Probing hybrid scenarios with primordial black holes and particle dark matter

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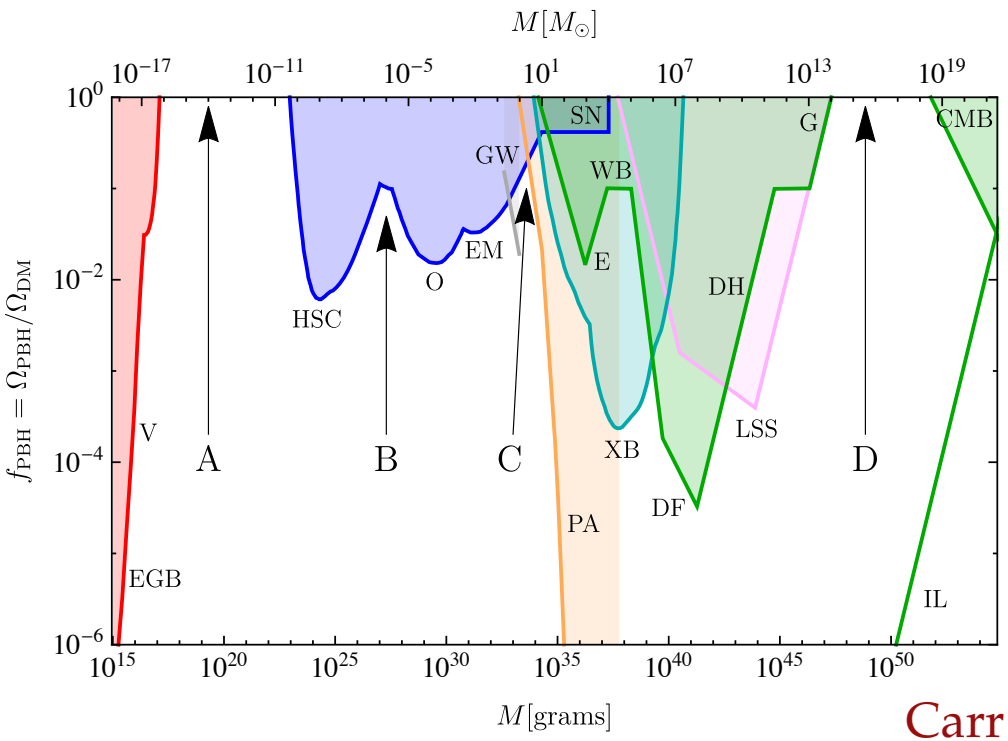
Introduction

- Renewed interest in primordial black holes (PBHs) as DM candidates with LIGO/Virgo detections of BH mergers
- Significant constraints on PBH fraction $f = \Omega_{\rm PBH}/\Omega_{\rm DM}$
- A few open mass windows (if monochromatic mass function)
- Complicated picture for more realistic assumptions



Carr & Kühnel 2020

$\rightarrow$ Hybrid DM models with PBHs + (annihilating) particles?

$\hookrightarrow$ WIMPs but not necessarily

Hybrid scenarios: formation of mini-halos of particle DM around PBHs

WIMPs + PBHs in the literature

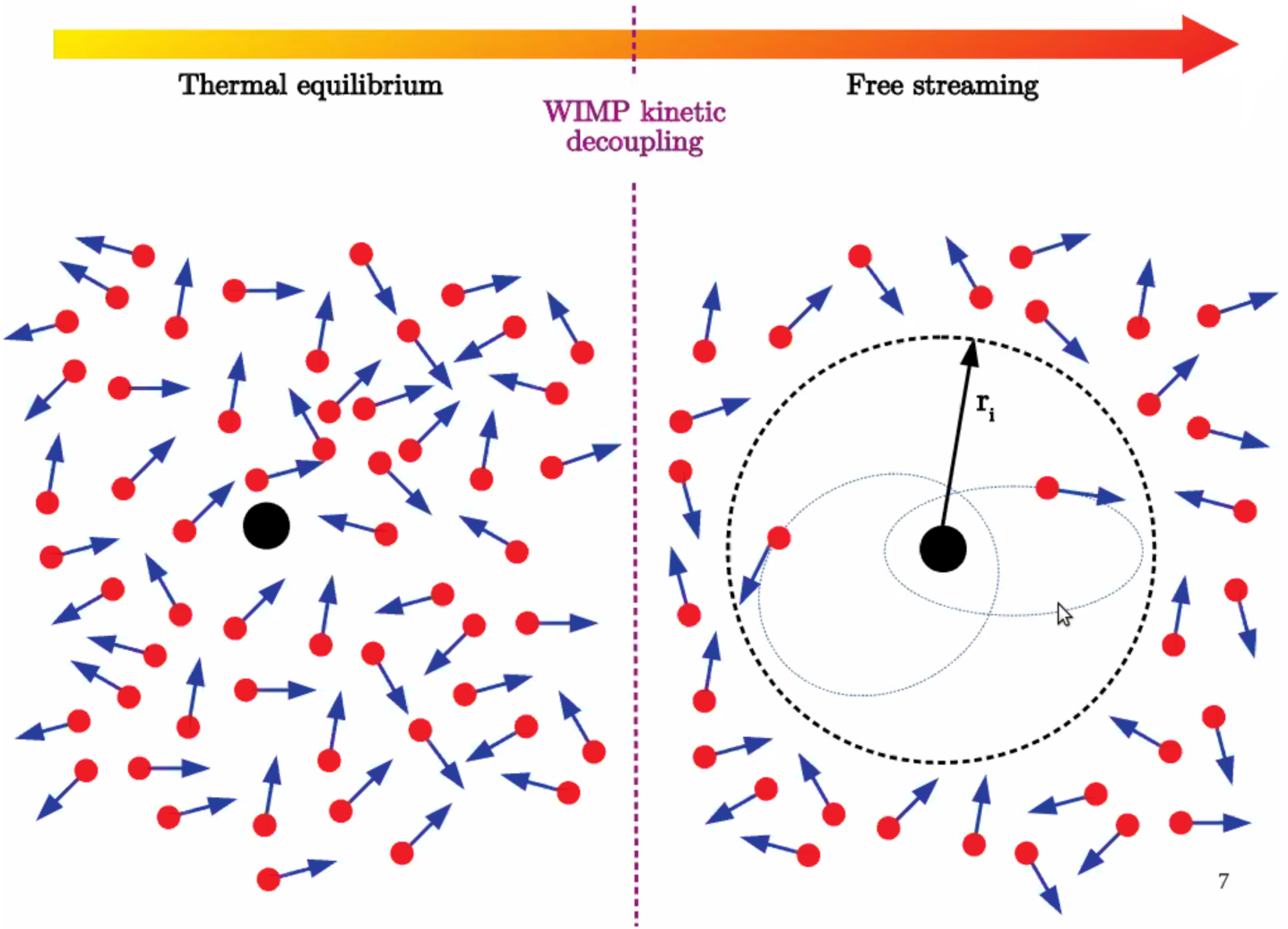
- Simple models for formation of mini-halos in the early Universe
  Mack+ 2007, Ricotti+ 2009, Lacki+ 2010, Saito+ 2010, Dong+ 2011
- Very concentrated objects (mini-spikes), $\rho \propto r^{-\gamma}$ with $\gamma \geq 3/2$
  $\Rightarrow$ strong γ-ray constraints from WIMP annihilation
- Effect of orbits of DM particles around the PBH (Eroshenko 2016)
- PBHs and WIMPs: "all or nothing" (Boucenna+ 16, Carr+ 2020)

This work

- In-depth study of formation process and dependence of profiles on PBH and particle DM parameters
- Reduce theoretical uncertainties
- Go beyond WIMPs: lighter DM candidates, smaller annihilation cross sections than $3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ $\rightarrow$ new constraints
- Use Galactic cosmic rays (CRs) in addition to γ-rays

Kinetic decoupling of DM particles and radius of influence of a PBH

$$\chi + \mathrm{SM} \longrightarrow \chi + \mathrm{SM}$$



Courtesy from M. Stref

Setting up the DM profile

Radius of influence of the BH

Decoupling from the Hubble flow: $\ddot{r} = -\dfrac{GM_{\rm BH}}{r^2} + \dfrac{\ddot{a}}{a} r = 0$

Equivalently: $M_{\rm BH} \approx \dfrac{4\pi}{3}\, r_{\rm infl}^3\, \rho_{\rm rad} \qquad (c = 1)$

$\Rightarrow$ Turnaround radius $r_{\rm infl}(t) \approx (2GM_{\rm BH}t^2)^{1/3}$

Onion-shell mini-spike profile

- Below $r_{\rm kd}$: all DM particles fall at same time $t_{\rm kd}$
- Above $r_{\rm kd}$: infall after kinetic decoupling and before matter-radiation equality
- Building the profile: $r_{\rm i} \equiv r_{\rm infl}(t_{\rm i})$

$$\rho_{\rm i} \equiv \rho_{\rm dm}(a_{\rm i}) \propto a_{\rm i}^{-3}, \quad a_{\rm i} \propto \rho_{\rm rad}^{-1/4} \quad \text{and} \quad \rho_{\rm rad} \propto r_{\rm i}^{-3}$$

$$\rho_{\rm i}(r_{\rm i}) \approx \begin{cases} \rho_{\rm i}^{\rm kd} \equiv \rho_{\rm dm}(t_{\rm kd}) & \text{if } r_{\rm i} \le r_{\rm kd}\,, \\ \rho_{\rm i}^{\rm kd}\,(r_{\rm i}/r_{\rm kd})^{-9/4} & \text{if } r_{\rm kd} \le r_{\rm i} \le r_{\rm eq} \end{cases}$$

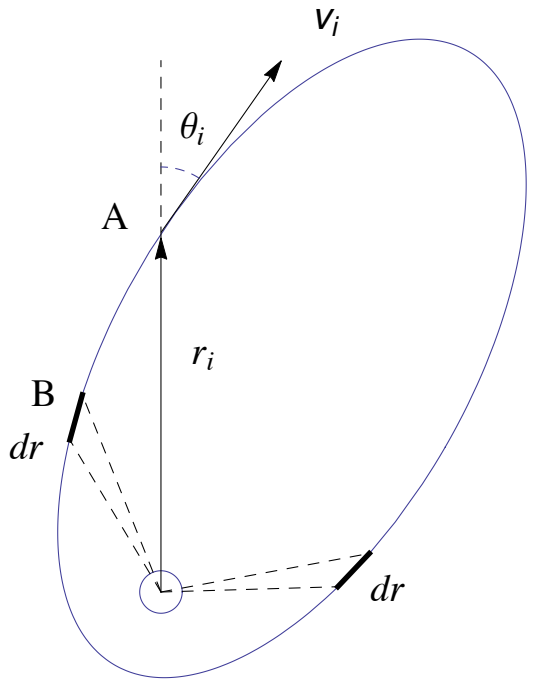
Free streaming and reshaping of the mini-spike profile

Final profile from particle orbits

- Redistribution from time spent at a given radius r

$$4\pi r^2 \rho_\chi(r)\,\mathrm{d}r = \int \mathrm{d}r_\mathrm{i}\, 4\pi r_\mathrm{i}^2 \rho_\mathrm{i}(r_\mathrm{i}) \times \int \mathrm{d}^3\vec{v}_\mathrm{i} f(\vec{v}_\mathrm{i}) \frac{2\mathrm{d}t/\mathrm{d}r}{T_\mathrm{orb}}\,\mathrm{d}r$$

- Strong dependence on initial velocity dispersion σ_i of DM particles

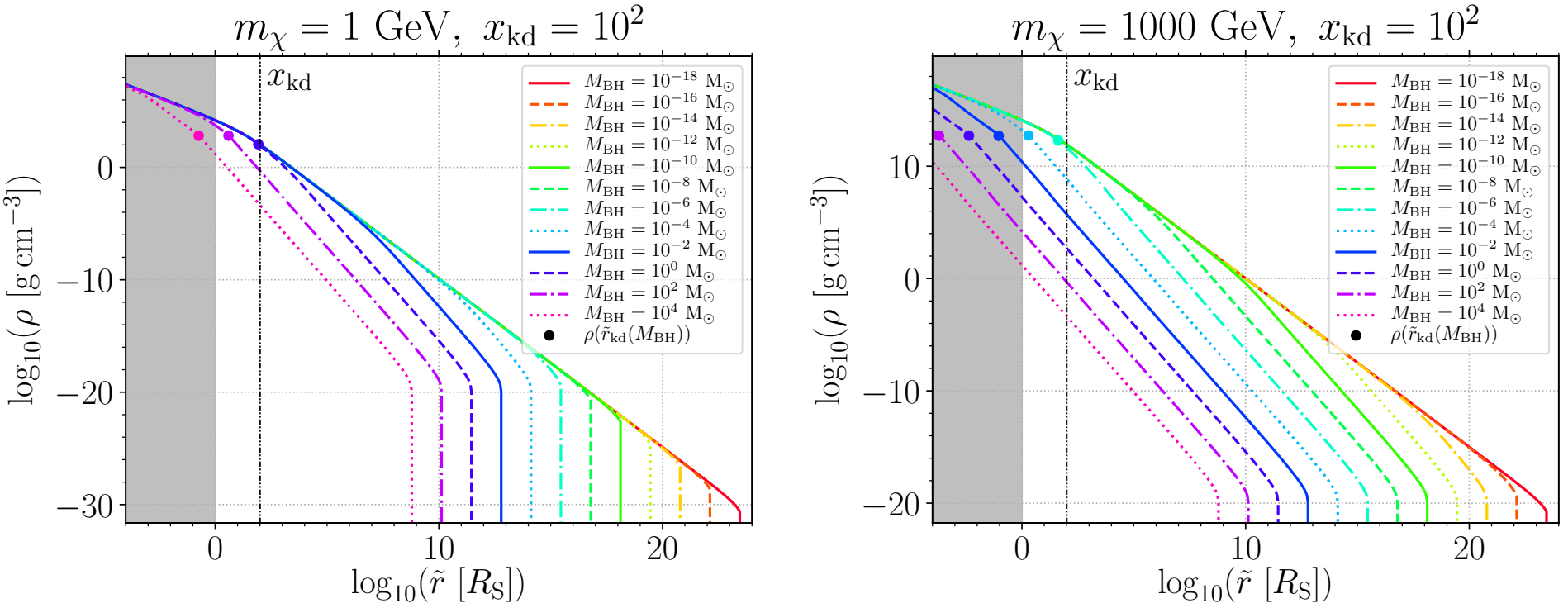


Eroshenko 2016

Wrong assumption in some previous studies

r corresponds to pericenter or apocenter of the orbit
$\Rightarrow$ cuts off significant portion of parameter space
$\Rightarrow$ underestimated profile for large BH masses

Mini-spike profiles



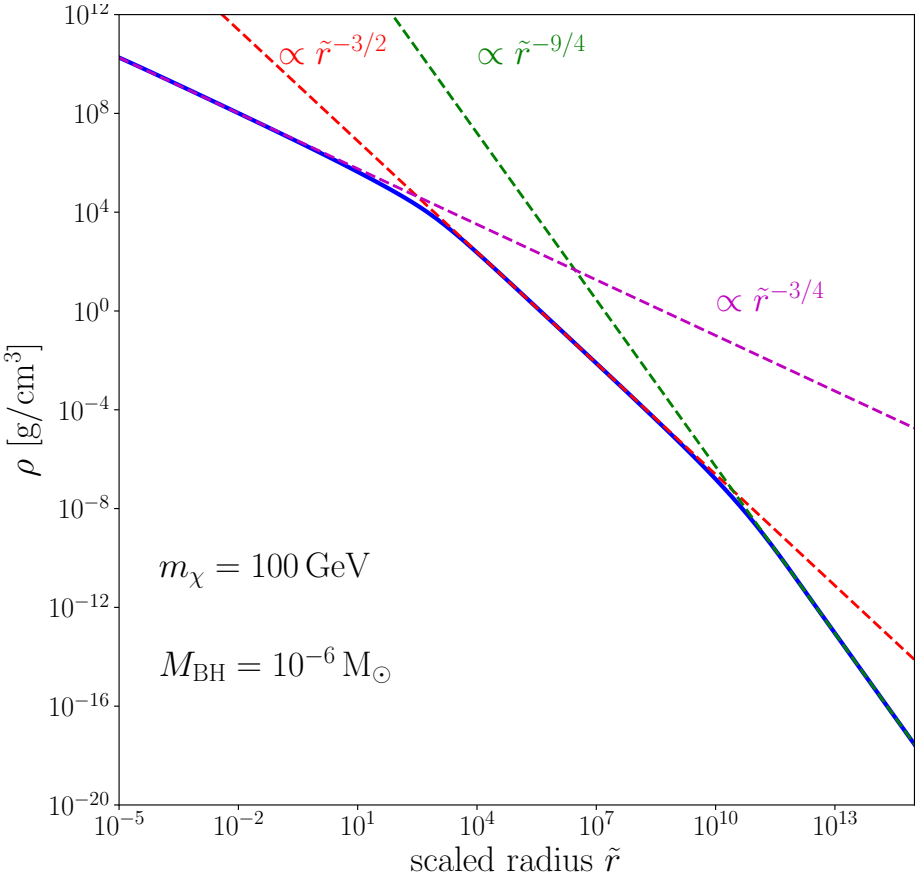
Boudaud+ 2021a, in prep.

- Slope $-3/2$ for light BHs, $-9/4$ for heavy BHs and both in intermediate regime + slope $-3/4$ at the center
- More complex behavior than simple power laws
- Strong dependence on $M_{\rm BH}$, m_χ and $x_{\rm kd} \equiv m_\chi / T_{\rm kd}$
- Truncation for annihilating DM

Physical origin of the various slopes

Qualitative explanations

- $-9/4$: Very small initial velocity dispersion of DM particles
  $\Rightarrow$ radial orbits
- $-3/2$: Related to the fraction of DM particles above escape speed
- $-3/4$: Connected to direction of initial velocity



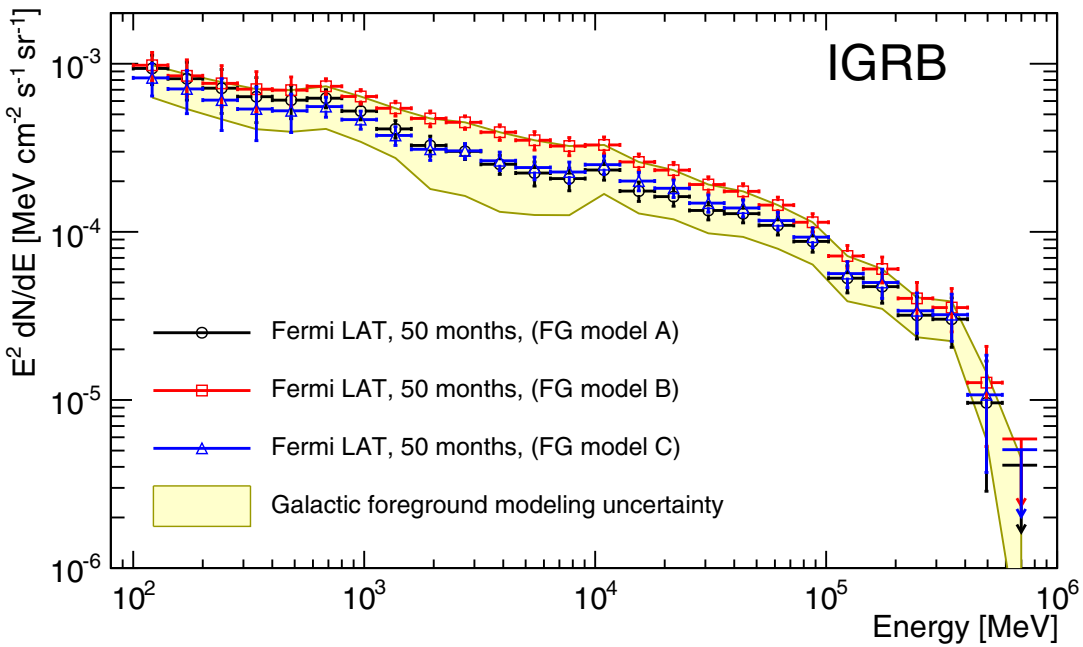
Boudaud+ 2021a, in prep.

Constraints from isotropic γ-ray background (IGRB)

DM-induced extragalactic γ-ray flux

$$\left.\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E}\right|_{\mathrm{ex}} = \frac{f(1-f)^2\Gamma_{\mathrm{BH}}}{M_{\mathrm{BH}}}\,\rho_{\mathrm{dm}}\int_0^\infty \mathrm{d}z\,\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}\,\frac{\mathrm{e}^{-\tau_{\mathrm{opt}}(z)}}{H(z)}$$

$\Gamma_{\mathrm{BH}} = \dfrac{\langle\sigma v\rangle}{2m_\chi^2}\int 4\pi r^2\rho_\chi^2(r)\,\mathrm{d}r$ annihilation rate per mini-spike



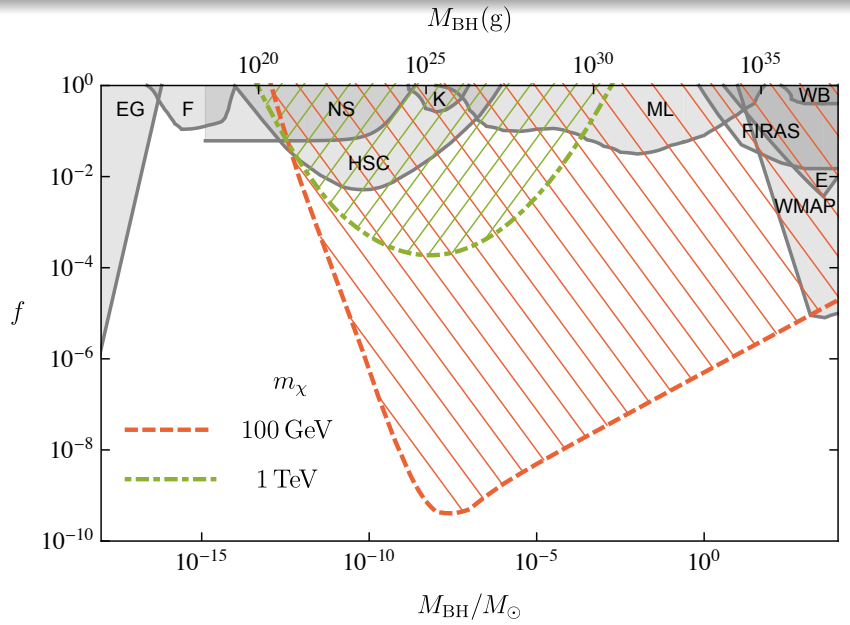
Ackermann+ 2015

Equivalent to DM particle decays with

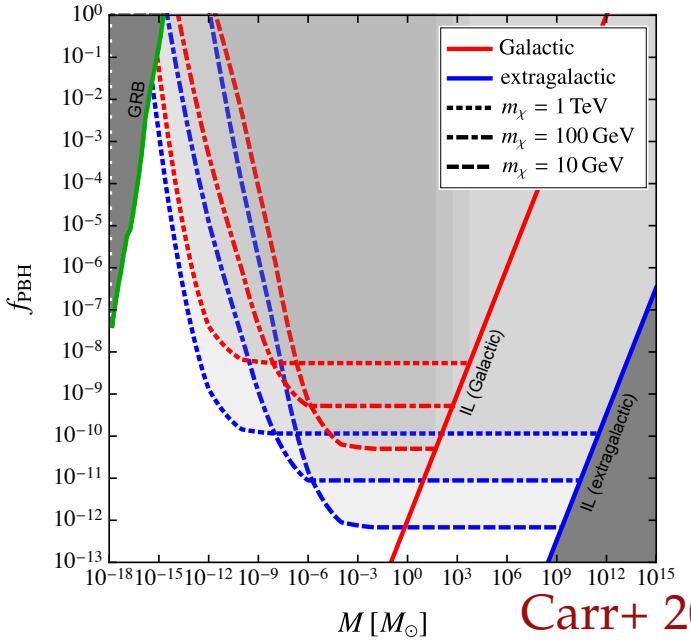
$$\frac{f(1-f)^2\Gamma_{\mathrm{BH}}}{M_{\mathrm{BH}}} = \frac{\Gamma_{\mathrm{decay}}}{m_\chi}$$

Boucenna+ 16

Limits on PBH fraction assuming the WIMP scenario from IGRB and CRs

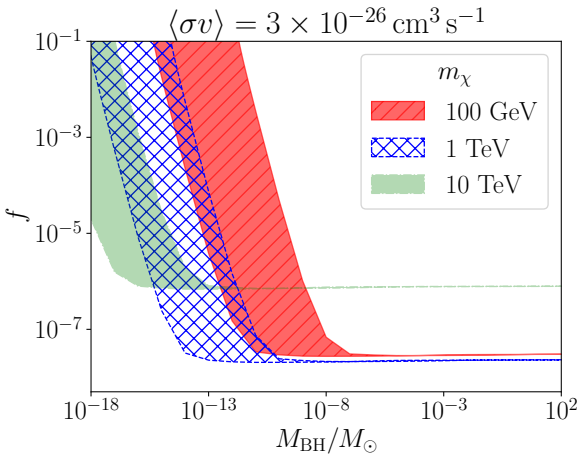


Boucenna+ 2016

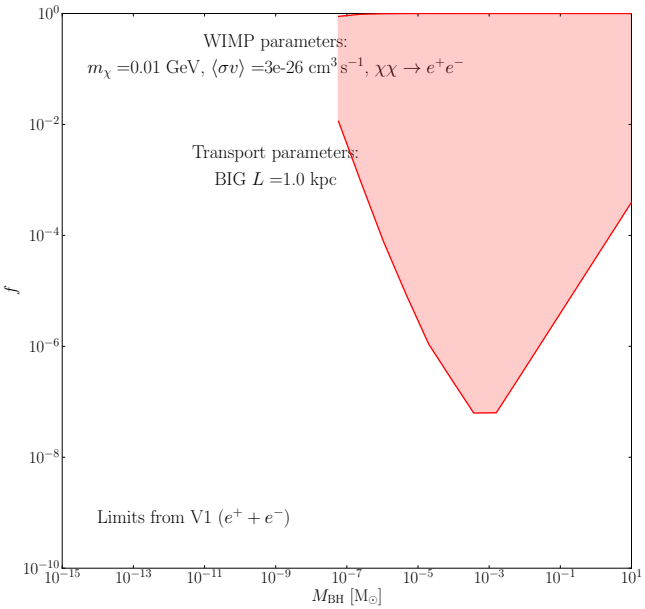


Carr+ 2020

- $f = \Omega_{\rm PBH}/\Omega_{\rm DM} \ll 1$ for WIMPs with $\langle\sigma v\rangle \sim 3\times10^{-26}\,{\rm cm^3\,s^{-1}}$
- Converse: $f_{\rm WIMP} \ll 1$ if $f \sim 1$
- Work in progress on theoretical uncertainties



Boudaud+ 2021b, in prep

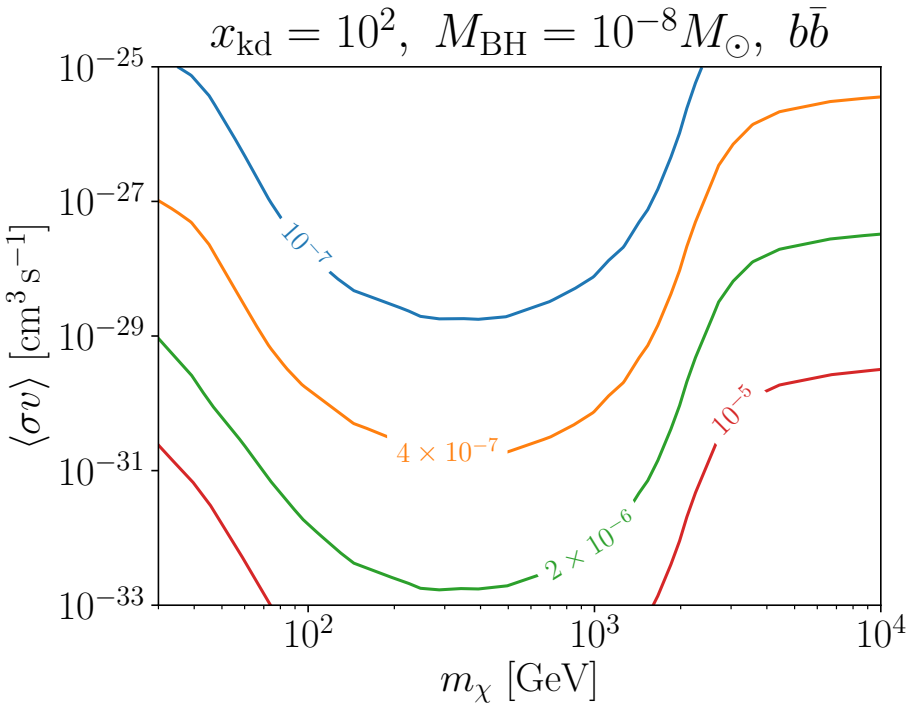


New probe of annihilating DM beyond WIMPs

Constraining annihilation cross section for given PBH fraction
$\Rightarrow$ probe very weakly annihilating DM

New probe for WIMP-like candidates

- Isotropic diffuse γ-ray background (*Fermi*-LAT)
- Very strong constraints on s-wave even for $f = \Omega_{\rm PBH}/\Omega_{\rm DM} \ll 1$
- Good prospects for p-wave suppressed annihilation



Boudaud+2021b, in prep.

Connection with concrete PBH models?

Conclusion

Particle DM mini-spikes around PBHs

- More complex density profiles than simple power laws
- Fully driven by properties of PBHs and DM particles
- Comparison with simulations?
  Need to extend study on stellar mass range (Adamek+ 19) to other masses

Signatures

- Concrete model for PBH "dresses" (Kavanagh+ 2018)
  $\rightarrow$ GW signatures of mini-spike mergers?
  $\rightarrow$ Impact on CMB constraints?
- Go further than "all or nothing" conclusion with γ-rays/CRs
  $\rightarrow$ new probe of very weakly annihilating DM particles:
  p-wave? Feebly interacting massive particles (FIMPs)?
- Complementary constraints from Galactic CRs to probe lighter particle DM candidates

Thank you for your attention!