# Can massive primordial black holes be the dark matter?

### Sébastien Clesse

based on: S.C., J. Garcia-Bellido, arXiv:1501.07565, arXiv:1603.05234

RWTH - Aachen University Institute for Theoretical Particle Physics and Cosmology (TTK)

Rethinking Quantum Field Theory DESY theory workshop Hamburg, 2016, September 27-30





### Dark Matter

Primordial Black Holes

PBH in Hybrid Inflation

Constraints on PBH abundances

After the GW detection by aLIGO/VIRGO...

Observable predictions

Conclusion and Perspectives Dark Matter accounts for  $\Omega_{\rm DM}=0.266\pm0.013$  of the Universe's energy density today (Planck 2015)

Observational evidences: CMB, weak gravitational lensing, galaxy rotation curves, large scale structures...



DM must be nearly collisionless, non relativistic and stable

- A Weakly Interacting Massive Particle (WIMP)
- Axion, LSP, gravitino, others...
- Black holes: the only already known candidate, but they must be massive and primordial



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- Primordial Black Holes (PBH) formed in the early Universe when sufficiently important density fluctuations collapse gravitationally
- When the size of the fluctuation becomes smaller than the Hubble horizon:  $k \leftrightarrow t$  so that  $k = a(t)H(t) \leftrightarrow M = \frac{M_{\rm pl}^2}{H_{\rm inf}} e^{2N_k}$
- $\bullet$  Fraction  $\beta$  of the Universe collapsing into PBH of mass M at  $t_M$  :

$$\beta^{\text{form}}(M) \equiv \left. \frac{\rho_{\text{PBH}}(M)}{\rho_{\text{tot}}} \right|_{t=t_k} = 2 \int_{\zeta_c}^{\infty} \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{\zeta^2}{2\sigma^2}} d\zeta$$

variance related to the power spectrum of curvature (density) fluctuations  $\sigma^2 = \mathcal{P}_{\zeta}(k_M)$ 

- Model parameter: threshold curvature fluctuation  $0.01 \lesssim \zeta_c \lesssim 1$  ( e.g.  $\zeta_c = 0.086$  in Harada et al., 1309.4201)
- At the time of formation,  $\beta \ll 1$ , but  $\rho_{\rm PBH} \propto 1/a^3$  whereas  $\rho_{\rm rad} \propto 1/a^4$  and thus one can have  $\beta \sim \mathcal{O}(1)$  and  $\Omega_{\rm PBH} = \Omega_{\rm DM} \simeq 0.27$  today.



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Conclusion and Perspectives Inflation with two scalar fields ( $\phi$  and  $\psi$ )  $\rightarrow$  HYBRID INFLATION It's like playing mini-golf... but the goal is to avoid the holes!



Fast waterfall: usual regime (less than 1-efold)  $\rightarrow$  DISFAVORED Mild waterfall: inflation continues... (> 60 e-folds)  $\rightarrow$  RULED OUT Transitory case: a few tens of e-folds (CMB  $\rightarrow$  inflation in the valley)



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$$V(\phi,\psi) = \Lambda \left[ \left( 1 - \frac{\psi^2}{M^2} \right)^2 + \frac{(\phi - \phi_{\rm c})}{\mu_1} - \frac{(\phi - \phi_{\rm c})^2}{\mu_2^2} + \frac{2\phi^2\psi^2}{M^2\phi_{\rm c}^2} \right]$$

Along  $\psi = 0$ , experts will recognize the first terms of a Taylor expansion of logarithmic radiative corrections (as in F-term, D-term, loop inflation)



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Conclusion and Perspectives Power spectrum of curvature perturbations calculated

- Numerically using the multi-field theory cosmological perturbations
- $\bullet$  Analytically and numerically using the  $\delta N$  formalism



Broad peak in the power spectrum Position, width and amplitude fixed by  $\Pi \equiv M \sqrt{\phi_c \mu_1} / M_{\rm pl}^2$ 



# Our model - PBH mass spectrum

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...and let PBH evolve until matter-radiation equality....



- ullet Surprisingly, reasonable values of  $\zeta_c 
  ightarrow$  Dark Matter abundance
- ullet Relatively broad spectrum, PBH mass related to the parameter  $\mu_1$



# **Constraints on PBH abundances**



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 $ightarrow 10-100 M_{\odot}$  still allowed



# Possible link with the aLIGO/VIRGO discovery

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# In September 2015, Advanced LIGO / VIRGO detected the merging of two BHs of 36 and 29 solar masses

Inferred merging rate:  $2 - 400 yr^{-1} Gpc^{-3}$ 

3H masses beyond expectations:

- More exotic scenario for the formation of BH binaries?
- The sign of a whole population of massive PBHs?

Is the inferred merging rate consistant with PBH dark matter ? S.C., J. Garcia-Bellido, 1603.05234, S. Bird et al., 1603.00464, M. Sasaki et al., 1603.08338

- No, if PBHs are uniformly distributed in the halo of massive galaxies
- Yes, if PBHs are regrouped in sub-halos such as ultra-faint dwarf galaxies



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# PBH merging rates - sharp vs. broad mass spectrum

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Conclusion and Perspectives 1. Sharp mass spectrum (all PBH have the same mass):

 $\tau \simeq 1.4 \times 10^{-8} f_{\rm DM} \delta_{\rm PBH}^{\rm loc} {\rm yr}^{-1} {\rm Gpc}^{-3}$ 

Density contrast  $\delta_{\rm PBH}^{\rm loc} \sim 10^{10} - 10^{11} \rightarrow {\rm LIGO}$  rates

### $\sim$ DM density contrast in ultra-faint dwarf galaxies

This may solve several problems :

- Missing satellite problem
- Too big to fail problem
- 9 Features in the X-ray and Infrared background
- 4 Lack of micro-lensing events
- § Broad spectrum: subdominant  $\sim 10^5 M_{\odot}$  seeds of sumermassive and intermediate BH
- 2. Broad mass spectrum



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# PBH merging rates - sharp vs. broad mass spectrum



Merging rates of BHs with masses  $m_{\rm A}$  and  $m_{\rm B}$ , the color scale representing  $\log(\tau \ {\rm yr} \ {\rm Gpc}^3)$ .

Reconstruction of the PBH mass spectrum with  $\sim \mathcal{O}(10^3)$  merging events



# **Observable predictions**

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- Merging events  $\rightarrow$  LIGO, VIRGO...
- Background of gravitational waves  $\rightarrow$  LIGO, VIRGO, eLISA, DECIGO, PTAs...
- $\textbf{0} \quad \text{Detection of ultra-faint dwarf galaxies} \rightarrow \textbf{DES, Euclid}$
- Correlated anomalies in the CIB and XCB, A. Kashlinski, 1605.04023
- Intersection State S
- $\textcircled{O} X\mbox{-ray heating due to PBH} \rightarrow \mbox{ionization of the IGM at high redshifts} \rightarrow 21\mbox{cm signal}$ 
  - $\rightarrow$  Square Kilometre Array (SKA)
- CMB distortions  $\rightarrow$  **PIXIE**
- I Heating of ultra-faint dwarf galaxies, A. Green, 1609.01143

### Testable scenario within the next few years!



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### 1. Dark Matter can be made of massive PBH

### 2. PBH regrouped in sub-halos → aLIGO merging rates

**3. Fully testable scenario in many ways and epochs** [aLIGO/VIRGO, eLISA, Planck, PIXIE, CORE, DES, GAIA, SKA, Euclid)

4. Link with QFT? Formation mechanism! Inflation: (SUSY/SUGRA/GUT) Hybrid inflation Phase transitions: QCD  $\rightarrow 10 - 100M_{\odot}$ 



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### Thank you for your attention



# Background of gravitational waves (preliminary)

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# Generalities about inflation

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# Slow-roll single-field inflation

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### Inflaton field $\phi$ evolves slowly along its potential $V(\phi)$

### Slow-roll dynamics

$$\begin{split} H^2 &= \frac{V(\phi)}{3M_{\rm pl}^2} \text{ and } 3H\dot{\phi} = -\frac{\mathrm{d}V}{\mathrm{d}\phi} \\ \text{Hubble-flow (slow-roll) parameters: } \epsilon_0 &\equiv \frac{H_{\rm ini}}{H} \text{ and } \epsilon_{i+1} \equiv \frac{\mathrm{d}\ln|\epsilon_i|}{\mathrm{d}N} \\ \text{In slow-roll : } \epsilon_1 &\simeq \frac{M_{\rm pl}^2}{2} \left(\frac{V,\phi}{V}\right)^2 \qquad \epsilon_2 \simeq 2M_{\rm pl}^2 \left[ \left(\frac{V,\phi}{V}\right)^2 - \frac{V,\phi\phi}{V} \right] \end{split}$$

### Observable predictions

Cosmological perturbations:

$$\phi(x,t) = \bar{\phi}(t) + \delta\phi(x,t), \qquad g_{\mu\nu} = \bar{g}_{\mu\nu} + \delta g_{\mu\nu}$$

- Scalar power spectrum amplitude:  $A_{
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- Scalar spectral index:  $n_{\rm s} = 1 2\epsilon_1 \epsilon_2$
- Tensor to scalar ratio:  $r \simeq 16\epsilon_1$

evaluated at  $t_*$  when the pivot scale  $k_* = 0.05 \,\mathrm{Mpc}^{-1}$  exits the Hubble radius  $(k_* = a(t_*)H(t_*))$ 



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# After Planck...

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### Contraints on $n_{\rm s}, r...$ (Planck 2015, 1502.02111)



If two scalar fields ( $\phi$  and  $\psi$ )  $\rightarrow$  HYBRID INFLATION

Playing hybrid inflation is like playing mini-golf... but the aim is to avoid the holes!



# After Planck...

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Problems with hybrid inflation:

- Original model (in the vacuum dominated regime) predicts  $n_{\rm s}>1$   $\rightarrow$  RULED OUT
- Supersymmetric realizations (F-term and D-term):  $0.98 \lesssim n_{\rm s} \lesssim 1$   $\rightarrow$  STRONGLY DISFAVORED
- Mild waterfall case ?  $n_{\rm s} \simeq 1-4/N_{k_{\rm p}} \lesssim 0.94$   $\rightarrow$  RULED OUT

Transitory case + two-field potential:

$$V(\phi,\psi) = \Lambda \left[ \left( 1 - \frac{\psi^2}{M^2} \right)^2 + \frac{(\phi - \phi_c)}{\mu_1} - \frac{(\phi - \phi_c)^2}{\mu_2^2} + \frac{2\phi^2\psi^2}{M^2\phi_c^2} \right]$$

Along  $\psi = 0$ , experts will recognize the first terms of a Taylor expansion of logarithmic radiative corrections (as in F-term, D-term, loop inflation)

•  $n_{\rm s} = 1 - \frac{4M_{\rm Pl}^2}{\mu_2^2}$  (dominated by  $\epsilon_2$ , i.e. the curvature of the potential) •  $\mathcal{P}_{\zeta}(k_{\rm p}) = \frac{\Lambda \mu_1^2}{12\pi^2 M_{\rm pl}^6} \left(\frac{k_{\rm p}}{k_{\phi c}}\right)^{n_{\rm s}-1}$ 



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### Summary of the model

- $\textbf{0} \text{ Hybrid inflation} + \text{mid-mild waterfall} \rightarrow \text{broad peak in } \mathcal{P}_{\zeta} \rightarrow \text{PBH}$
- In Right abundances for Dark Matter
- Passes all present astronomical constraints
- Seeds for SMBH at the center of galaxies and IMBH

### Possible link with the Advance LIGO discovery

- LIGO inferred merging rates if PBH are clustered
- Natural candidate: ultra-faint dwarf galaxies
- I A solution to missing satellites and too-big-to-fail problems
- Explains anomalies in the CIB and XCB
- Operation of the second sec



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- $\textbf{9} \quad \text{Microlensing, position and velocity of stars} \rightarrow \textbf{GAIA}$
- **2** 21cm signal at reionization  $\rightarrow$  Square Kilometre Array (SKA)
- $\textbf{O} CMB \text{ distortions} \rightarrow \textbf{PRISM-like mission}$

### Perspectives

- Background of gravitational waves
- Merging history (N-body simulations)
- 8 Refined picture for D-term inflation
- Influence of quantum diffusion at the critical instability point
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- Iink with GC excess?



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# Distortions of the CMB black-body spectrum

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- $\rightarrow$  Energy injection before last scattering
- $\rightarrow$  Spectral distortions of the CMB black-body spectrum

Peak in  $\mathcal{P}_{\zeta}$  at small scales  $\rightarrow$  CMB distortions are enhanced



# Our model of Primordial Black Holes Dark Matter in a sketch...



Sébastien Clesse (RWTH)