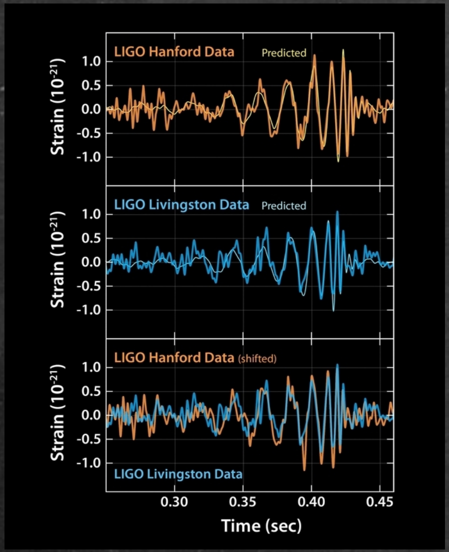
(Thermal) Dark Matter
and
Primordial Black Holes

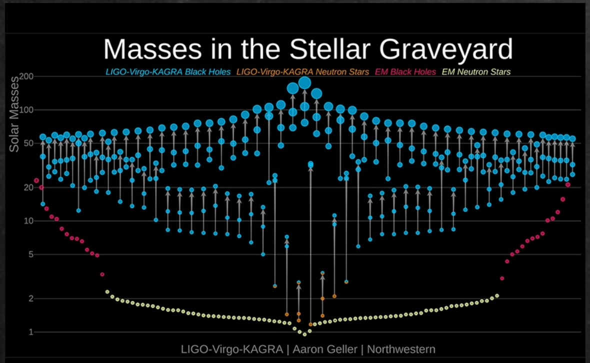
Julien Lavalle
CNRS – LUPM – Montpellier
*with **Mathieu Boudaud** (deceased), **Thomas Lacroix** (IFT-Madrid), **Pierre Salati**, and **Martin Stref** (LAPTh-Annecy)*
[mostly based on arXiv:2203.16440 and work in prep.]

INVISIBLES-22, Orsay-IJCLab, June 2022

The LIGO/VIRGO revival of PBHs

LIGO+VIRGO ‘15-16





LIGO/VIRGO/KAGRA (O3)
arXiv:2111.03606 – 2111.03634

Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]
[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

arXiv:1603.00464 (PRL)

Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

Misao Sasaki,[1] Teruaki Suyama,[2] Takahiro Tanaka,[3,1] and Shuichiro Yokoyama[4]

arXiv:1603.08338 (PRL)

The clustering of massive Primordial Black Holes as Dark Matter: measuring their mass distribution with Advanced LIGO

Sébastien Clesse[1,*] and Juan García-Bellido[2,†]

arXiv:1603.05234 (PDU)

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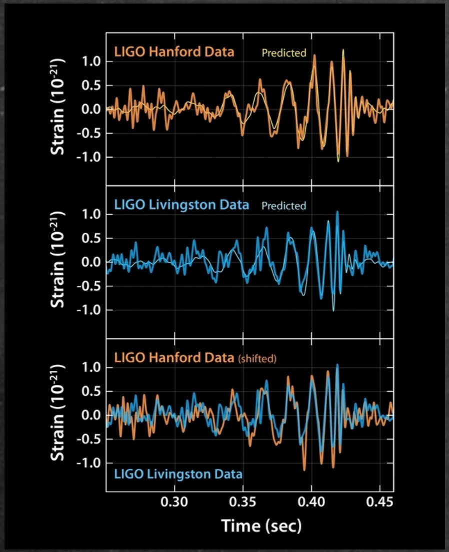

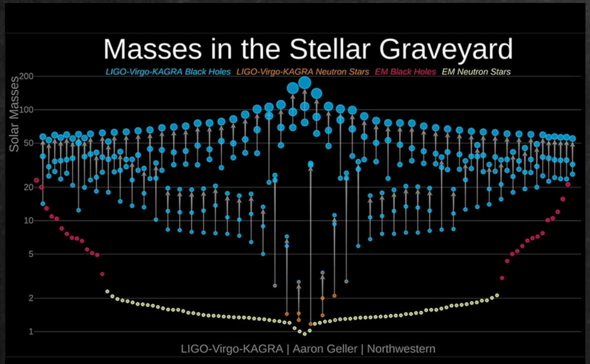

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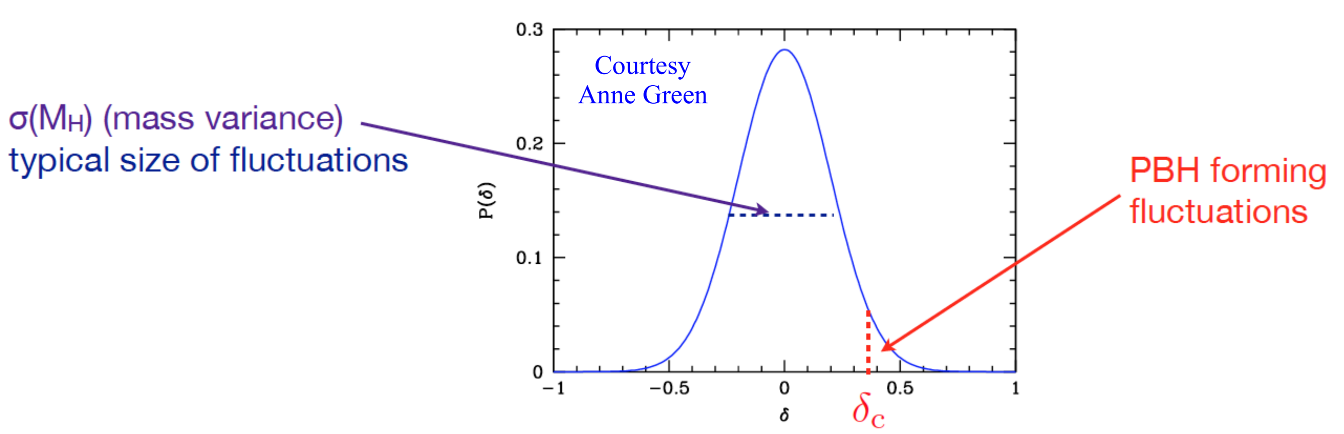
NB: Merger rate has now turned to a constraint on PBH DM
(clustering effects difficult to work out)
[Hütsi+, Ali-Haïmoud+, Jedamzik, etc.]

PBH links to power spectrum and constraints



Critical threshold
[Zeldovich, Novikov, Hawking, Carr]

$$\delta \geq \delta_{\rm c} \sim w = \frac{p}{\rho} = \frac{1}{3}$$

$$M_{\rm H} \sim 10^{15}\,{\rm g}\left(\frac{t}{10^{-23}\,{\rm s}}\right)$$

$$\beta(M) \sim \int_{\delta_{\rm c}}^{\infty} P(\delta(M_{\rm H}))\,{\rm d}\delta(M_{\rm H})$$

Gaussian spectrum

$$\beta(M) = {\rm erfc}\left(\frac{\delta_{\rm c}}{\sqrt{2}\sigma(M_{\rm H})}\right)$$

$$\sigma(M_{\rm H}) \sim 10^{-5}$$

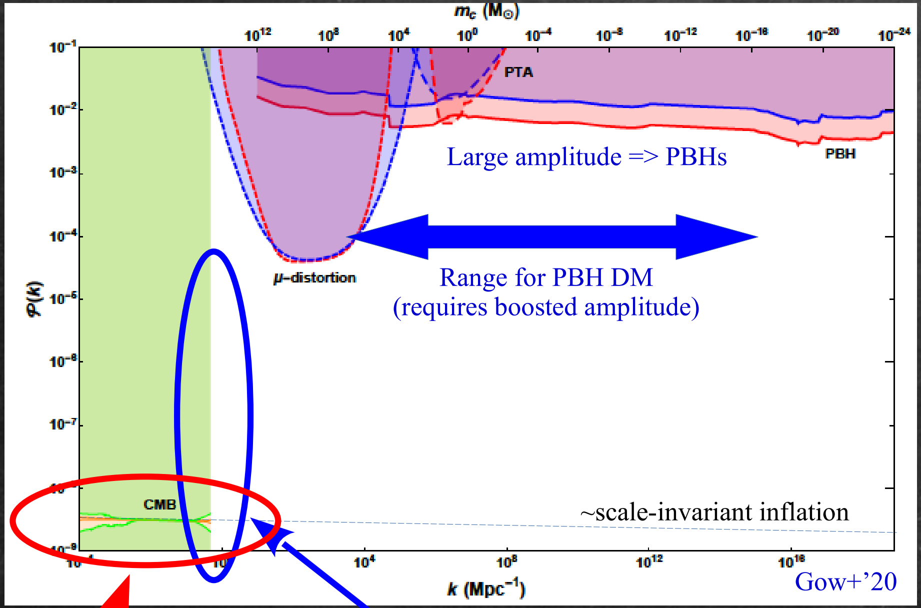
On CMB scales

$$\boxed{\sim 10^5 \exp\left[-(10^5)^2\right]}$$

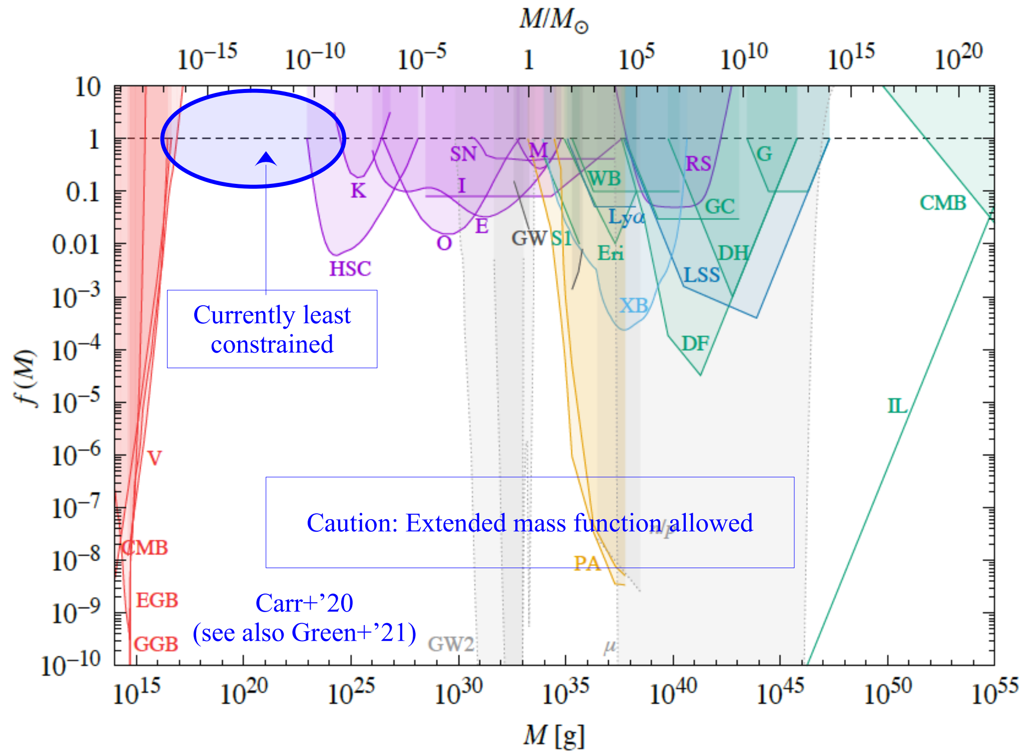
Mass fraction in PBHs strongly suppressed in standard inflation.

PBH links to power spectrum and constraints

Primordial power spectrum



Constraints on PBH DM fraction



Current CMB constraints
[Planck+'18]

Current LSS constraints
[e.g. Ly-alpha]

Non-trivial mass function expected [e.g. Jedamzik'97], but many constraints over the DM mass range: What if $f_{\rm PBH} < 1$?

Assume Thermal Particle DM (WIMPs) + PBHs

Composite DM
$\Omega_{DM} = \Omega_{PBH} + \Omega_{ThDM}$

PBH fraction:
$f_{PBH} = \Omega_{PBH}/\Omega_{ThDM}$

Rescaled thermal cross section:
$\langle \sigma v \rangle = \langle \sigma v \rangle_0 / (1-f_{PBH}) \propto \{\Omega_{DM}(1-f_{PBH})\}^{-1}$

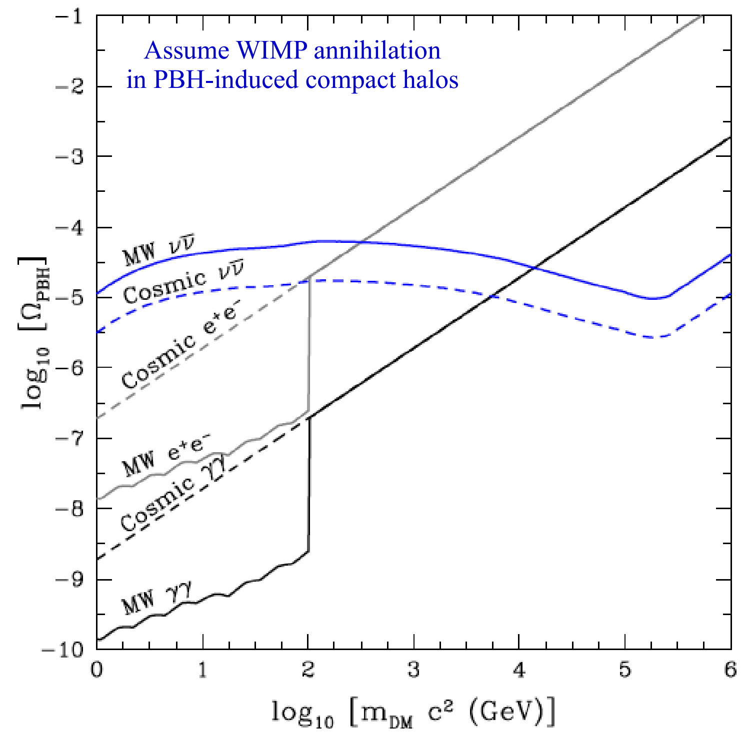
Formation of compact DM
spiky halos around PBHs
+ consequences

PBH + particle DM: past studies

Mack, Ostriker, Ricotti '07-08
→ Mass growth of PBH from DM accretion (very cuspy halos, with index ~ 9/4 or 3/2)
→ Dominated by accretion in matter era
→ Tentative sources of IMBHs + ULX
*** power-law density from radial infall

Lacki & Beacom '10
→ Assume PBHs + WIMPs
→ Accretion model of Mack+'07
→ Set limits on PBH fraction in a WIMP-DM universe

Constraints on PBH DM fraction



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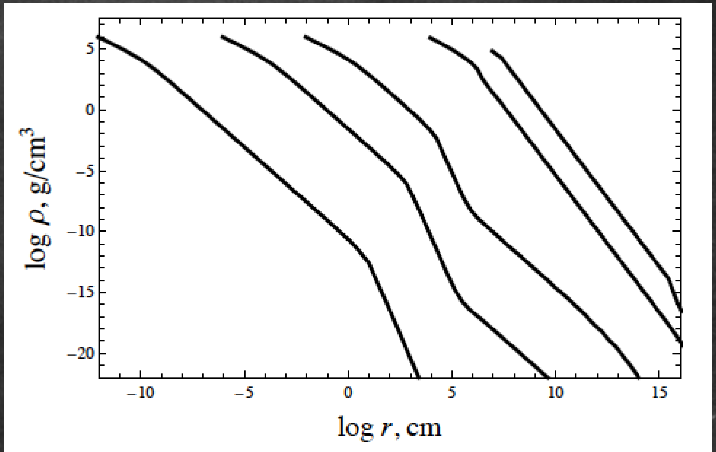
Dark Matter Density Spikes around Primordial Black Holes

Yu. N. Eroshenko[1,*]

arXiv:1607.00612



Eroshenko'16:
→ Can fully integrate the DM particle orbits in radiation era (full account of angular momentum).
→ Ultra-compact DM spikes with various indices
→ Used in Boucenna+'17, Carr, Kühnel+'20, etc. to revisit the WIMP/PBH constraints
→ Simulation of spike formation in Adamek+'19

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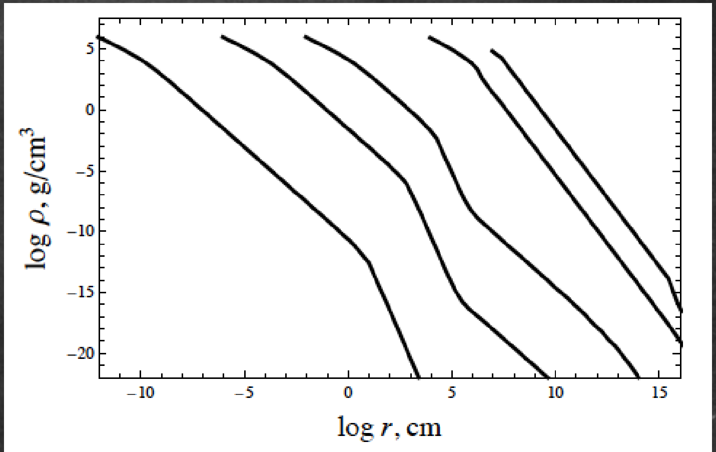


Lacki & Beacom '10
→ Assume PBHs + WIMPs
→ Accretion model of Mack+'07
→ Set limits on PBH fraction in a WIMP-DM universe

Can we understand this diversity of profiles?
→ Revisit the work of Eroshenko

Timeline

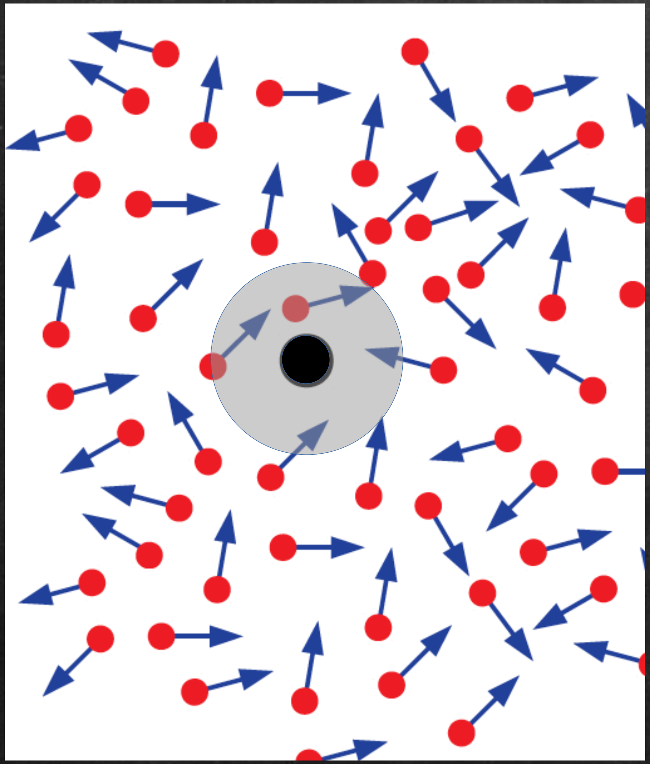
Radiation domination

Thermal freezout

Collisions with hot plasma

Equality

Matter domination



Coupled particles don’t feel the black hole

Timeline

Radiation domination

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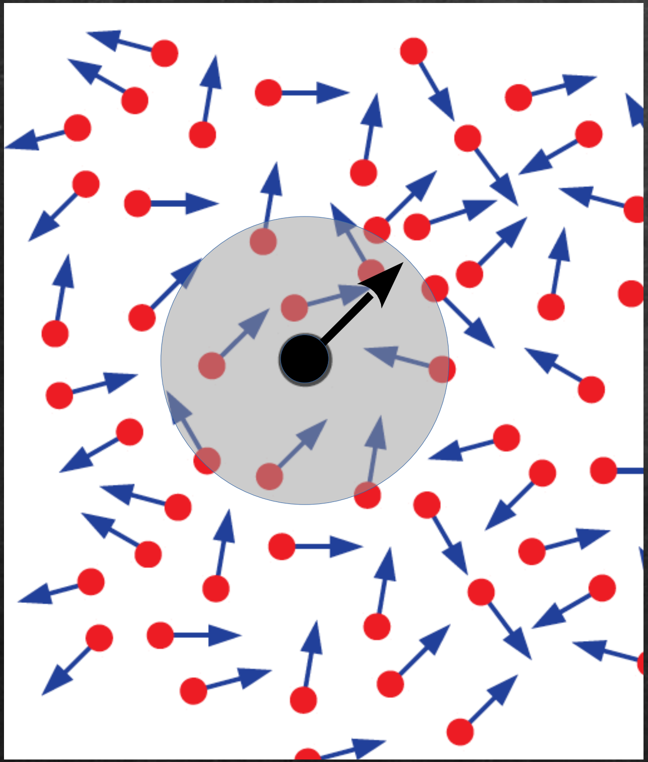
Collisions with hot plasma

Equality

Matter domination

Notion of gravitational influence radius

1) Imposing the BH sets the dynamics
[Eroschenko'16]



Coupled particles don't feel the black hole

$$M_{\mathrm{BH}} \geqslant \frac{4\pi}{3} r_{\mathrm{infl}}^3 \rho_{\mathrm{tot}}$$

$$H = \frac{\dot{a}}{a} = \left\{ \frac{8\pi G}{3} \rho_{\mathrm{tot}} \right\}^{1/2} = \frac{1}{2t}$$

$$\boxed{r_{\mathrm{infl}} = (8\, G M_{\mathrm{BH}})^{\frac{1}{3}}\ t^{2/3}}$$

Timeline

Radiation domination

Thermal freezout

Collisions with hot plasma

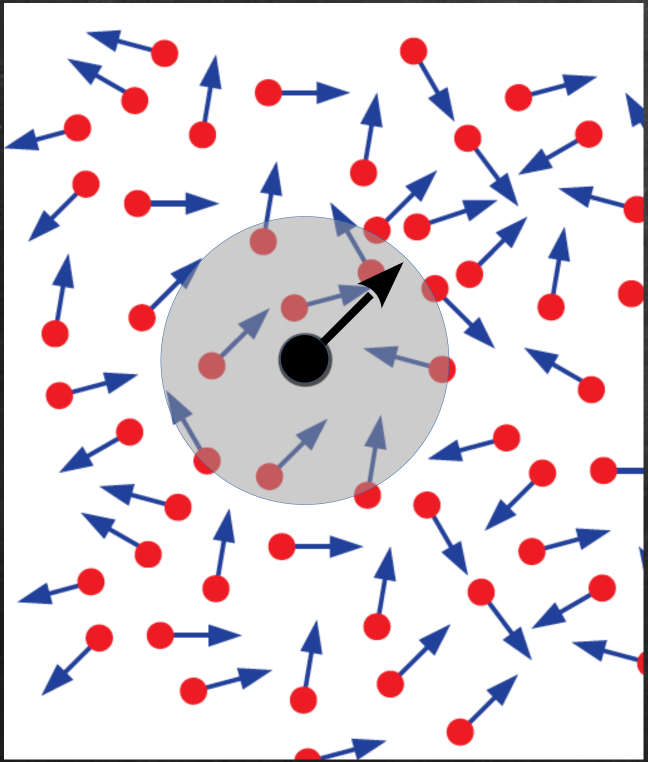
Equality

Matter domination

Notion of gravitational influence radius

2) Solving the equation of motion of a test particle

[Mack+'07, Adamek+'19]



Coupled particles don't feel the black hole

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

$$\frac{\ddot{a}}{a} = -\left\{\frac{1+3\omega}{2}\right\} H^2$$

Timeline

Radiation domination

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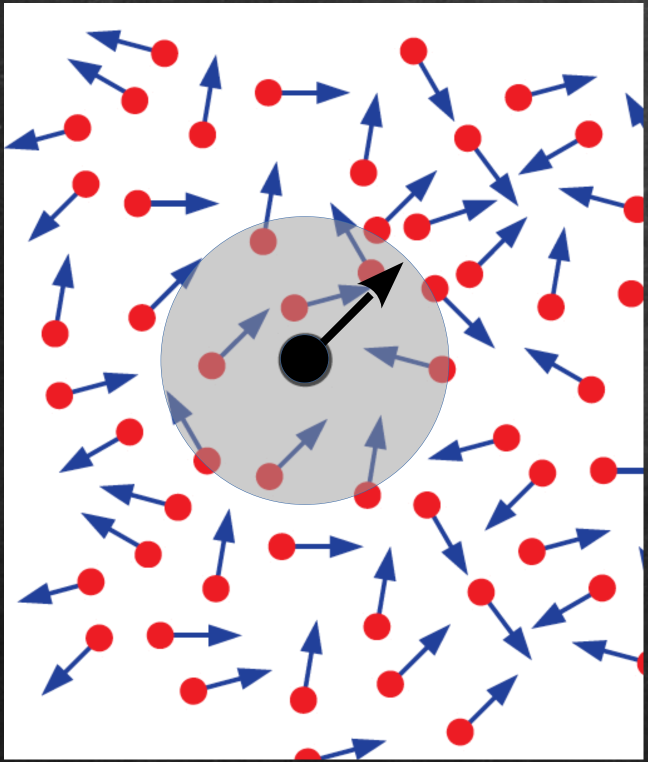
Collisions with hot plasma

Equality

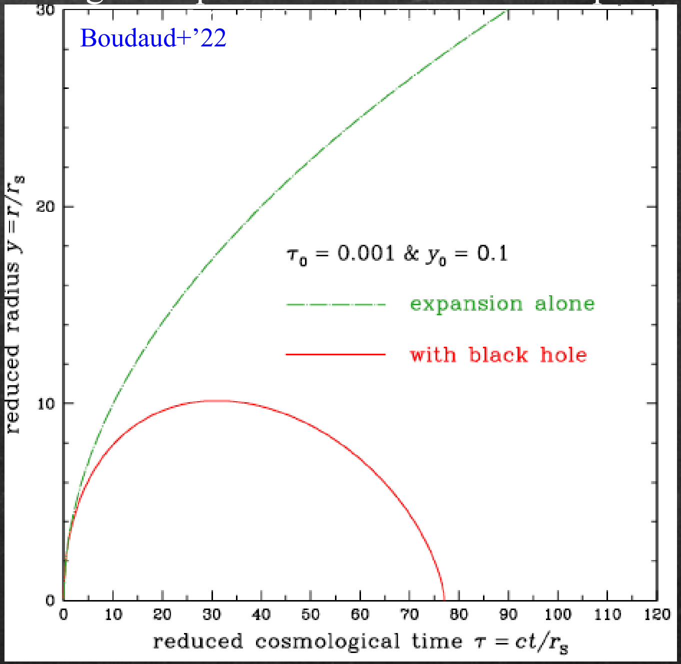
Matter domination

Notion of gravitational influence radius



Coupled particles don't feel the black hole

2) Solving the equation of motion of a test particle



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Timeline

Radiation domination

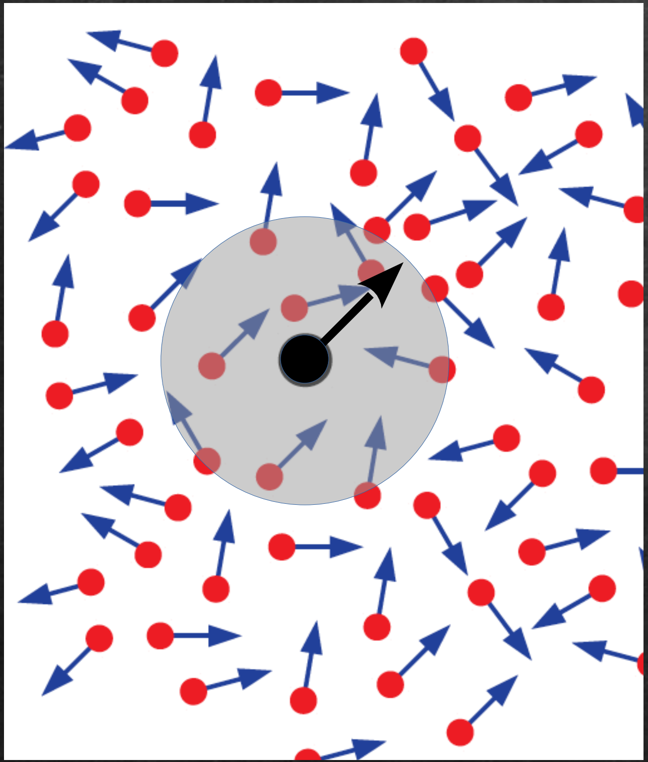
Equality

Matter domination

Thermal freezout

Collisions with hot plasma

Notion of gravitational influence radius



Coupled particles don't feel the black hole

Scale invariance

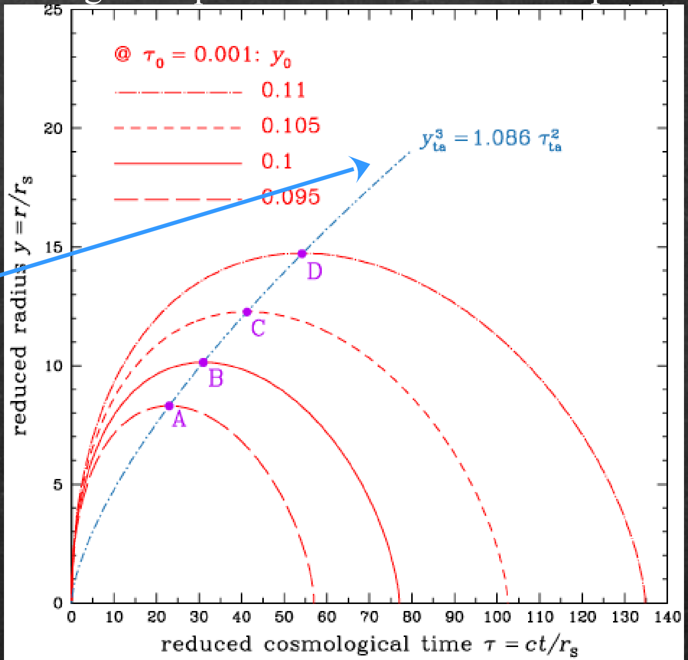
$$t \longrightarrow \lambda^{3/2}\,\tilde{t}$$
$$r \longrightarrow \lambda\,\tilde{r}$$

$$\tilde{r}_{\mathrm{ta}}^3 \propto \tilde{t}_{\mathrm{ta}}^2$$

$$r_{\mathrm{infl}}^3 \simeq 2.172\,G M_{\mathrm{BH}}\,t^2$$

$$M_{\mathrm{BH}} = \frac{16\pi}{3\eta_{\mathrm{ta}}}\,r_{\mathrm{infl}}^3\,\rho_{\mathrm{tot}}$$

2) Solving the equation of motion of a test particle



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Timeline

Radiation domination

Thermal freezout

Collisions with hot plasma

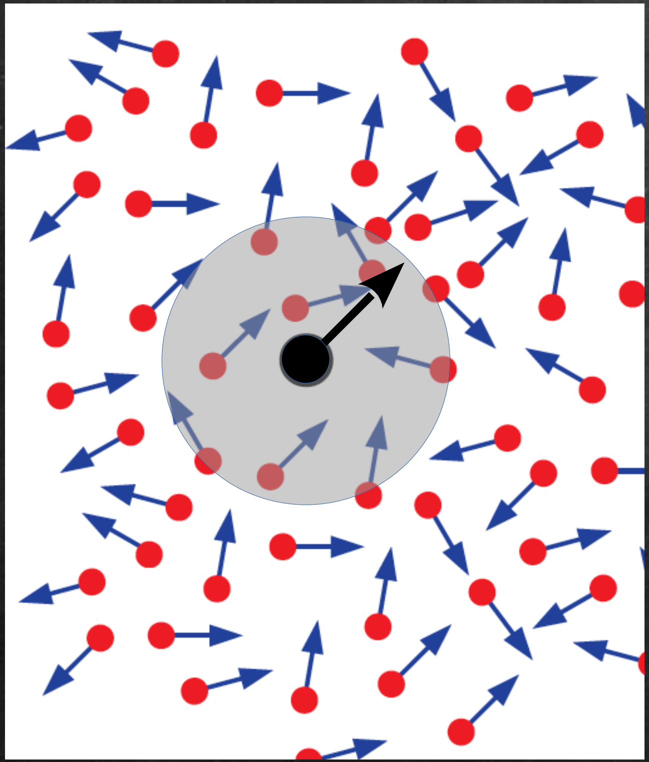
Kinetic decoupling

Free-streaming
=> spike formation

Equality

Matter domination

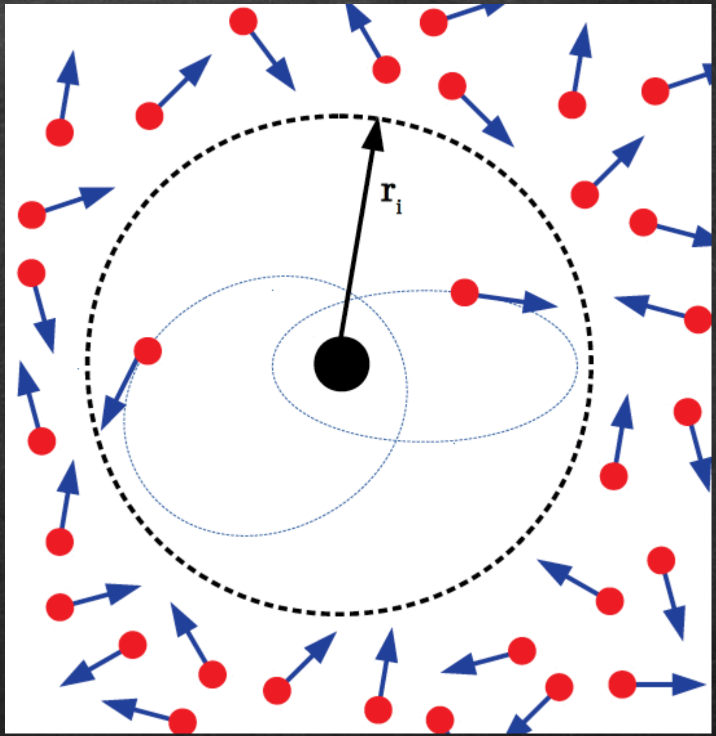
External growing



Coupled particles don't feel the black hole

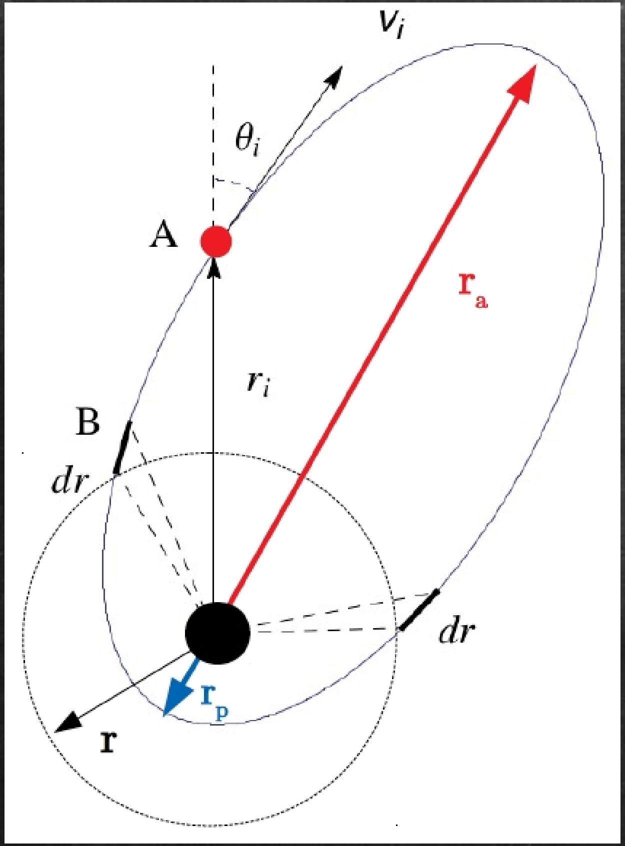
Important scale:
Influence radius
at kinetic decoupling

(it keeps on increasing after)



Free-streaming particles fall onto the black hole

Capture of (free-streaming) WIMPs by PBHs



[from M. Stref, Adapted from Eroshenko'16]

Condition for capture

$$E/m_\chi = \frac{1}{2} v_i^2 - \frac{G M_{\rm BH}}{r_i} < 0$$

Bounded orbit condition

$$r_{\rm p}(r_i, v_i, \theta_i) \leqslant r \leqslant r_{\rm a}(r_i, v_i, \theta_i)$$

Master equation for the density

$$\boxed{\rho(r)\, 4\pi\, r^2\, {\rm d}r = \int \frac{2\,{\rm d}t}{T_{\rm orb}}\, {\rm d}m_i}$$

$${\rm d}m_i = \rho_i(r_i)\, {\rm d}^3\vec{r}_i\, f_{\rm MB}(\vec{v}_i, r_i)\, {\rm d}^3\vec{v}_i$$

Initial accretion conditions

$$\rho_{\rm i}^{\rm approx}(\tilde{r}_{\rm i}) = \begin{cases} \rho_{\rm i}^{\rm kd} & \text{if } \tilde{r}_{\rm i} \leq \tilde{r}_{\rm kd}\,, \\ \rho_{\rm i}^{\rm kd}\,(\tilde{r}_{\rm i}/\tilde{r}_{\rm kd})^{-9/4} & \text{if } \tilde{r}_{\rm kd} \leq \tilde{r}_{\rm i} \leq \tilde{r}_{\rm eq} \end{cases}$$

$$f_{\rm MB}(\vec{v}_i, r_i) = (2\pi\sigma_i^2)^{-3/2}\, \exp\left[-\frac{v_i^2}{2\,\sigma_i^2}\right]$$

$$\sigma_{\rm i}(\tilde{r}_{\rm i}) = \begin{cases} \sigma_{\rm kd} & \text{if } \tilde{r}_{\rm i} \leq \tilde{r}_{\rm kd}\,, \\ \sigma_{\rm kd}\,(\tilde{r}_{\rm i}/\tilde{r}_{\rm kd})^{-3/4} & \text{if } \tilde{r}_{\rm kd} \leq \tilde{r}_{\rm i} \leq \tilde{r}_{\rm eq} \end{cases}$$

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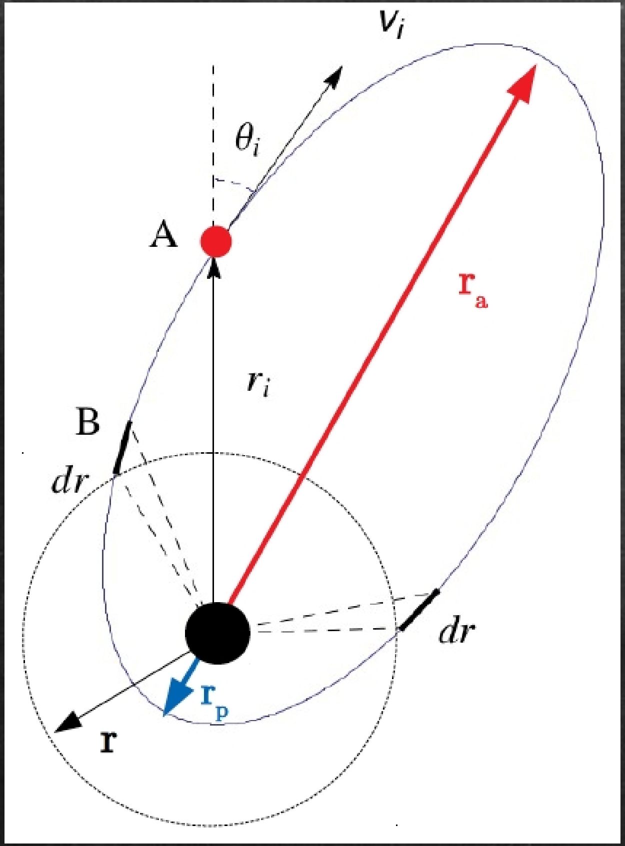


[from M. Stref, Adapted from Eroshenko'16]

Summary

$$\rho(\tilde{r}) = \frac{4}{\tilde{r}} \int_0^\infty \mathrm{d}(\beta_i^2)\, f_{\mathrm{MB}}(\beta_i, \tilde{r}_i) \int_{\tilde{r}_{\min}}^{\tilde{r}_{\max}} \mathrm{d}\tilde{r}_i\, \tilde{r}_i\, \rho_i(\tilde{r}_i) \times \left(\frac{1}{\tilde{r}_i} - \beta_i^2\right)^{3/2} \int_{y_0}^{1} \frac{\mathrm{d}y_i}{\sqrt{y_i^2 - Y_m}}$$

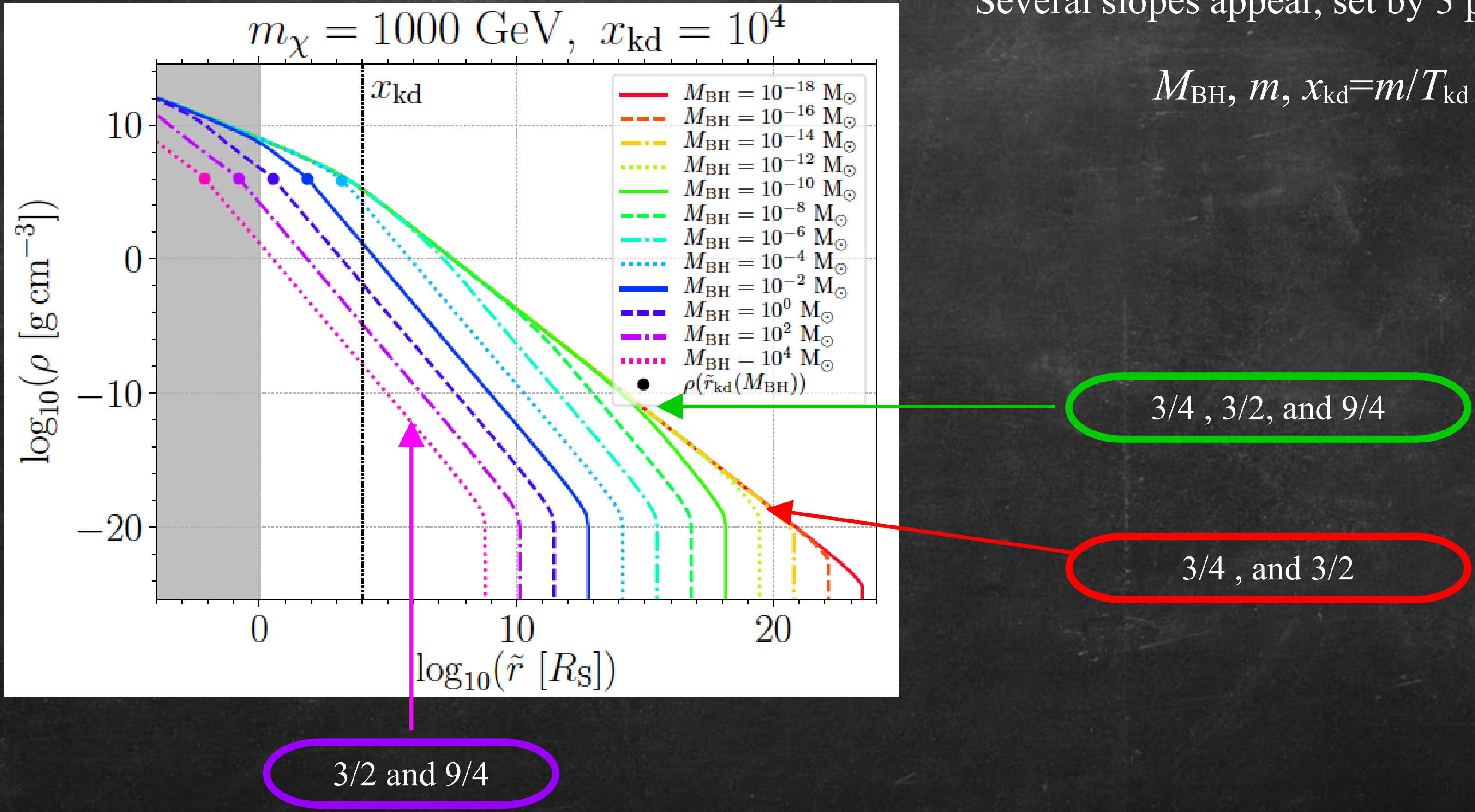
$y = \cos(\theta)$

$$y_0 = \begin{cases} \sqrt{Y_m} & \text{if } Y_m \geqslant 0 \\ 0 & \text{otherwise} \end{cases}$$

$$Y_m = 1 + \frac{\tilde{r}^2}{\tilde{r}_i^2} \left\{ \frac{1}{\beta_i^2} \left(\frac{1}{\tilde{r}_i} - \frac{1}{\tilde{r}} \right) - 1 \right\}$$

NB: Y_m<0 overlooked by Eroshenko, Boucenna, Kühnel+
→ strong impact on results in some cases

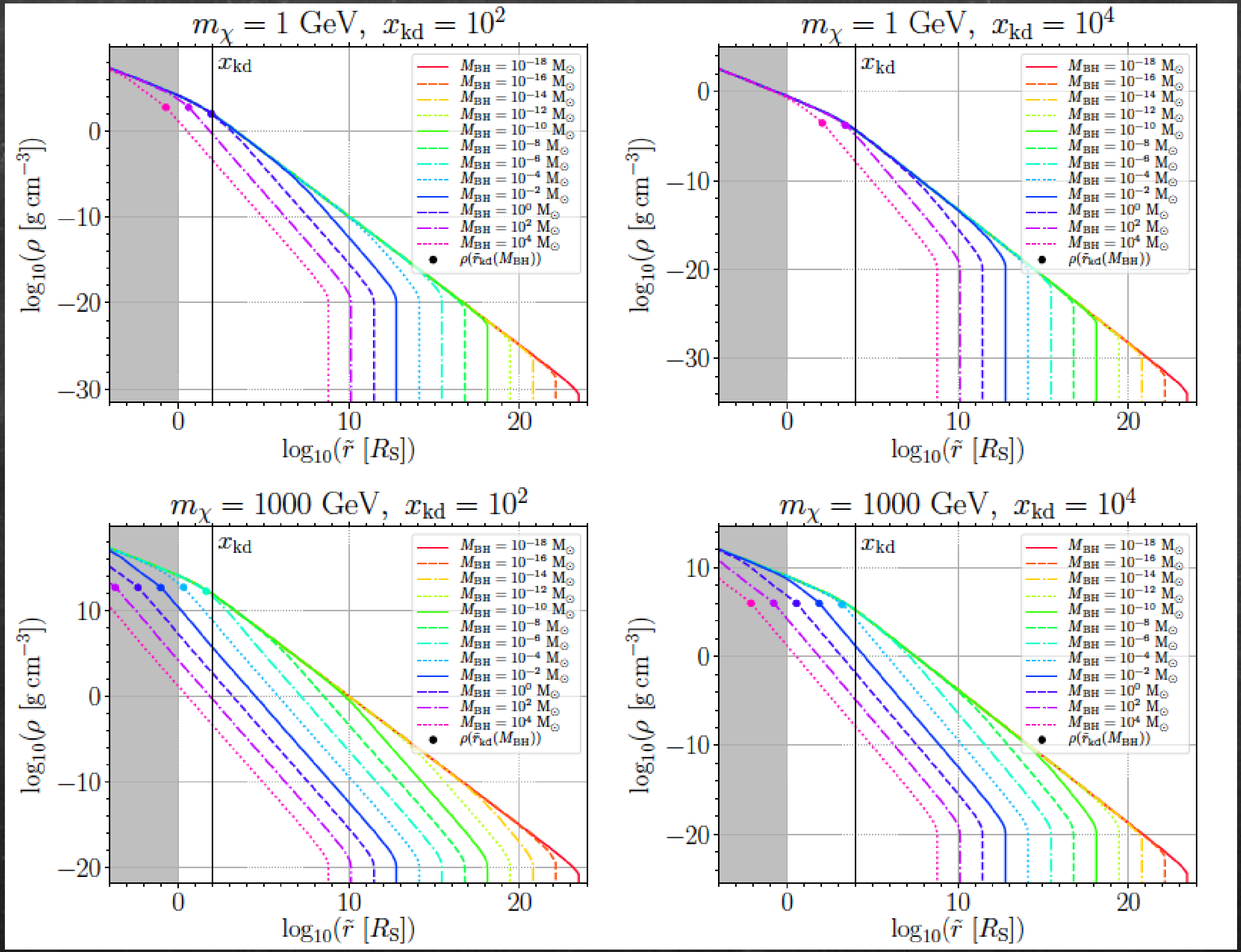
Numerical integration: density profiles at equivalence



Several slopes appear, set by 3 parameters:

$M_{\rm BH}$, m, $x_{\rm kd}=m/T_{\rm kd}$

Numerical integration: density profiles at equivalence



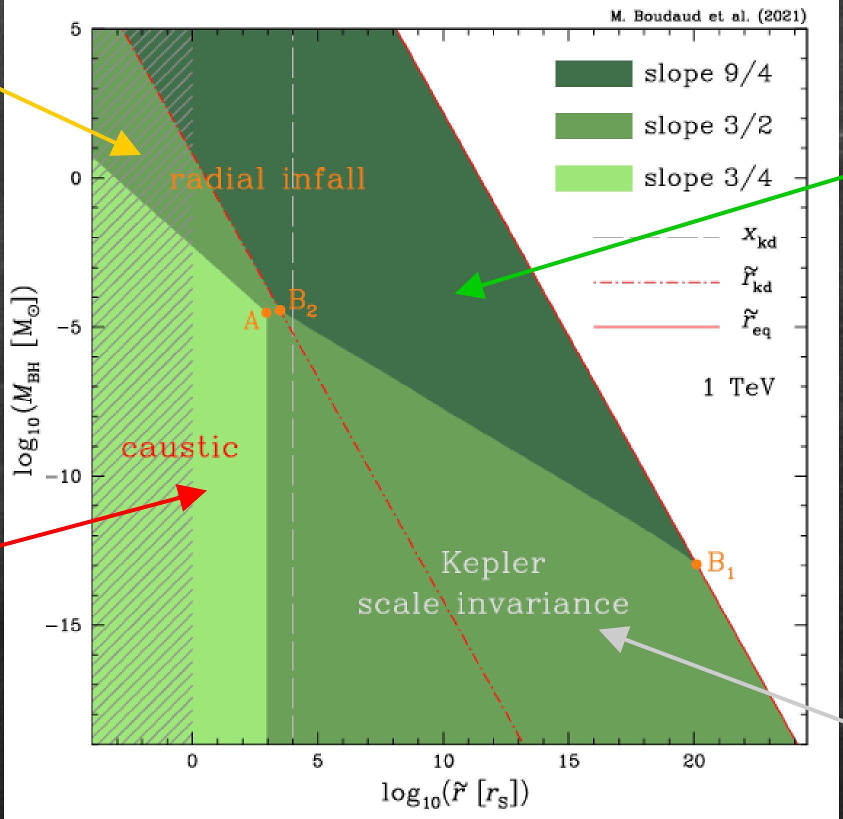
Can we make sense of that (analytically)?

Analytical understanding of slopes

Vanishing
Angular momentum

All start falling at t_{kd},
all converging to pericenter
(caustics)

Phase diagram of log indices



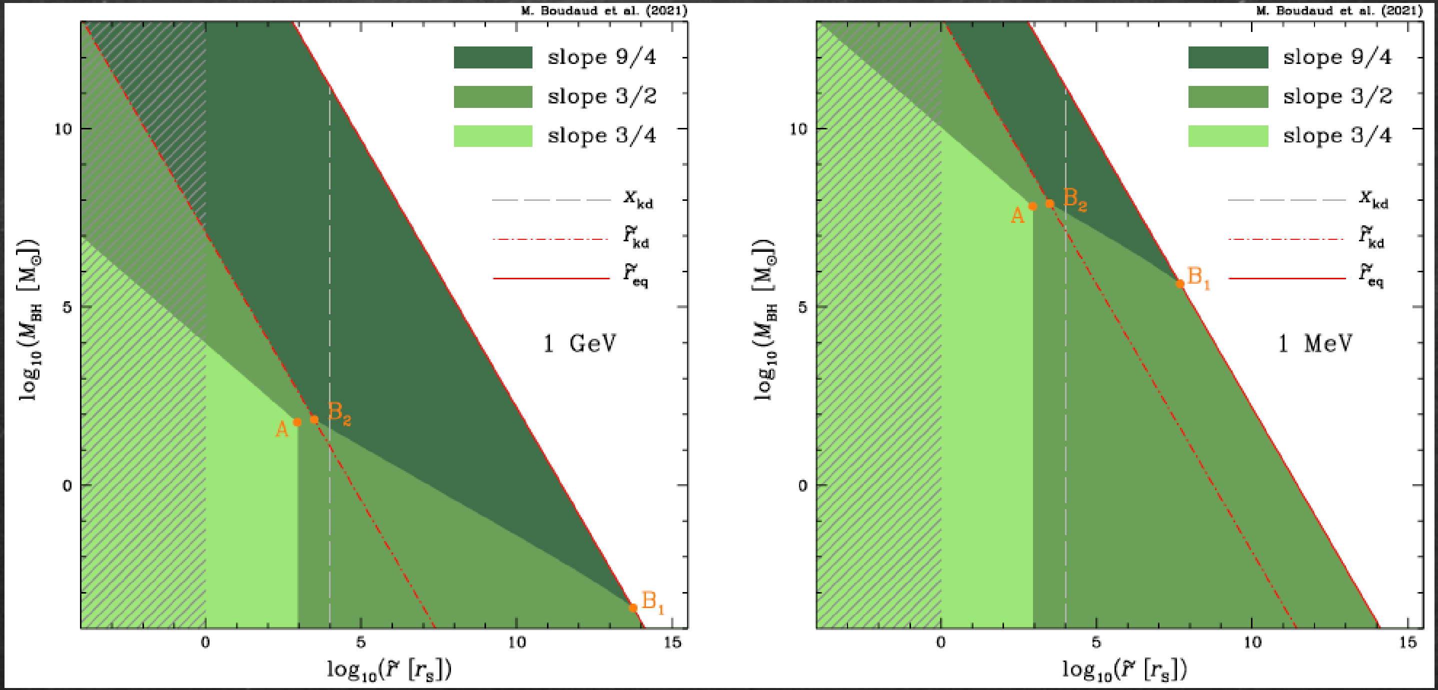
BH potential dominated

Initial speed > dispersion

Yes we can!

Analytical understanding of slopes

Phase diagrams of log indices



Turn to "constraints" on PBHs (for the WIMP believers)

Dressed PBHs can be viewed as "decaying" pseudo-particles

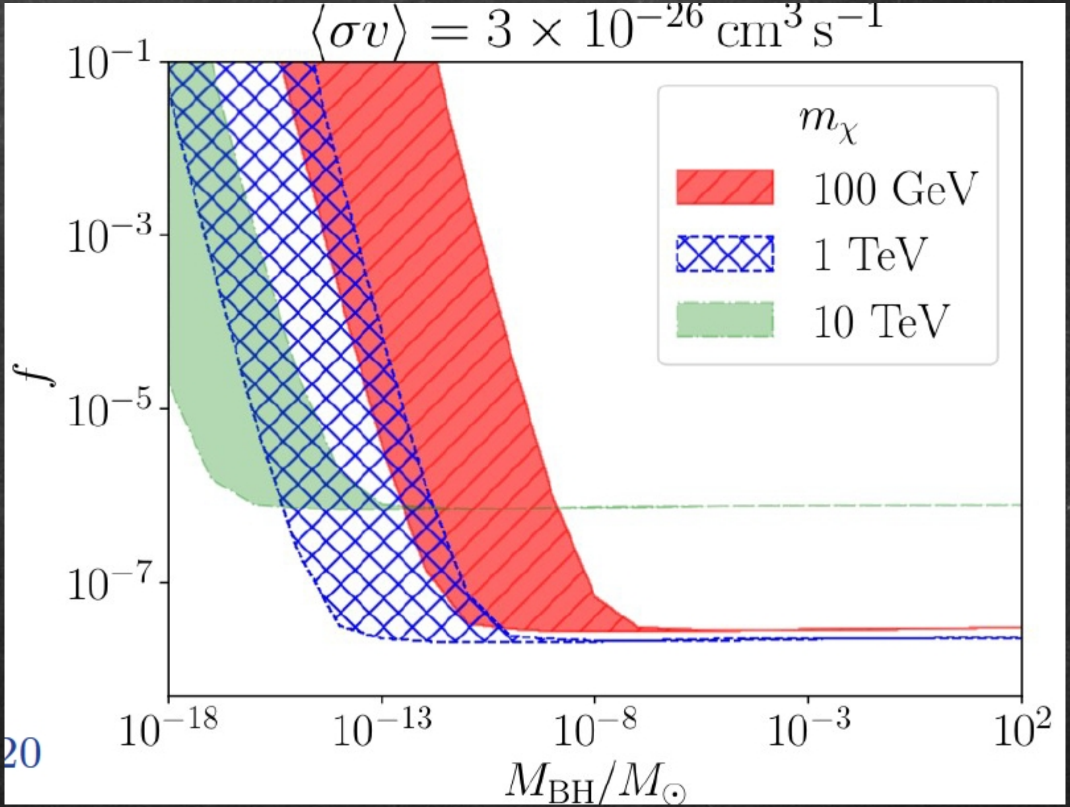
$$\Gamma_{\rm BH} = \langle \sigma_{\rm ann} v \rangle \int {\rm d}^3\vec{r} \left(\frac{\rho}{m_\chi}\right)^2$$

"Decays" (annihilation) can be probed with gamma-rays

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

Recast bounds from decaying DM [e.g. Ando & Ishiwata '15]

$$\frac{f\,(1-f)^2\,\Gamma_{\rm BH}}{M_{\rm BH}} = \frac{\Gamma_{\rm DM}}{m_{\rm DM}}$$

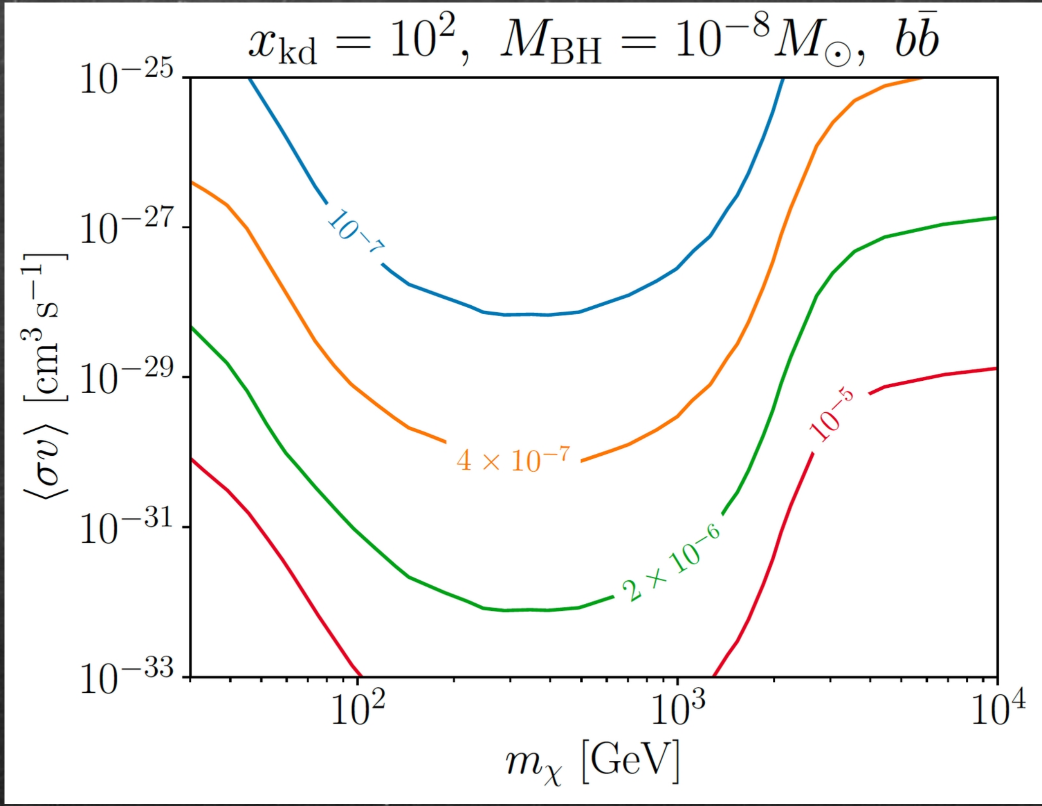


Roughly similar to Carr+'20

Turn to “constraints” on WIMPs (for the PBH believers)

PBH fraction > 10^{-7} can have
Strong impact on
WIMP parameter space:

→ **s-wave annihilation would be severely constrained**



Lacroix+ (in prep)
See also Eroschenko’16, Boucenna+’18,Carr+’21, Boudaud+’21

Summary

- PBHs a nice connection with physics of inflation or topological defects in early universe

- Currently directly probed by GW measurements (direct mergers)

- PBHs might be all of DM, but strong constraints over (almost) the whole mass range

- If fraction <<1, formation of compact halos of Particle DM through accretion in the early universe
[nice accretion model proposed by Eroshenko, integrating over all possible orbits – used in Boucenna+, Carr+, etc. – revisited by us]

- If self-annihilating through *s*-wave processes, thermal DM strongly constrained if $f_{PBH}>10^{-7}$
[not valid for *p*-wave ann.]

- If found even as a tiny DM subcomponent, PBHs are strong perturbers to DM pheno
[also axions, e.g. Rosa+'18, DM production from BH decays, e.g. Bernal+'21-22, etc.]

- Active research ongoing!

Backup

Impact of the overlooked phase-space volume