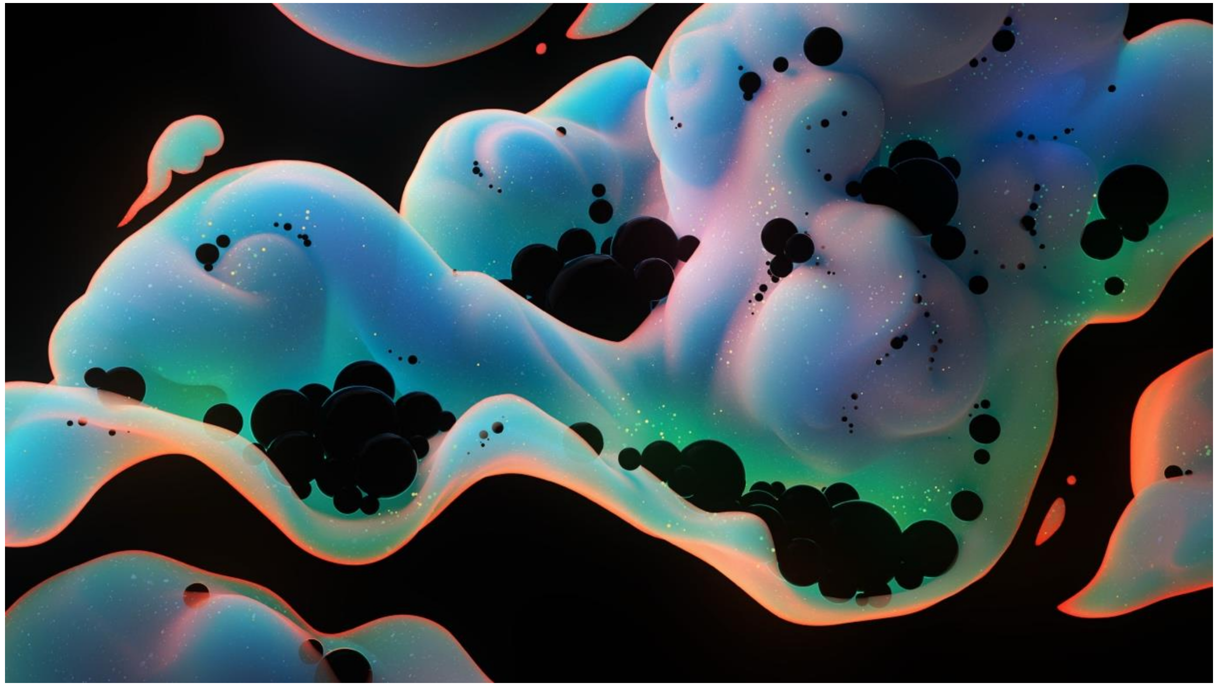
Stefano Profumo
University of California, Santa Cruz
Santa Cruz Institute for Particle Physics

Black Holes as Dark Matter



Korean Institute for Advanced Studies (KIAS)

Thursday October 30, 2025

*art by Olena Shmahalo
Quanta Magazine

Stefano Profumo
University of California
Santa Cruz

I wish I could be in Korea!

[next time, please!]

Contact me at profumo@ucsc.edu

If you are in California, reach out!

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University of California
Santa Cruz

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5/6

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University of California Santa Cruz

a new elementary particle

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what is an elementary particle?

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what is an elementary particle?

an irreducible, unitary representation of the Poincaré Group

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(m, J)

what do we know about m and J?

Eugene Wigner (1902-95)

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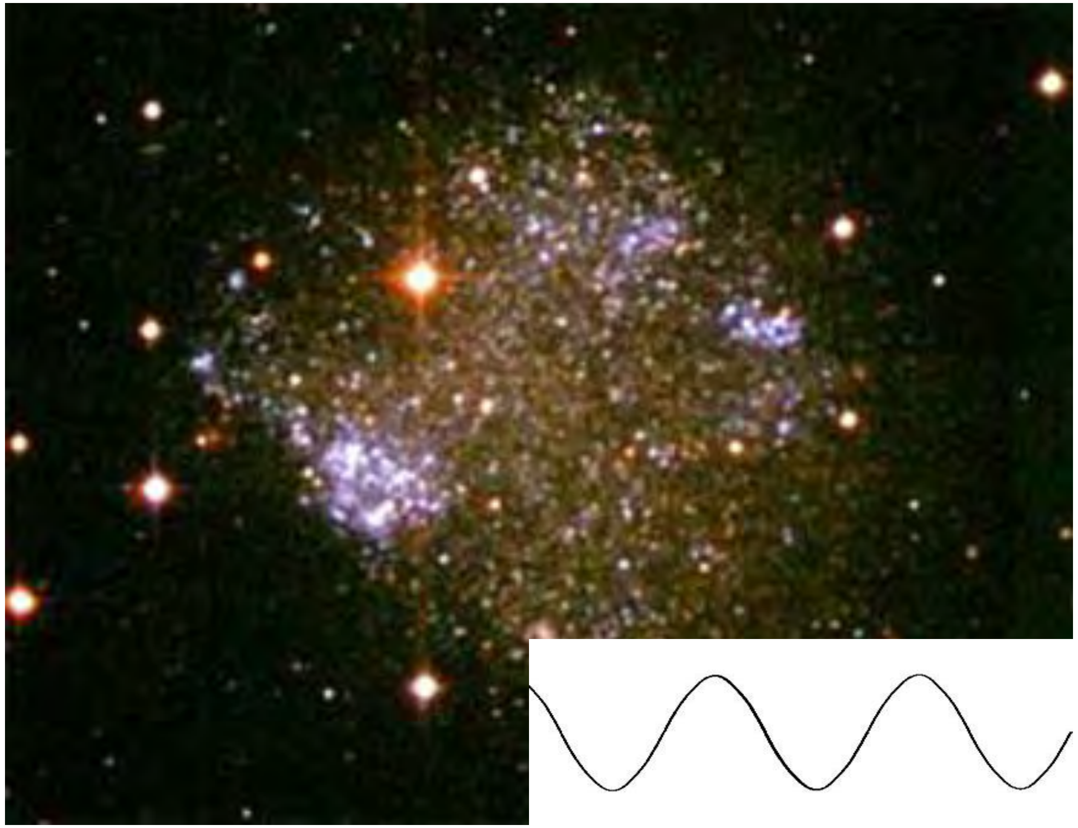

quantum effects must be smaller than halos!

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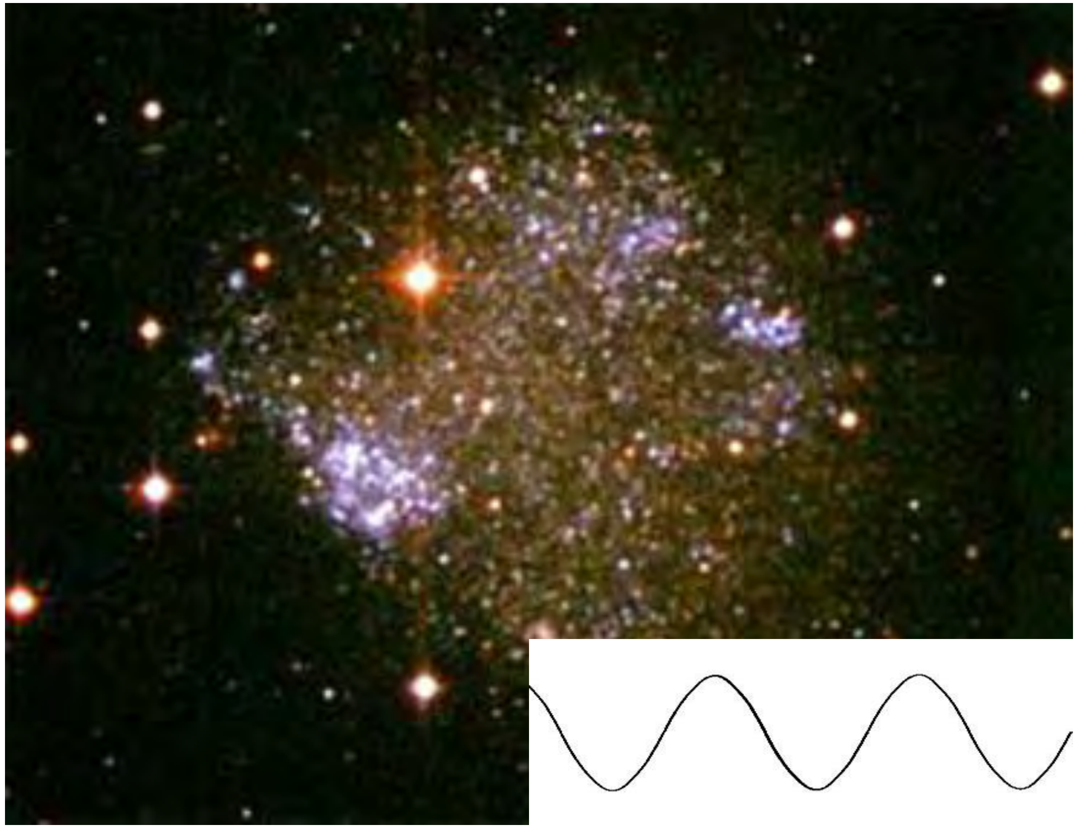

$$\lambda_{DB} = h/(mv) < 1\ \text{kpc}$$

$$\lambda_{DB} = 0.3\ \text{cm}\ (1\ \text{eV}/m) < 1\ \text{kpc} = 3\text{x}10^{21}\ \text{cm}$$

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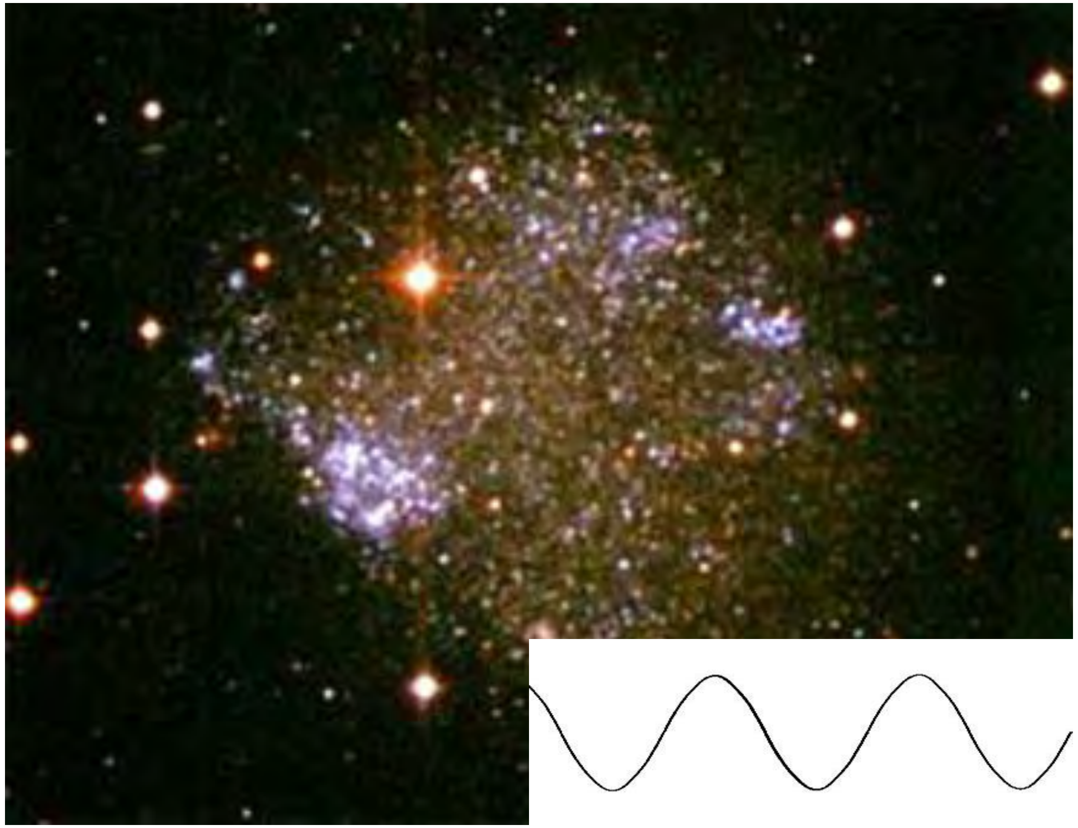

m>10^{-22} eV [bosons!]

$$\lambda_{DB} = 0.3\ \mathrm{cm}\ (1\ \mathrm{eV}/m) < 1\ \mathrm{kpc} = 3\times10^{21}\ \mathrm{cm}$$

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Ult… vould … e

State of the art: Koulen, Profumo & Smyth 2403.1901

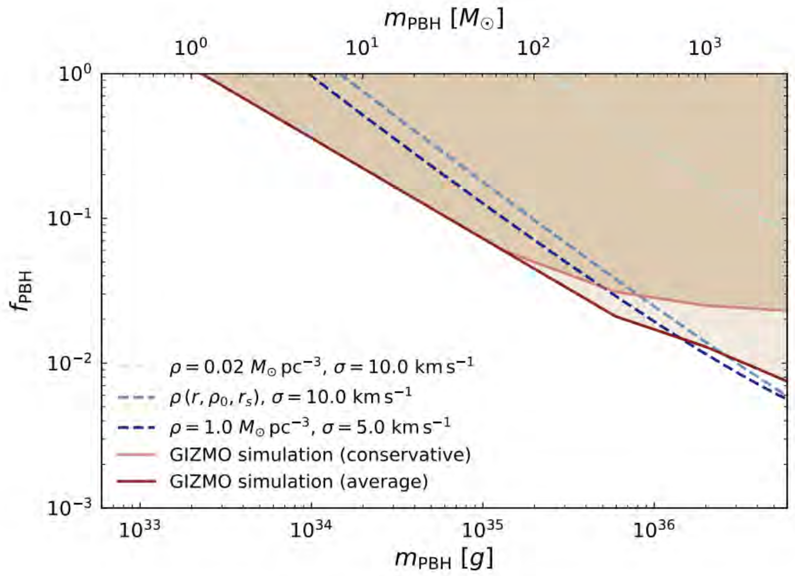
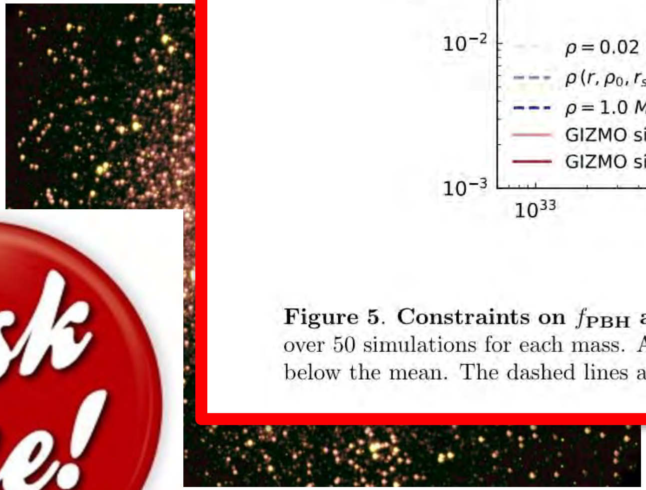
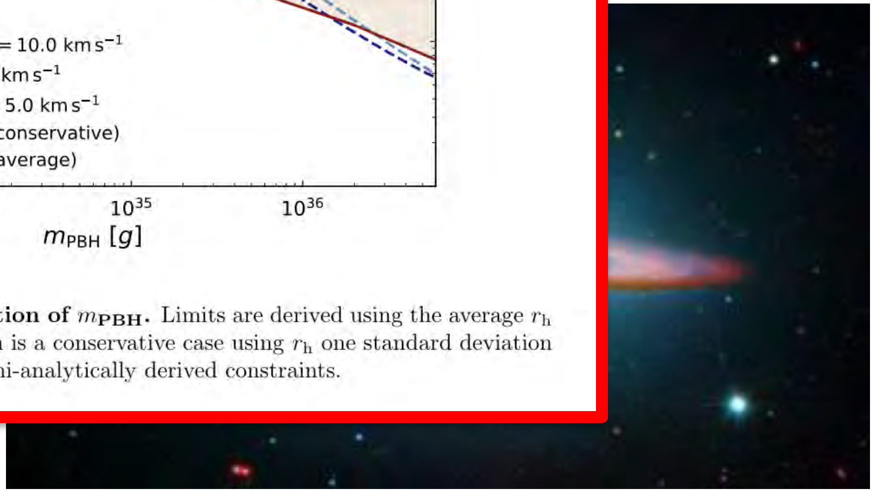


Figure 5. **Constraints on $f_{\rm PBH}$ as a function of $m_{\rm PBH}$.** Limits are derived using the average $r_{\rm h}$ over 50 simulations for each mass. Also shown is a conservative case using $r_{\rm h}$ one standard deviation below the mean. The dashed lines are the semi-analytically derived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





m < few solar masses *~ 10^{67} eV*

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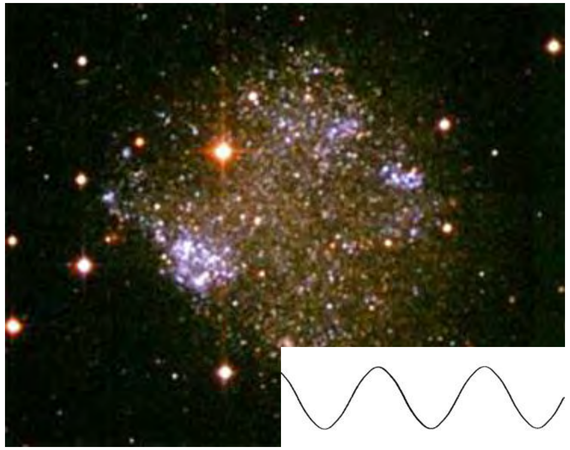
(m, J)



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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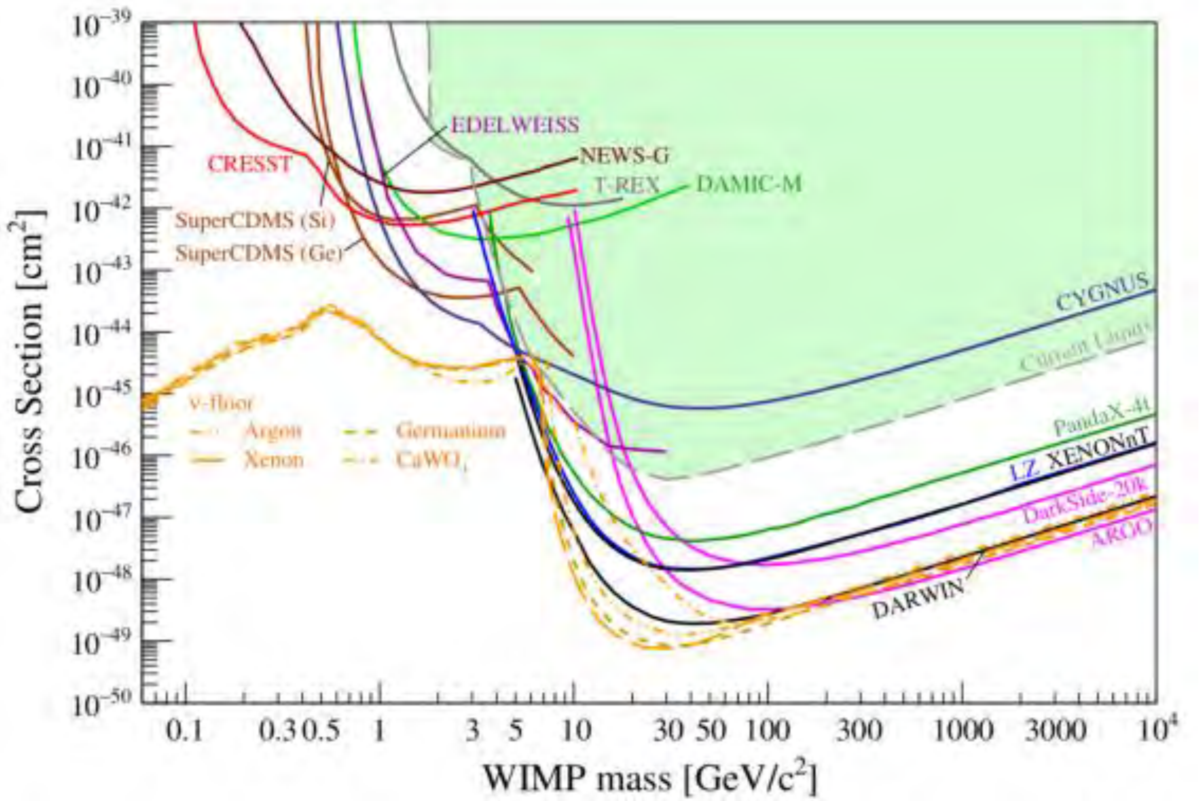

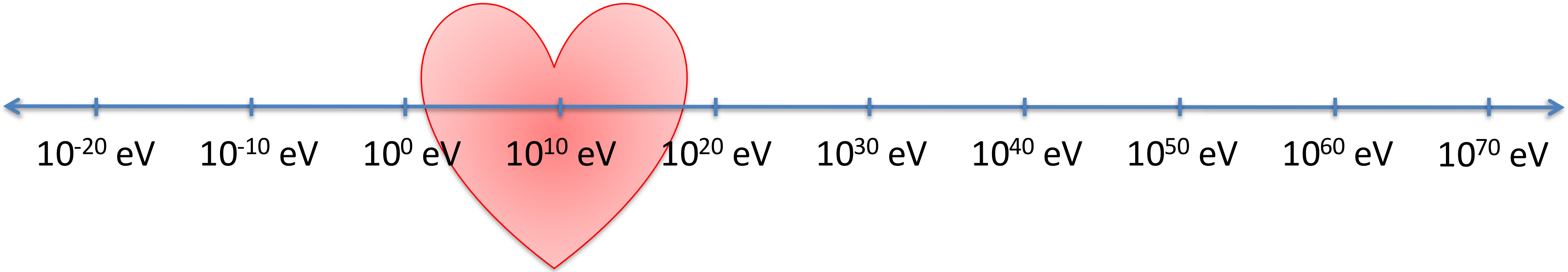

Electroweak scale

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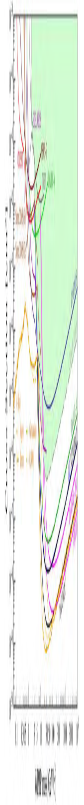

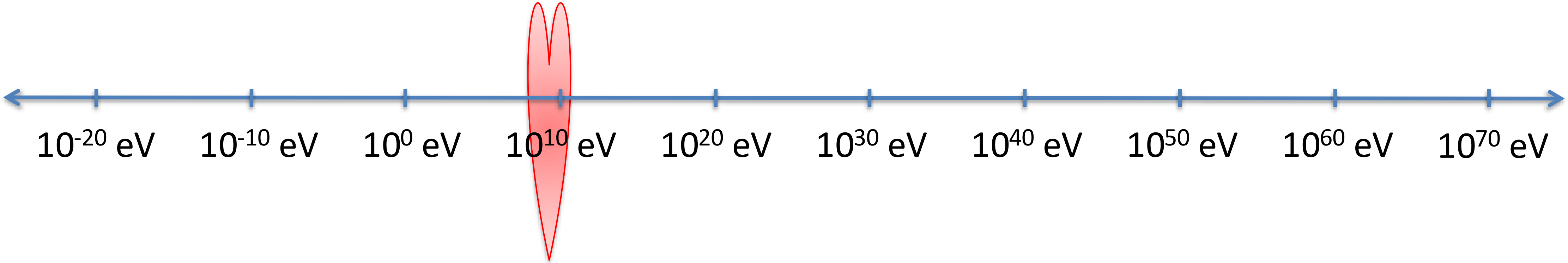

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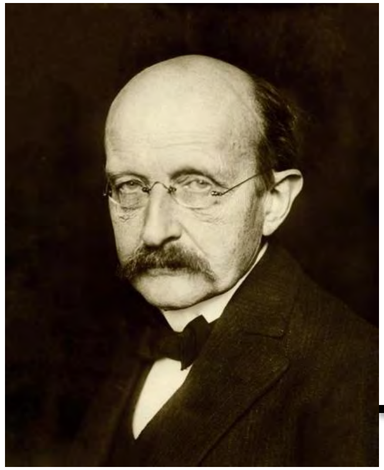
$$G = \frac{hc}{2\pi M_{\rm Pl}^2}$$

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

Schwarzschild radius

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

Compton wavelength



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

Elementary Particles?

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

(m, J)

My talk today

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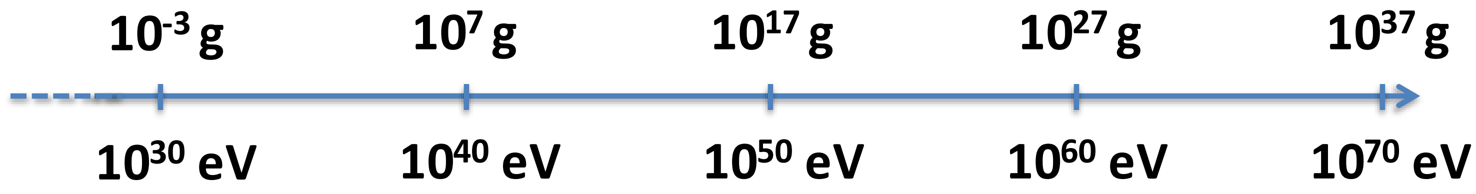
Santa Cruz

Black Holes as Dark Matter



(m, J)

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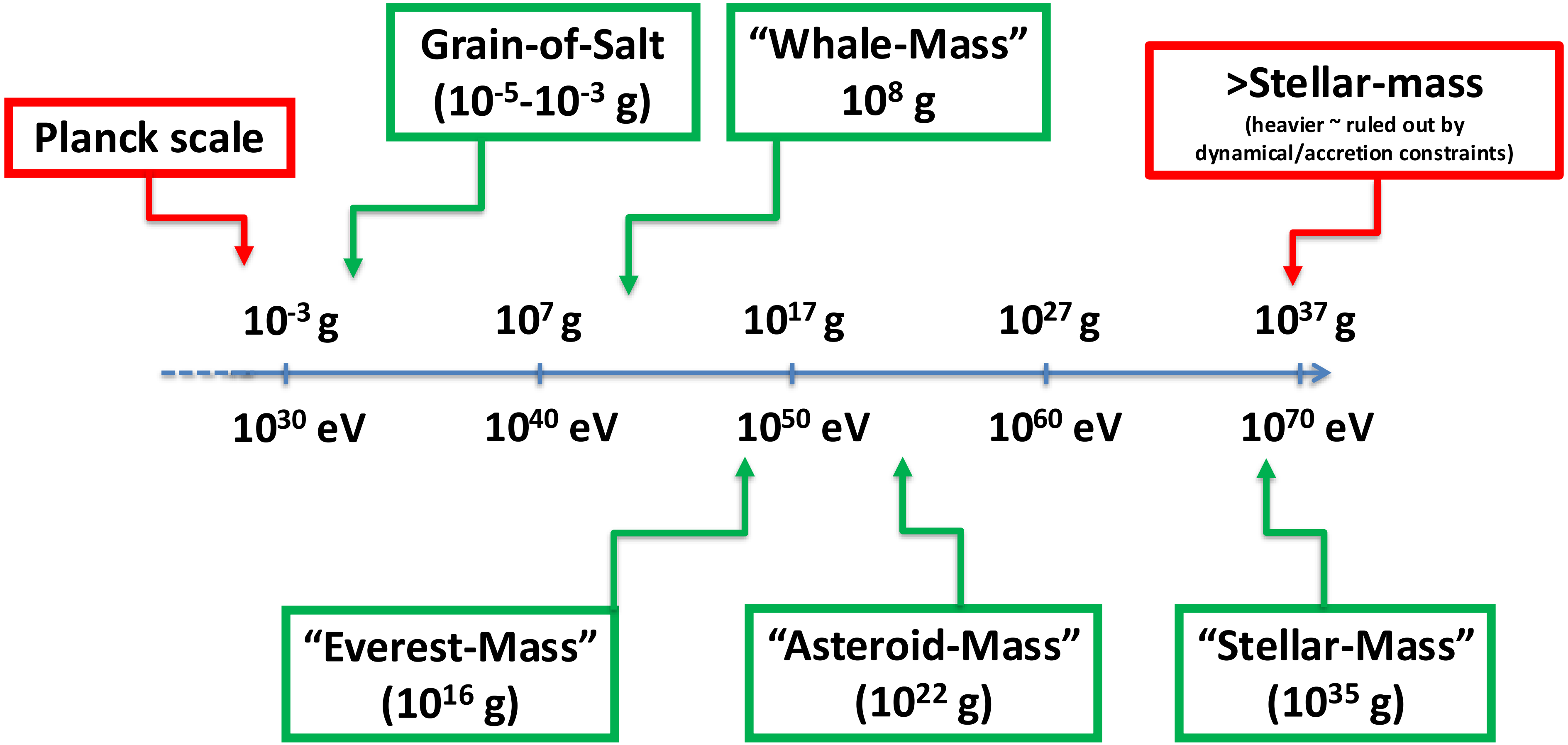
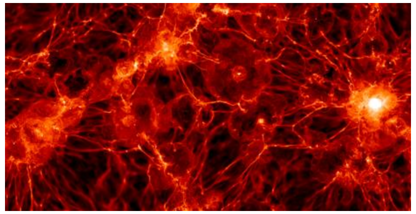
University of California Santa Cruz

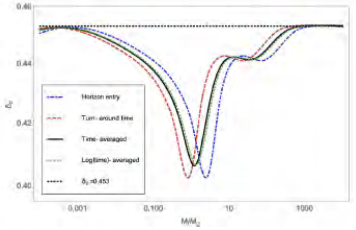


What I will **NOT** talk about today: how **Non-stellar Black Holes** form

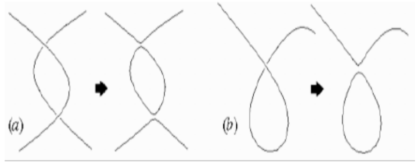
- Collapse of large density perturbations



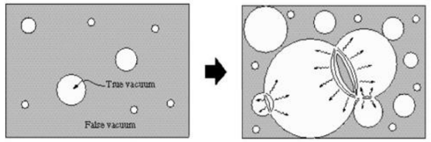
- Pressure Reduction



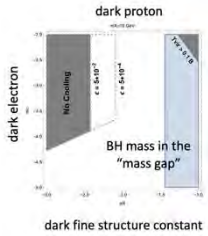
- Cosmic Strings Loops



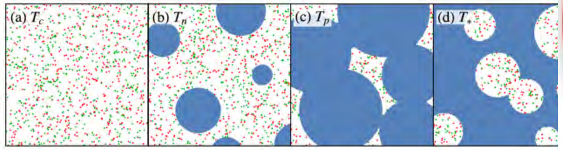
- Bubble Collisions



- Dark Stars Collapse*



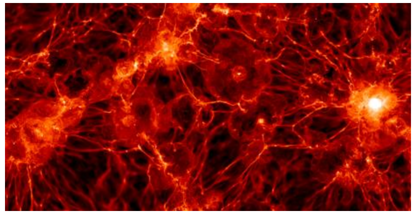
- Collapse of trapped fermions



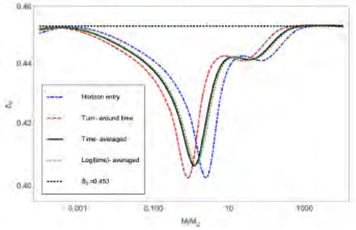
- Gravothermal collapse of self-interacting DM cores**

*Fernandez, Profumo+, 2208.08557
**Profumo et al, 2410.17480

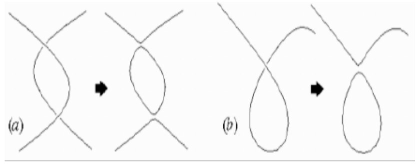
Different **formation** mechanism lead to different **mass functions**!



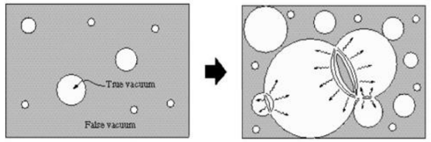
- ➢ **Collapse of large density perturbations**
- ➢ **Pressure Reduction**



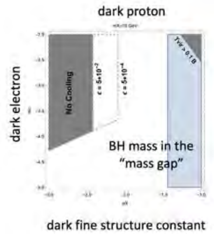
- ➢ **Cosmic Strings Loops**



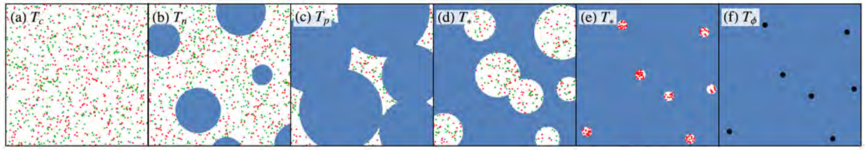
- ➢ **Bubble Collisions**



- ➢ **Dark Stars Collapse***



- ➢ **Collapse of trapped fermions**



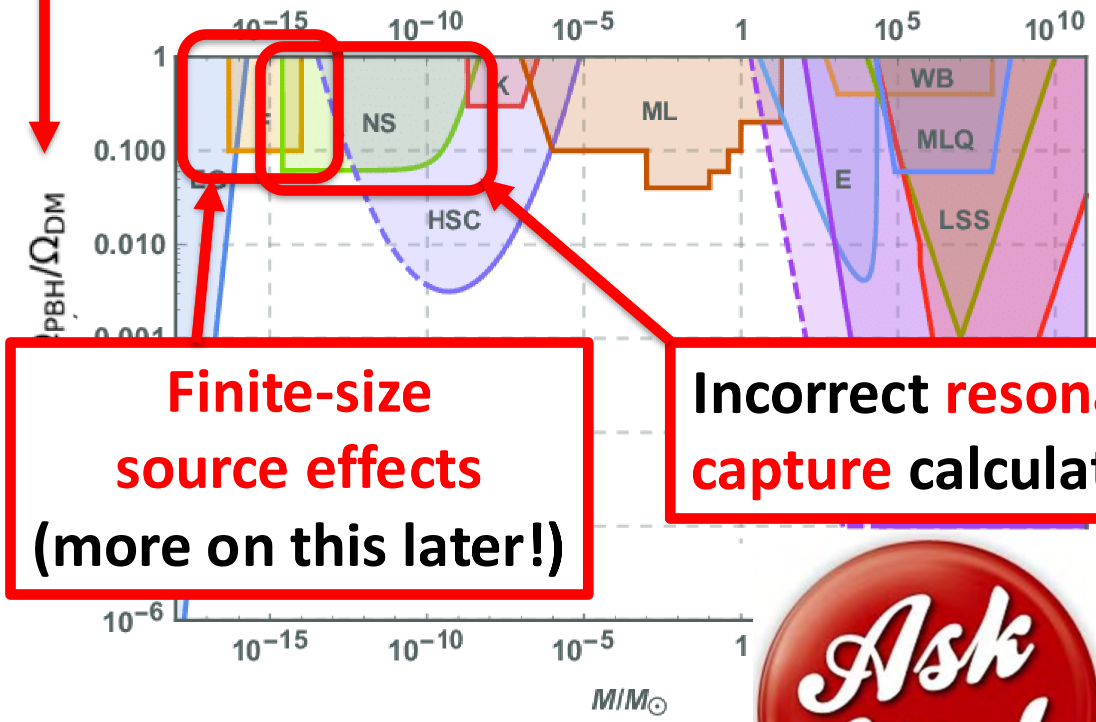
- ➢ **Gravothermal collapse of self-interacting DM cores****

*Fernandez, Profumo+, 2208.08557
**Profumo et al, 2410.17480

f_{PBH}: Fraction of the dark matter consisting of non-stellar BHs of given mass

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

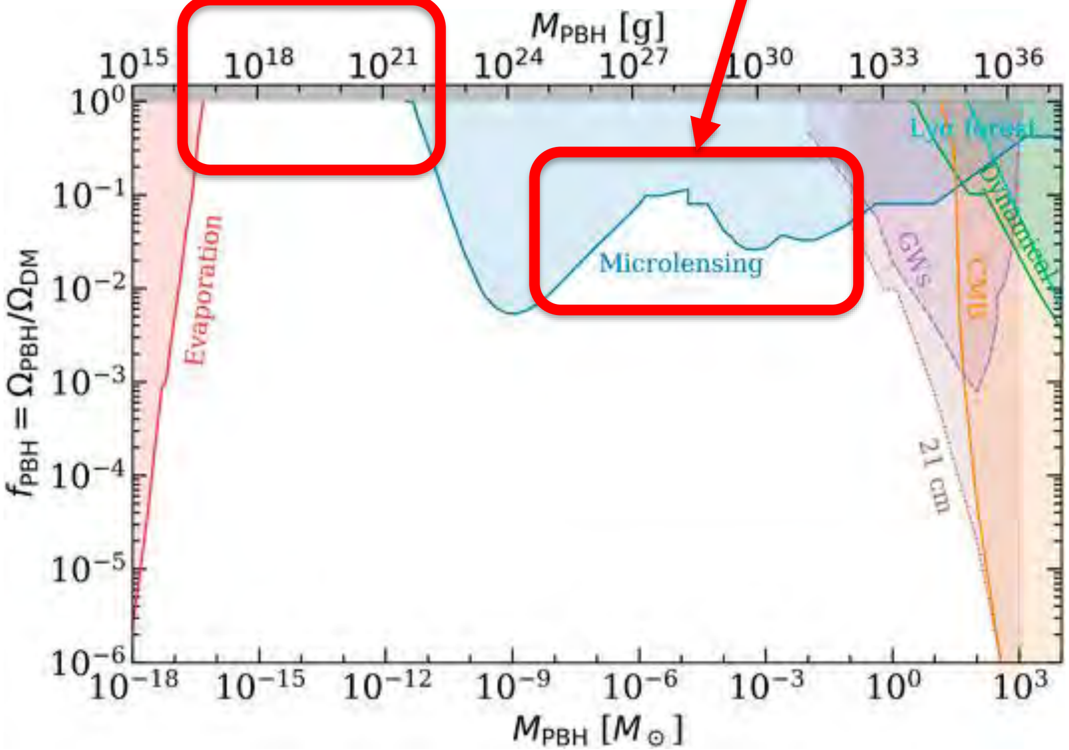
Earth mass and above PBH can be **1-10%** of the dark matter



Finite-size source effects (more on this later!)

Incorrect resonant capture calculation

<2019



Now

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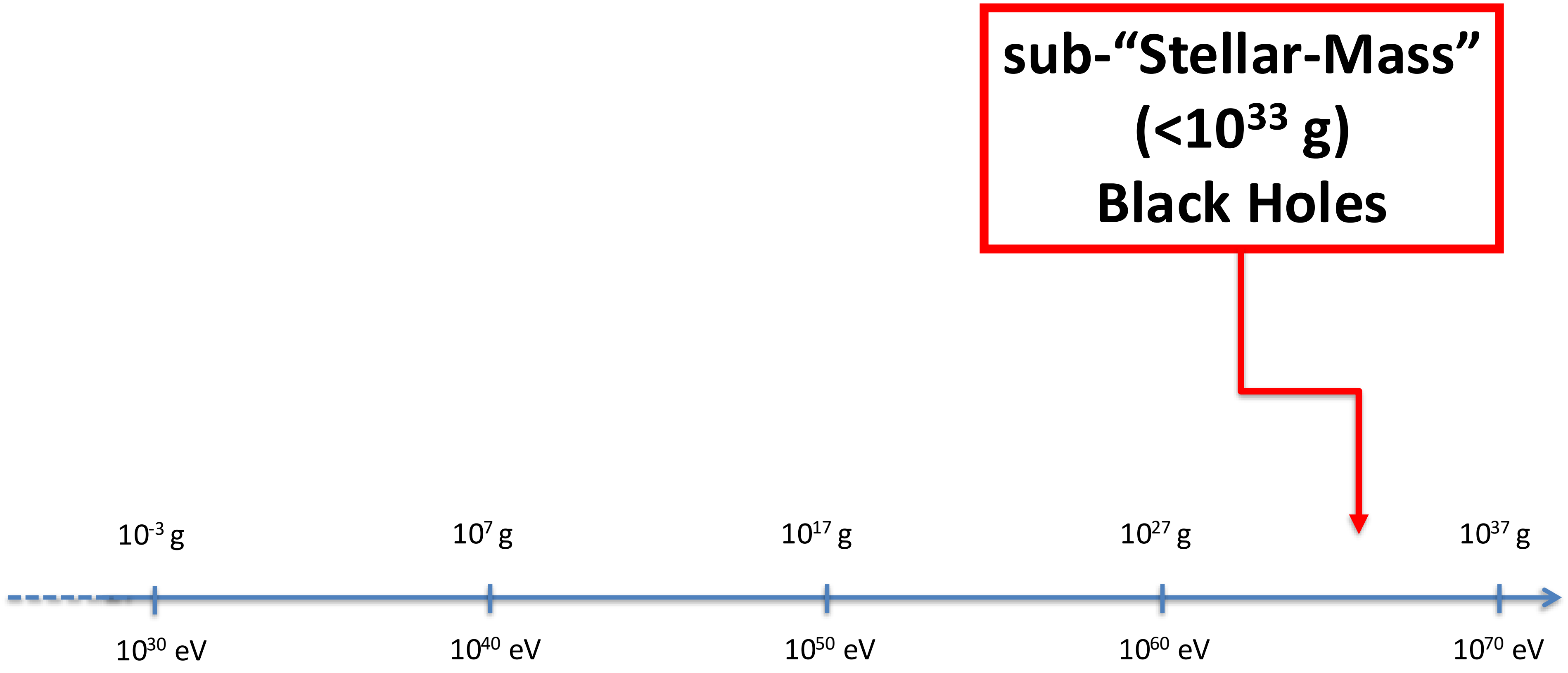
University of California Santa Cruz



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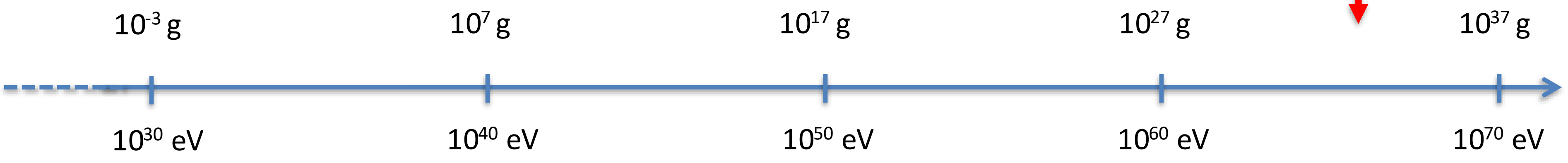
University of California Santa Cruz

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



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

Smoking gun: BH merger with a sub-TOV limit (~ $2xM_{sun}$) [or a Sub-Solar-Mass merger]

(possible "new physics" imposters such as strange quark stars, anomalously light or dark sector white dwarfs or neutron stars – but with different GW signals from tidal effects [Begnoni and Profumo*,])

v1 [astro-ph.CO] 4 Sep 2025

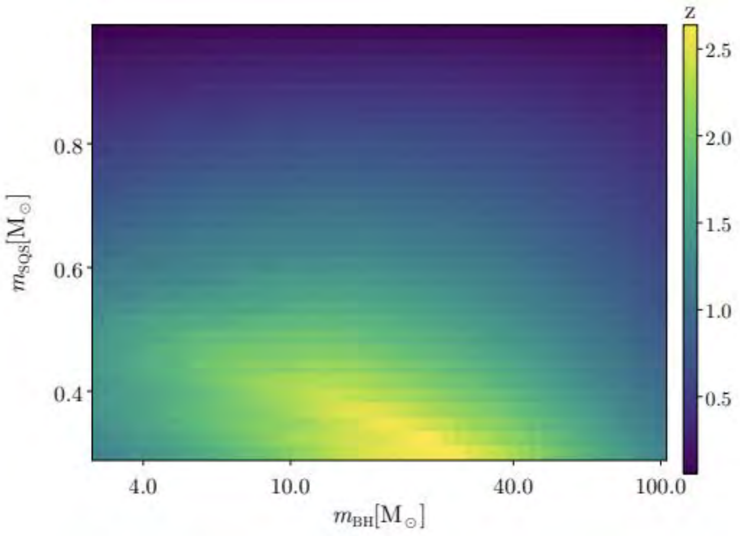
Primordial black holes versus their impersonators at gravitational wave observatories

Andrea Begnoni[a,b] **and Stefano Profumo**[c,d]

[a]Dipartimento di Fisica Galileo Galilei, Università di Padova, I-35131 Padova, Italy
[b]INFN Sezione di Padova, I-35131 Padova, Italy
[c]Santa Cruz Institute for Particle Physics, Santa Cruz, CA, 95064, USA
[d]Department of Physics, University of California, Santa Cruz Santa Cruz, CA, 95064, USA

E-mail: andrea.begnoni@phd.unipd.it, profumo@ucsc.edu

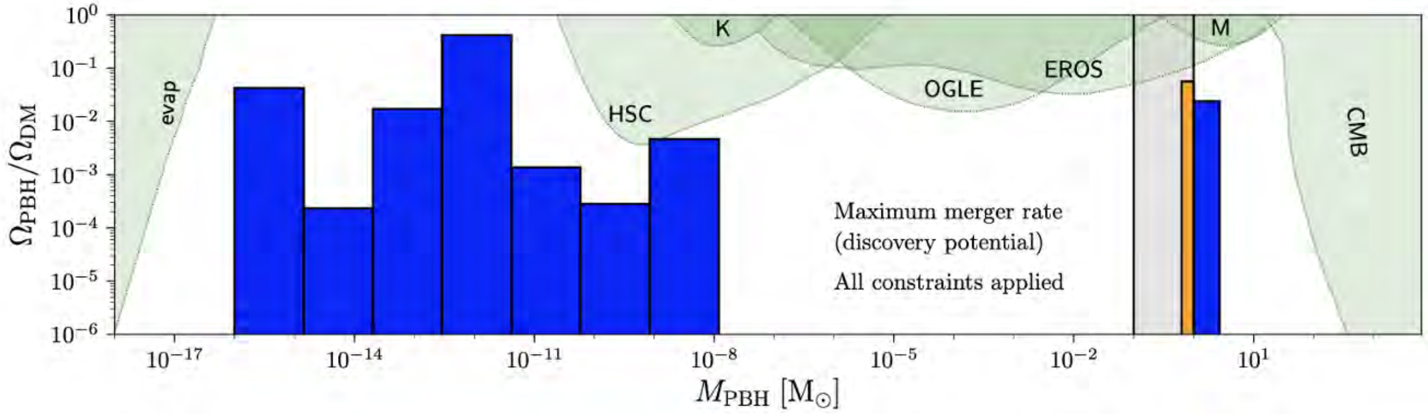
Abstract. The detection of primordial black holes (PBHs) would mark a major breakthrough, with far-reaching implications for early universe cosmology, fundamental physics, and the nature of dark matter. Gravitational wave observations have recently emerged as a powerful tool to test the existence and properties of PBHs, as these objects leave distinctive imprints on the

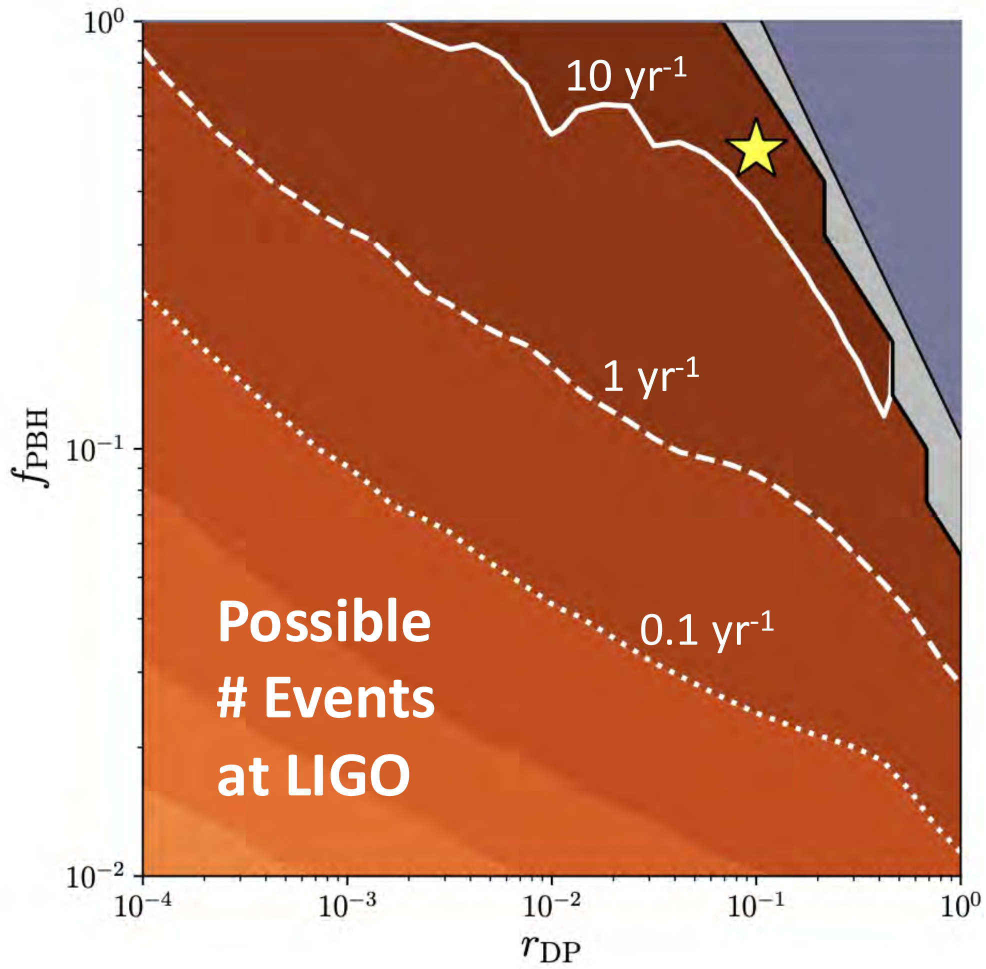


*2509.04028

Smoking gun: BH merger with a sub-TOV limit (~ $2xM_{sun}$) [or a Sub-Solar-Mass merger]

- We calculated the max and min event rate for a given f_{PBH} and fraction of "goldilocks" (light+detectable) PBH, and it can be sizable!*





(fraction of light+detectable PBHs)

*Lehmann, Profumo and Yant, MNRAS, 2022

Smoking gun: BH merger with a sub-TOV limit (~ $2xM_{sun}$) [or a Sub-Solar-Mass merger]

- We calculated the max and min event rate for a given f_{PBH} and fraction of "goldilocks" (light+detectable) PBH, and it can be sizable!*

- LIGO-VIRGO-KAGRA searches are ongoing, no confirmed events in O3/O4

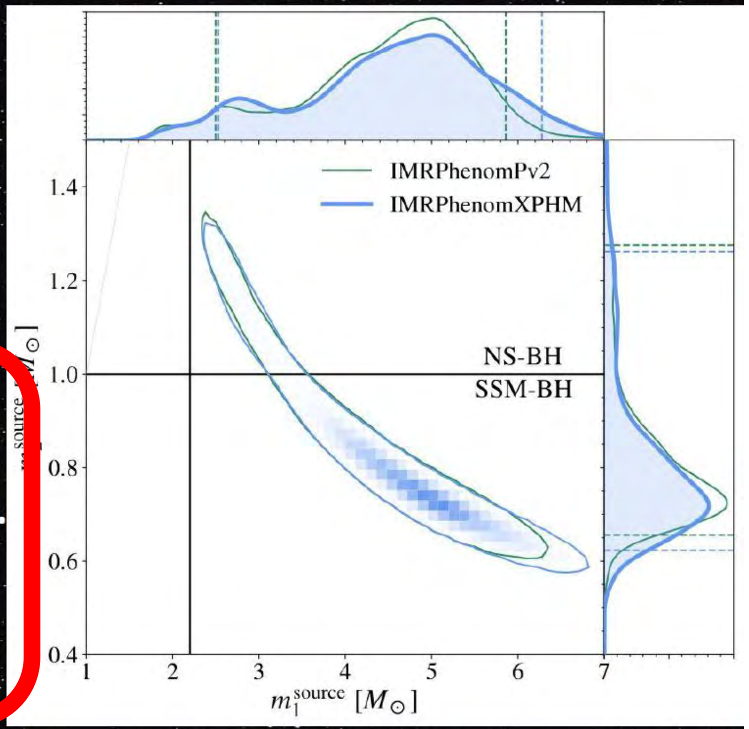
- …two candidate events, controversial and low-confidence, reported by independent groups!

*Lehmann, Profumo and Yant, MNRAS, 2022

SubSolarMass (SSB) 170401

[given time stamp, hopefully not April's fool joke]

- For 16% of the posterior we have $m_1 > 2.2 M_\odot$ and $m_2 > 1.0 M_\odot$, 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 $m_1 > 2.2 M_\odot$ and $m_2 < 1.0 M_\odot$, 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

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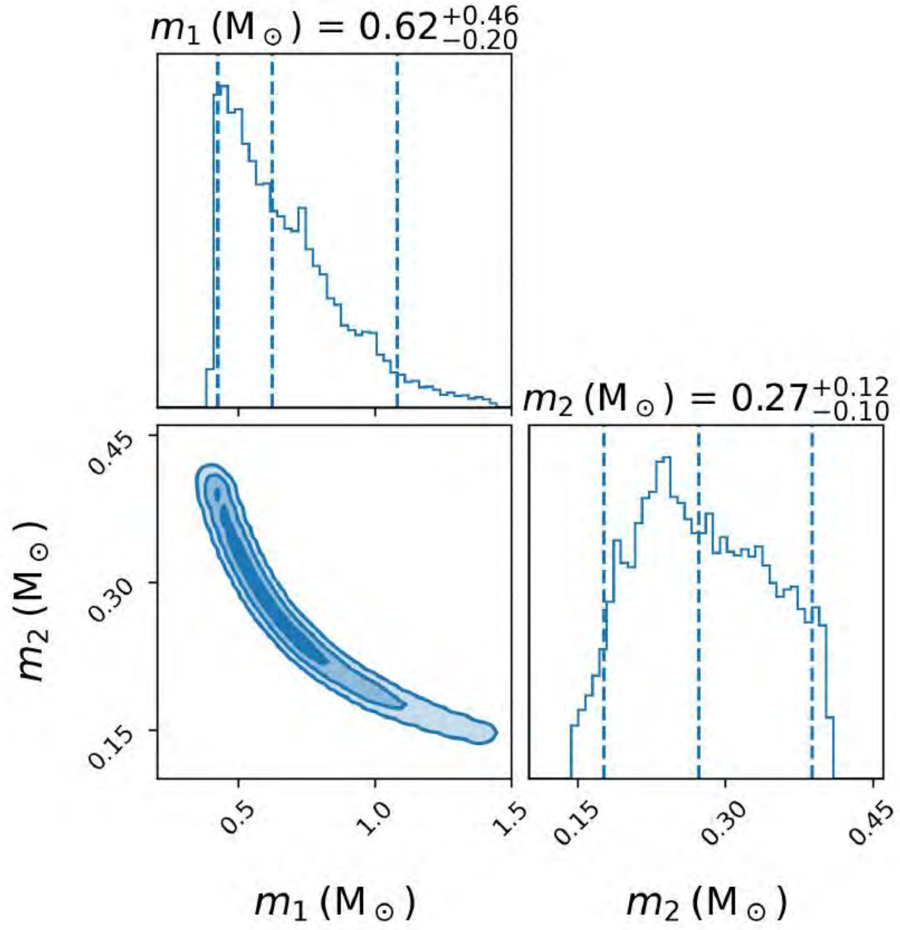
SubSolarMass (SSB) 200308



an in-depth analysis of one of the most significant candidates reported in the O3b search for SSM black hole binaries [12] with SNR = 8.90 and FAR = 0.20 yr^{-1}. Even if the candidate does not show enough significance to claim the firm detection of a gravitational wave event, it is of great interest to study and characterize the candidate. We also demonstrate that the ROQ method can be efficiently used to reduce the computational cost of the PE for such long signals. The inferred masses show that SSM200308, if coming from a GW event, is consistent with a binary of two SSM black holes; $m_1 = 0.62^{+0.46}_{-0.20}\,M_\odot$ and $m_2 = 0.27^{+0.12}_{-0.10}\,M_\odot$ (90% credible intervals). Given the very low masses of the candidate's components, their neutron star nature seems disfavoured [47, 64]. The question of the nature of the source of SSM200308 therefore remains open. The unusual characteristics of SSM200308 could be explained by the two components being black holes of primordial origin. If SSM200308 is a real signal, we can expect that improved detector sensitivities and longer observing time would within a few years allow for the firm detection of an SSM black hole.

* 2311.16085;   FAR: False Alarm Rate

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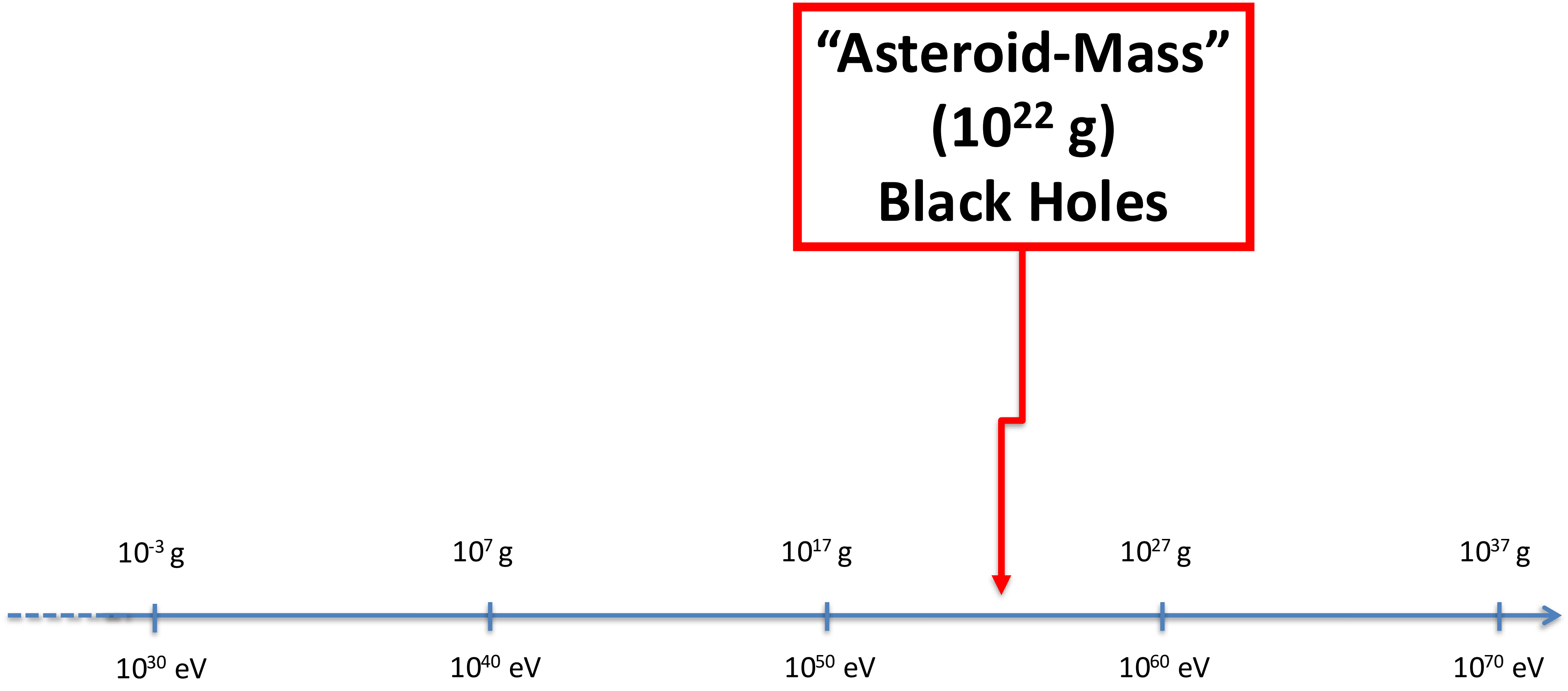
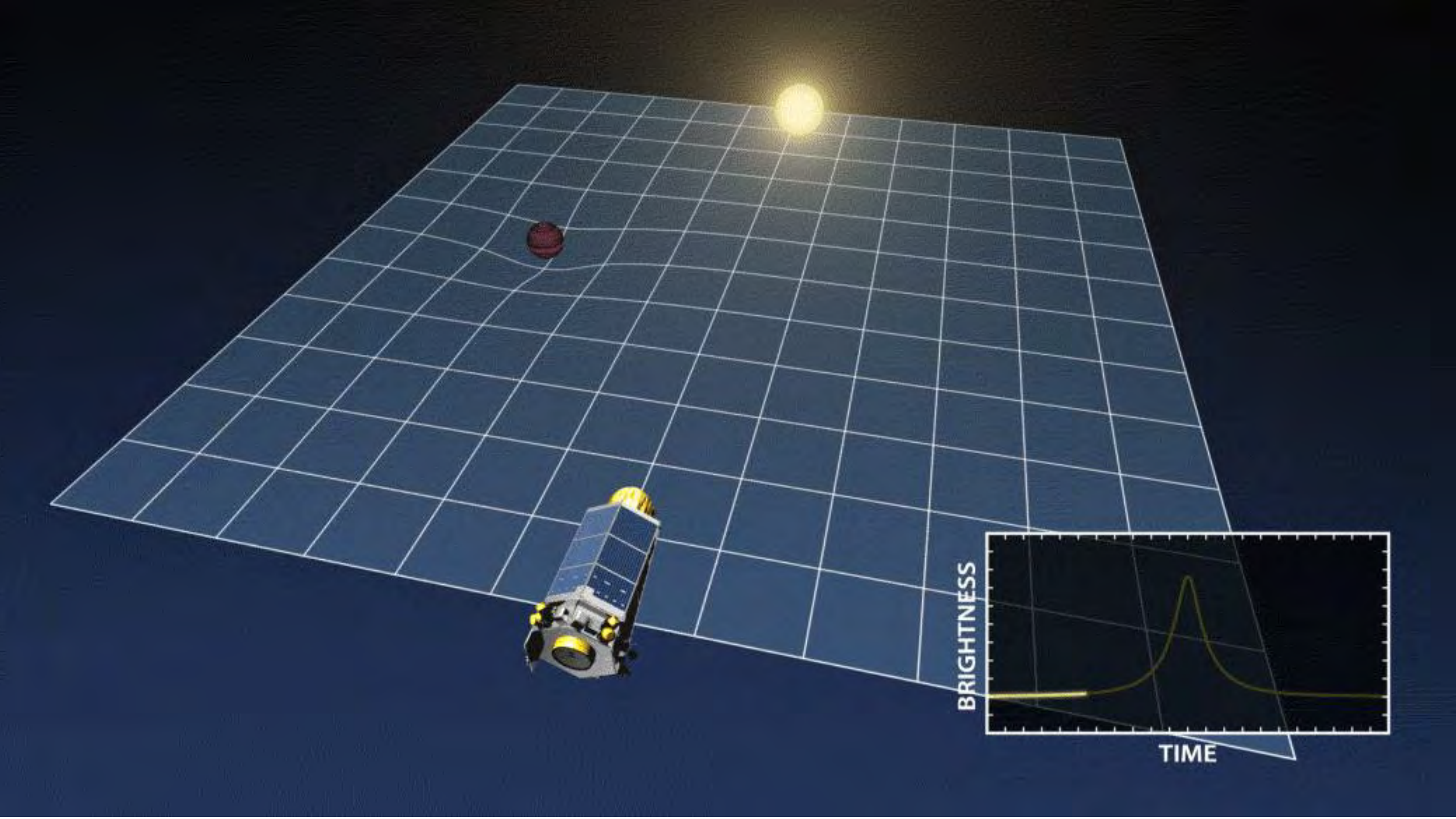
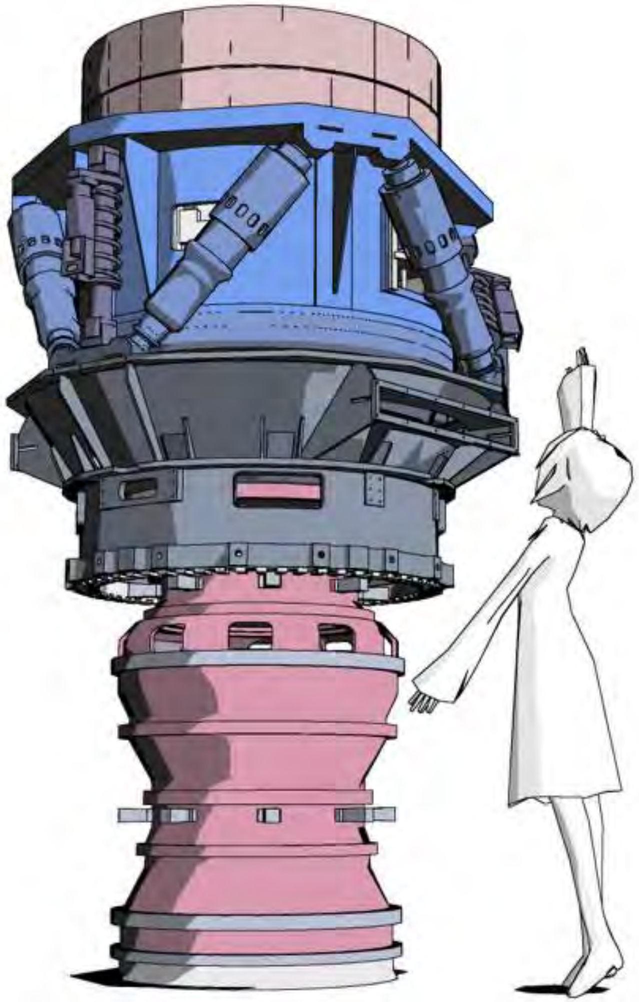


- ✓ **Can be 100% of the Dark Matter!**
- ✓ **Microlensing searches limitations**
- ✓ **How can we detect them?**


BRIGHTNESS
TIME

Strongest Microlensing Constraints on Light Black Holes

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



* Profumo, Smyth+ PRD 2020

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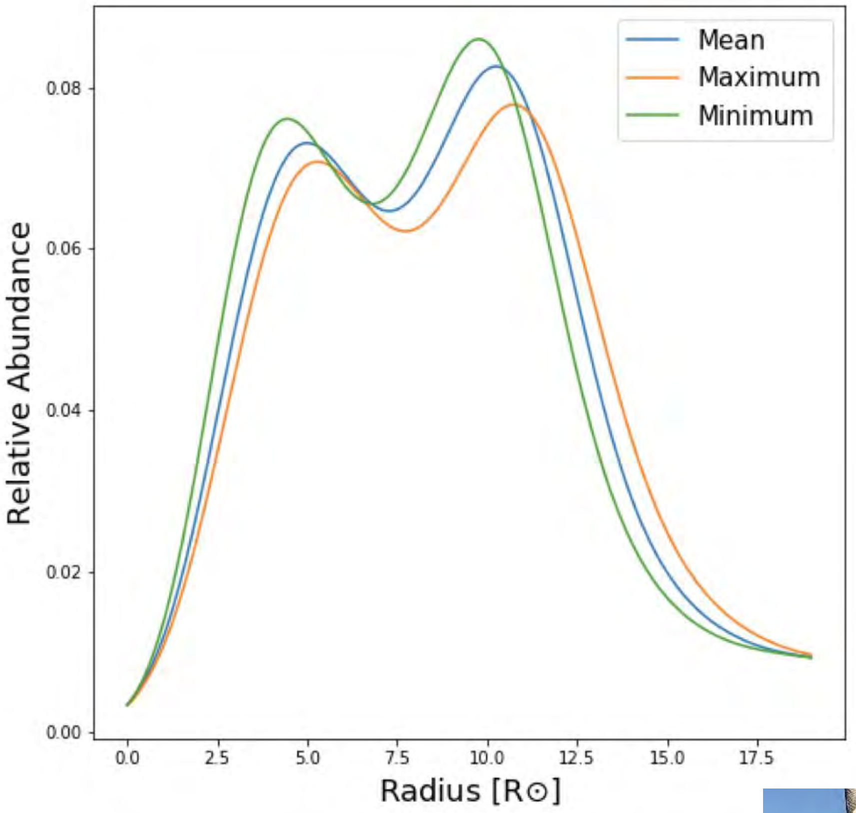
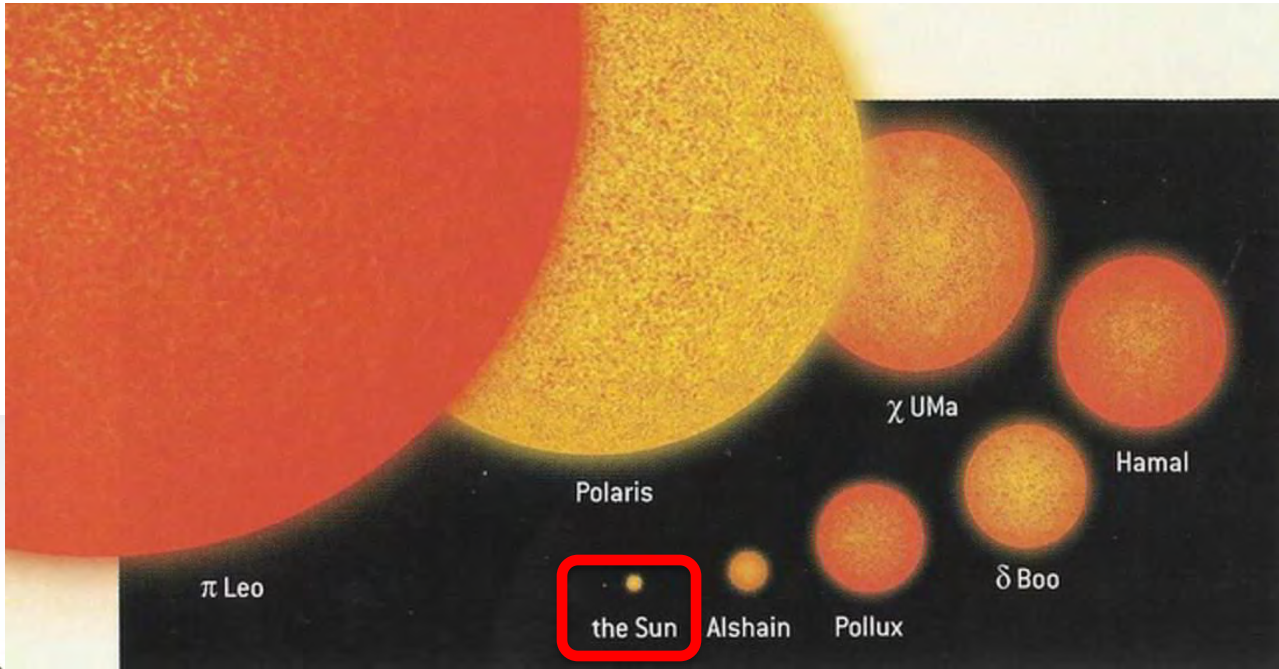
University of California Santa Cruz

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

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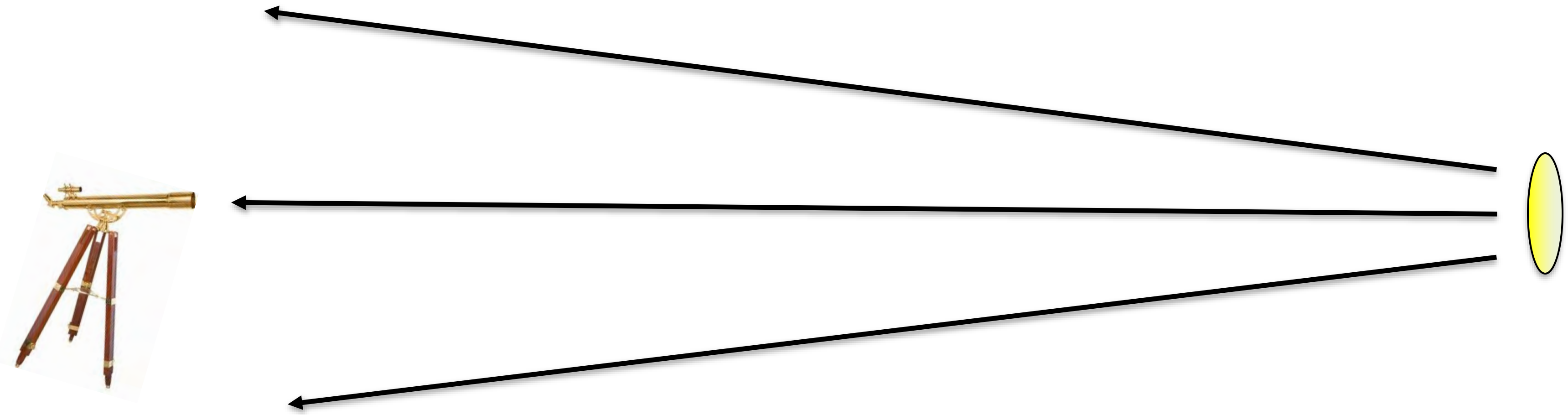
Key effect previously neglected; finite-source-size effects*!



* Profumo, Smyth+ PRD 2020

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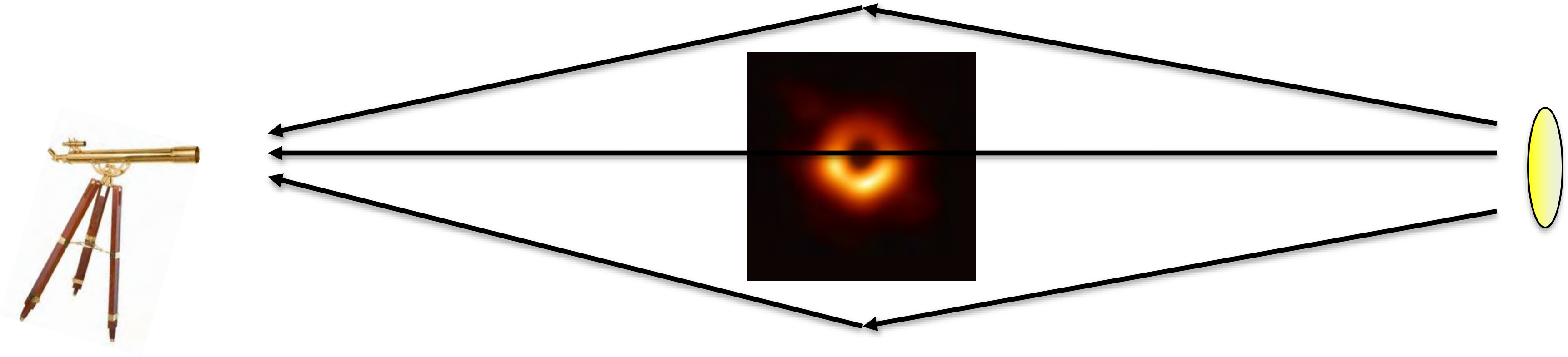

* Profumo, Smyth+ PRD 2020

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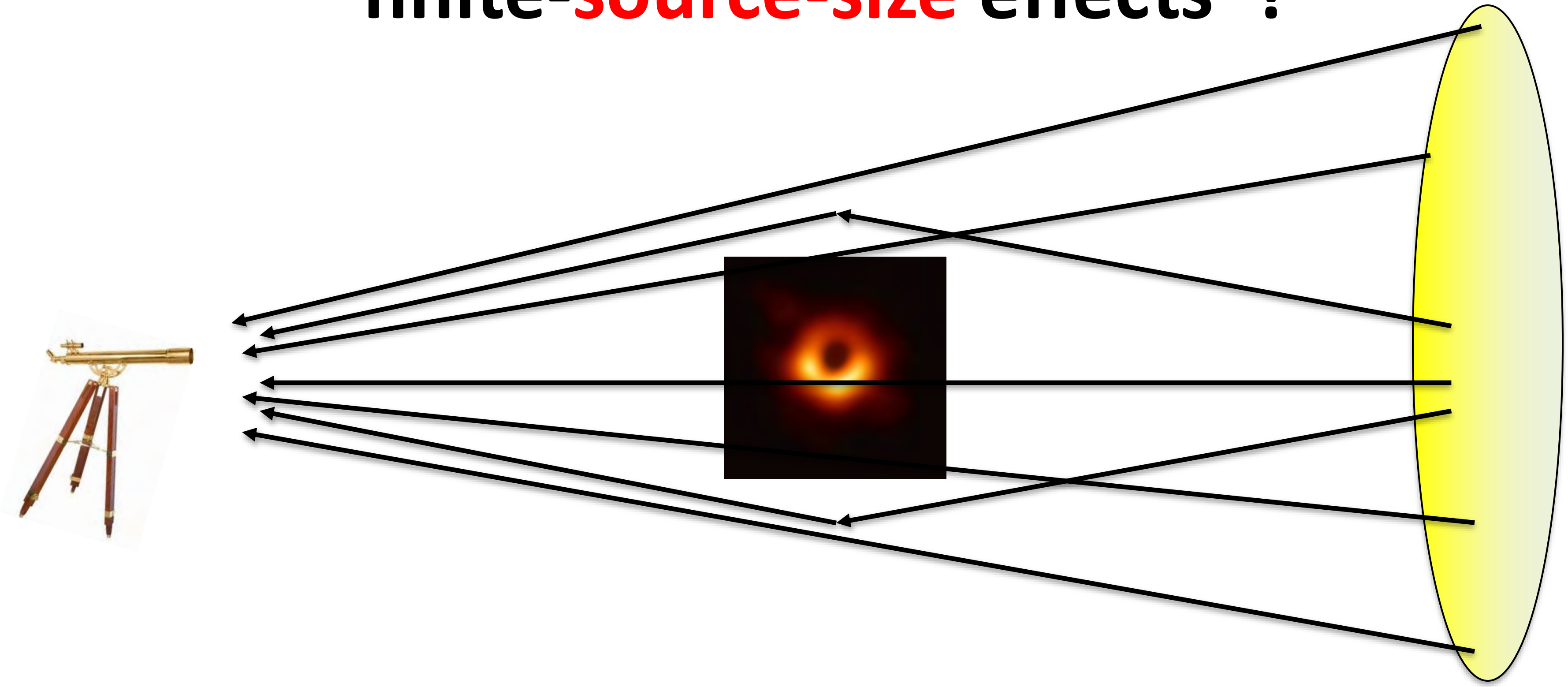
University of California Santa Cruz

Key effect previously neglected; finite-source-size effects*!



* Profumo, Smyth+ PRD 2020

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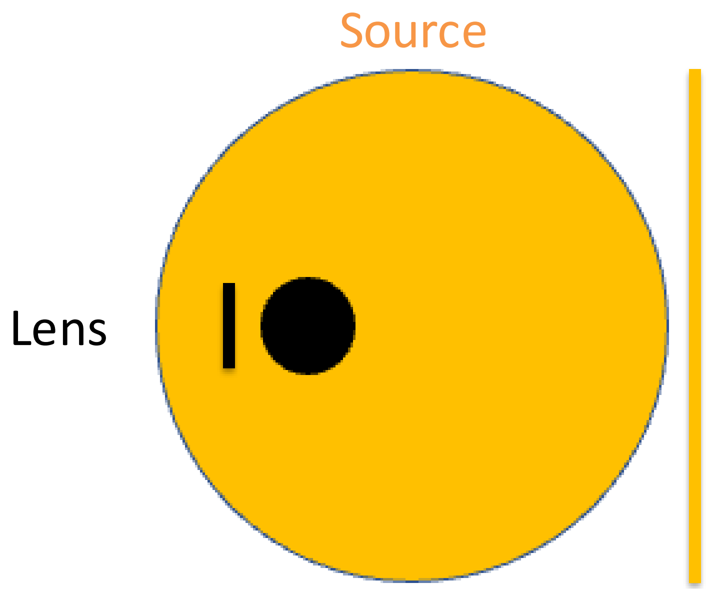
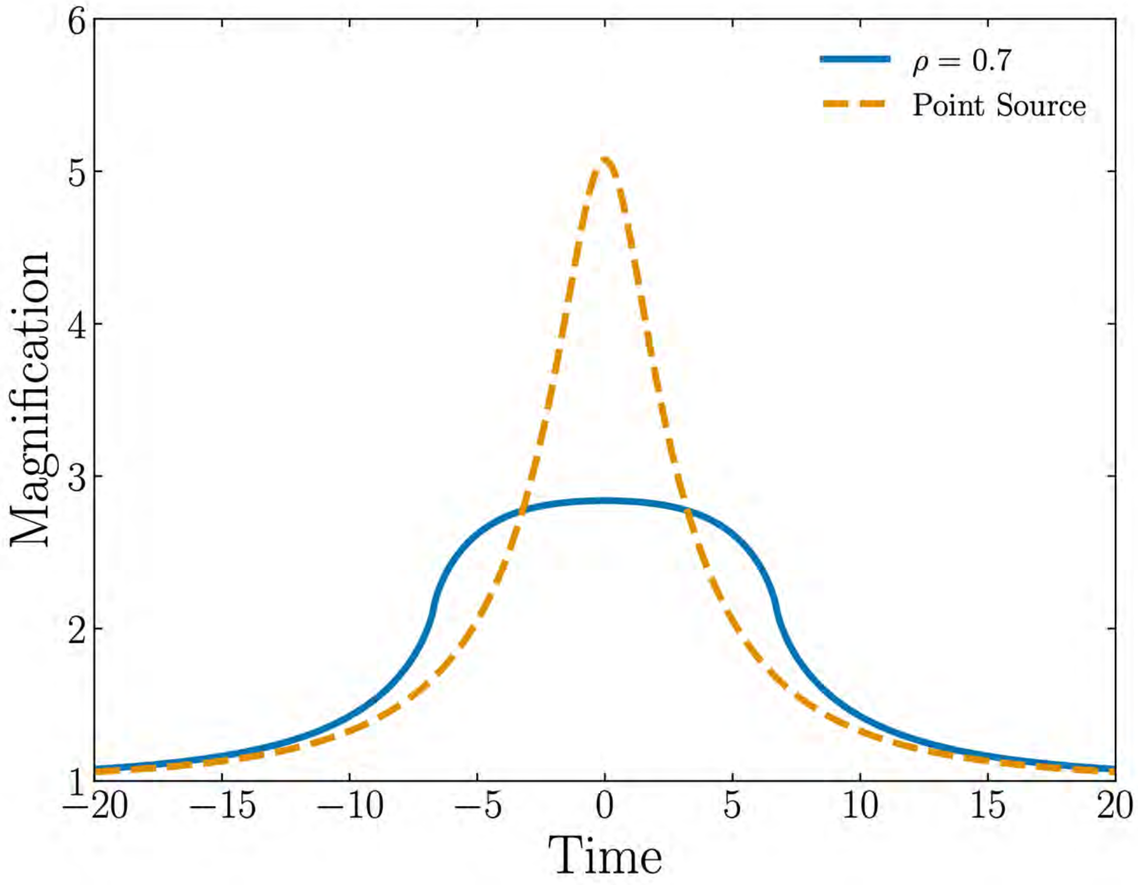
The bigger the star, the more important finite-source-size effects!



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



* slide credit: N. Smyth

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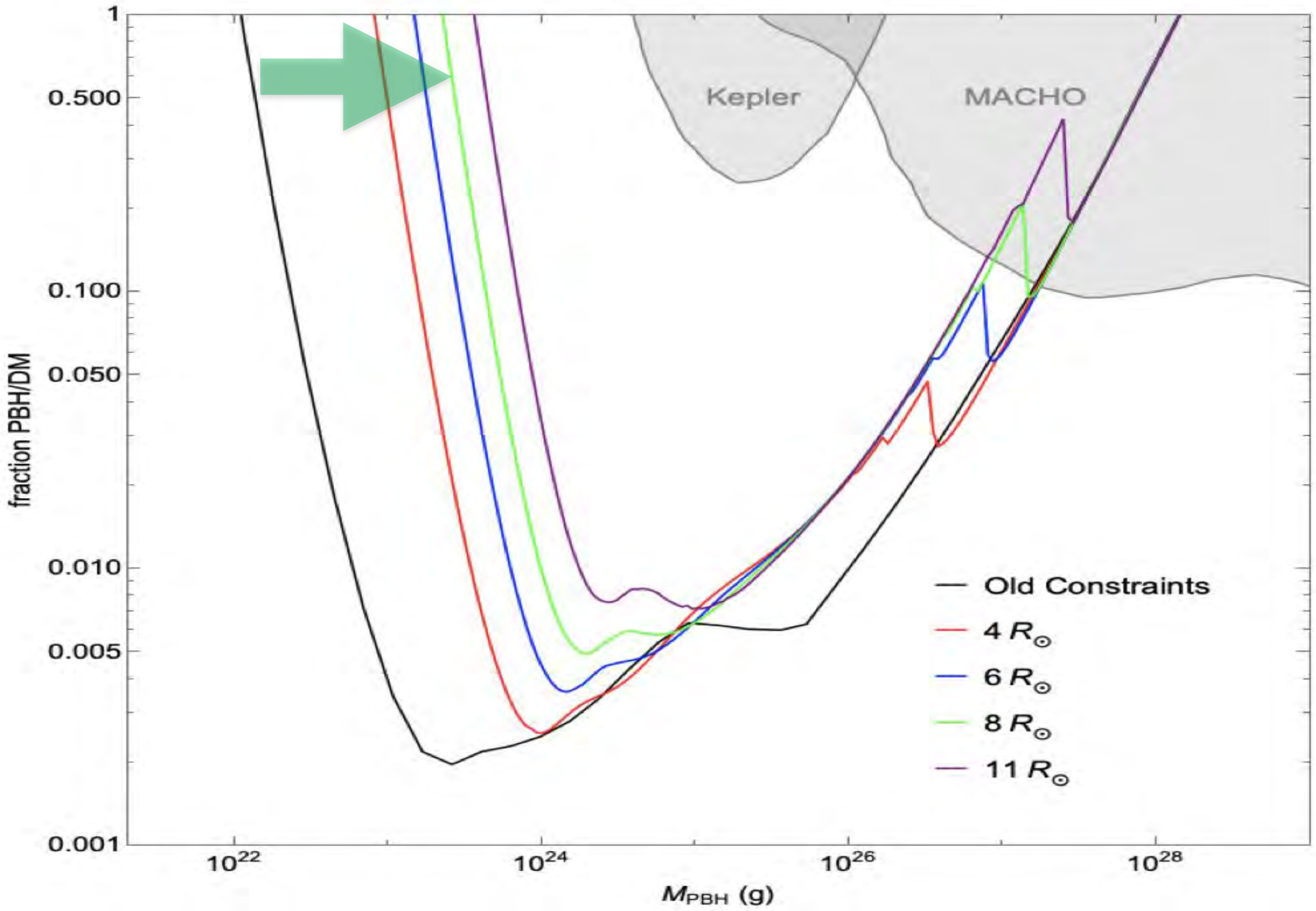

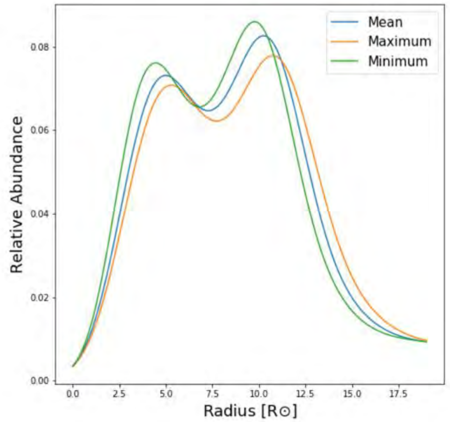

* Profumo, Smyth+ PRD 2020

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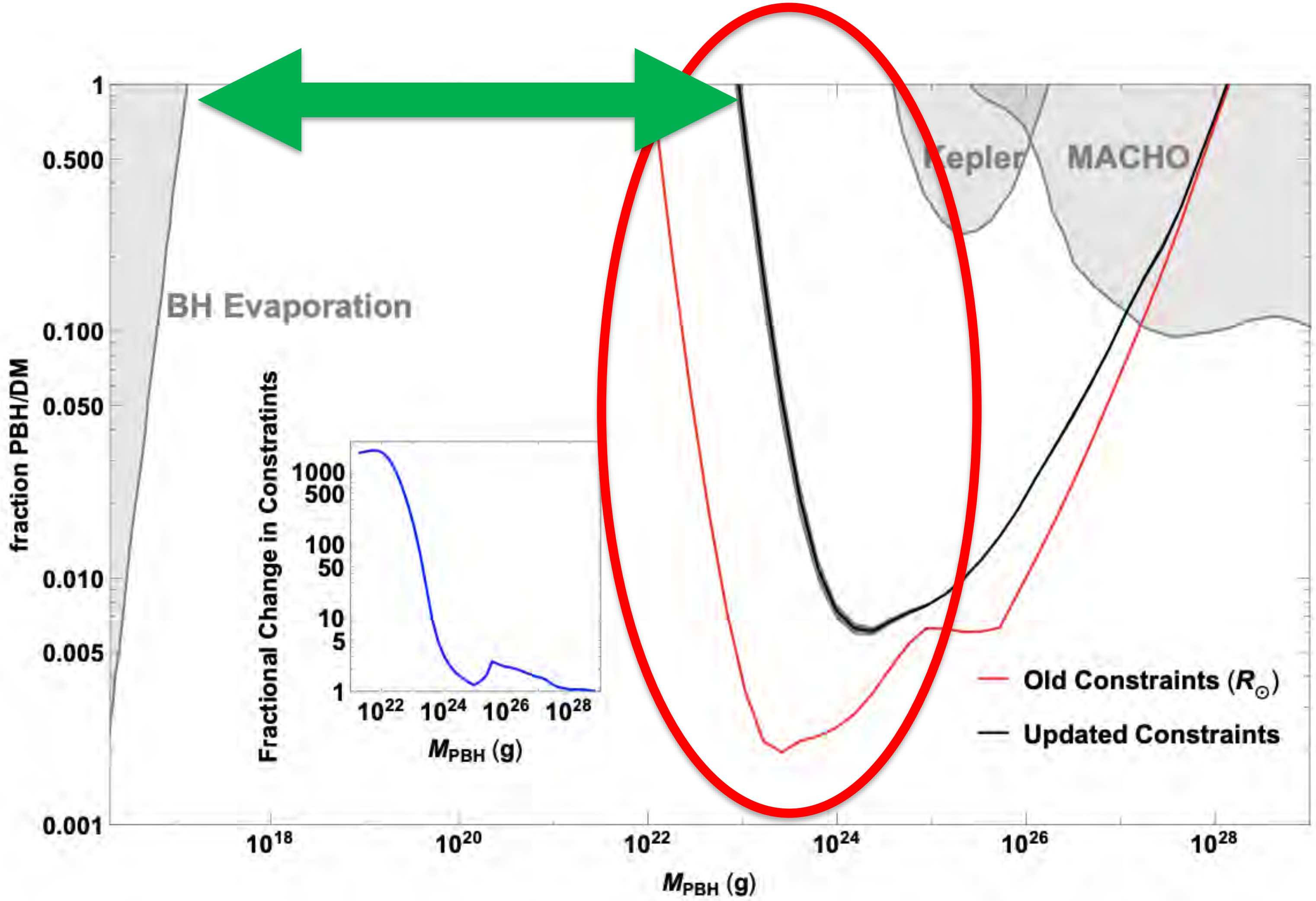
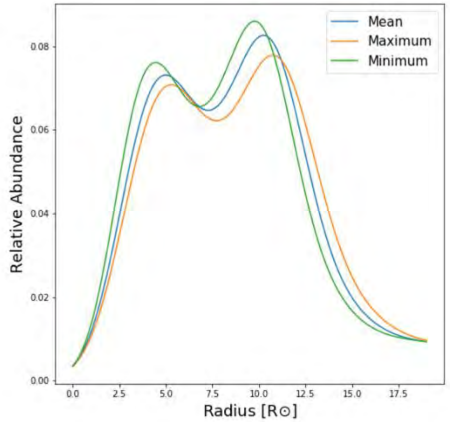
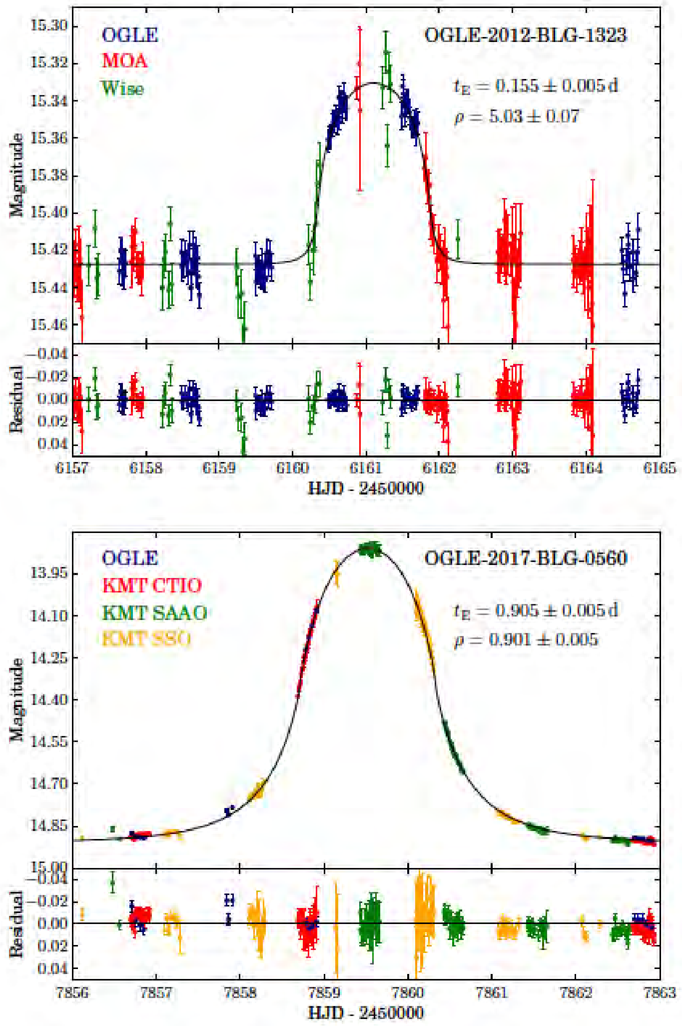
Black holes can be 100% of Dark Matter here!





* Profumo, Smyth+ PRD 2020

Microlensing events have been detected… most recently by OGLE

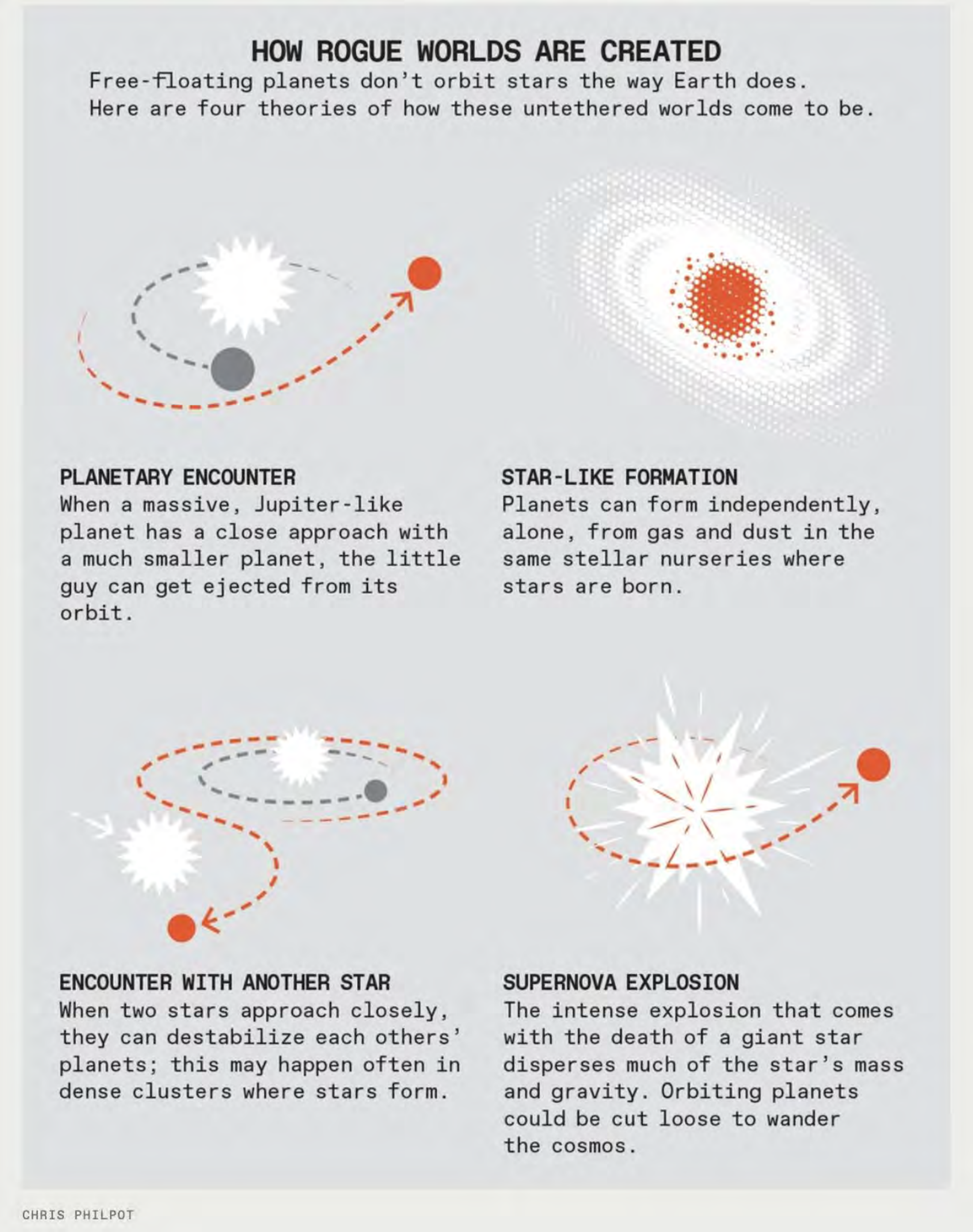


…but have we discovered PBH, or Freely-Floating Planets*?

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

Mroz+ 2017,…

FFPs are an irreducible **background** to searches for PBH …and **VICEVERSA**!



Stefano Profumo
University of California
Santa Cruz

Will Roman enable disentangling FFP versus FFP+PBH?

We studied the statistics of anticipated event duration distribution

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

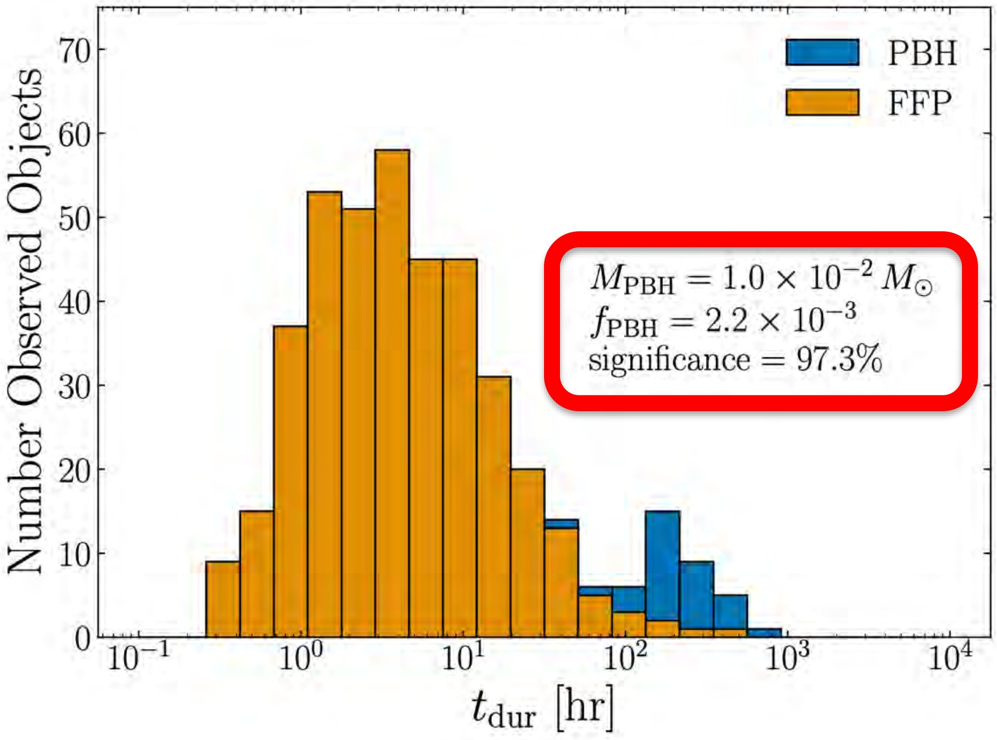
*DeRocco, Frangipane, Hamer Smyth, Profumo, PRD 2024

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

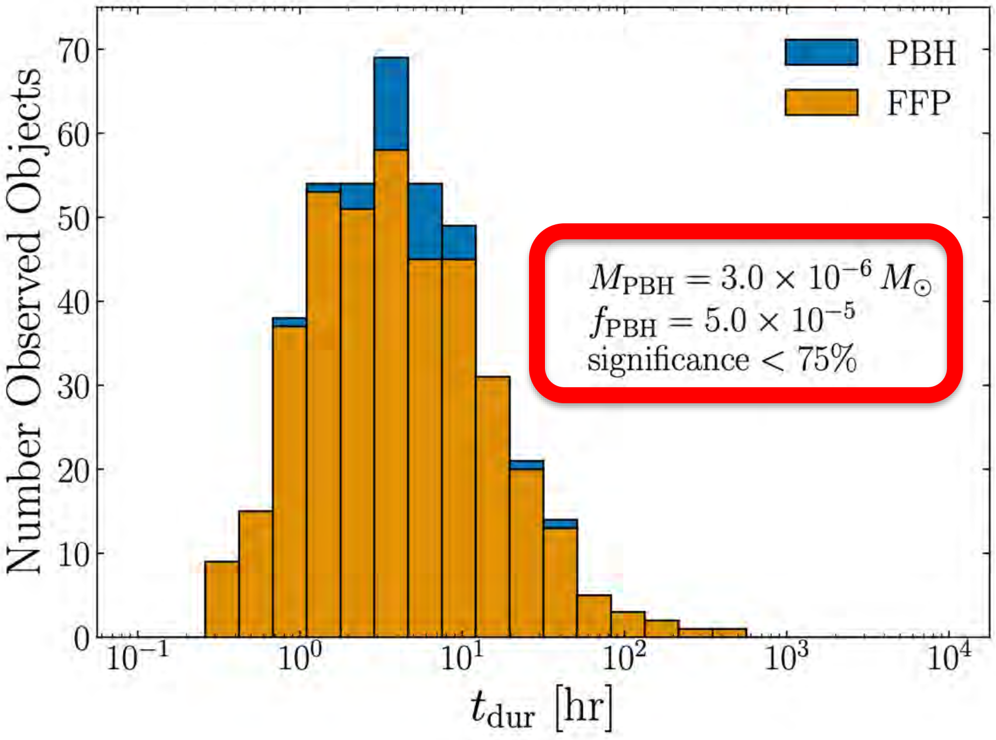
Stefano Profumo
University of California Santa Cruz

Will Roman enable disentangling FFP versus FFP+PBH?

Yes



No



Null Hypothesis: Only FFPs

Alternate Hypothesis: FFPs + PBHS

Statistical test: two-sample Anderson-Darling test

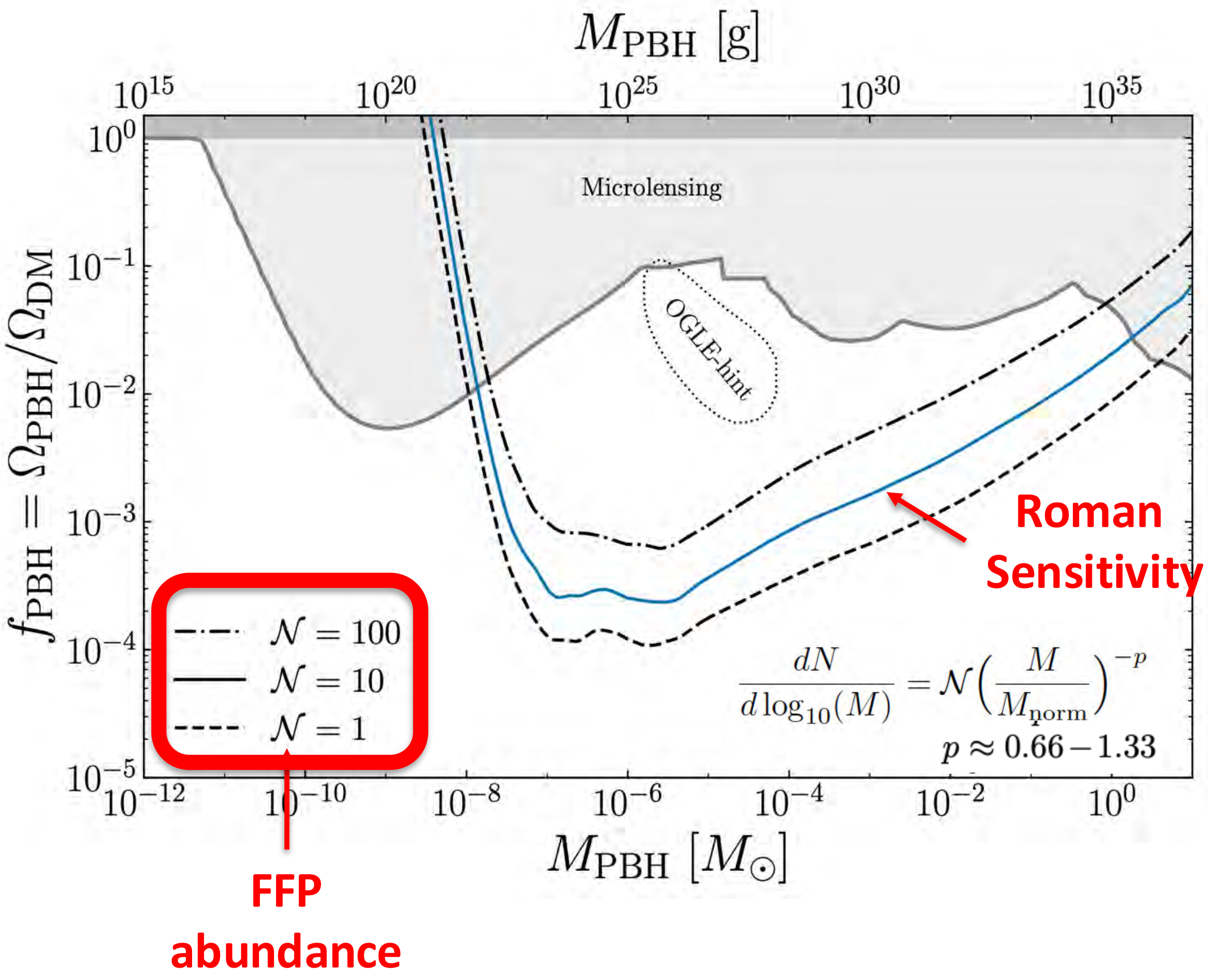
*DeRocco, Frangipane, Hamer Smyth, Profumo, PRD 2024

Stefano Profumo
University of California Santa Cruz

Can we find PBHs hidden in FFP background?

Roman: 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!



*DeRocco, Frangipane, Hamer Smyth, Profumo, PRD 2024

Stefano Profumo
University of California
Santa Cruz

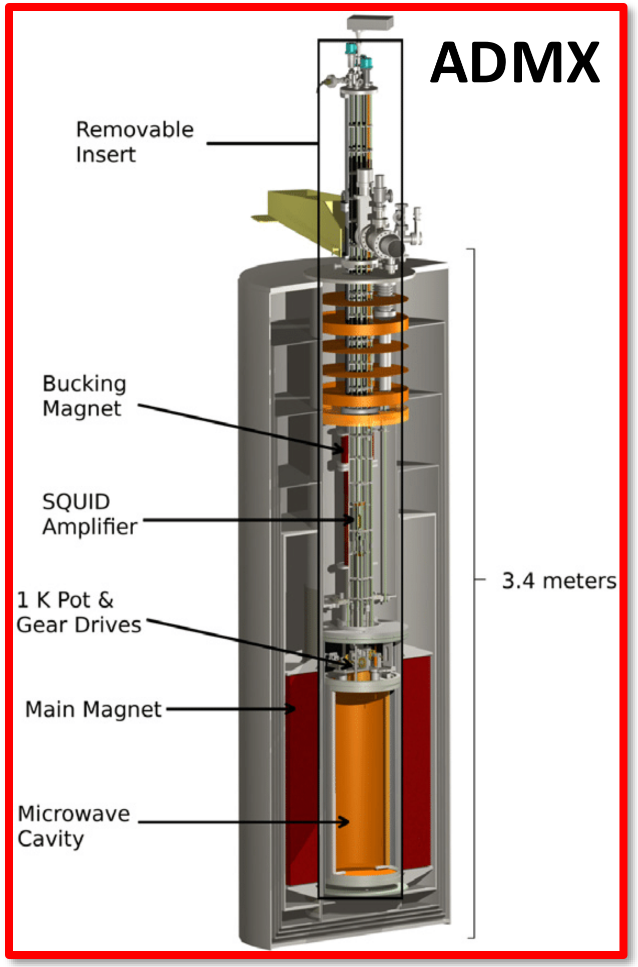
How can we access the "Asteroid Window"?

- Production mechanism can source e.g. Stochastic Gravitational Wave Background (but model dependent!)

- Lensing with higher-frequency observations, e.g. X-ray (but issue of statistics, observation length), or femtolensing (but again finite-size source effects!)

- LIGO-style BH-BH mergers?*

- Perturbations to planetary orbits?**

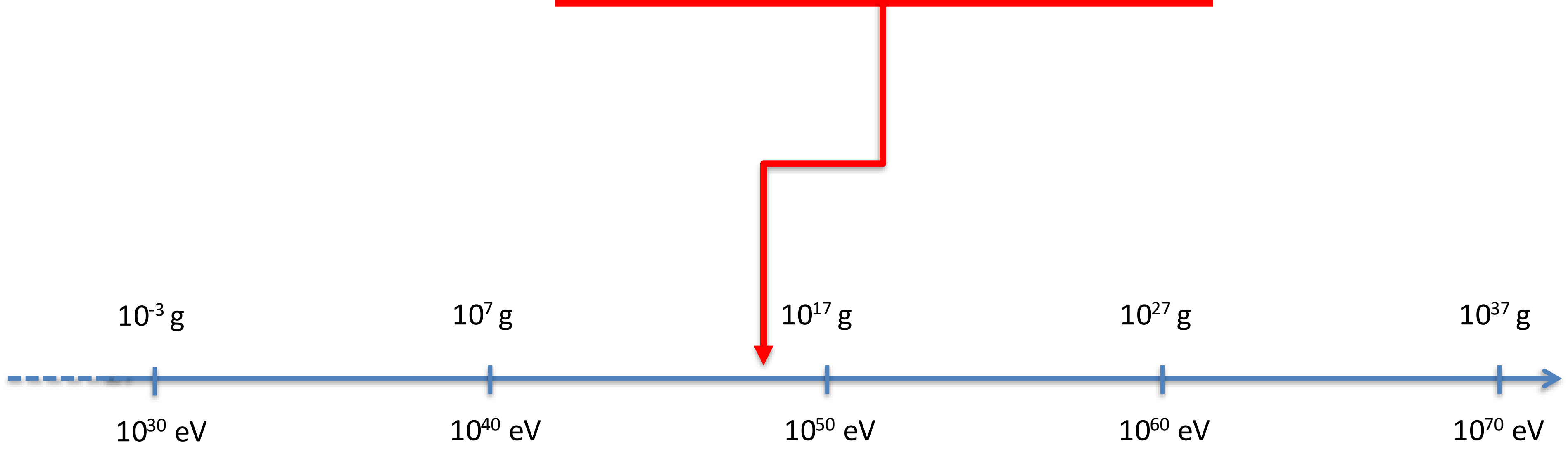


* Profumo et al, 2410.15400

** Geller, Lehmann et al, 2312.17217

Stefano Profumo
University of California Santa Cruz

"Exploding" Black Holes (10^{16} g)



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

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

[Stefan-Boltzmann]

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

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

[10^{10} grams units]

Black holes formed in the early universe, with a mass $M_U \sim 5 \times 10^{14}$ grams, T~100 MeV are exploding today**

*Hawking, 1974

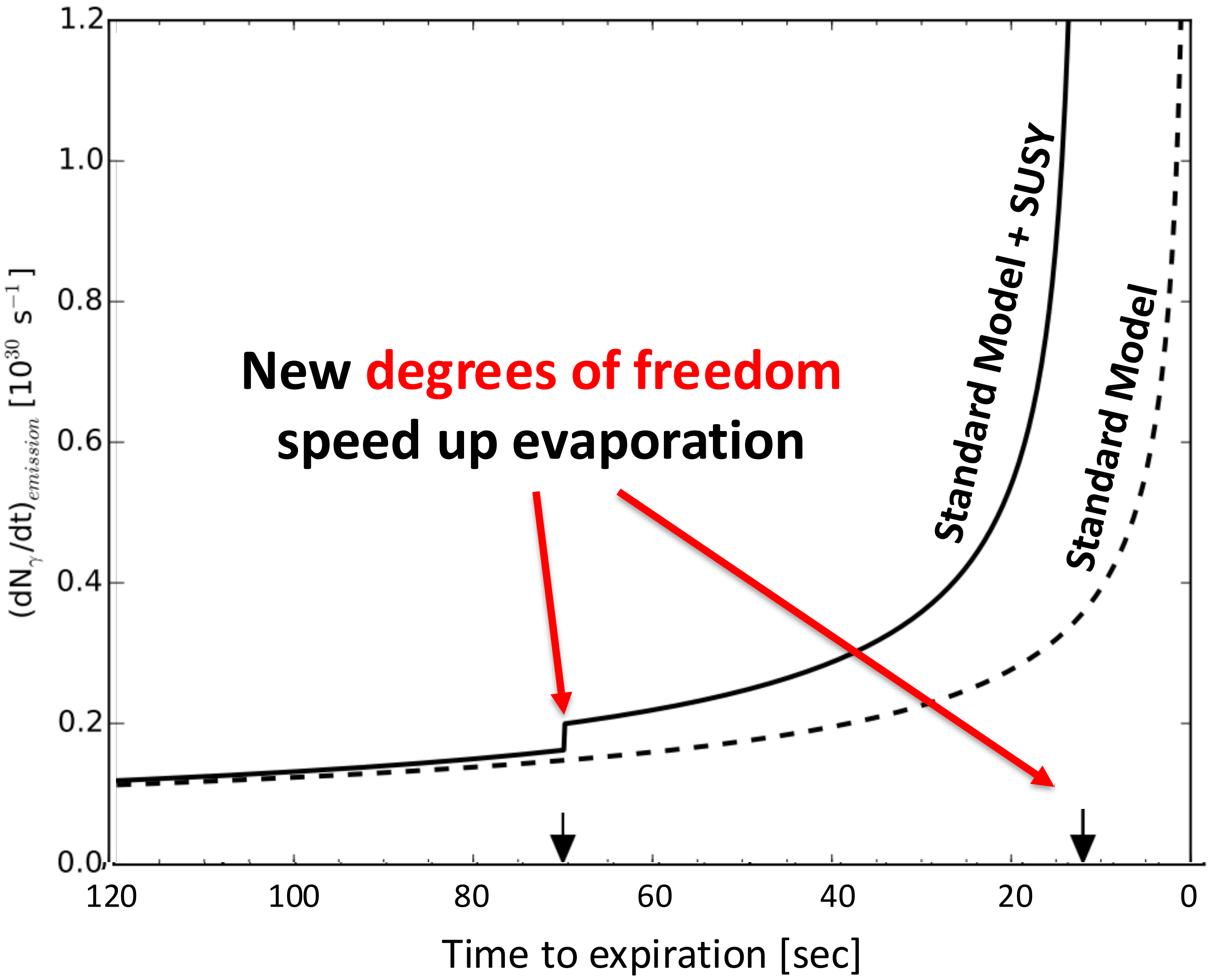
**or lighter, and formed later!

Stefano Profumo
University of California Santa Cruz

The (universal*) Black Hole Light-curve

Universal Luminosity
→ perfect
"standard candle"

"Backwards"
Gamma-Ray Burst



No afterglow
(BHs don't form a photosphere or chromosphere)

*for a given spin/charge, and evaporating d.o.f

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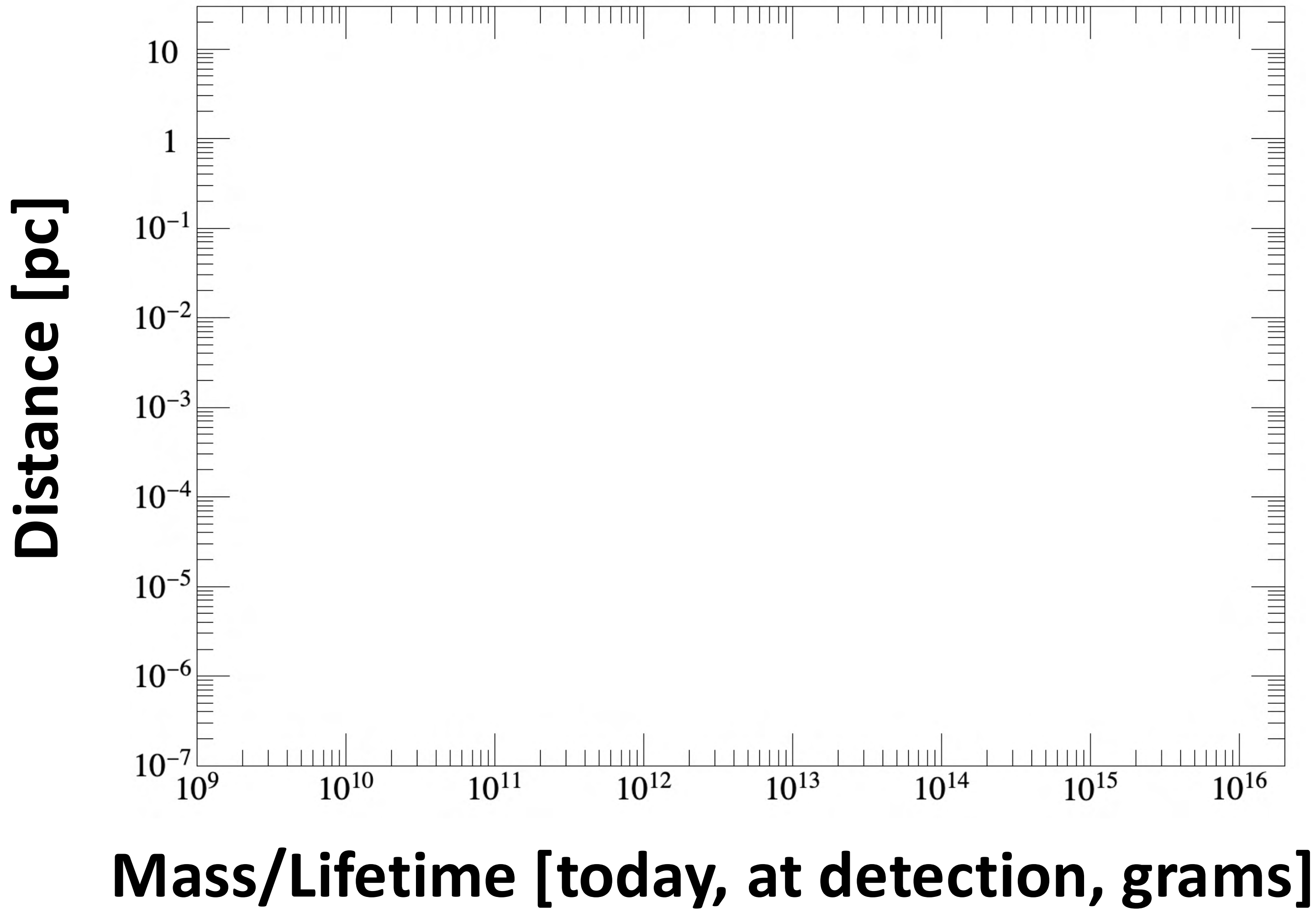
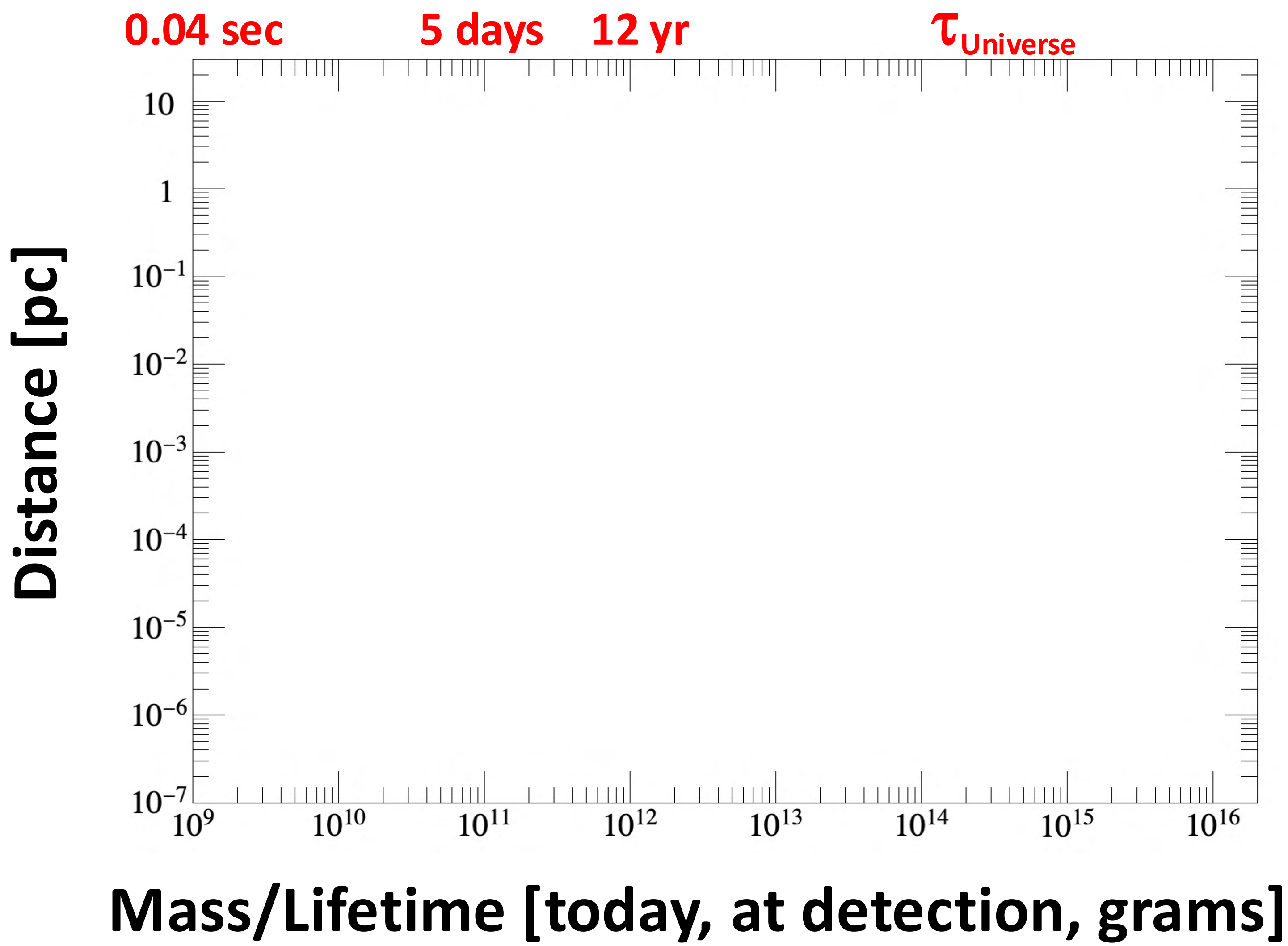
University of California Santa Cruz

How can we search for PBH explosions today?



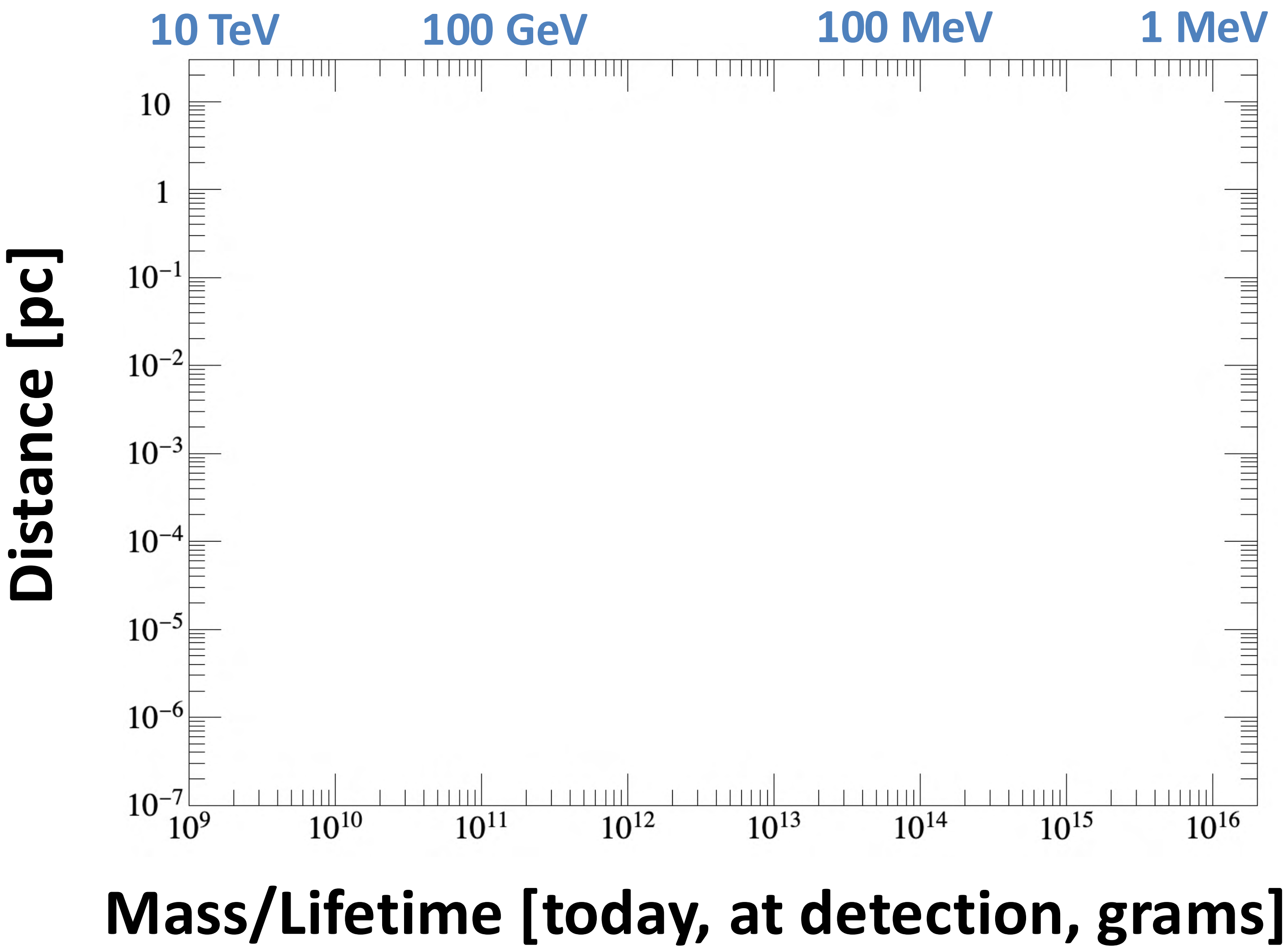
Remaining lifetime

$$\tau \simeq 400 \text{ sec} \left(\frac{M_{\mathrm{BH}}}{10^{10} \text{ g}}\right)^3$$



Temperature

$$T \simeq 1\ \mathrm{TeV} \left(\frac{10^{10}\ \mathrm{g}}{M_{\mathrm{BH}}} \right)$$



Stefano Profumo
University of California
Santa Cruz

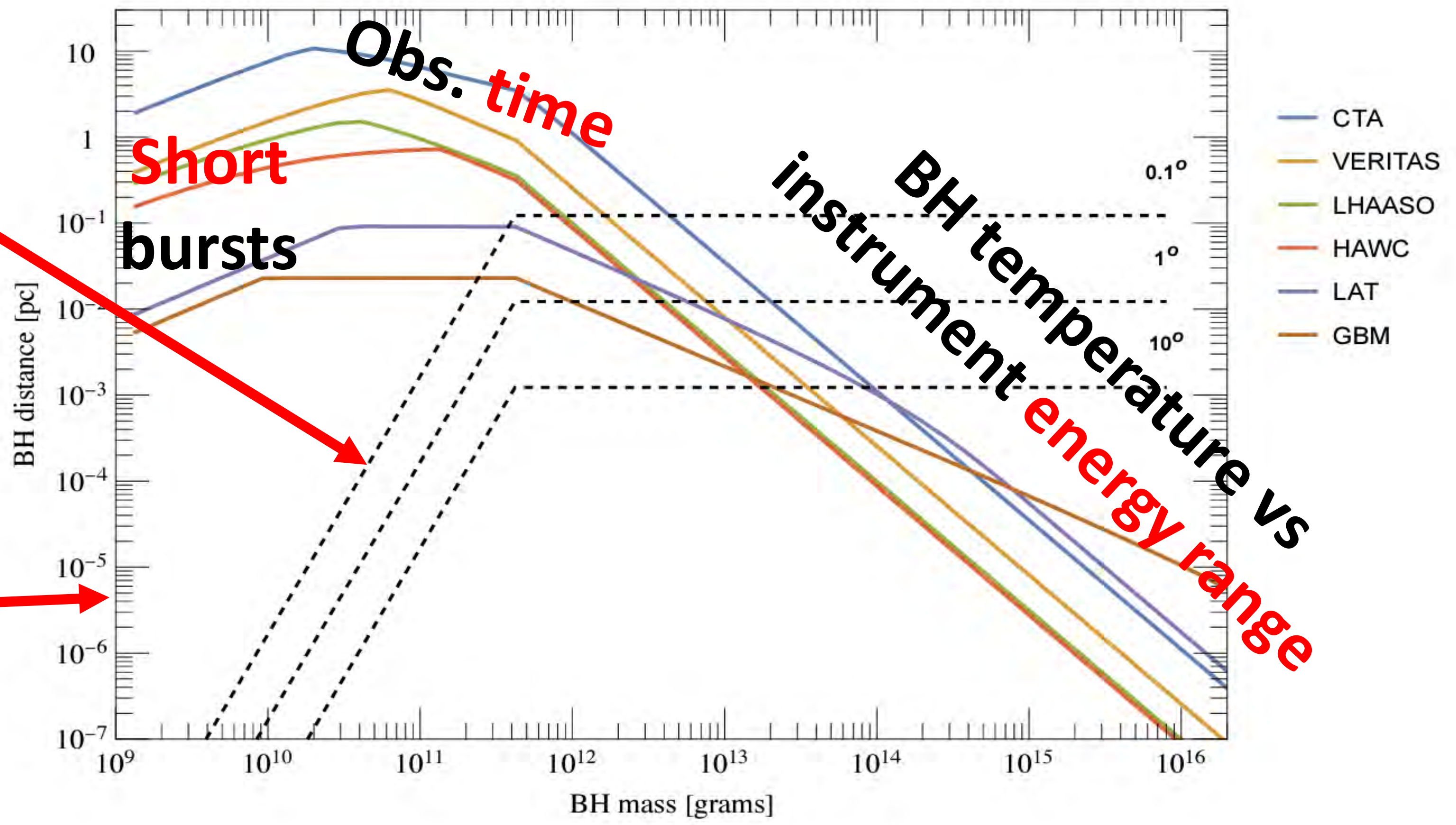
10 TeV 100 GeV 100 MeV 1 MeV

0.04 sec 5 days 12 yr τ_{Universe}

Average Proper motion

~1 A.U.

Distance



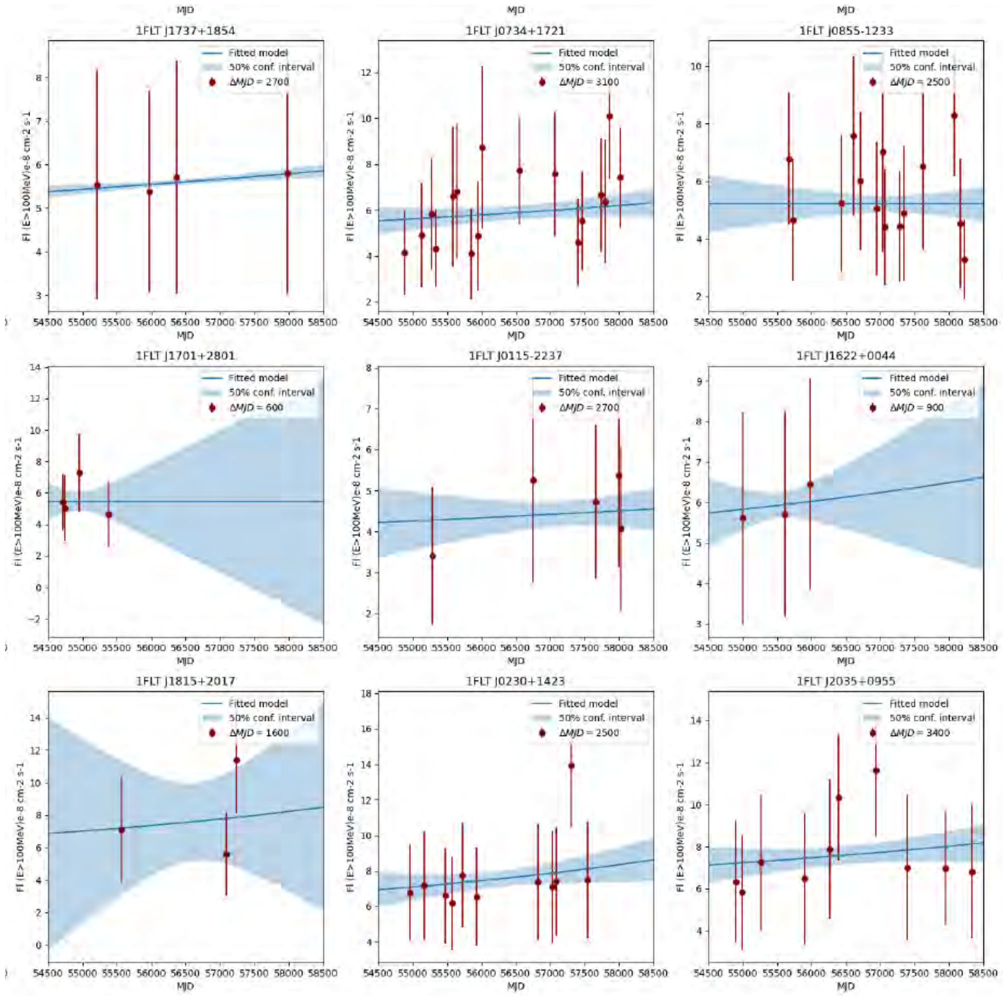
Gamma-Ray Observatory

Mass/Lifetime [today, at detection]

*Profumo, Boluna, Ble, Hennings, 2023 (JCAP)

Stefano Profumo
University of California Santa Cruz

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



time

*Profumo, Boluna, Ble, Hennings, 2023 (JCAP)

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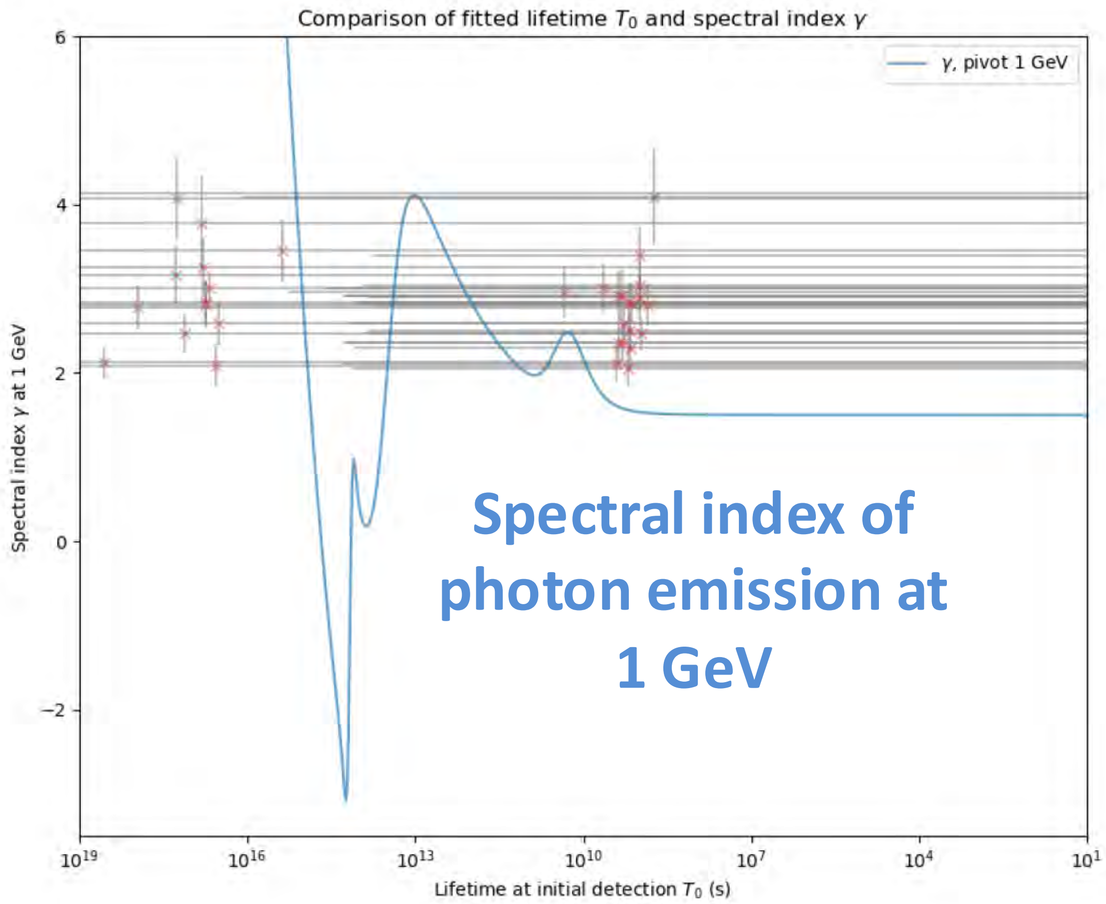
LAT and GBM Gamma-ray burst catalog
(2) LAT variable sources: spectral fit



Time-to-explosion

***Profumo, Boluna, Ble, Hennings, 2023 (JCAP)**

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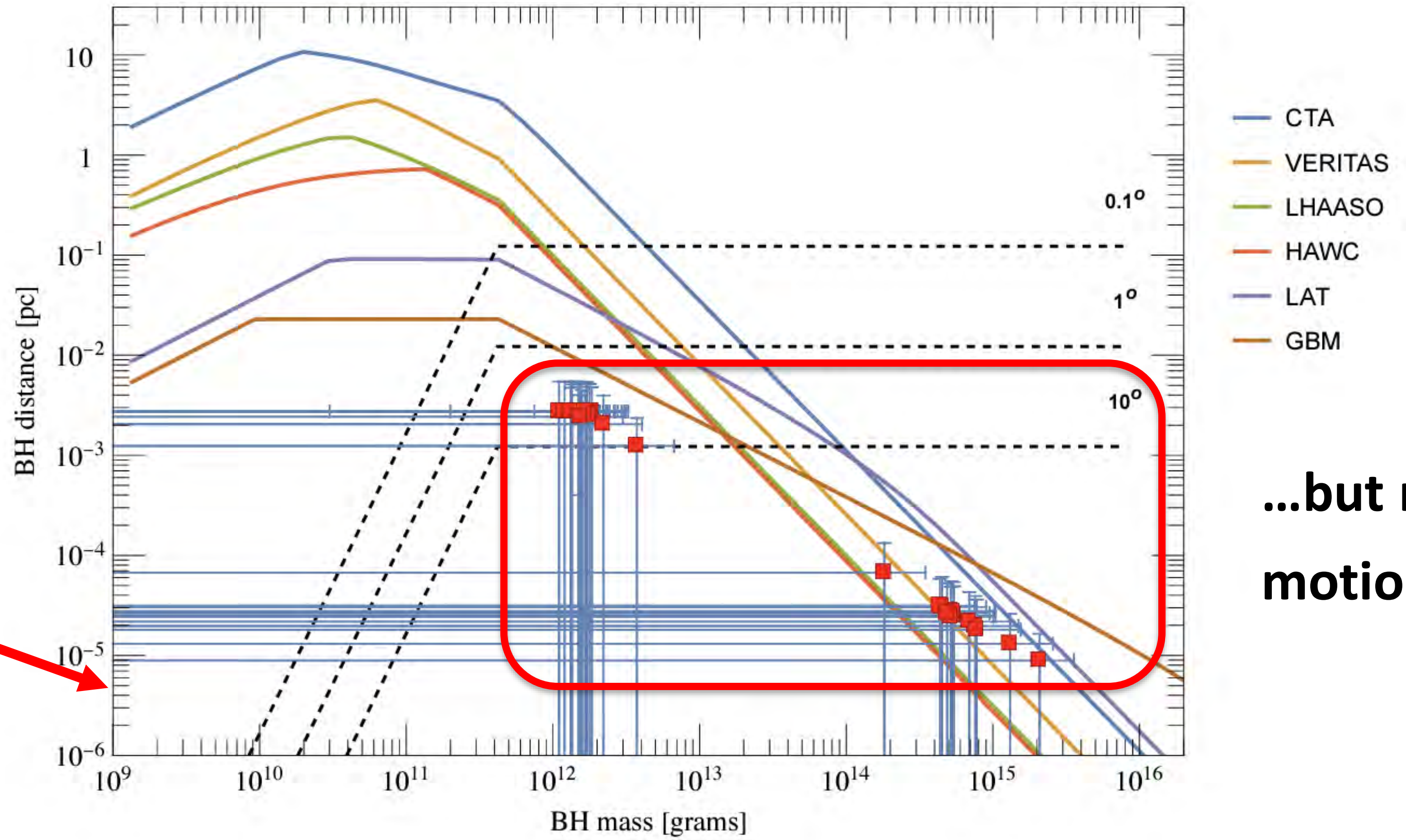
University of California Santa Cruz

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



~1 A.U.

…but no proper motion detected 😢

***Profumo, Boluna, Ble, Hennings, 2023 (JCAP)**

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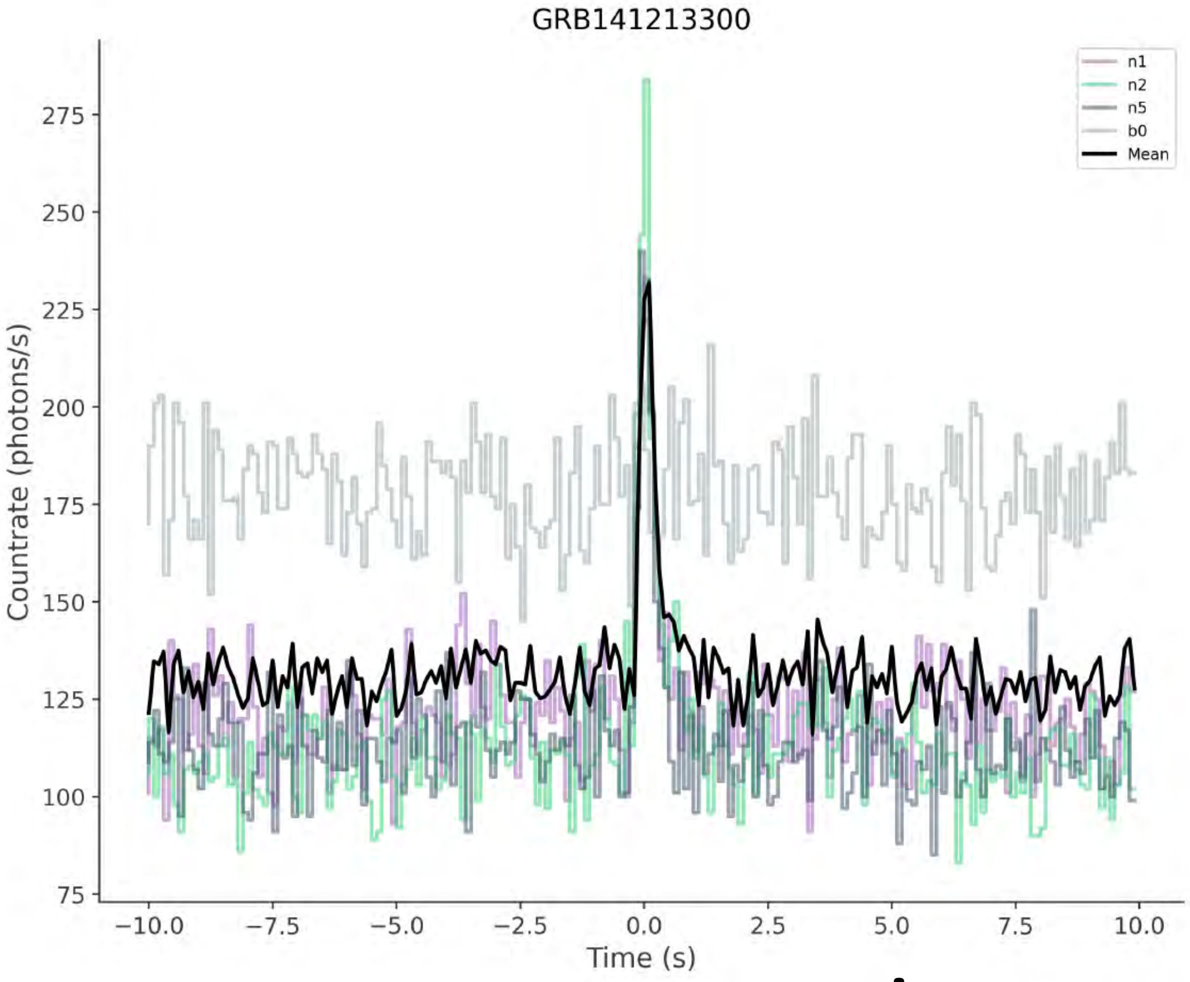
University of California Santa Cruz

LAT and GBM Gamma-ray burst catalog (4) Short duration: light curve



time

***Profumo, Boluna, Ble, Hennings, 2023 (JCAP)**

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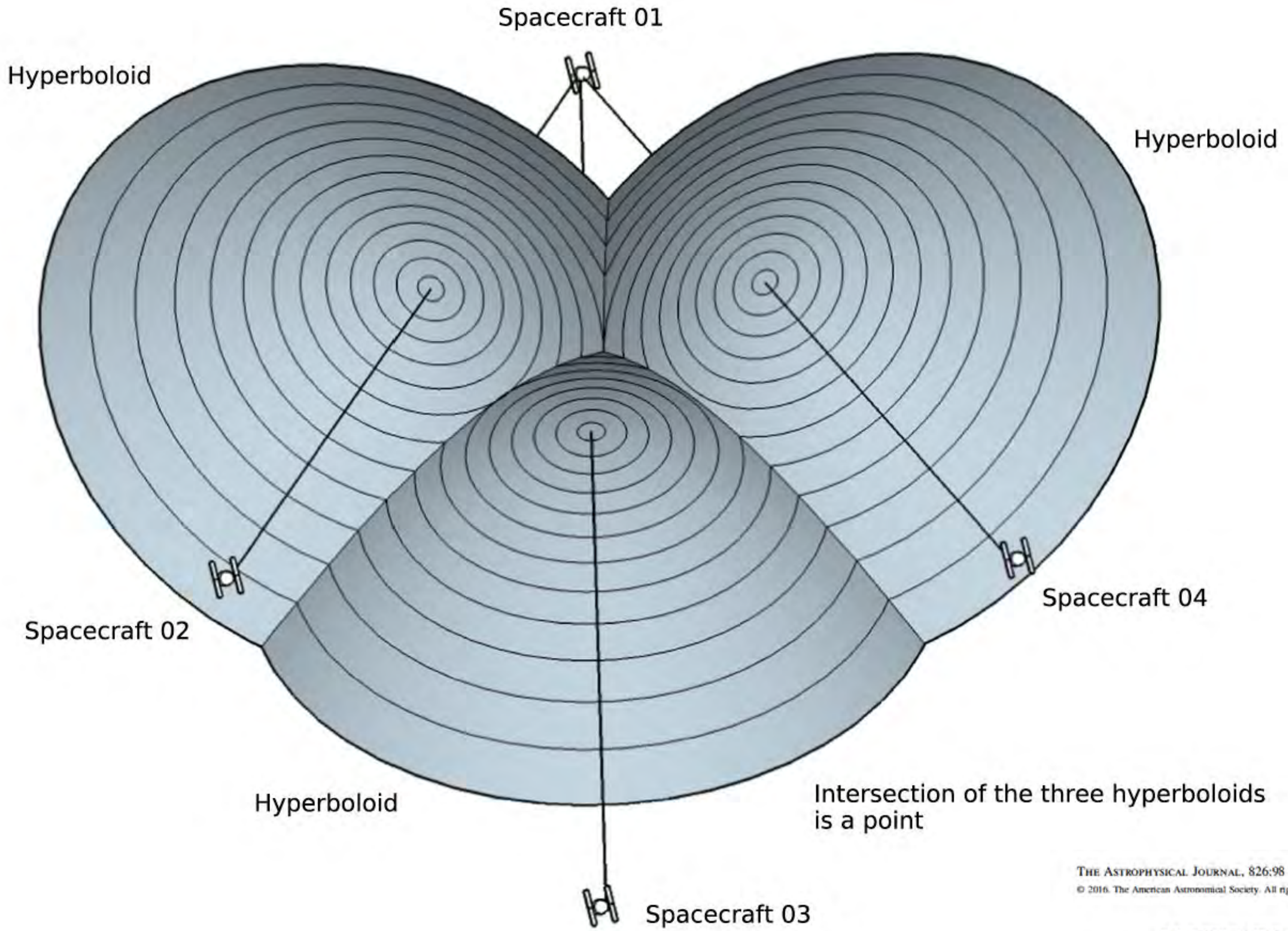
University of California Santa Cruz

(5) Interplanetary GRB monitors network (IPN)



Timing resolution distinguishes cosmological vs local events!

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

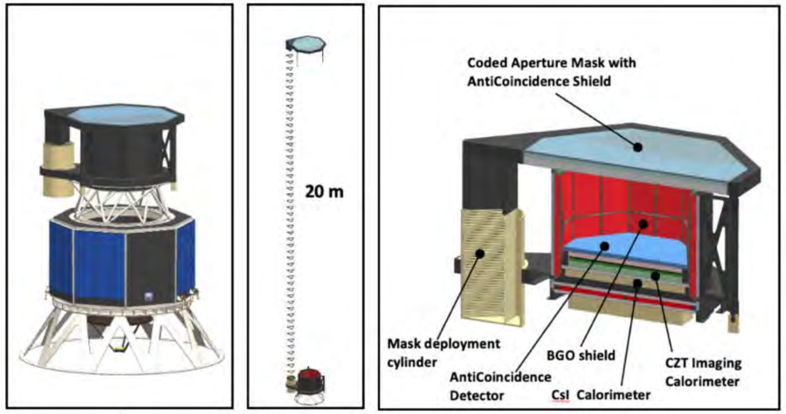
INVESTIGATION OF PRIMORDIAL BLACK HOLE BURSTS USING INTERPLANETARY NETWORK GAMMA-RAY BURSTS

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 (JCAP)**

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

GALACTIC COMPTON AND
GECCO
CODED APERTURE MASK EXPLORER



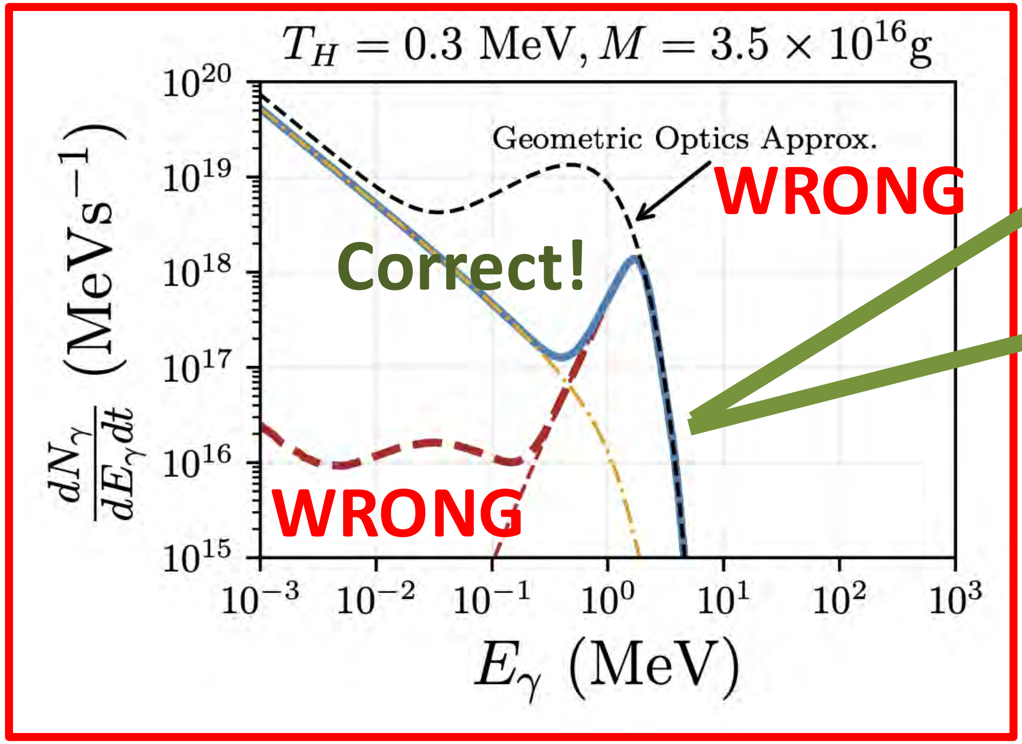
a) b) c)

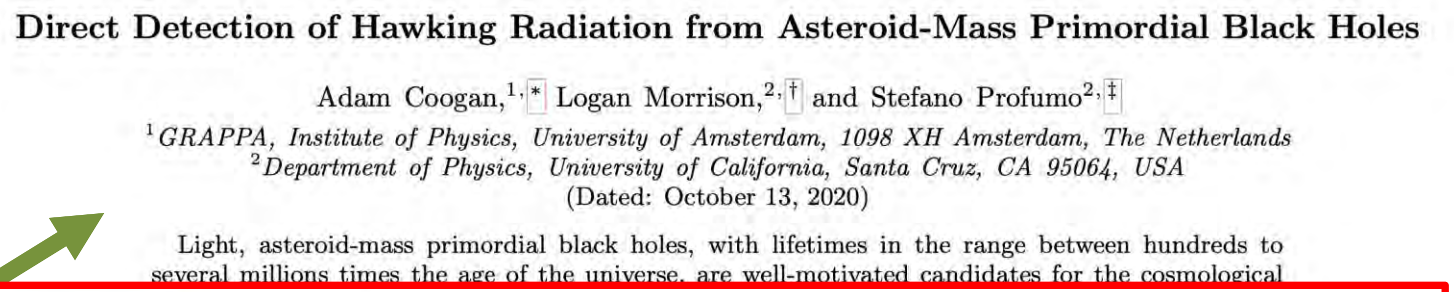
Issue: relevant temperature $T \sim T_{QCD}$

- Chiral Perturbation Theory
- Vector Meson Dominance
- Hadronic Form Factors

Bonus: can recycle for **MeV Dark Matter** pheno!

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



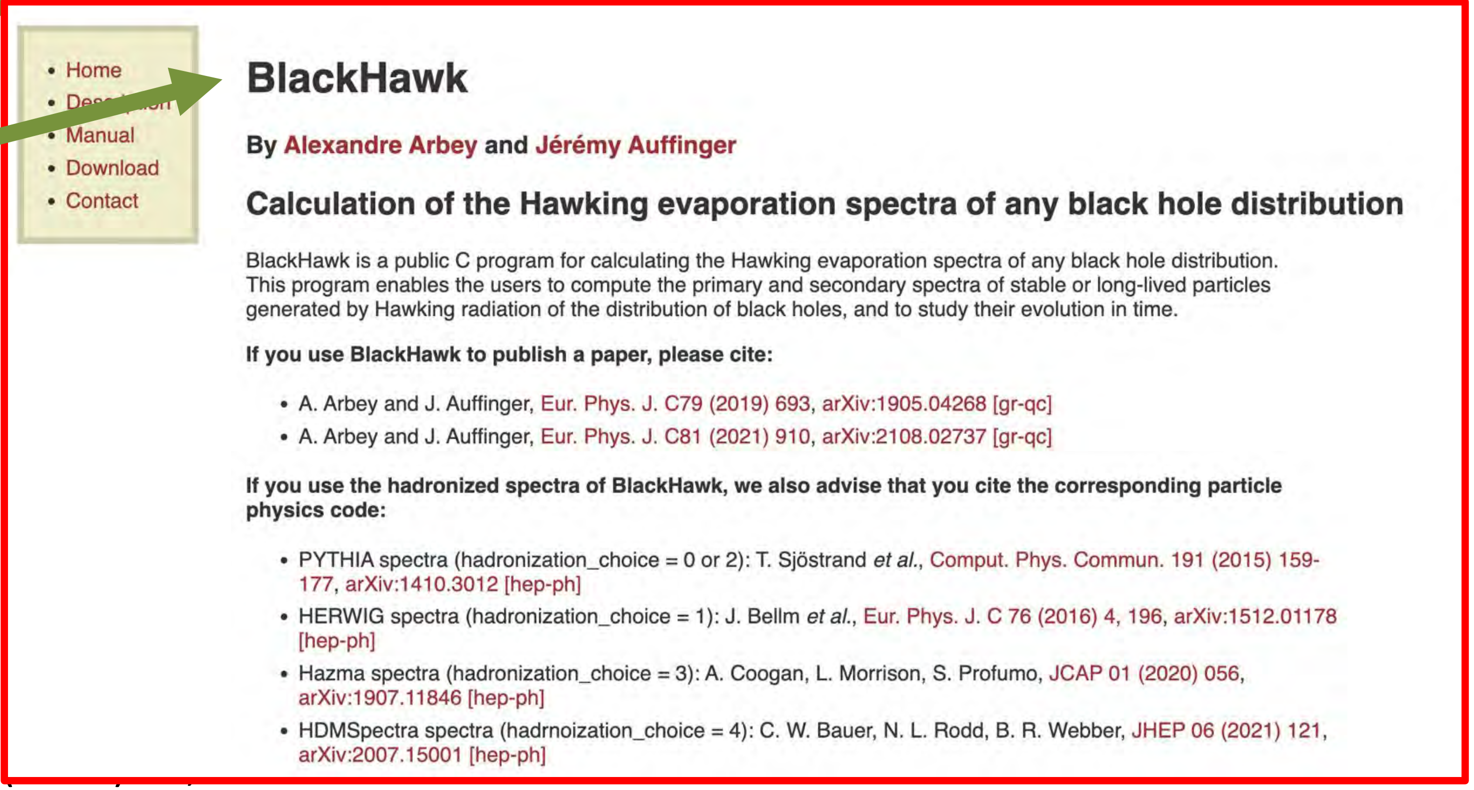


Direct Detection of Hawking Radiation from Asteroid-Mass Primordial Black Holes

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



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- Manual
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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]

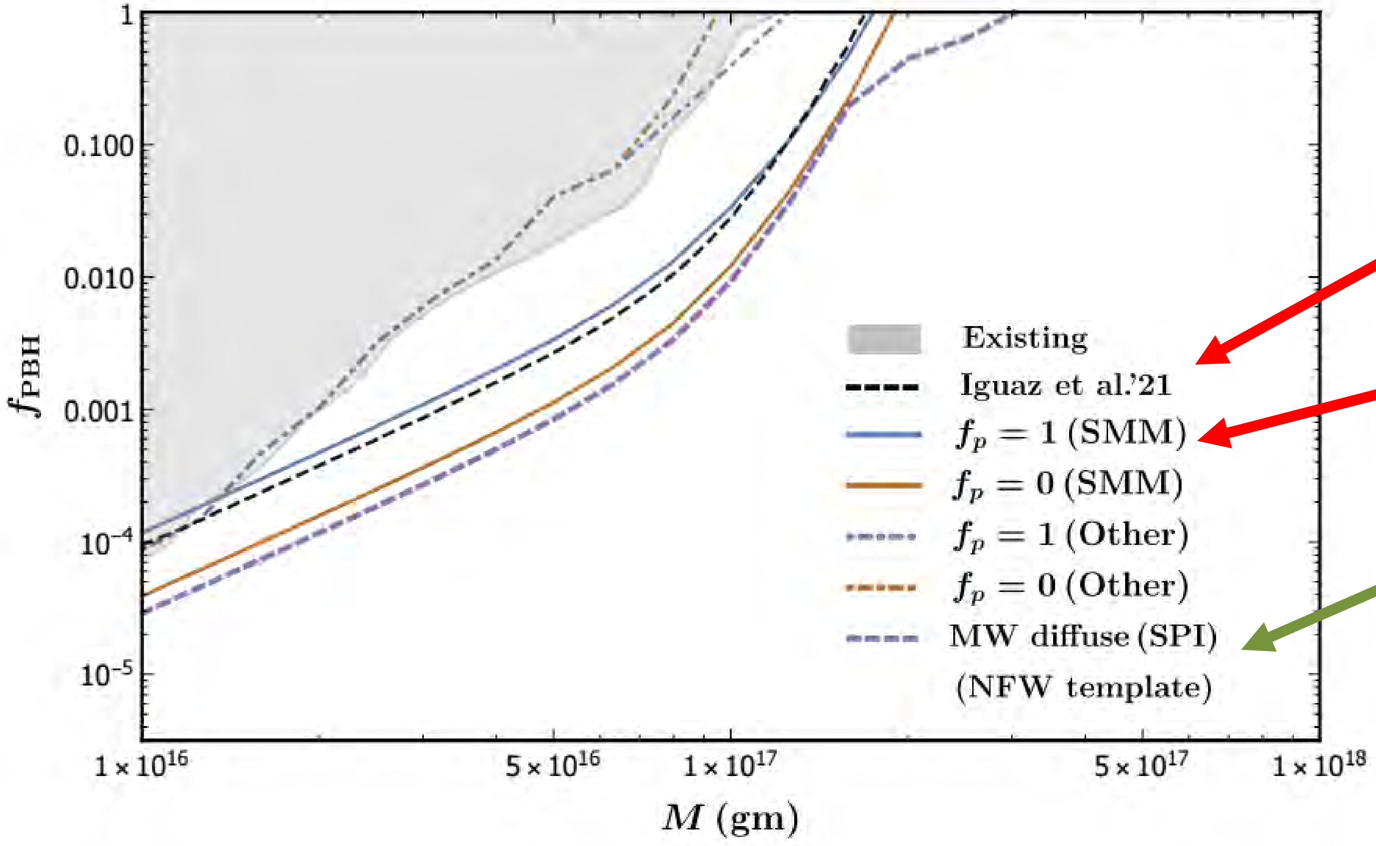
If you use the hadronized spectra of BlackHawk, we also advise that you cite the corresponding particle physics code:

- 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

Stefano Profumo
University of California Santa Cruz

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



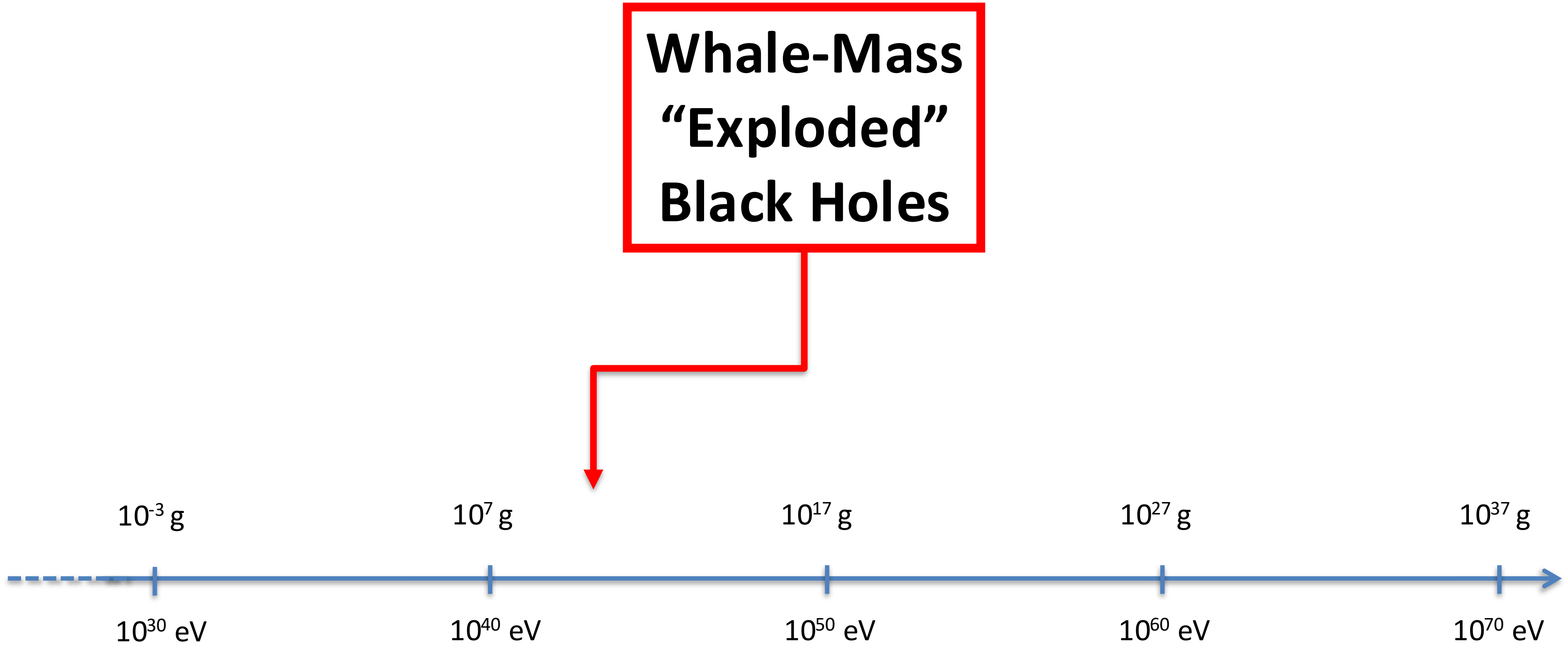
wrong by factor 2

unreliable data

use this!

Korwar and Profumo, 2302.04408, JCAP

Stefano Profumo
University of California
Santa Cruz



Stefano Profumo
University of California Santa Cruz

Exploded Black Holes

- **Can have sources both the dark matter and the baryon asymmetry via evaporation**
  [Morrison, Profumo, Yu, 2022]

- **Can have sourced both the dark matter and the baryon asymmetry via coupling of Kretschmann scalar to *B-L* current**
  [Profumo, Smyth, Santos-Olmsted, 2023]

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

- **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]

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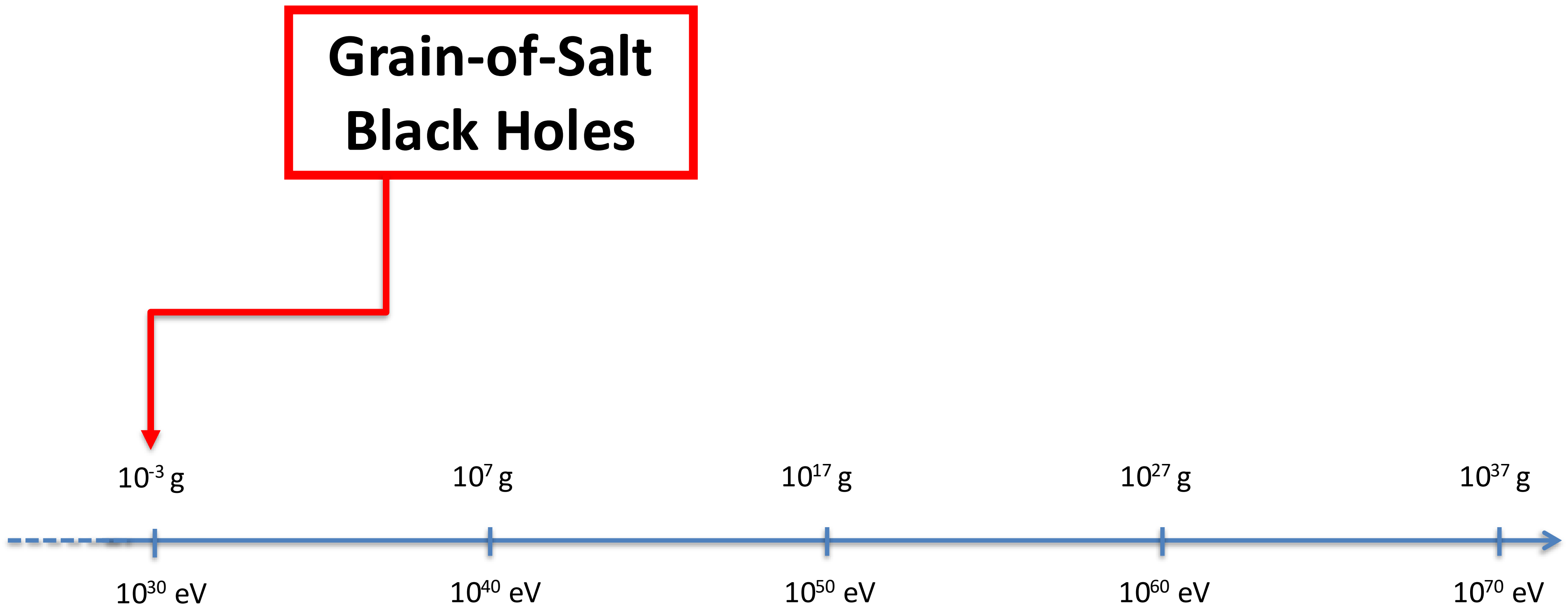
Santa Cruz



Stefano Profumo
University of California Santa Cruz

If evaporation stops around the Planck scale, the relic PBHs 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 (1) evaporation stops around the Planck scale (because of extremality (RN BH) or because of quantum gravity) AND (2) if Schwinger-pair discharge also stops we are left with a population of charged, Planck-scale relics!

* Page, 1977

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

Stefano Profumo
University of California Santa Cruz

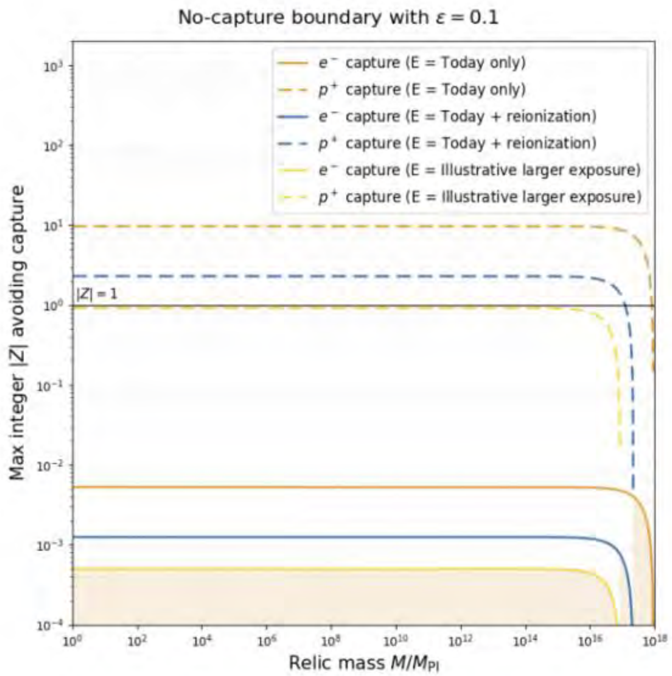
On the (Im)possibility of Electrically Charged Planck Relics

Stefano Profumo[a]

[a]Department of Physics and Santa Cruz Institute for Particle Physics (SCIPP), University of California, Santa Cruz, CA 95064, USA

E-mail: profumo@ucsc.edu

Abstract. I revisit whether black-hole remnants, from sub-Planckian compact objects to Planck relics and up to (super)massive black holes, can preserve Standard-Model (SM) electric charge. Two exterior-field mechanisms—Coulomb-focused capture from ambient media and QED Schwinger pair production—robustly neutralize such objects across cosmic history. I



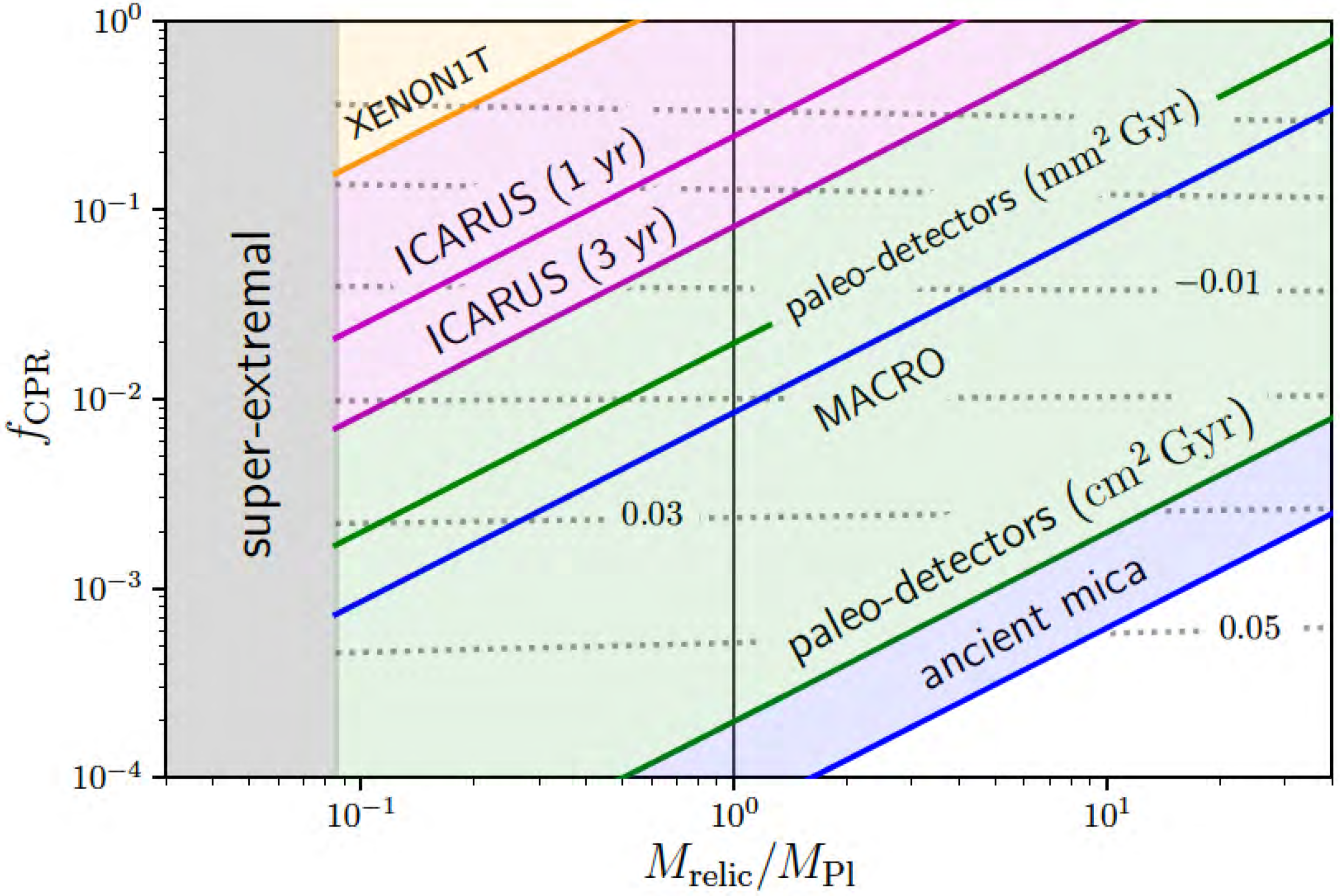
If (1) evaporation stops around the Planck scale (because of extremality (RN BH) or because of quantum gravity)
AND (2) if Schwinger-pair discharge also stops
we are left with a population of charged, Planck-scale relics!

...or are we?

* **Profumo, 2509.12520, JCAP**

Stefano Profumo
University of California Santa Cruz

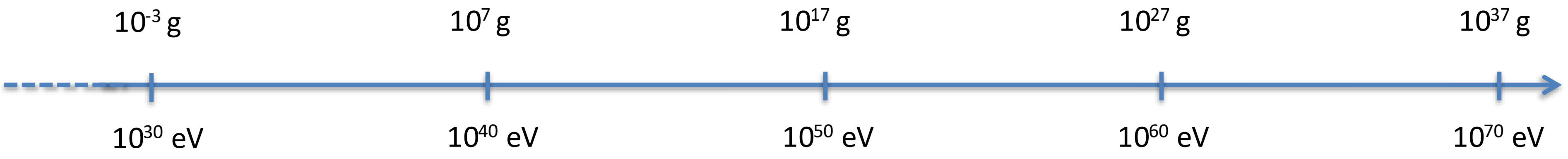
…should charged relics be around, best bet to "see" them: Paleo-detectors!



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

Stefano Profumo
University of California
Santa Cruz

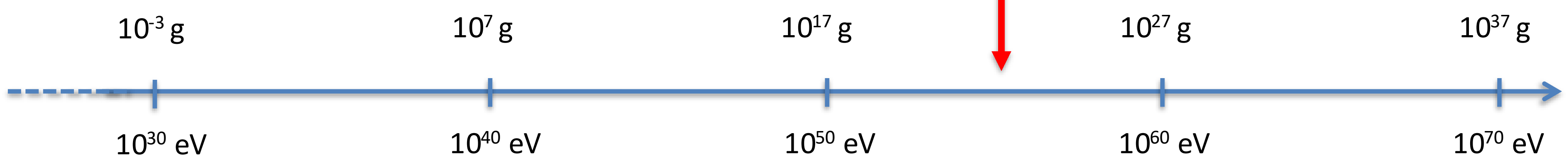
“Stellar-Mass” (10^{35} g) Black Holes



- ✓ **Sub-TOV goldilocks events! (beware of impostors!)**
- ✓ **Searches ongoing, perhaps already there!**

Stefano Profumo
University of California Santa Cruz

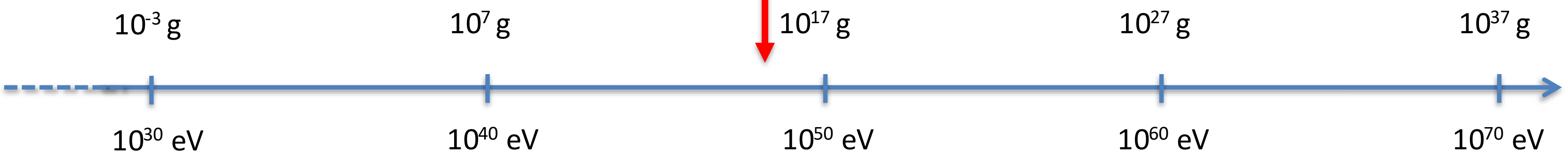
"Asteroid-Mass" (10^{22} g) Black Holes



- ✓ **Can be 100% of the Dark Matter!**
- ✓ **Microlensing trickier than previously thought (finite size source)!**
- ✓ **If detected, how do we distinguish PBH from rogue planets? Statistics!**

Stefano Profumo
University of California Santa Cruz

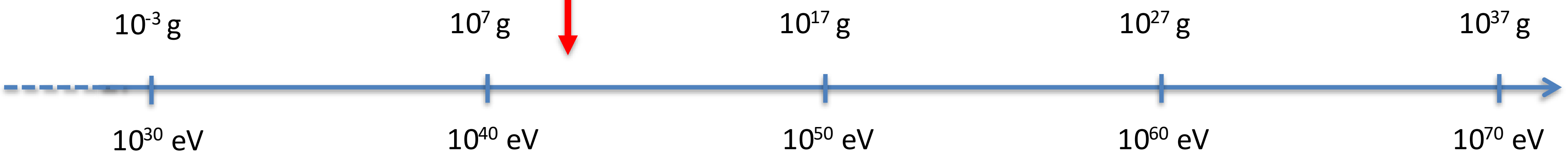
"Everest-Mass" (10^{16} g) "Exploding" Black Holes



- ✓ **BH explosions as "reverse GRBs"**
- ✓ **A window on Dark Sectors**
- ✓ **Best constraints: diffuse gamma-rays**

Stefano Profumo
University of California
Santa Cruz

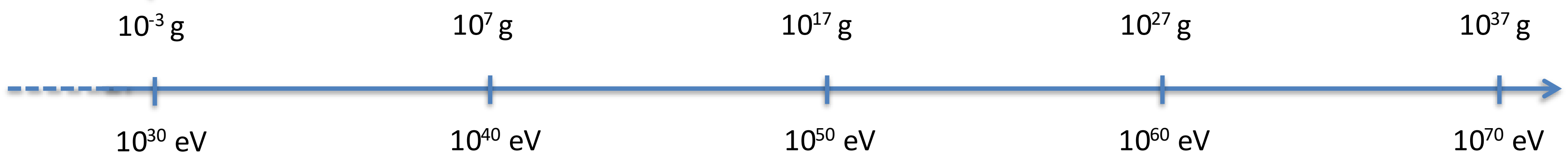
"Whale-Mass" Black Holes



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

Stefano Profumo
University of California
Santa Cruz

Grain-of-Salt Black Holes



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

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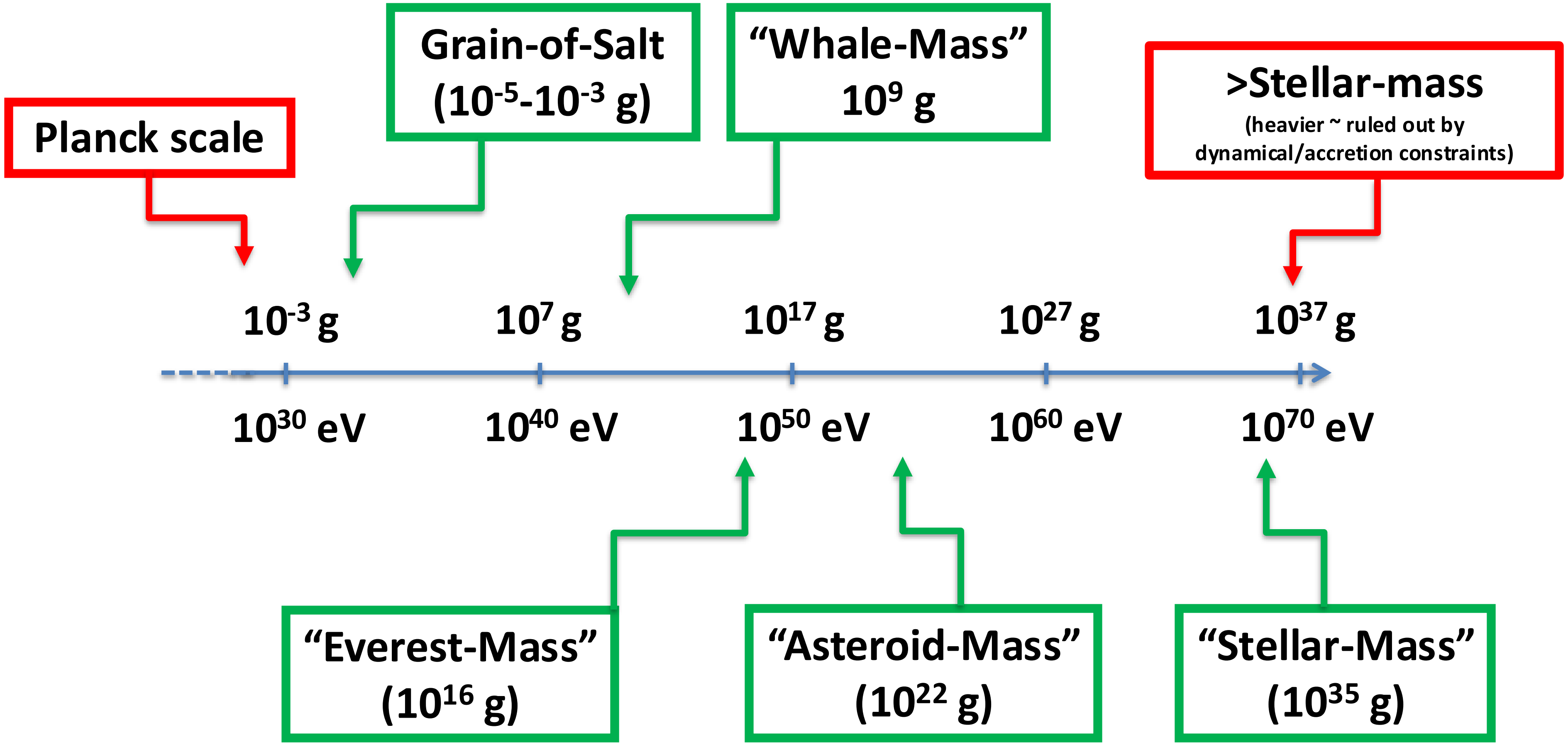
University of California
Santa Cruz



BACKUP SLIDES

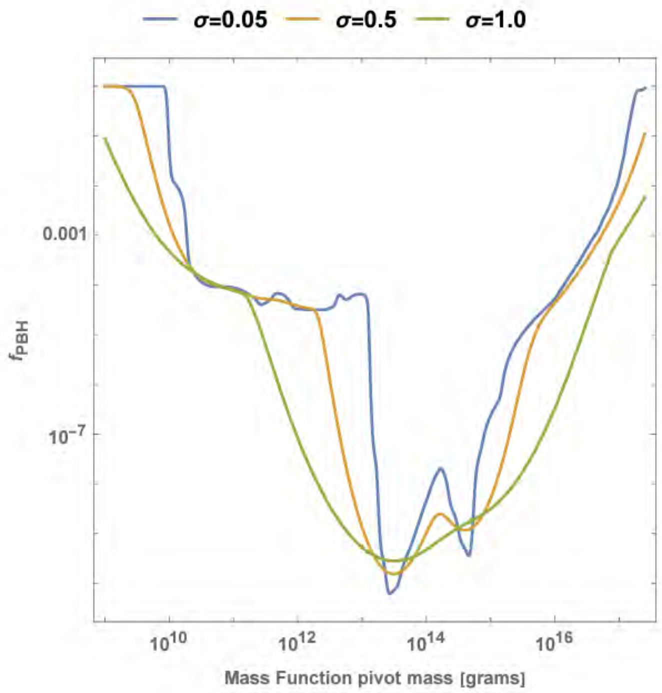
- Detection of Hawking radiation would be momentous!
- Unique opportunity to discover dark sectors!
- Number of handles to discriminate against GRBs
  - ✓ Light-curve
  - ✓ Spectrum
  - ✓ Distance
  - ✓ Afterglow

Given a mass function, constraints are calculated via

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

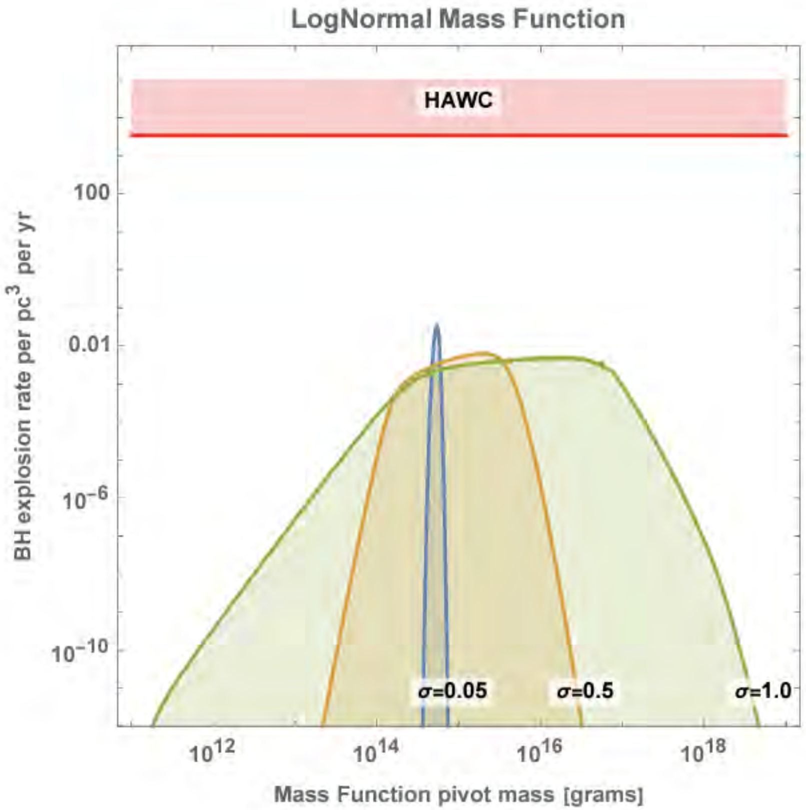
For instance, for a lognormal mass function (typical of a smooth, symmetric power spectrum density perturbation)

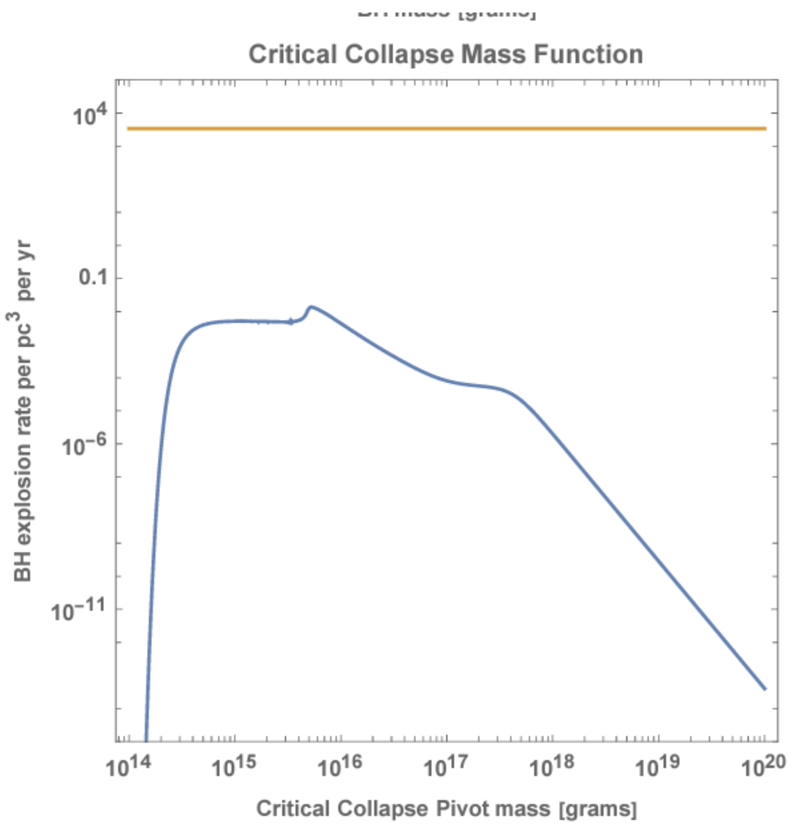
$$\psi(M) = \frac{f_{\mathrm{PBH}}}{\sqrt{2\pi}\sigma M} \exp\left(- \frac{\log^2(M/M_c)}{2\sigma^2} \right)$$



*Profumo, Boluna, Ble, Hennings, 2023

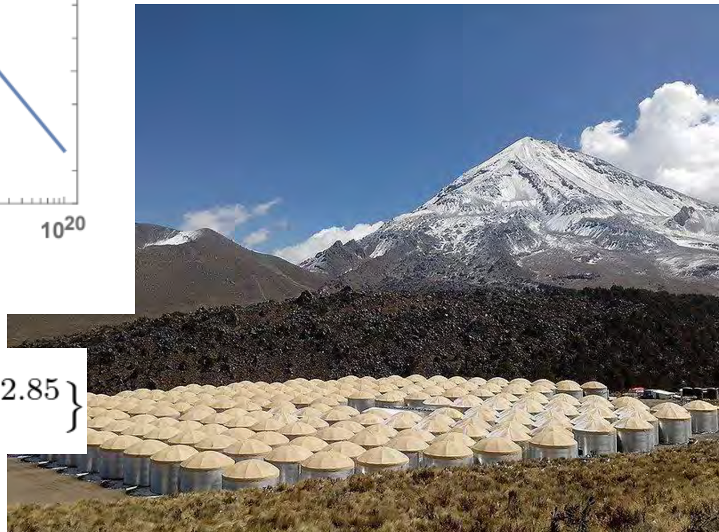
A given width σ and pivot mass M_* produce a different rate of PBH explosions today





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

HAWC

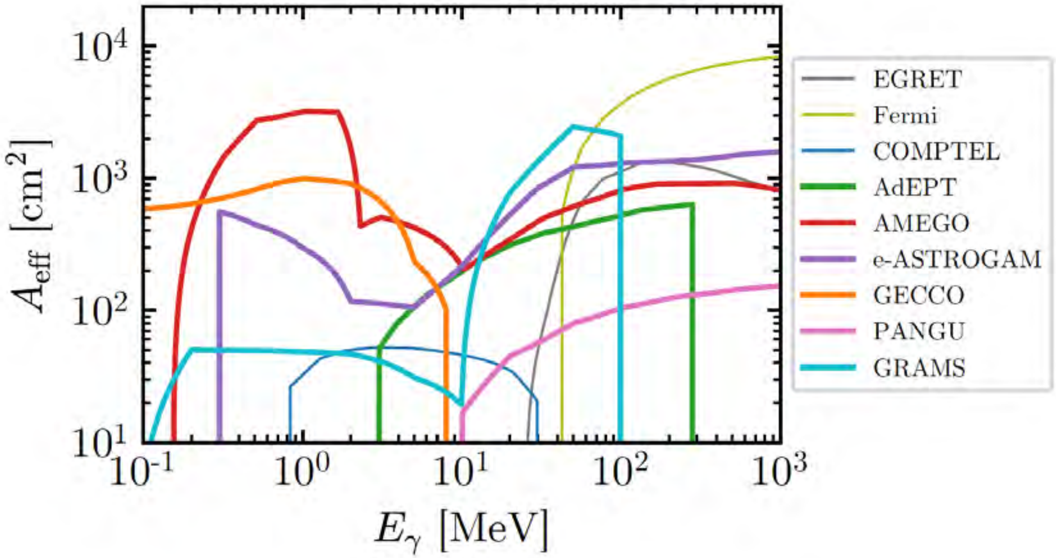


*Profumo, Boluna, Ble, Hennings, 2023

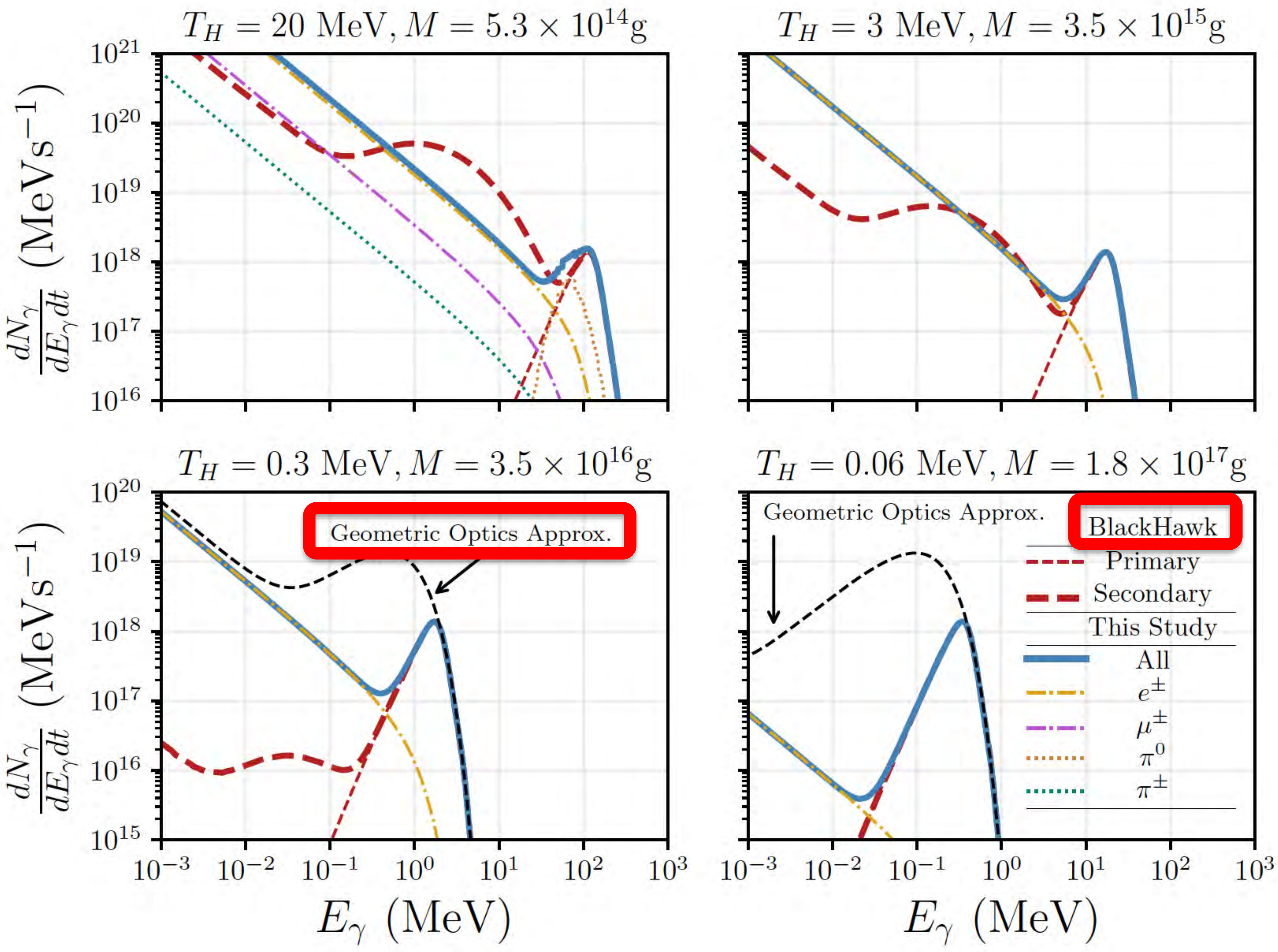
Lightest PBH that can be dark matter…

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

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

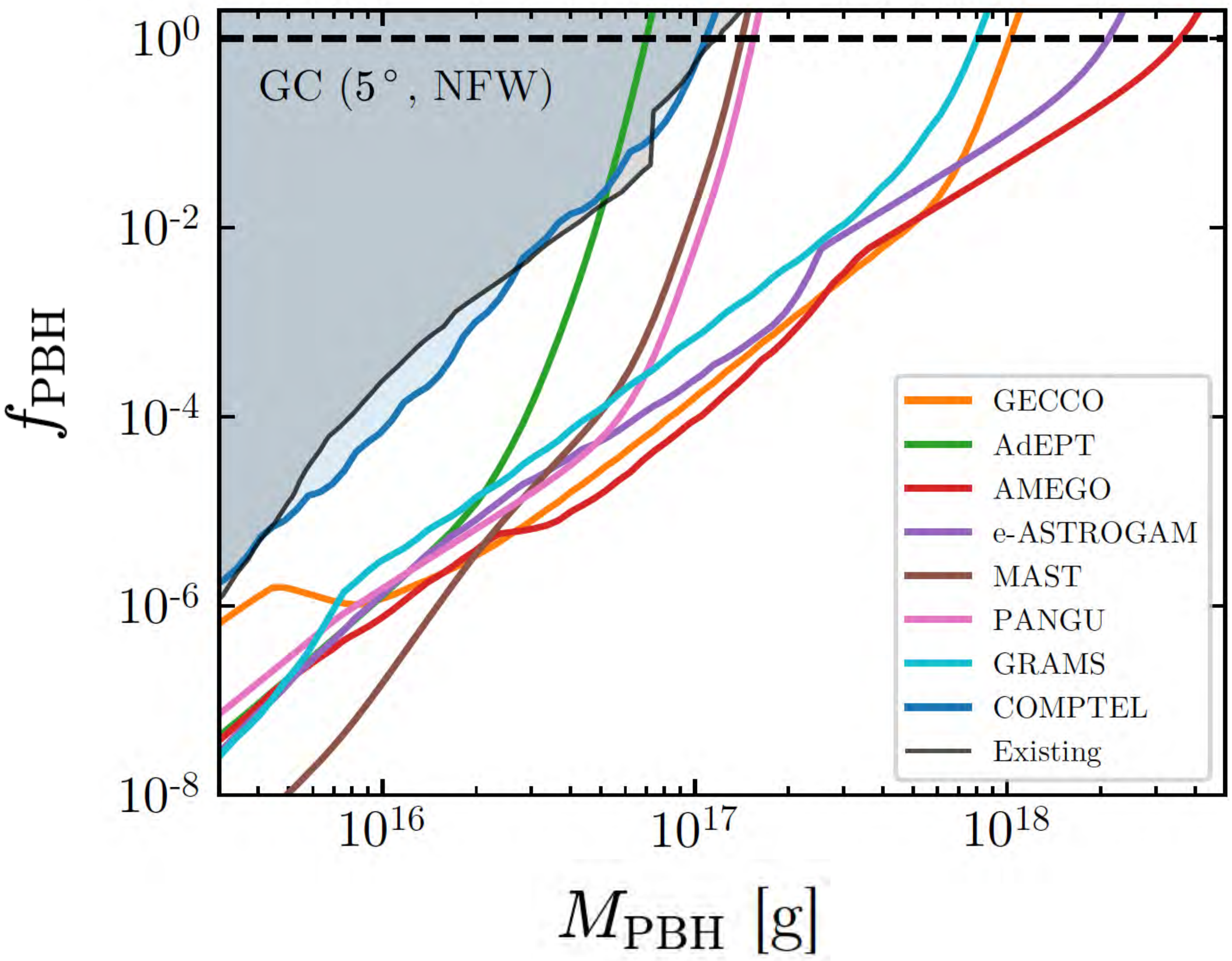


Coogan, Morrison & Profumo, 2010.04797, Phys. Rev. Letters



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

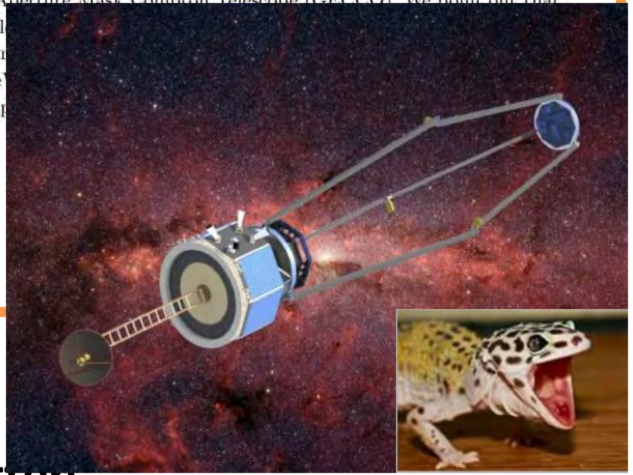
Hunting for Dark Matter and New Physics with (a) GECCO

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

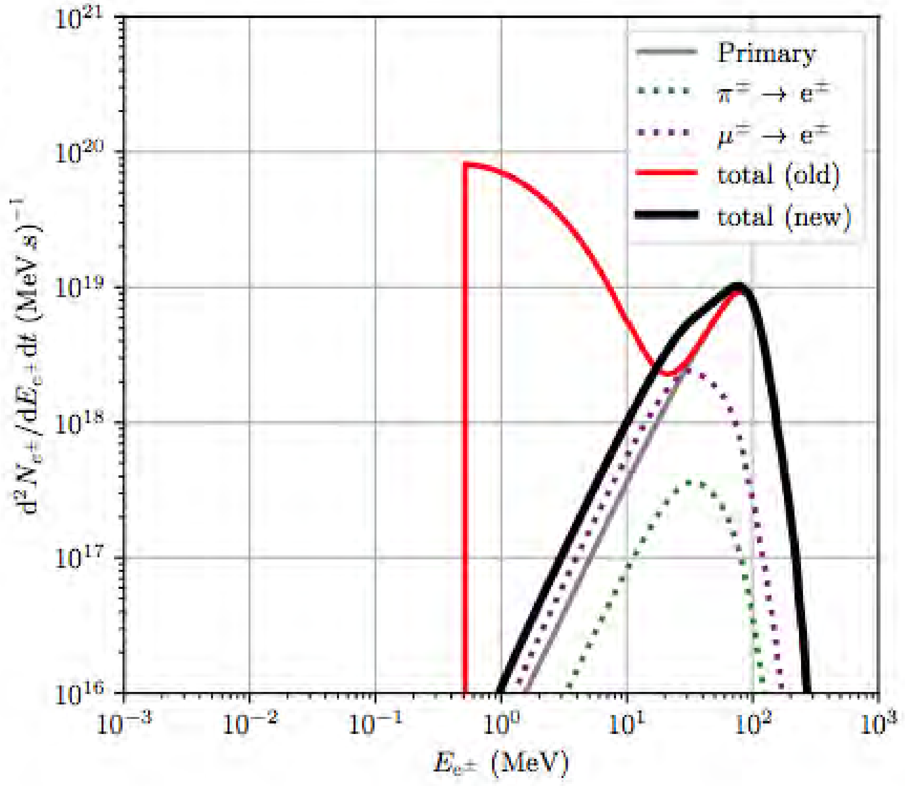
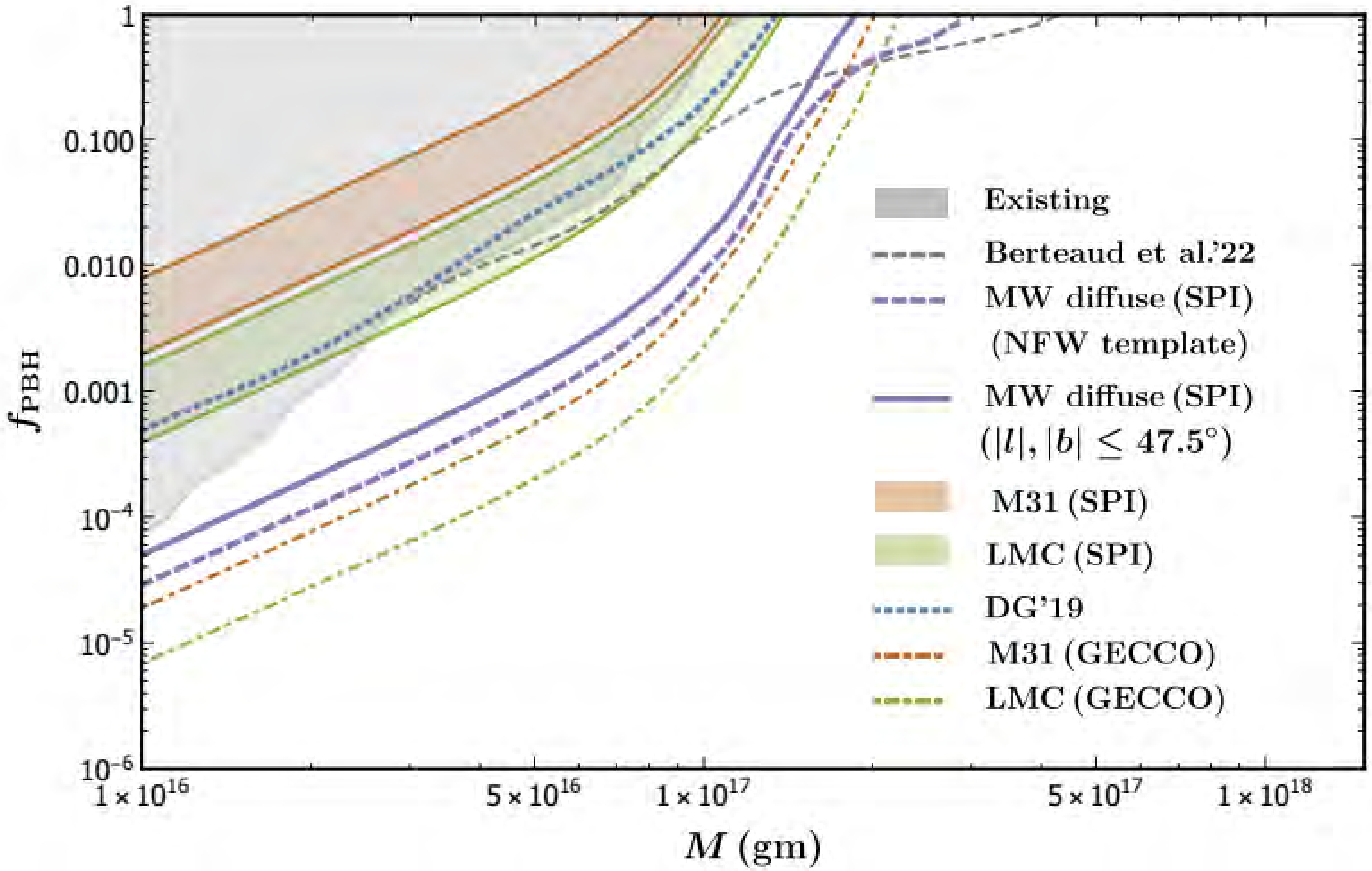


FIG. 5. Comparison between the old PYTHIA extrapolated (solid red) and new Hazma computed (solid black) BlackHawk instantaneous total electron spectrum for a $M_{BH} = 5.3 \times 10^{14}$ g. From left to right: primary electron spectrum (grey solid); muon decay (purple dotted); charged pion decay (green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

black hole dark matter.

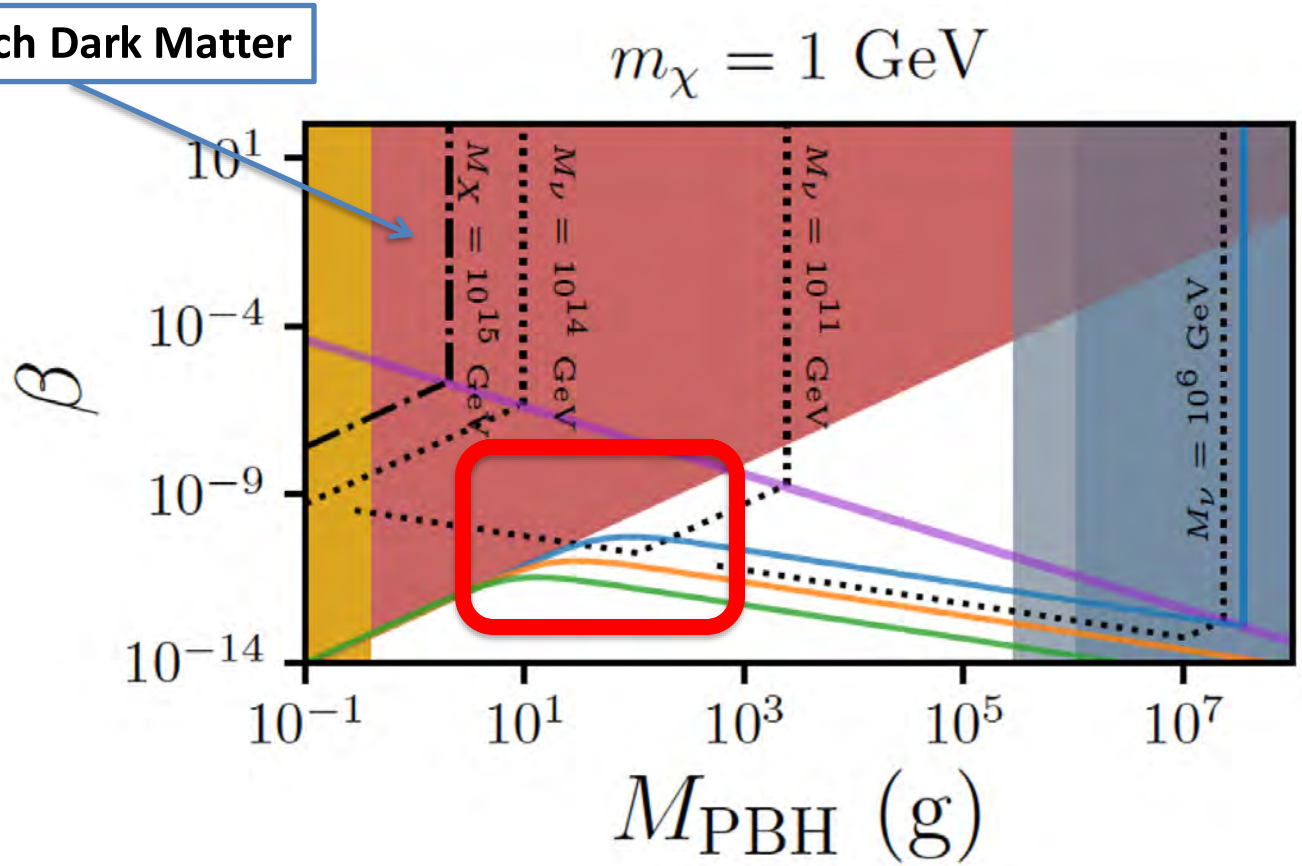
…speaking of which, most up-to-date constraints from Galactic 511 keV emission from INTEGRAL/SPI*



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, Phy
[1] Department of Theoretical P

17v1 [gr-qc] 11 Feb 2021

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.

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.

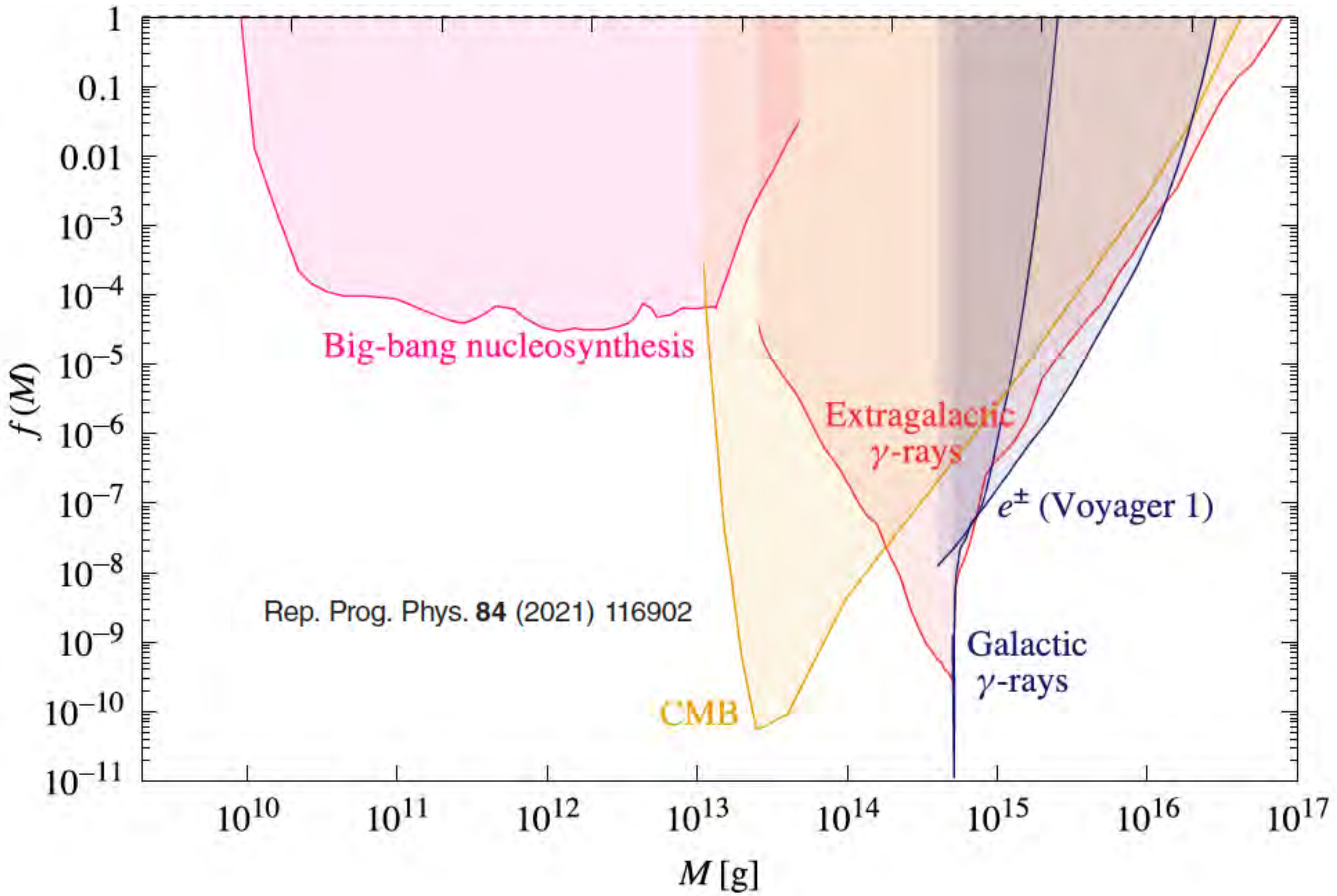
Black holes remnants have been considered as

…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

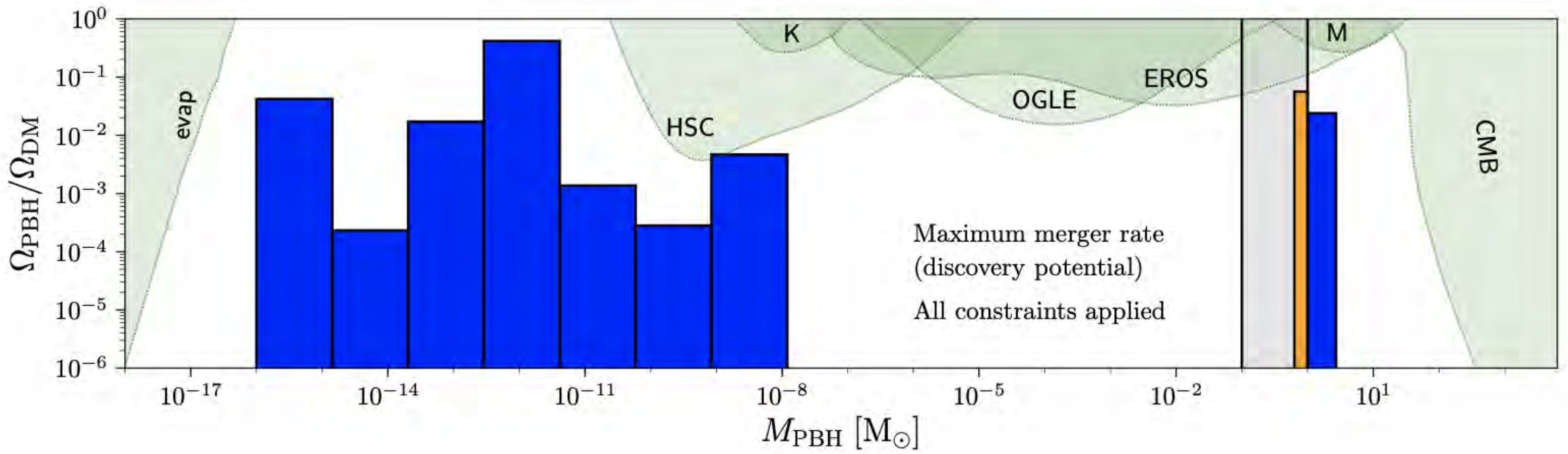
Here, perhaps, gravity waves! (but very high frequency!)*



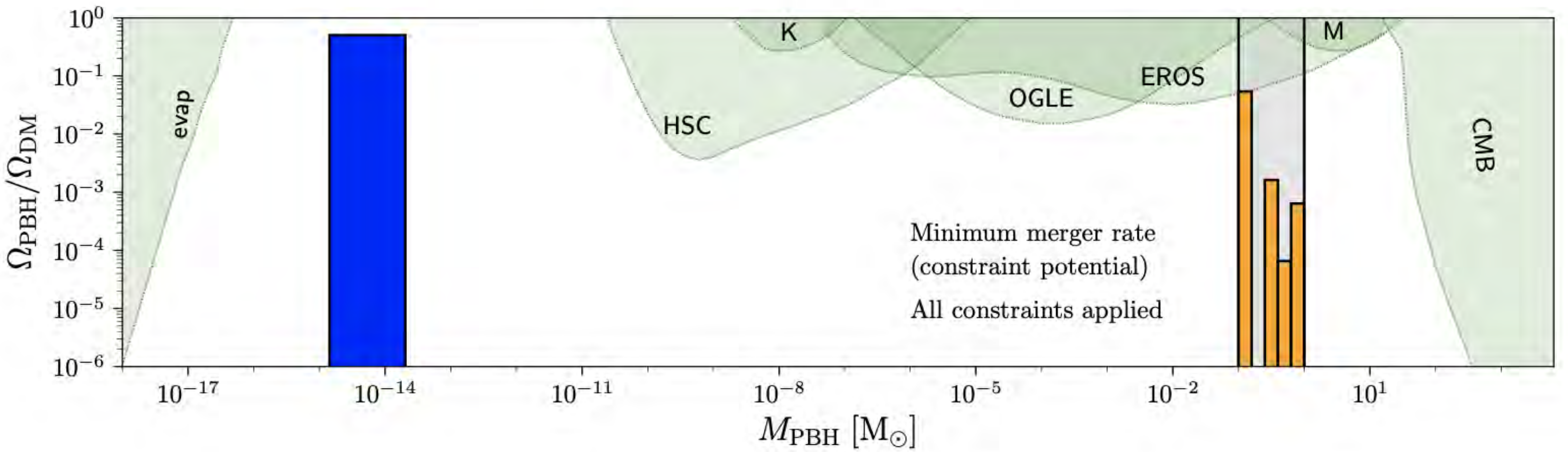
Notice that here M [g] is the initial mass at PBH formation

*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



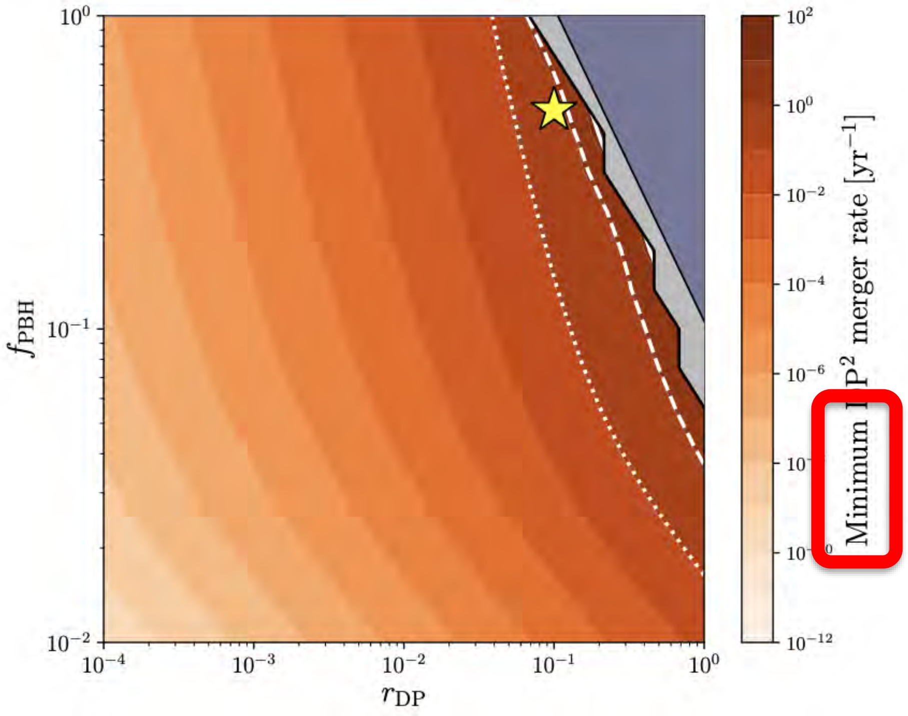
Maximum Merger Rate (@fixed f_{PBH}, r_{DP})

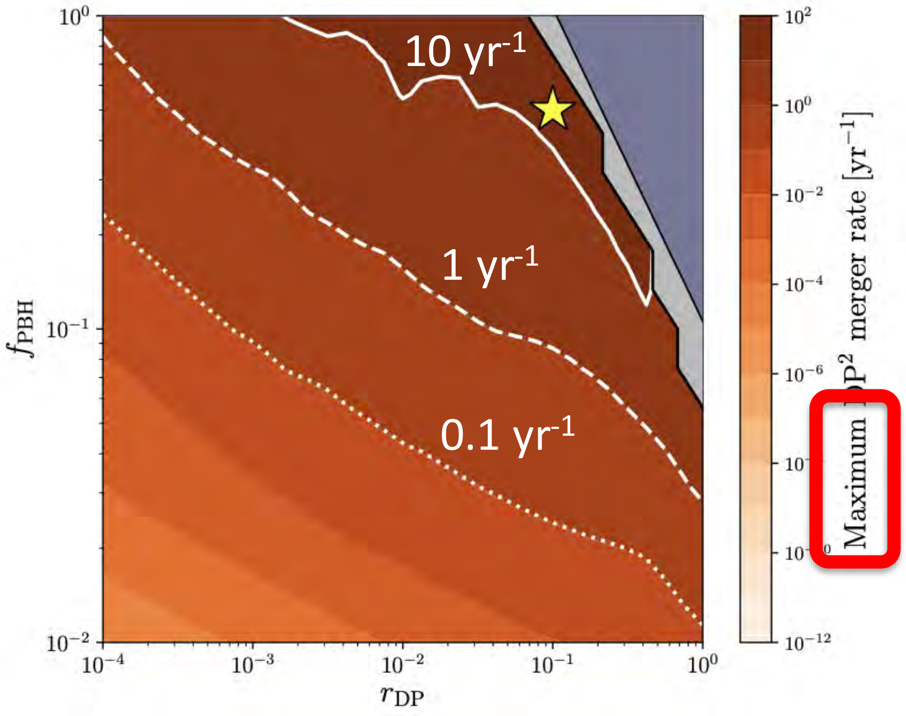


Minimum Merger Rate (@same f_{PBH}, r_{DP})

* 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!





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

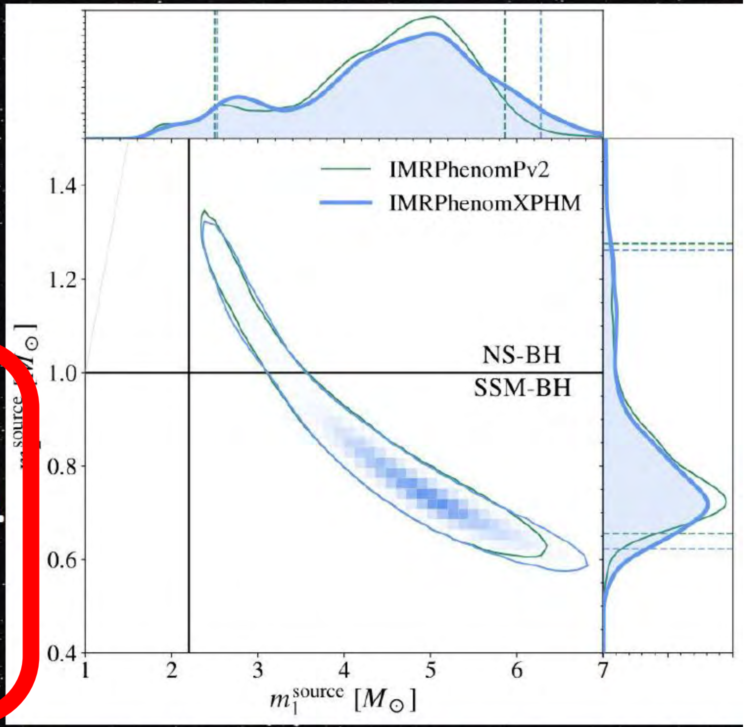
$$r_{\rm DP} = \frac{1}{f_{\rm PBH}} \int_{m_{\rm DP}^{\rm min}}^{m_{\rm DP}^{\rm max}} \mathrm{d}m\, \psi(m).$$

* 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 $m_1 > 2.2 M_\odot$ and $m_2 > 1.0 M_\odot$, 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 $m_1 > 2.2 M_\odot$ and $m_2 < 1.0 M_\odot$, 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.

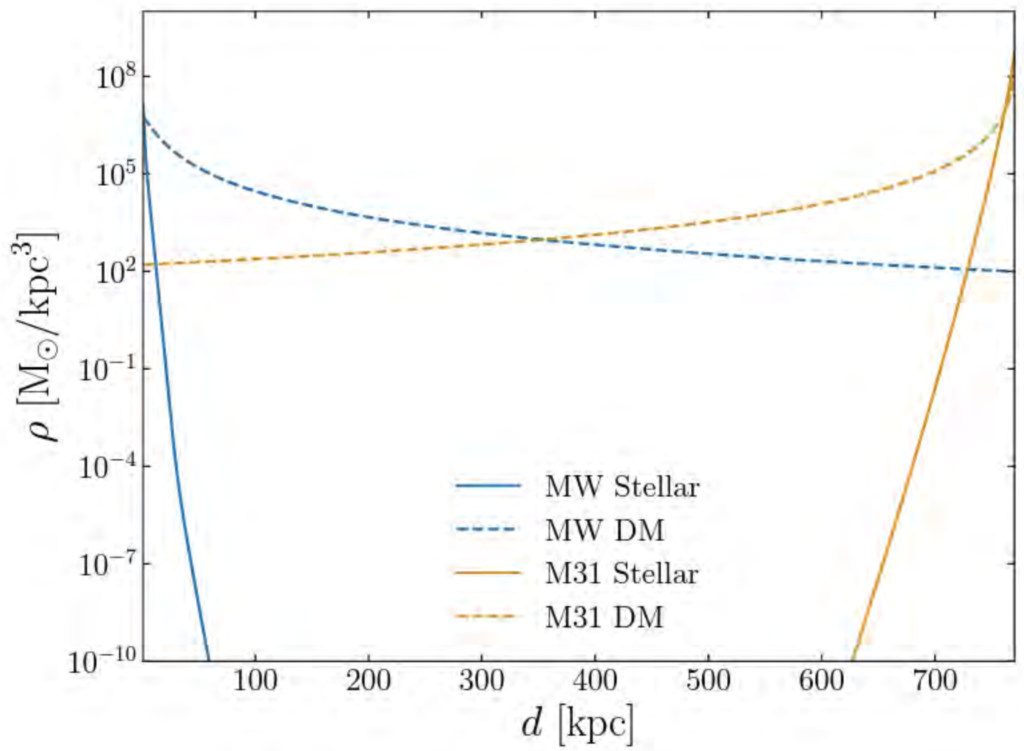


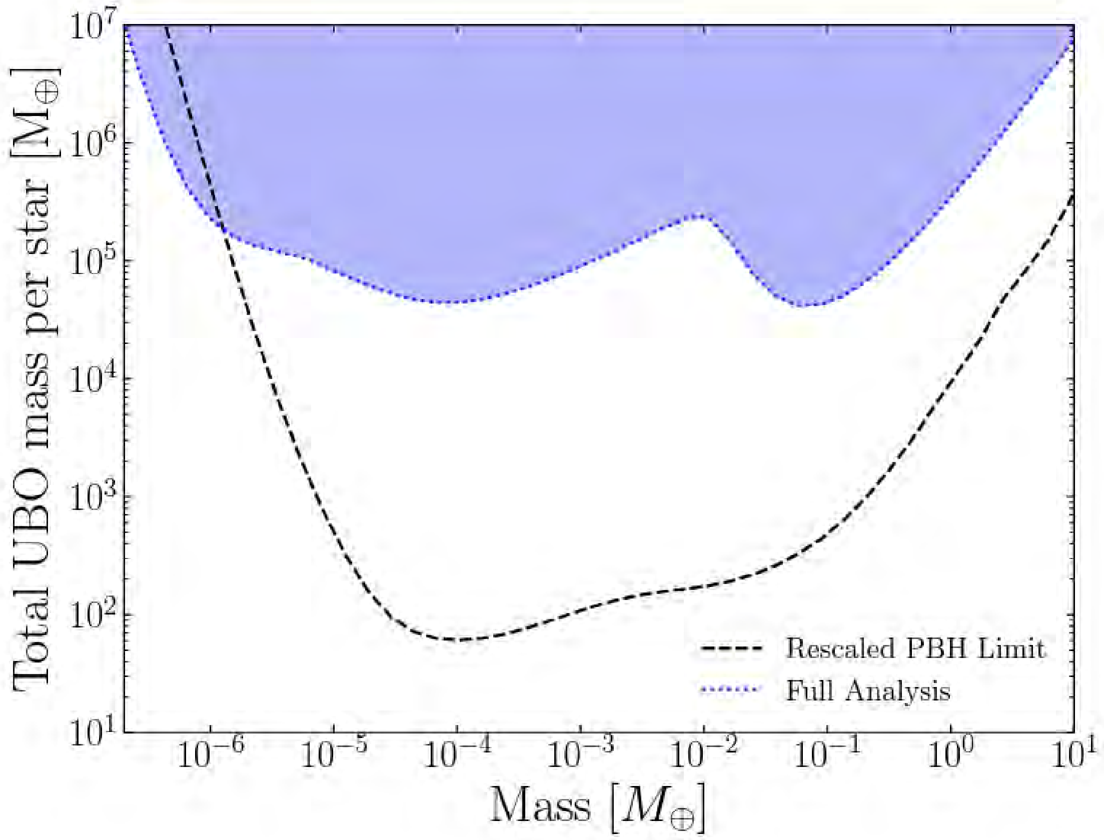
- In all cases, astrophysical models have problems generating a system with these masses

* 2301.11619, slide credit: Gonzalo Morras **given time stamp, hopefully not April's fool joke

Do the HSC observation provide any constraints on FFPs*?

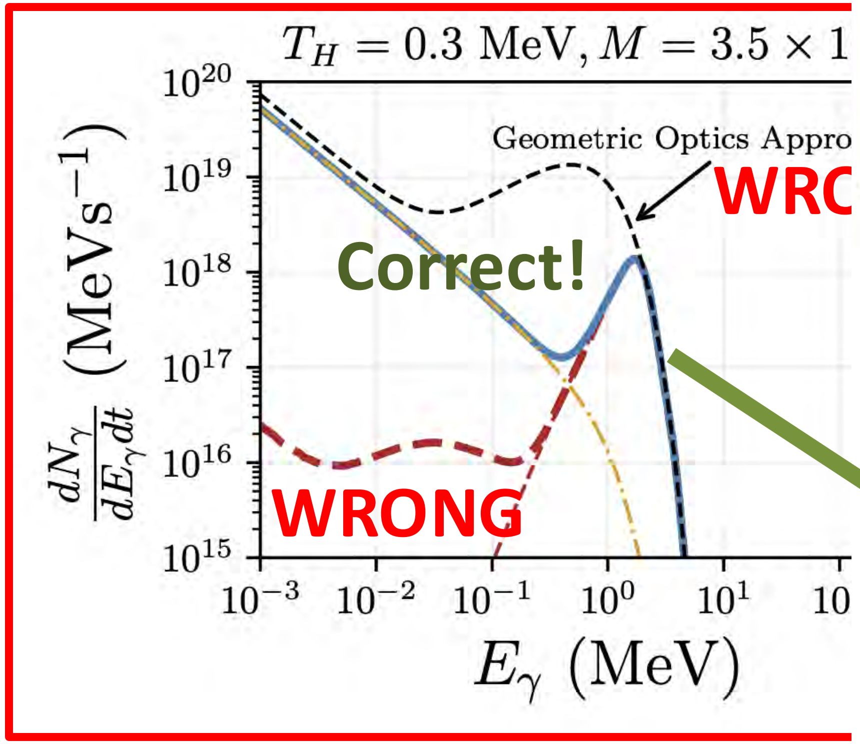
Simply rescaling the PBH limit vastly overestimate the HSC constraints!

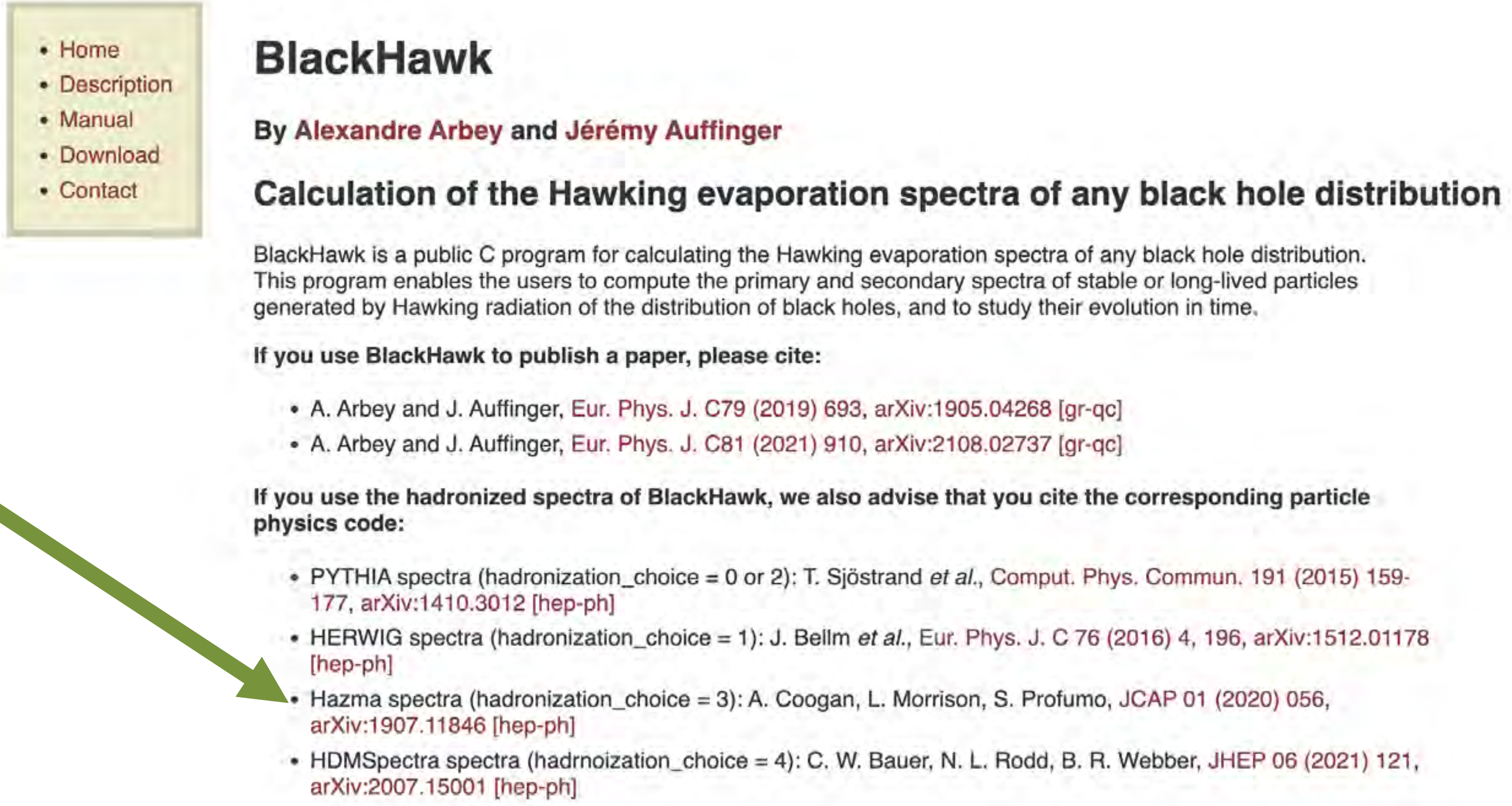




*DeRocco, Smyth, Profumo, 2023, MNRAS

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





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- Manual
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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

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

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

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

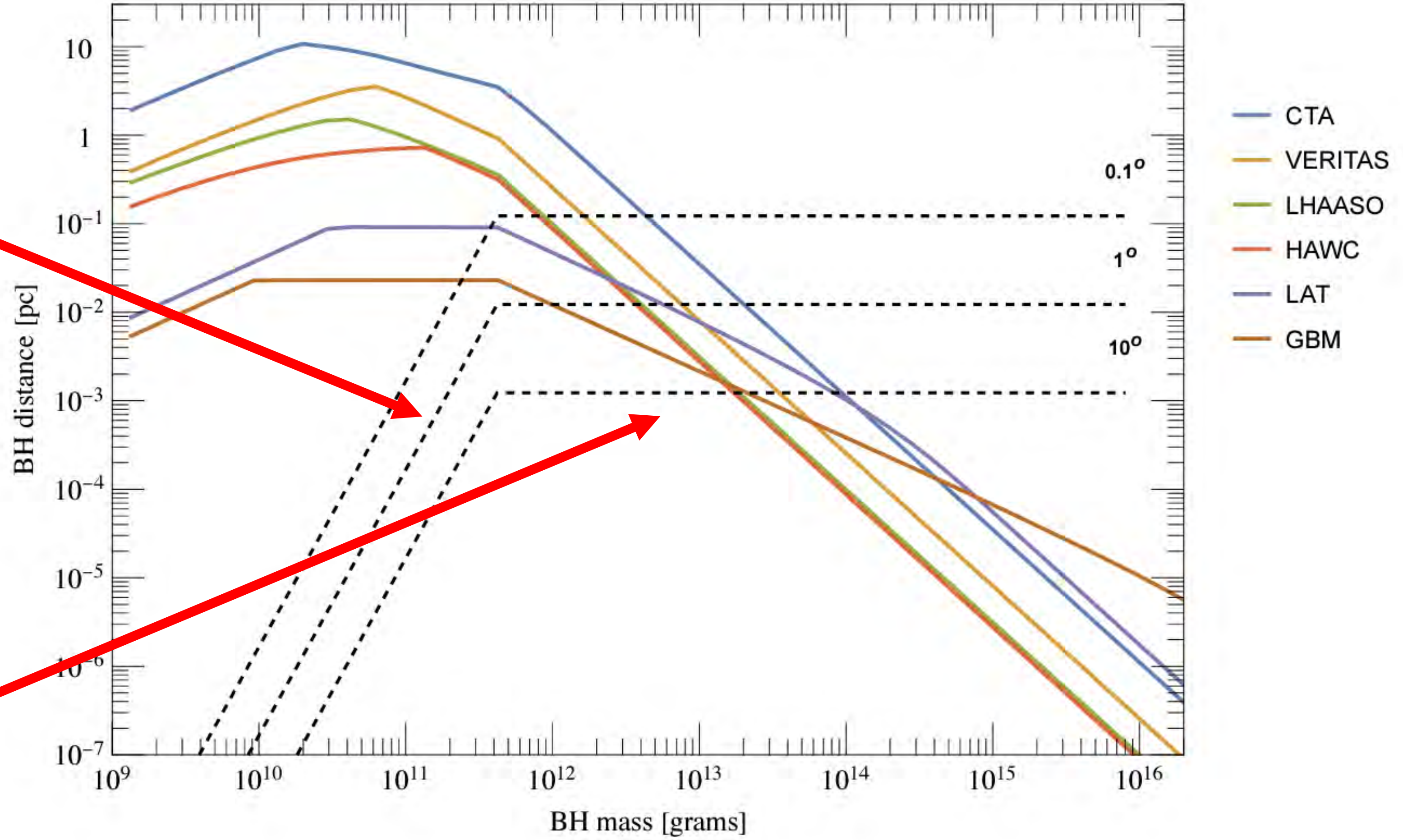
*Profumo, Boluna, Ble, Hennings, 2023

**Picker and Kusenko, 2023

How can we search for PBH explosions today?

Proper motion

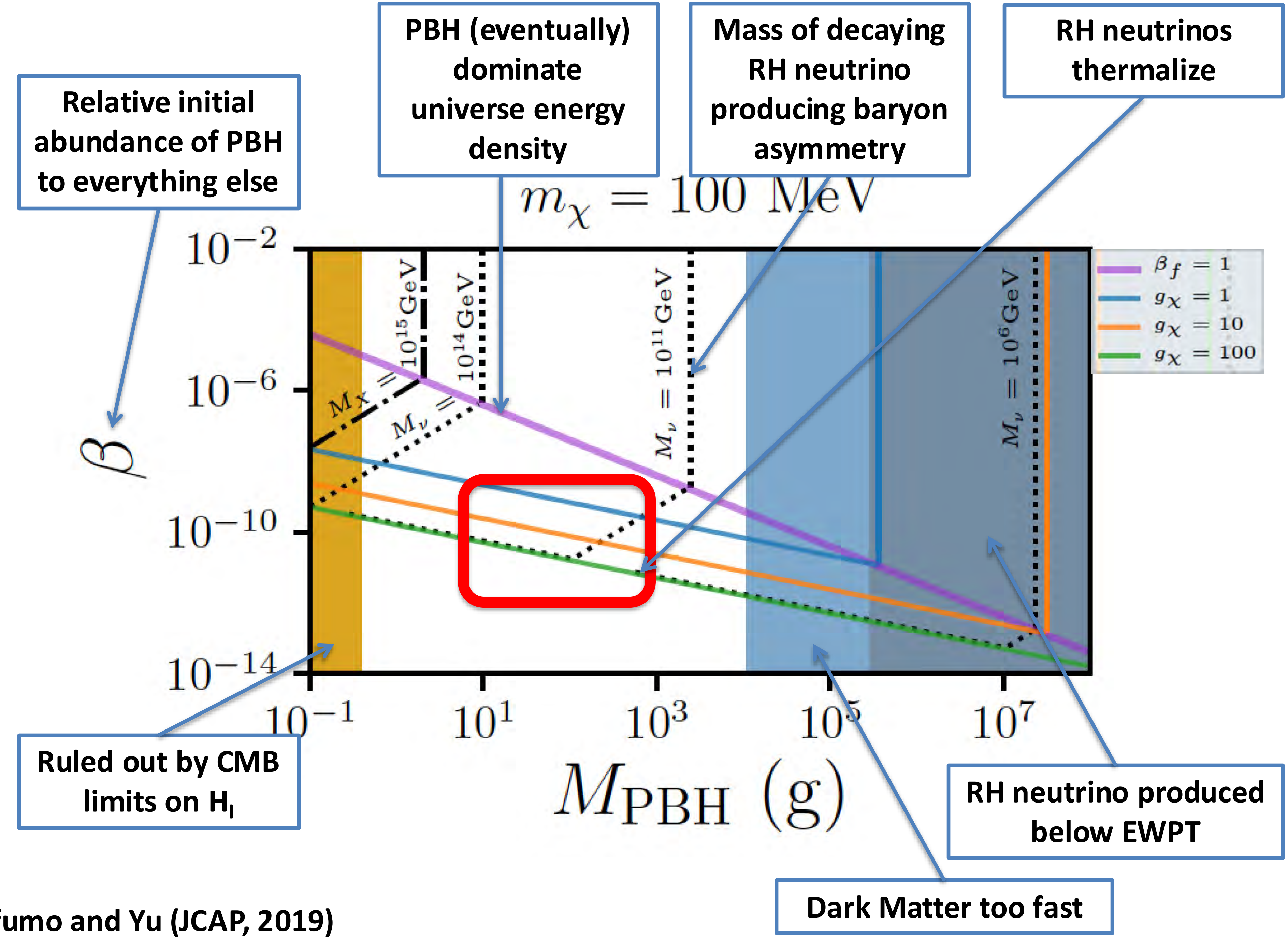
Distance



Evaporation time scale > Max observation time

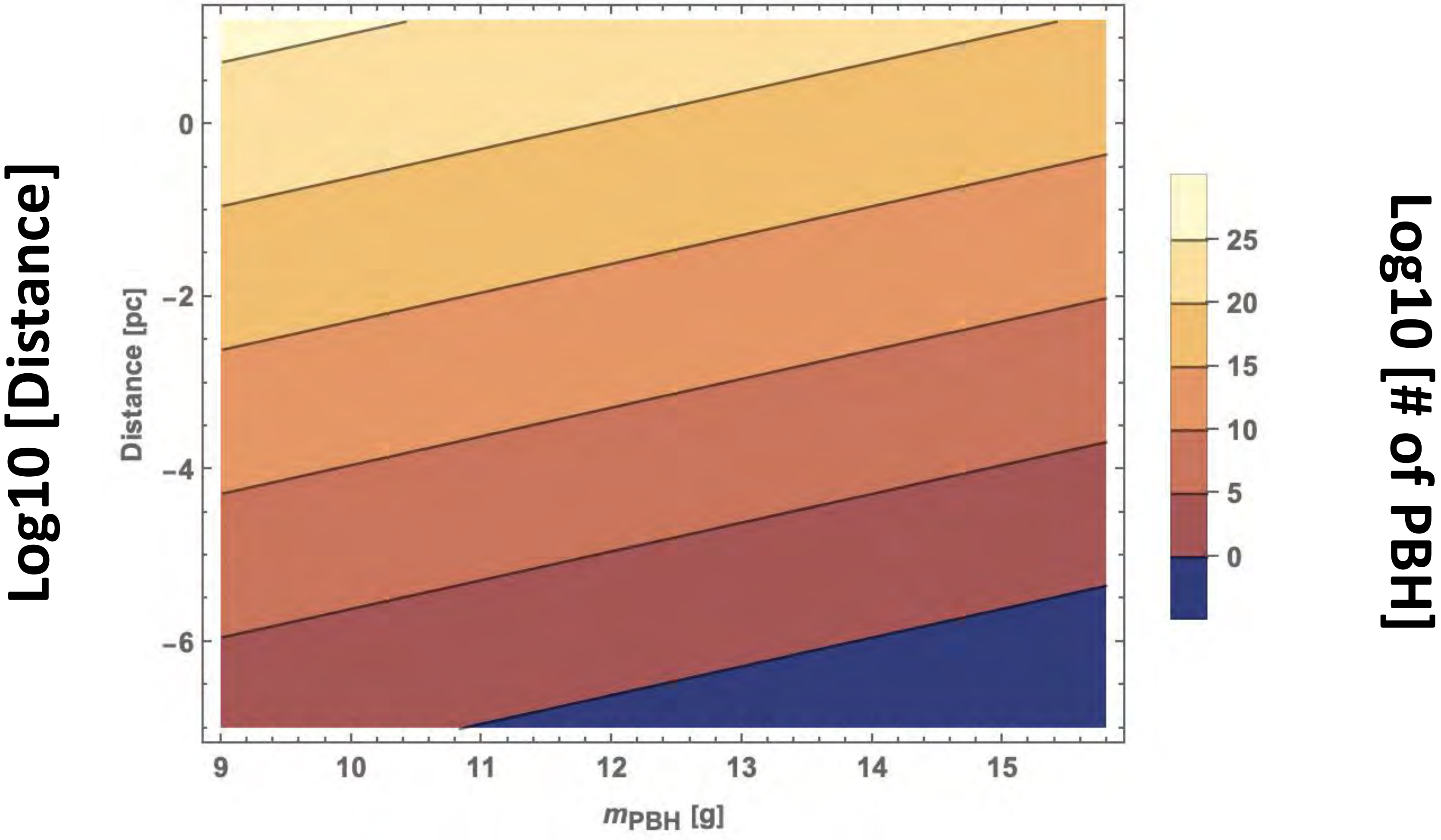
Mass/Lifetime

*Profumo, Boluna, Ble, Hennings, 2023



* Morrison, Profumo and Yu (JCAP, 2019)

[could there actually be PBH around, so close? Yes.]
[is the rate significant? It depends on the mass function]



Log10 (Mass/Lifetime) [today, at detection]

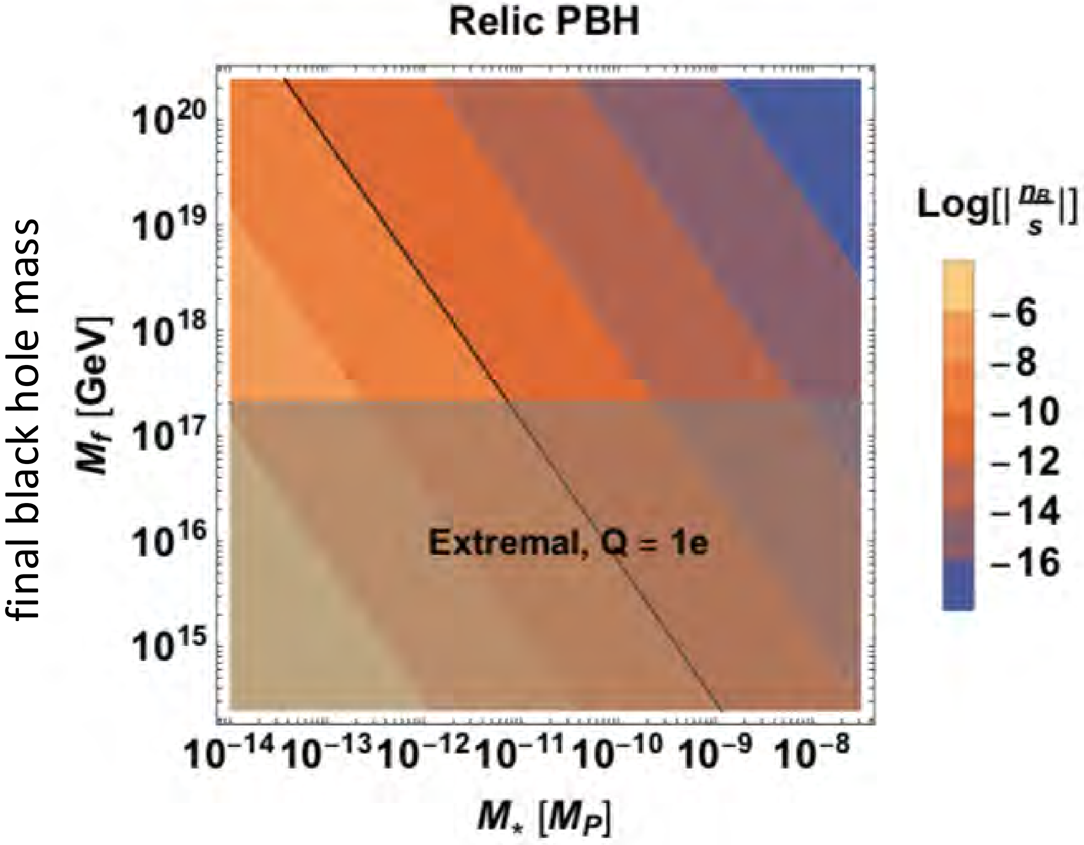
Alternately, evaporation can seed gravitational baryo- (or DM-) genesis

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**

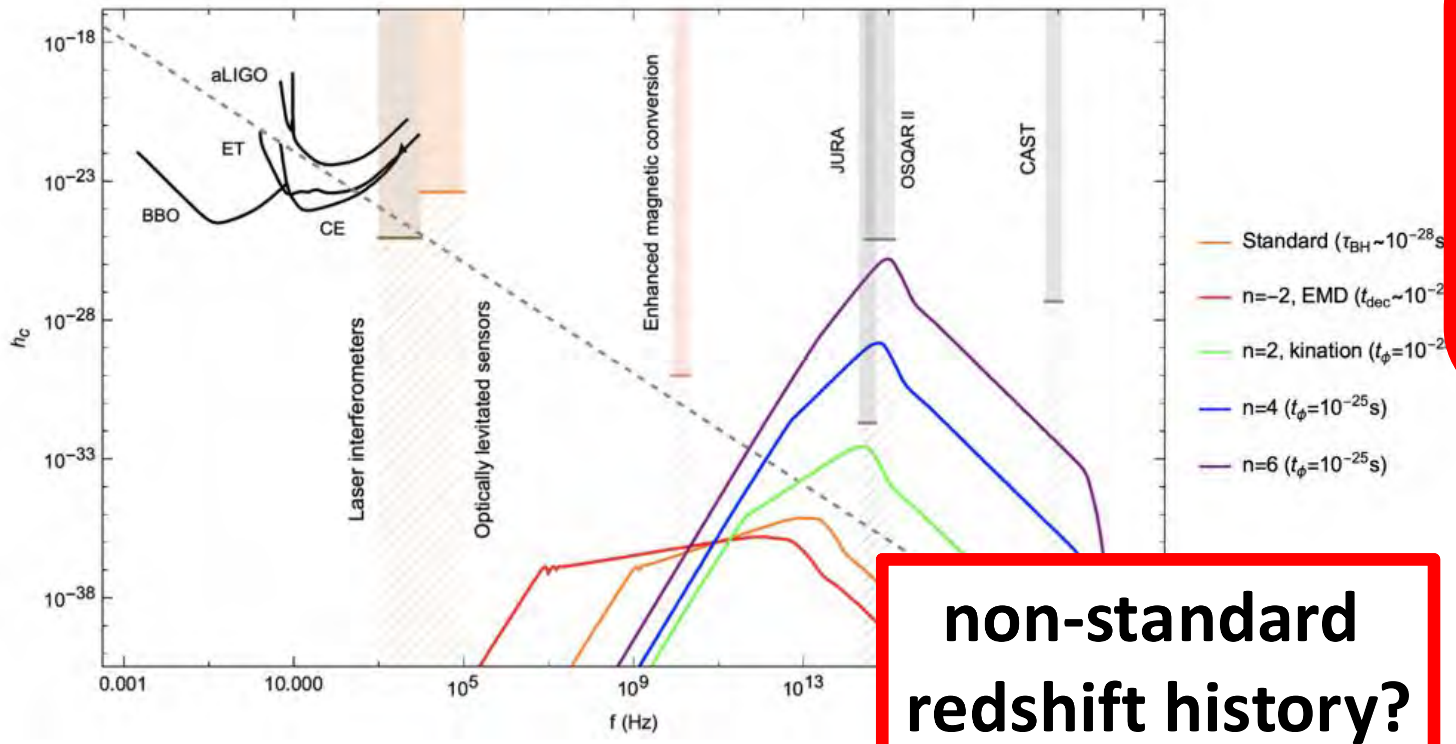
...even if PBH are NOT the dark matter, they can PRODUCE the dark matter AND the baryon asymmetry via Hawking evaporation!

Mass (g)	T_H (GeV)	τ (s)	$T_{\rm evap} = T(\tau)$ (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

* 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!



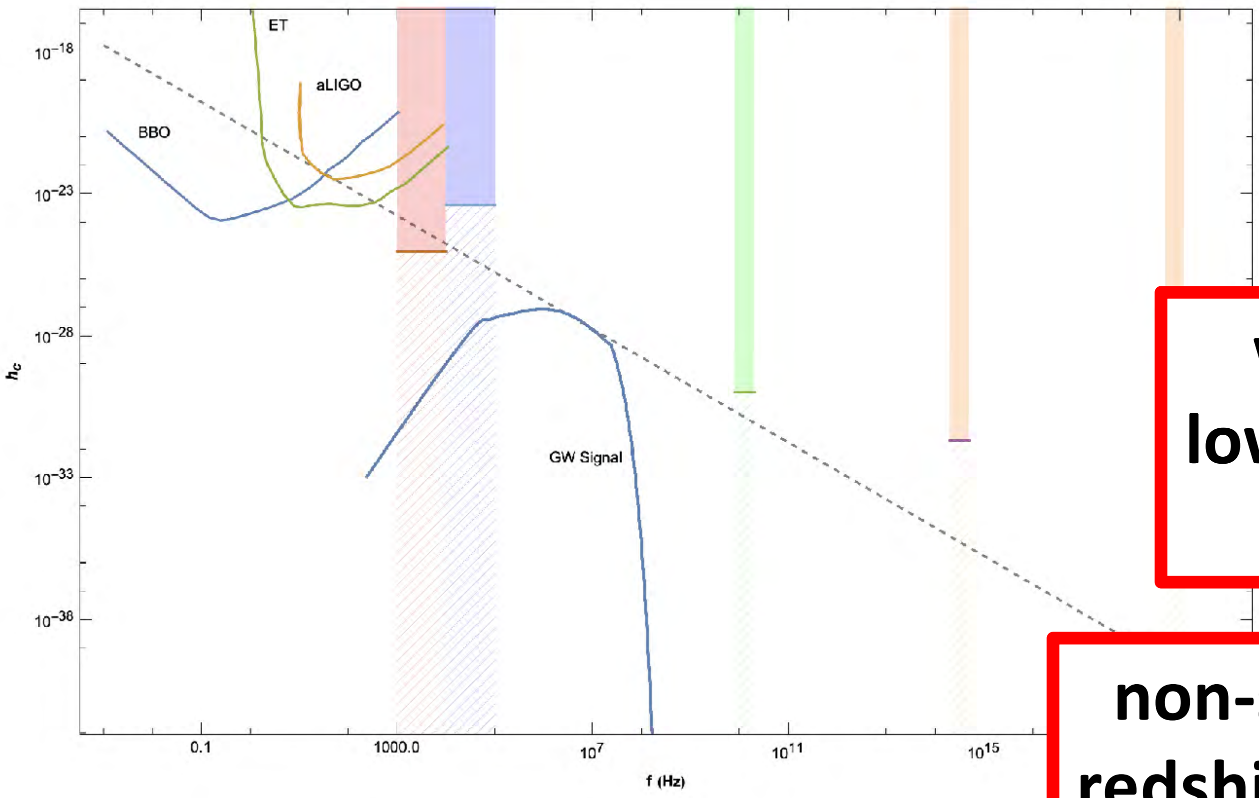
non-standard redshift history?

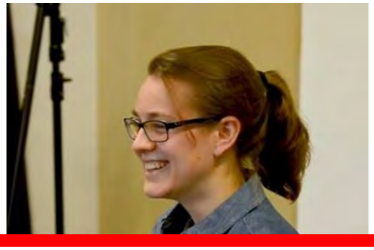
A. Ireland

J. Sharnhorst

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

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





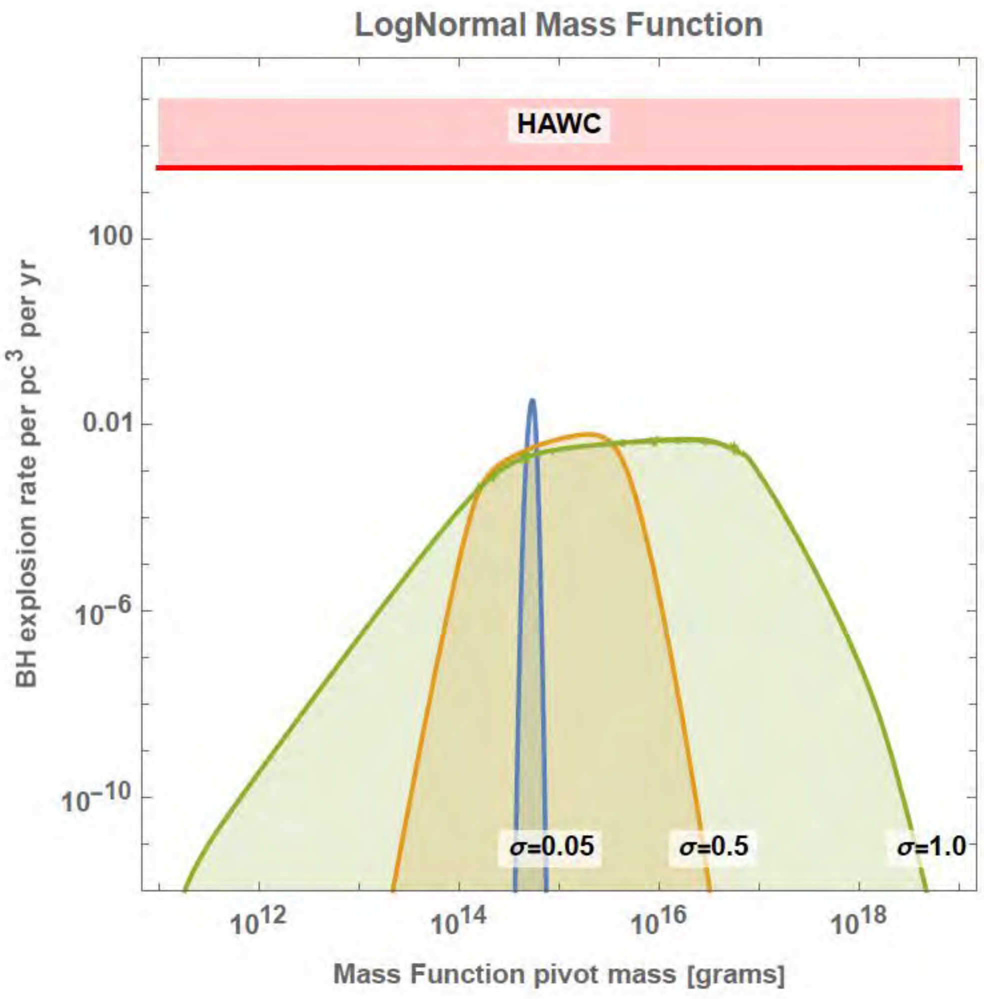
with extra dimensions, lower M_{Planck} peak can shift to low frequencies!

non-standard redshift history?

J. Sharnhorst

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

The rate of explosions today depends on the PBH mass function



$$\dot{n}_{\rm PBH} \simeq \frac{1.2 \times 10^{-3}\ {\rm pc}^{-3}{\rm yr}^{-1}}{\sigma},$$

Stefano Profumo
University of California Santa Cruz

…we need to stack lots of particles!

$N \sim 10^8\ M_{sun}/(10^{-22}\ \mathrm{eV}) \sim 10^{90}$

→ this mass limit can only apply to **bosons**, $J=n$

what if $J=(2n+1)/2$, i.e. **fermion**?

→ we expect fermions respecting Pauli's **exclusion principle** to be $10^{90/4}$ **fewer**, thus $m>10^{22.5}\ 10^{-22} \sim$ **few eV**

Stefano Profumo
University of California Santa Cruz

Phase space density is bounded : *f= gh⁻³*

Upper limit: highest observed phase space density: dSph!

$$\frac{g}{h^3} \geq n \cdot f_p \geq \frac{\rho_{\rm DM}}{m} \frac{1}{\left(m \cdot \sqrt{2\pi\sigma^2}\right)^3}$$ *(MB with exp=1)*

$$m^4 \geq \frac{\rho_{\rm DM} h^3}{[g(2\pi\sigma^2)^{3/2}]} \sim (25\ {\rm eV})^4$$

Tremaine-Gunn limit (1979)

m>25 eV

Stefano Profumo
University of California Santa Cruz

Asteroid mass PBH as dark matter **well established** …even **string theorists** take this seriously!

Monochromatic Mass Spectrum of Primordial Black Holes

Matthew Kleban and Cameron Norton

Center for Cosmology and Particle Physics, New York University, New York, NY

October 17, 2023

Abstract

During slow-roll inflation, non-perturbative transitions can produce bubbles of metastable vacuum. These bubbles expand exponentially during inflation to super-horizon size, and later collapse into black holes when the expansion of the universe is decelerating. In a broad class of models, the inflationary fine-tuning that gives rise to small density fluctuations causes these bubbles to appear only during a time interval that is short compared to the inflationary Hubble time. As a result, despite the fact that the final mass of the black hole is exponentially sensitive to the moment bubbles form during inflation, the resulting primordial black hole mass spectrum can be nearly monochromatic. If the transition occurs near the middle of inflation, the mass can fall in the "asteroid" range $10^{17} - 10^{22}$g in which all known observations are compatible with black holes comprising 100% of dark matter.

1 Introduction

One of the greatest mysteries in modern physics is the nature of dark matter. Despite accounting for over 25% of the energy density of our universe, its nature and origin remains uncertain. Decades of

The rate of explosions today depends on the PBH mass function

$$\psi(M) \propto M \frac{dn_{\rm PBH}}{dM} \qquad \int dM \psi(M) = f_{\rm PBH}$$

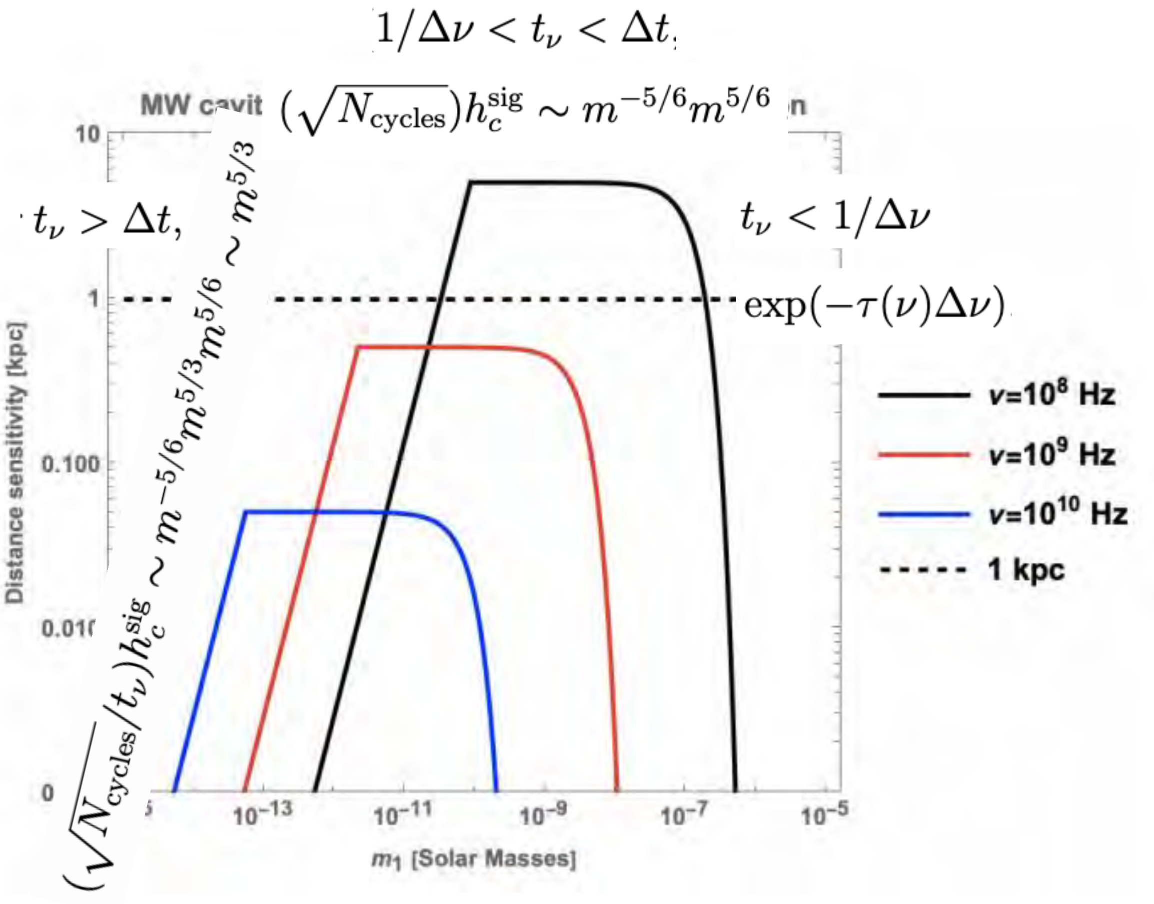
$$\dot{n}_{\rm PBH} = \frac{dn_{\rm PBH}}{dM}\left(-\frac{dM}{dt}\right) = \rho_{\rm DM}\frac{\psi(M)}{M}\frac{\alpha(M)}{M^2} \qquad \frac{\alpha(M)}{M^2} \simeq 4 \times 10^{-4}\,{\rm g/sec}$$

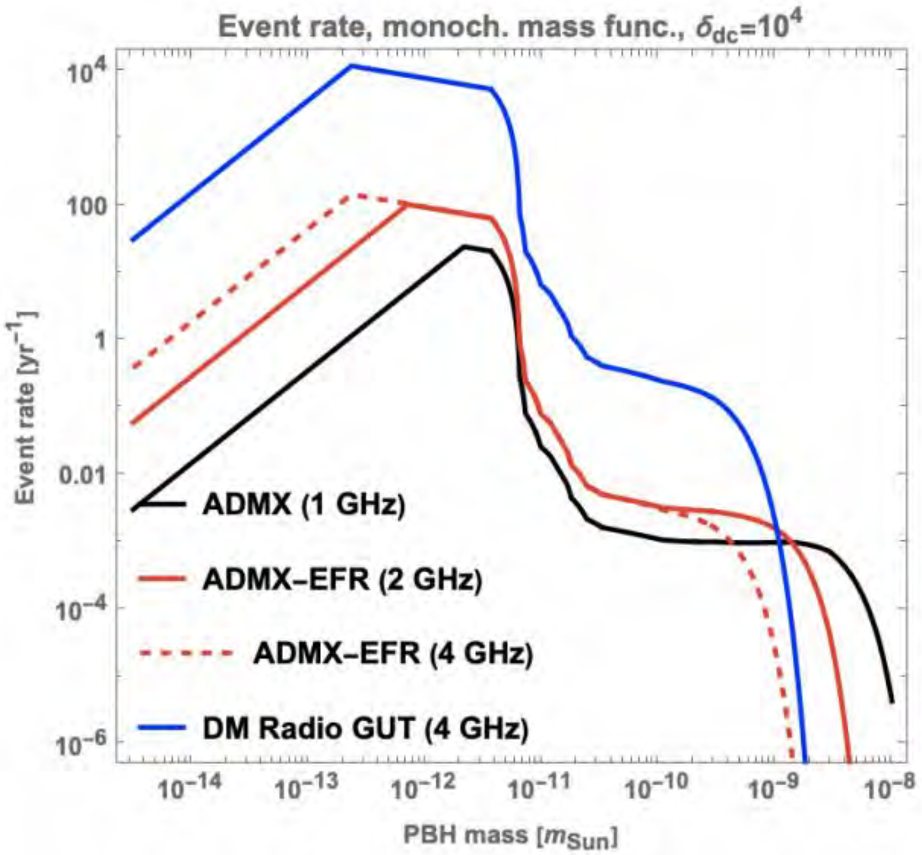
Considering an initial mass function Ψ_i the rate of PBH explosions today reads

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

*Profumo, Boluna, Ble, Hennings, 2023

Critical distance and event rate

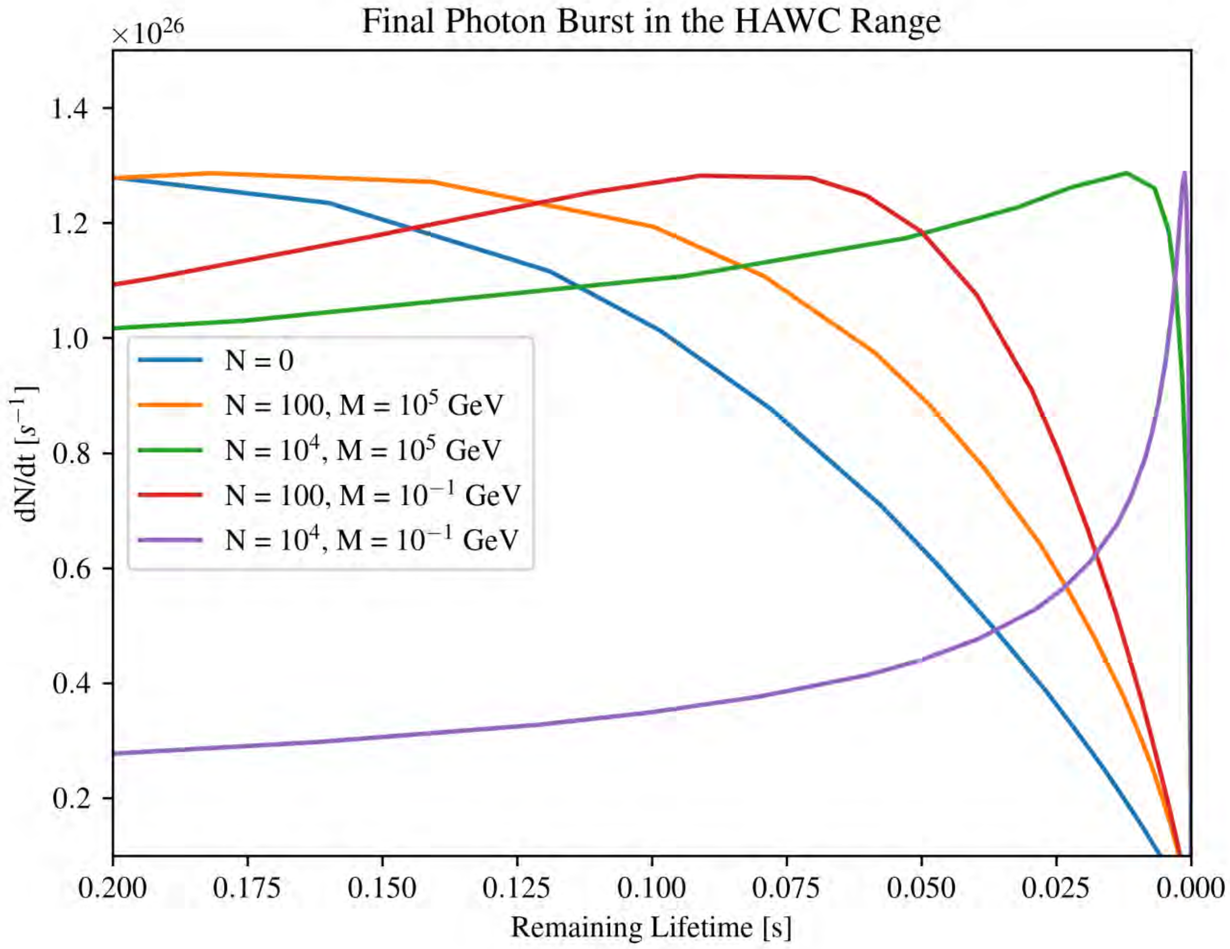




Stefano Profumo
University of California Santa Cruz

The (non-universal) Black Hole Light-curve

Photon Emission Rate at HAWC telescope



Time to Explosion

 # new degrees of freedom

Mass-scale of new d.o.f

SM emission from new d.o.f

K. Fedrico and S. Profumo, JCAP 2024