Dark Matter and Cosmic Rays from PBH hot spots

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What are Primordial Black Holes?

Non-stellar origin → No Chandrasekhar limit → $0.1\text{g} \lesssim M_{\text{PBH}}^{\text{ini}} \lesssim 10^{20} M_{\odot}$

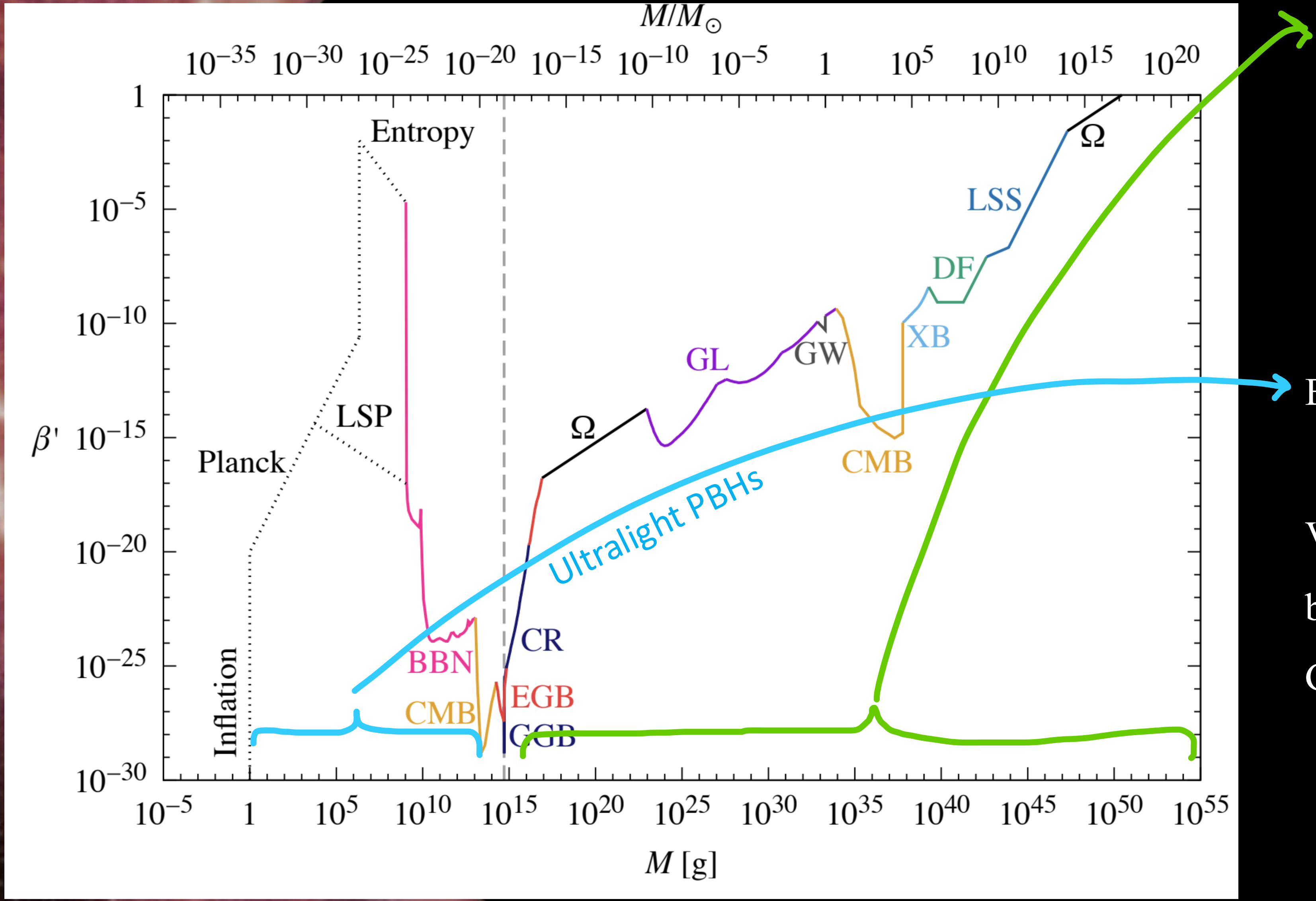
Black holes which form in the primordial universe from overdensity collapse

Could be part or all of the relic Dark Matter (DM) density

Drivers of Baryogenesis, DM production, matter domination

Constraints on PBHs

Carr, 2020



Still exist today

Subject to various observational constraints

Evaporated completely

Very difficult to constrain but increasingly subject to GW constraints

Black Hole Explosions

Black hole explosions?

QUANTUM gravitational effects are usually ignored in calculations of the formation and evolution of black holes. The justification for this is that the radius of curvature of space-time outside the event horizon is very large compared to the Planck length $(G\hbar/c^3)^{1/2} \approx 10^{-33}$ cm, the length scale on which quantum fluctuations of the metric are expected to be of order unity. This means that the energy density of particles created by the gravitational field is small compared to the space-time curvature. Even though quantum effects may be small locally, they may still, however, add up to produce a significant effect over the lifetime of the Universe $\approx 10^{17}$ s which is very long compared to the Planck time $\approx 10^{-43}$ s.

Stephen Hawking 1974, Nature

Black holes radiate all particles – finite lifetime

At the end of life, evaporation is extremely rapid

Essentially unobservable for stellar Black holes

$$\frac{\mathrm{dM_{PBH}}}{dt} \propto M_{\mathrm{PBH}}^{-2}$$

Currently under debate!

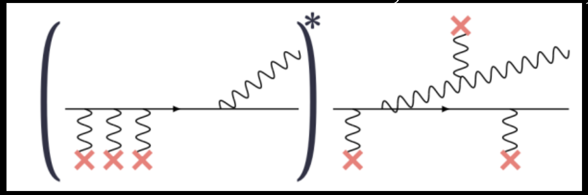
Light (primordial) black holes may evaporate extremely quickly

$$T_{\mathrm{BH}} = \frac{1}{8\pi G M_{\mathrm{PBH}}}$$

PBH reheating- LPM

PBHs do not evaporate in a vacuum!

Yamada, Mukhaida, Kohri



Hawking radiation interacts with the plasma

LPM suppressed collinear emission of soft gauge bosons is dominant

Energy is deposited close to the BH

Initially quasi-static, explosive at late times

LPM length/timescale depending on gauge coupling!

$$\Gamma_{\mathrm{LPM}} = \alpha^2 \sqrt{\frac{T^3}{k}}$$

Diffusion

$$r_{\rm core} \equiv \Gamma_{\rm LPM}^{-1}$$

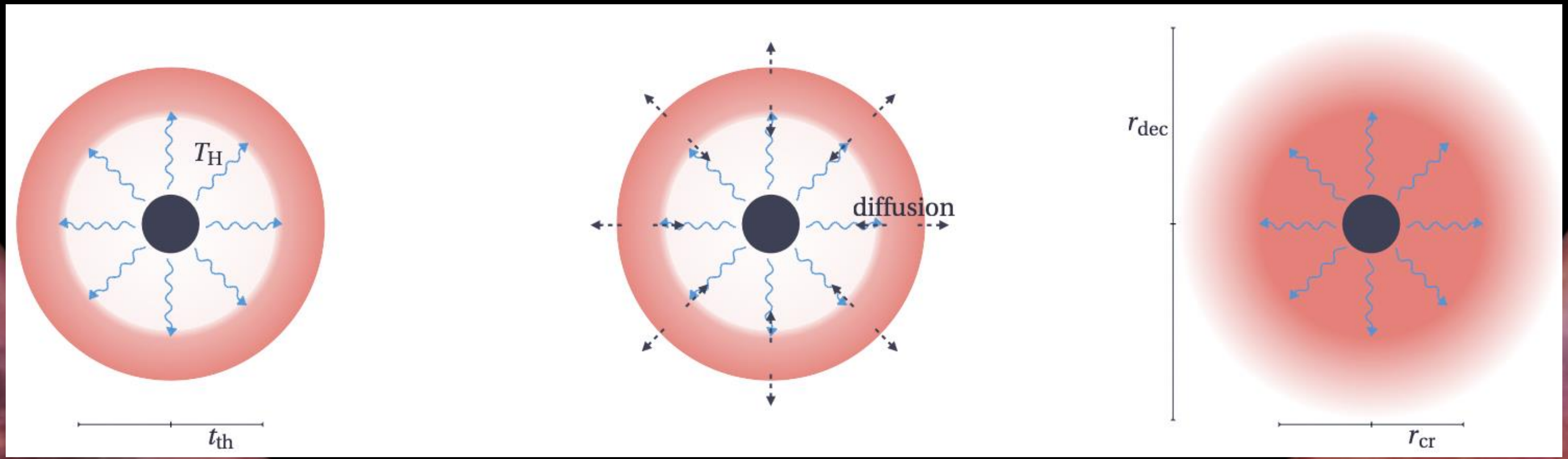
Average radius Hawking radiation deposits energy

$$t_d = \frac{r_{\rm core}^2}{t_{\rm el}}$$

Time to random walk rcore

$$t_d(M_{\rm PBH}) \leq t_{\rm ev}(M_{\rm PBH})$$

Efficient smoothing via diffusion



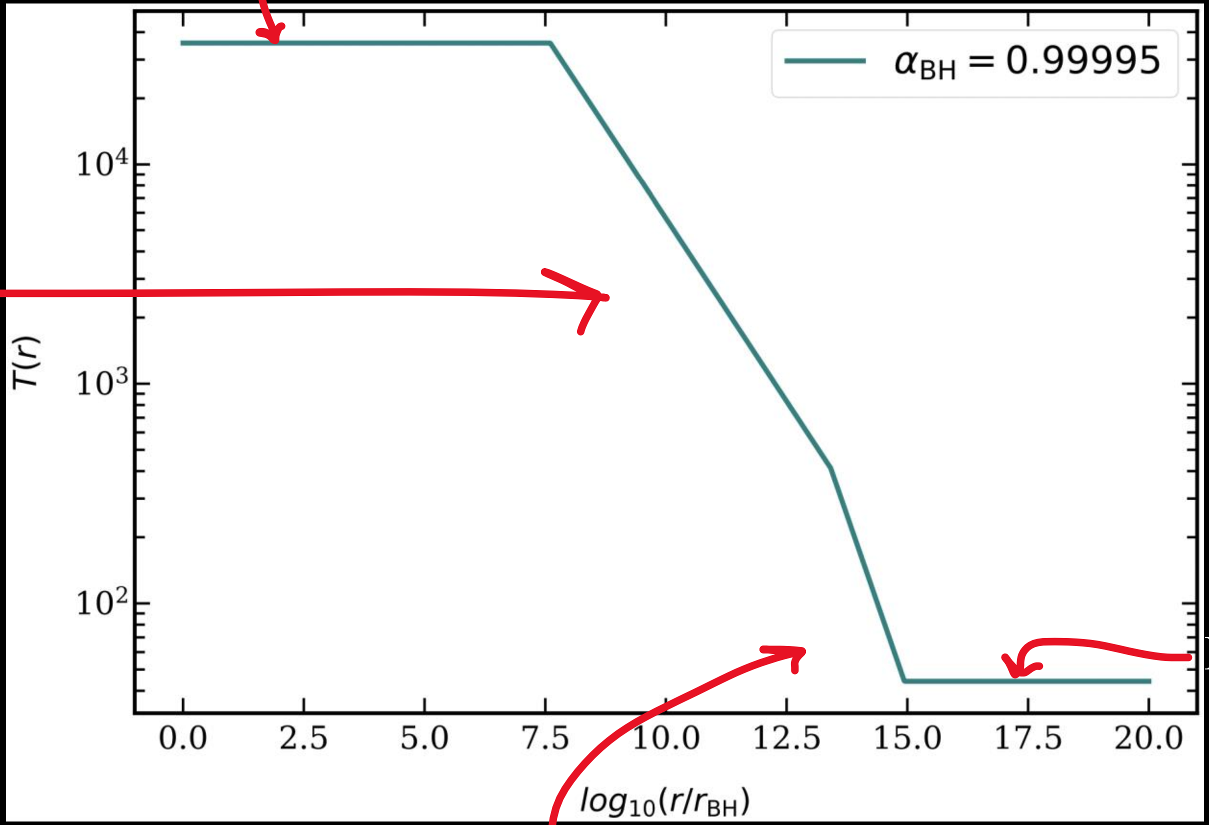
Minxi He, Kazunori Kohri, Kyohei Mukaida, Masaki Yamada

Hot spots – profile

Smooth inner "core" $T_{\rm core}^{\rm max} \approx 2 \times 10^9 \,\mathrm{GeV}$

Diffusive temperature gradient

$T(r) \propto r^{-\frac{1}{3}}$



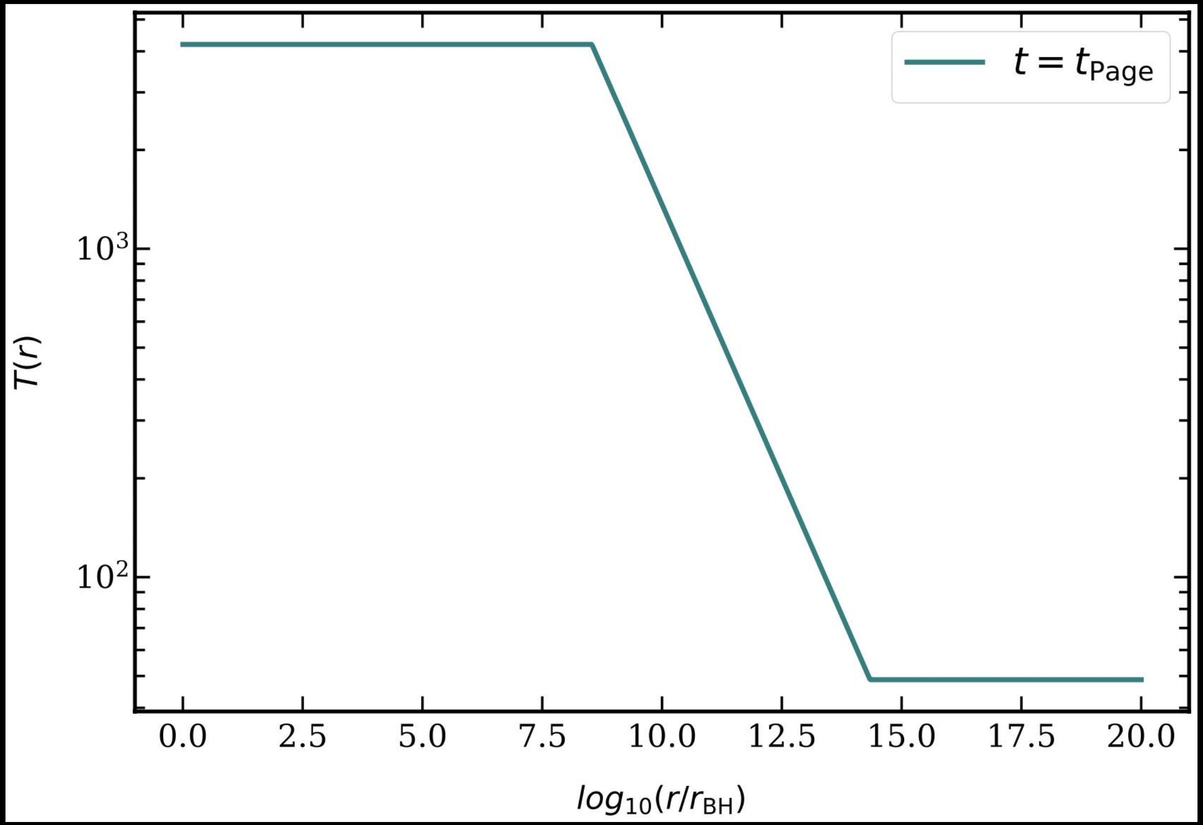
Background universe

Outer region frozen out of thermal contact

$T(r) \propto r^{-\frac{7}{11}}$

Memory Burden

Hot spots form before the Page time

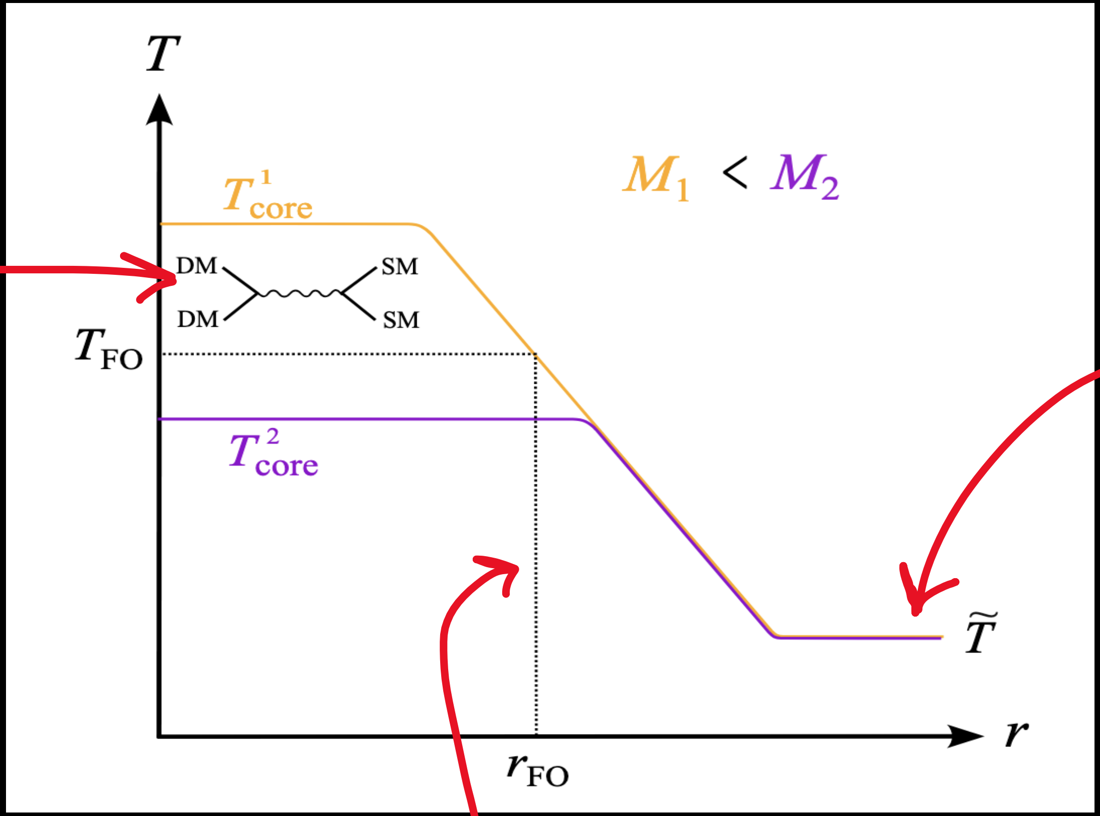


How hot spots evolve if memory burdened is unknown

Freeze-out

Large number density/interaction rate at small radii

$\Gamma(r_{\mathrm{core}}) \gg H$



Vanishing number density/interaction rate for

$r \geq r_{\mathrm{FO}}$

At some radius r_{FO} , $\Gamma(r_{\mathrm{FO}}) = H$

Particles trapped within

$r \leq r_{\mathrm{FO}}$

are scattered efficiently

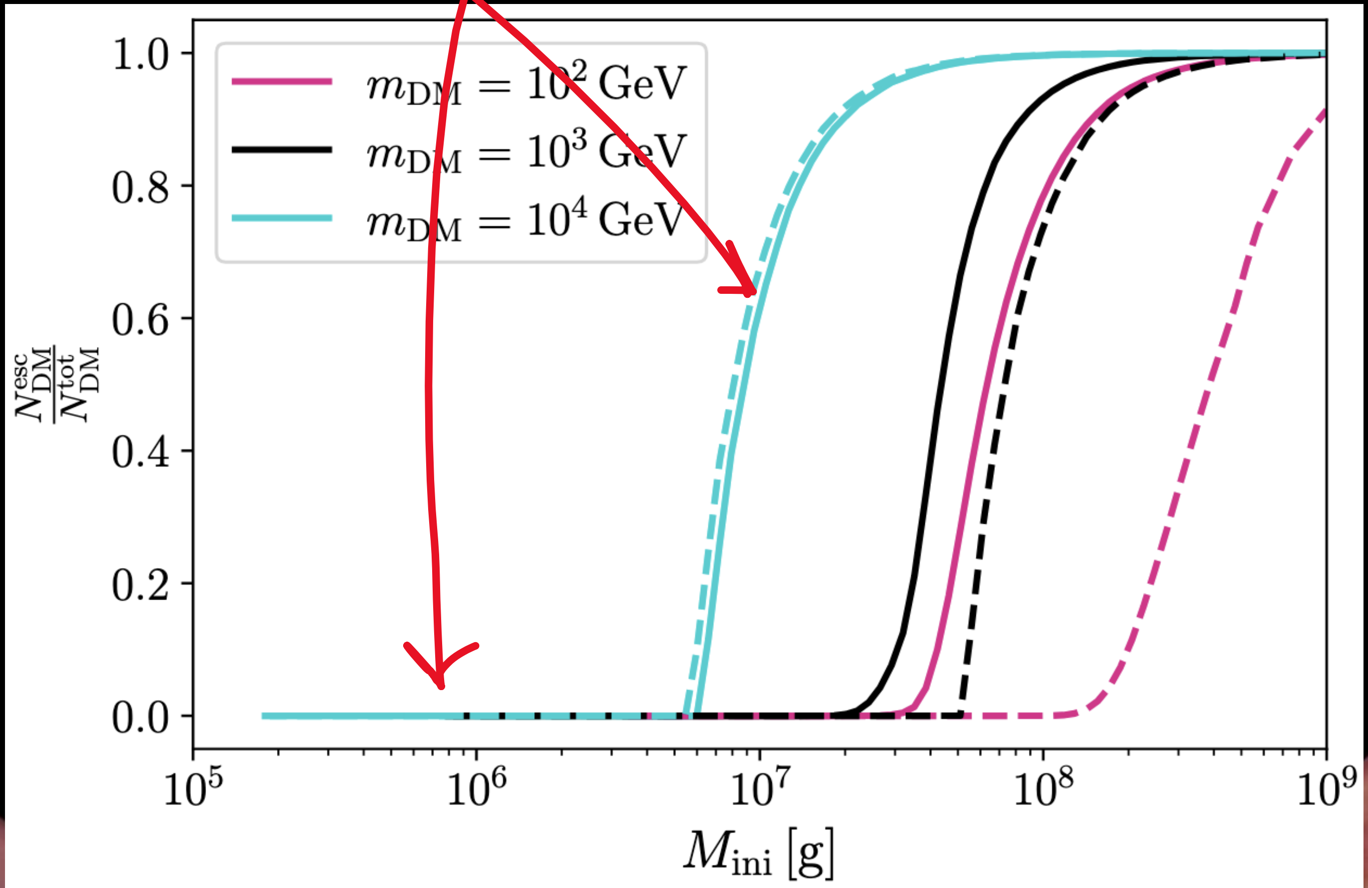
Particles which escape to large radii do not see the process

DM in hot spots

Fraction of produced DM which escapes

DM is absorbed by light PBHs

Additional contribution outside the hot spot



PBH produced-DM

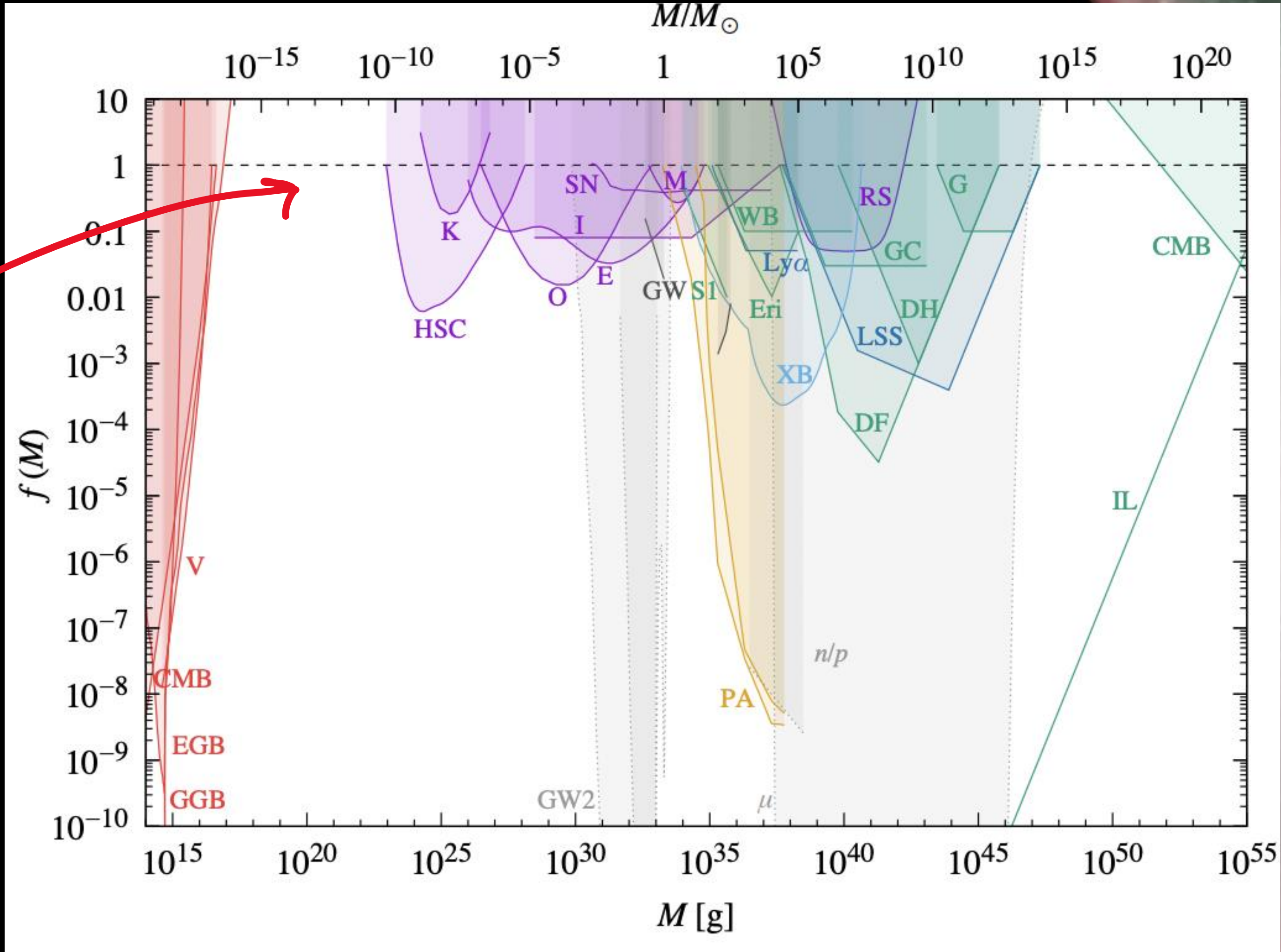
DM is absorbed close to the PBH → Non-homogeneous distribution of DM in the universe following evaporation → How does universe, structure evolve?

N-body simulations?

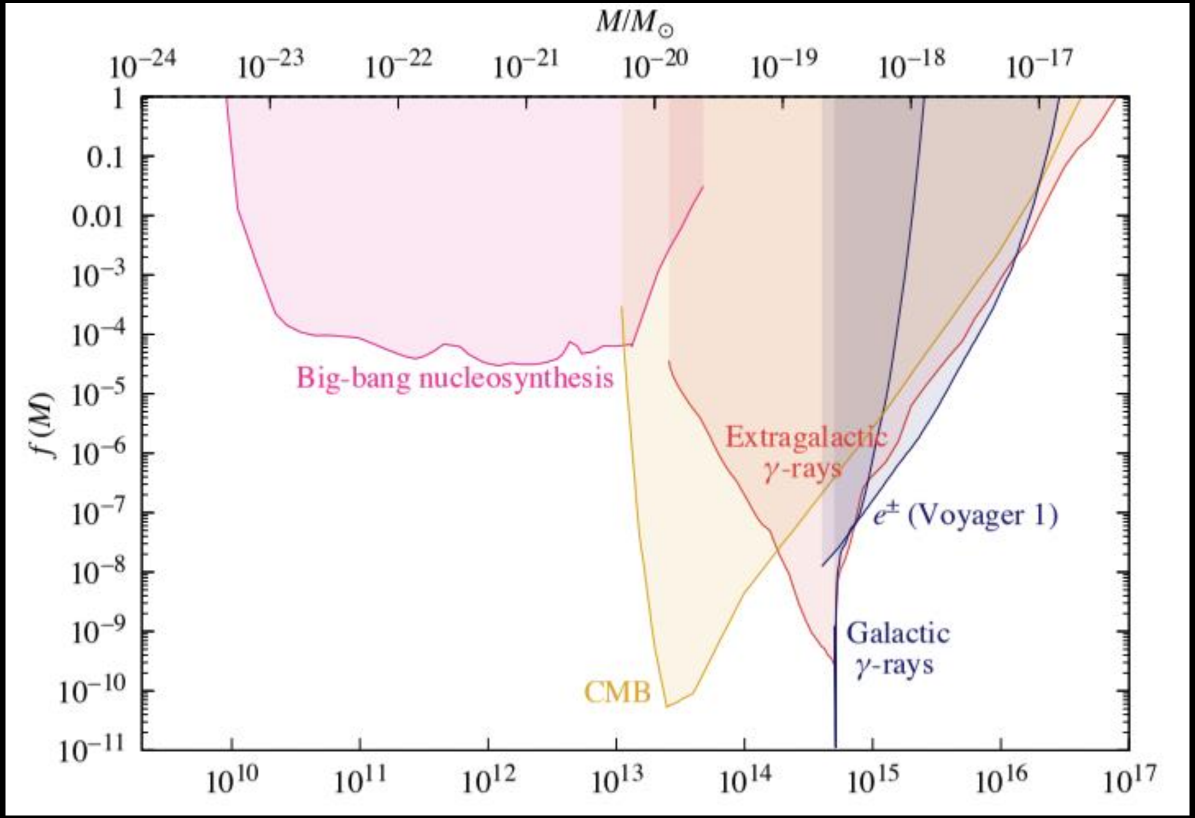
Analytical results from relativistic fluid hydrodynamics?

PBHs as DM

PBHs in the asteroid mass range could constitute all of the relic density of DM



PBHs as DM



Low mass end of this range is constrained by the non-observation of extragalactic gamma rays

Current constraints do not account for hot spots

Gamma rays in hot spots

$$P(r) = e^{-\int_0^r \Gamma_X(r')dr'}$$

Non zero probability for a gamma ray to scatter in the hot spot → Primary signal attenuation

$$T(r,t)$$ → How does this look in matter/DE dominated eras?

Gamma rays from hot spots

Hot spot processes may produce additional gamma rays → Secondary signal?

$$T_{\text{core}}^{\text{max}} \approx 2 \times 10^9 \,\text{GeV}$$

Maximum temperature – billions of GeV – is independent of the initial mass

But only if semiclassical evaporation valid after Page time

Conclusions

PBHs heat their local environments and form hot spots

Hot spots form soon after evaporation begins and may reach extreme temperature gradients

When DM is produced entirely or partially by PBHs, the final distribution in the universe would be non homogeneous

Hot spots may attenuate gamma ray signals from evaporating PBHs and produce secondary signals

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