Axions and ultralight dark photons: theory+searches

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w Hernandez-Chifflet, 1509.00039 (photons)
w Arvanitaki, Baryakhtar, Dimopoulos, Lasenby, 1604.03958 (axions)

"Theory" part:

is very short

- Axions are extremely well motivated:

Strong CP problem provides a tantalizing hint

May come abundantly with exponentially suppressed masses from zero modes of higher-dimensional gauge fields in the presence of cycles

- Ultra-light photons (of the kind considered in this talk), are less so

Gauge sectors definitely appear abundant both in nature and in theory

Exponentially light gauge field without light charged matter doesn't look that well motivated

Ultra-light stuff is fun to think about:
LIGHT=LARGE

Brings interesting opportunities: the whole Universe becomes a detector

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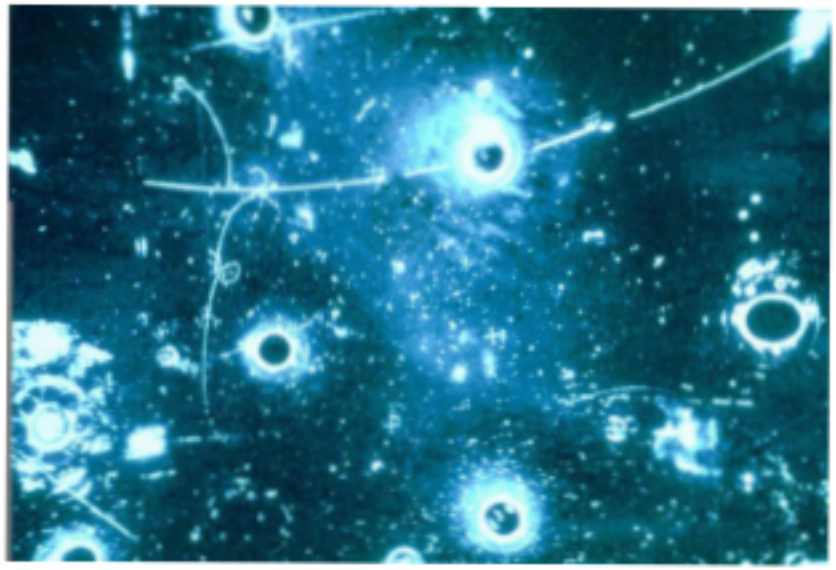
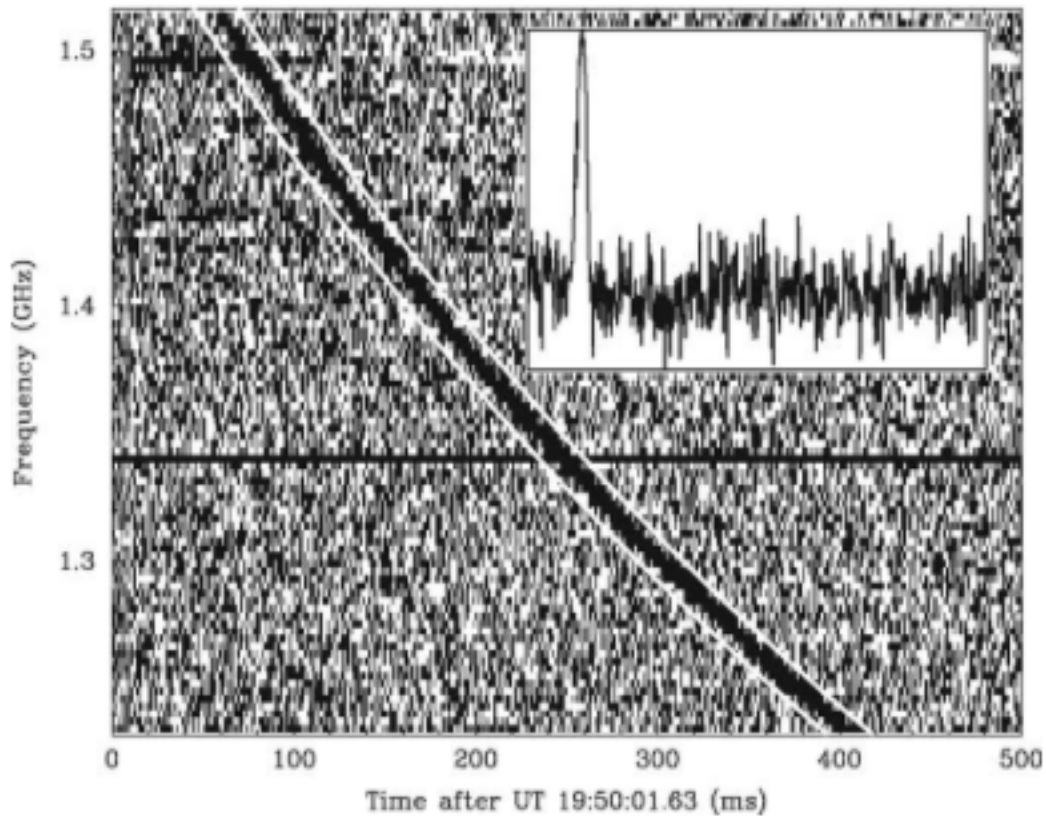
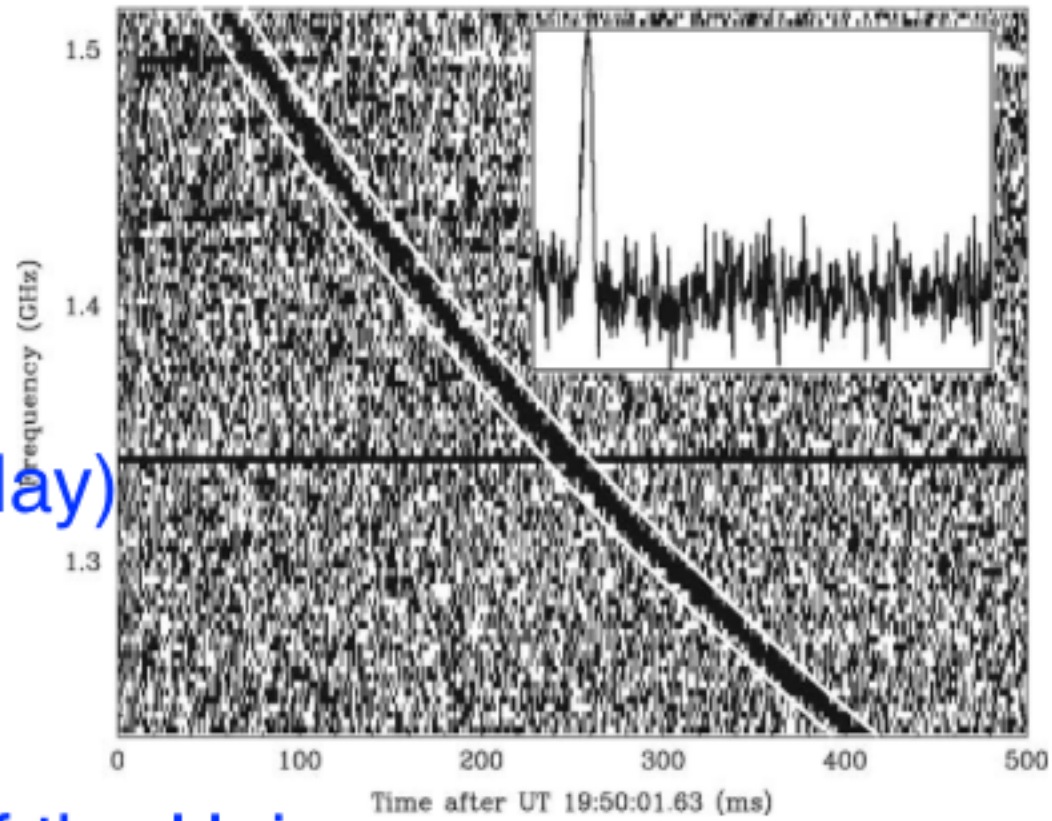


The initial question was triggered by this picture:



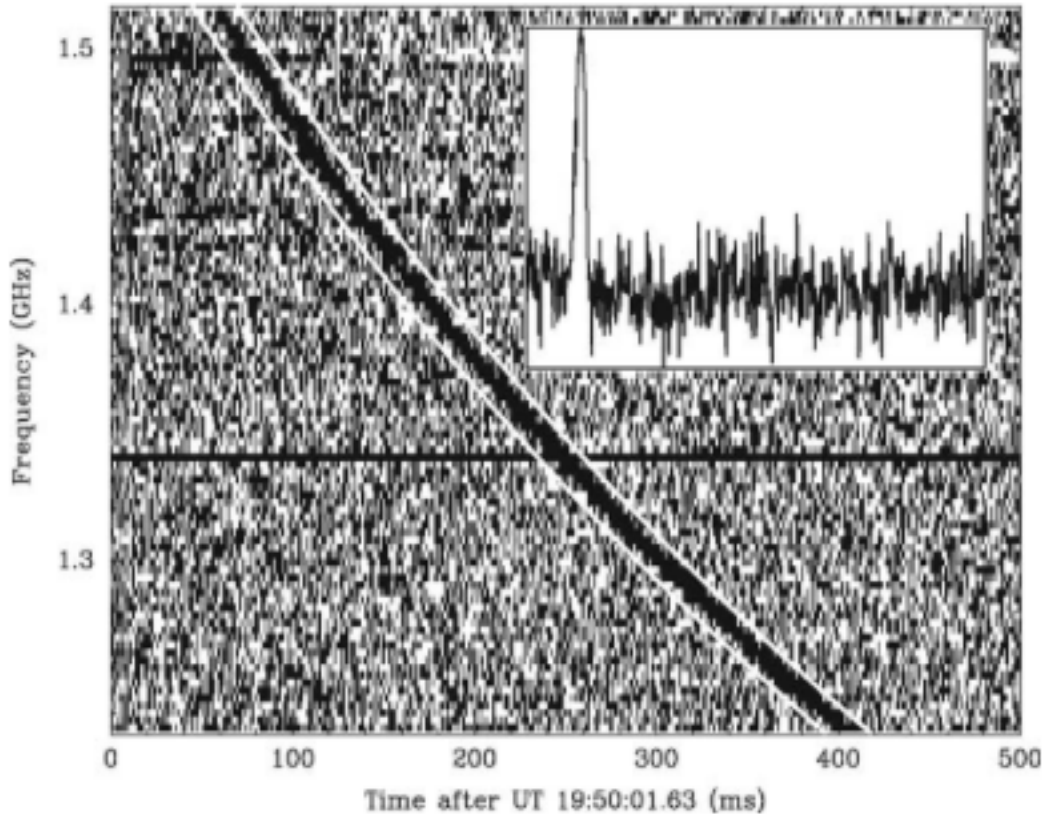
Fast Radio Bursts:



- Short (~few ms)
- Powerful (~10^{38} ergs)
- Frequent (~100's per day)
- Pulses of radio waves (~GHz)
- Traveling through all of the Universe

Can we (particle physicists) learn something here?

Set a bound on the photon mass?

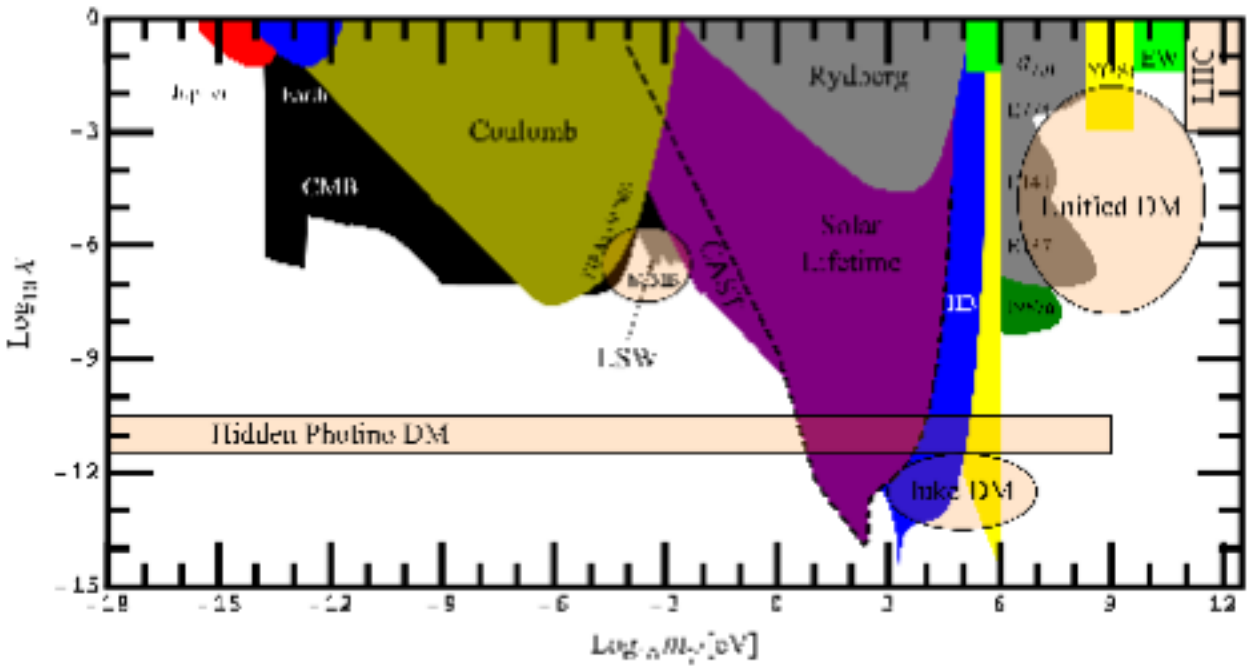


This is the photon mass!

$$\omega_p = \left(\frac{4\pi n_e \alpha}{m_e}\right) \approx 7.4 \cdot 10^{-12}\text{eV} \left(\frac{n_e}{0.04\ \text{cm}^{-3}}\right)^{1/2}$$

What about hidden photons?

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\tilde{F}_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{m^2}{2}\tilde{A}_\mu\tilde{A}^\mu - \frac{e}{(1+\varepsilon^2)^{1/2}}J^\mu\left(A_\mu + \varepsilon\tilde{A}_\mu\right)$$



Jaeckel & Redondo , 1002.0329

very weak constraints for $m \lesssim 10^{-14}$ eV

Can one get the second pulse from these guys?

The answer is *NO*

And this *NO* applies to some other ideas like

- Time dependent Zeeman effect *Nelson & Scholtz 1105.2812*
- Voyager magnetometric survey and future SQUID magnetometry

Pignol et al, 1507.06875

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\tilde{F}_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{m^2}{2}\tilde{A}_\mu\tilde{A}^\mu - \frac{e}{(1+\varepsilon^2)^{1/2}}J^\mu\left(A_\mu + \varepsilon\tilde{A}_\mu\right)$$

Hidden photon should become unobservable in the massless limit

Plasma Equations:

Transverse mode:

$$\left\{\vec{k}^2 - \omega^2 + (1+\varepsilon^2)^{-1}\begin{pmatrix} \Omega_p^2 & \Omega_p^2\varepsilon \\ \Omega_p^2\varepsilon & \Omega_p^2\varepsilon^2 + m^2(1+\varepsilon^2) \end{pmatrix}\right\}\begin{pmatrix} A_T \\ \tilde{A}_T \end{pmatrix} = 0$$

Longitudinal mode:

$$\left\{-\omega^2 + (1+\varepsilon^2)^{-1}\begin{pmatrix} \Omega_p^2 & \Omega_p^2\varepsilon \\ \Omega_p^2\varepsilon & \Omega_p^2\varepsilon^2 + \frac{m^2(1+\varepsilon^2)}{1-\frac{\vec{k}^2}{\omega^2}} \end{pmatrix}\right\}\begin{pmatrix} A_L \\ \tilde{A}_L \end{pmatrix} = 0$$

For $m \ll \Omega_p$

"our" photon $$\omega_v^2 = \Omega_p^2 \left(1 + \mathcal{O}\left(\frac{m^2}{\Omega_p^2}\right)\right)$$

hidden DM photon $$\omega_h^2 = \frac{m^2}{1+\varepsilon^2}\left(1 + \mathcal{O}\left(\frac{m^2}{\Omega_p^2}\right)\right)$$

DM photon mode:

$$A = -A_{DM}\frac{\varepsilon}{(1+\varepsilon^2)^{1/2}}\left(1 + \frac{m^2}{\Omega_p^2(1+\varepsilon^2)}\right) + \mathcal{O}\left(\frac{m^4}{\Omega_p^4}\right)$$

$$\tilde{A} = A_{DM}\frac{1}{(1+\varepsilon^2)^{1/2}}\left(1 - \frac{m^2\varepsilon^2}{\Omega_p^2(1+\varepsilon^2)}\right) + \mathcal{O}\left(\frac{m^4}{\Omega_p^4}\right) .$$

observable E&M field:

$$A_{\rm obs} = \frac{A + \varepsilon \tilde{A}}{(1+\varepsilon^2)^{1/2}} \approx -\frac{\varepsilon}{1+\varepsilon^2}\frac{m^2}{\Omega_p^2} A_{DM}.$$

Plasma Shielding:

Kills all the ideas above

So how to chase ultra-light photon DM?

Galaxy as a Calorimeter

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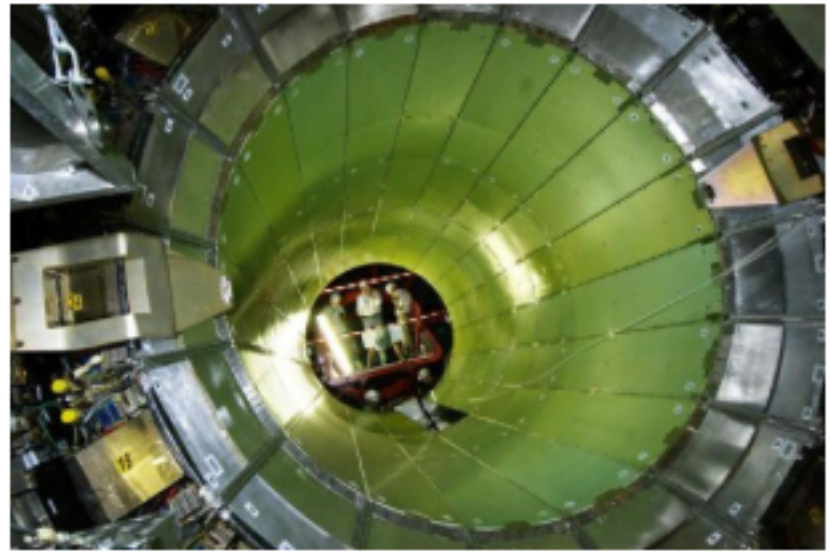


$$\Omega_p^2 \equiv \frac{\omega_p^2}{1 + \frac{i\nu}{\omega}} \quad \text{where} \quad \nu \approx 3 \cdot 10^{-21}\ \text{eV} \left(\frac{n_e}{0.04\ \text{cm}^{-3}}\right) \left(\frac{8000\ \text{K}}{T_e}\right)^{3/2}$$

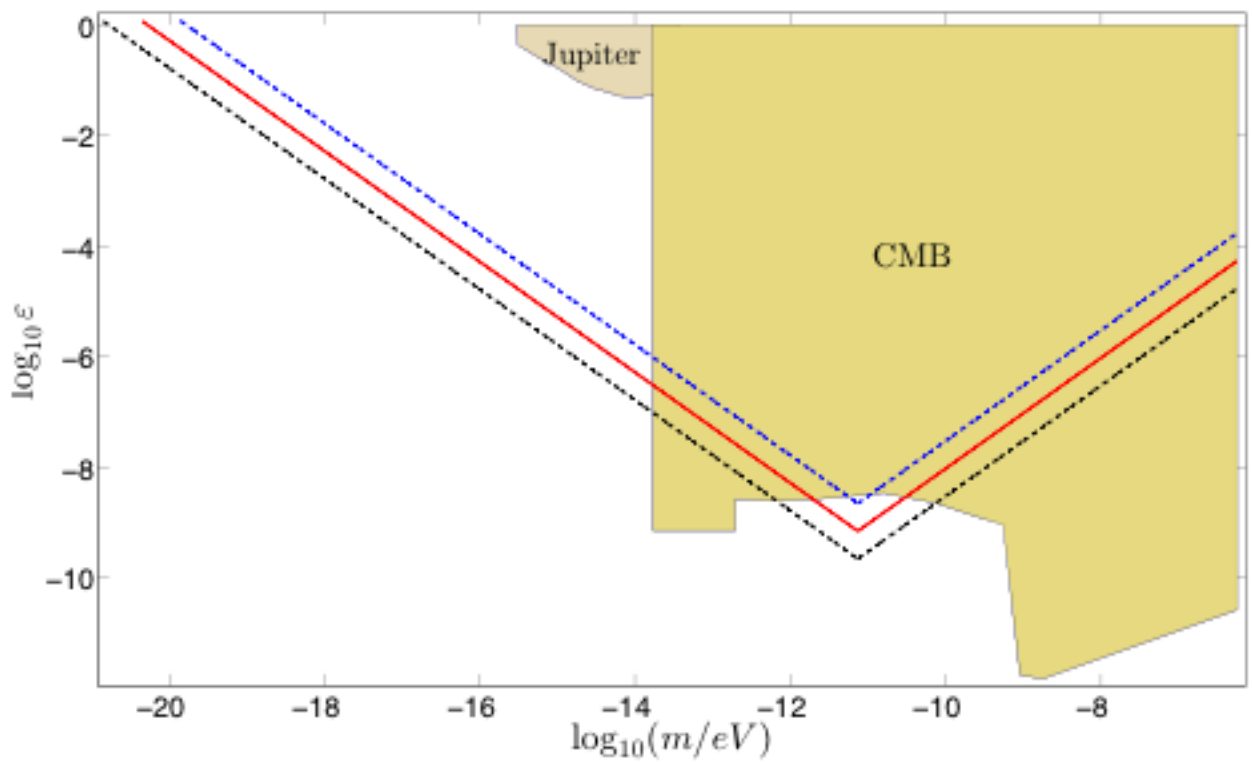
imaginary part of the frequency

$$\gamma_h = \begin{cases} -\nu \frac{m^2}{2\omega_p^2} \frac{\varepsilon^2}{1+\varepsilon^2} & \text{for } m \ll \omega_p \\ -\nu \frac{\omega_p^2}{2m^2} \frac{\varepsilon^2}{1+\varepsilon^2} & \text{for } m \gg \omega_p \end{cases}$$

The resulting heating rate

$$Q \approx 2 \cdot 10^{-9} \varepsilon^2 \frac{\text{erg}}{\text{s cm}^3} \left(\frac{m}{7.4 \cdot 10^{-12} \text{ eV}} \right)^2 \left(\frac{\rho_h}{0.3 \text{ GeV cm}^{-3}} \right) \left(\frac{8000 \text{ K}}{T_e} \right)^{3/2}$$

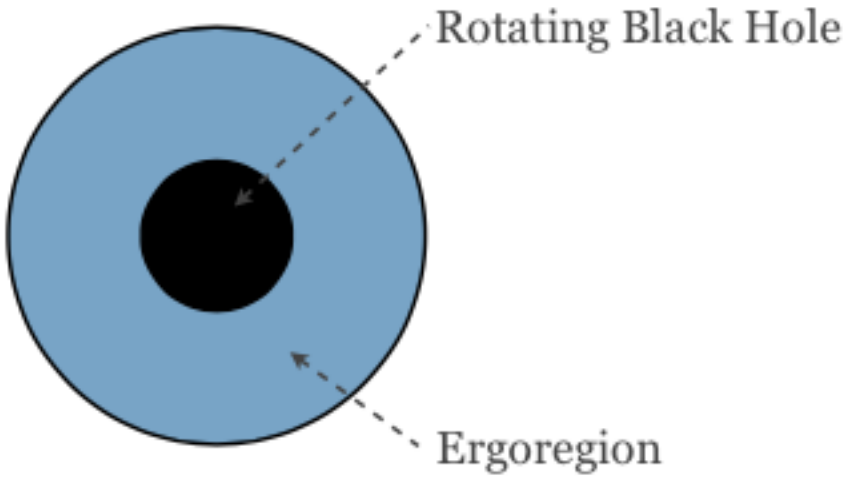
It should be smaller than the observed cooling rate:



Axions, Black Holes and LIGO

Penrose Process

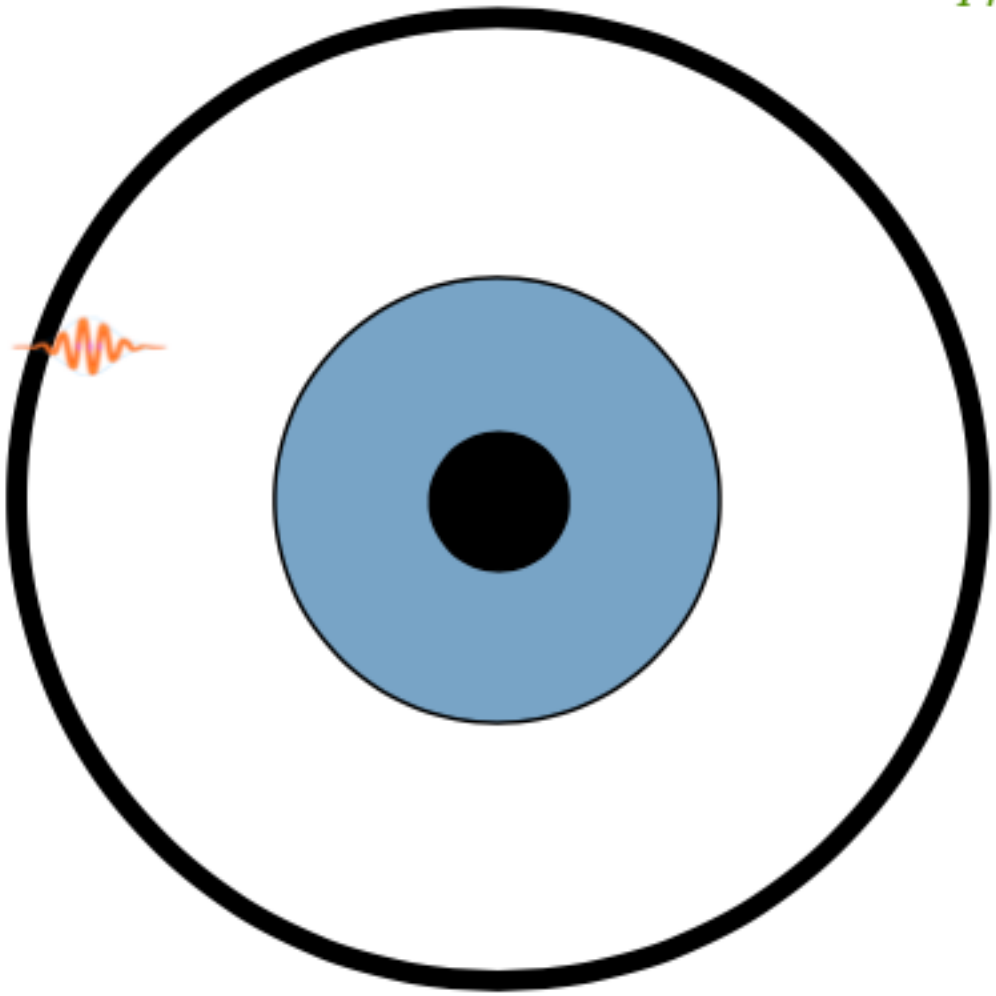
Penrose'69; Zeldovich'71; Misner'72; Starobinsky'73



Extracts angular momentum and mass from a spinning black hole

Black Hole Bomb

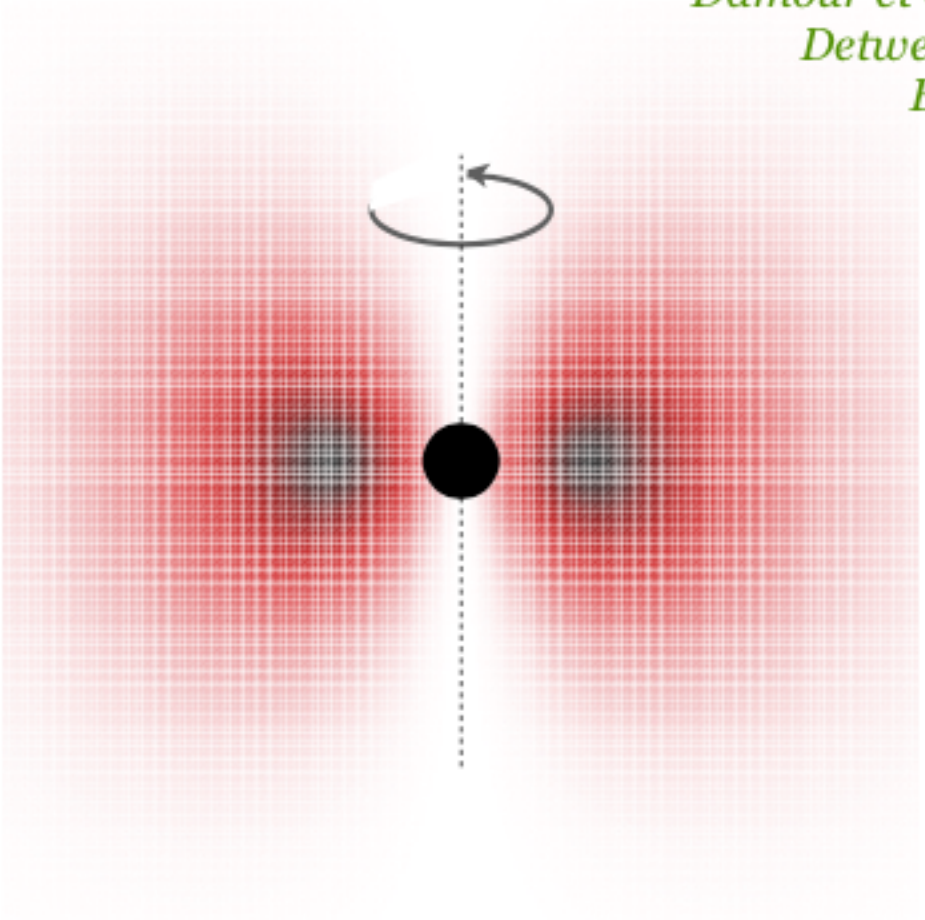
Press & Teukolsky'72



Photons reflected back and forth from the black hole
and through the ergoregion

Superradiance for a massive boson

Damour et al.'76; Gaina et al.'78; Detweiler'80; Zouros & Eardley'79;



Particle Compton Wavelength comparable to the size of the Black Hole

Gravitational Atom in the Sky

SD, Arvanitaki, Dimopoulos, Kaloper, March-Russel 0904.4720
SD, Arvanitaki 1004.3558

Far from the Black Hole: Newtonian Potential

$$\alpha_{EM} = \frac{e^2}{4\pi} \quad \longrightarrow \quad \alpha = G_{\rm N} M_{\rm BH} \mu_a = R_g \mu_a$$

$$E_{\rm binding} = -\frac{\alpha_{EM}^2 m_e}{2n^2} \quad \longrightarrow \quad E_{\rm binding} = -\frac{\alpha^2 \mu_a}{2n^2}$$

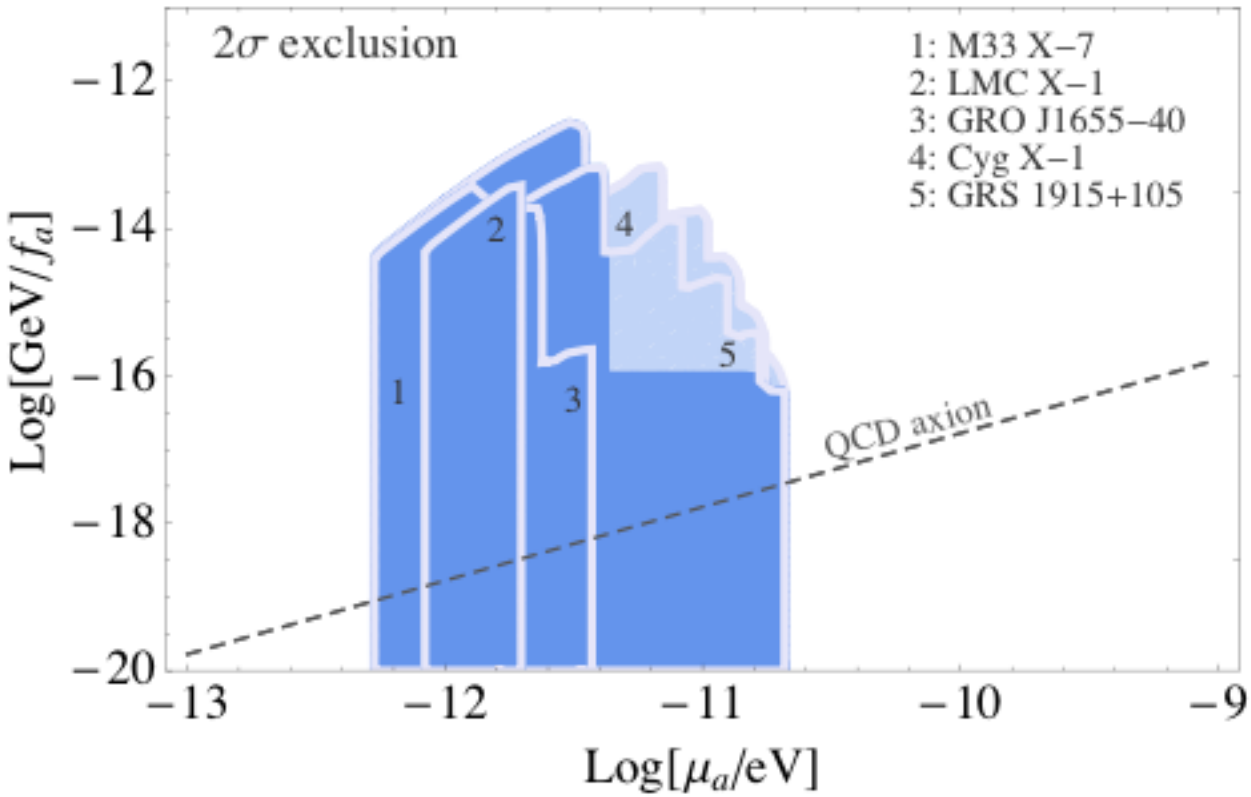
$$\text{fermions} \quad \longrightarrow \quad \text{bosons}$$

Occupation number

$$1 \quad \longrightarrow \quad 10^{75}$$

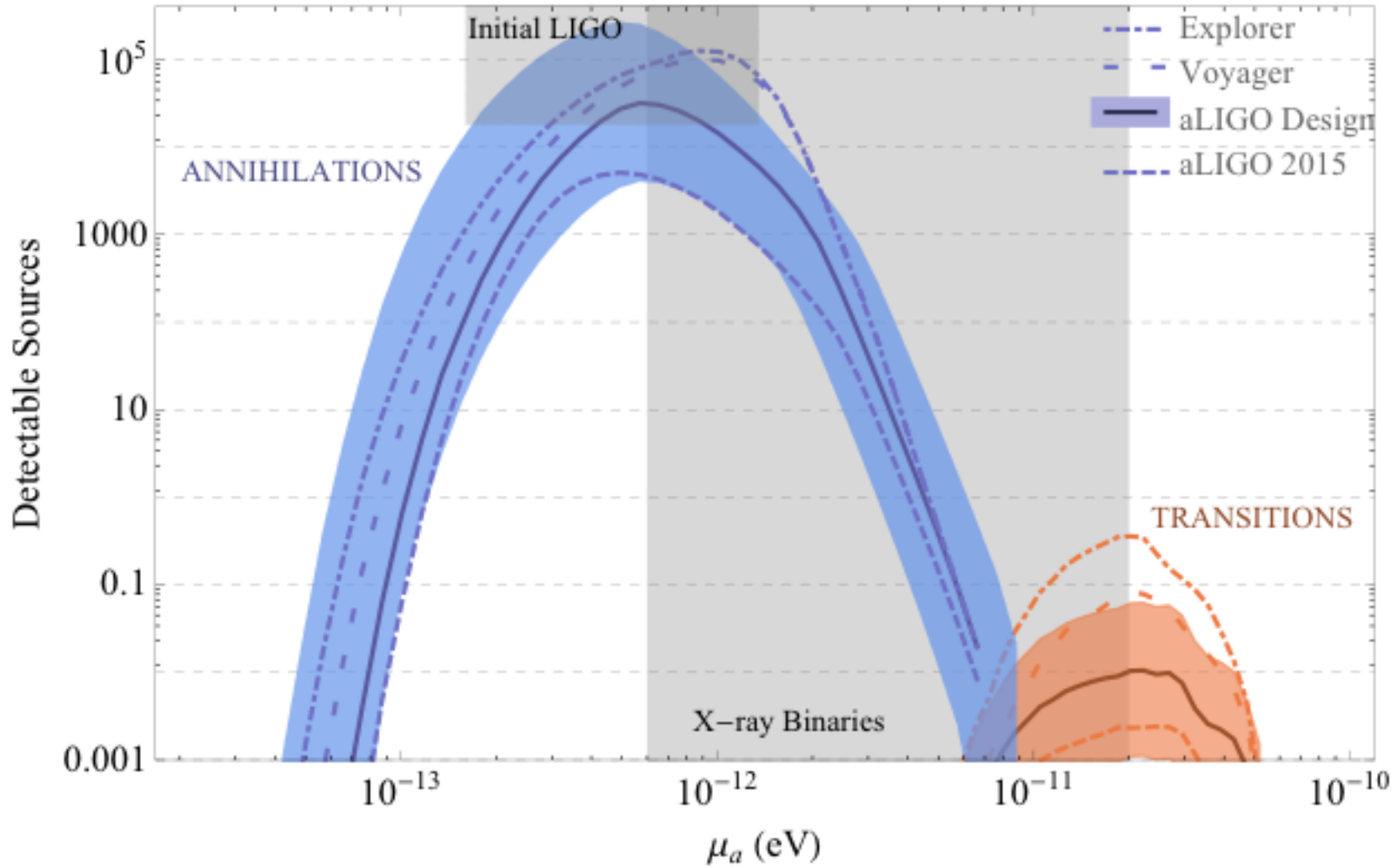
Combined Exclusion plot

Arvanitaki, Baryakhtar, Huang 1411.2263

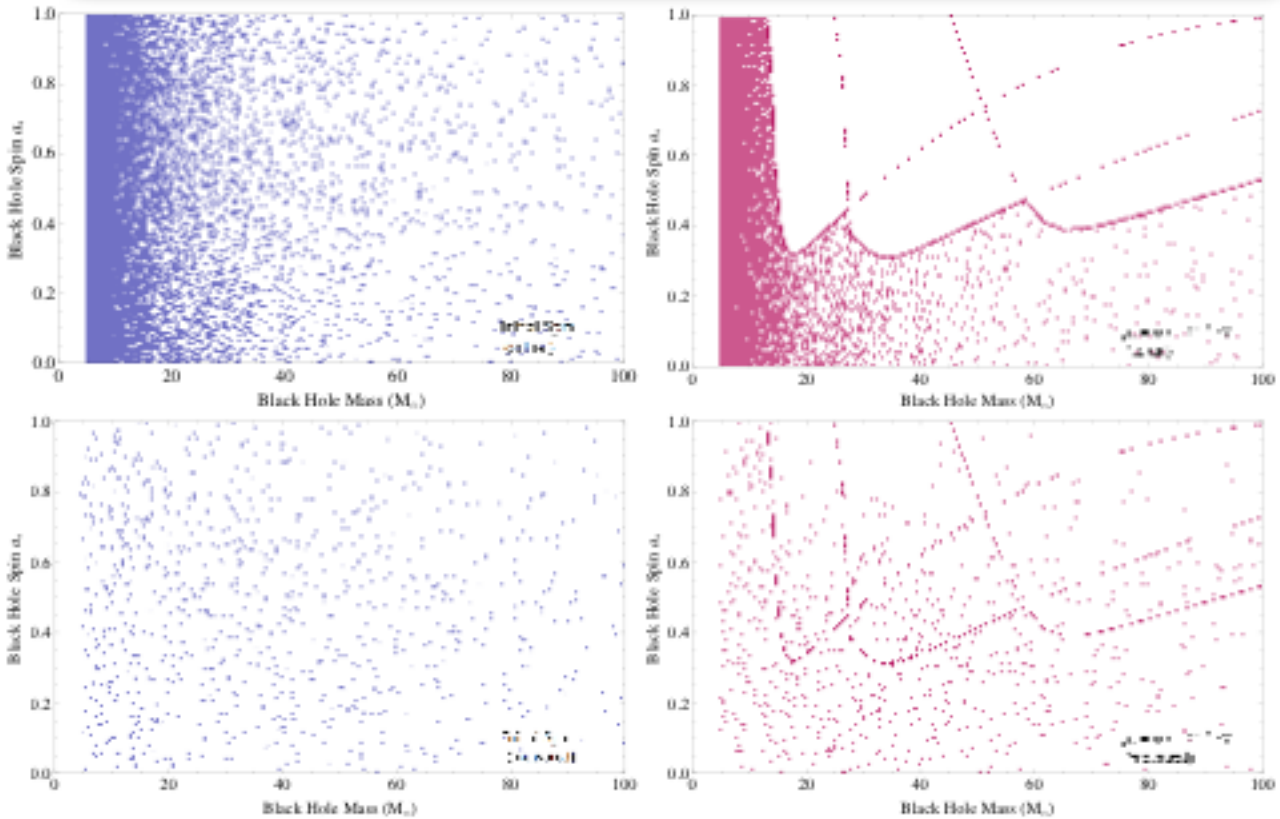


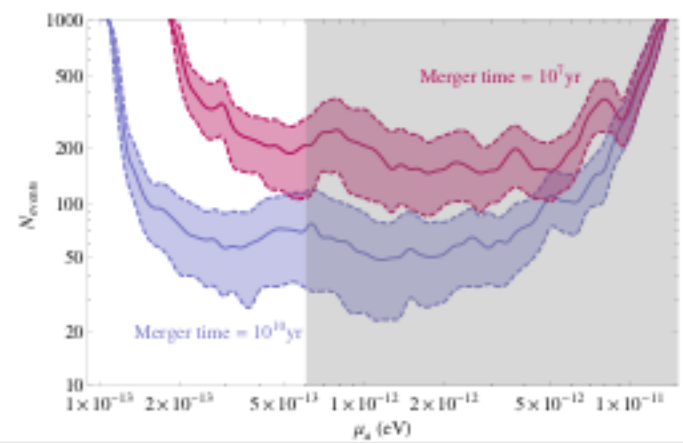
Whether LIGO observation adds anything to the story?

Direct Monochromatic Signal in a Blind Search

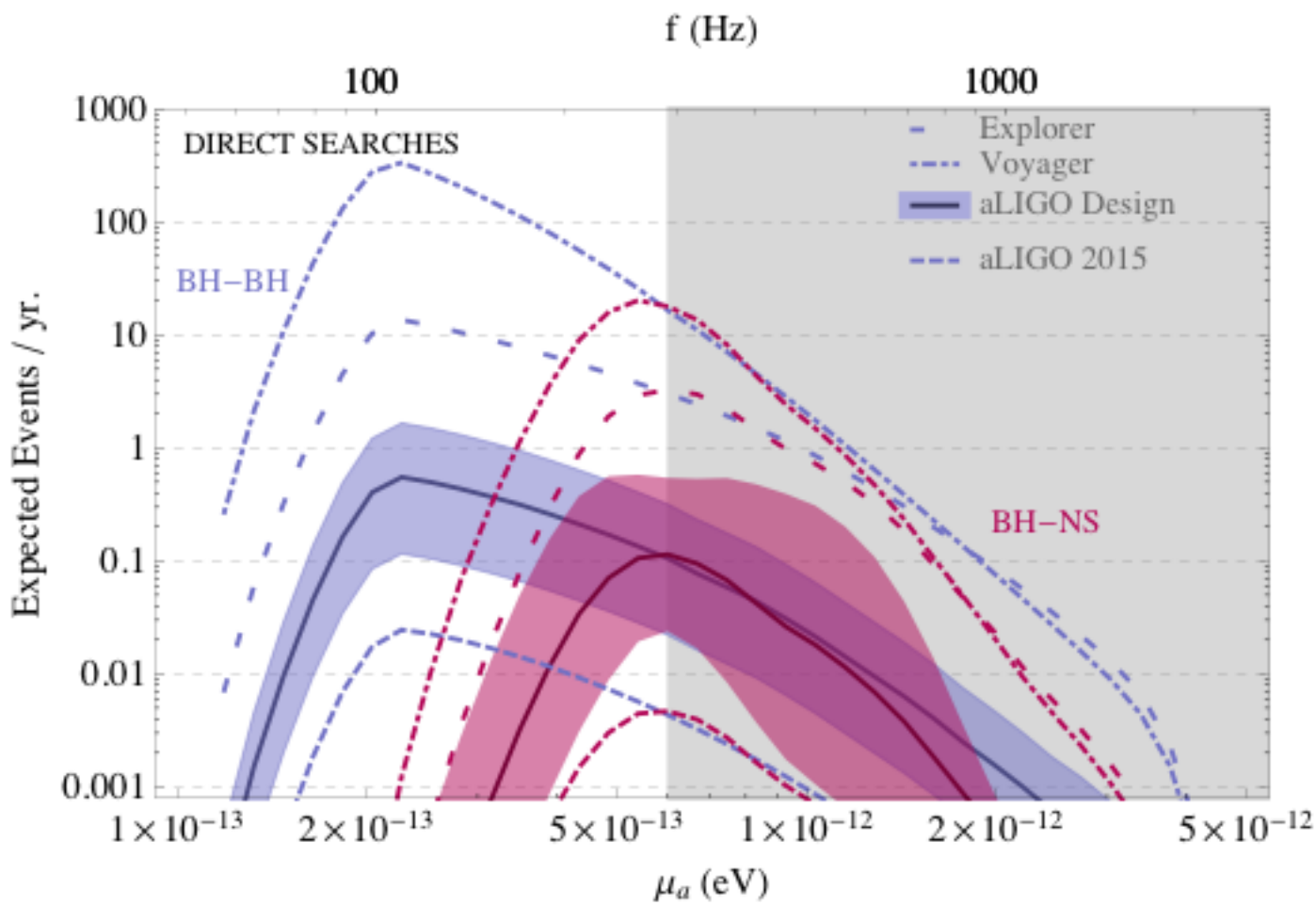


Statistics of Spin Distribution





Direct Monochromatic Signal from a BBH



Conclusions

- Ultra-light DM candidates provide unique and quite unusual observational opportunities

- QCD axion stands out as (one of ?) the most promising dark matter candidates. With LIGO covering the lightest mass range, and promising ideas how to probe higher masses it presents a very well-defined target for future searches.