Could massive primordial black holes be the dark matter?

Sébastien Clesse

based on:

S.C., J. Garcia-Bellido

arXiv:1501.07565, arXiv:1603.05234, arXiv:1610.08479

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Institute for Theoretical Particle Physics and Cosmology (TTK)

RWTH AACHEN UNIVERSITY

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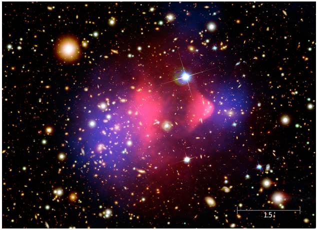
Outline

1. Dark Matter
2. Primordial Black Holes
3. PBH in Hybrid Inflation
4. Constraints on PBH abundances
5. After the GW detection by aLIGO/VIRGO...
6. Observable predictions
7. Conclusion and Perspectives

Dark Matter

Dark Matter accounts for $\Omega_{\rm DM} = 0.266 \pm 0.013$ 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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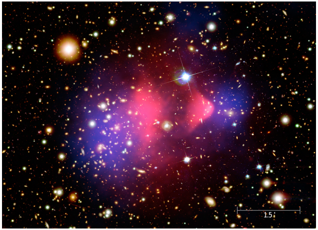

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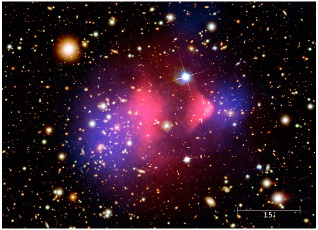

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PBH Dark Matter: formation

- 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 $k = a(t)H(t) \leftrightarrow M = \frac{M_{\rm pl}^2}{H_{\rm inf}} \mathrm{e}^{2N_k}$
- Fraction β of the Universe collapsing into PBH of mass M at t_M :

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

  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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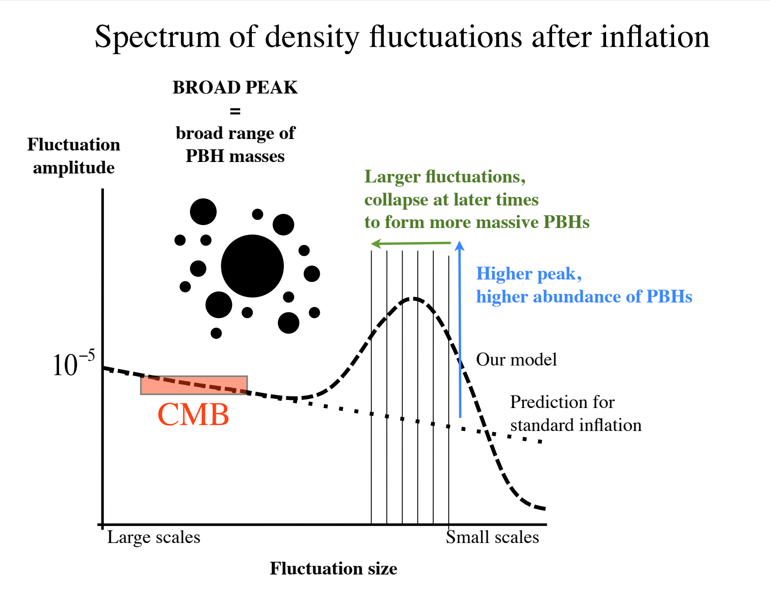
PBH Dark Matter: formation

credit: Ilia Musco, Sam Young

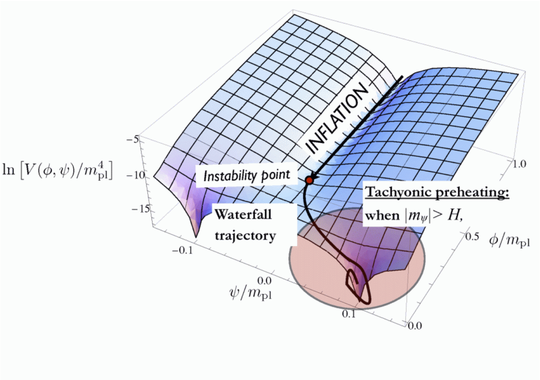
image.png


Spectrum of density fluctuations after inflation
BROAD PEAK
=
broad range of PBH masses
Fluctuation amplitude
10^{-5}
CMB
Larger fluctuations,
collapse at later times
to form more massive PBHs
Higher peak,
higher abundance of PBHs
Our model
Prediction for
standard inflation
Large scales
Small scales
Fluctuation size

Hybrid Inflation

Inflation with two scalar fields (ϕ and ψ) $\rightarrow$ 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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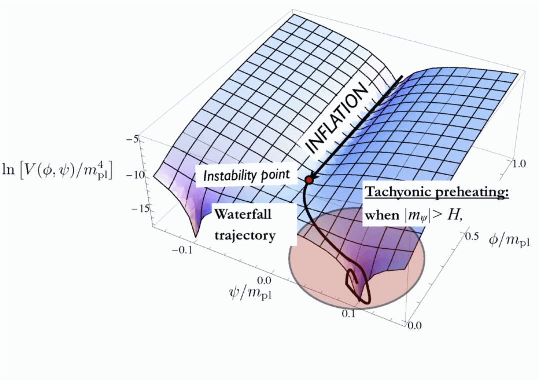

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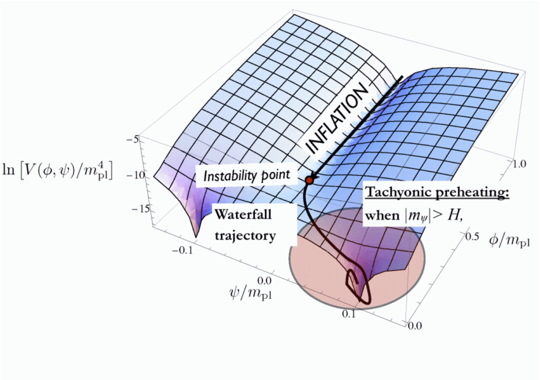

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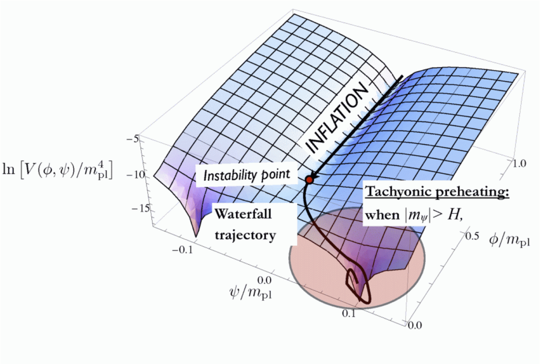


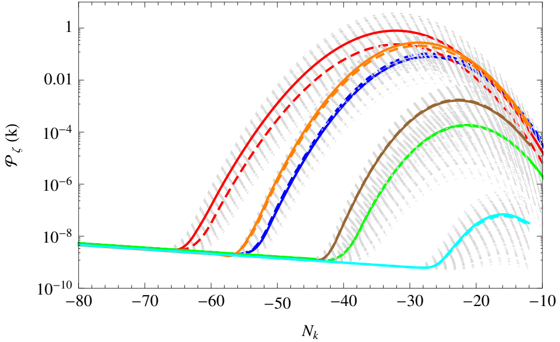
$$V(\phi,\psi) = \Lambda\left[\left(1-\frac{\psi^2}{M^2}\right)^2 + \frac{(\phi-\phi_{\rm c})}{\mu_1} - \frac{(\phi-\phi_{\rm c})^2}{\mu_2^2} + \frac{2\phi^2\psi^2}{M^2\phi_{\rm c}^2}\right]$$

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)

Our model - the primordial power spectrum

Power spectrum of curvature perturbations calculated

- Numerically using the multi-field theory cosmological perturbations
- Analytically and numerically using the δN formalism



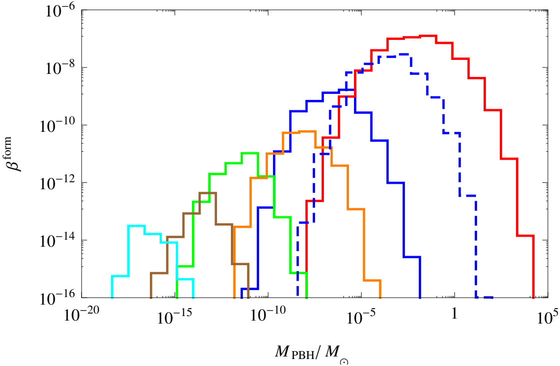
Broad peak in the power spectrum

Position, width and amplitude fixed by $\Pi \equiv M\sqrt{\phi_c \mu_1}/M_{\rm pl}^2$

Our model - PBH mass spectrum

Then use your formula for PBH formation...

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



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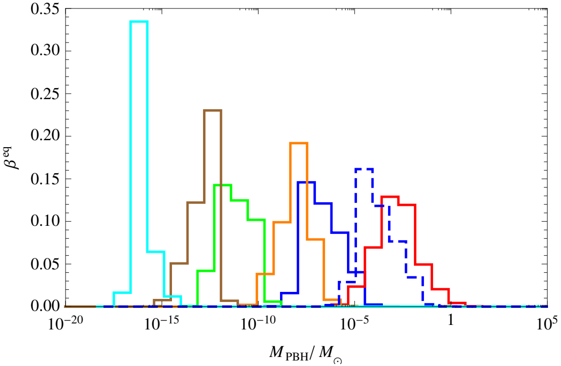
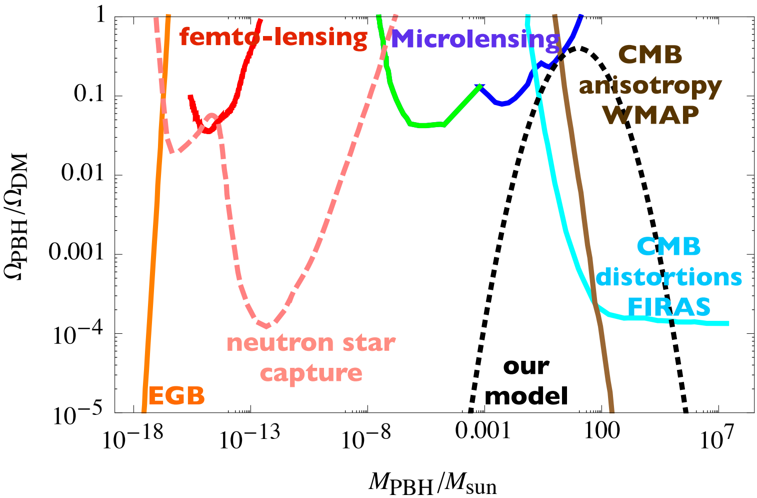
...and let PBH evolve until matter-radiation equality....



- **Surprisingly, reasonable values of $\zeta_c \rightarrow$ Dark Matter abundance**
- Relatively broad spectrum, PBH mass related to the parameter μ_1

Constraints on PBH abundances



BUT: FIRAS incorrect, CMB not robust, possible (early) clustering/merging $\rightarrow 10 - 100 M_{\odot}$ still allowed

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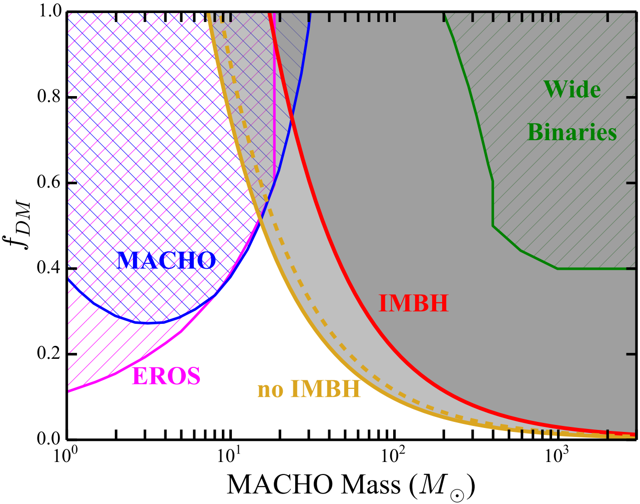

Eridanius II dwarf galaxy observations, `Li et al., 1611.05052`

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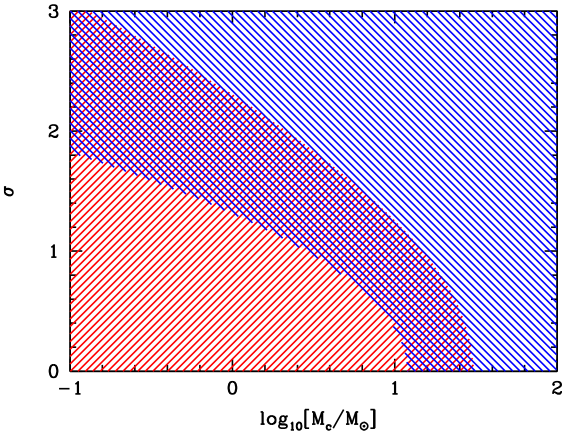
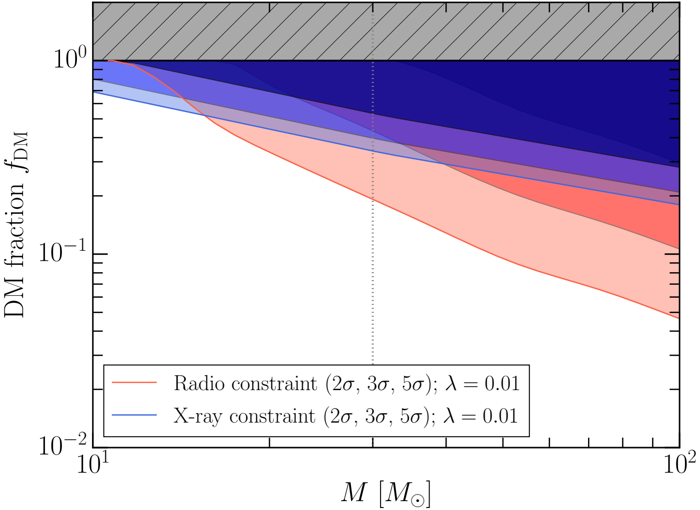


Constraints from Microlensing and Heating of dwarf galaxies
Broad log-normal distribution of width σ, `A. Green, 1609.01143`
But: effect of IMBH? Clustering in the halo?

Constraints on PBH abundances



Radio and X-rays from the Milky Way, Gaggero et al., 1612.00457

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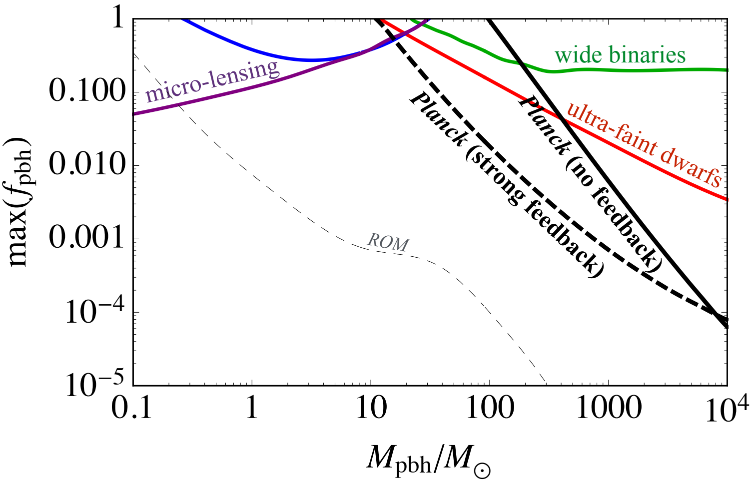

Revision of CMB constraints,

`Ali-Haïmout, Kamionkowski, 1612.005644`

Possible link with the aLIGO/VIRGO discovery

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

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

BH 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

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 $\delta_{\rm PBH}^{\rm loc} \sim 10^9 - 10^{10} \rightarrow$ LIGO rates

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

This may solve several problems :

1. Missing satellite problem
2. Too big to fail problem
3. Correlations in the X-ray and Infrared background
4. Evade micro-lensing and CMB constraints due to clustering
5. Broad spectrum: subdominant $\sim 10^5 M_\odot$ seeds of sumermassive and intermediate BH

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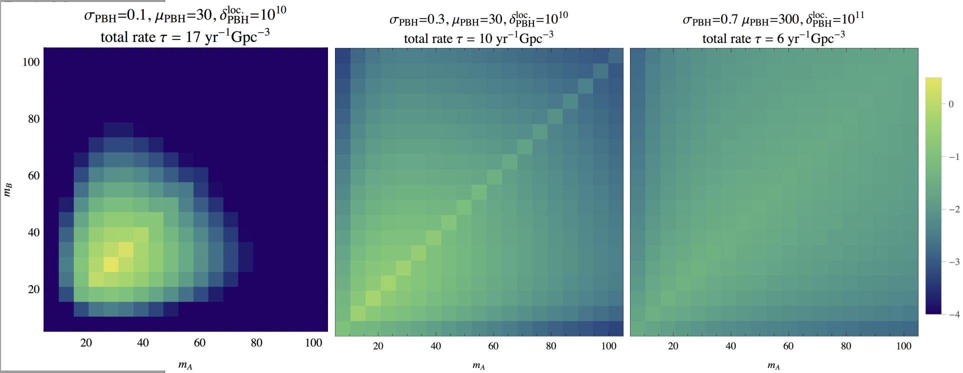


Merging rates of BHs with masses m_A and m_B, the color scale representing $\log(\tau \text{ yr Gpc}^3)$.

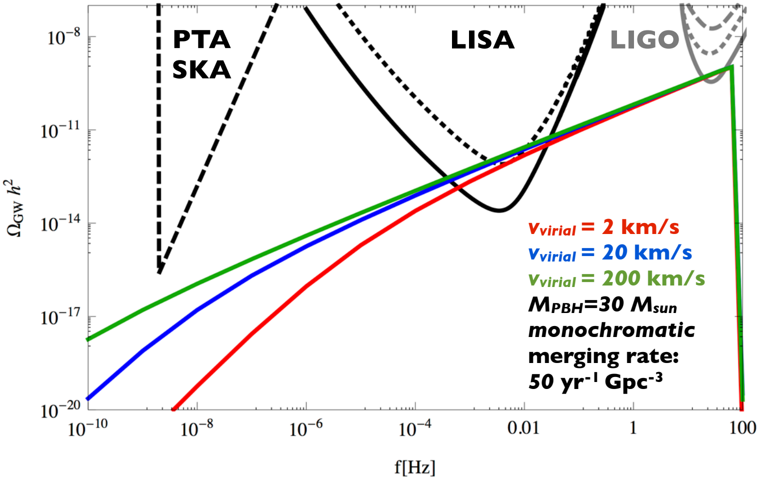
Reconstruction of the PBH mass spectrum with $\sim \mathcal{O}(10^3)$ merging events

Observable predictions

1. Merging events → **LIGO, VIRGO...**
2. Background of gravitational waves → **LIGO, VIRGO, eLISA, DECIGO, PTAs...**
3. Detection of ultra-faint dwarf galaxies → **DES, Euclid**
4. Correlated anomalies in the CIB and XCB, A. Kashlinski, 1605.04023
5. Microlensing events (and matching with X-ray sources) and monitoring of stars positions and velocities → **GAIA mission**
6. X-ray heating due to PBH → ionization of the IGM at high redshifts → 21cm signal → **Square Kilometre Array (SKA)**
7. CMB distortions → **PIXIE**
8. Heating of ultra-faint dwarf galaxies, A. Green, 1609.01143

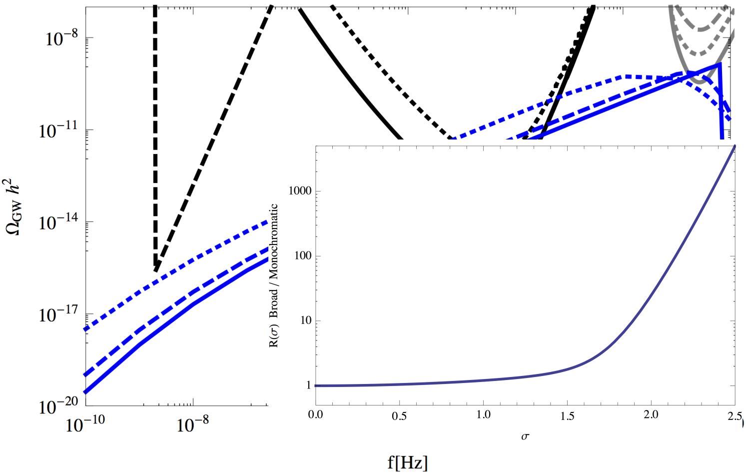
Testable scenario within the next few years!

Background of gravitational waves



Clustering allows to distinguish primordial from stellar BH

Background of gravitational waves

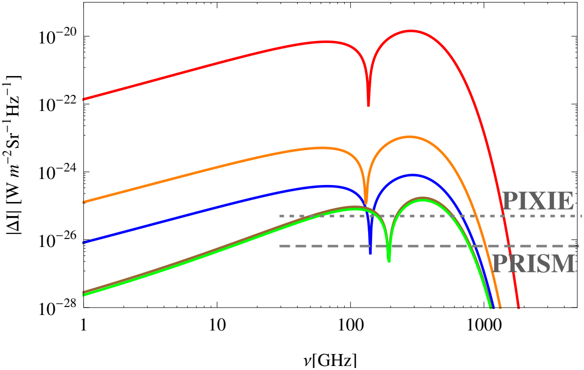


Broad spectrum enhances the GW spectrum, unlike stellar BH

Distortions of the CMB black-body spectrum

Silk damping at small scales
$\rightarrow$ 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



Conclusions

1. Dark Matter can be made of massive PBH

2. PBH regrouped in sub-halos
$\rightarrow$ aLIGO merging rates

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

Perspectives: formation mechanisms, setting new constraints, look for new signals...

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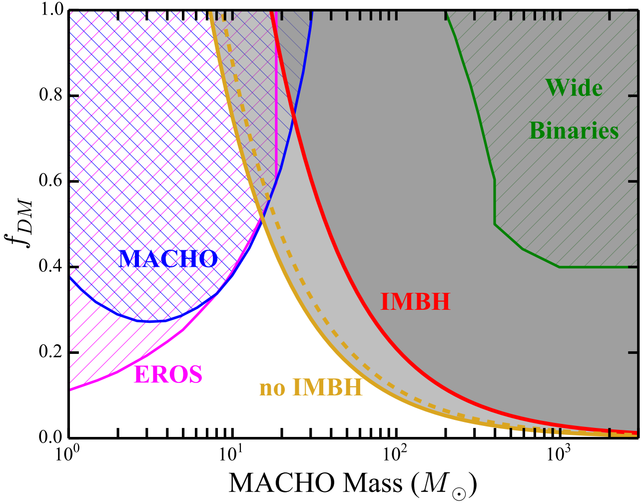
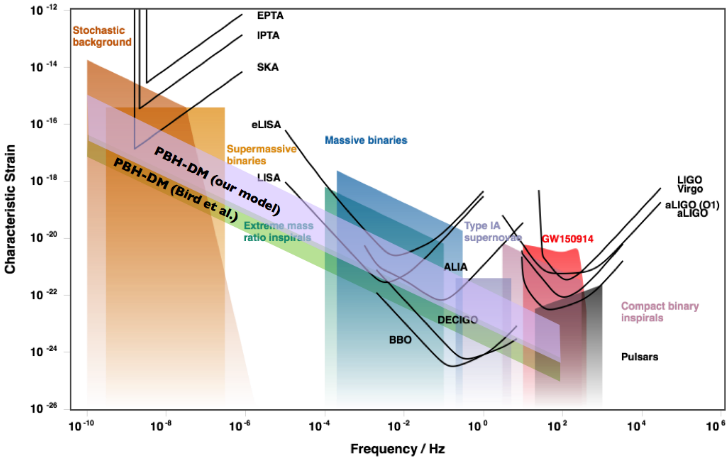
Thank you for your attention

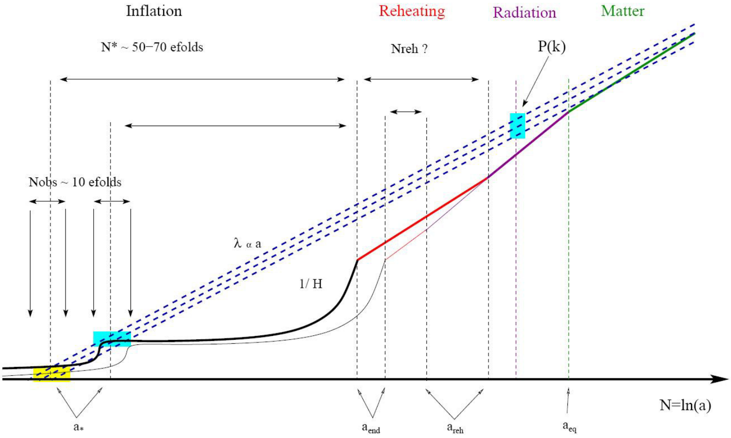
ERI II dwarf galaxy



Background of gravitational waves (preliminary)



Generalities about inflation



Slow-roll single-field inflation

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

Slow-roll dynamics

$H^2 = \frac{V(\phi)}{3M_{\rm pl}^2}$ and $3H\dot{\phi} = -\frac{\mathrm{d}V}{\mathrm{d}\phi}$

Hubble-flow (slow-roll) parameters: $\epsilon_0 \equiv \frac{H_{\rm ini}}{H}$ and $\epsilon_{i+1} \equiv \frac{\mathrm{d}\ln|\epsilon_i|}{\mathrm{d}N}$

In slow-roll : $\epsilon_1 \simeq \frac{M_{\rm pl}^2}{2}\left(\frac{V_{,\phi}}{V}\right)^2 \qquad \epsilon_2 \simeq 2M_{\rm pl}^2\left[\left(\frac{V_{,\phi}}{V}\right)^2 - \frac{V_{,\phi\phi}}{V}\right]$

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: $A_{\rm s} \equiv \mathcal{P}_\zeta(k_{\rm p}) \simeq \frac{H^2}{8\pi^2 M_{\rm pl}^2 \epsilon_1}$
- 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 ($k_* = a(t_*)H(t_*)$)

Slow-roll single-field inflation

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

Slow-roll dynamics

$H^2 = \frac{V(\phi)}{3M_{\rm pl}^2}$ and $3H\dot{\phi} = -\frac{{\rm d}V}{{\rm d}\phi}$

Hubble-flow (slow-roll) parameters: $\epsilon_0 \equiv \frac{H_{\rm ini}}{H}$ and $\epsilon_{i+1} \equiv \frac{{\rm d}\ln|\epsilon_i|}{{\rm d}N}$

In slow-roll : $\epsilon_1 \simeq \frac{M_{\rm pl}^2}{2}\left(\frac{V_{,\phi}}{V}\right)^2 \qquad \epsilon_2 \simeq 2M_{\rm pl}^2\left[\left(\frac{V_{,\phi}}{V}\right)^2 - \frac{V_{,\phi\phi}}{V}\right]$

Observable predictions

Cosmological perturbations:

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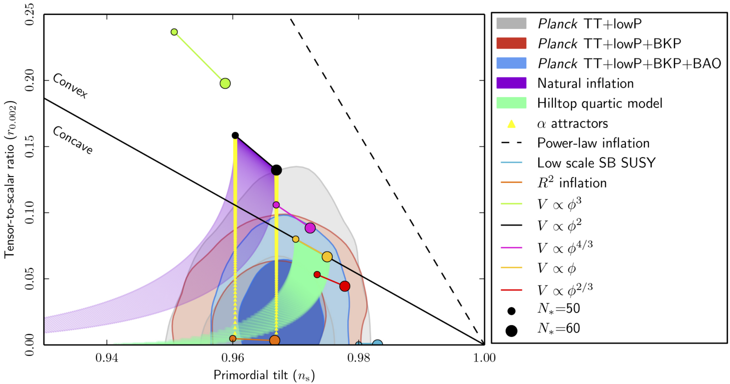
After Planck...

Contraints on n_s, r... (Planck 2015, 1502.02111)



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!

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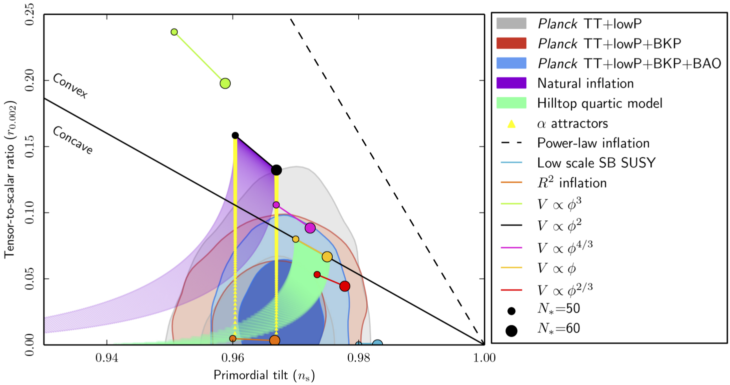

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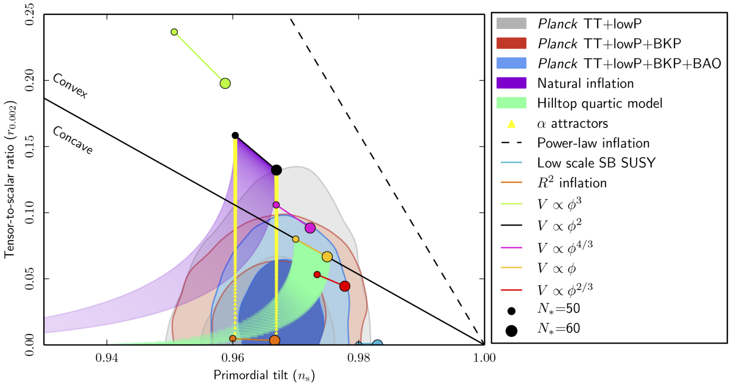

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Our model - the primordial power spectrum

Problems with hybrid inflation:

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

Transitory case + two-field potential:

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

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)

- $n_\mathrm{s} = 1 - \frac{4M_\mathrm{pl}^2}{\mu_2^2}$ (dominated by ϵ_2, i.e. the curvature of the potential)
- $\mathcal{P}_\zeta(k_\mathrm{p}) = \frac{\Lambda \mu_1^2}{12\pi^2 M_\mathrm{pl}^6} \left(\frac{k_\mathrm{p}}{k_{\phi_\mathrm{c}}}\right)^{n_\mathrm{s}-1}$

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Dark Matter
Primordial Black Holes
PBH in Hybrid Inflation
Constraints on PBH abundances
After the GW detection by aLIGO/VIRGO...
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Conclusion and Perspectives

Summary of the model

1. Hybrid inflation + mid-mild waterfall → broad peak in $\mathcal{P}_\zeta$ → PBH
2. Right abundances for Dark Matter
3. Passes all present astronomical constraints
4. Seeds for SMBH at the center of galaxies and IMBH

Possible link with the Advance LIGO discovery

1. LIGO inferred merging rates if PBH are clustered
2. Natural candidate: ultra-faint dwarf galaxies
3. A solution to *missing satellites* and *too-big-to-fail* problems
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Observable predictions

1. Microlensing, position and velocity of stars → **GAIA**
2. 21cm signal at reionization → **Square Kilometre Array (SKA)**
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1. Background of gravitational waves
2. Merging history (N-body simulations)
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Our model of Primordial Black Holes Dark Matter in a sketch...

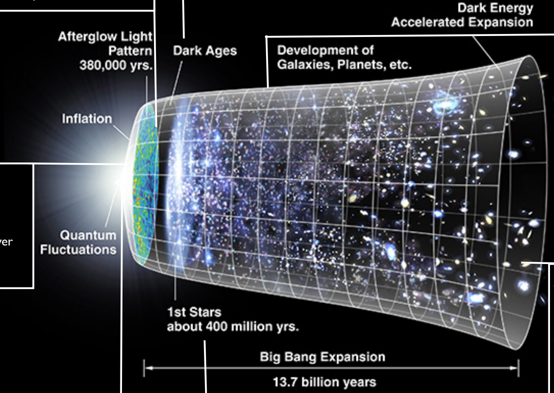
Cosmic Microwave Background:
Massive primordial black holes induce **distortions of the CMB**,. These could be probed with PIXIE.

21cm signal ***about 500 million years...***
X-rays emitted by **accreting matter** onto PBHs **ionize** the environment, leading to **detectable signatures in the 21cm signal.**

Over the cosmic evolution...

Binaries can form when PBH trajectories cross. After a spiraling phase, the two **PBH merge** and emit **gravitational waves**, such as the ones detected by **aLIGO/VIRGO**. PBH binaries also produce a **background of gravitational waves**, that will be probed by **eLISA**.

Halos of PBH induce **correlated anomalies** in the **Cosmic Infrared Background** (CIB) and **X-ray background.**



Hybrid Inflation :

Mild-waterfall

Broad peak in the power spectrum of density perturbations

Local Universe:
PBH are **regrouped in ultra-faint dwarf galaxies**. Their existence could solve the ***missing satellite*** and ***too-big-to-fail*** **problems.**
Some of them have been detected by the DES experiment.

In the Milky-Way:
The presence of PBH should induce **tiny variations in the position and velocity of stars** that are being monitored by **GAIA**.

Formation of primordial black holes (PBH) :
less than one second after the end of inflation...
Large inhomogeneities collapse gravitationally and **form massive primordial black holes,** which could be already **regrouped in dense halos.**

The seeds of supermassive black holes :
during the first billion years...
A **subdominant fraction** of very massive PBH could be the **seeds of SMBH**, then growing by successive merging and matter accretion.