Axions: from angles to particles

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Oxford Morning of Theoretical Physics

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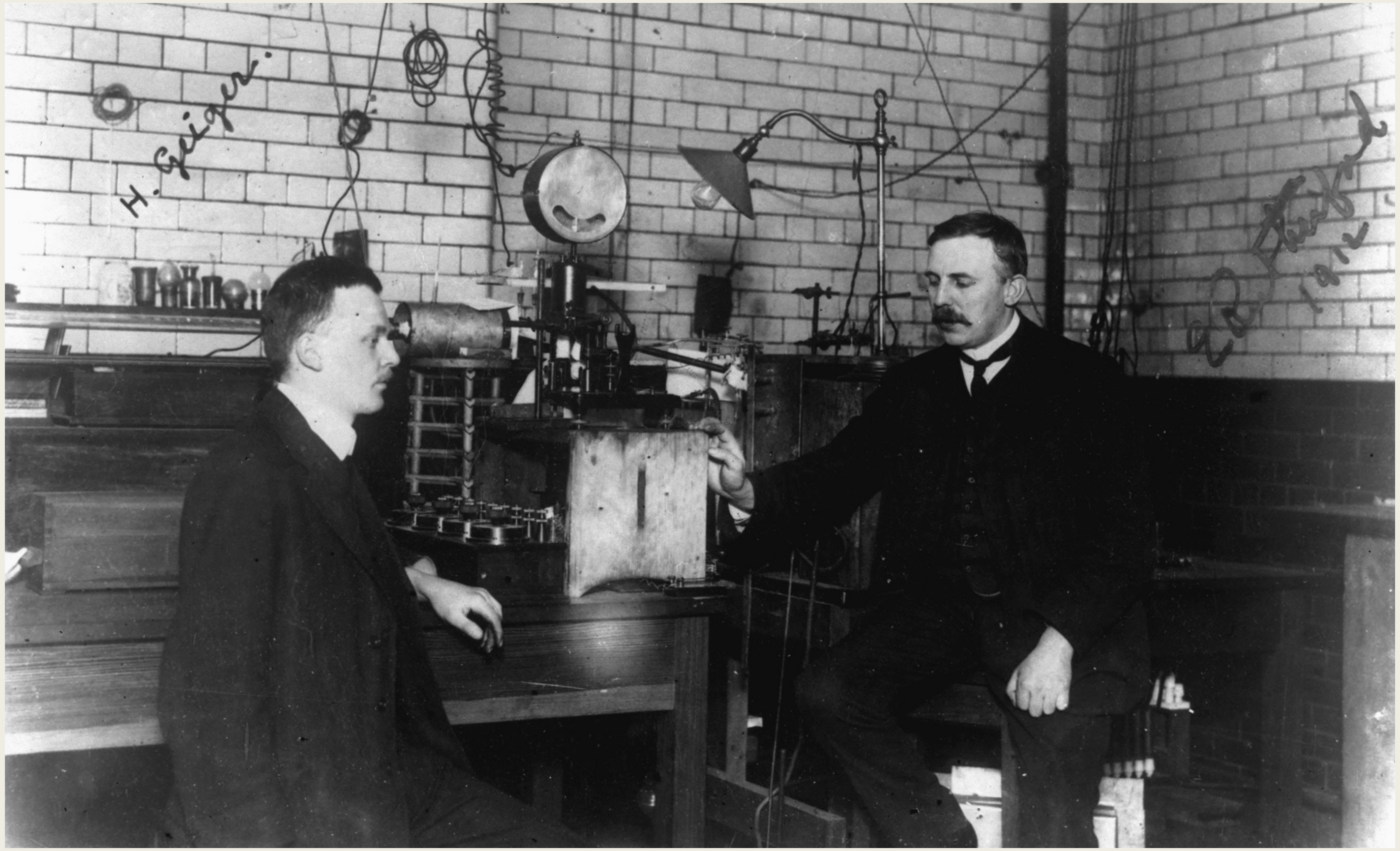
I. Prelude:Frontiers of New Physics



One of the fundamental questions of particle physics:

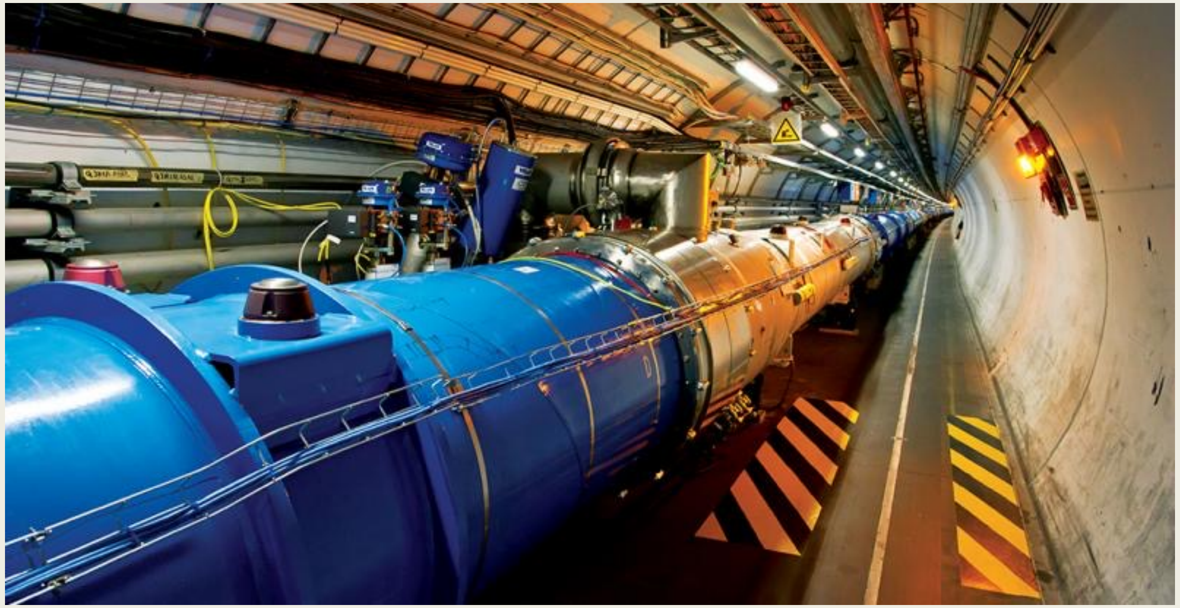
$$\mathcal{L}_{world} = \mathcal{L}_{Standard\ Model} + \mathcal{L}_{General\ Relativity} + \mathcal{L}_{????}$$

What is $\mathcal{L}_{????}$?

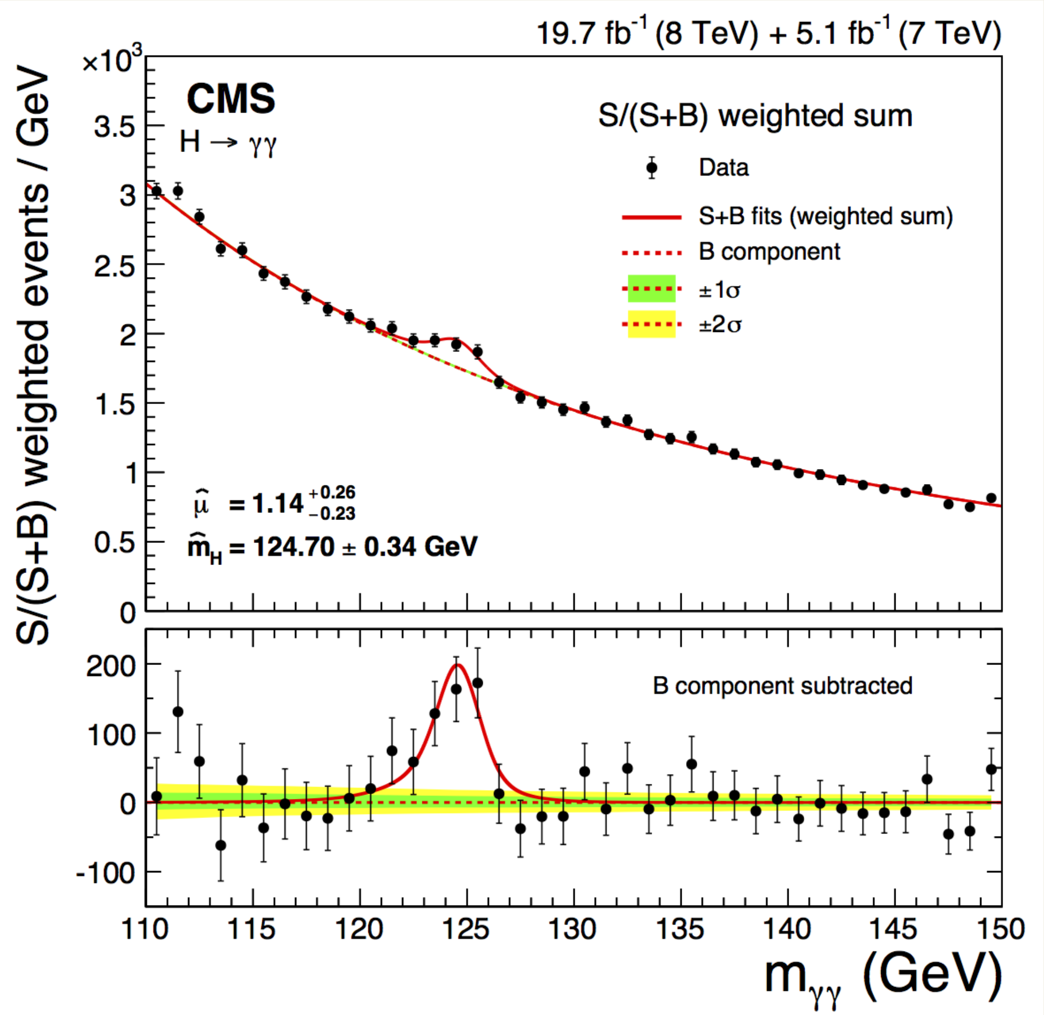
What new particles, interactions or forces lie beyond our current knowledge?

The Discovery of New Particles?

- Search for *heavy,* relatively *strongly interacting* particles, where *the barrier to discovery is insufficiently energetic phenomena.*

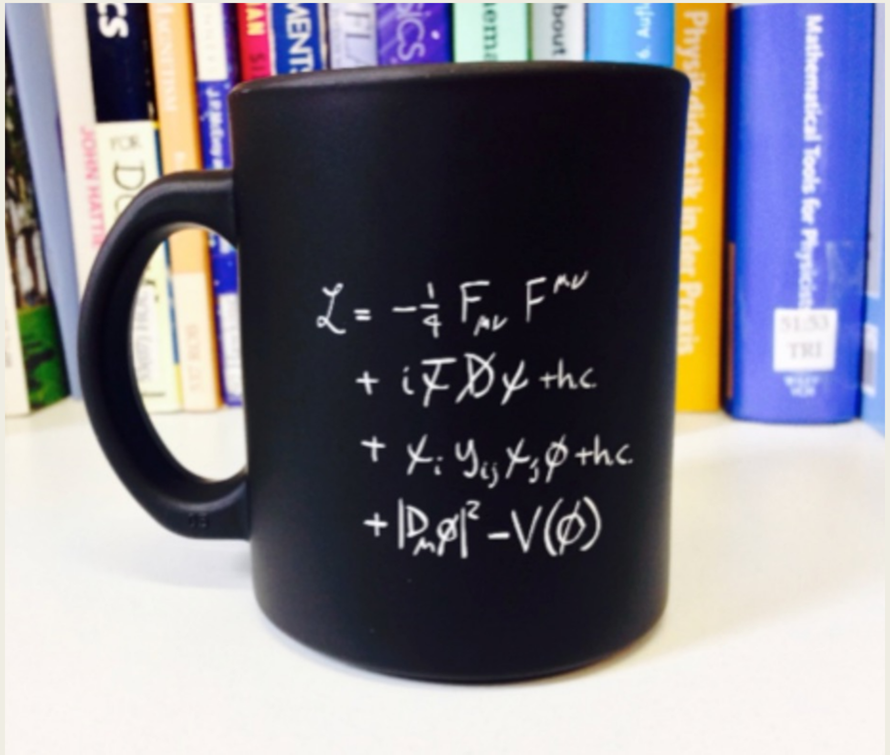


(CERN)



- LHC and Higgs discovery prime example of this

The Standard Model Of Particle Physics



What CERN sell you!

$$\frac{\theta}{8\,\pi^2}\ \epsilon^{\alpha\beta\mu\nu} F_{\mu\nu} F_{\alpha\beta}$$

What CERN don’t tell you!

Search Strategy II

- For *light, extremely weakly interacting* particles, LHC-style searches are not useful.

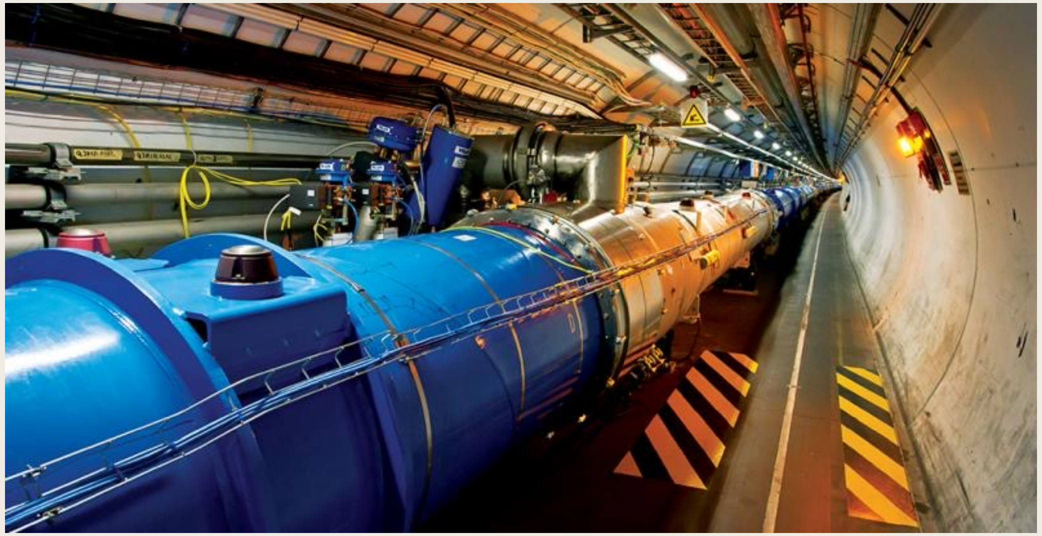
  (collisions at the LHC do not probe the gravitational force)

- For new physics with no energetic costs to production, but that is just very weakly coupled to the Standard Model, new strategies are needed.

- The *weak coupling* frontier of particle physics is almost orthogonal to the direction represented by the Large Hadron Collider.

Same Equations : Similar Physics

- Anderson-Higgs mechanism first described in condensed matter physics: symmetry breaking -> massive photon -> superconductivity



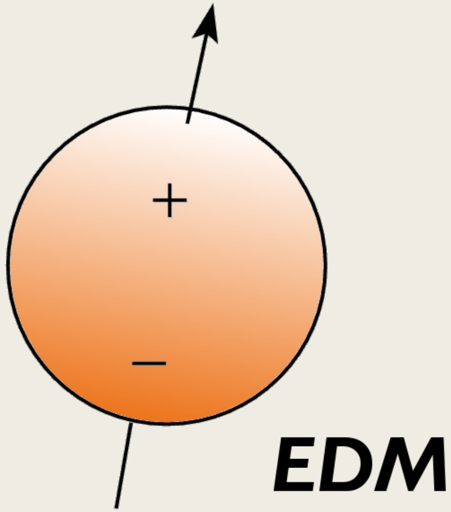
- Angle-valued fields (*axions)* also appear in condensed matter physics (Sid's talk)

II. Axions and Axion-Like Particles (ALPs)

The original QCD axion

- $\mathcal{L}_{QCD} = \frac{1}{4g^2} F^{a,\mu\nu} F^{a}_{\mu\nu} + \frac{\theta}{8\pi^2} \epsilon_{\alpha\beta\gamma\delta} F^{a,\mu\nu} F_{a}^{\mu\nu} + \Sigma_i m_i \bar{q}_i q_i$

- The θ term in the strong force (QCD) Lagrangian violates charge-parity. Its experimental consequence is an electric dipole moment for the neutron.
- A neutron is *udd* with a radius around 10^{-15} metres



- For typical values of θ (between 0 and 2π) this generates a neutron electric dipole moment of $\sim 10^{-17} e$ cm
- Current bound on neutron dipole moment is $< 3\times10^{-26} e$ cm - θ is very close to zero.

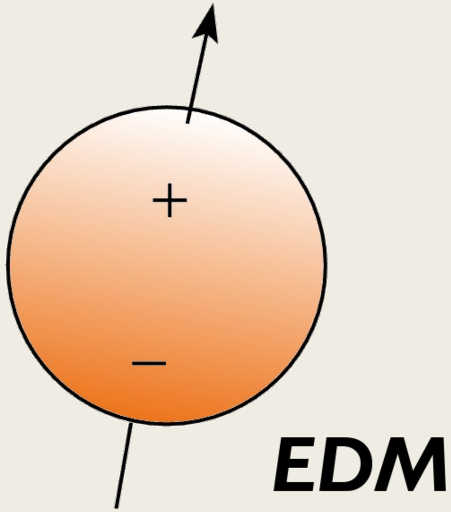
Axions and angles

- $\mathcal{L}_{QCD} = \frac{1}{4g^2} F^{a,\mu\nu} F^a_{\mu\nu} + \frac{\theta}{8\pi^2} \epsilon_{\alpha\beta\gamma\delta} F^{a,\mu\nu} F_a^{\mu\nu} + \Sigma_i m_i \bar{q}_i q_i$

- The θ term is an angle.

- The physics is invariant under a 2π shift in the value of θ

- In the pure Standard Model, this angle is non-dynamical



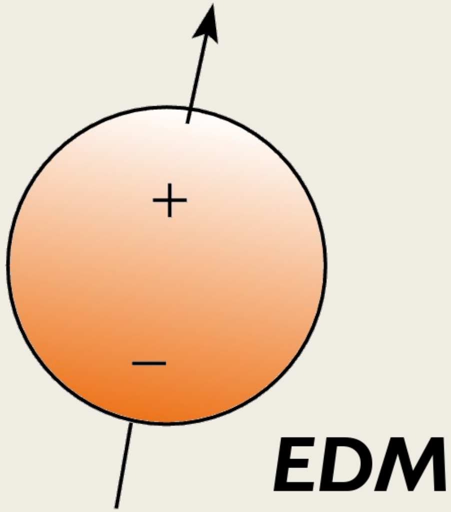
Axions and angles

- $\mathcal{L}_{QCD} = \frac{1}{4g^2} F^{a,\mu\nu} F^{a}_{\mu\nu} + \frac{\theta}{8\pi^2} \epsilon_{\alpha\beta\gamma\delta} F^{a,\mu\nu} F^{\mu\nu}_{a} + \Sigma_i m_i \bar{q}_i q_i$

- The axion arises from promoting this angle to a dynamical field

$$\theta \rightarrow \mathcal{L} = -\frac{1}{2} \partial_\mu a \partial^\mu a$$

$$\frac{\theta}{8\pi^2} \epsilon_{\alpha\beta\gamma\delta} F^{a,\mu\nu} F^{\mu\nu}_{a} \rightarrow \frac{a}{f_a} \epsilon_{\alpha\beta\gamma\delta} F^{a,\mu\nu} F^{\mu\nu}_{a}$$



- The physics is invariant under a 2π shift in the value of θ, equivalently $a \rightarrow a + 2\pi f_a$

- Quantum excitations of the field correspond to axion particles

Axions

- The axion is a field valued on a circle and so has an angular periodicity

- The basic axion Lagrangian is

$$\mathcal{L}_{ALP} = -\frac{1}{2}\partial_\mu a \partial^\mu a + V(a)$$

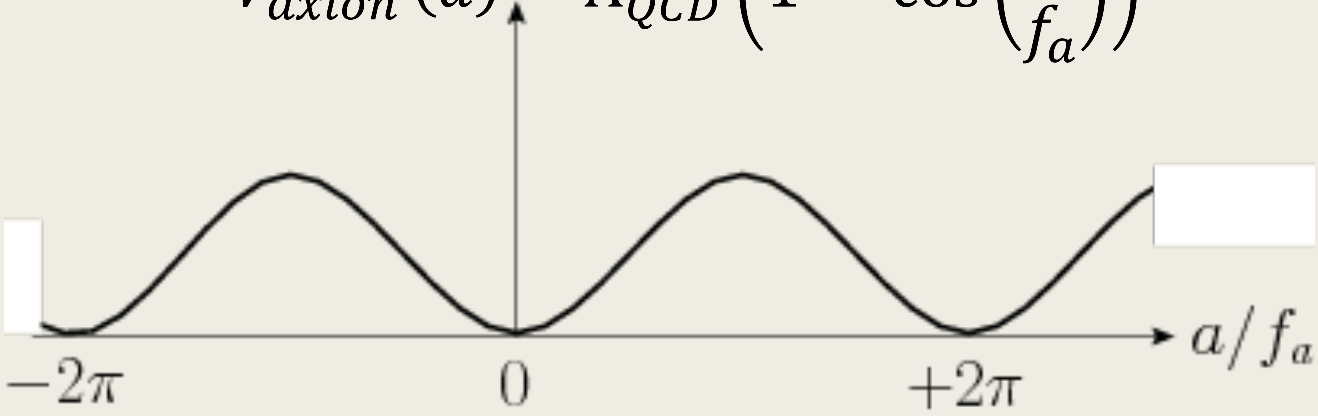
  subject to $V(a) \equiv V(a + 2\pi f_a)$

- The angular periodicity implies that direct 'perturbative' contributions to the potential such as $m_a a^2$or λa^4 are forbidden by the periodicity

- This has the key consequence that axion particles are naturally very light (or massless).

Non-perturbative QCD effects lead to a potential that depend on the θ angle and solves the strong CP problem -> no electron dipole moment for the neutron

$$V_{axion}(a) = \Lambda_{QCD}^4 \left(1 - \cos\left(\frac{a}{f_a}\right)\right)$$



$$m_a^2 = V''(a) = \frac{\Lambda_{QCD}^4}{f_a^2}, \qquad m_a \sim \left(\frac{10^{11}\text{GeV}}{f_a}\right) 10^{-3}\text{eV}$$

The QCD Axion (if it exists) is very light and has very weak interactions with the Standard Model

Axions in String Theory

- 30-year old result:

  String compactifications lead to a plenitude of axions in the low-energy theory

- ’Model-dependent‘ axions number O(100) for typical compactifications

- Axions are one of the most motivated targets in looking for signatures of string compactifications

Axion-Like Particles (ALPs)

- The original, QCD axion is defined by the additional coupling to the strong force

$$\frac{a}{f_a}\epsilon_{\alpha\beta\gamma\delta}F^{a,\mu\nu}F_a^{\mu\nu}$$

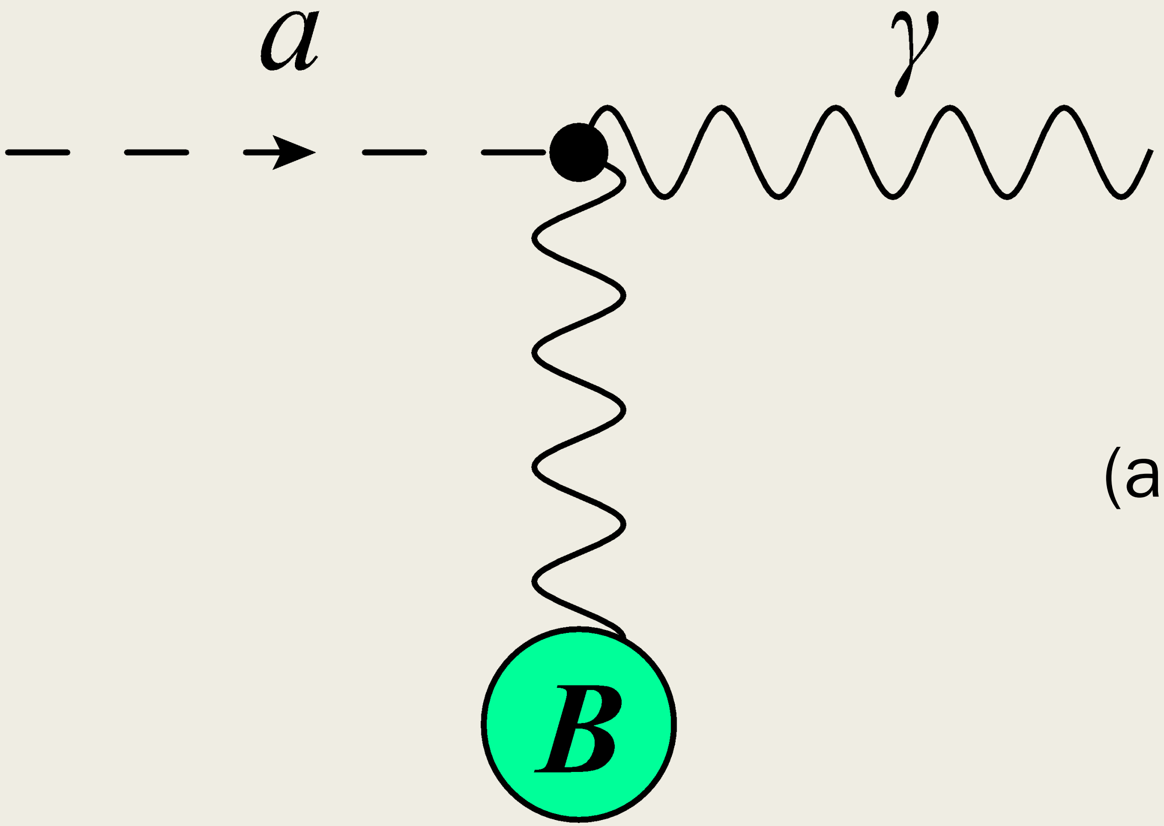
when the θ angle is promoted to be a dynamical variable.

- *Axion-like particles (ALPs)* have no coupling to the strong force and couple only to electromagnetism

$$\frac{a}{8\pi^2 f_a}\epsilon_{\alpha\beta\gamma\delta}F_{\mu\nu}F^{\mu\nu} \equiv a\, g_{a\gamma\gamma}\mathbf{E.B}$$

- This coupling sets the interaction between the ALP a and the Standard Model fields.

III. Axion Phenomenology



(also see JMR talk)

Axion Phenomenology

- The coupling

$$a\ g_{a\gamma\gamma}\mathbf{E.B}$$

is key to searches for both axions and ALPs

- In a fixed background magnetic field, this mixes the ALP a and the photon γ mass eigenstates.

$$\begin{array}{lcr} |\gamma_1> & & |\gamma_1> \\ |\gamma_2> & \rightarrow & \cos\phi|\gamma_2> + \sin\phi\ |a> \\ |a> & & \cos\phi\,|a> - \sin\phi\,|\gamma_2> \end{array}$$

- Analogous to neutrino oscillations, there are oscillations between the ‘flavour’ eigenstates a and γ, while the ’mass’ eigenstates are linear combinations of a and γ

$$P(a \to \gamma) = P(\gamma \to a) = \frac{{g_{a\gamma\gamma}}^2 B^2 L^2}{4}$$ QM!

Sikivie
Raffelt + Stodolsky

Here B is transverse magnetic field

L is magnetic field coherence length

$g_{a\gamma\gamma}$ is (dimensional) ALP-photon coupling

$$P(\gamma \to a) \sim 10^{-8} \left(\frac{g_{a\gamma\gamma}}{10^{-12}\mathrm{GeV}^{-1}}\right)^2 \left(\frac{B}{1\ \mu G}\right)^2 \left(\frac{L}{1\ \mathrm{kpc}}\right)^2$$

Astrophysical environments (B = $10^{-10} T$ L = 1 kpc) are overwhelmingly better than terrestrial environments (B = 10T, L = 10m)

AGN

Milli- parsec

Hundred kilo-parsecs

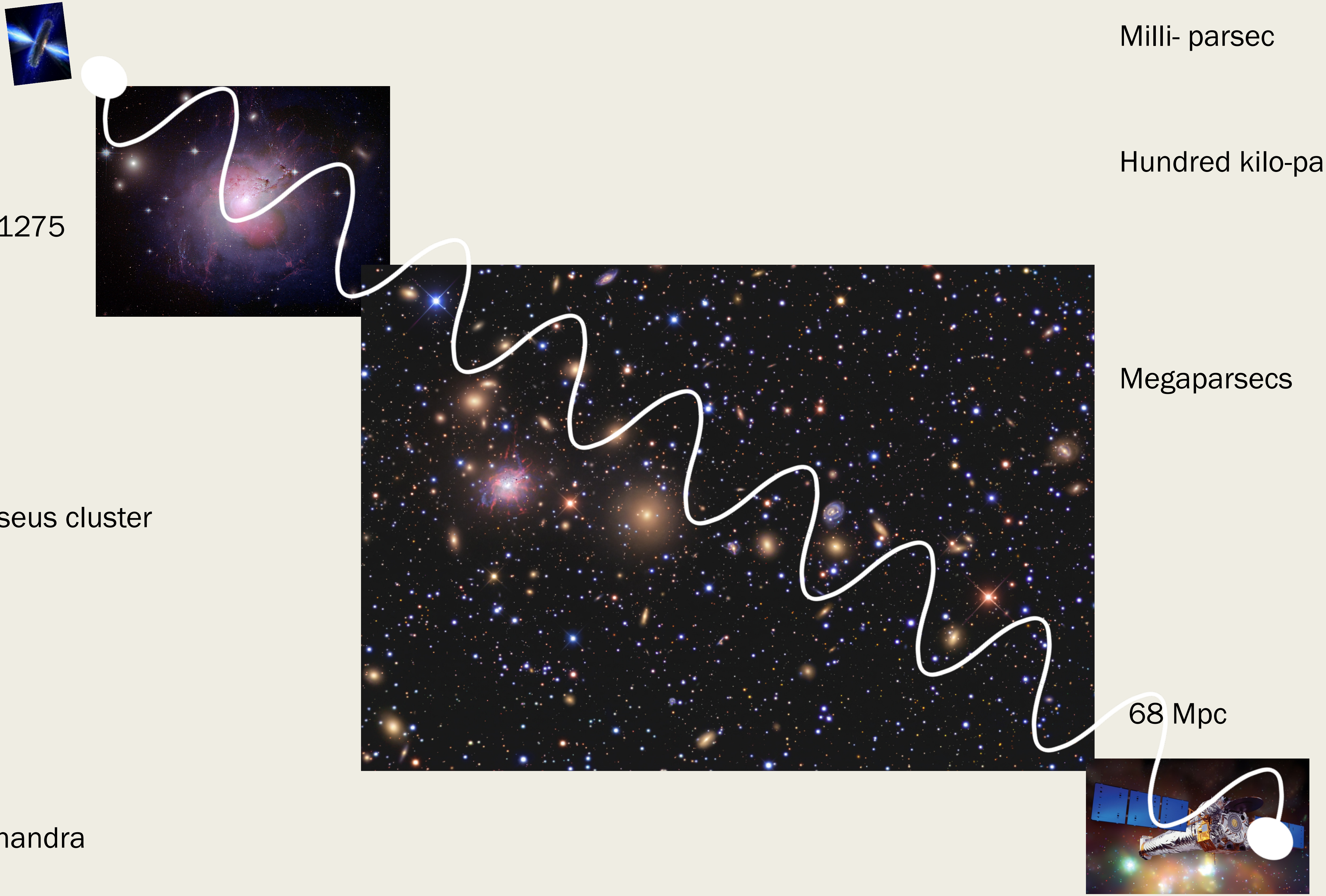
NGC1275

Megaparsecs

Perseus cluster

68 Mpc

Chandra



How to search for ALPs?

- The basic physics used here to look for ALPs is very simple.

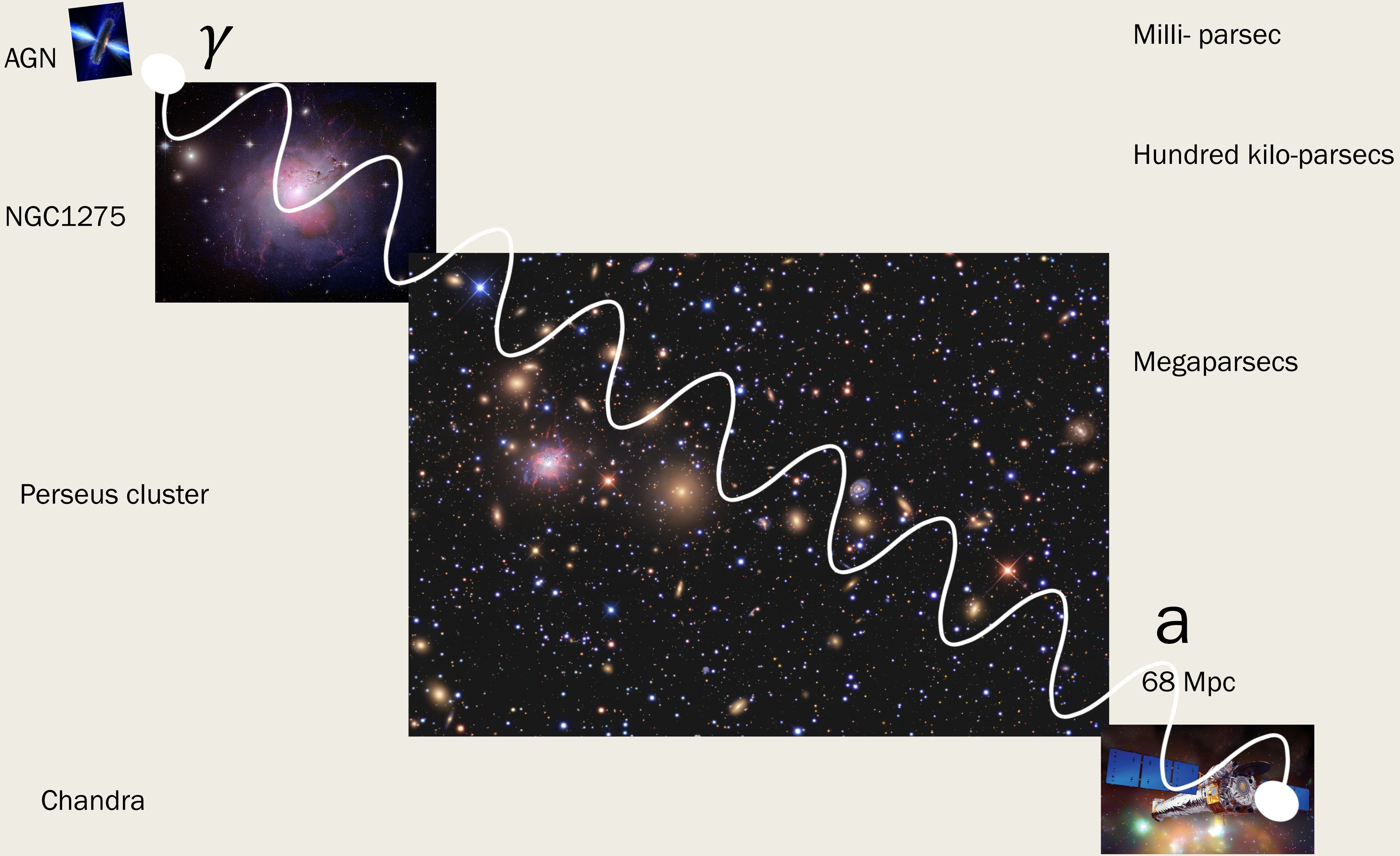
  1. Send photons from A to B

  2. Have a magnetic field inbetween A and B

  3. Photon-ALP interconversion causes some of these photons to oscillate into ALPs

  4. The photon spectrum on arrival at B will show modulations compared to the source photon spectrum at A.

- In our case, the source A will be the central AGN (Active Galactic Nucleus) of the Perseus galaxy cluster and B is the *Chandra* X-ray telescope



AGN
γ
Milli- parsec
NGC1275
Hundred kilo-parsecs
Megaparsecs
Perseus cluster
a
68 Mpc
Chandra

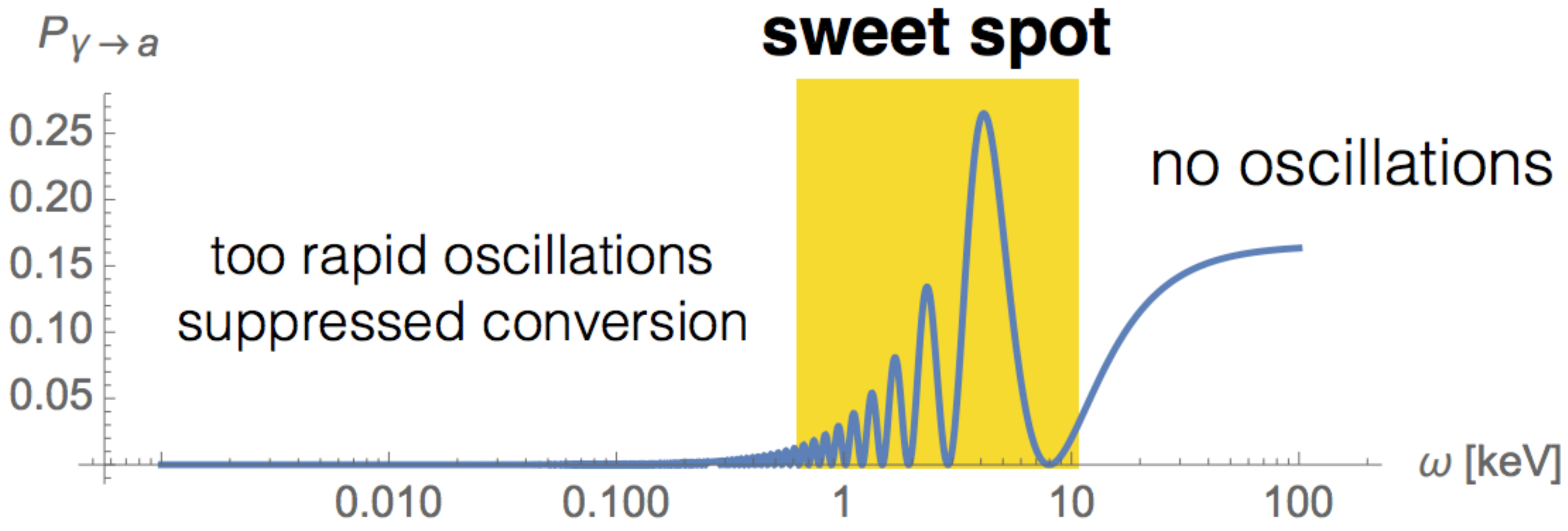
Photon-ALP Conversion – why X-rays?

- Axion-photon interconversion (for $m_a < 10^{-12}$eV, effectively massless) in galaxy clusters:

$$P_{\gamma\to a} = \frac{1}{2}\frac{\Theta^2}{1+\Theta^2}\sin^2\left(\Delta\sqrt{1+\Theta^2}\right)$$

$$\Theta = 0.28\left(\frac{B_\perp}{1\ \mu\mathrm{G}}\right)\left(\frac{\omega}{1\ \mathrm{keV}}\right)\left(\frac{10^{-3}\mathrm{cm}^{-3}}{n_e}\right)\left(\frac{10^{11}\mathrm{GeV}}{M}\right) \qquad \Delta = 0.54\left(\frac{n_e}{10^{-3}\mathrm{cm}^{-3}}\right)\left(\frac{L}{10\mathrm{kpc}}\right)\left(\frac{1\mathrm{keV}}{\omega}\right)$$

- Sweet spot at X-ray energies:



Optical image of Perseus, credit *R. Jay GaBany,* Cosmotography.com

Perseus in X-rays (NASA, Chandra)

X-ray image of the Perseus cluster: NGC1275 AGN is the central white dot

The AGN jets blow bubbles into the surrounding intra-cluster medium

Perseus Magnetic Field

Exact Perseus magnetic field along line of sight is unknown. We consider three magnetic field cases:

1. B_central = 25 μG, 100 domains between 3.5 and 10kpc (reasonable)
2. B_central = 15 μG, 100 domains between 0.7 and 10kpc (conservative)
3. B_central = 10 μG , 100 domains between 0.7 and 10kpc (ultra-conservative)

We generate simulated magnetic fields, compute the photon-ALP conversion probability and generate spectra corresponding to them.

We say $g_{a\gamma\gamma}$ is ruled out at 95% confidence if 95% of simulated spectra have worse chi-squared fits to an absorbed power-law than the actual data does.

Chandra X-ray telescope

~1.5 billion USD

15 years operation

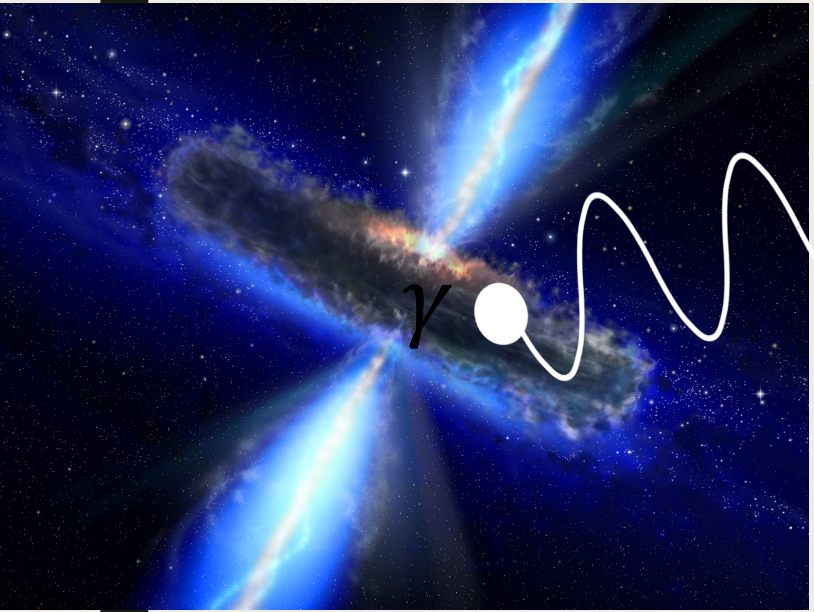
Mature, well understood instrument

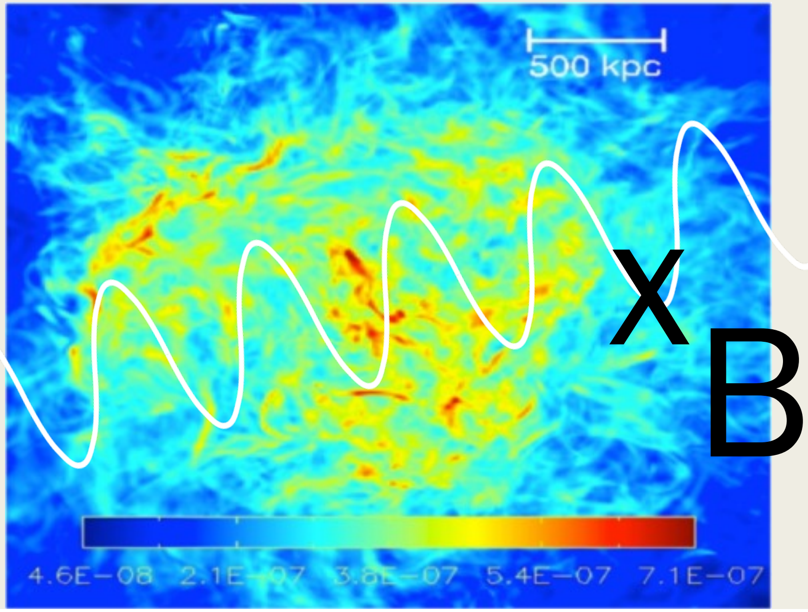
Large public observational data archive

ALPS

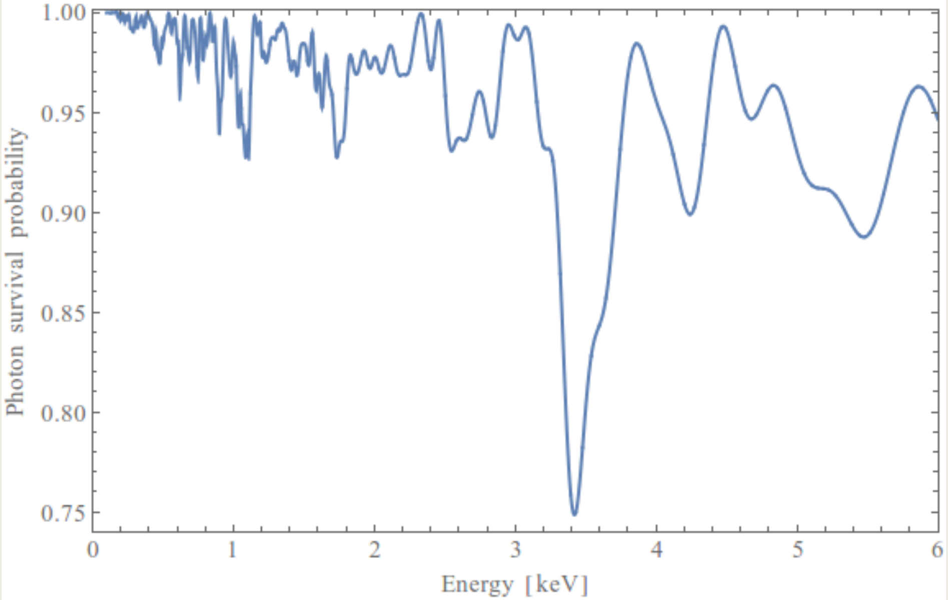
Photons pass through galaxy cluster magnetic field

AGNs are bright point sources of photons



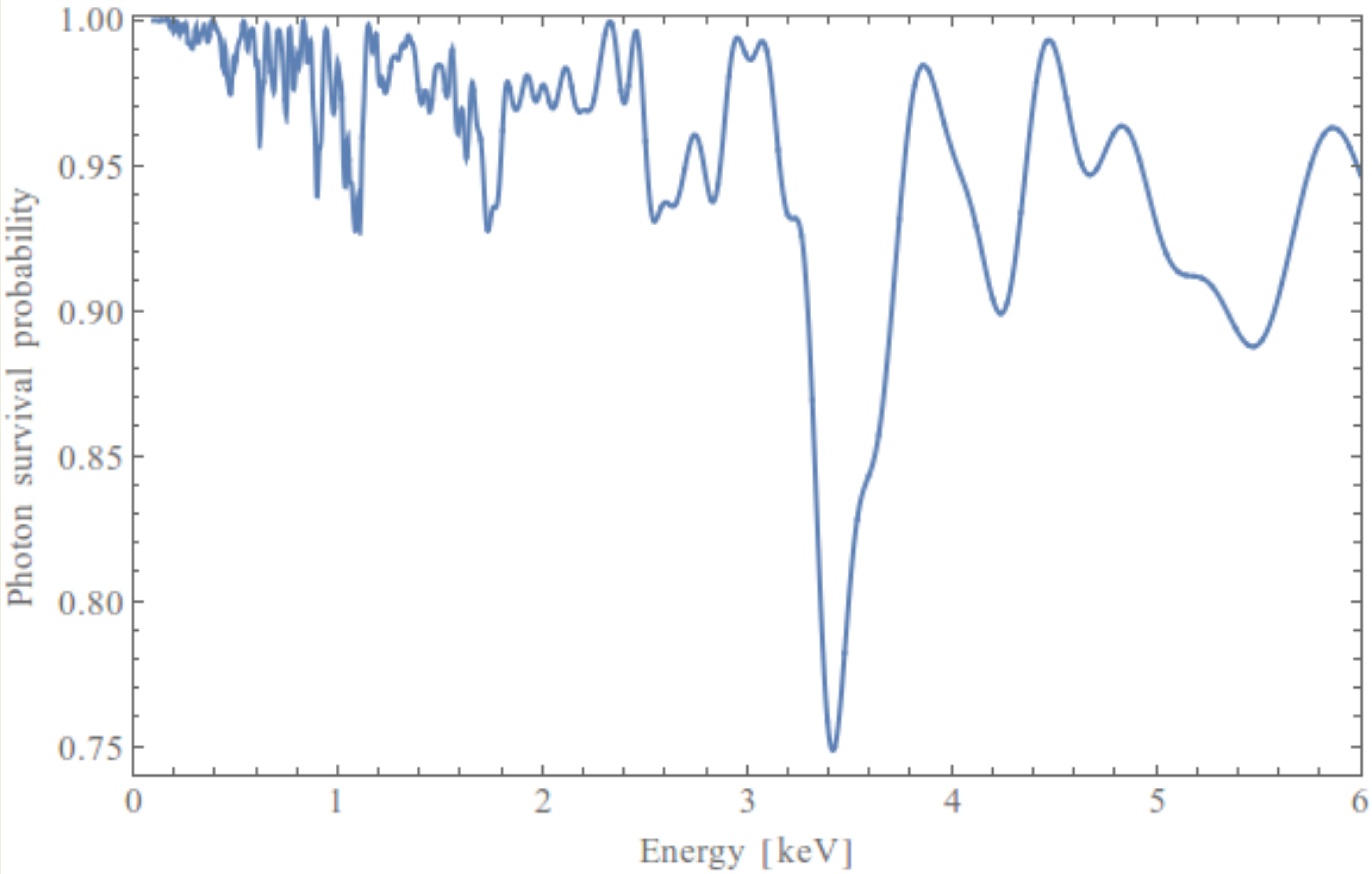


ALP-Photon conversion induces irregularities in observed X-ray spectrum



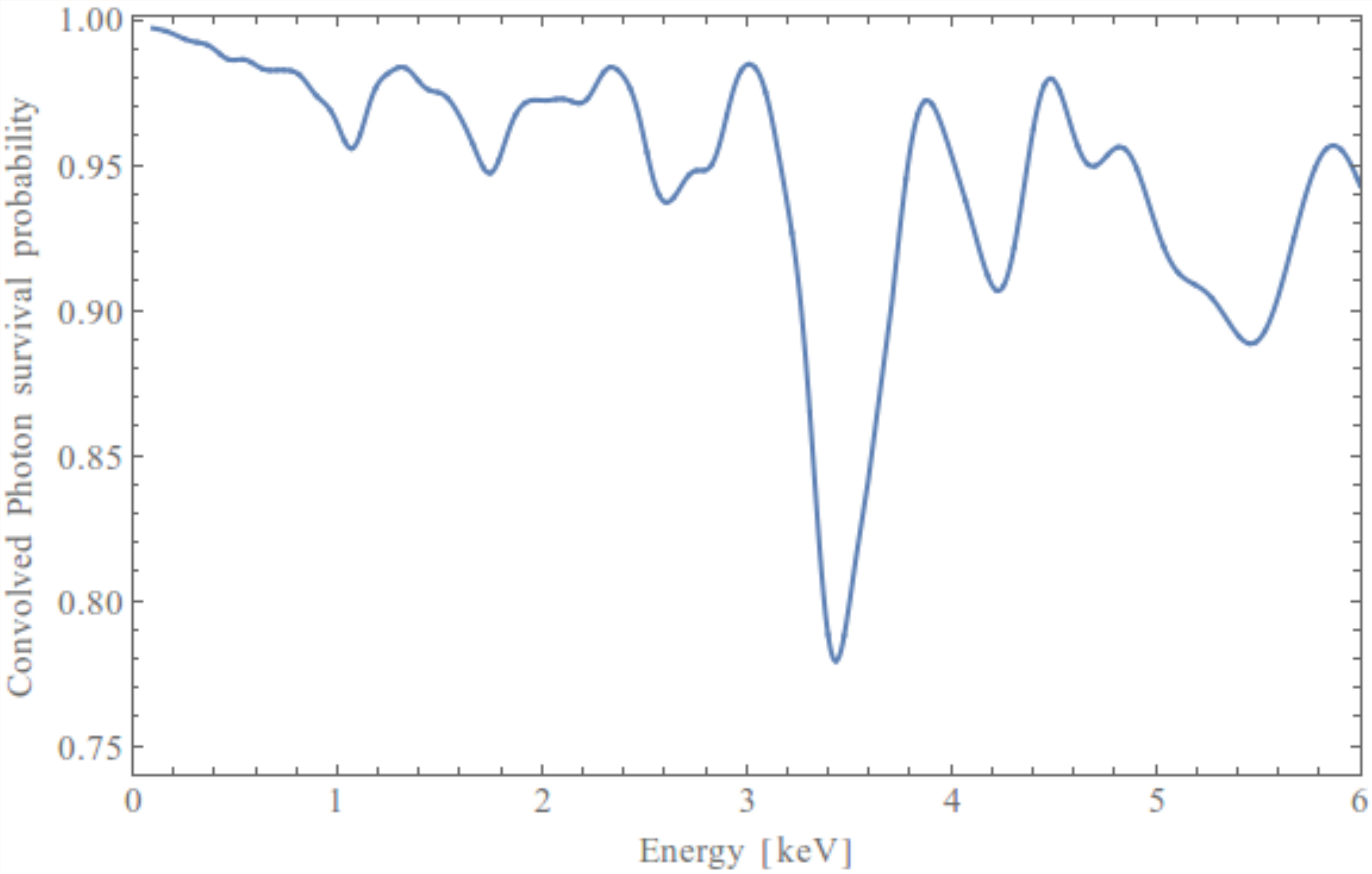
Precise form of modulations depends on cluster magnetic field

Simulated photon survival probability…



This would modulate the true spectrum

…now convolved with detector resolution



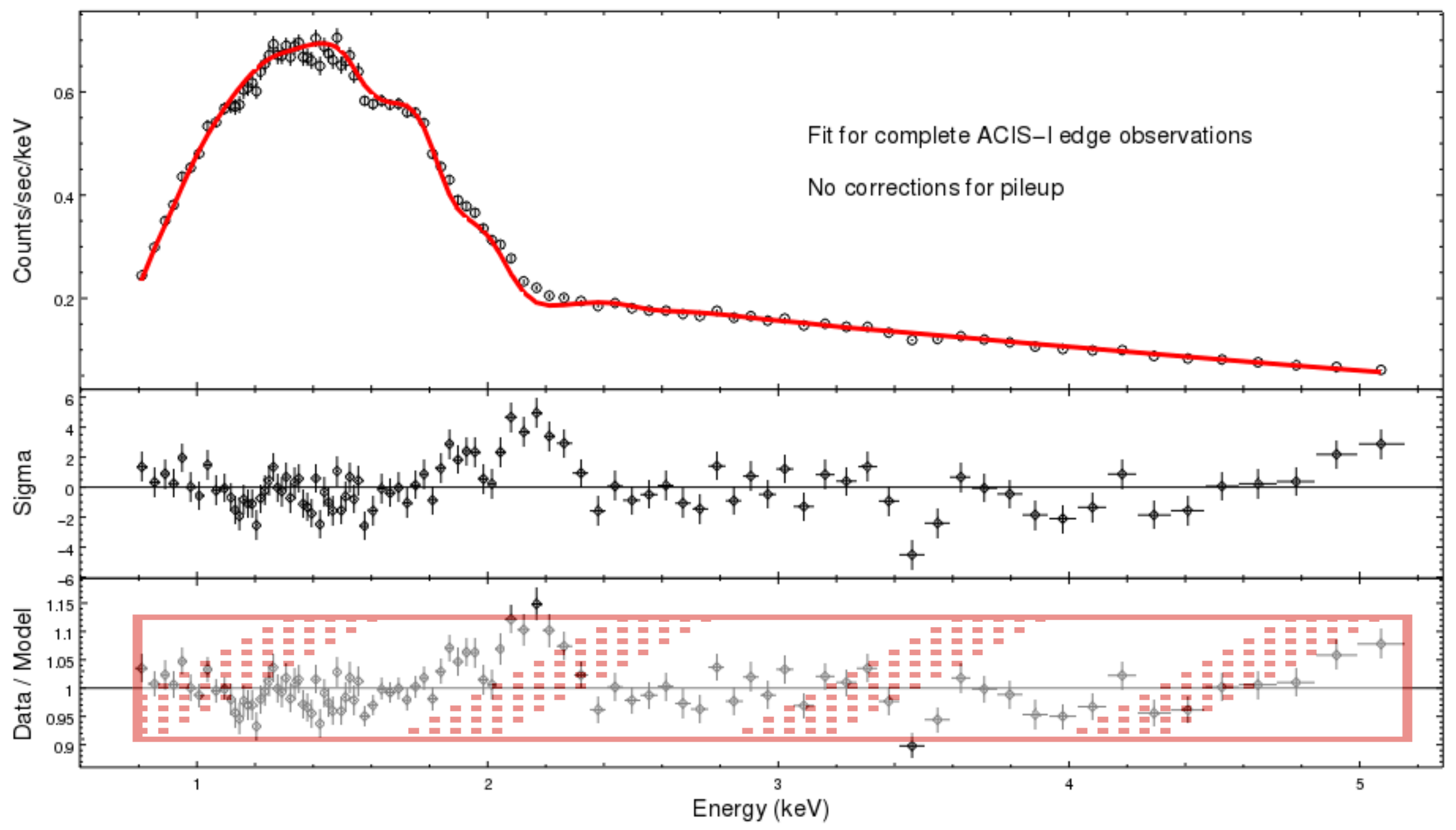
This would modulate the true spectrum

V. Data

ALP Constraints

Unambiguous statement – there are no spectral irregularities greater than 10%

ALP couplings leading to 20-30% irregularities are excluded



ALP Constraints

1. Reasonable case (B_central = 25 μG, 100 domains between 3.5 and 10kpc)

   $g_{a\gamma\gamma}$ < 1.5 x 10^{-12} GeV^{-1}

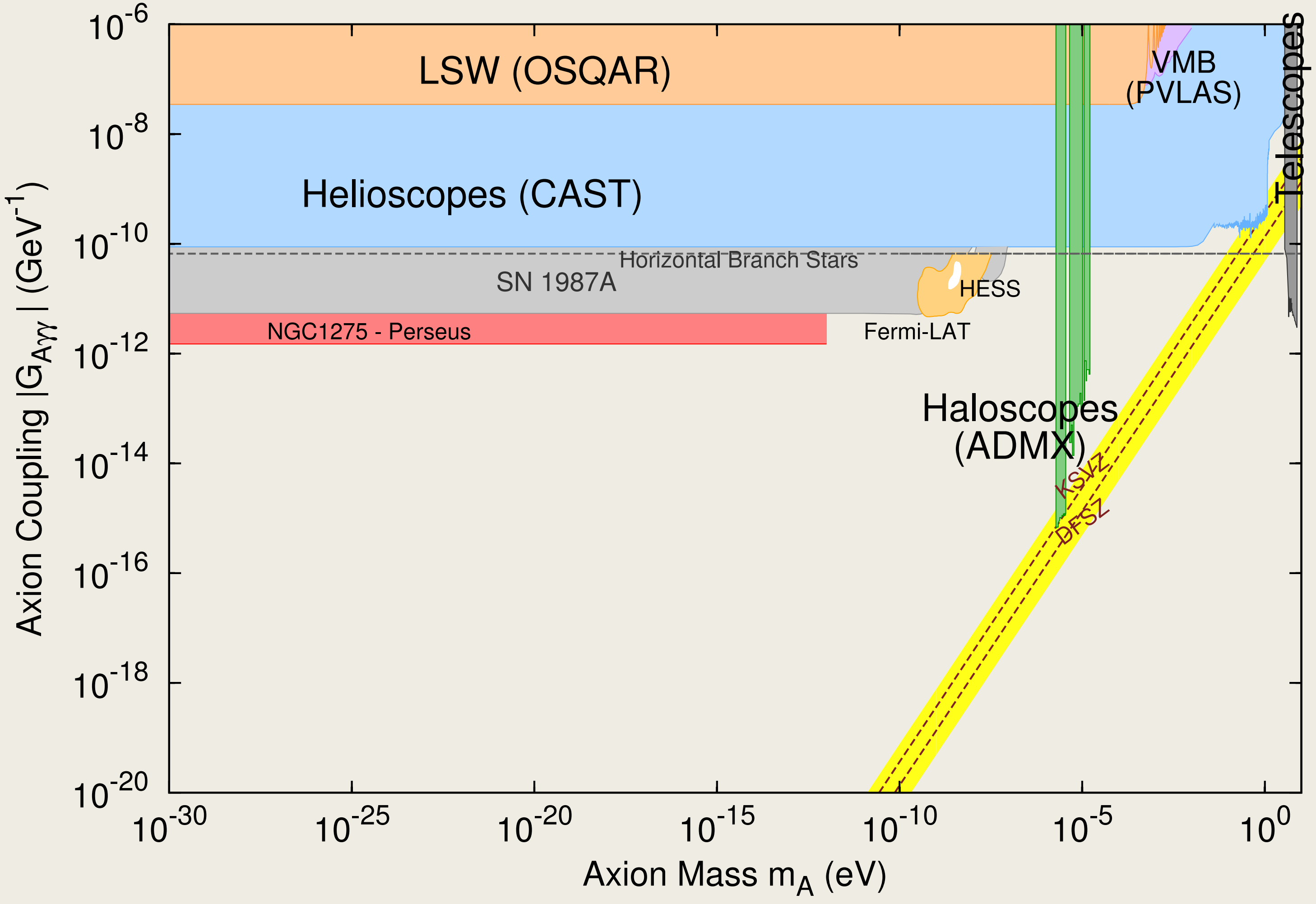
2. Conservative case: (B_central = 15 μG, 100 domains between 0.7 and 10kpc)

   $g_{a\gamma\gamma}$ < 3.8 x 10^{-12} GeV^{-1}

3. Ultra-conservative: (B_central = 10 μG , 100 domains between 0.7 and 10kpc)

   $g_{a\gamma\gamma}$ < 5.6 x 10^{-12} GeV^{-1}

Absence of any spectral modulations at 20-30% level extends bounds on ALP-photon coupling at small mass



(bounds since extended further with better data)

In 2028 ESA will launch the L-class mission ATHENA as the next generation X-ray satellite

We estimate this will deliver a further factor of ten improvement in sensitivity to $g_{a\gamma\gamma}$

VI. Conclusions

(credit: the Simpsons)

Conclusions

- Axions (and more generally ALPs) are well-motivated extensions of the Standard Model that require search strategies orthogonal to those used at high-energy colliders

- ALPs interconvert with photons in magnetic fields

- This conversion is highly efficient at X-ray energies and passing through galaxy cluster environments

- Existing and future X-ray observations of Active Galactic Nuclei located in or behind galaxy clusters offer excellent sensitivity to the ALP-photon coupling $g_{a\gamma\gamma}$