SCIPP
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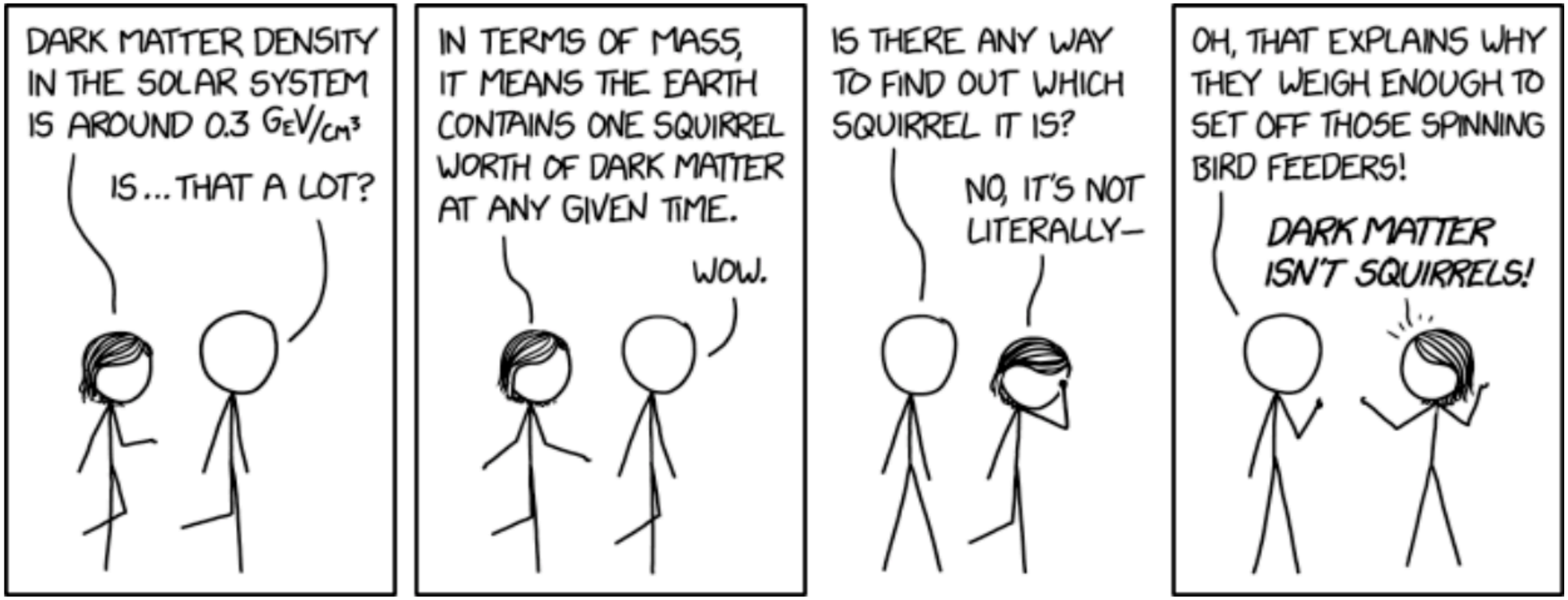
UC SANTA CRUZ

What is the Dark Matter?

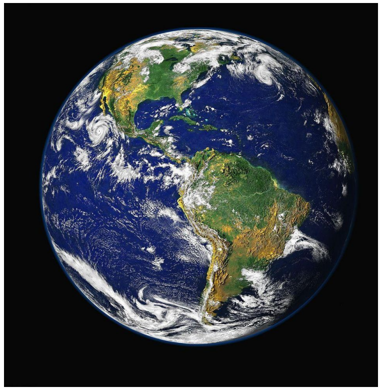


Pheno 2020

Wednesday May 6, 2020

* Credit: xqcd

5/6



a new

elementary particle

what is an elementary particle?

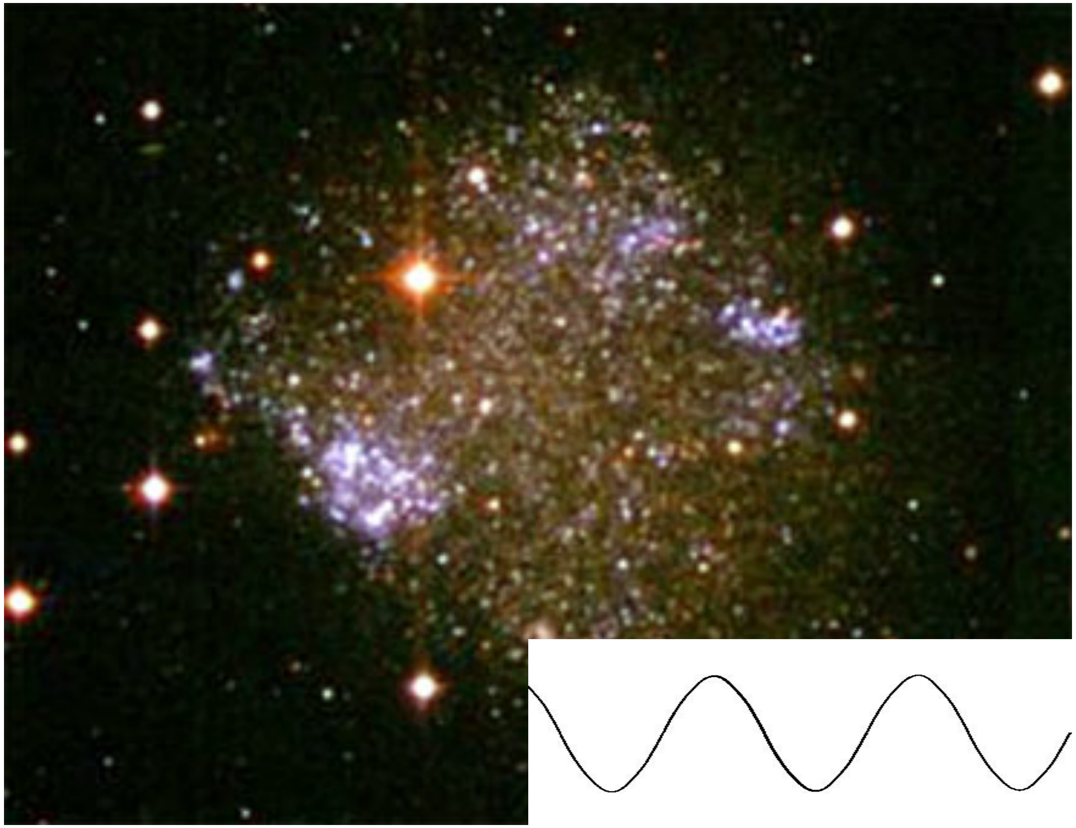
what is an

elementary particle?

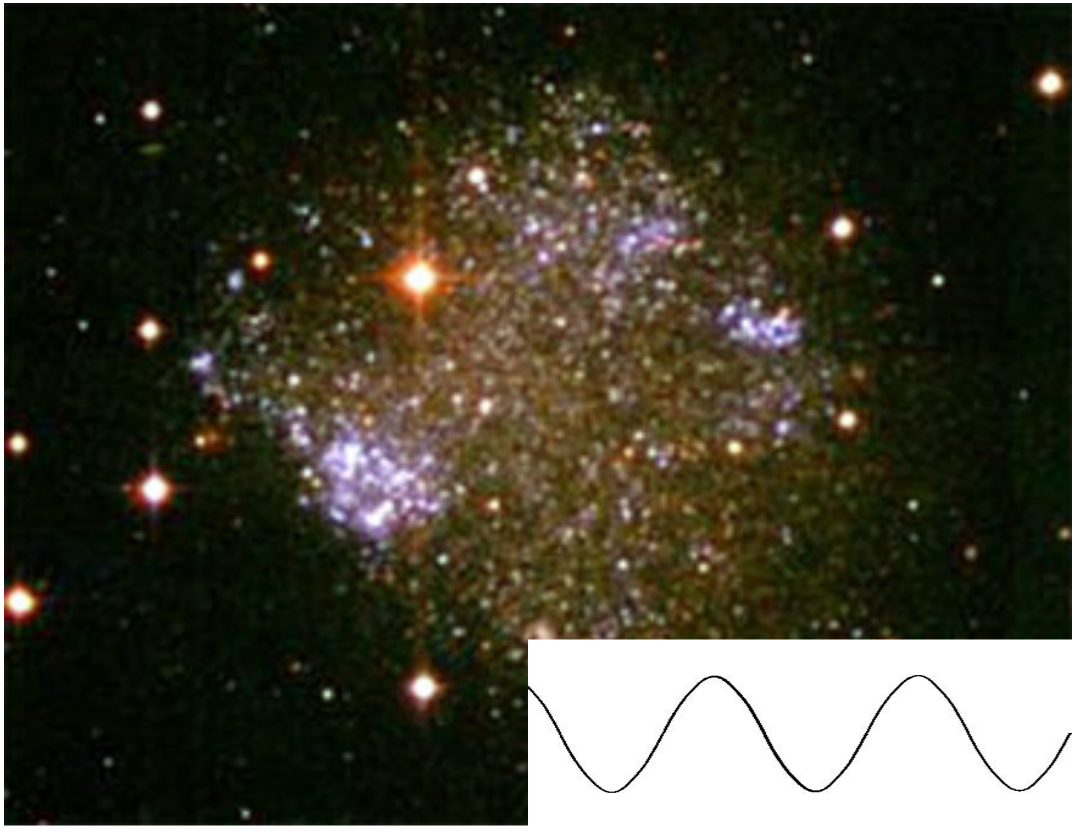
an irreducible, unitary representation of the Poincaré Group

(m, J)

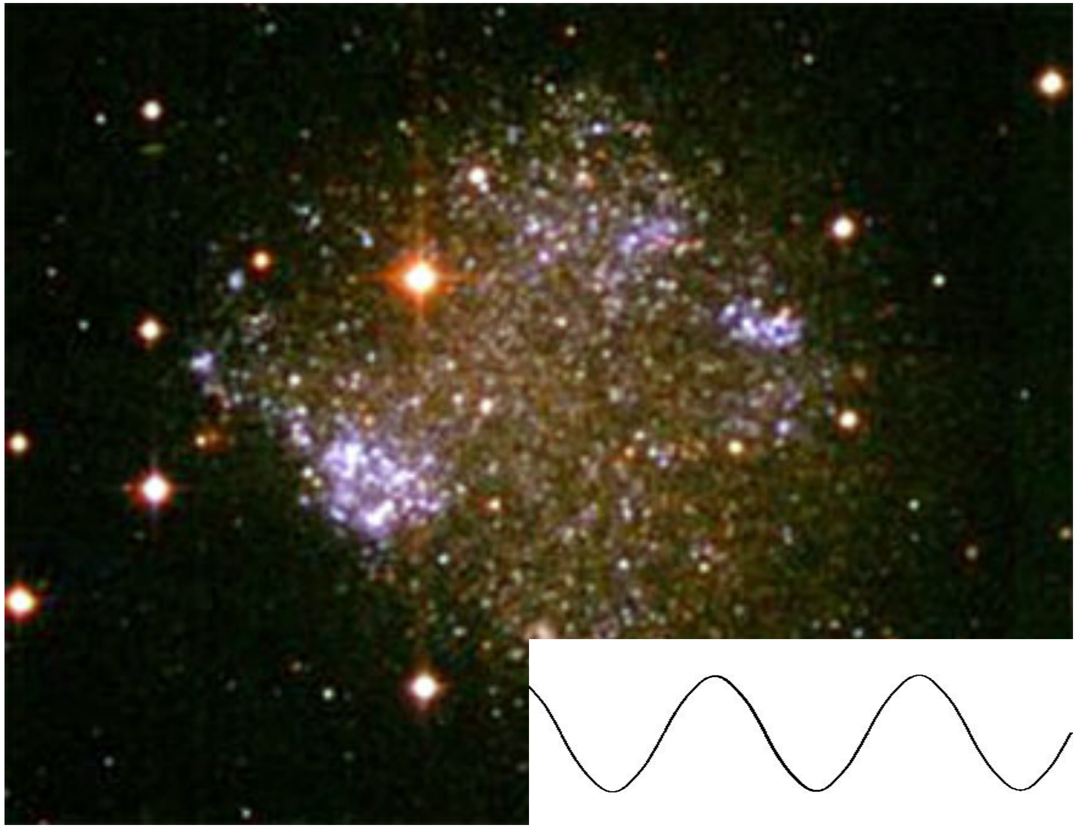
what do we know about m and J?



what do we know about m and J?

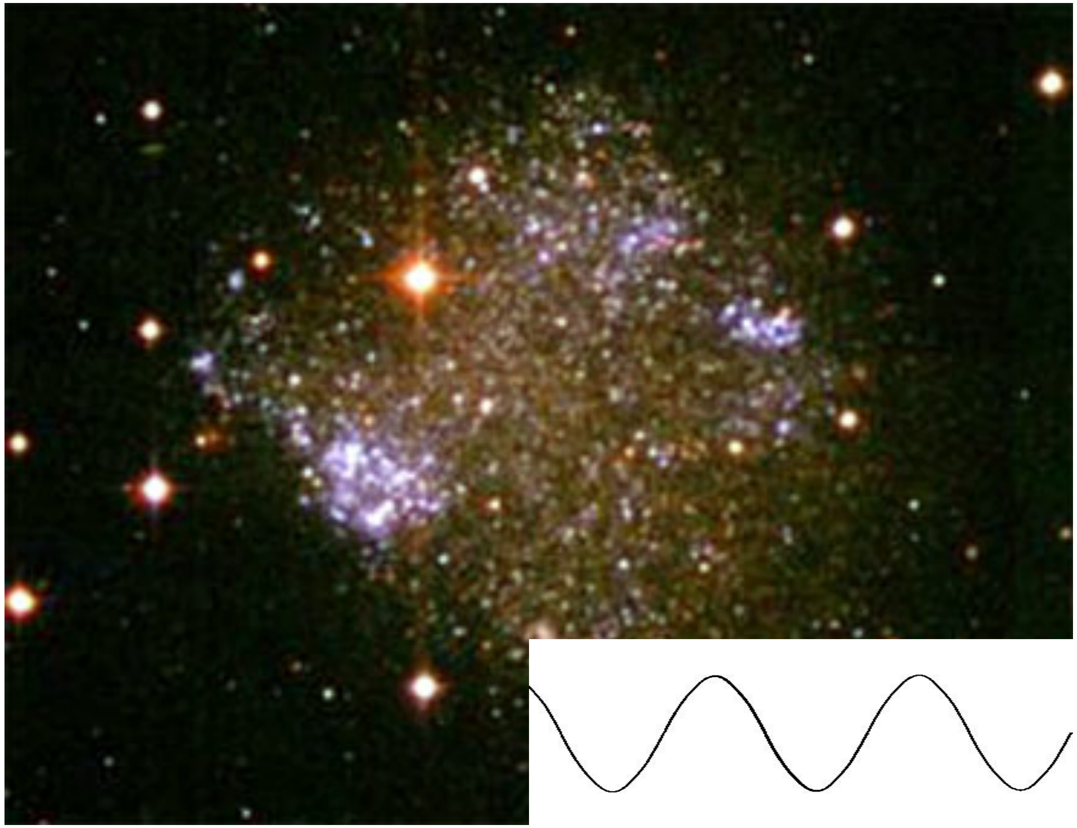


quantum effects must be smaller than halos!



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

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



$m > 10^{-22}$ eV

λ_{DB} = 0.3 cm (1 eV/m) < 3×10^{21} cm

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

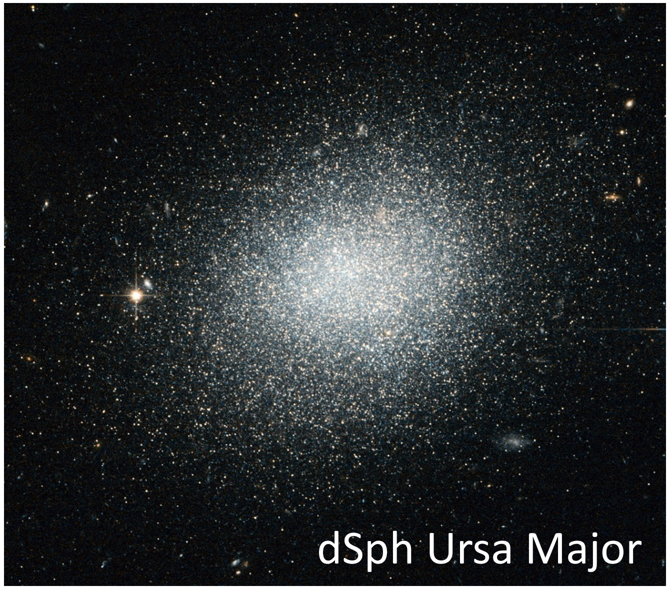
the **phase space** density is bounded (**Pauli** blocking): ***f= gh⁻³***

upper limit: highest observed phase space density: **dSph**!

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

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

Tremaine-Gunn limit (1979)



m>25 eV

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

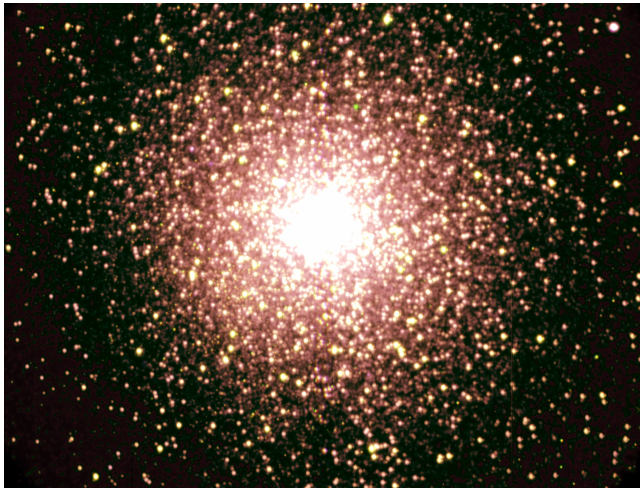
$m > 10^{-22}$ eV $m > 25$ eV

bosons   fermions

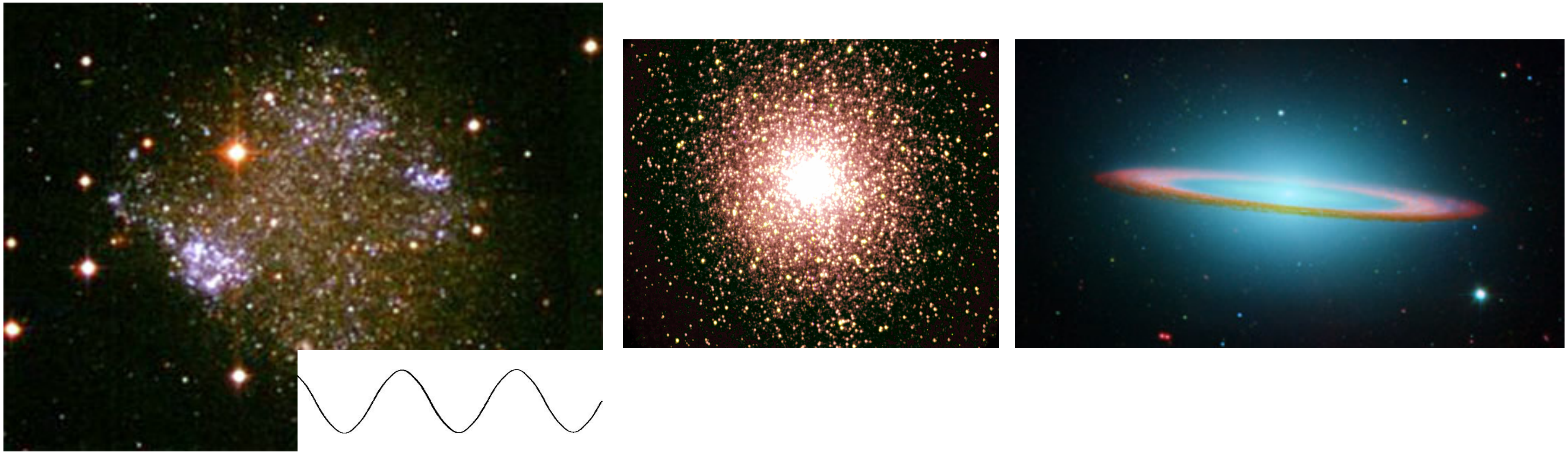
what is the upper limit
to the dark matter mass?

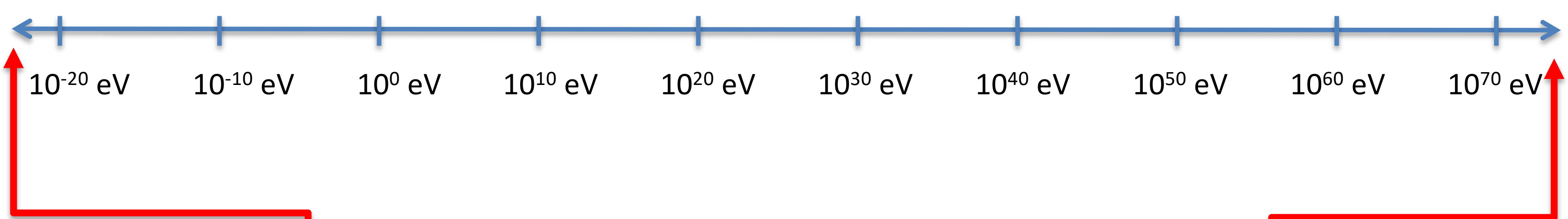
ultramassive DM: beyond M_P…
composite, primordial black holes!

Macroscopic Dark Matter would **tidally disrupt** structure



m < 10 ^{3} **solar masses** ***~ 10^{70} eV***





Macroscopic Quantum Effects

What else do we know about the DM?

Macroscopic Tidal Effects

The Standard Model contains some of the Dark Matter! Neutrinos

What else do we know about the DM?

The Standard Model contains some of the Dark Matter! Neutrinos

$$\Omega_\nu h^2 = \frac{\rho_\nu}{\rho_{\rm crit}} h^2 \simeq \frac{m_\nu}{91.5 \text{ eV}}$$

…we know at least two neutrinos are **massive**

$$\Delta m^2_{\rm sol} = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2 \qquad \Delta m^2_{\rm atm} = (2.44 \pm 0.06) \times 10^{-3} \text{ eV}^2$$

…thus, at a minimum,

$$\Omega_\nu h^2 > \frac{\Delta m_{\rm sun} + \Delta m_{\rm atm}}{91.5 \text{ eV}} \simeq \frac{0.058 \text{ eV}}{91.5 \text{ eV}} \simeq 0.00063$$

$$\frac{\Omega_\nu}{\Omega_{\rm DM}} > 0.53\%$$

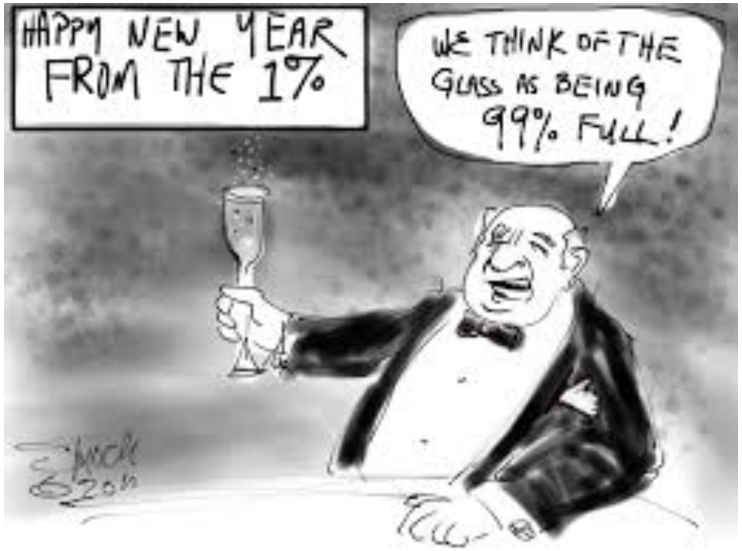
However, **CMB** constrains $\sum_j m_j \lesssim (0.3 - 1.3)\ \mathrm{eV}$

...adding **LSS** data $\sum_j m_j < 0.170\ eV, \quad 95\%\ \mathrm{CL.}$

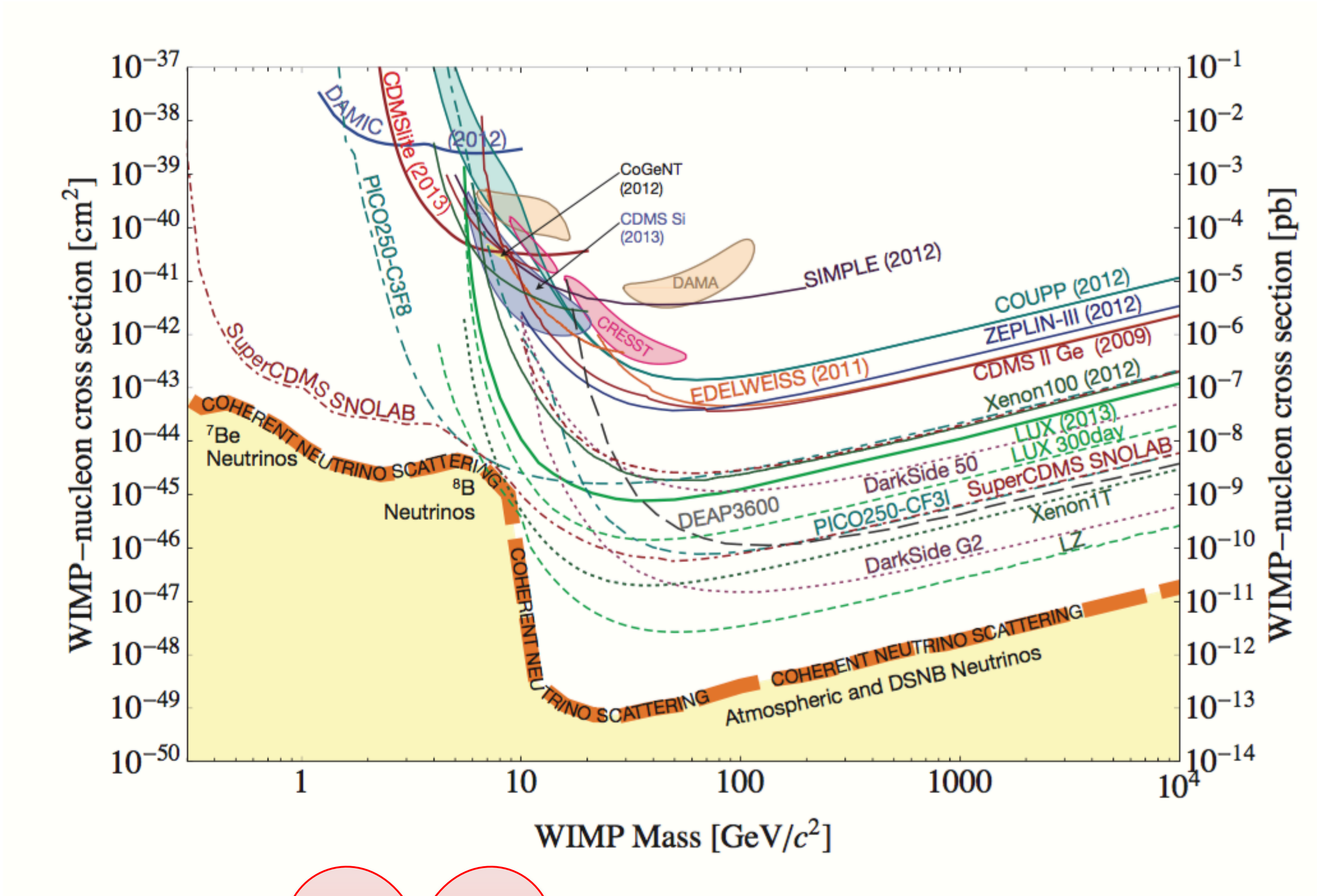
...putting the SM component of **neutrinos** as **DM** at

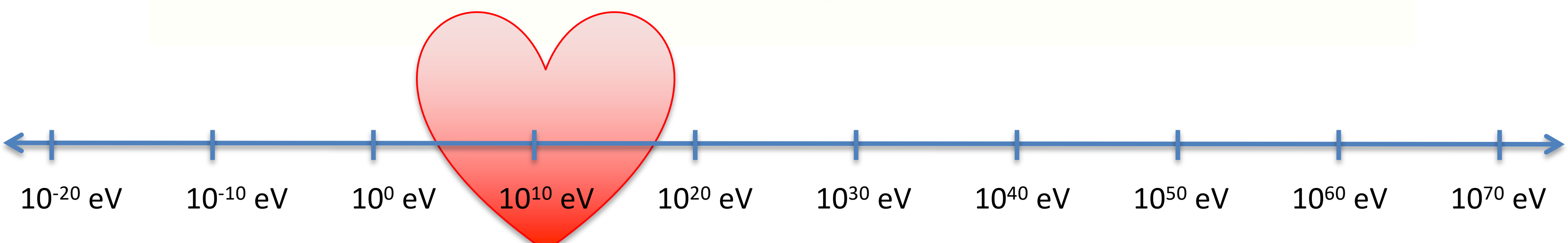
$$\Omega_\nu h^2 < \frac{0.170\ \mathrm{eV}}{91.5\ \mathrm{eV}} \simeq 0.0019$$

$$0.5\% < \frac{\Omega_\nu}{\Omega_{\mathrm{DM}}} < 1.6\%$$



What about the **99%**?


WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]
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
10^4
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
^{7}Be Neutrinos
^{8}B Neutrinos
COHERENT NEUTRINO SCATTERING
Atmospheric and DSNB Neutrinos


10^{-20} eV
10^{-10} eV
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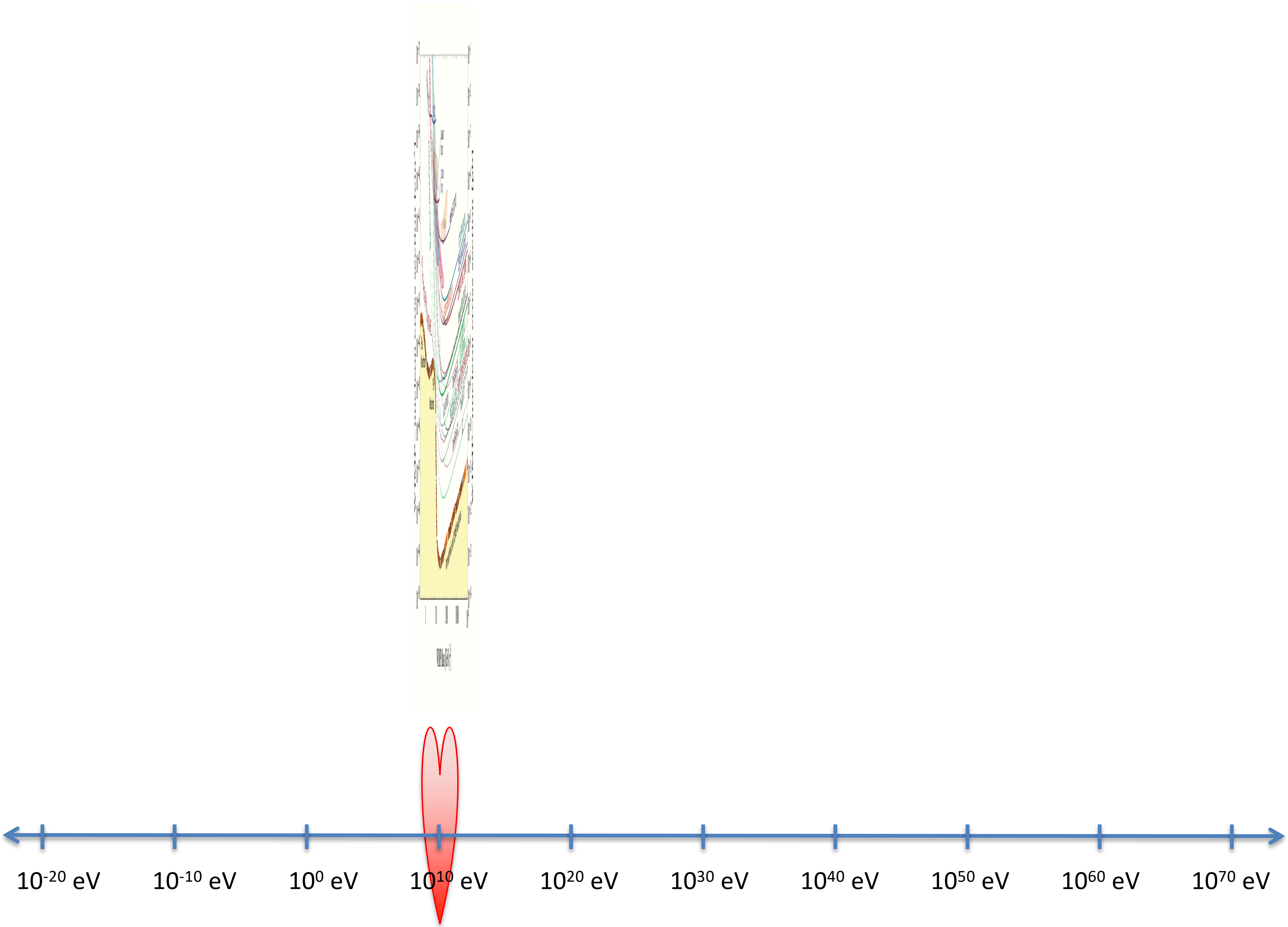
10^{60} eV
10^{70} eV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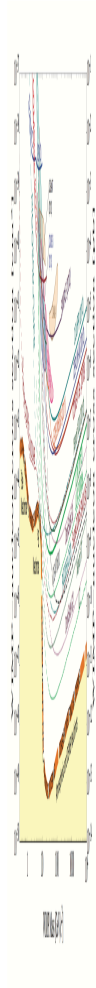
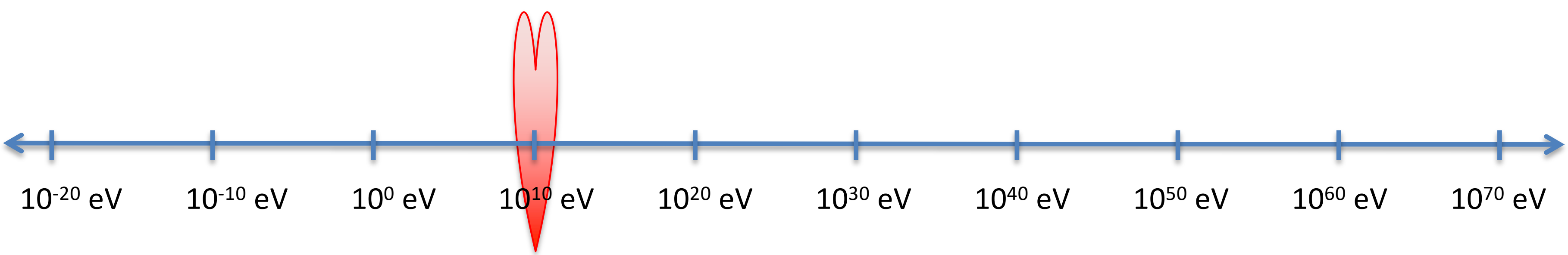
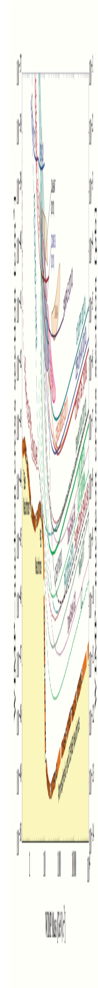


$$\left(\frac{\Omega_\chi}{0.2}\right) \simeq \frac{x_{\mathrm{f.o.}}}{20}\left(\frac{10^{-8}\ \mathrm{GeV}^{-2}}{\sigma}\right)$$

"right" (model-dependent)
combinations
of **masses** and **couplings** populate a much larger "rich **hidden sector**" parameter space

$$\sigma \sim g^4\, m^2_{DM} / m^4_{med}$$





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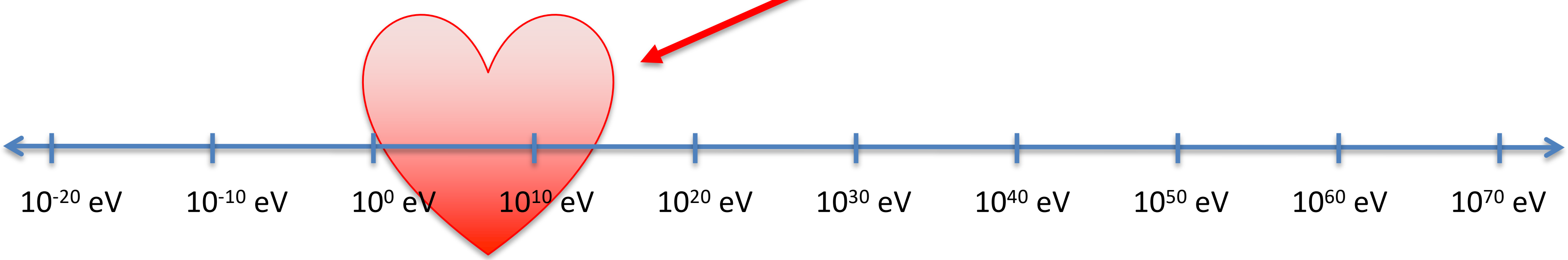

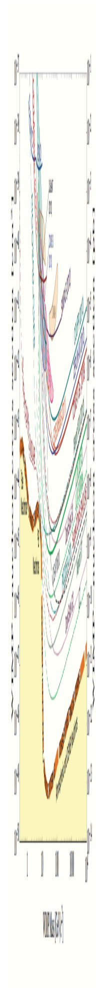

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combinations
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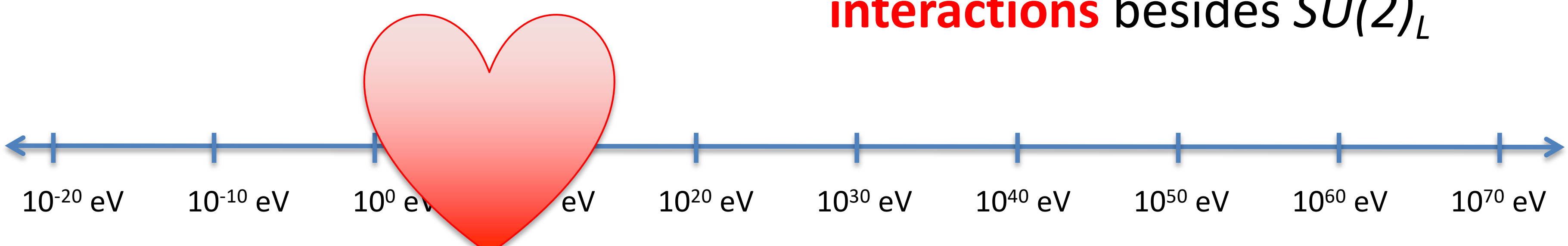
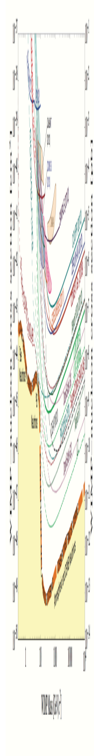
$$\sigma \sim g^4\, m^2_{DM} / m^4_{med}$$

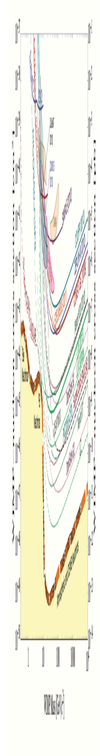
…price: must **invent** new **interactions** besides $SU(2)_L$





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

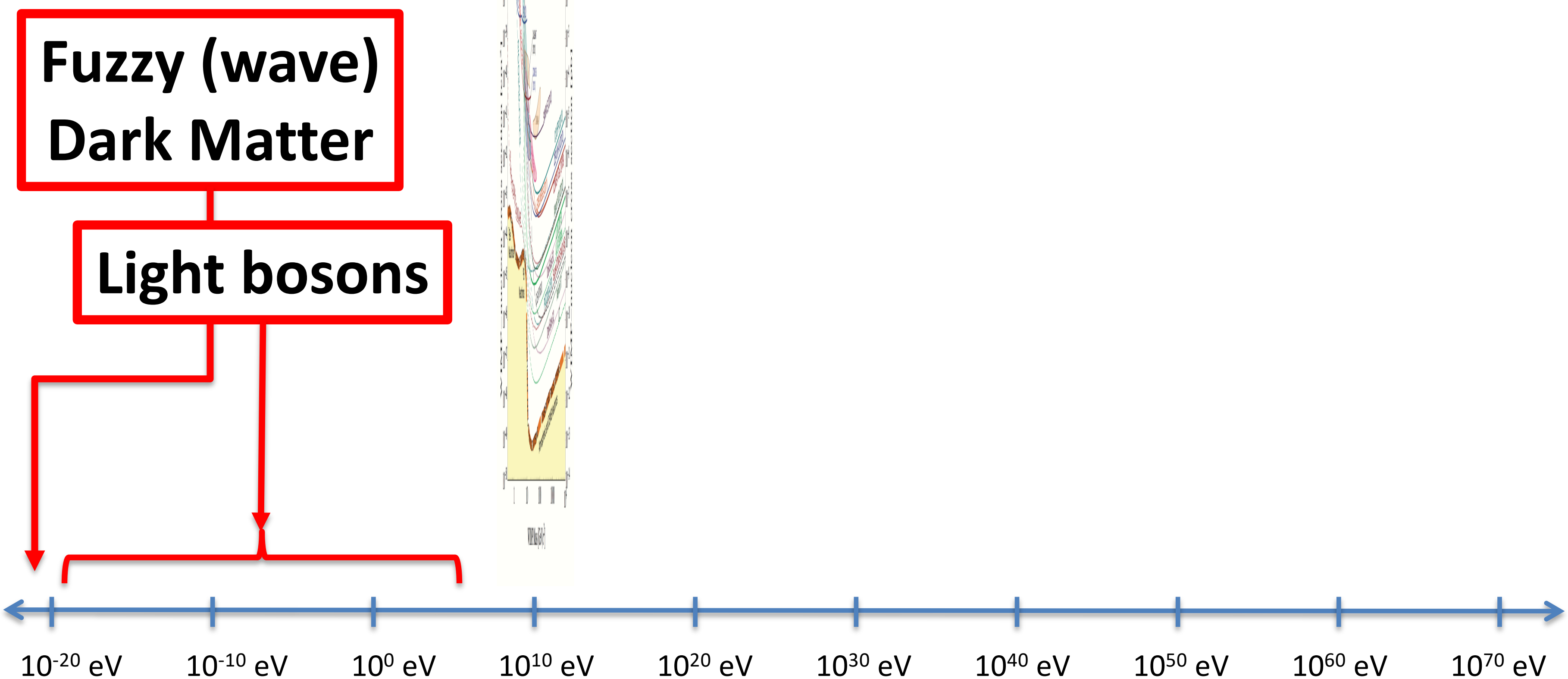
Fuzzy (wave) Dark Matter



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

- **Soliton-like core, of size ~$1/v_{DM}$**
- **Opportunities for new stellar surveys!**
- **Strong constraints from 21 cm line (no solution to small-scale issues)***

* Nebrin et al 2018

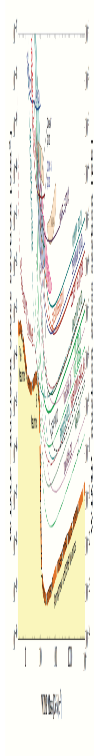


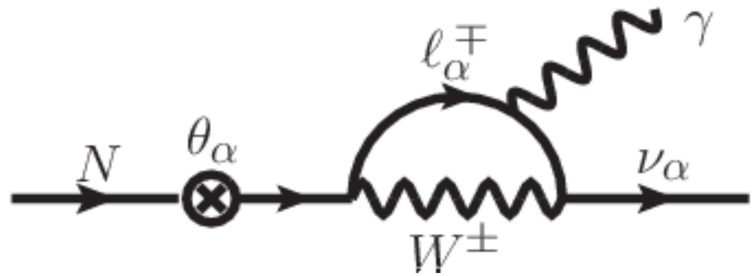
- **Many exciting new ideas!***

* ABRACADABRA, LC resonators, HAYSTAC, MW cavities…

Fuzzy (wave) Dark Matter

Light bosons

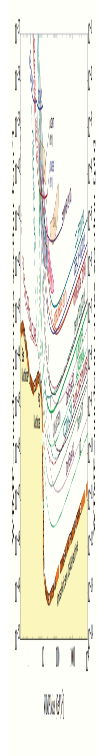




Sterile Neutrinos

- **We (might) need them (ν masses, leptogenesis)**
- **Detectable with X-rays**
- **Detected? (3.5 keV line) No: Draco, XMM Blank Fields!***

* Jeltema + Profumo ’16 MNRAS; Dessert+ ’19 Science



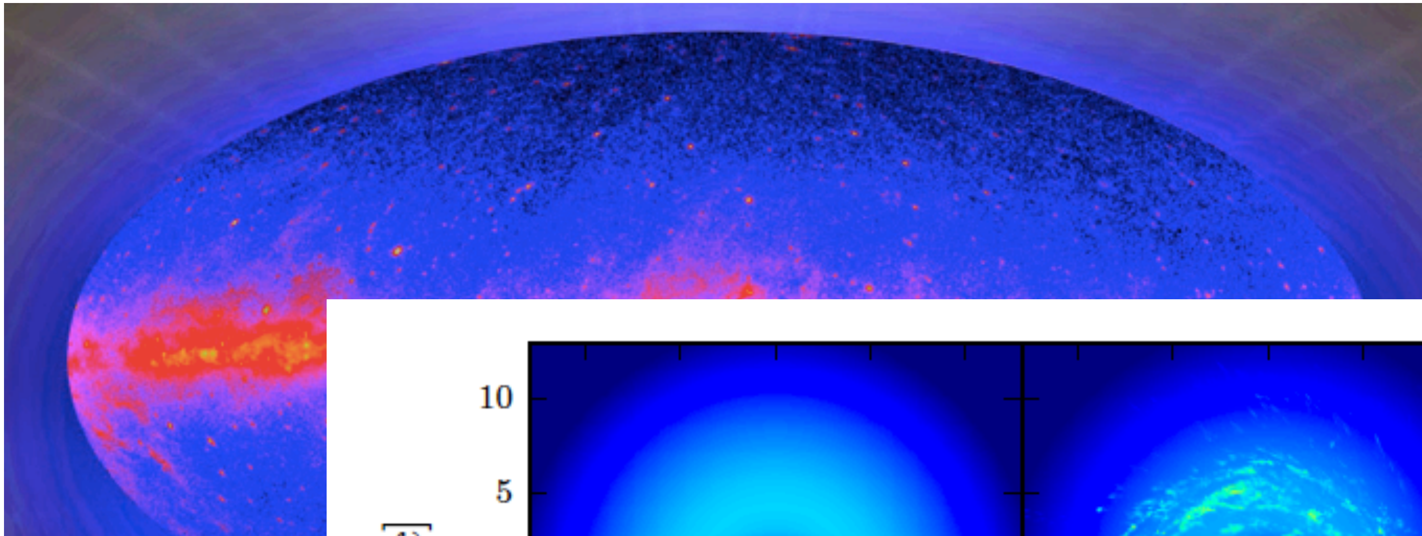
- Common in **BSM** weak-scale
- Very **advanced** direct detection program, **null** results
- Controversial **indirect** signals

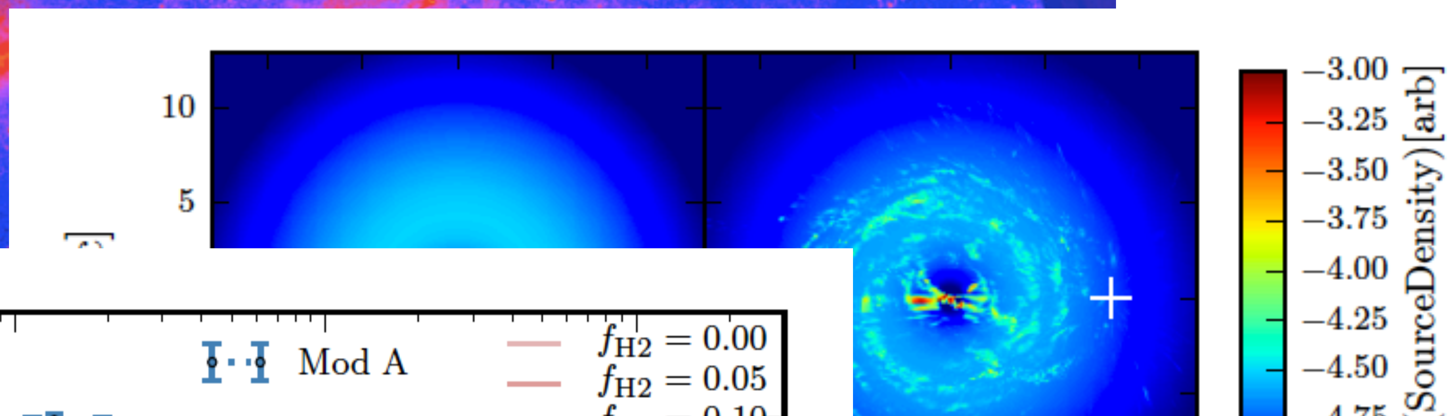
10^{-20} eV | 10^{-10} eV | 10^{0} eV | 10^{10} eV | 10^{20} eV | 10^{30} eV | 10^{40} eV | 10^{50} eV | 10^{60} eV | 10^{70} eV

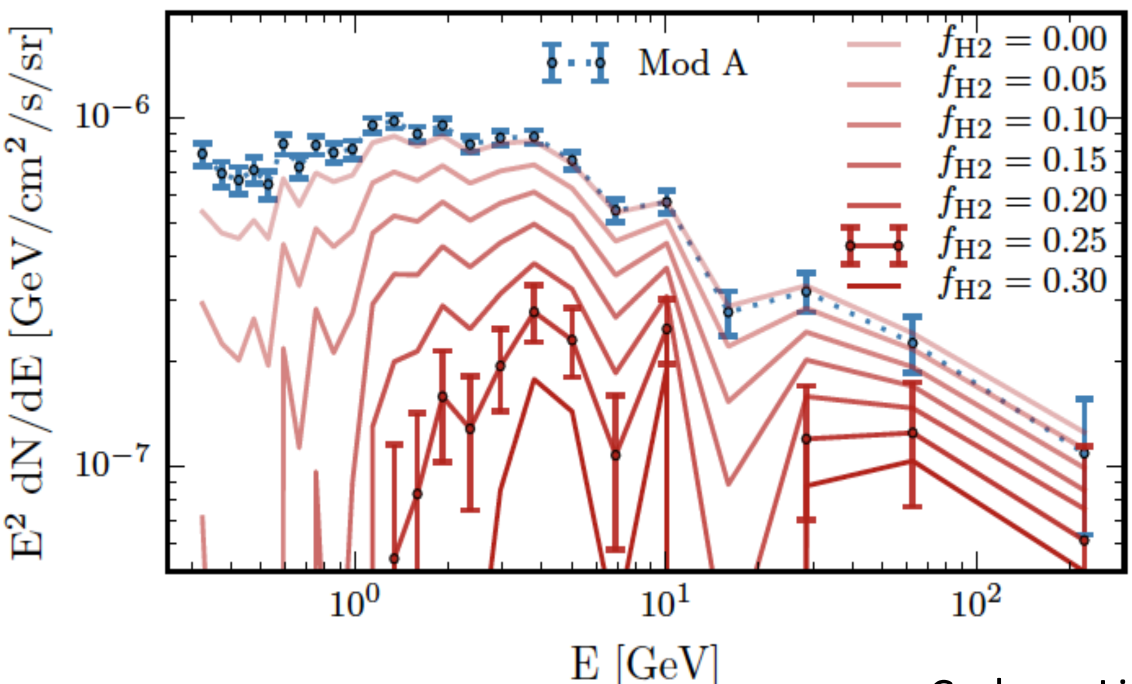
WIMPs

✓ **Galactic Center excess**

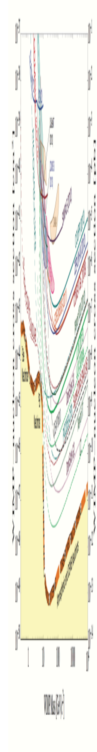
- ☐ Cosmic Ray **sources**
- ☐ Simplistic **Diffusion** Models
- ☐ Unresolved **GR** sources







Carlson, Linden, Profumo PRD, PRL (2016-18)



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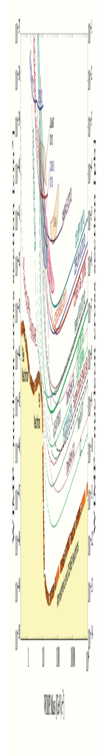
WIMPs

- ✓ **Galactic Center** excess
- ✓ other gamma-ray **excesses** (M31, M31 outer halo, Omega-Cen,…)



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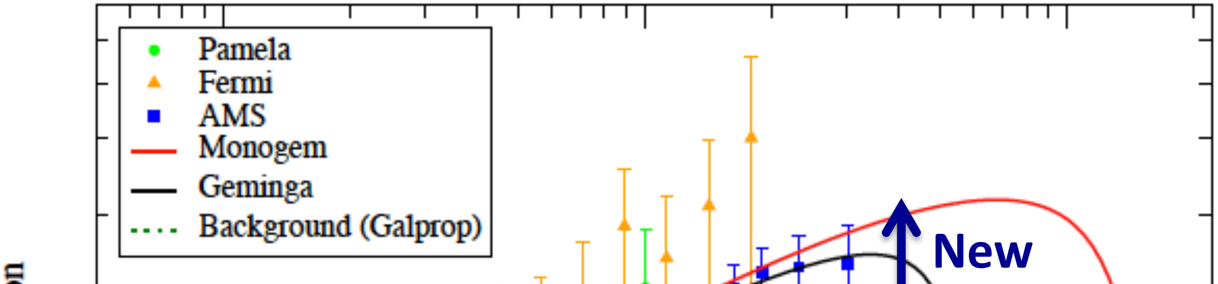
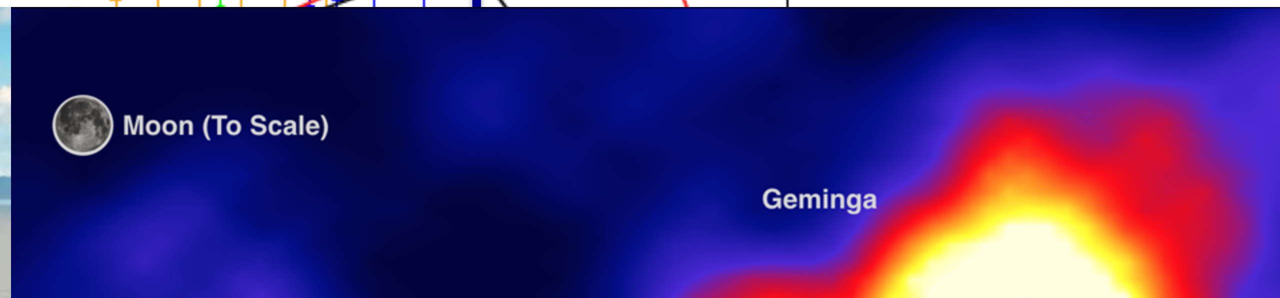
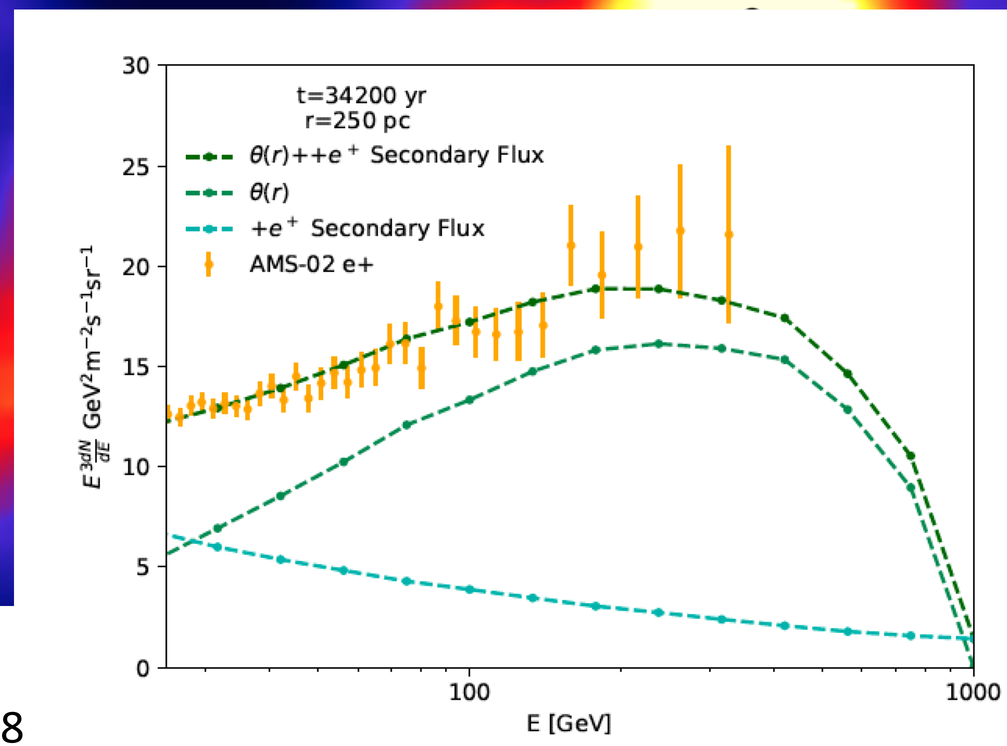
WIMPs

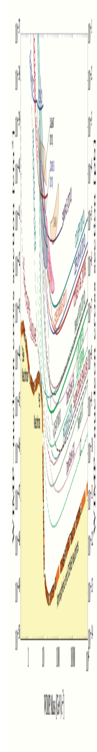
- ✓ **Galactic Center** excess
- ✓ other gamma-ray **excesses**
- ✓ **Positron** excess







Linden + Profumo 2013; Profumo et al 2018



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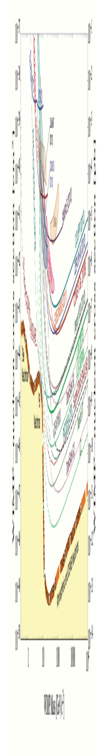
WIMPs

- ✓ **Galactic Center** excess
- ✓ other gamma-ray **excesses**
- ✓ **Positron** excess
- ✓ **Antiproton** excess



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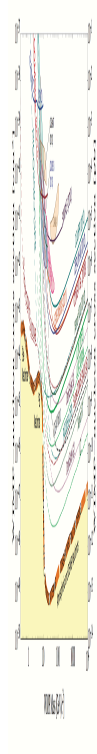
10^{-20} eV 10^{-10} eV 10^{0} eV 10^{10} eV 10^{20} eV 10^{30} eV 10^{40} eV 10^{50} eV 10^{60} eV 10^{70} eV

WIMPs

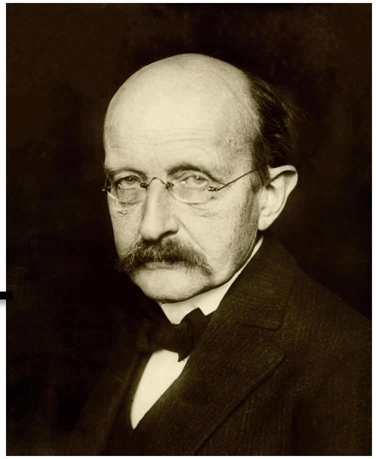
- ✓ **Galactic Center** excess
- ✓ other gamma-ray **excesses**
- ✓ **Positron** excess
- ✓ **Antiproton** excess
- ✓ ^{3}**He** events



- Non-thermally produced
- Could be **charged** $U(1)_{EM}$, SU(3)…
- If so, could be **detectable**

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

WIMPzillas



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

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

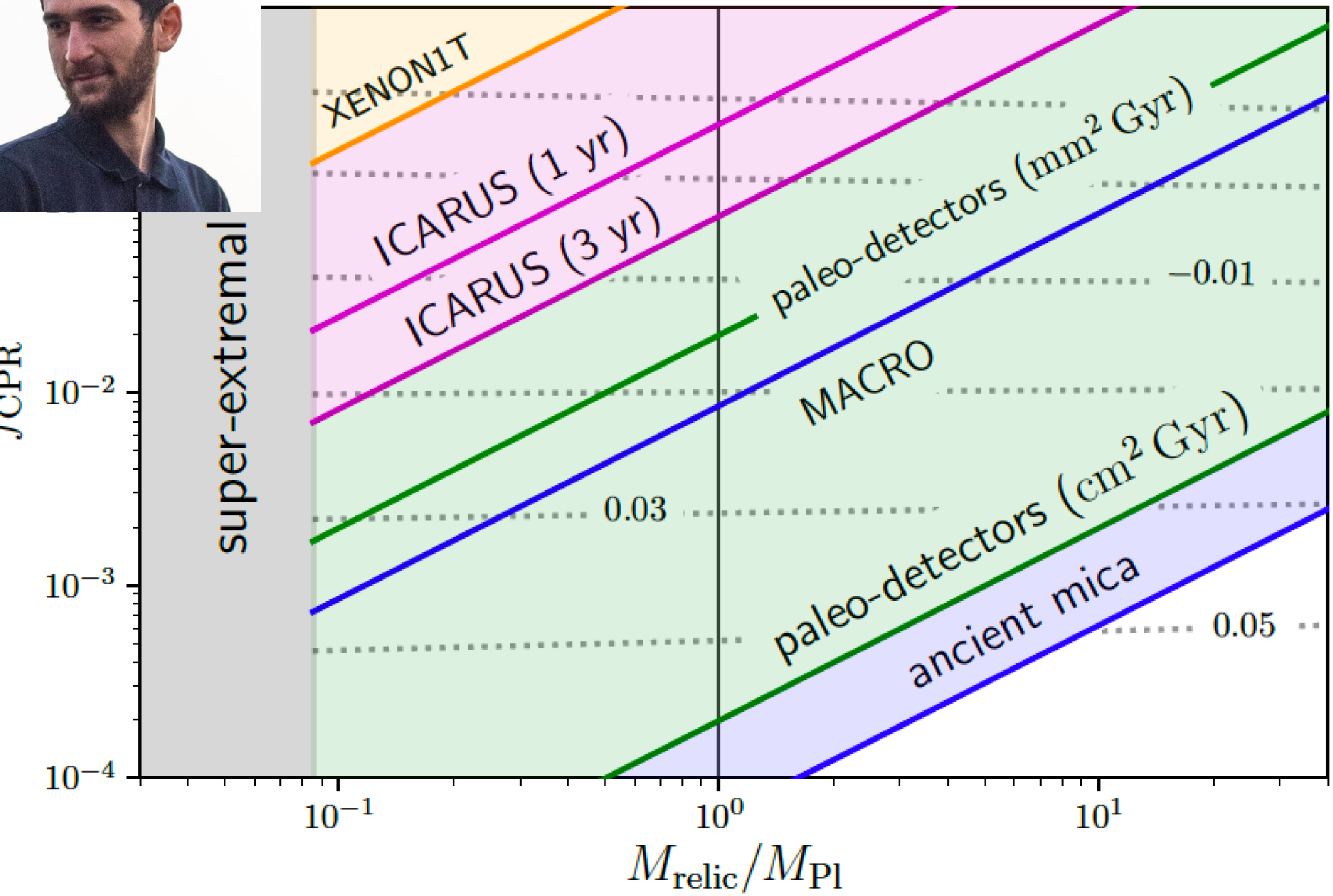
$$P(Q) \sim \exp\left(-4\pi\alpha(Q/e)^2\right)$$

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

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 (JCAP)

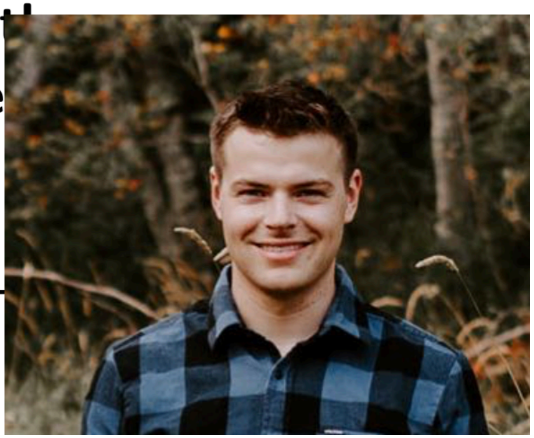


*** Lehmann, Johnson, Profumo and Schwemberger, 1906.06348**

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

tro-ph.CO] 27 Dec 2018

Melanopogenesis: Dark Matter of (almost) any Mass and Baryonic Matter from t[…] Evaporation of Primordial Black Hole[…] weighing a Ton (or less)



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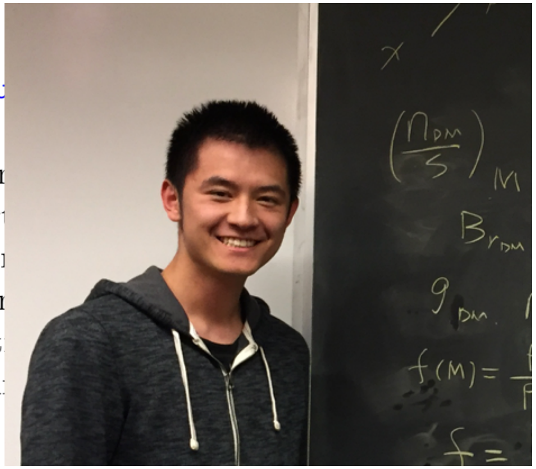
E-mail: loanmorr@ucsc.edu, profumo@ucsc.edu, yanyu@ucsc.edu

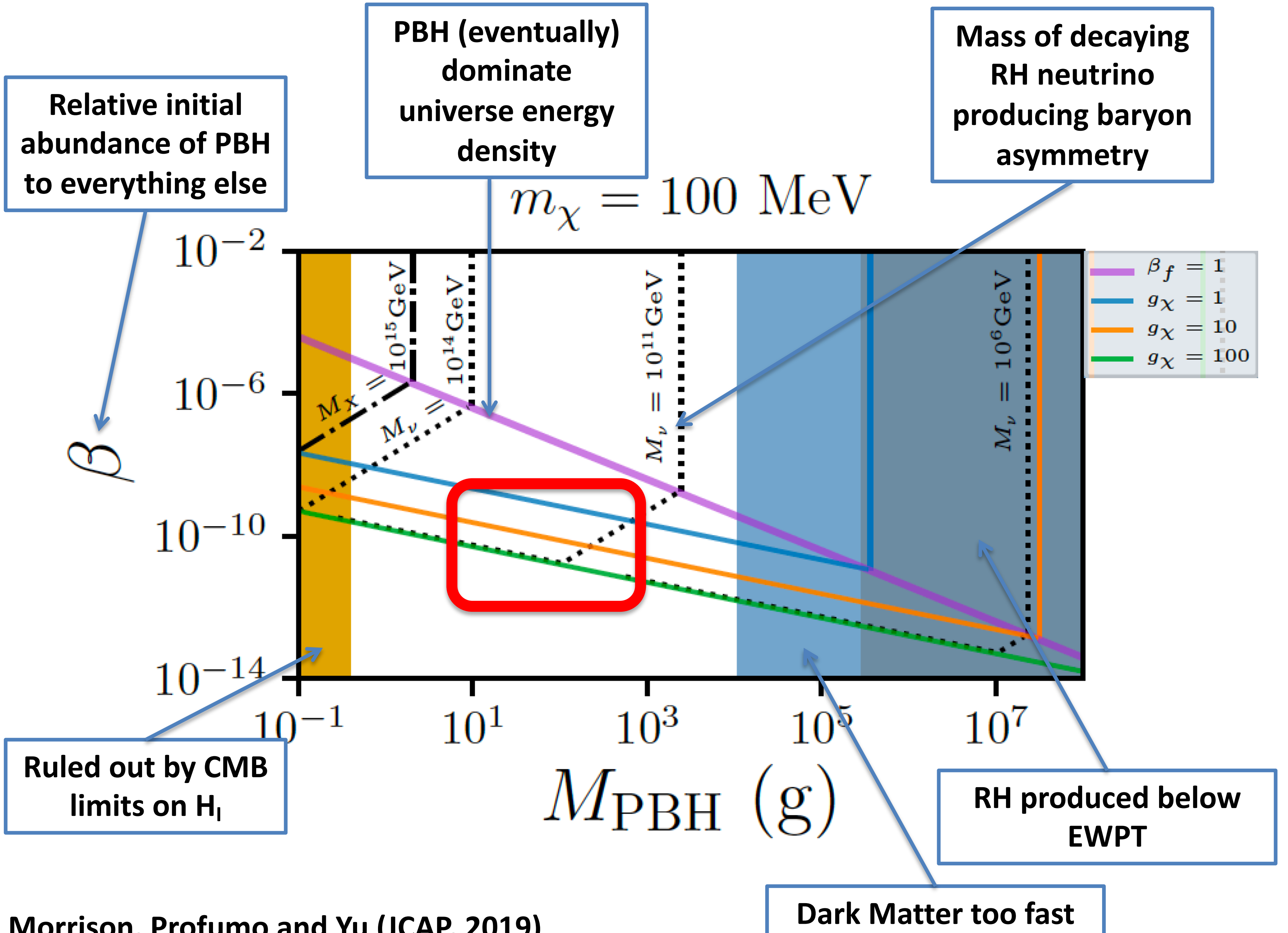


ABSTRACT: The evaporation of primordial black holes with a mass i[…] $M_{\rm PBH} \lesssim$1000 kg range can lead to the production of dark matter par[…] any mass in the range 0.1 MeV $\lesssim m_{\rm DM} \lesssim 10^{18}$ GeV with the right […] very early times, $\tau \lesssim 10^{-10}$ s. We calculate, as a function of the p[…] holes mass and initial abundance, the combination of dark matter part[…] number of effective dark degrees of freedom leading to the right abu[…]

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

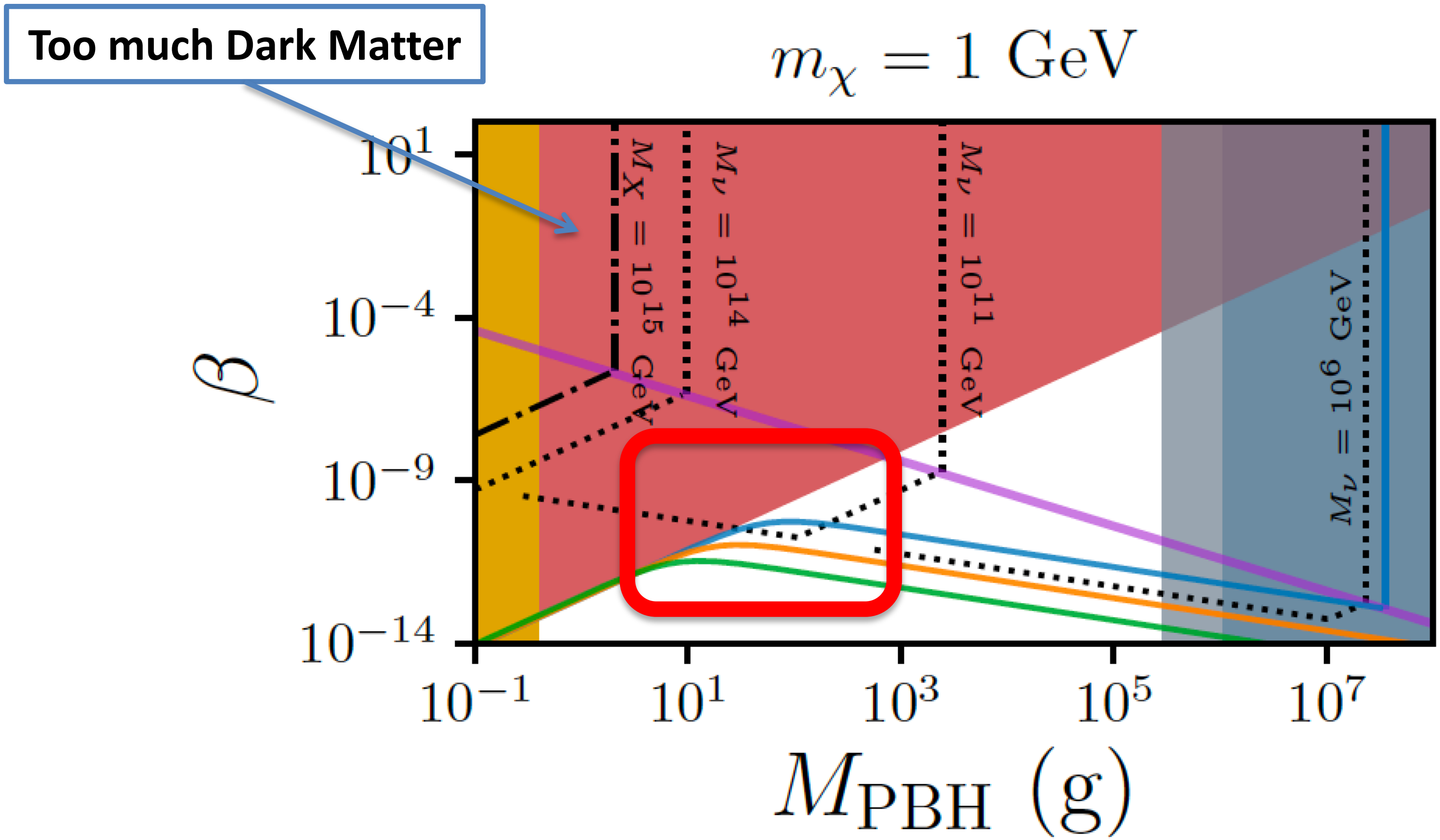
Mass (g)	T_H (GeV)	τ (s)	$T_{\rm evap} = T(\tau)$ (GeV)
$5M_P \simeq 10^{-4}$	1.7×10^{17}	10^{-41}	2×10^{17}
1	1.7×10^{13}	4×10^{-29}	2×10^{11}
10^3	1.7×10^{10}	4×10^{-20}	6×10^6
10^6	1.7×10^7	4×10^{-11}	200
10^9	1.7×10^4	0.04	0.006
10^{12}	17	$4 \times 10^7 \sim 1$ yr	~ 1 keV

*** Morrison, Profumo and Yu (JCAP, 2019)**

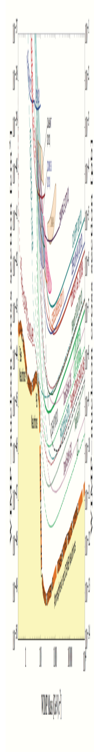


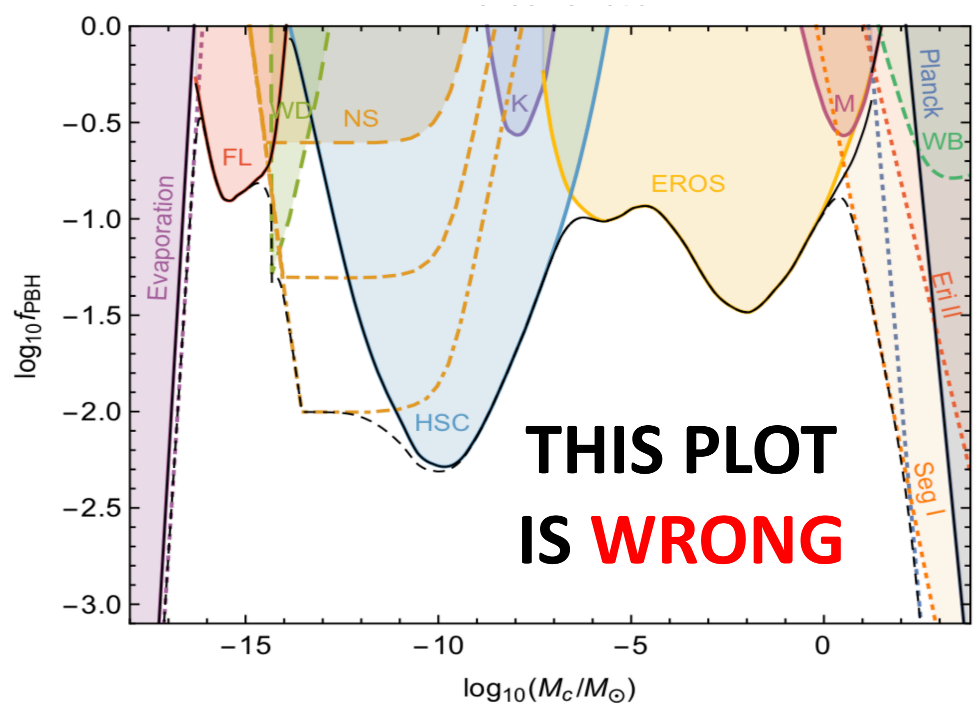
* Morrison, Profumo and Yu (JCAP, 2019)

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

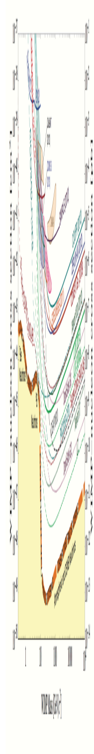


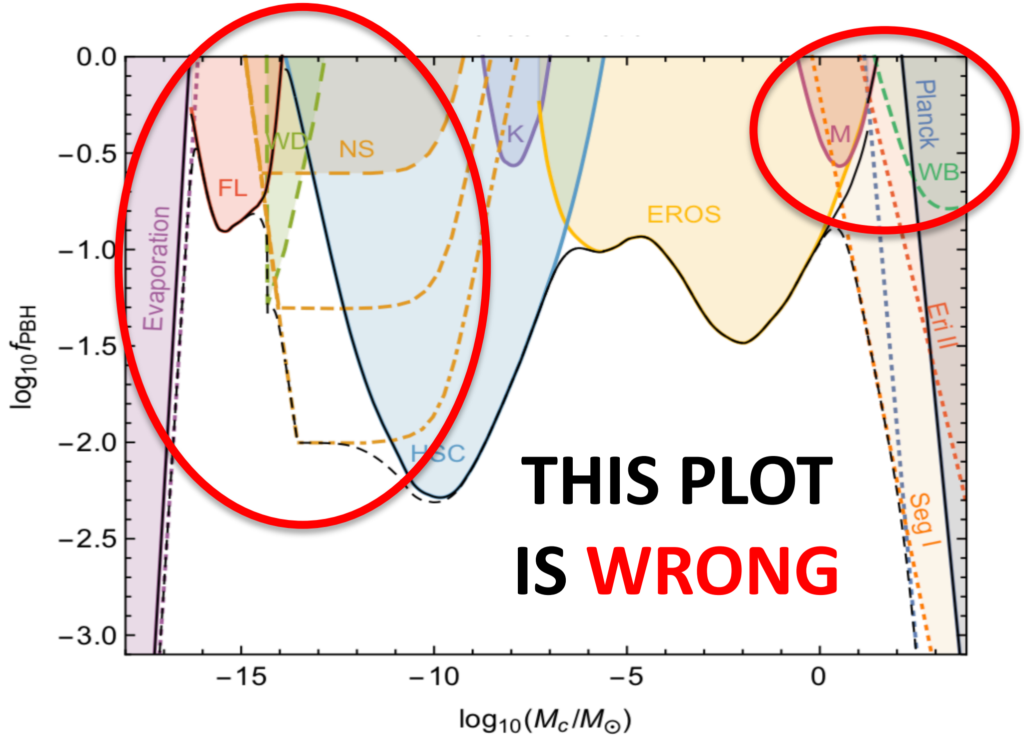
* Morrison, Profumo and Yu (JCAP, 2019)

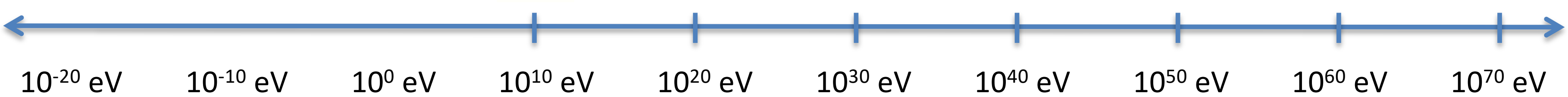




10^{-20} eV 10^{-10} eV 10^{0} eV 10^{10} eV 10^{20} eV 10^{30} eV 10^{40} eV 10^{50} eV 10^{60} eV 10^{70} eV

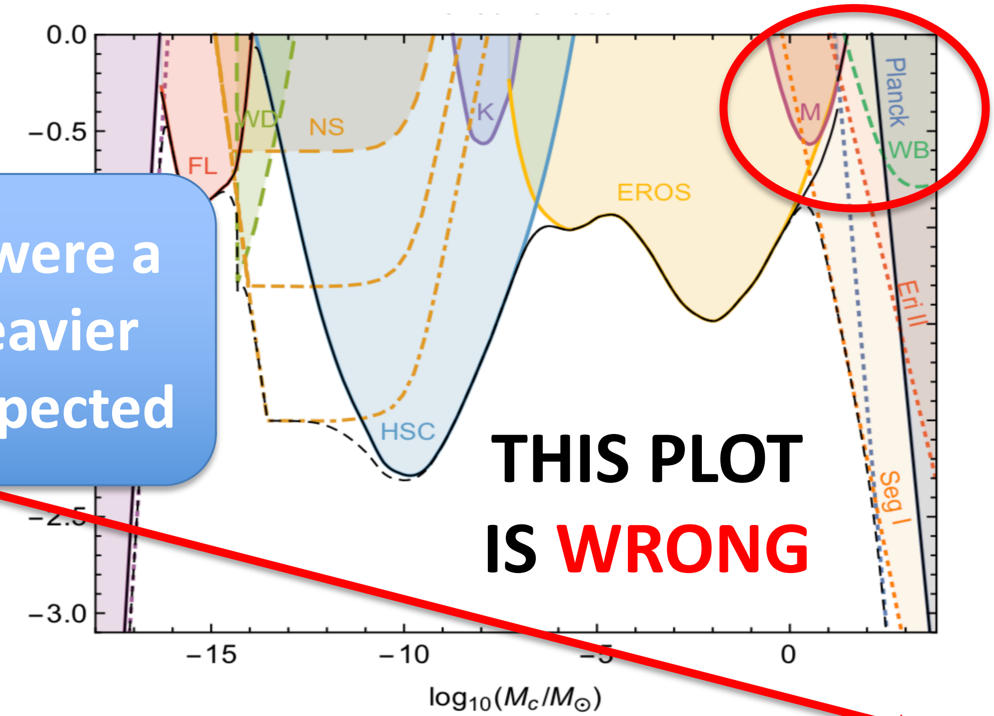



0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
$\log_{10} f_{PBH}$
−15
−10
−5
0
$\log_{10}(M_c/M_\odot)$
Evaporation
FL
WD
NS
K
EROS
HSC
M
Planck
WB
Eri II
Seg I
THIS PLOT
IS WRONG


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

The BH were a little heavier than I expected



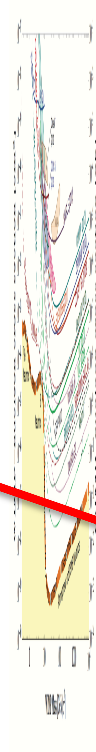
THIS PLOT IS WRONG

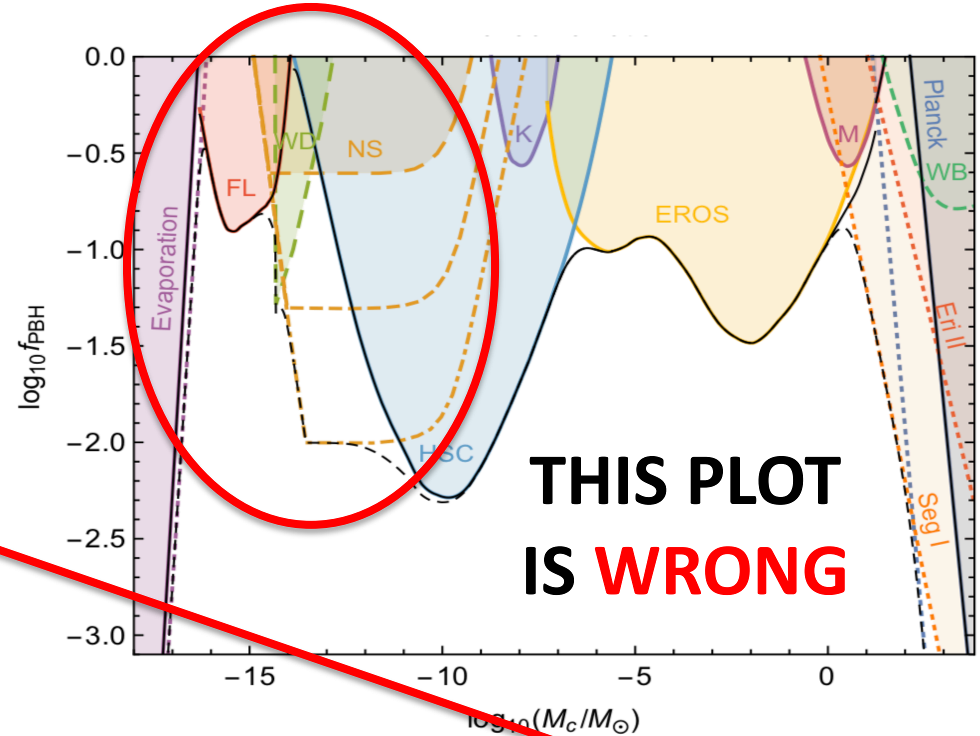
10^{-20} eV — 10^{-10} eV — 10^{0} eV — 10^{10} eV — 10^{20} eV — 10^{30} eV — 10^{40} eV — 10^{50} eV — 10^{60} eV — 10^{70} eV

- ✓ **How does accretion work?** (1)
- ✓ **Spins look a lot like PBH!** (2)
- ✓ **…or maybe they are low because of super-radiance?** (3)
- ✓ **Catch a sub-Chandrasekhar mass BH!** (4)

(1) SP+Lehmann (2) SP+Fernandez (3) SP+Fernandez+Ghalsasy (4) SP+Lehmann

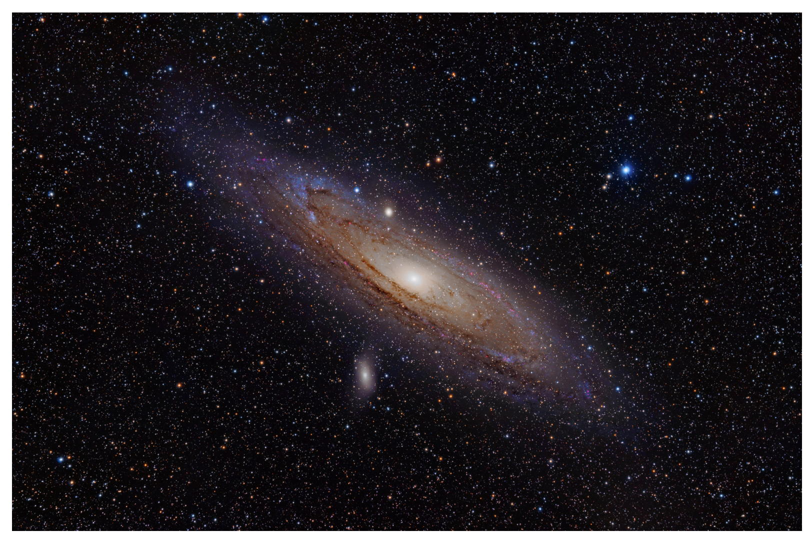
“Asteroid-Mass” (10^{22} g) Black Holes



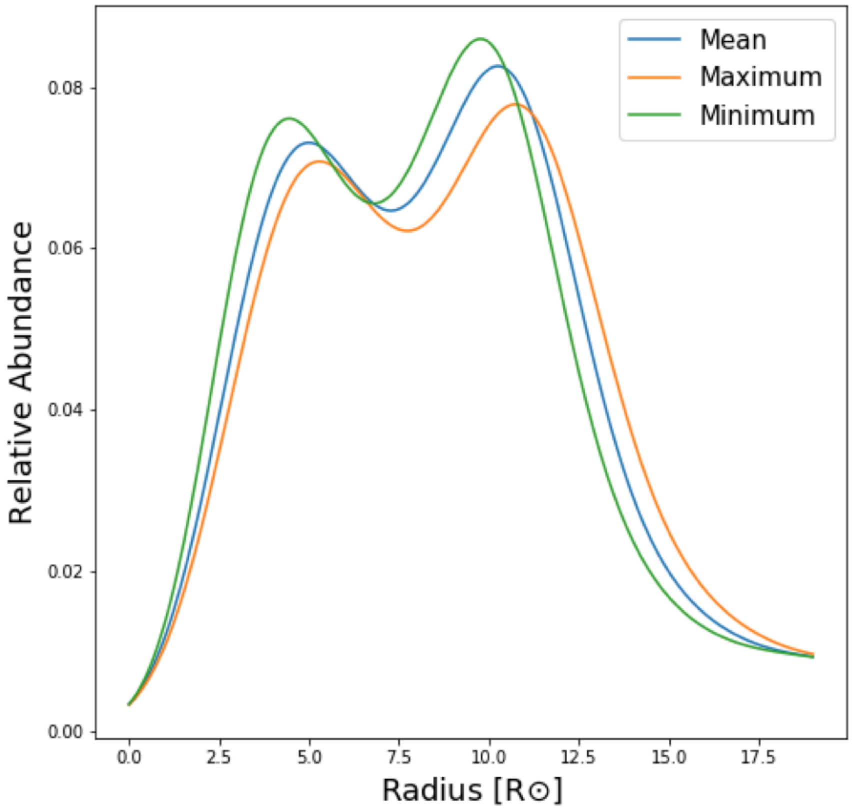


10^{-20} eV 10^{-10} eV 10^{0} eV 10^{10} eV 10^{20} eV 10^{30} eV 10^{40} eV 10^{50} eV 10^{60} eV 10^{70} eV

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



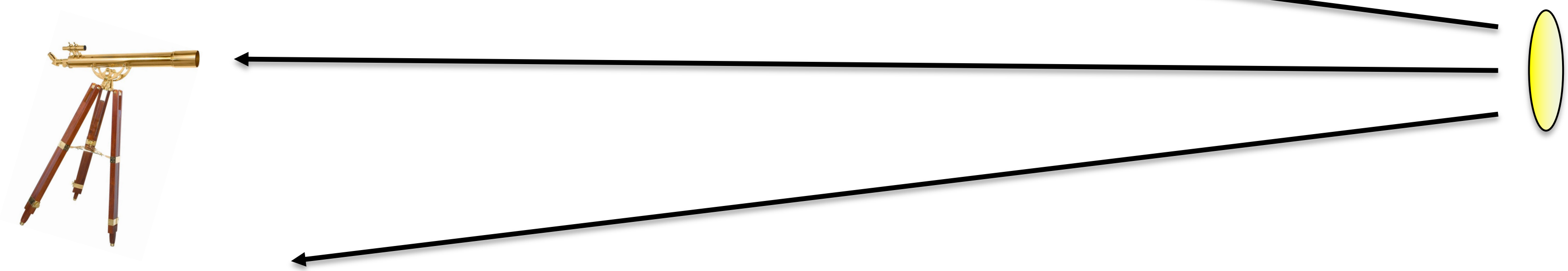
Sun-like stars are however too dim for HSC!



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

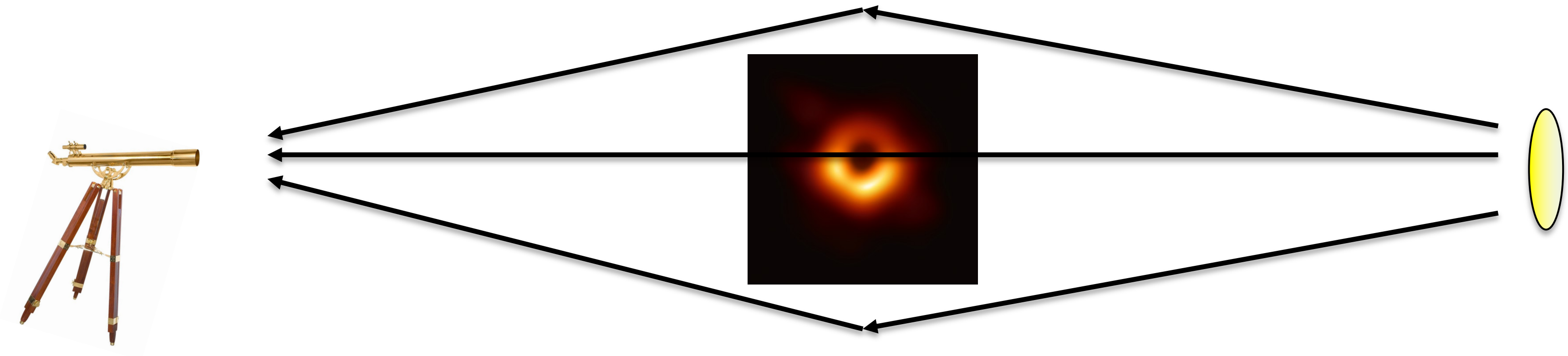
* Profumo, Smyth+ PRD 2020

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



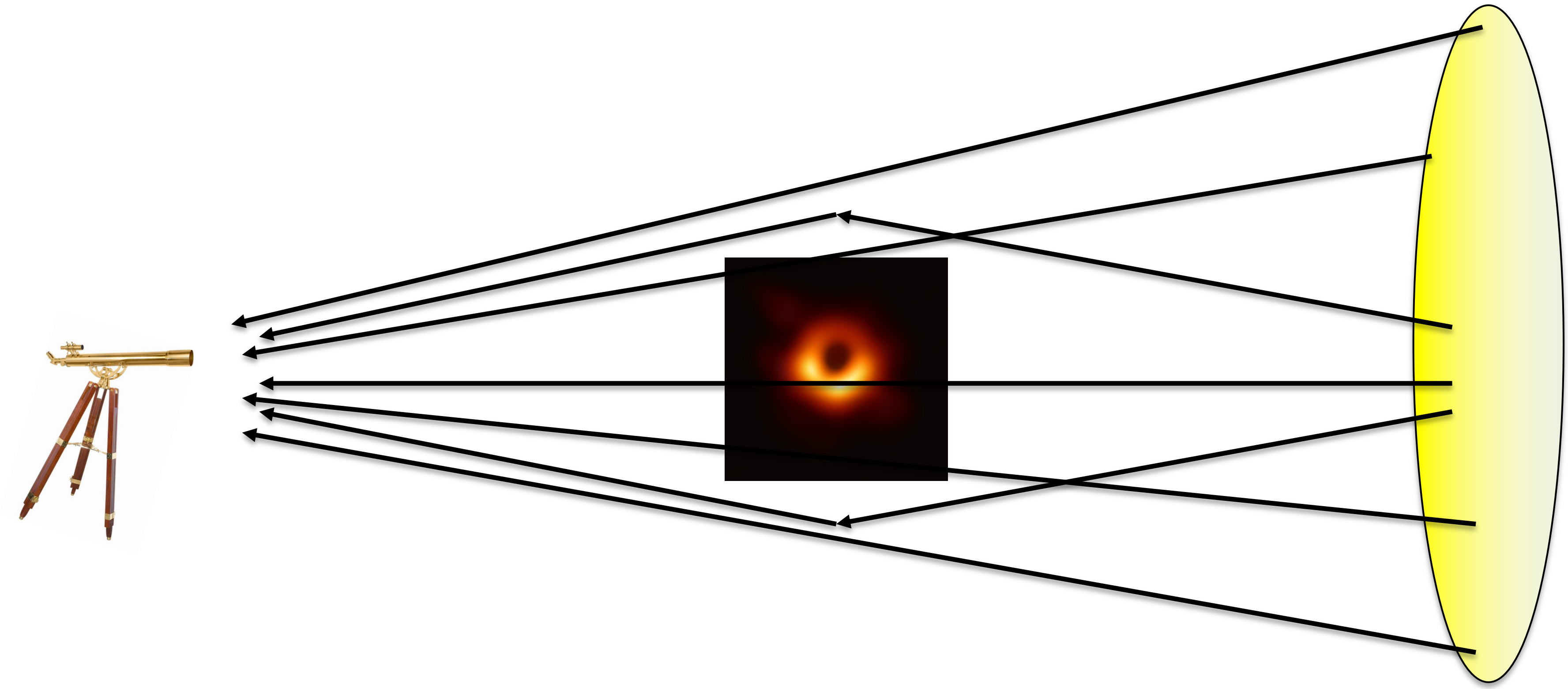
* Profumo, Smyth+ PRD 2020

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



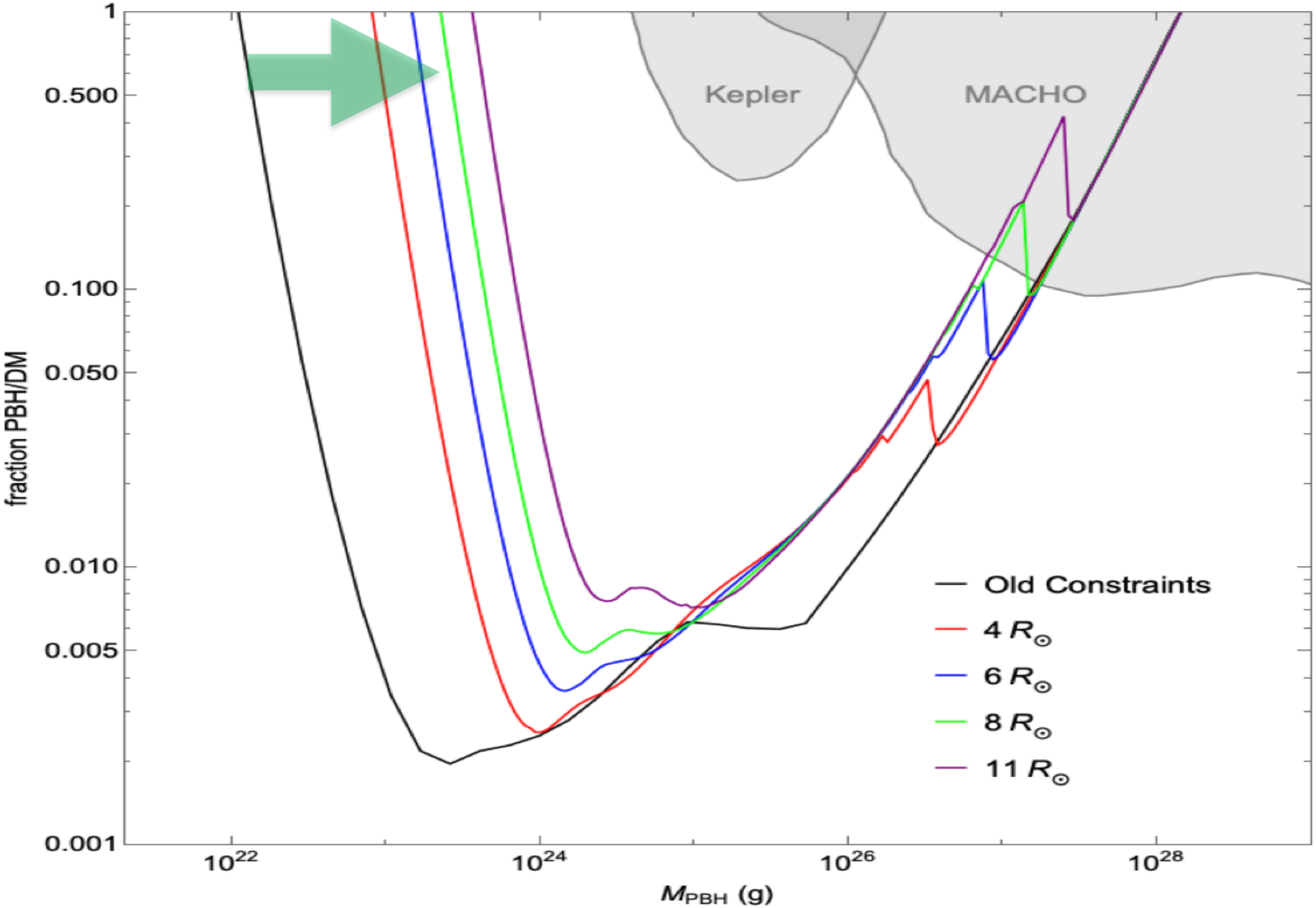
* Profumo, Smyth+ PRD 2020

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

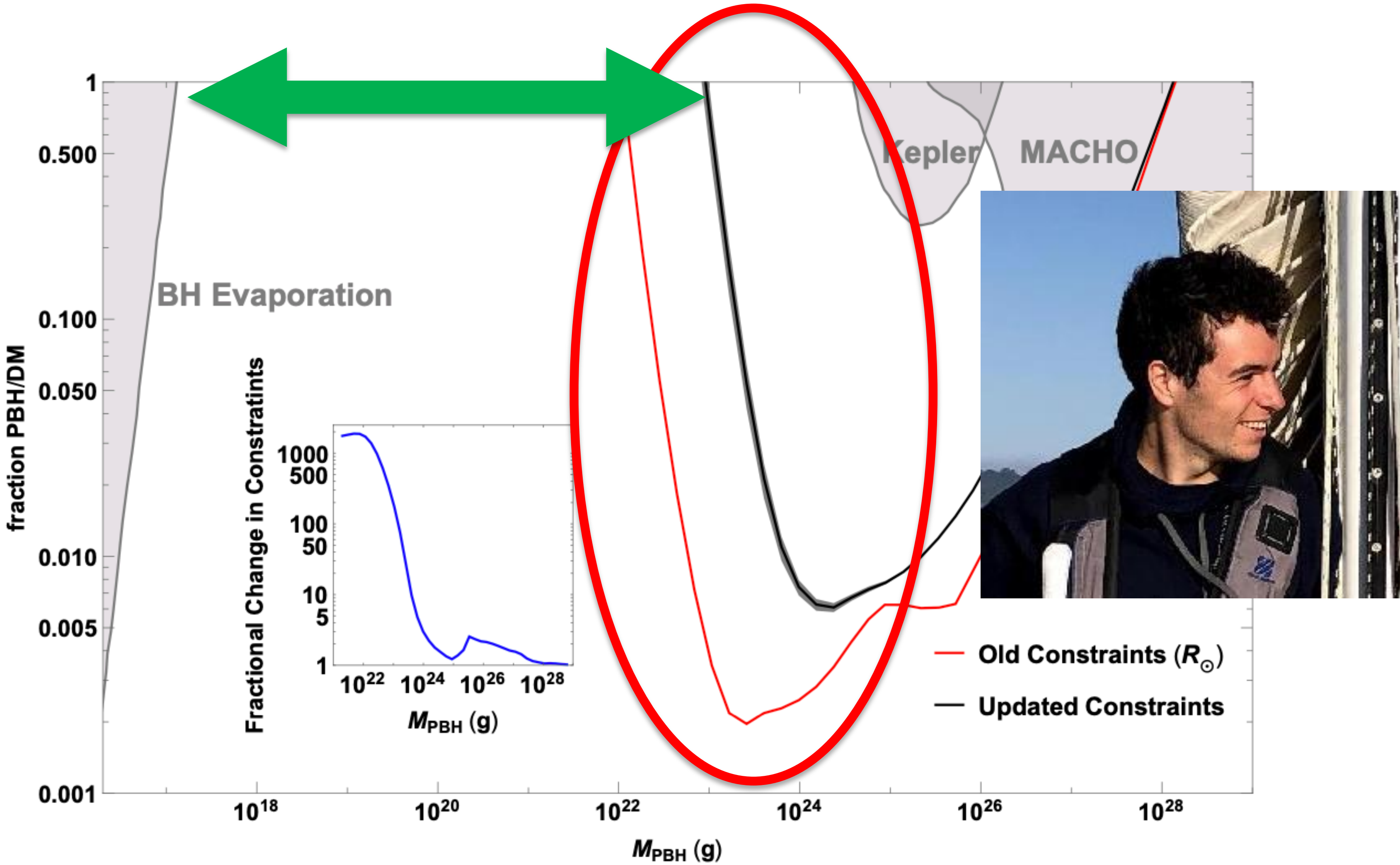


* Profumo, Smyth+ PRD 2020

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



* Profumo, Smyth+ PRD 2020



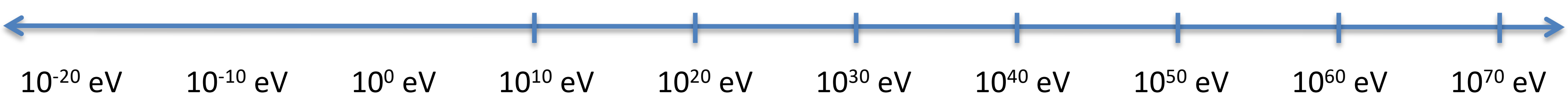
How do we go after them? Capture and perturbation around PSR?

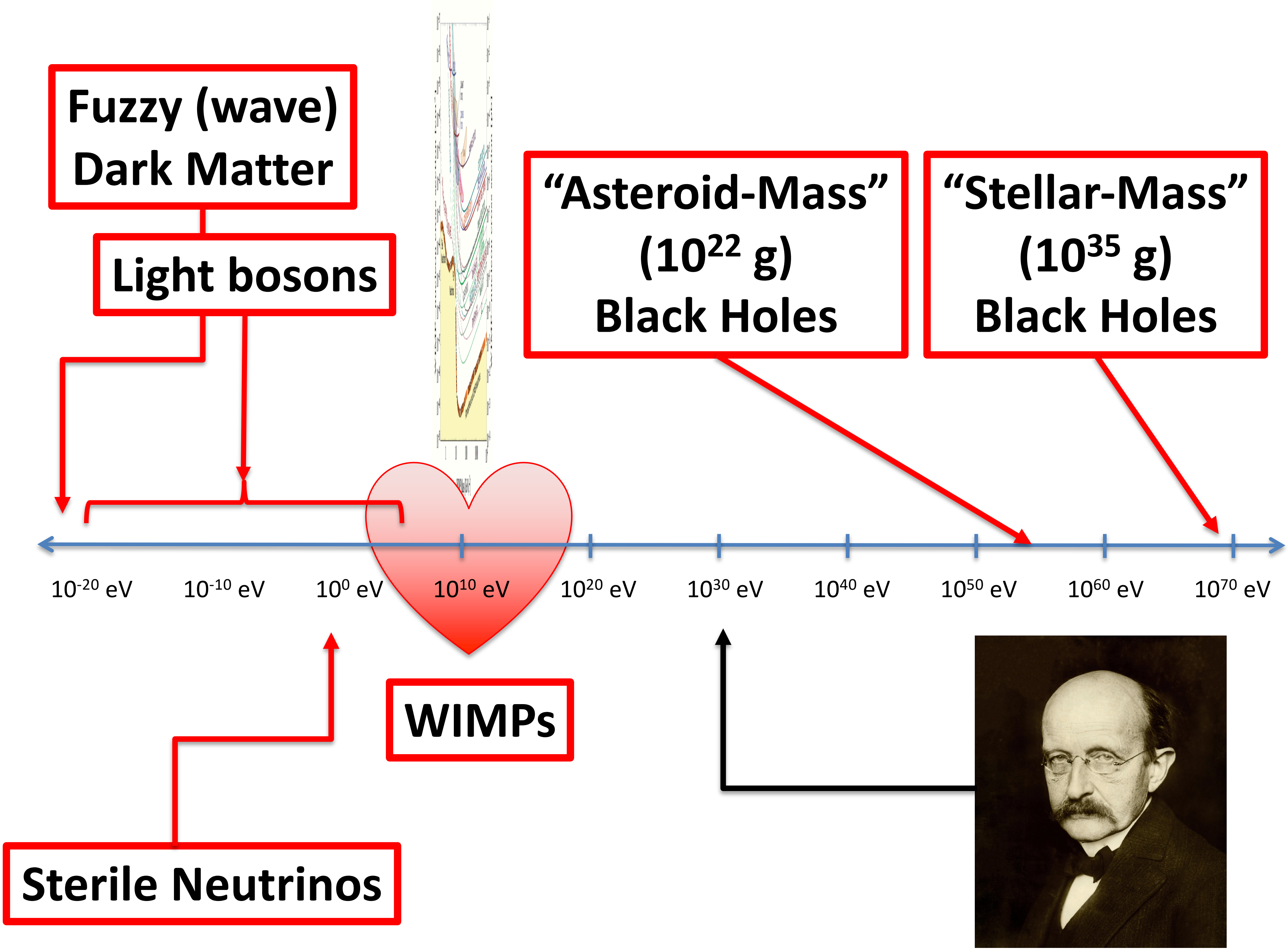
* Profumo, Smyth+ PRD 2020

✓We **know** what **0.5%** to **1.5%** of the Dark Matter is:

Standard Model Neutrinos!

✓…also, Dark Matter is neither **squirrels** nor **mosquitos**





Fuzzy (wave) Dark Matter
Light bosons
"Asteroid-Mass" (10^{22} g) Black Holes
"Stellar-Mass" (10^{35} g) Black Holes
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
WIMPs
Sterile Neutrinos