



SCIPP

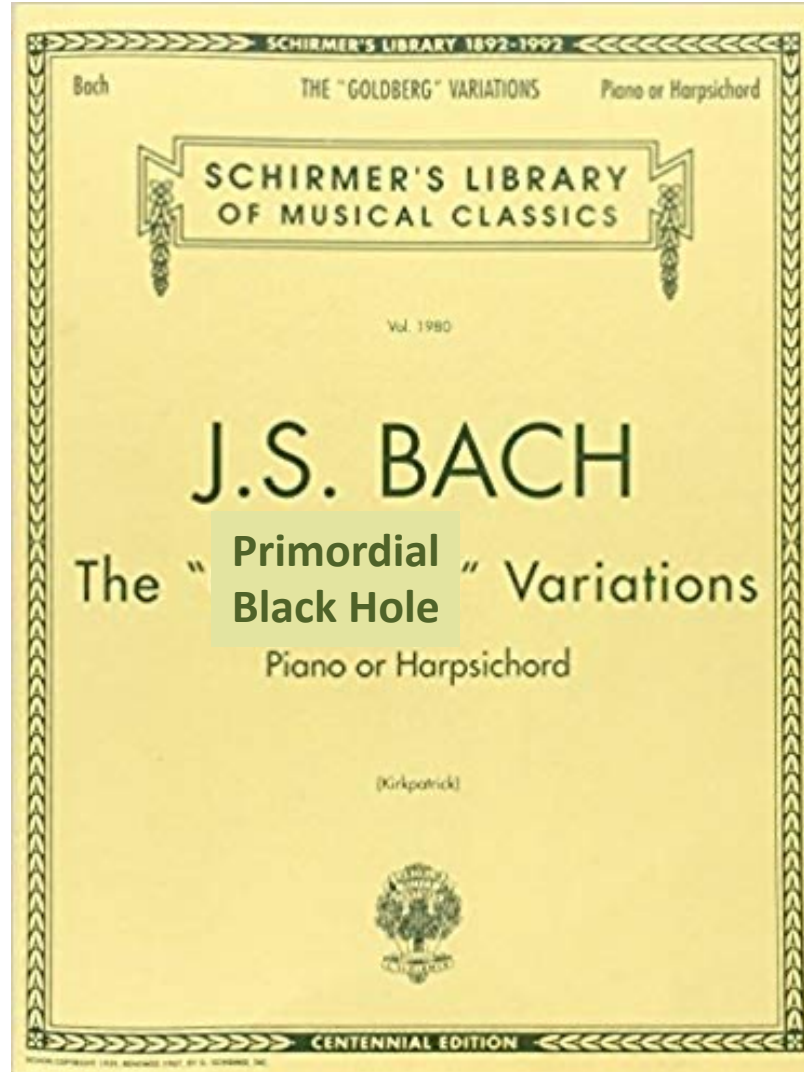
SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS

Stefano Profumo

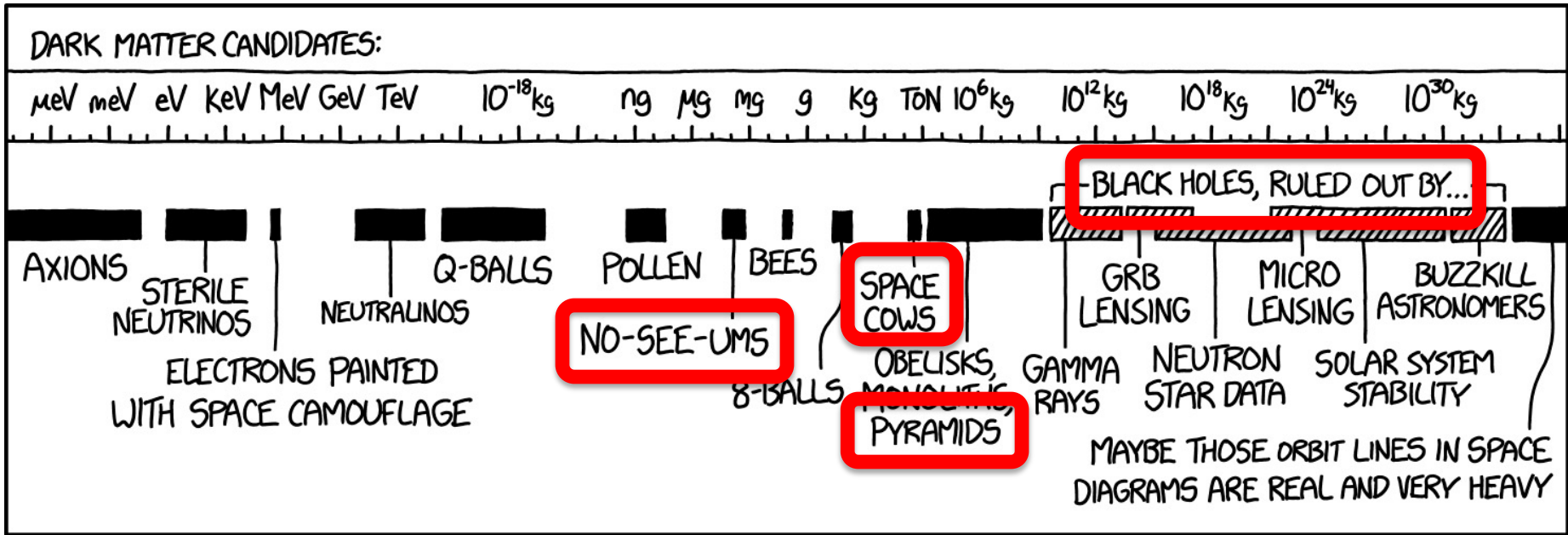
University of California, Santa Cruz



UC SANTA CRUZ



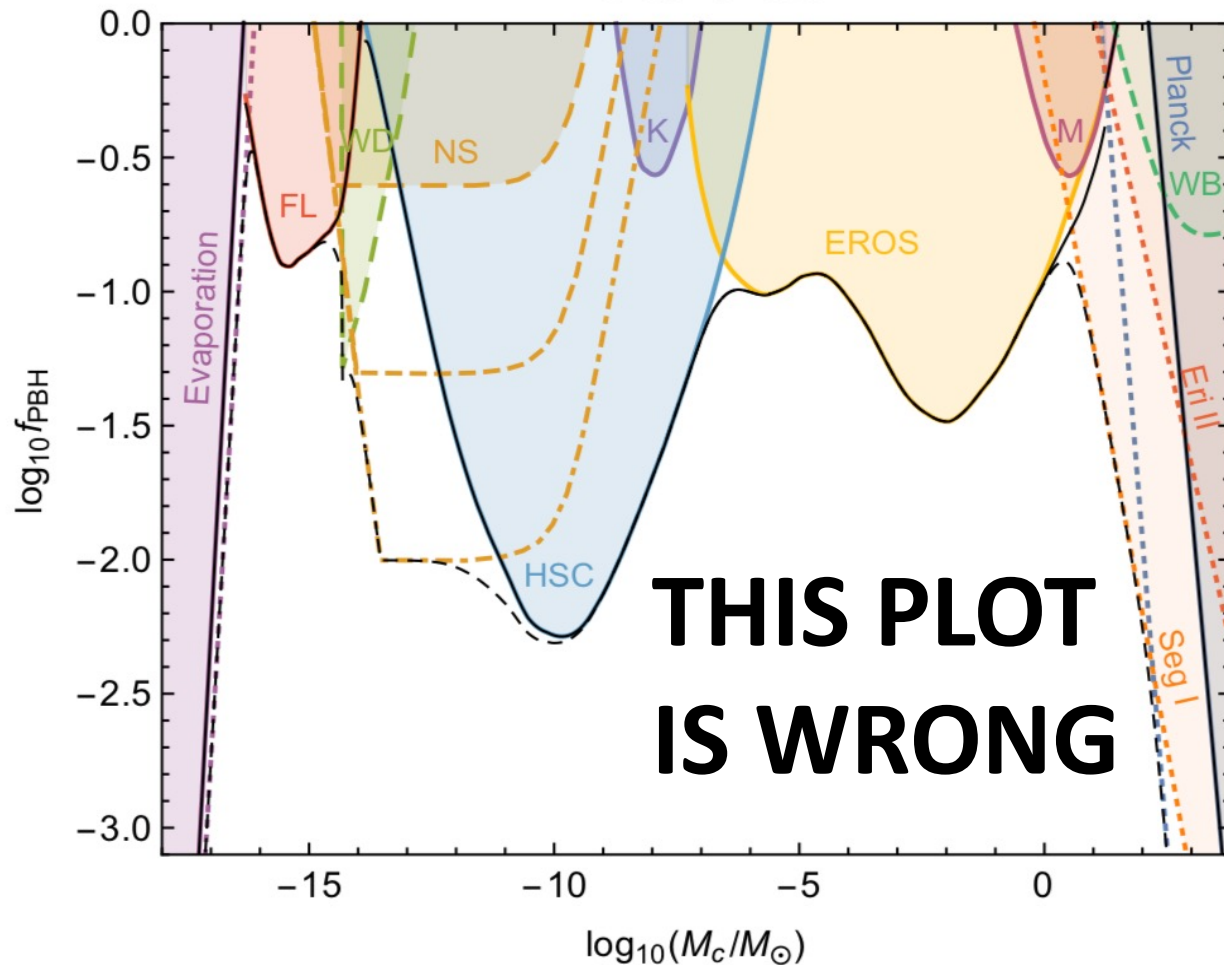
Beyond the Standard Model BSM2021 – March 31, 2021



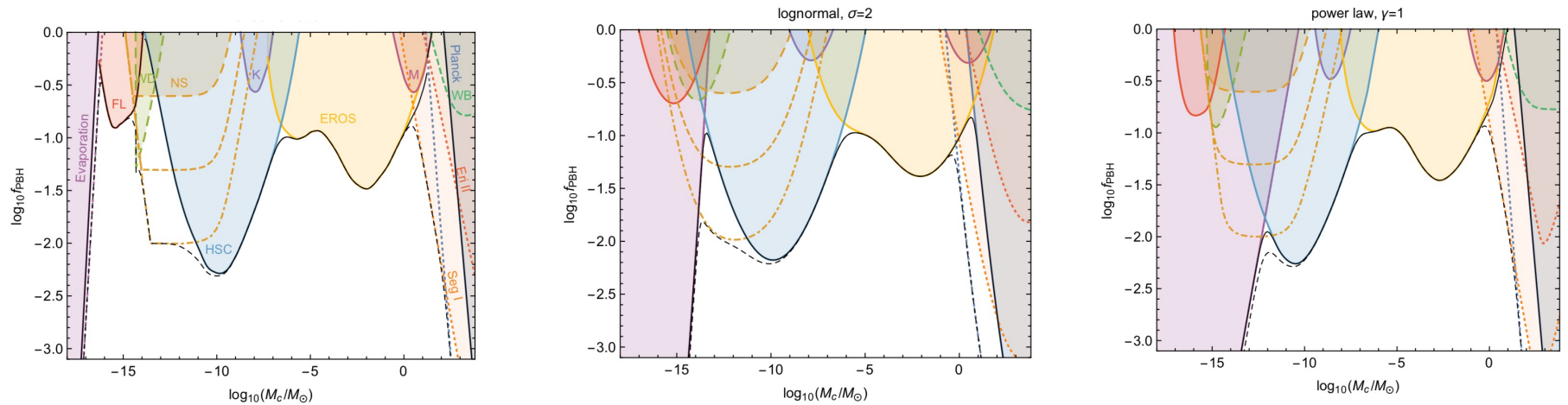
- **Why** it is interesting to consider **PBH** as **Dark Matter**
- **Where** it is interesting to **look** for PBH as Dark Matter
- ...some **"NO-SEE-UMS"**, **"SPACE COWS"**, **"PYRAMIDS"**

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

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



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**?

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

Benjamin V. Lehmann, Stefano Profumo and Jackson Yant

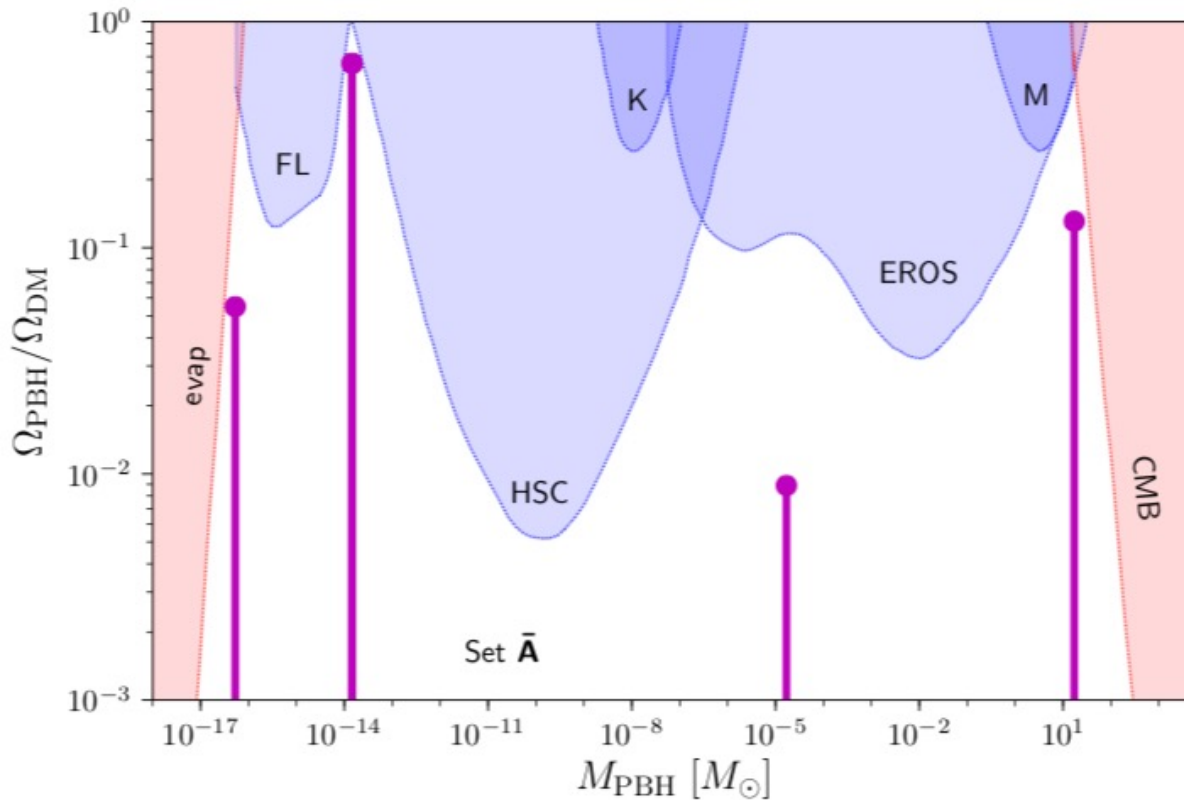
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Abstract. The advent of gravitational wave astronomy has rekindled interest in primordial black holes (PBH) as a dark matter candidate. As there are many different observational probes of the PBH density across different masses, constraints on PBH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

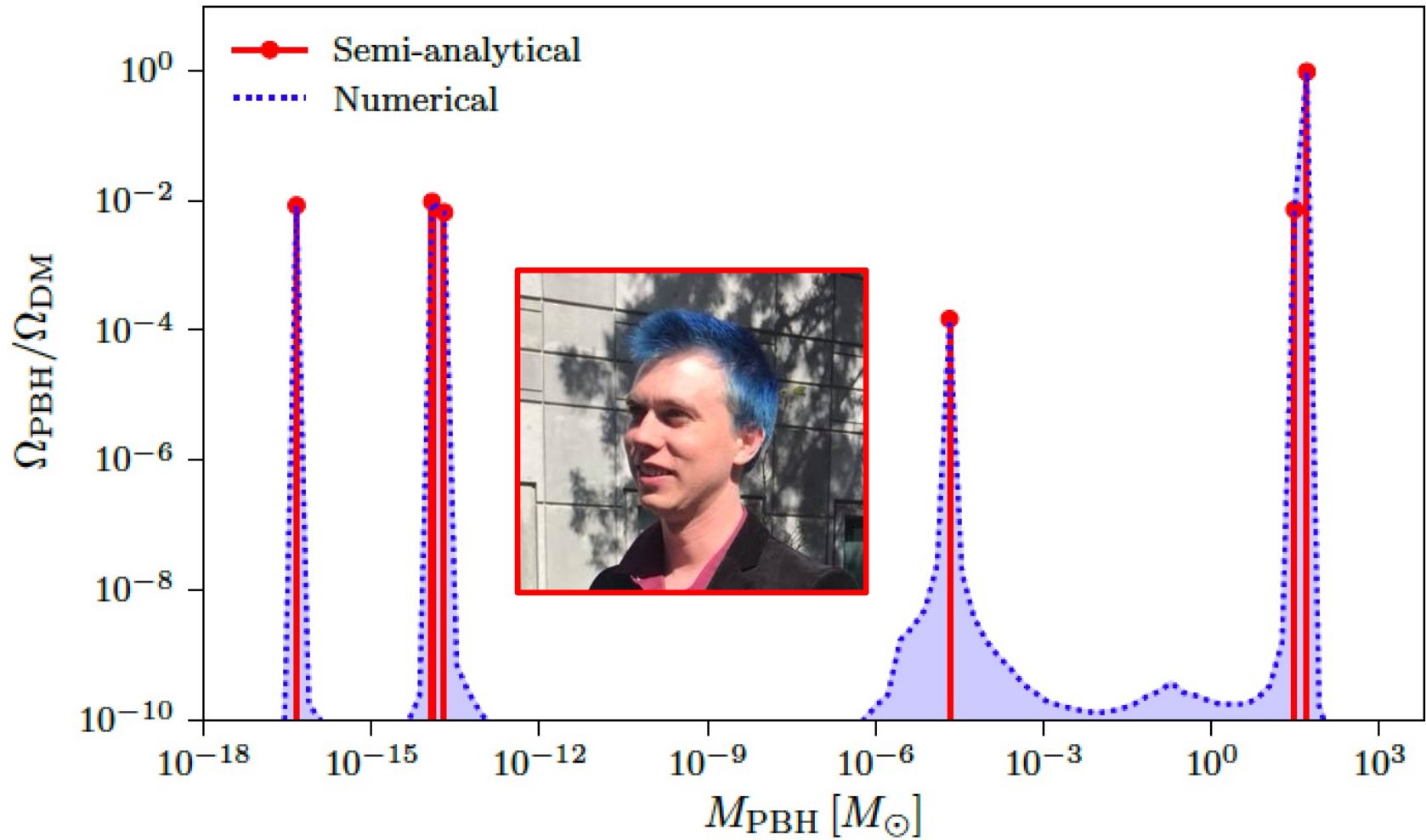
Answer: with N independent constraints, the optimal function is a linear combination of N delta functions with calculable relative weights

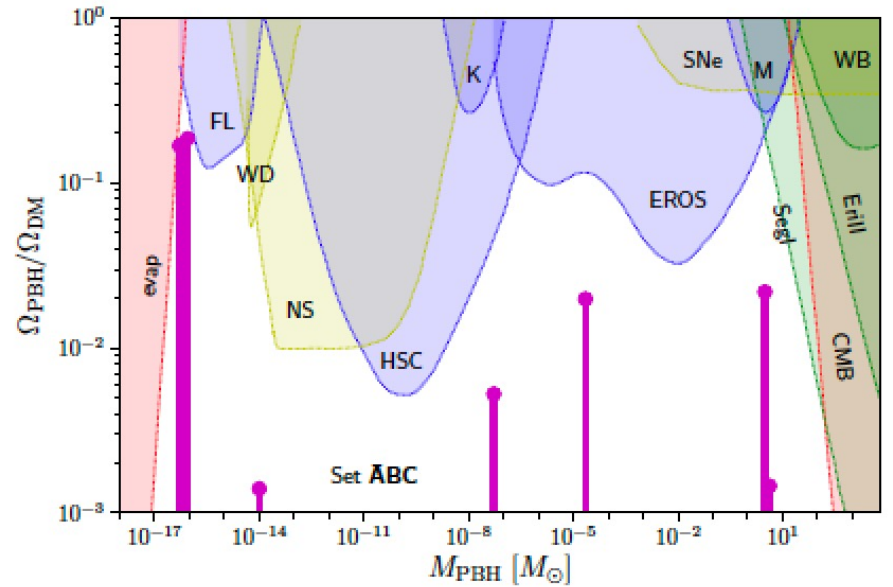
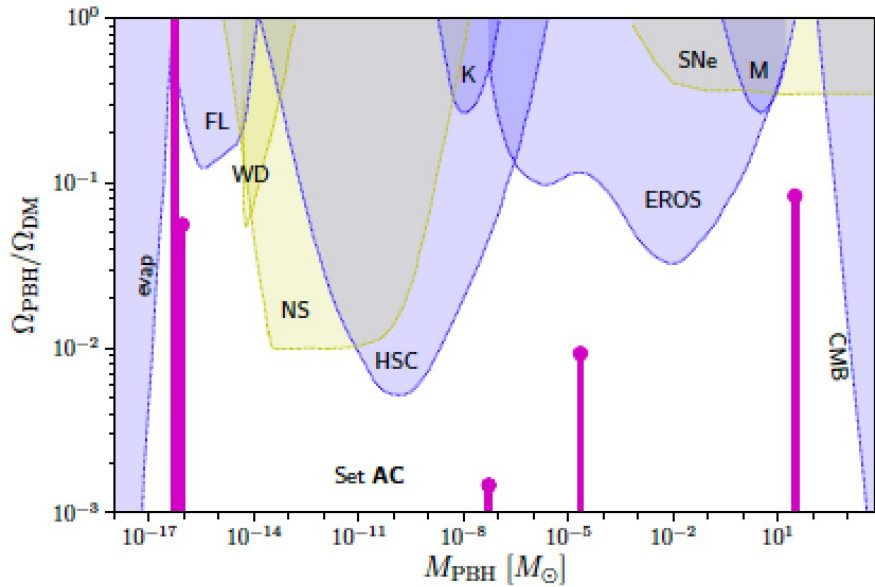
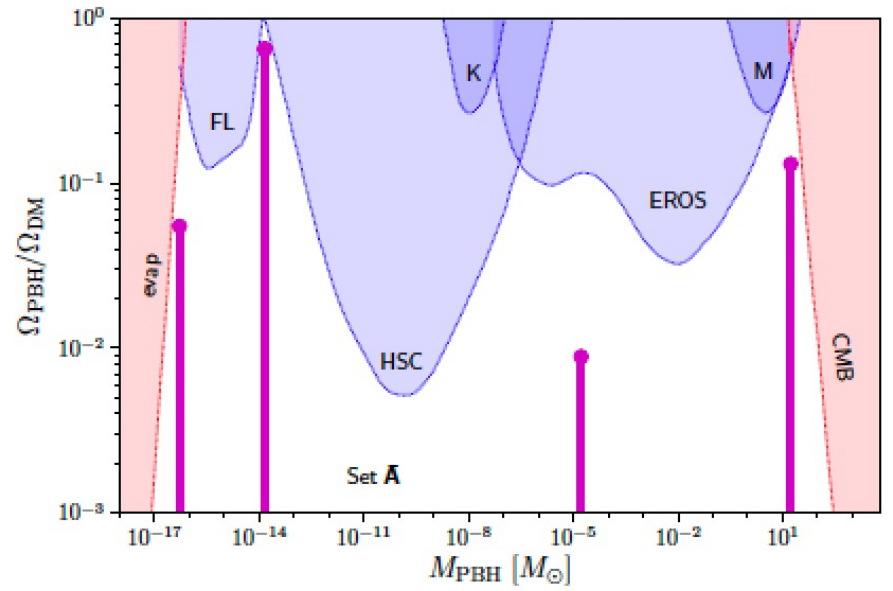
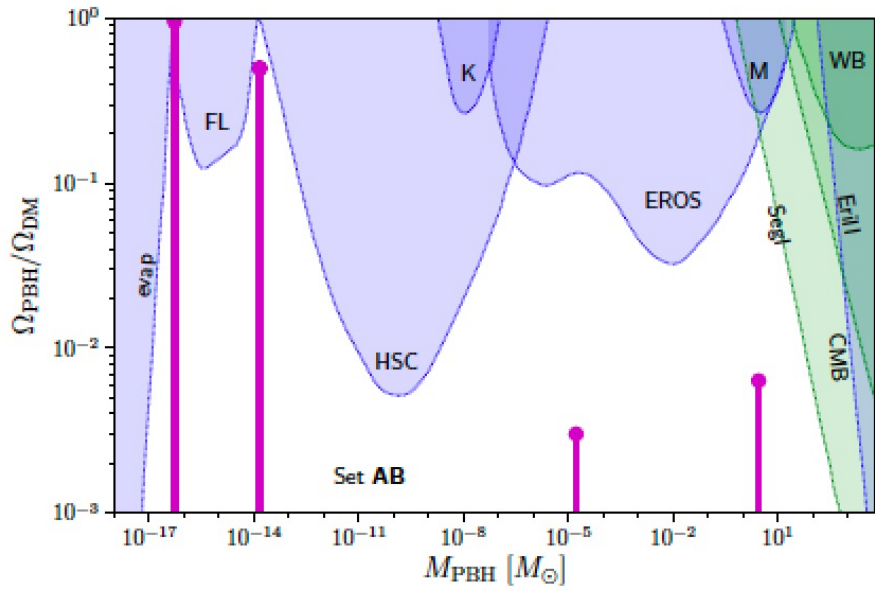
$$\min \{ \|\mathbf{x}\| \mid \mathbf{x} \in \text{conv} \{ \mathbf{g}(M) \mid M \in U \} \}$$



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

Numerical validation





	f_{mono}	$f_{\text{max.all}}$	$f_{\text{max,GW}}$	$\sigma[\psi]/M_{\odot}$	$\langle M/M_{\odot} \rangle$
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
$\bar{\text{A}}$	0.991	1.502	2.171	4.827	1.492
$\bar{\text{A}}\bar{\text{B}}$	0.991	1.437	11.07	0.221	0.017
$\bar{\text{A}}\bar{\text{C}}$	0.330	0.484	0.364	7.963	5.430
$\bar{\text{A}}\bar{\text{B}}\bar{\text{C}}$	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!

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

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

LIGO search results are out*

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

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

Given a **mass function**, one can calculate:

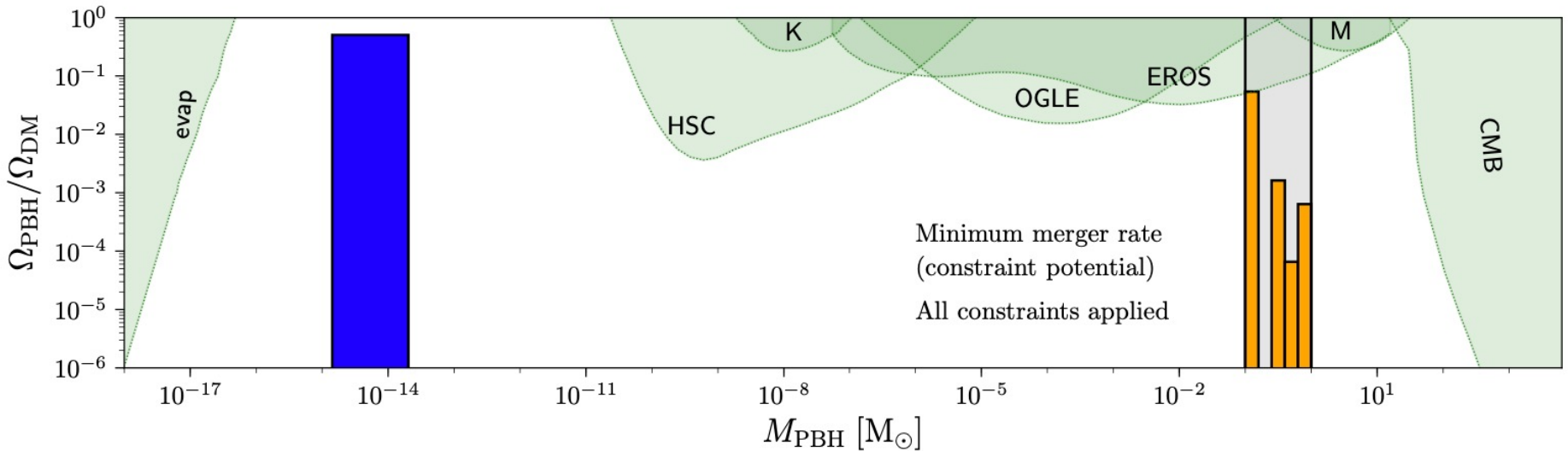
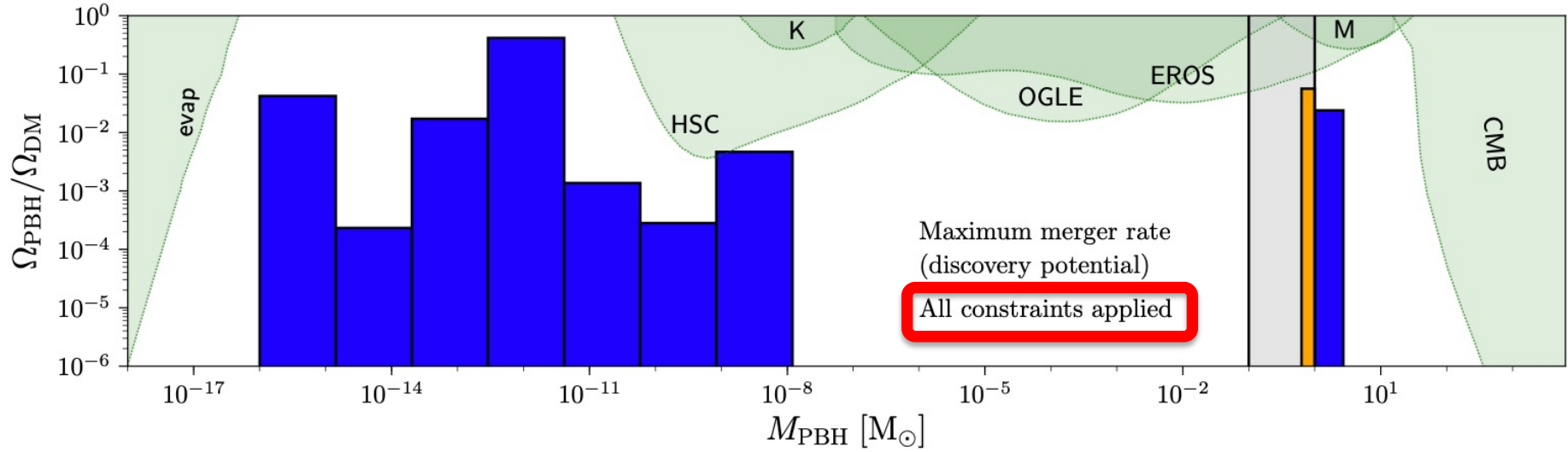
1. **Rate** of “goldilocks events”

$$R_{\text{DP}}(\psi) = \int_{\text{DP}^2} dm_1 dm_2 \mathcal{R}(m_1, m_2) V_{\text{eff}}(m_1, m_2),$$

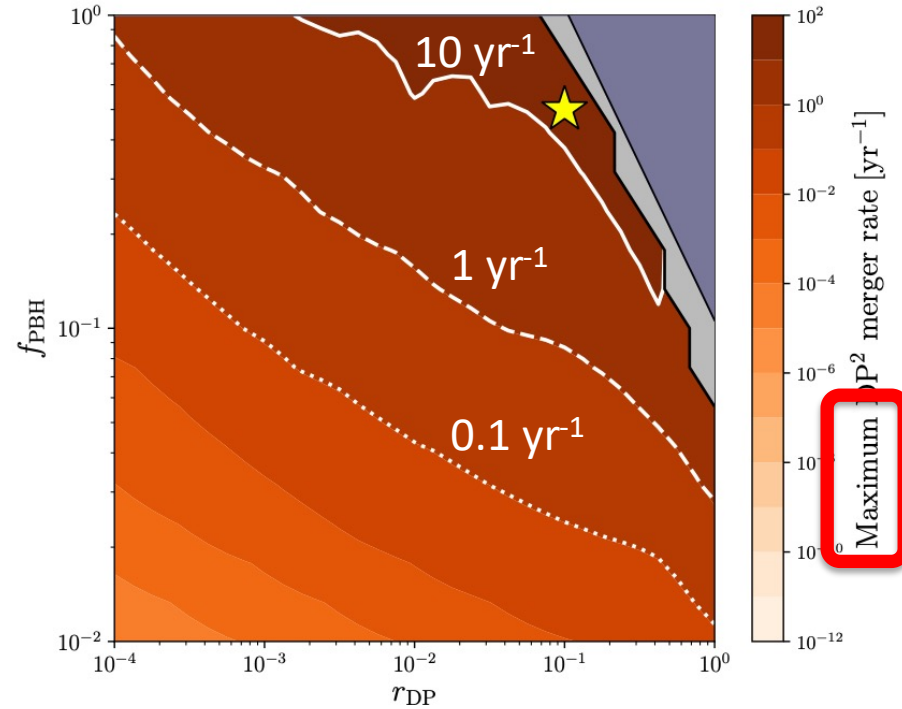
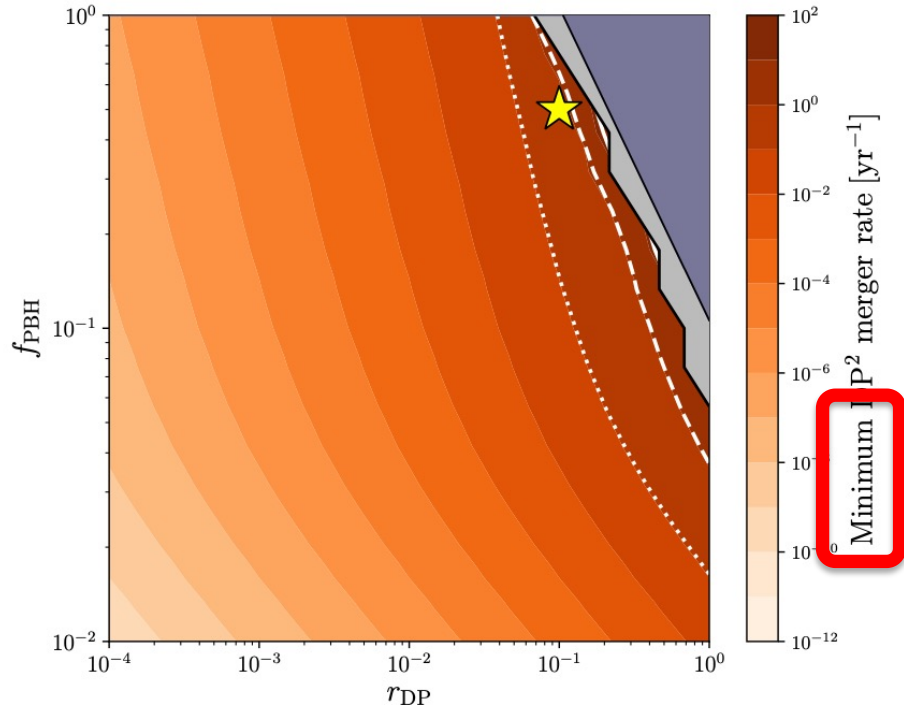
2. **Mass fraction** of **light+detectable** BHs

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

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



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



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

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

Besides the **mass**, LIGO informs us about the **spin** of BHs...

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LIGO/Virgo Collaboration arXiv:1811.12940

Event	m_1/M_\odot	m_2/M_\odot	M/M_\odot	χ_{eff}	M_f/M_\odot	a_f	$E_{\text{rad}}/(M_\odot c^2)$	$\ell_{\text{peak}}/(\text{erg s}^{-1})$	d_L/Mpc	z	$\Delta\Omega/\text{deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	180
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9} \times 10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.05}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.86^{+0.00}_{-0.00}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9} \times 10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

Masses

Spin



Slide credit: Nico Fernandez (UCSC → UIUC)

Effective Spin

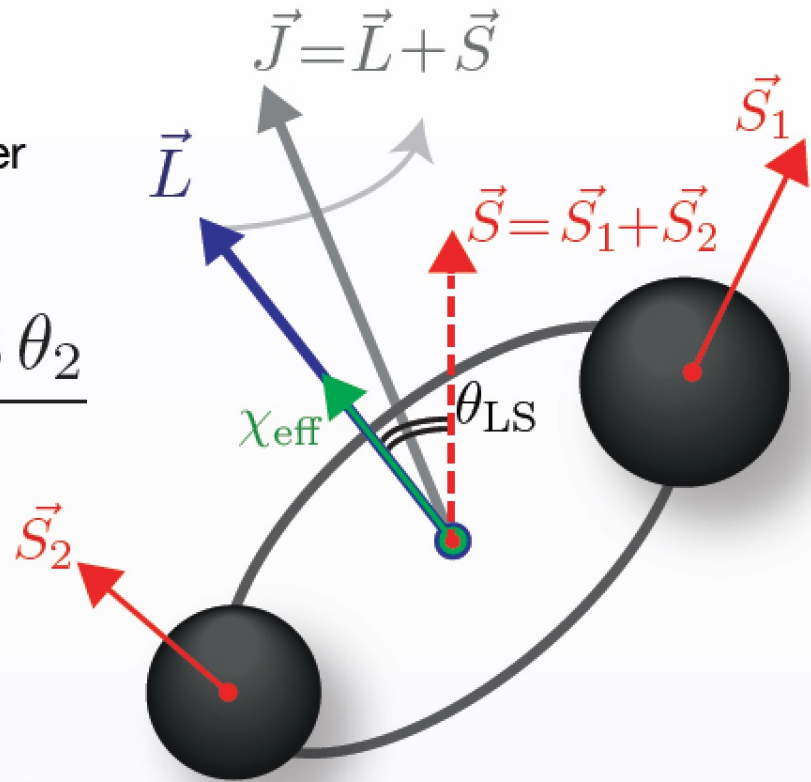
$$\chi = \frac{|\vec{S}|}{Gm^2}$$

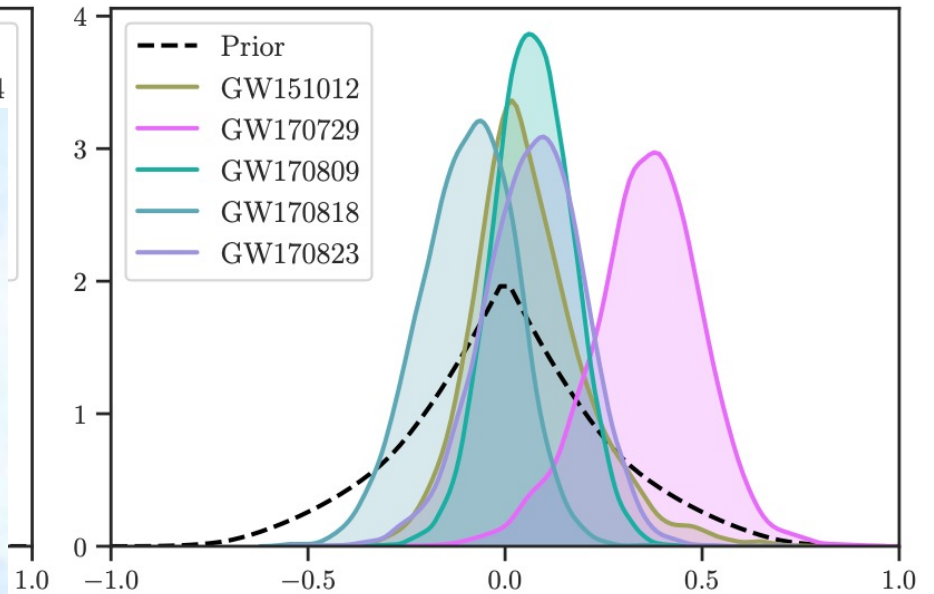
Dimensionless spin parameter

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

Information about:

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

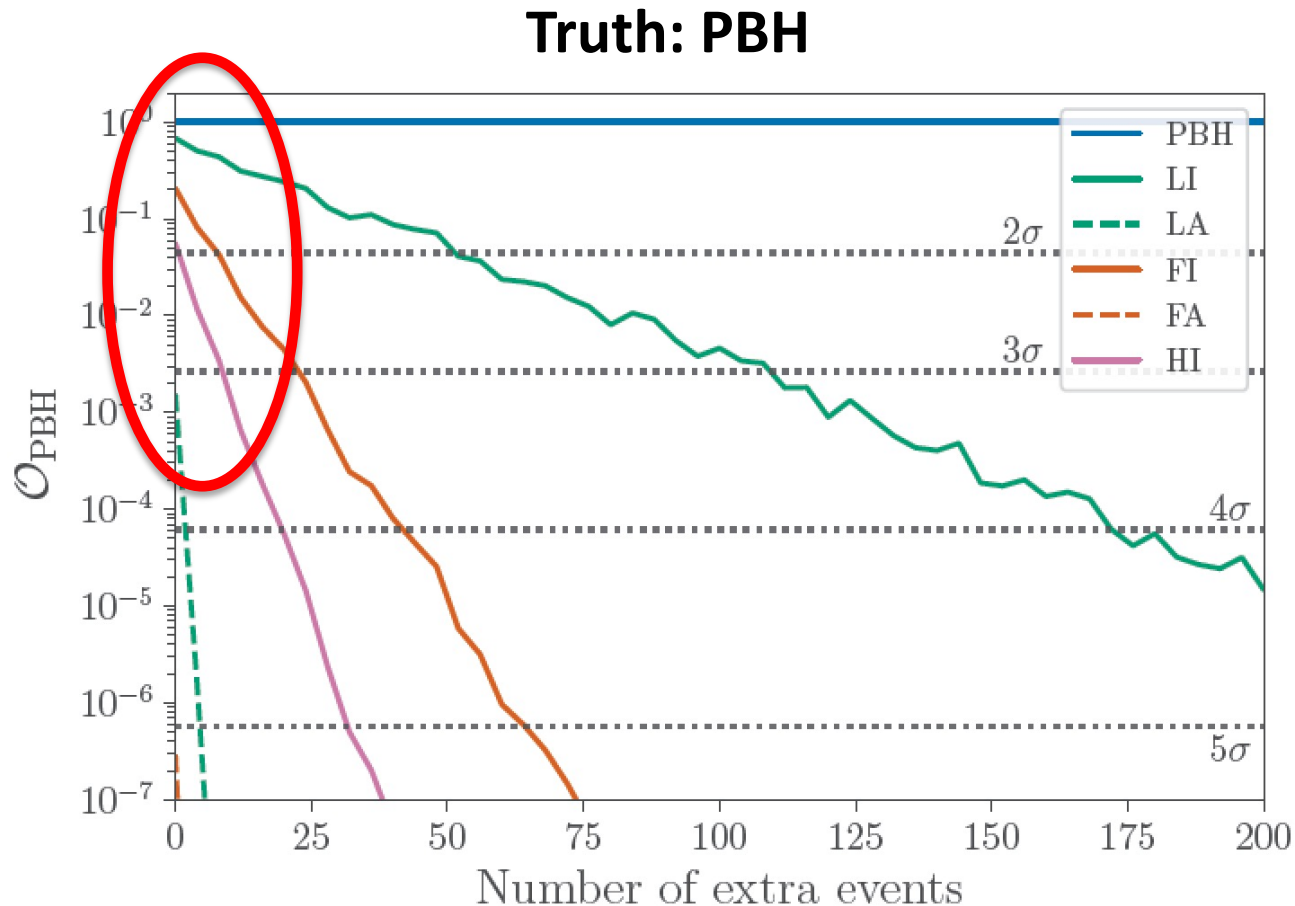




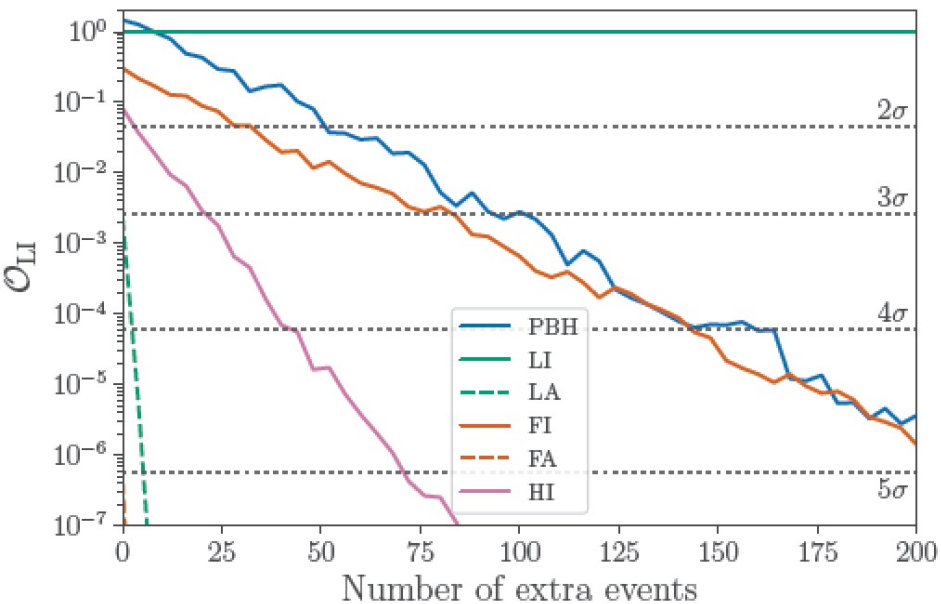
Odds ratios

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

Evolution of the Odds ratios



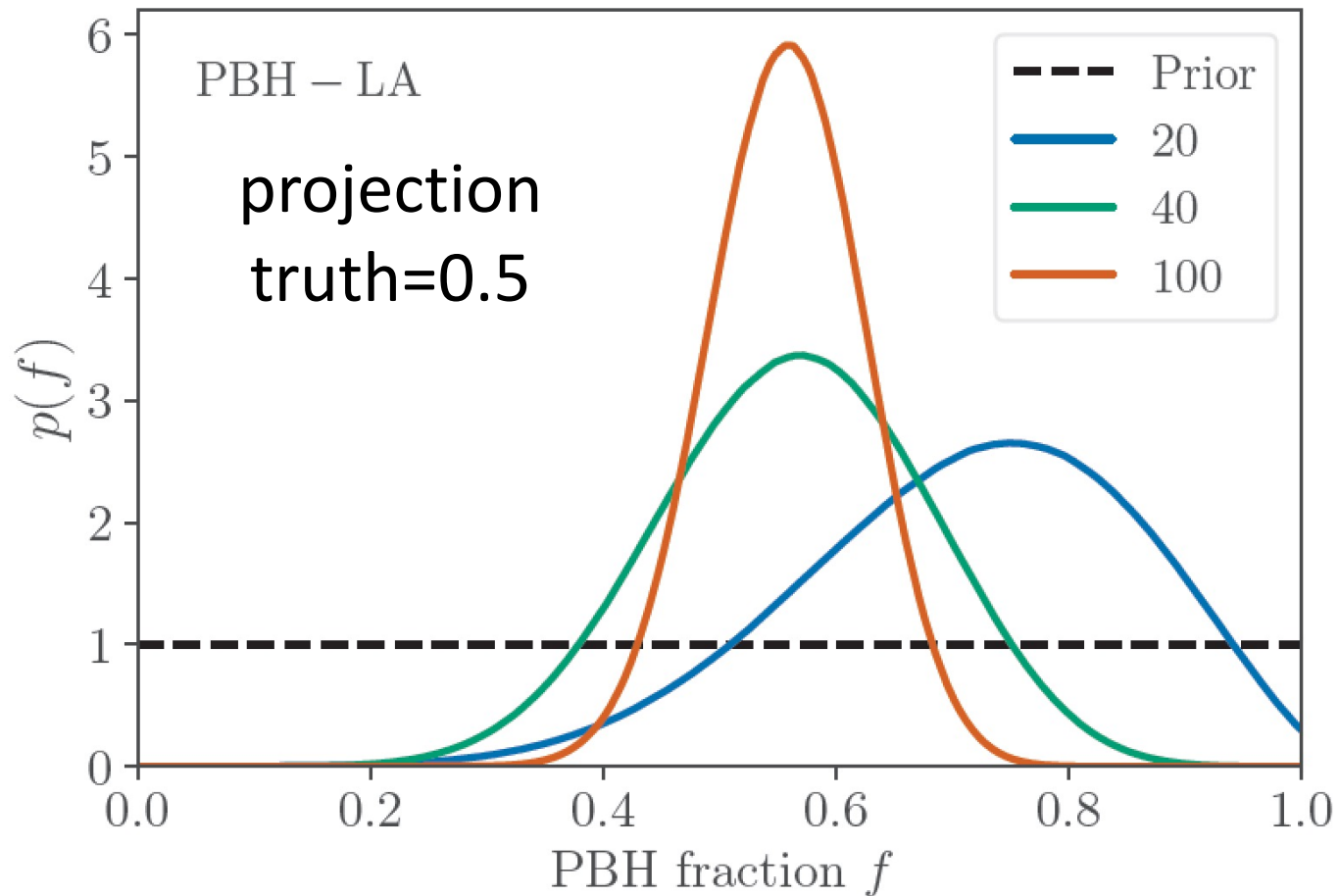
Evolution of the Odds ratios



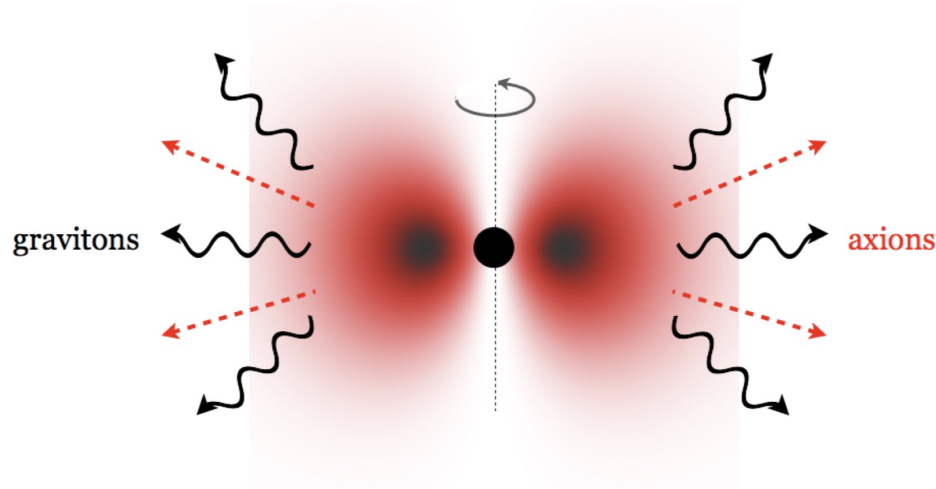
Truth: Low-isotropic

What about mixed models?

What about mixed models?



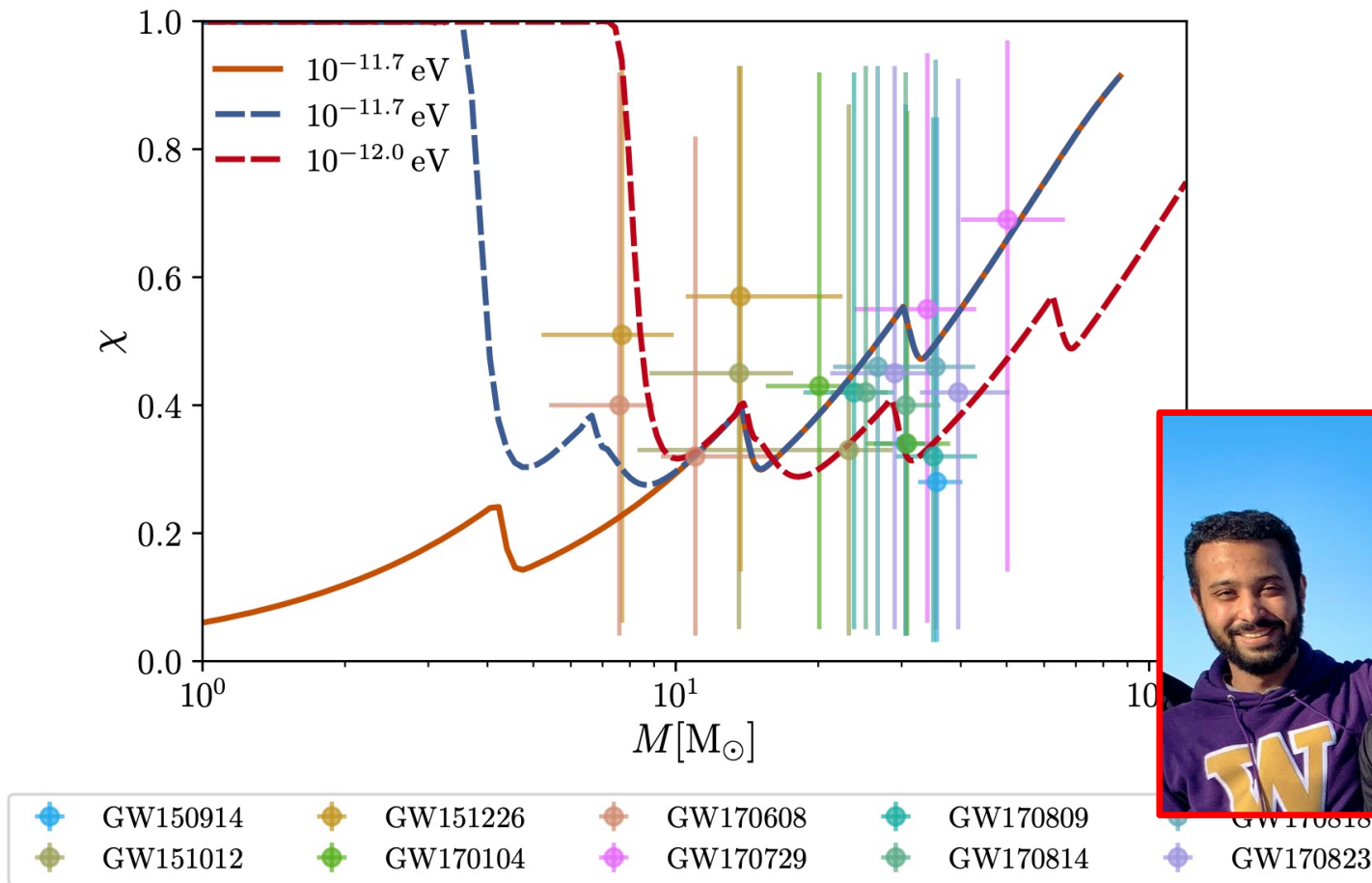
What else could **fake** a **low-spin PBH**? **Super-radiance!**



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

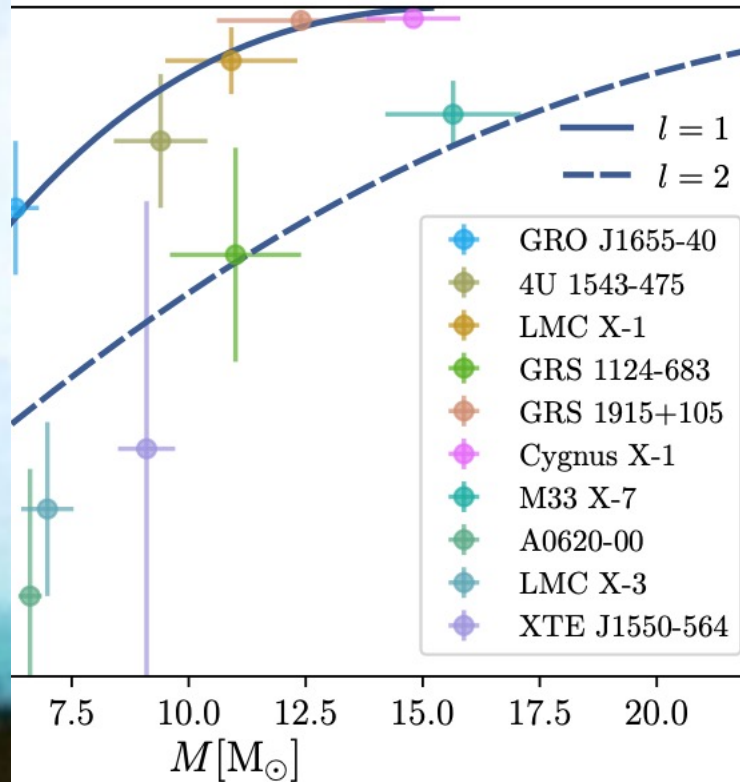
What else could fake a low-spin PBH? Super-radiance!



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

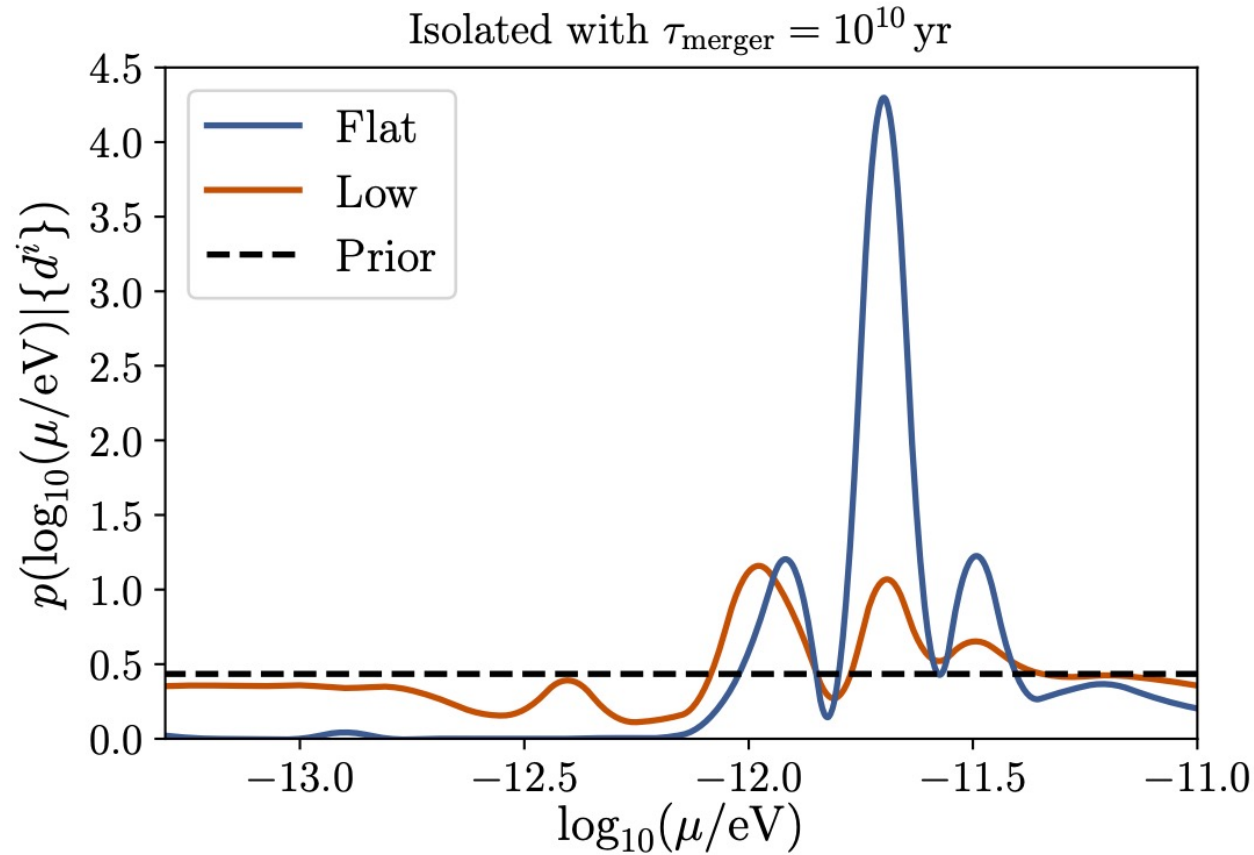
*Fernandez, Ghalsasy, Profumo, 1911.07862

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

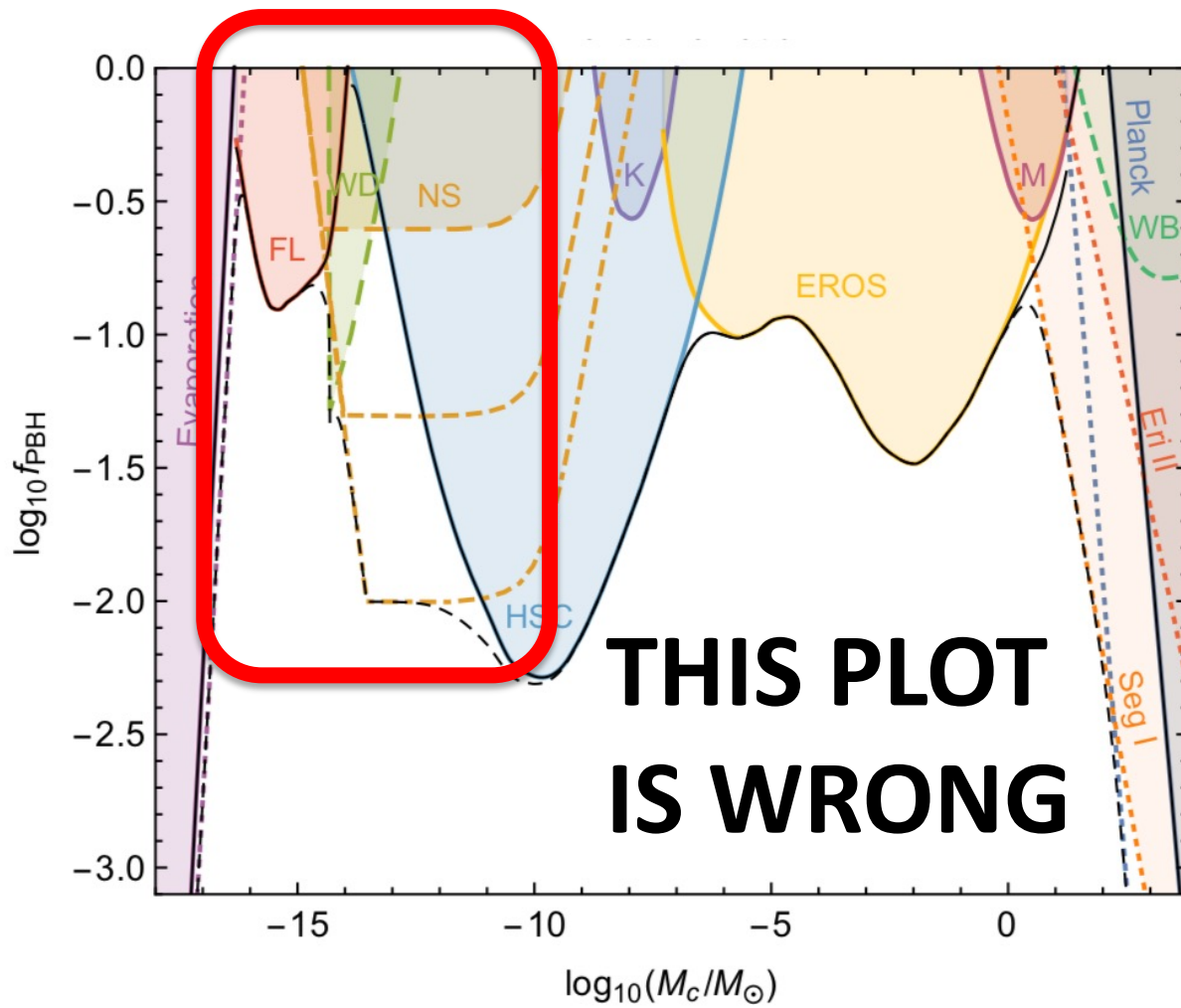


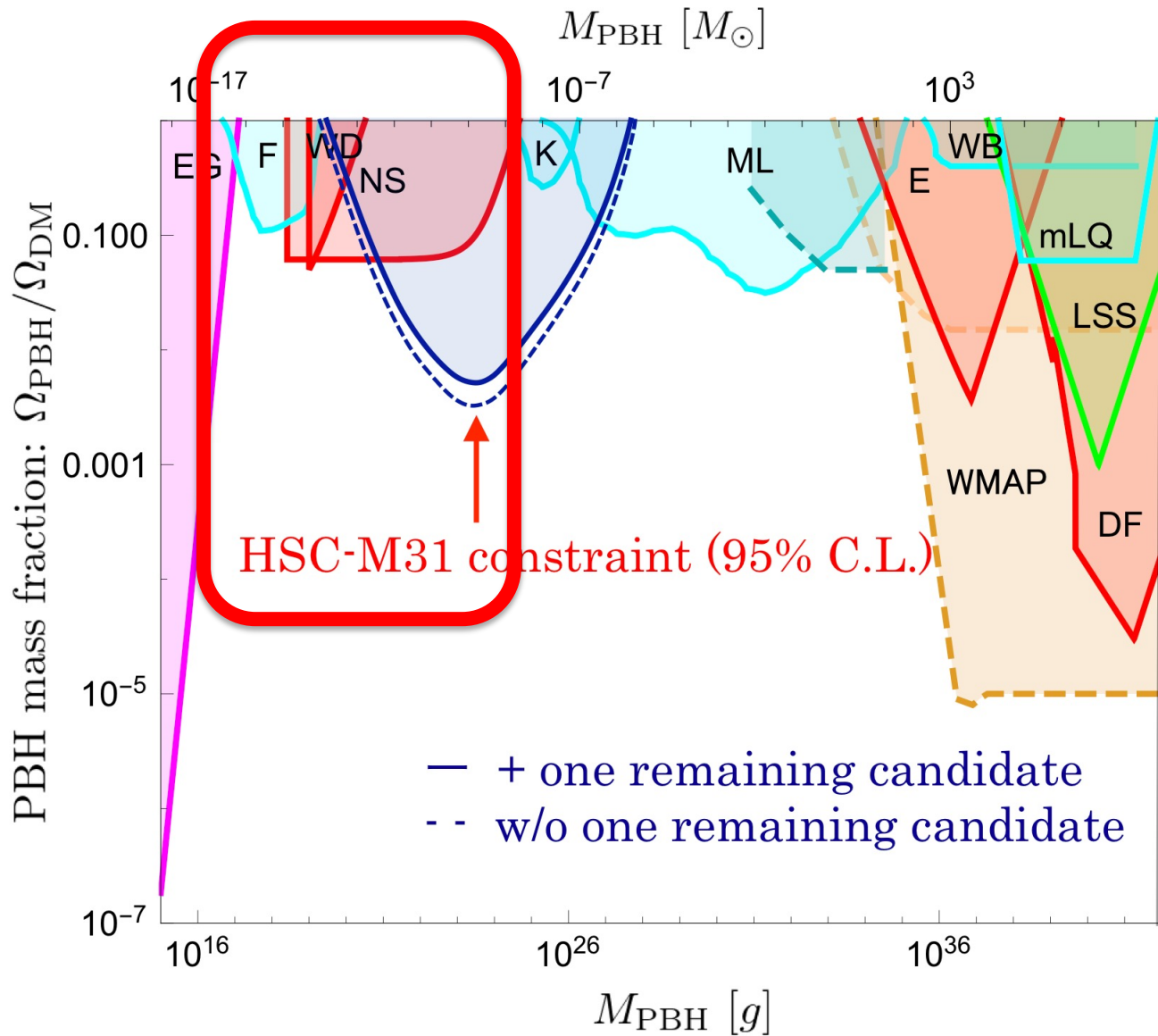
...but these are **massive**, so high- l is **non-super-radiant!**

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

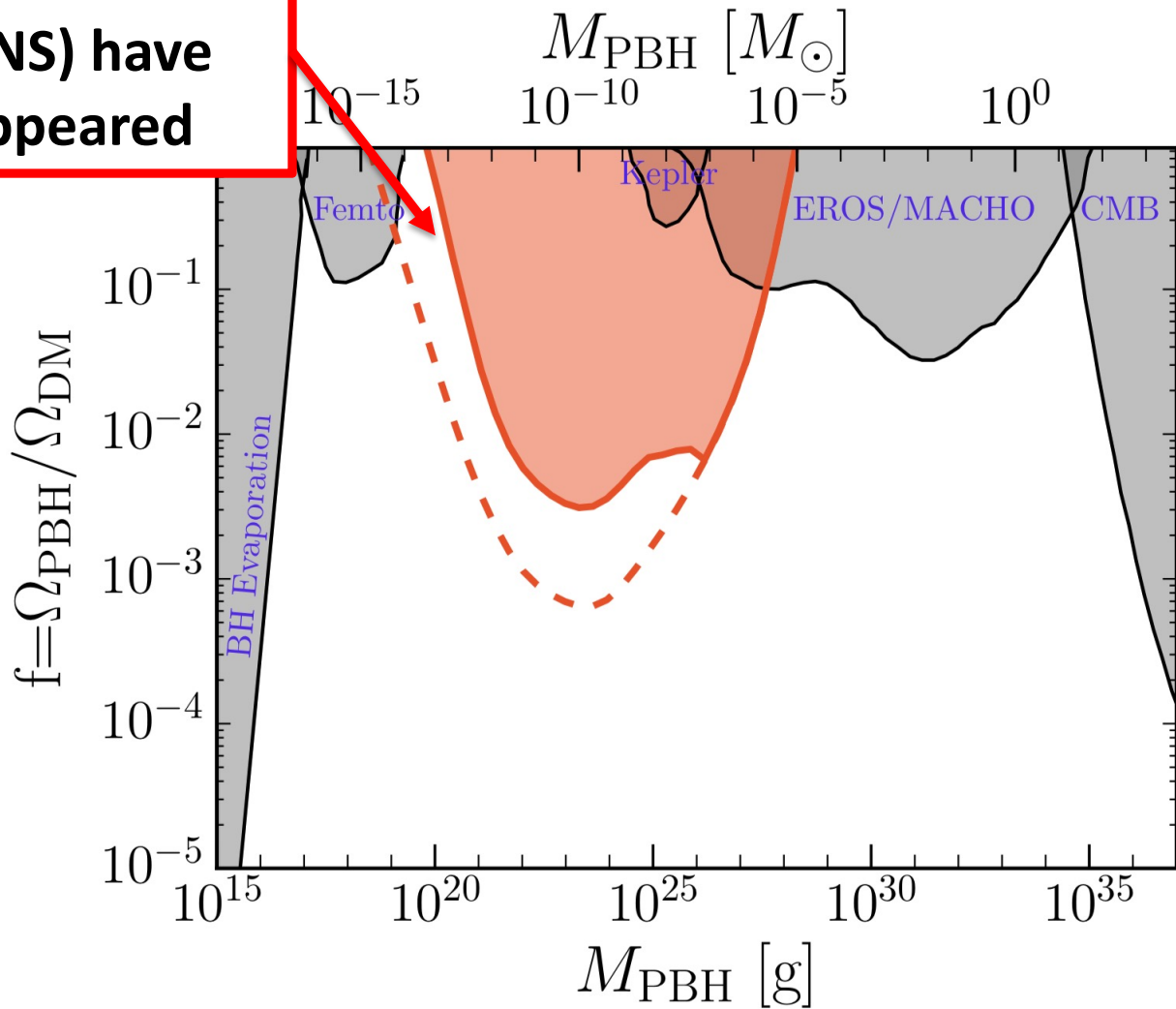


Posterior Probability for ALP mass



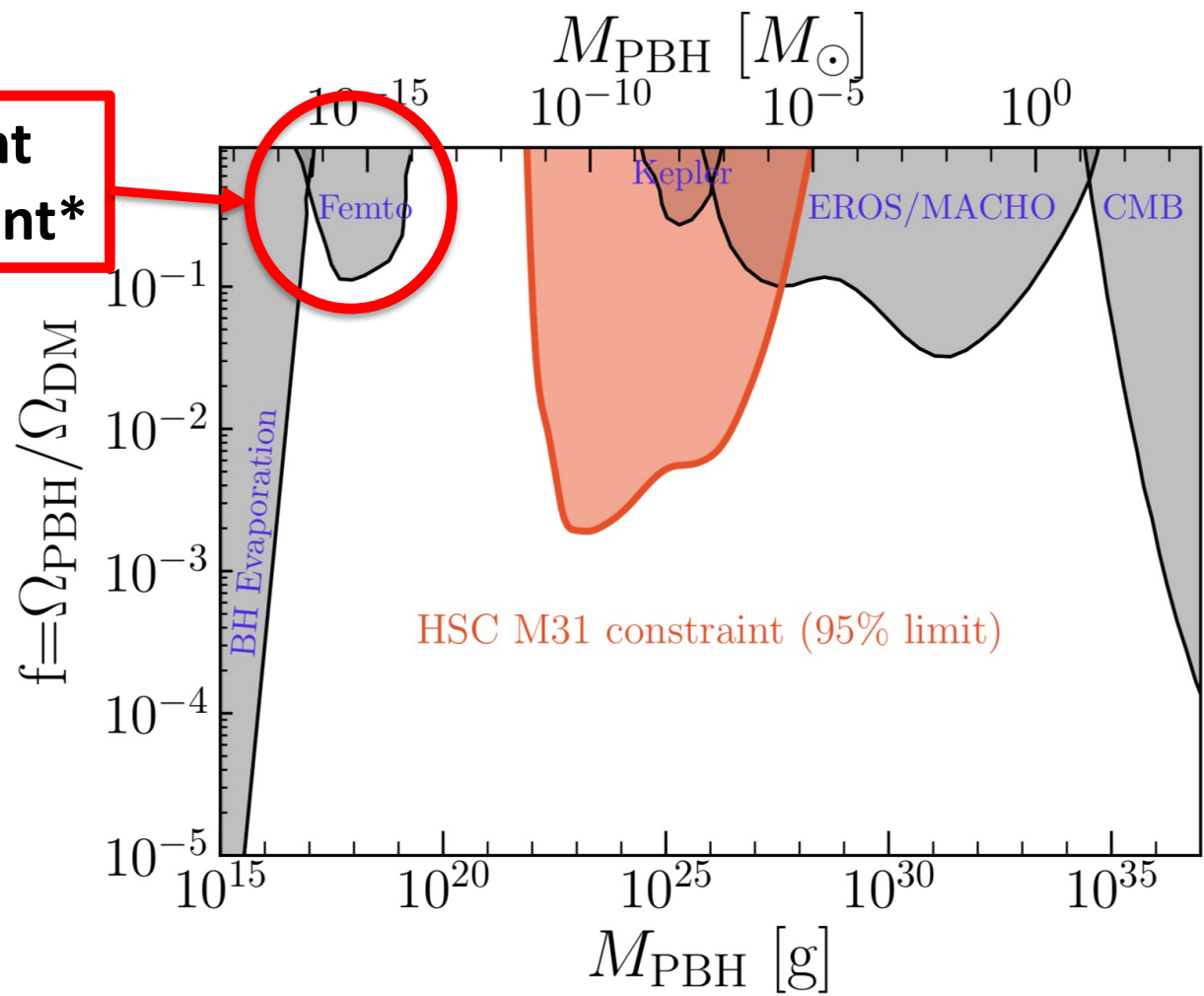


**wacky constraints
(WD, NS) have
disappeared**



* Katz et al, 1807.11495

This constraint also non-existent*



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**:

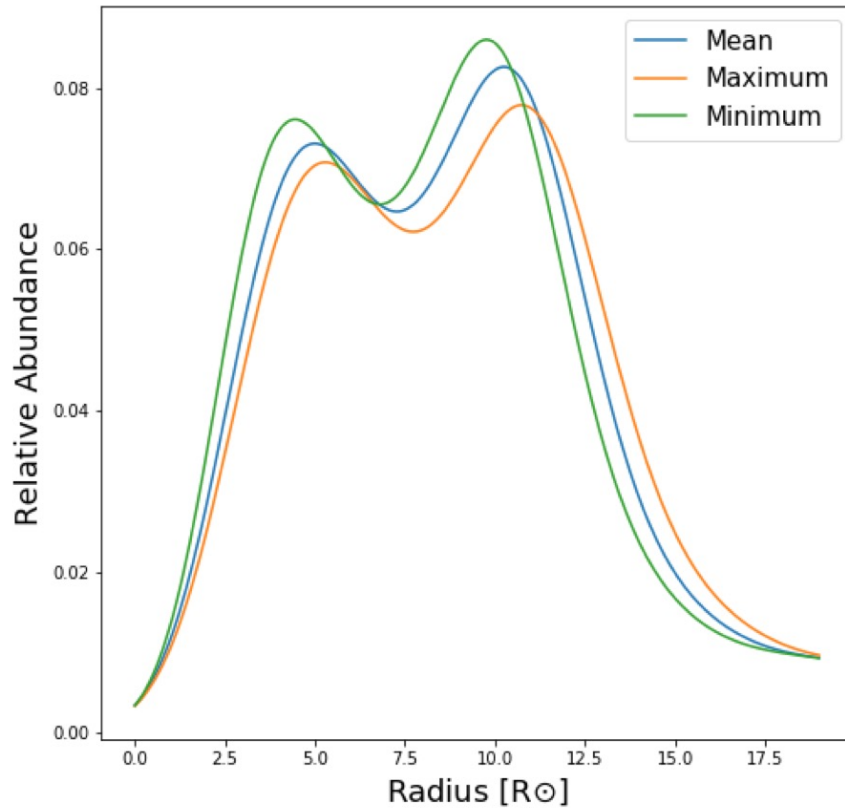
➤ All stars are at the same **distance**

➤ All stars have the same **size** ($1 R_{\text{sun}}$)

➤ DM is completely **smooth**

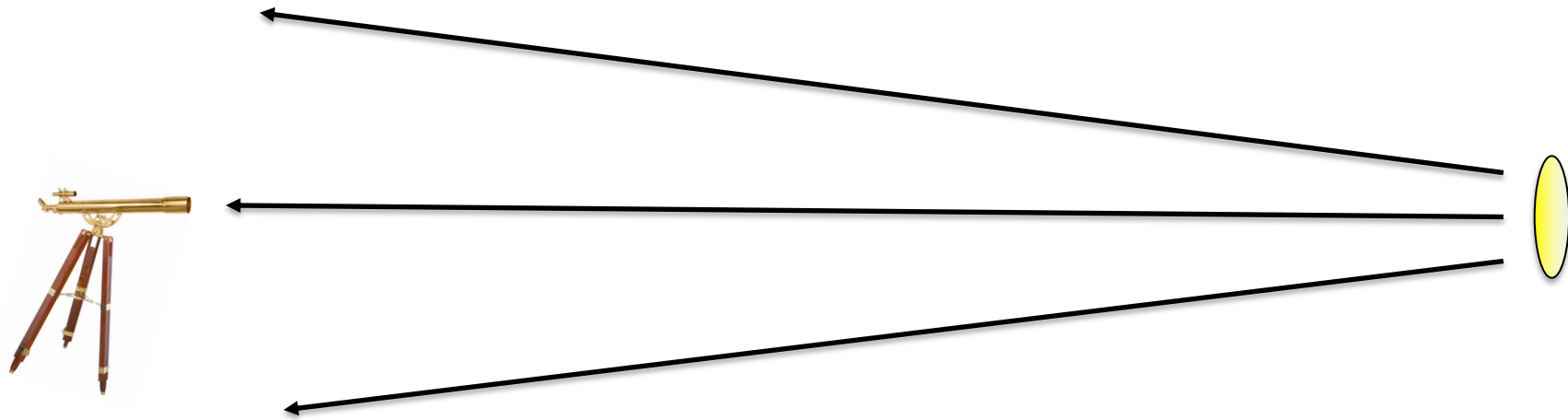


Sun-like stars are however **too dim** for HSC!

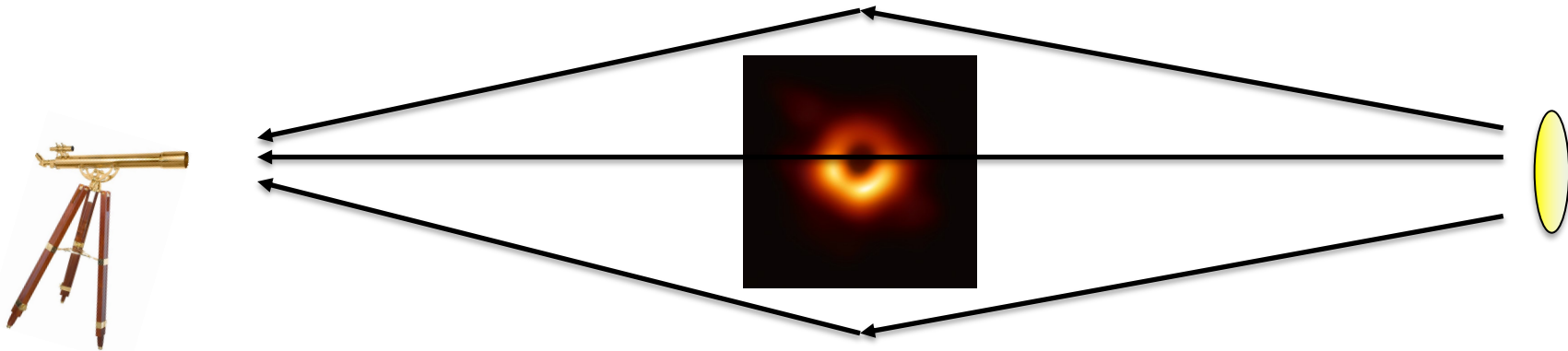


Stars that contribute to the microlensing constraints are **~ 100x larger in the sky** than the Sun!

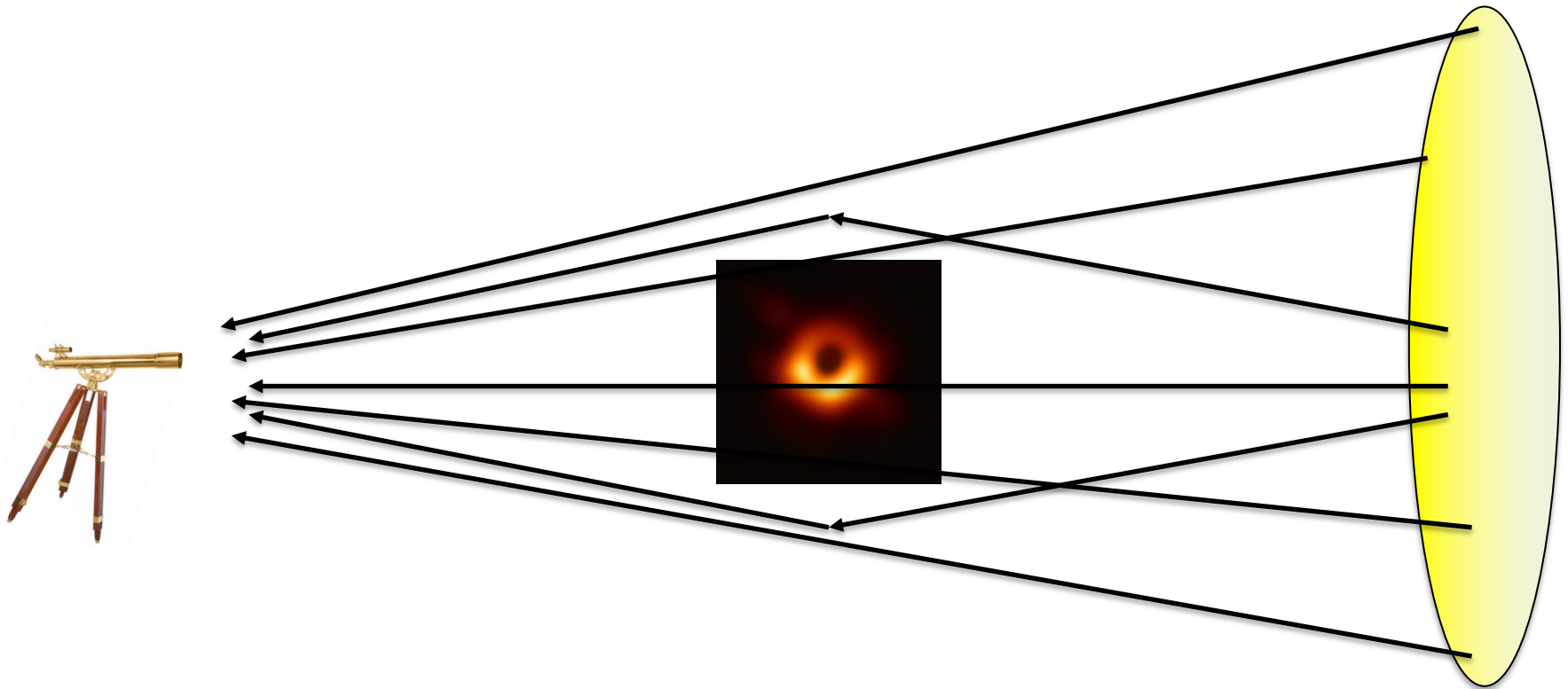
The bigger the star, the more important
finite-**source-size** effects!



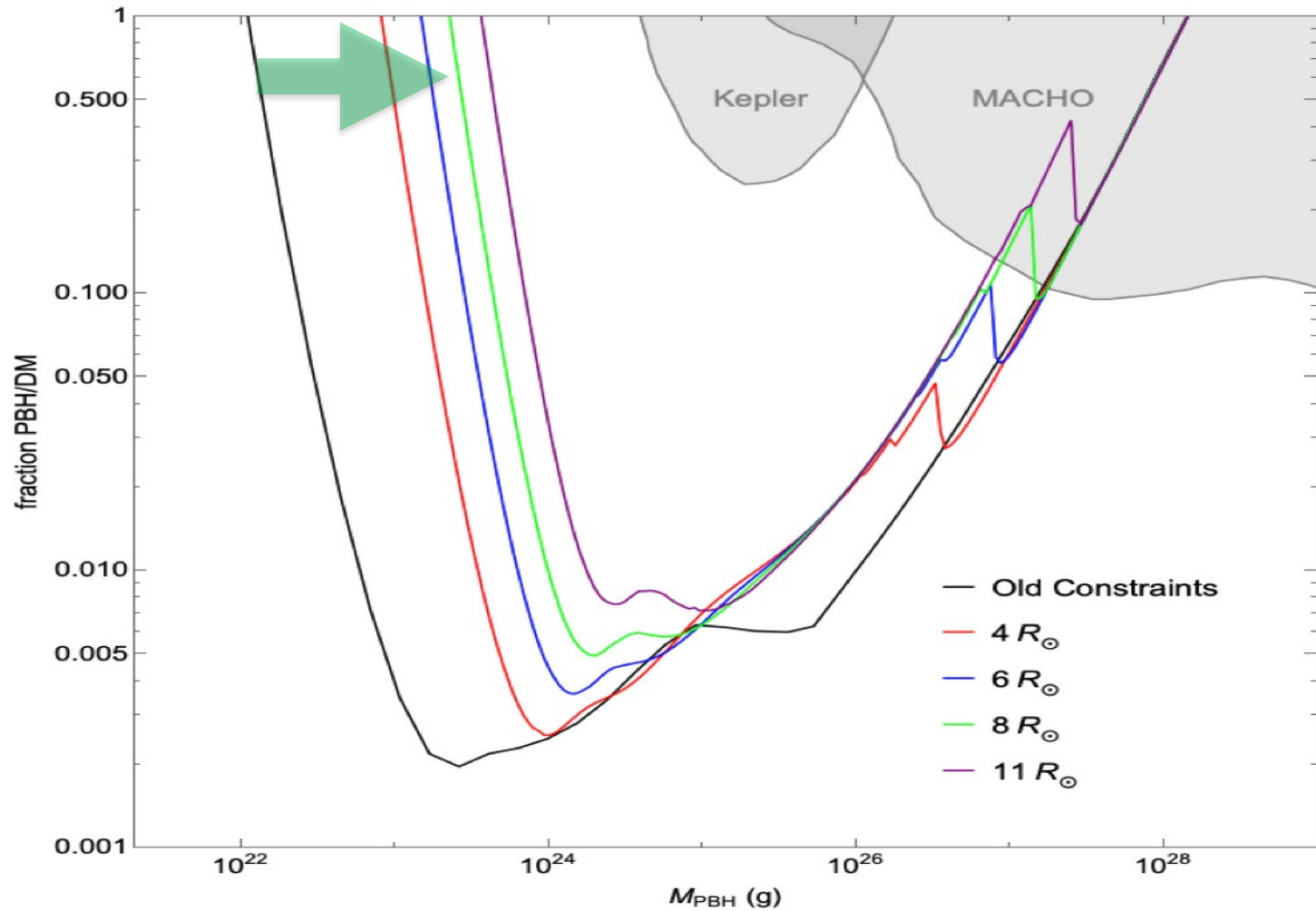
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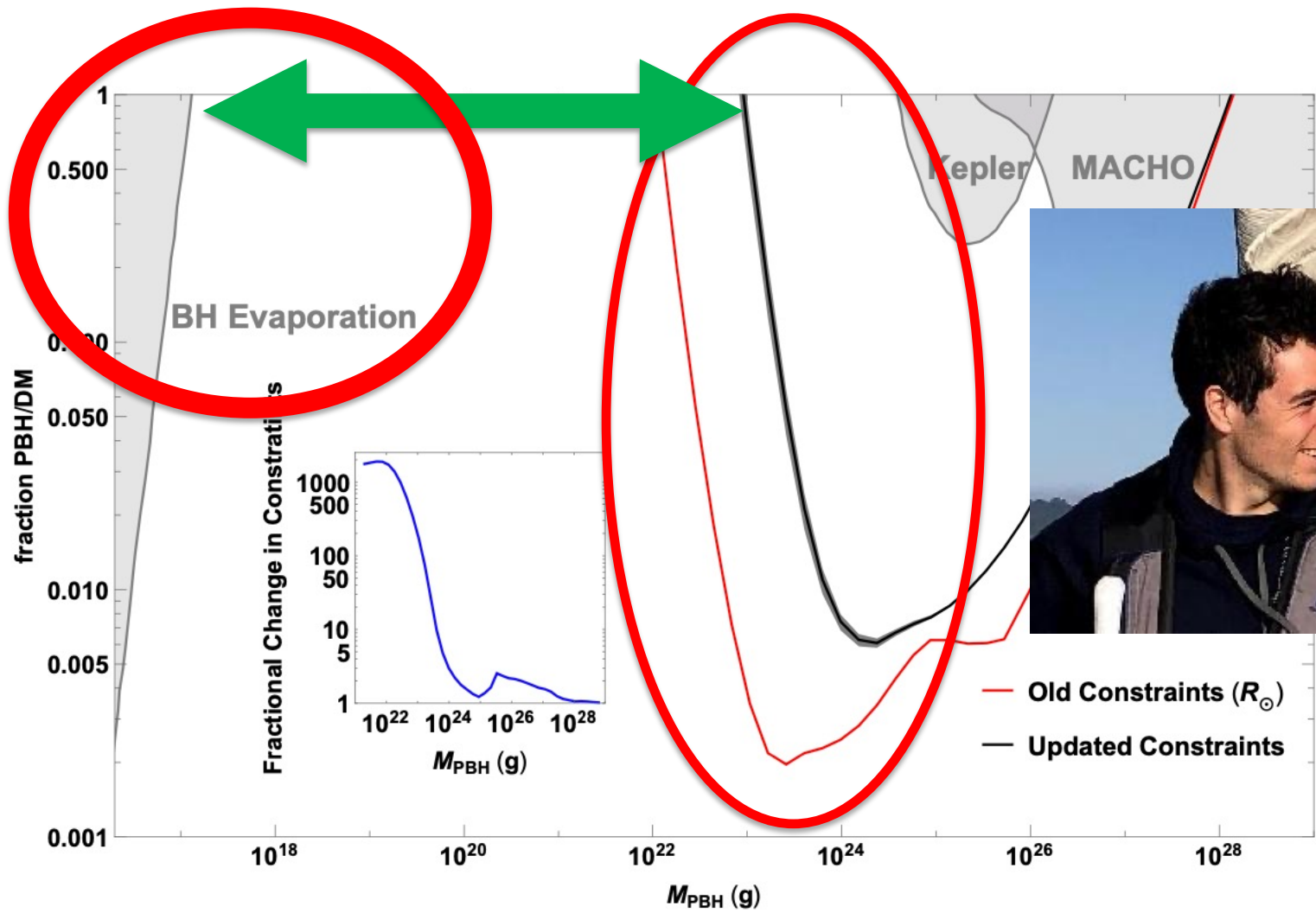


The bigger the star, the more important
finite-**source-size** effects!



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





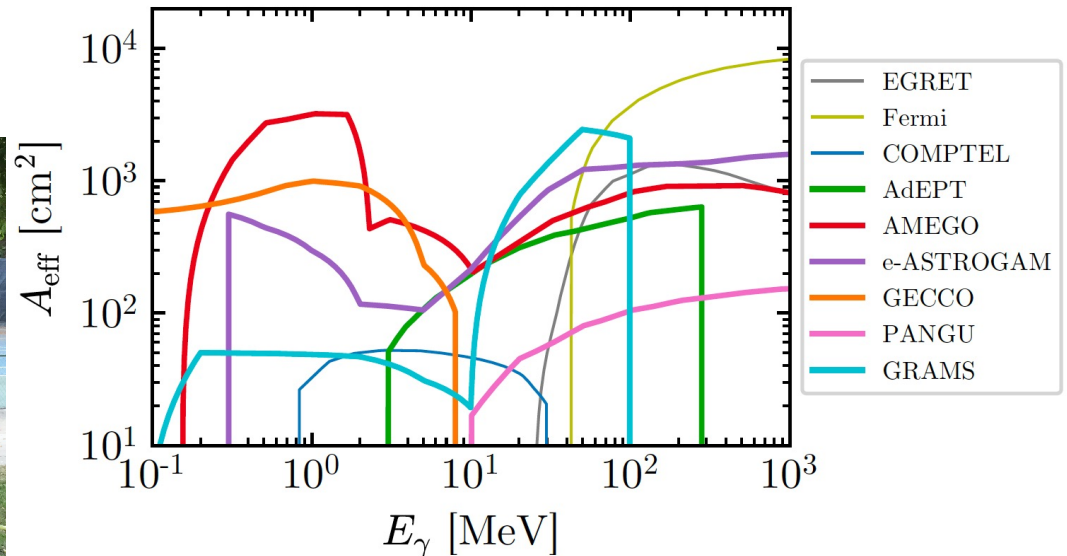
How do we **go after** them? Capture and perturbation around **PSR**?

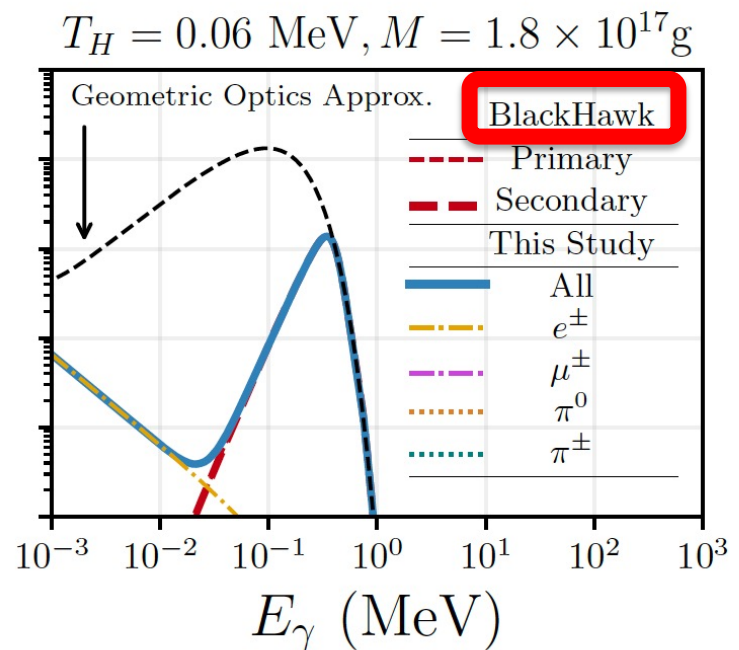
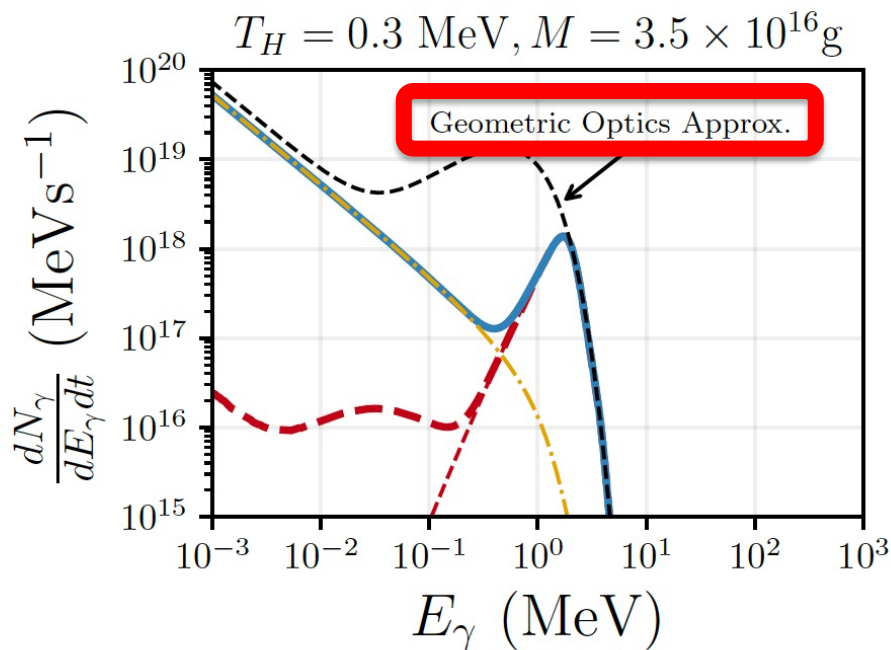
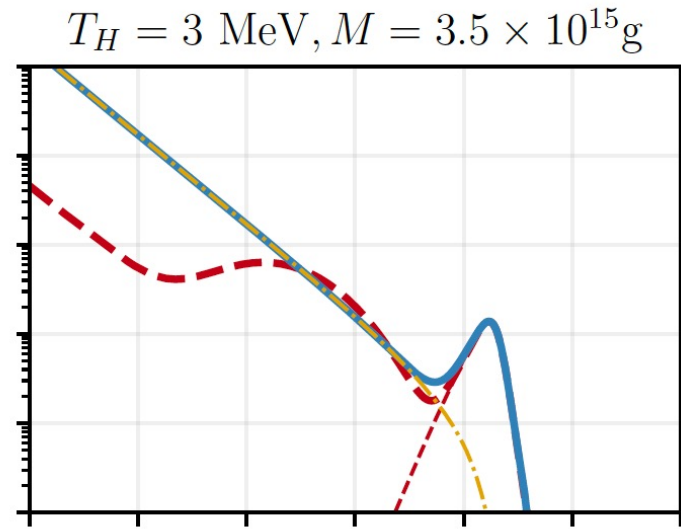
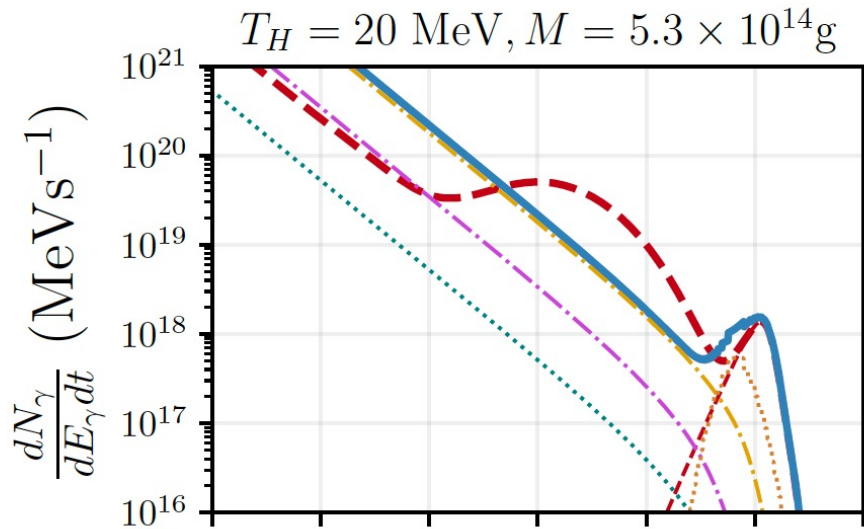
* Profumo, Smyth+ PRD 2020

Lightest PBH that can be dark matter...

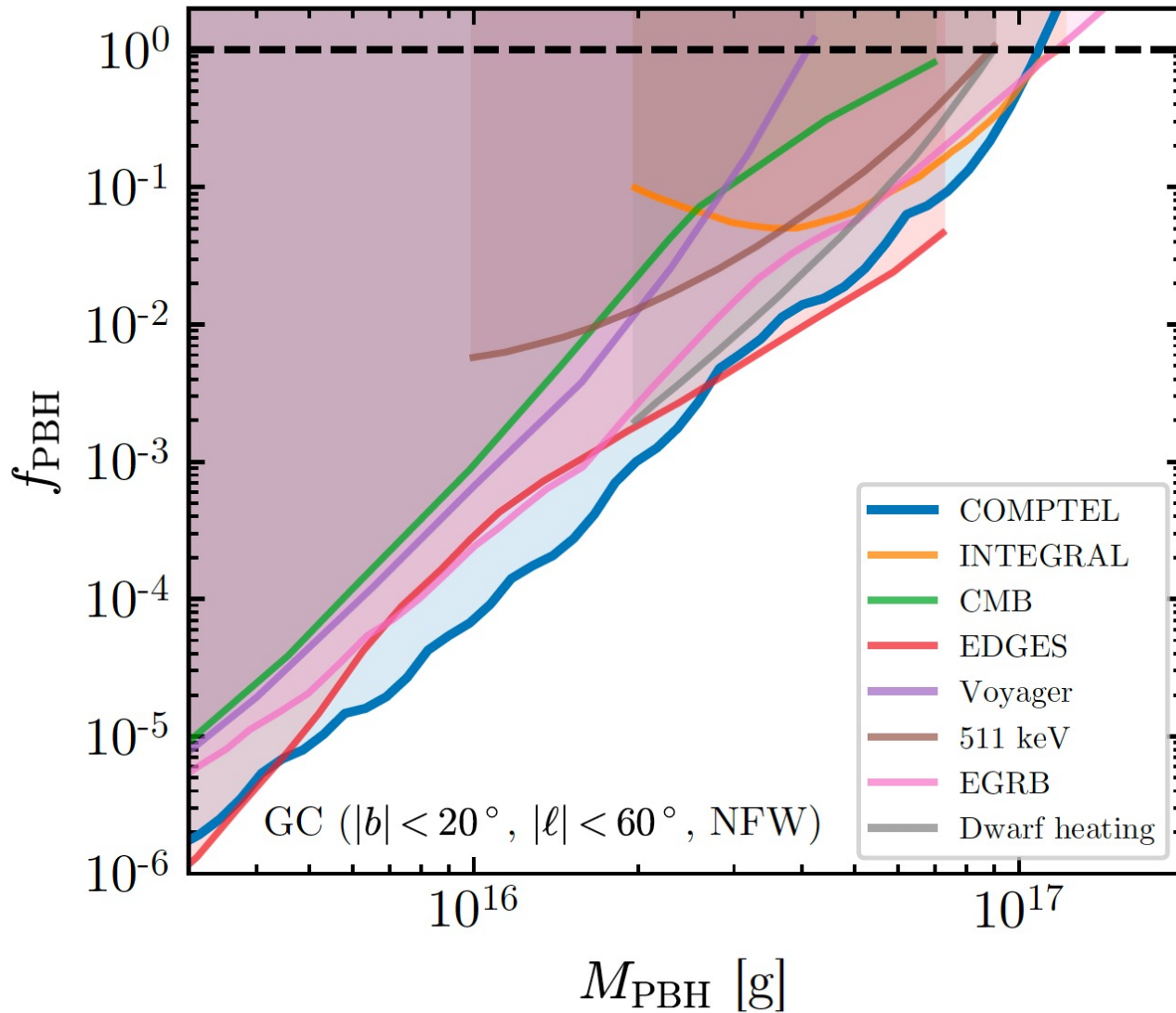
$$\tau(M) \simeq 200 \tau_U \left(\frac{M}{10^{15} \text{ g}} \right)^3 \simeq 200 \tau_U \left(\frac{10 \text{ MeV}}{T_H} \right)^3$$

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

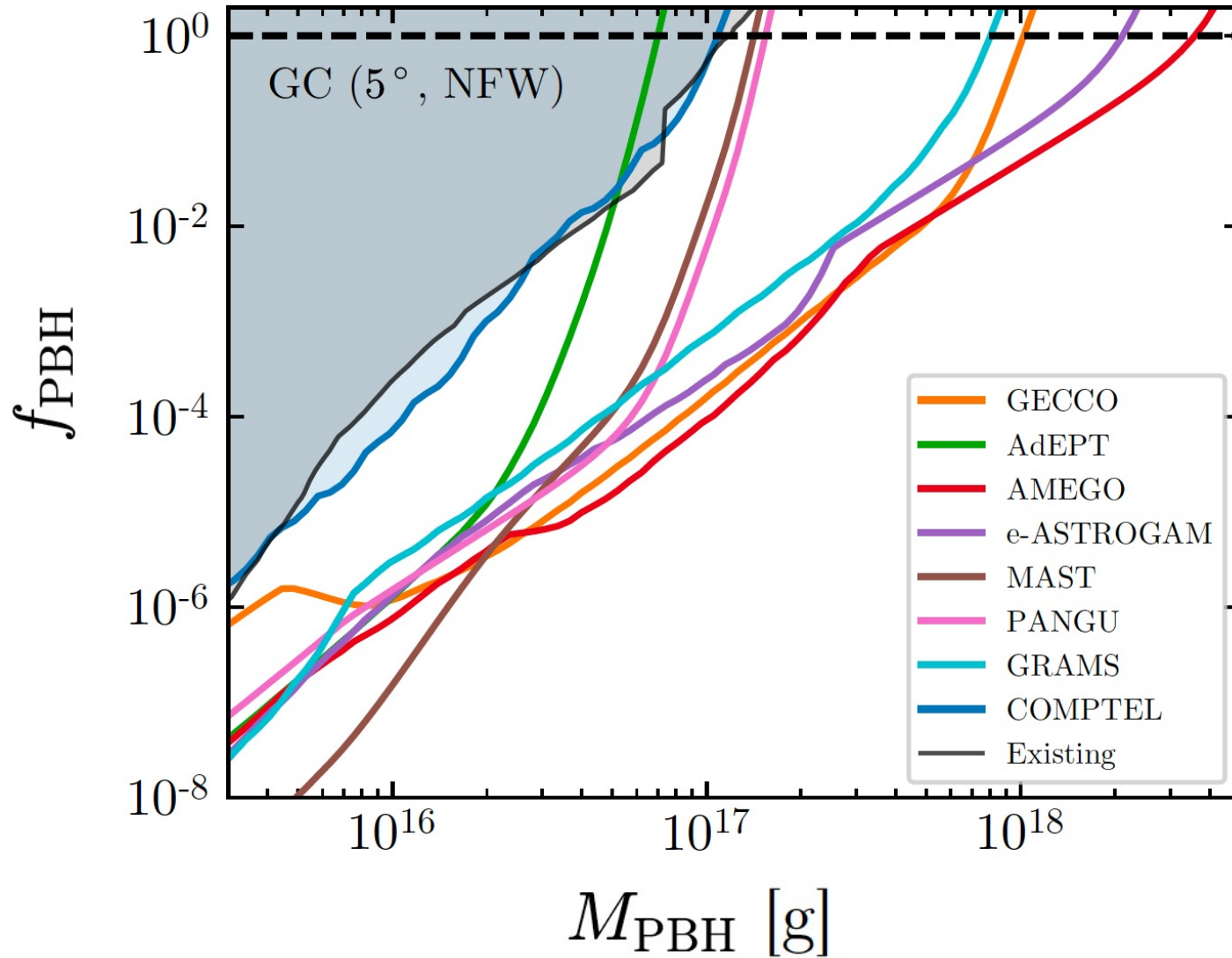




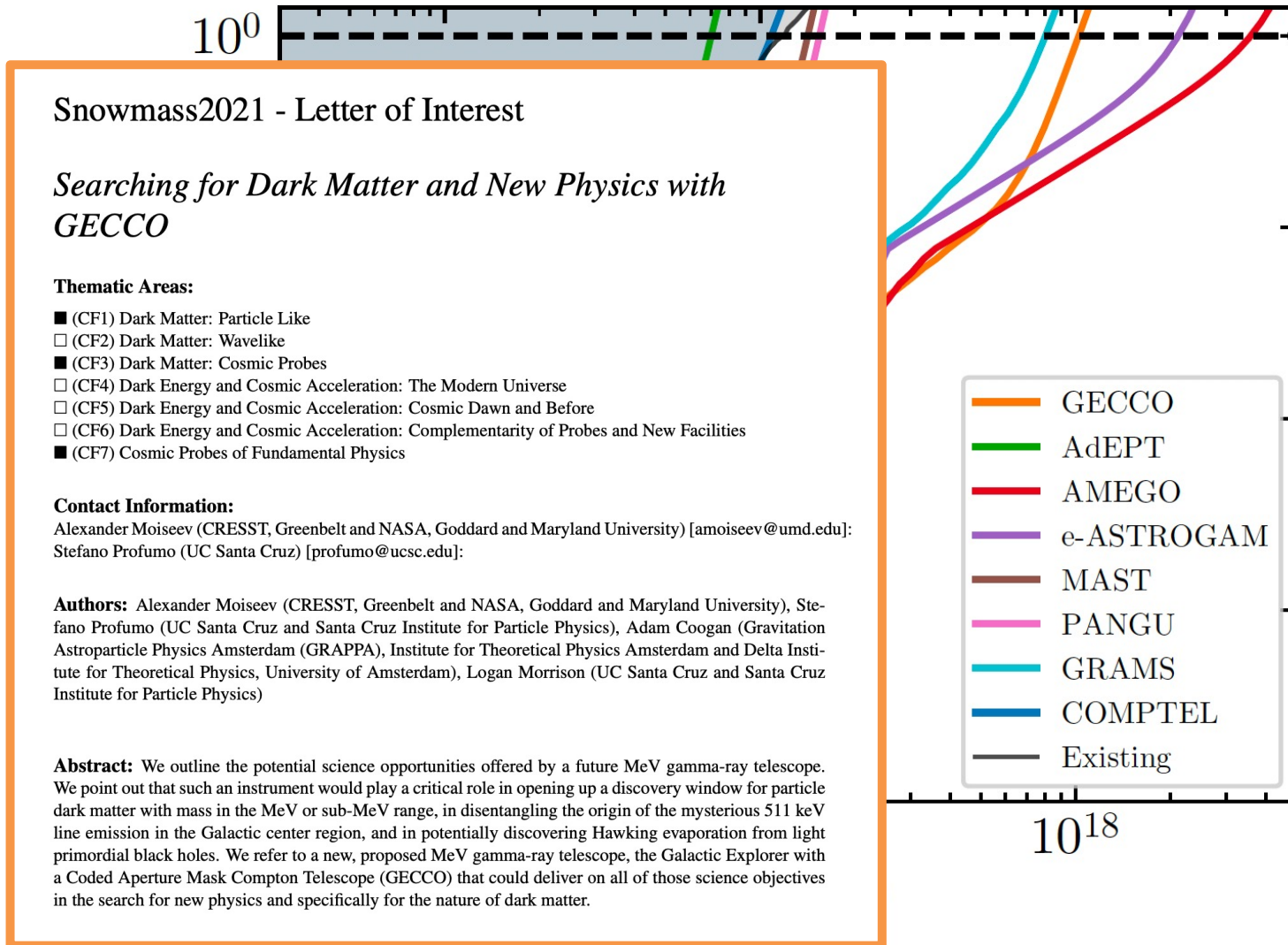
Our new COMPTEL constraints are among strongest/robust



New MeV Telescopes could discover Hawking evaporation!



New MeV Telescopes could discover Hawking evaporation!



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

Melanogenesis: Dark Matter of (almost)



WORLD CUBE ASSOCIATION



Search site

Information

Competitions


Results

Regulations




tro-ph.C

John Tamas

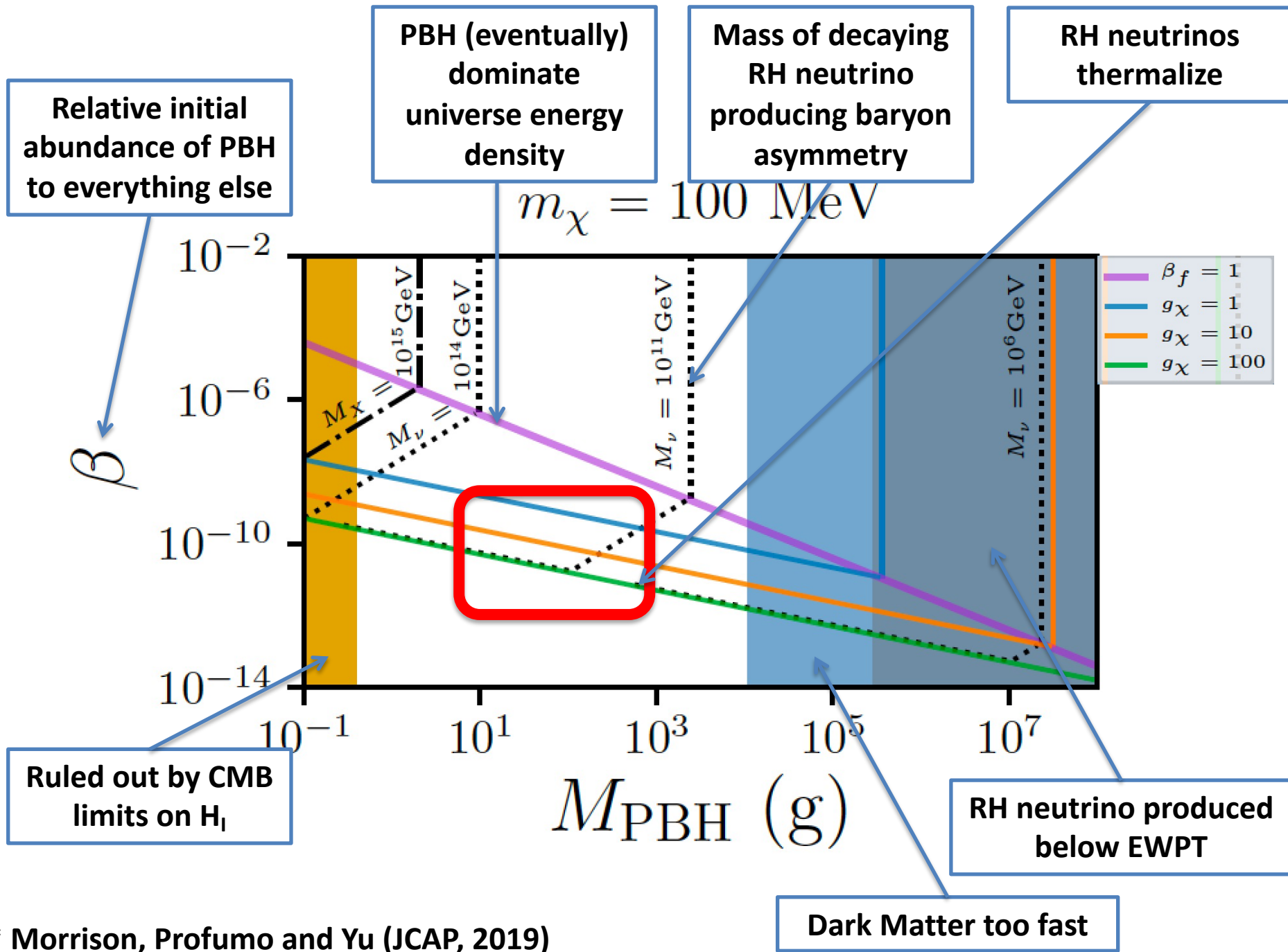
Country	WCA ID	Gender	Competitions
 United States	2007TAMA02	Male	41

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	

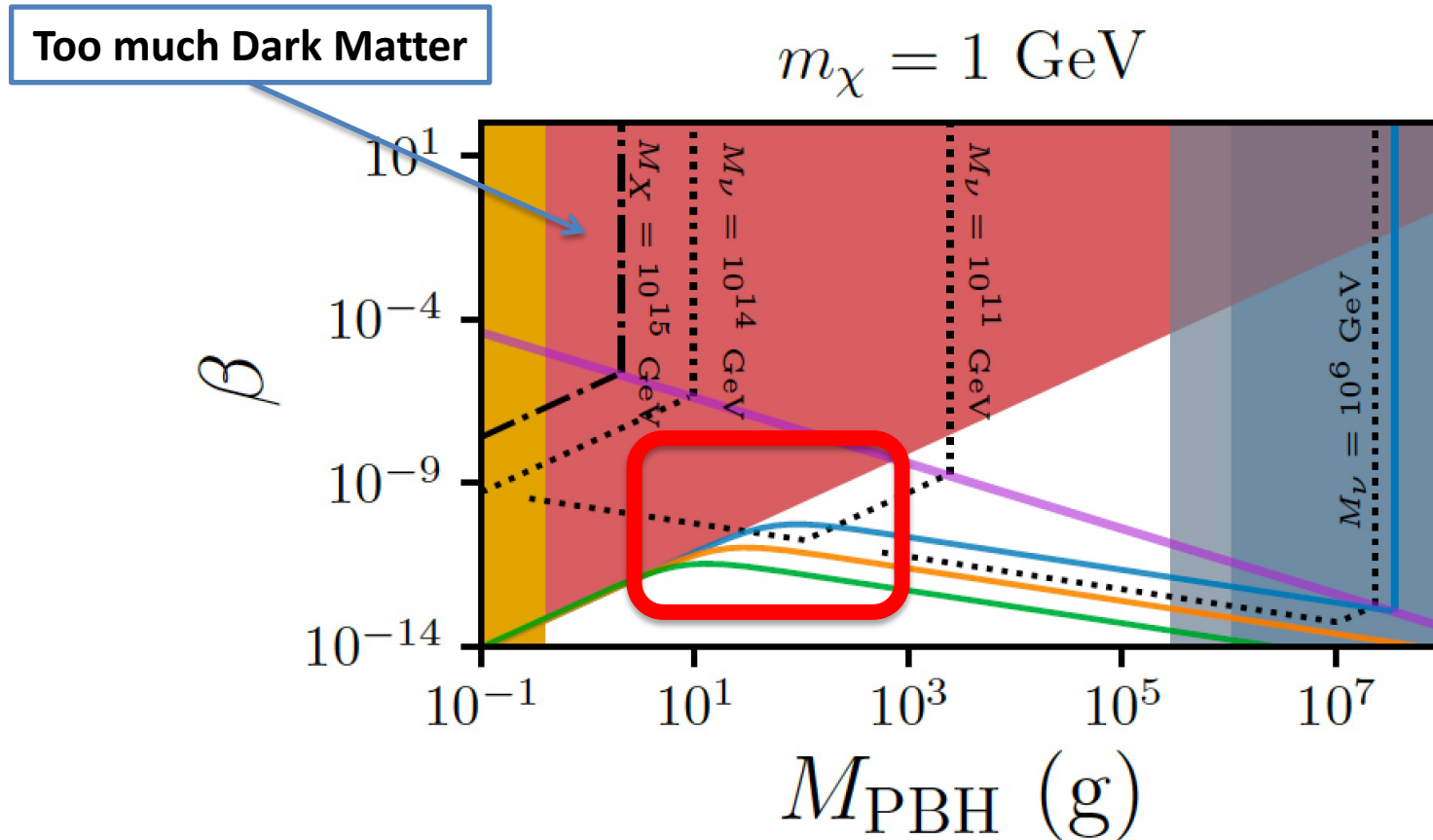
...even if PBH are **NOT** the dark matter, they can **PRODUCE** the dark matter via **Hawking evaporation!**

Mass (g)	T_H (GeV)	τ (s)	$T_{\text{evap}} = T(\tau)$ (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	$4 \times 10^7 \sim 1 \text{ yr}$	$\sim 1 \text{ keV}$



* 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!**



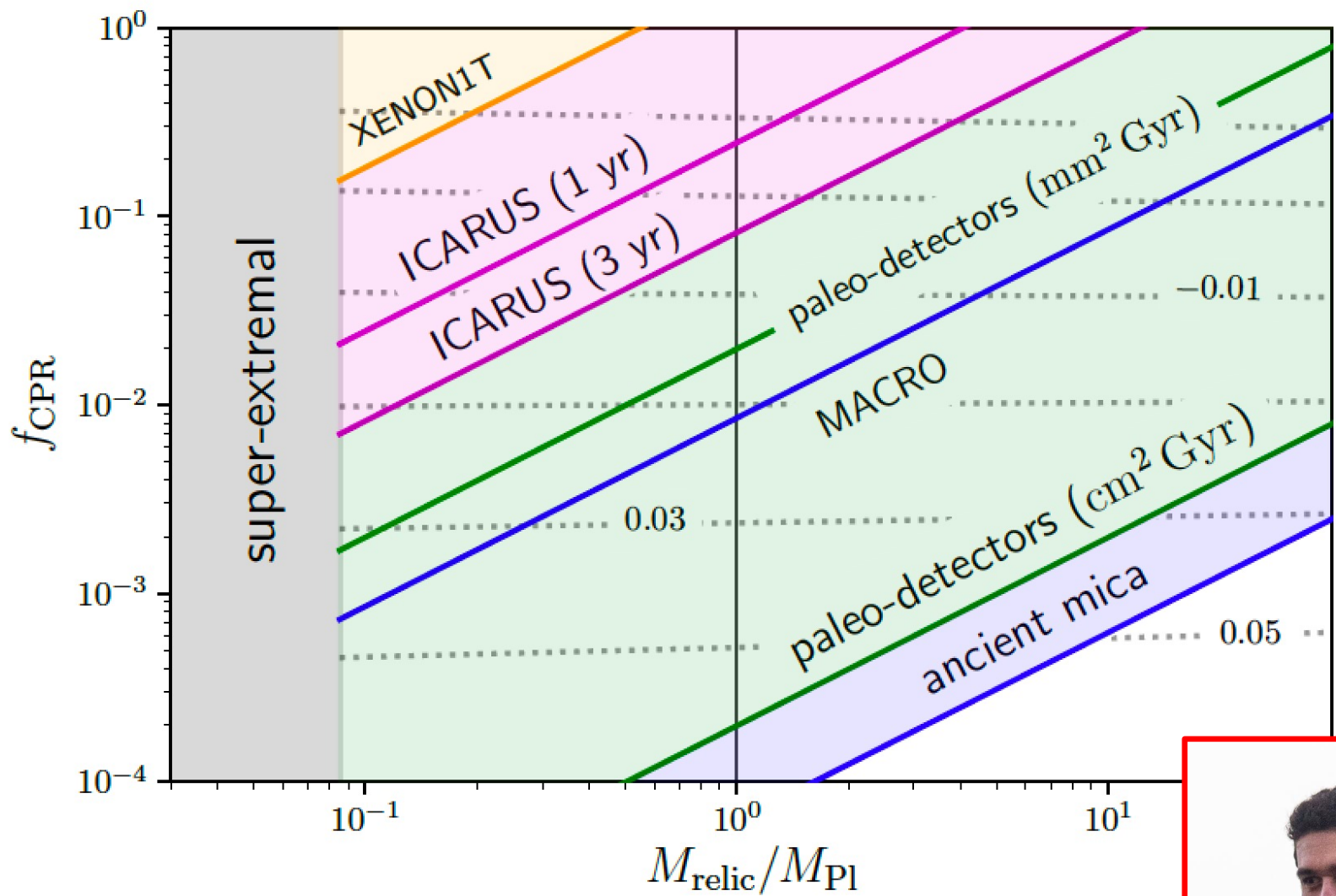
As BH approach the **Planck scale**, they can acquire a significant **relic electric charge**

(under simple **assumptions**) $P(Q) \sim \exp(-4\pi\alpha(Q/e)^2)$
the relic charge is
approximately **Gaussian*** $(8\pi\alpha)^{-1/2} \approx 2.34$

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



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

10^{-3} g

10^7 g

10^{17} g

10^{27} g

10^{37} g

10^{30} eV

10^{40} eV

10^{50} eV

10^{60} eV

10^{70} eV

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

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

10^{-3} g

10^7 g

10^{17} g

10^{27} g

10^{37} g

10^{30} eV

10^{40} eV

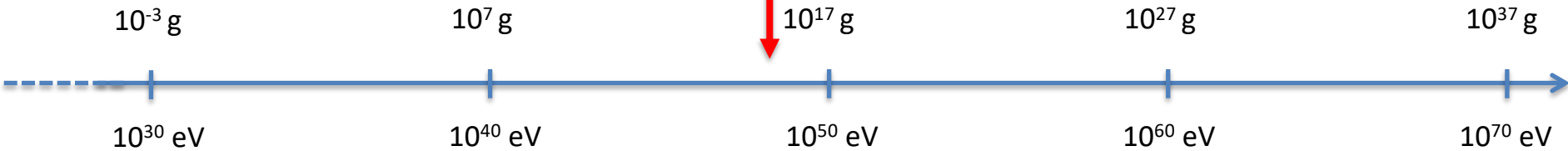
10^{50} eV

10^{60} eV

10^{70} eV

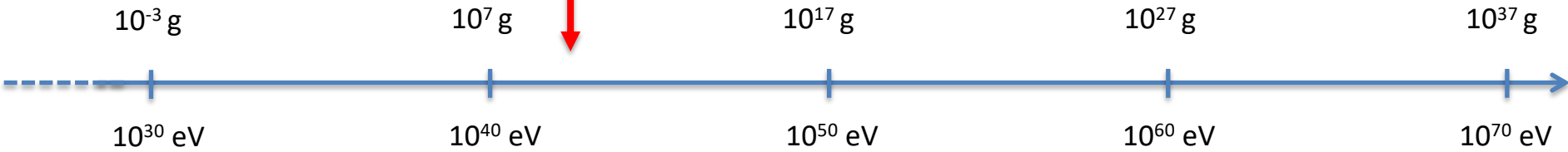
- ✓ **Microlensing a lot trickier than previously thought!**
- ✓ **Detection strategies? PTA?**

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



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

**Ton-size
"Space-cow"
Black Holes**



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

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

10^{-3} g

10^7 g

10^{17} g

10^{27} g

10^{37} g

10^{30} eV

10^{40} eV

10^{50} eV

10^{60} eV

10^{70} eV

- ✓ 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**

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

