Stefano Profumo

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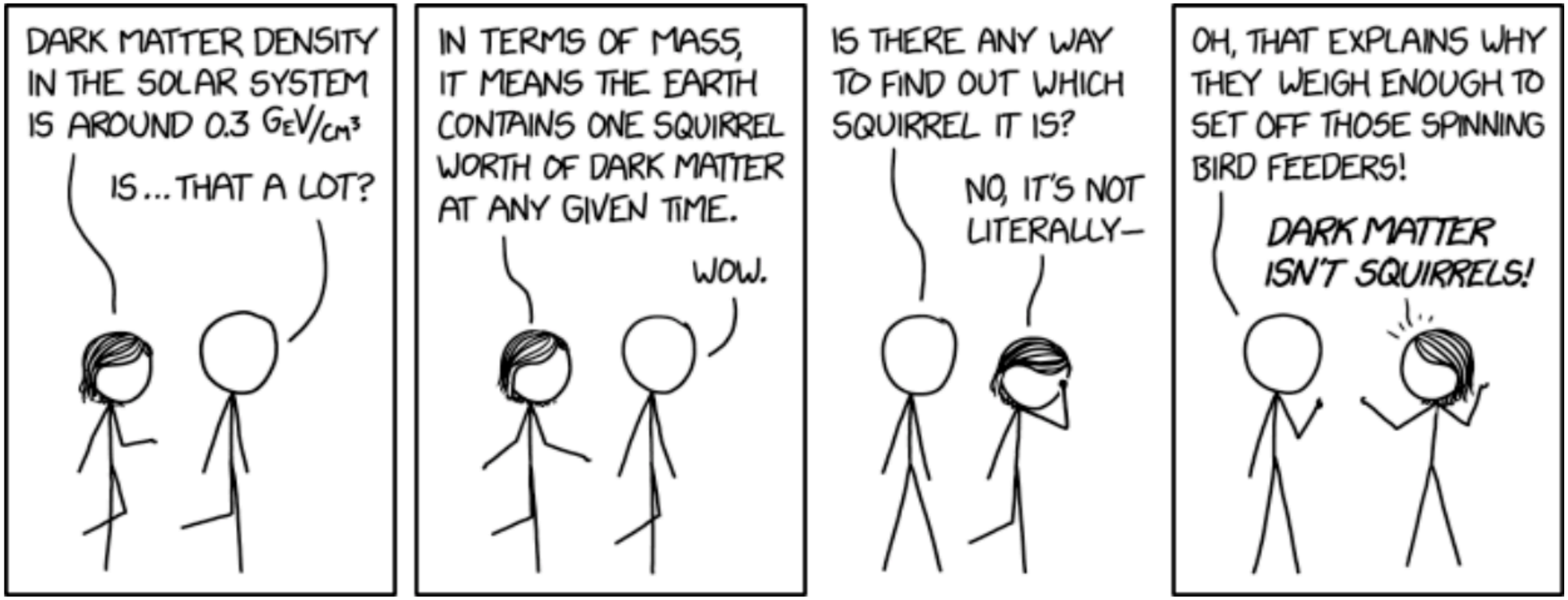
University of California, Santa Cruz

What is the Dark Matter?



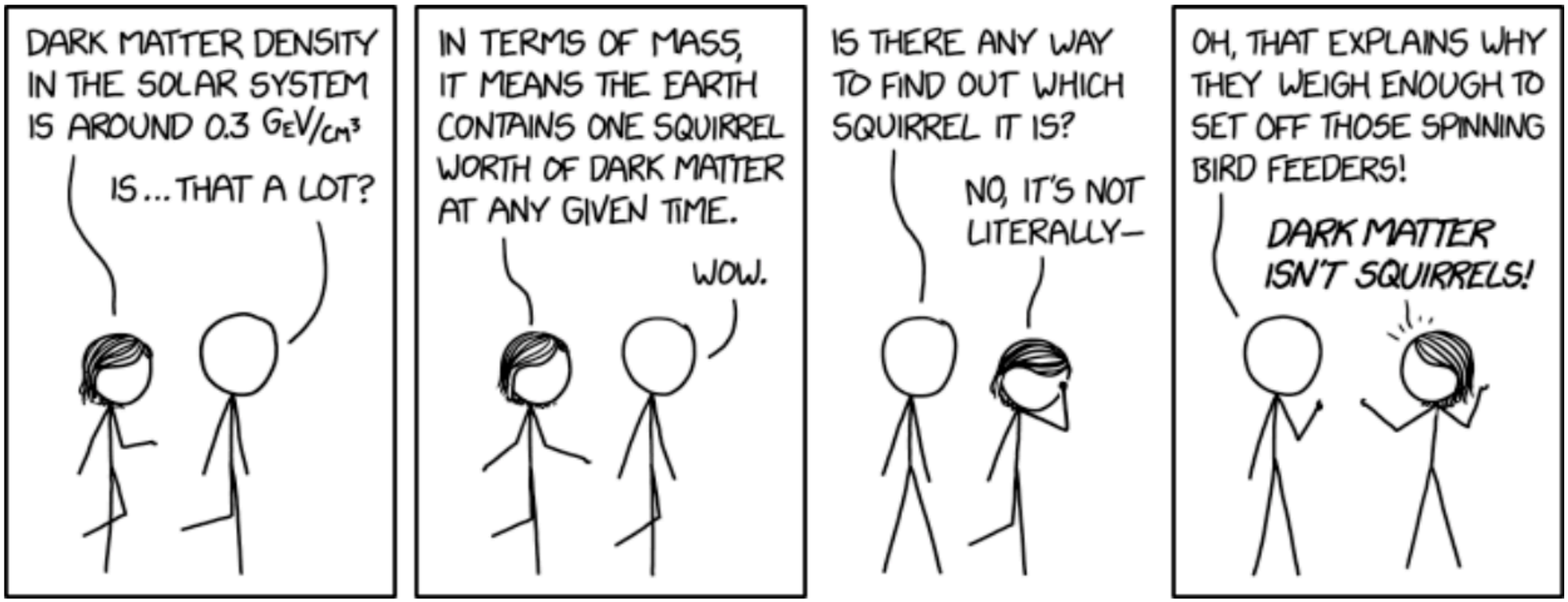
COFI Seminar

Wednsday April 8, 2020

* Credit: xqcd

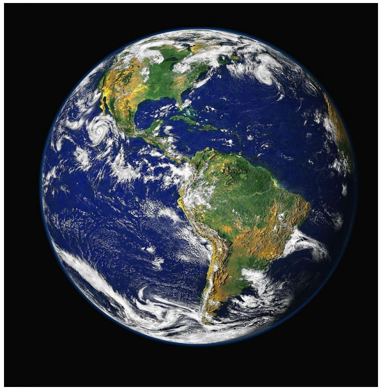
Let me know (PM me) if you'd like to share your research with the UC Santa Cruz group!

also PLEASE!
Interrupt & interact


DARK MATTER DENSITY IN THE SOLAR SYSTEM IS AROUND 0.3 GeV/cm³
IS... THAT A LOT?
IN TERMS OF MASS, IT MEANS THE EARTH CONTAINS ONE SQUIRREL WORTH OF DARK MATTER AT ANY GIVEN TIME.
WOW.
IS THERE ANY WAY TO FIND OUT WHICH SQUIRREL IT IS?
NO, IT'S NOT LITERALLY—
OH, THAT EXPLAINS WHY THEY WEIGH ENOUGH TO SET OFF THOSE SPINNING BIRD FEEDERS!
DARK MATTER ISN'T SQUIRRELS!

* Credit: xqcd

Squirrel ~ **500** grams



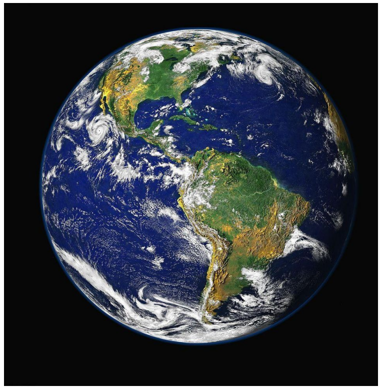
Volume of **Earth** ~ $\mathbf{10^{27}}$ cm^3

grams in a **GeV** ~ 1.8×10^{-24}

Density of **Dark Matter** here ~ 0.3 GeV/cm^3

1000 x 1.8 x 0.3 = **540** grams

Density of Dark Matter in the **Universe** ~ 10^{-5} than here



Density of **Dark Matter** here ~ 0.3 GeV/cm^3

1000 x 1.8 x 0.3 = **540** grams

5/6

a new

elementary particle

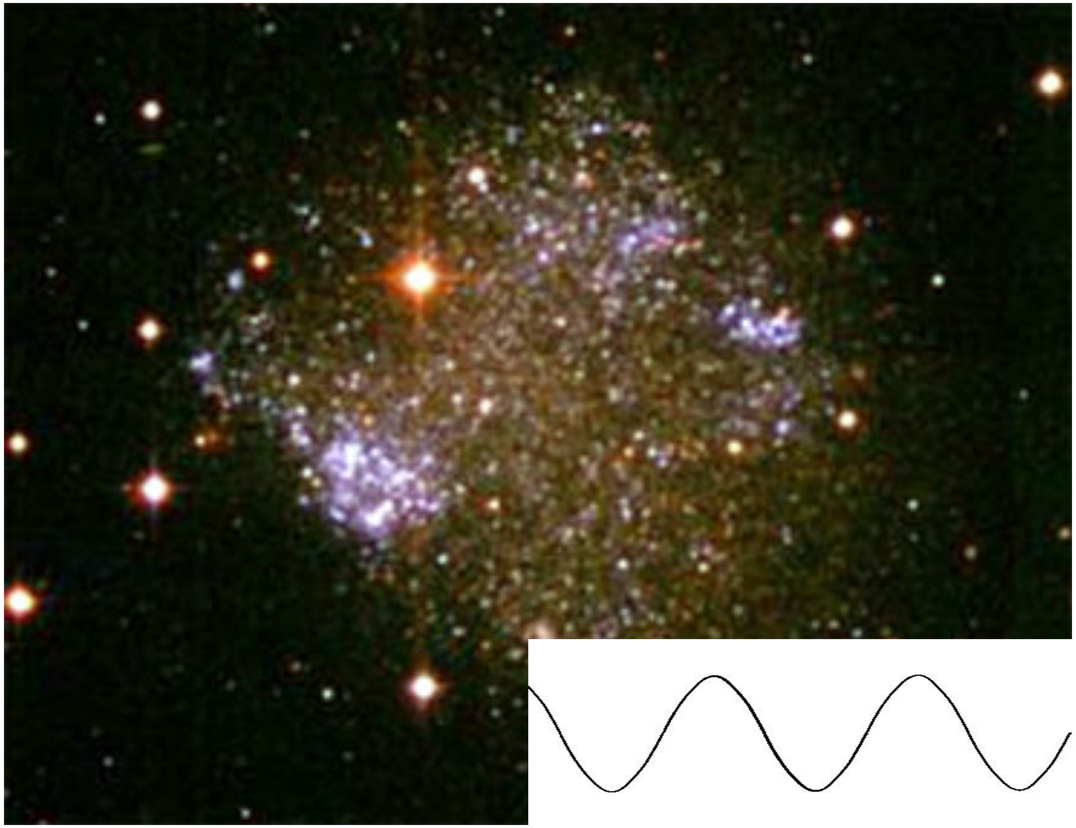
what is an **elementary particle**?

what is an
elementary particle?

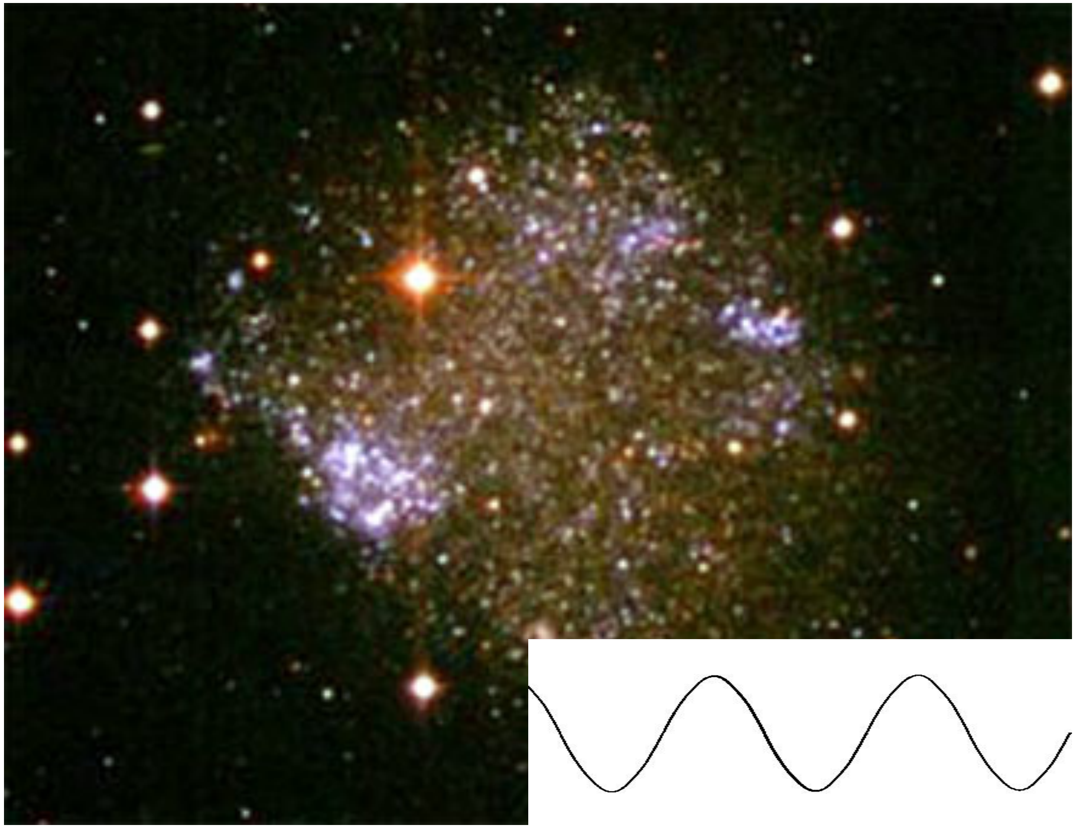
an irreducible, unitary representation of the Poincaré Group

(m, J)

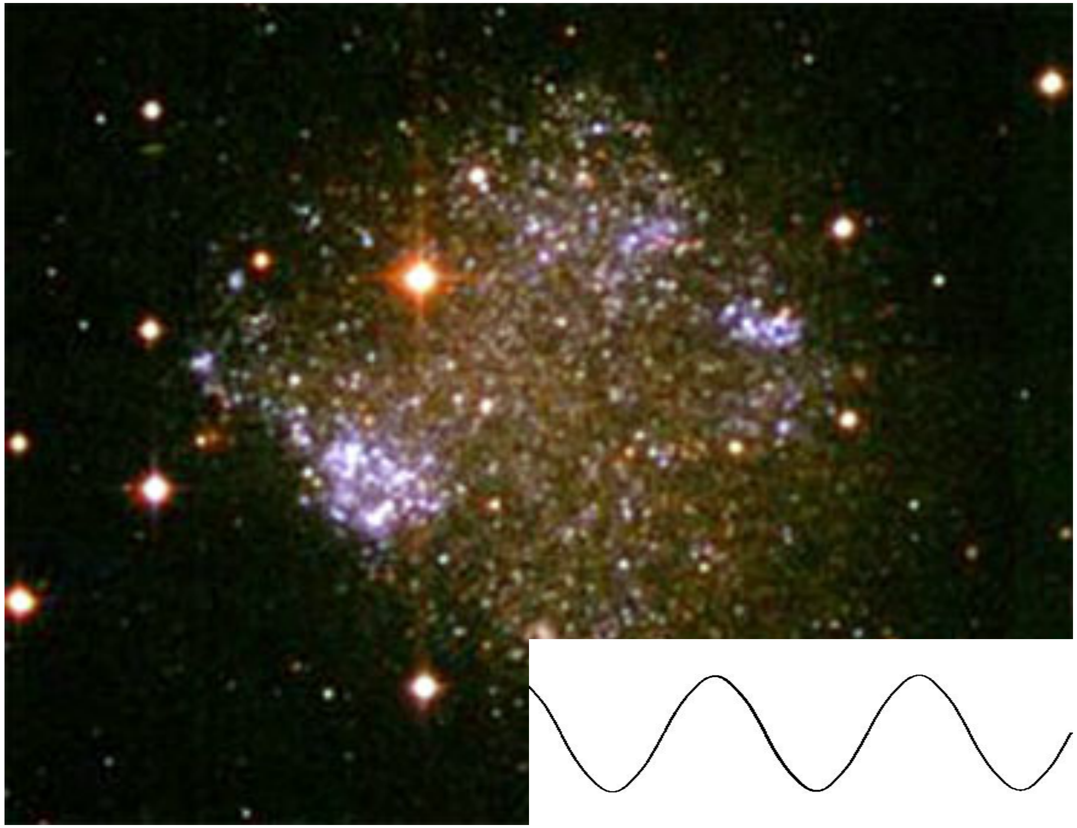
what do we know about m and J?



what do we know about m and J?

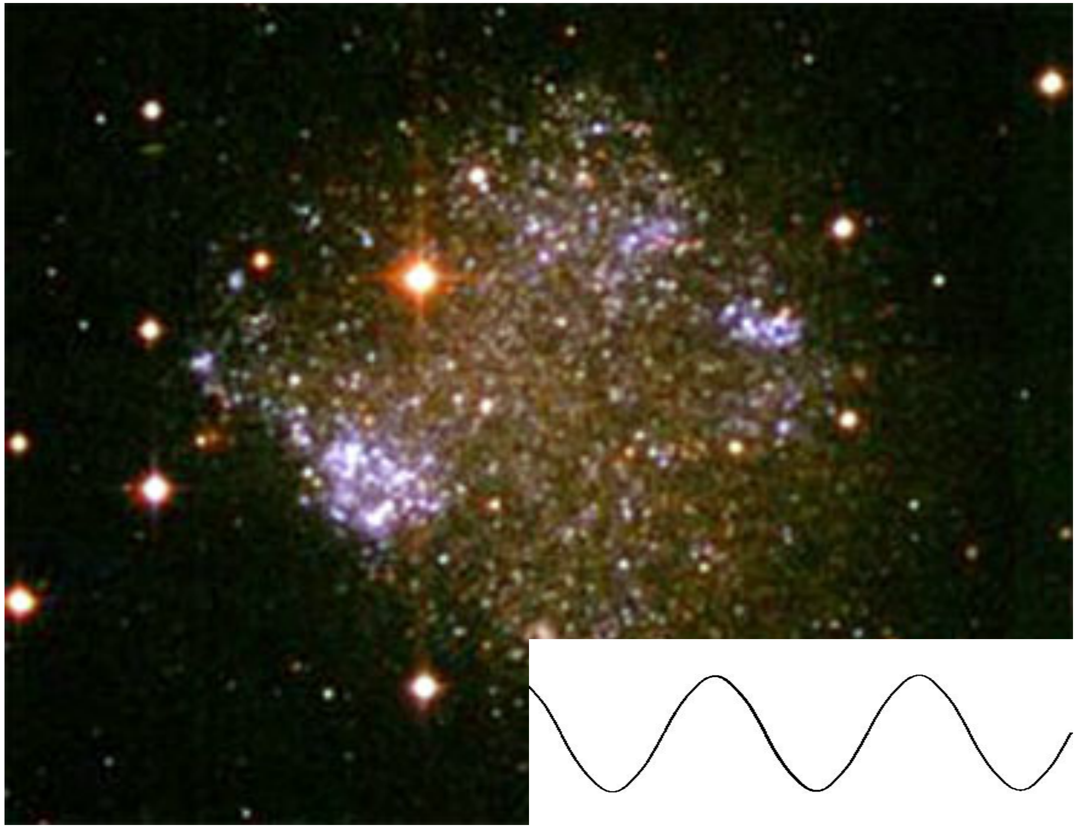


quantum effects must be smaller than halos!



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

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



$m > 10^{-22}$ eV

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

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

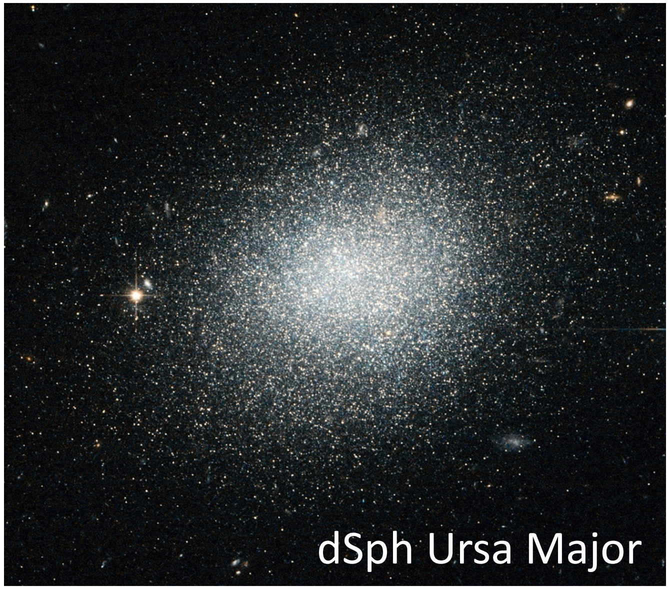
the **phase space** density is bounded (**Pauli** blocking): ***f= gh⁻³***

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?

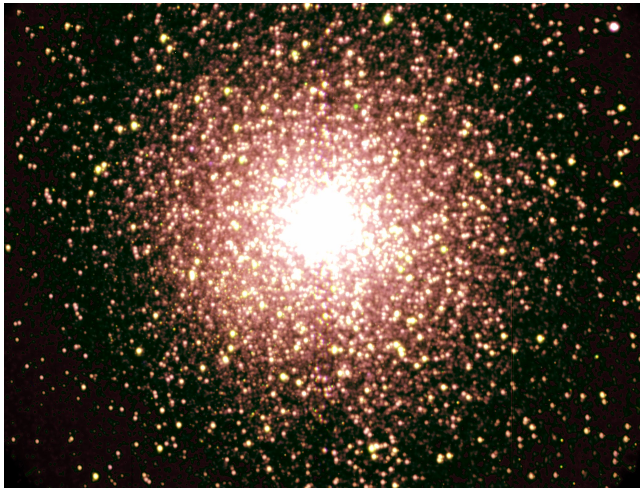
m>10^{-22} eV m>25 eV

bosons fermions

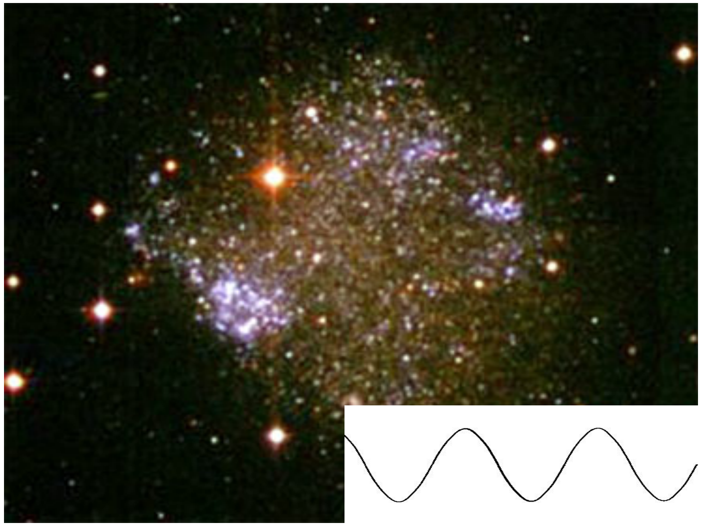
what is the upper limit
to the dark matter mass?

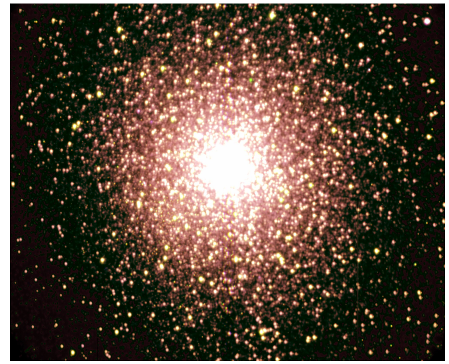
ultramassive DM: beyond M_P…
composite, primordial black holes!

Macroscopic Dark Matter would **tidally disrupt** structure



$m < 10^{3}$ **solar masses** ***$\sim 10^{70}$ eV***





Macroscopic Quantum Effects

What else do we know about the DM?

Macroscopic Tidal Effects

One thing we do **know well** about dark matter (CMB, clusters,…)

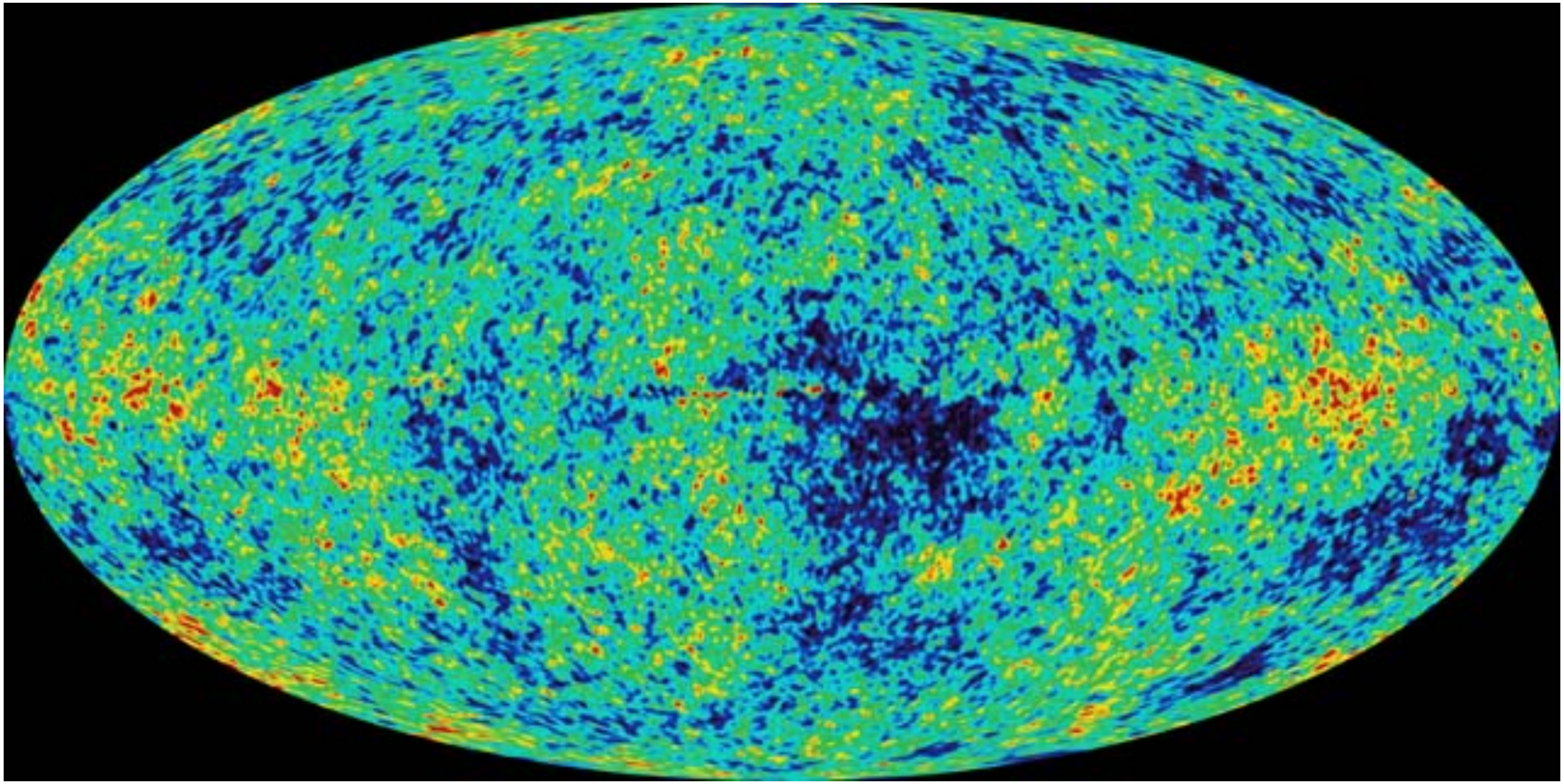
Global amount of dark matter in the **universe**

Knowledge of the dark matter average **density**
is a powerful **model-building** tool

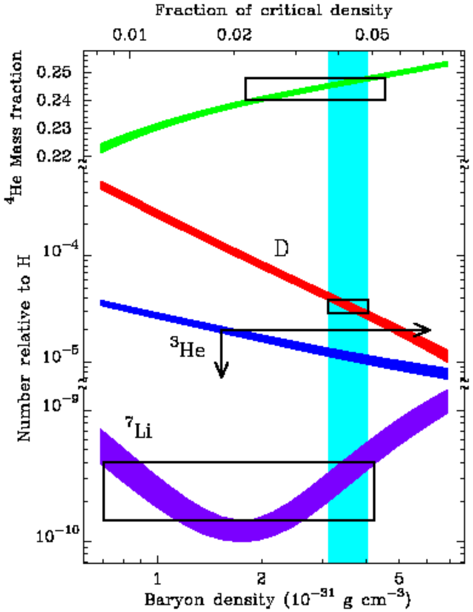
Models that **predict** the “right” **amount** of dark matter get kudos

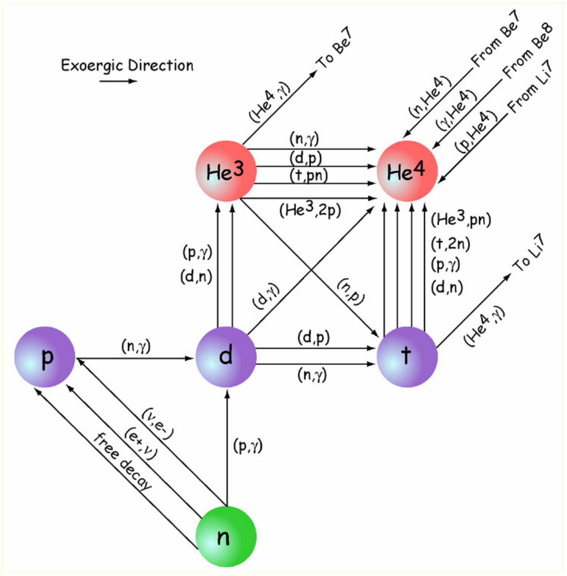
Dark Matter “**cosmogony**” well-motivated guideline to model building

A successful framework for the **origin of species** in the early universe: **thermal decoupling**



A successful framework for the **origin of species** in the early universe: **thermal decoupling**





A **synergy** of ***statistical mechanics***,
general relativity, and of ***nuclear and particle physics***
making **predictions** testable to exquisite accuracy
with ***astronomical*** observations!

The **abundance** of thermal relics depends on their kinematic state at the time of **decopupling** from thermal bath (**freeze-out**)

Hot relic: decouples when relativistic ($T_{fo} \gg m$)

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

Cold relic: decouples when non-relativistic ($T_{fo} \ll m$) ($x = m/T \gg 1$)

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

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

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

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

…thus, at a minimum,

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

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

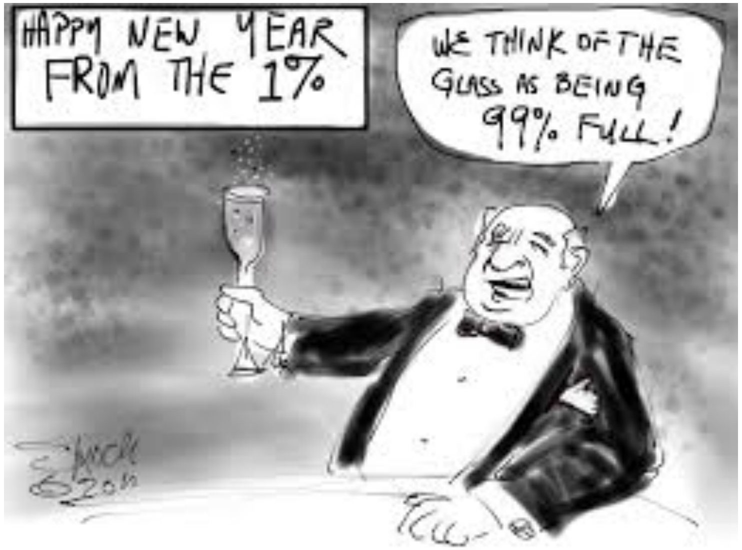
CMB by itself demands $\sum_j m_j \lesssim (0.3 - 1.3)\ \mathrm{eV}$

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

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

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

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



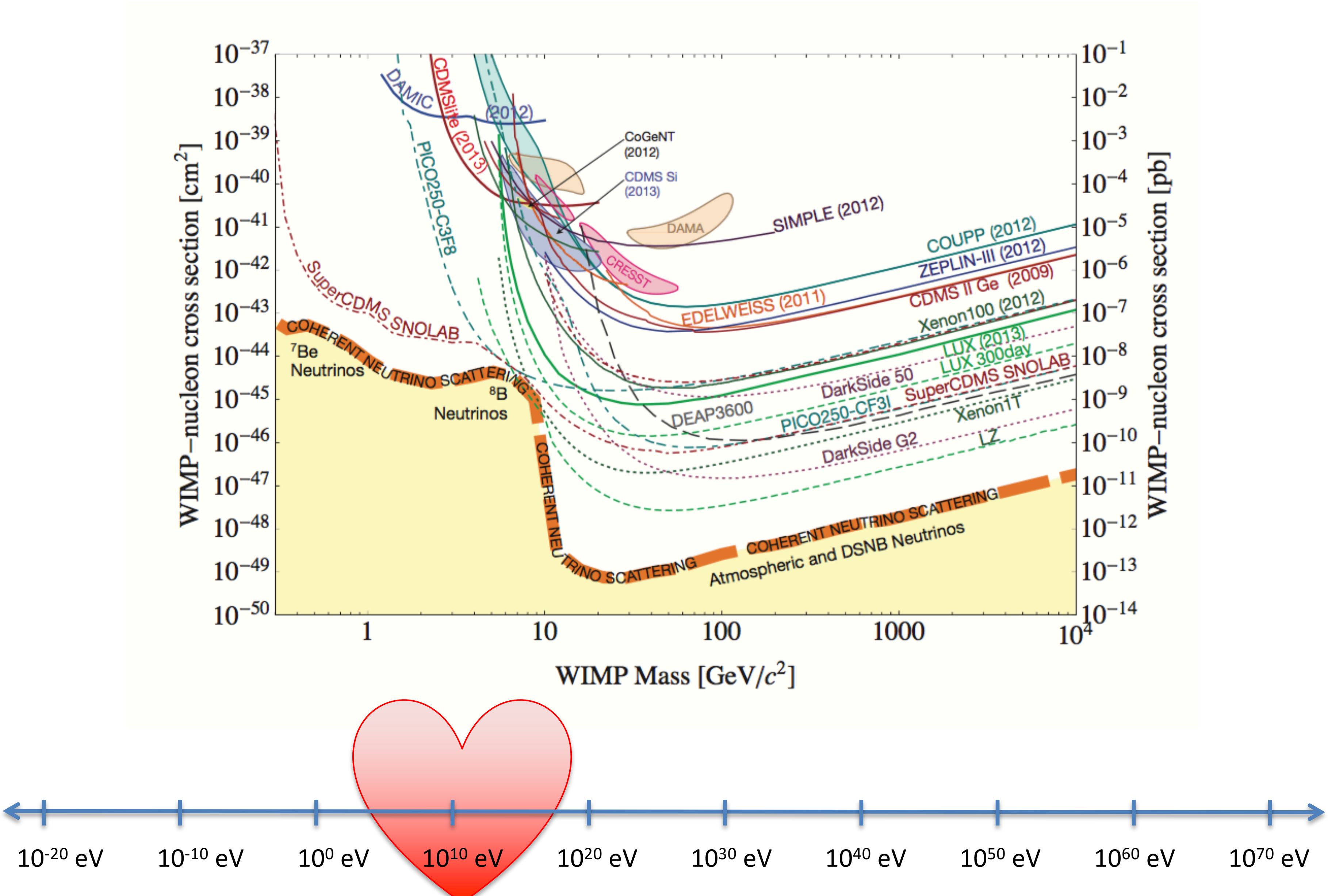
What about the **99%**?

Freeze-out while $m >> T$: **cold relic**

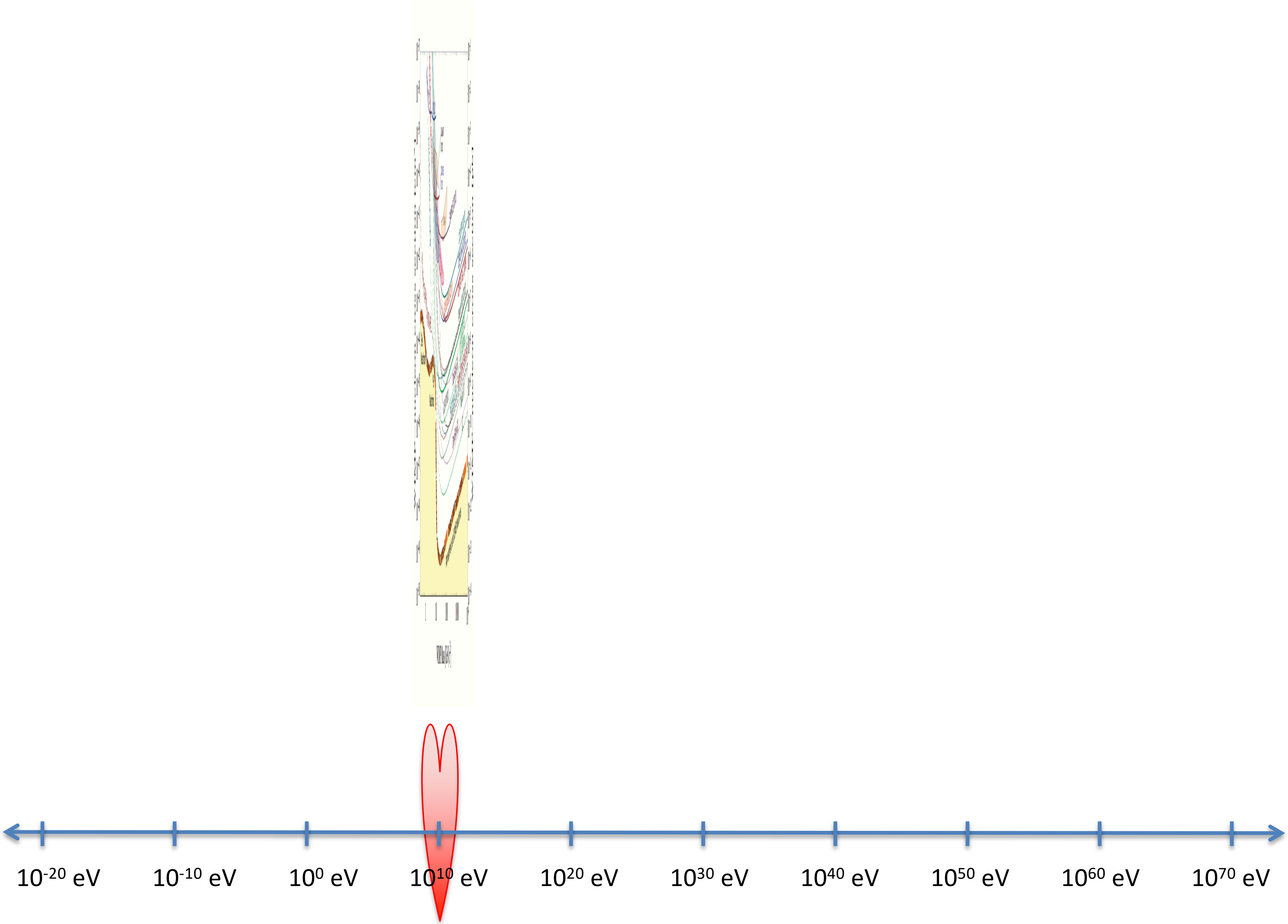
$$\left(\frac{\Omega_\chi}{0.2}\right) \simeq \frac{x_{\rm f.o.}}{20}\left(\frac{10^{-8}\ \mathrm{GeV}^{-2}}{\sigma}\right)$$

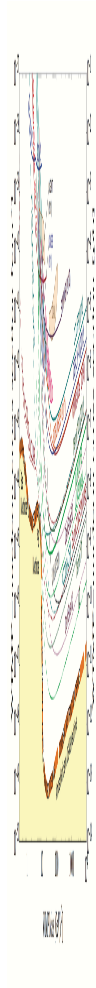
$$\sigma_{\rm EW} \sim G_F^2 T_{\rm f.o.}^2 \sim G_F^2\left(\frac{E_{\rm EW}}{20}\right)^2 \sim 10^{-8}\ \mathrm{GeV}^{-2},$$

WIMP miracle!



WIMP–nucleon cross section [cm²]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c²]
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
Atmospheric and DSNB Neutrinos
10⁻²⁰ eV
10⁻¹⁰ eV
10⁰ eV
10¹⁰ eV
10²⁰ eV
10³⁰ eV
10⁴⁰ eV
10⁵⁰ eV
10⁶⁰ eV
10⁷⁰ eV

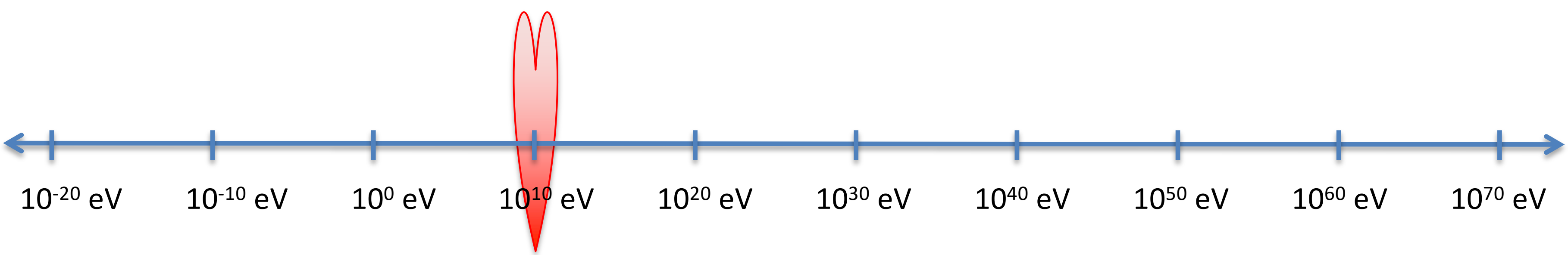

10^{-20} eV
10^{-10} eV
10^{0} eV
10^{10} eV
10^{20} eV
10^{30} eV
10^{40} eV
10^{50} eV
10^{60} eV
10^{70} eV

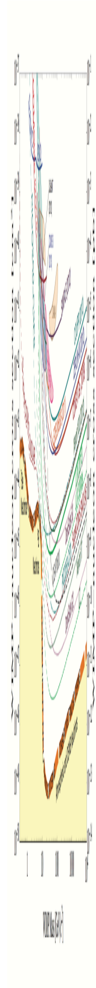


$$\left(\frac{\Omega_\chi}{0.2}\right) \simeq \frac{x_{\rm f.o.}}{20}\left(\frac{10^{-8}\ \mathrm{GeV}^{-2}}{\sigma}\right)$$

“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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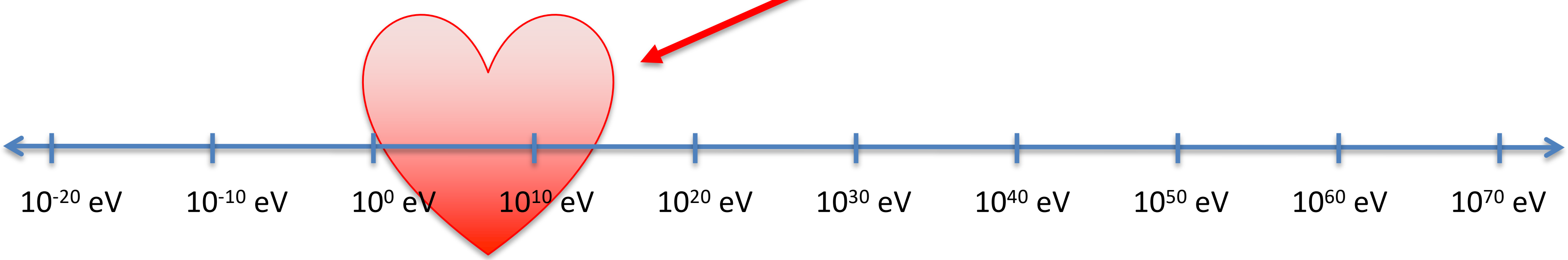

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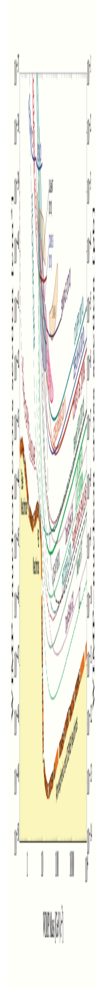
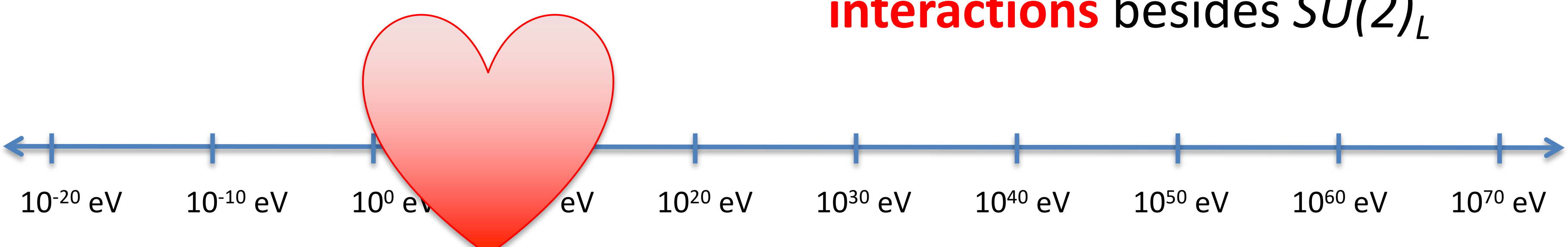
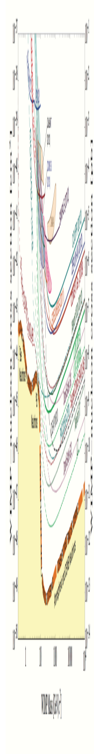


"right" (model-dependent) **combinations** of **masses** and **couplings** populate a much larger "rich **hidden sector**" parameter space

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

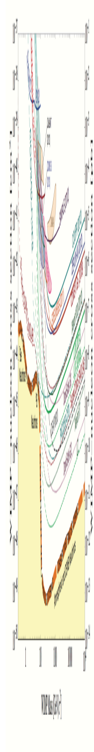
…price: must **invent** new **interactions** besides $SU(2)_L$






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



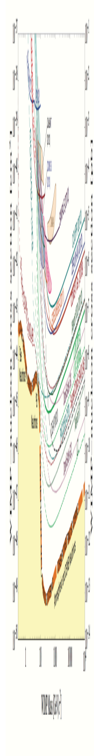
10^{-20} eV 10^{-10} eV 10^{0} eV 10^{10} eV 10^{20} eV 10^{30} eV 10^{40} eV 10^{50} eV 10^{60} eV 10^{70} eV

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

* Nebrin et al 2018

Fuzzy (wave) Dark Matter

Light bosons



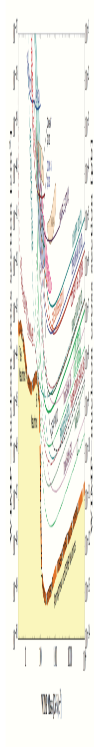
10^{-20} eV 10^{-10} eV 10^{0} eV 10^{10} eV 10^{20} eV 10^{30} eV 10^{40} eV 10^{50} eV 10^{60} eV 10^{70} eV

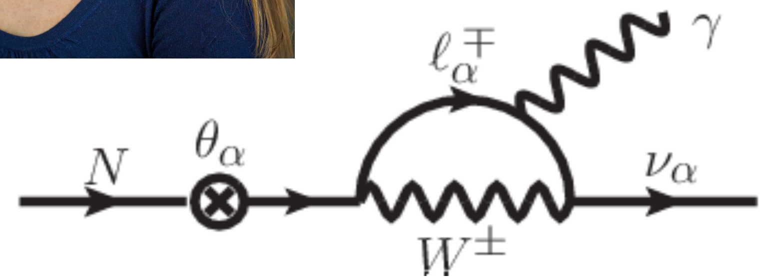
- **Many exciting new ideas!***

* ABRACADABRA, LC resonators, HAYSTAC, MW cavities…

Fuzzy (wave) Dark Matter

Light bosons





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

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; Dessert+ '19

PHYSICS

The Fate of a Dark Matter Theory Hinges on These Unidentified X-Rays

Ryan F. Mandelbaum
3/26/20 4:20PM • Filed to: DARK MATTER

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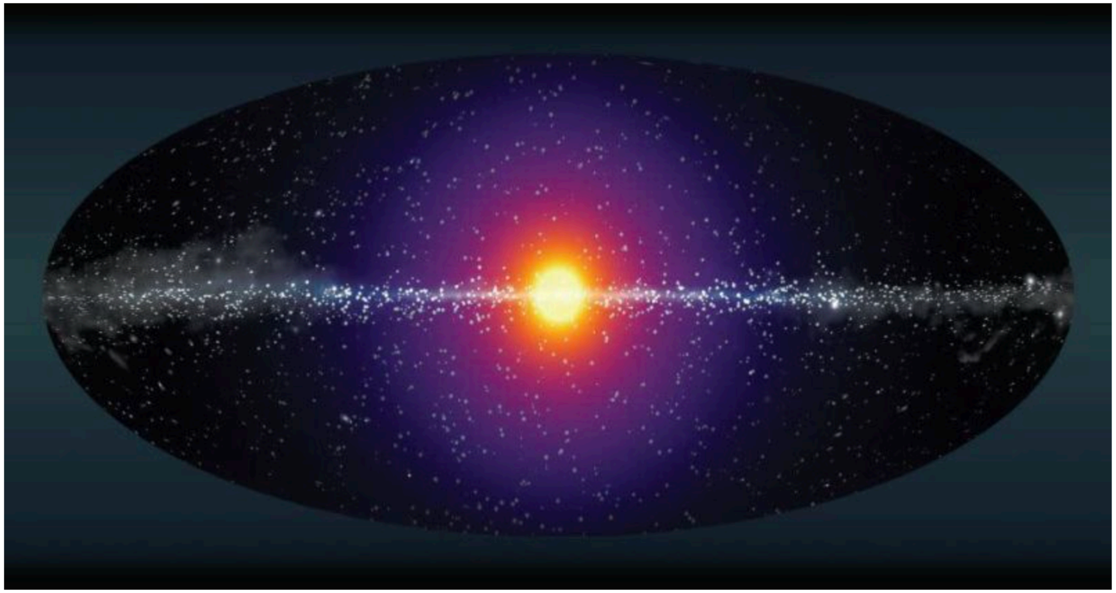
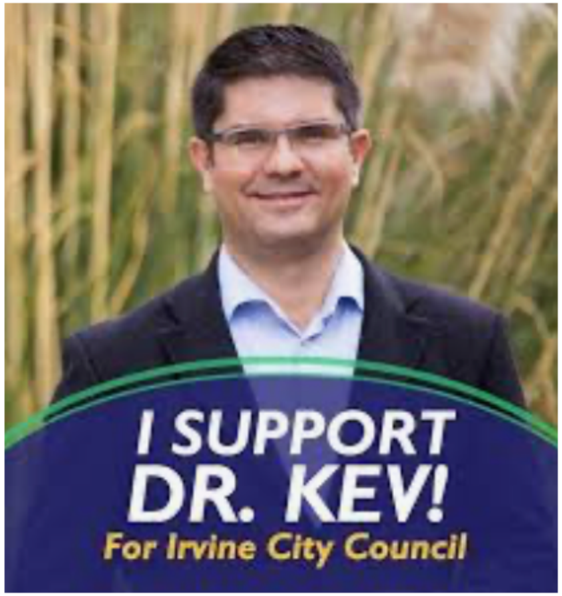


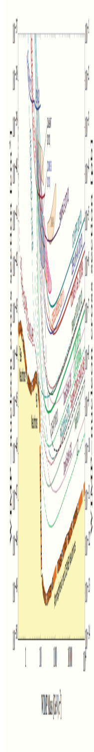
But when this paper first appeared on the arXiv physics preprint server over a year ago, some physicists took issue with its results. Boyarsky's team did find evidence of the line in XMM observations of the Milky Way halo. Boyarsky told Gizmodo that the new paper was "completely wrong." He disagreed with the way the new paper handled XMM-Newton's backgrounds, meaning the data it records that isn't the signal, and said that it obscured the signal his team did see.

Nicholas Rodd, another coauthor of the new paper, told Gizmodo via email that he was aware of Boyarsky and others' concerns about the paper. He agreed that the differences were in the statistics but said that "the Boyarsky team has suggested to us several modifications we could make to our analysis and alternate analysis frameworks. Examples include modeling speculative instrumental lines, amongst many more. We have performed every one of these checks… and each time our analysis remains robust: No line emerges, and the dark matter explanation for the 3.5 keV line remains excluded."

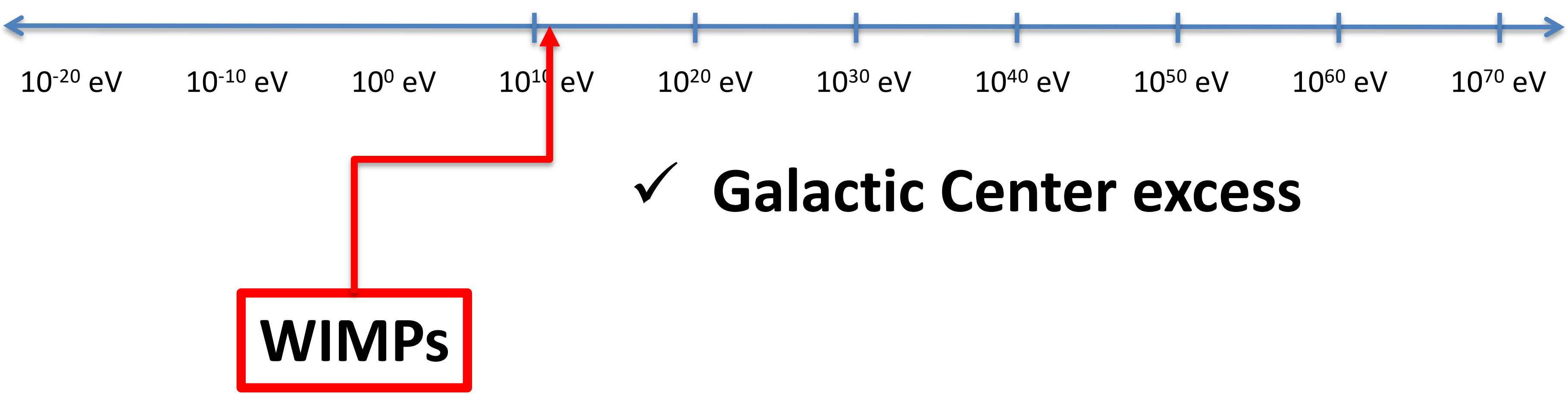


Physics and astronomy professor Kevork Abazajian at the University of California, Irvine thought it was a case of cherrypicking the data—that the range of frequencies the team hunted for was too thin, potentially removing the signal. "The short of it is, they don't have enough information to make a strong conclusion," he said.

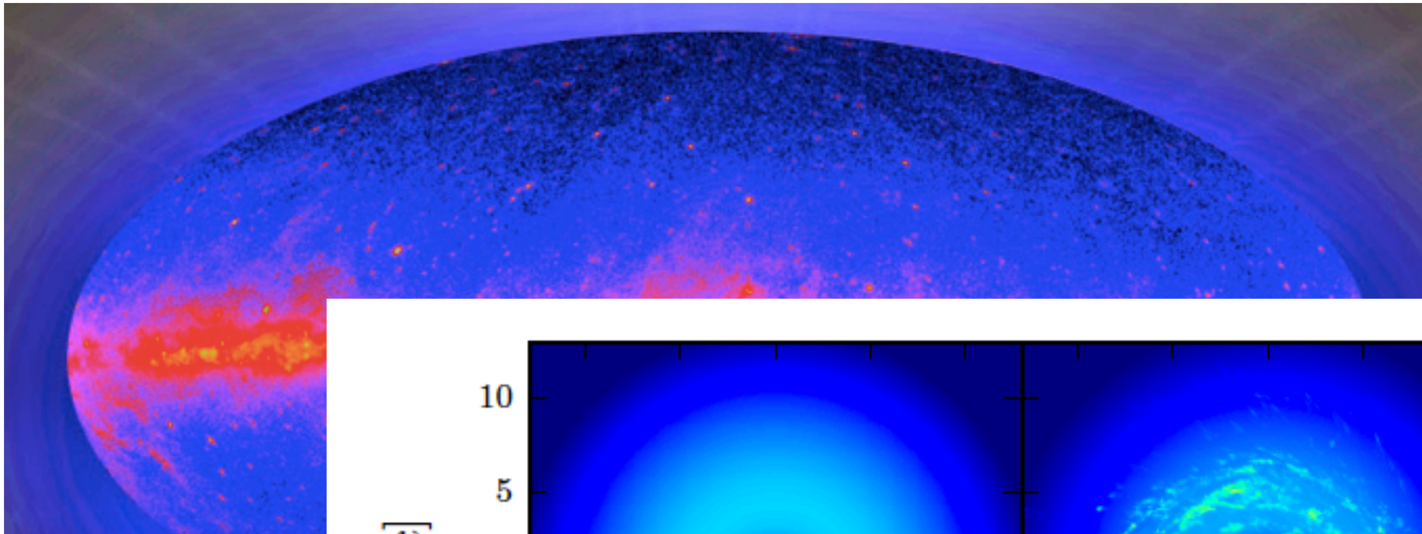
Tesla Jeltema, associate professor of physics at University of California, Santa Cruz, told Gizmodo in an email that this new paper, as well as the papers that first discovered the line, were all very careful analyses of the data. But, said Jeltema, "Regardless of who you think is 'right,' if there were such a thing, I would argue that if you can model the data in different, reasonable ways and sometimes you get an excess and sometimes you don't, the evidence for the need for new physics is not there." In other words, if the presence or absence of a phenomenon relies strongly on which statistical model you're using, then there isn't strong evidence that dark matter is the cause.

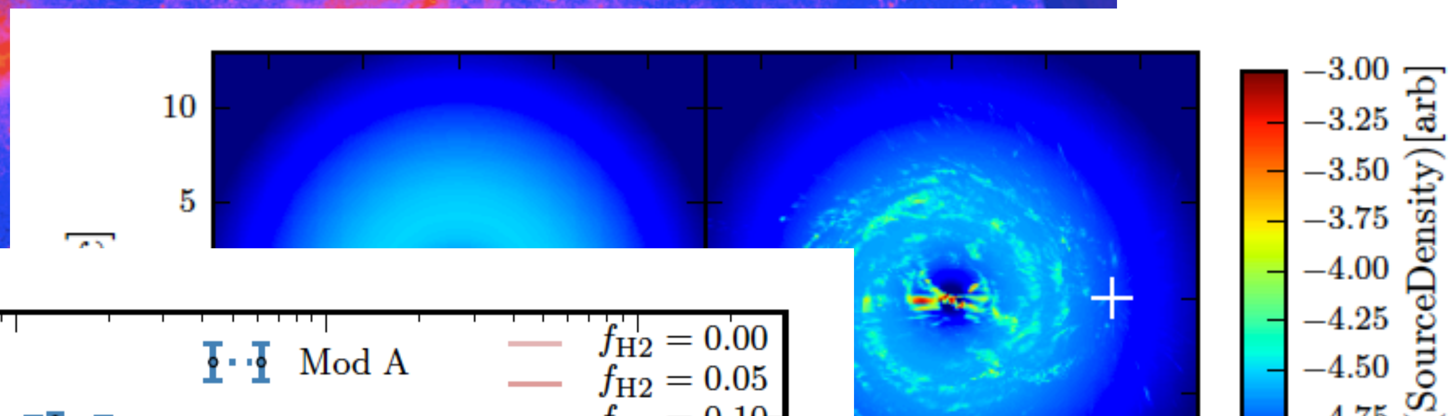


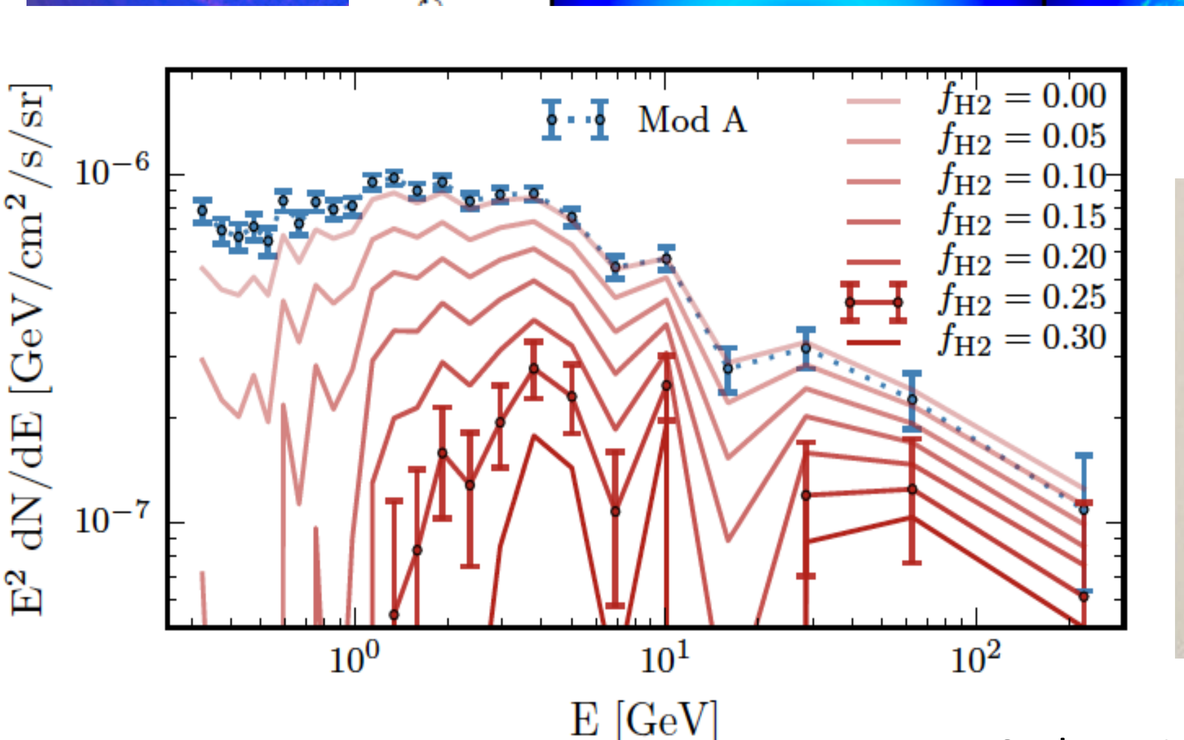
- Common in **BSM** weak-scale
- Very **advanced** direct detection program
- Controversial **indirect** signals



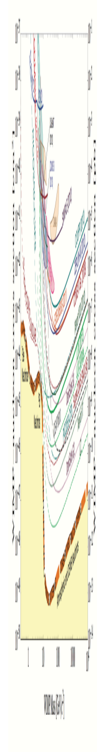
✓ Galactic Center excess







Carlson, Linden, Profumo PRD, PRL (2016)



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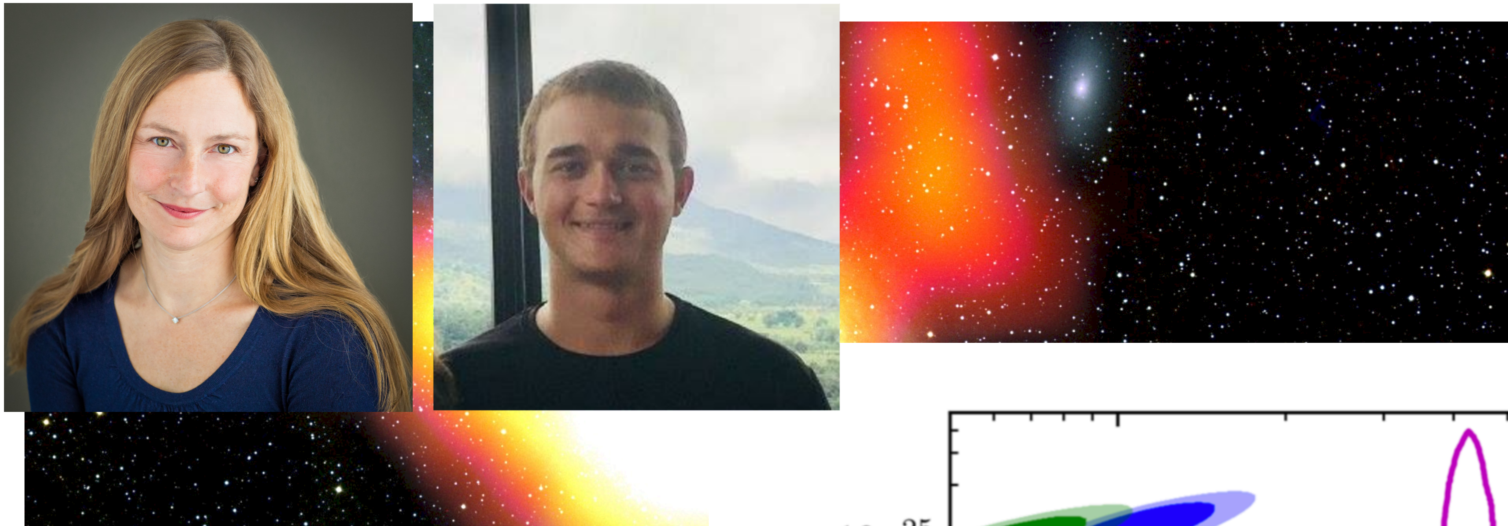
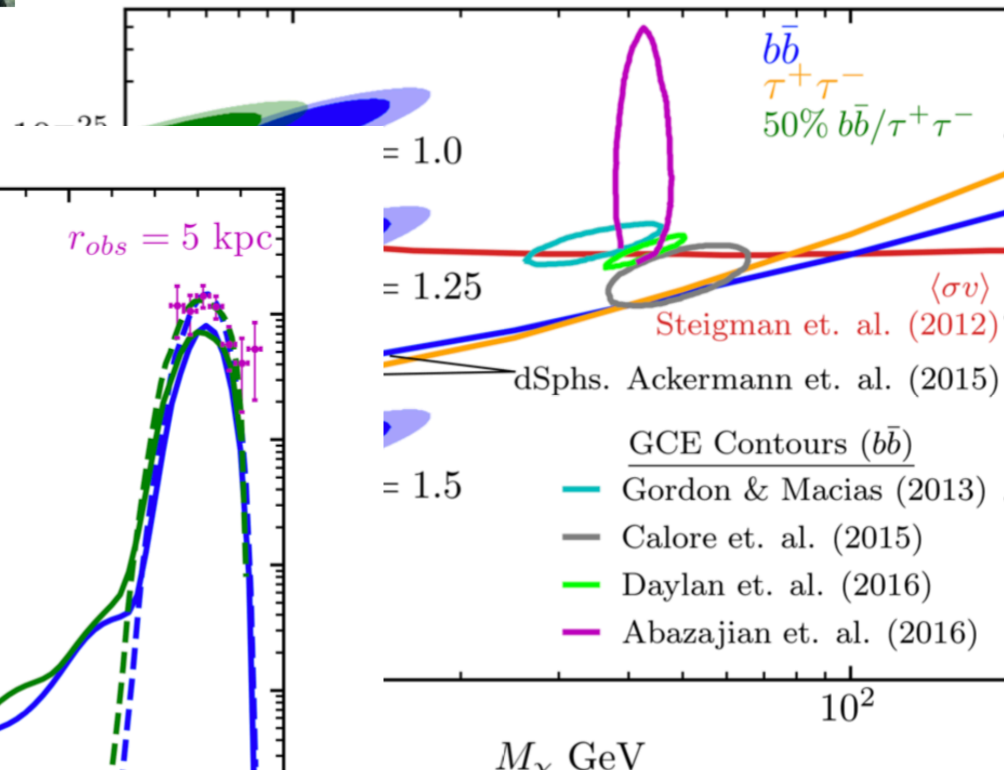
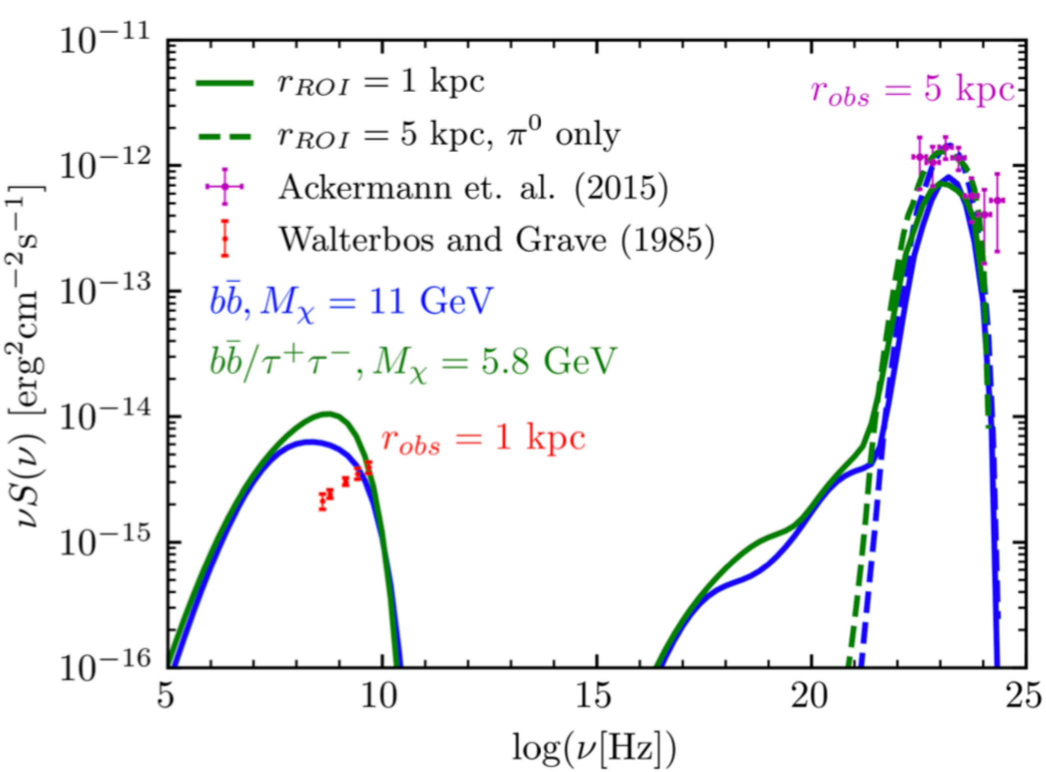
10^{-20} eV | 10^{-10} eV | 10^{0} eV | 10^{10} eV | 10^{20} eV | 10^{30} eV | 10^{40} eV | 10^{50} eV | 10^{60} eV | 10^{70} eV

WIMPs

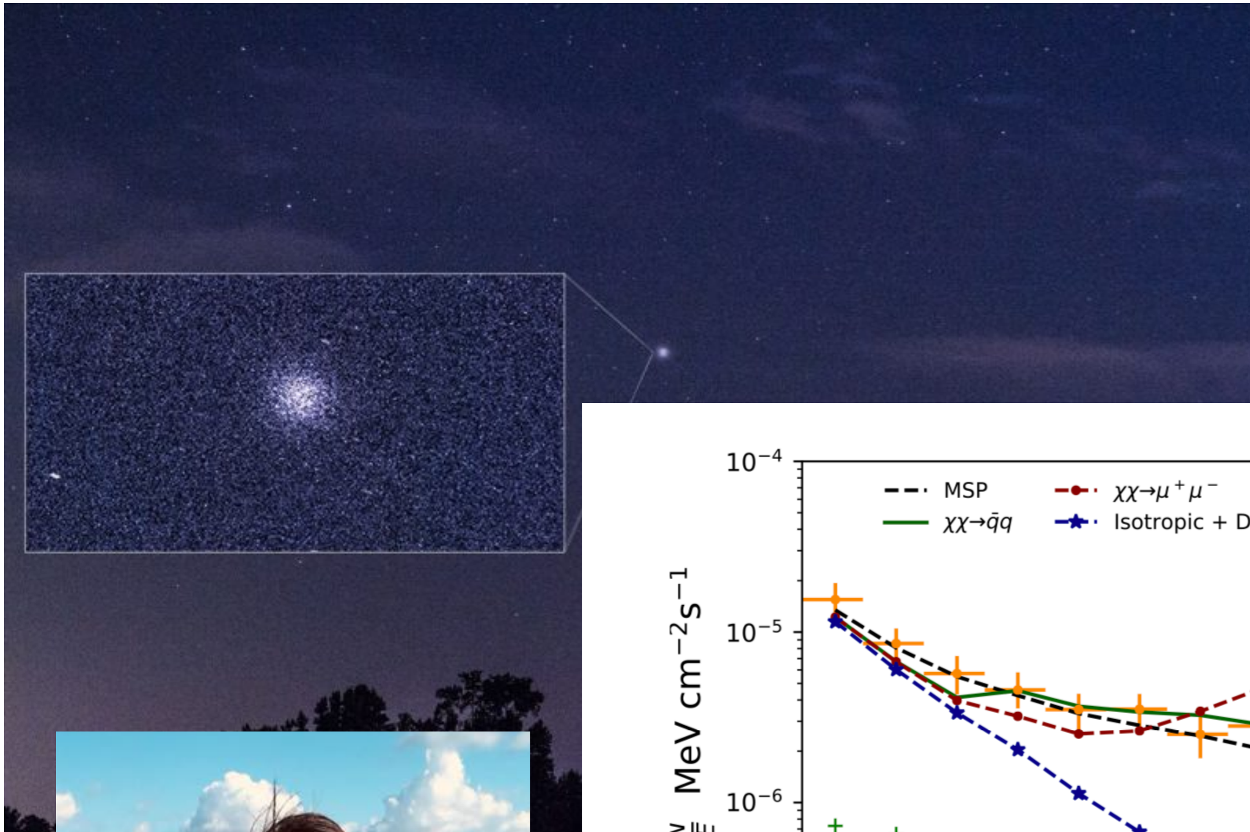
- ✓ Galactic Center excess
- ✓ other gamma-ray excesses

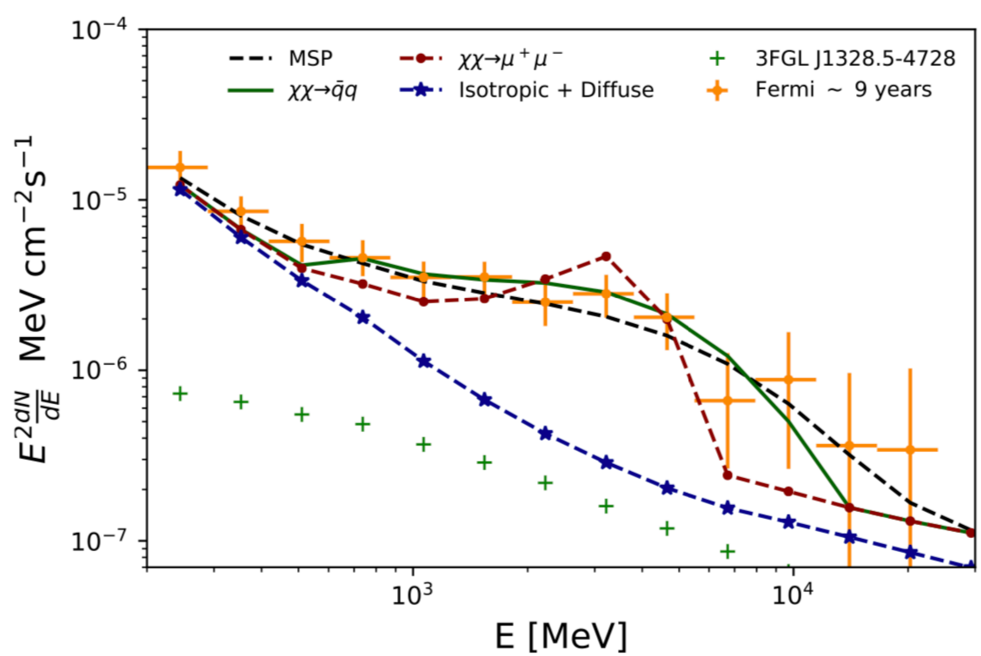




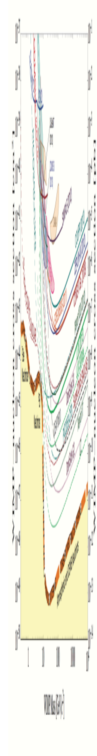


McDaniel, Jeltema, Profumo 2018, 2019





Reynoso, Profumo +, 2019

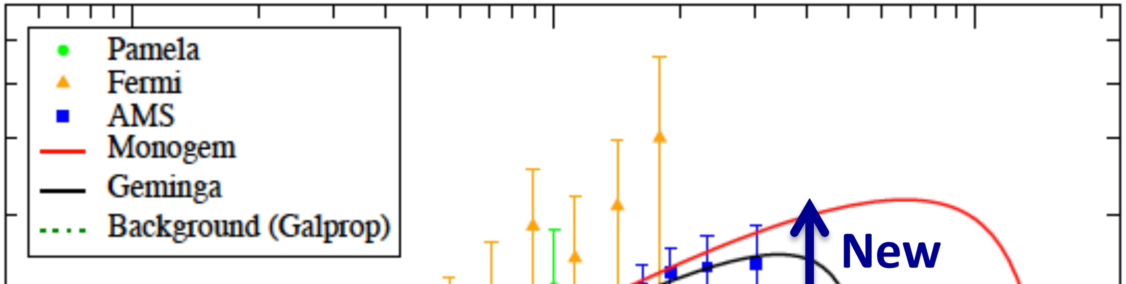


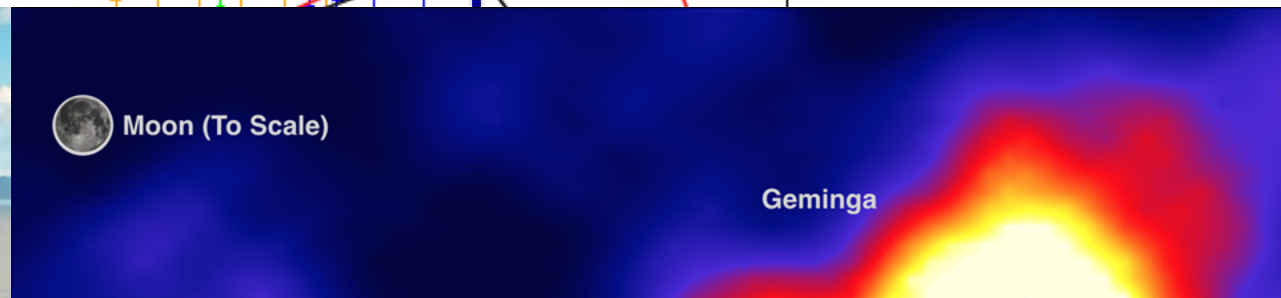
- Common in **BSM** weak-scale
- Very **advanced** direct detection program
- Controversial **indirect** signals

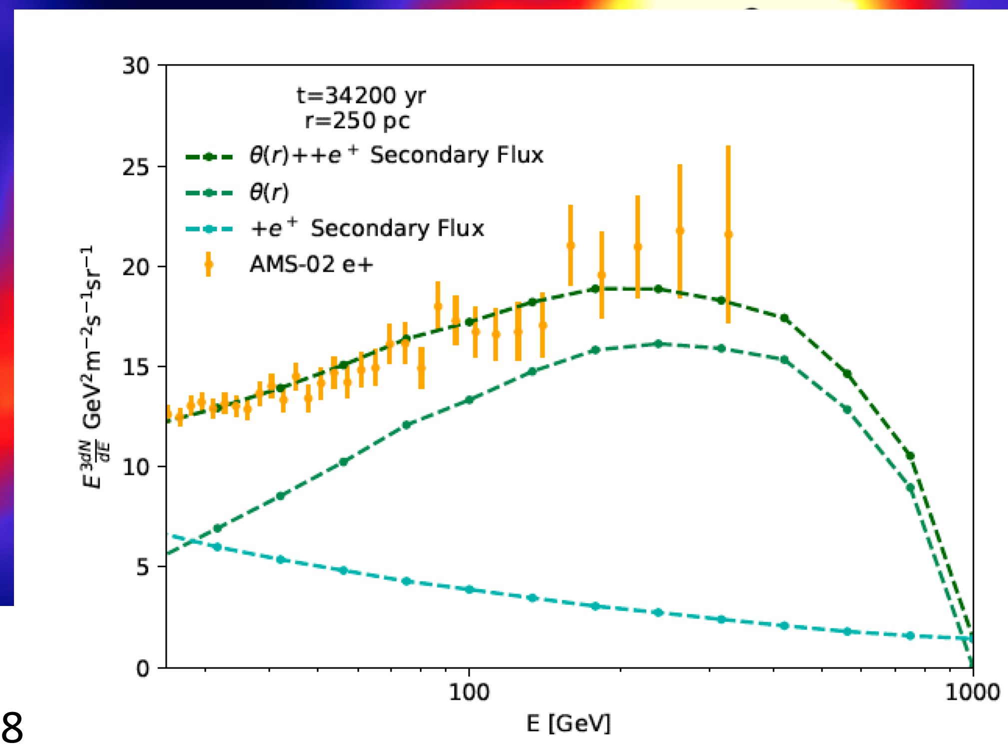
10^{-20} eV 10^{-10} eV 10^{0} eV 10^{10} eV 10^{20} eV 10^{30} eV 10^{40} eV 10^{50} eV 10^{60} eV 10^{70} eV

WIMPs

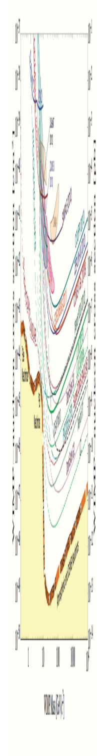
- ✓ Galactic Center excess
- ✓ other gamma-ray excesses
- ✓ Positron excess







Linden + Profumo 2013; Profumo et al 2018

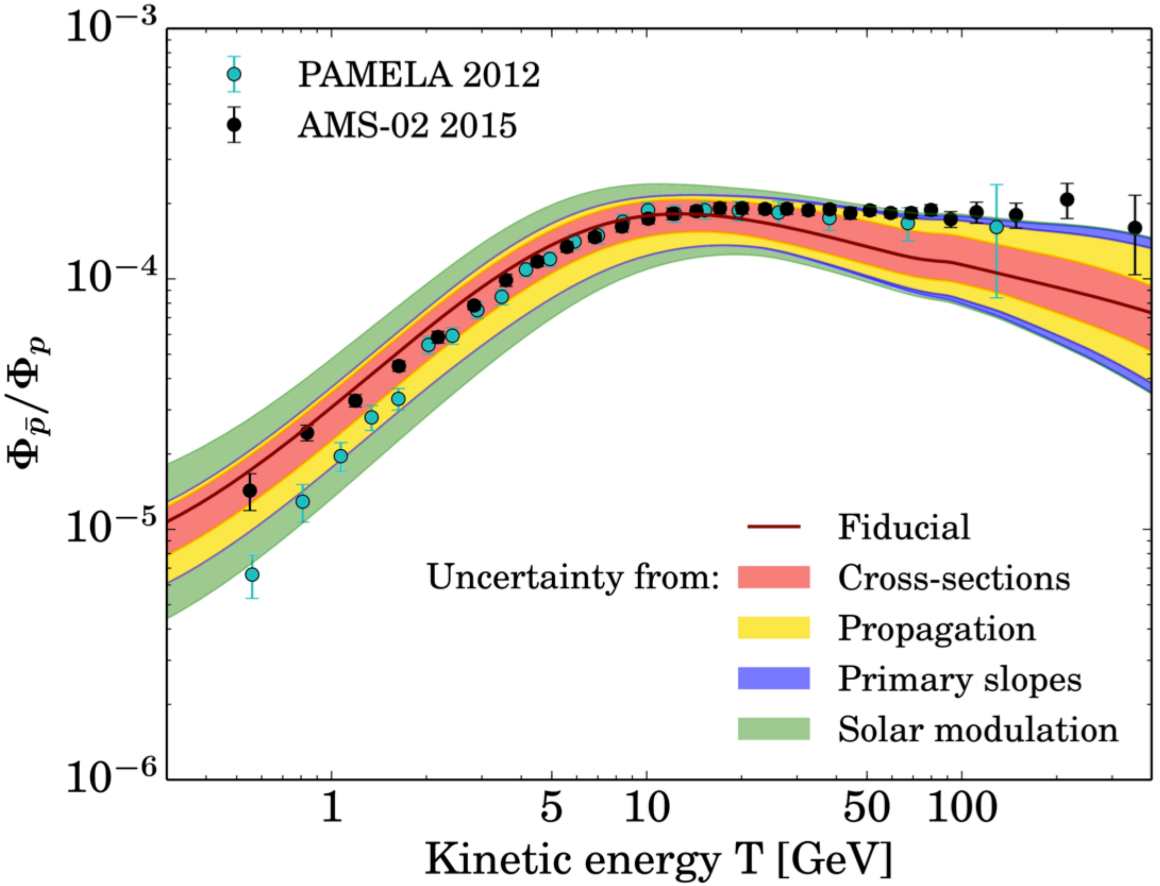


- Common in **BSM** weak-scale
- Very **advanced** direct detection program
- Controversial **indirect** signals

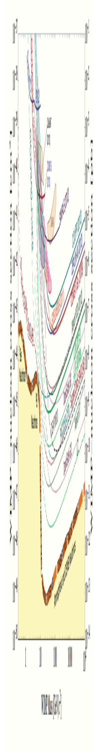
10^{-20} eV 10^{-10} eV 10^{0} eV 10^{10} eV 10^{20} eV 10^{30} eV 10^{40} eV 10^{50} eV 10^{60} eV 10^{70} eV

WIMPs

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



Resonaances: "experts unanimously agree that the **brown smudge** in the plot above **is actually just s**t**, rather than a range of predictions from the secondary production"

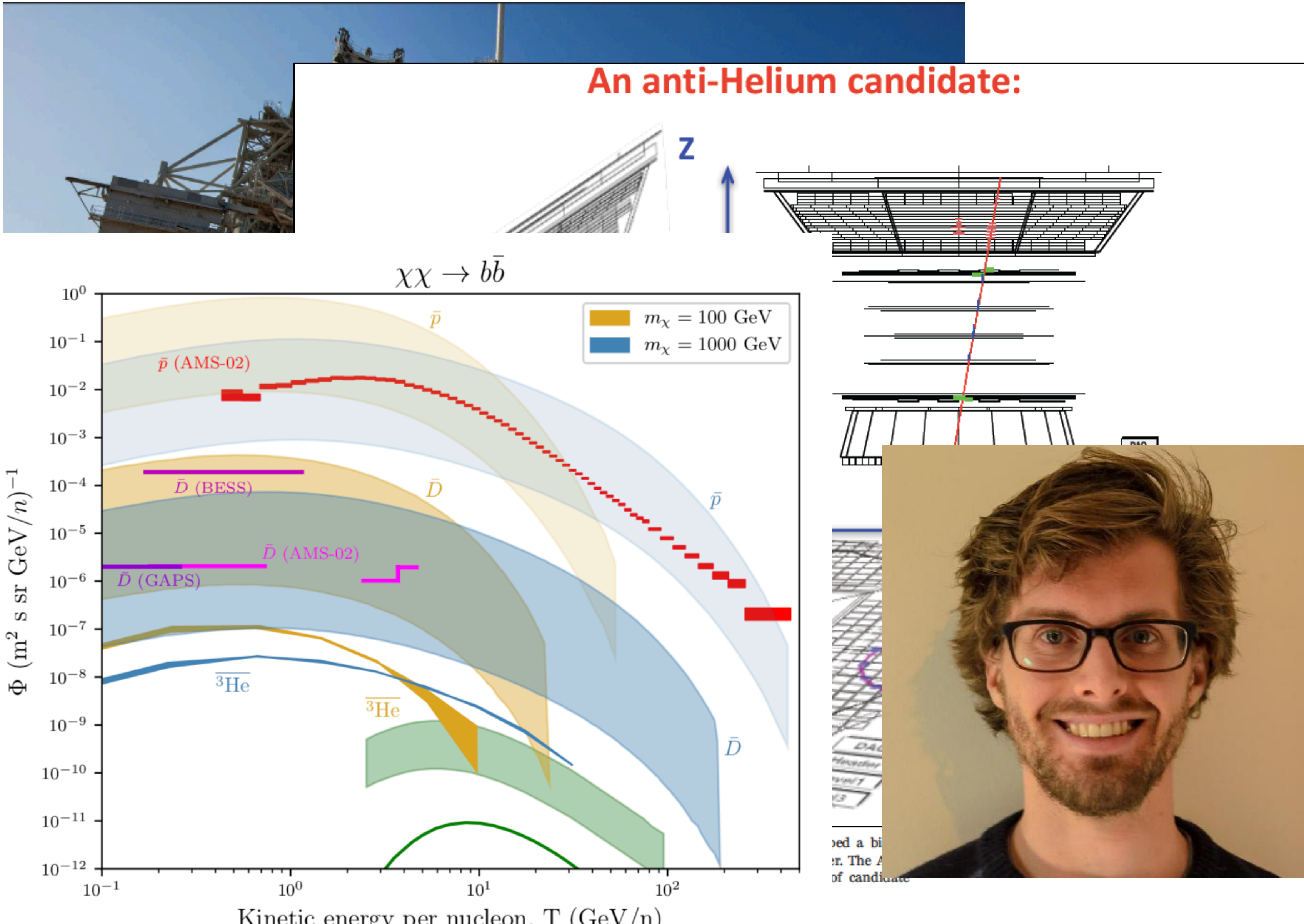


- Common in **BSM** weak-scale
- Very **advanced** direct detection program
- Controversial **indirect** signals

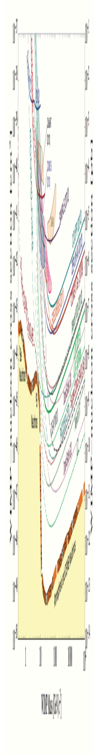
10^{-20} eV | 10^{-10} eV | 10^{0} eV | 10^{10} eV | 10^{20} eV | 10^{30} eV | 10^{40} eV | 10^{50} eV | 10^{60} eV | 10^{70} eV

WIMPs

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



Coogan and Profumo 2017



- **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*

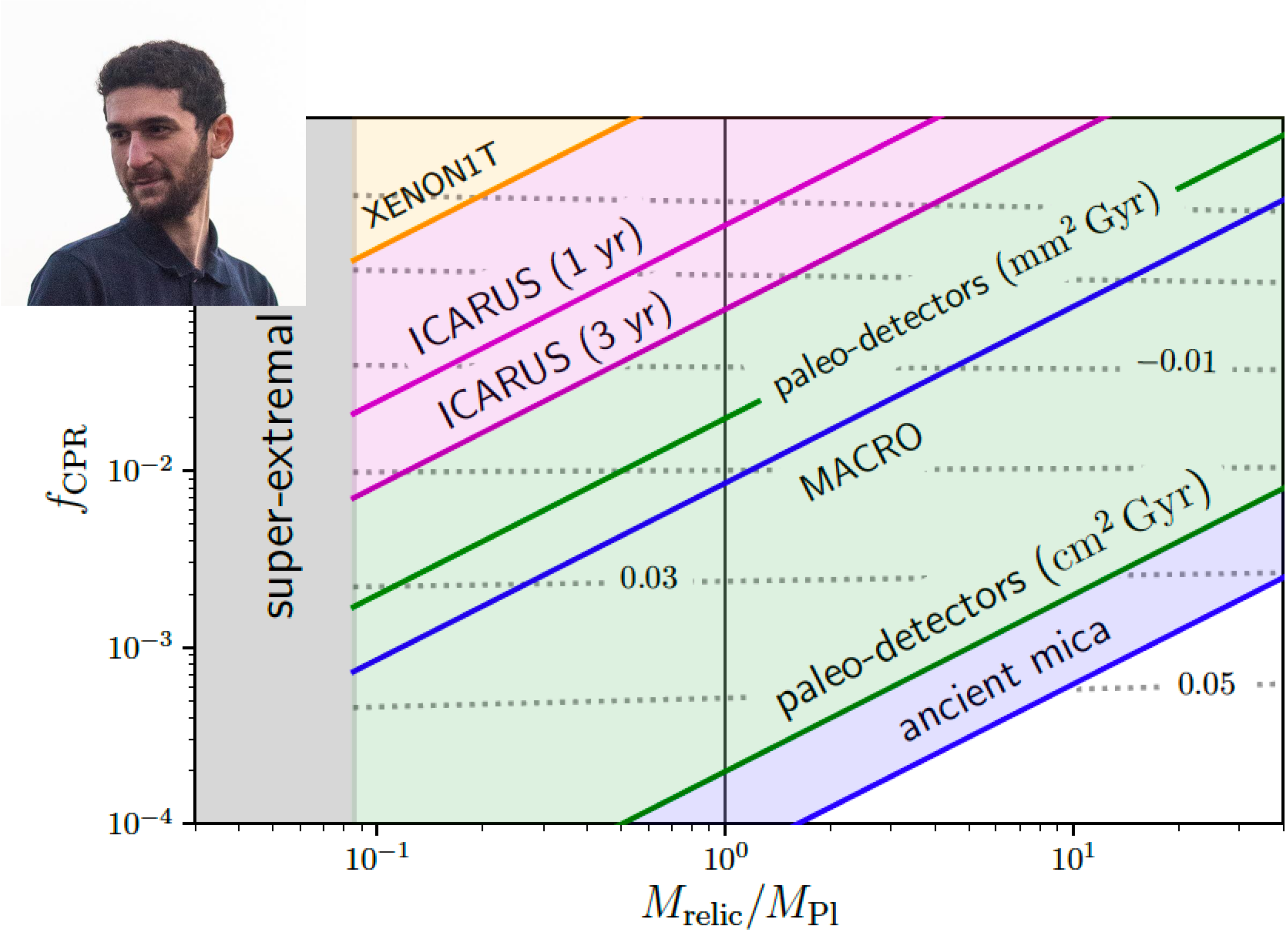
$$P(Q) \sim \exp\left(-4\pi\alpha(Q/e)^2\right)$$

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

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



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

…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

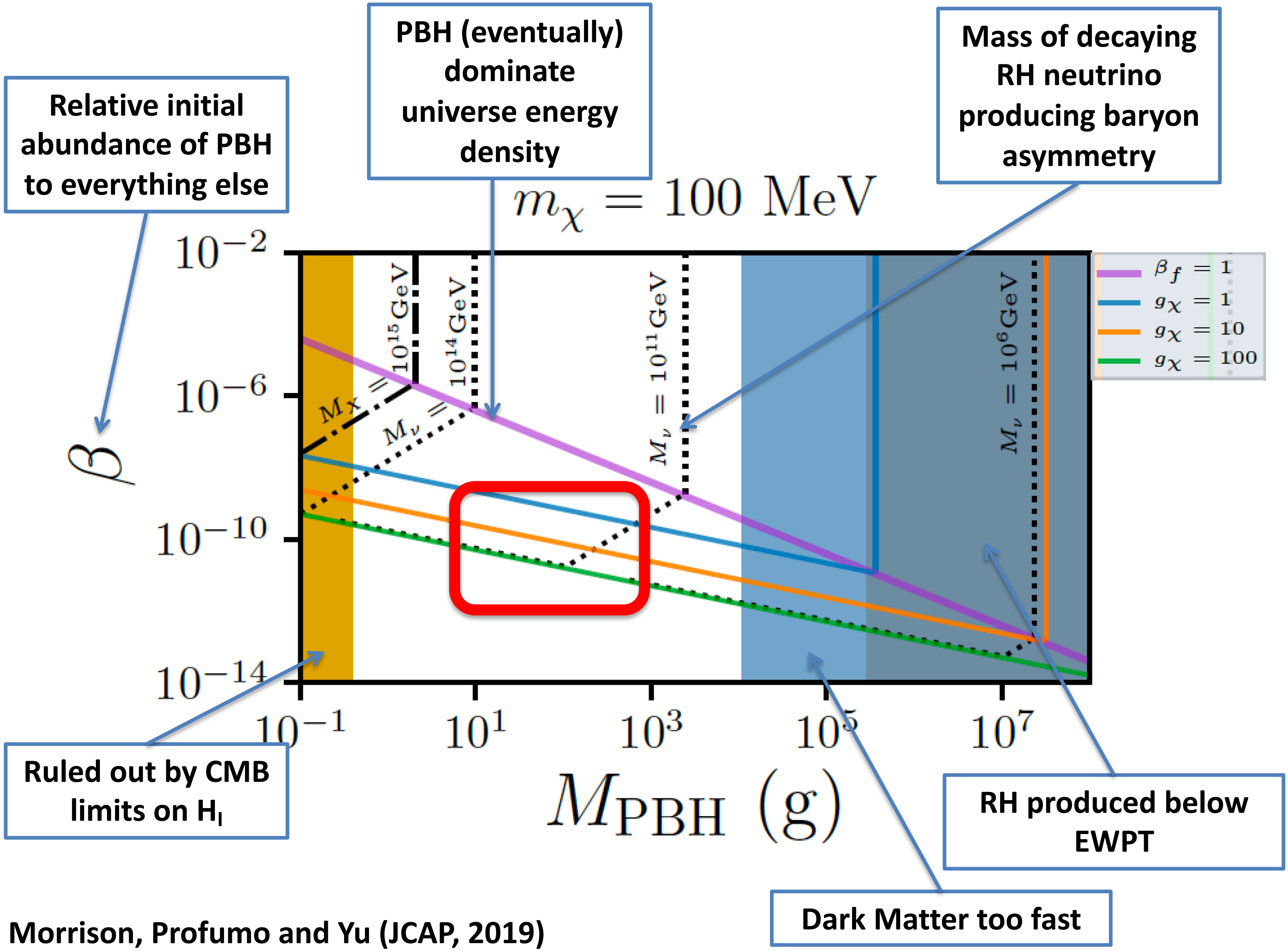
Current Personal Records

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!

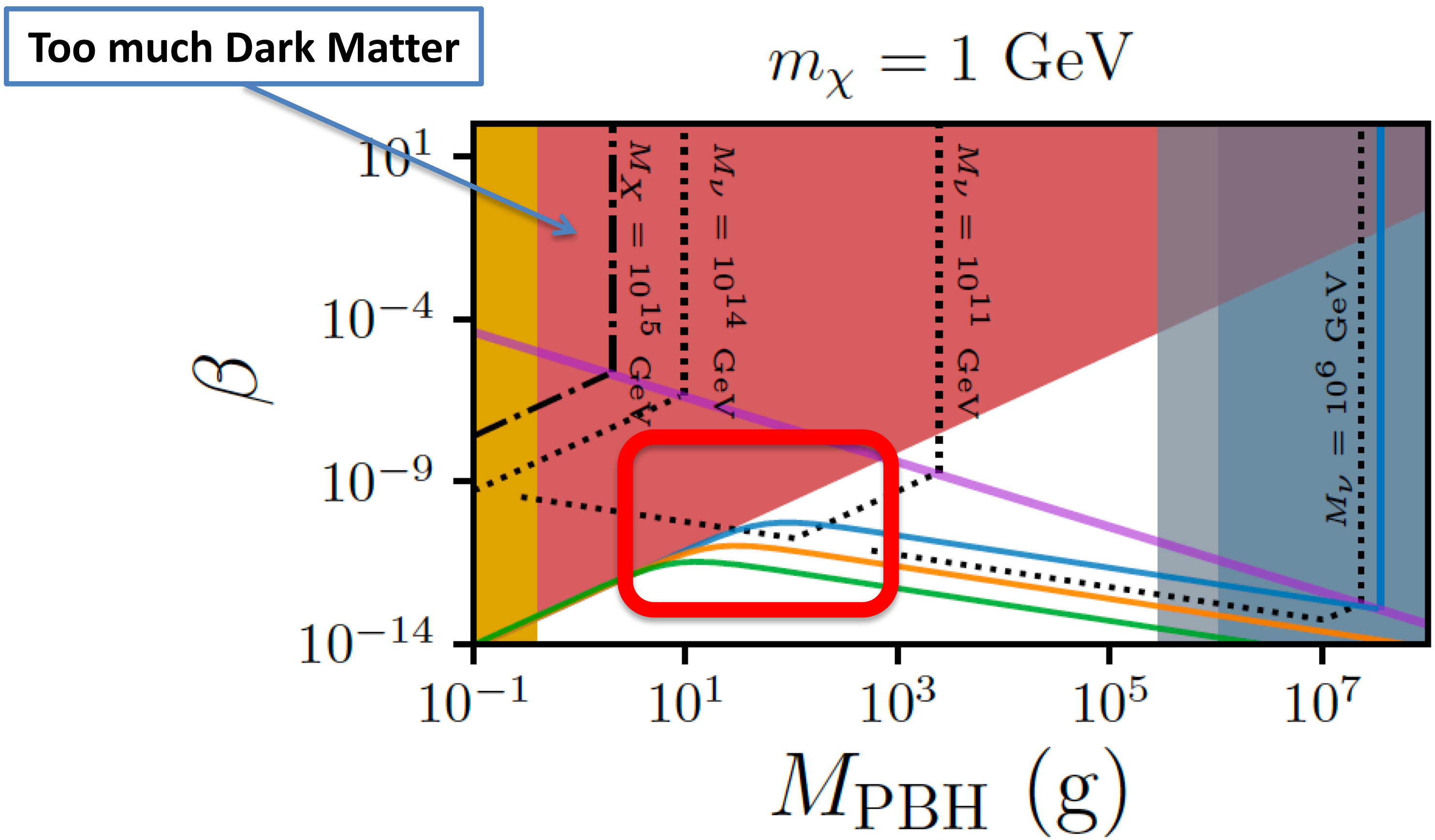
Mass (g)	T_H (GeV)	τ (s)	$T_{\rm evap} = T(\tau)$ (GeV)
$5M_P \simeq 10^{-4}$	1.7×10^{17}	10^{-41}	2×10^{17}
1	1.7×10^{13}	4×10^{-29}	2×10^{11}
10^3	1.7×10^{10}	4×10^{-20}	6×10^6
10^6	1.7×10^7	4×10^{-11}	200
10^9	1.7×10^4	0.04	0.006
10^{12}	17	$4 \times 10^7 \sim 1$ yr	~ 1 keV

* Morrison, Profumo and Yu (JCAP, 2019)

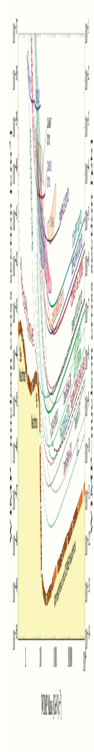


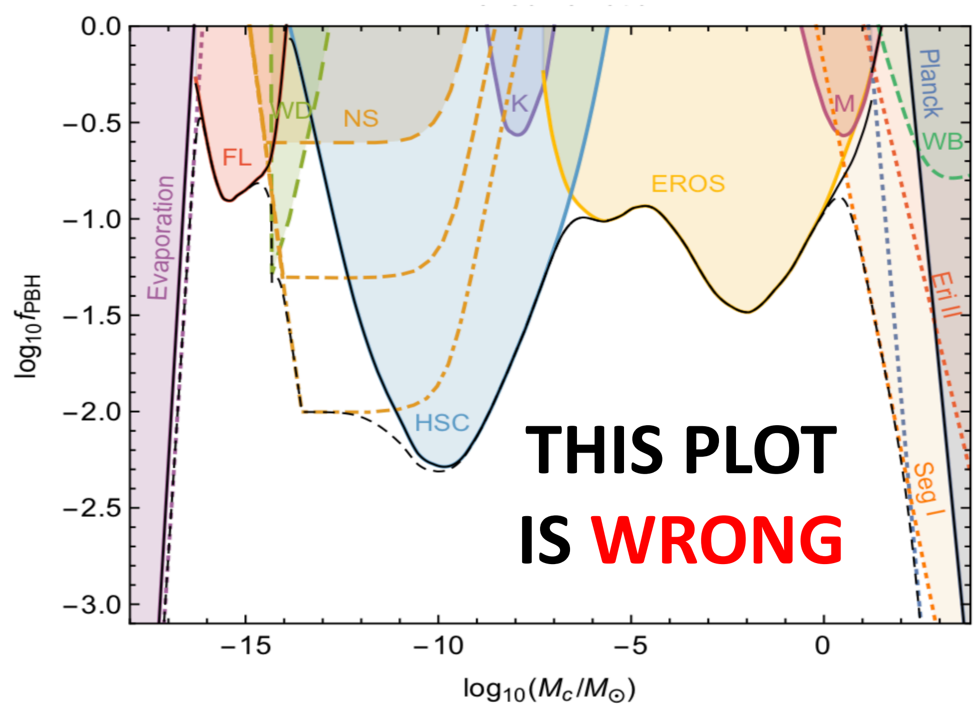
* Morrison, Profumo and Yu (JCAP, 2019)

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



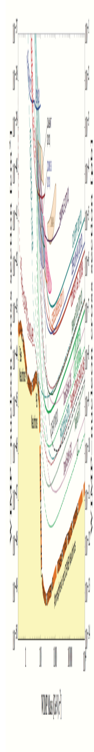
* Morrison, Profumo and Yu (JCAP, 2019)

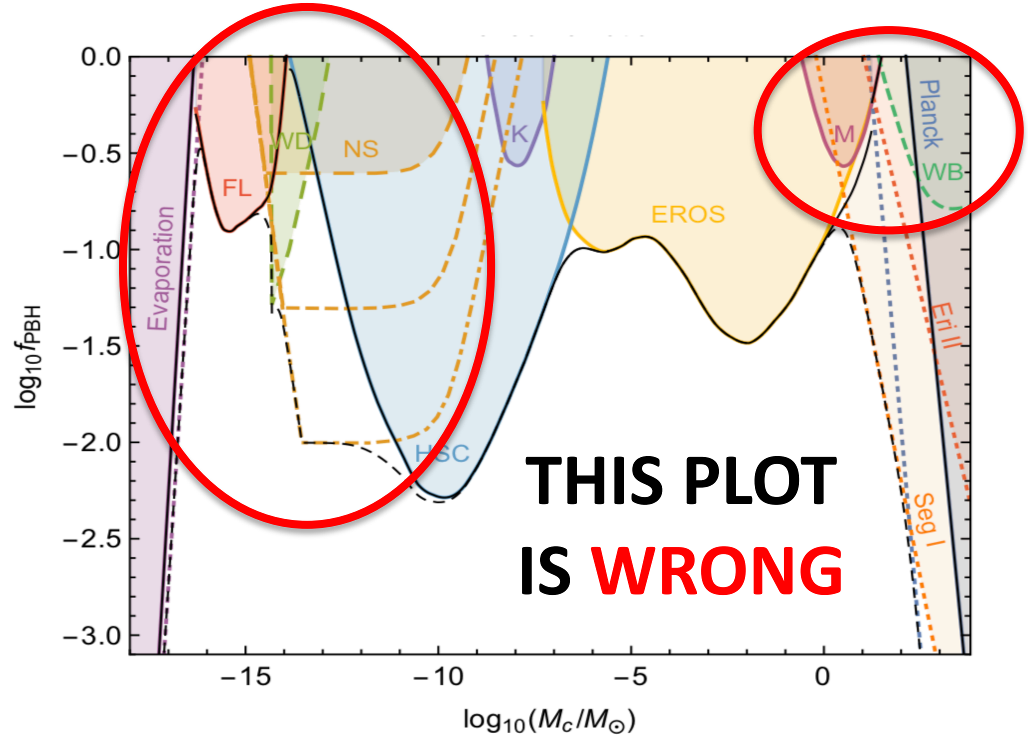




0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
$\log_{10} f_{\rm PBH}$
−15
−10
−5
0
$\log_{10}(M_c/M_\odot)$
Evaporation
FL
WD
NS
K
HSC
EROS
M
Planck
WB
Eri II
Seg I
THIS PLOT
IS WRONG

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

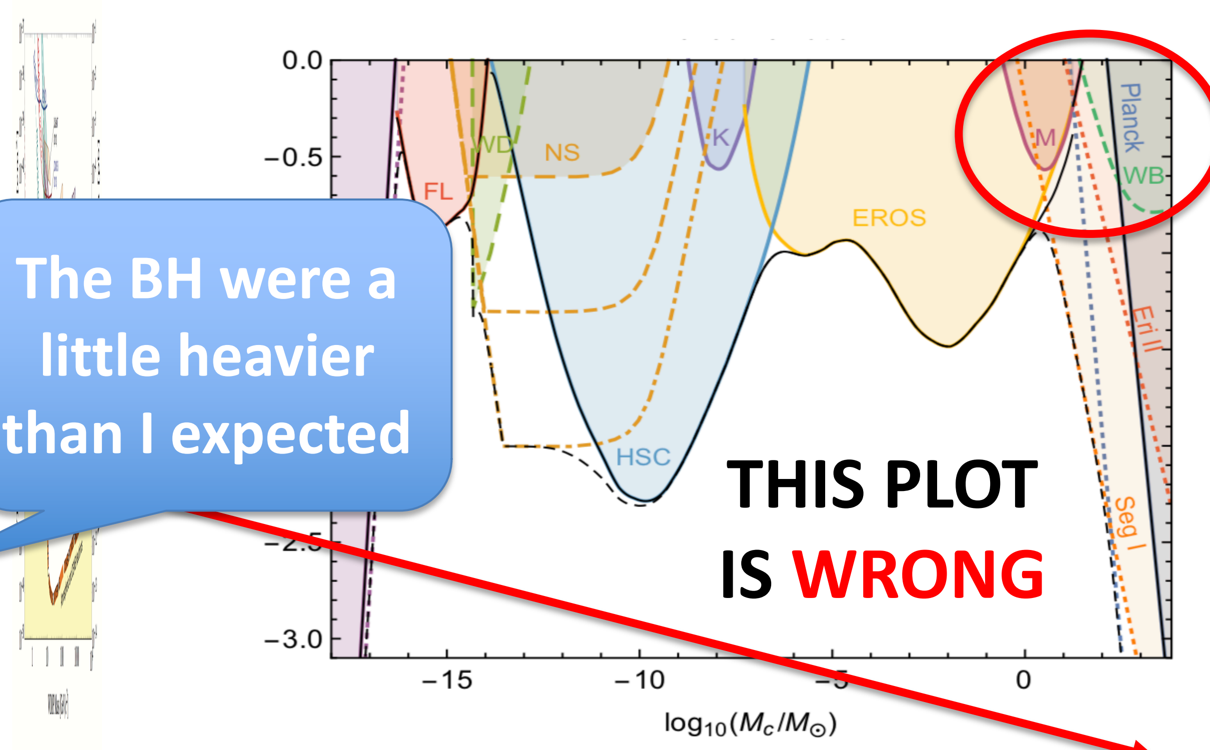




10^{-20} eV 10^{-10} eV 10^{0} eV 10^{10} eV 10^{20} eV 10^{30} eV 10^{40} eV 10^{50} eV 10^{60} eV 10^{70} eV

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

The BH were a little heavier than I expected



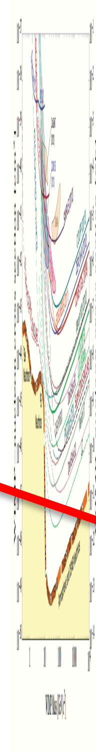
THIS PLOT IS WRONG

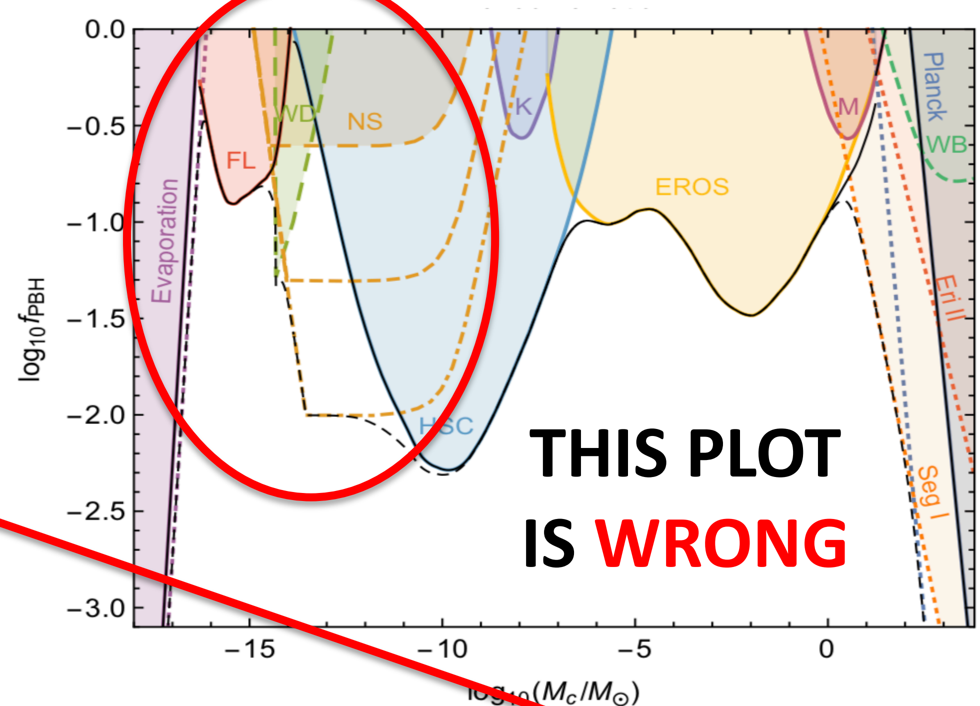
10^{-20} eV 10^{-10} eV 10^{0} eV 10^{10} eV 10^{20} eV 10^{30} eV 10^{40} eV 10^{50} eV 10^{60} eV 10^{70} eV

- ✓ **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

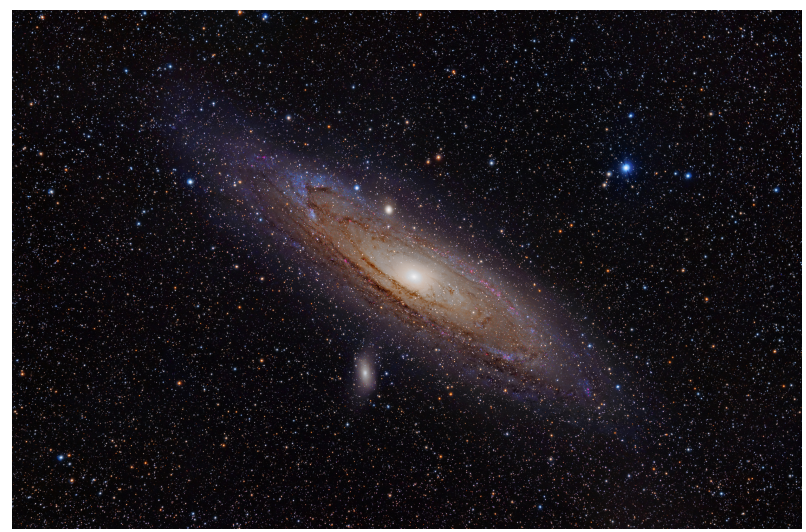
"Asteroid-Mass"
(10^{22} g)
Black Holes

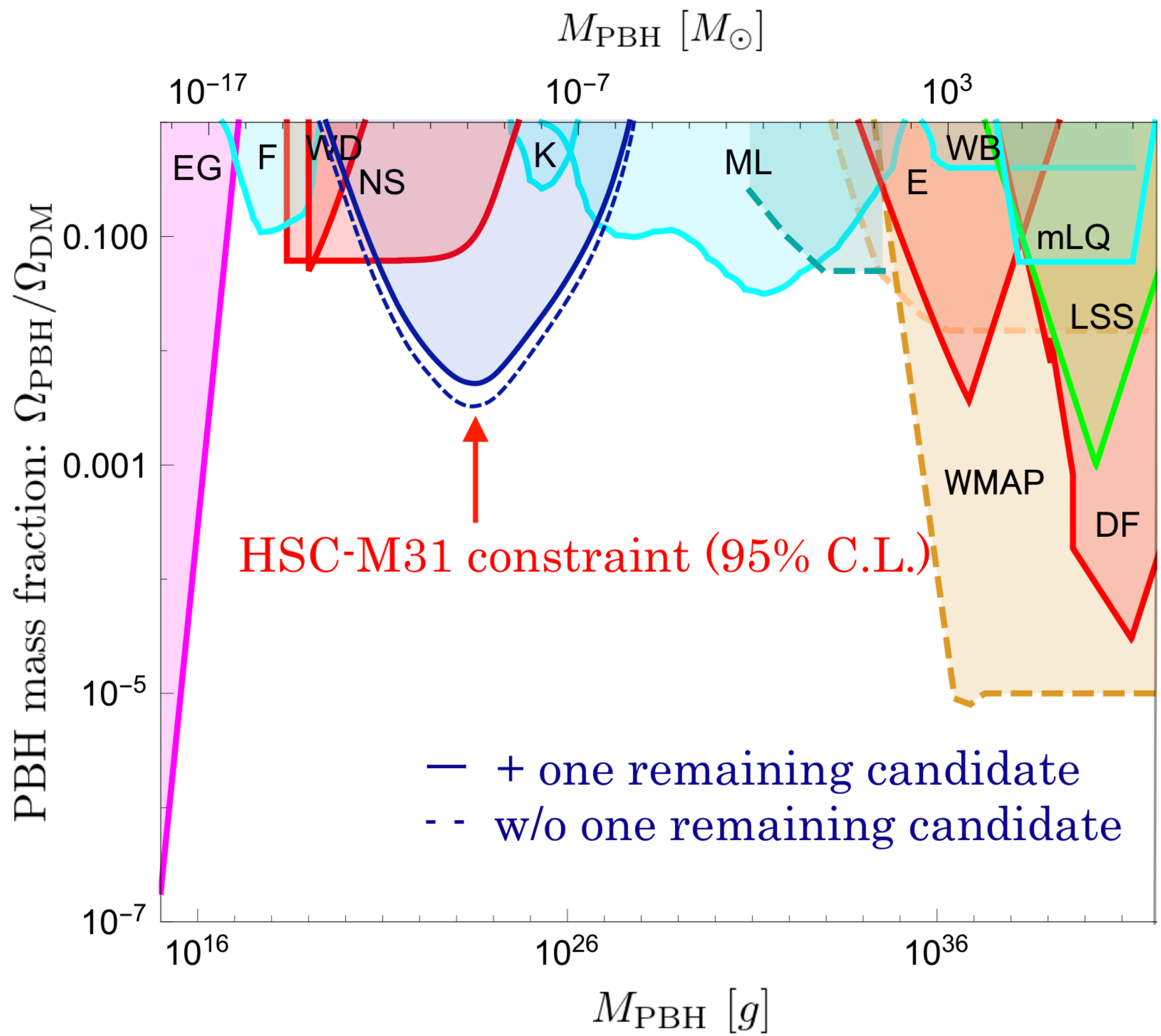




10^{-20} eV | 10^{-10} eV | 10^{0} eV | 10^{10} eV | 10^{20} eV | 10^{30} eV | 10^{40} eV | 10^{50} eV | 10^{60} eV | 10^{70} eV

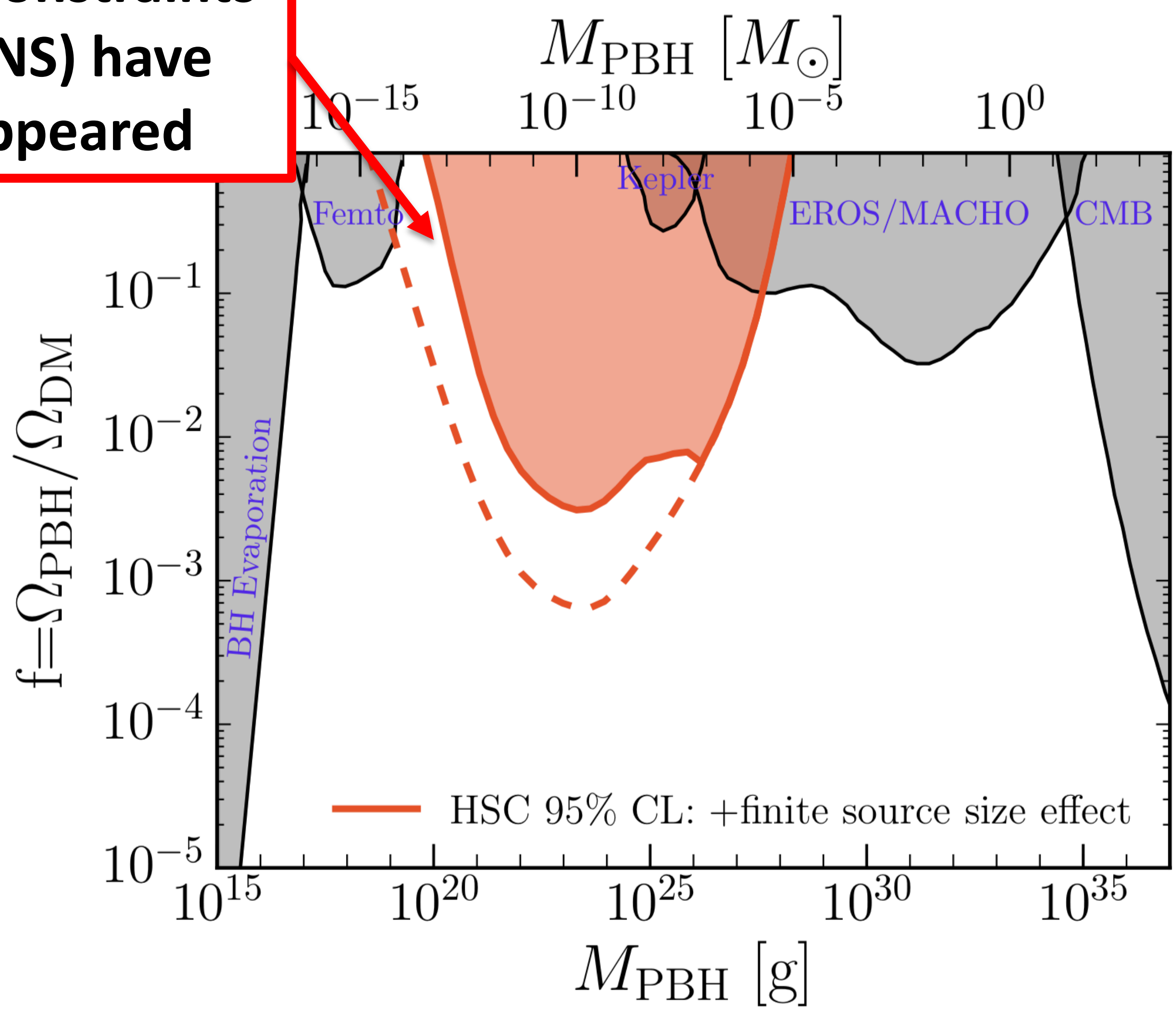
~ 7h observations of
O(10^6) stars in M31
with Subaru HSC





SUBARU HSC microlensing, 1701.02151 VERSION 1

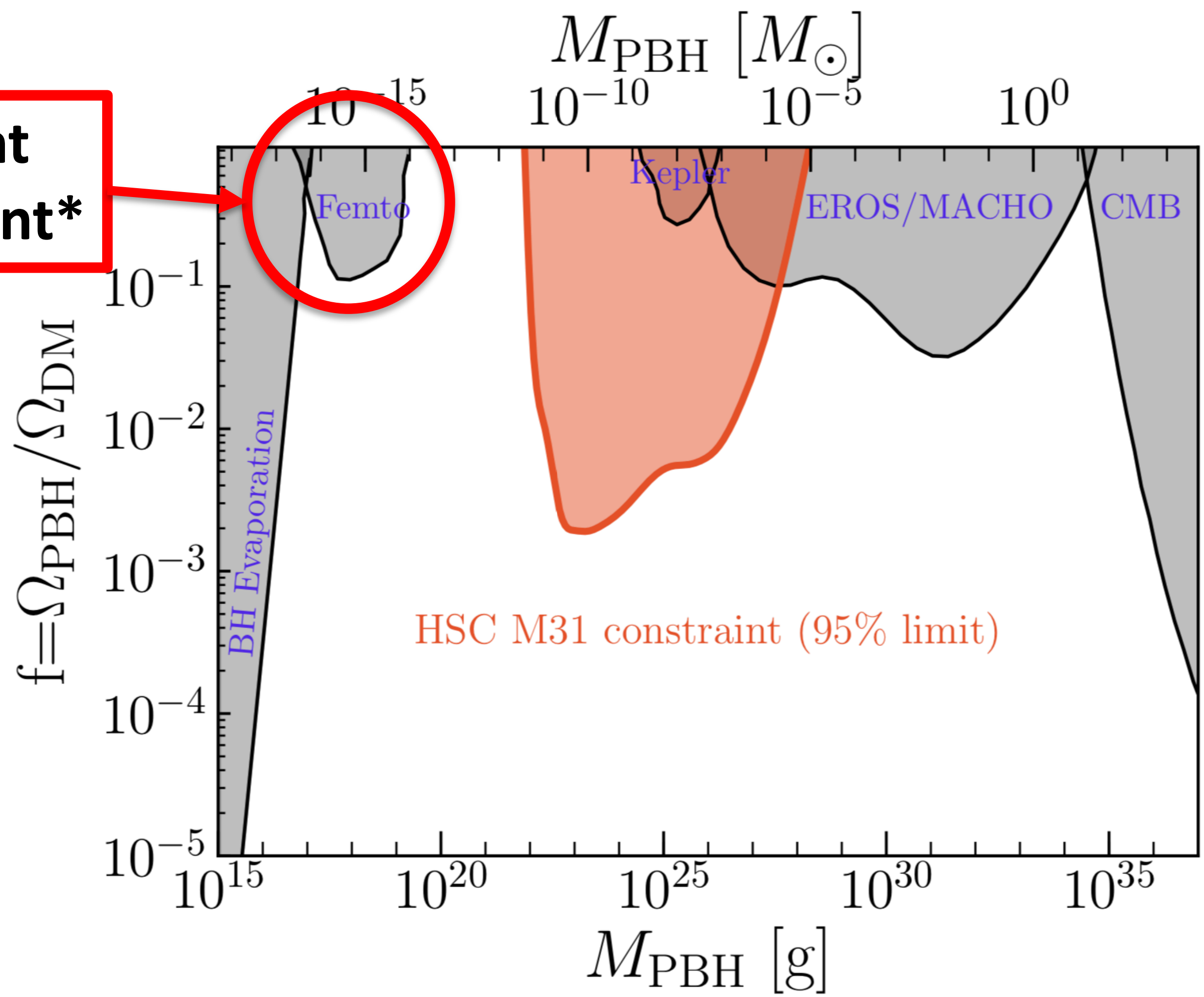
wacky constraints (WD, NS) have disappeared



SUBARU HSC microlensing, 1701.02151 VERSION 2: wave effects

* Katz et al, 1807.11495

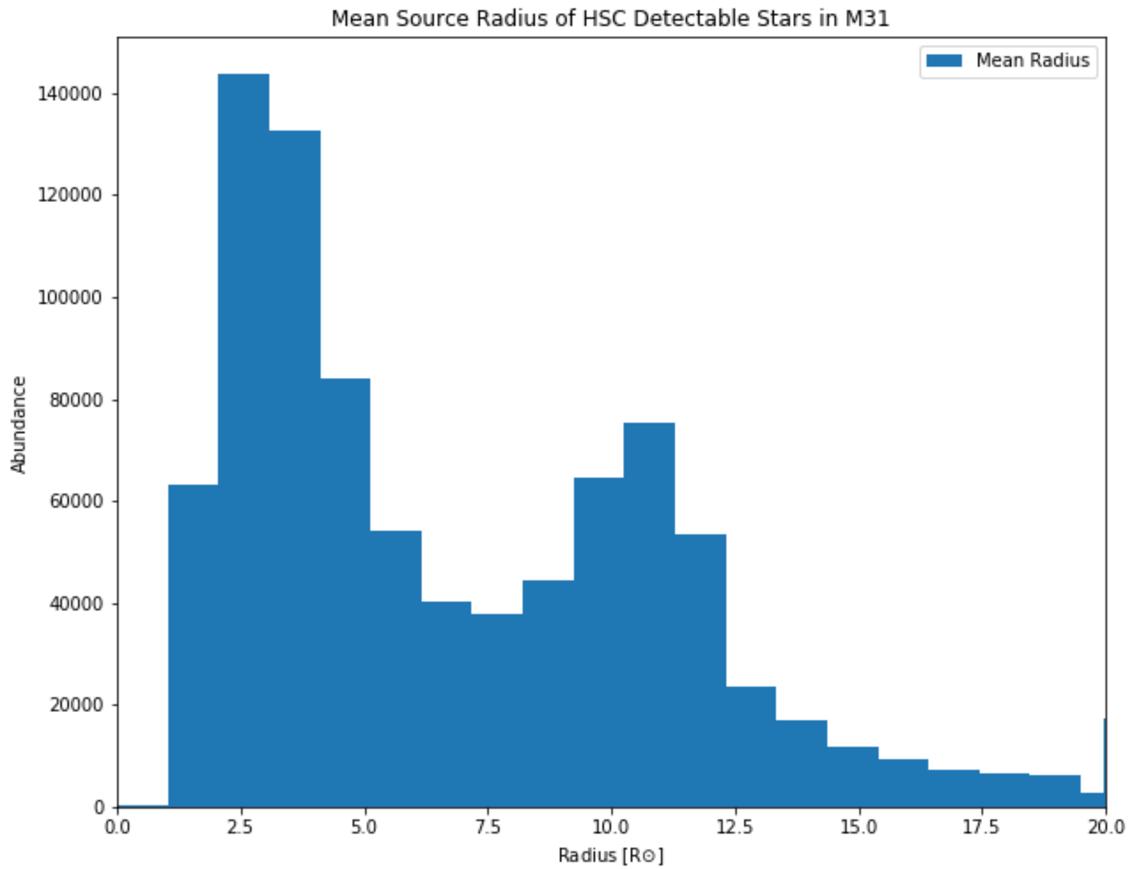
This constraint also non-existent*



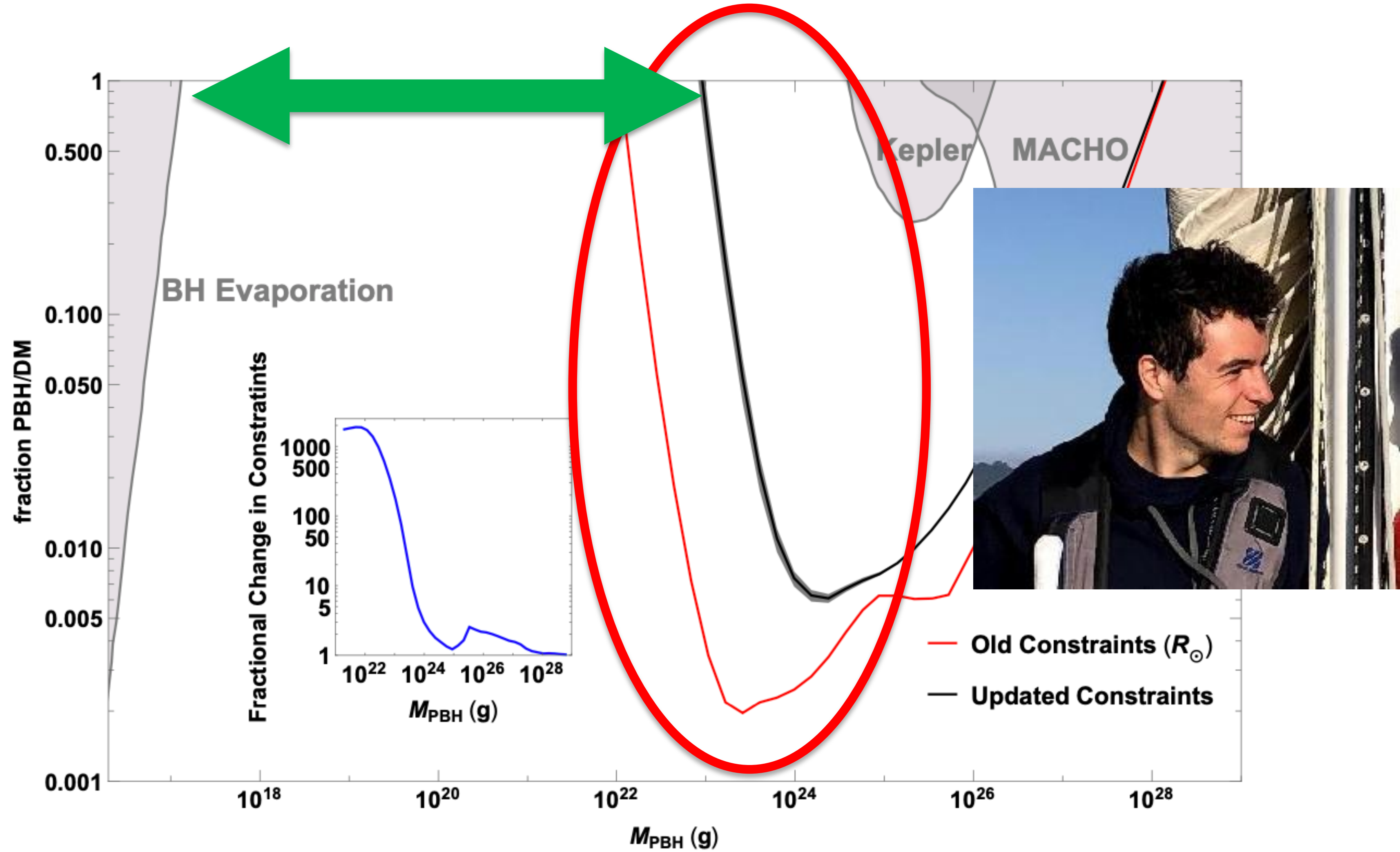
SUBARU HSC microlensing, VERSION 3: finite source AND wave effects

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

Sun-like stars are however too dim for HSC!

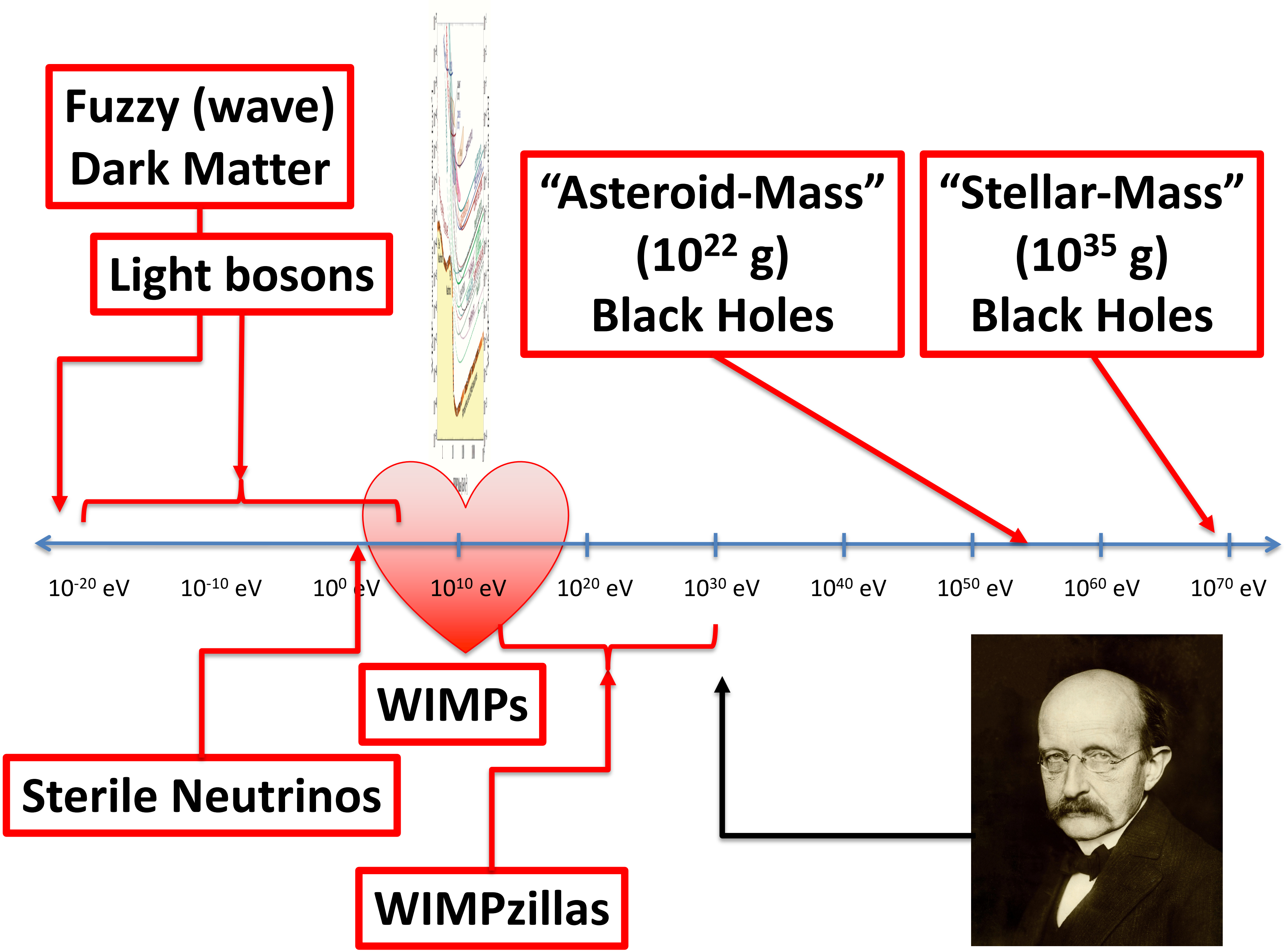


* Profumo, Smyth+ PRD 2020



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

* Profumo, Smyth+ PRD 2020



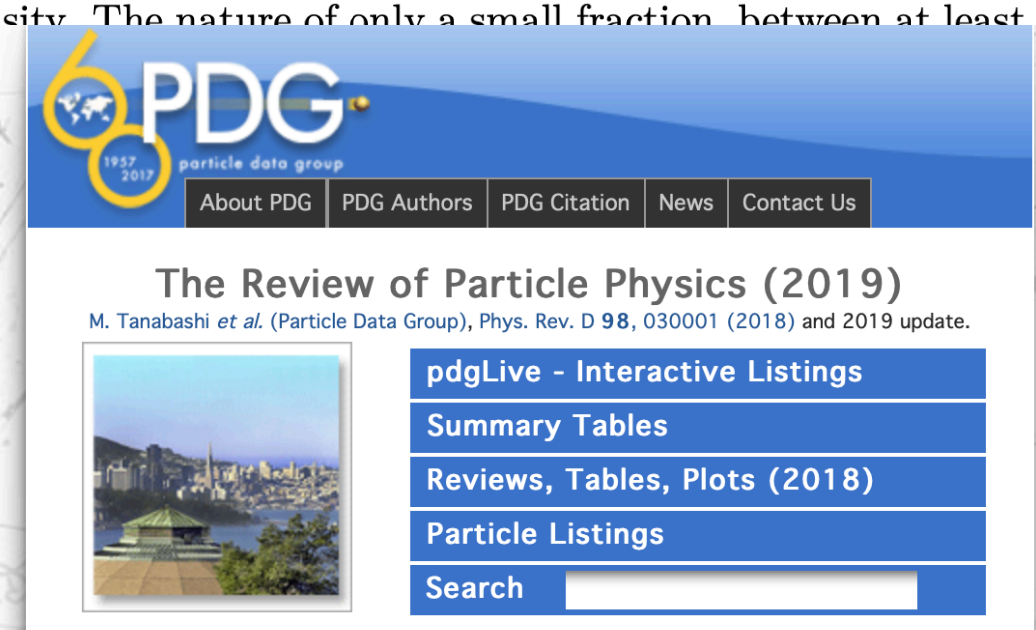
Fuzzy (wave) Dark Matter
Light bosons
"Asteroid-Mass" (10^{22} g) Black Holes
"Stellar-Mass" (10^{35} g) Black Holes
10^{-20} eV
10^{-10} eV
10^{0} eV
10^{10} eV
10^{20} eV
10^{30} eV
10^{40} eV
10^{50} eV
10^{60} eV
10^{70} eV
WIMPs
Sterile Neutrinos
WIMPzillas

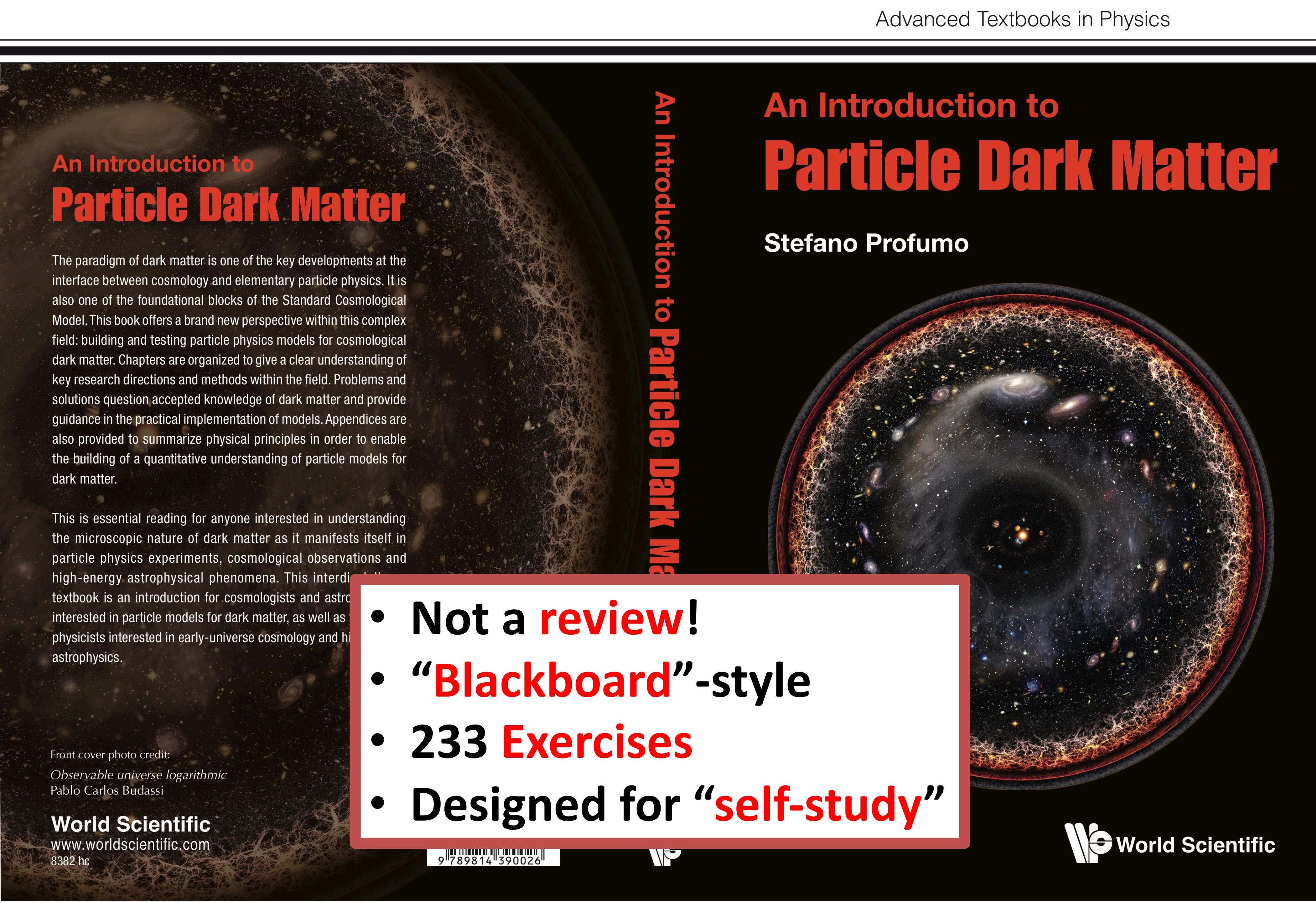
26. Dark Matter

Written August 2019 by L. Baudis (University of Zurich) and S. Profumo (UC Santa Cruz).

26.1 The case for dark matter

Modern cosmological models invariably include an electromagnetically close-to-neutral, non-baryonic matter species with negligible velocity from the standpoint of structure formation, generically referred to as "cold dark matter" (CDM; see The Big-Bang Cosmology—Sec. 21 of this *Review*). For the benchmark ΛCDM cosmology adopted in the Cosmological Parameters—Sec. 24 of this *Review*, the DM accounts for 26.4% of the critical density in the universe, or 84.4% of the total matter density. The nature of only a small fraction, between at least 0.5% (given neutrino os-





- Not a **review**!
- “**Blackboard**”-style
- 233 **Exercises**
- Designed for “**self-study**”