ASTROCENT

CAMK
PAN

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

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FUW seminarium “Teoria cząstek elementarnych i kosmologia”

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

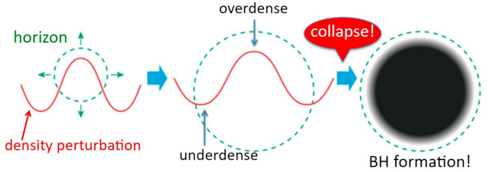
Based on: arXiv:2207.09462, arXiv:2107.00013 and arXiv:2107.00016

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

December 8, 2022

Primordial Black Holes

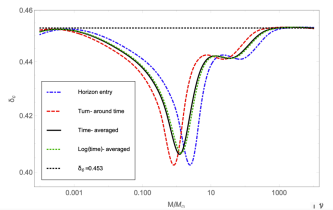
- Hypothetical black holes formed before stellar formation.
- Come from extremely dense matter fluctuations in the early Universe.
- These density perturbations are not produced in standard slow roll inflation.



[picture borrowed from N. Kitajima]

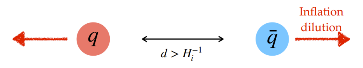
Production of PBHs

- 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]

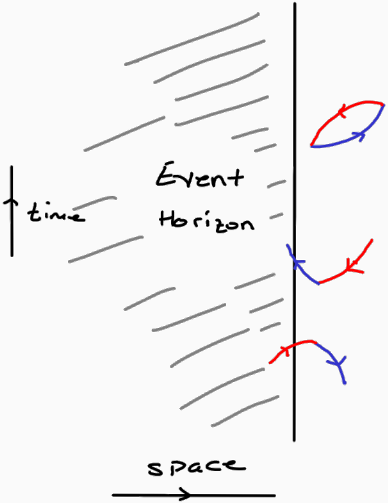


Hawking radiation

- Hawking radiation gives a lifetime to all BHs

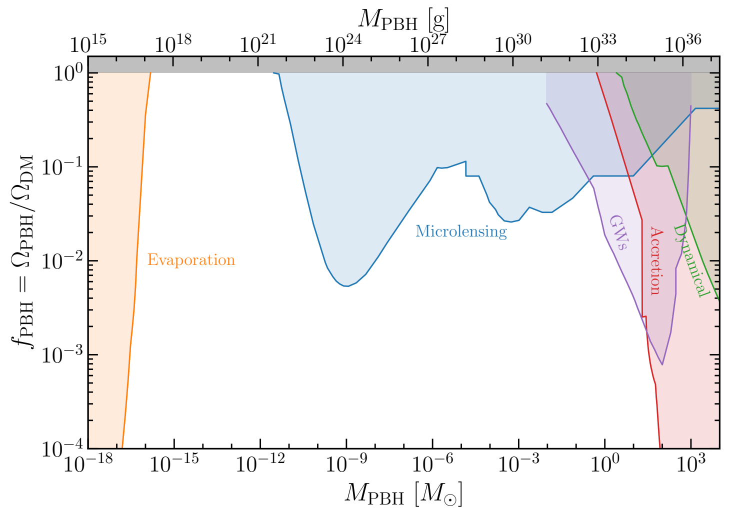
$$t_{\rm ev} \sim (M_{\rm BH}^{\rm in})^3/(3M_{\rm pl}^4)$$

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

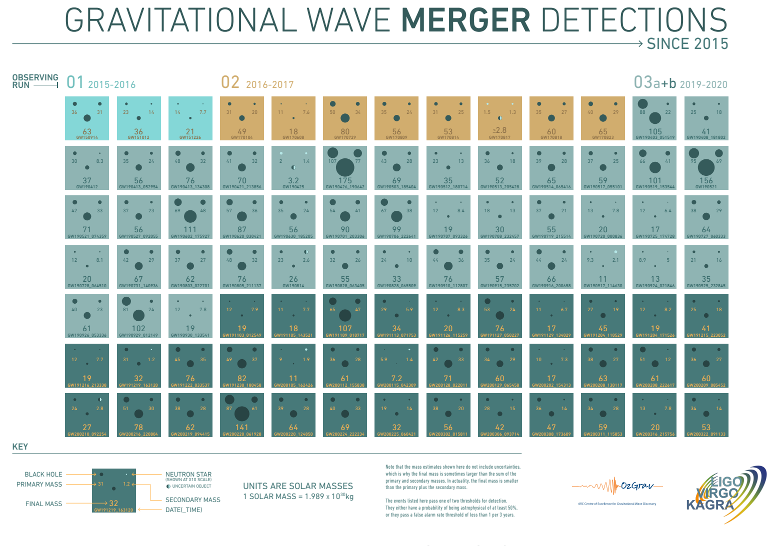


PBHs as dark matter

[B. Kavanagh and A. Green 2022]



Binary mergers provide hints to primordial black hole populations



GRAVITATIONAL WAVE **MERGER** DETECTIONS

→ SINCE 2015

OBSERVING RUN

O1 2015-2016

O2 2016-2017

O3a+b 2019-2020

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

KEY

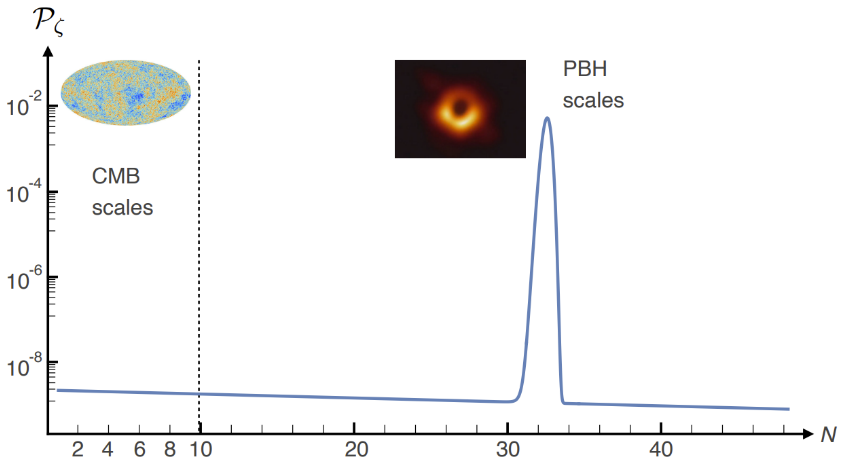
UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^{30}kg

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

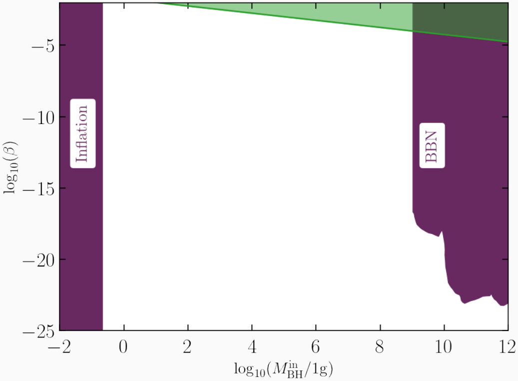
[From Florian Kuhnel talk]



A window of opportunity

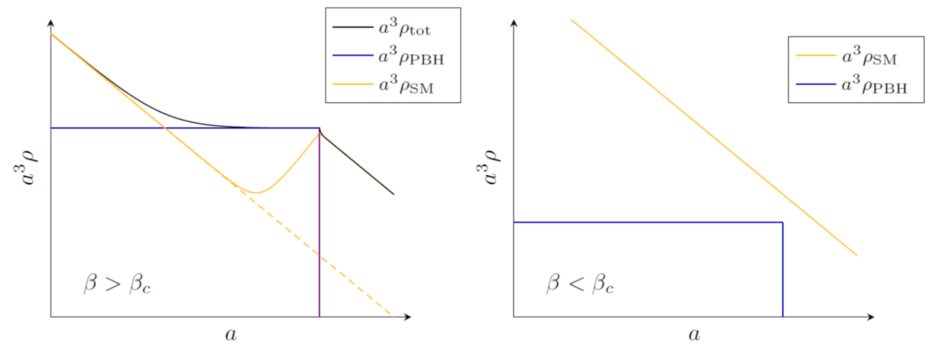
$$\beta' \equiv \gamma^{1/2} \left(\frac{g_\star(T_{\rm in})}{106.75} \right)^{-1/4} \frac{\rho_{\rm PBH}^{\rm in}}{\rho^{\rm in}}$$

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



Early matter domination is possible

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



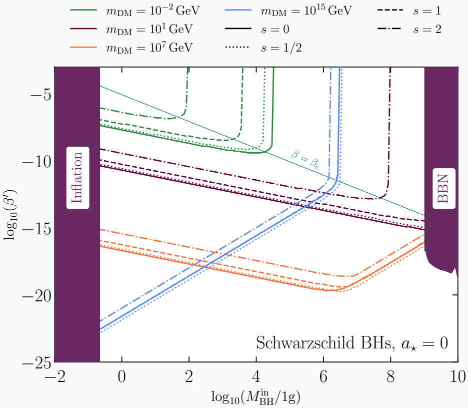
Evaporating BHs are a tantalizing prospect

- 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).

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

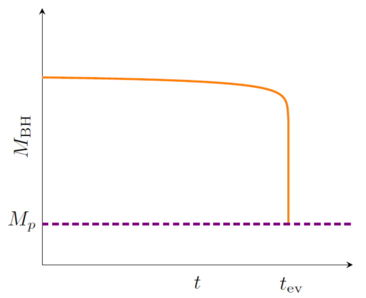
- If a stable particle exists, it will be produced in the process of Hawking evaporation.
- A very small number of BHs needed to produce the correct relic abundance
- $\beta' \equiv \gamma^{1/2} \left(\frac{g_\star(T_{\rm in})}{106.75} \right)^{-1/4} \frac{\rho_{\rm PBH}^{\rm in}}{\rho^{\rm in}}$

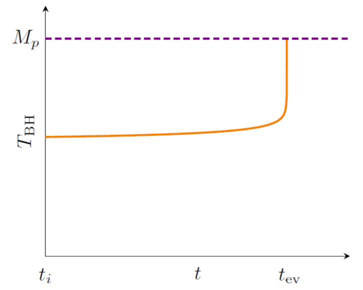
[AC, L. Heutier, Y. F. Perez-Gonzalez and J. Turner (2021)]



Basics of black hole evaporation

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



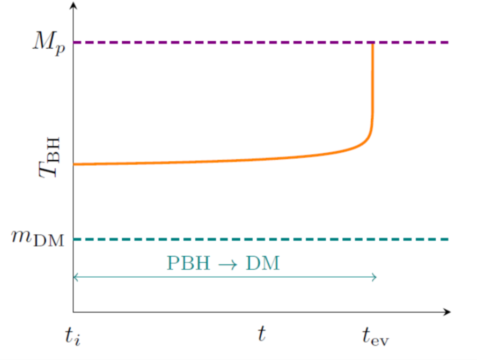


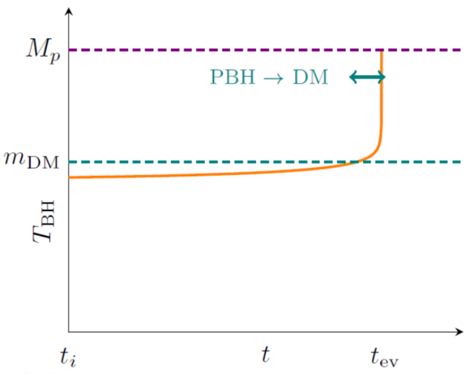
Any particles with $m < M_\mathrm{p}$ will be emitted

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

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

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

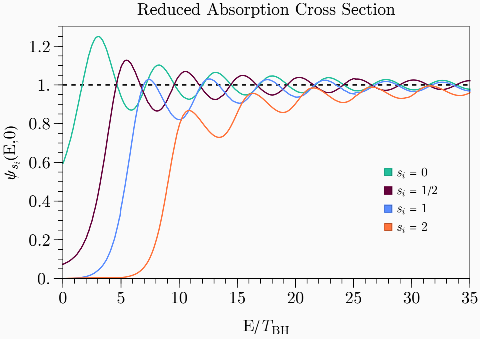




Particle emission depends on intrinsic particle nature

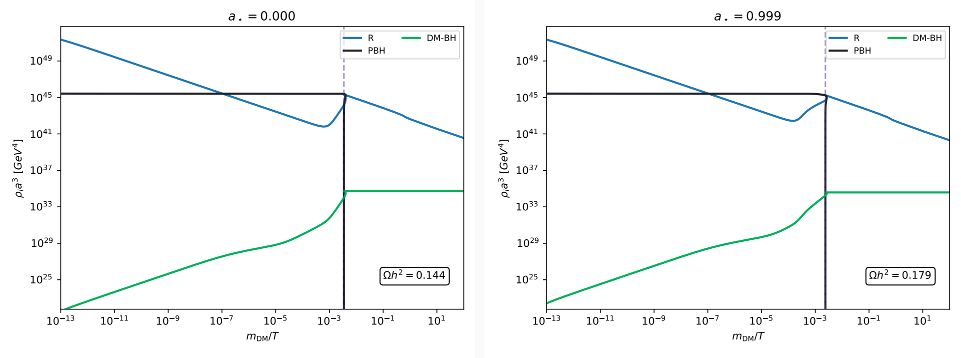
$$\frac{\mathrm{d}^2\mathcal{N}_i}{\mathrm{d}p\,\mathrm{d}t} = \frac{g_i}{2\pi^2}\frac{\sigma_{s_i}(M_{\rm BH},\mu_i,p)}{\exp\left[E_i(p)/T_{\rm BH}\right]-(-1)^{2s_i}}\frac{p^3}{E_i(p)}$$

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



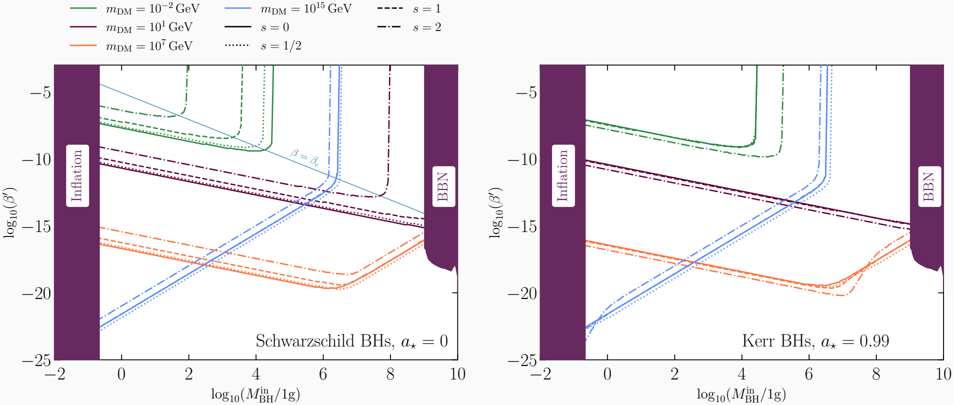
FRISBHEE tracks dark matter production

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



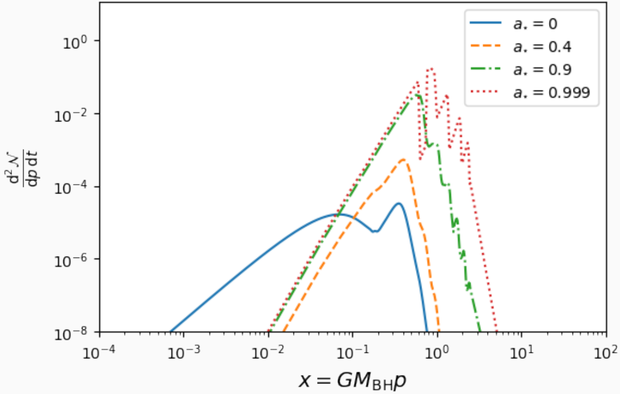
Dark Matter from only PBH evaporation

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



Spinning black holes preferentially emit higher spin particles

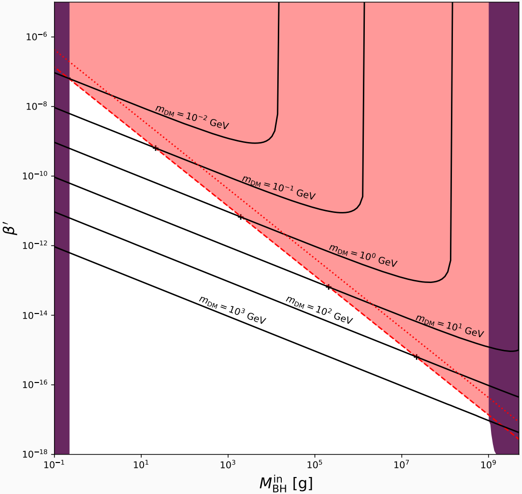
- It has long been known that Kerr black holes ($a_\star \neq 0$) shed their angular momentum by emitting higher spin particles.
- Closer to maximal $a_\star \to 1$, the more pronounced the enhancement is.



Warm dark matter constraints

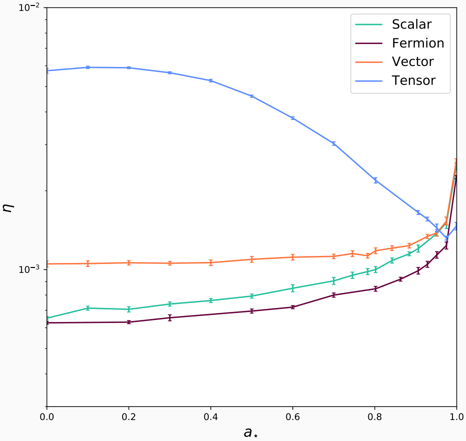
- Using `CLASS` one can get some constraints on the PBH→DM scenario from Lyman-α forest.
- For a given dark matter spin, constraint is independent of the dark matter mass itself.

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



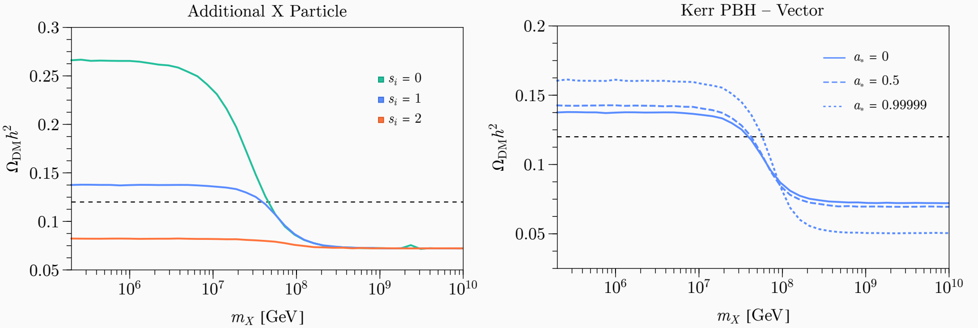
Warm dark matter constraints different spins

- 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_{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.



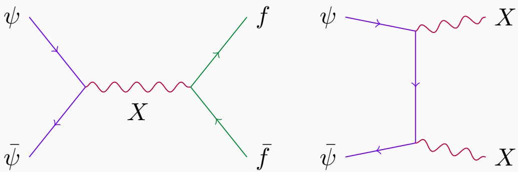
Effect of extended dark sectors

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



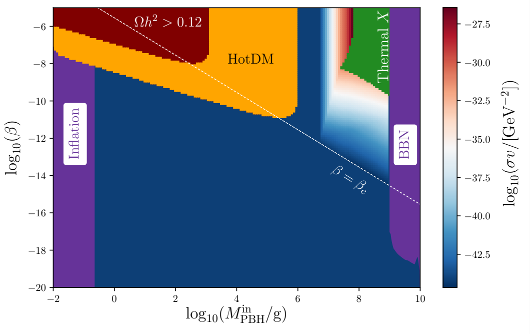
Freeze-In Dark Matter with PBHs

We considered a vector-mediated, Fermionic dark matter model



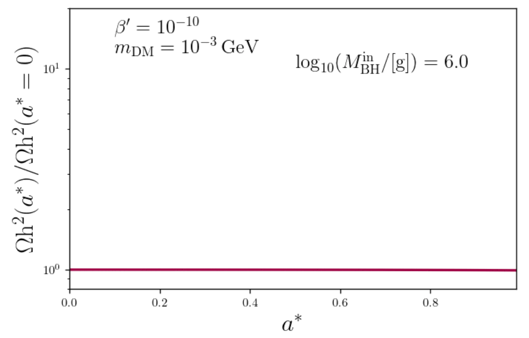
and systematically explore the parameter space

Here $m_{\rm DM} = 1$ 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 $T^{\mathrm{univ.}} \sim m_X$ for longer.
- On this resonance is when more DM particles are produced through standard freeze-in.

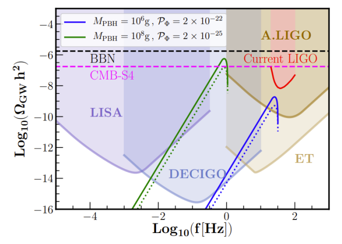


Testing the role of PBHs in the early Universe

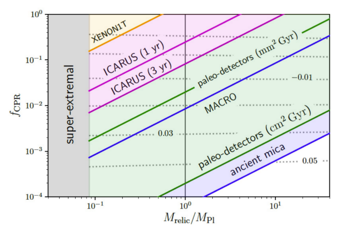
Detecting dark matter would have huge implications for pbhs in the early Universe.

- Gravitational wave production.
- 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

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

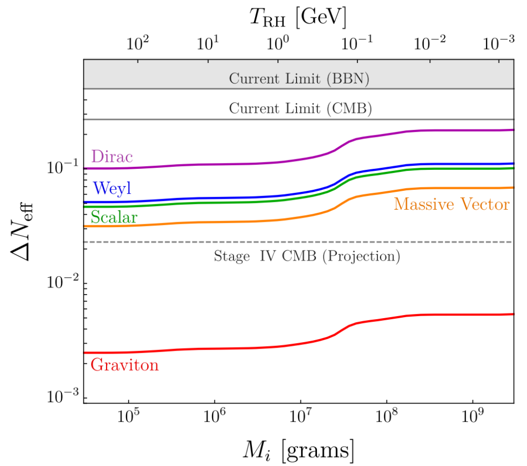
- Where ΔN_{eff} parametrises any additional contributions.
- Which, presumably would come from dark radiation $\rho_{\mathrm{R}} = \rho_{\mathrm{R}}^{\mathrm{SM}} + \rho_{\mathrm{DR}}$

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

Forms of dark radiation

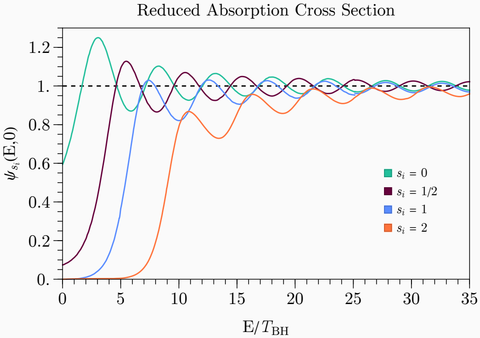
- Dark radiation: light particles that do not have significant couplings to the SM.
- Many proposed extensions to the SM.
- With the next generation of CMB probes, it seems that both early pbh domination and DR may become mutually exclusive.

Hooper et.al. 2019



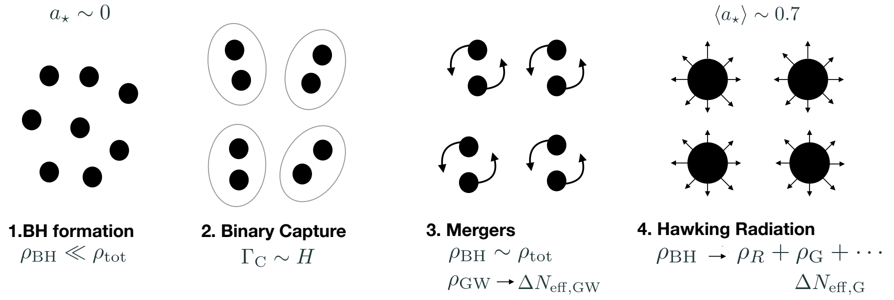
The graviton as a form of dark radiation

- *Hot take*: Graviton is basically a member of the SM.
- Black hole evaporation will produce them. So could be a probe of pbhs without invoking BSM.
- For Schwarzschild bhs, graviton production is highly suppressed.



Likelihood of Kerr population of pbhs?

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

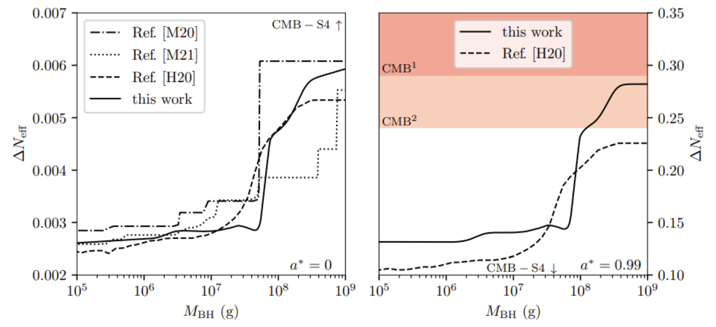


Hooper et.al. 2020

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]



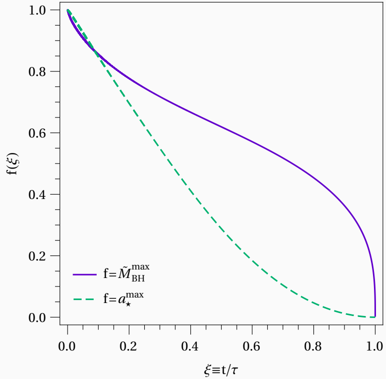
Spin evolution

- 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 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.



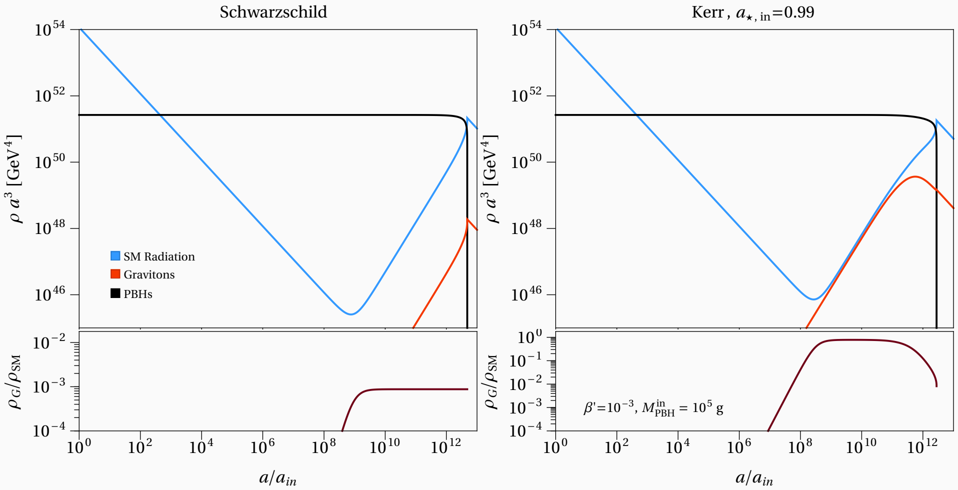
Motivation for FRISBHEE

- 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.

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

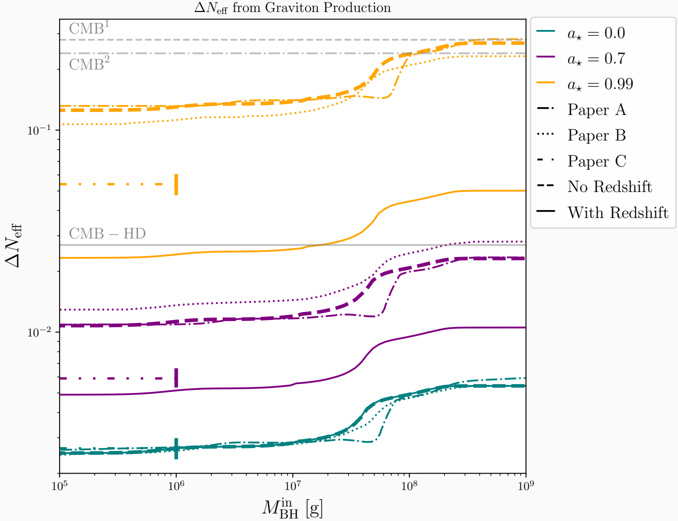
$$\dot\rho_{\rm R}^{\rm SM} + 4H\rho_{\rm R}^{\rm SM} = -\left.\frac{{\rm d}\log M_{\rm BH}}{{\rm d}t}\right|_{\rm SM}\rho_{\rm PBH}\,, \qquad \dot\rho_{\rm PBH} + 3H\rho_{\rm PBH} = \frac{{\rm d}\log M_{\rm BH}}{{\rm d}t}\rho_{\rm PBH}\,,$$

Entropy injection after $a_\star \sim 0$



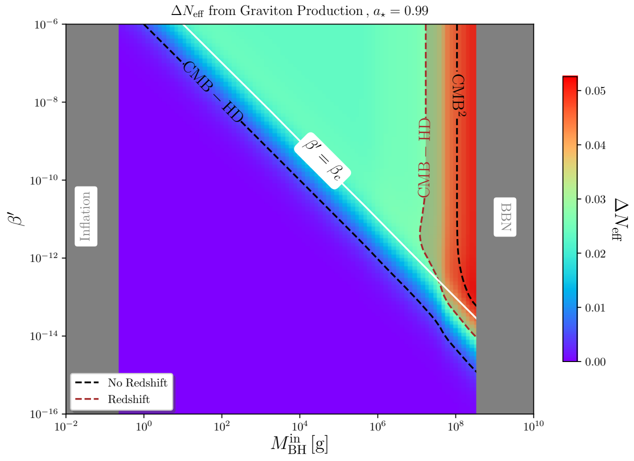
Results assuming PBH domination

- 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



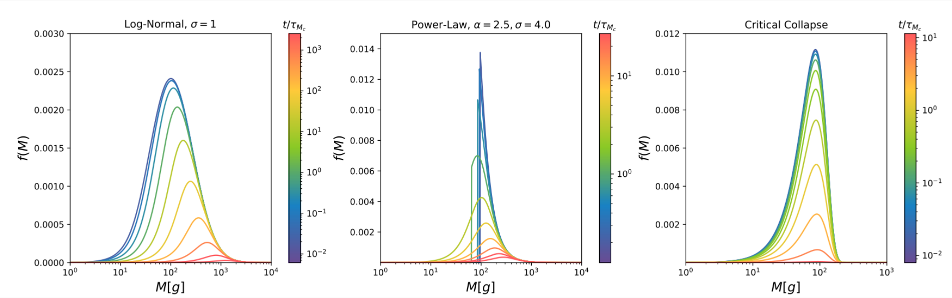
Scan results for graviton

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



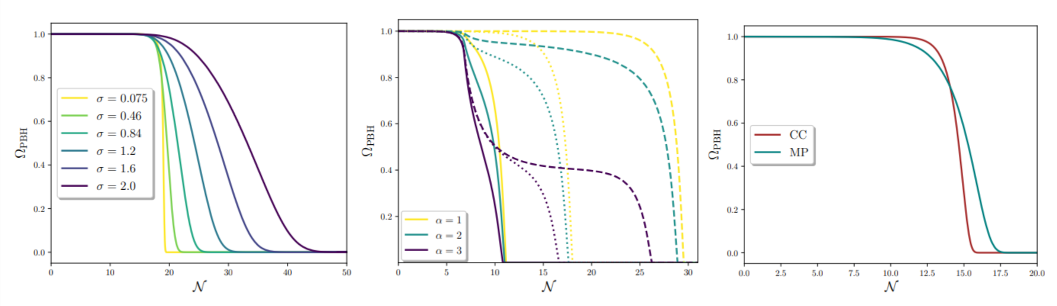
Distributions of PBHs

- 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.



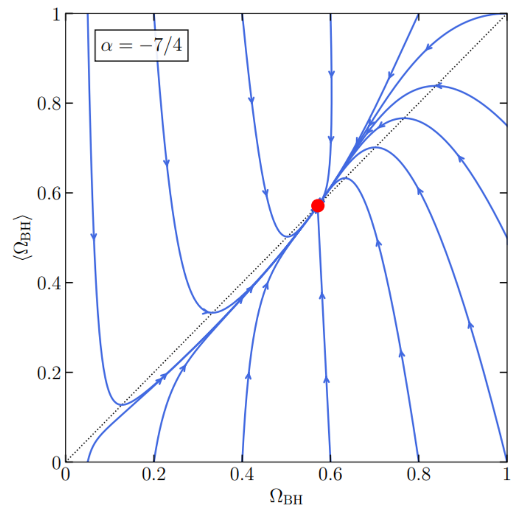
Distributed PBHs and effects

- The updated `FRISBHEE` tracks the cosmological evolution with distributed PBHs.
- Evaporation can occur over many e-folds.



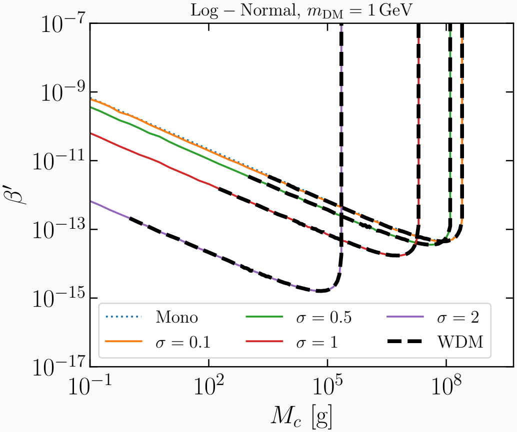
Stasis from a power law

- Pointed out by K. Diernes et. al (2022) and Barrow et. al. 1991, power law distributions lead to ‘cosmological stasis’.
- Abundance of matter and radiation remains constant despite cosmological expansion.



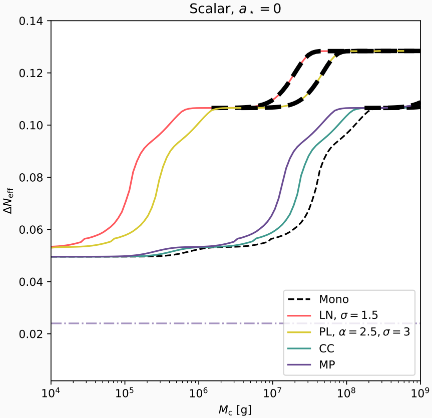
Effect on dark matter production

- Wide distributions with tail at high masses enable dark matter to be generated from lower β' values.
- This is because $N_{\rm DM} \propto (M_{\rm BH})^2$, having larger PBHs even if sub-dominant drives $\Omega_{\rm DM}$.
- Simultaneously, warm dark matter constraints get more aggressive.



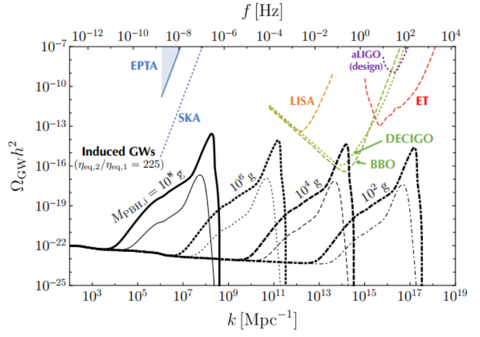
Effect on ΔN_{eff} with BSM radiation

- Fairly predictable behaviour for new dark radiation species with a mass distribution.
- BBN limits denoted by black dashed lines.



Gravitational Waves

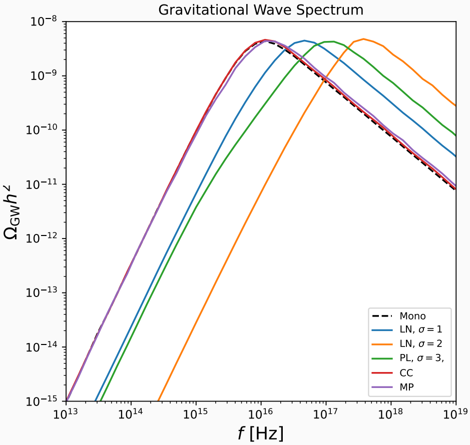
- PBH production and evaporation leads to Gravitational waves in multiple ways.
- One scenario is where the sudden transition from the PBH dominated to radiation dominated Universe causes the gravitational potential to oscillate, producing amplified GWs.
- The reliance on sudden transition in the equation of state is key.



[K. Inomata et. al. 2020]

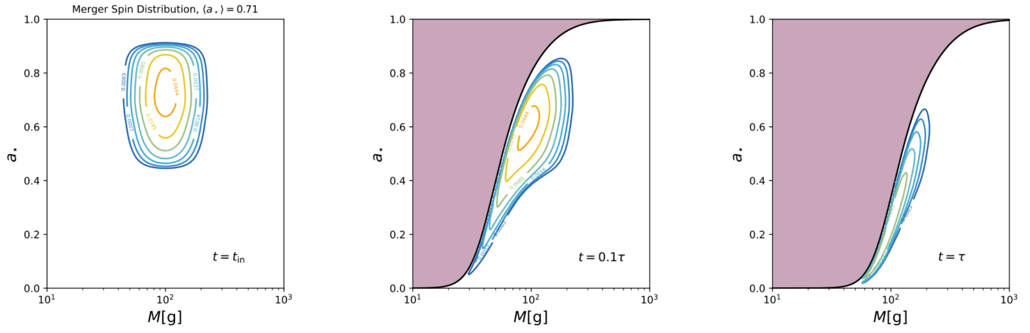
Gravitational Waves

- A high frequency gravitational wave background comes from the gravitons emitted from BHs.
- Important to note that overall amplitude is not diminished.



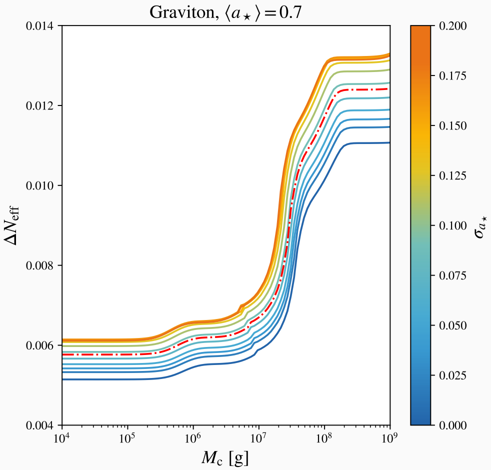
Spin distributions

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



Effect on ΔN_{eff} with SM + graviton

- Returning to our prediction for the graviton contribution to ΔN_{eff}.
- The red dot-dashed line shows the monochromatic spin.
- We see modest enhancement and with wide Gaussian of $\sigma \sim 0.2$, the enhancement starts to diminish.



Conclusions

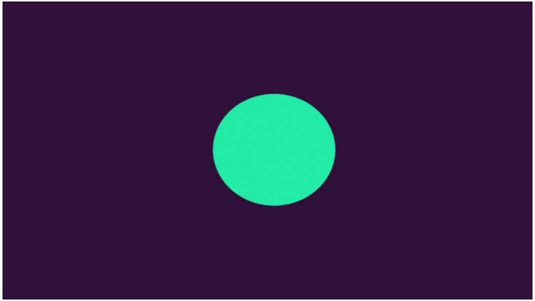
- PBHs may have been a big player in the Early Universe.
- If heavy BSM particles exist, evaporating BHs will produce them.
- One way to exclude PBHs is through measuring $\Delta N_{\rm eff}$.
- The graviton contribution counts as a SM contribution to dark radiation.
- Our tool `FRISBHEE` calculates this in the most accurate way, including the spin evolution of BHs.
- Recent update on `FRISBHEE` allows one to include distributed PBH populations.

Backup slides

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:

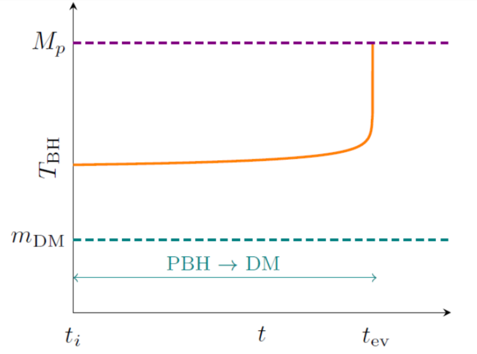
- Many models predict interactions between the SM and dark matter.
- Current and near future experiments may even measure this interaction.
- Dark matter detection could be an indirect probe into PBH's in early Universe.
- arXiv:2107.00016 is dedicated to this, where we make use of the code developed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

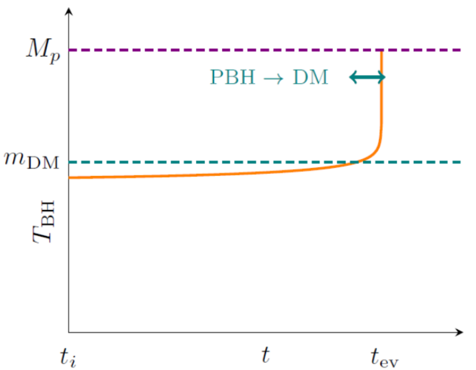
Any particles with $m_{\rm DM} < M_{\rm p}$ will be emitted

- Two separate regimes of particle production for stable particles

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

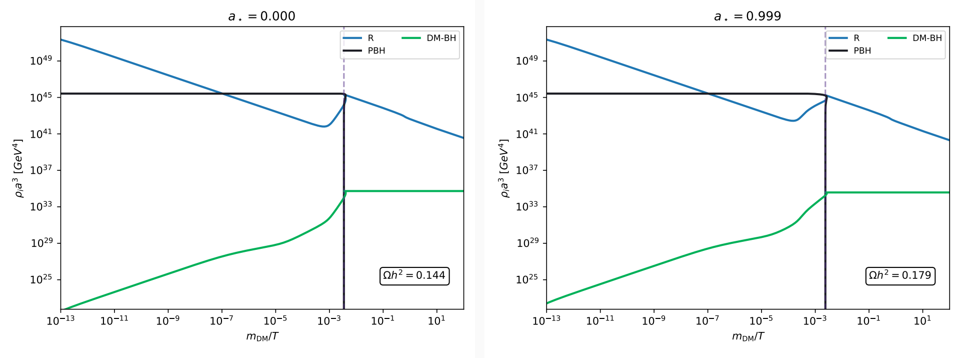
$$N_{\rm DM} \approx \frac{15\zeta(3)}{8\pi^5}\frac{g_i}{g_\star(T_{\rm BH})}\frac{M_{\rm pl}^2}{m_{\rm DM}^2}$$





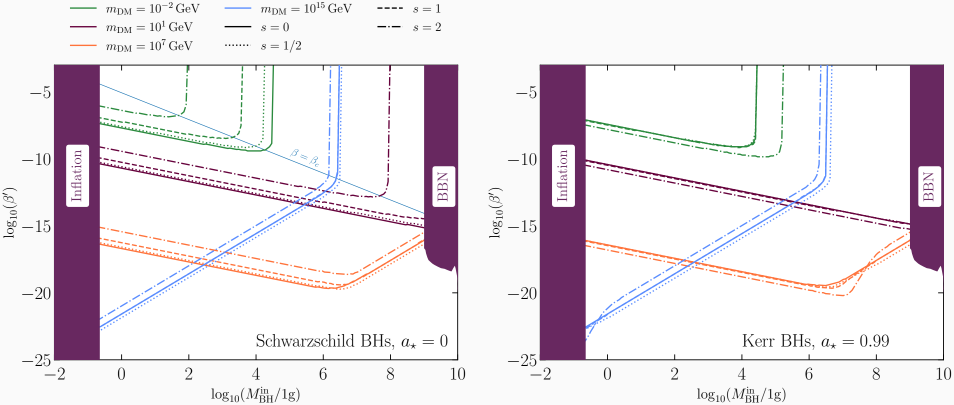
FRISBHEE tracks dark matter production

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



Dark Matter from only PBH evaporation

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

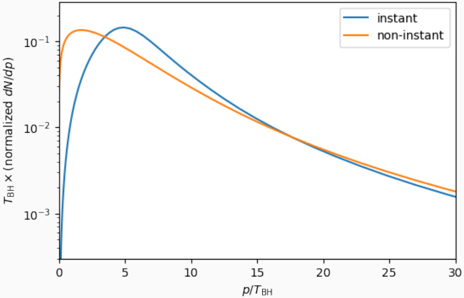


Dark matter distribution

- 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

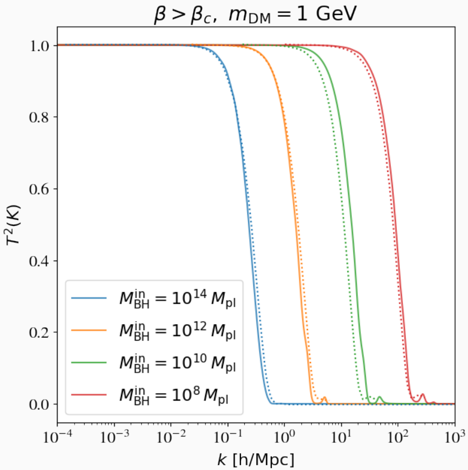


$$\frac{\mathrm{d}\mathcal{N}_{\rm DM}}{\mathrm{d}p} = \int_0^\tau \mathrm{d}t' \frac{a(\tau)}{a(t')} \times \frac{\mathrm{d}^2\mathcal{N}_{\rm DM}}{\mathrm{d}p'\mathrm{d}t'}\left(p\frac{a(\tau)}{a(t')}, t'\right)$$

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

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



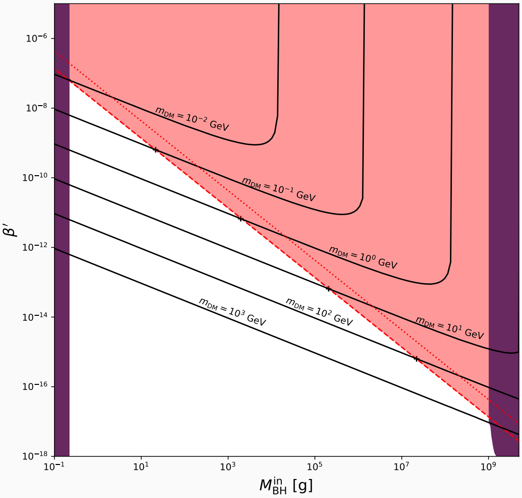
Consistent η relation

- To determine the constraint, can use

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

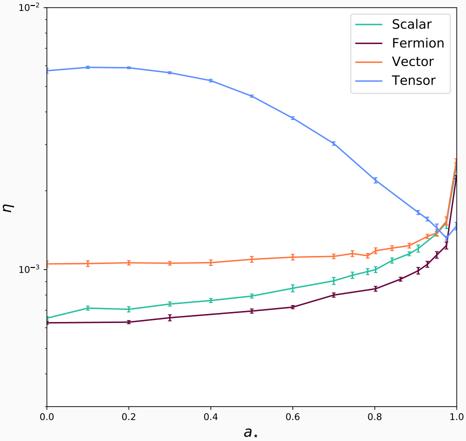
- Find the $M_{\mathrm{BH}}^{\mathrm{in}}$ value that $\alpha = 1.3 \times 10^{-2}\,\mathrm{Mpc}\,h^{-1}$.
- For a given dark matter spin, constraint is independent of the dark matter mass itself.

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



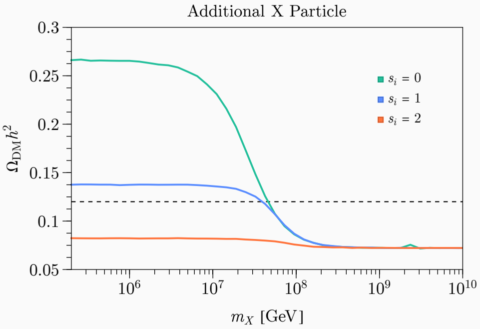
Warm dark matter constraints different spins

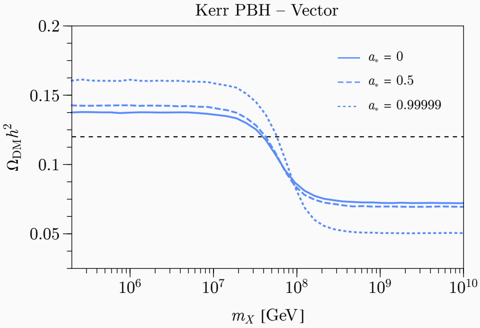
- How the constraint depends on particle spin and BH spin ($a_\star$) is non-trivial.
- The increased $a_\star$ comes with a greater momentum in the distribution $f_{\rm DM}$.
- At the same time the β' values required to produce the correct Ω alters.
- In the end the particle type most sensitive to $a_\star$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



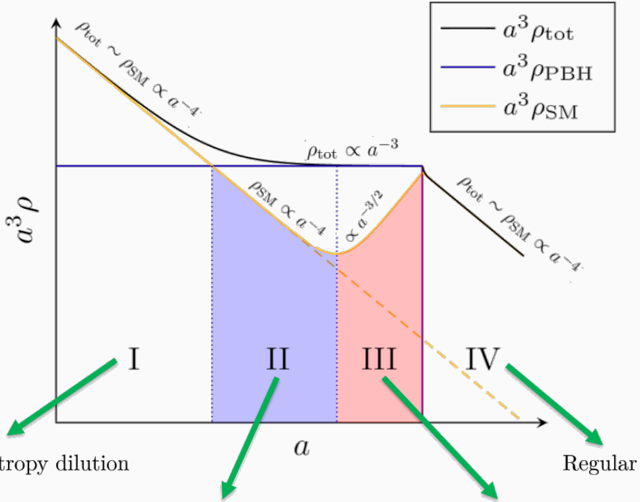
Effect of extended dark sectors

- 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



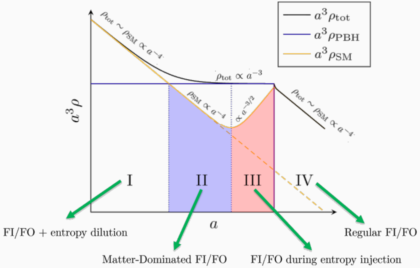
FI/FO + entropy dilution

Matter-Dominated FI/FO

FI/FO during entropy injection

Regular FI/FO

Interplay between interacting dark matter and pbh production



FI/FO + entropy dilution

Matter-Dominated FI/FO

FI/FO during entropy injection

Regular FI/FO

- The set of Boltzmann equations are now expanded

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

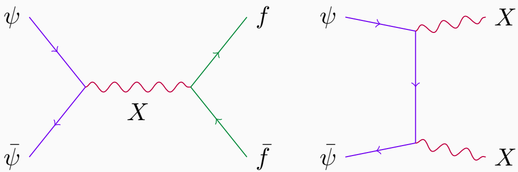
$$\dot{n}_X + 3Hn_X = g_X\int C[f_X]\frac{\mathrm{d}^3p}{(2\pi)^3} + \left.\frac{\mathrm{d}n_X}{\mathrm{d}t}\right|_{\rm BH}$$

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

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

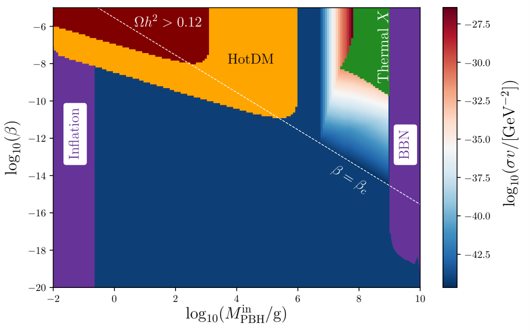
Freeze-In Dark Matter with PBHs

We considered a vector-mediated, fermionic dark matter model



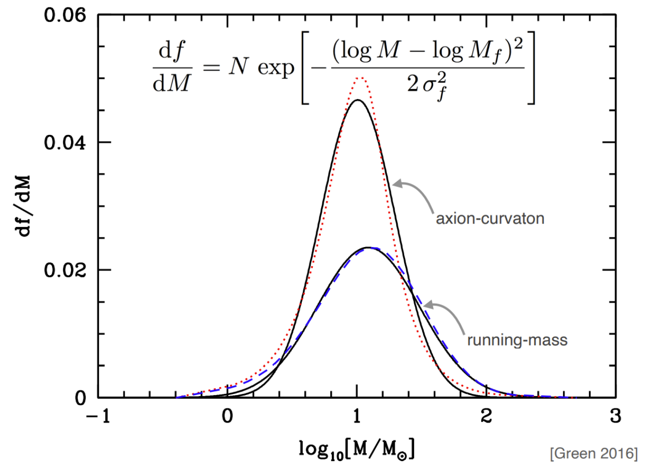
and systematically explore the parameter space

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



Current work: Distributions of PBHs

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



$$\frac{\mathrm{d}f}{\mathrm{d}M} = N \exp\left[-\frac{(\log M - \log M_f)^2}{2\,\sigma_f^2}\right]$$

[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.

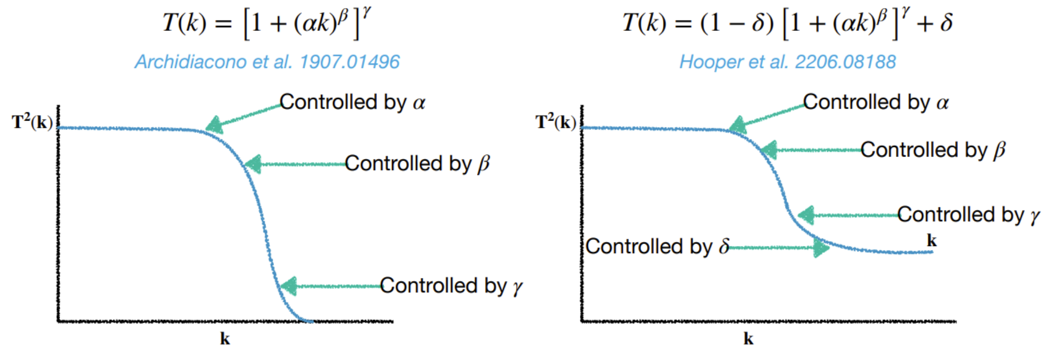
$$\Gamma_X \left\langle \frac{m_X}{E_X} \right\rangle_{\mathrm{ev}} \equiv \Gamma_X \int \frac{m_X}{E_X} f_{\mathrm{ev}}(p_X) \frac{\mathrm{d}^3 p_X}{(2\pi)^3}$$

- 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

BSM dark radiation and Kerr

- Many BSM scenarios predict new light 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 similar 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.