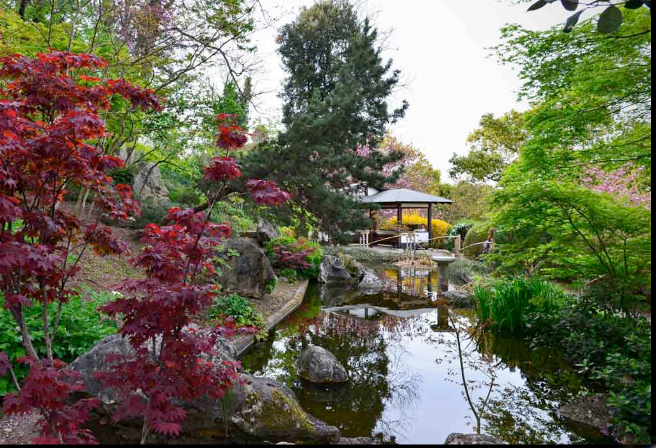
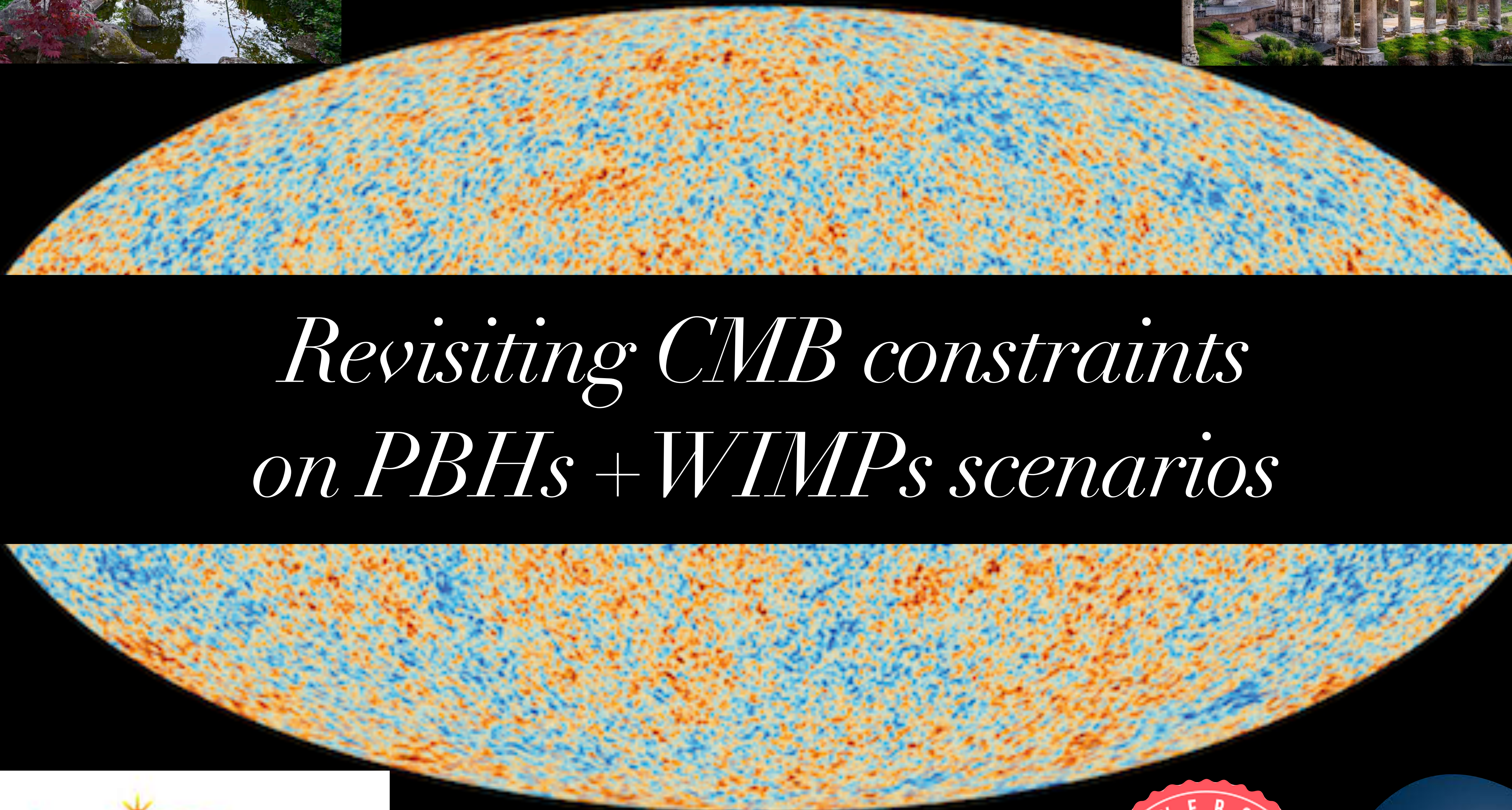


Future Perspectives on Primordial Black Holes

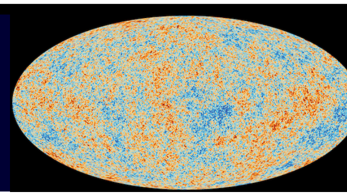


Revisiting CMB constraints on PBHs+WIMPs scenarios

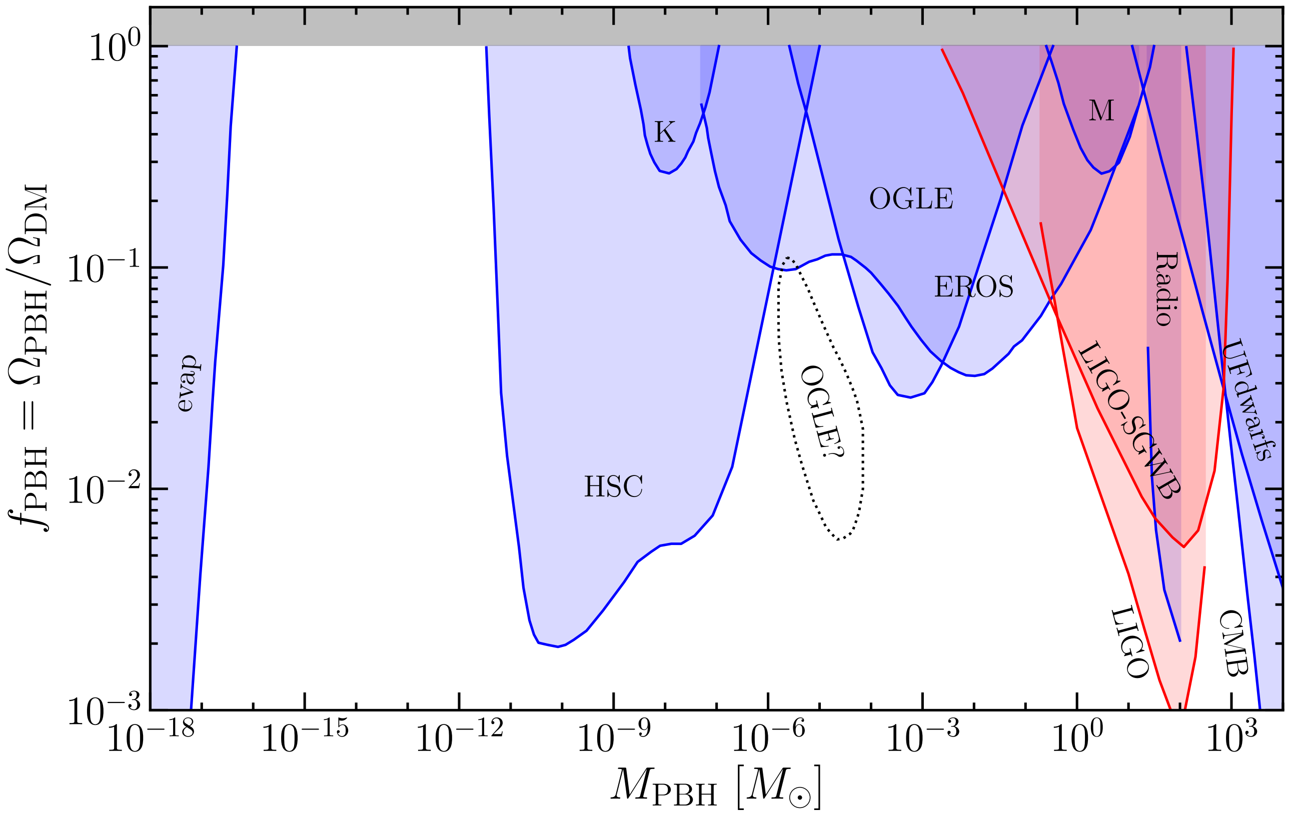
Francesca Scarcella

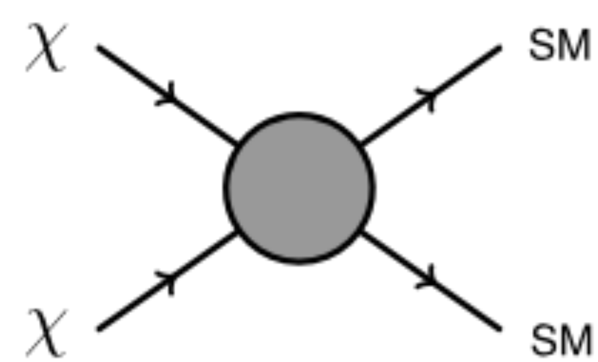
LABORATOIRE UNIVERS & PARTICULES MONTPELLIER

CMB bounds on PBHs + WIMPs

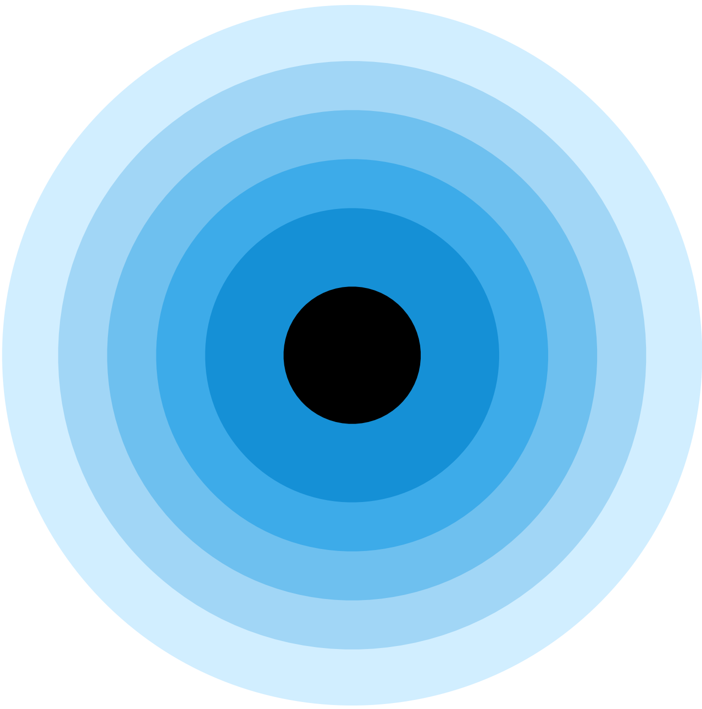


Credit: Bradley Kavanagh, https://github.com/bradkav/PBHbounds

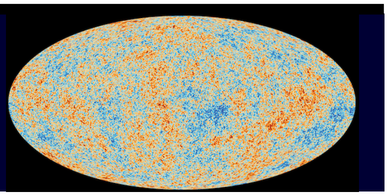




- Formation of WIMP over densities in the Early Universe → annihilation rate boosted

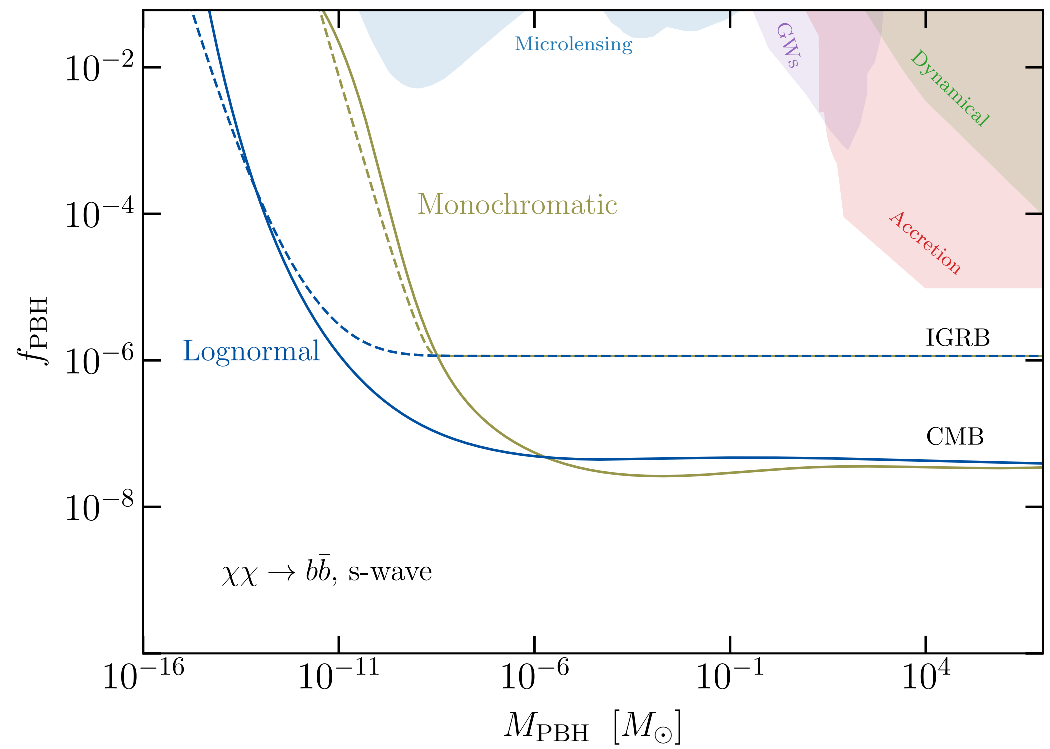


CMB bounds on PBHs + WIMPs



- Tashiro et al. 22104.09738
  9/4 spike profile

- Gines et al. 2207.09481:
  spike profile based on
  Carr et al. 2011.01930



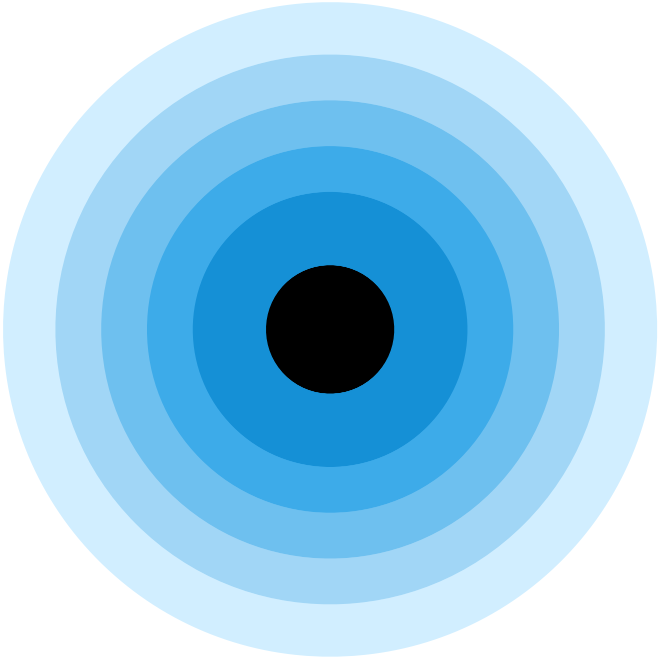
- This work (in progress) :
  spike profile based on
  Boudaud et al. 2106.07480

In collaboration with: Julien Lavalle, Pierre Salati, Vivian Poulin

Spike formation: initial profile

- Initial density

$$\rho(r) \simeq \rho(t_{\rm t.a.}(r))$$



$$\frac{\rho(r)}{\rho_0} \propto \left(\frac{a_{\rm t.a.}(r)}{a_0}\right)^3 \propto \left(\frac{r}{r_0}\right)^{9/4}$$

(radiation domination)

- Simple estimate

$$M_{\rm BH} = \frac{4\pi}{3} r^3 \rho_{\rm tot} \qquad \to r^3 \propto \rho_{\rm tot}^{-1} \propto a_{\rm t.a.}^4 \qquad \to a_{\rm t.a.} \propto r^{3/4}$$

- More "refined" calculation

$$\ddot{r} = \frac{\ddot{a}}{a} r - \frac{GM_{\rm BH}}{r^2} \qquad \to r^3(t_{\rm t.a.}) \simeq 2GM_{\rm BH} t_{\rm t.a.}^2 \propto a_{\rm t.a.}^4$$

WIMPs in the BH potential

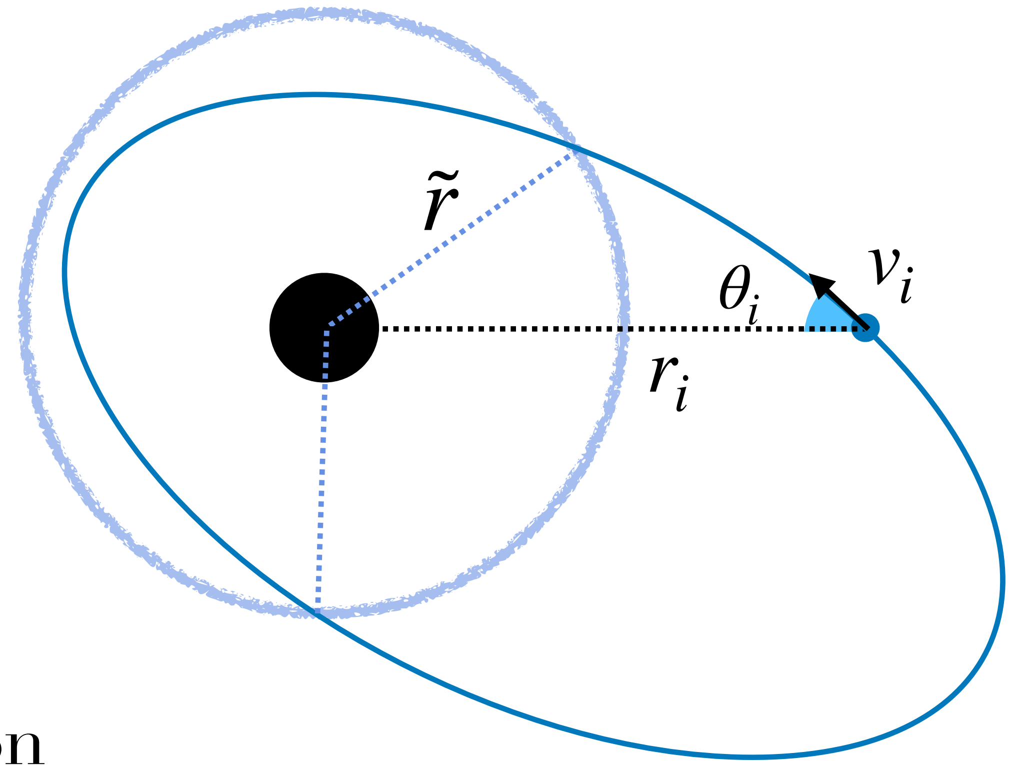
Eroshenko 1607.00612

- Non relativistic
- BH potential dominates (neglect particle-particle interaction)

$$\delta\rho(r) = \frac{m_\chi P(r\,|\,r_i, v_i, \theta_i)dr}{4\pi r^2 \mathrm{d}r}$$

$$\rho(r) = \int \mathrm{d}r_i \mathrm{d}v_i \mathrm{d}\theta_i \, P(r_i)P(v_i)P(\theta_i)\,\delta\rho(r)$$

$$P(r\,|\,r_i, v_i, \theta_i)\,\mathrm{d}r = \frac{2\,\mathrm{d}t}{T} = \frac{2}{T}\frac{1}{v_r}\mathrm{d}r$$

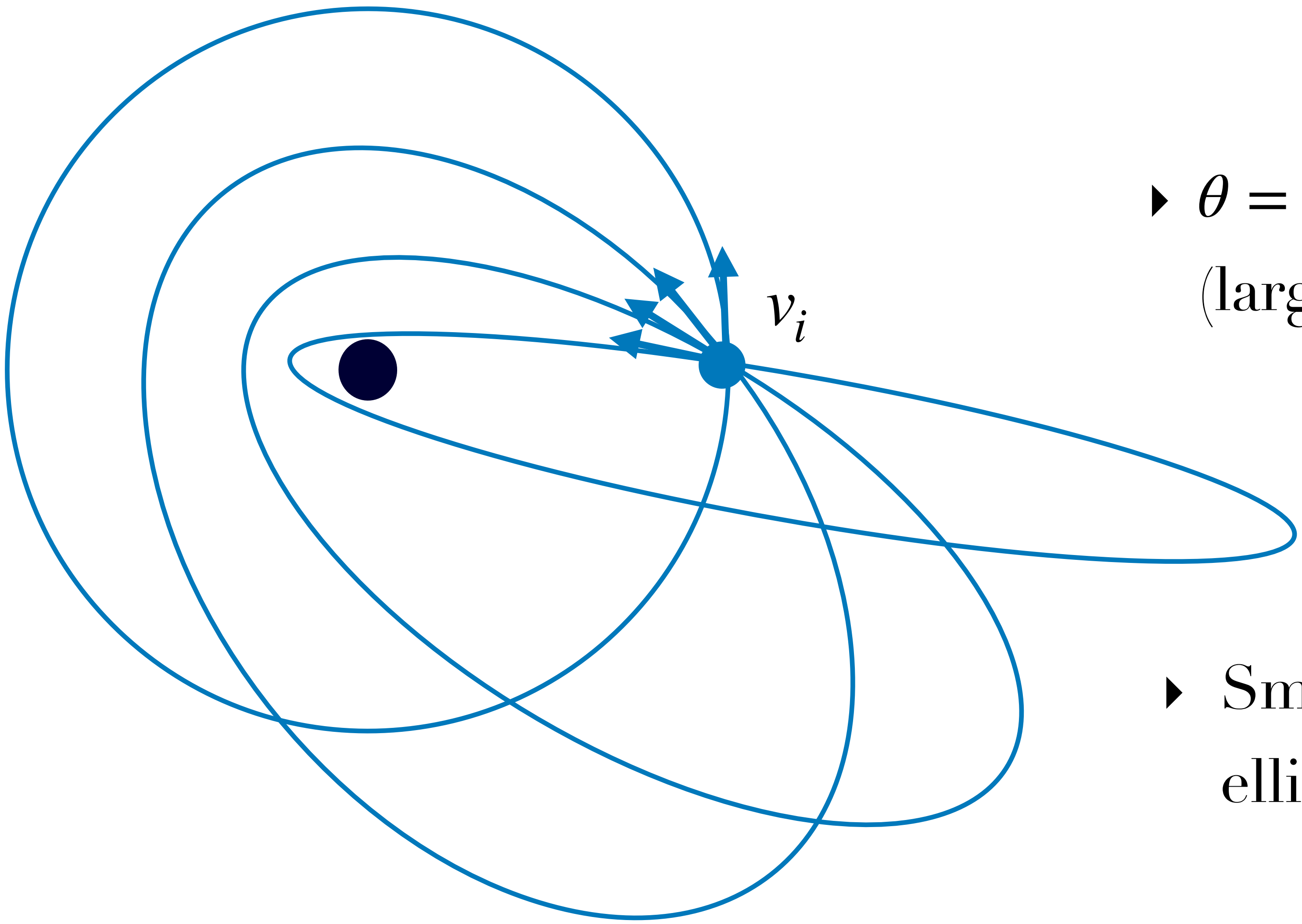


- Energy and angular momentum conservation

$$\begin{cases} J = m r_i v_i \sin\theta_i & \rightarrow v_r(r_i, v_i, \theta_i) \\ E = \dfrac{1}{2} m v_i^2 - \dfrac{G m M_{\mathrm{BH}}}{r_i} & \rightarrow T(r_i, v_i) \end{cases}$$

When does a solution exist?

- Given r_i, v_i which angles θ_i correspond to orbits that pass through $\tilde{r}$?

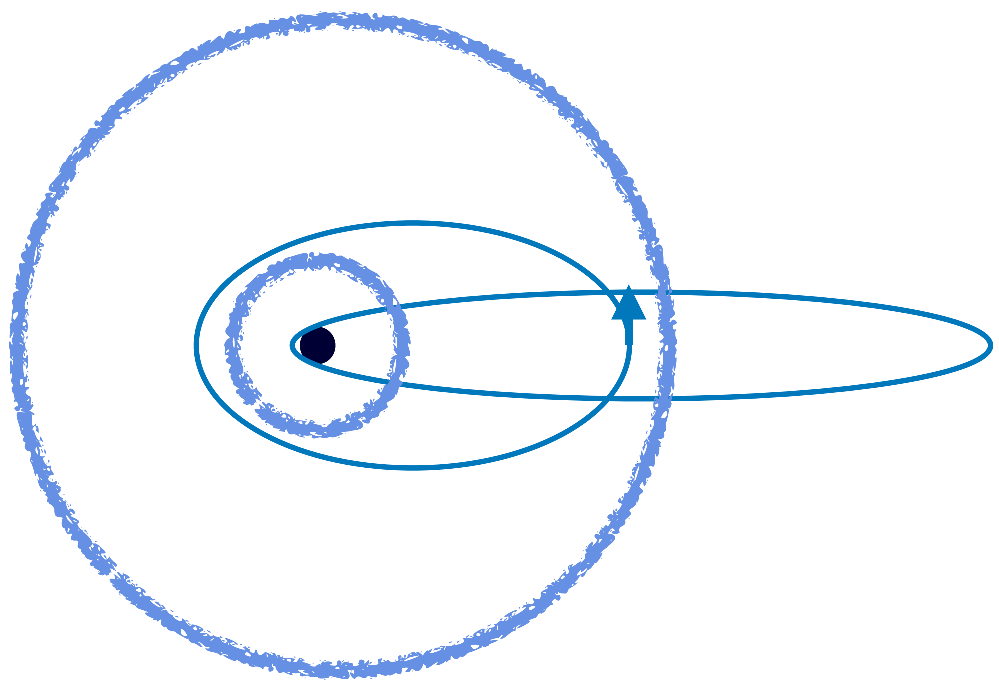


- $\theta = \pi/2 \rightarrow$ most circular orbit (largest L)

- Smaller angles $\rightarrow$ more ellipticity: smaller r_P, larger r_A

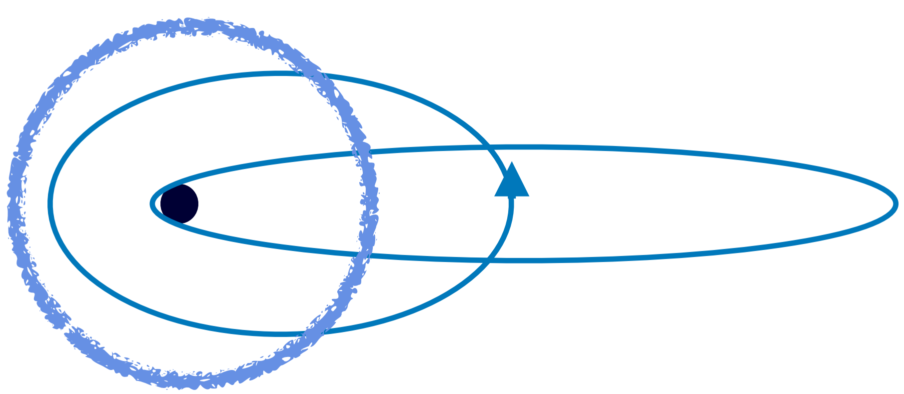
- Given r_i, v_i which angles θ_i correspond to orbits that pass through $\tilde{r}$?

- Case 1: θ_i^0 exists such that $v_r(\tilde{r}) = 0 \leftrightarrow \tilde{r} = r_P, r_A$



- Integrate over $0 \leq \theta_i \leq \theta_i^0$

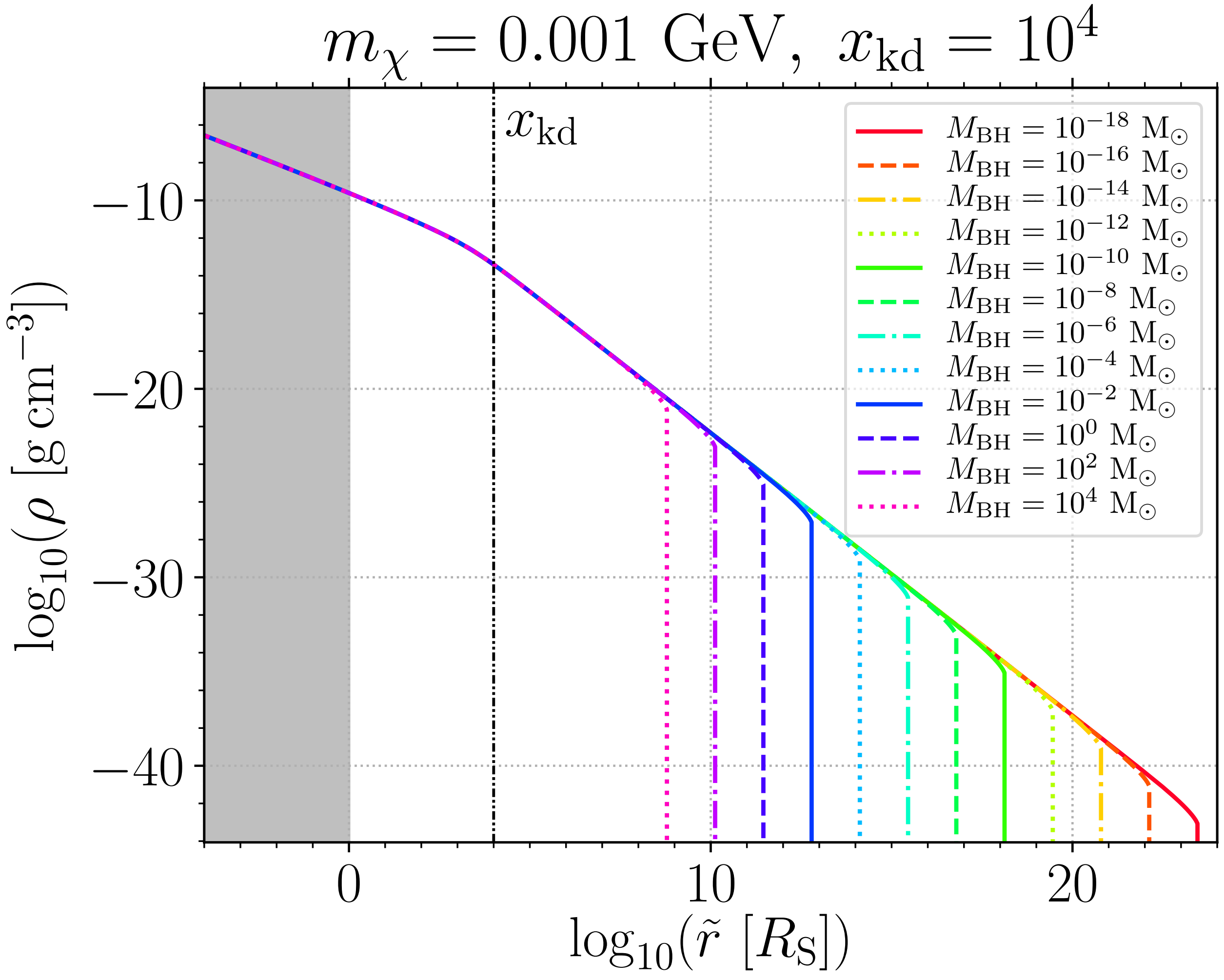
- Case 2: θ_i^0 does not exist

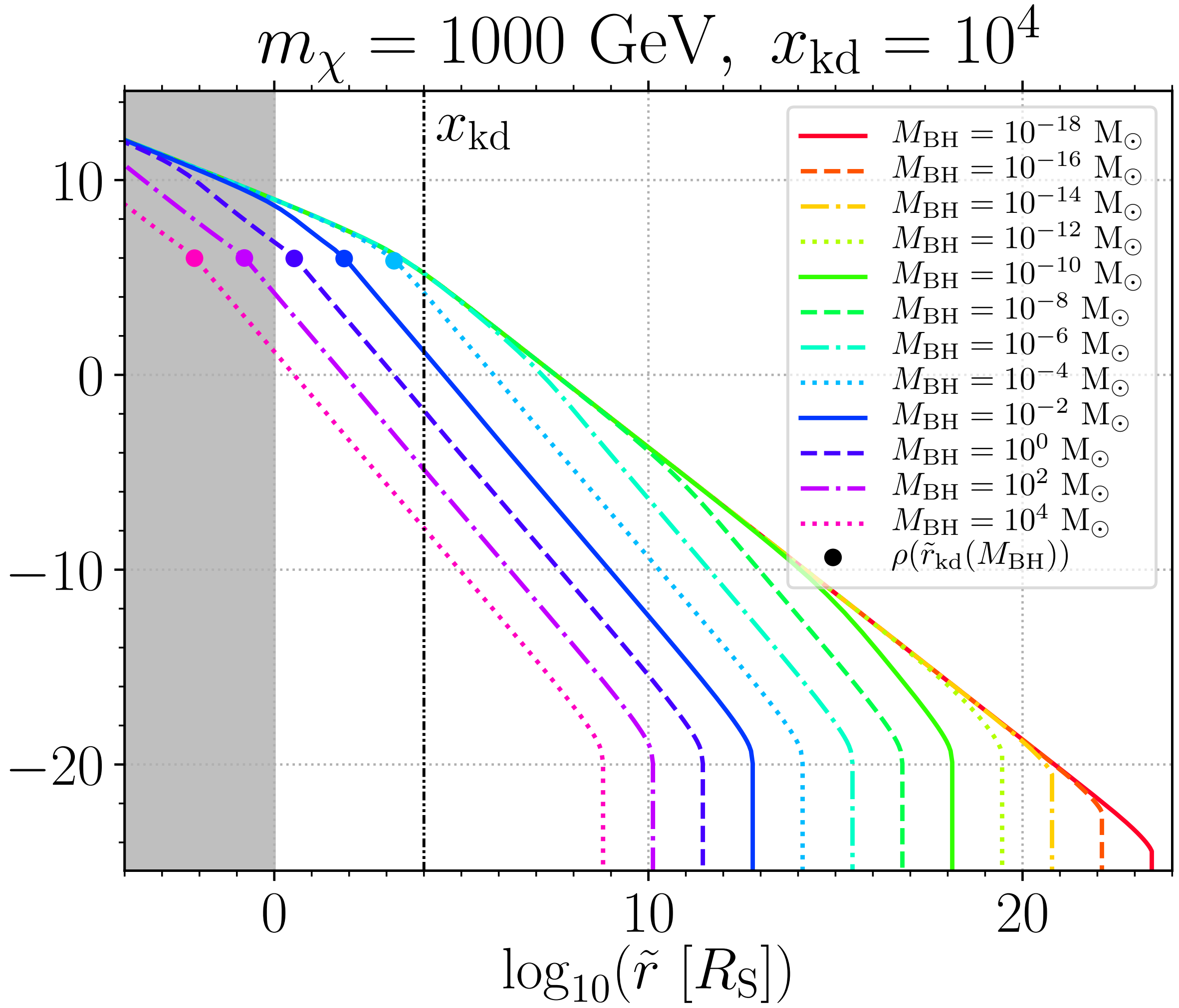


- Integrate over all values for θ_i

Spike profiles

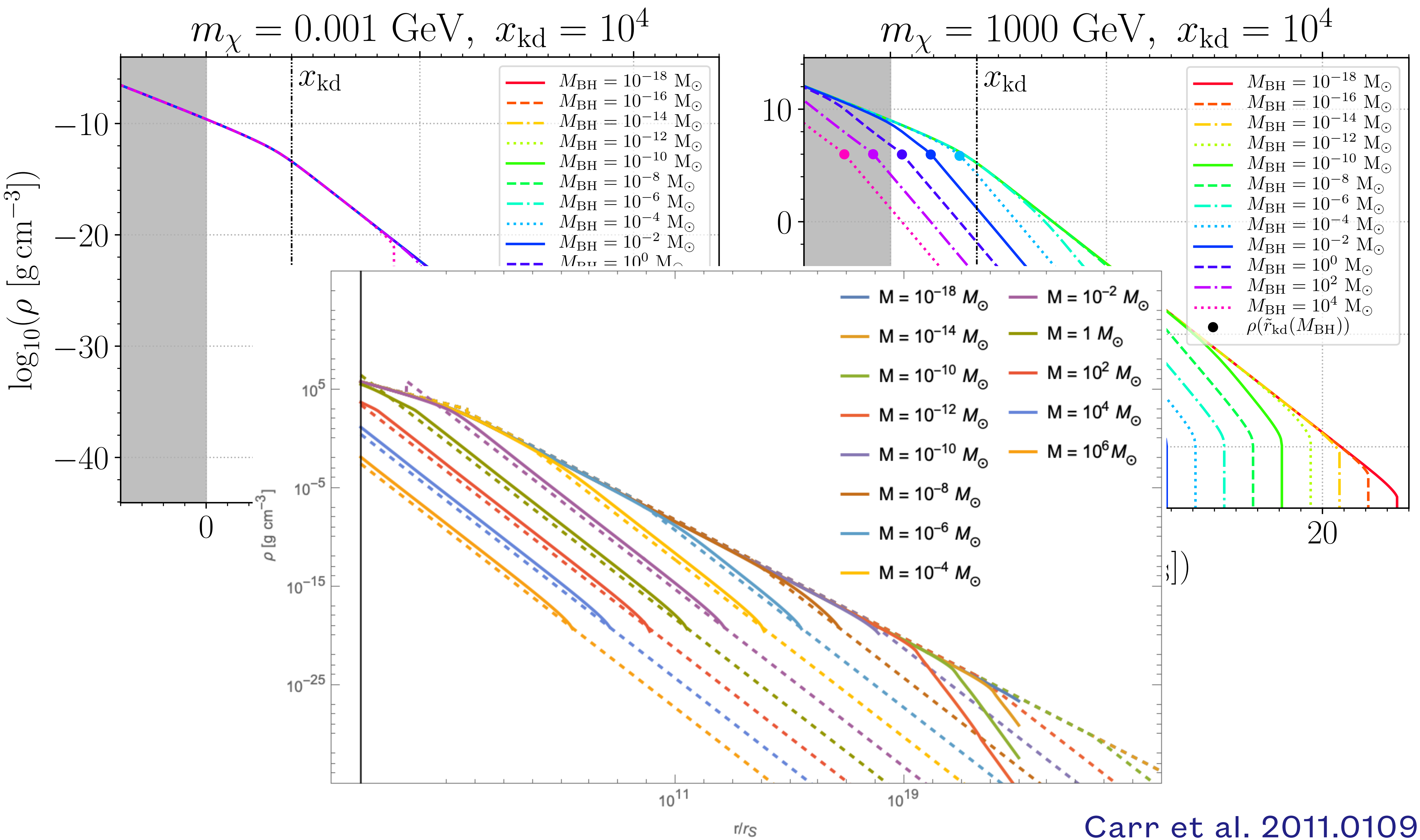
Boudaud et al. 2106.07480





Spike profiles

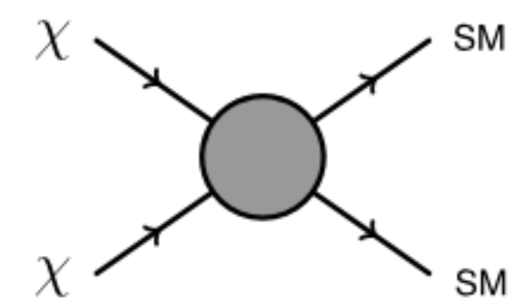
Boudaud et al. 2106.07480



Carr et al. 2011.010930
Gines et al. 2207.09481

Spike depletion: core formation

- DM annihilation leads to the formation of a flat core

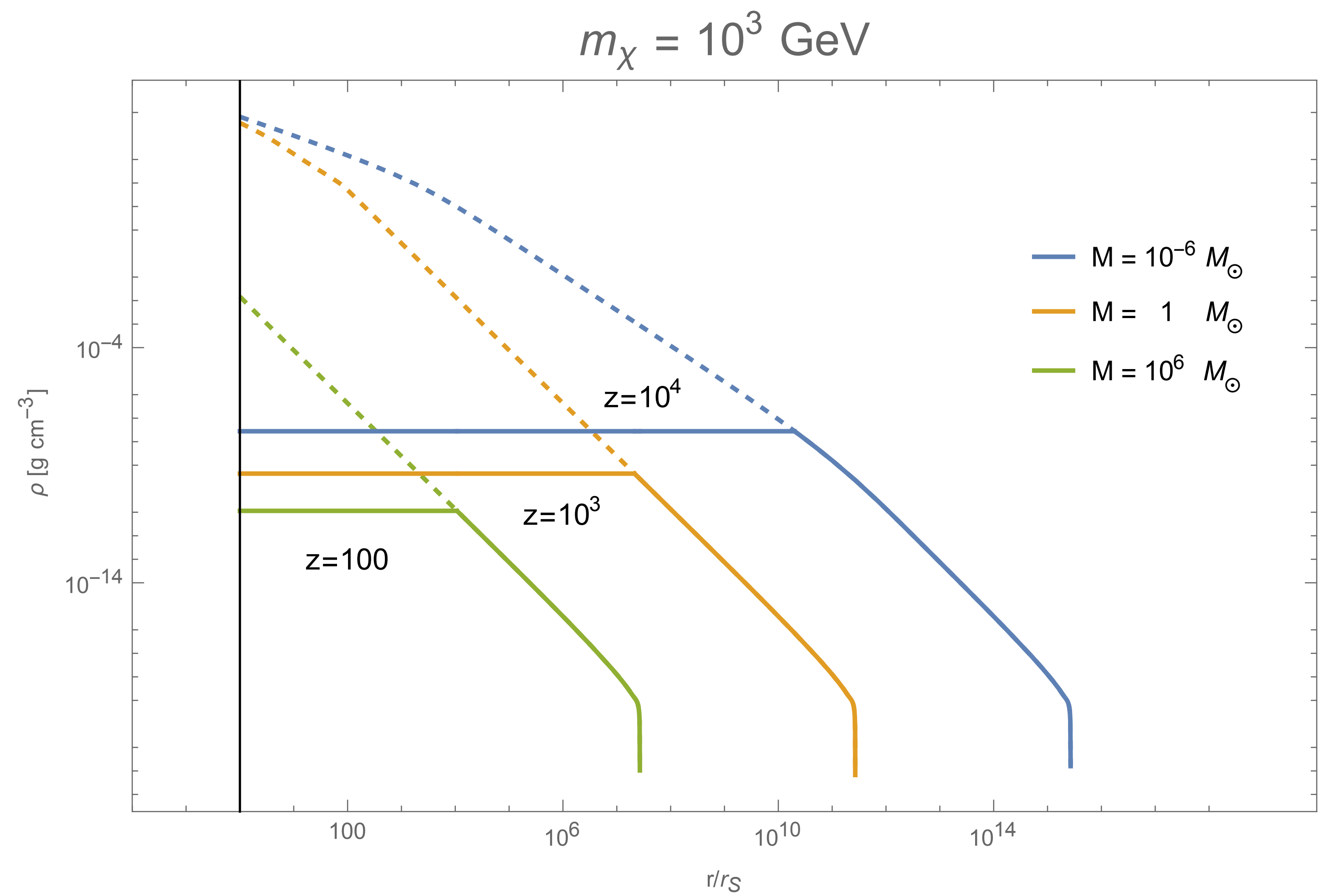


- Time scale of annihilation

$$t = \left(\left\{ n_\chi = \frac{\rho_\chi}{m_\chi} \right\} \langle \sigma v \rangle \right)^{-1}$$

- Time-dependent maximum density

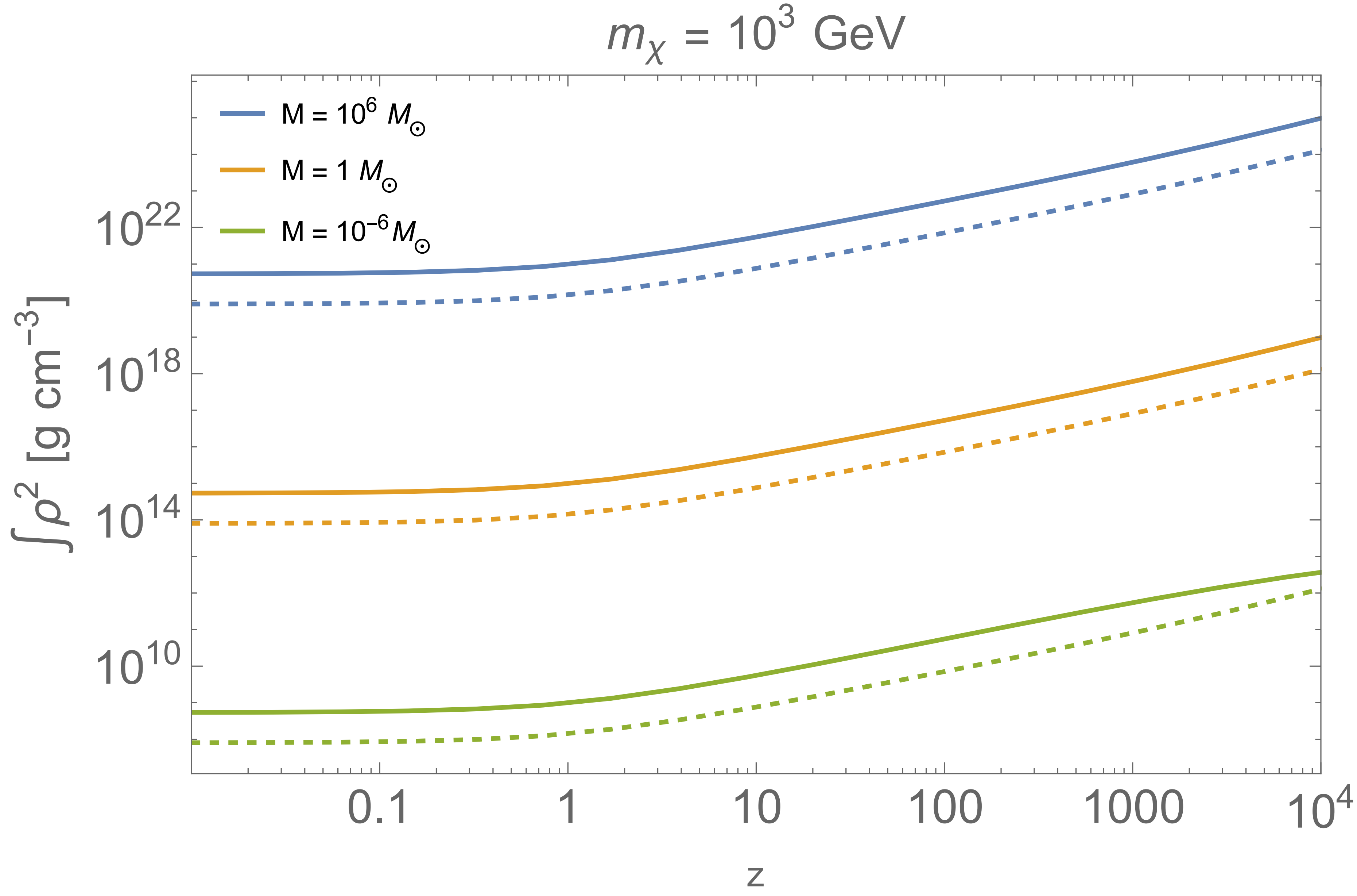
$$\rho_{\max} \simeq \frac{m_\chi}{\langle \sigma v \rangle \, t}$$



$$\langle \sigma v \rangle_{\rm th} = 3 \times 10^{-3} {\rm cm}^3 \, {\rm s}^{-1}$$

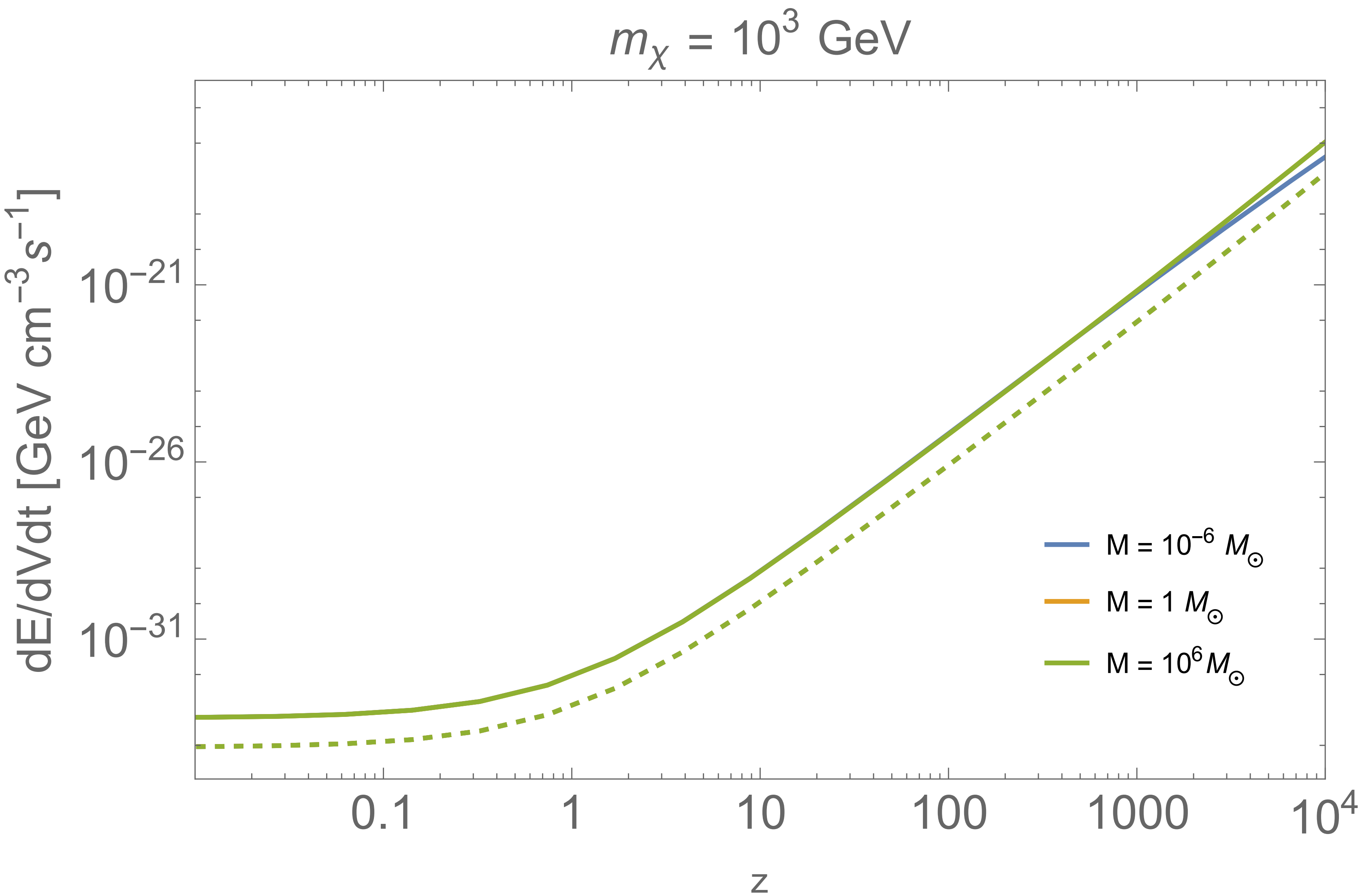
Energy injection rate

$$\left.\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t}\right|_{\mathrm{inj}} = n_{\mathrm{PBH}}\left\{\Gamma_{\mathrm{spike}} = \frac{1}{2}\int \mathrm{d}^3r\, n^2_{\mathrm{spike}}(r)\,\langle\sigma v\rangle\right\} \times 2m_\chi \quad = \quad \rho_{\mathrm{DM}}\frac{f_{\mathrm{PBH}}}{M_{\mathrm{PBH}}}\int \mathrm{d}^3r\,\rho^2_{\mathrm{spike}}(r) \times \frac{\langle\sigma v\rangle}{m_\chi}$$



Energy injection rate

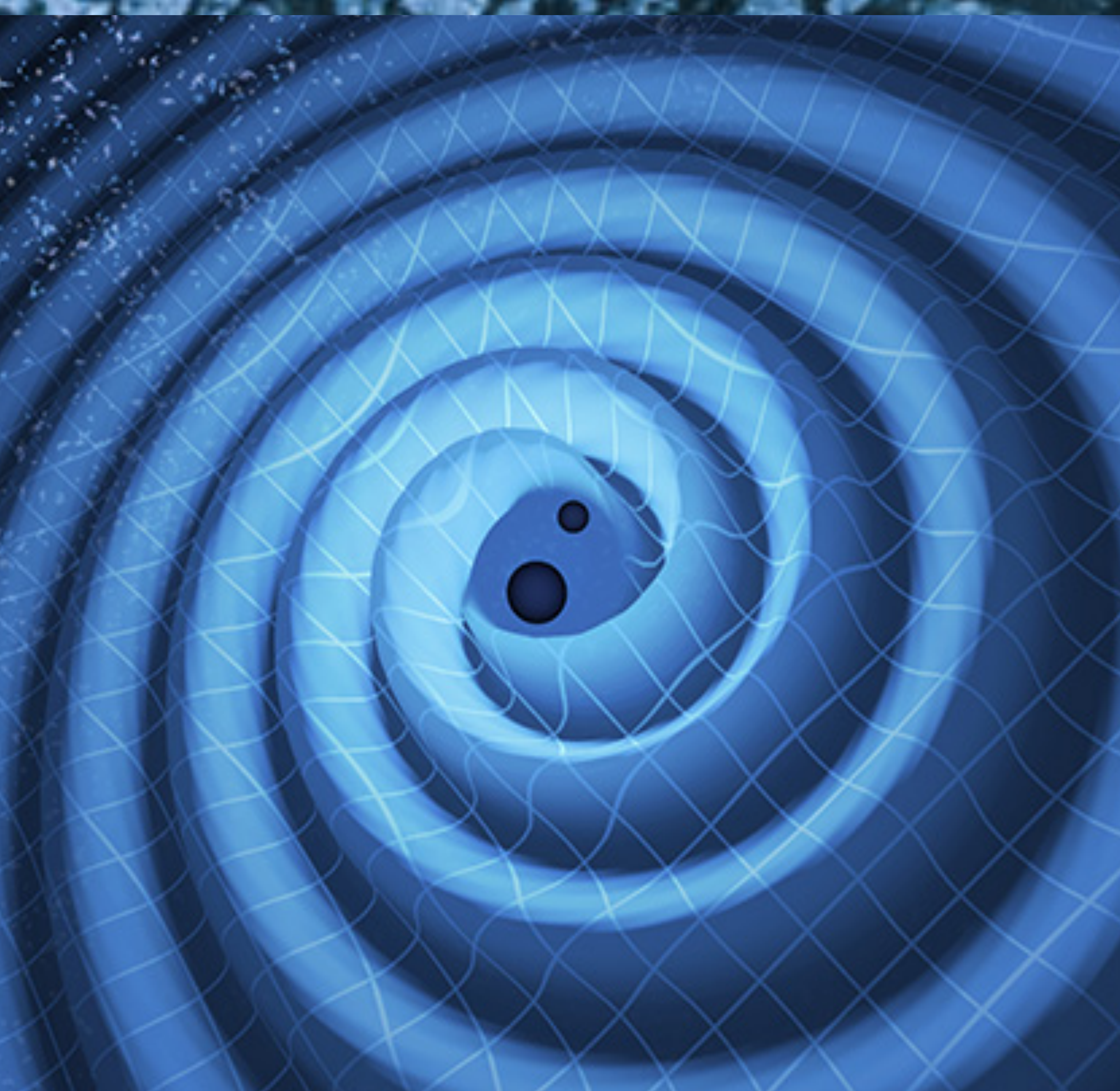
$$\left.\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t}\right|_{\mathrm{inj}} = n_{\mathrm{PBH}}\left\{\Gamma_{\mathrm{spike}} = \frac{1}{2}\int \mathrm{d}^3r\, n^2_{\mathrm{spike}}(r)\,\langle\sigma v\rangle\right\}\times 2m_\chi \quad = \quad \rho_{\mathrm{DM}}\frac{f_{\mathrm{PBH}}}{M_{\mathrm{PBH}}}\int \mathrm{d}^3r\,\rho^2_{\mathrm{spike}}(r)\,\times\frac{\langle\sigma v\rangle}{m_\chi}$$



Conclusions

- In progress: revisiting the bound on WIMPs+ PBHs based on a careful computation of spike density profile
- Preliminary results point to bound ~ order of magnitude stronger
- We expect the same to be true for constraints from $\gamma-$rays
- Full analysis soon!

Backup



Energy injection: z scaling

- For 9/4 slope

$$\int d^3r\, \rho^2_{\rm spike}(r) = \frac{4\pi}{3} r^3_{\rm core}\, \rho^2_{\rm max} K_\gamma \qquad r_{\rm core} \ll r_{\rm spike}: \quad K_\gamma \to 3$$

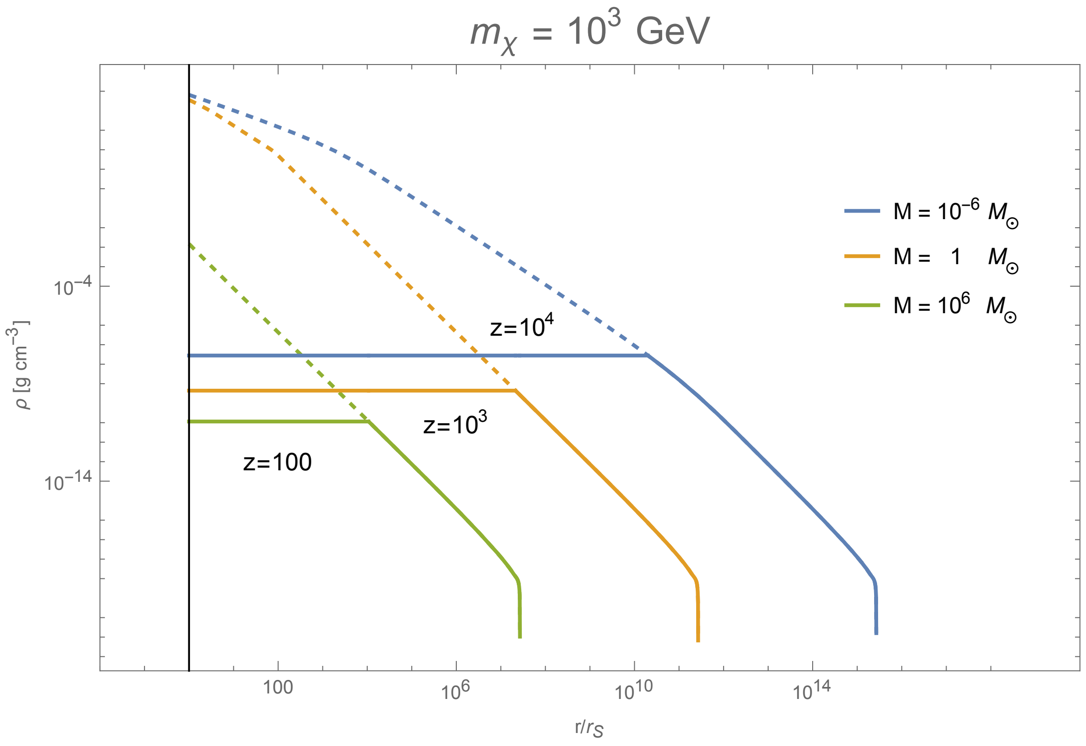
- For 9/4 slope, $r_{\rm core} \ll r_{\rm spike}$:

$$\left.\frac{dE}{dt\,dV}\right|_{\rm inj} = n_{\rm PBH} \times 4\pi r^3_{\rm core}\, \rho^2_{\rm max} \times \frac{\langle \sigma v \rangle}{m_\chi}$$

$$\rho_{\rm max} \simeq \frac{m_\chi}{\langle \sigma v \rangle\, t} \propto (1+z)^3$$

$$r^3_{\rm core} \propto (1+z)^{-2} \qquad \rightarrow \left.\frac{dE}{dt}\right|_{\rm inj} \propto (1+z)^4$$

$$n_{\rm PBH} \propto (1+z)^3$$



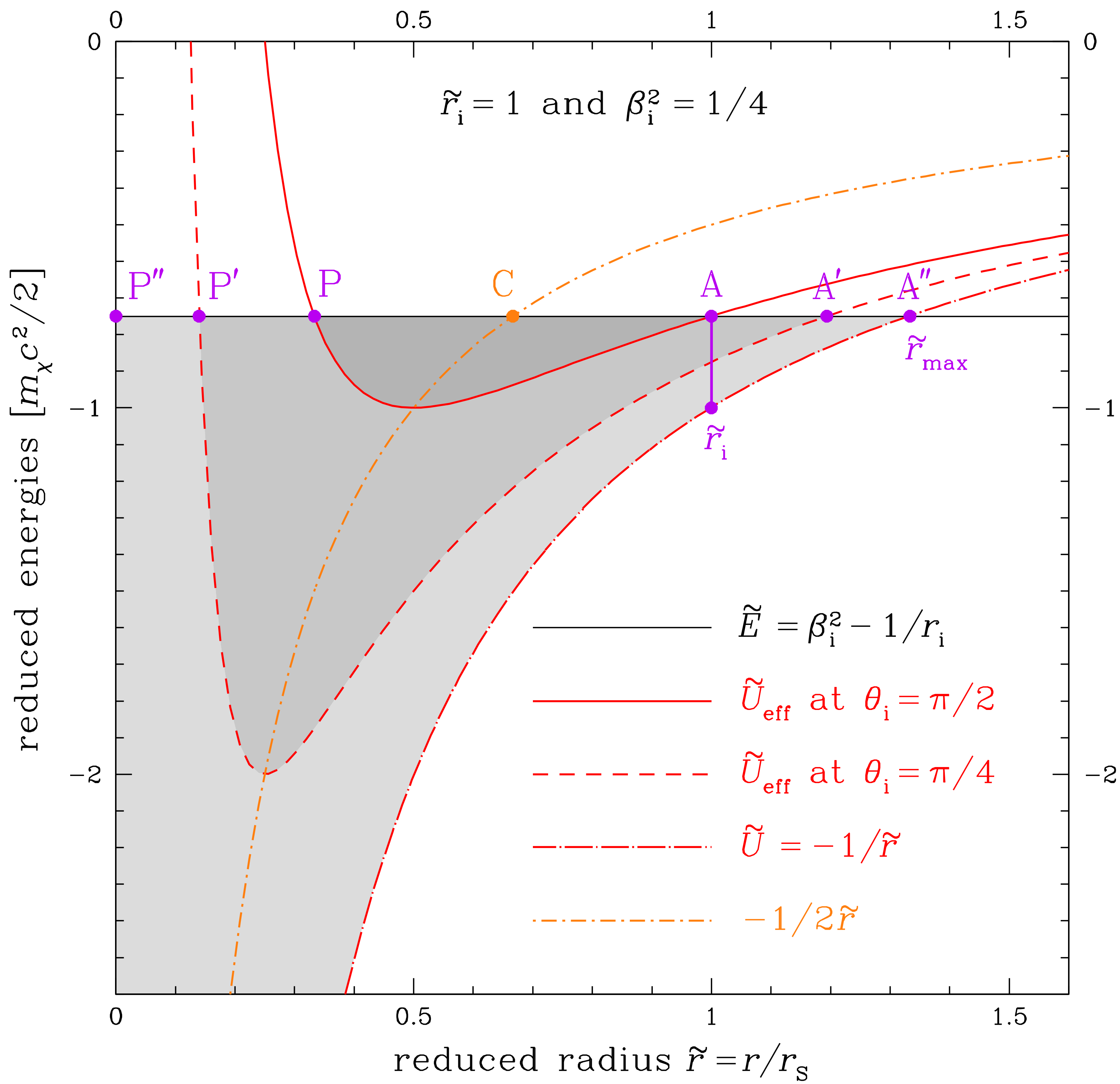
WIMPs

- For $m_\chi = 100$ GeV, $\langle \sigma v \rangle = \langle \sigma v \rangle_{\rm th} = 3 \times 10^{-3} {\rm cm}^3\,{\rm s}^{-1}$:

$$T_{KD} \sim 10\,{\rm MeV}$$

$$t_{KD} \sim 3\,{\rm ms}$$

Orbits



$\tilde{r}_i = 1$ and $\beta_i^2 = 1/4$
P″
P′
P
C
A
A′
A″
$\tilde{r}_{max}$
$\tilde{r}_i$
$\tilde{E} = \beta_i^2 - 1/r_i$
$\tilde{U}_{eff}$ at $\theta_i = \pi/2$
$\tilde{U}_{eff}$ at $\theta_i = \pi/4$
$\tilde{U} = -1/\tilde{r}$
$-1/2\tilde{r}$
reduced energies $[m_\chi c^2/2]$
reduced radius $\tilde{r} = r/r_s$
0
0.5
1
1.5
−1
−2