Title: Searching for New Physics Across the Spectra

Speakers: Masha Baryakhtar

Series: Particle Physics

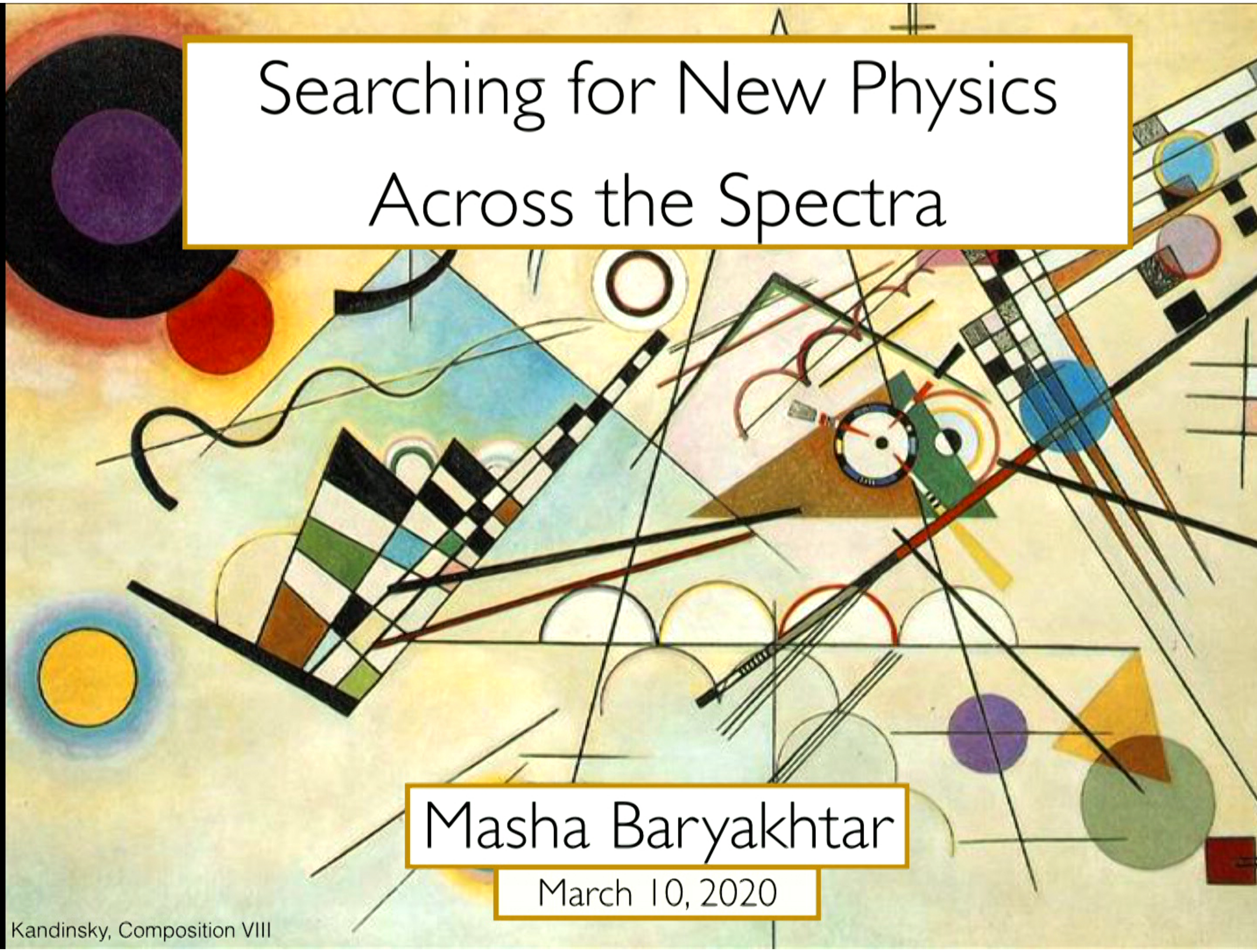
Date: March 10, 2020 - 11:00 AM

URL: http://pirsa.org/20030092

Abstract: Theories beyond the Standard Model of particle physics often predict new, light, feebly interacting particles whose discovery requires novel search strategies. A light particle, the QCD axion, elegantly solves the outstanding strong-CP problem of the Standard Model; cousins of the QCD axion can also appear, and are natural dark matter candidates. First, I will discuss my experimental proposal based on thin films, in which dark matter can efficiently convert to detectable single photons. A prototype experiment is underway, and current techniques promise to reach significant new dark matter parameter space.

Second, I will show how rotating black holes turn into axionic and gravitational wave beacons, creating nature's laboratories for ultralight bosons. When an axion's Compton wavelength is comparable to a black hole size, energy and angular momentum from the black hole source exponentially-growing bound states of particles, forming `gravitational atoms'.  These `gravitational atoms' emit monochromatic gravitational wave signals, enabling current searches at gravitational wave observatories to discover ultralight axions. If the axions interact with one another, instead of gravitational waves, black holes populate the universe with axion waves.

Searching for New Physics Across the Spectra

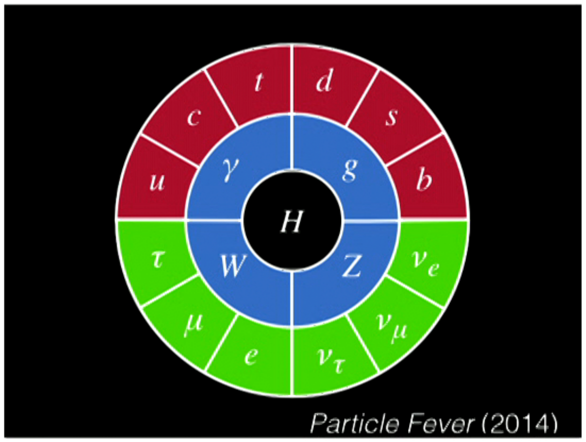


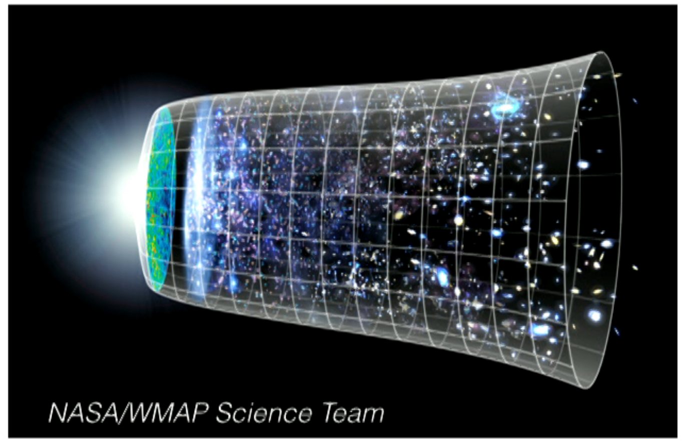
Masha Baryakhtar

March 10, 2020

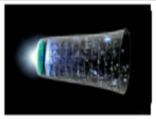
Kandinsky, Composition VIII

The Standard Models





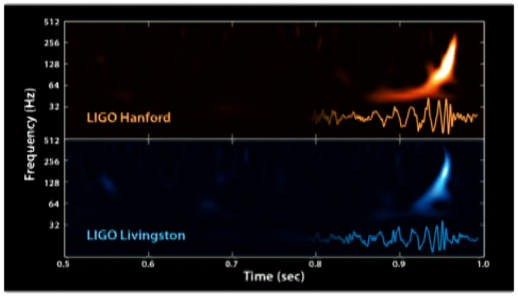
- Minimal set of particles and parameters that accurately describes our universe

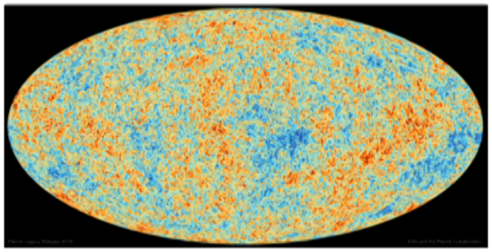


The Standard Models

Have had great successes….

Discovery of gravitational waves, further confirming general theory of relativity and opening an era of multimessenger astronomy



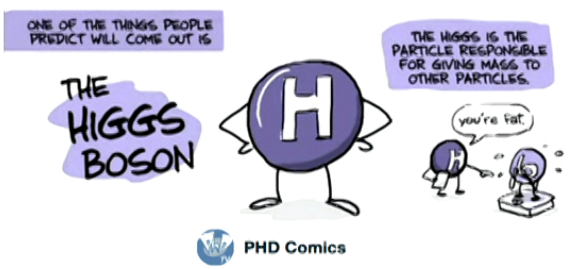


- Cosmic microwave background matches predication of LCDM to excellent precision

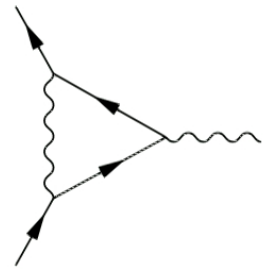
The Standard Models

Have had great successes….

Higgs boson discovery, confirming theory of masses and electroweak symmetry breaking



Excellent agreement between theory and experiment



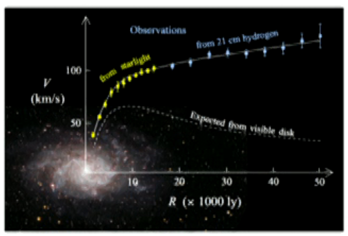
- Electron g-2 magnetic dipole moment

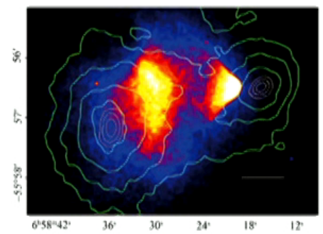
$$g/2 = 1.001\ 159\ 652\ 180\ 73\ (28) \quad [0.28\ \text{ppt}]\ \text{(measured)}$$
$$g(\alpha)/2 = 1.001\ 159\ 652\ 177\ 60\ (520) \quad [5.2\ \text{ppt}]\ \text{(predicted)}.$$

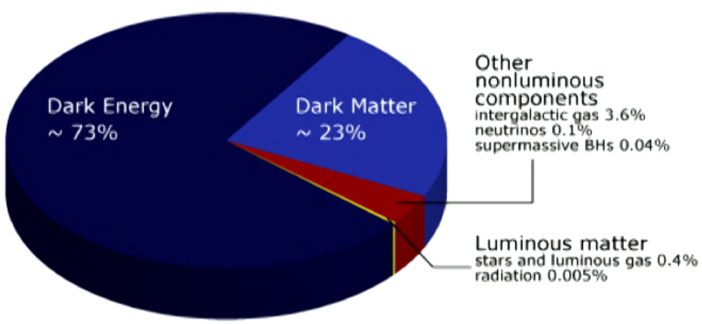
The Standard Models

… and great problems:

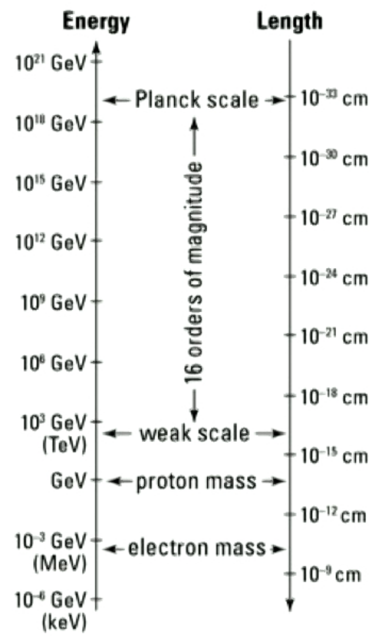
what are dark matter and dark energy that make up most of the energy content of the universe?





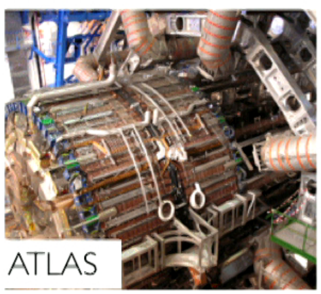


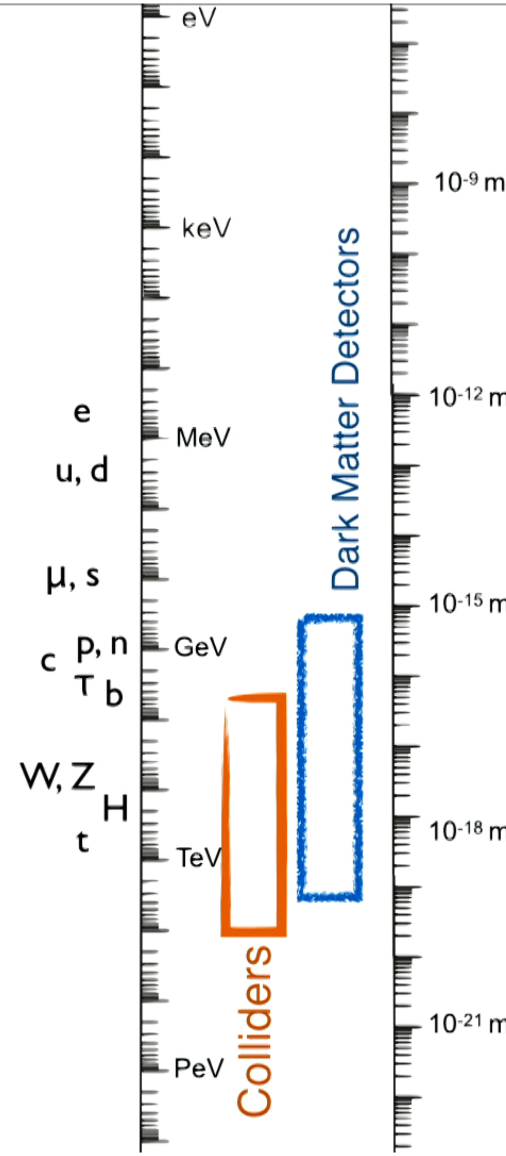
why is the Higgs so light, or why is gravity so much weaker than the other forces? ("Hierarchy Problem")



Searching for New Physics

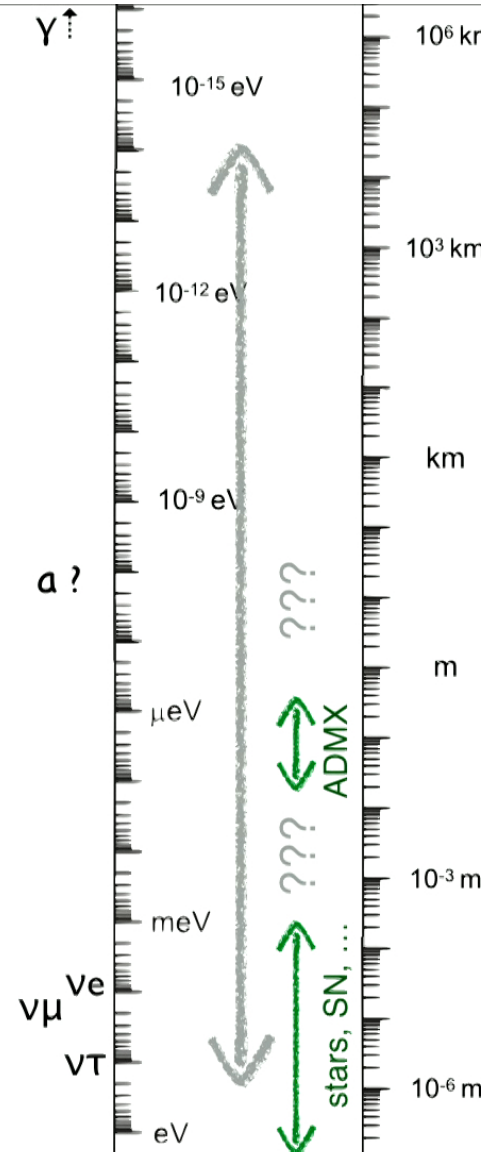
- Most of the standard model lies within several orders of magnitude in mass
- Other scales must enter in a complete theory





Searching for New Physics

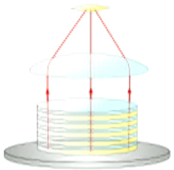
- Most of the standard model lies within several orders of magnitude in mass
- Other scales must enter in a complete theory
- Outstanding problems motivate searches at low energies
- Dark matter, strong-CP problem,…
  - QCD axion
    - Very weakly interacting
    - Long wavelength



Outline

- New bosons beyond the Standard Model

- Searches for dark matter with light

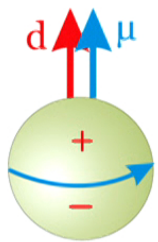


- Gravitational atoms and axionic beacons

The Strong-CP problem

- Theoretically expect significant CP violation in potential of strong interactions

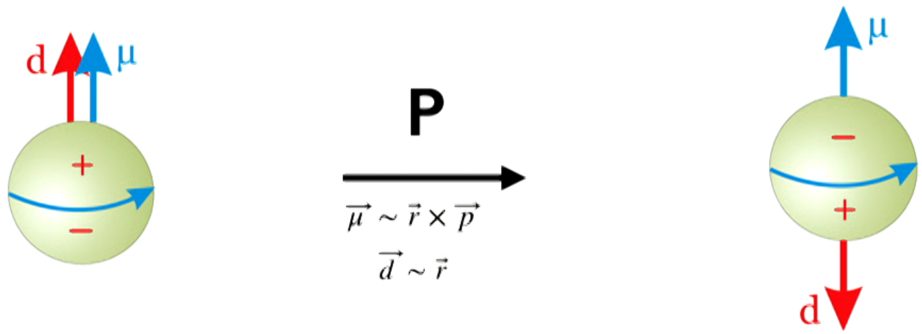
- This would give the neutron an electric dipole moment



The Strong-CP problem

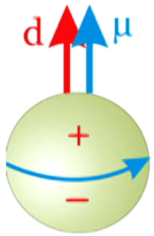
- Theoretically expect significant CP violation in potential of strong interactions

- This would give the neutron an electric dipole moment



$$\vec{\mu} \cdot \vec{d} \rightarrow -\, \vec{\mu} \cdot \vec{d}$$

The Strong-CP problem

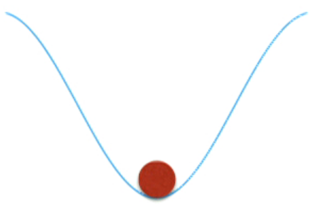


- Upper bound from measurements of neutron electric dipole moment,

$$\theta_0 + \arg\det M_q + < 10^{-10}$$

- Solve the problem by promoting θ to a dynamical field, the **axion:**

$$V \supset \frac{\alpha_s}{8\pi}\,\theta\, G\,\tilde{G}$$
$$\downarrow$$
$$V \supset \frac{\alpha_s}{8\pi}\left(\frac{a}{f} - \theta\right)\, G\,\tilde{G}$$



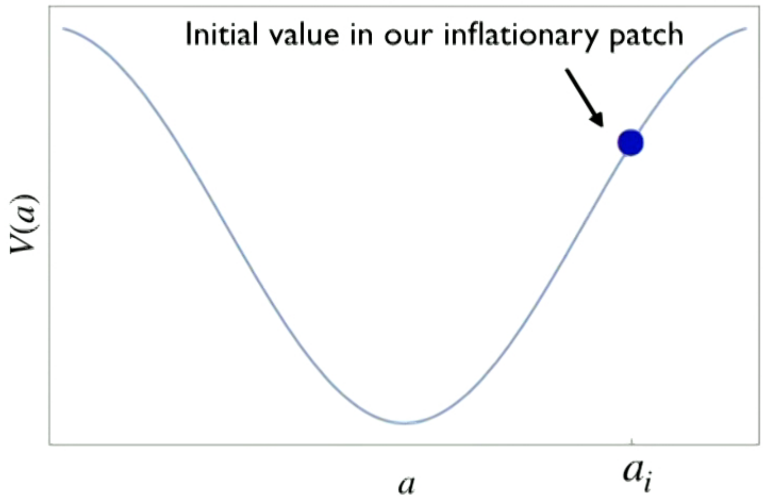
- Nonperturbative QCD effects create potential for the axion; at the minimum the strong-CP problem is solved (θ~$\boldsymbol{0}$)

Peccei and Quinn, PRL 38, 1440, 1977
Weinberg, PRL 40, 223, 1978
Wilczek, PRL 40, 279, 1978

Axion dark matter

- Cosmological evolution analogous to damped harmonic oscillator with frequency given by the mass and damping by Hubble friction:

$$\ddot{a} + 3H\dot{a} + m^2 a = 0$$



Preskill, Wise, Wilczek (1983)
Dine, Fischler (1982)
Abbott, Sikivie (1982)

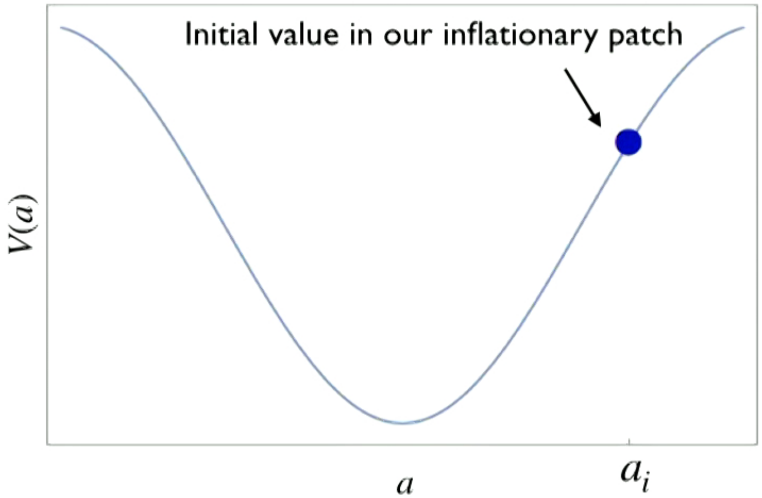
Axion dark matter

- Cosmological evolution analogous to damped harmonic oscillator with frequency given by the mass and damping by Hubble friction:

$$\ddot{a} + 3H\dot{a} + m^2 a = 0$$

- Early on, H >> m: frozen by Hubble friction

- When H < m: begins to oscillate; energy density dilutes as nonrelativistic matter



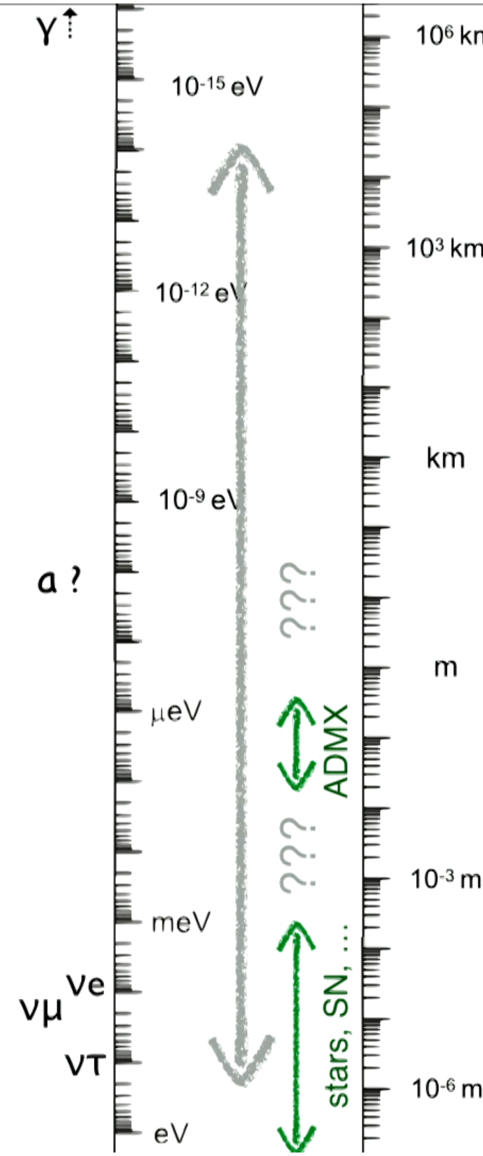
Predicts dark matter density as a function of axion mass and initial amplitude, set by inflation

Preskill, Wise, Wilczek (1983)
Dine, Fischler (1982)
Abbott, Sikivie (1982)

Searching for New Physics

- Axions are
  - Solutions to a theoretical puzzle of small numbers—the strong-CP problem
  - Approximately massless particle with mass and couplings fixed by a high scale f_a,

$$m_a = 5.70(6)(4)\,\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$



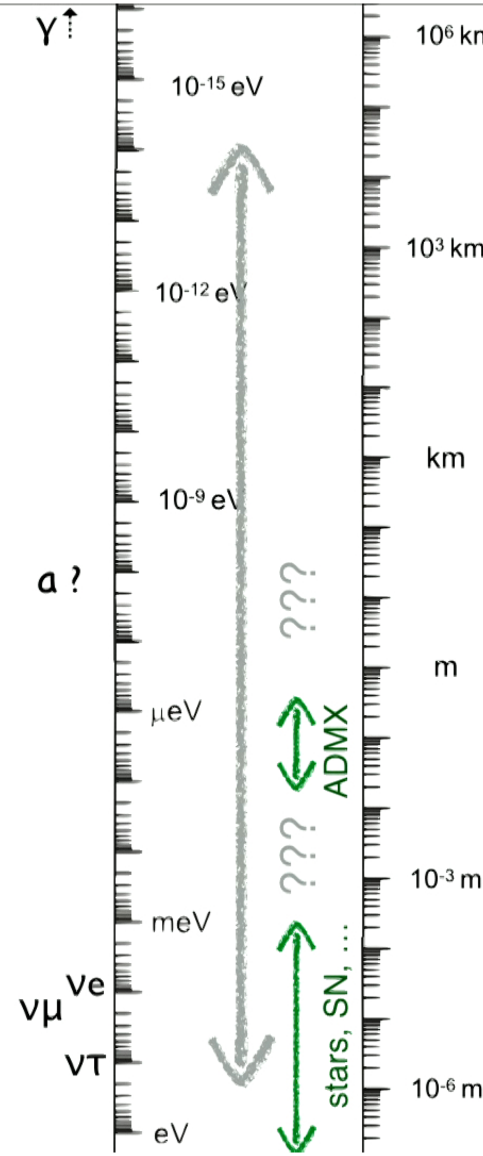
Searching for New Physics

- Axions are
  - Solutions to a theoretical puzzle of small numbers—the strong-CP problem.
  - Approximately massless particle with mass and couplings fixed by a high scale f_a,

$$m_a = 5.70(6)(4)\,\mu\text{eV}\,\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

  - Low-energy remnants of complex physics at high scales
    Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell
  - Candidates for the dark matter of the universe
    Nelson, Scholtz
    Arias, Cadamuro, Goodsell, Jaeckel, Redondo, Ringwald
    Graham, Mardon, Rajendran

    Preskill, Wise, Wilczek



Searching for New Physics

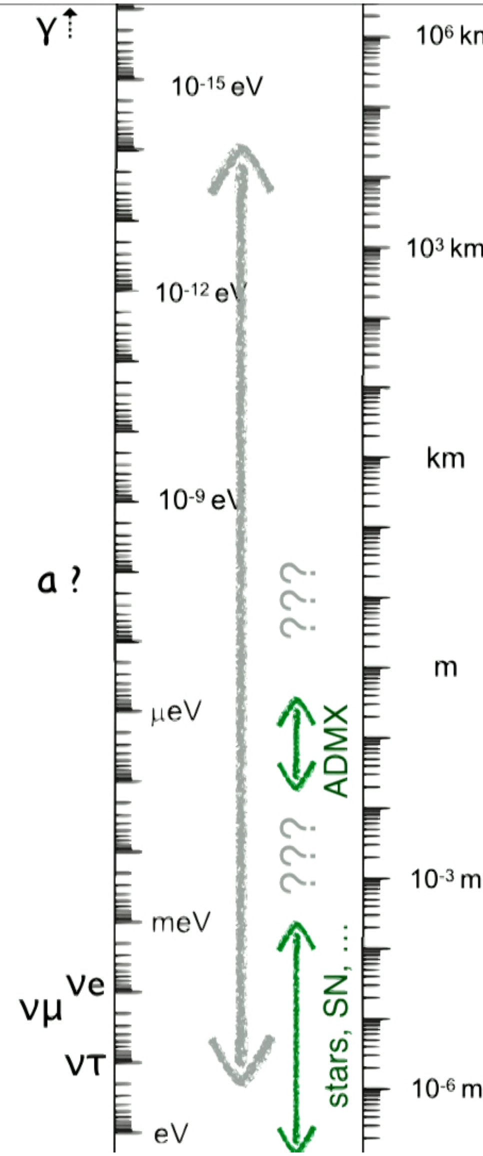
- Axions are
  - Solutions to a theoretical puzzle of small numbers—the strong-CP problem.
  - Approximately massless particle with mass and couplings fixed by a high scale f_a,

$$m_a = 5.70(6)(4)\,\mu\mathrm{eV}\left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)$$

Dark photons and axion like particles

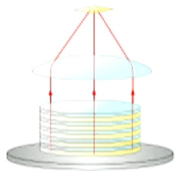
  - Low-energy remnants of complex physics at high scales
    Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell
  - Candidates for the dark matter of the universe
    Nelson, Scholtz
    Arias, Cadamuro, Goodsell, Jaeckel, Redondo, Ringwald
    Graham, Mardon, Rajendran

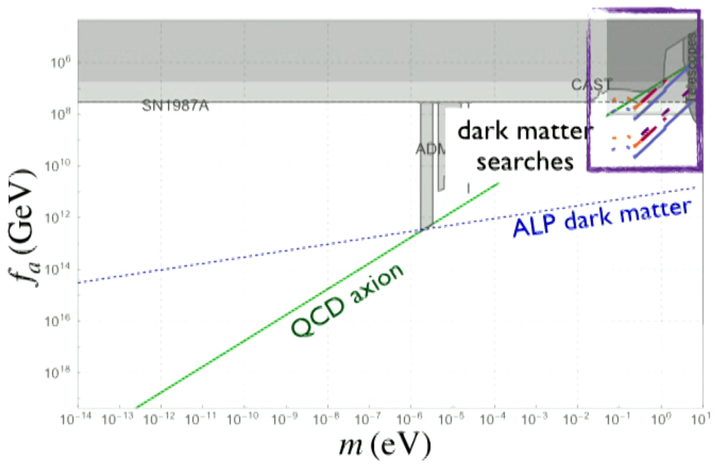
    Preskill, Wise, Wilczek



Outline

- New bosons beyond the Standard Model
- Searches for dark matter with light
- Gravitational atoms and axionic beacons



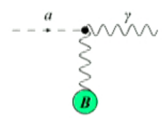


MB, J. Huang, R. Lasenby, PRD 2018

Funded Prototype Experiment, *Bosonic Dark Matter Search Using Superconducting Nanowire Single-Photon Detectors.*
PIs K. Berggren (MIT) & S.W. Nam (NIST)

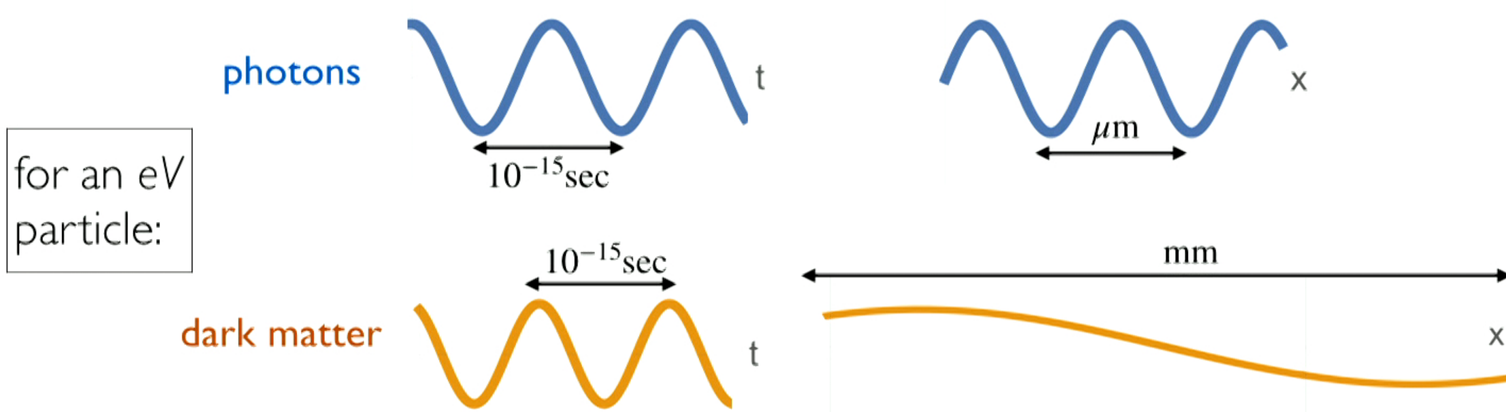
Light bosonic dark matter

- Amplitude of axion (dark photon) dark matter background acts as an oscillating ***current*** in Maxwell's equations with frequency equal to the particle mass



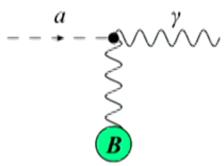
Axion 'current' $\boxed{J_a} = g_{a\gamma\gamma}\partial_t a\, B_{ext}$

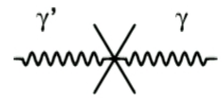
Dark photon 'current' $\boxed{J_{A'}} = \kappa m_A^2 A'$



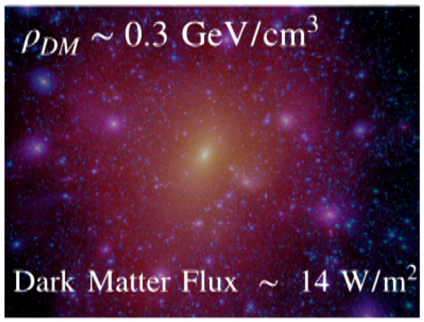
Light bosonic dark matter

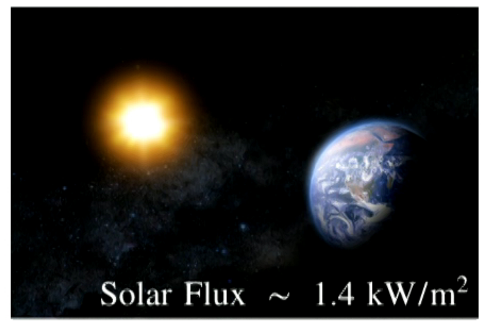
- Photon can convert into axion (dark photon) and back through E . B (kinetic mixing)





- Can we see axion or dark photon dark matter converting to photons?

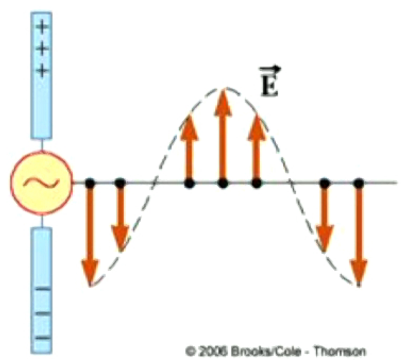




  - Impossible to conserve both energy and momentum: **photons** relativistic while **dark matter** is massive with a small velocity in our galaxy

  - Cannot change propagation of dark matter, but will be able to manipulate light in a medium to correct the mismatch

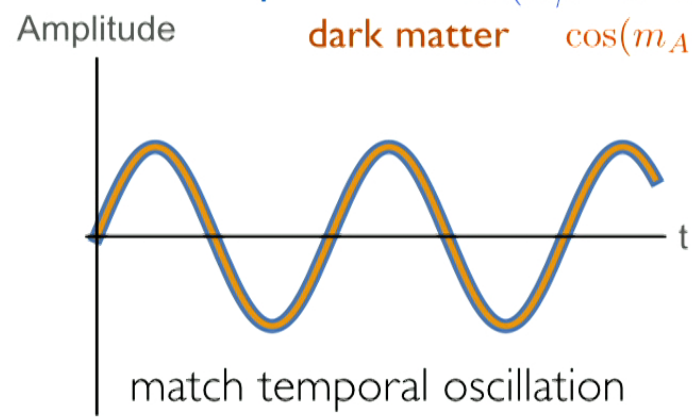
Light bosonic dark matter



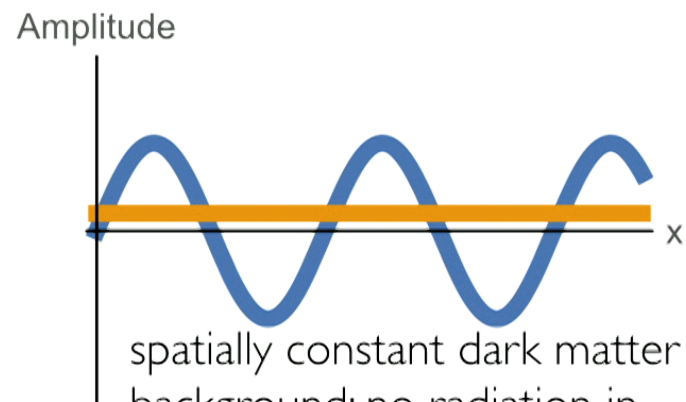
oscillating current can source electromagnetic radiation

photon $\cos(\omega_\gamma t - \vec{k} \cdot \vec{x})$

dark matter $\cos(m_A t)$

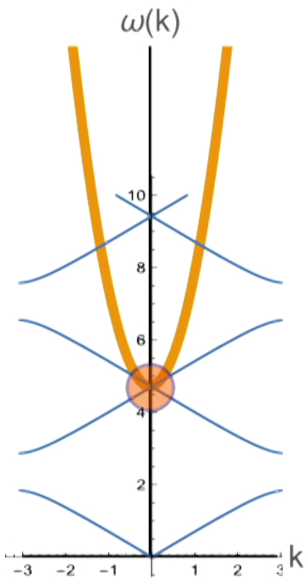


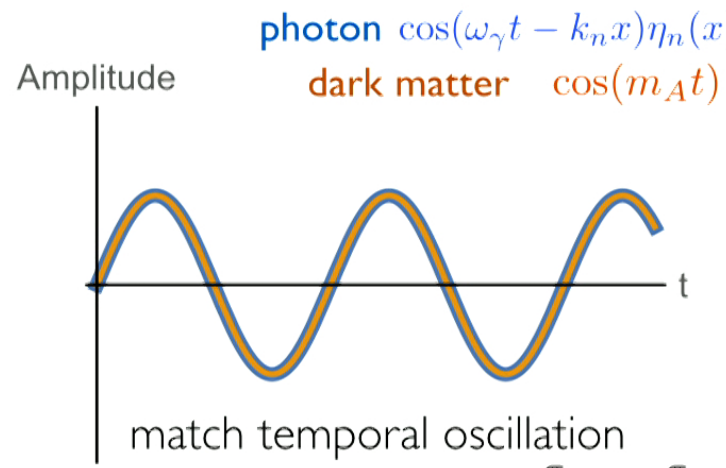
match temporal oscillation

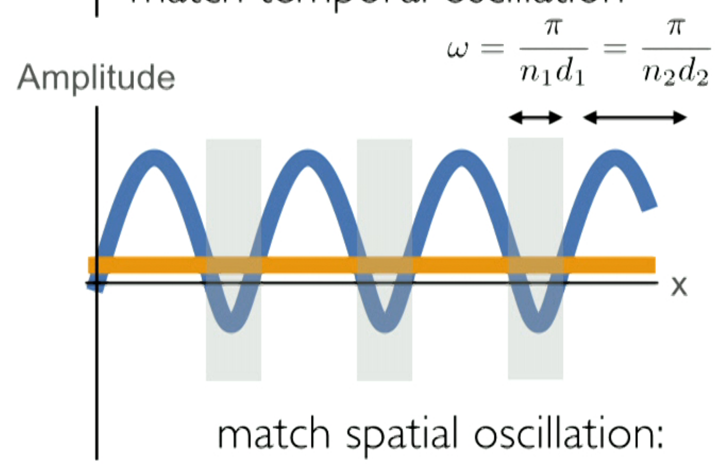


spatially constant dark matter background: no radiation in free space

Light bosonic dark matter



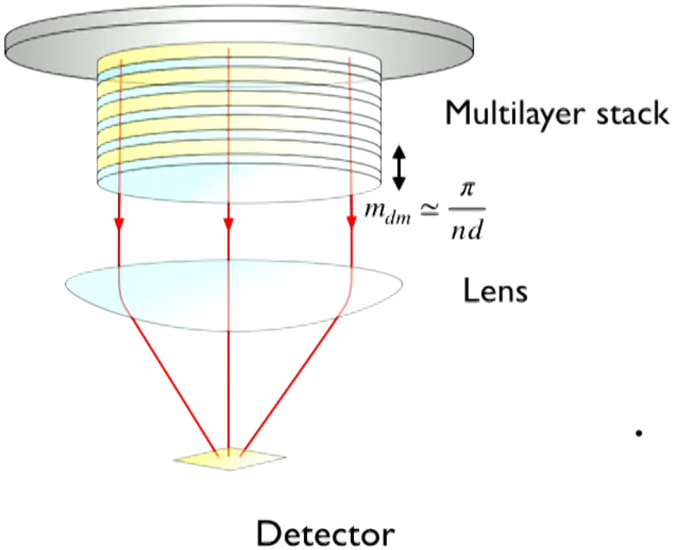




- Add periodicity in one dimension to correct momentum mismatch
- Periodic index of refraction changes free solutions of photon modes
- Electric field no longer integrates to zero against a constant DM background

source electromagnetic radiation

Searches for dark matter with light



MB, J. Huang, R. Lasenby, PRD 2018

Dark matter acts as time-varying background `current' which sources single photons

- Outgoing photon energy sourced by dark matter:

$$\omega_\gamma \simeq m_{dm} + \mathcal{O}(10^{-6} m_{dm})$$

- Outgoing photon momentum sourced by periodicity:

$$k_\gamma \simeq \frac{\pi}{nd} + \mathcal{O}(10^{-3} m_{dm})$$

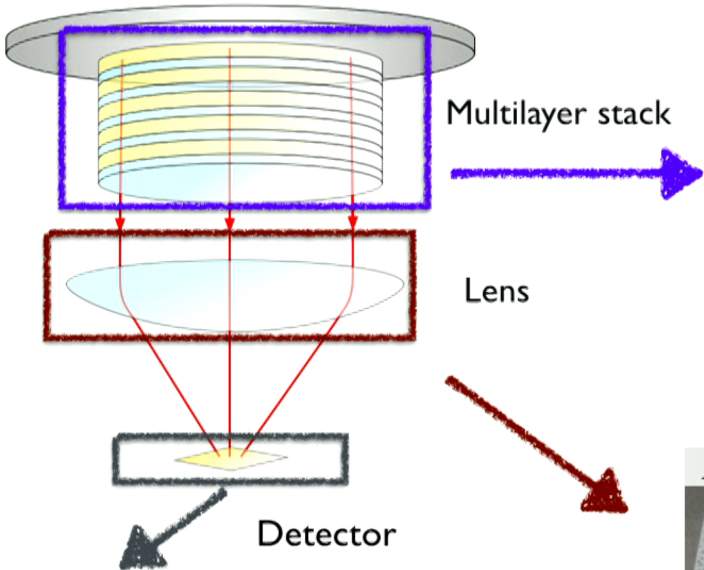
- Emission when DM mass matches periodicity:

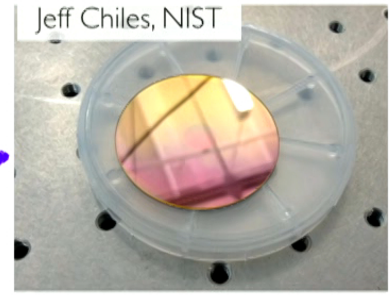
$$m_{dm} \simeq \frac{\pi}{nd}$$

Dielectric 'lattice' vector corrects mismatch between photon and dark matter momentum

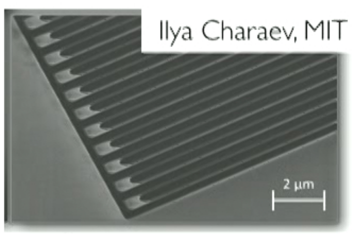
22

Nanowire Detection of Photons from the Dark Side

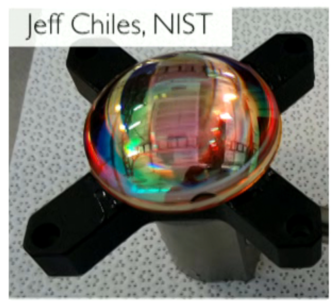




- High index of refraction contrast, more layers increase conversion
- e.g. silicon (n_2=3.4) and silica (n_1=1.46)



- Small area single photon detector with ultra low noise



- Signal photons perpendicular to stack: efficiently focused

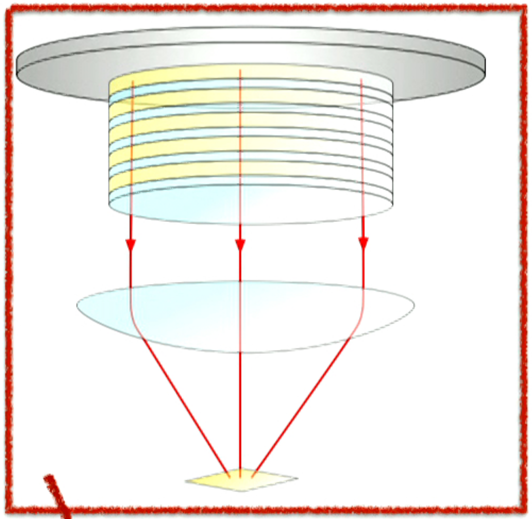
DOE QuantiSED grant, DE-SC0019129 ($300,000 for two years)

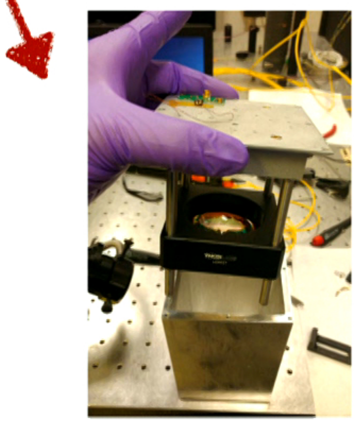
Bosonic Dark Matter Search Using Superconducting Nanowire Single-Photon Detectors.

PIs K. Berggren (MIT) & S.W. Nam (NIST)

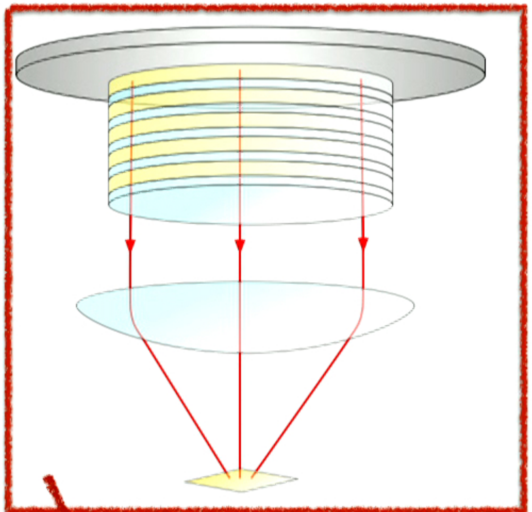
MB, J. Huang, R. Lasenby PRD 2018

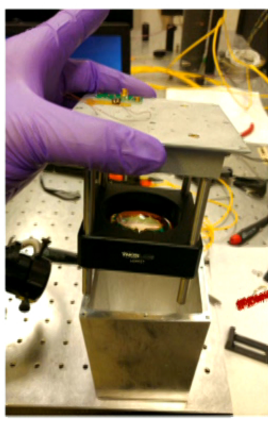
Nanowire Detection of Photons from the Dark Side

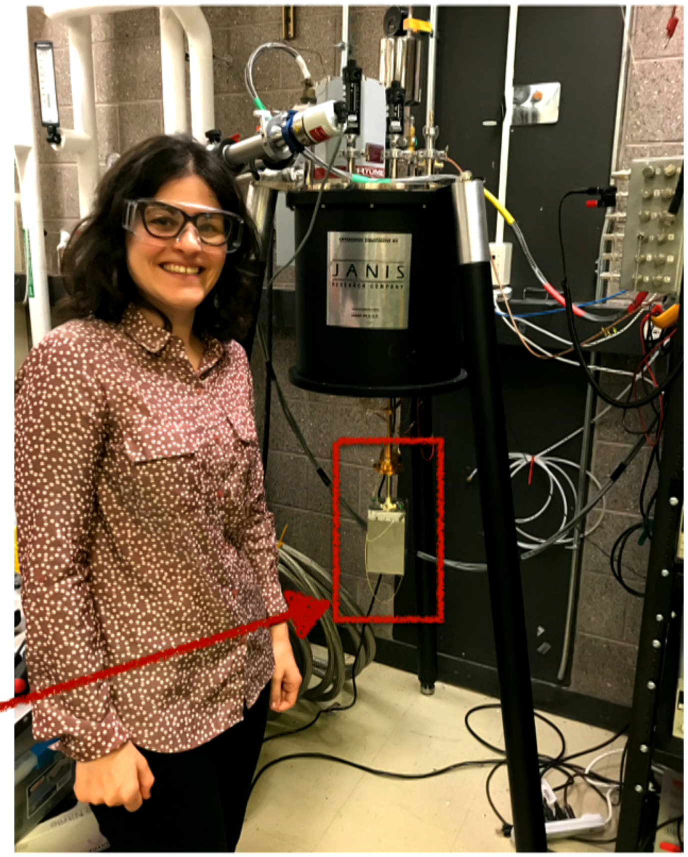




Nanowire Detection of Photons from the Dark Side

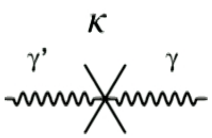


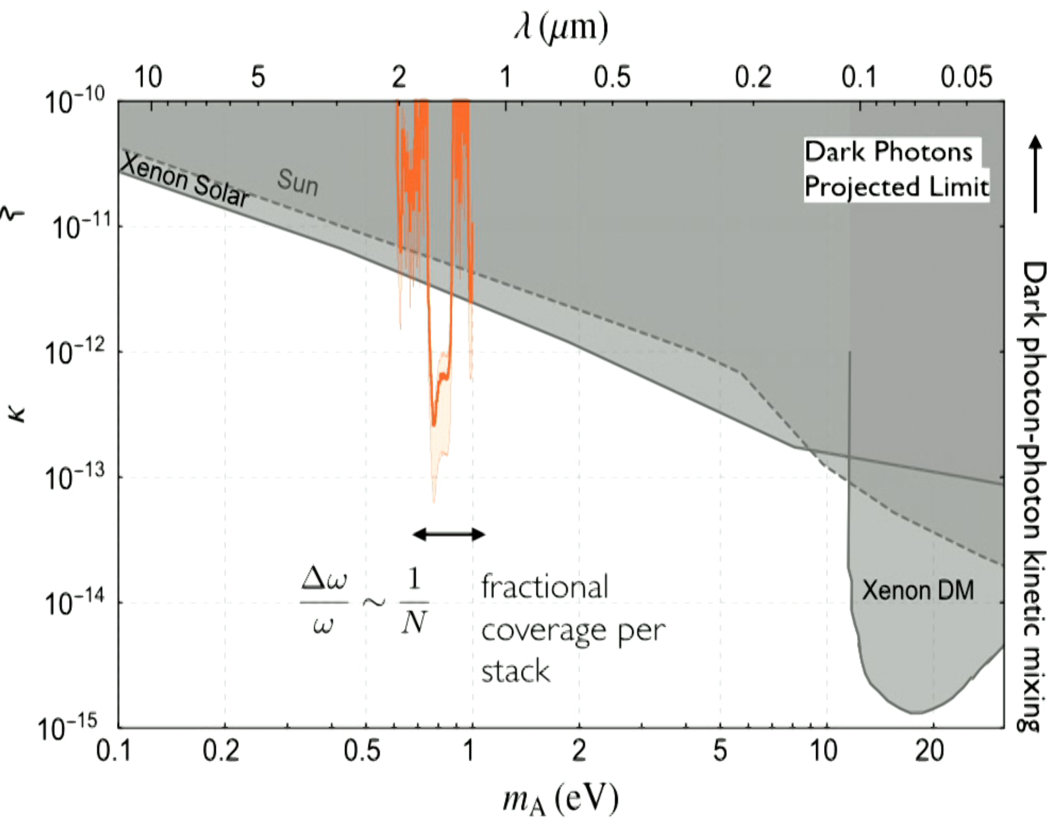




25

Searches for dark matter with light

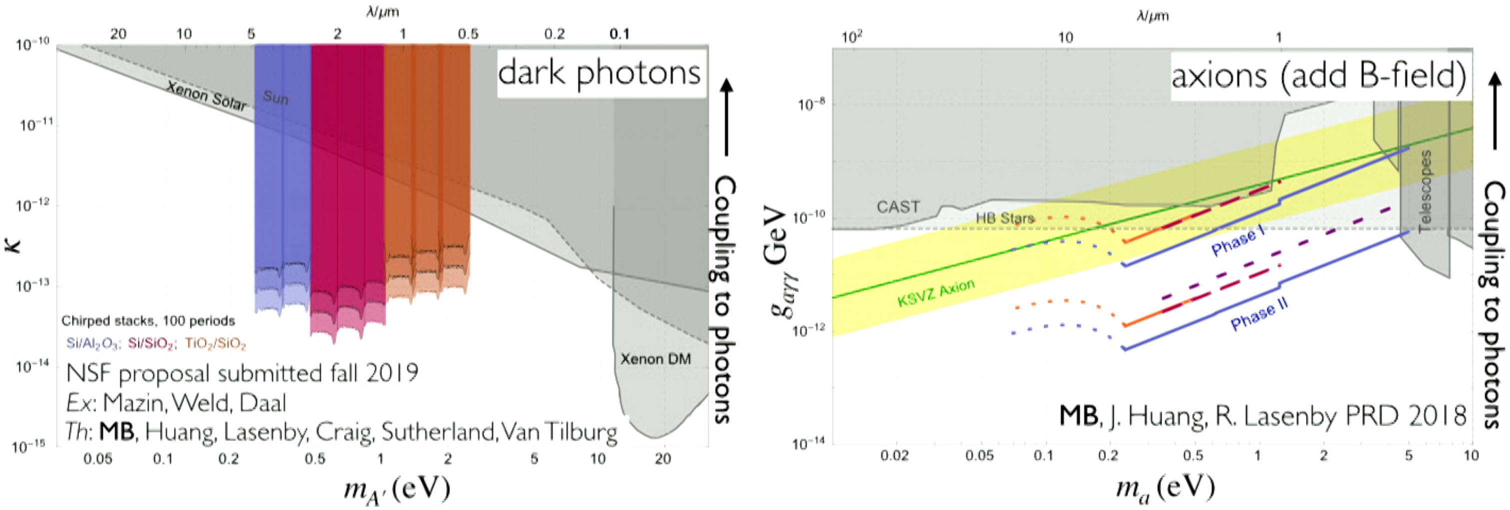




Bosonic Dark Matter Search Using Superconducting Nanowire Single-Photon Detectors.

- Prototype can already cut into new parameter space with weeks of runtime
- Currently performing experimental checks
- Longer run time, other frequencies planned

Searches for dark matter with light

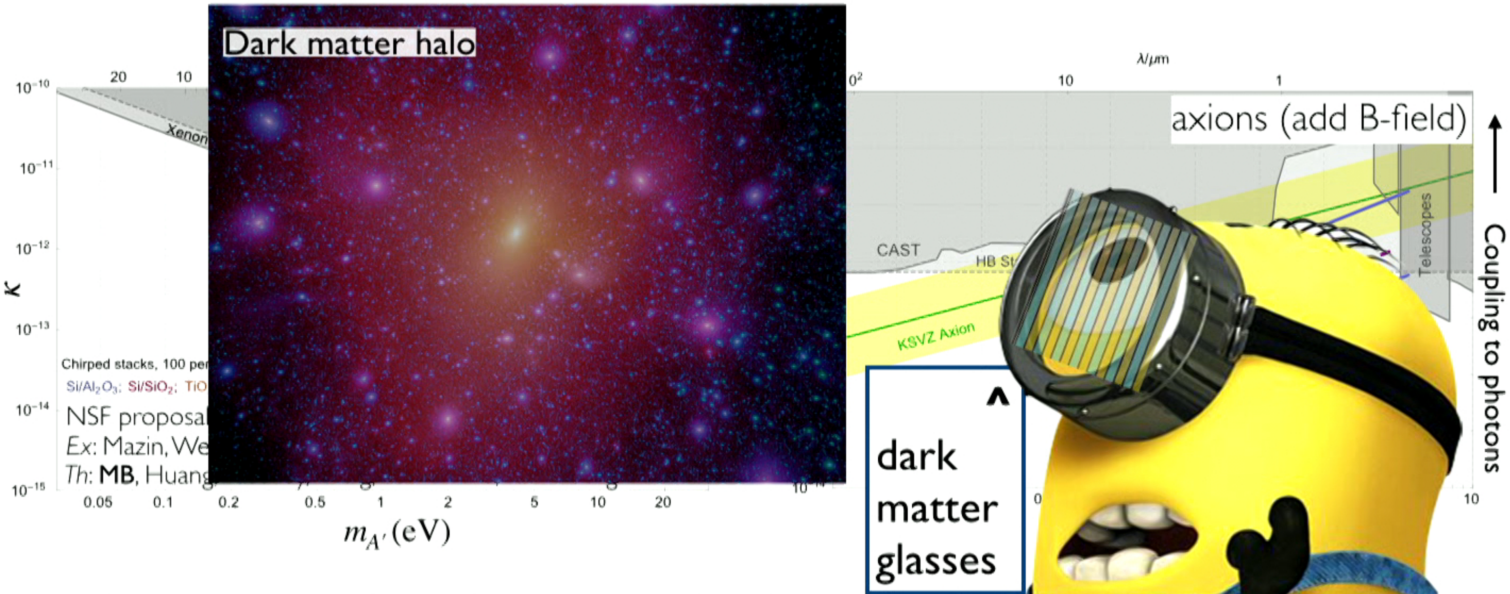


- Dielectric materials can help correct the dispersion mismatch in waves between a massless and massive particle of the same energy: this allows a conversion of axions into photons

- First steps underway, use well-established optics and detector technology; possible to reach very small couplings with larger setups

- Improve on parameter space by orders of magnitude, and perhaps see dark matter

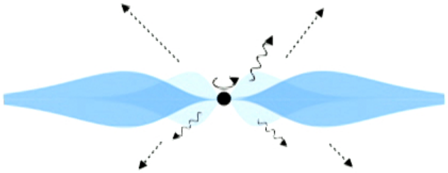
Searches for dark matter with light



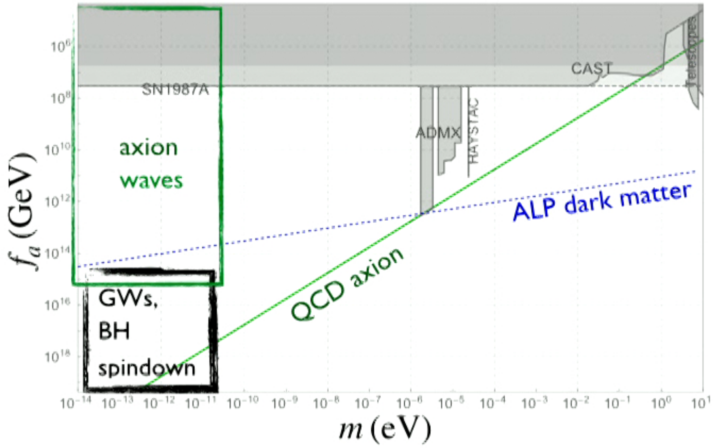
- Dielectric materials can help correct the dispersion misma[...] massless and massive particle of the same energy: this all[...] axions into photons
- First steps underway, use well-established optics and detec[...] to reach very small couplings with larger setups
- Improve on parameter space by orders of magnitude, and perh[...] matter

28

Outline



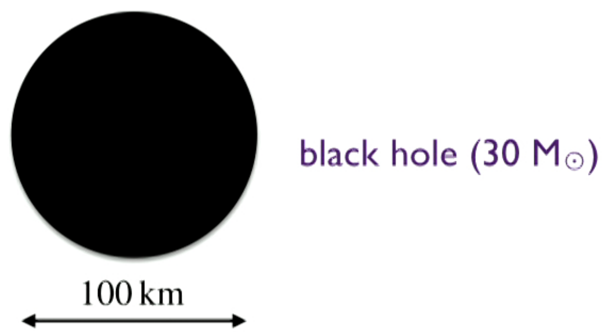
- New bosons beyond the Standard Model
- Searches for dark matter with light
- Gravitational atoms and axionic beacons



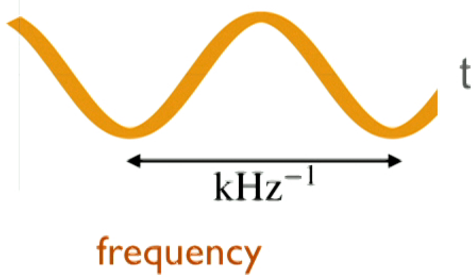
MB, Galanis, Lasenby, Simon (*in prep*)
Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein 2003.03359

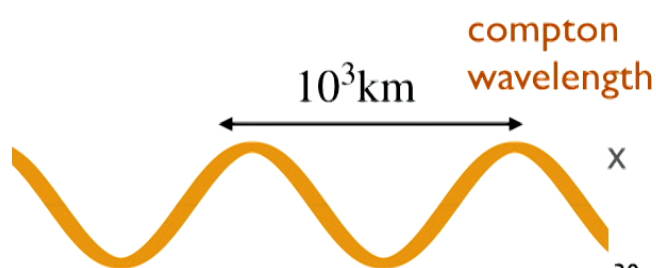
Astrophysical Black Holes and Ultralight Particles

- Moving to the opposite side of the mass spectrum: 'particle' does not fit in a laboratory
- Black holes in our universe provide nature's laboratories to search for light particles
- Set a typical length scale, and are a huge source of energy
- Sensitive to QCD axions with GUT- to Planck-scale decay constants f_a



for a 10^{-12} eV particle:



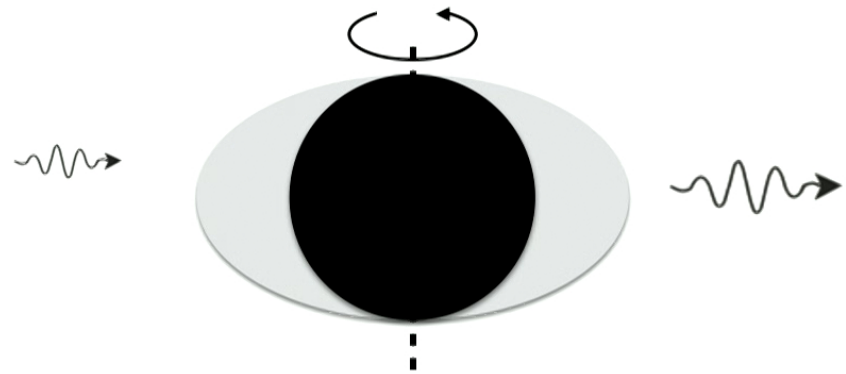


30

Superradiance

- A wave scattering off a rotating object can increase in amplitude by extracting angular momentum and energy.

- Growth proportional to probability of absorption when rotating object is at rest: **dissipation** necessary to increase wave amplitude



Superradiance condition:

Angular velocity of wave slower than angular velocity of BH horizon,

$$\Omega_a < \Omega_{BH}$$

Zel'dovich; Starobinskii; Misner

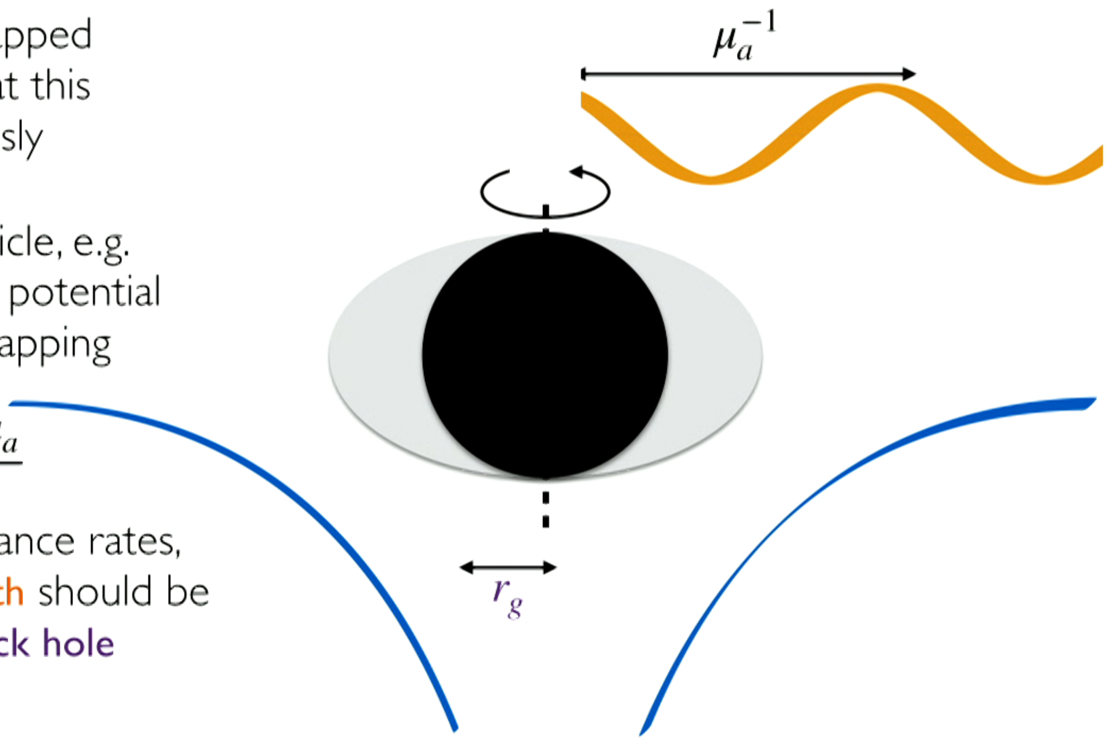
Superradiance

- Particles/waves trapped near the BH repeat this process continuously
- For a massive particle, e.g. axion, gravitational potential barrier provides trapping

$$V(r) = -\frac{G_N M_{BH} \mu_a}{r}$$

- For high superradiance rates, compton wavelength should be comparable to black hole radius:

$$r_g \lesssim \mu_a^{-1} \sim 3\,\mathrm{km}\,\frac{6\times 10^{-11}\,\mathrm{eV}}{\mu_a}$$

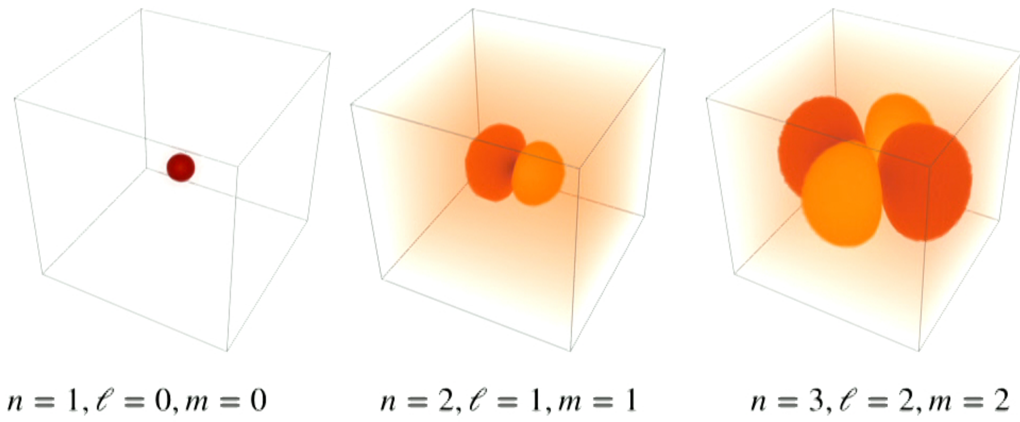


Zouros & Eardley'79; Damour et al '76; Detweiler'80; Gaina et al '78
Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell 2009; Arvanitaki, Dubovsky 2010

Gravitational Atoms

Axion
Gravitational Atoms

$$V(r) = -\frac{G_N M_{BH} \mu_a}{r}$$



Gravitational potential similar to hydrogen atom

`Fine structure constant`

$$\alpha \equiv G_N M_{BH} \mu_a \equiv r_g \mu_a$$

Radius

$$r_c \simeq \frac{n^2}{\alpha \mu_a} \sim 4 - 400 r_g$$

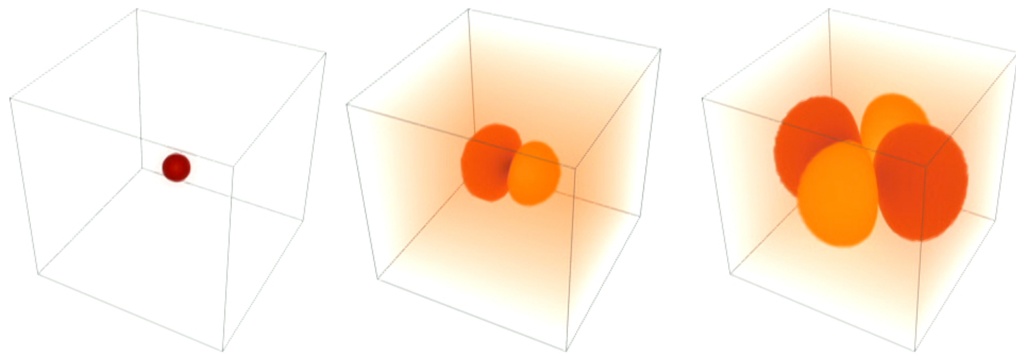
Occupation number

$$N \sim 10^{75} - 10^{80}$$

Gravitational Atoms

Axion
Gravitational Atoms

$$V(r) = -\frac{G_N M_{BH} \mu_a}{r}$$



$n = 1, \ell = 0, m = 0$ $\quad$ $n = 2, \ell = 1, m = 1$ $\quad$ $n = 3, \ell = 2, m = 2$

Gravitational potential similar to hydrogen atom

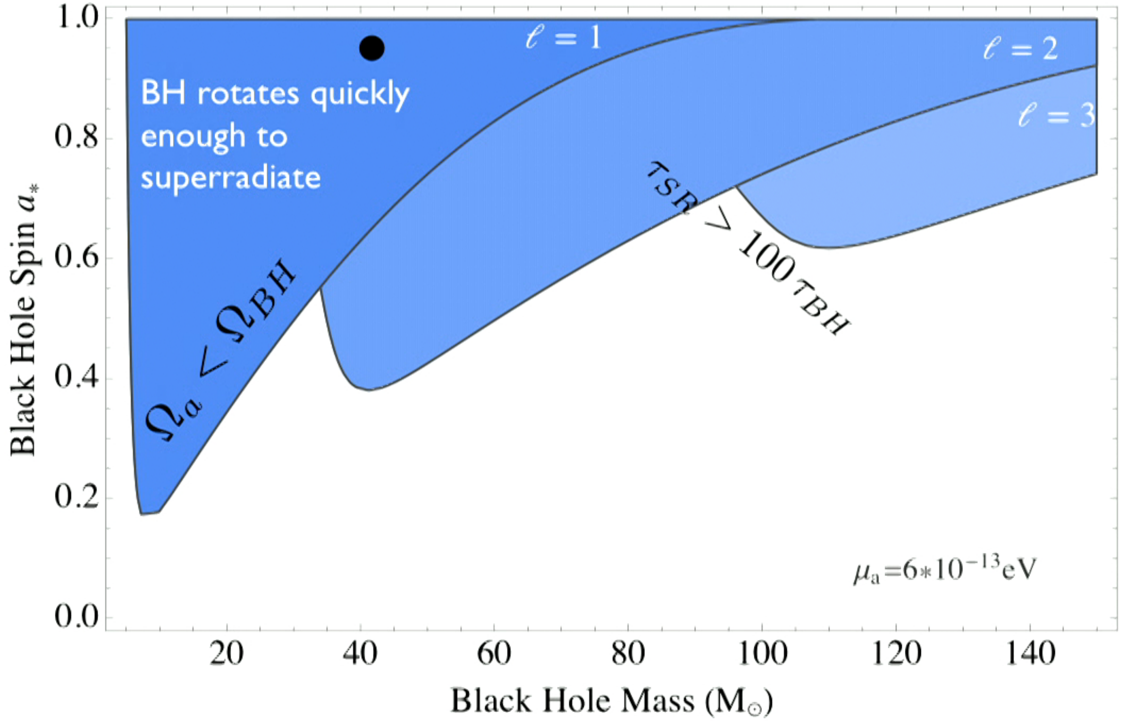
\`Fine structure constant\`	Radius	Occupation number
$\alpha \equiv G_N M_{BH} \mu_a \equiv r_g \mu_a$	$r_c \simeq \frac{n^2}{\alpha \, \mu_a} \sim 4 - 400 r_g$	$N \sim 10^{75} - 10^{80}$

Boundary conditions at horizon give imaginary frequency: **exponential growth of particle number around rapidly rotating black holes**

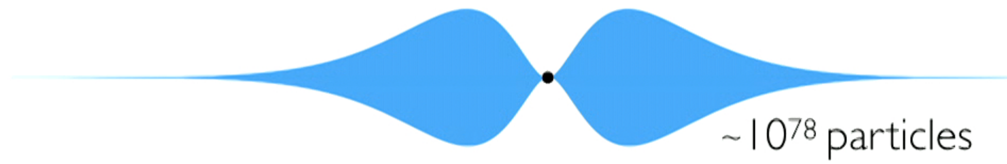
$$E \simeq \mu \left(1 - \frac{\alpha^2}{2n^2}\right) + i\Gamma_{sr}$$

Superradiance: a stellar black hole history

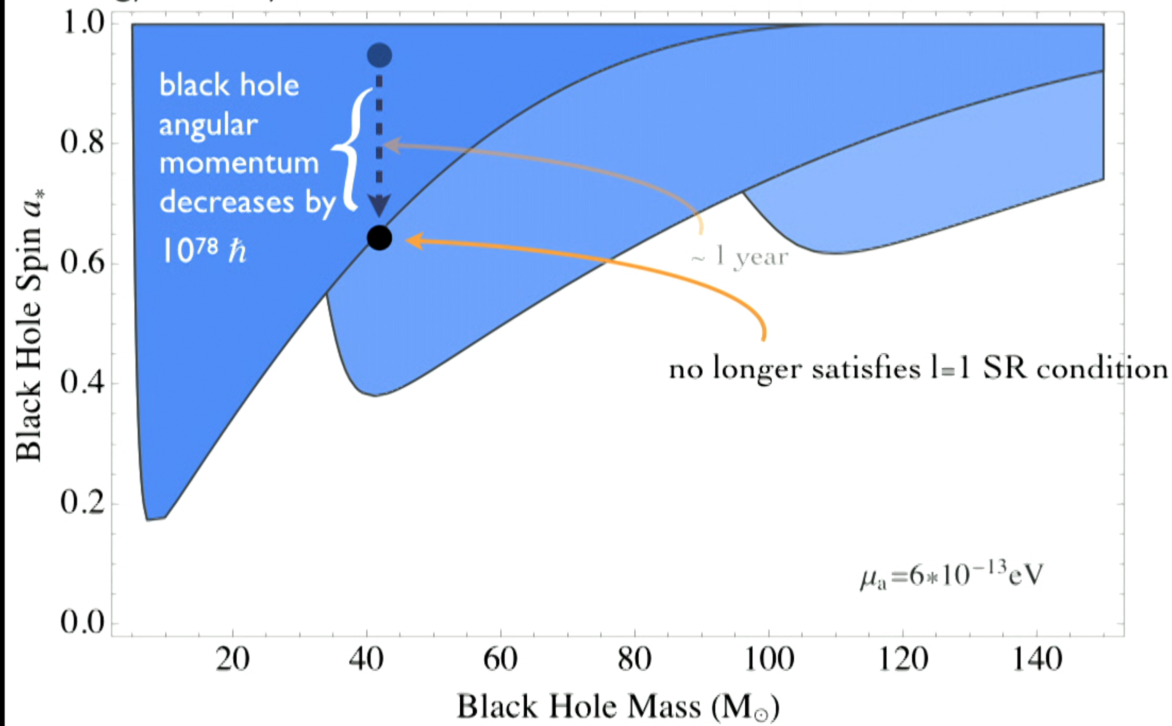
A black hole is born with spin a* = 0.95, M = 40 M⊙.



Superradiance: a stellar black hole history



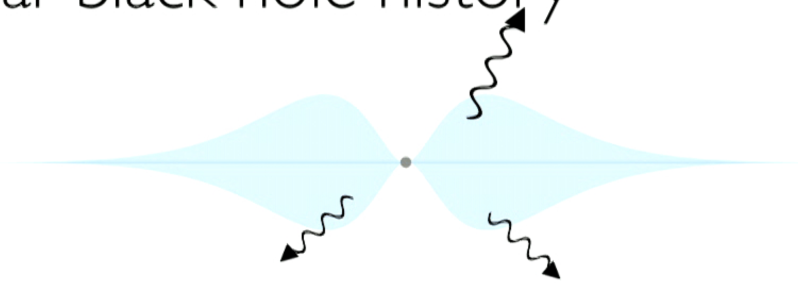
Cloud can carry up to a few percent of the black hole mass: huge energy density



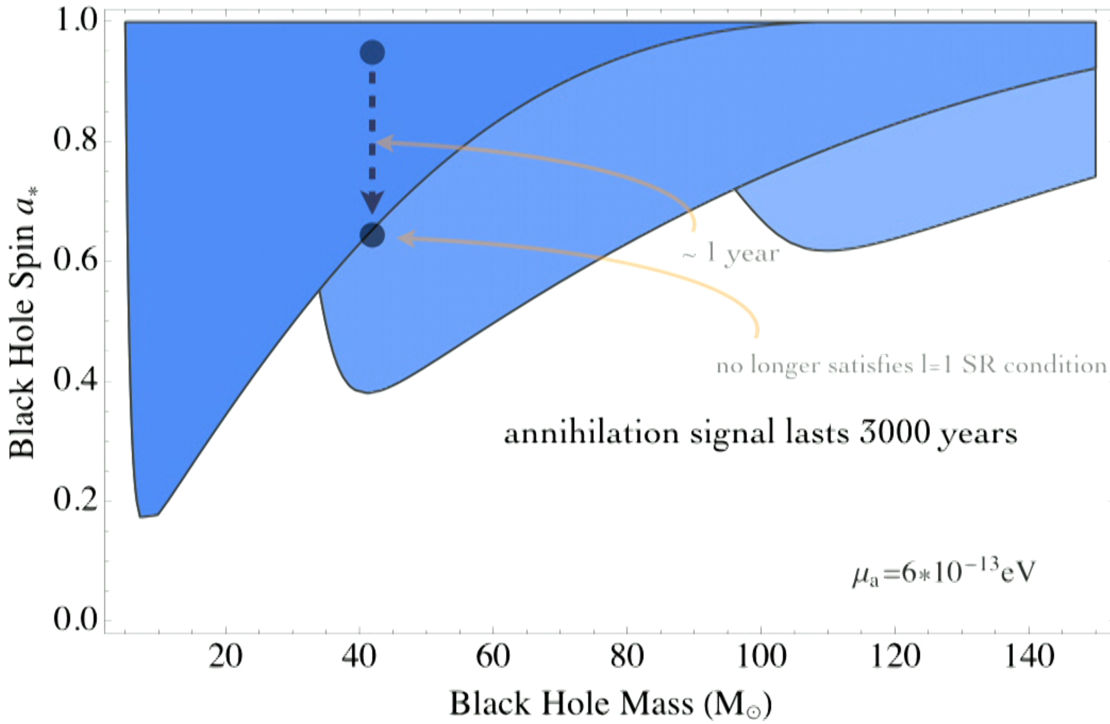
Black hole spins down

Can search for or exclude the presence of axions by measuring spins of astrophysical black holes

Superradiance: a stellar black hole history



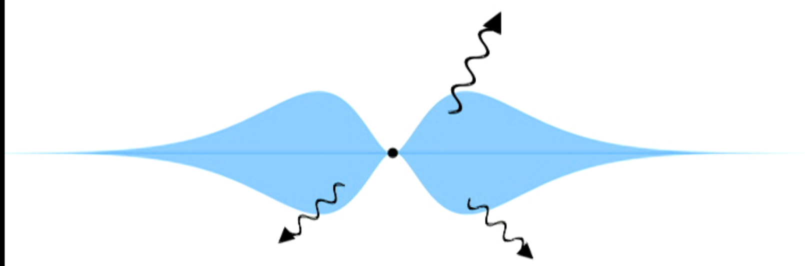
Cloud of axions sources coherent, monochromatic gravitational waves

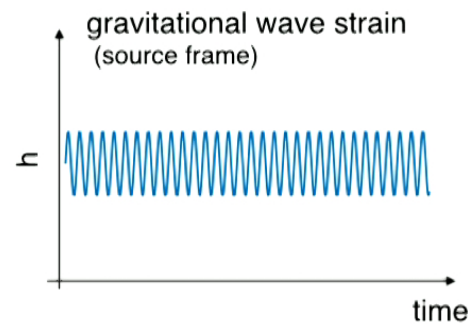


Gravitational wave frequency is set by twice the axion energy

Emission can be observed in LIGO continuous wave searches

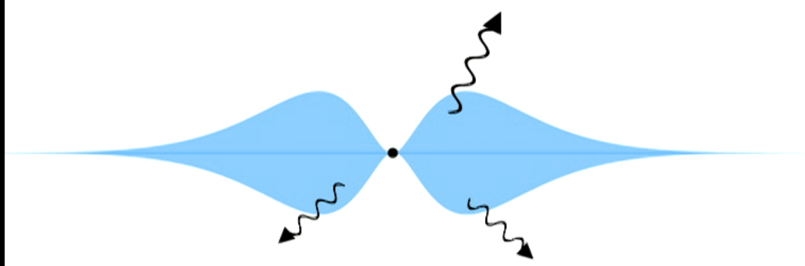
Gravitational Wave Signals

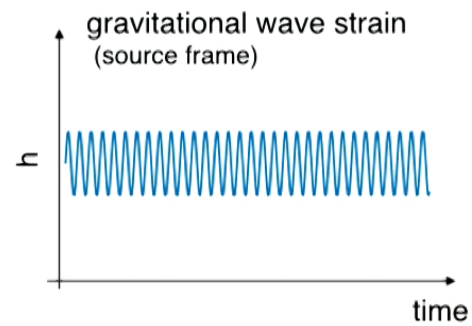




- **Weak, long signals** last for ~ thousand- billion years, visible from our galaxy
  - Event rates up to 10,000 — can be observed and studied in detail

Gravitational Wave Signals





- **Weak, long signals** last for ~ thousand- billion years, visible from our galaxy
  - Event rates up to 10,000 — can be observed and studied in detail

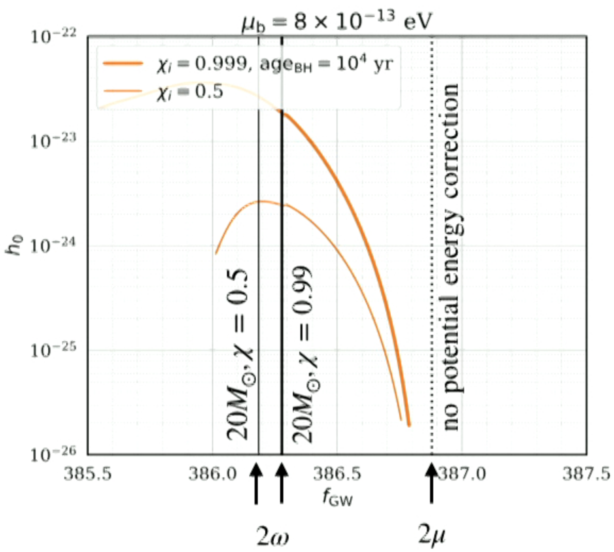
what are the near-term prospects of detection?

- **Loud, short signals** last for ~ days - months, observable from BBH or NS-NS merger events
  - Event rates <1/year at design aLIGO sensitivity, up to 100's at future observatories

Gravitational Wave Signals

- Signals appear in the detector clustered around single frequency at twice the axion mass
- Larger signals for larger black holes and lower frequencies (more binding energy, lower frequency)
- Cut off by BH mass distribution, SR condition, or signal time

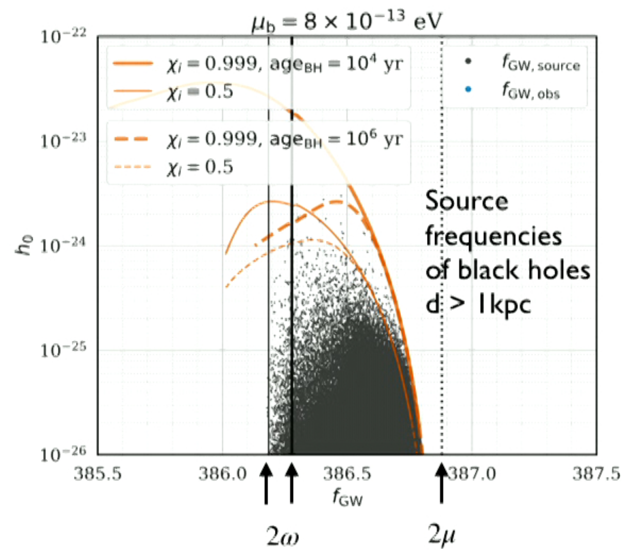
Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein (2003.03359)



Gravitational Wave Signals

- Signals appear in the detector clustered around single frequency at twice the axion mass
- Larger signals for larger black holes and lower frequencies (more binding energy, lower frequency)
- Cut off by BH mass distribution, SR condition, or signal time
- Signals get weaker over time
- Further, older black holes fill out distribution of weaker signals

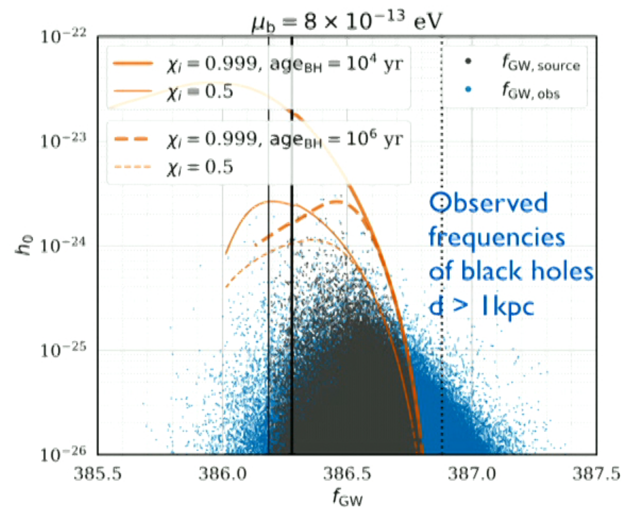
Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein (2003.03359)



Gravitational Wave Signals

- Signals appear in the detector clustered around single frequency at twice the axion mass
- Larger signals for larger black holes and lower frequencies (more binding energy, lower frequency)
- Cut off by BH mass distribution, SR condition, or signal time
- Signals get weaker over time
- Further, older black holes fill out distribution of weaker signals
- Doppler shift: larger spread for further sources (smaller strains)

Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein (2003.03359)

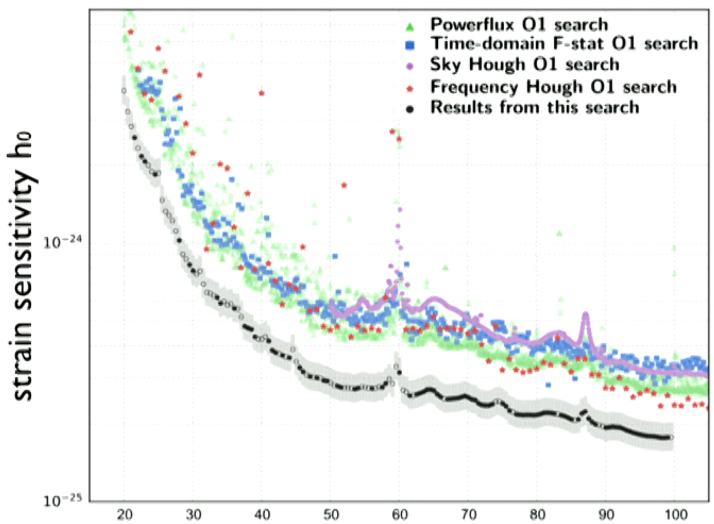


- If one signal is detectable, expect many with a unique strain vs. frequency profile

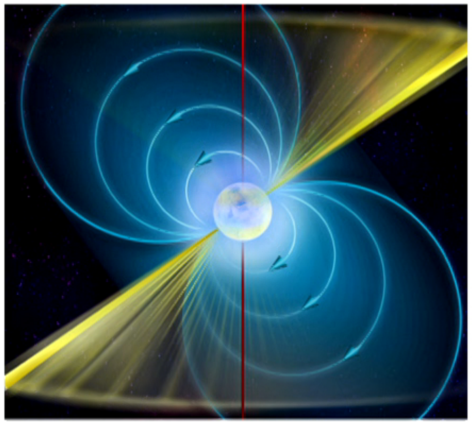
Gravitational Wave Signals

Current searches for gravitational waves from asymmetric rotating neutron stars

All-Sky O1 Upper Limits

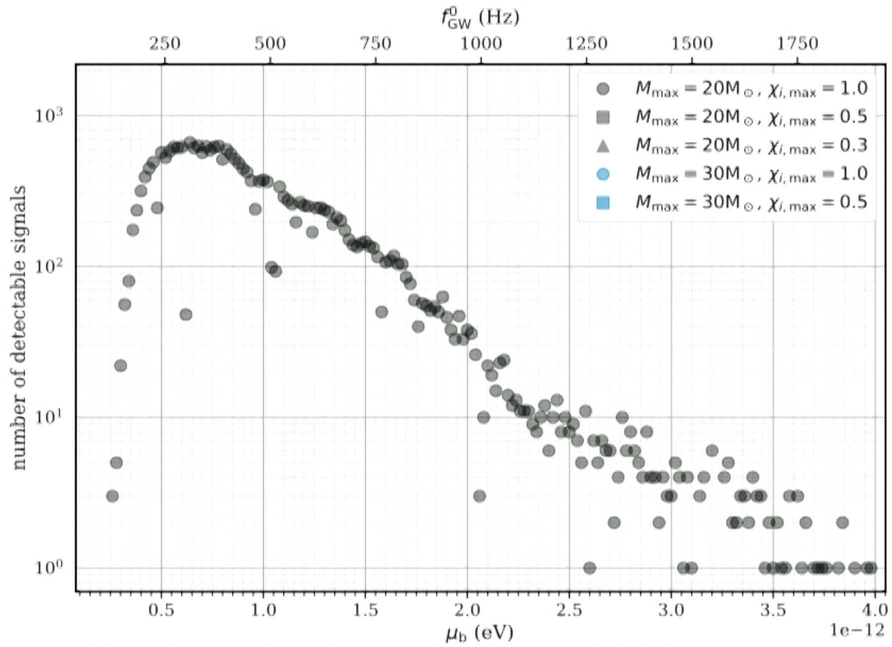


Abbott et al PRD 96, 122004 (2017)



Cambridge University Lucky Imaging Group

Gravitational Wave Signals

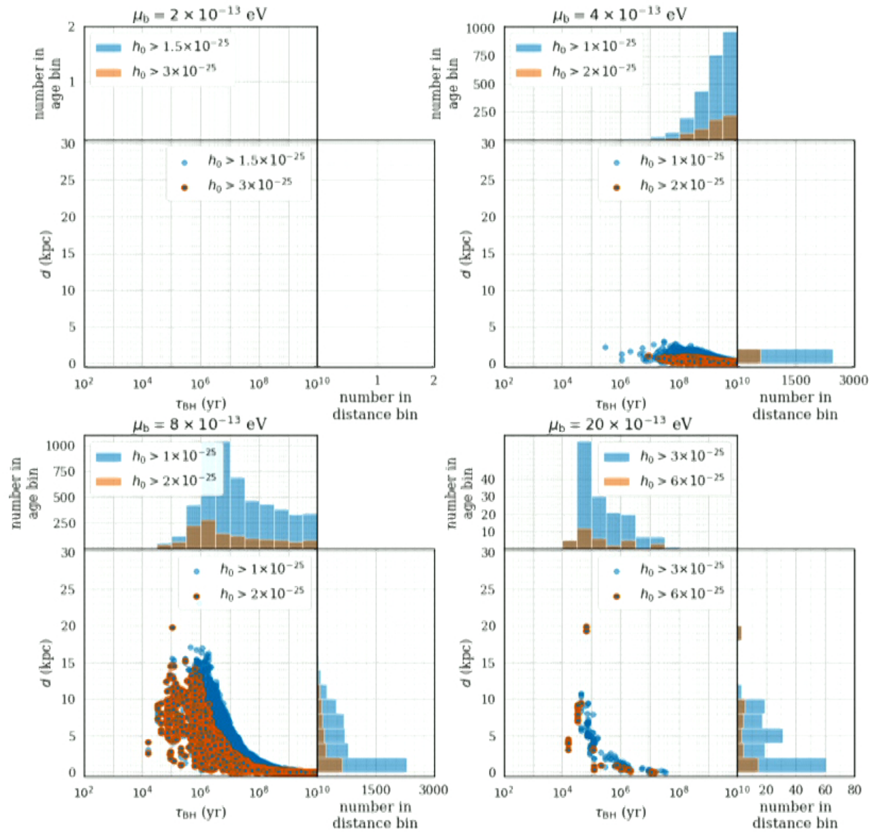


Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein (2003.03359)

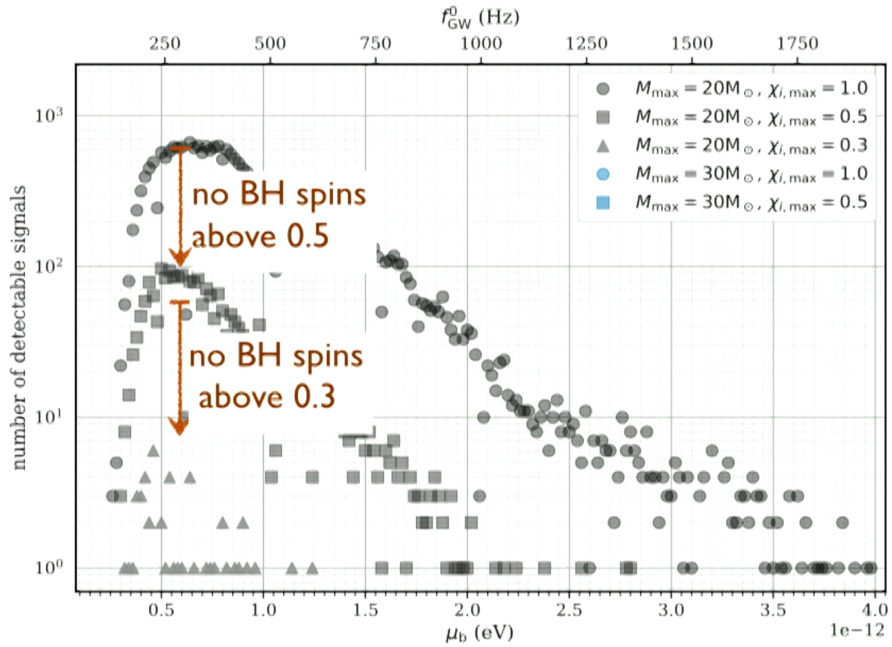
- **Weak, long signals** last for ~ million years, visible from our galaxy

Gravitational Wave Signals

- **Weak, long signals** last for ~ million years, visible from our galaxy, limited by LIGO noise floor
- Event rates up to 10,000 — can be observed and studied in detail
- Searches ongoing with O1/O2 data



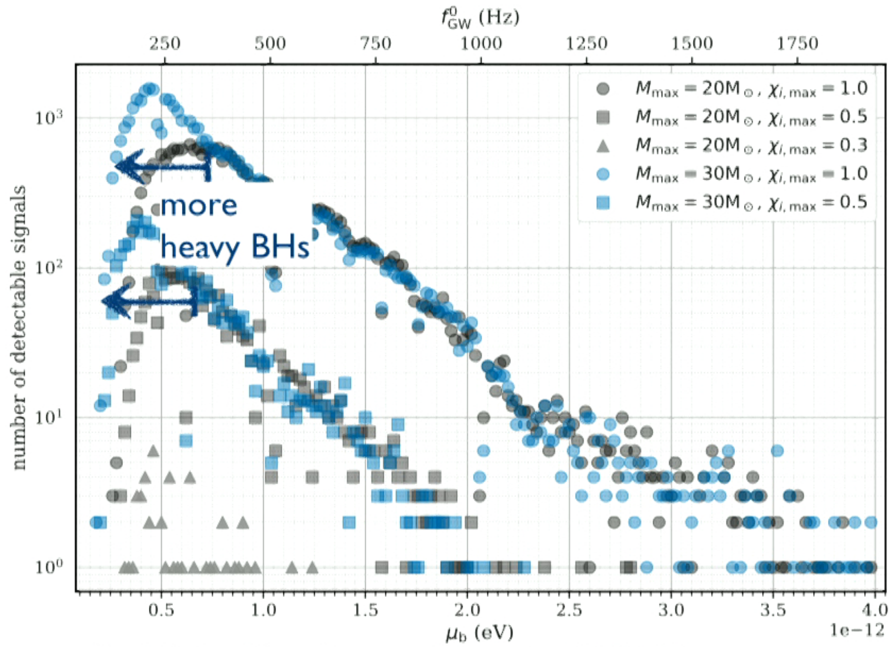
Gravitational Wave Signals



Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein (2003.03359)

- **Weak, long signals** last for ~ million years, visible from our galaxy
- Very sensitive to number of rapidly rotating black holes

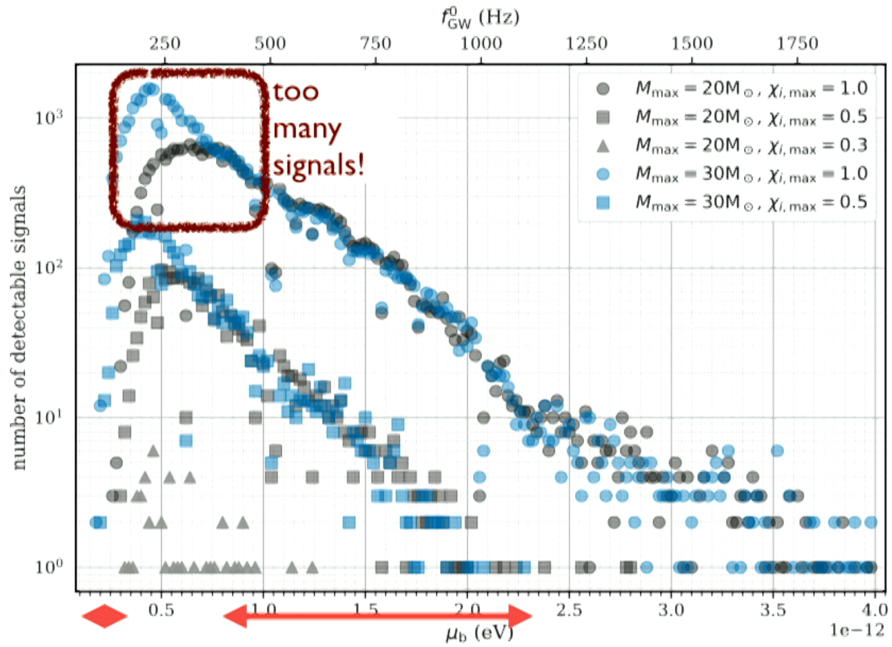
Gravitational Wave Signals



Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein (2003.03359)

- **Weak, long signals** last for ~ million years, visible from our galaxy
- Very sensitive to number of rapidly rotating black holes
- Weak dependence on mass distribution except at low axion masses

Gravitational Wave Signals



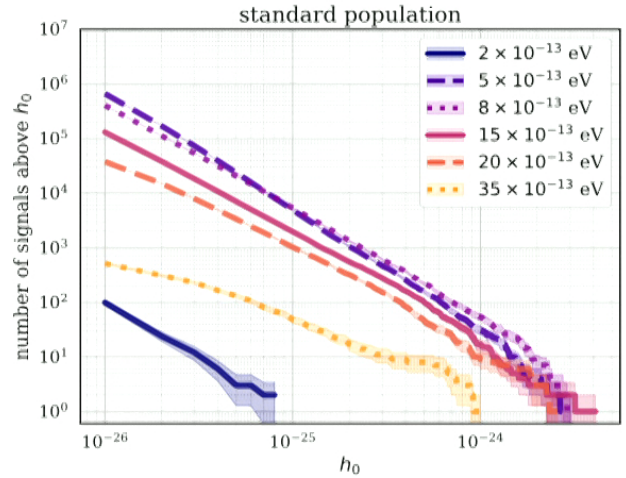
Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein (2003.03359)

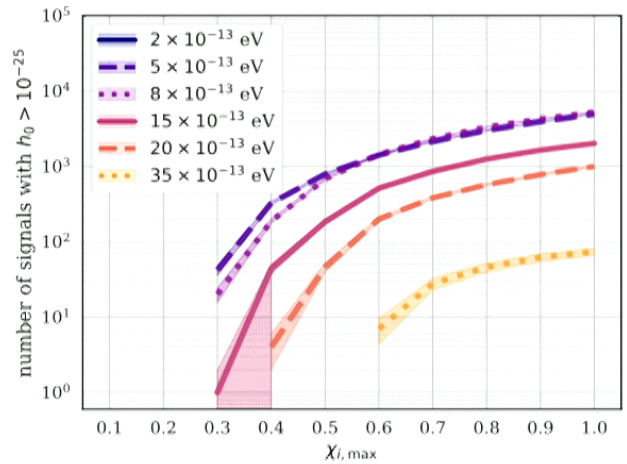
- **Weak, long signals** last for ~ million years, visible from our galaxy
- Very sensitive to number of rapidly rotating black holes
- Weak dependence on mass distribution except at low axion masses

- Up to 1000 signals above sensitivity threshold of Advanced LIGO searches today
- Can disfavor axions of mass ~10^{-12} eV with assumptions on black hole populations
- Futher characterization of continuous wave searches in dense signal regime is ongoing

Gravitational Wave Signals

- Expected signal number goes up quickly for lower h0 sensitivities
- Expected signal number decreases with decreasing upper spin



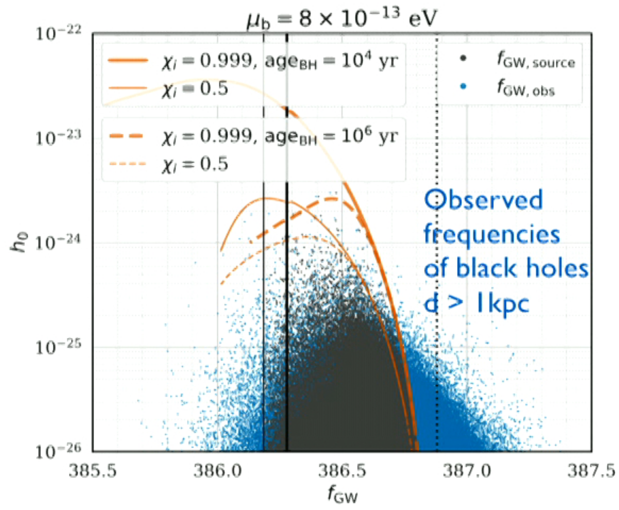


82

Gravitational Wave Signals

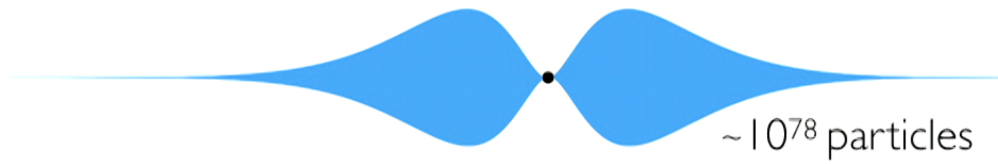
- Signals appear in the detector clustered around single frequency at twice the axion mass
- Larger signals for larger black holes and lower frequencies (more binding energy, lower frequency)
- Cut off by BH mass distribution, SR condition, or signal time
- Signals get weaker over time
- Further, older black holes fill out distribution of weaker signals
- Doppler shift: larger spread for further sources (smaller strains)

Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein (2003.03359)



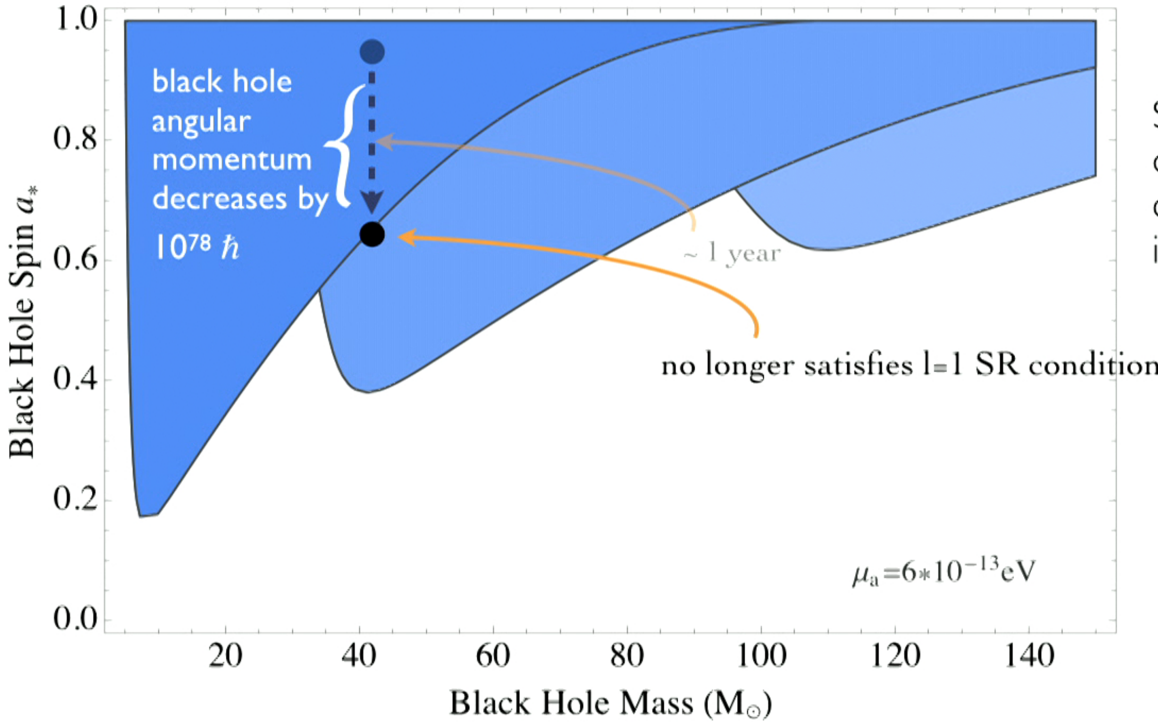
- If one signal is detectable, expect many with a unique strain vs. frequency profile

Superradiance: history with self-interactions



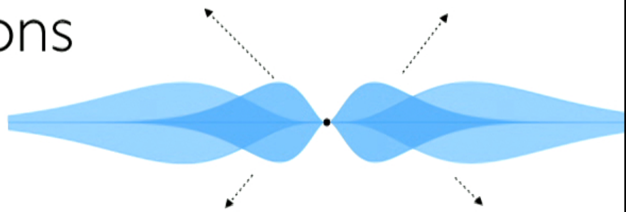
~10^{78} particles

Cloud can carry up to a few percent of the black hole mass: huge energy density



Self-interactions of axions in the cloud can become important

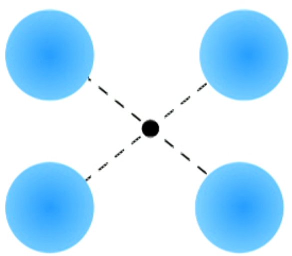
Self-Interactions

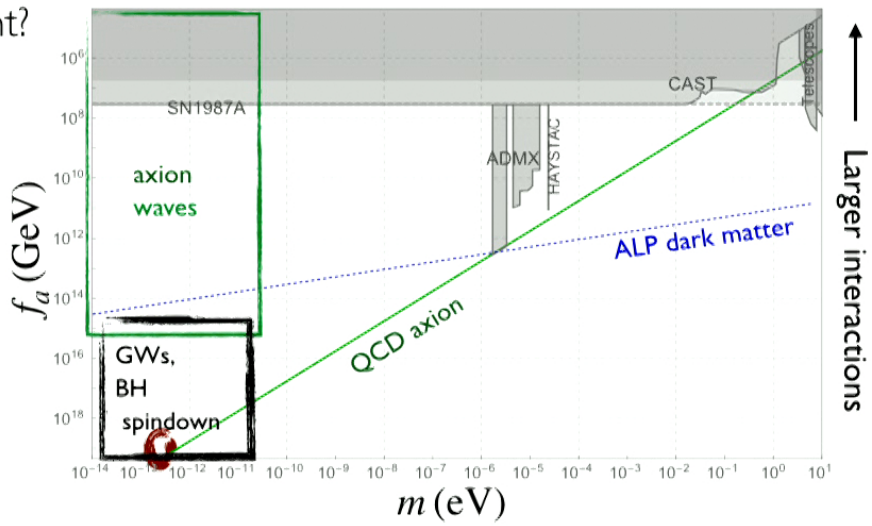


MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*

A. Gruzinov, 1604.06422

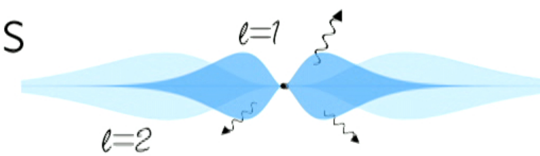
- So far, have focused on gravitational signatures of the axion
- What new effects arise when axion self-interactions become important?





50

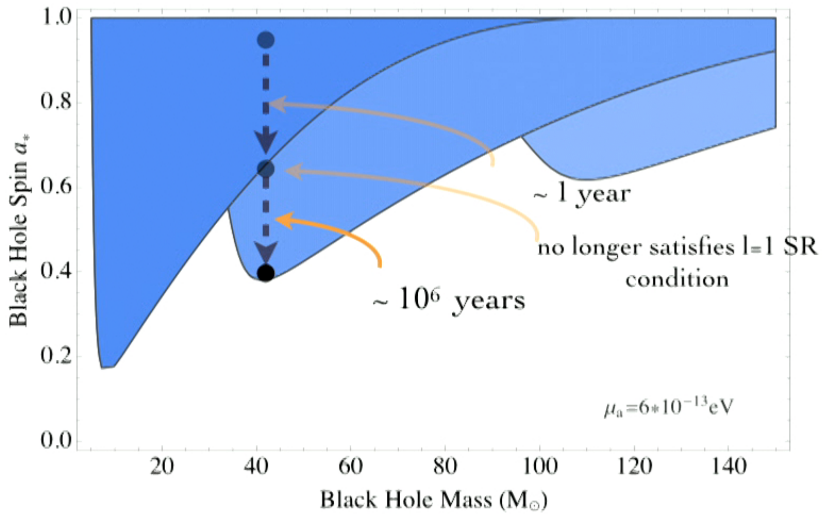
Self-Interactions



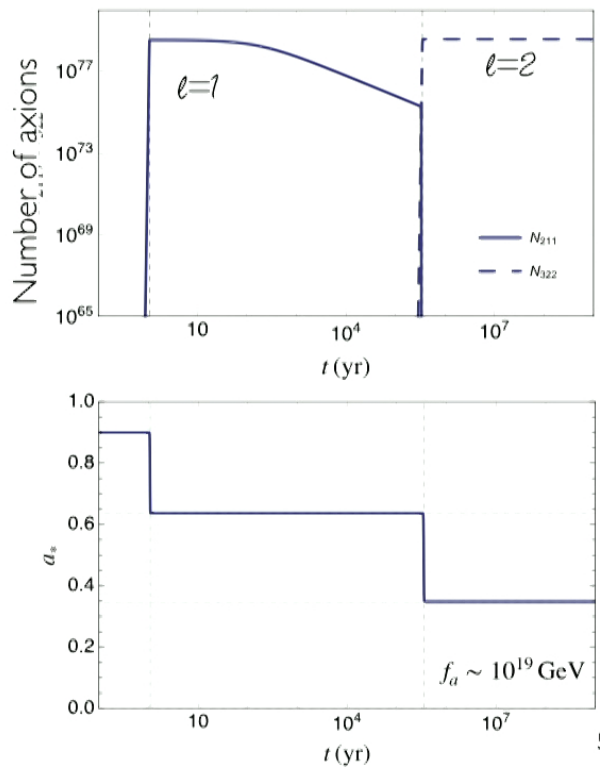
Small self-interactions: $f_a \sim M_{\rm Pl}$

MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*

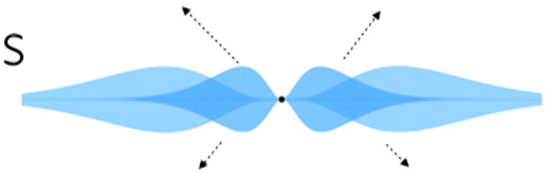
- BH spins down: next level formed; annihilations to GWs deplete first level
- Next level has a superradiance rate exceeding age of BH



Time evolution



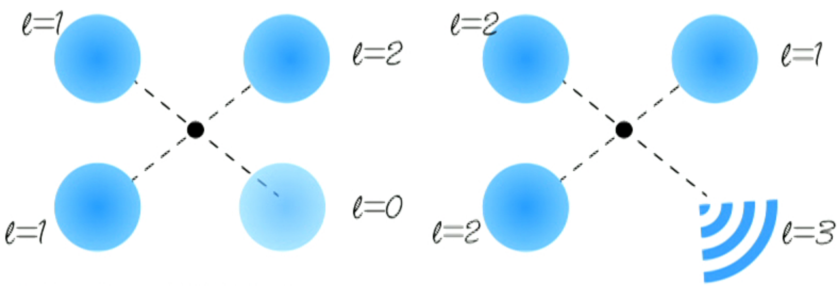
Self-Interactions



MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*

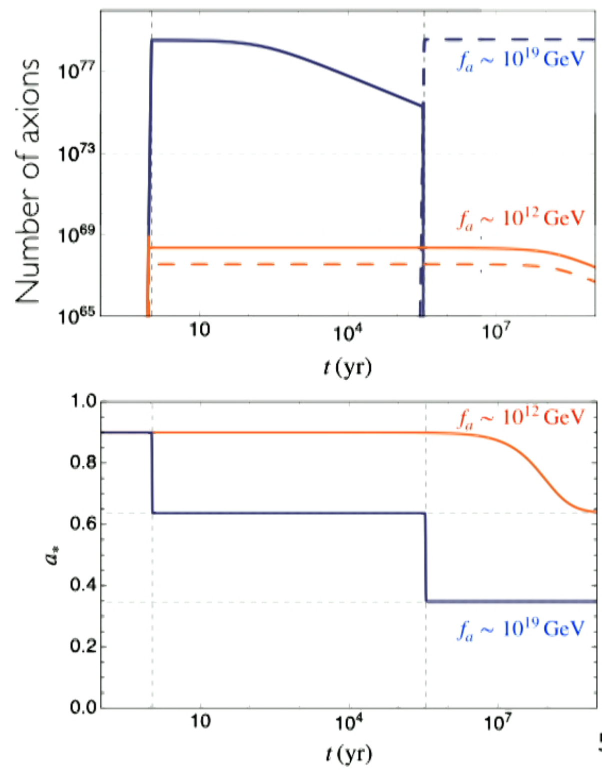
Larger self-interactions: $f_a \sim 10^{12}\mathrm{GeV}$

- Black hole energy sources the cloud through superradiance
- Second level populated through self-interactions
- Non-relativistic axion waves carry energy to infinity

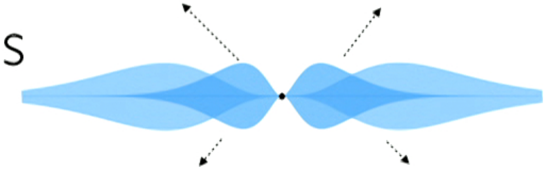


A. Gruzinov, 1604.06422

Time evolution



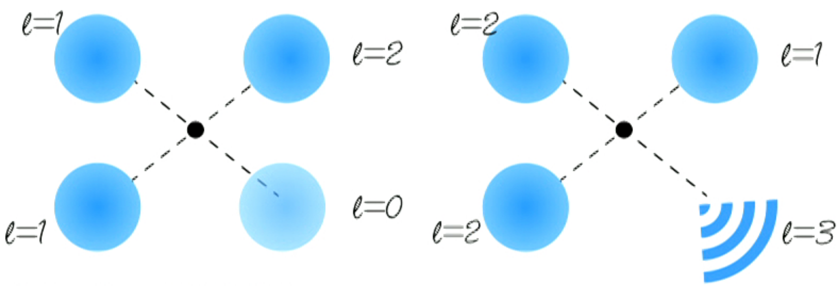
Self-Interactions



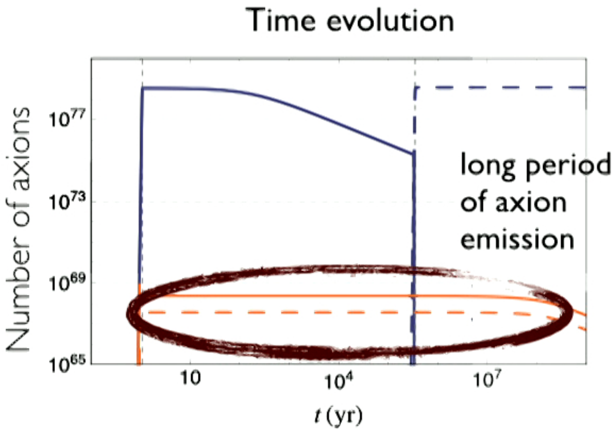
Larger self-interactions: $f_a \sim 10^{12}\text{GeV}$

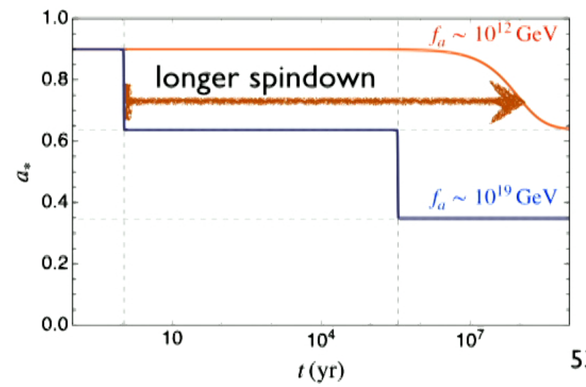
MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*

- Black hole energy sources the cloud through superradiance
- Second level populated through self-interactions
- Non-relativistic axion waves carry energy to infinity



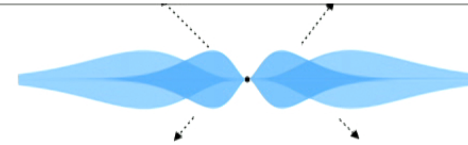
A. Gruzinov, 1604.06422





53

Axionic Beacons

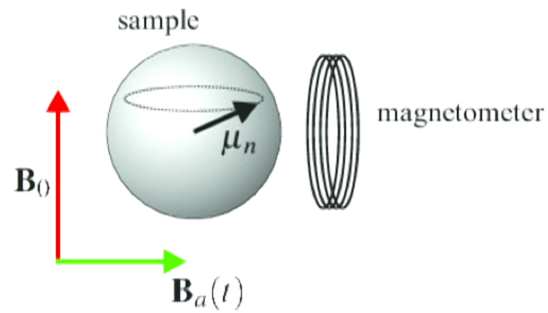


A new source of axions in the universe

- Black hole energy slowly and constantly converted to axion waves
- Can be detected directly if axions couple to the Standard Model
- Fractional field amplitude independent of self interactions, comparable to laboratory search targets

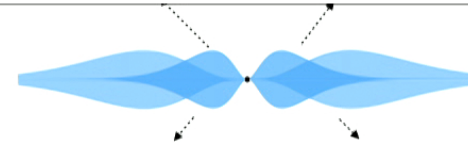
$$\frac{a}{f_a} \sim 10^{-17} \left(\frac{10^{-12}\text{eV}}{\mu}\right) \left(\frac{\alpha}{0.2}\right)^3 \left(\frac{\text{kpc}}{r}\right)$$

- Axion field gradient acts like a magnetic field on particle spins



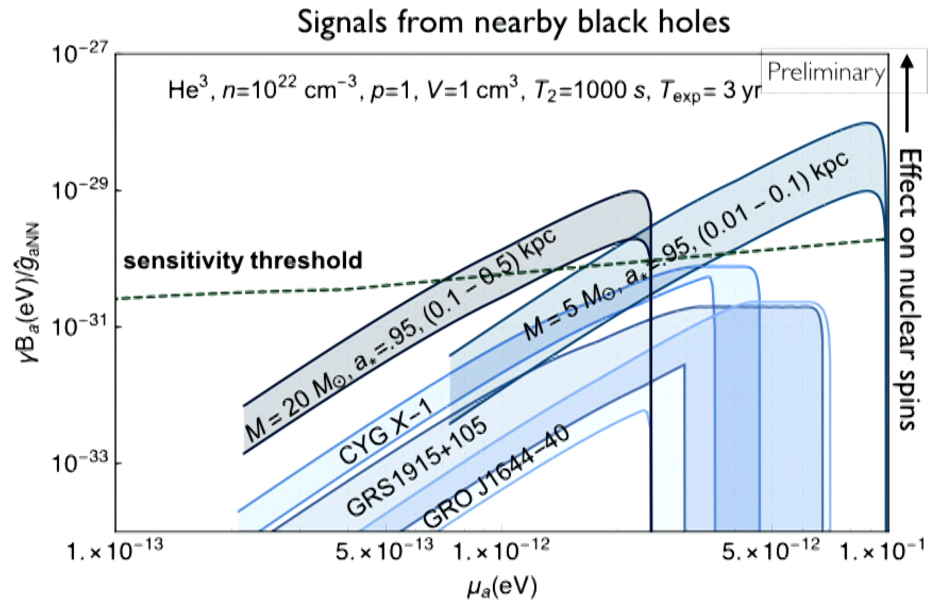
CASPEr Budker, Graham, Ledbetter, Rajendran, Sushkov (2014)
Kimball et al (2017)

Axionic Beacons



Black hole energy constantly converted to axion waves

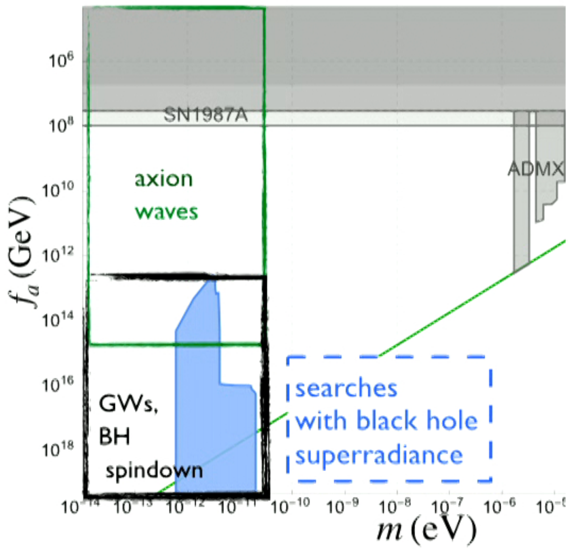
- Signal strength ***constant in time***, independent of self interaction strength at small f_a
- Axion waves observable in axion force/dark matter experiments (ARIADNE, CASPER…)
- Requires different data analysis strategies (*c.f.* LIGO continuous waves search)

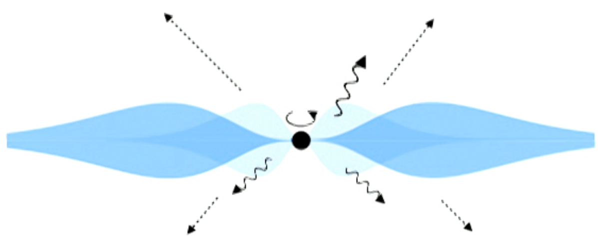


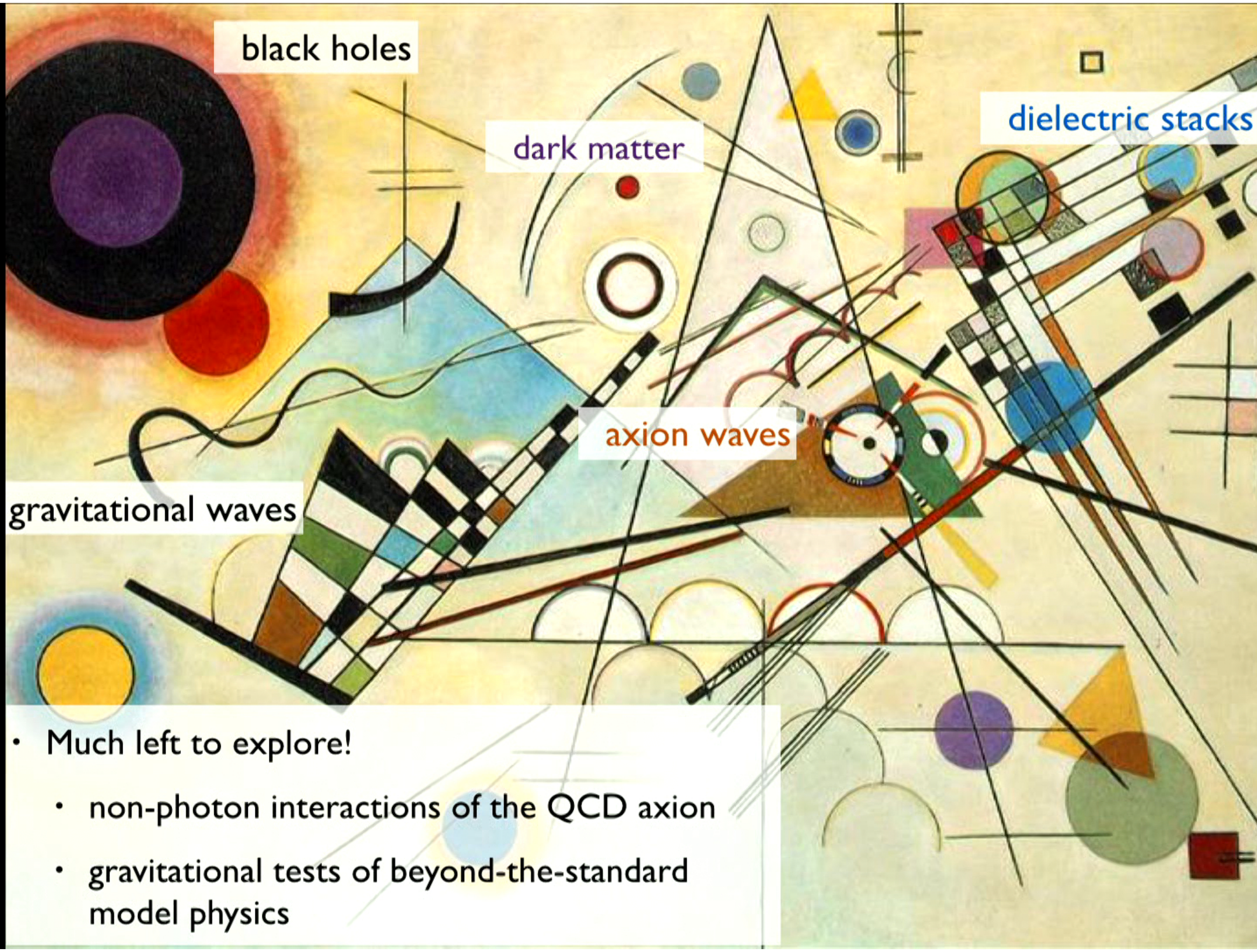
MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*

Gravitational Atoms and Axionic Beacons

- In the presence of ultralight axions, black holes spin down. Measurement of high spin black holes places exclusion limits; LIGO will provide more data points
- Axion clouds produce monochromatic wave radiation; we are looking for these signals in LIGO data
- Self-interactions of axions slow down energy extraction from black holes and populate the universe with axion waves







- Much left to explore!
  - non-photon interactions of the QCD axion
  - gravitational tests of beyond-the-standard model physics