Early clustering of DM particles around PBHs
Density profiles and signatures

Pierre Salati – LAPTh & Université Savoie Mont Blanc

Outline

1) PBHs & particle DM – Motivations

2) Dressing of PBHs with thermal DM

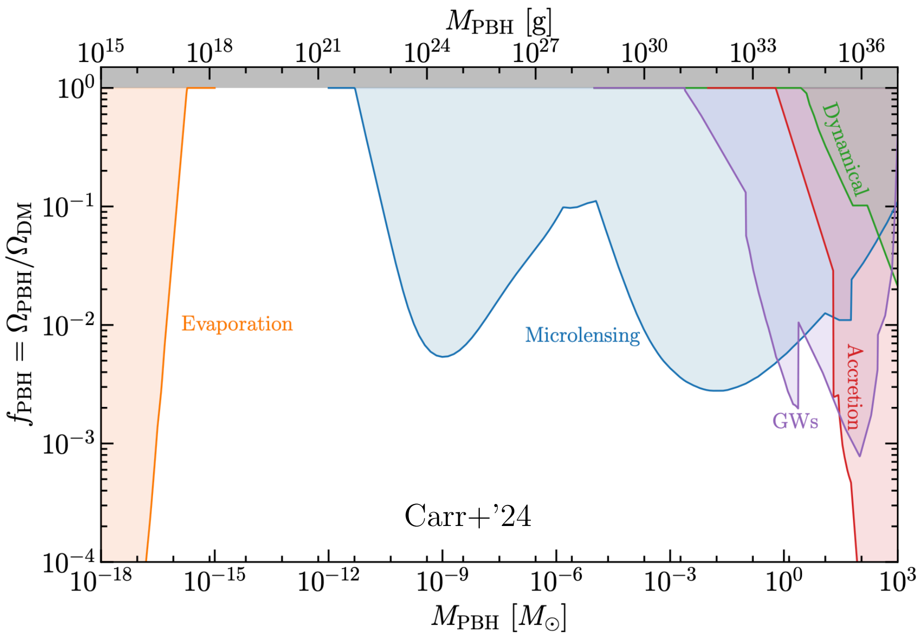
3) Signatures and observational constraints

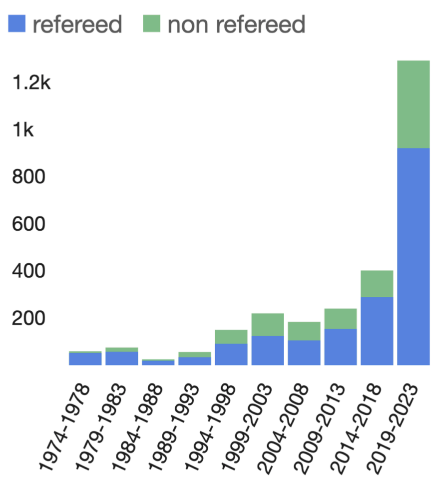
Based on arXiv:2106.07480

Collaboration with J. Lavalle, V. Poulin, P. Sandick, ...

News from the Dark – Episode 9 – Station Marine d'Endoume, Marseille – November 14, 2024

1) PBHs & particle DM – Motivations





# of articles in SAO/NASA Astrophysics Data System
with "Primordial Black Hole" in title in four-year bins

From early ideas to the search of evidence

• Carr & Hawking (1974) ⇒ BHs in the early universe
– Formation and accretion

{ from inflationary density perturbations
from phase transitions

– Evaporation and constraints ⇒ limits on $f_{\rm BH}$ vs $M_{\rm BH}$

• DM in the form of PBH in the window $[10^{18}, 10^{21}]$ g

• But many well-motivated candidates from HE physics
+ experiments to find them ⇒ models are falsifiable

• PBH as DM – almost all or nothing (Lacki+'10)
⇒ WIMPs collapsing on PBH during radiation era
⇒ very dense spikes ⇒ strong upper limits on $f_{\rm BH}$

• 2016 – Discovery of GW by LIGO+VIRGO '15-16

PBHs are no longer a theoretical fantasy

– Heavy BHs in coalescence events unexpected
– Renewed interest for PBHs and strong activity
– GW observatories target coalescence of **sub-solar** objects

$f_{\rm BH}$(sub-solar)
⇓
constraints on $\langle\sigma_{\rm ann} v\rangle$

1) PBHs & particle DM – Motivations

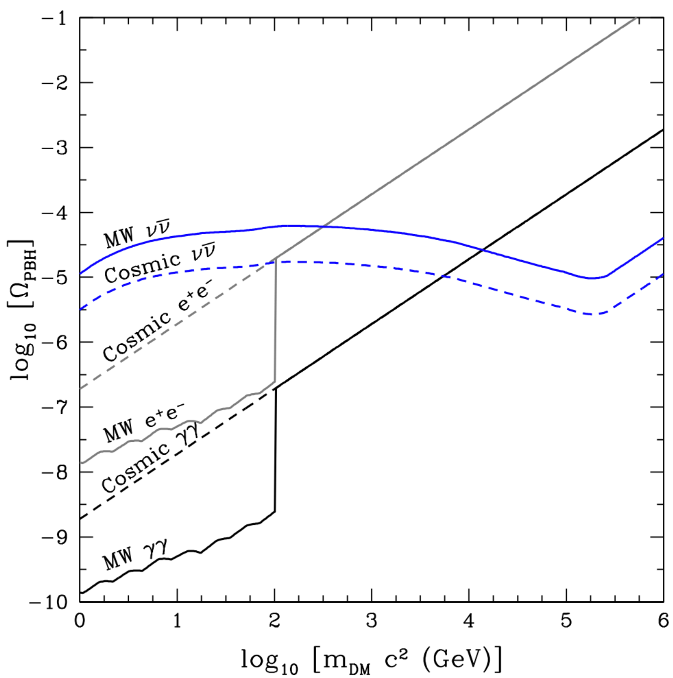


FIG. 1.— Upper bounds on the abundances of PBHs as a function of WIMP mass. Bounds on annihilation into gamma rays (*black*; Br(γ) = 1) and electrons (*grey*; Br(γ) = 0.01) are shown, as well as neutrinos (Br(ν) = 1) (*blue*). Cosmic background limits are solid and Galactic limits are dashed. Gamma-rays are the easiest final state to detect, while neutrinos are the hardest, and other Standard Model final states would give intermediate limits.

From early ideas to the search of evidence

- Carr & Hawking (1974) $\Rightarrow$ BHs in the early universe
– Formation and accretion
  - from inflationary density perturbations
  - from phase transitions
– Evaporation and constraints $\Rightarrow$ limits on $f_{\rm BH}$ vs $M_{\rm BH}$

- DM in the form of PBH in the window $[10^{18}, 10^{21}]$ g

- But many well-motivated candidates from HE physics
+ experiments to find them $\Rightarrow$ models are falsifiable

- PBH as DM – almost all or nothing (Lacki+'10)
$\Rightarrow$ WIMPs collapsing on PBH during radiation era
$\Rightarrow$ very dense spikes $\Rightarrow$ strong upper limits on $f_{\rm BH}$

- 2016 – Discovery of GW by LIGO+VIRGO '15-16

PBHs are no longer a theoretical fantasy

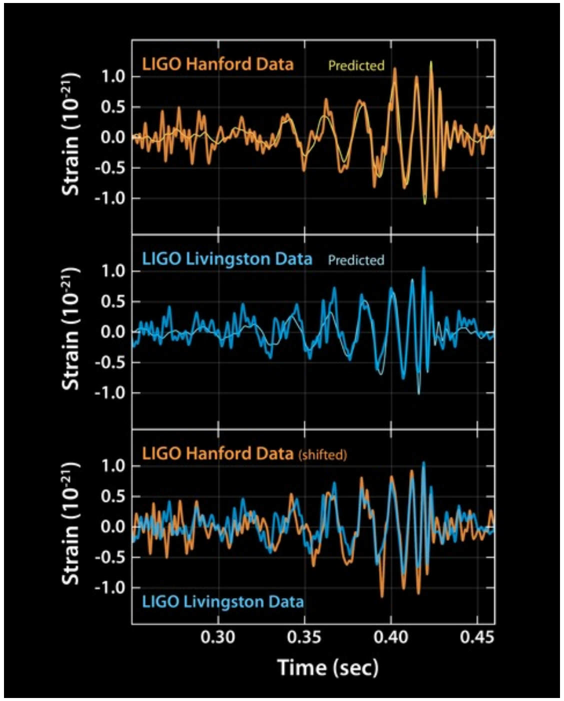
– Heavy BHs in coalescence events unexpected
– Renewed interest for PBHs and strong activity
– GW observatories target coalescence of **sub-solar** objects

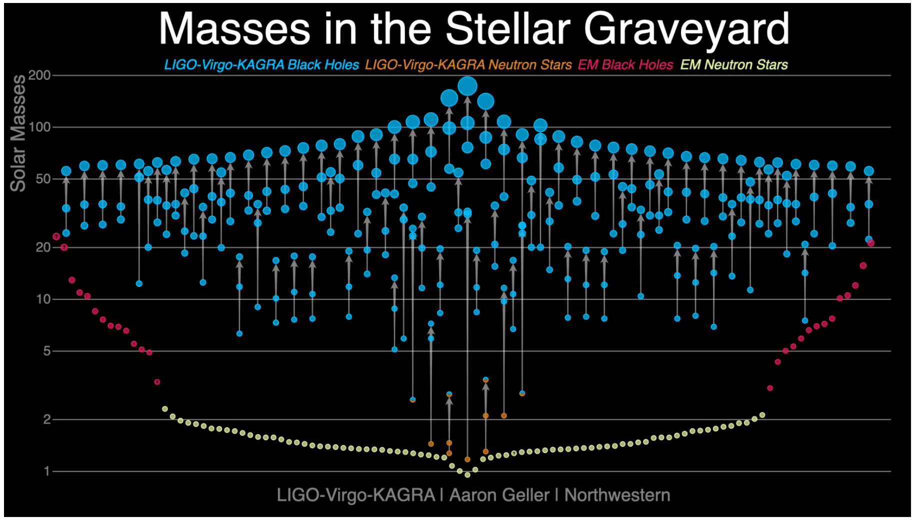
$f_{\rm BH}$(sub-solar)

$\Downarrow$

constraints on $\langle \sigma_{\rm ann} v \rangle$

1) PBHs & particle DM – Motivations





From early ideas to the search of evidence

- Carr & Hawking (1974) ⇒ BHs in the early universe

– Formation and accretion

{ from inflationary density perturbations
{ from phase transitions

– Evaporation and constraints ⇒ limits on $f_{\rm BH}$ vs $M_{\rm BH}$

- DM in the form of PBH in the window $[10^{18}, 10^{21}]$ g

- But many well-motivated candidates from HE physics

+ experiments to find them ⇒ models are falsifiable

- PBH as DM – almost all or nothing (Lacki+'10)

⇒ WIMPs collapsing on PBH during radiation era

⇒ very dense spikes ⇒ strong upper limits on $f_{\rm BH}$

- 2016 – Discovery of GW by LIGO+VIRGO '15-16

PBHs are no longer a theoretical fantasy

– Heavy BHs in coalescence events unexpected

– Renewed interest for PBHs and strong activity

– GW observatories target coalescence of **sub-solar** objects

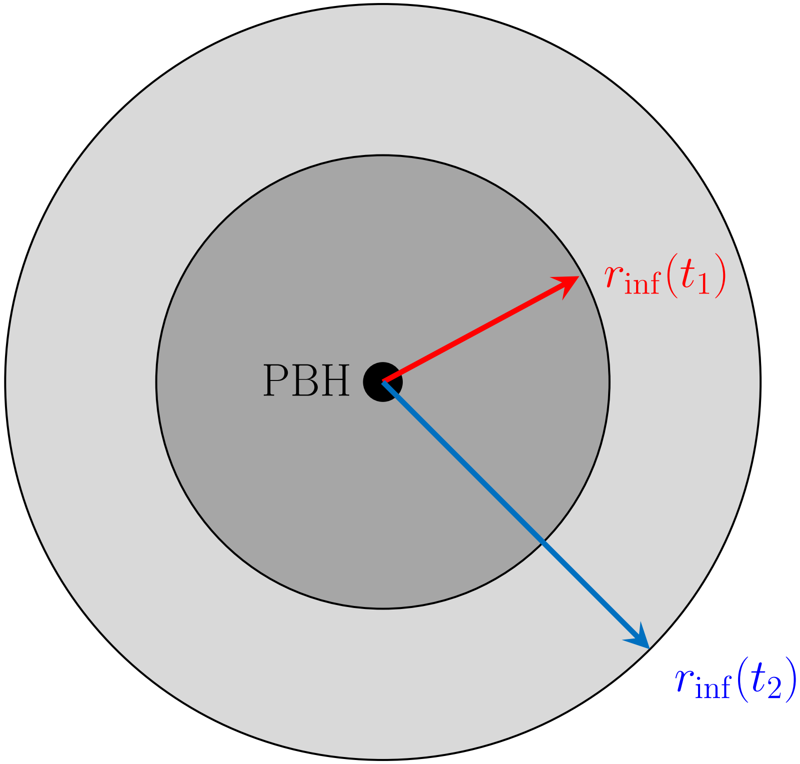
$f_{\rm BH}$(sub-solar)

⇓

constraints on $\langle \sigma_{\rm ann} v \rangle$

2) Dressing of PBHs with thermal DM

Radius of influence of a black hole in the radiation dominated era



• Naively, the sphere of influence of a black hole encloses as much plasma as $M_{\rm BH}$.

$$M_{\rm BH} = \frac{4\pi}{3}\, r_{\rm inf}^3(t)\, \rho_{\rm tot}(t)$$

As time t goes on, $\rho_{\rm tot}$ decreases and $r_{\rm inf}$ increases like $T^{-4/3}$ with T the plasma temperature.

• A more refined argument (Adamek+'19) is based on the acceleration of a test particle moving with the expanding plasma and feeling the BH gravitational drag.

$$\ddot{r} = \frac{\ddot{a}}{a}\, r - \frac{GM_{\rm BH}}{r^2} = -\frac{r}{4t^2} - \frac{GM_{\rm BH}}{r^2}$$

The turn-around radius of the trajectory is identified with the radius of influence $r_{\rm inf}$.

• In a radiation dominated cosmology, trajectories are scale-invariant with apices satisfying

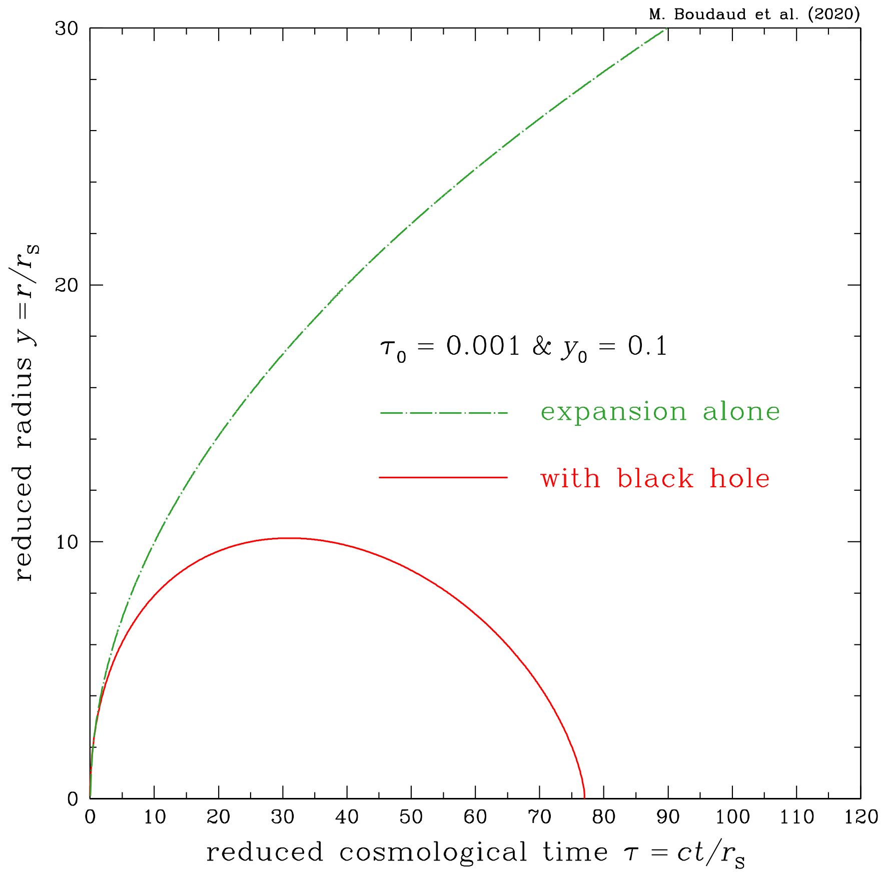
$$y_{\rm ta}^3 = \eta_{\rm ta}\, \tilde{\tau}_{\rm ta}^2 \quad \Longleftrightarrow \quad r_{\rm infl}^3 = 2\,\eta_{\rm ta}\, GM_{\rm BH}\, t^2\,,$$

where $\eta_{\rm ta} \simeq 1.086$ (Boudaud+'21). Expressing cosmic time t as a function of plasma density $\rho_{\rm tot}$ yields the new relation

$$M_{\rm BH} = \frac{16\pi}{3\eta_{\rm ta}}\, r_{\rm inf}^3(t)\, \rho_{\rm tot}(t)$$

2) Dressing of PBHs with thermal DM

Radius of influence of a black hole in the radiation dominated era



- Naively, the sphere of influence of a black hole encloses as much plasma as $M_{\rm BH}$.

$$M_{\rm BH} = \frac{4\pi}{3}\, r_{\rm inf}^3(t)\, \rho_{\rm tot}(t)$$

As time t goes on, $\rho_{\rm tot}$ decreases and $r_{\rm inf}$ increases like $T^{-4/3}$ with T the plasma temperature.

- A more refined argument (Adamek+'19) is based on the acceleration of a test particle moving with the expanding plasma and feeling the BH gravitational drag.

$$\ddot{r} = \frac{\ddot{a}}{a}\, r - \frac{G M_{\rm BH}}{r^2} = -\,\frac{r}{4t^2} - \frac{G M_{\rm BH}}{r^2}$$

The turn-around radius of the trajectory is identified with the radius of influence $r_{\rm inf}$.

- In a radiation dominated cosmology, trajectories are scale-invariant with apices satisfying

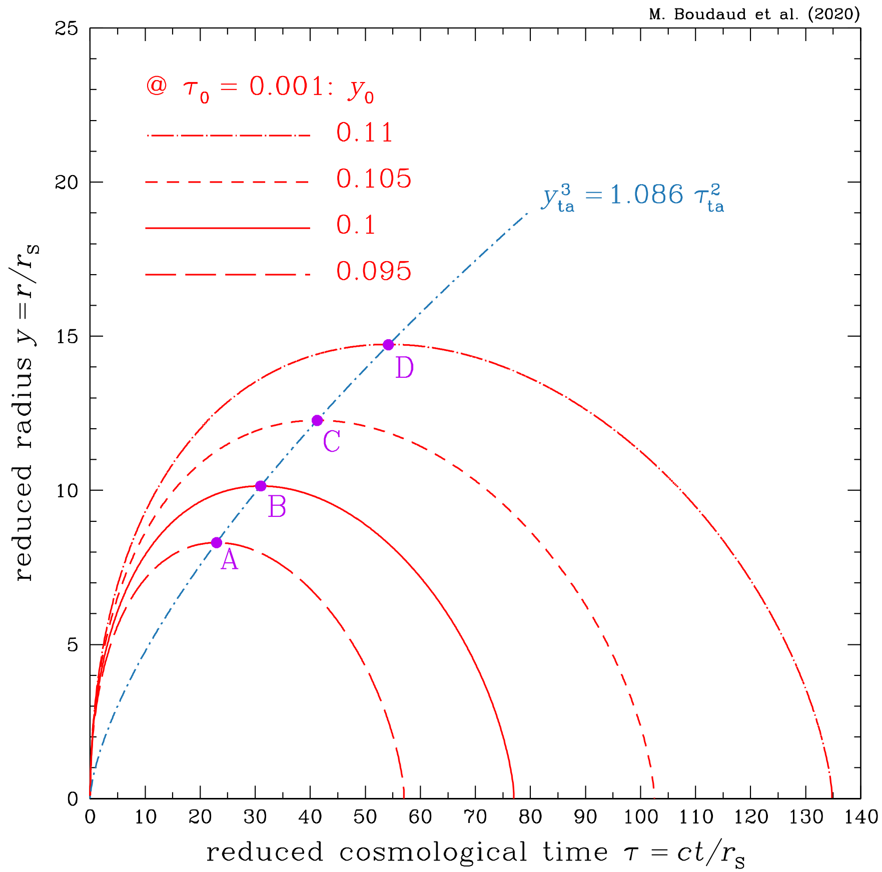
$$y_{\rm ta}^3 = \eta_{\rm ta}\, \tilde{\tau}_{\rm ta}^2 \quad \Longleftrightarrow \quad r_{\rm infl}^3 = 2\,\eta_{\rm ta}\, G M_{\rm BH}\, t^2\,,$$

where $\eta_{\rm ta} \simeq 1.086$ (Boudaud+'21). Expressing cosmic time t as a function of plasma density $\rho_{\rm tot}$ yields the new relation

$$M_{\rm BH} = \frac{16\pi}{3\eta_{\rm ta}}\, r_{\rm inf}^3(t)\, \rho_{\rm tot}(t)$$

2) Dressing of PBHs with thermal DM

Radius of influence of a black hole in the radiation dominated era



• Naively, the sphere of influence of a black hole encloses as much plasma as M_{BH}.

$$M_{BH} = \frac{4\pi}{3} r_{inf}^3(t)\, \rho_{tot}(t)$$

As time t goes on, ρ_{tot} decreases and r_{inf} increases like $T^{-4/3}$ with T the plasma temperature.

• A more refined argument (Adamek+'19) is based on the acceleration of a test particle moving with the expanding plasma and feeling the BH gravitational drag.

$$\ddot{r} = \frac{\ddot{a}}{a} r - \frac{GM_{BH}}{r^2} = -\frac{r}{4t^2} - \frac{GM_{BH}}{r^2}$$

The turn-around radius of the trajectory is identified with the radius of influence r_{inf}.

• In a radiation dominated cosmology, trajectories are scale-invariant with apices satisfying

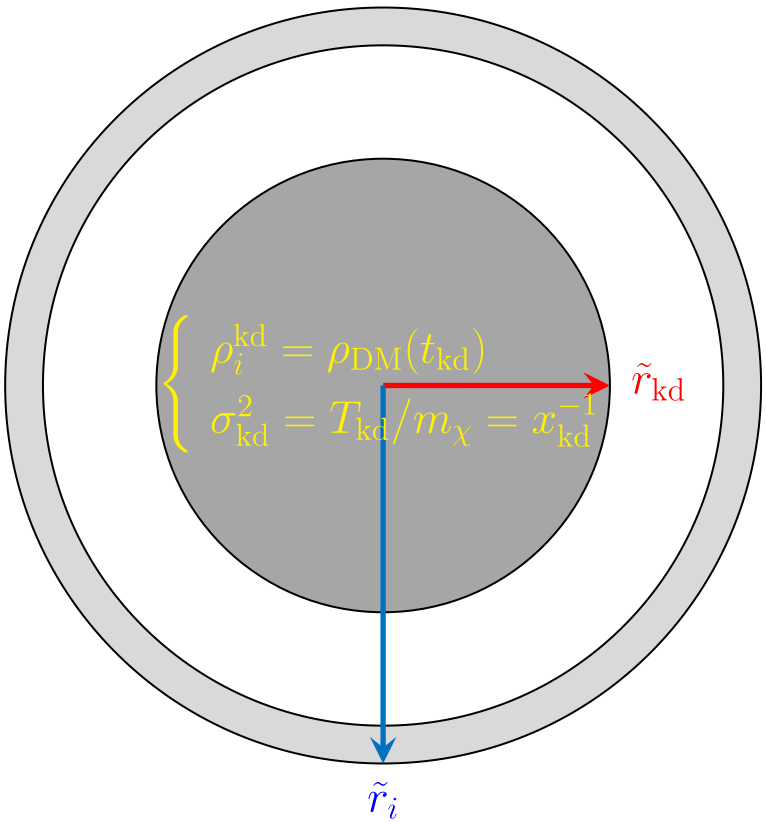
$$y_{ta}^3 = \eta_{ta}\, \tilde{\tau}_{ta}^2 \iff r_{infl}^3 = 2\, \eta_{ta}\, GM_{BH}\, t^2\,,$$

where $\eta_{ta} \simeq 1.086$ (Boudaud+'21). Expressing cosmic time t as a function of plasma density ρ_{tot} yields the new relation

$$M_{BH} = \frac{16\pi}{3\eta_{ta}} r_{inf}^3(t)\, \rho_{tot}(t)$$

2) Dressing of PBHs with thermal DM

Onion-shell dark matter mini-spike profile prior to collapse



$$\begin{cases} \rho_i = \rho_i^{\rm kd} \left(\tilde{r}_i/\tilde{r}_{\rm kd}\right)^{-9/4} \\ \sigma_i = \sigma_{\rm kd} \left(\tilde{r}_i/\tilde{r}_{\rm kd}\right)^{-3/4} \end{cases}$$

• $t < t_{\rm kd}$: prior to kinetic decoupling, DM particles are dragged by the expanding plasma.

• $t = t_{\rm kd}$: at kinetic decoupling, DM particles stop colliding on the plasma. Those inside the influence radius at that time start falling on the BH.

$$r_{\rm kd} = r_{\rm inf}(t_{\rm kd}) \quad \text{with} \quad \rho_i^{\rm kd} \equiv \rho_{\rm DM}(t_{\rm kd})$$

• $t_{\rm kd} \leq t_i \leq t_{\rm eq}$: at time t_i, DM particles located at $r_i = r_{\rm inf}(t_{\rm i})$ feel for the first time the BH drag and start falling onto it. Their cosmological density is $\rho_i = \rho_{\rm DM}(t_i)$.

$$\rho_i \propto a_i^{-3} \propto T_i^3 \propto r_{\rm inf}^{-9/4} \quad \text{while} \quad \sigma_i \propto a_i^{-1} \propto T_i \propto r_{\rm inf}^{-3/4}$$

$$\Downarrow$$

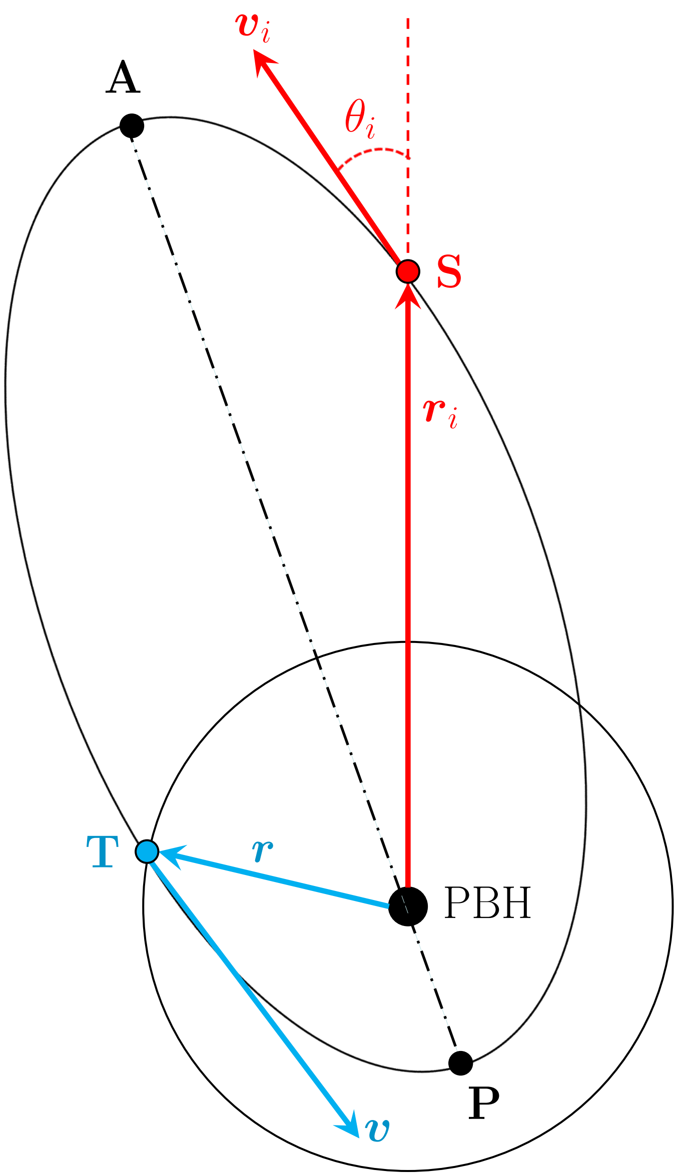
Expressing the radius r in units of the Schwarzschild radius $r_{\rm S}$ of the BH, we get the pre-collapse DM profile.

$$\rho_i(\tilde{r}_i) \simeq \begin{cases} \rho_i^{\rm kd} & \text{if } \tilde{r}_i \leq \tilde{r}_{\rm kd} \\ \rho_i^{\rm kd} \left(\tilde{r}_i/\tilde{r}_{\rm kd}\right)^{-9/4} & \text{if } \tilde{r}_{\rm kd} \leq \tilde{r}_i \leq \tilde{r}_{\rm eq} \end{cases}$$

• $t_{\rm eq} < t$: during the matter dominated era, the DM secondary infall leads to DM haloes with much lesser densities.

2) Dressing of PBHs with thermal DM

Orbital kinematics – Reaching T from the injection at S



- DM particles feel only the gravitational field of the BH.
- DM trajectories are hereafter determined in the framework of classical mechanics and Newtonian gravity.
- We can define the reduced orbital variables

$$\tilde{\boldsymbol{r}} = \frac{\boldsymbol{r}}{r_\mathrm{S}} \quad \text{and} \quad \boldsymbol{\beta} = \frac{\boldsymbol{v}}{c}$$

- Energy and orbital momentum are conserved throughout each trajectory.

$$\tilde{E} = \frac{E}{m_\chi c^2/2} = \beta^2 - \frac{1}{\tilde{r}} \quad \text{and} \quad \tilde{\boldsymbol{L}} = \tilde{\boldsymbol{r}} \wedge \boldsymbol{\beta}$$

- A DM particle injected at **S** reaches the target point **T** if its orbital variables fulfill the condition

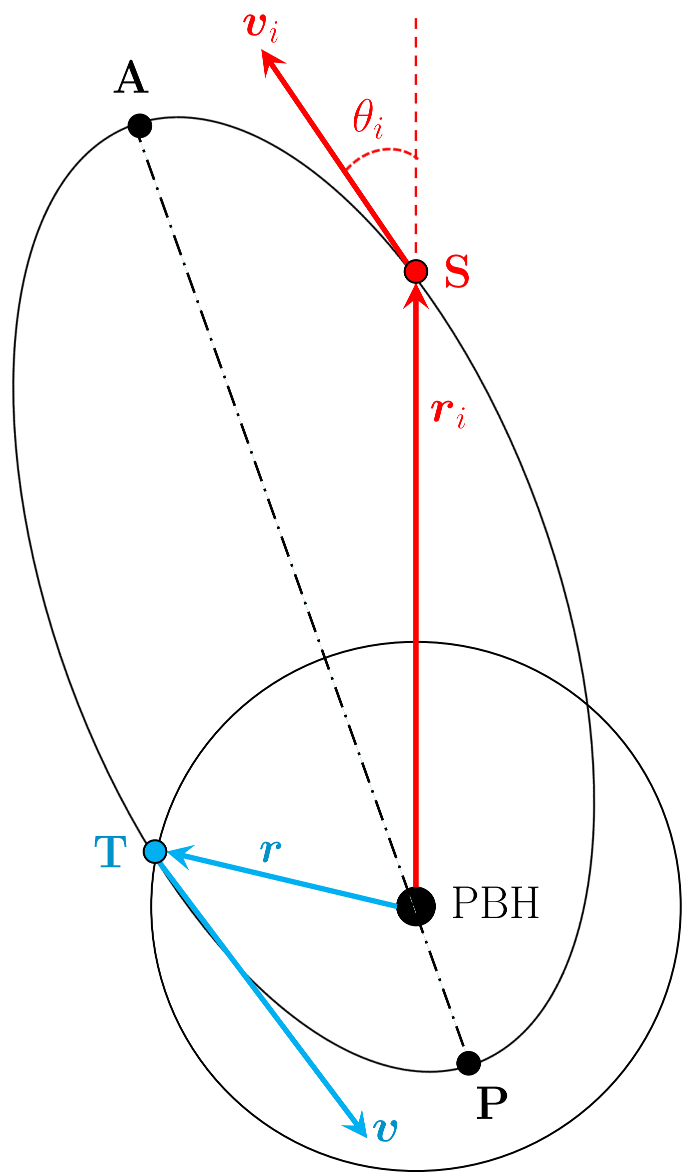
$$\tilde{E}(\mathbf{S}) = \beta_i^2 - \frac{1}{\tilde{r}_i} = \beta_r^2 + \left\{ \beta_\perp^2 \equiv \frac{\tilde{r}_i^2 \beta_i^2 \sin^2\theta_i}{\tilde{r}^2} \right\} - \frac{1}{\tilde{r}} = \tilde{E}(\mathbf{T})$$

where the orbital momentum is

$$\tilde{L}(\mathbf{S}) = \tilde{r}_i \beta_i \sin\theta_i = \tilde{r}\beta_\perp = \tilde{L}(\mathbf{T})$$

2) Dressing of PBHs with thermal DM

Orbital kinematics – Reaching T from the injection at S



The conservation of energy and orbital momentum between **S** and **T** has consequences on the DM phase space.

$$\beta_i^2 - \frac{1}{\tilde{r}_i} = \beta_r^2 + \frac{\tilde{r}_i^2 \beta_i^2 \sin^2\theta_i}{\tilde{r}^2} - \frac{1}{\tilde{r}}$$

1) DM at point **S** is trapped if $\tilde{E} < 0$.

$$\beta_i^2 - \frac{1}{\tilde{r}_i} < 0 \iff u \equiv \beta_i^2 \tilde{r}_i < 1$$

The variable u is the ratio of kinetic-to-potential energies.

2) At point **T**, the DM velocity squared β^2 must be positive.

$$\beta^2 = \frac{1}{\tilde{r}} + \beta_i^2 - \frac{1}{\tilde{r}_i} \geq 0 \iff u \geq 1 - X \text{ where } X \equiv \frac{\tilde{r}_i}{\tilde{r}}$$

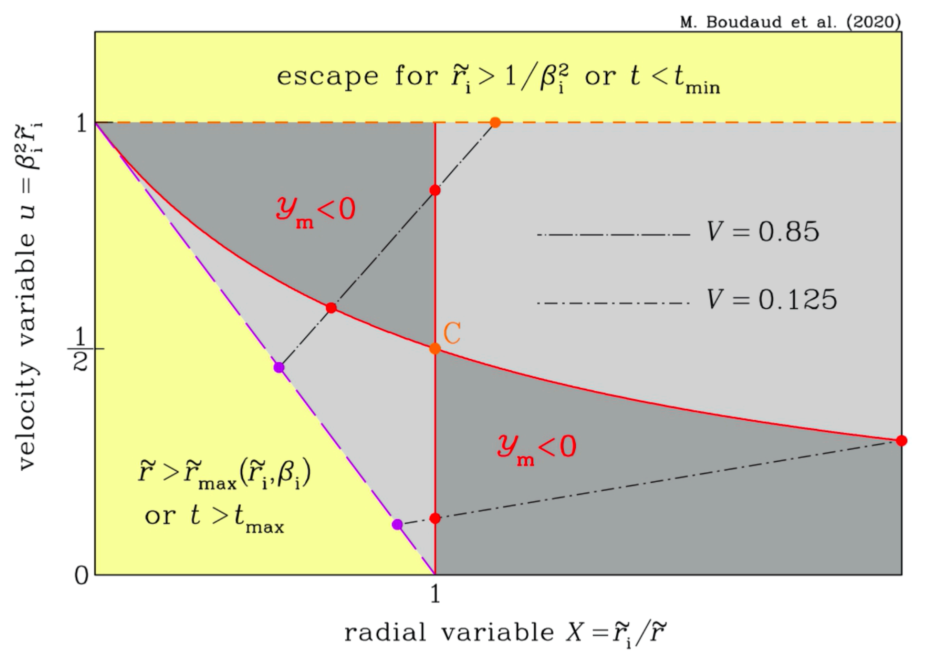
3) The equation for energy and orbital momentum conservation can be recast as

$$\sin^2\theta_i + \left\{\frac{\tilde{r}^2}{\tilde{r}_i^2 \beta_i^2}\right\}\beta_r^2 = \frac{\tilde{r}^2}{\tilde{r}_i^2}\left\{1 + \frac{1}{\beta_i^2}\left(\frac{1}{\tilde{r}} - \frac{1}{\tilde{r}_i}\right)\right\} \equiv 1 - \mathcal{Y}_{\rm m}\,.$$

The variable $\mathcal{Y}_{\rm m}$ cannot exceed 1 but can be negative.
In the past literature $0 \leq \mathcal{Y}_{\rm m} \leq 1$. See hereafter!

2) Dressing of PBHs with thermal DM

Orbital kinematics – Reaching **T** from the injection at **S**



The angular variable $\mathcal{Y}_m$ can be expressed in terms of the variables u and X as

$$\mathcal{Y}_m = 1 - \frac{1}{uX} - \left(1 - \frac{1}{u}\right) \frac{1}{X^2}\,.$$

It vanishes for $X = 1$ and $u = 1/(1+X)$.

The conservation of energy and orbital momentum between **S** and **T** has consequences on the DM phase space.

$$\beta_i^2 - \frac{1}{\tilde{r}_i} = \beta_r^2 + \frac{\tilde{r}_i^2 \beta_i^2 \sin^2\theta_i}{\tilde{r}^2} - \frac{1}{\tilde{r}}$$

1) DM at point **S** is trapped if $\tilde{E} < 0$.

$$\beta_i^2 - \frac{1}{\tilde{r}_i} < 0 \iff u \equiv \beta_i^2 \tilde{r}_i < 1$$

The variable u is the ratio of kinetic-to-potential energies.

2) At point **T**, the DM velocity squared β^2 must be positive.

$$\beta^2 = \frac{1}{\tilde{r}} + \beta_i^2 - \frac{1}{\tilde{r}_i} \geq 0 \iff u \geq 1 - X \text{ where } X \equiv \frac{\tilde{r}_i}{\tilde{r}}$$

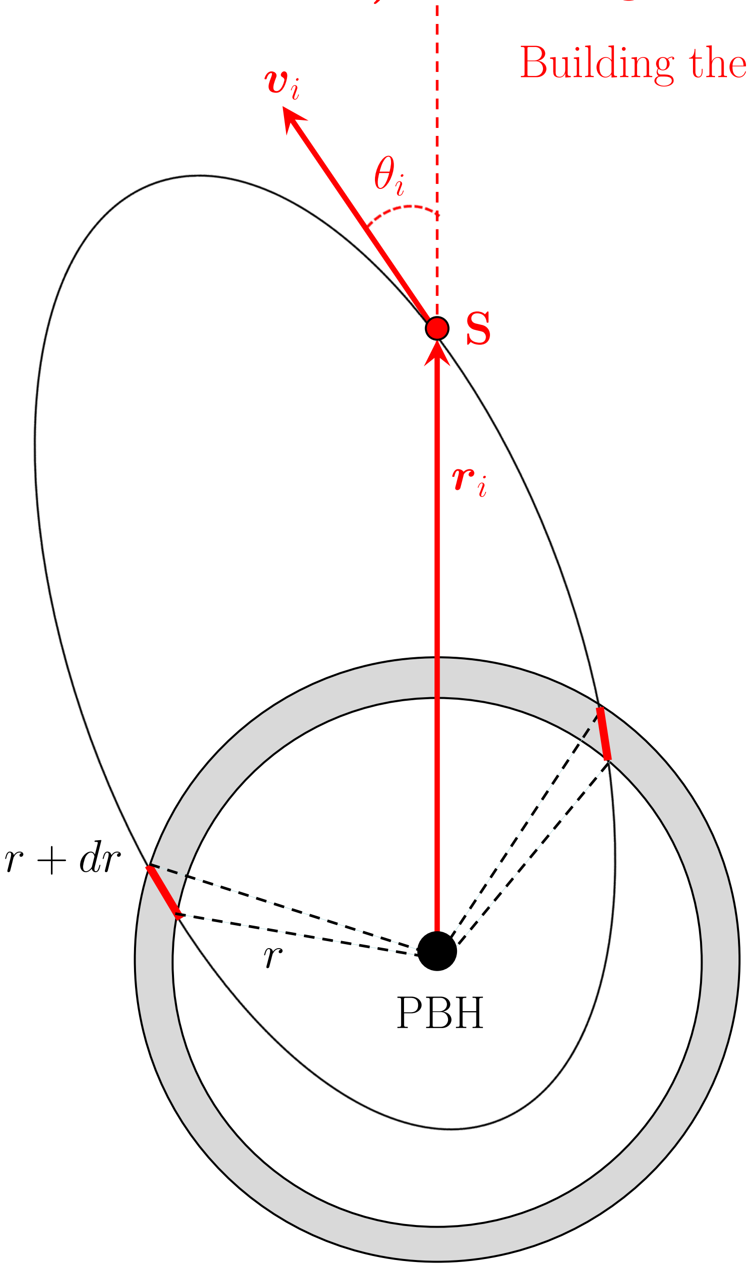
3) The equation for energy and orbital momentum conservation can be recast as

$$\sin^2\theta_i + \left\{\frac{\tilde{r}^2}{\tilde{r}_i^2 \beta_i^2}\right\} \beta_r^2 = \frac{\tilde{r}^2}{\tilde{r}_i^2} \left\{1 + \frac{1}{\beta_i^2}\left(\frac{1}{\tilde{r}} - \frac{1}{\tilde{r}_i}\right)\right\} \equiv 1 - \mathcal{Y}_m\,.$$

The variable $\mathcal{Y}_m$ cannot exceed 1 but can be negative.
In the past literature $0 \leq \mathcal{Y}_m \leq 1$. See hereafter!

2) Dressing of PBHs with thermal DM

Building the dark matter mini-spike



Ingredients & Recipe

- The injection of a single DM particle at **S** yields the averaged post-collapse density $\delta\rho$ such that

$$4\pi r^2 dr\, \delta\rho = m_\chi \times \frac{2dt}{T_{\rm orb}} \,.$$

- DM particles cross twice the shell of thickness dr in a time

$$dt = \frac{r_{\rm S}}{c}\,\frac{d\tilde{r}}{|\beta_r|} \quad \text{with} \quad |\beta_r| = \frac{\tilde{r}_i\beta_i}{\tilde{r}}\sqrt{\cos^2\theta_i - \mathcal{Y}_{\rm m}}\,.$$

- The orbital period follows Kepler's third law of planetary motion. At fixed $\tilde{r}_i$ and β_i, $T_{\rm orb}$ does not depend on θ_i.

$$T_{\rm orb} = \frac{\pi r_{\rm S}}{c}\,\tilde{r}_{\rm max}^{3/2} \quad \text{where} \quad \tilde{r}_{\rm max} = \frac{\tilde{r}_i}{1-u}$$

- To deal with the pre-collapse DM distribution in phase space, and not just with a single particle

$$m_\chi \to {\rm d}^6 m_i = \left\{\rho_i(\tilde{r}_i)\, 4\pi r_i^2 dr_i\right\} \times \left\{\mathcal{F}_{\rm MB}(\beta_i|\tilde{r}_i)\,\beta_i^2 d\beta_i d\Omega_i\right\}\,.$$

- DM velocities are distributed according to the Maxwellian

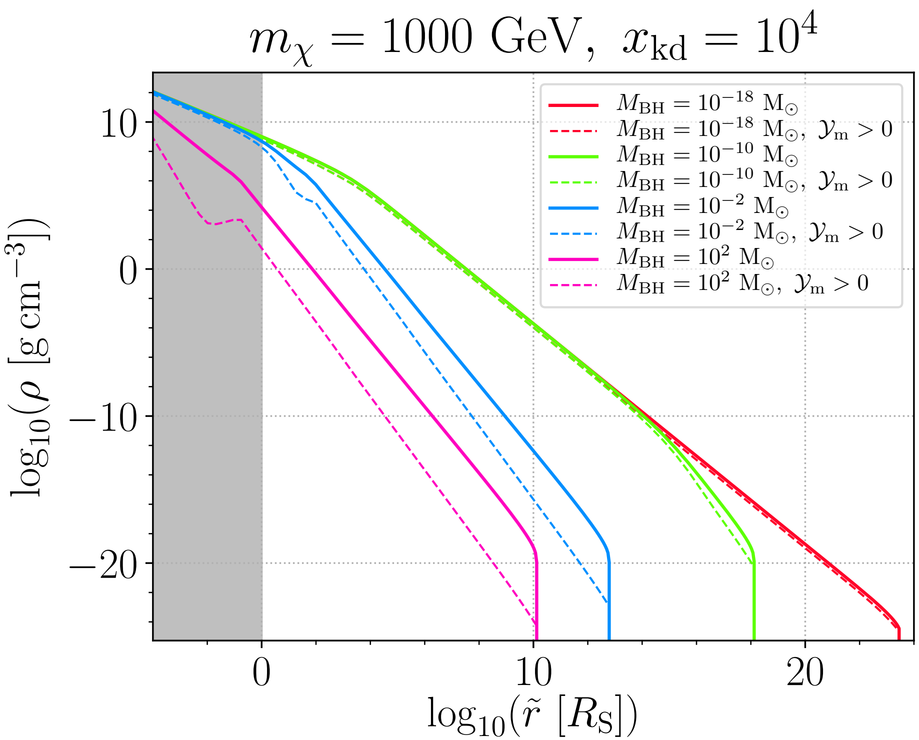
$$\mathcal{F}_{\rm MB}(\beta_i|\tilde{r}_i) \equiv \frac{1}{(2\pi\sigma_i^2)^{3/2}}\,\exp(-\beta_i^2/2\sigma_i^2)\,.$$

- The DM pre-collapse density ρ_i and dispersion velocity σ_i have the onion-like structure discussed above.

2) Dressing of PBHs with thermal DM

Post-collapse density profiles – numerical results

$$\rho(\tilde{r}) = \frac{4}{\tilde{r}} \iint \tilde{r}_i \, d\tilde{r}_i \, \rho_i(\tilde{r}_i) \times d\beta_i^2 \, \mathcal{F}(\beta_i|\tilde{r}_i) \times \left\{ \frac{1}{\tilde{r}_i} - \beta_i^2 \right\}^{3/2} \times \int_0^{\theta_i^0} \frac{d(-\cos\theta_i)}{\sqrt{\cos^2\theta_i - \mathcal{Y}_\mathrm{m}}}$$



Caveats

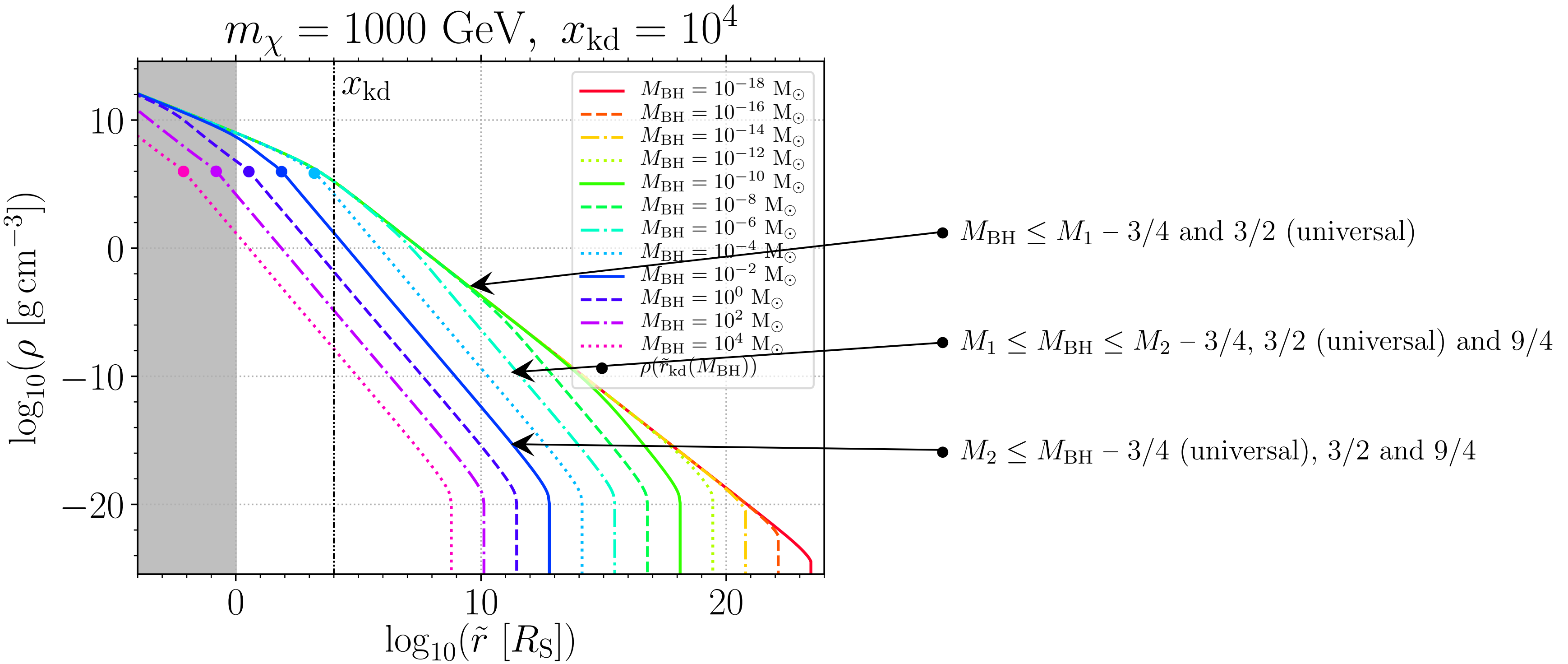
- Numerical integration is tricky (log divergences @ $\mathcal{Y}_\mathrm{m} = 0$)
- $\mathcal{Y}_\mathrm{m}$ originally defined as y_m^2 (Eroshenko'16) **can be negative**. Mistake propagated in other works.

$$\theta_i^0 = \begin{cases} \arccos(\sqrt{\mathcal{Y}_\mathrm{m}}) & \text{if } \mathcal{Y}_\mathrm{m} \geq 0 \\ \pi/2 & \text{if } \mathcal{Y}_\mathrm{m} \leq 0 \end{cases}$$

2) Dressing of PBHs with thermal DM

Post-collapse density profiles – numerical results

Intricate structure of DM spikes:
- 3 parameters: m_χ, $T_{\rm kd}$ & $M_{\rm BH}$
- power laws $\rho_{\rm DM}(\tilde{r}) \propto \tilde{r}^{-\gamma}$
- 3 slopes: 3/4, 3/2 & 9/4



- slopes 9/4, 3/2 and 3/4 already found but not discussed (Mack+'07, Lacki+'10, Eroshenko'16 & Boucenna+'17)
- Boudaud+'21: slopes and relation to $M_{\rm BH}$ explained

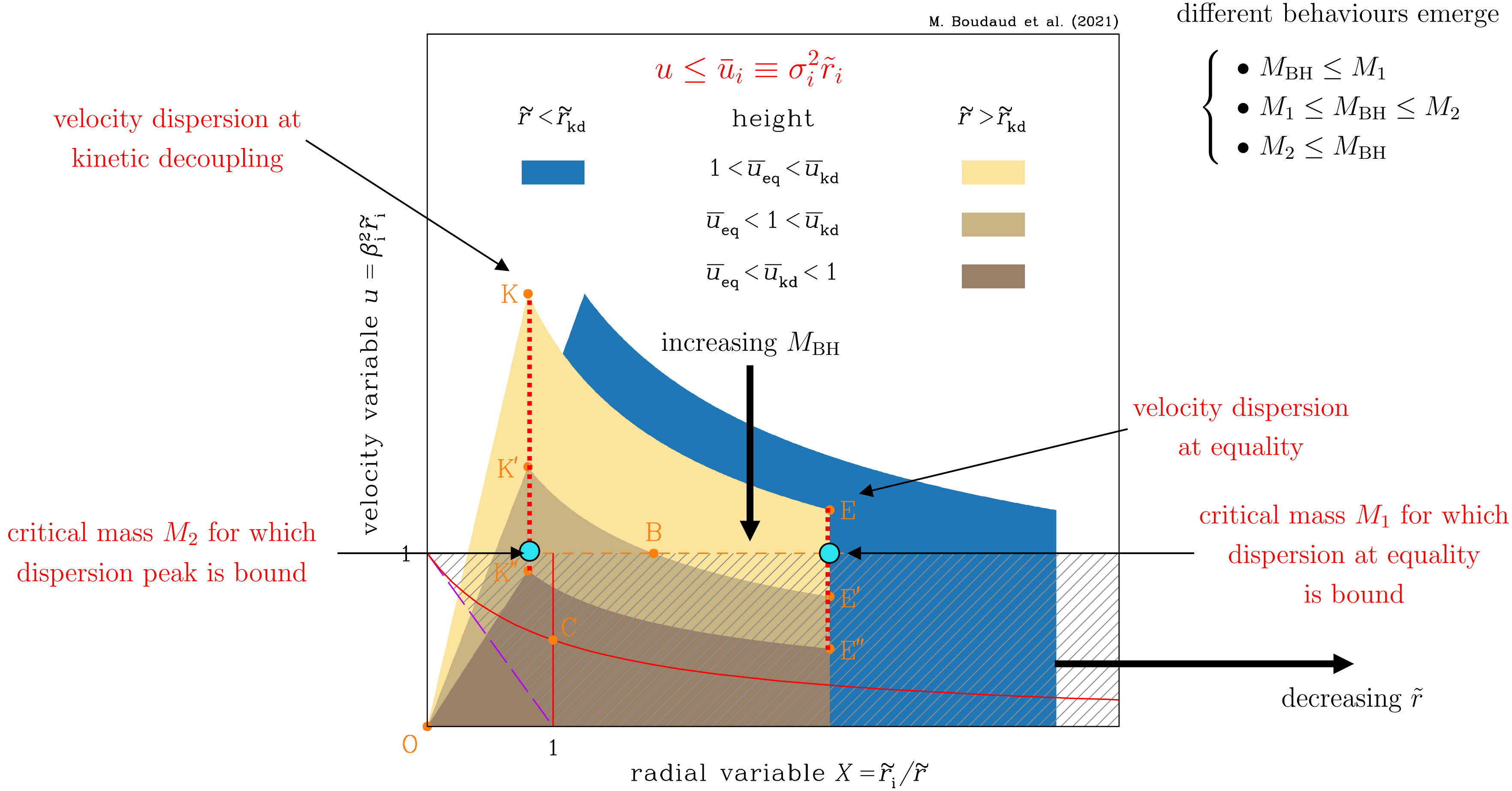
2) Dressing of PBHs with thermal DM

Post-collapse density profiles – the velocity triangle

$$\rho(\tilde{r}) = \sqrt{\frac{2}{\pi^3}}\,\frac{\rho_i^{\rm kd}}{\sigma_{\rm kd}^3}\,\frac{1}{\tilde{r}^{3/2}}\iint \frac{dX}{X^{3/2}}\,du\,(1-u)^{3/2}\,\mathcal{J}(\mathcal{Y}_{\rm m})\,\exp(-u/2\bar{u}_i)$$

Available vs bound phase space regions $\Longrightarrow$ depending on how they overlap different behaviours emerge

- $M_{\rm BH} \leq M_1$
- $M_1 \leq M_{\rm BH} \leq M_2$
- $M_2 \leq M_{\rm BH}$

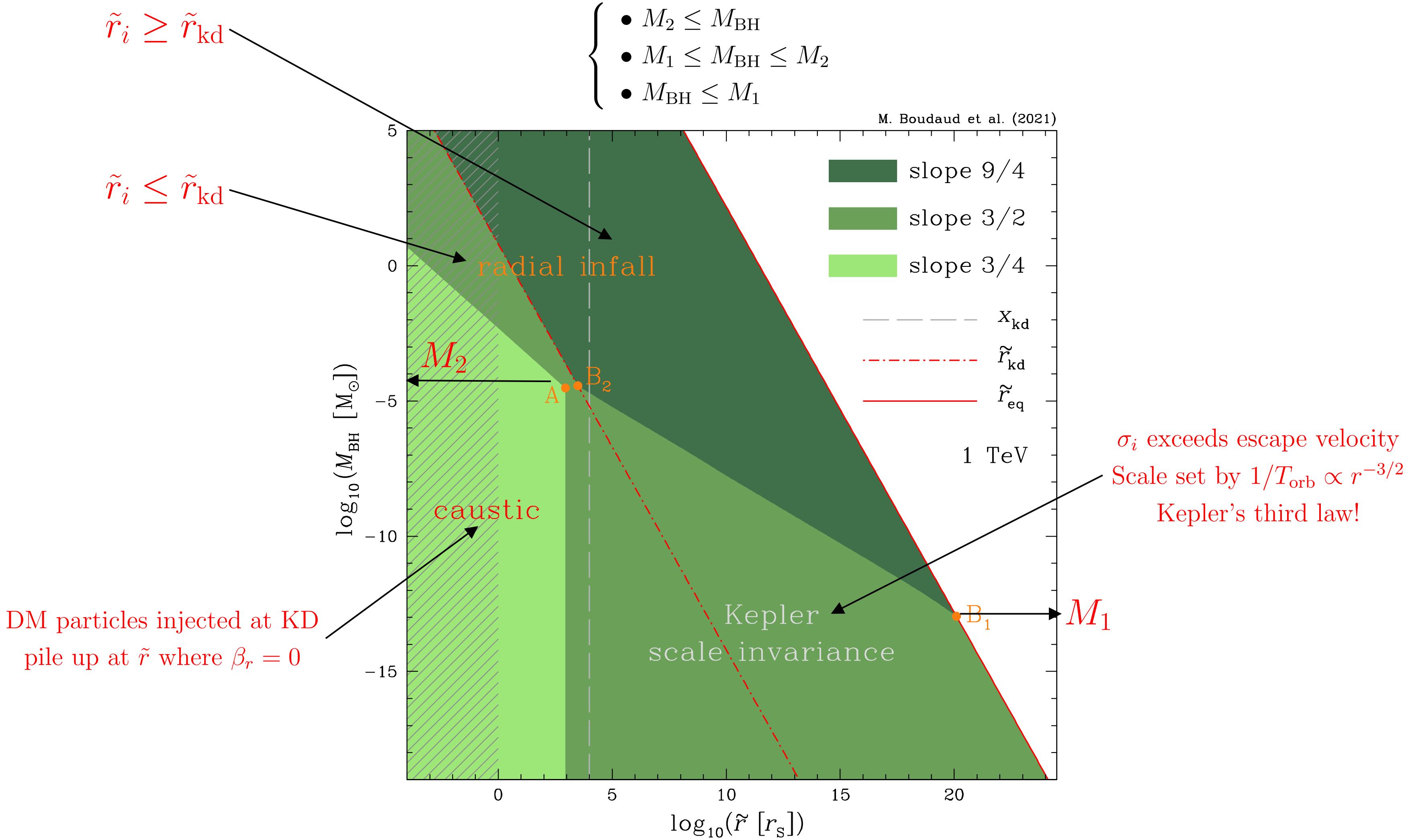


2) Dressing of PBHs with thermal DM

Post-collapse density profiles – phase diagram of logarithmic indices

3 regimes

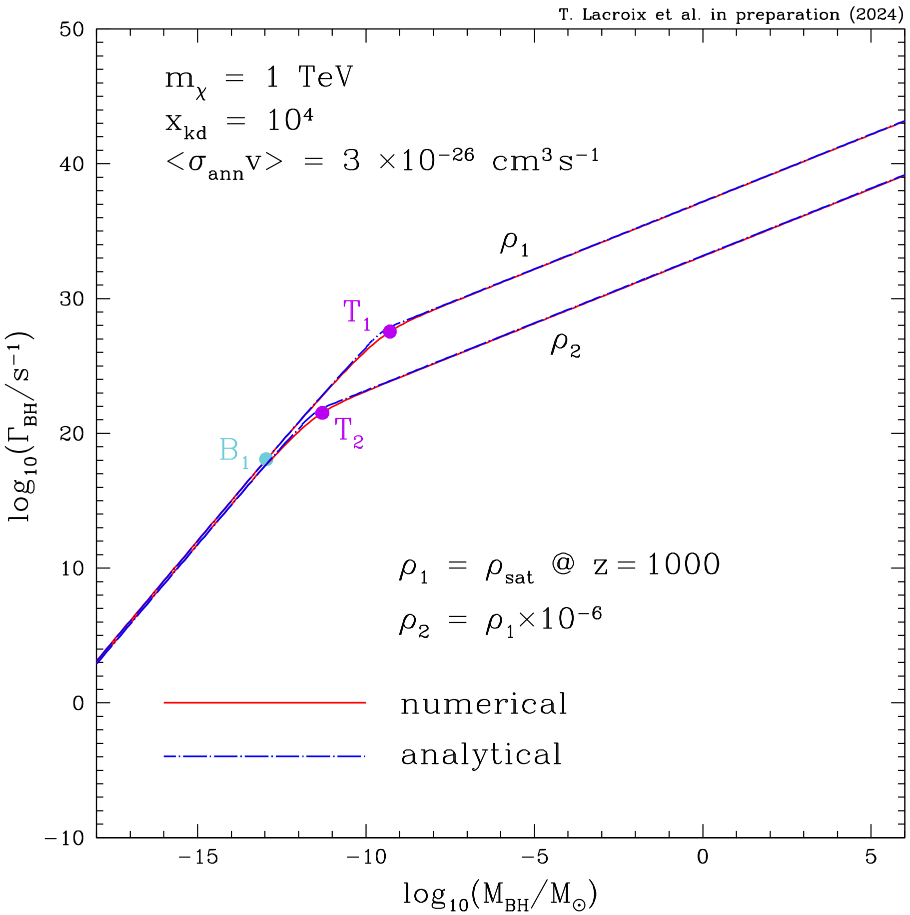
- $M_2 \leq M_{\rm BH}$
- $M_1 \leq M_{\rm BH} \leq M_2$
- $M_{\rm BH} \leq M_1$



3) Signatures and observational constraints

DM skirts around PBHs self-annihilate ⇒ γ-rays, ν and E injection

$$\Gamma_{\rm BH} = \frac{1}{2}\langle\sigma_{\rm ann}v\rangle \left\{\frac{\rho_{\rm sat}}{m_\chi}\right\}^2 r_{\rm S}^3 \int_1^{\tilde{r}_{\rm eq}} 4\pi\tilde{r}^2 {\rm d}\tilde{r} \left\{\frac{\rho(\tilde{r})}{\rho_{\rm sat}}\right\}^2$$



$\Gamma_{\rm BH}$ depends on m_χ, $T_{\rm kd}$, $M_{\rm BH}$ and $\rho_{\rm sat}$

- Inner DM distribution flattened by annihilations

$$\rho_{\rm sat} = \frac{m_\chi}{\langle\sigma_{\rm ann}v\rangle\,\tau} \quad \text{where} \quad \tau = t_{\rm U}(z) - t_{\rm eq}$$

- Transition in the $(\tilde{r}, M_{\rm BH})$ plane at $\tilde{r}_t$ and M_t such that

$$\rho_{\rm sat} = \rho_{3/2}(\tilde{r}_t) = \rho_{9/4}(\tilde{r}_t, M_t)$$

- At fixed $\rho_{\rm sat}$, 2 regimes for $\Gamma_{\rm BH}$ vs $M_{\rm BH}$

$$\Gamma_{\rm BH} \propto \begin{cases} M_{\rm BH}^3 & \text{if } M_{\rm BH} \leq M_t \\ M_{\rm BH} & \text{if } M_{\rm BH} \geq M_t \end{cases}$$

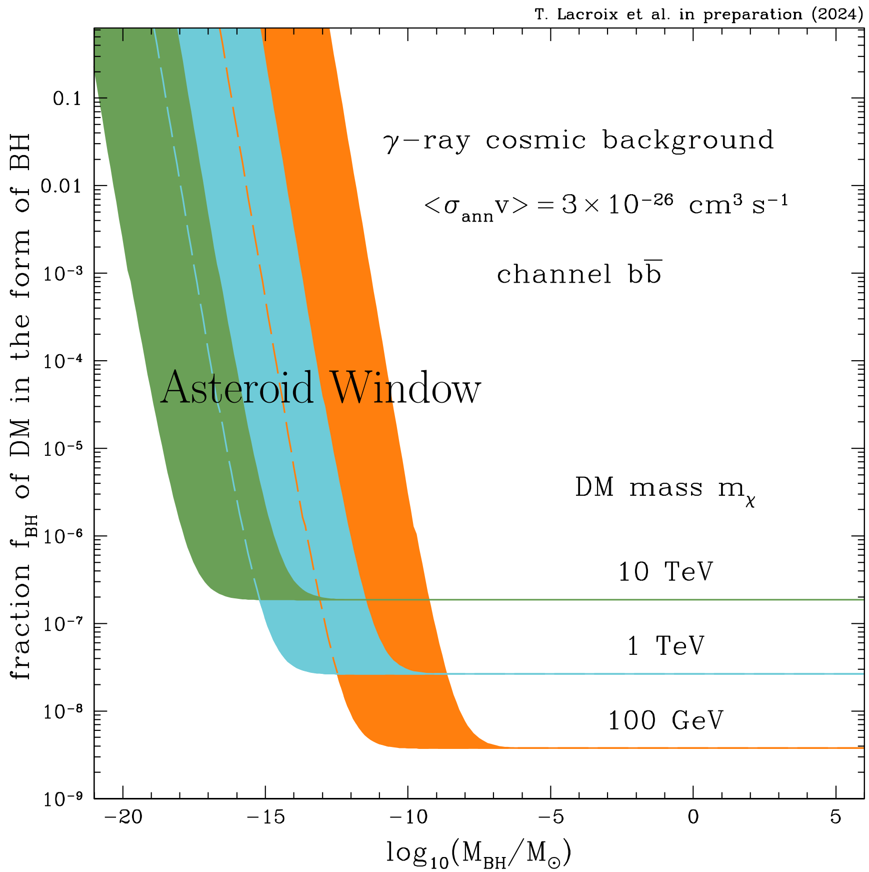
- At fixed $M_{\rm BH}$, 2 regimes for $\Gamma_{\rm BH}$ vs $\langle\sigma_{\rm ann}v\rangle$

$$\Gamma_{\rm BH} \propto \begin{cases} \langle\sigma_{\rm ann}v\rangle & \text{if } M_{\rm BH} \leq M_t \\ \langle\sigma_{\rm ann}v\rangle^{1/3} & \text{if } M_{\rm BH} \geq M_t \end{cases}$$

3) Signatures and observational constraints

DM skirts around PBHs self-annihilate ⇒ γ-rays, ν and E injection

$$\Phi_\gamma(E_\gamma) = \frac{c}{4\pi}\,\frac{f_{\rm BH}\,\rho^0_{\rm DM}}{M_{\rm BH}} \int \frac{dz}{H_z}\,\Gamma_{\rm BH}\,e^{-\tau_{\rm opt}}\,\frac{dN_\gamma}{dE_\gamma}\bigg|_{E'_\gamma}$$



see also Boucenna+'17, Carr+'21, Ginés+22, Chanda+'22

γ-ray flux from DM skirts around PBH

- If DM is mostly in the form of thermal particles
  upper limit on Φ_γ ⇒ upper limit on $f_{\rm BH}$

- Standard calculation

– $f_{\rm BH}$ is the contribution of PBHs to DM

– H_z is the expansion rate at redshift z

$$\frac{H_z}{H_0} = \sqrt{\Omega_\Lambda + \Omega_{\rm M}(1+z)^3}$$

– $\tau_{\rm opt}(E_\gamma, z)$ is the γ optical depth of the IGM

– The energy spectrum at injection is taken at

$$E'_\gamma = (1+z)E_\gamma$$

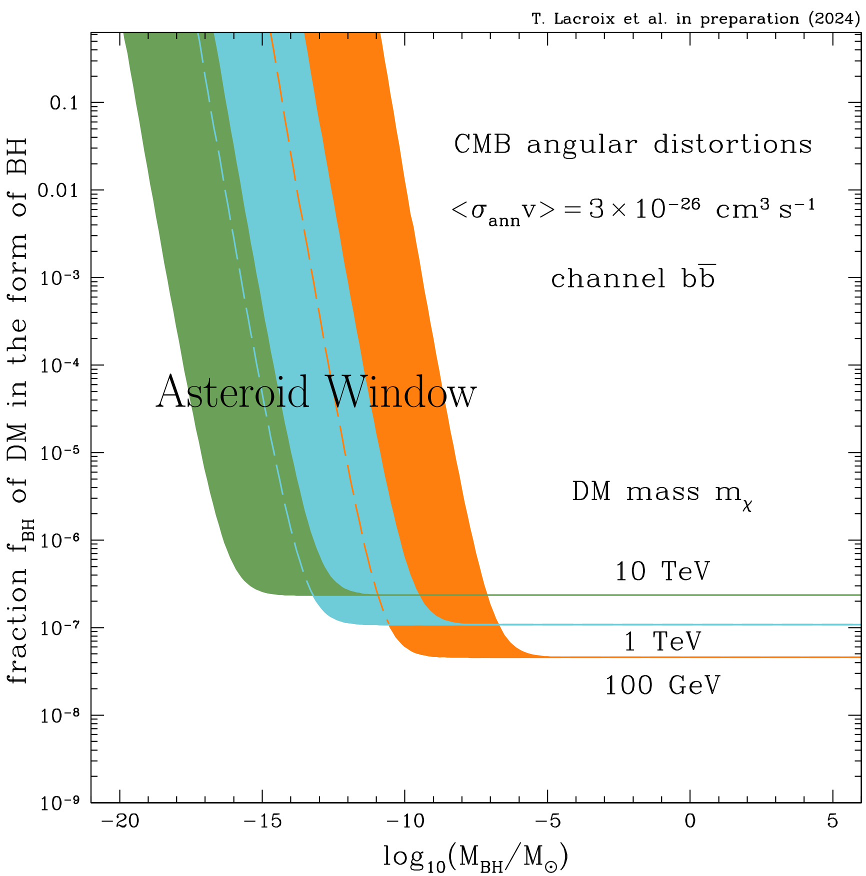
- Recasting bounds from decaying DM (Ando+'15)

$$f_{\rm BH} \leq \left\{\frac{M_{\rm BH}}{2m_\chi}\right\}\left\{\frac{1/\tau_\chi^{\rm inf}}{\Gamma_{\rm BH}}\right\}$$

3) Signatures and observational constraints

DM skirts around PBHs self-annihilate $\Rightarrow$ γ-rays, ν and E injection

$$\#\text{ annihilations cm}^{-3}\text{ s}^{-1}\text{ @ z} \;\Rightarrow\; \frac{1}{2}\langle\sigma_{\rm ann}v\rangle n_\chi^2(z) \equiv \Gamma_{\rm BH}(z) n_{\rm BH}(z)$$



see also Boucenna+’17, Carr+’21, Ginés+22, Chanda+’22

E injection ionizes the primordial plasma

- The number densities n_χ and $n_{\rm BH}$ are given by

$$n_\chi(z) = \frac{\rho^0_{\rm DM}}{m_\chi}(1+z)^3 \text{ and } n_{\rm BH}(z) = \frac{\rho^0_{\rm DM} f_{\rm BH}}{M_{\rm BH}}(1+z)^3$$

- Observational bound on DM energy injection obtained by the Planck collaboration (Aghanim+’18)

$$p_{\rm ann} = f_{\rm eff}\frac{\langle\sigma_{\rm ann}v\rangle}{m_\chi} \leq 3.2\times10^{-28}\text{ cm}^3\text{ s}^{-1}\text{ GeV}^{-1}$$

- Recasting CMB bounds on $p_{\rm ann}$ from annihilating DM into an upper limit on $f_{\rm BH}$ yields

$$f_{\rm BH} \leq \left\{\frac{M_{\rm BH}}{2m_\chi}\right\}\left\{\frac{\Gamma^{\rm sup}_{\rm CMB}}{\Gamma_{\rm BH}(z)}\right\}$$

where

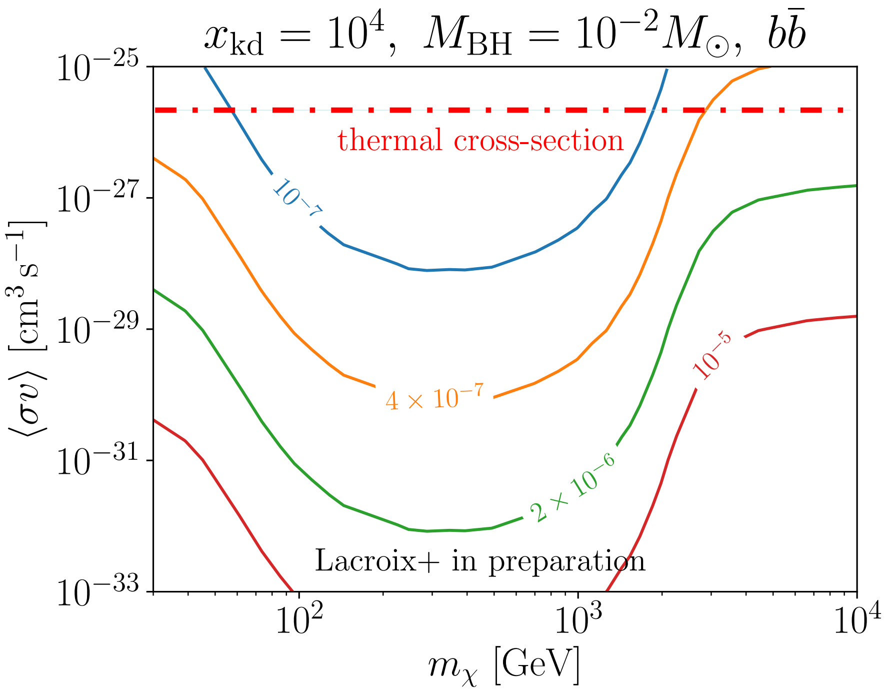
$$\Gamma^{\rm sup}_{\rm CMB} = \frac{p^{\rm sup}_{\rm ann}}{f_{\rm eff}}\,\rho^0_{\rm DM}(1+z)^3$$

- A fast but very crude result can be obtained using $z\sim600$. A more refined treatment requires implementation in CLASS.

3) Signatures and observational constraints

Inverting the reasoning, and going a step further

$$\Phi_\gamma(E_\gamma) = \frac{1}{4\pi}\frac{f_{\rm BH}\,\rho^0_{\rm DM}}{M_{\rm BH}}\int\frac{dz}{H_z}\,\Gamma_{\rm BH}\,e^{-\tau_{\rm opt}}\,\frac{dN_\gamma}{dE_\gamma}\Big|_{E'_\gamma} \Leftarrow m_\chi, x_{\rm kd}, \langle\sigma_{\rm ann}v\rangle, M_{\rm BH}, f_{\rm BH}$$



see also Bertone+'19

GW observatories target sub-solar BH

- Let us assume that $f_{\rm BH}$ has been measured below $1\,M_\odot$, and that PBHs with mass $M_{\rm BH}$ have been discovered in GW events.

measured $M_{\rm BH}$ & $f_{\rm BH}$ $\Rightarrow m_\chi, x_{\rm kd}, \langle\sigma_{\rm ann}v\rangle$

- Recasting bounds from decaying DM (Ando+'15)

$$2m_\chi\,\Gamma_{\rm BH} = \frac{M_{\rm BH}}{\tau_\chi f_{\rm BH}}$$

$$\Downarrow$$

upper limit on $\langle\sigma_{\rm ann}v\rangle$ vs m_χ at fixed $x_{\rm kd}$

$$\Downarrow$$

PBH fraction $> 10^{-7}$ strong impact on WIMP

s-wave annihilation severely constrained

Takeaway

- PBHs might be all of DM, but only in the asteroid window.
- DM could be made of several components – but Occam's razor.
- If mixed, thermal DM collapses around PBH into ultra-dense mini-spikes.
- Big step forward by Eroshenko $\Rightarrow$ orbital momentum matters!
- We reached a fully analytical understanding of the log indices (see analytical solutions in arXiv:2106.07480).
- $f_{\rm BH} > 10^{-7} \Rightarrow$ Thermal DM annihilating through s-wave strongly constrained.
- Currently directly probed by GW measurements through coalescence events.

If found even as a tiny DM subcomponent
PBHs are strong perturbers to DM pheno

Thanks for your attention