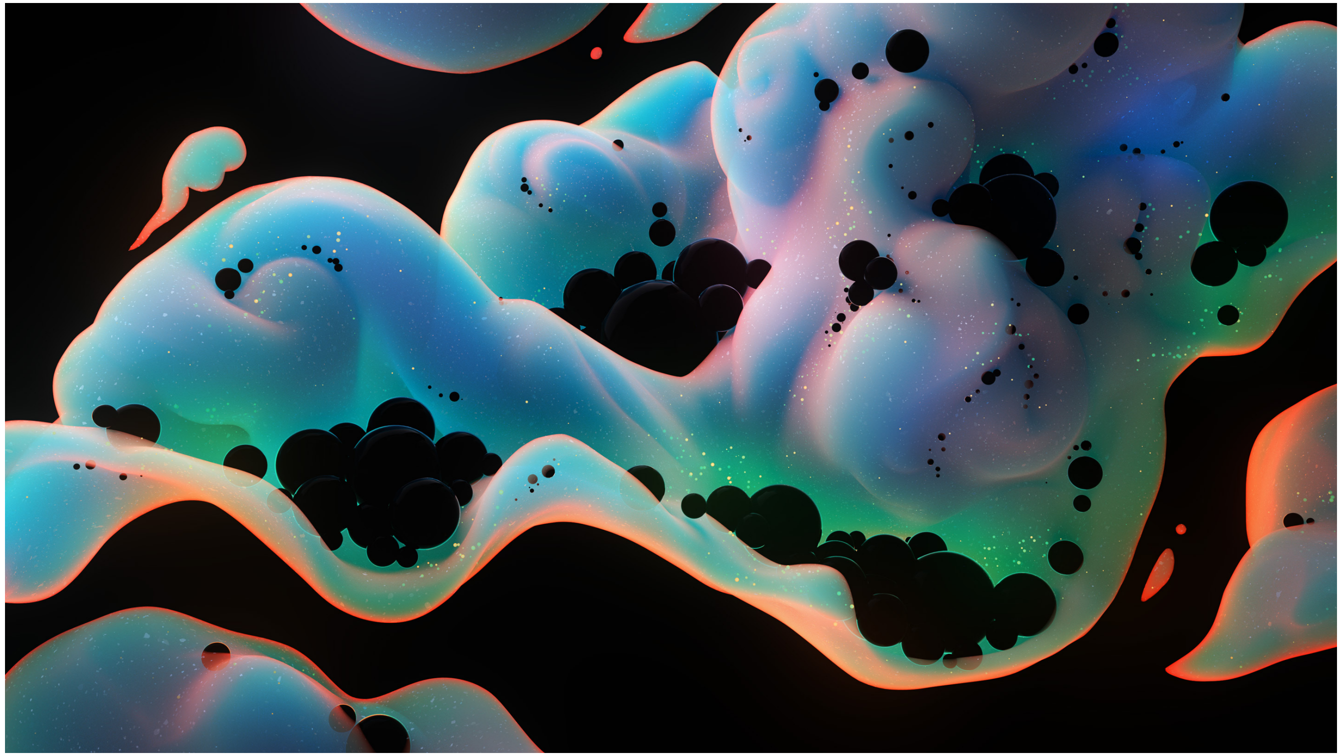
Stefano Profumo

University of California, Santa Cruz
Santa Cruz Institute for Particle Physics

Black Holes as Dark Matter



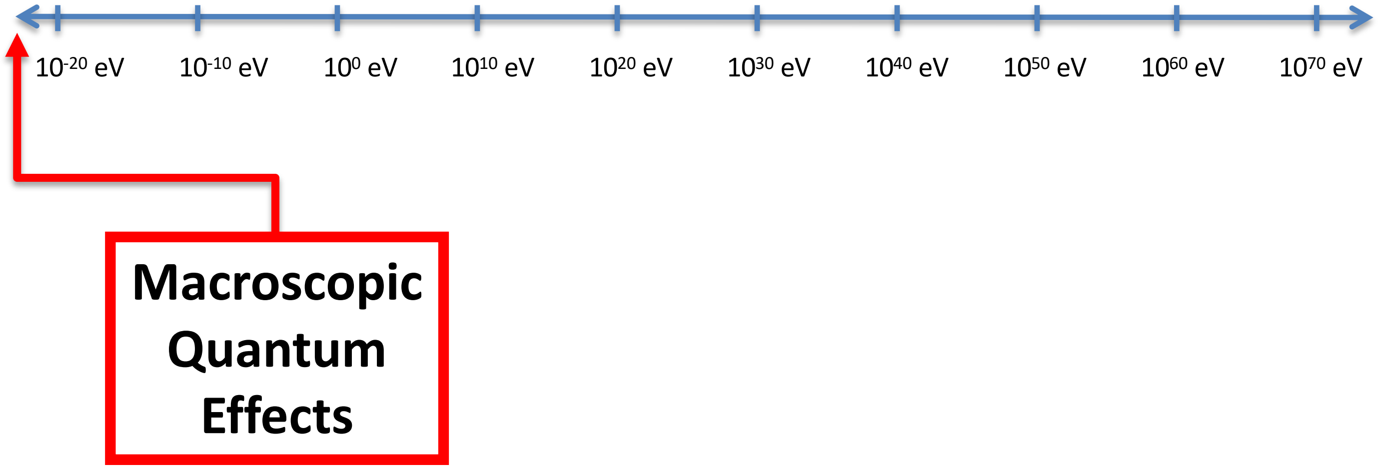
CATCH22+2

Dublin, May 2024

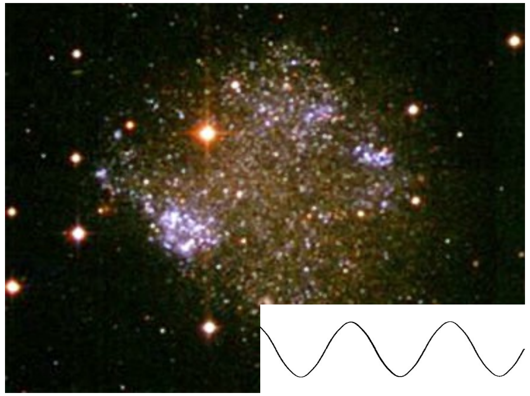
*art by Olena Shmahalo
Quanta Magazine

(m, J)

(m, J)



Macroscopic Quantum Effects



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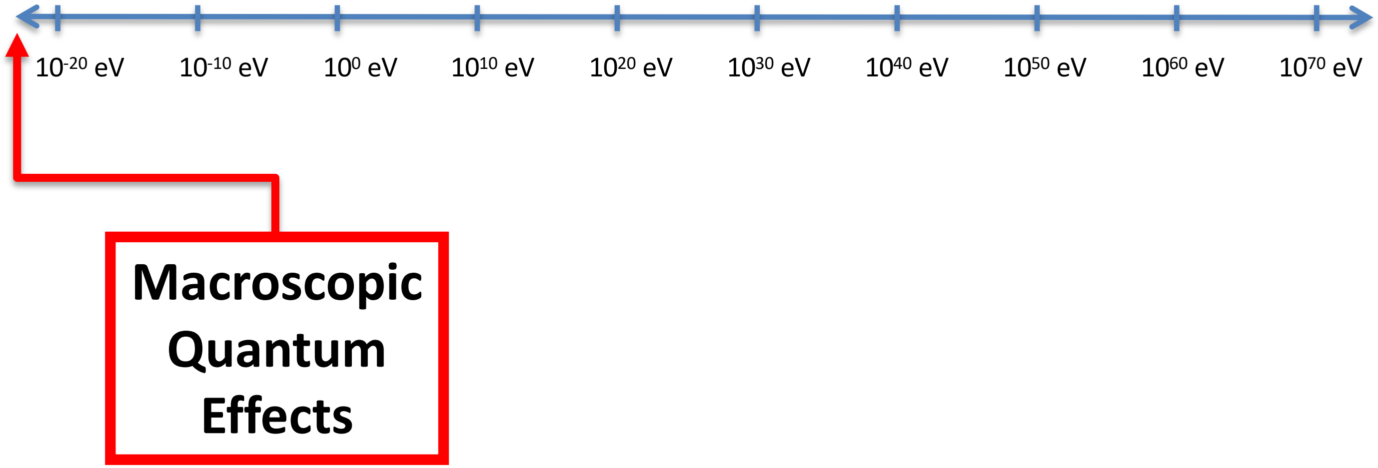

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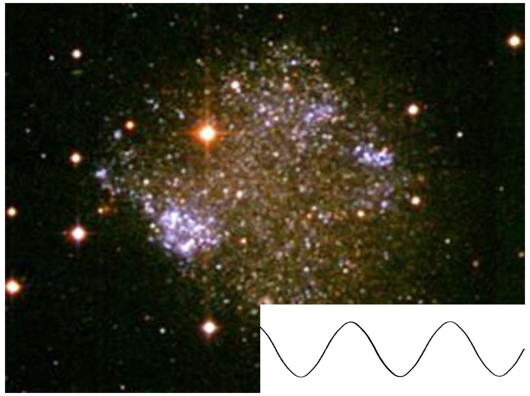
Macroscopic Quantum Effects



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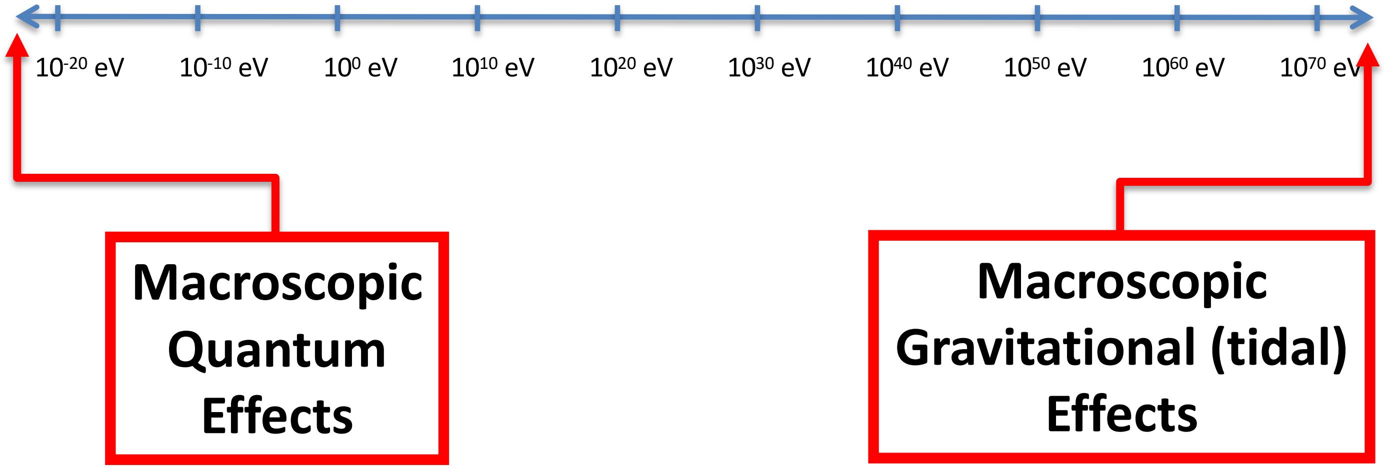
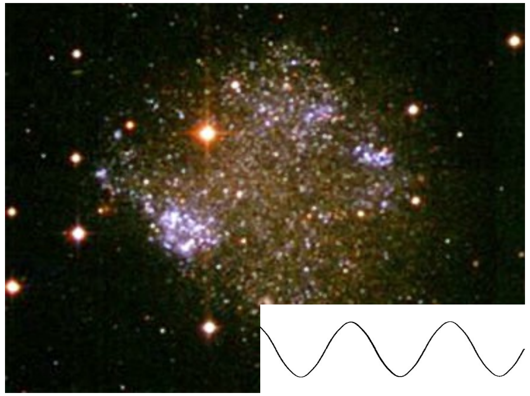


10^{-20} eV 10^{-10} eV 10^{0} eV 10^{10} eV 10^{20} eV 10^{30} eV 10^{40} eV 10^{50} eV 10^{60} eV 10^{70} eV

Macroscopic Quantum Effects

Macroscopic Gravitational (tidal) Effects



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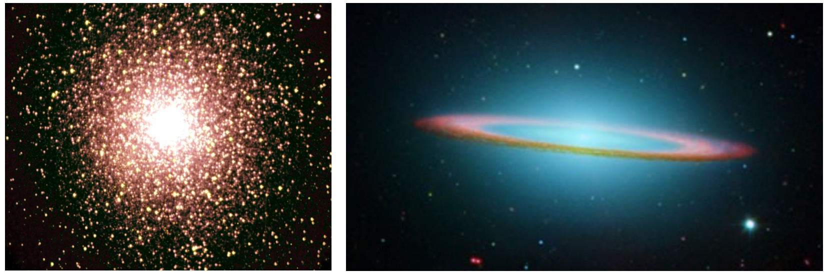
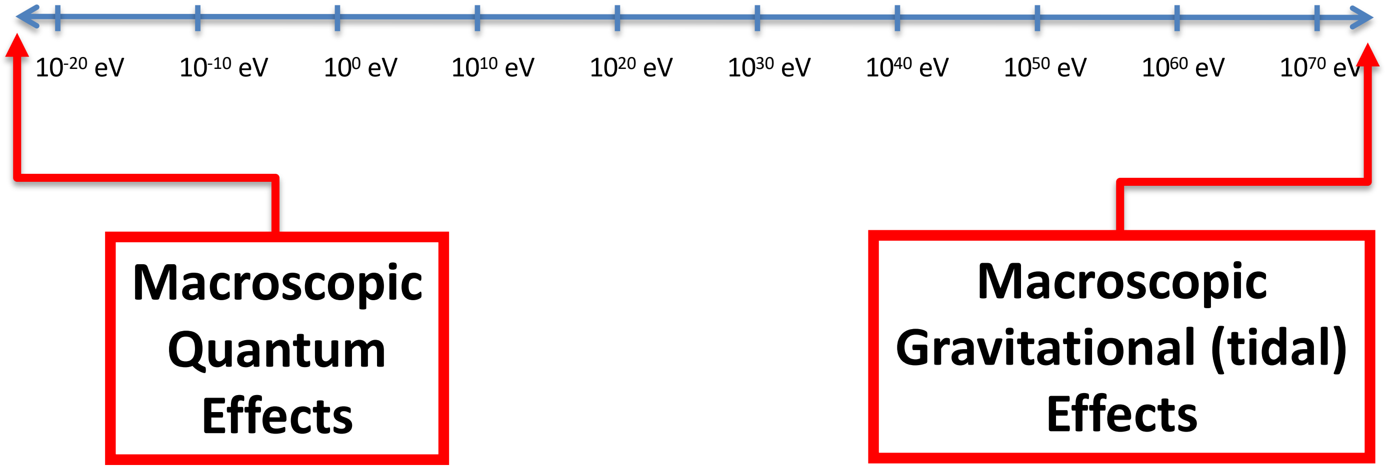
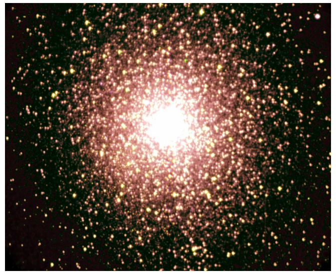




Macroscopic Quantum Effects

Macroscopic Gravitational (tidal) Effects

(m, J)



State of the art: Koulen, Profumo & Smyth 2403.1901

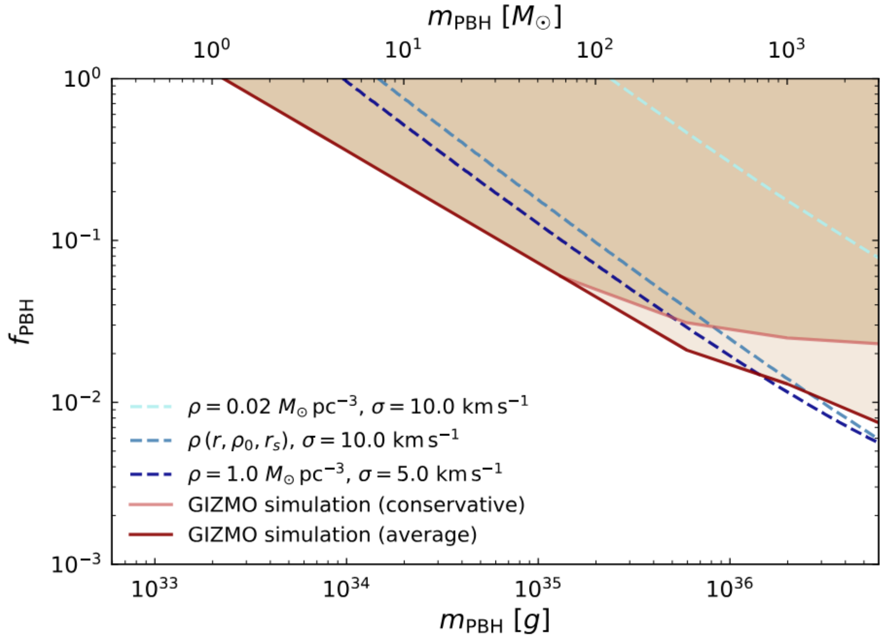
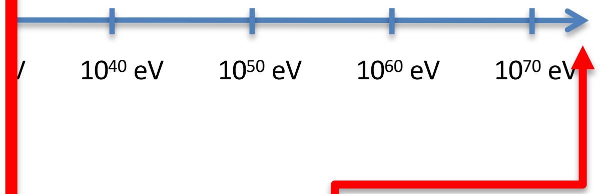
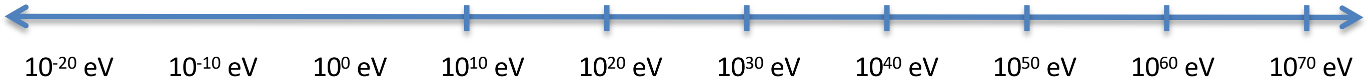


Figure 5. **Constraints on $f_{\rm PBH}$ as a function of $m_{\rm PBH}$.** Limits are derived using the average $r_{\rm h}$ over 50 simulations for each mass. Also shown is a conservative case using $r_{\rm h}$ one standard deviation below the mean. The dashed lines are the semi-analytically derived constraints.



Macroscopic Gravitational (tidal) Effects



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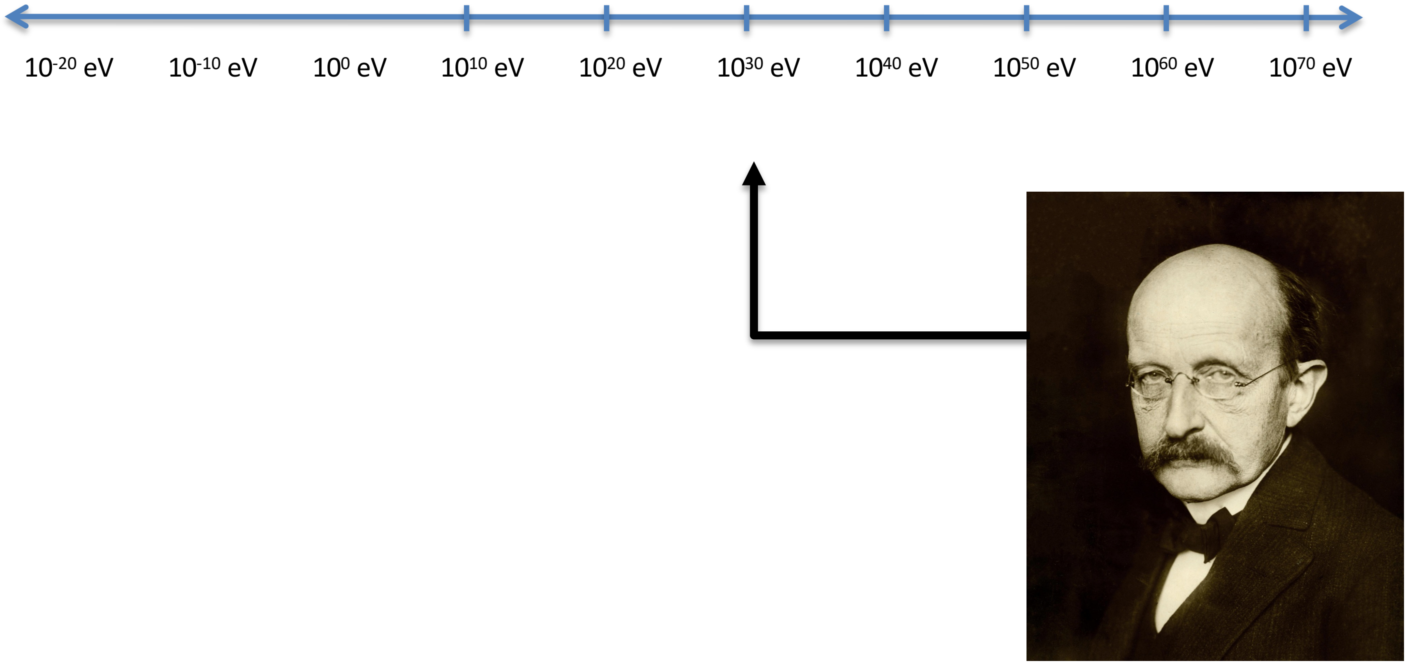


10^{-20} eV 10^{-10} eV 10^{0} eV 10^{10} eV 10^{20} eV 10^{30} eV 10^{40} eV 10^{50} eV 10^{60} eV 10^{70} eV

$$G = \frac{hc}{2\pi M_{\rm Pl}^2}$$

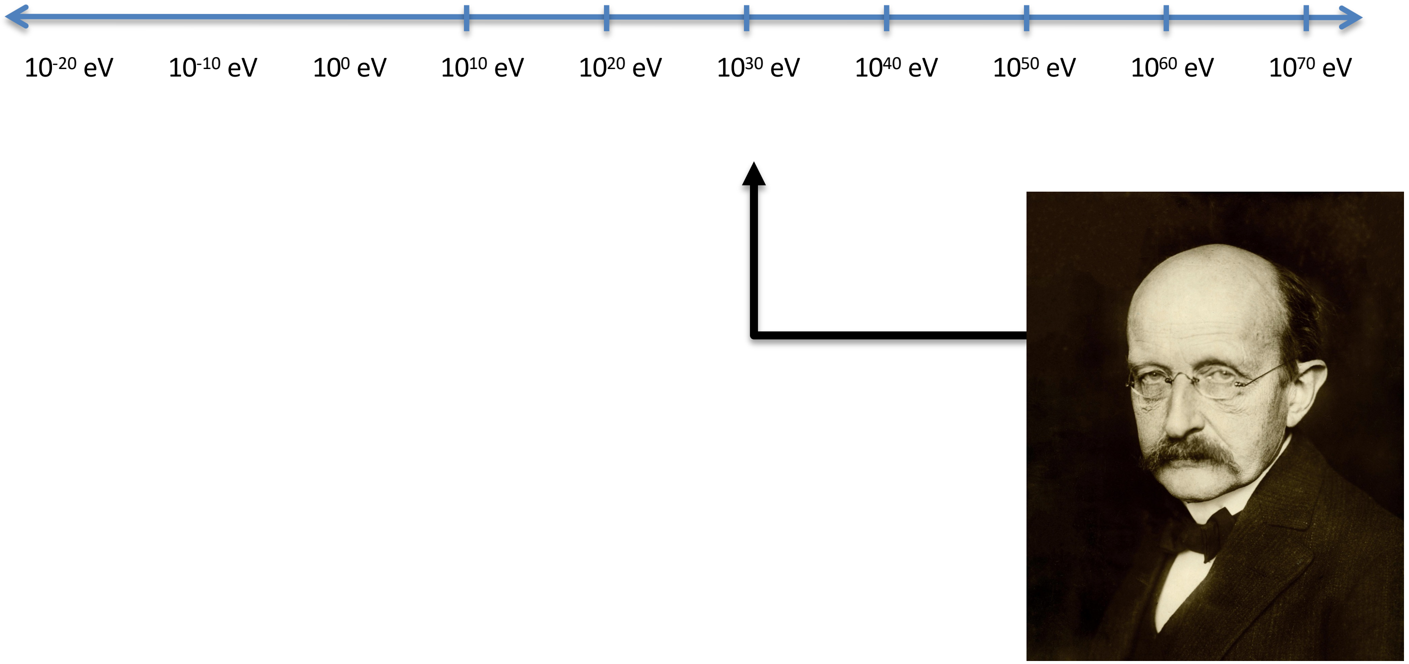
$$R_s = \frac{2Gm}{c^2}$$

Schwarzschild radius

$$\lambda = \frac{h}{mc}$$

Compton wavelength

$$\boxed{R_s(M_{\rm Pl}) = \frac{2hcM_{\rm Pl}}{2\pi c^2 M_{\rm Pl}^2} = \frac{h}{\pi M_{\rm Pl} c} \sim \lambda(M_{\rm Pl})}$$



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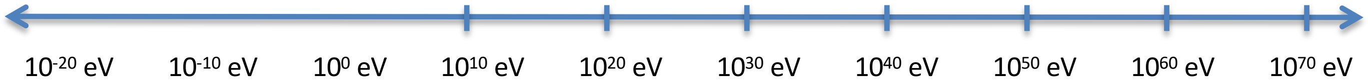
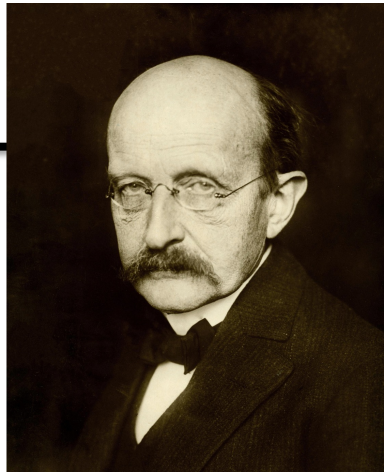


(m, J)



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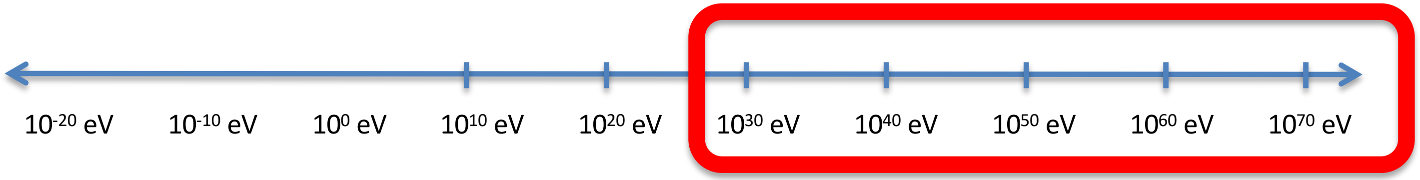

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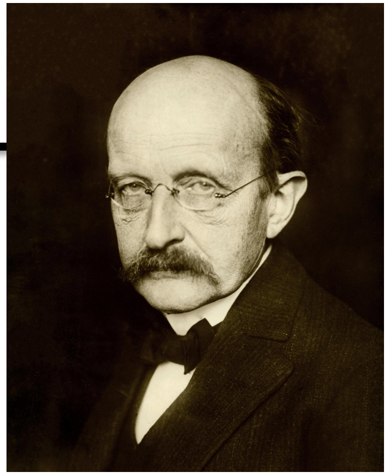
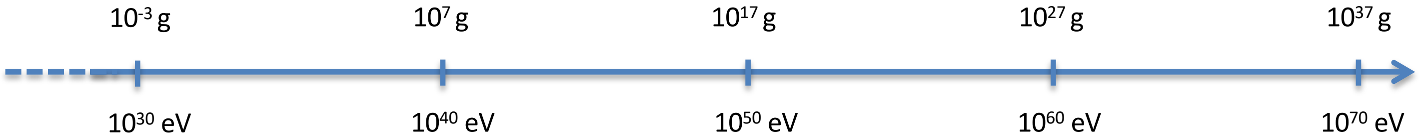
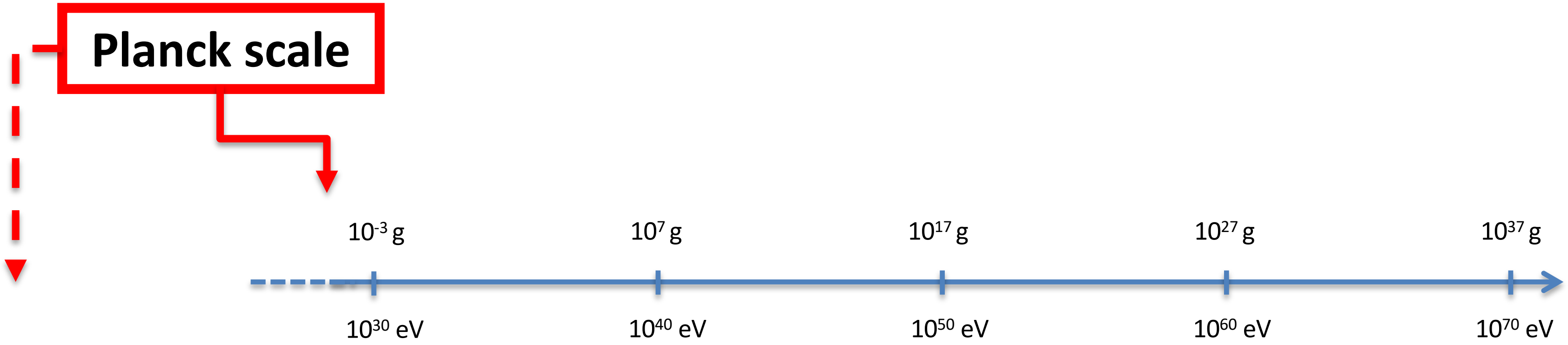


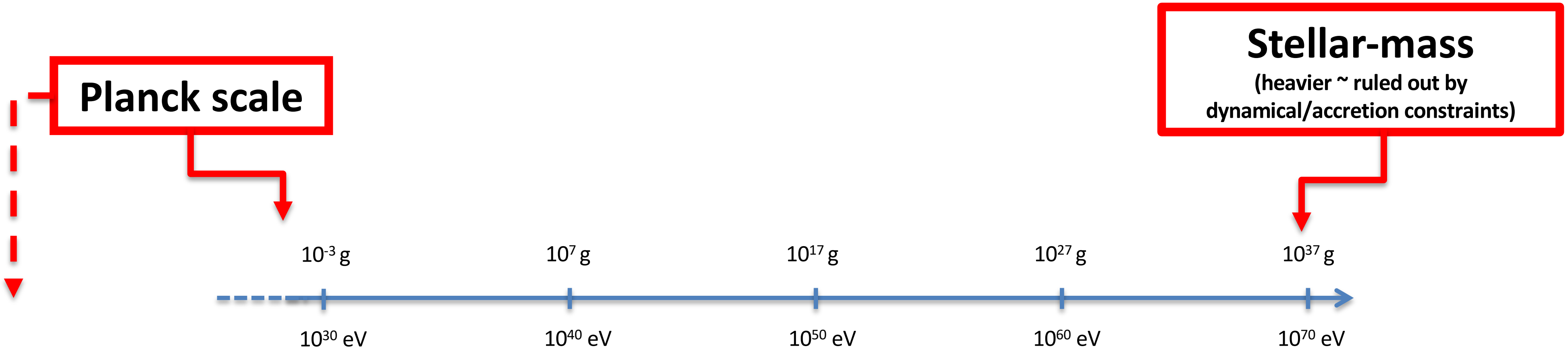


10^{-3} g, 10^{7} g, 10^{17} g, 10^{27} g, 10^{37} g

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



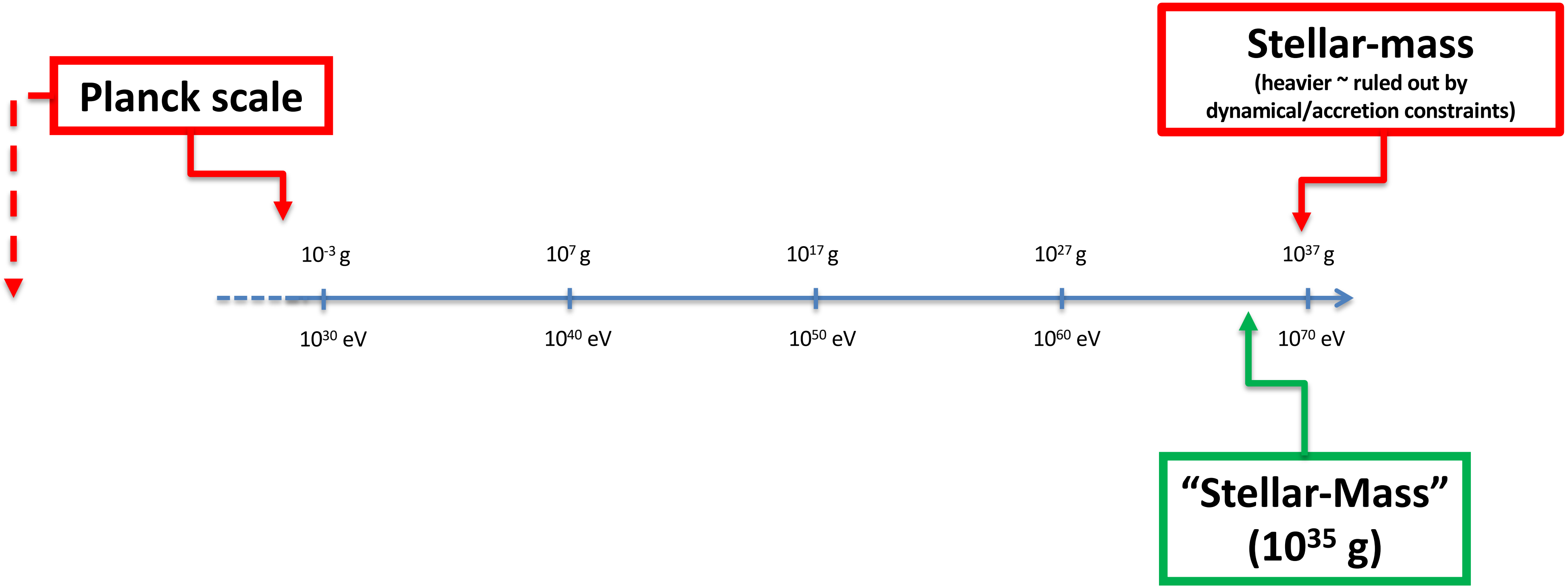
Planck scale



Planck scale

Stellar-mass

(heavier ~ ruled out by dynamical/accretion constraints)



Planck scale

Stellar-mass

(heavier ~ ruled out by dynamical/accretion constraints)

10^{-3} g

10^{7} g

10^{17} g

10^{27} g

10^{37} g

10^{30} eV

10^{40} eV

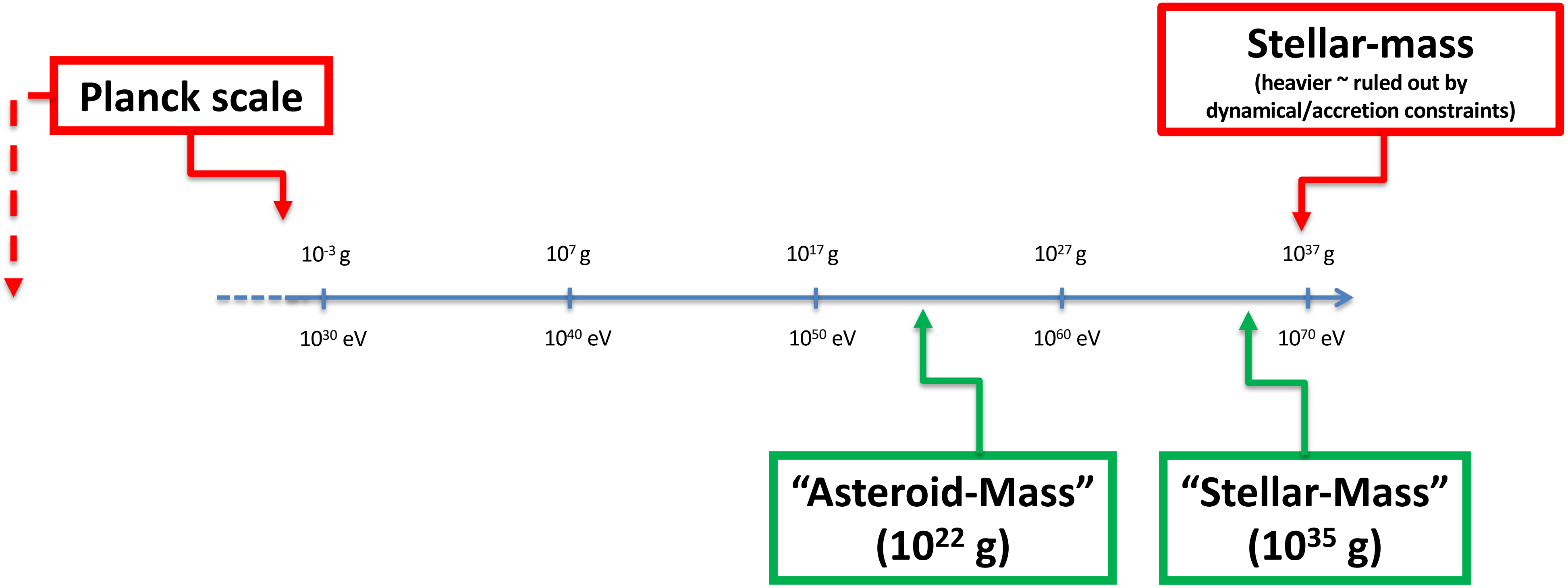
10^{50} eV

10^{60} eV

10^{70} eV

“Stellar-Mass”

(10^{35} g)



Planck scale

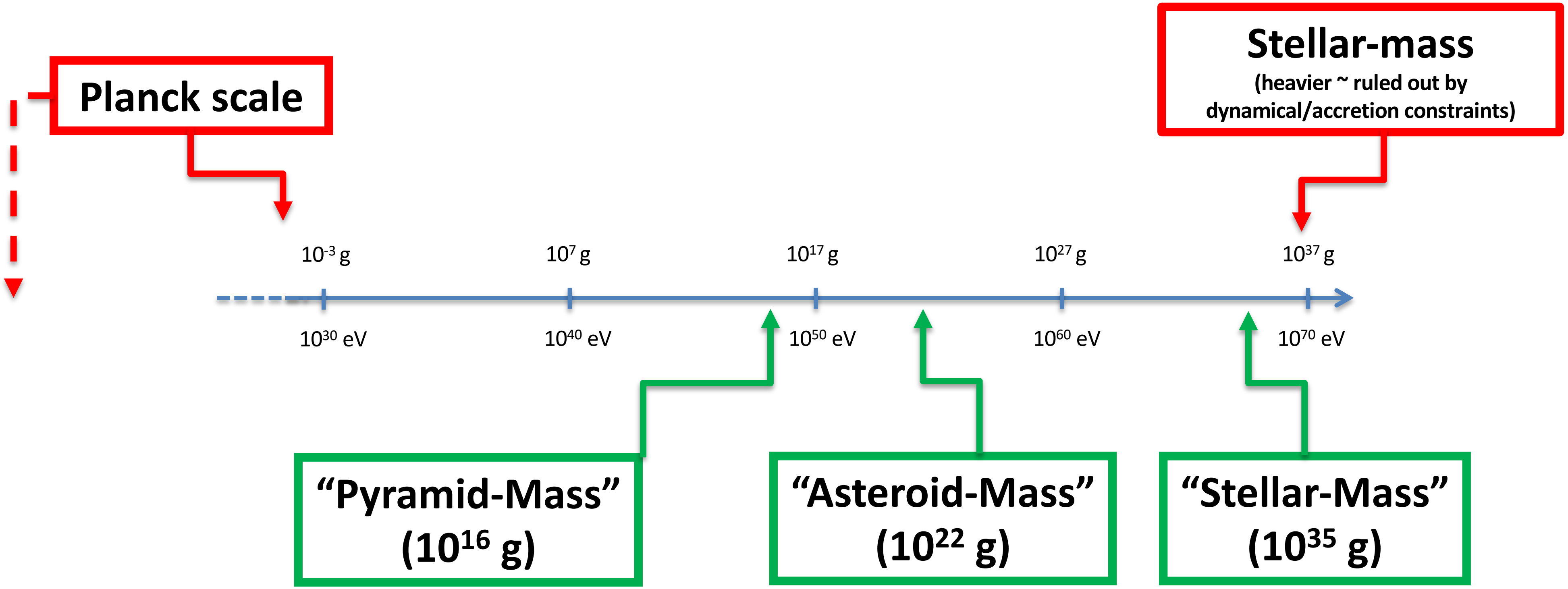
Stellar-mass
(heavier ~ ruled out by dynamical/accretion constraints)

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

“Asteroid-Mass”
(10^{22} g)

“Stellar-Mass”
(10^{35} g)



Planck scale

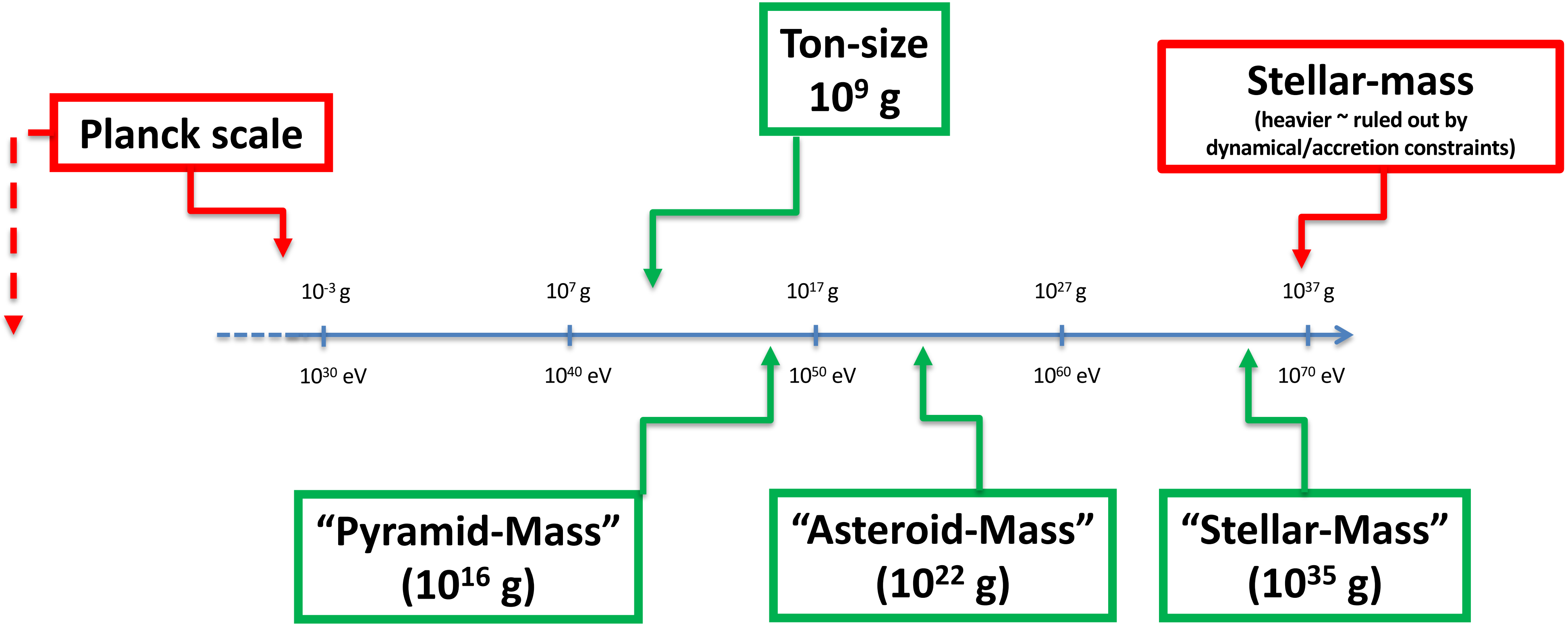
Stellar-mass

(heavier ~ ruled out by dynamical/accretion constraints)

“Pyramid-Mass” (10^{16} g)

“Asteroid-Mass” (10^{22} g)

“Stellar-Mass” (10^{35} g)



Planck scale

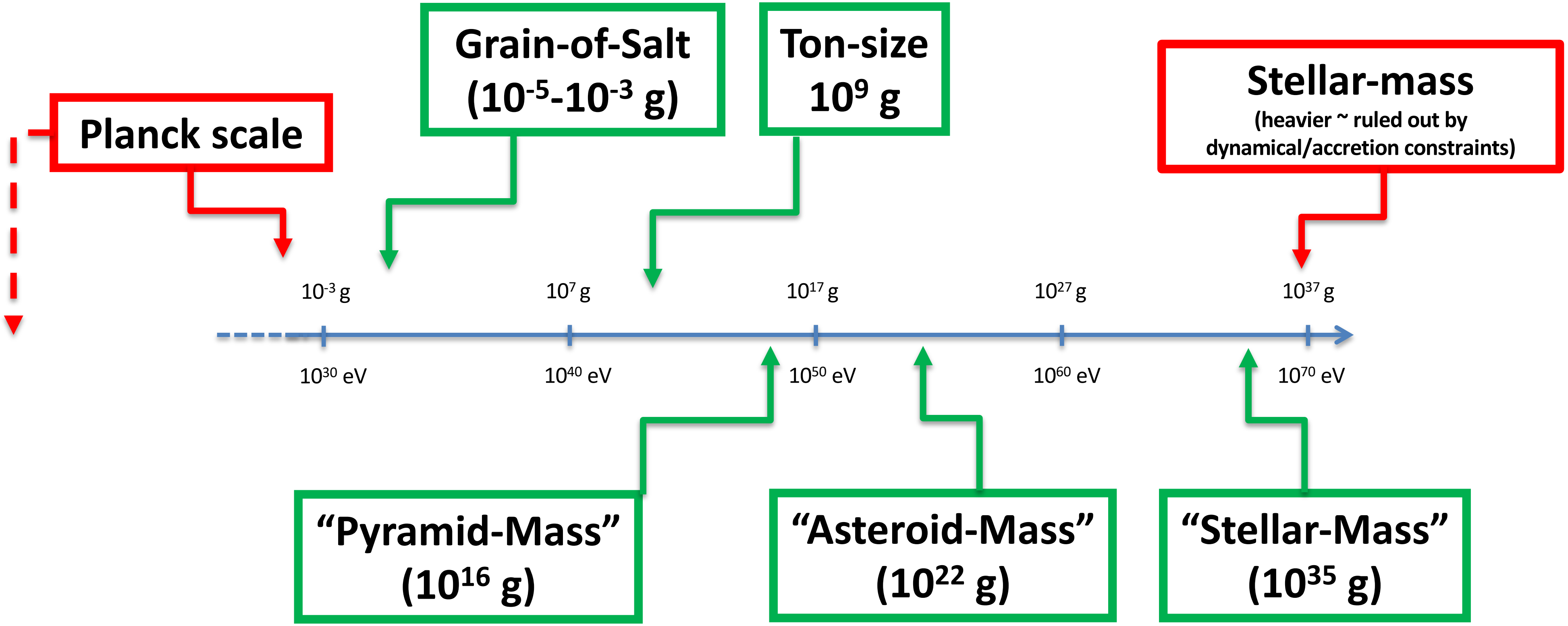
Ton-size
10^9 g

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

“Pyramid-Mass”
(10^{16} g)

“Asteroid-Mass”
(10^{22} g)

“Stellar-Mass”
(10^{35} g)



Planck scale

Grain-of-Salt
(10^{-5}-10^{-3} g)

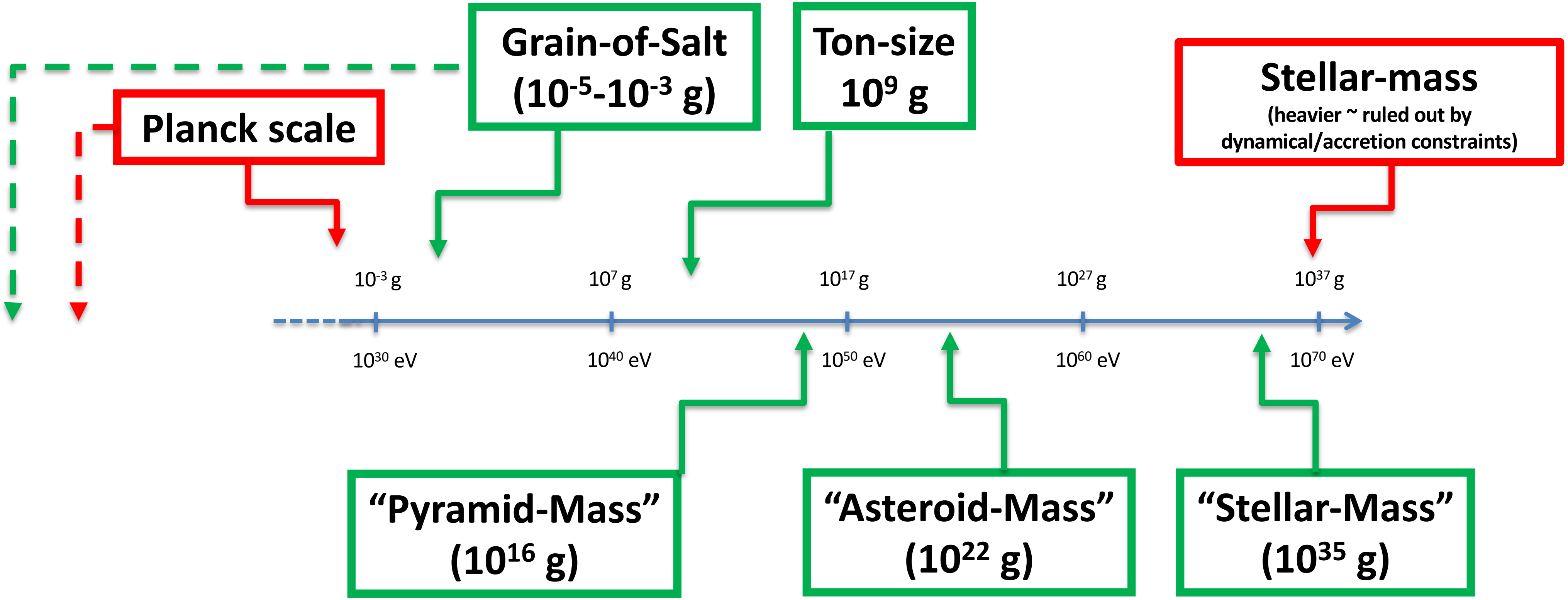
Ton-size
10^{9} g

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

“Pyramid-Mass”
(10^{16} g)

“Asteroid-Mass”
(10^{22} g)

“Stellar-Mass”
(10^{35} g)



Grain-of-Salt (10^{-5}-10^{-3} g)

Ton-size 10^{9} g

Planck scale

Stellar-mass

(heavier ~ ruled out by dynamical/accretion constraints)

"Pyramid-Mass" (10^{16} g)

"Asteroid-Mass" (10^{22} g)

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

If Black Holes are a significant fraction of the dark matter, they are not of stellar origin

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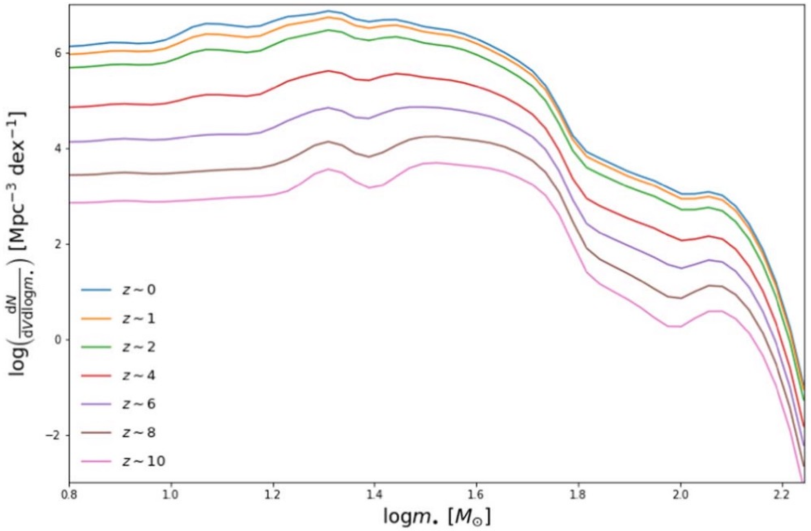
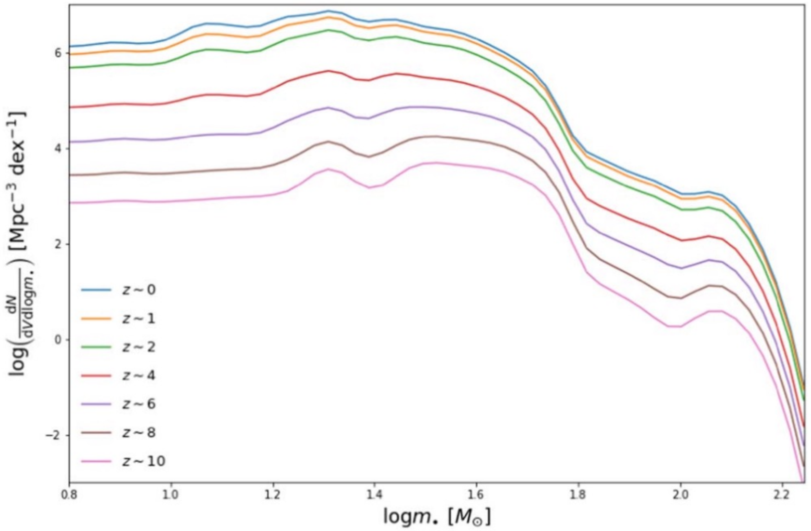


Figure 5. The stellar BH relic mass function $dN/dV\ d\log m_\bullet$ as a function of the BH mass $m_\bullet$ at different redshifts $z \sim 0$ (cyan), $z \sim 1$ (orange), $z \sim 2$ (green), $z \sim 4$ (red), $z \sim 6$ (violet), $z \sim 8$ (brown), and $z \sim 10$ (pink).

Stellar-mass BHs: <0.25% of CDM

*Sicilia+, 2022a; Sicilia+ 2022b

If Black Holes are a significant fraction of the dark matter, they are not of stellar origin



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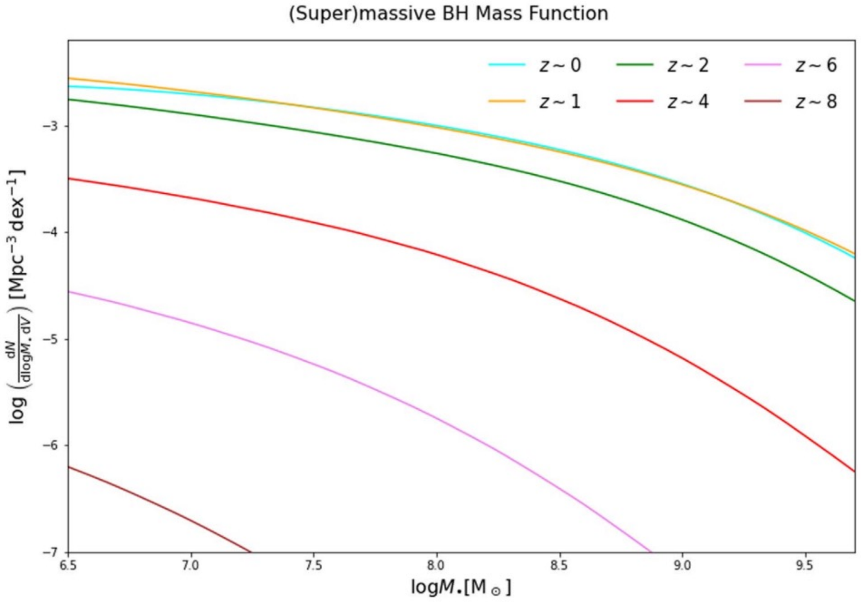


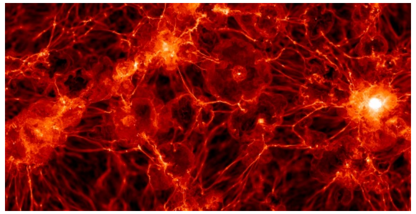
Stellar-mass BHs: <0.25% of CDM

SMBH: <0.002% of CDM

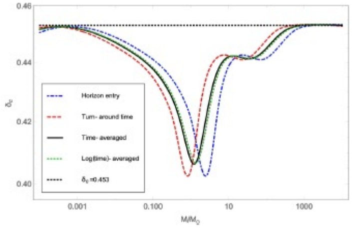
*Sicilia+, 2022a; Sicilia+ 2022b

What this talk will not be about (with apologies): where “primordial” black holes come from

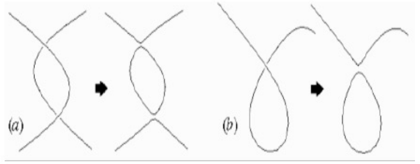
- ➢ **Collapse of large density perturbations**



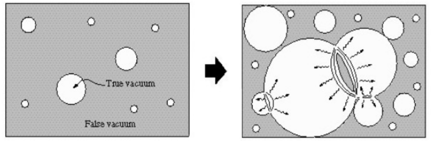
- ➢ **Pressure Reduction**



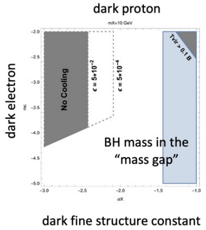
- ➢ **Cosmic Strings Loops**



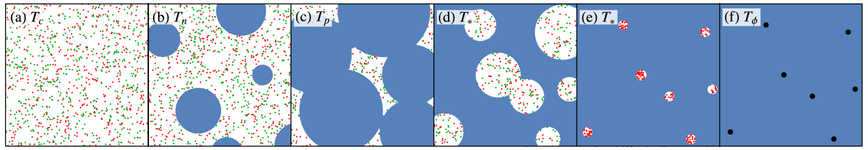
- ➢ **Bubble Collisions**



- ➢ **Dark Stars Collapse***



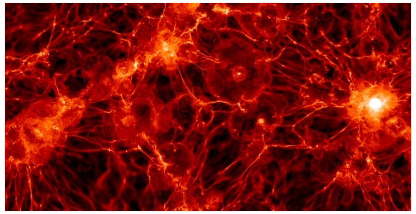
- ➢ **Collapse of trapped fermions**



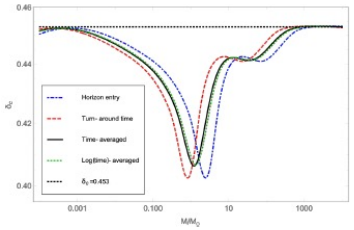
- ➢ **…**

*Fernandez, Profumo+, 2208.08557

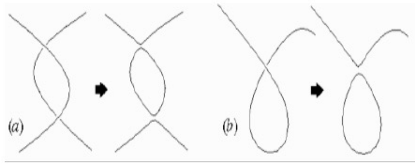
- Collapse of large density perturbations



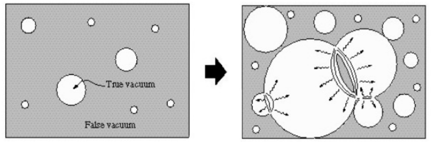
- Pressure Reduction



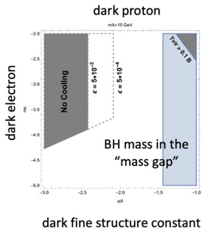
- Cosmic Strings Loops



- Bubble Collisions



- Dark Stars Collapse*



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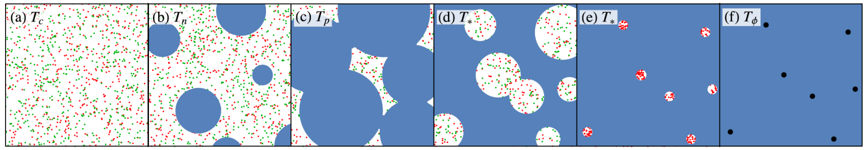
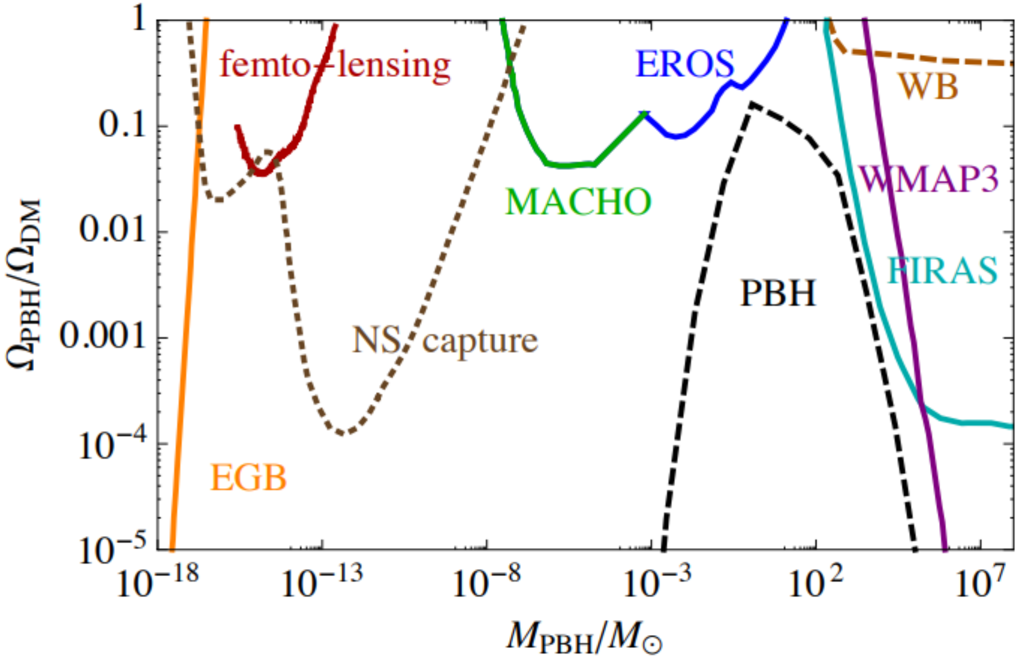


- …

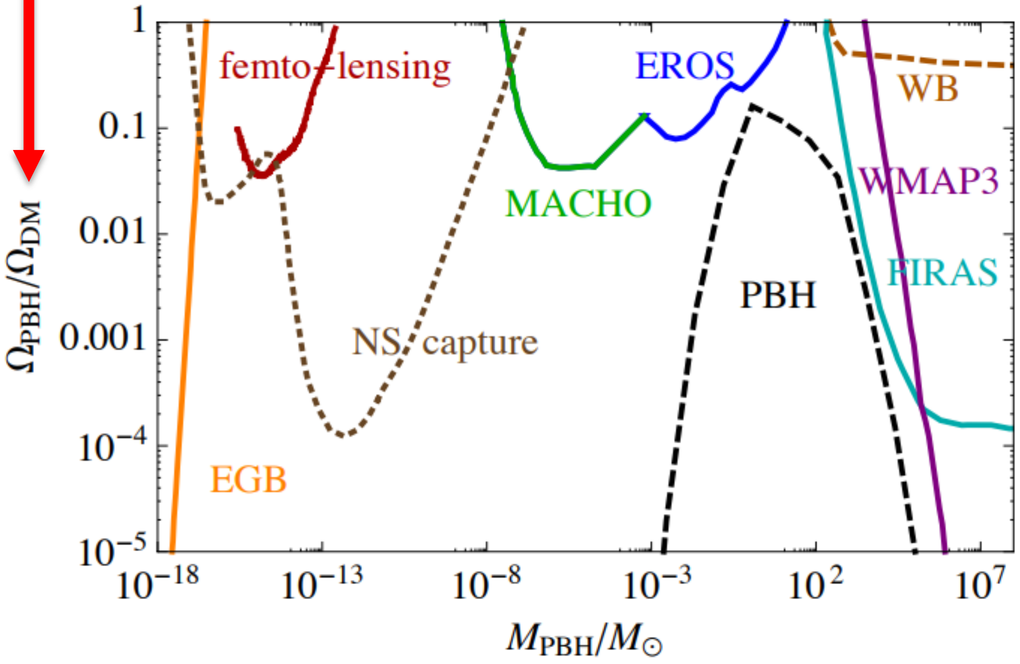
…see Syksy's talk next!

*Fernandez, Profumo+, 2208.08557


1
0.1
0.01
0.001
10^{-4}
10^{-5}
10^{-18}
10^{-13}
10^{-8}
10^{-3}
10^{2}
10^{7}
$\Omega_{\rm PBH}/\Omega_{\rm DM}$
$M_{\rm PBH}/M_\odot$
femto-lensing
EROS
WB
MACHO
WMAP3
FIRAS
PBH
NS capture
EGB

<2019

Fraction of the dark matter consisting of non-stellar BHs of given mass



<2019

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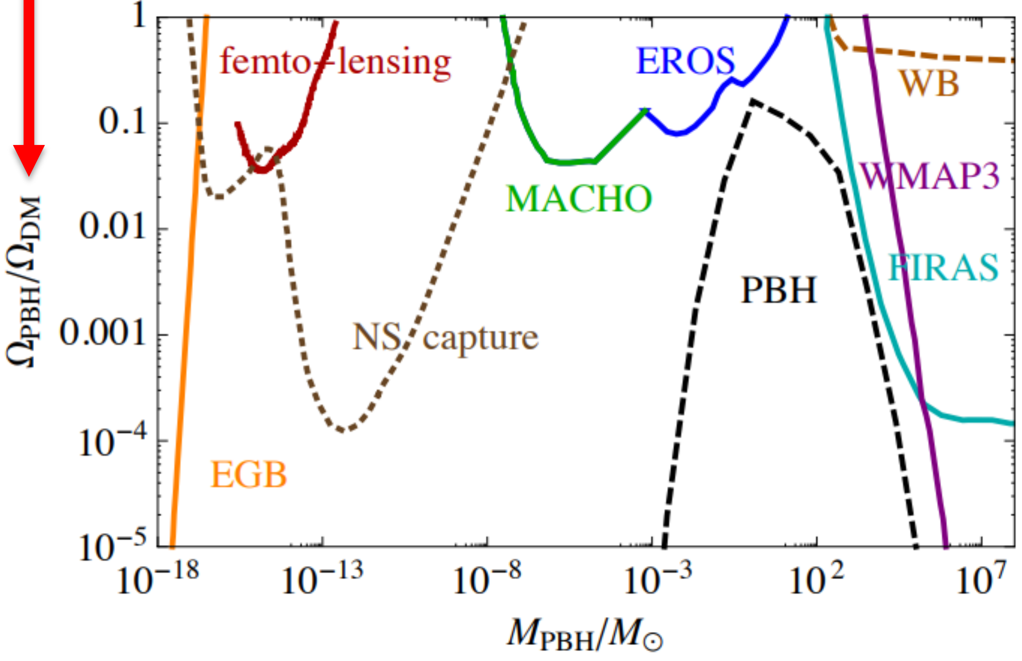

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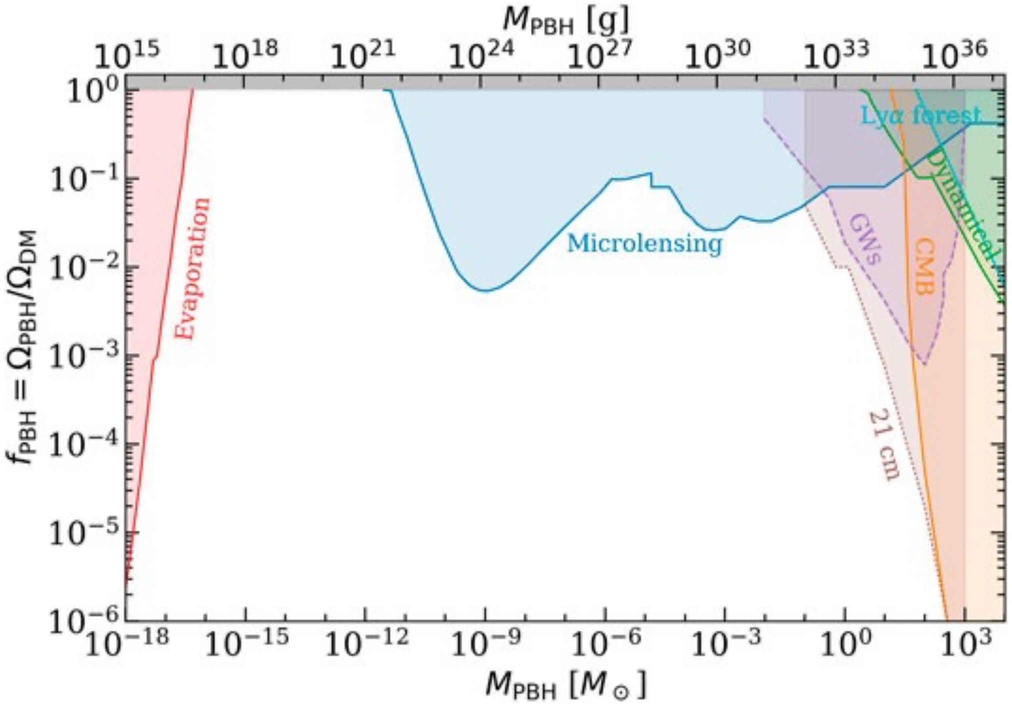
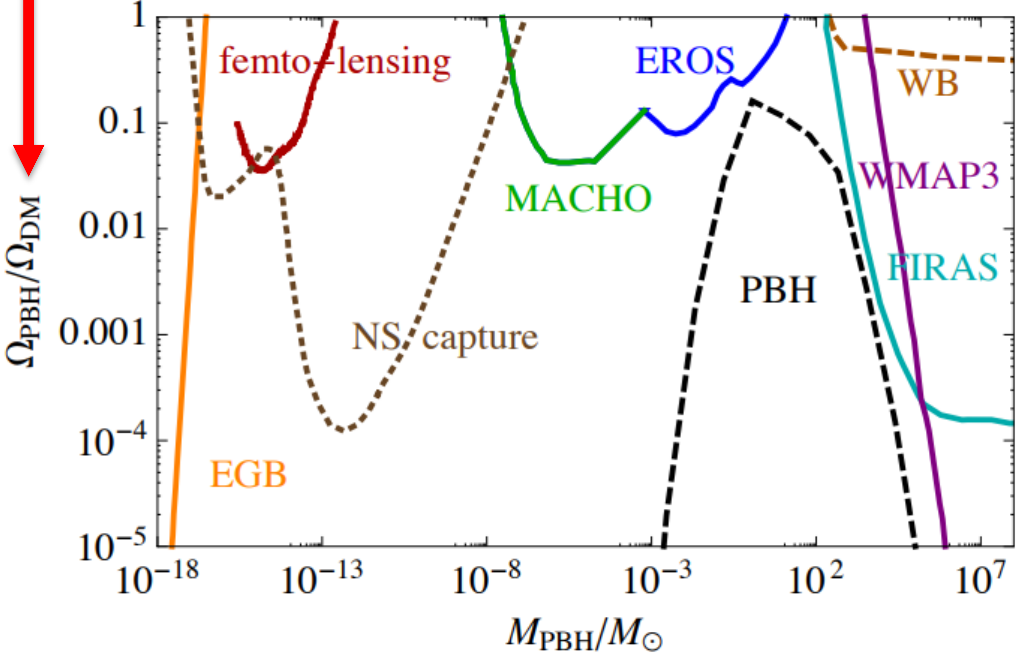


Now

Fraction of the dark matter consisting of non-stellar BHs of given mass

Asteroid-mass PBH can be 100% of the dark matter



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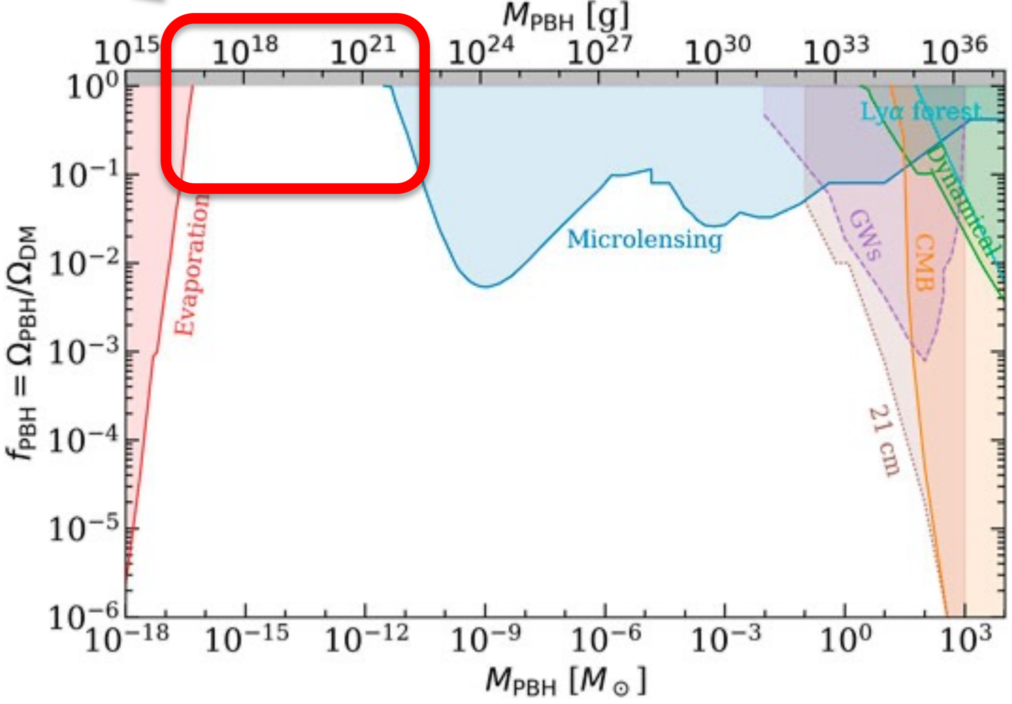
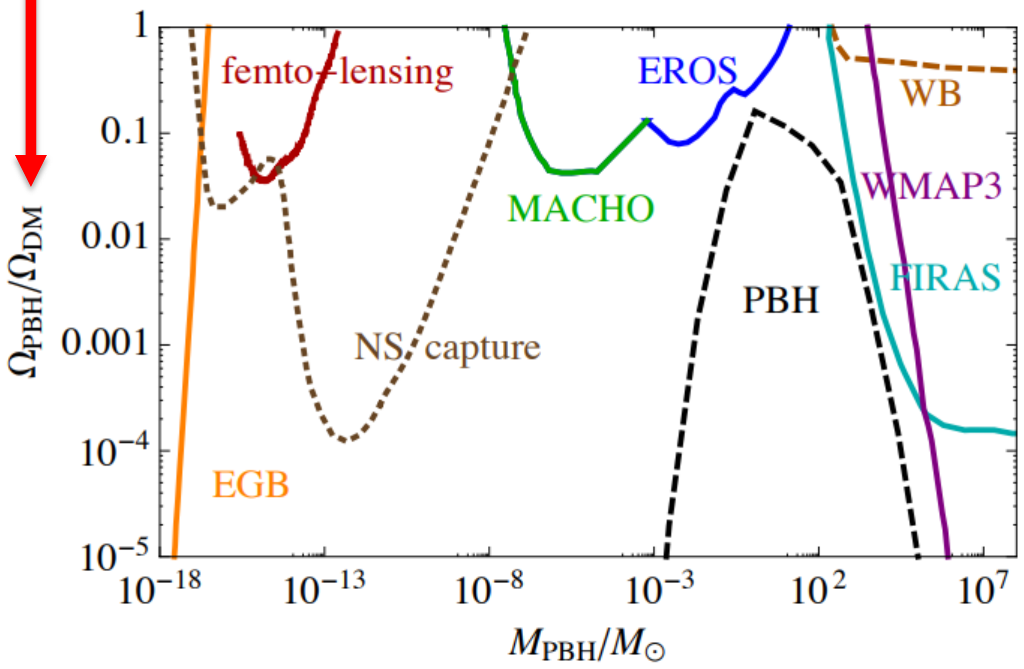


Now

Fraction of the
dark matter consisting of
non-stellar BHs
of given mass

Asteroid-mass
PBH can be **100%**
of the dark matter

Earth mass and above
PBH can be **1-10%**
of the dark matter



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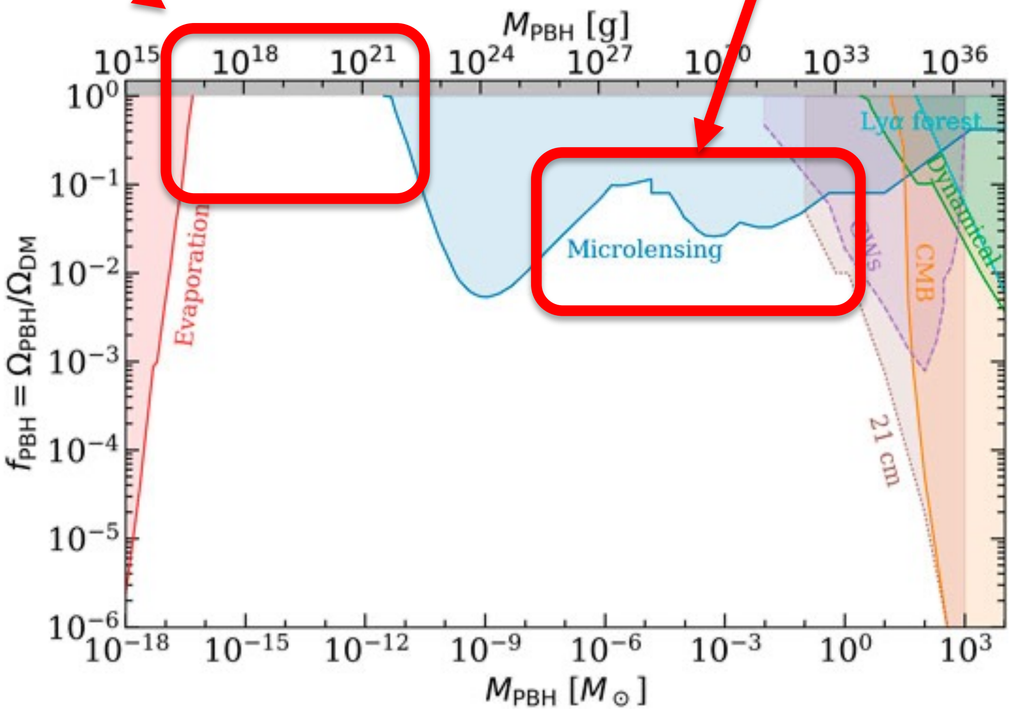
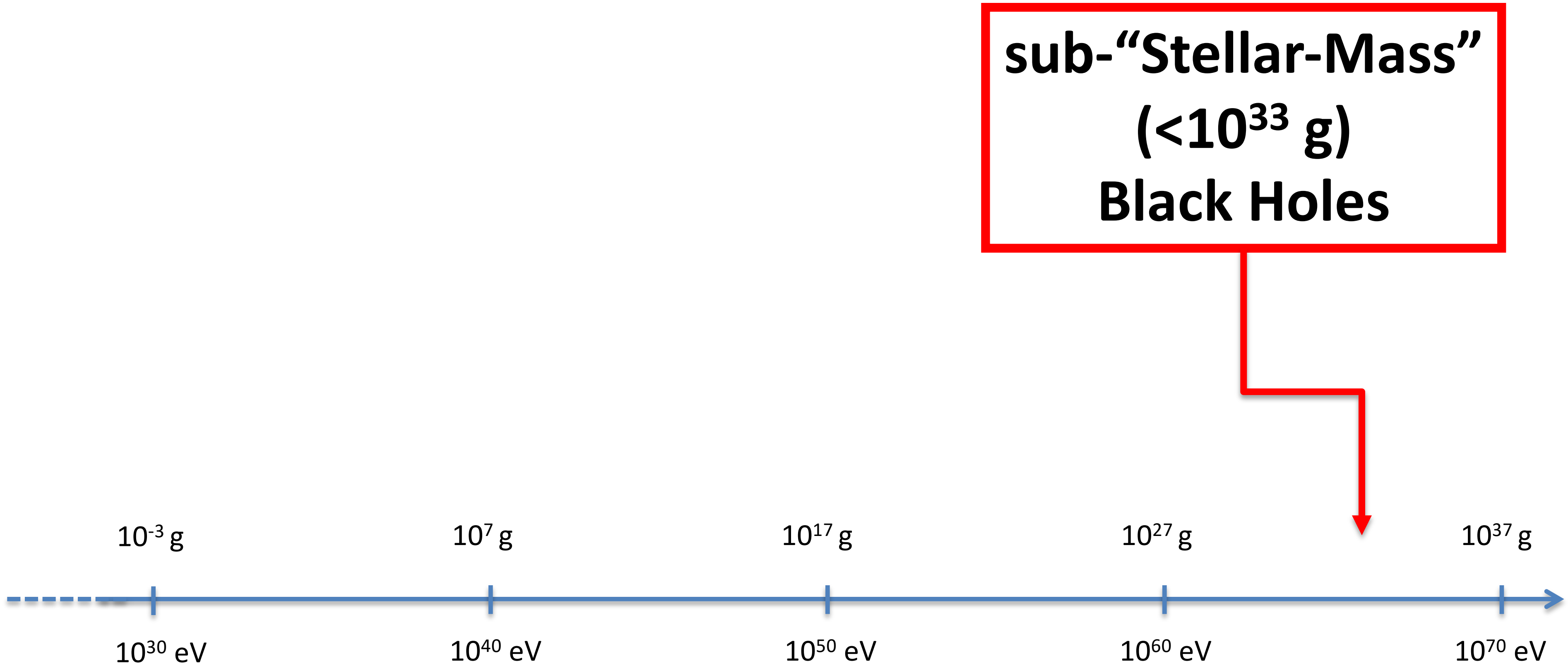
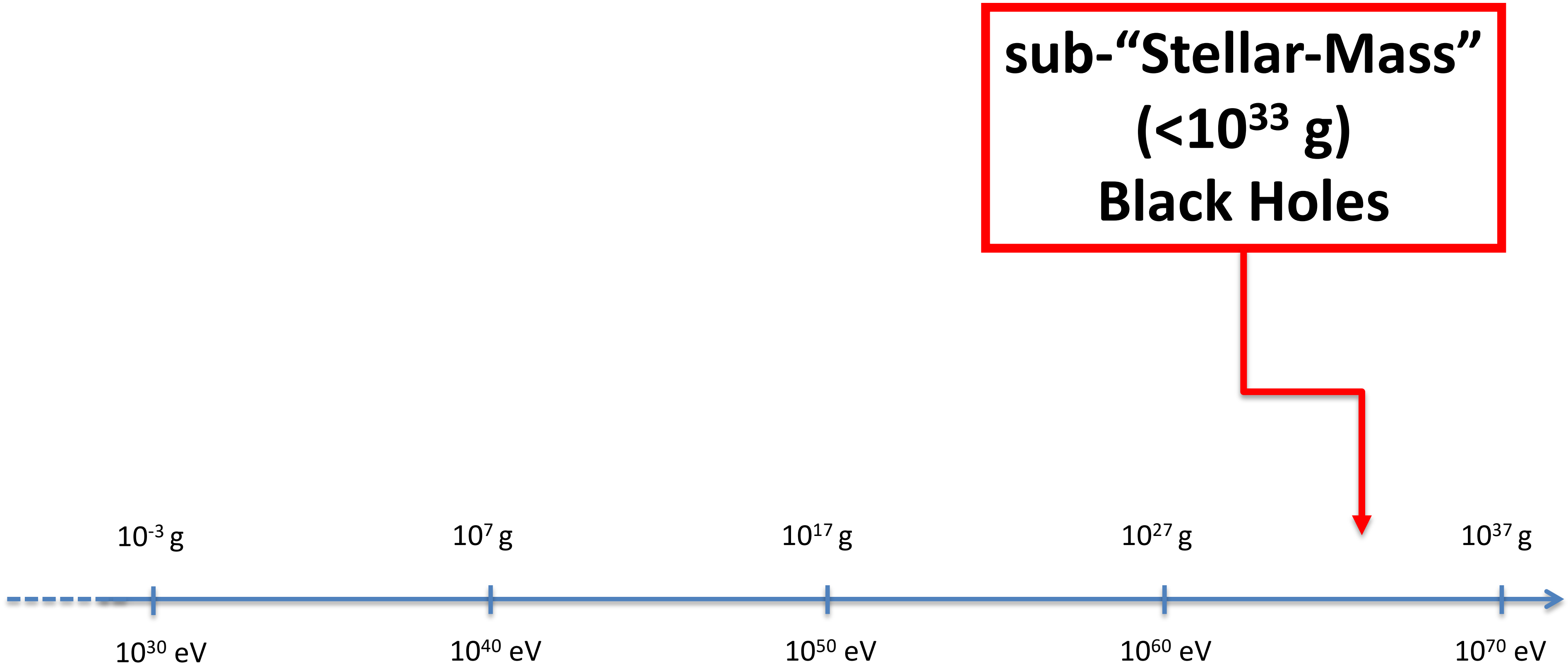


Now



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})

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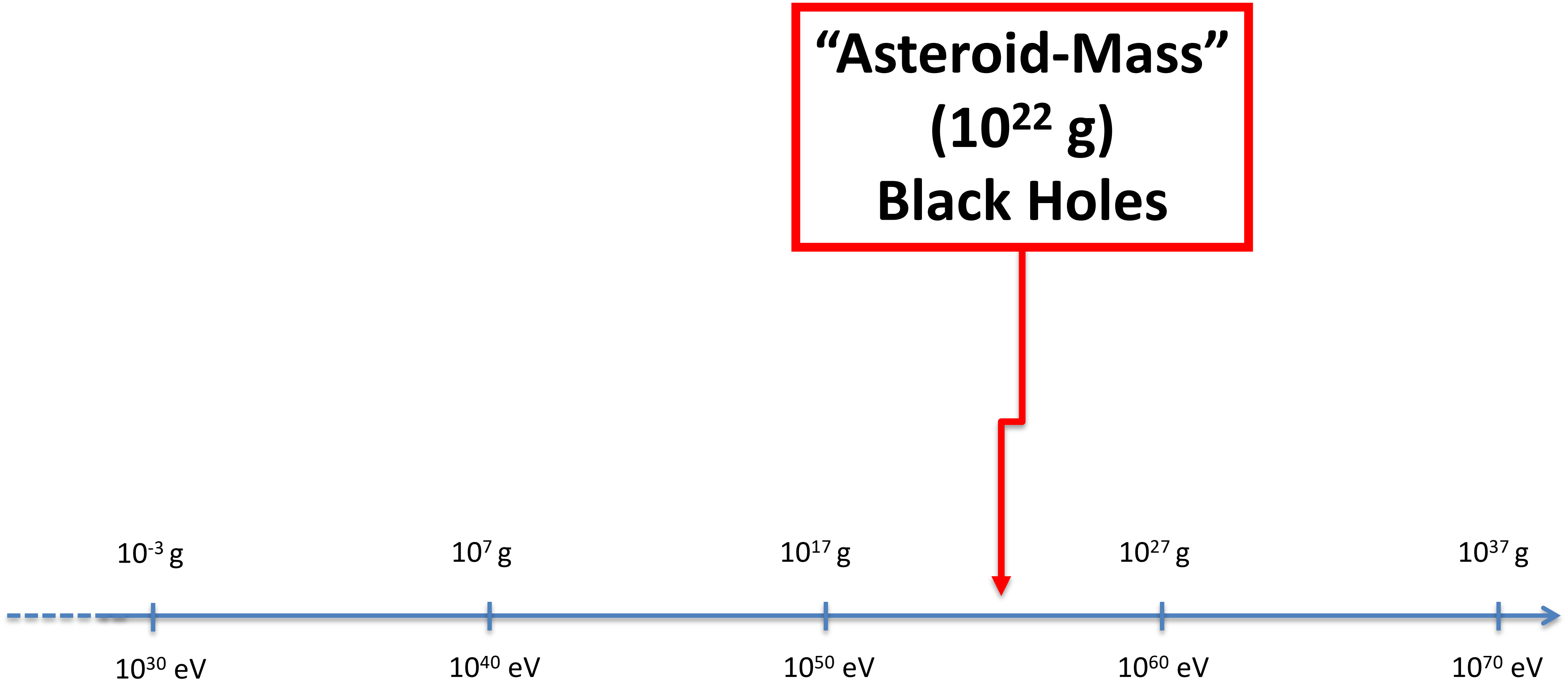
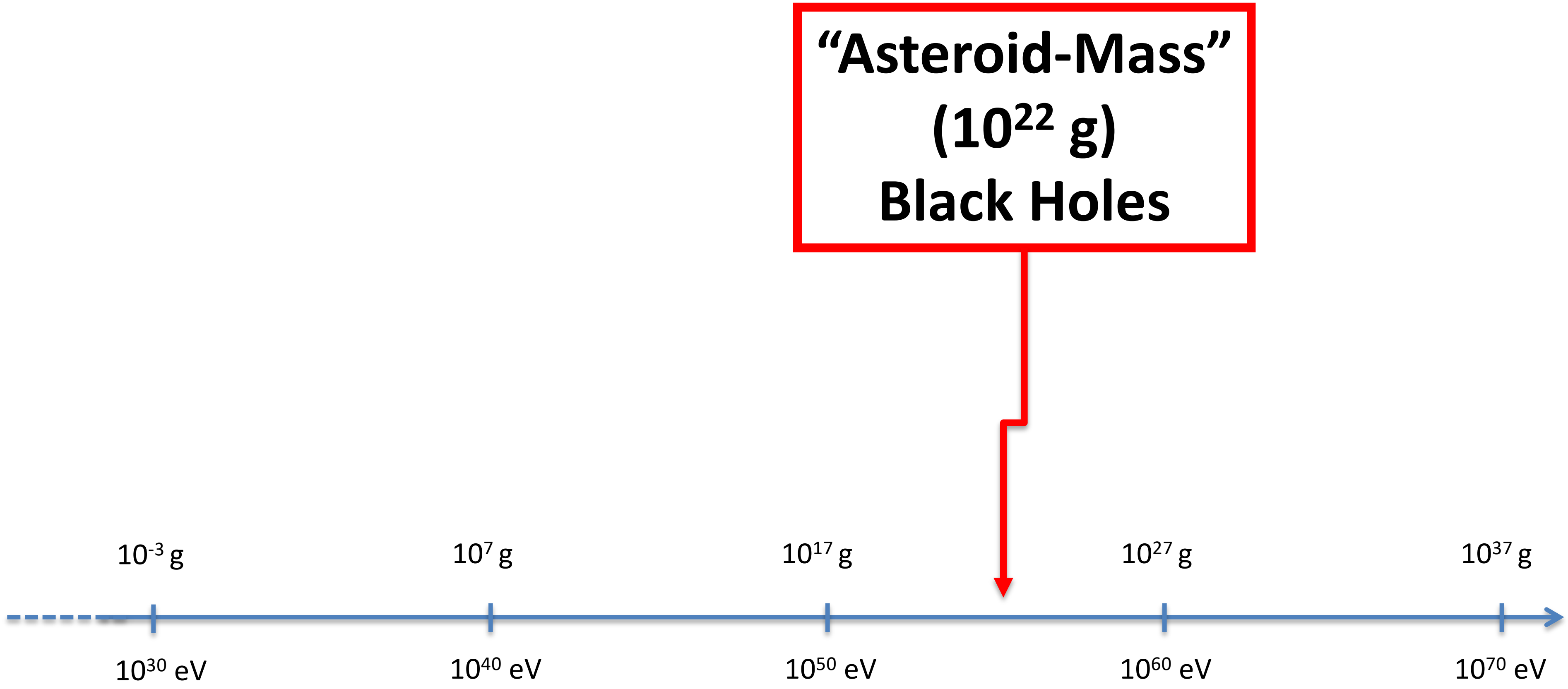
- **…one candidate event, albeit controversial, reported!**
  [2301.11619, Gonzalo Morras et al.]



“Asteroid-Mass”
(10^{22} g)
Black Holes



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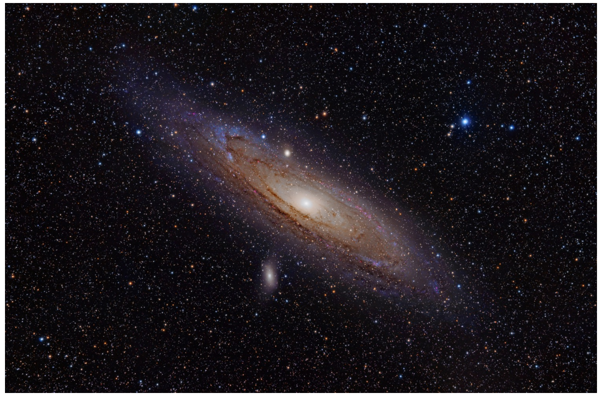
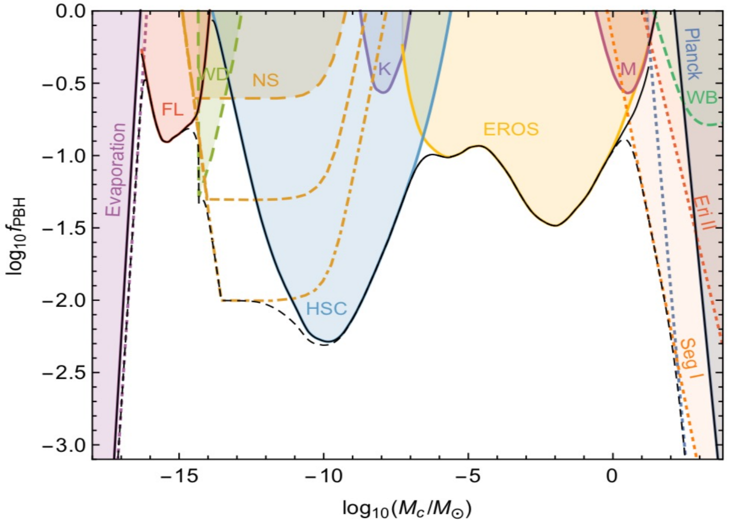
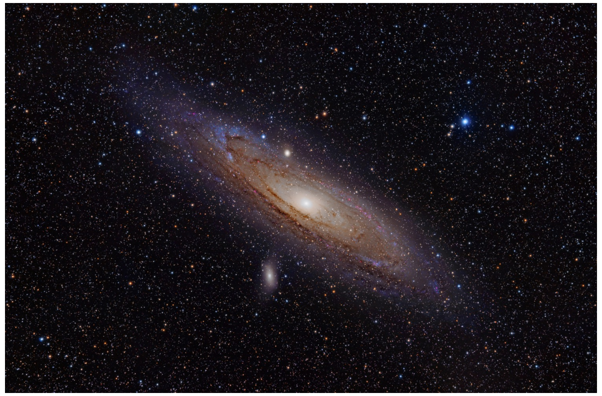


~ 7h observations of O(10^6) stars in M31 with Subaru HSC





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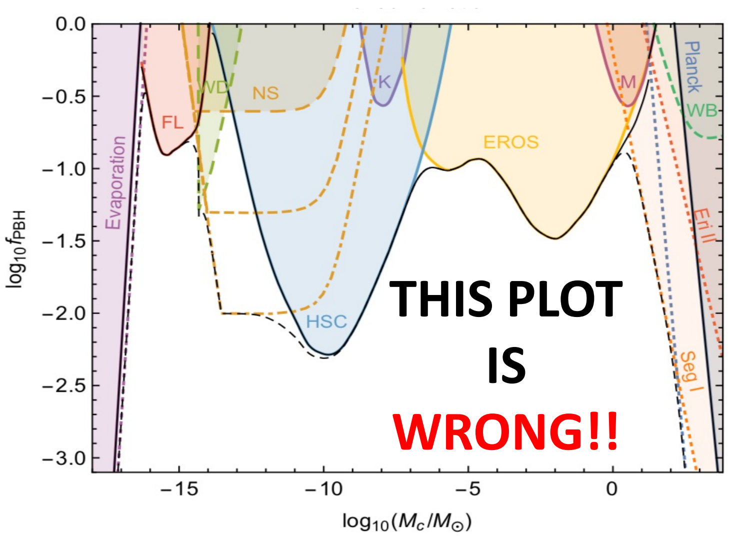
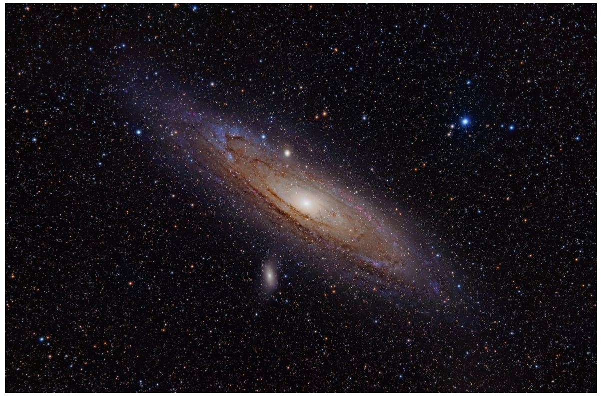


THIS PLOT IS WRONG!!



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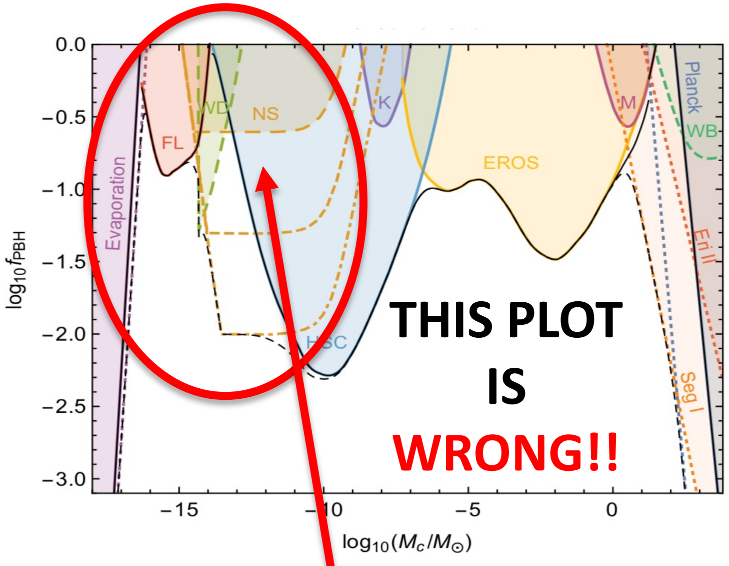

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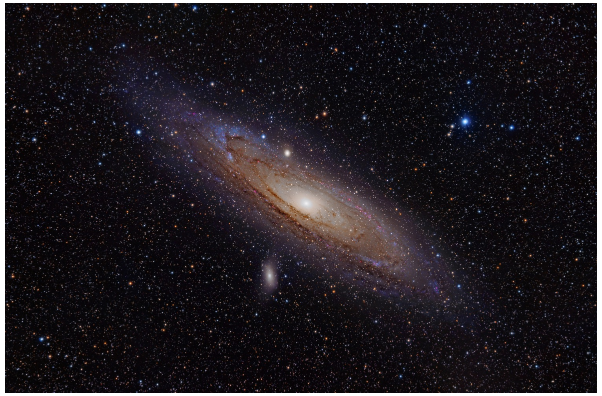

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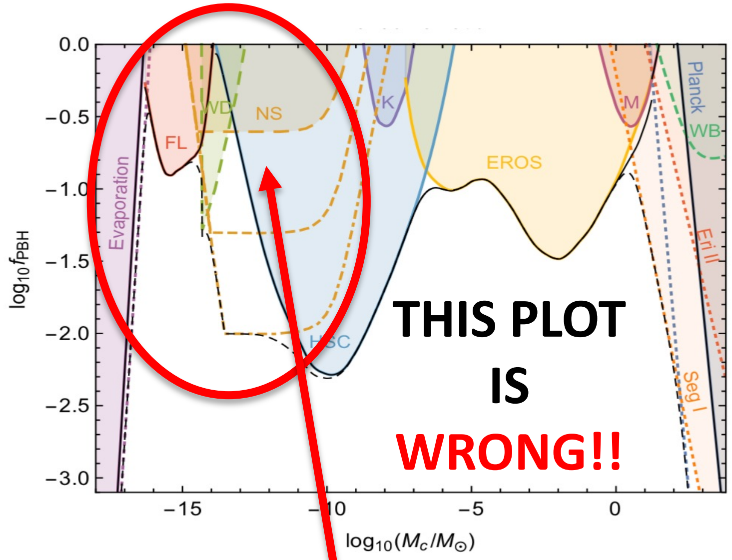


THIS PLOT IS WRONG!!

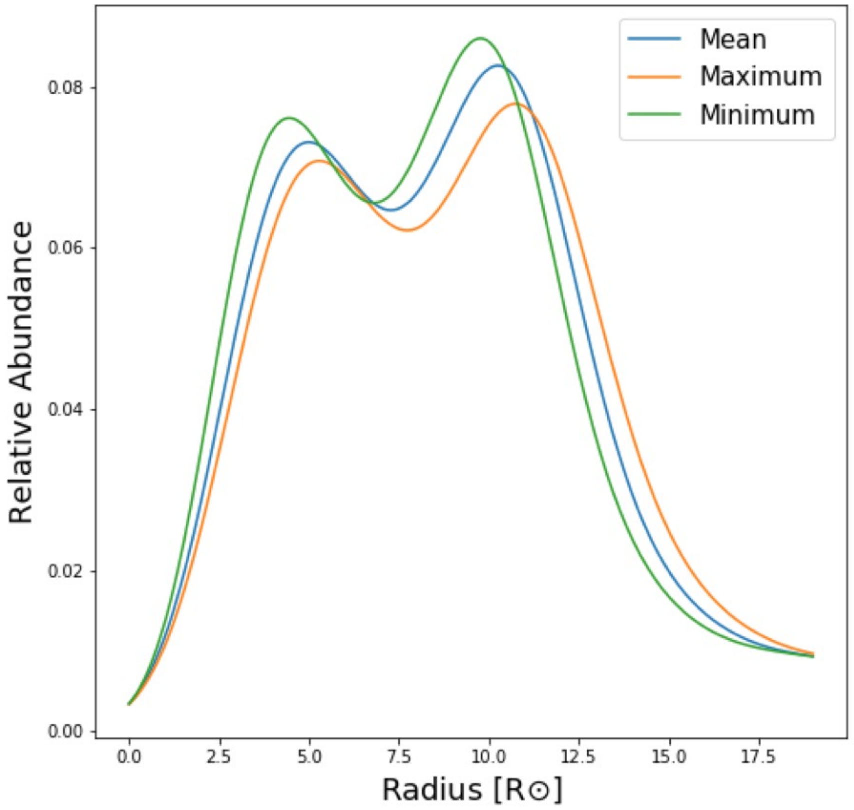
"Asteroid-Mass" (10^{22} g) Black Holes

N. Smyth

R. GuhaThakurta

T. Jeltema

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

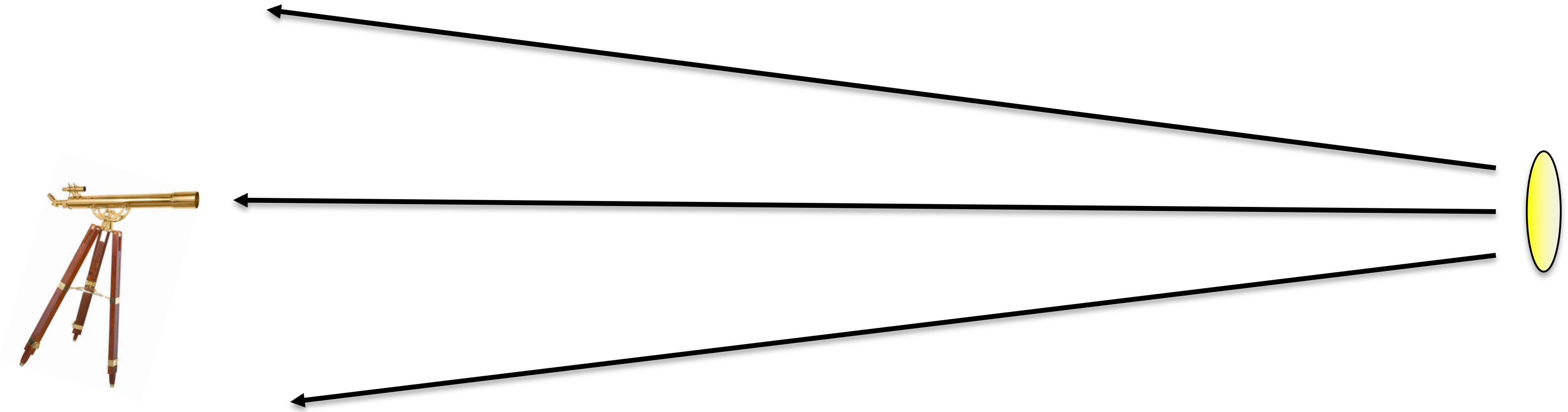


Stars that contribute to the microlensing constraints are ~ 100x larger in the sky than the Sun!

N. Smyth

* Profumo, Smyth+ PRD 2020

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



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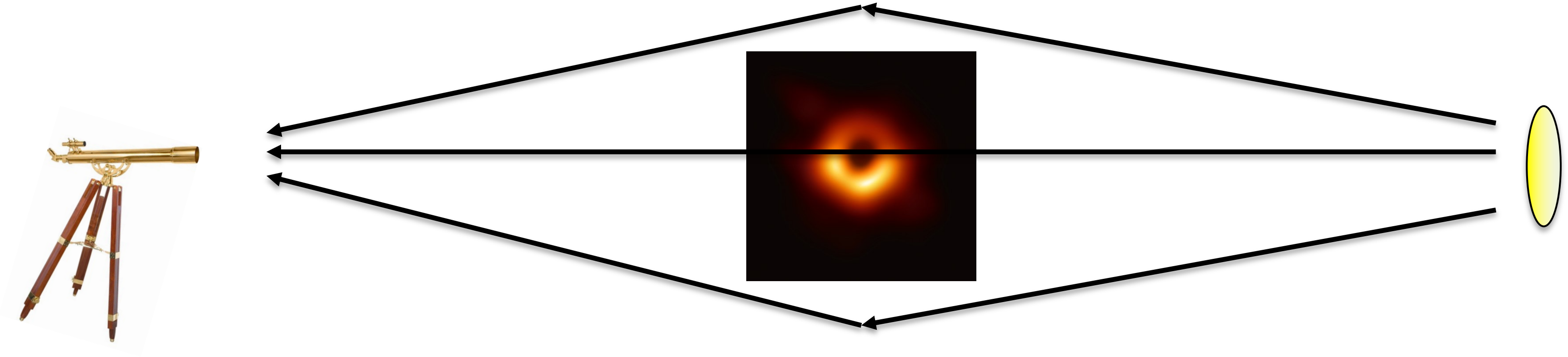

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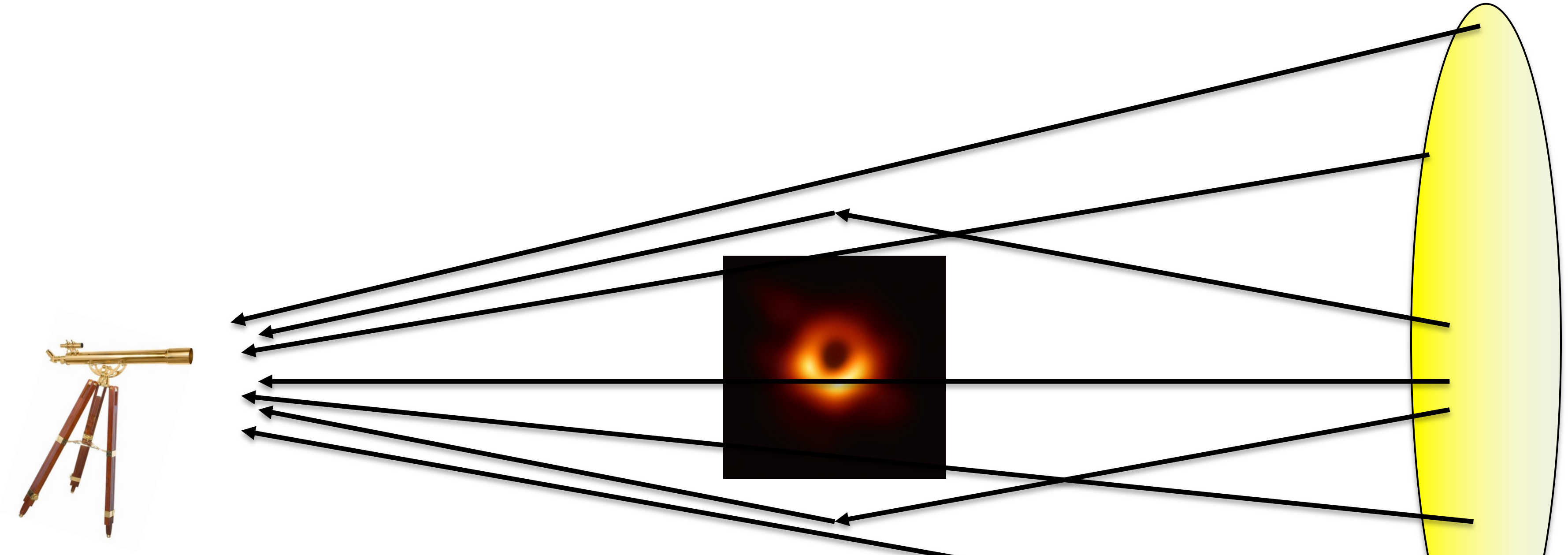

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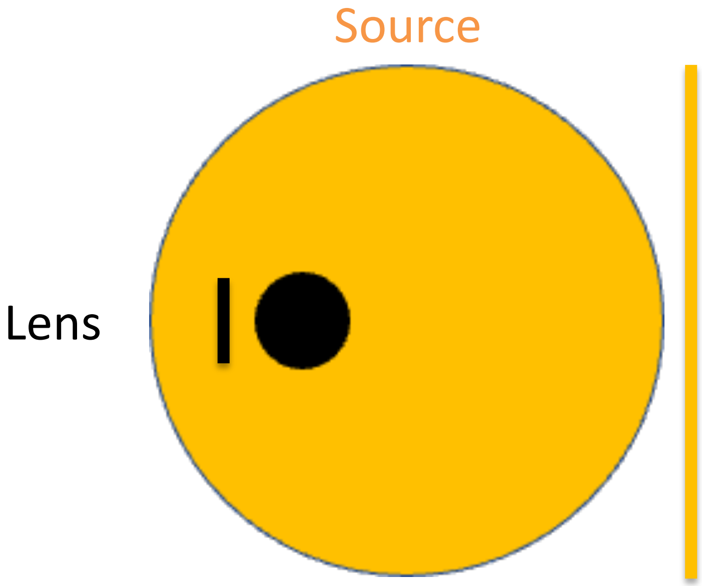
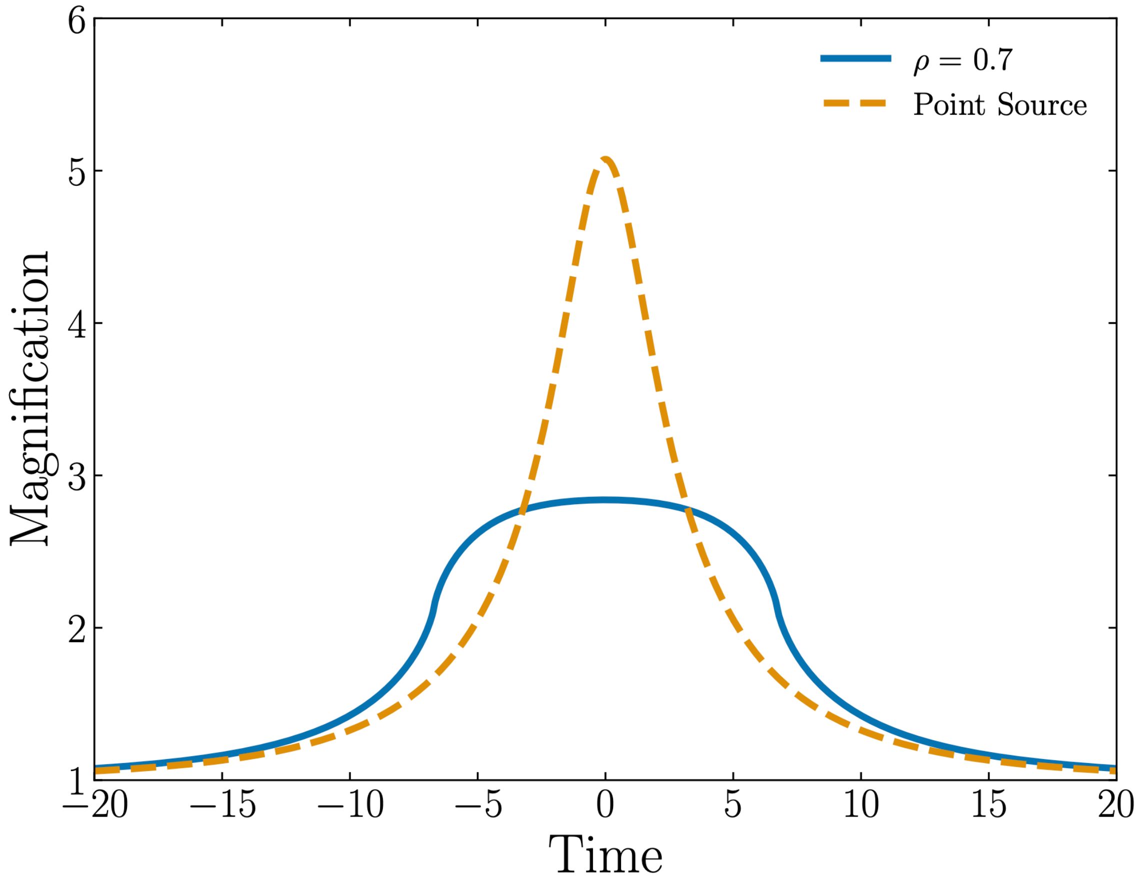


$$\rho \equiv \theta_S/\theta_E$$



* slide credit: N. Smyth

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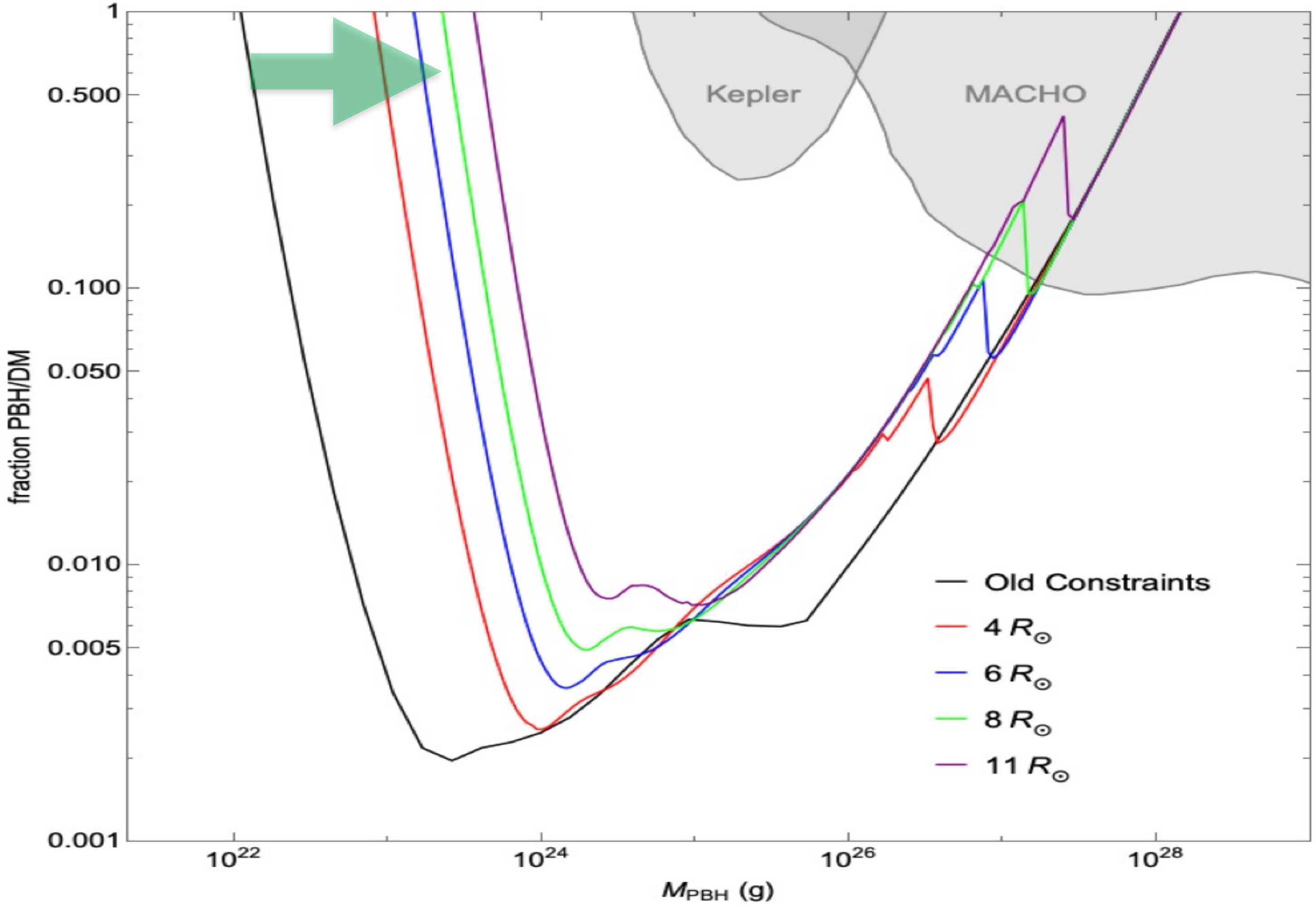

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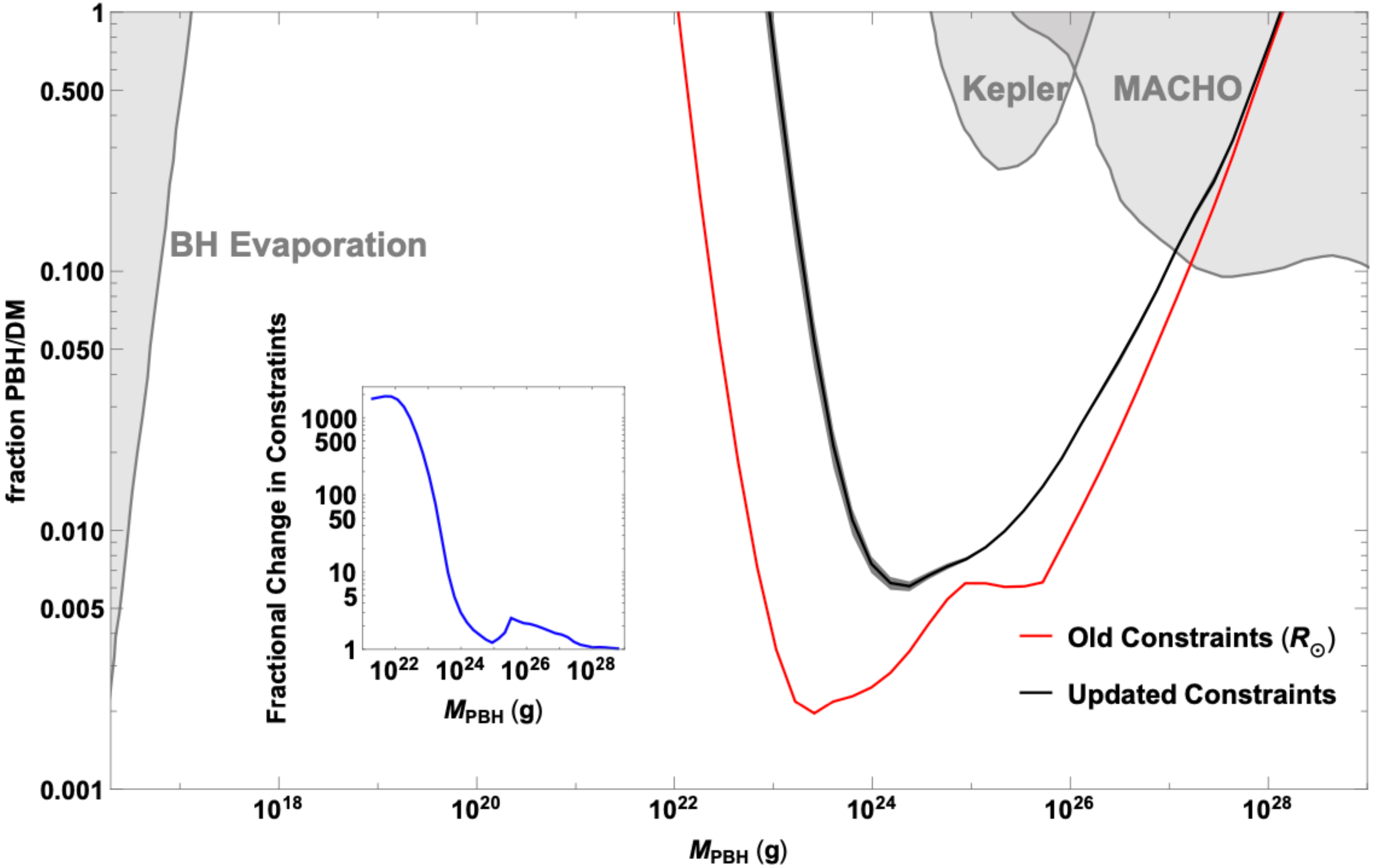

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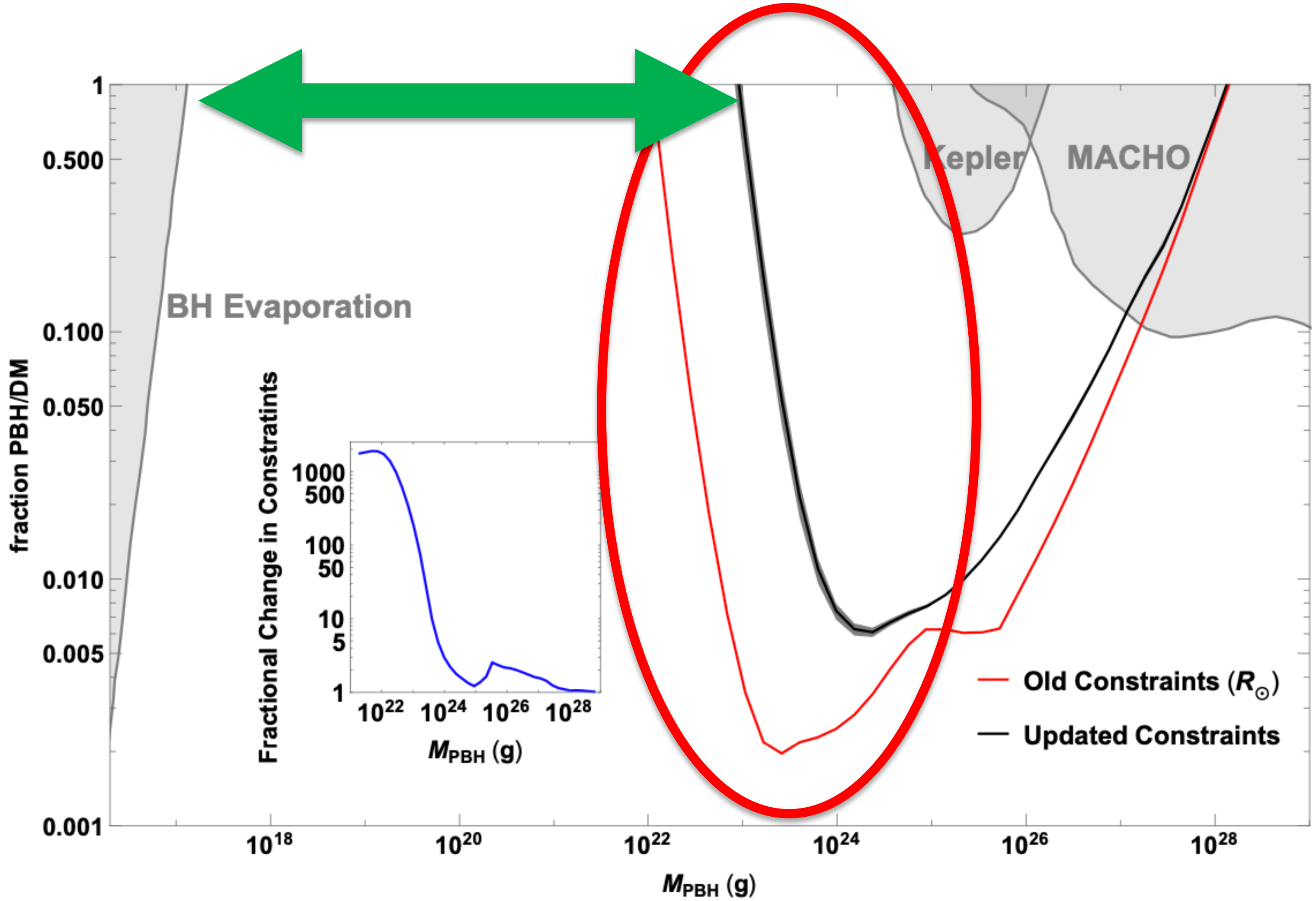

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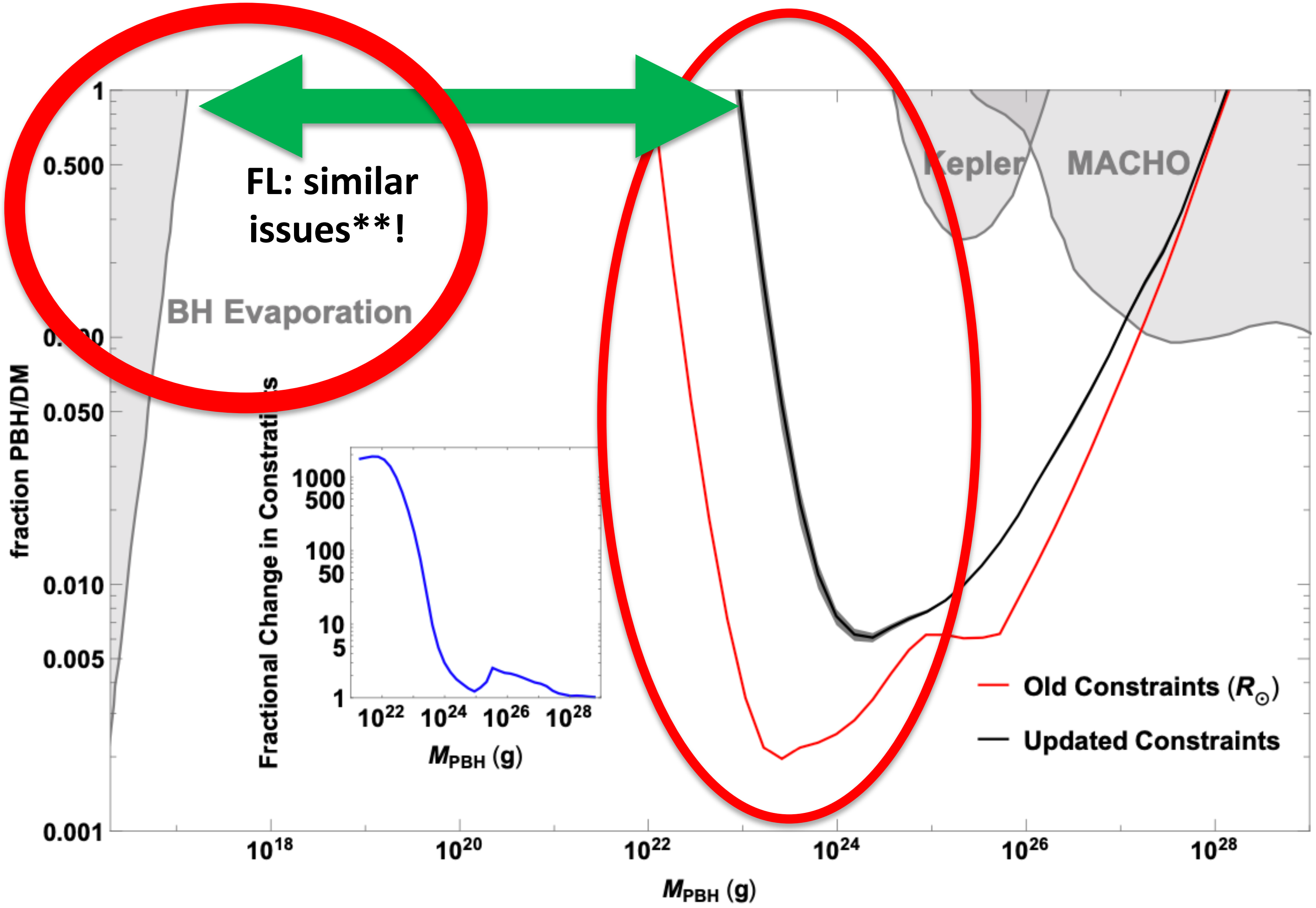
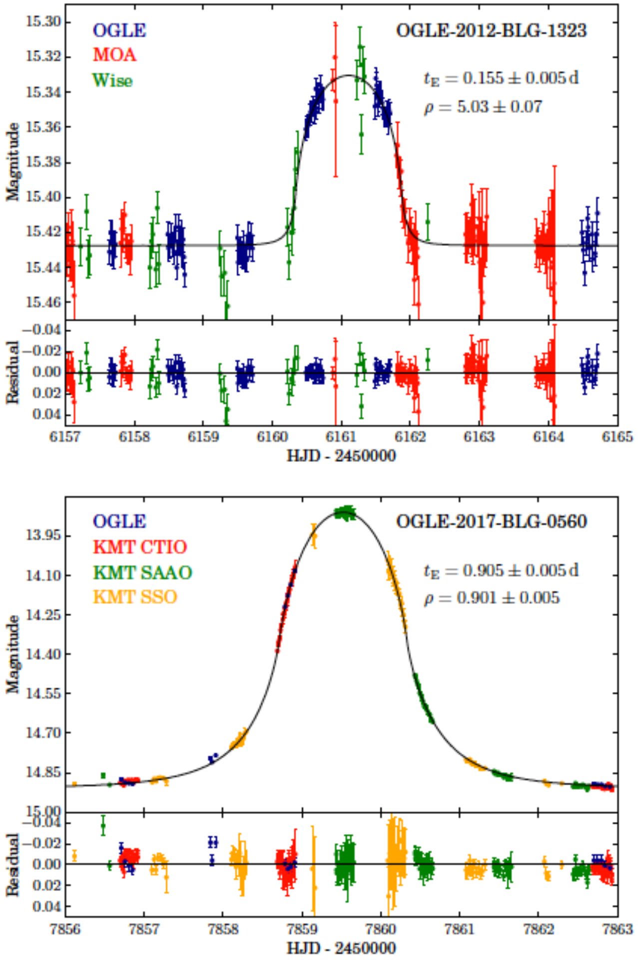


FL: similar issues**!

* Profumo, Smyth+ PRD 2020

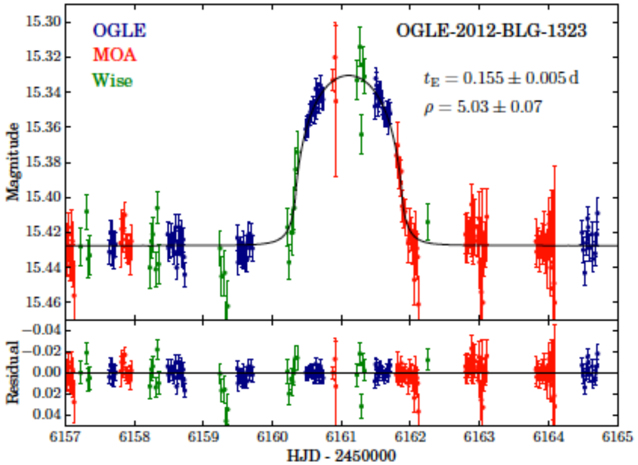
** Katz+ JCAP 2018

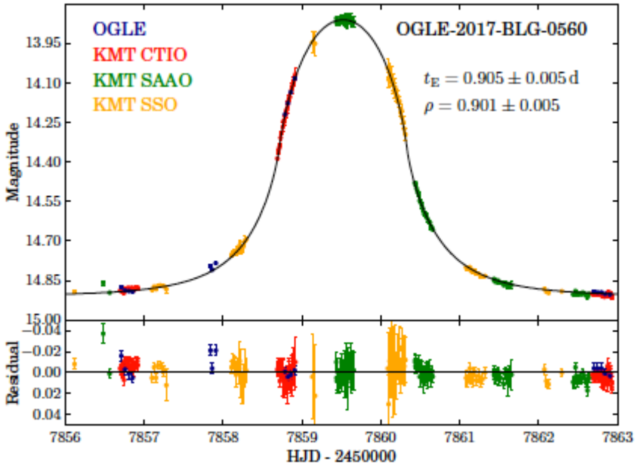
Microlensing events have been detected… most recently by OGLE



Mroz+ 2017

Microlensing events have been **detected**… most recently by **OGLE**





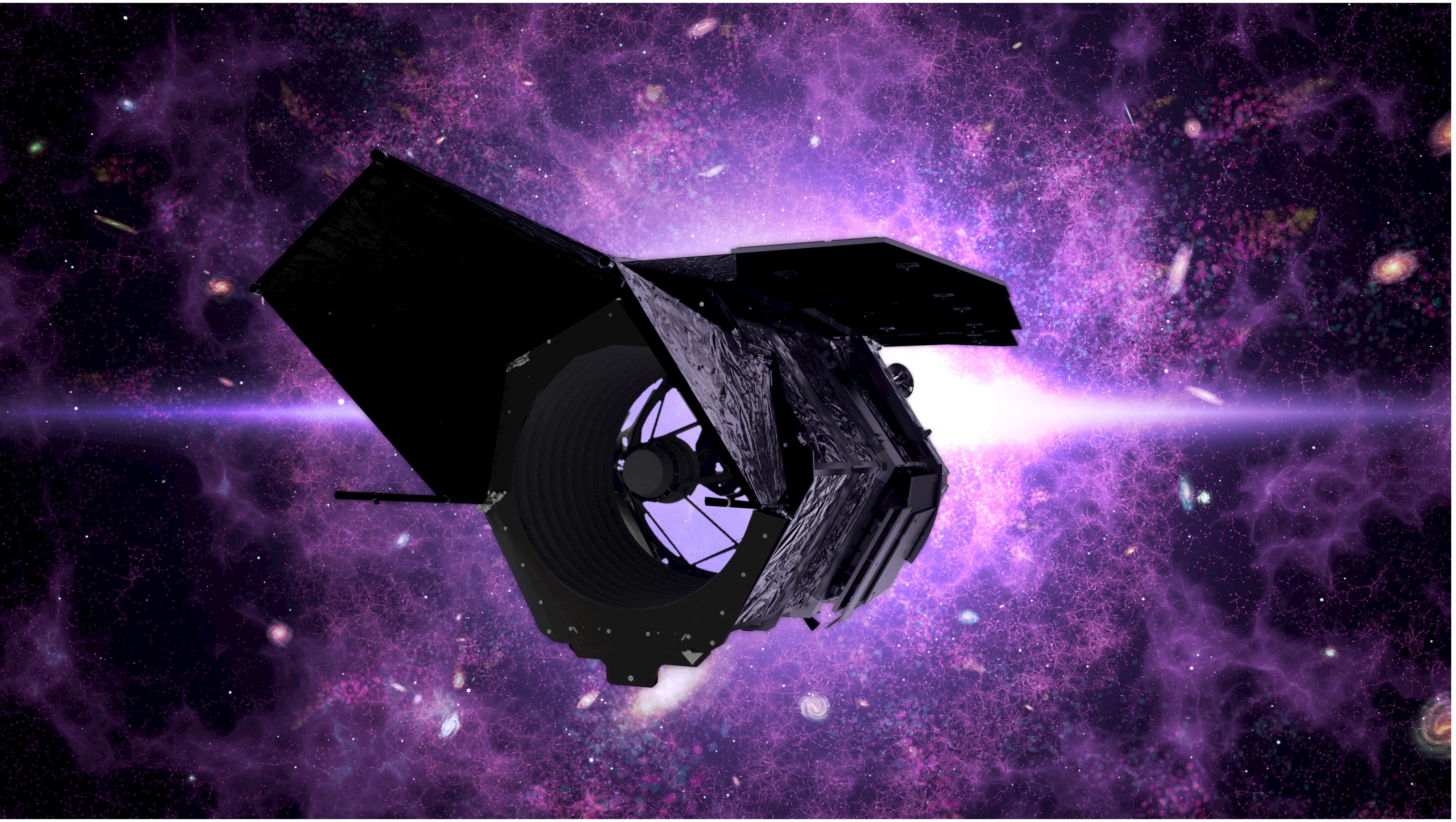
Mroz+ 2017

…key question: how can PBH be distinguished from **Freely-Floating Planets***?

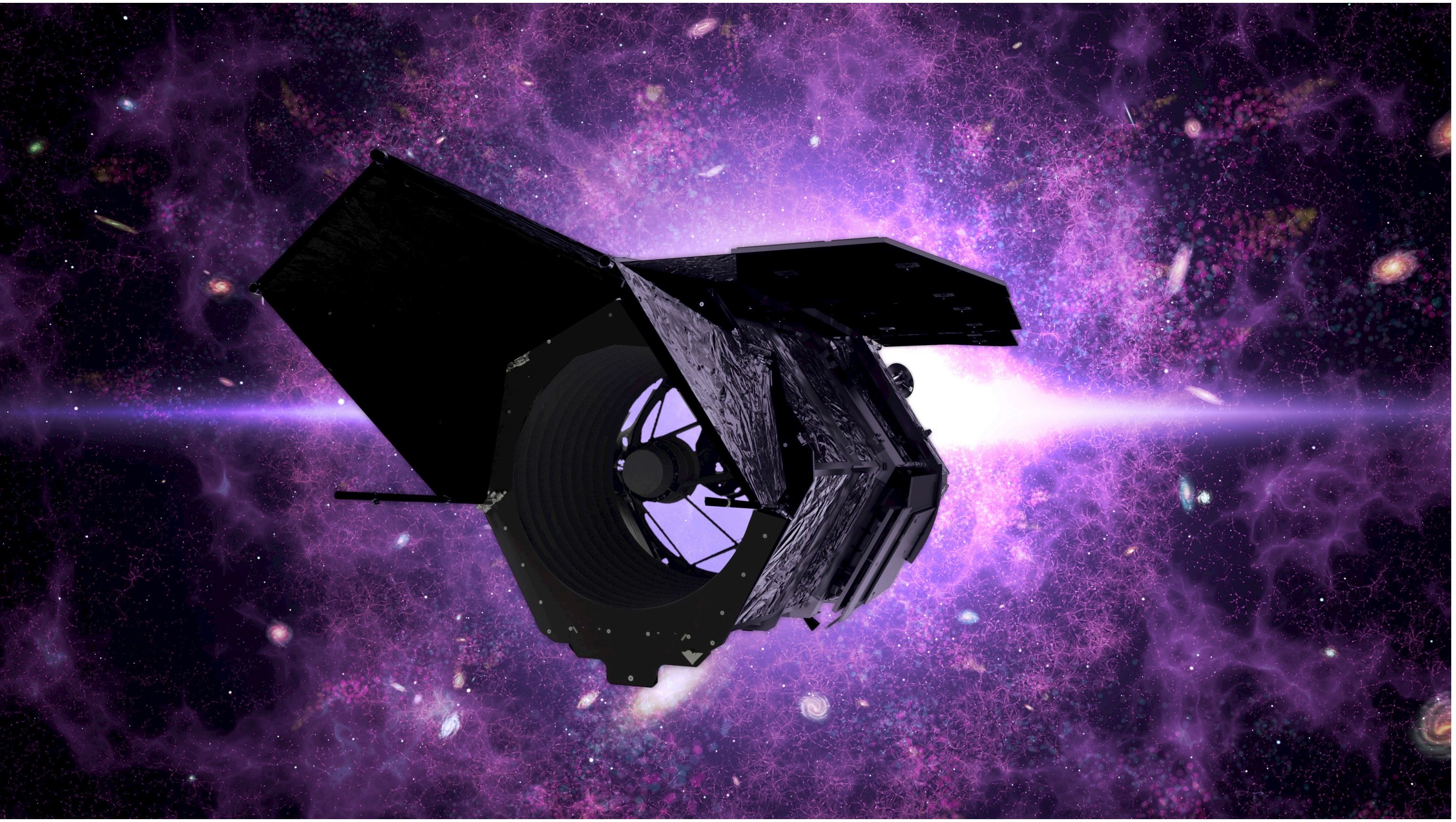
W. DeRocco

N. Smyth

***Freely-Floating Planet**: rogue planet not orbiting a star but, rather, floating in the MW



Nancy Grace Roman Telescope (May 2027?) expected to detect hundreds freely-floating planets (FFP), planets that have been ejected from their parent star system by dynamical interactions during the chaotic early phases of system formation



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FFPs are an irreducible background to searches for PBH AND VICEVERSA!

Will Roman enable disentangling FFP versus FFP+PBH?

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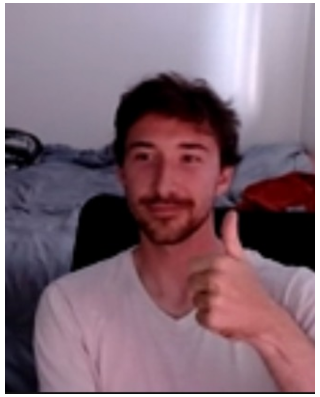
Evan Frangipane



Nick Hamer

W. DeRocco

N. Smyth

***DeRocco, Frangipane, Hamer Smyth, Profumo, 2023**

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We studied the statistics of anticipated event duration distribution (lens mass, distance and transit velocity are degenerate; finite-size source effects and follow-up observations may help partially breaking the degeneracy)


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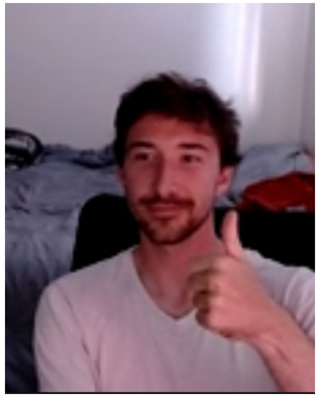
Nick Hamer


W. DeRocco


N. Smyth

***DeRocco, Frangipane, Hamer Smyth, Profumo, 2023**

****https://github.com/NolanSmyth/LensCalcPy**

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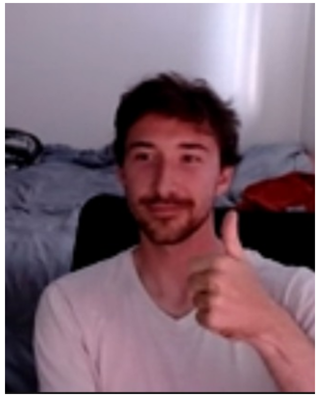
Bonus: we released a code that computes statistics of microlensing events highly efficiently, LensCalcPy**


Evan Frangipane


Nick Hamer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N. Smyth

***DeRocco, Frangipane, Hamer Smyth, Profumo, 2023**

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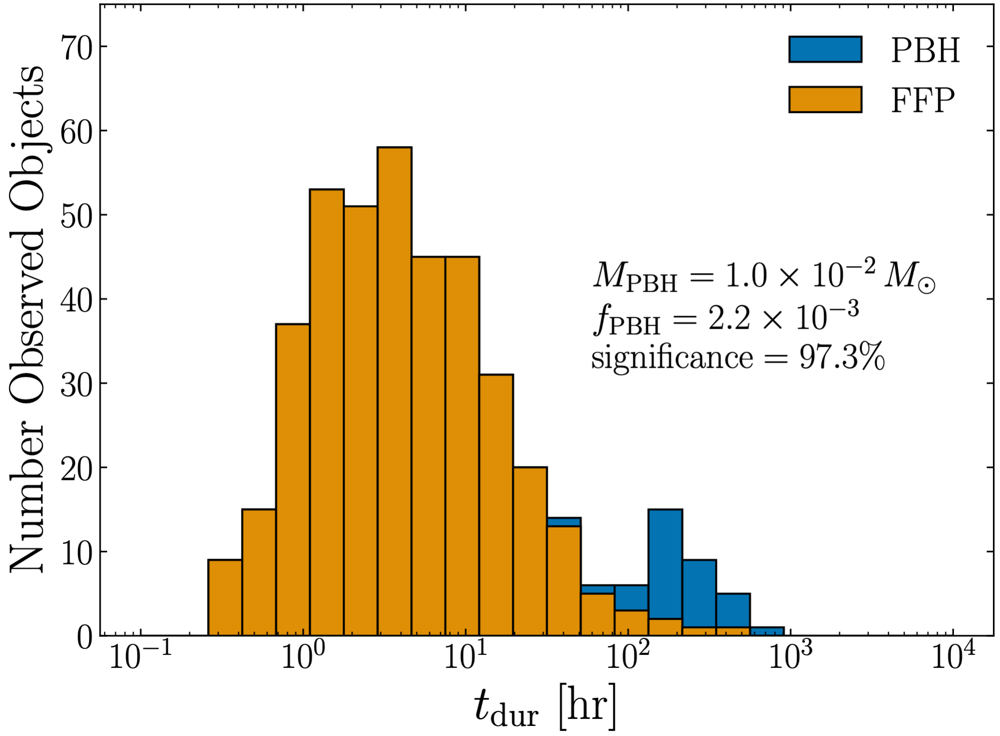
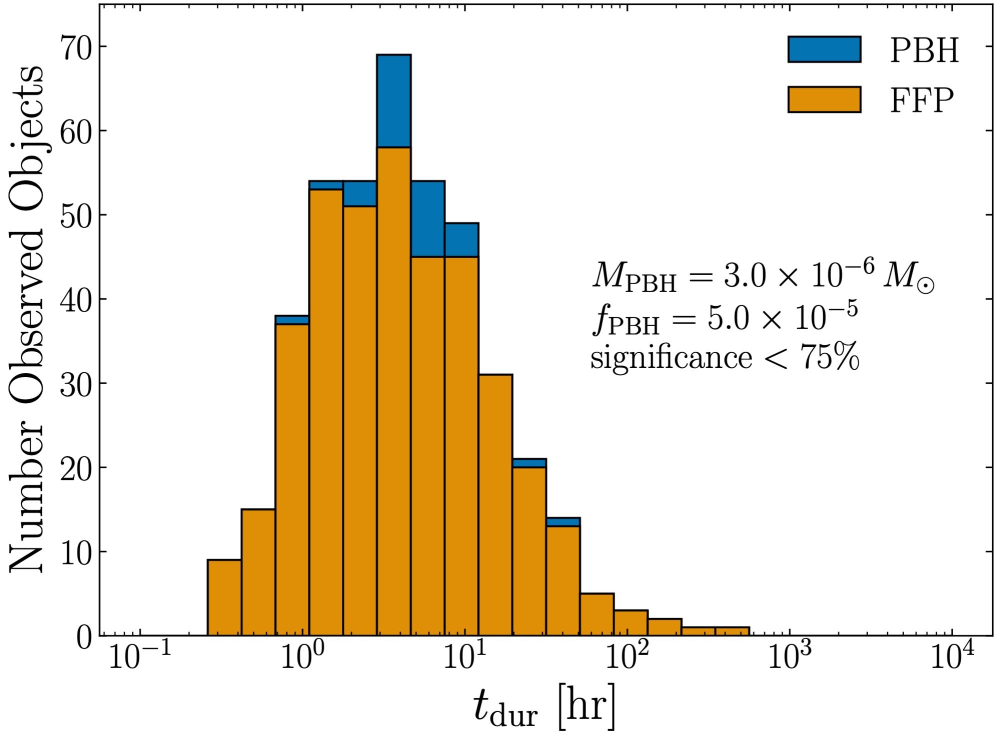
Can we find PBHs hidden in FFP background?

Yes



No



Null Hypothesis:
Only FFPs

Alternate Hypothesis: FFPs
+ PBHS

Statistical test: two-sample
Anderson-Darling test

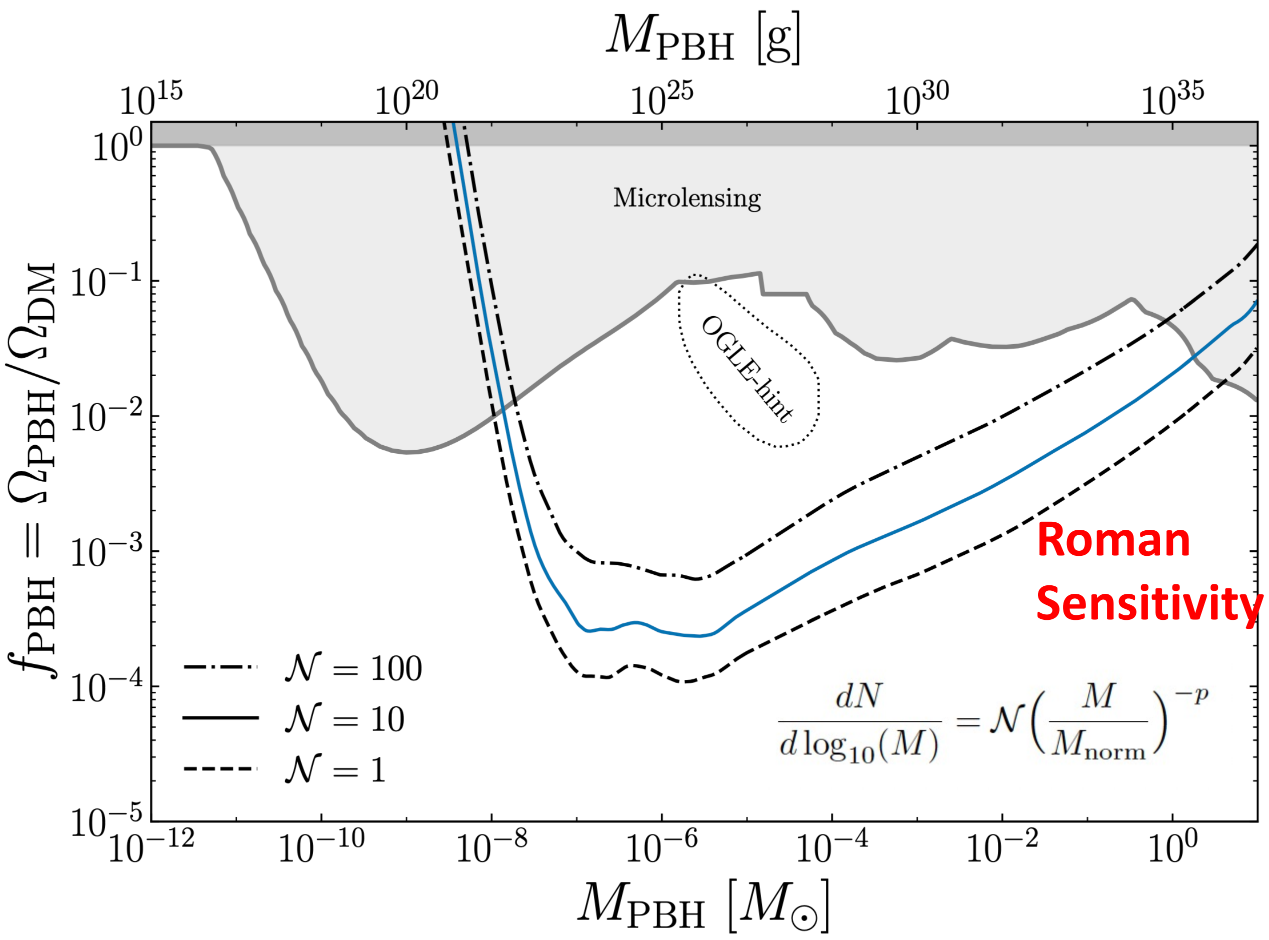
***DeRocco, Frangipane, Hamer Smyth, Profumo, 2023**

*slide credit: N. Smyth

Can we find PBHs hidden in FFP background?

Strongest bounds by far on PBHs as dark matter, even with substantial FFP background

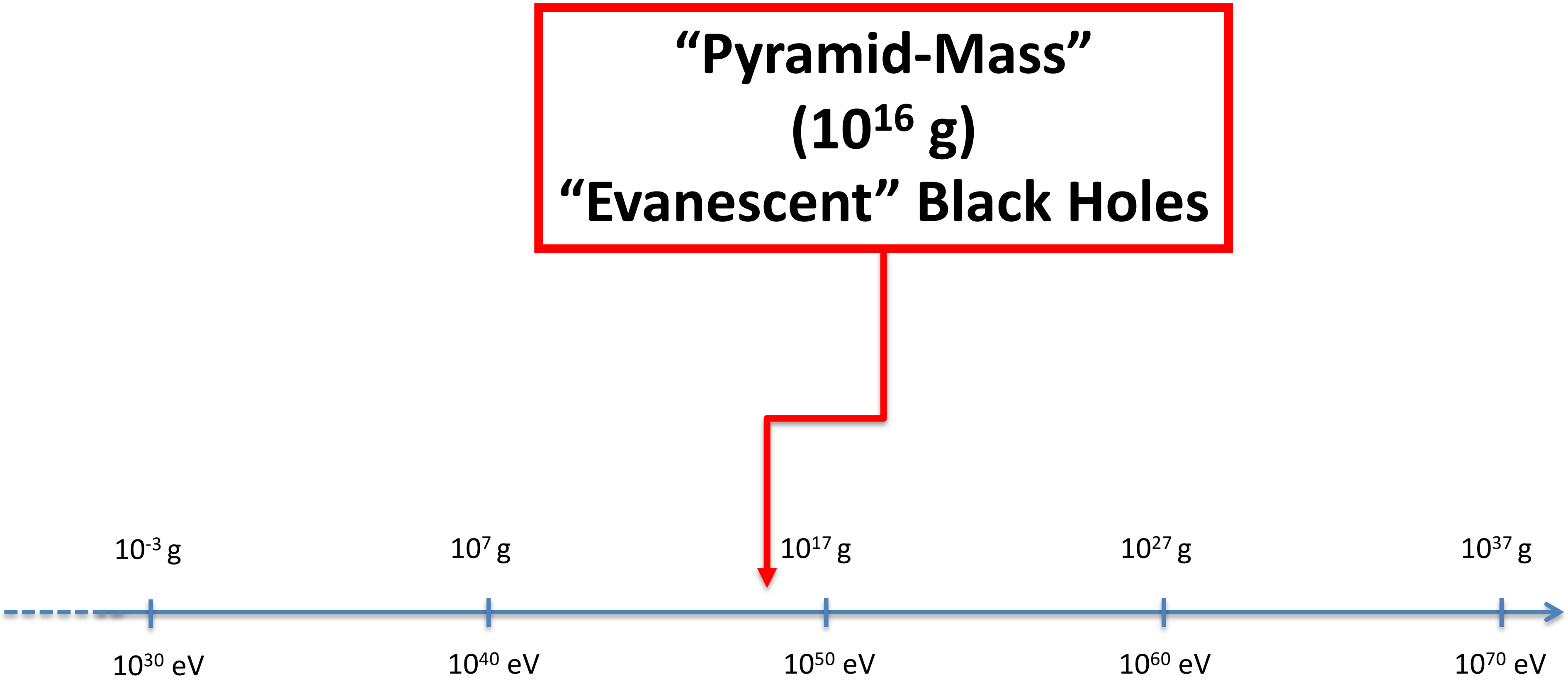
Will be able to completely probe the preferred OGLE PBH population!



Roman Sensitivity

***DeRocco, Frangipane, Hamer Smyth, Profumo, 2023**

*slide credit: N. Smyth



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

Evanescent (exploding) Black Holes

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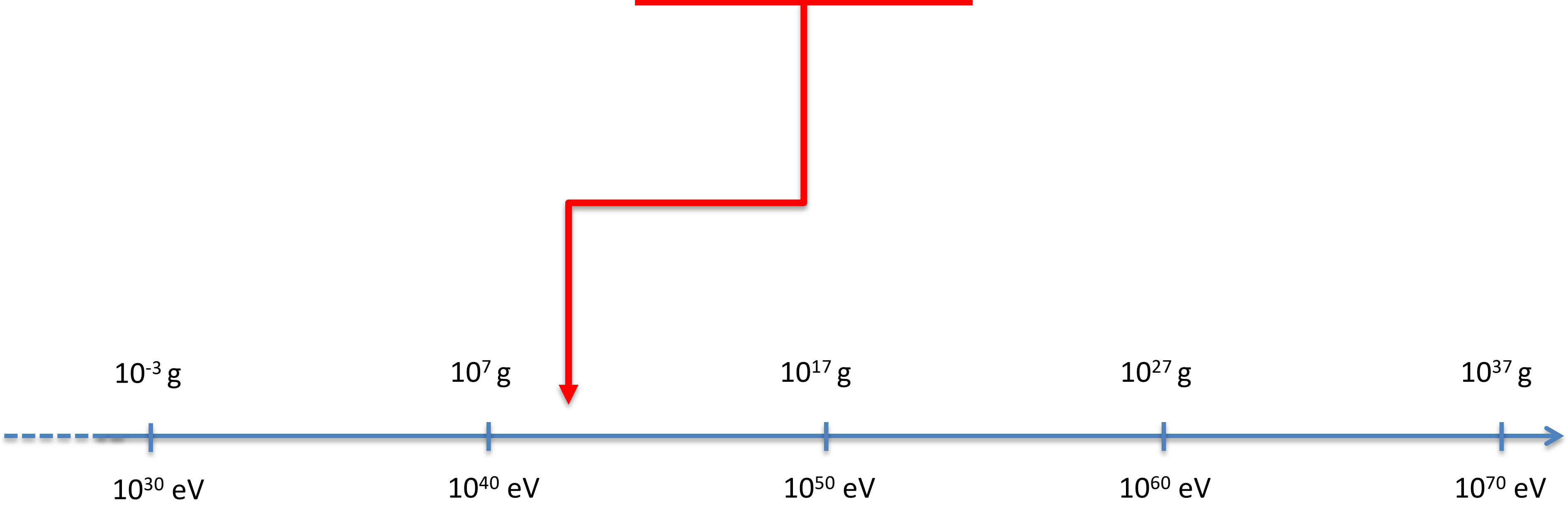
  [Korwar+Profumo, 2023-24]

- ➢ **Maybe black holes are currently exploding?**

  - ✓ **Searched for PBH explosions in LAT transient sources**
  - ✓ **Searched for PBH explosions in GRB catalogues**
  - ✓ **Searched for PBH explosions in the inter-planetary network GRB satellites**
    [Profumo et al, 2023-24]

Ton-size Black Holes



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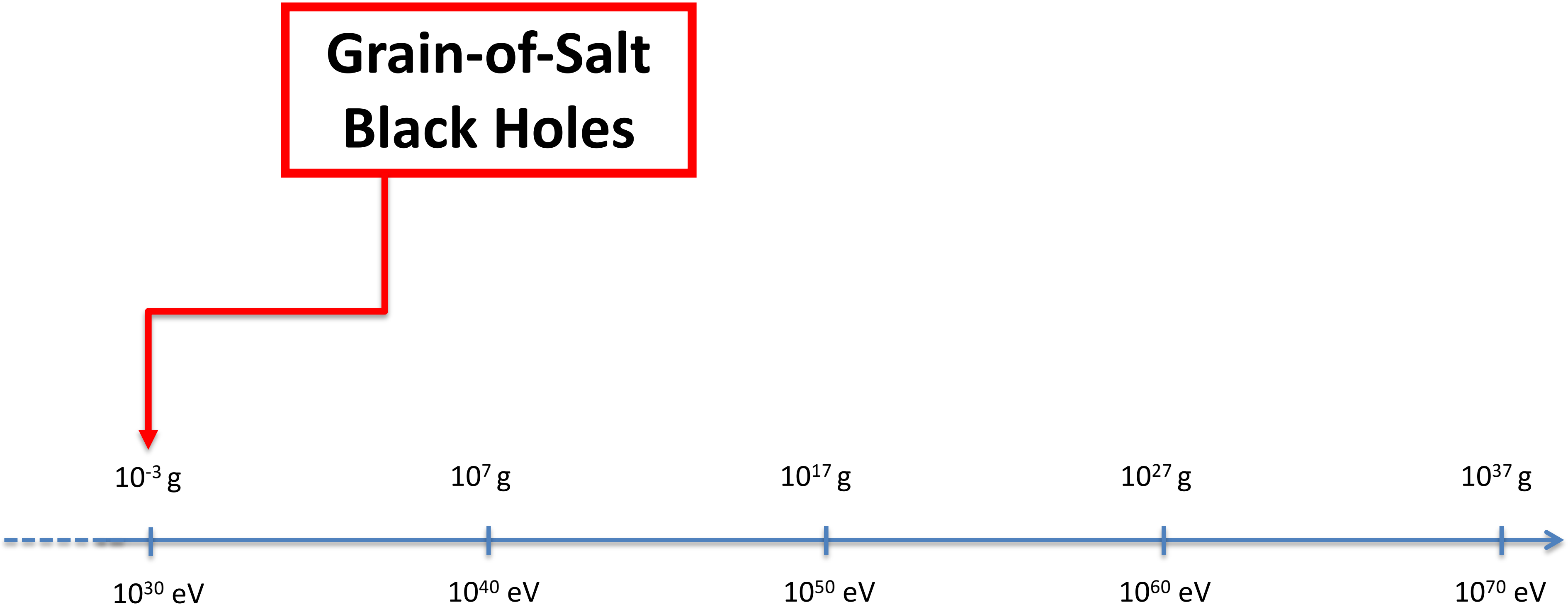
  [Profumo, Smyth, Santos-Olmsted, 2023]

- **Can seed high-frequency gravitational waves, especially if**

  - ✓ **…modified cosmology shifts the spectrum to reasonably low frequencies**
  - ✓ **…extradimensions lower the Planck scale and the frequency of GW at the end of evaporation**
    [Ireland, Profumo, Sharnhorst, 2023, 2024]



Grain-of-Salt Black Holes

If evaporation stops around the Planck scale, the relic PBHs can acquire a significant relic electric charge

* Page, 1977

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

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

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

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

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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!

---

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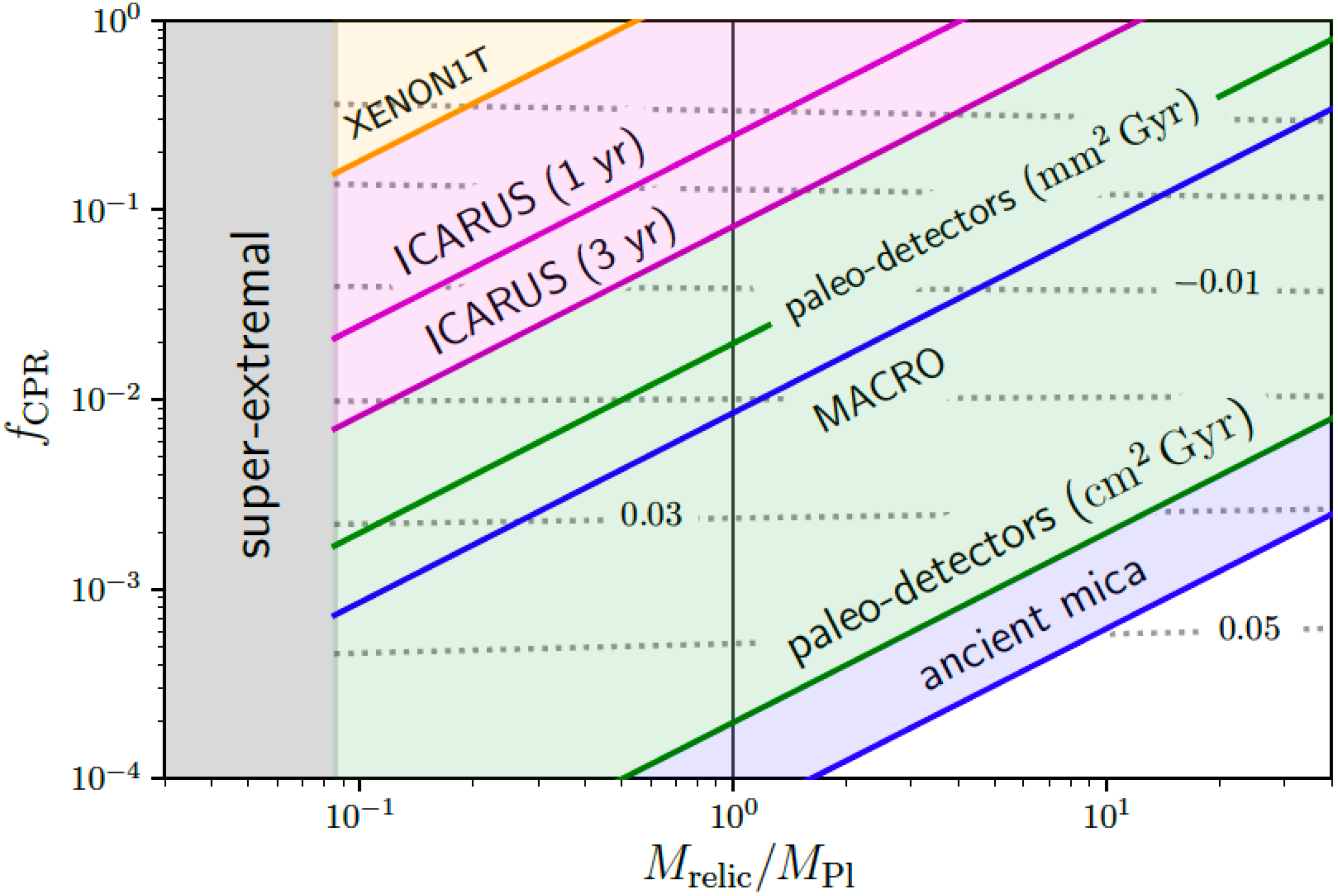

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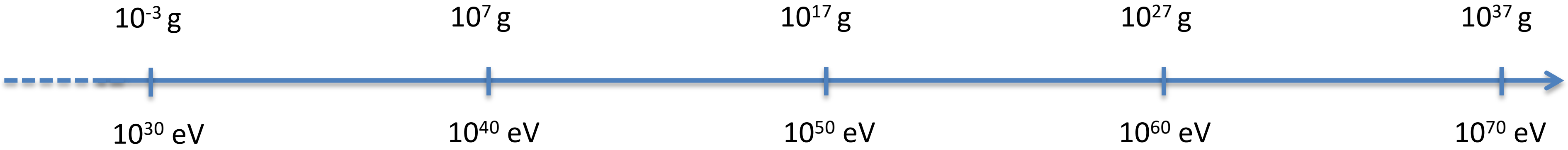


10^{-3} g

10^{7} g

10^{17} g

10^{27} g

10^{37} g

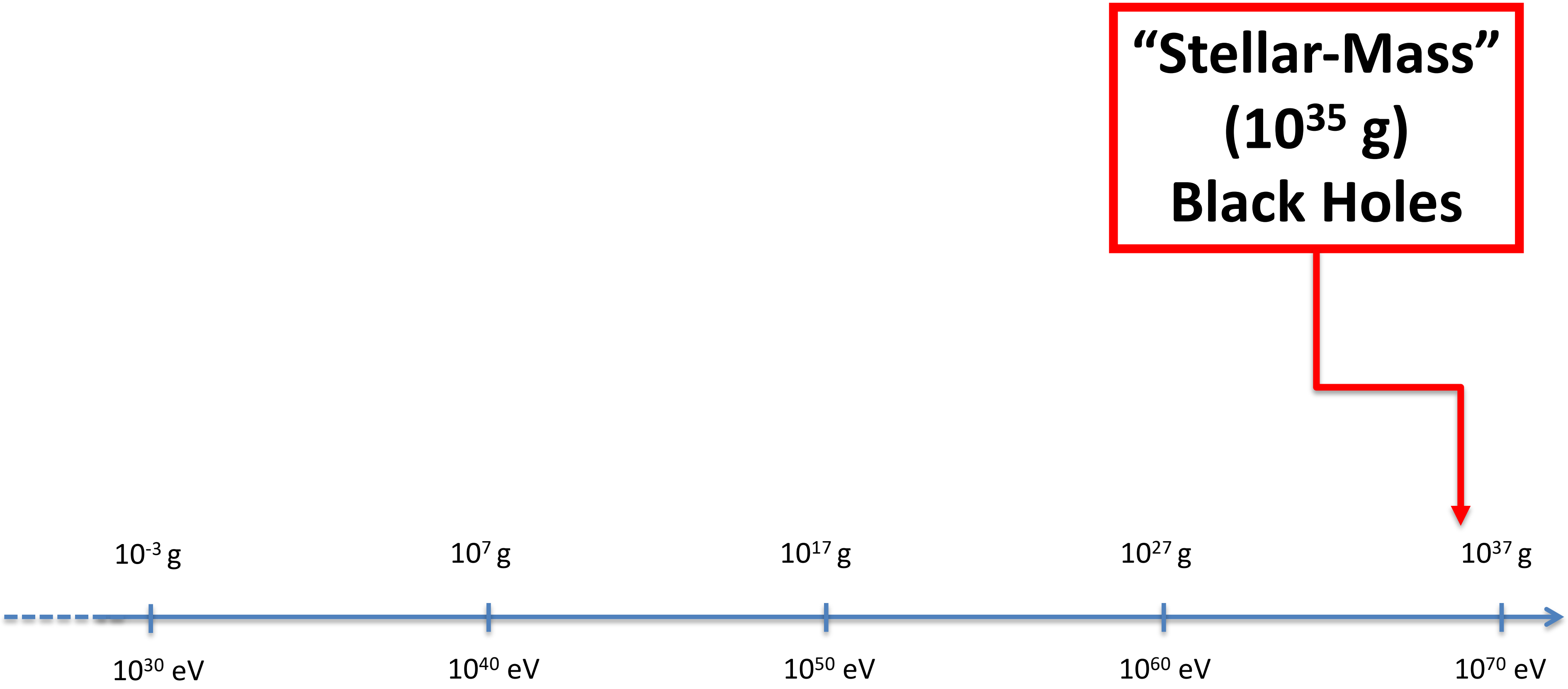
10^{30} eV

10^{40} eV

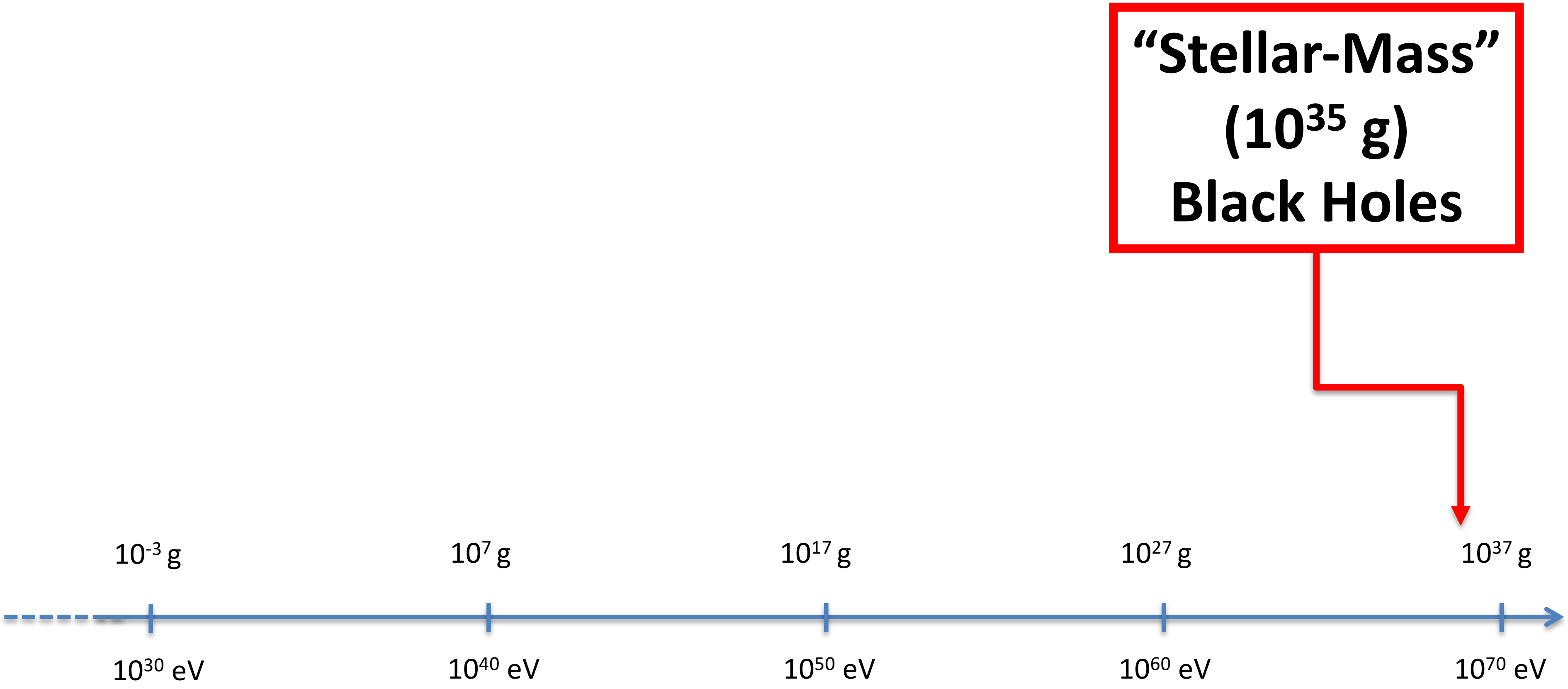
10^{50} eV

10^{60} eV

10^{70} eV



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



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

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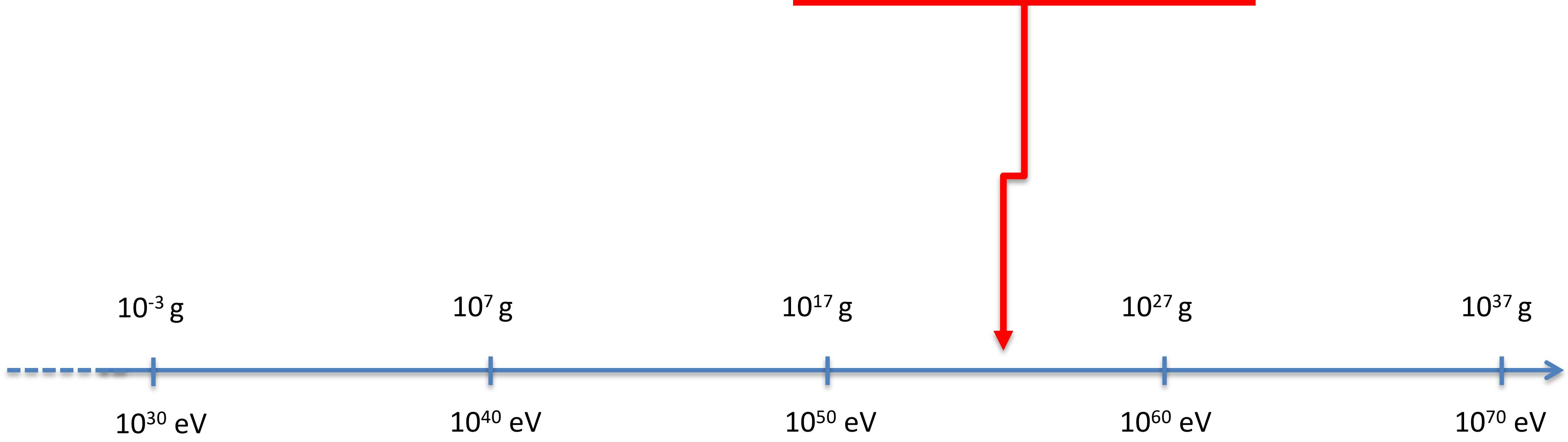
10^{30} eV | 10^{40} eV | 10^{50} eV | 10^{60} eV | 10^{70} eV

- ✓ **Sub-Chandrasekhar goldilocks!!**
- ✓ **Searches ongoing, perhaps already there!**

“Asteroid-Mass”
(10^{22} g)
Black Holes



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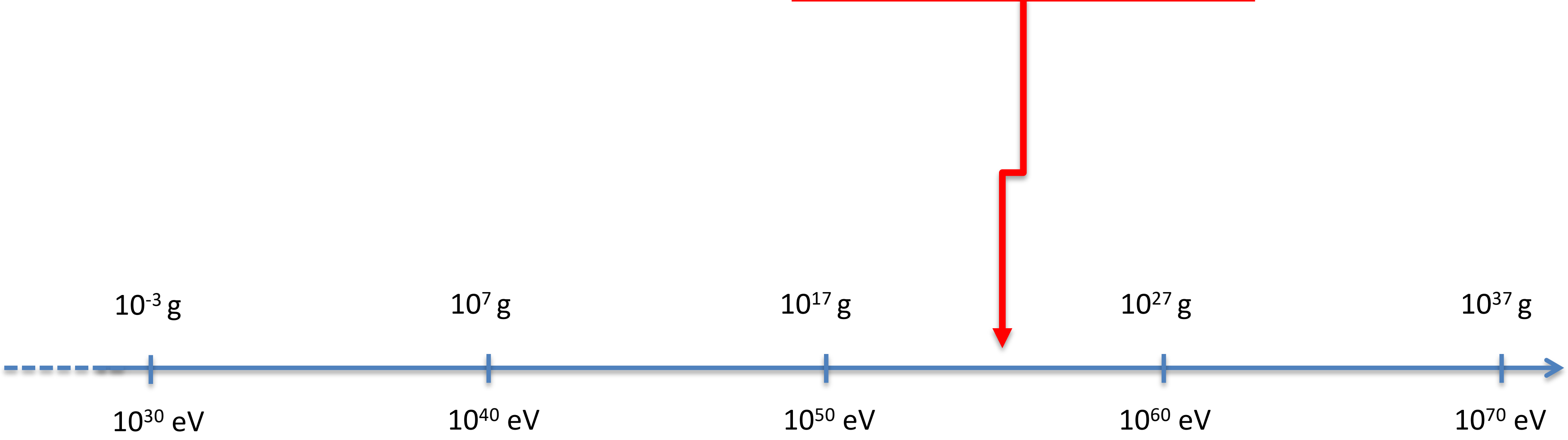
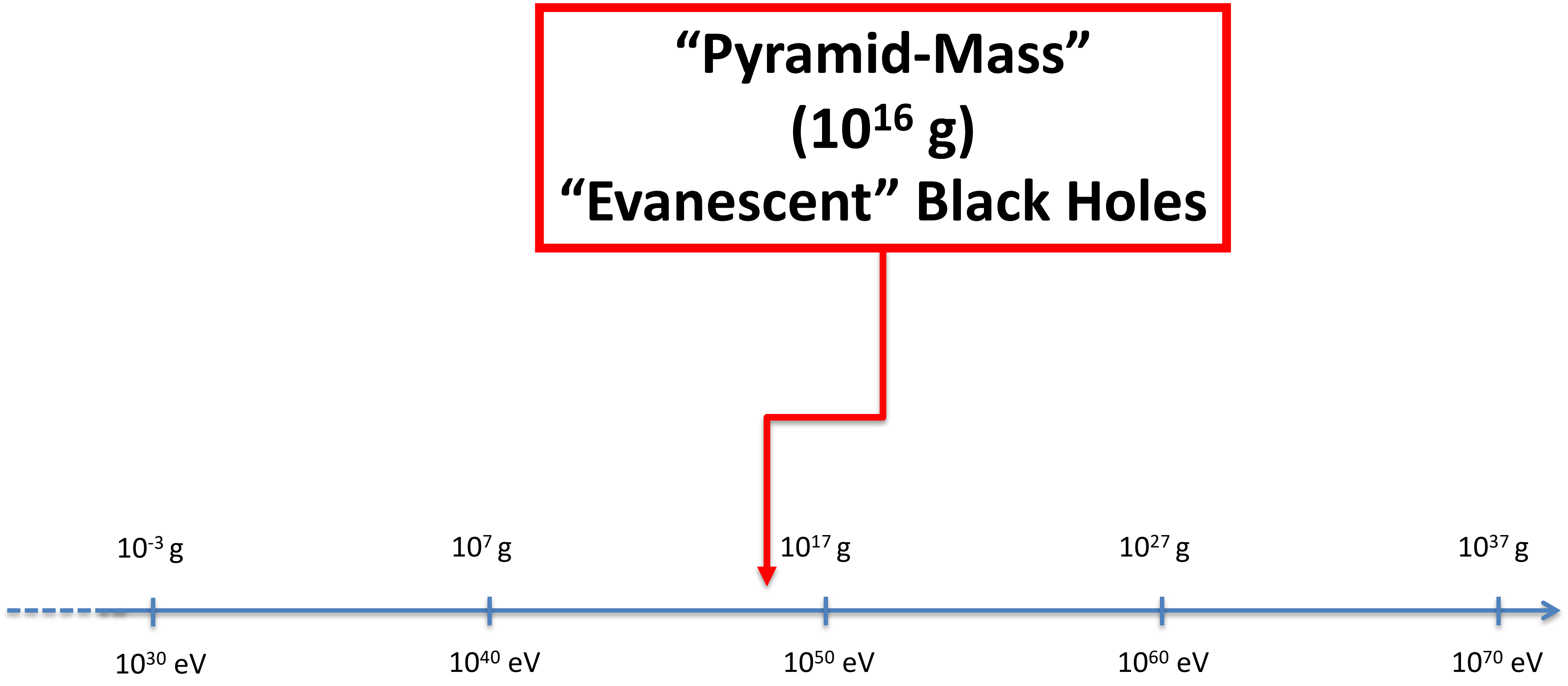
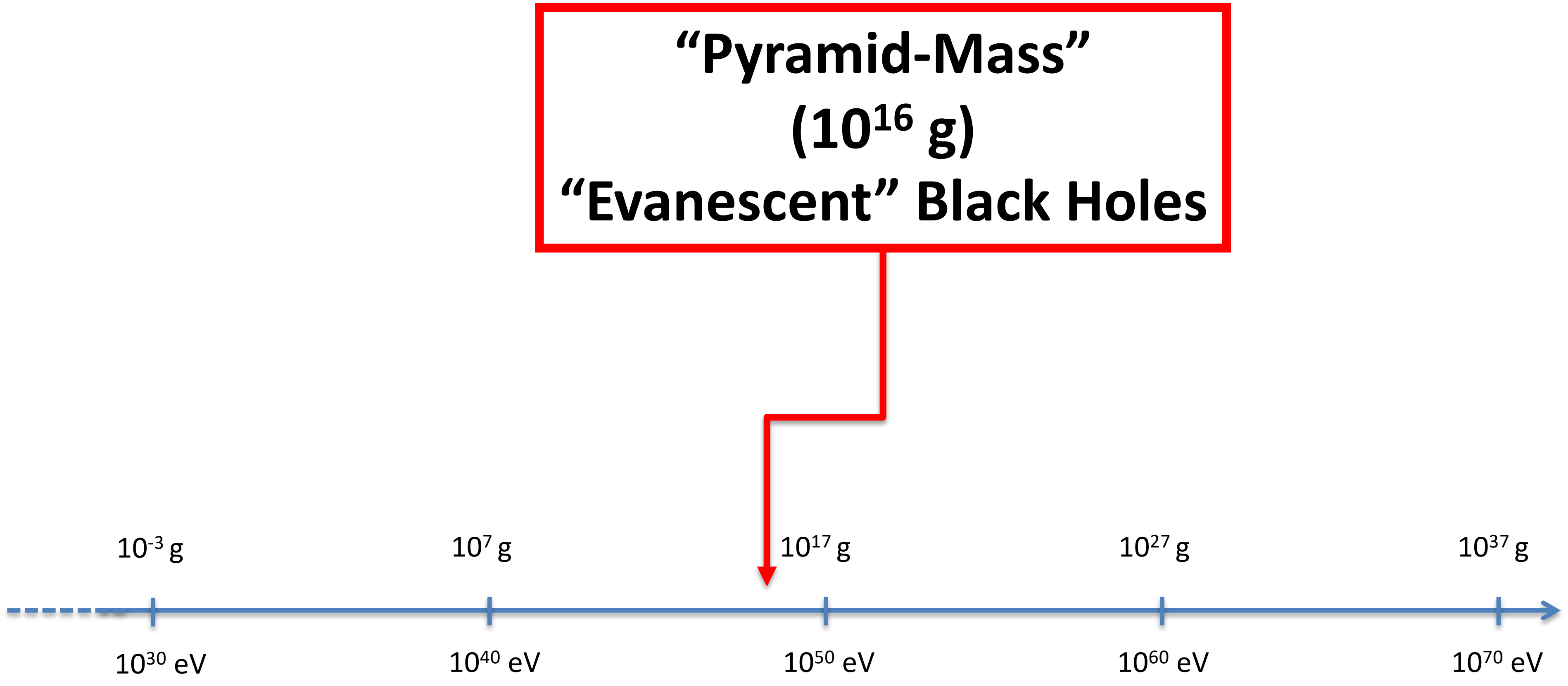


- ✓ **Microlensing a lot trickier than previously thought!**
- ✓ **If detected, how do we distinguish PBH from rogue planets? Statistics!**

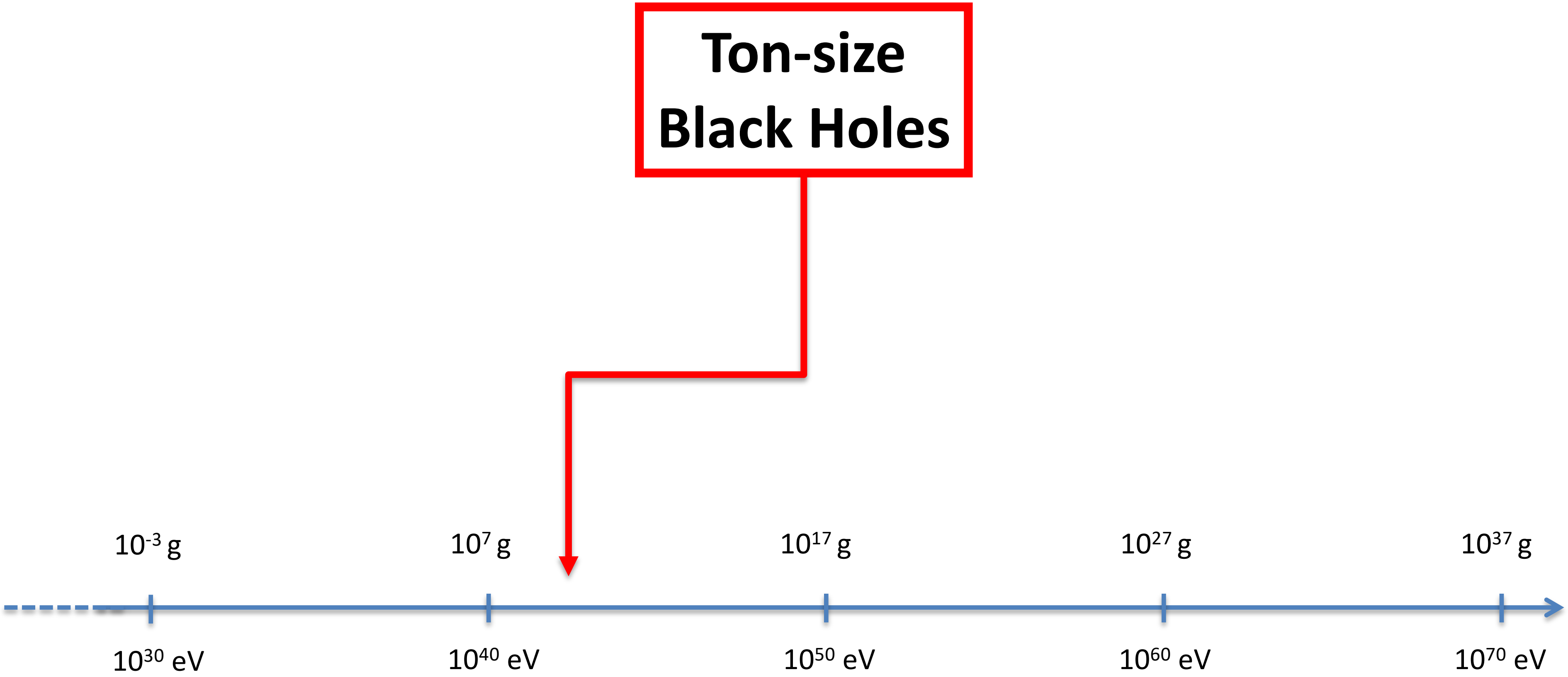


“Pyramid-Mass”
(10^{16} g)
“Evanescent” Black Holes



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

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



Ton-size Black Holes

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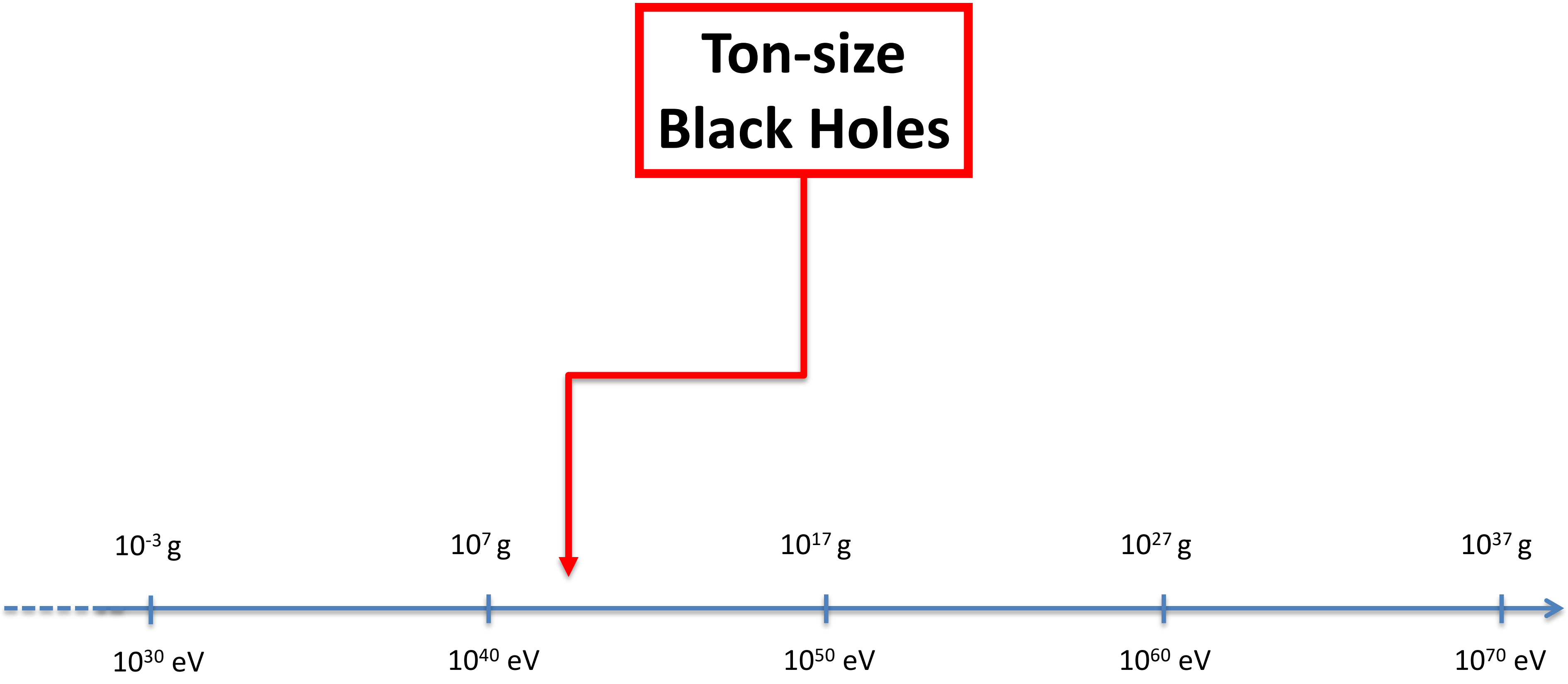
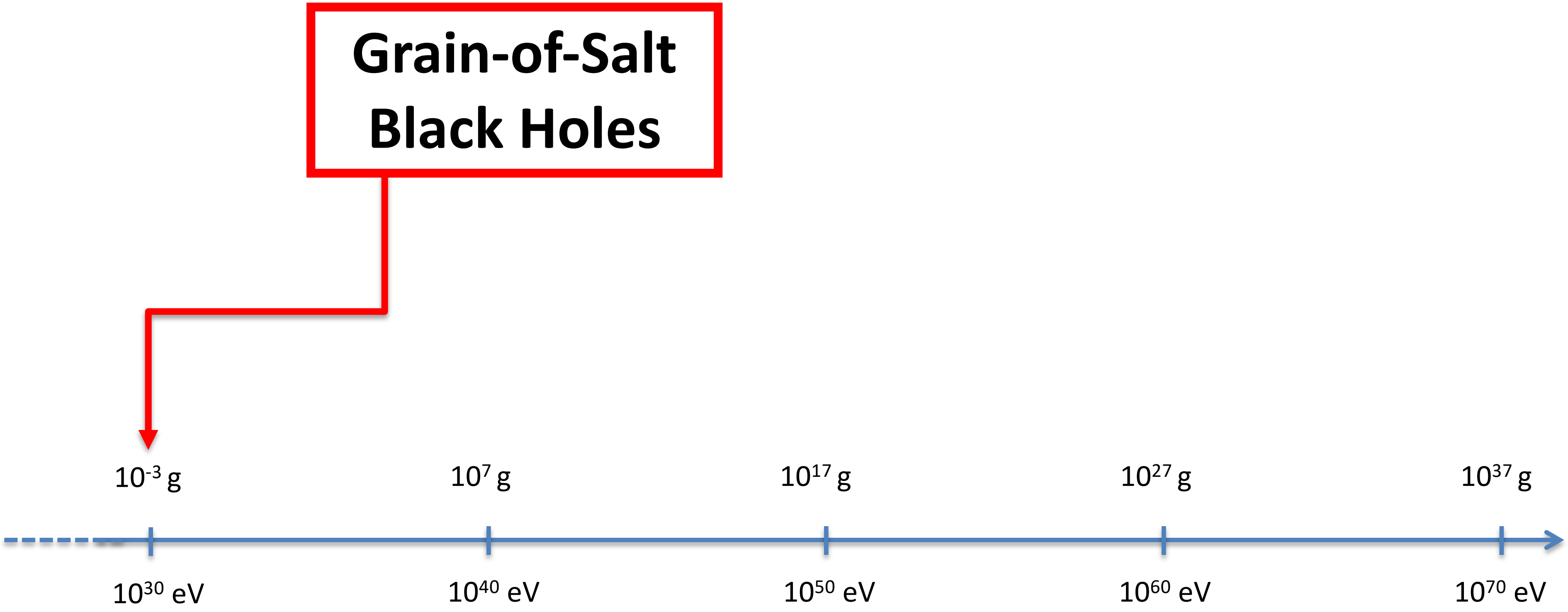


Ton-size Black Holes

- ✓ **Decays can produce DM, BAU, Gravitational Waves**



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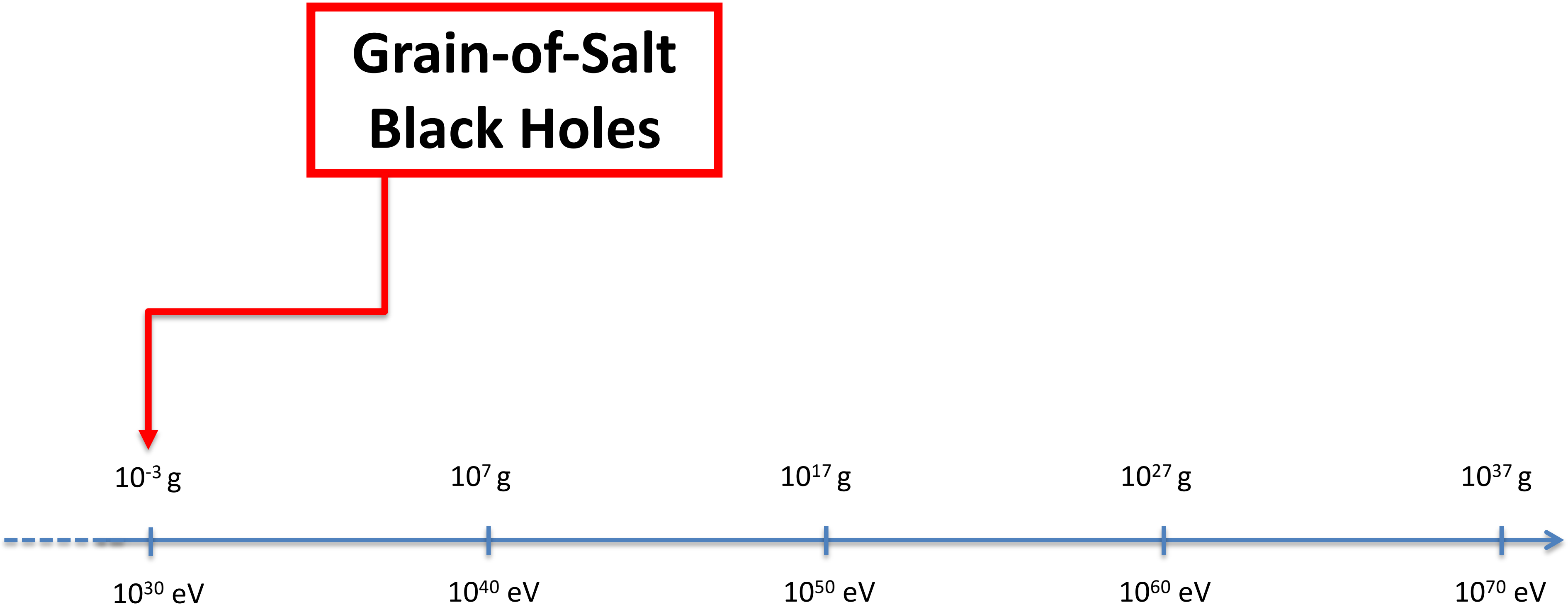


Grain-of-Salt Black Holes

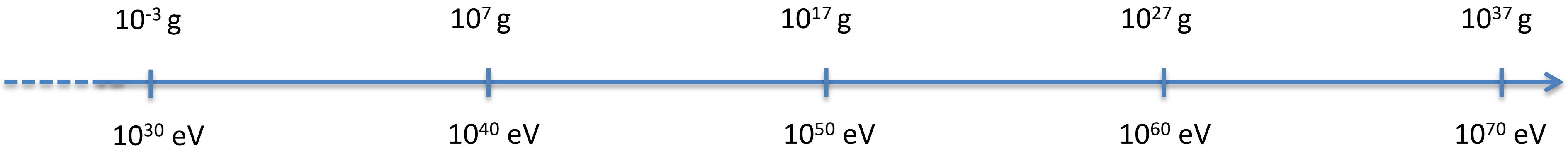
- ✓ **Likely (partly) charged**
- ✓ **Detectable! …best with Paleo-Detectors**

In the era of gravitational wave astronomy,

the physics of macroscopic DM candidates

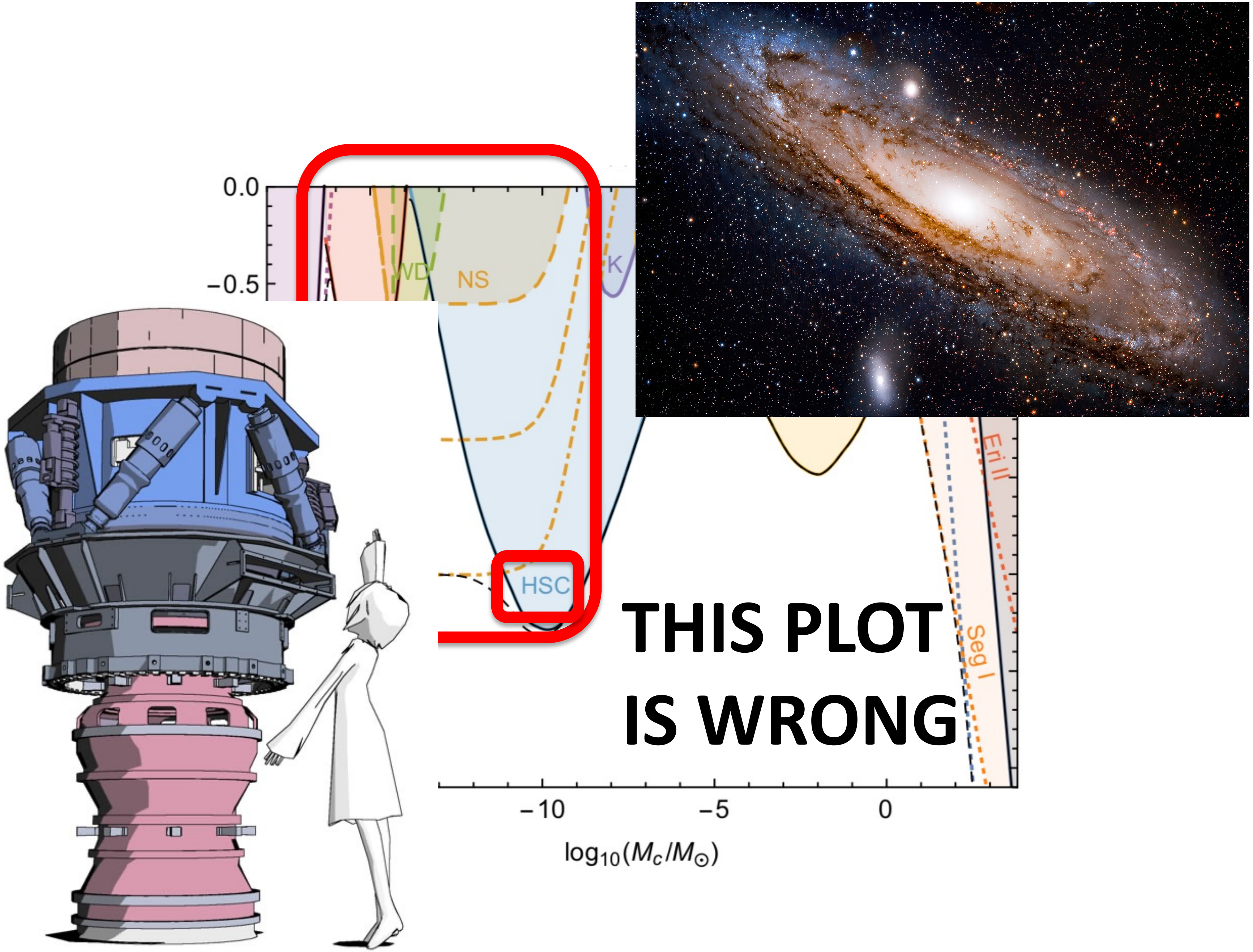
offers many opportunities for the ingenuity

of theorists and the craft of observers



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



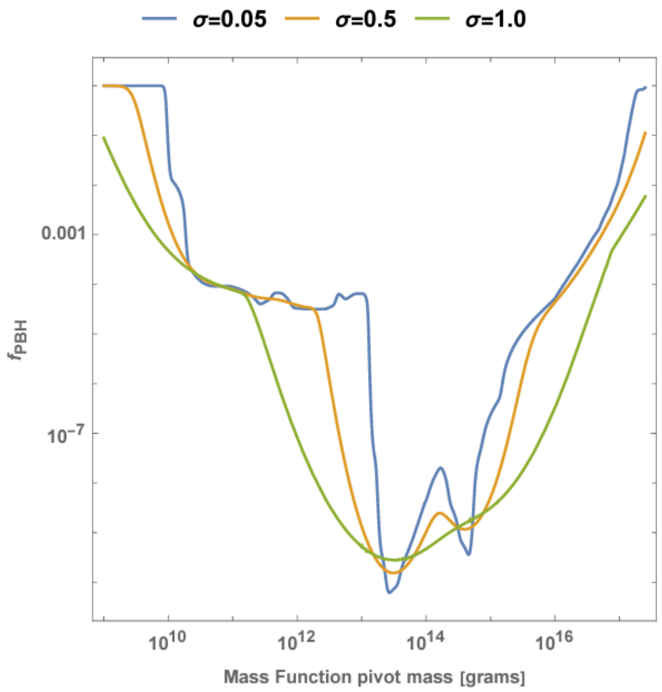
THIS PLOT
IS WRONG

Given a mass function, constraints are calculated via

$$\int \mathrm{d}M \frac{\psi(M)}{f_{\max}(M)} \leq 1.$$

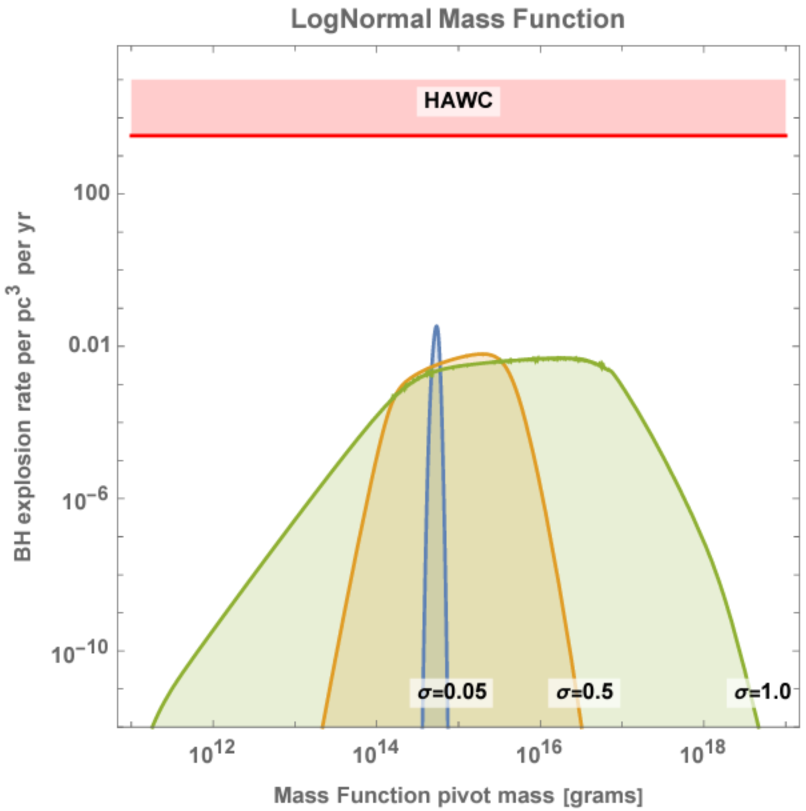
For instance, for a lognormal mass function (typical of a smooth, symmetric power spectrum density perturbation)

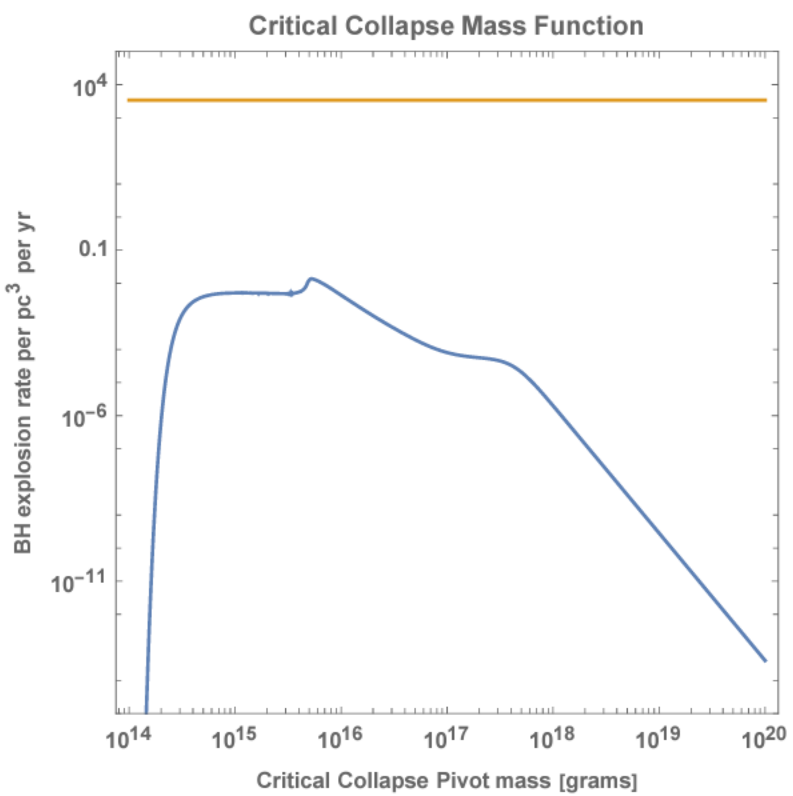
$$\psi(M) = \frac{f_{\mathrm{PBH}}}{\sqrt{2\pi}\sigma M} \exp\left(- \frac{\log^2(M/M_c)}{2\sigma^2} \right)$$



***Profumo, Boluna, Ble, Hennings, 2023**

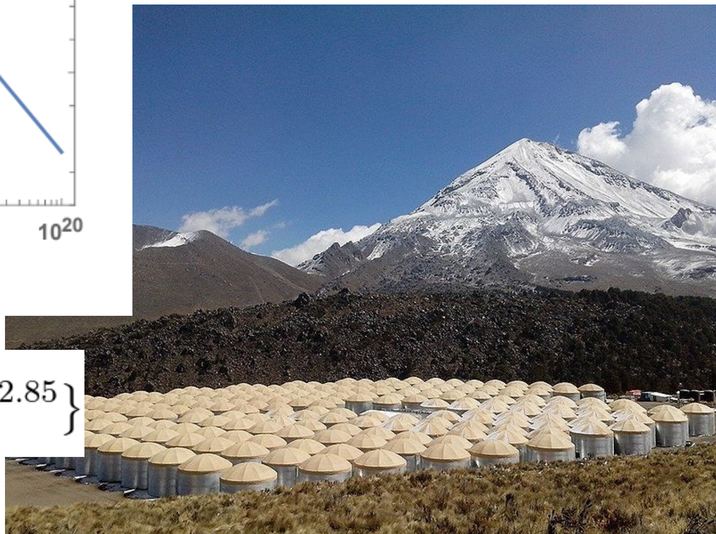
A given width σ and pivot mass M_* produce a different rate of PBH explosions today





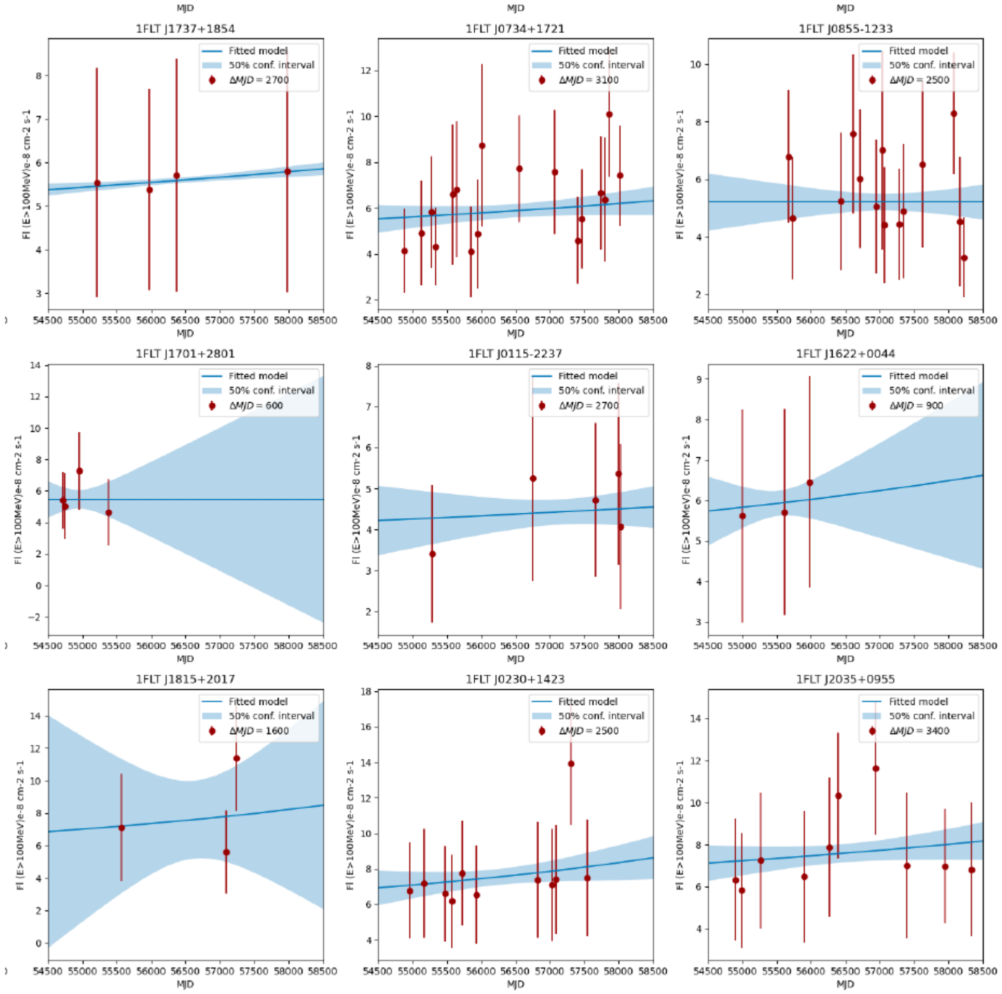
$$\psi(M, M_c) \propto M^{2.85} \exp\{-(M/M_c)^{2.85}\}$$

HAWC



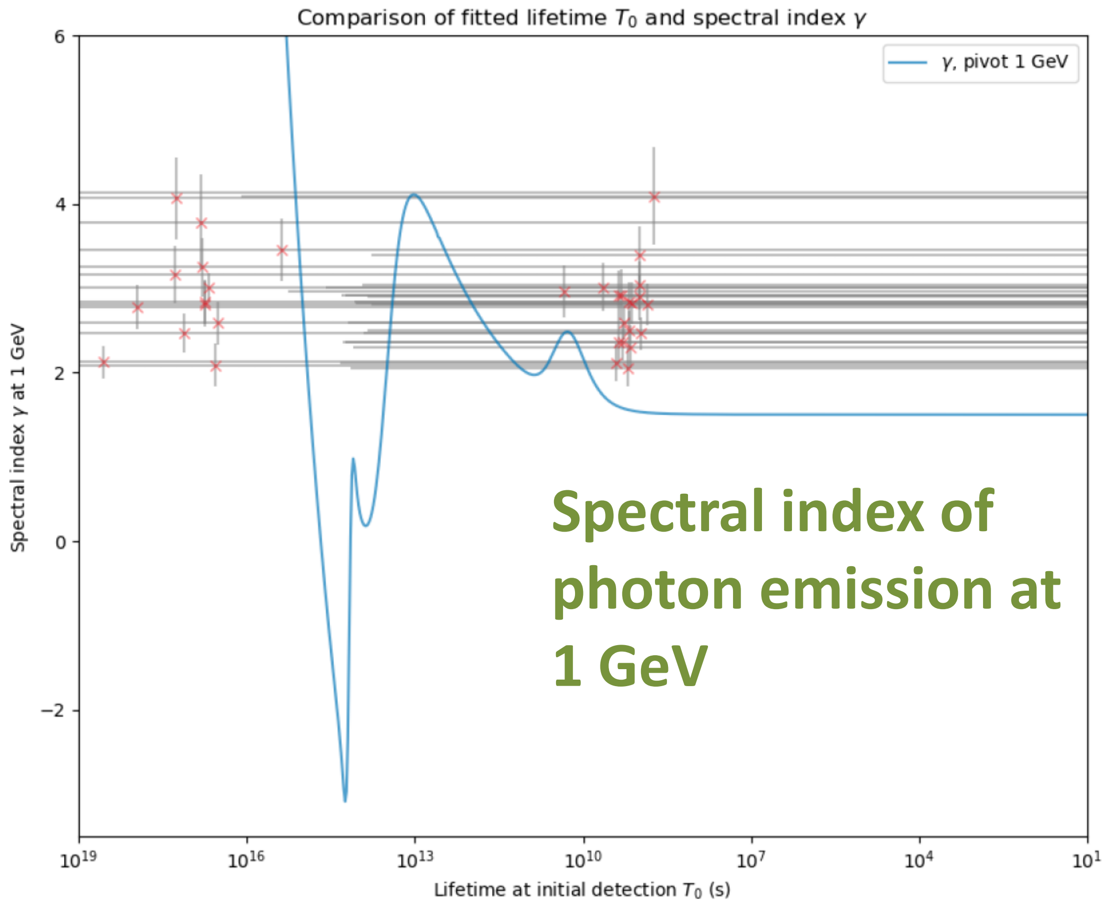
*Profumo, Boluna, Ble, Hennings, 2023

LAT and GBM Gamma-ray burst catalog
(1) LAT variable sources



*Profumo, Boluna, Ble, Hennings, 2023

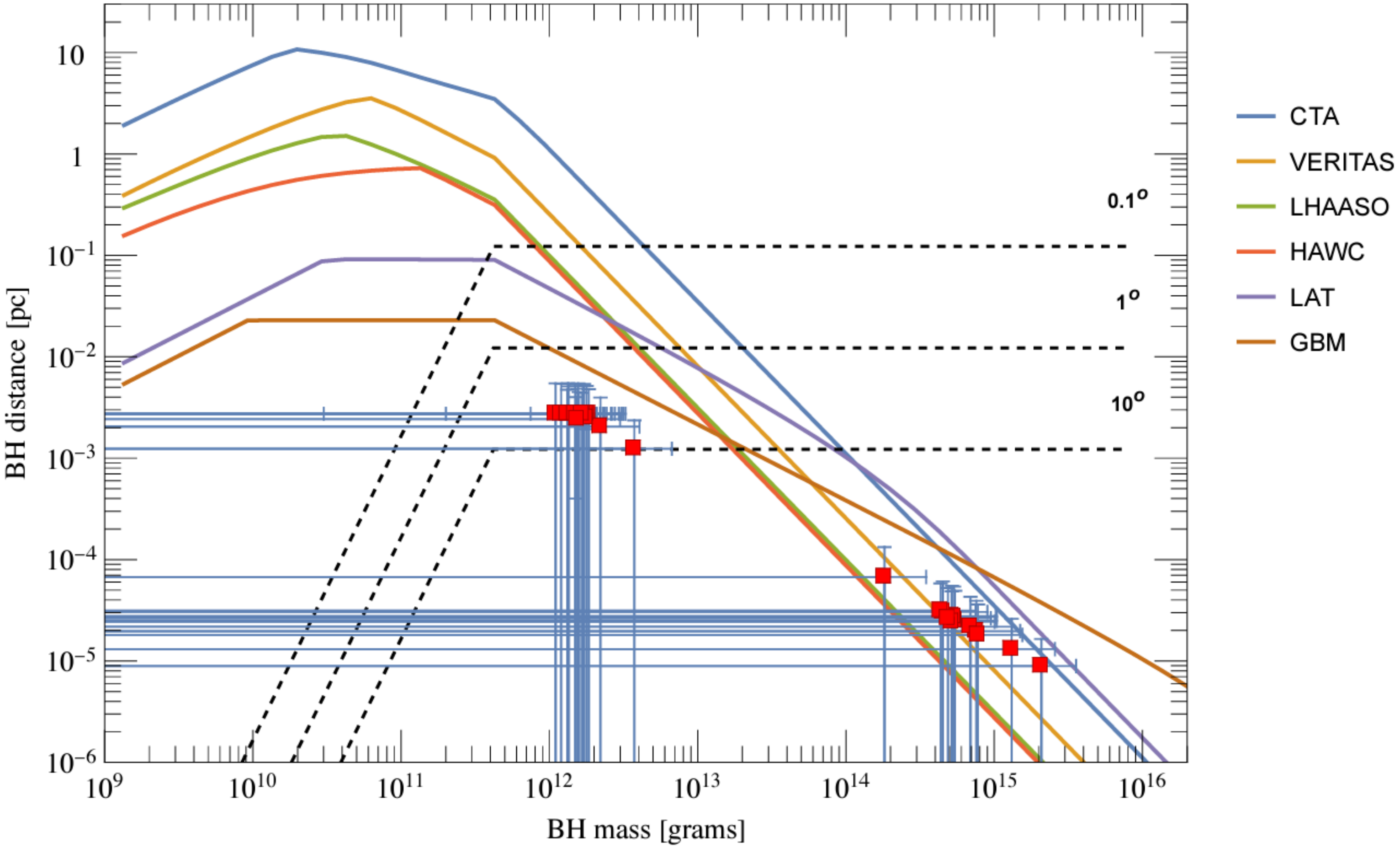
LAT and GBM Gamma-ray burst catalog
(2) LAT variable sources: spectral fit



Spectral index of photon emission at 1 GeV

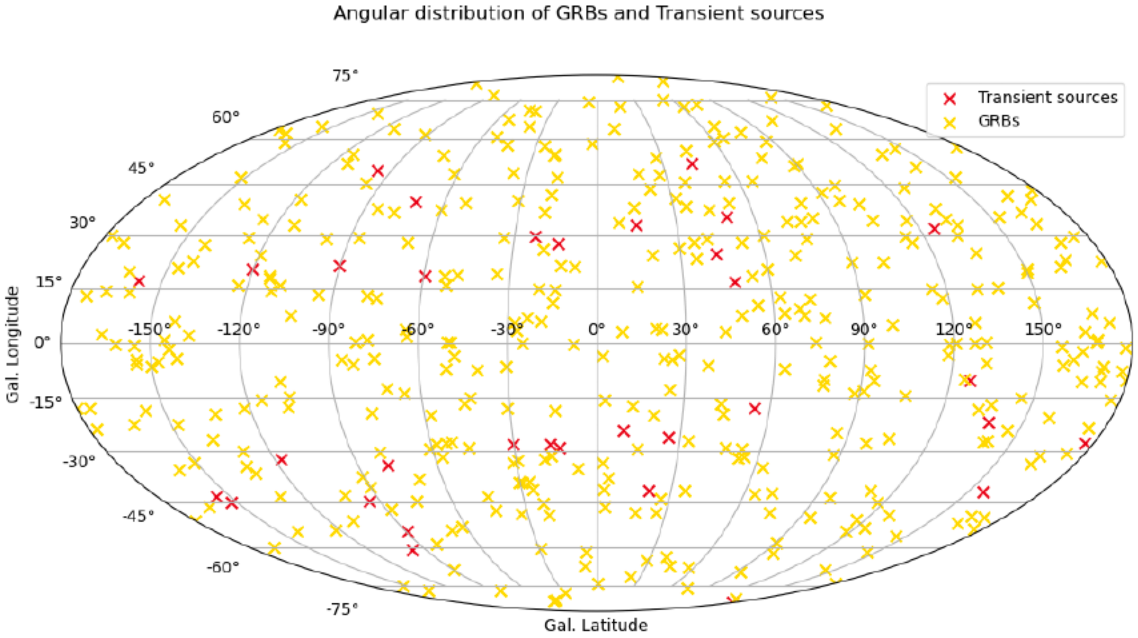
*Profumo, Boluna, Ble, Hennings, 2023

LAT and GBM Gamma-ray burst catalog
(3) LAT variable sources: distance-age fit



*Profumo, Boluna, Ble, Hennings, 2023

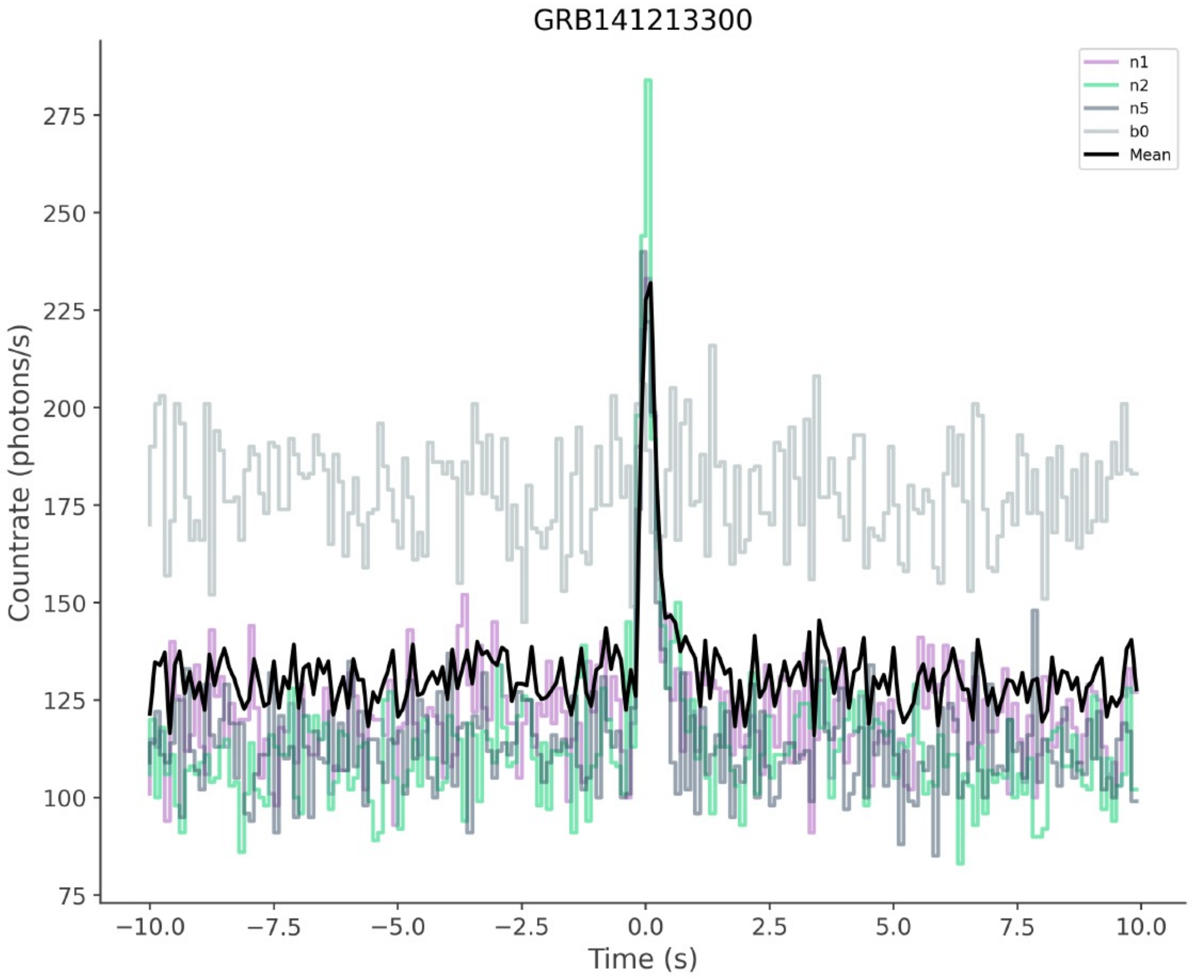
LAT and GBM Gamma-ray burst catalog
(4) LAT variable sources: angular distribution



In Gal. Lat/Long coords, the galactic center is at (0,0) and the plane is on the x-axis.

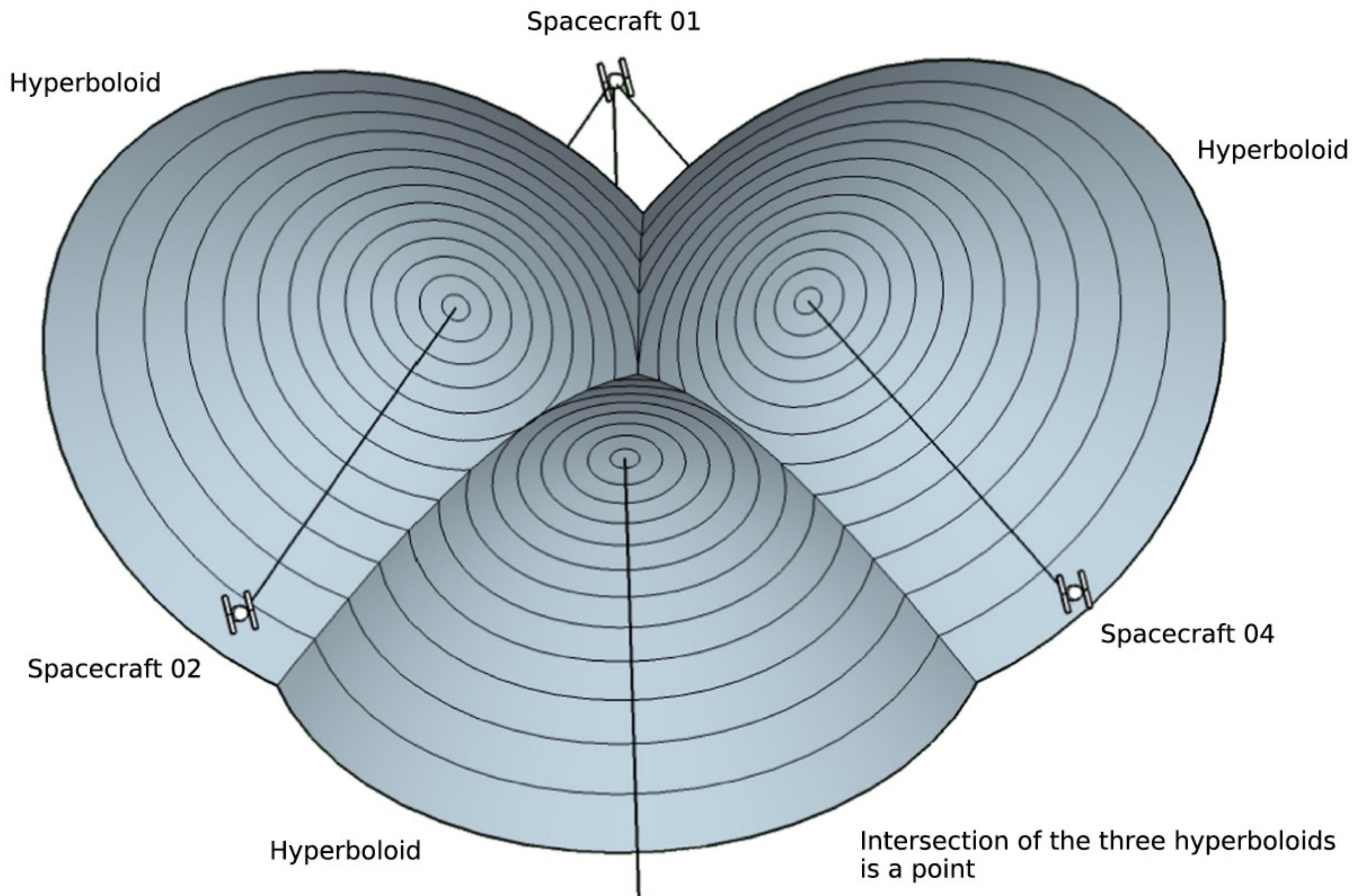
*Profumo, Boluna, Ble, Hennings, 2023

LAT and GBM Gamma-ray burst catalog
(5) Short duration: light curve

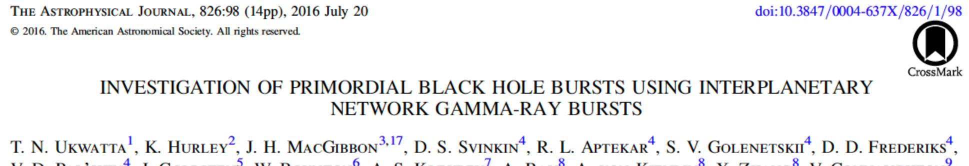


*Profumo, Boluna, Ble, Hennings, 2023

LAT and GBM Gamma-ray burst catalog
(6) Interplanetary GRB monitors



Intersection of the three hyperboloids
is a point


THE ASTROPHYSICAL JOURNAL, 826:98 (14pp), 2016 July 20 doi:10.3847/0004-637X/826/1/98

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INVESTIGATION OF PRIMORDIAL BLACK HOLE BURSTS USING INTERPLANETARY NETWORK GAMMA-RAY BURSTS

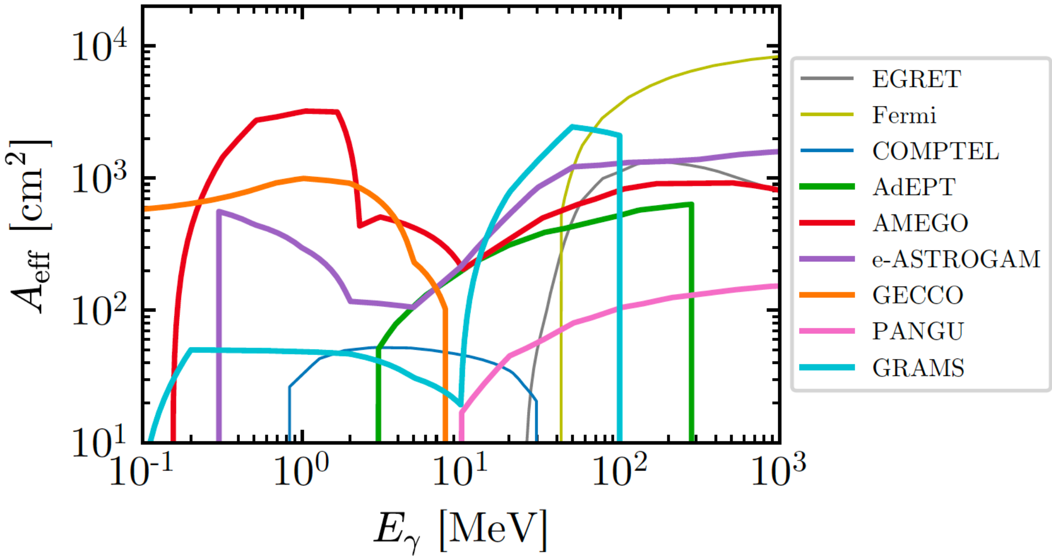
T. N. UKWATTA[1], K. HURLEY[2], J. H. MACGIBBON[3,17], D. S. SVINKIN[4], R. L. APTEKAR[4], S. V. GOLENETSKII[4], D. D. FREDERIKS[4],

*Profumo, Boluna, Ble, Hennings, 2023

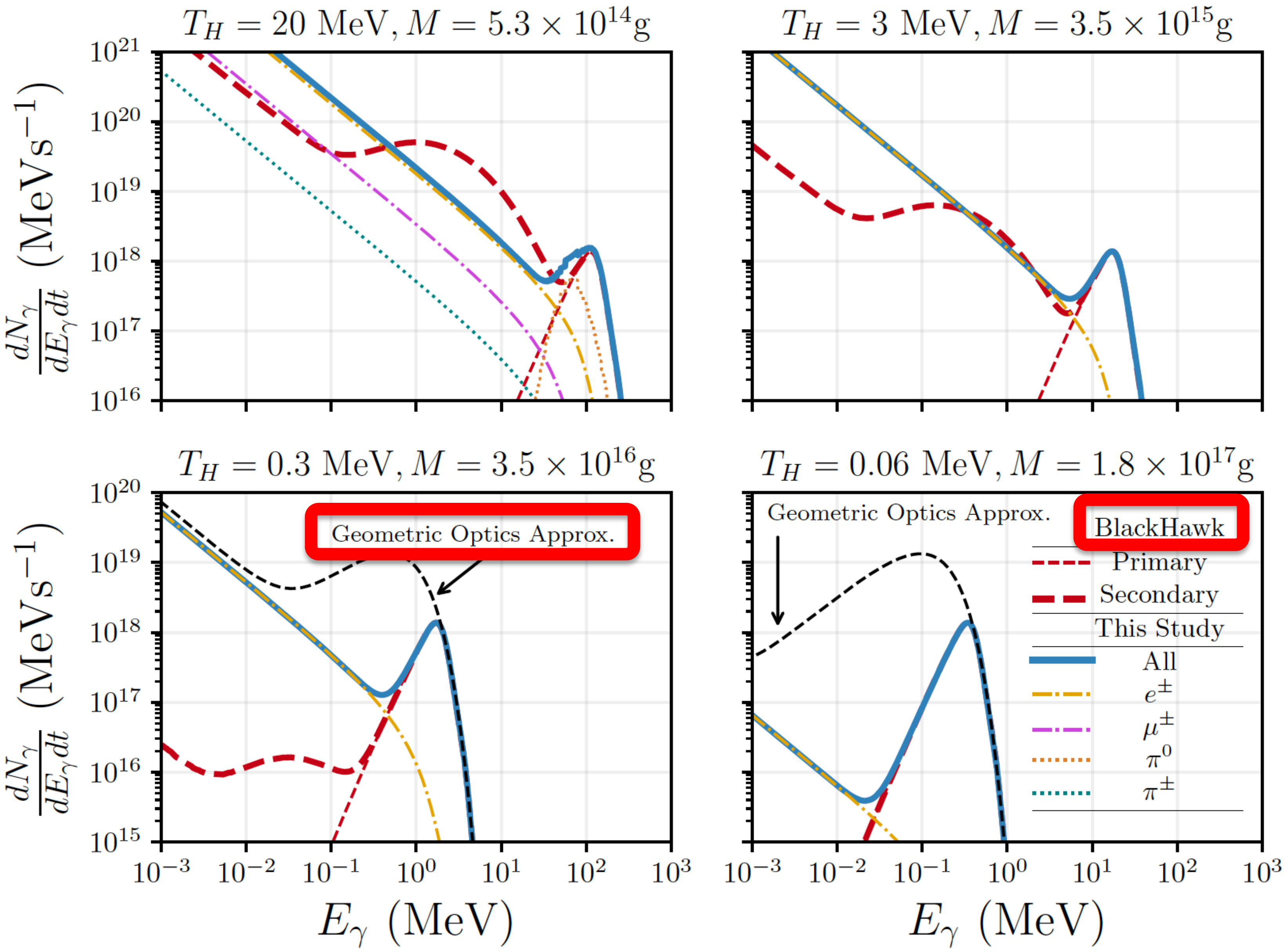
Lightest PBH that can be dark matter…

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

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

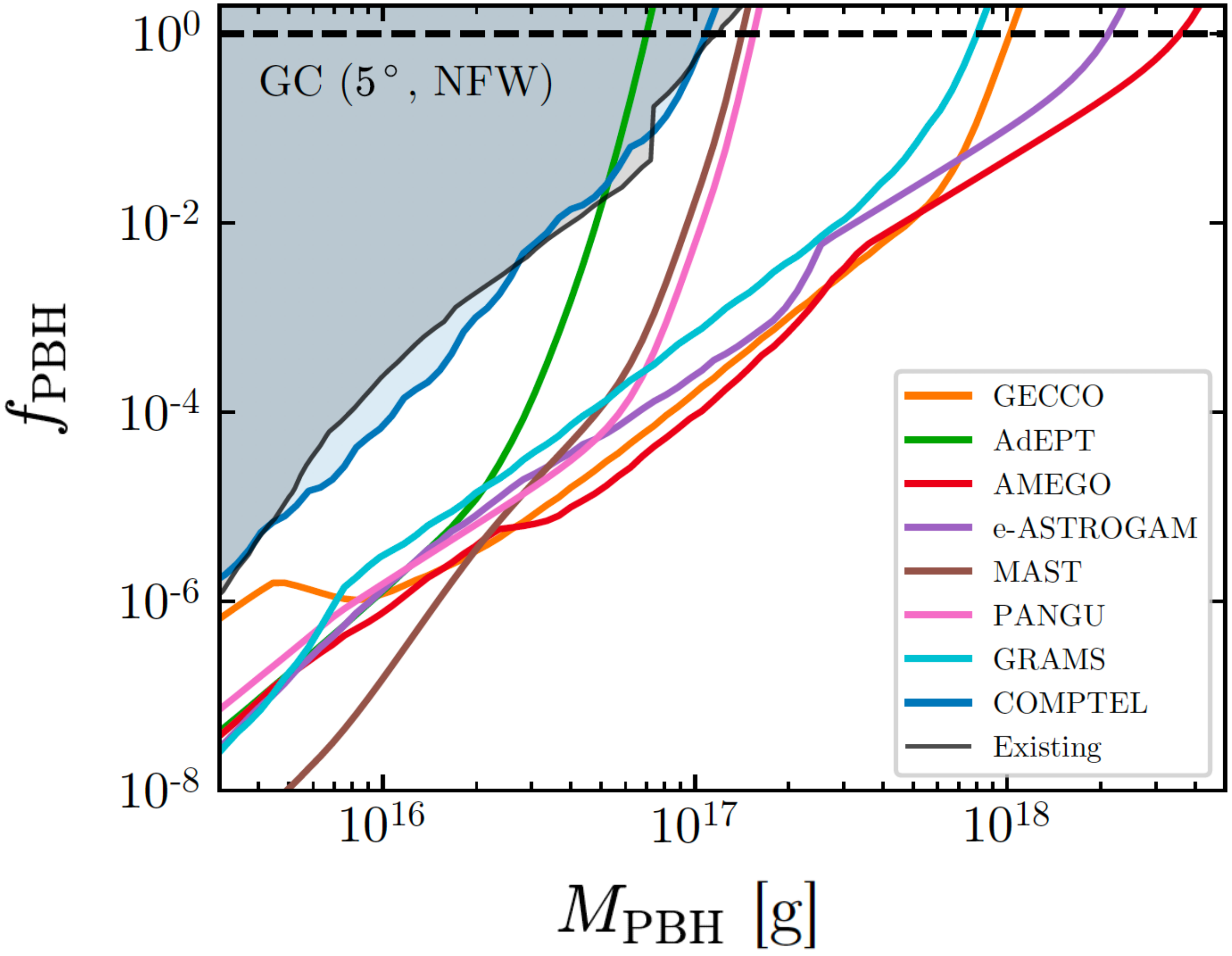


Coogan, Morrison & Profumo, 2010.04797, Phys. Rev. Letters



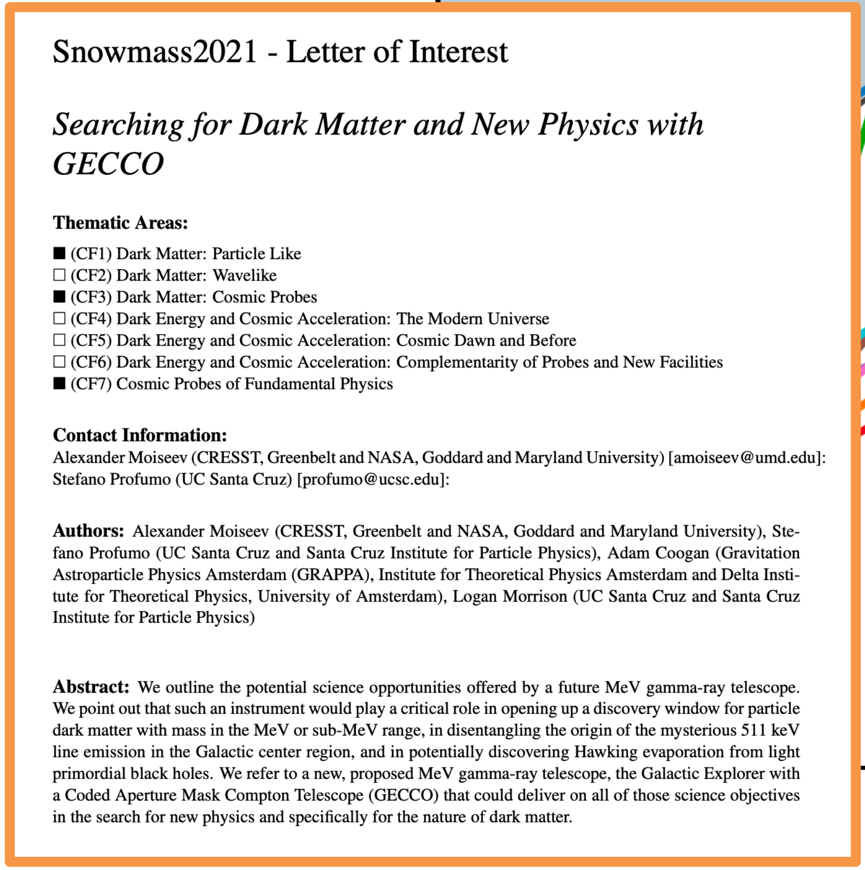
Coogan, Morrison & Profumo, 2010.04797, Phys. Rev. Letters

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

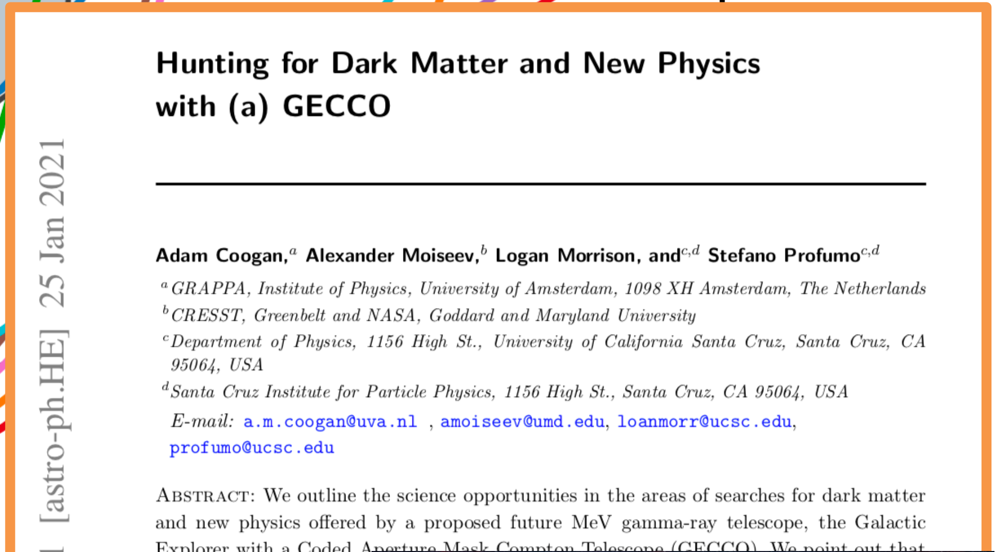
Thematic Areas:

■ (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:
Alexander Moiseev (CRESST, Greenbelt and NASA, Goddard and Maryland University) [amoiseev@umd.edu]:
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.



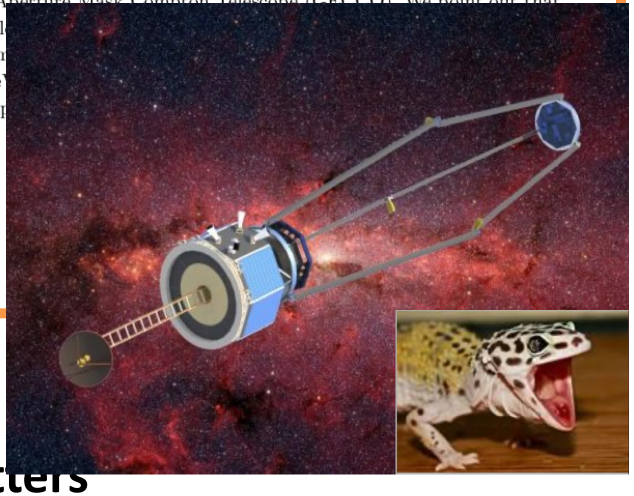
arXiv:2101.10370v1 [astro-ph.HE] 25 Jan 2021

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 Aperture Mask Compton Telescope (GECCO). We point out that
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

Constraints from Positron production also heavily affected

BlackHawk

By Alexandre Arbey and Jérémy Auffinger

Calculation of the Hawking evaporation spectra of any black hole distribution

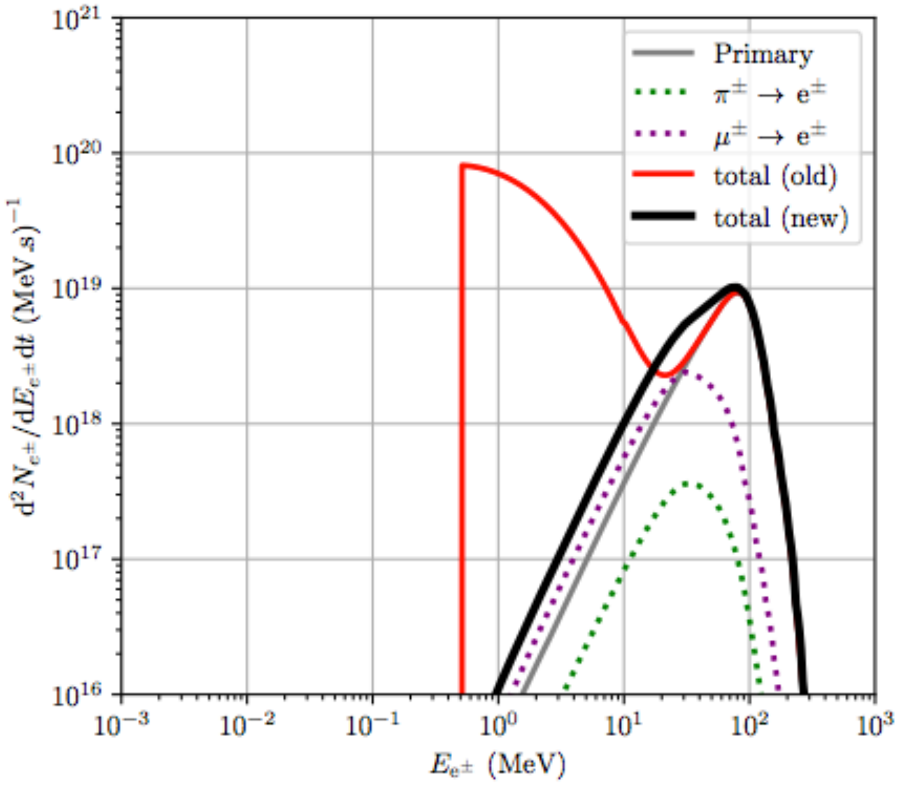
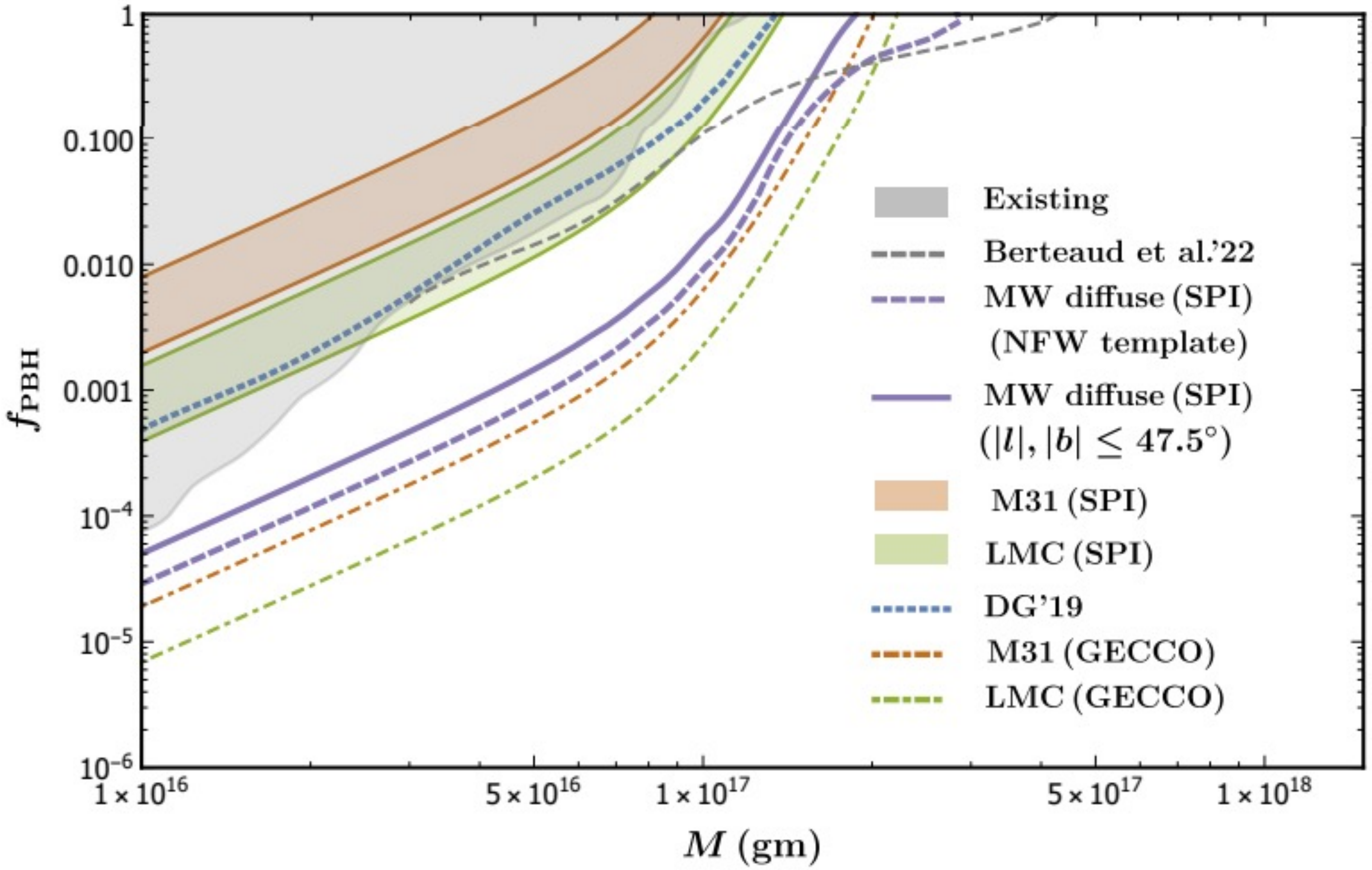
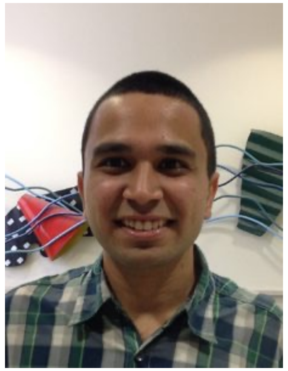


FIG. 5. Comparison between the old `PYTHIA` extrapolated (solid red) and new `Hazma` computed (solid black) `BlackHawk` instantaneous total electron spectrum for a $M_{\mathrm{BH}} = 5.3 \times 10^{14}$ g. From left to right: primary electron spectrum (grey solid); muon decay (purple dotted); charged pion decay (green dotted).

black hole dark matter.

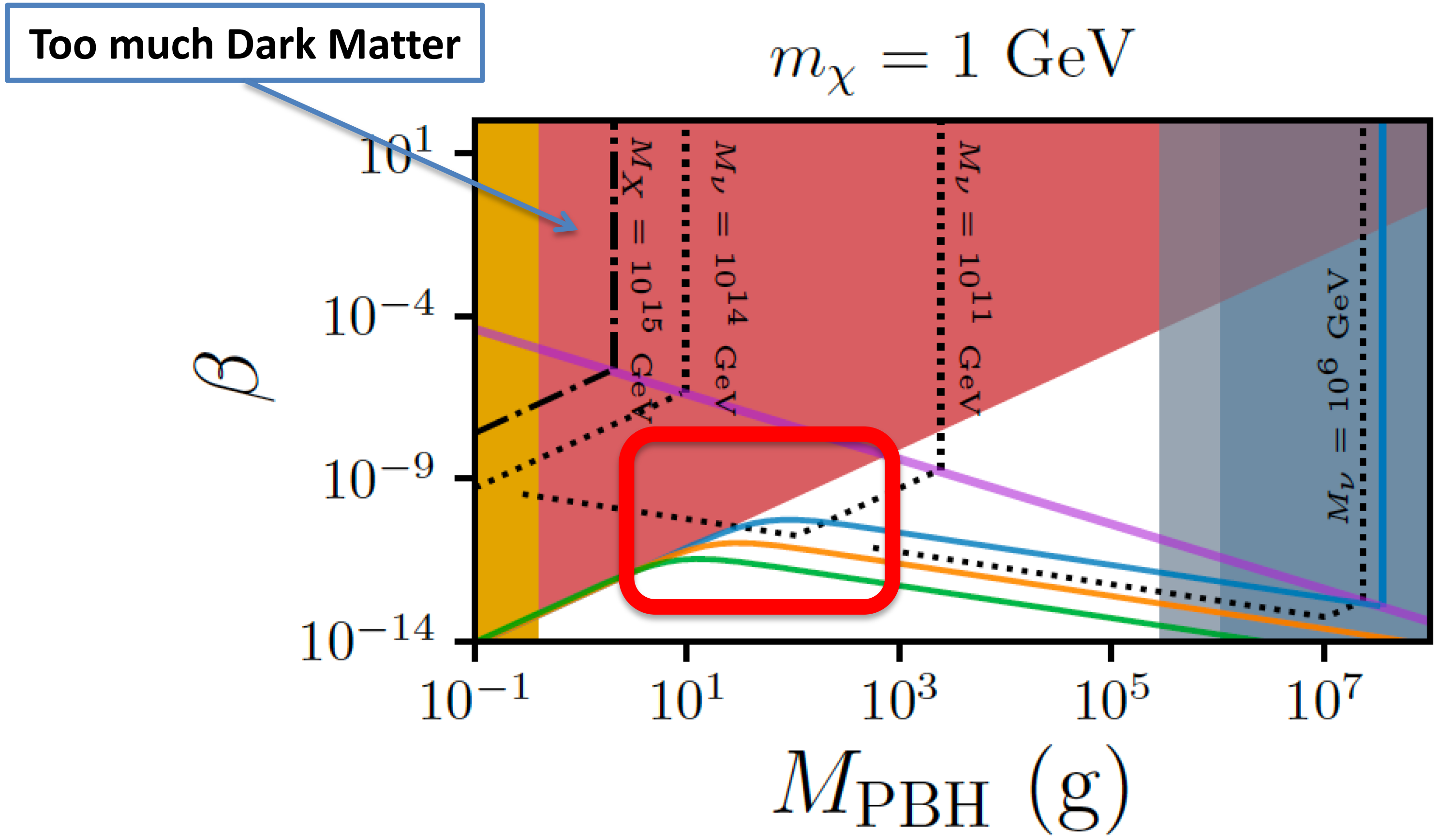
…speaking of which, most up-to-date constraints from Galactic 511 keV emission from INTEGRAL/SPI*



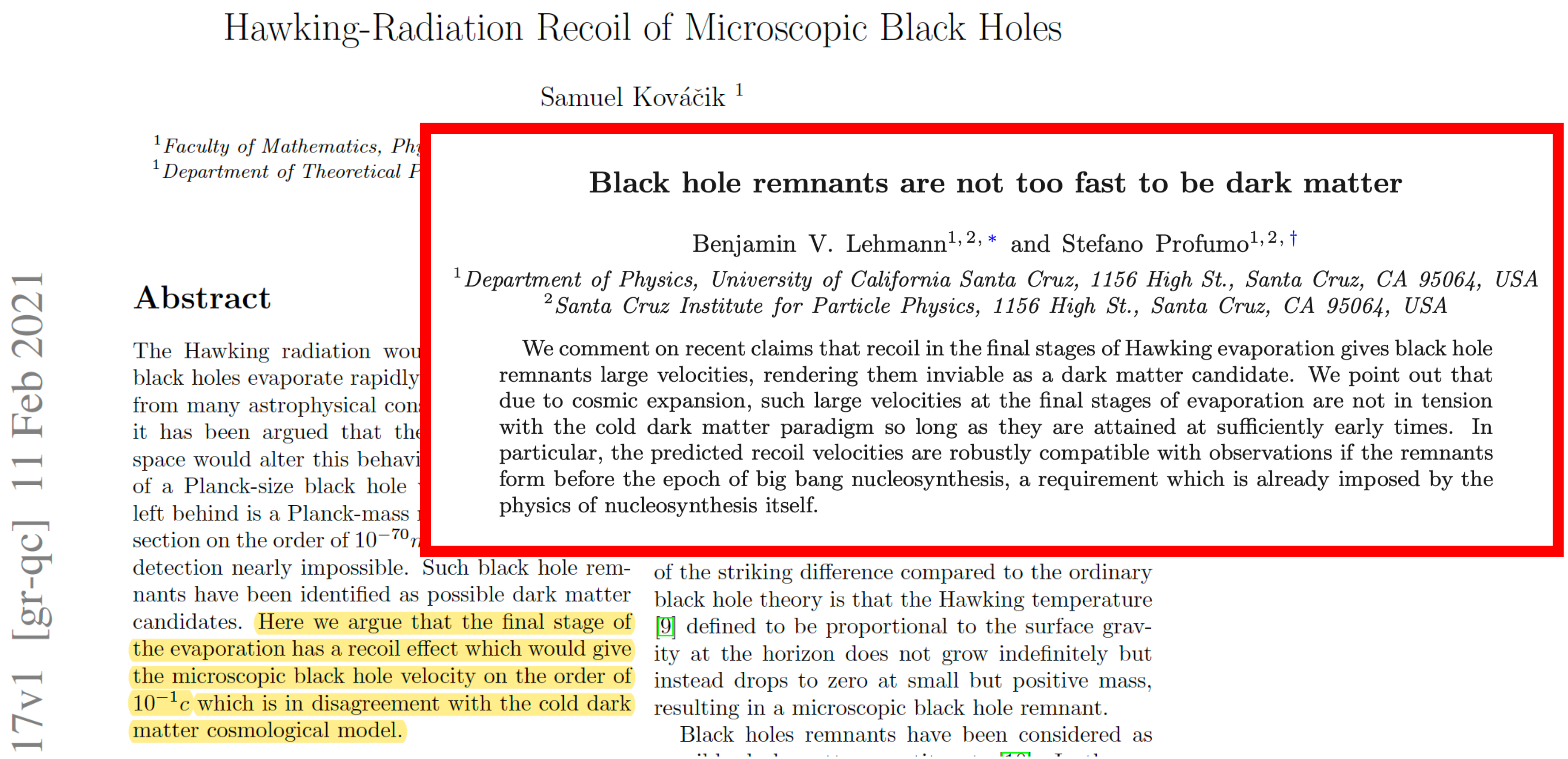


Korwar and Profumo, "*Updated Constraints on Primordial Black Hole Evaporation*", 2302.04408

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


Too much Dark Matter

* Morrison, Profumo and Yu (JCAP, 2019)



Hawking-Radiation Recoil of Microscopic Black Holes

Samuel Kováčik [1]

[1] *Faculty of Mathematics, Ph*
[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, †]

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

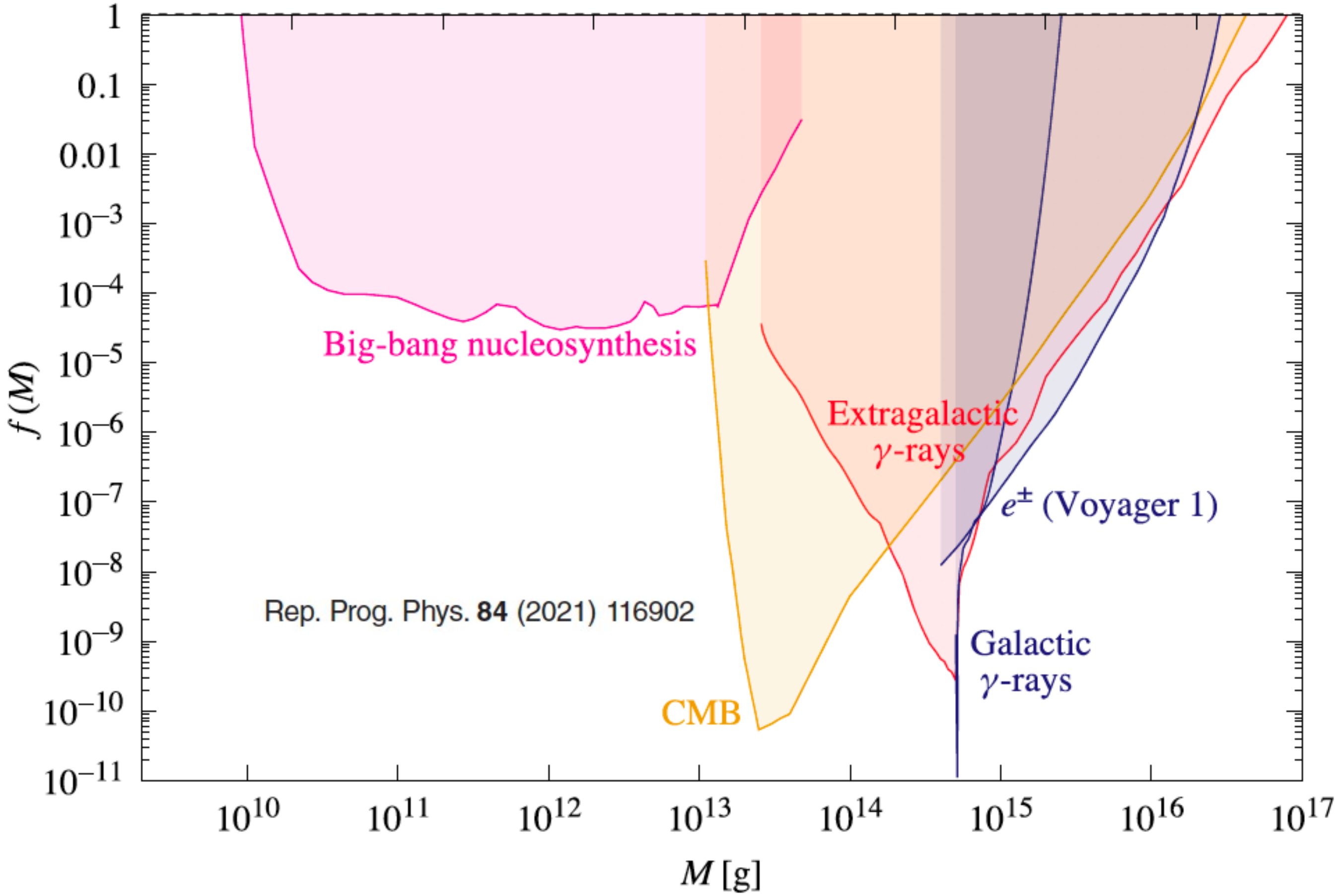
We comment on recent claims that recoil in the final stages of Hawking evaporation gives black hole remnants large velocities, rendering them inviable as a dark matter candidate. We point out that due to cosmic expansion, such large velocities at the final stages of evaporation are not in tension with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

At earlier times, evaporation perturbs BBN, CMB

Here, perhaps, gravity waves! (but very high frequency!)*

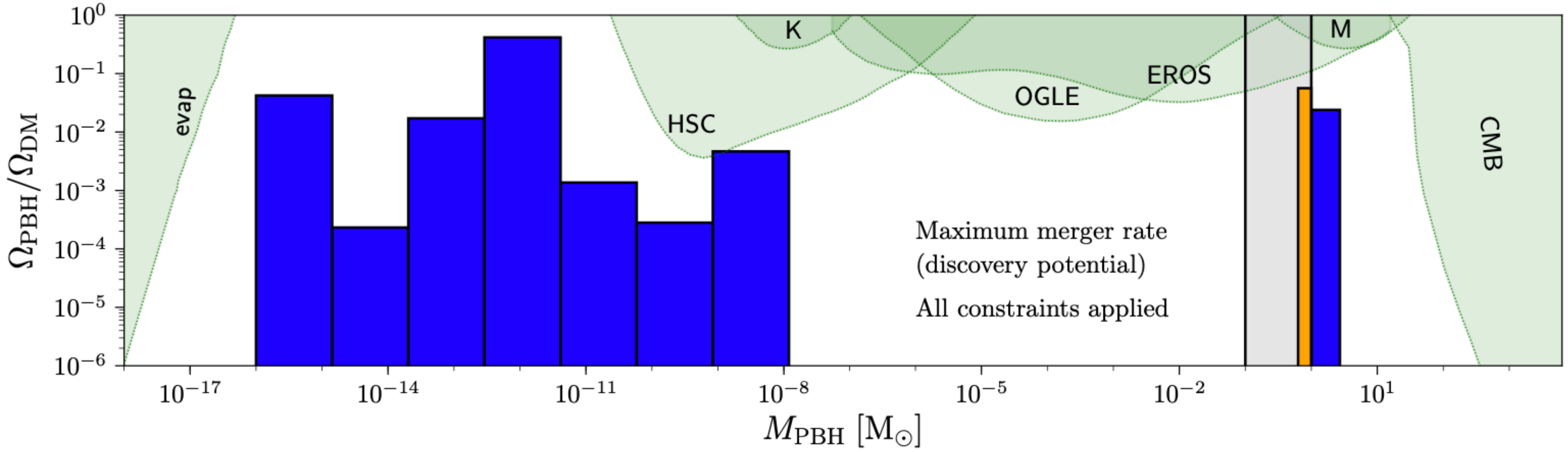


Rep. Prog. Phys. **84** (2021) 116902

Notice that here M [g] is the initial mass at PBH formation

*Ireland, Profumo and Scharnhorst, 2302.10188

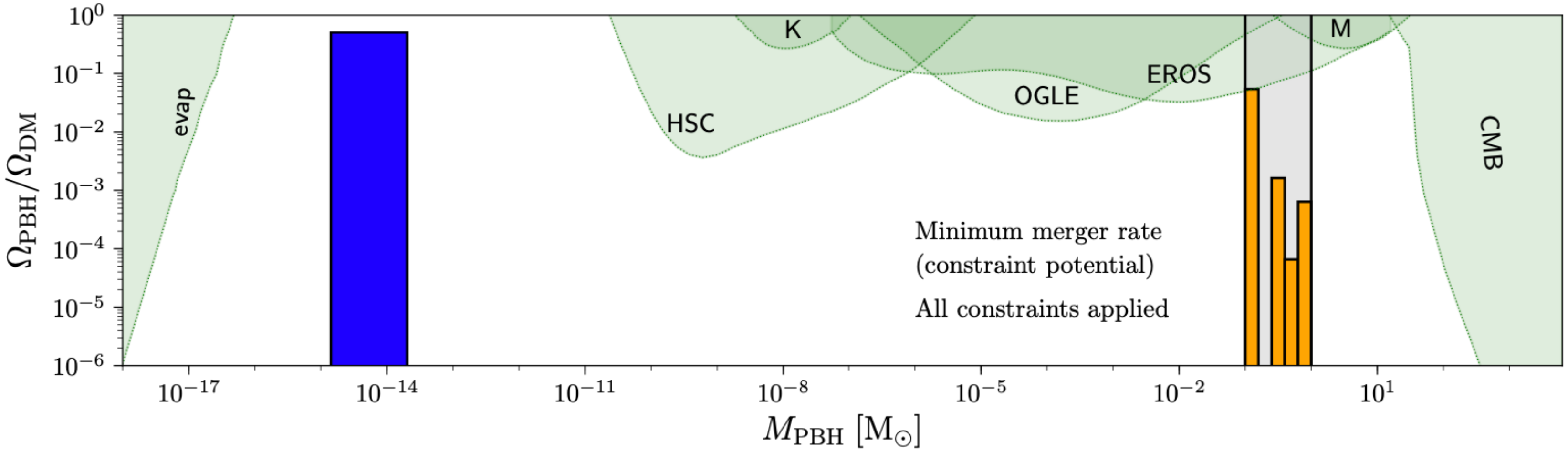
We can numerically compute the maximal and minimal possible "goldilocks event rate" for a given mass fraction of light+detectable BHs



Maximum

Merger Rate

(@fixed f_{PBH}, r_{DP})



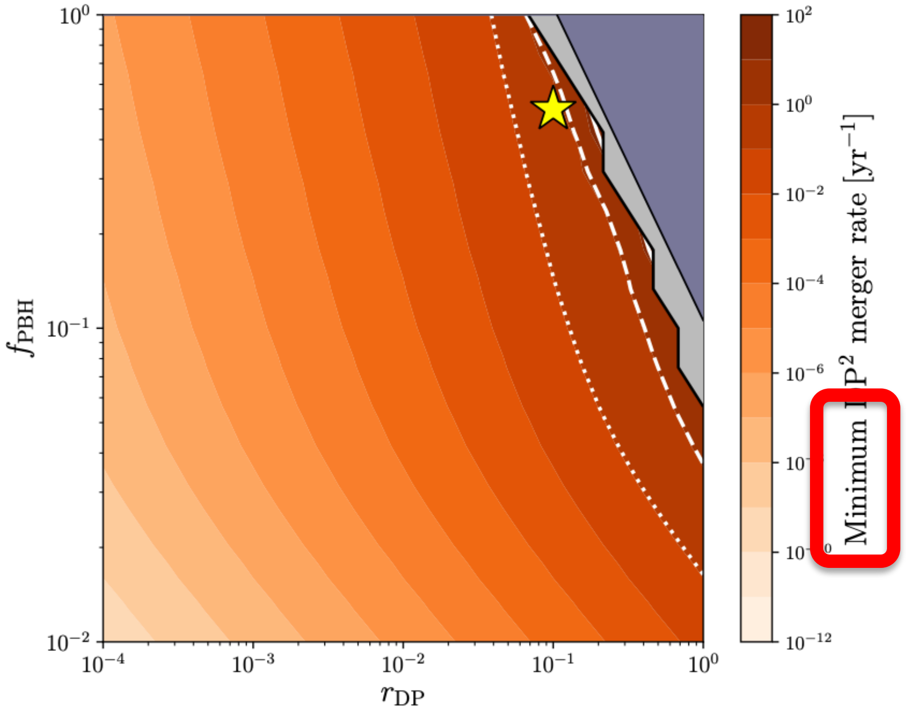
Minimum

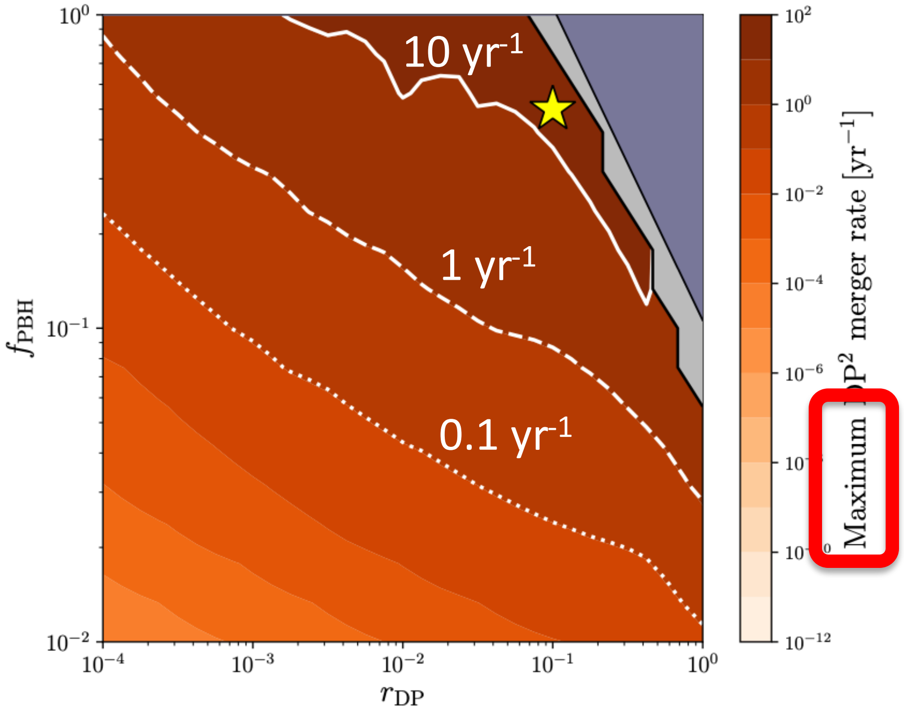
Merger Rate

(@same f_{PBH}, r_{DP})

* Lehmann, Profumo and Yant, MNRAS

…if at least some PBH are light+detectable, the minimum/maximum rate of “Goldilocks events” are encouraging! LIGO searches are ongoing!





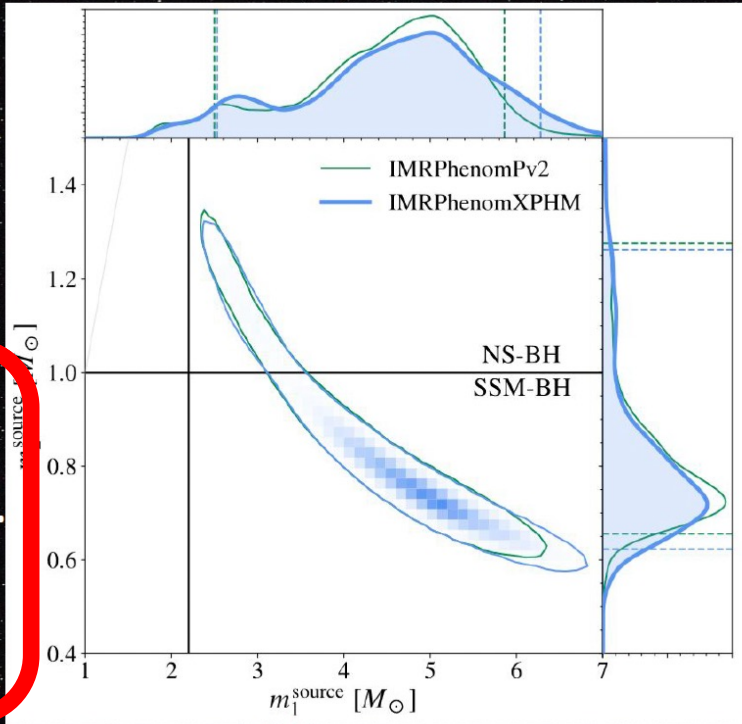
$$\int \mathrm{d}m\,\psi(m) = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} \equiv f_{\rm PBH}.$$

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

* Lehmann, Profumo and Yant, MNRAS

…if at least some PBH are light+detectable, the minimum/maximum rate of “Goldilocks events” are encouraging! LIGO searches are ongoing! [SSM170401]**

- For 16% of the posterior we have $m_1>2.2M_\odot$ and $m_2>1.0M_\odot$, i.e. masses compatible with an NS-BH.
  - The primary would be a BH in the mass gap
  - The secondary could be a NS or a BH
- For 84% of the posterior we have $m_1>2.2M_\odot$ and $m_2<1.0M_\odot$, i.e. masses compatible with an SSM-BH.
  - The primary can be in the mass gap or above
  - The secondary is an SSM black hole.



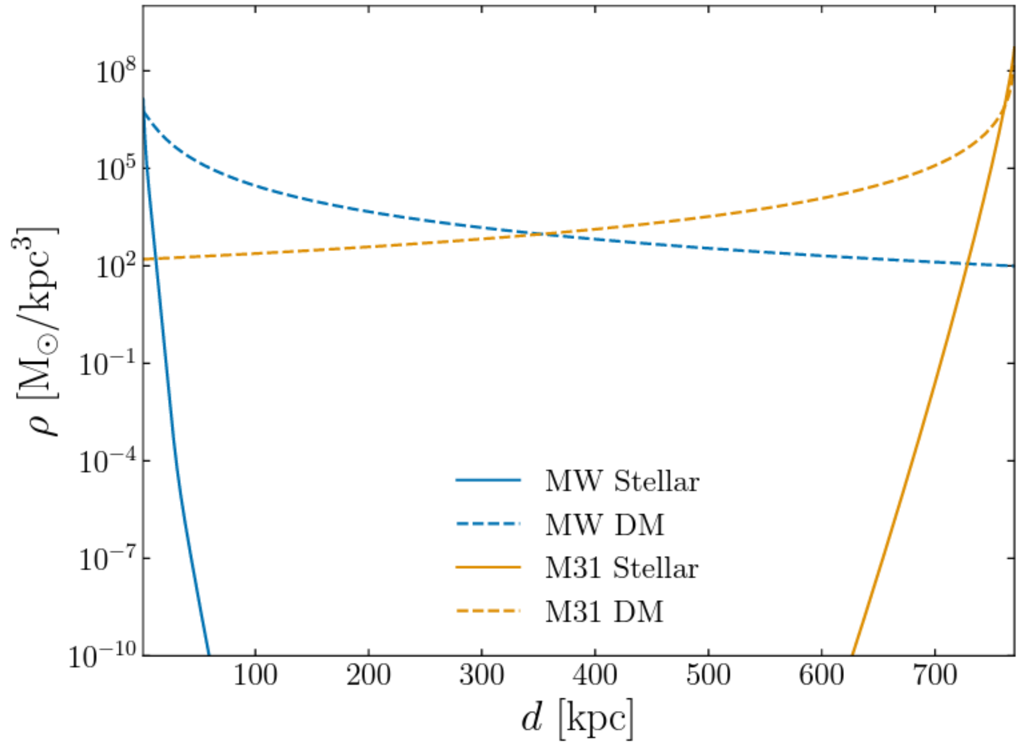
- In all cases, astrophysical models have problems generating a system with these masses

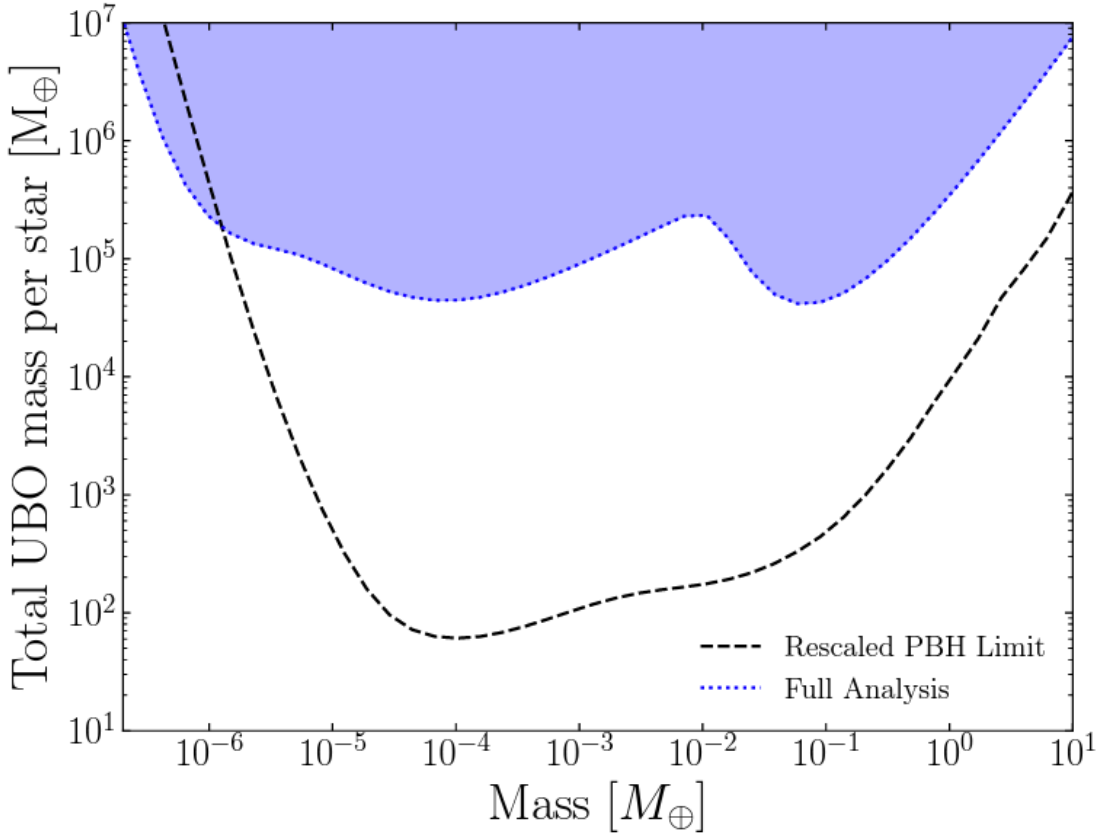
* 2301.11619, slide credit: Gonzalo Morras

**given time stamp, hopefully not April’s fool joke

Do the HSC observation provide any constraints on FFPs*?

Simply rescaling the PBH limit vastly overestimate the HSC constraints!





***DeRocco, Smyth, Profumo, 2023, MNRAS**

A field theory defined on a black-hole background is in a thermal state whose temperature at infinity is $T=M_P^2/M_{BH}$

Black holes radiate (~)like any black body, and, as such, shed their mass at a rate

$$\frac{dM}{dT} \propto A(T)T^4 \propto \frac{M^2}{M^4} \propto M^{-2}$$

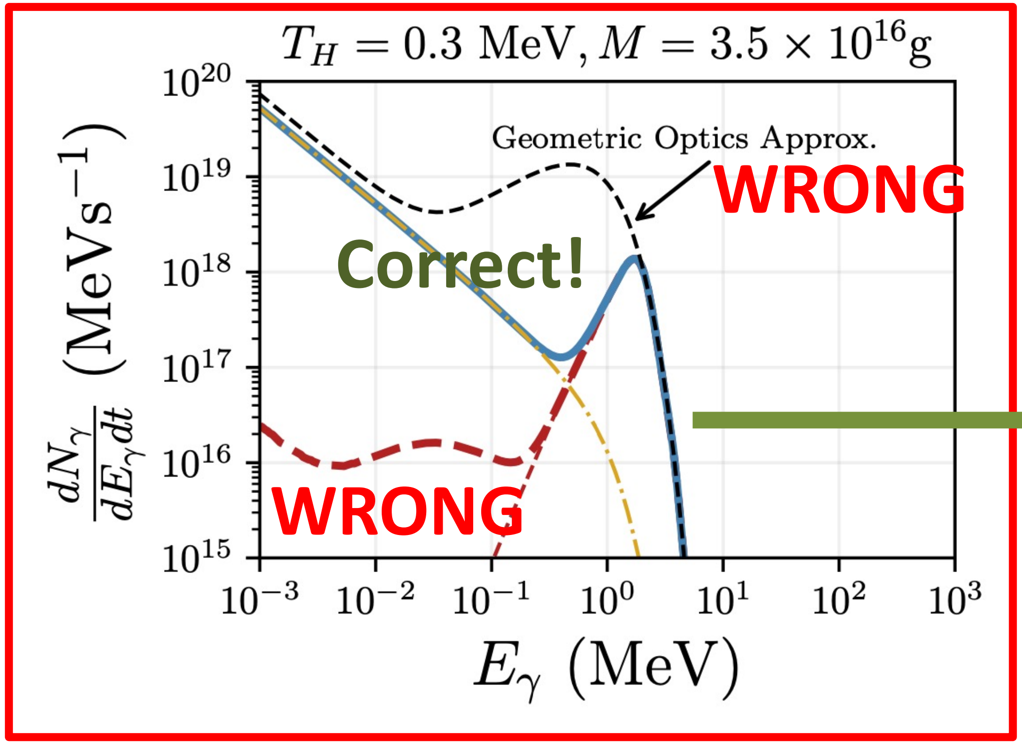
The resulting runaway evaporation process gives a lifetime "Black Hole Explosion"*

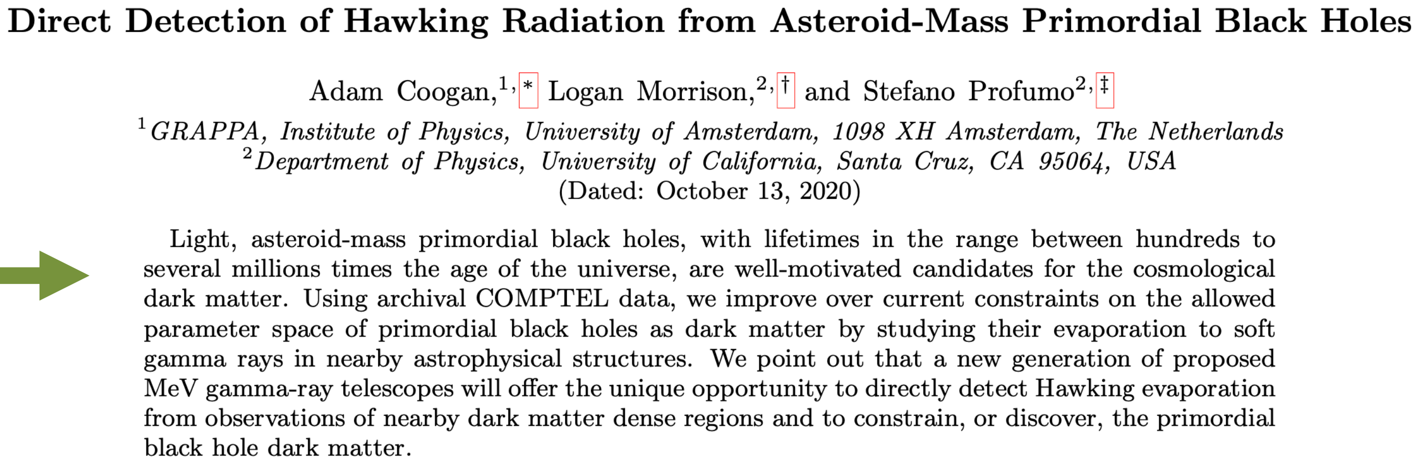
$$\tau \approx 407\left(\frac{f(M)}{15.35}\right)^{-1} M_{10}^3 \text{ s.}$$

Black holes formed in the early universe, with a mass M_U~ 5x10^{14} grams are exploding today

***Hawking, 1974**

Evaporation products (gamma rays, cosmic-ray positrons) are detectable, constraining the fraction of light PBH that can be the DM





Direct Detection of Hawking Radiation from Asteroid-Mass Primordial Black Holes

Adam Coogan,[1,*] Logan Morrison,[2,†] and Stefano Profumo[2,‡]

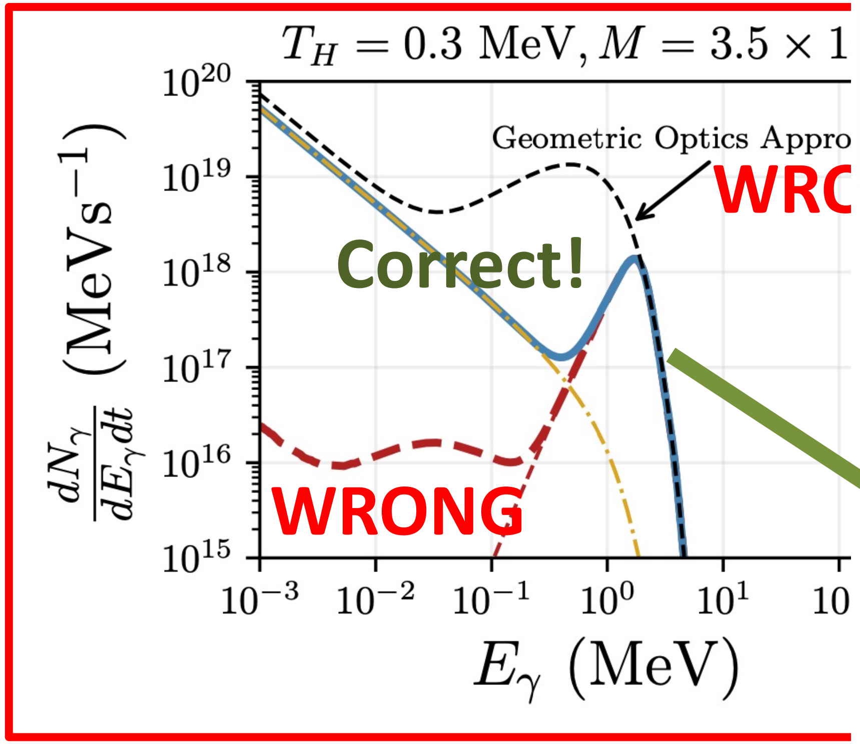
[1] *GRAPPA, Institute of Physics, University of Amsterdam, 1098 XH Amsterdam, The Netherlands*
[2] *Department of Physics, University of California, Santa Cruz, CA 95064, USA*

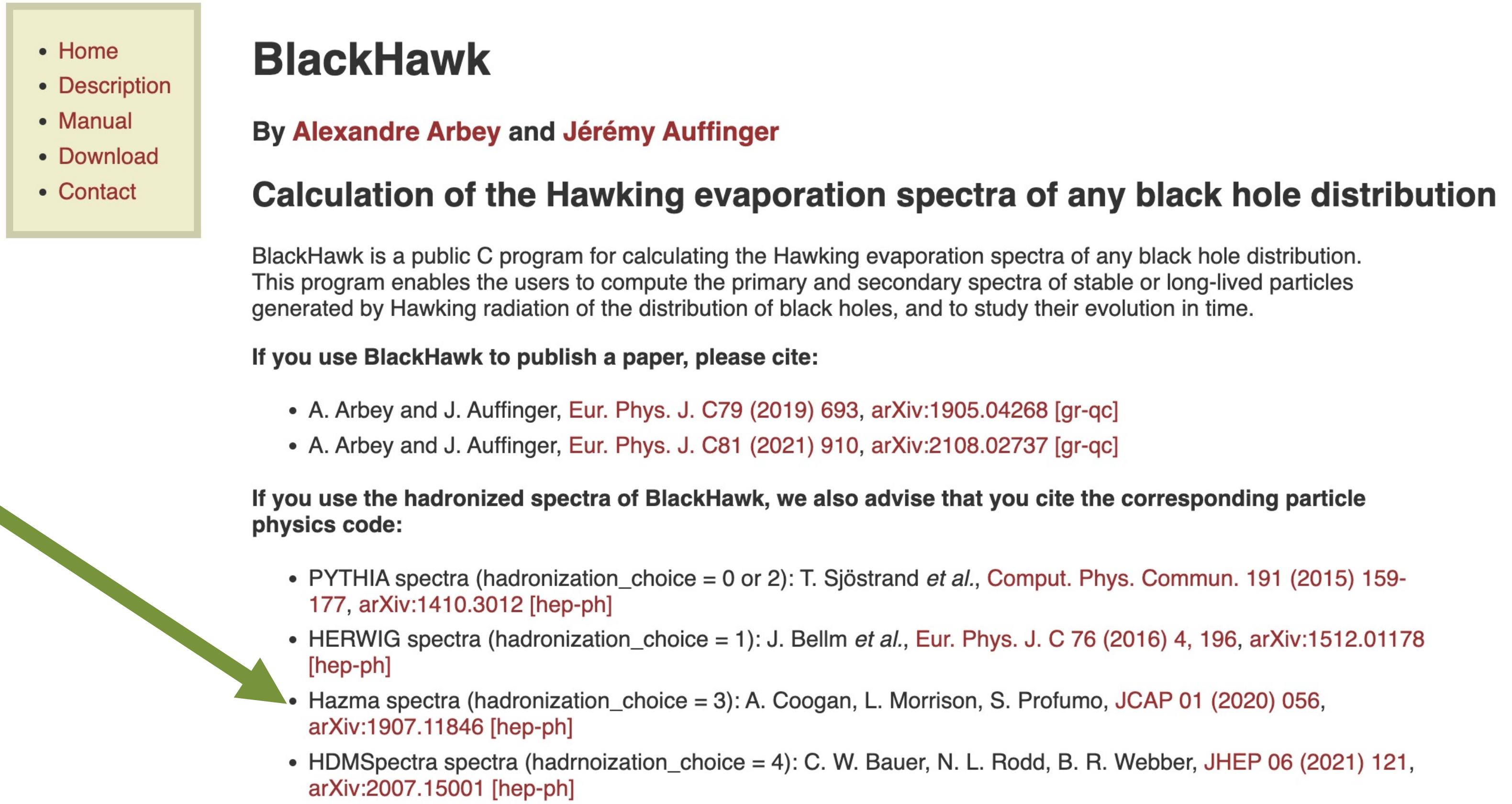
(Dated: October 13, 2020)

Light, asteroid-mass primordial black holes, with lifetimes in the range between hundreds to several millions times the age of the universe, are well-motivated candidates for the cosmological dark matter. Using archival COMPTEL data, we improve over current constraints on the allowed parameter space of primordial black holes as dark matter by studying their evaporation to soft gamma rays in nearby astrophysical structures. We point out that a new generation of proposed MeV gamma-ray telescopes will offer the unique opportunity to directly detect Hawking evaporation from observations of nearby dark matter dense regions and to constrain, or discover, the primordial black hole dark matter.

Coogan, Morrison and Profumo, 2010.04797, PRL 126 (2021) 17, 171101

Evaporation products (gamma rays, cosmic-ray positrons) are **detectable**, constraining the fraction of light PBH that can be the DM





BlackHawk

By Alexandre Arbey and Jérémy Auffinger

Calculation of the Hawking evaporation spectra of any black hole distribution

BlackHawk is a public C program for calculating the Hawking evaporation spectra of any black hole distribution. This program enables the users to compute the primary and secondary spectra of stable or long-lived particles generated by Hawking radiation of the distribution of black holes, and to study their evolution in time.

If you use BlackHawk to publish a paper, please cite:

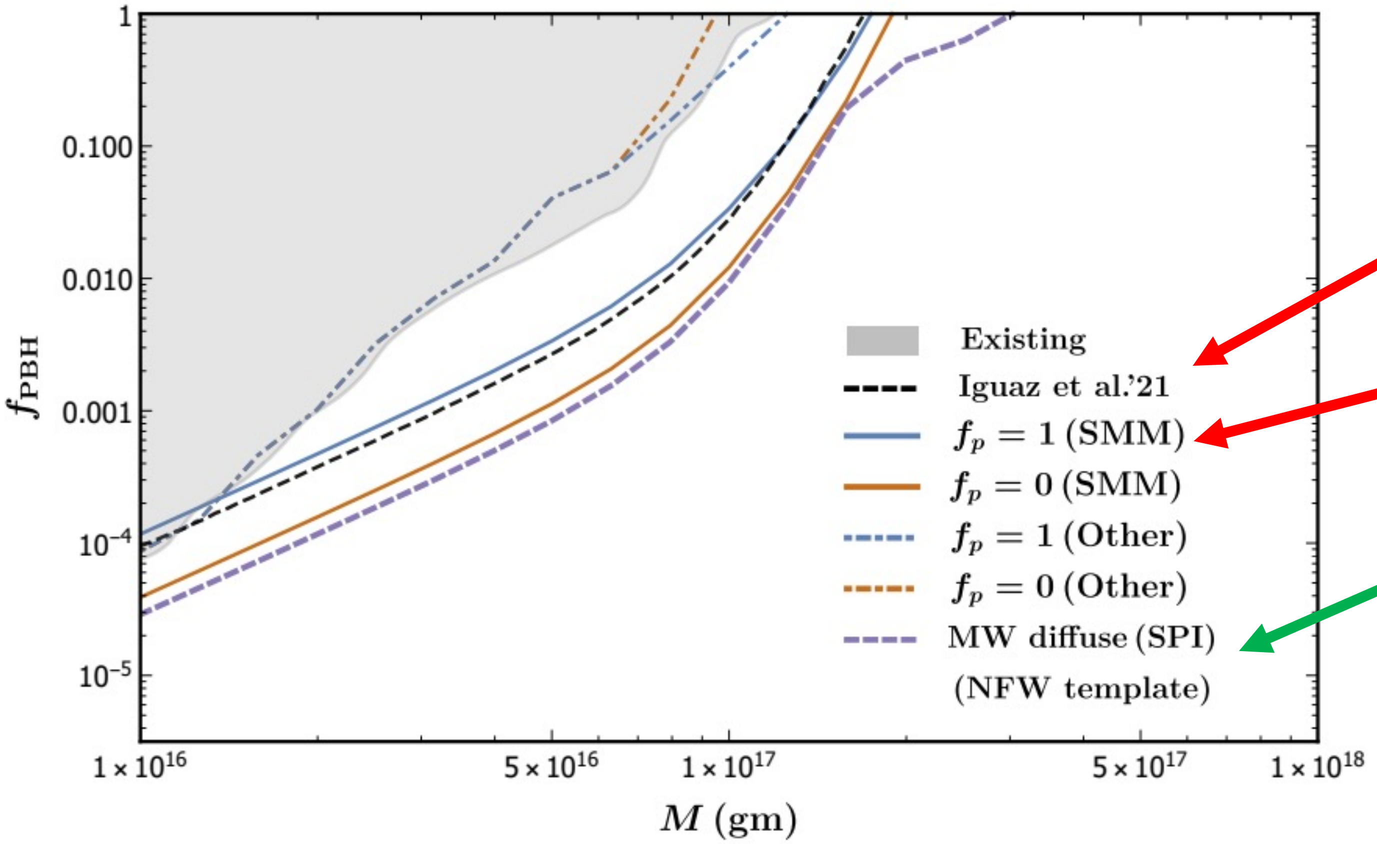
- A. Arbey and J. Auffinger, Eur. Phys. J. C79 (2019) 693, arXiv:1905.04268 [gr-qc]
- A. Arbey and J. Auffinger, Eur. Phys. J. C81 (2021) 910, arXiv:2108.02737 [gr-qc]

If you use the hadronized spectra of BlackHawk, we also advise that you cite the corresponding particle physics code:

- PYTHIA spectra (hadronization_choice = 0 or 2): T. Sjöstrand *et al.*, Comput. Phys. Commun. 191 (2015) 159-177, arXiv:1410.3012 [hep-ph]
- HERWIG spectra (hadronization_choice = 1): J. Bellm *et al.*, Eur. Phys. J. C 76 (2016) 4, 196, arXiv:1512.01178 [hep-ph]
- Hazma spectra (hadronization_choice = 3): A. Coogan, L. Morrison, S. Profumo, JCAP 01 (2020) 056, arXiv:1907.11846 [hep-ph]
- HDMSpectra spectra (hadrnoization_choice = 4): C. W. Bauer, N. L. Rodd, B. R. Webber, JHEP 06 (2021) 121, arXiv:2007.15001 [hep-ph]

Coogan, Morrison and Profumo, 2010.04797, PRL 126 (2021) 17, 171101

Strongest constraints to date: MW diffuse gamma-ray emission from Integral-SPI, including the 511 keV line



wrong by factor 2

unreliable data

use this!

Korwar and Profumo, 2302.04408, JCAP

An exciting possibility is to see the terminal PBH explosion!

The rate of explosions today depends on the PBH mass function

Considering an initial mass function Ψ_i the rate of PBH explosions today reads

$$\boxed{\dot{n}_{\mathrm{PBH}} = \rho_{\mathrm{DM}} \frac{\psi_i\left(M_U\right)}{3t_U}}$$

Additionally, PBH can be "spawned" at late times**

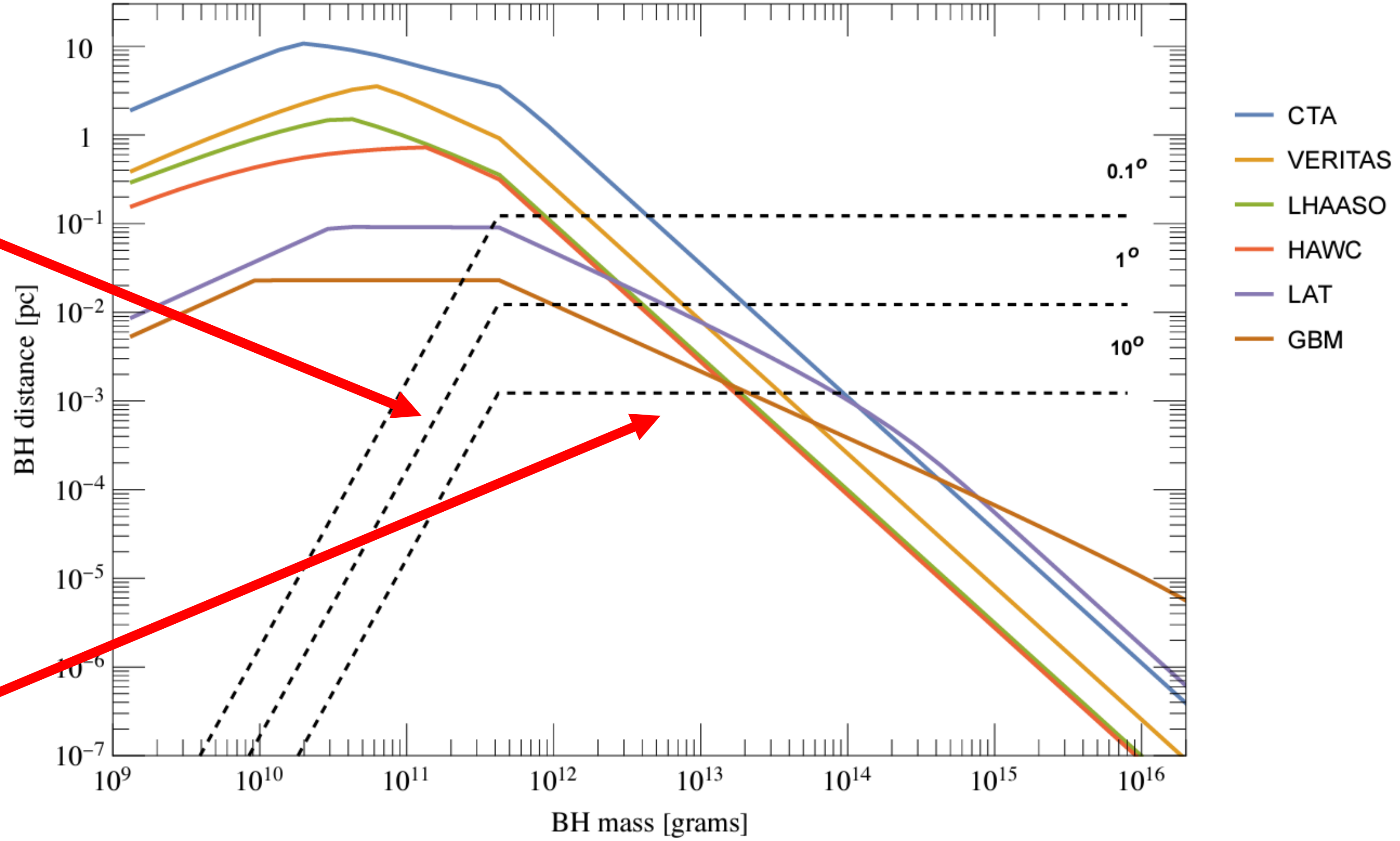
*Profumo, Boluna, Ble, Hennings, 2023

**Picker and Kusenko, 2023

How can we search for PBH explosions today?

Proper motion

Distance



Evaporation time scale > Max observation time

Mass/Lifetime

*Profumo, Boluna, Ble, Hennings, 2023

A “backwards” Gamma-ray Burst!

- Lightcurve (flux as a function of time)
- Absolute brightness (“luminosity distance”)
- Spectrum (flux as a function of energy)
- Sky distribution

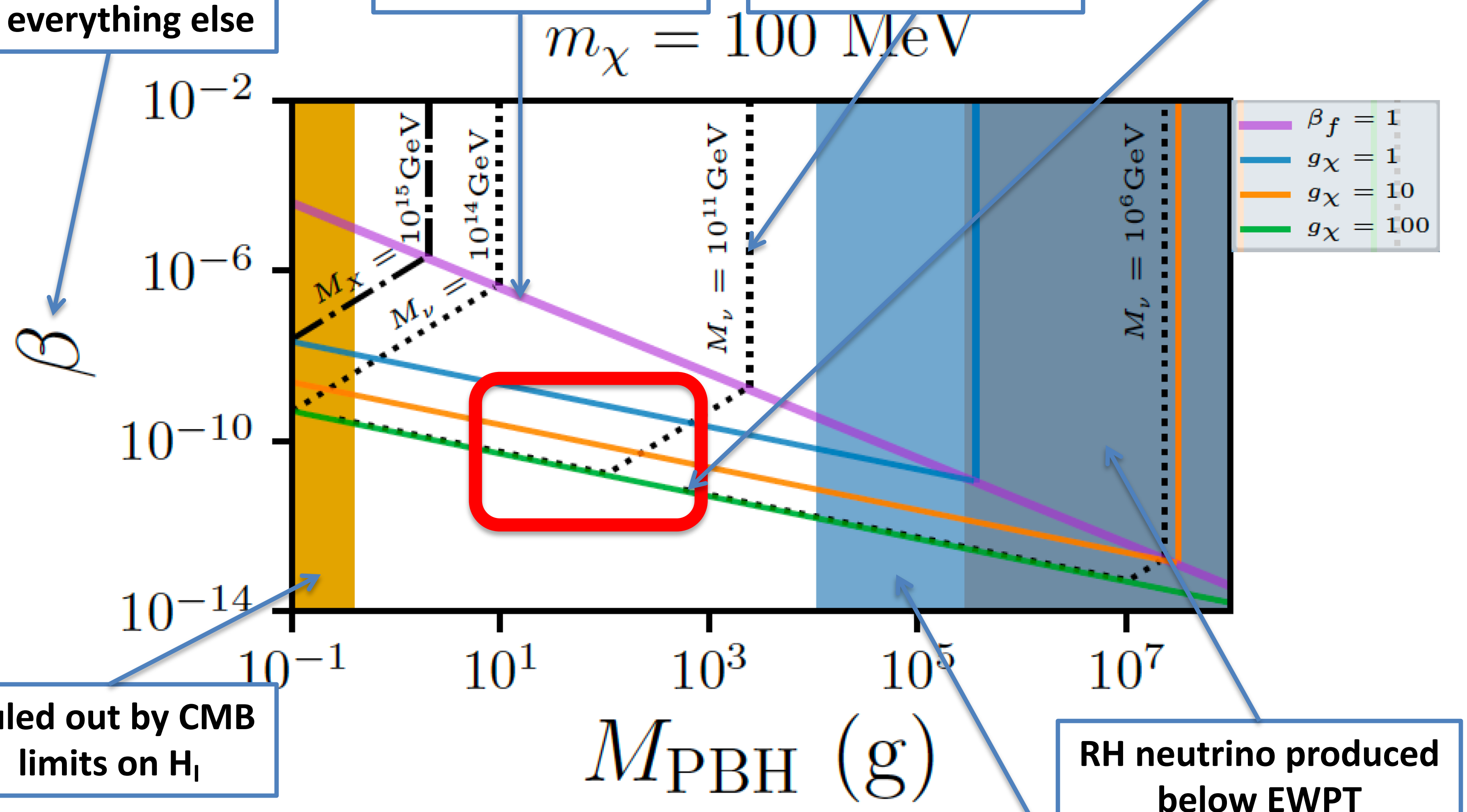
*Profumo, Boluna, Ble, Hennings, 2023

Relative initial abundance of PBH to everything else

PBH (eventually) dominate universe energy density

Mass of decaying RH neutrino producing baryon asymmetry

RH neutrinos thermalize



Ruled out by CMB limits on H_I

RH neutrino produced below EWPT

Dark Matter too fast

* Morrison, Profumo and Yu (JCAP, 2019)

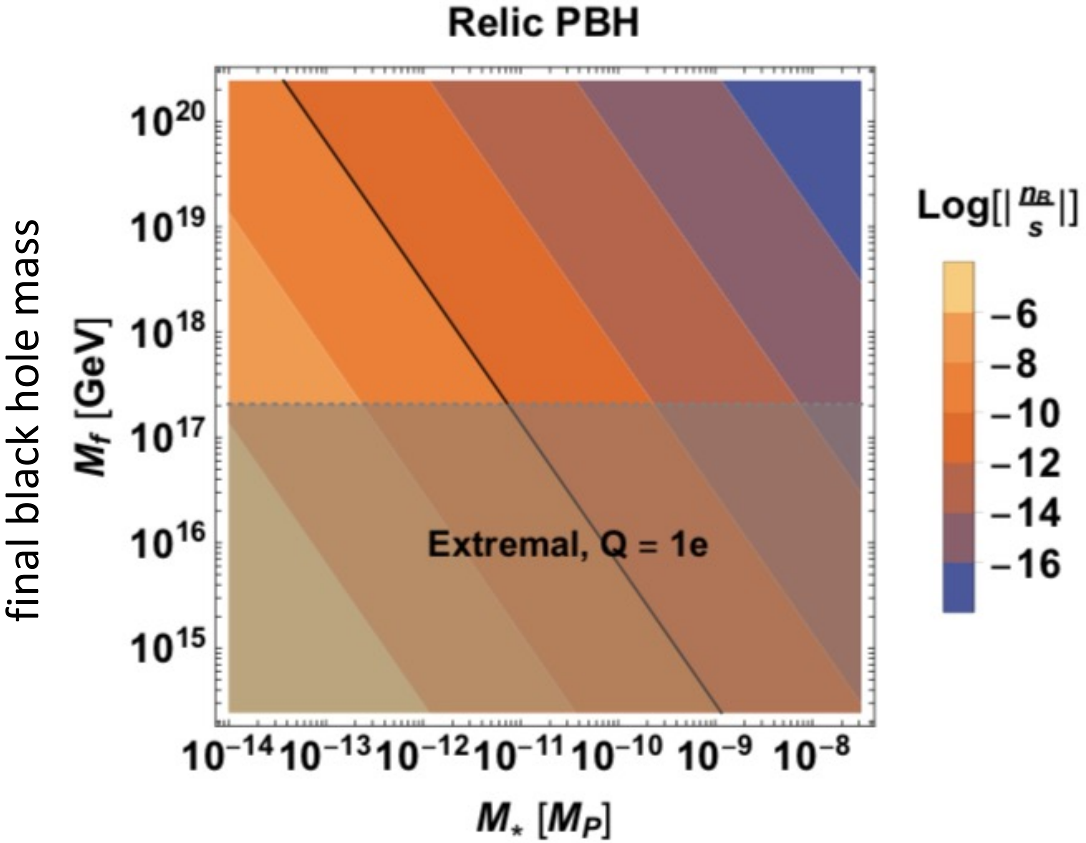
Alternately, evaporation can seed gravitational baryo- (or DM-) genesis

L. Santos-Olmsted

N. Smyth

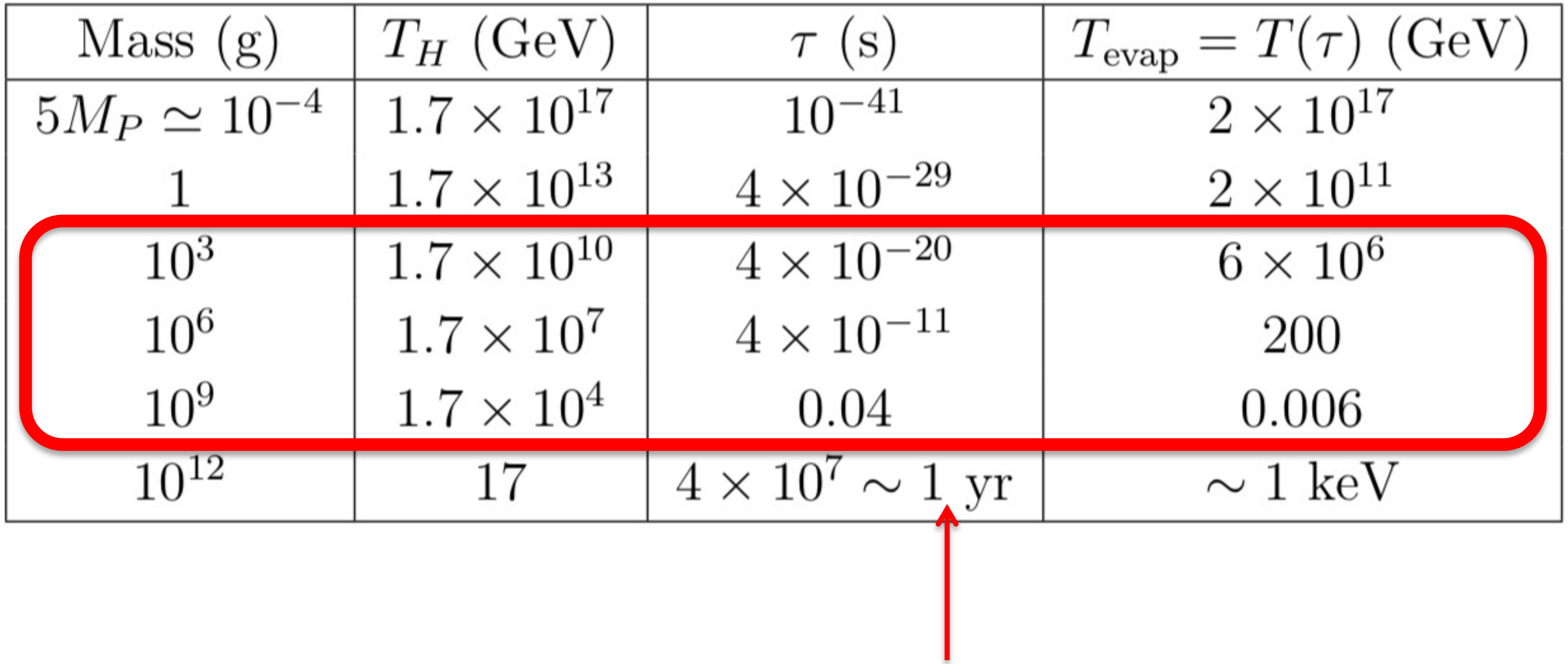
$$\mathcal{S} \supset \frac{1}{M_*^4}\partial_\alpha(\mathcal{R}_{\mu\nu\rho\sigma}\mathcal{R}^{\mu\nu\rho\sigma})J^\alpha_{\mathrm{B-L}}$$

Kretschmann scalar



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

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

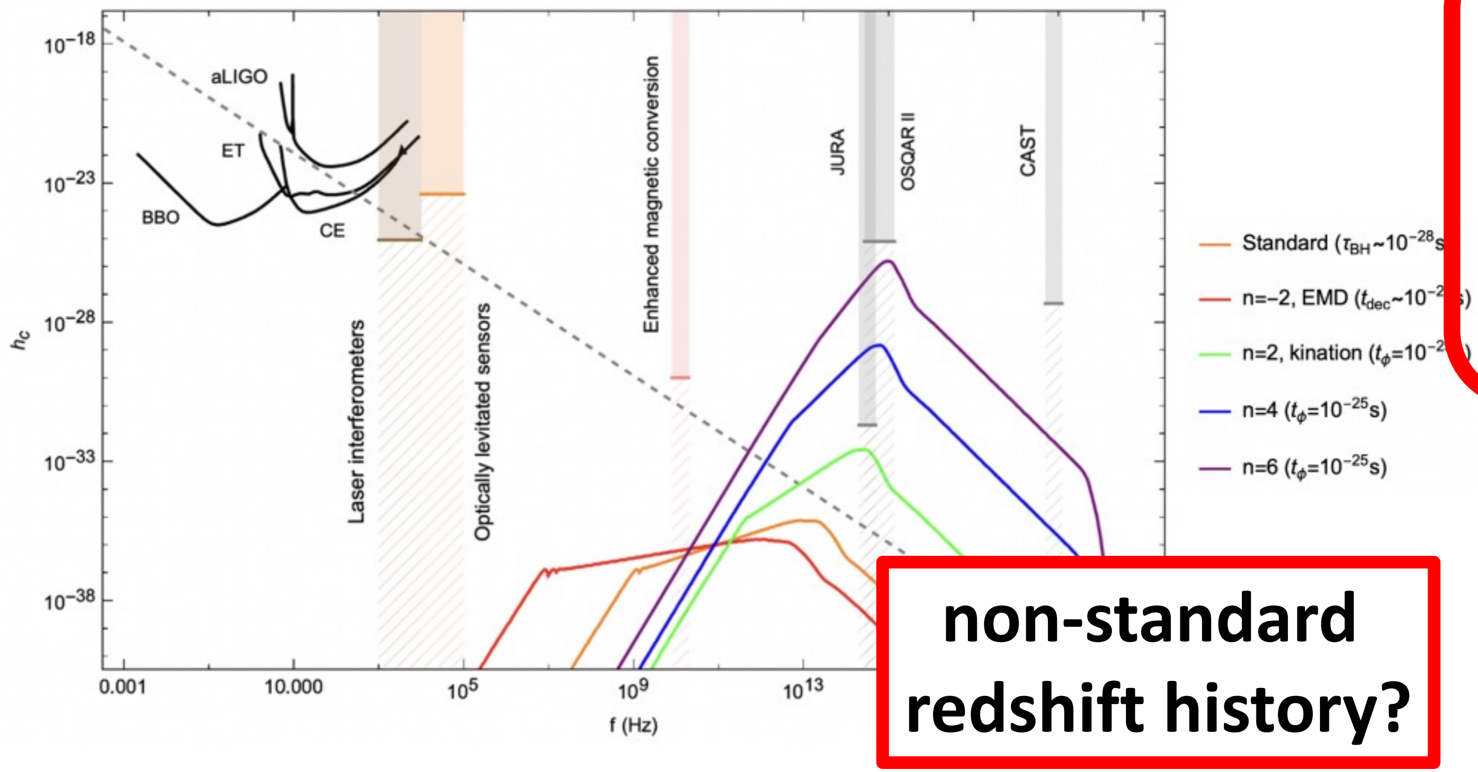


Mass (g)	T_H (GeV)	τ (s)	$T_{\text{evap}} = T(\tau)$ (GeV)
$5M_P \simeq 10^{-4}$	1.7×10^{17}	10^{-41}	2×10^{17}
1	1.7×10^{13}	4×10^{-29}	2×10^{11}
10^3	1.7×10^{10}	4×10^{-20}	6×10^6
10^6	1.7×10^7	4×10^{-11}	200
10^9	1.7×10^4	0.04	0.006
10^{12}	17	$4 \times 10^7 \sim 1$ yr	~ 1 keV

ruled out by **BBN**

* Morrison, Profumo and Yu (JCAP, 2019)

If evaporation completes in the very early universe ($\tau \ll t_{BBN}$), the only relic that could be observable today is gravitational waves!



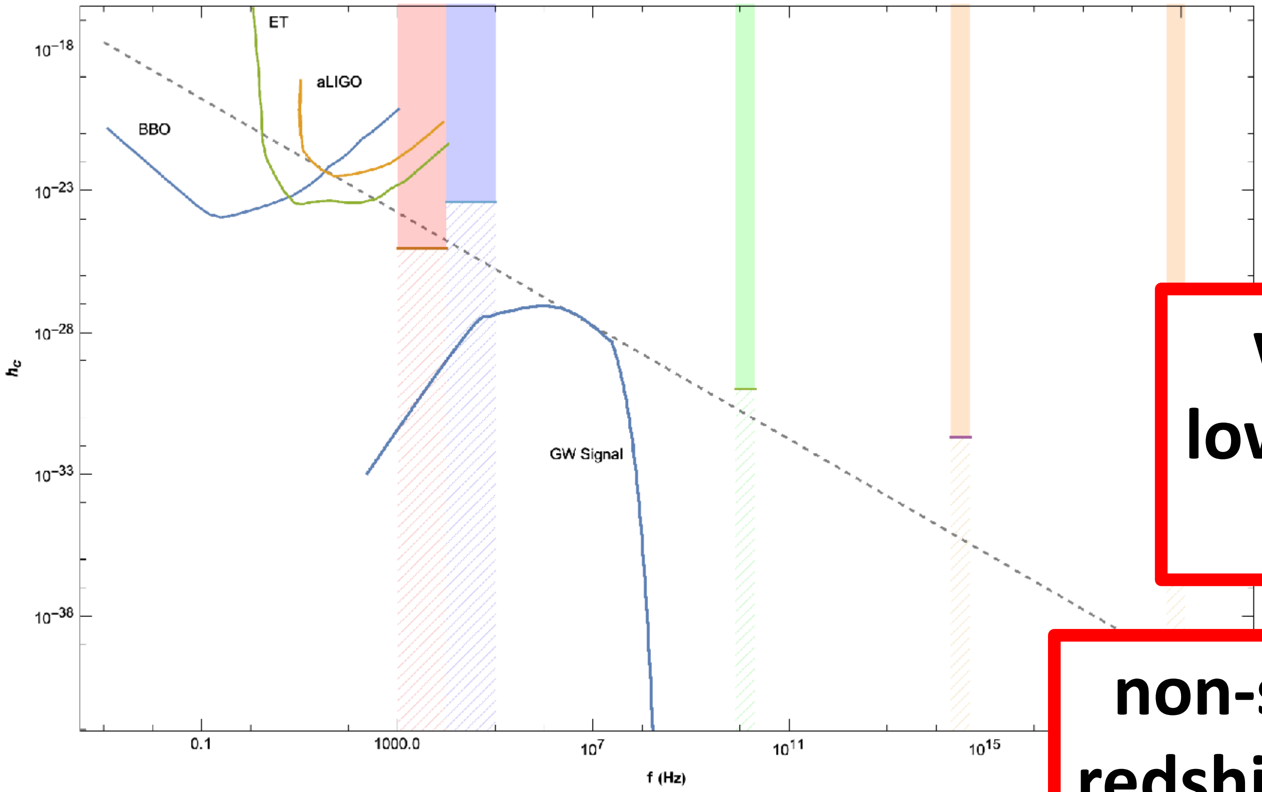
non-standard redshift history?

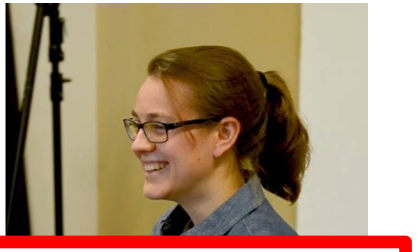
A. Ireland

J. Sharnhorst

***Ireland, Profumo, Sharnhorst, 2302.10188**

If evaporation completes in the very early universe ($\tau \ll t_{BBN}$), the only relic that could be observable today is gravitational waves!





with extra dimensions, lower M_{Planck} peak can shift to low frequencies!

non-standard redshift history?

J. Sharnhorst

***Ireland, Profumo, Sharnhorst, 2302.10188, and just out!**