Primordial Black Holes as SUSY Dark Matter

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PBH as DM

- Black holes
  - astrophysical → old stars

- Why get excited about PBH DM?
  - no clear signs of particle DM
  - GW astronomy [Sasaki, Thorne+, 1997; Bird+, 2016; Garcia-Bellido+, 2015...]
  - already appear in standard cosmology (but unlikely)
  - generic in many BSM models
  - help resolve astro puzzles (e.g. seed massive BHs) [Kawasaki, Kusenko, Yanagida, 2012]
Status

[Sasaki+, 2017]
assume too much DM in clusters

lensing/source effects

[Sasaki+, 2017]
Status

[Sasaki+, 2017]
How to form PBHs?
The “standard scenario”

- **Radiation-era formation**: large perturbations ($\delta \sim 1$) enter horizon $\rightarrow$ collapse

[Kawasaki, Sasaki, Yanagida ...]

The “standard scenario”

- **Radiation-era formation**: large perturbations \((\delta \sim 1)\) enter horizon \(\rightarrow\) collapse
  
  \[\text{[Kawasaki, Sasaki, Yanagida ...]}\]

- Need to fine tune inflaton potential

- Sensitive to restrictions on scalar field behavior
  
  - Example: “string swampland conjectures” \([\text{Kawasaki, VT, Phys. Rev. D., 2018}]\)
New generic PBH production mechanism:

scalar field fragmentation

[Cotner, Kusenko, VT, Sasaki, \textit{in preparation}] - general analytic framework
Scalars from SUSY

- **Scalar fields exist**: Higgs

- Scalars are generic in BSM constructions (e.g. moduli)

- SUSY predicts many scalar fields with vanishing potentials (100+ in MSSM) → “flat directions”

- Many flat directions carry a U(1) charge (baryon or lepton number)

[Gerghetta+, 1995]
Scalar evolution in early universe

- Take complex field $\phi = R(x, t)e^{i\Omega(x,t)}$ charged under U(1) & spectator to inflaton
- During inflation scalar fields can acquire large VEVs due to quantum jumps
- After inflation the field rolls down to minimum and coherently oscillates
Instabilities, self-interactions and Q-balls

- With self-interactions: unstable growing oscillation modes, very general conditions
  \[ U''(R) - \dot{\Omega}^2 < 0 \]  
  [Kusenko, Shaposhnikov, 1997]

** popular “tachyonic resonance” is a special case ( \( U'' < 0 \) )
**Instabilities, self-interactions and Q-balls**

- **With self-interactions**: unstable growing oscillation modes, very general conditions

\[ U''(R) - \dot{\Omega}^2 < 0 \]  

[Kusenko, Shaposhnikov, 1997]

** popular “tachyonic resonance” is a special case** ( \( U'' < 0 \) )

- **The field eventually fragments into soliton gas**: **Q-balls**  

[Coleman, 1985]

** existence of Q-balls can be rigorously shown from energetics**

- **Q-balls are big** (~ % of horizon at formation) & **stable** (conserved charge)
Alternative simple heuristic argument

- Self-interaction instability analogous to Jeans instability from gravity

- A general potential $U(\phi) \sim |\phi|^n$ gives pressure-density relation

$$p = \left( \frac{n-2}{n+2} \right) \rho$$  

[Enqvist, McDonald, 1997]

- When $n < 2$ (attractive self-interactions) $\rightarrow$ pressure is negative ($p < 0$) $\rightarrow$ condensate collapse until some stable radius set by charge $\rightarrow$ **Q-balls**
Lattice simulations

[Multamaki, Vilja, 2002]
PBH formation

- Fragmentation is random process & lumps are big: large density fluctuations → density fluctuations independent from inflation

- Lumps scale as matter, in radiation background (inflaton decayed away)

- Matter perturbations grow → some collapse to black holes

- Q-balls that don’t collapse decay away, left with PBHs
Resulting PBHs
Resulting PBHs
Resulting PBHs

“PBH miracle”
"PBH miracle"

- Take SUSY scalar condensate to dominate energy density $\rho \sim \Lambda_{\text{SUSY}}^{4}$

- The horizon mass is then $m_H \sim \frac{M_{\text{Pl}}^3}{\Lambda^2} = 10^{23} \ g \left( \frac{100 \ \text{TeV}}{\Lambda_{\text{SUSY}}} \right)^2$

- Break horizon into $\sim 100$ Q-balls, take $\sim 10$ Q-balls to make typical PBH

$$m_{\text{PBH}} \sim 10^{-1} \left( \frac{M_{\text{Pl}}^3}{\Lambda^2} \right) = 10^{22} \ g \left( \frac{100 \ \text{TeV}}{\Lambda_{\text{SUSY}}} \right)^2$$
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PBH in open parameter space from low-scale SUSY!
# Production summary

<table>
<thead>
<tr>
<th>PBH Production Scenario</th>
<th>Inflationary Perturbations (common mechanism)</th>
<th>Field Fragmentation (our mechanism)</th>
</tr>
</thead>
<tbody>
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<td>Source and type of large (CMB-scale) perturbations</td>
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</tr>
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<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>
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<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>
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<td>PBH spin ($a$)</td>
<td>$a \sim 0$</td>
<td>$a \sim \mathcal{O}(1)$ possible</td>
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Novel ideas to probe open parameter space?
Compact stars as PBH laboratories

- PBHs can be effectively captured by NS or WD in DM-rich environments (e.g. Galactic Center)

- Captured PBH settle and grow inside, destroy star → new signals, can help with open problems

→ r-process nucleosynthesis, 511 keV, FRBs
  + Viewpoint Highlight by H.-T. Janka

→ solar-mass BHs, GRBs, microquasars
   VT, Phys. Lett. B., 2018]
Summary

- Renaissance era in PBH research
  → strong synergy with emerging field of multi-messenger astronomy

- Simple very general formation mechanism: scalar field fragmentation
  → avoids usual issues of fine-tuning

- SUSY provides a natural setting for PBHs as DM
  → low-scale SUSY gives interesting PBH masses