Ultralight Scalar, Vector and Tensor Dark Matter via Pulsar Timing Arrays and Superradiance

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C. Ünal [arXiv: 2301.08267]

C. Ünal, F. Pacucci, A. Loeb JCAP 05 (2021) 7 [arXiv: 2012.12790]

C. Ünal and A. Loeb MNRAS 495 (2020) 1 [arXiv: 2002.11778]

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Ultralight Particles + Pulsar Timing Arrays Khmelnitsky, Rubakov '14

"*ultralight*" *particles*, $m \sim 10^{-27} - 10^{-10}\, eV$.

- Motivated by string theory and other UV completion suggestions
- $m^2 \sim \frac{\Lambda^4}{f^2}$

Can we probe such particles even if they don't interact with us (Standard Model)?
Yes, via gravitational effects!

Neglect the expansion, then for $V = \frac{1}{2} m^2 \phi^2$ we have $\phi = \mathcal{A}(x)\cos(mt + \beta)$
Nearly constant energy density $\rho = \dot{\phi}^2/2 + V \simeq \frac{1}{2} m^2 \mathcal{A}^2$
and oscillating pressure $p = \dot{\phi}^2/2 - V \simeq \rho \cdot \cos(2\pi f t + 2\beta)$

with $2\pi f = w = 2m$, $\qquad f = 5 \cdot 10^{-9}\mathrm{Hz} \left(\frac{m}{10^{-23}\,\mathrm{eV}}\right)$

Gravitational Signatures

Khmelnitsky, Rubakov '14; Ünal, Urban, Kovetz '22

$\frac{\nu' - \bar{\nu}}{\bar{\nu}} = \psi(x,t) - \psi(x_p, t_p) - \int_{t_p}^{t} n_i \partial_i (\Phi + \psi) dt'$ 2nd term suppressed by k/m

$\psi \sim \frac{G_N \rho_{ultralight}}{m^2}$

$\delta\Delta t = \int_{t_p}^{t} \frac{\nu' - \bar{\nu}}{\bar{\nu}} dt = \frac{\psi_c}{m} \sin(mD_{\mathrm{pulsar}} + \beta_e - \beta_p)\ \cos(2mt - mD_{pulsar} + \beta_e + \beta_p)$

Typical amplitude via root-mean-square

$$\sqrt{\langle(\delta\Delta t)^2\rangle} = \sqrt{\frac{1}{L}\int_0^L dl\,(\delta\Delta t)^2} = \mathcal{P}\cdot\psi/m$$

$L \equiv D_{pulsar}$ and $\mathcal{P}$ is defined as

$$\mathcal{P} = \frac{1}{\sqrt{2}}\left(1 - \frac{\sin(2\,m\,L)}{2\,m\,L}\right)^{\frac{1}{2}}$$

$m \cdot D_{pulsar} > 1$ and $m \cdot T_{obs} > 1 \ \rightarrow \mathcal{P} \simeq 1.$
$m \cdot D_{pulsar} \ll 1$ extra suppression ie $\mathcal{P} \propto m\,D_{pulsar}$

Finally, connect characteristic strain with time : $\sqrt{\langle(\delta\Delta t)^2\rangle} = h_c/f \propto \psi/f \propto \rho/m$

Gravitational Potential Fluctuation vs Sensitivity of current(IPTA) and future(SKA) PTAs

Ünal, Urban, Kovetz '22

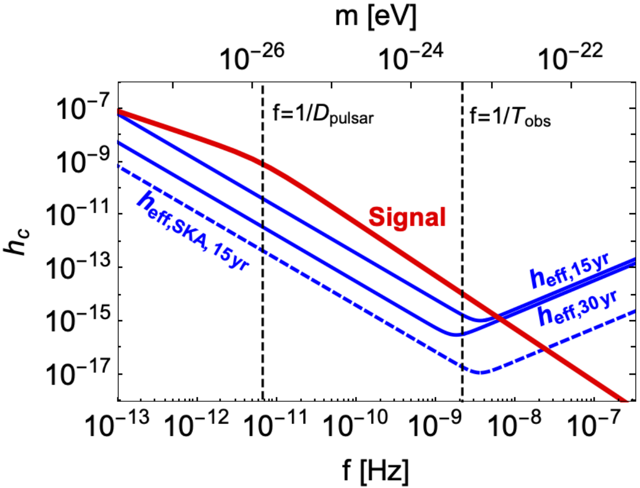


Figure: 3 regimes: $f < 1/D_{pulsar}$, $1/D_{pulsar} < f < 1/T_{obs}$, $f > 1/T_{obs}$

Ultralight Scalar Dark Matter in current(IPTA), near and future(SKA) PTAs

Ünal, Urban, Kovetz '22

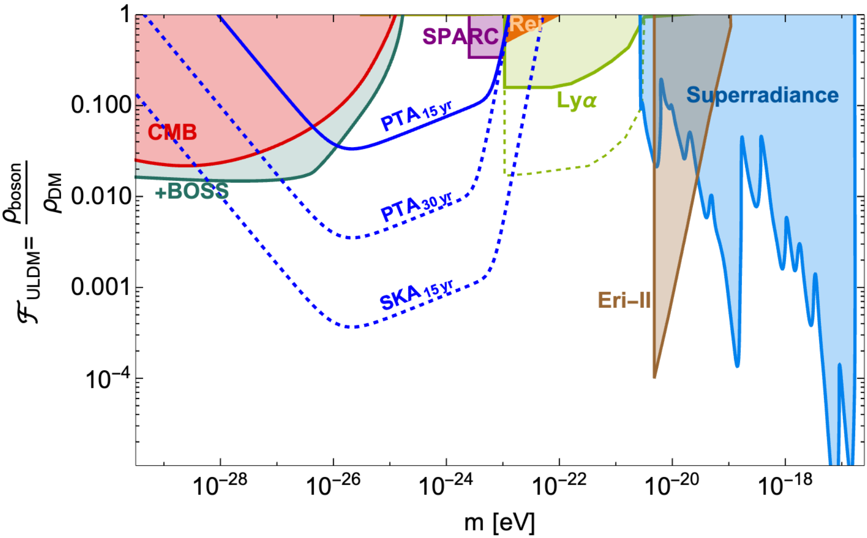
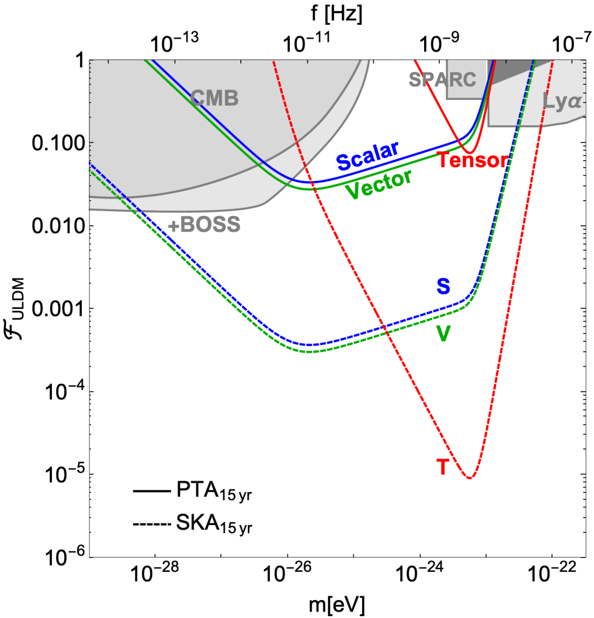


Figure: Ultralight Particles as Part of Dark Sector as a Function of Mass

Scalar + Vector(spin-1) + Tensor (spin-2) Ünal, Urban, Kovetz '22



Summary and Conclusions

- Ultralight particles highly motivated in high energy models, typical masses $10^{-27} - 10^{-10} eV$.

- Scalar, vector and tensor ultralight particles has a pressure term oscillating with a frequency twice(same) with their mass, which results in oscillation in metric/spacetime

- They modify arrival times of PTA pulses and can be probed sensitively

  1-10% with current IPTA. (60 pulsars 15 year obs.)

  0.1-1% with near future IPTA (60 pulsars 30 year obs.)

  0.01-0.1% with SKA (5K pulsars 15 year obs.)

BH Spin in Fundamental Plane of Black Hole Activity and Properties of Ultralight Particles

Mainly based on

C. Ünal [arXiv: 2301.08267]

C. Ünal, F. Pacucci, A. Loeb JCAP 05 (2021) 7 [arXiv: 2012.12790]

C. Ünal and A. Loeb MNRAS 495 (2020) 1 [arXiv: 2002.11778]

Brief Summary of Fundamental Plane (FP) of BH Activity

Merloni, Heinz, Matteo '03; Falcke, Koerding, Markoff '04

- Accretion power (probed by X-ray, OIII line, ...) $\sim \dot{m}^b \cdot M^c \cdot f_{acc}(a)$
- Jet power (probed by radio) $\sim \dot{m}^d \cdot M^e \cdot f_{jet}(a)$
- One can write an equation $logL_{jet} + c_1\, logL_{bol} + c_2\, logM + constant = 0$

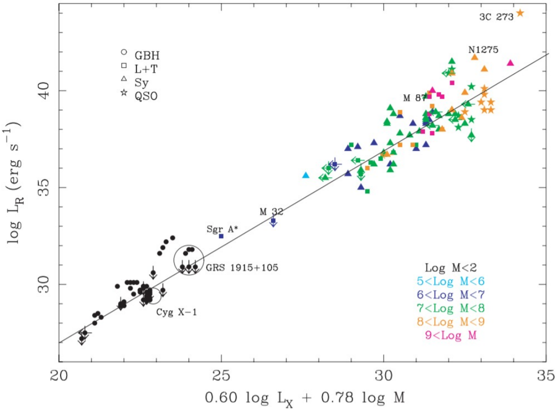


Figure: Merloni, Heinz, Matteo '03

Motivation for a New Variable in FP

- Fundamental Plane variables are derived from two main variables : **mass** and **accretion rate**.

- However, the 3 AGNs : 3C120, IRAS 00521-7054 and MRK 79
  nearly same masses (around $10^{7.75} M_{\odot}$)
  and X-ray power (around $10^{43/44} erg\ s^{-1}$)
  but 3 orders of magnitude different radio luminosity
  This fact motivates us to suggest **spin** as an additional variable.

- Accretion and jet outflow have different spin dependence which might lead to deviations in FP

Spin Dependence of Radiation Efficiency/Accretion Power

Radiation efficiency , $\mathcal{E}(\tilde{a})$, shows the radiation conversion efficiency of accreting matter, expressed via equatorial geodesic equation as Bardeen+ '72.

$$\mathcal{E}(\tilde{a}) = 1 - \frac{\tilde{r}^{3/2} - 2\tilde{r}^{1/2} \pm \tilde{a}}{\tilde{r}^{3/4}\left(\tilde{r}^{3/2} - 3\tilde{r}^{1/2} \pm 2\tilde{a}\right)^{1/2}} \Bigg|_{\tilde{r}=\tilde{r}_{ISCO}} , \quad (1)$$

where $\tilde{r} = r/GM$. This formula produces familiar results such as $\mathcal{E}(\tilde{a} = 0) \simeq 0.057$ and $\mathcal{E}(\tilde{a} = 1) \simeq 0.423$.

Efficiency grows as ISCO comes closer to horizon as more energy can be extracted

Spin Dependence of Jet Power

Jet Power Blandford and Znajek '77

$$
\begin{aligned}
L_{jet} &= \int S^r \, dA \\
&= \int \Omega_A(\Omega_H - \Omega_A) \left(\frac{A_{\phi,\theta}}{\Sigma}\right)^2 \left(r^2 + a^2\right) \Sigma \sin\theta \, d\theta \, d\phi \, \Big|_{r=r_H}
\end{aligned}
\tag{2}
$$

where Ω_A is the angular frequency of the field lines, Ω_H is the angular frequency of the horizon (defined below) and $dA = \Sigma \sin\theta$ with $\Sigma = r^2 + a^2 \cos^2\theta$.

$$
\begin{aligned}
L_{jet} &\simeq \int \frac{w_H^2(\tilde{a})}{4} (B^r)^2 \left(2\, \tilde{r}_H(\tilde{a})\right) \sin^3\theta \, \Sigma \, d\theta \, d\phi \\
&\simeq w_H^2(\tilde{a}) \, \tilde{r}_H^2 \, (GM)^2 \, (B^r)^2 \, \mathcal{I}(\theta)
\end{aligned}
\tag{3}
$$

$$
\Omega_H \equiv \frac{1}{2GM} \frac{\tilde{a}}{1 + \sqrt{1 - \tilde{a}^2}} \qquad w_H(\tilde{a}) \equiv \frac{\tilde{a}}{1 + \sqrt{1 - \tilde{a}^2}} \tag{4}
$$

where $\mathcal{I}(\theta) \sim \mathcal{O}(1)$ can be modified by the polar dependence of the magnetic field.

Spin Dependence of Jet Power II

Equipartition via Magnetorotational Instability

$$\frac{B^2}{8\pi} \equiv \beta \cdot P_{gas} = \beta \cdot (\rho\, c_s^2) \simeq \mathcal{O}\left(\rho\, \frac{(L/\mu)^2}{r^2}\right) \propto \mu \cdot n \cdot \gamma \cdot (L/\mu)^2 \,/\, r^2 \,, \qquad (5)$$

Number Density Conservation

$J^\nu = n \cdot u^\nu$, which can be expressed as $J^\nu_{;\nu} = \frac{1}{\sqrt{-g}} \left(\sqrt{-g} \cdot J^\nu\right)_{,\nu} = 0$. Assuming stationarity and axisymmetry, partial derivatives of time and azimuthal angle vanish.

$$(n \cdot \Sigma\, u^r), r = 0 \quad \Rightarrow -\frac{\dot{M}}{\mu} \equiv n \cdot \Sigma\, u^r \qquad \text{where} \quad u^r = \gamma \cdot v_r \,, \qquad (6)$$

Specific Angular Momentum of Particles

$$\mathcal{L} \equiv \frac{L}{G\, M\, \mu} = \frac{\left(\tilde{r}^2 \mp 2\tilde{a}\tilde{r}^{1/2} + \tilde{a}^2\right)}{\tilde{r}^{3/4} \left(\tilde{r}^{3/2} - 3\tilde{r}^{1/2} \pm 2\tilde{a}\right)^{1/2}} \,, \qquad (7)$$

Spin Dependence of Jet Power III

Innermost Stable Circular Orbit

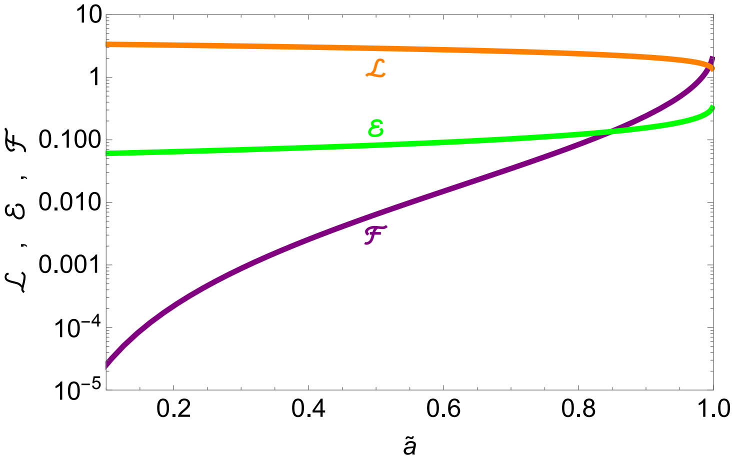
$$r_{ISCO} \ / \ G\,M \equiv \mathcal{S}(\tilde{a}) = \left(3 + Z_2 \mp [(3 - Z_1)(3 + Z_1 + 2Z_2)]^{1/2}\right) , \qquad (8)$$

where $\mp$ indicating the prograde/retrograde rotation respectively, with $Z_1 = 1 + (1 - \tilde{a}^2)^{1/3}[(1 + \tilde{a})^{1/3} + (1 - \tilde{a})^{1/3}]$ and $Z_2 = \left(3\tilde{a}^2 + Z_1^2\right)^{1/2}$ $\mathcal{S}(0) = 6$ $(r_{ISCO}(\tilde{a} = 0) = 6GM)$ and $\mathcal{S}(1) = 1$ $(r_{ISCO}(\tilde{a} = 1) = GM)$.

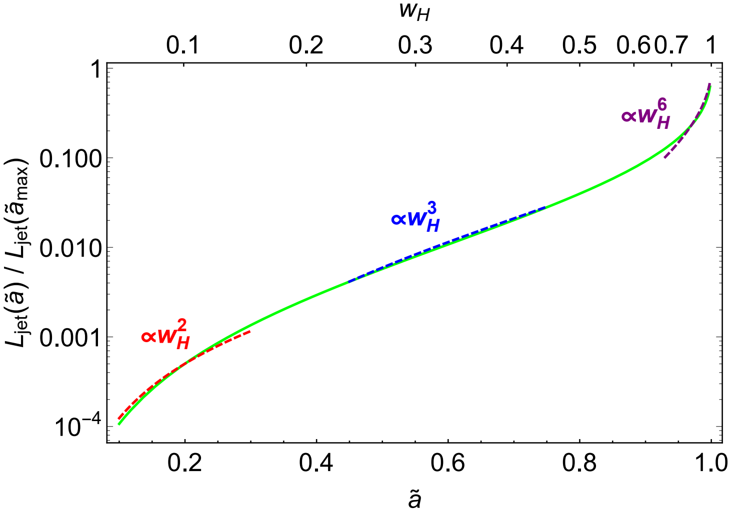
Magnetic Field Estimate Ünal, Loeb '20

$$B_H^2 \propto \frac{\mathcal{L}_{in}^2\,(GM)^2\;\dot{m}}{r_{in}^4\;v_r}\;L_{Edd} \propto \frac{\mathcal{L}_{in}^2\;\dot{m}\;\left(GM\right)^{-2}}{\mathcal{S}^{7/2}(\tilde{a})}\;L_{Edd}\;. \qquad (9)$$

Spin Dependent Functions



Nonlinear Spin Dependence of BZ Process Unal, Loeb '20



Spin Modified Fundamental Plane (SMFP) Ünal, Loeb '20

SMFP relation

$$\log \frac{L_R}{\left(\frac{w_H^2\ \tilde{r}_H^2\ \mathcal{L}^2}{\mathcal{S}^{7/2}(\tilde{a})}\right)^{\frac{17}{12}}} = 0.6\left(\log \frac{L_X}{\mathcal{E}(\tilde{a})}\right) + 0.78 \log M + constant \qquad (10)$$

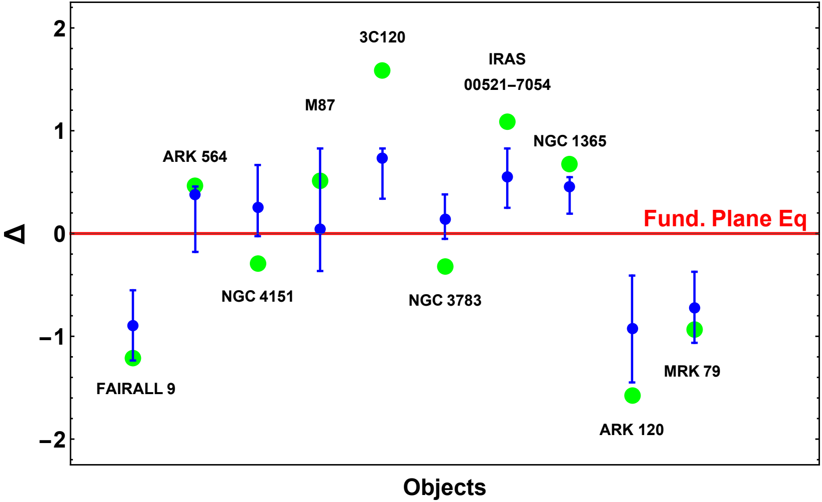
Scatter in FP and SMFP

$$\Delta \equiv \log \frac{L_{R,38}}{10^{-0.37} \cdot \left(\frac{M_{BH}}{10^8 M_\odot}\right)^{0.78} \cdot (L_{X,40})^{0.6}} \qquad (11)$$

In the SMFP, this function is predicted as

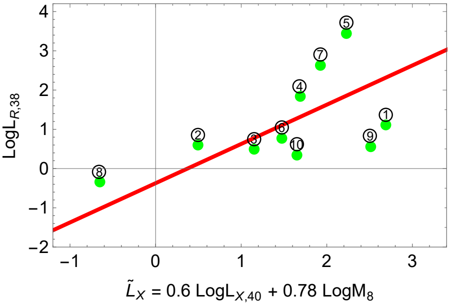
$$\Delta_{SMFP} \equiv \mathcal{D} + \frac{17}{12} \log\left(w_H^2\ \tilde{r}_H^2\ \mathcal{L}^2\ / \mathcal{S}^{7/2}\right) - 0.6 \log\left(\mathcal{E}\right) \qquad (12)$$

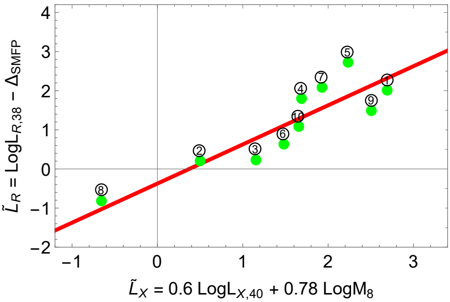
Scatter of Data



Comparison bw FP and SMFP Once Again Ünal, Loeb '20

$\sigma_{Fund.\,Plane} \sim 1$ $\qquad$ $\sigma_{Spin\,Mod.\,Fund.\,Plane} \lesssim 0.45$





OIII Instead of X-ray Luminosity and Spin Modified FP as Spin Estimator Ünal, Pacucci, Loeb '21

- Include relativistic effects on the observational data by employing bulk Lorentz boost factor (Γ_j) and viewing angle (θ_j), which allow us to write SMFP equation with radio-OIII-M-a variables as

$$\log_{10} L^{obs}_{radio}/\delta_j^2 - 0.83 \log_{10} L^{obs}_{OIII} - 0.82 \log_{10} M = \log_{10}\mathcal{F}(a) + \mathcal{D} \qquad (13)$$

δ_j is boost factor and $\mathcal{D} \simeq 0.1$ is set by the minimization of the χ^2 error and a is the dimensionless spin parameter defined as J/GM^2. $\mathcal{F}$ shows the spin dependence of the FP relation and it is given by

$$\mathcal{F}(a) = \left[\, a^2\, \mathcal{L}^2\, \mathcal{E}^4 \,\right]^{1.42} \,/\, \mathcal{E}^{\,0.83} \qquad (14)$$

- Then derive lower bounds for spins of blazers including errors: Intrinsic scatter, $L_{\rm bol} - L_{\rm OIII}$, Bulk Lorentz factor and viewing angle, Luminosity measurements, those errors can modify eqn 1 about 0.8 dex on average

Superradiance in 1 slide

Superradiance: Compton wavelength of light particles ($\frac{hc}{m}$) $\sim$ BH Horizon ($G \cdot M$)

i) $w \simeq \mu > \Omega_{BH}$

$$\Omega_H \equiv \frac{a}{2r_g\left(1+\sqrt{1-a^2}\right)} = \frac{1}{2r_g}\; w_H$$

ii) $\tau_{BH} > \tau_{SR}$

$$\tau_{BH} \simeq \frac{\mathcal{E}}{1-\mathcal{E}} \frac{5\times10^8}{f_{edd}} \text{ years.}$$

$$\tau_{SR} = \frac{log(N_m)}{\Gamma_b}$$

$$\Gamma_S \simeq \#_S\, w_H \left(r_g\, \mu\right)^{8-2S} \mu$$

Minimum mass and spin (Scalar, vector and tensor have different SR rate)

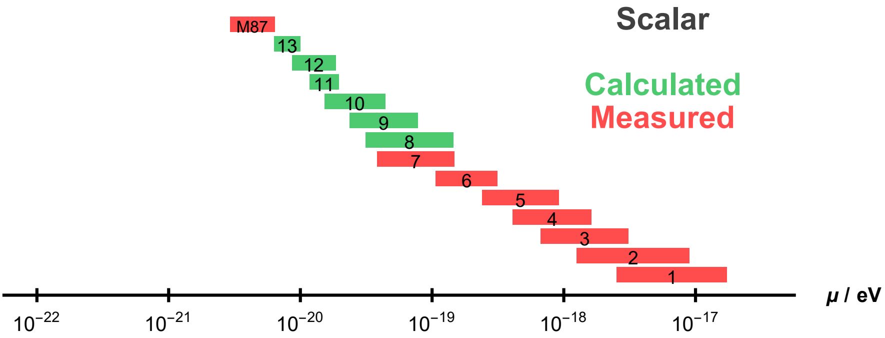
$$\Omega \geq \mu \geq \Omega_{min} = \mu_{min}\Big|_{\tau_{BH}=\tau_{SR}}$$

List of Quasars Being Analyzed

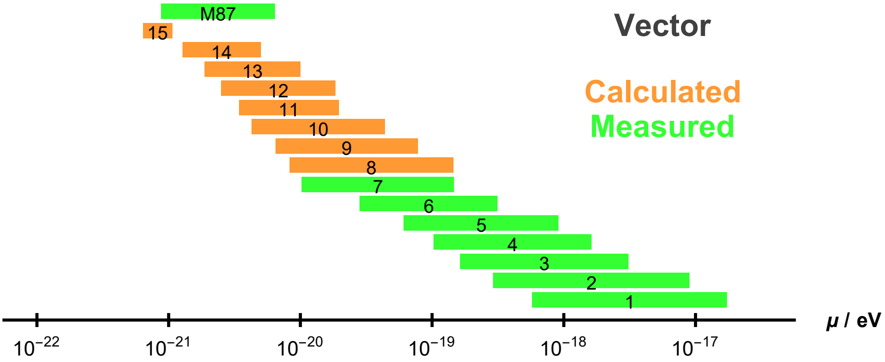
Object	$M/10^6 M_\odot$	L^{obs}_{radio} [GHz]	L^{obs}_{OIII}	Γ_j	θ_j	a
[8] B2 0218+35	4×10^2	43.1 (0.074)	41.2	16	3°	≥ 0.99
(*) [8] B2 2155+312	4×10^2	43.2 (0.074)	41.5	12.2	3°	≥ 0.99
[8] PMN 2345+155	4×10^2	44.4 (20)	42.0	13	3°	≥ 0.73
[9] PKS 0142-278	6×10^2	43.4 (0.080)	42.0	12.9	3°	≥ 0.97
(*) [9] PKS 1055+018	6×10^2	43.5 (0.080)	42.4	12.	3°	≥ 0.94
[9] TXS 0716-332	6×10^2	43.2 (0.074)	42.1	12.2	3°	≥ 0.94
[9] PKS 1057-79	6×10^2	44.9 (20)	42.2	11	3°	≥ 0.79
[10] 4C 55.17 0954+556	1×10^3	43.2 (0.038)	41.3	13	2.5°	≥ 0.99
(*) [10] PKS 0528+134	1×10^3	46.6 (15)	43.3	13	3°	≥ 0.92
[10] PKS 0048-071	1×10^3	43.6 (0.074)	42.8	15.3	3°	≥ 0.87
[10] DA55 0133+47	1×10^3	45.4 (15)	42.6	13	3°	≥ 0.80
[11] GB6 J0805+6144	1.5×10^3	45.6 (5)	42.9	14	3°	≥ 0.86
(*) [11] S4 0820+560	1.5×10^3	43.7 (0.151)	43.0	14	3°	≥ 0.74
[11] PHL 5225 2227-088	1.5×10^3	43.0 (0.080)	42.9	12	3°	≥ 0.69
[12] PKS 0537-441	2×10^3	45.9 (18.5)	42.5	11	3.5°	≥ 0.89
(*) [12] PKS 0537-286	2×10^3	46.5 (22)	43.1	15	3°	≥ 0.85
[12] PKS 1508-055	2×10^3	44.0 (0.074)	43.2	13	3°	≥ 0.83
[12] PKS 0215+015	2×10^3	46.1 (22.5)	43.0	13	3°	≥ 0.80
[13] PKS 2023-07	3×10^3	43.9 (0.080)	42.8	11.8	3°	≥ 0.85
(*) [13] 4C 71.07 0836+710	3×10^3	44.0 (0.038)	43.8	14	3°	≥ 0.75
[13] S4 1030+61	3×10^3	42.9 (0.038)	42.7	12.2	3°	≥ 0.73
[13] PKS 1127-145	3×10^3	45.5 (5)	43.5	11.8	3°	≥ 0.66
[14] 4C 38.41 1633+382	5×10^3	46.2 (10.6)	43.3	12.9	3°	≥ 0.73
(*) [14] PKS 0332-403	5×10^3	45.3 (5)	43.2	10	3°	≥ 0.66
[14] PKS 0347-211	5×10^3	45.8 (8.6)	43.3	12.9	3°	≥ 0.64
[14] PKS 2149-306	5×10^3	46.0 (8.6)	43.6	15	3°	≥ 0.64
[15] PKS 2126-158	1×10^4	46.1 (8.6)	44.3	14.1	3°	≥ 0.47
(*) [15] J075303+423130	1.3×10^4	44.5 (0.354)	44.2	15	3°	≥ 0.40
[15][HB89] 0329-385	1.3×10^4	44.5 (4.85)	44.2	15	3°	≥ 0.19

Superradiance and Ultralight Particles Ünal, Pacucci, Loeb '21

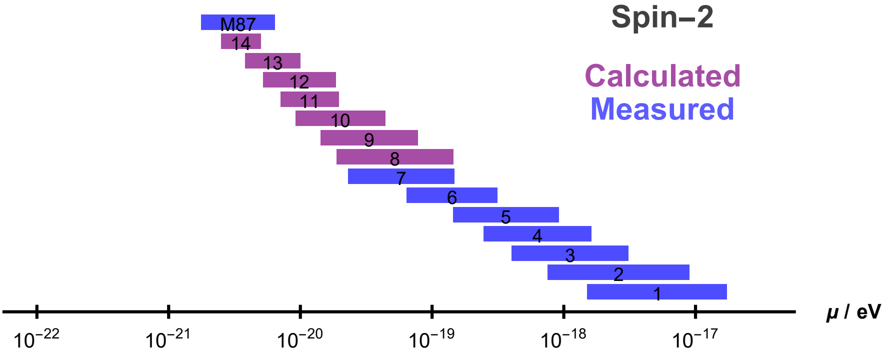
Superradiance: Compton wavelength of light particles ($\frac{hc}{m}$) $\sim$ BH Horizon ($G \cdot M$)



Vector Ultralight Particles



Spin-2 Ultralight Particles



Axion Decay Constant f_{axion} Ünal, Pacucci, Loeb '21

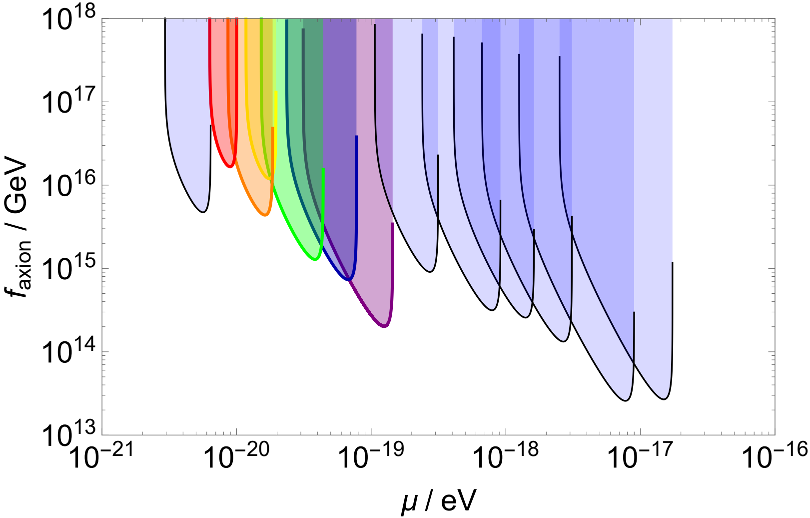
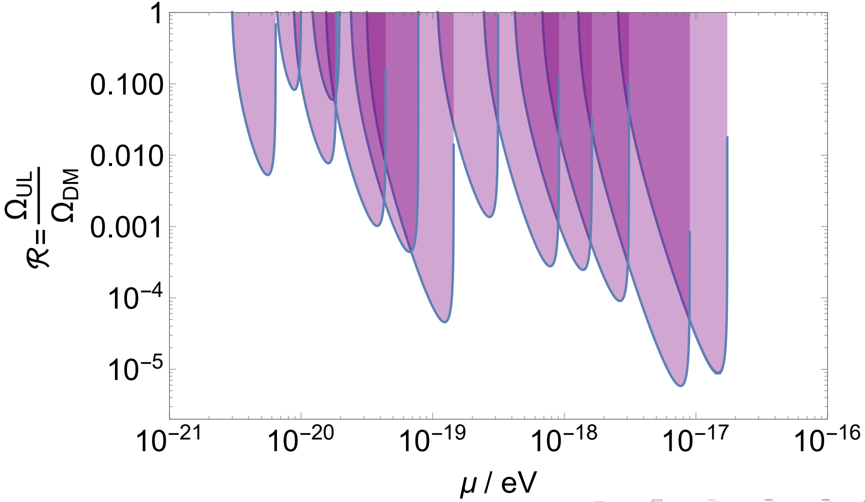


Figure: Self-interaction strength is inversely proportional to f_{axion}, hence larger values imply less self-interaction and small ones imply larger interaction

Are Ultralight Particles Dark Matter? Ünal, Pacucci, Loeb '21

$$\mathcal{R}_{Ultra\ Light} \equiv \frac{\Omega_{UL}}{\Omega_{DM}} \sim \left(\frac{\mu}{10^{-21}\,\mathrm{eV}}\right)^{1/2} \left(\frac{f_a}{10^{17}\,\mathrm{GeV}}\right)^2 \quad (15)$$



Conclusions

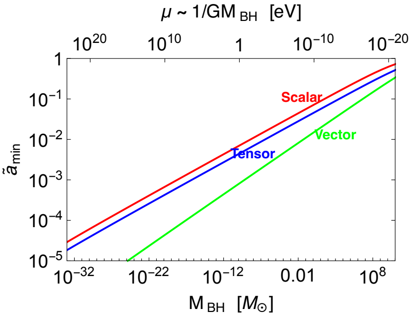
- There is a statistical evidence that Fundamental Plane of BH activity scaling relation includes the spin of the BH
- We derive semi-analytic results for the Blandford Znajek process : At low spin values, jet power depends on the second power of spin while for larger spin values, jet power depends on spin value with higher powers of spin (even 6) and this result remarkably matches with the simulation results
- Spin Modified Fundamental Plane with L_{radio}-M-OIII-a is a considerably robust spin estimator with the link between jet and accretion
- Spinning heavy BHs probe/constrain the properties (energy density, mass and self-interaction strength) of Ultralight particles via Superradiance
- Using SMFP and measured spin values, we close the largest parameter space of UL particles and claim that they can constitute at most $1 - 10\%$ of the dark matter in the mass range $10^{-21} < \mu/eV < 10^{-17}$

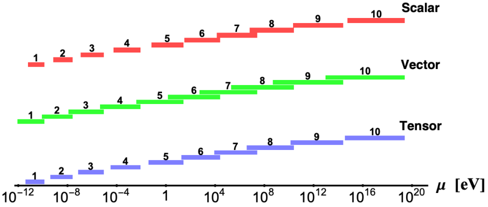
Superradiance of Light BHs & $10^{-12} - 10^{21}$eV Bosons

Ünal '23

- Superradiance requirements i) $w \simeq \mu > \Omega_{BH}$ $ii) \tau_{BH} > \tau_{SR}$
- Minimum mass and spin (Scalar, vector and tensor have different SR rate)

$$\Omega \geq \mu \geq \Omega_{min} = \mu_{min}\Big|_{\tau_{BH}=\tau_{SR}}$$





$$M_{BH\,1-10} = \{0.2,\ 10^{-3}, 10^{-5.5},\ 10^{-8.5},\ 10^{-12},\ 10^{-15},\ 10^{-18},\ 10^{-21},\ 10^{-25},\ 10^{-30}\}$$

- Superradiance in the presence of self-interaction
  $\Gamma_{SR}\, \tau_{BH}\; (N_{BOSE}/N_m) > log N_{BOSE}$
  $N_{BOSE} \simeq 5 \cdot 10^{44} \frac{n^4}{(r_g\, \mu)^3} \left(\frac{M}{10^{-8}\, M_\odot}\right)^2 \left(\frac{f_a}{10^{10}\,\mathrm{GeV}}\right)^2$
- Energy Density
  $\mathcal{R} \equiv \frac{\Omega_{scalar}}{\Omega_{DM}} \sim \left(\frac{\mu}{10^{-9}\,\mathrm{eV}}\right)^{1/2} \left(\frac{f_a}{10^{14}\,\mathrm{GeV}}\right)^2$