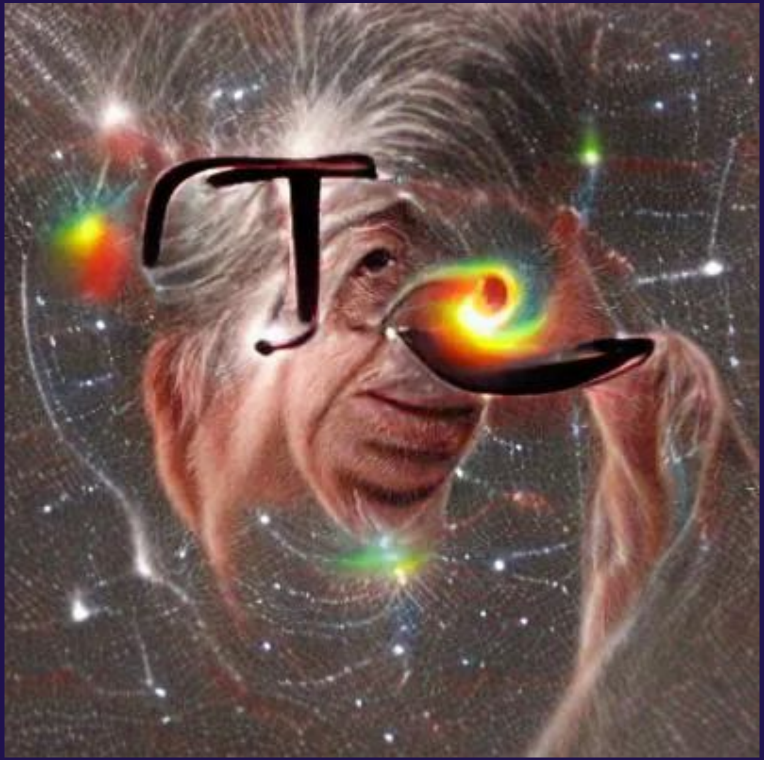
The theory of theory

A theoretical guide to writing your own theoretical physics paper

(special ‘black holes as dark matter’ worked solutions included)

Zachary S. C. Picker



An easy three-step guide

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University of Sydney

1. Learn broadly
2. Follow the flaw flow form
3. Accept rejection

1. Learn Broadly

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1. Learn Broadly
(or find a supervisor who does…)

Unfortunately, they have done a lot of physics in the 1000+ years before you were born

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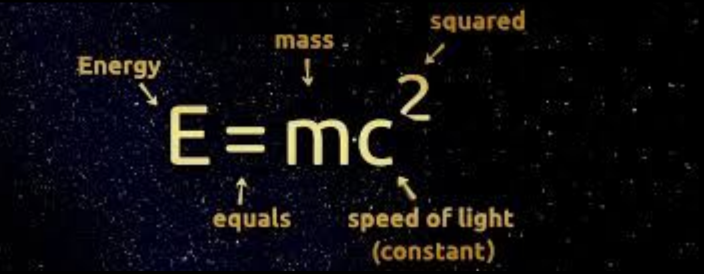

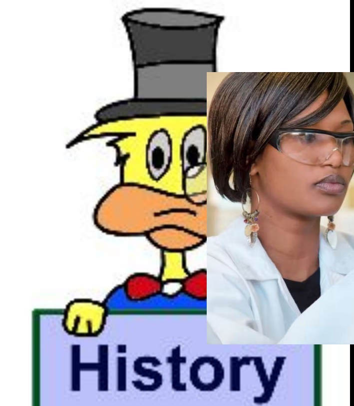

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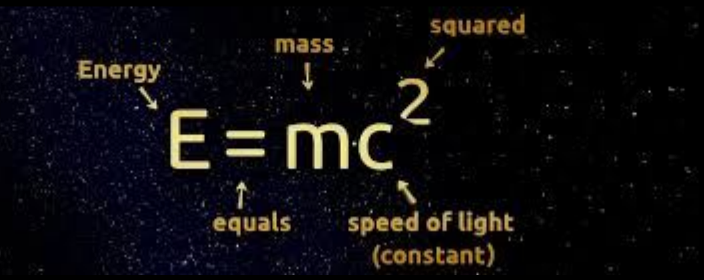
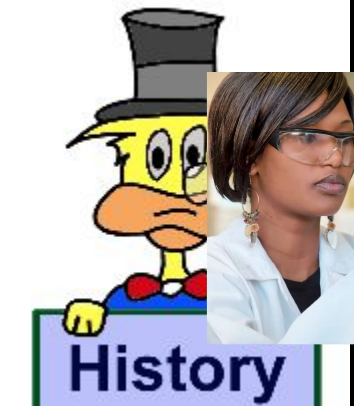
(This step might take a while)





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For example

how much do you have to know to answer:

Can black holes be dark matter?

Let’s see…

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There's evidence for dark matter at every* scale

smaller scale

larger scale

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Globular clusters (velocity dispersion)

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<u>smaller scale</u>

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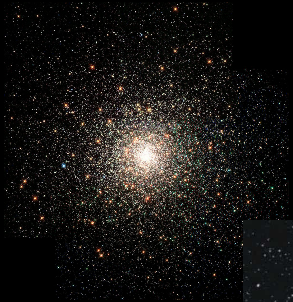
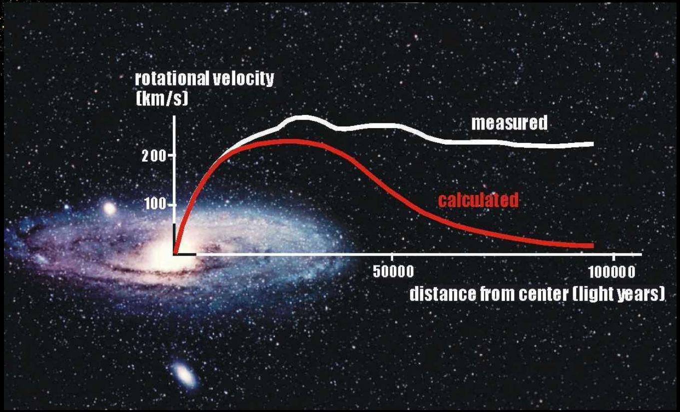


Galaxy rotation curves



Globular clusters (velocity dispersion)

There’s evidence for dark matter at every scale

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<u>smaller scale</u>

<u>larger scale</u>

Globular clusters (velocity dispersion)

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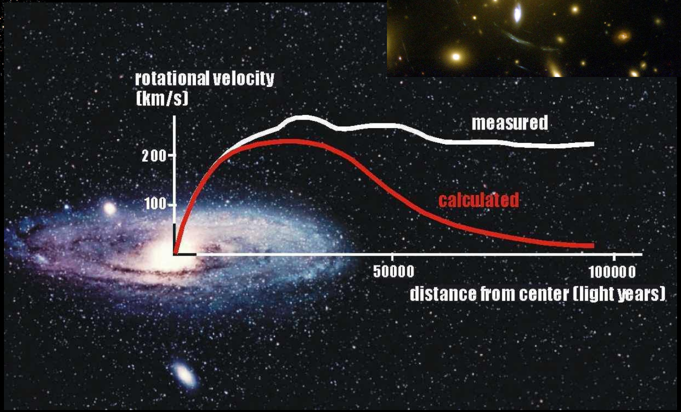

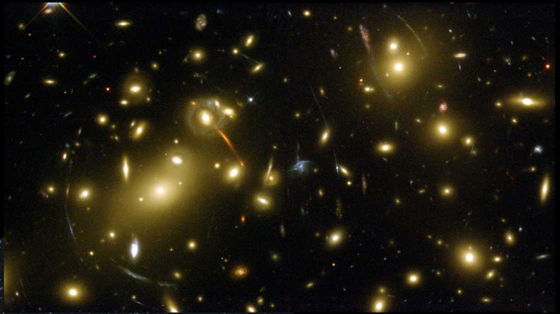

Galaxy clusters (lensing, galaxy velocities, gas temperature)

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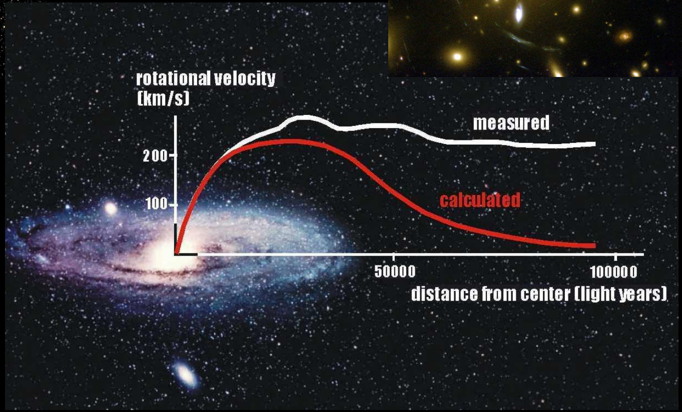
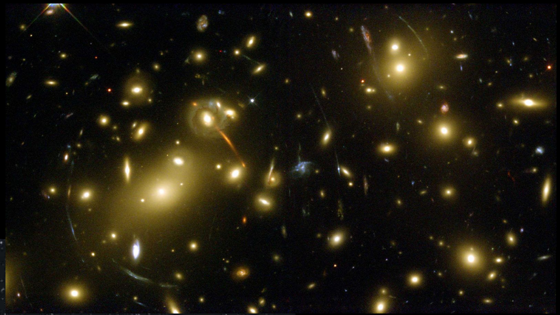
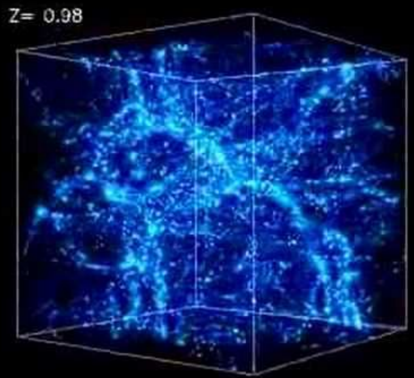




Galaxy clusters (lensing, galaxy velocities, gas temperature)

Structure formation



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There's evidence for dark matter at every scale

<u>smaller scale</u>

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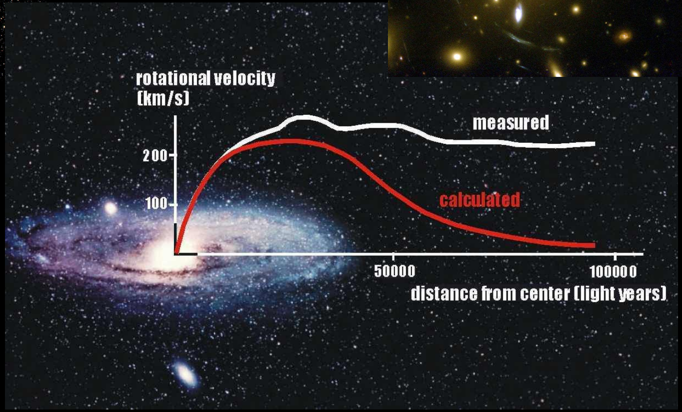

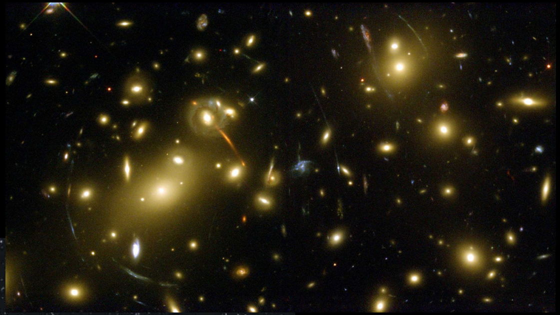

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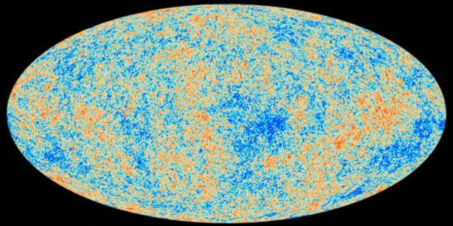

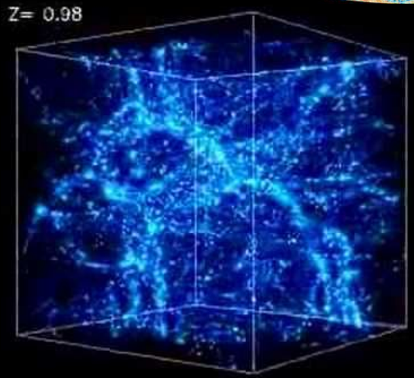

CMB

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…and they've already tried so many candidates

Particles

Modified gravity

Compact objects

Plot by Ciaran O'Hare

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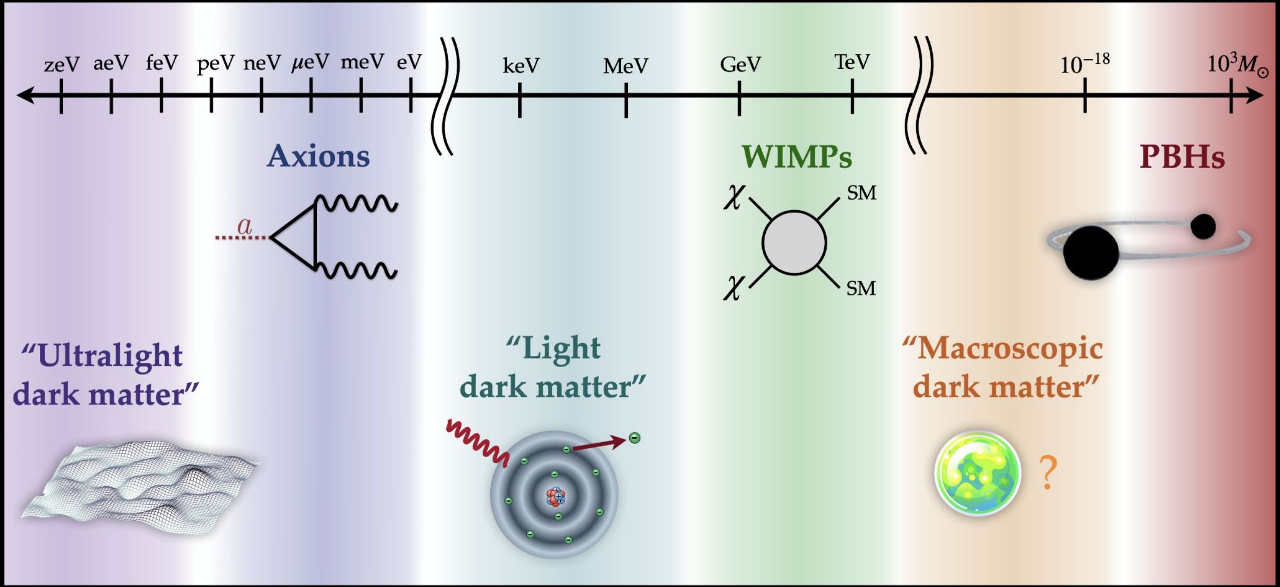

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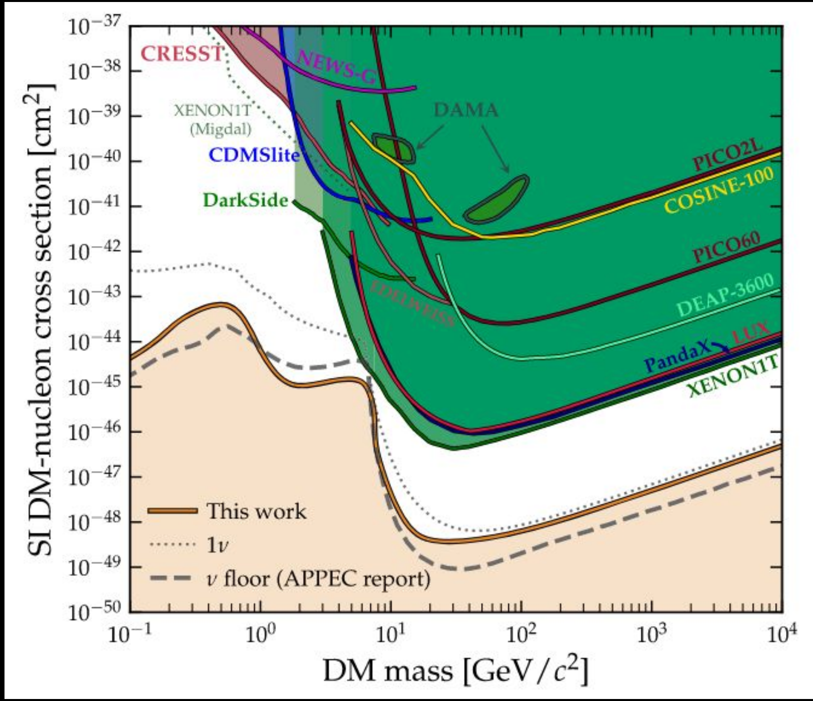
…and they've already tried so many candidates

Particles Modified gravity Compact objects

'Weakly interacting massive particles' (WIMPS)

- ~weak boson scales
- Increasingly excluded



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Particles | Modified gravity | Compact objects

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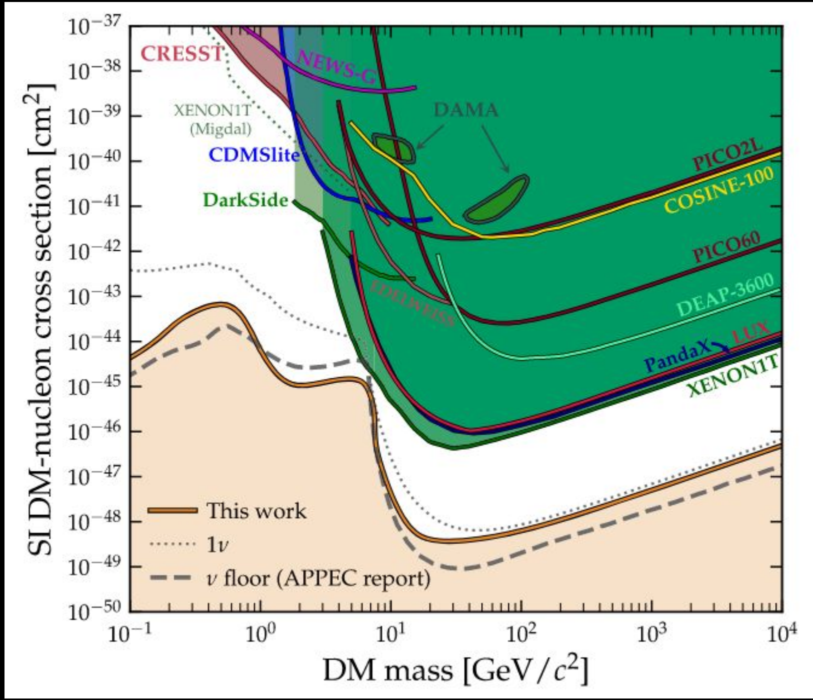
    - increasingly unpopular…



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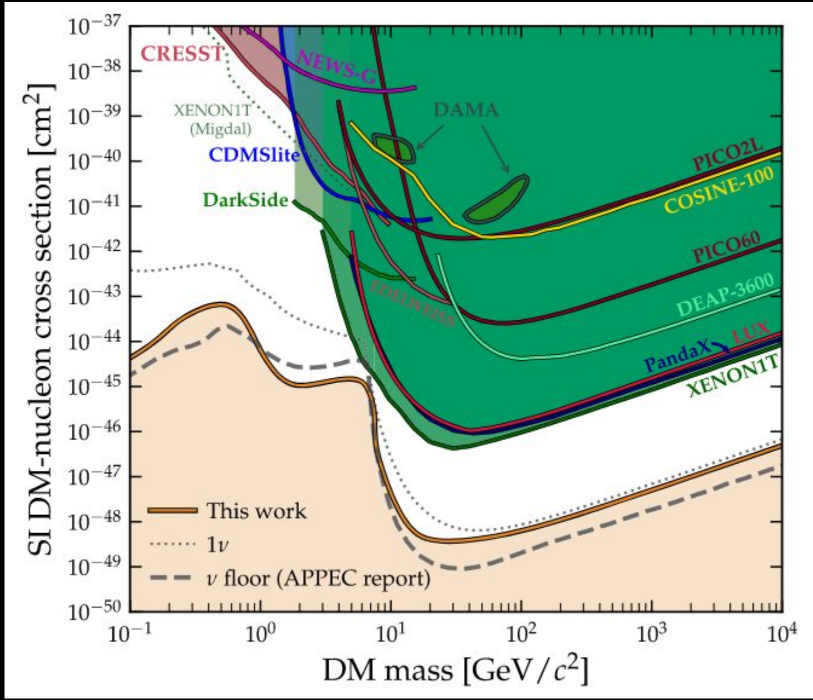
…and they've already tried so many candidates

Particles
Modified gravity
Compact objects

'Weakly interacting massive particles' (WIMPS)

- ~weak boson scales
- Increasingly excluded
    - increasingly unpopular…
- May be motivated by supersymmetry
    - But maybe not



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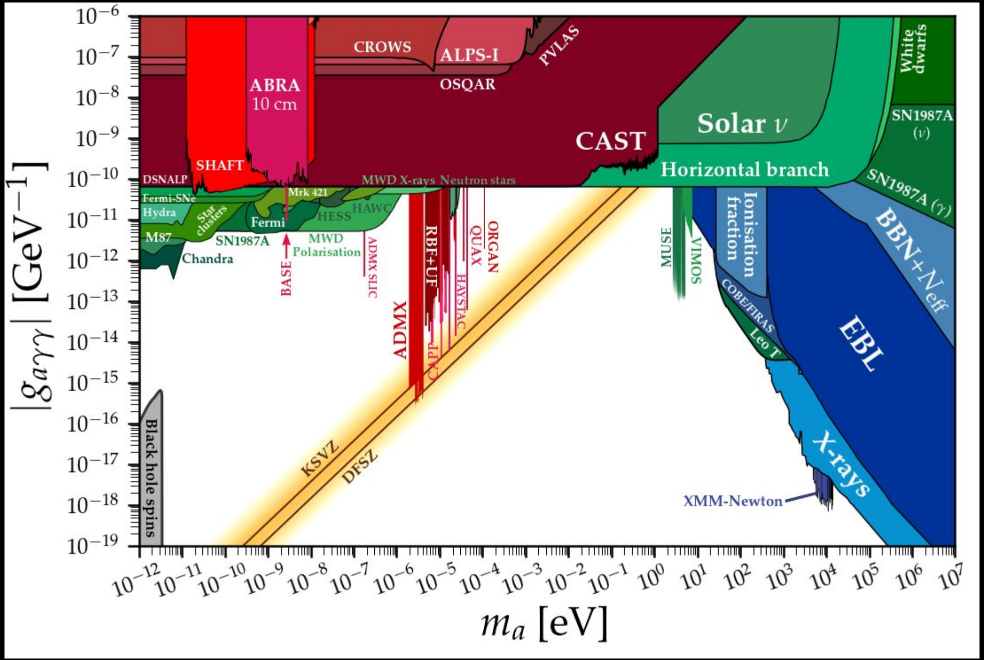
…and they've already tried so many candidates

Particles | Modified gravity | Compact objects

'Axions'

- Needed to 'clean up' strong force problems
  - (only on yellow band)



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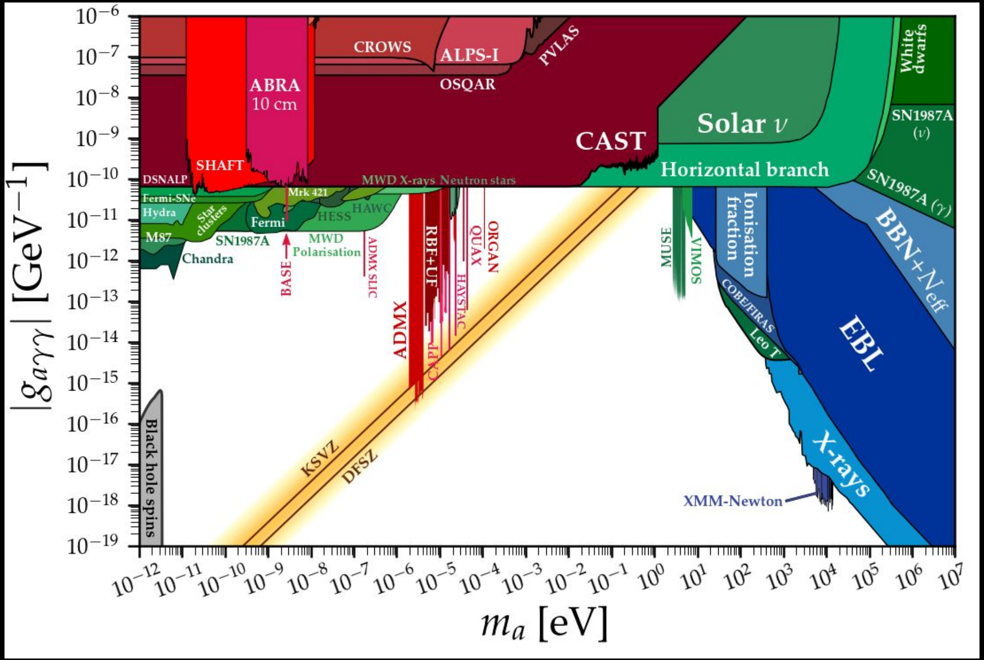
…and they've already tried so many candidates

Particles | Modified gravity | Compact objects

'Axions'

- Needed to 'clean up' strong force problems
  - (only on yellow band)
- Red: helio/halo-scopes
  - And light-shining-
    -through-walls
- Green: astrophysics
- Blue: early universe



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…and they've already tried dozens of candidates

Particles | Modified gravity | Other objects

- General relativity is incredibly well-tested
  - Still, it *should* be modified (quantum mechanics, etc)

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…and they've already tried dozens of candidates

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…and they've already tried dozens of candidates

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…and they've already tried dozens of candidates

Particles | **Modified gravity** | Other objects

- General relativity is incredibly well-tested
  - Still, it *should* be modified (quantum mechanics, etc)
- Goal: write a more complicated version that limits to GR
  - And explains dark matter
- Attempts: can't quite explain all the observations…

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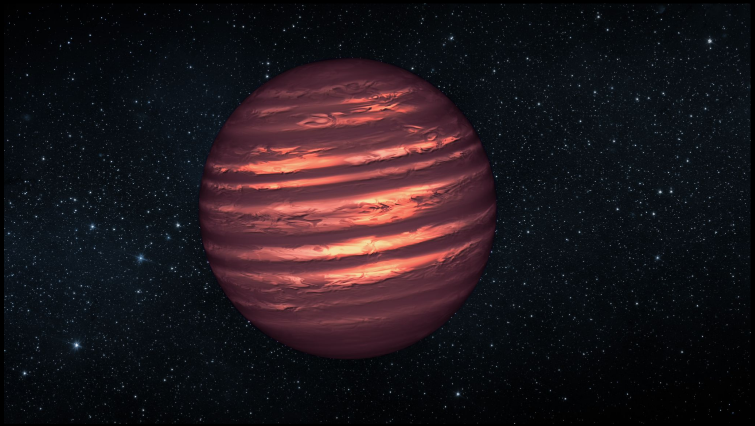
…and they've already tried dozens of candidates

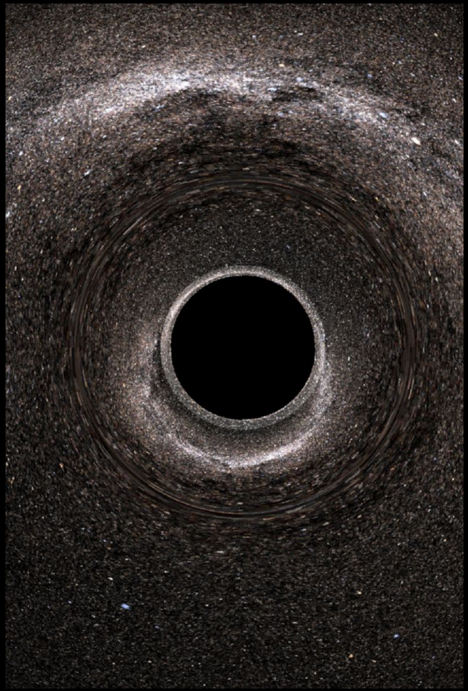
Particles

Modified gravity

Other objects

- Black holes
  - 'Schwarzschild' metric is oldest GR solution
- Stellar remnants
- Exotic things…
  - Eg Axion stars? Weird lumps? Dyson spheres? (not really)





…the black hole is the only one that definitely exists though

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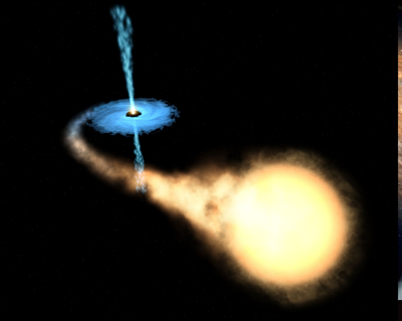

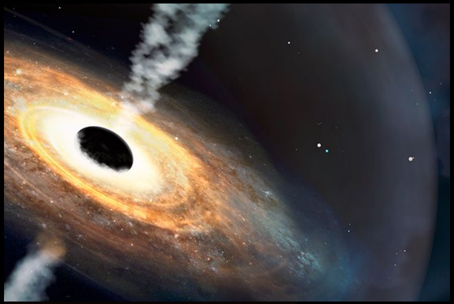

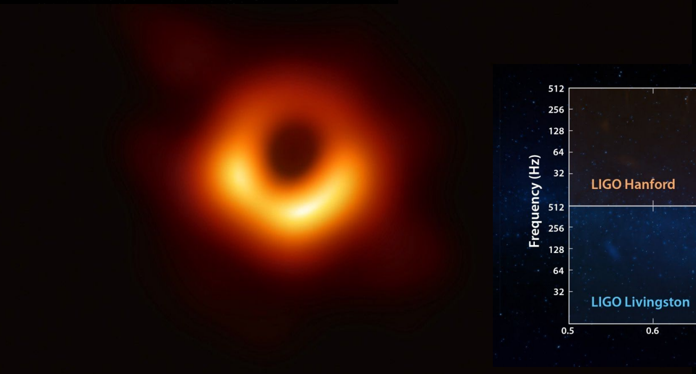

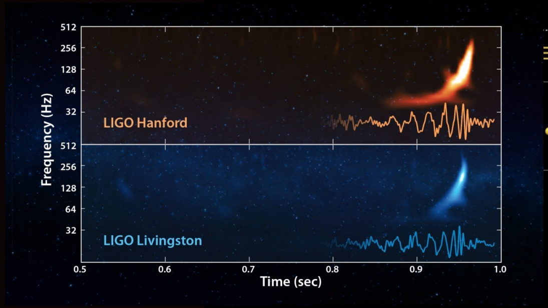

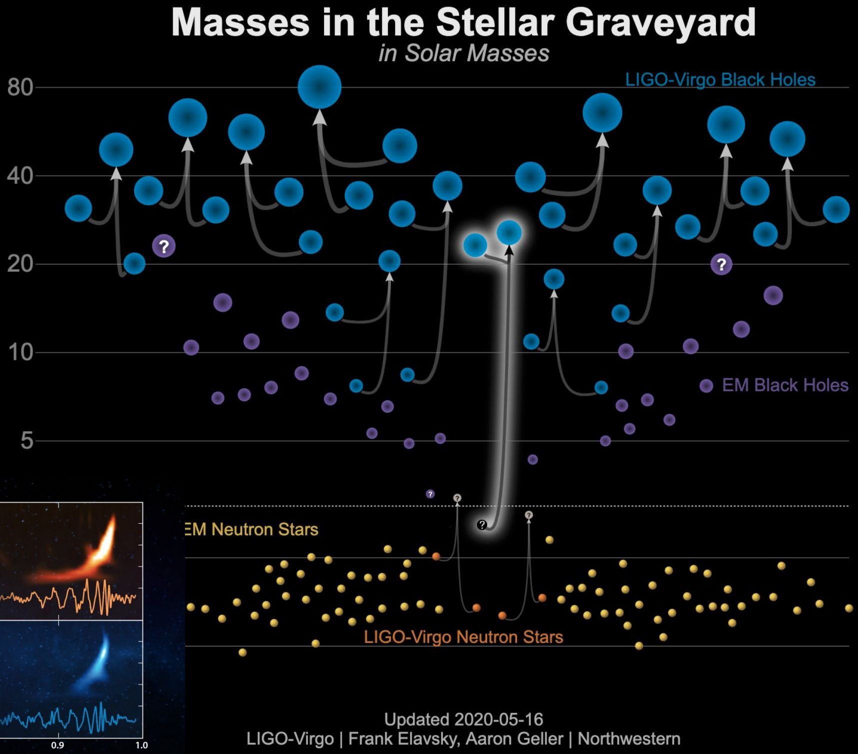

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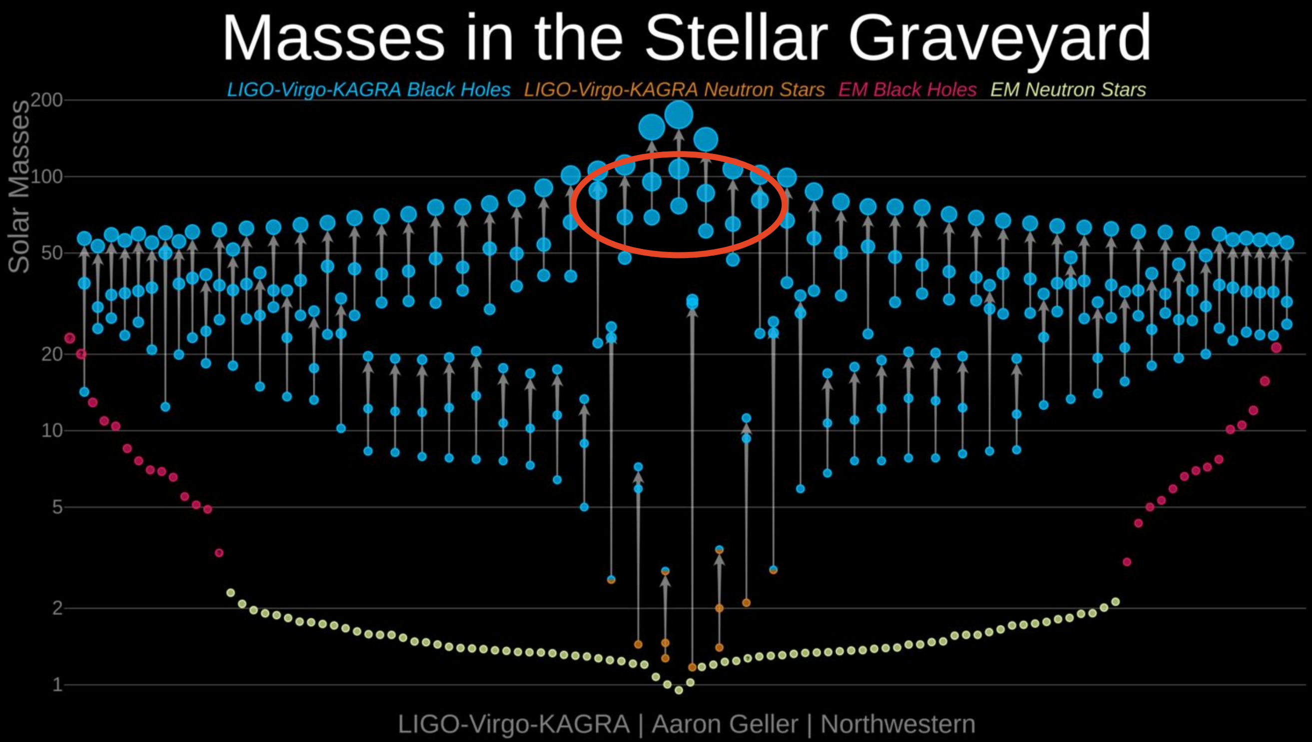
The black hole is the only one that definitely exists though

What kind of stars could make these black holes?

- ‘Pair-instability’ supernova destroys them
- Mergers?
- Or maybe… primordial?



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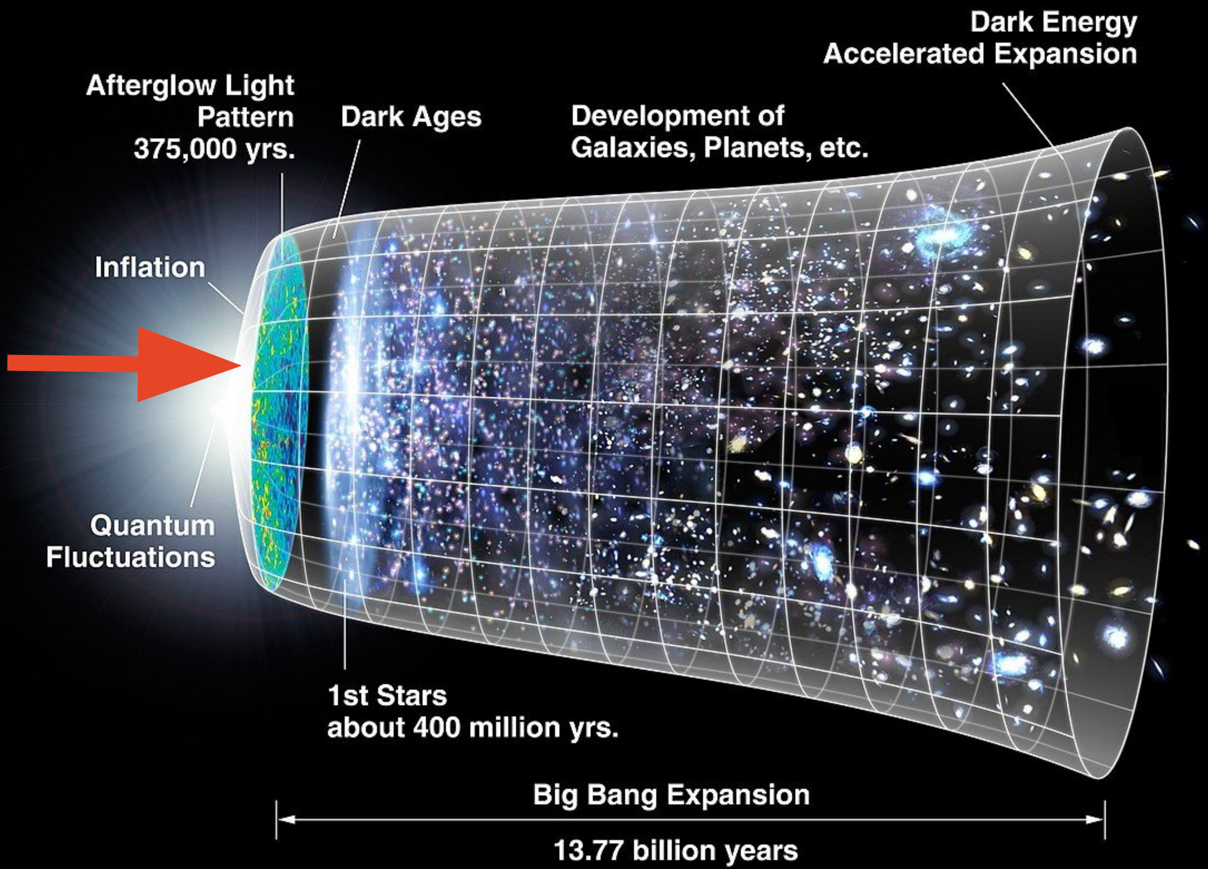
Could 'primordial' black holes be dark matter?



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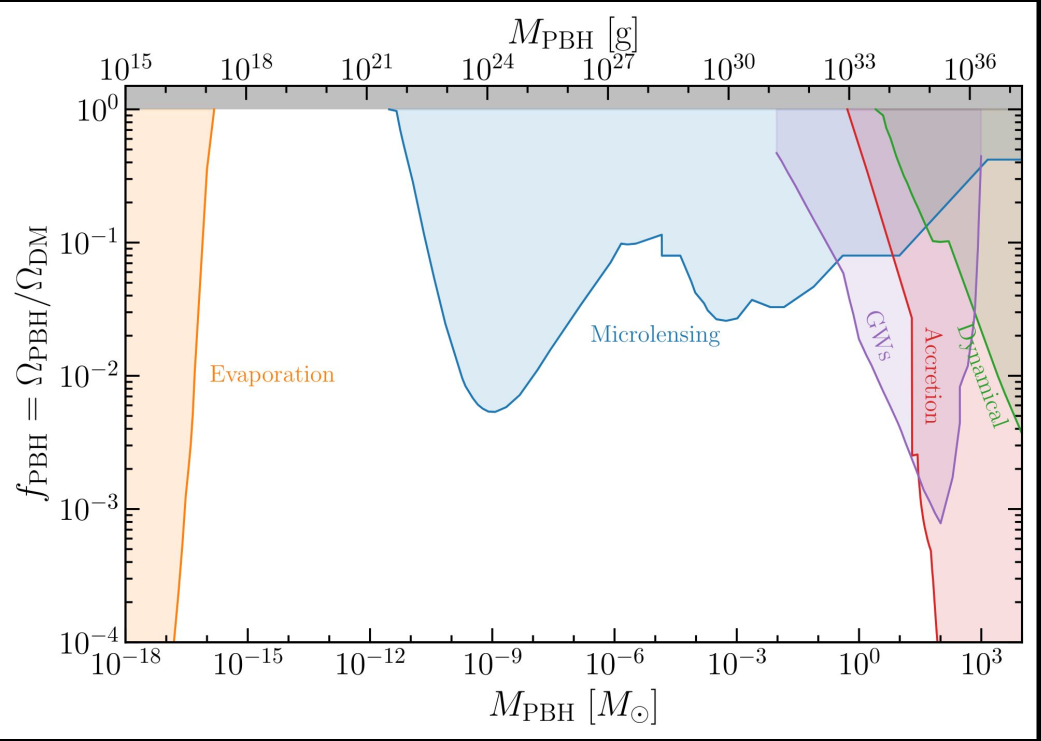

Plot by Bradley Kavanagh

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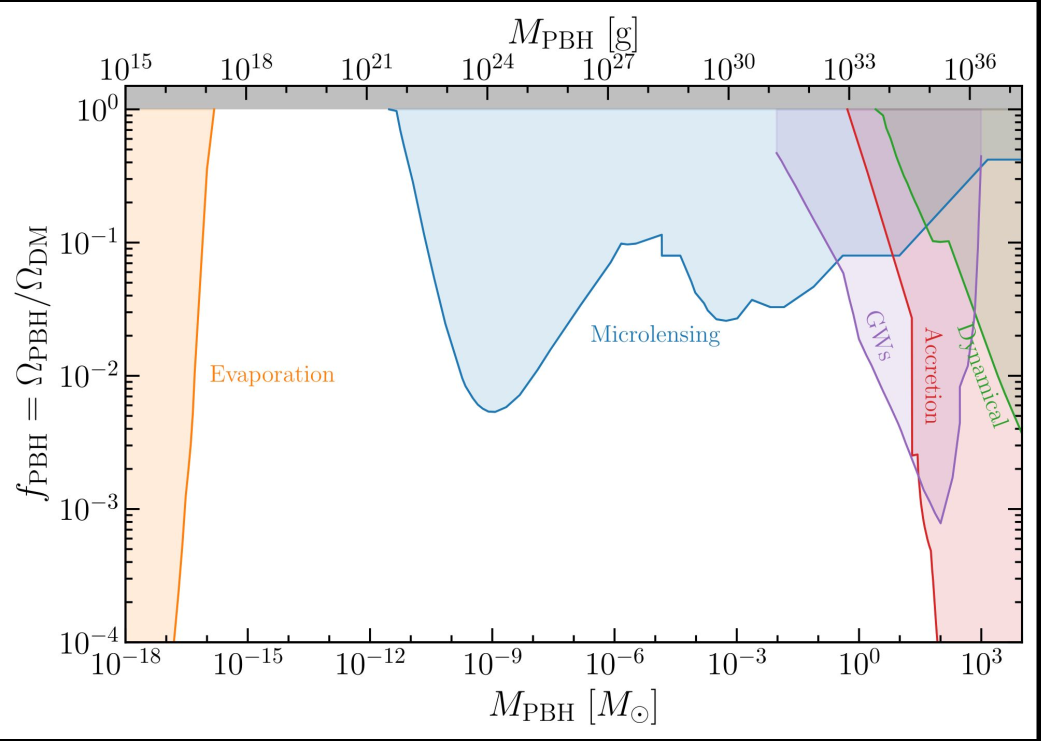
Could ‘primordial’ black holes be dark matter?

Hawking evaporation

- Black holes have temperature:

$$T_{\mathrm{H}} = \frac{\hbar c^3}{8\pi G k_{\mathrm{B}} M}$$

- If they radiate too much, we would see in:
  - CMB shape
  - Gamma rays
  - Cosmic rays



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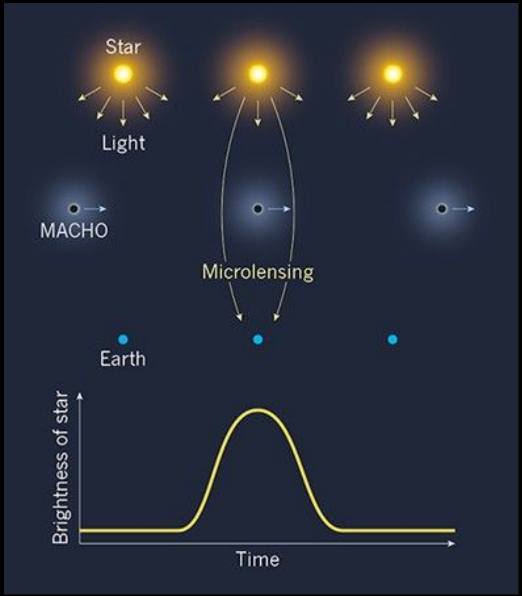
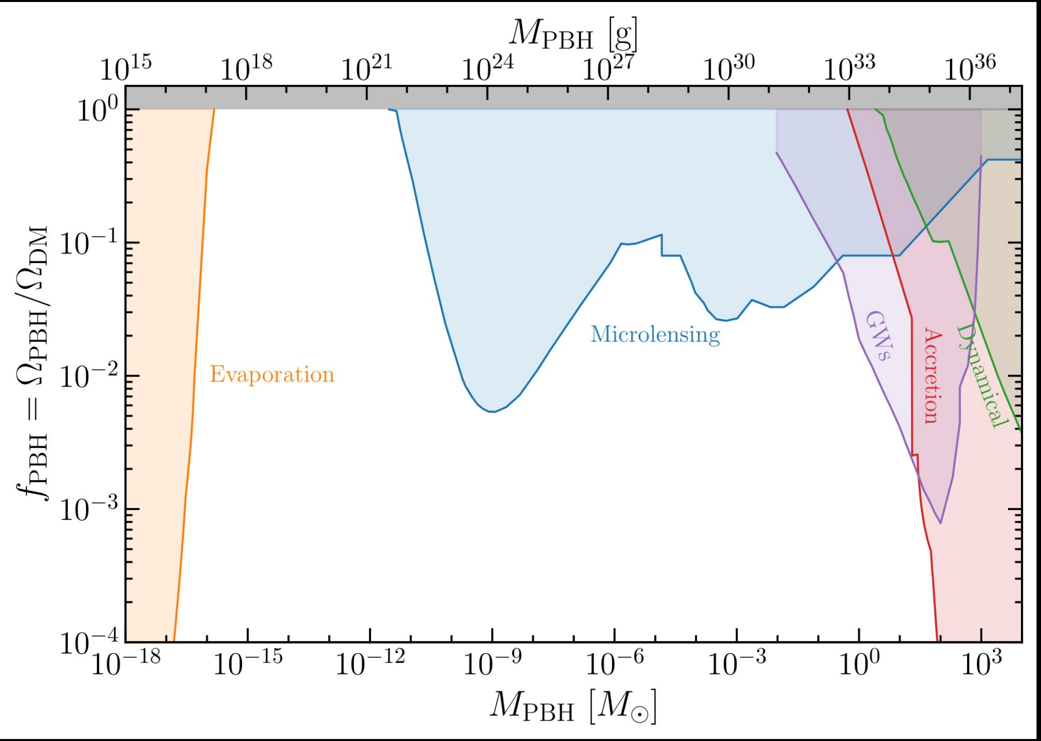
Could ‘primordial’ black holes be dark matter?

Microlensing





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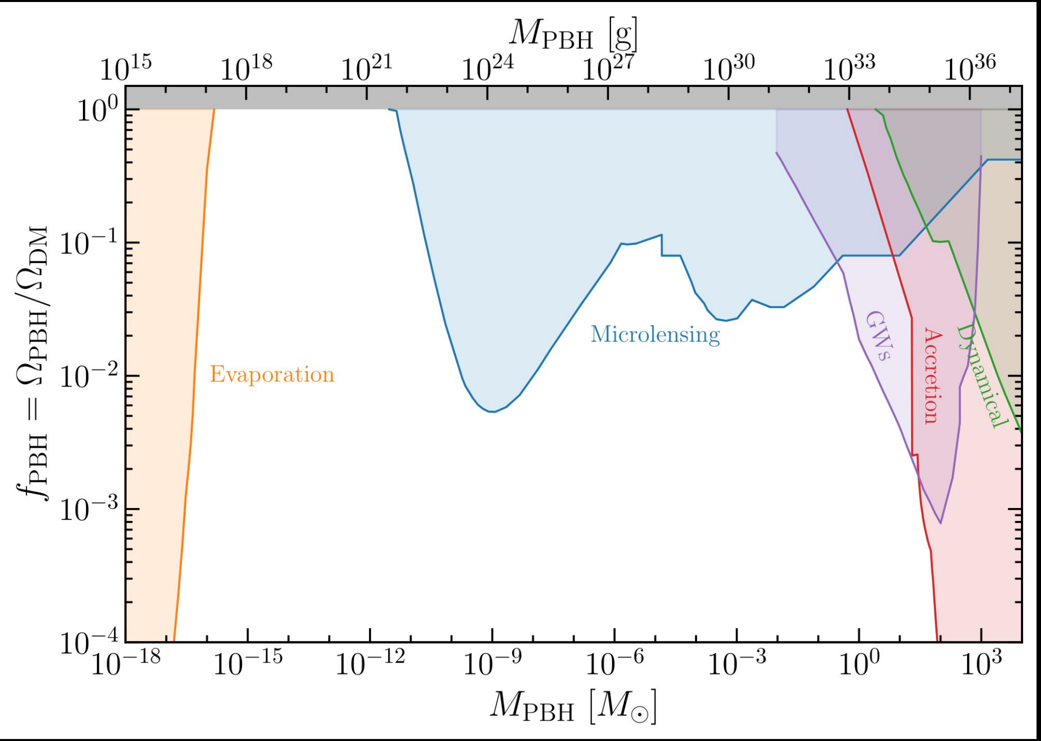
Could ‘primordial’ black holes be dark matter?

Gravitational Waves

- Binaries form in early universe

- Many could coalesce today



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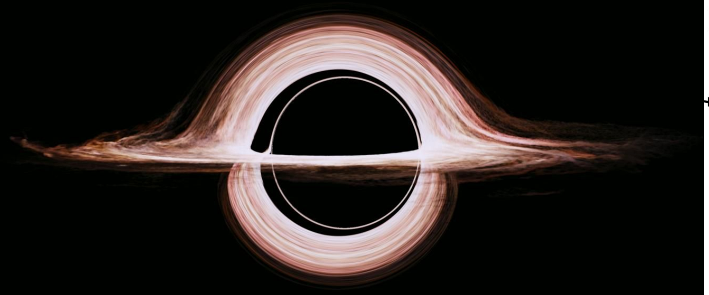
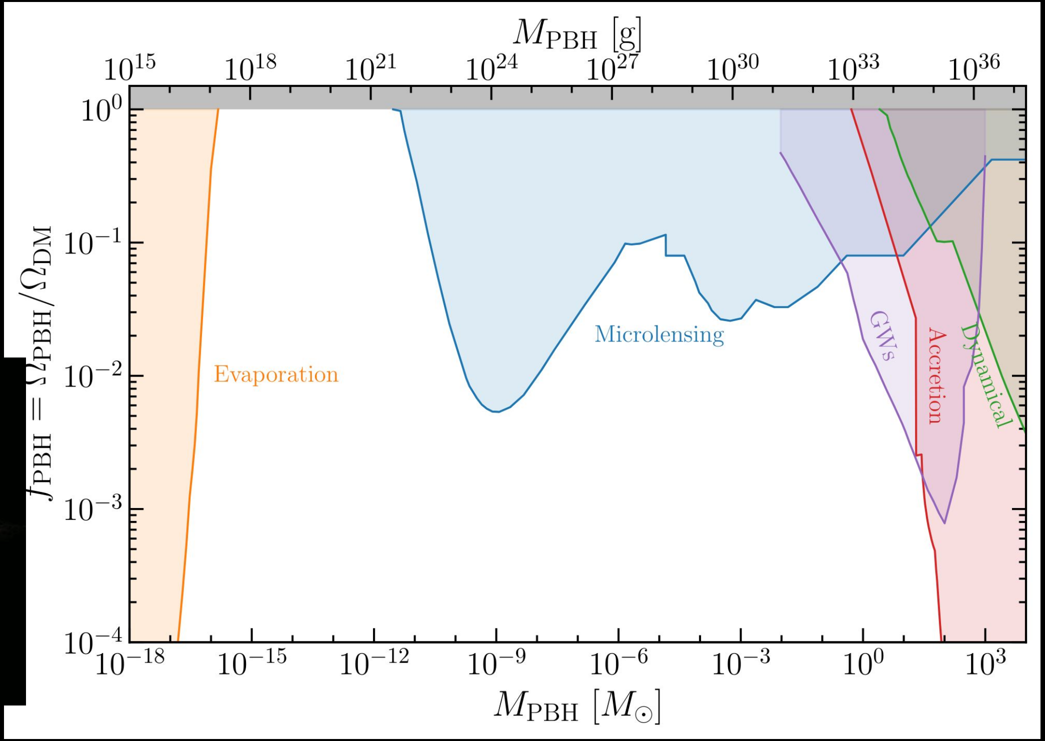
Could 'primordial' black holes be dark matter?

Accretion

- Gas falls onto black holes and heats up
- X-rays, radio, etc





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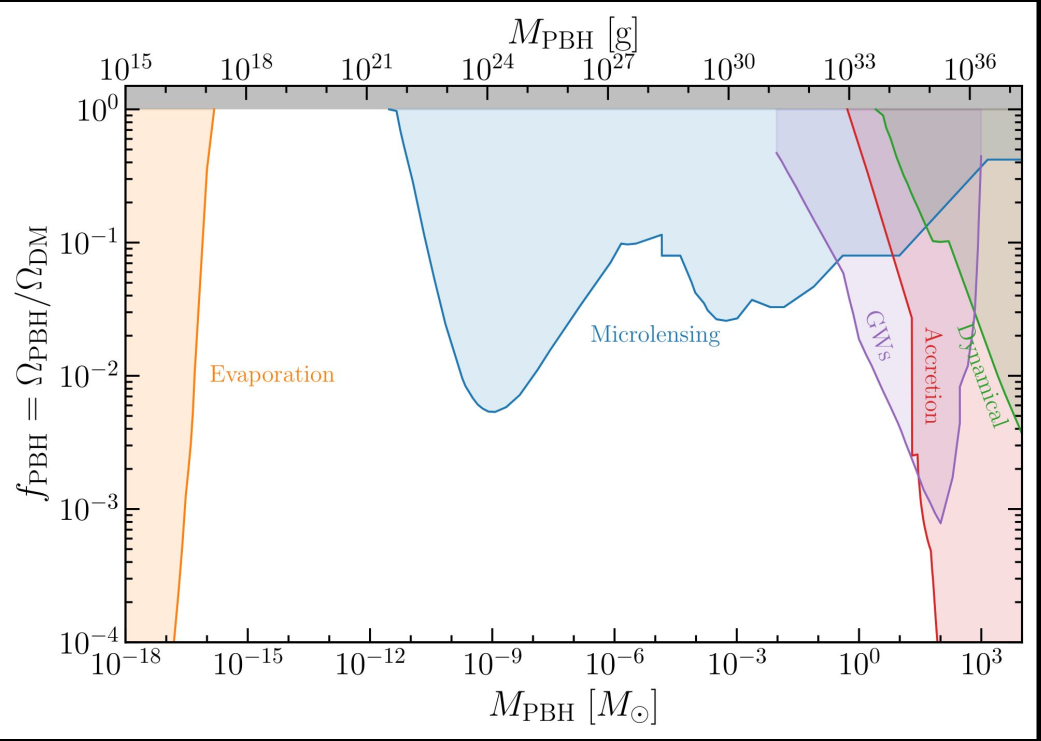
Could ‘primordial’ black holes be dark matter?

Dynamical

- Black holes disrupt big structures
  - ‘Heat up’ star clusters
  - Break up wide binary stars



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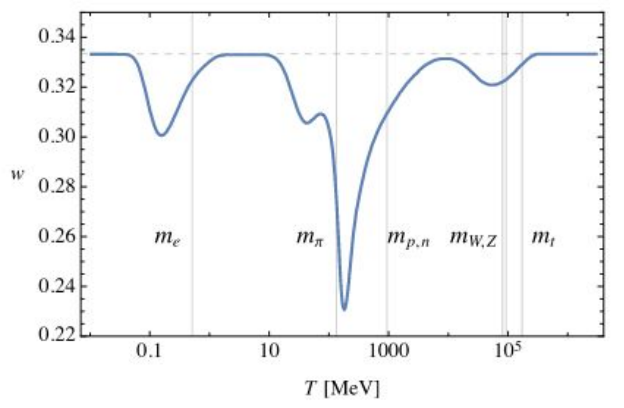
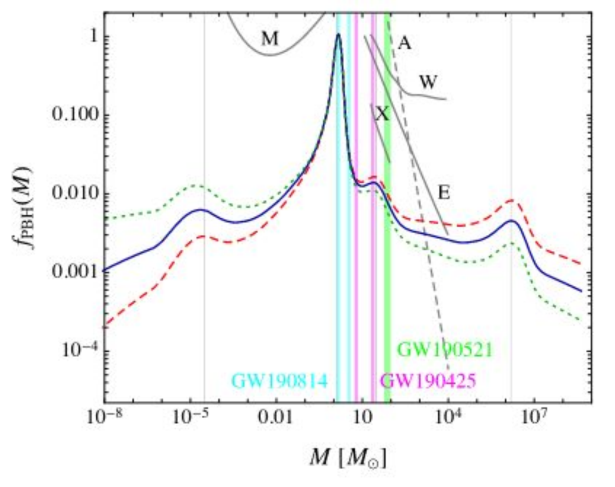
You could have a PBH spectrum though

Every time the universe gets colder than a particle, it gets easier to make PBHs



End up with spectrum which could explain LIGO and evade constraints…



Carr, Clesse, Garcia-Bellido, Kuhnel 2020

So—we have (finally) gotten up-to-date on the question, 'Can black holes be dark matter?'

I'll let you decide the answer…

But we're here to write a paper

2. The flaw flow form

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1. Flaw

2. Solution

3. Effects

(4. Repeat as necessary)

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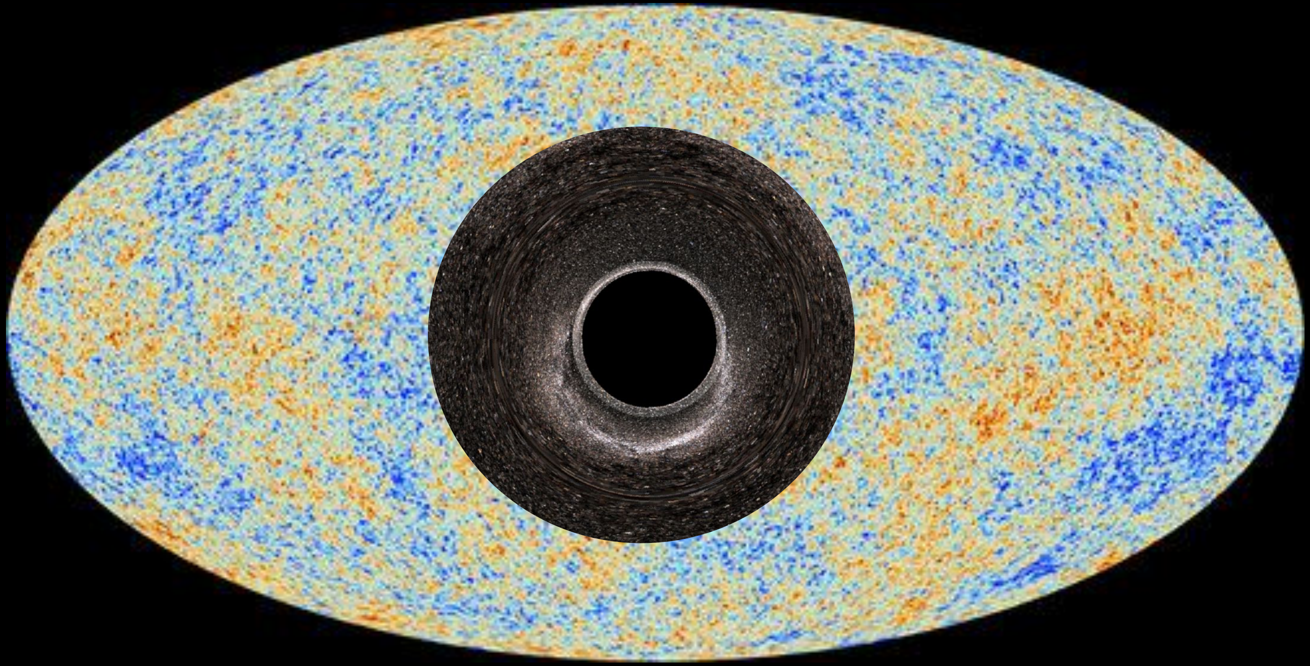
1. Flaw:
Schwarzschild black holes are in empty space (but the early universe is not empty)



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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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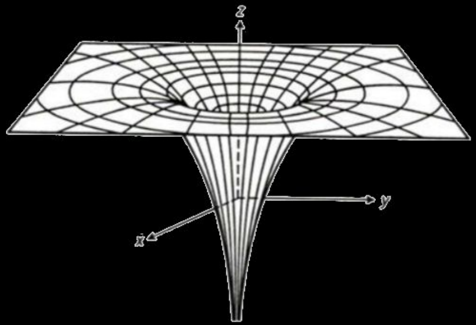
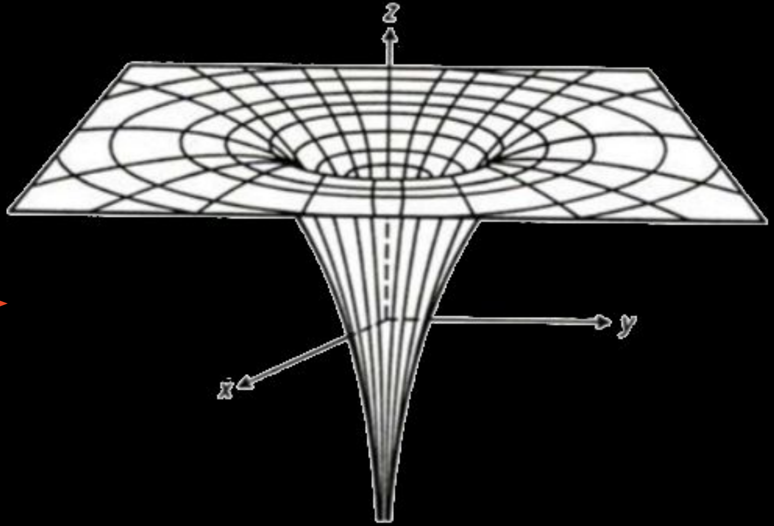
2. Solution:
The *Thakurta metric*
is a simple cosmological black hole

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



$$\approx ma$$



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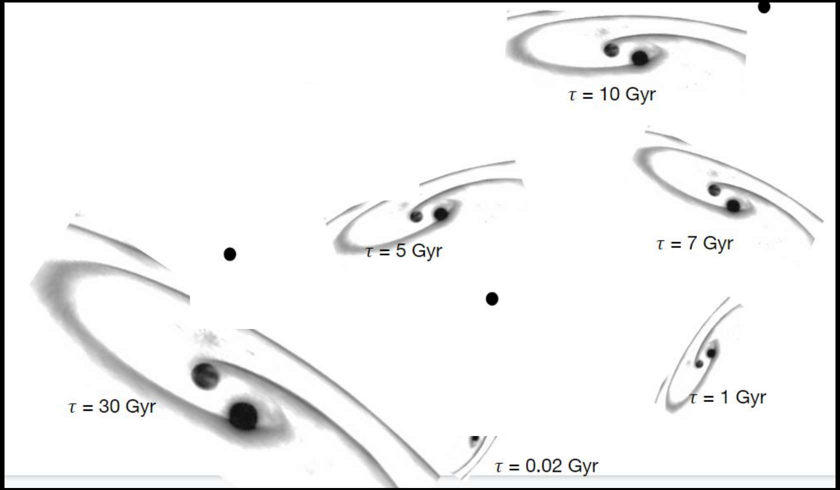
3. Effect: Thakurta black holes do not form binaries

<u>Schwarzschild PBHs:</u>

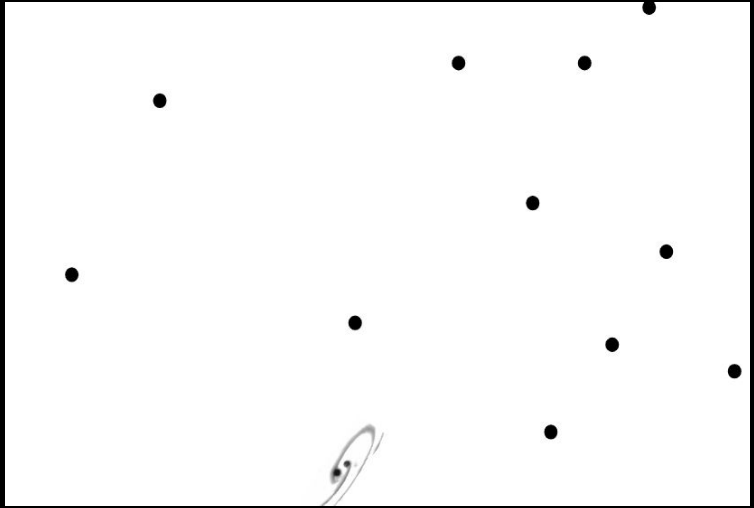
After ~few thousand years



Many of these coalesce ~today

<u>Thakurta PBHs:</u>

After ~few thousand years



τ_{max} ~ 100 sec (!)

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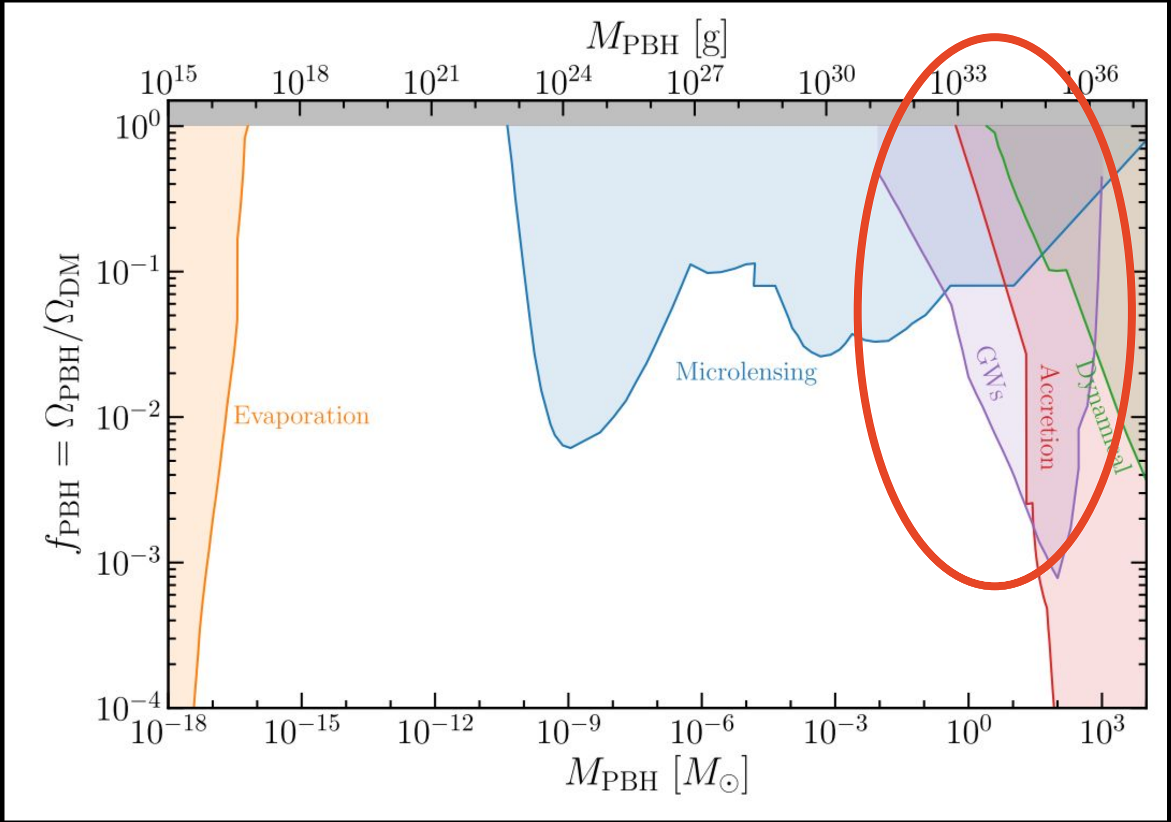
3. Effect 2: LIGO bounds disappear…



4. Keep flawing on: what other constraints happen in the early universe?

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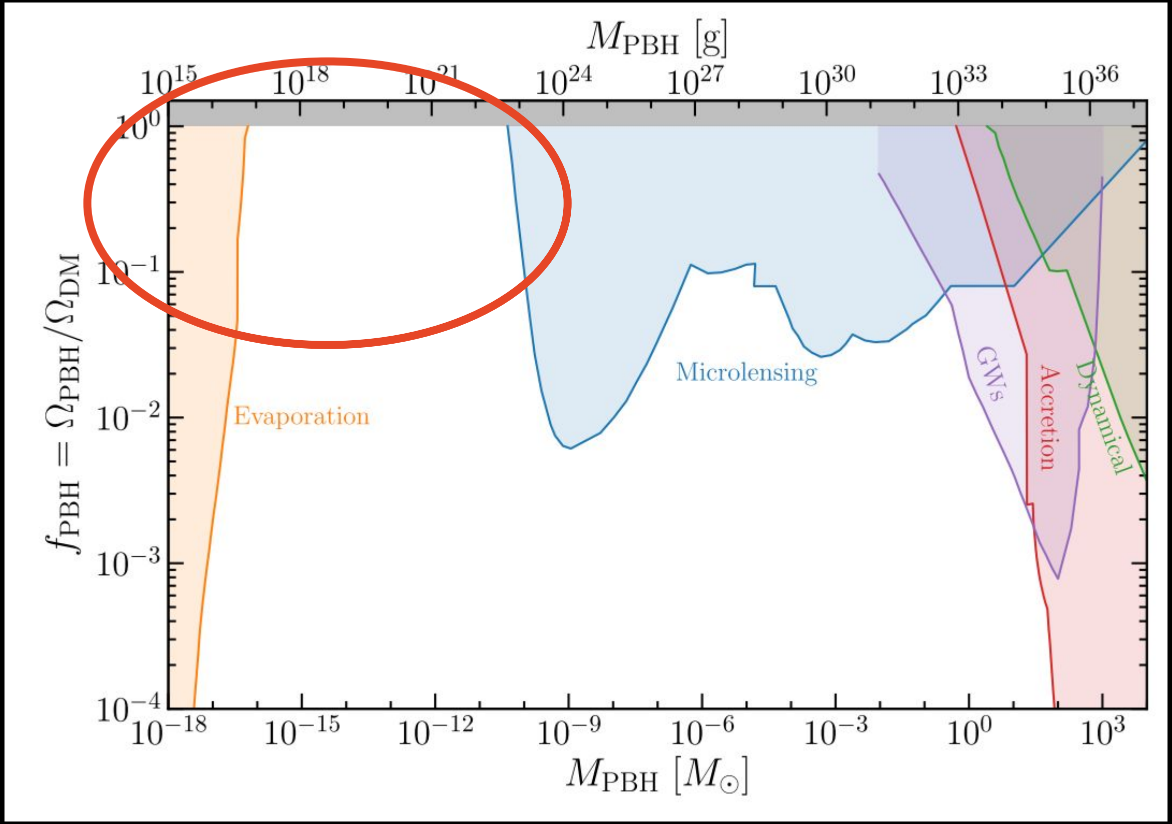
University of Sydney

(a hint:)



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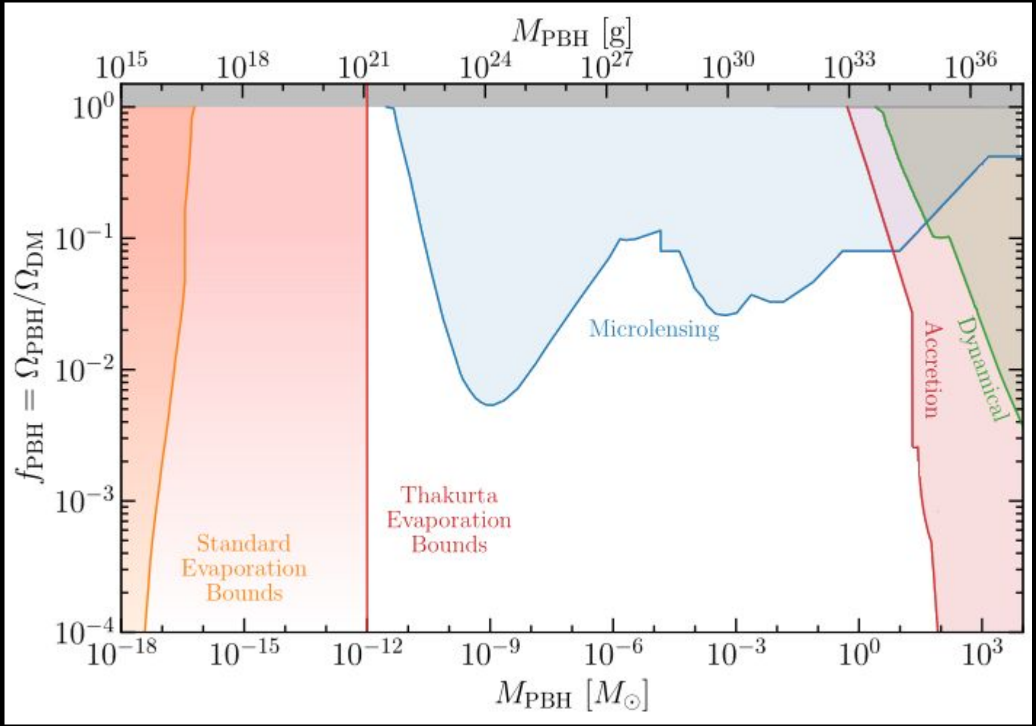
Thakurta black holes evaporate extremely rapidly



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University of Sydney

3. Accept rejection

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University of Sydney

3. Accept and/or reject rejection

3. Accept and/or reject rejection and/or acception

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Accept rejection

Therefore, at this time, I cannot recommend publication.

These comments suggest that the present manuscript is not suitable for publication in the Physical Review.

We regret to inform you that your submission JCAP_042P_0321 has not been accepted for publication in JCAP.

Dear Dr Picker,

I am sending to you the two reports. As you will see one says reject and one gives you a reprieve.

My issues with this manuscript remain, so I cannot recommend publication.

I, therefore, recommend not to accept this manuscript, a

On the basis of the resulting report, it is our judgment that the paper is unsuitable for publication in Physical Review Letters.

we very much regret that we cannot publish your paper

Given my skepticism on the very use of such an approach, very unfort nately I can't recommend the paper for publication. Of course, the auth may be disappointed by my verdict and find it unjust. In this case the pap

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Reject rejection

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Reject rejection

I have indeed lodged a formal appeal. The referee's statement and accusations are patently false---the papers there are cited in my manuscript, and discussed at some length (see, sec. II.b.).

Accept acception

not bad

Eliminating the LIGO bounds on primordial black hole dark matter

#7

Céline Boehm (Sydney U.), Archil Kobakhidze (Sydney U.), Ciaran A.J. O'hare (Sydney U.), Zachary S.C. Picker (Sydney U.), Mairi Sakellariadou (King's Coll. London) (Aug 24, 2020)

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pdf DOI cite 32 citations

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Reject acception?

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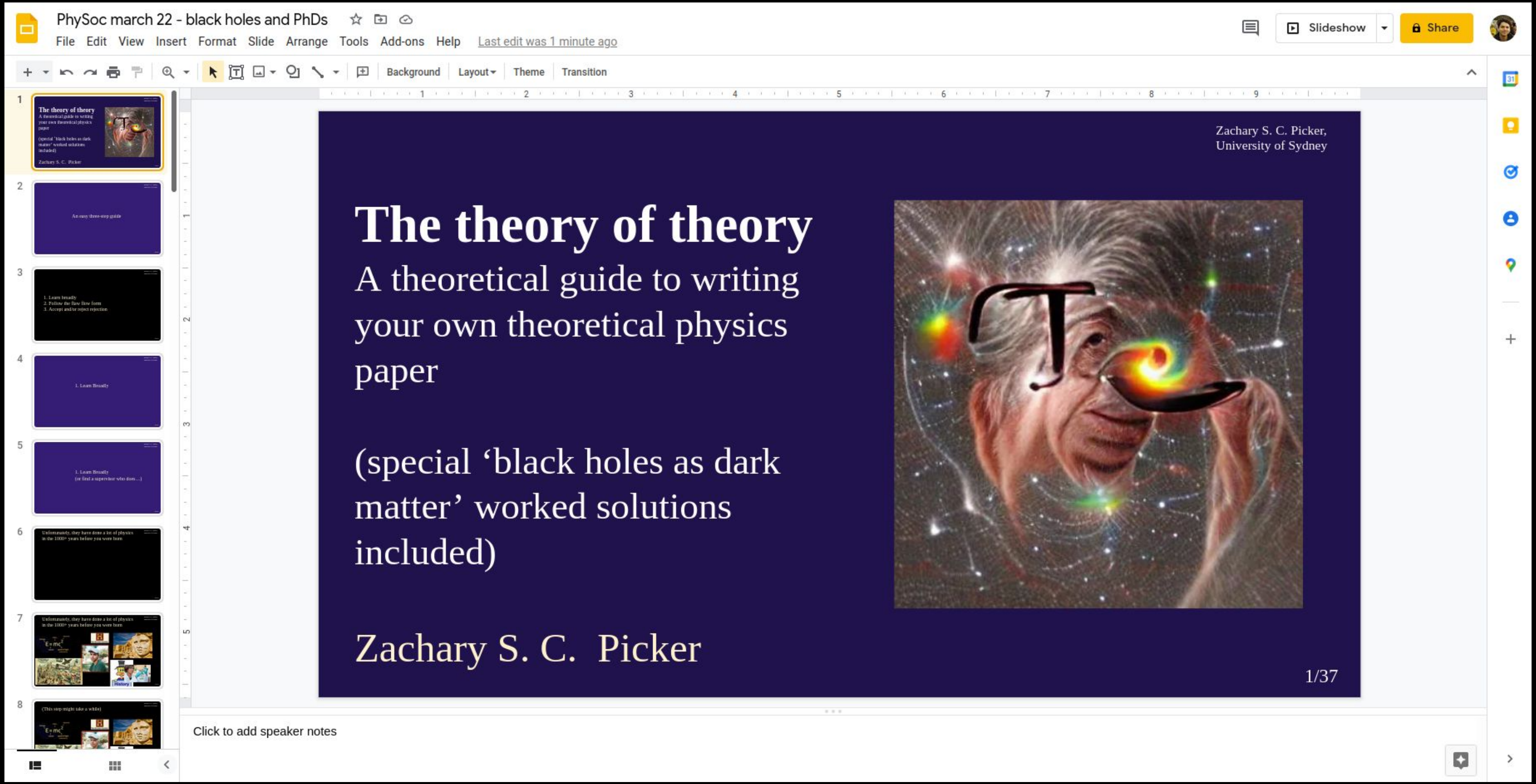
Reject acception?



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To summarize:

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University of Sydney

To summarize:

1. Learn broadly
2. Follow the flaw flow form
3. Accept and/or reject rejection

For example, we plowed through all of

- Dark matter
- Gravity
- Black holes
- Primordial black holes

Just to get to something new!

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University of Sydney

To summarize:

1. Learn broadly
2. Follow the flaw flow form
3. Accept and/or reject rejection

For example, we
- Realized you need a different black hole in the early universe
- Showed that there were serious effects from changing models
  - No binaries and quick evaporation

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University of Sydney

To summarize:

1. Learn broadly
2. Follow the flaw flow form
3. Accept and/or reject rejection and/or acception

For example, we

- Got rejected a lot

goodbye

Zachary S. C. Picker,
University of Sydney

Thakurta black holes

- Misner-sharp mass: $= ma(t) + \frac{H^2 R^3}{2Gf(R)}$ $\quad f(R) = 1{-}2Gma(t)/R$
- Apparent horizon: $R_{\mathrm{b}} = \frac{1}{2H}\left(1 - \sqrt{1 - 8HGma(t)}\right)$ $\quad \approx 2ma$
- Surface gravity: $\kappa = \frac{1 - 2\left(\frac{\partial}{\partial R} M_{\mathrm{MS}}(R_{\mathrm{b}})\right)}{2R_{\mathrm{b}}}$ $\quad T = \kappa/2\pi$
- Source:

$$T_{\mu\nu} = (\rho + P)\, u_\mu u_\nu + g_{\mu\nu} P + q_{(\mu} u_{\nu)}$$
$$q_\mu = (0, q, 0, 0)\ ,$$
$$u_\mu = (u, 0, 0, 0)\ .$$

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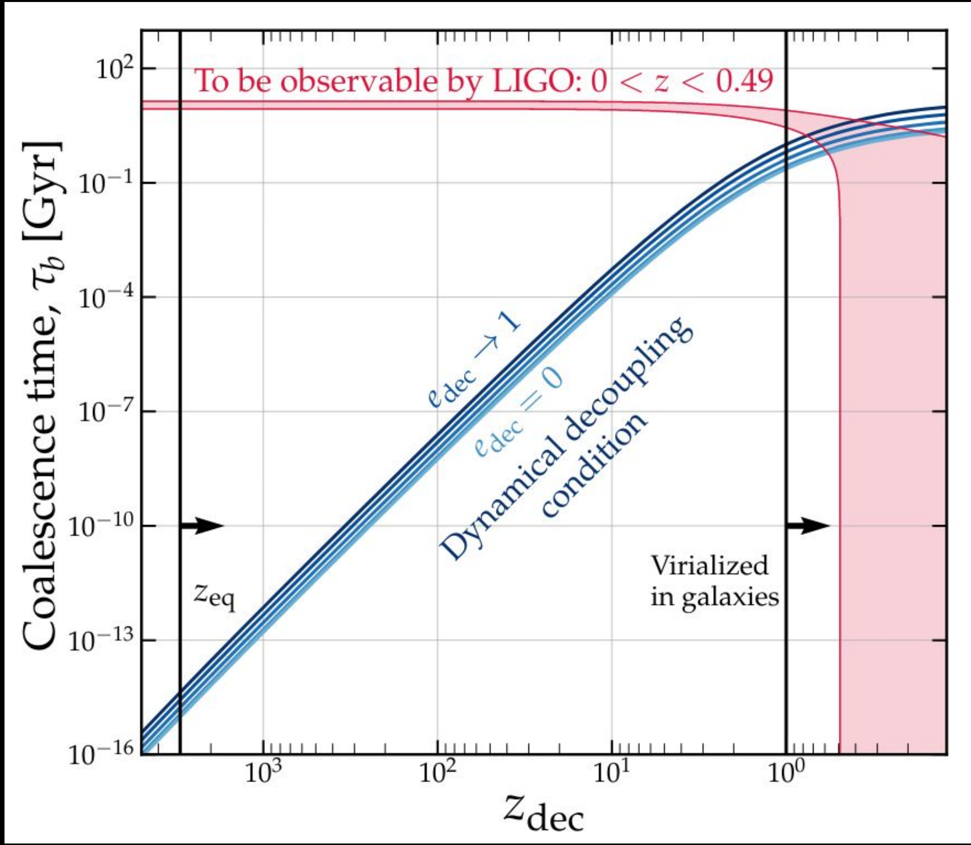
Bonus: thakurta binary formation plot



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Bonus: thakurta hawking radiation plot