Massive Primordial Black Holes from Inflation as Dark Matter and the seeds of Galaxies

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based on:
S.C., J. Garcia-Bellido, arXiv:1501.07565
S.C., J. Garcia-Bellido, *in preparation*

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Outline

Massive Primordial Black Holes from Inflation as Dark Matter and the seeds of Galaxies

Dark Matter

Dark Matter accounts for $\Omega_{\rm DM} = 0.266 \pm 0.013$ of the Universe's energy density today (`Planck 2015 release`)

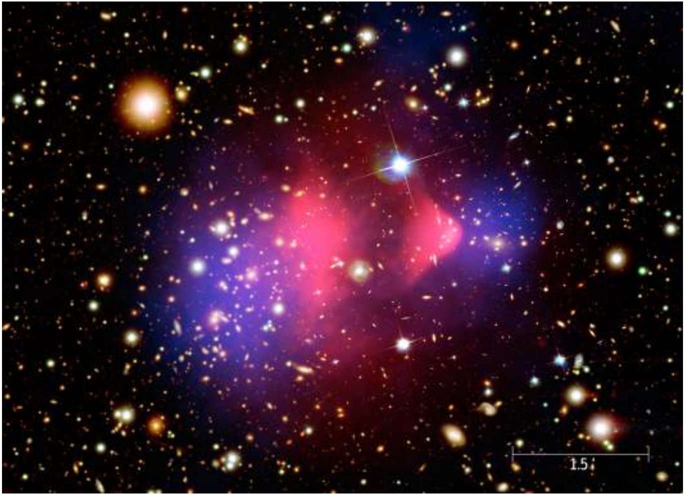
Observational evidences:

- Cosmic Microwave Background - Angular power spectrum of temperature fluctuations
- Weak gravitational lensing from galaxy clusters (e.g. Bullet Cluster)
- Galaxy rotation curves
- Large Scale Structures (BAO oscillations), SN-Ia...
- N-body simulations of structure formation

What could be Dark Matter?

- A Weakly Interacting Massive Particle (WIMP)
- A Massive Compact Halo Object (MACHO) e.g. **Primordial Black Holes (PBH)**
- others....

Bullet Cluster (HST): Mass distribution reconstructed from weak lensing vs. X-ray observations by Chandra



Primordial Black Holes

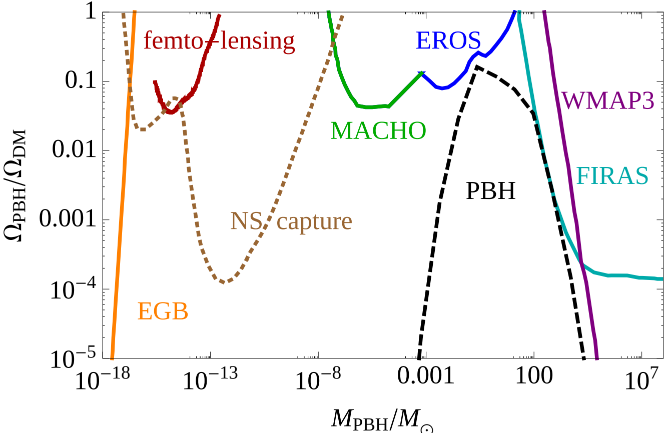
- Primordial Black Holes (PBH) formed in the early Universe when sufficiently important density fluctuations collapse gravitationally
- When the size of the fluctuation becomes smaller than the horizon: $k \leftrightarrow t \leftrightarrow M$
- Fraction β of the Universe collapsing into PBH of mass M at time of formation t_M :

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

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

- Critical density fluctuation ζ_c taken as a model parameter with $0.01 \lesssim \zeta_c \lesssim 1$ (e.g. $\zeta_c = 0.086$ for a three zones model `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.

Constraints on PBH abundances:



Massive Primordial Black Holes - Seeds of galaxies

Recent hints in favor of massive PBH:

- Discovery by Chandra and XMM-Newton of tens BH candidates in central region of M31 (more than expected),
  `Barnard et al., 1406.6091`
- Alignement of DM with light distribution in galaxy cluster collisions
  `Soucail et al., 1505.01031`

Problems with the standard picture of structure formation:

- Formation of supermassive BH (SMBH) ($m_{BH} \sim 10^{10} M_\odot$) at high redshift (up to $z \sim 7$ quasars)
  $\rightarrow$ Typically needs $10^5 M_\odot$ seeds
- Ultra-luminous X-ray sources $\rightarrow$ Itermediate Mass BH (IMBH)

Massive PBH + broad spectrum $\rightarrow$ Seeds of galaxies (in the queue of the spectrum)?

Inflation

Inflation: quasi-exponential expansion ($\times e^{60}$ in 10^{-35}s)
Solving some problems of the standard cosmological model:

- Horizon problem (CMB identical in regions apparently causally disconnected)
- Flat Universe
- Nearly scale invariant spectrum of density fluctuations (slope $n_s - 1$ with scalar spectral index $n_s = 0.968 \pm 0.006$)

How to realize inflation?

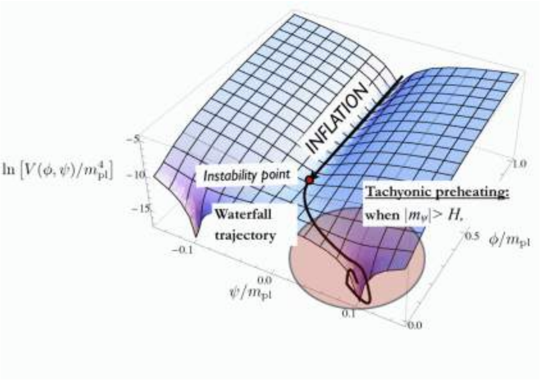
- Fill the Universe with an homogeneous scalar field
- Apply the laws of general relativity
- If the log of the scalar field potential is flat $\rightarrow$ INFLATION
- Quantum fluctuations during inflation $\rightarrow$ Nearly scale-invariant spectrum of density fluctuations

If two scalar fields (ϕ and ψ) $\rightarrow$ HYBRID INFLATION

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

Inflation

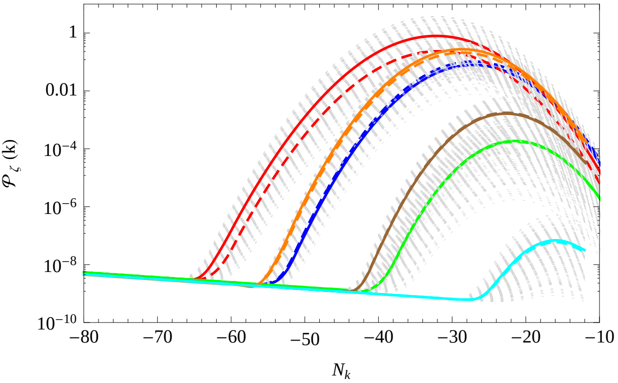
The playing field is the ($\log$ *of the) scalar field potential*



Fast waterfall: usual regime (less than 1-efold)
Mild waterfall: inflation continues... (more than 60 e-folds)
Transitory case: a few tens of e-folds, observable modes of density fluctuations probe inflation in the valley → **our model!**

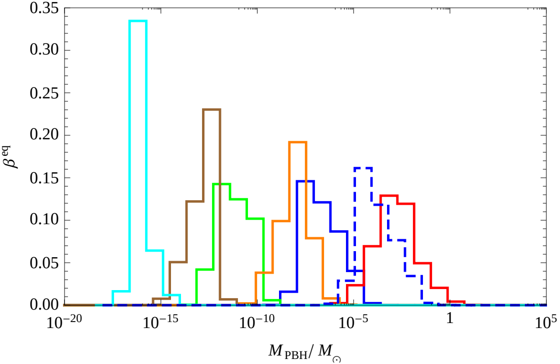
Our model and its observable predictions

Multi-field linear theory of cosmological perturbations:
$g_{\mu\nu}(x) = \bar{g}_{\mu,\nu} + \delta g_{\mu,\nu}(x)$, $\phi(x) = \bar{\phi} + \delta\phi(x)$, $\psi(x) = \bar{\psi} + \delta\psi(x)$
Power spectrum of density (curvature ζ) fluctuations:



Our model and its observable predictions

Then use your formula for PBH formation, and let PBH evolve until matter-radiation equality....



Open question: how efficient is PBH merging from this time?

Our model and its observable predictions

Summary of the model

1. Hybrid inflation with a broad peak in $\mathcal{P}_z eta$
2. PBH formation
3. Good abundances for Dark Matter
4. Seeds for SMBH in the center of galaxies
5. Passes all present astronomical constraints

Observable predictions

1. Microlensing events (and matching with X-ray sources) $\rightarrow$ **GAIA mission**
2. More stellar mass BH than expected in nearby galaxies $\rightarrow$ **Chandra, XMM-Newton**
3. Background of gravitational waves $\rightarrow$ **eLISA mission**
4. CMB distortions $\rightarrow$ **PRISM-like mission**

If those are not observed $\rightarrow$ MODEL KILLED
If all are observed $\rightarrow$ STRONG EVIDENCE

Thank you for your attention