Axion Dark Matter in the Time of Primordial Black Holes

Based on:
NB, Fazlollah Hajkarim & Yong Xu   arXiv:2107.13575

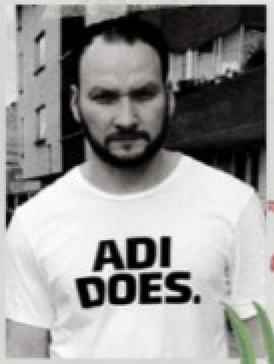

Nicolás BERNAL

UNIVERSIDAD ANTONIO NARIÑO

CoCo 2o21
September 8 – 10, 2021

El conocimiento es de todos

Minciencias



Javier Humberto Ordoñez

Julieth Ramírez Meza

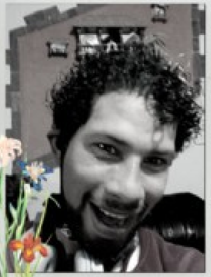
Lorwan Estiwen Mendoza

Julieth Ramírez Meza

Julián Mauricio González

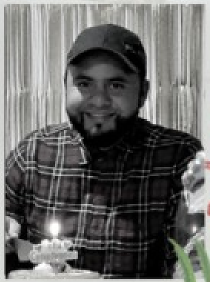
Murdered by the Police September 2020

Andrés Felipe Rodríguez Ávila



Anthony Gabriel Estrada Espinoza

Angie Paola Baquero Rojas



Christian Andrés Hurtado Menecés

Cristian Camilo Hernández Yara

Freddy Alexander Mahecha

Jaider Fonseca Castillo

Germán Smyth Puentes Valero

Strong CP Problem

$$\underbrace{\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} G_{\mu\nu a} G_a^{\mu\nu} + \sum_q i\, \bar{q} \gamma^\mu D_\mu q - m_q\, \bar{q} q}_{\text{CP conserving}}$$

Strong CP Problem

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usually forgotten!

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Electric dipole moment of the neutron…

$$d_n = (2.4 \pm 1.0)\,\theta \times 10^{-3}\ e\ \mathrm{fm}$$

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usually forgotten!

Electric dipole moment of the neutron… *not observed!*

$$d_n = (2.4 \pm 1.0)\,\theta \times 10^{-3}\ e\ \text{fm}$$

$$|\theta| < 1.3 \times 10^{-10}$$

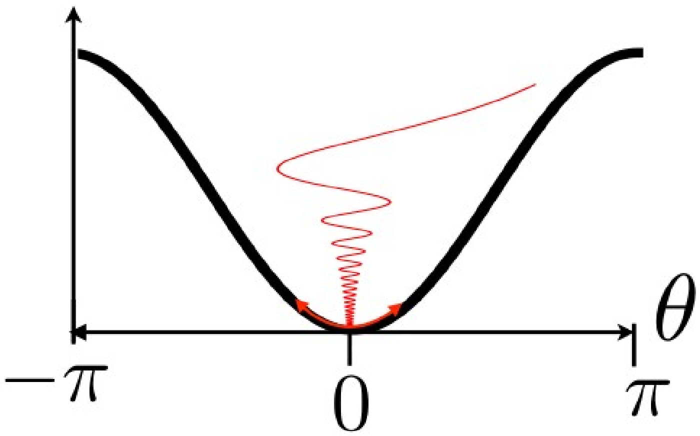
← **Strong CP problem!**

Axion

Talk by Moira

If θ is a *dynamical field*, QCD will relax it to its minimum…
→ Strong QCD problem explained!

Peccei & Quinn '77



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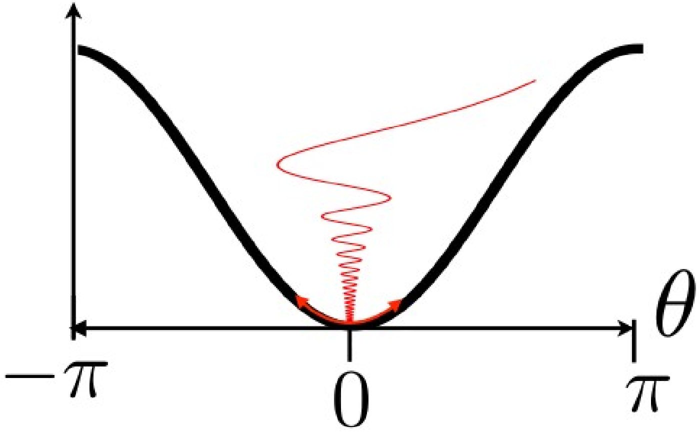
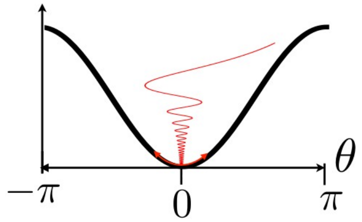


Axion oscillates in a ~ quadratic potential
→natural *cold dark matter* candidate

Misalignment: Producing Axion DM



Effective axion potential $V(\theta) = \chi(T)\,(1 - \cos\theta)$

Evolution of the axion field $\ddot{\theta} + 3\,H(T)\,\dot{\theta} + m_a^2(T)\,\sin\theta = 0$

Axion energy density $\rho_a(T) = \frac{1}{2} f_a^2 \dot{\theta}^2 + m_a^2(T)\,f_a^2\,(1 - \cos\theta)$

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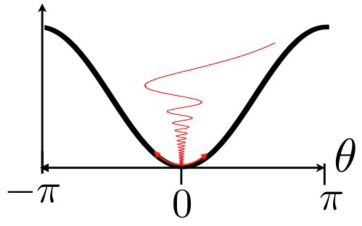

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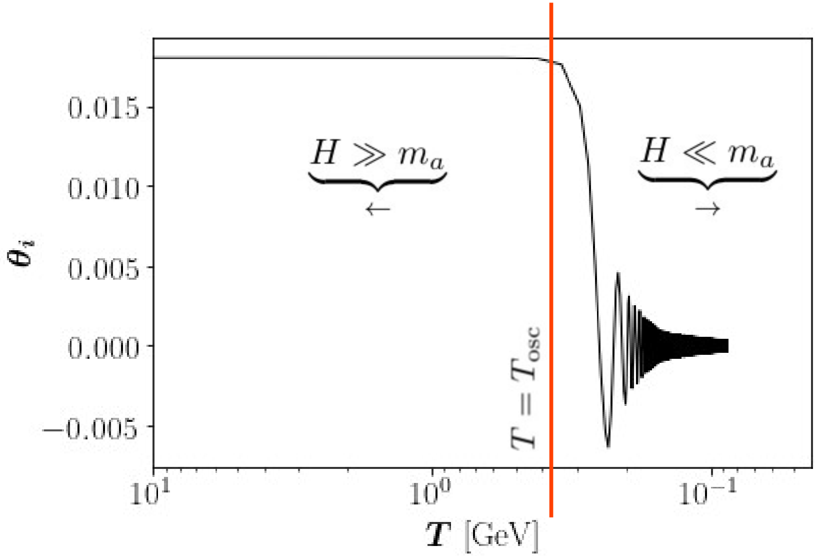

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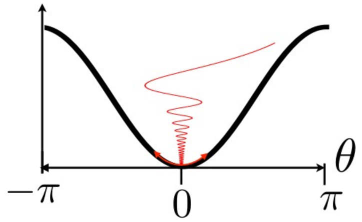

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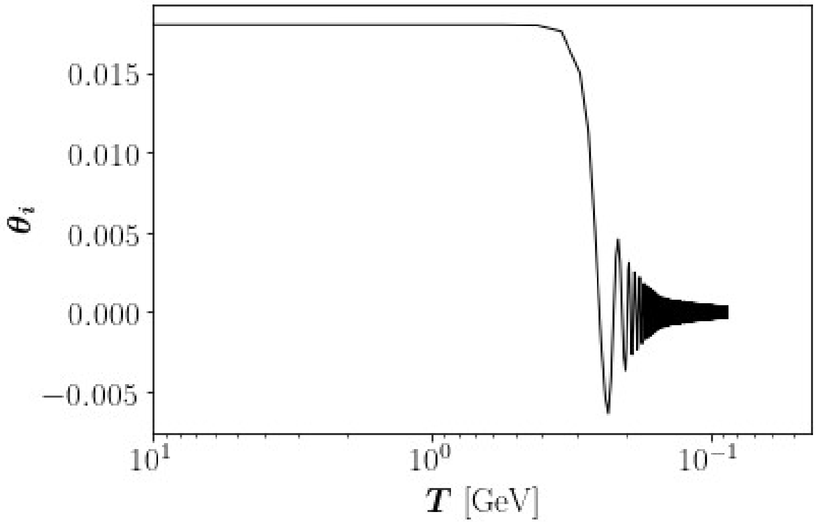

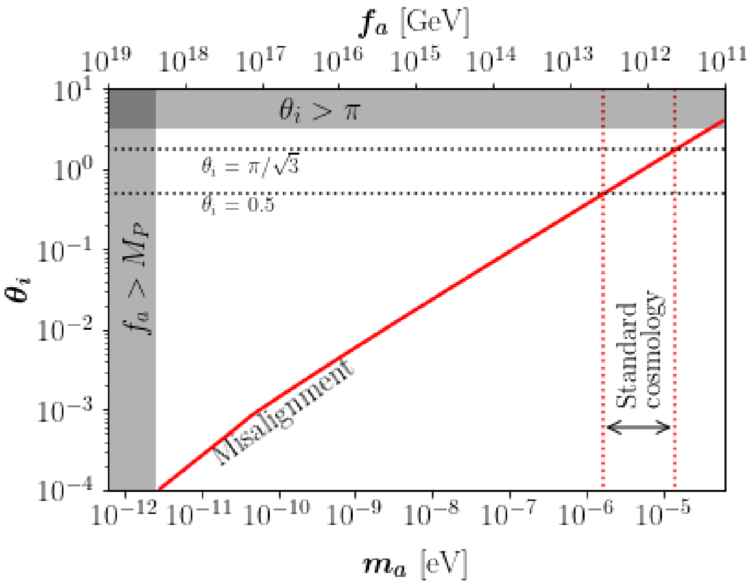

Misalignment in the Time of Primordial Black Holes

Primordial Black Holes

Talks by Ashadul & Satyabrata

* Density fluctuations can collapse into a PBH in the early universe

* Lose mass by emitting *all* particles via Hawking evaporation
  → PBH have a ~black body spectrum, with temperature $T_{BH} \sim 1/M_{BH}$
  → PBHs unavoidable radiate DM!

* If $M_{in} < 10^9$ g, PBH completely evaporate before BBN
  → poorly constrained

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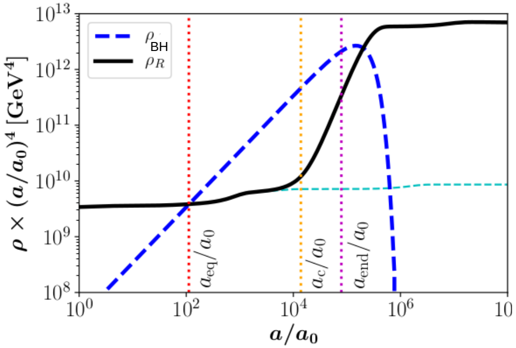
Effective theory: Two free parameters
* A single PBH characterized by its mass at formation $\boldsymbol{M_{in}}$
(or equivalently, by the SM temperature T_{in} at formation)

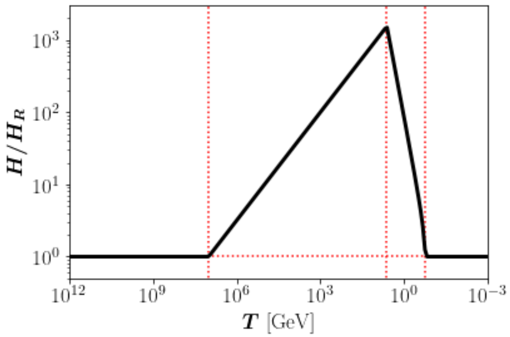
* Initial PBH energy density $\boldsymbol{\beta} = \rho_{BH}/\rho_{SM}$

PBHs can dominate the total energy density: Non-standard cosmology

Talk by Moira

Hubble expansion rate modified





$$H(T) \simeq \begin{cases} H_R(T) & \text{for } T \geq T_{\rm eq}\,, \\ H_R(T_{\rm eq}) \left[\frac{g_{\star s}(T)}{g_{\star s}(T_{\rm eq})} \left(\frac{T}{T_{\rm eq}}\right)^3\right]^{1/2} & \text{for } T_{\rm eq} \geq T \geq T_{\rm c}\,, \\ H_R(T_{\rm ev}) \left[1 - \frac{720}{\pi\, g_\star(T_{\rm in})} \frac{M_{\rm in}^3}{M_P^4} \frac{H_R^2(T_{\rm ev}) - H_R^2(T)}{H_R(T_{\rm ev})}\right] & \text{for } T_{\rm c} \geq T \geq T_{\rm ev}\,, \\ H_R(T) & \text{for } T_{\rm ev} \geq T\,, \end{cases}$$

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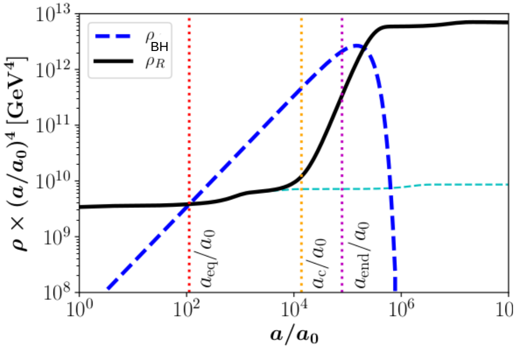
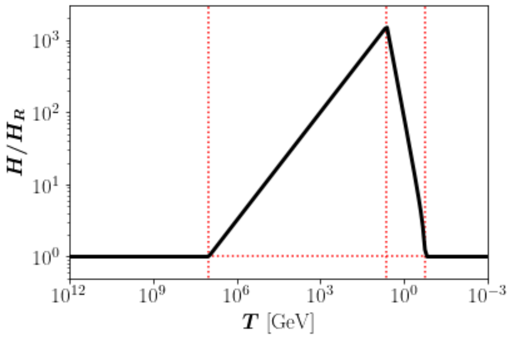
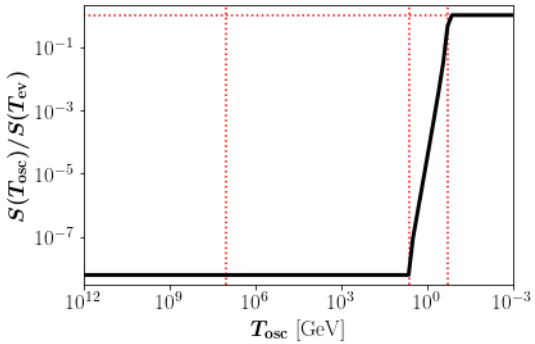




$$H(T) \simeq \begin{cases} H_R(T) & \text{for } T \geq T_{\rm eq}\,, \\ H_R(T_{\rm eq}) \left[\dfrac{g_{\star s}(T)}{g_{\star s}(T_{\rm eq})} \left(\dfrac{T}{T_{\rm eq}}\right)^3\right]^{1/2} & \text{for } T_{\rm eq} \geq T \geq T_{\rm c}\,, \\ H_R(T_{\rm ev}) \left[1 - \dfrac{720}{\pi\, g_\star(T_{\rm in})} \dfrac{M_{\rm in}^3}{M_P^4} \dfrac{H_R^2(T_{\rm ev}) - H_R^2(T)}{H_R(T_{\rm ev})}\right] & \text{for } T_{\rm c} \geq T \geq T_{\rm ev}\,, \\ H_R(T) & \text{for } T_{\rm ev} \geq T\,, \end{cases}$$

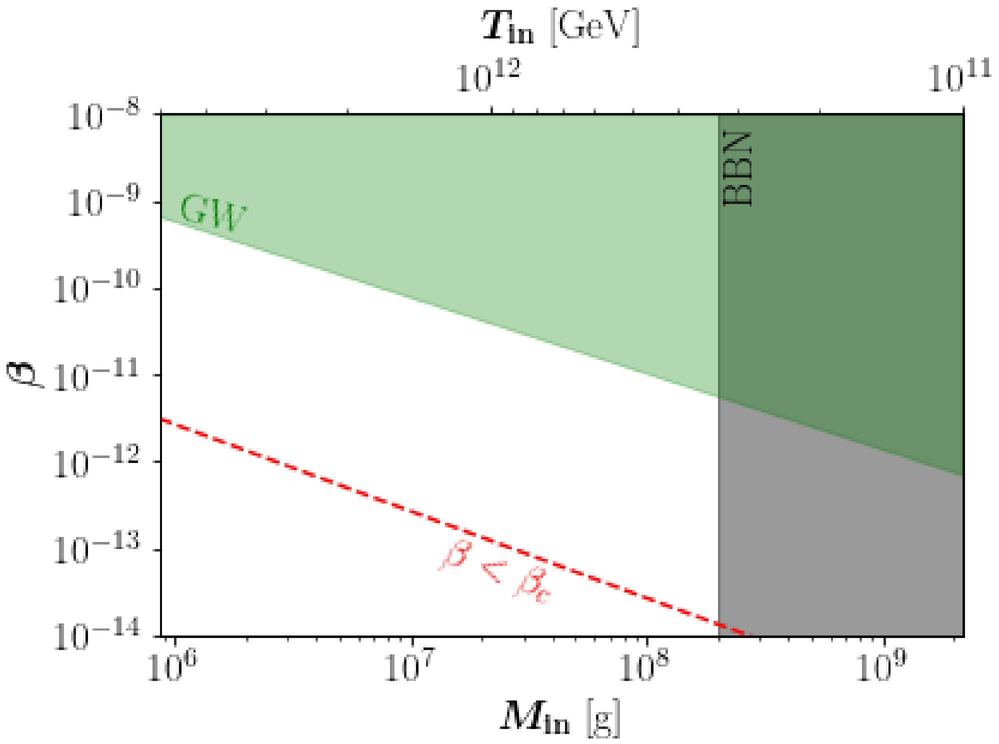
Entropy injection

PBHs evaporate,
Hawking radiating all SM particles...



$$\frac{S(T)}{S(T_{\rm ev})} \simeq \begin{cases} \dfrac{g_{\star s}(T_{\rm eq})}{g_{\star s}(T_{\rm ev})} \dfrac{g_\star(T_{\rm ev})}{g_\star(T_{\rm eq})} \dfrac{T_{\rm ev}}{T_{\rm eq}} & \text{for } T \geq T_{\rm c}\,, \\ \dfrac{g_{\star s}(T)}{g_{\star s}(T_{\rm ev})} \left(\dfrac{T}{T_{\rm ev}}\right)^3 \left[1 - \dfrac{720}{\pi\, g_\star(T_{\rm in})} \dfrac{M_{\rm in}^3}{M_P^4} \dfrac{H_R^2(T_{\rm ev}) - H_R^2(T)}{H_R(T_{\rm ev})}\right]^{-2} & \text{for } T_{\rm c} \geq T \geq T_{\rm ev}\,, \\ 1 & \text{for } T_{\rm ev} \geq T\,. \end{cases}$$

Misalignment with PBHs



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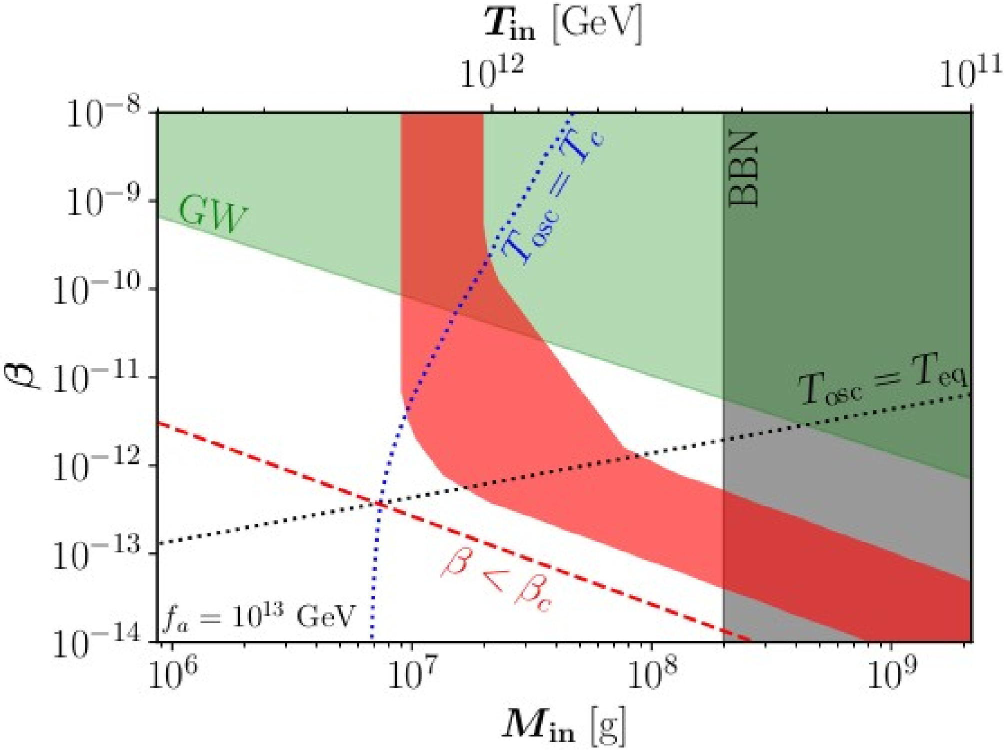

$$m_a \simeq 6 \times 10^{-7}\ \text{eV}$$

$$\frac{\Omega_a h^2}{0.12} \simeq \begin{cases} \left(\frac{\theta_i}{1}\right)^2 \left(\frac{m_a}{10^{-7}\ \text{eV}}\right)^{-\frac{3}{2}} \left(\frac{\beta}{10^{-13}}\right)^{-1} \left(\frac{M_{\rm in}}{10^8\ \text{g}}\right)^{-1} & \text{for } T_{\rm osc} \geq T_{\rm eq}\,, \\ \left(\frac{\theta_i}{1}\right)^2 \left(\frac{m_a}{10^{-8}\ \text{eV}}\right)^{-2} \left(\frac{M_{\rm in}}{10^8\ \text{g}}\right)^{-\frac{3}{2}} & \text{for } T_{\rm eq} \geq T_{\rm osc} \geq T_{\rm c}\,, \\ \left(\frac{\theta_i}{1}\right)^2 \left(\frac{m_a}{10^{-8}\ \text{eV}}\right)^{-2} \left(\frac{M_{\rm in}}{10^8\ \text{g}}\right)^{-\frac{3}{2}} & \text{for } T_{\rm c} \geq T_{\rm osc} \geq T_{\rm ev}\,, \\ \left(\frac{\theta_i}{10^{-3}}\right)^2 \left(\frac{m_a}{m_a^{\rm QCD}}\right)^{-\frac{3}{2}} & \text{for } T_{\rm ev} \geq T_{\rm osc}\,. \end{cases}$$

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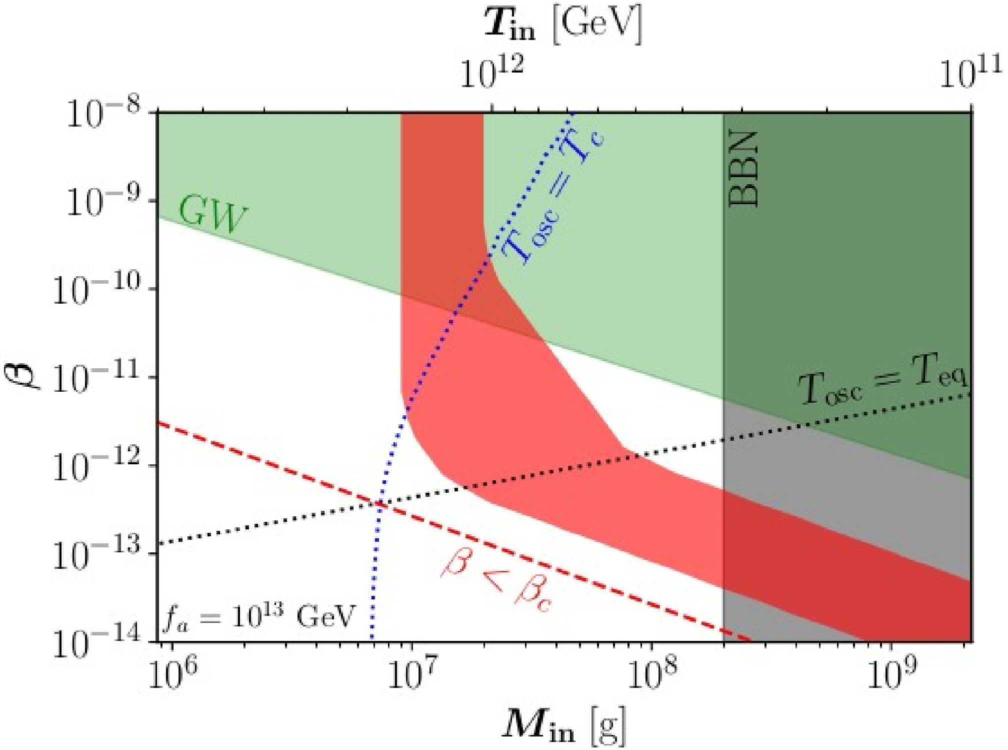
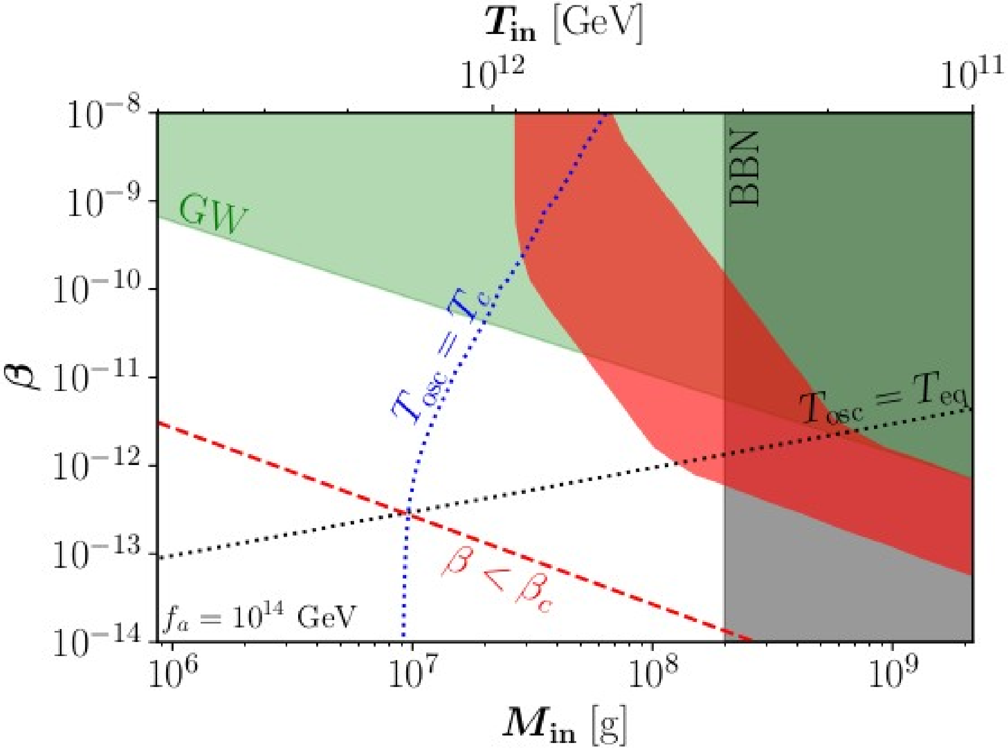
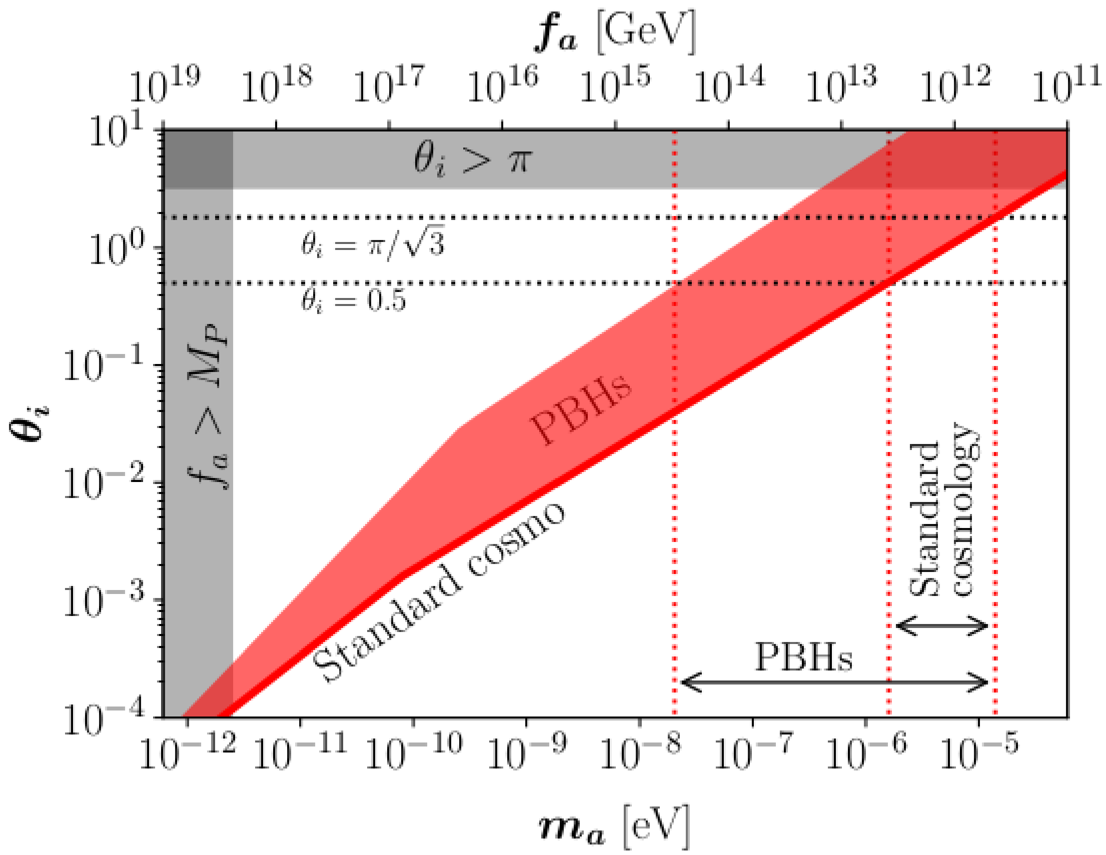


$m_a \simeq 6 \times 10^{-7}$ eV



$m_a \simeq 6 \times 10^{-8}$ eV

Misalignment with PBHs



Axions radiated by PBHs

PBHs *inevitably* radiate axions during their Hawking evaporation

As these axions are ultra-relativistic:

→ can't be the cold DM

→ contribute to dark radiation $\Delta N_{\rm eff} \simeq 0.04$

within the reach of future CMB-S4 experiment!

Conclusions

- QCD axion solved the strong CP problem
- QCD axion is a viable DM candidate
- PBHs formed in the early universe
- 0.1 g < M_{in} < 10^9 g evaporate before BBN
- PBHs Hawing radiate ultra-relativistic axions (dark radiation) → tested by CMB-S4
- PBHs could generate a period of non-standard cosmology
- Strong impact on axion production by misalignment
- Hubble expansion enhanced → oscillation gets delayed
- Entropy injection → axion density gets diluted
- Standard axion window is enlarged: *lighter axion allowed* → $m_a > 10^{-8}$ eV

  → could be tested by ABRACADABRA, KLASH, and ADMX

¡Muchas gracias!