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 ~ 100 eV by the Pauli exclusion principle. In this talk I will discuss a new probe of DM at the 10^{-21} eV scale from the Event Horizon Telescope's measurement of M87*. This scale is relevant for fuzzy DM models that aim to explain the core-cusp problem. I will also 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, 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 ~ 16 orders of magnitude.

The Lightest Dark Matter

Peter B. Denton

Sussex

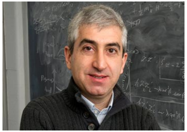
October 19, 2020

1904.09242

with Hooman Davoudiasl

2008.06505

with Hooman Davoudiasl and David McGady



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Dark matter: what we know

Astrophysically/gravitationally: lots

Particle nature:

- Coupling to SM? 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 ~ 100 eV can't be squeezed into a galaxy

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

Outline

1. A new constraint on fuzzy dark matter from black holes
2. A new way to push down on Tremaine-Gunn bound with Lots of species
3. Lots of constraints on Lots of species

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The first picture of a black hole opens a new era of astrophysics

The supermassive beast lies in a galaxy called M87 more than 50 million light-years away

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HPC wire

TACC Supercomputers Play Pivotal Role in Event Horizon Telescope's First-Ever Black Hole Image

April 15, 2019

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The Two Scientific Ways We Can Improve Our Images Of Event Horizons

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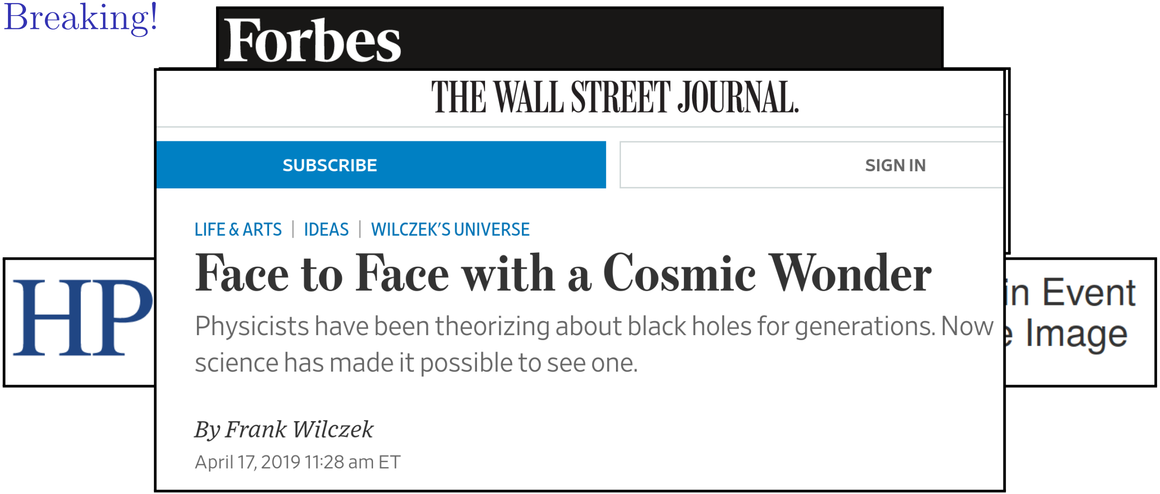

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Face to Face with a Cosmic Wonder

Physicists have been theorizing about black holes for generations. Now science has made it possible to see one.

By Frank Wilczek

April 17, 2019 11:28 am ET

in Event

e Image

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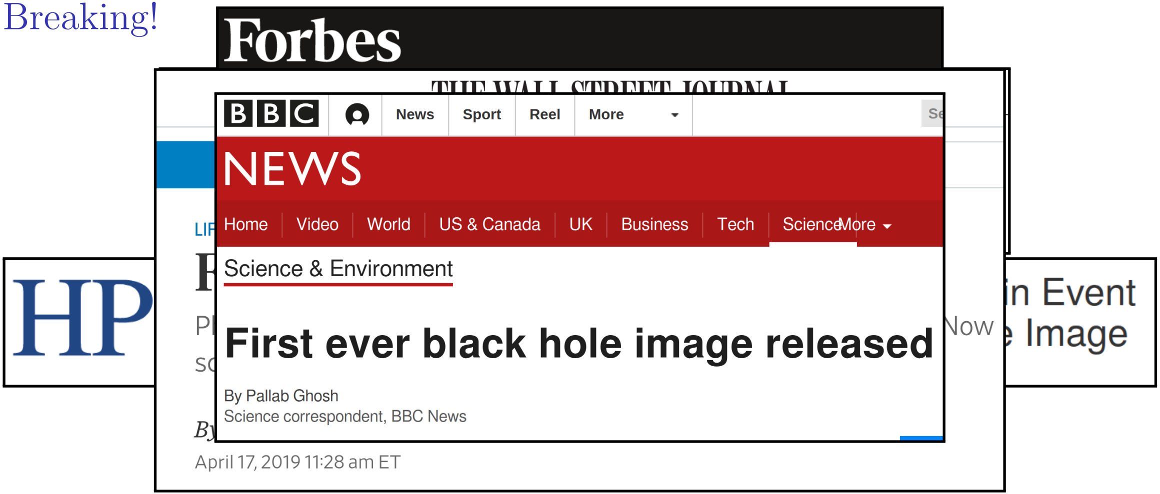
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April 17, 2019 11:28 am ET
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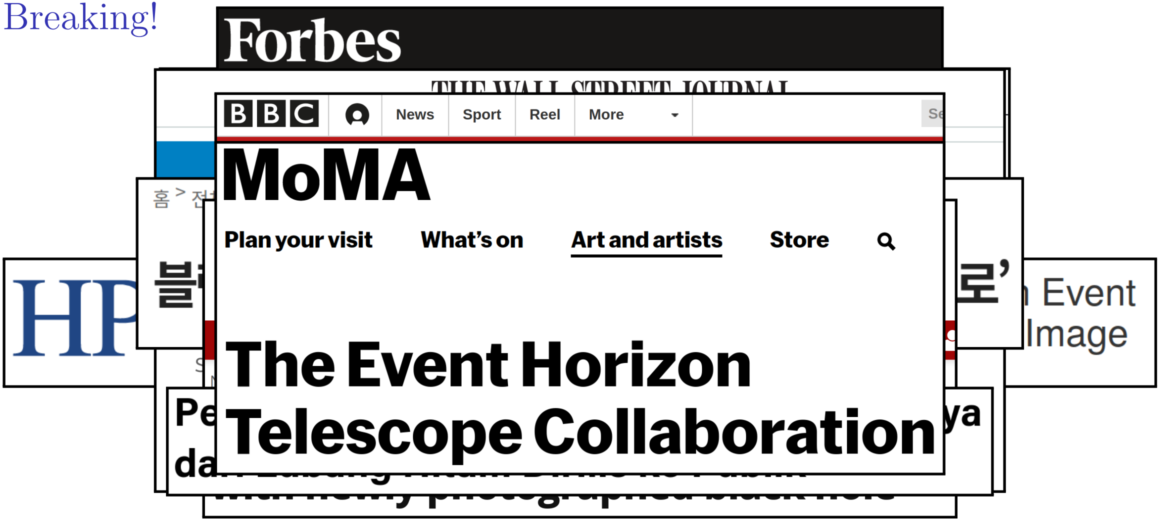

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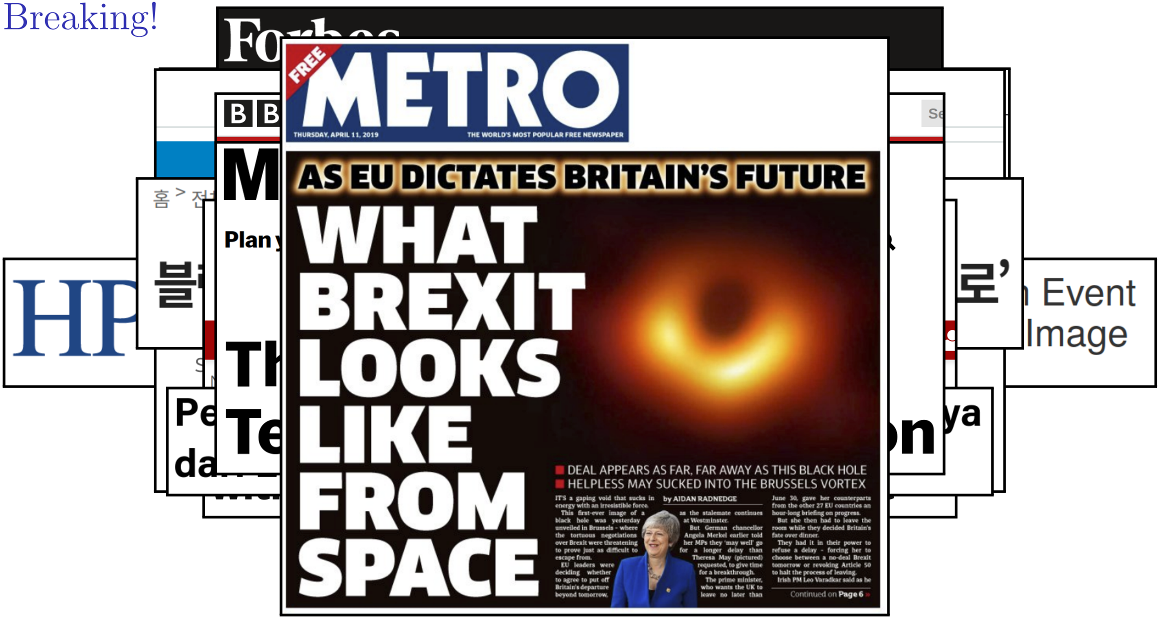

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THURSDAY, APRIL 11, 2019

THE WORLD'S MOST POPULAR FREE NEWSPAPER

AS EU DICTATES BRITAIN'S FUTURE

WHAT BREXIT LOOKS LIKE FROM SPACE

- DEAL APPEARS AS FAR, FAR AWAY AS THIS BLACK HOLE
- HELPLESS MAY SUCKED INTO THE BRUSSELS VORTEX

by AIDAN RADNEDGE

IT'S a gaping void that sucks in energy with an irresistible force.

This first-ever image of a black hole was yesterday unveiled in Brussels – where the tortuous negotiations over Brexit were threatening to prove just as difficult to escape from.

EU leaders were deciding whether to agree to put off Britain's departure beyond tomorrow, as the stalemate continues at Westminster.

But German chancellor Angela Merkel earlier told her MPs they 'may well' go for a longer delay than Theresa May (pictured) requested, to give time for a breakthrough.

The prime minister, who wants the UK to leave no later than June 30, gave her counterparts from the other 27 EU countries an hour-long briefing on progress.

But she then had to leave the room while they decided Britain's fate over dinner.

They had it in their power to refuse a delay – forcing her to choose between a no-deal Brexit tomorrow or revoking Article 50 to halt the process of leaving.

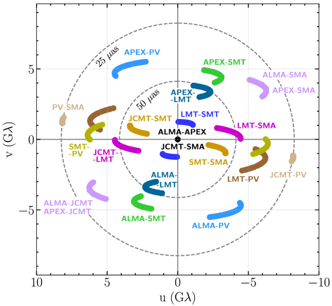
Irish PM Leo Varadkar said as he

Continued on Page 6 »

Event Horizon Telescope: ApJL 875 L1 (2019)

How they did it

M87*



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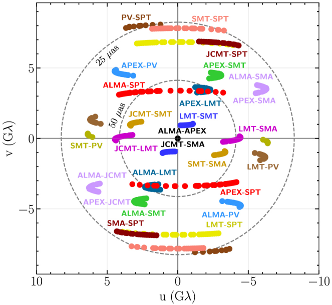
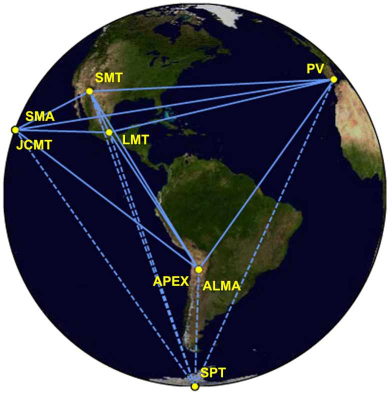
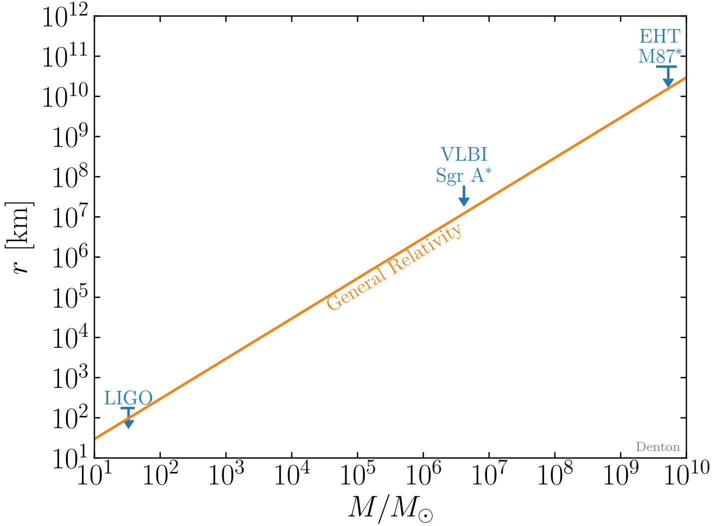




Hard drives by the pound

What is this good for?

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



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:

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

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

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:

$$\mu_B > \Omega_H$$

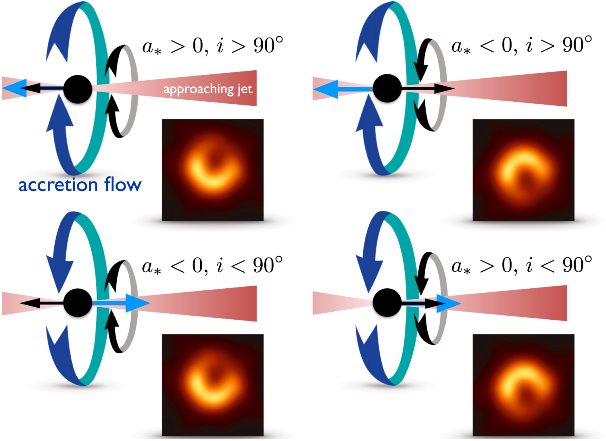
Angular velocity:

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

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): $|a^*| \gtrsim 0.5$
- 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

- 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

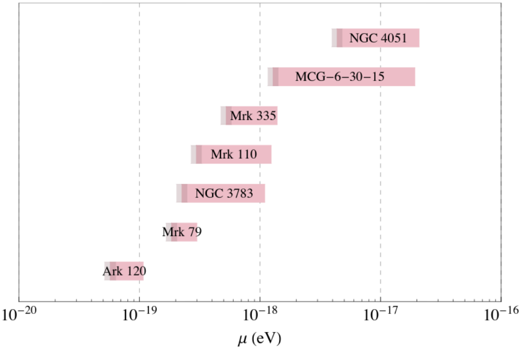
- From the Eddington limit, $\tau_{\rm Salpeter} \sim 4.5 \times 10^7$ yrs
- EHT: $\dot{M}_{\rm M87^*}/\dot{M}_{\rm Edd} \sim 2 \times 10^{-5}$
- Mergers: one $\sim 10^9$ yrs ago with a much smaller galaxy

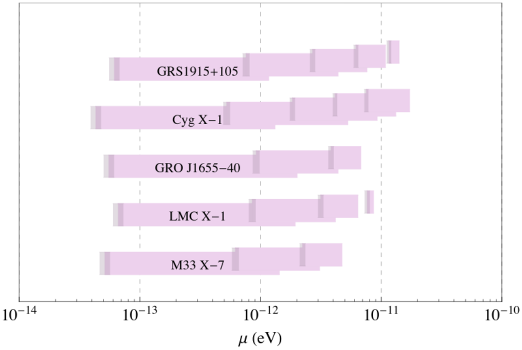
A. Longobardi, et al. 1504.04369

- 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

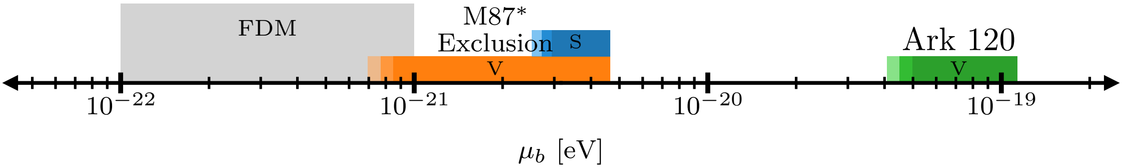




Spin-1 constraints

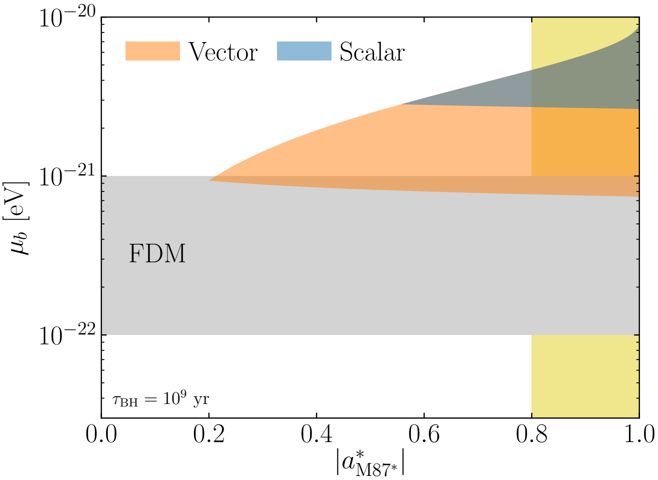
M. Baryakhtar, R. Lasenby, M. Teo 1704.05081

New constraints from M87*



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

Spin dependence



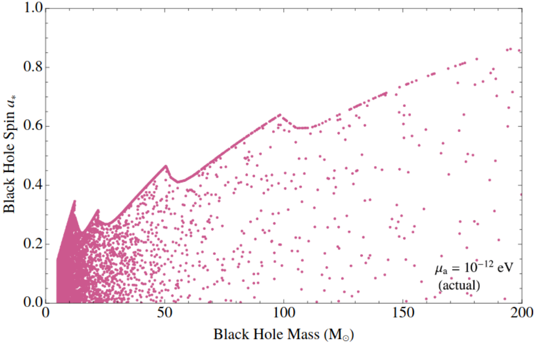
Dark matter

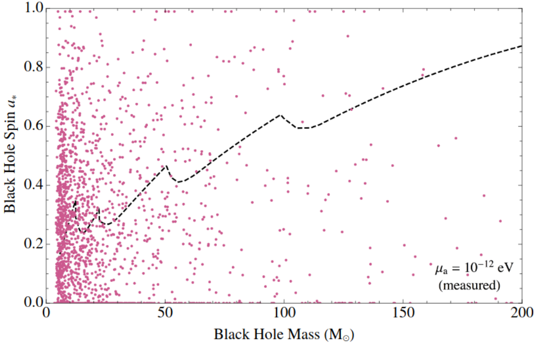
Core-cusp is an interesting topic

- Galaxy simulations suggest a cuspy central DM distribution
- Data suggests many galaxies are cored
- Baryonic feedback could play a role
- Fuzzy DM with $\lambda_{\rm DM} \sim 1$ kpc ($\sim [10^{-22}, 10^{-21}]$ eV) could also explain this
- M87* rules out upper part of the region for spin-1 particles

Our constraints don't care if it's present in the center of Galaxies,
nor do they care if the particle has any couplings: SM, self, dark sector, ...

How to detect ultra light bosons with superradiance





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

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

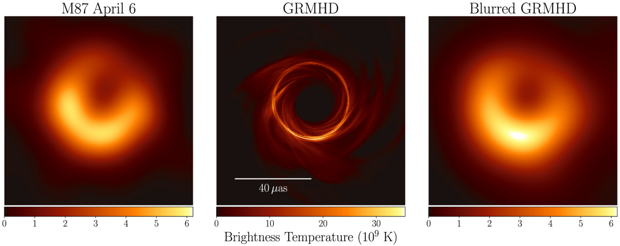
M. Baryakhtar, R. Lasenby, M. Teo 1704.05081

Key points

- Superradiance causes BHs to spin down
- Happens efficiently when a boson of $\mu_B \sim 1/M_{\rm BH}$ exists   Interactions don't matter!
- EHT observed M87*: constrains bosons in fuzzy DM region
- M87* has the most angular momentum of any measured single object!

Future:

- TON 618 is one order of magnitude more massive ($\sim$ 200x farther away)



EHT: ApJL 875 L5 (2019)

1904.09242

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

These differ by 19%

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

Focus on #2

Light fermionic dark matter

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Two issues:

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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 (2σ) — D. Savchenko, A. Rudakovskyi 1903.01862
- 130 eV (2σ) — J. Alvey 2010.03572

Evading Tremaine-Gunn

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

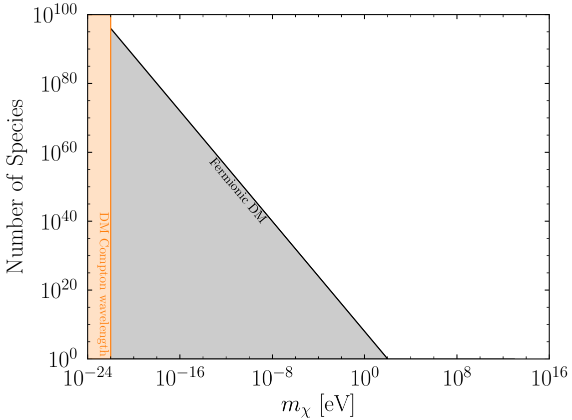
L. Randall, J. Scholtz, J. Unwin 1611.04590

Perhaps Kaluza-Klein modes:
Constraint is more complicated

Extrapolation!

Let's extrapolate this as far as possible!

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



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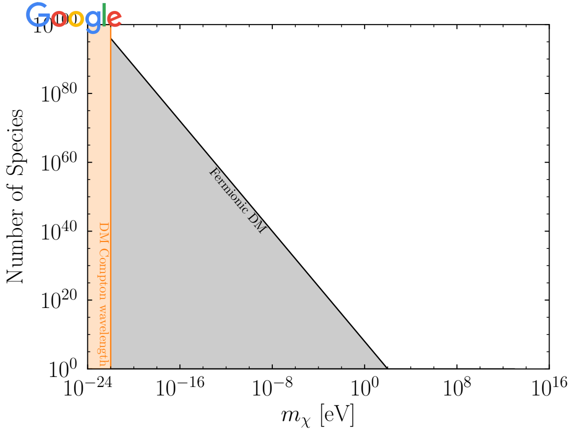


Extrapolation!

Let's extrapolate this as far as possible!

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

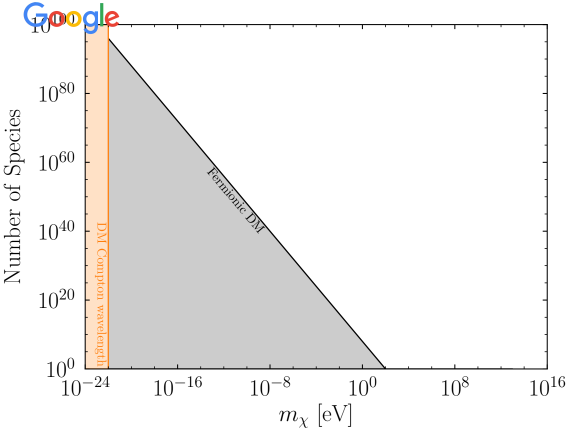
How many DM particles would there be in a galaxy in this case?

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



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

Too many species

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

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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

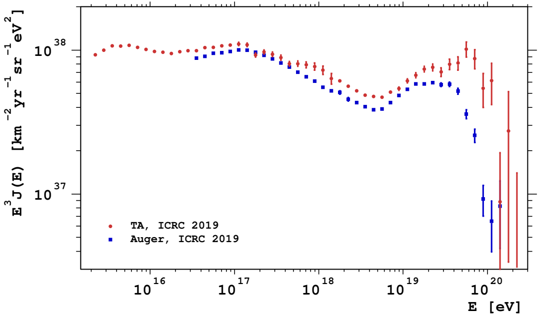
Could be photo-pion production (GZK)

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

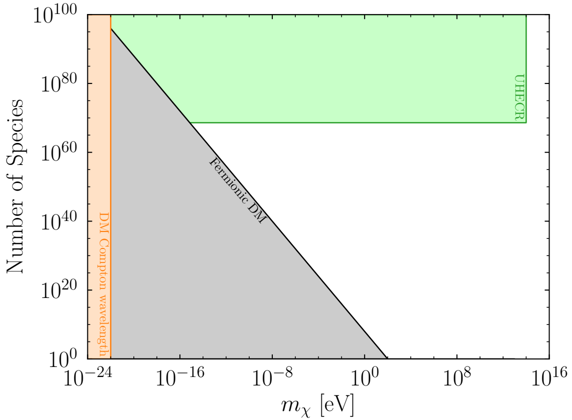


Cosmic ray constraints

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

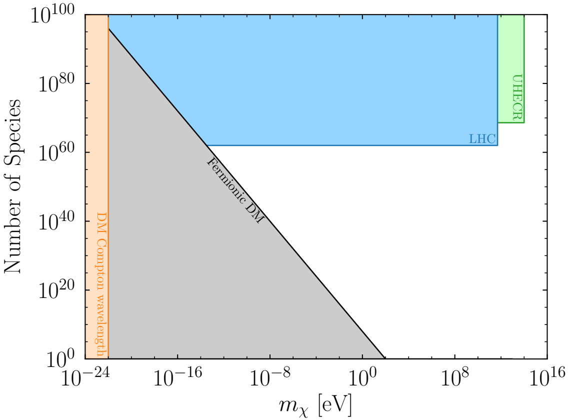
Lower energy, better precision

- 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

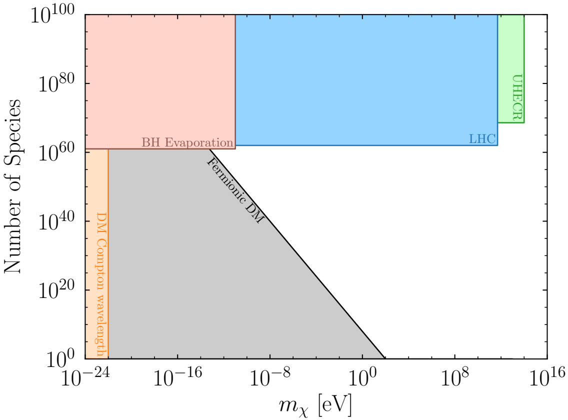
$$N \lesssim 10^{62} \qquad \text{for} \qquad m \lesssim 500\ \text{GeV}$$



BH evaporation

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

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

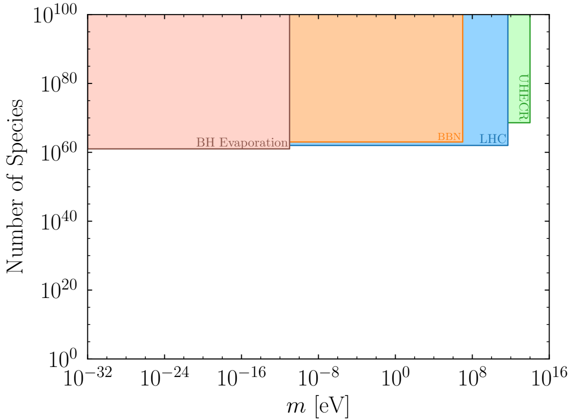
Need $\sim 10^{61}$ quasi-degenerate species

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



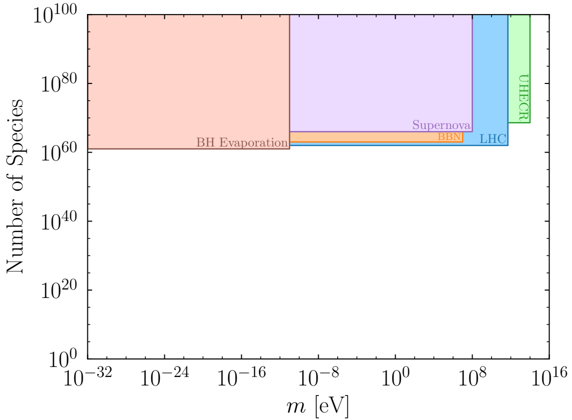
$$N \lesssim 10^{63} \qquad \text{for} \qquad m \lesssim 10 \text{ MeV}$$

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

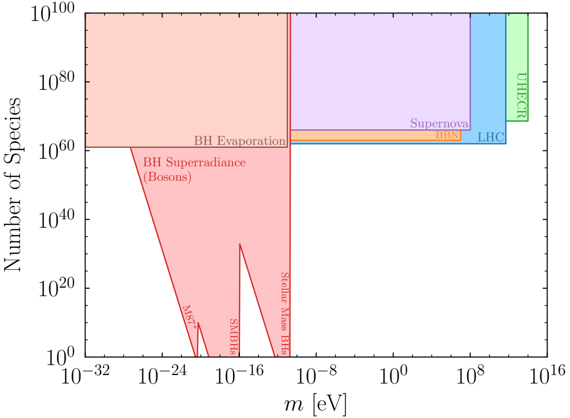
$N \lesssim 10^{66}$ for $m \lesssim 100$ MeV



Superradiance with bosons

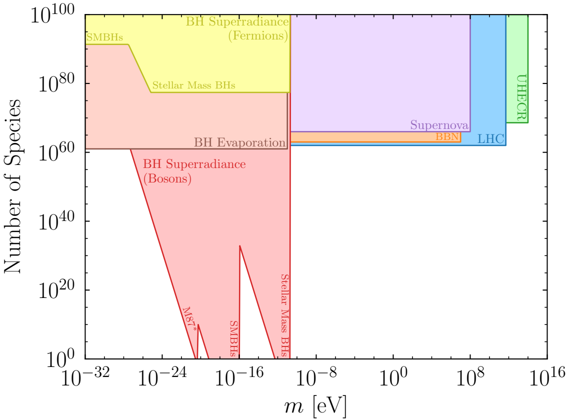
Narrow applicability range, apply down to $N_B = 1$ for bosons

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



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

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

L. Hui, et al. 1610.08297

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

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

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

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

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

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:

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

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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P. Fayet 1712.00856

S. Schlamminger, et al. 0712.0607

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

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

Summary

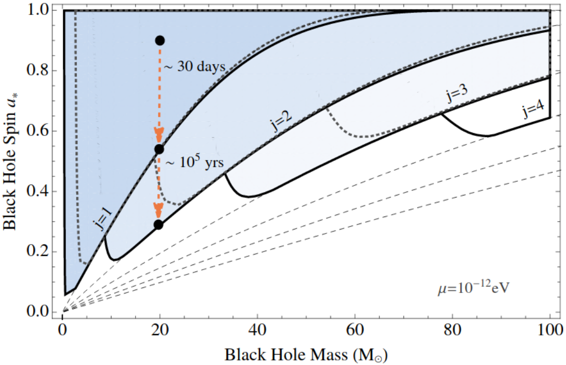
- The largest BHs can constrain lightest DM
- The "number of species" axis for DM is interesting
- Fermionic DM can be as light as 10^{-13} eV with key constraints from BH lifetimes and the LHC
- Many similar constraints on the number of species from cosmic rays, LHC, BH lifetimes, BBN, and SNe
- More work to be done on this topic in many directions: pheno and theory

Thanks!

Backups

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