ASTROCENT

CAMK PAN

Primordial Black Hole Evaporation: implications for dark matter and dark radiation

NEHOP 2023

Andrew Cheek, L. Heurtier, Y. F. Perez-Gonzalez, J. Turner

Based on: arXiv:2212.03878, arXiv:2207.09462, arXiv:2107.00013 and arXiv:2107.00016

All in *Phys. Rev. D* last two as "Editors suggestion"

June 20, 2023

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952480

Dark Wave

European Funds Smart Growth

Republic of Poland

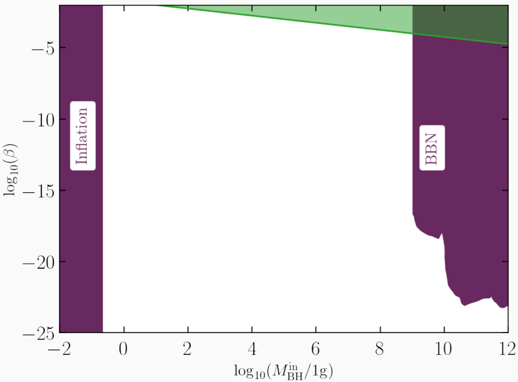
FNP Foundation for Polish Science

European Union European Regional Development Fund

A window of opportunity in PBH space

- Big Bang Nucleosynthesis (BBN) and inflation provide constraints on PBHs, but lots of space between!
- Evidence for evaporated PBHs would be interesting in of itself.
- For BSM, they provide high scales at *late times*, implications for Baryogenesis and leptogenesis.
- Topics on the edge of understanding, PBH assisted vacuum decay, Planck relics, extra dimensions.

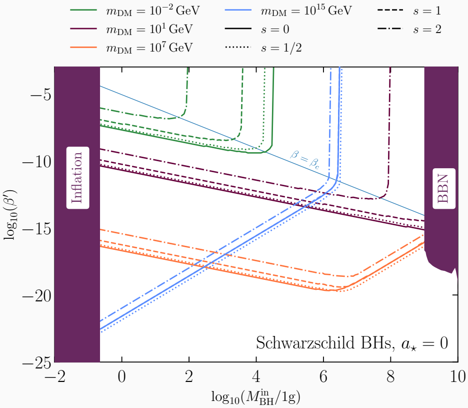
$$\beta' \equiv \gamma^{1/2} \left(\frac{g_\star(T_{\rm in})}{106.75} \right)^{-1/4} \frac{\rho_{\rm PBH}^{\rm in}}{\rho^{\rm in}}$$



Black Hole evaporation is a very efficient way to produce dark matter!

- If a stable particle exists, it will be produced in the process of Hawking evaporation.
- If these particles feebly interact with SM they will form dark matter or dark radiation.
- A very small number of BHs needed to produce the correct relic abundance for dark matter.
- $\beta' \equiv \gamma^{1/2} \left(\frac{g_\star(T_{\rm in})}{106.75} \right)^{-1/4} \frac{\rho_{\rm PBH}^{\rm in}}{\rho^{\rm in}}$

[AC, L. Heutier, Y. F. Perez-Gonzalez and J. Turner (2021)]



What is FRISBHEE?

- Our code `FRISBHEE`, FRIedmann Solver for Black Hole Evaporation in the Early universe, solves the system of coupled Friedmann and Boltzmann equations fully.
- Publicly available on GitHub and ready to use!

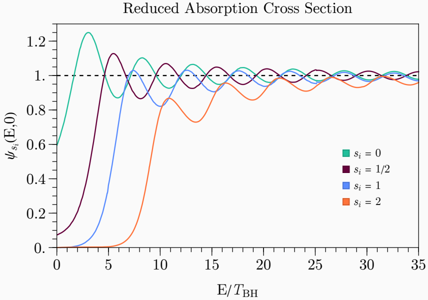
$$\frac{3H^2 M_p^2}{8\pi} = \rho_{\rm R}^{\rm SM} + \rho_{\rm DR} + \rho_{\rm PBH}\,, \qquad \dot\rho_{\rm DR} + 4H\rho_{\rm DR} = -\left.\frac{{\rm d}\log M_{\rm BH}}{{\rm d}t}\right|_{\rm DR}\rho_{\rm PBH}\,,$$

$$\dot\rho_{\rm R}^{\rm SM} + 4H\rho_{\rm R}^{\rm SM} = -\left.\frac{{\rm d}\log M_{\rm BH}}{{\rm d}t}\right|_{\rm SM}\rho_{\rm PBH}\,, \qquad \dot\rho_{\rm PBH} + 3H\rho_{\rm PBH} = \frac{{\rm d}\log M_{\rm BH}}{{\rm d}t}\rho_{\rm PBH}\,,$$

Why is FRISBHEE?

- First public code which tracks the evolution of dark sector and PBH distribution in a evolving Universe.
- We encode the effects from particle properties and track with T_{BH}.

- This allows for accurate exploration of the physics.
- A staging area for more complicated scenarios.



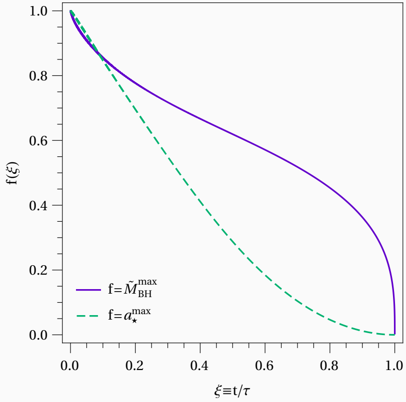
Spin evolution

- Tracking the spin evolution, proved to be an important use case for `FRISBHEE`.

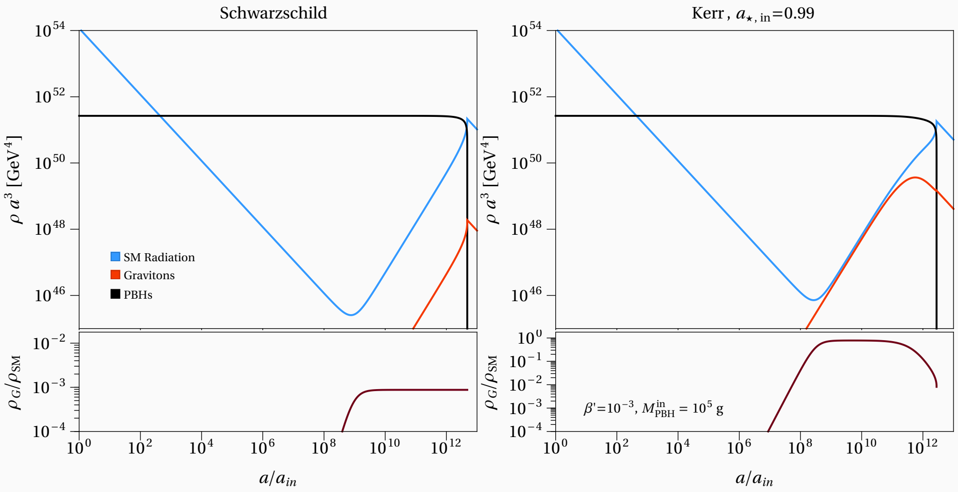
$$\frac{\mathrm{d}M_{\mathrm{BH}}}{\mathrm{d}t} = -\epsilon(M_{\mathrm{BH}}, a_\star)\frac{M_p^4}{M_{\mathrm{BH}}^2}\,,$$

$$\frac{\mathrm{d}a_\star}{\mathrm{d}t} = -a_\star[\gamma(M_{\mathrm{BH}}, a_\star) - 2\epsilon(M_{\mathrm{BH}}, a_\star)]\frac{M_p^4}{M_{\mathrm{BH}}^3}\,,$$

- It has been known for almost 50 years that Kerr BHs shed angular momentum sooner than their mass. See e.g. Page 1976.
- For maximally spinning BHs only around 40% of mass has been lost when 90% of the spin has gone.

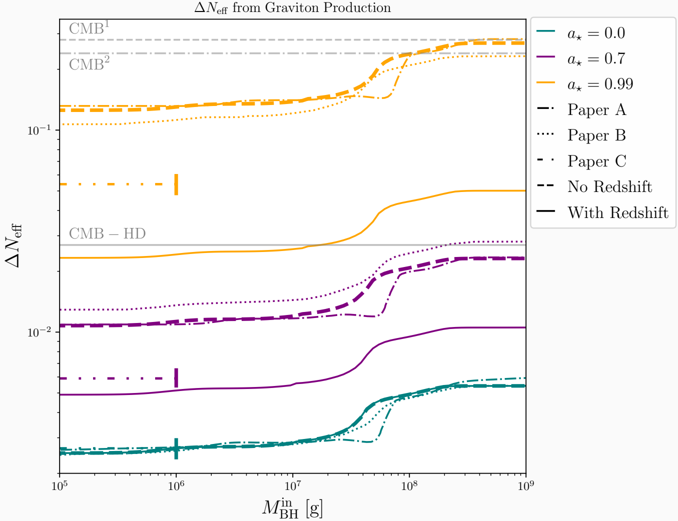


Entropy injection after $a_\star \sim 0$



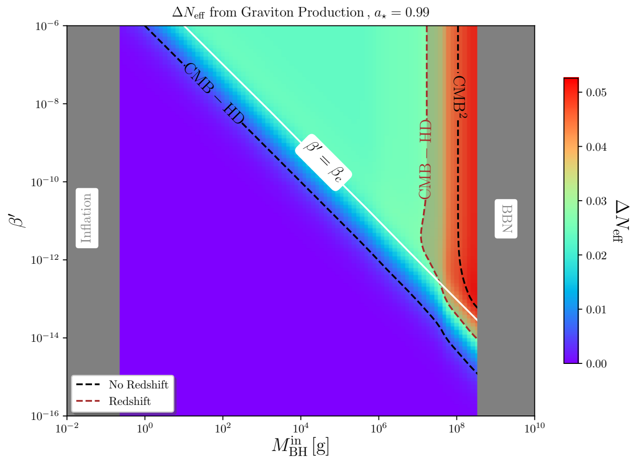
Results assuming PBH domination

- Previous studies calculated the contribution to ΔN_{eff}.
- Paper A = Hooper et.al. 2020
- Paper B = Arbey et.al. 2021
- Paper C = Masina 2021
- The prospects for future CMB probes are now less optimistic.



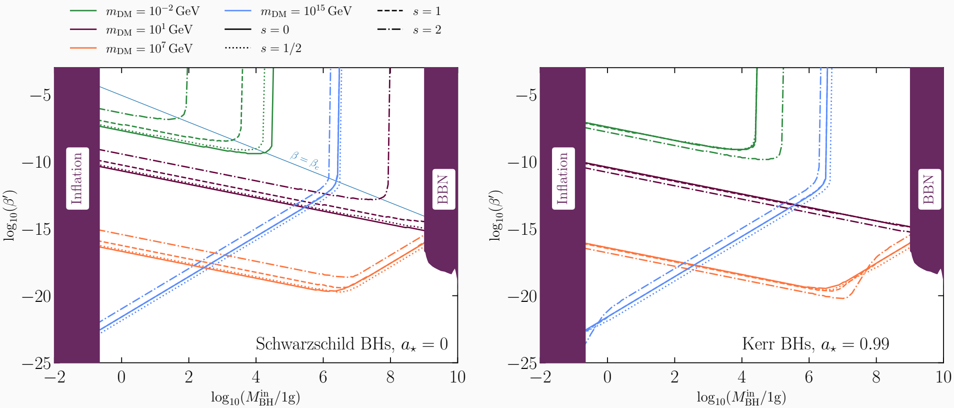
Scan results for graviton

- With FRISBHEE we can perform full scans.
- Can determine the effects even when there isn't pbh domination.
- CMB-HD will constrain maximally spinning BHs below β_c for very high $M_{\rm BH}^{\rm in.}$.



Features in dark matter relic lines

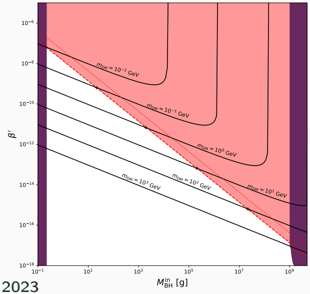
- We calculate $\Omega_{\rm DM} h^2$ for different particle spins.
- Effects of spinning BHs ($a_\star \neq 0$).

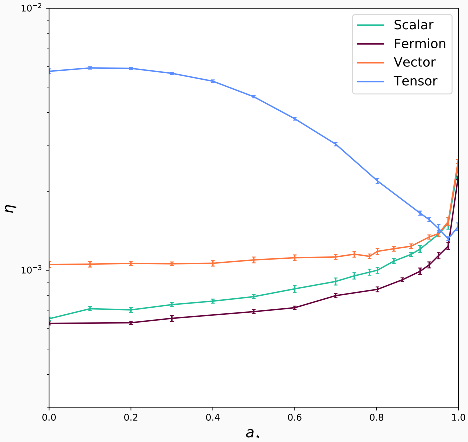


Warm dark matter constraints different spins

- How Lyman-α constraints depend on particle spin and BH spin ($a_\star$) is non-trivial.
- Define constraint parameter η by

$$\beta' \leq \eta \left(\frac{M_{\rm pl}}{M_{\rm BH}^{\rm in}} \right)$$

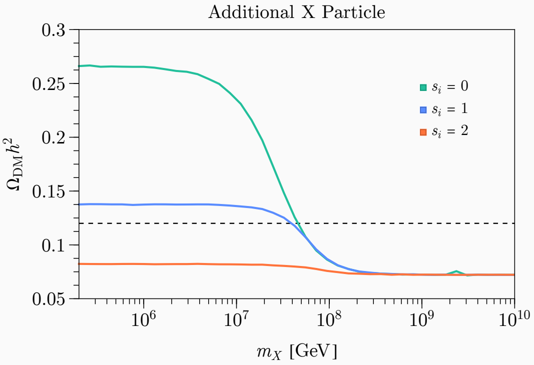




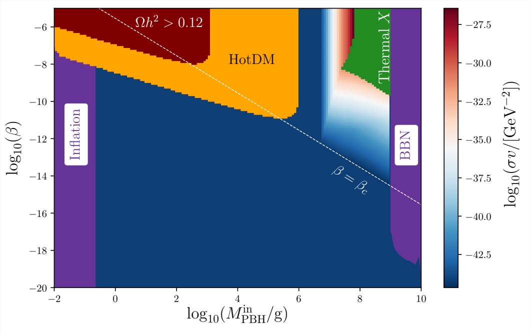
Dark sectors, interacting dark matter etc.

- FRISBHEE also allows for exploration of more complicated dark sectors

Non-interacting

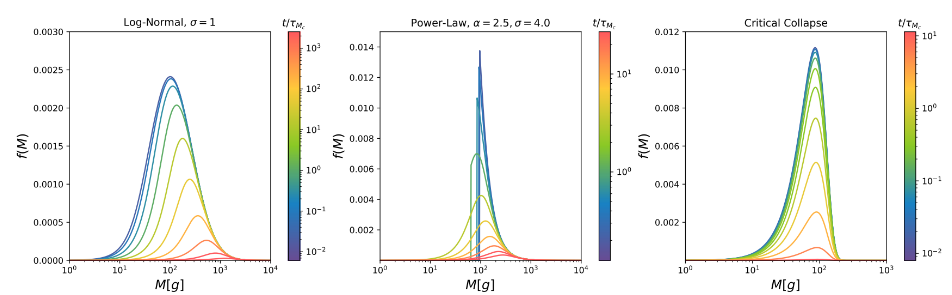


Interacting



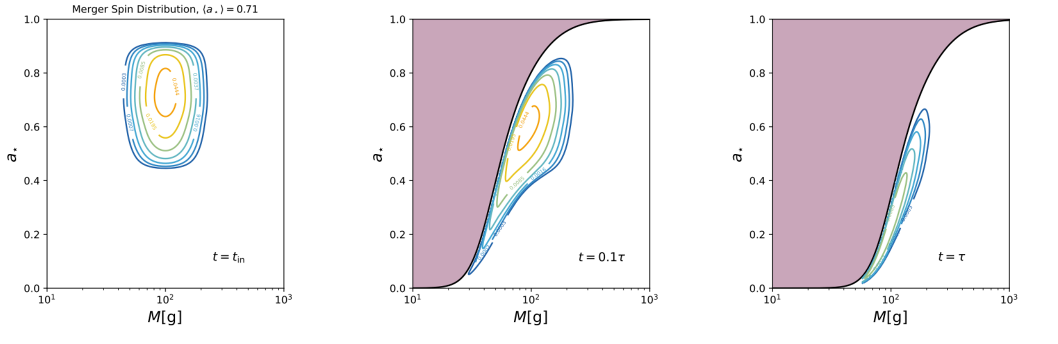
Distributions of PBHs

- All work above has been monochromatic in $M_{\rm PBH}$ and $a_\star$.
- Many PBH production mechanisms lead to distributions.
- The updated `FRISBHEE` can now track mass and spin distributions.

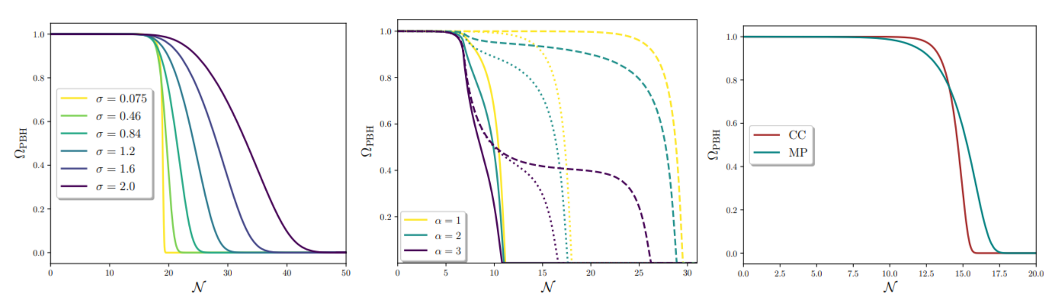


Mass and Spin distributions

- FRISBHEE can evaluate the effects of non-trivial spin and mass distributions.

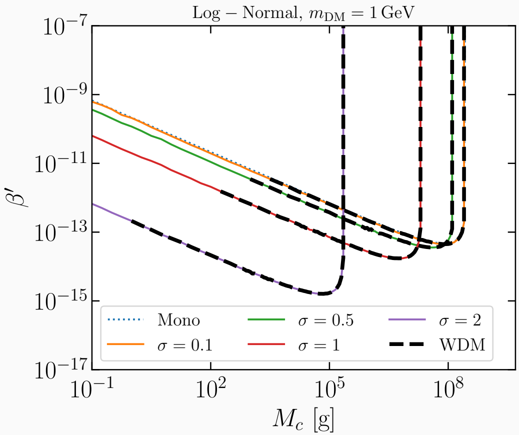


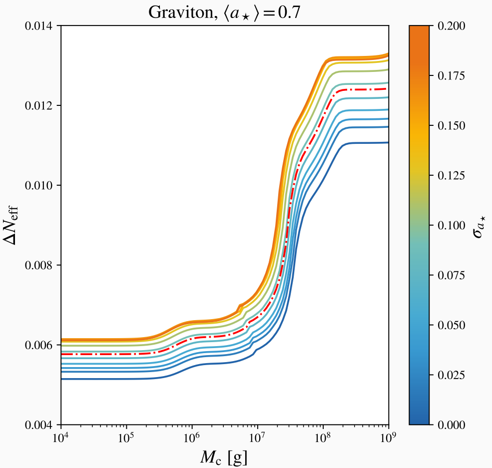
- Evaporation can occur over many e-folds.



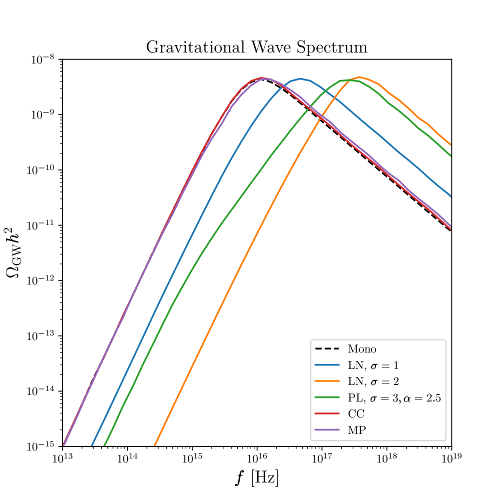
For power law we see the example of matter-radiation stasis
[K. Diernes et. al (2022) and Barrow et. al. 1991]

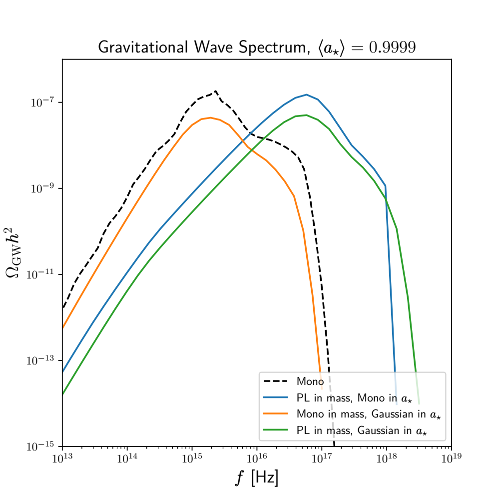
Distribution effects on phenomenology





Effect on high-frequency gravitational waves





Conclusions

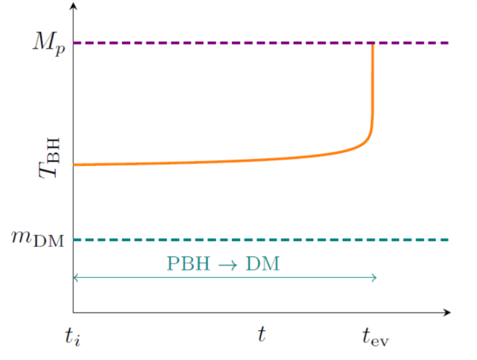
- `FRISBHEE` is available to all!
- Accurately tracking the system of equations has lead to insights already.
- CMB probes of ΔN_{eff} are less constraining than previously thought.
- Dark matter will be produced in evaporation and the interplay can be complicated.
- `FRISBHEE` now can evolve broad distributions of PBHs, in M_{BH} in $a_{\star}$.
- Download it today github.com/yfperezg/frisbhee

Backup slides

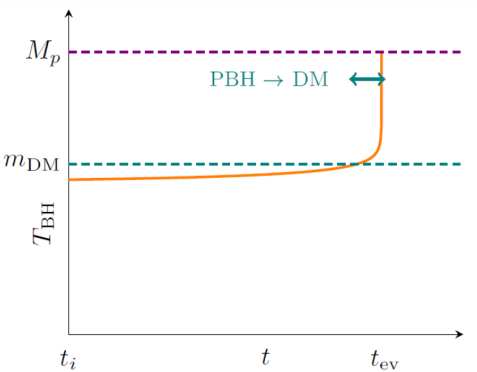
Any particles with $m_{\rm DM} < M_{\rm p}$ will be emitted

- Two separate regimes of particle production for stable particles

$$N_{\rm DM} \approx \frac{120\zeta(3)}{\pi^3}\frac{g_i}{g_\star(T_{\rm BH})}\frac{M_{\rm BH}^2}{M_{\rm pl}^2}\,.$$

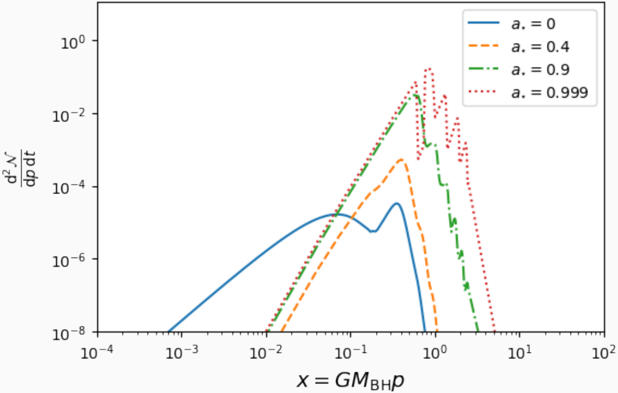


$$N_{\rm DM} \approx \frac{15\zeta(3)}{8\pi^5}\frac{g_i}{g_\star(T_{\rm BH})}\frac{M_{\rm pl}^2}{m_{\rm DM}^2}$$



Spinning black holes preferentially emit higher spin particles

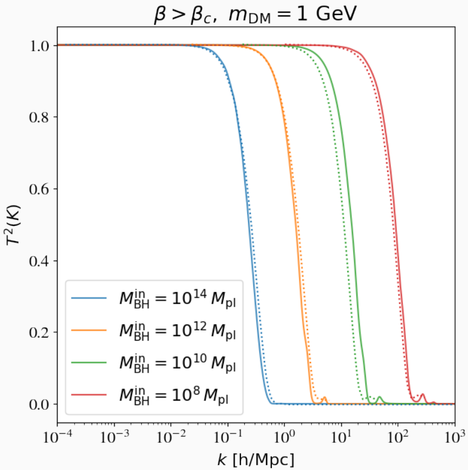
- It has long been known that Kerr black holes ($a_\star \neq 0$) shed their angular momentum by emitting higher spin particles.
- Closer to maximal $a_\star \to 1$, the more pronounced the enhancement is.



Lyman-α constraints on dark matter

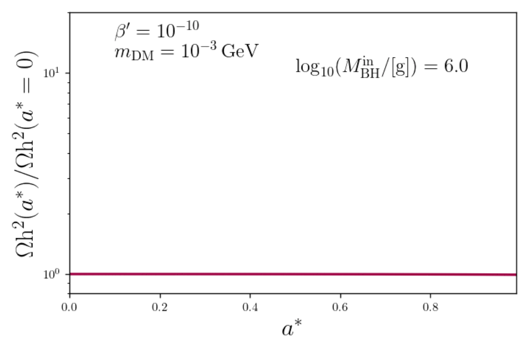
- Lyman-α forest traces inhomogeneities in IGM.
- Provides measurements on the matter power spectrum at high redshift ($2 \leq z \leq 5$) and small scales ($0.5\, h/\mathrm{Mpc} \leq k \leq 20\, h/\mathrm{Mpc}$).
- Measurements down to this scale are consistent with cold dark matter

$$P_\chi(k) = P_{\mathrm{CDM}}(k) T_\chi^2(k)$$

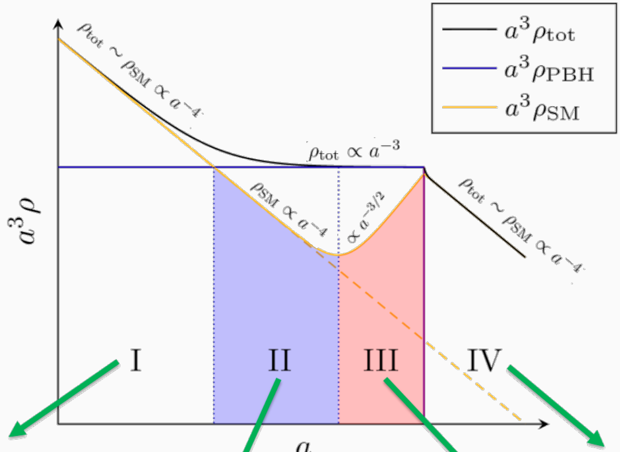


Freeze-In Dark Matter with PBHs

- The way PBHs reheat the thermal plasma depends on $a_\star$.
- This can mean that $T^{\mathrm{univ.}} \sim m_X$ for longer.
- On this resonance is when more DM particles are produced through standard freeze-in.



Interplay between interacting dark matter and pbh production



FI/FO + entropy dilution

Matter-Dominated FI/FO

FI/FO during entropy injection

Regular FI/FO

[image from Lucien Heurtier]