PBH assisted search for QCD axion Dark Matter

Work in collaboration with E. Schiappacasse
arXiv : 2205.02255

Gongjun Choi (CERN)

CERN-CKC workshop, 7/Jun/2022

Can $f_{PBH}=O(0.1)-O(1)\%$ be of a help in search for (large decay constant) QCD axion DM?

Outline

- Large decay constant axion & EMD era
- Higher chance of PBH formation
- Ultra Compact Minihalo (UCMH) formation
- PBH-assisted search for QCD axion DM

Large decay constant axion

- Correct axion DM relic abundance with $\theta_i \sim O(1)$

$$\Omega_a h^2 \simeq (2 \times 10^4) \times \theta_{\rm i}^2 \times \left(\frac{F_a}{10^{16}\mathrm{GeV}}\right)^{\frac{7}{6}}$$

→ $F_a < 10^{12}$ GeV

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G. Dvali (9505253)

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P. Agrawal, G. Marques-Tavares, and W. Xue (JHEP, 1983)

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EMD era & Entropy production

- Not really a contrived set-up
  if we can naturally accommodate a heavy particle

- In SUSY models or string theory
  → saxion or moduli (σ)

- If σ decays before BBN & produces enough radiation
  → Ω_a can be sufficiently diluted

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- Necessarily accompanied by
  early matter dominated (EMD) era!

EMD era & Entropy production

- Quantifying the newly produced entropy

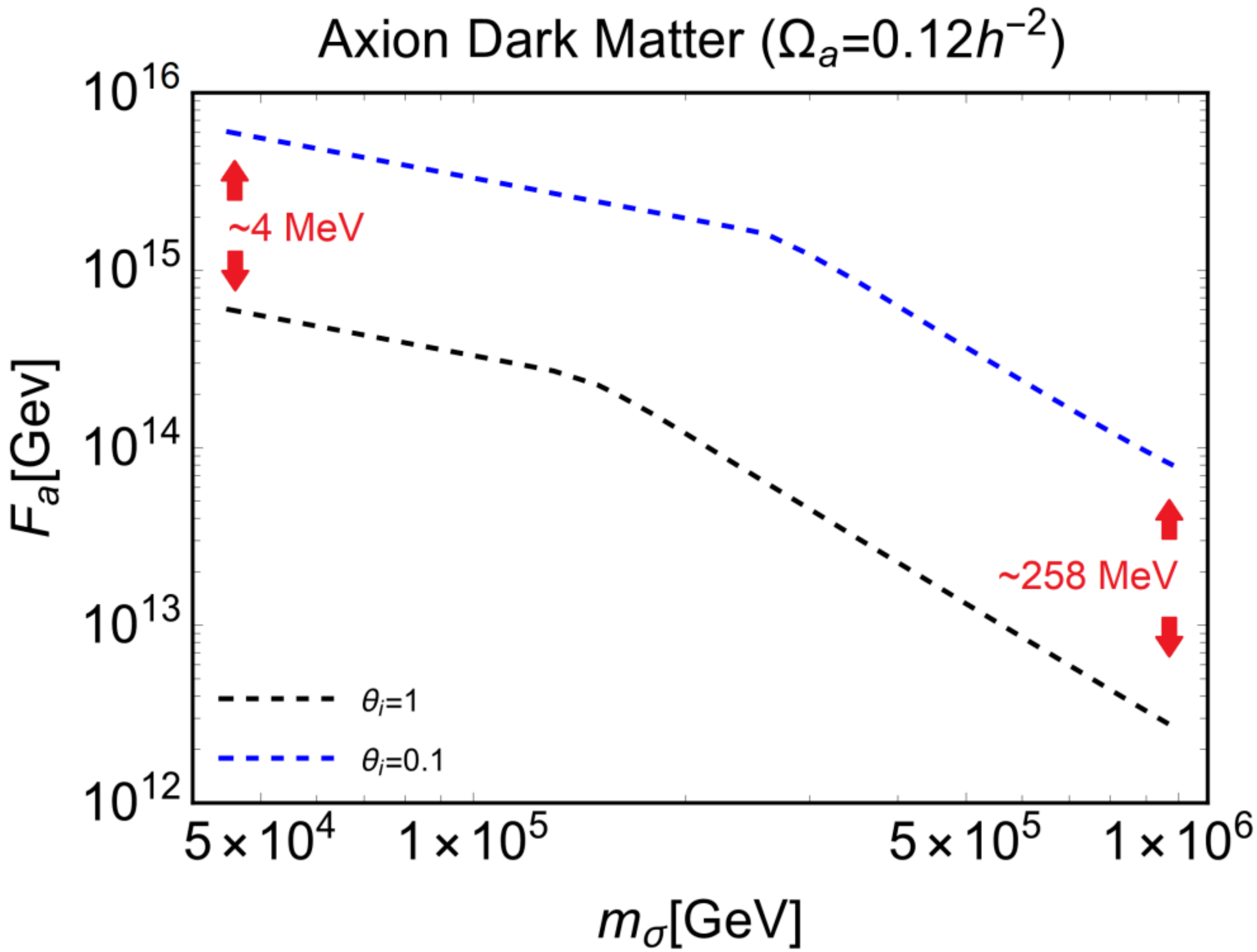
$$\Delta \equiv \frac{S_{\rm new}}{S_{\rm old}} = \frac{s_{\rm new}(R_{\rm rh2})R_{\rm rh2}^3}{s_{\rm old}(R_{\rm osc})R_{\rm osc}^3} = \frac{s_{\rm new}(R_{\rm rh2})}{s_{\rm old}(R_{\rm rh2})}$$

$$\begin{aligned}\Omega_a h^2 &= \frac{m_a s_0 h^2}{\rho_{\rm cr,0}}\left(\frac{n_a(R_{\rm rh2})}{s_{\rm new}(R_{\rm rh2})}\right) \\ &= \frac{m_a s_0 h^2}{\rho_{\rm cr,0}}\left(\frac{n_a(R_{\rm rh2})}{s_{\rm old}(R_{\rm rh2})}\right)\left(\frac{s_{\rm old}(R_{\rm rh2})}{s_{\rm new}(R_{\rm rh2})}\right) \\ &= \frac{m_a s_0 h^2}{\rho_{\rm cr,0}}\left(\frac{n_a(R_{\rm osc})}{s_{\rm old}(R_{\rm osc})}\right)\Delta^{-1} \\ &= \Omega_{a,\rm old} h^2 \Delta^{-1}\end{aligned}$$

$$\frac{4\rho_\sigma(R_{\rm rh2})}{3T_{\rm rh2}} = s_{\rm new}(R_{\rm rh2})$$

EMD era & Entropy production

- Diluting axion abundance by σ-decay



PBH formation probability

- PBH formation probability ($\beta \equiv \rho_{\rm PBH}/\rho_{\rm tot}$)
  → much higher in MD era than RD era

$$\beta_{\rm MD} \simeq 0.056\,\sigma^5 \quad >> \quad \beta_{\rm RD}(M) \simeq {\rm erfc}[\delta_c/\sqrt{2}\sigma(M))]$$

T. Harada et al. (Astrophys.J, 2016)

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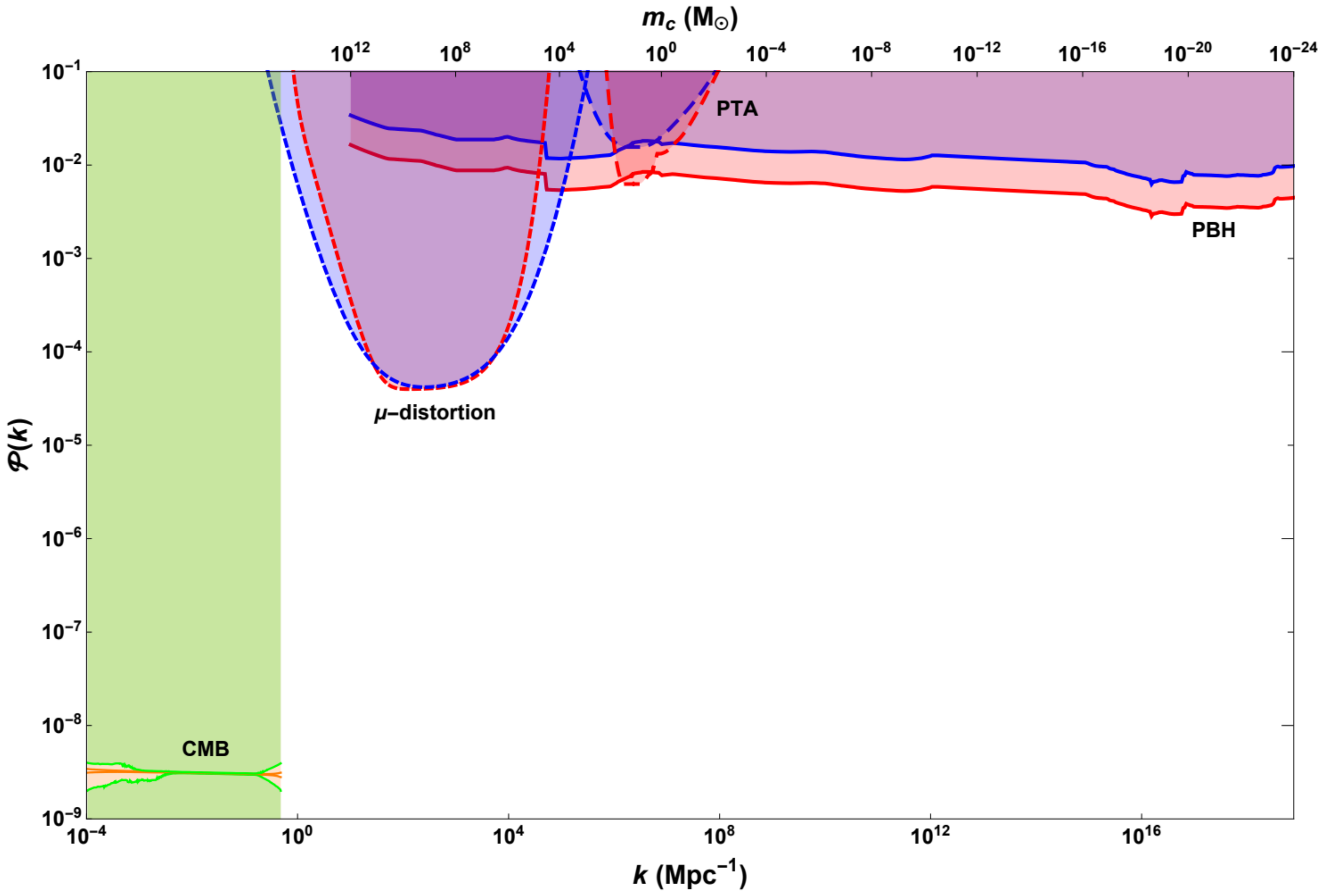
EMD era motivated by large F_a > 10^{12}GeV can serve as the environment facilitating formation of PBHs

Can we have a large enough $P_\zeta(k)$?

- In fact, $P_\zeta(k)$ in small scales are much less constrained than CMB scale

A. Gow et al. arxiv: 2008.03289



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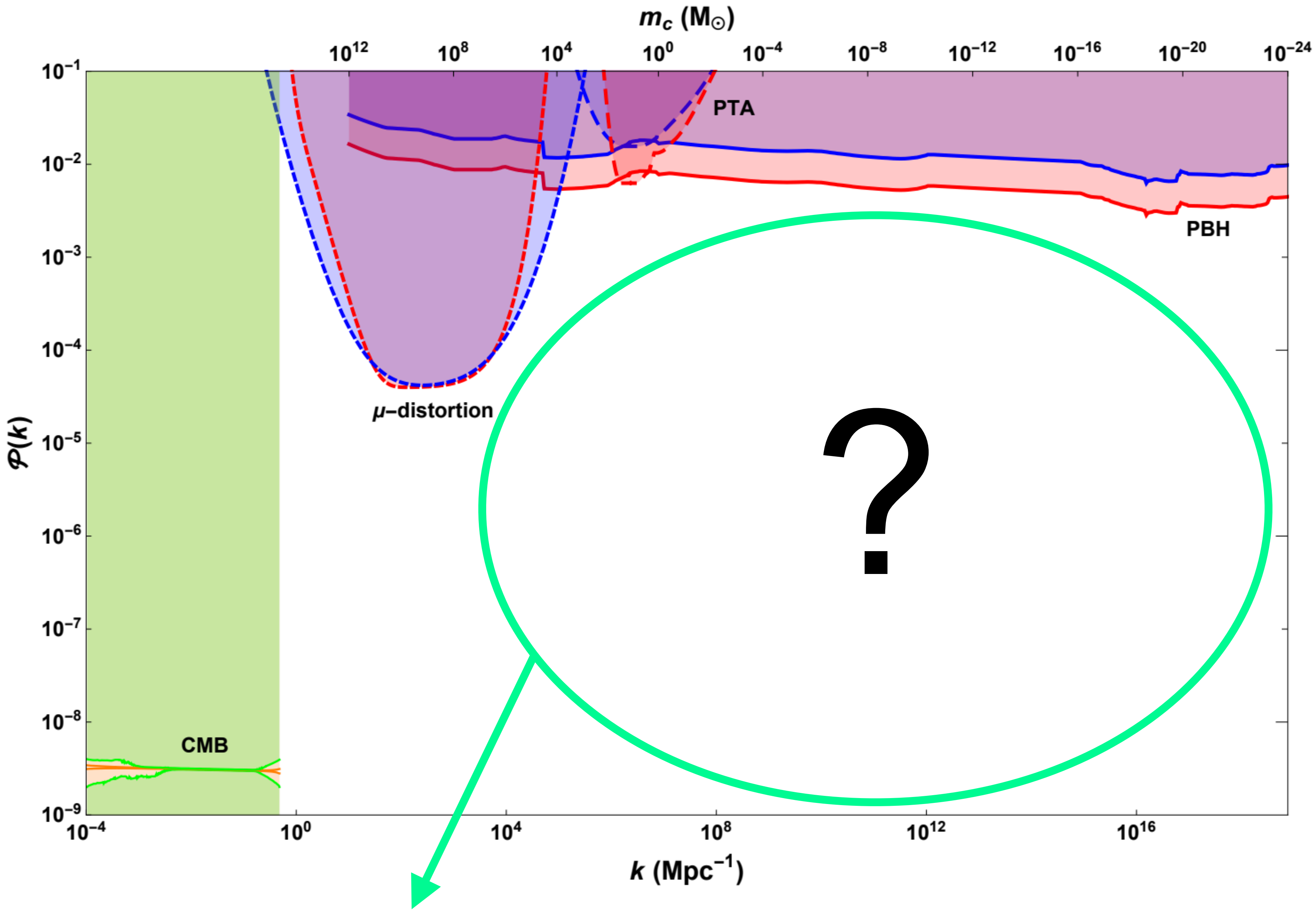
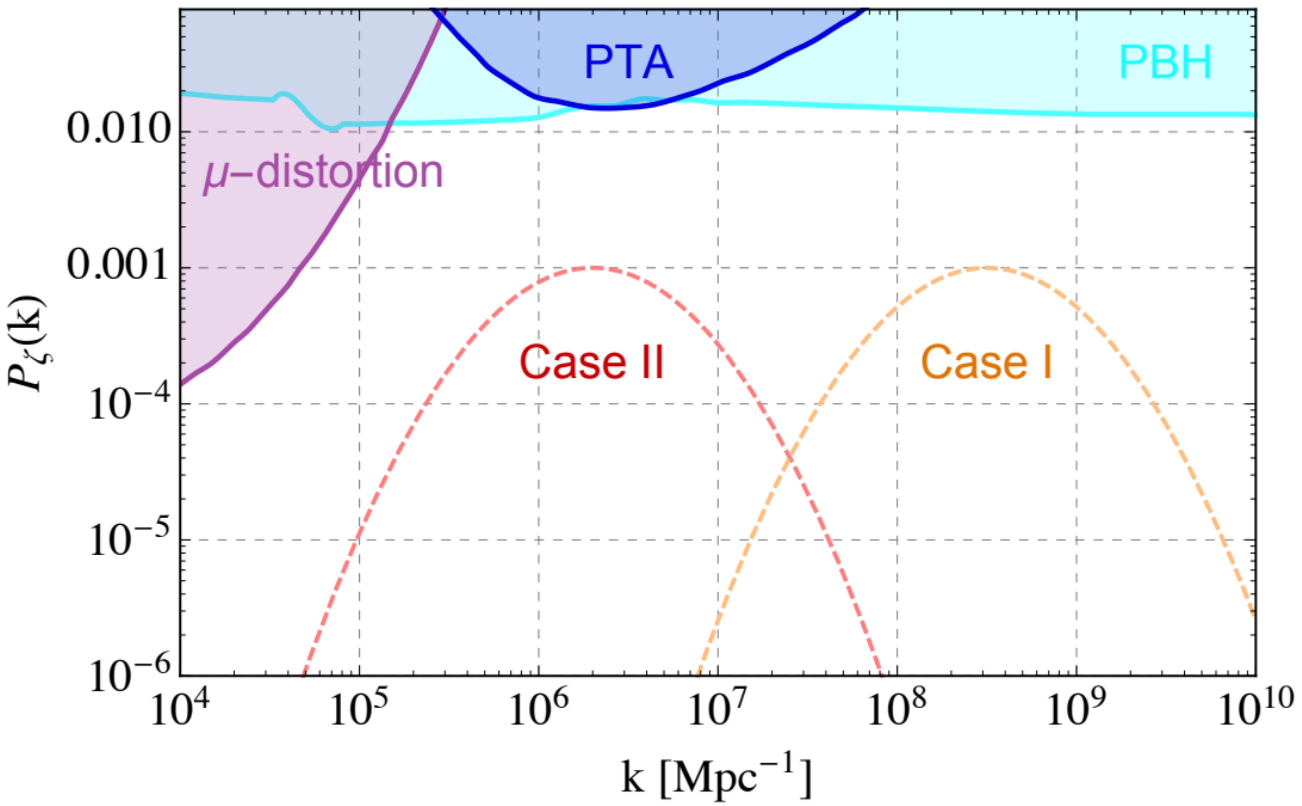


No reason why we can't assume enhanced $P_\zeta(k)$ on small scales

$P_\zeta(k)$ on small scales & $f_{\rm PBH}$

$$P_\zeta(k) = A_s \left(\frac{k}{k_{\rm CMB}}\right)^{n_s-1} + A_p e^{-\frac{(N_k-N_p)^2}{2\sigma_p^2}}$$
$$\simeq A_s \left(\frac{k}{k_{\rm CMB}}\right)^{n_s-1} + A_p e^{-\frac{(\log(k/k_p))^2}{2\sigma_p^2}}$$



$P_\zeta(k)$ on small scales & $f_{\rm PBH}$

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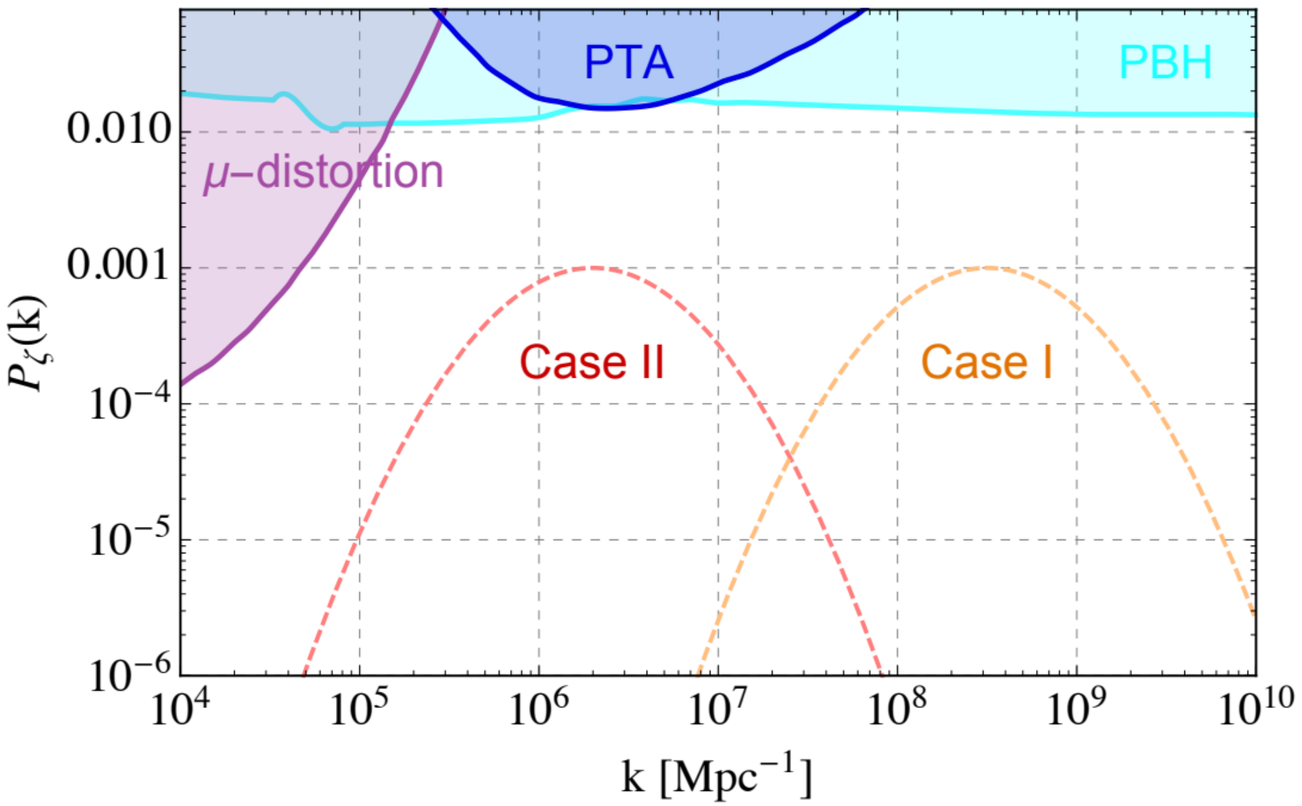

$$f_{\rm PBH}(M) \simeq (2.35\times 10^5)$$
$$\times\ P_\zeta(k)^{5/2} \times \left(\frac{m_\sigma}{100{\rm TeV}}\right)^{3/2}$$

$P_\zeta(k)$ on small scales & f_{PBH}

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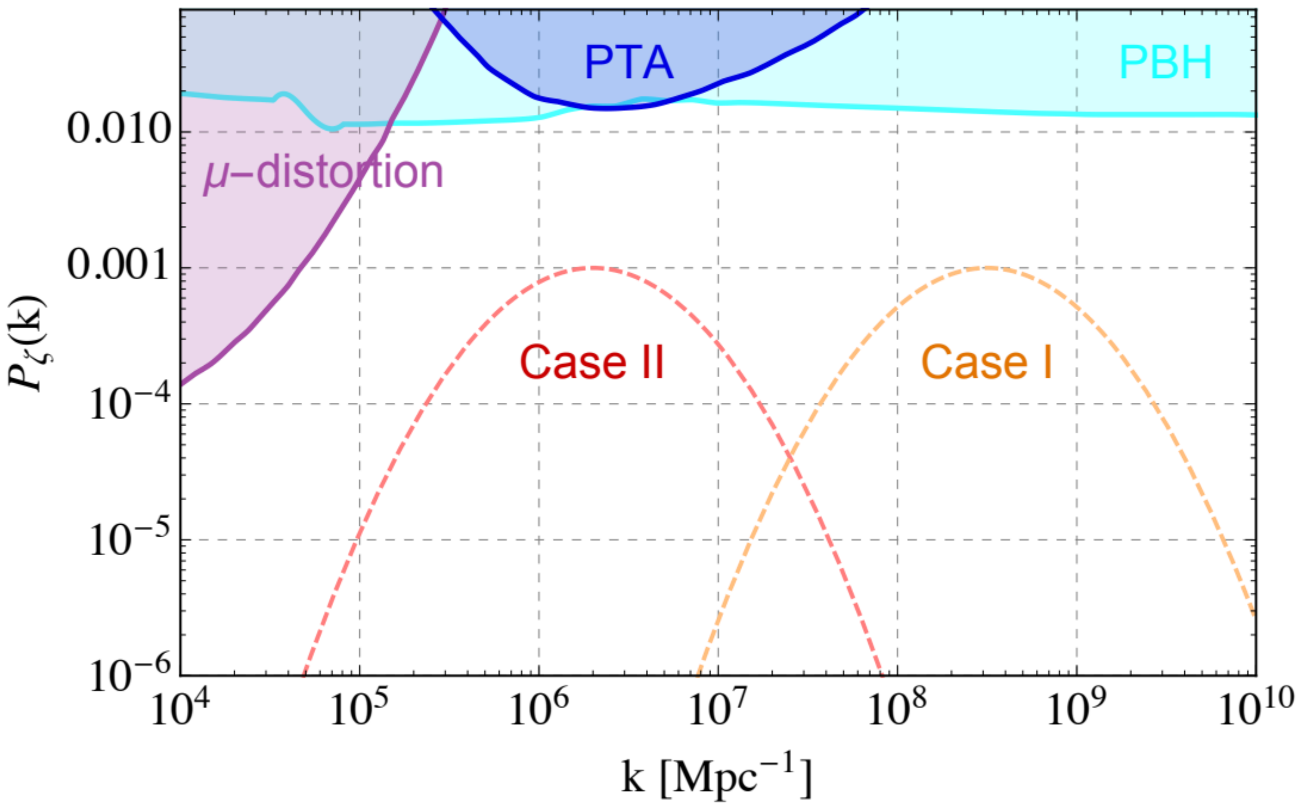

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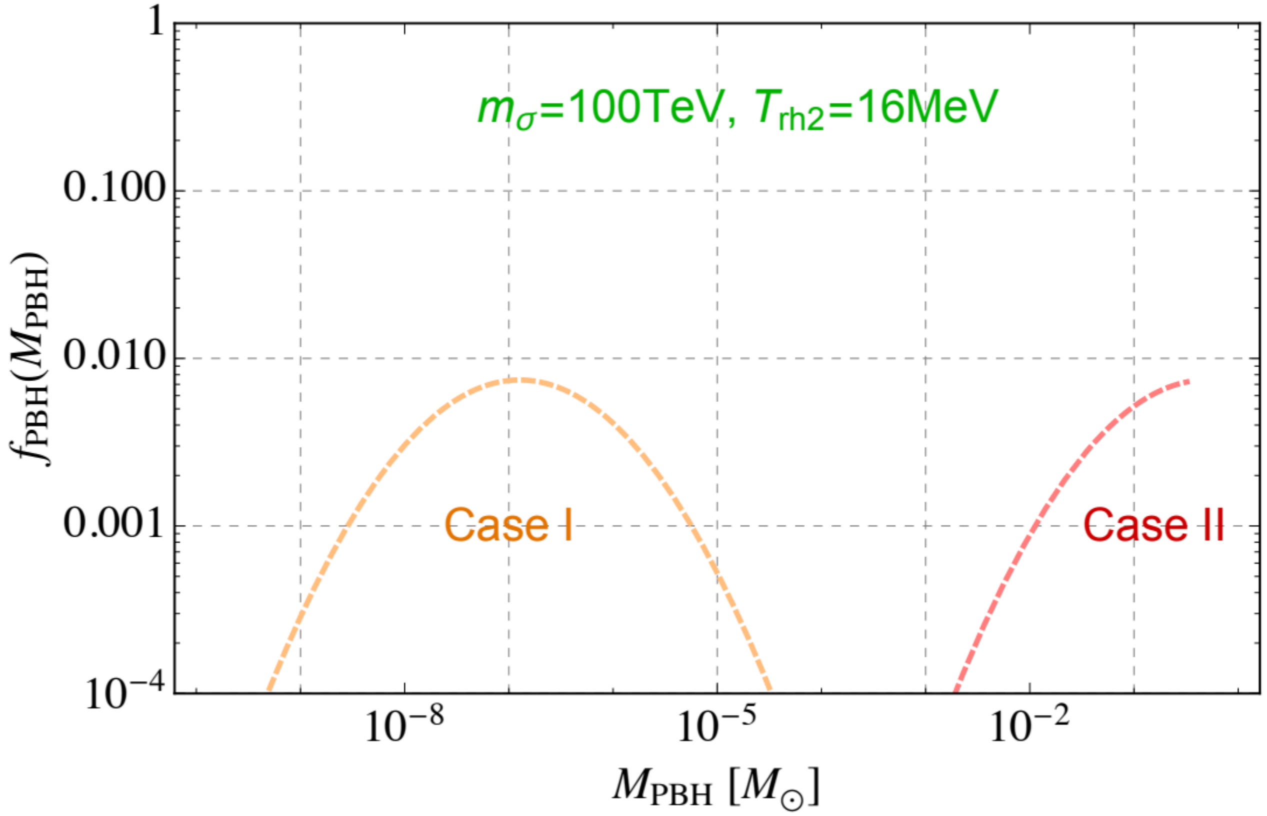

UCMH (PBH+axion halo) formation

- Axion accretion around (stationary and isolated) PBH
  → UCMH formation
  → efficient during matter-dominated era

E. Bertschinger (APJS 58, 39 (1985))
K. Mack, J. Ostriker, M. Ricotti (Astrophys. J. 665, 1277 (2007))
M. Ricotti, A. Gould (Astrophys. J. 707, 979 (2009))

$$M_{\rm UCMH}(z) = 3\left(\frac{1000}{1+z}\right) M_{\rm PBH}\,,$$

$$R_{\rm UCMH}(z) = 0.019\,{\rm pc}\left(\frac{1000}{z+1}\right)\left(\frac{M_{\rm UCMH}(z)}{M_\odot}\right)^{1/3}$$

$$\rho_{\rm UCMH}(r) \approx 0.23\,M_\odot {\rm pc}^{-3}\left(\frac{R_{\rm UCMH}}{r}\right)^{9/4}\left(\frac{10^2\,M_{\rm PBH}}{M_{\rm UCMH}}\right)^3$$

Axion Tidal Stream

Axion tidal stream (ATS)

- Inside UCMH, $\rho_a > \rho_{DM}$
  → If disruption happens, this gives axion tidal streams
  → If ρ_a in the tidal stream satisfies $\rho_a > \rho_{DM}$,
  this can be of help to direct axion DM searches

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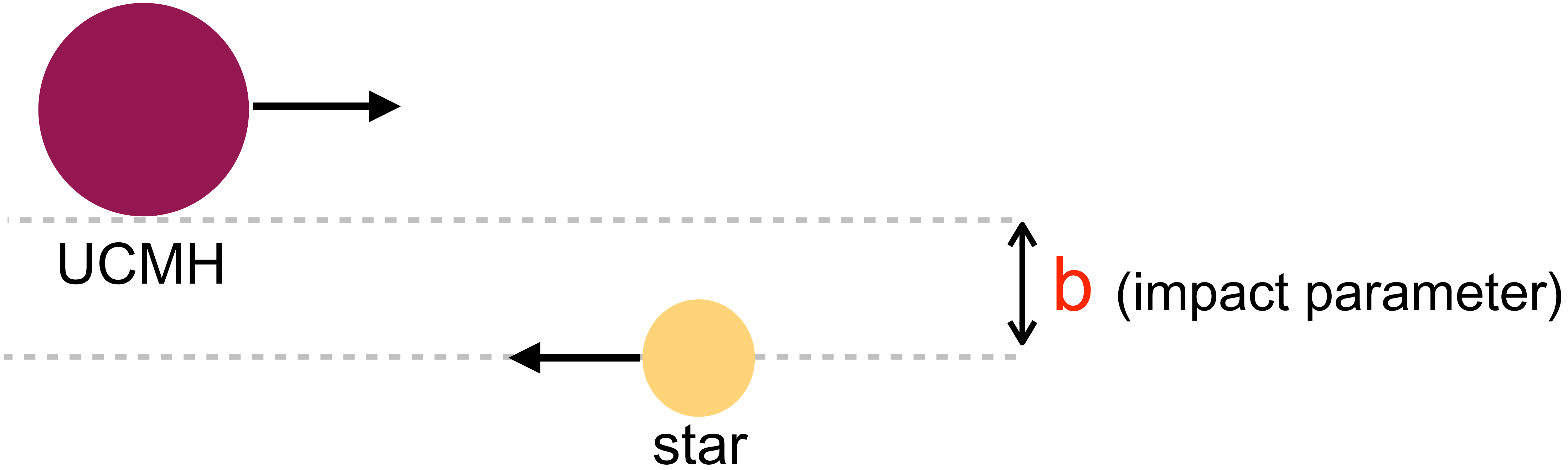
Q. For what M_{PBH}, can ATS be helpful to direct axion DM searches?

→ need to know
(1) disruption probability & (2) the encounter rate

Disruption probability



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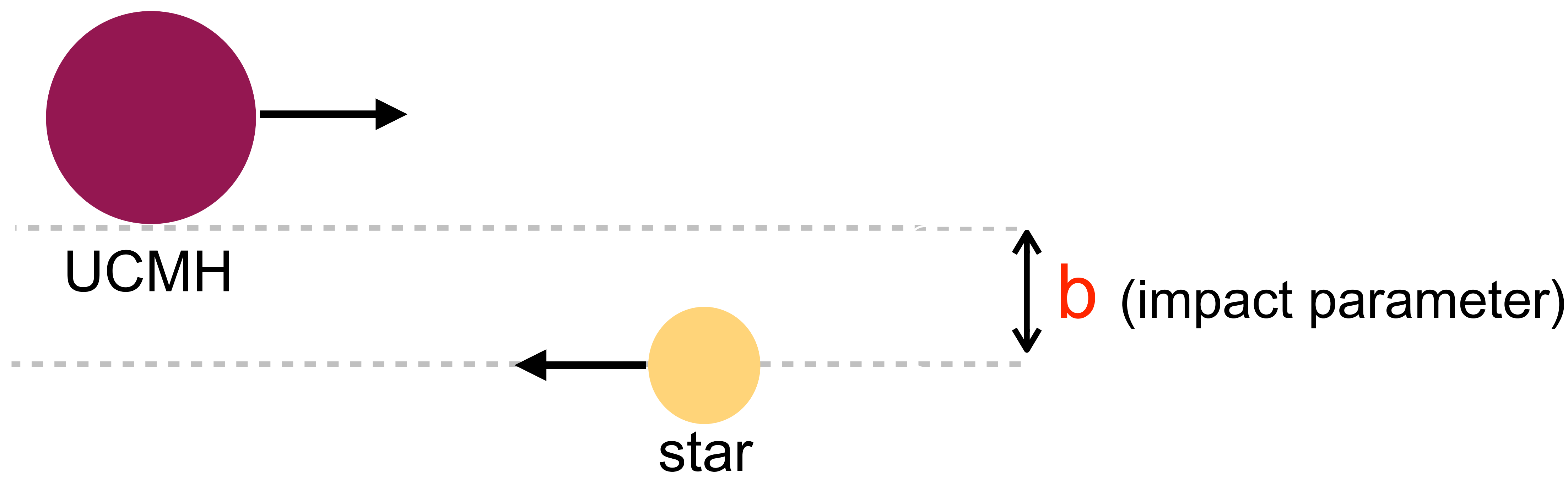
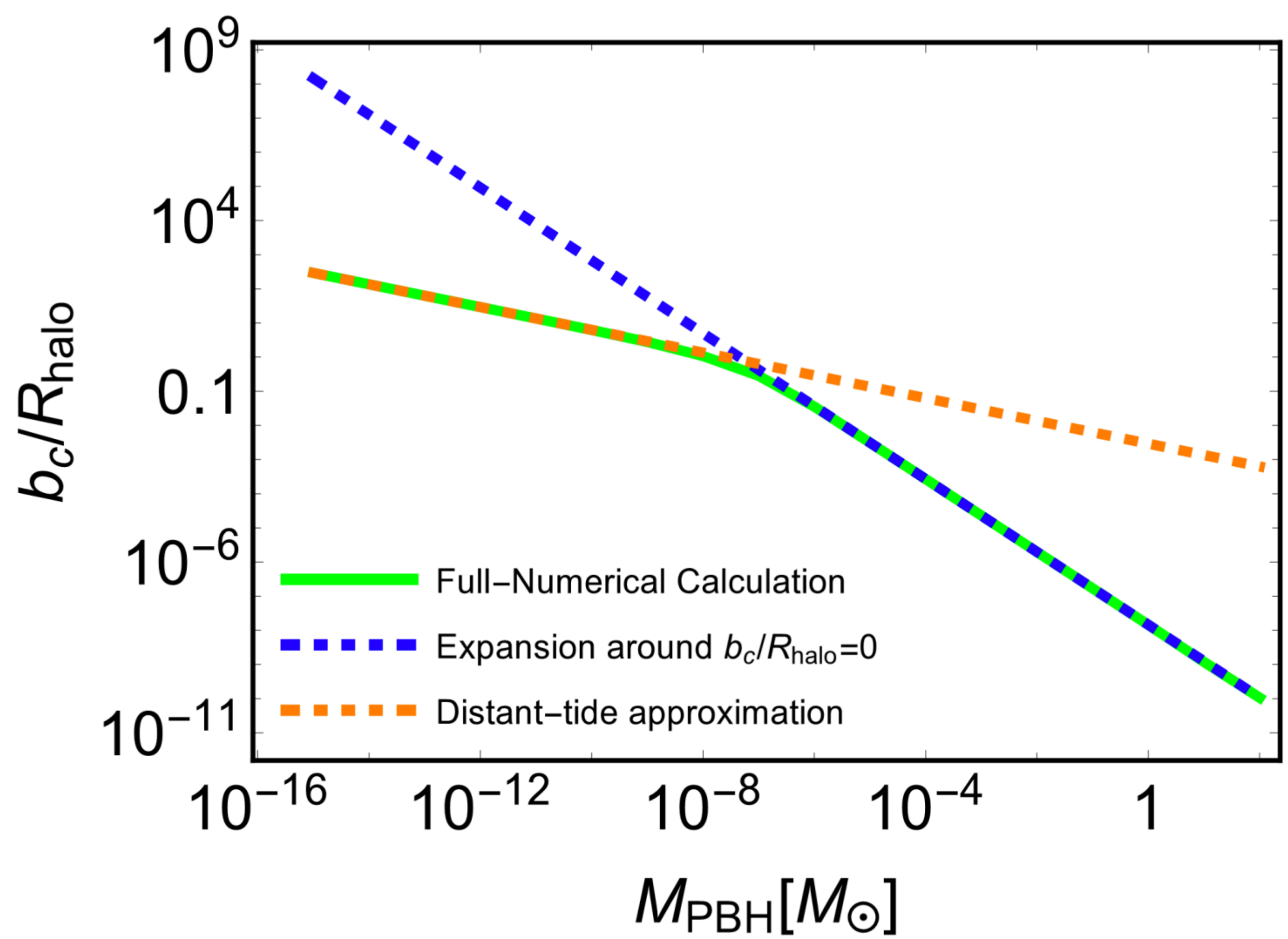


- $\Delta E_{int}(b_c) = E_{binding}$



Disruption probability

- disruption probability for a single encounter
  → $\Delta E_{int}/E_{binding}$
- Total = one-off disruptive events ($b < b_c$)
  + contribution from multiple encounters ($b > b_c$)

$$P_s = 2\pi n_\star v_{\rm rel} t_{\rm cross}$$

$$\times \left(\int_0^{b_c} b db + \frac{1}{E_b} \int_{b_c}^{\infty} \Delta E(b) b db \right)$$

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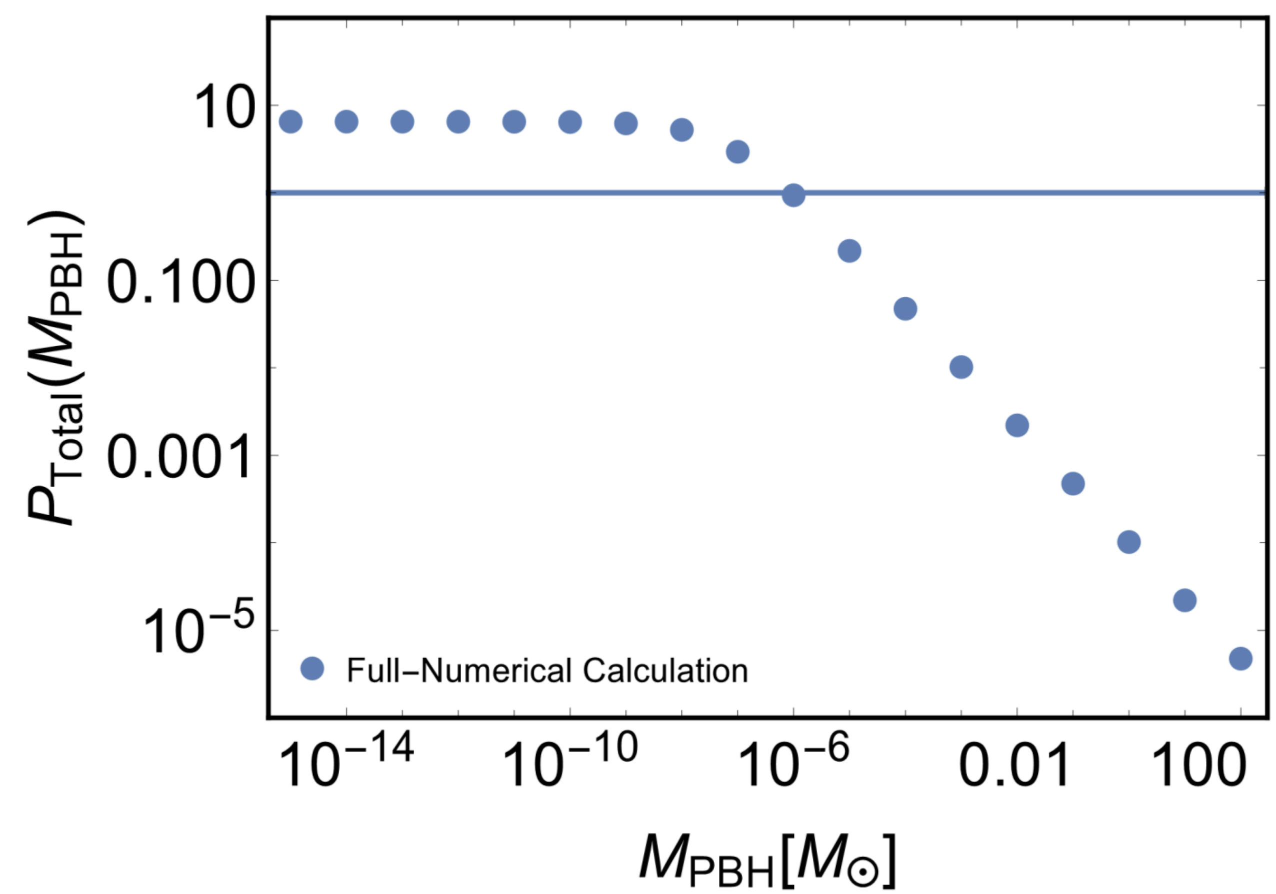

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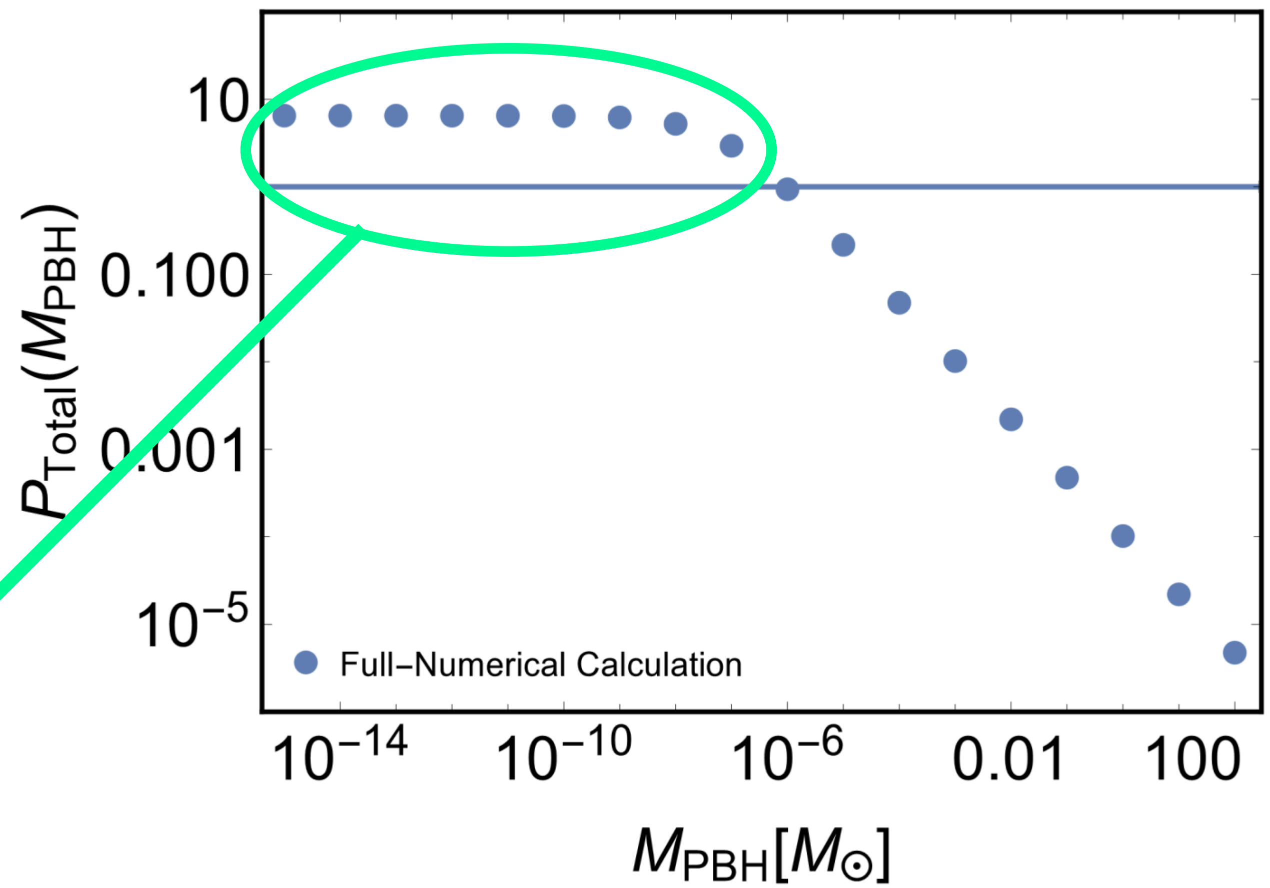

Total disruption for $M_{PBH} < 10^{-6} M_{sun}$!

Encounter rate

- The rate for earth to encounter the axion stream?

$$\Gamma_{\mathrm{st}-\oplus}(r) = \frac{\mathrm{FF}(r)}{\tau(r)} = \mathrm{FF}(r) \times \frac{v_{\mathrm{rel}}}{2r}$$

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$$\mathrm{FF(r)} = \left(\frac{f_{\mathrm{PBH}}\rho_{\mathrm{local}}}{M_{\mathrm{PBH}}}\right) \times \left(\frac{4\pi r^3}{3}\frac{\sigma_a(r)\Delta t}{r}\right),$$

$$\approx 0.001\left(\frac{f_{\mathrm{PBH}}}{10^{-2}}\right)\left(\frac{r/R_{\mathrm{UCMH}}}{10^{-2}}\right)^{15/8}\left(\frac{M_{\mathrm{UCMH}}}{10^2\, M_{\mathrm{PBH}}}\right)^{5/2}$$

$$\tau(r) \approx 0.6\,\mathrm{yr}\left(\frac{r/R_{\mathrm{UCMH}}}{10^{-2}}\right)\left(\frac{M_{\mathrm{UCMH}}}{10^2\, M_{\mathrm{PBH}}}\right)^{4/3}\left(\frac{M_{\mathrm{PBH}}}{10^{-8} M_{\odot}}\right)^{1/3}$$

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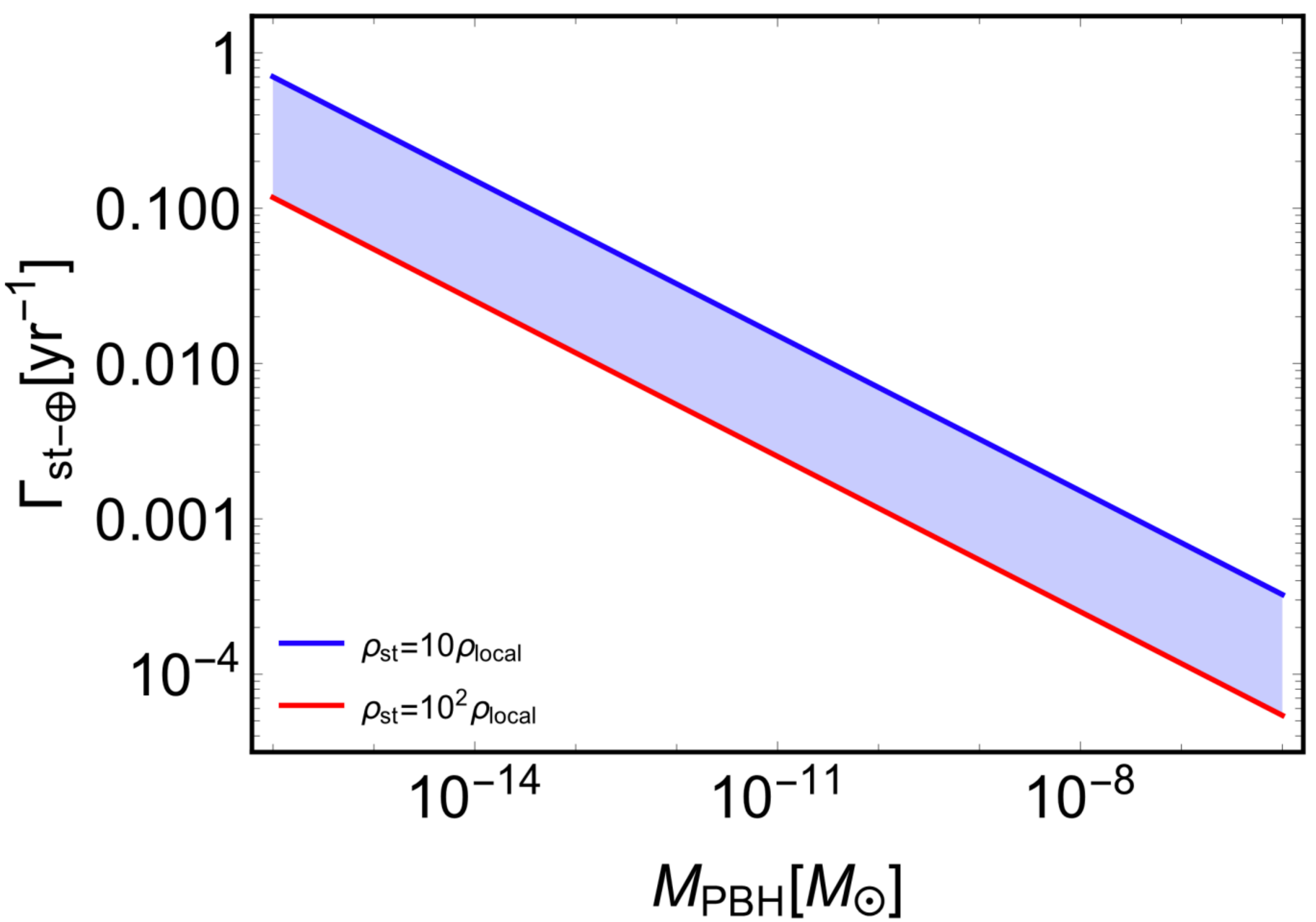

Encounter rate

- Enhancement in ρ_a
  → improve the sensitivity of experimental search

- For instance, in ABRACADABRA

Y. Kahn, B. R. Safdi, J. Thaler (PRL, 2016)

oscillating magnetic field flux through pick-up loop

$$\Phi_a(t) = g_{a\gamma\gamma}|\vec{B}_0|\sqrt{2\bar{\rho}_a}\cos(m_a t)$$

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$100\rho_a$ → one order improvement in $g_{a\gamma\gamma}$

Transient Radio Signal

Transient radio signals

- UCMH encounter with a neutron star
  → at r satisfying $m_a = w_p$ (conversion radius),
  resonant axion conversion to photon

- Power per solid angle

$$\frac{d\mathcal{P}(\theta)}{d\Omega} \approx \frac{g_{a\gamma\gamma}^2 B_0^2 \rho_a(r_c) \pi v_c}{6 m_a} \left(\frac{R_{\rm NS}^2}{r_c} \right)^3 \left[3\cos^2(\theta) + 1 \right]$$

A. Hook, Y. Kahn, B. R. Safdi, Z. Sun (PRL, 2018)

Transient radio signals

- What matters in terms of detection
  → "spectral flux density", i.e. $S = (d\mathcal{P}/d\Omega)/(d^2\Delta\nu)$

$$S(\theta) = \tilde{S} \times \frac{3\cos^2(\theta) + 1}{|3\cos^2(\theta) - 1|^{7/6}}$$

$$\tilde{S} \sim \mu\mathrm{Jy}\left(\frac{\rho_a(r_c)}{0.23\,M_\odot\mathrm{pc}^3}\right)\left(\frac{P}{1\,\mathrm{s}}\right)^{7/6}\left(\frac{B_0}{10^{14}\,\mathrm{G}}\right)^{5/6} \times$$

$$\left(\frac{g_{a\gamma\gamma}}{10^{-12}\,\mathrm{GeV}^{-1}}\right)^2\left(\frac{R_{\mathrm{NS}}}{10\,\mathrm{km}}\right)^{5/2}\left(\frac{M_{\mathrm{NS}}}{M_\odot}\right)^{1/2}\left(\frac{m_a}{\mathrm{GHz}}\right)^{4/3} \times \left(\frac{100\,\mathrm{pc}}{d}\right)^2\left(\frac{1\,\mathrm{kHz}}{\Delta\nu}\right)$$

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For example, at $r \sim O(10^{-6})$ - $O(10^{-5}) R_{UCMH}$, $\sim 10^{10}$-$10^{11} \rho_{DM}$

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$$\Delta\nu \sim 4\,\mathrm{MHz} \left(\frac{m_a}{\mathrm{GHz}}\right)^{1/3} \left(\frac{\mathrm{s}}{P}\right)^{4/3} \left(\frac{B_0}{10^{14}\,\mathrm{G}}\right)^{1/3} \left(\frac{R_{\mathrm{NS}}}{10\,\mathrm{km}}\right) \sin\theta_m$$

R. A. Battye et al. (JHEP, 2021)

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We look at $m_a \sim$ 50MHz - 1GHz ($F_a = 10^{12} \sim 5\mathrm{x}10^{13}$ GeV)

Transient radio signals

- Compare to minimum detectable flux of the chosen radio telescope (SKA1-low, SKA-mid)

$$S_{\rm min} = {\rm SNR}_{\rm min} \frac{\rm SEFD}{\eta_s \sqrt{2 \Delta B \Delta t_{\rm obs}}} \qquad ,$$

$$\sim 220\,\mu{\rm Jy} \left(\frac{{\rm SNR}_{\rm min}}{5}\right) \left(\frac{\rm SEFD}{10\,{\rm Jy}}\right) \left(\frac{0.9}{\eta_s}\right) \left(\frac{1\,{\rm kHz}}{\Delta B}\right)^{1/2} \left(\frac{1\,{\rm yr}}{\Delta t_{\rm obs}}\right)^{1/2}$$

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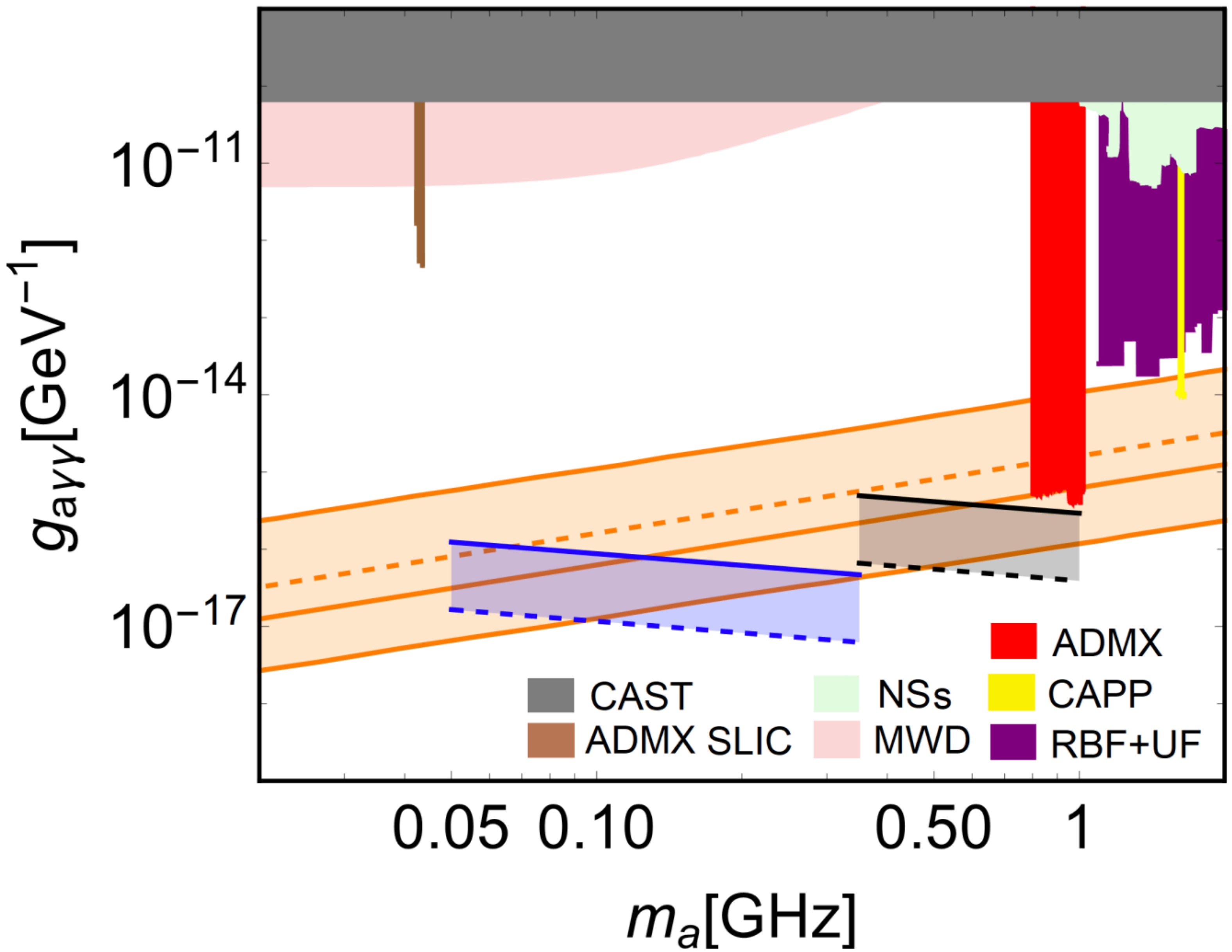

Summary

- Large decay constant axion DM may imply early matter domination (EMD) era
- EMD era can be the environment facilitating PBH formation
- 0.1-1% PBH + axion DM evolve to UCMH
- $M_{PBH} \sim 10^{-15}$-$10^{-14} M_{sun}$ can gives O(10) enhancement in axion DM energy density via tidal stream
- SKA can probe $m_a \sim$ 50MHz - 1GHz ($F_a = 10^{12} \sim 5 \times 10^{13}$ GeV) via detection of transient radio signal