Early clustering of DM particles around PBHs
Density profiles and signatures

Pierre Salati – LAPTh & Université Savoie Mont Blanc

Outline

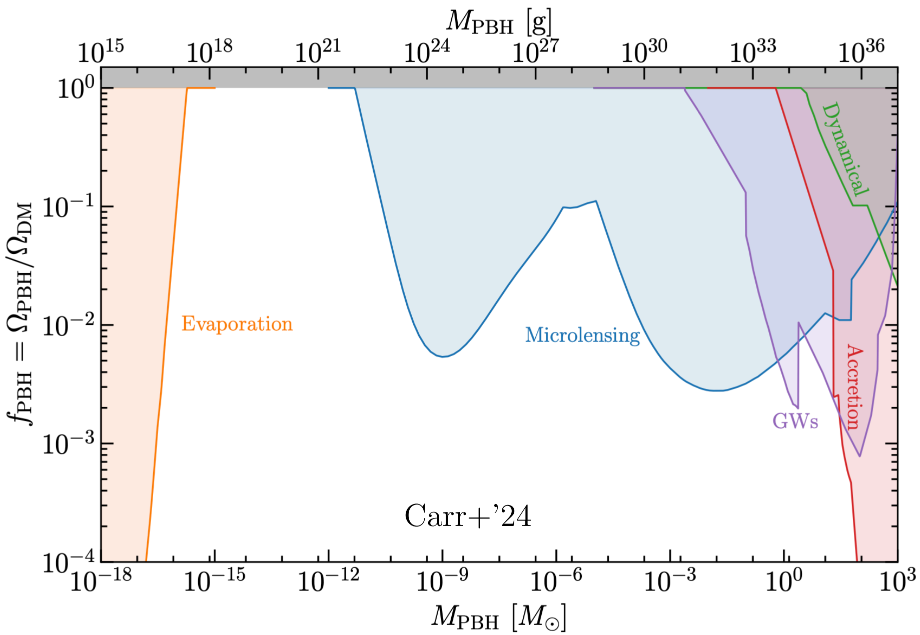
1) PBHs & particle DM – Motivations

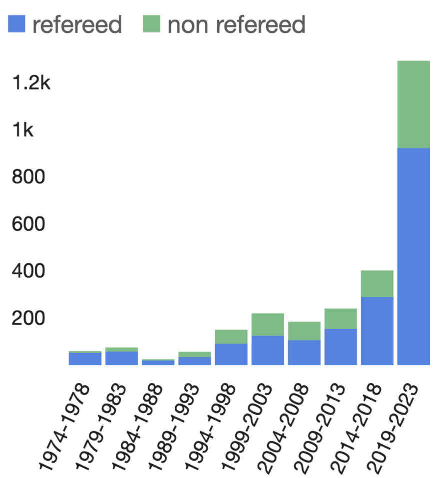
2) Dressing of PBHs with thermal DM

3) Signatures and observational constraints

RICAP-24 Roma International Conference on AstroParticle Physics – Frascati – September 26,2024

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

$\left\{ \begin{array}{l} \text{from inflationary density perturbations} \\ \text{from phase transitions} \end{array} \right.$

– 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)

$\Downarrow$

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

1) PBHs & particle DM – Motivations

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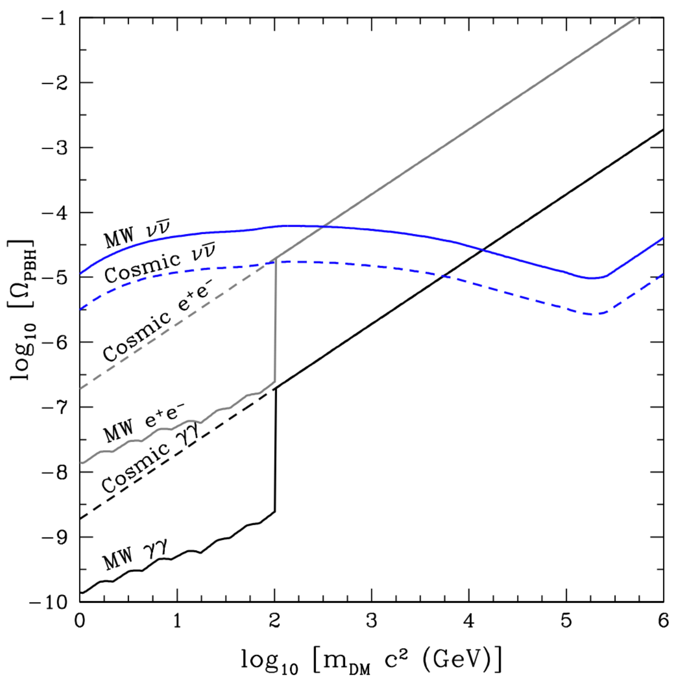

FIG. 1.— Upper bounds on the abundances of PBHs as a function of WIMP mass. Bounds on annihilation into gamma rays (*black*; Br(γ) = 1) and electrons (*grey*; Br(γ) = 0.01) are shown, as well as neutrinos (Br(ν) = 1) (*blue*). Cosmic background limits are solid and Galactic limits are dashed. Gamma-rays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

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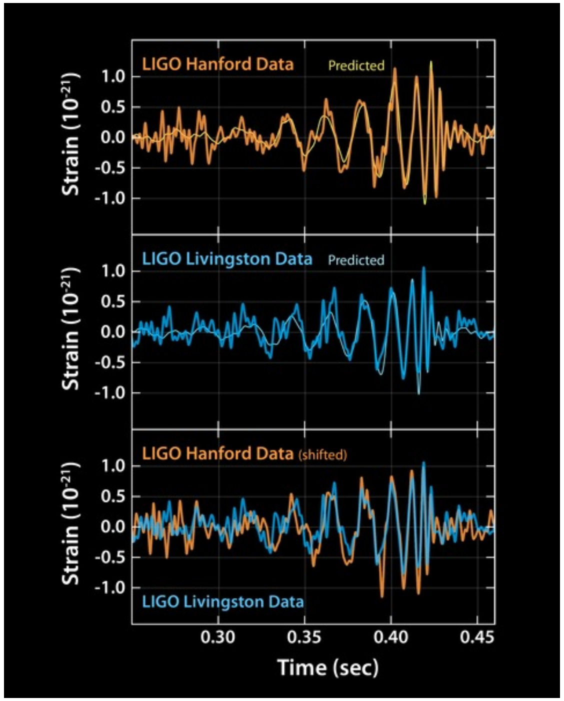

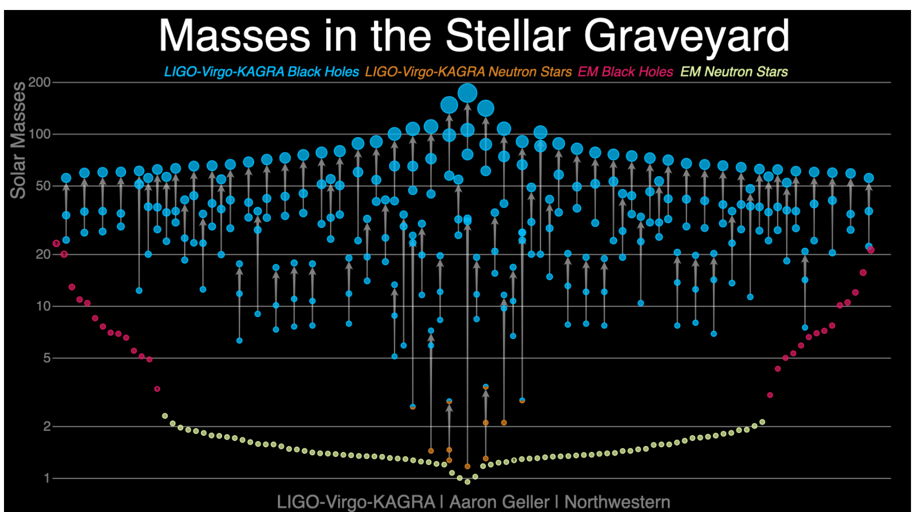

From early ideas to the search of evidence

- Carr & Hawking (1974) $\Rightarrow$ BHs in the early universe

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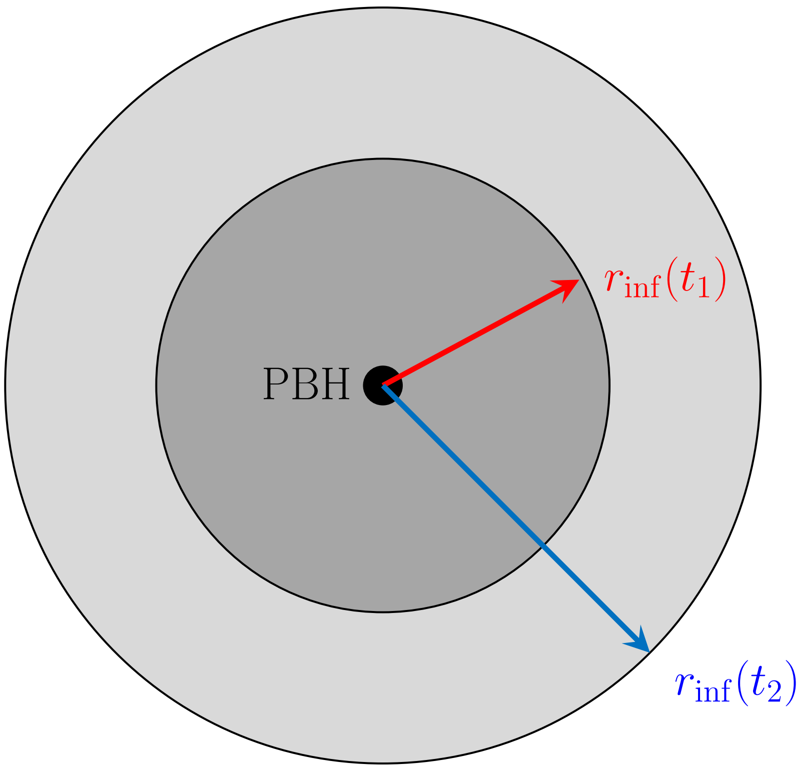
2) Dressing of PBHs with thermal DM

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}.

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

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.

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

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

$$y^3_{\text{ta}} = \eta_{\text{ta}}\, \tilde{\tau}^2_{\text{ta}} \quad \Longleftrightarrow \quad r^3_{\text{infl}} = 2\, \eta_{\text{ta}}\, G M_{\text{BH}}\, t^2 \,,$$

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

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

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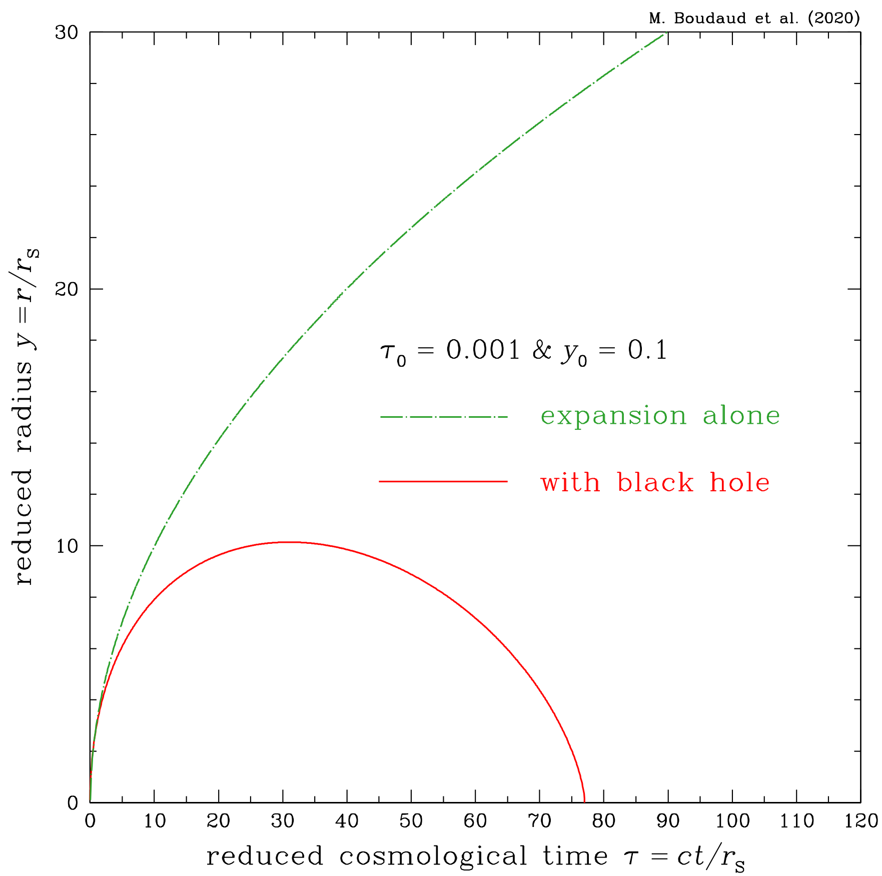

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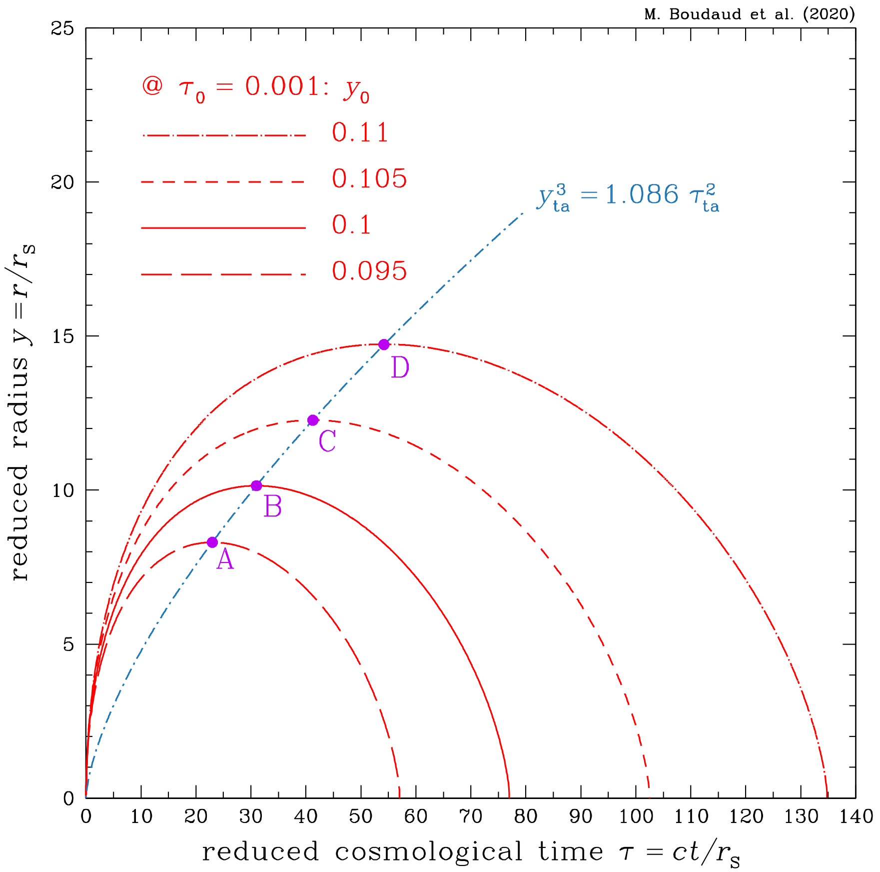

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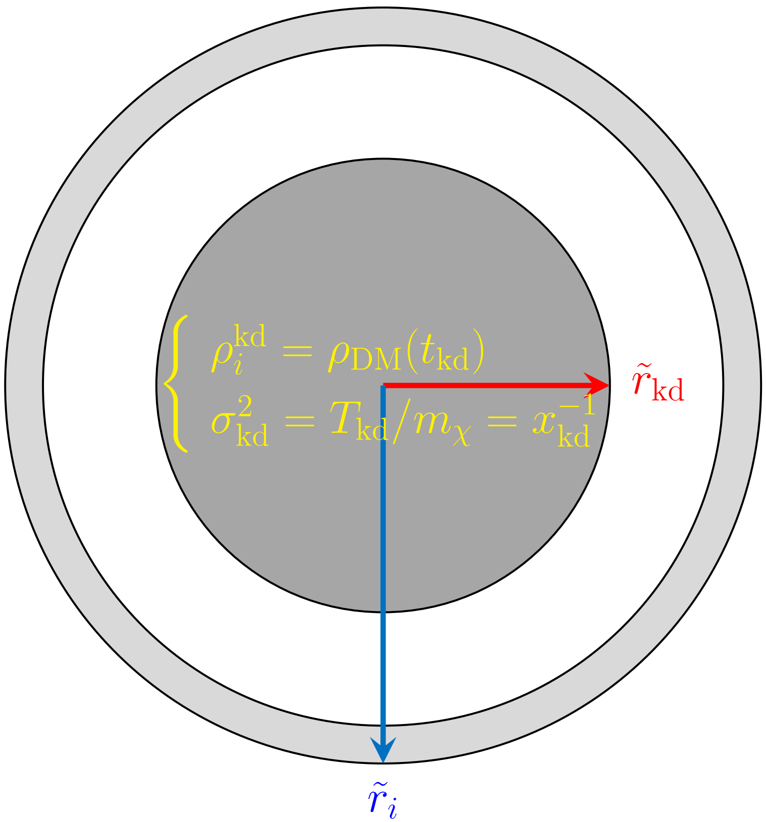
2) Dressing of PBHs with thermal DM

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



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

• $t < t_{\rm kd}$: 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 $\rho_i = \rho_{\rm DM}(t_i)$.

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

$$\Downarrow$$

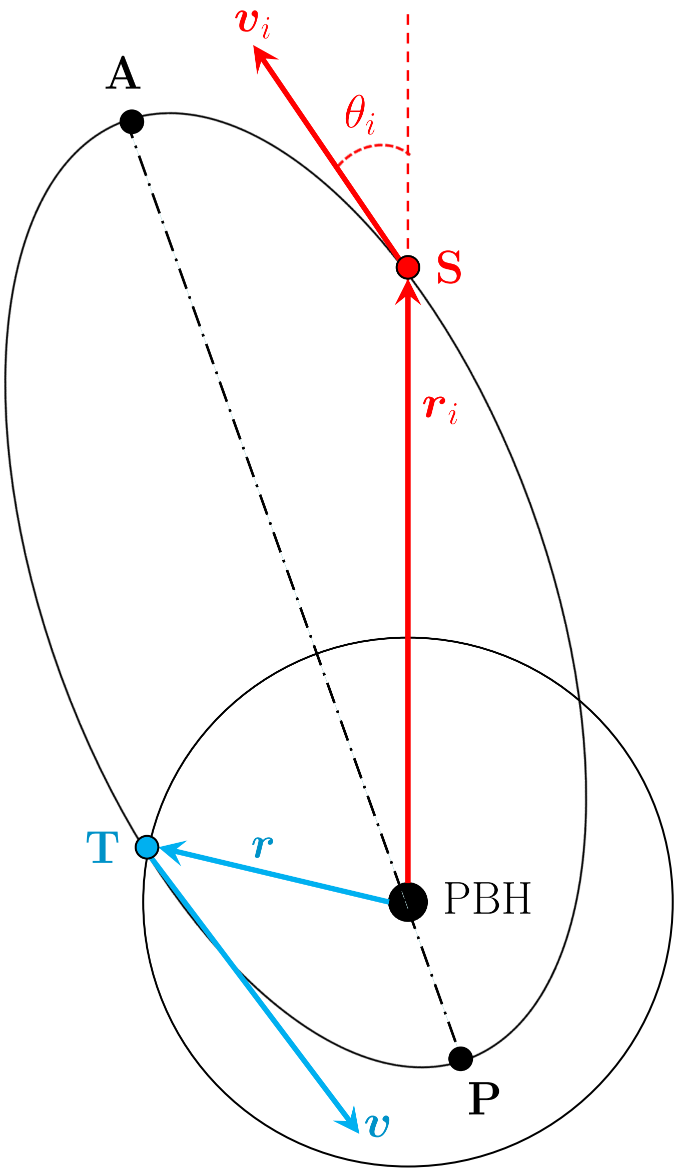
Expressing the radius r in units of the Schwarzschild radius $r_{\rm S}$ of the BH, we get the pre-collapse DM profile.

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

• $t_{\rm eq} < t$: 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

$$\tilde{\boldsymbol{r}} = \frac{\boldsymbol{r}}{r_S} \quad \text{and} \quad \boldsymbol{\beta} = \frac{\boldsymbol{v}}{c}$$

- 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

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

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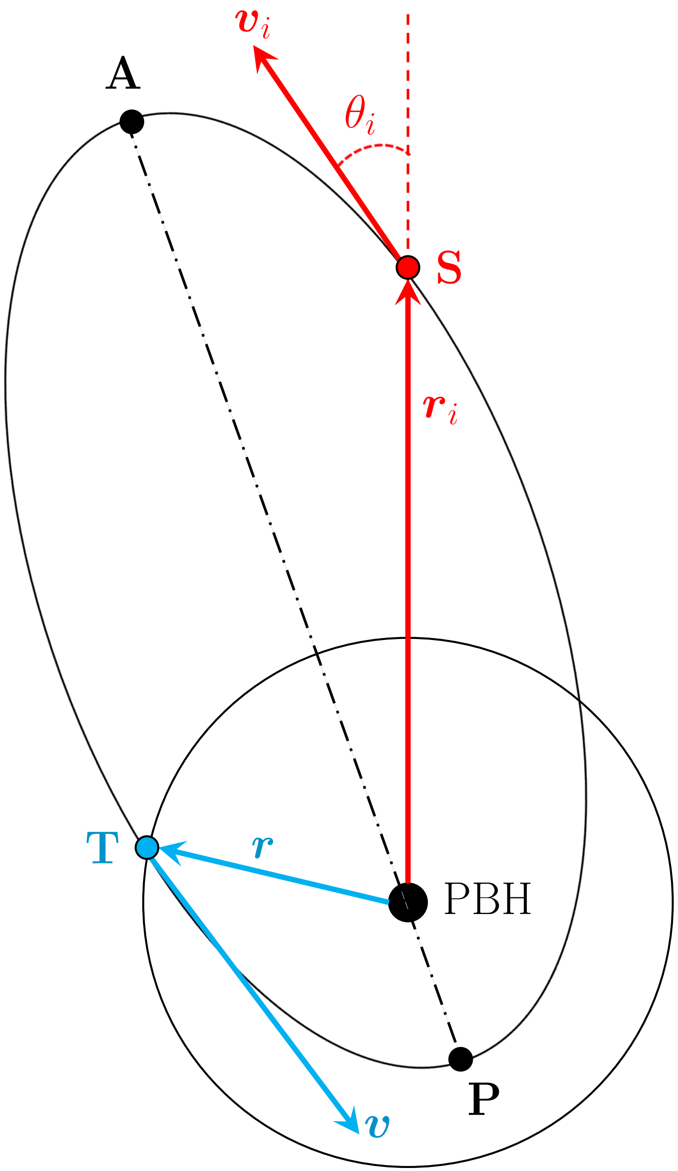

The conservation of energy and orbital momentum between **S** and **T** has consequences on the DM phase space.

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

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

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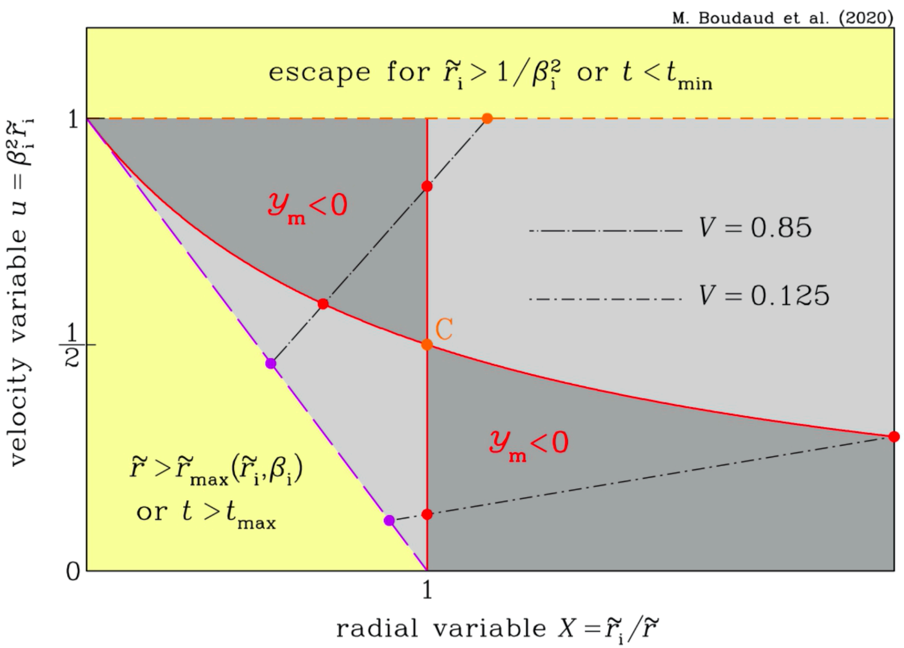

The angular variable $\mathcal{Y}_m$ can be expressed in terms of the variables u and X as

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

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

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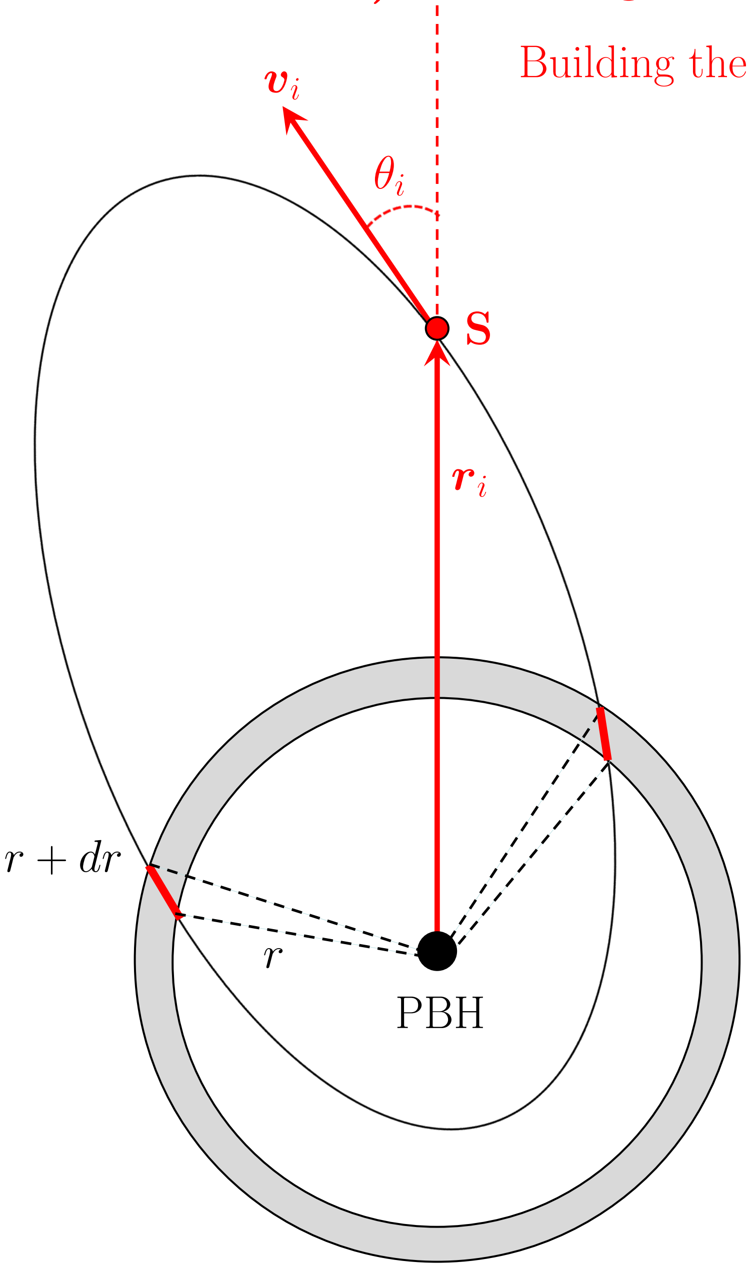


Building the dark matter mini-spike

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

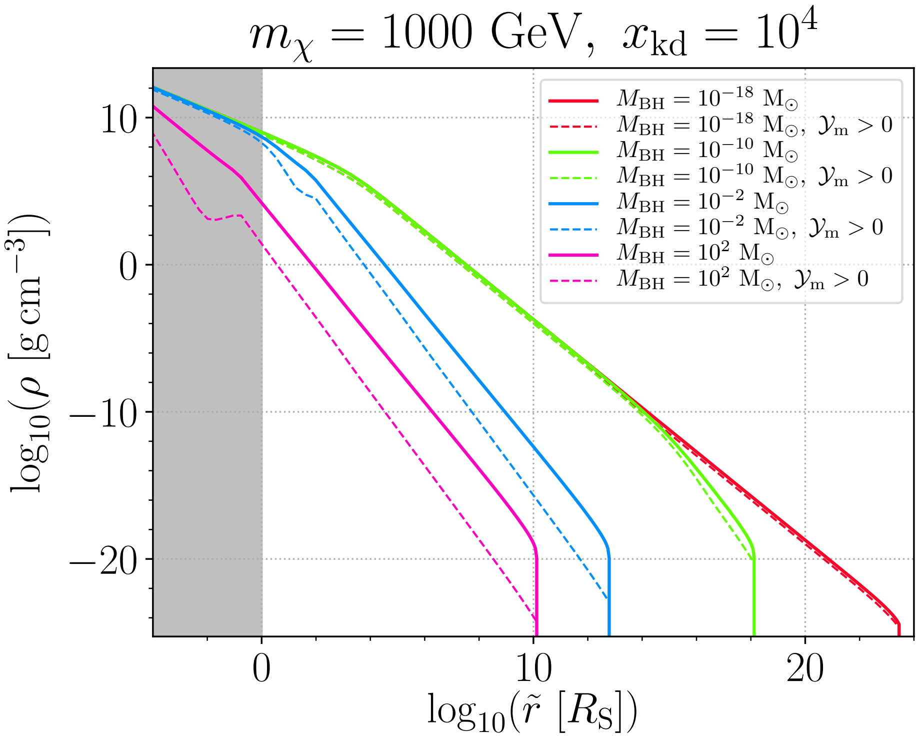
$$\mathcal{F}_{\rm MB}(\beta_i|\tilde{r}_i) \equiv \frac{1}{(2\pi\sigma_i^2)^{3/2}}\,\exp(-\beta_i^2/2\sigma_i^2)\,.$$

- 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

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



Caveats

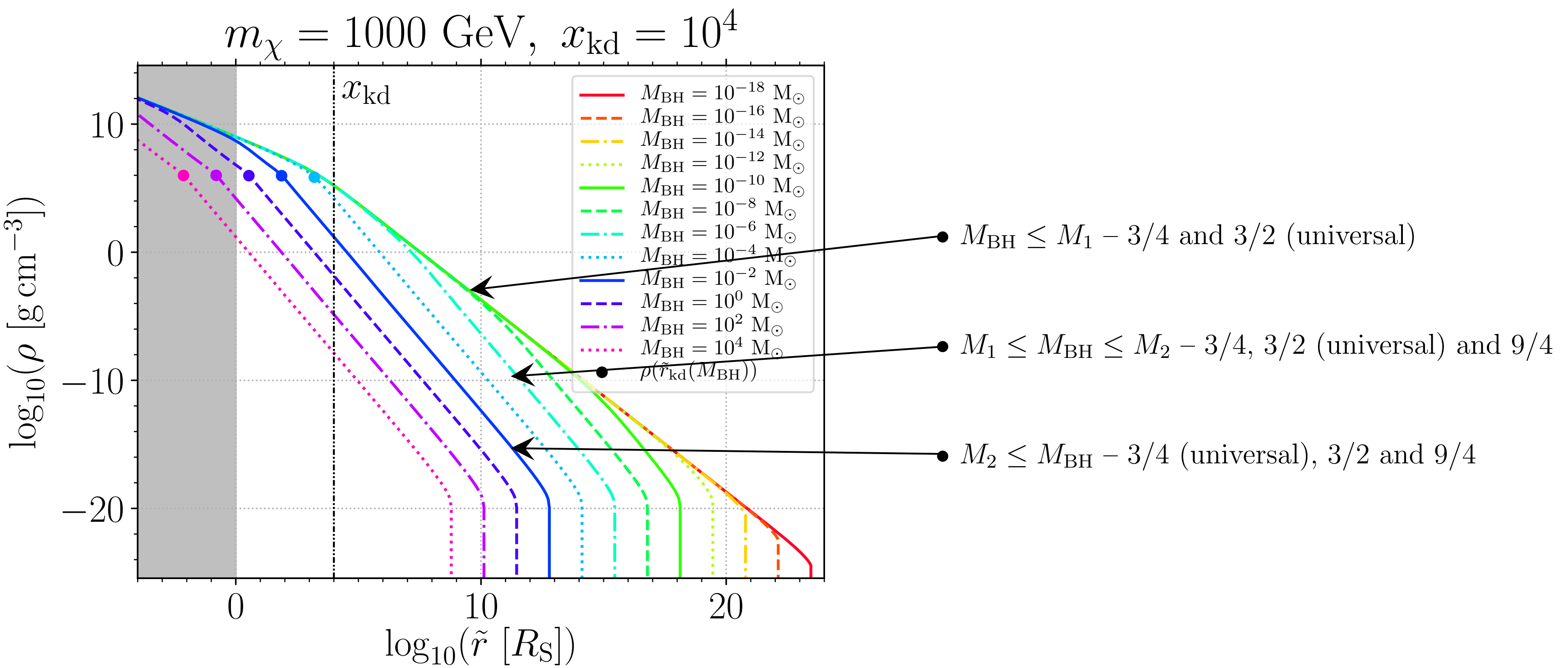
- Numerical integration is tricky (log divergences @ $\mathcal{Y}_{\rm m} = 0$)
- $\mathcal{Y}_{\rm m}$ originally defined as $y_{\rm m}^2$ (Eroshenko'16) **can be negative**. Mistake propagated in other works.

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

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

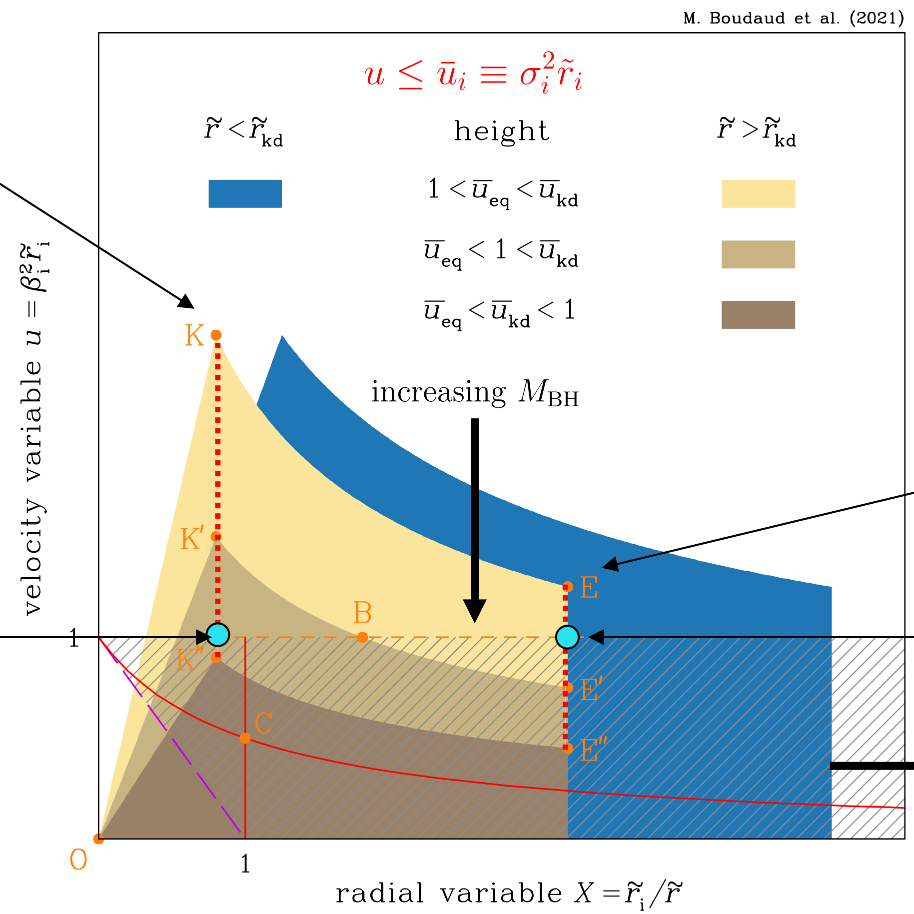
$$\rho(\tilde{r}) = \sqrt{\frac{2}{\pi^3}}\,\frac{\rho_i^{\rm kd}}{\sigma_{\rm kd}^3}\,\frac{1}{\tilde{r}^{3/2}}\iint \frac{dX}{X^{3/2}}\,du\,(1-u)^{3/2}\,\mathcal{J}(\mathcal{Y}_{\rm m})\,\exp(-u/2\bar{u}_i)$$

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

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

velocity dispersion at kinetic decoupling

critical mass M_2 for which dispersion peak is bound



velocity dispersion at equality

critical mass M_1 for which dispersion at equality is bound

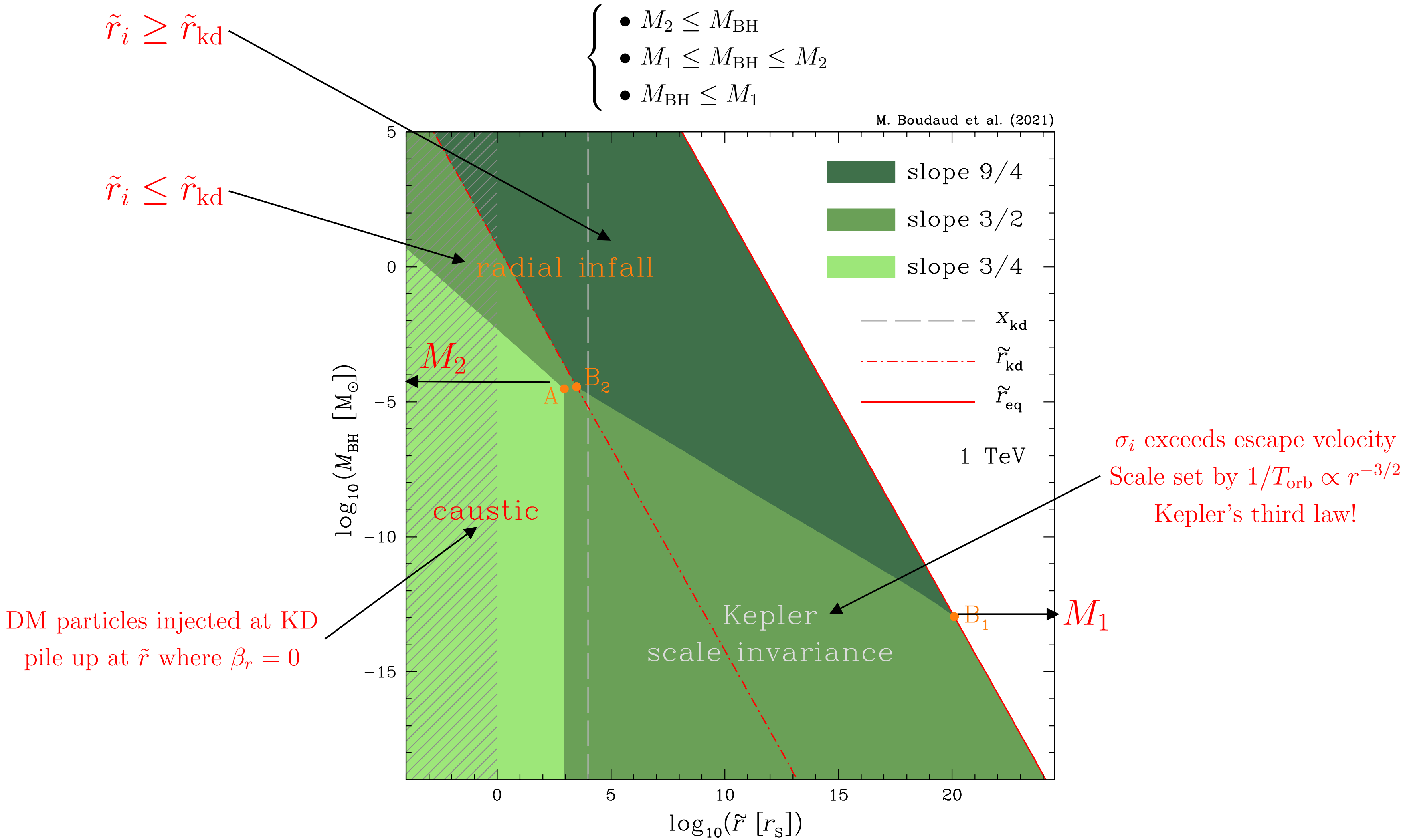
decreasing $\tilde{r}$

2) Dressing of PBHs with thermal DM

Post-collapse density profiles – phase diagram of logarithmic indices

3 regimes

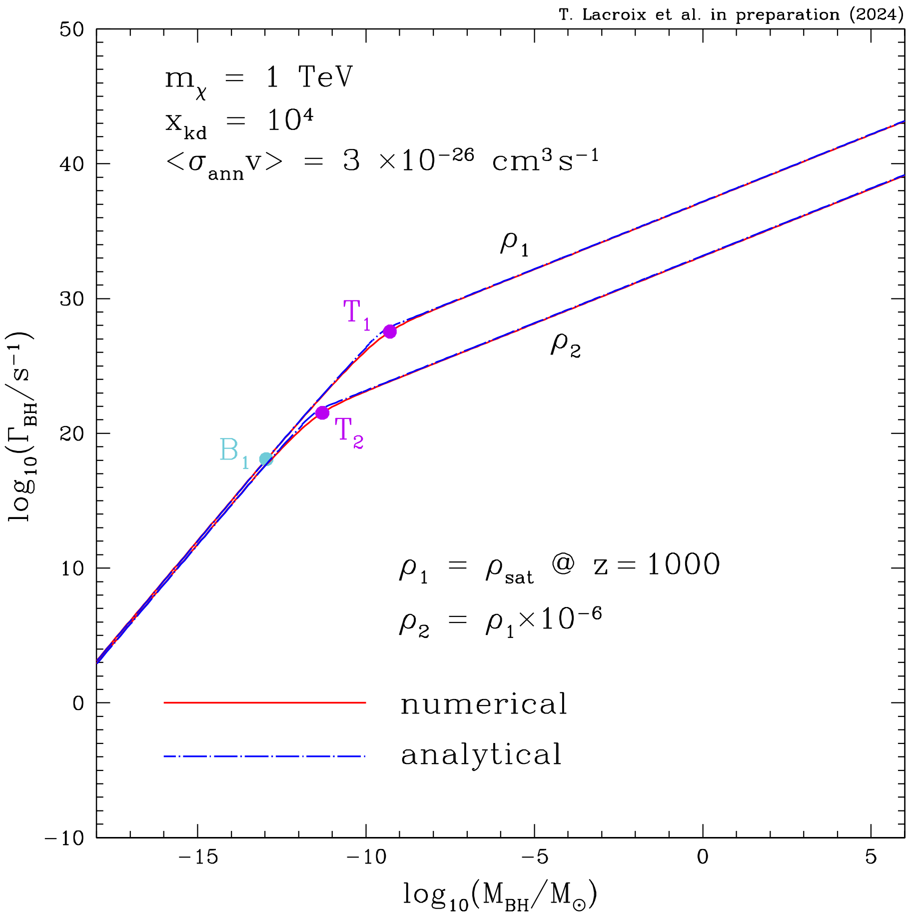
- $M_2 \leq M_{\rm BH}$
- $M_1 \leq M_{\rm BH} \leq M_2$
- $M_{\rm BH} \leq M_1$



3) Signatures and observational constraints

DM skirts around PBHs self-annihilate $\Rightarrow$ 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 $\langle\sigma_{\rm ann}v\rangle$

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

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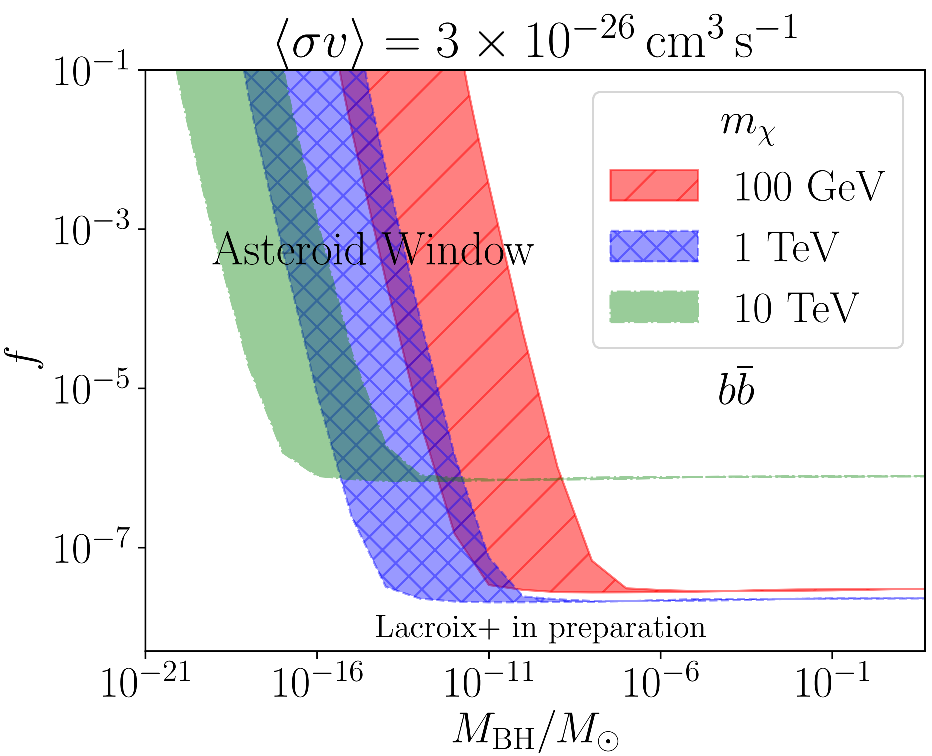
DM skirts around PBHs self-annihilate ⇒ γ-rays, ν and E injection

$$\Phi_\gamma(E_\gamma) = \frac{1}{4\pi}\,\frac{f_{\rm BH}\,\rho^0_{\rm DM}}{M_{\rm BH}} \int \frac{dz}{H_z}\,\Gamma_{\rm BH}\,e^{-\tau_{\rm opt}}\,\frac{dN_\gamma}{dE_\gamma}\Big|_{E'_\gamma}$$



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 fraction of DM in PBH

– 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 optical deph of the IGM

– The energy spectrum at injection is taken at

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

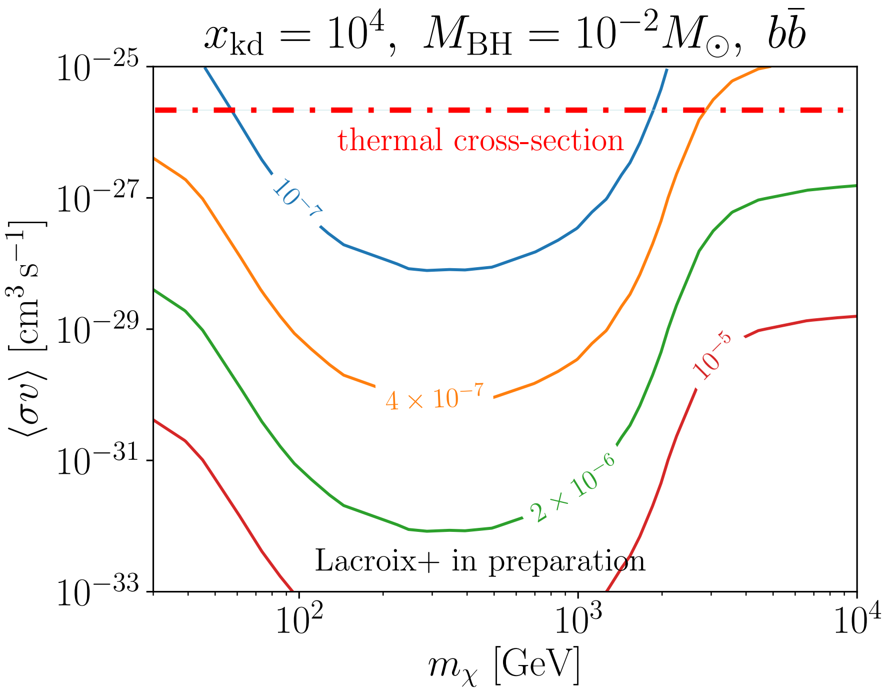
- Recasting bounds from decaying DM (Ando+'15)

$$\frac{\rho^0_{\rm DM}}{\tau_\chi m_\chi} \equiv \frac{f_{\rm BH}\,\rho^0_{\rm DM}\Gamma_{\rm BH}}{M_{\rm BH}} \quad [{\rm cm^{-3}\,s^{-1}}]$$

3) Signatures and observational constraints

Inverting the reasoning, and going a step further

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



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)

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

$$\Downarrow$$

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 are a nice connection with inflation or topological defects in early universe.

- Currently directly probed by GW measurements through coalescence events.

- PBHs might be all of DM, but only in the asteroid window.

- If $f_{\rm BH} < 1 \Rightarrow$ 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:2203.16440).

- $f_{\rm BH} > 10^{-7} \Rightarrow$ Thermal DM annihilating through s-wave strongly constrained.

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

Thanks for your attention