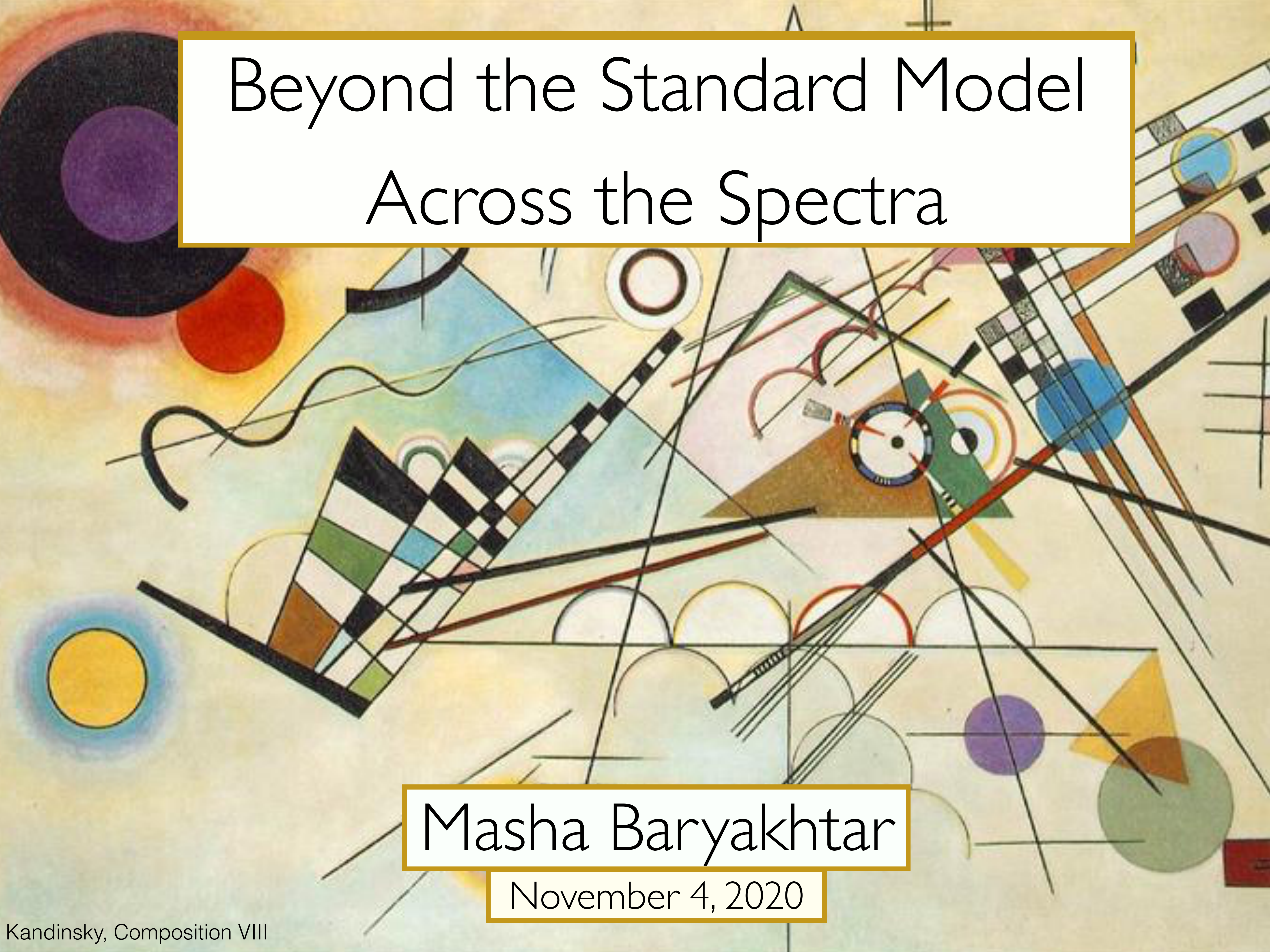
Beyond the Standard Model
Across the Spectra

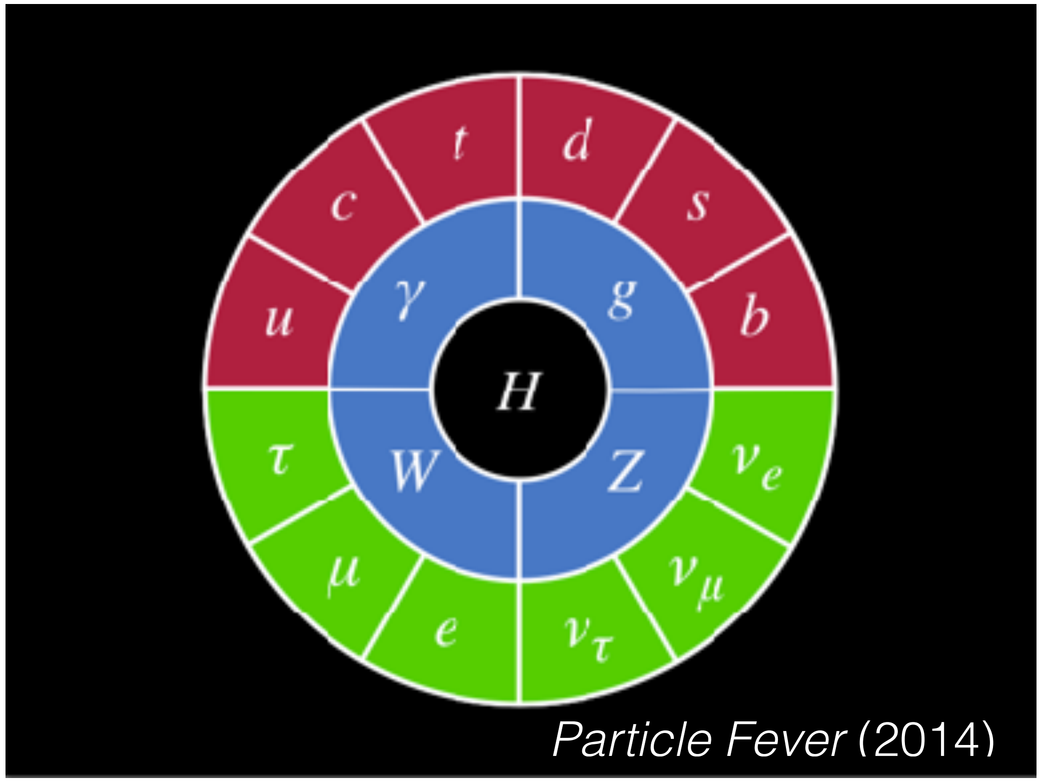
Masha Baryakhtar

November 4, 2020

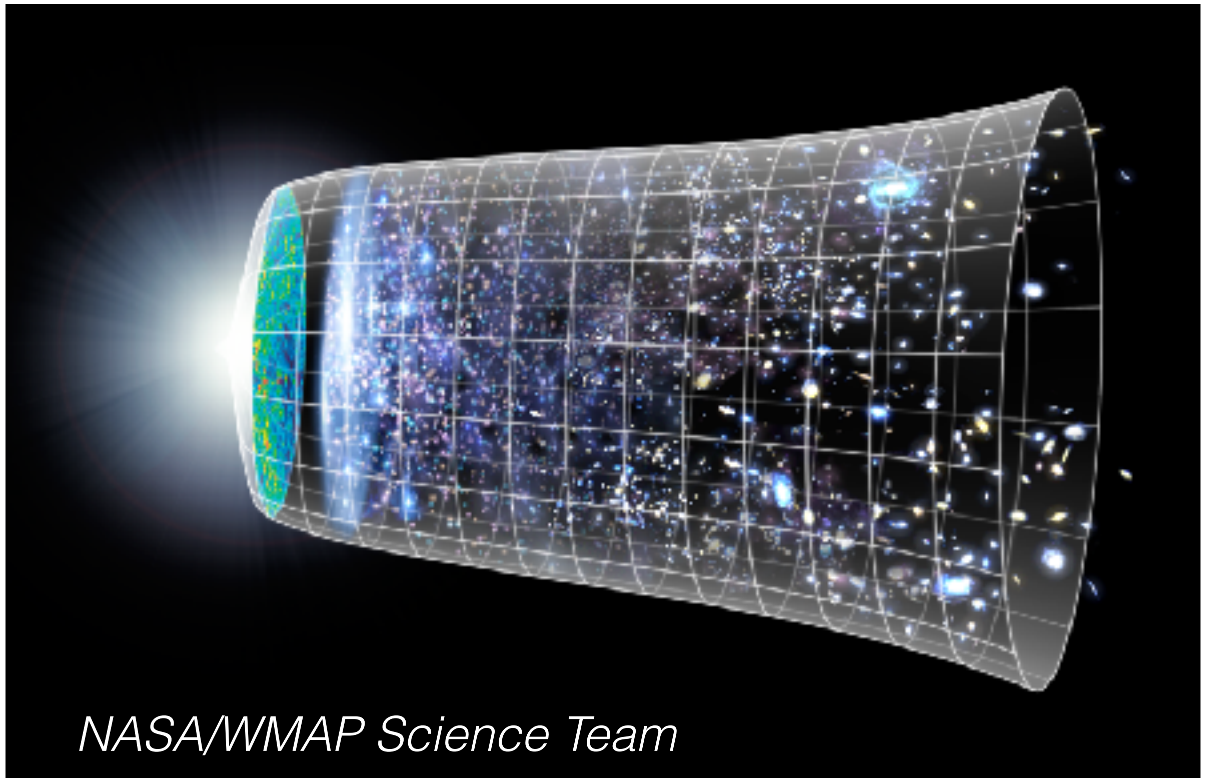


Kandinsky, Composition VIII

The Standard Models

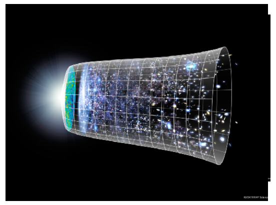


Particle Fever (2014)



NASA/WMAP Science Team

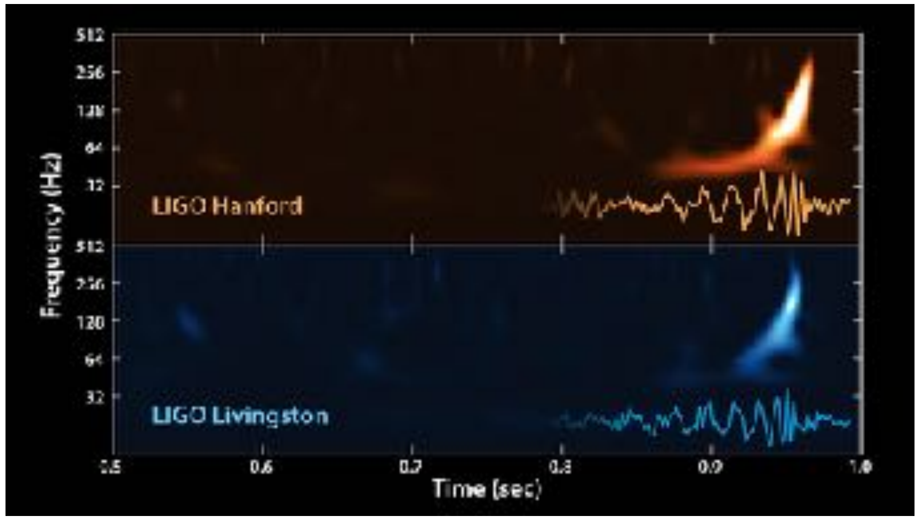
- Minimal set of particles and parameters that accurately describes our universe

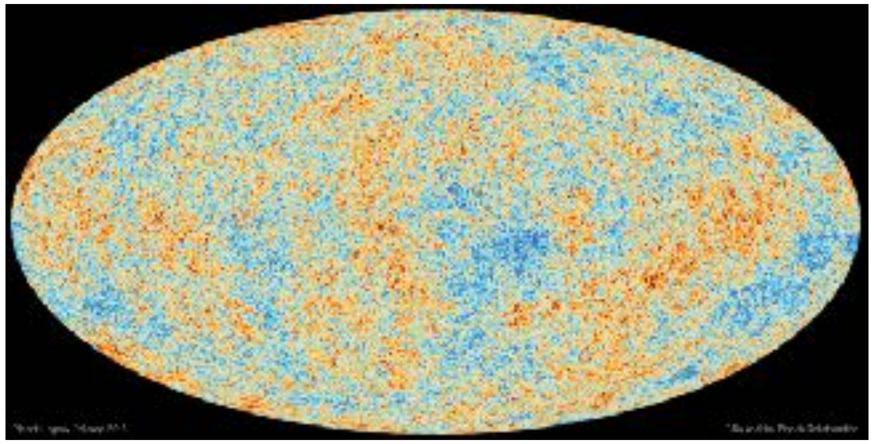


The Standard Models

Have had great successes….

Discovery of gravitational waves, further confirming general theory of relativity and opening an era of multi-messenger astronomy





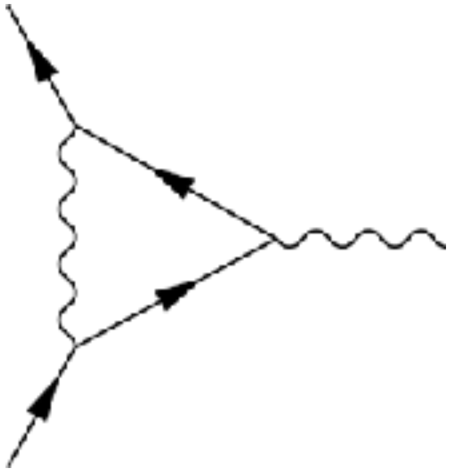
- Cosmic microwave background matches prediction of LCDM to excellent precision

The Standard Models

Have had great successes….

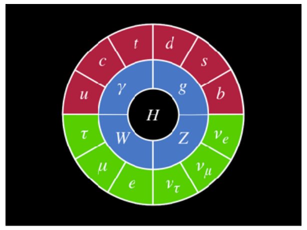
Higgs boson discovery, confirming theory of masses and electroweak symmetry breaking

Excellent agreement between theory and experiment

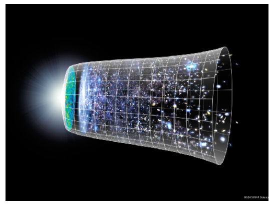


- Electron g-2 magnetic dipole moment

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

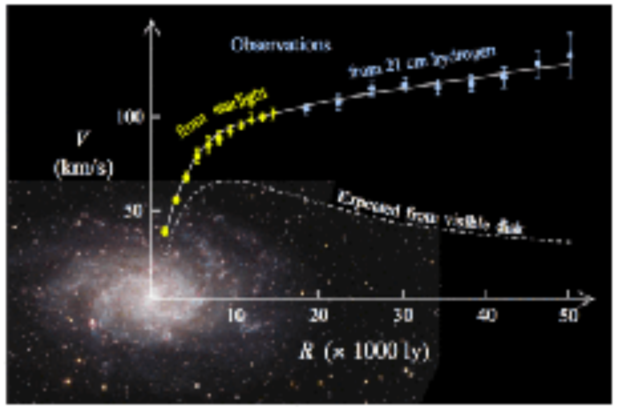


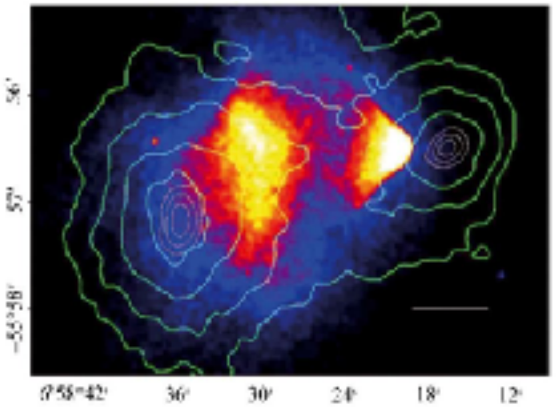
The Standard Models

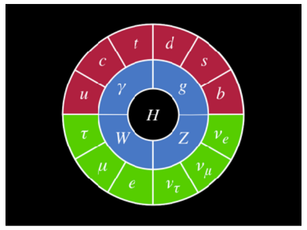


… and great problems:

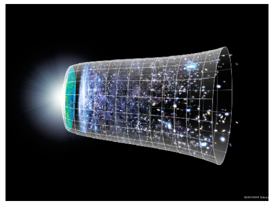
what is the **dark** matter that makes up most of the matter content of the universe?





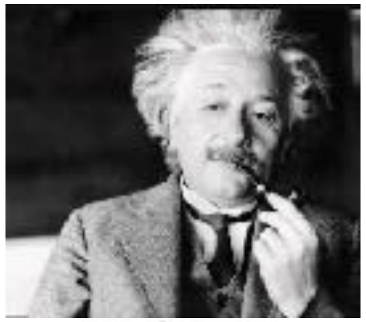


The Standard Models

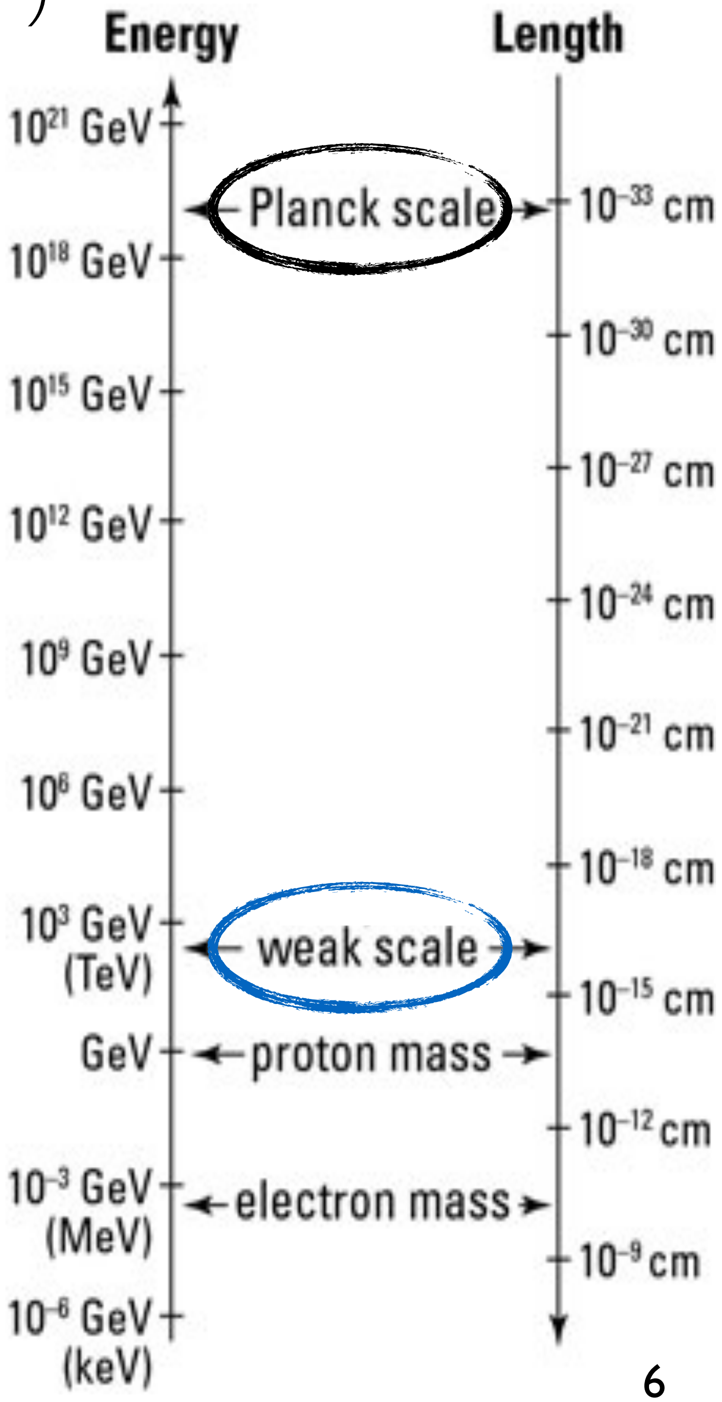


… and great problems:

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

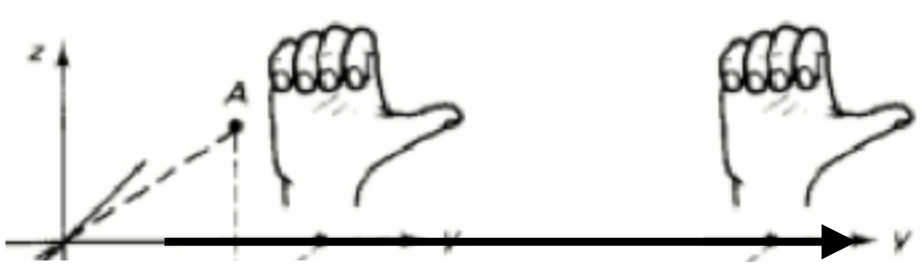


16 orders of magnitude

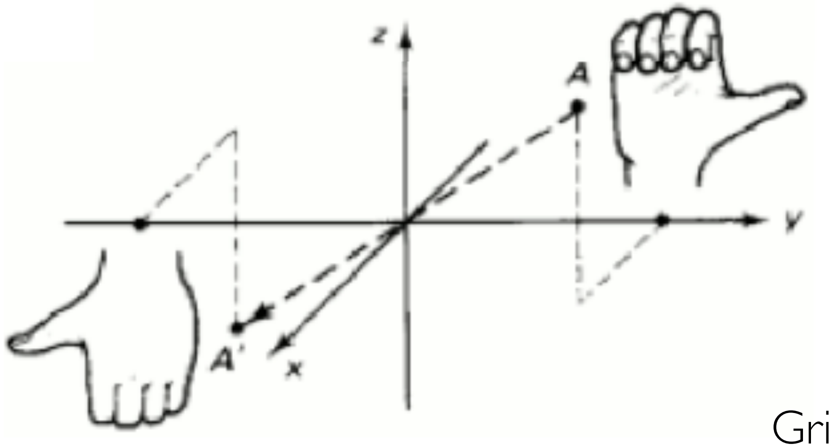


Symmetries and New Particles

- Symmetries and conservation laws are central to our understanding of particles and interactions
    - Can be continuous or discrete
        - invariance under translation symmetry: conservation of momentum
        - invariance under spatial inversion: parity symmetry



translation

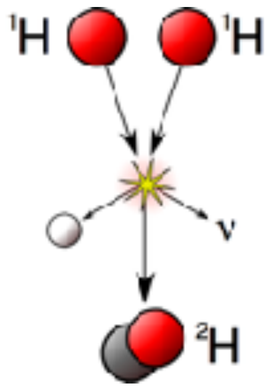


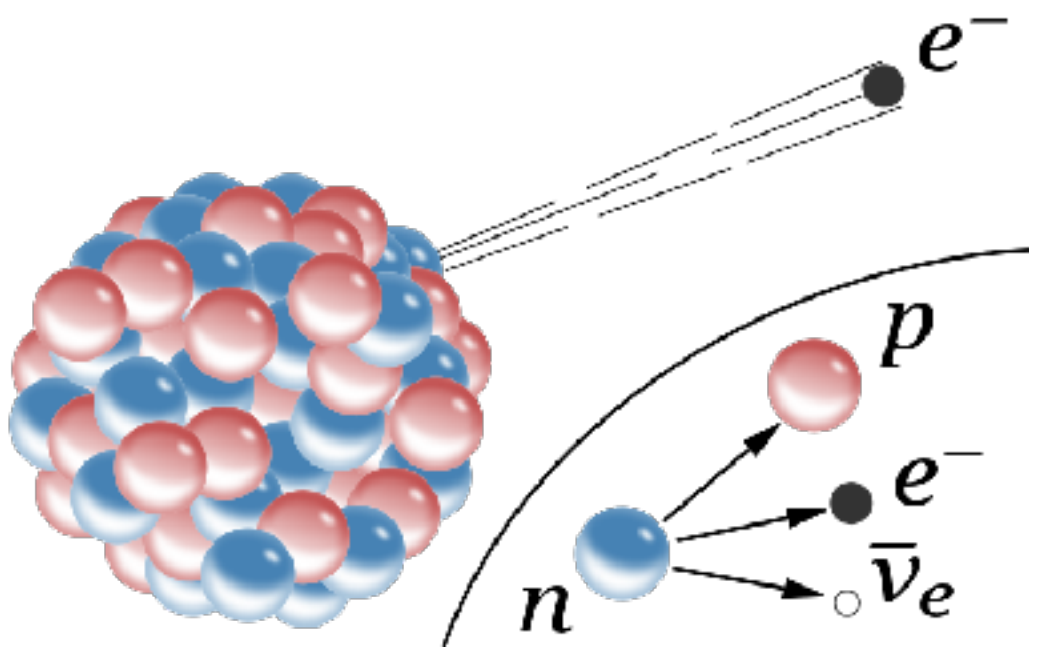
Griffiths

parity transformation

Symmetries and New Particles

- Symmetries and conservation laws have been used to successfully predict new particles
  - Pauli (1930) proposed the neutrino to preserve energy & momentum conservation in beta decays
  - Bethe (1938) developed theory of stellar nucleosynthesis, making use of the neutrino in the proton-proton process
  - Direct detection of reactor antineutrinos in proton capture discovered by Reines and Cowan (1956)

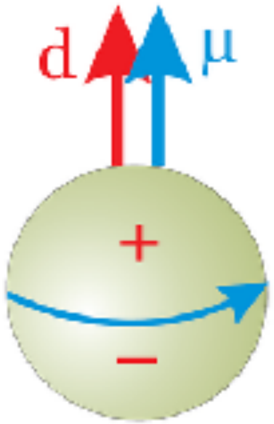




Symmetries and New Particles

- Theoretically expect significant CP violation in potential of strong interactions

- This would give the neutron an electric dipole moment



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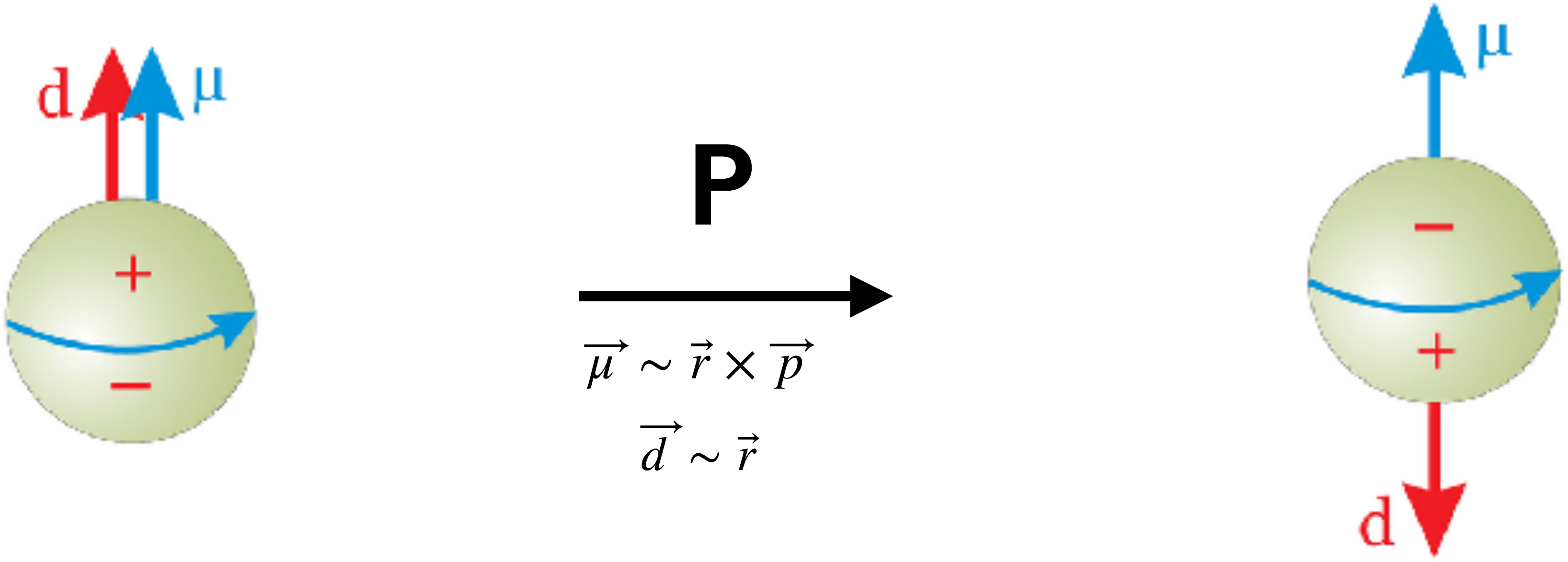


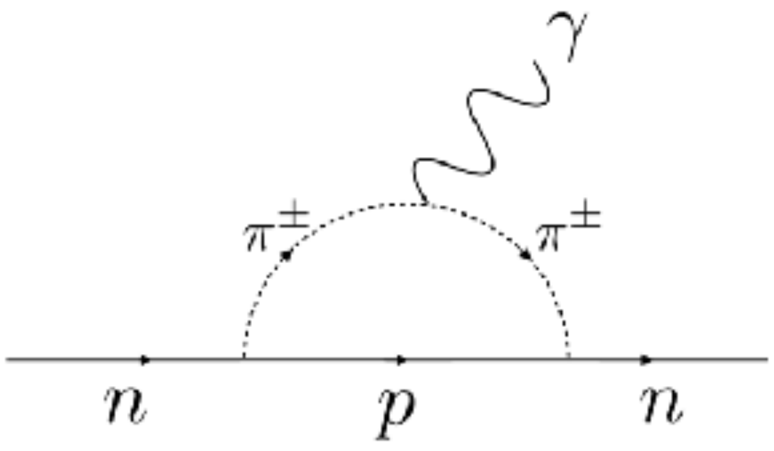
$$\vec{\mu} \sim \vec{r} \times \vec{p}$$

$$\vec{d} \sim \vec{r}$$

$$\overrightarrow{\mu} \cdot \overrightarrow{d} \rightarrow -\overrightarrow{\mu} \cdot \overrightarrow{d}$$

The Strong-CP problem

- Can we calculate the expected size of the neutron electric dipole moment?

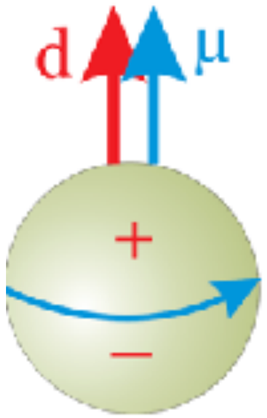


$$|d_n| \sim 2 \times 10^{-16}\theta \cdot e \cdot \mathrm{cm}$$

- Experimental upper bound:

$$|d_n| < 10^{-26} \cdot e \cdot \mathrm{cm} \longrightarrow \theta < 10^{-10}$$

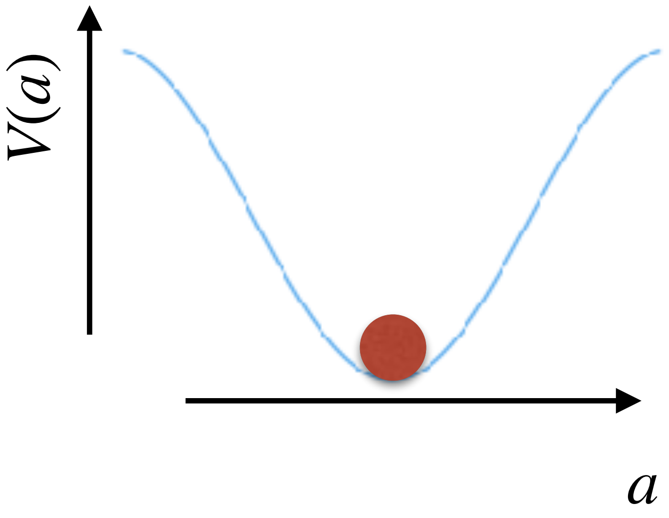
The Strong-CP problem



- If θ is a fixed parameter of the theory, this is a huge unexplained tuning

- Solve the problem by promoting θ to a dynamical field, the axion $\boldsymbol{a}$, allowing it to adjust to minimize energy

- QCD effects give axion a mass, and it relaxes the CP angle to zero, solving the strong-CP problem



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

Very Weakly Interacting New Physics

- Axions are
  - Solutions to a theoretical puzzle of symmetries: the strong-CP problem
  - Approximately massless with mass and couplings determined by a single high scale f_a,

$$\mu_a \simeq 6 \times 10^{-12}\mathrm{eV}\left(\frac{10^{18}\mathrm{GeV}}{f_a}\right)$$

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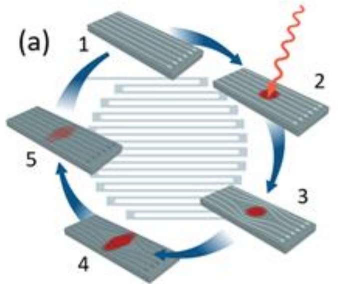
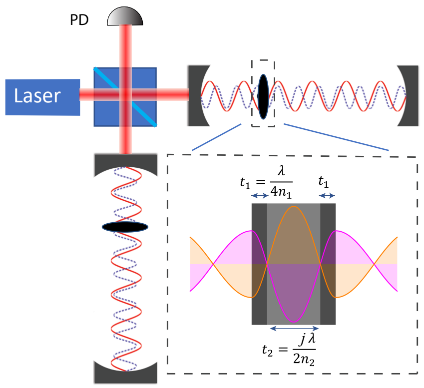
Difficult to detect:
requires precision measurement





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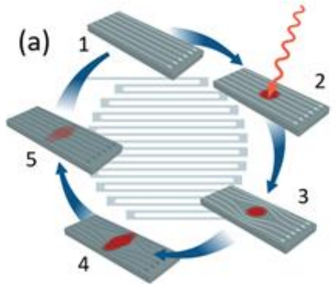
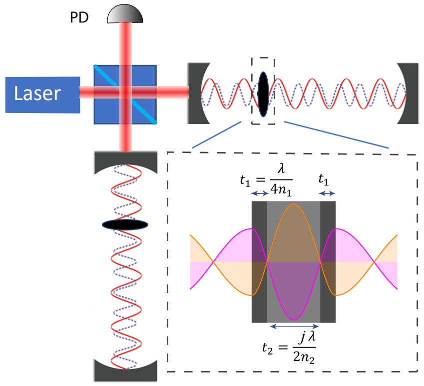
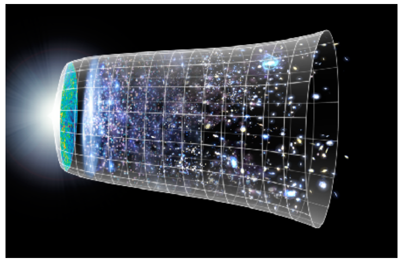
Difficult to detect:
requires precision measurement

Difficult to produce:
requires large temperatures/densities





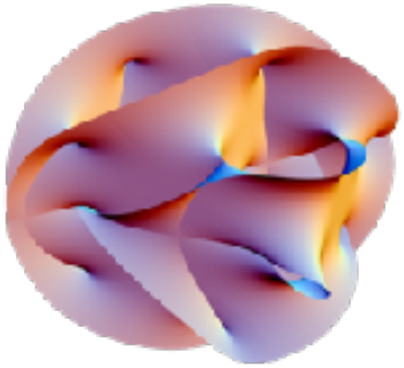


Cousins of the QCD Axion:
Axion-like Particles, Scalars, and Dark Photons

- Complex string compactifications produce multiplicity of light string axions, moduli, dilatons, dark photons

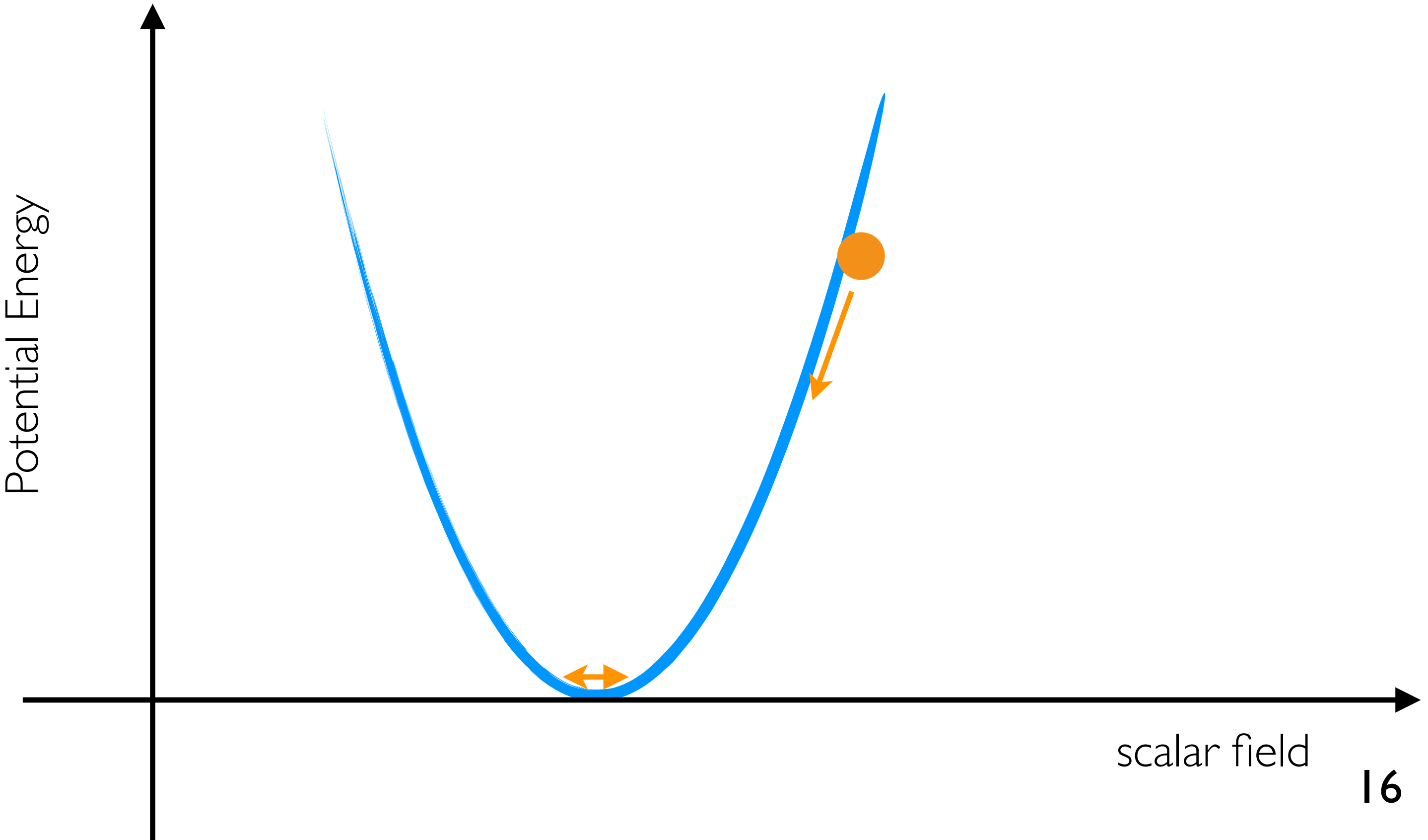
Svrcek , Witten 2006
Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell 2009
Dimopoulos, Giudice 1996

Cicoli, Goodsell, Jaeckel, Ringwald 2011
P. G. Cámara, L. E. Ibáñez, and F. Marchesano 2011



- Automatically generated in the early universe (inflation or phase transition)

Preskill, Wise, Wilczek (1983)
Dine, Fischler (1982)
Abbott, Sikivie (1982)
Graham, Mardon, Rajendran 2015



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Dark photons, scalars, axion like particles

  - Signatures of high scale physics
  - Candidates for the dark matter of the universe

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Dark photons, scalars, axion like particles $\Bigg\{$

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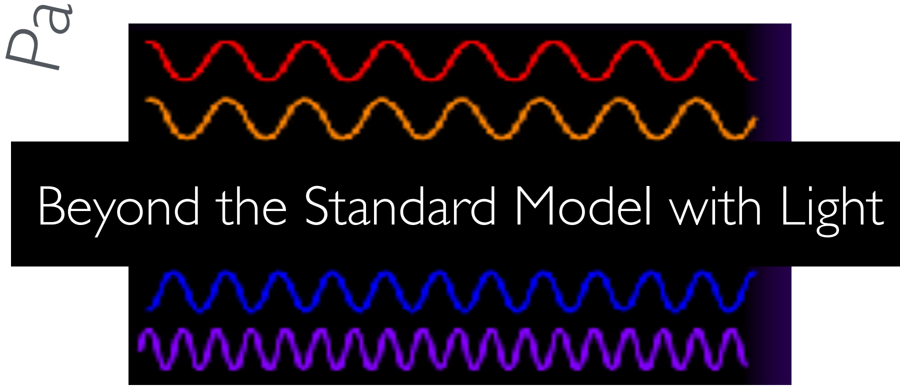
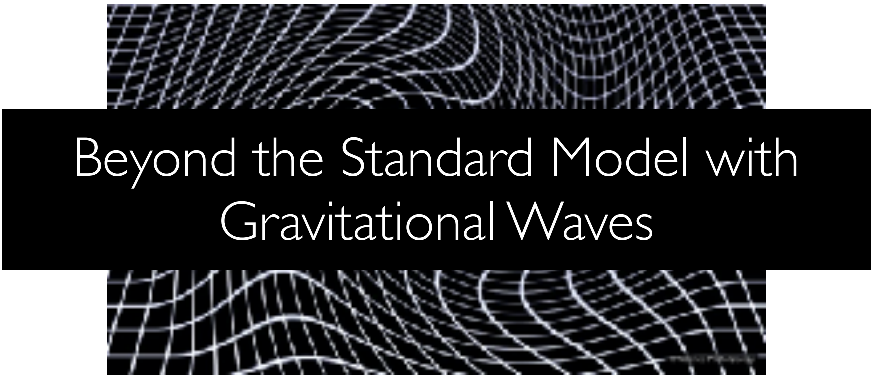
Part 1

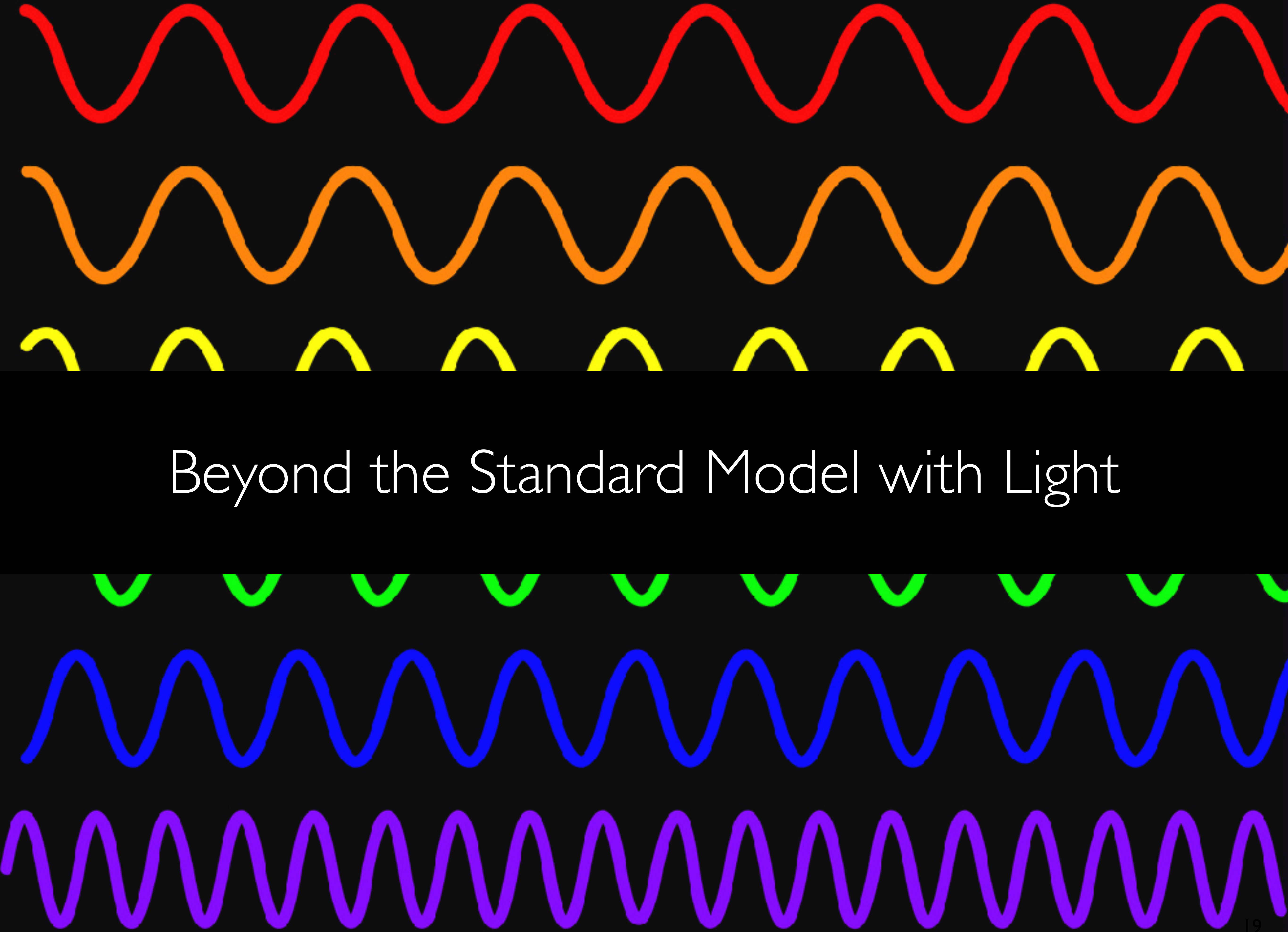


Beyond the Standard Model with Light

Part 2



Beyond the Standard Model with Gravitational Waves



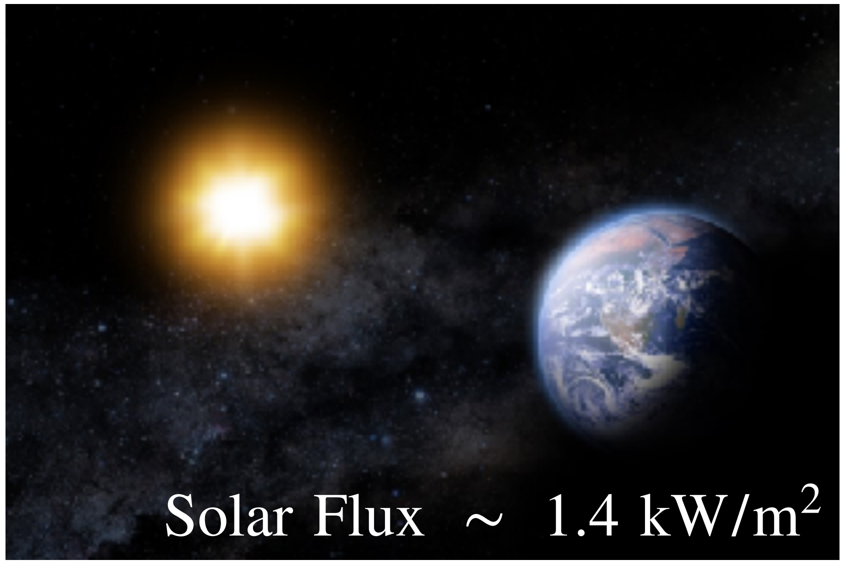
Beyond the Standard Model with Light

Light bosonic dark matter

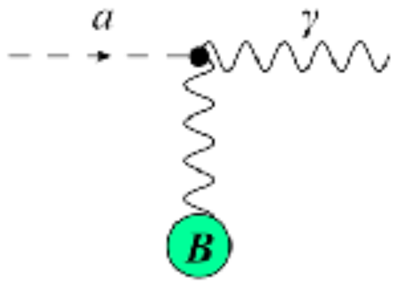
- Universe prepares a large density of dark matter for us locally


$\rho_{DM} \sim 0.3\ \mathrm{GeV/cm^3}$

Dark Matter Flux $\sim$ 14 $\mathrm{W/m^2}$


Solar Flux $\sim$ 1.4 $\mathrm{kW/m^2}$

- Axion (scalar, dark photon) can convert to photons through E . B term (kinetic mixing)



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

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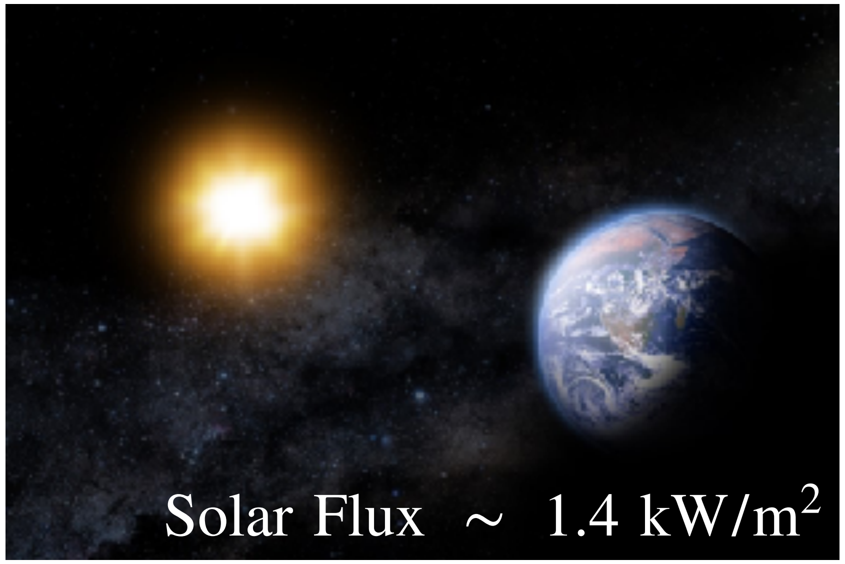

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infinitesimal couplings

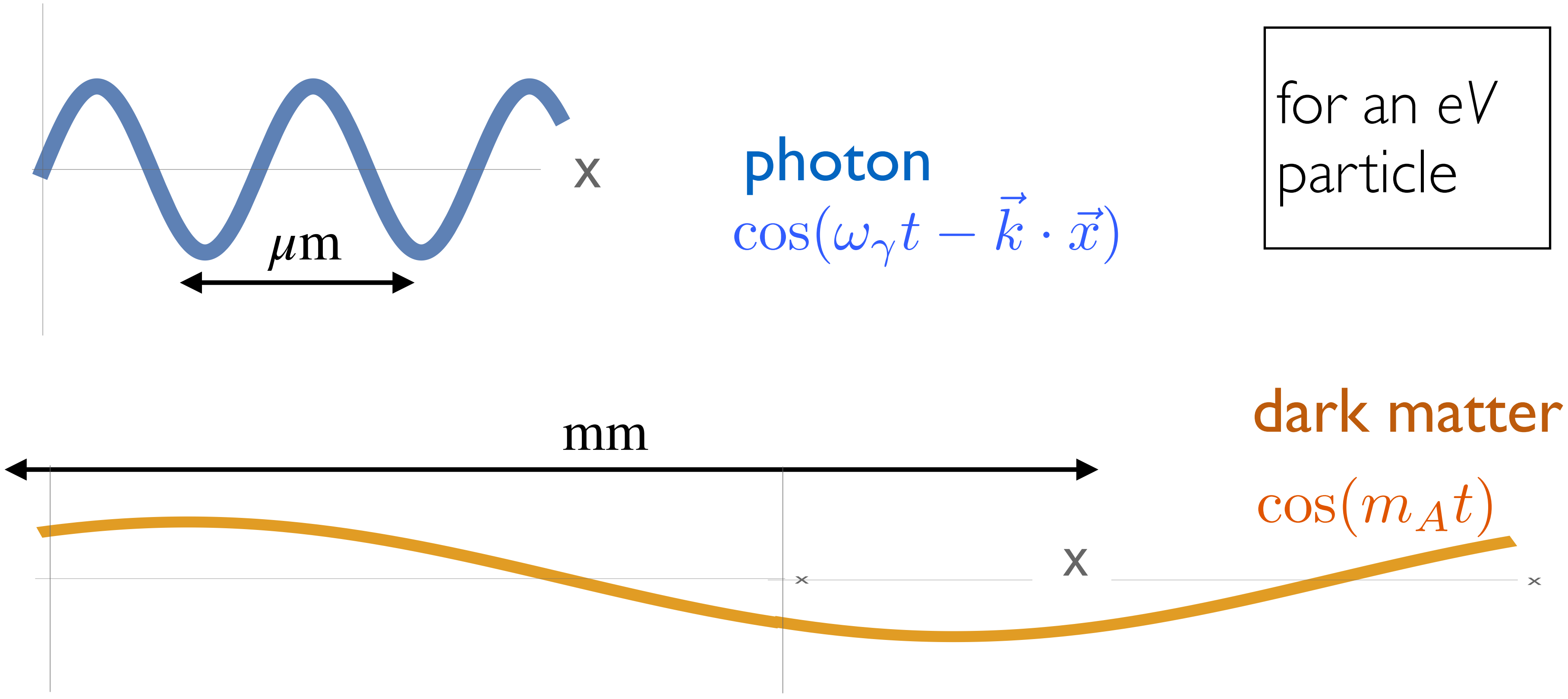
- Can we see axion or dark photon dark matter converting to photons?

Light bosonic dark matter

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

mismatch in spatial oscillation between photon and dark matter

overall, no conversion



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

for an eV particle

dark matter
$\cos(m_A t)$

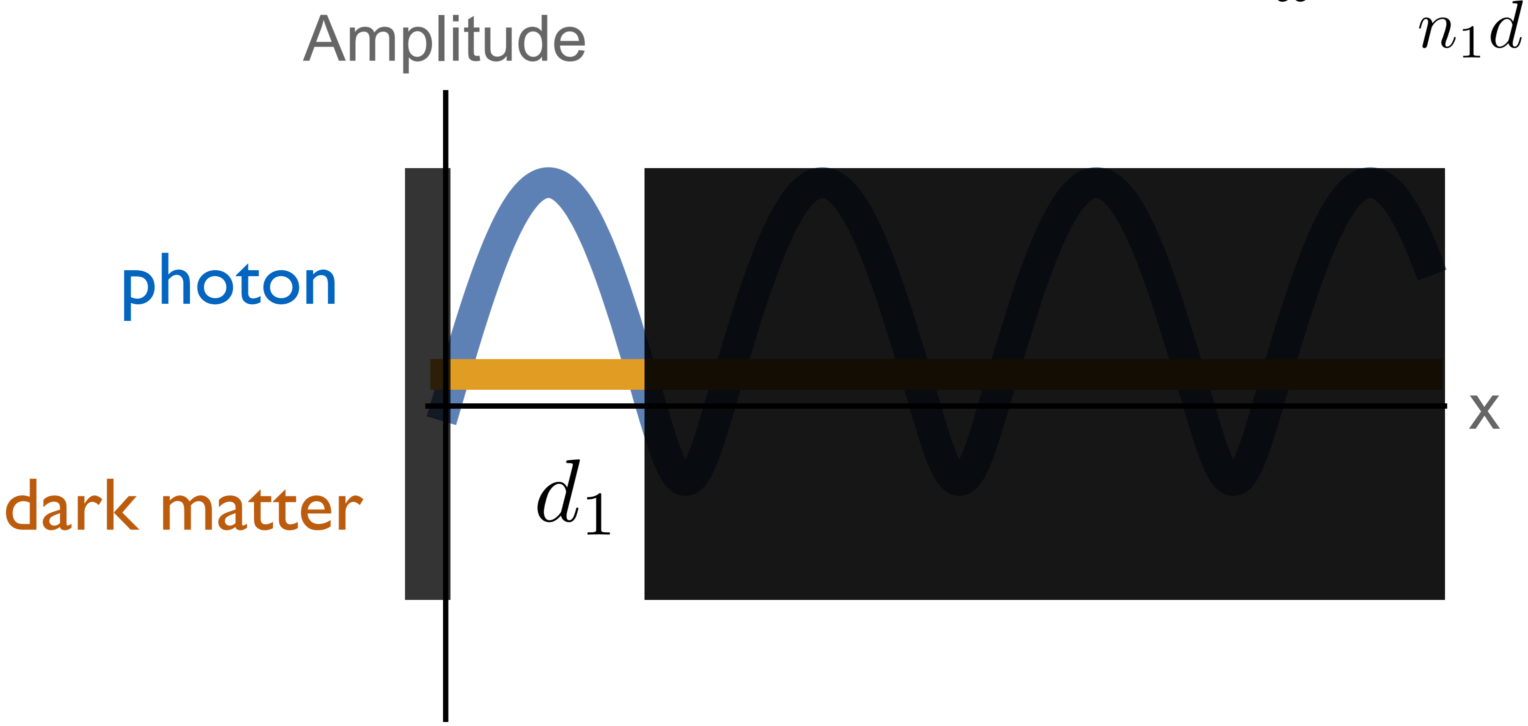
- Cannot change propagation of dark matter, but can manupulate light

Converting Dark Matter to Light

- **Boundary conditions**
  - Create `gapped modes' for photons
  - Standing waves have high energy, low momentum

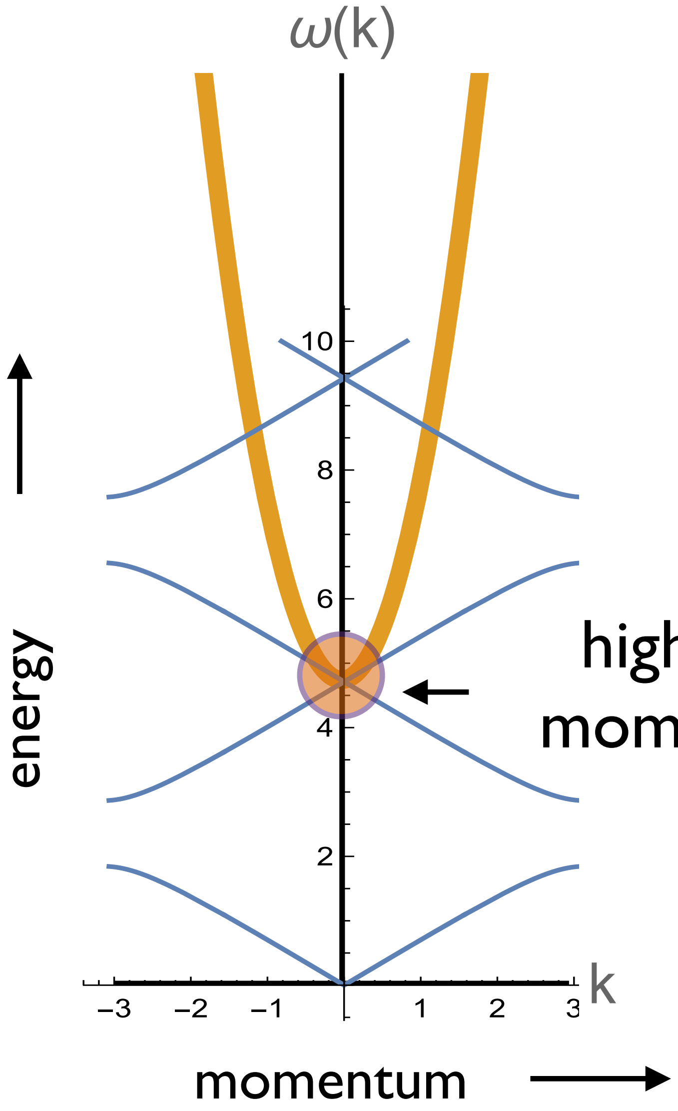
- ADMX: First axion DM experiment to reach QCD axion parameter space

$$\omega = \frac{\pi}{n_1 d_1}$$

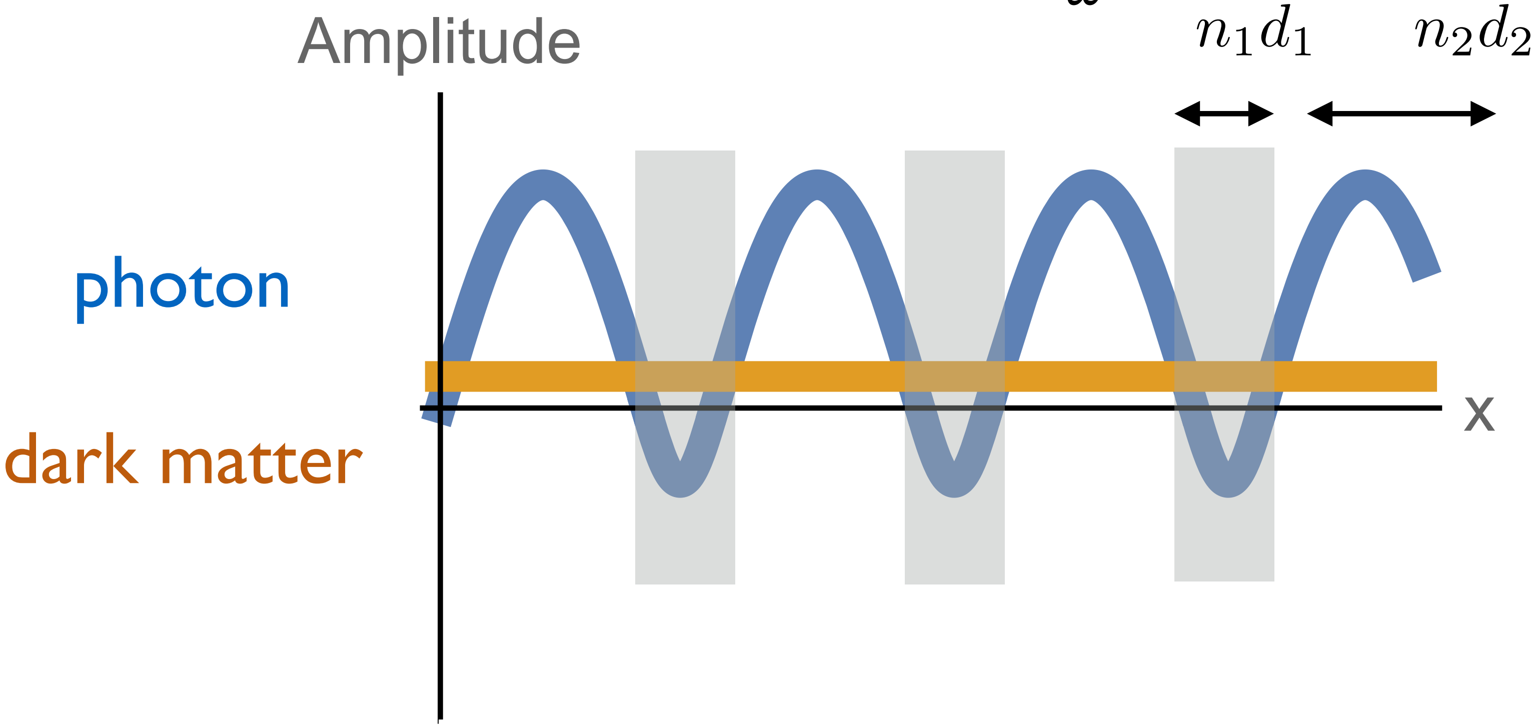


Converting Dark Matter to Light

- **Dielectric layers**
  - Add periodicity in the medium in which photons propagate
  - Periodic index of refraction changes free solutions of photon modes
  - Efficient dark matter to photon conversion



high energy, low momentum modes



$$\omega = \frac{\pi}{n_1 d_1} = \frac{\pi}{n_2 d_2}$$

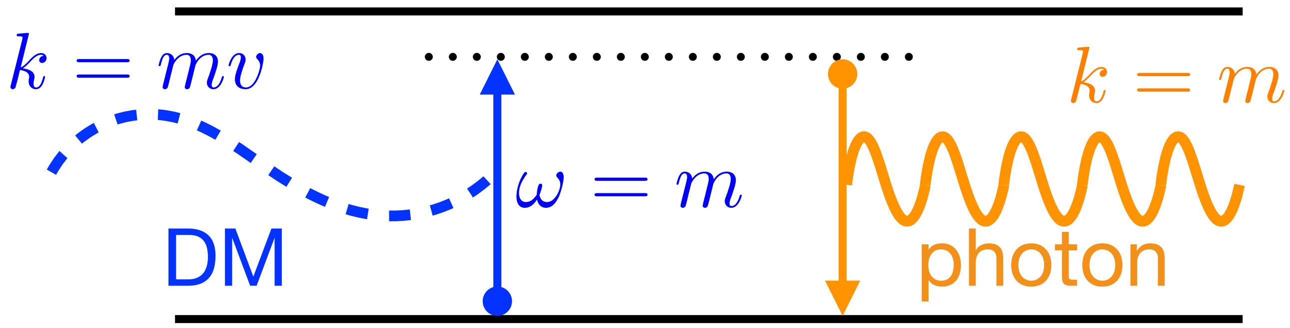
MB, J. Huang, R. Lasenby PRD 2018

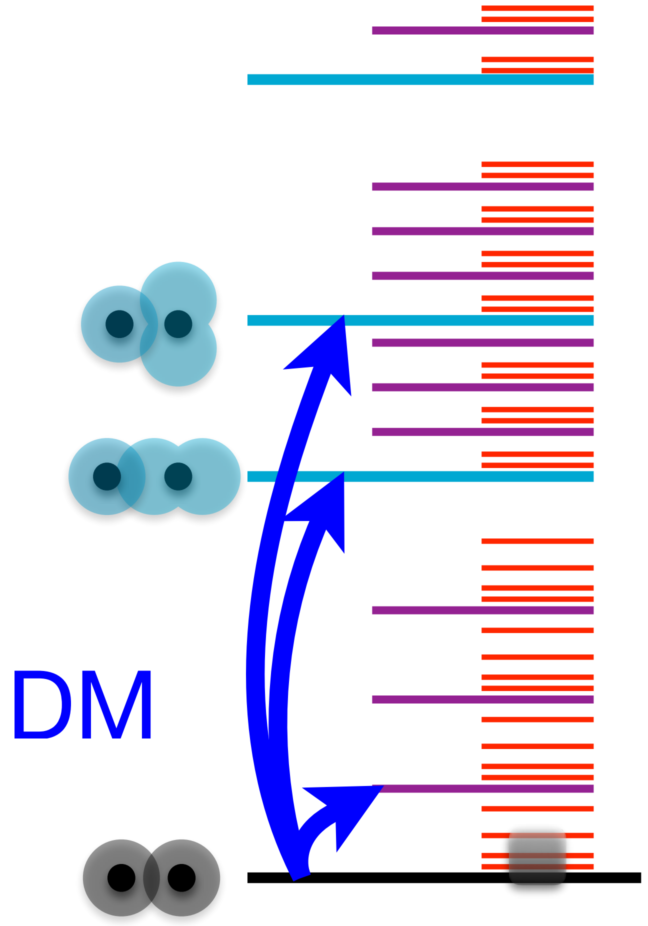
MADMAX proposal

Electric Tiger

Converting Dark Matter to Light

- **Molecules**
    - Energy splitting between states sets dark matter absorption, followed by photon reemission



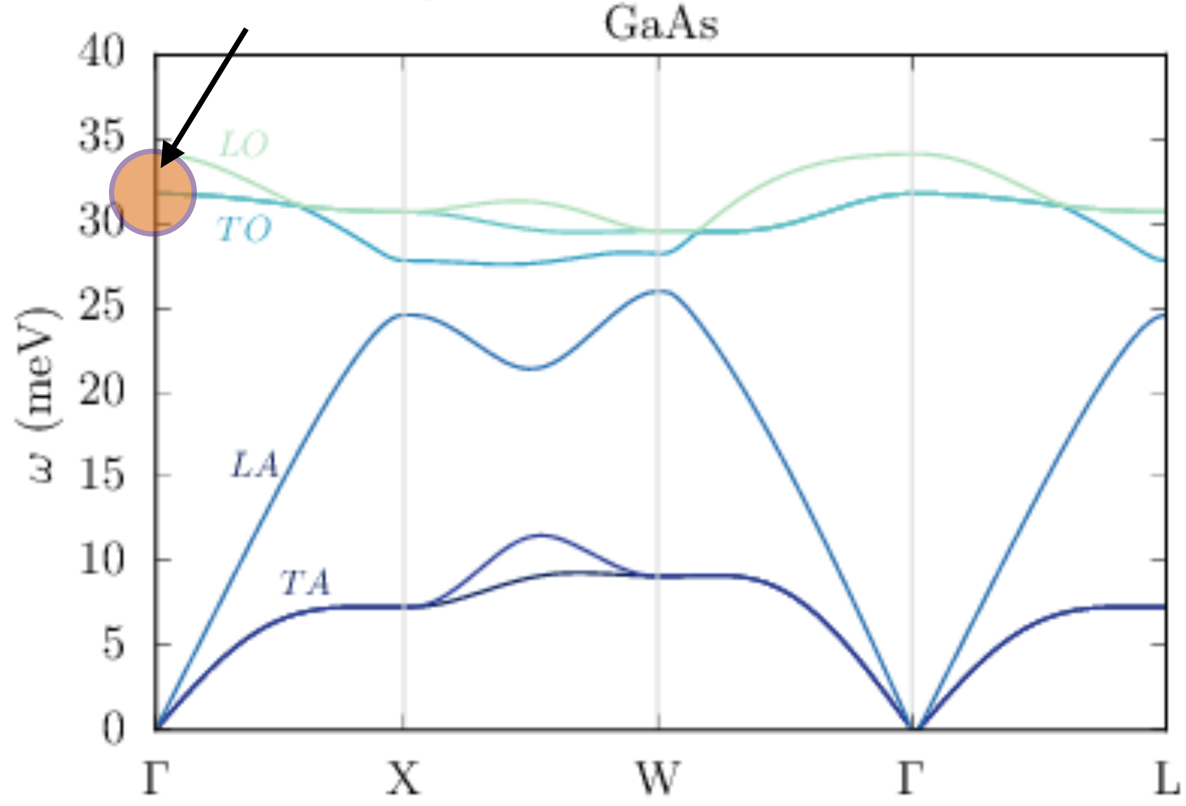


Arvanitaki, Dimopoulos, Van Tilburg (2017)

Converting Dark Matter to ~~Light~~ Sound

- **Crystals**:
  - Specific periodic structures create `optical' phonon modes with `non-relativistic' dispersion
  - Efficient dark matter to phonon conversion

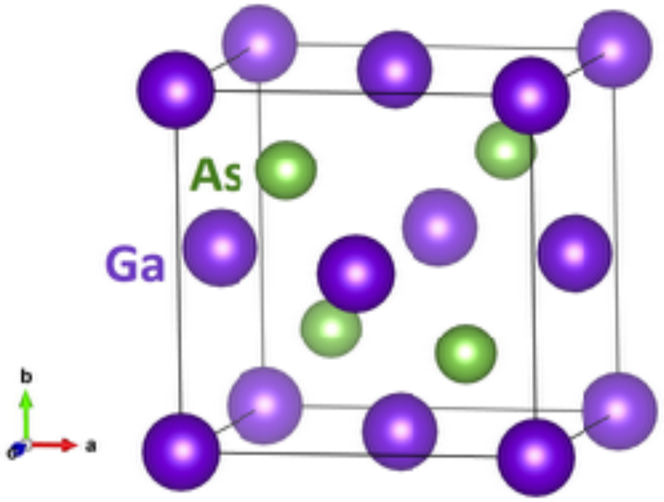
high energy, low momentum modes



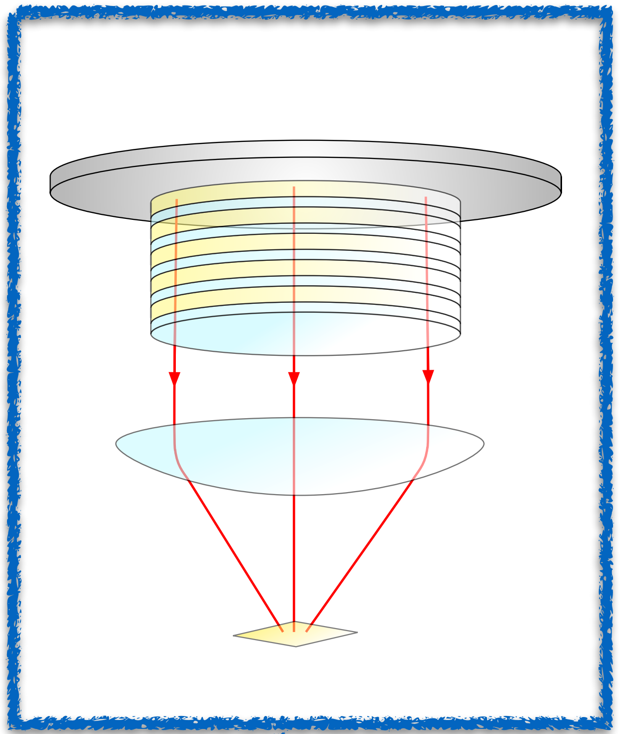
energy

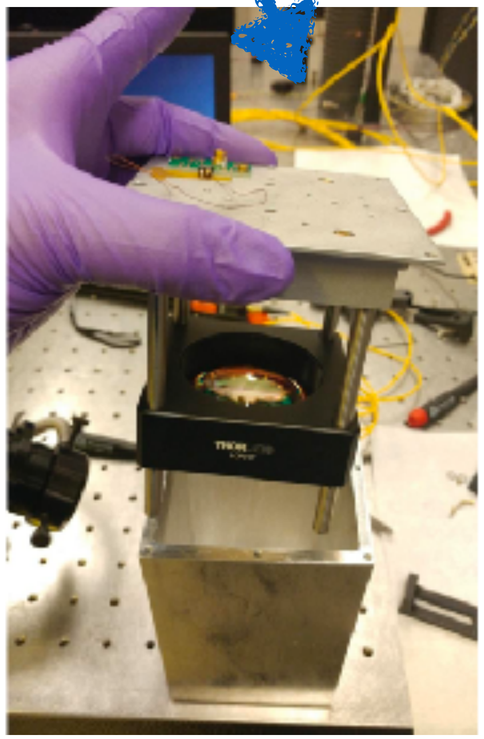
momentum

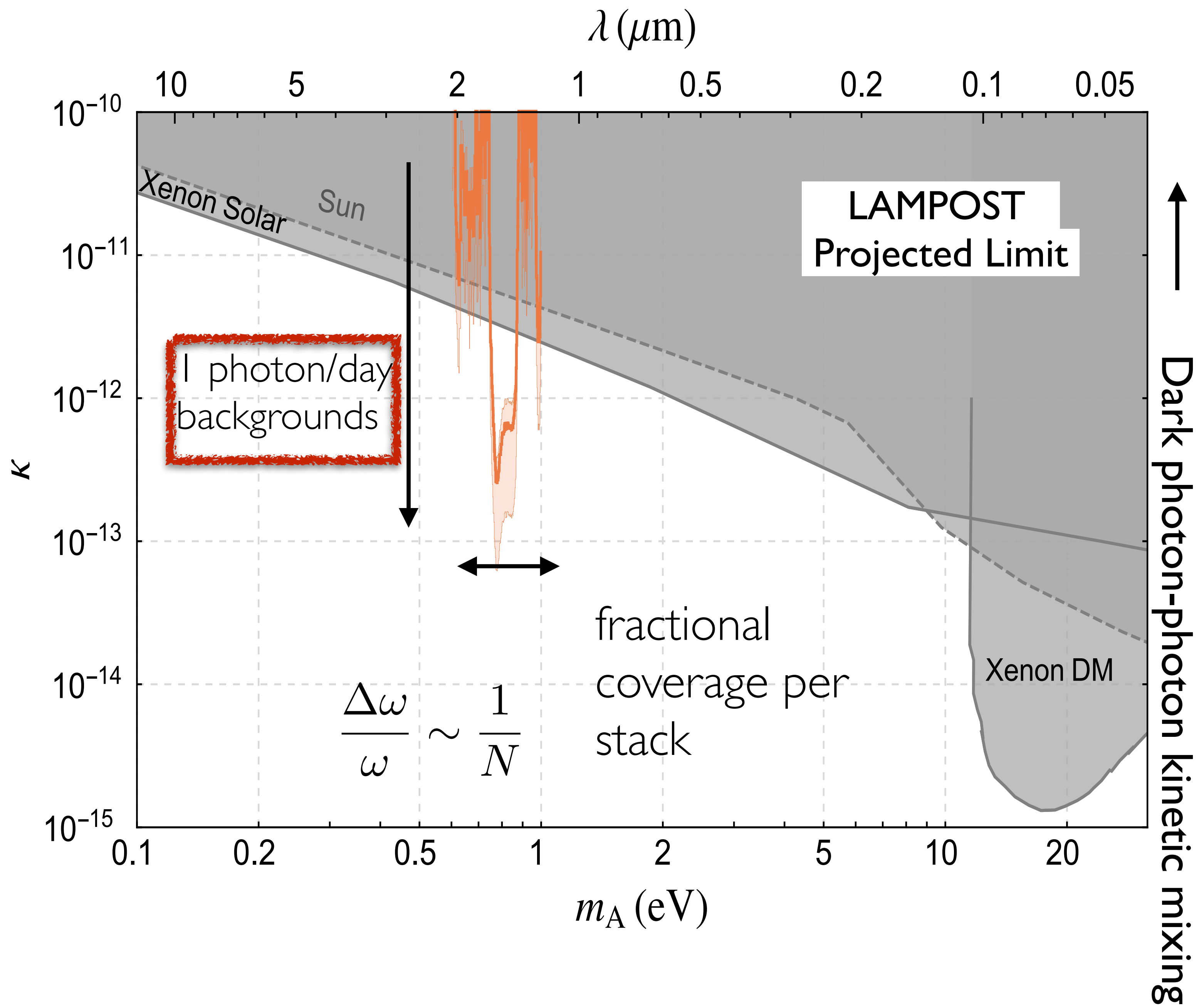
Griffin, Knapen, Lin, Zurek (2018)



Nanowire Detection of Photons from the Dark Side







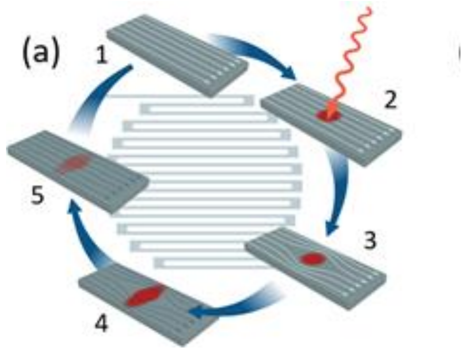
$$\frac{\Delta\omega}{\omega} \sim \frac{1}{N}$$

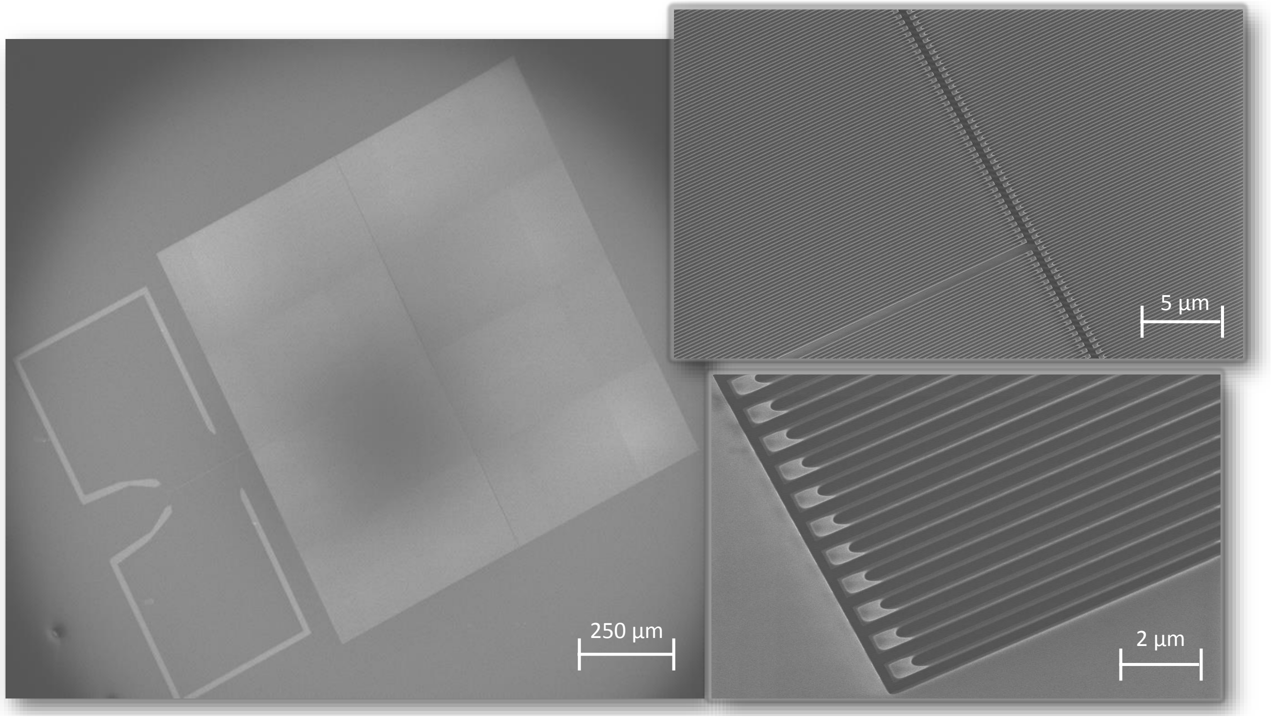
- First steps underway, use well-established optics and detector technology; possible to reach very small couplings / axions with larger setups

(Exp) Berggren, Charaev; Chiles, Nam; (Th) Arvanitaki, **MB,** Huang, Lasenby, Van Tilburg
expanding collaboration
Funded by DoE QUANTISED initiative

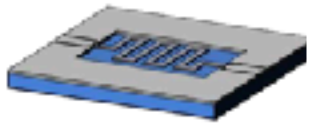
Requires State-of-the-Art Photodetection Techniques

- Use superconducting nanowire single photon detector (SNSPDs)
  - Small area, *extremely low* dark count rates
  - *High efficiency* in optical frequency range





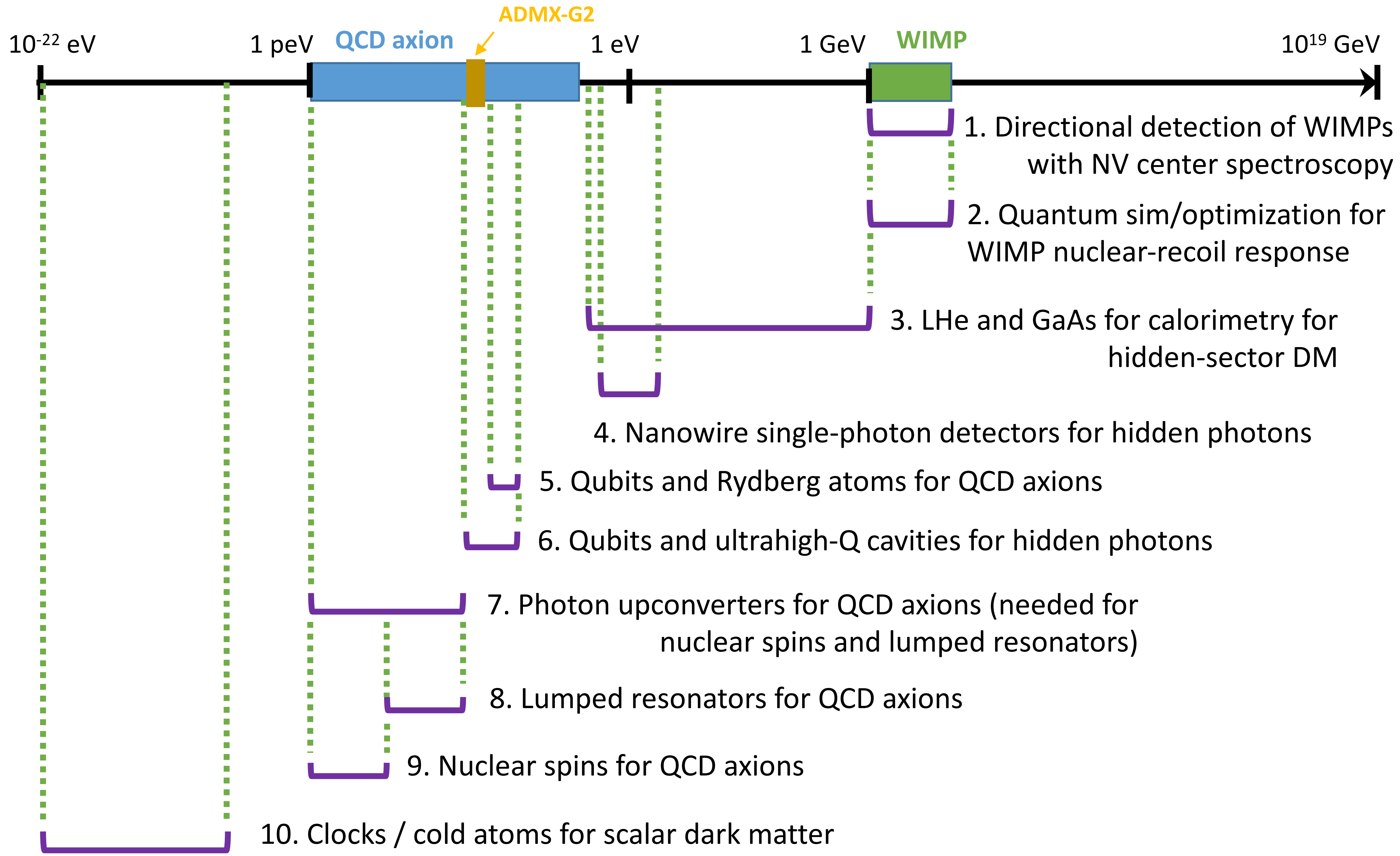
Deposition of 7 nm WSi film on silicon oxide substrate



Pattern WSi nanowires using e-beam lithography and reactive ion etching

Fabricated by Ilya Charaev, MIT

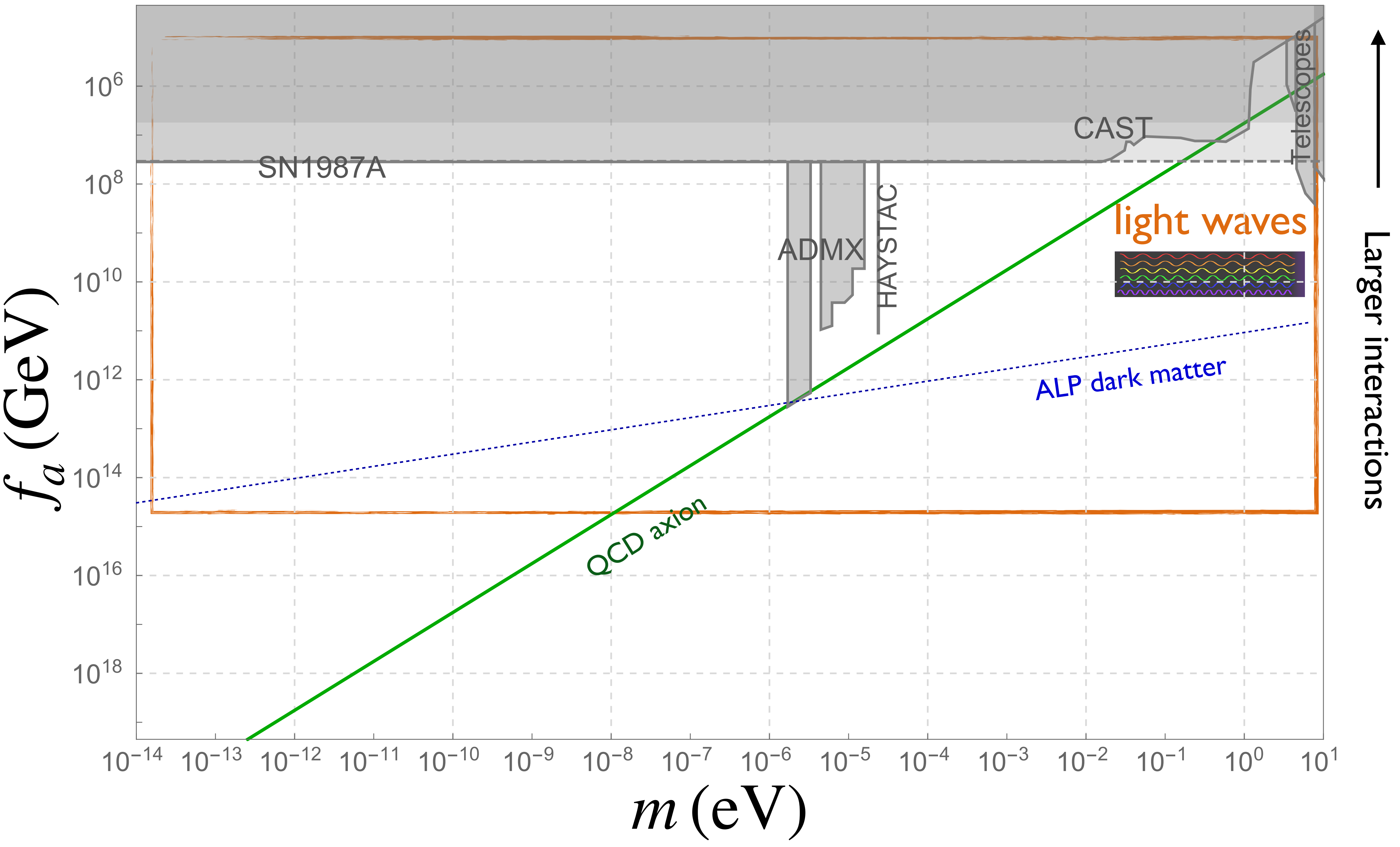
Requires State-of-the-Art Detection Techniques

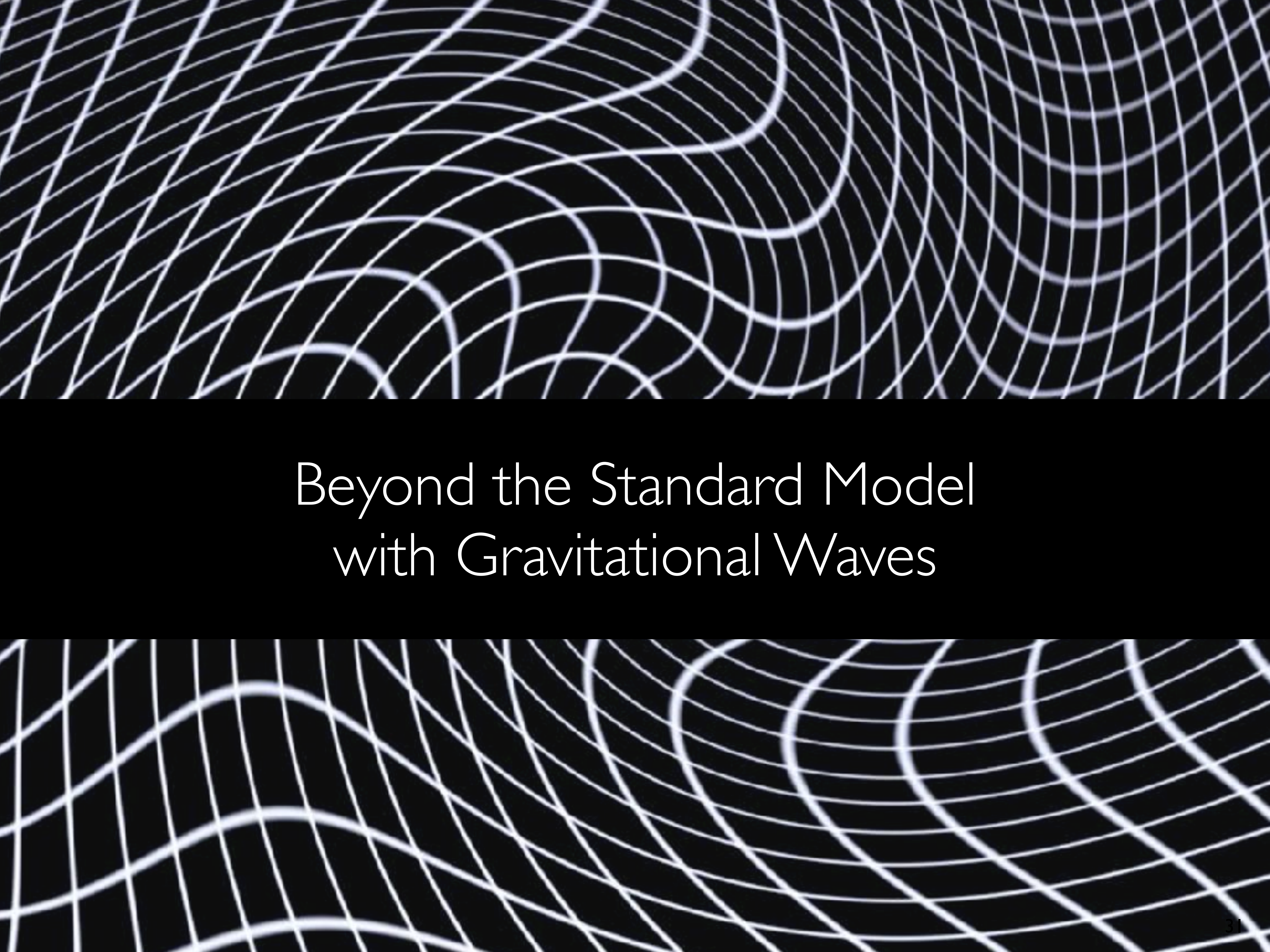


1. Directional detection of WIMPs with NV center spectroscopy
2. Quantum sim/optimization for WIMP nuclear-recoil response
3. LHe and GaAs for calorimetry for hidden-sector DM
4. Nanowire single-photon detectors for hidden photons
5. Qubits and Rydberg atoms for QCD axions
6. Qubits and ultrahigh-Q cavities for hidden photons
7. Photon upconverters for QCD axions (needed for nuclear spins and lumped resonators)
8. Lumped resonators for QCD axions
9. Nuclear spins for QCD axions
10. Clocks / cold atoms for scalar dark matter

Adapted from K. Irwin

Searches of dark matter with light

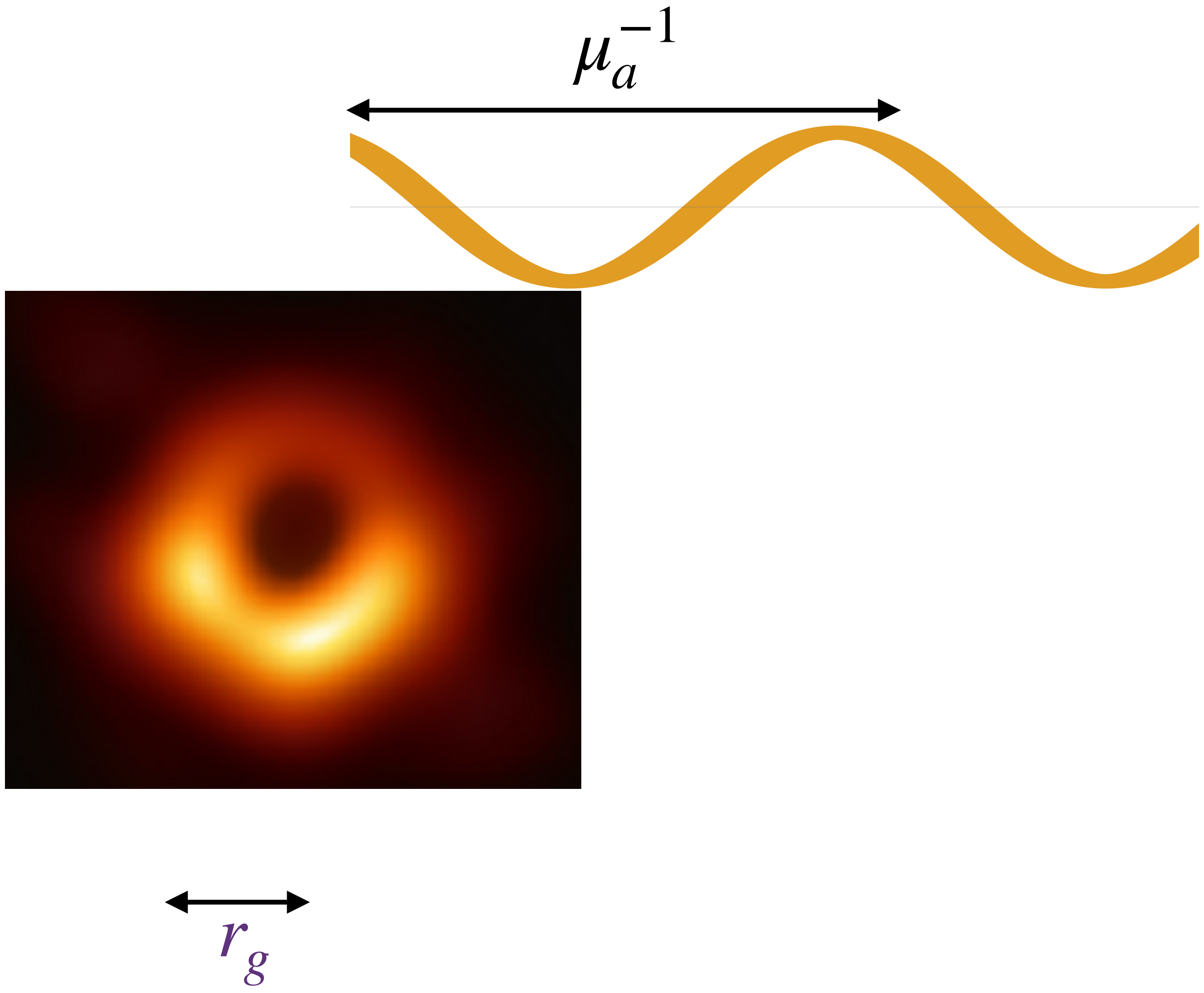




Beyond the Standard Model with Gravitational Waves

Black holes and Gravitational Waves

- Ultralight bosons with **compton wavelength** comparable to **black hole radius** can form `gravitational atoms', bound by gravity

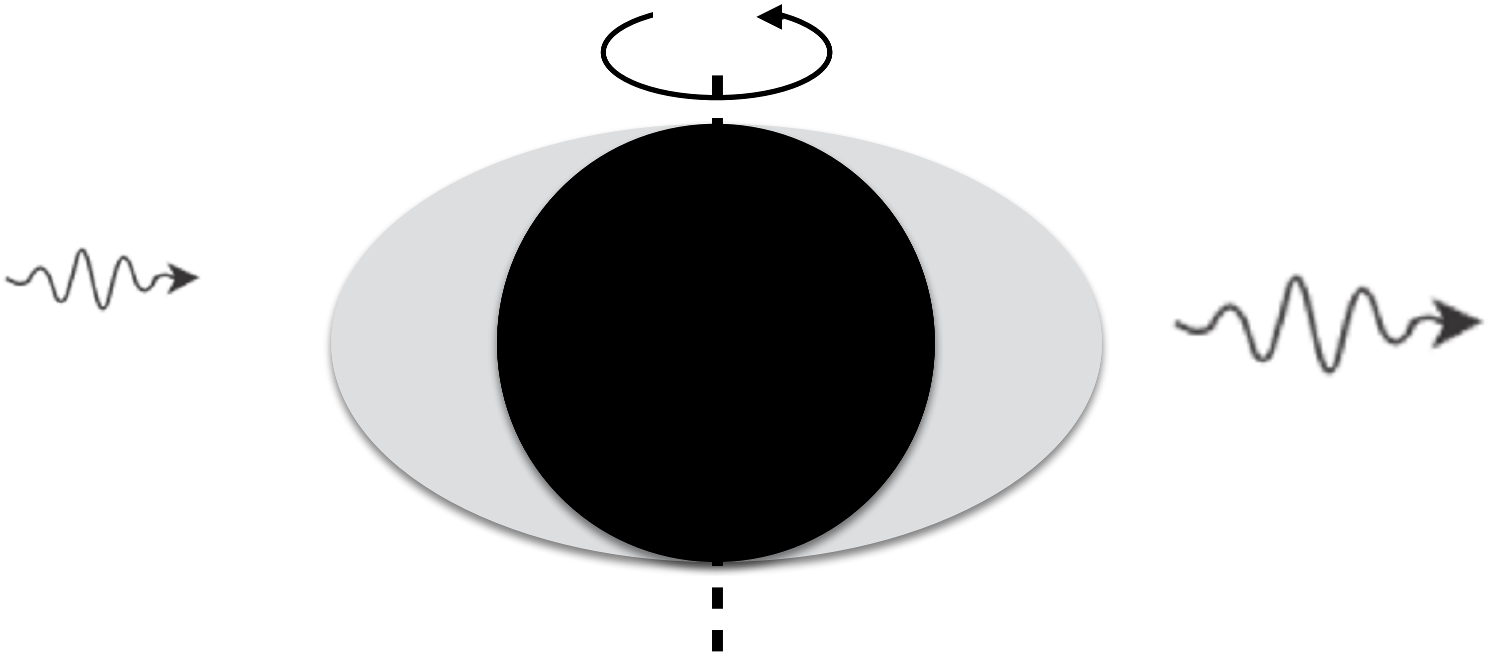


- These `gravitational atoms' grow spontaneously when a rapidly rotating black hole is formed

- Boson density in each bound state reaches exponentially large values by extracting the black hole's angular momentum and leads to gravitational wave emission

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

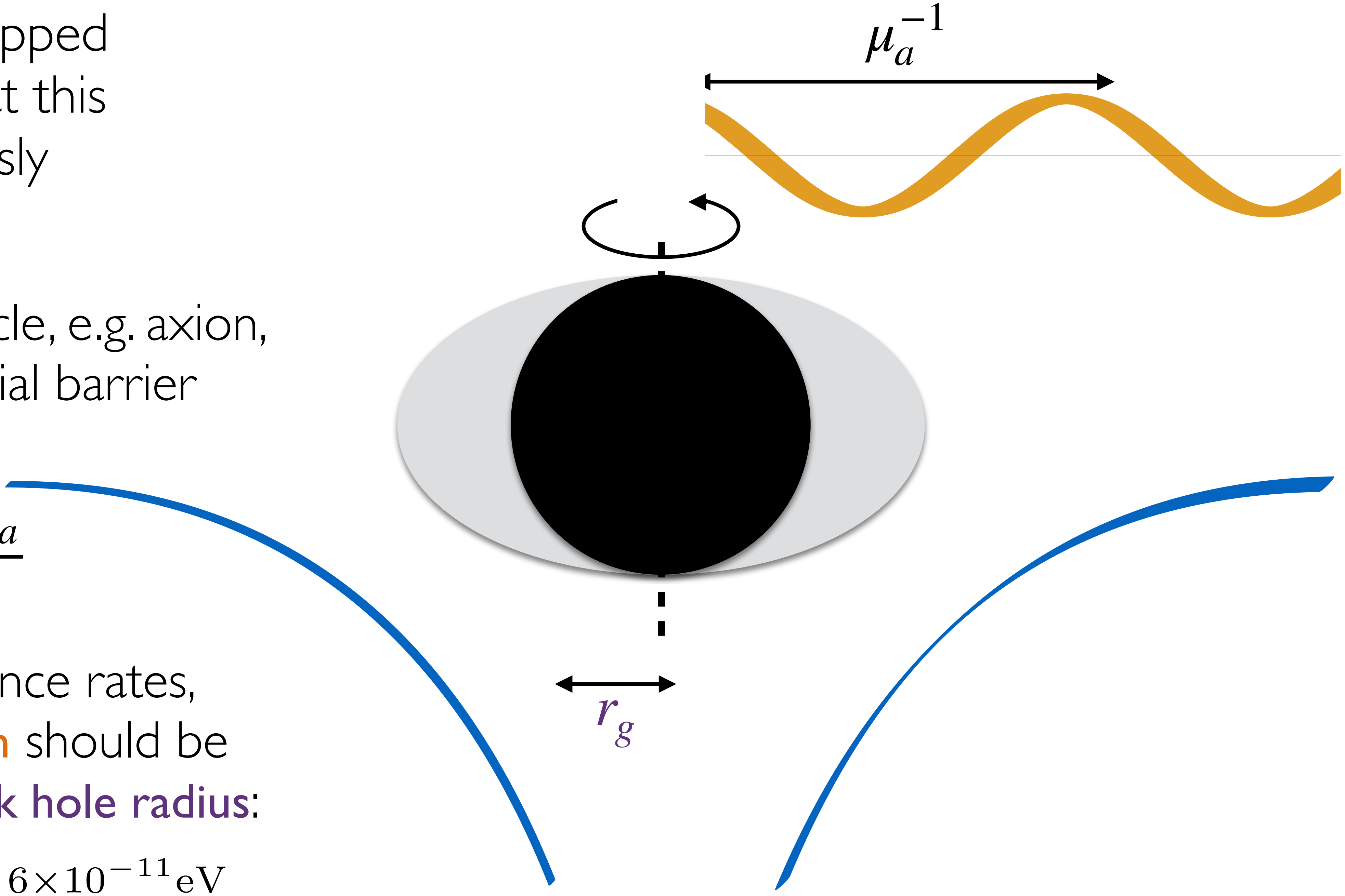
- Particles/waves trapped near the BH repeat this process continuously

- 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**:

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

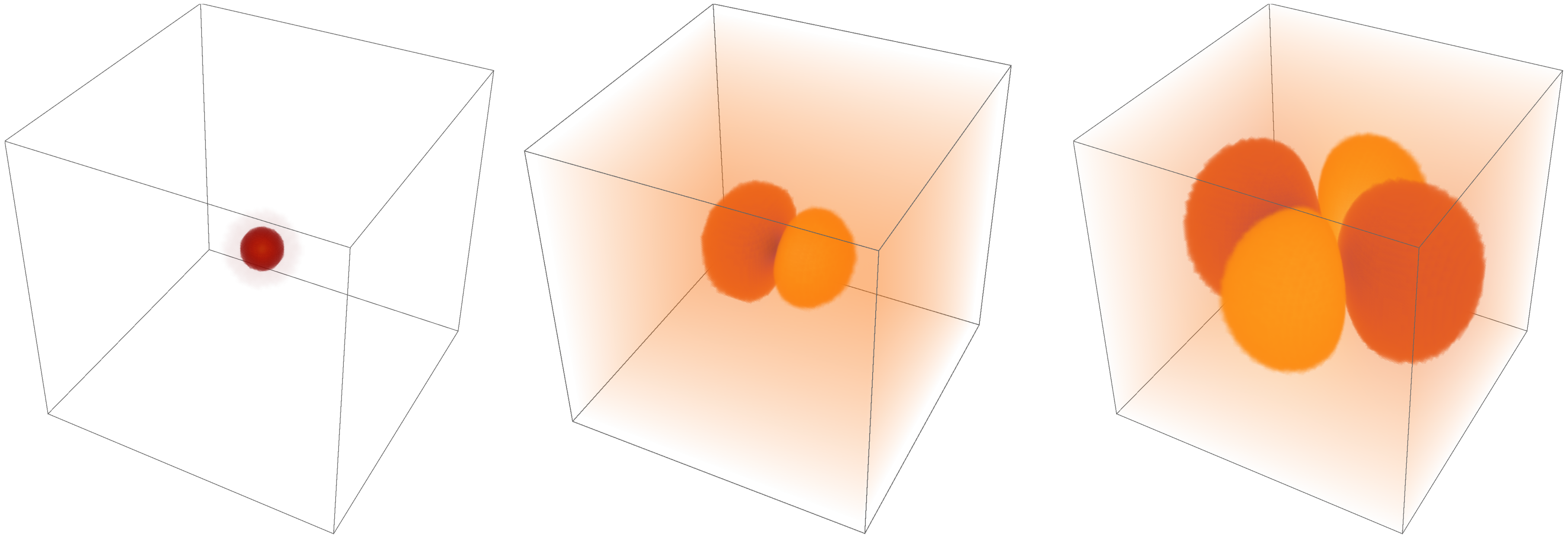


Zouros & Eardley'79; Damour et al '76; Detweiler'80; Gaina et al '78
Tool to search for axions:
Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell 2009; Arvanitaki, Dubovsky 2010

Gravitational Atoms

Axion
Gravitational Atoms

$$V(r) = -\frac{G_{\rm N} M_{\rm BH} \mu_a}{r}$$



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

Gravitational potential similar to hydrogen atom

`Fine structure constant`

$$\alpha \equiv G_{\rm N} M_{\rm BH} \mu_a \equiv r_g \mu_a$$

Radius

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

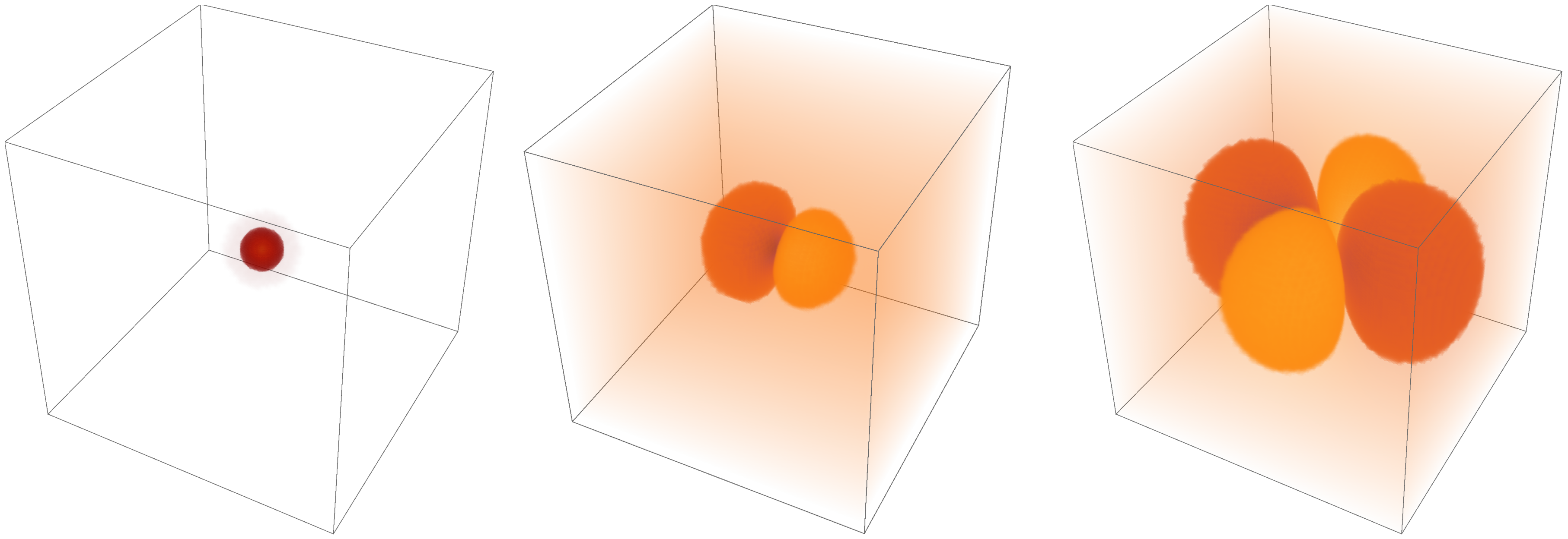
Occupation number

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

Gravitational Atoms

Axion
Gravitational Atoms

$$V(r) = -\frac{G_{\rm N} M_{\rm BH} \mu_a}{r}$$



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Radius

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

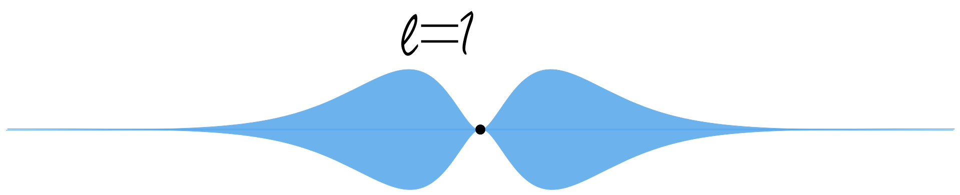
Occupation number

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

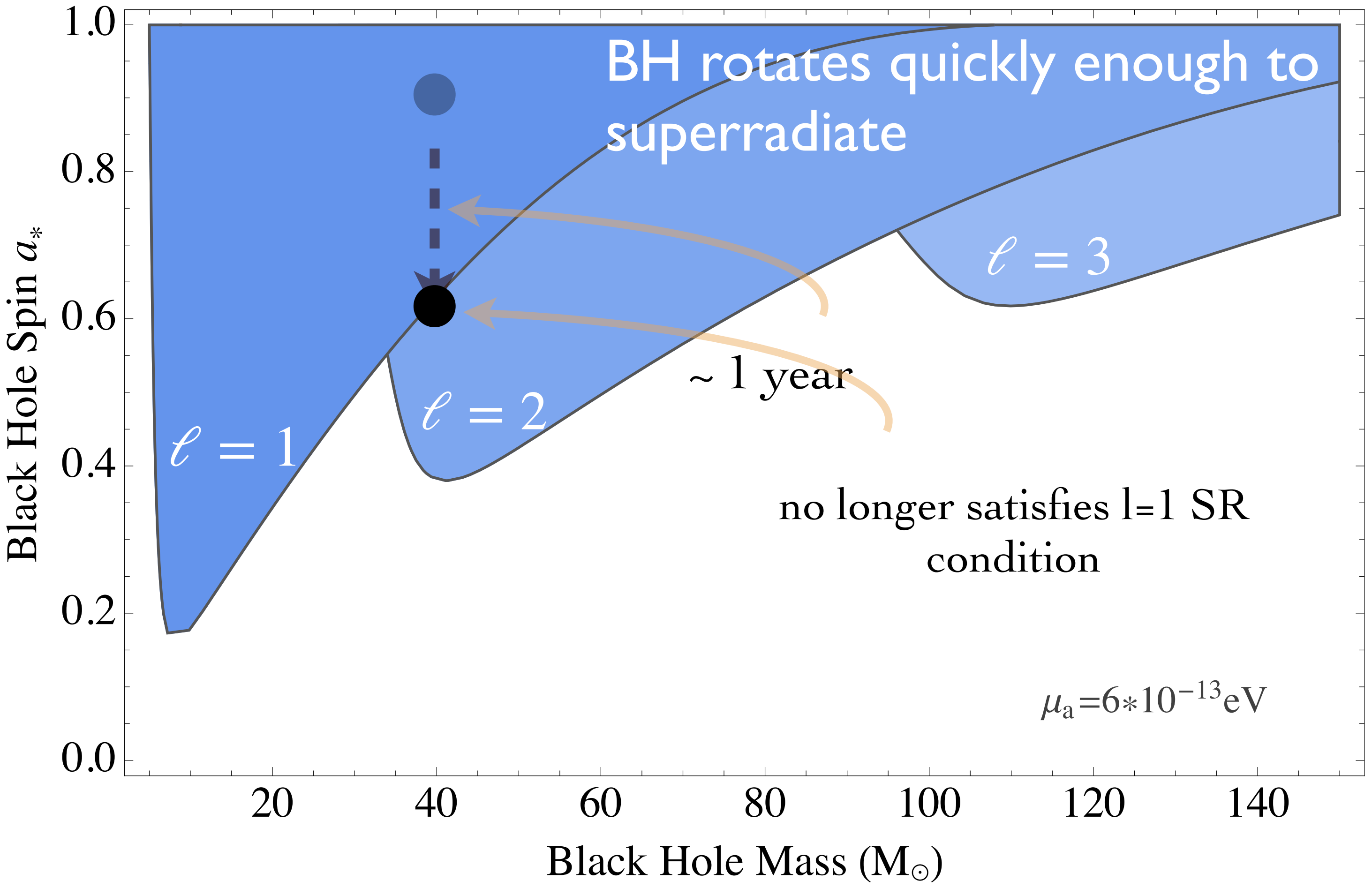
Boundary conditions at horizon give imaginary frequency: **exponential growth of particle number around rapidly rotating black holes**

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

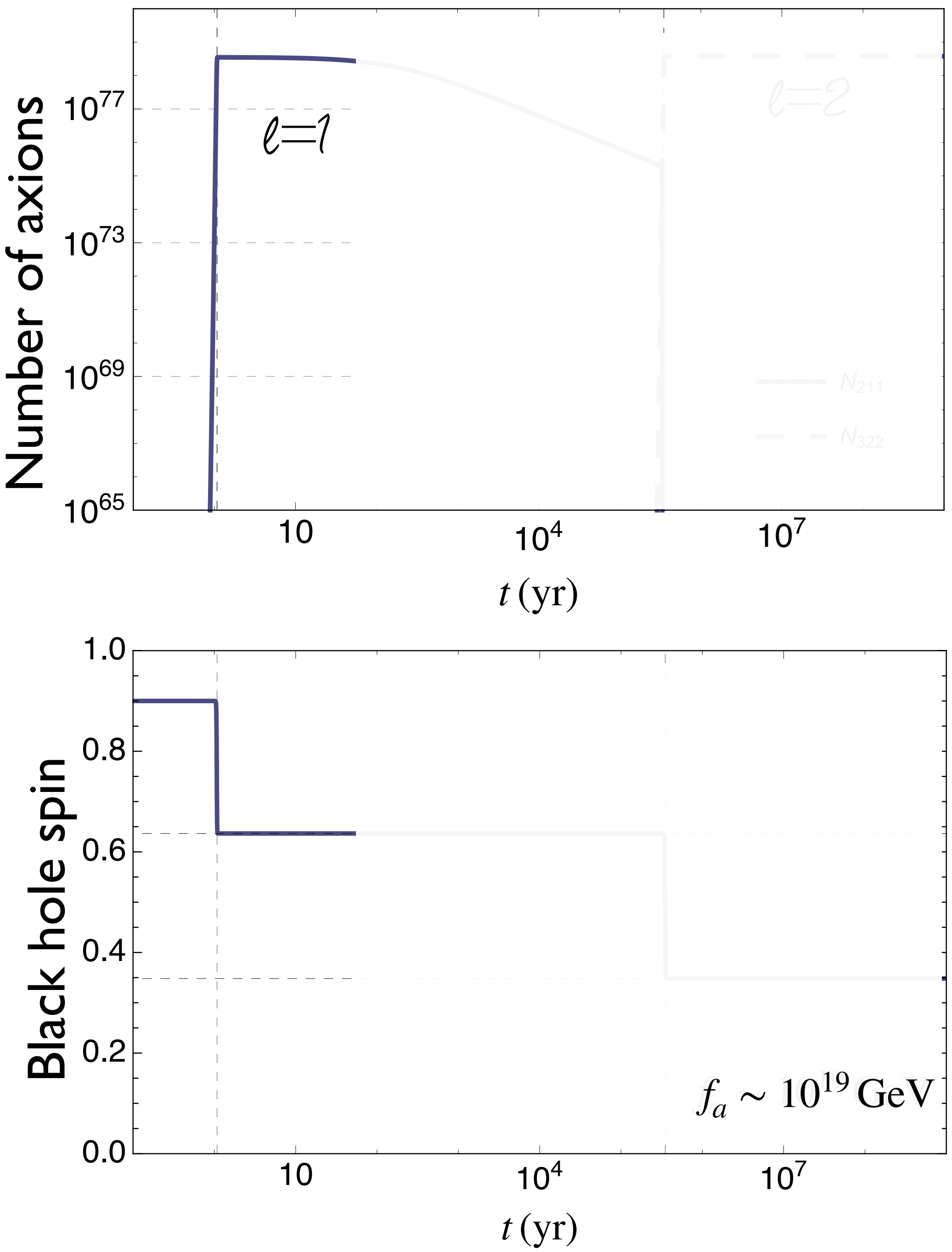
Superradiance



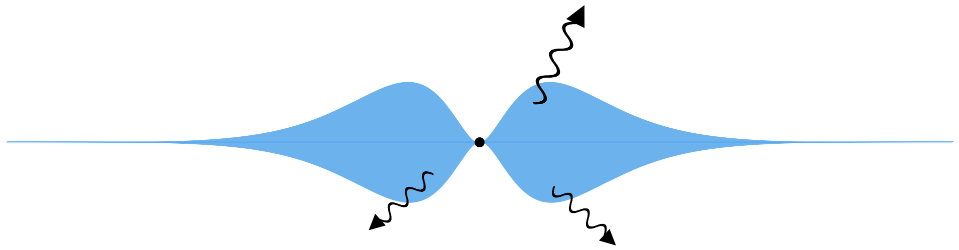
- If new light axions exist, fast-spinning black holes will superradiate: lose energy and angular momentum to exponentially growing bound states of axions



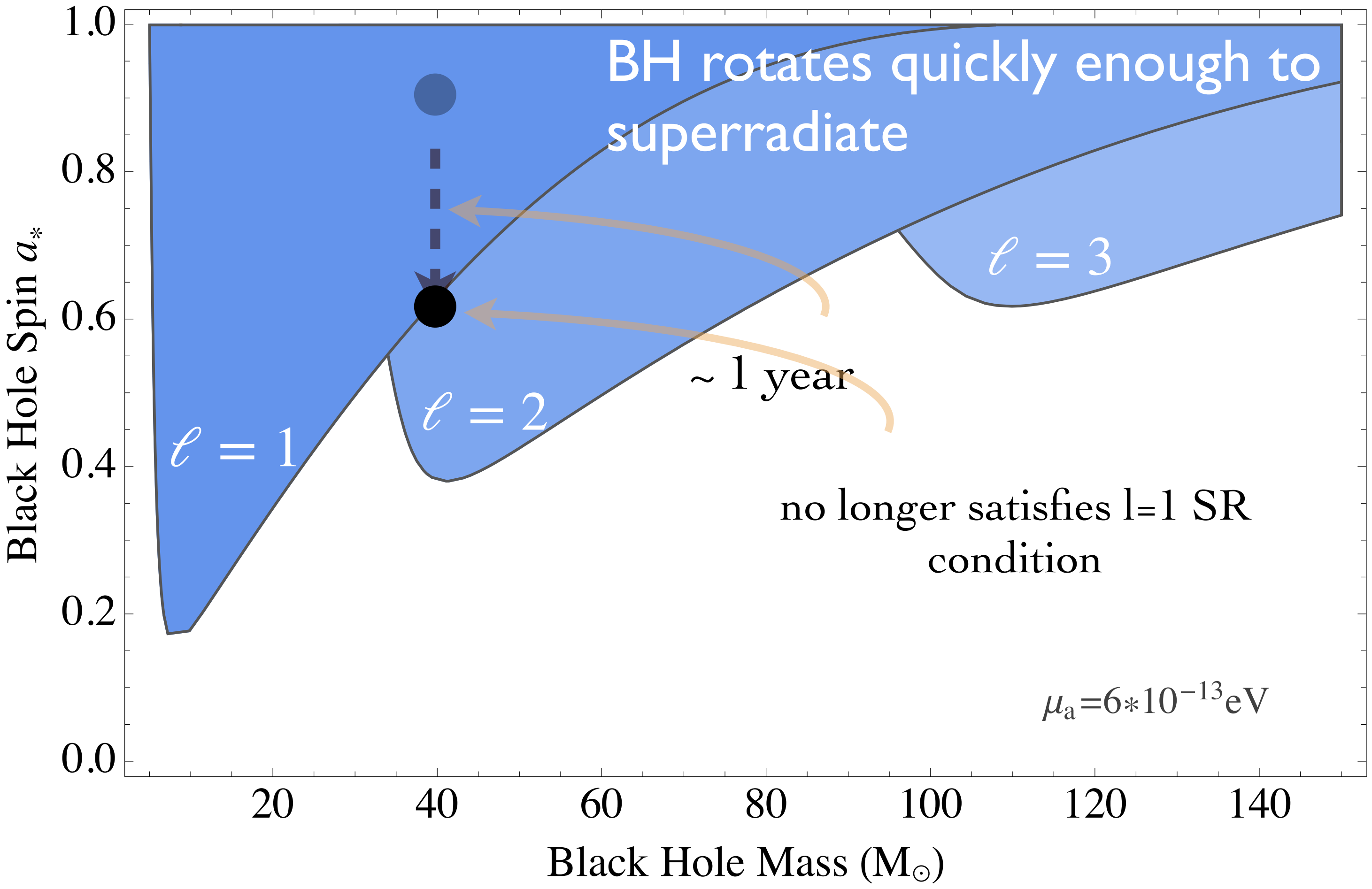
Time evolution



Superradiance



- Large energy density in the cloud, with time dependence set by the axion mass
- Sources monochromatic gravitational wave radiation
- Axion cloud depletes on long timescales through GW emission

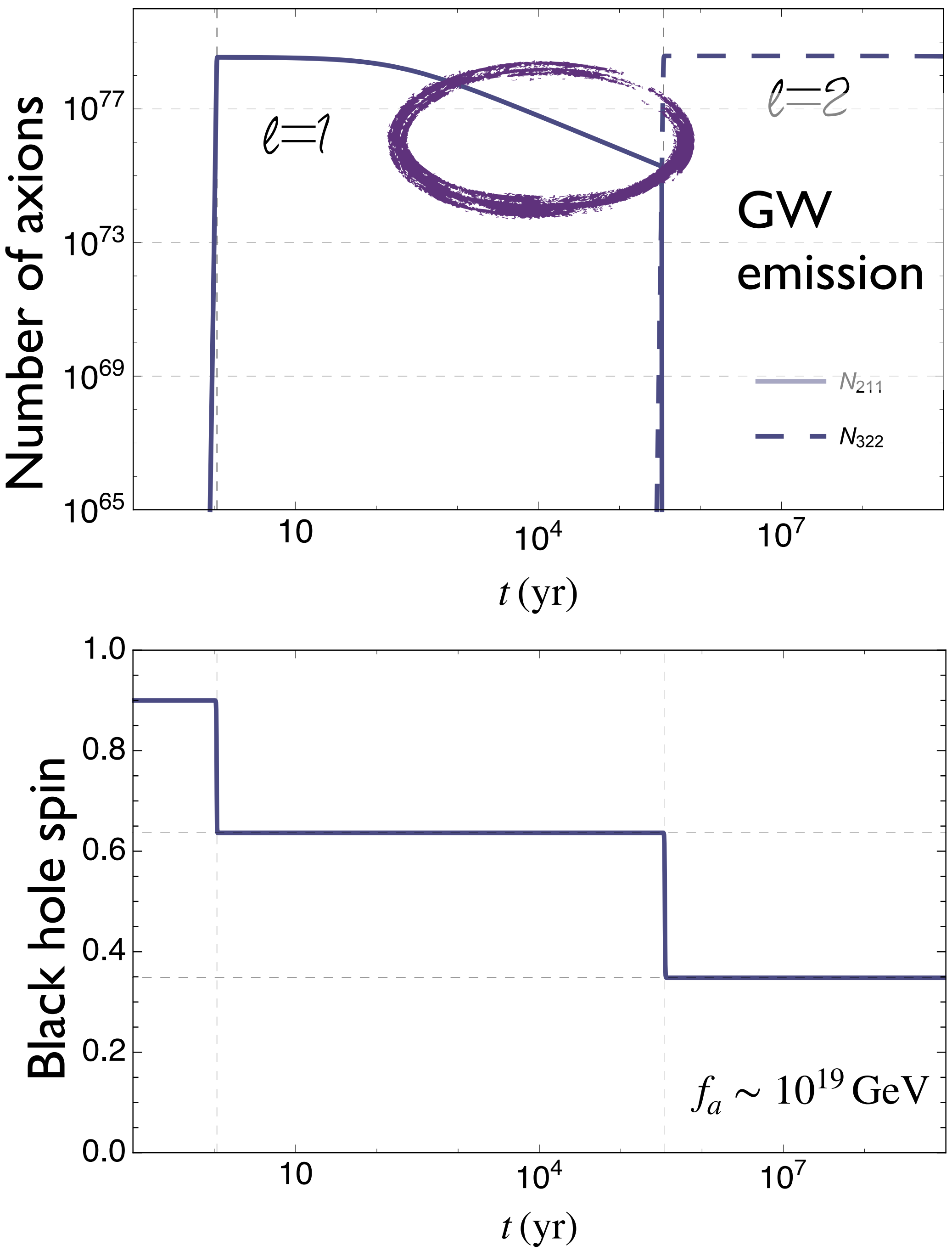


BH rotates quickly enough to superradiate

~ 1 year

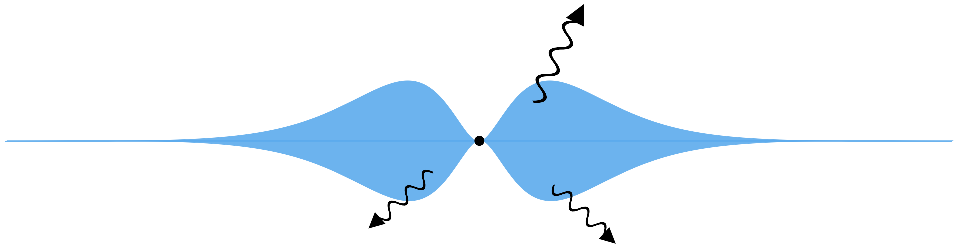
no longer satisfies l=1 SR condition

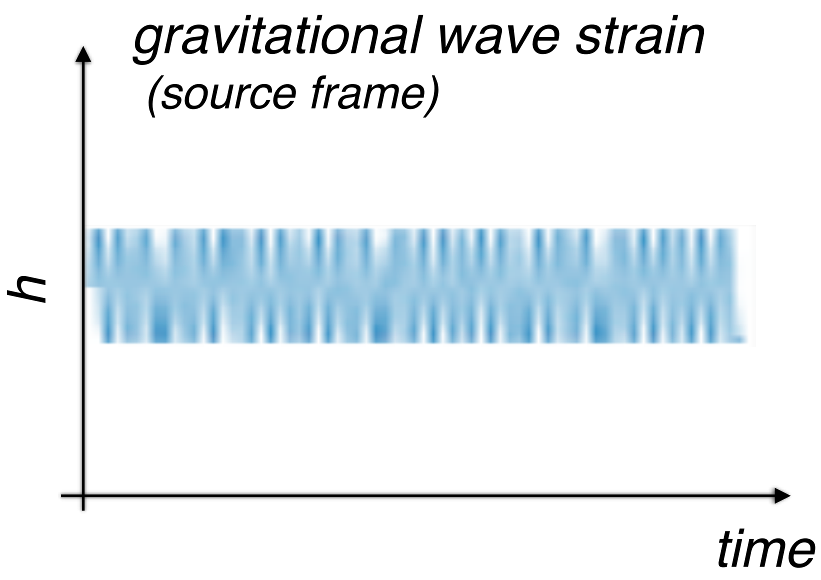
Time evolution



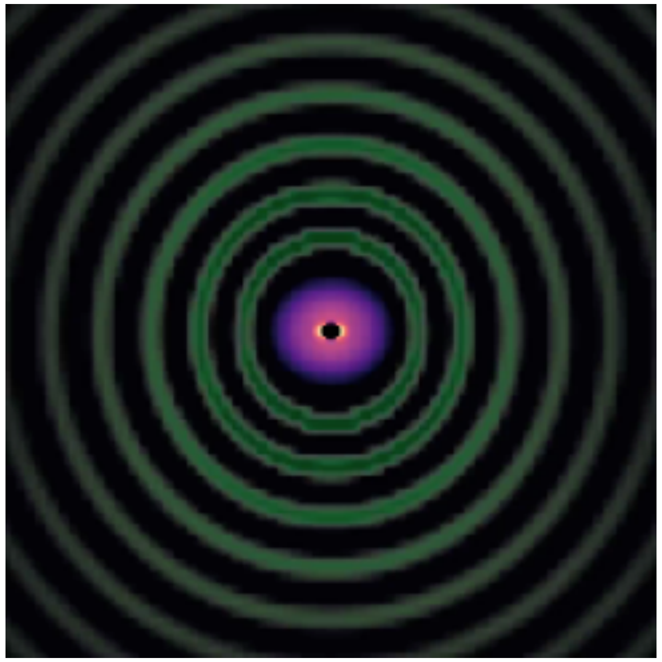
GW emission

Gravitational Wave Signals



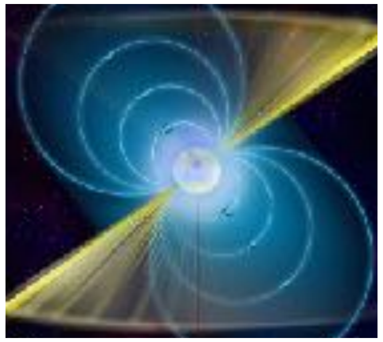


Arvanitaki, **MB**, Dimopoulos, Dubovsky, Lasenby (2017)
Isi, Sun, Brito, Melatos (2019)
Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein (2020)



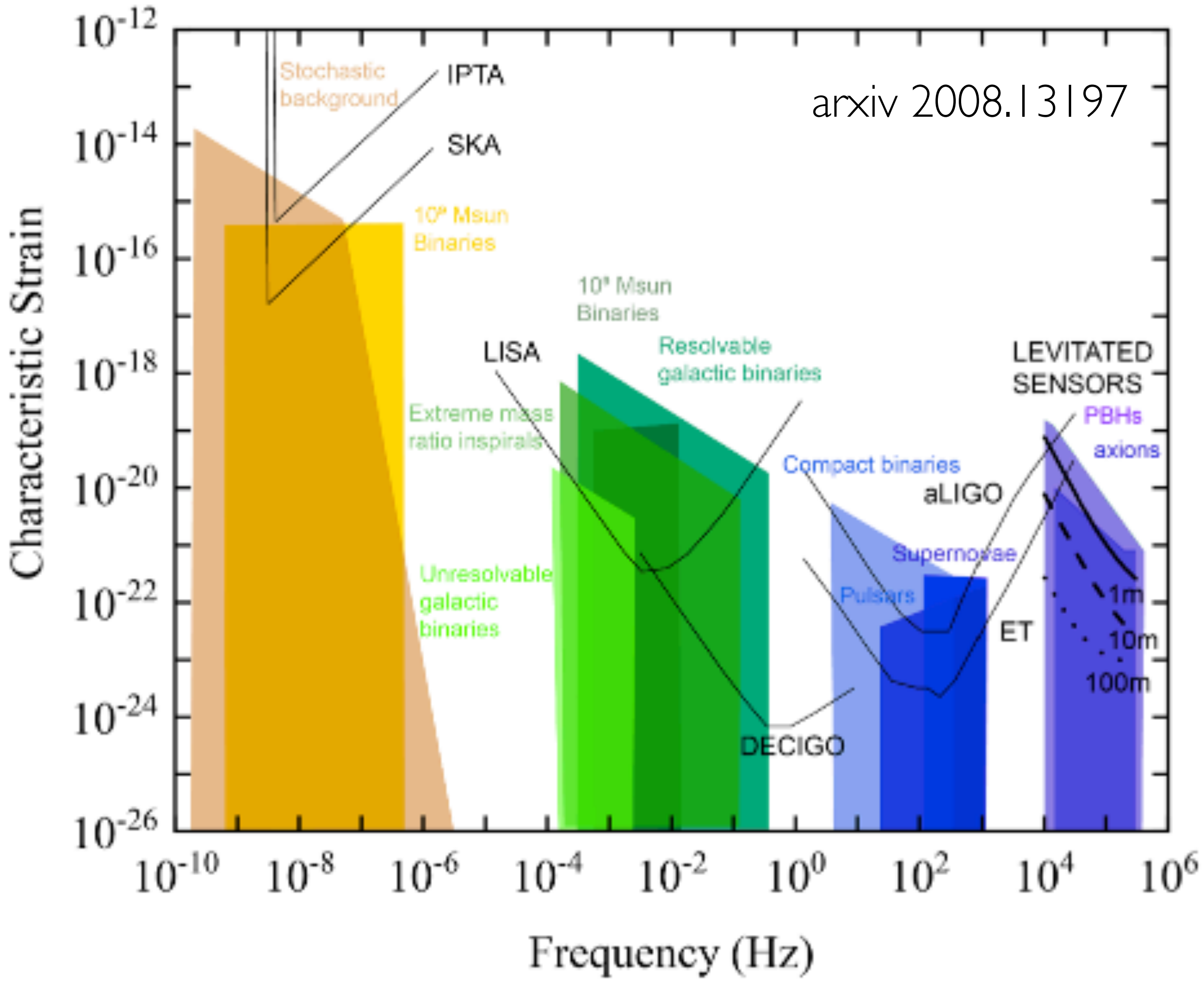
Numerical GR simulation by Will East (dark photon)

- **Weak, long signals** last for ~ thousand- billion years, visible from our galaxy
  - Event rates up to thousands
  - Search strategy similar to continuous wave searches for gravitational waves from rotating asymmetric pulsars



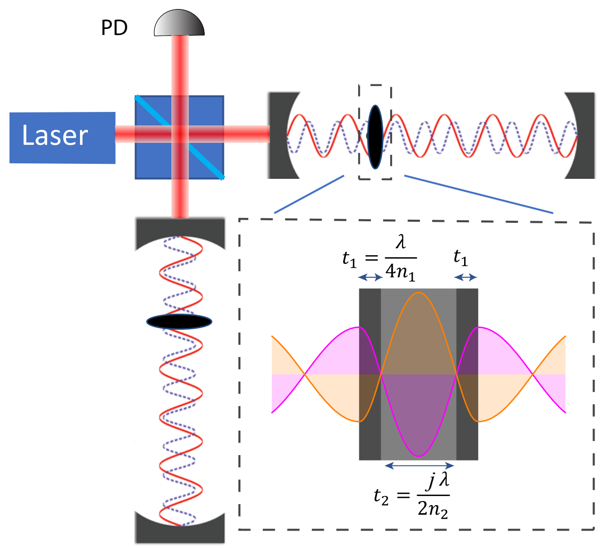
Gravitational Wave Searches

- Future searches across frequencies: continued development of precision techniques

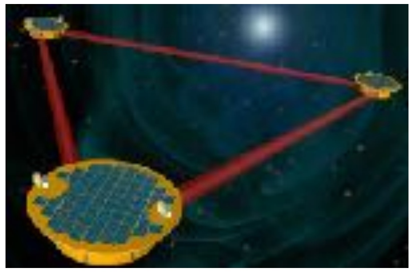


arxiv 2008.13197

N. Aggarwal et al 2010.13157



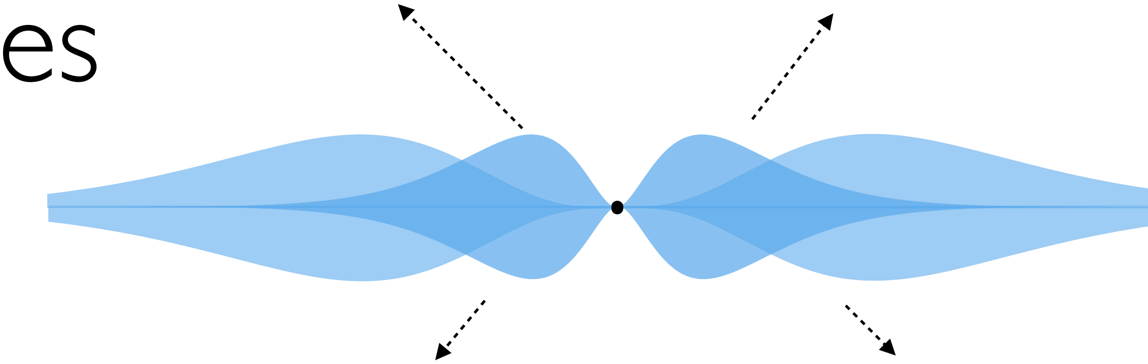
Precision force measurements with levitated sensors

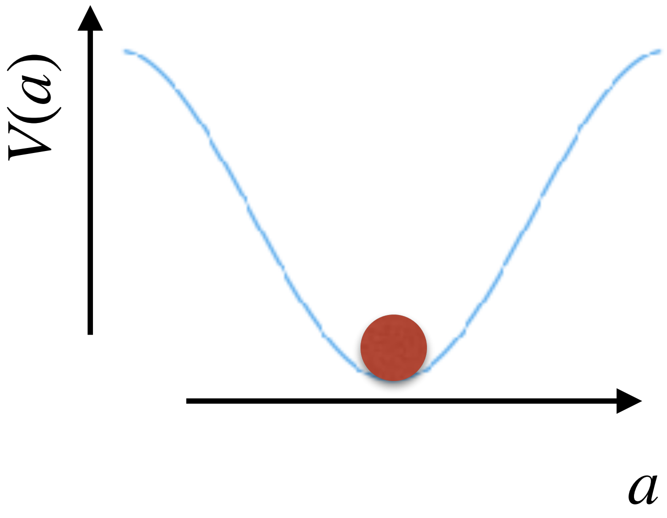


Space-based missions

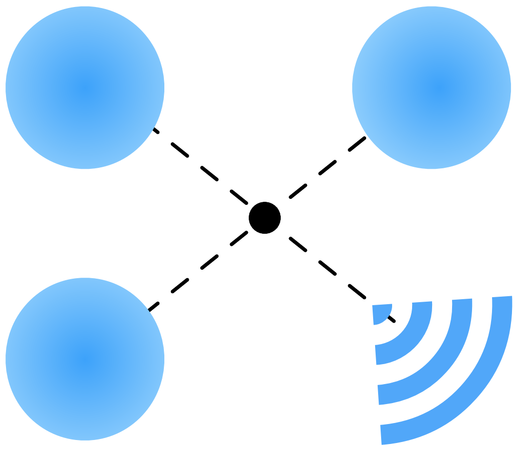
Atom interferometry

Axion Waves



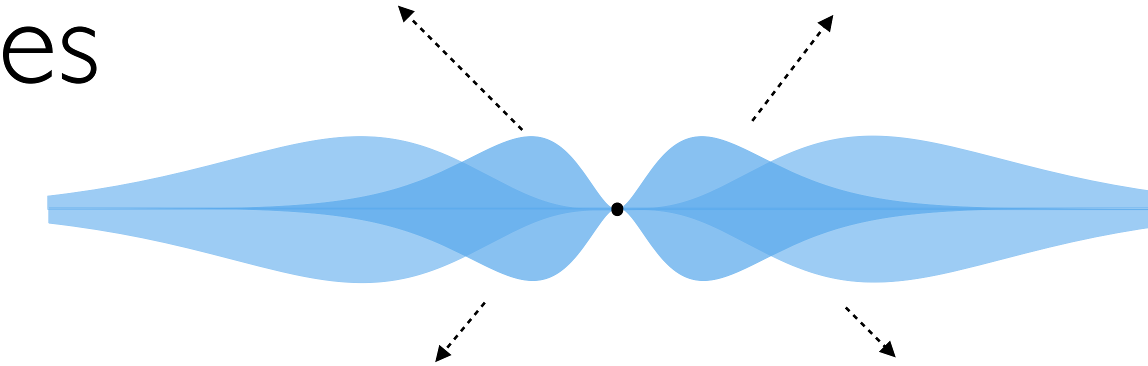


- Axion potential introduces self-interactions as well as a mass
- Self-interactions can source non-relativistic axion waves and lead to new dynamics

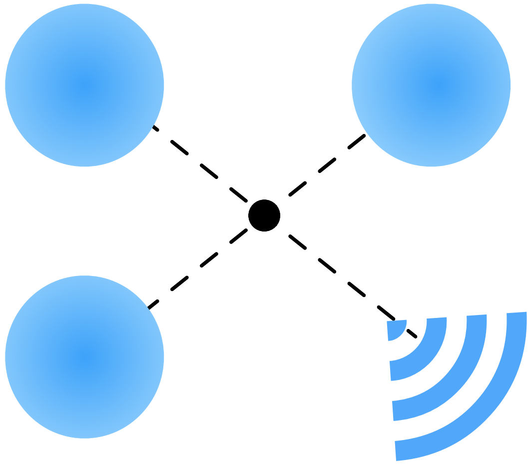


MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*

Axion Waves



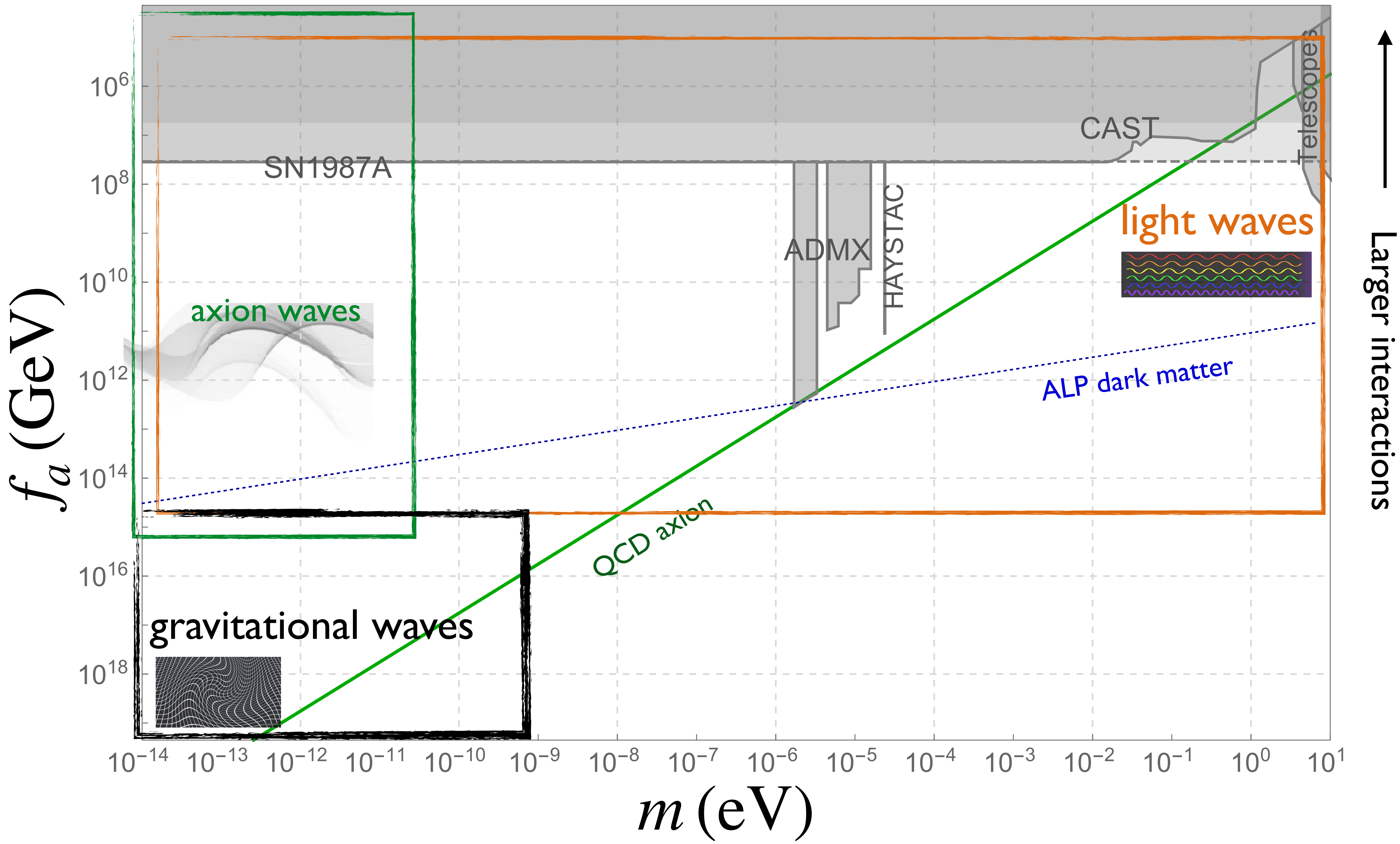
In the presence of self-interactions, black hole energy is constantly converted to axion waves

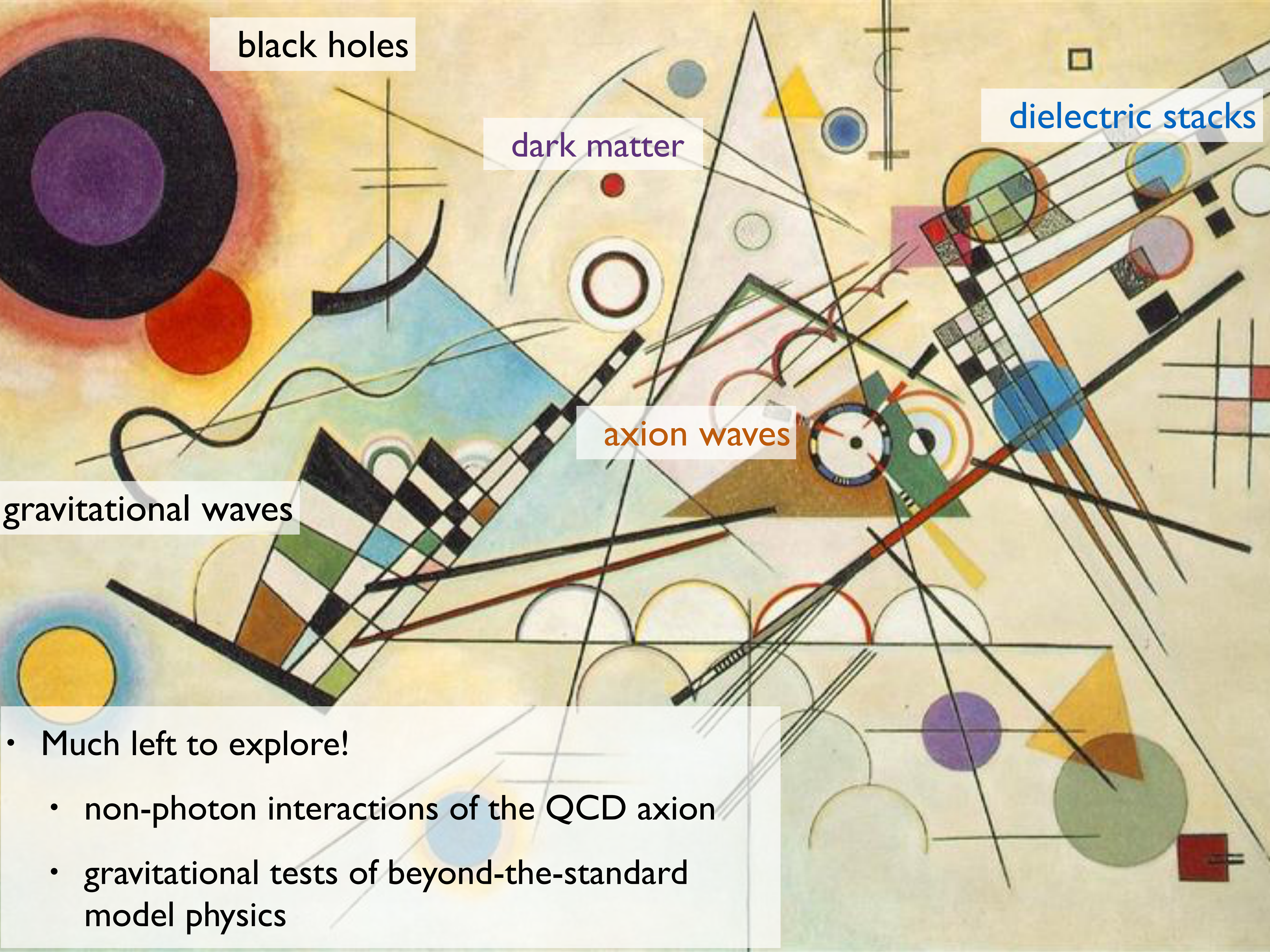


- Signal strength ***constant in time***
- Axion waves observable in dark matter spin precession experiments (e.g. CASPER)
- Requires different data analysis strategies (*c.f.* LIGO continuous waves search)

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

Searches with black holes and gravitational waves





black holes

dark matter

dielectric stacks

axion waves

gravitational waves

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