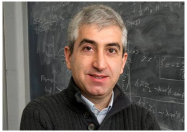
Abstract

Dark matter (DM) is known to interact gravitationally. If it is ultralight then there will be unique macroscopic effects that may be probable in the same environments that we see the evidence for DM. I will discuss how ultralight DM can be fermionic, evading the Tremaine-Gunn bound, and the new relevant constraints including those from supermassive black holes. Finally, I will present a specific model that addresses some interesting hints/anomalies in terms of early supermassive black hole formation, ultrafaint dwarf galaxies, and possible gravitational wave signatures.

Connecting the Extremes: A Story of Supermassive Black Holes and Ultralight Dark Matter



Peter B. Denton

UCSD

October 21, 2024

1904.09242 w/ Hooman Davoudiasl
2008.06505 w/ Hooman Davoudiasl and David McGady
2109.01678 w/ Hooman Davoudiasl and Julia Gehrlein

Brookhaven™ National Laboratory

Outline

Superradiance, M87*, ultralight bosons, fuzzy DM

1. Superradiance probes the existence of ultralight bosons
2. M87* provides constraints
3. Relevant for fuzzy DM

Ultralight fermionic DM

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?

A model at 10 keV

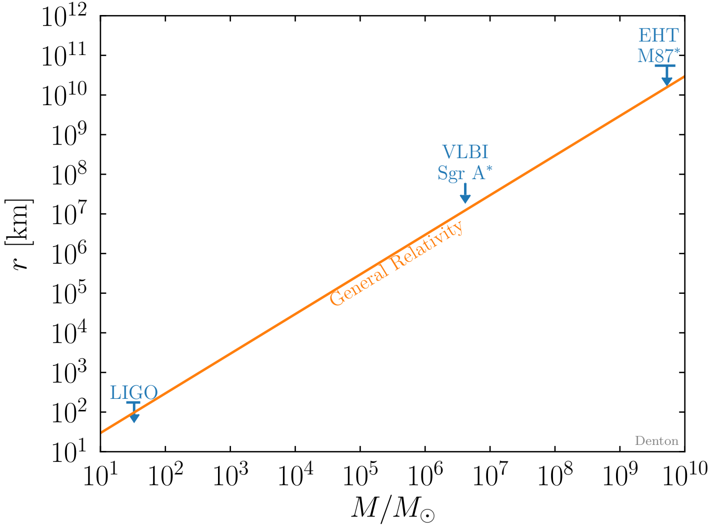
1. Early production of supermassive black holes
2. Axion dark matter
3. Gravitational waves

Superradiance, M87*, Fuzzy DM

Event Horizon Telescope: ApJL 875 L1 (2019)

What is this good for?

Black holes seem to follow $r \propto M$ over a huge range of masses



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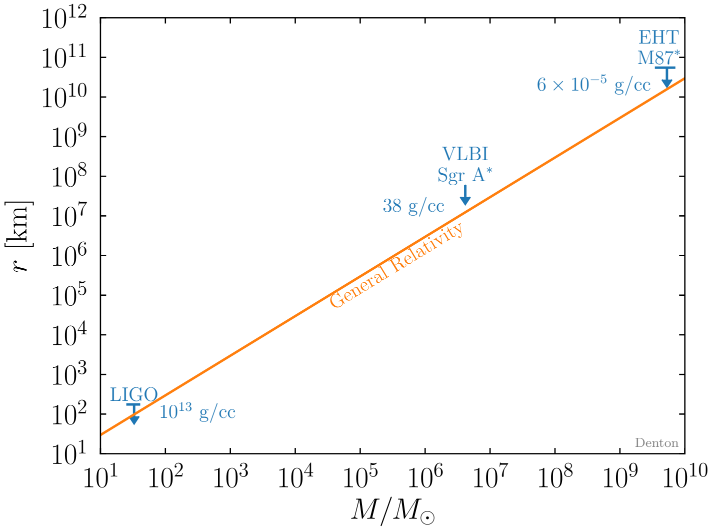


Superradiance

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 ⇒ no fermions[1]

Care is needed for axions[2]

[1]See slide 16

[2]See slide 50

Superradiance

Boson cloud growth rate:

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

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

Leading to an occupation number after spinning down Δa^*:

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

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:

$$\mu_B > \Omega_H$$

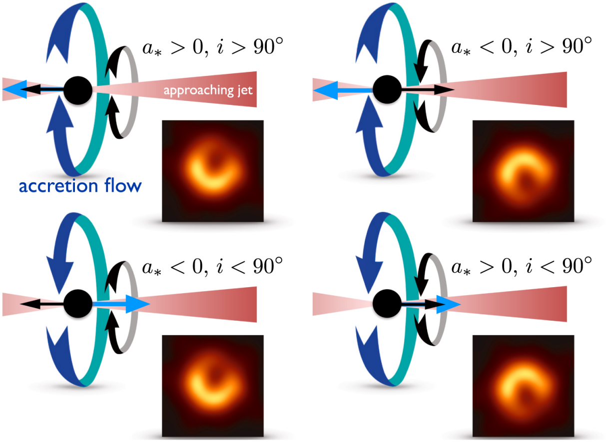
Angular velocity:

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

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): $|a^*| \gtrsim 0.5$
- Circularity: No real power yet

C. Bambi, et al. 1904.12983

- Twisted light: $|a^*| = 0.9 \pm 0.05$ at 95%

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

rules out $a^* = 0$ at 6 σ

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

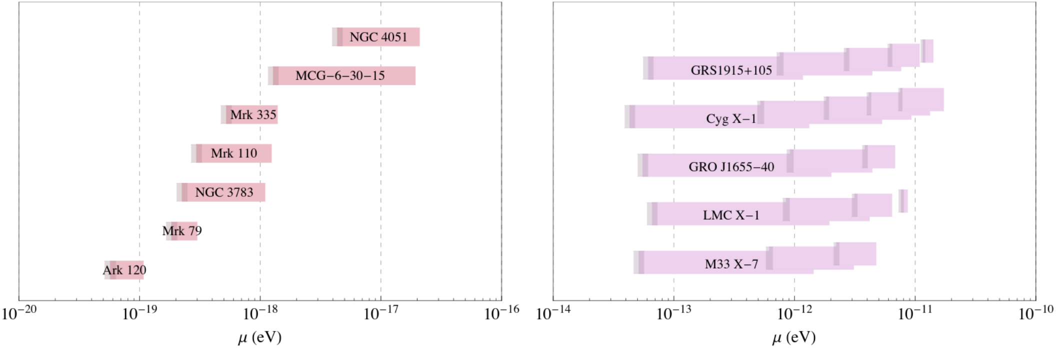
- From the Eddington limit, $\tau_{\rm Salpeter}\sim4.5\times10^7$ yrs
- EHT: $\dot M_{\rm M87^*}/\dot M_{\rm Edd}\sim2\times10^{-5}$
- Mergers: one $\sim10^9$ yrs ago with a much smaller galaxy

A. Longobardi, et al. 1504.04369

- μ_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

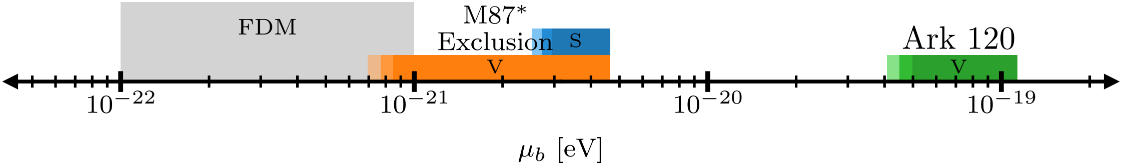
Past ultra light boson constraints



Spin-1 constraints

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

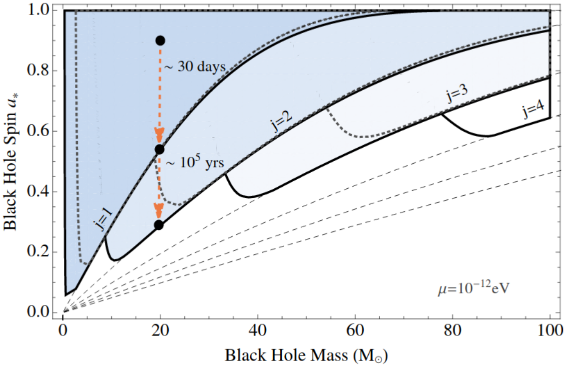
New constraints from M87*



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

Superradiance Spin-down

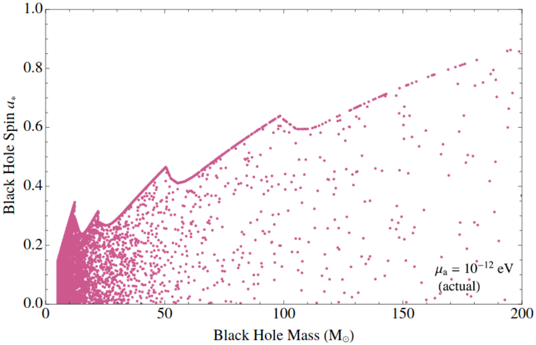
Different spherical harmonic modes leads to different maximum spins

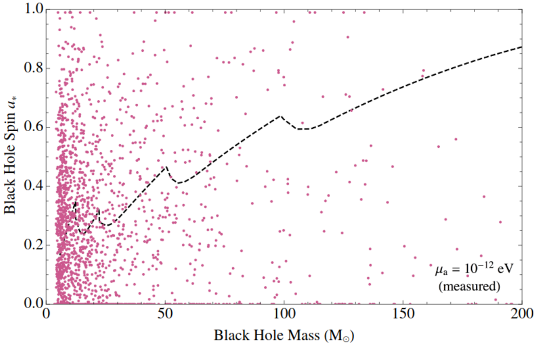


Vector (scalar) in bold (dotted) for $\mu_B = 10^{-12}$ eV

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

Superradiance conclusions

- Superradiance is a powerful probe of ultralight bosons
- Constraints from M87* relevant for fuzzy DM
- Discovering ultralight bosons is hard

Ultralight Fermionic DM

Dark matter: what we know

Astrophysically/gravitationally: lots

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
  - Small scale structures weakly suggests $\sim 10^{-22} - 10^{-21}$ eV

See slide 38

- Fermionic DM lighter than ~ 100 eV can't be squeezed into a galaxy

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

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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2. Pauli exclusion principle

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 (2σ) — D. Savchenko, A. Rudakovskyi 1903.01862
- 130 eV (2σ) — 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.

“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!

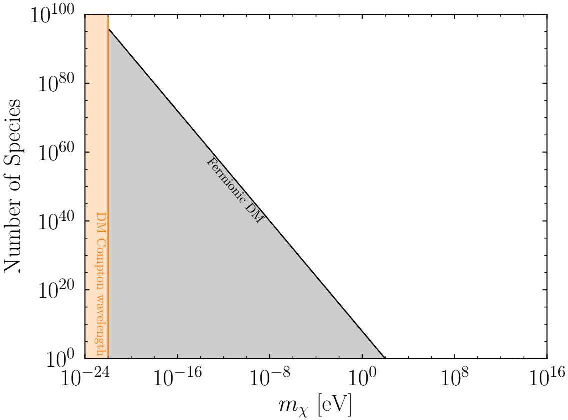
$m \gtrsim 10^{-22}$ eV $\Rightarrow N_F \gtrsim 10^{96}$

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

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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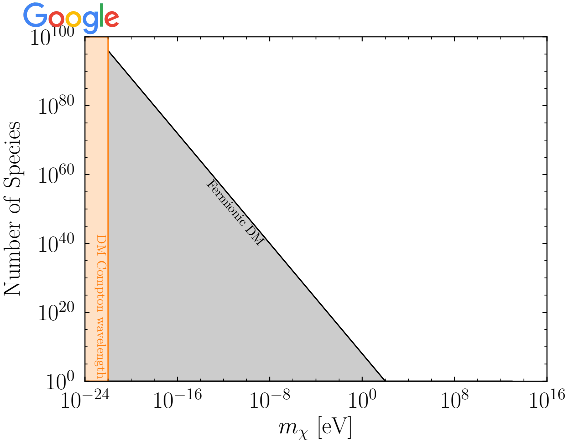

Too many species

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,
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

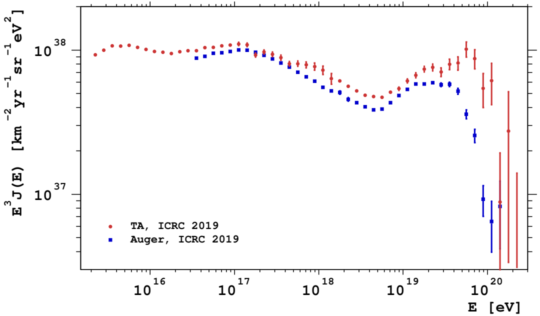
Could be photo-pion production (GZK)

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

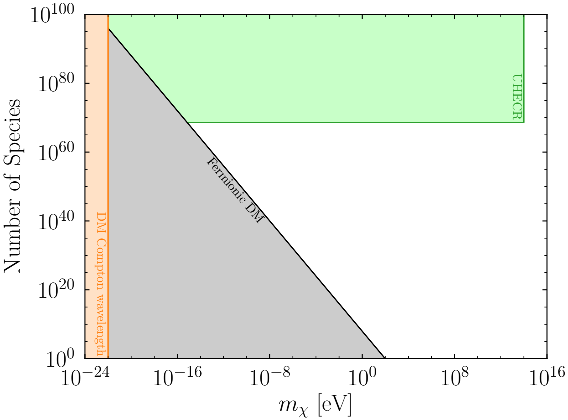


Cosmic ray constraints

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

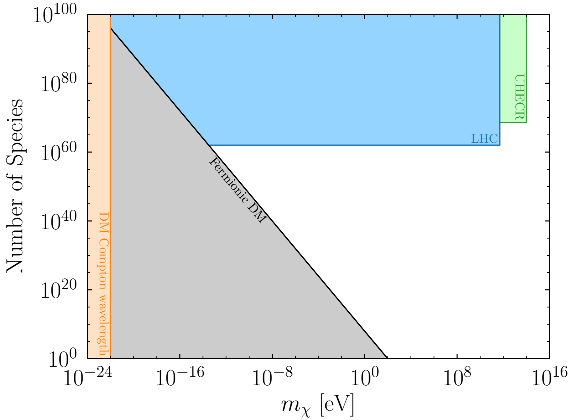
Lower energy, better precision

- 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

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

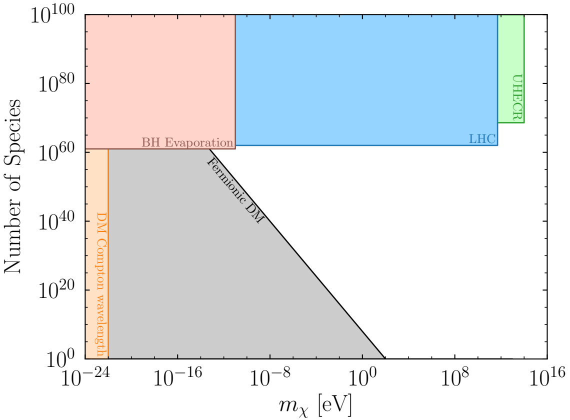


100 TeV will improve by $\sim 2+$ orders of magnitude

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

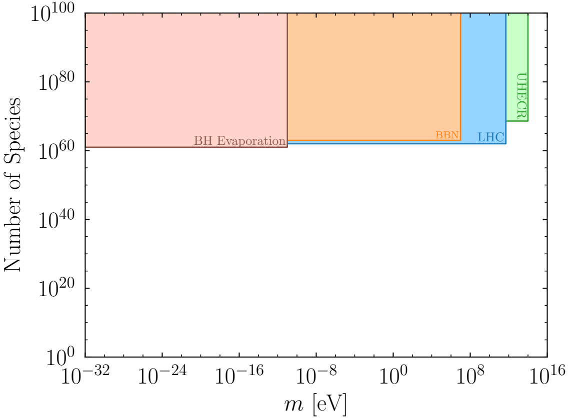
Need $\sim 10^{61}$ quasi-degenerate species

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



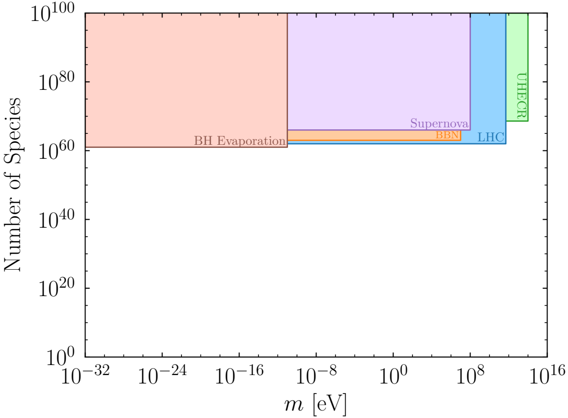
$$N \lesssim 10^{63} \qquad \text{for} \qquad m \lesssim 10 \text{ MeV}$$

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
- $N \lesssim G_F^2 M_P^4$

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



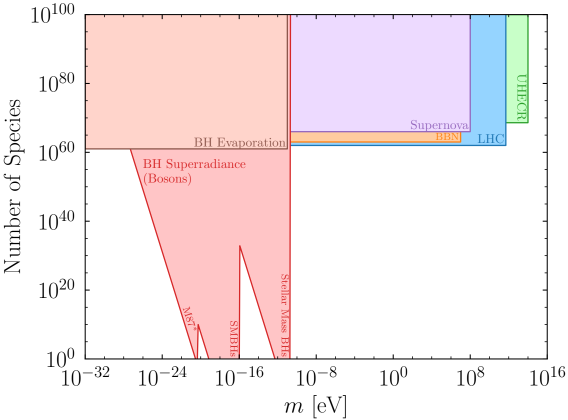
Superradiance with bosons

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

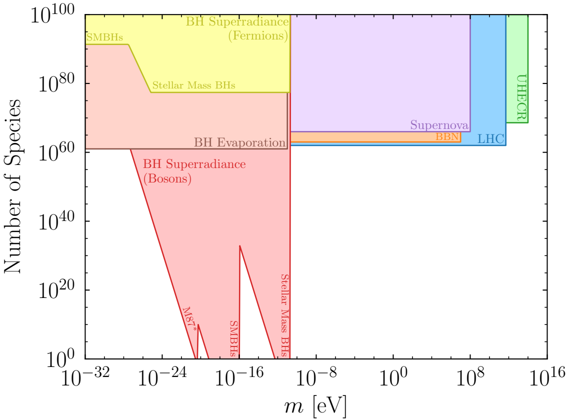
H. Davoudiasl, PBD 1904.09242

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



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

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

$$P(\nu_\ell \to \chi) \sim N_F P(\nu_\ell \to \chi_i) \lesssim 0.1$$

$$N_F \xi_i^2 \lesssim 10^{-25}$$

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

Nucleon decay

One can write down this 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 at $m \sim 1$ TeV

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:

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

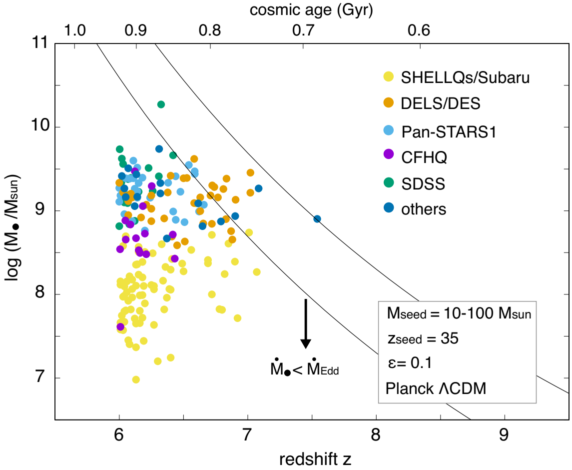
Fermionic dark matter conclusions

- 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
- More work to be done on this topic in many directions: pheno and theory
- Recently, analysis updated and confirmed

C. Ewasiuk, S. Profumo 2409.11359

A model at 10 keV

Early supermassive black holes



K. Inayoshi, E. Visbal, Z. Haiman 1911.05791

- Appears SMBHs are forming larger/faster than expected
- Some are known to be sub-Eddington
- Masses are probably under estimated
- Seems like they can't form conventionally

Ultralight dark matter hints

- Core-cusp might indicate fuzzy DM $\sim 10^{-21}$ eV

W. Hu, R. Barkana, A. Gruzinov astro-ph/0003365

D. Marsh 1510.07633

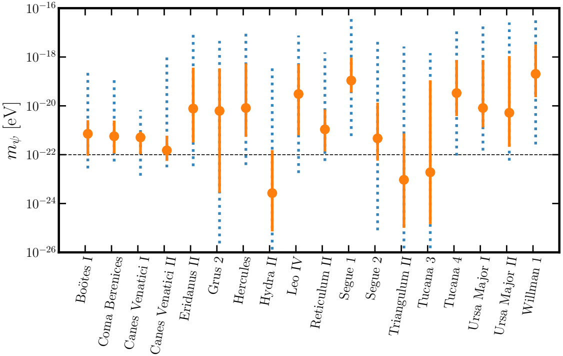
L. Hui, et al 1610.08297

- Ultra faint dwarf galaxies great place to look
- Baryonic feedback expected to be negligible

A. Lazar et al 2004.10817

- Ultrafaint dwarf galaxies might prefer ultralight DM
- Strongest: Segue 1 prefers $\sim 10^{-19}$ eV
- See also Lyman-α

K. Rogers, H. Peiris 2007.12705



K. Hayashi, E. Ferreira, H. Chan 2102.05300

Simple start

- Evidence suggests stringy models have many $\mathcal{O}(100-1000)$ axions

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

A. Arvanitaki, et al 0905.4720

- Expect decay constant similar to reduced Planck mass

$$f_a \sim \bar{M}_p \sim 2 \times 10^{18} \text{ GeV}$$

$$m_a \sim \frac{\mu_a^2}{f_a} \sim 10^{-20} \text{ eV} \left(\frac{\mu_a}{\text{keV}}\right)^2 \left(\frac{10^{17} \text{ GeV}}{f_a}\right)$$

Early black hole formation

Suppose the BH forms in the early universe somehow:

$$\frac{M_{\rm BH}}{M_P^2} \sim R_{\rm BH} \sim H^{-1}$$

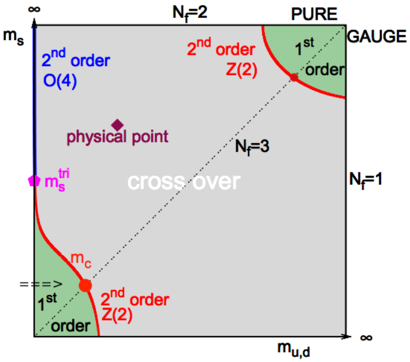
$$H \sim \frac{T^2}{M_P}$$

$$M_{\rm BH} \sim \frac{M_P^3}{T^2}$$

For $M_{\rm BH} \sim 10^9 M_\odot$ we get $H \sim 10^{-19}$ eV and $T \sim 10$ keV
Matches with fuzzy DM set from near the Planck scale

Two sides of the same coin

Ultralight DM and early SMBH formation linked via first order phase transition



P. Forcrand, M. D'Elia 1702.00330

- SU(3)$_\mathrm{d}$
- Heavy quarks $m_\Psi \sim f_a \sim 10^{17}$ GeV
- Confinement scale $\mu_a \sim 10$ keV
- This leads to a FOPT at $T \sim 10$ keV
- Drop of pressure allows SMBH formation
- PQ charges leads to dark quark-dark gluon couplings

$$\mathcal{L} \supset \frac{a}{f_a} G_{d\,\mu\nu} \tilde{G}_d^{\mu\nu}$$

Under the rug

Dark gluons are populated in the early universe as glueballs
Contribute to N_{eff}

$$\Delta N_{\text{eff}} = \frac{4}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{T_d}{T}\right)^4 N_{dG} \lesssim 0.3$$

Planck 1807.06209

$$\Rightarrow T_d \lesssim 0.36T$$

Glueballs decay to new light states, redshift as radiation

$$\Rightarrow \Delta N_{\text{eff}} \sim 0.1$$

Other predictions: gravitational waves

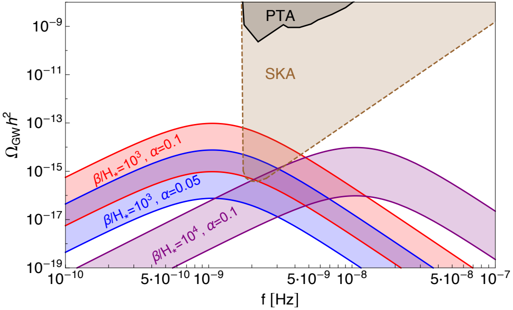
FOPT produce GWs in various ways

1. vacuum bubble collisions
2. sound waves ✓
3. magnetohydrodynamic turbulence

We assume:

- Energy released in FOPT is $\alpha < 1$
- Velocity is large $\beta/H_* \sim 10^4$

A. Helmboldt, J. Kubo, S. Woude 1904.07891



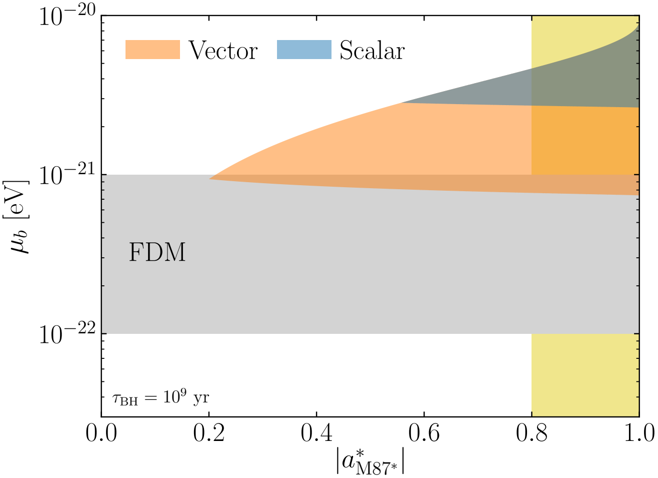
10 keV model conclusions

- Hints of anomalous early SMBH formation
- Hints of ultralight DM
- Dark SU(3) FOPT at 10 keV forms SMBHs
- With scale set by string theory, get axion DM
- Axion DM explains fuzzy DM hints
- Predict small correction to $\Delta N_{\rm eff}$
- Predict GWs for future PTAs

Thanks!

Backups

Spin dependence



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

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

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

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

This is not as strong as the 10^{32} arguments

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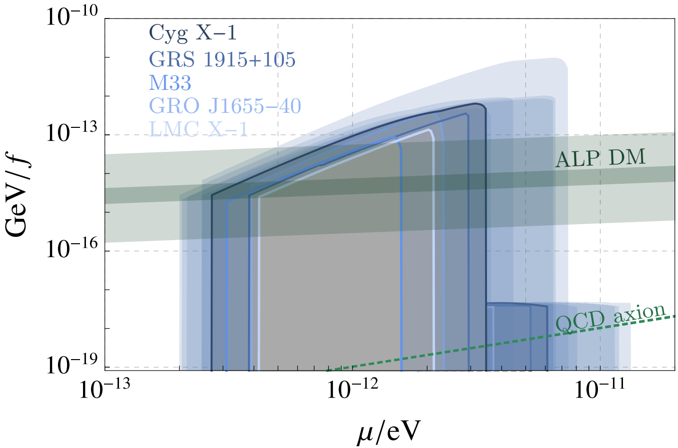
At $N \sim 10^{60}$ and $m \sim 10^{-3}$ eV consistent with theory arguments on previous slide

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

Close to current constraints

J. Lee, et al. 2002.11761

Superradiance constraints with interactions



M. Baryakhtar, et al. 2011.11646