Primordial black holes from nontopological solitons

PBH Focus Week - University of Tokyo IPMU

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Work based on PRL 119 (2017) no.3, 031103 [arXiv:1612.02529] and PRD 96 (2017) no.10, 103002 [arXiv:1706.09003] (EC, Alexander Kusenko), and article in preparation (EC, Alexander Kusenko, and Volodymyr Takhistov)

Outline

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History

- Primordial black holes (PBH) were first proposed by Zeldovich, Novikov [1], Hawking [2], and Carr and Hawking [3]
- Fundamentally different from stellar BH created from the collapse of a star
- Density perturbations within the horizon can decouple from the Hubble expansion and recollapse, forming black holes with mass on the order of the horizon mass
- If perturbations enter the horizon during a radiation-dominated era, they must be over a critical density contrast $\delta_c \sim 1$ (estimates vary) to collapse
- If perturbations are within the horizon during a matter-dominated era, they can be amplified: $\delta(t) = \delta_0 a(t) = \delta_0 (t/t_0)^{2/3}$, increasing the probability of collapse

Experimental constraints

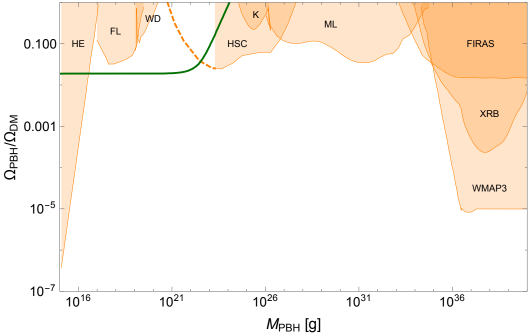


Figure 1: Summary of PBH fraction constraints assuming monochromatic mass distribution. (Kawasaki et. al. 2016 [4], Carr, Kuhnel, Sandstad 2016 [5], Inomata et. al. 2017 [6], Inoue, Kusenko 2017 [7], Fuller, Kusenko, Takhistov 2017 [8], Niikura et. al. 2017 [9]).

Sampling of production mechanisms

There are multiple different physical mechanisms which can create these PBHs

- Perturbations from inflation (Carr, Lidsey, 1993 [10], Kawasaki, Kusenko, Tada, Yanagida 2016 [4], Clesse, Garcia-Bellido 2015 [11], Garcia-Bellido, Ruiz Morales 2017 [12])
- Shrinking of cosmic strings (Hawking 1989 [13])
- Collision of bubble walls during 1st-order PT (Crawford, Schramm 1982 [14], Hawking, Moss, Stewart 1982 [15], La 1989 [16])
- Soft equation of state ($p = w\rho$ with $w \ll 1/3$) (Polnarev, Khlopov 1985 [17], Khlopov 1980 [18])

Motivation - issues

- A lot of models typically assume source of density perturbations are due to fluctuations from inflation
- Specifically requires blue power spectrum ($n_s > 1$) or positive running of the coupling ($d \ln n_s / dk > 0$) to get large power on short scales, which is disfavored by CMB
- Requires modifications to inflaton potential to get sufficient PBH abundance (flat regions/inflections)
- Is there a way around this? Is there another source of perturbations which is decoupled from inflation?

Motivation - solution

- Amplitude of Poisson fluctuations scales as $1/\sqrt{N}$, which are heavily suppressed in typical thermal bath: $N \sim \rho_R V_H/T \sim 10^{-3}(M_p/T)^3 \approx 10^{64}(T/\mathrm{MeV})^{-3}$
- But in matter dominated era, “particle" number depends on “particle" mass: $N \sim \rho_M V_H/m$
- Solitons can be created in the early universe with very large masses due to composite nature, leading to smaller number of “particles" per horizon ($10^4 \sim 10^8$)
- *Fragmentation of a scalar condensate produces its own density fluctuations from Poisson noise - no modifications to inflaton required*

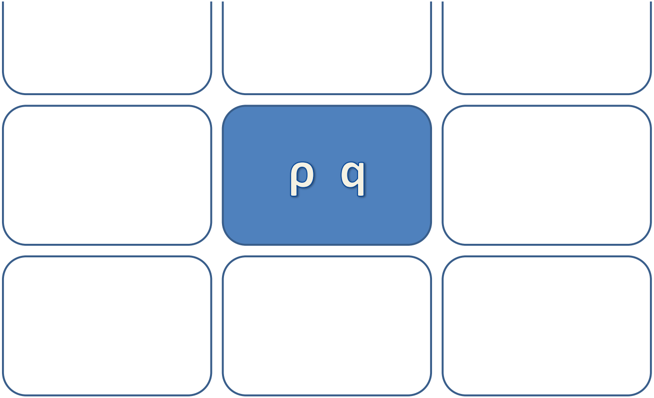
Motivation - solution

- Nonlinear mass-charge relationship ($M \propto Q^{\alpha}$, $\alpha < 1$) leads to further density perturbations, depending on the way the charges are distributed amongst the solitons
- Highly chaotic fragmentation scenario leads to nonuniform distribution of matter and large density perturbations
- Perturbations are further amplified by growth during matter/soliton dominated epoch ($\delta \propto a$), and eventually collapse into black holes ($\delta > \delta_c$)
- Many theories containing scalar fields (SUSY scalars, axion, inflaton, etc.) allow for creation of such solitons in the early universe, making this a fairly general mechanism

Summary of mechanism

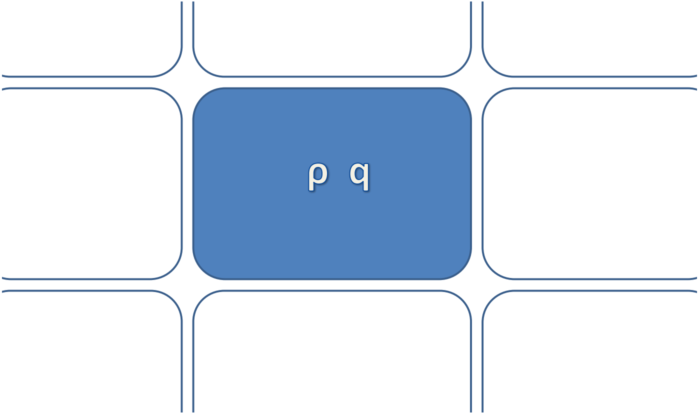
- Scalar field reaches large vev during/after inflation (Affleck-Dine mechanism for charged scalars, misalignment for axions, coherent oscillations for inflaton...)
- Condensate fragments into $10^4 \sim 10^8$ solitons per horizon of varying charge
- Stochastic/chaotic fragmentation event leads to large number/energy density fluctuations
- Since solitons are NR matter, the universe enters a MD era; soliton perturbations begin to form clusters
- Some fraction of soliton clusters collapse and form PBHs
- Solitons decay (destabilized through broken U(1), decay/evaporation to lighter particles, etc.)
- PBHs survive to present day

Some intuition – in pictures



ρ q

Some intuition – in pictures



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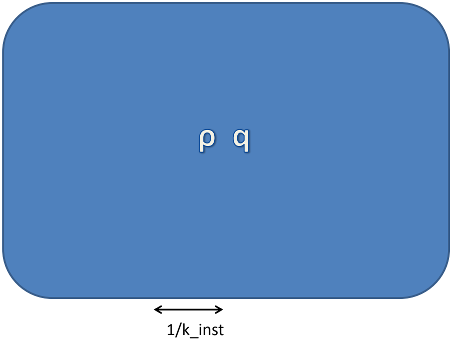
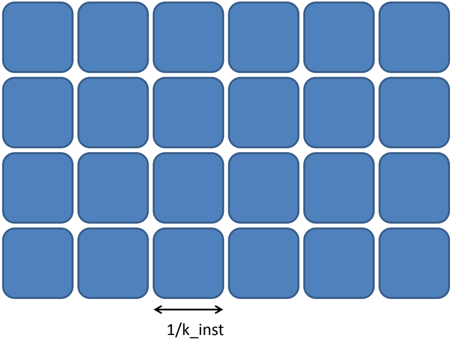


ρ q

1/k_inst

Some intuition – in pictures



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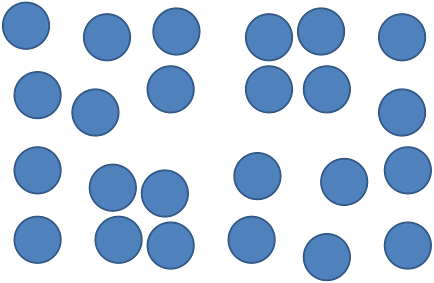

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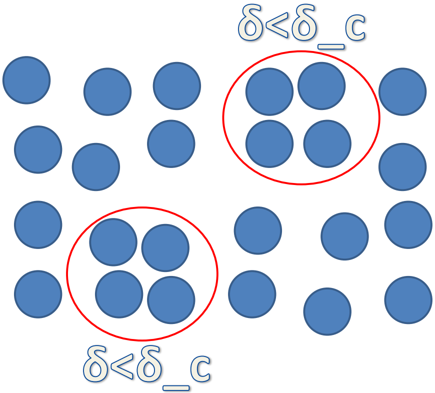

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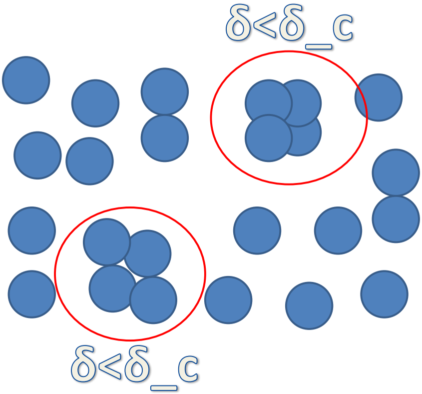

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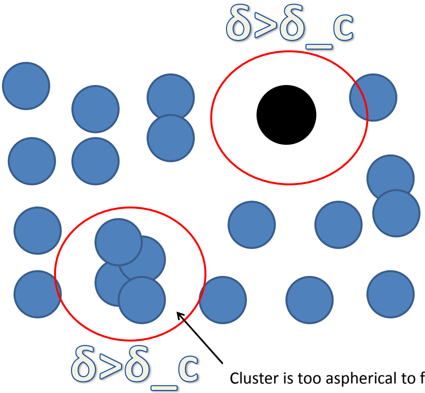
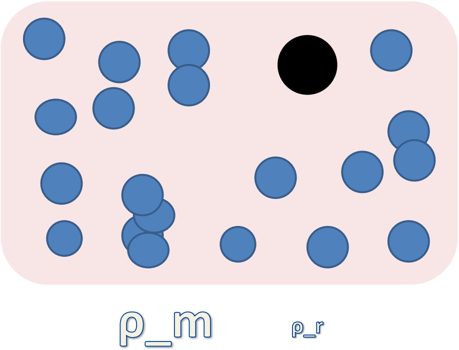


Cluster is too aspherical to form BH

Some intuition – in pictures



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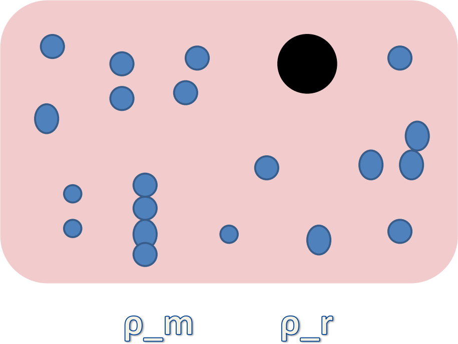

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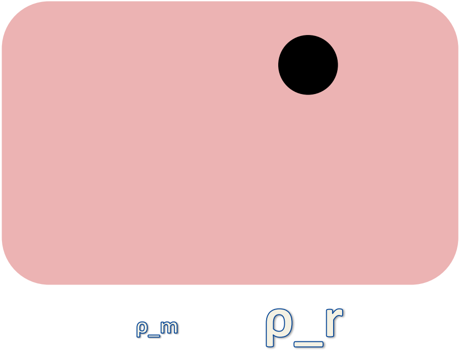

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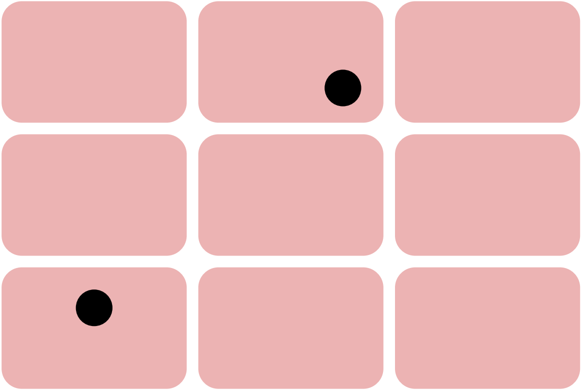


Summary of mechanism

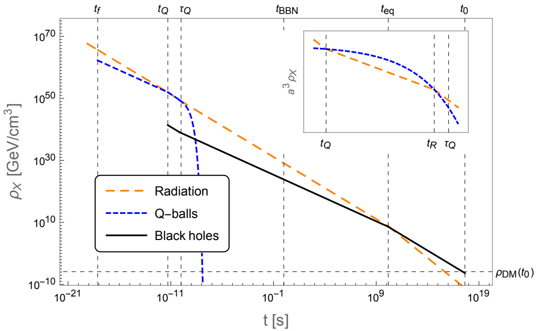


Figure 2: Diagram of cosmological evolution of the energy density of different species of interest. Inset in upper right is a close-up of region $t_Q < t < \tau_Q$, where structure growth and Q-ball decay occurs.

Outline

Primordial black holes
- Background
- Nontopological Solitons
- Physics of Q-ball clustering
- Production of PBH
- Work to be done
- Summary

Solitons

- Solitons are stable, localized solutions to field equations - field configurations with a particle-like character
- Come in two flavors: topological and nontopological:
- Topological:
    - Gain stability from a topological charge: i.e. winding/Chern-Simons number (Skyrmions, hopfions)
    - Typically associated with gauge fields: e.g. hedgehog/monopole solutions
- Nontopological (Q-balls):
    - Gain stability due to internal symmetry and energy conservation: e.g. field with U(1) symmetry, mass m and conserved charge Q can form soliton with mass $M < mQ$
    - Symmetry can be either global or gauged
    - Pseudo-stable solitons can form from systems that have approximate symmetry at low energy (e.g. oscillons/oscillitons/axitons) due to semi-conserved adiabatic charge (Kasuya, Kawasaki, Takahashi 2002 [19], Kawasaki, Takahashi, Takeda 2015 [20])

Q-balls - theory

- Q-balls have two fairly general requirements for existence:
    - Unbroken global/local symmetry and conserved charge ($\phi \to e^{i\boldsymbol{T}\cdot\boldsymbol{\theta}}\phi \implies \exists\, J^\mu$ s.t. $\partial_\mu J^\mu = 0$)
    - Region of potential exists where field energy is suppressed relative to equivalent energy of free particles ($\exists\, \phi_*$ s.t. $V(\phi_*) < m^2|\phi_*|^2$)
- Gives rise to time-dependent (oscillatory) localized solutions of the field equations $\phi(\boldsymbol{x}, t) = \phi(\boldsymbol{x})e^{i\omega t}$ with mass less than the sum of the masses of same number of free particles ($M < mQ$)

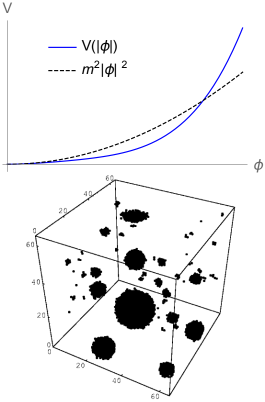


Figure 3: Q-ball simulation by Kasuya, Kawasaki [21]

Q-balls - production, evolution and interactions

- Form very naturally in supersymmetric extensions to the SM due to flat directions in scalar potential, and large number of scalar superpartners (squarks and sleptons) (Kusenko 1997 [22])
- Coherent scalar condensate $\Phi(\boldsymbol{x}, t) = \phi e^{i\theta}$ created from Affleck-Dine mechanism, where field gets large vev during inflation by jumping up the potential
- Once $V''(\phi) < \dot{\theta}^2$, condensate develops an instability and fragments into Q-balls
- Can be destabilized by breaking the symmetry through higher-dim operators, coupling to lighter degrees of freedom, etc.
  - Decay of Q-balls could also aid in baryo(lepto)-genesis
- Global U(1) symmetry $\implies$ only short-range, contact interactions - acts like pressureless dust
- Gauging the symmetry can create some interesting effects (supercurrents/magnetic dipoles, maximum size) and introduces long-range interactions (ignore these types for now)

Outline

Derivation of PDF from charge distribution I

Assume Q-ball charge Q is a random variable with PDF $f_Q(Q)$; $\int dQ\, f_Q = 1$. Mass of a collection of N Q-balls (each with mass $\Lambda |Q|^\alpha$) is

$$M = \sum_{i=1}^{N} \Lambda |Q_i|^\alpha \qquad (1)$$

where $\Lambda^4 \sim V(\langle\phi\rangle)$ and $\alpha = 3/4$ for SUSY “flat direction" (FD) Q-balls, $\alpha = 2/3$ for “curved direction" (CD) Q-balls.

Derivation of PDF from charge distribution II

PDF to find mass M composed of N Q-balls is given by

$$f_M(M|N) = \left(\prod_{i=1}^{N} \int dQ_i\, f_Q(Q_i)\right) \delta\left(M - \sum_{i=1}^{N} \Lambda |Q_i|^{\alpha}\right) \qquad (2)$$

$$\tilde{f}_M(\mu|N) = \left[\int dQ'\, e^{i\mu\Lambda|Q'|^{\alpha}} f_Q(Q')\right]^N \qquad (3)$$

$$f_Q(Q) = \delta(Q - Q_0) \implies f_M(M|N) = \delta(M - NM_0); \qquad M_0 \equiv \Lambda Q_0^{\alpha} \qquad (4)$$

Will assume monochromatic charge distribution for simplicity.
Now we need to find how N is distributed! $p(x, y) = p(x|y)p(y)$

Derivation of PDF from charge distribution III

Given $\mathcal{N}$ particles uniformly distributed in a box of volume L^3, what is probability to find $N < \mathcal{N}$ particles contained within subvolume $V \ll L^3$?

$$p(N|V) = \binom{\mathcal{N}}{N}\left(\frac{V}{L^3}\right)^N\left(1-\frac{V}{L^3}\right)^{\mathcal{N}-N} \quad \text{(Binomial dist.)} \quad (5)$$

$$\xrightarrow{\mathcal{N},L\to\infty} \quad e^{-nV}\frac{(nV)^N}{N!}, \quad n = \mathcal{N}/L^3 \quad \text{(Poisson dist.)} \quad (6)$$

Distribution normalized to unity, independent of n or V.

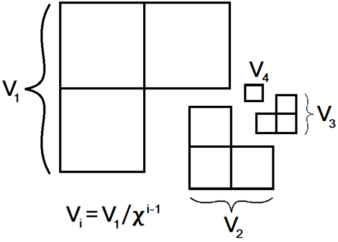
Derivation of PDF from charge distribution IV

- Results in joint distribution $F_Q(M, N|V) = f_M(M|N, V)p(N|V)$ (mixed continuous/discrete distribution), normalized for any V
  - Follows from “chain rule" of probability: $P(a, b|c) = P(a|b, c)P(b|c)$
- F_Q gives probability density (in M) for finding N Q-balls with total mass M within *fixed volume* V
- Need a method for “summing" over V to account for contributions from all relevant length scales
- Must devise a procedure to coarse-grain/smear out contributions from single scale V

Derivation of PDF from charge distribution V

$$\sum_{\{V\}} g(V) = g(V_1) + g(V_2) + \cdots = \sum_{i=1}^{I_{\max}} g(V_i) \approx \int_1^{I_{\max}} di\, g(V_1/\chi^{i-1})$$

$$= \frac{1}{\ln \chi} \int_{V_{\min}}^{V_1} \frac{dV}{V} g(V),$$



$\chi \sim$ few is factor related to degree of coarse-graining. Will assume $\chi = e$ for simplicity.

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Density perturbations

- Fluctuations in the Q-ball distribution of mass M contained within volume V give rise to a local density contrast

$$\delta_0(M, V) = \frac{\delta\rho}{\rho} = \frac{\rho - \langle\rho\rangle}{\langle\rho\rangle} = \frac{M/V}{\langle\rho_Q\rangle} - 1 \tag{9}$$

  where $\langle\rho_Q\rangle = \langle M\rangle / V = M_0 n$ is average energy density of Q-balls.
- Fluctuations grow proportional to scale factor during MD era: $\delta(t_R) = \delta_0(t_R/t_Q)^{2/3}$.
- Probability/fraction of collapse in MD era is given to be $\beta = \gamma\delta_0^{13/2}(M/M_{\rm hor})^{13/3}$, with $\gamma \approx 0.02$ (Polnarev, Khlopov 1985 [17]).
- Ensure that only overdensities with $\delta(t_R) > \delta_c$ are counted towards PBH production $\implies \beta \leftarrow \beta \times [\delta(t_R) \geq \delta_c]$

PBH density I

We calculate the average PBH energy density at redshift $a(t) > a(\tau_Q)$ by computing the average Q-ball energy at time t_f weighted by β to find the fraction that *will go into* PBHs when they form, then redshifting this appropriately:

$$\langle \rho_{\rm BH} \rangle = \left(\frac{a(t_f)}{a(t)} \right)^3 \int \frac{dV}{V} \, \langle \beta M \rangle \, \frac{V_1}{V} \frac{1}{V_1} \tag{10}$$

$$= \left(\frac{a(t_f)}{a(t)} \right)^3 \sum_{N=0}^{\infty} \int \frac{dV}{V} \int dM \, F_Q \frac{\beta M}{V} \tag{11}$$

PBH density II

Differential density spectrum as function of M can by found by dropping integral over M, and the differential DM fraction found by dividing by $\rho_{\rm DM}$:

$$\frac{d\left<\rho_{\rm BH}\right>}{dM} = \left(\frac{a(t_f)}{a(t)}\right)^3 \sum_{N=0}^{\infty} \int \frac{dV}{V} F_Q \frac{\beta M}{V} \qquad \frac{df_{\rm PBH}}{dM} = \frac{1}{\rho_{\rm DM}} \frac{d\left<\rho_{\rm BH}\right>}{dM} \tag{12}$$

Can get rough idea of contribution to dark matter fraction by looking at first equation, and exact contribution by looking at second:

$$f_{\rm PBH}(M) = M \frac{df_{\rm PBH}}{dM} \qquad f_{\rm PBH} = \int dM \frac{df_{\rm PBH}}{dM} \tag{13}$$

Radiation density

Need to ensure that thermal history is self-consistent:

- Before/after the MD era: standard cosmology:
  $\rho_R(t < t_Q) \approx \frac{\pi^2 M_p^2}{327 t^2}$
- At beginning of MD era:
  $$\rho_R = \rho_Q \implies \frac{\pi^2 M_p^2}{327 t_Q^2} = \langle \rho_Q \rangle \left(\frac{a_f}{a_Q} \right)^3 e^{-t_Q/\tau_Q}$$
- During MD era: $\rho_R =$
  $\left[\rho_{R0} + \rho_{X0} \int_{x_0}^{x} dx' \, z(x') e^{-x'} \right] z^{-4}, \quad x = \Gamma_X t, \; z = (x/x_0)^{2/3}$
  (Scherrer, Turner 1985 [23])
- Matching boundary conditions gives us
  $$e^{r_R - r_Q} \left(\frac{r_Q}{r_R} \right)^{2/3} \left[1 + r_R^{-2/3} \Gamma\left(\tfrac{5}{3}, r_Q, r_R \right) \right] = 1, \quad r_i = t_i/\tau_Q$$

Results

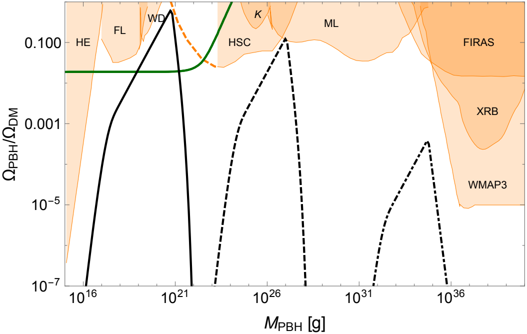

Figure 4: Plot of $f_{PBH}(M)$ together with constraints. Dark matter fraction for each curve is 1, 0.2, and 0.001 (left to right). Reheat temperature after Q-ball decay approaches BBN bound as $M_{BH} \gtrsim 1\ M_\odot$.

Preliminary oscillon results I

- PBH production from oscillons (solitons made of real scalar fields) is also possible (subject to some constraints).
  - Oscillons don't have conserved charge, so they are only approximately stable (have approximately conserved adiabatic charge (Kasuya, Kawasaki, Takahashi 2002 [19], Kawasaki, Takahashi, Takeda 2015 [20])
  - Arguments involving slicing charge up into different configurations doesn't work - need to look at energy constraints
  - Institute cutoff in density spectrum so that average density never exceeds energy density of field before fragmentation
  - Requires parametric resonance to amplify unstable wave modes, which become oscillons
- Inflaton is ideal candidate - oscillons produced in coherent oscillations after inflation ends, avoids issue of fine-tuning matter domination to coincide with soliton decay

Preliminary oscillon results II

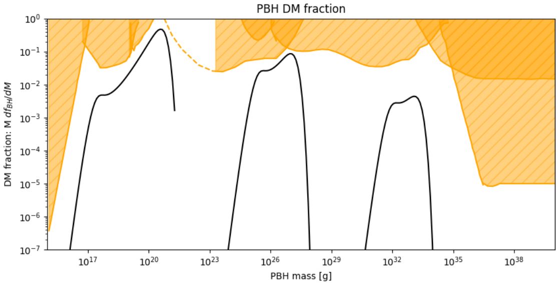

Figure 5: Comparison of predicted DM fraction of PBH generated from oscillons with observational constraints.

m_ϕ (GeV)	$t_i = 1/H_i$ (sec)	Γ_I (GeV)	t_R (sec)	$T_{\rm RH}$ (GeV)	$f_{\rm DM}$	peak $M_{\rm BH}$ (g)
5×10^{-5}	2.7×10^{-18}	9.8×10^{-11}	6.7×10^{-15}	4×10^3	1.0	3.5×10^{20}
1.5×10^{-12}	3.3×10^{-11}	9.3×10^{-17}	7.1×10^{-9}	4.3	0.23	1×10^{27}
9×10^{-19}	4.2×10^{-5}	1.9×10^{-22}	3.4×10^{-3}	5.6×10^{-3}	0.013	1.3×10^{33}

Outline

Work to be done

- Apply to models of scalar fields this mechanism could work with
    - Inflaton, axion, AD with SUSY, etc.
- Verify mechanism through numerical simulation - could be difficult since PBH only form in very small fraction of horizons.
- Investigate possible GW wave signal from early PBH production.
- Investigate effects of angular momentum during collapse and high spin (Harada, Yoo, Kohri, Nakao 2017 [24])

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Summary

- Scalar field fragmentation mechanism generates solitons in early universe
- Distribution of solitons can create very large density fluctuations in the early universe
- Leads to copious PBH production
- Advantages:
  - Possible with a variety of bosonic fields, including sfermions, inflaton, axion...
  - Does not require fluctuations from inflation to work
  - Fairly general mechanism, has potential to create PBH with sufficient abundance to explain DM

Summary

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Phys. Rev., D96(8):083517, 2017.

Backup I

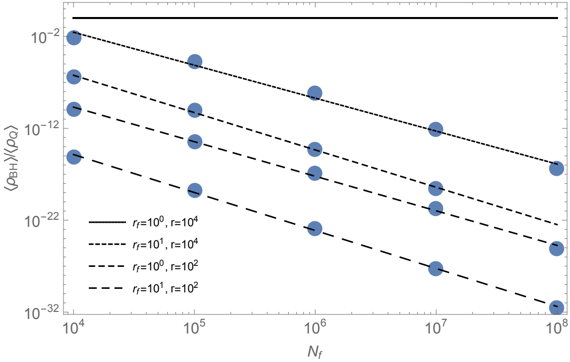
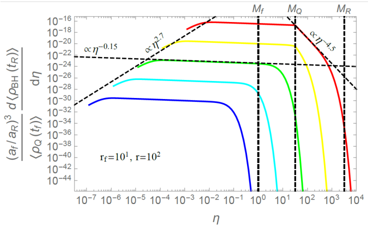
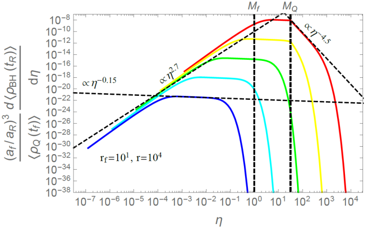


Figure 6: Fraction of Q-ball energy density that goes into PBH.

Backup II


$\frac{(a_f/a_R)^3}{\langle\rho_Q(t_f)\rangle}\frac{d\langle\rho_{BH}(t_R)\rangle}{d\eta}$
M_f
M_Q
M_R
$\propto\eta^{-0.15}$
$\propto\eta^{2.7}$
$\propto\eta^{-4.5}$
$r_f=10^1$, $r=10^2$
10^{-16} 10^{-18} 10^{-20} 10^{-22} 10^{-24} 10^{-26} 10^{-28} 10^{-30} 10^{-32} 10^{-34} 10^{-36} 10^{-38} 10^{-40} 10^{-42} 10^{-44}
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4}
η


$\frac{(a_f/a_R)^3}{\langle\rho_Q(t_f)\rangle}\frac{d\langle\rho_{BH}(t_R)\rangle}{d\eta}$
M_f
M_Q
$\propto\eta^{-0.15}$
$\propto\eta^{2.7}$
$\propto\eta^{-4.5}$
$r_f=10^1$, $r=10^4$
10^{-8} 10^{-10} 10^{-12} 10^{-14} 10^{-16} 10^{-18} 10^{-20} 10^{-22} 10^{-24} 10^{-26} 10^{-28} 10^{-30} 10^{-32} 10^{-34} 10^{-36} 10^{-38}
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4}
η

Backup III

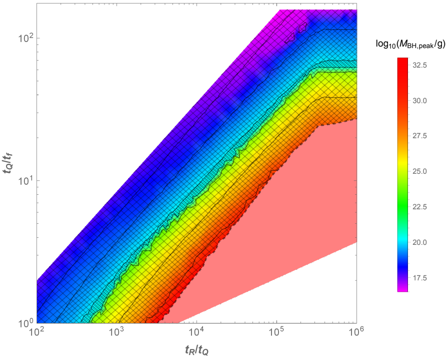


Figure 7: Parameter space available without violating experimental constraints.