Interplay between primordial black holes and dark matter

Mathieu Gross

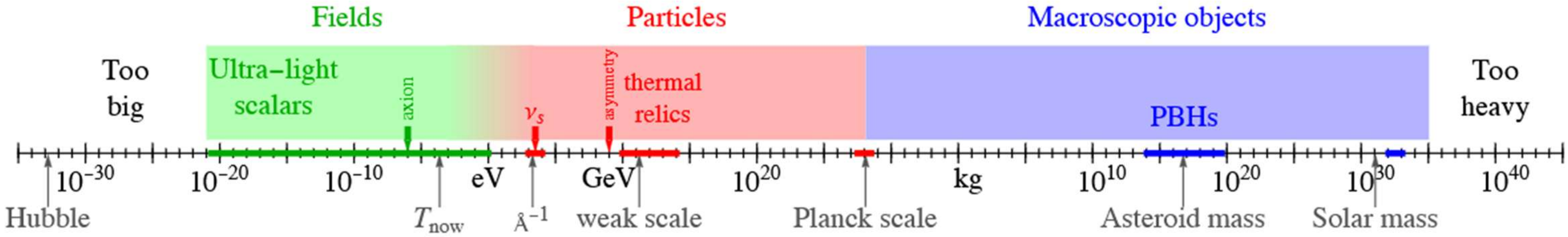
Dark matter day

06/05/2026

Outline

1. Introduction
2. Primordial black holes, Hawking evaporation, and dark matter
3. PBH hotspot
4. Conclusion

Introduction



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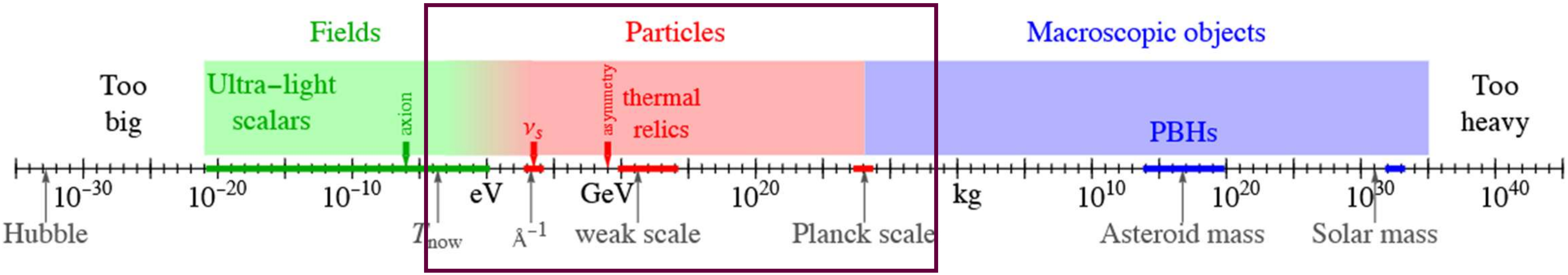

Yann's talk

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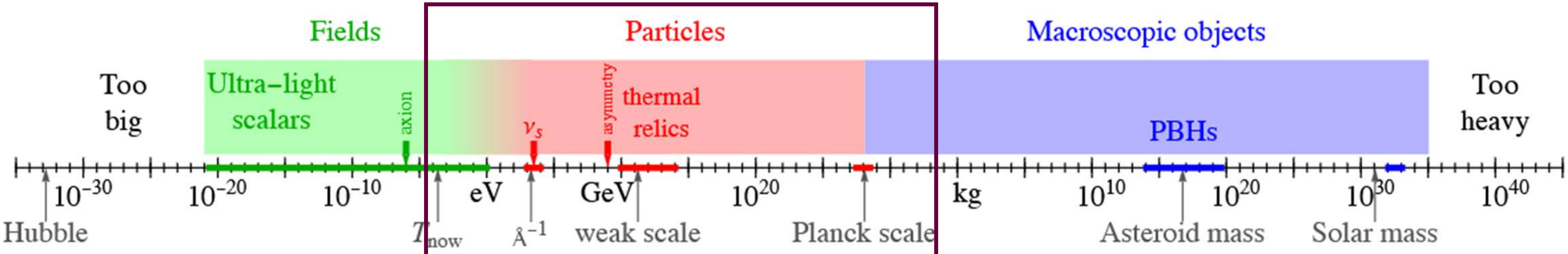
Introduction

WIMP/FIMP/UFO/FISC



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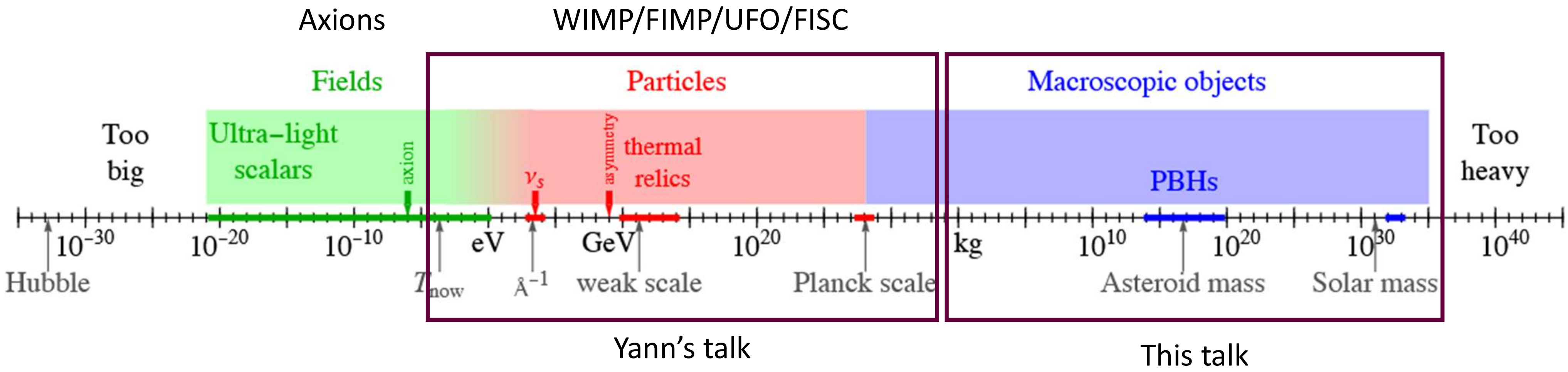

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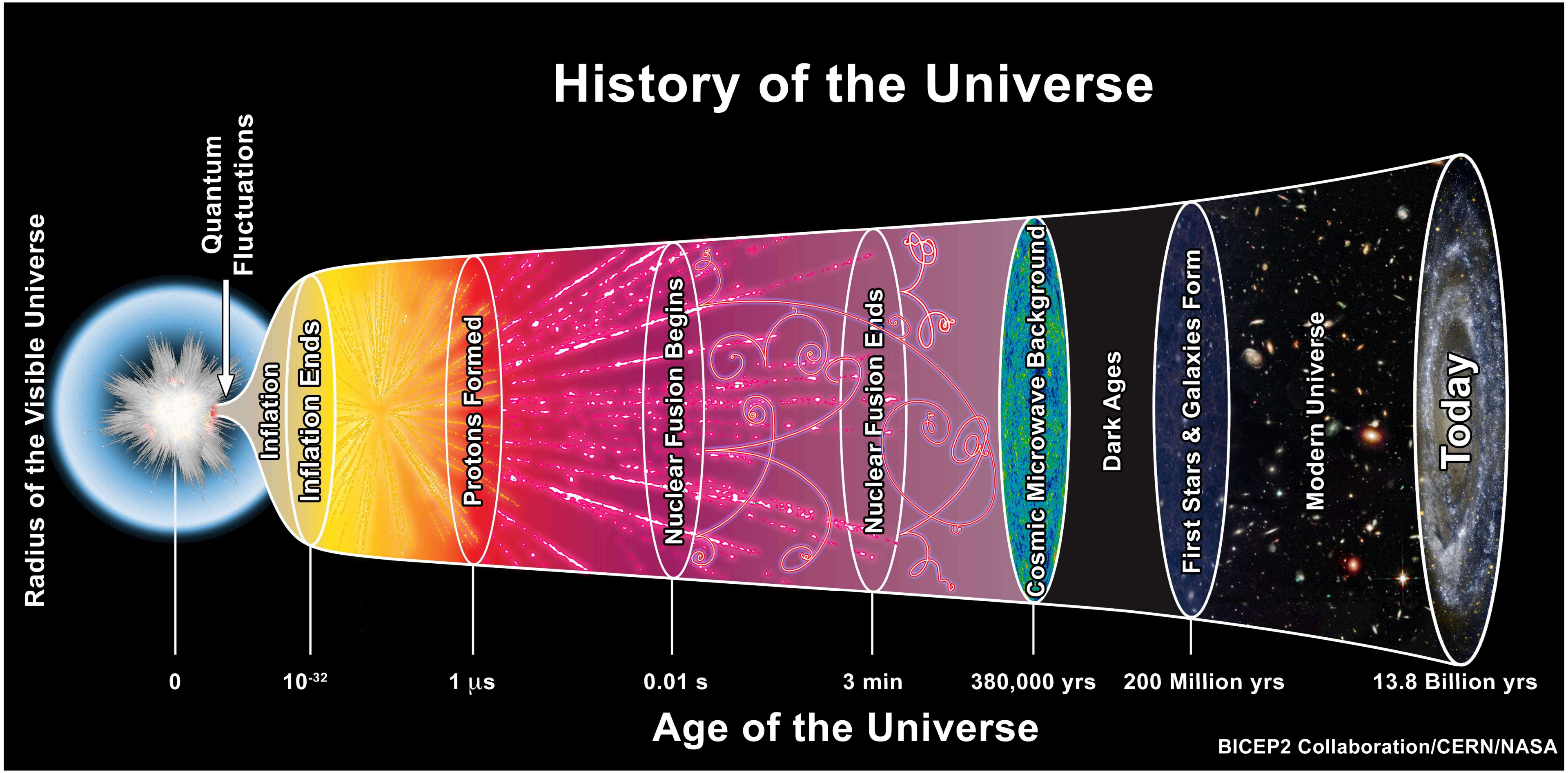
Primordial black holes?



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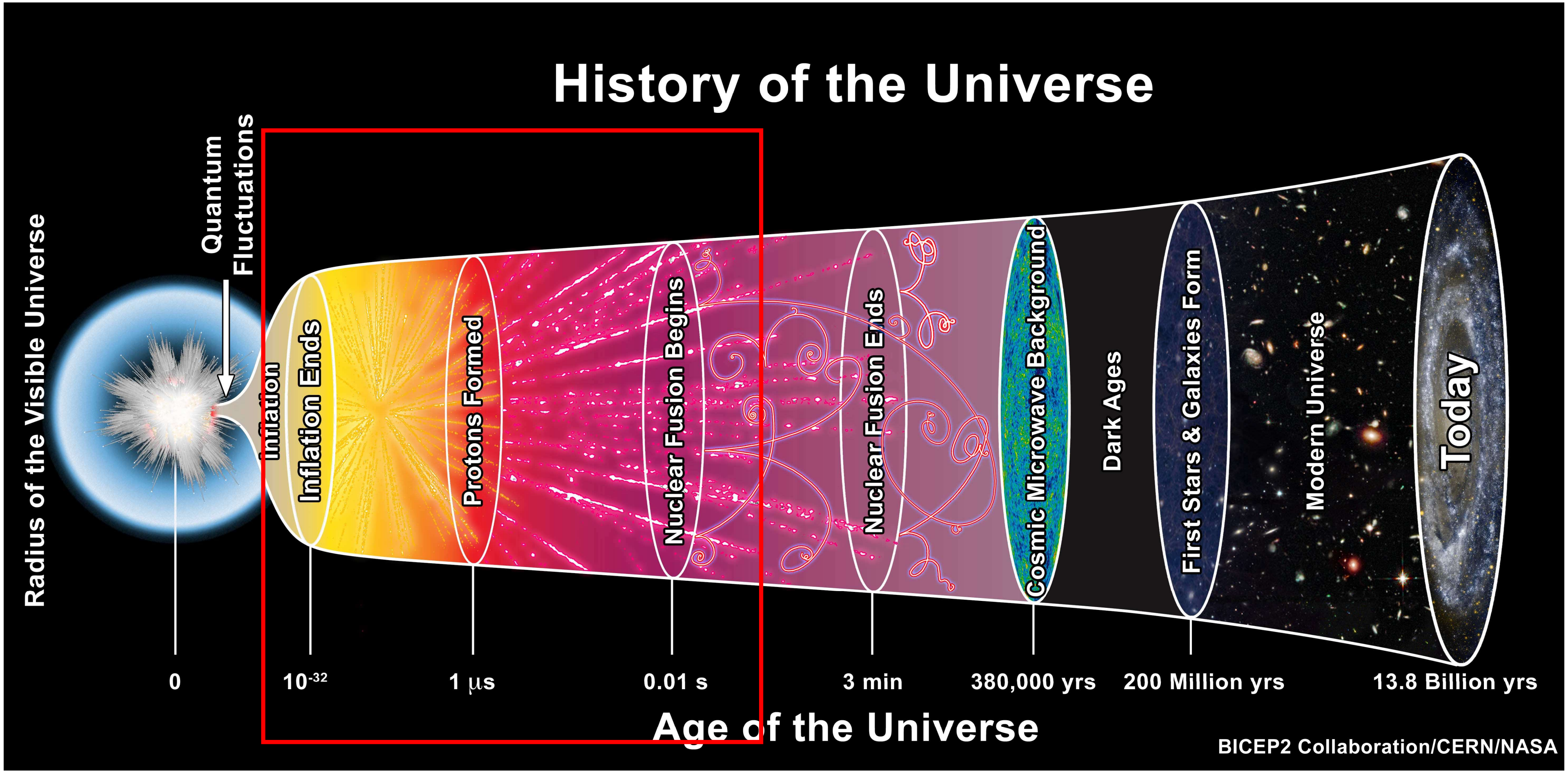
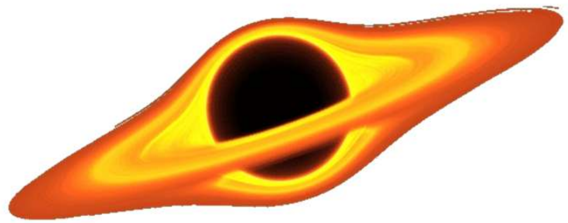


Forming primodial black holes



- Primordial inhomogeneities (Yukawa forces, Qballs…)
- Inflationary fluctuations collapse
- Topological defect collapse (Domain walls, cosmic string ...)
- Phase transitions

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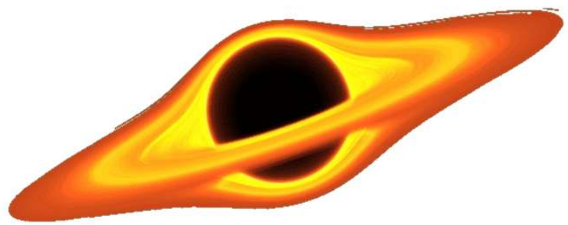

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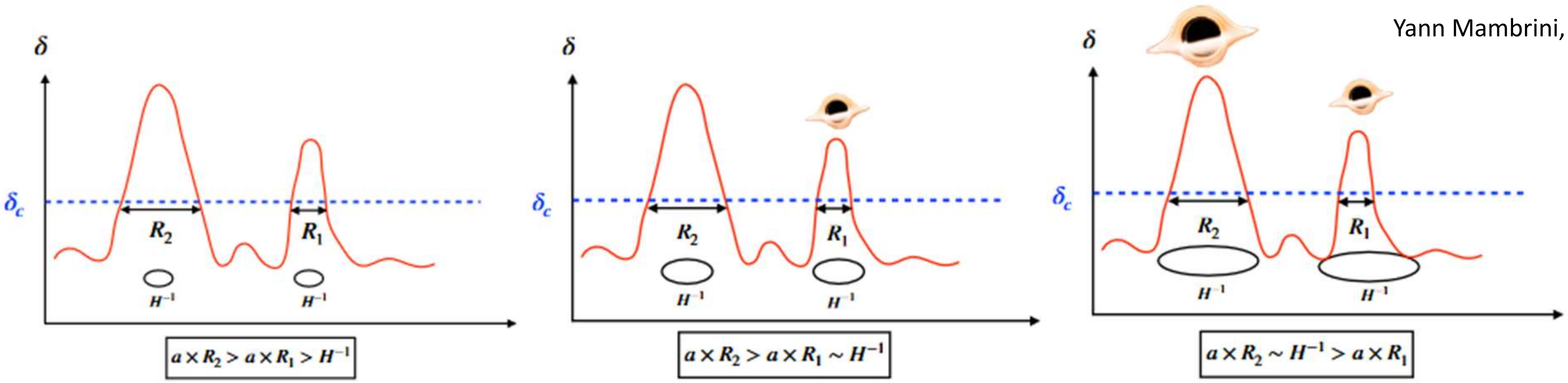
Yann Mambrini, Particles in the Dark Universe



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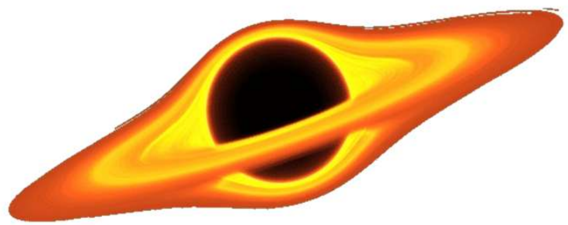

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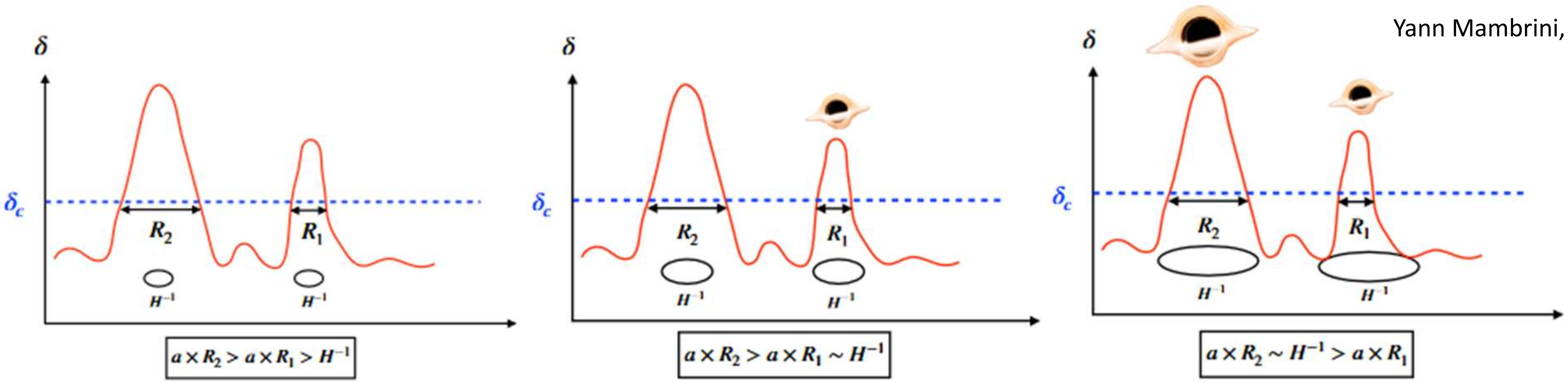


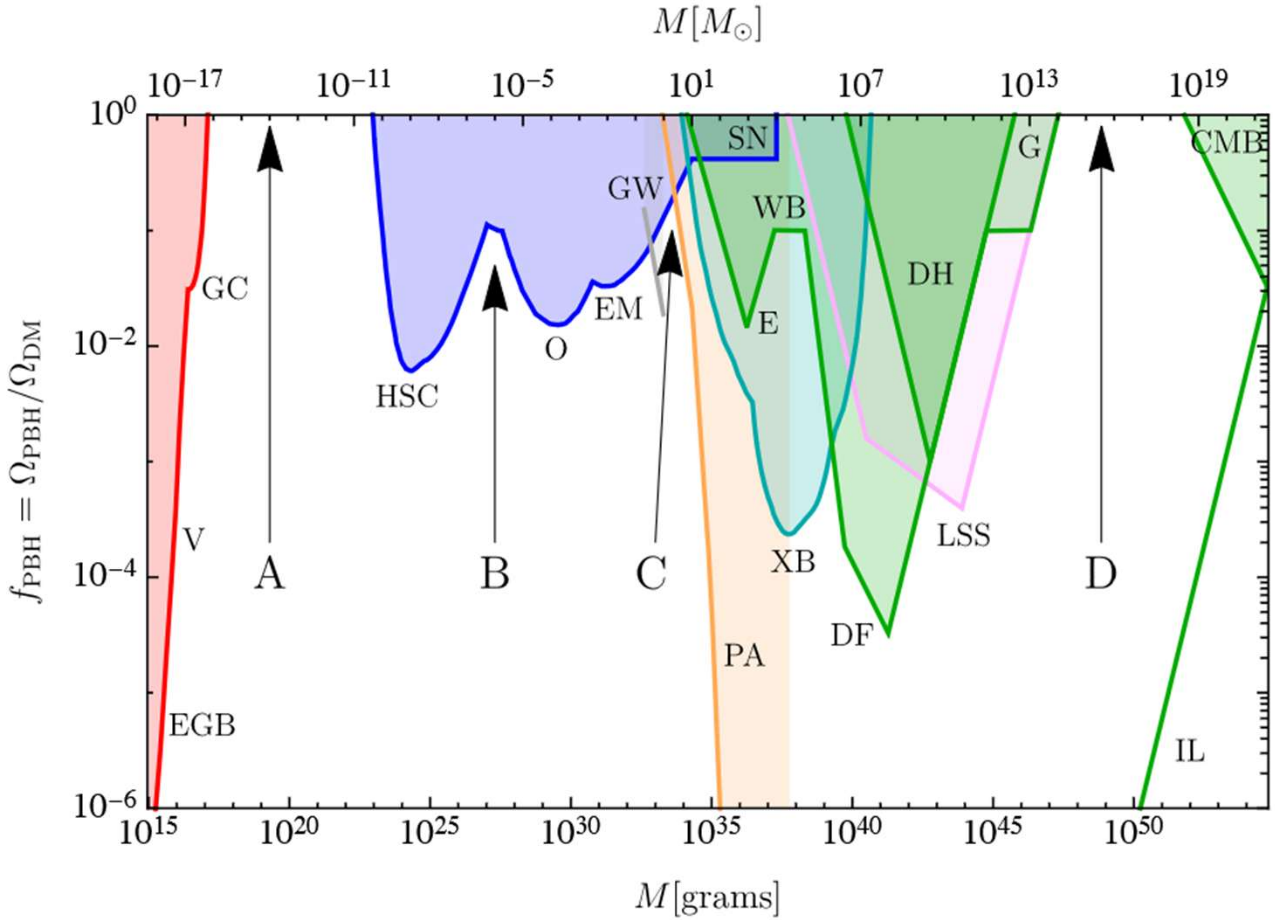
Evaporated by now

$M_{\rm in} \sim 10^{15}\,{\rm g}$

Stable today

M_{in}

What do we know about PBH



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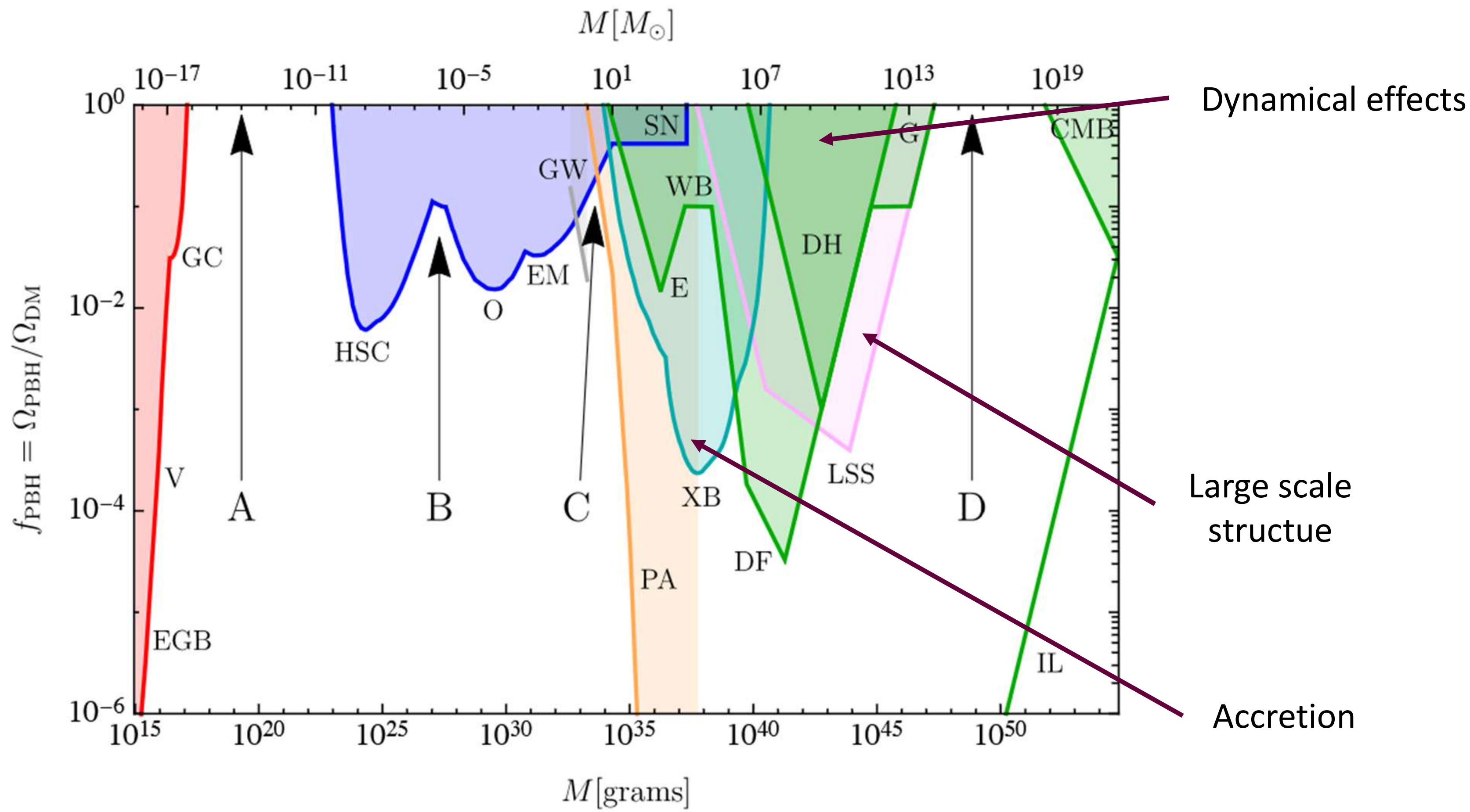

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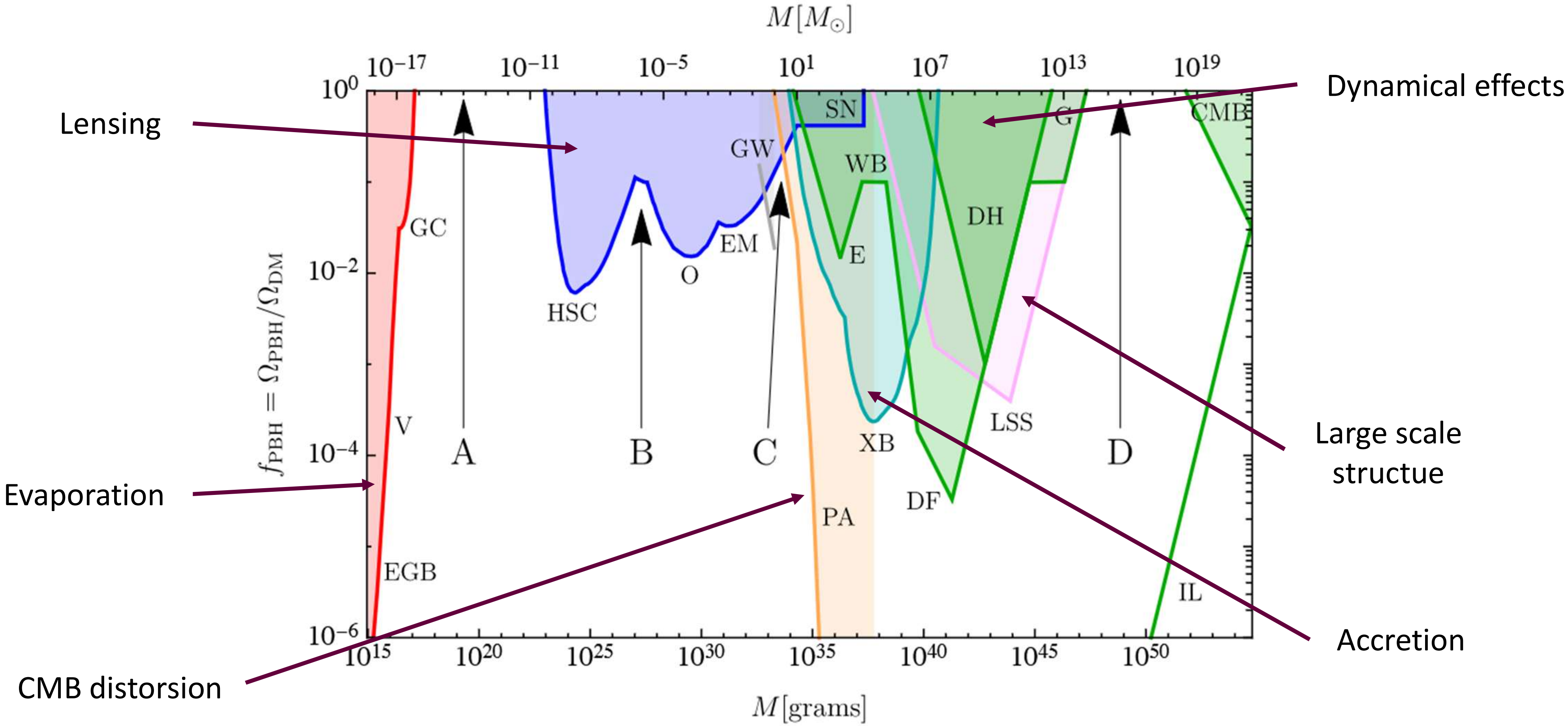

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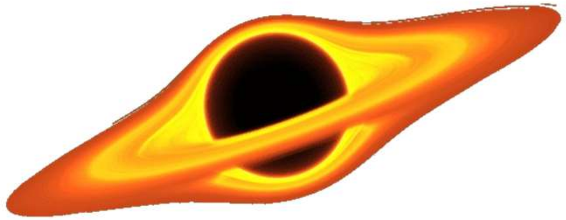
Hawking evaporation

Schwarzschild ansatz

$$ds^2 = \left(1 - \frac{R_s}{r}\right) dt^2 - \left(1 - \frac{R_s}{r}\right)^{-1} dr^2 - r^2 d\theta^2 - r^2 \sin^2\theta \, d\phi^2.$$



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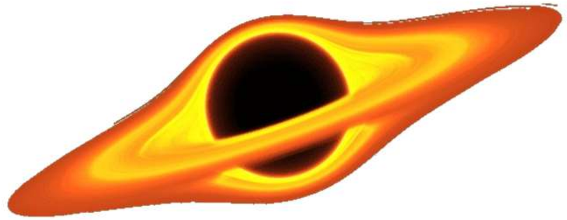

Near the horizon

$$ds^2 = e^{2a\zeta}(d\eta^2 - d\zeta^2) \qquad a = \frac{1}{2R_s} \qquad \Rightarrow \qquad T_{\mathrm{BH}} = \frac{a}{2\pi} = \frac{M_P^2}{M}$$

Black hole evaporate!

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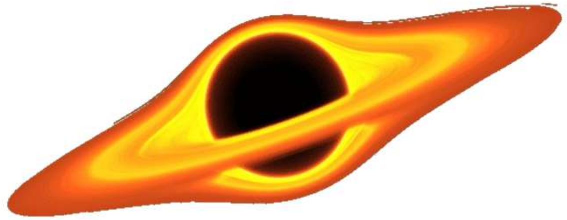

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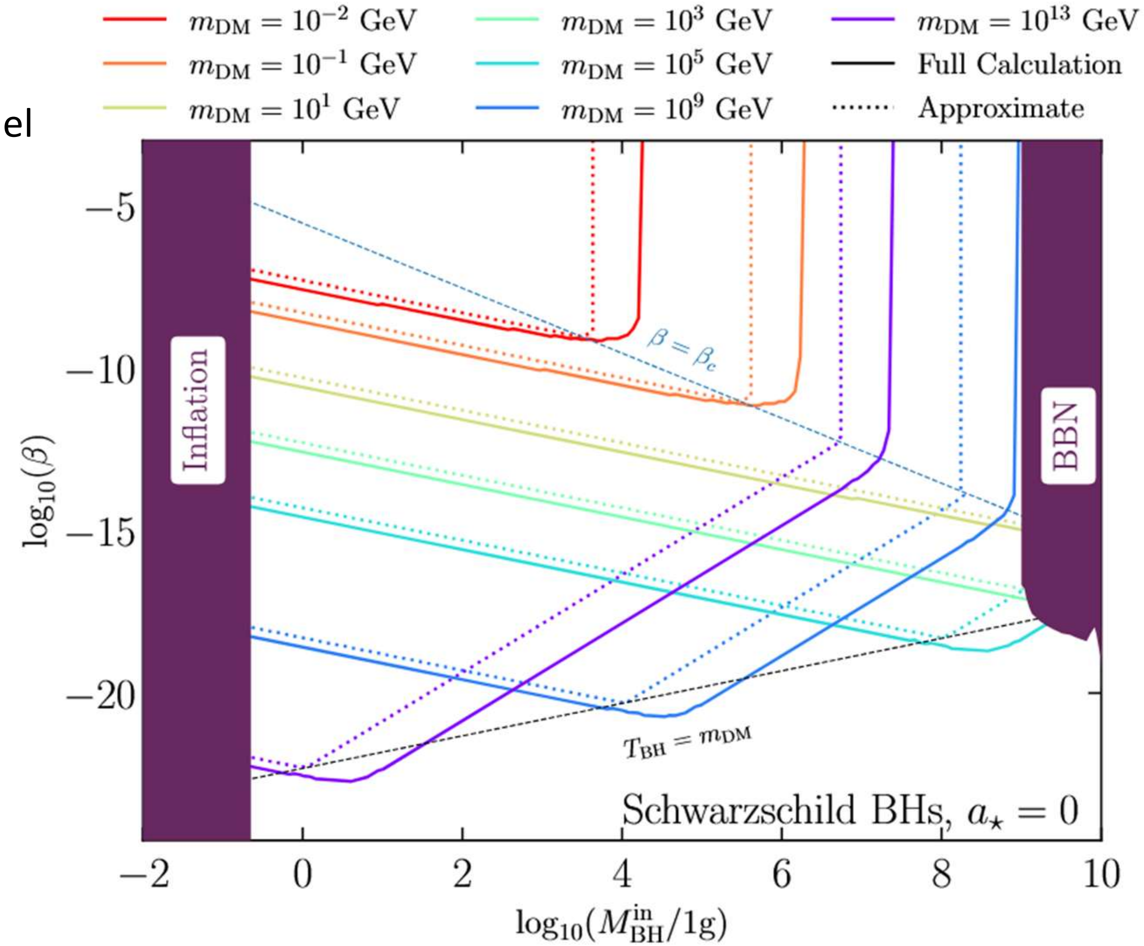
Black hole evaporate!

$$\frac{dM_{\rm BH}}{dt} = -\epsilon \frac{M_P^4}{M_{\rm BH}^2} \qquad \Gamma_{\rm BH} = 3\epsilon \frac{M_P^4}{M_{in}^3} \quad \Rightarrow \quad M_{\rm in} \sim 10^{15}\,{\rm g}$$

PBH as the only source of dark matter

Dark matter does not interact with the Standard Model
(only coupled to gravity)

$$\mathcal{L} = \sqrt{-g}(\mathcal{L}_{\rm EH} + \mathcal{L}_{\rm DM})$$



Andrew Cheek, Lucien Heurtier, Yuber F. Perez-Gonzalez, and Jessica Turner Phys. Rev. D **105**, 015023 (2022)

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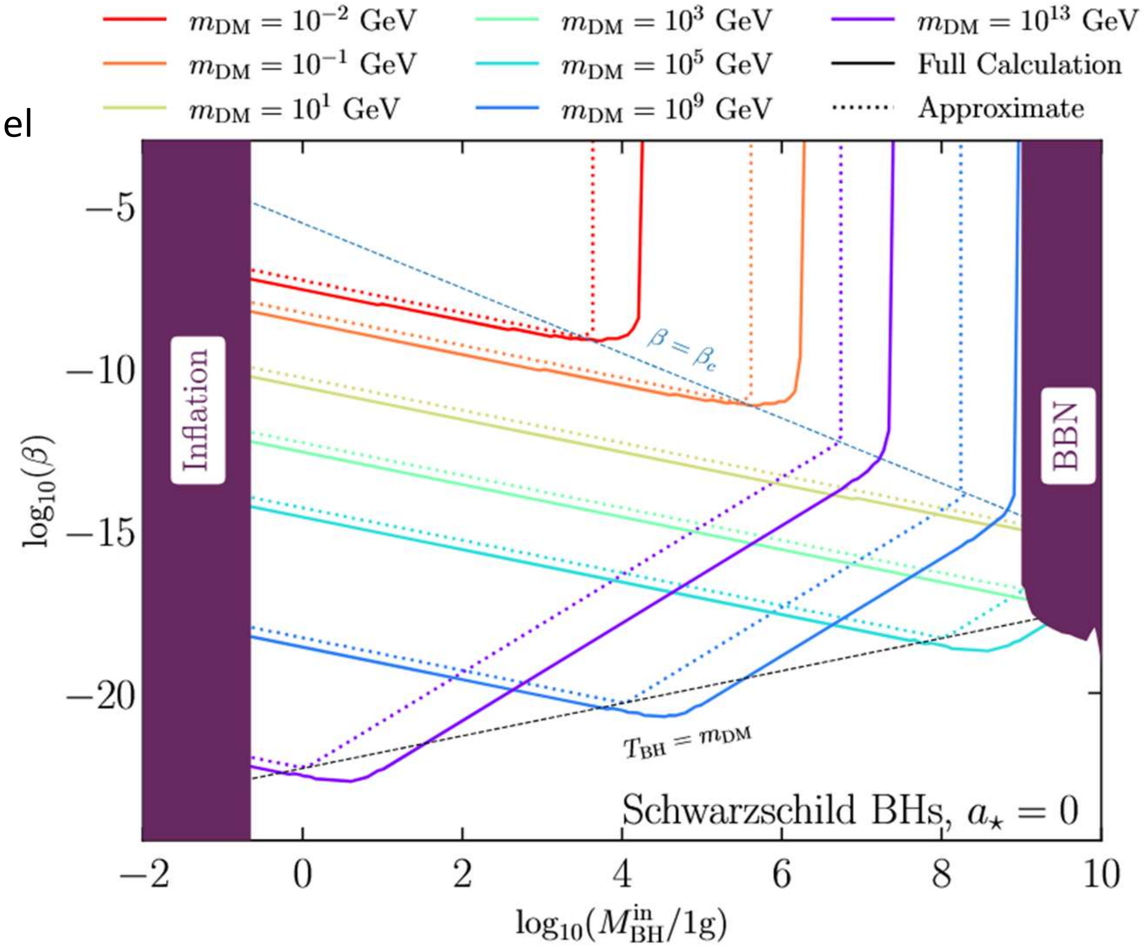
PBH are usually taken as an extra independent source of dark matter



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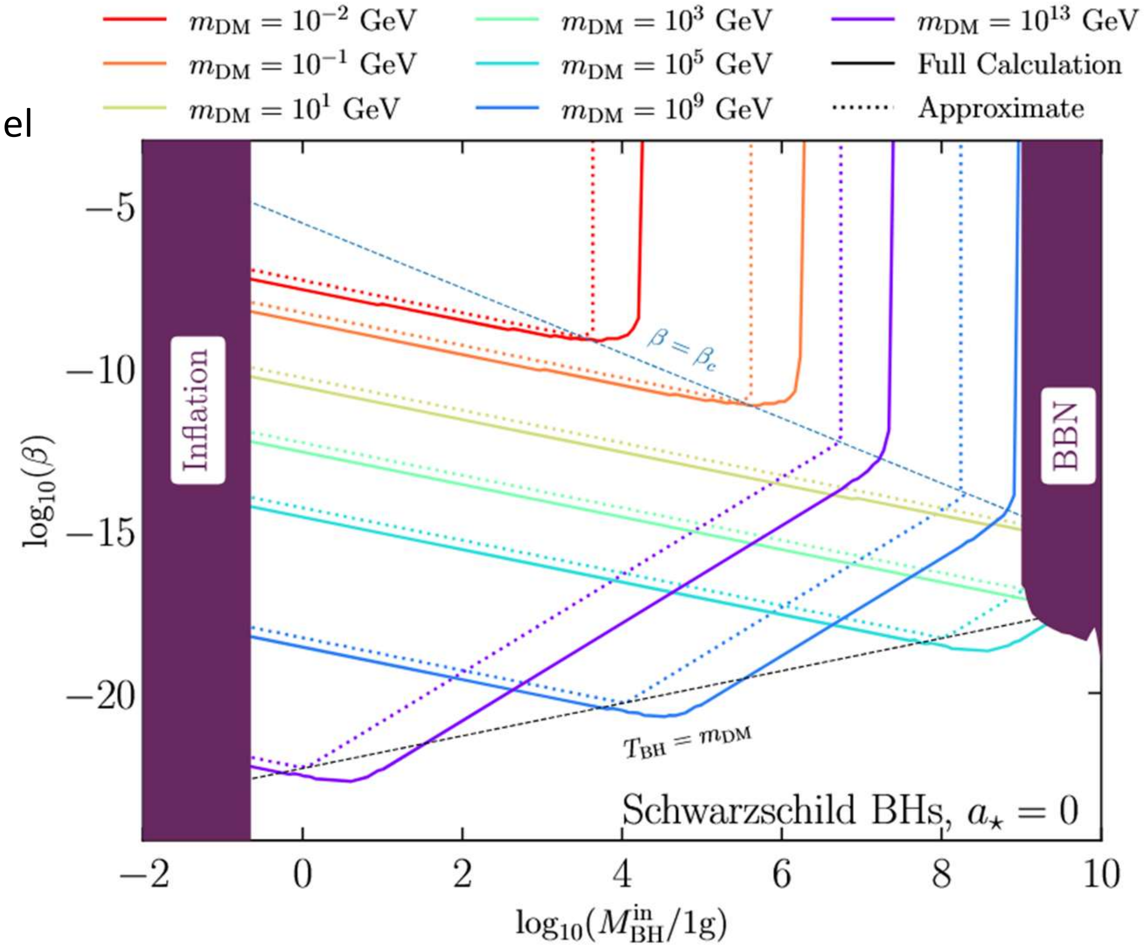
$$\Omega_{\chi,tot}h^2 = \Omega_{\chi,p}h^2 + \Omega_{\chi,PBH}h^2$$



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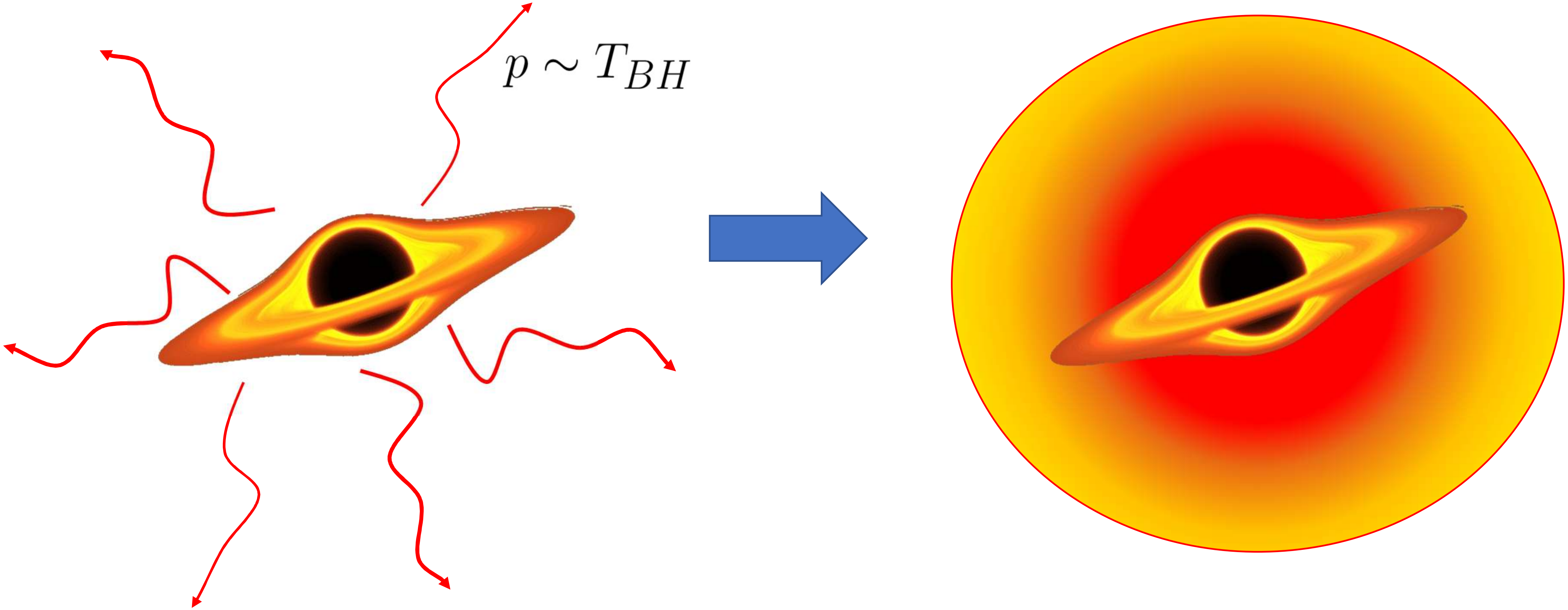
Hotspot and thermal equilibrium dark matter



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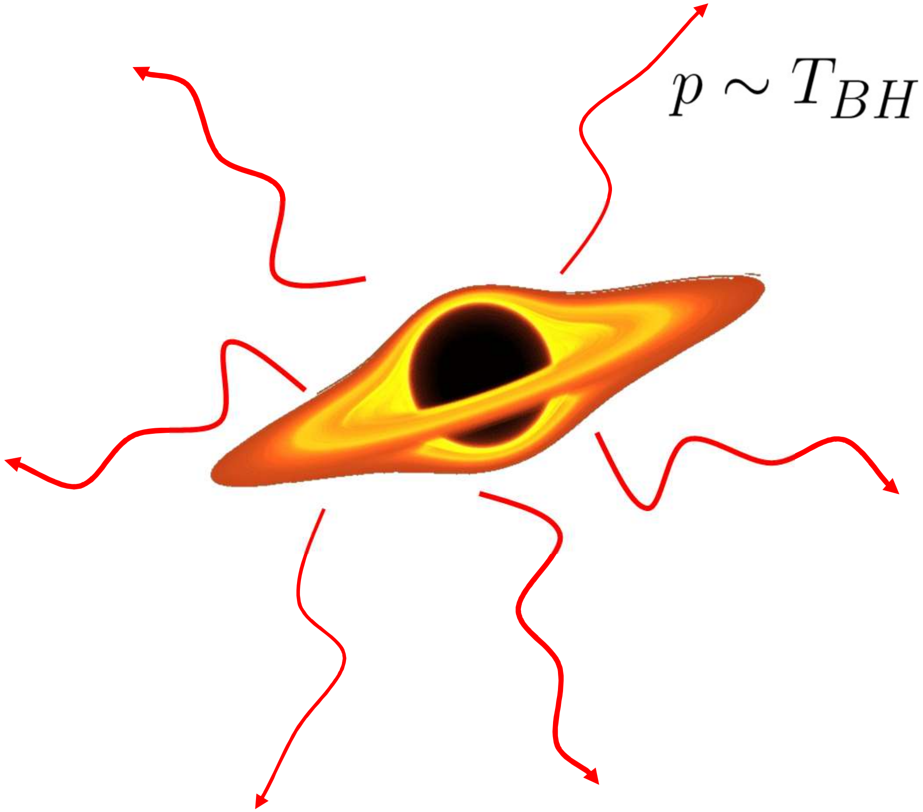
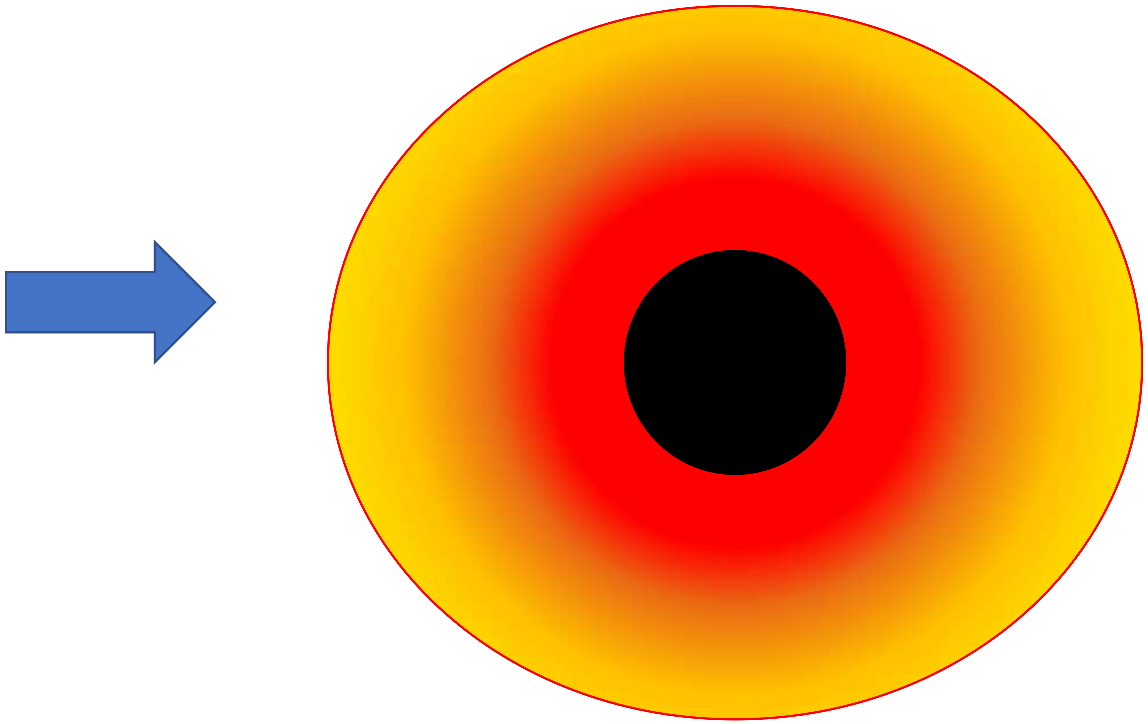




PBH hotspot

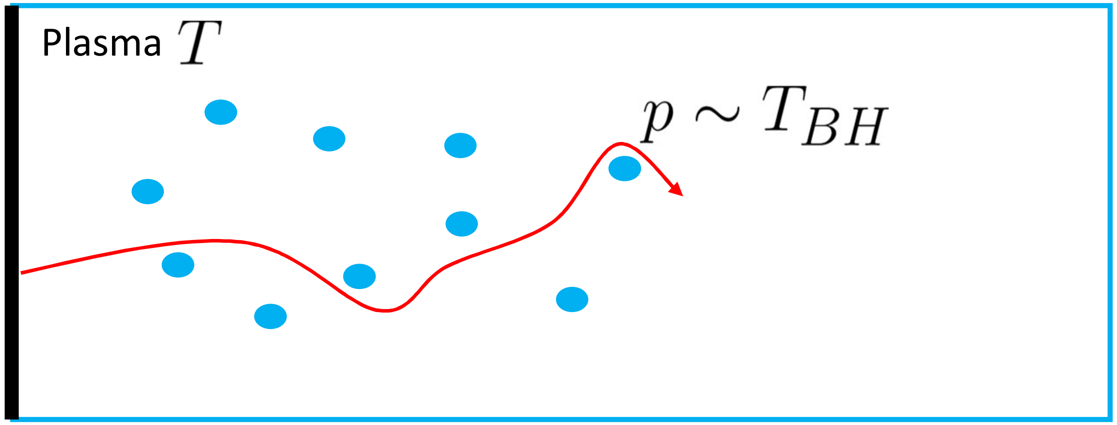
Energy deposition model:

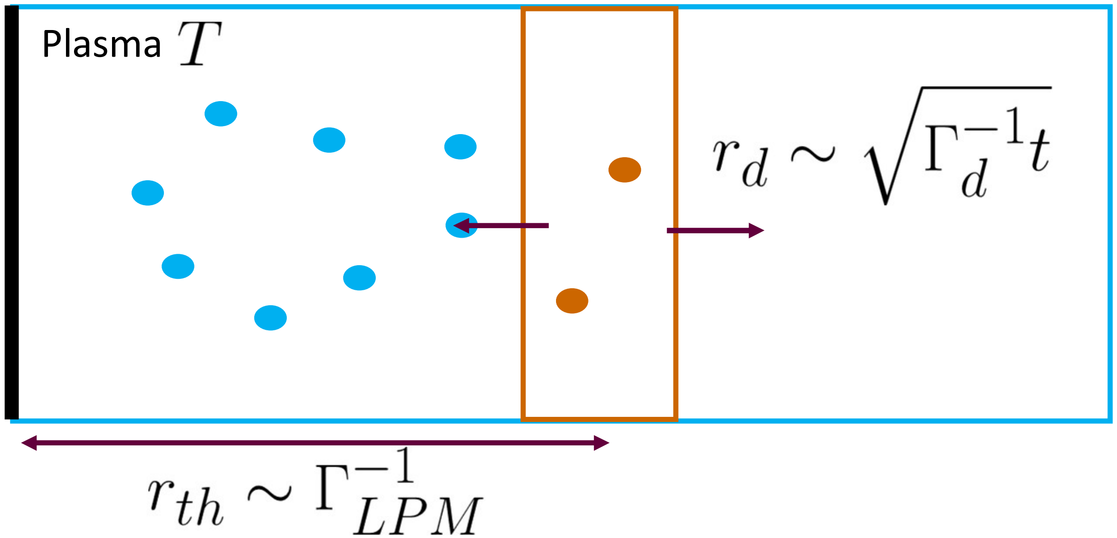
$$\Gamma_{LPM} \sim \alpha^2 T \sqrt{\frac{T}{p}}$$

Difusion:

$$\Gamma_d \sim \alpha^2 T$$

We will take : $\alpha \sim 0.1$





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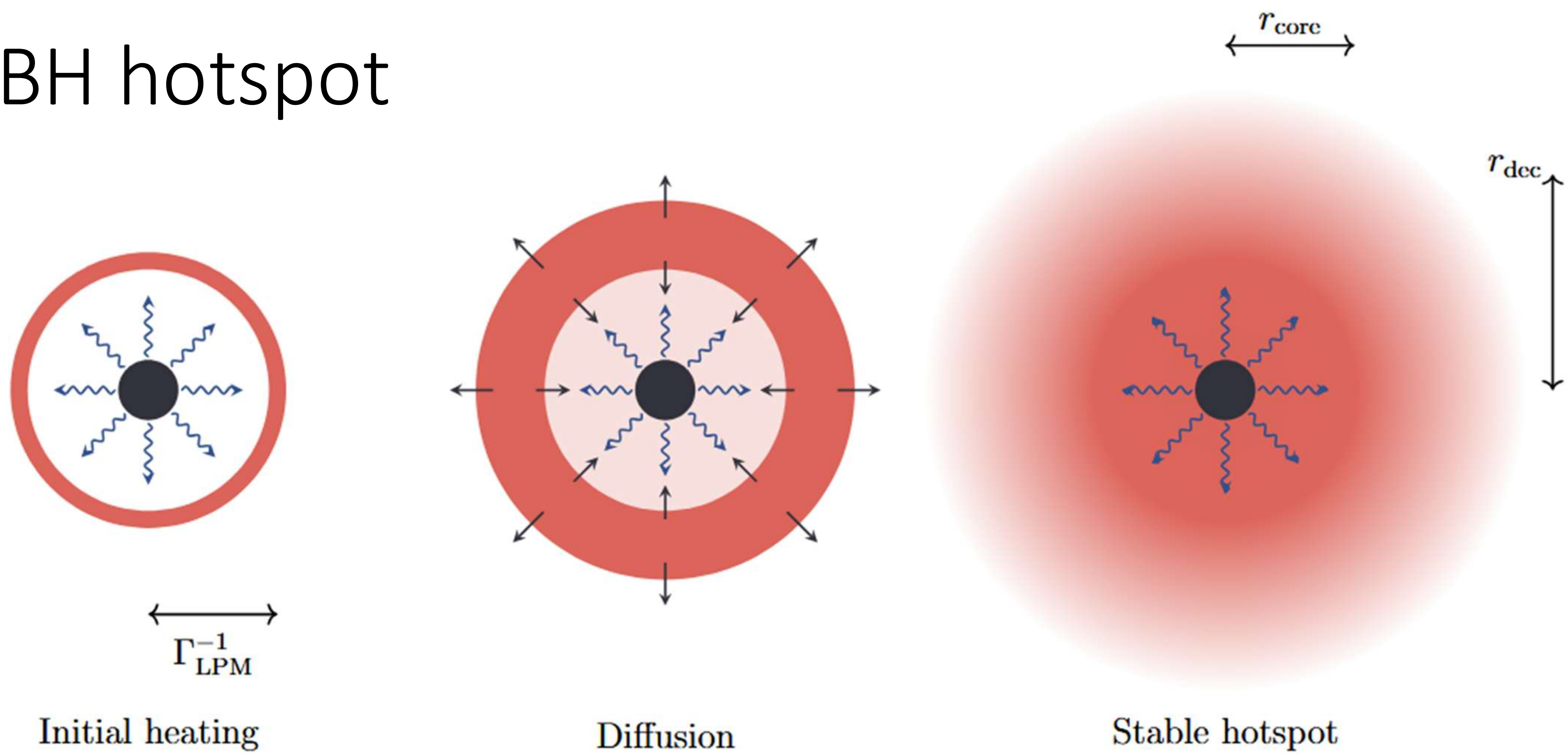
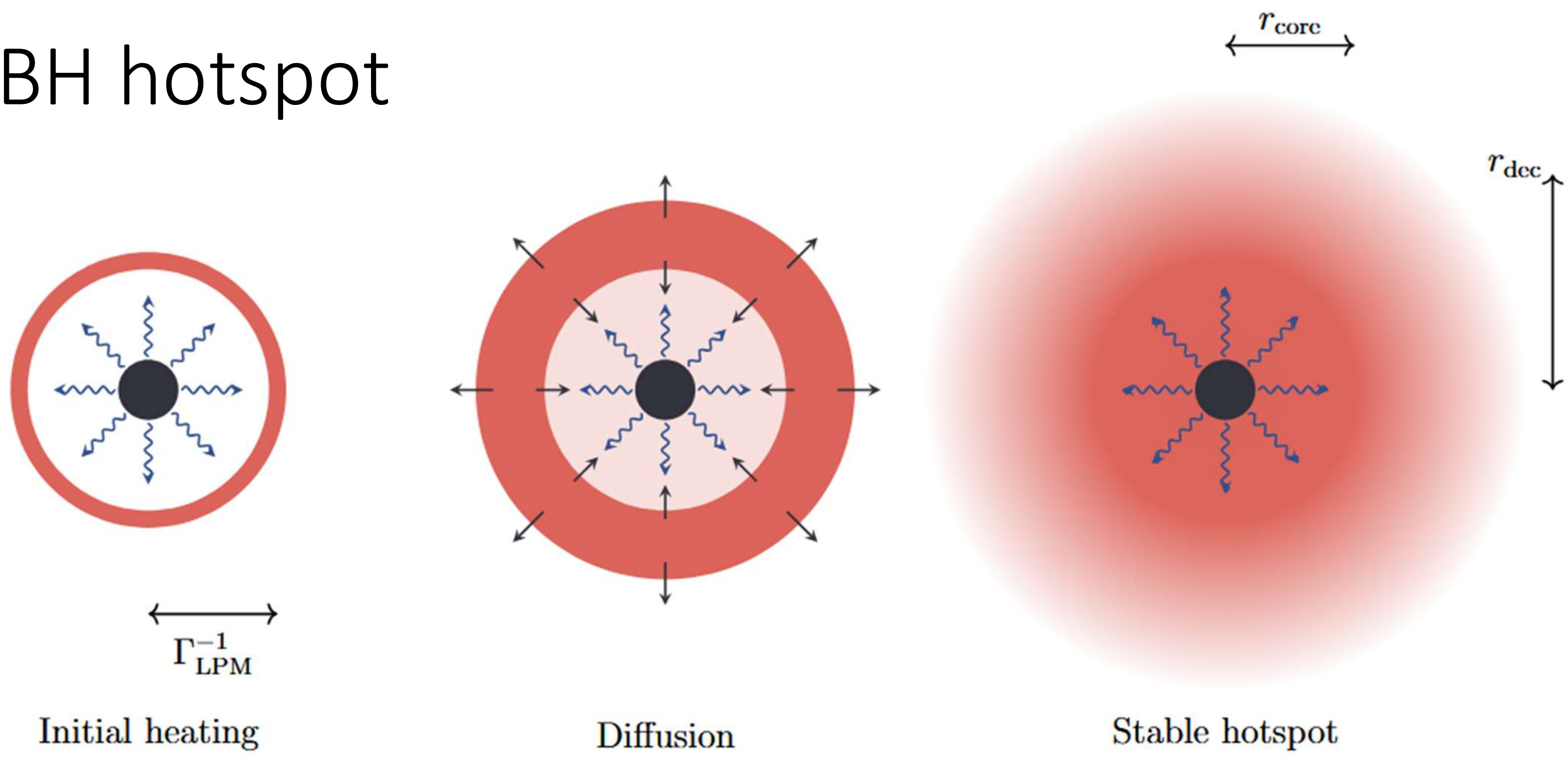


$r_{\rm core}$
$r_{\rm dec}$
$\Gamma_{\rm LPM}^{-1}$
Initial heating
Diffusion
Stable hotspot

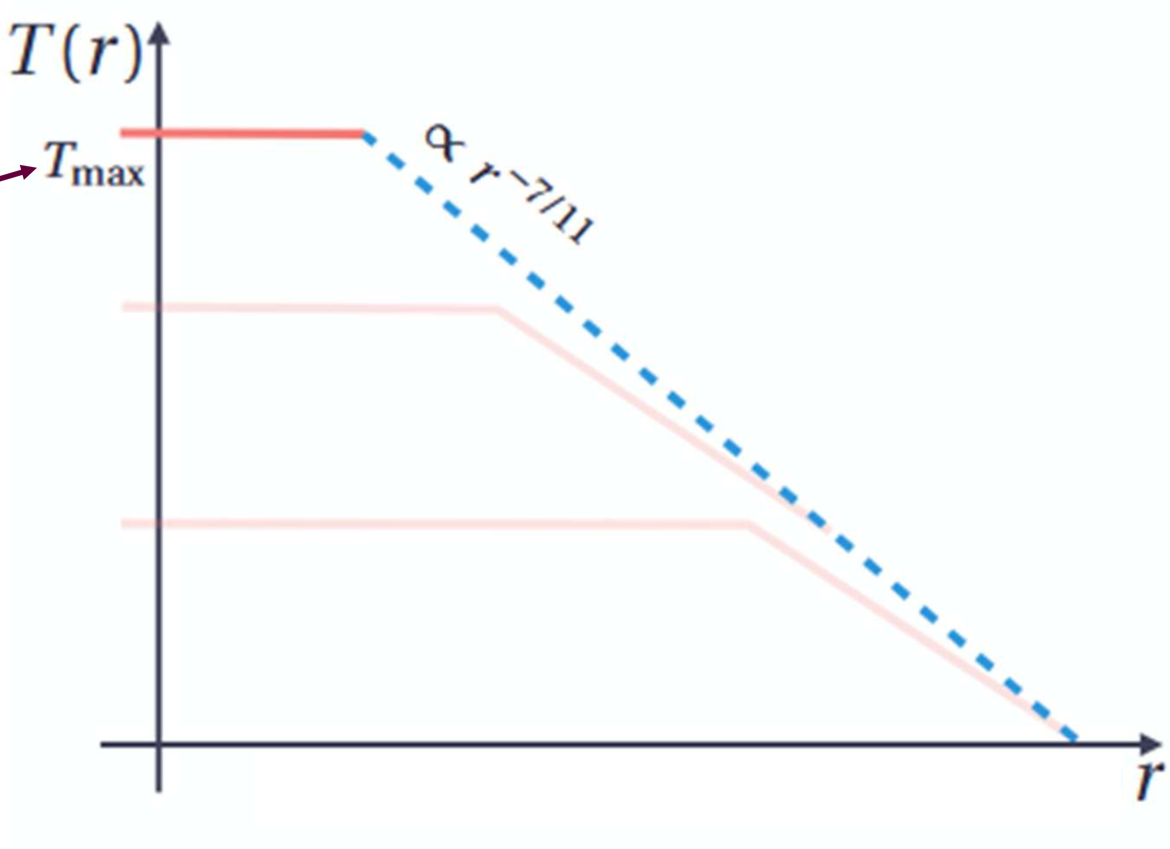
PBH hotspot



The hotspot will be sustained until evaporation

Temperature profile at evaporation

$$T_{max} \sim 10^9 \, GeV$$



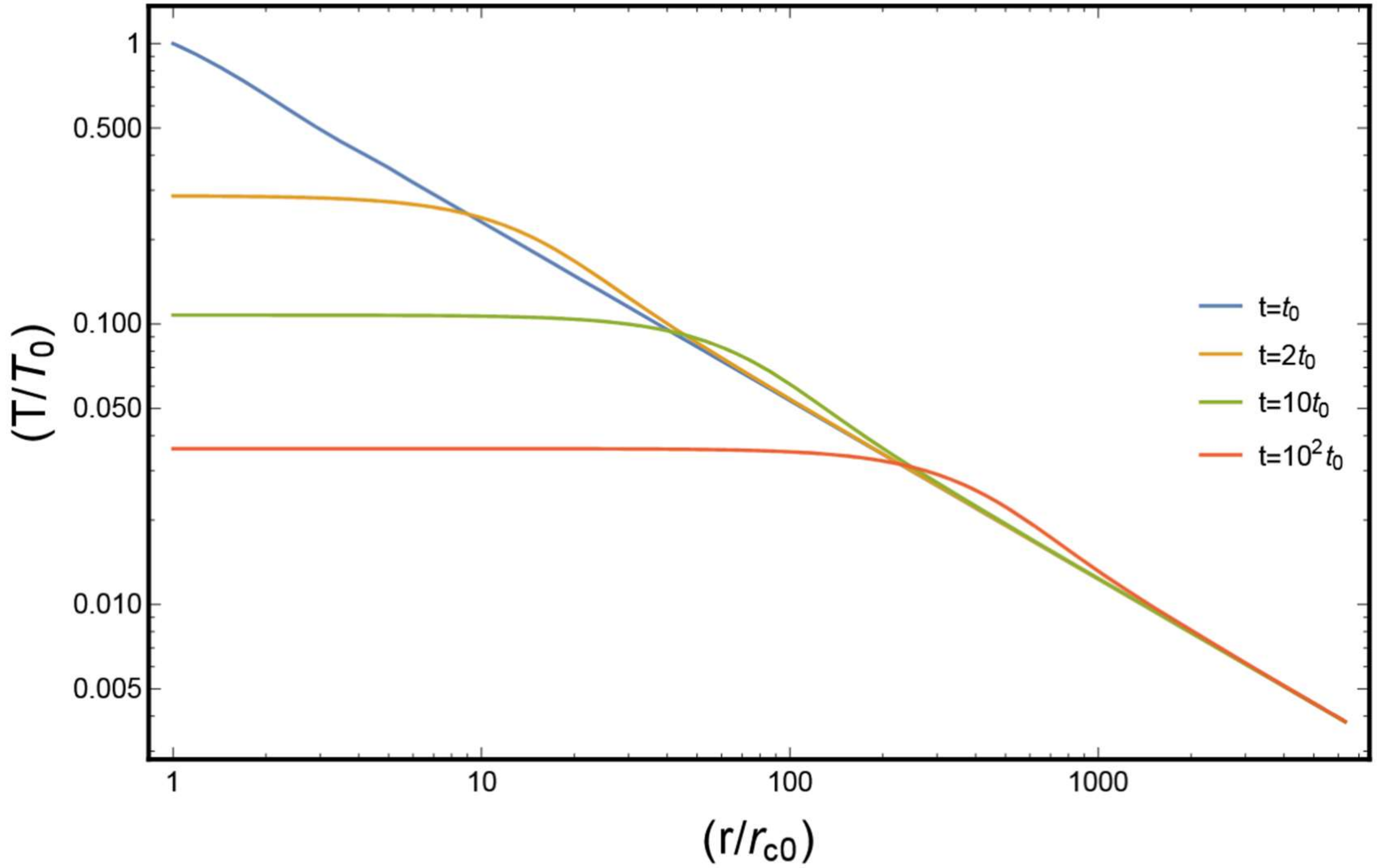
At evaporation the maximal temperature is independant on the PBH mass!

Hotspot cooling

Das, S., Hook, A. *J. High Energ. Phys.* **2021**, 145 (2021)

$$T_{\rm in} \sim t^{-\frac{7}{15}}$$

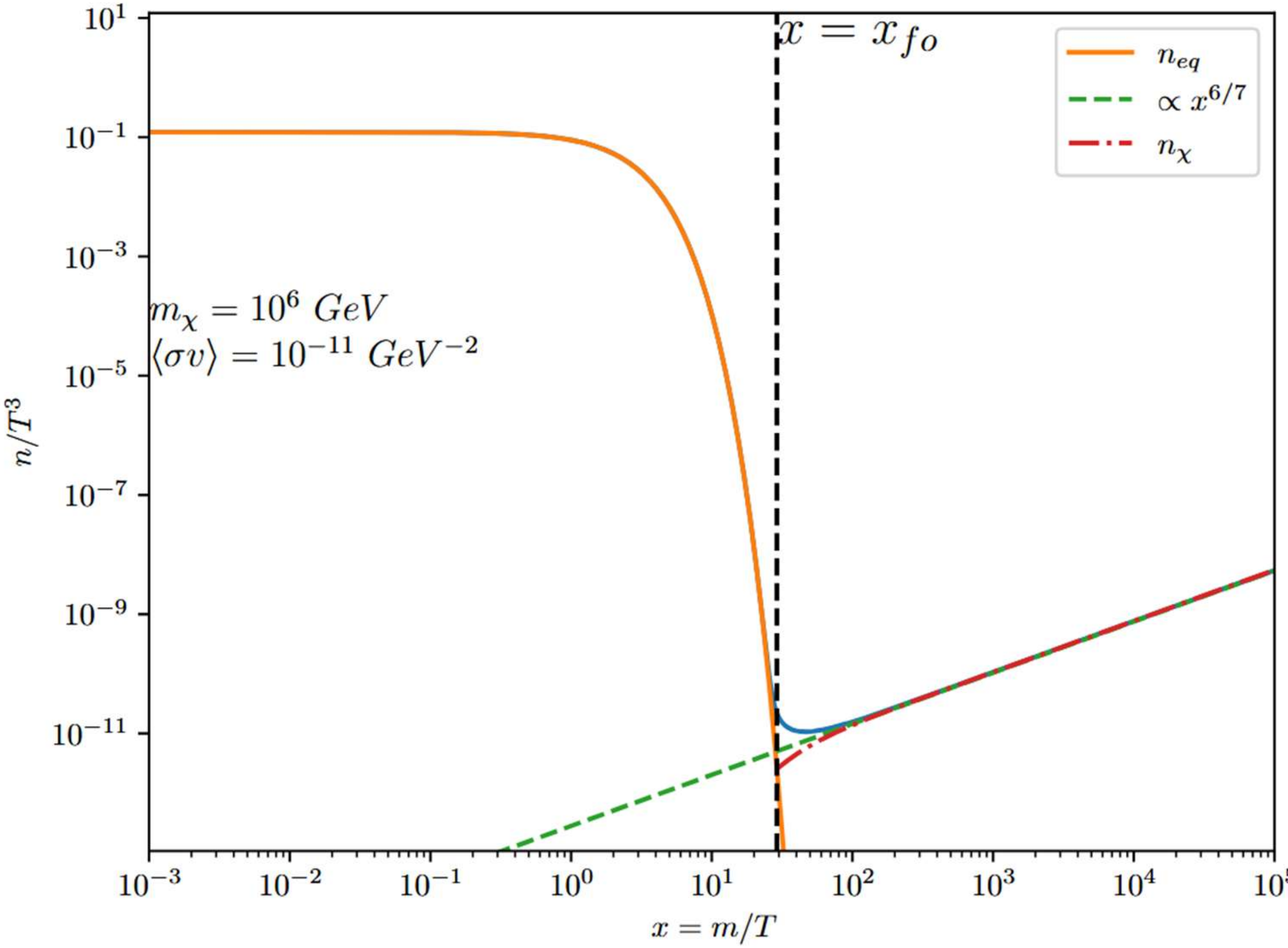
$$\tau_{\rm cool} \sim \tau_{\rm min} \left(\frac{T_{\rm max}}{T}\right)^{15/7}$$



Freeze-out in the hotspot

$$\langle \sigma v \rangle \sim \frac{T^l}{\Lambda^{l+2}}$$

$$\frac{dn_\chi}{dx} = -\frac{\langle \sigma v \rangle}{x\tau_{\rm cool}^{-1}}(n_\chi^2 - (n_\chi^{eq})^2)$$



Dark matter timeline

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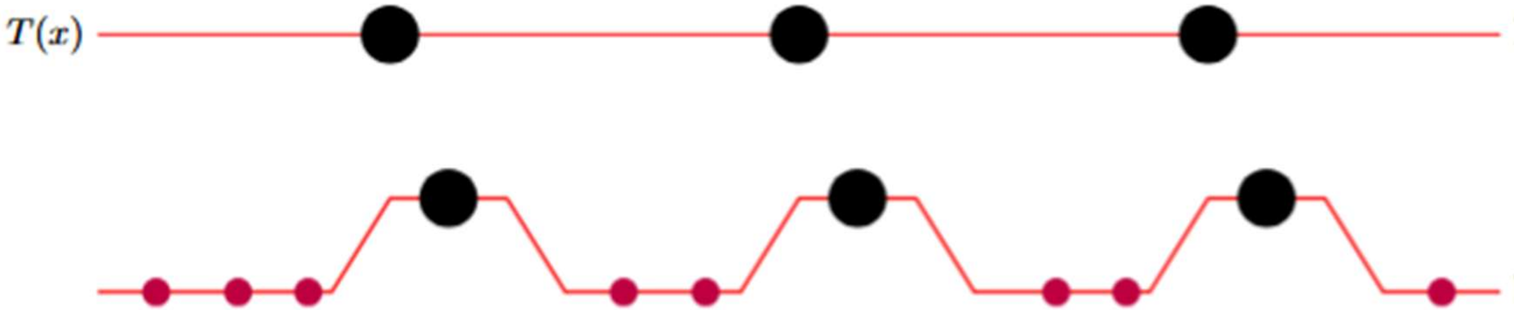

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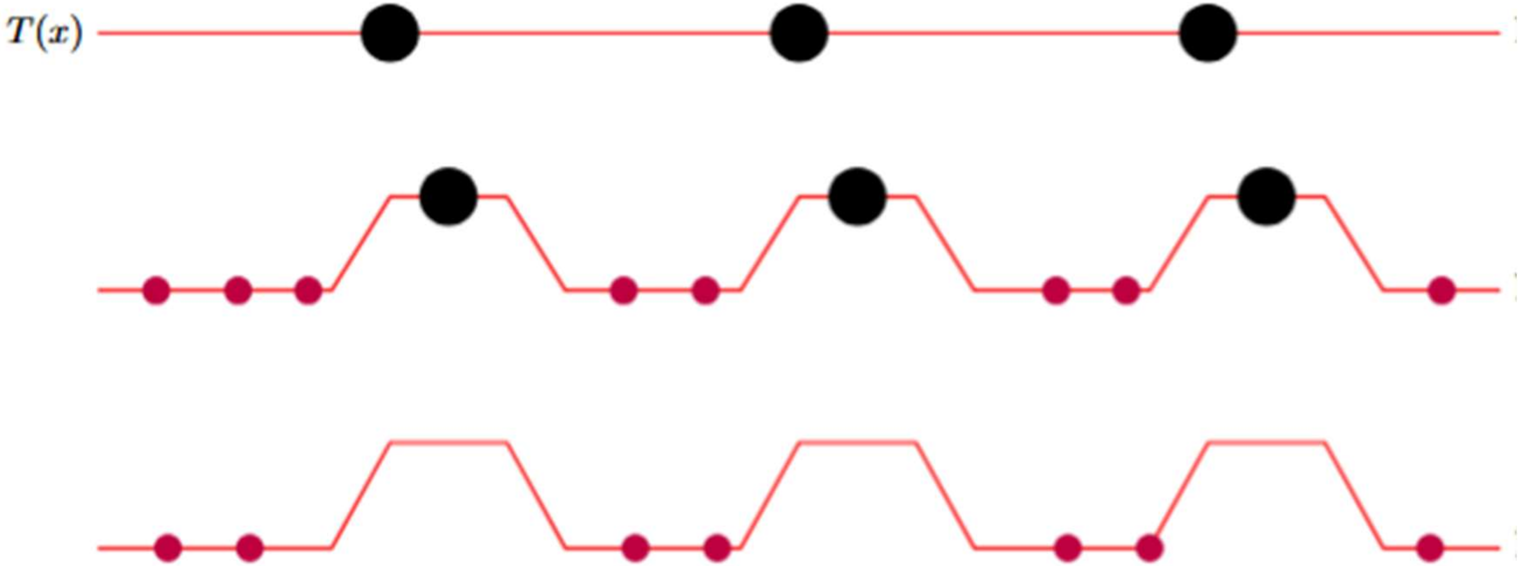

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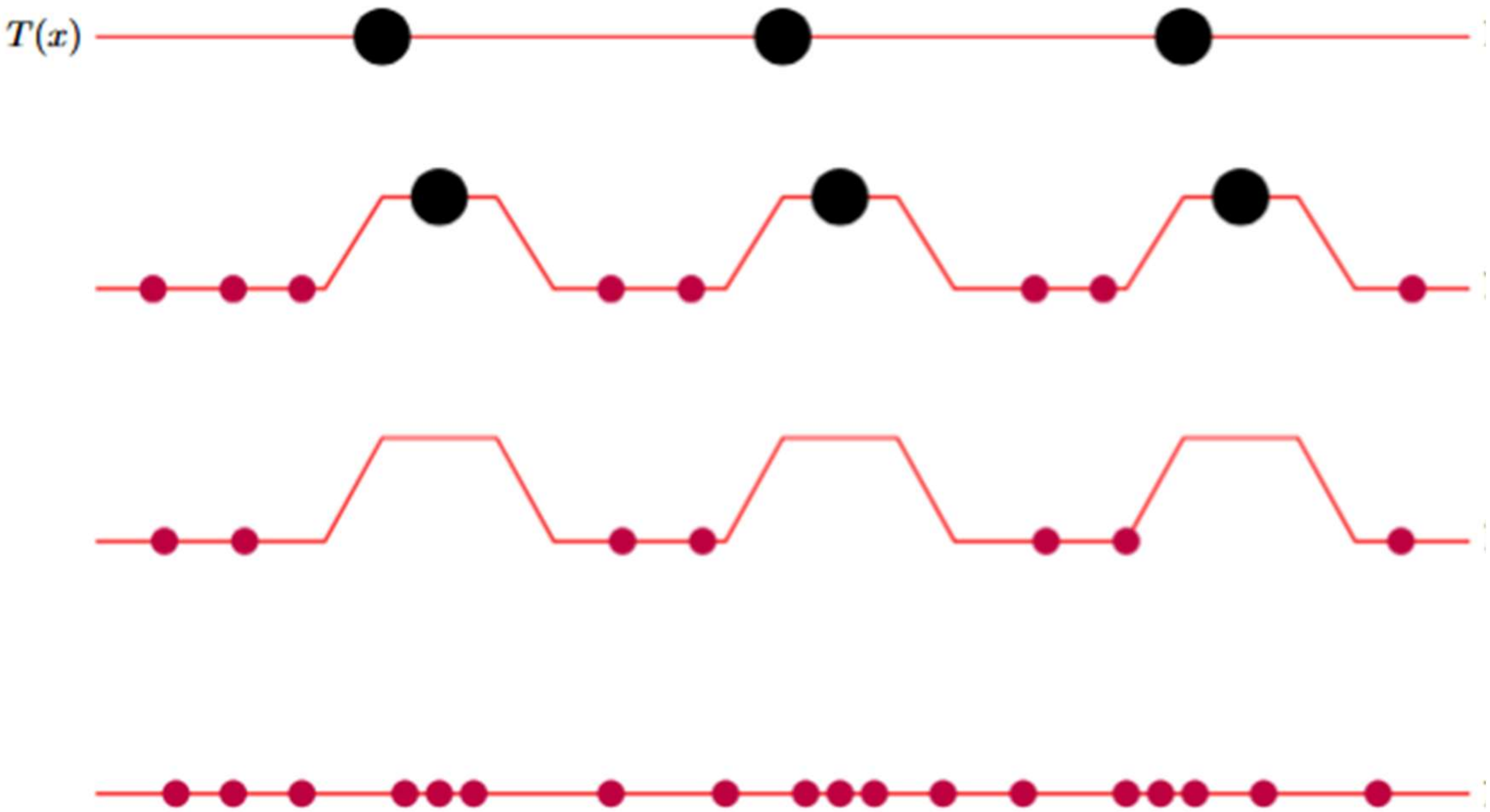

Impact on a preproduced abundance

Initial dark matter production: $$Y_0 \simeq (l+1)\frac{\pi}{3}\sqrt{\frac{g_*}{10}}\frac{\Lambda^{l+2}}{M_P T_{fo,p}^{l+1}}$$

Dark matter freeze out in the background

Impact on a preproduced abundance

Initial dark matter production:

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Dark matter freeze out in the background

A fraction of the universe is still hot:

$$f = n_{pbh,ev}\frac{4\pi}{3}r_{in}^3(T_{fo,PBH}) \propto \beta_{in}$$

Hotspot generates hot region with DM in equilibrium

Impact on a preproduced abundance

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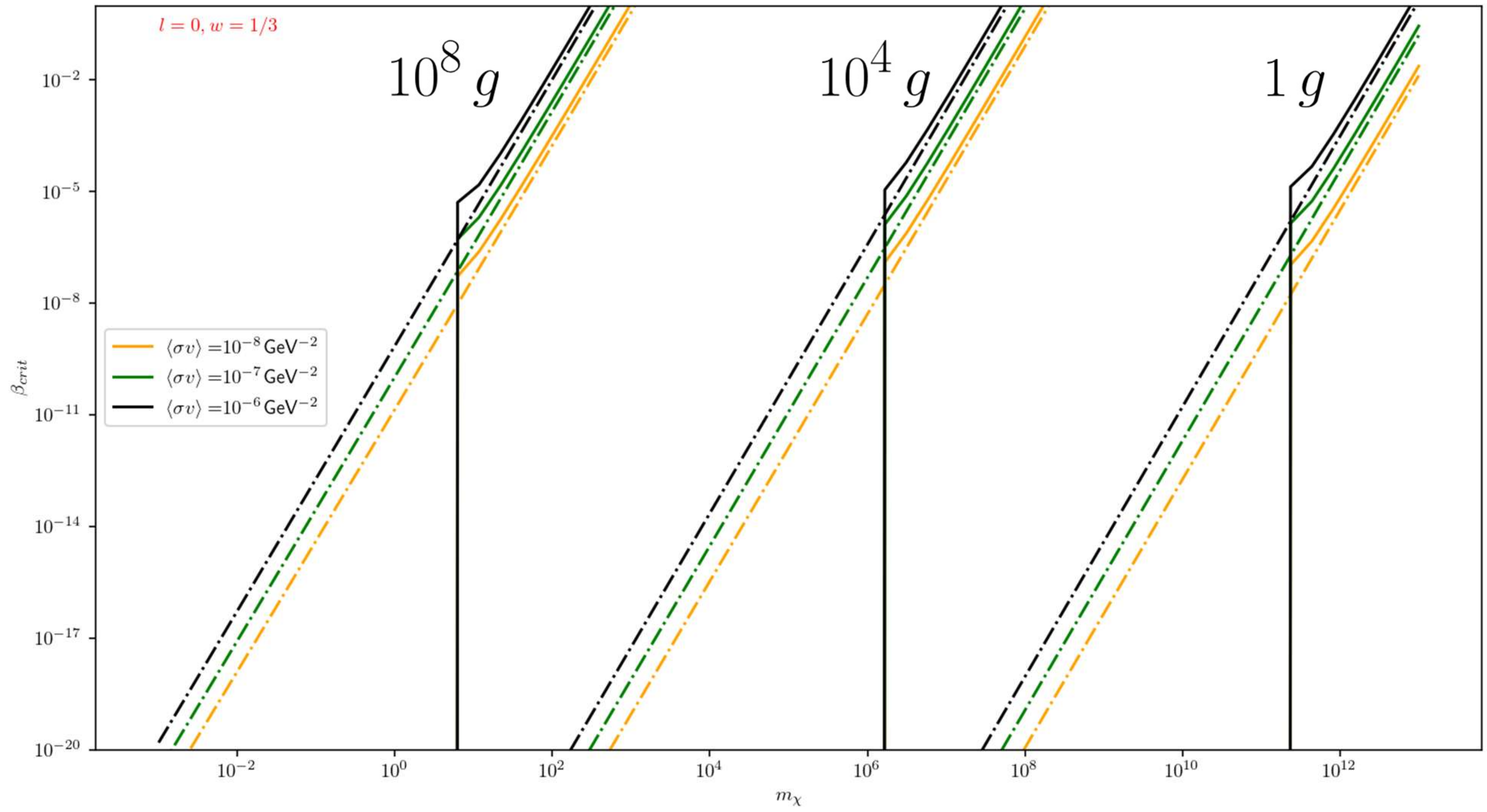
Hotspot generates hot region with DM in equilibrium

In those patch, the dark matter is brought back to thermal equilibrium implying:

$$\Omega_\chi h^2 = \Omega_{fo}h^2 + f(\Omega_{fo,PBH}h^2 - \Omega_{fo}h^2)\,.$$

A second freeze-out is induced by hotspot cooling

Producing the right relic abundance



Conclusion

1) PBH can be formed in many different scenarios

2) Depending on their mass, they can be (part) of the dark matter or contribute to its sourcing

3) PBH can induce a local hotspot, which enhances DM production (incompatibility with WIMP).

Thank you!

Backup

PBH hotspot

Define a difusion time:

$$r_d(t_d, T) = r_{th}$$

For a stable hotspot to form we require :

$$\frac{\pi^2 g_*}{30} T^4 \frac{4\pi}{3} r_{th}^3(T_{BH}, T) \approx -t_d(M_{BH}, T) \frac{dM_{BH}}{dt}$$

$$\Rightarrow T_{core} \sim \left(\frac{90\alpha^4}{4\pi^3 g_*} \epsilon \right)^{\frac{2}{3}} T_{BH}$$

Size of the central homogeneous patch:

$$r_{core} = r_{th}(T_{BH}, T_{core}) \sim \left(\frac{4\pi^3 g_*}{90\alpha^6 \epsilon} \right) \frac{1}{T_{BH}}$$

Difusion generates a homogeneous central region until:

$$t_d \lesssim t_{th}$$

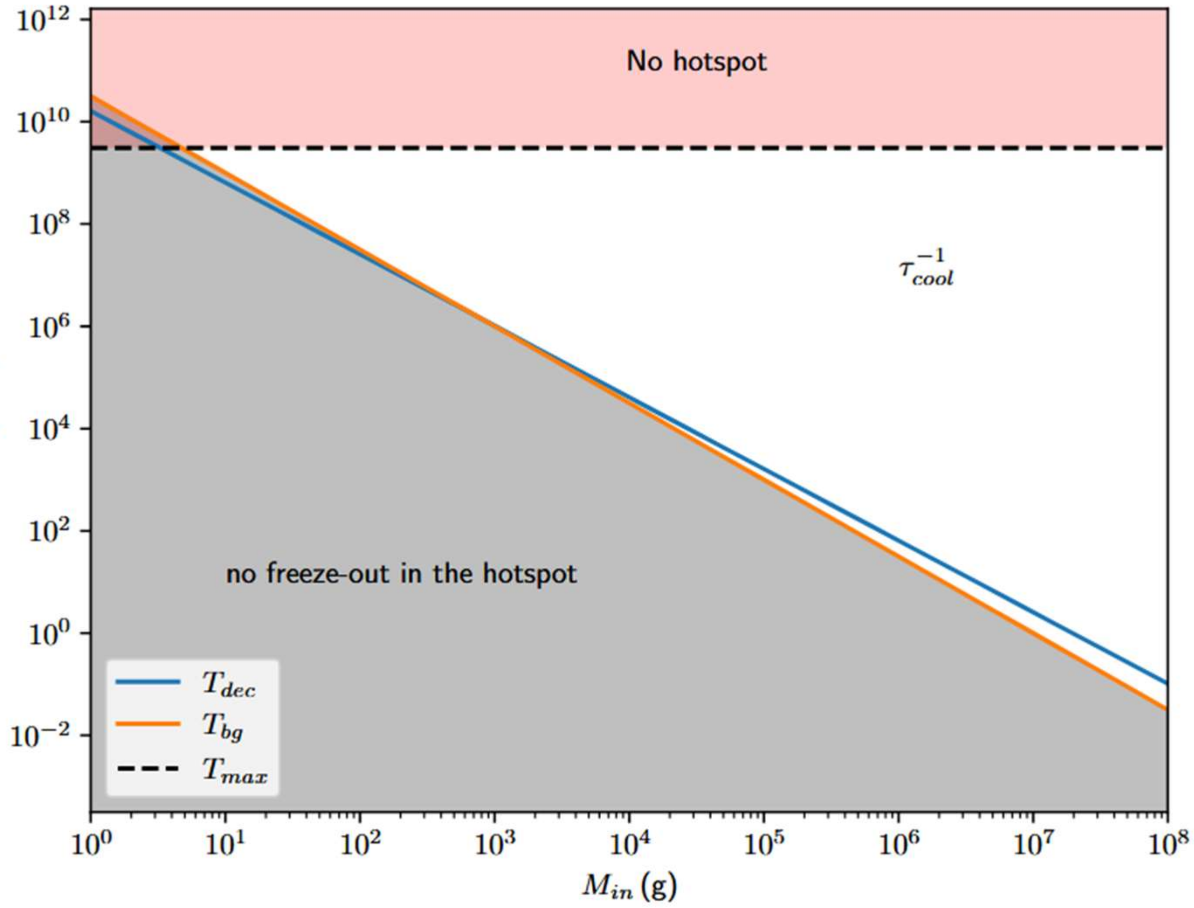
$$M > M_* \equiv \left(\frac{4\pi^3 g_*}{90} \right)^{\frac{2}{3}} \frac{3^{\frac{3}{6}}}{2^{\frac{1}{6}} \alpha^{\frac{11}{3}}} \frac{M_P}{\epsilon^{\frac{1}{6}}}$$

Freeze-out in the hotspot

Hotspot freeze-out imply:

$$\tau_{cool}^{-1}(T) > H(T_{bg})$$

$$T > \underbrace{T_{max}\left(\sqrt{\frac{g_*}{10}}\frac{\pi}{3}\frac{T_{bg}^2\tau_{min}}{M_P}\right)^{\frac{7}{15}}}_{T_{dec}}$$



Freeze-out in the hotspot

Can PBH evaporate after background freeze-out?

Relativistic Freeze-out

Non relativistic Freeze-out