase Transitions

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(Dated: May 18, 2021)

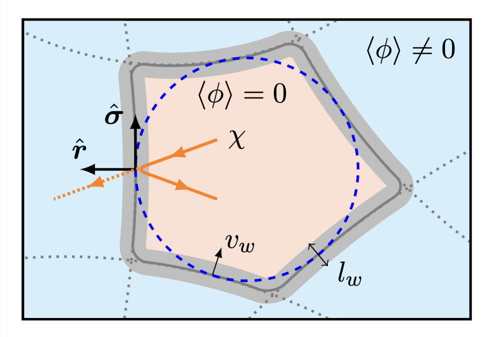
We discuss the possibility of forming primordial black holes during a first-order phase transition in the early Universe. As is well known, such a phase transition proceeds through the formation of true-vacuum bubbles in a Universe that is still in a false vacuum. When there is a particle species whose mass increases significantly during the phase transition, transmission of the corresponding particles through the advancing bubble walls is suppressed. Consequently, an overdensity can build up in front of the walls and become sufficiently large to trigger primordial black hole formation. We track this process quantitatively by solving a Boltzmann equation, and we determine the resulting black hole density and mass distribution as a function of model parameters.

General Idea

Consider two fields ϕ, χ, where the scalar ϕ develops a non-zero vev v in a FOPT, is in thermal contact to the SM, and the fermion χ gets a mass correction from v.

$$\mathcal{L} \supset -y_\chi \phi \overline{\chi}\chi - m_\chi^0 \overline{\chi}\chi - V(\phi) \tag{3}$$

Consider shrinking spherical bubbles of false vacuum:



Heuristic Criteria/Jeans Instability

- Due to energy conservation only highly energetic χ particles can transverse bubble wall, since the kinetic energy must be larger than the mass gained in the true vacuum $\implies$ can be ignored in heuristical argument
- Assume initial bubble radius (radius at nucleation) fulfills $r_\omega(0) < r_H \equiv H^{-1}$
- Energy density of χ, which increases as the bubble shrinks, is

$$\rho_\chi = \left(\frac{r_\omega(0)}{r_\omega(t)}\right)^3 \frac{\pi^2}{30} g_\chi T_n^4, \tag{4}$$

where T_n is the **nucleation temperature**.

Heuristic Criteria/Jeans Instability

PBH formation will happen, when the free-fall time for a spherical symmetric volume gets smaller than the time it takes a sound wave to cross the volume, which is the **Jeans instability criterion**

$$t_{\text{ff}} = \sqrt{\frac{3\pi}{32G\Delta\rho}} < t_s = \frac{r_\omega(t)}{c_s}, \tag{5}$$

where $\Delta\rho$ is the local overdensity, and is equal to ρ_χ if no χ-particles leave the bubble.
Using the Friedmann equation $H^2 = 8\pi G/3(\pi^2/30)g_*(T_n)T_n^4$, this can be rewritten as

$$\frac{r_\omega(t)}{r_\omega(0)} < \frac{4}{\pi^2 c_s^2}\frac{r_\omega^2(0)}{r_H^2}\frac{g_\chi}{g_*(T_n)} \tag{6}$$

For $g_* \sim 100$, $r_\omega(0) \sim 0.5 r_H$, this is satisfied at $r_\omega(t) \sim r_\omega(0)/80$.
(Not *a priori* clear this could be satisfied.)

Further Physical Effects

Heuristic discussion takes following things **not** into account:

1. χ needs energy and angular momentum dissipation mechanism (e.g. via scattering on ϕ) and χ must be able to overcome Fermi degeneracy pressure
2. χ particles reflecting on the wall get momentum boost $\Longrightarrow$ criterion fulfilled more easily
3. some χ particles will traverse the wall due to their high momentum
4. χ particles may annihilate via $\chi\overline{\chi} \leftrightarrow \phi\phi$
5. scattering could change momentum distribution and decrease fraction of χ particles that can traverse the wall
6. χ bouncing off the wall will slow down the latter
7. growing ρ_χ will increase gravitational force to reinforce overdensity

Further Physical Effects

- first 4 effects have been taken into account in the numerical simulation
- momentum redistribution is assumed to be small due to high occupation of low momentum states and Pauli blocking
- at small y_χ, slowdown of the wall due to χ will be unimportant if other particles coupled to ϕ dominate friction
- neglecting gravity will render the result conservative

Numerical Simulation

- $\mathcal{L} \supset -y_\chi \phi \overline{\chi} \chi - m_\chi^0 \overline{\chi} \chi - V(\phi)$
- $m_\chi = m_\chi^0 + y_\chi v$
- assume $m_\chi^0 \ll T_n \ll y_\chi v \implies \chi$ relativistic
- FOPT paramterised by T_n, order parameter v/T_n, wall thickness l_ω, initial wall velocity v_ω.
- asumme no significant temperature variation during FOPT, ϕ in thermal contact with the SM, and $v_\omega \ll 1$.

Numerical Simulation

The phase space distribution function

$$f_\chi = f_\chi(r, p_r, p_\sigma, t)$$

of χ is tracked by numerically solving the **Boltzmann-equation**

$$L[f_\chi] = C[f_\chi], \tag{7}$$

where $L[f_\chi]$ accounts for the evolution of f_χ in absence of hard interactions, while $C[f_\chi]$ accounts for creation and annihilation of χ particles via $\chi\overline{\chi} \leftrightarrow \phi\phi$.

The equation is solved with methods from Baker, Kopp, and Long 2020, using $f_\chi(r, p_r, p_\sigma, t) = \mathcal{A}(r, p_r, p_\sigma, t) f_{\mathrm{eq}}$, and the **method of characteristics**, which transforms the Boltzmann-eqn (PDE) to a system of ODEs (details will appear in a forthcoming paper)

Numerical Simulation

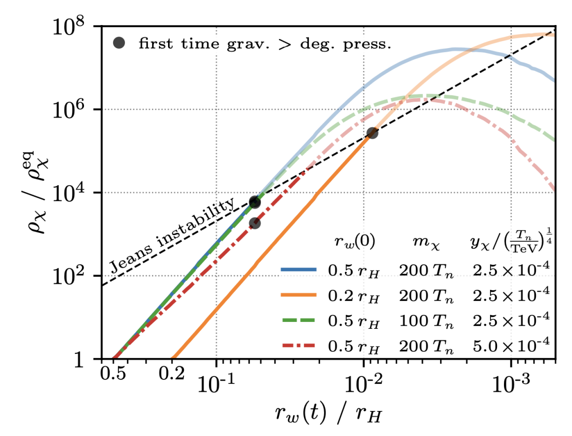
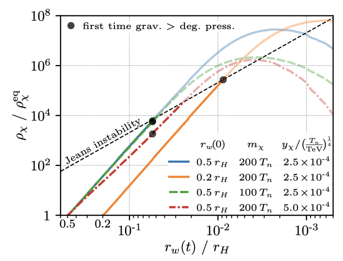


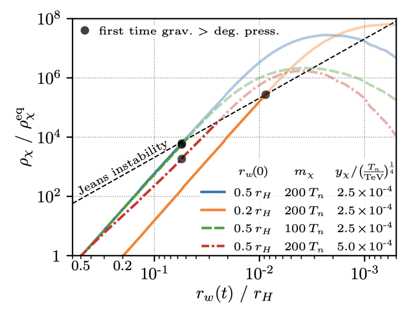
Fig: Spatially averaged $\chi+\overline{\chi}$ energy density inside the bubbles as function of bubble radius

Numerical Simulation



- Initially ρ_χ increases as $1/r_\omega^4(t)$, since energy gain of particle reflected on the wall is $dE = 2v_\omega E$, while the time between two collisions is $dt = 2r_\omega(t) = 2(r_\omega(0) - v_\omega t)$. This leads to $E \propto 1/r_\omega(t)$. The other factor is due to increase in number density due to compression. Jeans criteria is satisfied when bubble has shrunk by factor of 10 → more easily satisfied than heuristically expected
- Flattening occurs because of annihilation and increased probability for χ particles to cross the wall, but at this point collapse has already started
- beyond black points Fermi degeneracy pressure cannot halt gravitational collapse

Numerical Simulation



- To avoid too much annihilation, small y_χ is needed, and also large m_χ/T_n to suppress χ transmission through the bubble wall $\Longrightarrow$ As $m_\chi \sim y_\chi v$, this shows that **large v/T_n is needed**
- It has been checked that free fall time is shorter than completion of FOPT (?)
- χ remained in thermal equilibrium, allowing efficient dissipation of energy and angular momentum.

PBH Population

Mass of black holes formed during radiation domination is given by, Carr et al. 2020,

$$m_{\mathrm{BH}} \sim \frac{r_\omega^3(0)}{G r_H^2}. \tag{8}$$

Black hole relic abundance as fraction of dark matter relic abundance is

$$f \equiv \frac{\Omega_{\mathrm{PBH}}(T)}{\Omega_{\mathrm{DM}}(T)} = \frac{n_{\mathrm{PBH}}(T_n) m_{\mathrm{BH}}}{\Omega_{\mathrm{DM}} \rho_{\mathrm{crit}}(T_0)} \frac{g_*(T_0) T_0^3}{g_*(T_n) T_n^3} = 3.7 \times 10^9 \mathfrak{p} \left(\frac{T_n}{1 \mathrm{GeV}}\right), \tag{9}$$

with $n_{\mathrm{PBH}}(T_n) = 3\mathfrak{p} H^3/(4\pi)$, and $\mathfrak{p}$ being the probability that a BH will form in a given Hubble volume. Accretion and Hawking evaporation are ignored here.

PBH Population

$\mathfrak{p}$ depends on the details of the FOPT.

- PBH formation can only happen when relatively large bubbles $r_\omega(0) \sim r_h$ can form unimpeded. If new bubbles form before collapse, the in-falling particle population will be split, making black hole formation impossible. $\rightarrow$ The rate at which this happens depends exponentially on the parameter β/H of the FOPT, where it has to be small so bubbles to not form too fast. $\implies$ again **super-cooled phase transitions** are ideal, since the have small β/H and v/T_n can be large.

PBH Population

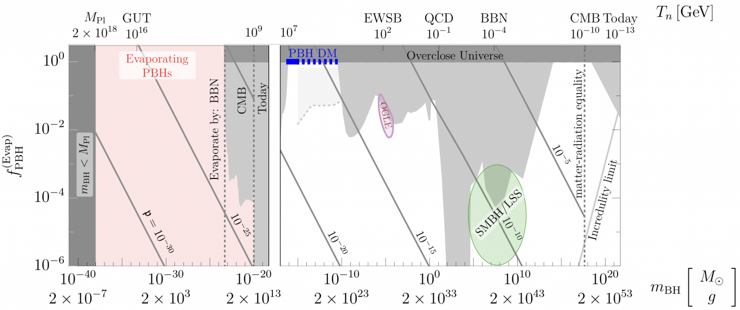


FIG. 3. The BH mass and abundance, $f = \Omega_{\rm PBH}/\Omega_{\rm DM}$, for BHs produced during a phase transition at temperature T_n, and assuming that the probability to form a PBH in a given Hubble volume is $\mathfrak{p}$ (diagonal contours). In the red region PBHs have already evaporated (and their abundance is shown at the time of evaporation), in the blue region they could account for all the dark matter in the Universe, in the purple region they could explain the OGLE hint [72], and in the green region they could provide seeds for supermassive black holes and large scale structure [9, 26–30]. The grey region shows the relevant observational constraints [9].

T_n and $m_{\rm PBH}$ in one-to-one correspondence by always taking $r_\omega(0) \sim r_H$

PBHs by collapse of Fermi-Balls

Fermi-ball dark matter from a first-order phase transition

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We propose a novel dark matter (DM) scenario based on a first-order phase transition in the early universe. If dark fermions acquire a huge mass gap between true and false vacua, they can barely penetrate into the new phase. Instead, they get trapped in the old phase and accumulate to form macroscopic objects, dubbed Fermi-balls. We show that Fermi-balls can explain the DM abundance in a wide range of models and parameter space, depending most crucially on the dark-fermion asymmetry and the phase transition energy scale (possible up to the Planck scale). They are stable by the balance between fermion's quantum pressure against free energy release, hence turn out to be macroscopic in mass and size. However, this scenario generally produces no detectable signals (which may explain the null results of DM searches), except for detectable gravitational waves (GWs) for electroweak scale phase transitions; although the detection of such stochastic GWs does not necessarily imply a Fermi-ball DM scenario.

Primordial black holes from a cosmic phase transition: The collapse of Fermi-balls

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We propose a novel primordial black hole (PBH) formation mechanism based on a first-order phase transition (FOPT). If a fermion species gains a huge mass in the true vacuum, the corresponding particles get trapped in the false vacuum as they do not have sufficient energy to penetrate the bubble wall. After the FOPT, the fermions are compressed into the false vacuum remnants to form non-topological solitons called Fermi-balls, and then collapse to PBHs due to the long-range Yukawa attractive force. We derive the PBH mass and abundance, showing that for a $\mathcal{O}(\text{GeV})$ FOPT the PBHs could be $\sim 10^{17}$ g and explain all of dark matter. If the FOPT happens at higher scale, PBHs are typically overproduced and extra dilution mechanism is necessary to satisfy current constraints.

While Hong, Jung, and Xie 2020[2008.04430v2] does predict **Fermi-balls**, but not PBHs, a recently released follow-up paper to this work, Kawana and Xie 2021[2106.00111], does discuss the **collapse of Fermi-balls to PBHs**.

Fermi-Balls as Dark Matter

Hong, Jung, and Xie 2020 assumes same general setup regarding ϕ which undergoes FOPT, and χ fermion receiving a mass by that FOPT.
Fermi-balls are compact macroscopic objects consisting of χ particles, and forming under three conditions:

- huge mass gap for χ between true and false vacua, so they cannot penetrate into true vacuum
- asymmetry of number density between χ and $\overline{\chi}$
- χ should carry global conserved $U(1)_Q$ charge, so the Fermi-balls are stable

PBHs by collapse of Fermi-Balls

In Kawana and Xie 2021, the χ are interacting via an attractive Yukawa potential

$$V(r) = -\frac{y_\chi^2}{4\pi r} e^{-M_\phi r}, \tag{10}$$

where the range of the force is determined by the effective mass at the false vacuum

$$M_\phi^2 = \left.\frac{d^2 U(\phi, T)}{d\phi^2}\right|_{\phi=0} = \mu^2 + cT^2. \tag{11}$$

When the universe cooled down to $T_\phi = \sqrt{-\mu^2/c}$, and $\mu^2 < 0$, the force becomes long range, resulting in collapse of Fermi-balls into PBHs.
Claim that this **process is more generic** as the one in Baker, Breitbach, et al. 2021, since it does not need $y_\chi < 10^{-3}$ and $m_\chi > 200 T_n$.

Any questions, comments (or answers to my open questions :-))?

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