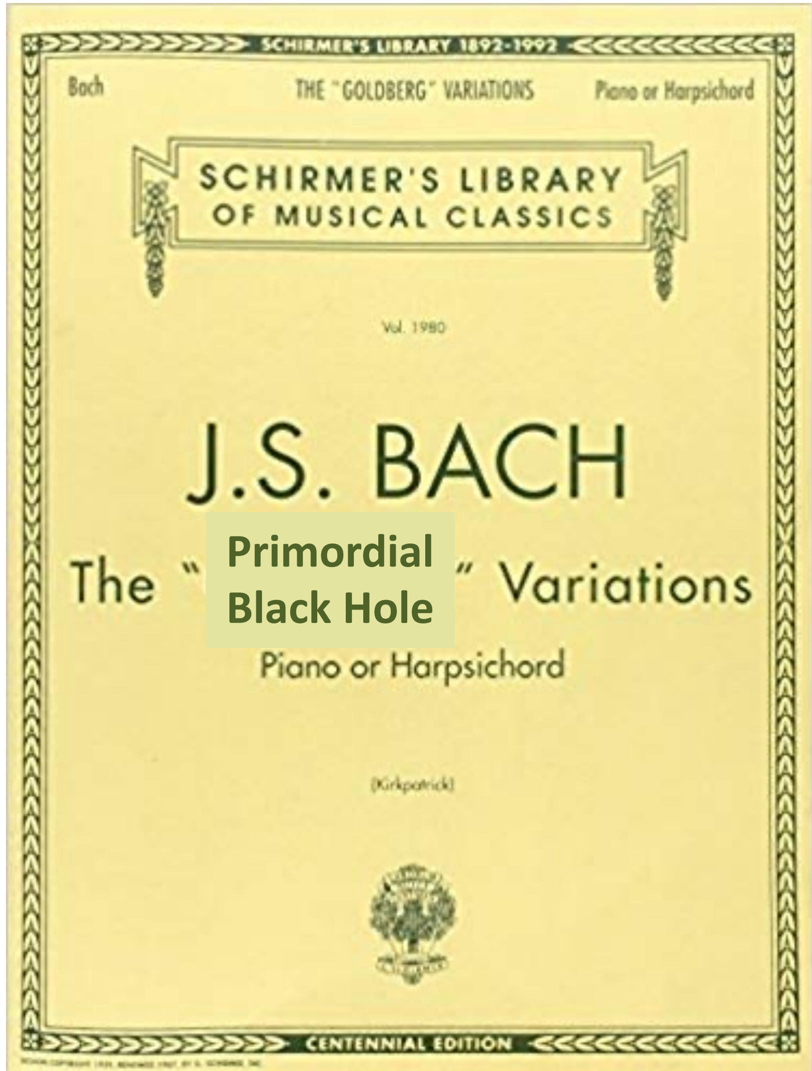
SCIPP
Santa Cruz Institute for Particle Physics

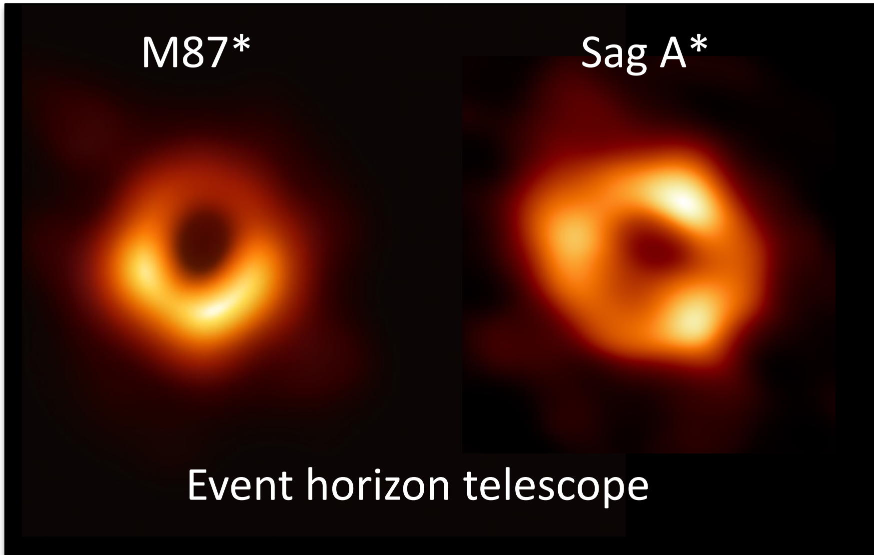
Stefano Profumo

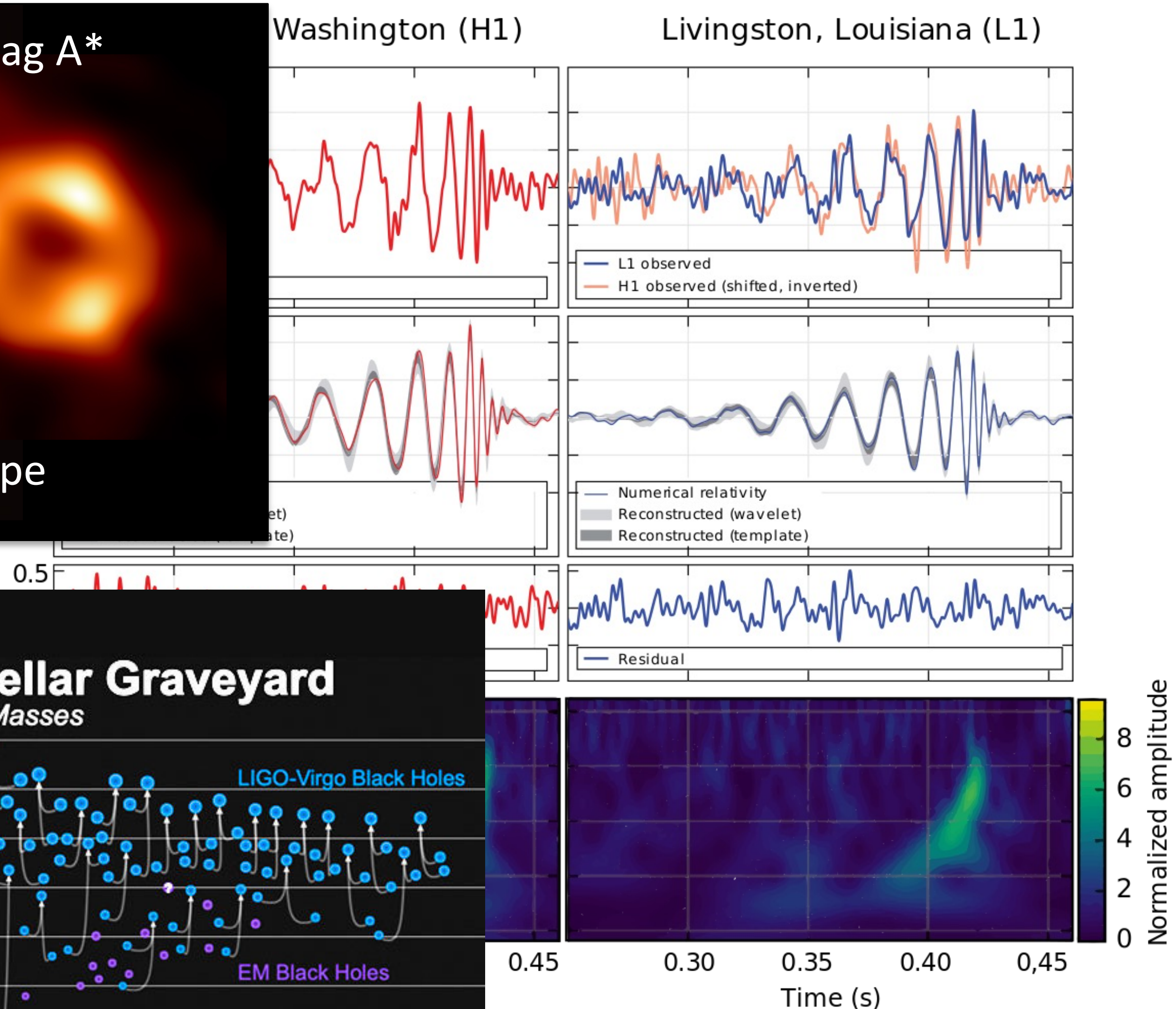
University of California, Santa Cruz

UC SANTA CRUZ

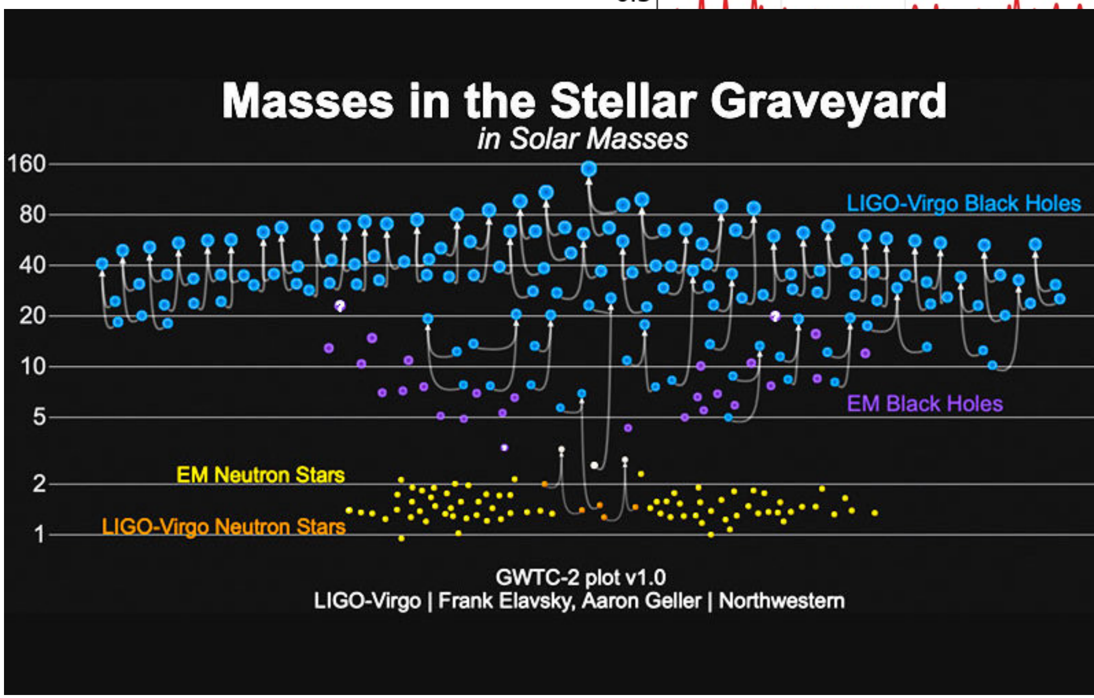


The Mitchell Conference on Collider, Dark Matter, and Neutrino Physics 2022 – May 26, 2022


M87*
Sag A*
Event horizon telescope

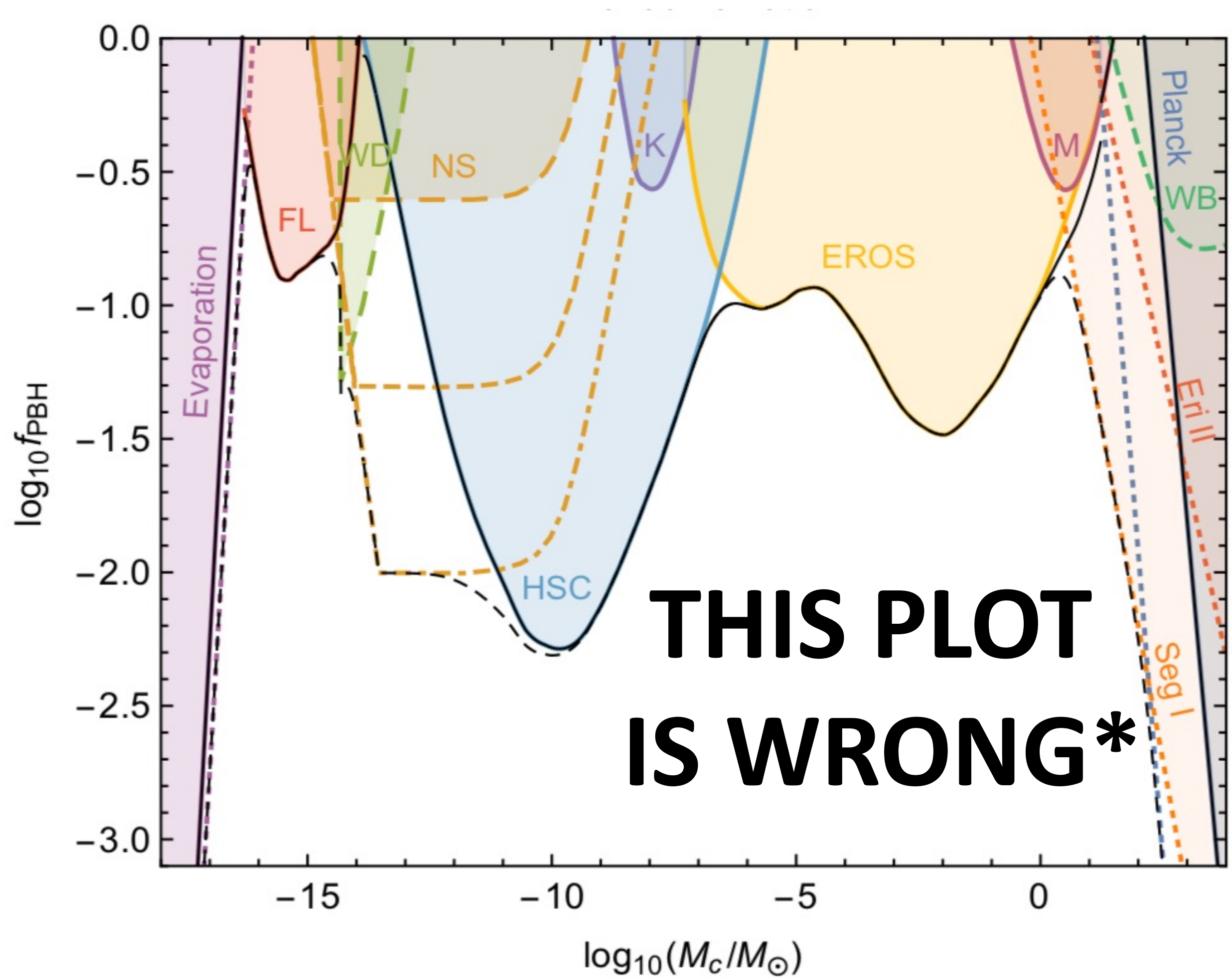

Washington (H1)
Livingston, Louisiana (L1)
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
0.5
Residual
0.45
0.30
0.35
0.40
0,45
Time (s)
Normalized amplitude
8
6
4
2
0

GW150914


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

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

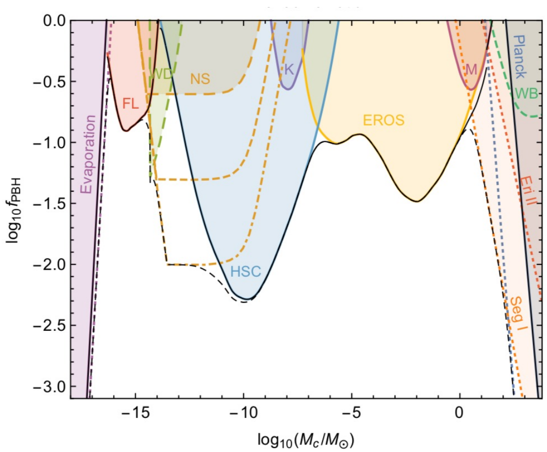
What is the **maximal fraction** of **dark matter** in **PBH**?



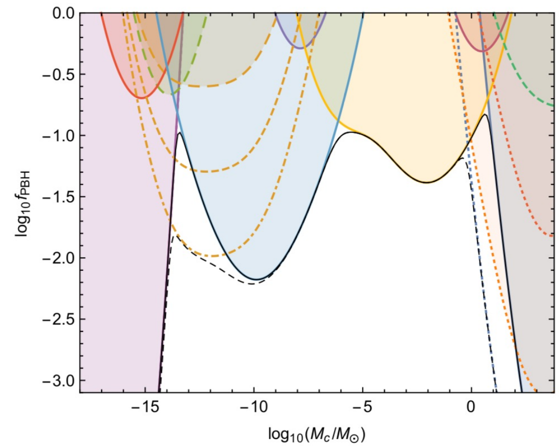
*Carr has since corrected it!

Carr et al, 2017

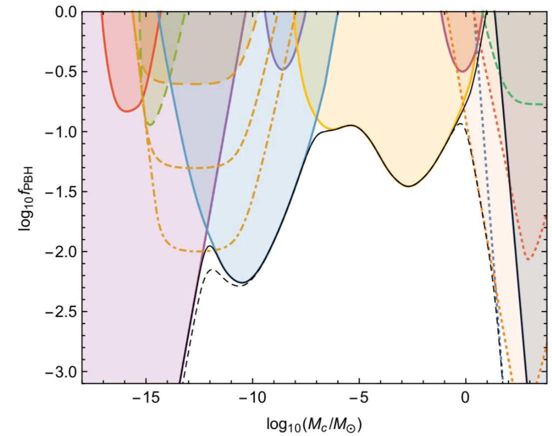
The **fraction** of PBH that could be the **dark matter** depends on the **mass function**!



LOGNORMAL



POWER-LAW



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

Carr et al, 2017

B. Lehmann

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

Benjamin V. Lehmann, Stefano Profumo and Jackson Yant

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1156 High St., Santa Cruz, CA 95064, USA
Santa Cruz Institute for Particle Physics,
1156 High St., Santa Cruz, CA 95064, USA

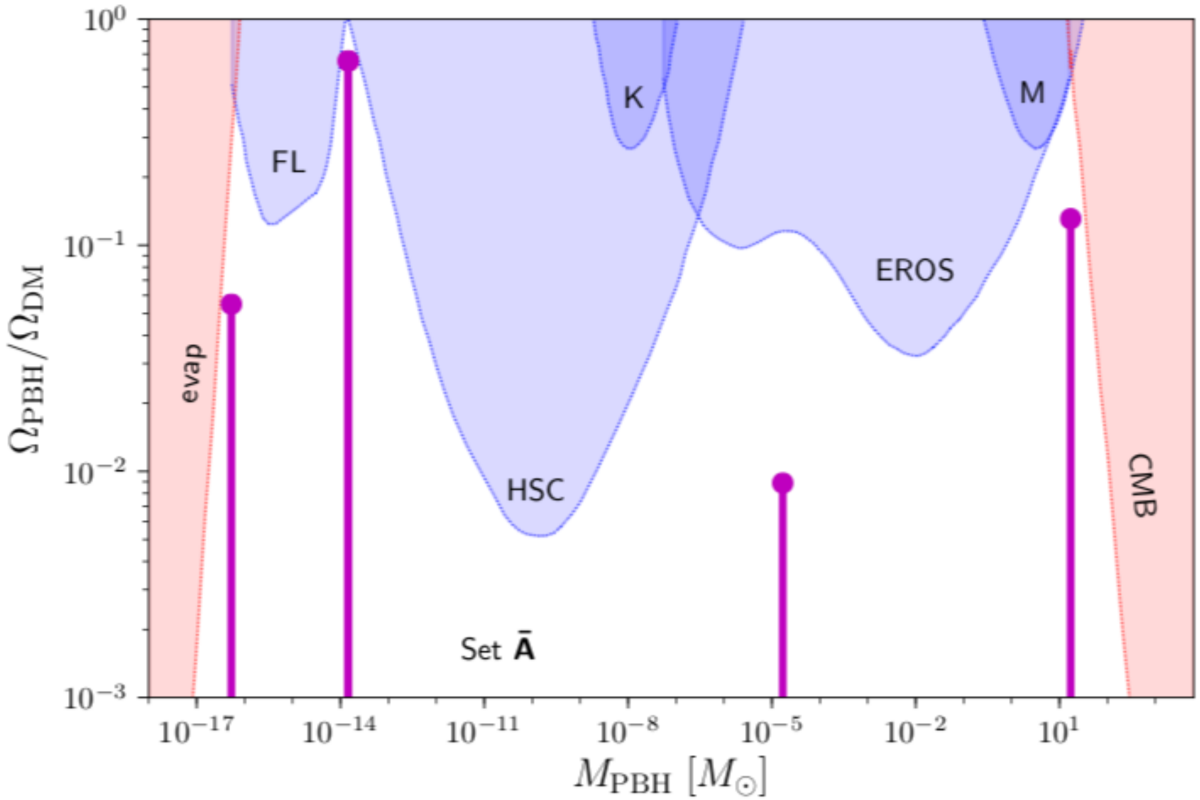
E-mail: blehmann@ucsc.edu, profumo@ucsc.edu, jyant@ucsc.edu

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

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

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

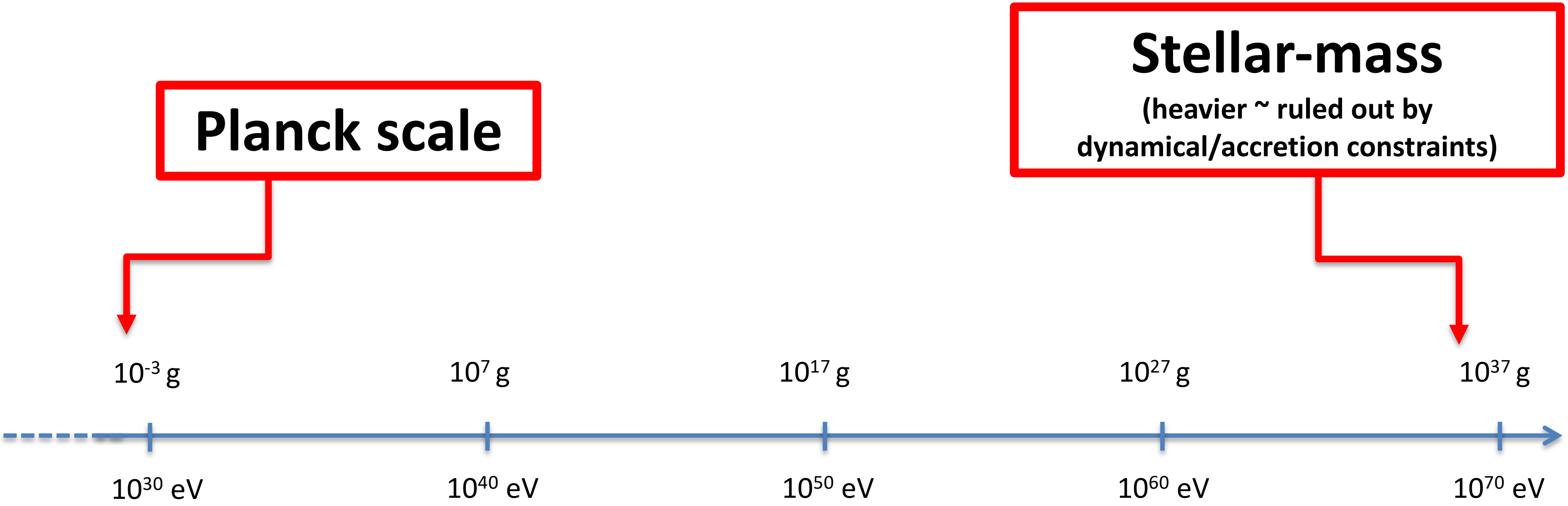
* Lehmann, Profumo and Yant, JCAP 2018



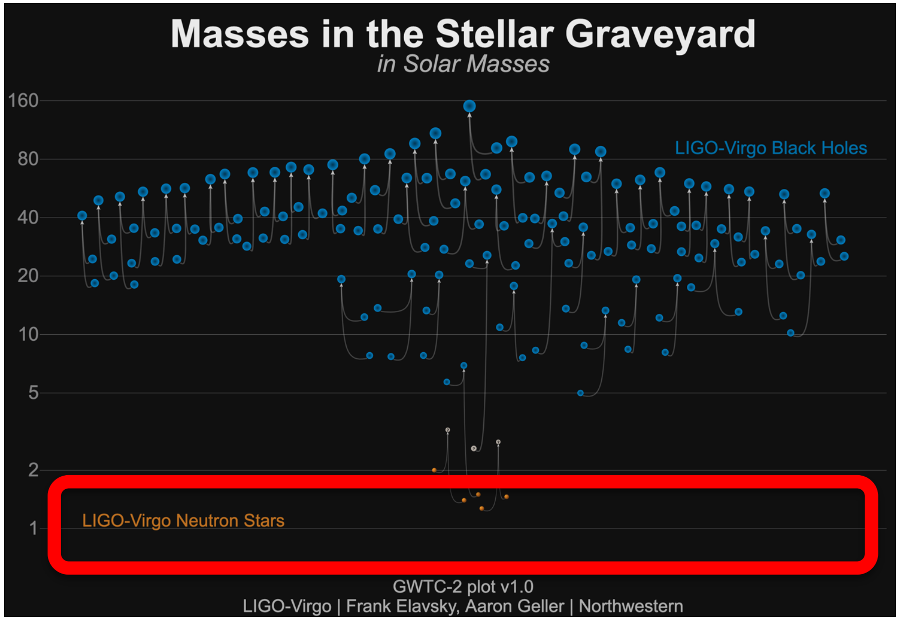
Answer: with *N* independent constraints, the optimal function is a linear combination of *N* delta functions with calculable relative weights

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

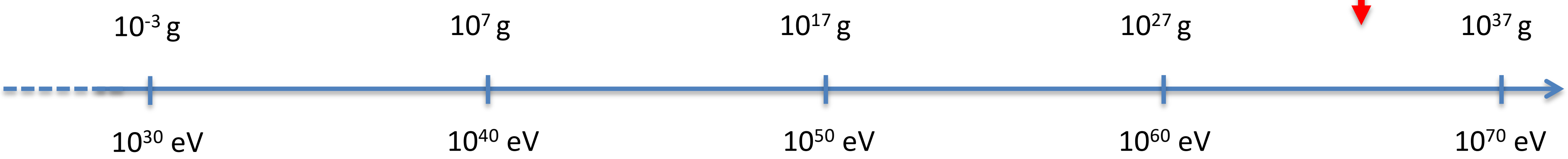
* Lehmann, Profumo and Yant, JCAP 2018



Stellar-mass
(heavier ~ ruled out by
dynamical/accretion constraints)
Planck scale
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



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:

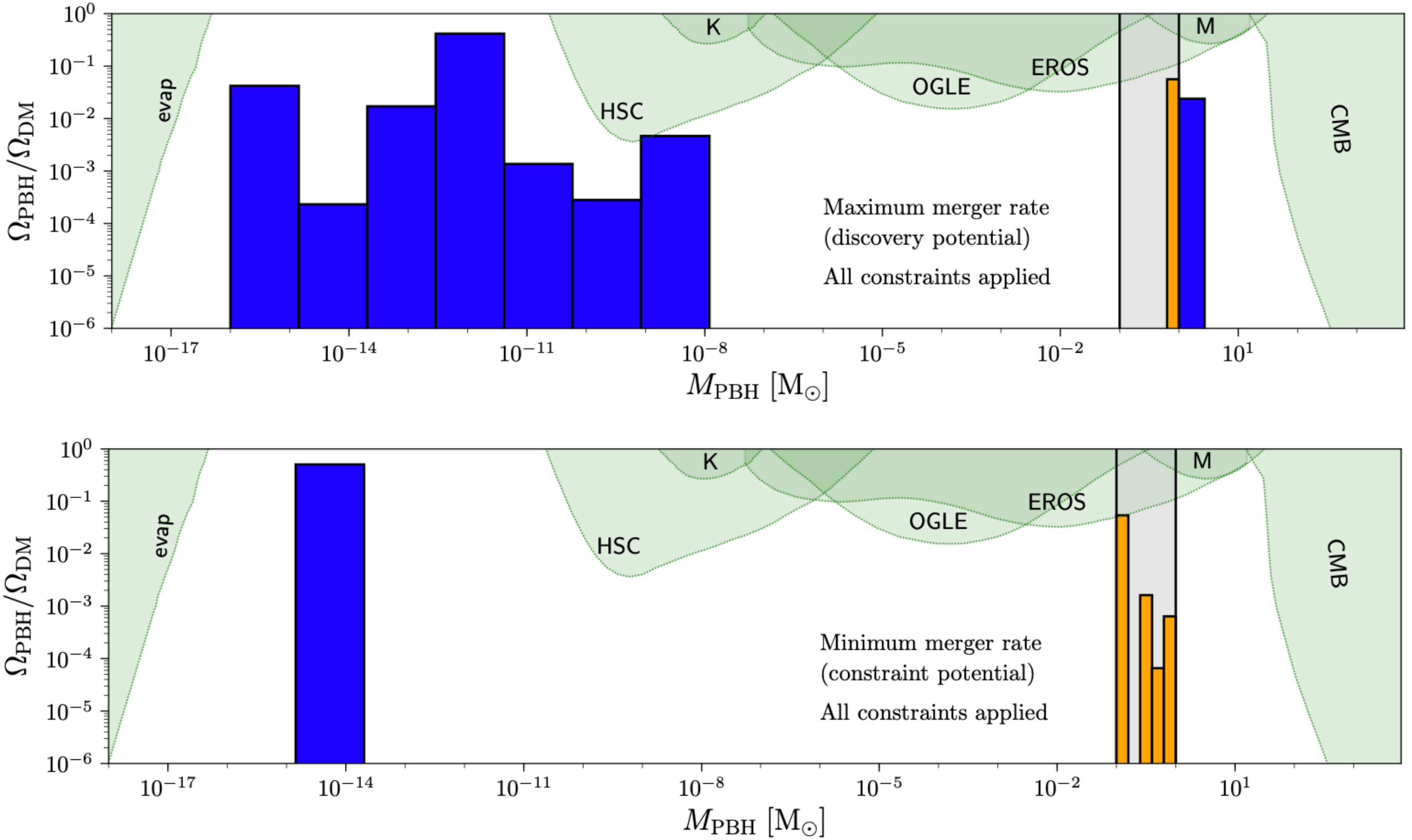
1. **Rate of "goldilocks events"**

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

2. **Mass fraction of light+detectable BHs**

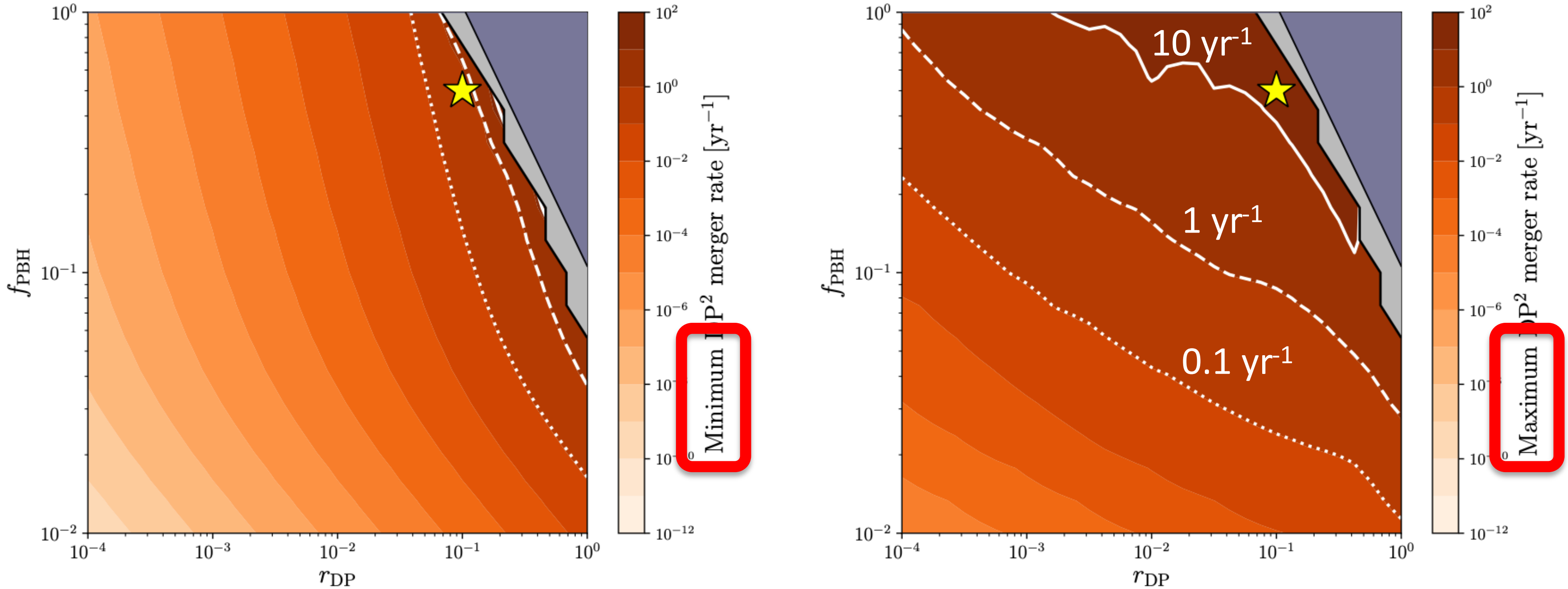
$$r_{\rm DP} = \frac{1}{f_{\rm PBH}} \int_{m_{\rm DP}^{\rm min}}^{m_{\rm DP}^{\rm max}} {\rm d}m\, \psi(m).$$

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



* Lehmann, Profumo and Yant, MNRAS

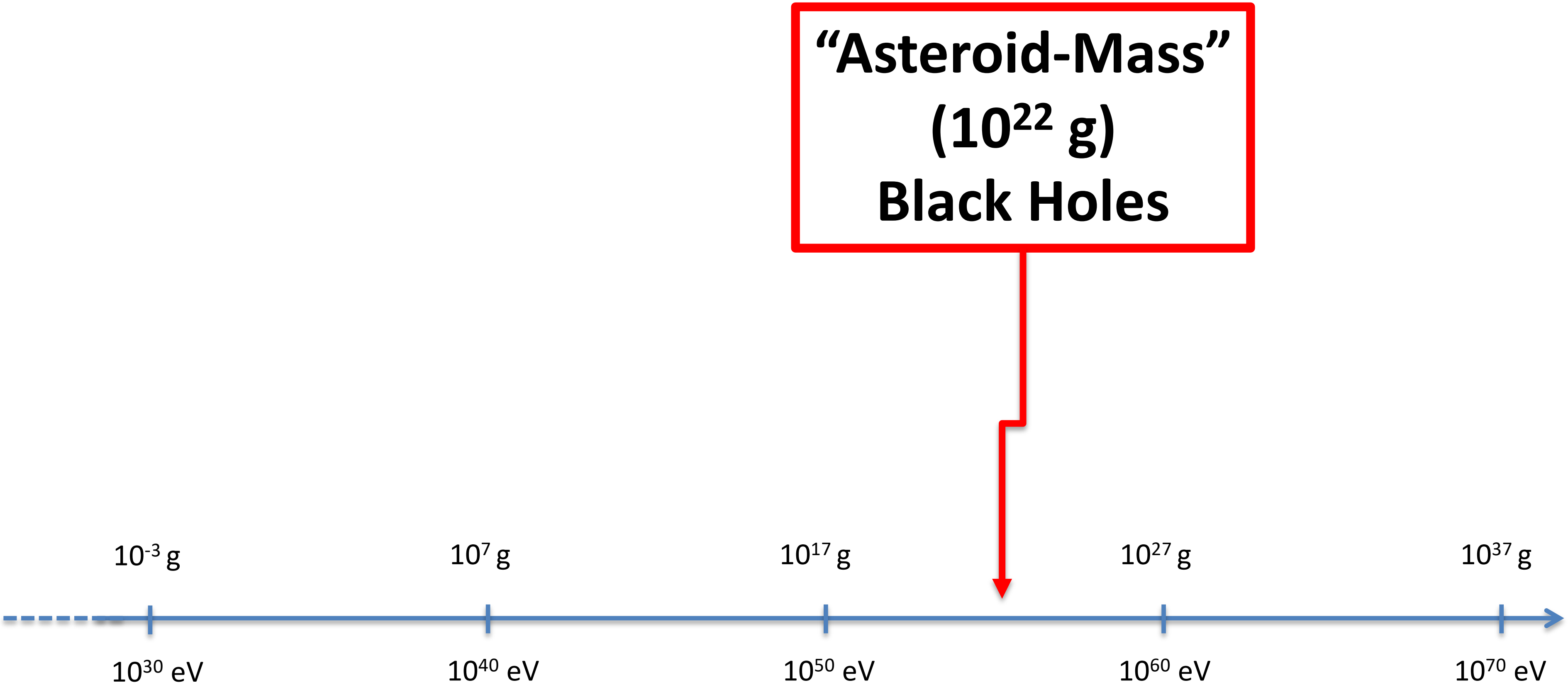
We can numerically compute the maximal and minimal possible "goldilocks event rate"



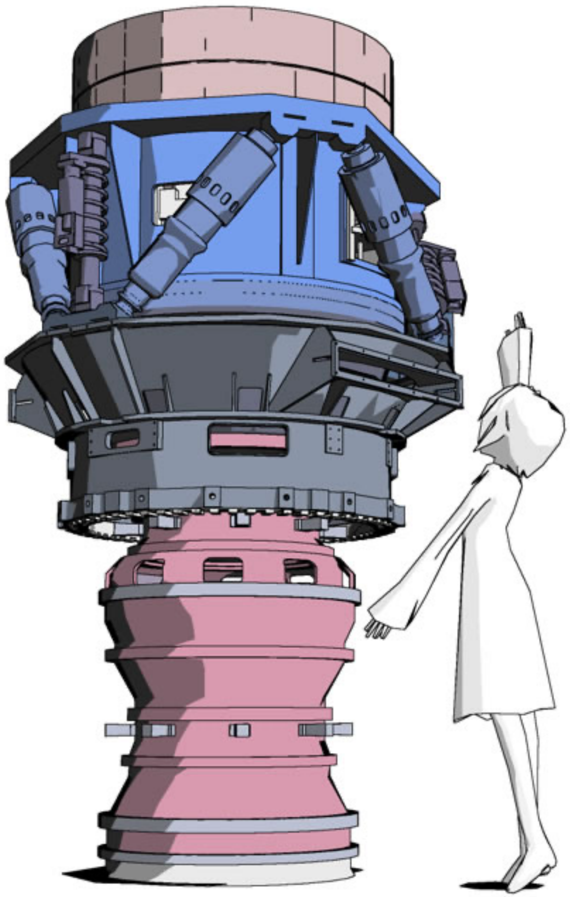
$$\int \mathrm{d}m\, \psi(m) = \frac{\Omega_{\mathrm{PBH}}}{\Omega_{\mathrm{DM}}} \equiv f_{\mathrm{PBH}}.$$

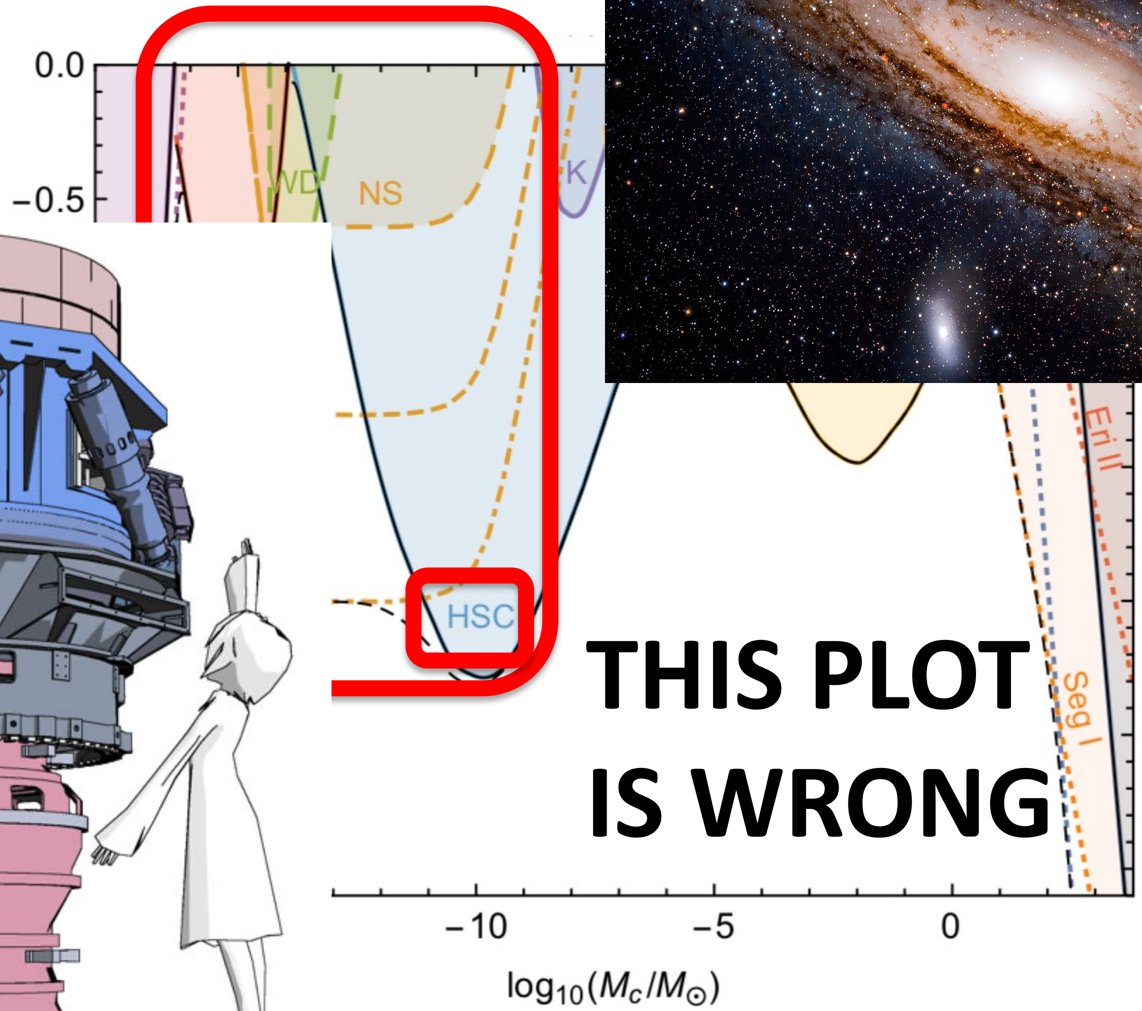
$$r_{\mathrm{DP}} = \frac{1}{f_{\mathrm{PBH}}} \int_{m_{\mathrm{DP}}^{\mathrm{min}}}^{m_{\mathrm{DP}}^{\mathrm{max}}} \mathrm{d}m\, \psi(m).$$

* Lehmann, Profumo and Yant, MNRAS



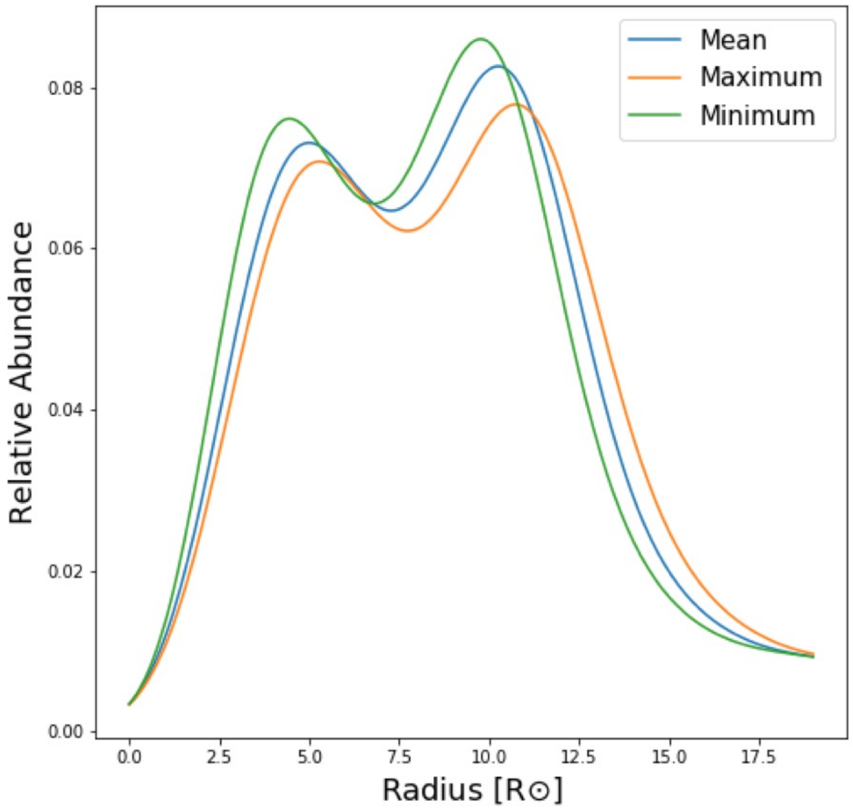
✓ **Microlensing a lot trickier than previously thought!**





THIS PLOT IS WRONG

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

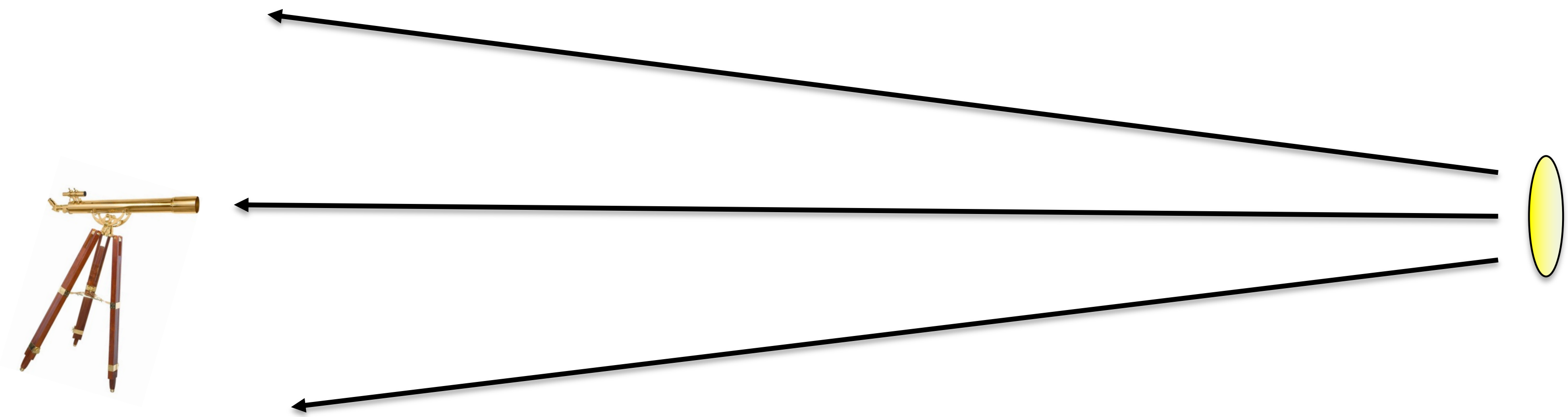


Stars that contribute to the microlensing constraints are ~ 100x larger in the sky than the Sun!

N. Smyth

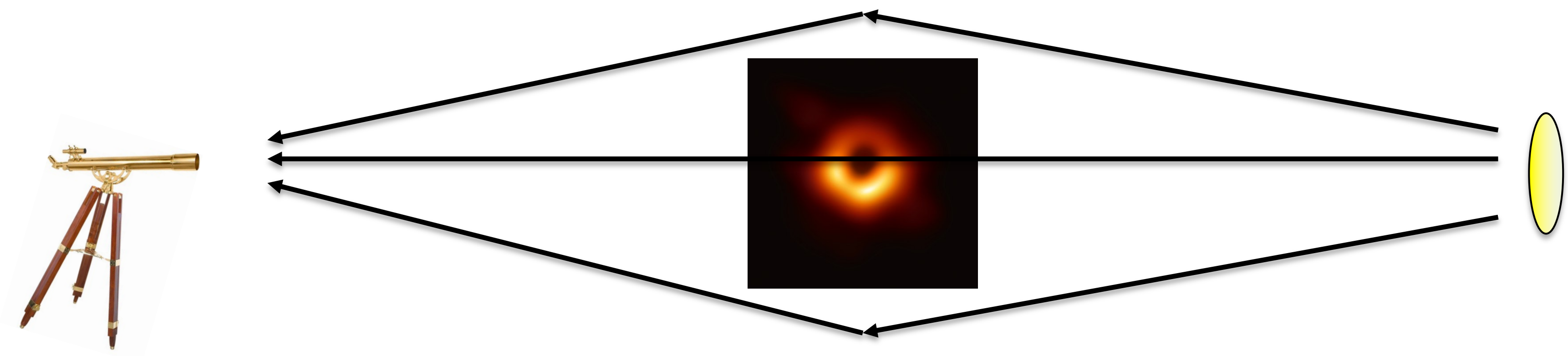
* Profumo, Smyth+ PRD 2020

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



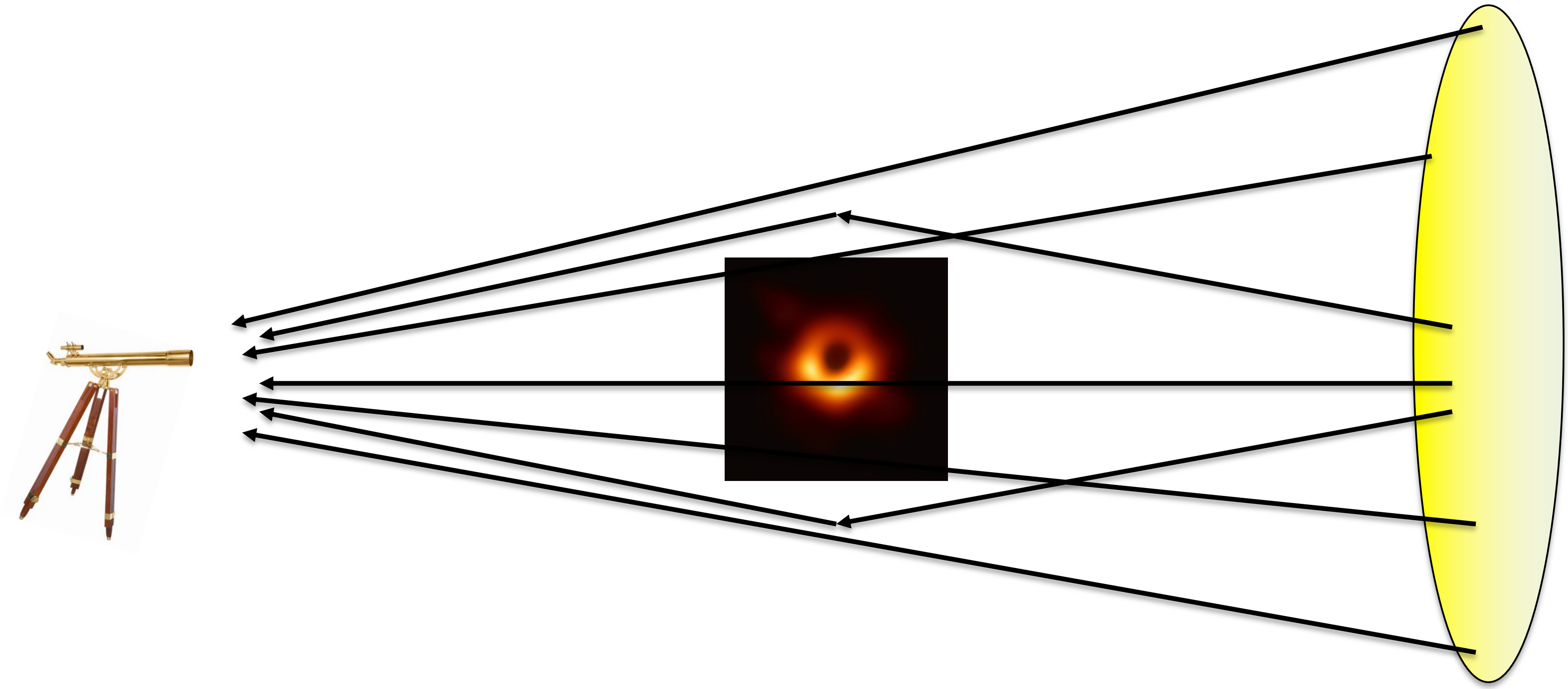
* Profumo, Smyth+ PRD 2020

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



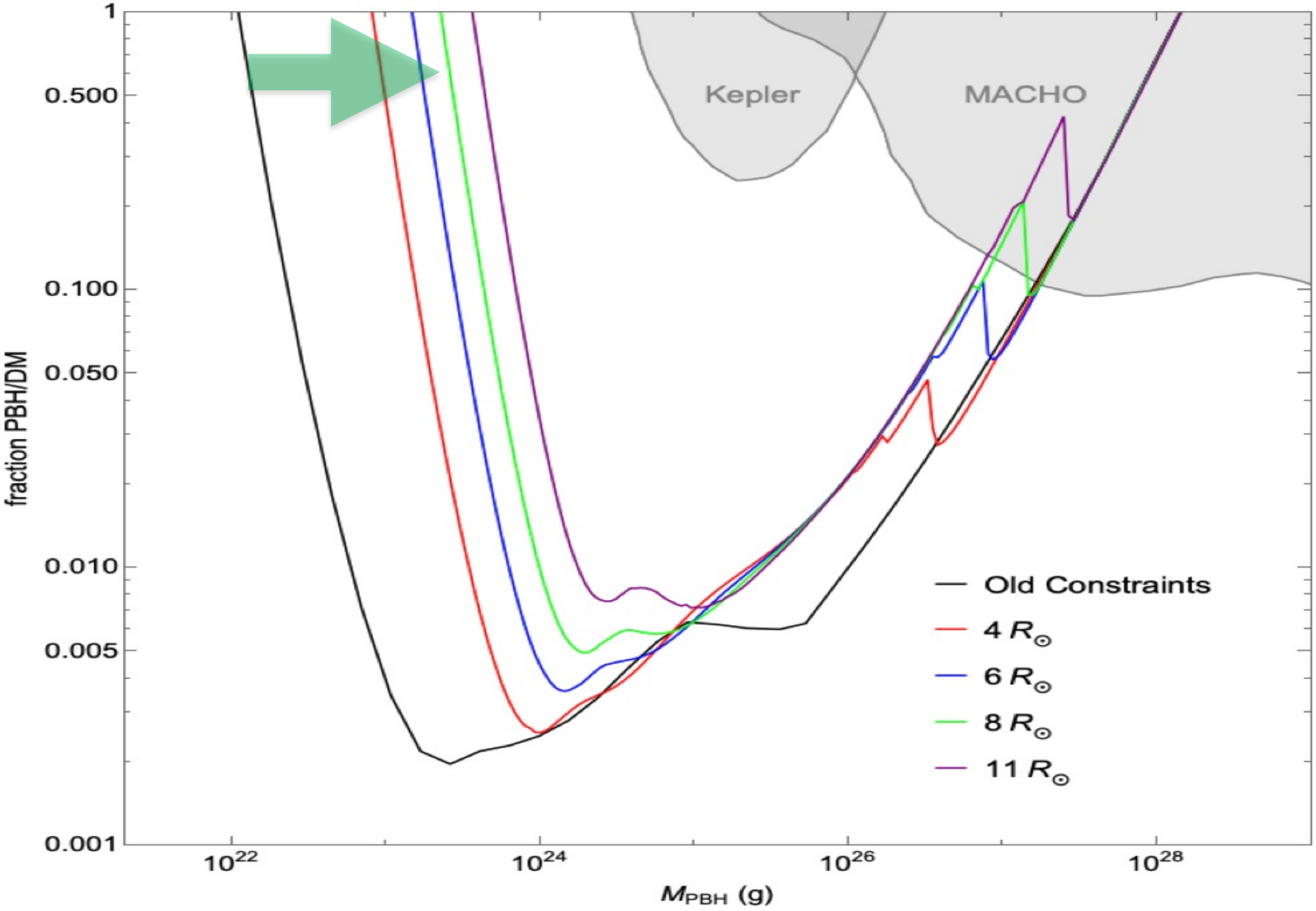
* Profumo, Smyth+ PRD 2020

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

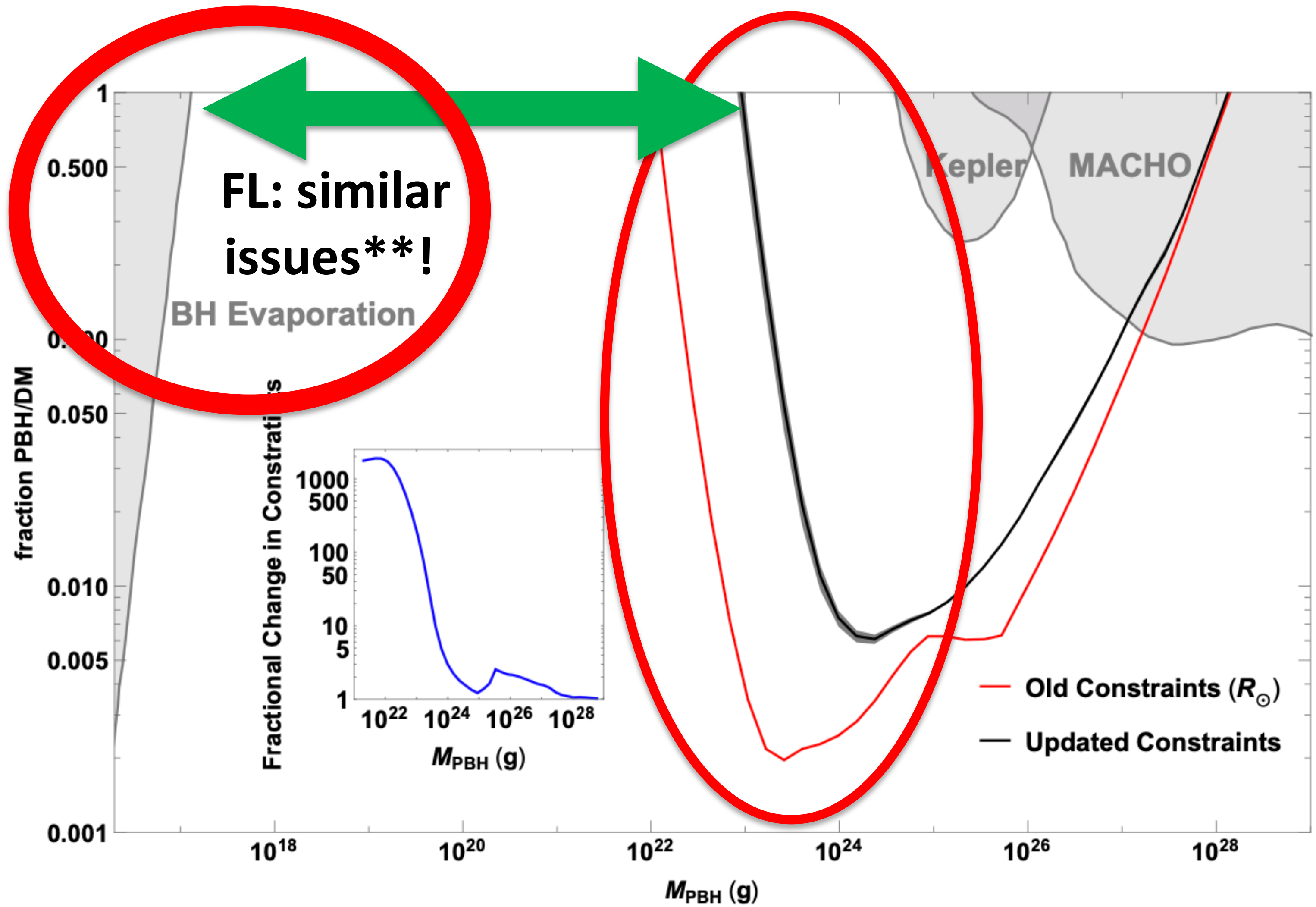


* Profumo, Smyth+ PRD 2020

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

Three-body capture, ejection, and the demographics of bound objects in binary systems

Benjamin V. Lehmann [★] Olivia G. Ross [†] Ava Webber [‡] and Stefano Profumo [§]
Department of Physics, University of California Santa Cruz, 1156 High St, Santa Cruz, CA 95064, USA
Santa Cruz Institute for Particle Physics, 1156 High St, Santa Cruz, CA 95064, USA

Capture of dark compact objects in extrasolar systems

Benjamin V. Lehmann, Ava Webber, Olivia G. Ross, and Stefano Profumo

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Santa Cruz Institute for Particle Physics, 1156 High St., Santa Cruz, CA 95064, USA

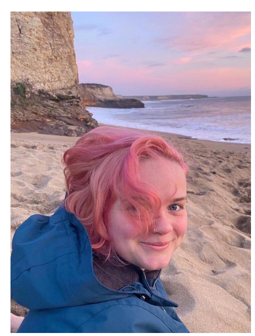
Unraveling the origin of black holes from effective spin measurements with LIGO-Virgo

Nicolas Fernandez[a,b] and Stefano Profumo[a,b]

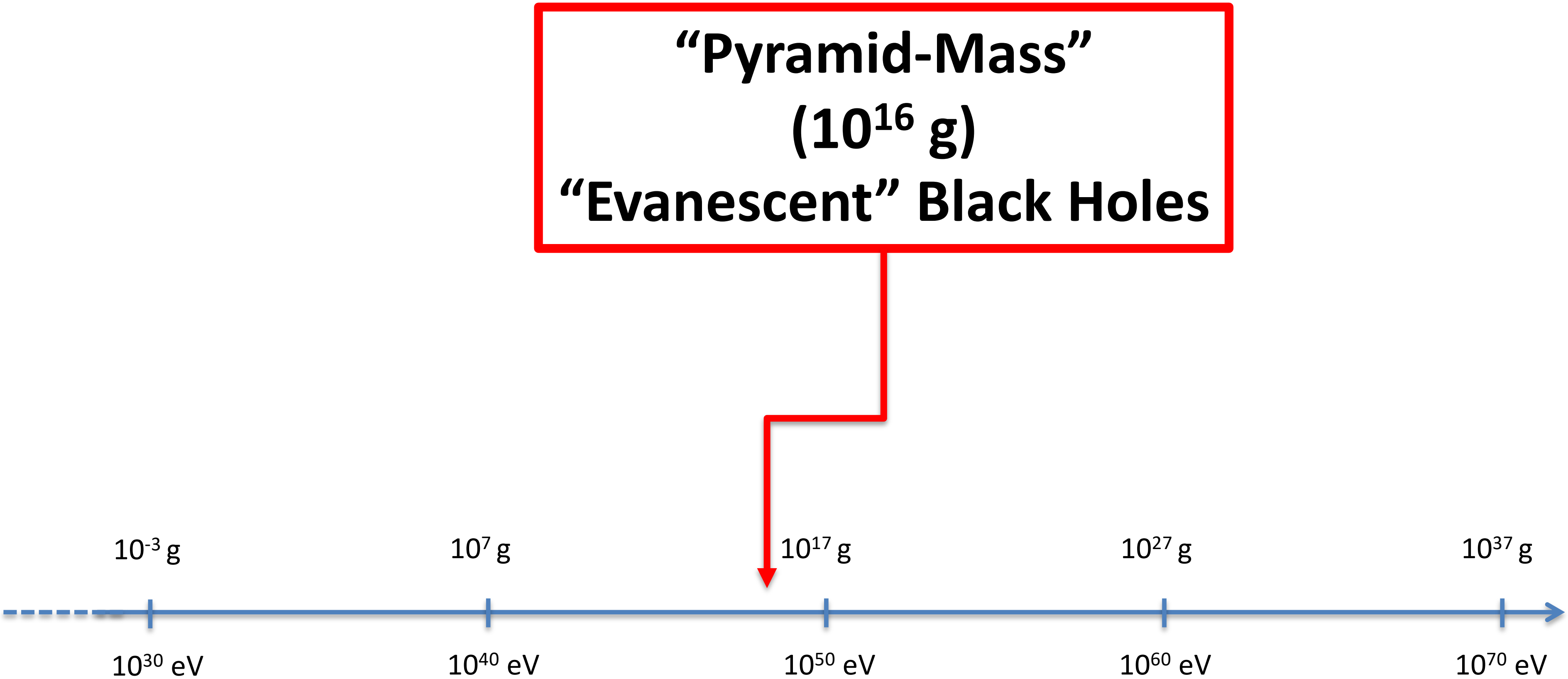
[a]Department of Physics, 1156 High St., University of California Santa Cruz, Santa Cruz, CA 95064, USA
[b]Santa Cruz Institute for Particle Physics, 1156 High St., Santa Cruz, CA 95064, USA


N. Fernandez


A. Webber


O. Ross

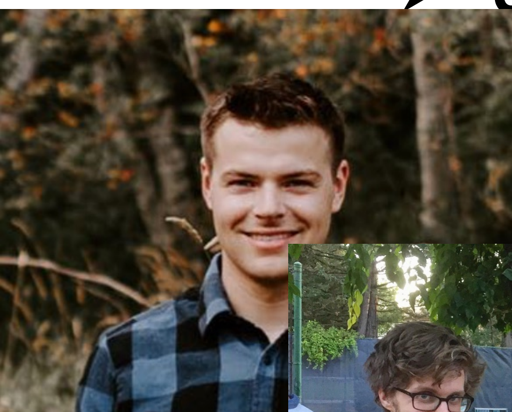

B. Lehmann

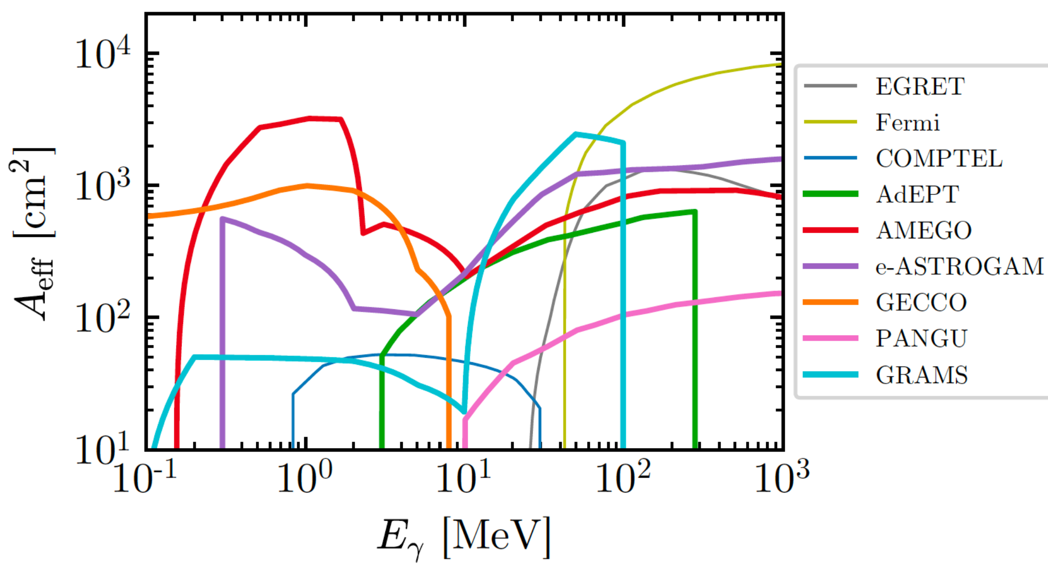

“Pyramid-Mass”
(10^{16} g)
“Evanescent” Black Holes
10^{-3} g
10^{7} g
10^{17} g
10^{27} g
10^{37} g
10^{30} eV
10^{40} eV
10^{50} eV
10^{60} eV
10^{70} eV

Lightest PBH that can be dark matter…

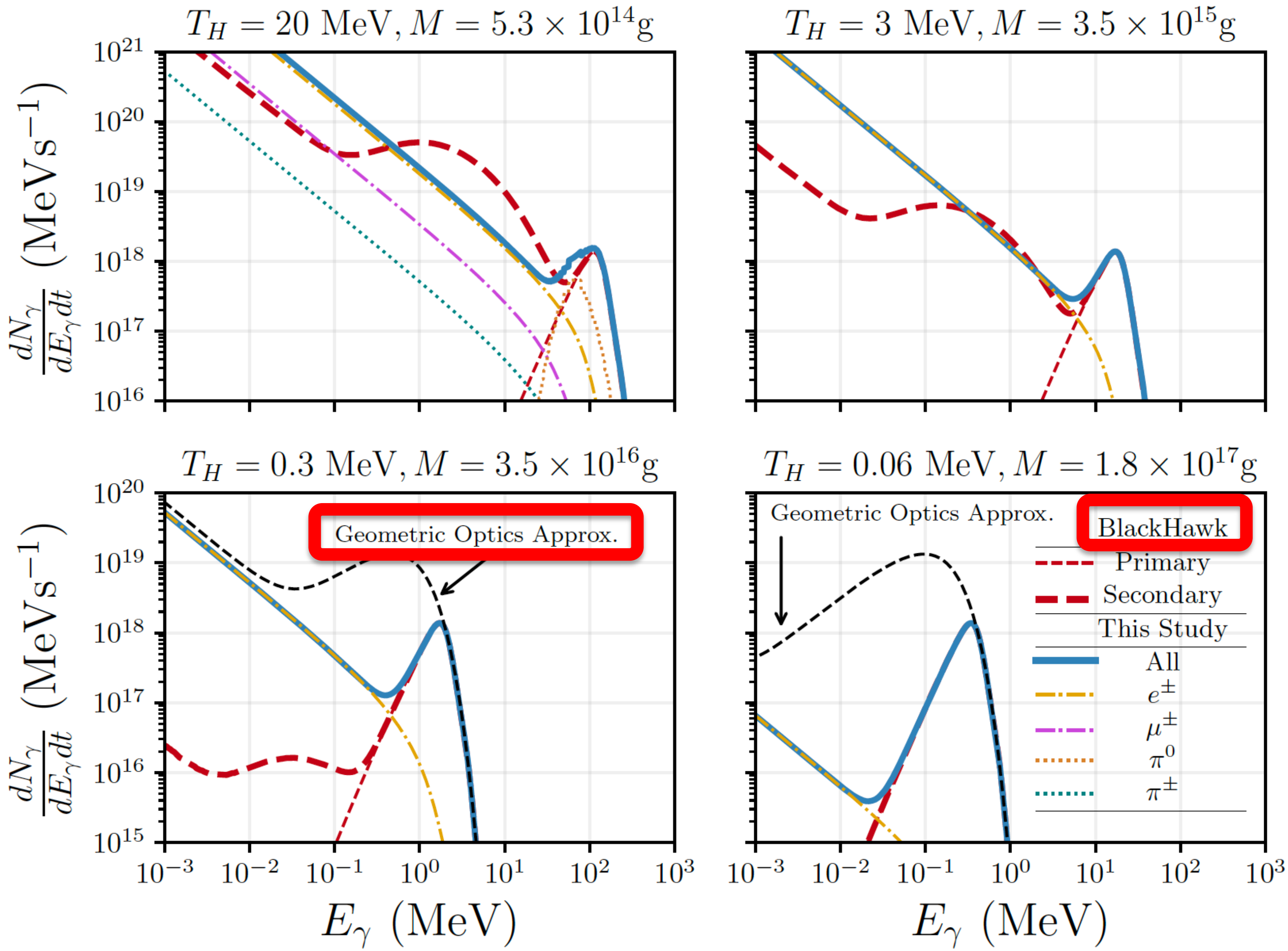
$$\tau(M) \simeq 200\ \tau_U \left(\frac{M}{10^{15}\ \mathrm{g}}\right)^3 \simeq 200\ \tau_U \left(\frac{10\ \mathrm{MeV}}{T_H}\right)^3$$

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



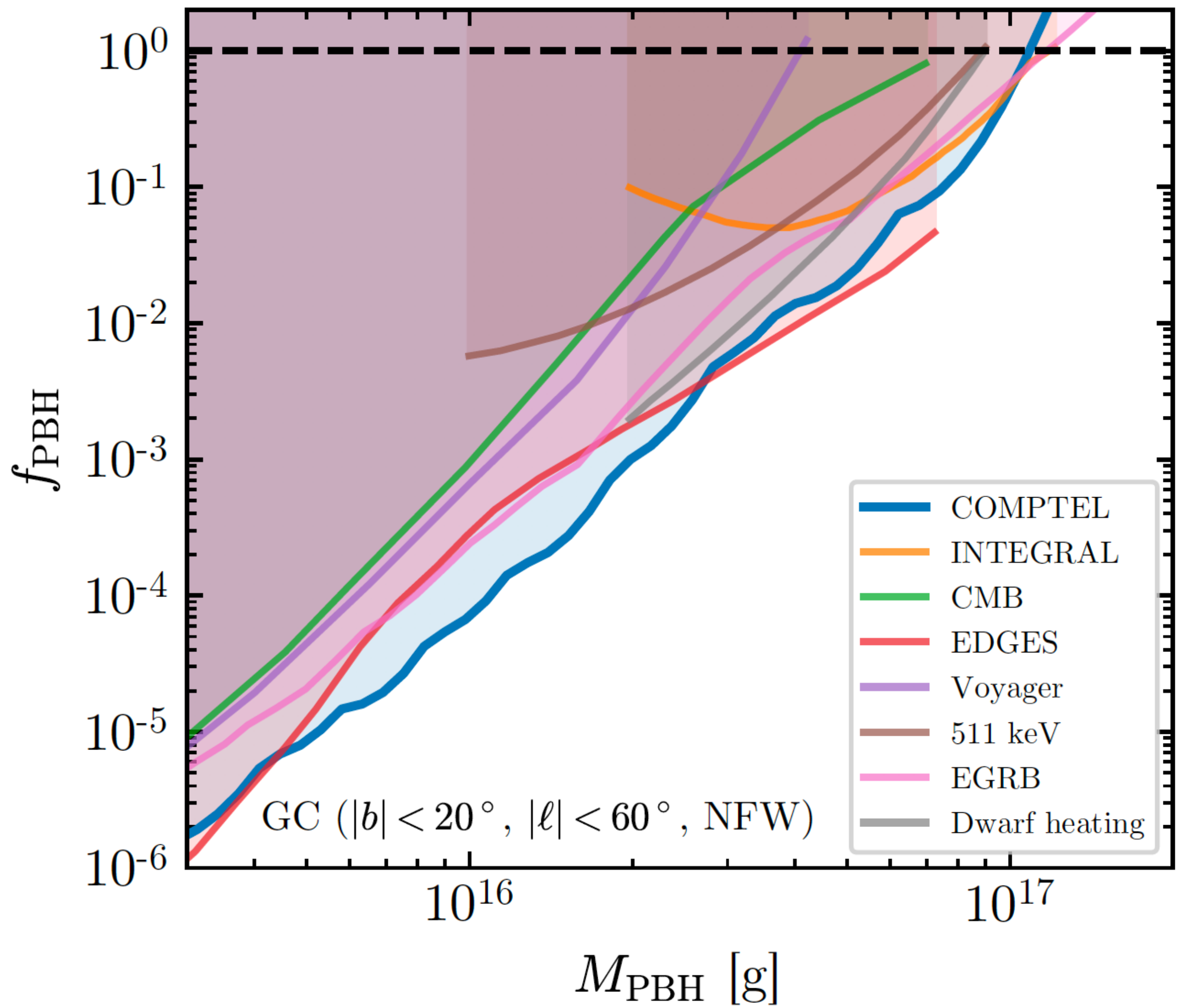


Coogan, Morrison & Profumo, 2010.04797, Phys. Rev. Letters



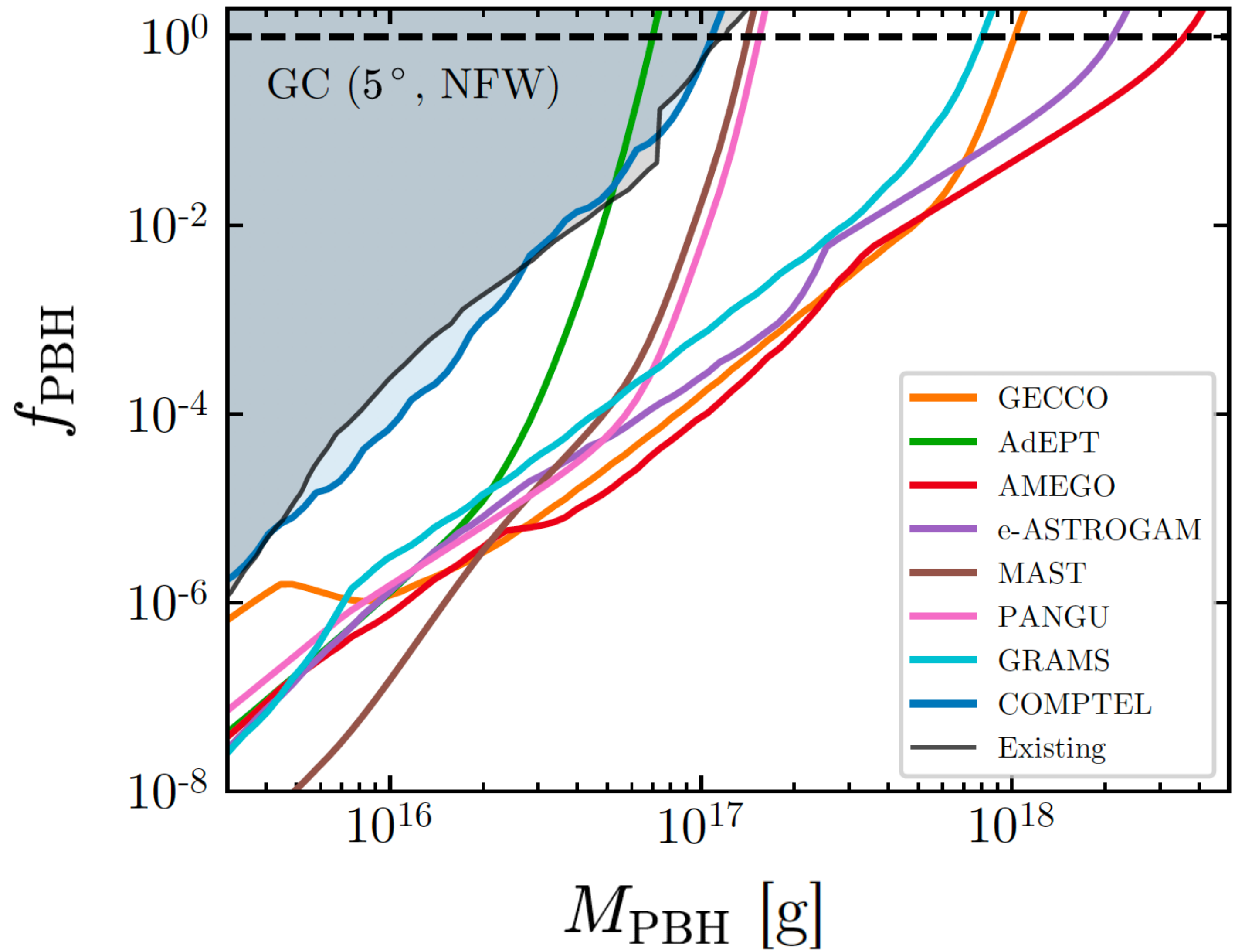
Coogan, Morrison & Profumo, 2010.04797, Phys. Rev. Letters

Our new COMPTEL constraints are among strongest/robust



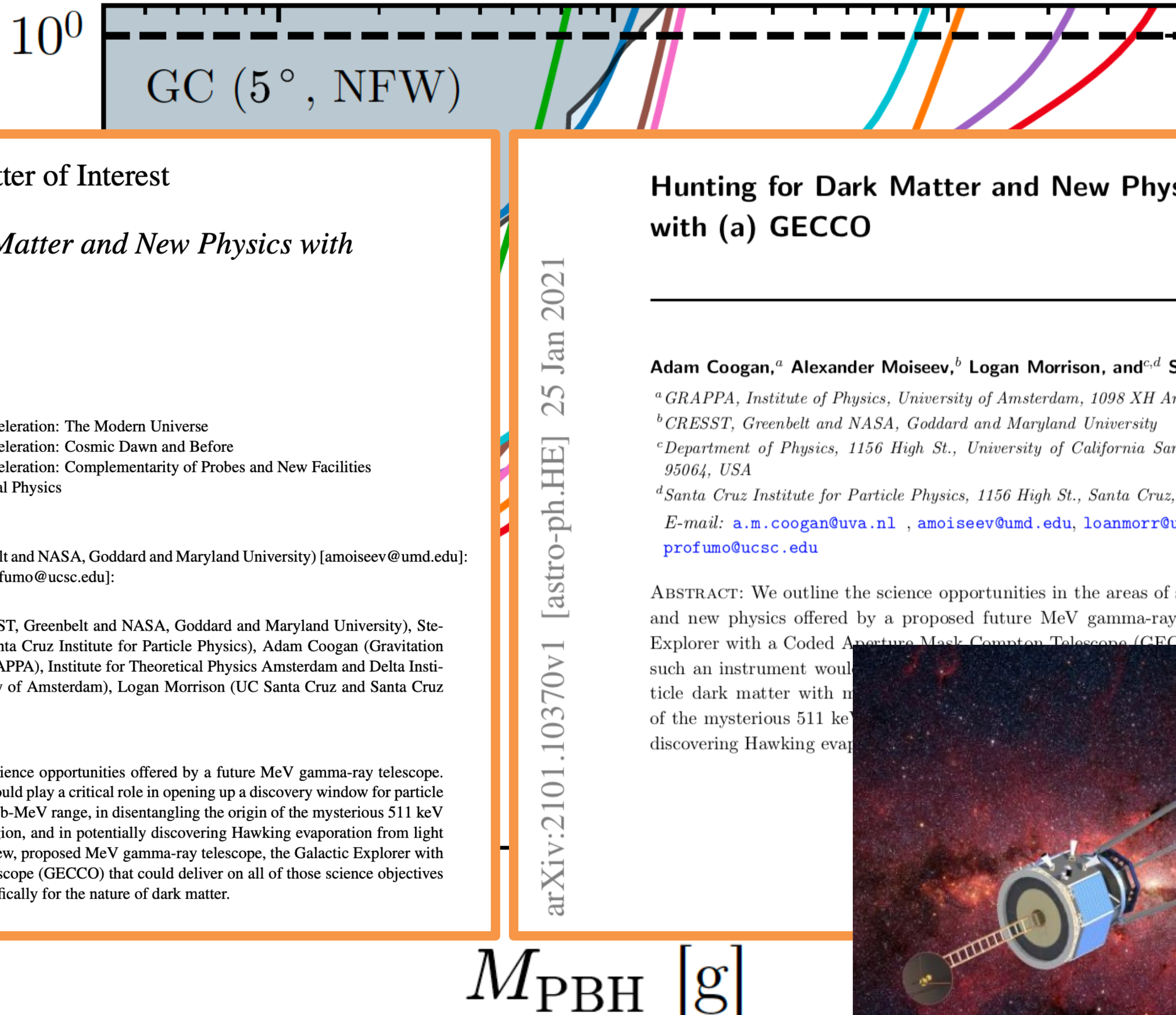
Coogan, Morrison & Profumo, 2010.04797, Phys. Rev. Letters

New MeV Telescopes could discover Hawking evaporation!



Coogan, Morrison & Profumo, 2010.04797, Phys. Rev. Letters

New MeV Telescopes could discover Hawking evaporation!



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

Contact Information:
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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.

arXiv:2101.10370v1 [astro-ph.HE] 25 Jan 2021

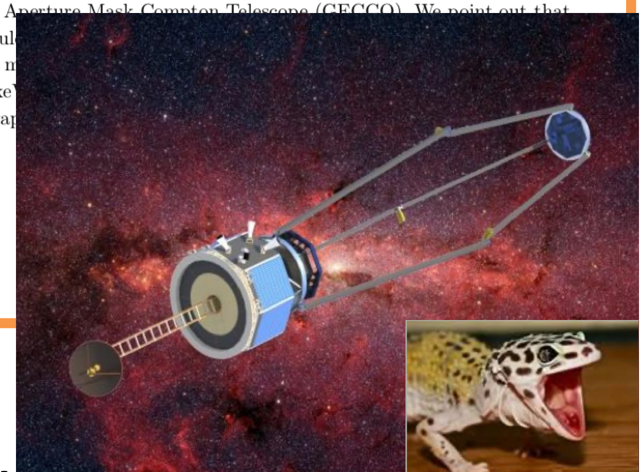
Hunting for Dark Matter and New Physics with (a) GECCO

Adam Coogan,[a] **Alexander Moiseev,**[b] **Logan Morrison, and**[c,d] **Stefano Profumo**[c,d]

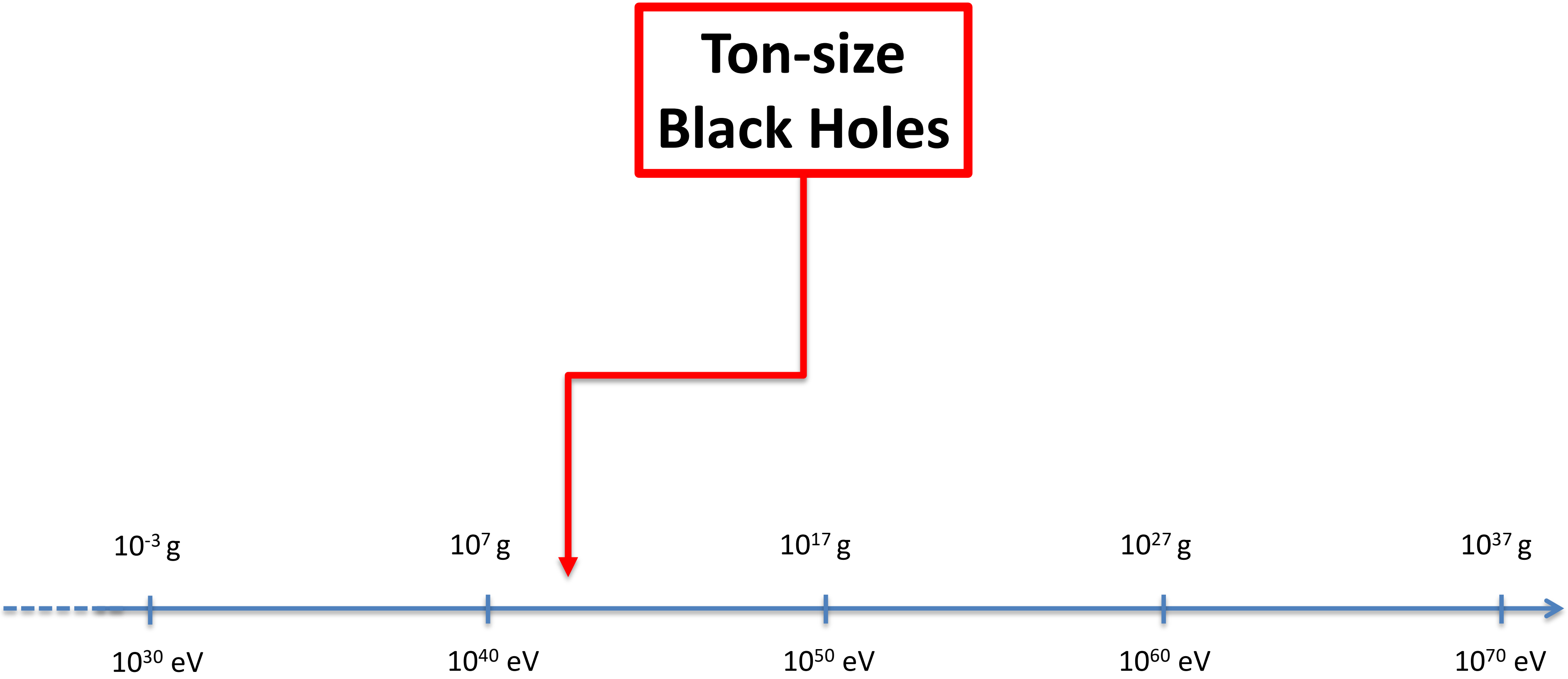
[a] *GRAPPA, Institute of Physics, University of Amsterdam, 1098 XH Amsterdam, The Netherlands*
[b] *CRESST, Greenbelt and NASA, Goddard and Maryland University*
[c] *Department of Physics, 1156 High St., University of California Santa Cruz, Santa Cruz, CA 95064, USA*
[d] *Santa Cruz Institute for Particle Physics, 1156 High St., Santa Cruz, CA 95064, USA*

E-mail: a.m.coogan@uva.nl , amoiseev@umd.edu, loanmorr@ucsc.edu, profumo@ucsc.edu

Abstract: We outline the science opportunities in the areas of searches for dark matter and new physics offered by a proposed future MeV gamma-ray telescope, the Galactic Explorer with a Coded A... such an instrument woul... ticle dark matter with m... of the mysterious 511 ke... discovering Hawking evap...



Coogan, Morrison & Profumo, 2010.04797, Phys. Rev. Letters



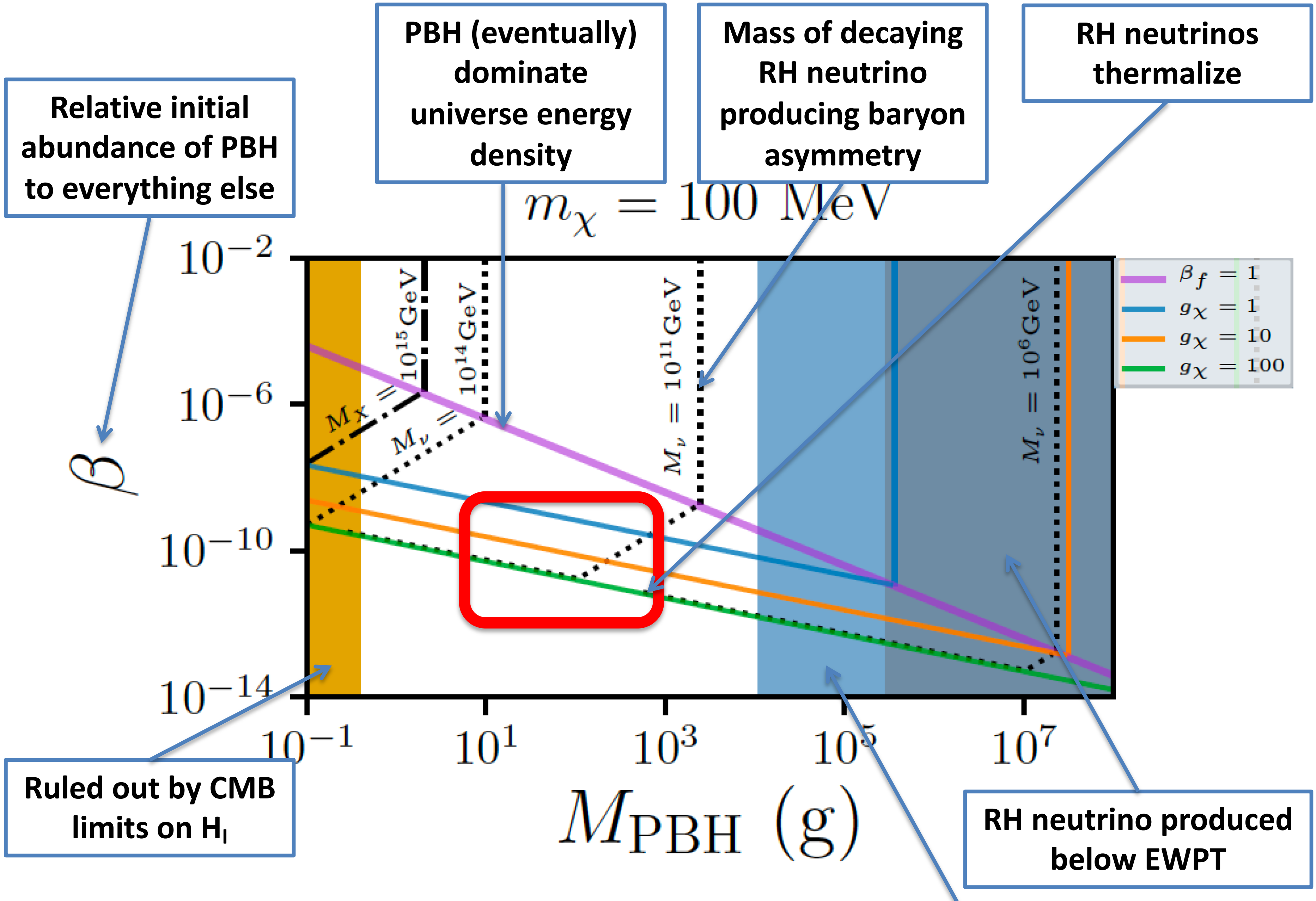
Ton-size
Black Holes
10^-3 g
10^7 g
10^17 g
10^27 g
10^37 g
10^30 eV
10^40 eV
10^50 eV
10^60 eV
10^70 eV

...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

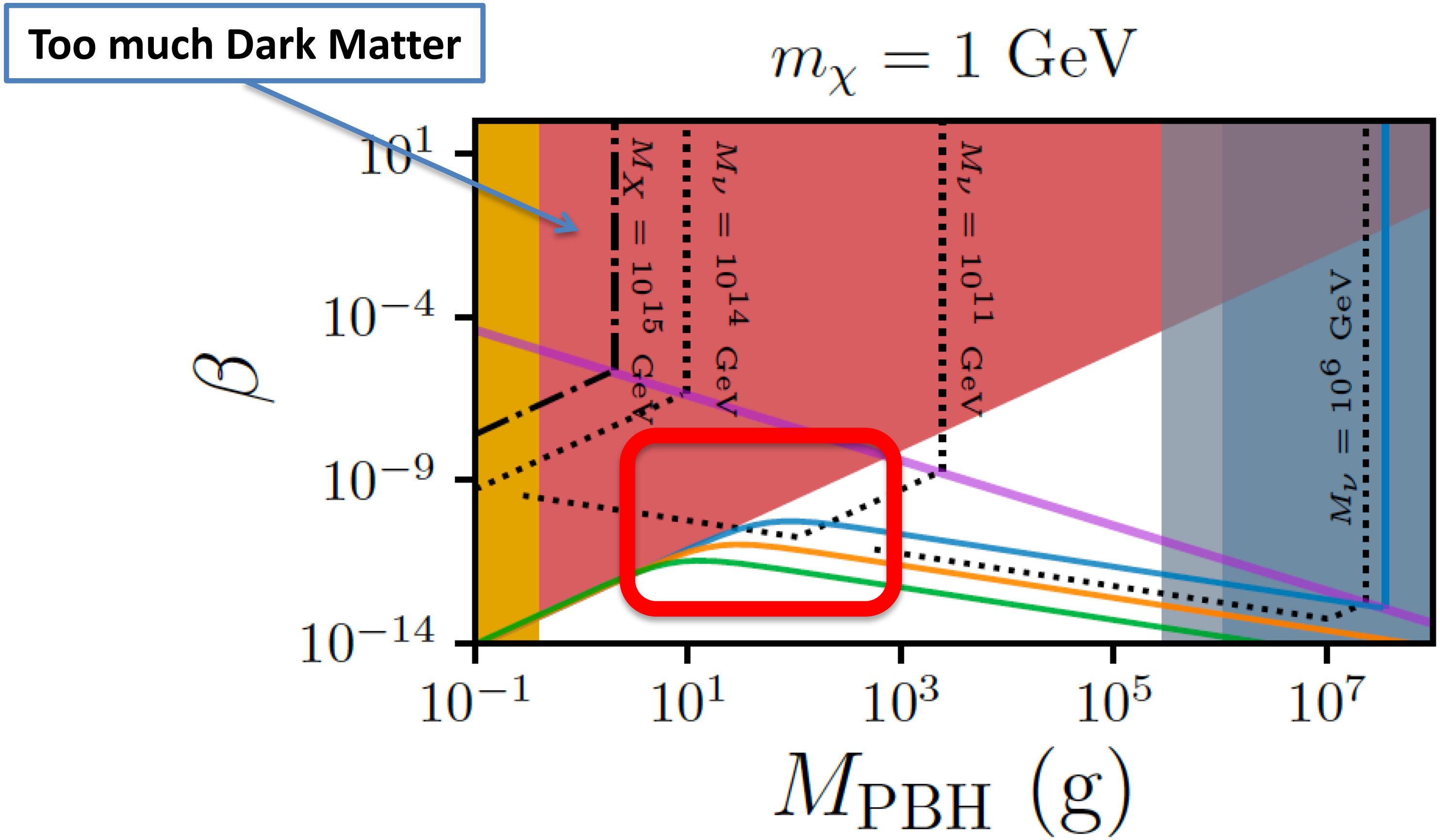
ruled out by BBN (more on that later!)

* Morrison, Profumo and Yu (JCAP, 2019)



* Morrison, Profumo and Yu (JCAP, 2019)

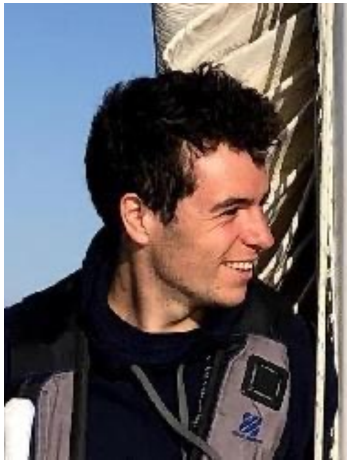
Dark Matter can be a mix of Planck-scale relics from PBH evaporation, and stuff the PBH evaporated into!



* Morrison, Profumo and Yu (JCAP, 2019)

Alternately, evaporation can seed gravitational baryo- (or DM-) genesis

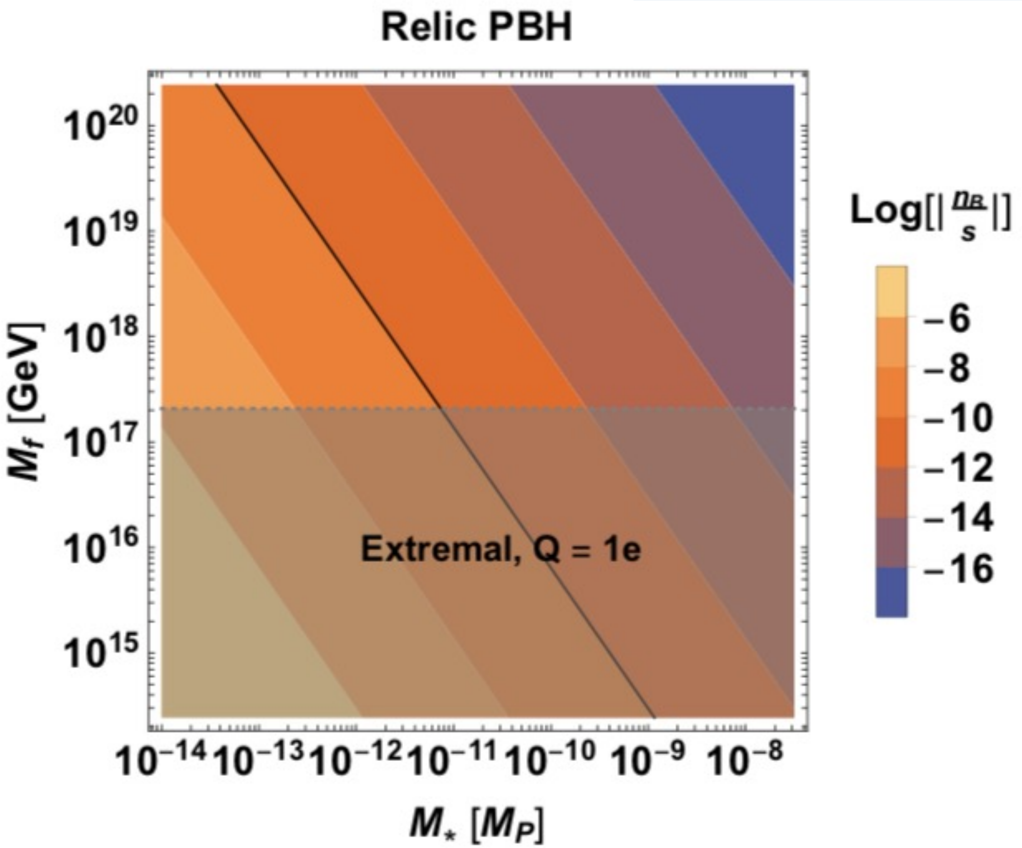
L. Santos-Olmsted



N. Smyth

$$\mathcal{S} \supset \frac{1}{M_*^4}\partial_\alpha(\mathcal{R}_{\mu\nu\rho\sigma}\mathcal{R}^{\mu\nu\rho\sigma})J^\alpha_{\mathrm{B-L}}$$

Kretschmann scalar



*** Smyth, Santos-Olmsted, Profumo 2110.14660 (2021)**

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

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

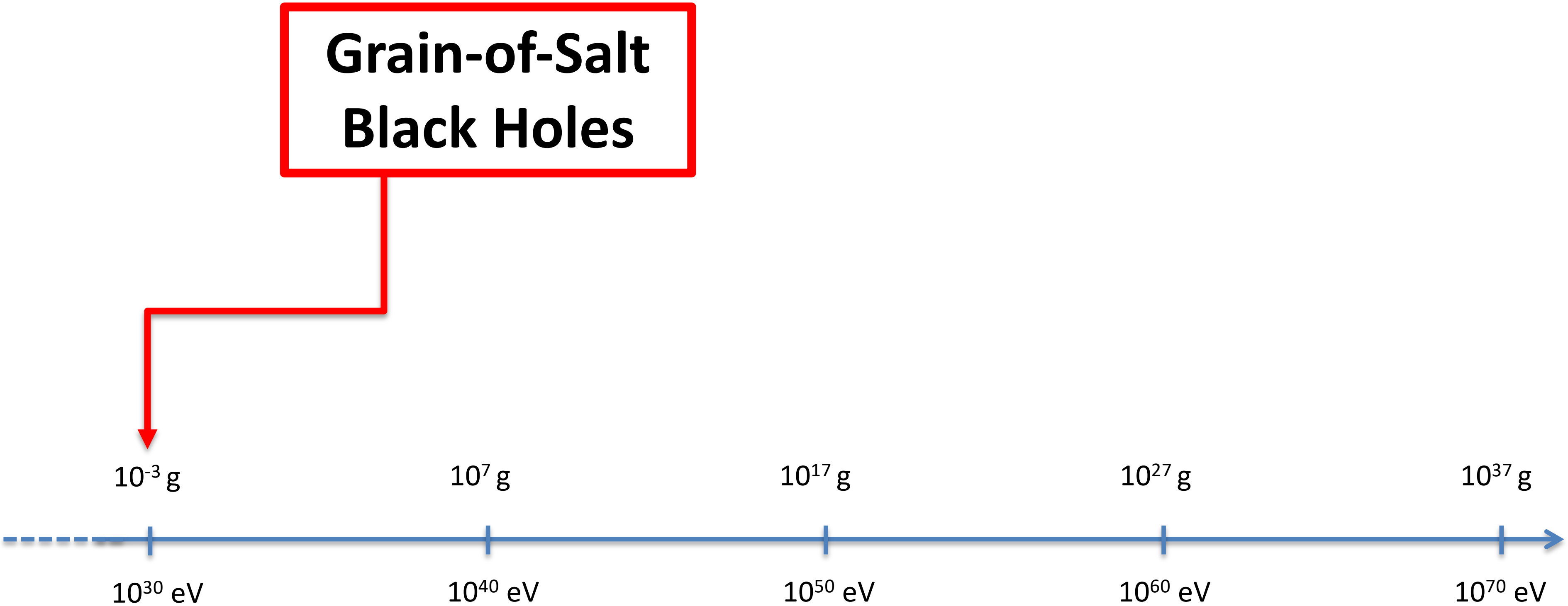
$$P(Q) \sim \exp\left(-4\pi\alpha(Q/e)^2\right)$$

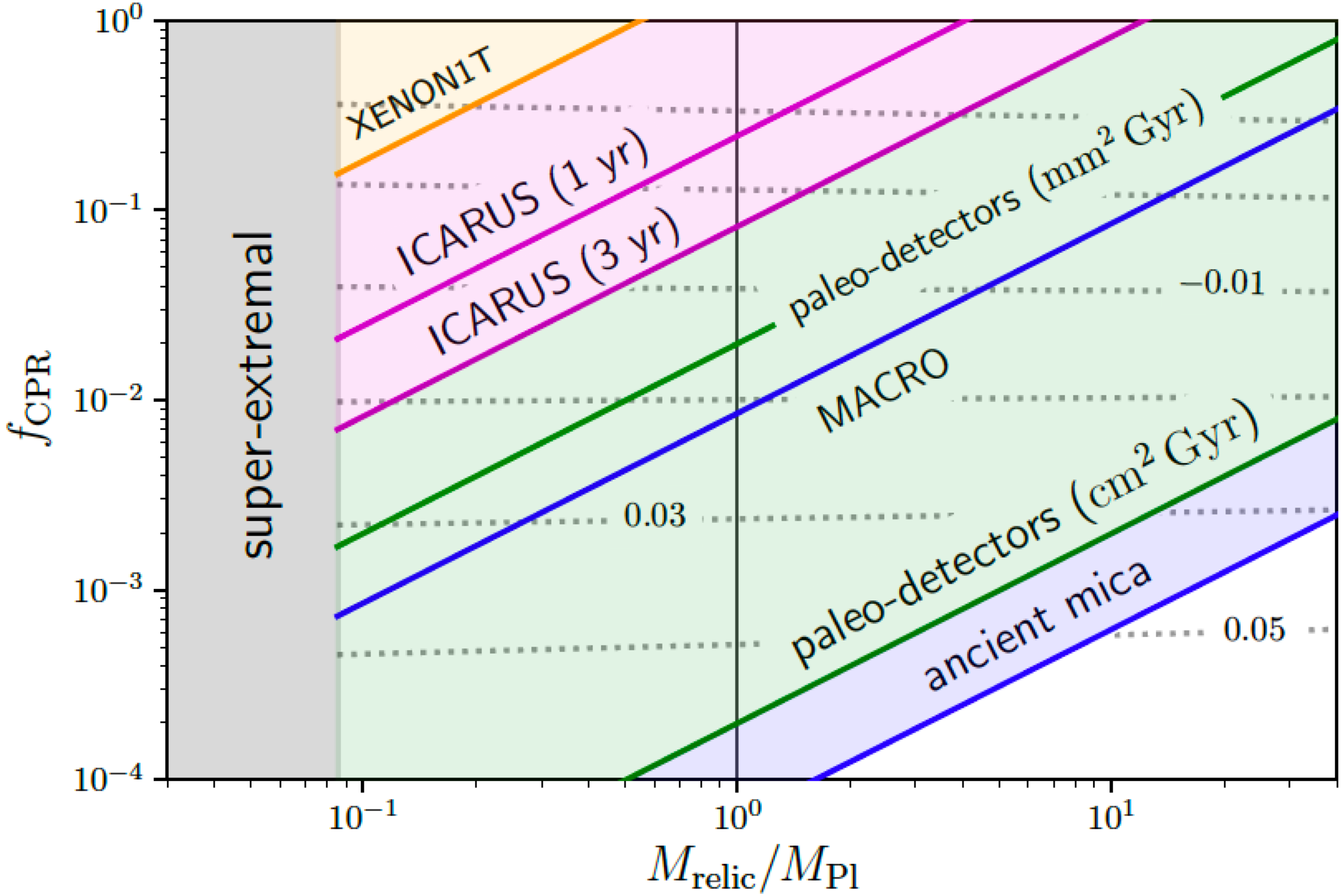
$$(8\pi\alpha)^{-1/2} \approx 2.34$$

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]

[1] *Faculty of Mathematics, Phy*
[1] *Department of Theoretical P*

17v1 [gr-qc] 11 Feb 2021

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

Benjamin V. Lehmann[1,2,*] and Stefano Profumo[1,2,†]

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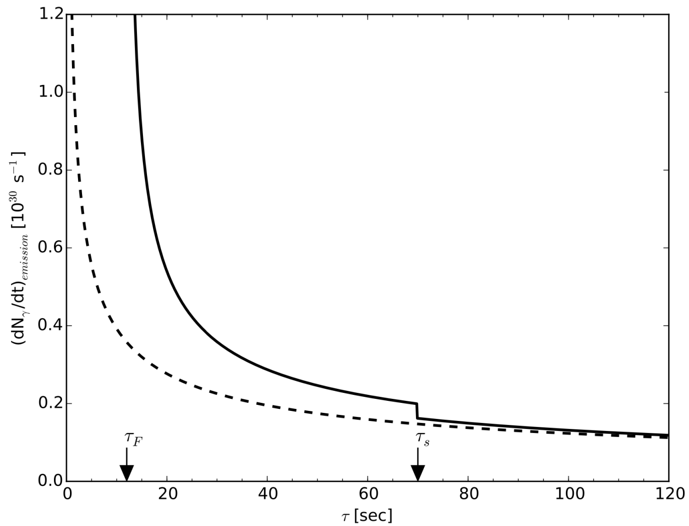
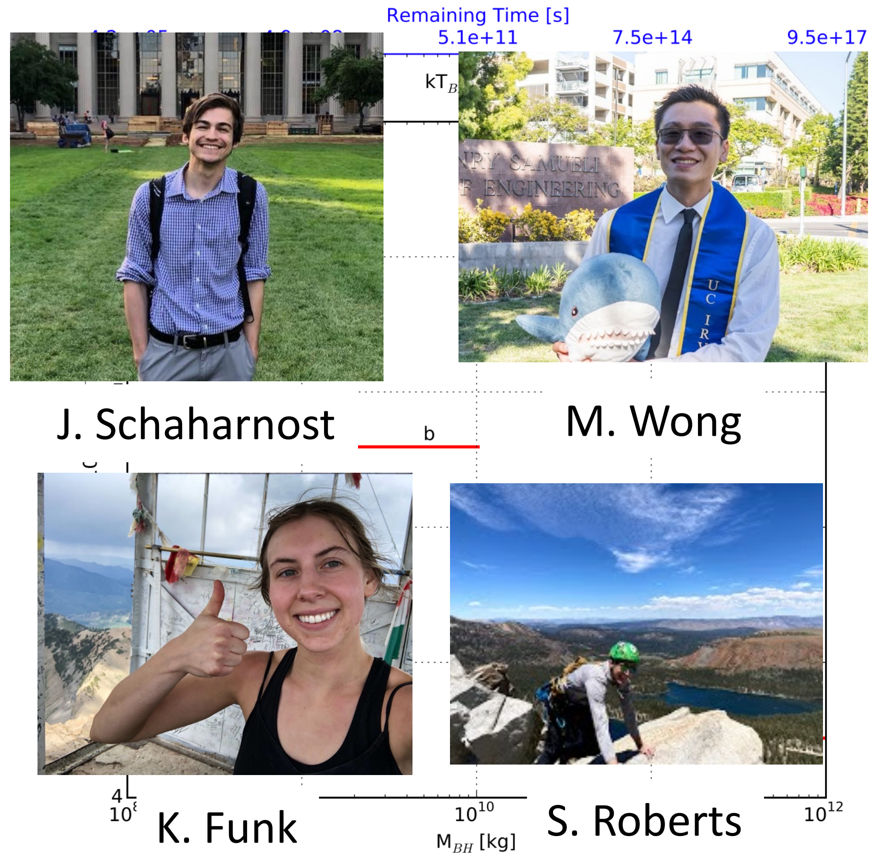
We comment on recent claims that recoil in the final stages of Hawking evaporation gives black hole remnants large velocities, rendering them inviable as a dark matter candidate. We point out that due to cosmic expansion, such large velocities at the final stages of evaporation are not in tension with 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**

What if the dark matter is completely secluded?





…if we observed a rapidly evaporating black hole, we could do a complete particle census!

What if the dark matter is completely secluded?

how can such small (~10^{10} grams) and rapidly evaporating black holes emerge?

very late-time phase transitions?
collisions of sub-critical macroscopic dark matter clumps (e.g. strangelets)??

W. DeRocco

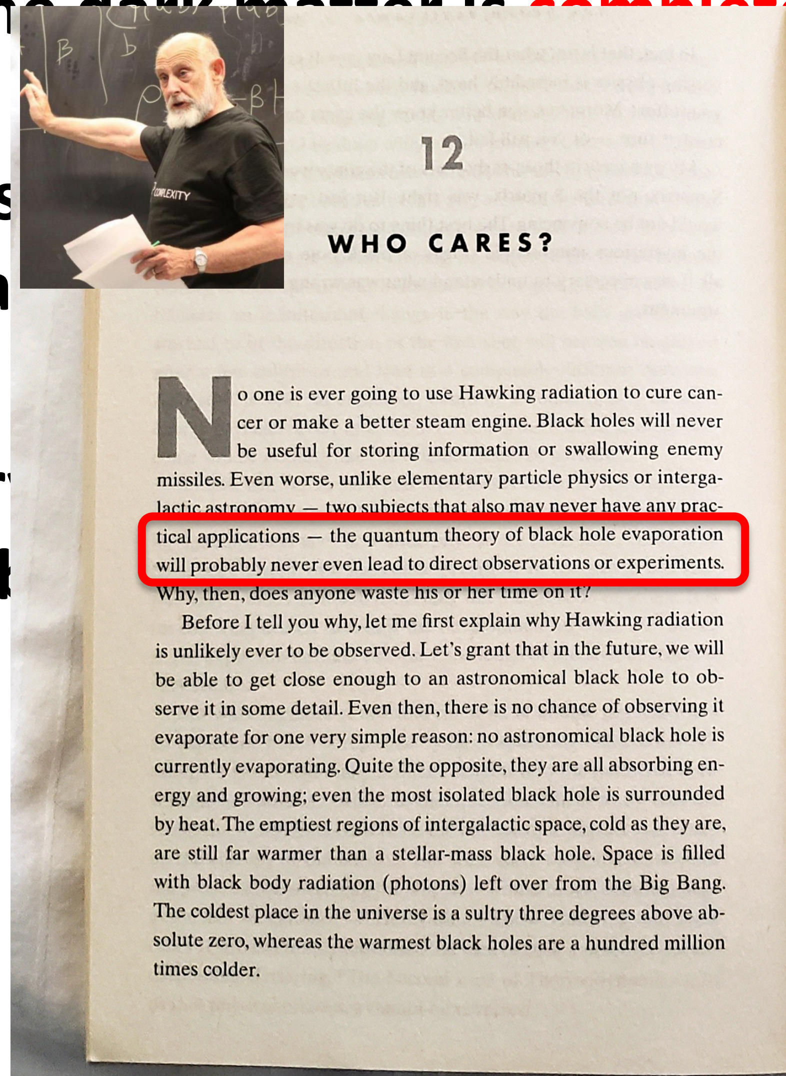
What if th ... ely secluded?

how can s ... nd rapidly

eva ... rge?

ver ... ons?

collisions of sub ... k matter clumps



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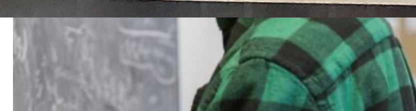
WHO CARES?

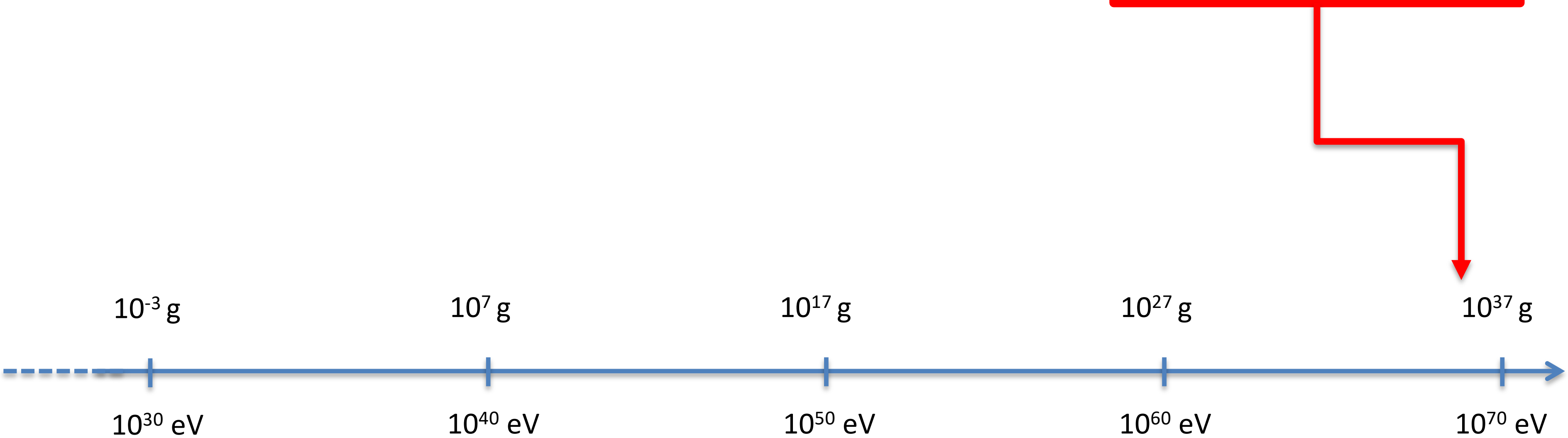
No one is ever going to use Hawking radiation to cure cancer or make a better steam engine. Black holes will never be useful for storing information or swallowing enemy missiles. Even worse, unlike elementary particle physics or intergalactic astronomy — two subjects that also may never have any practical applications — the quantum theory of black hole evaporation will probably never even lead to direct observations or experiments. Why, then, does anyone waste his or her time on it?

Before I tell you why, let me first explain why Hawking radiation is unlikely ever to be observed. Let's grant that in the future, we will be able to get close enough to an astronomical black hole to observe it in some detail. Even then, there is no chance of observing it evaporate for one very simple reason: no astronomical black hole is currently evaporating. Quite the opposite, they are all absorbing energy and growing; even the most isolated black hole is surrounded by heat. The emptiest regions of intergalactic space, cold as they are, are still far warmer than a stellar-mass black hole. Space is filled with black body radiation (photons) left over from the Big Bang. The coldest place in the universe is a sultry three degrees above absolute zero, whereas the warmest black holes are a hundred million times colder.

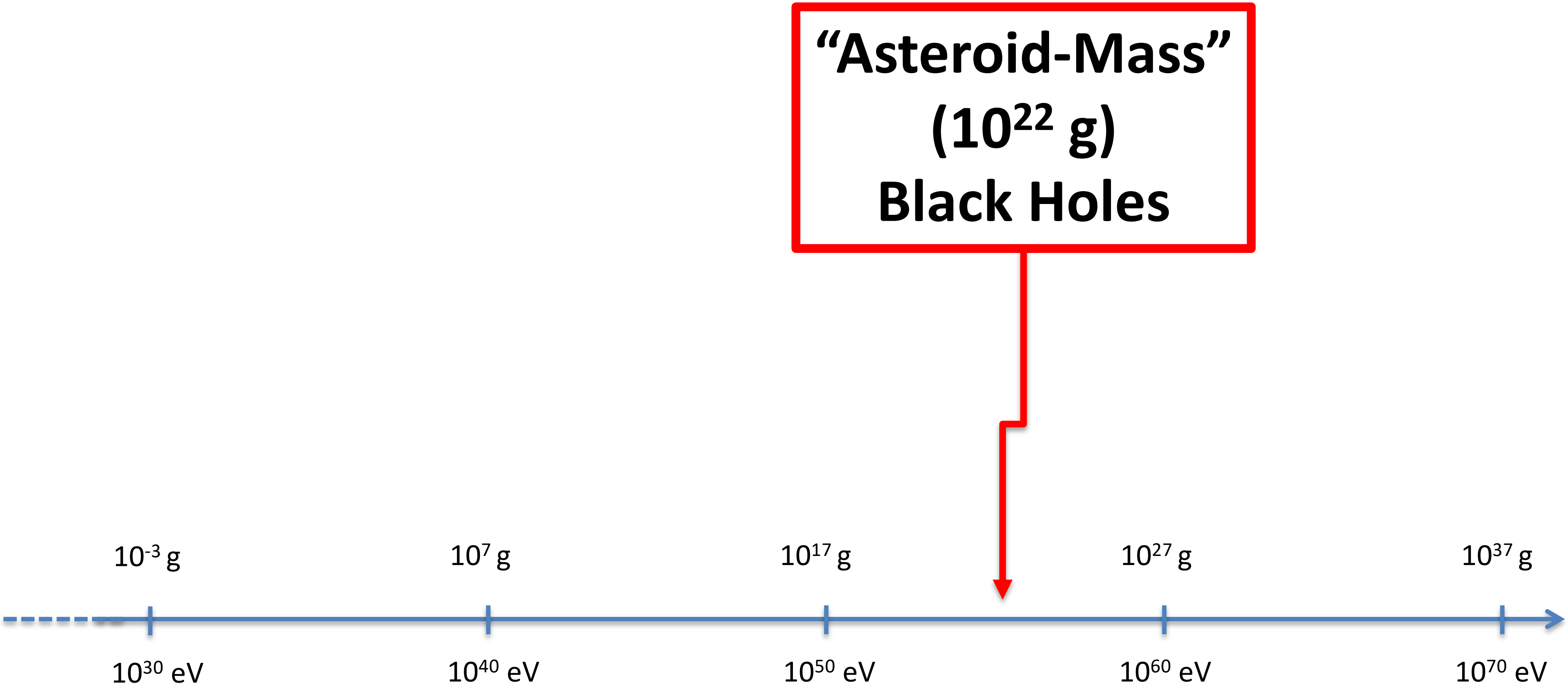


W. DeRocco

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

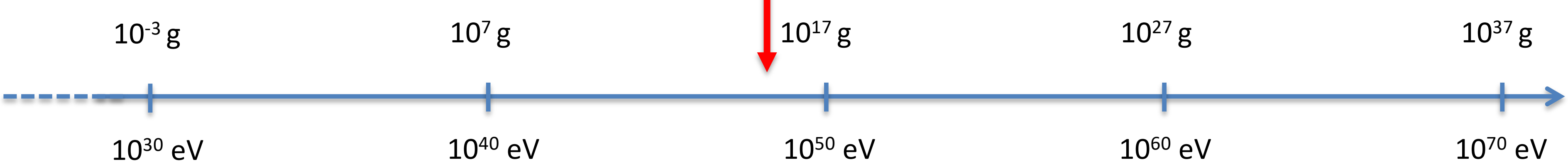


- ✓ **Sub-Chandrasekhar goldilocks!!**
- ✓ **How do they arise? Dark QED sector?**



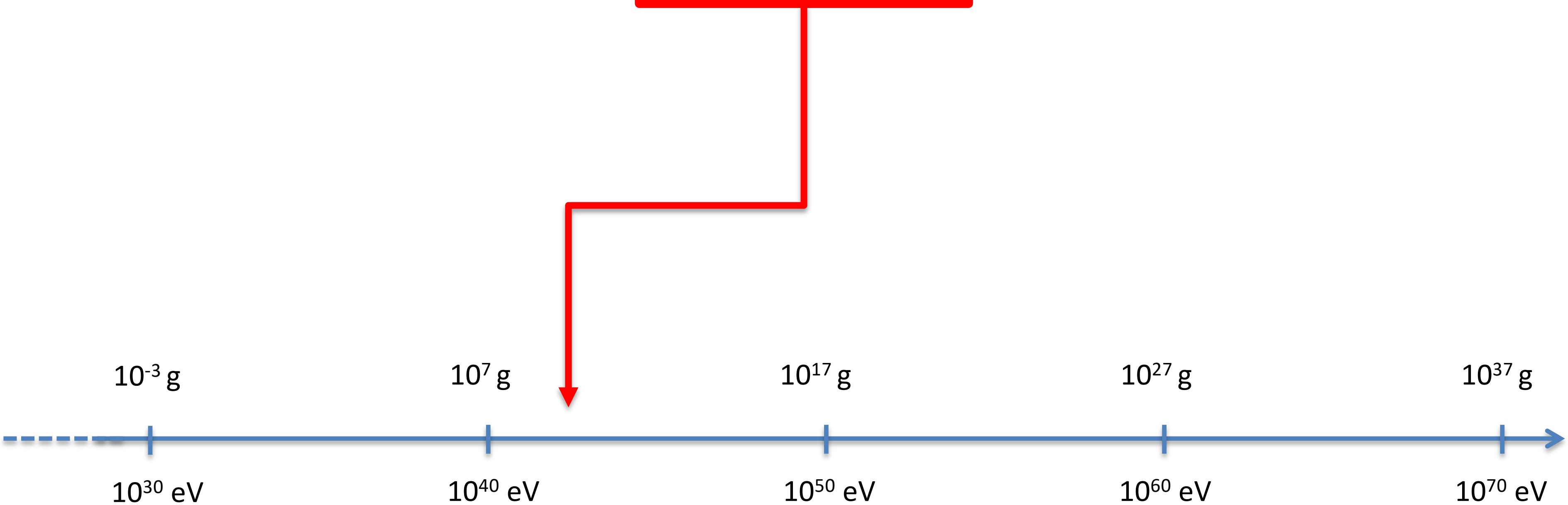
✓ **Microlensing a lot trickier than previously thought!**

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

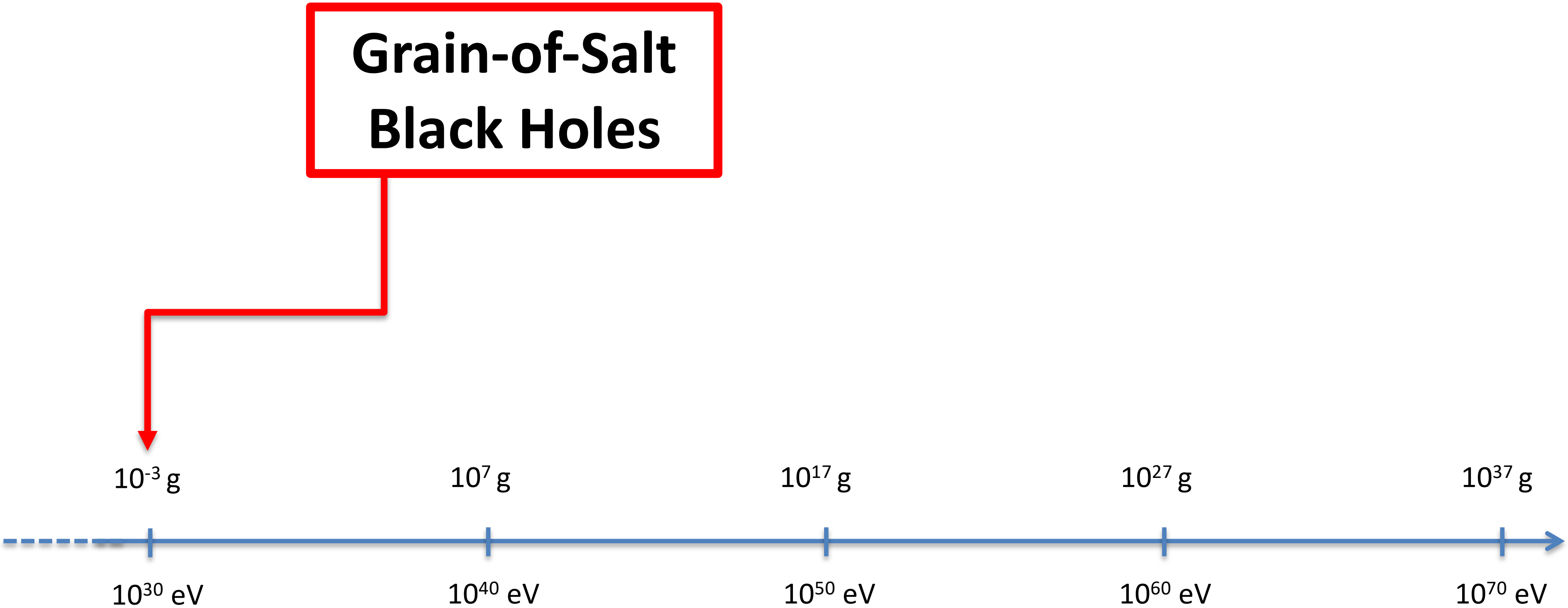


- ✓ **Best constraints: COMPTEL**
- ✓ **Future MeV telescopes**

Ton-size Black Holes



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



- ✓ **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