Primordial black holes as dark matter: formation and astrophysical consequences

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Primordial black holes

- Black holes can be produced in the early universe [Zeldovich, Novikov (1967); Hawking (1971), Carr]
- Can account for dark matter. The only dark matter candidate that is not necessarily made of new particles. (Although new physics usually needed to produce PBHs)
- Can seed supermassive black holes
- Can probably contribute to the LIGO signal
- Can account for all or part of r-process nucleosynthesis
- ...and 511 keV line from the Galactic Center
Formation scenarios

- Inflation [Carr; Garcia-Bellido, Linde et al. ...] Spectrum of primordial density perturbations may have an extra power on some scale $\rightarrow$ PBH
- Violent events, such as phase transitions, domain walls collapse.
- Matter-dominated phase is an opportunity [Zeldovich, Novikov; Khlopov, Polnarev, Zeldovich; Carr, Tenkanen; Georg, Melcher, Watson]
- Scalar field fragmentation: matter-dominated epoch with relatively few extremely massive particles per horizon $\Rightarrow$ fluctuations are large
  [Cotner, AK; Fuller, AK, Takhistov; Cotner, AK, Takhistov, Vitagliano, Sasaki]
- Multiverse from inflation producing baby universes collapsing to PBH: extended mass function affords new ways to detect [Vilenkin et al., AK et al.]
Experimental constraints
HSC search for PBH [Takada et al.]
A candidate microlensing event Subaru HSC obs. of M31

Consistent with PBH mass $\sim 10^{-7} \, M_\odot$

Need follow-up observations


**Figure 13.** One remaining candidate that passed all the selection criteria of microlensing event. The images in the upper plot show the postage-stamped images around the candidate as in Fig. 7: the reference image, the target image, the difference image and the residual image after subtracting the best-fit PSF image, respectively. The lower panel shows that the best-fit microlensing model gives a fairly good fitting to the measured light curve.
Early Universe

- **Inflation**
  - $p<0$
  - Origin of primordial perturbations

- **Radiation dominated**
  - $p=(\frac{1}{3})\rho$
  - $\rho \propto a^{-4}$
  - Structures don’t grow

- **Matter dominated**
  - $p=0$
  - $\rho \propto a^{-3}$
  - Structures grow

- **Modern era**
  - $p<0$
  - (Dark energy dominated)
Scalar fields

Simplest spin-zero object

Examples:

- Higgs field that gives an electron and other particles masses
- Supersymmetry - many scalar fields, including 100+ flat directions [Gherghetta et al., ’95]
Scalar fields in de Sitter space during inflation

A scalar with a small mass develops a VEV
[Bunch, Davies; Affleck, Dine]
Scalar fields in de Sitter space during inflation

- If \( m=0, V=0 \), the field performs random walk:
- Massive, non-interacting field:
- Potential \( V(\phi) = \frac{1}{2} m^2 \phi^2 + \frac{\lambda}{4} \phi^4 \)

\[
\langle \phi^2 \rangle = \frac{H^3}{4\pi^2 t}
\]

\[
\langle \phi^2 \rangle = \frac{3H^4}{8\pi^2 m^2}
\]

\[
H \partial_t \langle \phi^2 \rangle = \frac{H^4}{4\pi^2} - \frac{2m^2}{3} \langle \phi^2 \rangle - 2\lambda \langle \phi^2 \rangle^2
\]

\[
\langle \phi^2 \rangle \rightarrow \frac{H^2}{\pi \sqrt{8\lambda}} \quad \text{for} \quad m = 0
\]
Scalar fields in de Sitter space during inflation

A scalar with a small mass develops a VEV
[Bunch, Davies; Affleck, Dine]
Scalar fields: an instability

Gravitational instability can occur due to the attractive force of gravity.

Similar instability can occur due to scalar self-interaction which is attractive:

\[ U(\phi) \supset \lambda_3 \phi^3 \quad \text{or} \quad \lambda_\chi \phi \phi \phi \phi^\dagger \phi \]
Scalar fields: an instability (Q-balls)

homogeneous solution \( \varphi(x, t) = \varphi(t) \equiv R(t)e^{i\Omega(t)} \)

\[
\delta R, \delta \Omega \propto e^{S(t) - ik\vec{x}}
\]

\[
\ddot{\Omega} + 3H(\dot{\Omega}) - \frac{1}{a^2(t)} \Delta(\delta \Omega) + \frac{2\dot{R}}{R}(\dot{\delta} \Omega) + \frac{2\dot{\Omega}}{R}(\dot{\delta} R) - \frac{2\dot{R}\dot{\Omega}}{R^2}\delta R = 0,
\]

\[
\ddot{R} + 3H(\dot{R}) - \frac{1}{a^2(t)} \Delta(\delta R) - 2R\dot{\Omega}(\dot{\delta} \Omega) + U''\delta R - \dot{\Omega}^2\delta R = 0.
\]

\[(\dot{\Omega}^2 - U''(R)) > 0 \Rightarrow \text{growing modes: } 0 < k < k_{\text{max}} \]

Also of interest: oscillons

\[k_{\text{max}}(t) = a(t)\sqrt{\dot{\Omega}^2 - U''(R)}\]

AK, Shaposhnikov, hep-ph/9709492
Numerical simulations of scalar field fragmentation

[Multamaki].

[Kasuya, Kawasaki]
Q-balls: the min of energy for a fixed U(1) global number

Complex scalar field with a U(1) symmetry (e.g. B, L, B-L in SUSY)

U(1):

\[ \phi \rightarrow e^{i\theta} \phi. \]

Ground state with Q≠0?

vacuum: \[ \phi = 0 \]

conserved charge: \[ Q = \frac{1}{2\pi} \int \left( \phi^\dagger \overset{\to}{\partial}_0 \phi \right) d^3x \]

\[ Q \neq 0 \Rightarrow \phi \neq 0 \text{ in some finite domain} \]
\[ \Rightarrow \text{Q-ball} \ ] [Rosen; Friedberg, Lee, Sirlin; Coleman]

Q-balls exist if

\[ U(\phi) / \phi^2 = \min, \text{ for } \phi = \phi_0 > 0 \]
Q-balls in a flat potential (as in SUSY)

Q=global charge (e.g. baryon number) = number of particles

\[ \text{Mass} \propto Q^{3/4} \Rightarrow \]

\( (\text{Mass per particle}) \propto (Q^{3/4}/Q) = Q^{-1/4} = \text{decreases for large } Q \Rightarrow \)

- min of energy
- stick together
- size fluctuations \( \Rightarrow \)

mass fluctuations
Early Universe

Inflation

origin of primordial perturbations

radiation dominated

\[ p = \left(\frac{1}{3}\right) \rho \]
\[ \rho \propto a^{-4} \]
structures don't grow

matter dominated

\[ p = 0 \]
\[ \rho \propto a^{-3} \]
structures grow

modern era (dark energy dominated)
Scalar lump (Q-ball) formation can lead to PBHs

Intermittent matter dominated epoch in the middle of radiation dominated era

Few big lumps create large fluctuations

Matter-dominated phase has been considered before, but

- usually, fluctuations are not big enough
- non-linear evolution cannot be reliably invoked: virialized systems do not make black holes
- in linear regime, PBH formation is suppressed in the absence of large fluctuations

Small number of large “particles” ⇒ large fluctuations, enough PBH for DM

Must account for suppression from non-spherical configurations, etc. -- still OK.
Many particles $\Rightarrow$ only small Poisson fluctuations
FEW GIANT PARTICLES ⇒ LARGE POISSON FLUCTUATIONS
Scalar lump (oscillon) formation can lead to PBHs

Intermittent matter dominated epoch immediately after inflation

[Cotner, AK, Takhistov, Phys.Rev. D98 (2018), 083513 ]
PBH from Supersymmetry: natural mass range

Flat directions lifted by SUSY breaking terms, which determine the scale of fragmentation.

\[ M_{\text{hor}} \sim r_f^{-1} \left( \frac{M_{\text{Planck}}^3}{M_{\text{SUSY}}^2} \right) \sim 10^{23} g \left( \frac{100 \text{ TeV}}{M_{\text{SUSY}}} \right)^2 \]

\[ M_{\text{PBH}} \sim r_f^{-1} \times 10^{22} g \left( \frac{100 \text{ TeV}}{M_{\text{SUSY}}} \right)^2 \]

\[ 10^{17} \text{ g} \lesssim M_{\text{PBH}} \lesssim 10^{22} \text{ g} \]

Cotner, AK, Sasaki, Takhistov, JCAP 1910 (2019) 077]
Scalar lump formation $\Rightarrow$ PBHs with different masses

$\Omega_{\text{PBH}} = 1, \quad 0.2, \quad 0.001$

Cotner, AK, Sasaki, Takhistov, JCAP 1910 (2019) 077]
# Comparison with PBH from inflationary perturbations

<table>
<thead>
<tr>
<th>PBH Production Scenario</th>
<th>Inflationary Perturbations (common mechanism)</th>
<th>Field Fragmentation (our mechanism)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source and type of large (CMB-scale) perturbations</td>
<td>inflaton fluctuations, curvature</td>
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<tr>
<td>Source and type of small (PBH-scale) perturbations</td>
<td>inflaton fluctuations, curvature</td>
<td>stochastic field fragmentation, isocurvature (fragment-lumps)</td>
</tr>
<tr>
<td>PBH source field</td>
<td>inflaton</td>
<td>inflaton or spectator field</td>
</tr>
<tr>
<td>Required potential condition</td>
<td>inflaton potential fine tuning</td>
<td>no new restrictions on inflaton potential, scalar field potential shallower than quadratic (attractive self-interactions)</td>
</tr>
<tr>
<td>PBH formation era ($t_{PBH}$) and type</td>
<td>$t_{BBN} \gtrsim t_{PBH} \gtrsim t_{reh}$, after reheating, radiation-dominated era</td>
<td>$t_{BBN} \gtrsim t_{PBH} \gtrsim t_{inf}$, before or after reheating, temporary matter-dominated era</td>
</tr>
<tr>
<td>PBH size ($r_{BH}$) vs. horizon ($r_H$) at formation</td>
<td>$r_{BH} \sim r_H \sim H^{-1}$</td>
<td>$r_{BH} \ll r_H \sim H^{-1}$</td>
</tr>
<tr>
<td>PBH spin ($a$)</td>
<td>$a \sim 0$</td>
<td>$a \sim O(1)$ possible</td>
</tr>
</tbody>
</table>
Another mechanism: inflationary multiverse

Tail of the mass the function $\propto M^{-1/2}$, accessible to HSC

**PBH and neutron stars**

- Neutron stars can capture PBH, which consume and destroy them from the inside.
- Capture probability high enough in DM rich environments, e.g. Galactic Center
- Missing pulsar problem...
  [e.g. Dexter, O'Leary, arXiv:1310.7022]
- What happens if NSs really are systematically destroyed by PBH?

**Neutron star destruction by black holes**

⇒ r-process nucleosynthesis, 511 keV, FRB

MSP spun up by an accreting PBH

- MSP with a BH inside, spinning near mass shedding limit: elongated spheroid
- Rigid rotator: viscosity sufficient even without magnetic fields [Kouvaris, Tinyakov]; more so if magnetic field flux tubes are considered
- Accretion leads to a decrease in the radius, increase in the angular velocity (by angular momentum conservation)
- Equatorial regions gain speed in excess of escape velocity: ejection of cold neutron matter

Numerical simulations by David Radice (Princeton)

Preliminary results by David Radice (Princeton U. and IAS)

Initial PBH mass for this simulation:

\[ M_{\text{PBH}} = 0.03 \, M_\odot \]

(preliminary results)
r-process nucleosynthesis: site unknown

- s-process cannot produce peaks of heavy elements
- Observations well described by r-process
- Neutron rich environment needed
- Site? SNe? NS-NS collisions?..
r-process nucleosynthesis: site unknown

- SN? Problematic: neutrinos
- NS mergers? Can account for all r-process?
r-process material: observations

Milky Way (total): \(M \sim 10^4 \, M_\odot\)

Ultra Faint Dwarfs (UFD): most of UFDs show no enhancement of r-process abundance.

However, **Reticulum II** shows an enhancement by factor \(10^2-10^3!\)

“Rare event” consistent with the UFD data: one in ten shows r-process material [Ji, Frebel et al. Nature, 2016]
NS disruptions by PBHs

- Centrifugal ejection of cold neutron-rich material ($\sim 0.1 \, M_\odot$) MW: $M \sim 10^4 \, M_\odot$ ✔

- UFD: a rare event, only one in ten UFDs could host it in 10 Gyr ✔

- Globular clusters: low/average DM density, but high density of millisecond pulsars. Rates OK. ✔

[Fuller, AK, Takhistov, PRL 119 (2017) 061101]
also, a Viewpoint PRL article by Hans-Thomas Janka
NS disruptions by PBHs

- Weak/different GW signal
- No significant neutrino emission
- Fast Radio Bursts
- Kilonova type event **without** a GW counterpart, but with a possible coincident FRB
- 511 keV line

Origin of positrons unknown. Need to produce $10^{50}$ positrons per year. Positrons must be produced with energies below 3 MeV to annihilate at rest. [Beacom, Yuksel ‘08]

Cold, neutron-rich material ejected in PBH-NS events is heated by $\beta$-decay and fission to $T\sim0.1$ MeV

\[ \rightarrow \text{generate } 10^{50} \text{ e}^+/\text{yr} \text{ for the rates needed to explain r-process nucleosynthesis.} \]

Positrons are non-relativistic.

\[ \Gamma(e^+e^- \rightarrow \gamma\gamma) \sim 10^{50}\text{yr}^{-1} \]
Fast Radio Bursts (FRB)

Origin unknown. One repeater, others: non-repeaters. $\tau \sim$ ms.

PBH - NS events: final stages dynamical time scale $\tau \sim$ ms.

NS magnetic field energy available for release: $\sim 10^{41}$ erg

**Consistent with observed FRB fluence.**

Massive rearrangement of magnetic fields at the end of the NS life, on the time scale $\sim$ms produces an FRB.

(Of course, there are probably multiple sources of FRBs.)
GW detectors can discover small PBH...

PBH + NS

↓

BH of 1-2 \( M_\odot \)

...if it detects mergers of 1-2 \( M_\odot \) black holes (not expected from evolution of stars)

[Takhiriev, arXiv:1707.05849]
Conclusion

- Simple formation mechanism in the early universe: PBH from a scalar field fragmentation, PBH from vacuum bubbles
- PBH with masses $10^{-14} - 10^{-10} \, M_{\odot}$, motivated by 1-100 TeV scale supersymmetry, can make up 100% (or less) of dark matter
- PBH is a generic dark matter candidate in SUSY
- If >10% of dark matter is PBH, they can contribute to r-process nucleosynthesis
- Signatures of PBH:
  - Kilonova without a GW counterpart, or with a weak/unusual GW signature
  - An unexpected population of 1-2 M$_{\odot}$ black holes (GW)
  - Galactic positrons, FRB, etc.
  - Microlensing (HSC) can detect the tail of DM mass function.