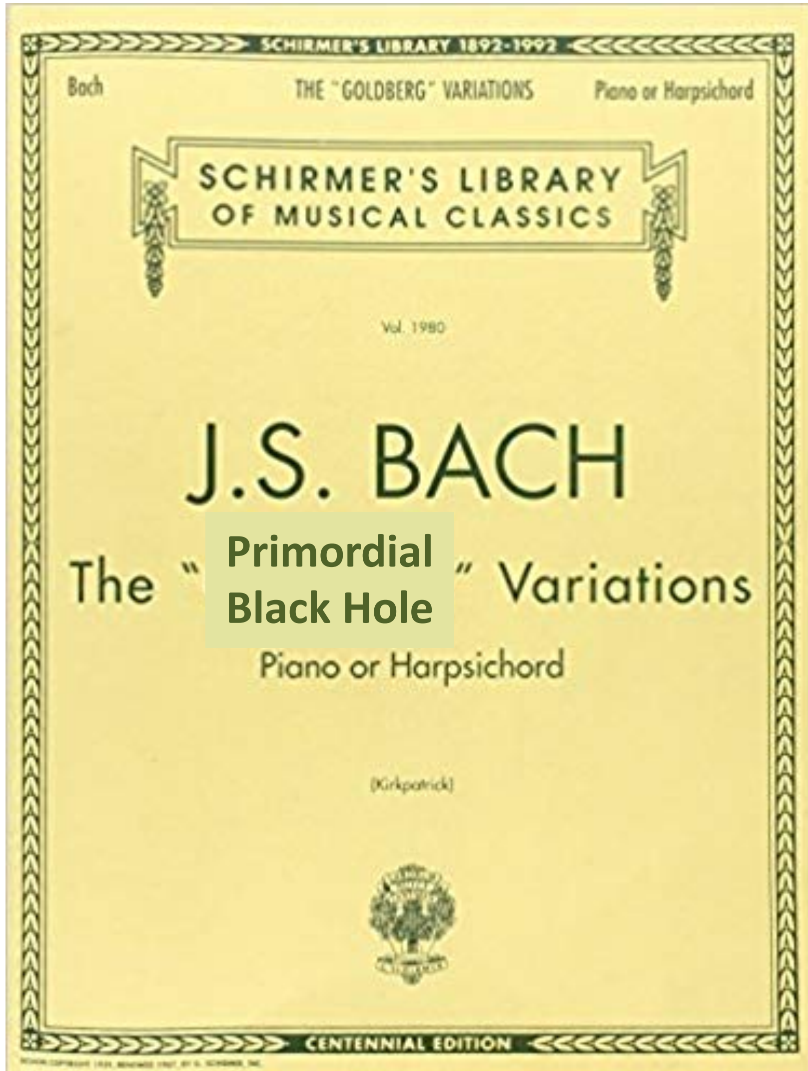
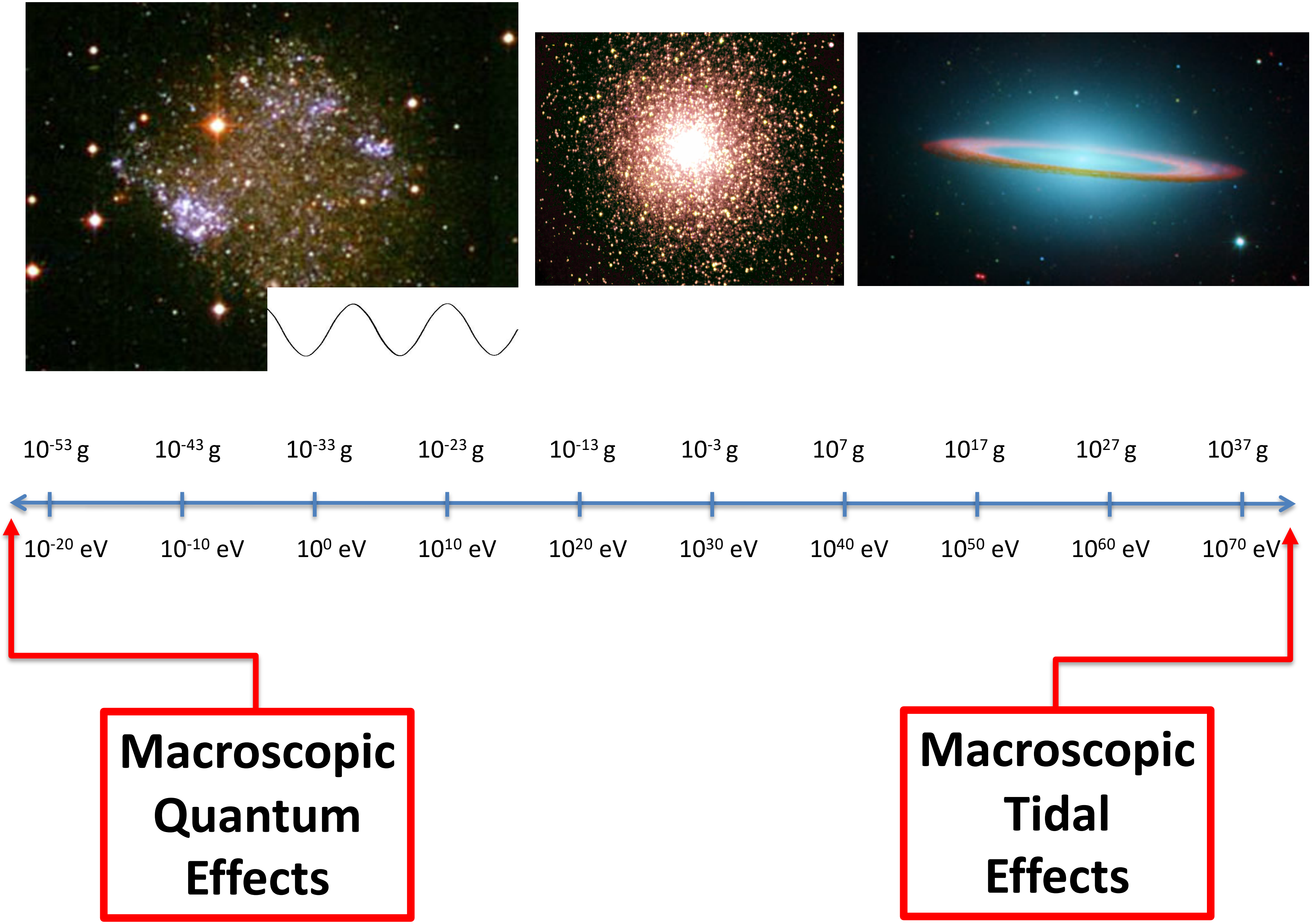
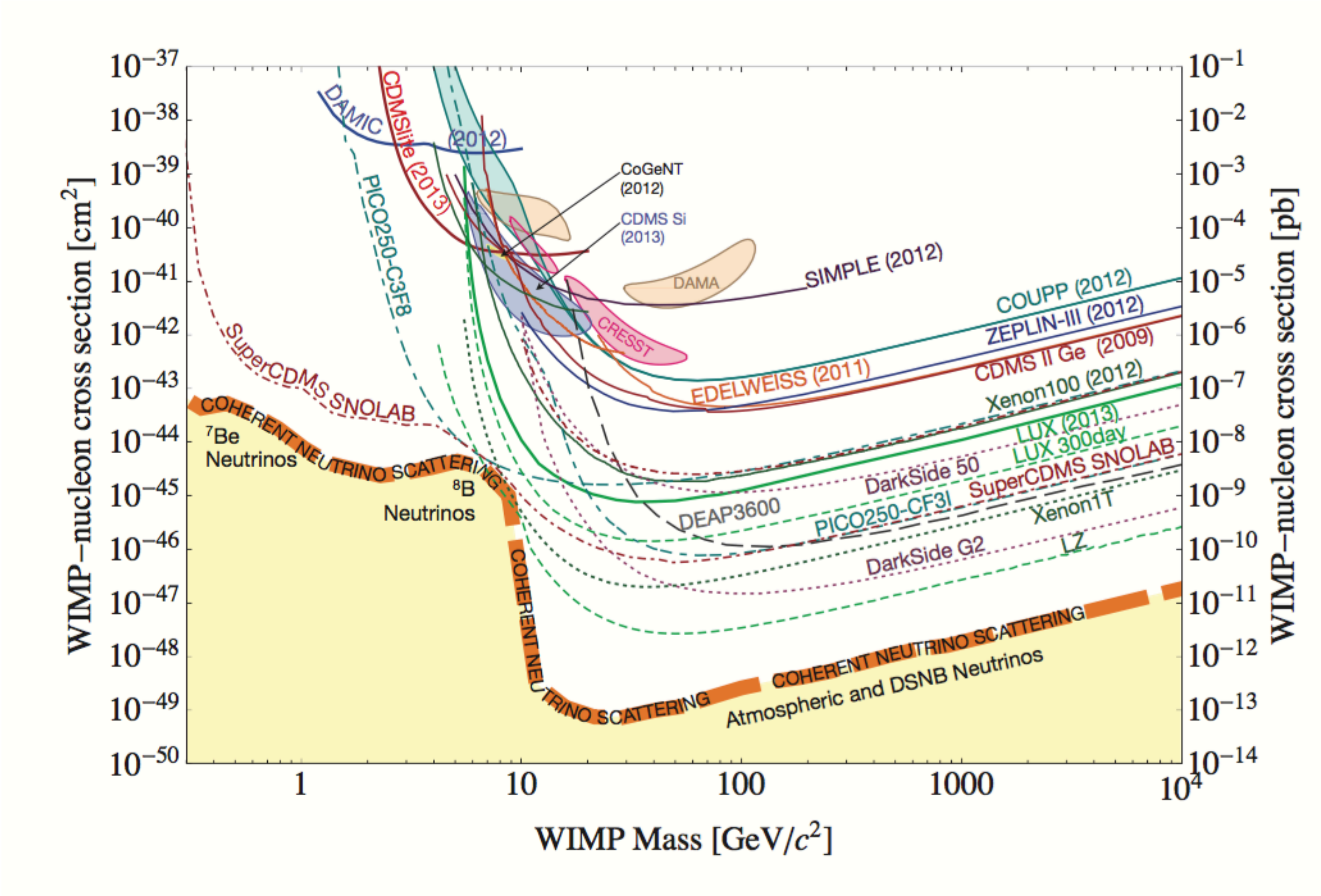
Stefano Profumo

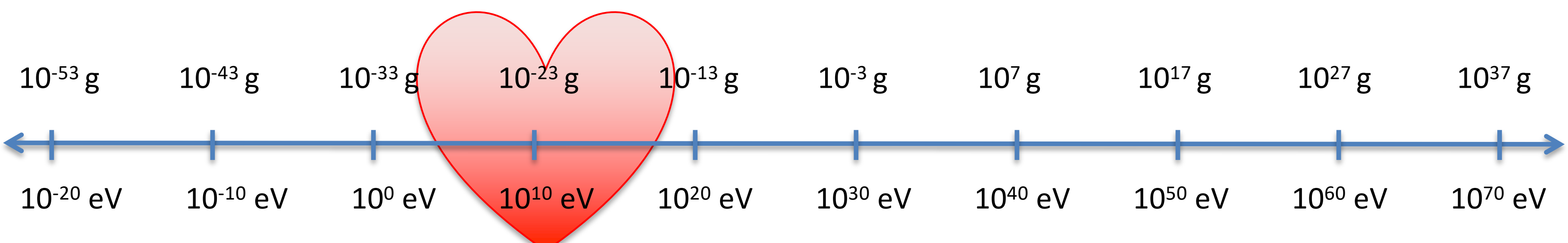
University of California, Santa Cruz

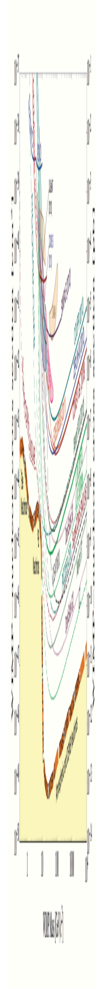


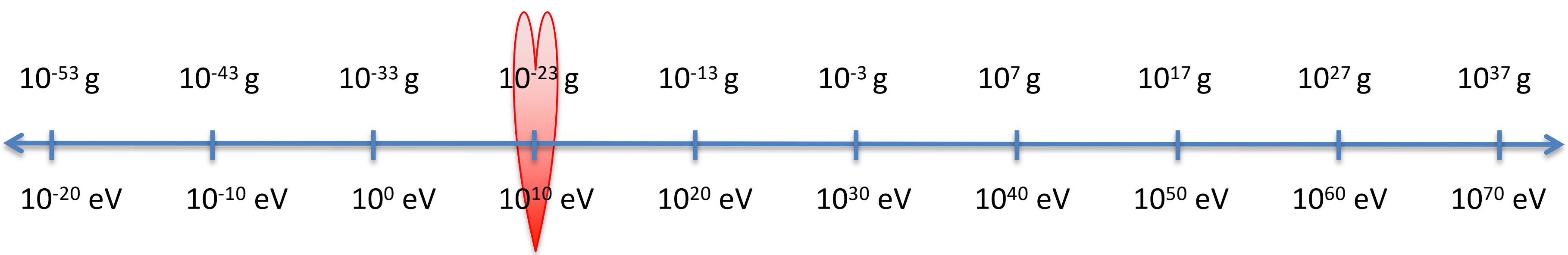
GGI Institute, Florence, September 11, 2019

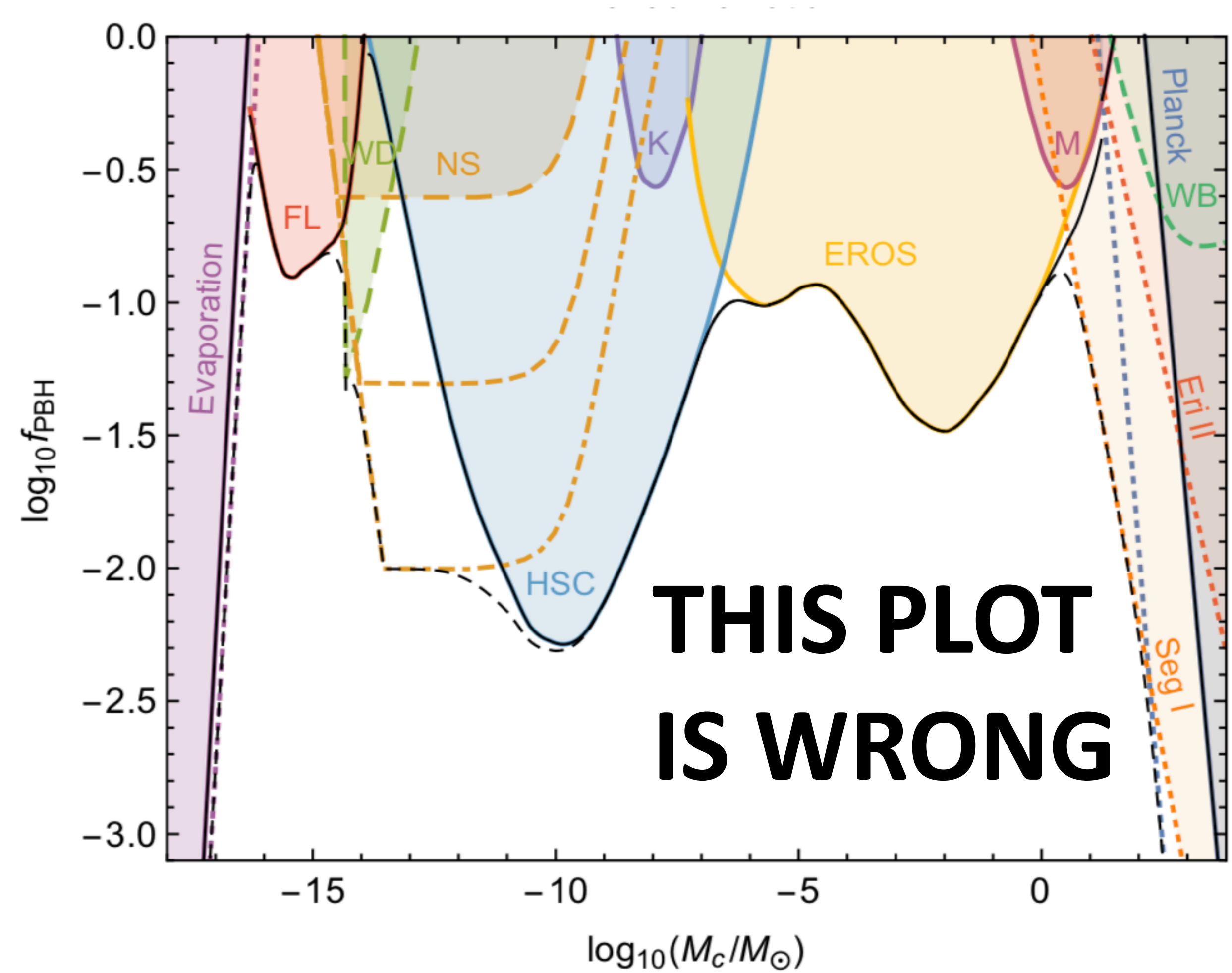

10^{-53} g
10^{-43} g
10^{-33} g
10^{-23} g
10^{-13} g
10^{-3} g
10^{7} g
10^{17} g
10^{27} g
10^{37} g
10^{-20} eV
10^{-10} eV
10^{0} eV
10^{10} eV
10^{20} eV
10^{30} eV
10^{40} eV
10^{50} eV
10^{60} eV
10^{70} eV
Macroscopic Quantum Effects
Macroscopic Tidal Effects

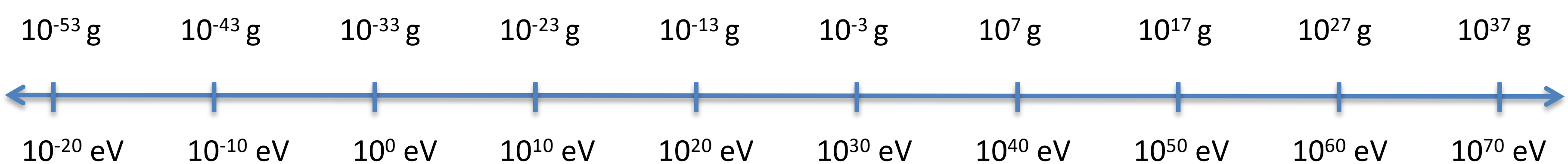

WIMP−nucleon cross section [cm²]
WIMP−nucleon cross section [pb]
WIMP Mass [GeV/c²]
10⁻³⁷
10⁻³⁸
10⁻³⁹
10⁻⁴⁰
10⁻⁴¹
10⁻⁴²
10⁻⁴³
10⁻⁴⁴
10⁻⁴⁵
10⁻⁴⁶
10⁻⁴⁷
10⁻⁴⁸
10⁻⁴⁹
10⁻⁵⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
1
10
100
1000
10⁴
DAMIC
CDMSlite (2013)
(2012)
PICO250-C3F8
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
⁷Be Neutrinos
⁸B Neutrinos
COHERENT NEUTRINO SCATTERING
Atmospheric and DSNB Neutrinos


10⁻⁵³ g
10⁻⁴³ g
10⁻³³ g
10⁻²³ g
10⁻¹³ g
10⁻³ g
10⁷ g
10¹⁷ g
10²⁷ g
10³⁷ g
10⁻²⁰ eV
10⁻¹⁰ eV
10⁰ eV
10¹⁰ eV
10²⁰ eV
10³⁰ eV
10⁴⁰ eV
10⁵⁰ eV
10⁶⁰ eV
10⁷⁰ eV




10-53 g
10-43 g
10-33 g
10-23 g
10-13 g
10-3 g
107 g
1017 g
1027 g
1037 g
10-20 eV
10-10 eV
100 eV
1010 eV
1020 eV
1030 eV
1040 eV
1050 eV
1060 eV
1070 eV


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


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
10^{-10} eV
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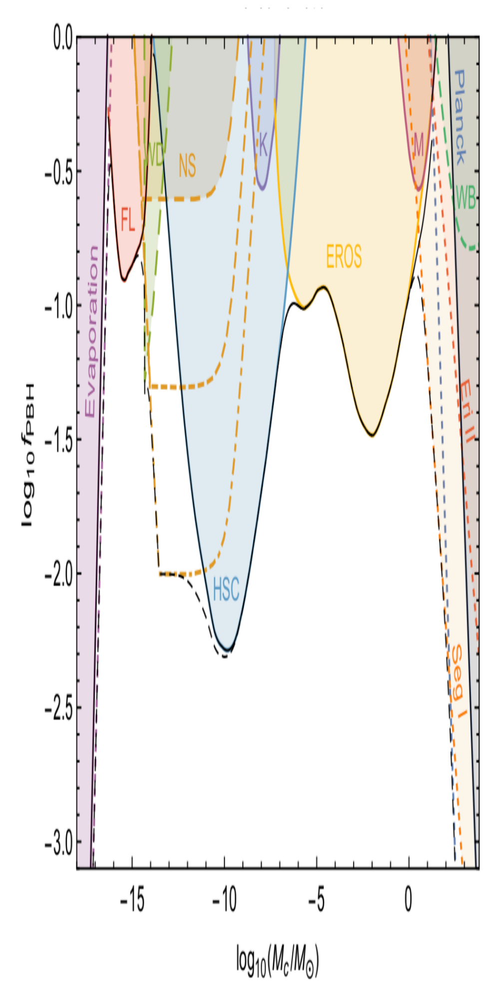
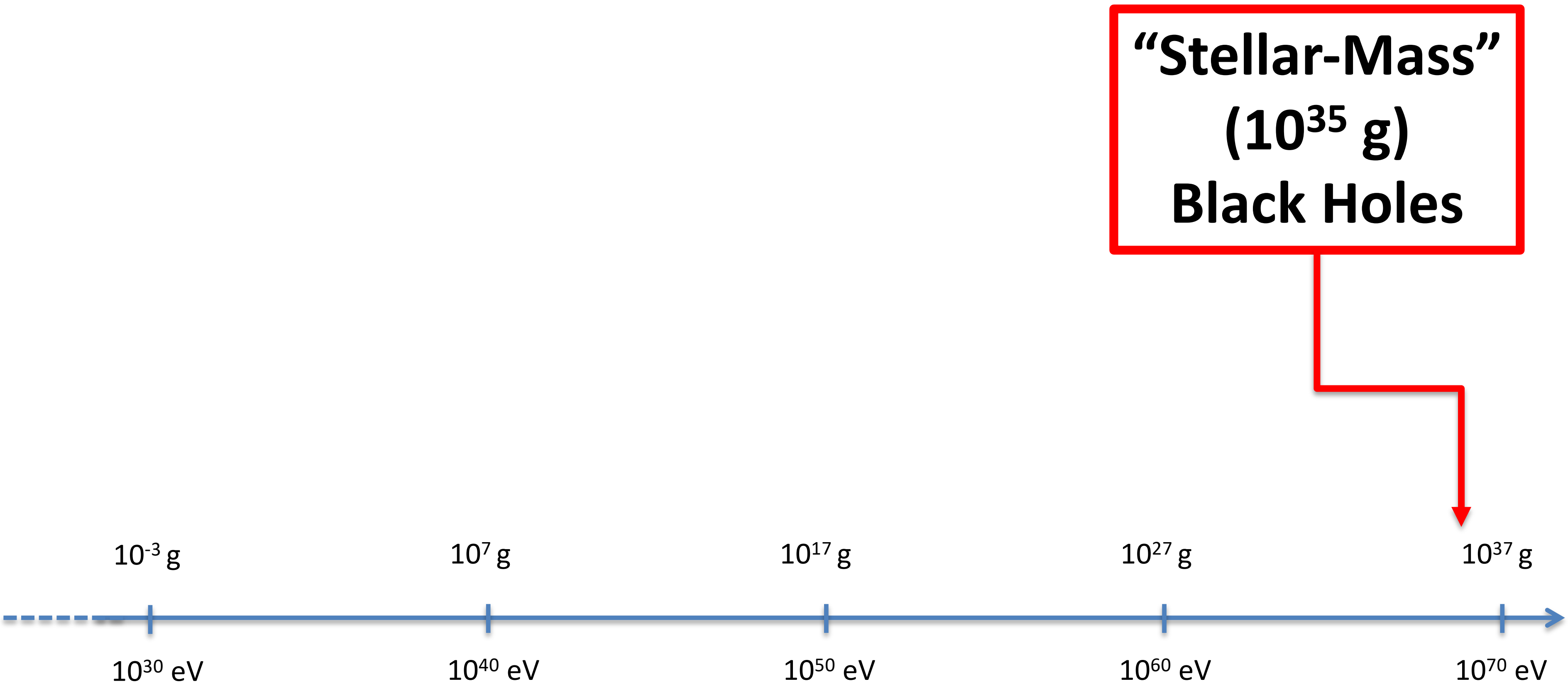
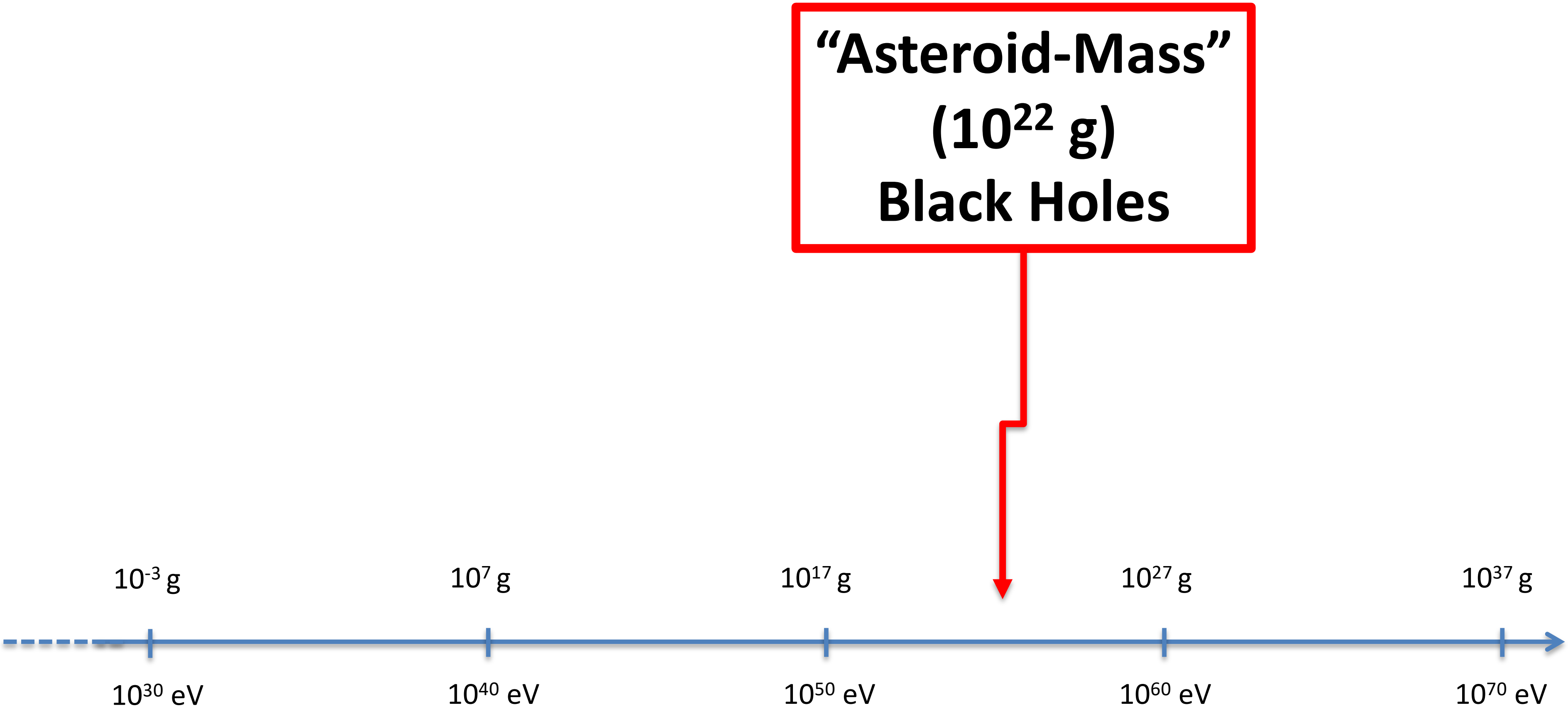
10^{60} eV
10^{70} eV

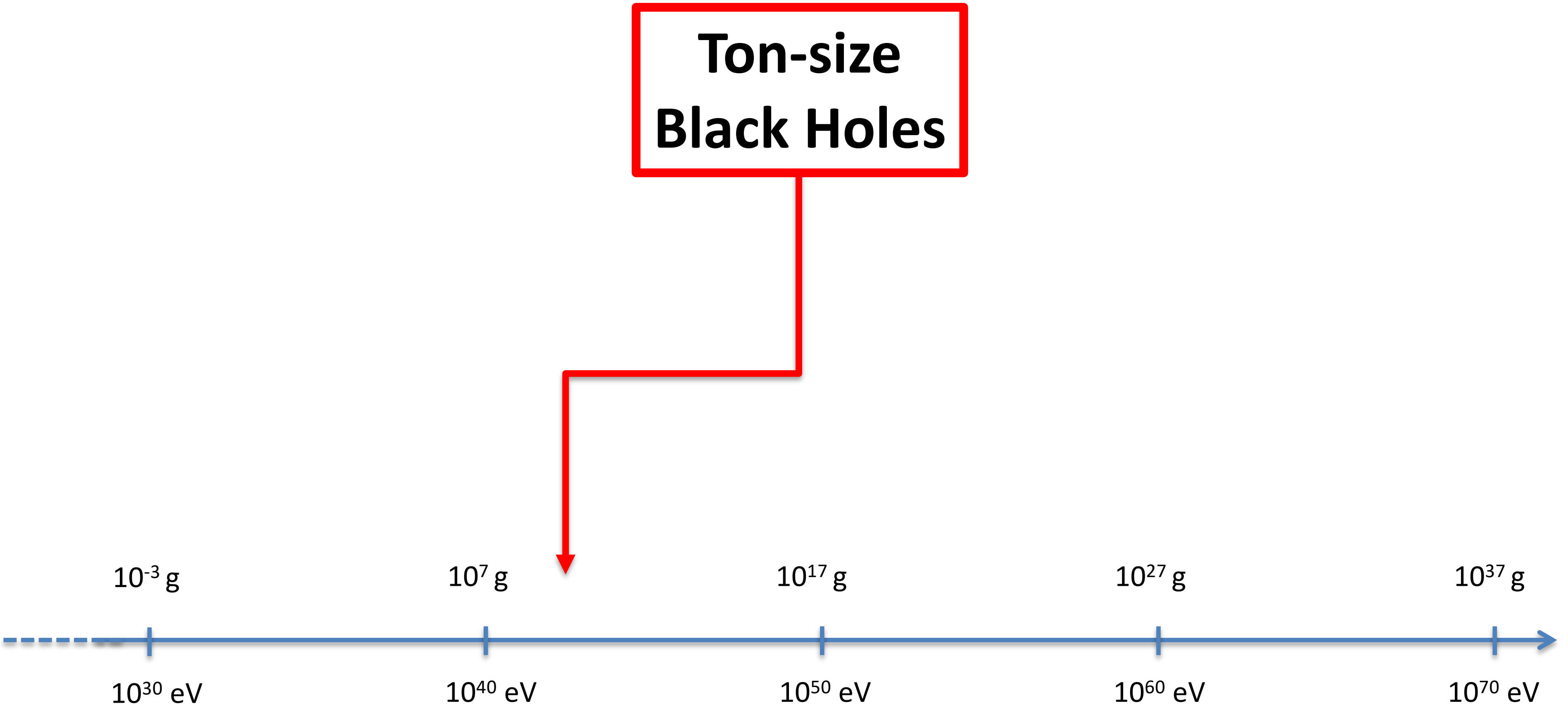


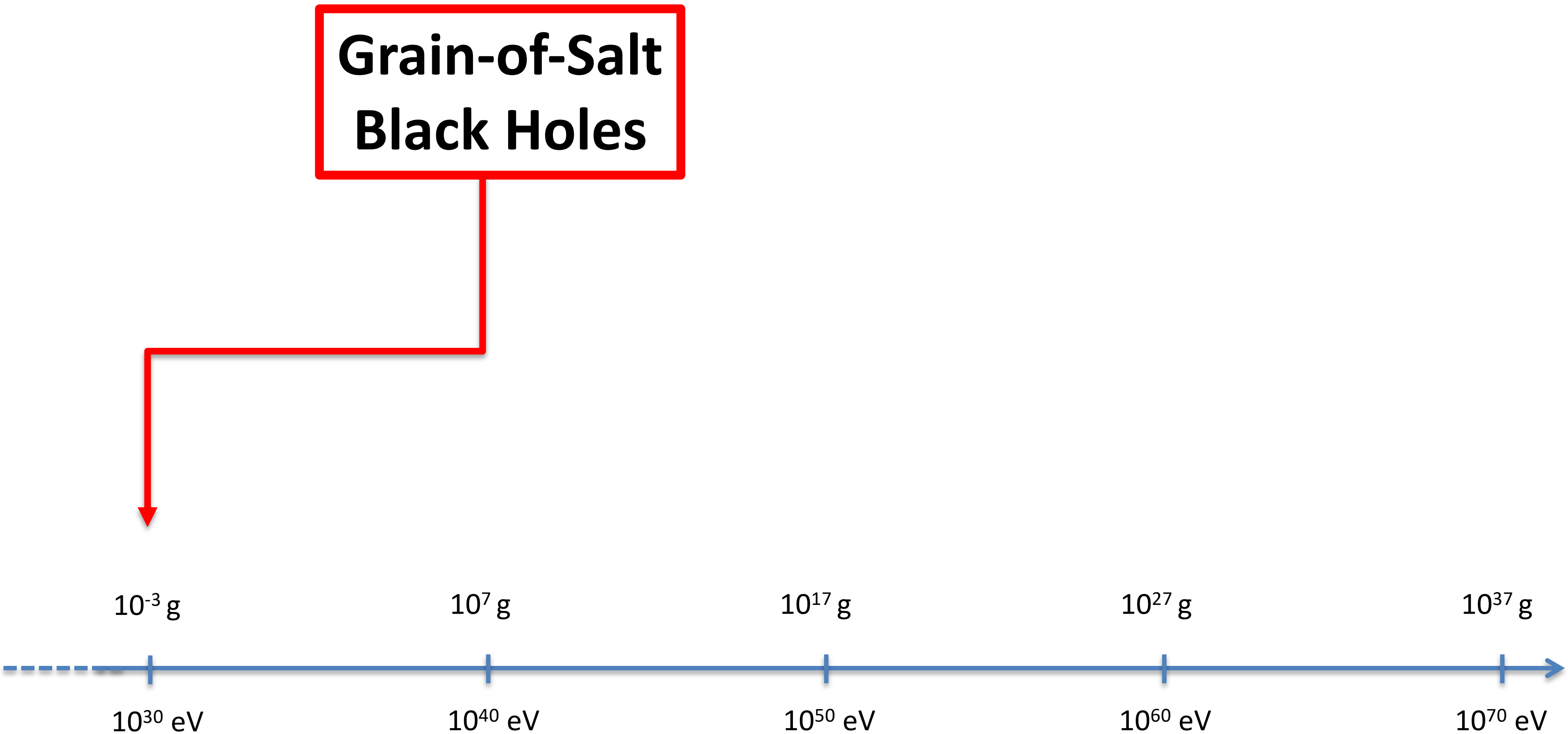
10^-53 g	10^-43 g	10^-33 g	10^-23 g	10^-13 g	10^-3 g	10^7 g	10^17 g	10^27 g	10^37 g
10^-20 eV	10^-10 eV	10^0 eV	10^10 eV	10^20 eV	10^30 eV	10^40 eV	10^50 eV	10^60 eV	10^70 eV



“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

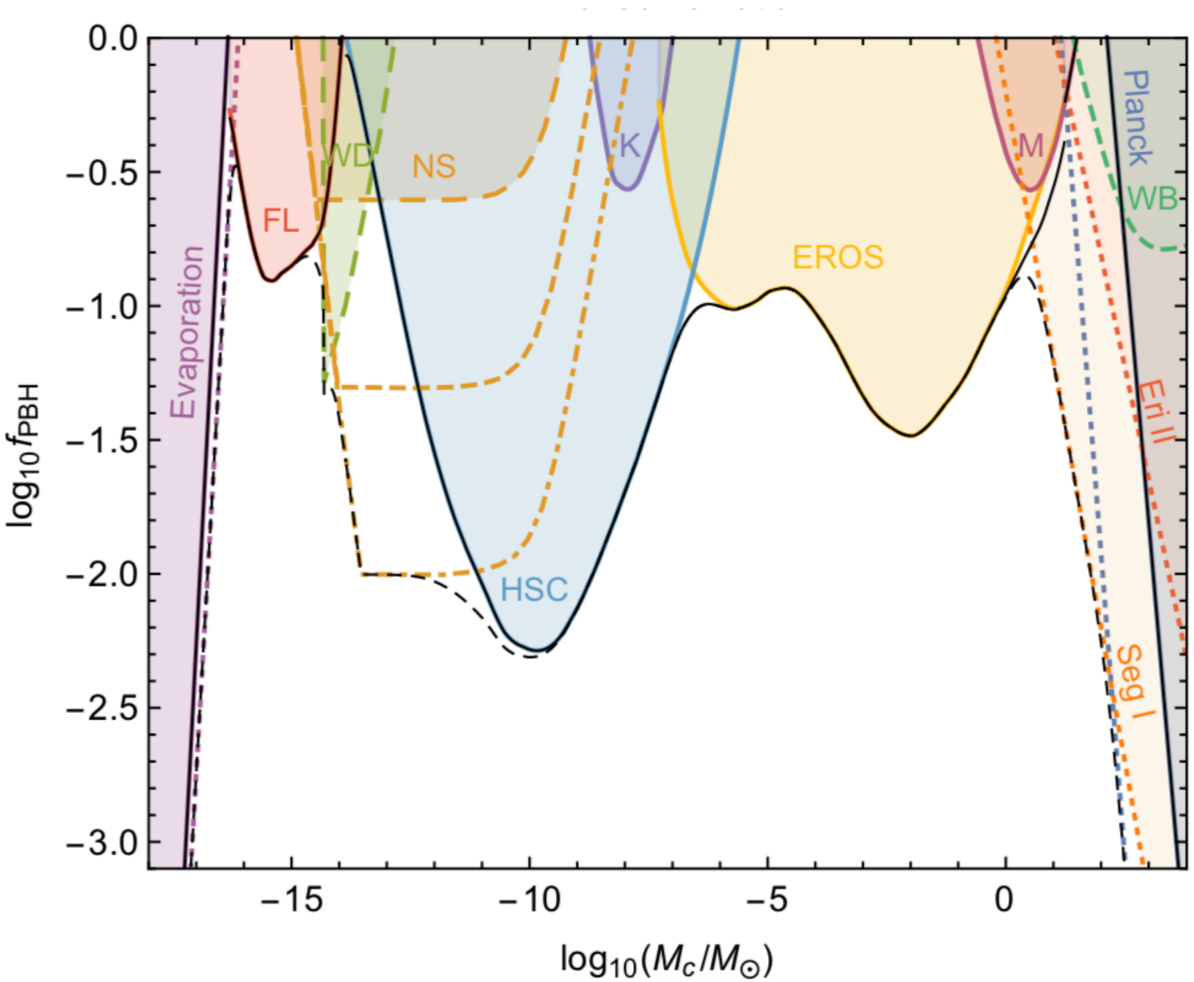

"Asteroid-Mass"
(10^22 g)
Black Holes
10^-3 g
10^7 g
10^17 g
10^27 g
10^37 g
10^30 eV
10^40 eV
10^50 eV
10^60 eV
10^70 eV


Ton-size
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


Grain-of-Salt 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

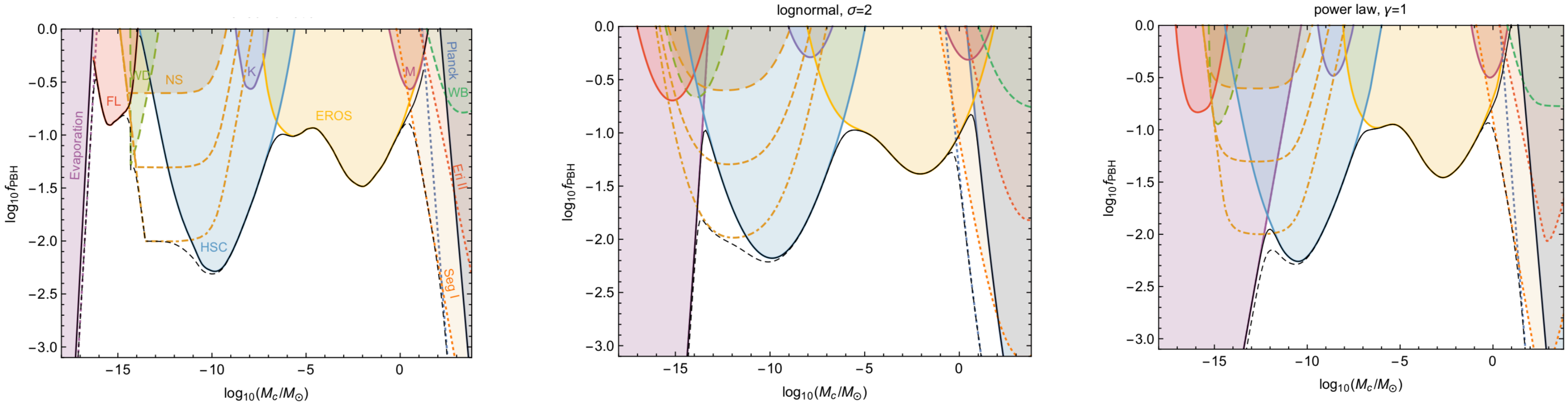
First question: Can there be **enough** PBH around to be the **DM**?

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 their mass distribution!



…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

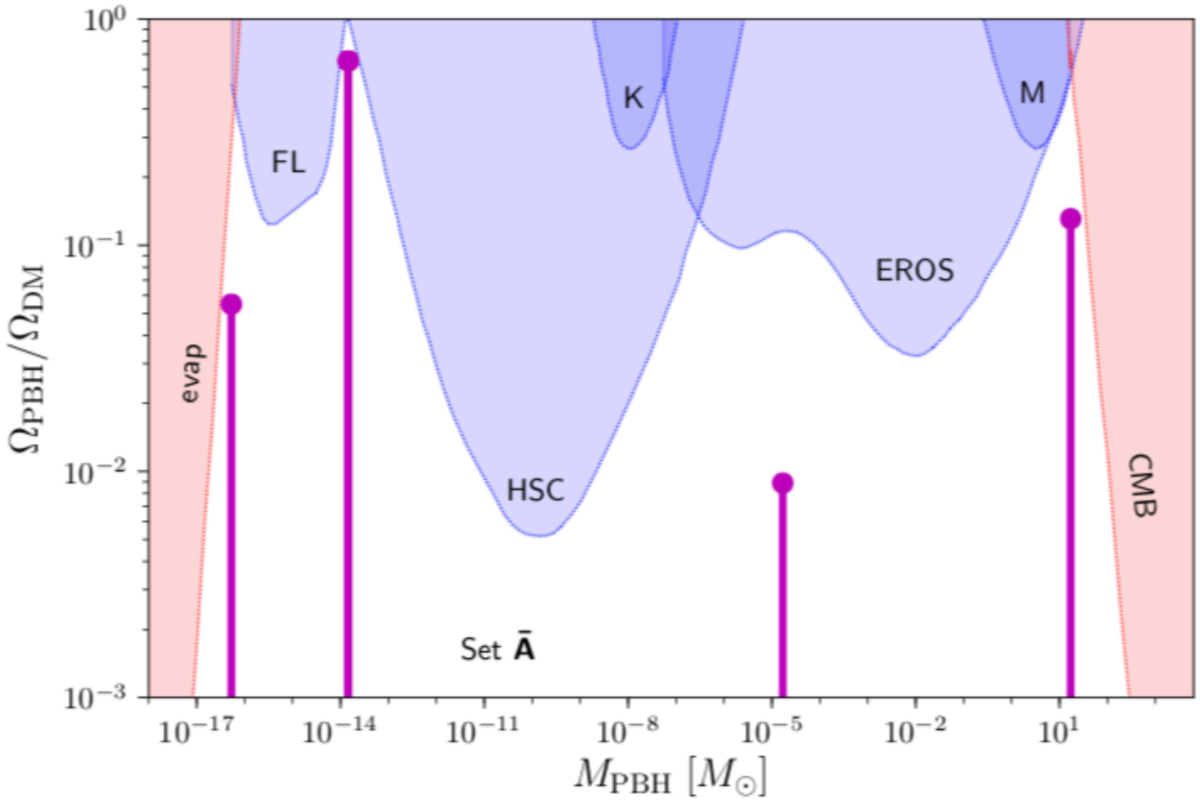
Department of Physics, University of California Santa Cruz,
1156 High St., Santa Cruz, CA 95064, USA
Santa Cruz Institute for Particle Physics,
1156 High St., Santa Cruz, CA 95064, USA

E-mail: blehmann@ucsc.edu, profumo@ucsc.edu, jyant@ucsc.edu

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

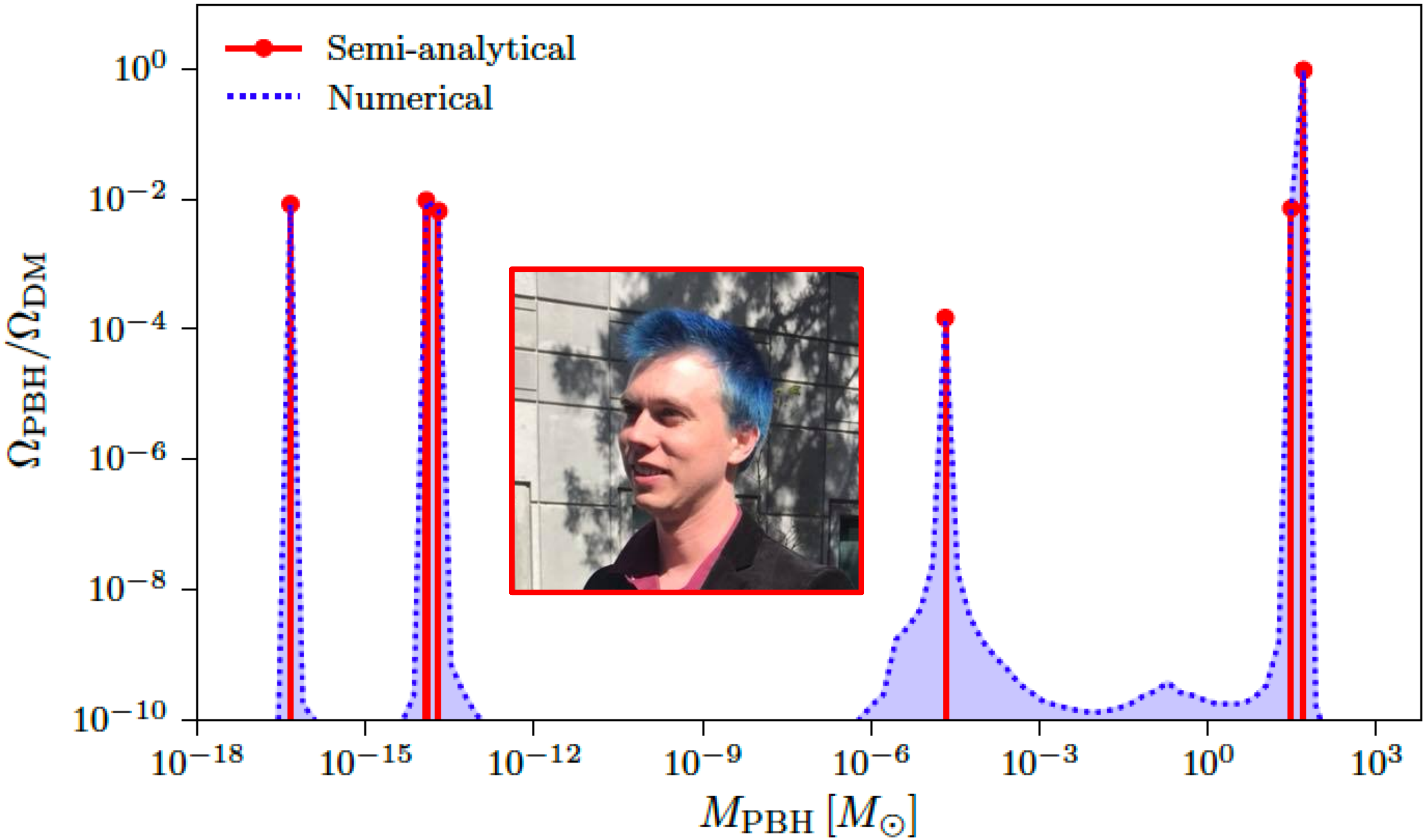
* Lehmann, Profumo and Yant, JCAP 2018



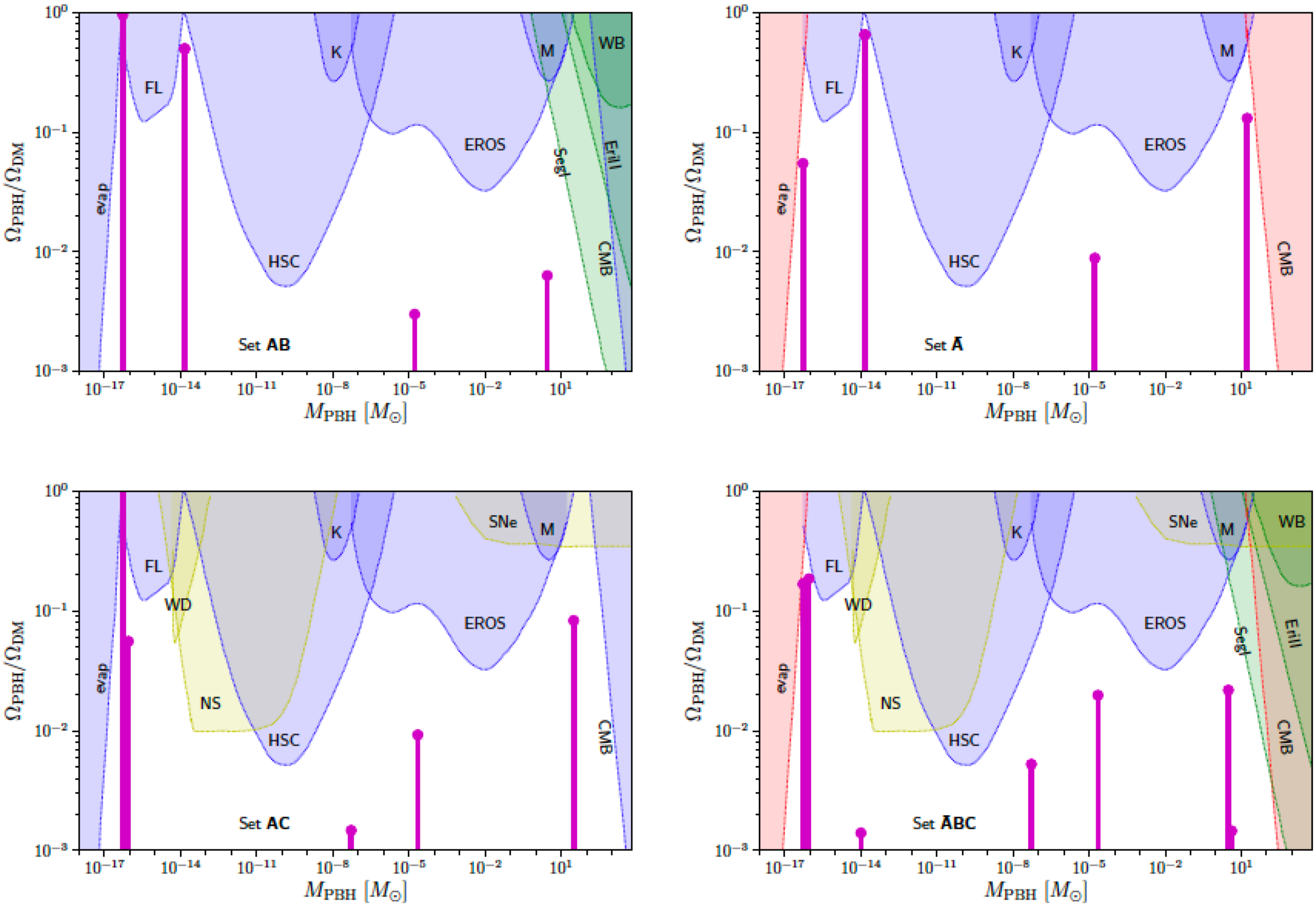
Answer: with *N* independent constraints, the optimal function is a linear combination of *N* delta functions with calculable relative weights

* 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 in principle sensitive to 10^{-5} M_{sun} merging BH
(although low priority now; also low V_{eff})

Given a mass function, one can calculate

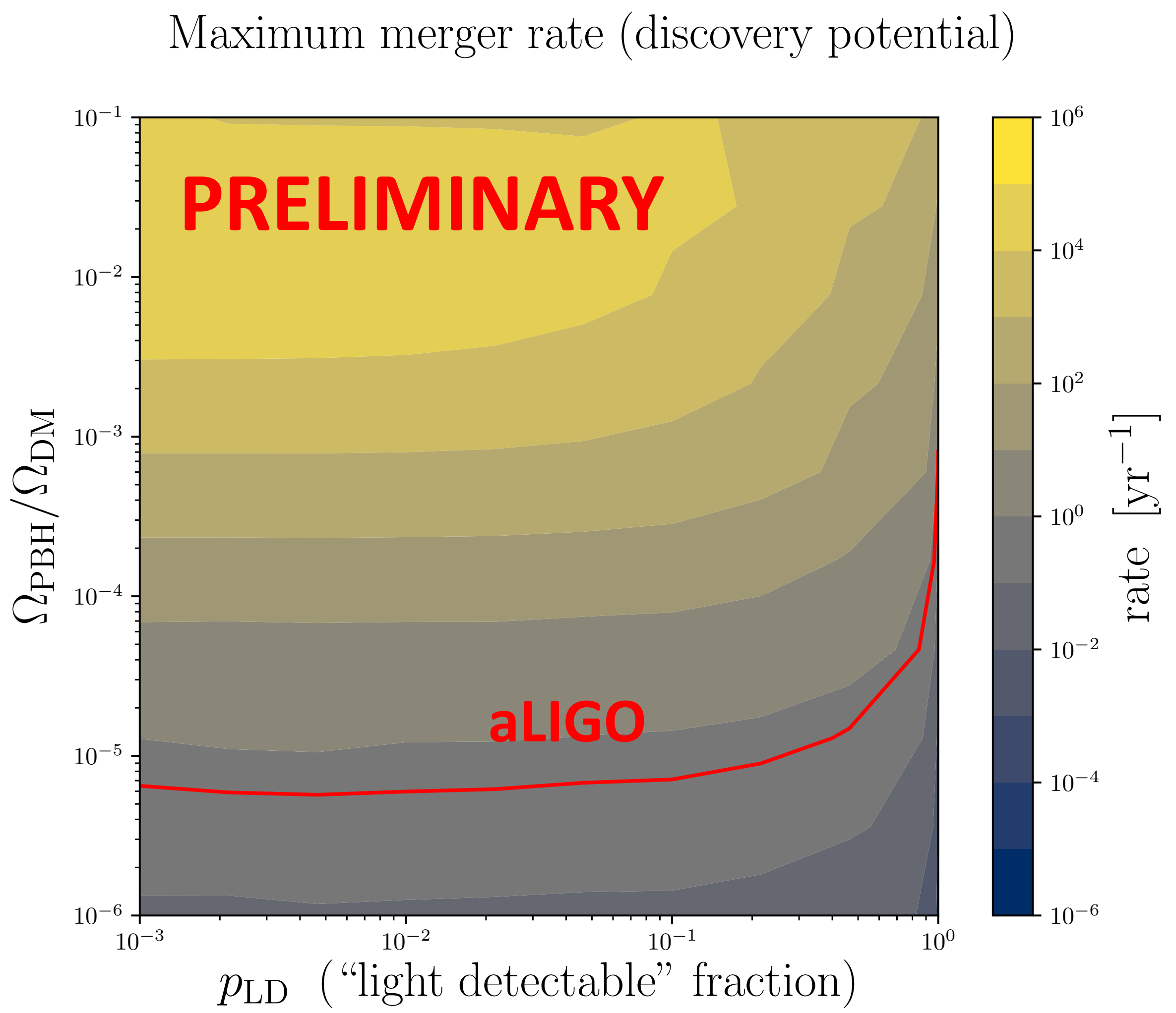
1. **Rate of "goldilocks events"**

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

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

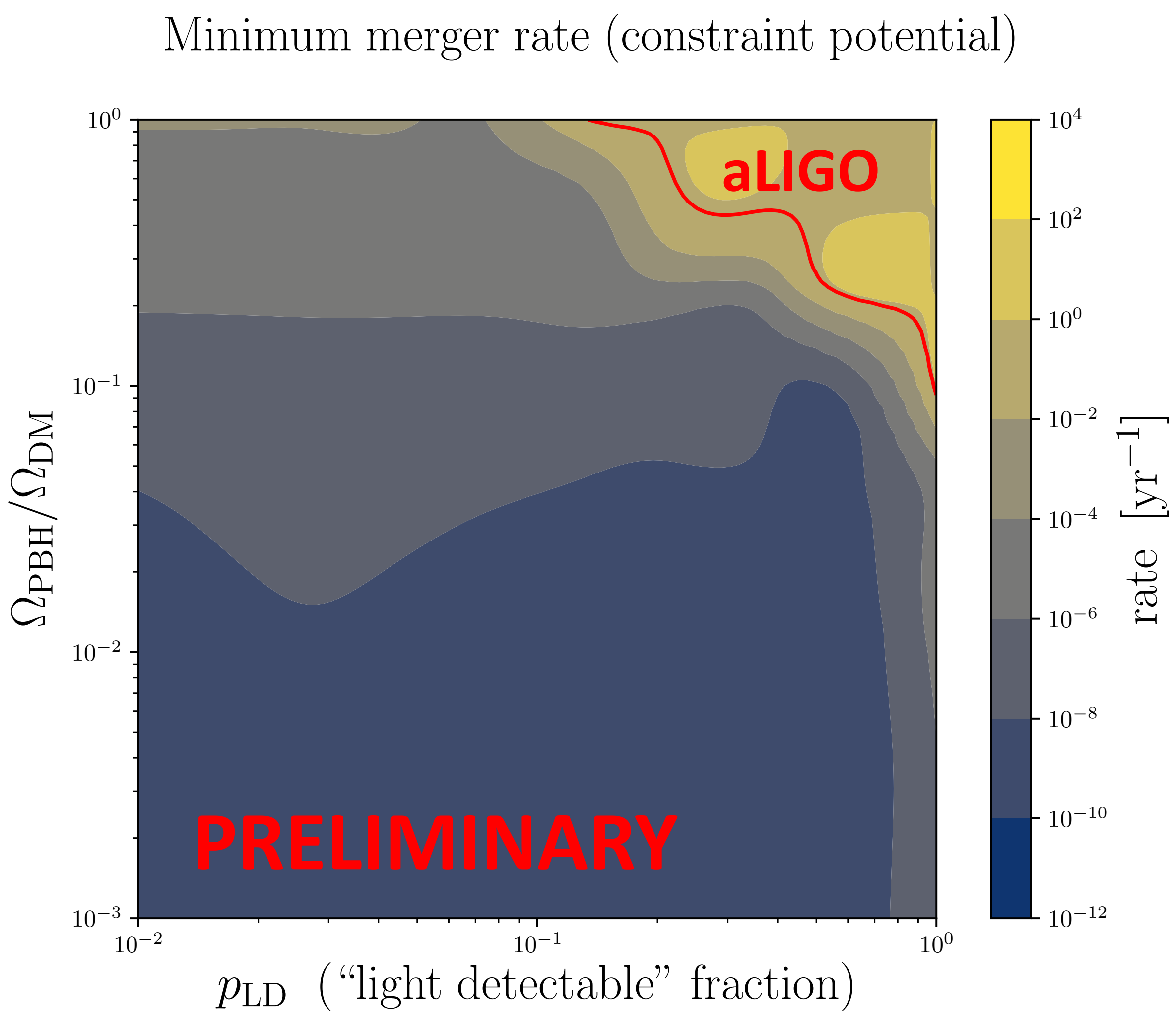
$$p_{\mathrm{LD}} = \frac{\int_{M_{\mathrm{LD,min}}}^{M_{\mathrm{LD,max}}} \mathrm{d}M \, \psi(M)}{\int_0^\infty \mathrm{d}M \, \psi(M)}.$$

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

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	$m_1/\mathrm{M}_\odot$	$m_2/\mathrm{M}_\odot$	$\mathcal{M}/\mathrm{M}_\odot$	$\chi_{\rm eff}$	$M_{\rm f}/\mathrm{M}_\odot$	$a_{\rm f}$	$E_{\rm rad}/(\mathrm{M}_\odot c^2)$	$\ell_{\rm peak}/(\mathrm{erg\ s}^{-1})$	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

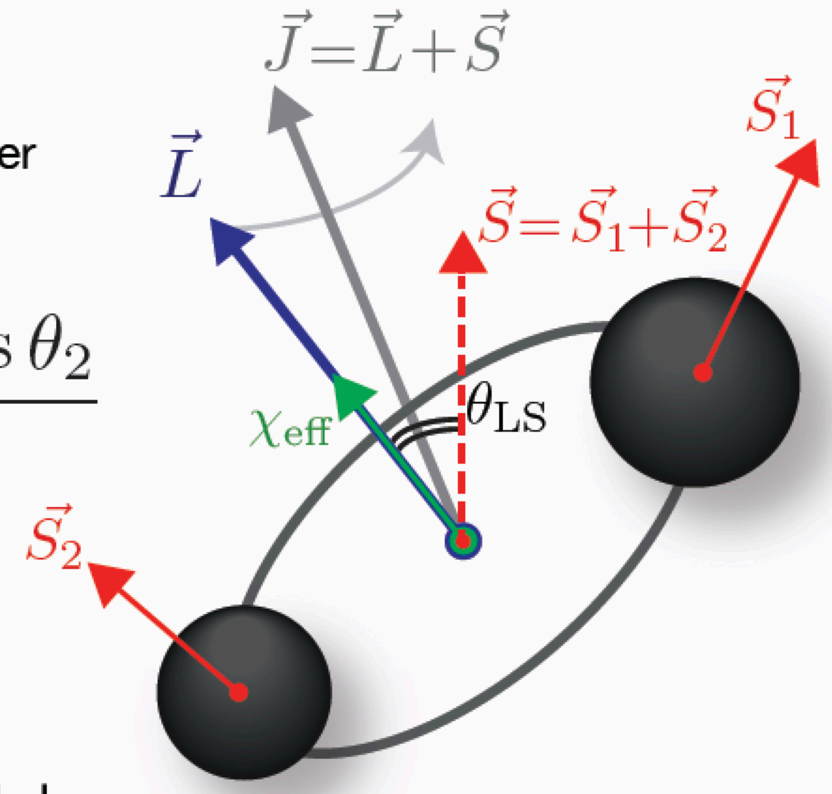
Slide credit: Nico Fernandez (UCSC → UIUC)

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:

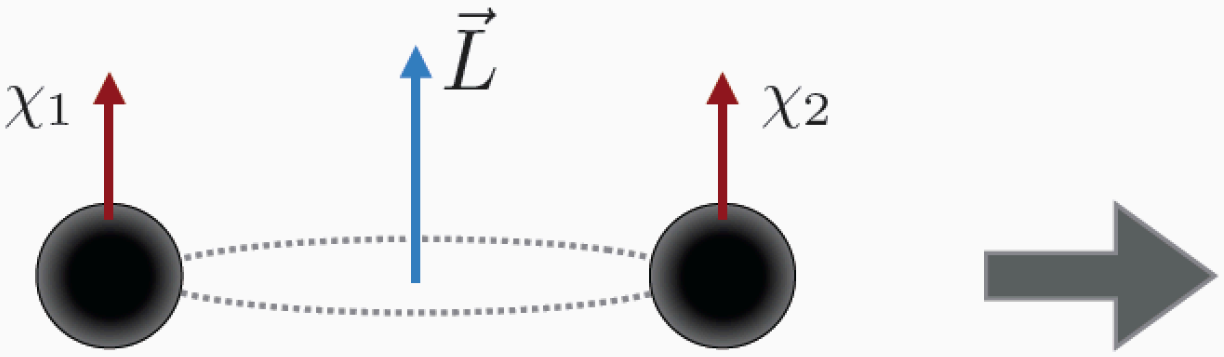
- Direction. +++
- Spin magnitude. ++
- masses. +

Slide credit: Nico Fernandez (UCSC → UIUC)

Effective Spin = 1

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

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



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

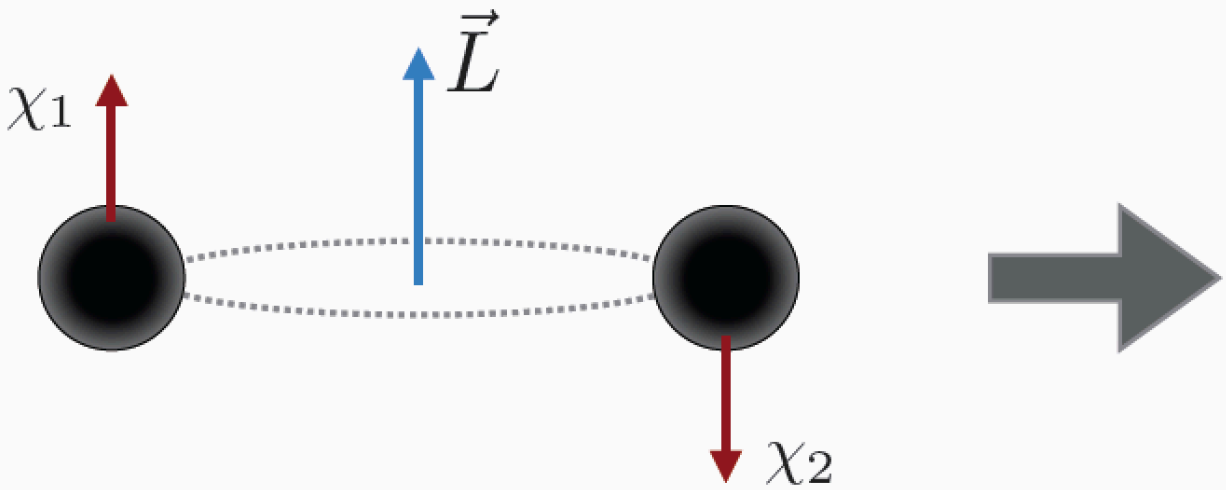
Most black holes from stellar binaries probably start off with their spins aligned

Slide credit: Nico Fernandez (UCSC → UIUC)

Effective Spin = 0

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

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



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

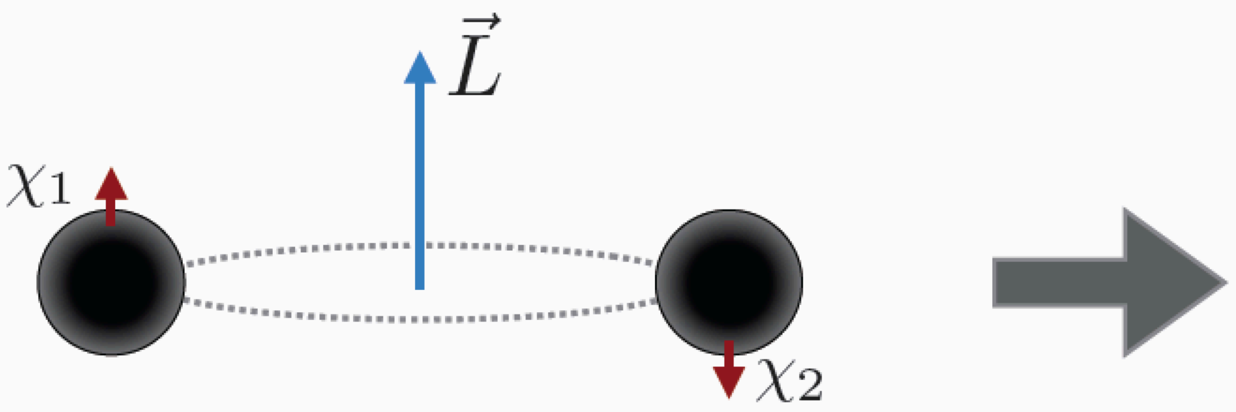
Spins are essentially isotropic in the dynamical formation scenario. Binary was probably formed in a cluster

Slide credit: Nico Fernandez (UCSC → UIUC)

Effective Spin = 0

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

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



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

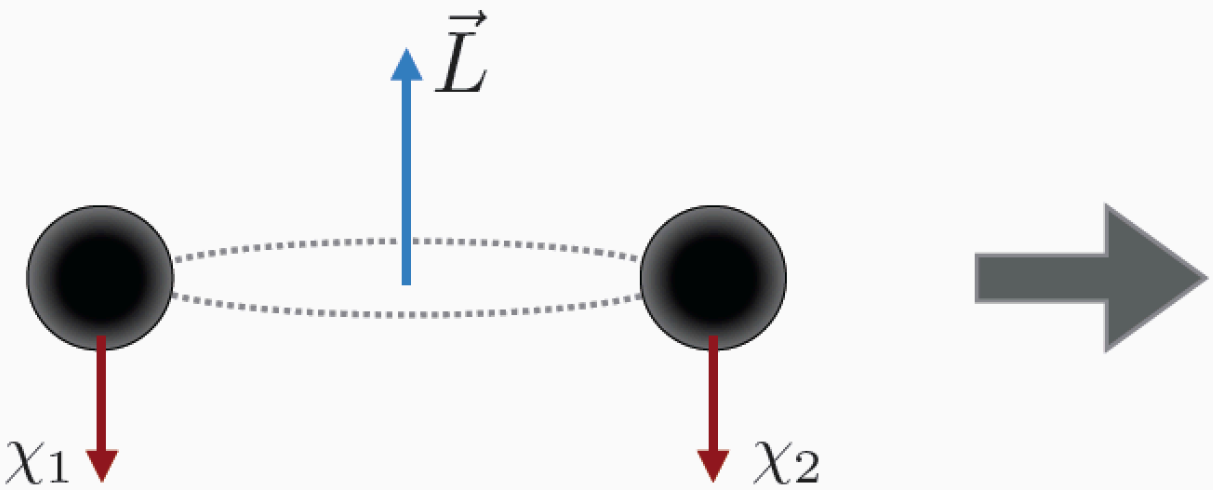
Spin magnitudes are close to zero (expected from PBHs).

Slide credit: Nico Fernandez (UCSC → UIUC)

Effective Spin = -1

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

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

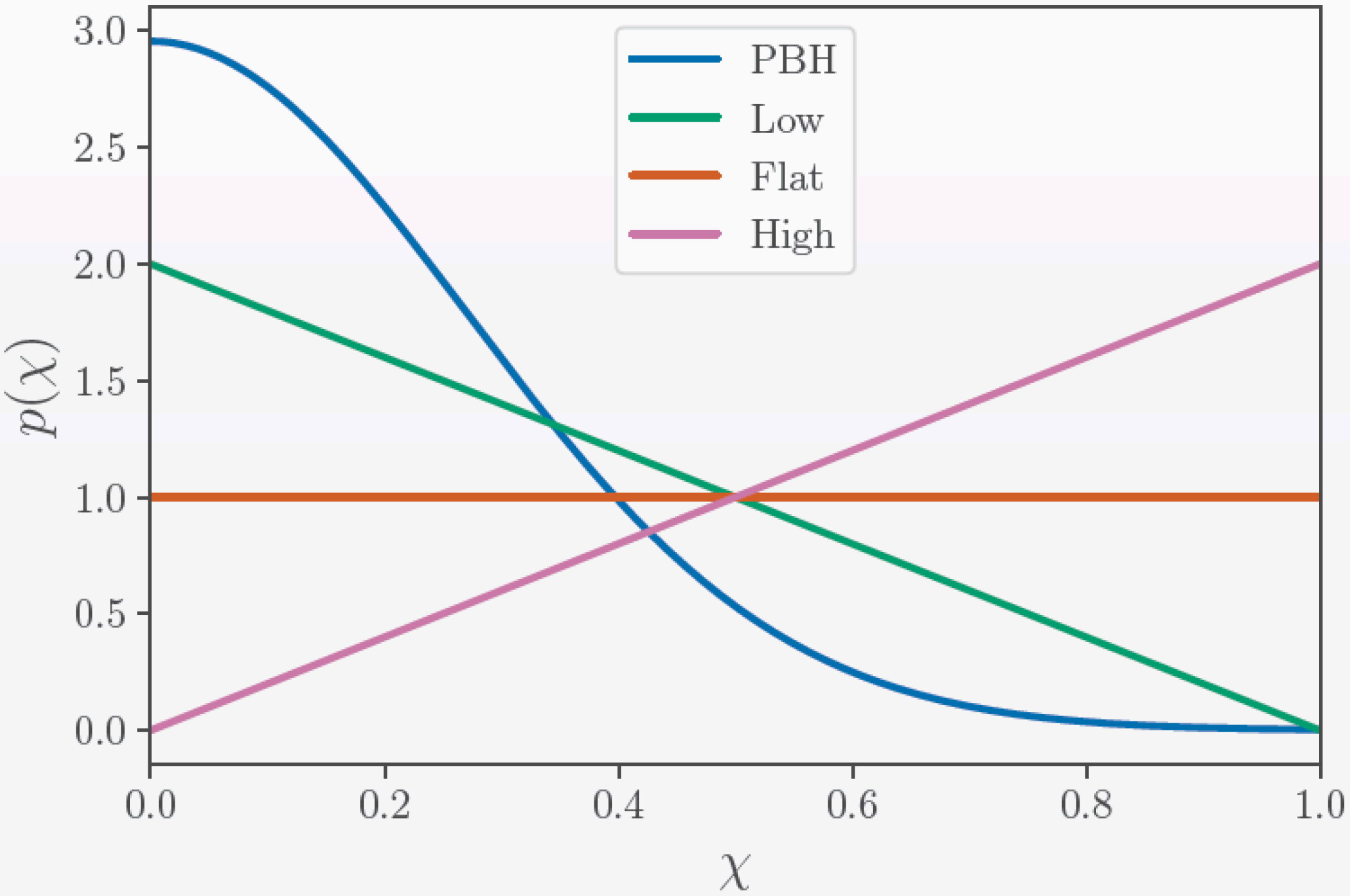


$$\chi_{\text{eff}} \approx -1$$

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)

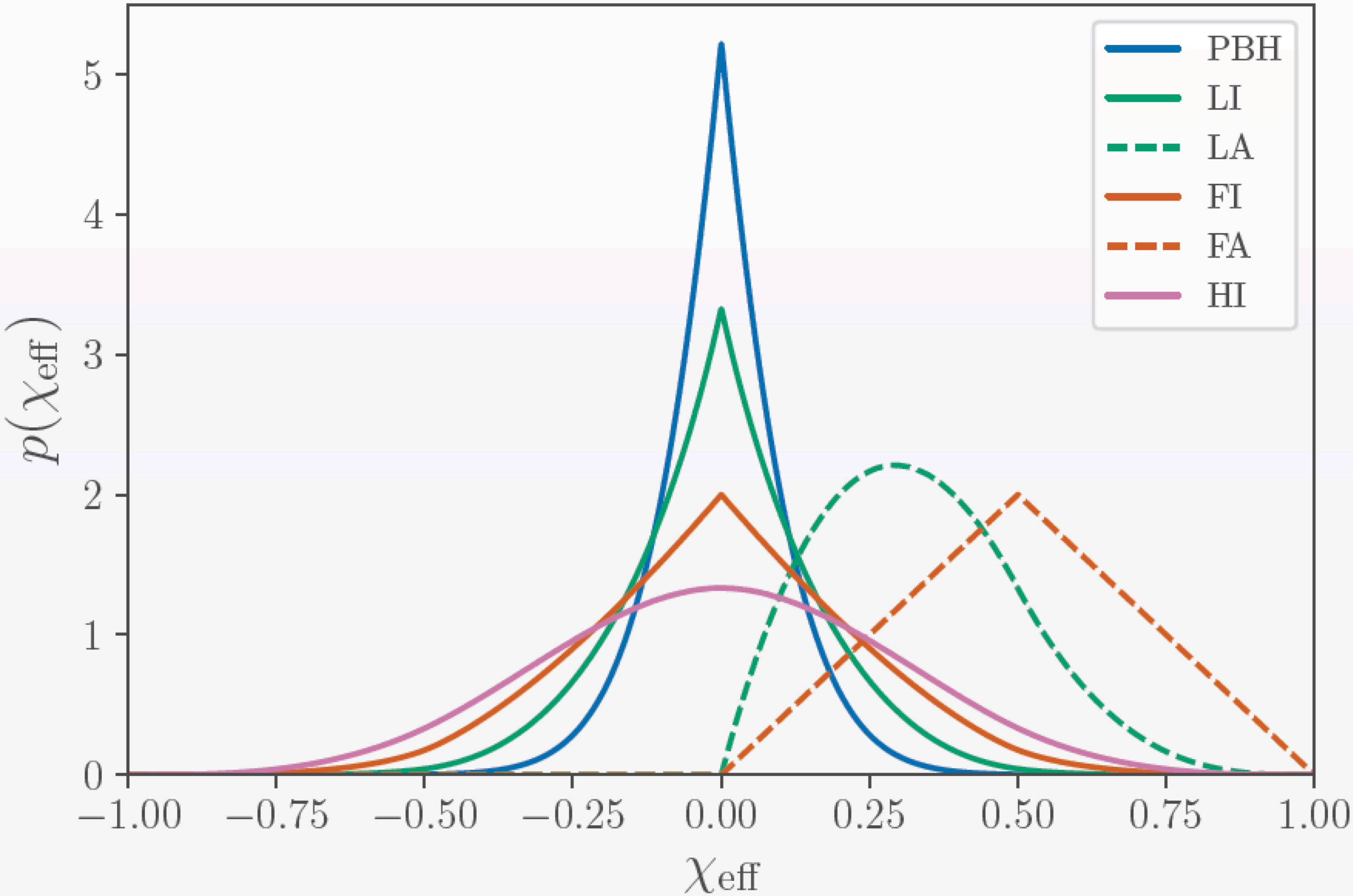
Model Selection

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

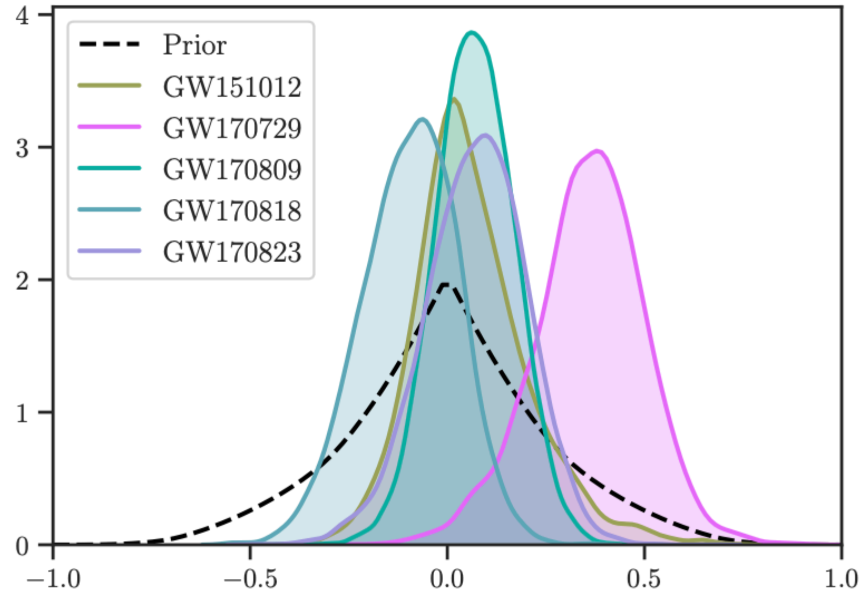
Example:
FI = Flat spin magnitude and isotropic spins (LIGO)
FA = Flat spin magnitude and align spins

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)



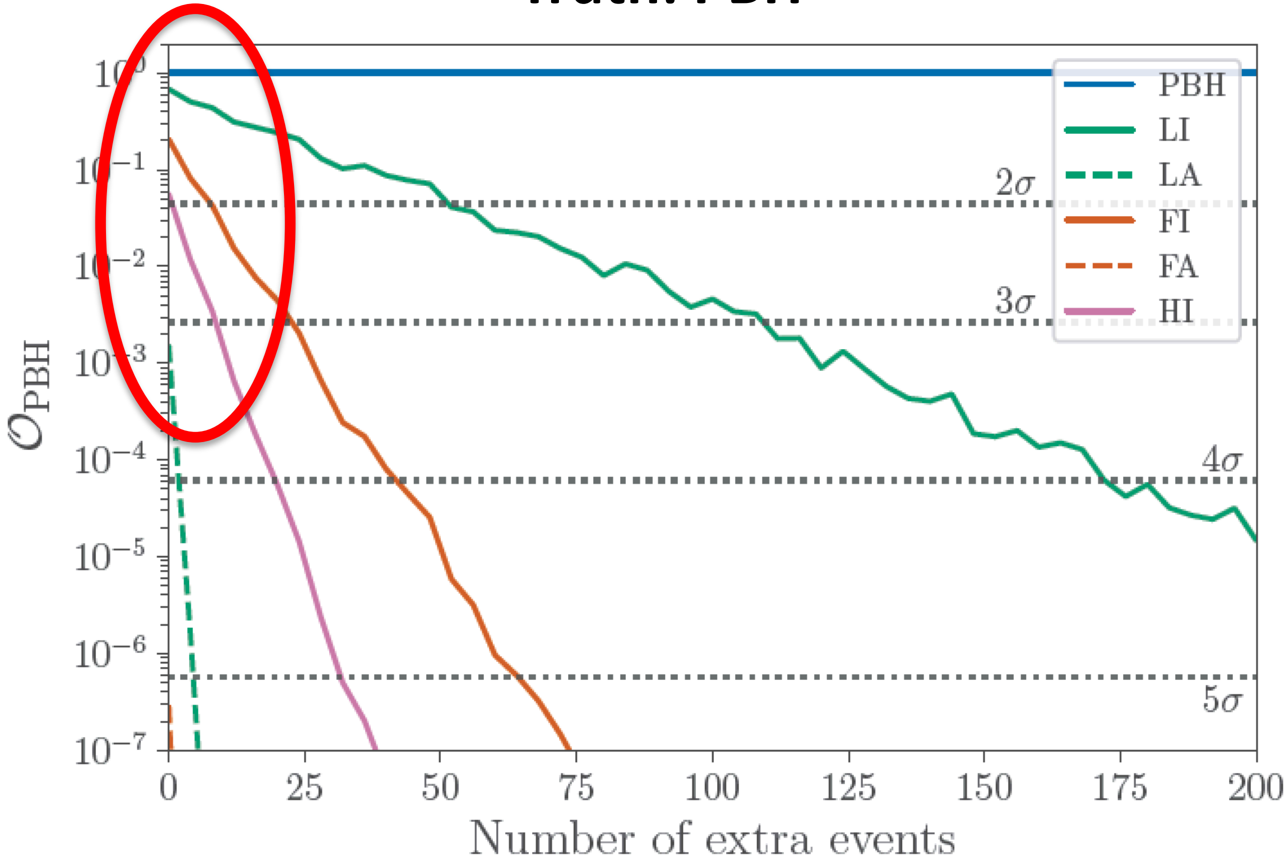
Odds ratios

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)

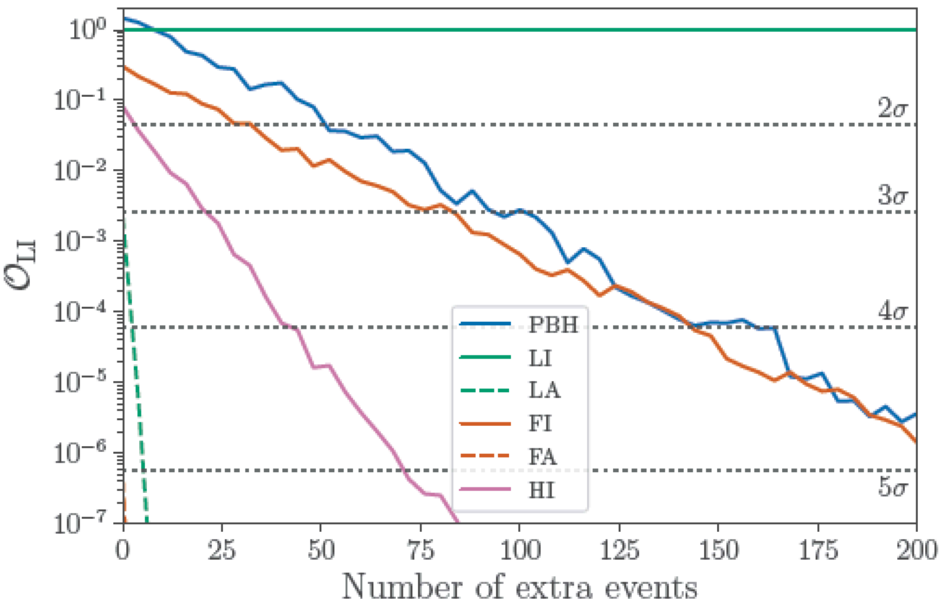
Evolution of the Odds ratios

Truth: PBH



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

Evolution of the Odds ratios



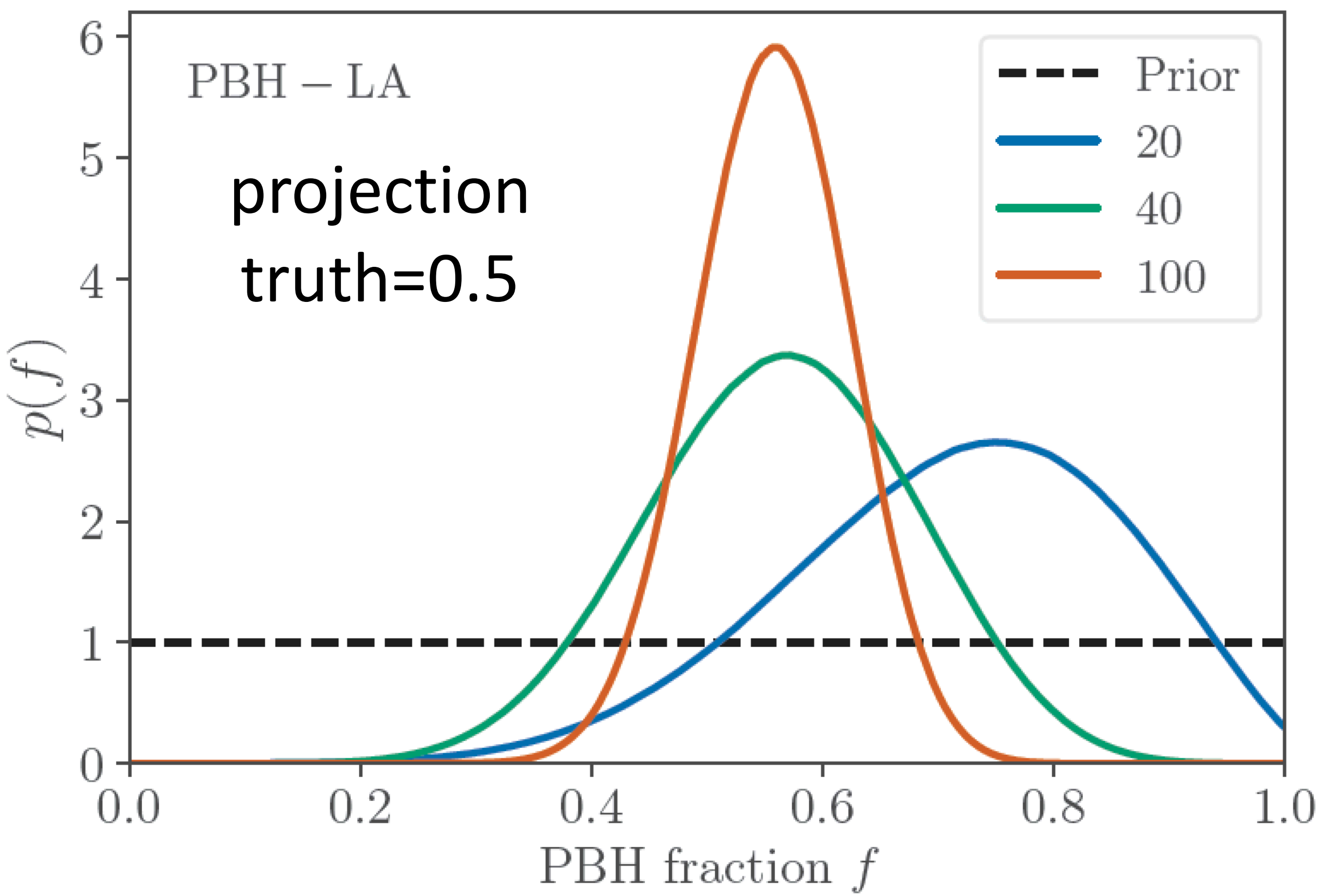
Truth: Low-isotropic

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

What about mixed models?

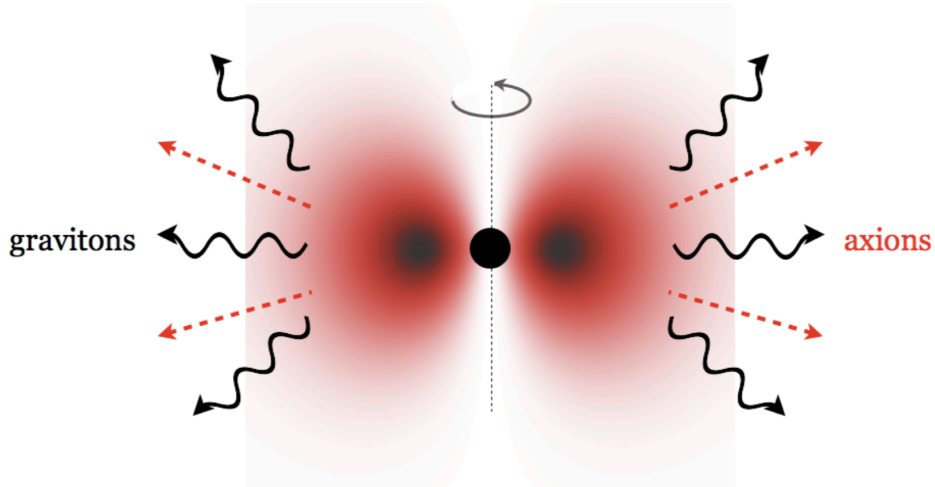
Fernandez and Profumo, 1905.13109 (JCAP); Slide credit: Nico Fernandez (UCSC → UIUC)

What about mixed models?



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

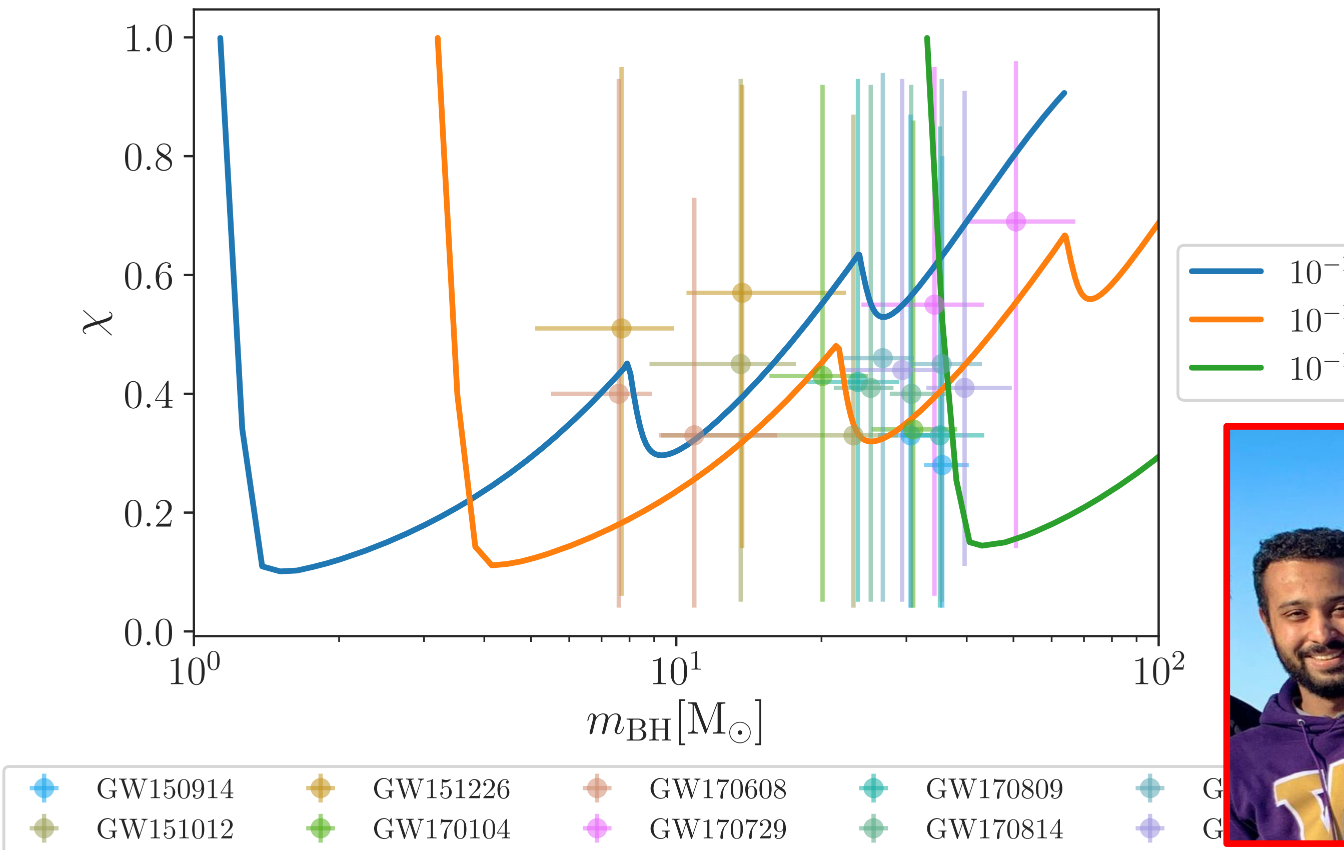
What else could fake a low-spin PBH? Super-radiance!



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

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

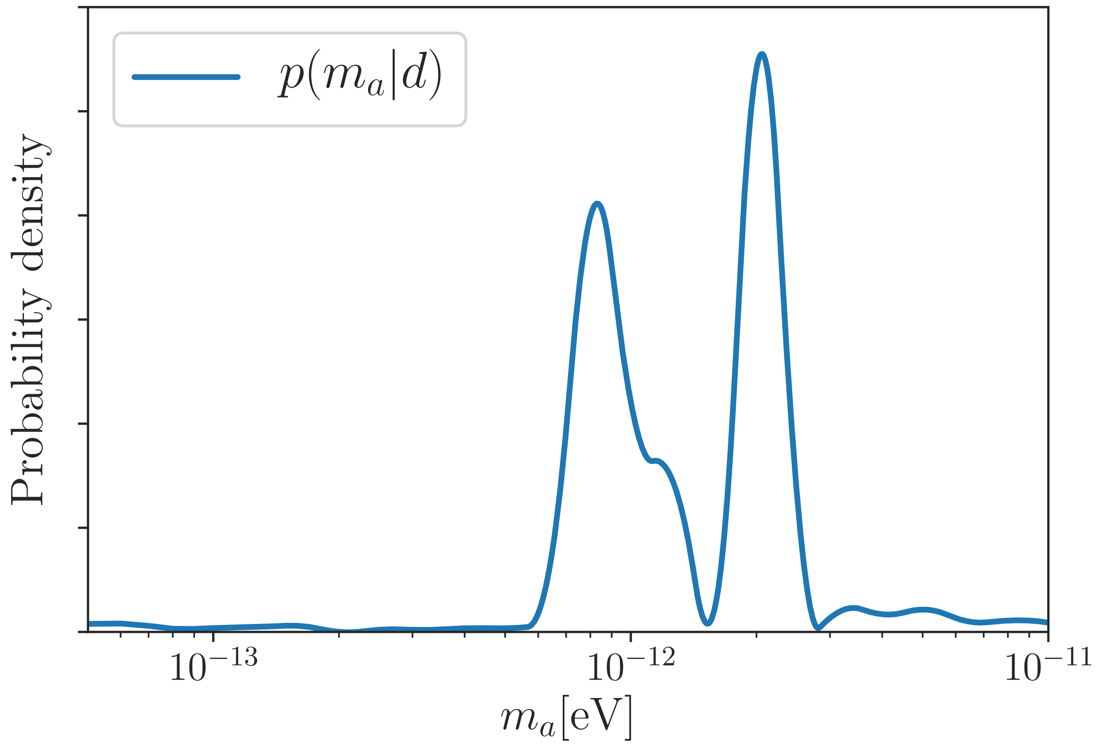
What else could fake a low-spin PBH? Super-radiance!



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

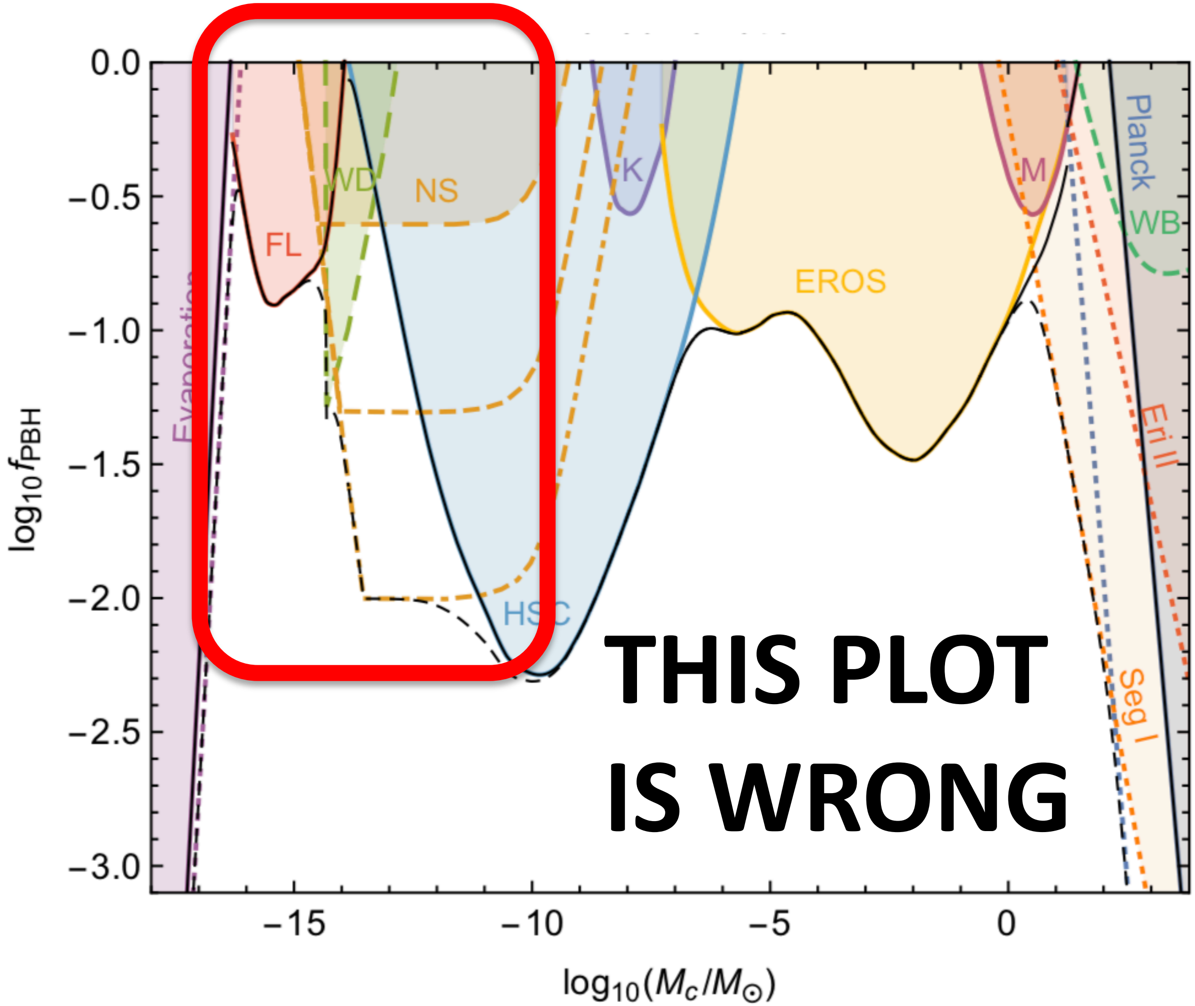
*Fernandez, Ghalsasy, Profumo, in progress

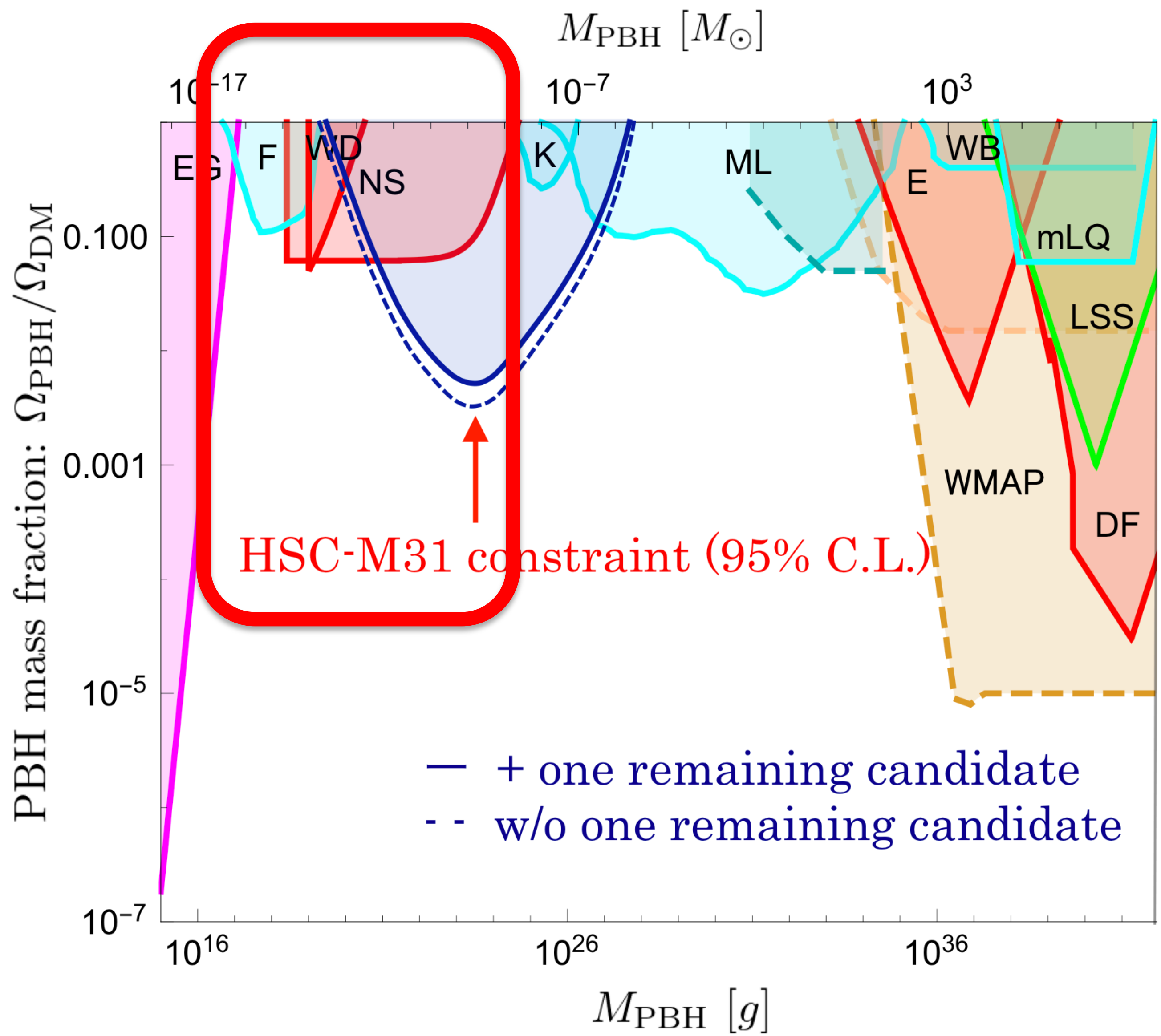
What else could fake a low-spin PBH? Super-radiance!



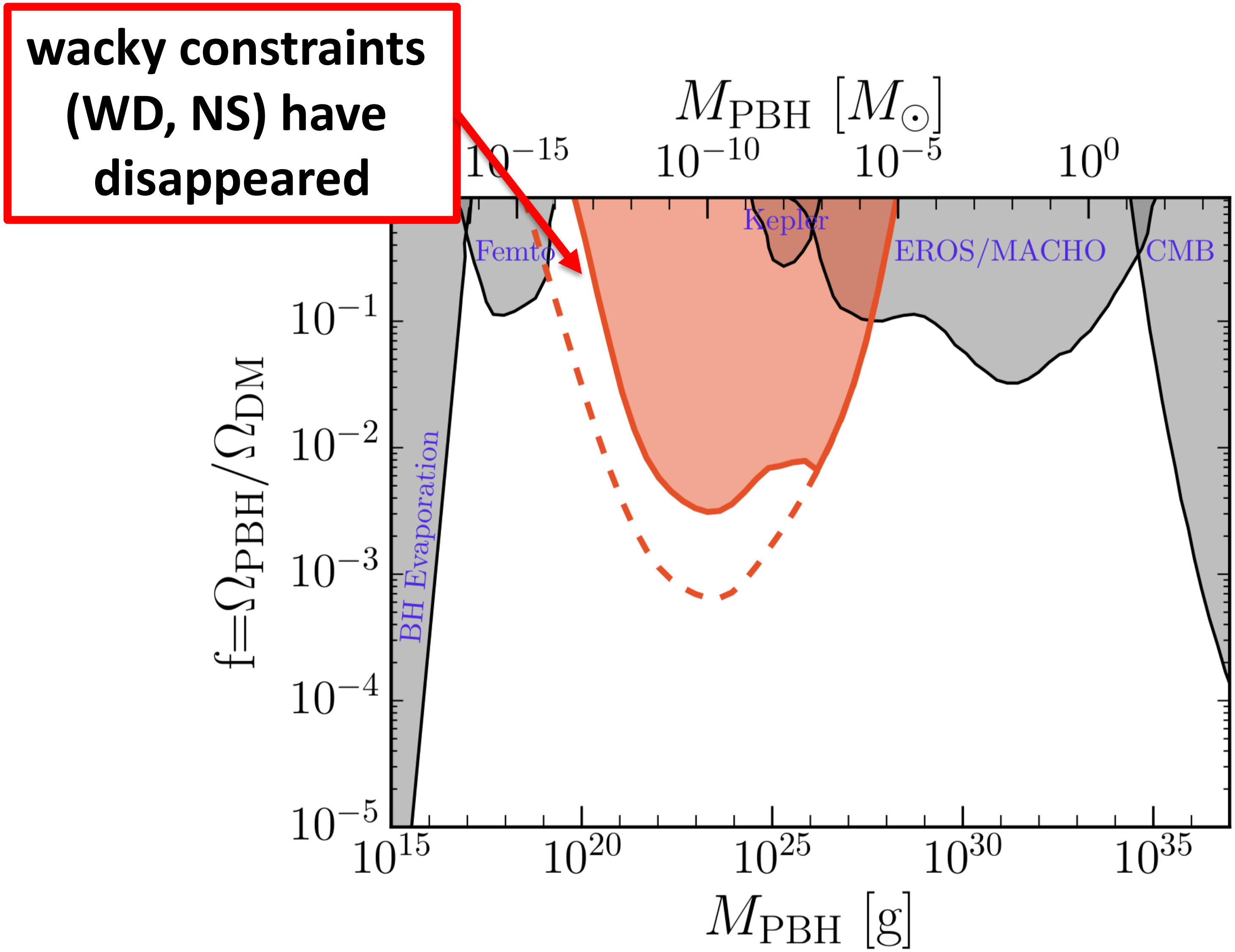
Probability density for ALP mass

*Fernandez, Ghalsasy, Profumo, in progress


0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−15
−10
−5
0
log10 fPBH
log10(Mc/M⊙)
Evaporation
FL
WD
NS
HSC
K
EROS
M
Planck
WB
Eri II
Seg I
THIS PLOT
IS WRONG

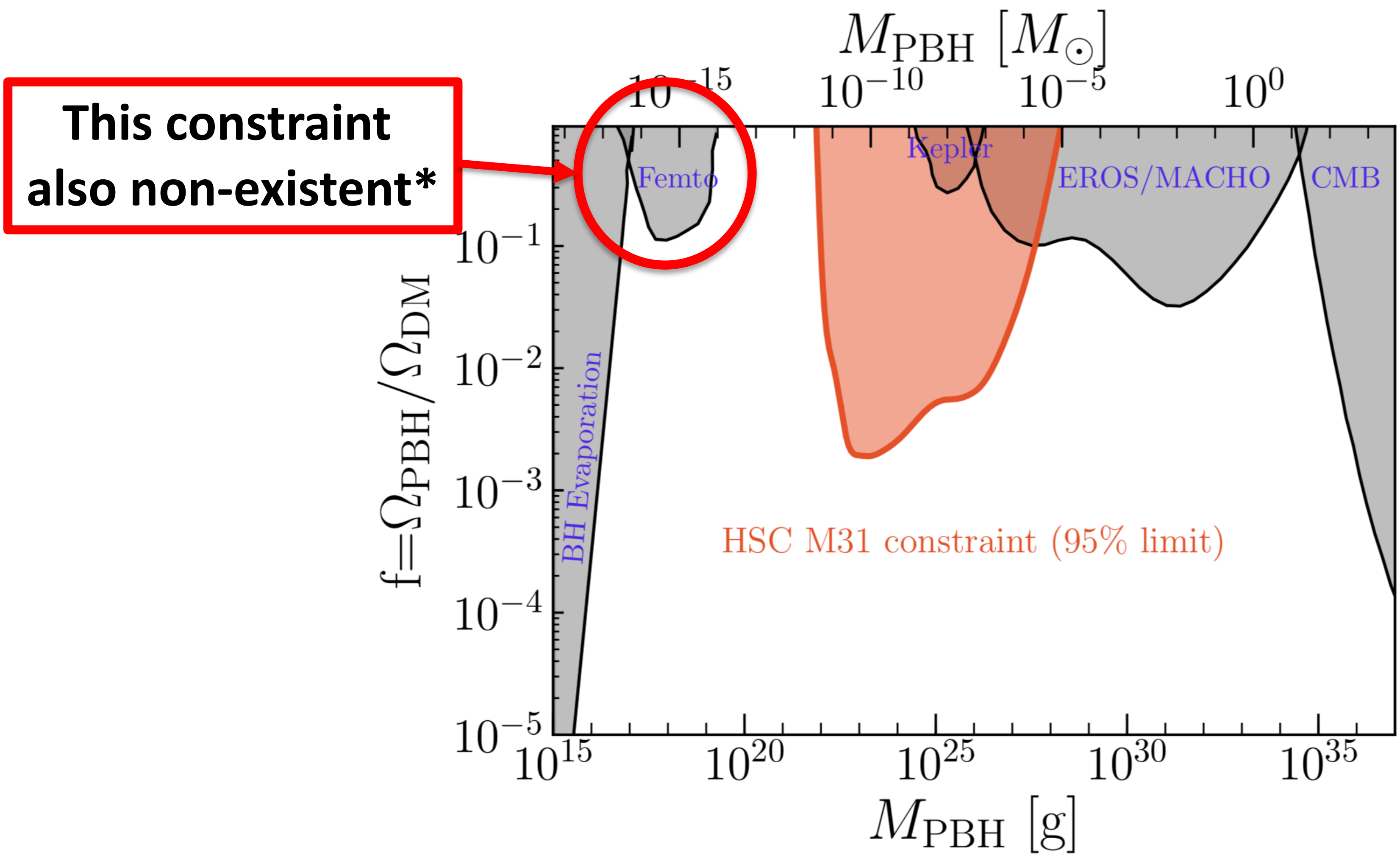


SUBARU HSC microlensing, 1701.02151 VERSION 1



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 $R = R_{sun}$!

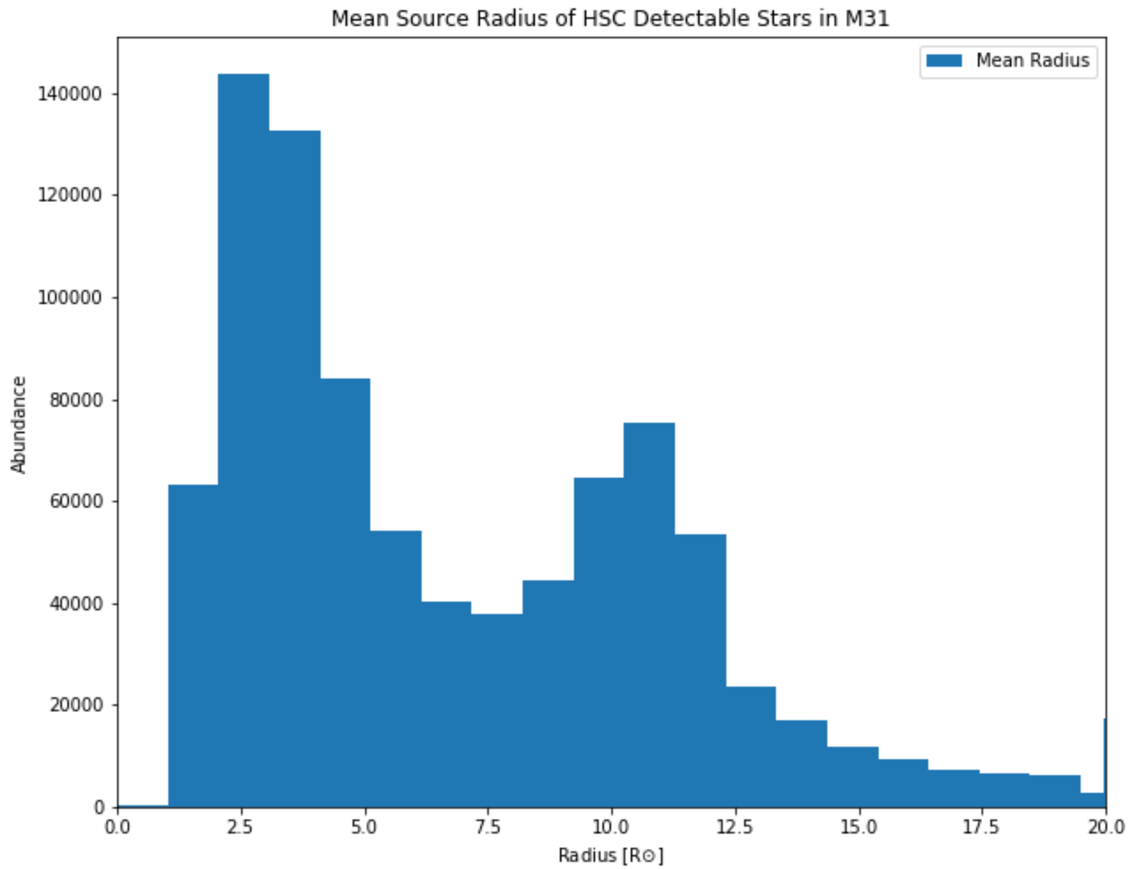
…but are these bounds robust?

A few (worrisome) assumptions:

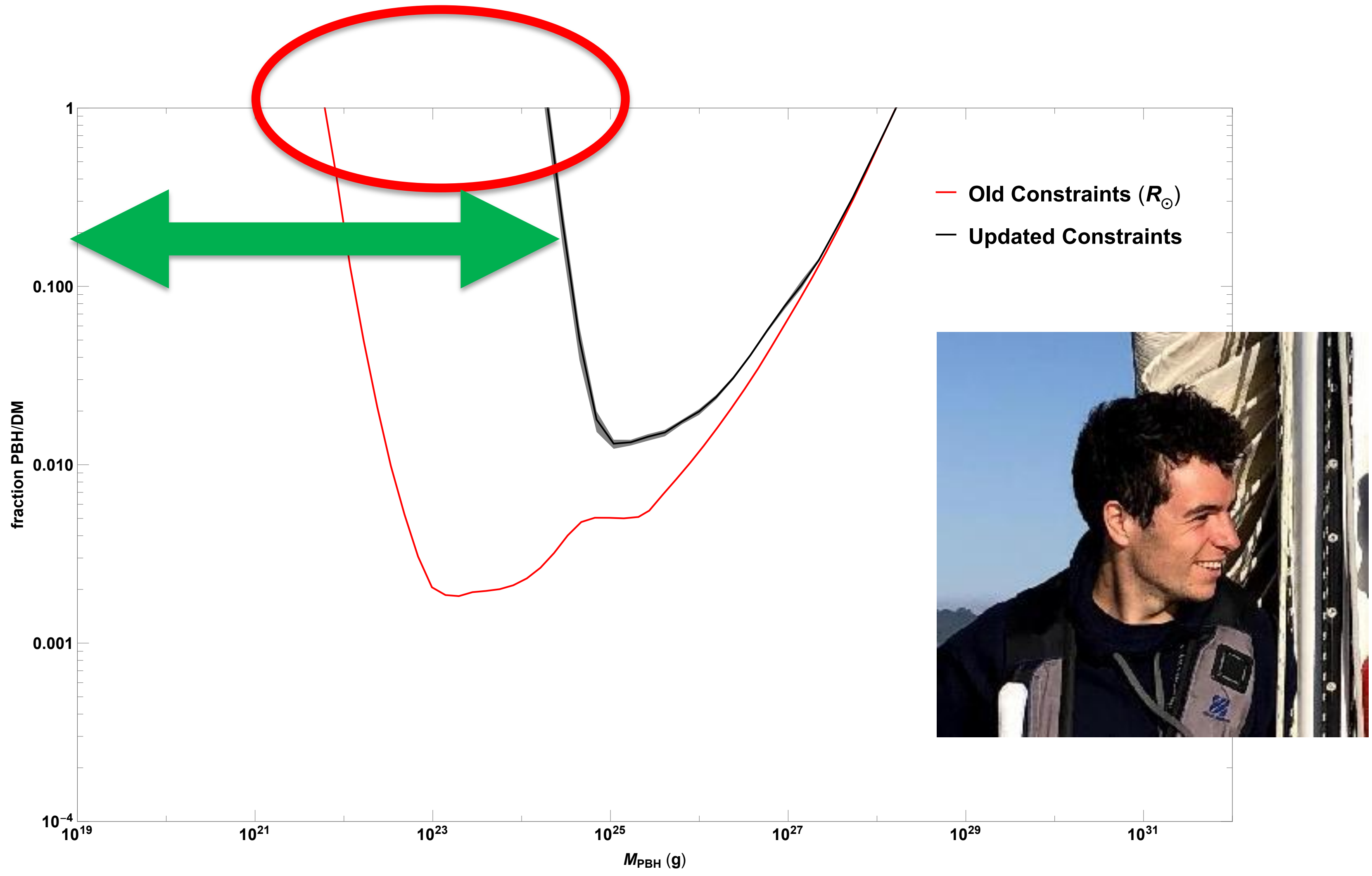
- All stars are at the same distance
- All stars have the same size (1 R_{sun})
- DM is completely smooth

* Profumo and Smyth in progress

Sun-like stars are however too dim for HSC!



* Profumo and Smyth in progress



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

* Profumo and Smyth in progress

…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

tro-ph.C

John Tamanas

Country	WCA ID	Gender	Competitions
United States	2007TAMA02	Male	41

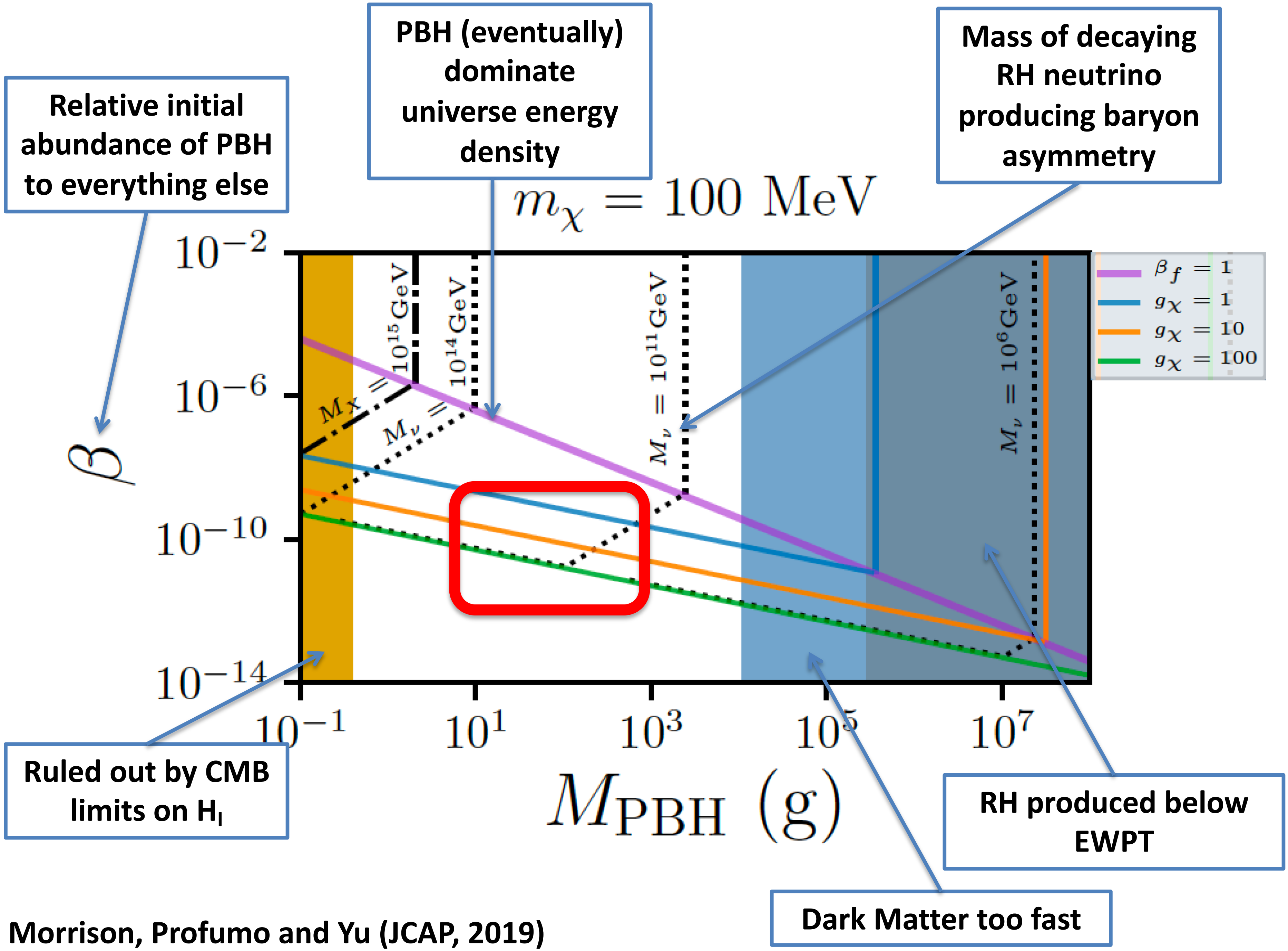
Current Personal Records

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!

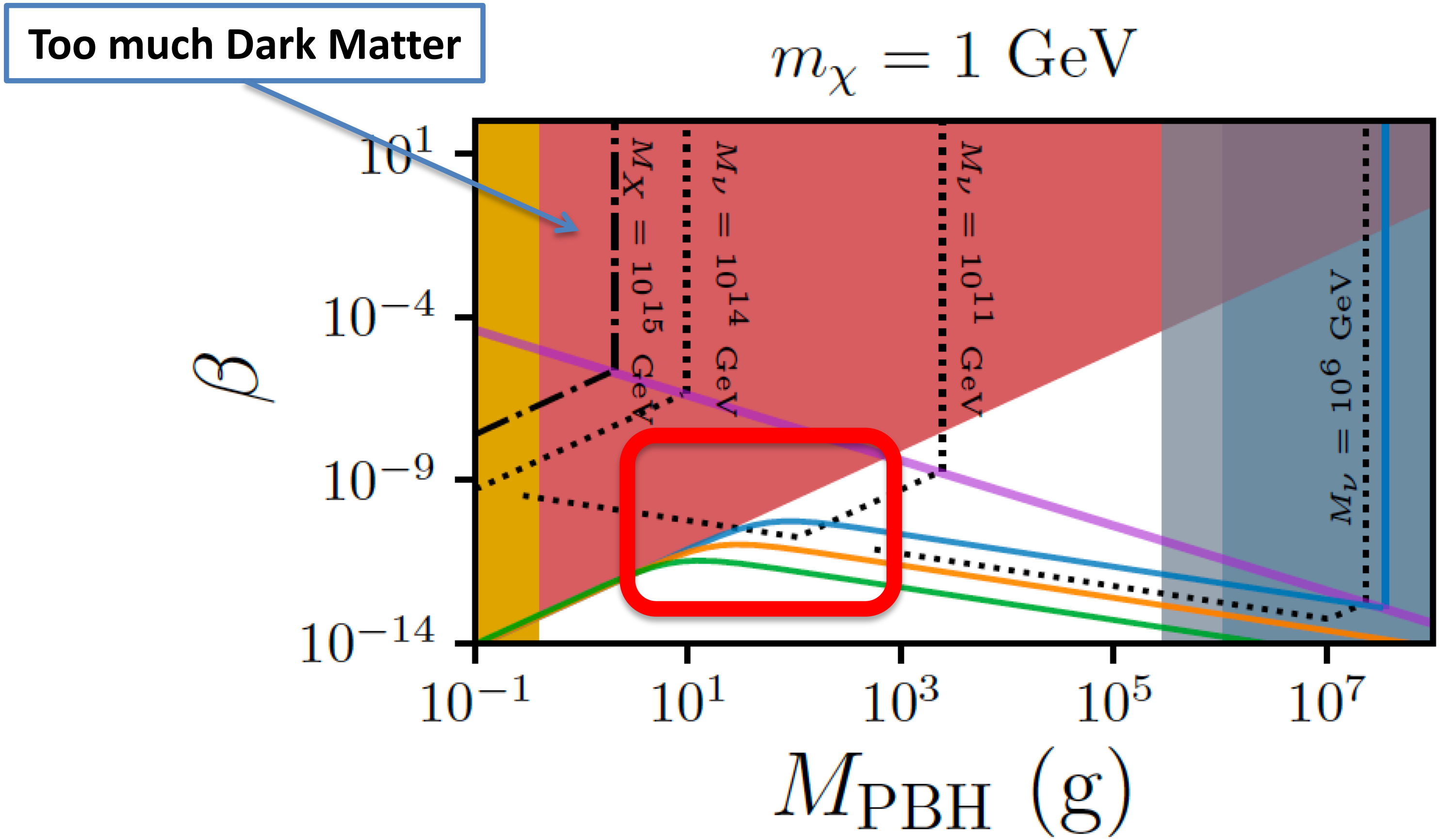
Mass (g)	T_H (GeV)	τ (s)	$T_{\rm evap} = T(\tau)$ (GeV)
$5M_P \simeq 10^{-4}$	1.7×10^{17}	10^{-41}	2×10^{17}
1	1.7×10^{13}	4×10^{-29}	2×10^{11}
10^3	1.7×10^{10}	4×10^{-20}	6×10^6
10^6	1.7×10^7	4×10^{-11}	200
10^9	1.7×10^4	0.04	0.006
10^{12}	17	$4 \times 10^7 \sim 1$ yr	~ 1 keV

* 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*

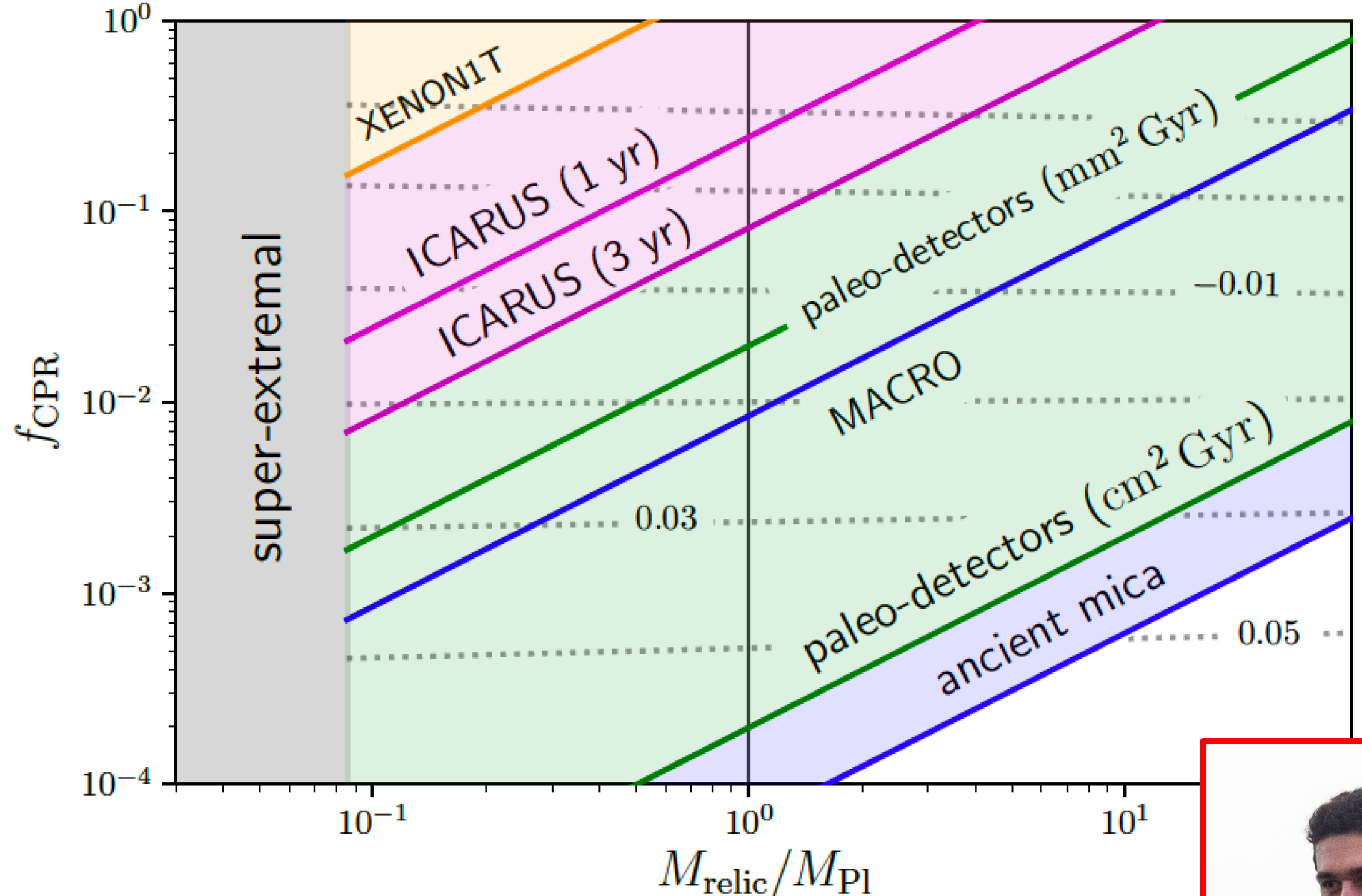
$$P(Q) \sim \exp\left(-4\pi\alpha(Q/e)^2\right)$$

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

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!

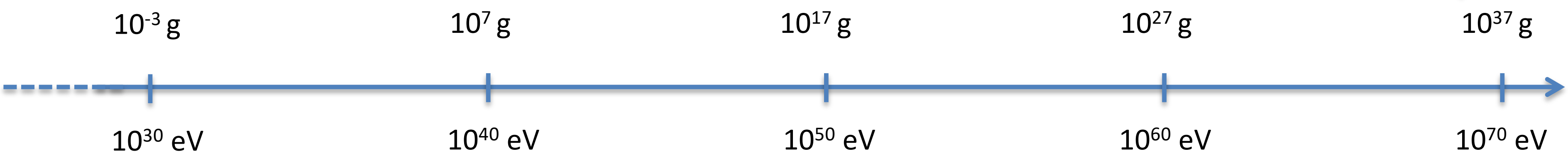
* Page, 1977

** Lehmann, Johnson, Profumo and Schwemberger, 1906.06348



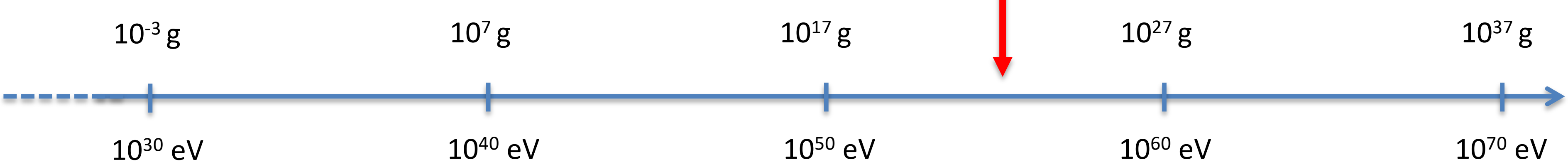
*** Lehmann, Johnson, Profumo and Schwemberger, 1906.06348**

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

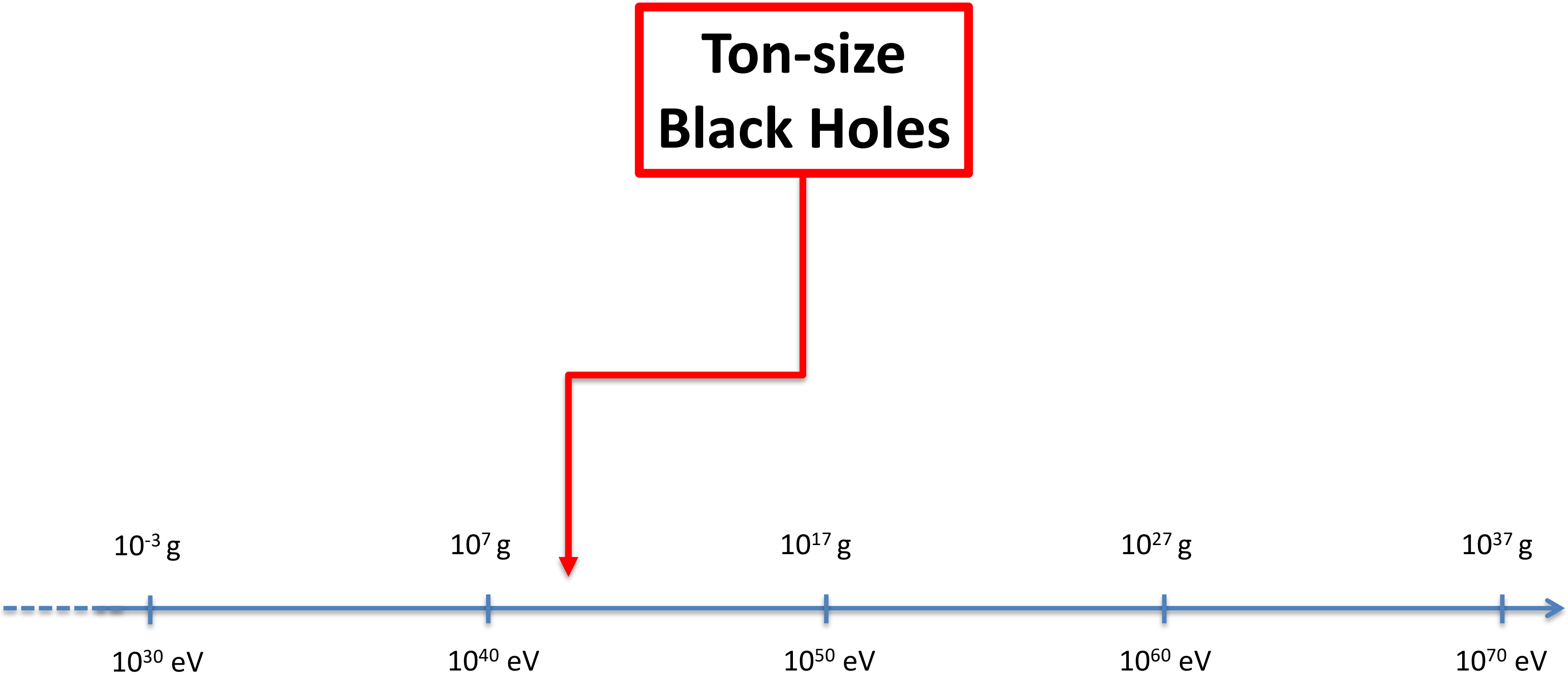


- ✓ **Spins look a lot like PBH!**
- ✓ **…or maybe they are low because of superradiance?**

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

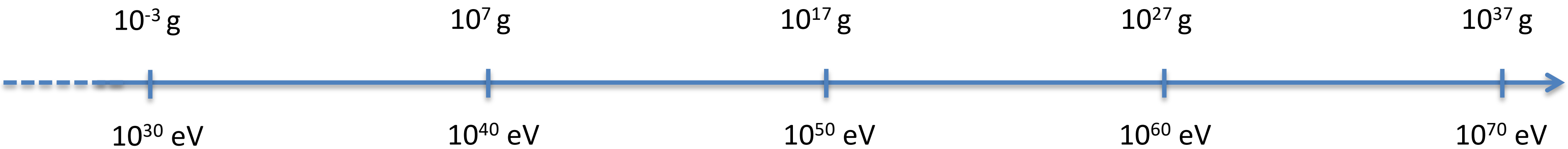


- ✓ **Microlensing a lot trickier than previously thought!**
- ✓ **Detection strategies?**



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

Grain-of-Salt 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