# Abstract

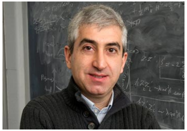
The particle nature of dark matter is not well understood. The one thing that is well understood is that its mass is bounded from above at $\sim 100\ M_\odot$ and below at $\sim 10^{-22}$ eV. In addition, fermionic DM is thought to be bounded from below at $\sim 100$ eV by the Pauli exclusion principle. In this talk, I will discuss a simple way to push down the bound on fermionic DM by considering a scenario with a large number of species. Fermionic DM cannot be as light as bosonic DM because the vast number of species required ($\sim 10^{100}$) provides problems for cosmic rays, the LHC, BH evaporation, BH superradiance, early universe constraints, and others. I will present estimates of these constraints on the mass and number of species of particles. Combining all of this relaxes the bound on fermionic DM by $\sim 16$ orders of magnitude.

# Ultra-light fermionic dark matter

Peter B. Denton

Workshop on Asymptotic Safety and Dark Matter

December 9, 2020



2008.06505

with Hooman Davoudiasl and David McGady

BROOKHAVEN
NATIONAL LABORATORY

# Dark matter: what we know

**Astrophysically/gravitationally**: lots

See many of yesterday's talks

**Particle nature**:

- Coupling to SM/self? Could be zero (other than gravity)
- Heavier than $\sim 100\ M_\odot$ leads to tidal disruption effects
- Lighter than $\sim 10^{-22}$ eV, at $v \sim 10^{-3}$, Compton wavelength is too big
  - Core/cusp suggests $\sim 10^{-22} - 10^{-21}$ eV
- Fermionic DM lighter than $\sim 100$ eV can't be squeezed into a galaxy

S. Tremaine, J. Gunn PRL 42, 407 (1979)

See P. Fox's overview talk yesterday

See M. Fairbairn's talk an hour ago

# Outline

1. Fermionic dark matter **can** be lighter than 100 eV
2. New limits arise from LHC, cosmic rays, black holes, ...
3. Strong gravity becomes important
4. How many species of particles are there?

# Light fermionic dark matter

Light fermionic dark matter $m < 100$ eV can't be squeezed into galaxies

Two issues:

1. Getting light thermal population into low momentum states is difficult
2. Pauli exclusion principle

S. Tremaine, J. Gunn PRL 42, 407 (1979)

Focus on #2

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S. Tremaine, J. Gunn PRL 42, 407 (1979)

Focus on #2

Modern treatments find that the limit is

- 100 eV — C. Di Paolo, et al. 1704.06644
- 190 eV ($2\sigma$) — D. Savchenko, A. Rudakovskyi 1903.01862
- 130 eV ($2\sigma$) — J. Alvey, et al. 2010.03572

# Evading Tremaine-Gunn

Dark matter could be composed of many different species

The correct bound on light fermionic DM:

$$N_F \gtrsim \left(\frac{100 \text{ eV}}{m}\right)^4$$

- One power: lighter DM requires more species
- Three powers: phase space

So 1 eV fermionic DM is possible if there are $N_F \gtrsim 10^8$ species.

# Caveats

1. Focused on late time DM effects
2. Numbers are correct to within a factor of 2 (or a factor of 10)

Require no interactions

# “Model”

Different species can be degenerate:

$$\mathcal{L} \supset -m \sum_{i=1}^{N_F} \bar{\chi}_i \chi_i$$

Perhaps SU($\sqrt{N_F}$) which leads to quasi-degenerate states:

$$\frac{m_i - m_j}{m_1} \sim \frac{\lambda^2}{16\pi^2} \log \frac{m_1}{\Lambda}$$

$m_1$ is the lightest mass

L. Randall, J. Scholtz, J. Unwin 1611.04590

Perhaps Kaluza-Klein modes:

Constraint is more complicated

# Extrapolation!

Let's extrapolate this as far as possible!

$m \gtrsim 10^{-22}$ eV $\Rightarrow N_F \gtrsim 10^{96}$

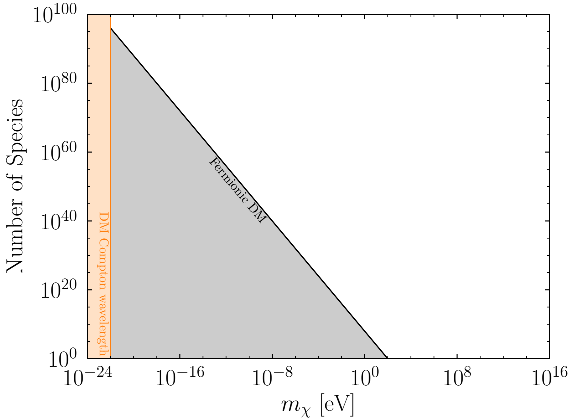
How many DM particles would there be in a galaxy in this case?

Dwarf spheroidals have $\sim 10^{96}$ DM particles if $m \sim 10^{-22}$ eV

Coincidence

Below this the fourth power scaling law drops to $N_F \gtrsim (\frac{100 \text{ eV}}{m})^1$

No more Pauli exclusion



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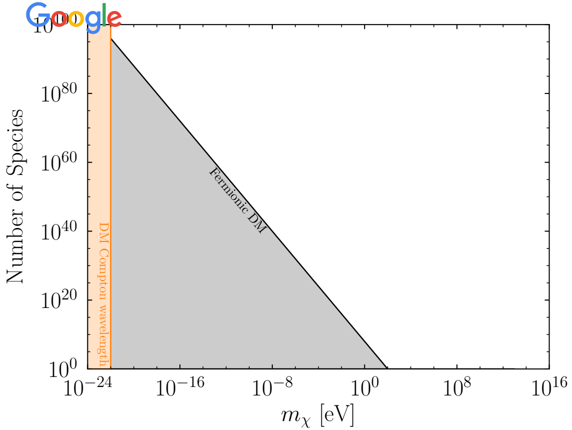

# Too many species

Claim:

$$10^{96} \text{ species is Too Many}$$

SM has $10^2$ species

From now it doesn't matter:

1. if the species are DM,
2. if they are fermions, or
3. if their masses are degenerate

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Gravitational effects are suppressed by $M_P$, but enhanced by $N$

$$\sum_i^N \sigma_i \sim N \frac{E^2}{M_P^4}$$

# Cosmic ray constraints

Highest energy collisions recorded are UHECRs

Telescope Array and the Pierre Auger Observatory see a suppression at $10^{19.5}$ eV

O. Deligny for TA and Auger 2001.08811

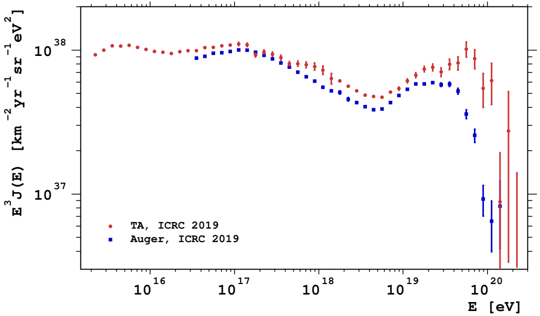
Could be photo-pion production (GZK)

K. Greisen PRL 16, 748 (1966)

G. Zatsepin, V. Kuzmin JETP Lett. 4, 78 (1966)

Could be end of sources

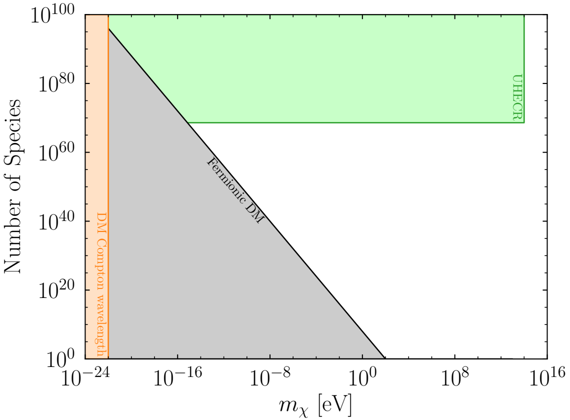
See e.g. R.A. Batista, et al. 1903.06714



# Cosmic ray constraints

Can use cosmic rays to constrain large number of species

1. As $N$ increases, $BR(pp \to \chi\chi) \to 1$
2. Showers would be reconstructed at a lower energy
3. There would appear to be a suppression to the flux
4. No suppression is seen below $E_{\rm LAB} \sim 10^{19.5}$ eV ($\sqrt{s} = 250$ TeV)




$$N \lesssim 4 \times 10^{68} \qquad \text{for} \qquad m \lesssim 100 \text{ TeV}$$

# LHC

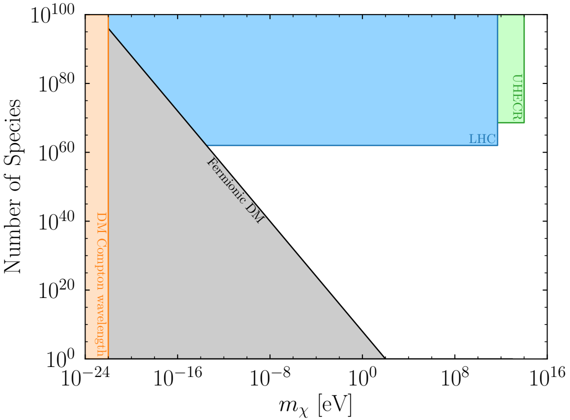
Lower energy, better precision

- Searches for monojets
- Detected 245 events with $E_T^{miss} > 1$ TeV
- Expected 238±23
  - Mostly $Z \to \nu\nu$ with ISR or brem

ATLAS 1711.03301

- $G \to \chi\chi$ looks the same
- Include 3-body $(4\pi)^{-3}$ factor

$$N \lesssim 10^{62} \qquad \text{for} \qquad m \lesssim 500 \text{ GeV}$$

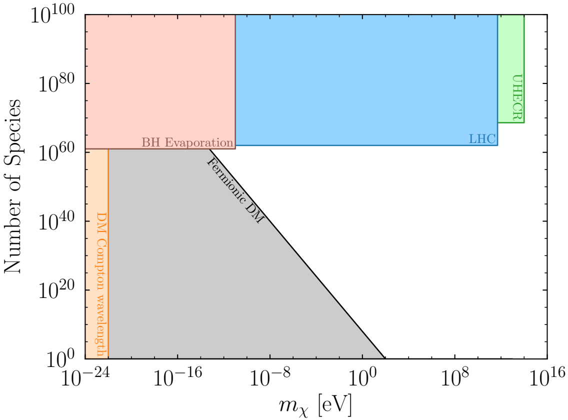



100 TeV will improve by $\sim$ 2+ orders of magnitude

# BH evaporation

- $t_{evap} \sim \frac{10^{67}}{N}\left(\frac{M_{BH}}{M_\odot}\right)^3$ yr
- We assume that $M_{BH} \sim 10 M_\odot$ have been around for $\sim 10^9$ yr
- $10 M_\odot \to T_{BH} \sim 10^{-11}$ eV

$$N \lesssim 10^{61} \qquad \text{for} \qquad m \lesssim 10^{-11} \text{ eV}$$



Fermionic DM can be as light as $\sim 10^{-13}$ eV

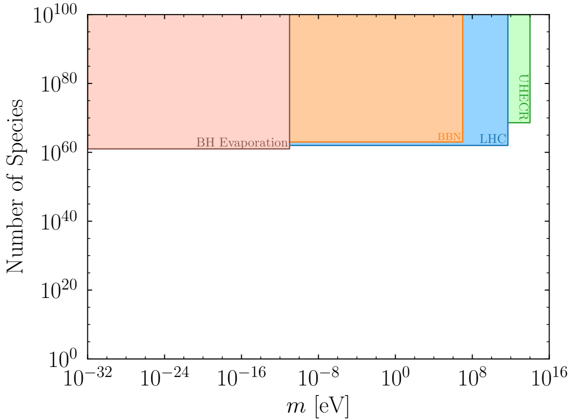
Need $\sim 10^{61}$ quasi-degenerate species

These constraints apply regardless of whether it is DM, fermionic, or quasi-degenerate

# BBN

Low energies but high densities

- New states populated via gravity in the early universe
- Don't want $\rho_\chi \gtrsim \rho_\gamma$
- $\rho_\chi/\rho_\gamma \sim NT^3/M_P^3$
- Implies a maximum reheat temperature
- BBN requires $T_{rh} \gtrsim 10$ MeV



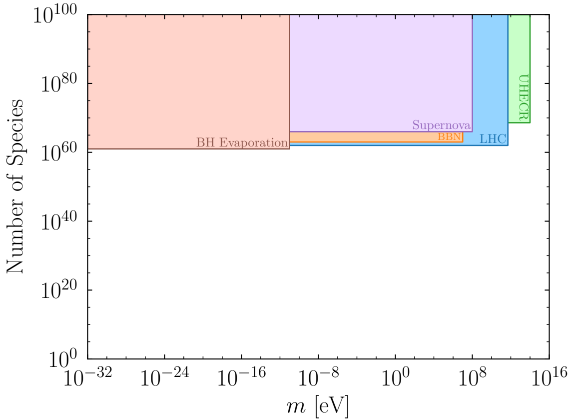

$N \lesssim 10^{63}$ for $m \lesssim 10$ MeV

# Supernovae

Low energies but high densities and more measurements

- Neutrino production $\sigma_\nu \sim E^2 G_F^2$
- Dark sector production $\sigma_\chi \sim N E^2 / M_P^4$
- Can't have a significant amount of energy to dark sector
- $N \lesssim G_F^2 M_P^4$

$$N \lesssim 10^{66} \qquad \text{for} \qquad m \lesssim 100 \text{ MeV}$$



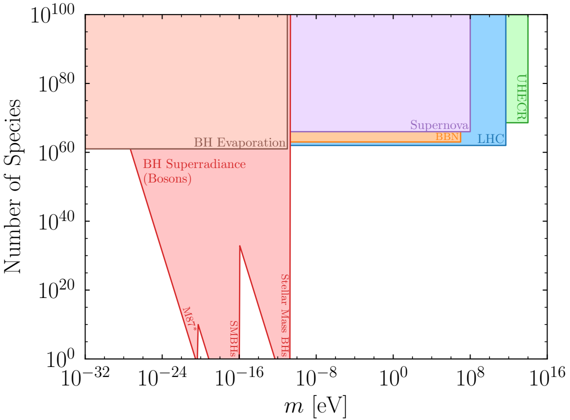
# Superradiance with bosons

Narrow applicability range, apply down to $N_B = 1$ for bosons

- Power law for small masses $m^{-9}$
- Exponential for large masses
- Conservatively take constraints on $S = 0$
- Different regions are distinct constraints

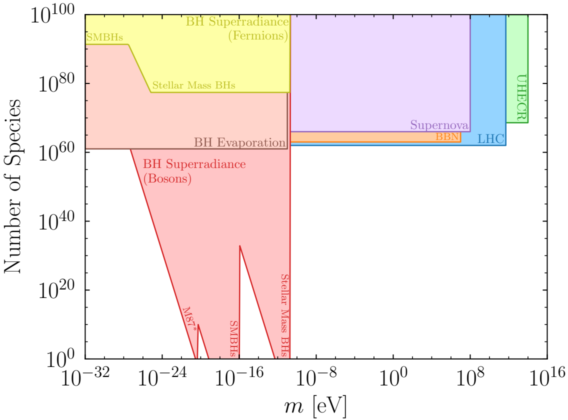
H. Davoudiasl, PBD 1904.09242

M. Baryakhtar, R. Lasenby, M. Teo 1704.05081



# Superradiance with fermions

- Power law for small masses $m^{-6}$
- Exponential for large masses
- Conservatively take constraints on $S = \frac{1}{2}$
- Different regions are distinct constraints
- If $N_F \lesssim$ cloud occupation number, superradiance stops
  - Occupation number $\sim 10^{77}$ for stellar mass BH



# Superradiance combinatorics

Assumed that generating $N_F$ particles out of $N_F$ species yields $N_F$ distinct species

Just because a large number of particles spanning a large number of species are produced doesn't mean that they are actually different

The expected number of distinct species is

$$N_F \left[1 - \left(\frac{N_F - 1}{N_F}\right)^{N_F}\right] \to N_F \left(1 - \frac{1}{e}\right) \approx 0.63 N_F$$

Less than factor of two $\Rightarrow$ we're good

# Neutrino oscillations

If neutrinos get mass via usual seesaw, can write down:

$$\xi_i H^* \bar{\ell} \chi_i$$

leads to oscillations

$$P(\nu_\ell \to \chi_i) \sim \frac{\xi_i^2 \langle H \rangle^2}{m_\nu^2} \sin^2\left(\frac{m_\nu^2 L}{4E}\right)$$

Assume $m_{\nu,\text{lightest}}$ is not too light

$\langle H \rangle^2 / m_\nu^2 \sim 10^{24}$

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To be competitive with LHC, need $\xi_i \gtrsim e^{-97}$

Instanton effects should suppress by $\sim e^{-100}$

L. Abbott, M. Wise NPB 325, 687 (1989)

R. Kallosh, et al. hep-th/9502069

P. Svrcek, E. Witten hep-th/0605206

H. Davoudiasl 2003.04908

L. Hui, et al. 1610.08297

# Proton decay

One can write down this proton decay operator

$$\mathcal{O} \sim \frac{udd\chi_i}{M_P^2}$$

$$\Gamma(p \to \pi^+ + \chi) \sim N_F \frac{m_p^5}{M_P^4}$$

$$N_F \lesssim 10^{12} \qquad \text{for} \qquad m \lesssim 100 \text{ MeV}$$

If there is an associated global $U(1)$ charge, an instanton would suppress this rate by $e^{-200} \sim 10^{87}$

# Strong gravity

Literature suggests that at $N \sim 10^{32}$ something happens with strong gravity

G. Dvali 0806.3801

I. Antoniadis, et al. hep-ph/9804398

S. Adler PRL 44, 1567 (1980)

N. Arkani-Hamed, S. Dimopoulos, G. Dvali hep-ph/9807344

X. Calmet, S. Hsu, D. Reeb 0803.1836

G. Dvali, M. Redi 0905.1709

A. del Rio, R. Durrer, S. Patil 1808.09282

$N \sim 10^{32}$ species with $m \lesssim 1$ TeV may pull $M_P$ to electroweak

According to Dvali or Adler:

$$G^{-1}(\mu) \sim G^{-1}(0) - Nm^2 \log \frac{\mu^2}{m^2}$$

$G^{-1}(0) = M_P^2$

This leads to

$$m\sqrt{N} \lesssim M_P$$

Calmet:

$$G^{-1}(\mu) \sim G^{-1}(0) - \frac{N\mu^2}{12\pi}$$

# Summary

- The “number of species” axis for DM is interesting
- Fermionic DM can be as light as $10^{-13}$ eV with key constraints from BH lifetimes and the LHC
- Many similar constraints on the number of species from cosmic rays, LHC, BH lifetimes, BBN, and SNe
- Certain DM considerations leads to strong gravity questions
- More work to be done on this topic in many directions: pheno and theory

# Thanks!

# Backups

# Superradiance

Rotating BHs will create particles on-shell out of the vacuum:
Extracts angular momentum

Y. Zeldovich JETP Lett. 14, 180 (1971)

Conceptually similar to Hawking and Unruh radiation

Phenomenologically: BHs can constrain the *existence* of bosons, independent of coupling

A. Arvanitaki, et al. 0905.4720

A cloud of particles forms around the BH $\Rightarrow$ no fermions*

Care is needed for axions

# Superradiance

Boson cloud growth rate:

$$\Gamma_0 = \frac{1}{24} a^* G^8 M^8 \mu_B^9 \,, \qquad \Gamma_1 = 4a^* G^8 M^8 \mu_B^7$$

$a^* \equiv J/GM^2 \in [-1, 1]$

Leading to an occupation number after spinning down $\Delta a^*$:

$$N = GM\Delta a^*$$

Superradiance depletes the spin of a BH if:

$$e^{\Gamma_B \tau_{\rm BH}} > N$$

$\tau_{\rm BH} \sim$ time to spin the BH back up

Wavelength has to enter into the ergosphere:

$$\mu_B > \Omega_H$$

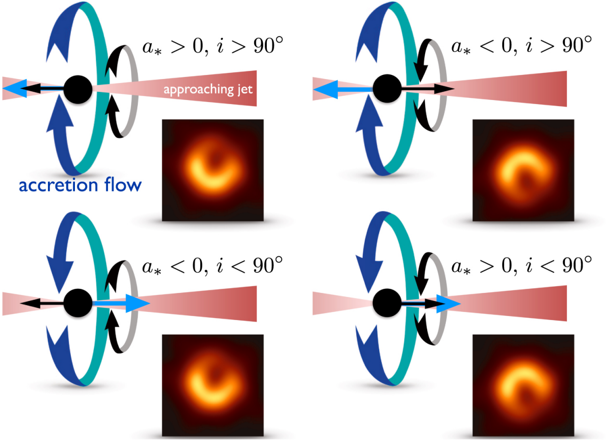
Angular velocity:

$$\Omega_H \equiv \frac{1}{2GM} \frac{a^*}{1 + \sqrt{1 - a^{*2}}}$$

Only include dominant
$m = 1$ spherical harmonic mode

M. Baryakhtar, R. Lasenby, M. Teo 1704.05081

# Spin




EHT: ApJL 875 L5 (2019)

- EHT can infer the spin
- Some degeneracies with disk properties
- EHT (conservative): $|a^*| \gtrsim 0.5$
- Twisted light: $|a^*| = 0.9 \pm 0.05$ at 95%

  F. Tamburini, B. Thidé, M. Valle 1904.07923

  rules out $a^* = 0$ at 6 $\sigma$
- Circularity: No real power yet

  C. Bambi, et al. 1904.12983

**If a BH with large $|a^*|$ is measured, it could not have spun down much**

# Time scale

Astrophysics can spin the BH back up, possibly faster than superradiance

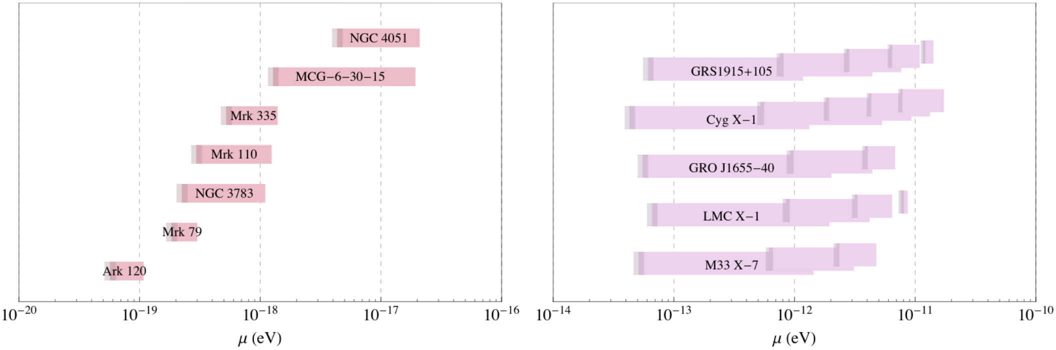
- From the Eddington limit, $\tau_{\rm Salpeter}\sim4.5\times10^7$ yrs
- EHT: $\dot M_{\rm M87^*}/\dot M_{\rm Edd}\sim2\times10^{-5}$
- Mergers: one $\sim10^9$ yrs ago with a much smaller galaxy

A. Longobardi, et al. 1504.04369

- $\mu_B$ constraint has very weak dependence: $\tau_{\rm BH}^{-1/7}$ or $\tau_{\rm BH}^{-1/9}$

We take $\tau_{\rm BH}=10^9$ yrs

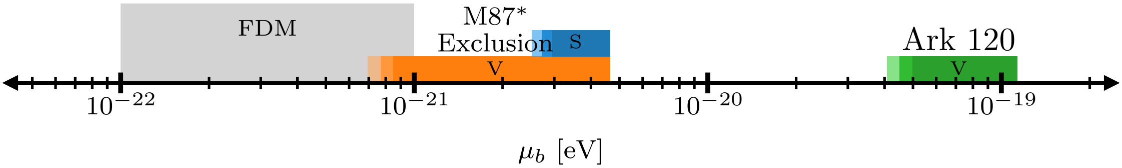
# Past ultra light boson constraints




Spin-1 constraints

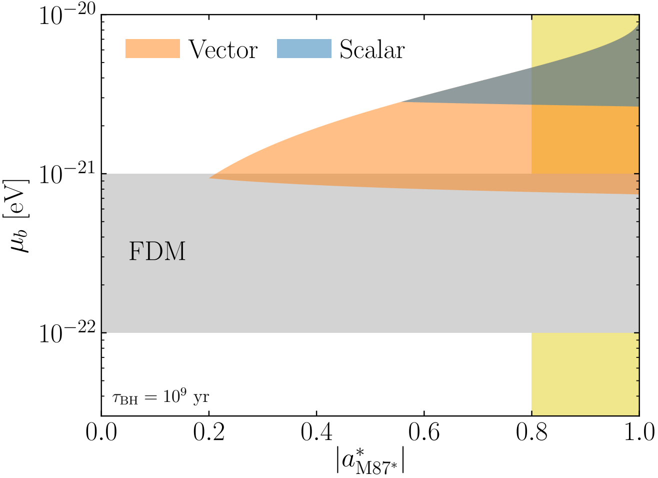
M. Baryakhtar, R. Lasenby, M. Teo 1704.05081

# New constraints from M87*



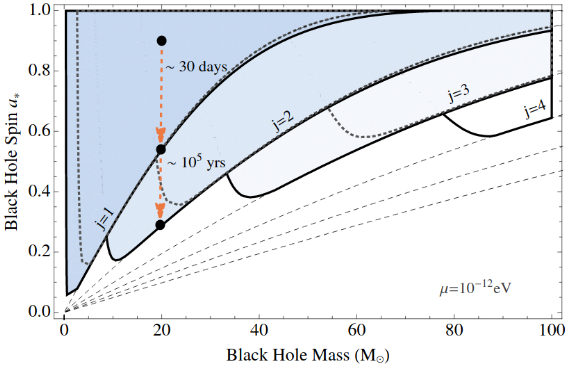

Bosons with masses in the regions in color are ruled out.

# Spin dependence



# Superradiance Spin-down

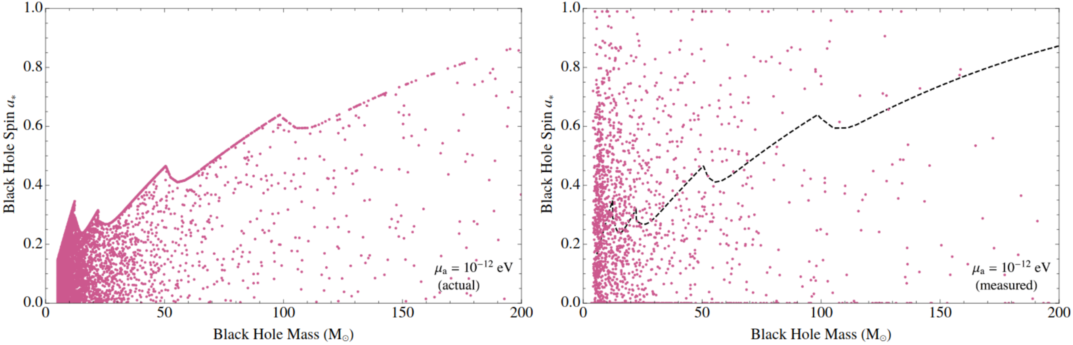
Different spherical harmonic modes leads to different maximum spins




Vector (scalar) in bold (dotted) for $\mu_B = 10^{-12}$ eV

M. Baryakhtar, R. Lasenby, M. Teo 1704.05081

# How to detect ultra light bosons with superradiance




Vector with $\mu_B = 10^{-12}$ eV

$\sigma_{a^*} \sim 0.3$, $\sigma_M/M \sim 10\%$

M. Baryakhtar, R. Lasenby, M. Teo 1704.05081

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# Strong gravity: deviations

A running in $G$ would lead to variations in gravity on different scales

$$\frac{\delta G}{G} \lesssim 10^{-9} \qquad \text{for} \qquad \ell \gtrsim 10^3 \text{ km} \to 10^{-13} \text{ eV}$$

P. Fayet 1712.00856

S. Schlamminger, et al. 0712.0607

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At $N \sim 10^{60}$ and $m \sim 10^{-3}$ eV consistent with theory arguments on previous slide

$$\Rightarrow \frac{\delta G}{G} \sim 10^{-2} \qquad \text{for} \qquad \ell \sim 0.1\ \text{mm}$$

Close to current constraints

J. Lee, et al. 2002.11761

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