SCIPP
Santa Cruz Institute for Particle Physics

Stefano Profumo

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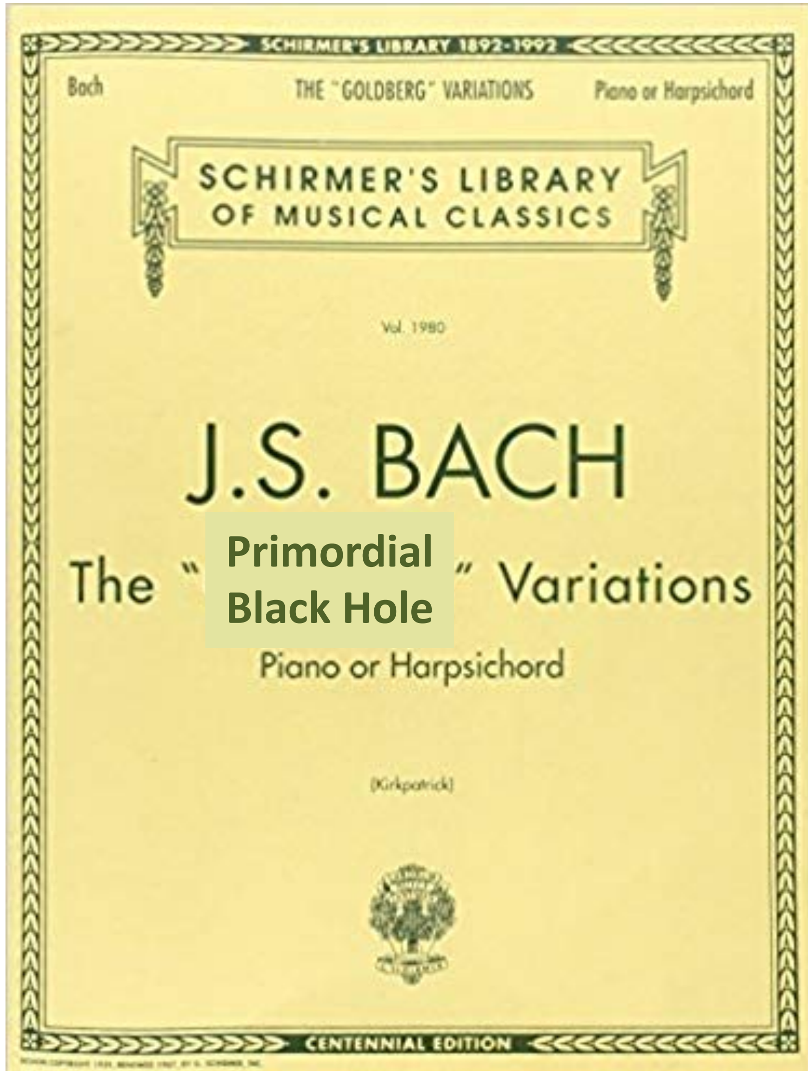
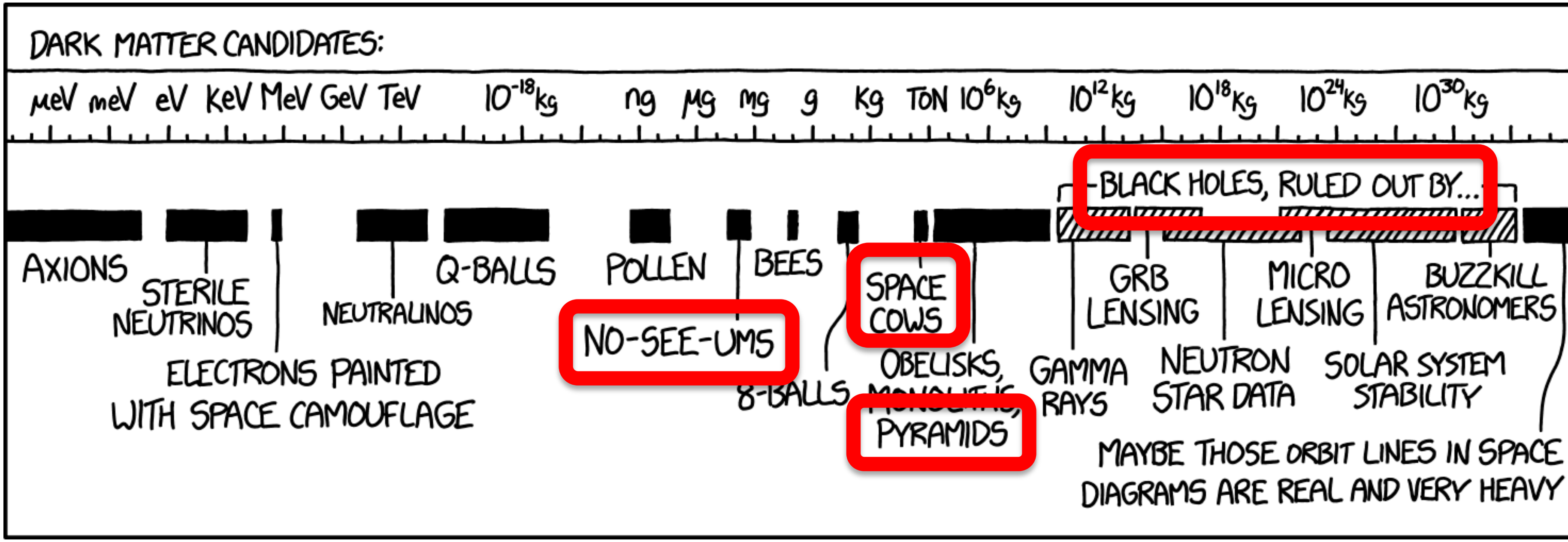
UC SANTA CRUZ



ICTS - Less travelled path of Dark Matter – November 12, 2020

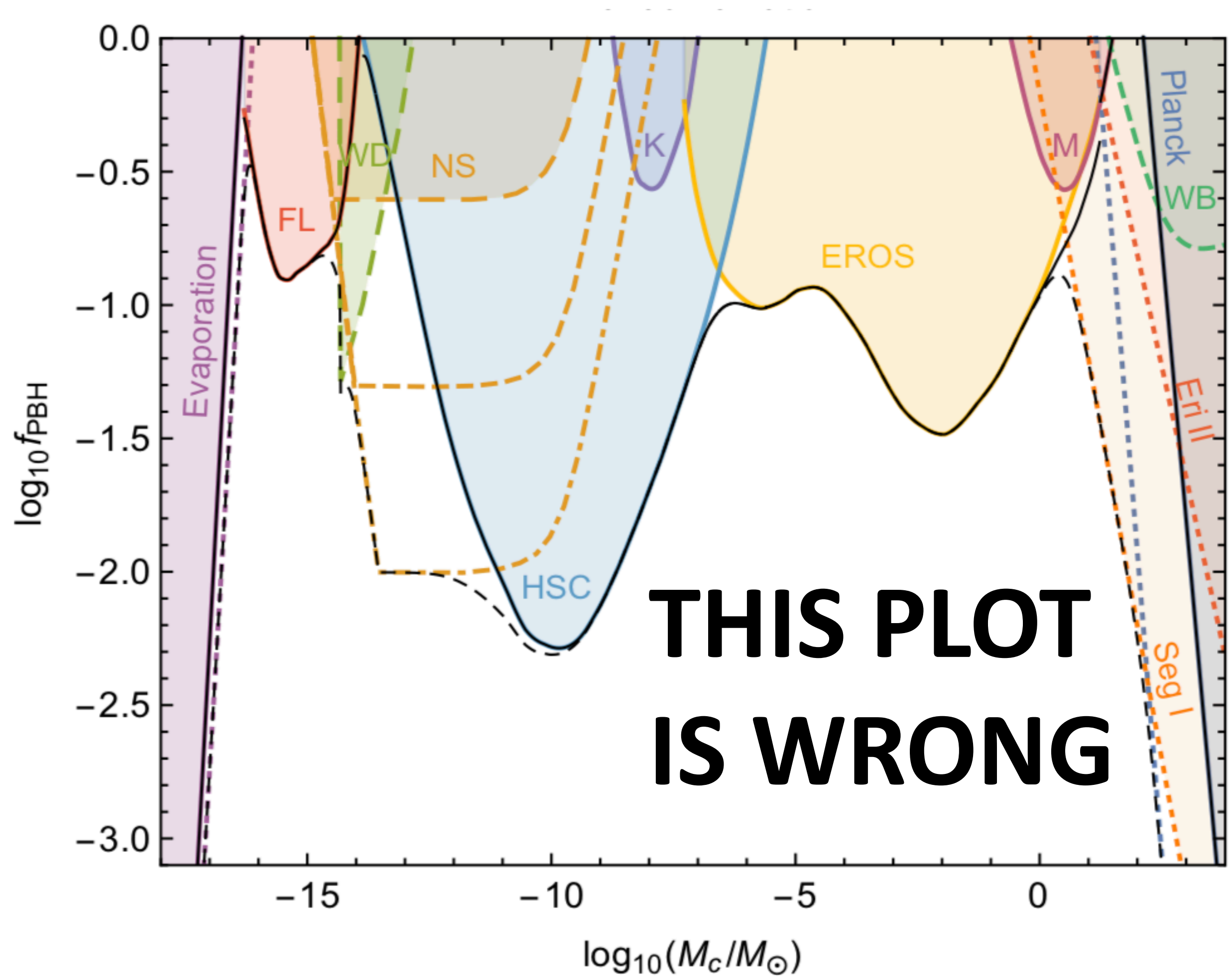


- **Why** it is interesting to consider **PBH** as **Dark Matter**
- **Where** it is interesting **to look** for PBH as Dark Matter
- …some “**NO-SEE-UMS**”, “**SPACE COWS**”, “**PYRAMIDS**”

source: xkcd

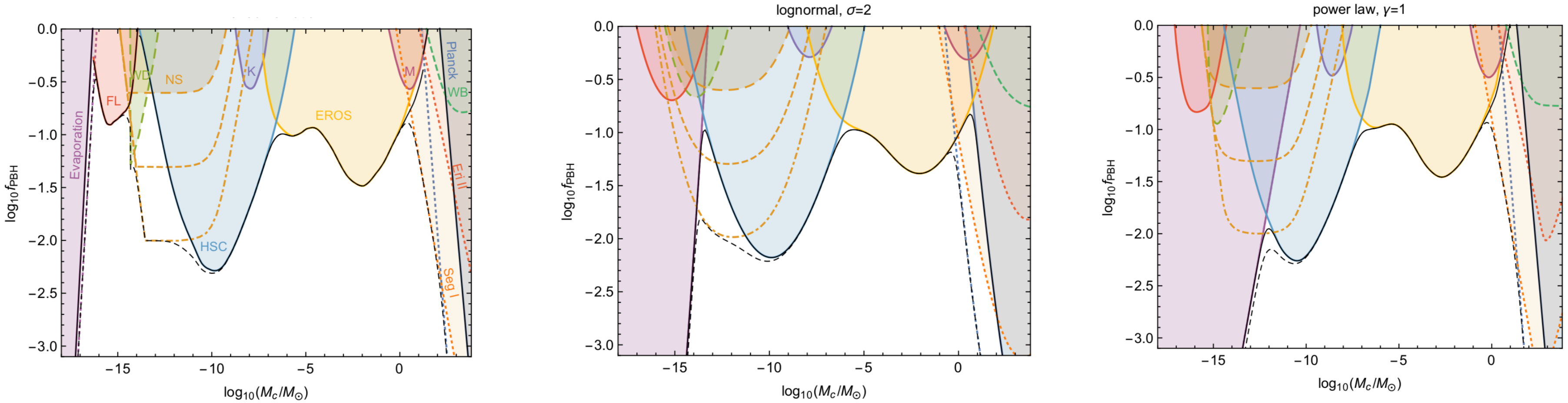
Can there be **enough** PBH around to be the **DM**?

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



Carr et al, 2017

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



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

Carr et al, 2017

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

Benjamin V. Lehmann, Stefano Profumo and Jackson Yant

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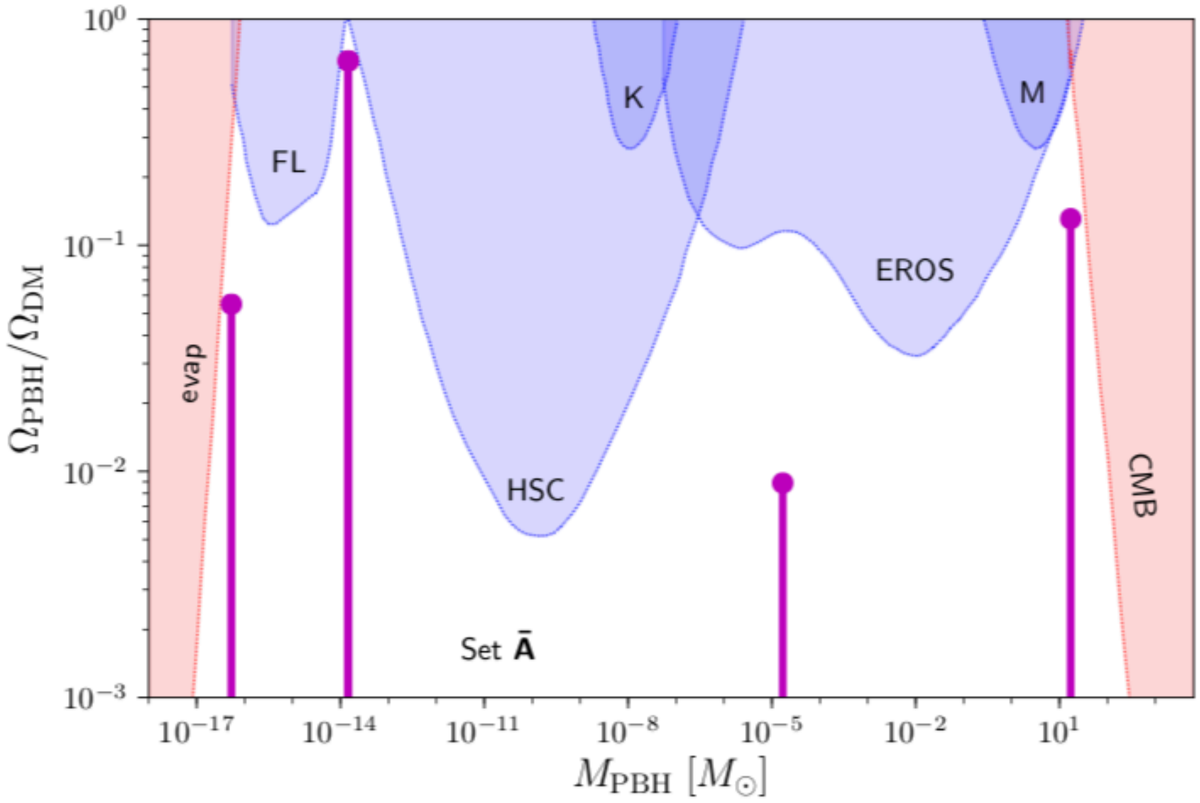
Abstract. The advent of gravitational wave astronomy has rekindled interest in primordial black holes (PBH) as a dark matter candidate. As there are many different observational probes of the PBH density across different masses, constraints on PBH models are dependent

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

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

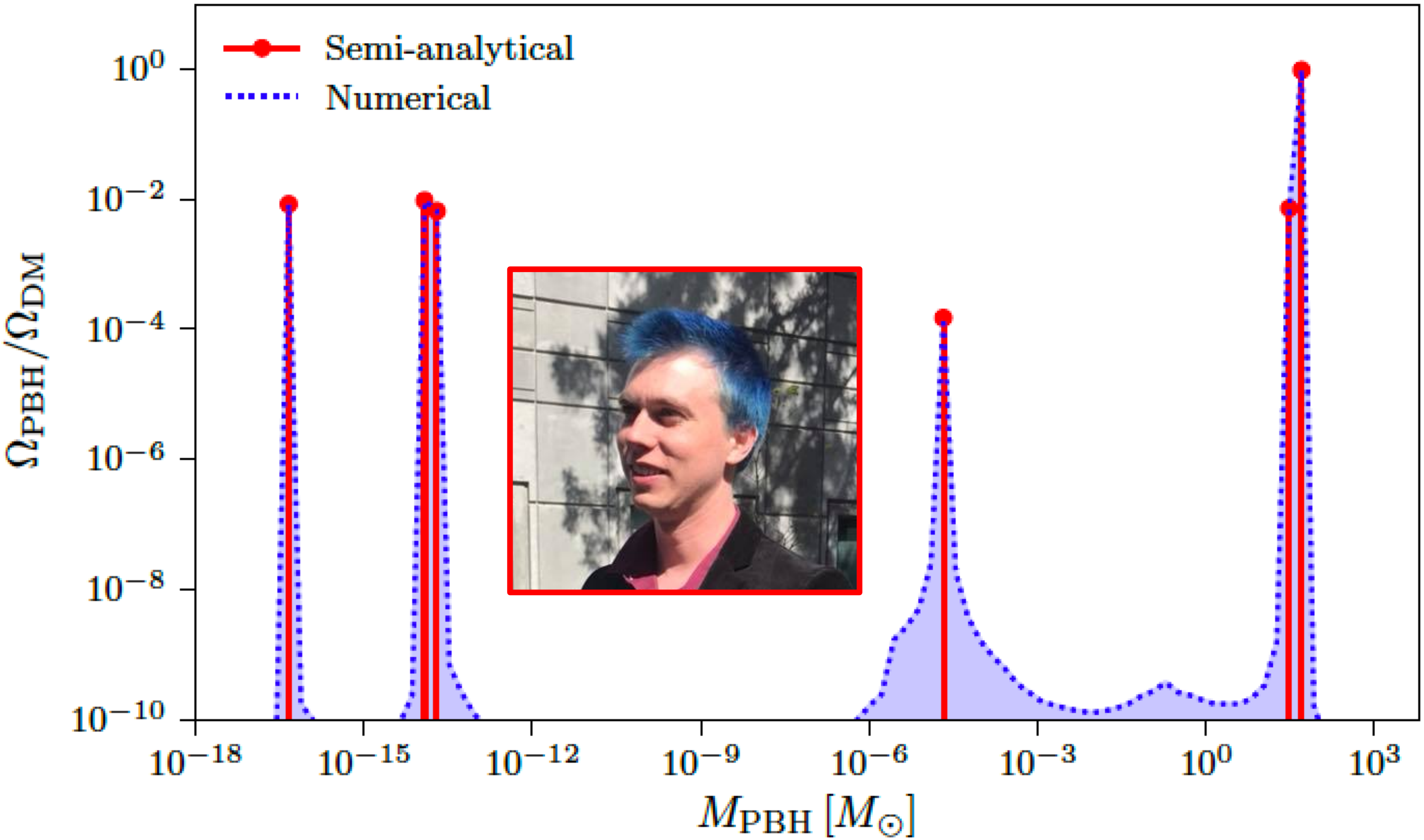
* Lehmann, Profumo and Yant, JCAP 2018



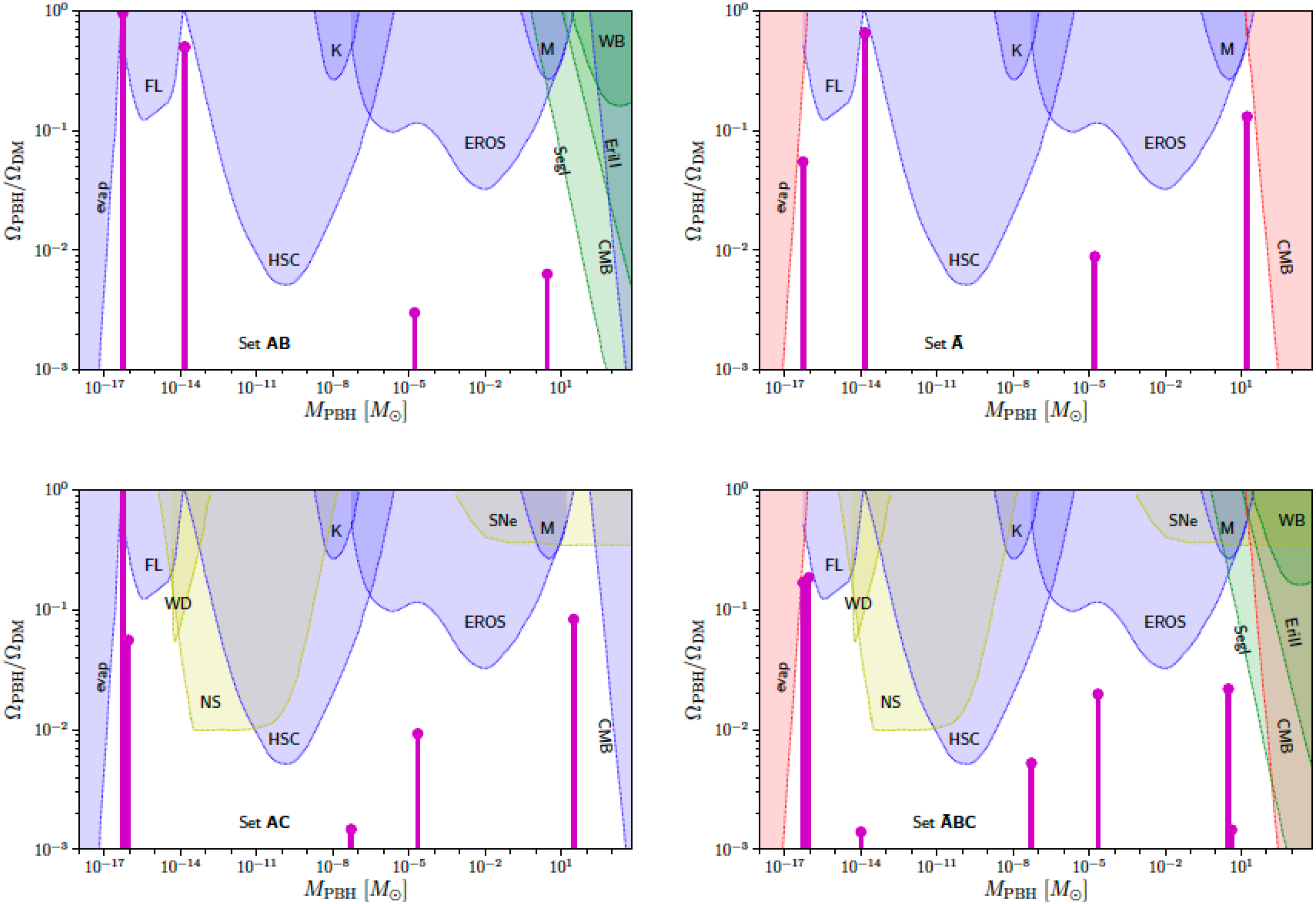
Answer: with *N* independent constraints, the optimal function is a linear combination of *N* delta functions with calculable relative weights

* Lehmann, Profumo and Yant, JCAP 2018

Numerical validation



* Lehmann, Profumo and Yant, JCAP 2018



* Lehmann, Profumo and Yant, JCAP 2018

	f_{mono}	$f_{\mathrm{max,all}}$	$f_{\mathrm{max,GW}}$	$\sigma[\psi]/M_\odot$	$\langle M/M_\odot \rangle$
A	27.17	27.25	2.580	2.259	31.09
AB	1.372	1.965	5.139	0.162	0.009
AC	1.371	1.443	0.566	7.294	1.807
ABC	1.371	1.402	2.936	0.220	0.015
Ā	0.991	1.502	2.171	4.827	1.492
ĀB	0.991	1.437	11.07	0.221	0.017
ĀC	0.330	0.484	0.364	7.963	5.430
ĀBC	0.330	0.405	0.982	0.741	0.182

So YES, depending on the constraints choice, PBH can be 100% of the dark matter!

* Lehmann, Profumo and Yant, JCAP 2018

Is there a **goldilocks** signature of **PBH**?

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

LIGO **search results** are out*

Is there a goldilocks signature of PBH?

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

Given a mass function, one can calculate:

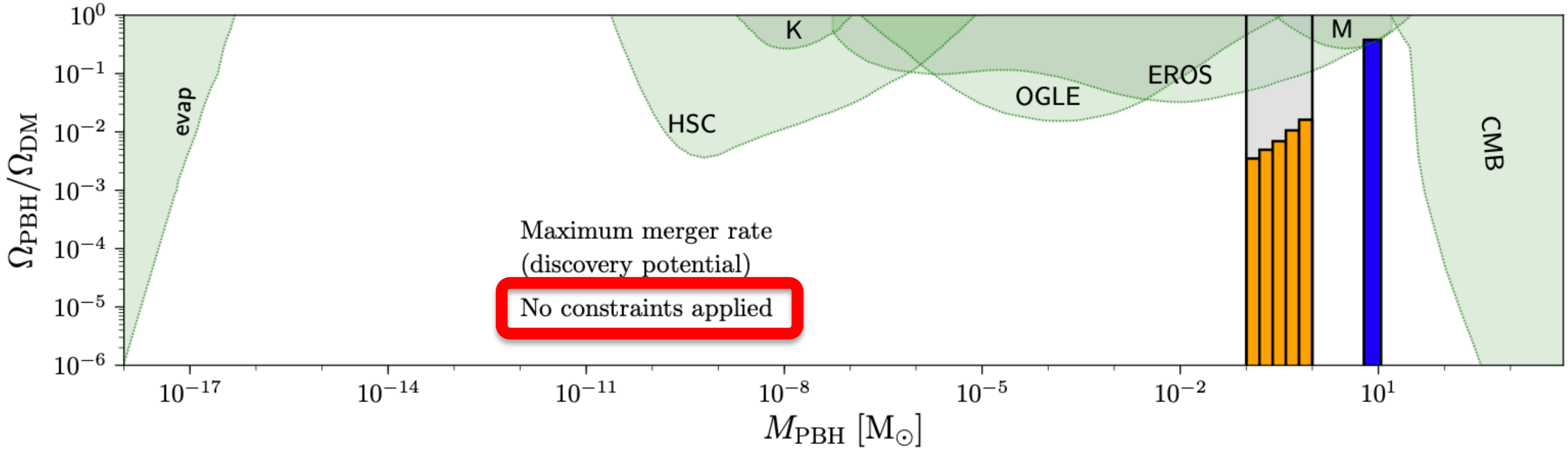
1. **Rate of "goldilocks events"**

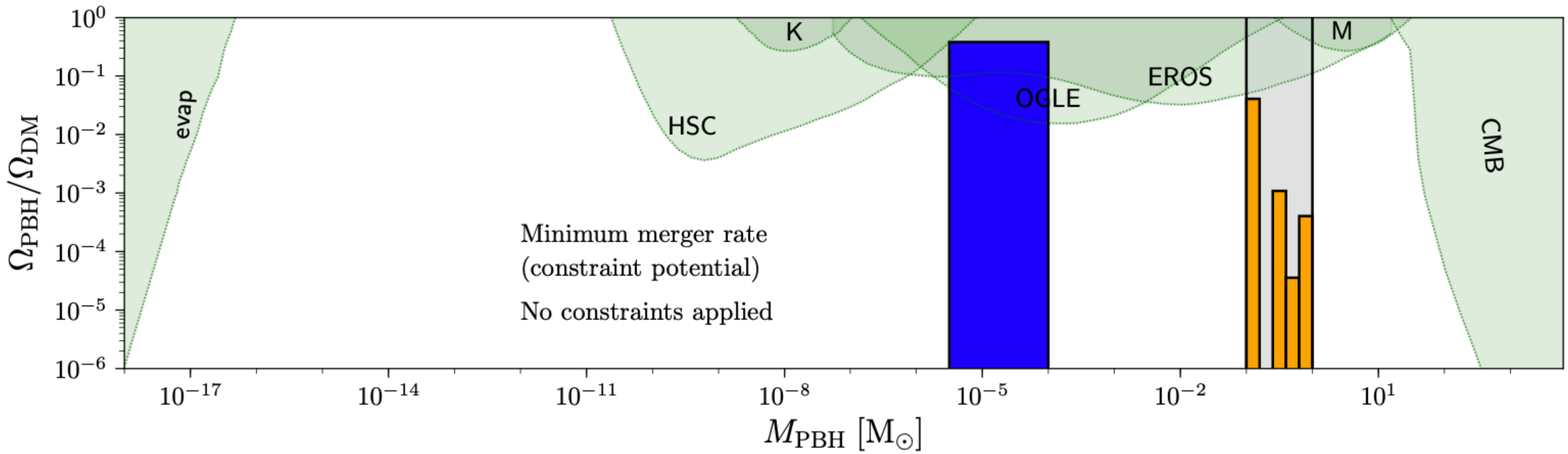
$$R_{\rm DP}(\psi) = \int_{\rm DP^2} {\rm d}m_1\, {\rm d}m_2\, \mathcal{R}(m_1, m_2) V_{\rm eff}(m_1, m_2),$$

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

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

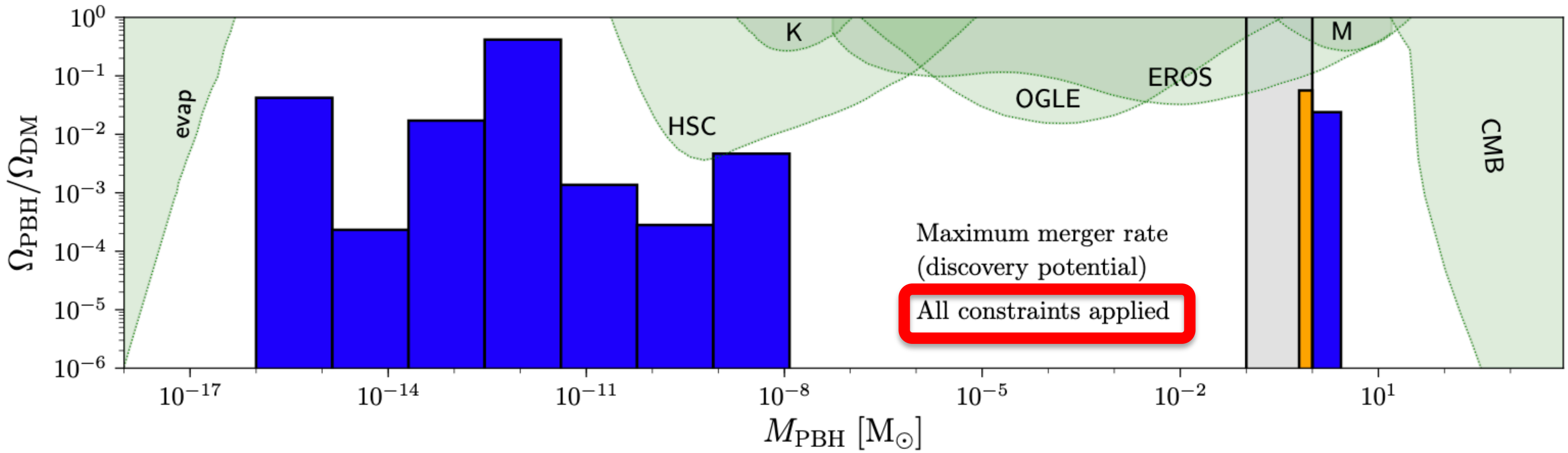
We can numerically compute the maximal and minimal possible "goldilocks event rate"

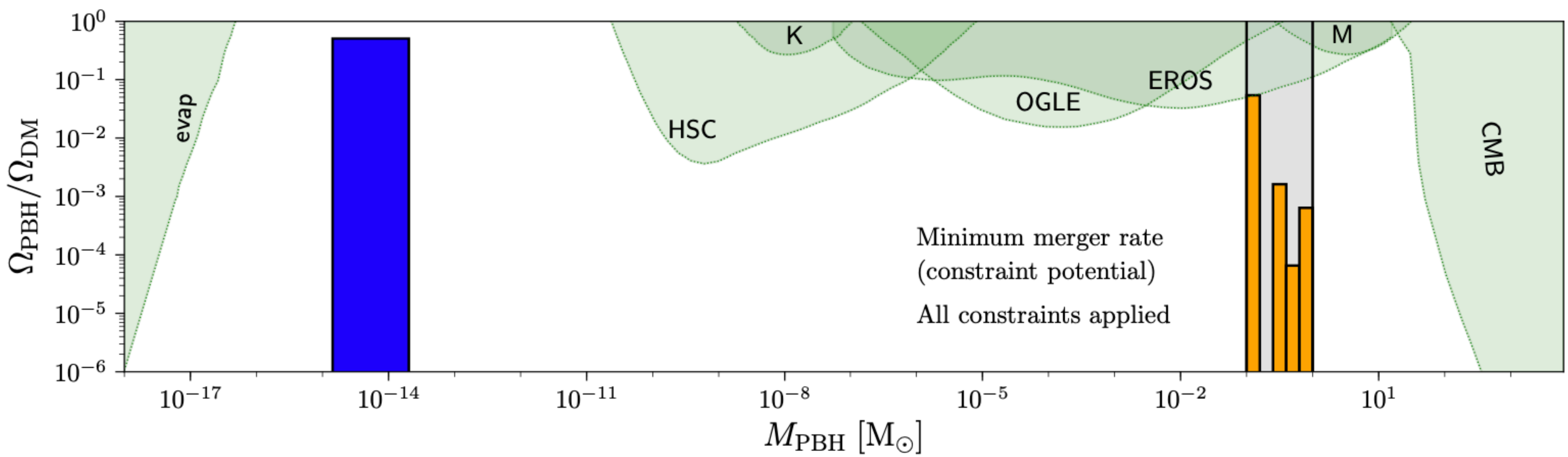




* Lehmann, Profumo and Yant, MNRAS

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





* Lehmann, Profumo and Yant, MNRAS

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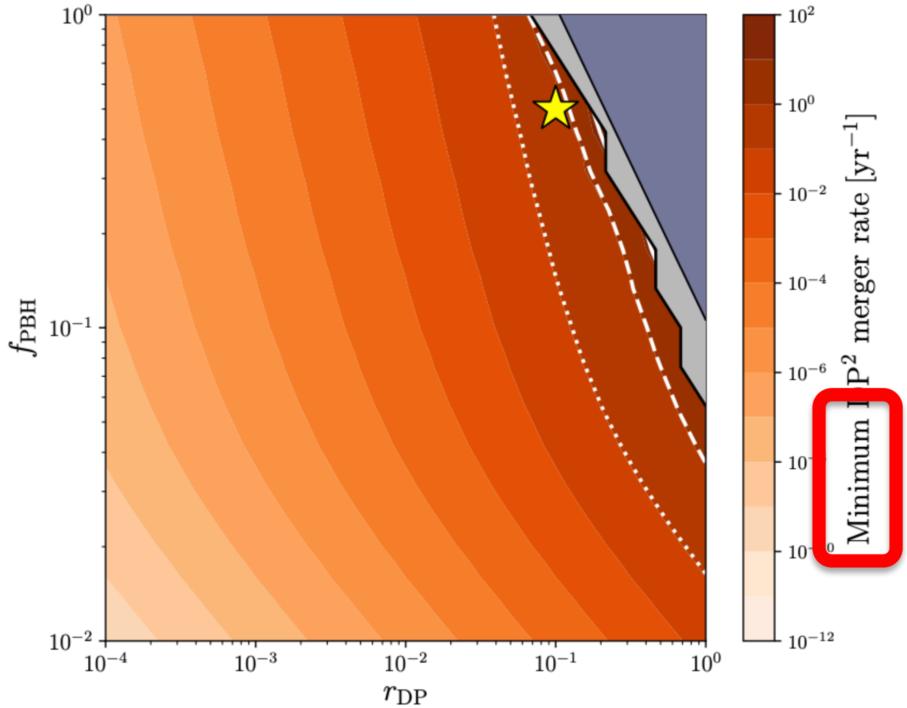
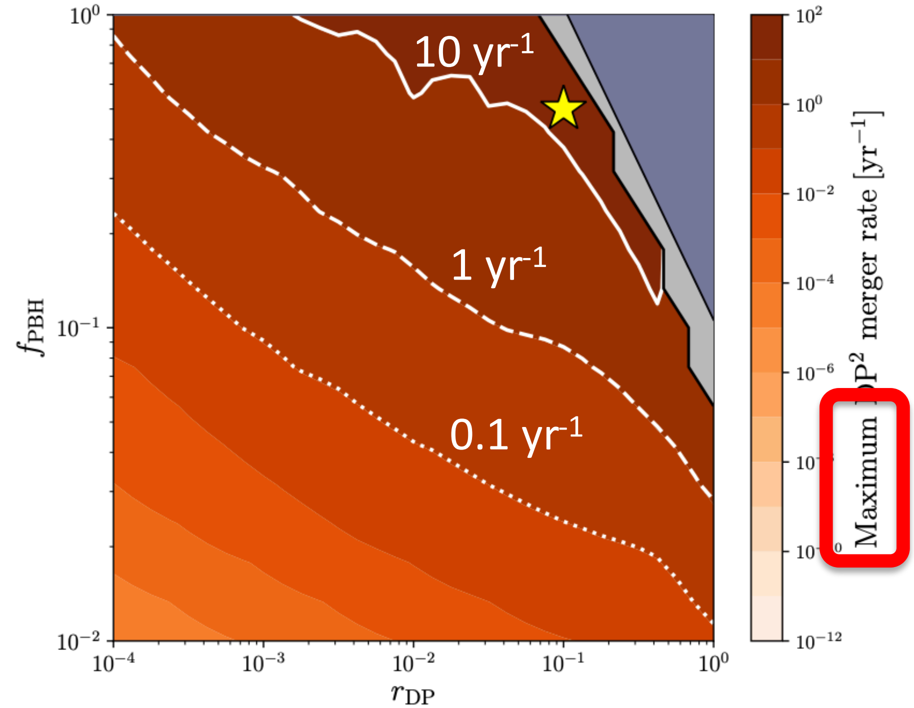




$$\int dm\, \psi(m) = \frac{\Omega_{PBH}}{\Omega_{DM}} \equiv f_{PBH}.$$

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

* Lehmann, Profumo and Yant, MNRAS

Besides the mass, LIGO informs us about the spin of BHs…

Besides the mass, LIGO informs us about the spin of BHs…

LIGO/Virgo Collaboration arXiv:1811.12940

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	χ_{eff}	$M_f/M_\odot$	a_f	$E_{rad}/(M_\odot c^2)$	$\ell_{peak}/(\mathrm{erg\,s^{-1}})$	d_L/Mpc	z	$\Delta\Omega/\mathrm{deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4}\times10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	180
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7}\times10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7}\times10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9}\times10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.05}_{-0.1}$	$3.5^{+0.4}_{-1.3}\times10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5}\times10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9}\times10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5}\times10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$.186^{+0.00}_{-0.00}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1\times10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7}\times10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9}\times10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

Masses

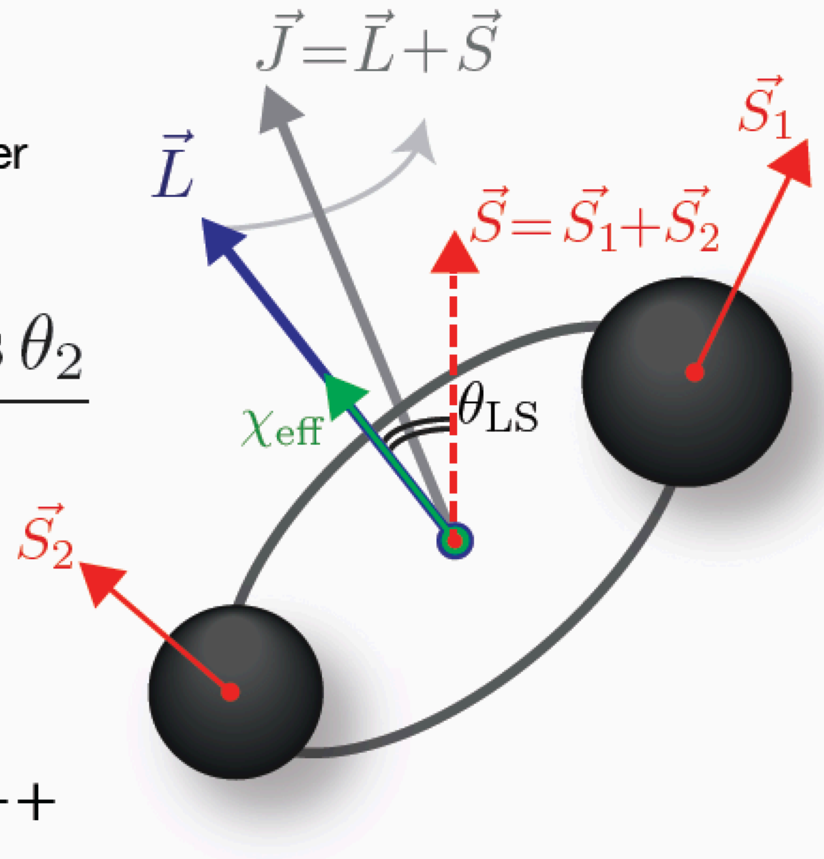
Spin

Slide credit: Nico Fernandez (UCSC → UIUC)

Effective Spin

$$\chi = \frac{|\vec{S}|}{Gm^2}$$ Dimensionless spin parameter

$$\chi_{\text{eff}} = \frac{m_1\chi_1 \cos\theta_1 + m_2\chi_2\cos\theta_2}{m_1 + m_2}$$



Information about:

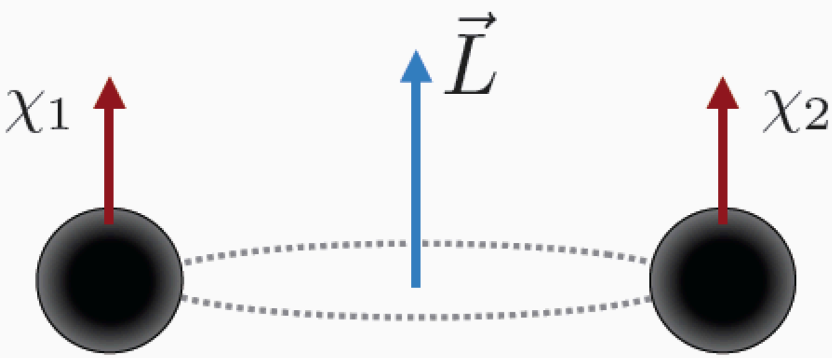
- Direction. +++
- Spin magnitude. ++
- masses. +

Slide credit: Nico Fernandez (UCSC → UIUC)

Effective Spin = 1

$$\chi_{\rm eff} = \frac{m_1 \chi_1 \cos\theta_1 + m_2 \chi_2 \cos\theta_2}{m_1 + m_2}$$

$$\cos\theta = \hat{\chi} \cdot \hat{L}$$



$$\chi_{\rm eff} \approx 1$$

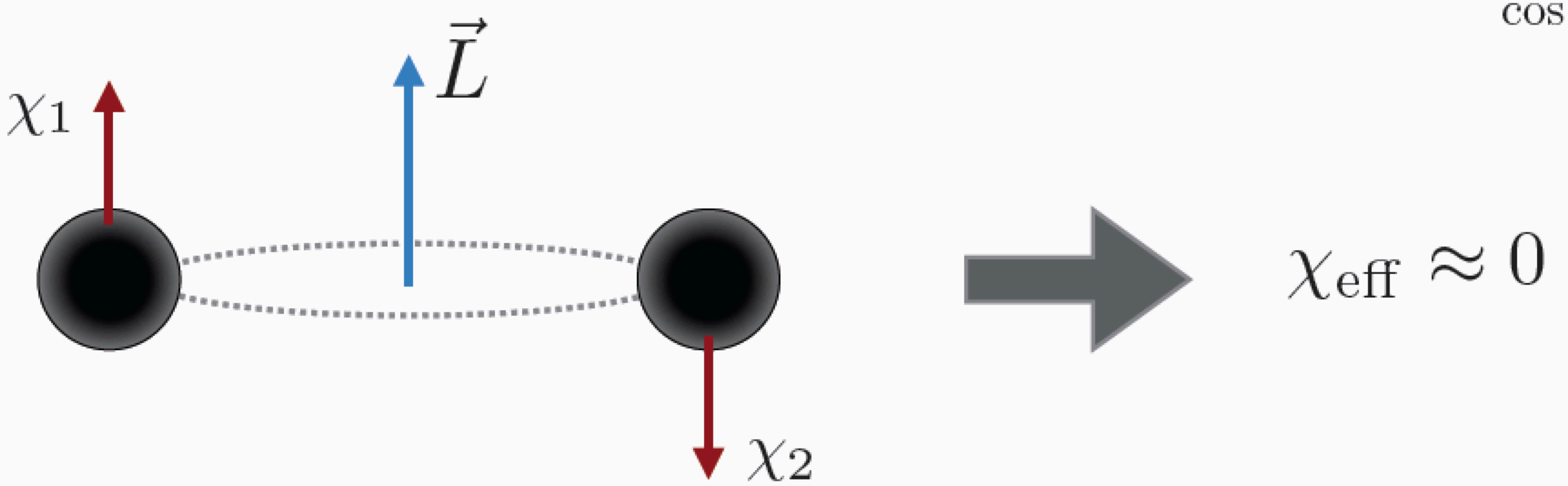
Most black holes from stellar binaries probably start off with their spins aligned

Slide credit: Nico Fernandez (UCSC → UIUC)

Effective Spin = 0

$$\chi_{\rm eff} = \frac{m_1\chi_1\cos\theta_1 + m_2\chi_2\cos\theta_2}{m_1+m_2}$$

$$\cos\theta = \hat{\chi}\cdot\hat{L}$$



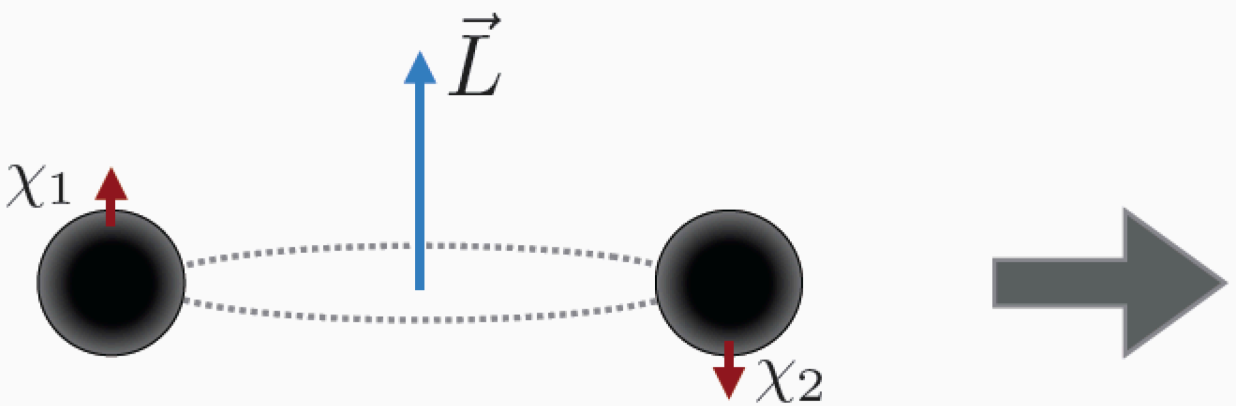
Spins are essentially isotropic in the dynamical formation scenario. Binary was probably formed in a cluster

Slide credit: Nico Fernandez (UCSC → UIUC)

Effective Spin = 0

$$\chi_{\rm eff} = \frac{m_1\chi_1\cos\theta_1 + m_2\chi_2\cos\theta_2}{m_1+m_2}$$

$$\cos\theta = \hat{\chi}\cdot\hat{L}$$



$$\chi_{\rm eff} \approx 0$$

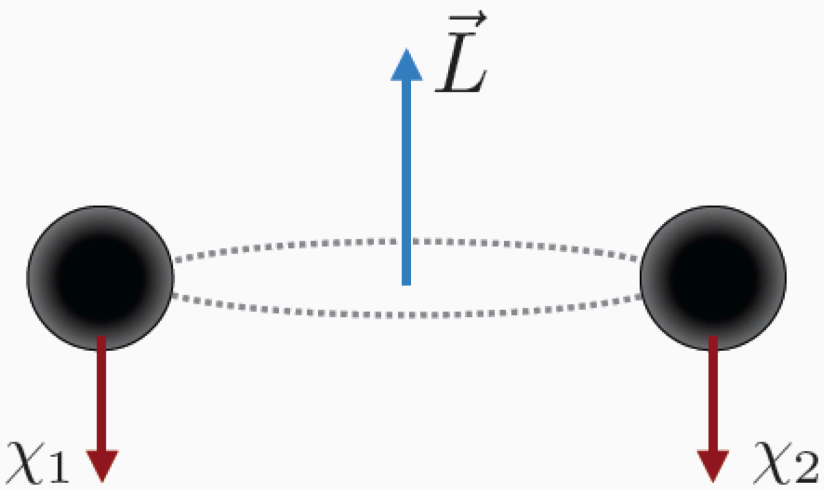
Spin magnitudes are close to zero (expected from PBHs).

Slide credit: Nico Fernandez (UCSC → UIUC)

Effective Spin = -1

$$\chi_{\mathrm{eff}} = \frac{m_1 \chi_1 \cos\theta_1 + m_2 \chi_2 \cos\theta_2}{m_1 + m_2}$$

$$\cos\theta = \hat{\chi} \cdot \hat{L}$$

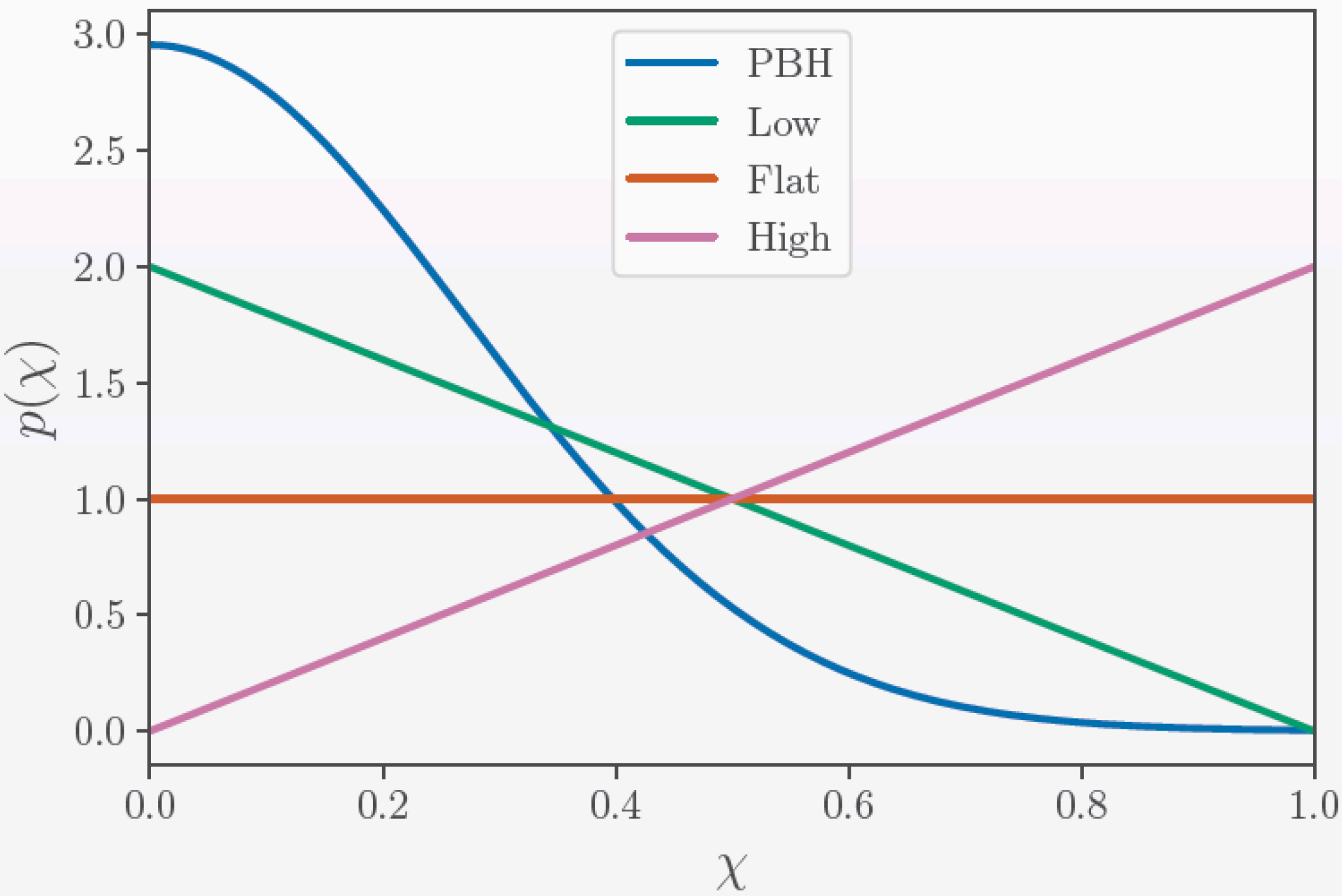


$$\chi_{\mathrm{eff}} \approx -1$$

Both spins are anti-aligned with its orbit (rare)

Slide credit: Nico Fernandez (UCSC → UIUC)

Magnitude Spin Priors



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

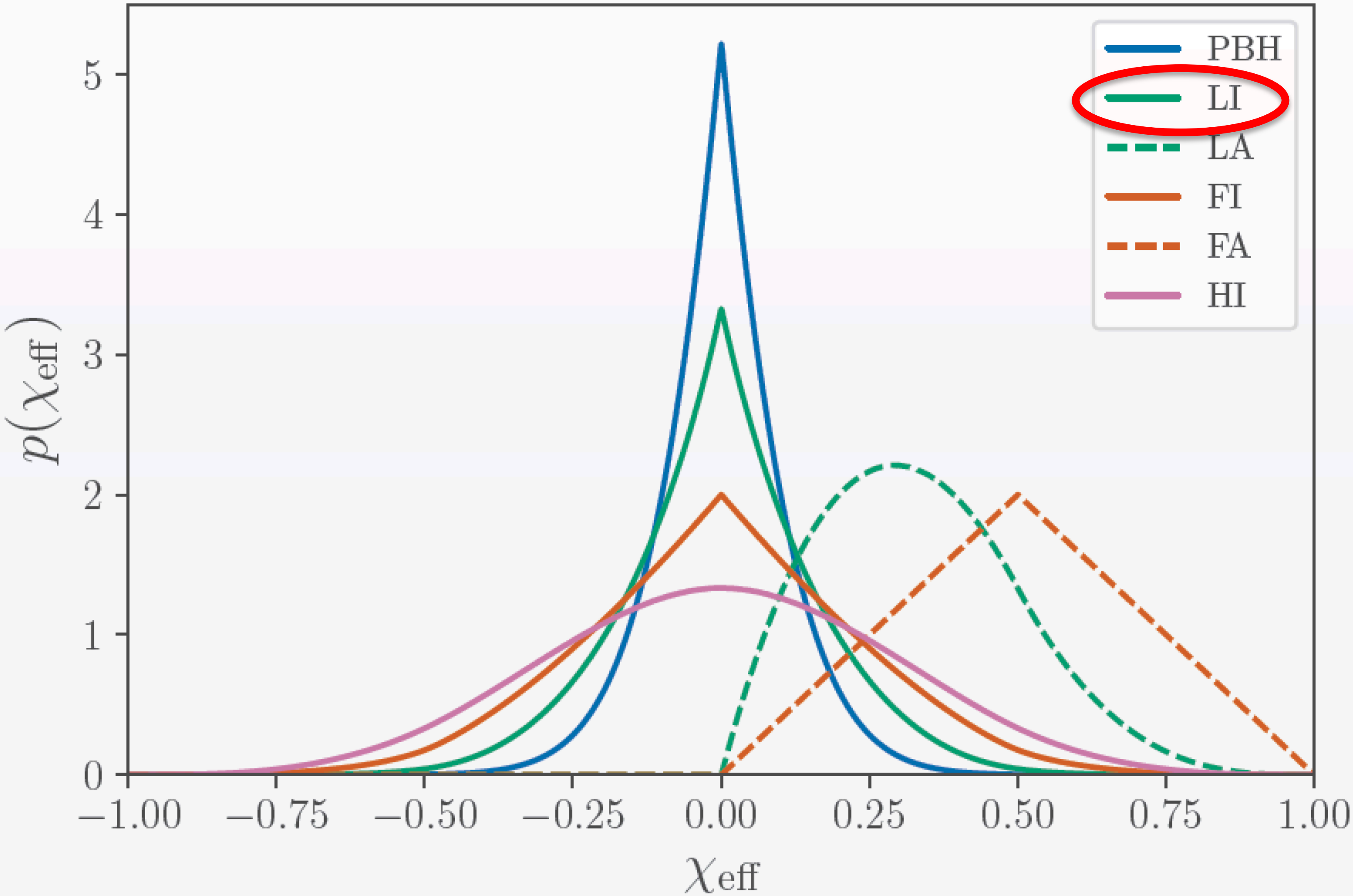
Model Selection

- Spin magnitude: Low (**L**), Flat (**F**) , High (**H**) and PBH
- Spin orientations: Isotropic (**I**) and Aligned (**A**)

Example:
FI = Flat spin magnitude and isotropic spins (LIGO)
FA = Flat spin magnitude and align spins

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

Effective Spin Priors



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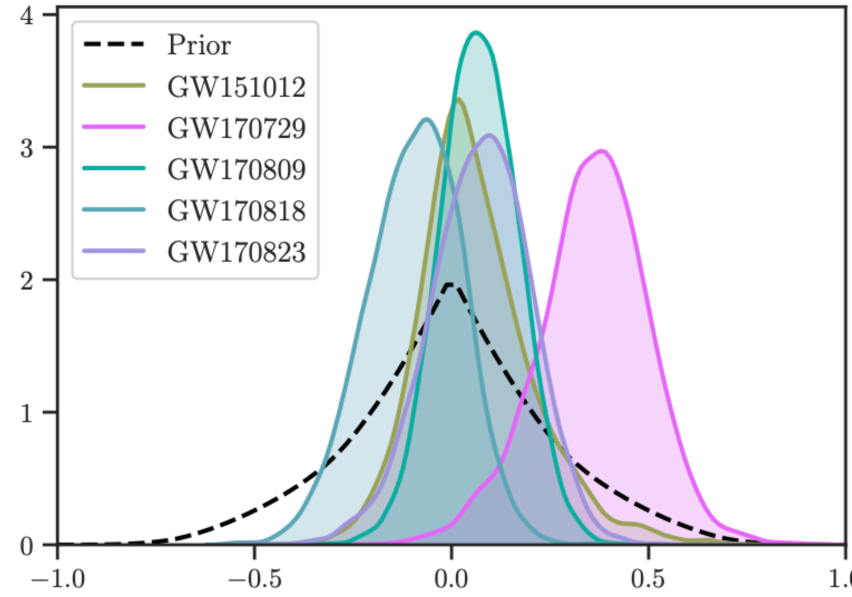


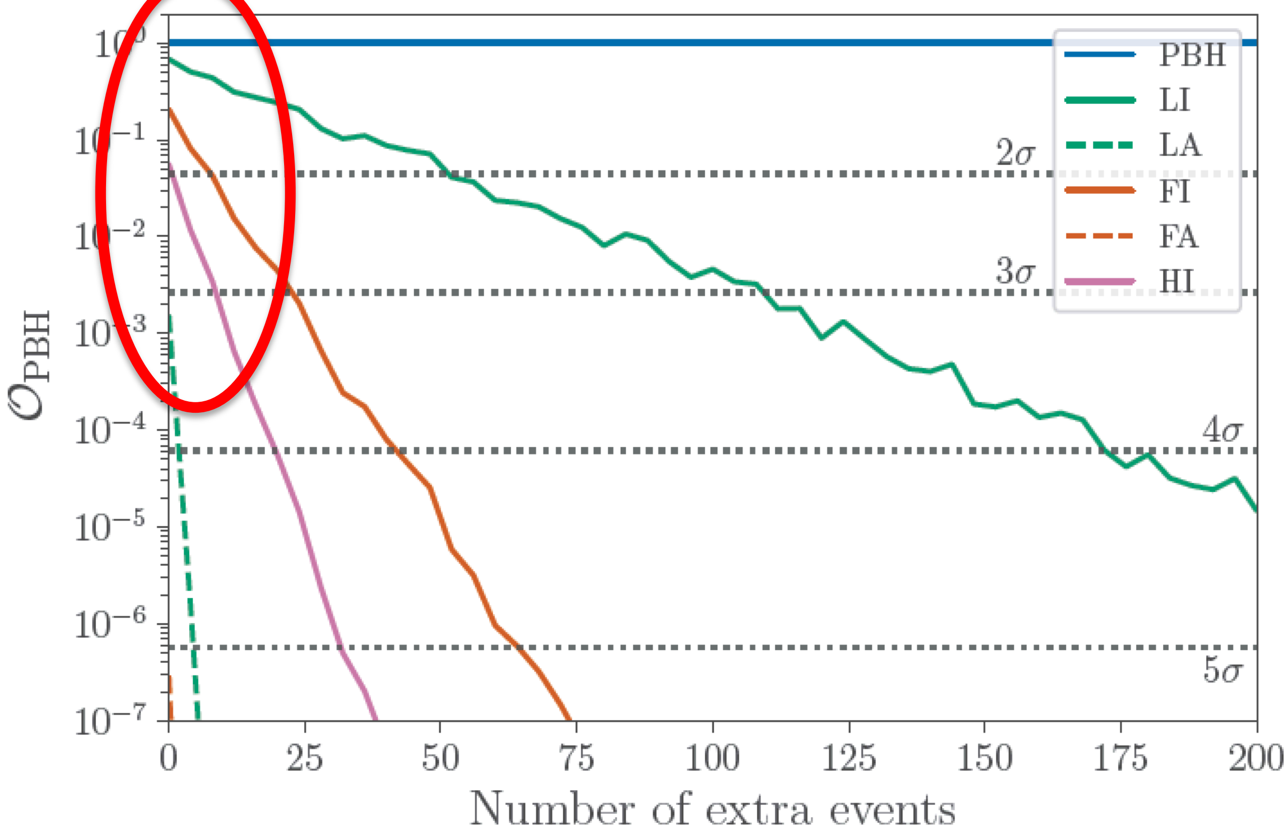
Odds ratios

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

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

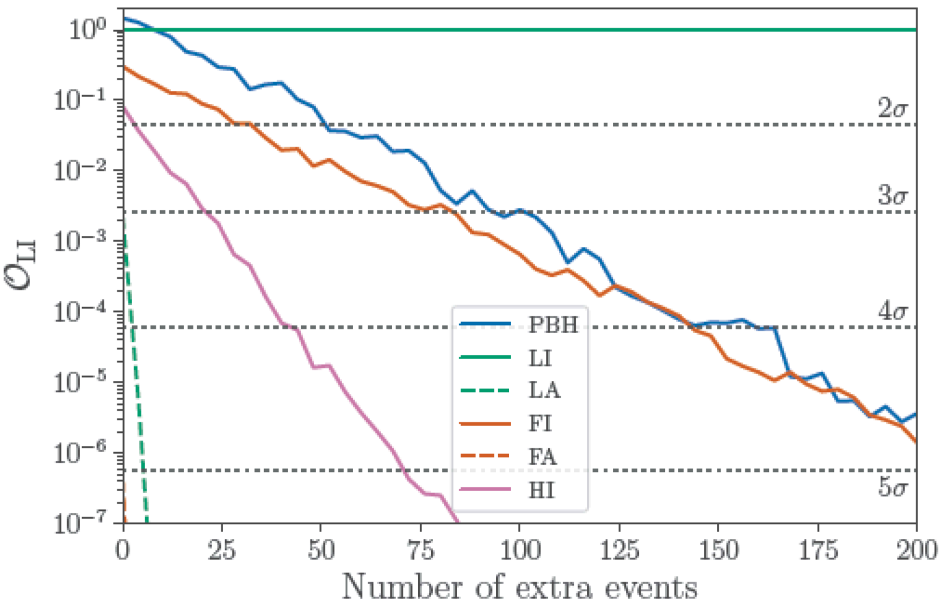
Evolution of the Odds ratios

Truth: PBH



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

Evolution of the Odds ratios



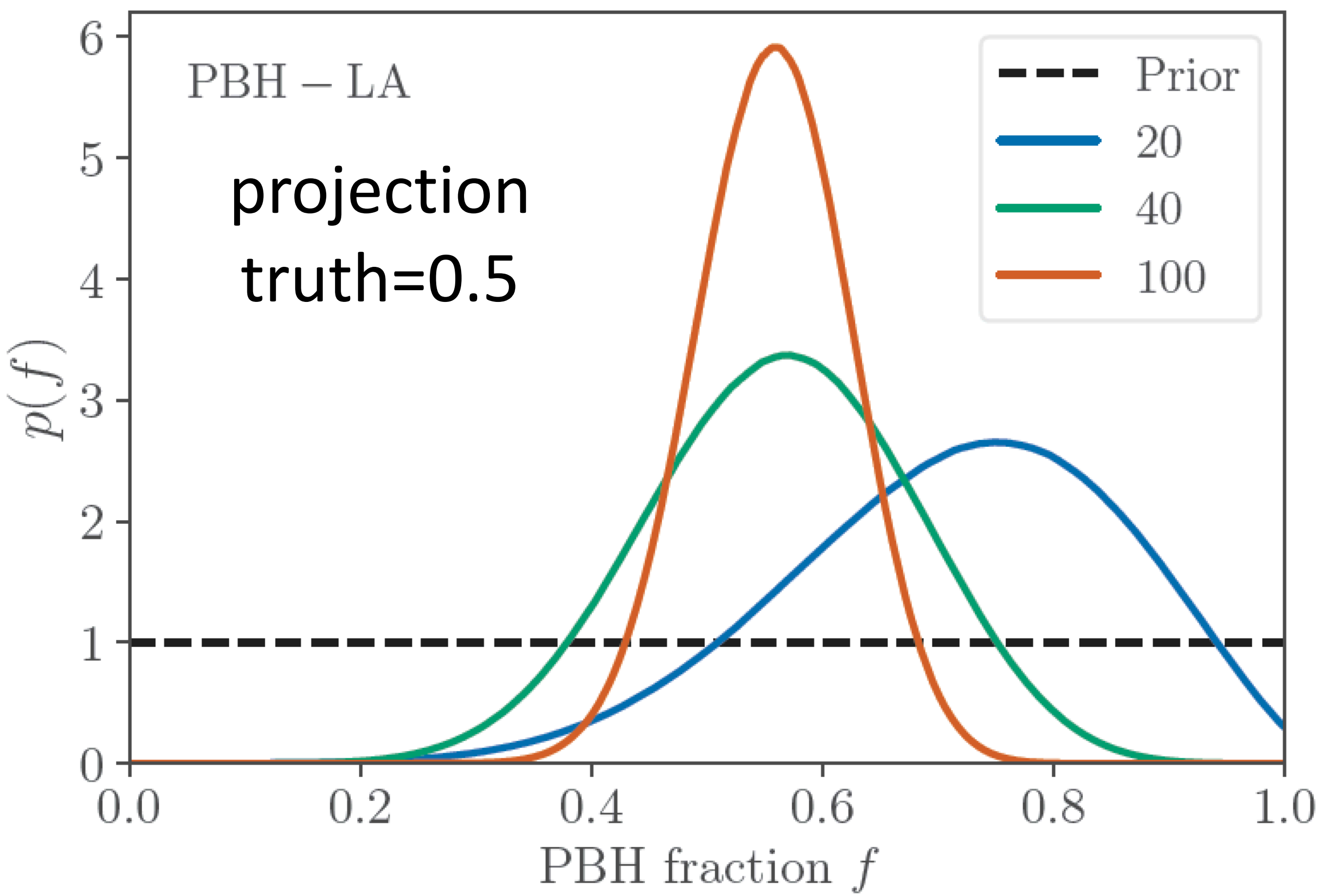
Truth: Low-isotropic

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

What about mixed models?

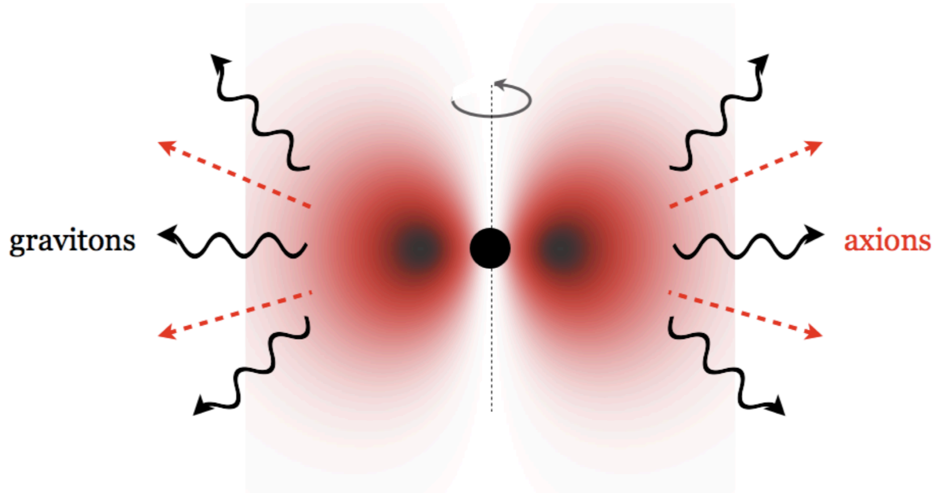
Fernandez and Profumo, 1905.13109 (JCAP); Slide credit: Nico Fernandez (UCSC → UIUC)

What about mixed models?



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

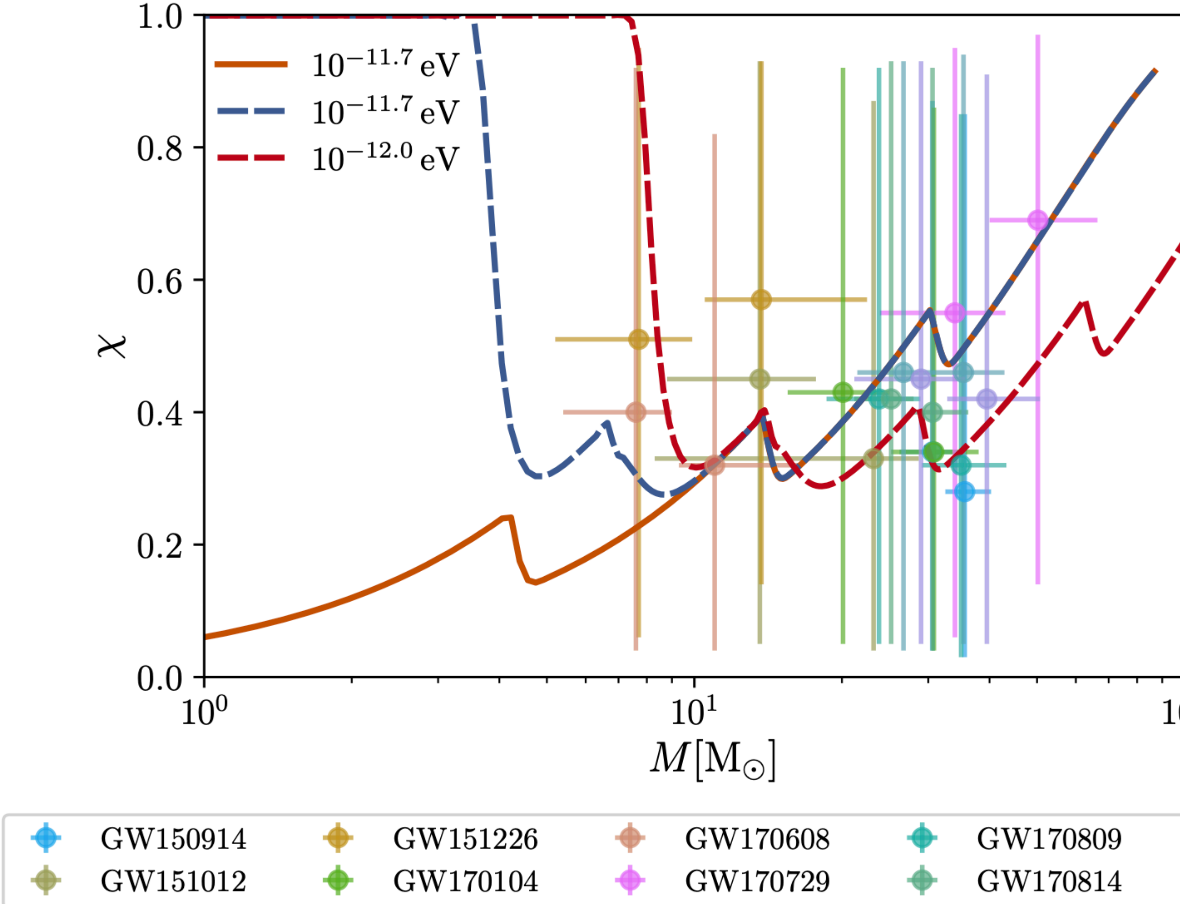
What else could fake a low-spin PBH? Super-radiance!



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

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

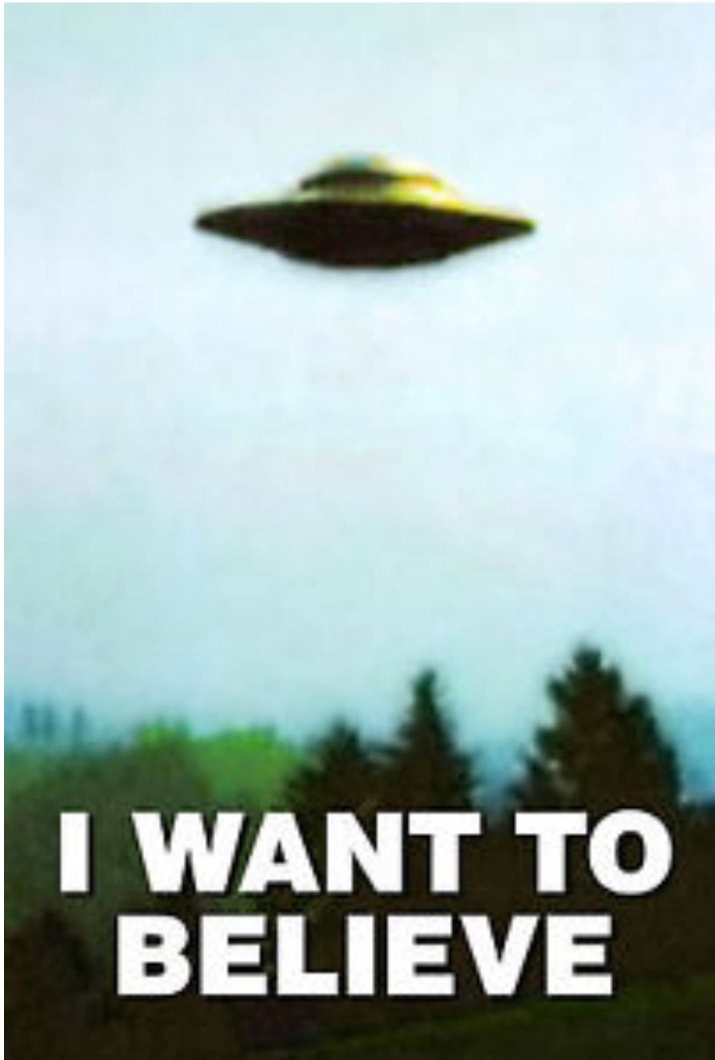
What else could fake a low-spin PBH? Super-radiance!

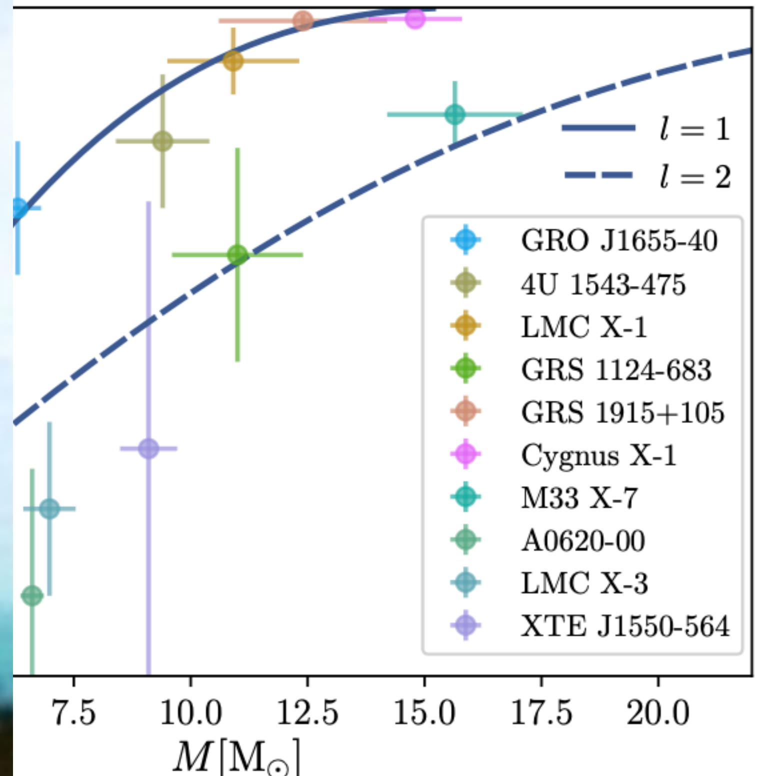


Regge plot (effective spin vs mass) assuming
Flat priors for both mass and spin*

*Fernandez, Ghalsasy, Profumo, 1911.07862

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



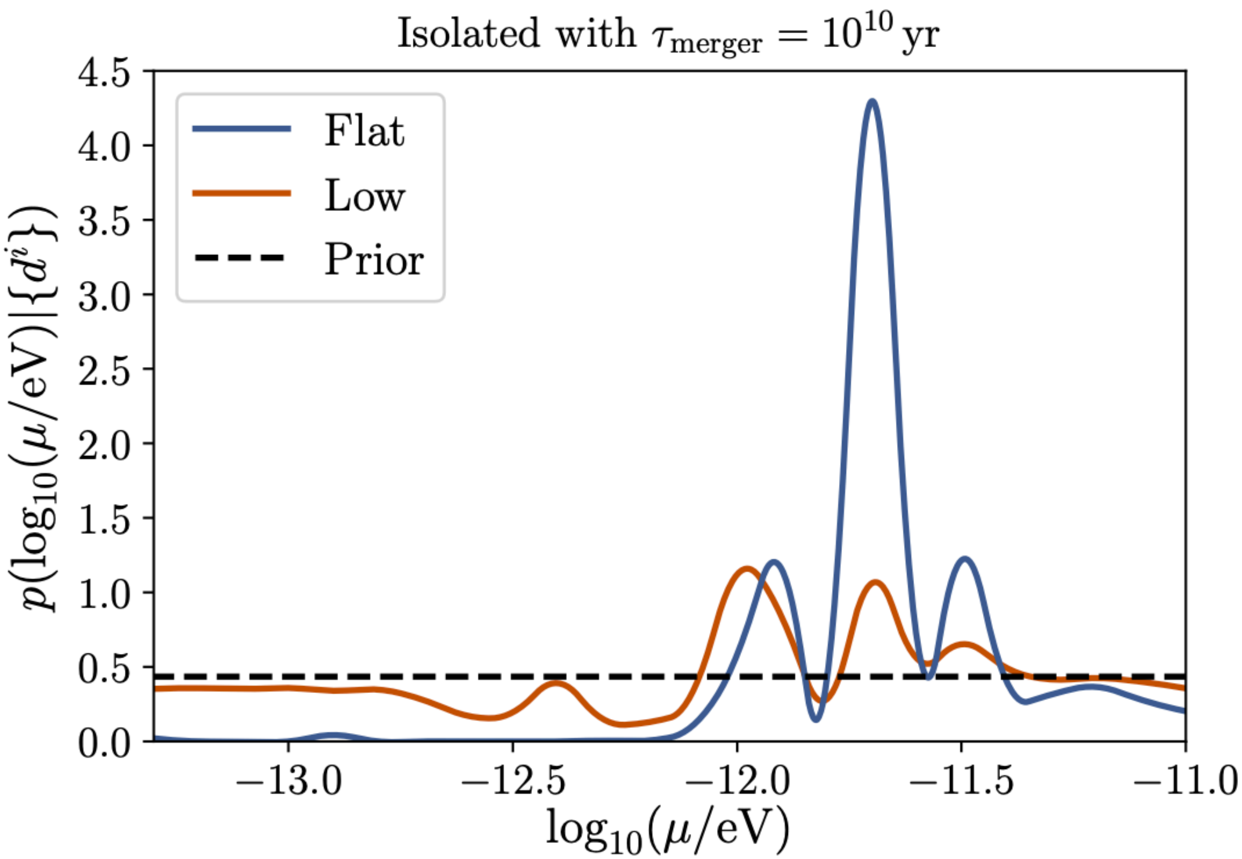


binaries tend to have large spins…

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

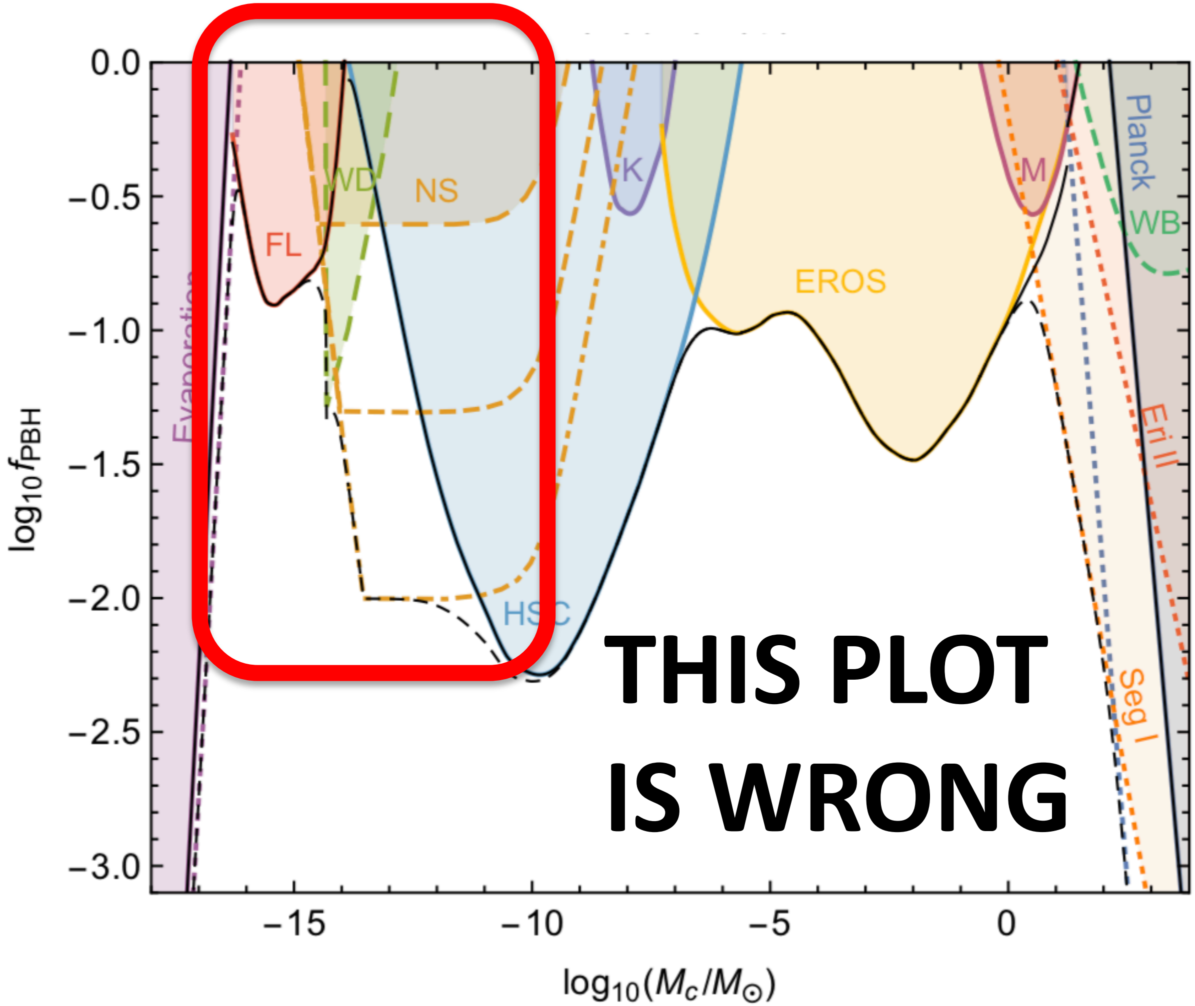
*Fernandez, Ghalsasy, Profumo, 1911.07862

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

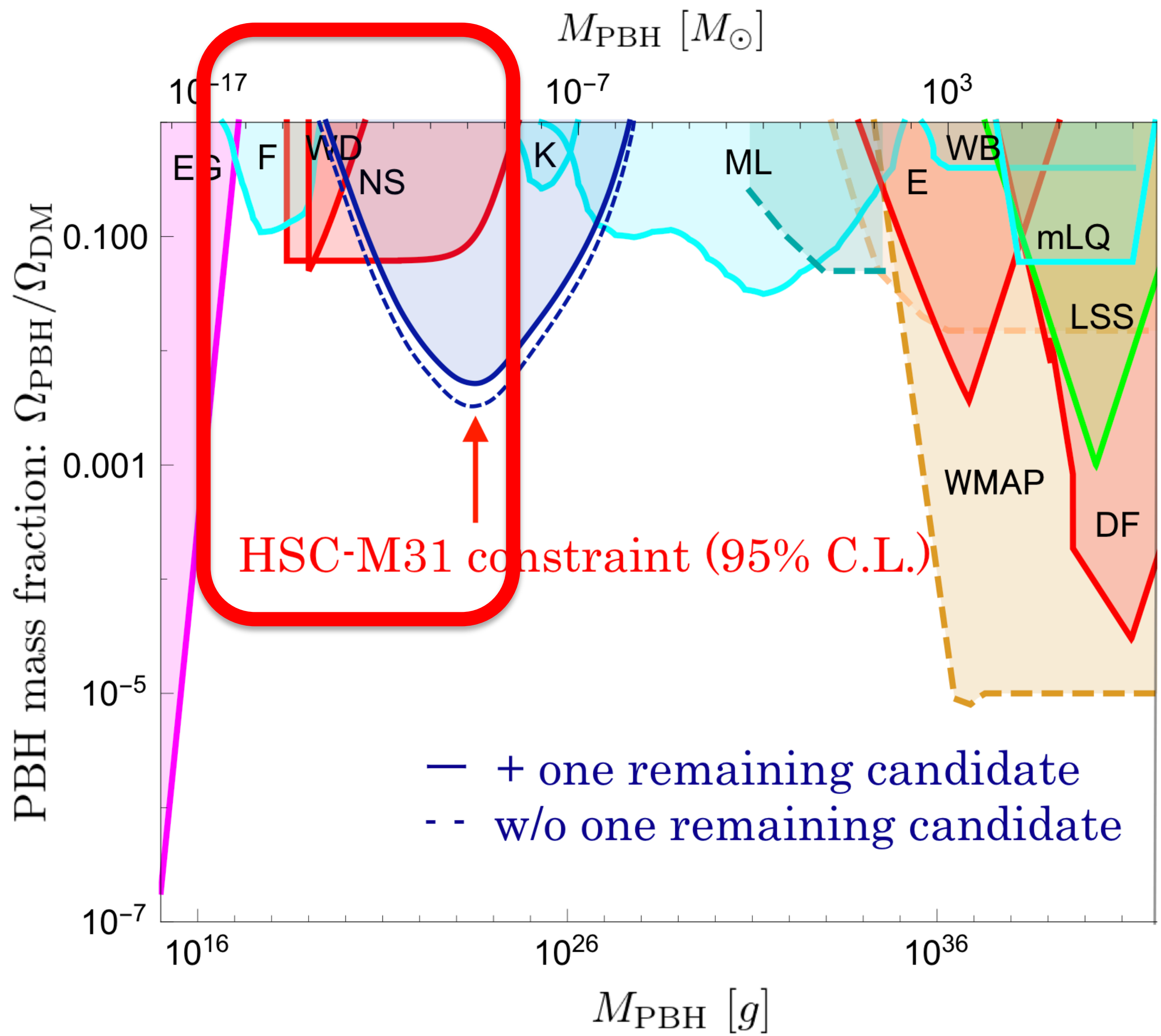


Posterior Probability for ALP mass

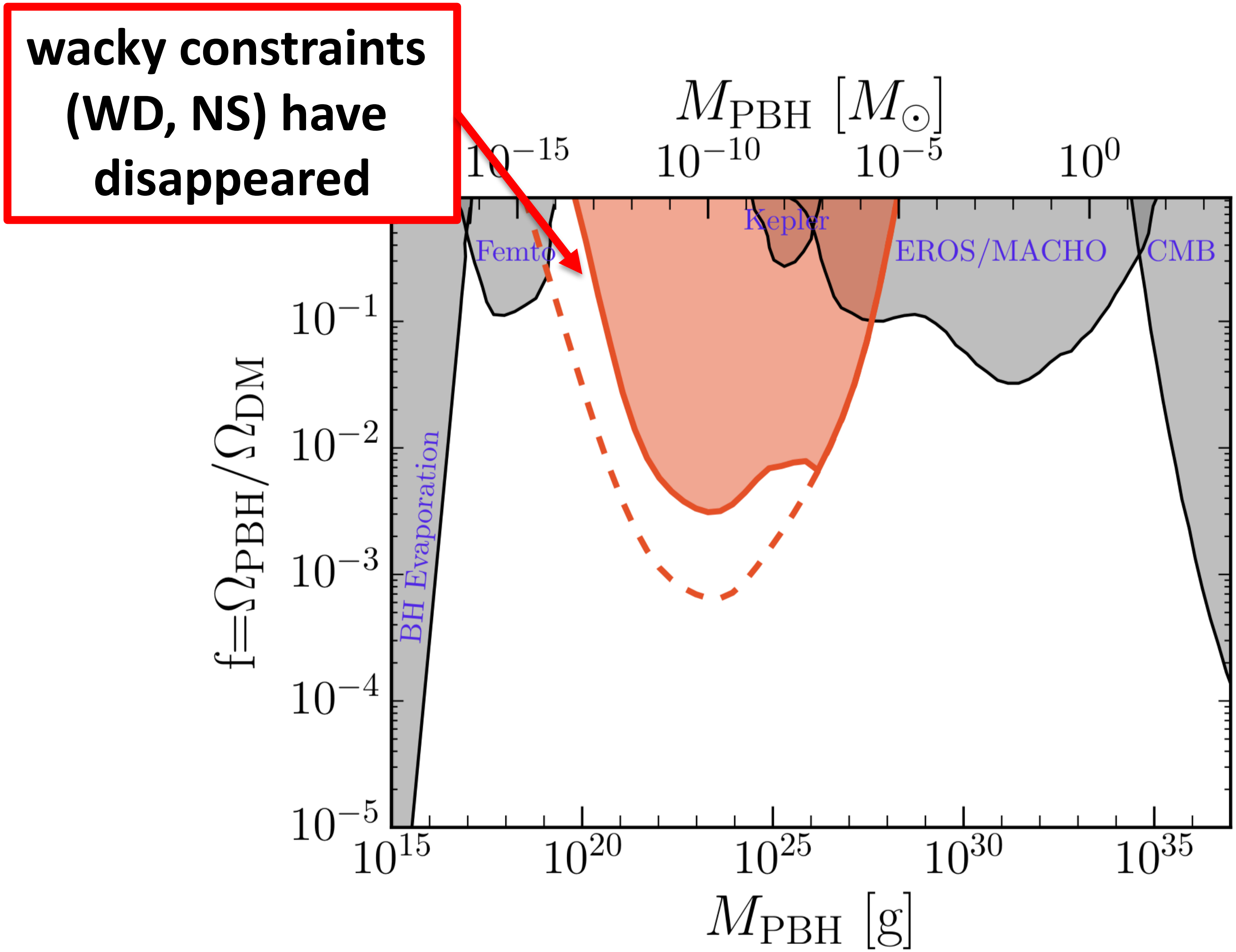
*Fernandez, Ghalsasy, Profumo, 1911.07862



0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−15
−10
−5
0
$\log_{10} f_{PBH}$
$\log_{10}(M_c/M_\odot)$
FL
WD
NS
K
M
Planck
WB
EROS
HSC
Eri II
Seg I
THIS PLOT IS WRONG

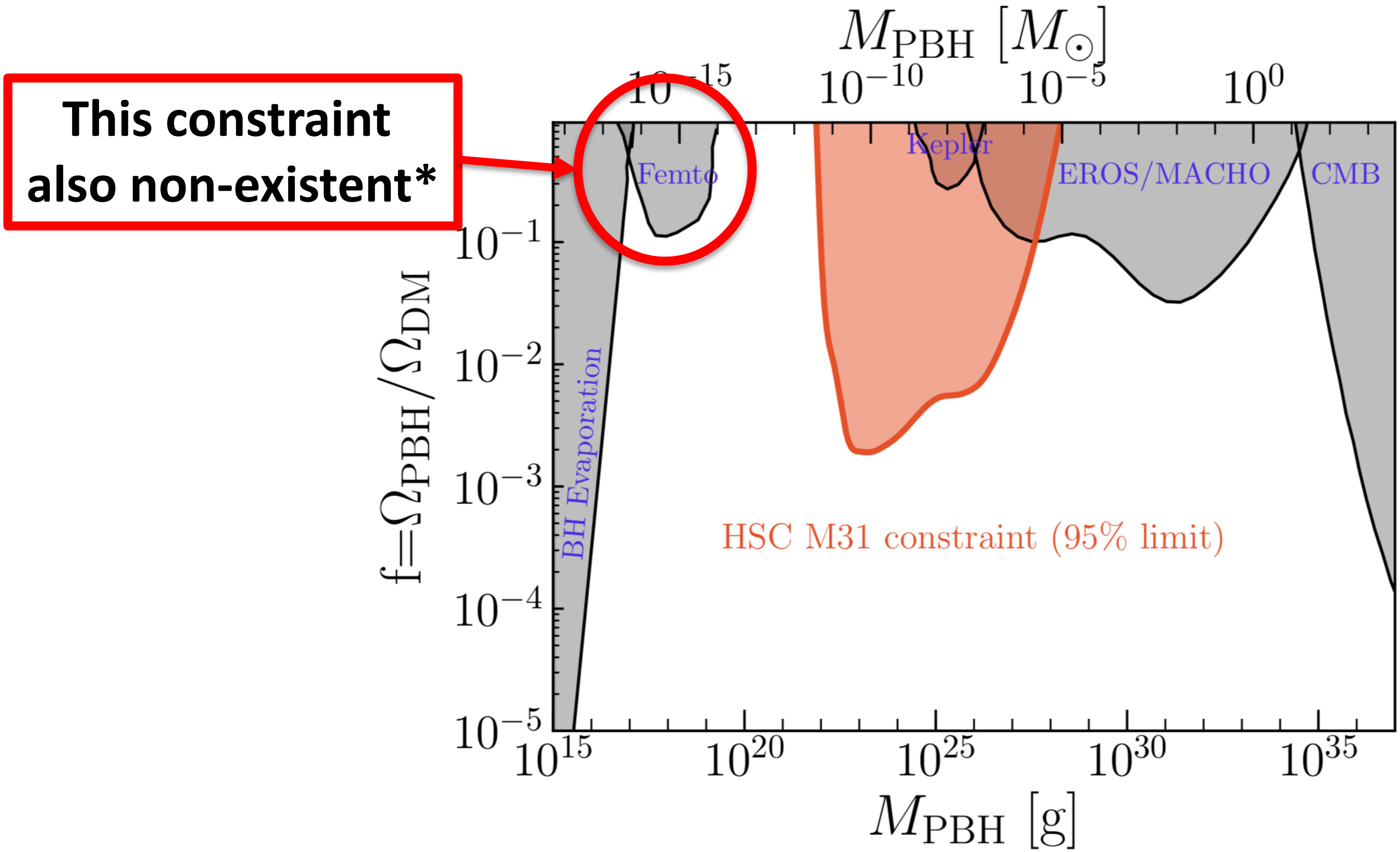


SUBARU HSC microlensing, 1701.02151 VERSION 1



SUBARU HSC microlensing, 1701.02151 VERSION 2: wave effects

* Katz et al, 1807.11495



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

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

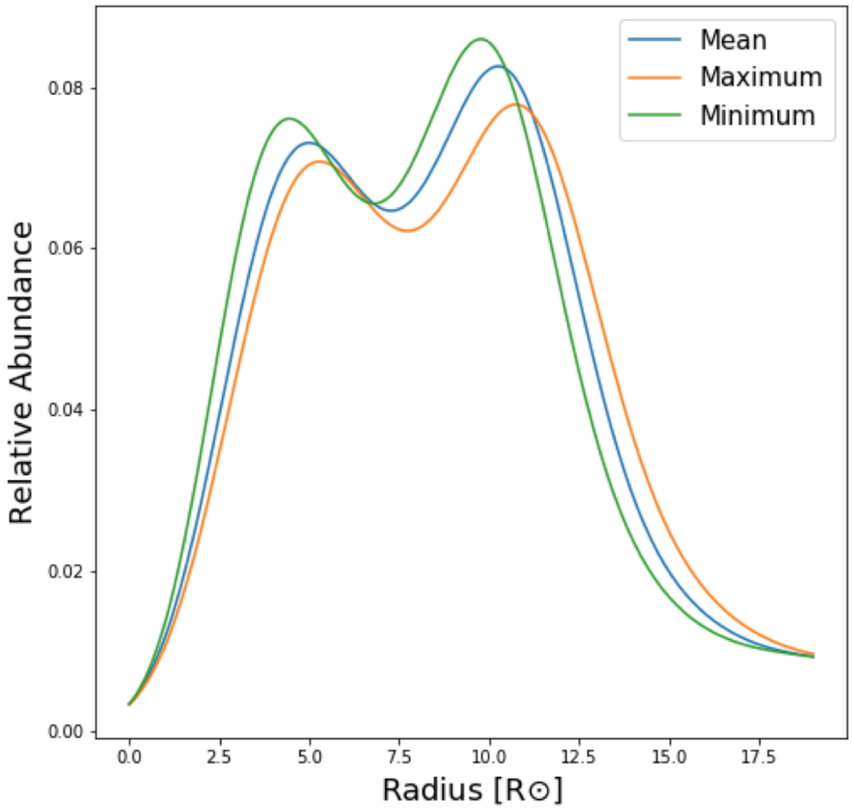
…but are these bounds **robust**?

A few (worrisome) **assumptions**:

- All stars are at the same **distance**
- All stars have the same **size** (1 R_{sun})
- DM is completely **smooth**

* Smyth, Profumo et al, 1910.01285, PRD

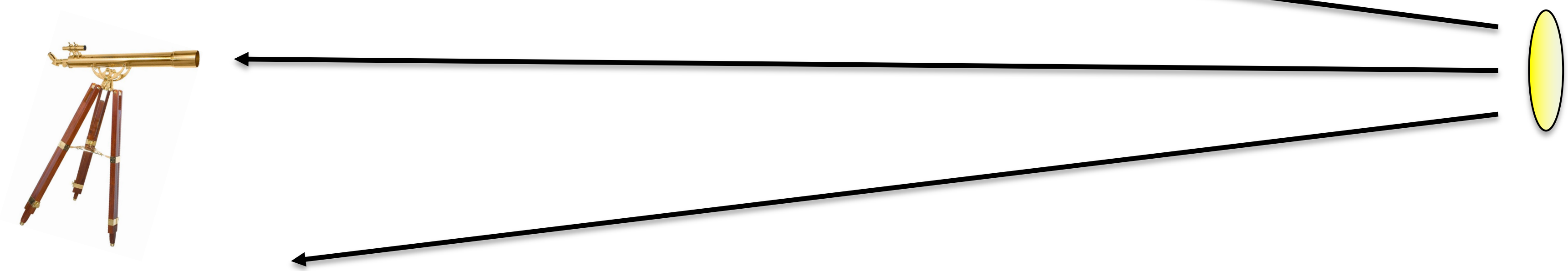
Sun-like stars are however too dim for HSC!



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

* Profumo, Smyth+ PRD 2020

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



* Profumo, Smyth+ PRD 2020

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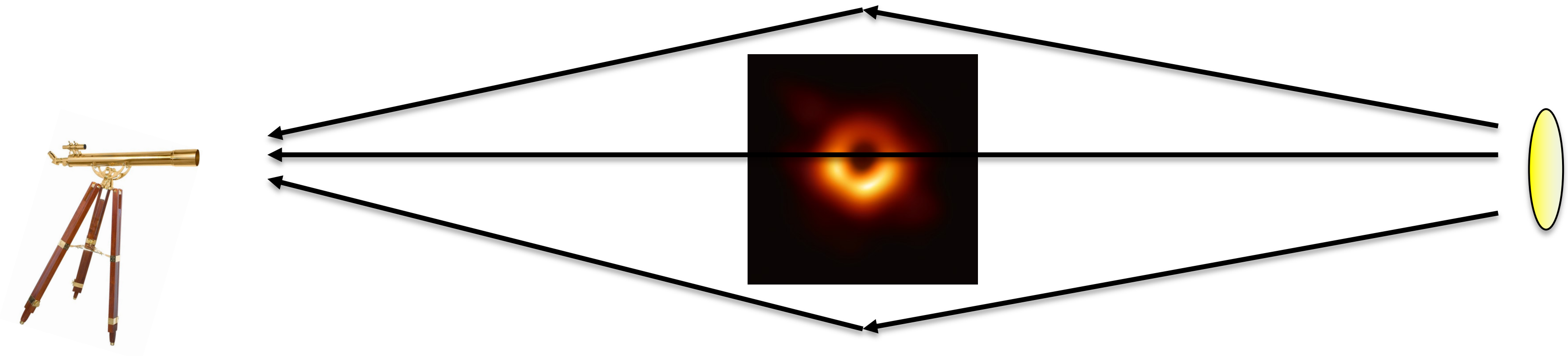

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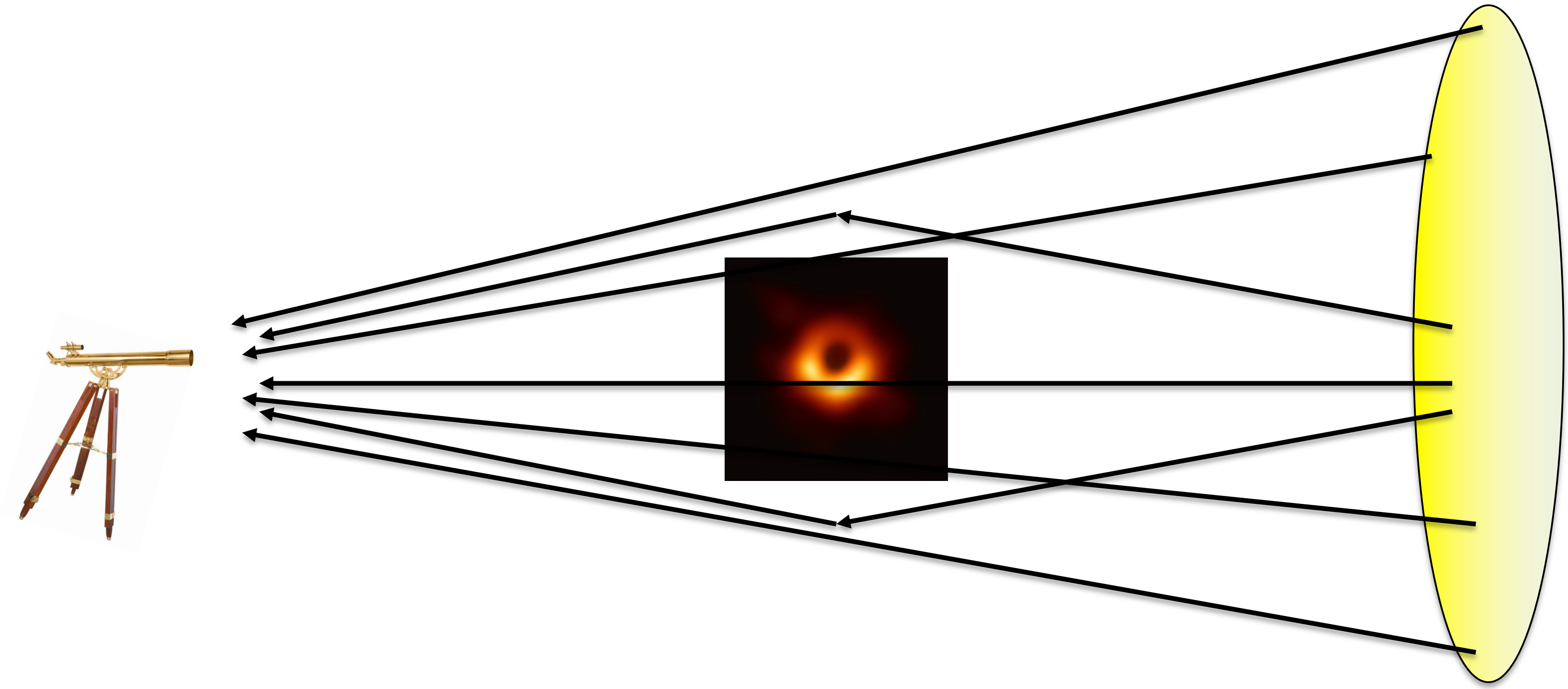

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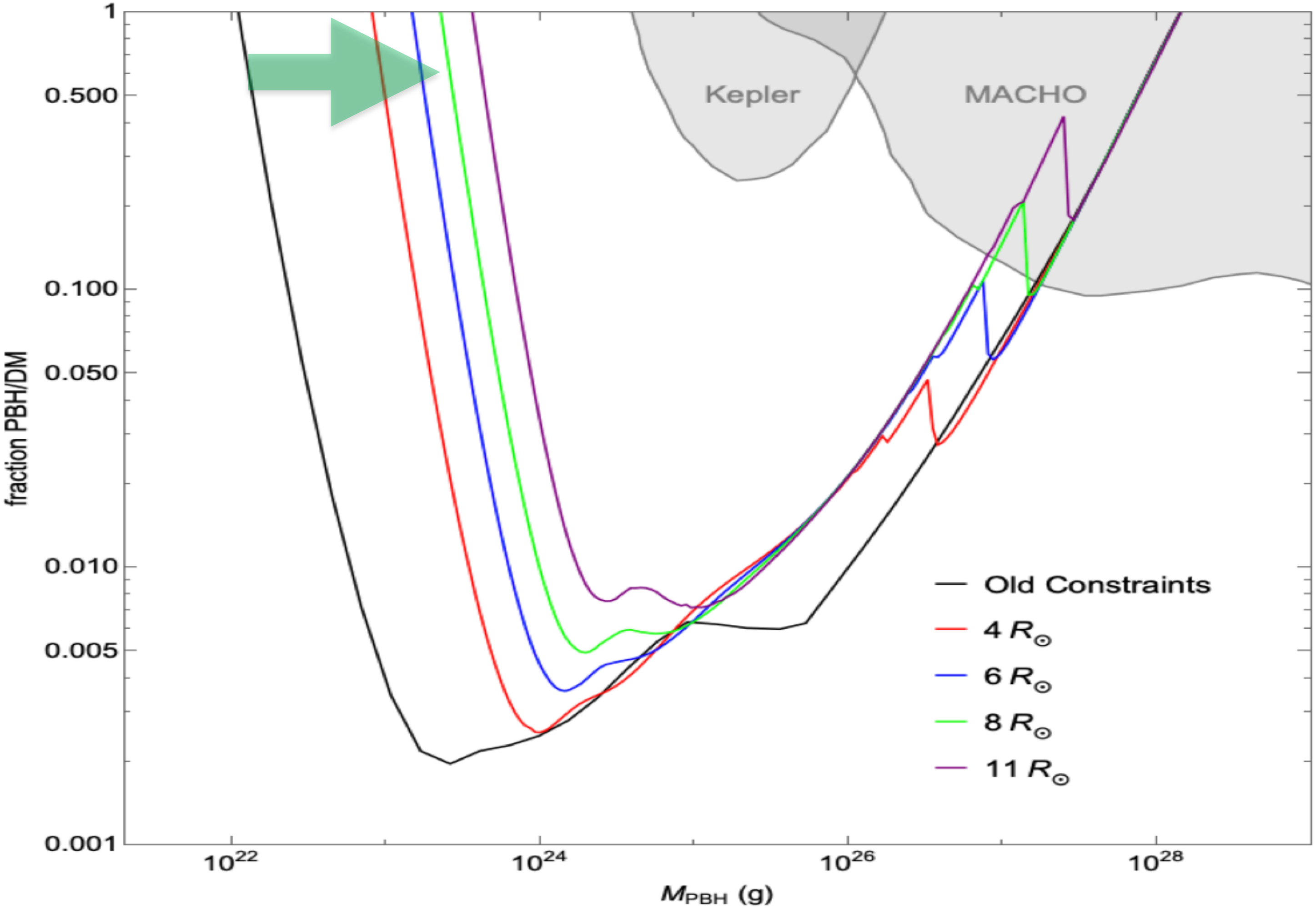
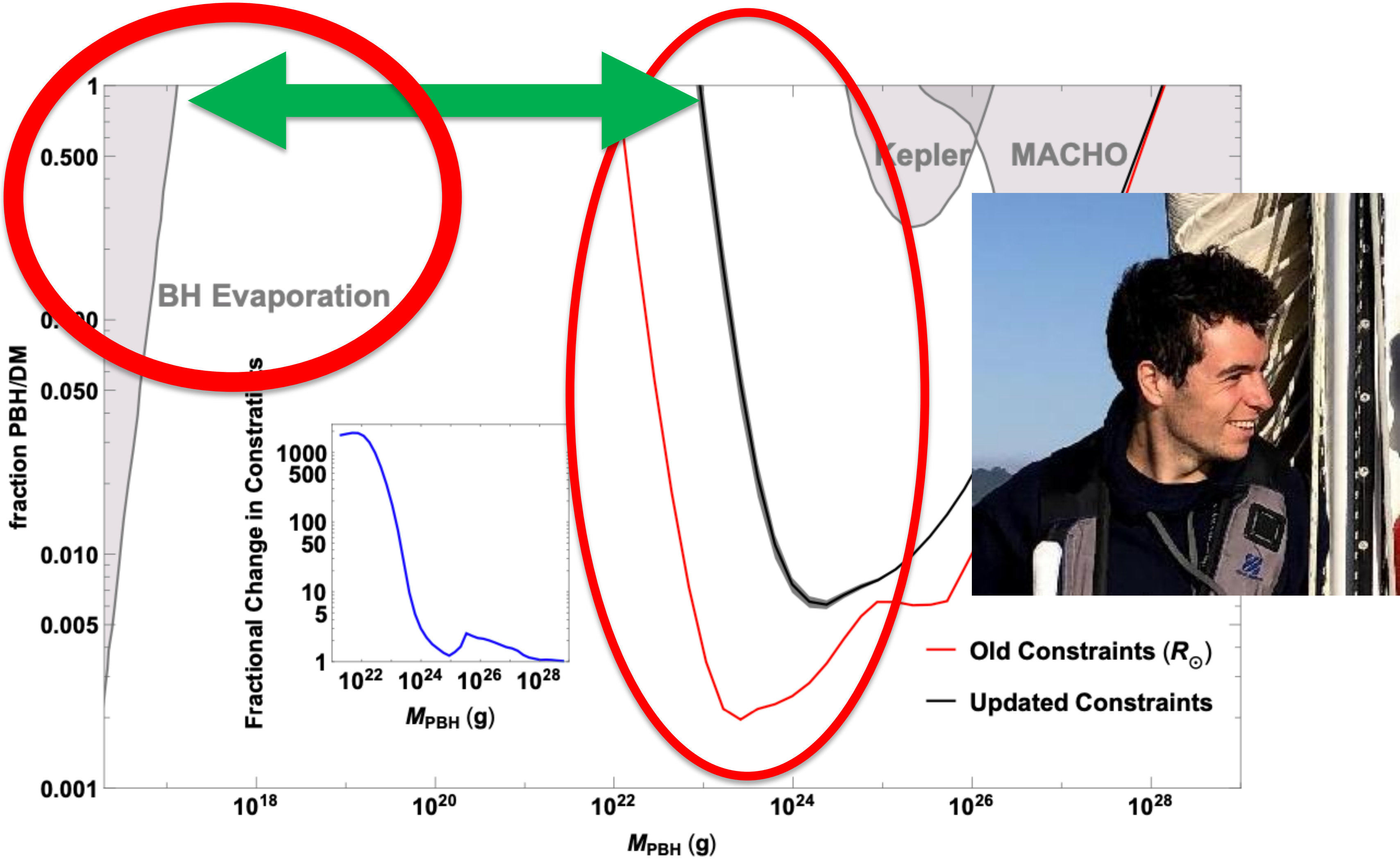


* Profumo, Smyth+ PRD 2020



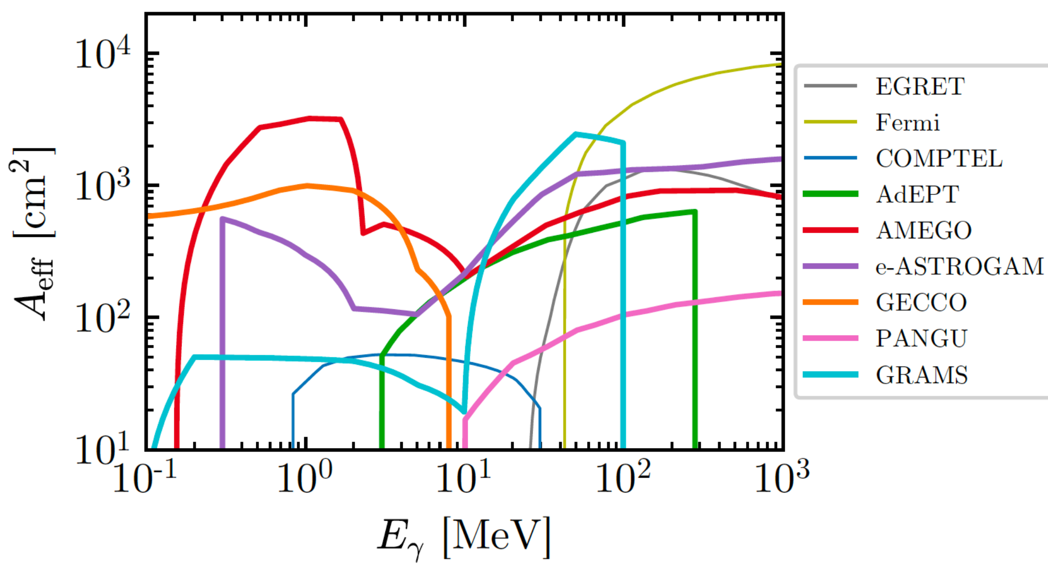
How do we go after them? Capture and perturbation around PSR?

* Profumo, Smyth+ PRD 2020

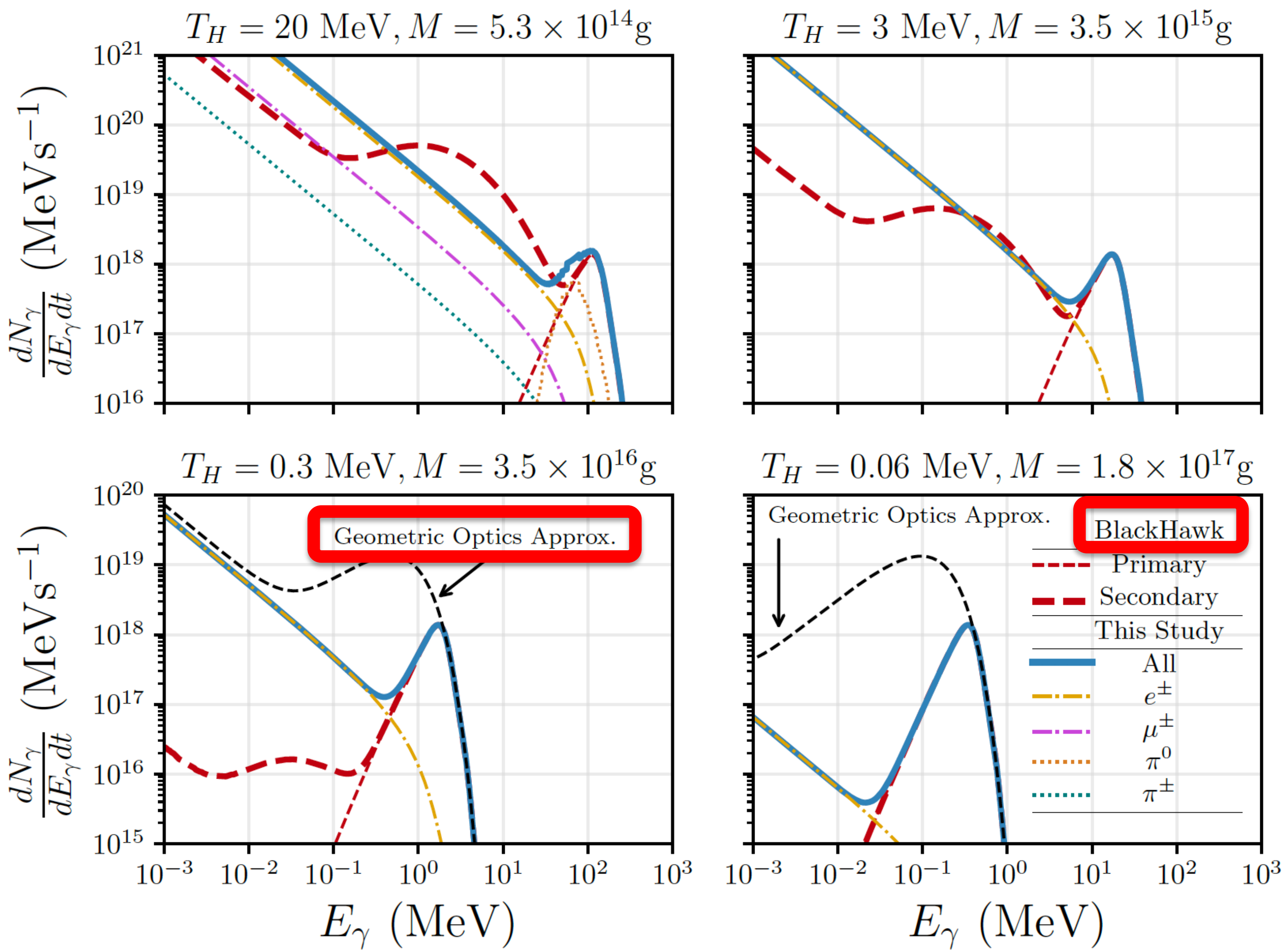
Lightest PBH that can be dark matter…

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

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

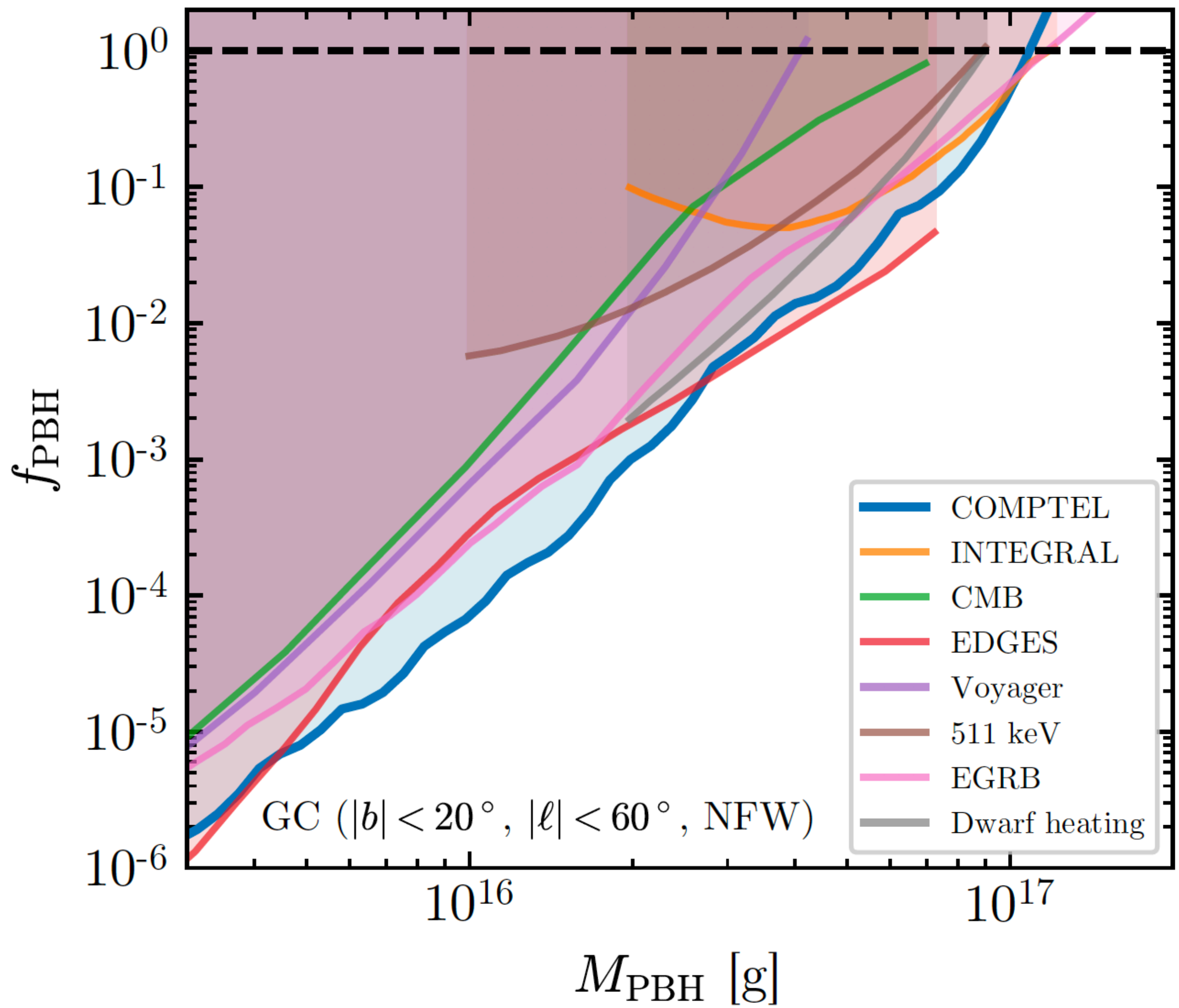


Coogan, Morrison & Profumo, 2010.04797



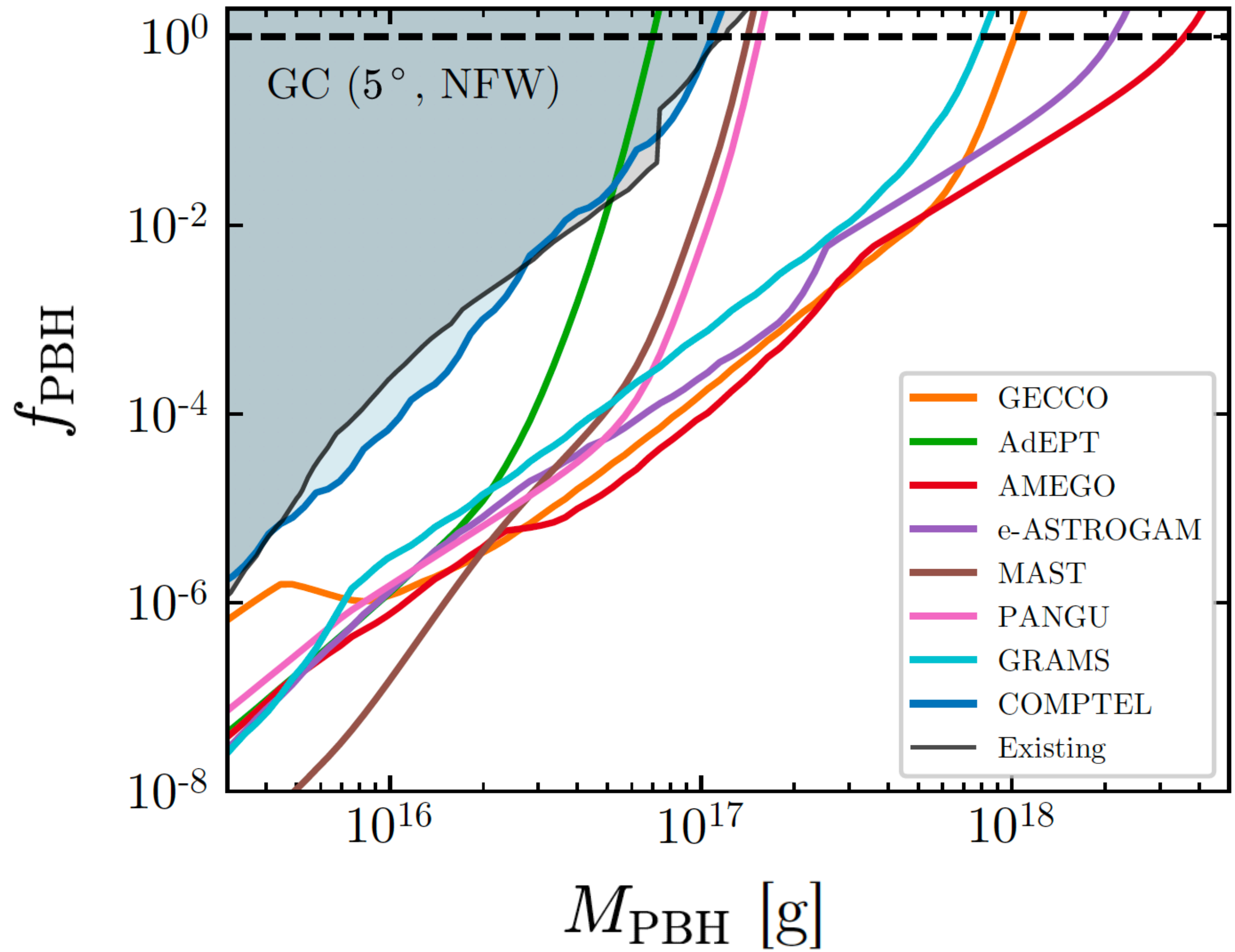
Coogan, Morrison & Profumo, 2010.04797

Our new COMPTEL constraints are among strongest/robust



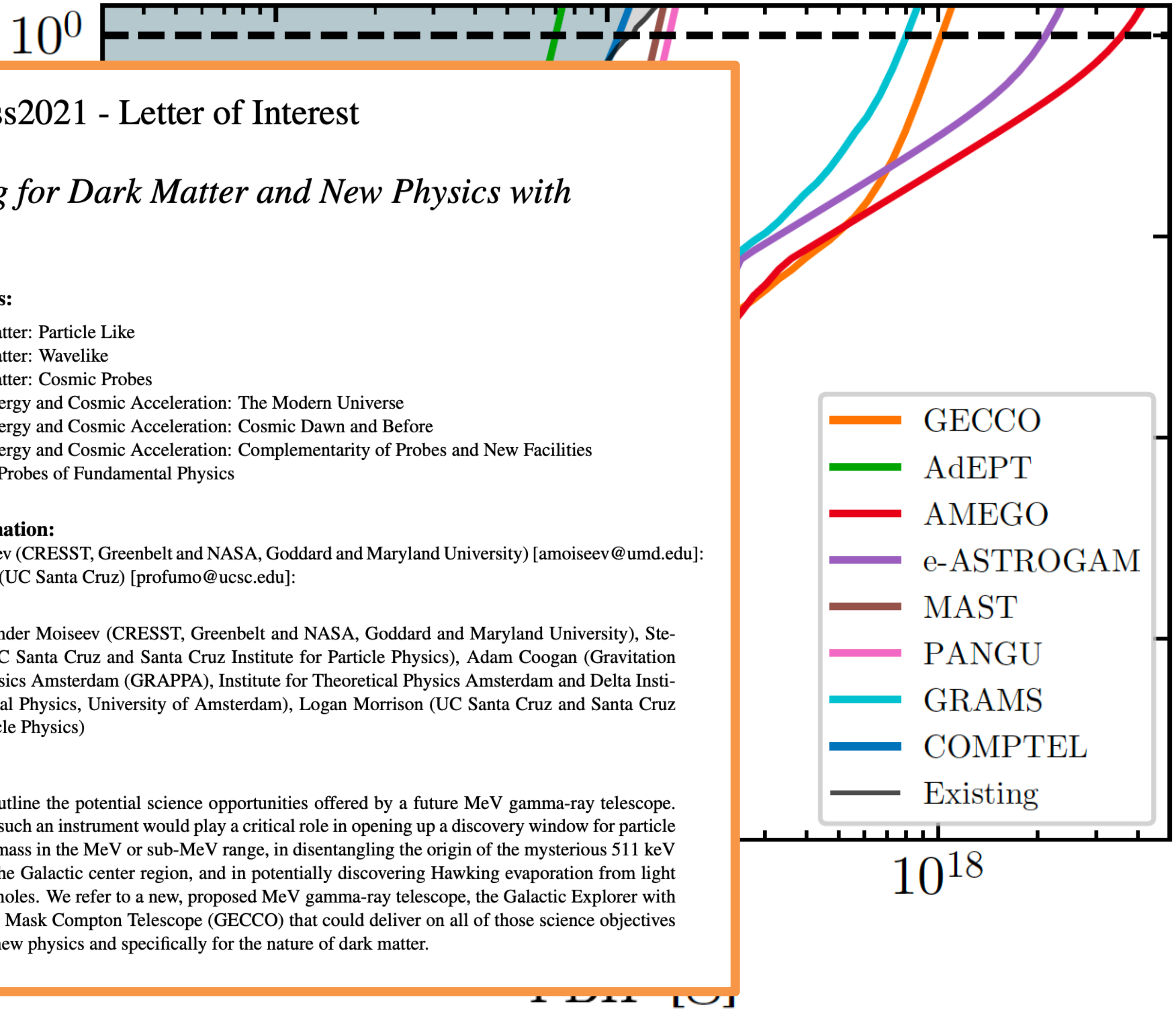
Coogan, Morrison & Profumo, 2010.04797

New MeV Telescopes could discover Hawking evaporation!



Coogan, Morrison & Profumo, 2010.04797

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

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

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

Coogan, Morrison & Profumo, 2010.04797

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

Melanopogenesis: Dark Matter of (almost)

WORLD CUBE ASSOCIATION

Search site

Information | Competitions | Results | Regulations

John Tamanas

Country	WCA ID	Gender	Competitions
United States	2007TAMA02	Male	41

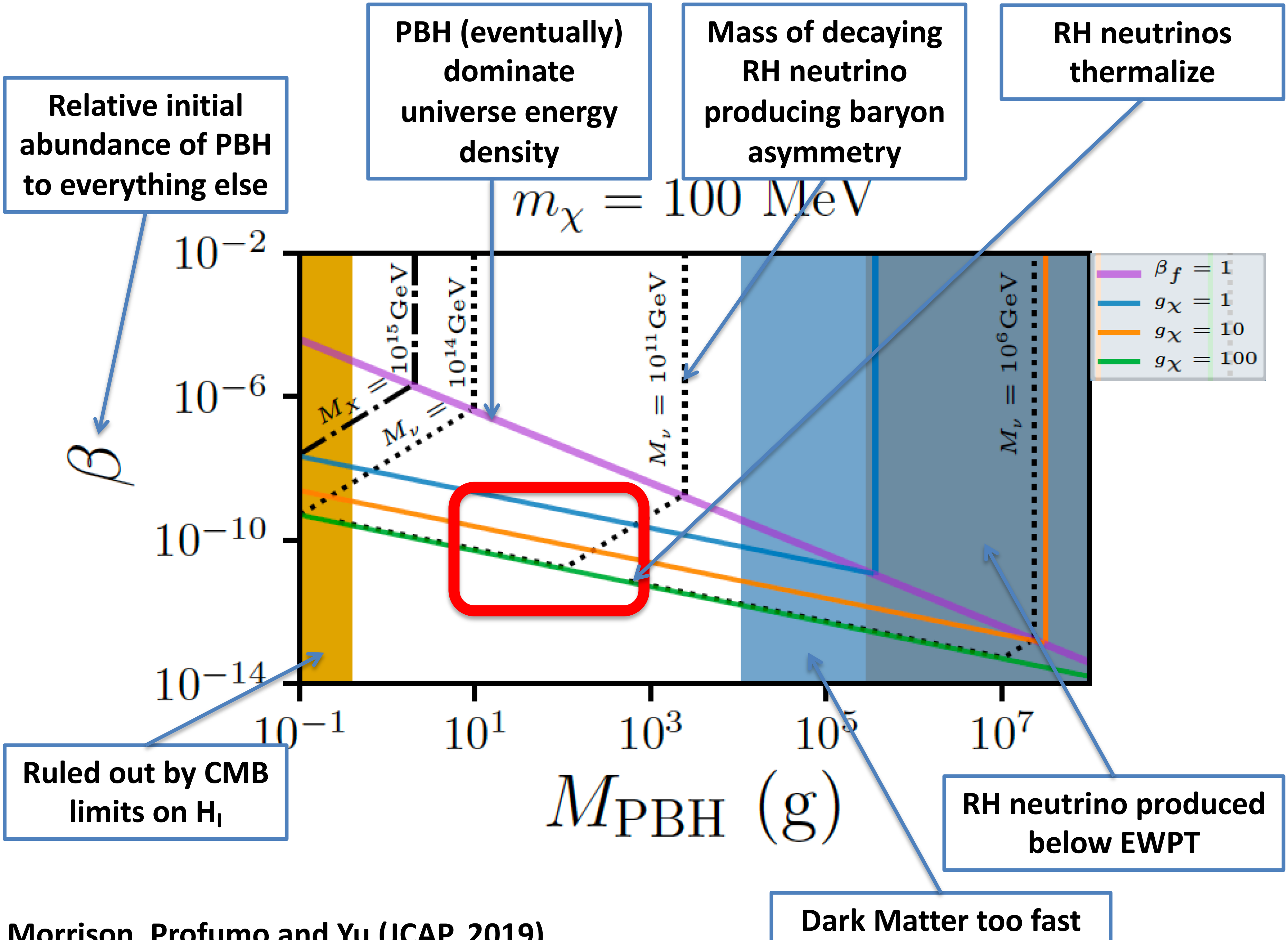
Current Personal Records

Event	NR	CR	WR	Single	Average
3x3x3 Cube	330	424	1485	**8.16**	**10.13**
2x2x2 Cube	195	265	901	**1.55**	**3.49**
4x4x4 Cube	1115	1644	7465	**51.91**	**58.40**
5x5x5 Cube	1654	2403	9997	**2:28.52**	**2:43.81**
3x3x3 Blindfolded	666	900	4609	**5:47.28**	

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

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

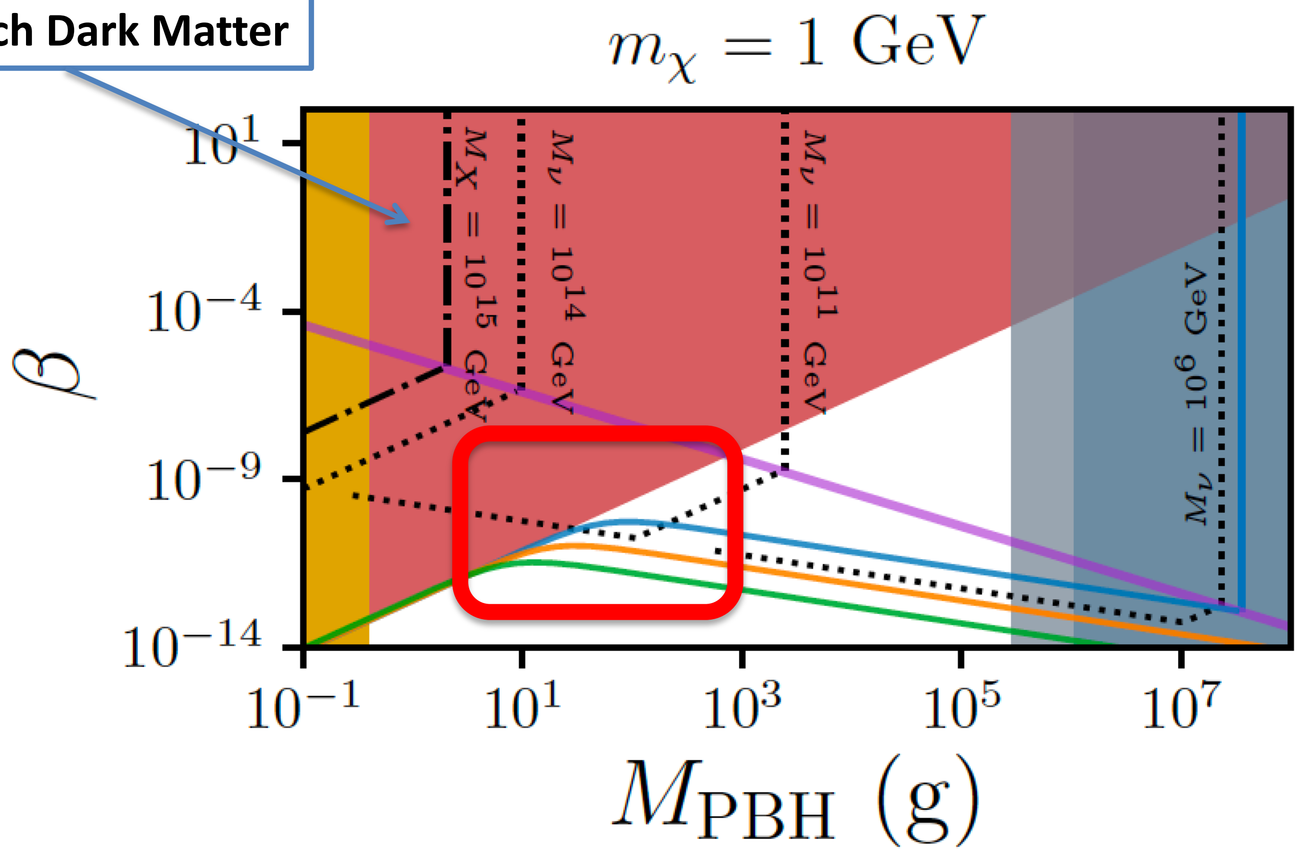
* Morrison, Profumo and Yu (JCAP, 2019)



* Morrison, Profumo and Yu (JCAP, 2019)

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

Too much Dark Matter



* Morrison, Profumo and Yu (JCAP, 2019)

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

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

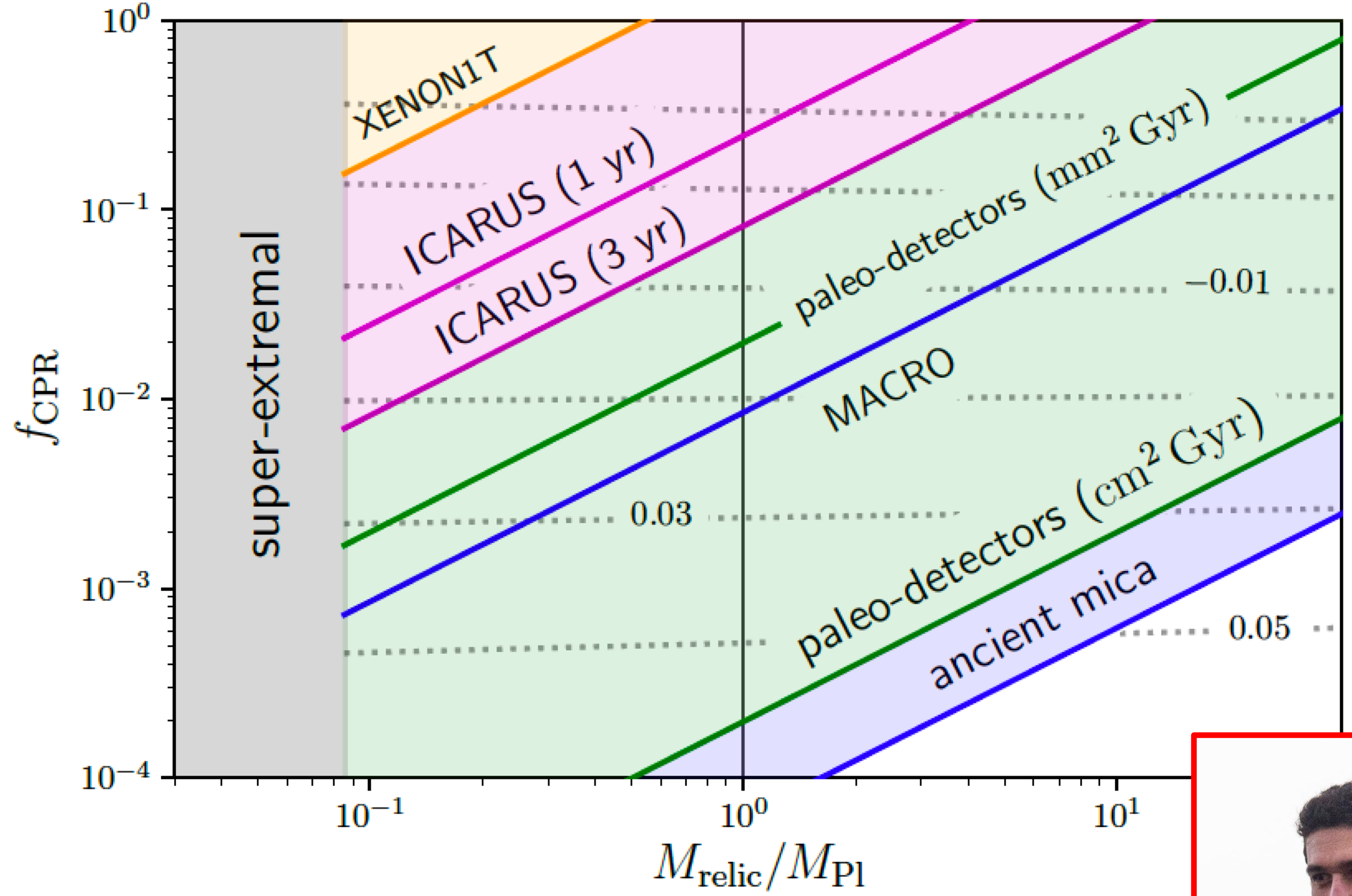
$$P(Q) \sim \exp\left(-4\pi\alpha(Q/e)^2\right)$$

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

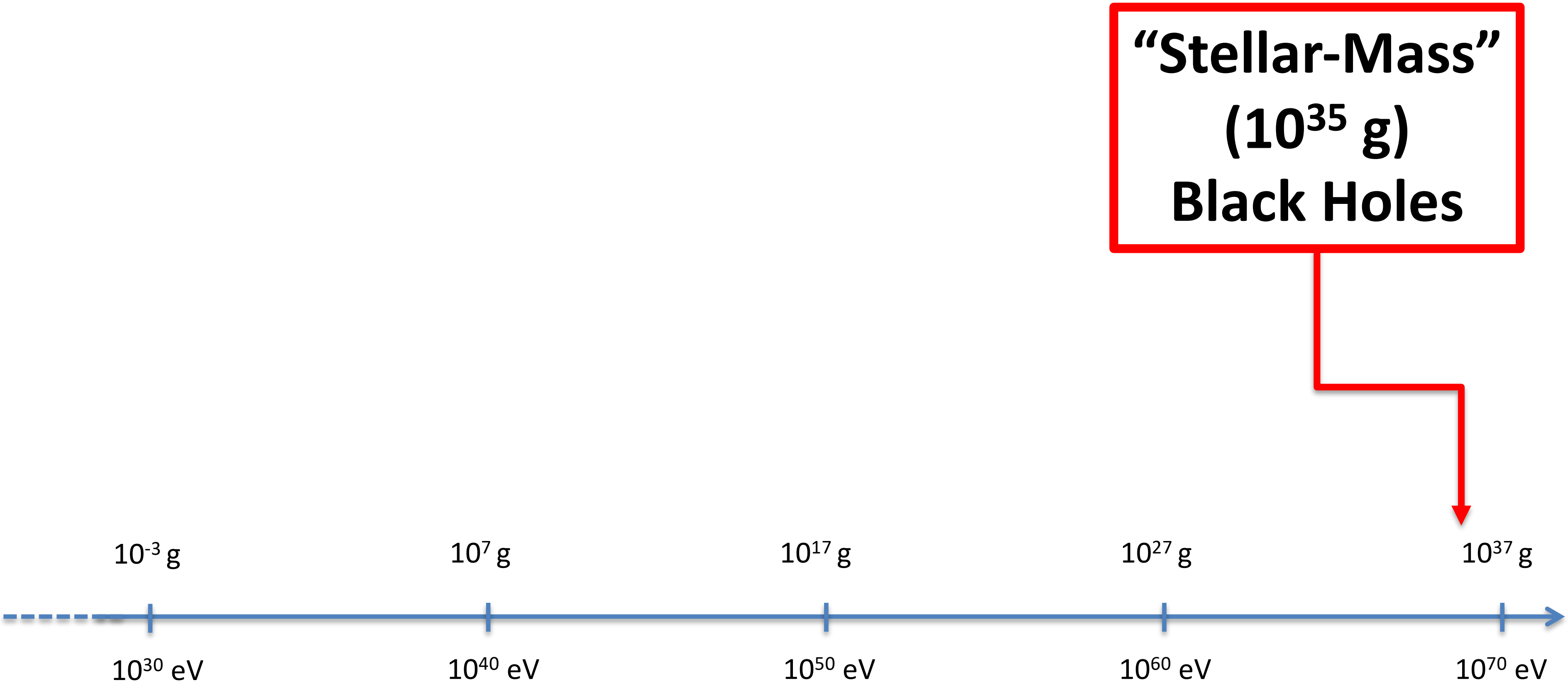
If evaporation stops around the Planck scale (because of extremality, or because of quantum gravity) we are left with a population of charged, Planck-scale relics!

* Page, 1977

** Lehmann, Johnson, Profumo and Schwemberger, 1906.06348



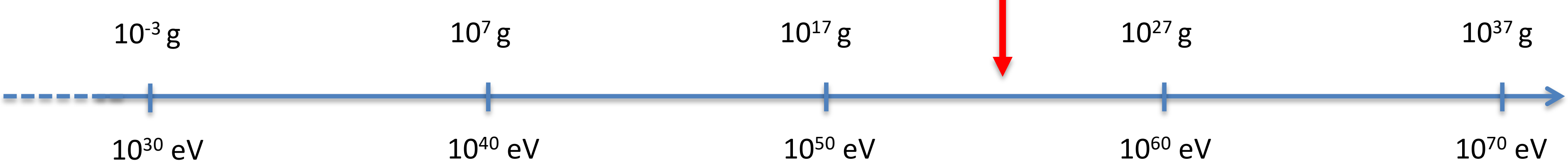
* Lehmann, Johnson, Profumo and Schwemberger, 1906.06348



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

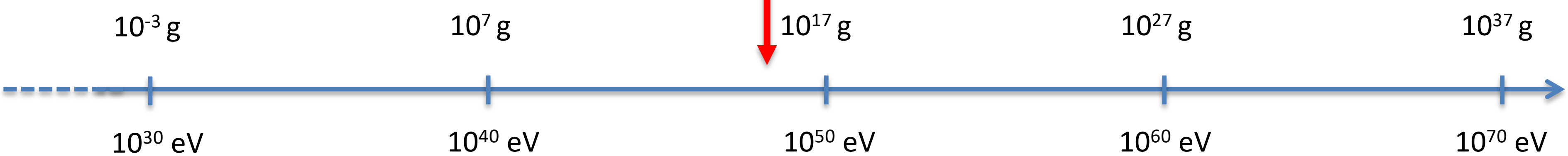
*** Gaspari, Lehmann, Profumo, in preparation**

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

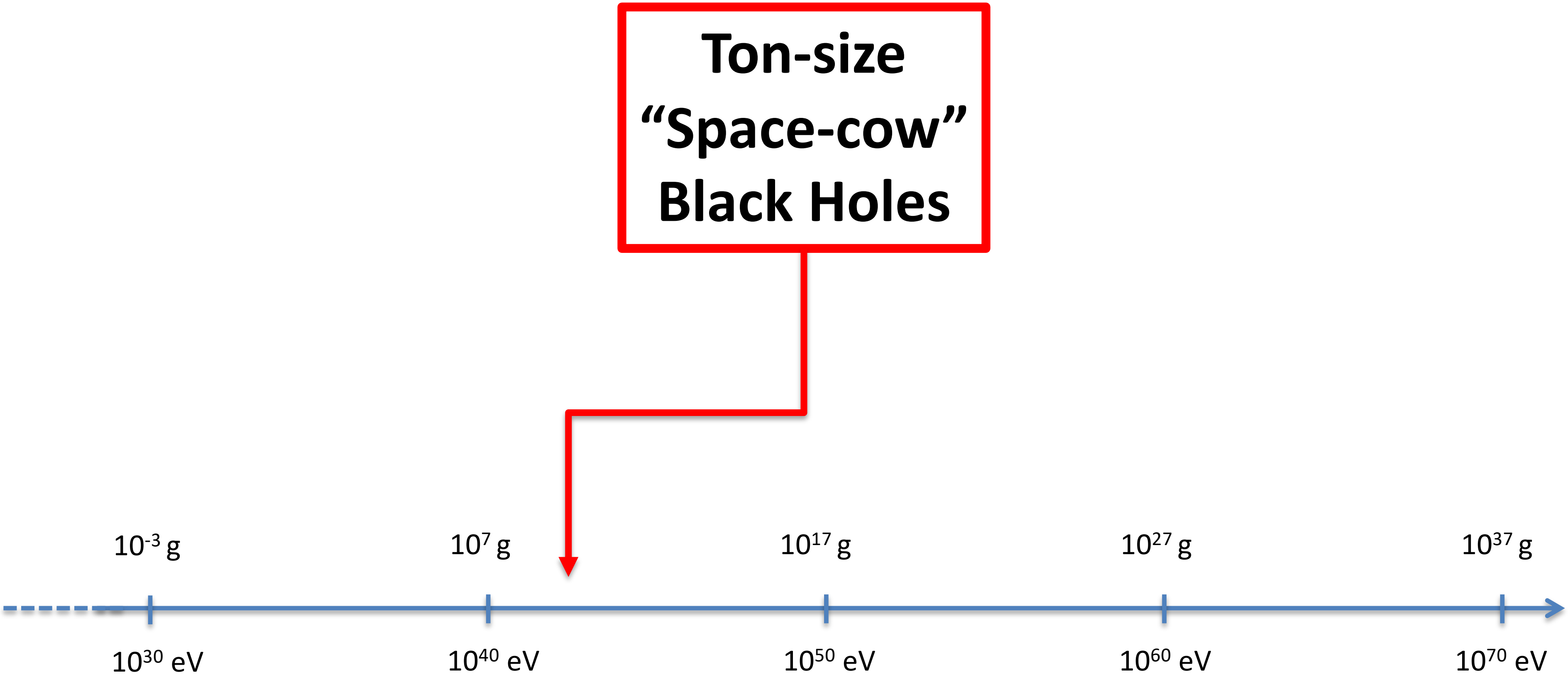


- ✓ **Microlensing a lot trickier than previously thought!**
- ✓ **Detection strategies? PTA?**

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

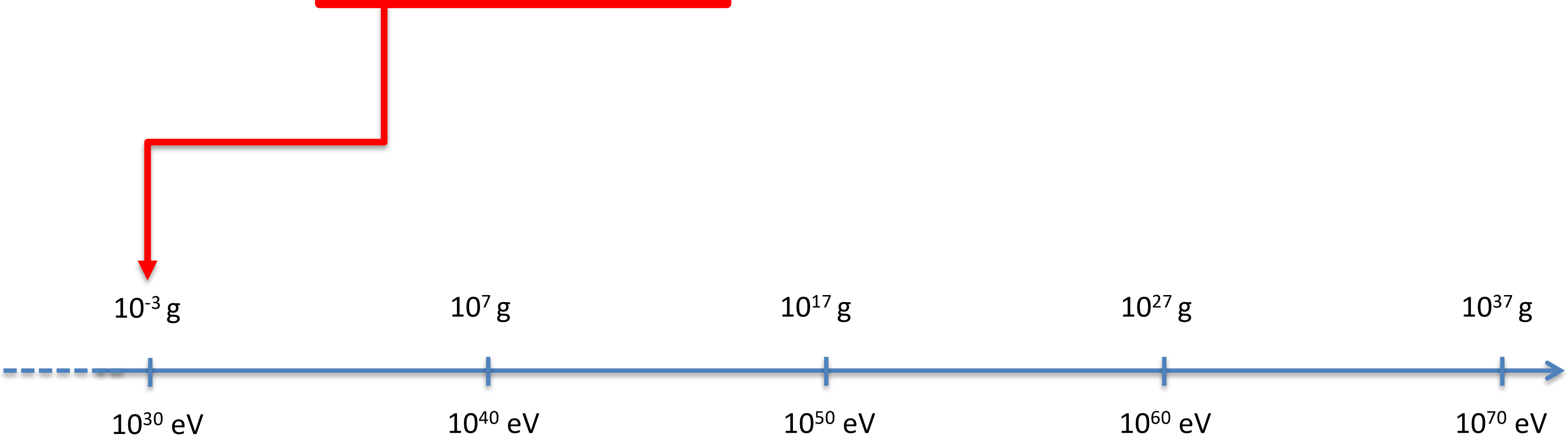


- ✓ **Best constraints: COMPTEL**
- ✓ **Future MeV telescopes**



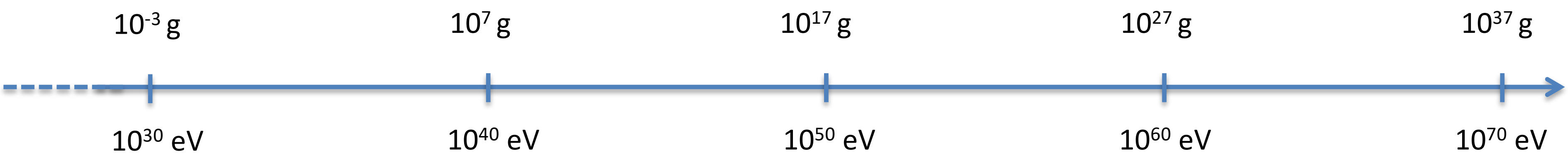
✓ **Decays can produce DM, BAU, Planck relics**

Grain-of-Salt “No-see-ums” Black Holes



- ✓ **Likely (partly) charged**
- ✓ **Detectable!**

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

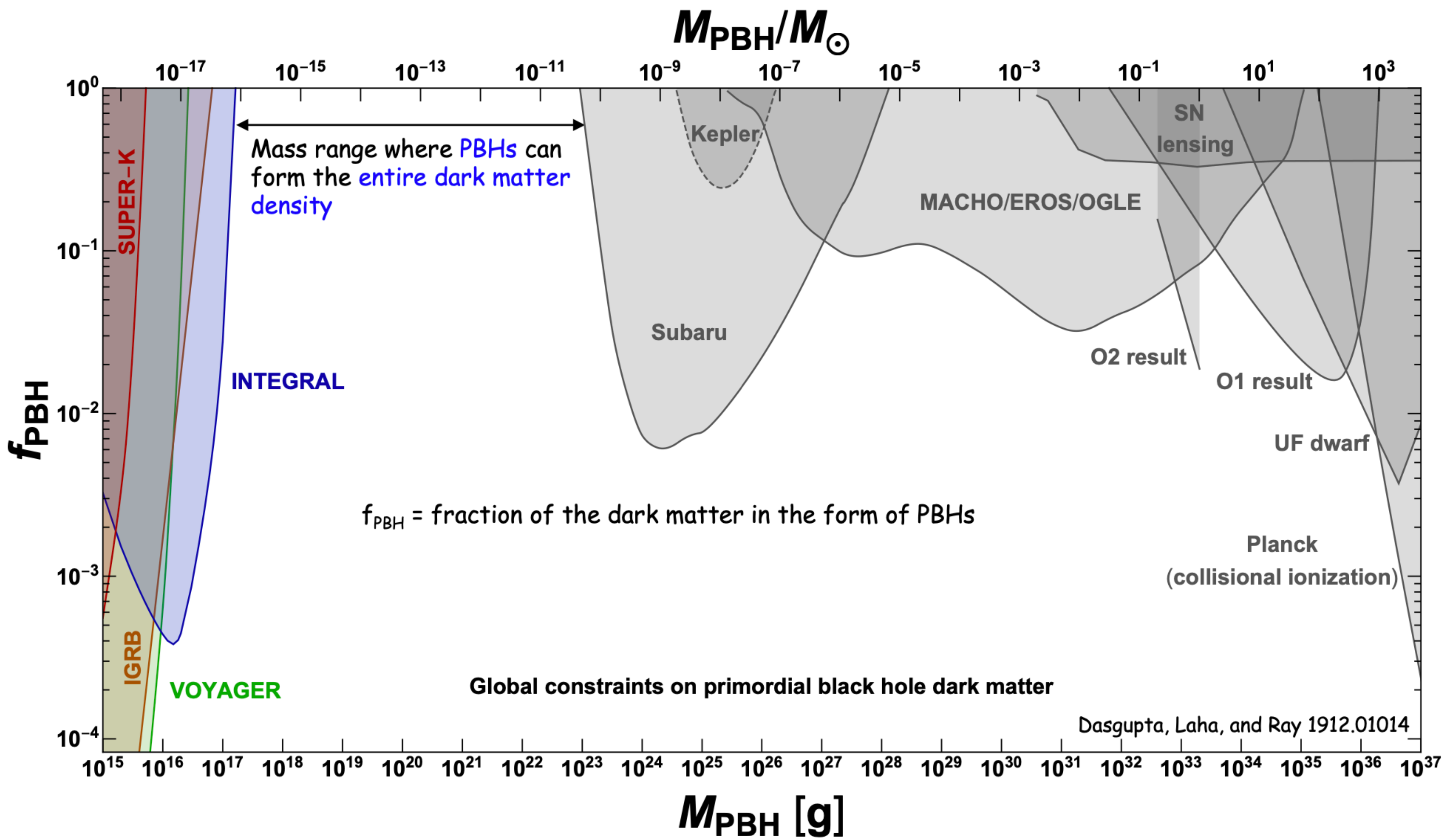


Merger rate calculation (Cheng+Huang, 2018; Raidal +, 2017)

$$\tilde{\tau}(m_1, m_2, m_3) = \frac{348}{85} \frac{\alpha^4 \beta^7 a_{\mathrm{eq}}^4 m_3^7 \tilde{x}(m_1, m_2)^4}{G^3 m_1 m_2 (m_1 + m_2)^8}.$$

$$\mathcal{G}(\psi;\ m_1, m_2, m_3) = \Gamma\left(\frac{58}{37},\ \frac{\tilde{N}(\psi;\ m_1, m_2)\, t^{3/16}}{\tilde{\tau}(m_1, m_2, m_3)^{3/16}}\right) - \Gamma\left(\frac{58}{37},\ \frac{\tilde{N}(\psi;\ m_1, m_2)\, t^{-1/7}}{\tilde{\tau}(m_1, m_2, m_3)^{-1/7}}\right),$$

$$\mathcal{R}(m_1, m_2) = \frac{9\bar{m}(\psi)^3 \tilde{N}(\psi;\ m_1, m_2)^{\frac{53}{37}}}{296\pi \delta_{\mathrm{dc}} \tilde{x}(m_1, m_2)^3 t^{34/37}} \times \frac{\psi(m_1)\psi(m_2)}{m_1 m_2} \int \mathrm{d}m_3\, \frac{\mathcal{G}(\psi;\ m_1, m_2, m_3)}{\tilde{\tau}(m_1, m_2, m_3)^{3/37}} \frac{\psi(m_3)}{m_3}.$$



$M_{PBH}/M_\odot$
f_{PBH}
SUPER-K
INTEGRAL
IGRB
VOYAGER
Mass range where PBHs can form the entire dark matter density
Kepler
Subaru
MACHO/EROS/OGLE
SN lensing
O2 result
O1 result
UF dwarf
Planck (collisional ionization)
f_{PBH} = fraction of the dark matter in the form of PBHs
Global constraints on primordial black hole dark matter
Dasgupta, Laha, and Ray 1912.01014
M_{PBH} [g]