AstroCeNT

CAMK
PAN

Primordial Black Hole Evaporation and Dark Matter Production

KCL TPPC Seminar

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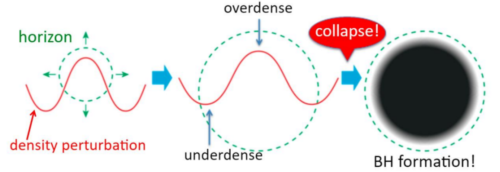
Based on: arXiv:2207.09462, arXiv:2107.00013 and arXiv:2107.00016

Last two in PRD as “Editors suggestion”

September 21, 2022

Primordial Black Holes

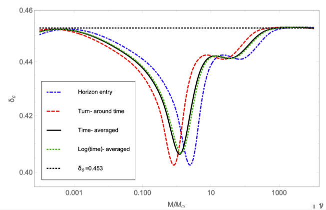
- Hypothetical black holes formed before stellar formation.
- Come from extremely dense matter fluctuations in the early Universe.
- These density perturbations are not produced in standard slow roll inflation.



[picture borrowed from N. Kitajima]

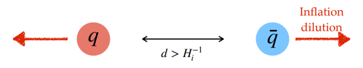
Production of PBHs

- Overdensities in the primordial power spectrum
- Phase transitions (pressure variations)
- Cosmic strings
- Bubble Collisions
- Quark confinement
- Multiverse ...



[Byrnes *et al.* 2018]

[G. Dvali et. al. 2021]

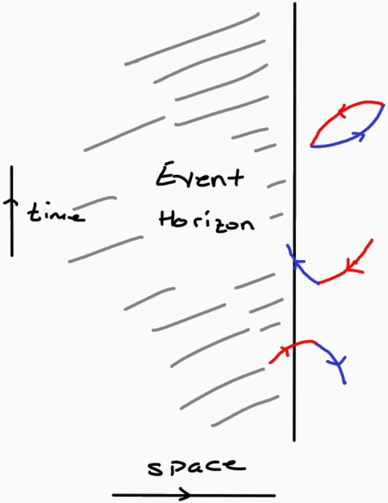


Hawking radiation

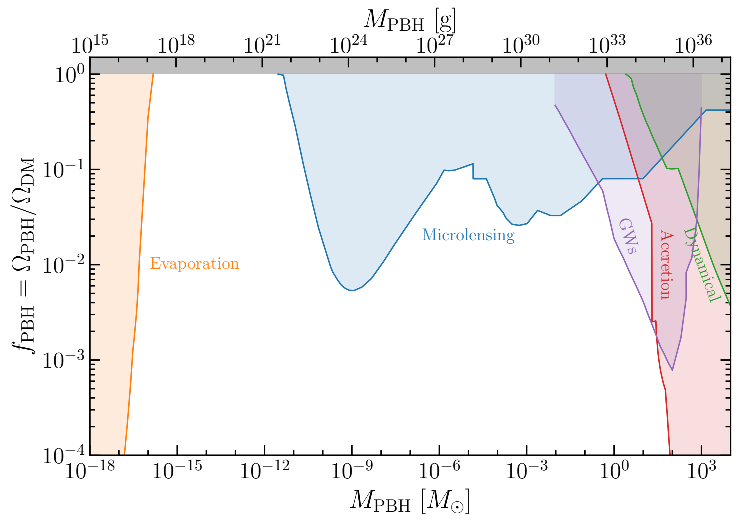
- Hawking radiation gives a lifetime to all BHs

$$t_{\mathrm{ev}} \sim (M_{\mathrm{BH}}^{\mathrm{in}})^3/(3M_{\mathrm{pl}}^4)$$

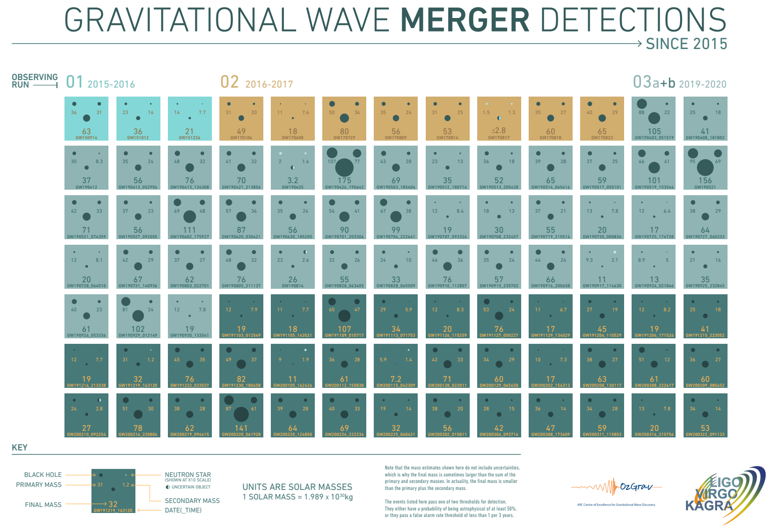
- Since $t_{\mathrm{univ.}} \sim 13 \times 10^9\,\mathrm{yr}$, PBHs with $M_{\mathrm{BH}}^{\mathrm{in}} \lesssim 10^{14}\,\mathrm{g}$ would no longer exist.
- Stable BHs will contribute to $\Omega_{\mathrm{DM}}h^2$ (Not the topic of this talk).
- However BHs radiate all particles, regardless of interactions, so they could produce non-interacting dark matter!



PBHs as dark matter



Binary mergers provide hints to primordial black hole populations



GRAVITATIONAL WAVE **MERGER** DETECTIONS → SINCE 2015

OBSERVING RUN: 01 2015-2016 · 02 2016-2017 · 03a+b 2019-2020

36 31 63 GW150914	23 14 36 GW151012	14 7.7 21 GW151226	31 20 49 GW170104	11 7.6 18 GW170608	50 34 80 GW170729	35 24 56 GW170809	31 25 53 GW170814	1.5 1.3 ≤2.8 GW170817	35 27 60 GW170818	40 29 65 GW170823	88 22 105 GW190403_051519	25 18 41 GW190408_181802
30 8.3 37 GW190412	35 24 56 GW190413_052954	48 32 76 GW190413_134308	41 32 70 GW190421_213856	2 1.4 3.2 GW190425	107 77 175 GW190426_190642	43 28 69 GW190503_185404	23 13 35 GW190512_180714	36 18 52 GW190513_205428	39 28 65 GW190514_065416	37 25 59 GW190517_055101	66 41 101 GW190519_153544	95 69 156 GW190521
42 33 71 GW190521_074359	37 23 56 GW190527_092055	69 48 111 GW190602_175927	57 36 87 GW190620_030421	35 24 56 GW190630_185205	54 41 90 GW190701_203306	67 38 99 GW190706_222641	12 8.4 19 GW190707_093326	18 13 30 GW190708_232457	37 21 55 GW190719_215514	13 7.8 20 GW190720_000836	12 6.4 17 GW190725_174728	38 29 64 GW190727_060333
12 8.1 20 GW190728_064510	42 29 67 GW190731_140936	37 27 62 GW190803_022701	48 32 76 GW190805_211137	23 2.6 26 GW190814	32 26 55 GW190828_063405	24 10 33 GW190828_065509	44 36 76 GW190910_112807	35 24 57 GW190915_235702	44 24 66 GW190916_200658	9.3 2.1 11 GW190917_114630	8.9 5 13 GW190924_021846	21 16 35 GW190925_232845
40 23 61 GW190926_053336	81 24 102 GW190929_012149	12 7.8 19 GW190930_133541	12 7.9 19 GW191103_012549	11 7.7 18 GW191105_143521	65 47 107 GW191109_010717	29 5.9 34 GW191113_071753	12 8.3 20 GW191126_115259	53 24 76 GW191127_050227	11 6.7 17 GW191129_134029	27 19 45 GW191204_110529	12 8.2 19 GW191204_171526	25 18 41 GW191215_223052
12 7.7 19 GW191216_213338	31 1.2 32 GW191219_163120	45 35 76 GW191222_033537	49 37 82 GW191230_180458	9 1.9 11 GW200105_162426	36 28 61 GW200112_155838	5.9 1.4 7.2 GW200115_042309	42 33 71 GW200128_022011	34 29 60 GW200129_065458	10 7.3 17 GW200202_154313	38 27 63 GW200208_130117	51 12 61 GW200208_222617	36 27 60 GW200209_085452
24 2.8 27 GW200210_092254	51 30 78 GW200216_220804	38 28 62 GW200219_094415	87 61 141 GW200220_061928	39 28 64 GW200220_124850	40 33 69 GW200224_222234	19 14 32 GW200225_060421	38 20 56 GW200302_015811	28 15 42 GW200306_093714	36 14 47 GW200308_173609	34 28 59 GW200311_115853	13 7.8 20 GW200316_215756	34 14 53 GW200322_091133

KEY

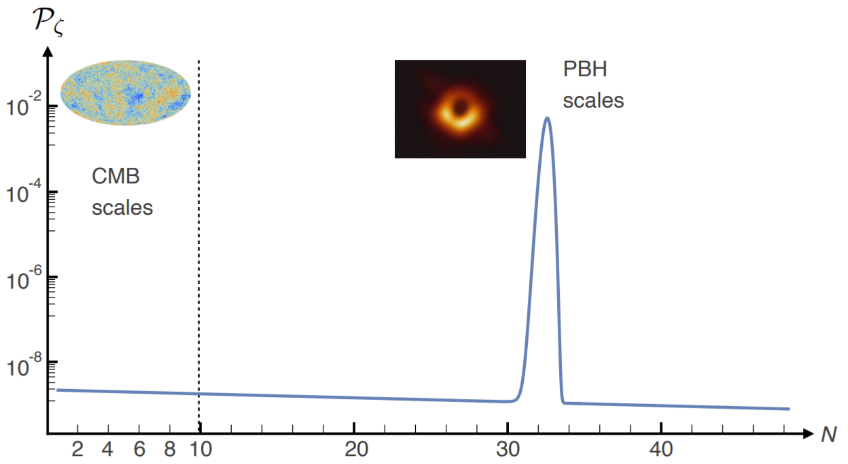
UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^{30}kg

Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

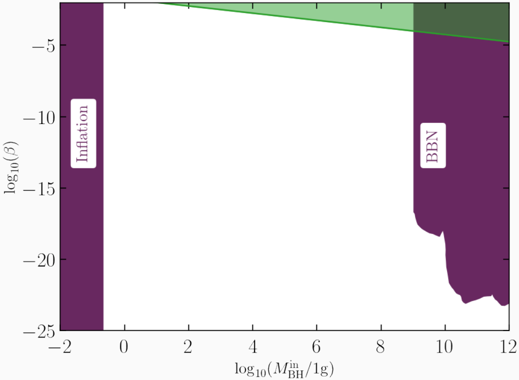
Power spectrum could be very different

[From Florian Kuhnel talk]



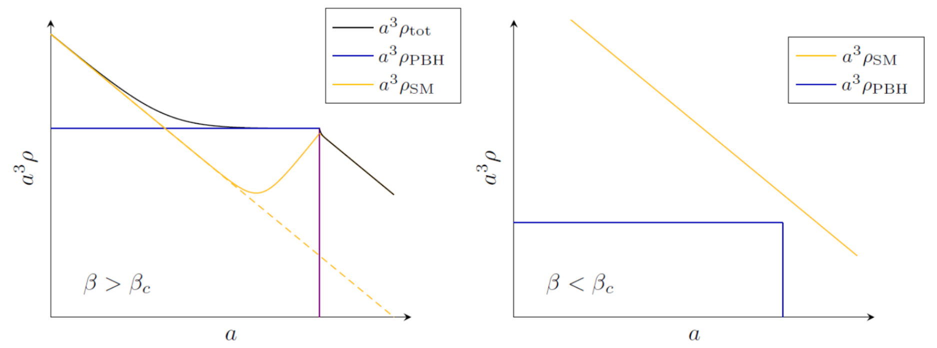
A window of opportunity

- Late time injection of SM particles disrupts Big Bang Nucleosynthesis.
- Provides strong constraints $M_{\rm BH} \sim 10^9$ g
- At the lower scale, the limit is taken from the CMB, which constrains the hubble scale during inflation.
- Model dependent lower limit $M_{\rm BH} \sim 10^{-1}$ g



Early matter domination is possible

- Substantial region of parameter space which allows early matter domination.

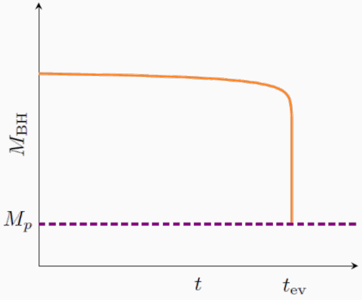


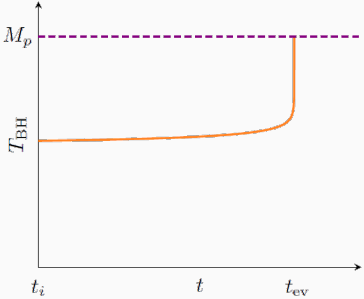
Evaporating BHs are a tantalizing prospect

- Hawking radiation is quantum mechanics in a curved spacetime, intrinsically interesting.
- They will have an active role in Early Universe.
- New physics between electroweak and Planck scales is well motivated, may even be implied by Higg's metastability (Gregory et. al. 2015).
- Black hole evaporation would provide such high scales at "late times" (still before BBN).

Basics of black hole evaporation

- Black hole temperature increases as $M_{\rm BH}$ decreases $T_{\rm BH} = \dfrac{1}{8\pi G M_{\rm BH}}$.
- Evaporation goes like $\dfrac{\mathrm{d}M_{\rm BH}}{\mathrm{d}t} = -\varepsilon(M_{\rm BH})\dfrac{M_{\rm pl}^4}{M_{\rm BH}^2}$.



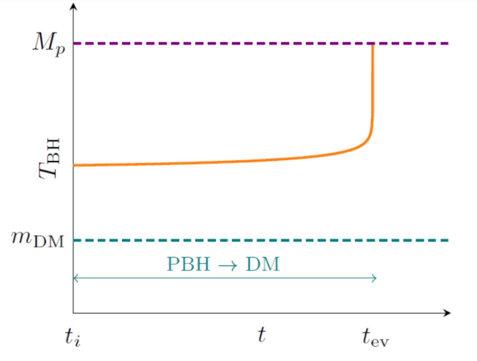


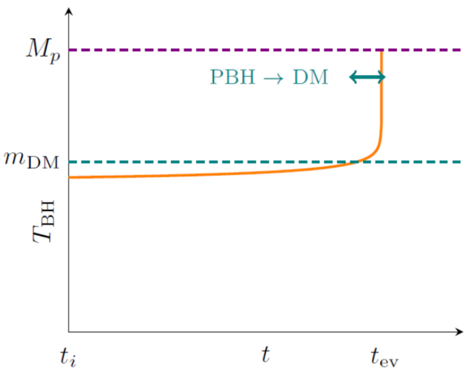
Any particles with $m < M_\mathrm{p}$ will be emitted

Since particle i is emitted when $T_\mathrm{BH} \gtrsim m_i$

$$N_i \approx \frac{120\zeta(3)}{\pi^3}\frac{g_i}{g_\star(T_\mathrm{BH})}\frac{M_\mathrm{BH}^2}{M_\mathrm{pl}^2} .$$

$$N_i \approx \frac{15\zeta(3)}{8\pi^5}\frac{g_i}{g_\star(T_\mathrm{BH})}\frac{M_\mathrm{pl}^2}{m_i^2}$$

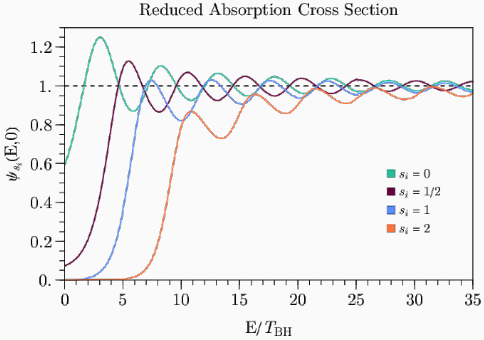




Particle emission depends on intrinsic particle nature

$$\frac{\mathrm{d}^2\mathcal{N}_i}{\mathrm{d}p\,\mathrm{d}t} = \frac{g_i}{2\pi^2}\frac{\sigma_{s_i}(M_{\mathrm{BH}},\mu_i,p)}{\exp\left[E_i(p)/T_{\mathrm{BH}}\right]-(-1)^{2s_i}}\frac{p^3}{E_i(p)}$$

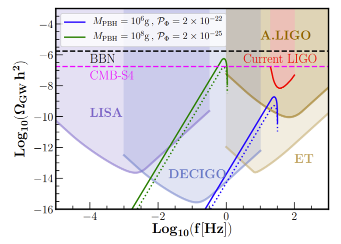
- Absorption cross-section σ describes possible back-scattering due to gravitational and centrifugal potentials.
- Oft-used geometrical optics limit $\sigma_{s_i}(E,\mu)|_{\mathrm{GO}} = 27\pi G^2 M_{\mathrm{BH}}^2$
- Define $\psi_{s_i}(E,\mu) \equiv \dfrac{\sigma_{s_i}(E,\mu)}{27\pi G^2 M_{\mathrm{BH}}^2}$.



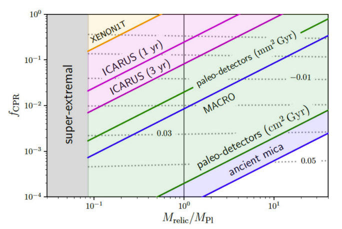
Remnants of PBH domination?

- Without assuming BSM particle production, what experimental signals are there for early pbh domination?
- Gravitational wave production
- Possible charged black hole remnants?

[Domenech et. al. 2021]



[Lehman et. al. 2019]



Dark radiation and relativistic degrees of freedom

- All SM particles, including neutrinos are in thermal equilibrium at high temperatures.
- Around matter-radiation equality, radiation energy density can be accounted for by

$$\rho_{\rm R} \equiv \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)\left(N_{\rm eff}^{\rm SM} + \Delta N_{\rm eff}\right)\right]$$

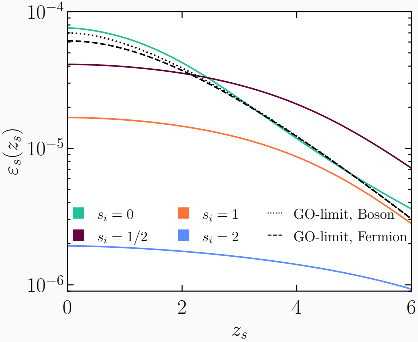
- Where $\Delta N_{\rm eff}$ parameterises any additional contributions.
- Which, presumably would come from dark radiation $\rho_{\rm R} = \rho_{\rm R}^{\rm SM} + \rho_{\rm DR}$

$$\Delta N_{\rm eff} \equiv \left\{\frac{8}{7}\left(\frac{4}{11}\right)^{-\frac{4}{3}} + N_{\rm eff}^{\rm SM}\right\}\frac{\rho_{\rm DR}}{\rho_{\rm R}^{\rm SM}},$$

The graviton as a form of dark radiation

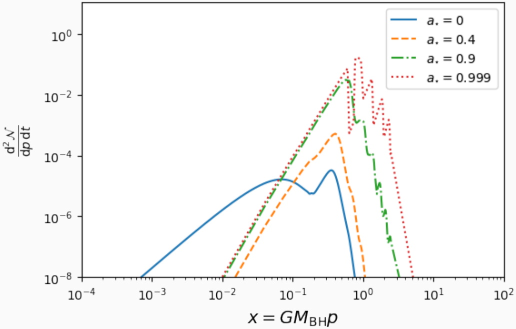
- Graviton is too weakly interacting to be in equilibrium with the SM bath.
- Black hole evaporation will produce them.
- We see that a spin-2 particle is emitted less that scalar or fermionic particles.

$$\varepsilon_i(M_{\rm BH}, a_\star) = \frac{g_i}{2\pi^2}\int_0^\infty \sum_{l=s_i}\sum_{m=-l}^{l} \frac{\mathrm{d}^2\mathcal{N}_{ilm}}{\mathrm{d}p\,\mathrm{d}t} E\,\mathrm{d}E$$



Kerr hawking radiation

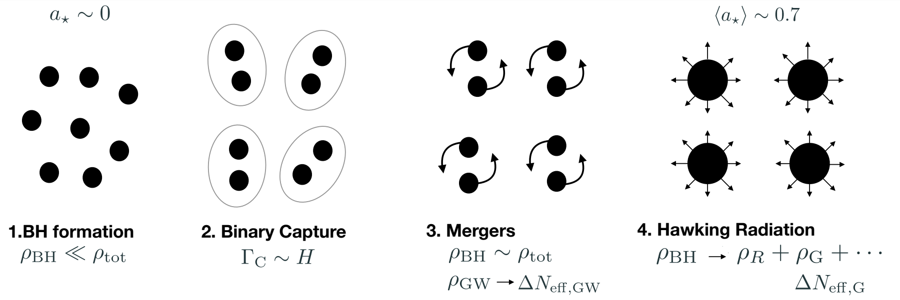
- Kerr black holes ($a_\star \neq 0$) start to preferentially emit high spin particles.
- Much more pronounced when close to maximal $a_\star \sim 0.99$.



Binary formation to Kerr

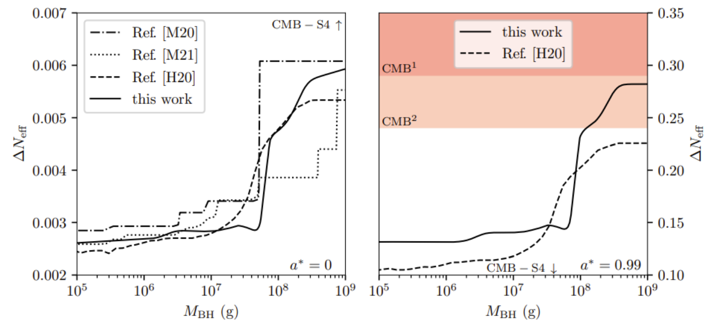
- It is conceivable that primodial black holes are formed with angular momentum.
- It is even possible that a population of Schwarzschild black holes develop into a poplation of Kerr black holes via early binary mergers.
- Expectation when this happens is $\langle a_\star \rangle \approx 0.7$

Hooper et.al. 2020



Current and Future CMB measurements show promise

- With upcoming improved CMB measurements, it looks like spinning pbhs can be constrained.
- Two assumptions, pbhs dominate, evaporation is instantaneous.



[Arbey et. al 2021]

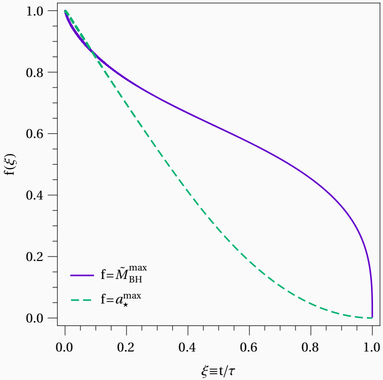
Spin evolution

- Evaporation is dictated by the spin of the black hole.

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

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

- It has been known for decades that Kerr BHs preferentially shed angular momentum.
- For maximally spinning BHs only around 40% of mass has been lost when 90% of the spin has gone.



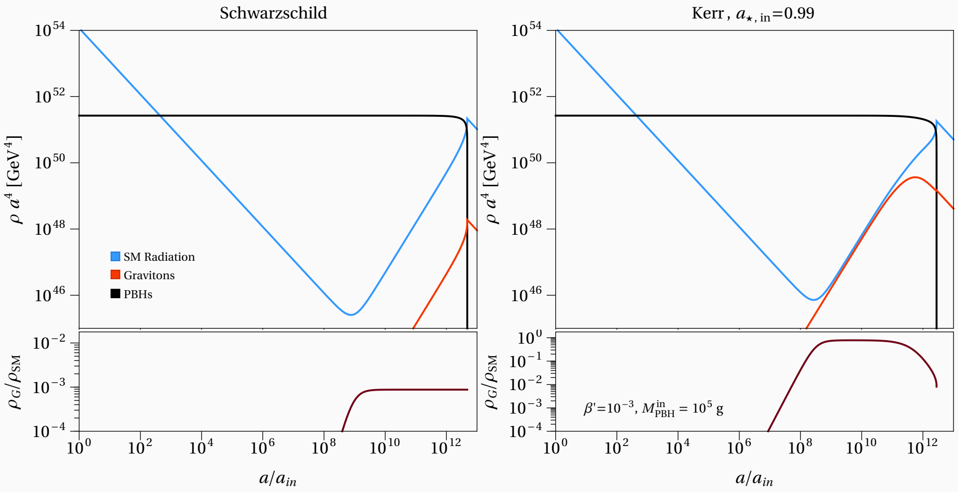
Motivation for FRISBHEE

- To determine the effect of approximating instantaneous evaporation, one would need to solve the system of coupled Friedmann and Boltzmann equations.
- Our code `FRISBHEE`, FRIedmann Solver for Black Hole Evaporation in the Early universe, does just that.

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

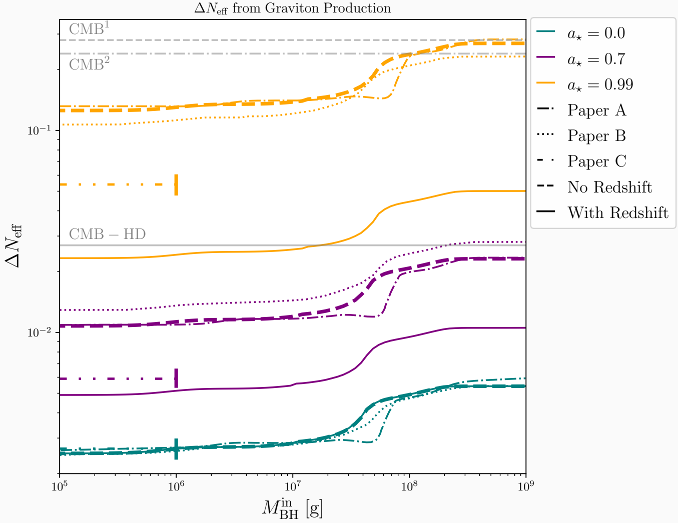
$$\dot{\rho}_{\rm R}^{\rm SM} + 4H\rho_{\rm R}^{\rm SM} = -\left.\frac{{\rm d}\log M_{\rm BH}}{{\rm d}t}\right|_{\rm SM}\rho_{\rm PBH}\,, \qquad \dot{\rho}_{\rm PBH} + 3H\rho_{\rm PBH} = \frac{{\rm d}\log M_{\rm BH}}{{\rm d}t}\rho_{\rm PBH}\,,$$

Entropy injection after $a_\star \sim 0$



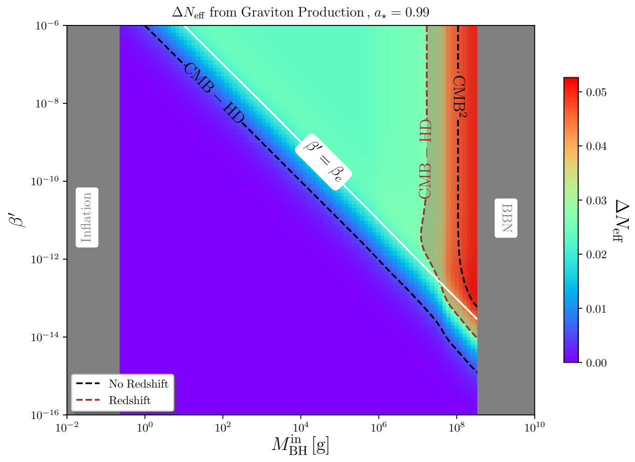
Results assuming PBH domination

- The prospects for future CMB probes are now less optimistic.
- Paper A = Hooper et.al. 2020
- Paper B = Arbey et.al. 2021
- Paper C = Masina 2021



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 $M_{\rm BH}^{\rm in.}$.

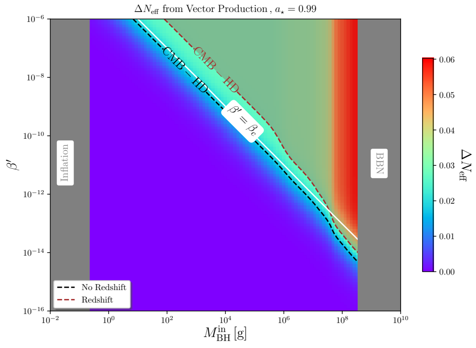


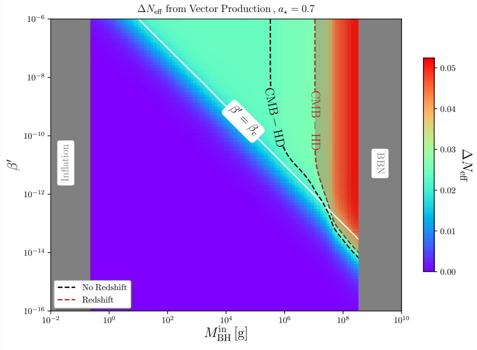
Other BSM: vector most interesting

- Much motivation for all sorts of new particles.
- The effect of spin evolution is most pronounced on higher spin particles.
- So we focus on dark radiation by way of vector. Fermion and scalar results are the same for Kerr and Schwarzschild.
- Emmission is less enhanced at $a_\star \sim 0.99$ but less supressed at $a_\star = 0$ so dilution is less pronounced.

Vector scan results

If there is evidence for a new light and feebly interacting vector boson, CMB-HD will be able to probe much larger regions of parameter space than with just the graviton.



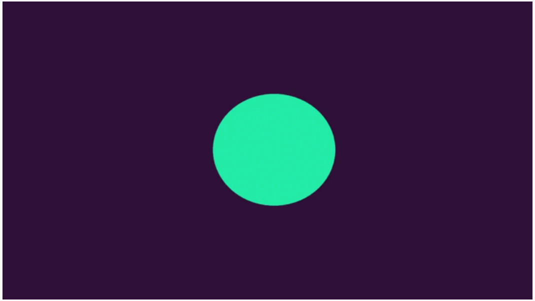


Dark matter from evaporating black holes

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

Pessimist's motivation to study it:

- We have a way of producing dark matter which doesn't require any interactions other than gravity.
- This would be very difficult to test.
- We use `FRISBHEE` to fully track the coupled system in probably the most precise way. arXiv:2107.00013.



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

Optimist's motivation to study it:

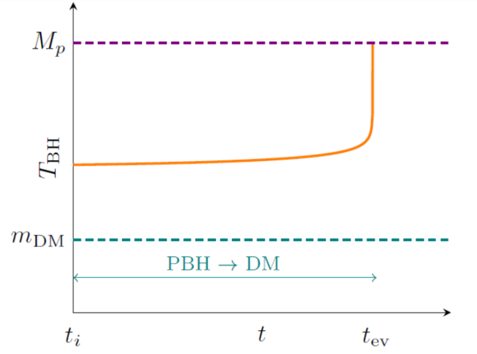
- Many models predict interactions between the SM and dark matter.
- Current and near future experiments may even measure this interaction.
- Dark matter detection could be an indirect probe into PBH's in early Universe.
- arXiv:2107.00016 is dedicated to this, where we make use of the code developed and now include an interacting dark matter model.

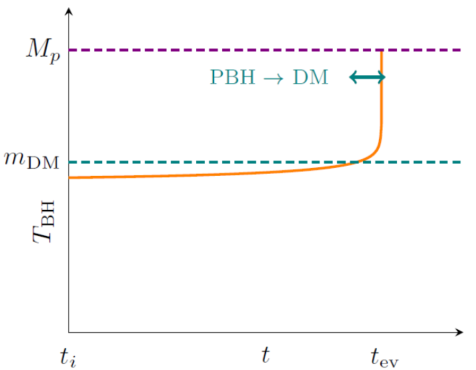
Any particles with $m_{\rm DM} < M_{\rm p}$ will be emitted

- Two separate regimes of particle production for stable particles

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

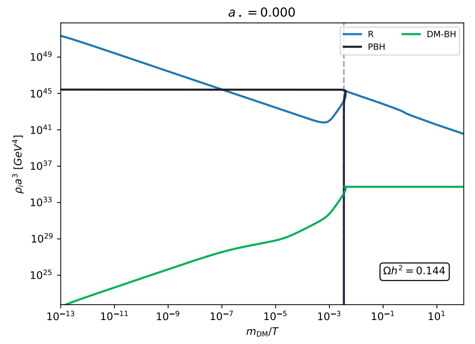
$$N_{\rm DM} \approx \frac{15\zeta(3)}{8\pi^5}\frac{g_i}{g_\star(T_{\rm BH})}\frac{M_{\rm pl}^2}{m_{\rm DM}^2}$$

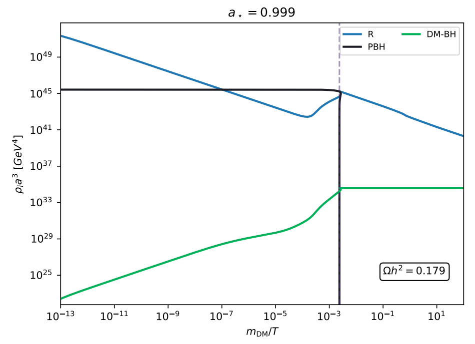




FRISBHEE tracks dark matter production

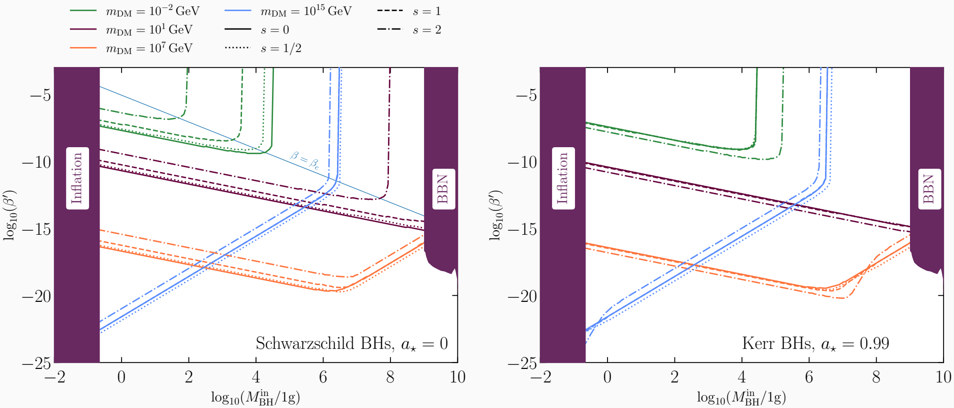
$$\dot{n}_{\rm DM} + 3Hn_{\rm DM} = n_{\rm BH}\,\Gamma_{\rm BH\to DM}(M_{\rm BH}, a_\star)$$





Dark Matter from only PBH evaporation

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



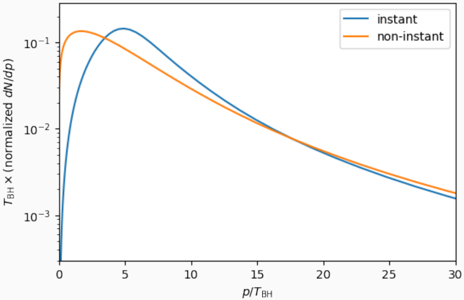
Dark matter distribution

- The dark matter phase space distribution is calculated by

$$f_{\rm DM} = \frac{n_{\rm BH}\left(t_{\rm in}\right)}{g_{\rm DM}} \left(\frac{a(t_{\rm in})}{a(t)}\right)^3 \frac{1}{p^2} \frac{\mathrm{d}\mathcal{N}_{\rm DM}}{\mathrm{d}p}\bigg|_{t=t_{\rm ev}}$$

- Where the redshifting of emitted particles is accounted for in

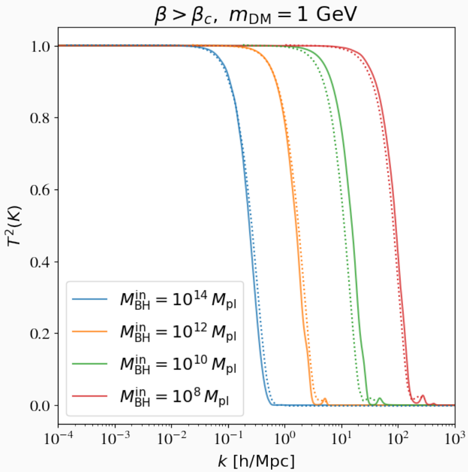
$$\frac{\mathrm{d}\mathcal{N}_{\rm DM}}{\mathrm{d}p} = \int_0^{\tau} \mathrm{d}t' \frac{a(\tau)}{a(t')} \times \frac{\mathrm{d}^2\mathcal{N}_{\rm DM}}{\mathrm{d}p'\mathrm{d}t'}\left(p\frac{a(\tau)}{a(t')}, t'\right)$$



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

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



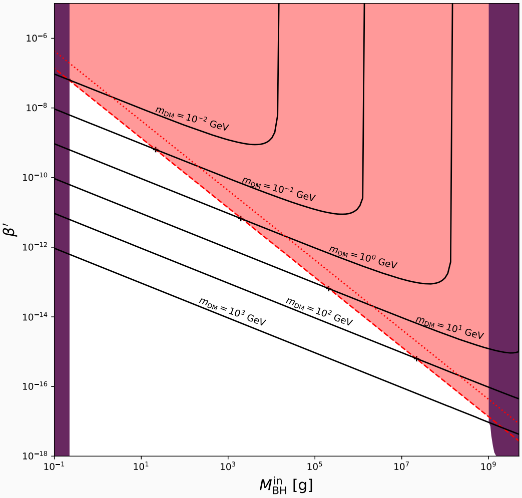
Consistent η relation

- To determine the constraint, can use

$$T(k) = (1 + (\alpha k)^{2\mu})^{-5/\mu}$$

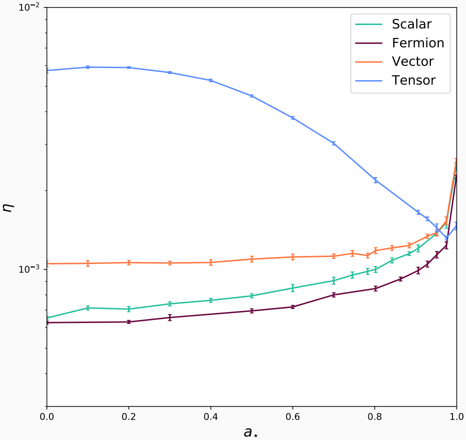
- Find the $M_{\rm BH}^{\rm in}$ value that $\alpha = 1.3 \times 10^{-2}\,{\rm Mpc}\,h^{-1}$.
- For a given dark matter spin, constraint is independent of the dark matter mass itself.

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



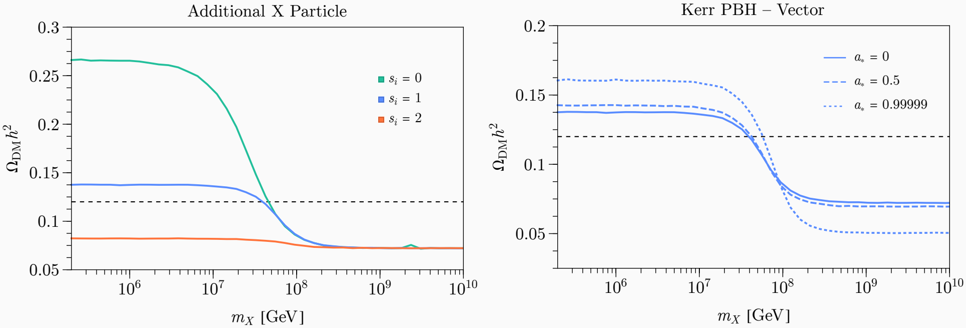
Warm dark matter constraints different spins

- How the constraint depends on particle spin and BH spin ($a_\star$) is non-trivial.
- The increased $a_\star$ comes with a greater momentum in the distribution $f_{\rm DM}$.
- At the same time the β' values required to produce the correct Ω alters.
- In the end the particle type most sensitive to $a_\star$ is spin-2 dark matter.

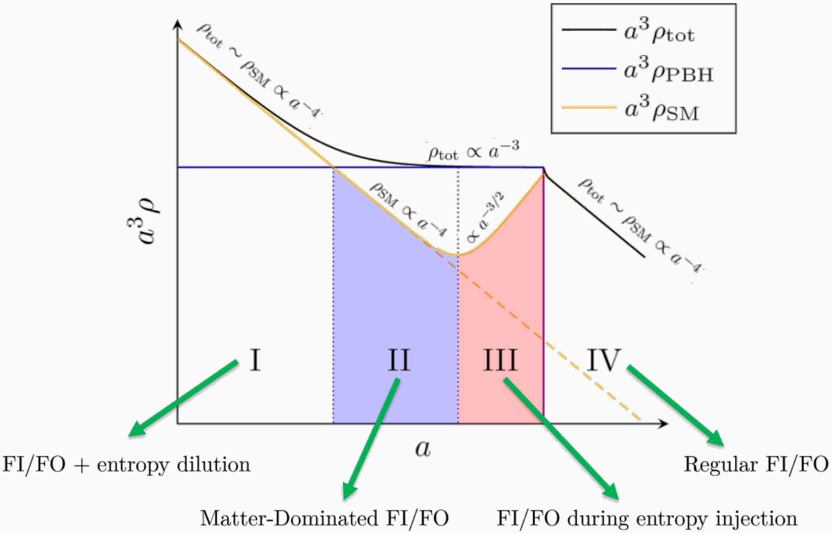


Effect of extended dark sectors

- Multiple particles are predicted in many BSM models, with dark matter being the lightest one.
- Consider one extra particle and fermionic DM, $X \to 2\mathrm{DM}$.



Interplay between interacting dark matter and pbh production



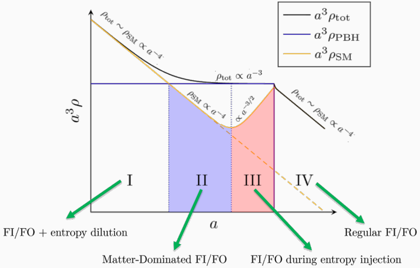
FI/FO + entropy dilution

Regular FI/FO

Matter-Dominated FI/FO

FI/FO during entropy injection

Interplay between interacting dark matter and pbh production



- The set of Boltzmann equations are now expanded

$$\dot{n}_{\rm DM} + 3Hn_{\rm DM} = g_{\rm DM}\int C[f_{\rm DM}]\frac{{\rm d}^3p}{(2\pi)^3} + \left.\frac{{\rm d}n_{\rm DM}}{{\rm d}t}\right|_{\rm BH}$$

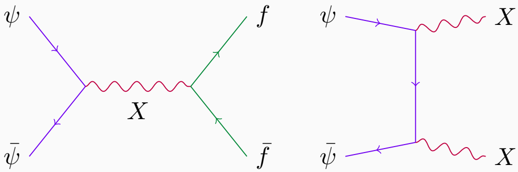
$$\dot{n}_X + 3Hn_X = g_X\int C[f_X]\frac{{\rm d}^3p}{(2\pi)^3} + \left.\frac{{\rm d}n_X}{{\rm d}t}\right|_{\rm BH}$$

$$\dot{\rho}_{\rm SM} + 4H\rho_{\rm SM} = \left.\frac{{\rm d}M}{{\rm d}t}\right|_{\rm SM}$$

- In this work we make use of the momentum averaged Boltzmann equation.

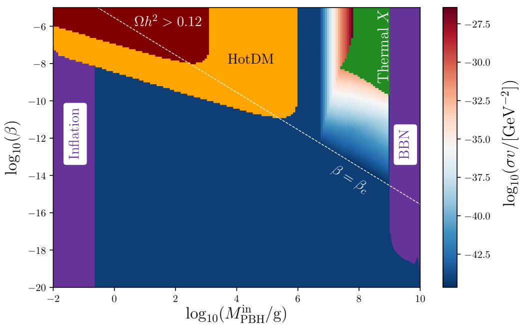
Freeze-In Dark Matter with PBHs

We considered a vector-mediated, fermionic dark matter model



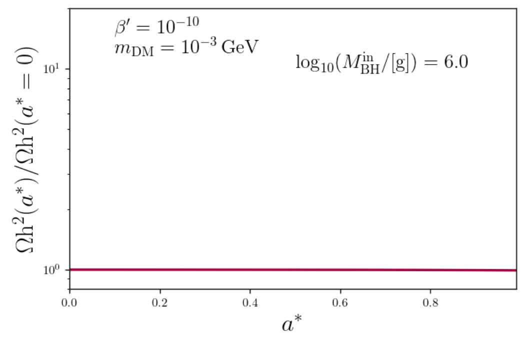
and systematically explore the parameter space

Here $m_{\mathrm{DM}} = 1$ MeV and $m_X = 1$ TeV



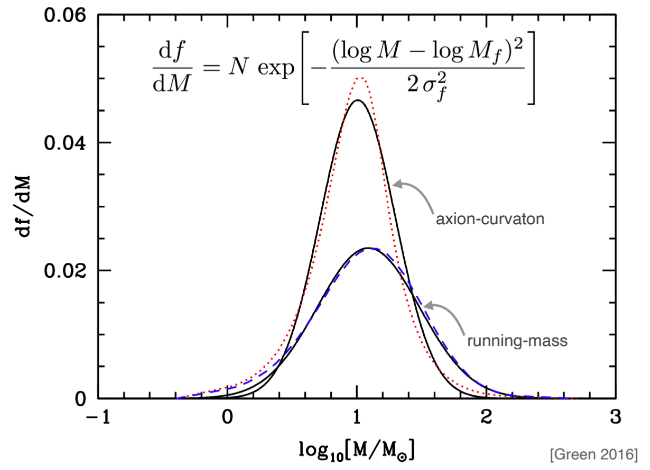
Freeze-In Dark Matter with PBHs

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



Current work: Distributions of PBHs

- All work above has been monochromatic in M_{PBH} and $a_\star$



[Green 2016]

Current work: treating rethermalization

- In the derivation of the momentum averaged Boltzmann equations, only one explicit use of the phase space distribution from evaporated particles is made.

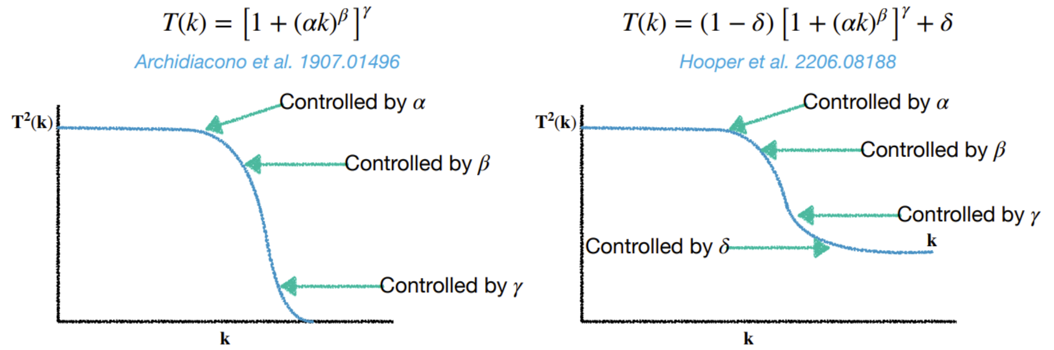
$$\Gamma_X \left\langle \frac{m_X}{E_X} \right\rangle_{\mathrm{ev}} \equiv \Gamma_X \int \frac{m_X}{E_X} f_{\mathrm{ev}}(p_X) \frac{\mathrm{d}^3 p_X}{(2\pi)^3}$$

- Where we determine the boosting effect on the lifetime of X.
- However, it's possible that the evaporated particles can self interact or interact with the plasma such that rethermalization occurs and one would have to calculate

$$\langle \sigma \cdot v \rangle_{T_1 T_2} = \frac{\int \sigma \cdot v f_1 f_2 \mathrm{d}^3 \vec{p}_1 \mathrm{d}^3 \vec{p}_2}{\left[\int \mathrm{d}^3 \vec{p}_1 f_1\right] \left[\int \mathrm{d}^3 \vec{p}_2 f_2\right]}$$

Current work: sub-dominant pbh dark matter

- Warm dark matter constraints are for when PBH produces all Ω
- Working on the mixed scenerio, important if dark matter is detected elsewhere.



$$T(k) = \left[1 + (\alpha k)^{\beta}\right]^{\gamma}$$

Archidiacono et al. 1907.01496

$$T(k) = (1-\delta)\left[1 + (\alpha k)^{\beta}\right]^{\gamma} + \delta$$

Hooper et al. 2206.08188

Conclusions

- PBHs could have been a big player in the Early Universe.
- If heavy BSM particles exist, evaporating BHs will produce them.
- One way to exclude PBHs is through measuring $\Delta N_{\rm eff}$.
- `FRISBHEE` calculates this in the most accurate way.
- PBHs are efficient for producing non-interacting dark matter.
- Future detection of dark matter would have implications for the fairly unconstrained region of $M_{\rm PBH} \sim [10^{-1}, 10^{9}]\,{\rm g}$.