Looking for Primordial Black Holes as Dark Matter in the CMB

Vivian Poulin
LAPTh and RWTH Aachen University

Based on:
V.P, J. Lesgourgues and P. Serpico
JCAP 1703 (2017) no.03, 043

VP, P. Serpico, F. Calore, S. Clesse & K. Kohri,
arXiv:1707.04206

Rencontres du Vietnam
26.07.2017
Many models in the literature, e.g.:
- From extended inflation models (Hybrid, curvaton, multi-field ...)
  - Garcia-Bellido et al., PRD54, pp. 6040–6058, 1996; Bugaev et al., PRD85, p. 103504, 2012; Kohri et al., PRD87, no. 10, p. 103527, 2013; Kawasaki et al., PRD94, no. 8, p. 083523, 2016; and many more...
- 1st and 2nd order phase transitions can lower the threshold

PBH are created by large density contrast in the early universe when they re-enter the Horizon.

PBH as Dark Matter in the CMB

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  *Carr, ApJ., 1975*

- $\zeta_c = \text{threshold for formation} \approx 1.$
  
  *Harada et al., 1309.4201*

- Masse ≈ matter in the Horizon.

- Small scales (i.e. small masses) enter first.

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  *Jedamzik & Nemeyer, PRD59, p. 124014, 1999; Rubin et al., JETP, vol. 91, pp. 921–929, 2001*
PBHs are great DM candidates

- Do not emit light;
- Non-relativistic;
- Nearly collisionless;
- Formed before BBN;
- They can be probed in many ways!
- They are subjects to many observational constraints ...

MACHOs or WIMPs ??
Could Ligo have detected Dark Matter?

- Surprisingly high masses:
  Stellar population peaks below 15 M☉
  « A new population of black holes »

- Merging rate: 14-158 Gpc⁻³ yr⁻¹
  Compatible with a population of PBH making the Dark Matter!
  
  S. Bird et al., 1603.00464
  S. Clesse & J. Garcia-Bellido, 1603.05234

LIGO/Caltech/MIT/Sonoma State (Aurore Simonnet)
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This claim is model dependent.
It could be too low...

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How to distinguish their primordial origin?
Impact of the peculiar power spectrum:

- Enhanced adiabatic primordial power spectrum
  => CMB spectral distortions.

  Chluba et al., ApJ. 758 (2012) 76
  Kohri et al., PRD90 (2014) no.8, 083514

- Iso-curvature modes further enhanced by non-gaussianity
  => CMB anisotropies / Large Scale Structures.

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**Impact of the PBHs:**

- PBH of small masses can evaporate into SM particles.

  Carr et al., PRD81 (2010) 104019

- PBH of high masses can accrete matter, leading to photon emission.

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PBH & the CMB

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We revisit evaporation and accretion with an improved treatment
==> leads to stronger & more realistic constraints
E.m. energy injection can modify the ionization and temperature history

\[
\frac{dx_e}{dz} = \frac{1}{(1 + z)H(z)} \left[ R_s(z) - I_s(z) - I_X(z) \right]
\]

\[
\frac{dT_M}{dz} = \frac{1}{1 + z} \left[ 2T_M + \gamma(T_M - T_{CMB}) + K_h \right]
\]

\[I_X(z) \text{ and } K_h(z) \propto \frac{dE}{dV dt}\mid_{\text{dep,c}}\]

The « three levels atom »
Peebles 1968
Zeldovich, Kurt, Sunyaev 1968
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Typical parametrization through the \( f_c(z, x_e) \) functions:

\[ \left. \frac{dE}{dV dt} \right|_{\text{dep,c}}(z) = f_c(z, x_e) \left. \frac{dE}{dV dt} \right|_{\text{inj}}(z) \]

Slatyer 2015, arXiv:1506.03812

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\( f_c(z, x_e) \) is the key quantity, it encodes:

- What fraction of the injected energy is left to interact with the IGM
- How this energy is distributed among each channel: 'heat', 'ionization', 'excitation'
Problematic of accretion onto a point mass $M$ is old: seminal papers focused on accretion by star in an infinite gas cloud.

*Hoyle & Lyttleton, 1939, 1940; Bondy & Hoyle 1944; Bondi 1952*

Famous result by Bondi derived in the context of spherical accretion

\[
\dot{M}_{\text{HB}} = 4\pi \lambda \rho_{\infty} v_{\text{eff}} r_{\text{HB}}^2 \equiv 4\pi \lambda \rho_{\infty} \frac{(GM)^2}{v_{\text{eff}}^3}
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Essential on PBH accretion

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This is a « geometrical » result ! Area of an accreting sphere of radius $r_{\text{HB}} = GM/v_{\text{eff}}^2$

what is $v_{\text{eff}}$? No exact calculation exists... Proxy: $v_{\text{eff}}^2 = c_{s,\infty}^2 + v_{\text{rel}}^2$
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  - Relative velocity between gas & BH

- $\lambda \approx 1$: accretion eigenvalue. Take into account gas pressure, interaction with CMB...
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The accreted matter gets heated $T_S \approx 10^9 - 10^{11}$K: bremsstrahlung emission.

\[
L = \epsilon \dot{M}_{HB} c^2 \quad \epsilon \simeq 10^{-3} - 10^{-5} \frac{\dot{M}}{\dot{M}_{\text{edd}}} \quad L_\nu \propto \nu^{-0.5} \exp(-\nu/T_S) \quad \text{Shapiro 1973, 1974}
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This formalism is applied to disk accretion with appropriate values:

\[ \lambda \approx 10^{-1} - 10^{-2} \quad \epsilon \approx 10^{-1} - 10^{-3} \frac{\dot{M}}{\dot{M}_{edd}} \quad \text{Review: Narayan&Yuan 2014} \]
Current constraints on accreting PBH

- Until now: CMB constraints obtained with this formalism, assuming spherical accretion holds.

- Exercise is thus to compute the right $v_{\text{rel}}$, $\lambda$, and $\epsilon$.

- Ricotti et al, 2007: PBH as 100% of the DM with masses $M > 0.1 M_{\odot}$ are excluded!  

- But wrong $v_{\text{rel}}$ and $\epsilon$... Ali-Haimoud & Kamionkowski: $M > 100 M_{\odot}$ (conservative case).  
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Is spherical accretion a good approximation??

If the accreted gas has a high angular momentum, it cannot fall straight onto the BH.

Energy is dissipated but angular momentum is conserved ==> Accretion disk forms.

How high should be the angular momentum?

=> Keplerian angular momentum for a rotation around the BH at a distance $r_D$.

$$l_D \simeq r_D v_{\text{Kep}}(r_D) \simeq \sqrt{GMr_D}$$

Now the (specific) angular momentum is simply

\[ l \approx \left( \frac{\delta \rho}{\rho} + \frac{\delta v}{v_{\text{eff}}} \right) v_{\text{eff}} r_{\text{HB}} \]

Density gradients perp. to the BH motion

Typical velocity dispersion on small scales
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Typical velocity dispersion on small scales

We find that the radius of the disk \( r_D \gg r_S \) if:

\[
\left. \frac{\delta \rho}{\rho} \right|_{k \sim r_{BH}^{-1}} \gg 10^{-4}
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\delta v \gg 1.5 \left( \frac{1+z}{1000} \right)^{3/2} \text{ m/s}
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This is easily satisfied because of the enhanced power spectrum on small scales!

At \( z=1000 \), \( k_{\text{NL}} \approx 10^3 \text{Mpc}^{-1} \ll k_{\text{BH}} \approx 10^5 \text{Mpc}^{-1} \)

Gong&Kitajima, 1704.04132
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Although spherical accretion leads to conservative constraints, in the early universe, it seems unrealistic!
What disk forms?

- Optimistic: Thin Disk, high radiative efficiency, leads to the strongest constraints.
- Caveat: never observed, probably not realise in nature.

Review: Narayan & Yuan 2014

Shakura & Sunyaev 1973
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- More realistic and conservative: Thick disk with inefficient cooling — **ADAF** (Advection Dominated Accretion Flow).
  - Results of numerical simulations confirmed by observations!
  - Relatively low radiative efficiency and accretion rate.

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CMB constraints

Quy Nhon, 26.07.2017

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Vivian Poulin - LAPTh/RWTH
PBH as Dark Matter in the CMB

Review: Narayan&Yuan 2014
Ichimaru 1977, Narayan&Yi 1994
Xie&Yuan 2012
Energy deposition function

- Power law shape up to 100 keV energies from synchrotron and bremsstrahlung.
- Depend on PBH mass and accretion rate.

Review: Narayan & Yuan 2014

Delayed recombination, higher freeze-out plateau, early reionization
Impact on the CMB power spectra

- Delayed recombination: shift peaks and damping tail enhanced.
- Early reionization: step-like suppression and reionization bump enhanced.

\[ C_{\ell}^{TT} = \frac{1}{2\pi} [\ell(\ell+1)C_{\ell}] \]

\[ C_{\ell}^{EE} = \frac{1}{2\pi} [\ell(\ell+1)C_{\ell}] \]

\[ M_{PBH} = 30M_\odot, \lambda_{ADAF} = 10^{-2} \]

V.P, J. Lesgourgues and P. Serpico
JCAP 1703 (2017) no.03, 043
Constraints on disk-accreting PBH

VP, P. Serpico, F. Calore, S. Clesse & K. Kohri, arXiv:1707.04206

- We find constraints from two to three orders of magnitude stronger.
- Main uncertainty: relative velocities between PBH and baryons.
- Could be improved thanks to better understanding of PBH/baryons structures.
PBH is a great DM candidate:

- All good properties, can get good relic abundance and many ways to test the scenario.
- Unfortunately there are already many strong constraints.
**Take-Home message**

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I presented CMB constraints on:
- The very high masses — accreting — PBHs: until now all studies have assumed spherical accretion.
- This approximation is unrealistic: a disk should form typically after recombination.
- Conservatives constraints are two orders of magnitude stronger: \( M > 2M_\odot \).
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CMB can also constrain evaporating PBH: *Poulin et al.*
- They are **as good as or better** than EGB constraints.

*Poulin et al.*

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CMB can also constrain merging rate of PBH! (see my poster)
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**Next step:**
- Improve understanding of non-linear PBH structures and the capture of baryons.
- Revisit constraints on the power spectrum itself.
Thanks for your attention!
PBH are created by large density contrast in the early universe;


Credit: Sebastien Clesse
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When a local density fluctuation exceeds some threshold value, it collapses gravitationally and form a primordial black hole.

\[ \zeta_c = \text{threshold for formation} \approx 1 \]

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$\zeta_c = \text{threshold for formation} \approx 1$

If fluctuations are gaussian, fraction of PBH at formation is:

$$\beta \equiv \frac{\rho_{PBH}}{\rho_{total}} \bigg|_{\text{formation}} \approx \int_{\zeta_c}^{\infty} P(\zeta) \, d\zeta,$$

$$\beta \simeq \frac{1}{\sqrt{2\pi}\sigma} \int_{\zeta_c}^{\infty} \exp\left(-\frac{1}{2} \frac{\zeta^2}{\sigma^2}\right) \, d\zeta = \frac{1}{2} \text{erfc}\left(\frac{\zeta_c}{\sqrt{2}\sigma}\right).$$

$\zeta_c \approx 1 \implies \sigma(k) = P(k)^{1/2} \text{ of } \approx 1$


Harada et al., 1309.4201

Credit: Sebastien Clesse
Rough power law shape from synchrotron and bremsstrahlung;
Depend on PBH mass (right panel) and accretion rate (left panel)
Energy deposition function

- Heat
- Spherical accretion
- Ionization
- 30 $M_\odot$
- 1000 $M_\odot$

Energy deposition function $f_c(z)$

$1+z$

$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
\[
\frac{dn}{dM} = \frac{1}{\sqrt{2\pi}\sigma M} \exp\left(\frac{-\log_{10}(M/\mu_{\text{PBH}})^2}{2\sigma_{\text{PBH}}^2}\right)
\]
Density contrast

\[ \frac{\delta \rho}{\rho} \bigg|_{k \sim r_{BH}^{-1}} \gg 10^{-4} \]

- No IC Modes
- \( M_{PBH} = 1 \, M_\odot \)
- \( M_{PBH} = 100 \, M_\odot \)
- \( M_{PBH} = 10^4 \, M_\odot \)

\( z = 1000 \)
Constraints for WIMP DM

Bringmann, Scott & Akrami 1110.2484
In the L.O.S formalism:

(Here, I only recall computation of Temp. anisotropies at 1st order, Newt. gauge)

\[ C_{\ell}^{\text{TT}} = \int \frac{dk}{k} \mathcal{P}_{R}(k) [\Theta_{\ell}(\tau_{0}, k)]^{2} \]

\[ \Theta_{\ell}(\tau_{0}, k) = \int_{\tau}^{\tau_{0}} d\tau S_{T}(\tau, k) j_{\ell}(k(\tau_{0} - \tau)) \]

\[ S_{T}(k, \tau) \equiv g(\Theta_{0} + \psi) + (gk^{-2}\theta_{B})' + e^{-\kappa}(\phi' + \psi') + \text{polarisation} \]

\[ g(\tau) \equiv -\kappa' e^{-\kappa} \quad \kappa(\tau) = \int_{\tau}^{\tau_{0}} d\tau \sigma_{Tan} n_{e} x_{e} \]

Temperature power spectrum

Transfer function

Temperature source function

Visibility function, optical depth
From perturbation to power spectrum

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Temperature power spectrum

Transfer function

Temperature source function

Visibility function, optical depth

e.m. energy injection: modify visibility function \( g \) and optical depth \( \kappa \)

see e.g. textbook « The Cosmic Microwave Background » by R. Durrer; « Neutrino Cosmology » By Lesgourgues et al. or original papers Seljak & Zaldarriaga APJ. 469 (1996) 437-444; Kamionkowski et al. PRD55 (1997) 7368-7388
BHs emit SM particles with a black body spectrum at a temperature

\[ T_{\text{BH}} = \frac{1}{8\pi GM} \simeq 1.06 \left( \frac{10^{10} \text{g}}{M} \right) \text{TeV} \]

\textit{nb: Our formalism is reliable for } M < 10^{17} \text{g}

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Energy injection rate is proportional to the mass-loss rate

\[ \frac{dE}{dV \, dt}_{\text{ini, PBH}} = \frac{\Omega_{\text{DM}} \rho c^2 (1+z)^3 f_{\text{PBH}} c^2}{M_{\text{PBH}}} \frac{dM}{M_{\text{ini}} \, dt}_{\text{e.m.}} \]

\[ \frac{dM}{dt} = -5.34 \times 10^{-15} \mathcal{F}(M) M^{-2} \text{ g s}^{-1} \]
Evaporating PBH

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\[ \left. \frac{dM}{dt} \right|_{\text{e.m.}} = -5.34 \times 10^{-15} F(M) M^{-2} \text{ g s}^{-1} \]


- Constraints on evaporating PBH

\[ M_{PBH} = 10^{15} g, \quad M_{PBH} = 5 \times 10^{16} g \]

Energy deposition function \( f_c(z) \)

- Ionization

- Heating

Ionization fraction \( x_e(z) \)

- \( f_{PBH} = 1 \), \( M_{PBH} = 5 \times 10^{16} g \)

- \( f_{PBH} = 10^{-7} \), \( M_{PBH} = 10^{15} g \)

- \( f_{PBH} = 10^{-8} \), \( M_{PBH} = 5 \times 10^{13} g \)

- No evaporating PBH

\( z_{reio} = 8.24 \)
CMB dominates at low masses and is very competitive until $3 \times 10^{16} \text{g}$!
Constraints on « monochromatic » population

Extrapolation to broad mass spectrum can be non-trivial...

B. Carr et al., 1705.05567