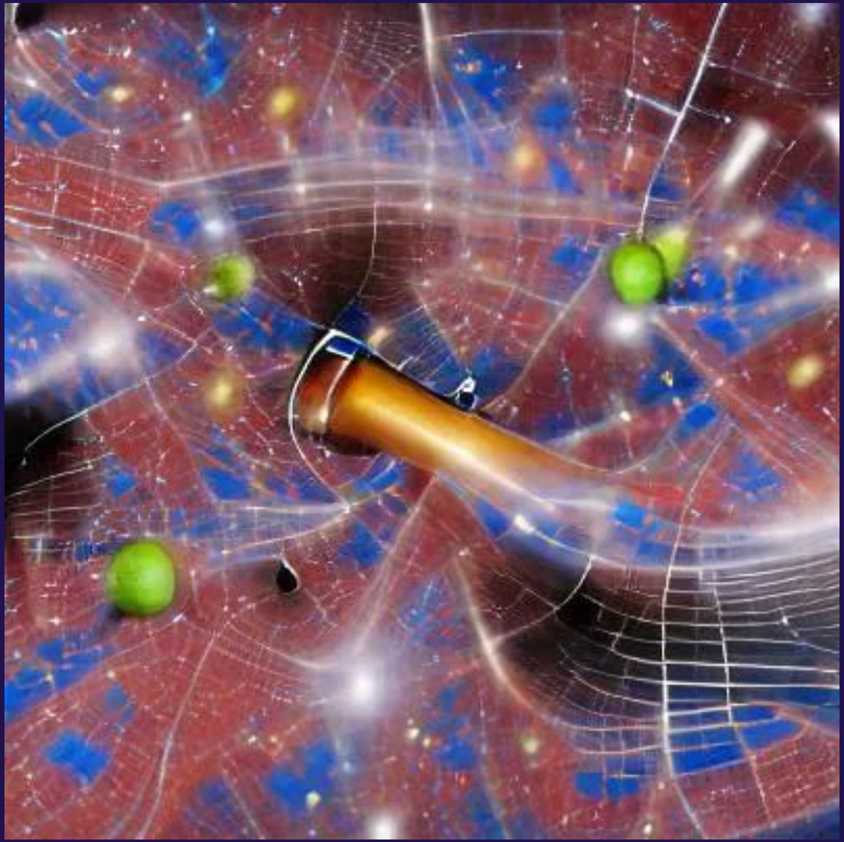
Zachary S. C. Picker,
University of Sydney

Probing the universe at the intersection of gravity and particle physics



Zachary Picker

CPPC Seminar, Oct 2021

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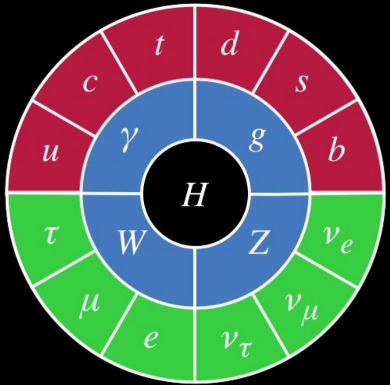
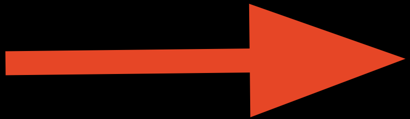
Gravity and particle physics are exciting partners





Most successful theory…

ever?

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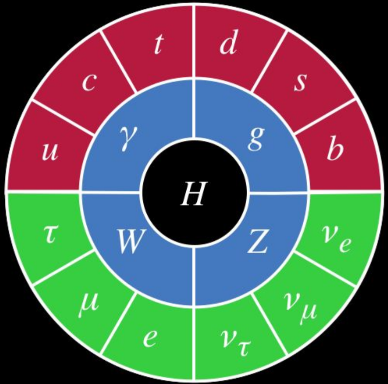
Gravity and particle physics are exciting partners



+

- Quantum gravity?
- Black holes?
- Cosmological constant problem?
  - (least successful prediction… ever?)
- Dark matter?

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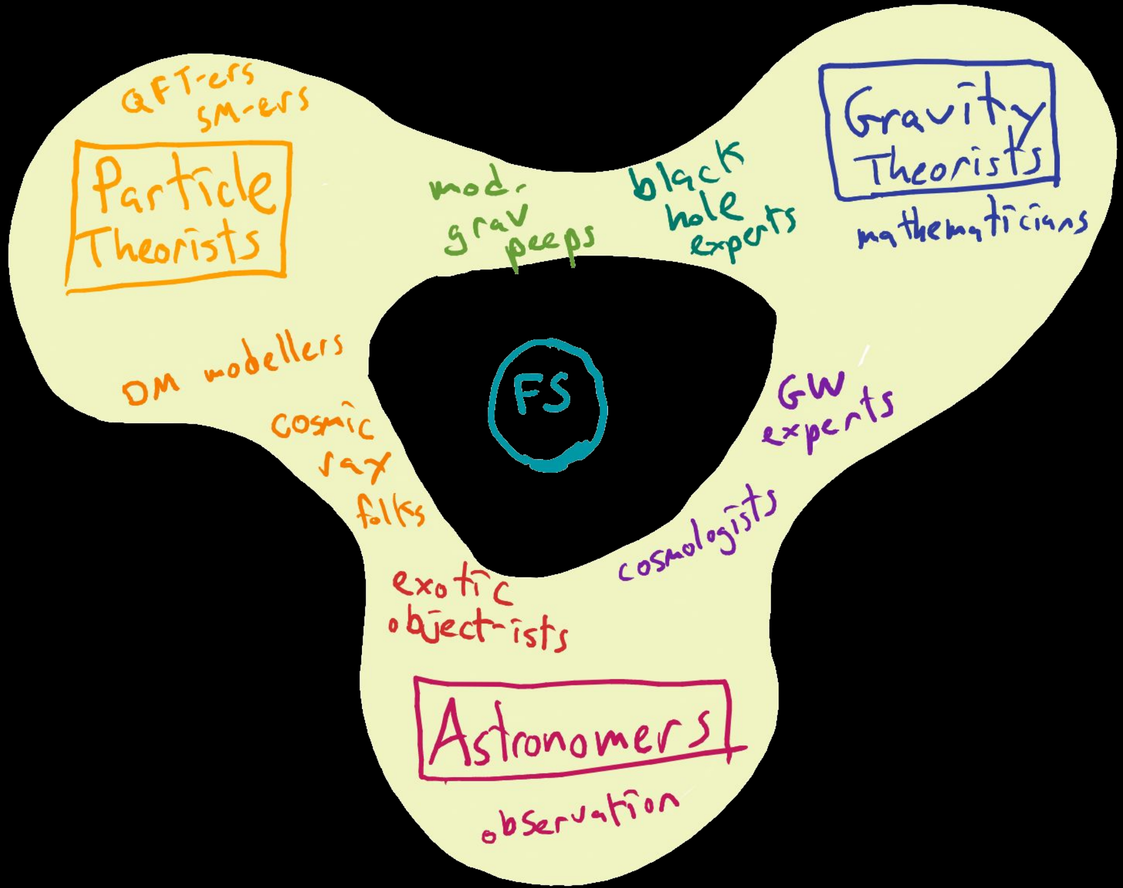
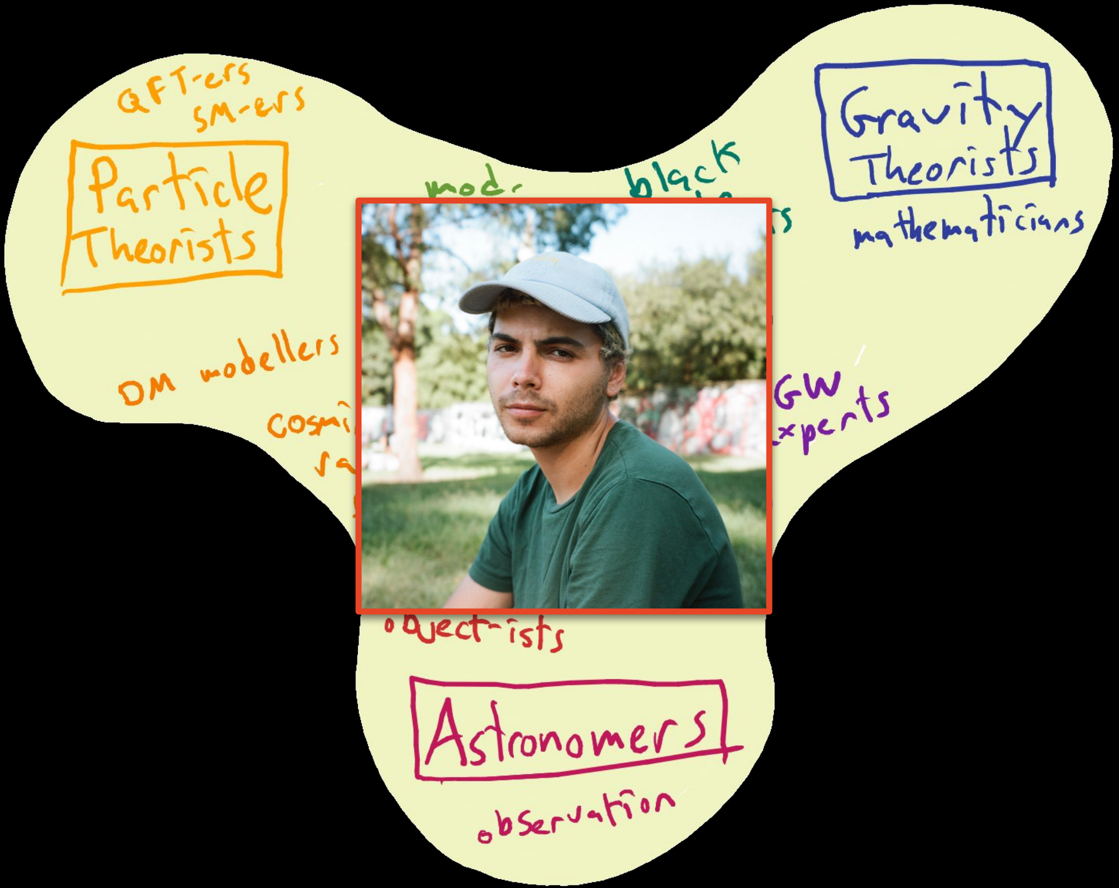
You have to know a lot to make progress...



You have to know a lot to make progress...



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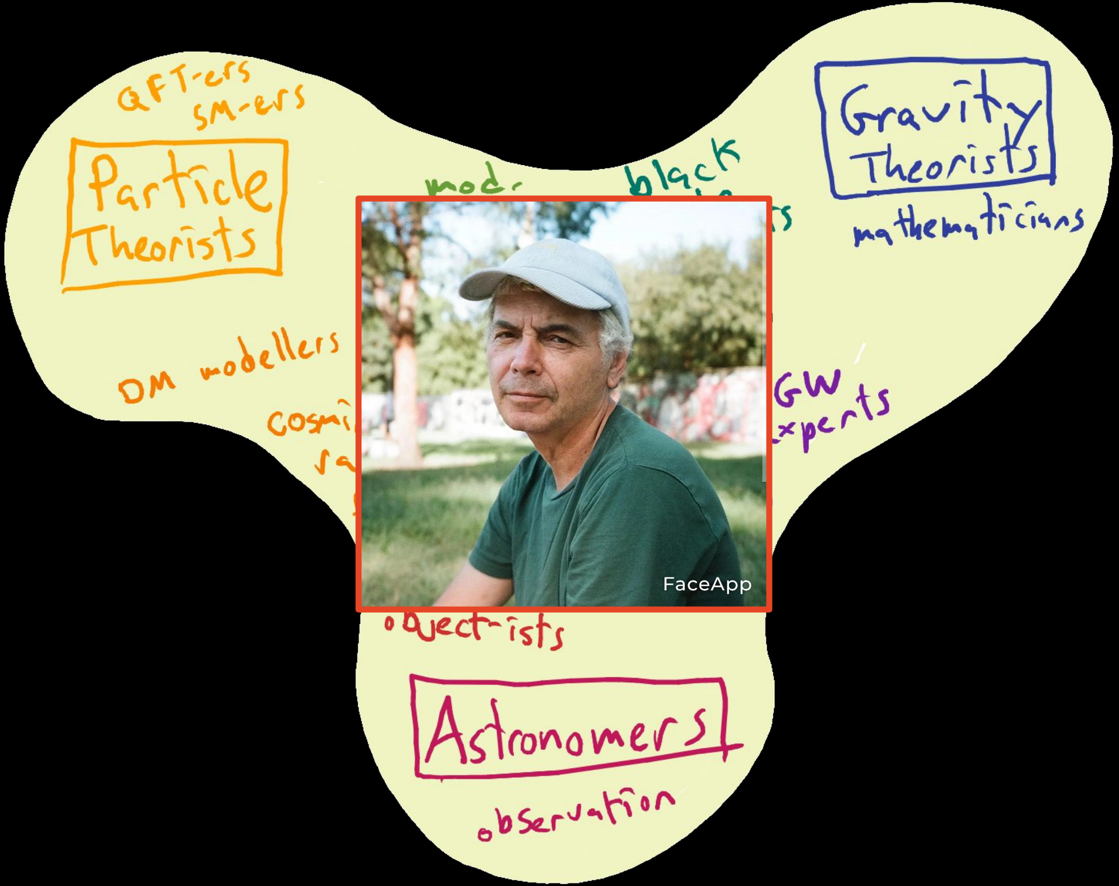
You have to know a lot to make progress...



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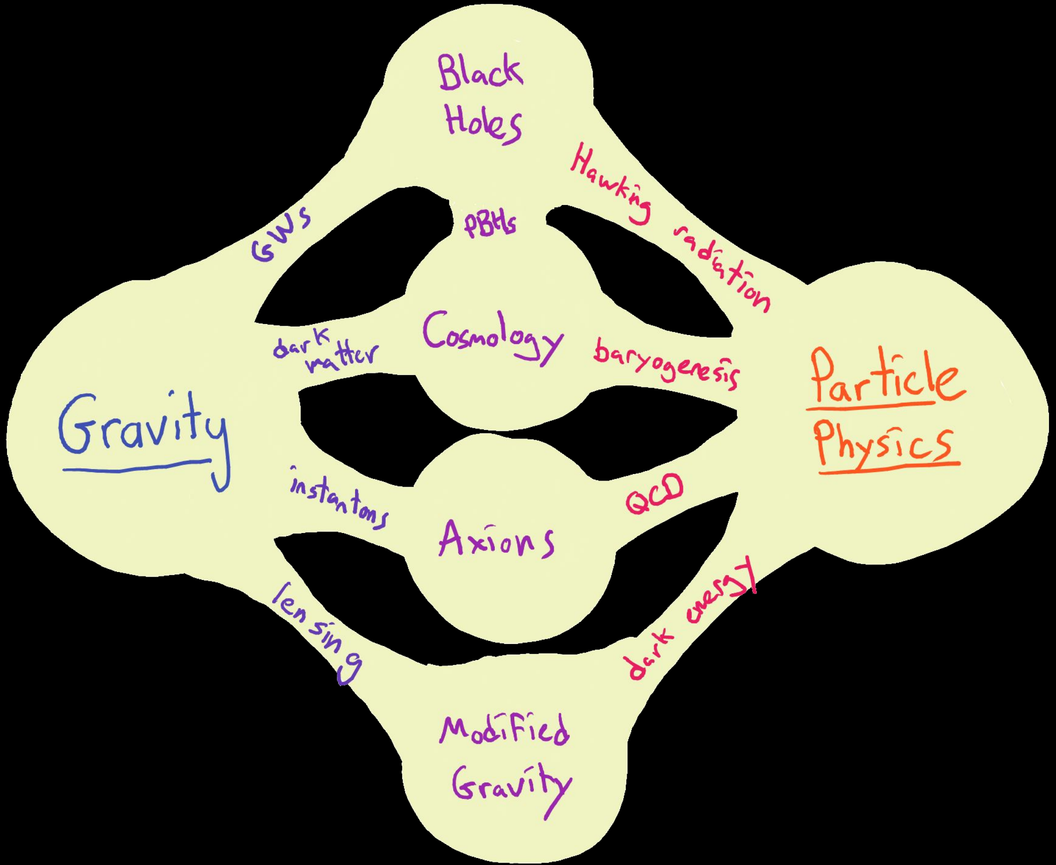
Gravity + PP is a useful lens to study phenomenology



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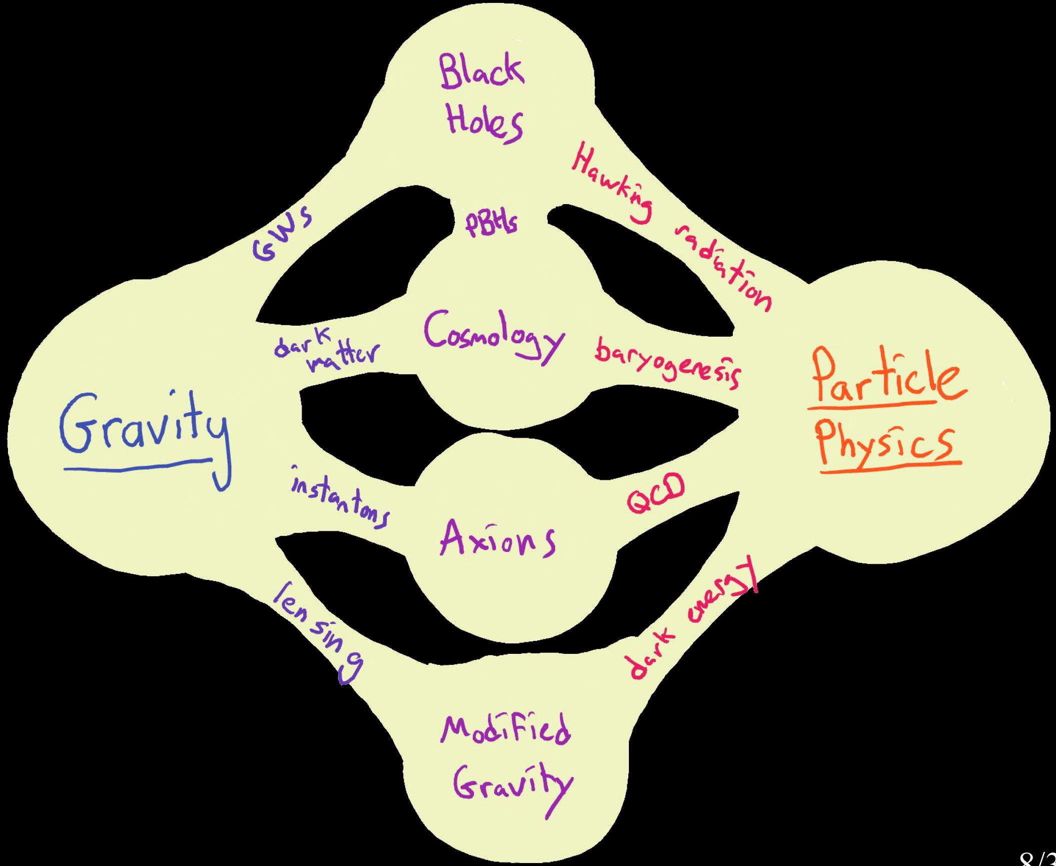
Three questions for finding new physics



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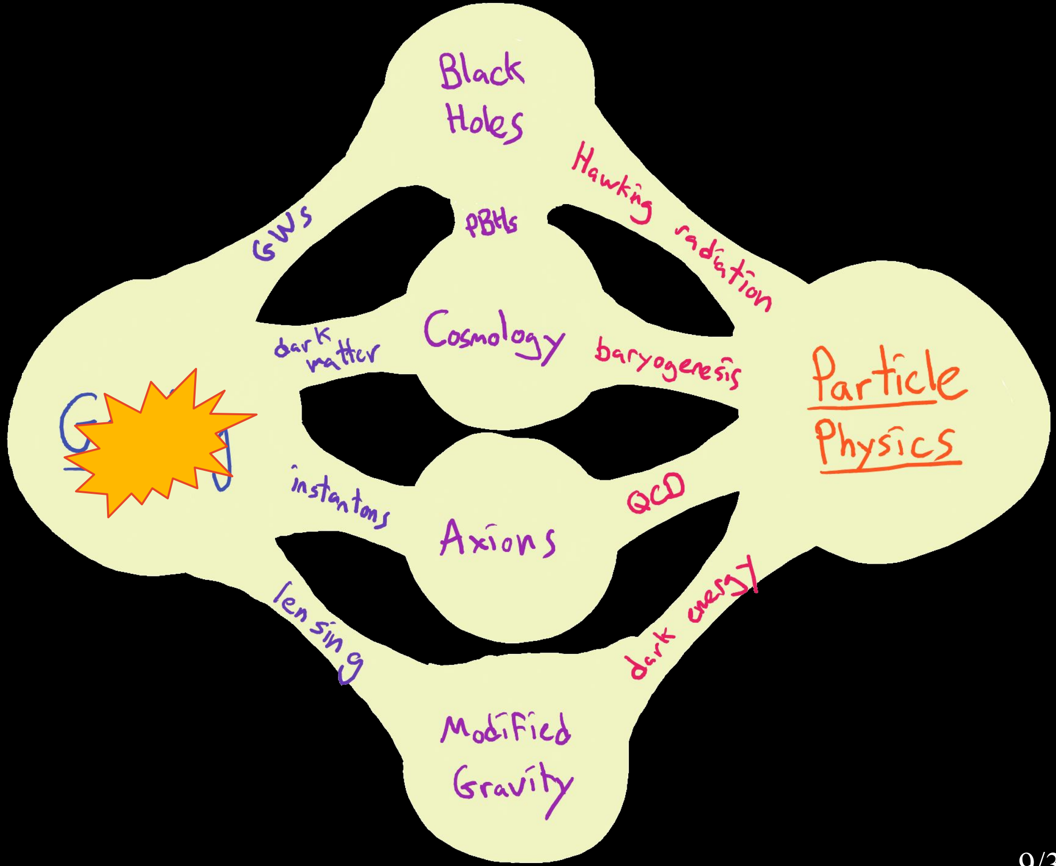
Three questions for finding new physics

1. What happens when we modify gravity?



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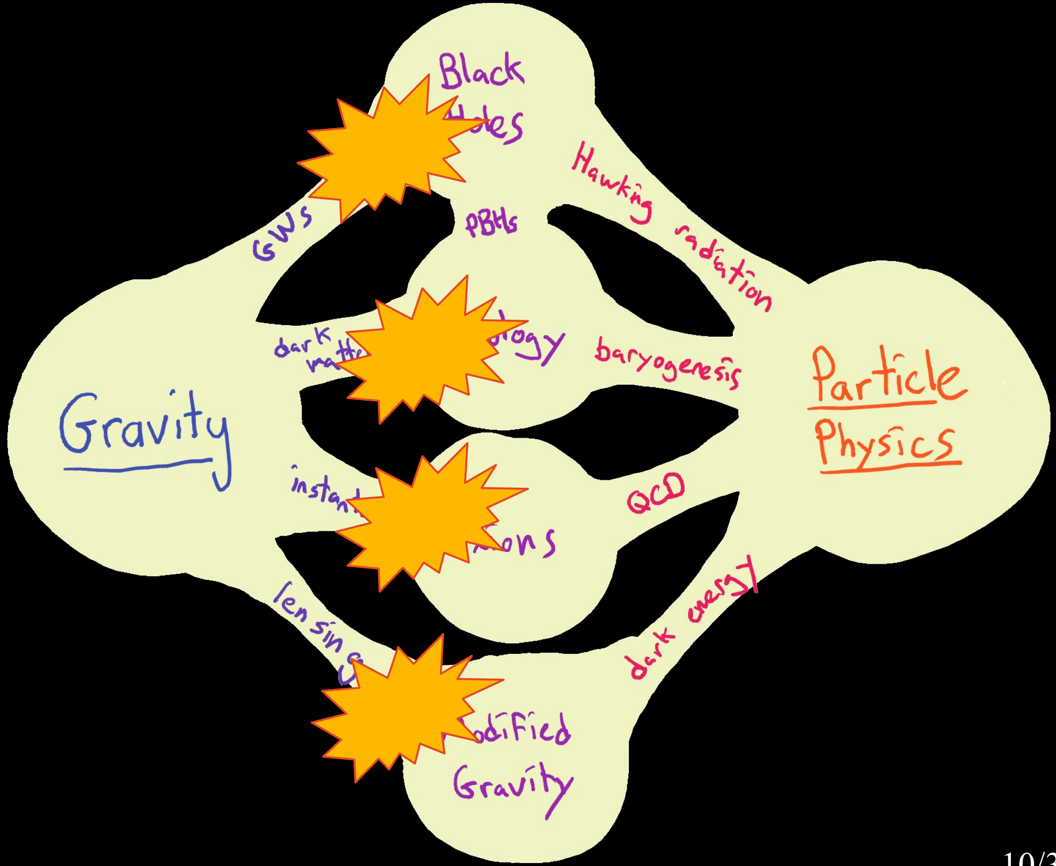
Three questions for finding new physics

1. What happens when we modify gravity?
2. What happens when we find new solutions within GR?



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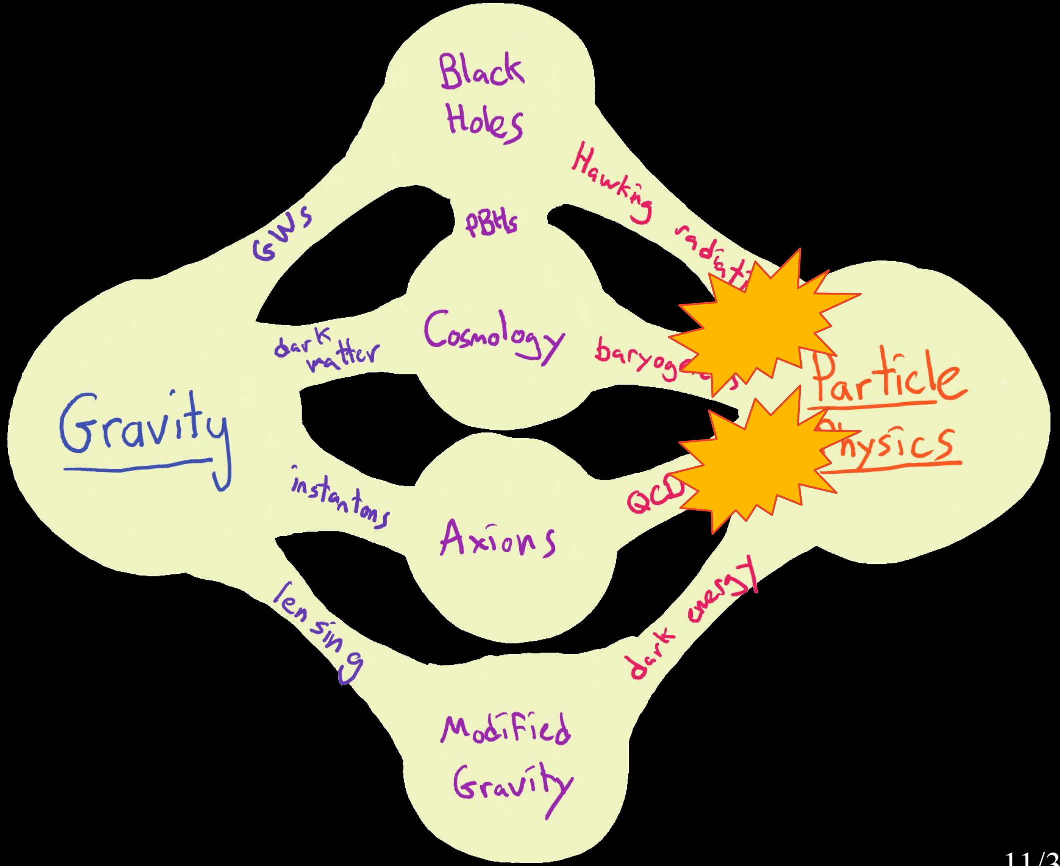
Three questions for finding new physics

1. What happens when we modify gravity?
2. What happens when we find new solutions within GR?
3. What happens when we add gravity to particle physics?



1. What happens when we change gravity?

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Using observation to constrain theory...GWs

'Quadratic gravity':

- Extra massive scalar and spin-2 gravitons
- BH Binaries deplete energy faster

$\Rightarrow$ tightests constraints on theory

$$m_{\phi,\pi} \gtrsim 7.0 \cdot 10^{-12}\ \text{eV}$$

arXiv:1906.12034, Kim, Kobakhidze, Picker

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Using theory to reexamine constraints...microlensing

Quadratic gravity

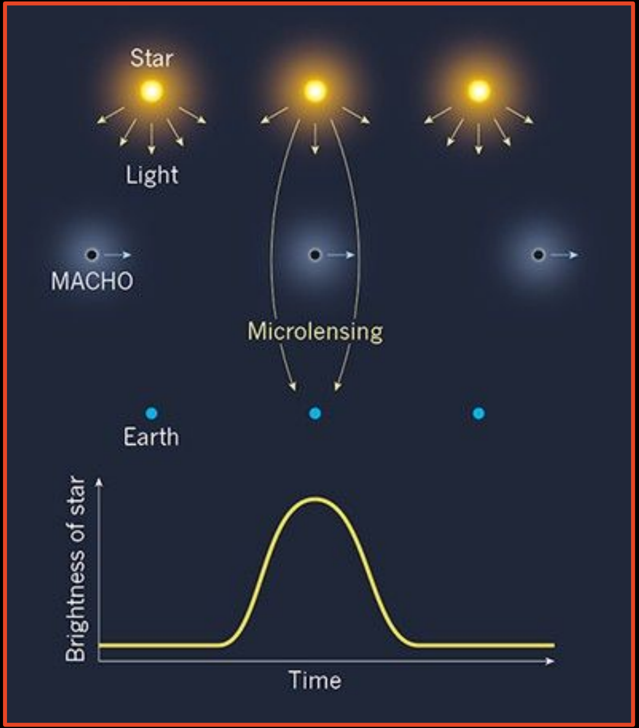
- Too constrained (by us!)

'Bimetric gravity'

- Coupled to massive graviton
- Screened at close range

  ⇒ need much farther sources,

  or more massive lenses...



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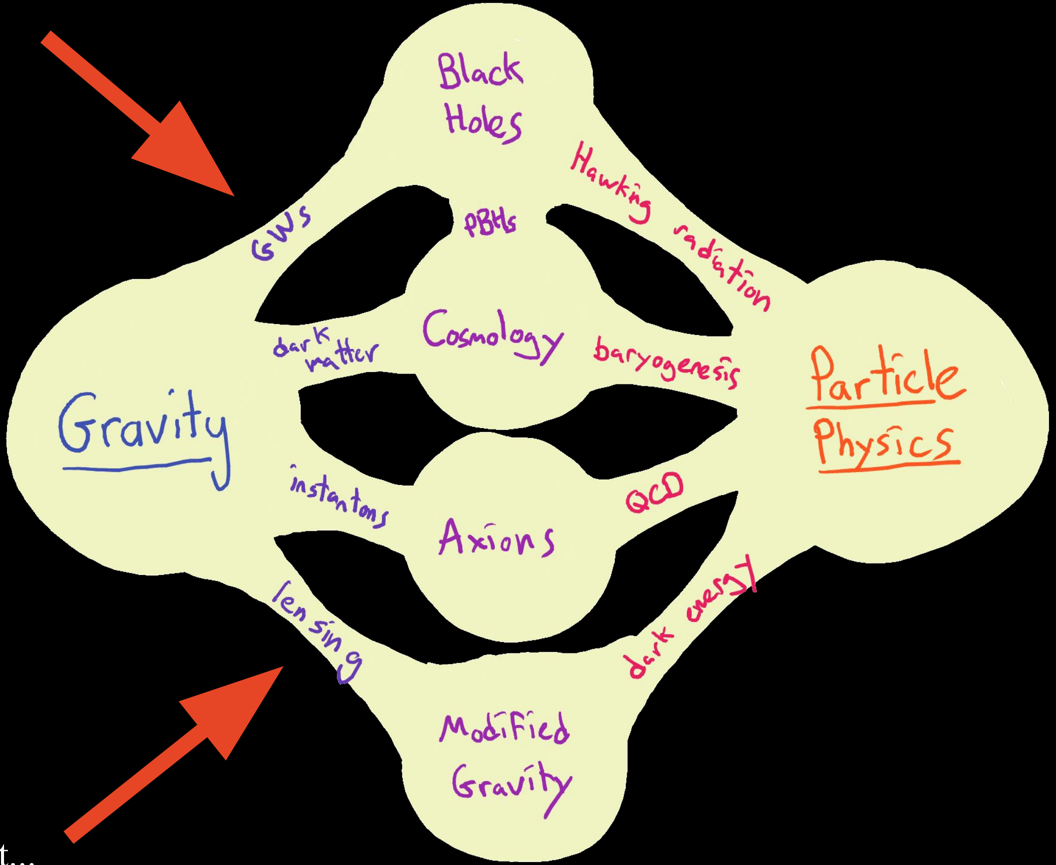
arXiv:1906.12034
Probing Quadratic
Gravity with
Binary Inspirals



'Null' result...

2. What happens when we find new solutions?

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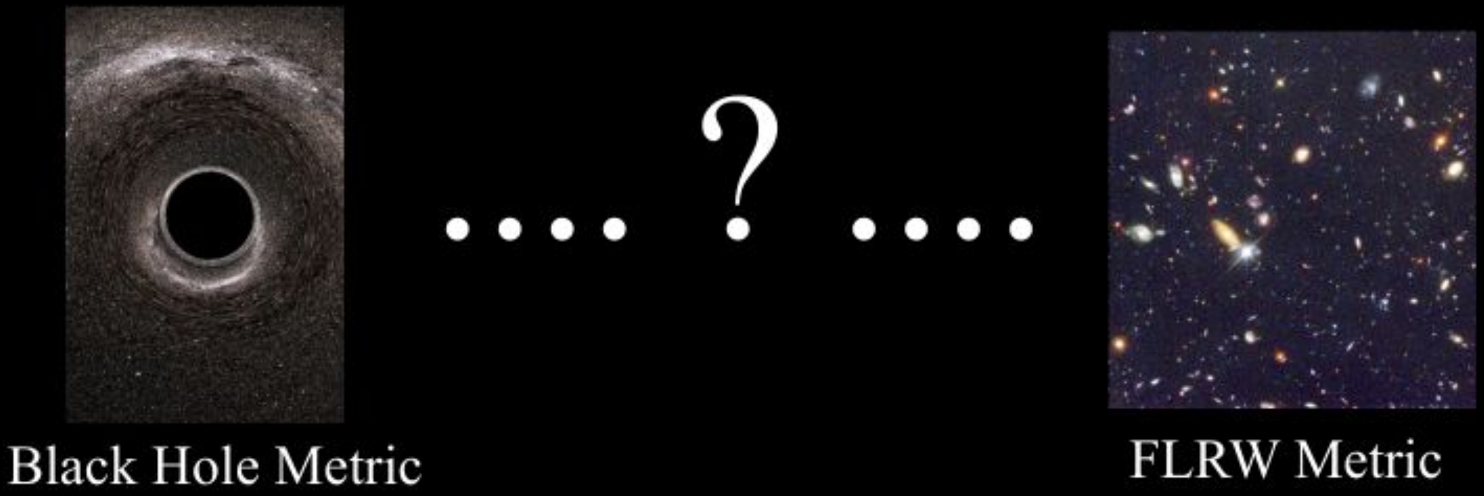
Primordial black holes can't be Schwarzschild BHs...



Primordial black holes can't be Schwarzschild BHs...

THE HYPOTHESIS OF CORES RETARDED DURING EXPANSION AND THE HOT COSMOLOGICAL MODEL

Ya. B. Zel'dovich and I. D. Novikov

Translated from Astronomicheskii Zhurnal, Vol. 43, No. 4,
pp. 758-760, July-August, 1966
Original article submitted March 14, 1966

The existence of bodies with dimensions less than $R_g = 2GM/c^2$ at the early s
pansion of the cosmological model leads to a strong accretion of radiation by
If further calculations confirm that accretion is catastrophically high, the hyp
cores retarded during expansion [3, 4] will conflict with observational data.

BLACK HOLES IN THE EARLY UNIVERSE

B. J. Carr and S. W. Hawking

(Received 1974 February 25)

SUMMARY

The existence of galaxies today implies that the early Universe must have been inhomogeneous. Some regions might have got so compressed that they underwent gravitational collapse to produce black holes. Once formed, black holes in the early Universe would grow by accreting nearby matter. A first estimate suggests that they might grow at the same rate as the Universe during the radiation era and be of the order of 10^{15} to 10^{17} solar masses now. The observational evidence however is against the existence of such giant black holes. This motivates a more detailed study of the rate of accretion which shows that black holes will not in fact substantially increase their original mass by accretion. There could thus be primordial black holes around now with masses from 10^{-5} g upwards.

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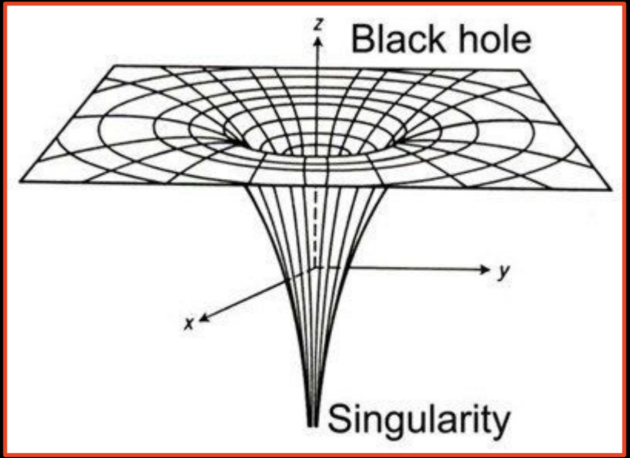
The Thakurta metric is a simple cosmological black hole



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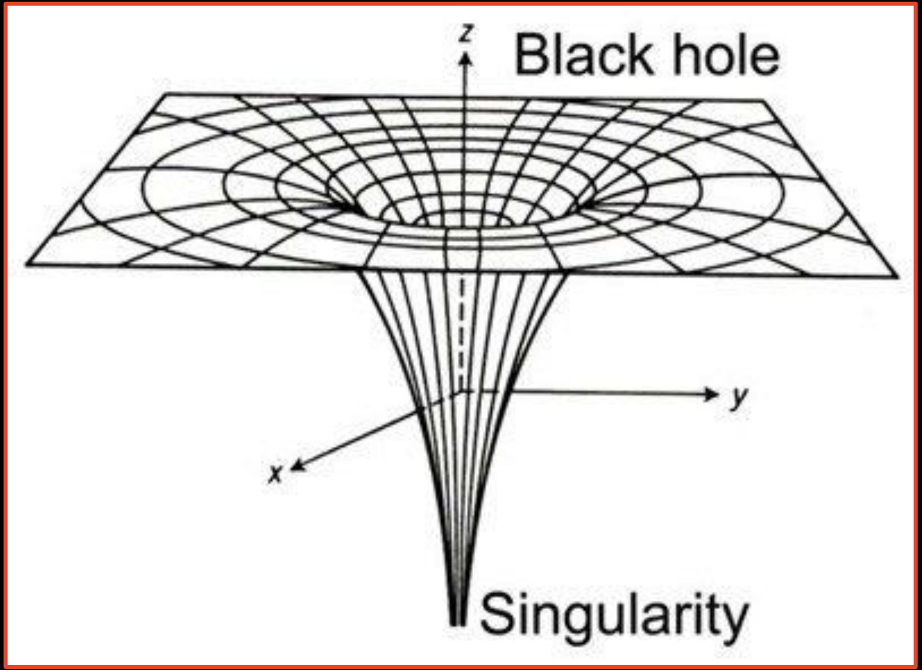

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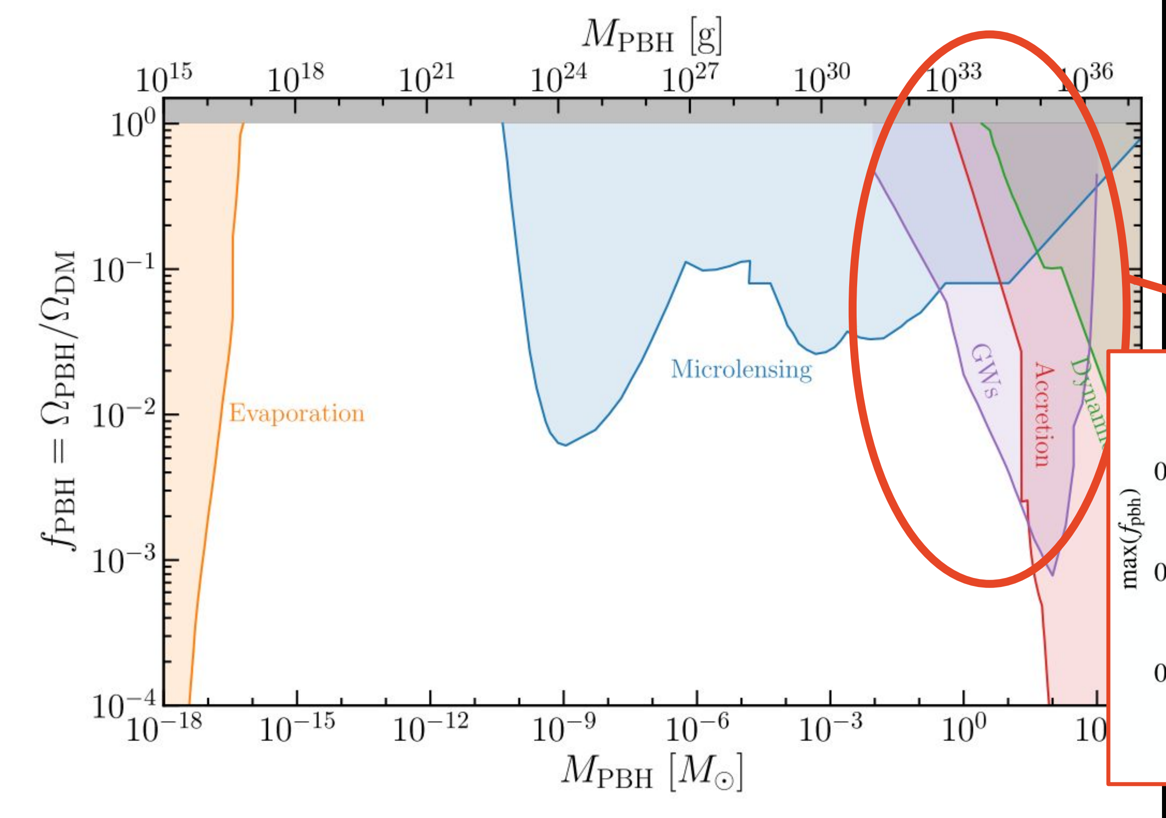
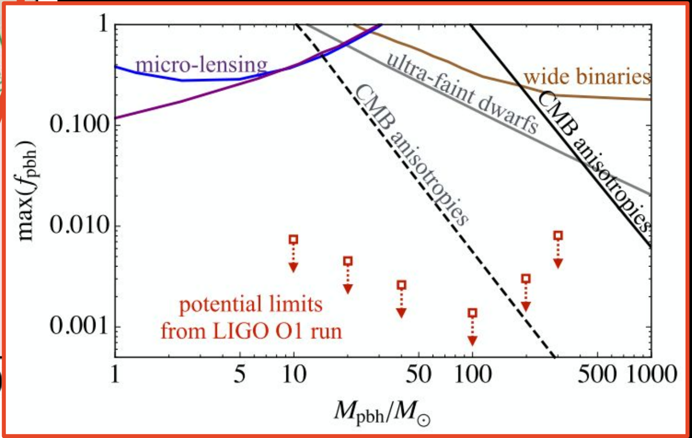
Could LIGO-sized PBHs be dark matter?





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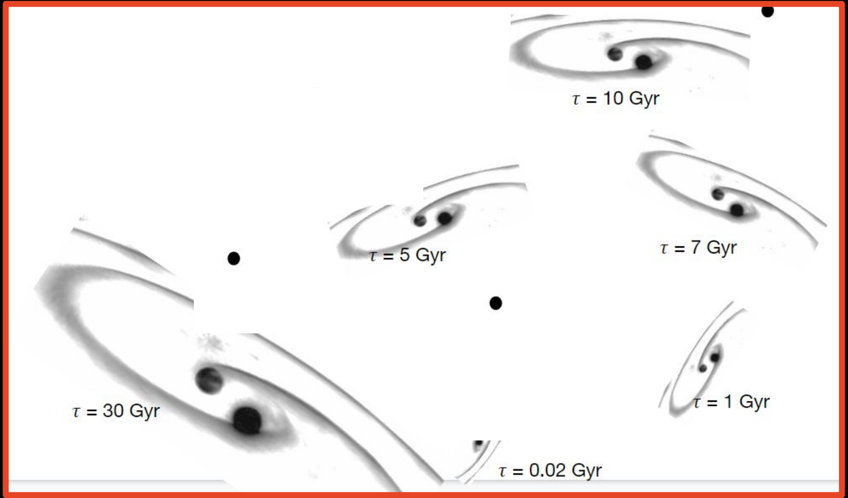
Thakurta black holes do not form binaries

Schwarzschild PBHs:

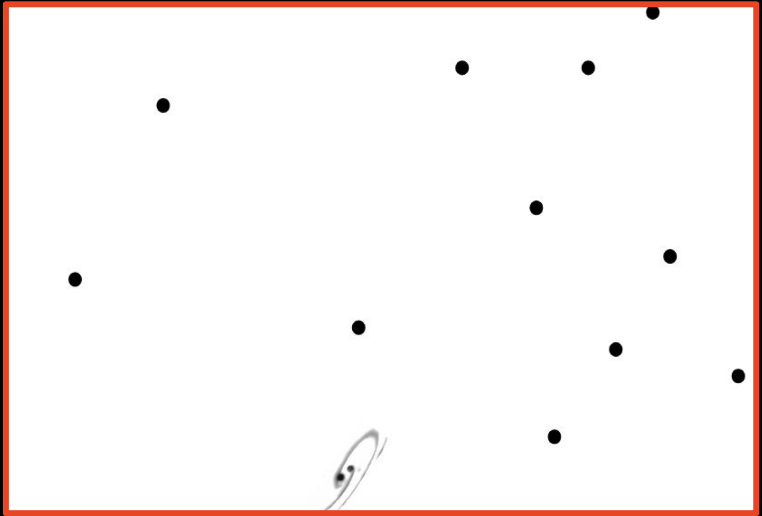
At matter-radiation equality:



Many of these coalesce ~today

Thakurta PBHs:

At matter-radiation equality:



$\tau_{max} \sim 100$ sec (!)

arXiv:2008.10743, Boehm, Kobakhidze, O'Hare, Picker, Sakellariadou

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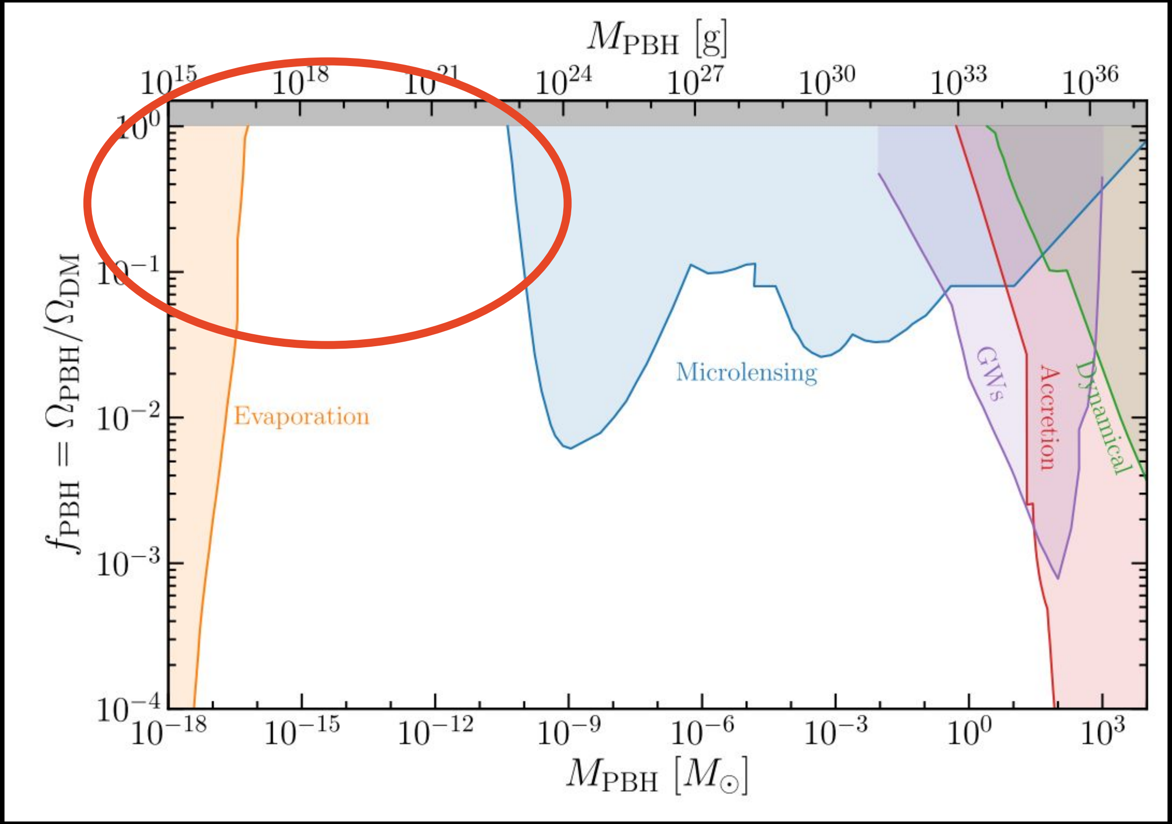
Asteroid-mass PBHs are not constrained



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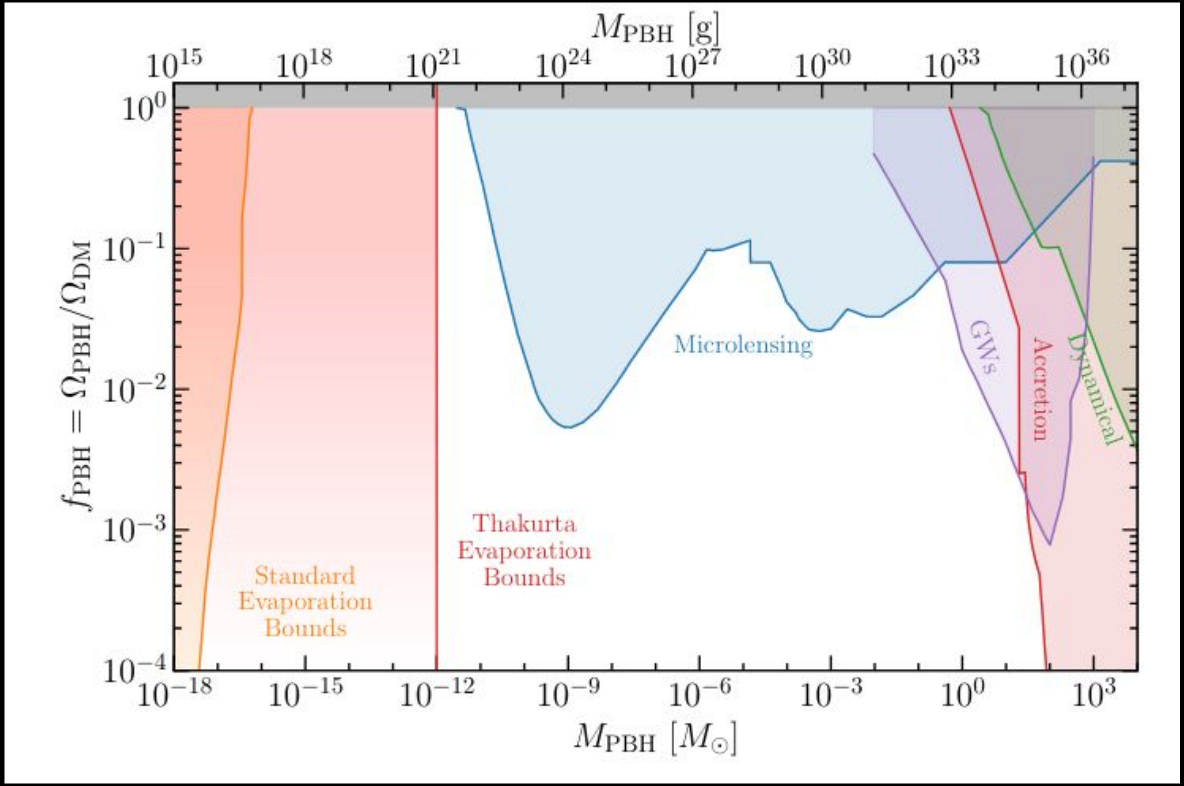
Thakurta black holes evaporate extremely rapidly



arXiv:2103.02815, Picker

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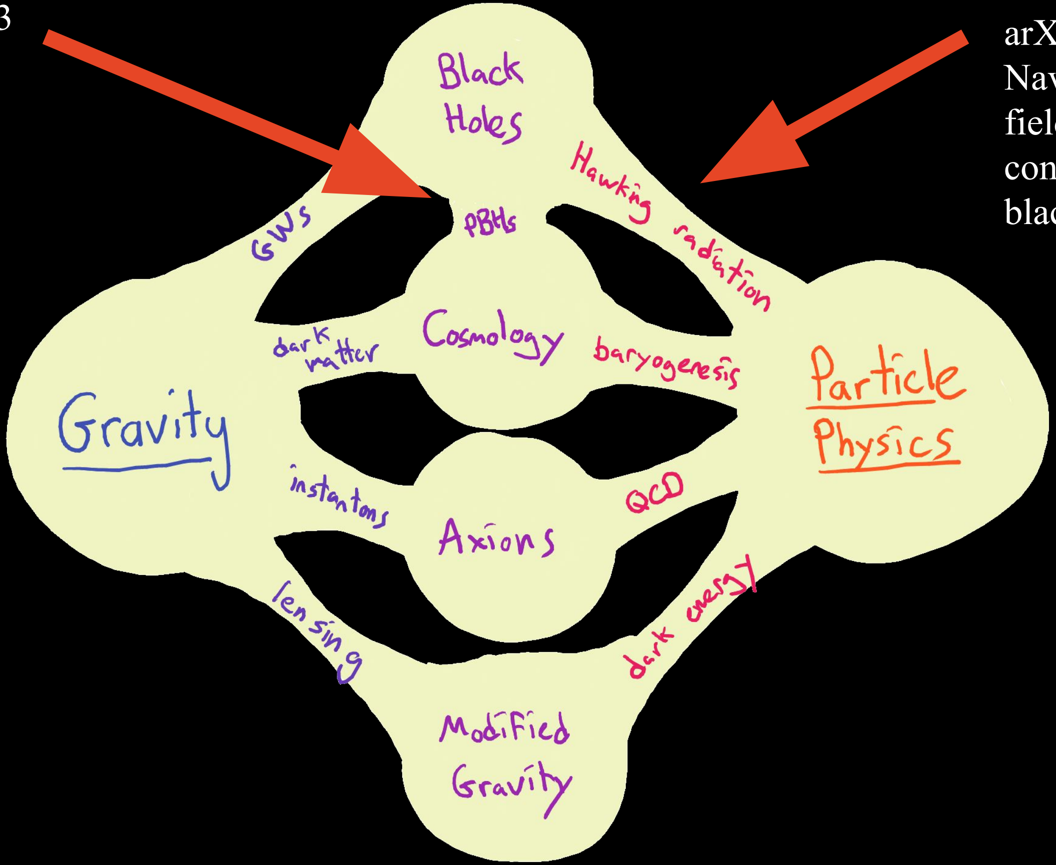
arXiv:2008.10743
Eliminating the LIGO bounds on primordial black hole dark matter

arXiv:2103.02815
Navigating the asteroid field: new evaporation constraints for primordial black holes as dark matter



3. What happens when we add gravity to PP?

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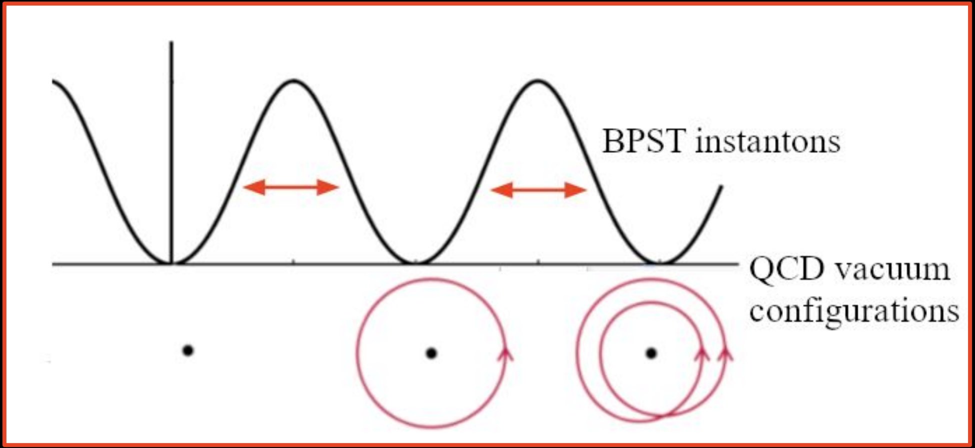
The ‘axion’ solves the strong-CP problem



$$\delta\mathcal{L} \propto \theta \, G \cdot \widetilde{G}$$

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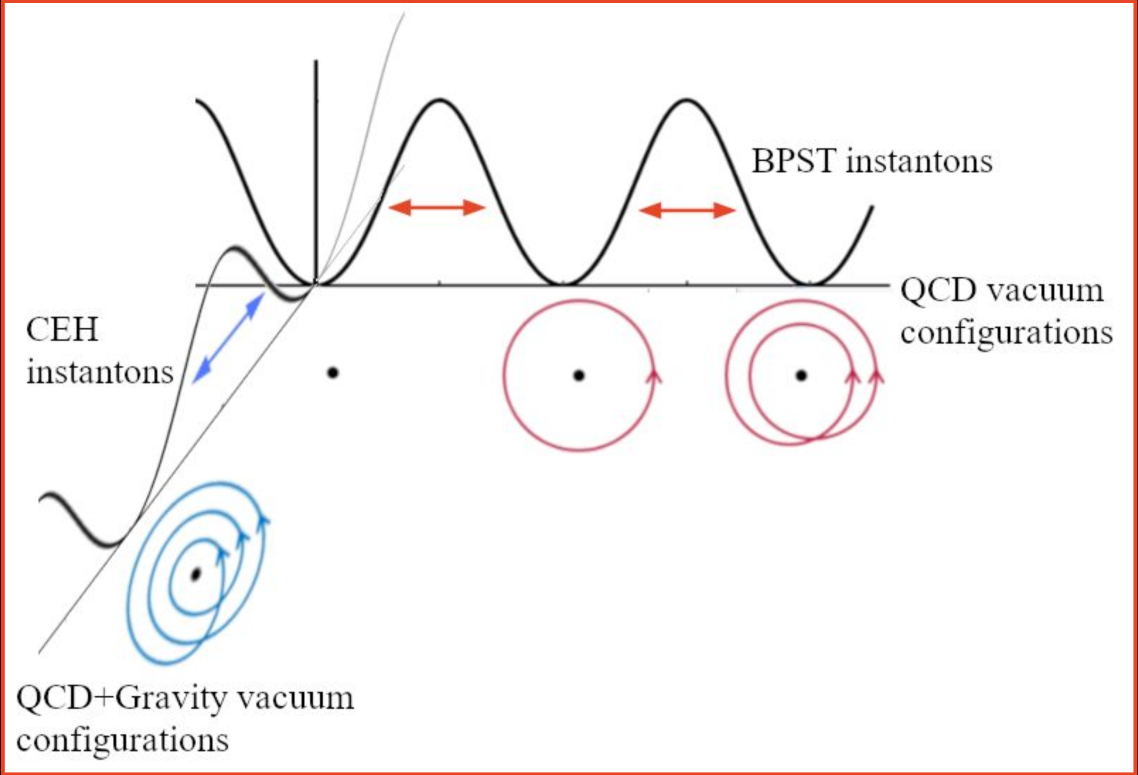
When we add gravity, we need a second axion



$$\delta\mathcal{L}_{\rm QCD} \propto \theta_{\rm QCD}\ G\cdot\widetilde{G}$$
$$\delta\mathcal{L}_{\rm CEH} \propto \theta_{\rm CEH}\ R\cdot\widetilde{R}$$

arXiv:2108.05549, Chen, Kobakhidze

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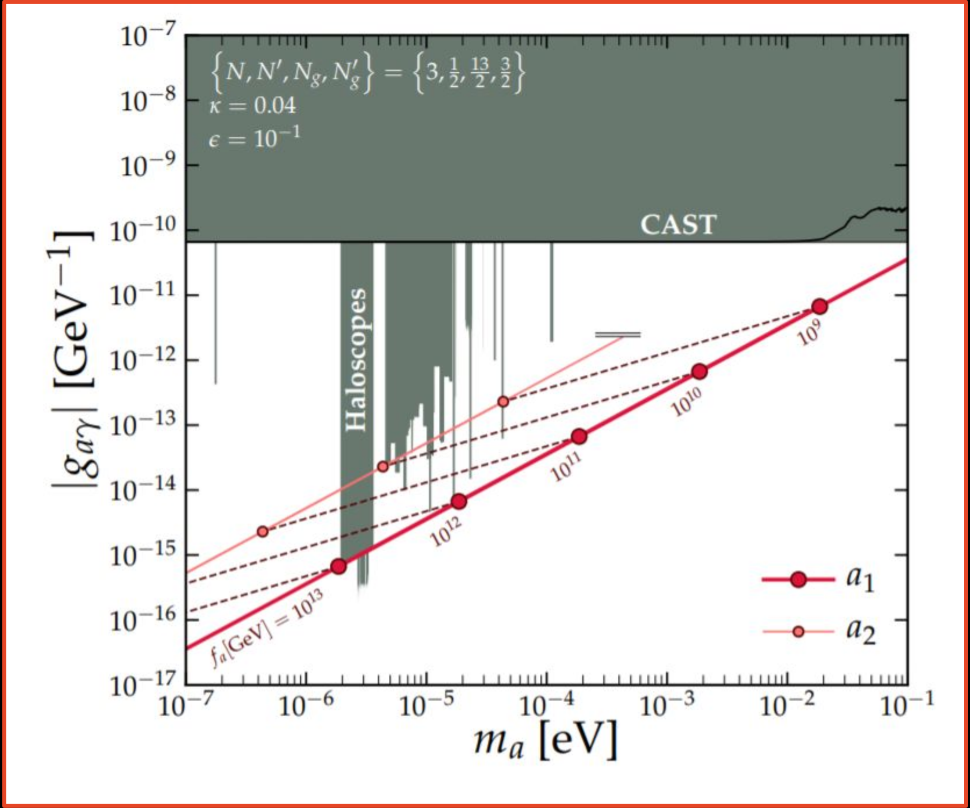
The second axion is coupled to the 'usual' one



arXiv:2109.12920, Chen, Kobakhidze, O'Hare, Picker, Pierobon

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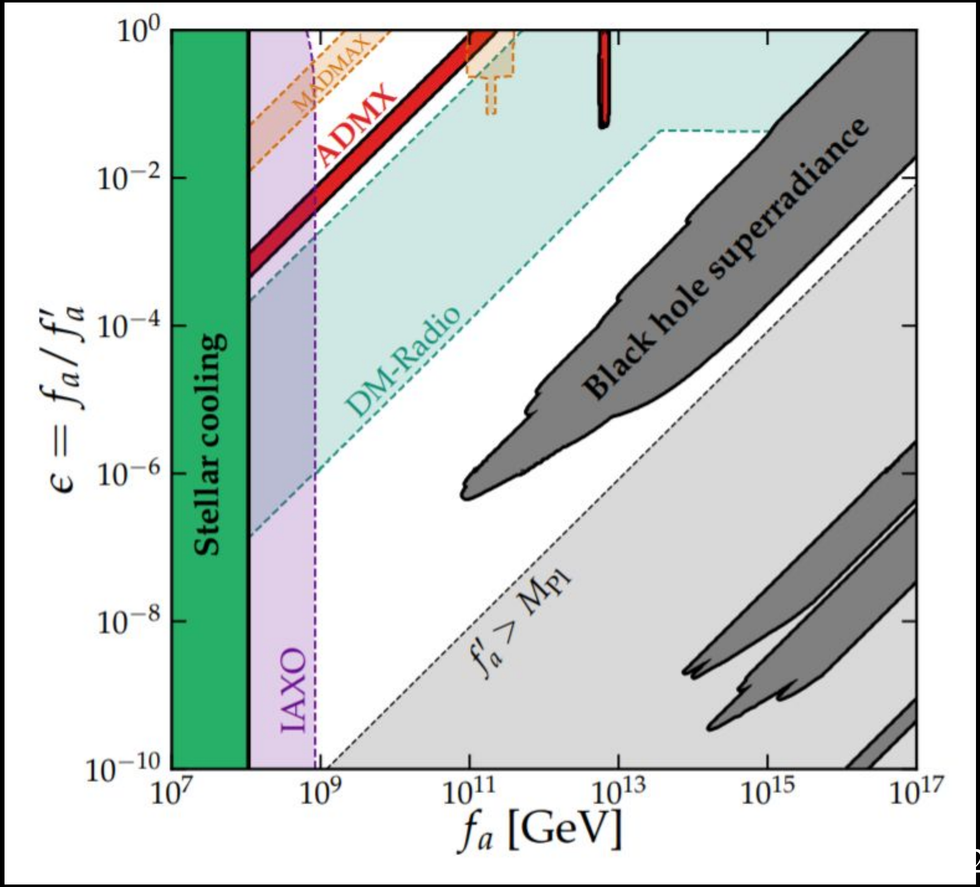
Both axions couple to the photon



arXiv:2109.12920, Chen, Kobakhidze, O'Hare, Picker, Pierobon

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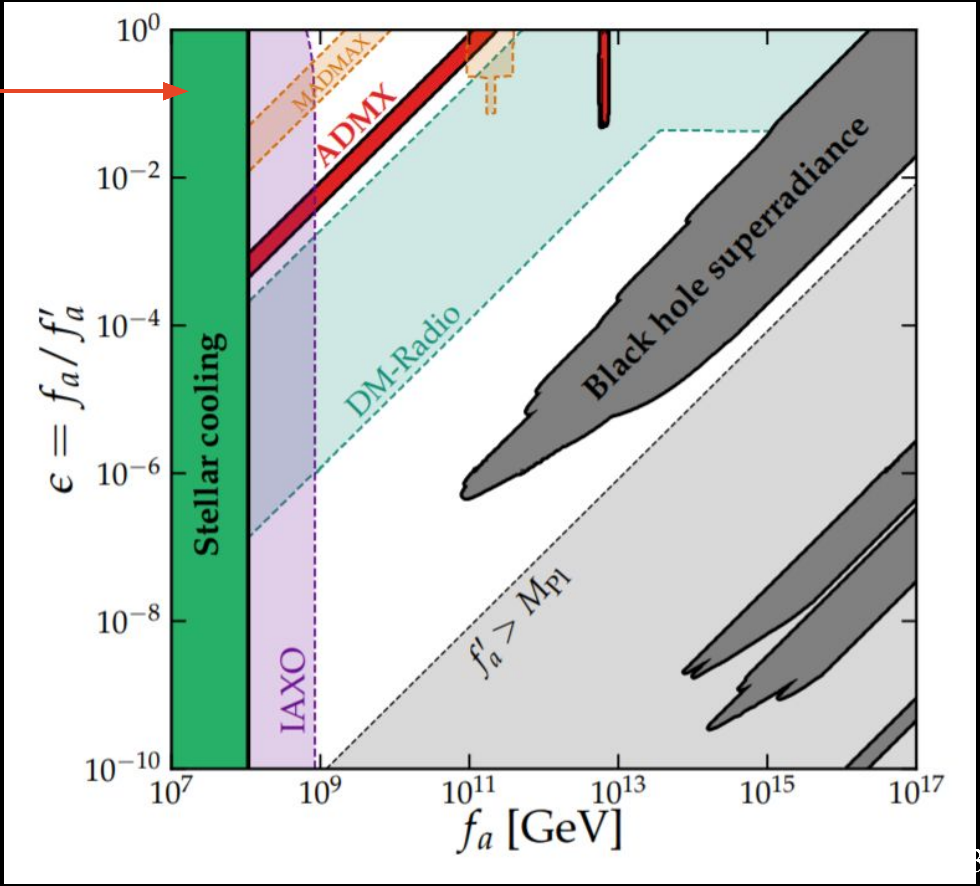
Both axions couple to the photon

– Axion production cools stars



arXiv:2109.12920, Chen, Kobakhidze, O'Hare, Picker, Pierobon

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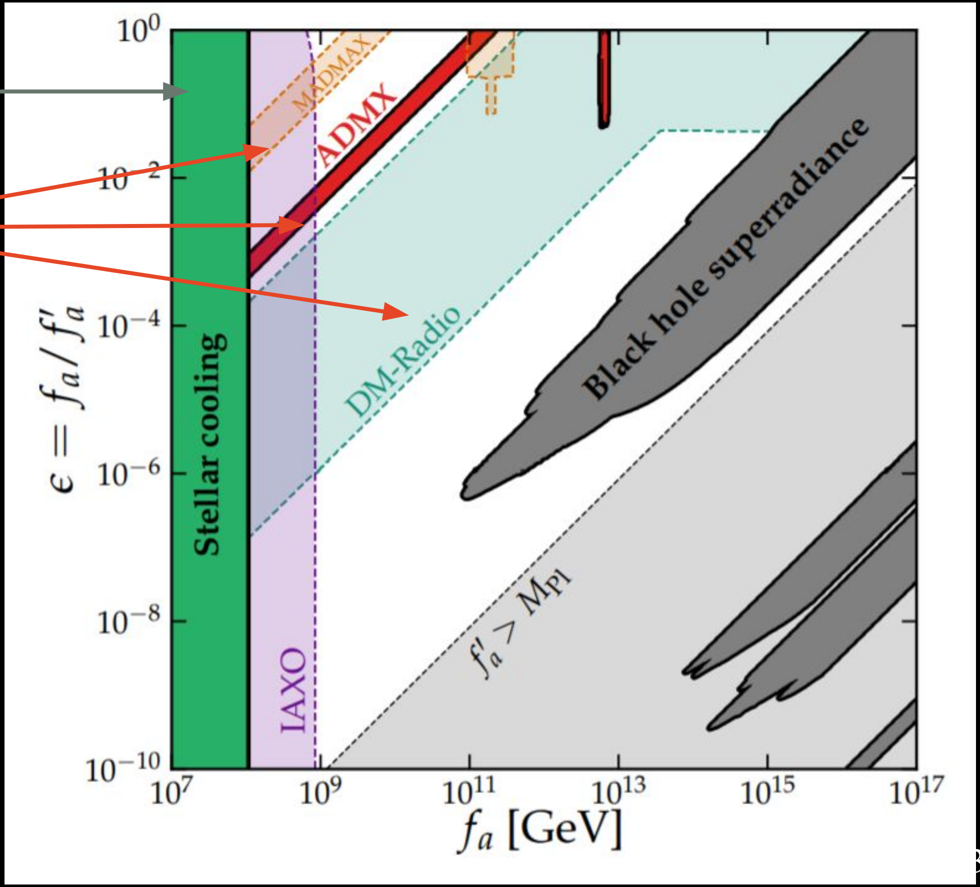
Both axions couple to the photon

- Axion production cools stars
- Haloscopes: detect axions in dark matter halo using resonant cavity



arXiv:2109.12920, Chen, Kobakhidze, O'Hare, Picker, Pierobon

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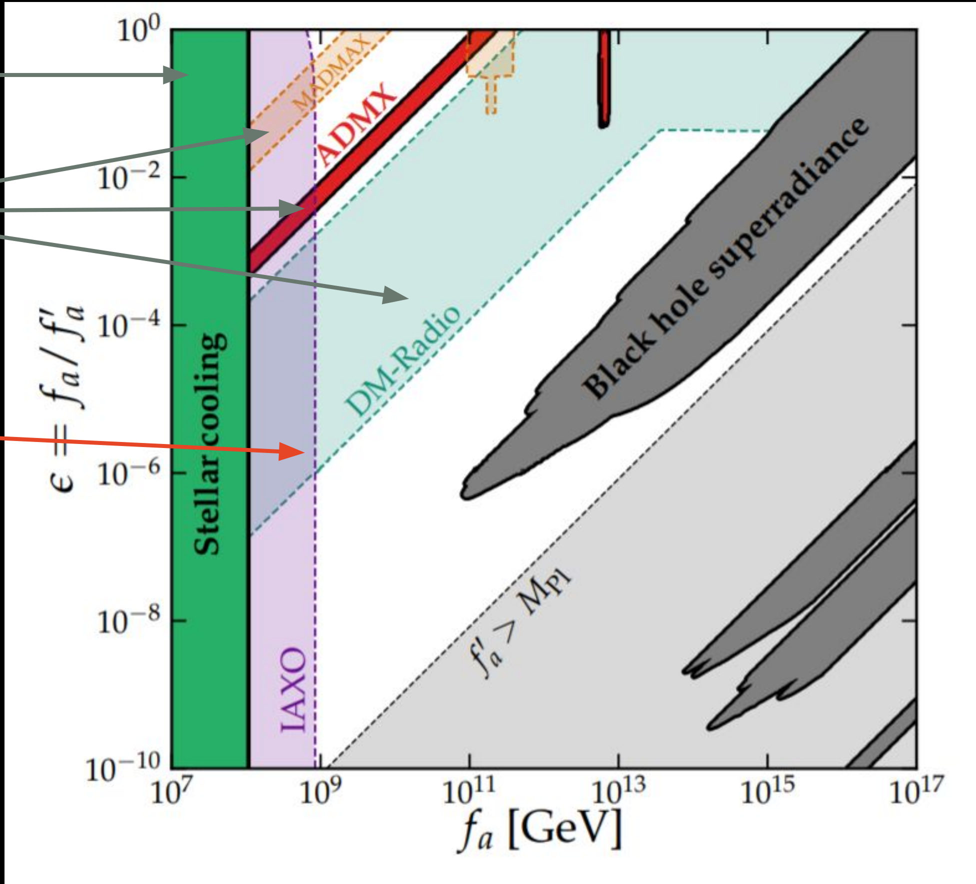
Both axions couple to the photon

- Axion production cools stars
- Haloscopes: detect axions in dark matter halo using resonant cavity
- Helioscopes: detect stellar axions by converting back to photons



arXiv:2109.12920, Chen, Kobakhidze, O'Hare, Picker, Pierobon

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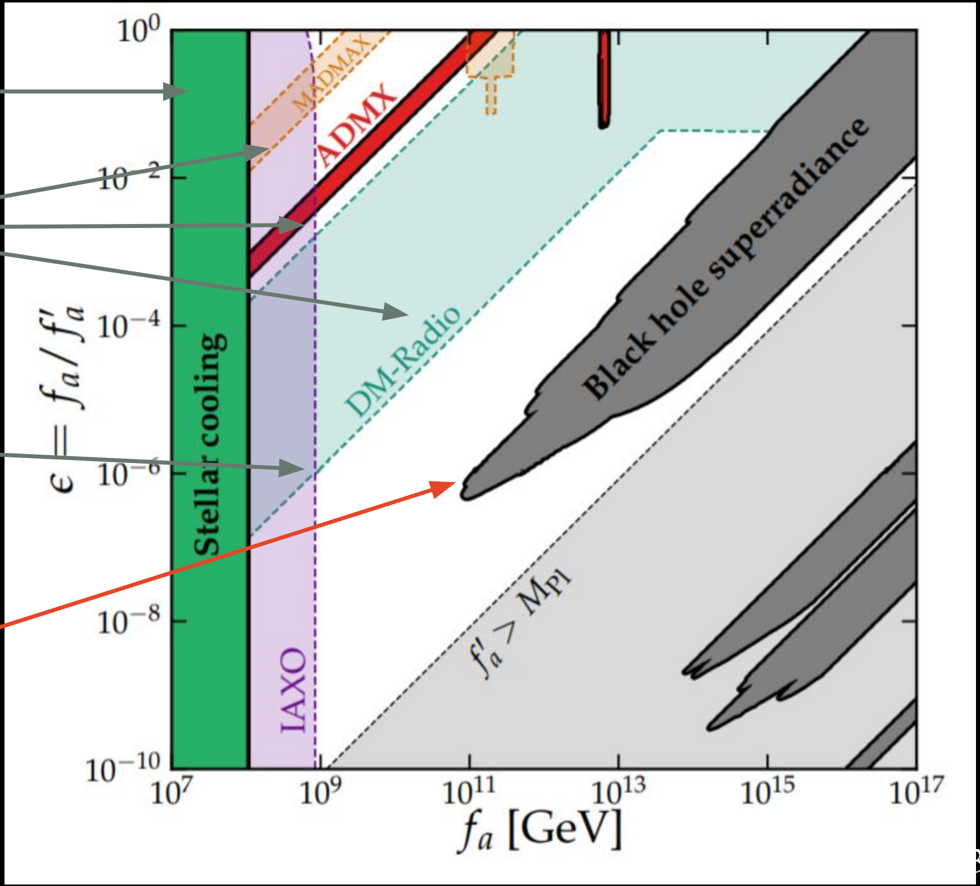
Both axions couple to the photon

- Axion production cools stars
- Haloscopes: detect axions in dark matter halo using resonant cavity
- Helioscopes: detect stellar axions by converting back to photons
- Spin down black holes



arXiv:2109.12920, Chen, Kobakhidze, O'Hare, Picker, Pierobon

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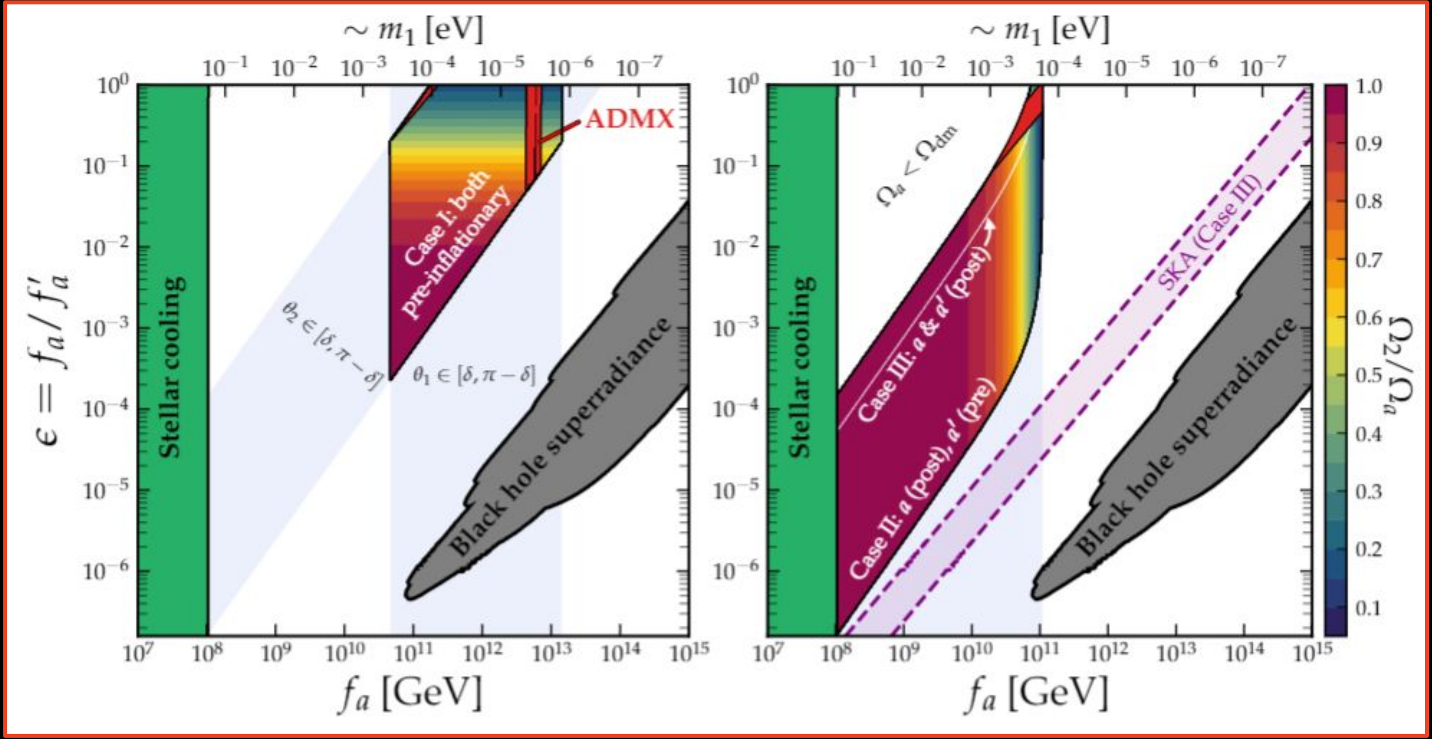
Both axions can be DM, and produce GWs...
(and solve the domain wall problem)



Forthcoming, Chen, Kobakhidze, O'Hare, Picker, Pierobon

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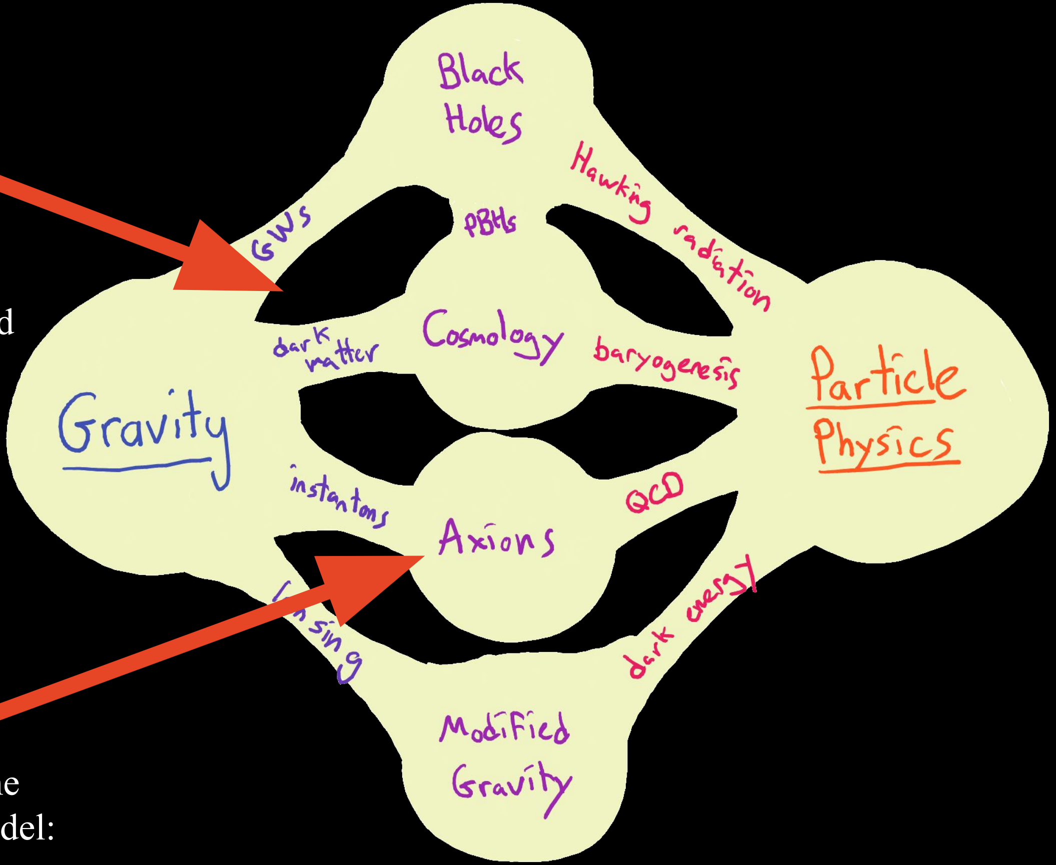
Forthcoming… tomorrow?? Cosmology of the companion-axion model: dark matter, gravitational waves, and primordial black holes



arXiv:2109:12920 Phenomenology of the companion-axion model: photon couplings

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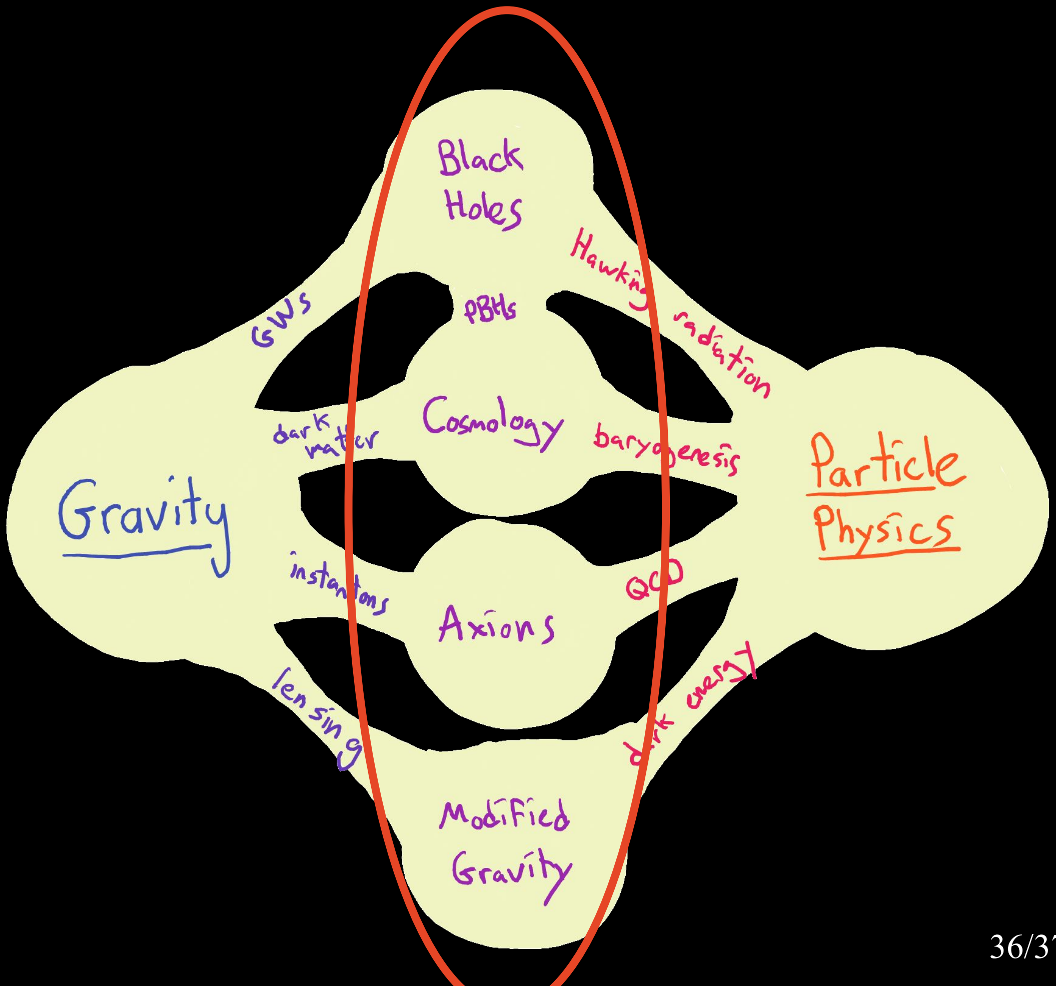
Morals and takeaways

- Frontier of physics between gravity and PP
- Lots of unanswered questions...
  - ⇒ lots of surprising phenom
- Tweak any bit and see what happens!



Thanks!

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Bonus: quadratic gravity

$$S = \int d^4x \sqrt{-g}\left[\frac{R}{2\kappa} + \beta R^2 + \gamma R^{\mu\nu} R_{\mu\nu}\right]$$

$$S = \int d^4x \sqrt{-\tilde{g}}\left[\frac{\tilde{R}}{2\kappa} - \frac{1}{2}\left(\partial_\mu \phi \partial^\mu \phi + m_\phi^2 \phi^2\right) - \frac{1}{2}\left(\partial_\mu \pi^{\alpha\beta} \partial^\mu \pi_{\alpha\beta} + m_\pi^2 \pi^{\alpha\beta} \pi_{\alpha\beta}\right)\right]$$

$$0 \leq \gamma \lesssim 5.9 \cdot 10^{76},$$
$$-\frac{\gamma}{4} \leq \beta \lesssim 9.8 \cdot 10^{75} - \frac{\gamma}{4}$$

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Bonus: thakurta metric details

$$\mathrm{d}s^2 = a^2 \mathrm{d}s^2_{schw.}$$

$$f(R) = 1 - 2Gma(t)/R$$

$$\mathrm{d}s^2 = f(R)\left(1 - \frac{H^2R^2}{f^2(R)}\right)\mathrm{d}t^2 + \frac{2HR}{f(R)}\mathrm{d}t\,\mathrm{d}R - \frac{\mathrm{d}R^2}{f(R)} - R^2\left(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2\right)$$

$$m_{\mathrm{MS}} = ma(t) + \frac{H^2R^3}{2Gf(R)}$$

$$R_{\mathrm{b}} = \frac{1}{2H}\left(1 - \sqrt{1 - 8HGma(t)}\right) \approx 2ma$$

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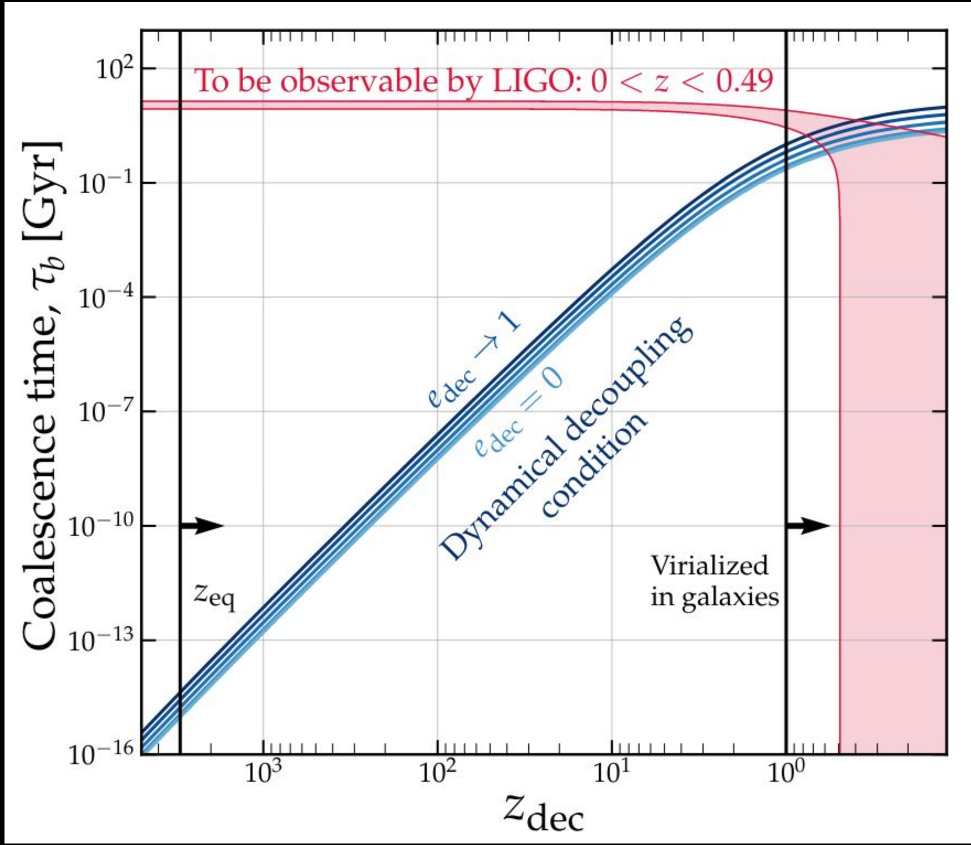
Bonus: thakurta binary formation plot



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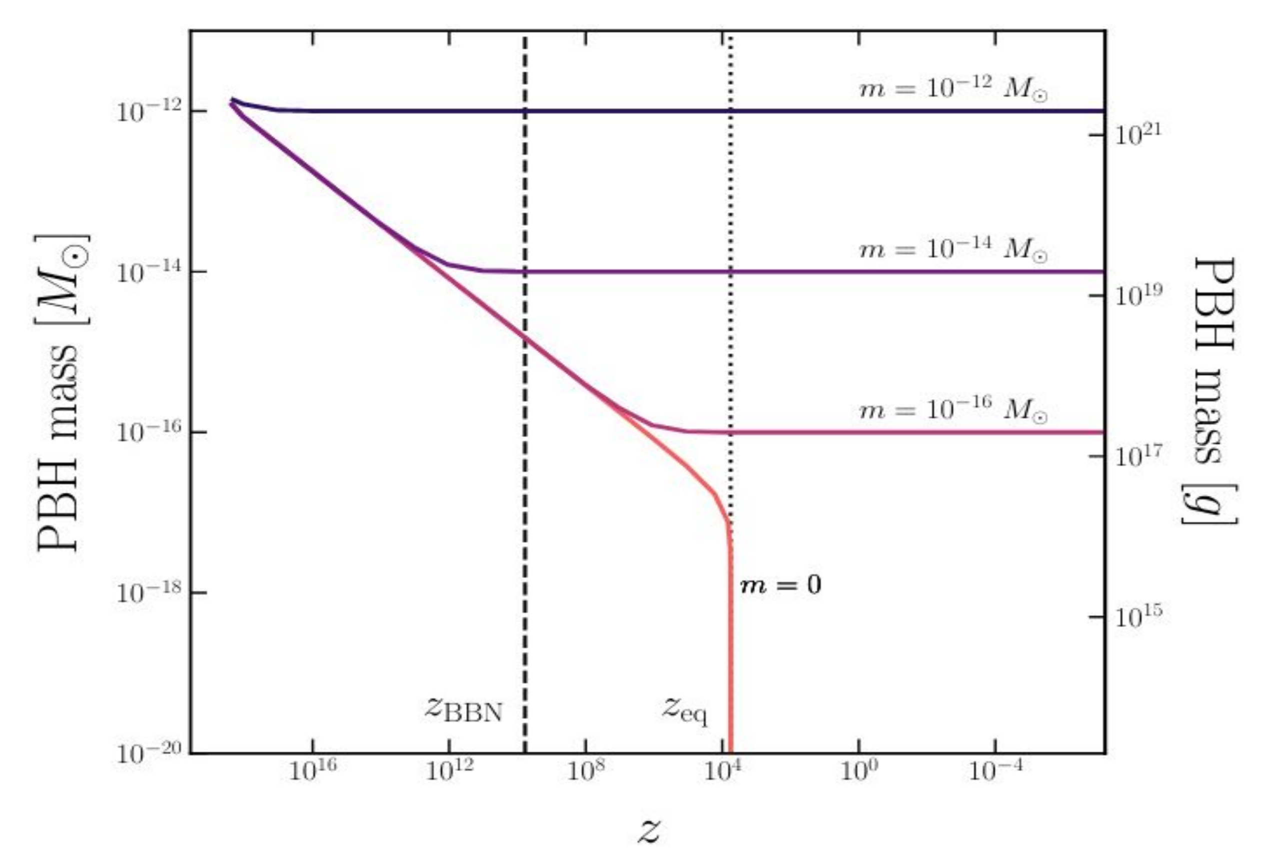
Bonus: thakurta hawking radiation plot



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Bonus: companion axion details

$$V(a, a') = -2K \cos\left(N\frac{a}{f_a} + N'\frac{a'}{f'_a} + \theta\right) - 2\kappa K \cos\left(N_g\frac{a}{f_a} + N'_g\frac{a'}{f'_a} + \theta_g\right)$$

For gravity, ~ 0.04 — 0.6

$$m_1 \propto 1/f_a$$
$$m_2 \approx \epsilon \sqrt{\kappa}\, m_1$$
$$\epsilon \equiv f_a/f'_a$$

$$\mathcal{L}_{a\gamma} = \frac{1}{4}\left(a g_{a\gamma} + a' g'_{a\gamma}\right) F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\frac{\Omega_{a_2}}{\Omega_{a_1}} \sim \frac{\theta_2^2}{\theta_1^2}\kappa^{0.41}\epsilon^{-1.19}$$

$$ds^2 = \frac{1}{1-\frac{a^4}{r^4}}dr^2 + \frac{r^2}{4}\left[d\theta^2 + \sin^2\theta d\phi^2 + \left(1-\frac{a^4}{r^4}\right)(d\psi + \cos\theta d\phi)^2\right],$$