La de Din particios Deirin's bronnes and signatures Early clustering of DM particles around PBHs Density profiles and signatures J Statisting of Din particles around 1

Pierre Salati – LAPTh & Université Savoie Mont Blanc α oniversity payone mone Diane

AMS-02 and possible and possible and possible and possible anti-He events and possible anti-He events and possible and 1) Particle DM – Motivations of DM – Motivations of DM – Motivations of DM – Motivations of DM – Motivations o 2) Dressing of PBHs with thermal DM Ω dressing of Ω

 \sim DOU \sim $2)$ $\frac{1}{2}$ $\frac{1}{$ 2) Dressing of PBHs with thermal Di 3) Signatures and observational constraints 1) DRHs frontiele DM 2) Dressing of PRHs with therma RICAP-24 Roma International Conference on AstroParticle Physics – Frascati – September 26,2024 1) PBHs & particle DM – Motivations 2) Dressing of PBHs with thermal DM $1)$ PHs α particle DM – M 2) Dressing of PHs with the 3) Signatures and observational $\begin{array}{c} \begin{array}{c} \text{1} \end{array} \\ \text{2) B} \end{array}$ $\overline{\mathbf{a}}$ dressing of PBHs with the P 3) Signatures and observational constraints

4) 35.90.07% 3He archives
Gollaboration with J Lavalle V Poul Based on arXiv:2106.07480 Collaboration with J. Lavalle, V. Poulin, P. Sandick, ...

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

1) PBHs $\&$ particle DM – Motivations $F_{\rm F}$ is the search of evidence to the search of evidence to the search of evidence to the search of evidence $1)$ PRHs ℓ particle

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

$M_{\text{PBH}}\text{ [g]}$ $M_{\text{PBH}}\text{ [g]}$ 10^{30} 10^{33} 10^{36} From early ideas to the search of evidence

• Carr & Hawking $(1974) \Rightarrow$ BHs in the early universe rct tct – Formation and accretion *•* Carr & Hawking (1974)) BHs in the early universe

 \int from inflationary density party-hotions. from muationa
from phase tra rom phase transitions $\sqrt{ }$ from inflationary density perturbations from phase transitions

- $\frac{1}{\sqrt{2}}$ Evaporation and constraints \Rightarrow limits on *f*_{BH} vs *M*_{BH}
- $\frac{1}{2}$ OM 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*_{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

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

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

1) PBHs & particle DM – Motivations $F_{\rm F}$ is the search of evidence to the search of evidence to the search of evidence to the search of evidence

FIG. 1. - Upper bounds on the abundances of PBHs as a function of WIMP mass. Bounds on annihilation into gamma rays (black; $Br(\gamma) = 1$) 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. Gammarays 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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*r*2 PBHs are no longer a theoretical fantasy

- The turn-around radius of the turn-around radius of the turn-around terms is identified with the turn-around terms really **phs** in coarcscence – Heavy BHs in coalescence events unexpected
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Radius of influence of a black hole in the radiation dominated era 2) Dressing of PBHs with thermal DM 2) Dressing of PBHs with the α Radius of influence of a black hole in the radiation dominated era 2) Dressing of PBHs with the

 \overline{C} dramatic of PBHs with the PBHs with the \overline{C} Radius of influence of a black hole in the radiation dominated era

 \bullet rearvery, the sphere of influence of a black hole enclose *•* Naively, the sphere of influence of a black hole encloses as

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

²_{inf} increase As time t goes on, ρ_{tot} decreases and r_{inf} increases like $T^{-4/3}$ which I and plasma domperadure. with *T* the plasma temperature.

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

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

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

• In a radiation dominated cosmology, trajectories are scaleinvariant 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 $\eta_{\text{ta}} \simeq 1.086$ (Boudaud+'21). Expressing cosmic time *t* as a function of plasma density ρ_{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 2) Dressing of PBHs with thermal DM 2) Dressing of PBHs with the α Radius of influence of a black hole in the radiation dominated era

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

 $\frac{\text{2020}}{1}$ much plasma as M_{BH} . *•* Naively, the sphere of influence of a black hole encloses as

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2) Dressing of PBHs with thermal DM *ⁱ* / *r* σ with thermal DM 2) Dressing of PRHs with thermal DM 2) Dressing of PBHs with thermal I

) nion-shell dark matter mini-spike profile prior to collapse α Onion-shell dark matter mini-spike profile prior to collapse Onion-shell dark matter mini-spike profile prior to collapse

Expressing the radius *r* in units of the Schwarzschild radius *r*^S • $t < t_{kd}$: prior to kinetic decoupling, DM particles are dragged by the expanding plasma. by the expanding plasma.

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

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

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

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

Expressing the radius r in units of the Schwarzschild radius r_S of the BH, we get the pre-collapse DM profile.

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

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

2) Dressing of PBHs with thermal DM Expressing the radius *r* in units of the Schwarzschild radius *r*^S \tan thermal $\tan N$ tion at **S** α of DDH₂ **...:**
 ι ¹ / *r*₂ *a*³ *ⁱ* ⌘ ⇢DM(*t*kd) inf while *ⁱ* / *^a*¹ \tilde{z} Expression the injection at \mathbf{S} αf **PRH**_q with the mal DM die Leads with the much \mathbf{D} **PBHs** with thermal DM eaching \mathbf{T} from the injection of \mathbf{S} Orbital kinematics – Reaching ${\bf T}$ from the injection at ${\bf S}$ \mathbf{b} the expanding plasma \mathbf{b} *• t* = *t*kd : at kinetic decoupling, DM particles stop colliding on 2) Dressing of PBHs with thermal

*• t*eq *< t* : during the matter dominated era, the DM secondary infactor to DM haloes with much less with much less to DM. • DM particles feel on **i** is a *revitational field of the* • DM particles reel only the gravitational field of the BH. **e** DM particles feel only the gravitational field of the BH. \bullet DM particles feel only the gravitational field of the BH.

 \bullet DM trajectories are hereafter determined in Contrajectories are necessary determined in the framework of
classical mechanics and Newtonian gravity. \overline{a} and \overline{b} \bullet DM trajectories are hereafter determined in the framework of $\frac{1}{2}$ $\frac{1}{2}$

• We can denne the reduced orbital variables \bullet We can define the reduced orbital variables

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

 α *inergy* and orbital momentum are conserving \bullet Energy and orbital momentum are conserved throughout each trainertown Δ As time *t* goes on, ⇢tot decreases and *r*inf increases like *T* 4*/*³ frajectory.

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

I particl ⇢kd *ⁱ* if ˜*rⁱ r*˜kd • A DM particle injected at S reaches the target point T if its orbital regulation • *A DM* particle injected at *B* reaches the target point **1** in its orbital variables fulfill the condition

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

⇢*i*(˜*ri*) ' 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** Expressing the radius *r* in units of the Schwarzschild radius *r*^S \tan thermal $\tan N$ tion at **S** α of DDH₂ \ldots ²/₂ \ldots ²/₄ \ldots ²/₄ *ⁱ* ⌘ ⇢DM(*t*kd) \tilde{z} Expression the injection at \mathbf{S} αf **PRH**_q with the mal DM die Leads with the much \mathbf{D} PBHs with thermal DM eaching \mathbf{T} from the injection of \mathbf{S} infall leads to DM haloes with much lesser densities. Orbital kinematics – Reaching ${\bf T}$ from the injection at ${\bf S}$ \mathbf{b} the expanding plasma \mathbf{b} *• t* = *t*kd : at kinetic decoupling, DM particles stop colliding on 2) Dressing of PBHs with thermal

 θ_i and **T** has consequences on the DM phase space. The conservation of energy and orbital momentum between ${\bf S}$ The conservation of energy and orbital momentum between S *r*kd = *r*inf(*t*kd) with ⇢kd

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

1) DM at point **S** is trapped if $E < 0$. **for the first time the first transport of** \tilde{F} **1)** DM at point **S** is trapped if $\tilde{E} < 0$. $\frac{4}{1}$

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

 $\frac{4}{1}$ The variable u is the ratio of r_i
The variable u is the ratio of kinetic-to-potential energies. *• t*kd *tⁱ t*eq : at time *ti*, DM particles located at *rⁱ* = *r*inf(*t*i)

 $\mathbf{r} = \mathbf{r} \cdot \mathbf{r}$ is defined by sequence $\mathbf{r} = \mathbf{r} \cdot \mathbf{r}$ **2)** At point **T**, the DM velocity squared β^2 must be positive. $\sum_{i=1}^{n}$ in units of the Schwarzschild radius $\sum_{i=1}^{n}$ in units of $\sum_{i=1}^{n}$ \blacktriangleright \blacktriangler 2) At point T, the DM velocity squared β^2 must be positive.

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

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

$$
\sin^2\theta_i\,+\,\left\{\frac{\tilde r^2}{\tilde r^2_i\beta^2_i}\right\}\beta^2_r=\frac{\tilde r^2}{\tilde r^2_i}\left\{1+\frac{1}{\beta^2_i}\left(\frac{1}{\tilde r}-\frac{1}{\tilde r_i}\right)\right\}\equiv1-\mathcal Y_{\mathrm m}\,.
$$

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

2) Dressing of PBHs with thermal DM Orbital kinematics – Reaching **T** from the injection at **S** $\frac{1}{2}$ *r*bital kinematics – Reaching **T** from the injection at **S** 2) Dressing of PBHs with thermal

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

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

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

 $>1/\beta$ ² or $t < t_{\text{min}}$ and T has consequences on the DM phase space. The conservation of energy and orbital momentum between S

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

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

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

*• t*kd *tⁱ t*eq : at time *ti*, DM particles located at *rⁱ* = *r*inf(*t*i) The variable *u* is the ratio of kinetic-to-potential energies.

feel for the first time time the $\frac{1}{2}$ drag and start falling onto it. Their falling onto it. Their falling one is the start falling on $\frac{1}{2}$ $\sum_{i=1}^{\infty}$ is point $\sum_{i=1}^{\infty}$, the *DM* velocity is 2) At point T, the DM velocity squared β^2 must be positive.

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2) Dressing of PBHs with thermal DM $\sqrt{}$ \ddot{o} DDM haloes with much less with much less to \ddot{o} . s s s ing of PBHs with thermal DM $2)$ Dressing of PRHs with therm

¹ Building the dark matter mini-spike Expressing the radius *r* in units of the Schwarzschild radius *r*^S

I_{re} readigate ℓ , D_{co} in ϵ ingredients $\&$ Recipe. edients & Recipe $\ddot{}$ Ingredients & Recipe

 \blacksquare \blacksquare The injection of a single DNI particle at \blacksquare yields the averaged $\frac{i}{\sqrt{2}}$ • The injection of a single DM particle at S yields the averaged θ *t* is density θ ρ such that post-collapse density $\delta \rho$ such that

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

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

 T_{SUSY} and T_{SUSY} and T_{SUSY} and T_{SUSY} and T_{SUSY} and T_{SUSY} and T_{SUSY} **•** The orbital period follows Kepler's third law of planetary mo- \overline{a} tion. At fixed \tilde{r}_i and β_i , T_{orb} does not depend on θ_i .

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

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

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

• DM velocities are distributed according to the Maxwellian

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

• 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 2) Dressing of PBHs with thermal DM 2) Dressing of PRHs with the

Post-collapse density profiles – numerical results Post-collapse density profiles – numerical results 2) Dressing of PBHs with thermal DM \mathbf{P} and \mathbf{P} and

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

Caveats **Caveats**

^pcos²✓*ⁱ ^Y*^m

• Numerical integration is tricky (log divergences @ *Y*^m = 0) • Numerical integration is tricky (log divergences $\mathcal{Q} \mathcal{Y}_m = 0$)

> *• Y*^m originally defined as *y*² ^m (Eroshenko'16) can be negative. • \mathcal{Y}_{m} originally defined as y_{m}^2 (Eroshenko'16) **can be negative.** ∕iista Mistake propagated in other works.

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

2) Dressing of PBHs with thermal DM Post-collapse density profiles – numerical results *f* Dressing of PBHs v \mathbf{u} *i*th t ³*/*² Γ DM *i* DWI

est[.] $Post\text{-collasse density profiles} - num\epsilon$

2) Dressing of PBHs with thermal DM : DRH_q with thermal I kinetik win) Dressing of PBHs with thermal DM critical mass *M*¹ for which

Post-collapse density profiles – the velocity triangle Post-collapse density profiles – the velocity tries \sim - the velocity trial - 3 parameters: *m*, *T*kd & *M*BH $\ddot{}$ ZZ *dX* \mathcal{B} *A COCITY* triang Post-collapse density profiles – the velocity triangle

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

2) Dressing of PBHs with thermal DM \triangleright with thermal \triangleright \overline{r} 2) Dressing of PBHs with thermal DM Post-collapse density profiles – phase diagram of logarithmic indices *i* except velocity α scale set by 1*/T*orb / *r*3*/*²

Post-collapse density profiles – phase diagram of logarithmic indices *•* $\frac{1}{2}$ \mathbf{R}

3) Signatures and observational constraints 3) Signatures and observational

DM skirts around PBHs self-annihilate $\Rightarrow \gamma$ -rays, ν and E injection ⇢⇢sat ² Z *^r*˜eq ⇢⇢(˜*r*) $\frac{1}{2}$ DM skirts around PBHs self-annihilate $\Rightarrow \gamma$ -rays, *v* 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 $\rho_{\rm sat}$ BH depends on *m*, *T*kd, *M*BH and ⇢sat

B
Bhade depends on *M. Jistuikation Ast*toned by smalleled *•* 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 $(\tilde{r}, M_{\text{BH}})$ plane at \tilde{r}_t and M_t such that

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

⇢sat = ⇢3*/*2(˜*rt*) = ⇢9*/*4(˜*rt, Mt*) • At fixed ρ_{sat} , 2 regimes for Γ_{BH} vs M_{BH}

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

 $\frac{9}{100}$ rogimes for $\Gamma_{\rm pt}$ • At fixed M_{BH} , 2 regimes for Γ_{BH} vs $\langle \sigma_{\text{ann}} v \rangle$

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

3) Signatures and observational constraints 3) Signatures and observational constraints 3) Signatures and observational **3**) Signatures and observational 1 ^{α} *f*BH \overline{r} $\frac{1}{2}$ $observat$ α $\ddot{}$ i \mathbf{I} Ť, 3) Signatures and observational constraints Description of the proper versioner computation

DM skirts around PBHs self-annihilate $\Rightarrow \gamma$ -rays, ν and E injection DM skirts around PBHs self-annihilate $\Rightarrow \gamma$ -rays, ν and E injection *H*⁰ $\alpha \Rightarrow \gamma$ -rays. ν and

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

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

 γ -ray flux from DM skirts around PBH

- ¹ *•* μ ^{*p*}*•* μ **^{***γ***}** \rightarrow μ **^{***γ***}** \rightarrow μ **^{***γ***}** $e^{iS^{-1}}$ is more upper limit on $\Phi_{\gamma} \Rightarrow$ upper limit on f_{BH} ⌘ MN is ac background \bullet If DM is mostly in the form of thermal particles
	- \bullet Standard calculation $=$ Stephend col *•* Standard calculation
		-
- $\frac{1}{2}$ H_z is the expansion rate at redshift *z*

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

 $\begin{array}{r} \n\text{for } P \text{ is the } \gamma \text{ operator of the form} \\
\text{- The energy spectrum at injection is taken at} \n\end{array}$ r
J H_0 $-\tau_{\text{opt}}(E_{\gamma}, z)$ is the γ optical depth of the IGM

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

 \mathbf{u} *M*BH if *M*BH *M*¹ • 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 3) Signatures and observational constraints DM skirts around PBHs self-annihilate $\Rightarrow \gamma$ -rays, ν and E injection **3**) Signa 1 ^{α} *f*BH \overline{r} $\frac{1}{2}$ $observat$ α $\ddot{}$ i \mathbf{I} Ť, $\frac{1}{\sqrt{2}}$ $\ddot{\text{a}}$ and upservational *H^z H*⁰ and PBHs self-annihilate $\Rightarrow \gamma$ -rays, ν and E injection **3**) S .
ignature \sim *m* and o bserva t ional constr $\overline{\text{max}}$ aints: \overline{a}

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

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

• • If α *E* injection ionizes the primordial plasma

 $\frac{1}{\sqrt{2}}$ The number densities n_x and n_{BH} are given is • The number densities n_χ and n_{BH} are given by

ions
_{1³ s⁻¹} =
$$
n_{\chi}(z) = \frac{\rho_{\text{DM}}^0}{m_{\chi}} (1+z)^3
$$
 and $n_{\text{BH}}(z) = \frac{\rho_{\text{DM}}^0 f_{\text{BH}}}{M_{\text{BH}}} (1+z)^3$

⇢sat ⁼ *^m* = p⌦⇤ + ⌦M(1 + *z*)³ *ⁿ*(*z*) = ⇢⁰ DM Planck c where μ is the contract of ¹ by the Planck collaboration (Aghanim+'18) *m* ervational bound on DM energ em \bullet Observational bound on DM energy injection obtained

$$
p_{\rm{ann}} = f_{\rm{eff}} \frac{\langle \sigma_{\rm{ann}} v \rangle}{m_{\chi}} \leq 3.2 \times 10^{-28} \text{ cm}^3 \text{ s}^{-1} \text{ GeV}^{-1}
$$

Example 5
• Recasting CMB bounds on p_{env} f **10 TeV into an upper limit on** f_{BH} **yields** • Recasting CMB bounds on p_{ann} from annihilating DM

1

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

 $\frac{1}{2}$ where

$$
\Gamma_{\rm CMB}^{\rm sup} = \frac{p_{\rm ann}^{\rm sup}}{f_{\rm eff}} \,\rho_{\rm DM}^0 (1+z)^3
$$

more r ²/₂ if α ₁ if α ₂ if $\$ A more refined treatment requires implementation in CLASS. $f(x)$ • A fast but very crude result can be obtained using $z \sim 600$.

3) Signatures and observational constraints 3) Signatures and observational constraints \mathbf{S}) \mathbf{S} is an and observational constraints and observational constraints and observational constraints and \mathbf{S} Inverting the rate of the respect α step functions around PBH skirts around $\frac{1}{2}$ Signatures and observational constant (*m, x*kd*,*hann*v*i*, M*BH*, f*BH

Inverting the reasoning, and going a step further d voing a stop further *f*Burning, and β ^ong a stop

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

GW observatories target sub-solar BH

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

 m_{BH} and *H* μ_{BH} have been discovered in GW events.

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

> $\frac{M}{M}$ bounds from decaying DM (Ando+ 15) • Recasting bounds from decaying DM (Ando+'15)

$$
2m_{\chi} \Gamma_{\text{BH}} = \frac{M_{\text{BH}}}{\tau_{\chi} f_{\text{BH}}}
$$
\n
$$
\downarrow
$$
\nupper limit on $\langle \sigma_{\text{ann}} v \rangle$ vs m_{χ} at fixed x_{kd} \n
$$
\downarrow
$$
\n10⁴

 $\overline{\mathbf{n}}$ wave annihilation severely constrained + *s*-wave annihilation severely constrained PBH fraction $> 10^{-7}$ strong impact on WIMP

Takeawa

- 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).
- $f_{\text{BH}} > 10^{-7} \Rightarrow$ 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