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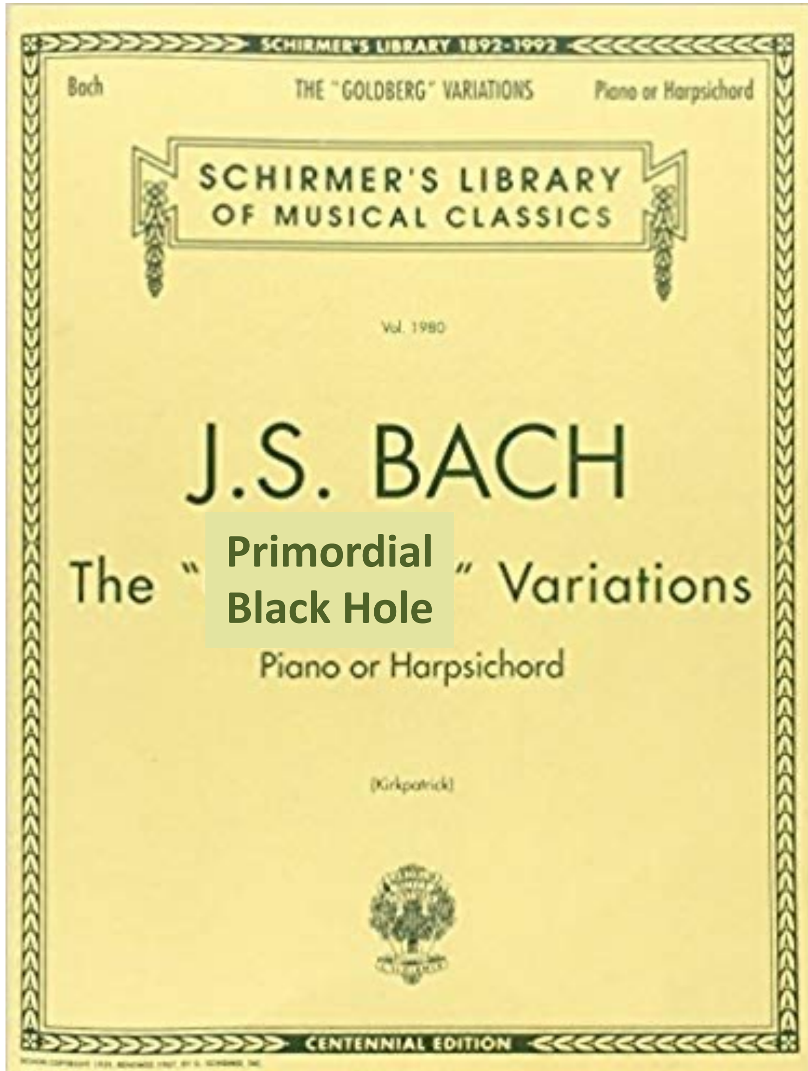
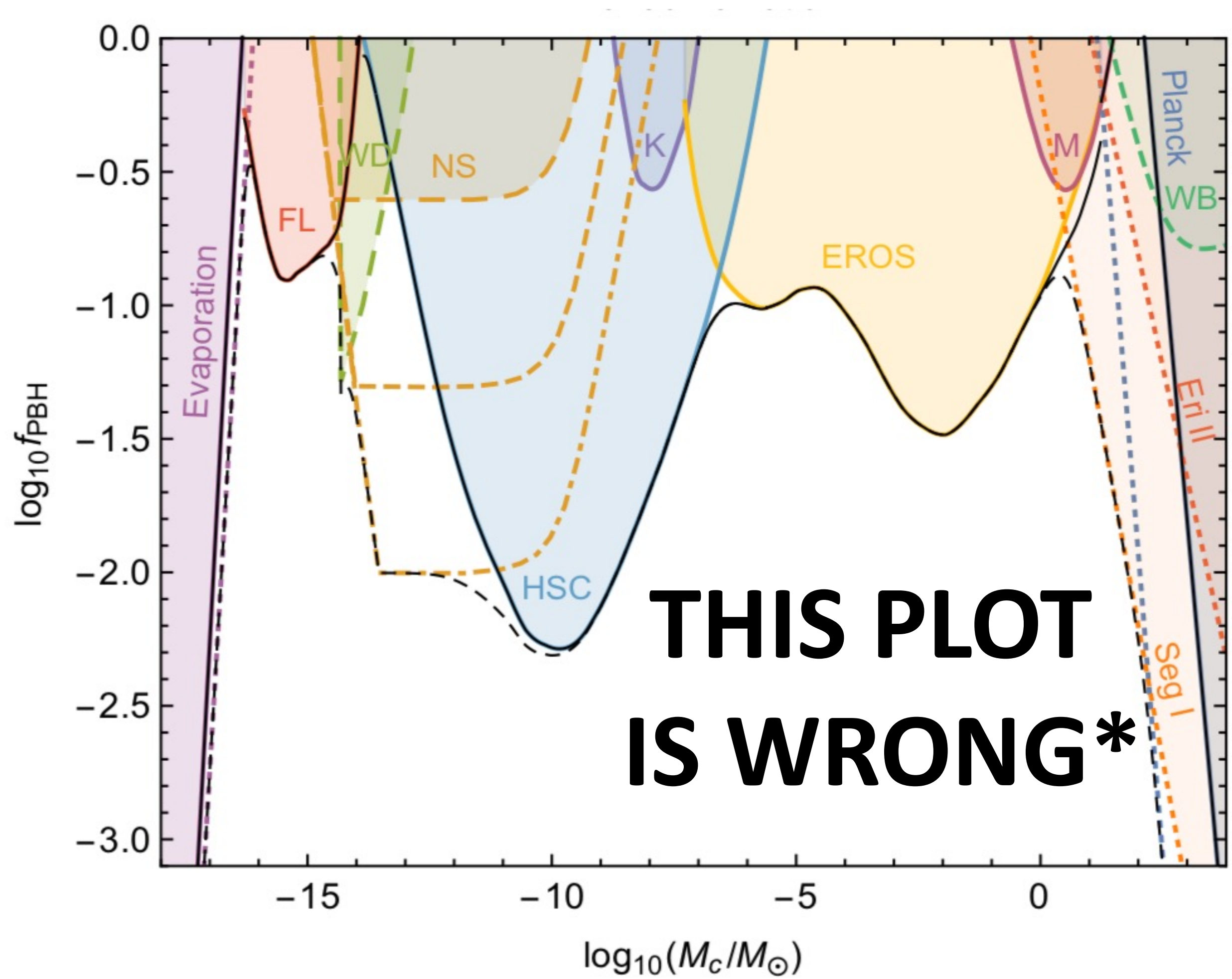


Phenomenology 2021 Symposium – May 26, 2021

Can there be **enough** PBH around to be the **DM**?

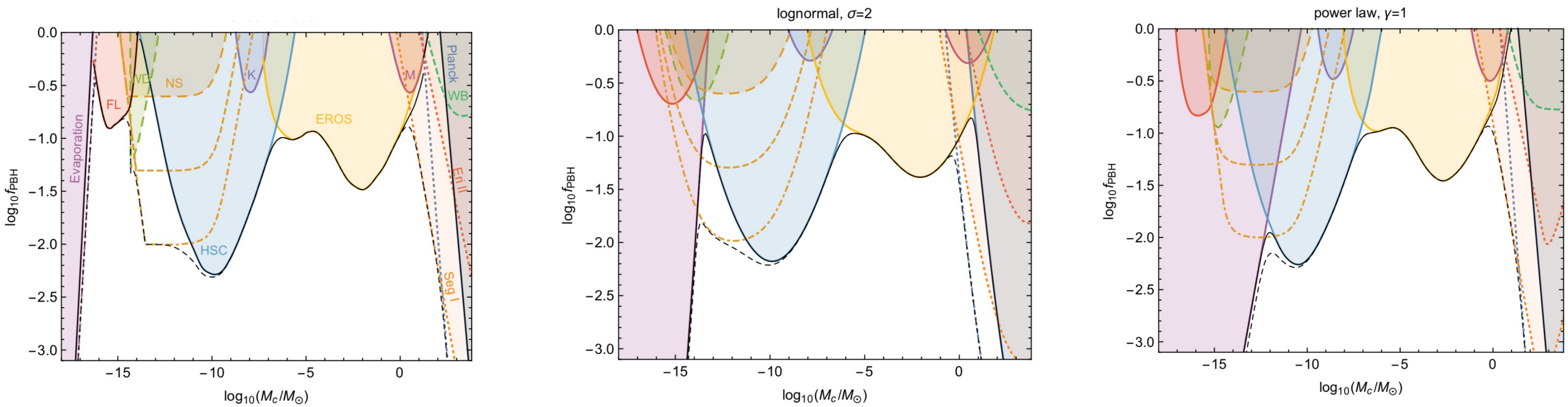
What is the **maximal fraction** of **dark matter** in **PBH**?



*Carr has since corrected it!

Carr et al, 2017

The **fraction** of PBH that could be the **dark matter** depends on the **mass function**!



…what is the mathematical function that **maximizes** the **mass fraction** of primordial black holes compatibly with **constraints**?

Carr et al, 2017

The Maximal-Density Mass Function for Primordial Black Hole Dark Matter

Benjamin V. Lehmann, Stefano Profumo and Jackson Yant

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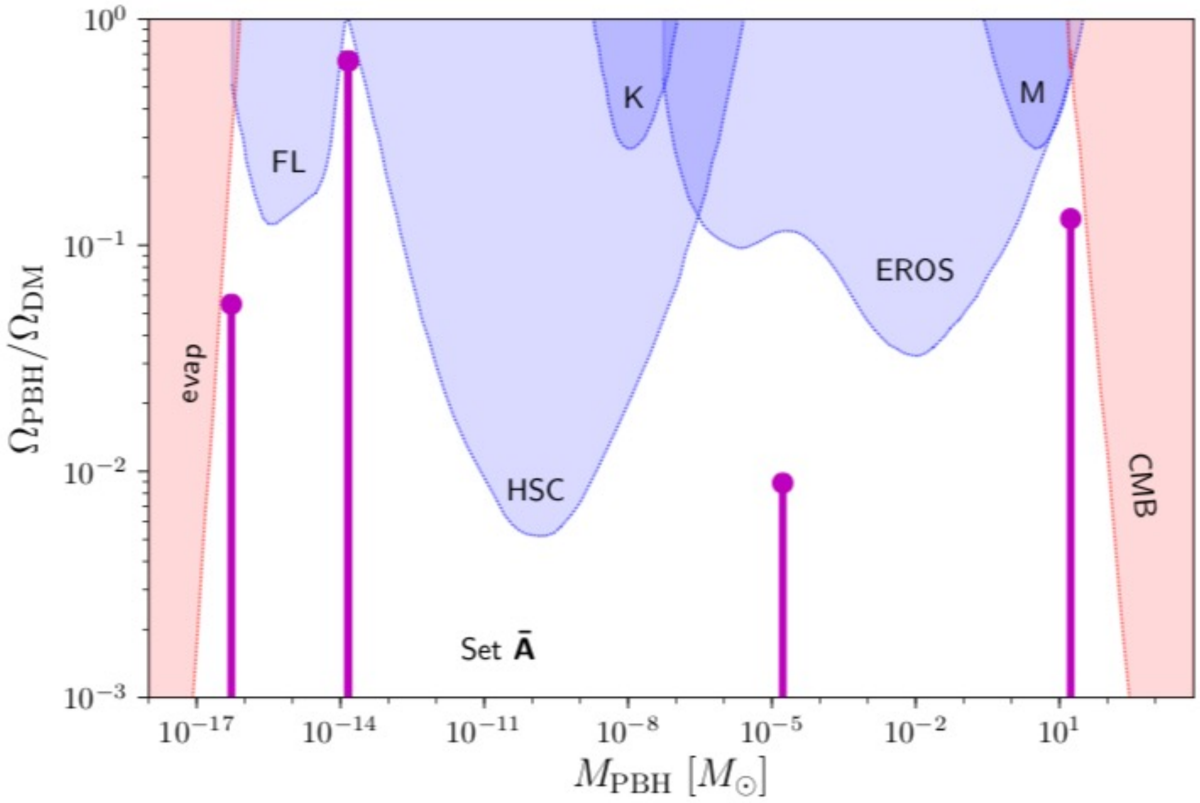
Abstract. The advent of gravitational wave astronomy has rekindled interest in primordial black holes (PBH) as a dark matter candidate. As there are many different observational probes of the PBH density across different masses, constraints on PBH models are dependent on the functional form of the PBH mass function. This complicates general statements about

Answer: with *N* independent constraints, the optimal function is a linear combination of *N* delta functions with calculable relative weights

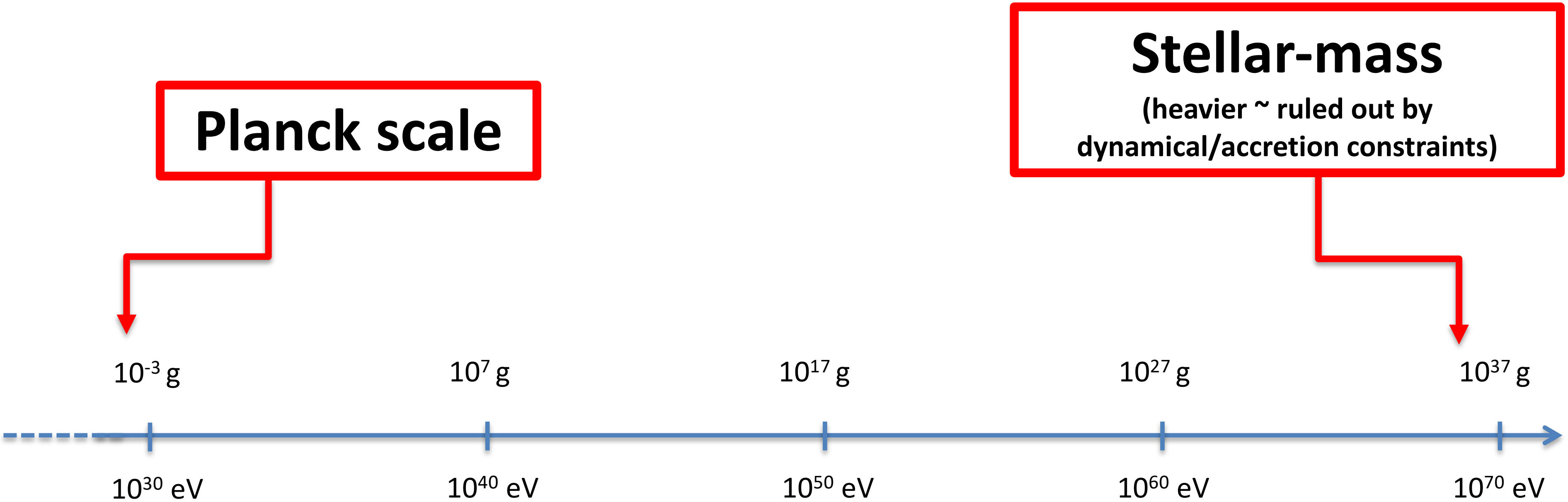
$$\min\left\{\|\mathbf{x}\| \mid \mathbf{x} \in \operatorname{conv}\left\{\mathbf{g}(M) \mid M \in U\right\}\right\}$$

* Lehmann, Profumo and Yant, JCAP 2018

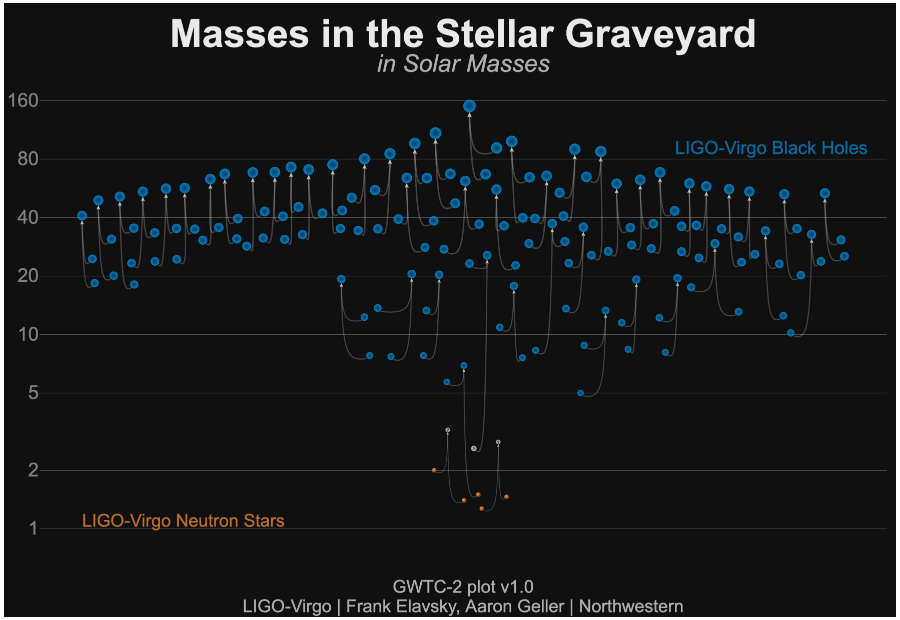


Answer: with *N* independent constraints, the optimal function is a linear combination of *N* delta functions with calculable relative weights

* Lehmann, Profumo and Yant, JCAP 2018



Planck scale
Stellar-mass
(heavier ~ ruled out by
dynamical/accretion constraints)
10-3 g
107 g
1017 g
1027 g
1037 g
1030 eV
1040 eV
1050 eV
1060 eV
1070 eV



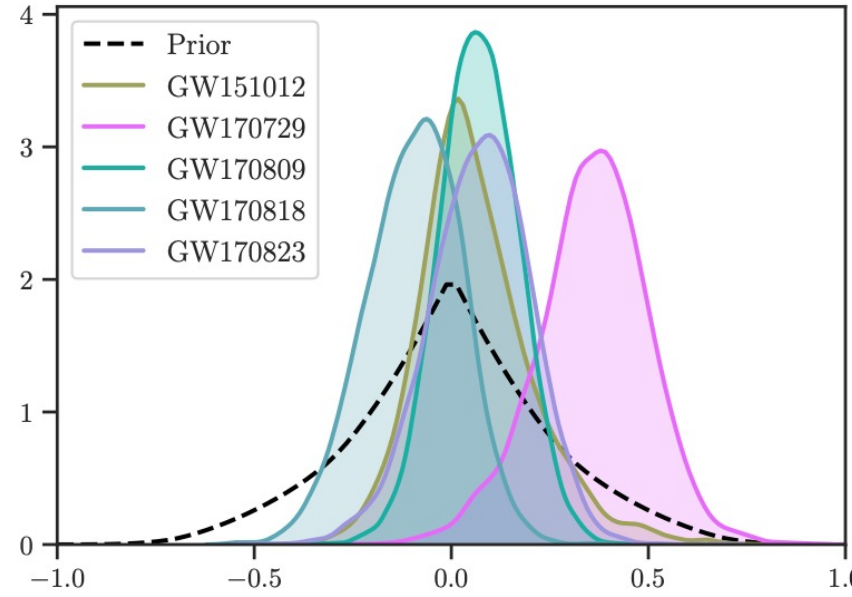
"Stellar-Mass" (10^{35} g) Black Holes

10^{-3} g | 10^{7} g | 10^{17} g | 10^{27} g | 10^{37} g

10^{30} eV | 10^{40} eV | 10^{50} eV | 10^{60} eV | 10^{70} eV

✓ **Spins look a lot like PBH!***

*** Fernandez and Profumo, 2019**



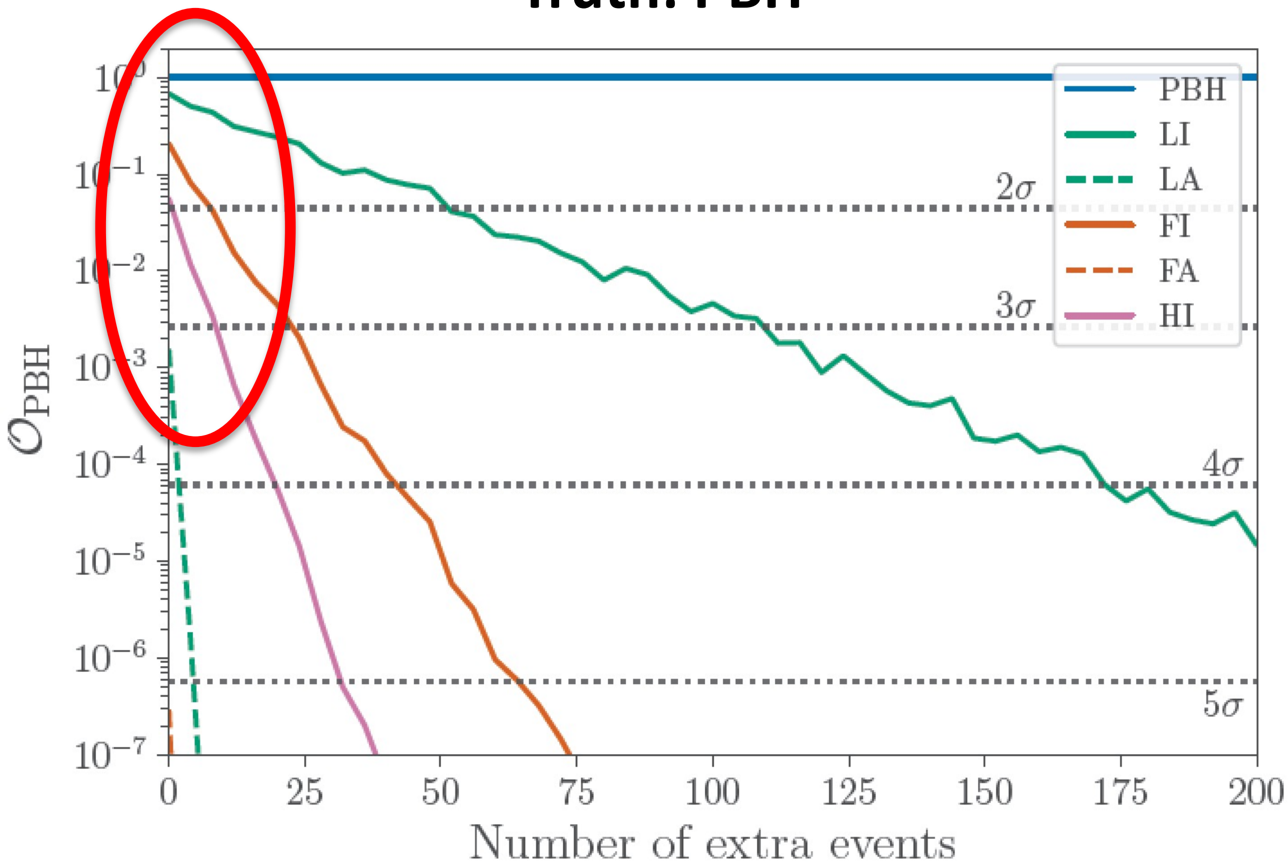
Odds ratios

Flat	High	PBH
−1.18	−2.49	0.39
−14.65	−36.41	

Fernandez and Profumo, 1905.13109 (JCAP); Slide credit: Nico Fernandez (UCSC → UIUC)

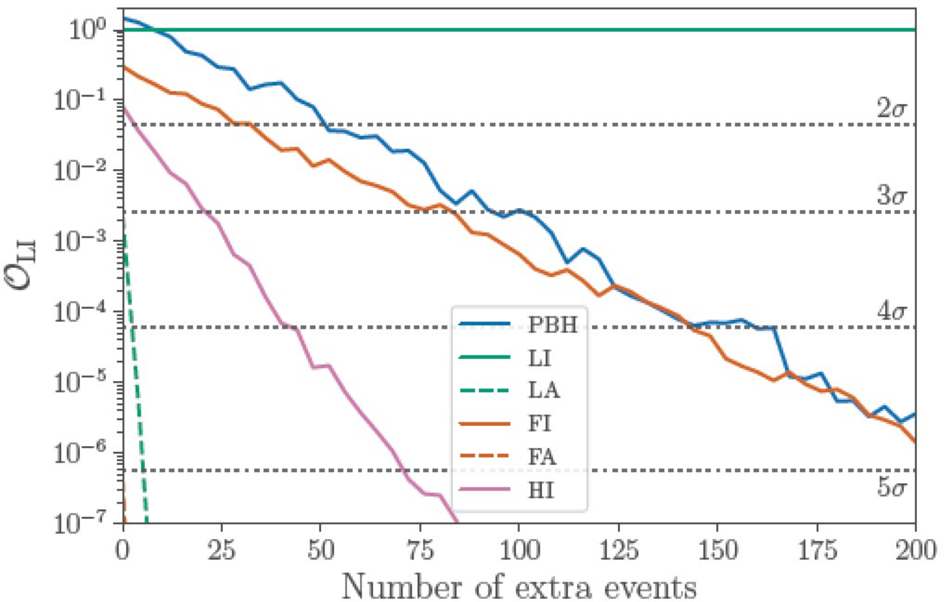
Evolution of the Odds ratios

Truth: PBH



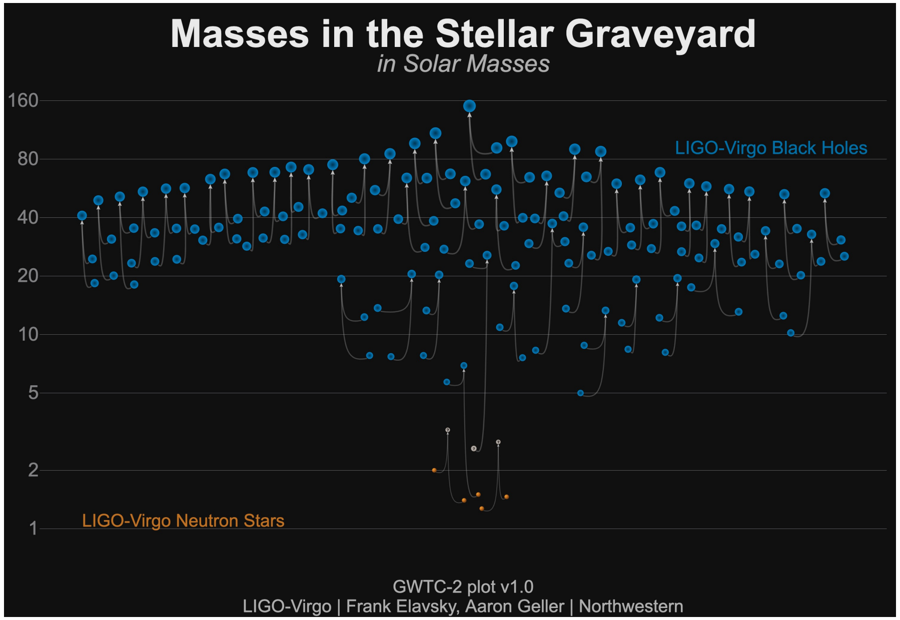
Fernandez and Profumo, 1905.13109 (JCAP); Slide credit: Nico Fernandez (UCSC → UIUC)

Evolution of the Odds ratios

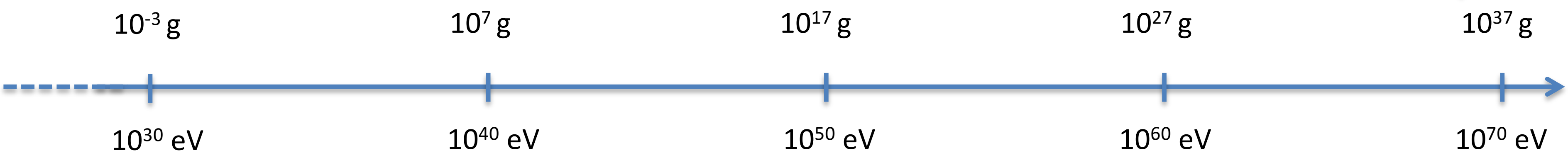


Truth: Low-isotropic

Fernandez and Profumo, 1905.13109 (JCAP); Slide credit: Nico Fernandez (UCSC → UIUC)



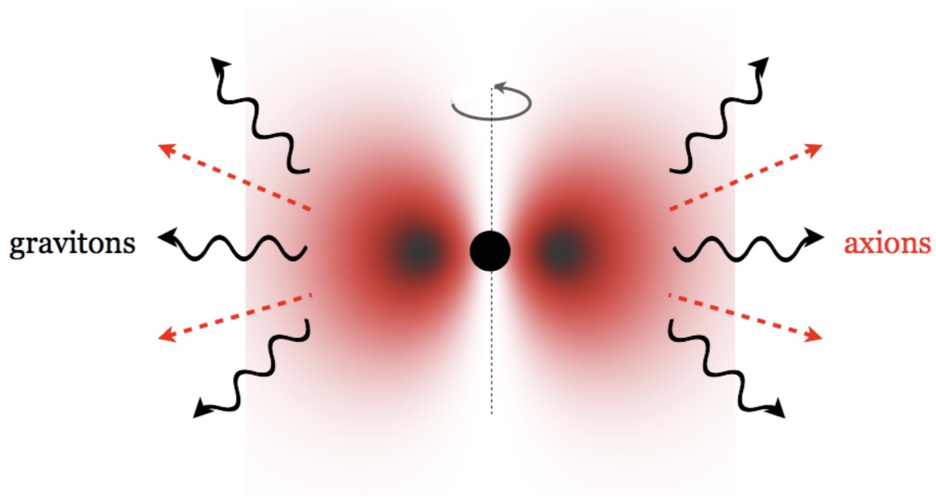
"Stellar-Mass" (10^{35} g) Black Holes



- ✓ **Spins look a lot like PBH!**
- ✓ **…or maybe they are low because of superradiance*?**

*** Fernandez, Ghalsasi, Profumo, 2020**

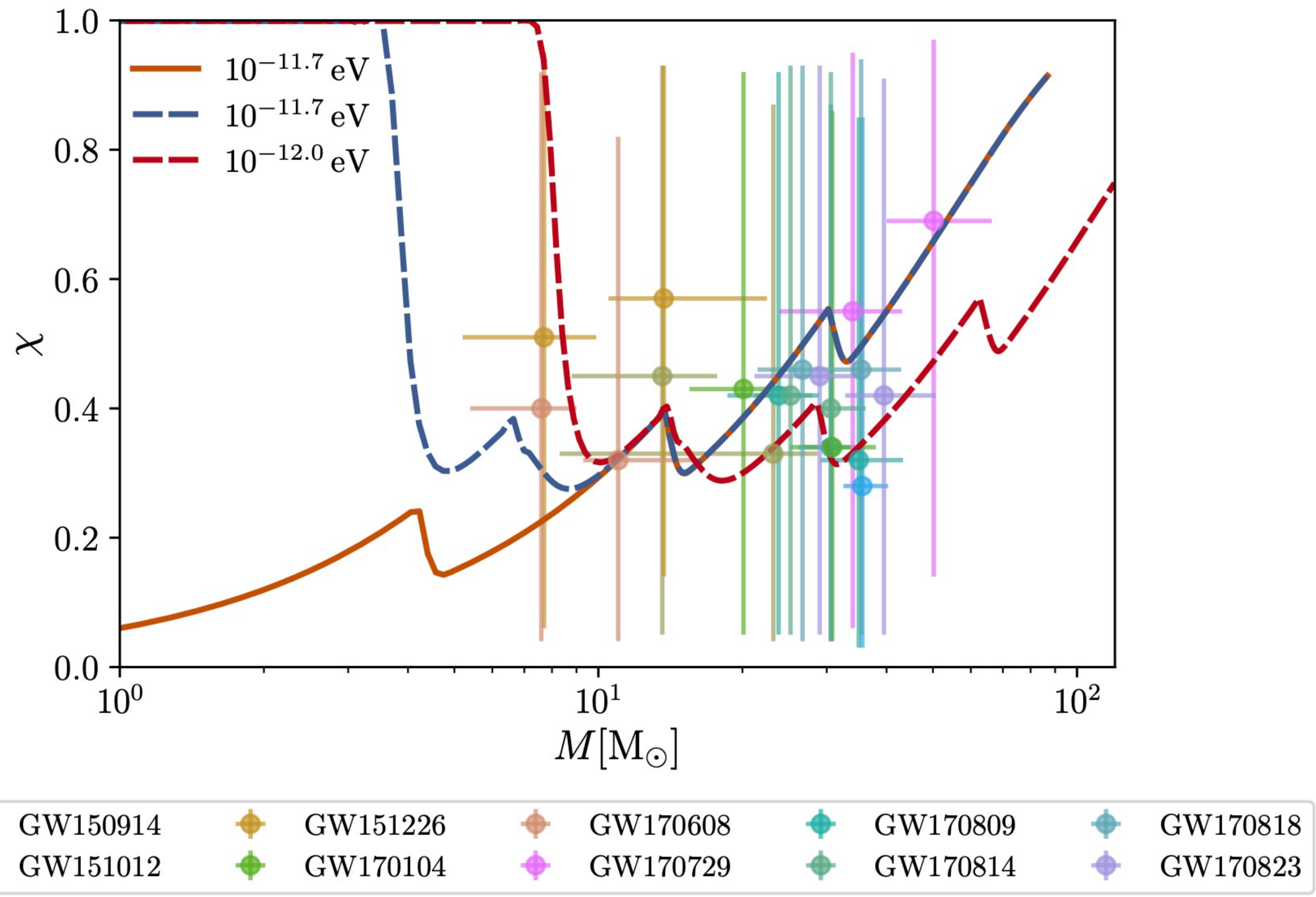
What else could fake a low-spin PBH? Super-radiance!



Assuming an initial spin and alignment distribution, one can compute the "best-fit" axion mass

Similarly, spin measurements can put constraints on axion-like particles

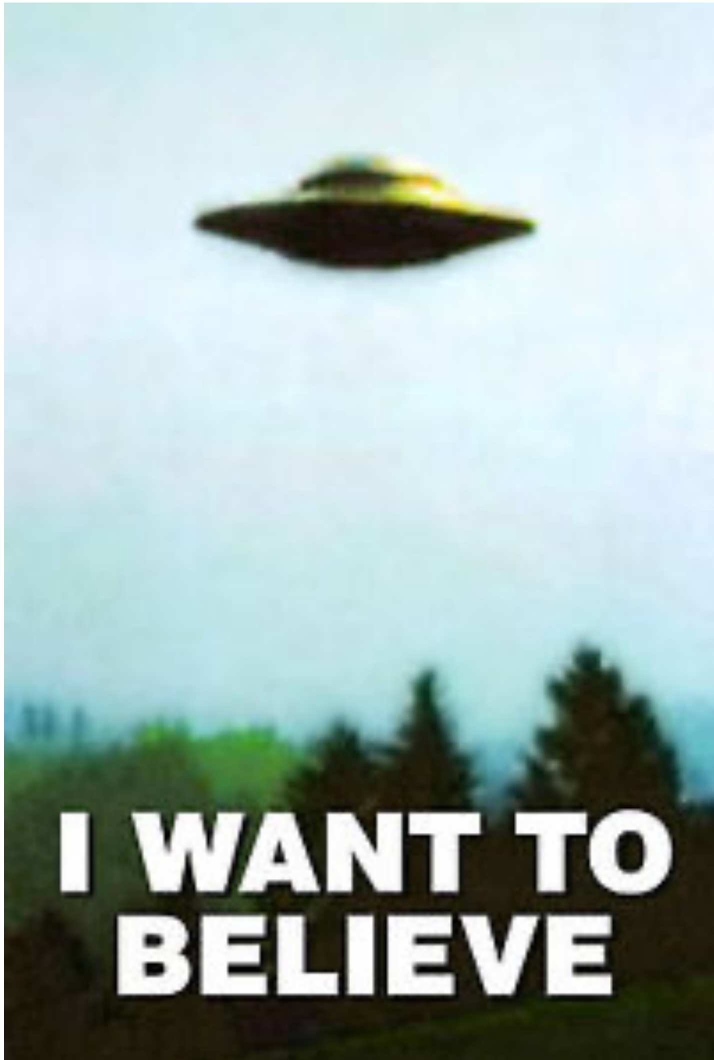
What else could fake a low-spin PBH? Super-radiance!

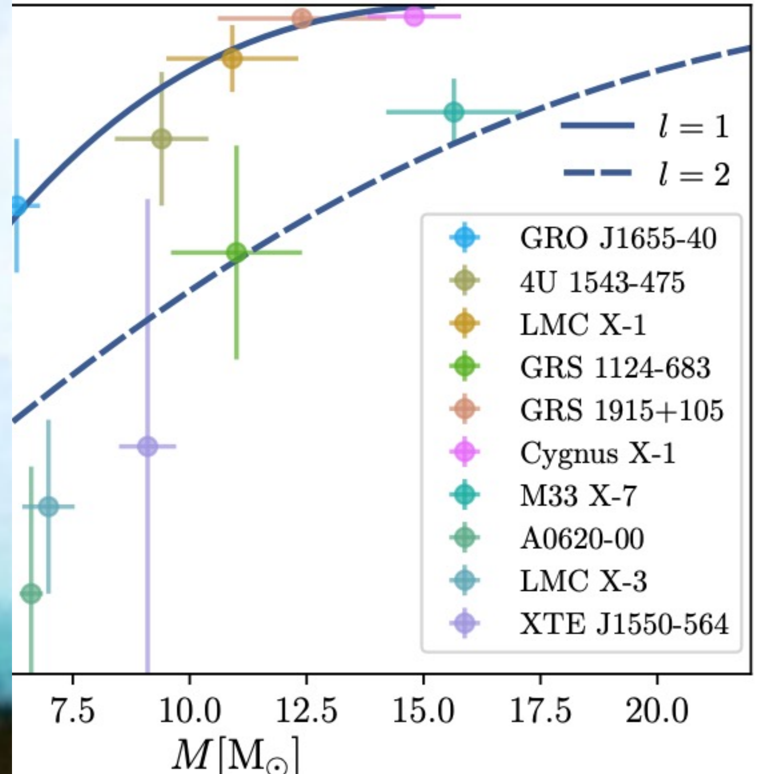


Regge plot (effective spin vs mass) assuming Flat priors for both mass and spin*

*Fernandez, Ghalsasy, Profumo, 1911.07862

What else could **fake** a **low-spin PBH**? **Super-radiance**!



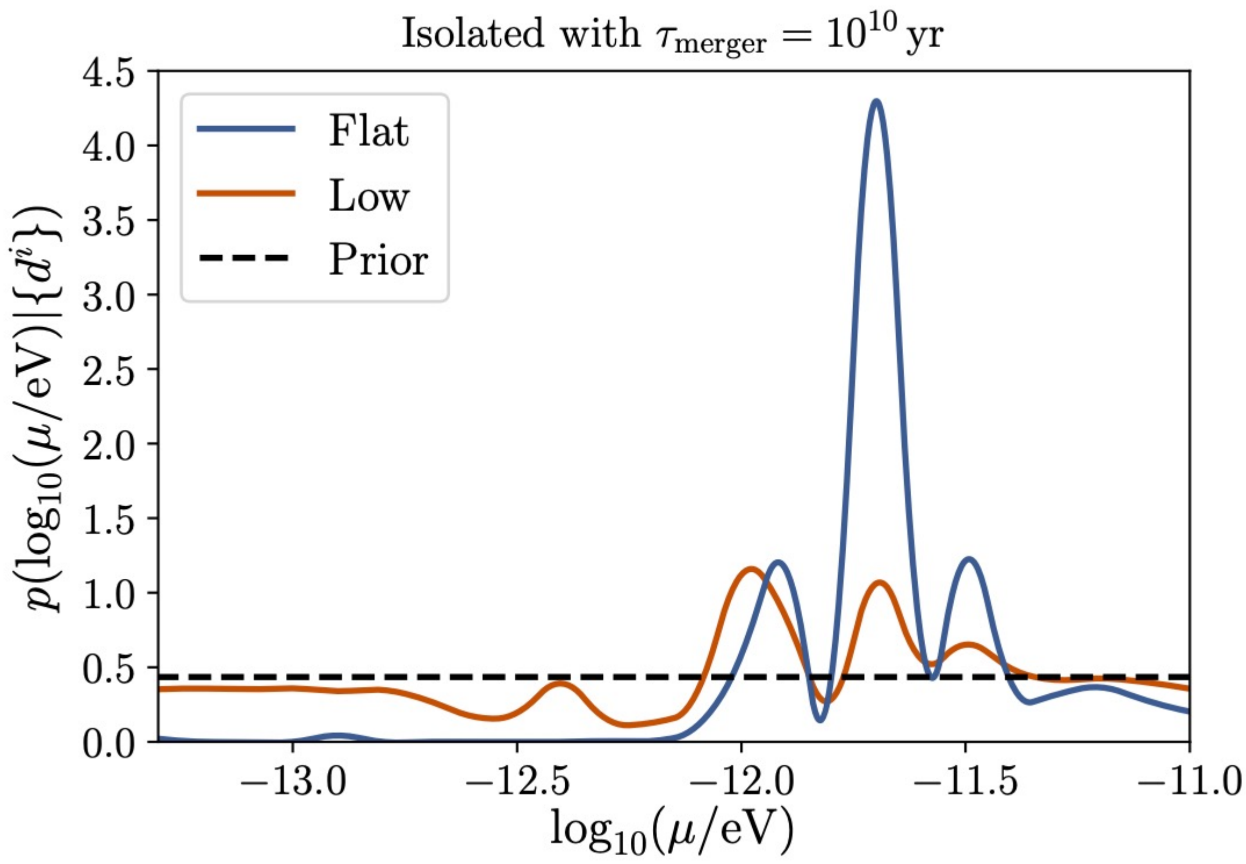


binaries tend to have large spins…

…but these are **massive**, so high-l is **non-super-radiant**!

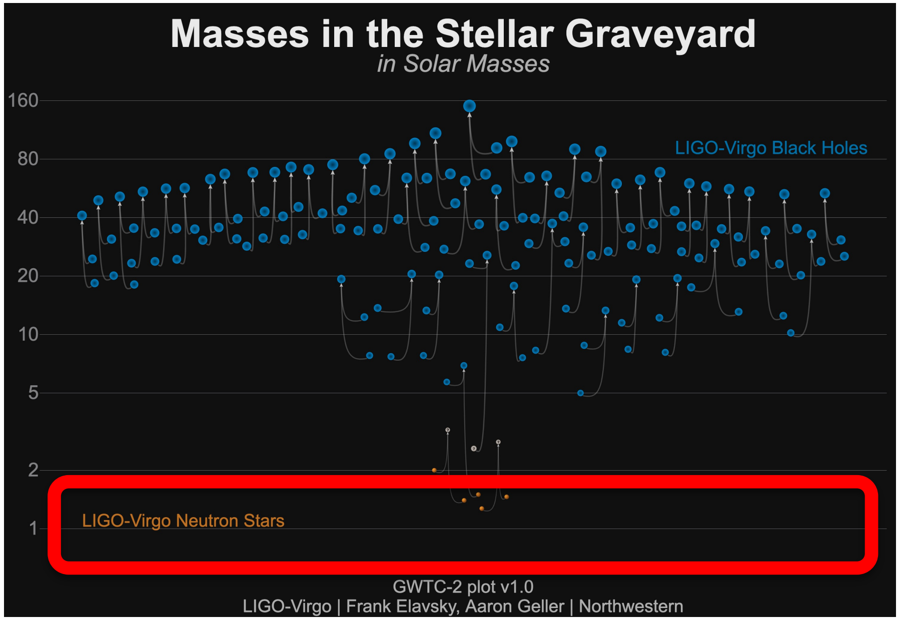
*Fernandez, Ghalsasy, Profumo, 1911.07862

What else could fake a low-spin PBH? Super-radiance!

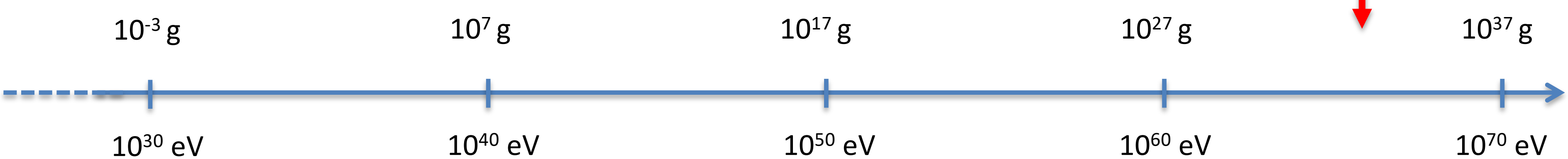


Posterior Probability for ALP mass

*Fernandez, Ghalsasy, Profumo, 1911.07862



sub-“Stellar-Mass” ($<10^{33}$ g) Black Holes



✓ **Is there an unmistakable signature for PBH as DM?**

Yes! BH merger with a sub-Chandrasekhar mass (1.4 M_{sun})

Preliminary LIGO search results are out!

Given a mass function, one can calculate:

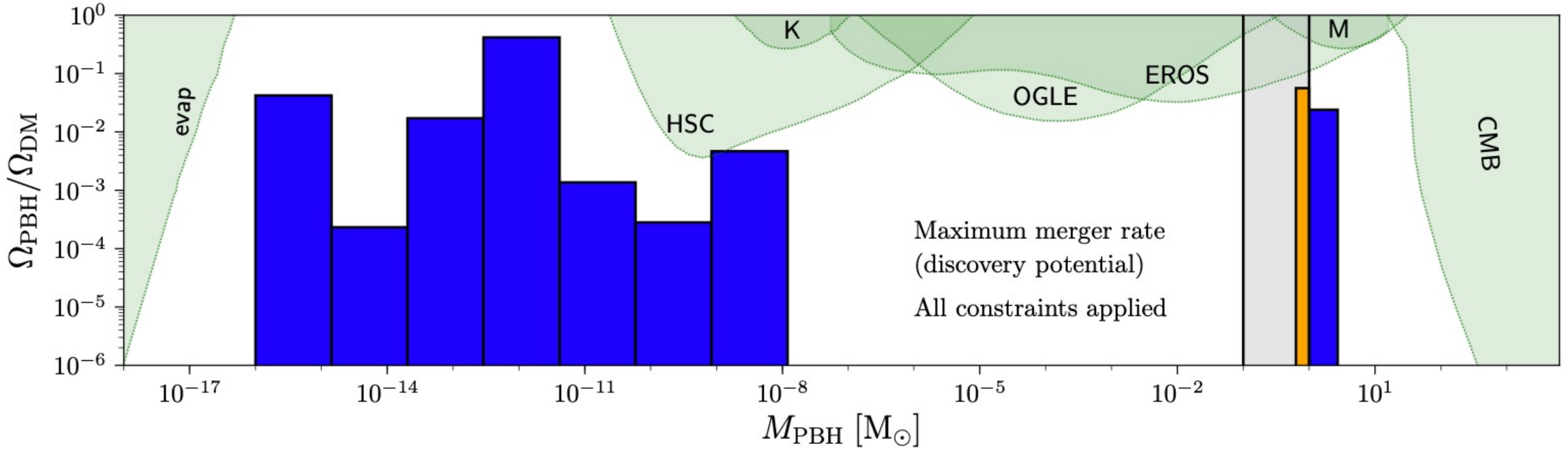
1. Rate of "goldilocks events"

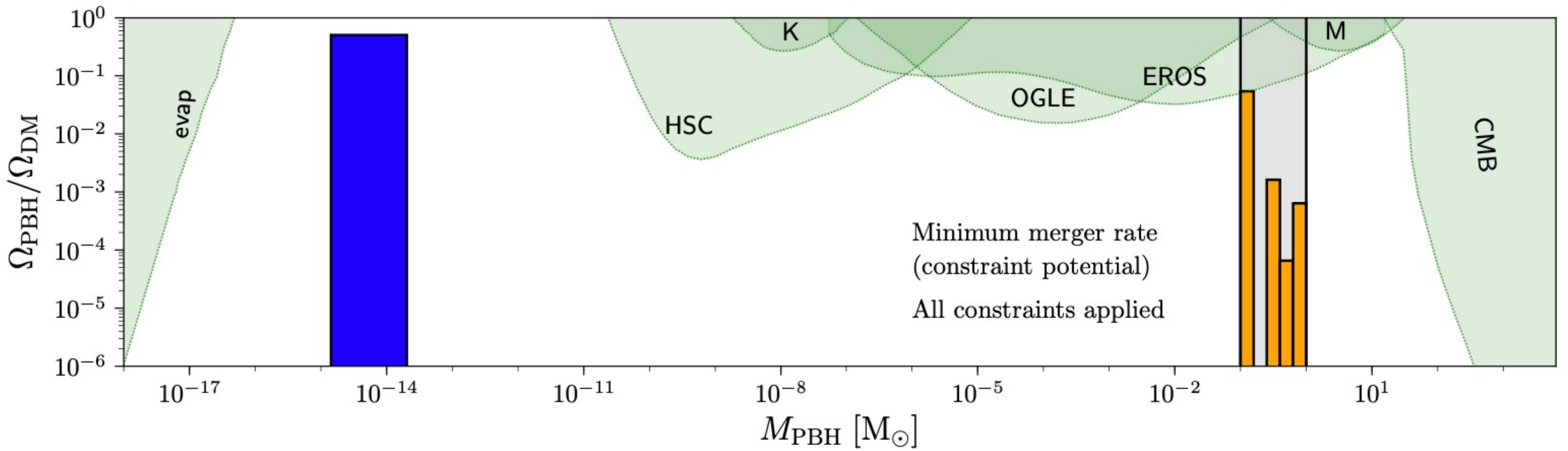
$$R_{\rm DP}(\psi) = \int_{\rm DP^2} {\rm d}m_1\, {\rm d}m_2\, \mathcal{R}(m_1, m_2) V_{\rm eff}(m_1, m_2),$$

2. Mass fraction of light+detectable BHs

$$r_{\rm DP} = \frac{1}{f_{\rm PBH}} \int_{m_{\rm DP}^{\rm min}}^{m_{\rm DP}^{\rm max}} {\rm d}m\, \psi(m).$$

We can numerically compute the maximal and minimal possible "goldilocks event rate"





* Lehmann, Profumo and Yant, MNRAS

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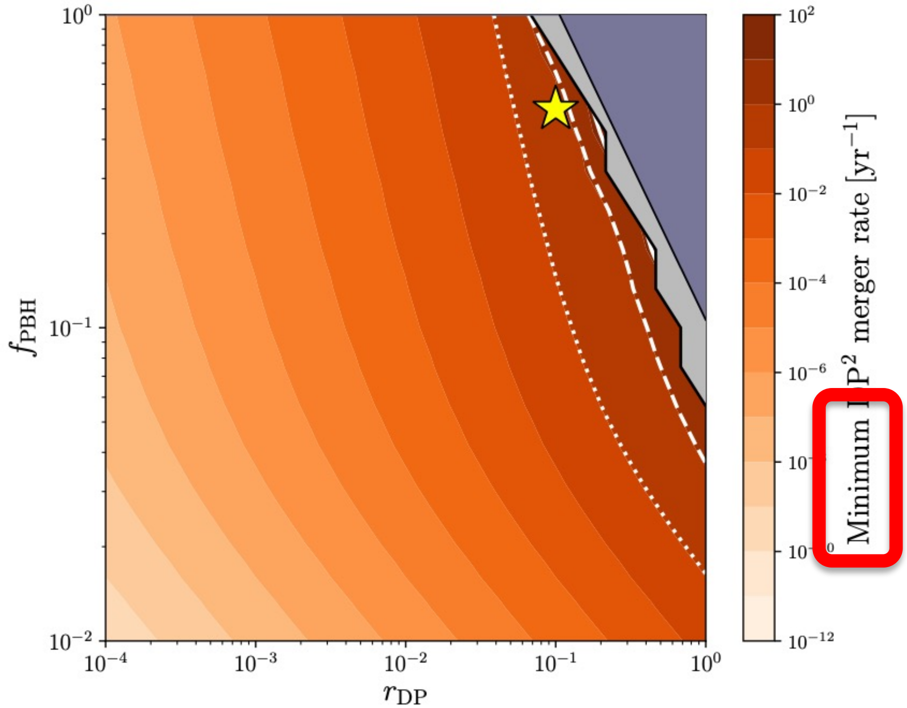
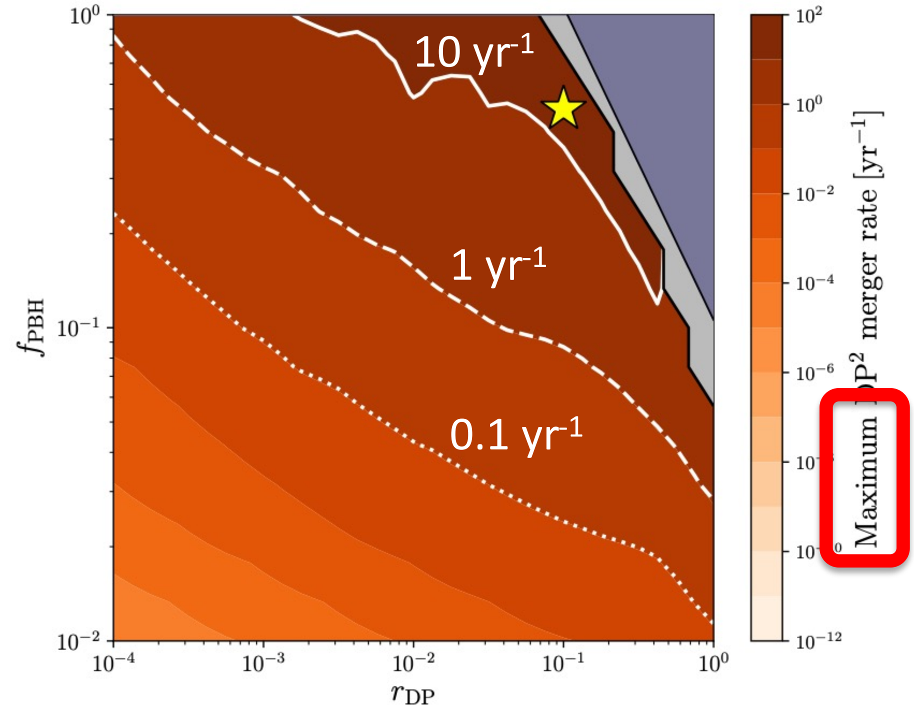
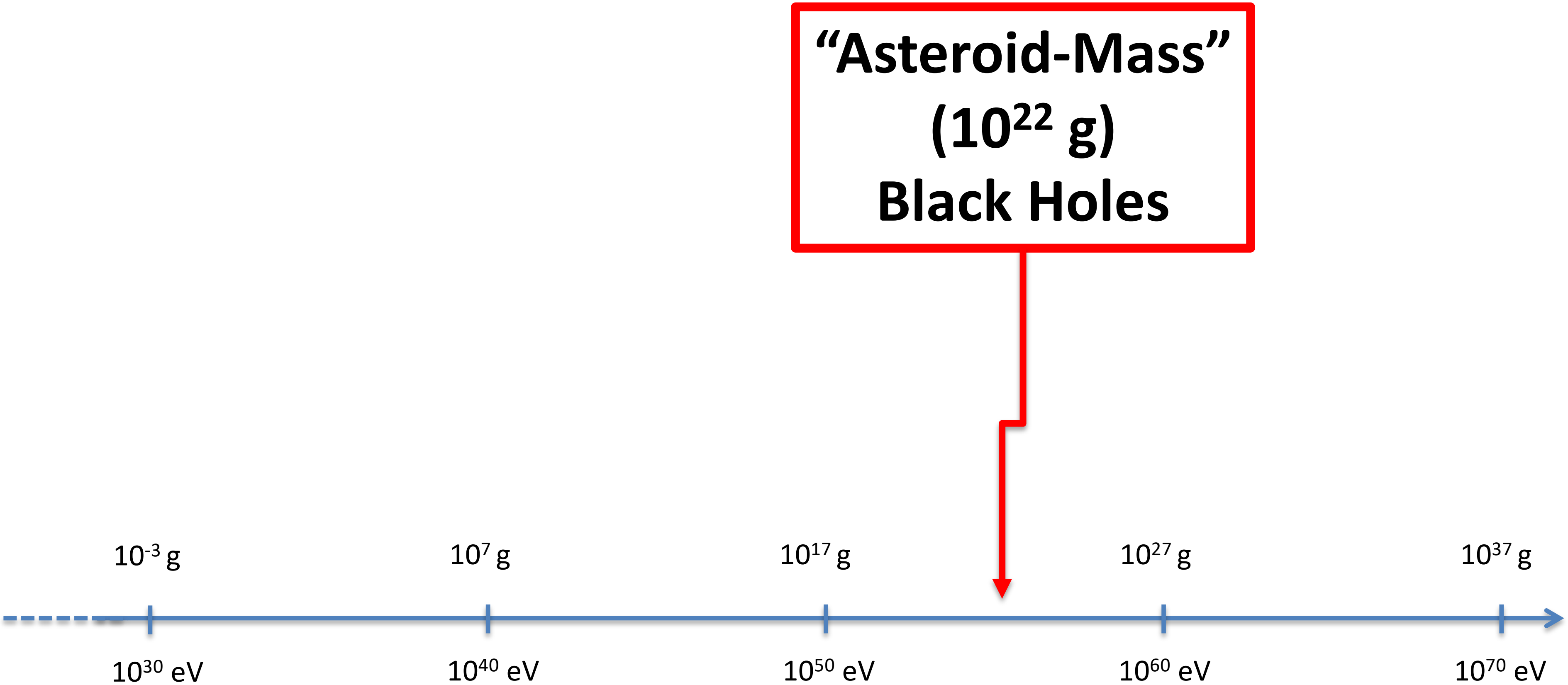




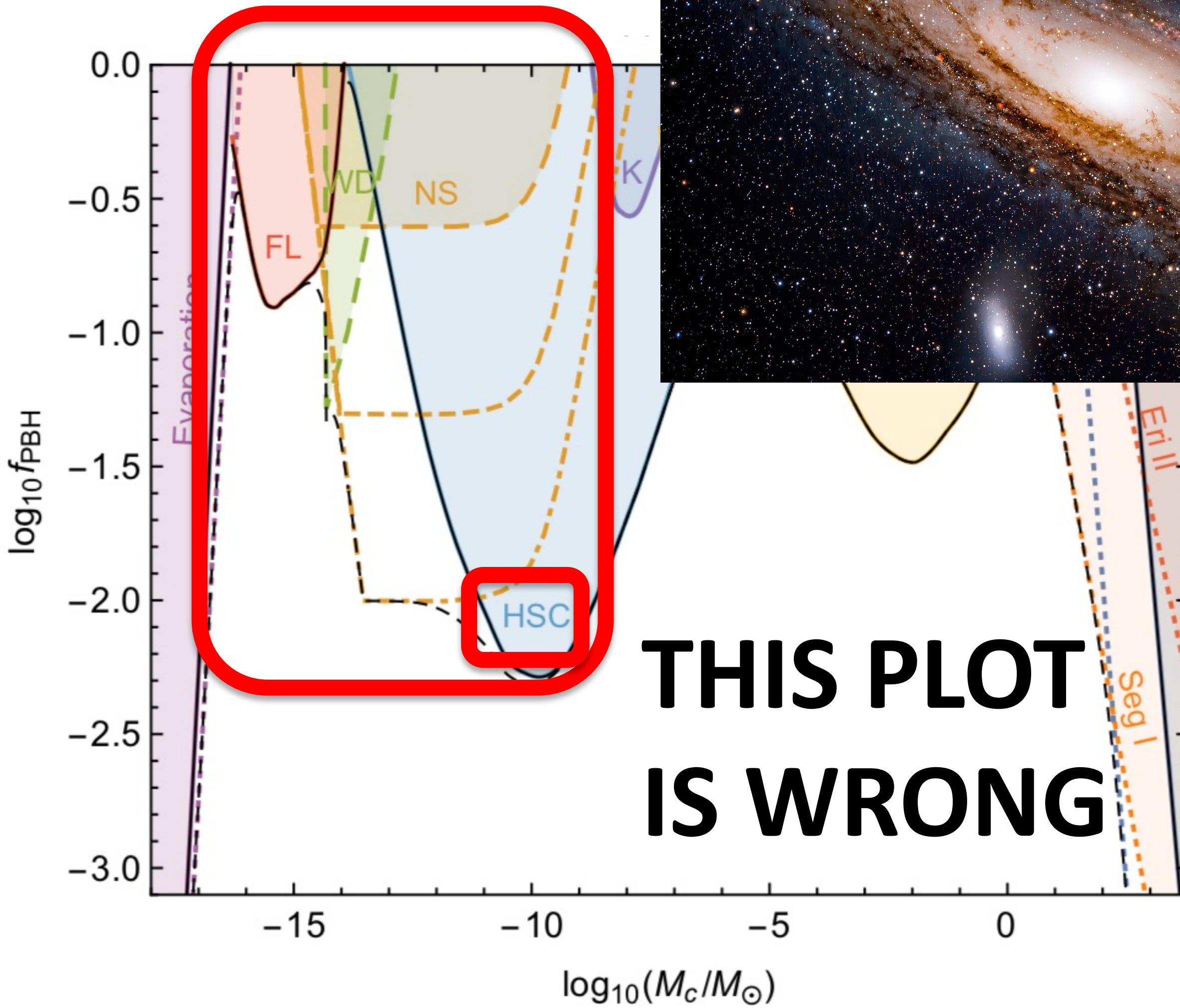
$$\int \mathrm{d}m\, \psi(m) = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} \equiv f_{\rm PBH}.$$

$$r_{\rm DP} = \frac{1}{f_{\rm PBH}} \int_{m_{\rm DP}^{\rm min}}^{m_{\rm DP}^{\rm max}} \mathrm{d}m\, \psi(m).$$

* Lehmann, Profumo and Yant, MNRAS

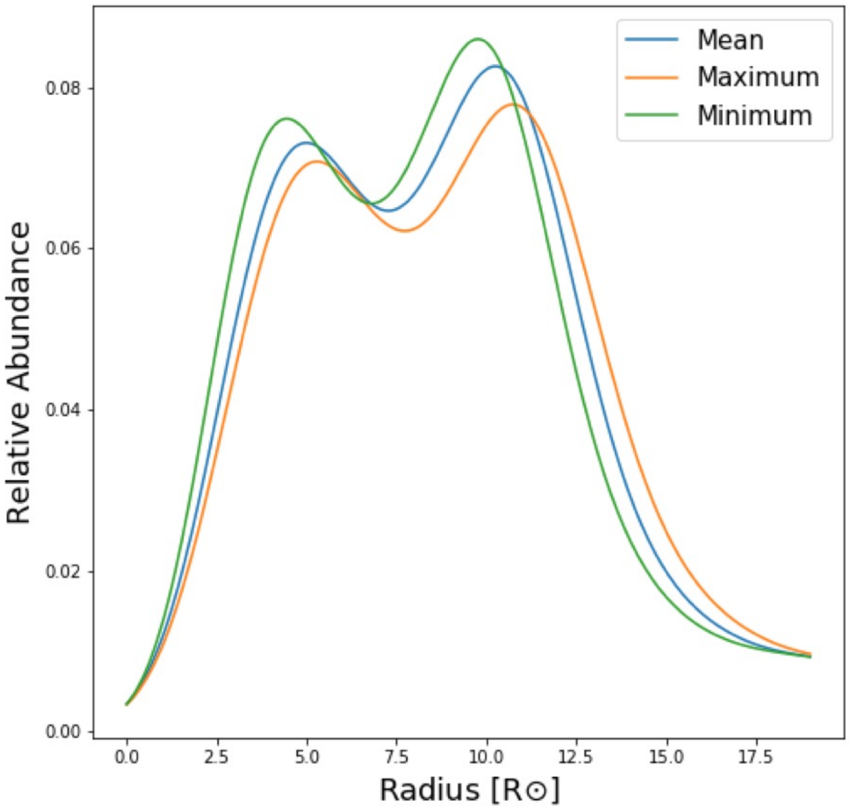


✓ **Microlensing a lot trickier than previously thought!**



THIS PLOT IS WRONG

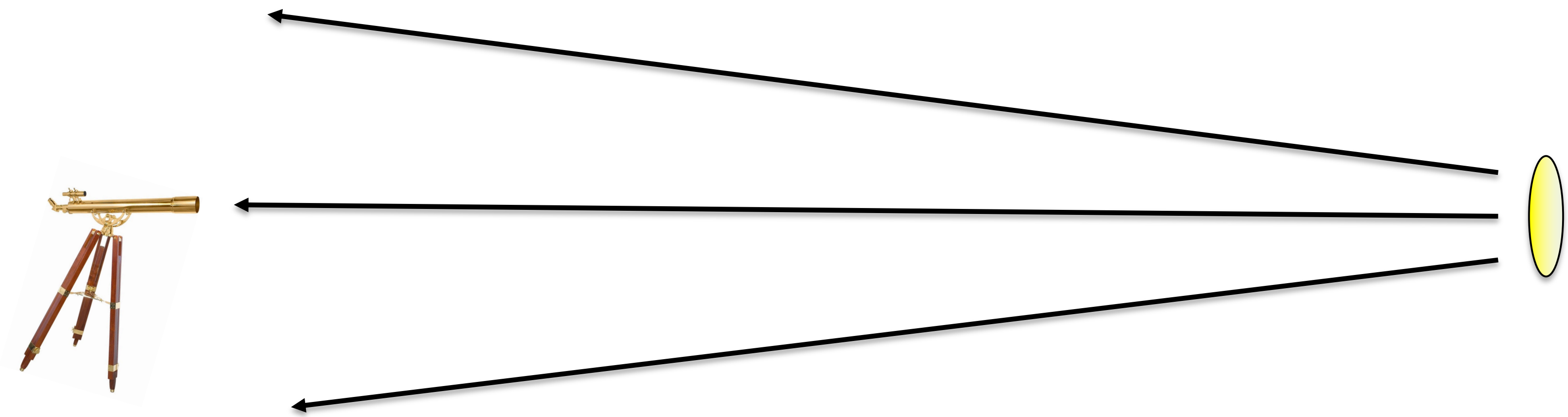
HSC study assumes all stars in M31 are Sun-like… but Sun-like stars are too dim for HSC!



Stars that contribute to the microlensing constraints are ~ 100x larger in the sky than the Sun!

* Profumo, Smyth+ PRD 2020

The bigger the star, the more important finite-source-size effects!



* Profumo, Smyth+ PRD 2020

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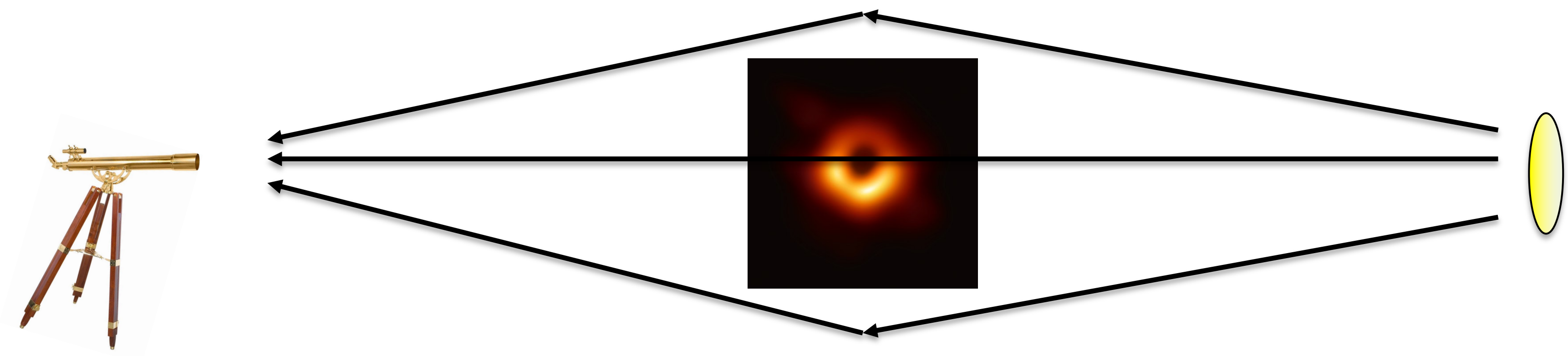

* Profumo, Smyth+ PRD 2020

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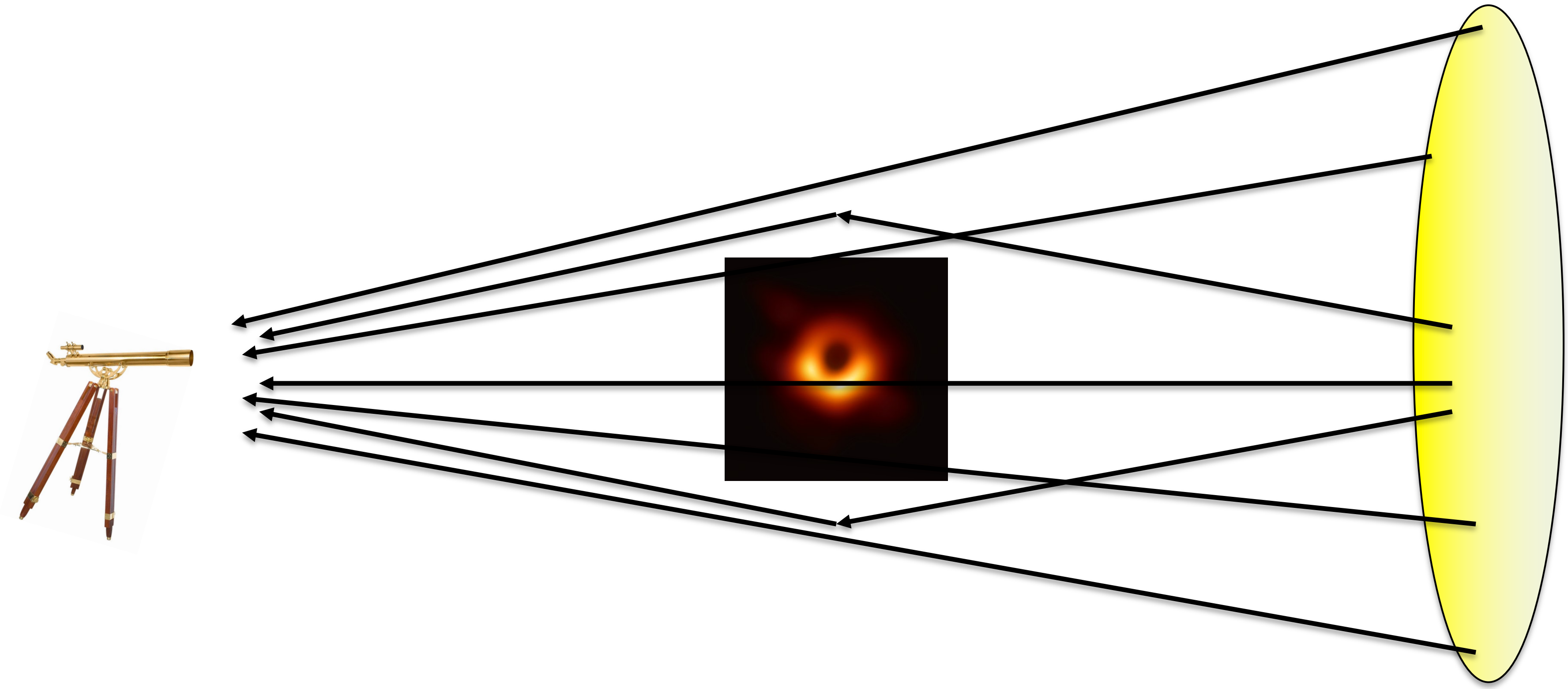
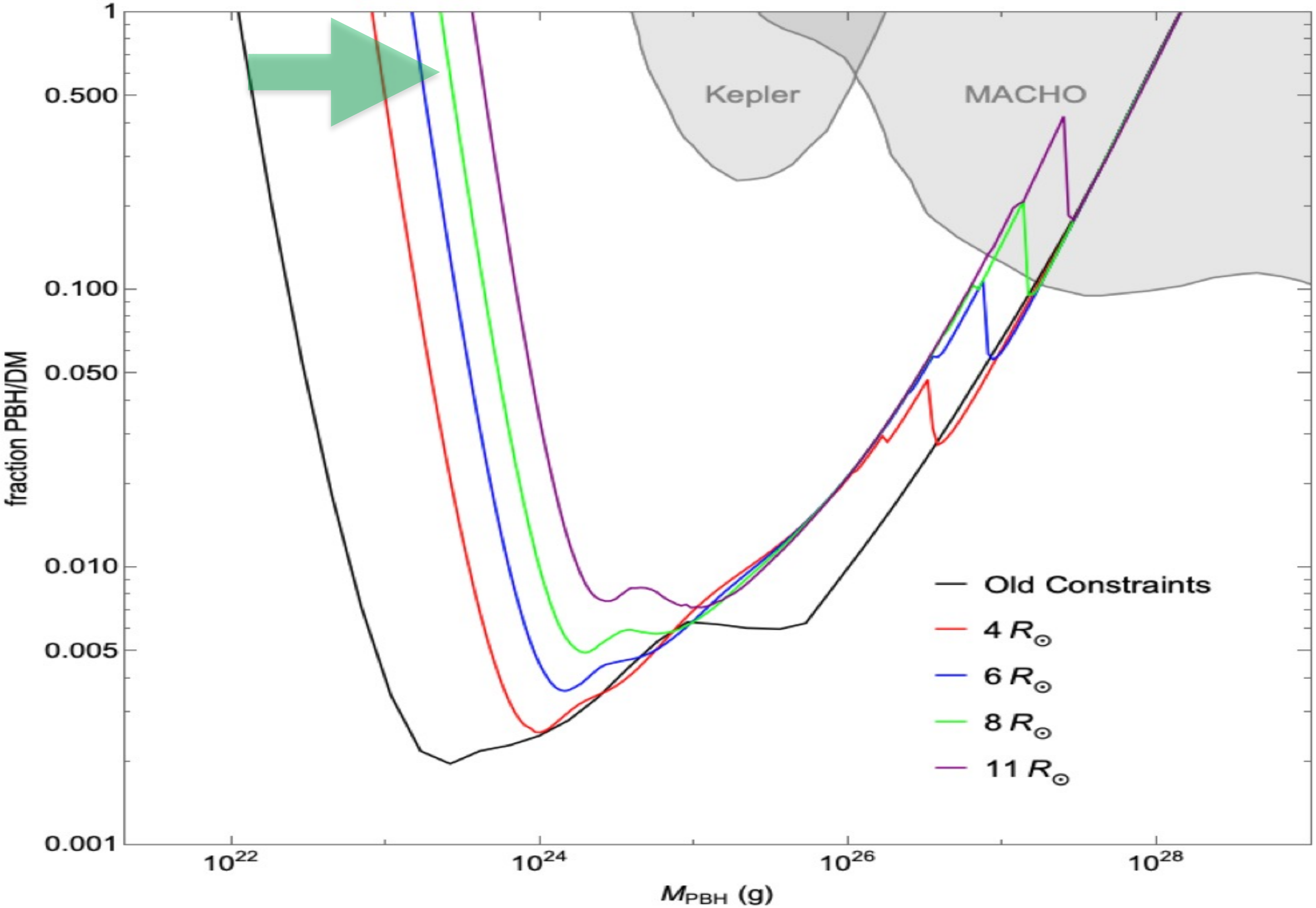
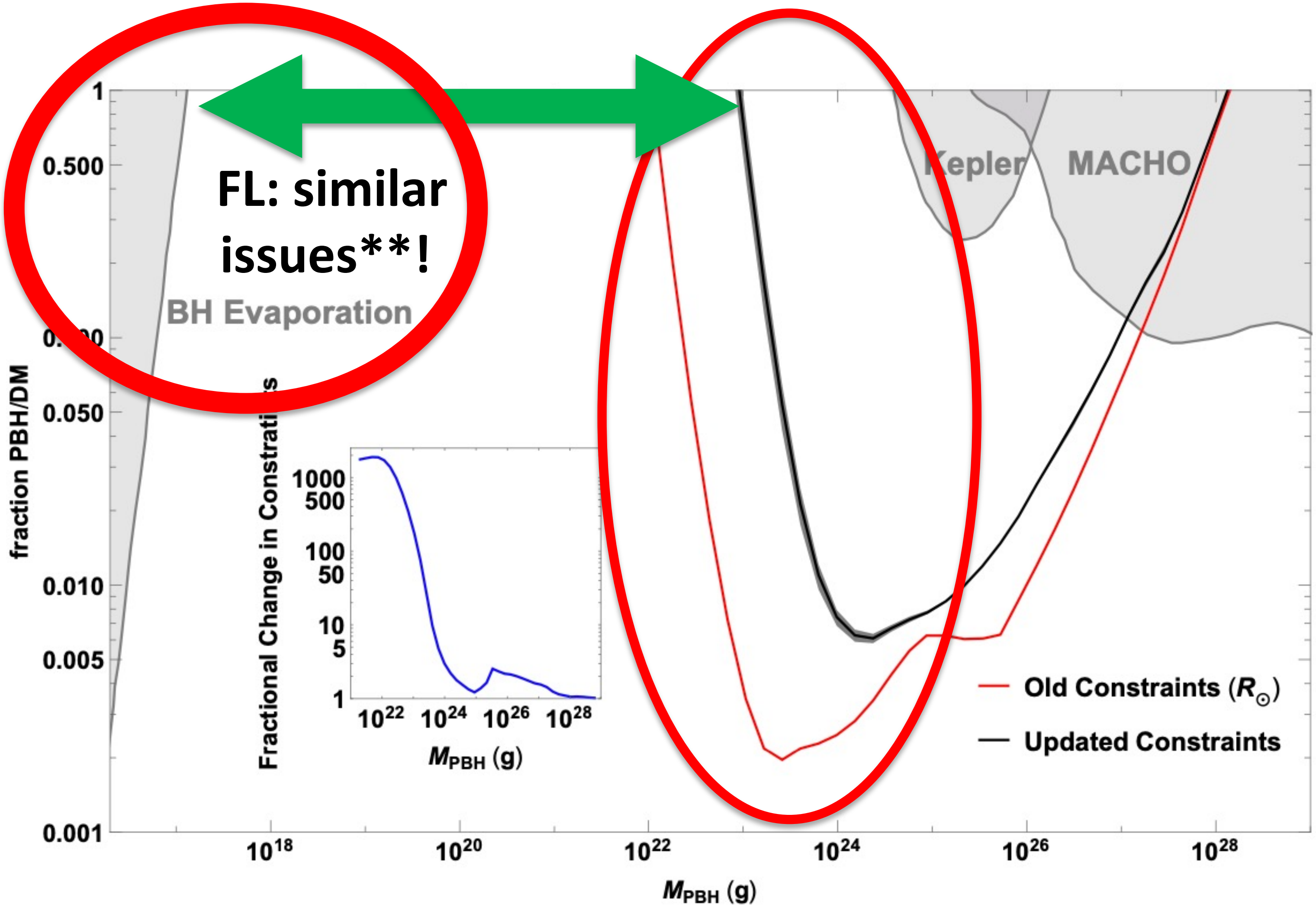


* Profumo, Smyth+ PRD 2020

The bigger the star, the more important finite-source-size effects!

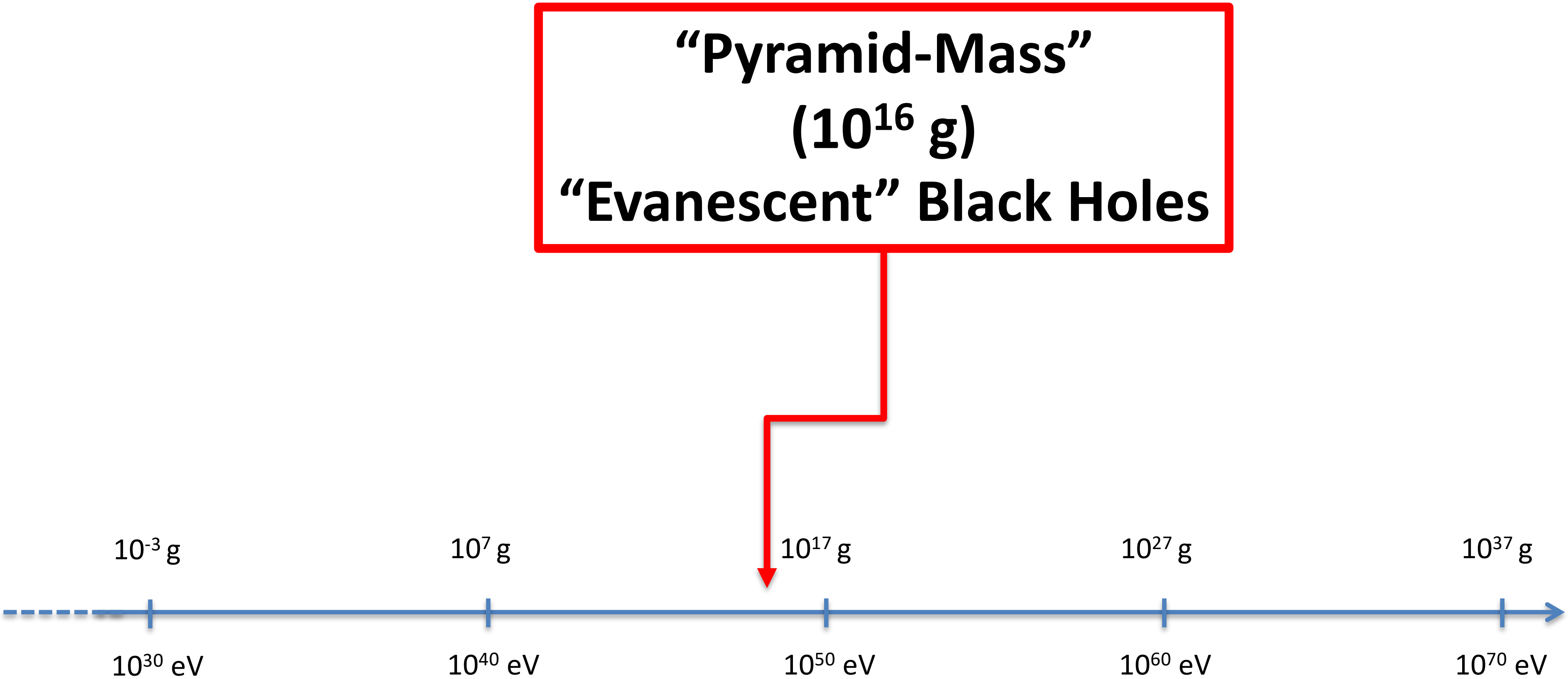


* Profumo, Smyth+ PRD 2020



How do we go after them? Capture and perturbation around PSR?

* Profumo, Smyth+ PRD 2020 ** Katz+ JCAP 2018

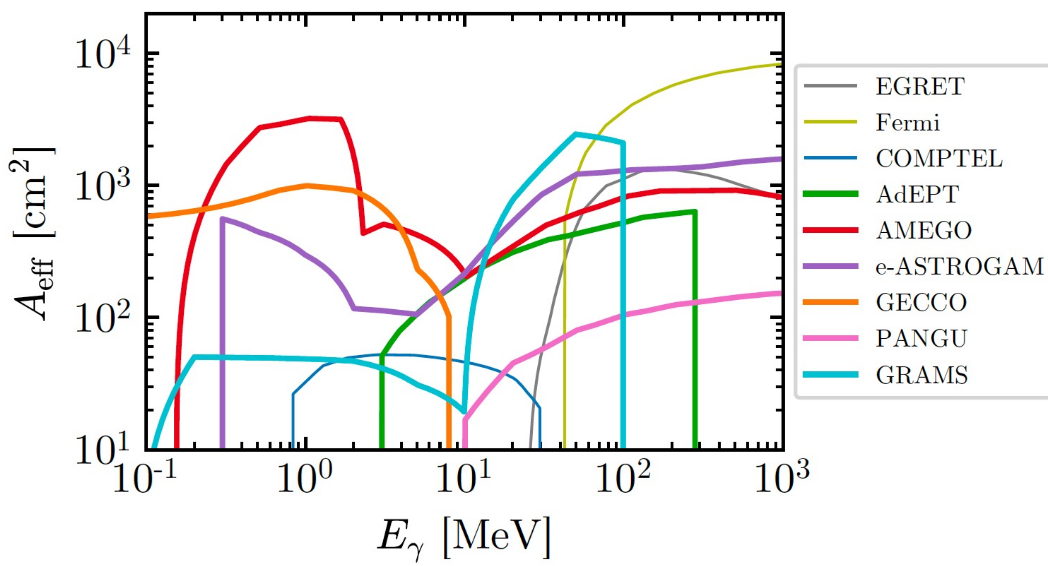


“Pyramid-Mass”
(10^16 g)
“Evanescent” Black Holes
10^-3 g
10^7 g
10^17 g
10^27 g
10^37 g
10^30 eV
10^40 eV
10^50 eV
10^60 eV
10^70 eV

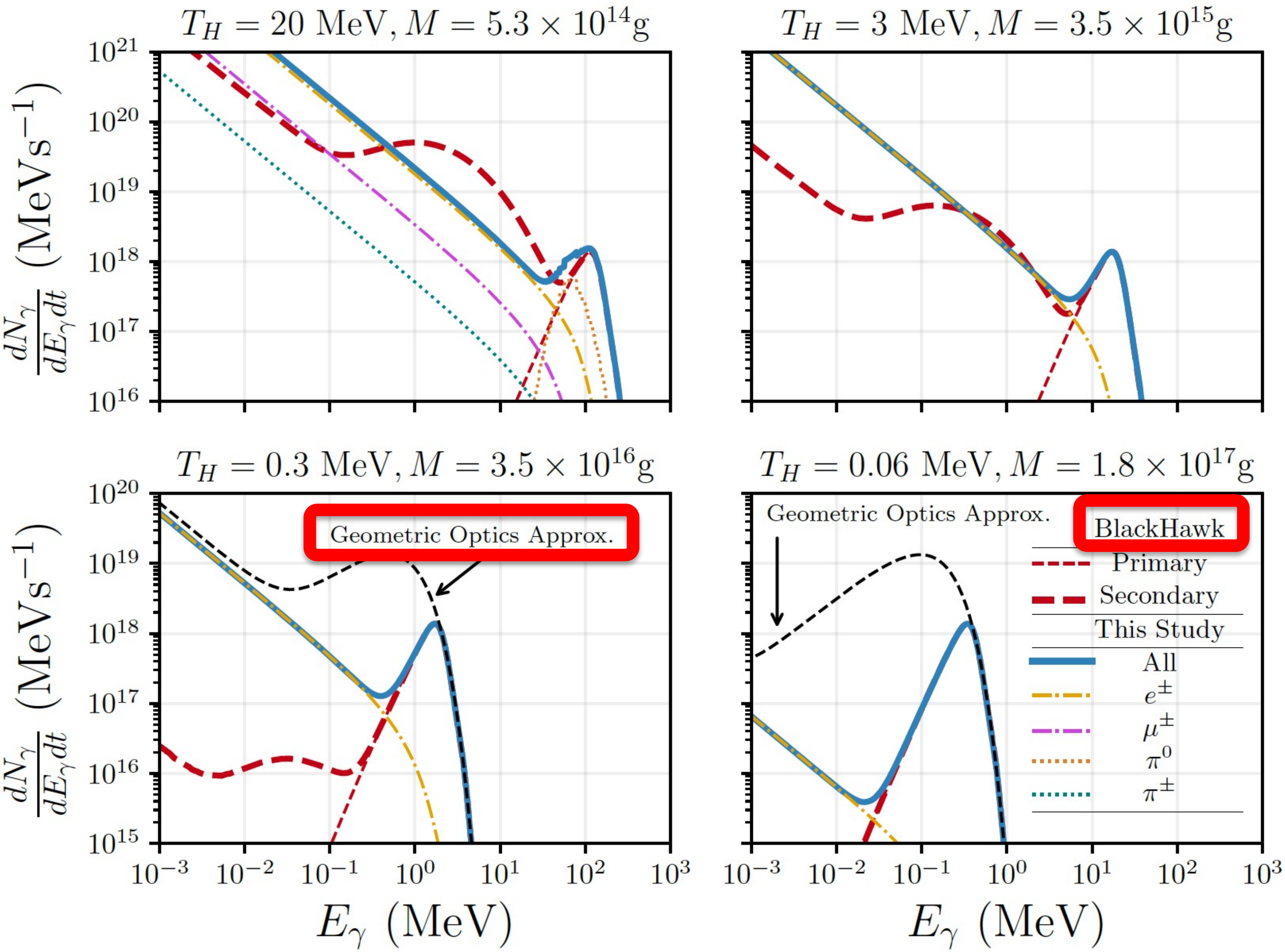
Lightest PBH that can be dark matter…

$$\tau(M) \simeq 200\ \tau_U \left(\frac{M}{10^{15}\ \mathrm{g}}\right)^3 \simeq 200\ \tau_U \left(\frac{10\ \mathrm{MeV}}{T_H}\right)^3$$

- are ~ asteroid/comet/PYRAMID mass
- can't be much hotter than 10 MeV

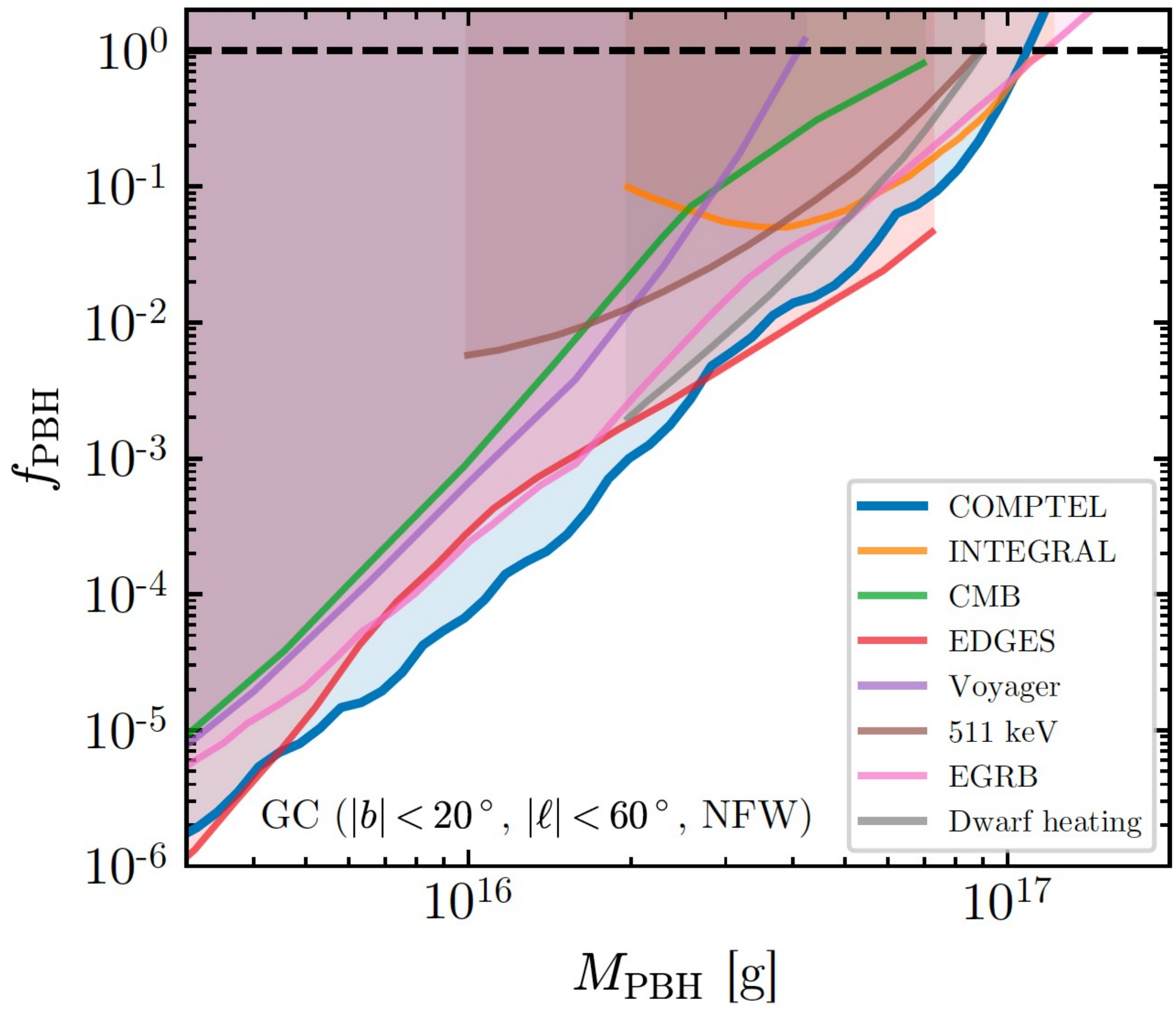


Coogan, Morrison & Profumo, 2010.04797



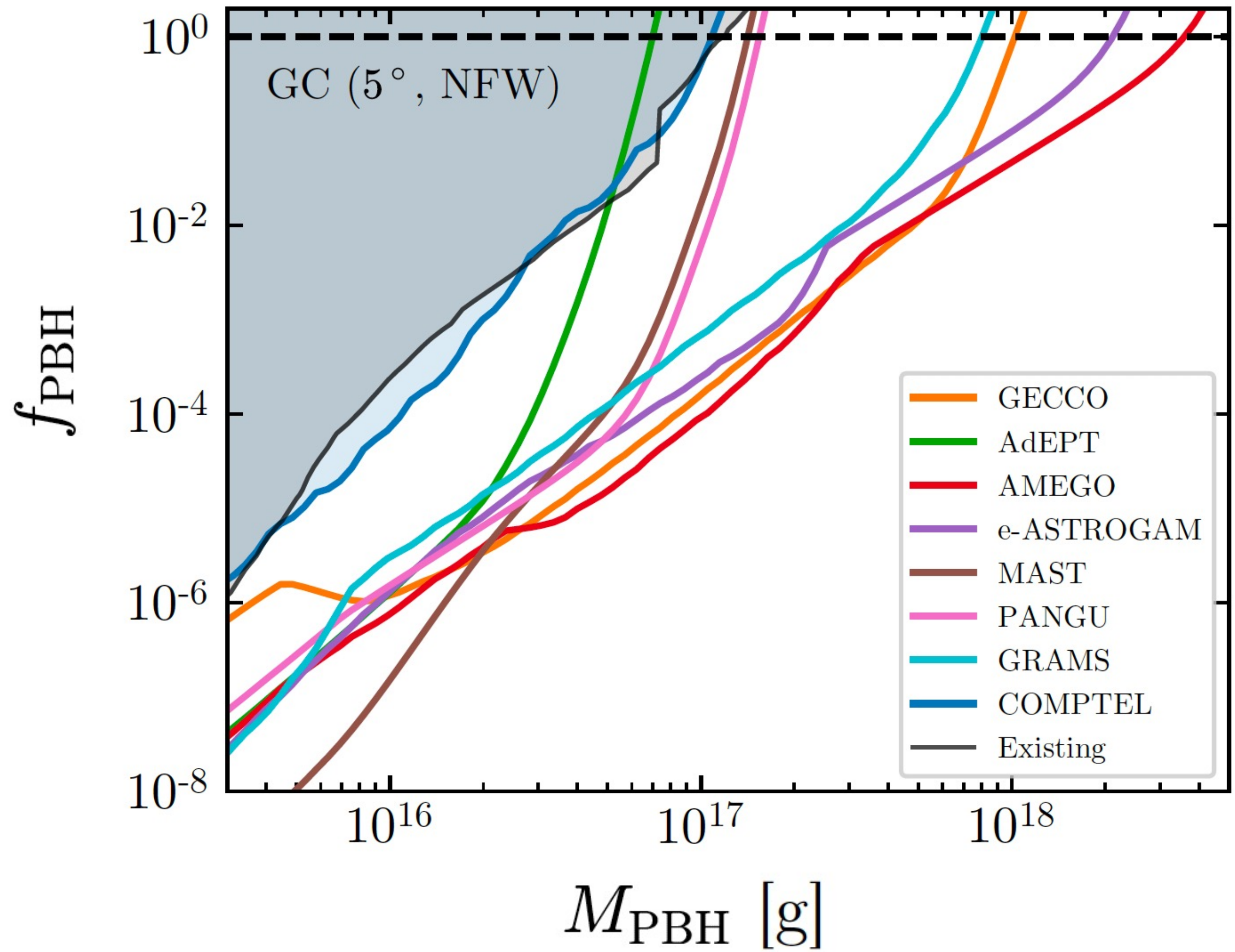
Coogan, Morrison & Profumo, 2010.04797

Our new COMPTEL constraints are among strongest/robust



Coogan, Morrison & Profumo, 2010.04797

New MeV Telescopes could discover Hawking evaporation!



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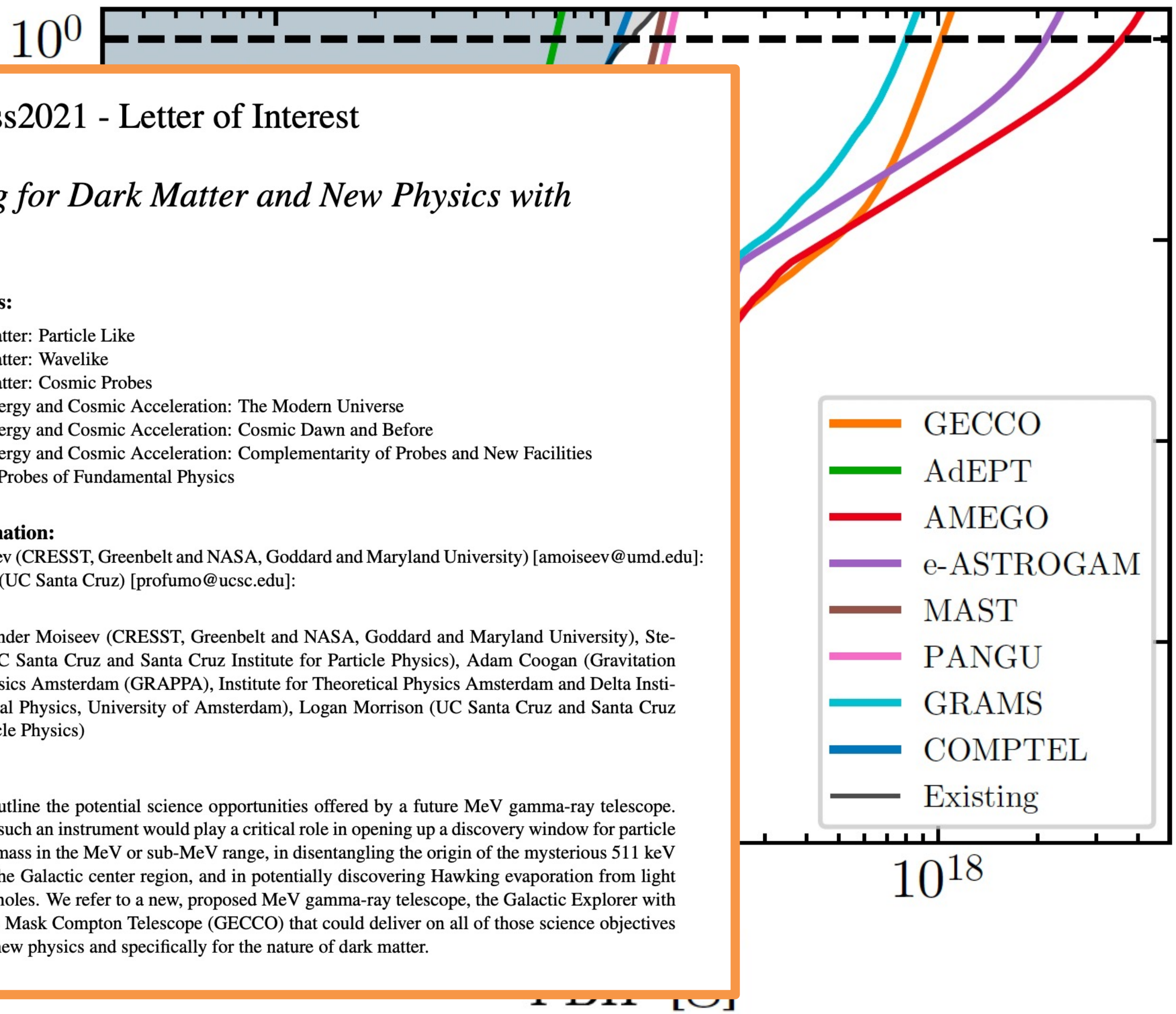

Snowmass2021 - Letter of Interest

Searching for Dark Matter and New Physics with GECCO

Thematic Areas:

■ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics

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Stefano Profumo (UC Santa Cruz) [profumo@ucsc.edu]:

Authors: Alexander Moiseev (CRESST, Greenbelt and NASA, Goddard and Maryland University), Stefano Profumo (UC Santa Cruz and Santa Cruz Institute for Particle Physics), Adam Coogan (Gravitation Astroparticle Physics Amsterdam (GRAPPA), Institute for Theoretical Physics Amsterdam and Delta Institute for Theoretical Physics, University of Amsterdam), Logan Morrison (UC Santa Cruz and Santa Cruz Institute for Particle Physics)

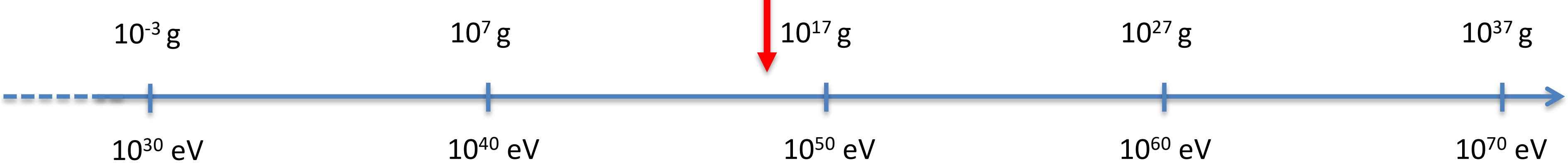
Abstract: We outline the potential science opportunities offered by a future MeV gamma-ray telescope. We point out that such an instrument would play a critical role in opening up a discovery window for particle dark matter with mass in the MeV or sub-MeV range, in disentangling the origin of the mysterious 511 keV line emission in the Galactic center region, and in potentially discovering Hawking evaporation from light primordial black holes. We refer to a new, proposed MeV gamma-ray telescope, the Galactic Explorer with a Coded Aperture Mask Compton Telescope (GECCO) that could deliver on all of those science objectives in the search for new physics and specifically for the nature of dark matter.

Coogan, Morrison & Profumo, 2010.04797

“Pyramid-Mass”

(10^{16} g)

“Evanescent” Black Holes

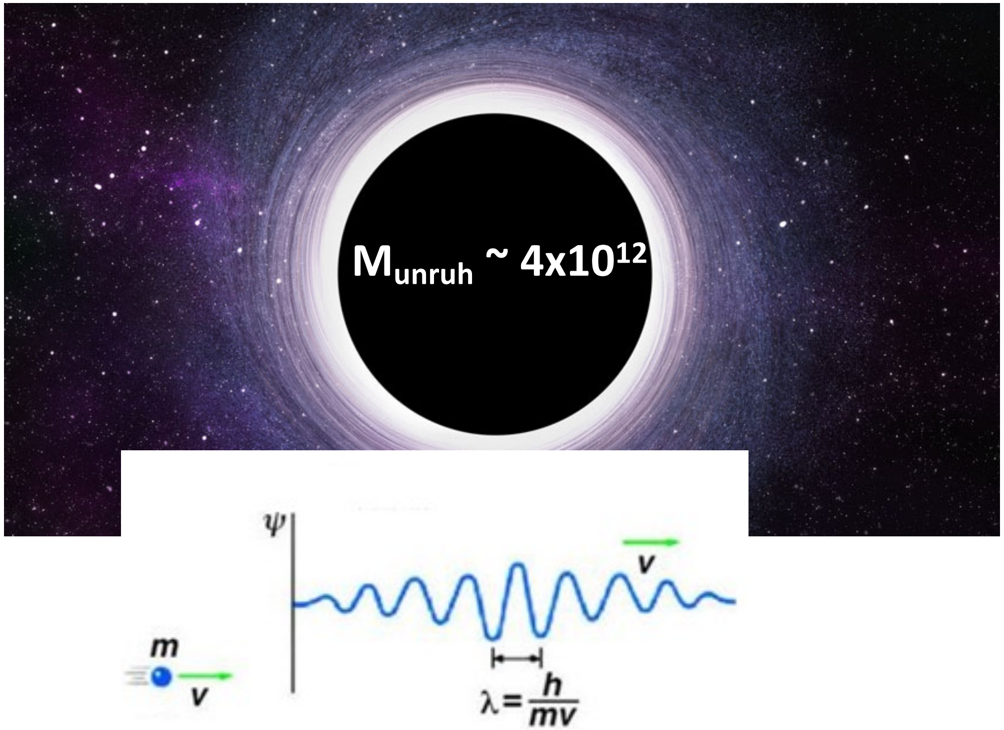


- ✓ **Best constraints: COMPTEL**
- ✓ **Future MeV telescopes**
- ✓ **NS quantum death!**

Hot off the press!!

Neutron Star Quantum Death by Small black holes

Bondi spherical fluid accretion breaks down if the accreting black hole has size ~ neutron de Broglie wavelength!



Giffin, Lloyd, McDermott & Profumo, 2105.06504, PRL submitted

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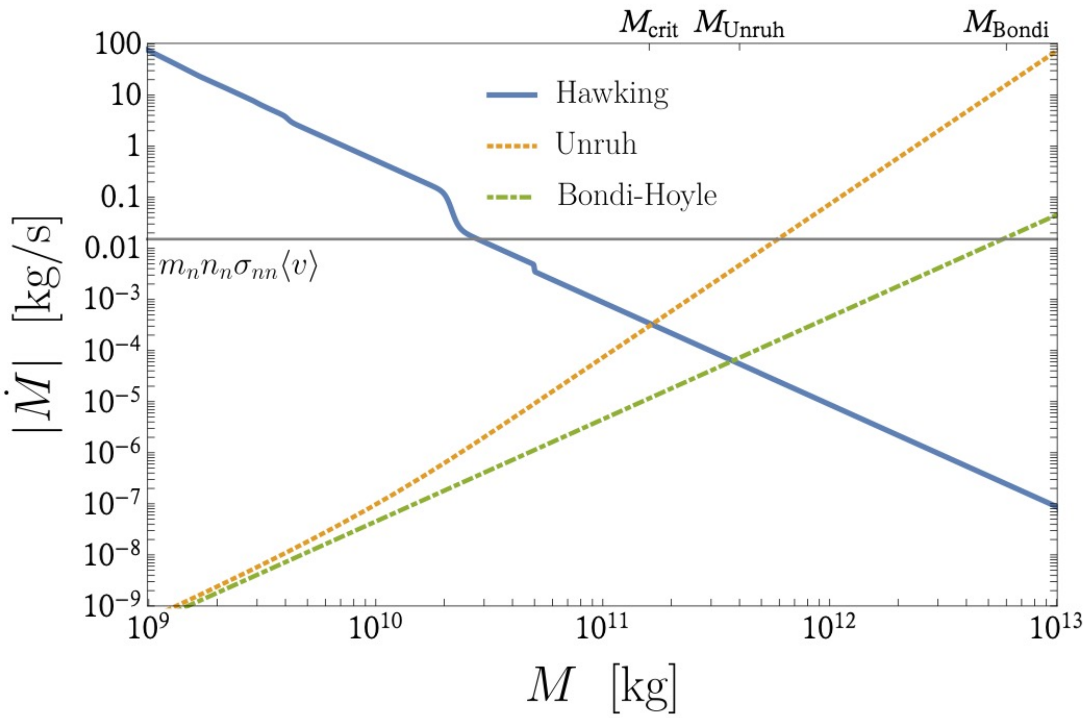
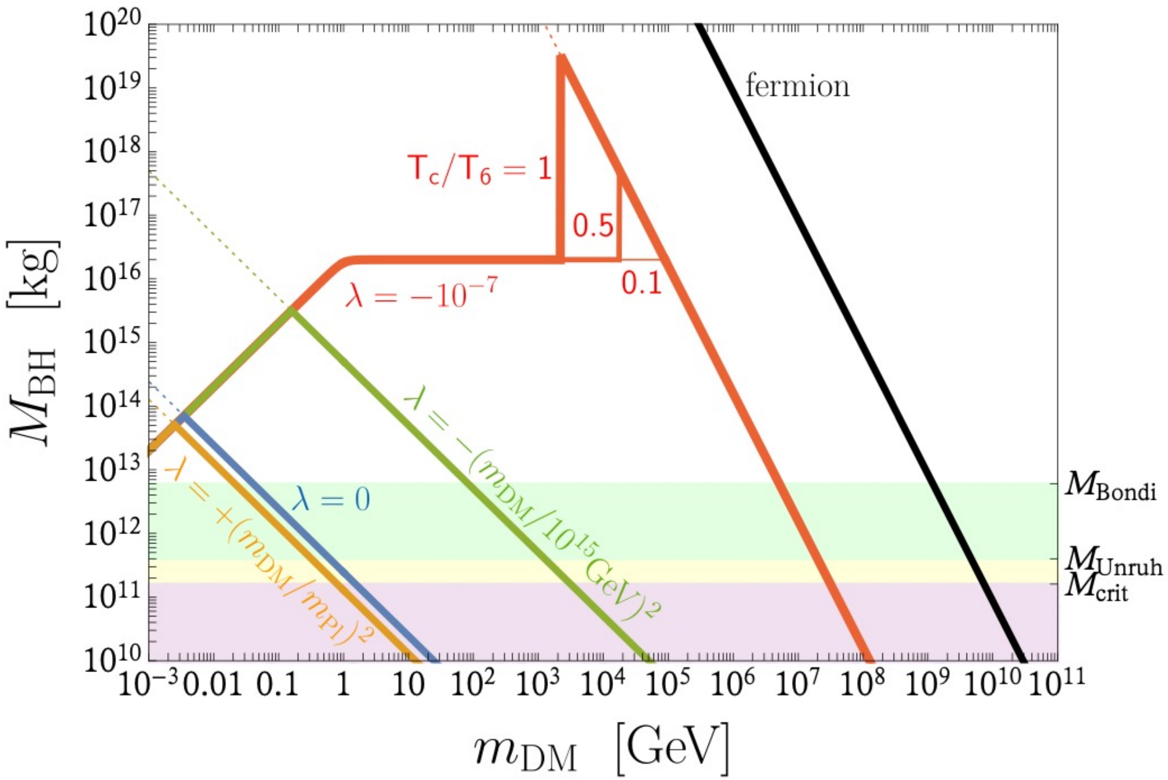


Giffin, Lloyd, McDermott & Profumo, 2105.06504, PRL submitted

Hot off the press!!

Neutron Star Quantum Death by Small black holes

The initial size of the black hole in a NS depends on the dark matter spin/mass/interaction properties



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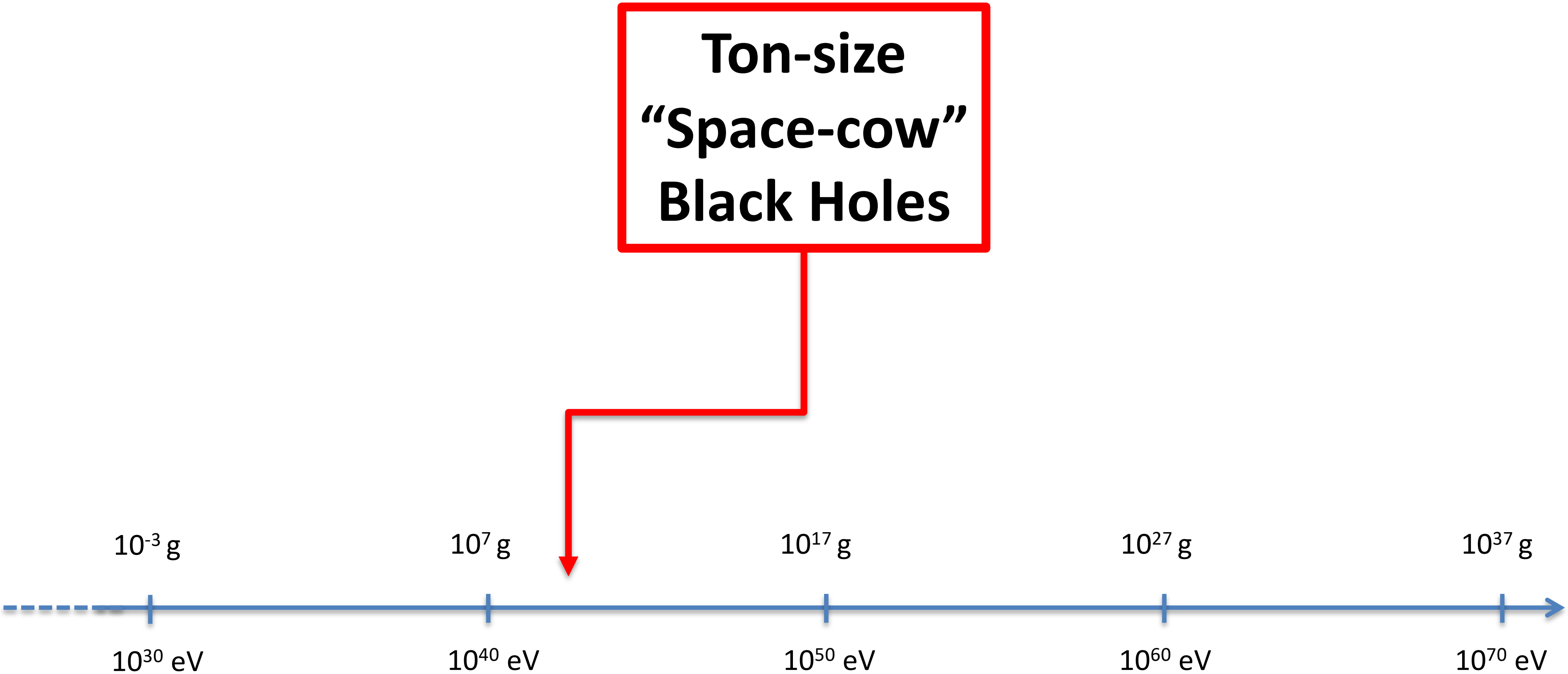


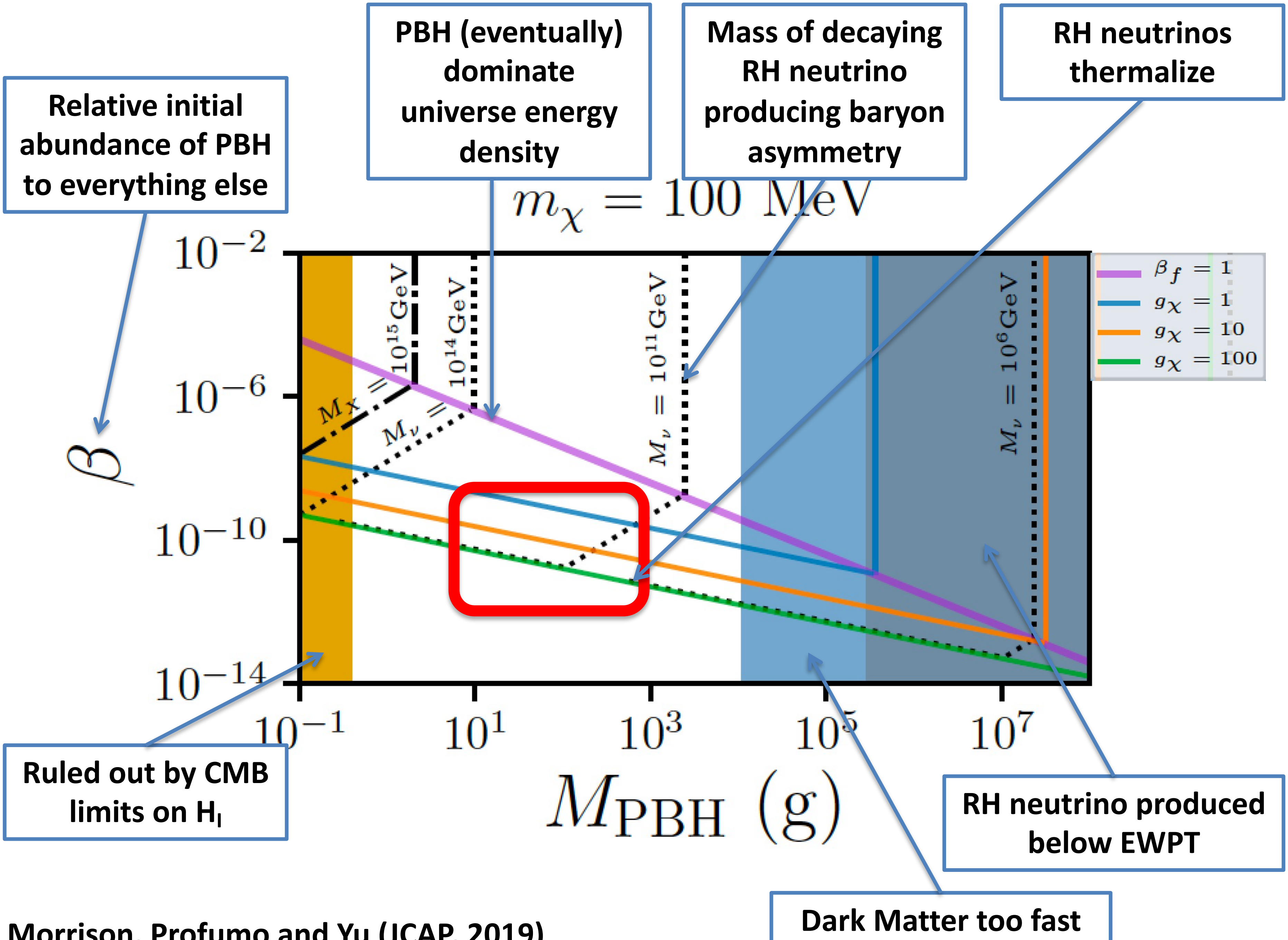
Ton-size
“Space-cow”
Black Holes
10-3 g
10^7 g
10^17 g
10^27 g
10^37 g
10^30 eV
10^40 eV
10^50 eV
10^60 eV
10^70 eV

…even if PBH are NOT the dark matter, they can PRODUCE the dark matter via Hawking evaporation!

Mass (g)	T_H (GeV)	τ (s)	$T_{\rm evap} = T(\tau)$ (GeV)
$5M_P \simeq 10^{-4}$	1.7×10^{17}	10^{-41}	2×10^{17}
1	1.7×10^{13}	4×10^{-29}	2×10^{11}
10^3	1.7×10^{10}	4×10^{-20}	6×10^6
10^6	1.7×10^7	4×10^{-11}	200
10^9	1.7×10^4	0.04	0.006
10^{12}	17	$4 \times 10^7 \sim 1$ yr	~ 1 keV

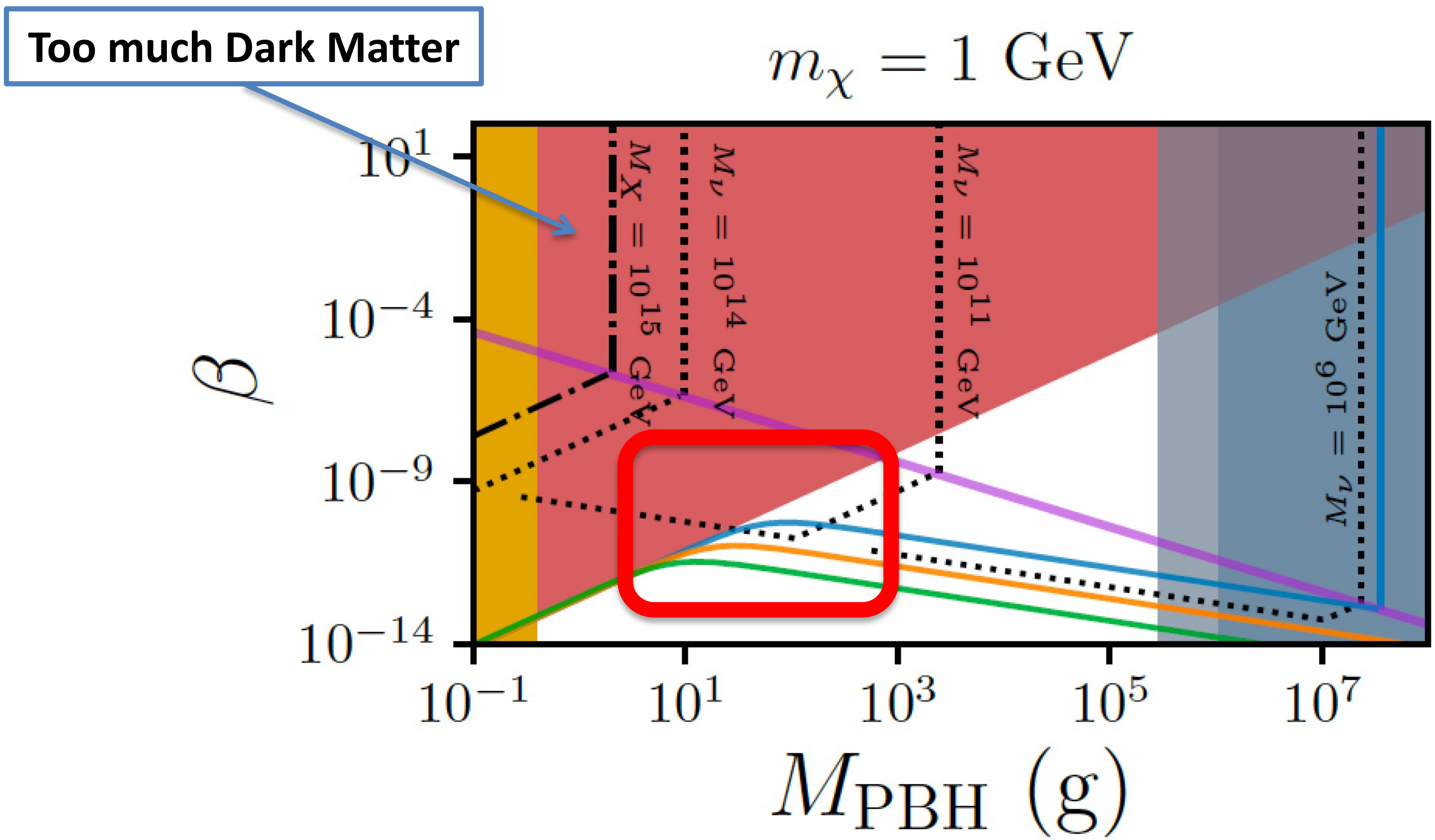
ruled out by BBN (more on that later!)

* Morrison, Profumo and Yu (JCAP, 2019)



* Morrison, Profumo and Yu (JCAP, 2019)

Dark Matter can be a mix of Planck-scale relics from PBH evaporation, and stuff the PBH evaporated into!



* Morrison, Profumo and Yu (JCAP, 2019)

As BH approach the Planck scale, they can acquire a significant relic electric charge

(under simple assumptions) the relic charge is approximately Gaussian*

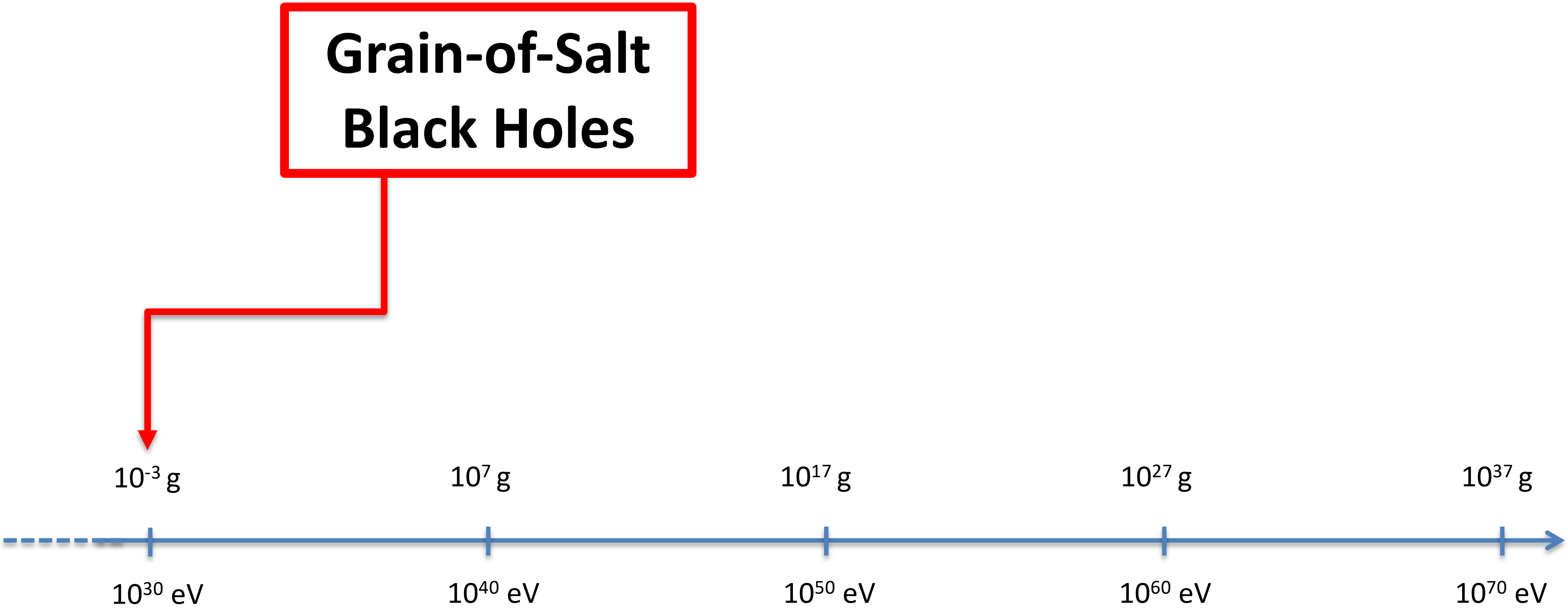
$$P(Q) \sim \exp\left(-4\pi\alpha(Q/e)^2\right)$$

$$(8\pi\alpha)^{-1/2} \approx 2.34$$

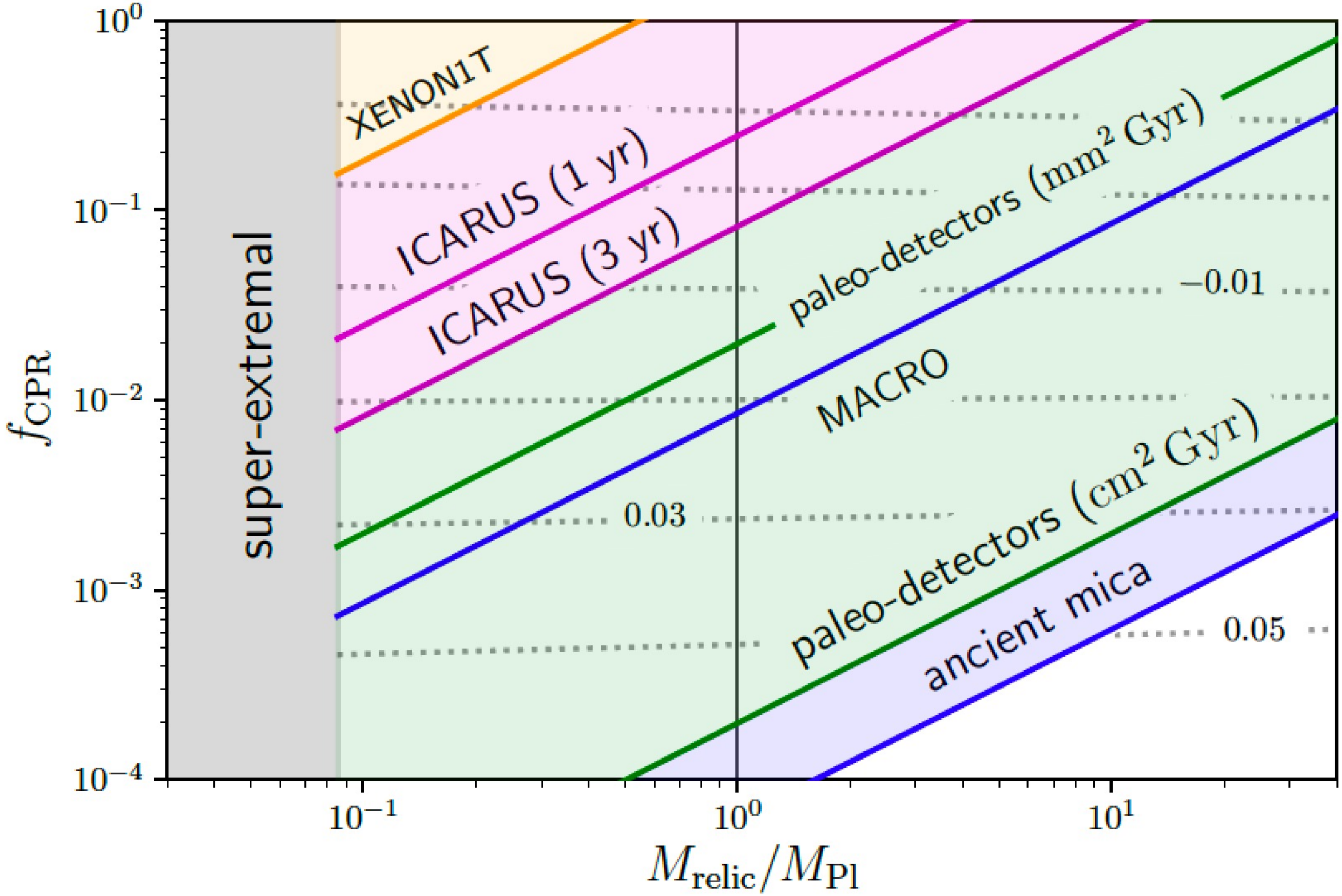
If evaporation stops around the Planck scale (because of extremality, or because of quantum gravity) we are left with a population of charged, Planck-scale relics!

* Page, 1977

** Lehmann, Johnson, Profumo and Schwemberger, 1906.06348 (JCAP10(2019)046)



Grain-of-Salt Black Holes
10^{-3} g
10^{7} g
10^{17} g
10^{27} g
10^{37} g
10^{30} eV
10^{40} eV
10^{50} eV
10^{60} eV
10^{70} eV



*** Lehmann, Johnson, Profumo and Schwemberger, 1906.06348 (JCAP10(2019)046)**

Hawking-Radiation Recoil of Microscopic Black Holes

Samuel Kováčik [1]

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Abstract

The Hawking radiation wou
black holes evaporate rapidly
from many astrophysical con
it has been argued that the
space would alter this behavi
of a Planck-size black hole
left behind is a Planck-mass
section on the order of 10^{-70}
detection nearly impossible. Such black hole remnants have been identified as possible dark matter candidates. Here we argue that the final stage of the evaporation has a recoil effect which would give the microscopic black hole velocity on the order of $10^{-1}c$ which is in disagreement with the cold dark matter cosmological model.

of the striking difference compared to the ordinary black hole theory is that the Hawking temperature [9] defined to be proportional to the surface gravity at the horizon does not grow indefinitely but instead drops to zero at small but positive mass, resulting in a microscopic black hole remnant.

Black holes remnants have been considered as

Black hole remnants are not too fast to be dark matter

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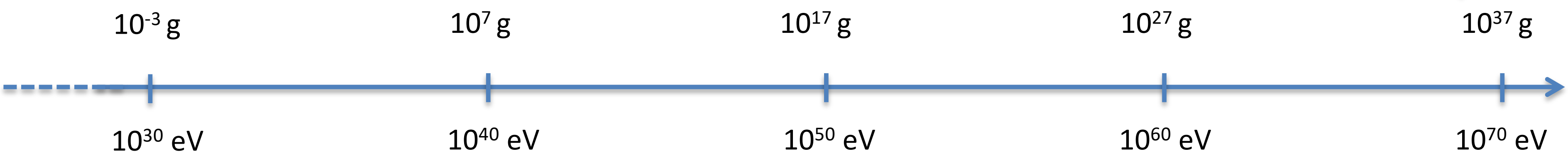
We comment on recent claims that recoil in the final stages of Hawking evaporation gives black hole remnants large velocities, rendering them inviable as a dark matter candidate. We point out that due to cosmic expansion, such large velocities at the final stages of evaporation are not in tension with the cold dark matter paradigm so long as they are attained at sufficiently early times. In particular, the predicted recoil velocities are robustly compatible with observations if the remnants form before the epoch of big bang nucleosynthesis, a requirement which is already imposed by the physics of nucleosynthesis itself.

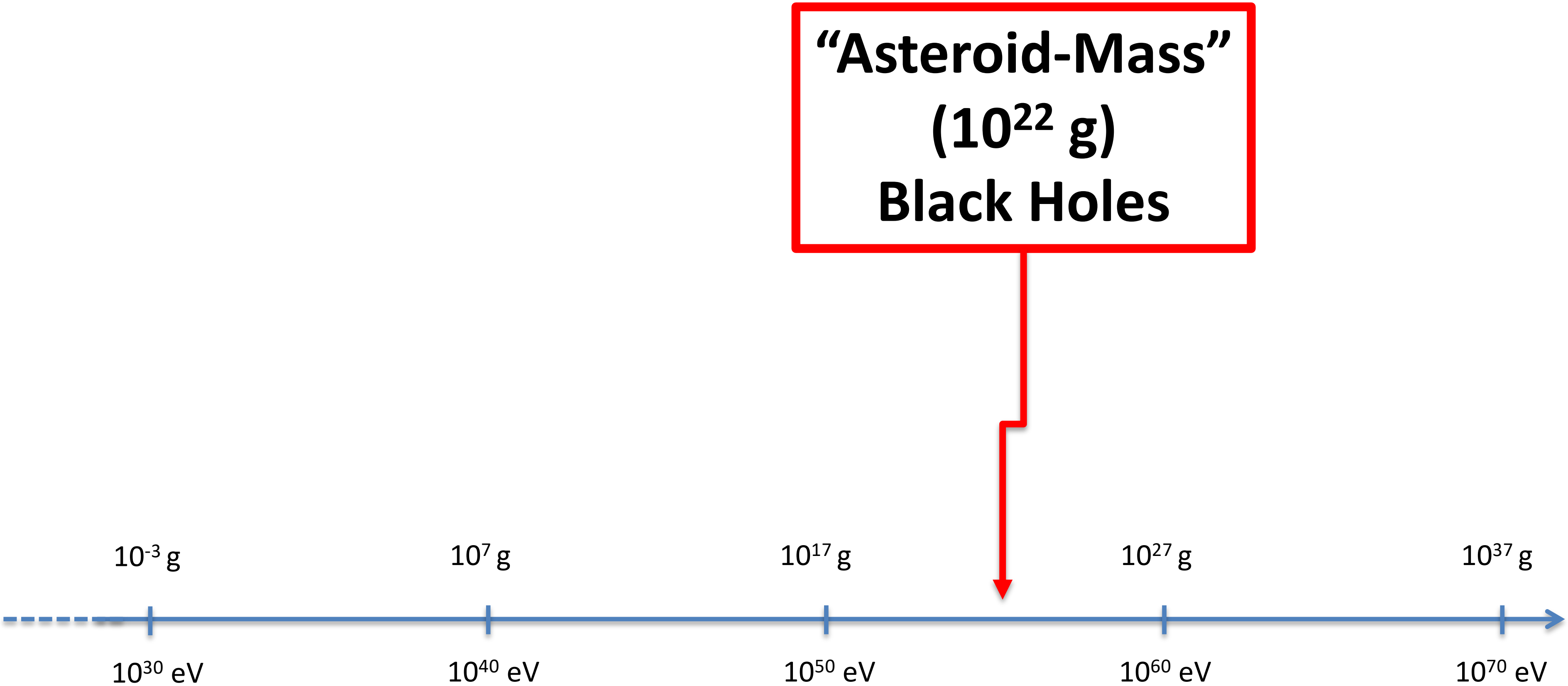
...true only if evaporation stops very late (much later than BBN), which cannot happen!

*** Lehmann and Profumo, 2105.01627**

“Stellar-Mass” (10^{35} g) Black Holes

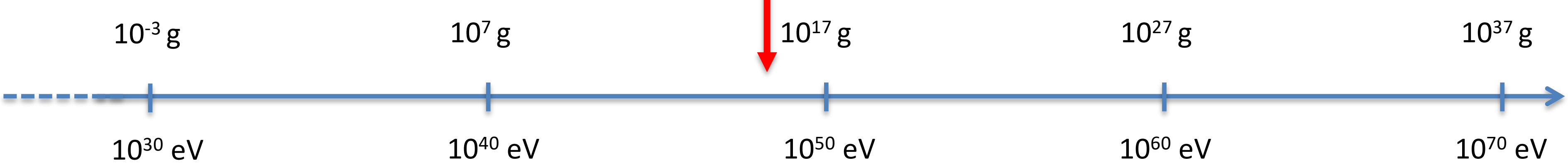


- ✓ **Spins look a lot like PBH!**
- ✓ **…or maybe they are low because of superradiance?**
- ✓ **Sub-Chandrasekhar goldilocks!!**

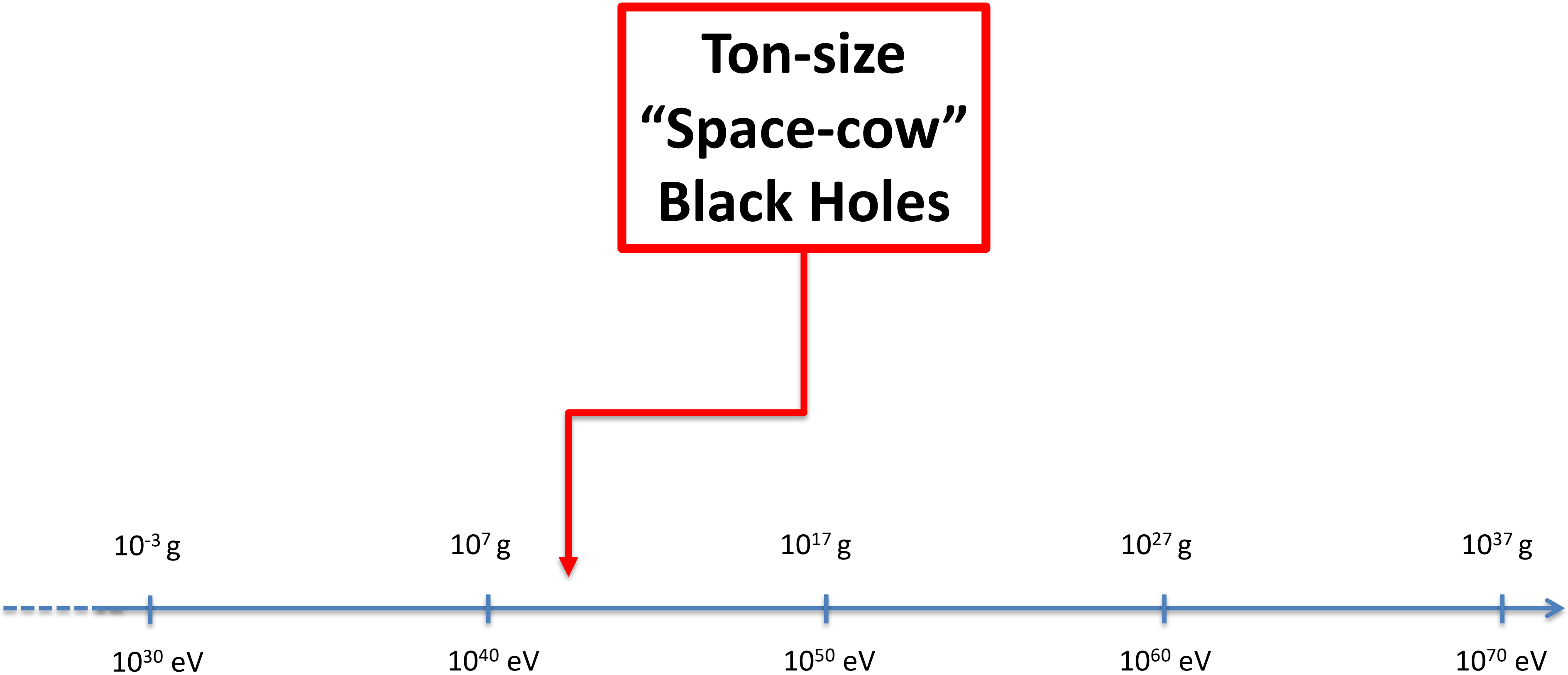


✓ **Microlensing a lot trickier than previously thought!**

“Pyramid-Mass”
(10^{16} g)
“Evanescent” Black Holes

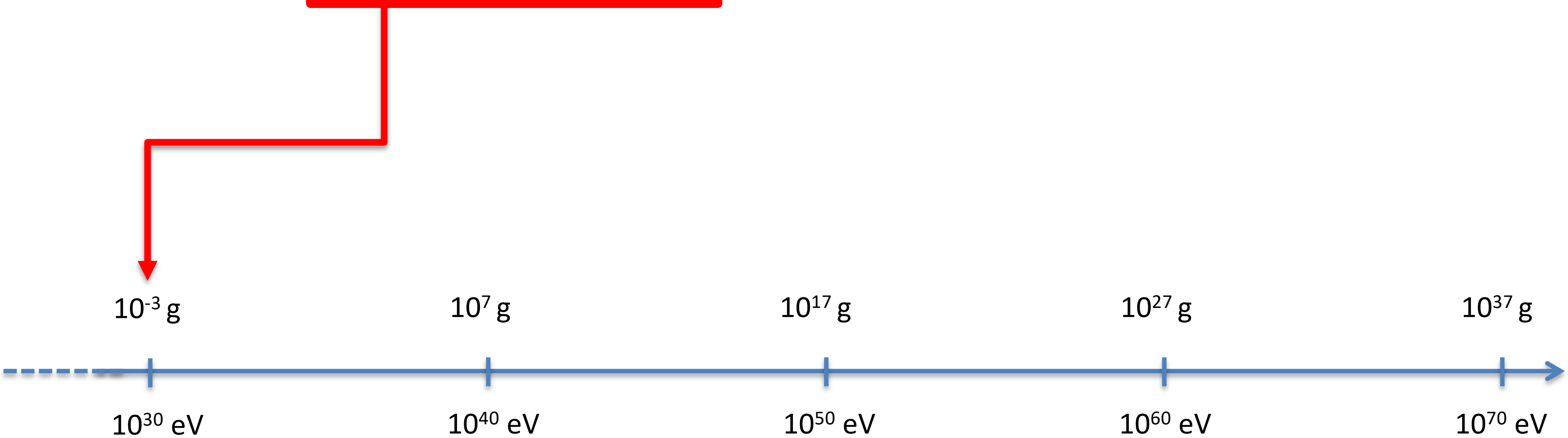


- ✓ **Best constraints: COMPTEL**
- ✓ **Future MeV telescopes**
- ✓ **NS quantum death!**



✓ **Decays can produce DM, BAU, Planck relics**

Grain-of-Salt Black Holes



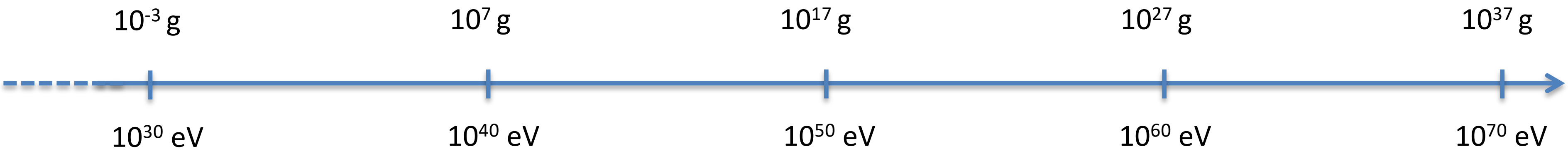
- ✓ **Likely (partly) charged**
- ✓ **Detectable!**
- ✓ **Not too fast!**

In the era of gravitational wave astronomy,

the physics of macroscopic DM candidates

offers many opportunities for the ingenuity

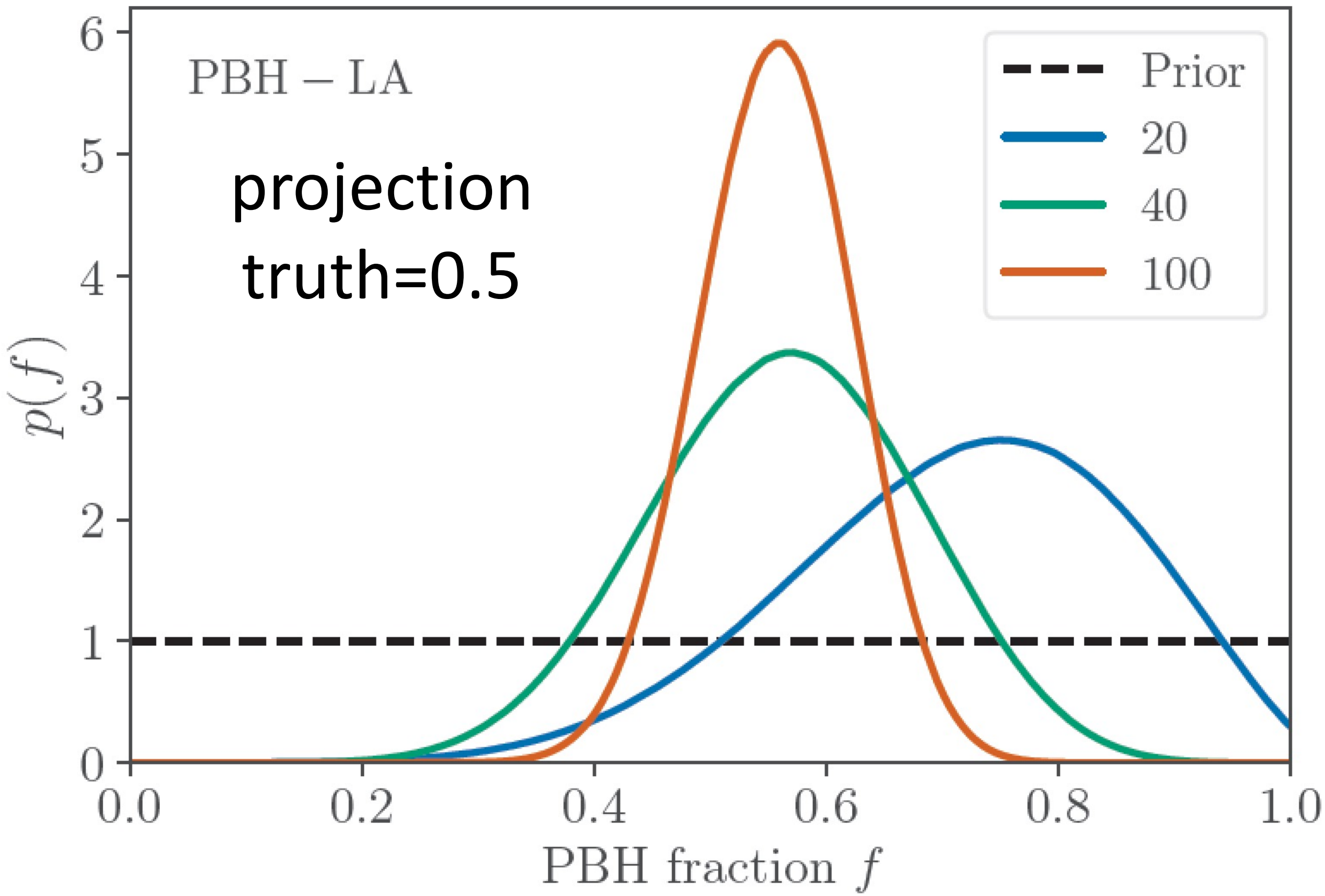
of theorists and the craft of observers



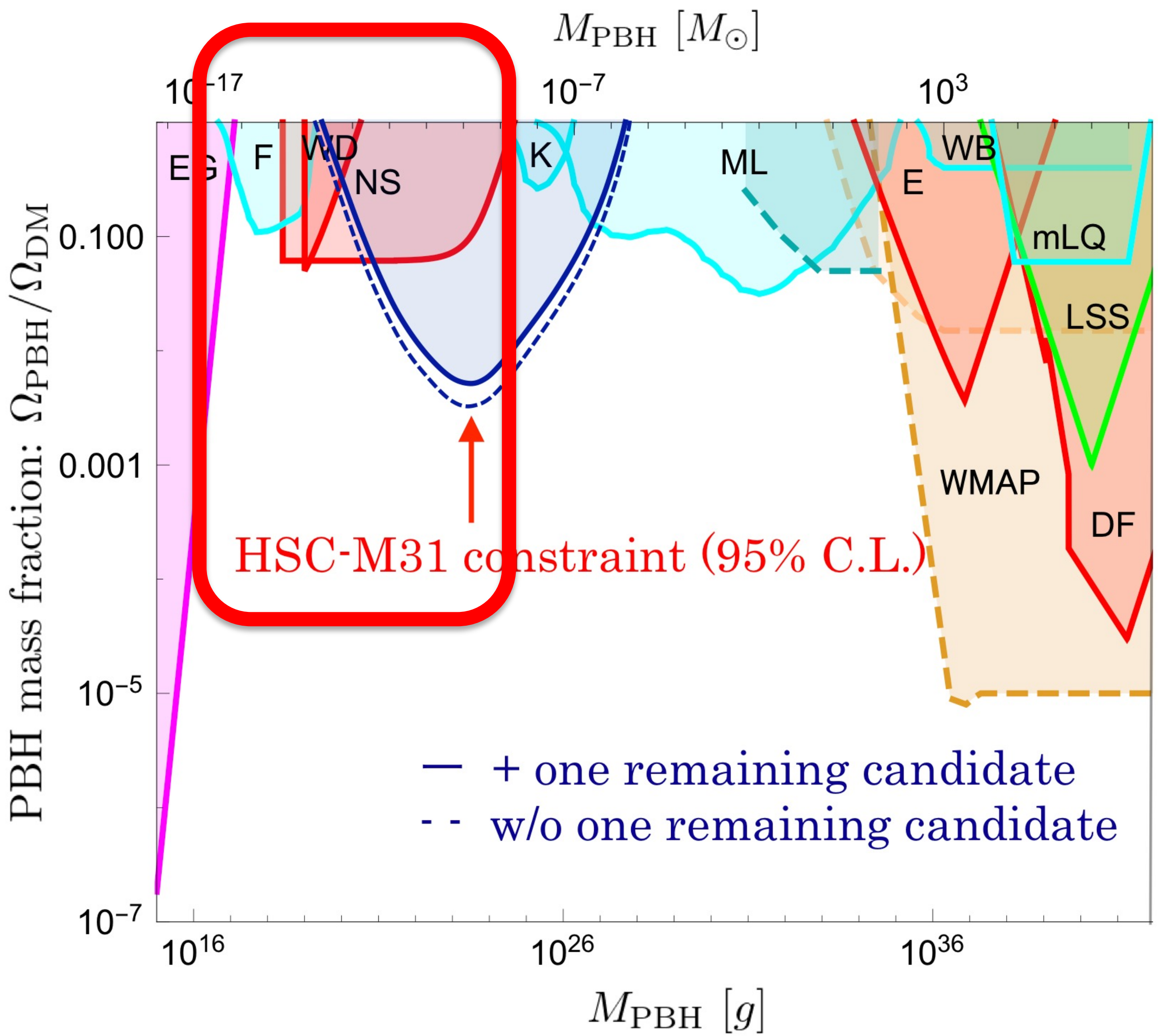
What about mixed models?

Fernandez and Profumo, 1905.13109 (JCAP); Slide credit: Nico Fernandez (UCSC → UIUC)

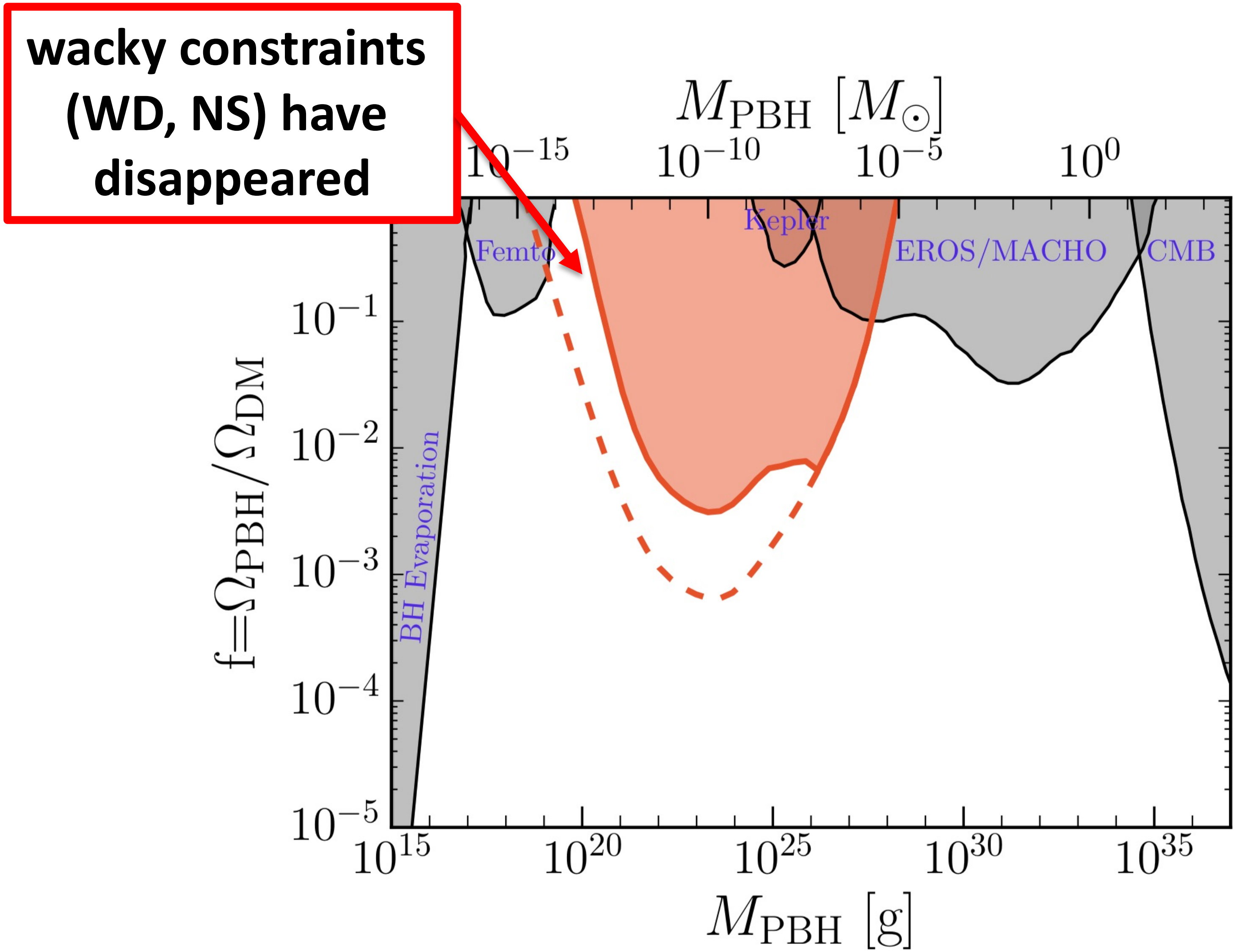
What about mixed models?



Fernandez and Profumo, 1905.13109 (JCAP); Slide credit: Nico Fernandez (UCSC → UIUC)

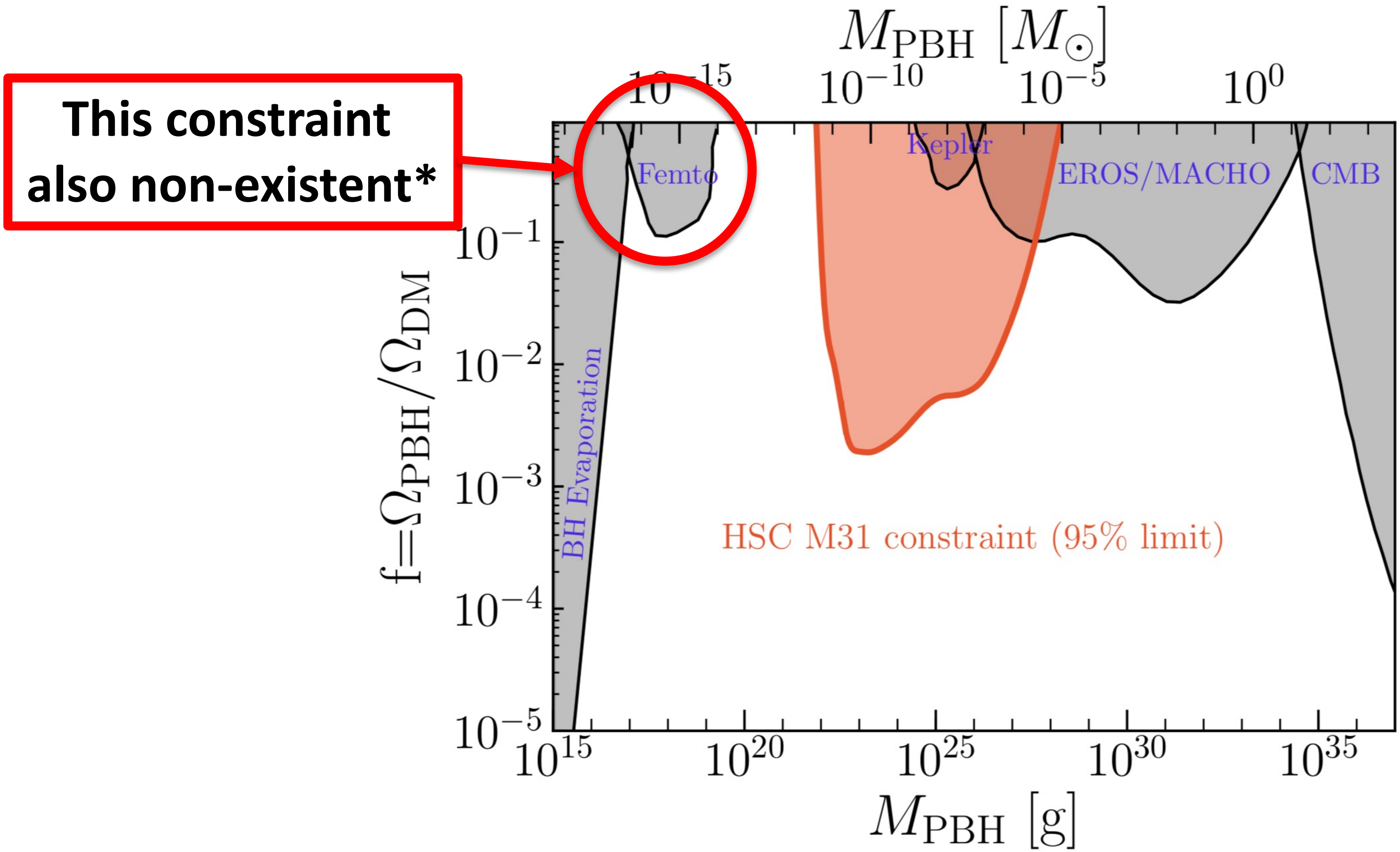


SUBARU HSC microlensing, 1701.02151 VERSION 1



SUBARU HSC microlensing, 1701.02151 VERSION 2: wave effects

* Katz et al, 1807.11495



SUBARU HSC microlensing, VERSION 3: finite source AND wave effects

...but assuming all stars have $R = R_{sun}$!