Ioannis Dalianis, NTUA

Primordial Black Holes and Primordial Black Hole remnants as dark matter: Inflationary model building and observational constraints

10/9/2019,

Workshop on Connecting Insights in Fundamental Physics: Standard Model and Beyond

EISA, Corfu

A talk based on the works:

1. ID+Kehagias+Tringas, arXiv:1805.09483 (JCAP)
2. ID, arXiv:1812.09807 (JCAP)
3. ID +Tringas, arXiv:1905.017, (to appear in PRD)
4. ID+Karydas+Papantonopoulos, (in progress)

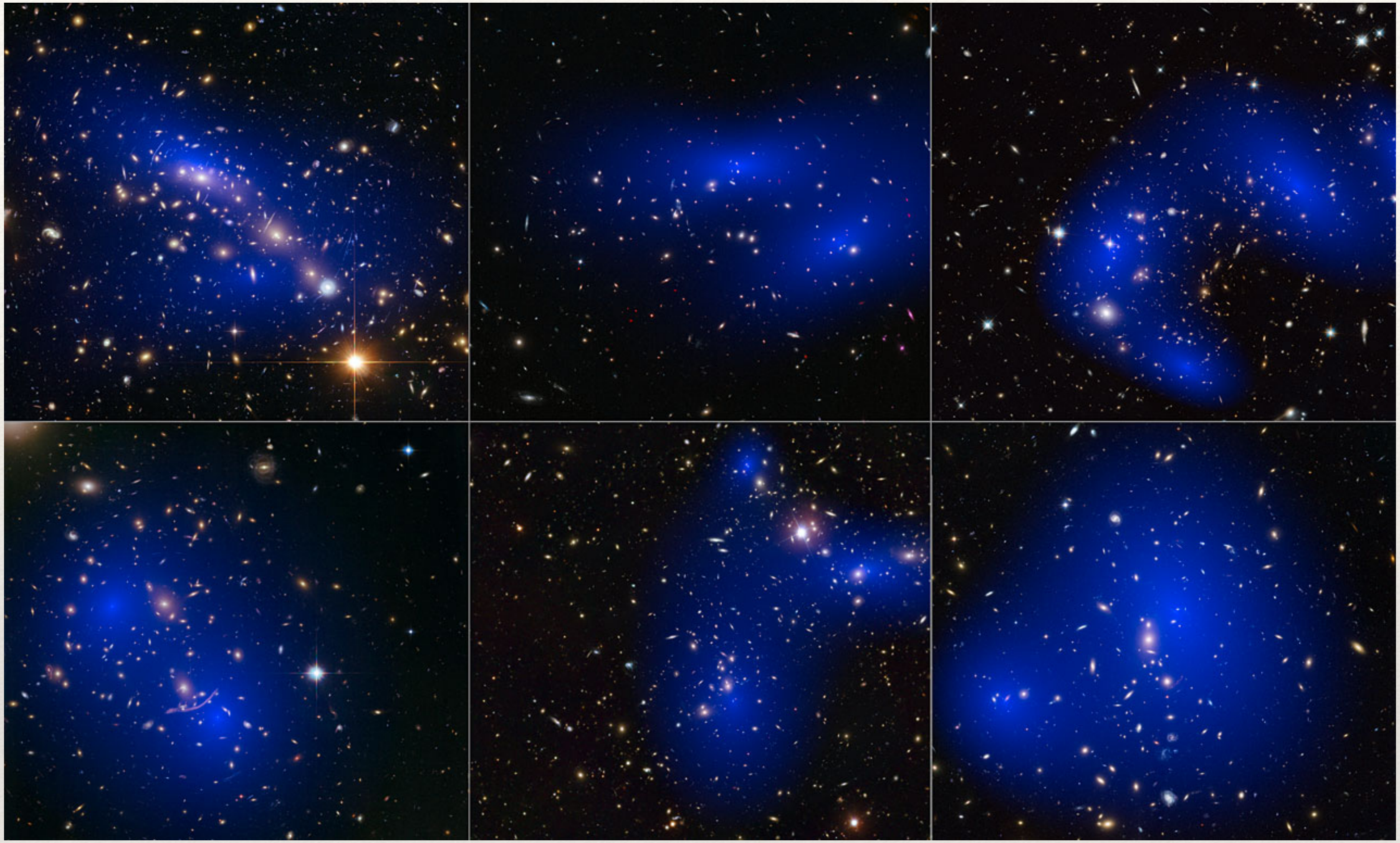
Outline of the talk

- Dark matter: the PBH scenario
- The early universe cosmology of the PBHs
- Constraints on the primordial perturbations at all scales
- Inflationary models that generate PBHs
- PBHs and PBH remnants as dark matter

Let us start with

the universe observed

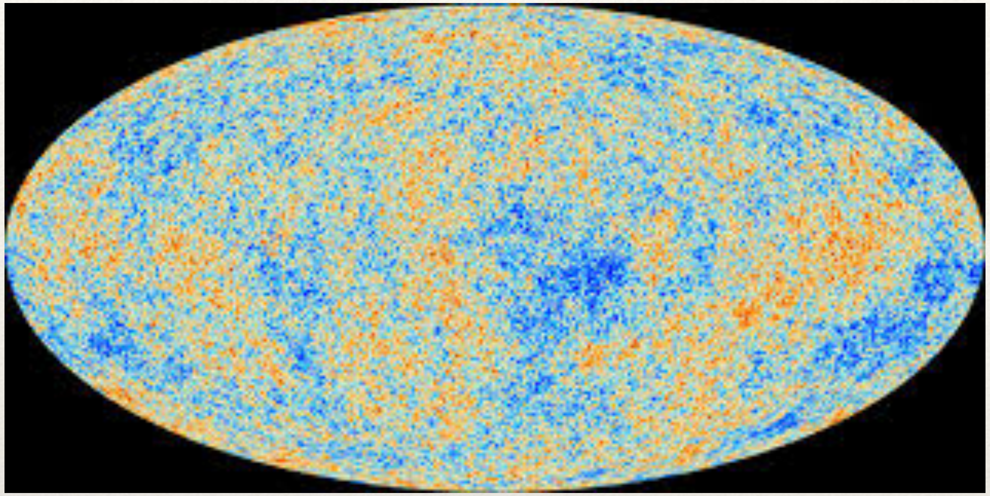
There is more GRAVITY than what we expect from the amount of the visible matter

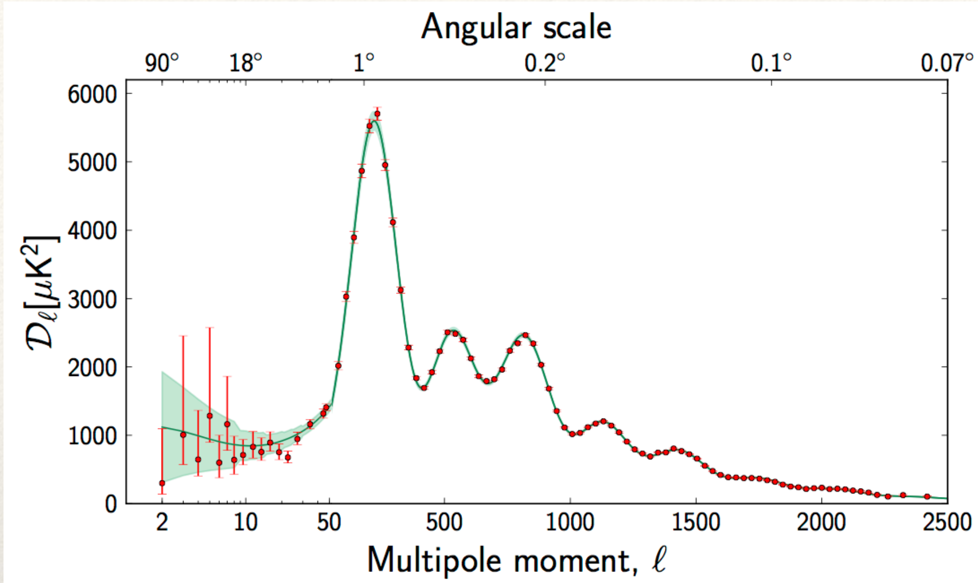


Conclusion:

Dark matter is the dominant matter in the universe today

There is more GRAVITY than what we expect from the amount of the visible matter



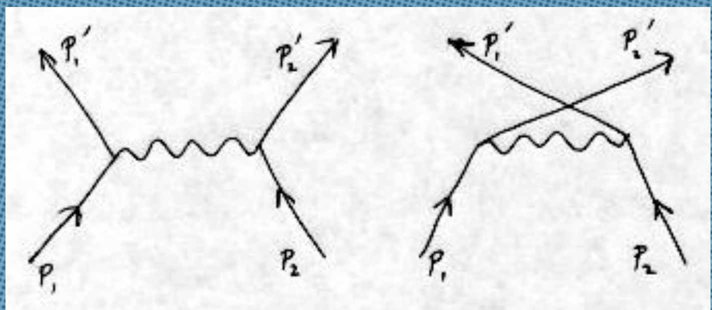


Conclusion :

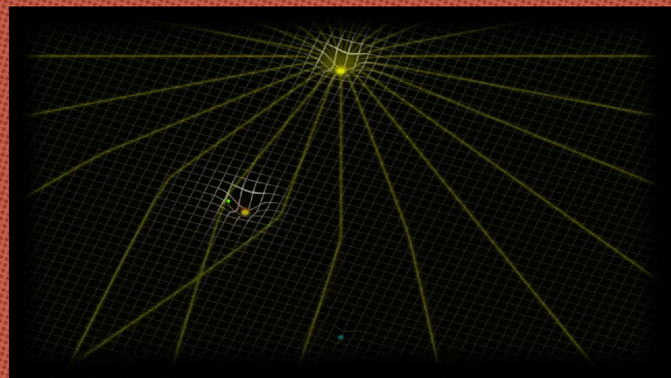
There is Dark Matter in the early universe

Dark Matter Scenarios

It is a particle



It is an object



Dark Matter Scenarios

It is a particle:

LSP
ALPS
Asymmetric
Exotic Neutrinos
...

It is an object:

MACHOS
Black Holes
...

Dark Matter Scenarios

It is a particle:

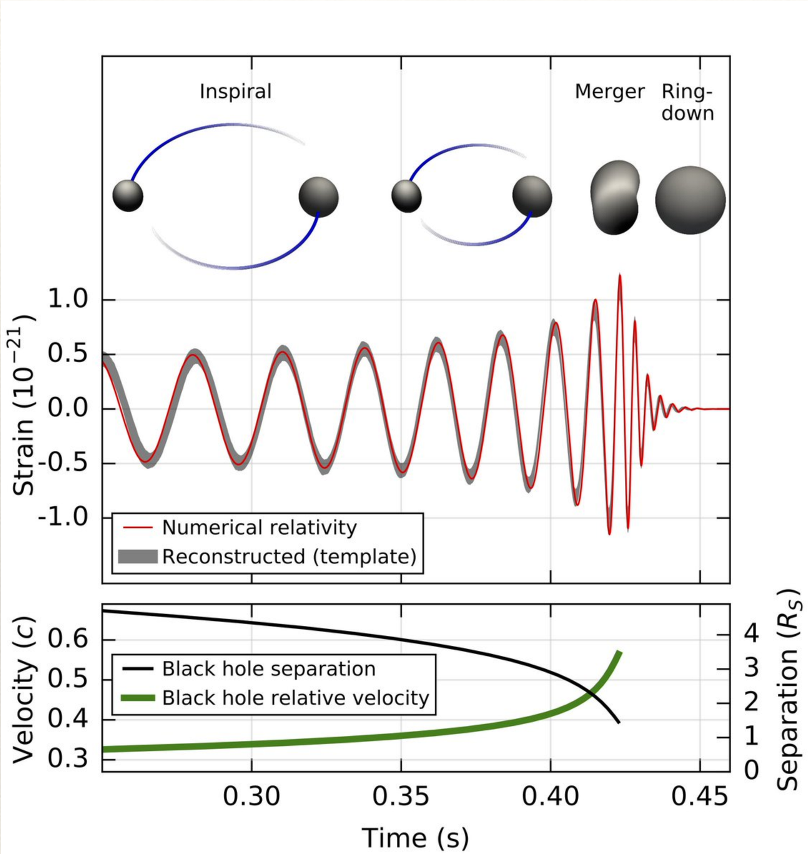
LSP
ALPS
Asymmetric
Exotic Neutrinos
…

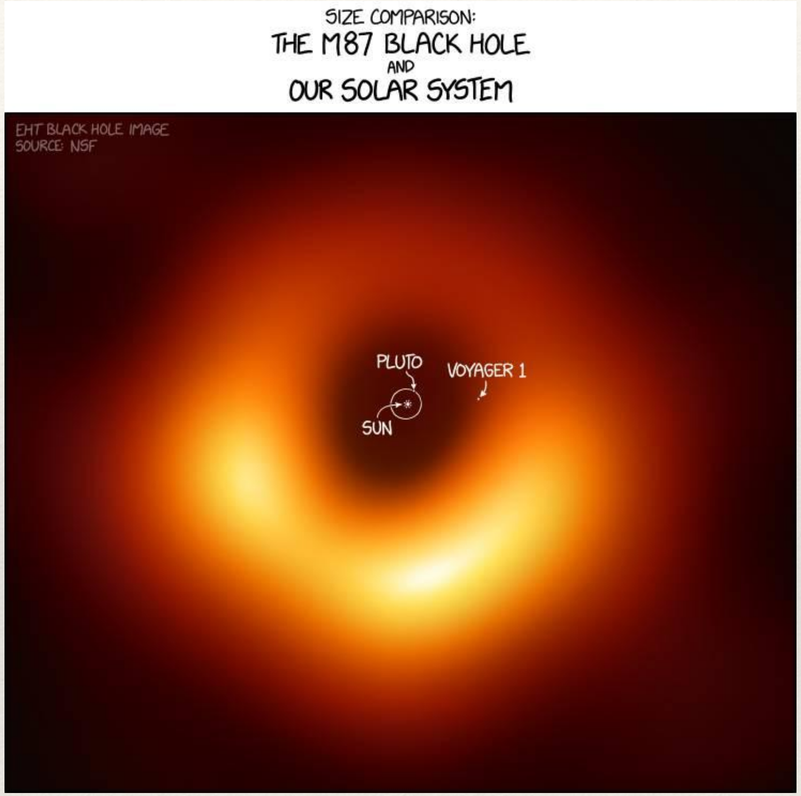
It is an object:

~~MACHOs~~
~~Stellar Black Holes~~
Primordial Black Holes
…

Remember: Upper bounds on the PBH abundance can be seen as lower bounds for the particle dark matter abundance

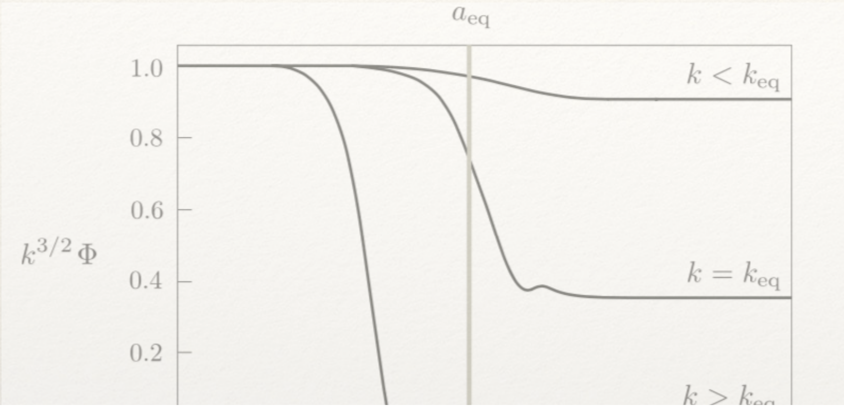
Black Holes (2019)

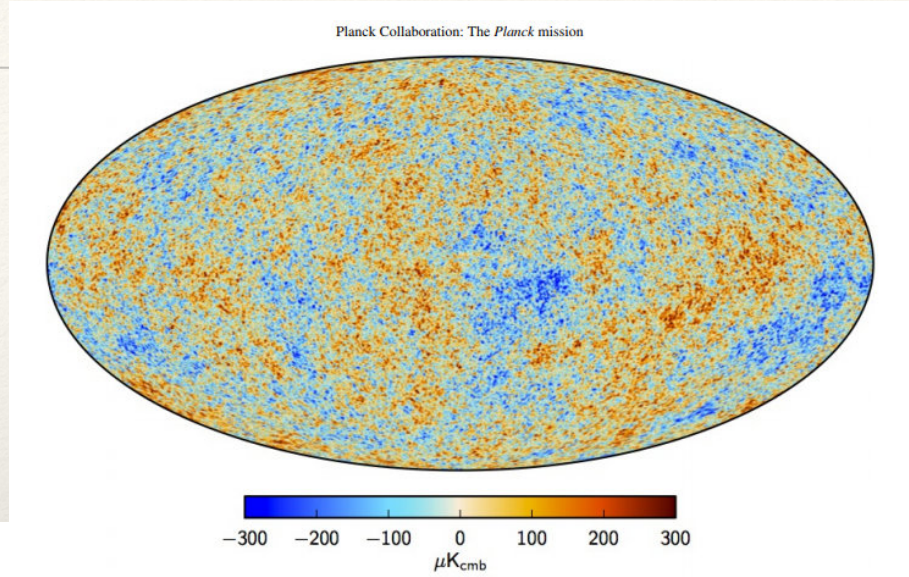


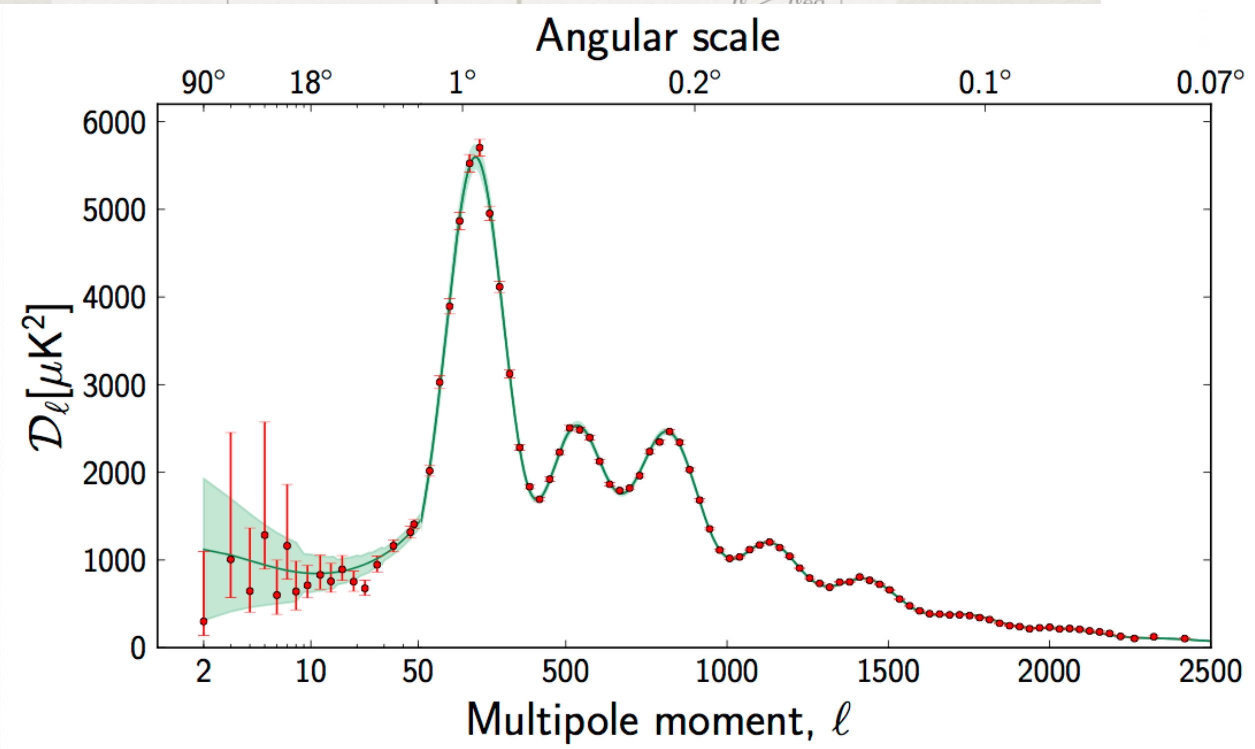


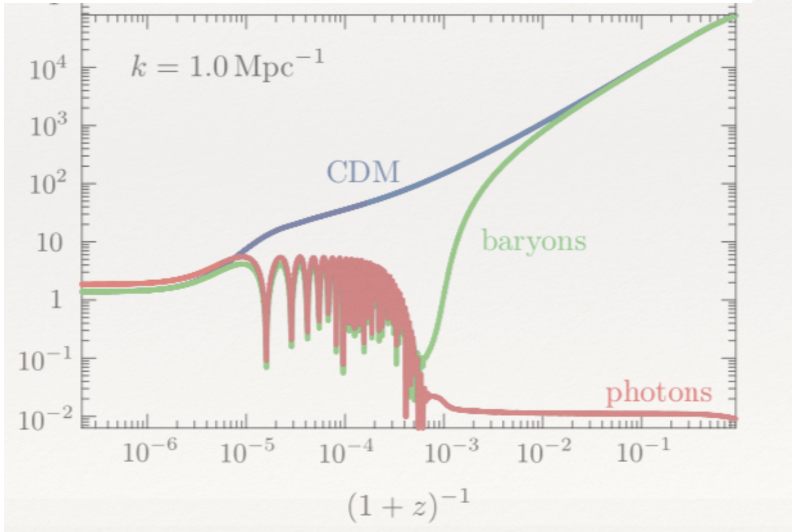
Of primordial origin ?

Preliminaries: Linear evolution of fluctuations









Basics of PBHs

- PBHs form from the collapse of large-amplitude inhomogeneities.

• B. J. Carr and S. W. Hawking (1974). P. Meszaros, (1974), B. J. Carr (1975), I. D. Novikov, A.G. Polnarev, A. A. Starobinsky and Ya. B. Zeldovich, (1979)

- In order to decouple from the background expansion it has to be $GM/R \sim 1$, for a region of mass M over a scale R.

- Carr formulated a criterion for an overdensity to form a PBH: The size of the overdensity at the maximum expansion R_{max} should be larger than the Jeans radius (the Jeans criterion) but smaller than the Hubble horizon size

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$$R_J \sim \sqrt{w} R_H \lesssim R_{\max} \lesssim R_H \Rightarrow$$

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- However there is some ambiguity in the choice of the Jeans radius

- Harrada, Yoo, Kohri (2013),

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- In order to decouple from the background expansion it has to be GM/R ~ 1, for a region of mass M over a scale R.

- The formation criterion: the sound crossing time over the radius of the over-density be longer than the free fall time from the maximum expansion to complete collapse

$$R_J = a_{\max} \sin\left(\frac{\pi\sqrt{w}}{1+3w}\right) \to \delta_c^{UH} = \sin^2\left(\frac{\pi\sqrt{w}}{1+3w}\right)$$

$$\delta_c^{com} = \frac{3(1+w)}{5+3w}\sin^2\left(\frac{\pi\sqrt{w}}{1+3w}\right)$$

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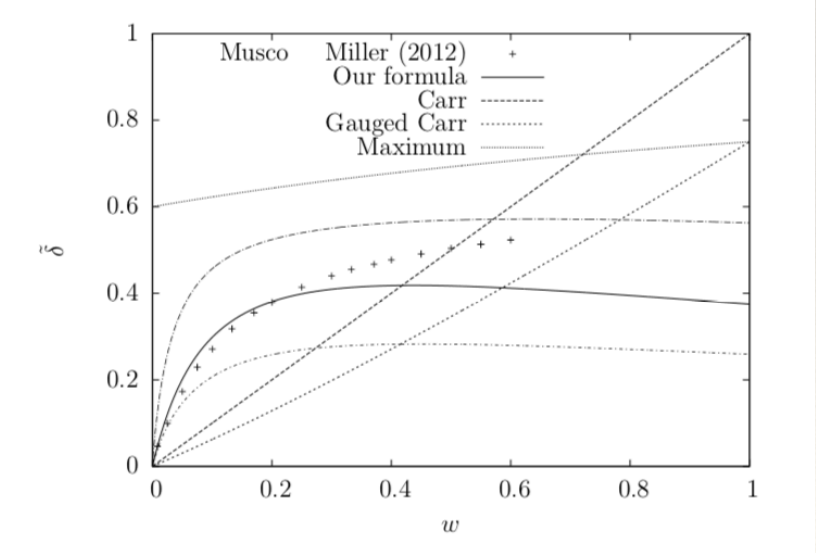

Basics of PBHs

- ***Large primordial inhomogeneities can be achieved if the power spectrum is enhanced at a scale $R^{-1} \sim k$, characteristic of the PBH mass, by many orders of magnitude.***

Basics of PBHs

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- Large wavenumbers yield light PBH which if they have mass $M < 10^{15}$ g evaporate at timescales less than the age of the universe.

S. W. Hawking, (1974,1975)

- PBHs with $M > 10^{15}$ g would still survive today and would be dynamically cold component of the dark matter in galactic structures.

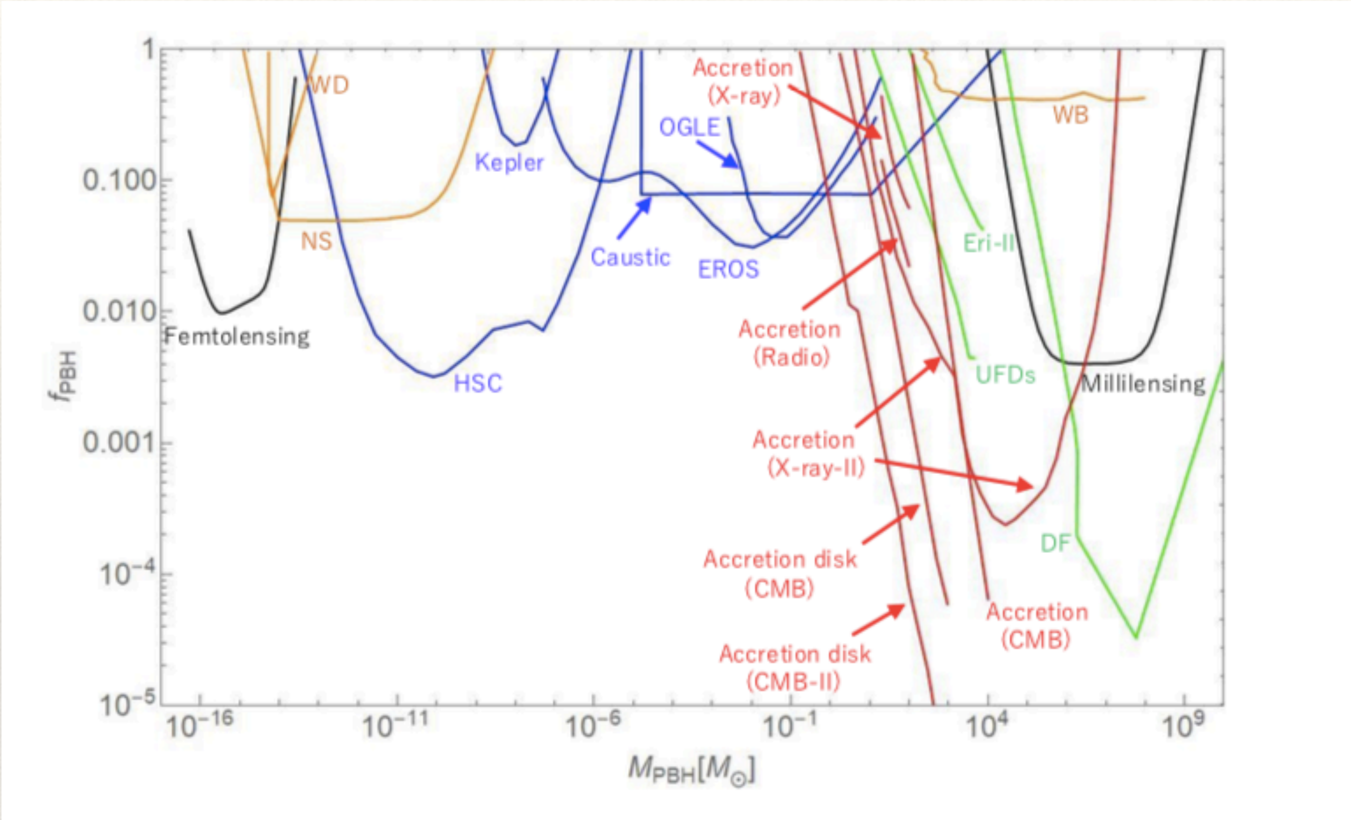
Extra Motivation:
PBH scenarios can be tested observationally !

PBHs make their presence manifest due to :

- Accretion of CMB photons
- Ultra Faint Dwarf Galaxies
- Lensing effects
- White Dwarfs
- Hawking radiation
- Gravitational Waves

See also talks of Martti Raidal & Sunghoon Jung

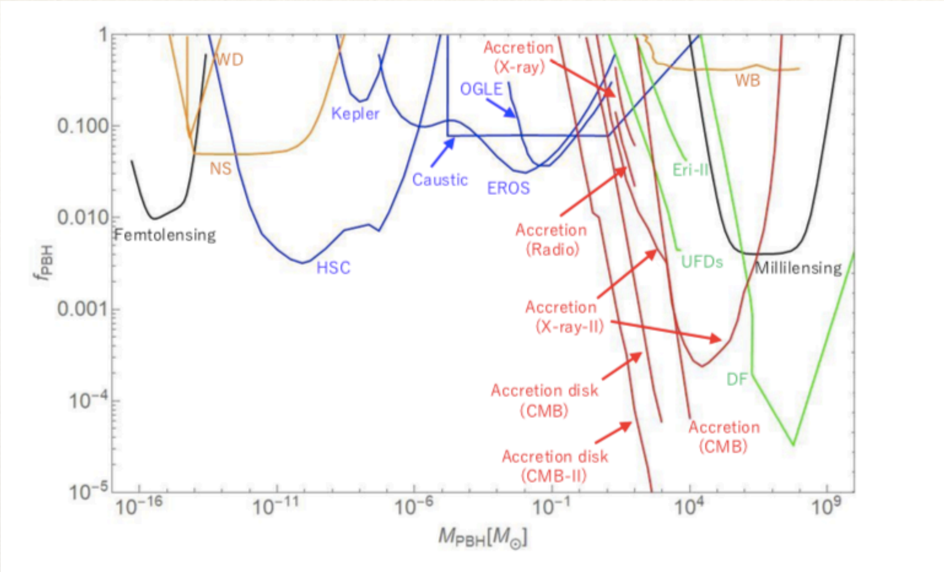
Observational constraints

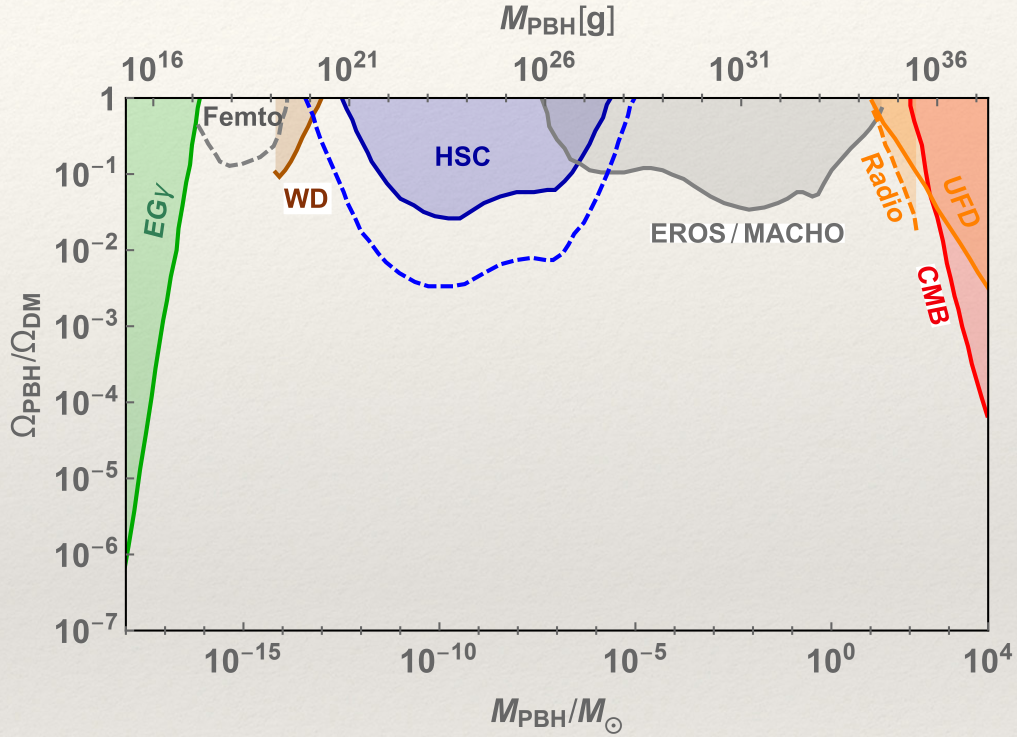


M. Sasaki, T. Suyama, T. Tanaka and S. Yokoyama (2018)

Upper limit on fPBH = $\frac{\Omega_{PBH}}{\Omega_{DM}}$ for various PBH mass (assuming monochromatic mass function)

Updated observational constraints

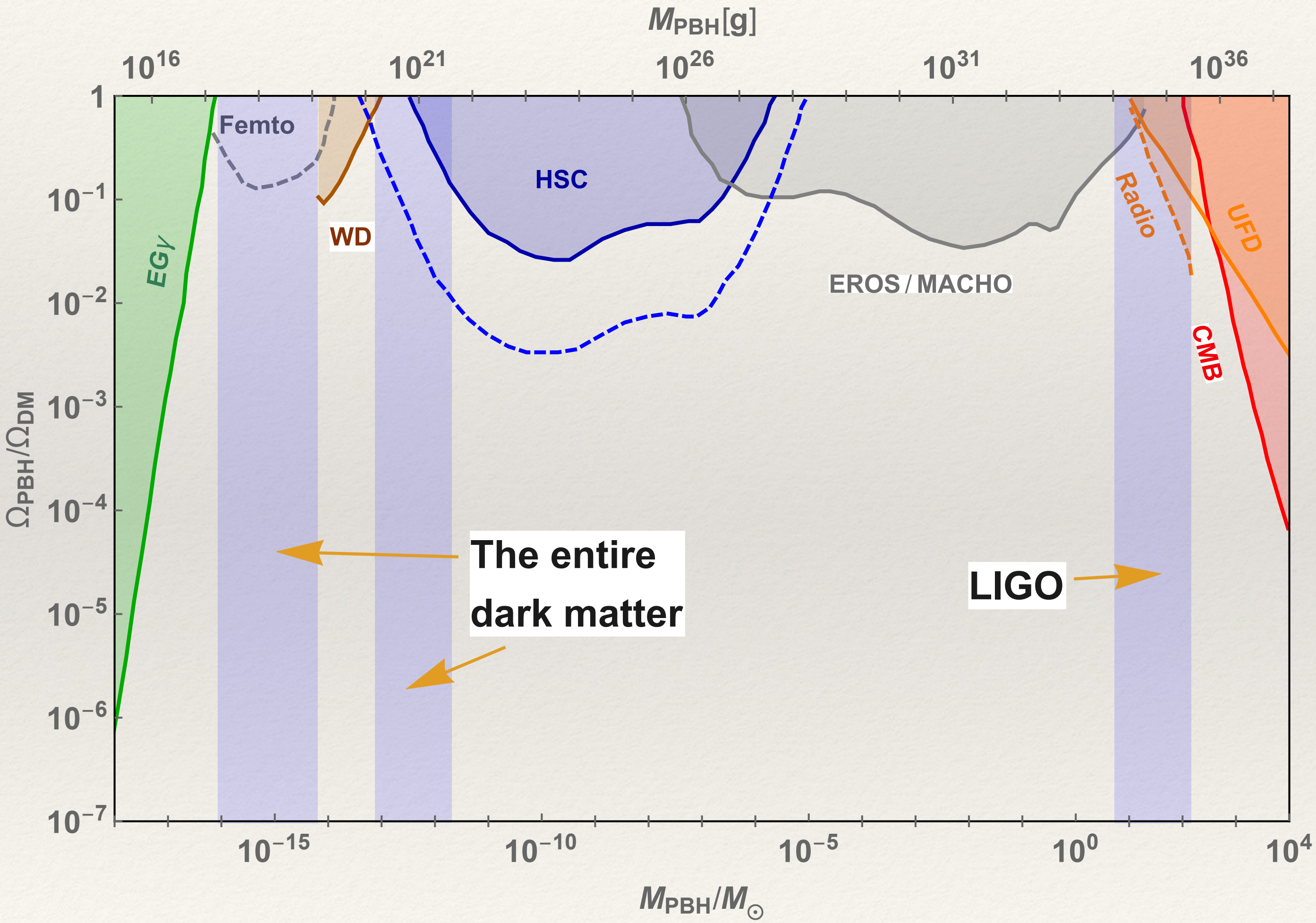




A. Katz, J. Kopp, S. Sibiryakov and W. Xue (2018)

Upper limit on fPBH = $\frac{\Omega_{PBH}}{\Omega_{DM}}$ for various PBH mass (assuming monochromatic mass function)

Motivated PBH mass windows



From the power spectrum to the PBH abundance

Radiation Domination

$$f_{PBH}(M) \simeq \left(\frac{\beta(M)}{10^{-14}}\right)\left(\frac{\gamma}{0.12}\right)^{3/2}\left(\frac{M}{M_{\rm sun}}\right)^{-1/2}$$

$$\beta(M) = \int_{\delta_c} d\delta \frac{1}{\sqrt{2\pi\sigma^2(k)}} e^{-\frac{\delta^2}{2\sigma^2(k)}}$$

$$\sigma^2(k) \sim \left(\frac{4}{9}\right)^2 \mathcal{P}_{\mathcal{R}}(k)$$

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Matter Domination

$$f_{PBH} \simeq \gamma \left(\frac{\beta(M)}{10^{-19}}\right)\left(\frac{T_{\rm rh}}{10^{10}\,{\rm GeV}}\right)$$

$$\beta(M) = 0.056\,\sigma^5(k)$$

$$\beta(M) = 2\times 10^{-7}\sigma^2(k)\, e^{-0.143\frac{I^{4/3}}{\sigma^{2/3}(k)}}$$

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If the reheating temperature is *not maximal*, PBH formation during matter era has to be taken into account

The amplitude of the primordial inhomogeneities

The most attractive mechanism to generate PBHs is **inflation**.

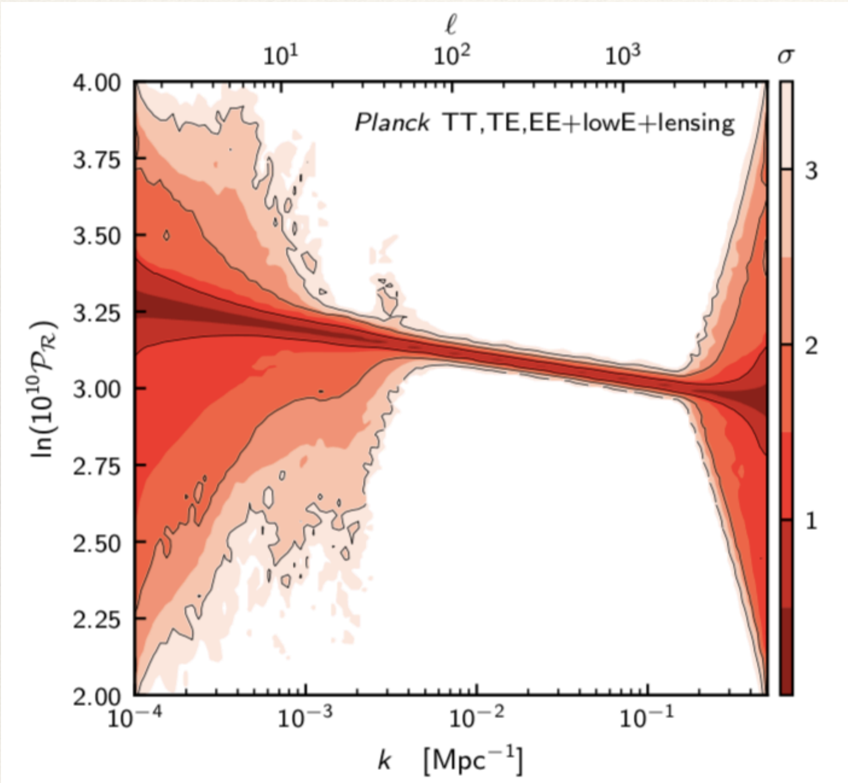
Due to the natural generation of large scale perturbations from quantum fluctuations, inflation is the dominant paradigm that cosmologists follow to explain the origin of the large scale structure and has been, so far, successfully tested by the CMB precision measurements.

Inflation does not seed large scale perturbations only,
it seeds perturbations in all scales.

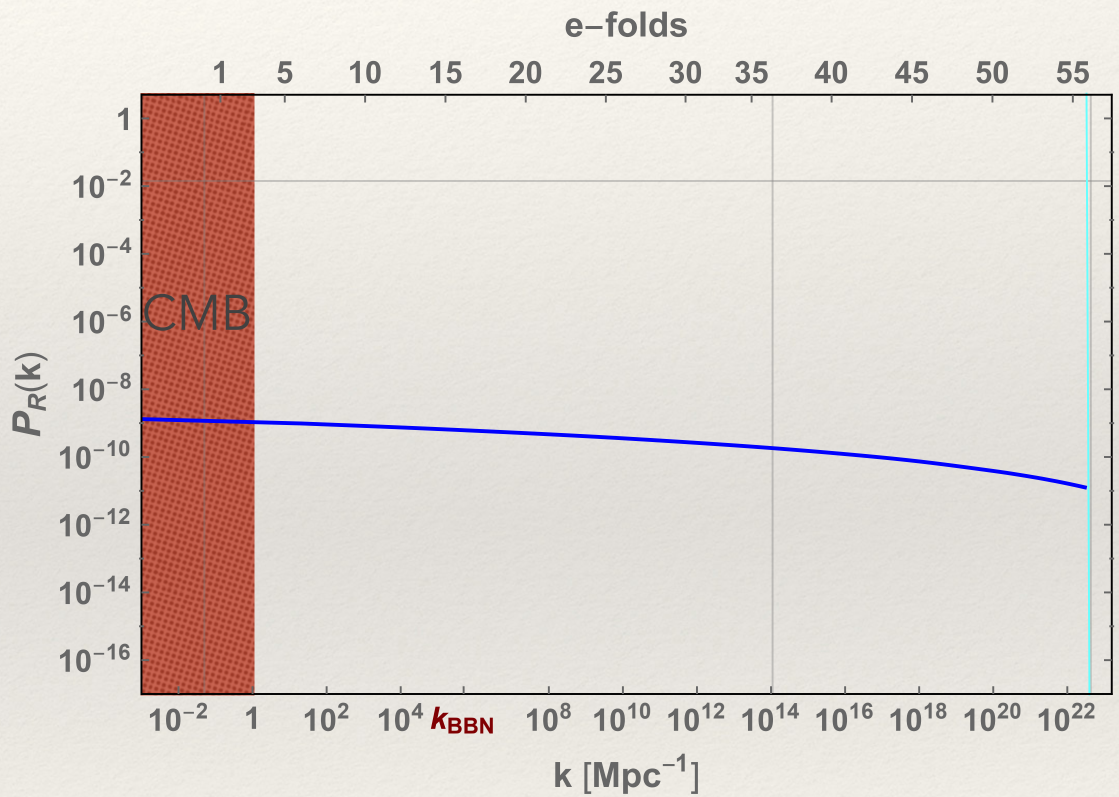
Hence, PBHs can form if perturbations strong enough to collapse are produced in scales $k^{-1} \ll k_{\rm cmb}^{-1}$ characteristic of the PBH mass.

The power spectrum of the curvature perturbations

Planck 2018



The PS of a "conventional" inflationary model with red scalar tilt:



Q: How many PBHs in our observable universe?

A: According to the PS there is the probability factor : $6 \times 10^{-38,180,513}$

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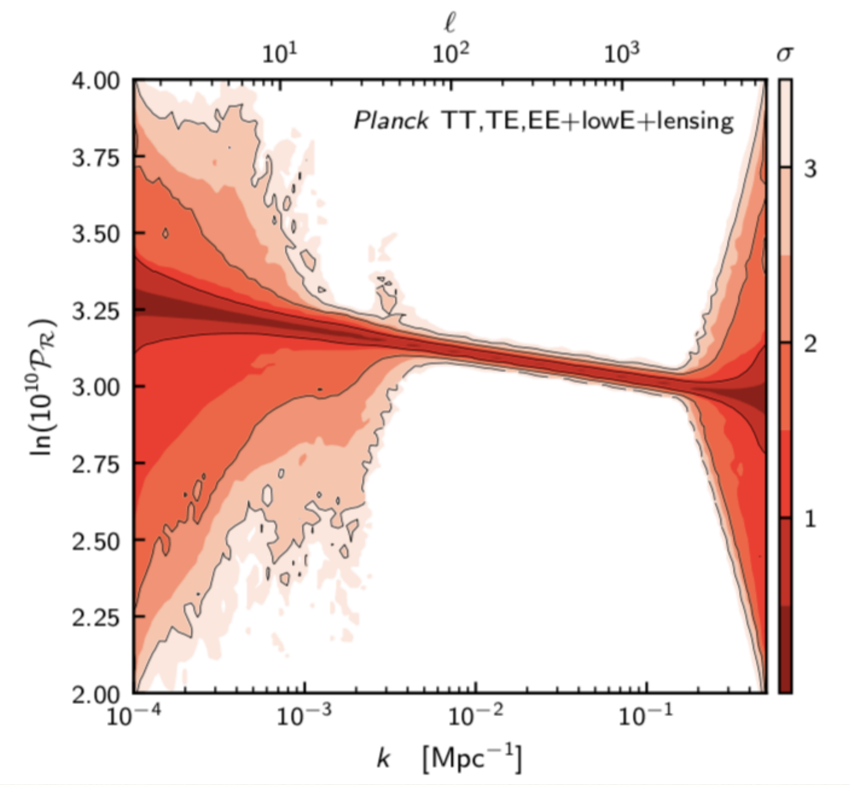

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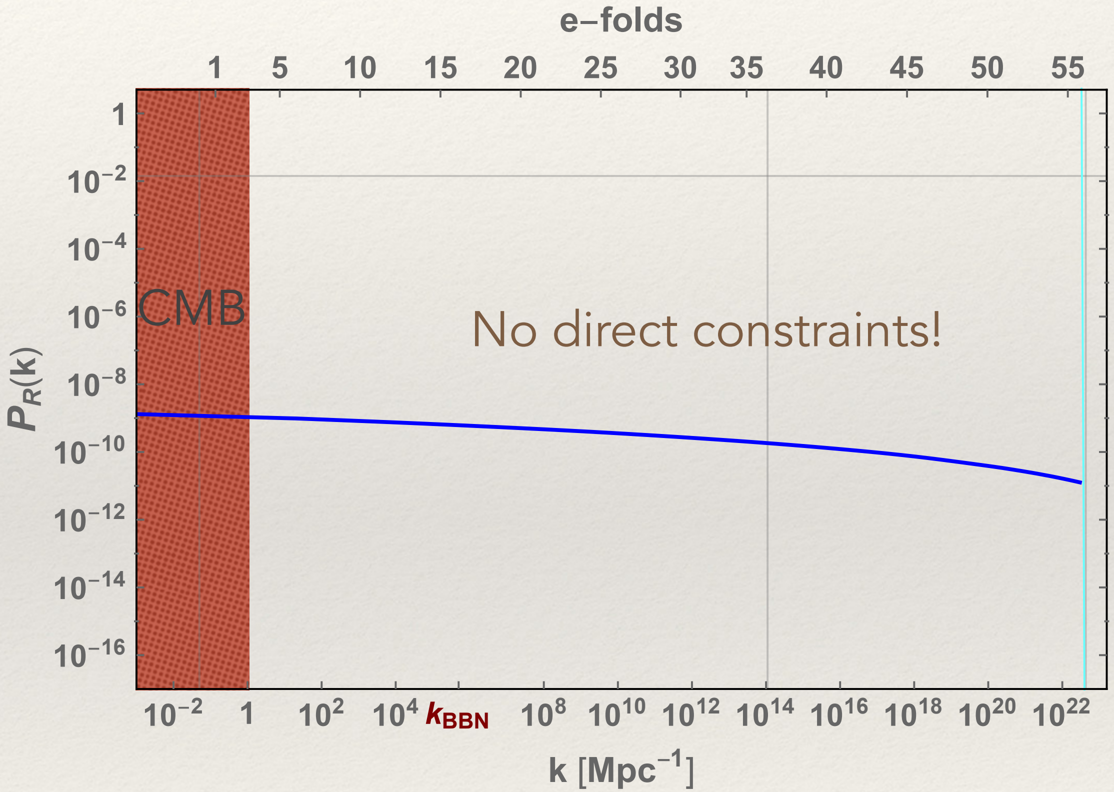

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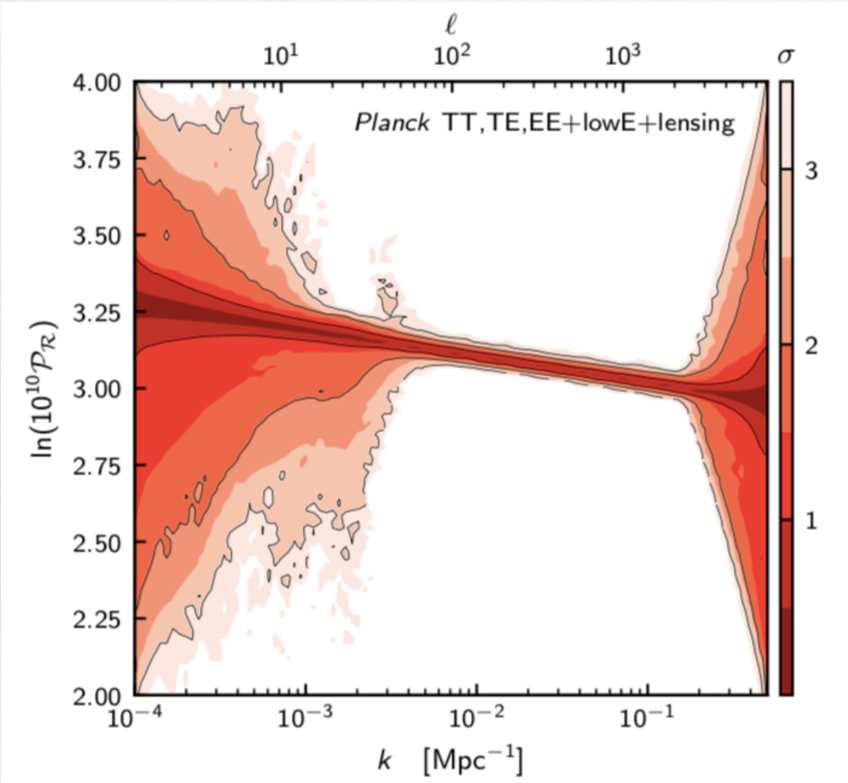

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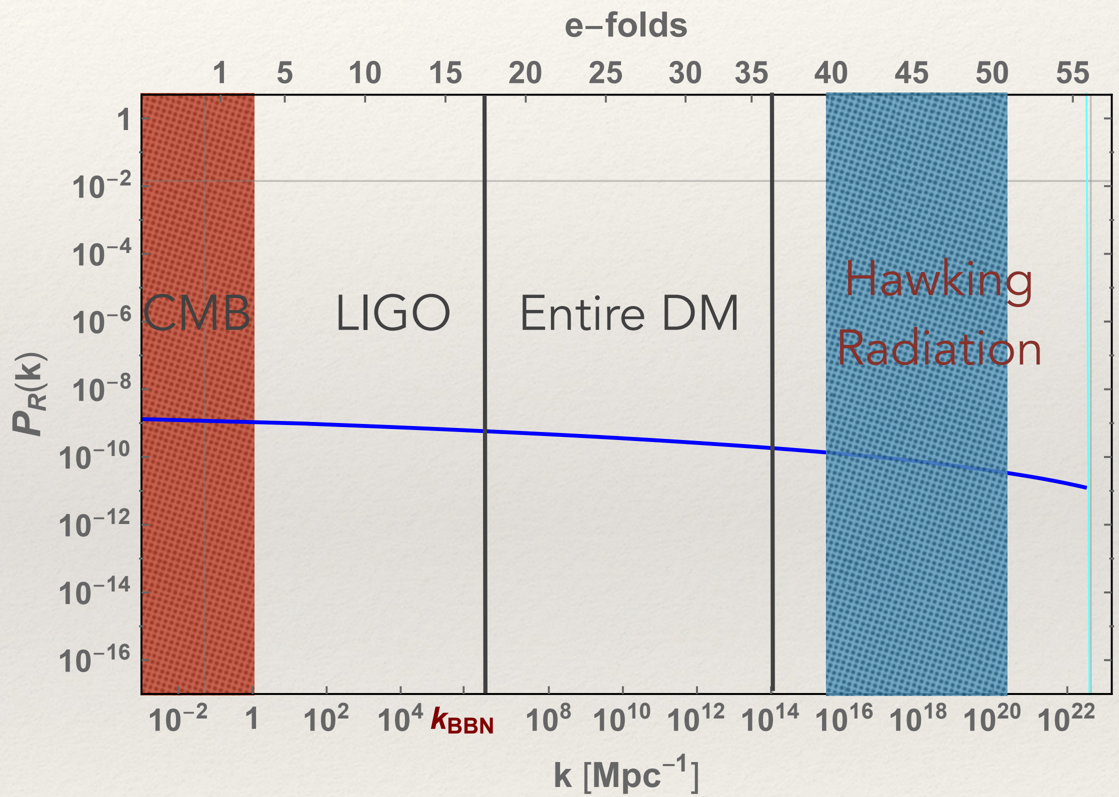

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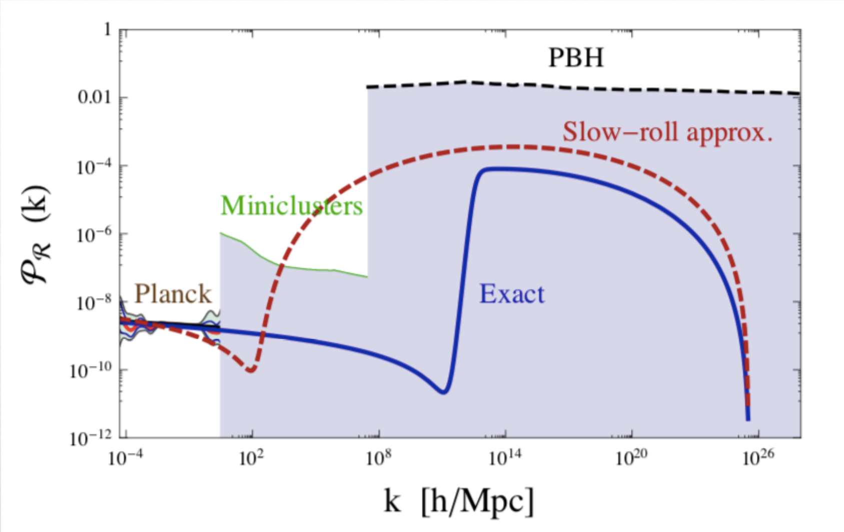
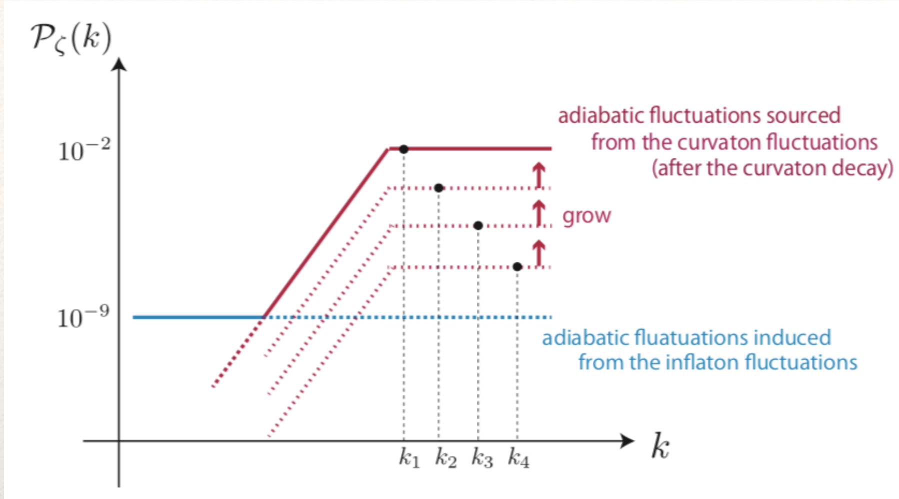
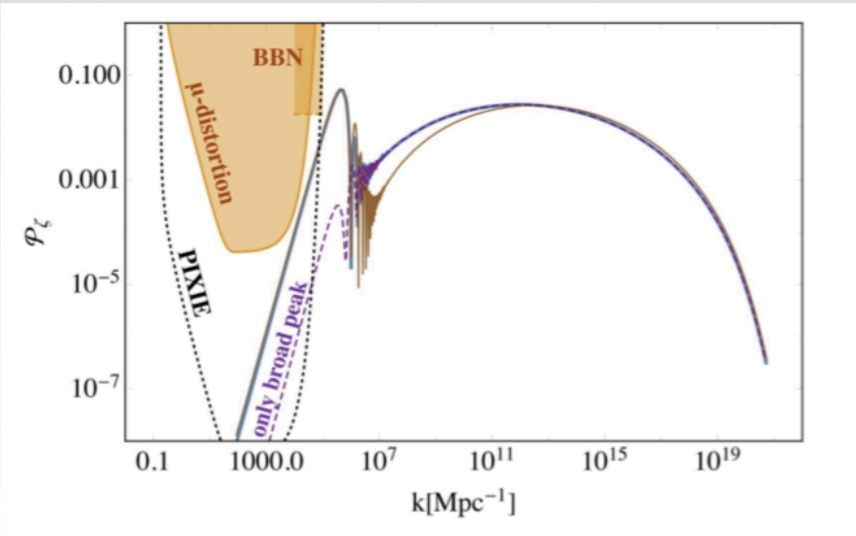
Examples of power spectra from, arXiv:1702.03901, arXiv:1711.06129, arXiv:1801.05235, arXiv:1709.05565

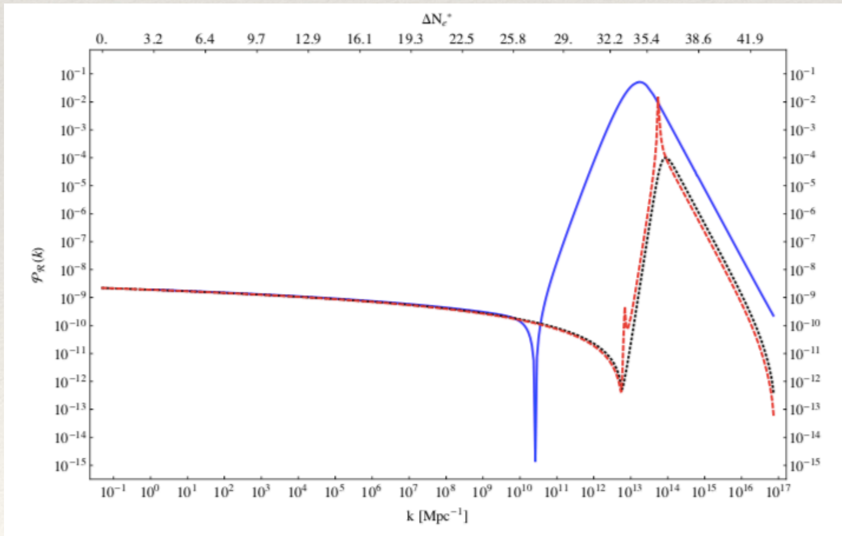
Bellido et.al



Sasaki et.al







Yanagida et.al

Ballesteros et.al

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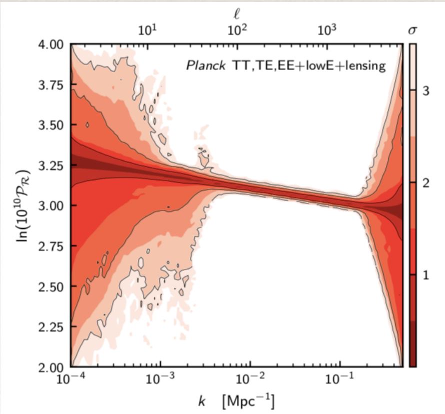
A: No, for two reasons:

1. The spectral index value
2. The ultra light PBHs evaporate fast



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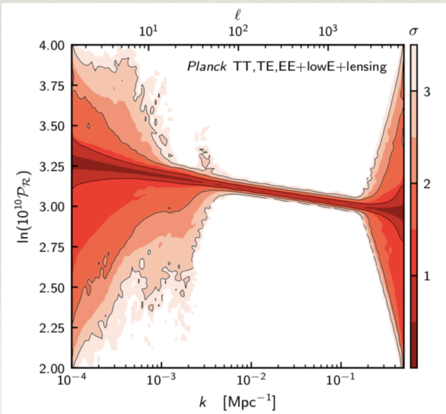

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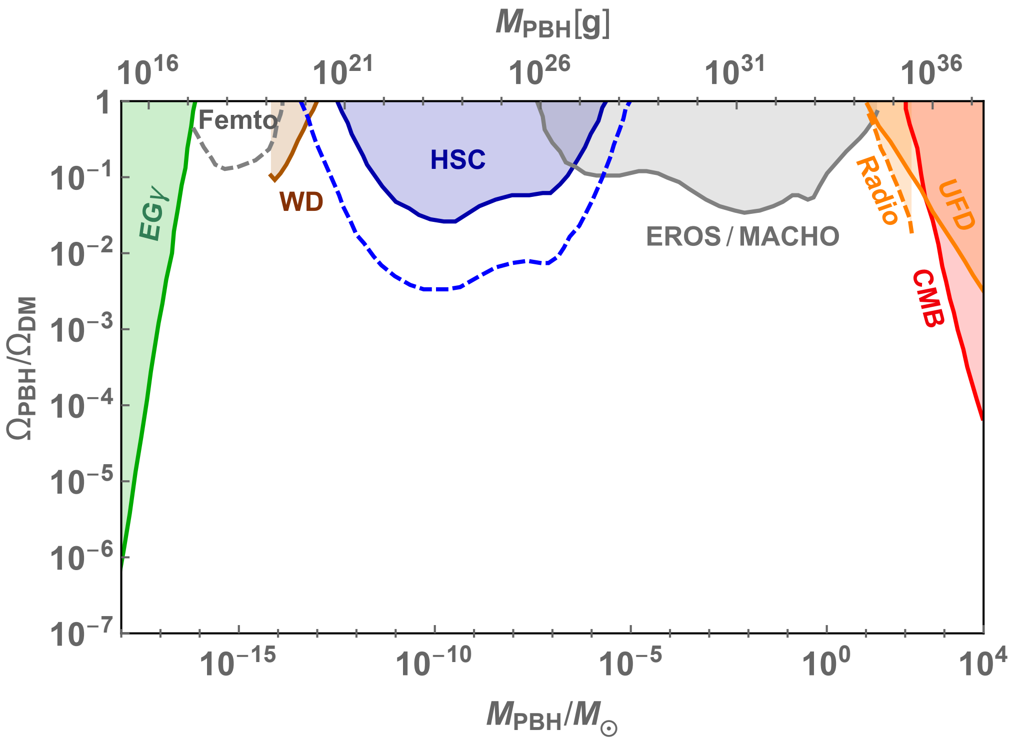
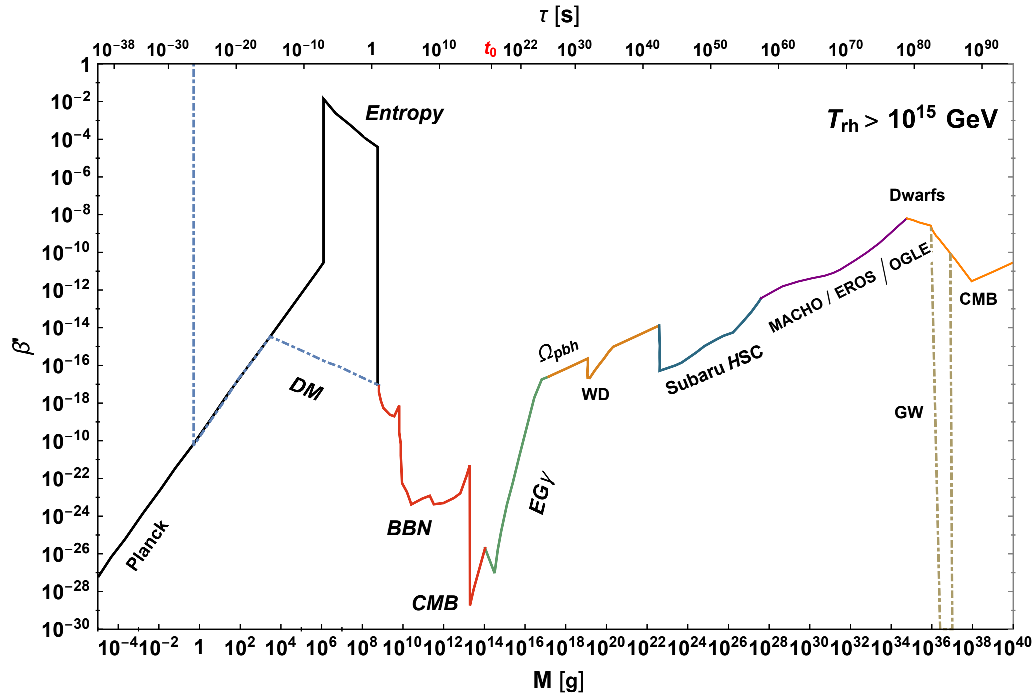
Can we formulate a constraint from the Hawking radiation?

Power spectrum constraints at all scales

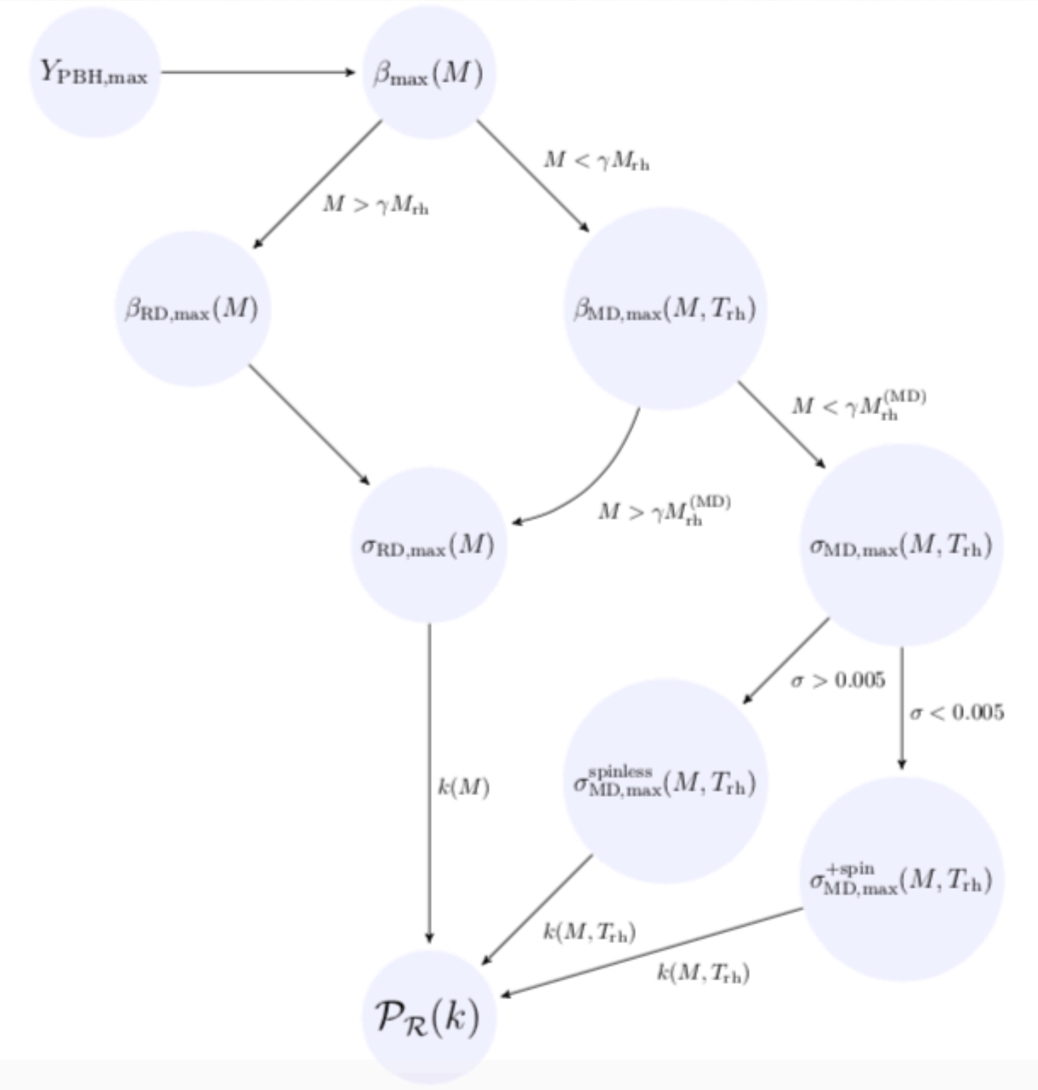




B.J.Carr, K. Kohri, Y. Sendouda and J.Yokoyama (2010)

The fractional abundance of PBHs (**f**) and the mass fraction of the universe that collapsed (**β**)

Transforming the PBH abundance constraints into power spectrum constraints

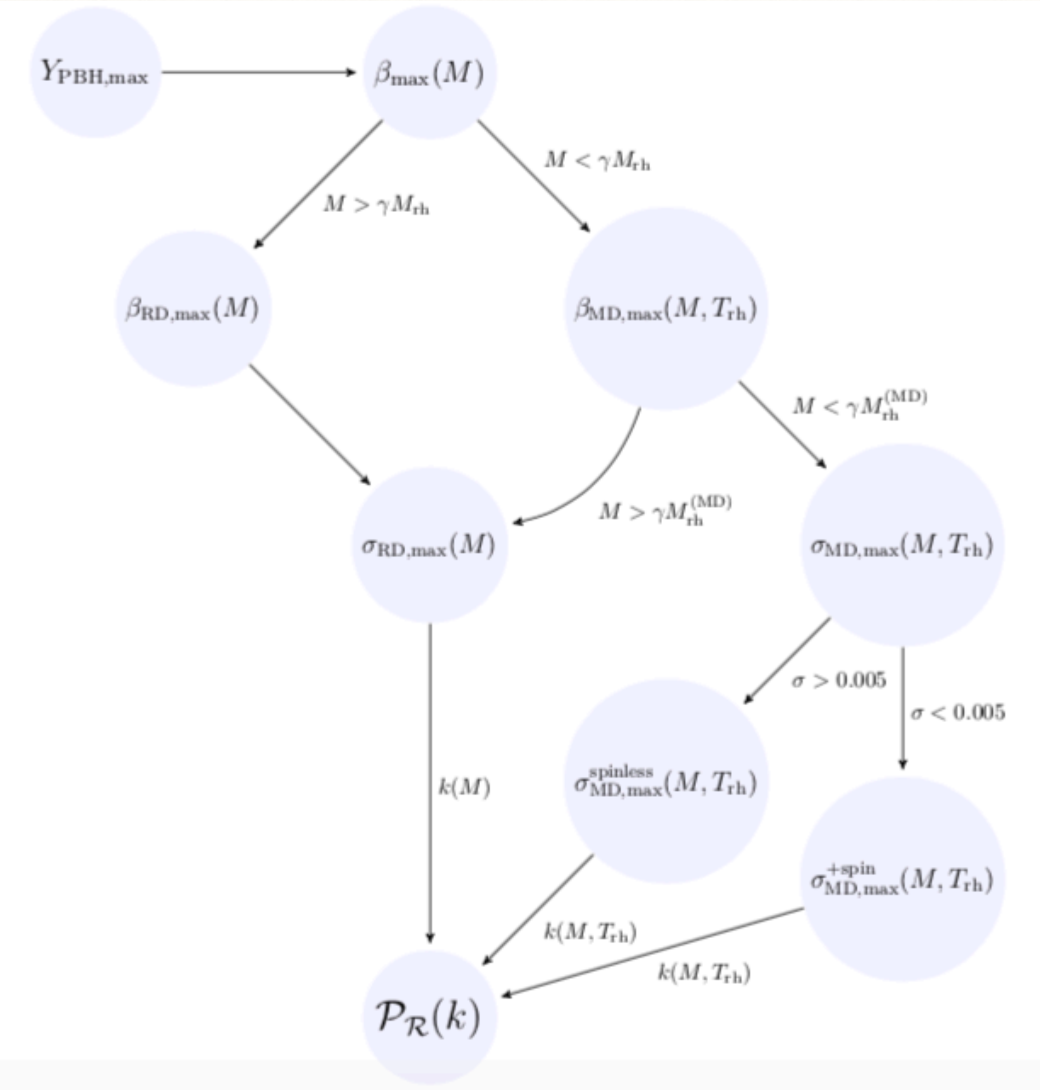


ID, JCAP 2019 (2020)

The steps one has to follow to derive upper bounds for the spectrum of the comoving curvature perturbations

Transforming the PBH abundance constraints into power spectrum constraints

ID, JCAP 2019



- The knowledge of the β can constrain the PS only if one assumes a model for the PBH formation.
- I assume spherical symmetric Gaussian primordial perturbations and that the PBHs form on the high σ-tail according to the Press-Schechter formalism
- I follow the monochromatic mass spectrum approximation and assume a one-to-one correspondence between the scale of perturbation and the mass of PBHs.
- I do not consider possible impacts on the power spectrum from non-Gaussianities and diffusion

$$\sigma^2(k) = \left(\frac{4}{9}\right)^2 \int \frac{dq}{q} W^2(qk^{-1})(qk^{-1})^4 \mathscr{P}_{\mathscr{R}}(q) \,,$$

$$\beta_{RD}(M_k) = \int_{\delta_c} d\delta \frac{1}{\sqrt{2\pi\sigma^2(k)}} e^{-\frac{\delta^2}{2\sigma^2(k)}}$$

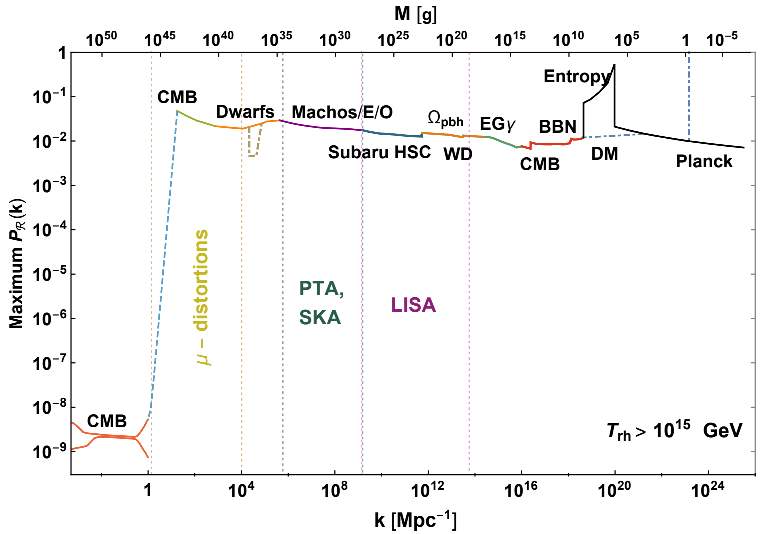
$$\beta(M) = 0.056\, \sigma^5(k)$$

$$\beta(M) = 2\times 10^{-7} \sigma^2(k)\, e^{-0.143\frac{\mathcal{I}^{4/3}}{\sigma^{2/3}(k)}}$$

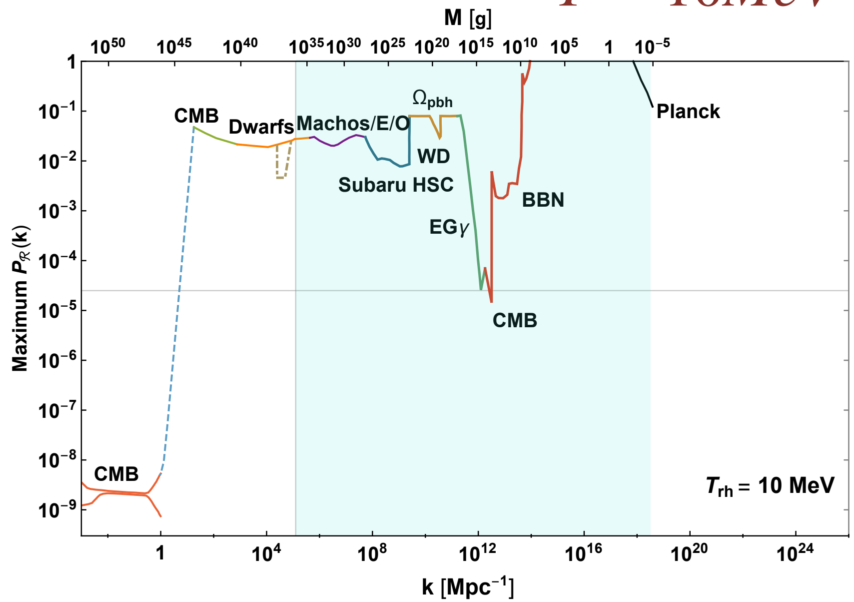
Power spectrum constraints at all scales

ID, JCAP 2020 (2019)

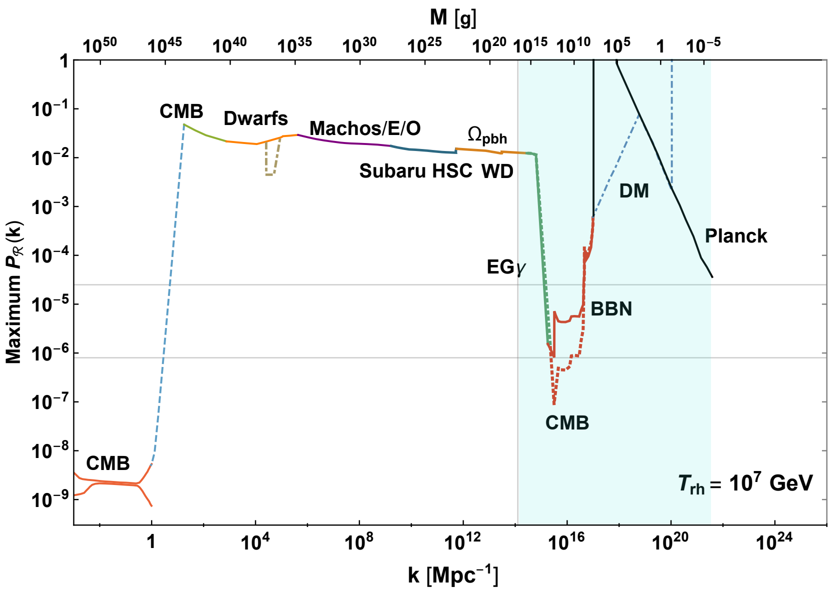
$T > 10^{15} GeV$



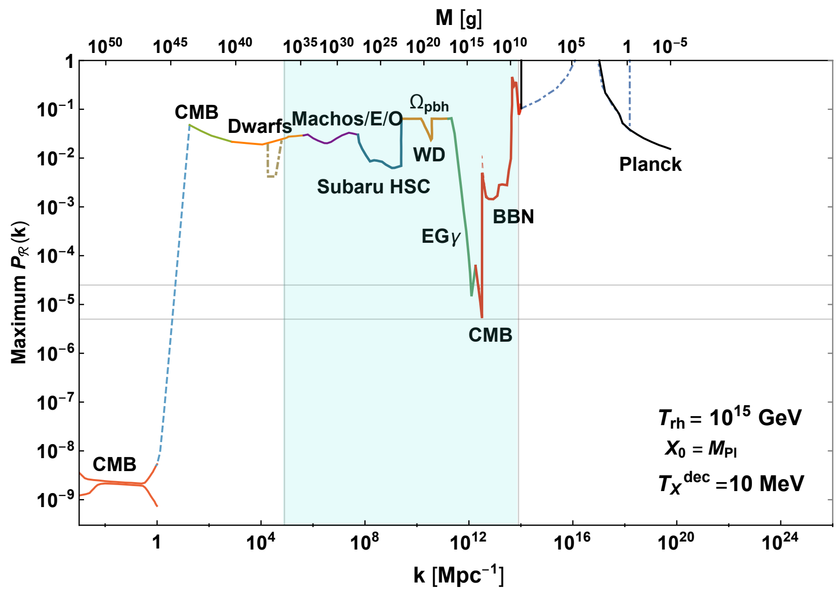
$T = 10 MeV$



$T = 10^{7} GeV$



Moduli case

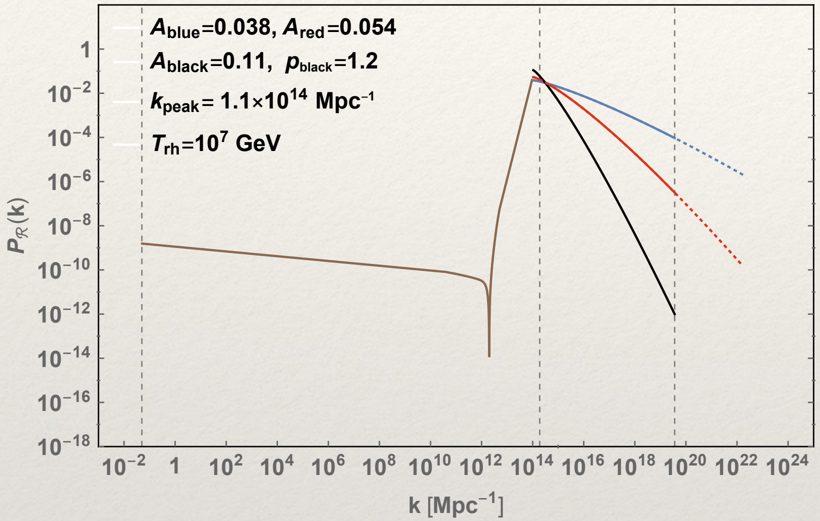


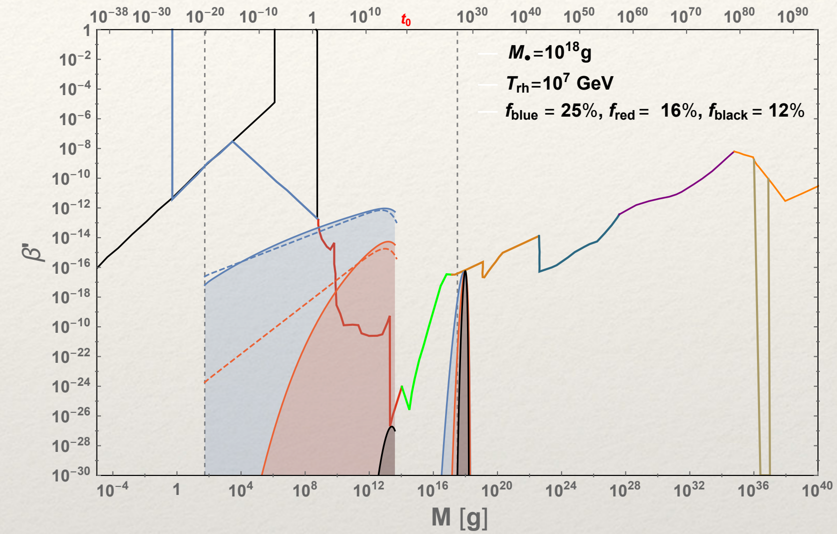
From the PBH abundance bounds to PS bounds

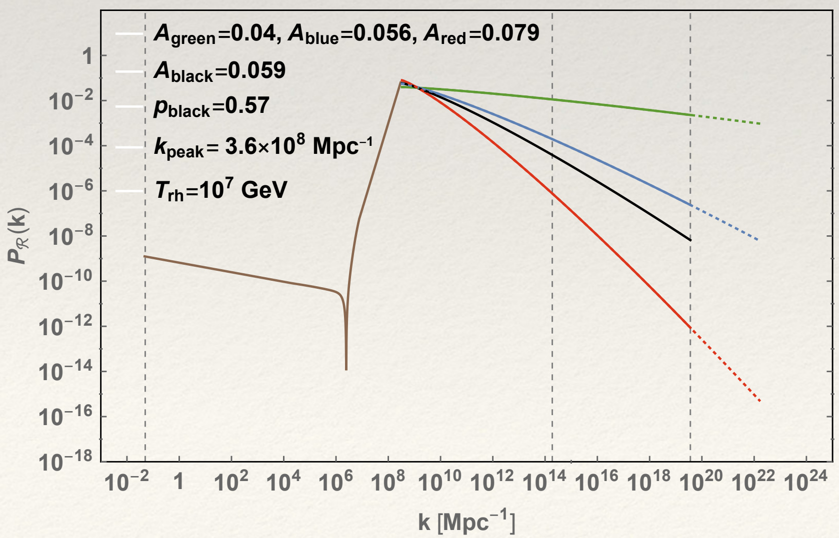
To be more explicit: The power spectrum has to be particularly narrow

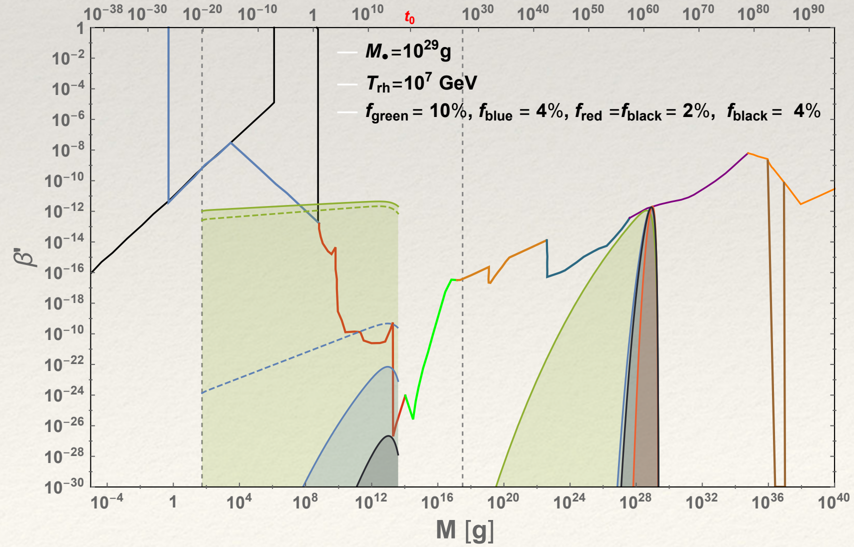
$$\mathscr{P}_{\mathscr{R}}(k \geq k_{peak}) = A_{max}\left(k/k_{peak}\right)^{-p}, \quad p = 0.1, 0.5, 1$$

ID, JCAP 2020 (2019)



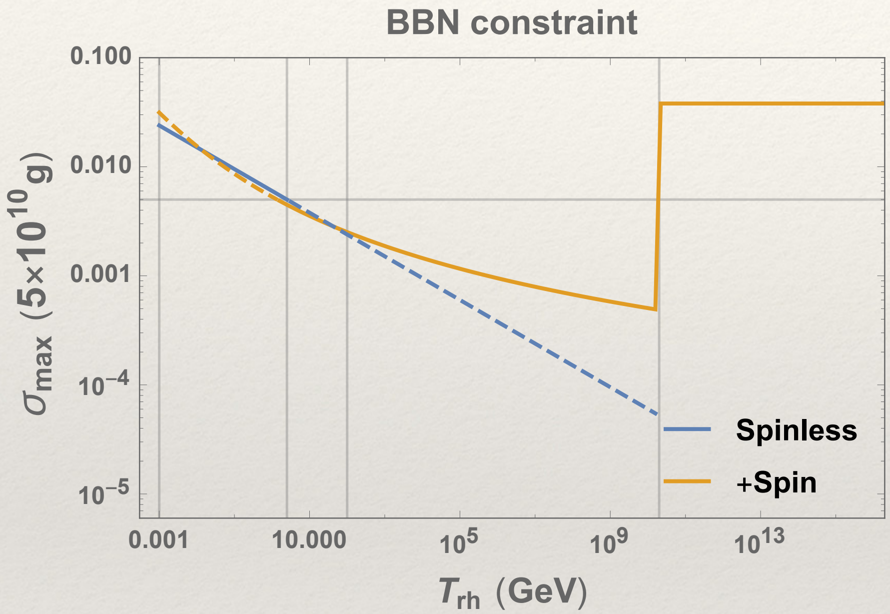


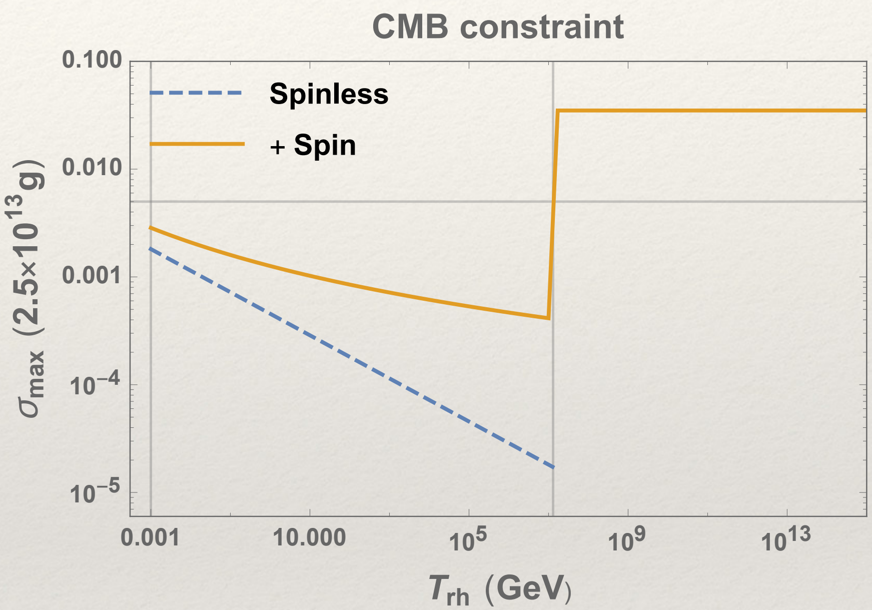




A constraint for the variance of the density perturbations is obtained

$$T_{\rm rh} < T^{(MD)}_{bbn} \equiv \left(\frac{2}{5}\mathscr{I}\right)^{1/2} T_{bbn}\,\sigma^{1/2}(M_{bbn}) \simeq 4\times 10^{8}\text{GeV} \quad \text{and} \quad T_{\rm rh} < T^{(MD)}_{cmb} \equiv \left(\frac{2}{5}\mathscr{I}\right)^{1/2} T_{cmb}\,\sigma^{1/2}(M_{cmb}) \simeq 2\times 10^{7}\text{GeV}$$





$$\sigma(5\times10^{10}\text{g})\Big|_{+\text{spin}} \lesssim \text{Exp}\left[-4.74 + 0.23\,\ln\frac{T_{\rm rh}}{\text{GeV}} + 8.4\times10^{-3}\left(\ln\frac{T_{\rm rh}}{\text{GeV}}\right)^2 - 1.5\times10^{-5}\left(\ln\frac{T_{\rm rh}}{\text{GeV}}\right)^3\right] \quad \text{(BBN)}$$

$$\sigma(2.5\times10^{13}\text{g})\Big|_{+\text{spin}} \lesssim \text{Exp}\left[-6.67 - 0.098\,\ln\frac{T_{\rm rh}}{\text{GeV}} + 2.4\times10^{-3}\left(\ln\frac{T_{\rm rh}}{\text{GeV}}\right)^2 - 4\times10^{-5}\left(\ln\frac{T_{\rm rh}}{\text{GeV}}\right)^3\right] \quad \text{(CMB)}$$

A constraint for the variance of the density perturbations is obtained

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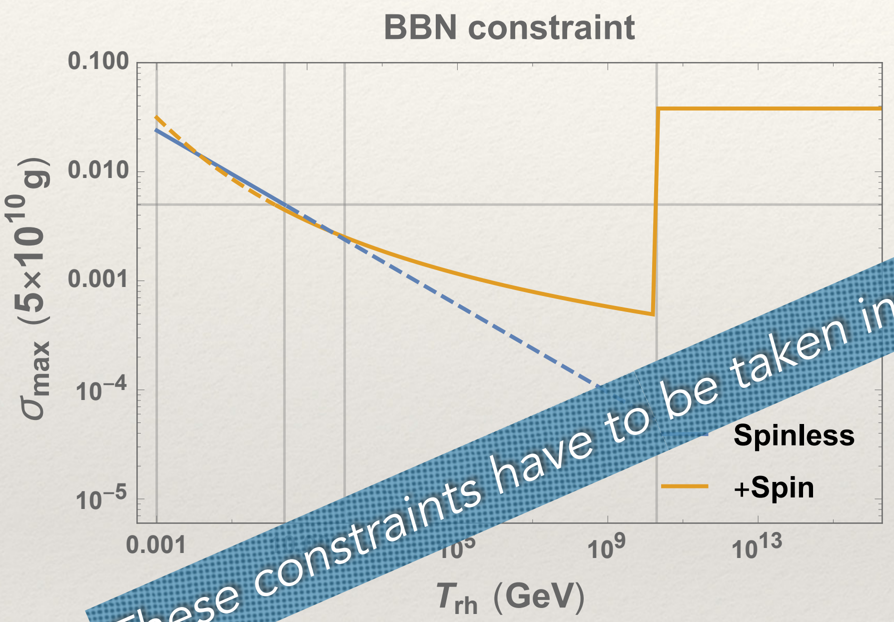

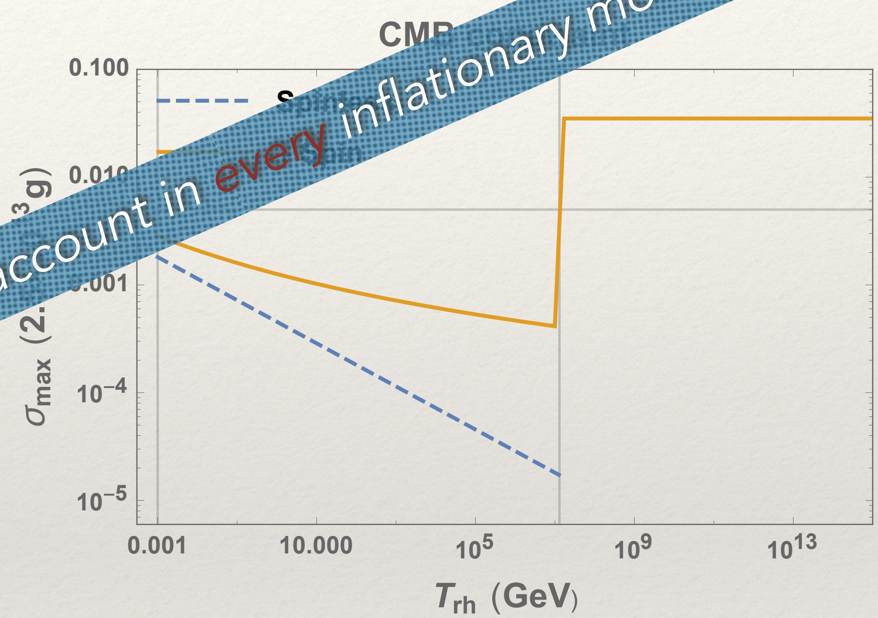

These constraints have to be taken into account in *every* inflationary model

$$\sigma(5\times 10^{10}\mathrm{g})\Big|_{+\rm spin} \lesssim \mathrm{Exp}\left[-4.74 + 0.23\,\ln\frac{T_{\rm rh}}{\rm GeV} + 8.4\times 10^{-3}\left(\ln\frac{T_{\rm rh}}{\rm GeV}\right)^2 - 1.5\times 10^{-5}\left(\ln\frac{T_{\rm rh}}{\rm GeV}\right)^3\right] \quad \text{(BBN)}$$

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Building single field inflationary models that generate PBHs

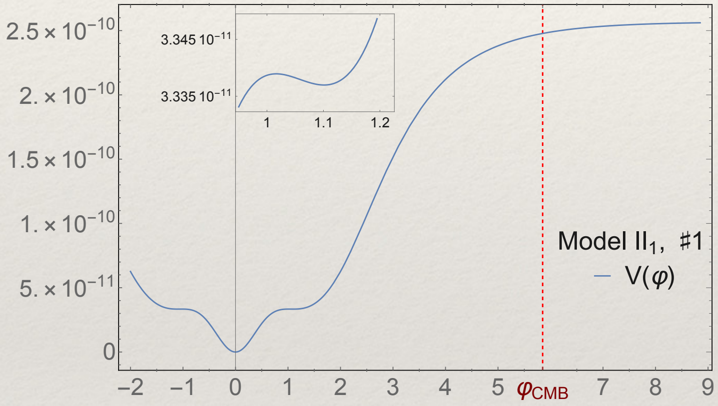
1. Due to infection point in the potential

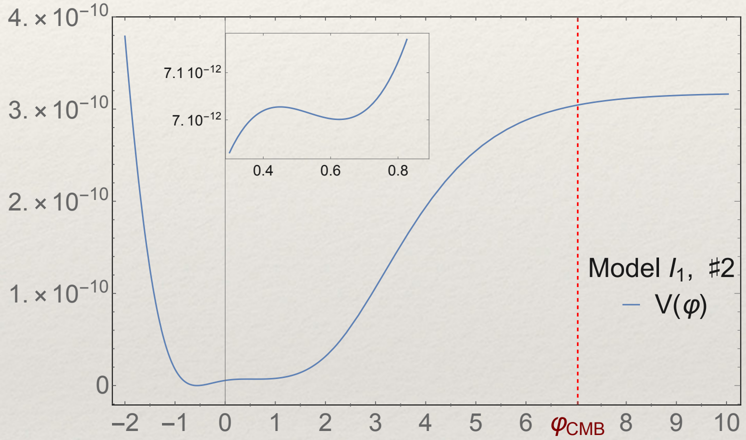
2. Due to non-canonical kinetic terms

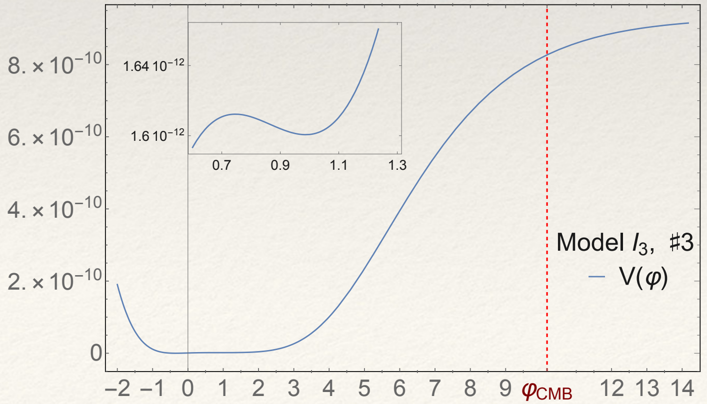
Superconformal α-Attractor inflationary models

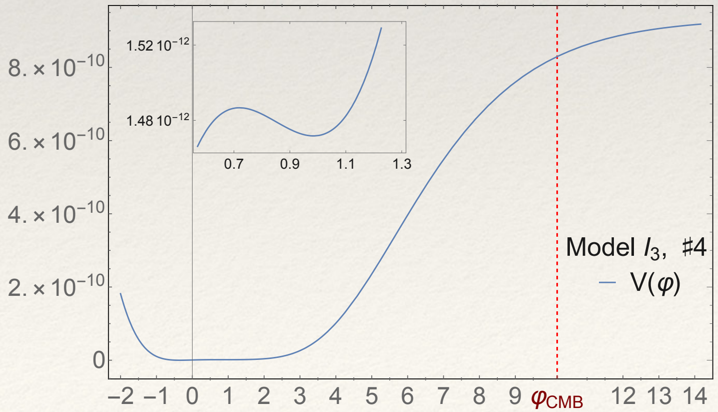
$$V(\varphi) = V_0 \left\{ c_0 + c_1 \tanh\left(\frac{\varphi}{\sqrt{6\alpha}}\right) + c_2 \tanh^2\left(\frac{\varphi}{\sqrt{6\alpha}}\right) + c_3 \tanh^3\left(\frac{\varphi}{\sqrt{6\alpha}}\right) \right\}^2$$

$$V(\varphi) = V_0 \left[\tanh(\varphi/\sqrt{6}) + A \sin\left(\tanh(\varphi/\sqrt{6})/\theta\right) \right]^2$$



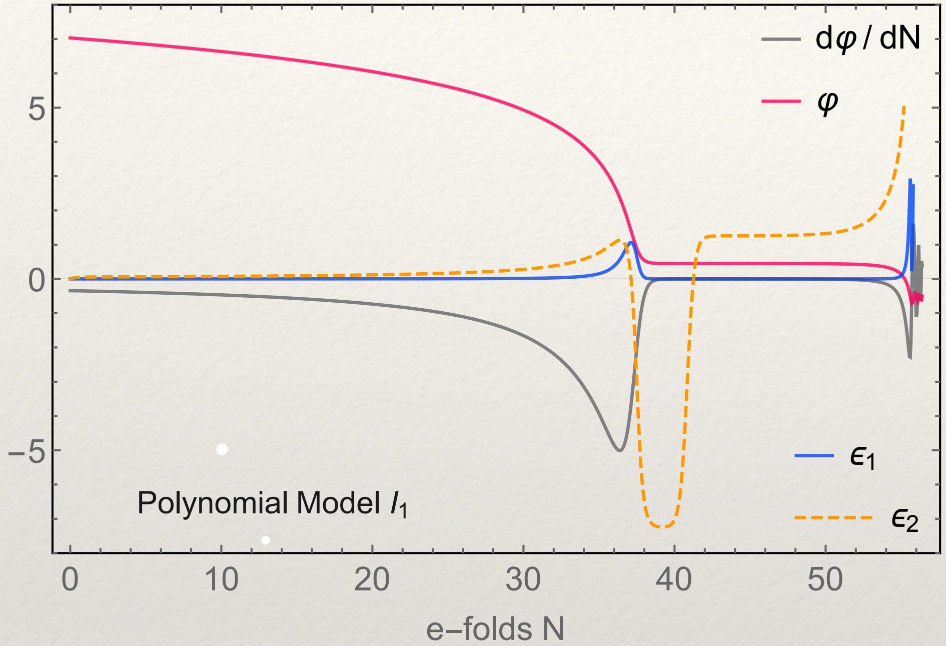


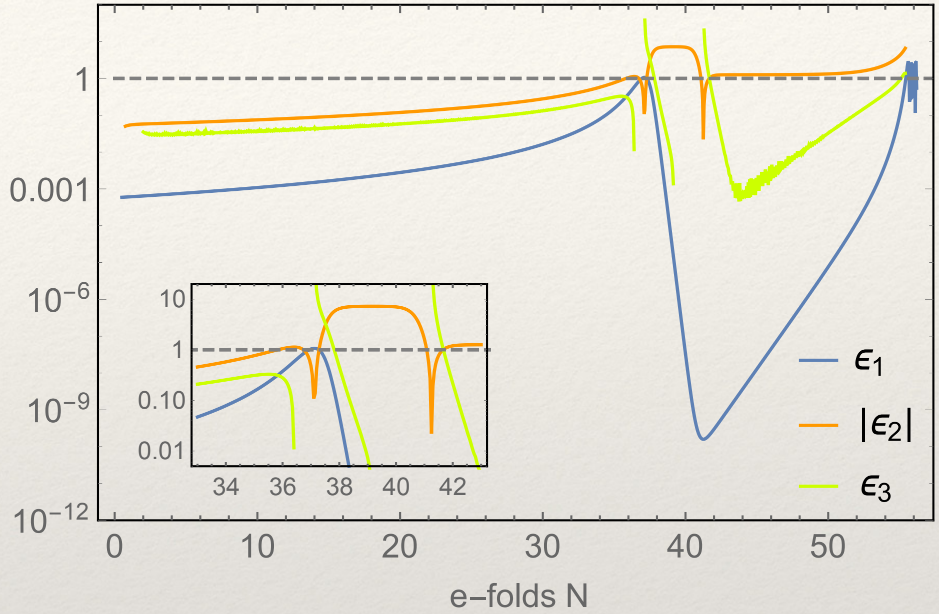




ID + Kehagias + Tringas, JCAP 1901 (2019) 037

Superconformal α-Attractor inflationary models





$$S_{(2)} = \frac{1}{2}\int \mathrm{d}^4x\sqrt{-g}\,a^3\frac{\dot{\varphi}^2}{H^2}\left[\dot{\mathscr{R}}^2 - \frac{(\partial_i\mathscr{R})^2}{a^2}\right]$$

The Mukhanov-Sasaki equation has to be solved numerically

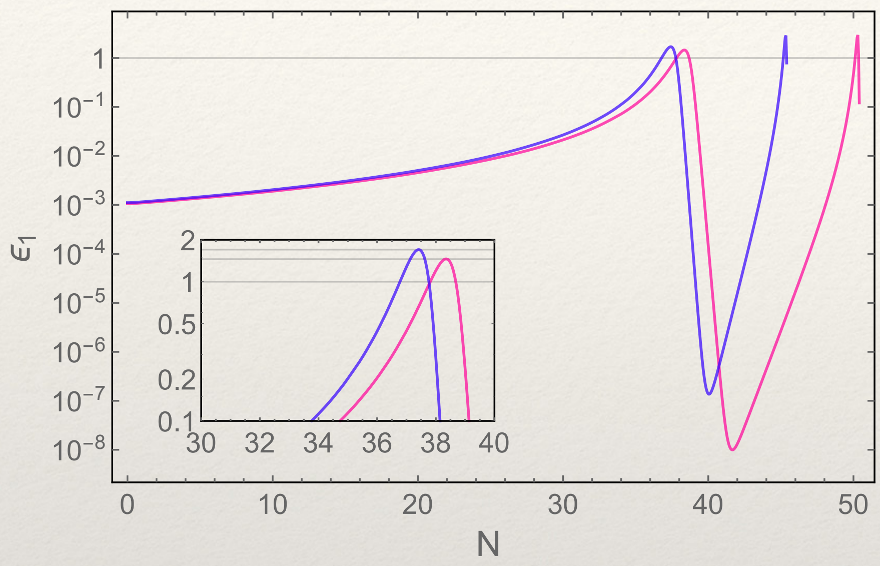
$$v_k'' + \left(k^2 - \frac{z''}{z}\right)v_k = 0$$

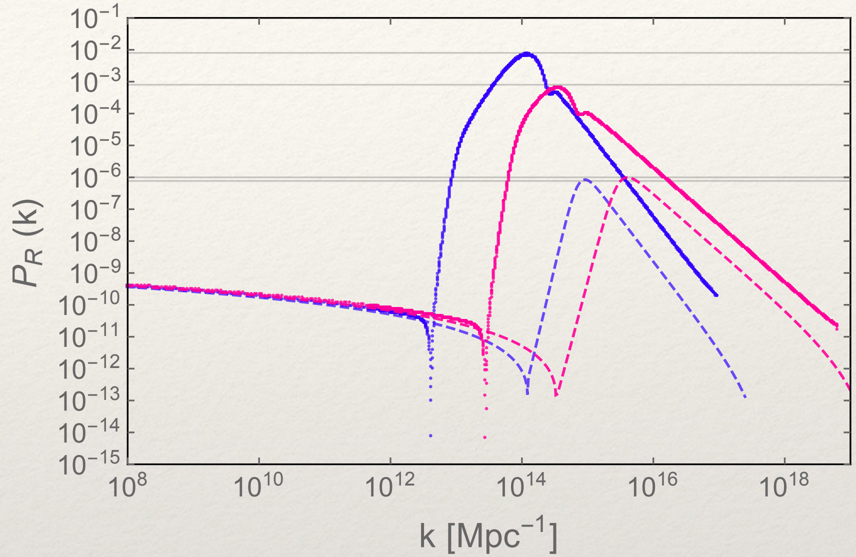
$$\frac{z''}{z} = (aH)^2\left[2 - \epsilon_1 + \frac{3}{2}\epsilon_2 - \frac{1}{2}\epsilon_1\epsilon_2 + \frac{1}{4}\epsilon_2^2 + \frac{1}{2}\epsilon_2\epsilon_3\right]$$

$$\mathscr{P}_{\mathscr{R}} = \frac{k^3}{2\pi^2}\frac{|v_k|^2}{z^2}\Bigg|_{k\ll aH}$$

ID + Kehagias + Tringas, JCAP 1901 (2019) 037

Superconformal α-Attractor inflationary models





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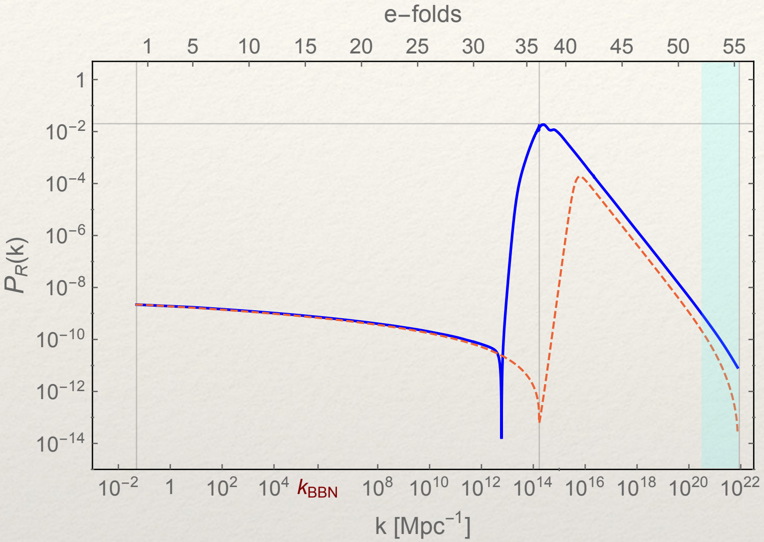
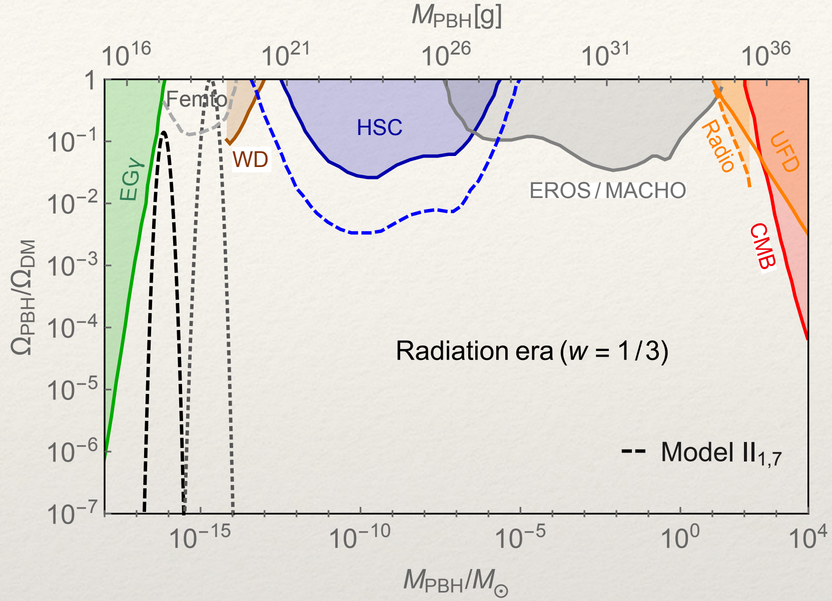
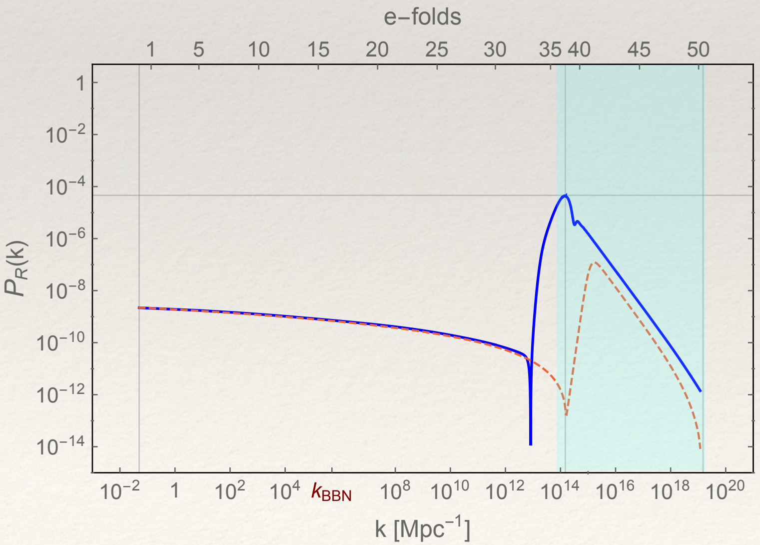
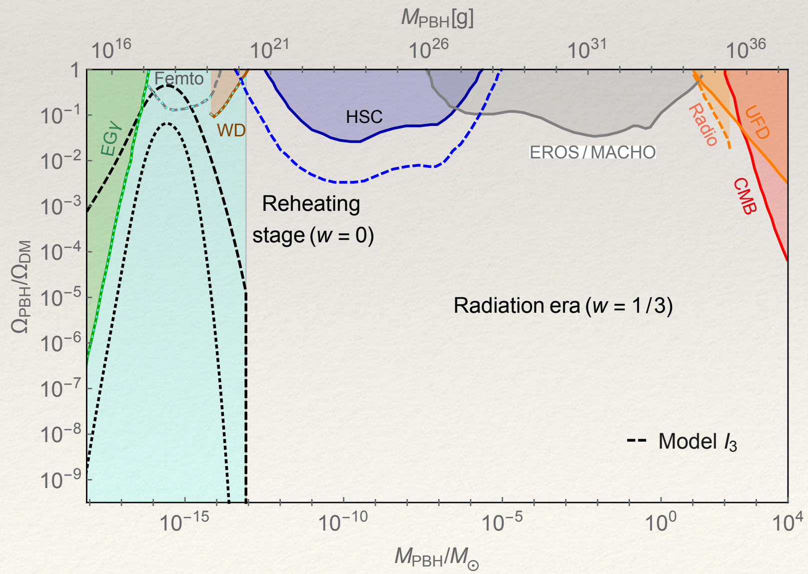
The predicted PBH abundance from α-Attractor inflationary models

ID + Kehagias + Tringas, JCAP 1901 (2019) 037









ID + Karydas+ Papantonopoulos (in progress)

Horndeski Theories

- One of the most well studied **scalar-tensor theories** is the one resulting from the Horndeski Lagrangian

- Horndeski theories are technically manageable because they give second-order field equations and are consistent **without ghost instabilities**

- In Horndeski theory, among other terms, there is the **non-minimal derivative coupling of the scalar field to Einstein tensor** (NMDC).

$$\mathscr{L}_5 = G_5(\phi, X) G^{\mu\nu} \partial_\mu \phi \partial_\nu \phi$$

We consider derivative couplings of the form:

$$G_5(\phi, X) = \alpha \frac{\phi^{\alpha-1}}{M^{\alpha+1}} \quad \text{or} \quad G_5(\phi, X) = \frac{e^{\lambda\phi}}{M^2}$$

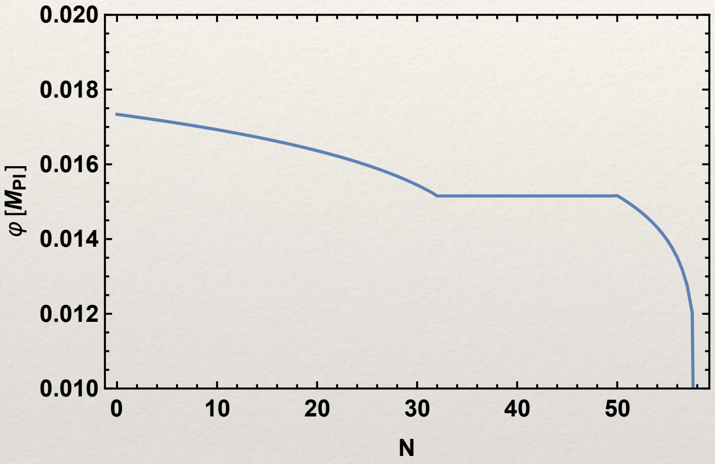
- **Higgs inflation**
- **Exponential inflation**

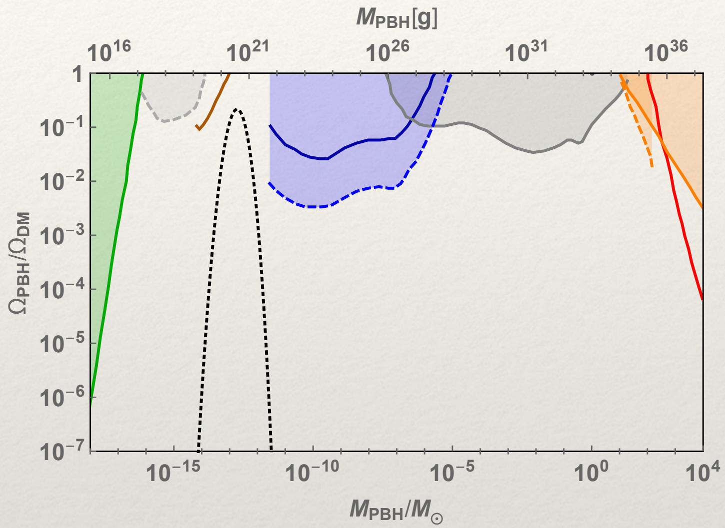
The instabilities during the oscillating phase can be avoided !

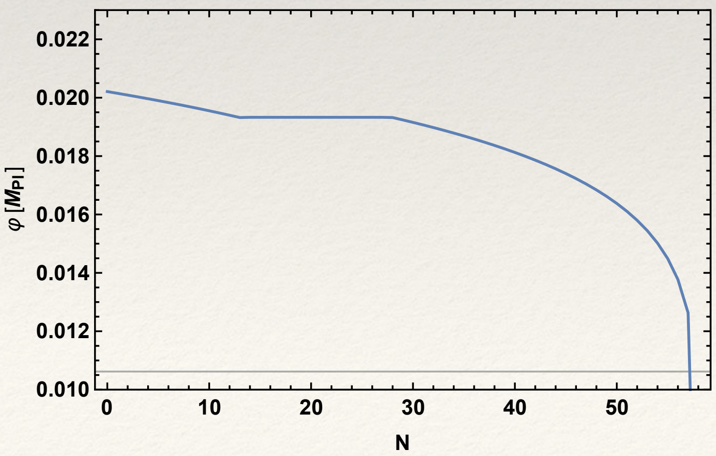
ID + Karydas+ Papantonopoulos (in progress)

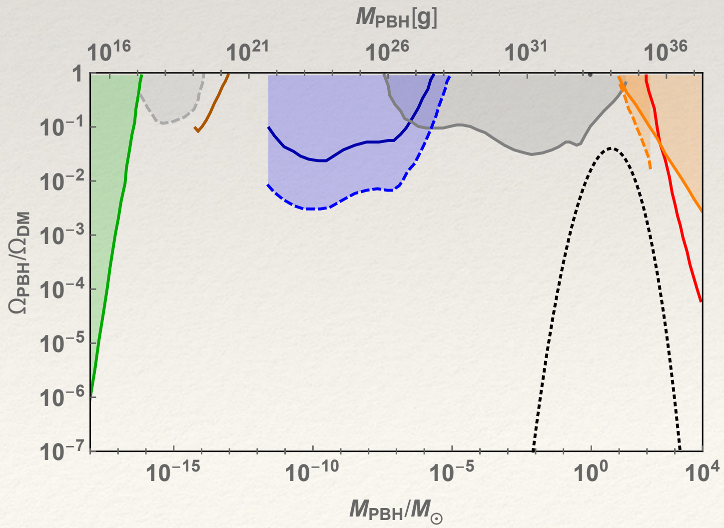
Horndeski Theories

$$G_5(\phi, X) = \alpha \frac{\phi^{\alpha-1}}{M^{\alpha+1}} \left(1 + d_0\, Exp \left[\frac{-(\phi - \phi_0)^2}{c_0^2} \right] \right)$$







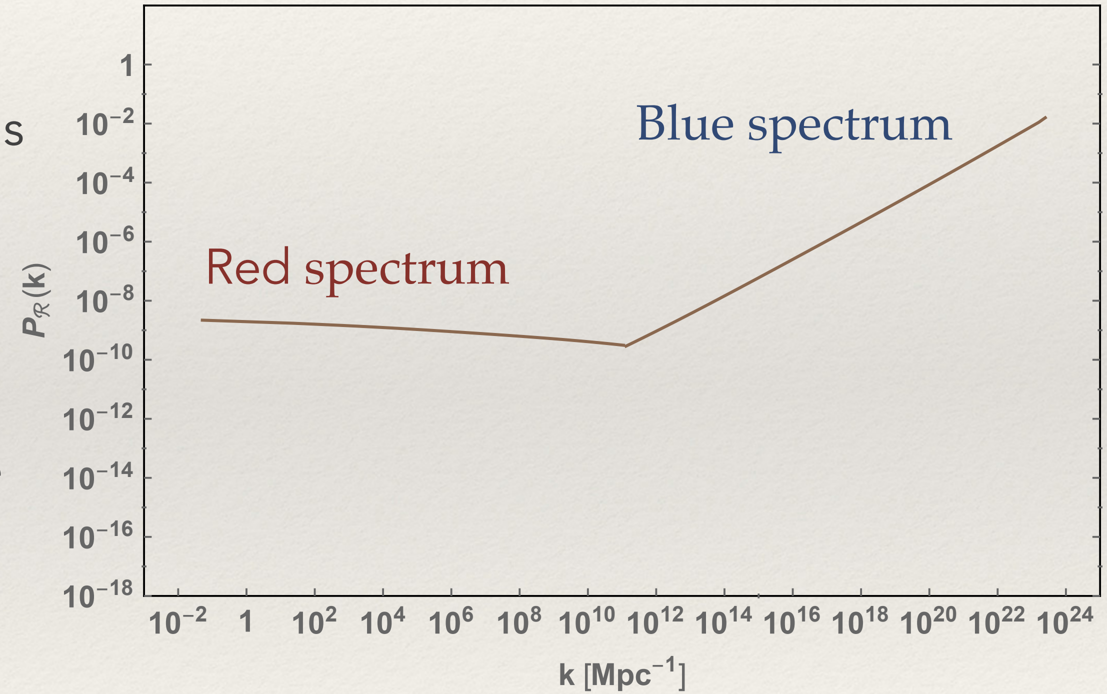


Q: What if the Power Spectrum peak is at the very end?

A: The dark matter might consists of PBH remnants

A simple Power Spectrum that gives ultra light PBHs

- If the power spectrum changes from red to blue then we expect an enhanced PBH production probability.
- In the literature there are plenty of models that yield a blue scalar tilt
- A turn over is necessary
- The PBHs will evaporate promptly in the very early universe



PBH remnants

J.D. Barrow, E.J. Copeland and A.R. Liddle (1992)

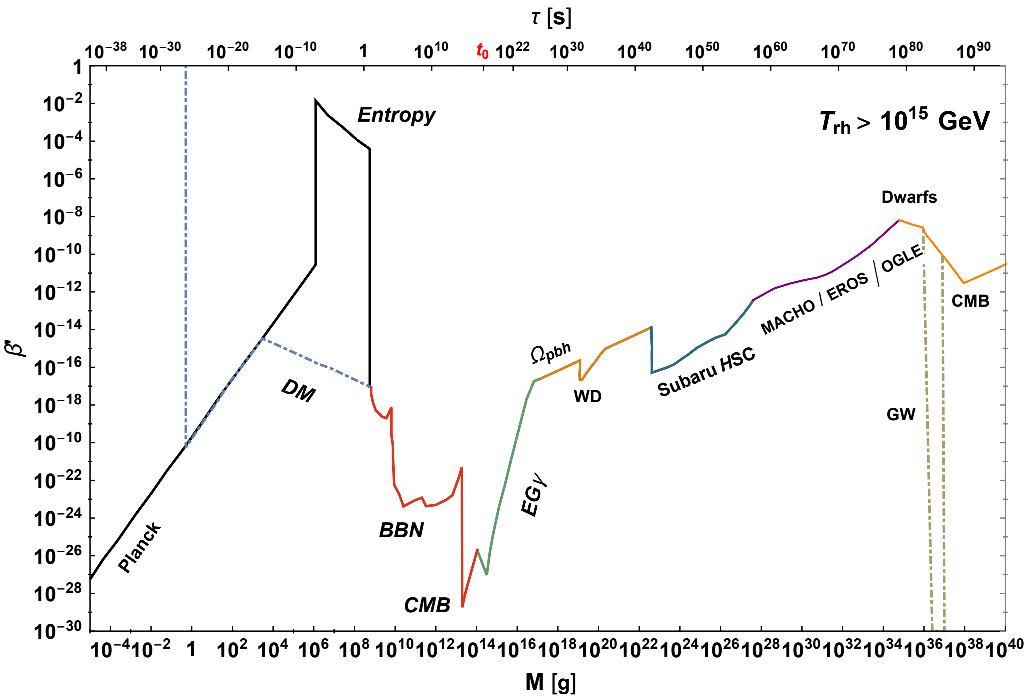
B.J. Carr, J.H. Gilbert and J.E. Lidsey (1994)

There are several theoretical reasons to anticipate that black holes do not evaporate completely but leave behind a stable mass state.
The Hawking radiation is derived by treating matter fields quantum mechanically, while treating the space-time metric classically.

There are arguments based on :
- **Hawking temperature cannot become infinite**
- The information loss paradox
- Black holes with quantum hair
- A generalized uncertainty principle
- Extra spatial dimensions
- Higher order corrections to the action of general relativity

See Chen et. al arXiv:1412.8366 for a review

$$M_{rem} = \kappa\, m_{Pl}$$



PBH remnants cosmology

ID + Tringas (2019)

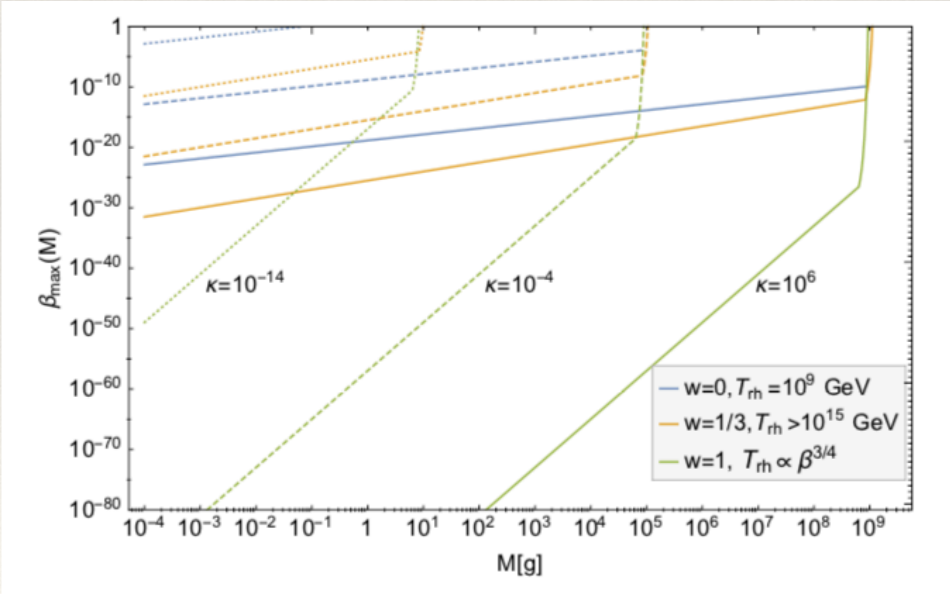
- PBH remnants can be a significant fraction of the dark matter in the universe only if $M \lesssim \kappa^{2/5} 10^6 g$

- Possible range for the PBH remnant masses $10^{-24}\,\mathrm{g} < M_{\rm rem} \ll 10^8\,\mathrm{g}$

$$f_{rem}(M) \simeq \kappa \left(\frac{\beta}{10^{-12}}\right) \left(\frac{\gamma}{0.2}\right)^{\frac{3}{2}} \left(\frac{M}{10^5\mathrm{g}}\right)^{-3/2}$$

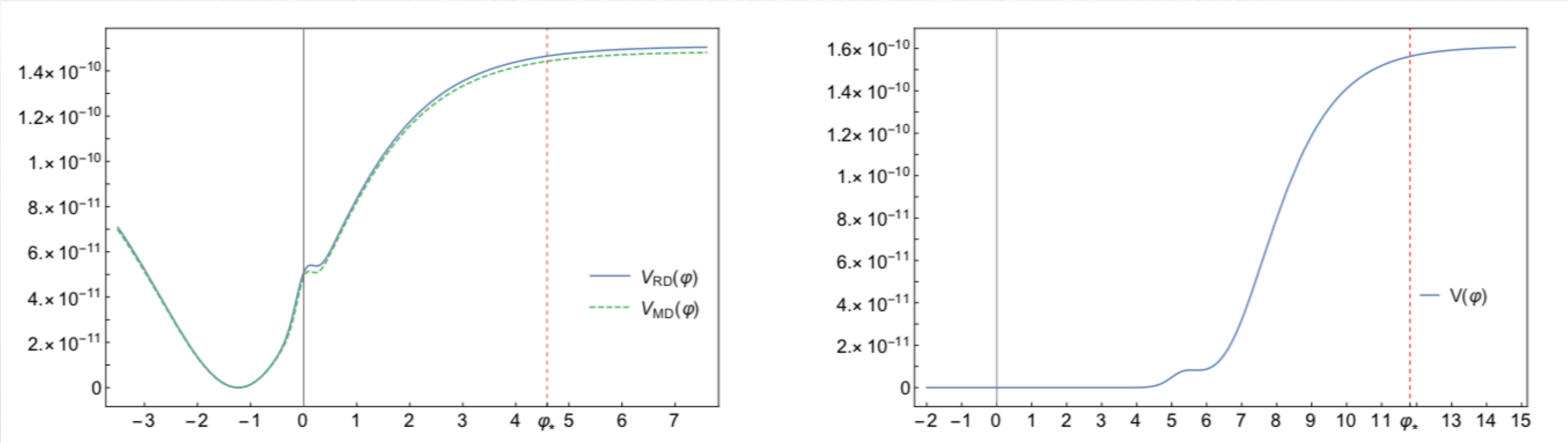
$$f_{rem}(M, M_{rh}) \simeq 3\,\kappa\gamma \left(\frac{\beta}{10^{-9}}\right) \left(\frac{M_{rh}}{10^{10}\mathrm{g}}\right)^{-1/2} \left(\frac{M}{10^5\mathrm{g}}\right)^{-1}$$

$$f_{rem}(M) \simeq 4\,\kappa\sqrt{\gamma} \left(\frac{\beta}{10^{-32}}\right)^{1/4} \left(\frac{M}{10^5\mathrm{g}}\right)^{-2}$$



Potentials for PBH remnants dark matter

ID + Tringas (2019)

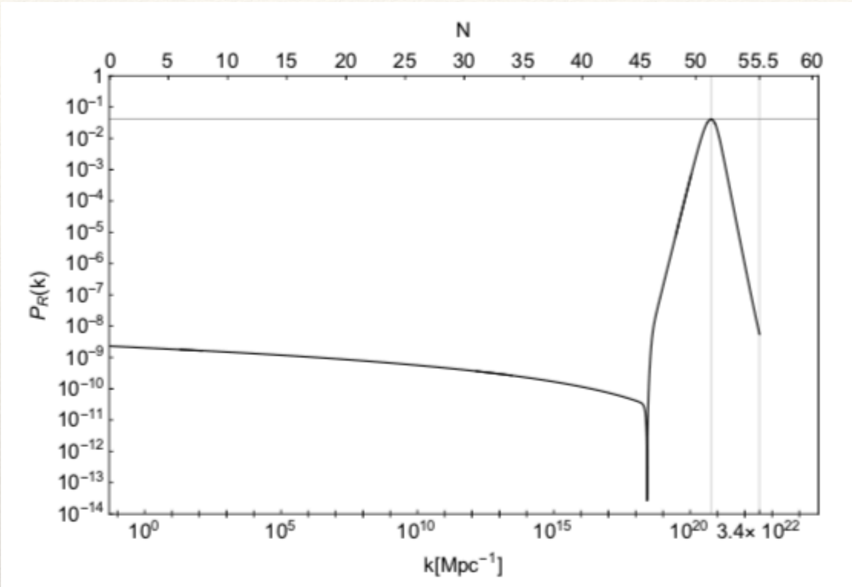


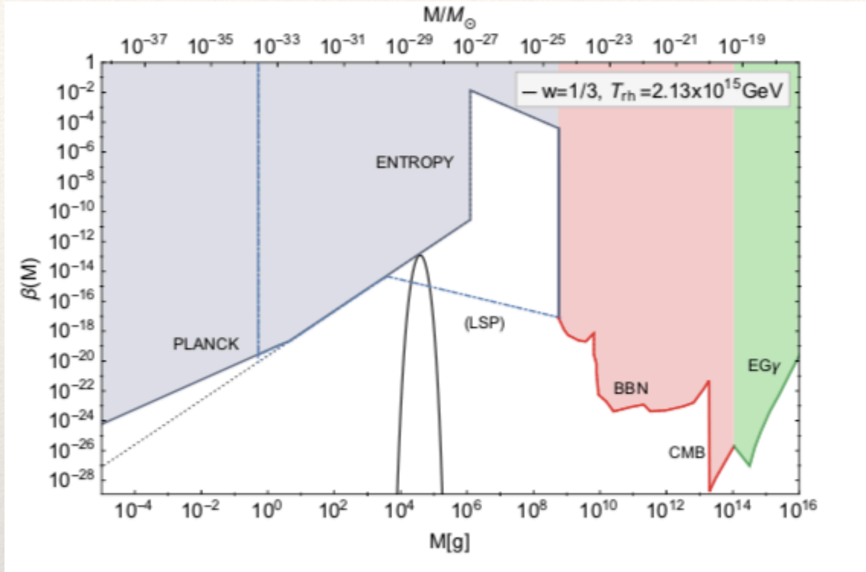
Oscillatory: $$V(\varphi) = f_0^2 \left(c_0 + c_1 e^{\lambda_1 \tanh \varphi/\sqrt{6}} + c_2 e^{\lambda_2 (\tanh \varphi/\sqrt{6})^2} \right)^2$$

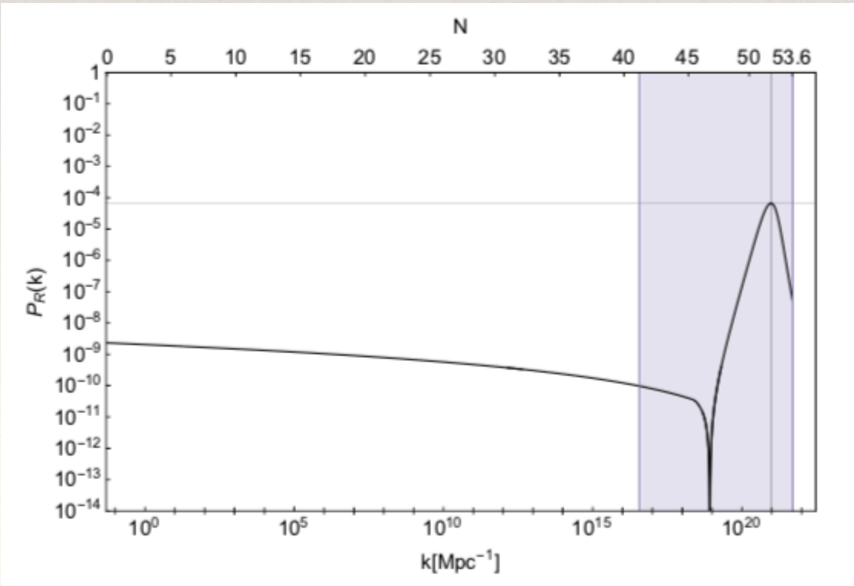
Runaway: $$V(\varphi) = f_0^2 \left[c_0 + c_1 e^{\lambda_1 \tanh \varphi/\sqrt{6}} + c_2 e^{\lambda_2 \left(\tanh(\varphi/\sqrt{6}) - \tanh(\varphi_P/\sqrt{6}) \right)} \right]^2$$

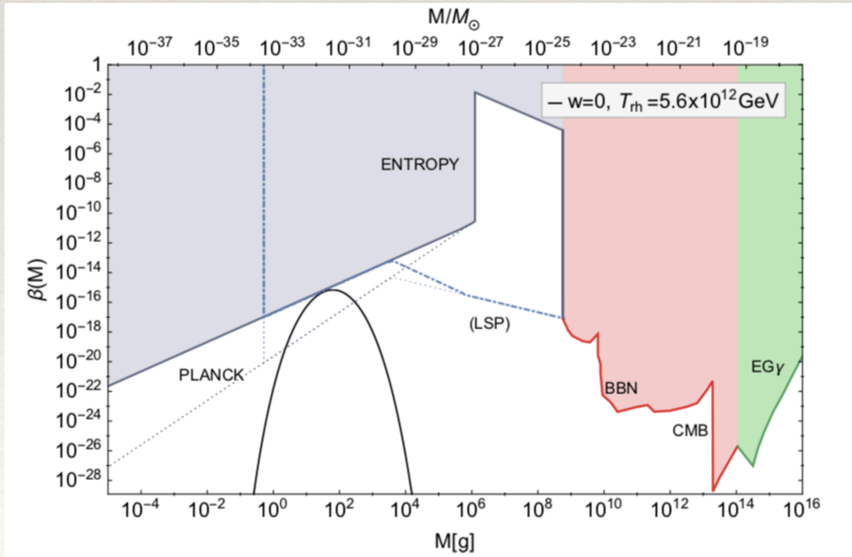
PS for PBH remnants dark matter

ID + Tringas (2019)



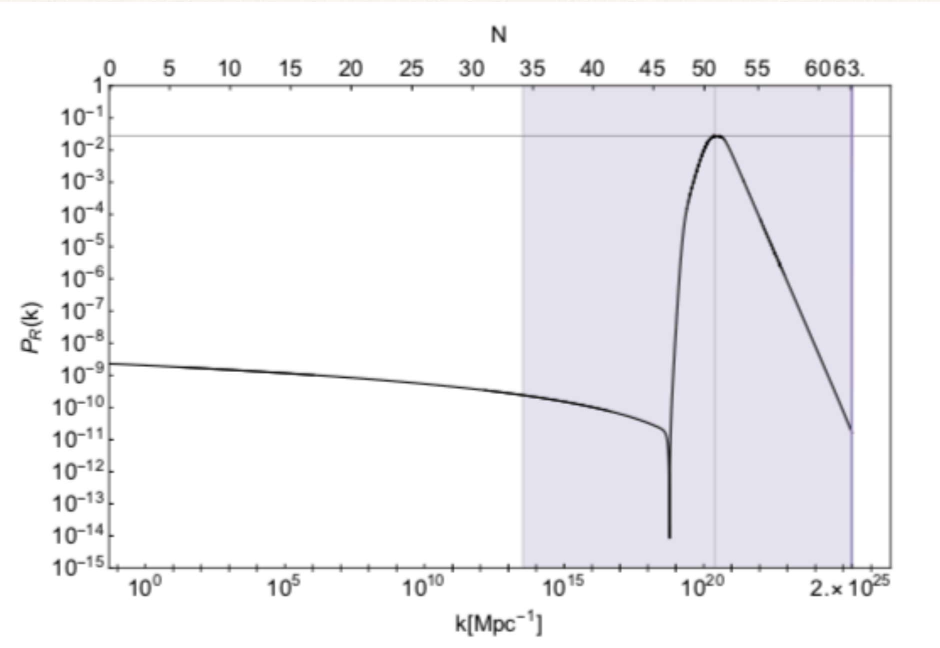


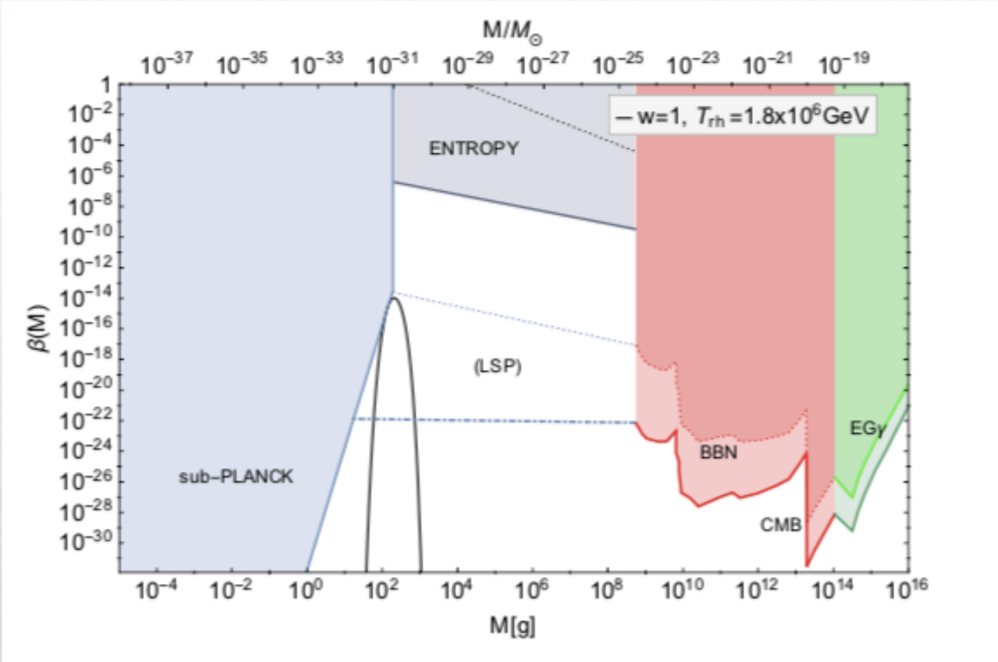




PBH remnants, Runaway model

ID + Tringas (2019)



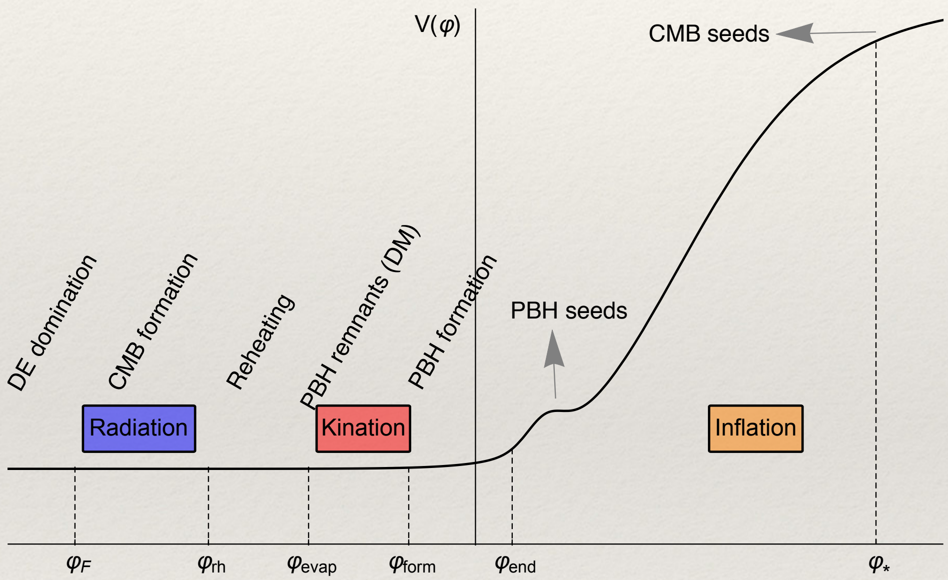


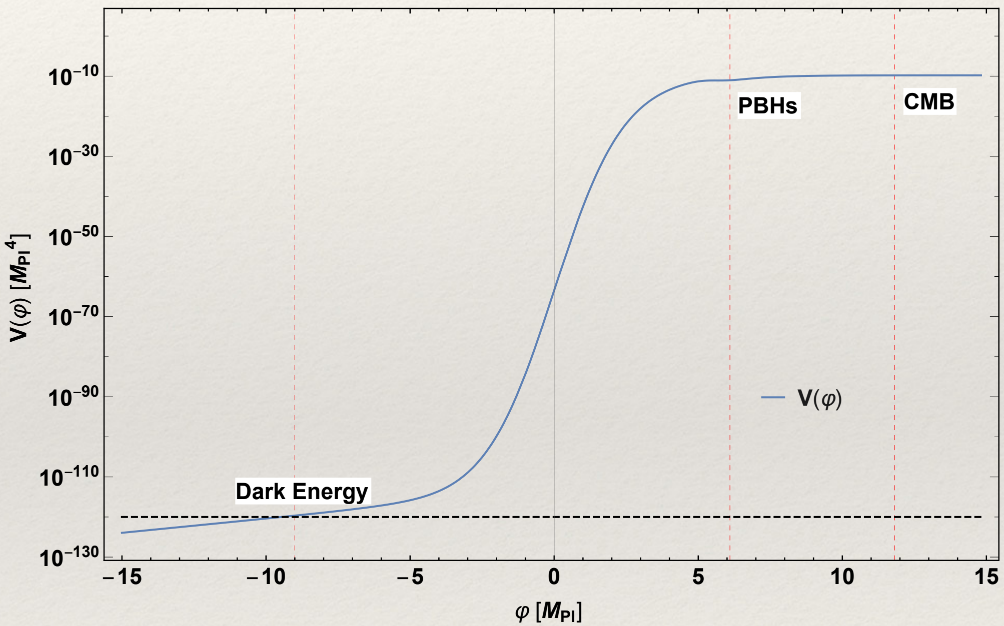
GW constraints:

$$T_{\rm rh} \equiv 6.3\,{\rm MeV}\left(\frac{\beta}{10^{-28}}\right)^{3/4}\gamma^{3/2}g_*^{-1/2}$$

$$\frac{\kappa}{10^{-10}} \lesssim 8.5\,\gamma^{-5/2}\left(\frac{H_{end}}{10^{-6}\,M_{Pl}}\right)^{-10/3}\left(\frac{g_*}{106.75}\right)^{-5/6}.$$

Runaway inflationary models + PBHs



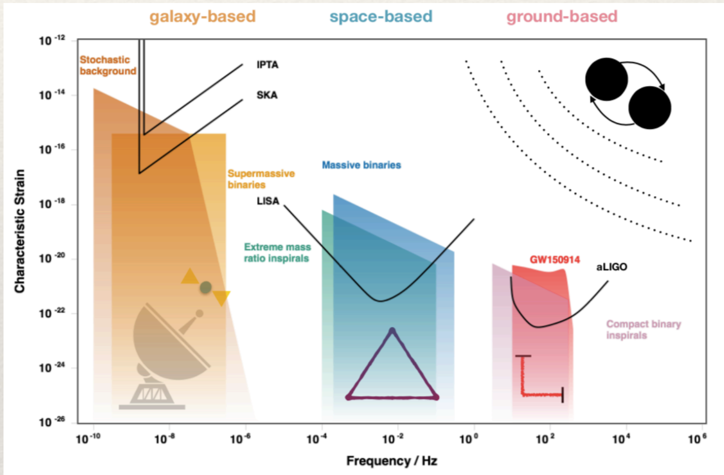


A runaway inflationary model introduced that produces PBHs that explain the dark matter with their evaporation remnants, reheats the Universe and implements a wCDM late time cosmology.

Conclusions

- The LIGO might have detected PBHs, but not the dominant dark matter
- PBH with asteroid-moon like mass can be generated by inflationary models in accordance with the Planck 2018 constraints
- PBH remnants, if long lived, are a very attractive dark matter candidate
- Minimal BSM extensions are necessary for PBH/PBH remnants dark matter

- Current and future Gravitational Detection Experiments can significantly constrain the PBH dark matter scenario



- PBHs give us insights into the dynamics of inflation even if PBHs do not comprise the observed dark matter in the Universe

- **Upper bounds** on the PBH abundance can be seen as **lower bounds** for the particle dark matter abundance

Conclusions

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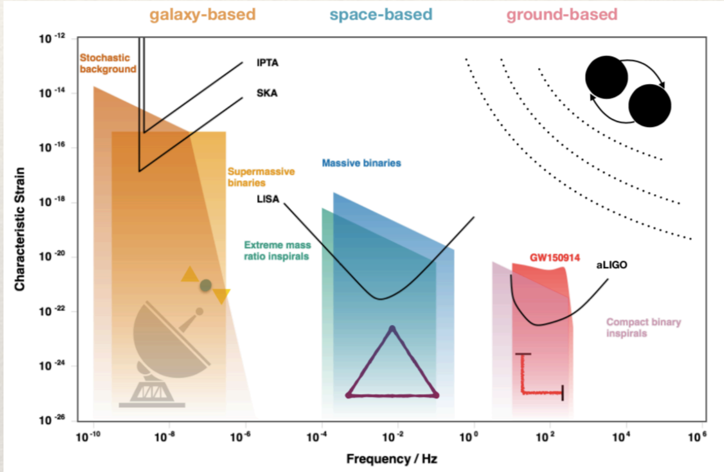

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Thank you!