SCIPP
SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS

Stefano Profumo

University of California, Santa Cruz

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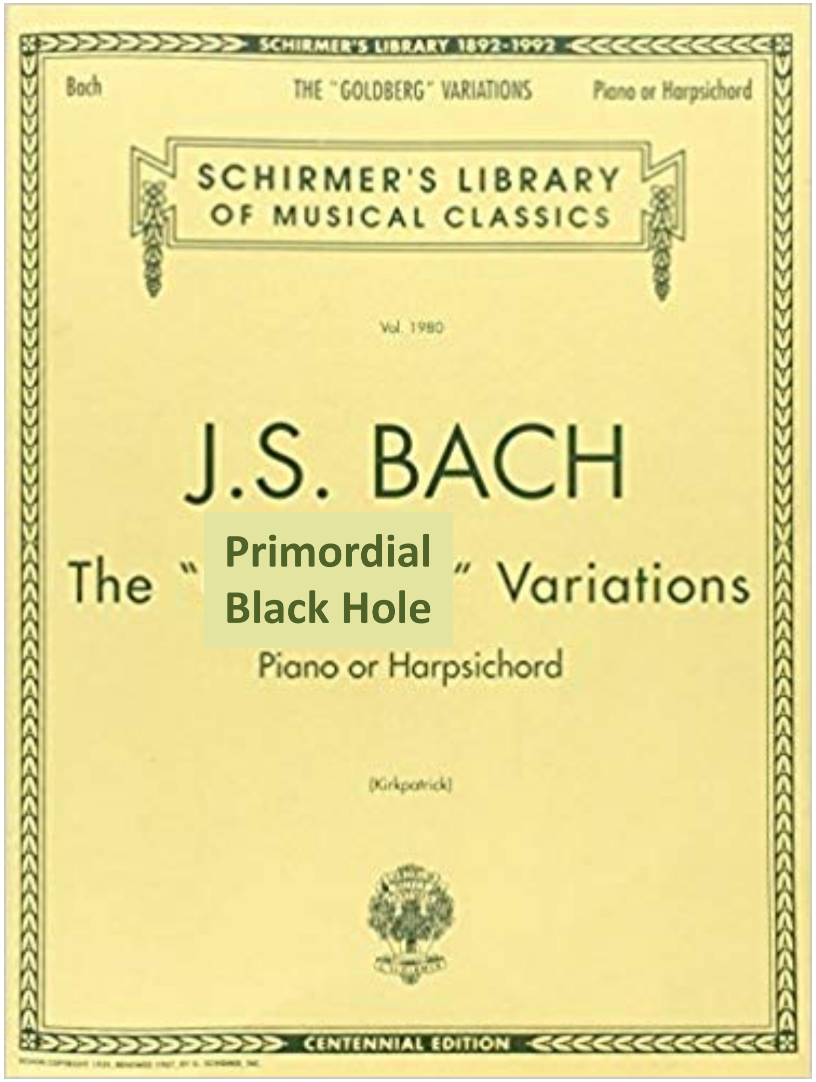

KITP, Santa Barbara (CA), February 4, 2020

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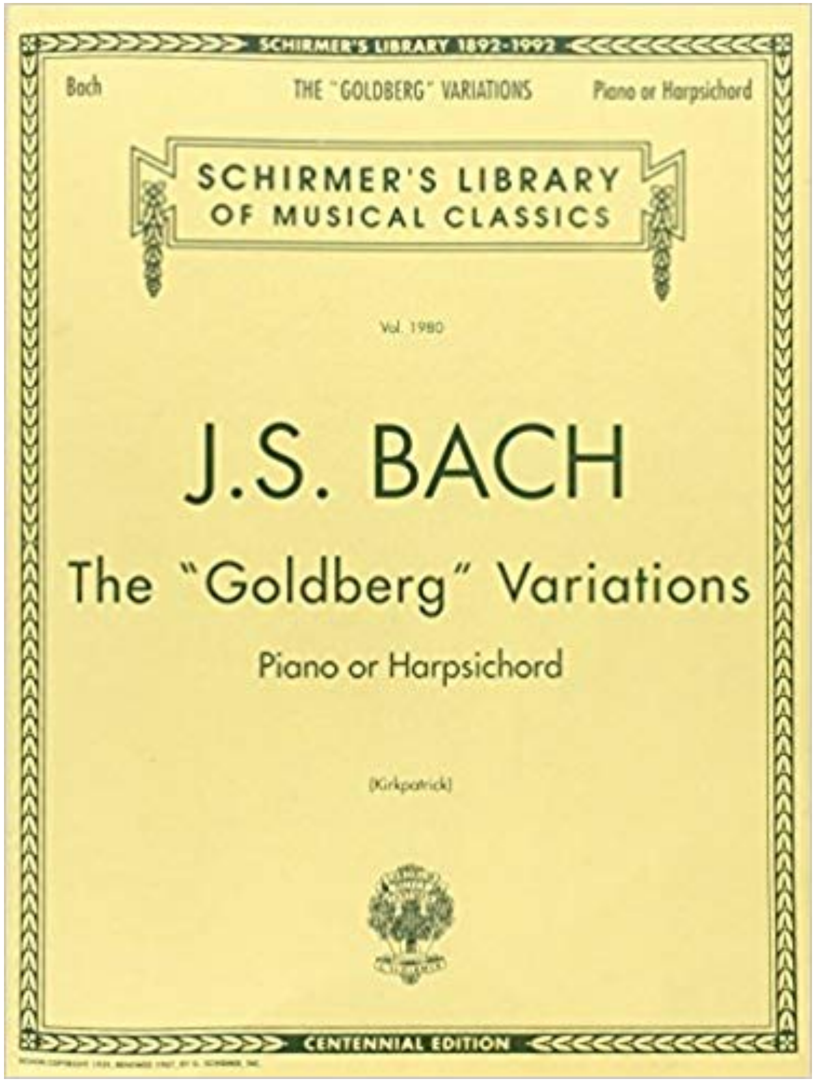
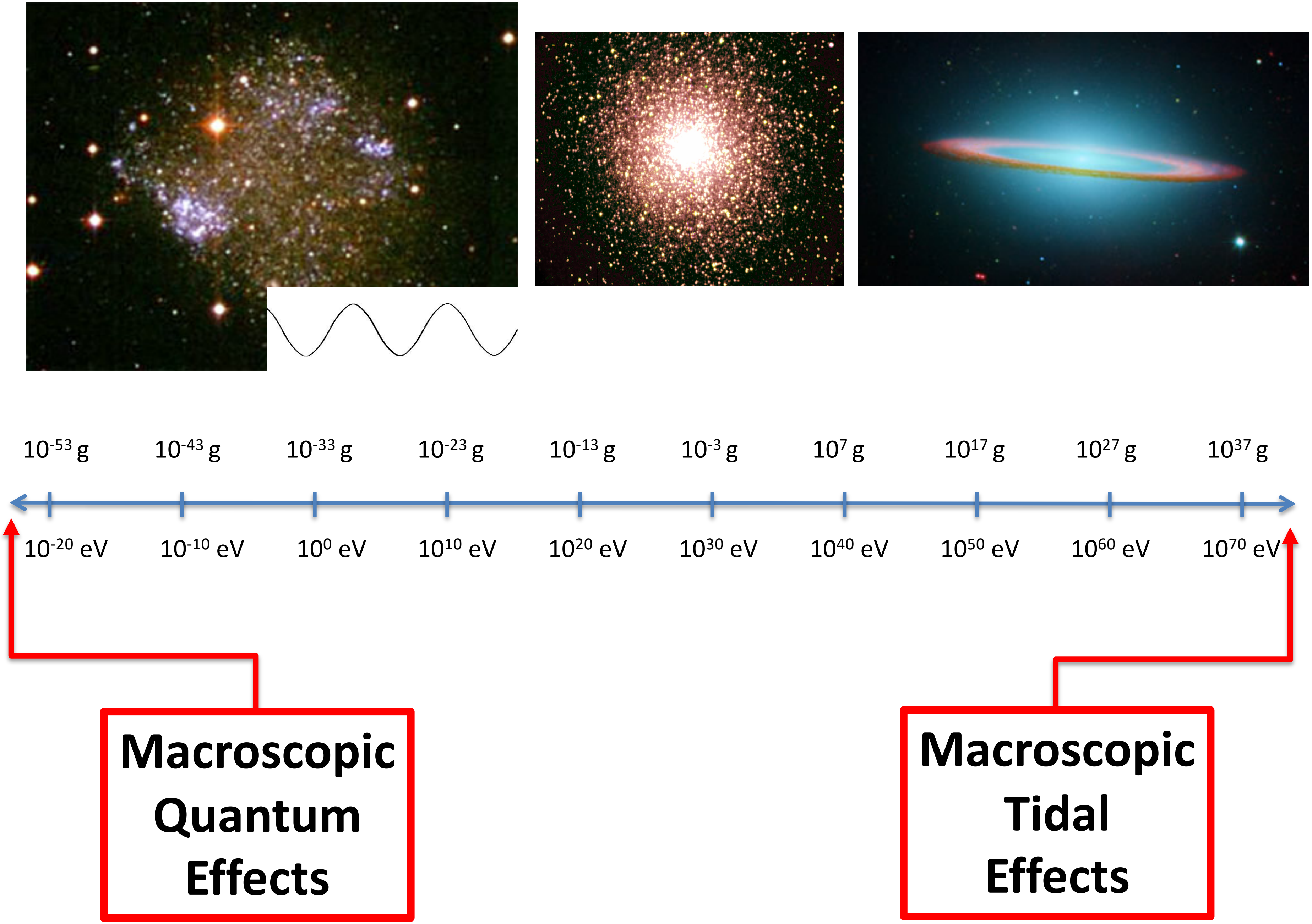


KITP, Santa Barbara (CA), February 4, 2020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10^{7} g
10^{17} g
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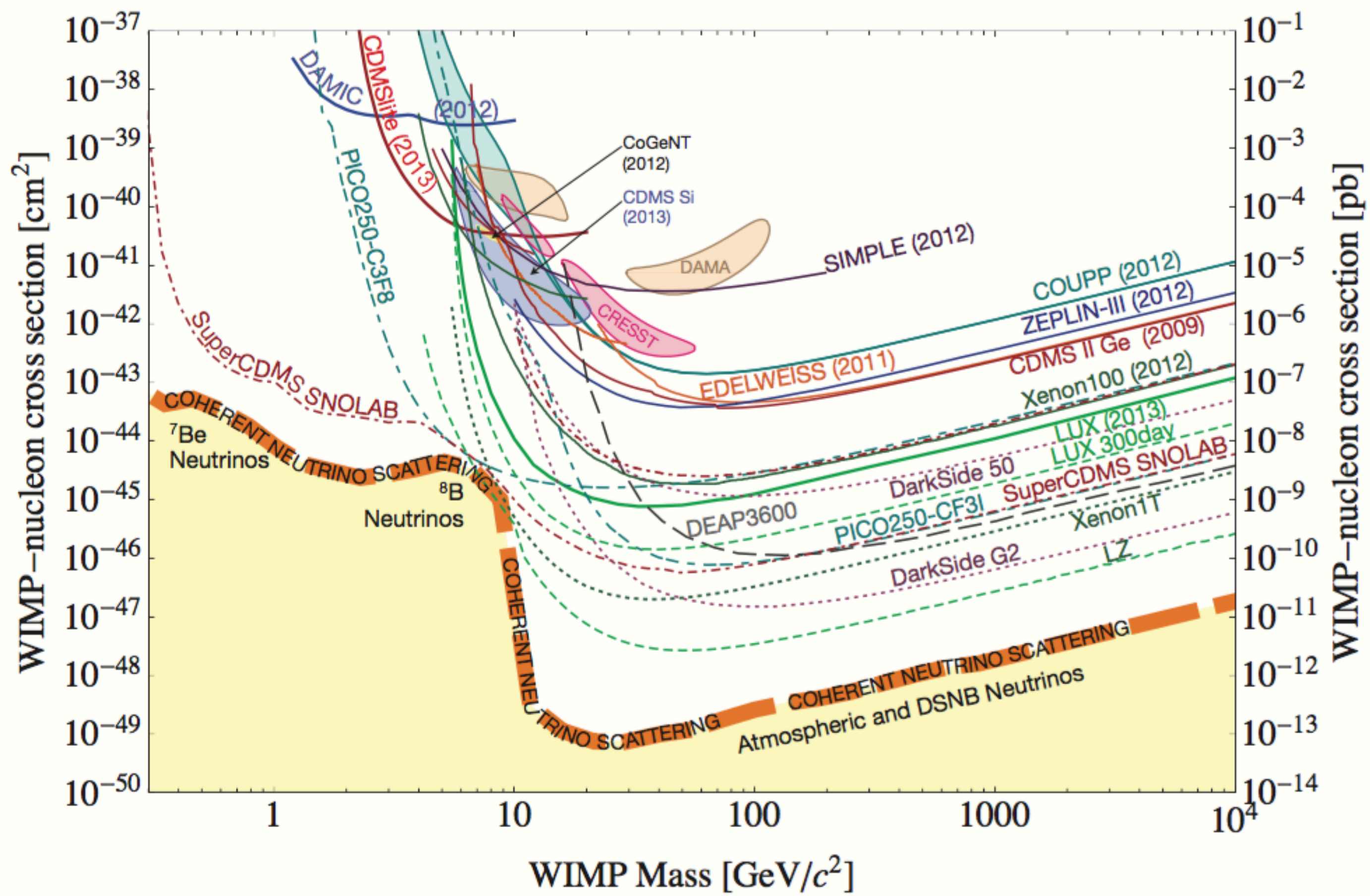
10^{37} g
10^{-20} eV
10^{-10} eV
10^{0} eV
10^{10} eV
10^{20} eV
10^{30} eV
10^{40} eV
10^{50} eV
10^{60} eV
10^{70} eV
Macroscopic Quantum Effects
Macroscopic Tidal Effects


WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]
10^{-37}
10^{-38}
10^{-39}
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10^{-41}
10^{-42}
10^{-43}
10^{-44}
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10^{-46}
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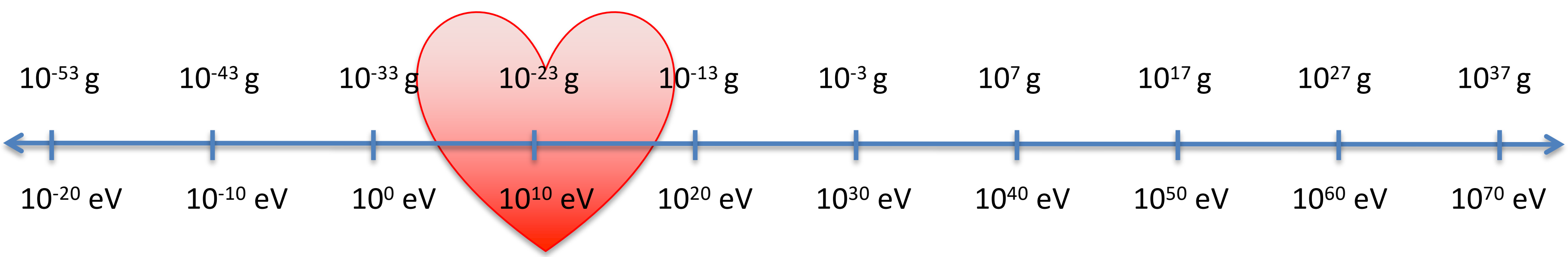
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
1
10
100
1000
10^4
DAMIC
(2012)
CDMSlite (2013)
PICO250-C3F8
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
LUX 300day
SuperCDMS SNOLAB
DarkSide 50
DEAP3600
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
SuperCDMS SNOLAB
COHERENT NEUTRINO SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
Atmospheric and DSNB Neutrinos


10^{-53} g
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10^{-33} g
10^{-23} g
10^{-13} g
10^{-3} g
10^{7} g
10^{17} g
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10^{37} g
10^{-20} eV
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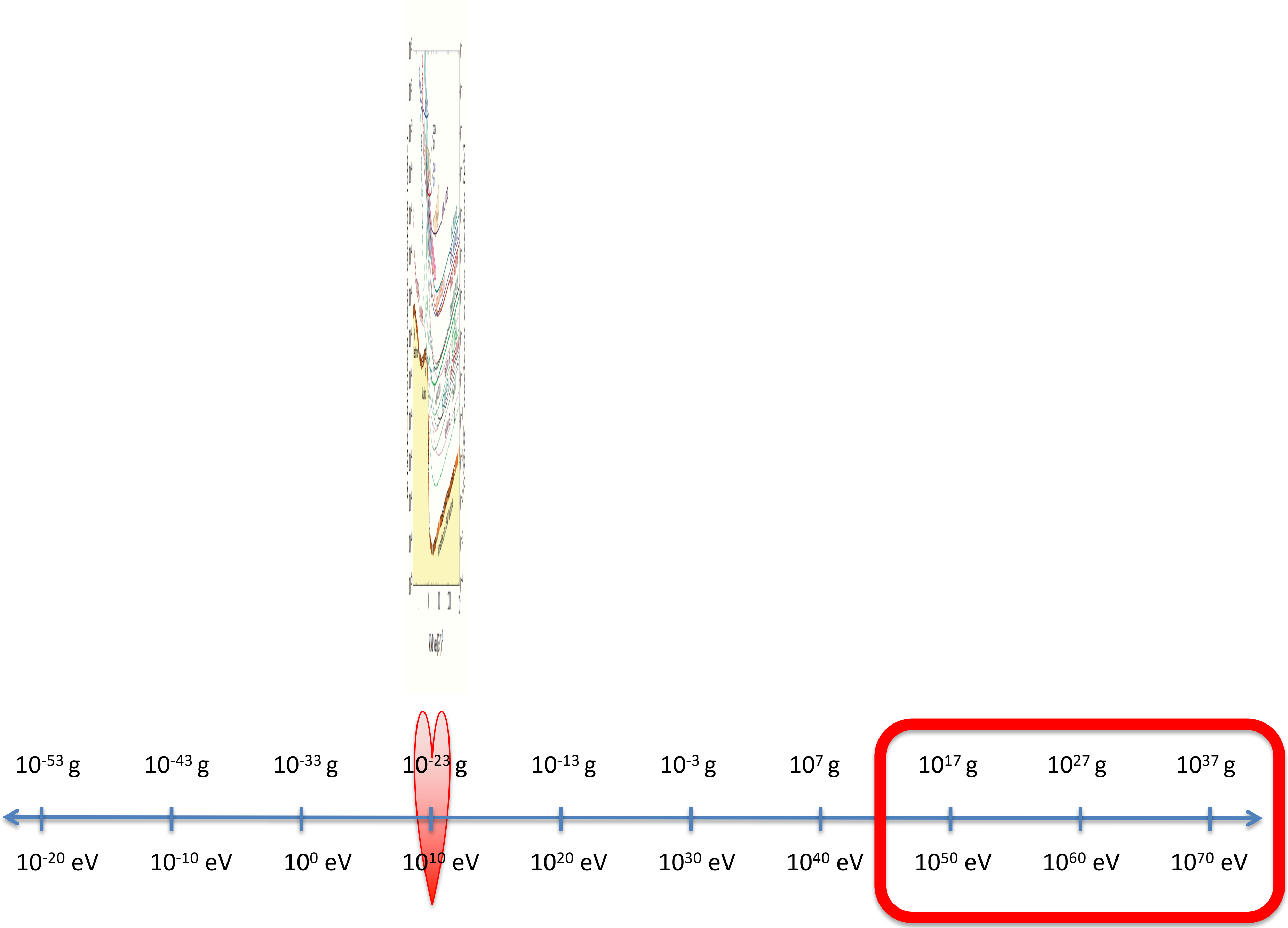
10^{60} eV
10^{70} eV



10^-53 g
10^-43 g
10^-33 g
10^-23 g
10^-13 g
10^-3 g
10^7 g
10^17 g
10^27 g
10^37 g
10^-20 eV
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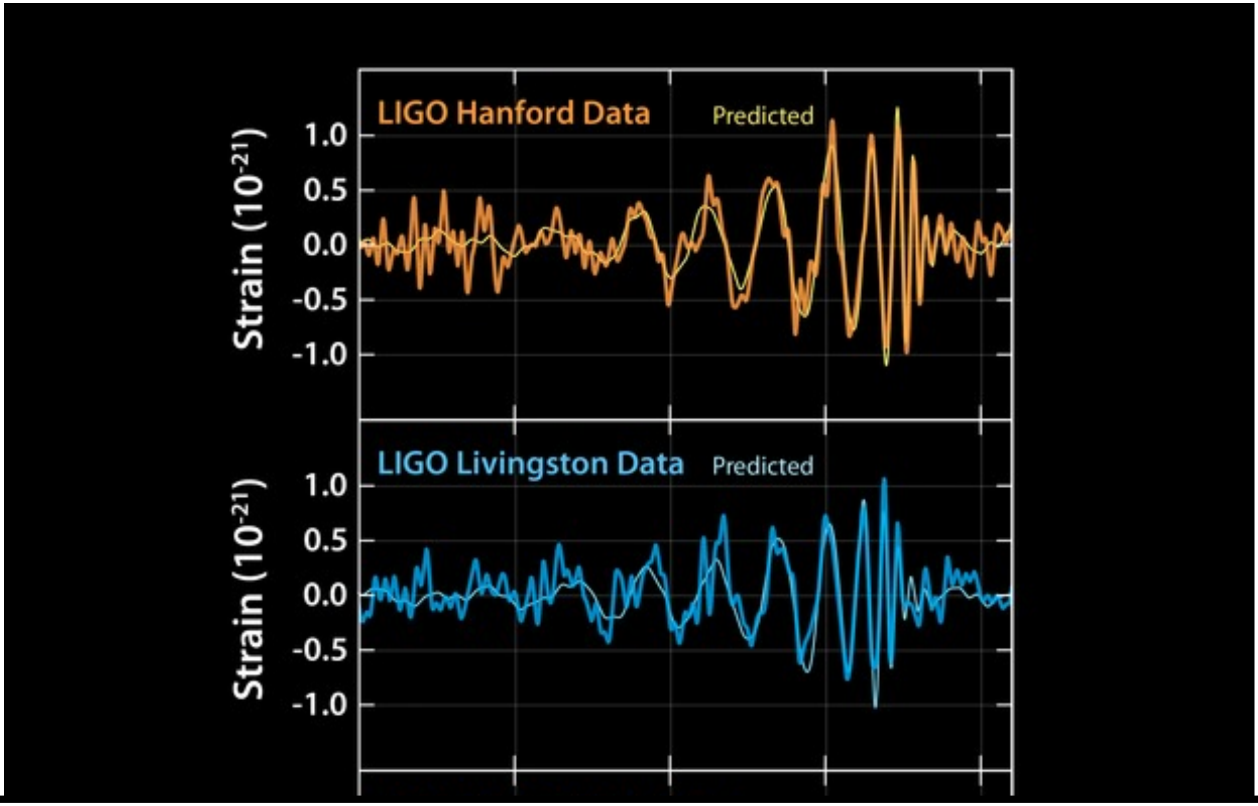
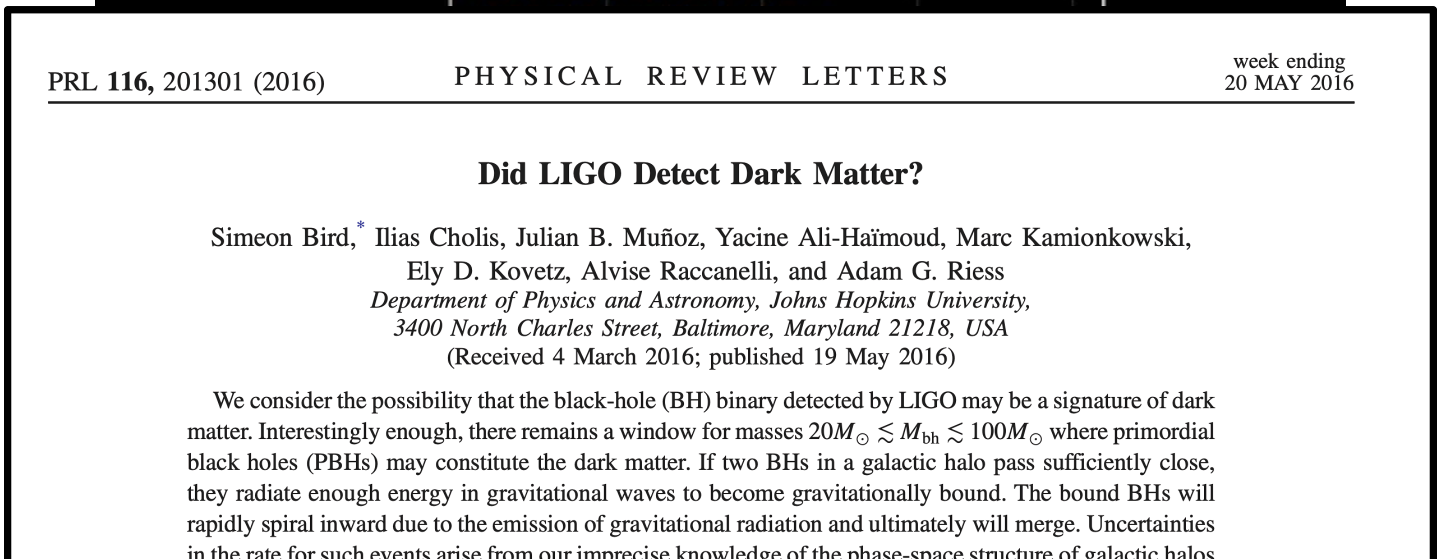
10^60 eV
10^70 eV

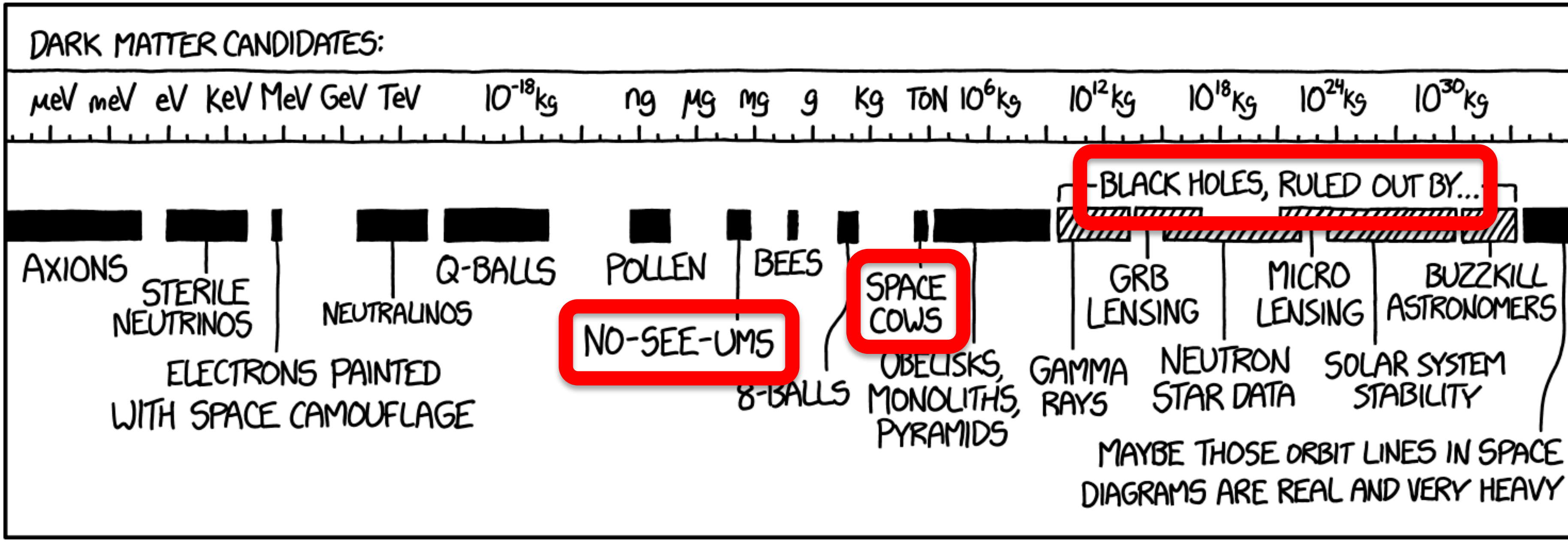



PRL **116,** 201301 (2016) PHYSICAL REVIEW LETTERS week ending 20 MAY 2016

Did LIGO Detect Dark Matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess
Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, Maryland 21218, USA
(Received 4 March 2016; published 19 May 2016)

We consider the possibility that the black-hole (BH) binary detected by LIGO may be a signature of dark matter. Interestingly enough, there remains a window for masses $20M_\odot \lesssim M_{\rm bh} \lesssim 100M_\odot$ where primordial black holes (PBHs) may constitute the dark matter. If two BHs in a galactic halo pass sufficiently close, they radiate enough energy in gravitational waves to become gravitationally bound. The bound BHs will rapidly spiral inward due to the emission of gravitational radiation and ultimately will merge. Uncertainties in the rate for such events arise from our imprecise knowledge of the phase-space structure of galactic halos

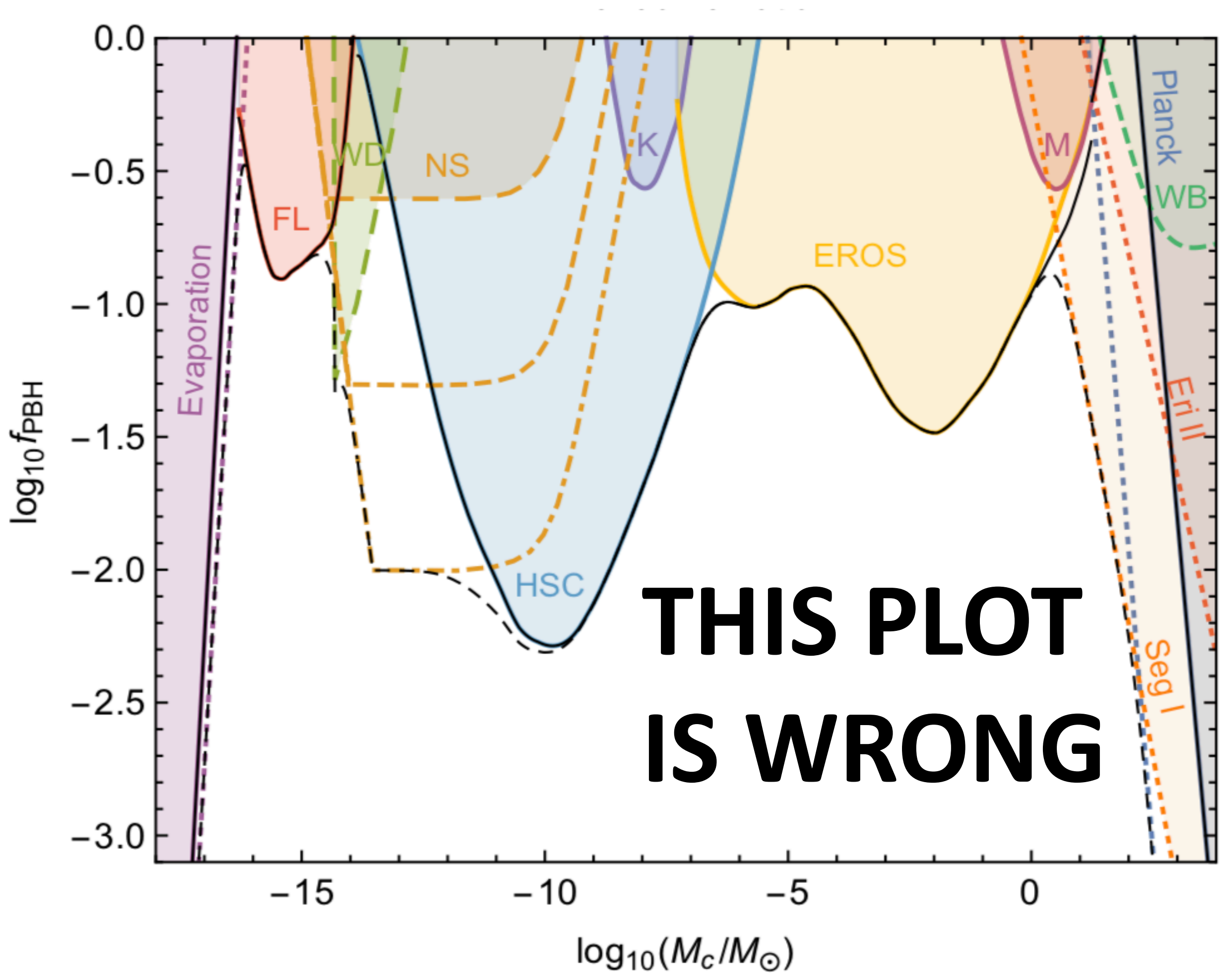


- **Why** it is interesting to consider **PBH** as **Dark Matter**
- **Where** it is interesting **to look** for PBH as Dark Matter
- **…some "NO-SEE-UMS" AND "SPACE COWS"**

source: xkcd

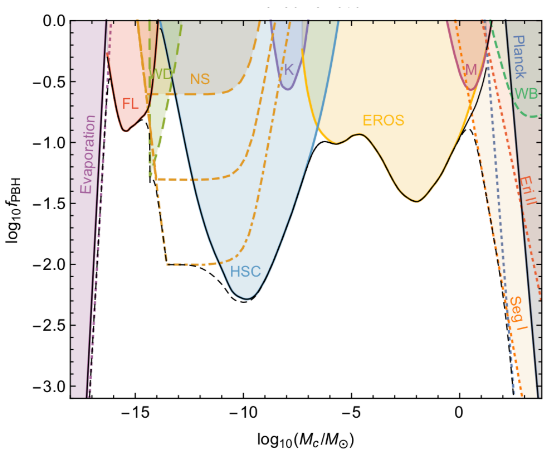
First question: Can there be enough PBH around to be the DM?

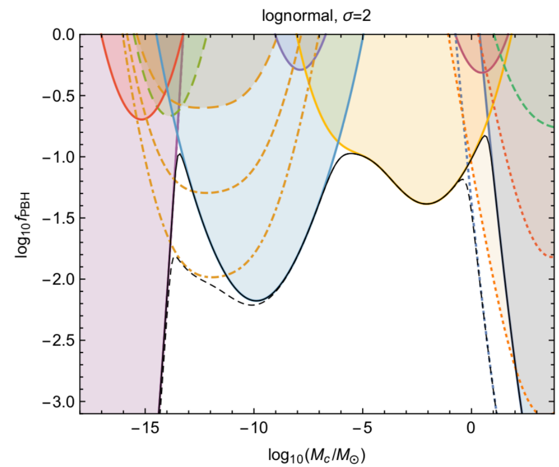
What is the maximal fraction of dark matter in PBH?

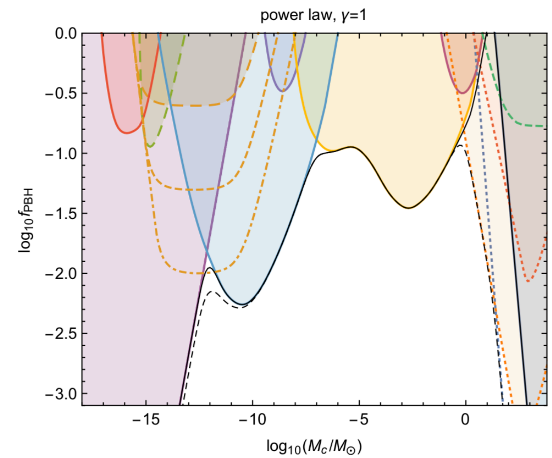


Carr et al, 2017

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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1156 High St., Santa Cruz, CA 95064, USA
Santa Cruz Institute for Particle Physics,
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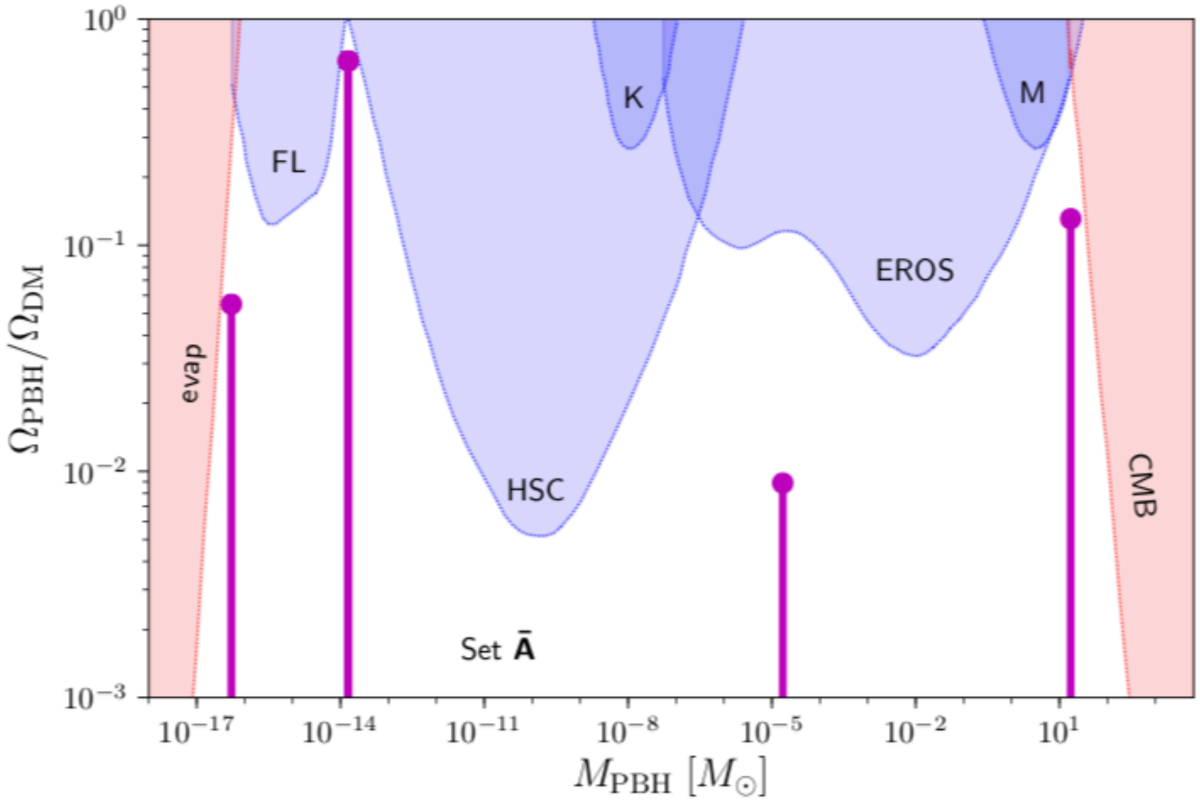
Abstract. The advent of gravitational wave astronomy has rekindled interest in primordial black holes (PBH) as a dark matter candidate. As there are many different observational probes of the PBH density across different masses, constraints on PBH models are dependent

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

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

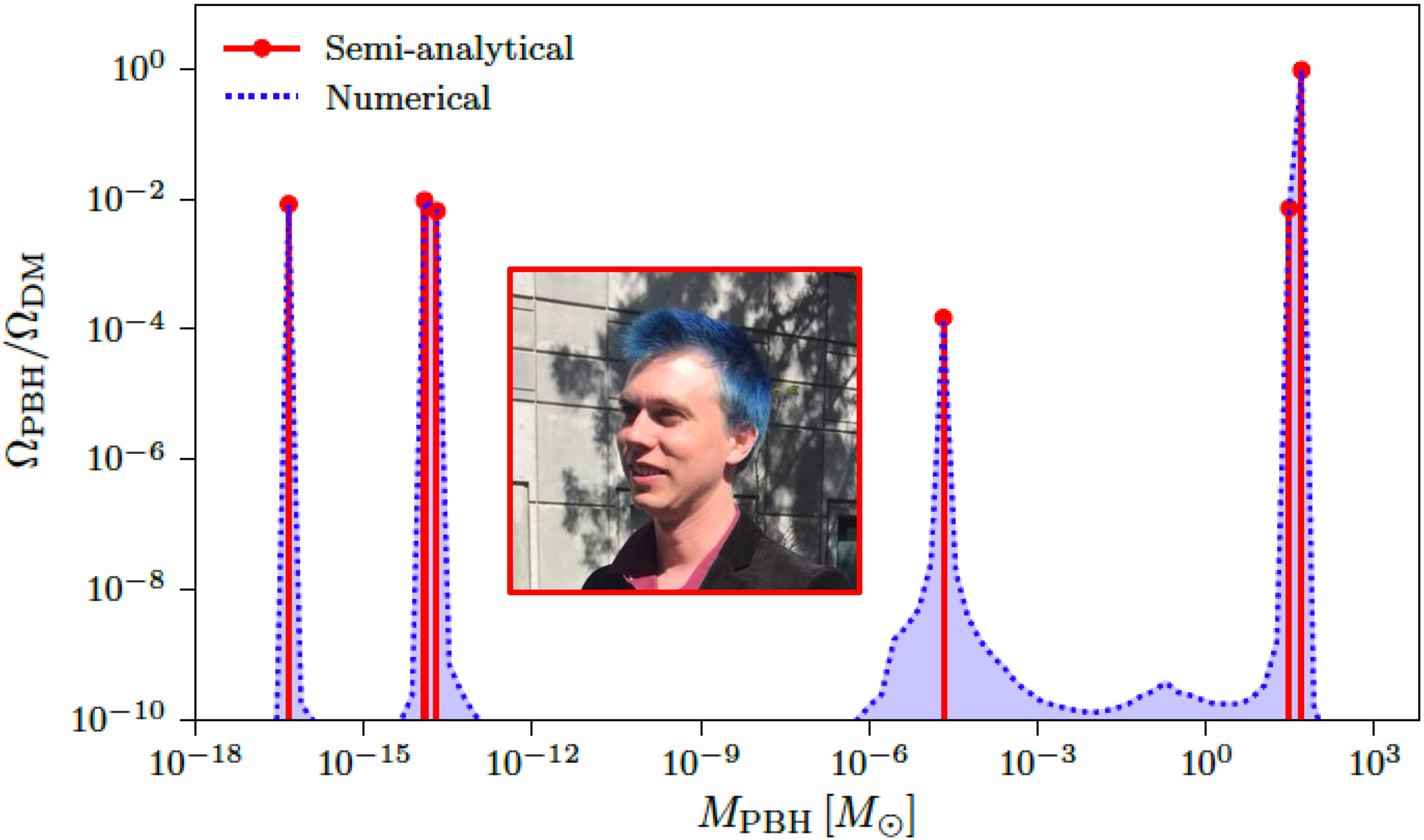
* Lehmann, Profumo and Yant, JCAP 2018



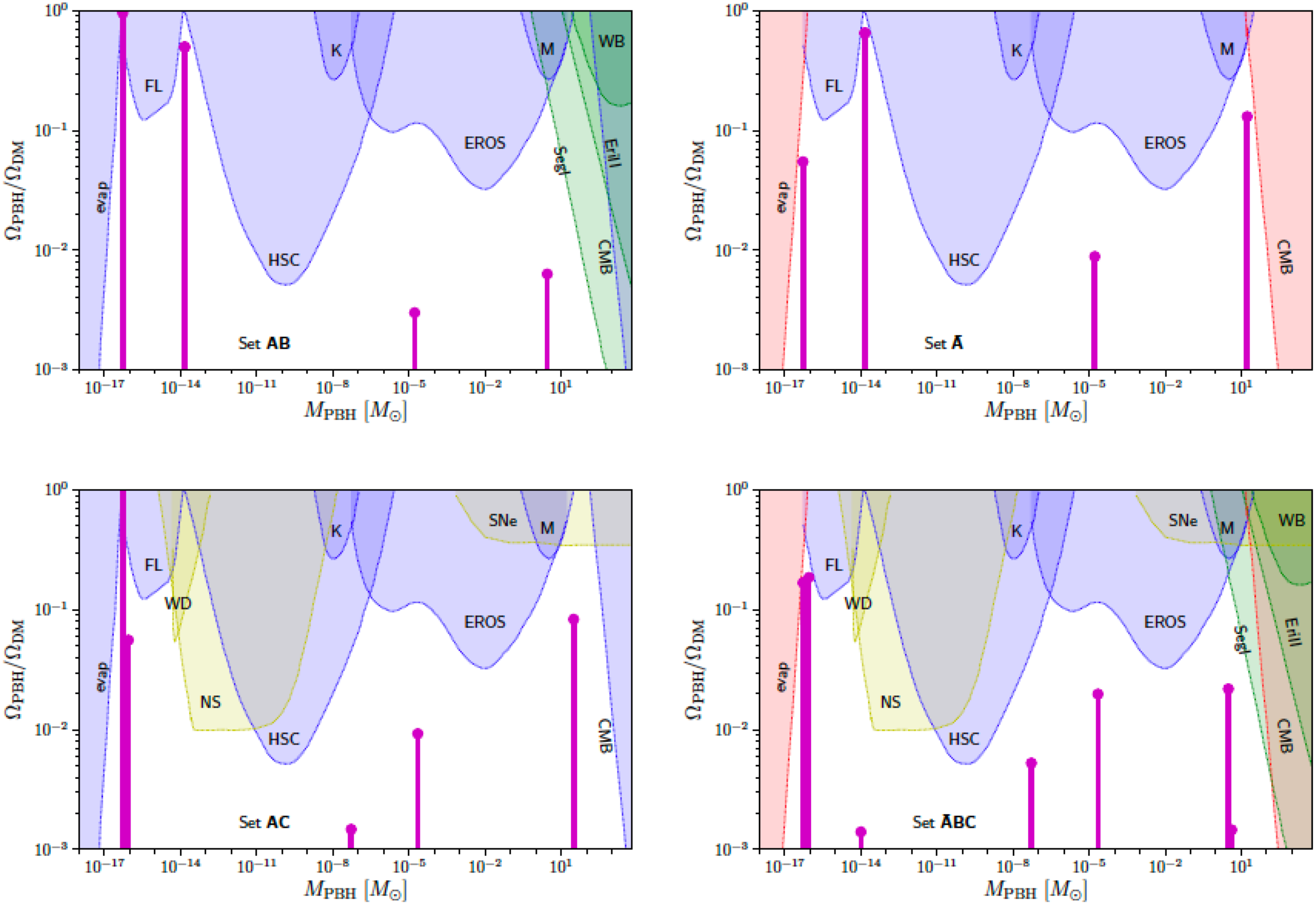
Answer: with *N* independent constraints, the optimal function is a linear combination of *N* delta functions with calculable relative weights

* Lehmann, Profumo and Yant, JCAP 2018

Numerical validation



* Lehmann, Profumo and Yant, JCAP 2018



* Lehmann, Profumo and Yant, JCAP 2018

	$f_{\rm mono}$	$f_{\rm max,all}$	$f_{\rm max,GW}$	$\sigma[\psi]/M_\odot$	$\langle M/M_\odot \rangle$
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* (thanks Sarah!)

Is there a goldilocks signature of PBH?

C. Talbot,[6] D. B. Tanner,[30] D. Tao,[1] M. Tápai,[132] A. Tapia,[27] J. D. Tasson,[98] R. Taylor,[1] R. Tenorio,[102] L. Terkowski,[135] M. Thomas,[7] P. Thomas,[47] S. R. Thondapu,[60] K. A. Thorne,[7] E. Thrane,[6] Shubhanshu Tiwari,[118,119] Srishti Tiwari,[136] V. Tiwari,[107] K. Toland,[46] M. Tonelli,[20,21] Z. Tornasi,[46] A. Torres-Forné,[190] C. I. Torrie,[1] D. Töyrä,[13] F. Travasso,[29,41] G. Traylor,[7] M. C. Tringali,[74] A. Tripathee,[138] A. Trovato,[26] L. Trozzo,[191,21] K. W. Tsang,[37] M. Tse,[14] R. Tso,[48] L. Tsukada,[82] D. Tsuna,[82] T. Tsutsui,[82] D. Tuyenbayev,[109] K. Ueno,[82] D. Ugolini,[192] C. S. Unnikrishnan,[136] A. L. Urban,[2] S. A. Usman,[93] H. Vahlbruch,[10] G. Vajente,[1] G. Valdes,[2] M. Valentini,[118,119] N. van Bakel,[37] M. van Beuzekom,[37] J. F. J. van den Brand,[75,37] C. Van Den Broeck,[37,193] D. C. Vander-Hyde,[42] L. van der Schaaf,[37] J. V. VanHeijningen,[66] A. A. van Veggel,[46] M. Vardaro,[53,54] V. Varma,[48] S. Vass,[1] M. Vasúth,[50] A. Vecchio,[13] G. Vedovato,[54] J. Veitch,[46] P. J. Veitch,[57] K. Venkateswara,[179] G. Venugopalan,[1] D. Verkindt,[34] F. Vetrano,[63,64] A. Viceré,[63,64] A. D. Viets,[24] S. Vinciguerra,[13] D. J. Vine,[133] J.-Y. Vinet,[65] S. Vitale,[14] T. Vo,[42] H. Vocca,[40,41] C. Vorvick,[47] S. P. Vyatchanin,[61] A. R. Wade,[1] L. E. Wade,[122] M. Wade,[122] R. Walet,[37] M. Walker,[27] L. Wallace,[1] S. Walsh,[24] H. Wang,[13] J. Z. Wang,[138] S. Wang,[19] W. H. Wang,[109] Y. F. Wang,[94] R. L. Ward,[8] Z. A. Warden,[35] J. Warner,[47] M. Was,[34] J. Watchi,[103] B. Weaver,[47] L.-W. Wei,[9,10] M. Weinert,[9,10] A. J. Weinstein,[1] R. Weiss,[14] F. Wellmann,[9,10] L. Wen,[66] E. K. Wessel,[19] P. Weßels,[9,10] J. W. Westhouse,[35] K. Wette,[8] J. T. Whelan,[62] B. F. Whiting,[30] C. Whittle,[14] D. M. Wilken,[9,10] D. Williams,[46] A. R. Williamson,[143,37] J. L. Willis,[1] B. Willke,[10,9] W. Winkler,[9,10] C. C. Wipf,[1] H. Wittel,[9,10] G. Woan,[46] J. Woehler,[9,10] J. K. Wofford,[62] J. L. Wright,[46] D. S. Wu,[9,10] D. M. Wysocki,[62] S. Xiao,[1] R. Xu,[110] H. Yamamoto,[1] C. C. Yancey,[77] L. Yang,[121] Y. Yang,[30] Z. Yang,[43] M. J. Yap,[8] M. Yazback,[30] D. W. Yeeles,[107] Hang Yu,[14] Haocun Yu,[14] S. H. R. Yuen,[94] A. K. Zadrożny,[109] A. Zadrożny,[157] M. Zanolin,[35] T. Zelenova,[29] J.-P. Zendri,[54] M. Zevin,[58] J. Zhang,[66] L. Zhang,[1] T. Zhang,[46] C. Zhao,[66] G. Zhao,[103] M. Zhou,[58] Z. Zhou,[58] X. J. Zhu,[6] A. B. Zimmerman,[194] M. E. Zucker,[1,14] and J. Zweizig[1]

(LIGO Scientific Collaboration and the Virgo Collaboration)

S. Shandera[89]

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:

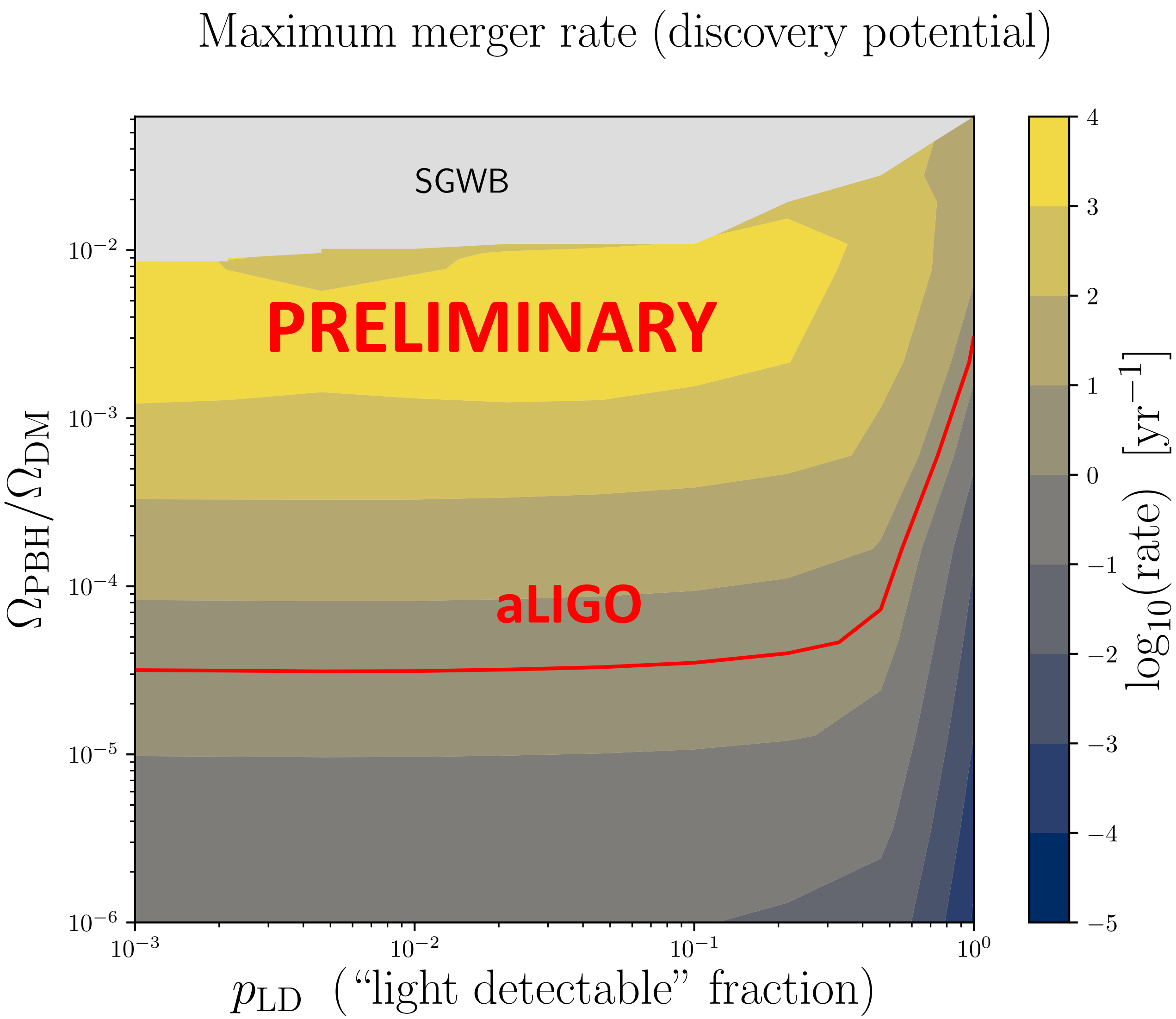
1. **Rate of "goldilocks events"**

$$R(\psi) = \int \mathrm{d}m_1 \, \mathrm{d}m_2 \, \mathcal{R}(\psi;\ m_1, m_2) V_{\mathrm{eff}}(m_1, m_2)$$

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

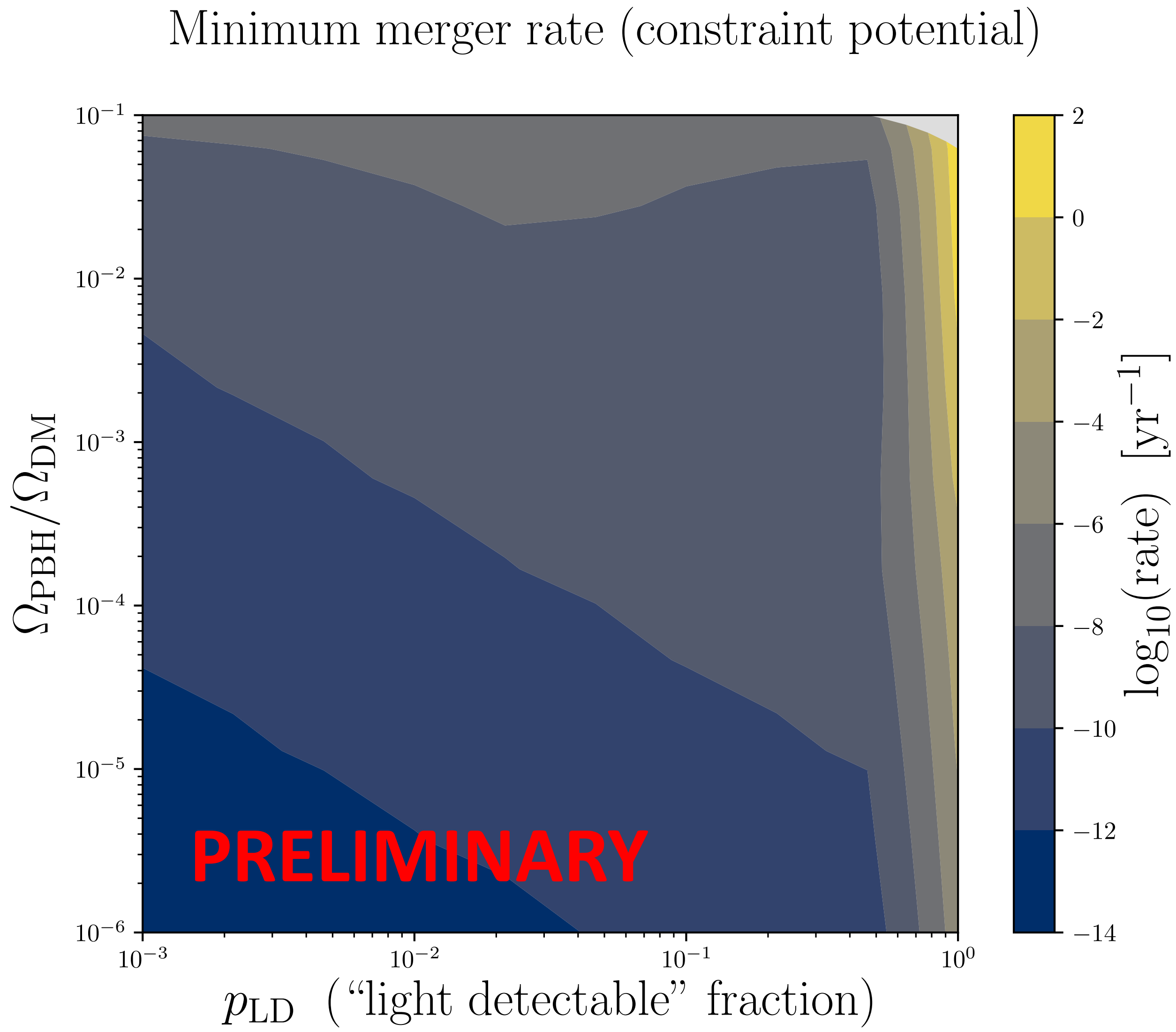
$$p_{\mathrm{LD}} = \frac{\int_{M_{\mathrm{LD,min}}}^{M_{\mathrm{LD,max}}} \mathrm{d}M \, \psi(M)}{\int_0^\infty \mathrm{d}M \, \psi(M)}.$$

We can **numerically** compute the **maximal** possible "**goldilocks event rate**"



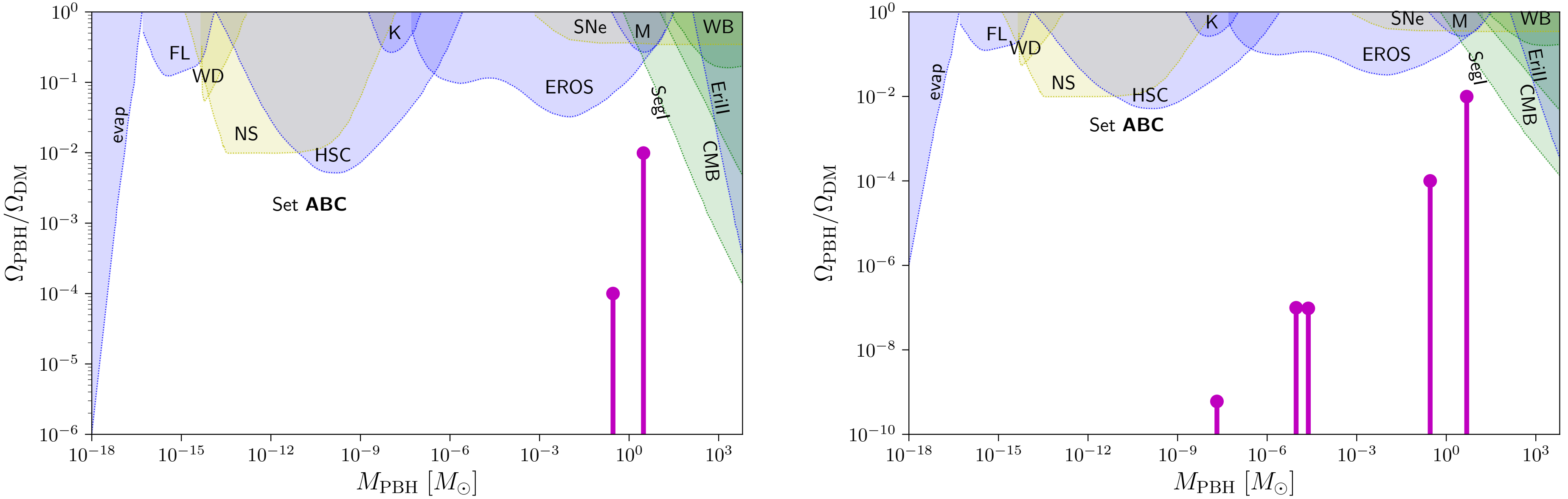
* Lehmann, Profumo and Yant, in progress

…but given a light+detectable fraction, and a total mass fraction, a minimal rate also exists!



* Lehmann, Profumo and Yant, in progress

...and we can calculate an "optimal" mass fraction



PRELIMINARY

* Lehmann, Profumo and Yant, in progress

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	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	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	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$.186^{+0.00}_{-0.00}$	$0.00^{+0.02}_{-0.01}$	≤ 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

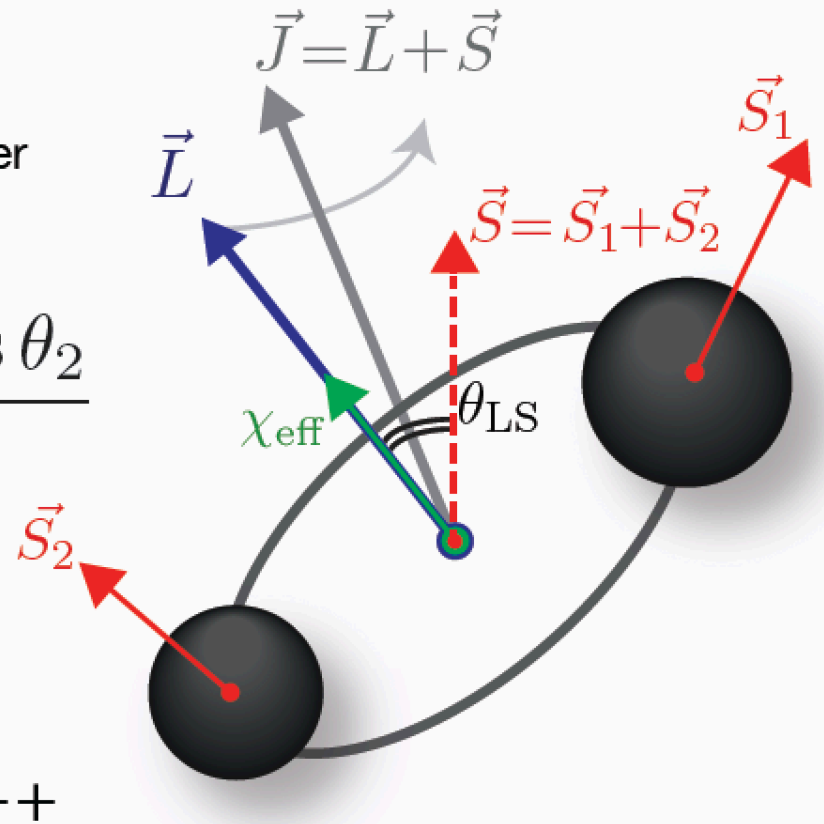
Spin

Slide credit: Nico Fernandez (UCSC → UIUC)

Effective Spin

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

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



Information about:

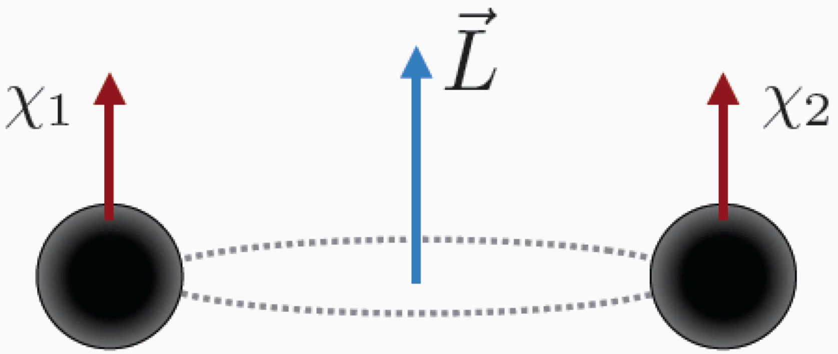
- Direction. +++
- Spin magnitude. ++
- masses. +

Slide credit: Nico Fernandez (UCSC → UIUC)

Effective Spin = 1

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

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



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

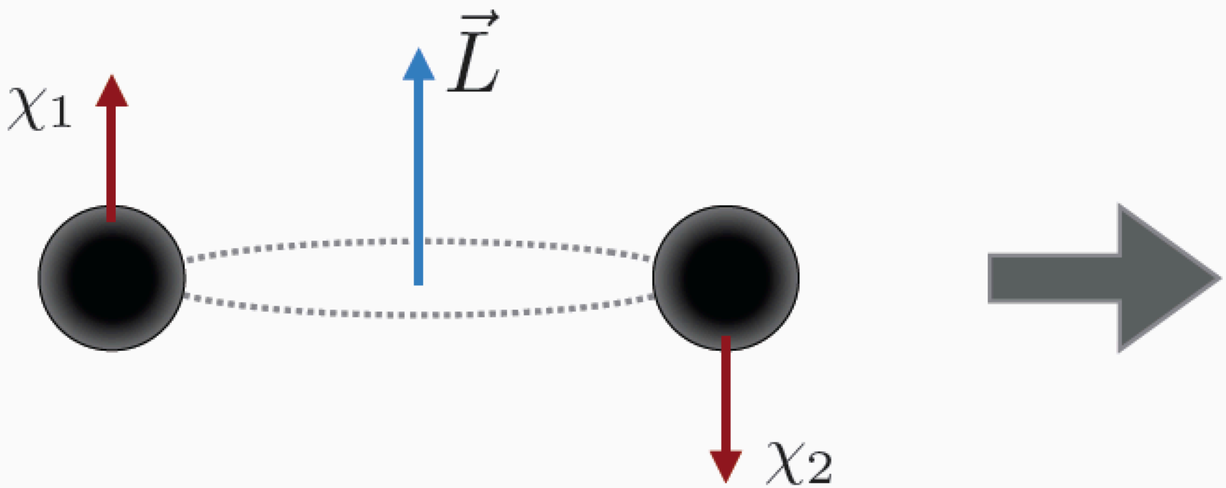
Most black holes from stellar binaries probably start off with their spins aligned

Slide credit: Nico Fernandez (UCSC → UIUC)

Effective Spin = 0

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

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



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

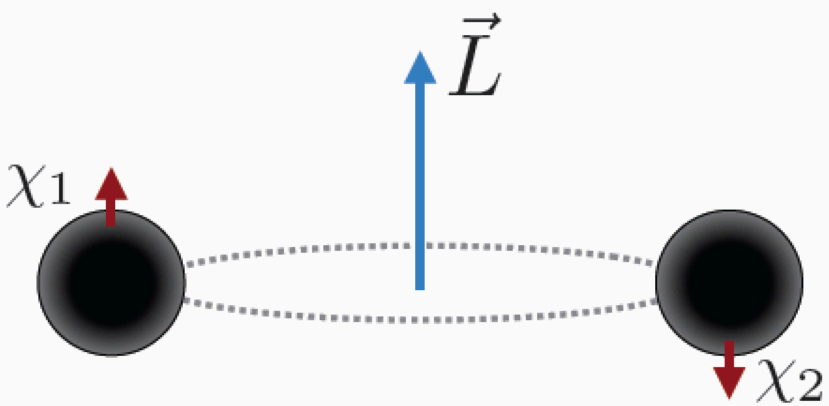
Spins are essentially isotropic in the dynamical formation scenario. Binary was probably formed in a cluster

Slide credit: Nico Fernandez (UCSC → UIUC)

Effective Spin = 0

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

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



$$\Rightarrow \quad \chi_{\text{eff}} \approx 0$$

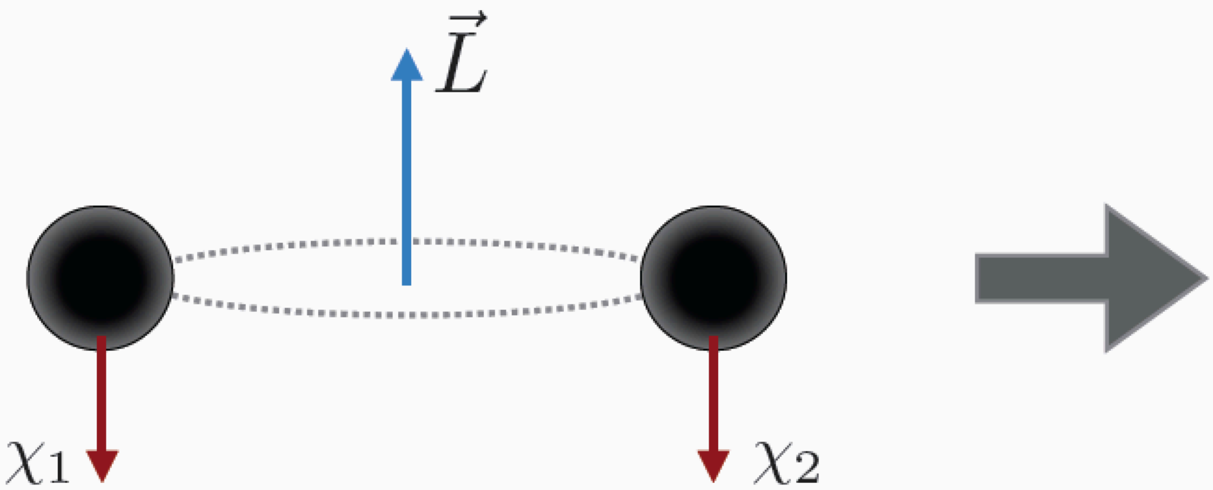
Spin magnitudes are close to zero (expected from PBHs).

Slide credit: Nico Fernandez (UCSC → UIUC)

Effective Spin = -1

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

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

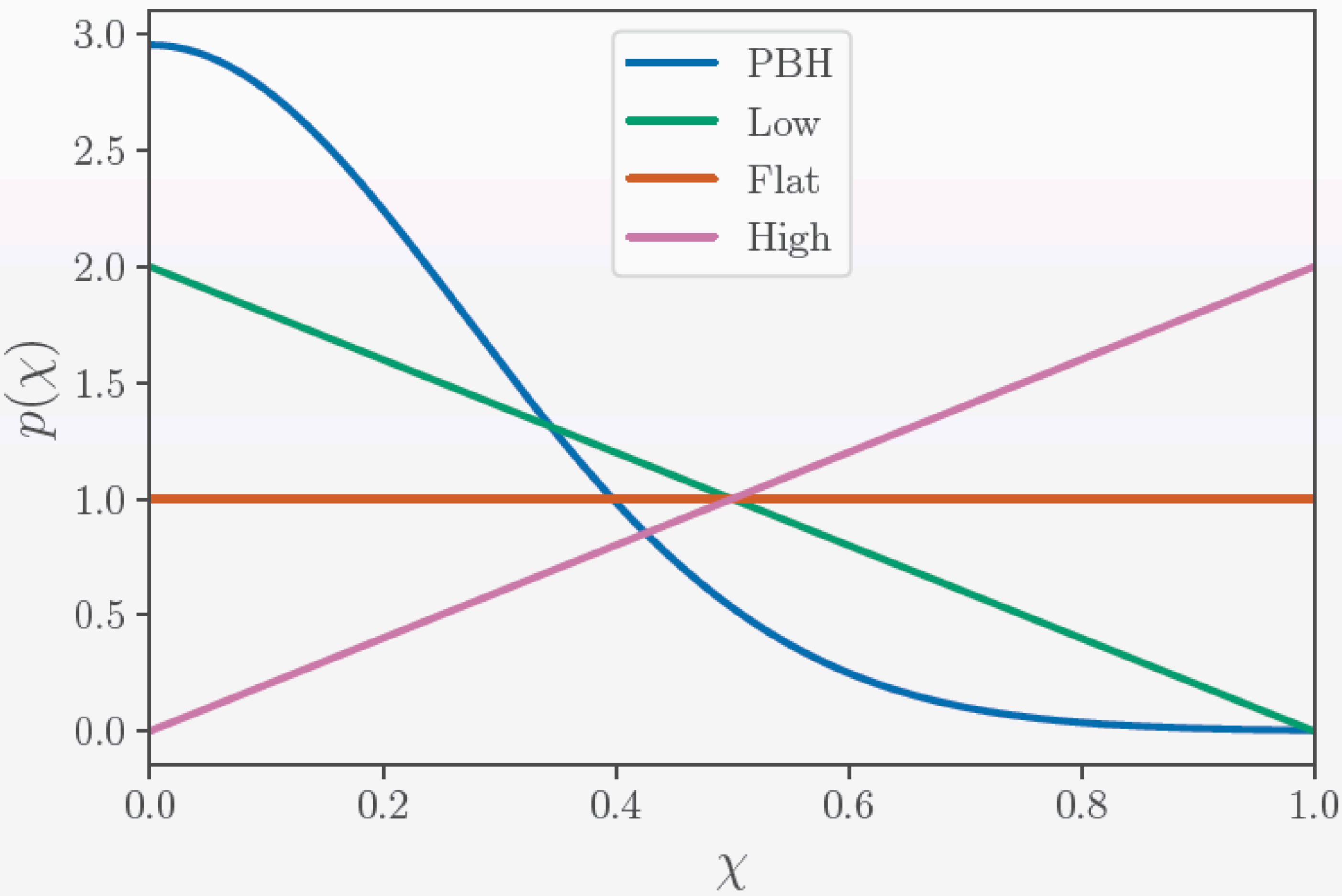


$$\chi_{\rm eff} \approx -1$$

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)

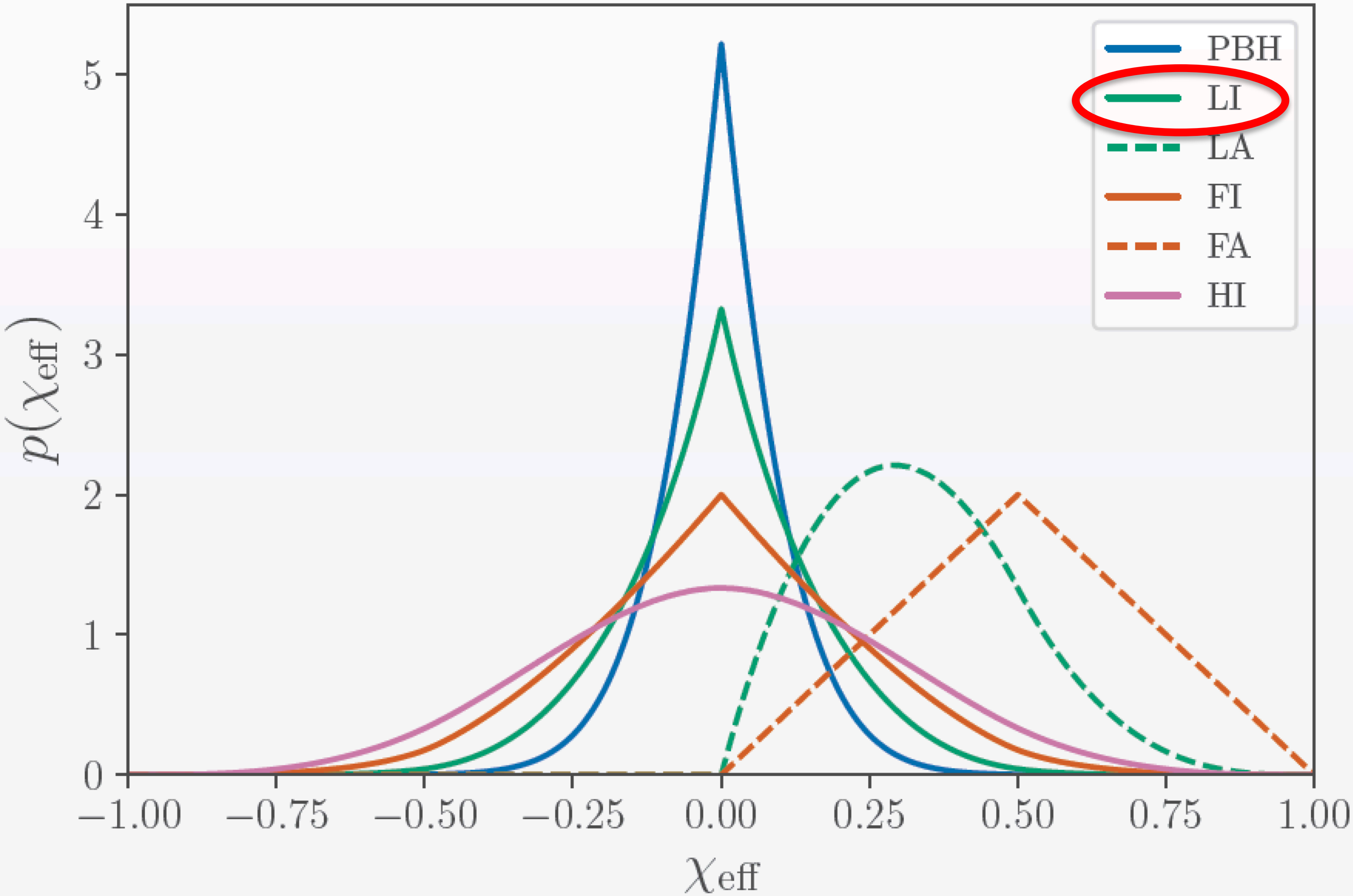
Model Selection

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

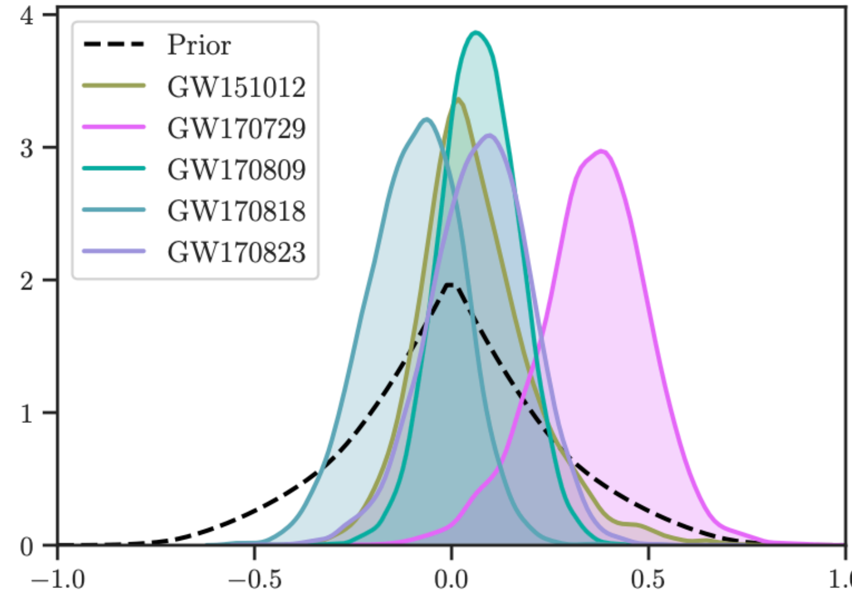
Example:
FI = Flat spin magnitude and isotropic spins (LIGO)
FA = Flat spin magnitude and align spins

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

Effective Spin Priors



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



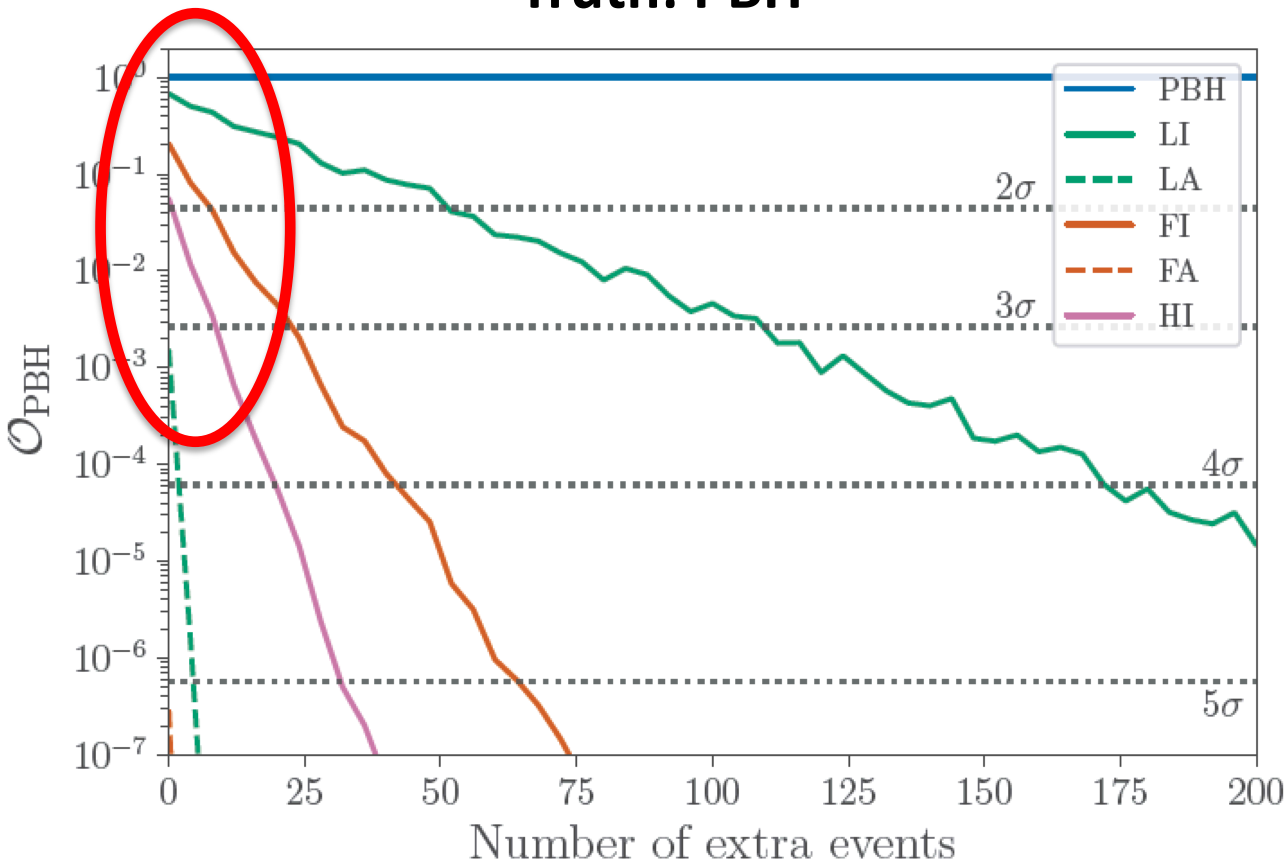
Odds ratios

	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)

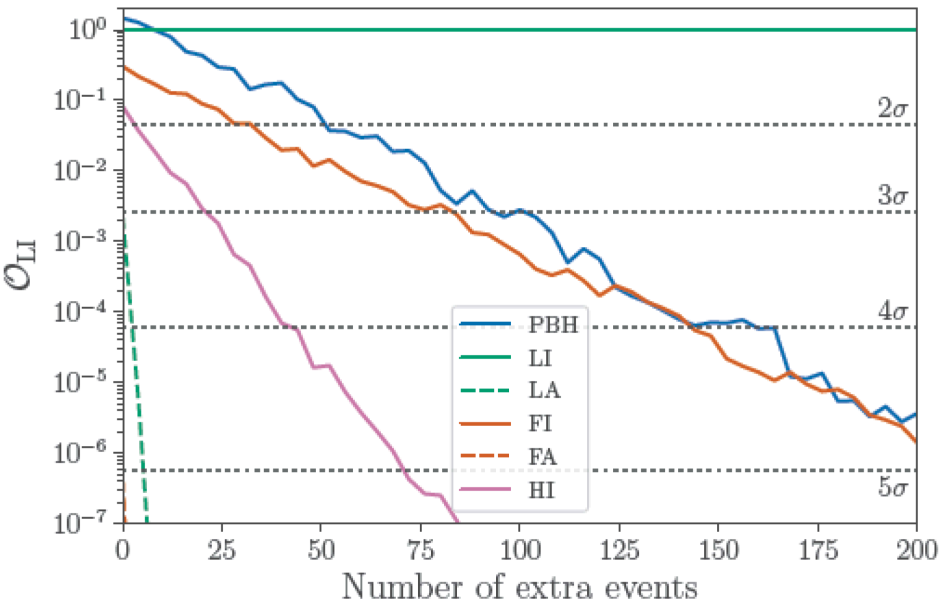
Evolution of the Odds ratios

Truth: PBH



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

Evolution of the Odds ratios



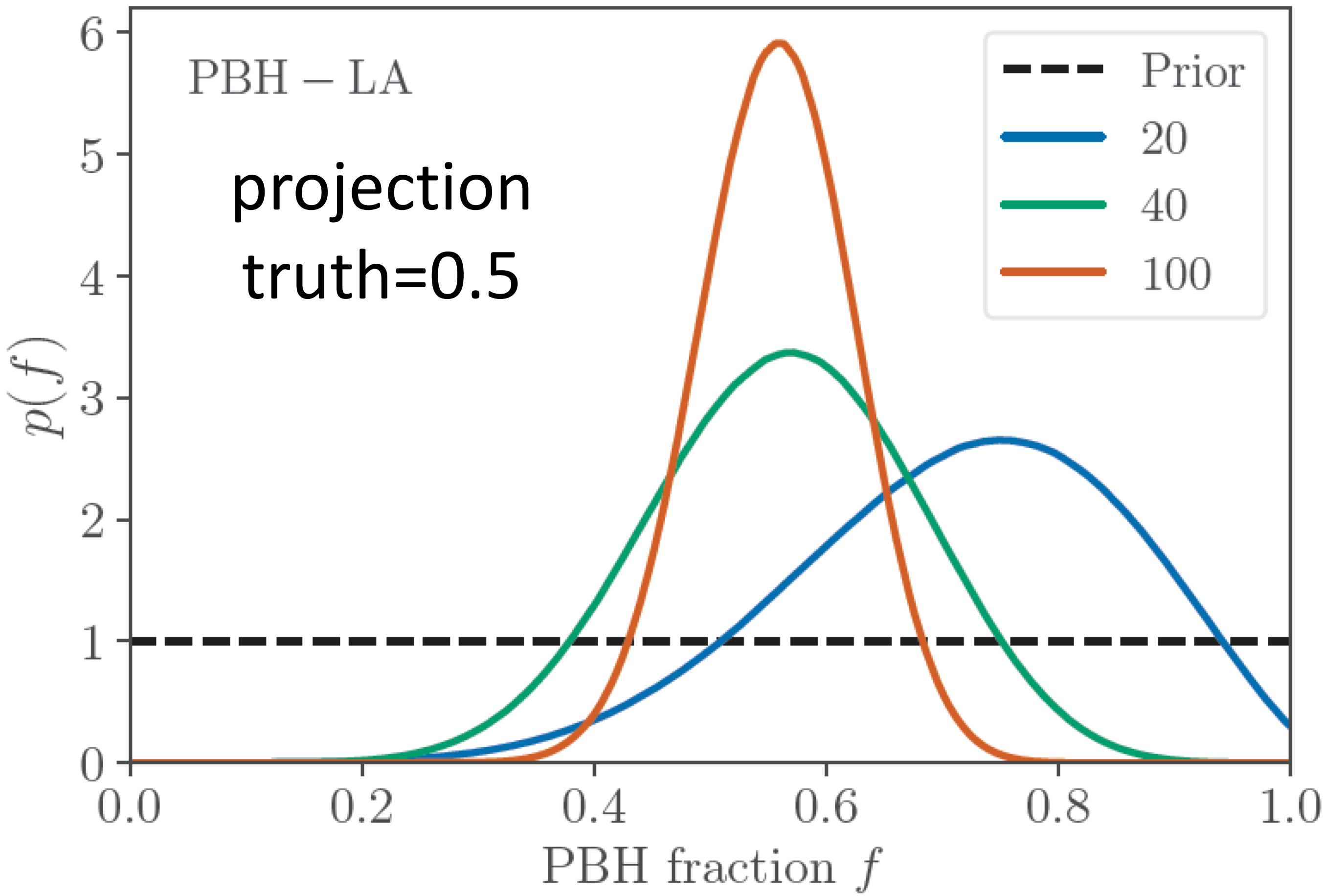
Truth: Low-isotropic

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

What about mixed models?

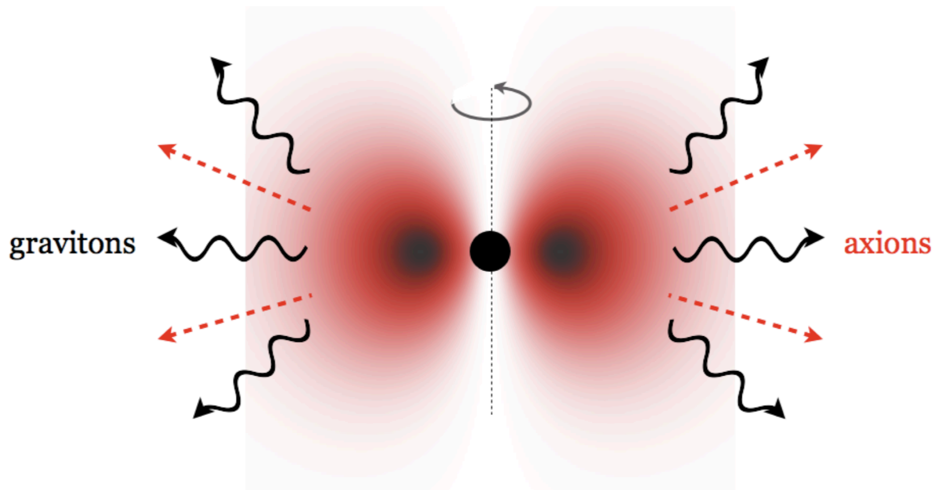
Fernandez and Profumo, 1905.13109 (JCAP); Slide credit: Nico Fernandez (UCSC → UIUC)

What about mixed models?



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

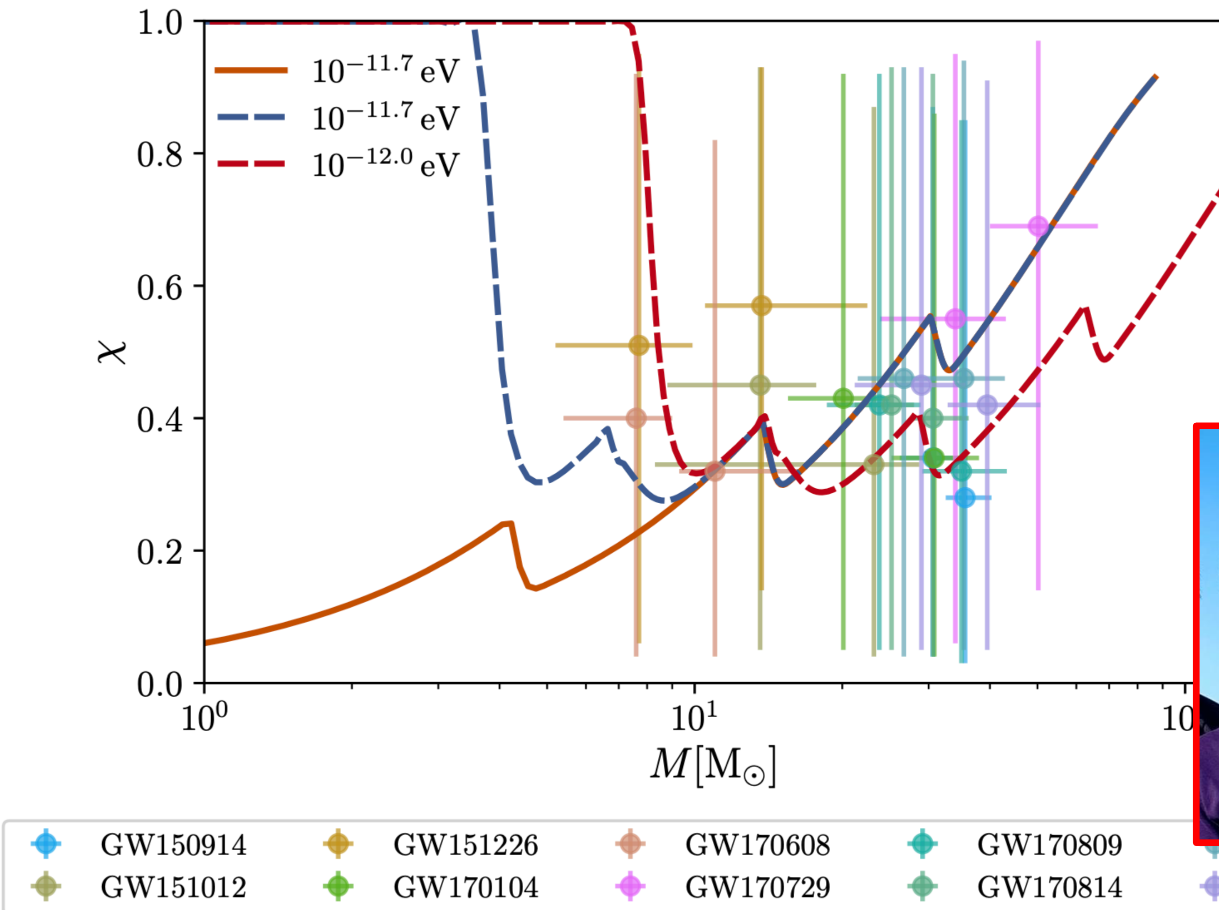
What else could fake a low-spin PBH? Super-radiance!

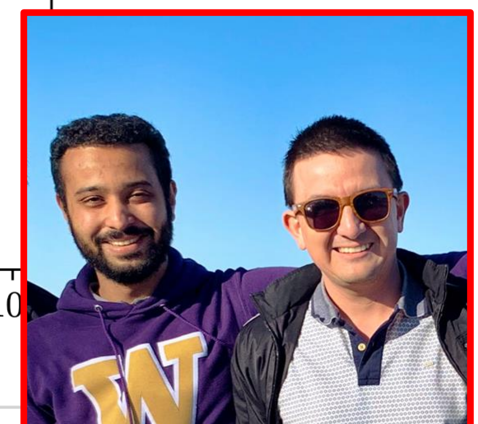


Assuming an initial spin and alignment distribution, one can compute the "best-fit" axion mass

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

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

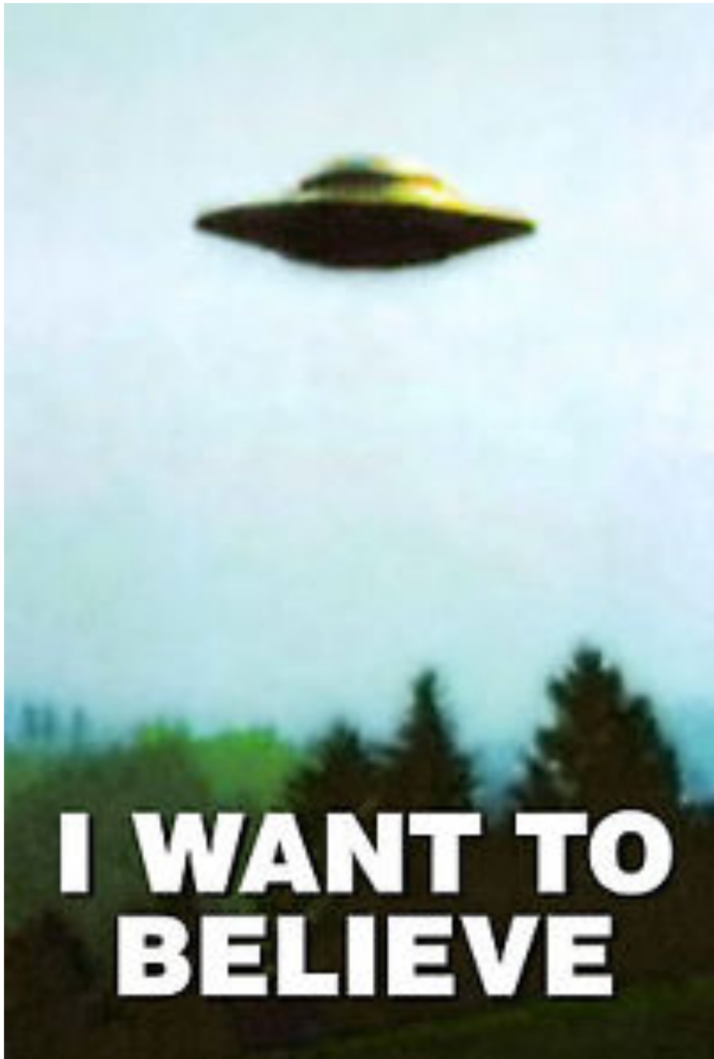


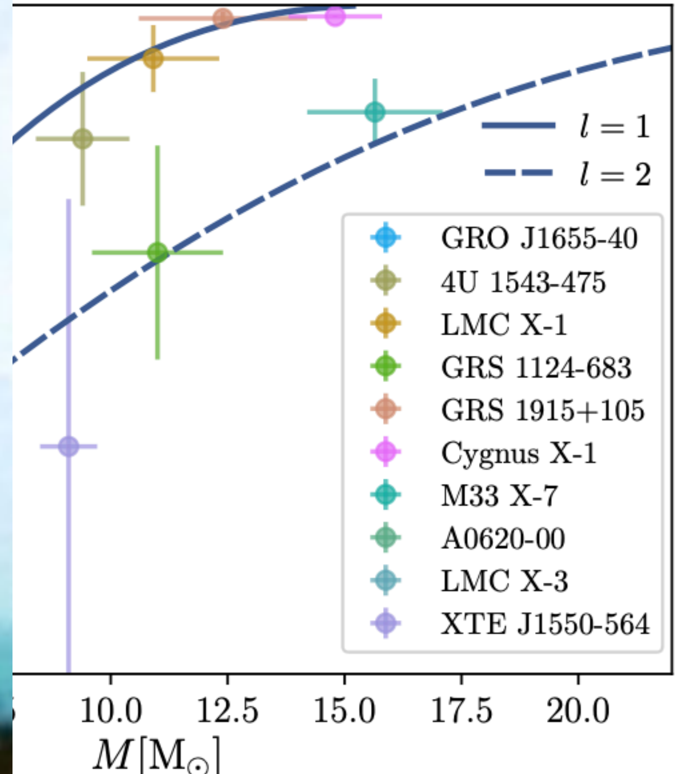


Regge plot (effective spin vs mass) assuming Flat priors for both mass and spin*

*Fernandez, Ghalsasy, Profumo, 1911.07862

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



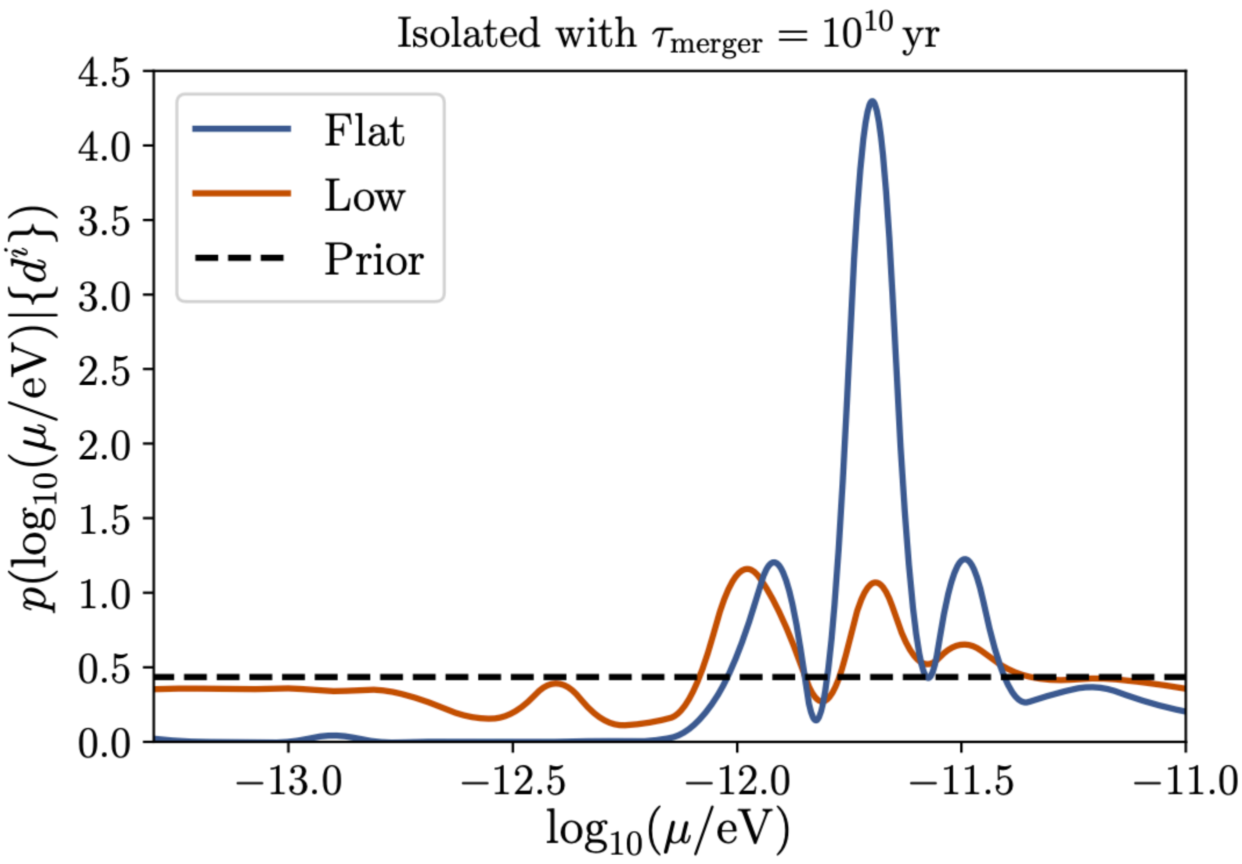


pin vs mass) assuming

Flat priors for both mass and spin*

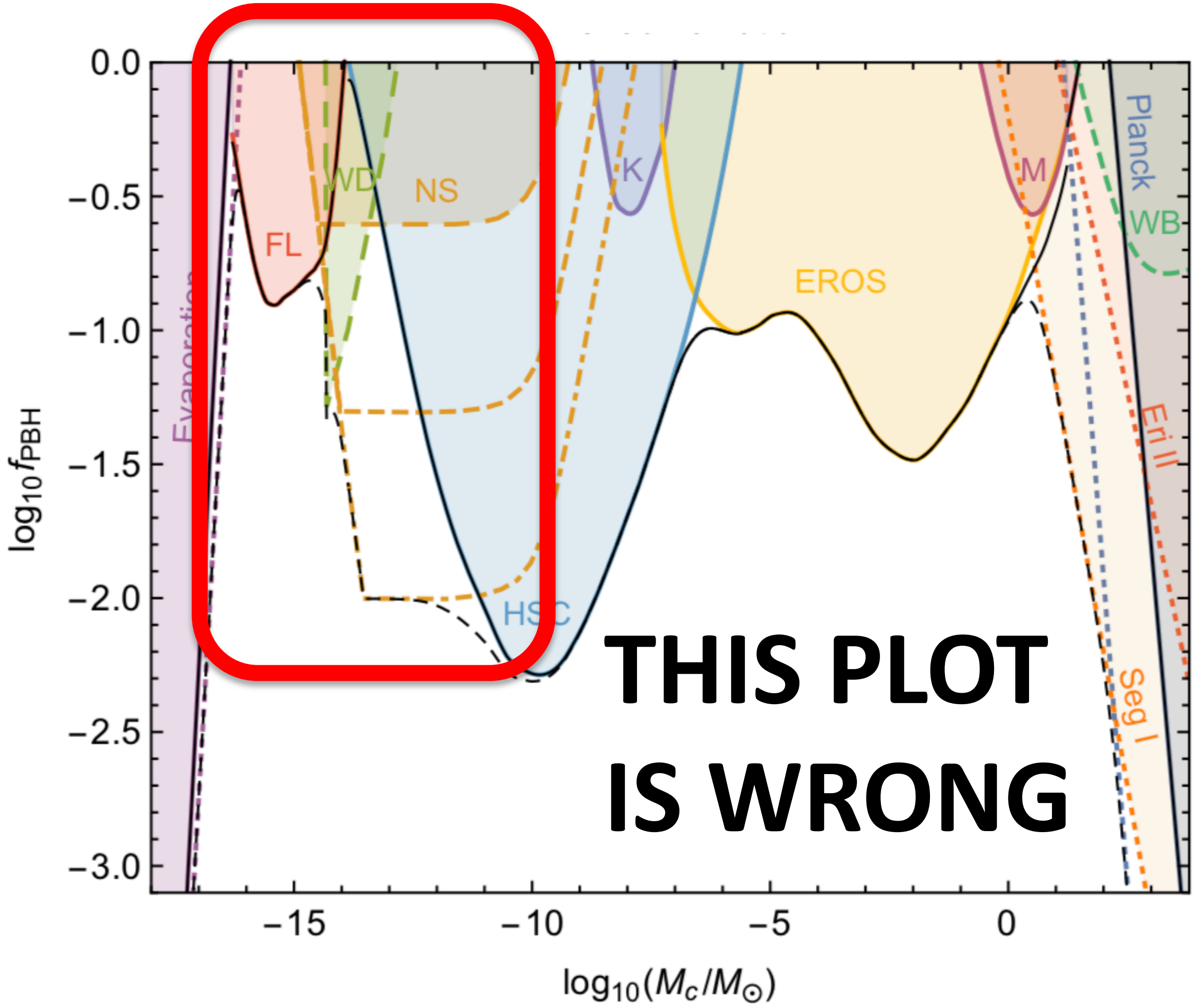
*Fernandez, Ghalsasy, Profumo, 1911.07862

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

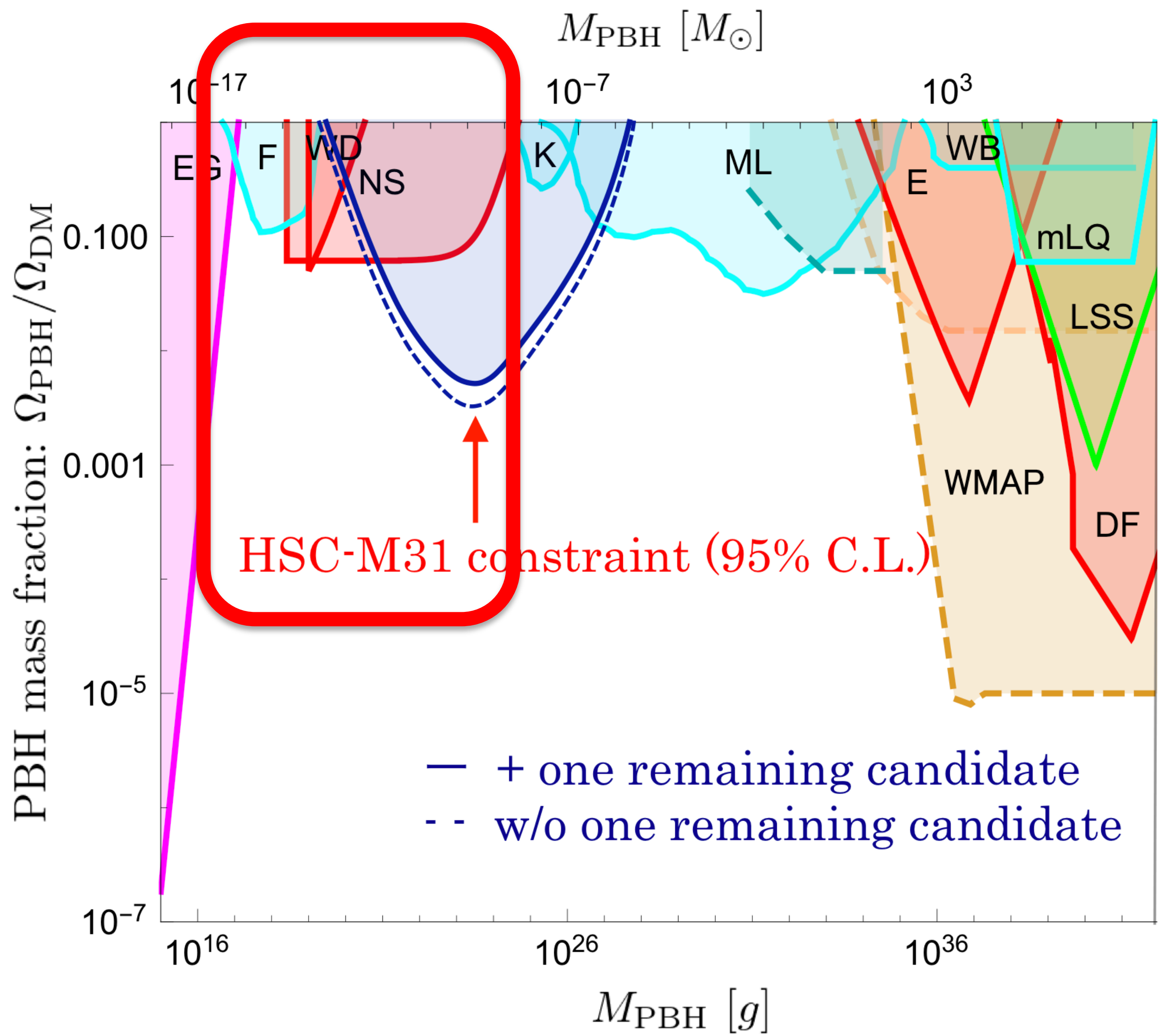


Posterior Probability for ALP mass

*Fernandez, Ghalsasy, Profumo, 1911.07862

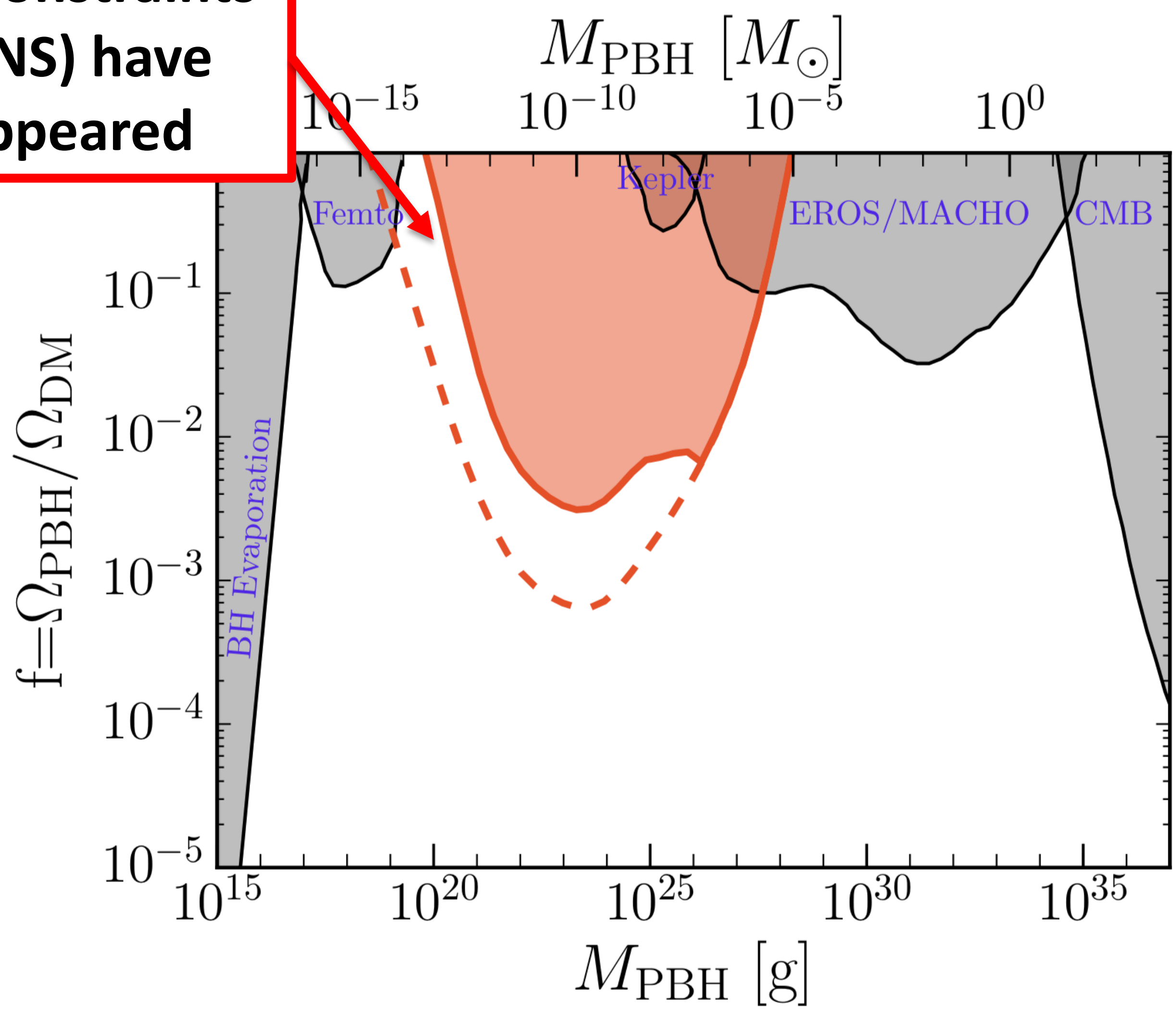


[9]There have been suggestions that the actual energy loss is much greater than given by the dynamical friction formula when the sum over modes is taken into account [74], due to generation of surface waves. See, however, Ref. [98], who find a much smaller surface wave contribution. We have done our own derivation of Eq. (13) of Ref. [98] using Fourier (definite k_x and k_y) instead of cylindrical modes, and find the same result.



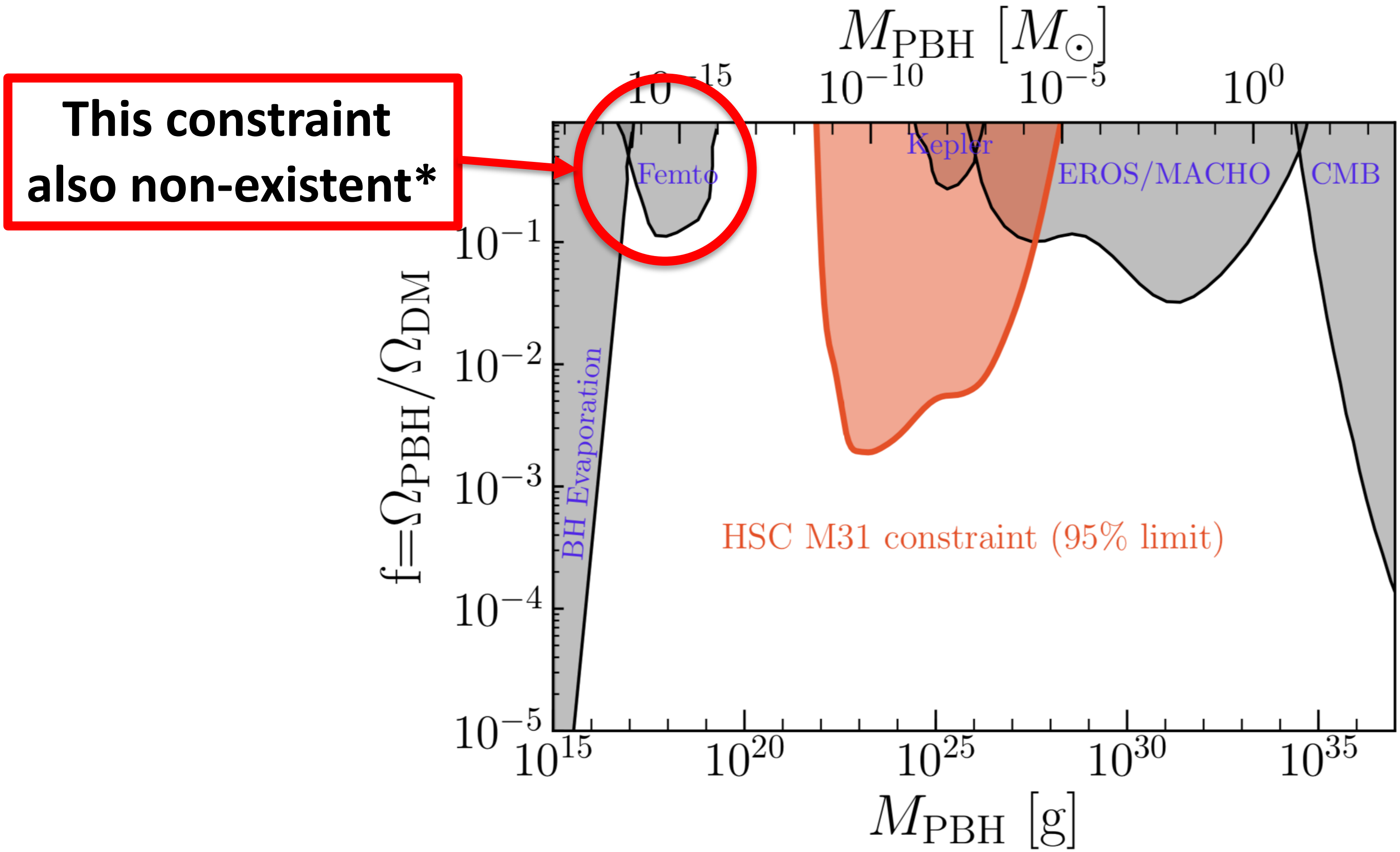
SUBARU HSC microlensing, 1701.02151 VERSION 1

wacky constraints (WD, NS) have disappeared



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 $R = R_{sun}$!

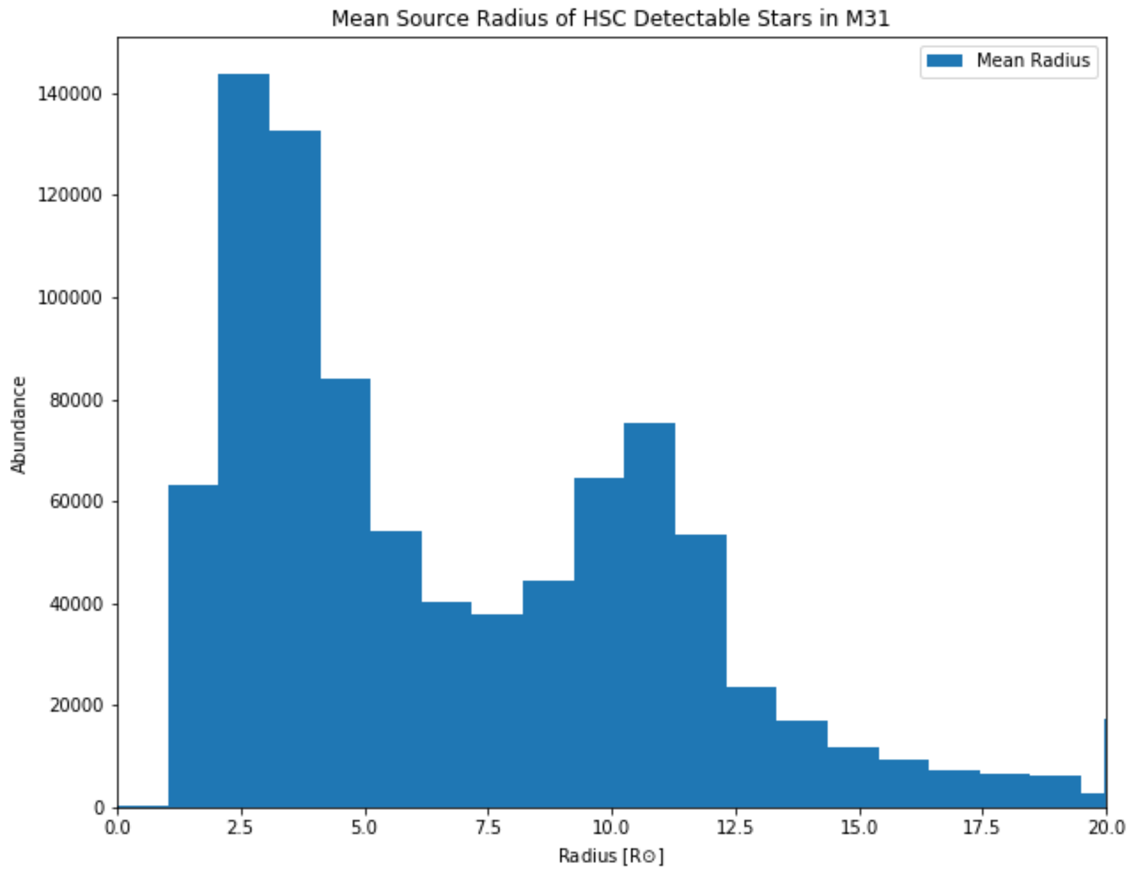
…but are these bounds robust?

A few (worrisome) assumptions:

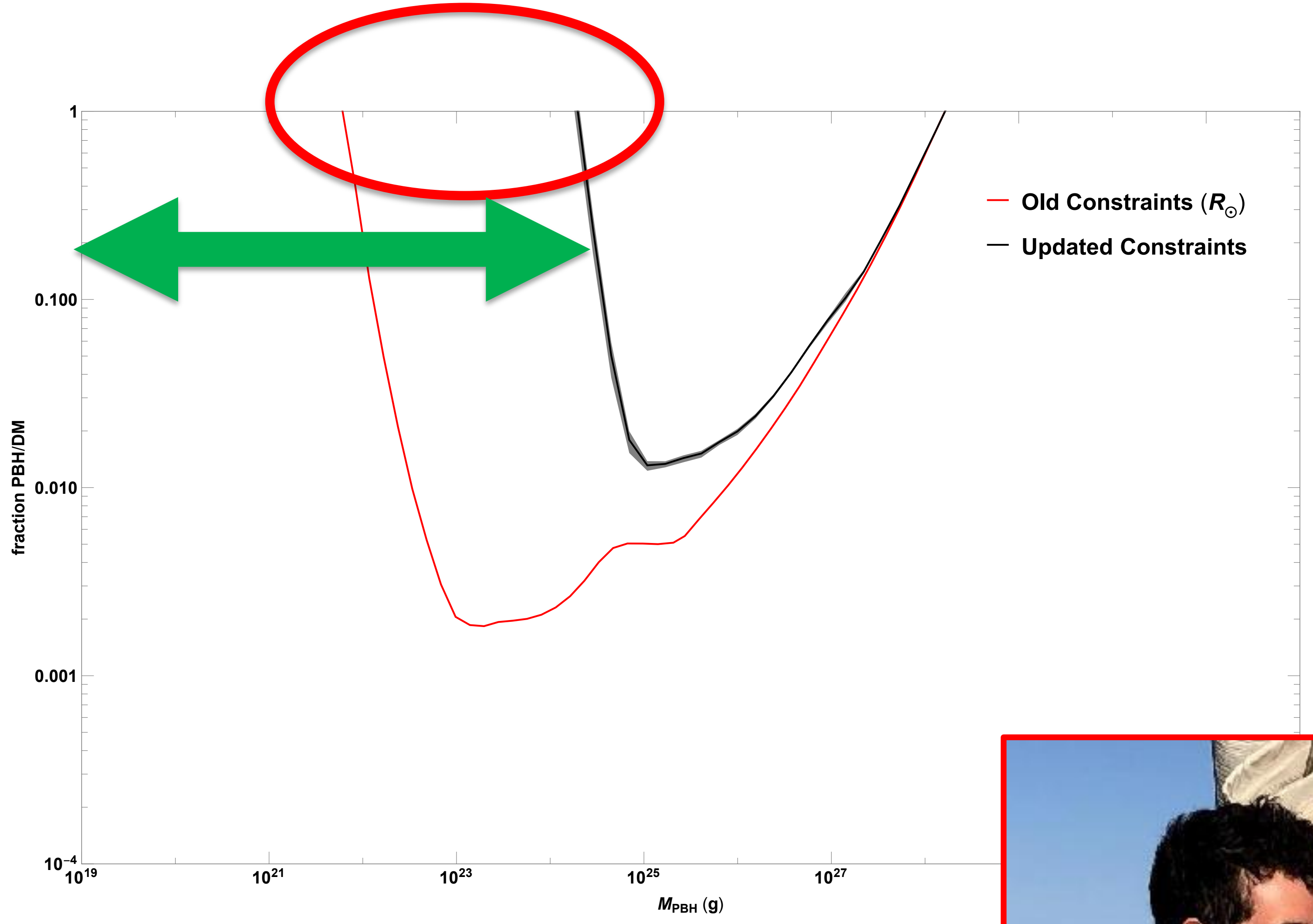
- All stars are at the same distance
- All stars have the same size (1 R_{sun})
- DM is completely smooth

* Smyth, Profumo et al, 1910.01285, PRD

Sun-like stars are however too dim for HSC!



* Smyth, Profumo et al, 1910.01285, PRD



How do we **go after** them?

Capture and perturbation around **PSR**?

* Smyth, Profumo et al, 1910.01285, PRD

…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

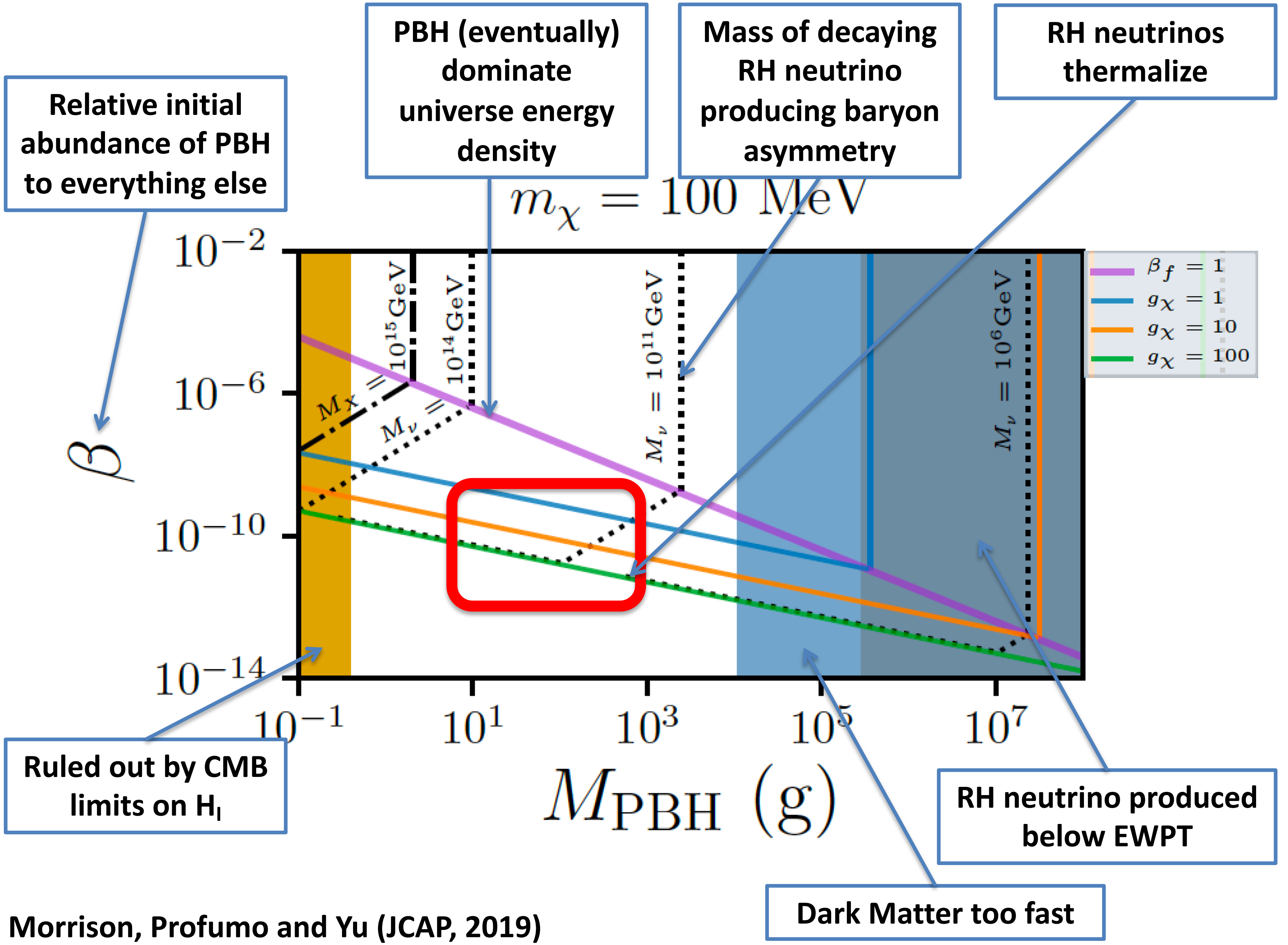
Current Personal Records

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!

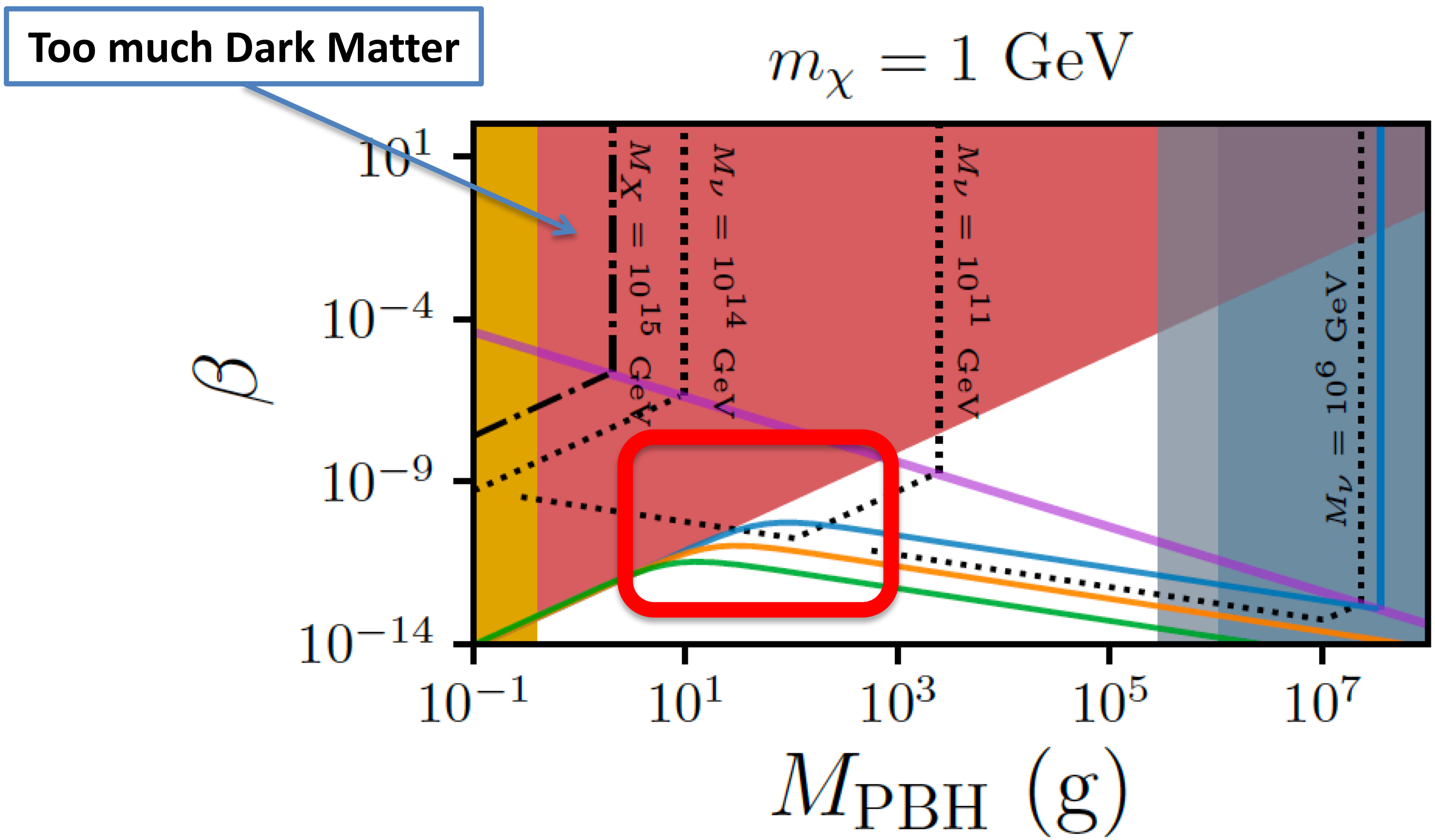
Mass (g)	T_H (GeV)	τ (s)	$T_{\rm evap} = T(\tau)$ (GeV)
$5M_P \simeq 10^{-4}$	1.7×10^{17}	10^{-41}	2×10^{17}
1	1.7×10^{13}	4×10^{-29}	2×10^{11}
10^3	1.7×10^{10}	4×10^{-20}	6×10^{6}
10^6	1.7×10^{7}	4×10^{-11}	200
10^9	1.7×10^{4}	0.04	0.006
10^{12}	17	$4 \times 10^{7} \sim 1$ yr	~ 1 keV

* 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!



* **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*

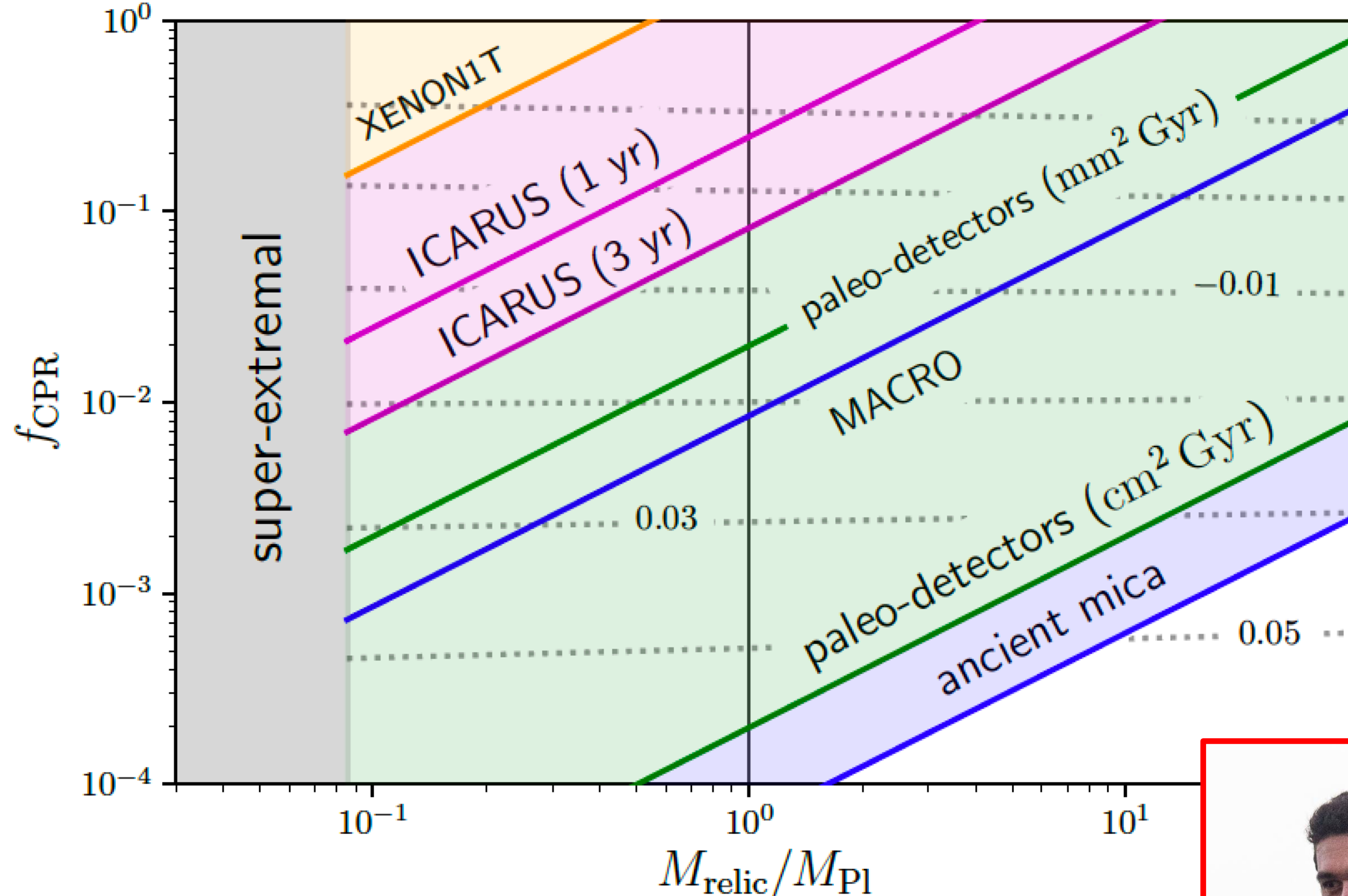
$$P(Q) \sim \exp\left(-4\pi\alpha(Q/e)^2\right)$$

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

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!

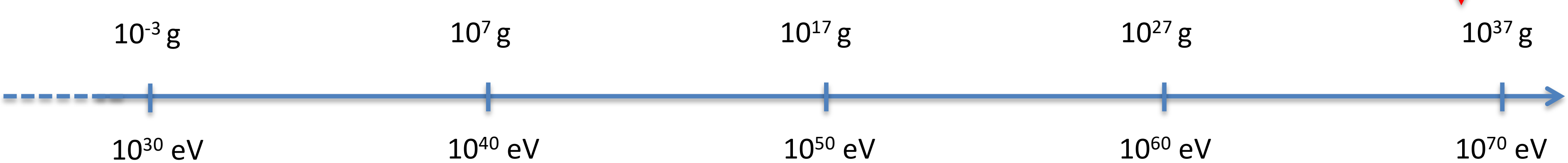
* Page, 1977

** Lehmann, Johnson, Profumo and Schwemberger, 1906.06348



* Lehmann, Johnson, Profumo and Schwemberger, 1906.06348

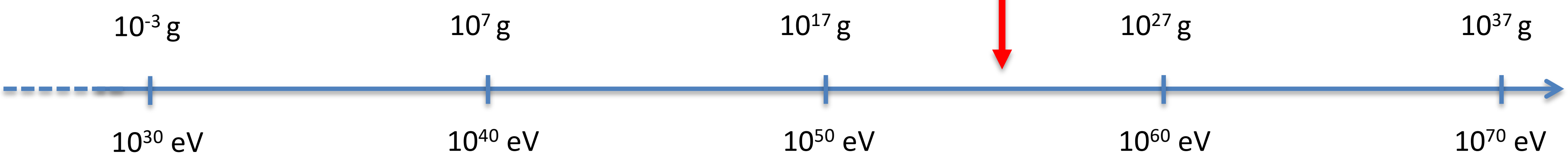
“Stellar-Mass” (10^{35} g) Black Holes



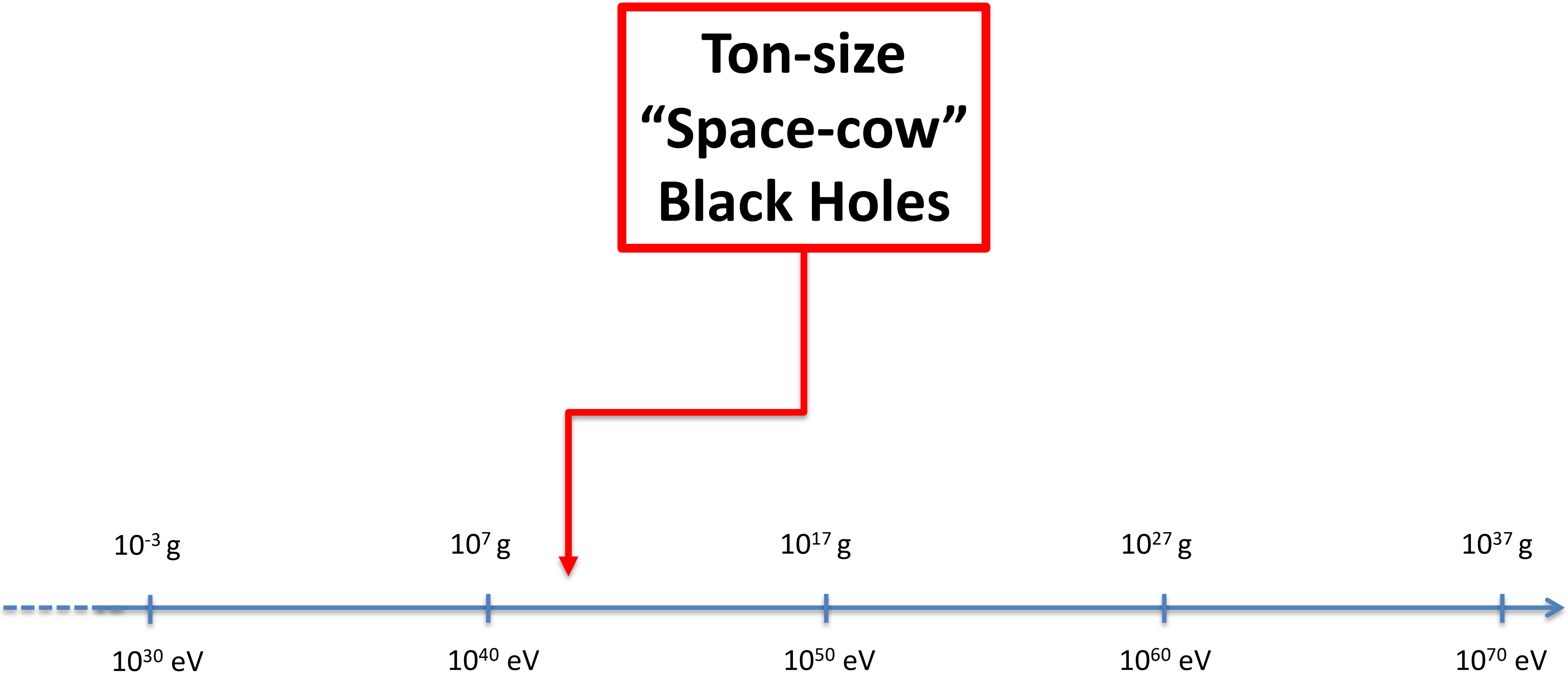
- ✓ **Spins look a lot like PBH!**
- ✓ **…or maybe they are low because of superradiance?**
- ✓ **Do they disrupt CMB*?**

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

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

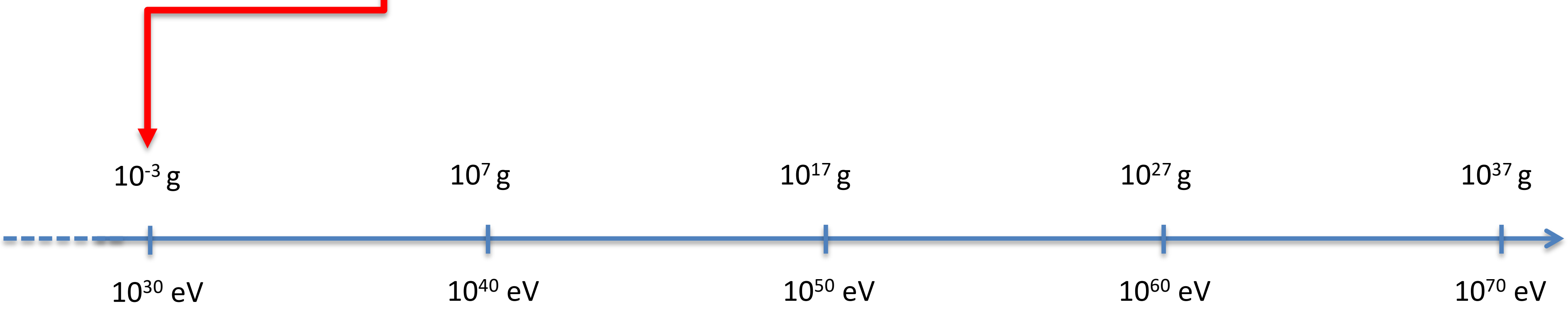


- ✓ **Microlensing a lot trickier than previously thought!**
- ✓ **Detection strategies? PTA?**



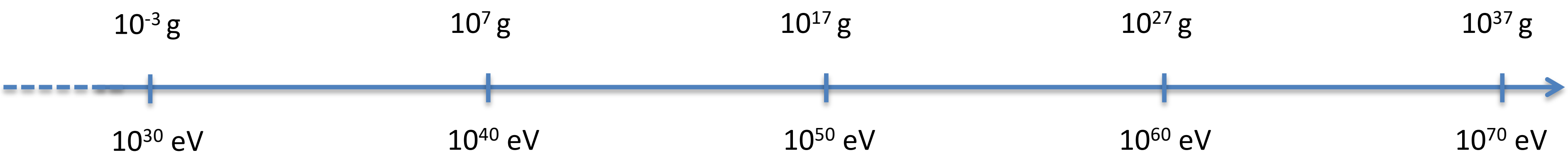
✓ **Decays can produce DM, BAU, Planck relics**

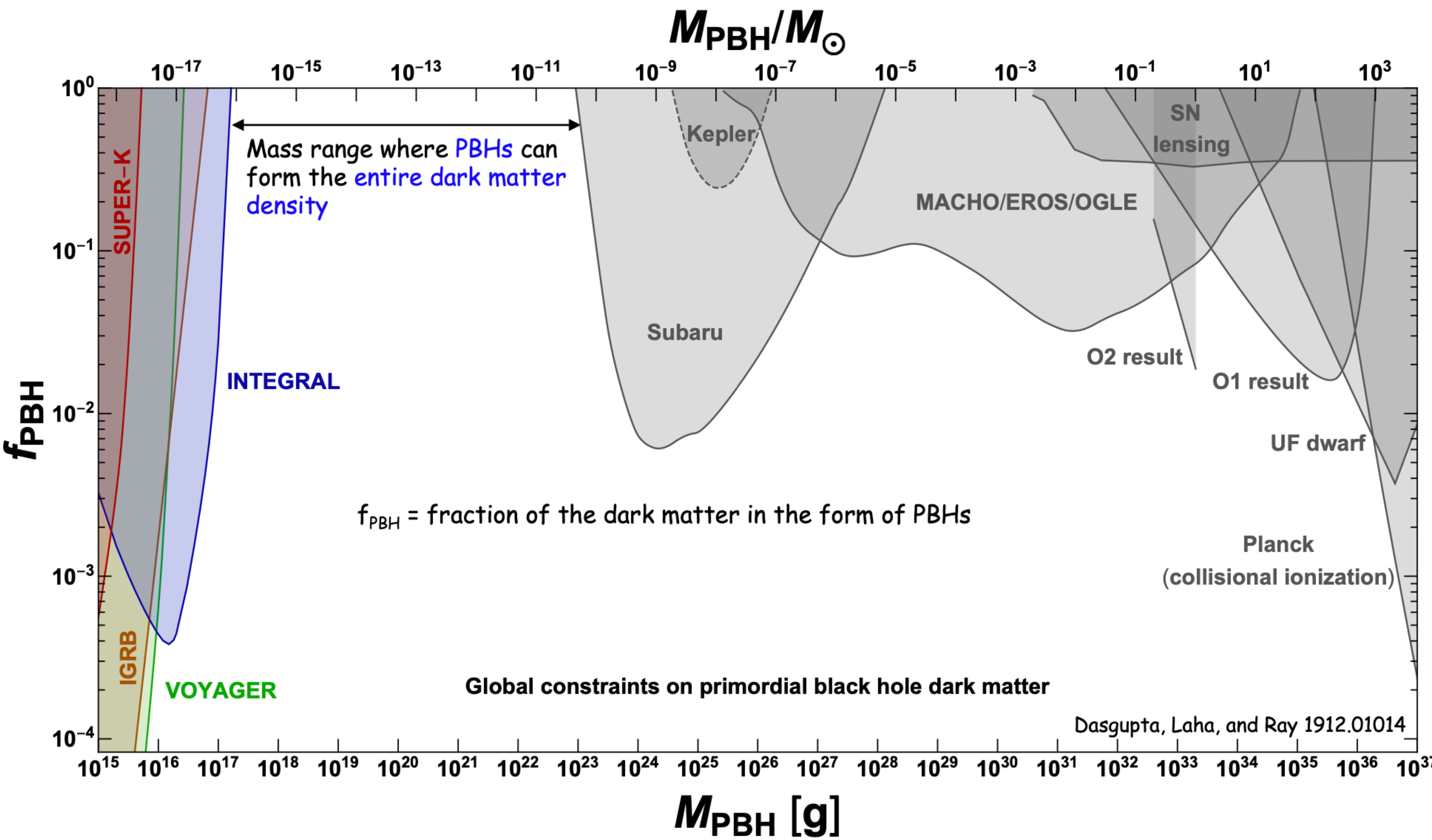
Grain-of-Salt
“No-see-ums”
Black Holes



- ✓ **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





$M_{PBH}/M_\odot$
10^{-17} 10^{-15} 10^{-13} 10^{-11} 10^{-9} 10^{-7} 10^{-5} 10^{-3} 10^{-1} 10^{1} 10^{3}
10^{0} 10^{-1} 10^{-2} 10^{-3} 10^{-4}
f_{PBH}
SUPER-K
Mass range where PBHs can form the entire dark matter density
Kepler
SN lensing
MACHO/EROS/OGLE
Subaru
INTEGRAL
O2 result
O1 result
UF dwarf
f_{PBH} = fraction of the dark matter in the form of PBHs
Planck (collisional ionization)
IGRB
VOYAGER
Global constraints on primordial black hole dark matter
Dasgupta, Laha, and Ray 1912.01014
10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21} 10^{22} 10^{23} 10^{24} 10^{25} 10^{26} 10^{27} 10^{28} 10^{29} 10^{30} 10^{31} 10^{32} 10^{33} 10^{34} 10^{35} 10^{36} 10^{37}
M_{PBH} [g]