String Theory and Cosmology: Ships That Pass In The Night?

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Talk Structure

1. String Theory and Cosmology
2. Dark radiation: reheating and modulus decays
3. (TransPlanckian Inflation and Tensor Modes)
4. Searches for Axion-Like Particles

De Vliegende Hollander

I

STRING THEORY AND COSMOLOGY

Precision Cosmology

This is the age of precision cosmology.

A six-parameter ΛCDM model provides a good fit to the large-scale properties of the universe.

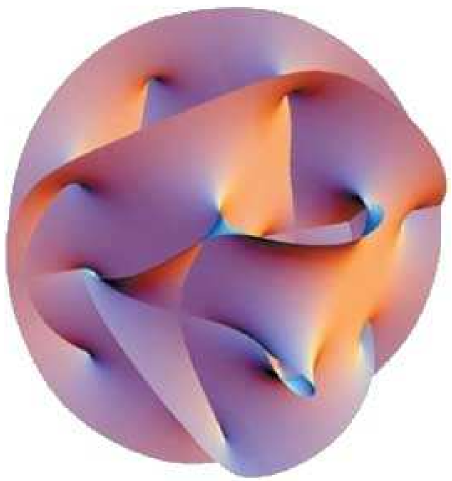
Baryon density	$\Omega_b h^2$	0.022
Dark matter density	$\Omega_c h^2$	0.119
Age of the universe	t_0	1.38×10^{10} years
Scalar spectral index	n_s	0.967
Density perturbations	Δ_R^2	2.44×10^{-9}
Optical depth to reionisation	τ	0.066

The String Landscape

String theory requires extra dimensions.

There are a very large number of compactification manifolds.

There is an even larger number of flux choices on these manifolds.



The String Landscape

These different choices give different low energy physics.

- Different gauge groups
- Different matter content
- Different symmetry breaking scales

With so many different choices, how is it possible to be predictive?

The String Landscape

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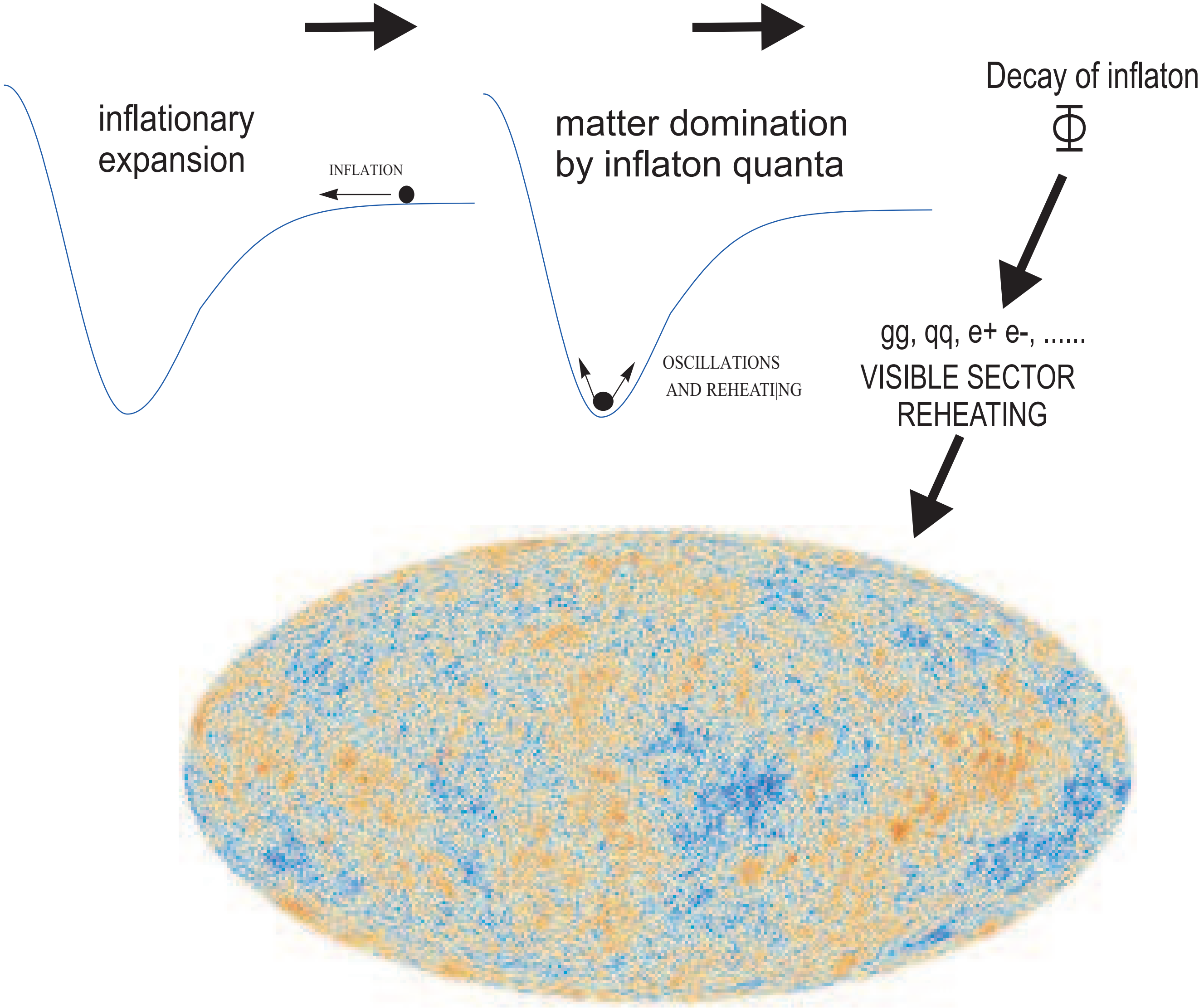
With so many different choices, how is it possible to be predictive?

With 10^{500} choices, how can one ever say something useful?

The Standard Cosmology



The Standard Cosmology

What have string theory and cosmology to do with each other?

Where is a fundamental theory of the Planck scale relevant to cosmology and astrophysics?

II
DARK RADIATION

Reheating

Central to inflationary cosmology is reheating: the transfer of energy from the inflationary perturbations back into Standard Model degrees of freedom.

Reheating proceeds from decays of a scalar field, often in a simplified framework with a single field responsible both inflation and reheating. However:

- Non-relativistic matter redshifts as $\rho_\Phi \sim a^{-3}$
- Radiation redshifts as $\rho_\gamma \sim a^{-4}$
- $$3 < 4$$

Reheating is dominated by the LAST scalar to decay NOT the first.

Decay Rates

How long do particles survive?

- Perturbative decay

$$\Gamma = \frac{g^2}{8\pi} m_\Phi, \qquad \tau = \frac{8\pi}{g^2 m_\Phi}$$

- Loop decay

$$\Gamma = \frac{g^2}{8\pi} \frac{g^4}{16\pi^2} m_\Phi, \qquad \tau = \frac{8\pi}{g^2} \frac{16\pi^2}{g^4} \frac{1}{m_\Phi}$$

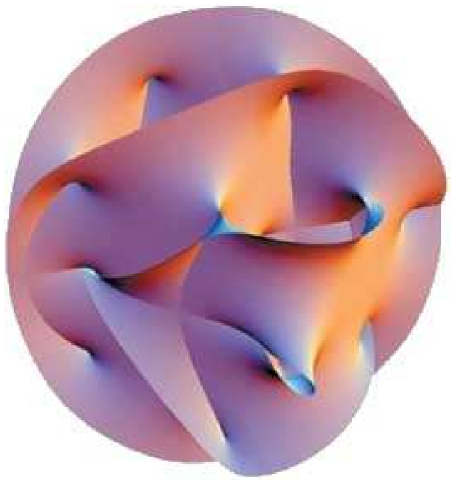
- Non-renormalisable decay suppressed by scale Λ

$$\Gamma = \frac{1}{8\pi} \frac{m_\Phi^3}{\Lambda^2}, \qquad \tau = 8\pi \frac{\Lambda^2}{m_\Phi^3}$$

Particles with couplings suppressed by M_P live the longest

Decay Rates

In string theory, there are extra dimensions, and the size and shape of these extra dimensions are parametrised by moduli - the 'normal modes'.



Moduli are massive scalars that interact only via 'gravitational' couplings suppressed by M_P^{-1}.

Their existence is a generic consequence of extra dimensions and is independent of the 'landscape'.

Moduli are generically displaced from their final minimum during inflation, and subsequently oscillate as non-relativistic matter.

Moduli Dynamics

Moduli are assumed to displace from their minimum after inflation.

Neglecting anharmonicities their equation of motion is

$$\ddot{\phi} + 3H\dot{\phi} + m_{\phi}^2 \phi = 0$$

and so oscillations start at $3H \sim m$.

Moduli redshift as matter and come to dominate universe energy density.

Hot Big Bang is recovered after moduli decay and reheat Standard Model.

Cosmological Moduli Problem

Moduli can decay via 2-body processes, e.g. $\Phi \to gg$, $\Phi \to qq$, etc

For direct couplings such as

$$\frac{\Phi}{4M_P} F_{\mu\nu} F^{\mu\nu} \qquad \text{or} \qquad \frac{\Phi}{2M_P} \partial_\mu C \partial^\mu C$$

the 'typical' moduli decay rate is

$$\Gamma \sim \frac{1}{16\pi} \frac{m_\phi^3}{M_P^2}$$

with a lifetime

$$\tau \sim \left(\frac{40\text{TeV}}{m_\phi} \right)^3 1\ \text{s} \equiv \left(\frac{4 \times 10^6 \text{GeV}}{m_\phi} \right)^3 10^{-6} s$$

Theoretical Motivation

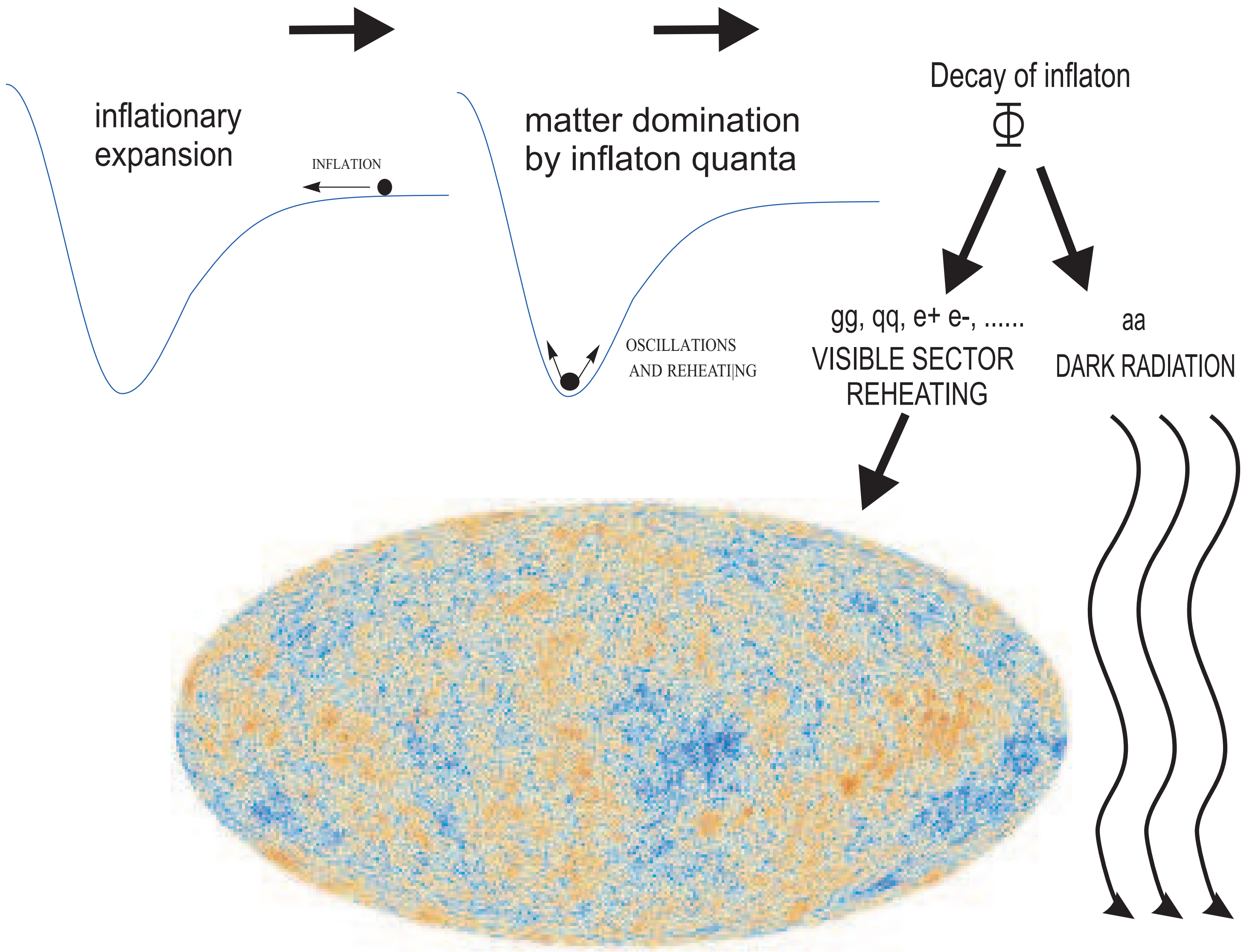
As gravitationally coupled particles, moduli generally couple to everything with M_P^{-1} couplings.

$$\begin{array}{rcl} \text{Visible sector} & : & \frac{\Phi}{4M_P} F_{\mu\nu}^{color} F^{color,\mu\nu}, \ \frac{\partial_\mu \partial^\mu \Phi}{M_P} H_u H_d, \ldots \\ \text{Hidden sector} & : & \frac{\Phi}{2M_P} \partial_\mu a \partial^\mu a, \ \frac{\Phi}{4M_P} F_{\mu\nu}^{hidden} F^{hidden,\mu\nu} \ldots \end{array}$$

This is supported by explicit studies of string effective field theories

Axionic decay modes naturally arise with BR$(\Phi \to aa) \sim 0.01 \to 1$.

The Standard Cosmology + ΔN_{eff}



Dark Radiation

The observable sensitive to non-Standard Model radiation is N_{eff}.

N_{eff} measures the 'effective number of neutrino species' at BBN/CMB: in effect, any hidden radiation decoupled from photon plasma (not necessarily connected to neutrinos).

At CMB times,

$$\rho_{total} = \rho_\gamma \left(1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{eff} \right).$$

For a canonical Hot Big Bang, $N_{eff} = 3.046$: $\Delta N_{eff} = N_{eff} - 3.046$ represents dark radiation - additional radiation decoupled from SM thermal bath.

Magnitude of Dark Radiation

Decays to any massless weakly coupled hidden sectors (axions, ALPs, hidden photons, RR $U(1)$s etc), gives dark radiation.

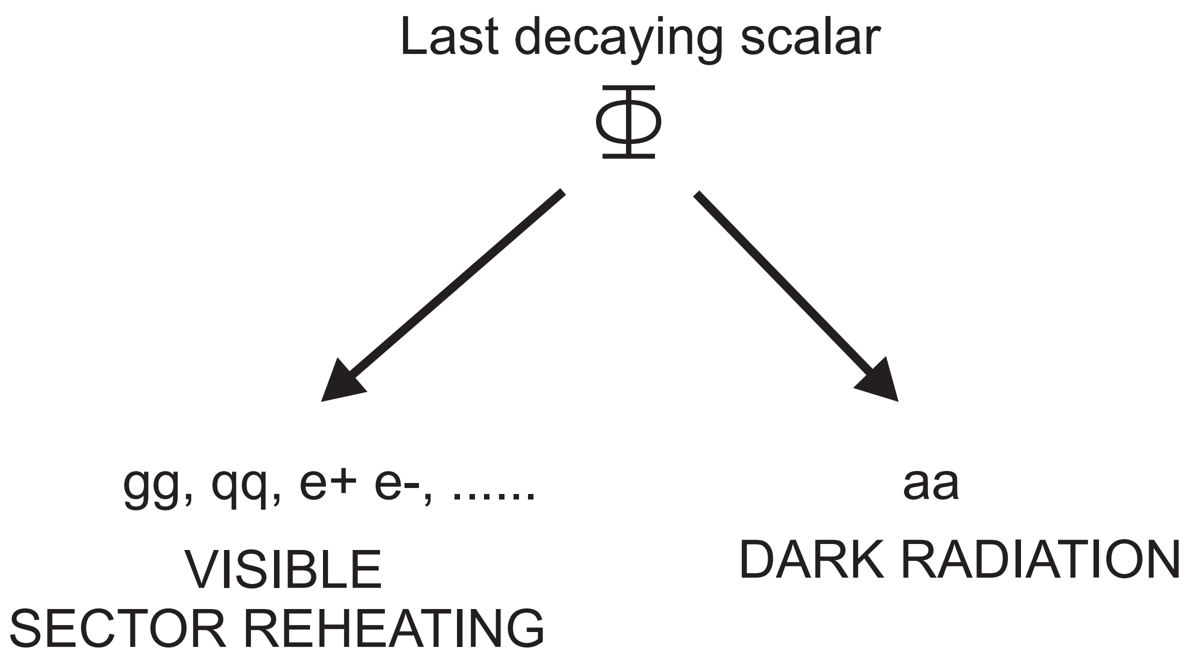
Visible/hidden branching ratio sets magnitude of dark radiation.

$$\Phi \to \textit{hidden} \text{ with branching ratio } f_{hidden}$$
$$\Phi \to gg, \gamma\gamma, qq, \ldots \text{ with branching ratio } 1 - f_{hidden}$$

$$\begin{aligned} \Delta N_{eff} &= \frac{43}{7} \frac{f_{hidden}}{1 - f_{hidden}} \left(\frac{g(T_{\nu\, dec})}{g(T_{reheat})} \right)^{1/3} \\ &\simeq 3.43 \frac{f_{hidden}}{1 - f_{hidden}} \qquad (T_{reheat} = 1\text{GeV}) \end{aligned}$$

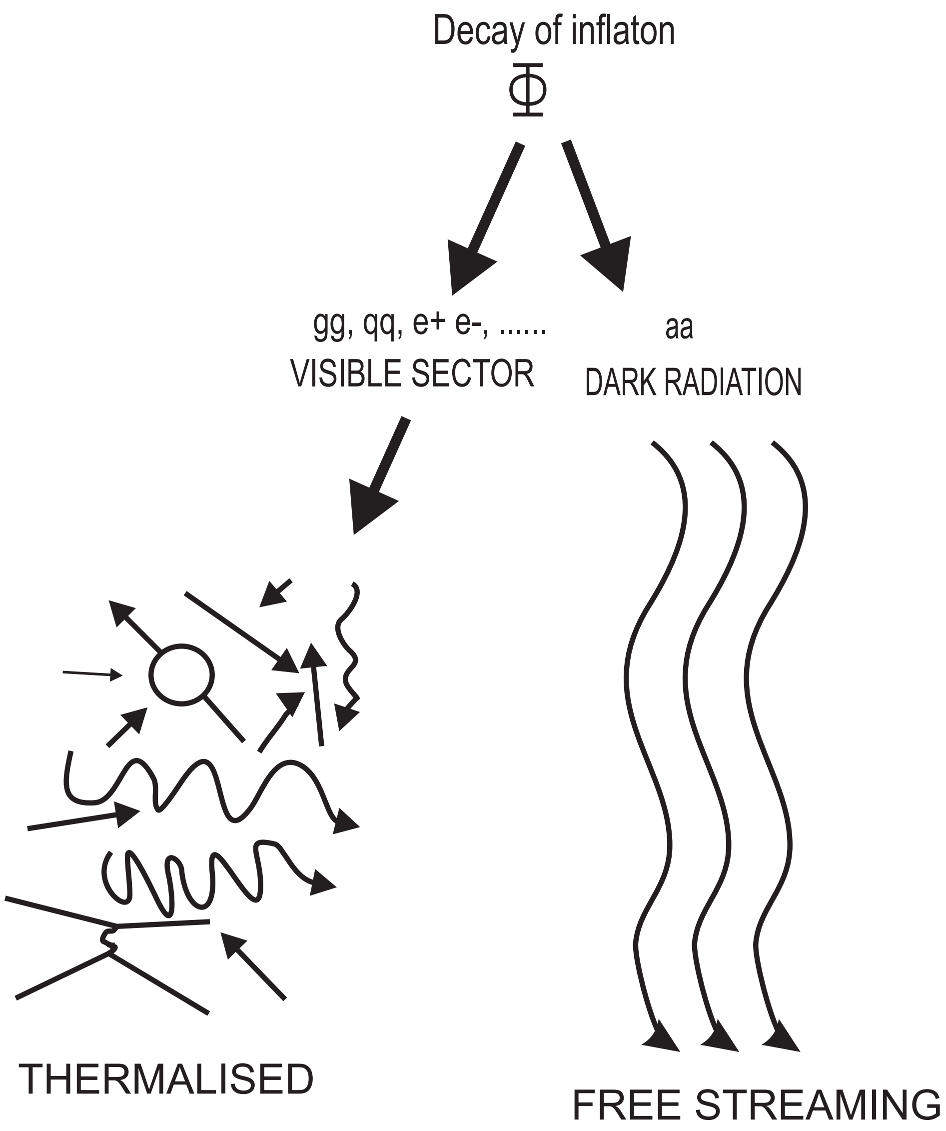
$\Delta N_{eff} \sim 0.01$ (stage-IV CMB) probes $f_{hidden} \sim 0.003$.

Dark radiation occurs whenever reheating involves decays to a massless hidden sector as well as the Standard Model.



Such massless hidden sectors exist in many BSM constructions - QCD axion, axion-like particles, hidden photons, WISPs, chiral fermions....

A Cosmic Axion Background



A Cosmic Axion Background

$$\Phi \to gg, \ldots : \qquad \text{Decays thermalise} \qquad T_\gamma \sim T_{reheat} \sim \frac{m_\Phi^{3/2}}{M_P^{\frac{1}{2}}}$$

$$\Phi \to aa : \qquad \text{Axions never thermalise} \qquad E_a = \frac{m_\Phi}{2}$$

Thermal bath cools into the CMB while axions never thermalise and freestream to the present day:

Ratio of axion energy to photon temperature is

$$\frac{E_a}{T_\gamma} \sim \left(\frac{M_P}{m_\Phi}\right)^{\frac{1}{2}} \sim 10^6 \left(\frac{10^6 \text{GeV}}{m_\Phi}\right)^{\frac{1}{2}}$$

This suggests an $\mathcal{O}(keV)$ relic cosmic axion background....

Axion-like particles

- Light axion-like particles (ALPs) are one of the most motivated ways to extend the Standard Model
- They arise generically in string theory.
- Phenomenologically, they are parametrised by the coupling

$$a\ g_{a\gamma\gamma}\mathbf{E.B} \equiv \frac{\boldsymbol{a}}{\boldsymbol{M}}\mathbf{E.B}$$

- In the presence of a background **B** field, the ALP a and photon γ eigenstates mix, leading to photon-ALP oscillations (cf neutrino oscillations)

Axion-Like Particles 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

- Axion-like particles are one of the most motivated targets in looking for signatures of string compactifications

X-Ray Searches for Axions

How to search for ALPs?

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

  1. Send photons from A to B

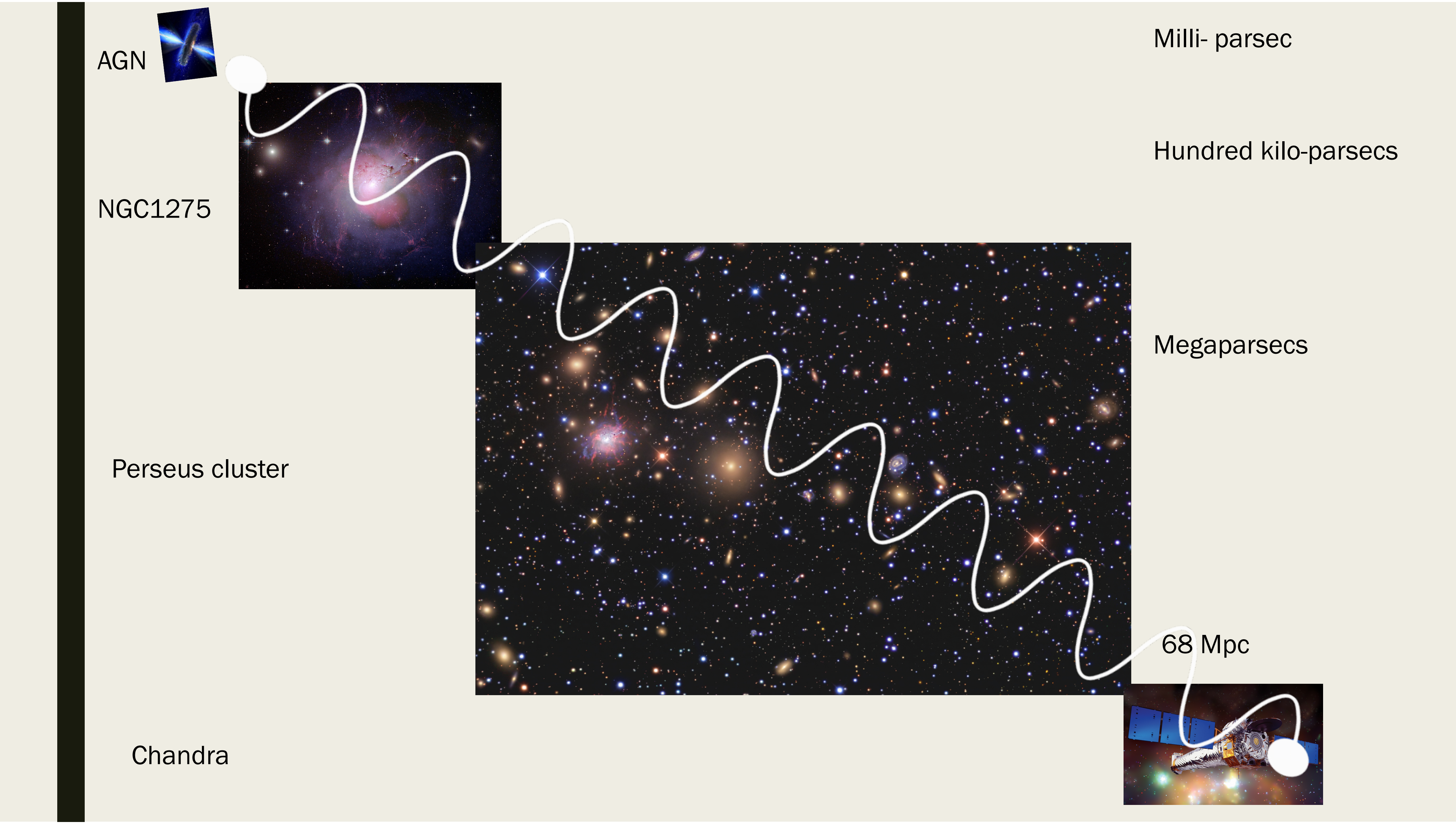
  2. Have a magnetic field inbetween A and B

  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

Originally Wouters + Brun 2013

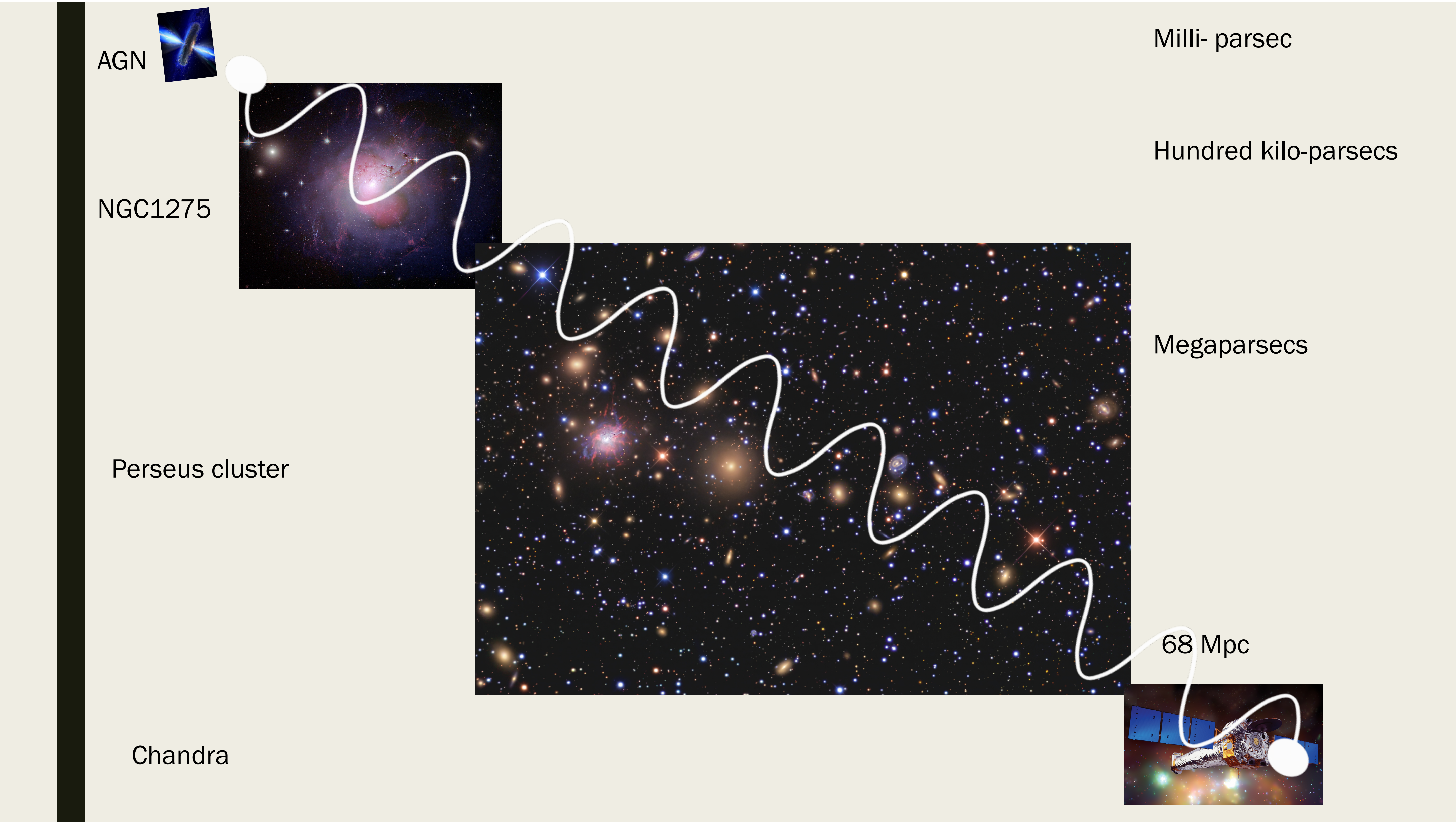

AGN
Milli- parsec
Hundred kilo-parsecs
NGC1275
Megaparsecs
Perseus cluster
68 Mpc
Chandra

AGNs are Unique Probes of Fundamental Physics

- Light comes from within a FEW SCHWARZSCHILD RADII of the central black hole – interesting physics
- Black holes are fundamental objects - cf superradiance
- Large number of photon counts – high statistics
- Photons experience an identical line of sight through the host galaxy and galaxy cluster – uniform effect
- They experience a dark matter column density larger than almost any other line of sight in the local universe – extreme conditions
- Sensitive to milli-parsec dark matter spikes near central Black Hole – unique sensitivity

NGC 1275

- NGC1275 is the central supergiant elliptical galaxy of the Perseus cluster
- It is located at a redshift of 0.0176 (68 Mpc distant)
- At its centre is a very bright AGN, powered by accretion onto the supermassive black hole.
- The AGN brightness is time-variable (1980 brightness was 20x bigger than in 2001, progressive increase in brightness since 2001)
- The AGN is unobscured, and shines to us through both NGC1275 and the Perseus cluster


AGN
Milli- parsec
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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

Photon-ALP Conversion

- The fundamental ALP-photon coupling is

$$a\ g_{a\gamma\gamma}\mathbf{E.B} \equiv \frac{\boldsymbol{a}}{\boldsymbol{M}}\mathbf{E.B}$$

- In a magnetic field, this gives a 2-particle interaction between the ALP and the photon
- The ALP and photon eigenstates mix – the ‘mass’ eigenstates are no longer the same as the ’flavour’ eigenstates (a and γ)
- Propagating through the magnetic field, photon eigenstates oscillate into ALP eigenstates

Photon-ALP Conversion

- Source is NGC1275, destination is earth: intervening magnetic field is magnetic field of the Perseus cluster.
- Galaxy clusters are particularly good locations for photon-ALP interconversion
- Magnetic fields extend over approx. 1 Mpc regions, with coherence lengths in 1- 10kpc region.
- Magnetic field strengths are 1 – 10 microGauss.
- Photon-ALP couplings $g_{a\gamma\gamma}$ of 10^{-12} to 10^{-11} GeV^{-1} generate conversion probabilities of order 10 – 50%.
- No exact knowledge of Perseus magnetic field; central value should be in range 10 – 25 microGauss.

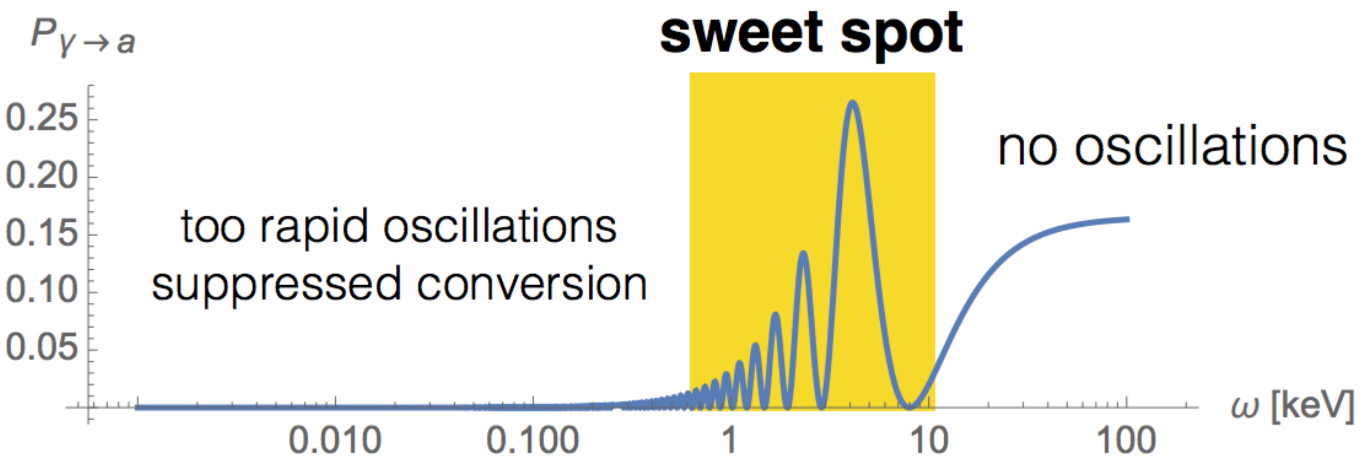
Photon-ALP Conversion – why X-rays?

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

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

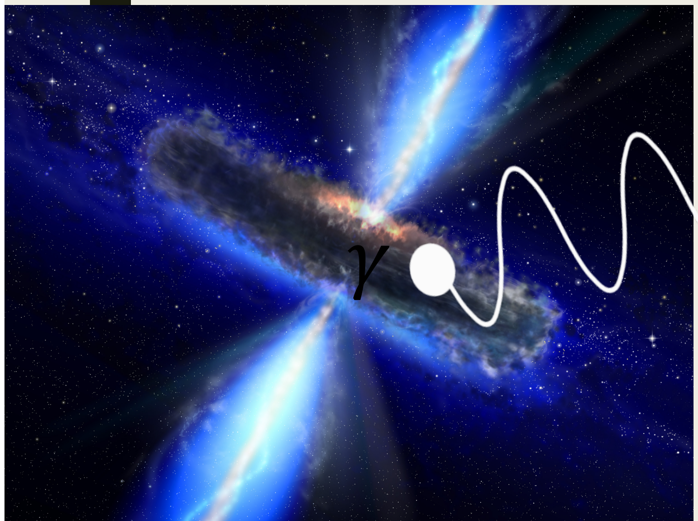
$$\Theta = 0.28 \left(\frac{B_\perp}{1\ \mu\mathrm{G}}\right)\left(\frac{\omega}{1\ \mathrm{keV}}\right)\left(\frac{10^{-3}\mathrm{cm}^{-3}}{n_e}\right)\left(\frac{10^{11}\mathrm{GeV}}{M}\right) \qquad \Delta = 0.54\left(\frac{n_e}{10^{-3}\mathrm{cm}^{-3}}\right)\left(\frac{L}{10\mathrm{kpc}}\right)\left(\frac{1\mathrm{keV}}{\omega}\right)$$

- Sweet spot at X-ray energies:

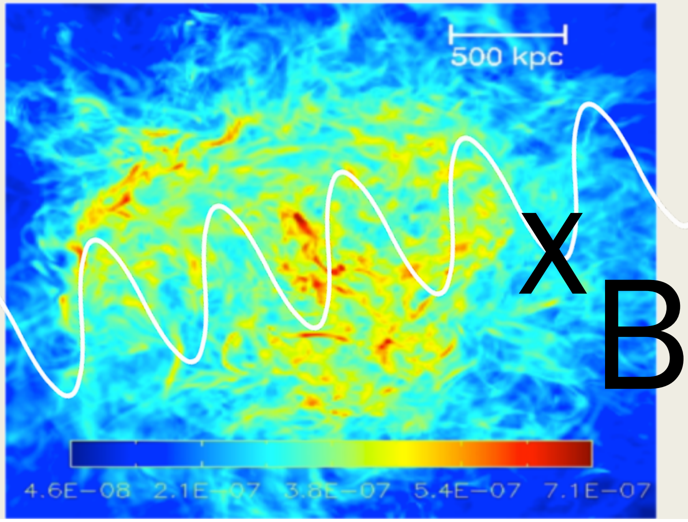


ALPS

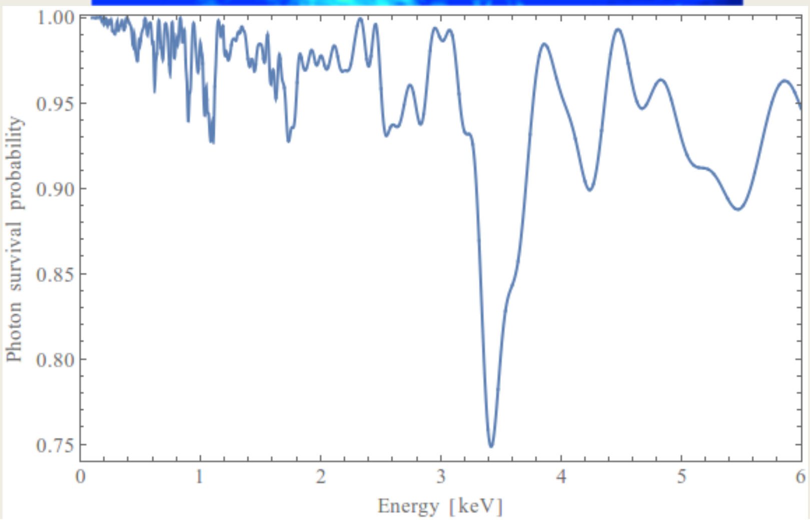
AGNs are bright point sources of photons



Photons pass through galaxy cluster magnetic field

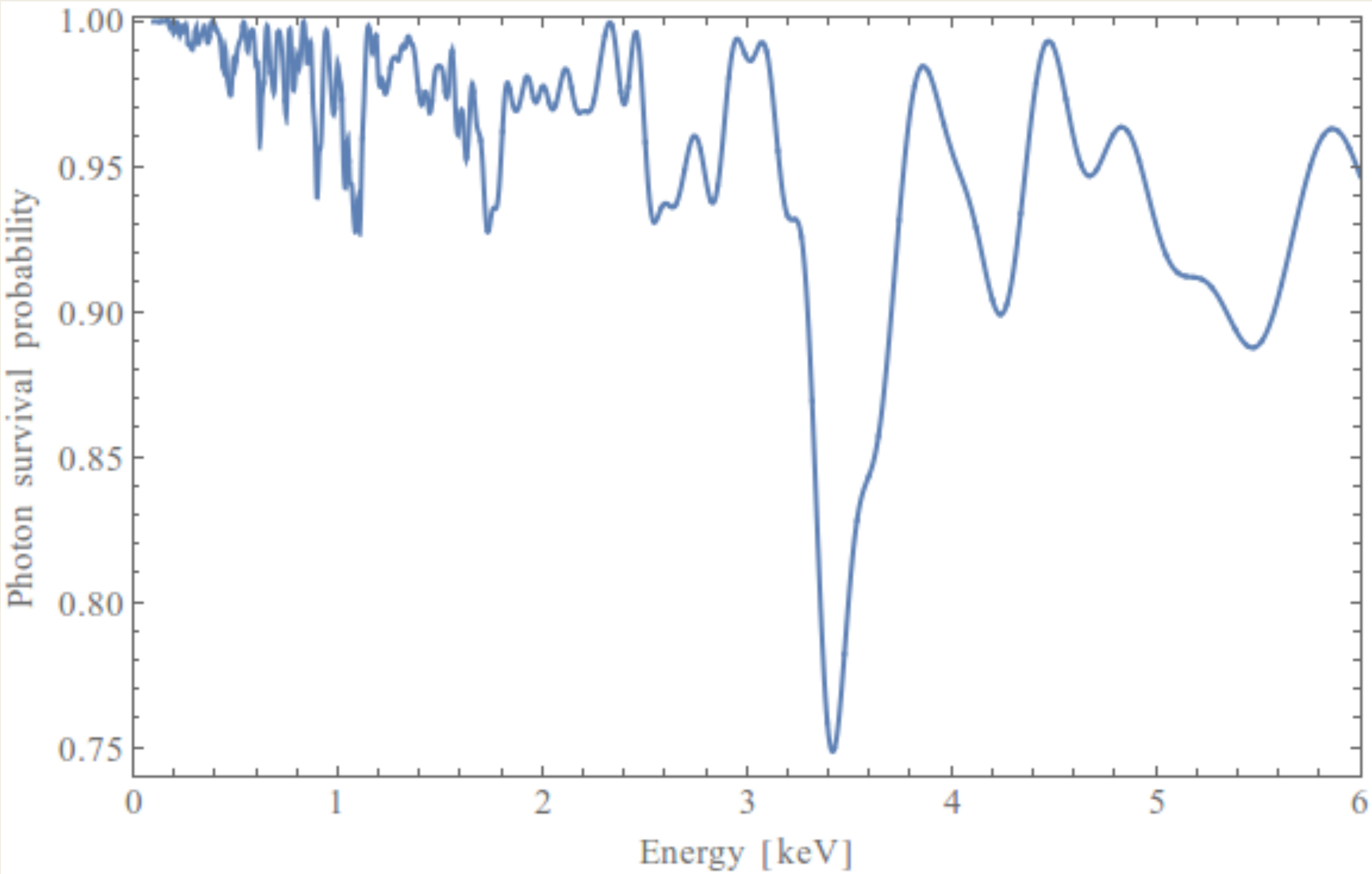


ALP-Photon conversion induces irregularities in observed X-ray spectrum



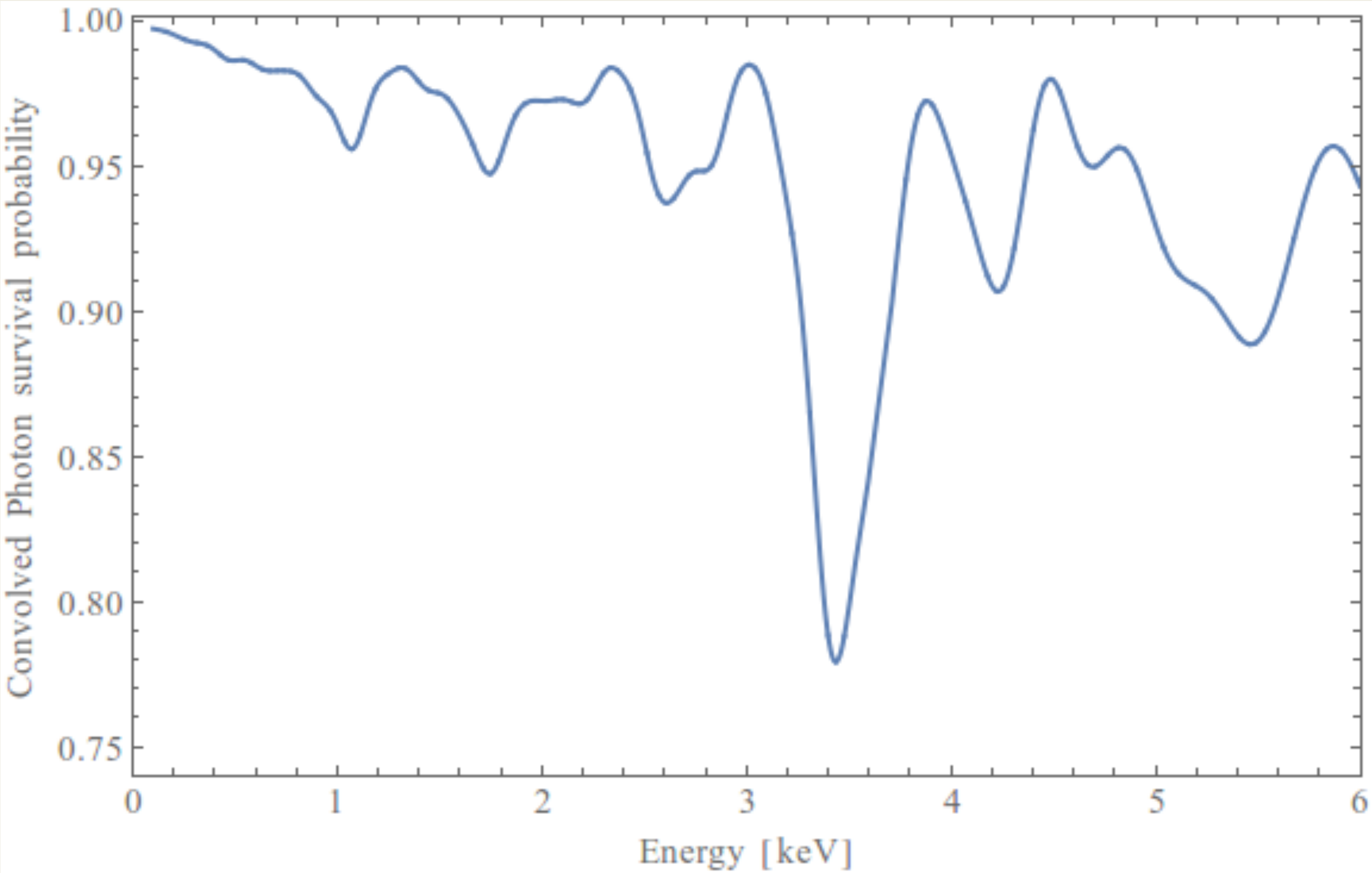
Precise form of modulations depends on cluster magnetic field

Simulated photon survival probability…



This would modulate the true spectrum

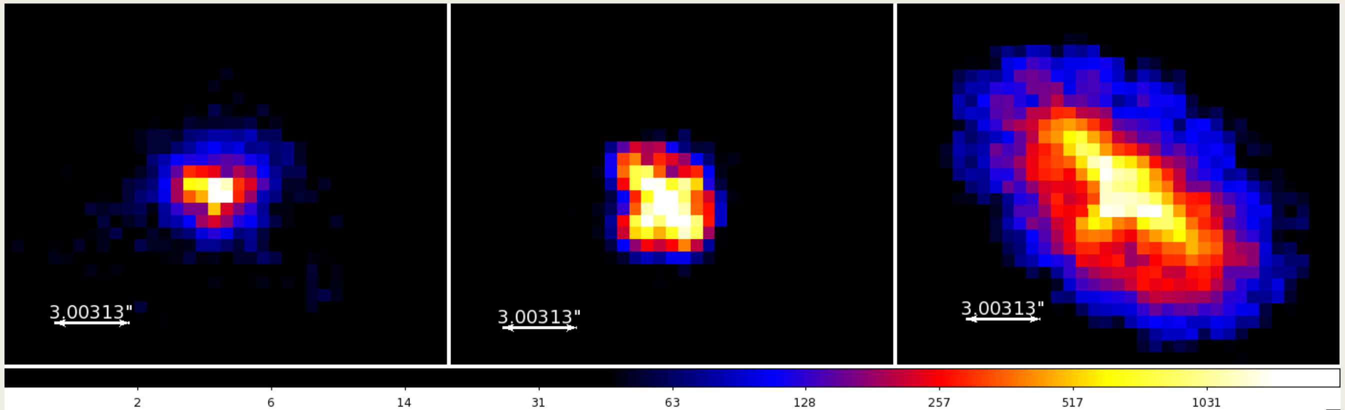
…now convolved with detector resolution



This would modulate the true spectrum

The Observations

- NGC1275 observed by *Chandra* in 2002 and 2004 for 1Ms with ACIS-S and 0.5 Ms in 2009 with ACIS-I.
- In ACIS-S observations, NGC1275 is on-axis, in 2009 observations 300ks with NGC1275 around 4 arcmin off-axis and 200ks with NGC1275 around 8 arcmin off-axis.
- Treat these three sets separately, focus on last case.
- *Chandra* on-axis point spread function is around 0.5 arcsec diameter on-axis, broadening to around 10 arcsec diameter when source is around 8 arcmin off-axis.



The Observations

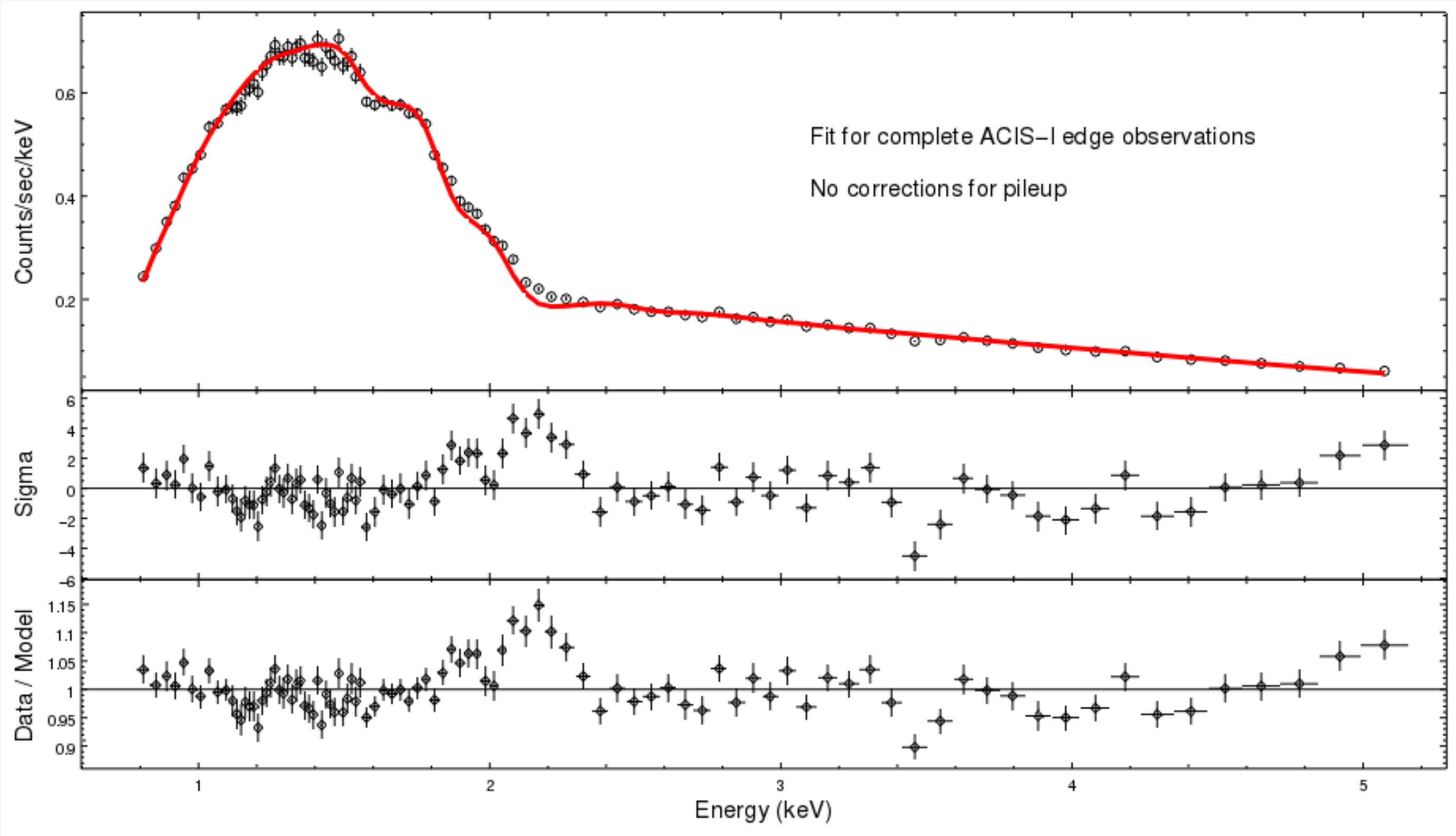
- We extract the AGN spectrum and subtract nearby cluster emission for background.
- We fit the AGN spectrum between 0.8 and 5 keV with an absorbed power law
- We examine these spectra and look for residuals
- Counts are grouped so that there are approximately one hundred bins in total
- Total counts from AGN is

1. 230000 for 2009 ACIS-I ‘edge’ observations (cleanest dataset) FOCUS ON THIS!

2. 242000 for 2009 ACIS-I ‘midway’ observations – heavy pileup contamination

3. 183000 for 2002-4 ACIS-S on-axis observations – heavy pileup contamination

Complete extraction for ACIS-I edge



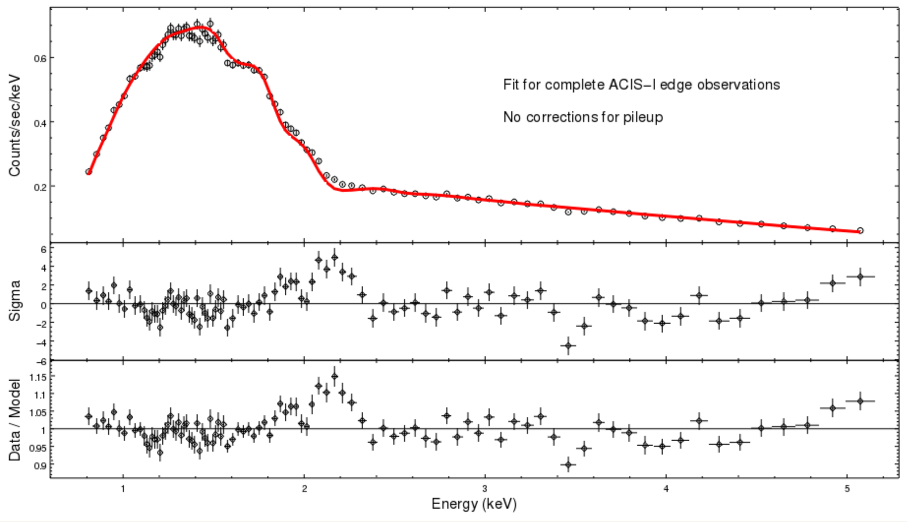
Fit to absorbed power law gives two main features – excess at 2 – 2.2 keV, deficit at 3.4 – 3.5 keV

Features in ACIS-I Edge Data

Two main features:

1. Excess at 2 – 2.2 keV

Subtle because of effective area dip at these energies



Possible to generate fake excesses via energy mismeasurement

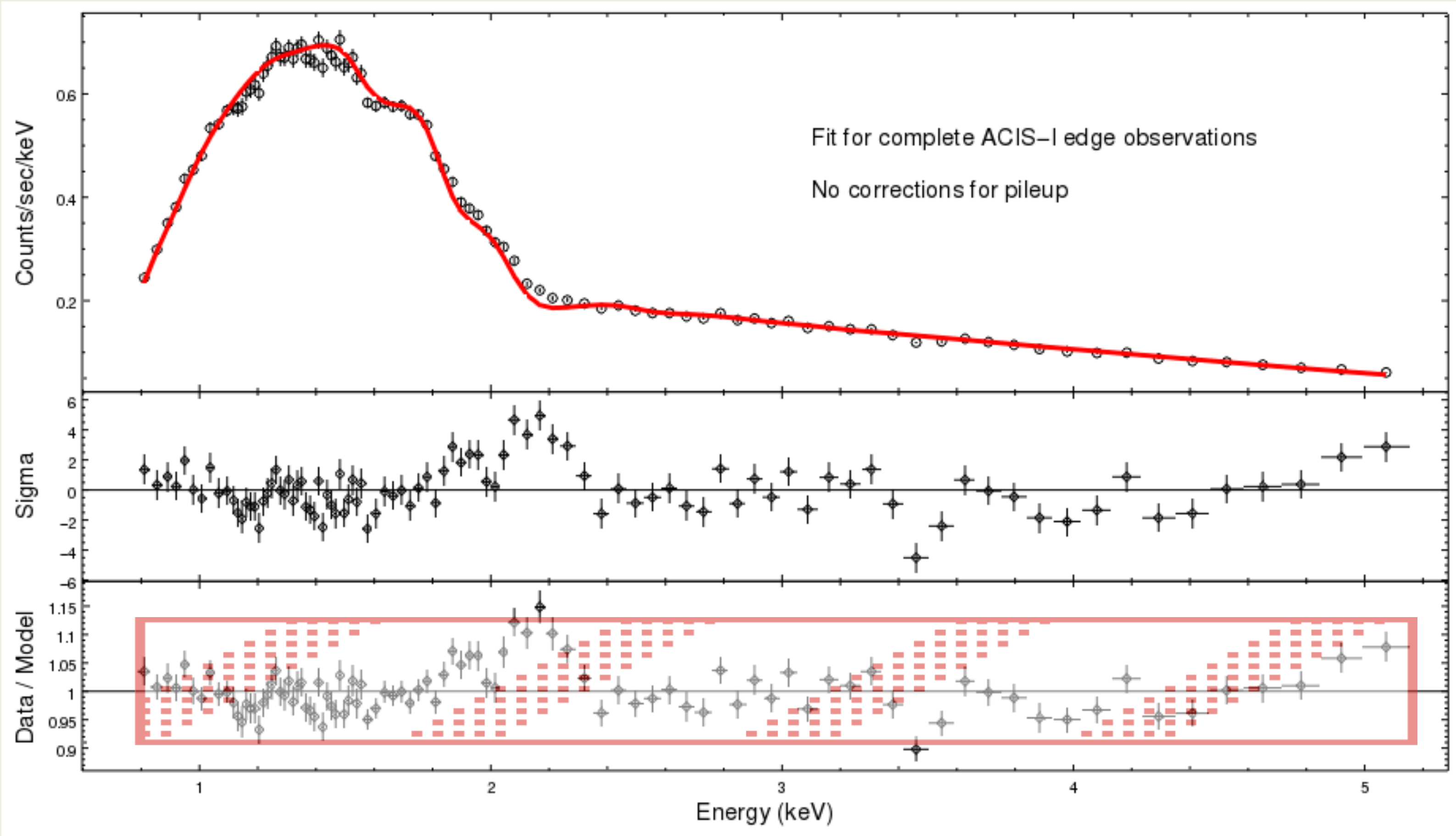
2. Deficit at 3.4 – 3.5 keV

Possible connection to 3.5 keV line – not discuss here

ALP Constraints

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

ALP couplings leading to 20-30% irregularities are excluded



ALP Constraints

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.

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}

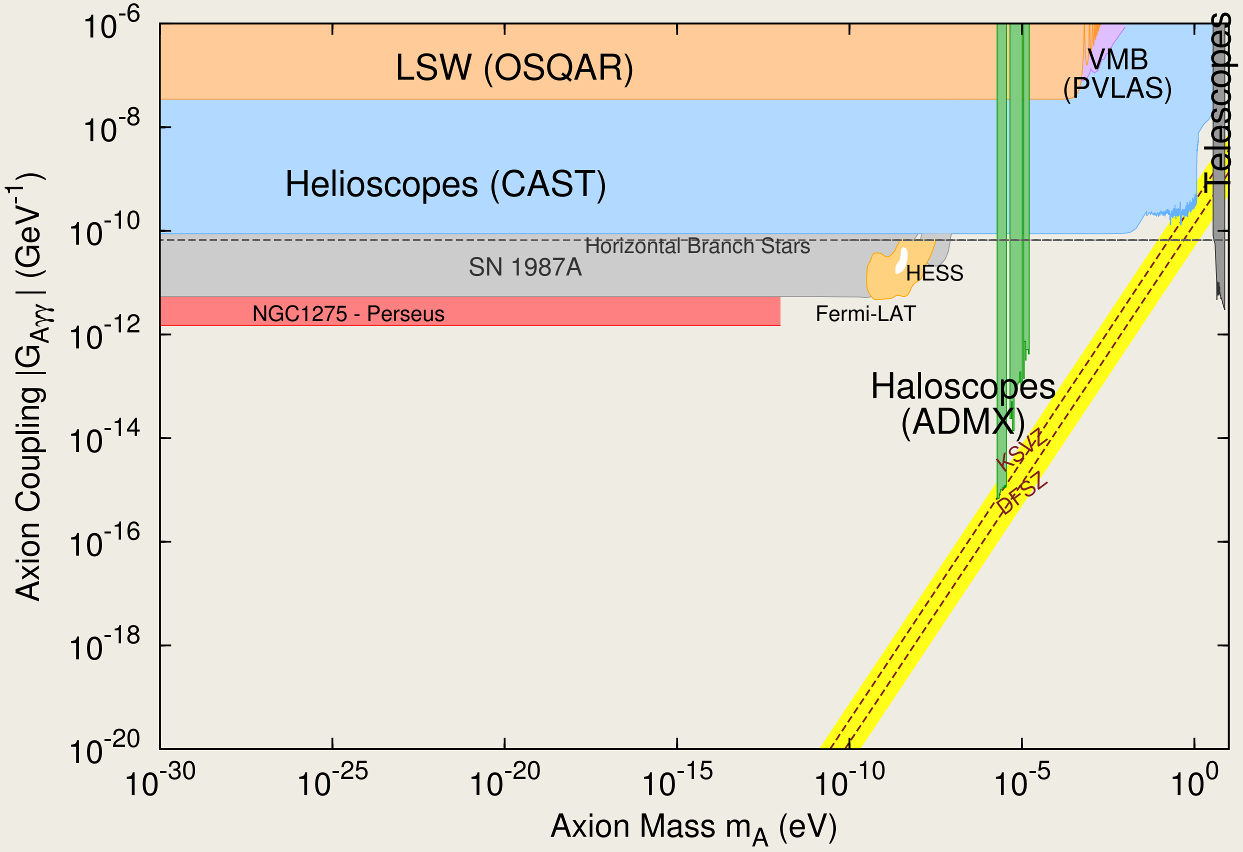
2. Conservative case: (B_central = 15 μG, 100 domains between 0.7 and 10kpc)

   $g_{a\gamma\gamma}$ < 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 gives leading bounds on ALP-photon coupling at small mass



Bounds would be stronger still if we knew that either

2 - 2.2 keV feature

or

3.4 – 3.5 feature

were definitely not real……