Probing Axion-like Particles with Galaxy Clusters

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Workshop on "Off-the-beaten-track Dark Matter and Astrophysical Probes of Fundamental Physics"
ICTP Trieste, 13th April 2015

Outline

- Axion-like particles
- The cluster soft X-ray excess
- Motivating a cosmic ALP background
- Simulations of ALP-photon conversion in clusters

Based on

1312.3947: Angus, Conlon, Marsh, AP, Witkowski

1411.4172: AP

- ALPs from supernovae in galaxy clusters.

1504.?????: Conlon, AP

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Axion-like Particles

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ALP-photon Conversion

- Axion-like particle lagrangian $\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{a}{M} E \cdot B$ where we set $m_a < 10^{-13}\ \mathrm{eV}$, such that it can be consistently neglected.
- Second term allows ALP-photon conversions in external electric or magnetic fields.

Raffelt & Stodolsky '88
Raffelt '86
See also Raffelt talk

- In an external magnetic field the ALP-photon wavefunctions become mixed leading to oscillations.
- Photons (ALPs) scattering off the electric field of a charged particle can convert into ALPs (photons) → Primakoff effect.

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ALP-photon Coupling

- Inverse coupling **M** between ALPs and photons can be constrained in a number of ways.
- Laboratory: light shining through walls and solar ALP experiments.
- CAST experiment bound: $M > 1 \times 10^{10}$ GeV CAST Coll. 1106.3919
- Astrophysics: the ALP-photon coupling affects a number of astro-physical systems.

See Raffelt Talk

- Supernova 1987a gamma burst bound: $M > 2 \times 10^{11}$ GeV

Brockway et al. Astro-ph/9605197, Grifols et al. astro-ph/9606028
Payez et al. 1410.3747, also Mirizzi talk Thursday

- Next-gen experimental reach (IAXO): $M \lesssim 5 \times 10^{11}$ GeV

See Garcia Irastorza talk

The Cluster Soft X-ray Excess

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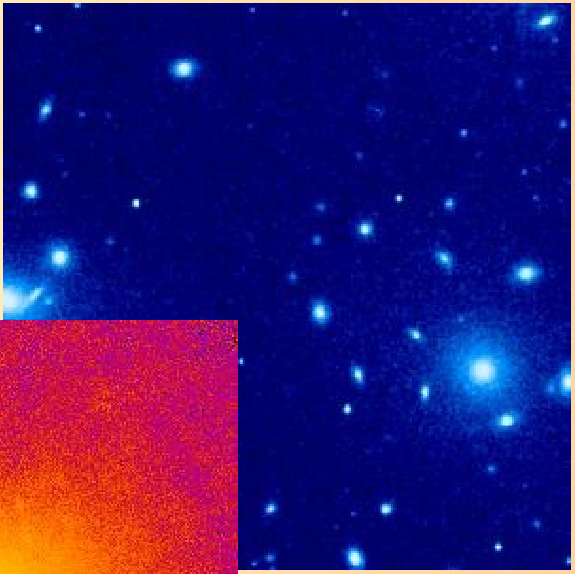
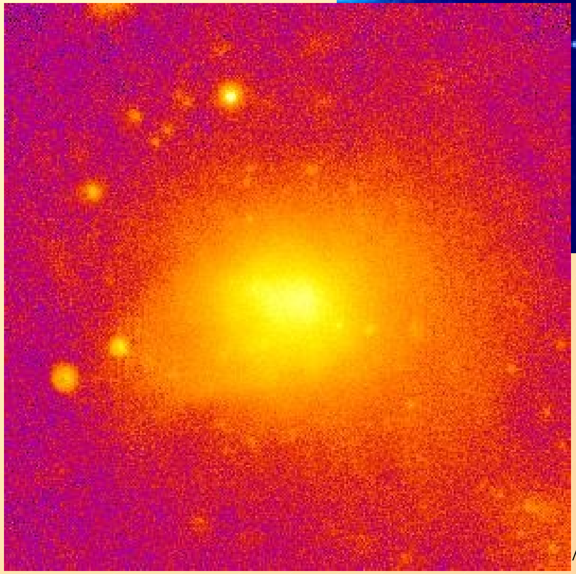
Galaxy Clusters

- Largest virialised objects in the universe.
- Galaxy clusters mostly dark matter (~85%) and hot, ionised gas (~10%) – the **intra-cluster medium** (ICM).
- Intra-cluster medium is keV temperature, emits thermally across the X-ray regime through bremsstrahlung, + many atomic emission lines.
- The ICM also supports a **Mpc**-sized, **μG** magnetic field.

e.g. Govoni & Feretti astro-ph/0410182
Bonafede Talk tomorrow





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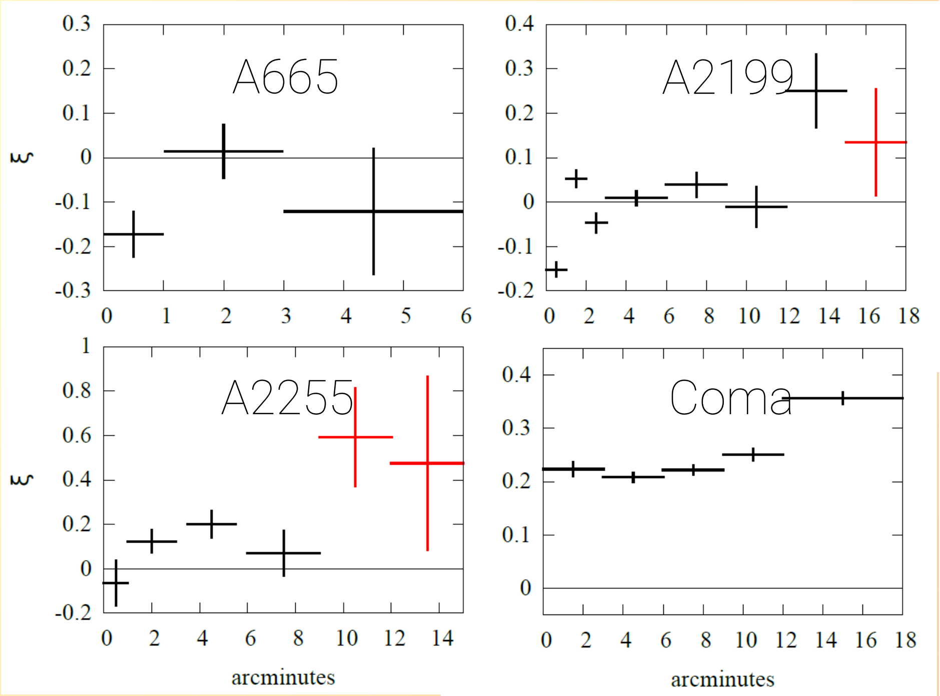
The Cluster Soft Excess

- Can model the X-ray emission using bremsstrahlung spectrum.
- **Excess emission** seen in many galaxy clusters at energies $\sim 0.2\ \mathrm{keV}$ (soft X-ray).
- Review: Durret et al. (2008) 0801.0977
  Also Bonamente talk Thurs.
- Seen with **several satellites**:
  EUVE, ROSAT and XMM-Newton.
- **1/3** of all clusters have an excess:

  Bonamente et al. 2002 studied 38 clusters, 13 of which showed a statistically significant excess



- Astrophysical explanations unsatisfactory.

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A Cosmic ALP Background

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A Cosmic ALP Background

- A background of relativistic ALPs is well motivated in string theory models of the early universe. Conlon, Marsh 1304.1804
- Decay of moduli into the visible sector drives reheating.
- The moduli will also decay to hidden sectors → most notably to very light (massless) ALPs.
- Producing a homogeneous background of non-interacting, relativistic ALPs → a cosmic ALP background (CAB).

A Cosmic ALP Background

- There are strict bounds on the energy density in relativistic particles from **CMB** and **BBN** observations.
- The CAB contributes to the excess relativistic energy density → **dark radiation**.
- This is usually parameterised as excess neutrino species:

$$\Delta N_{eff} = \frac{8}{7}\left(\frac{4}{11}\right)^{-4/3}\frac{\rho_{\text{dark rad}}}{\rho_\gamma}.$$

- Current CMB observations bound at $\Delta N_{eff} < \mathbf{0.5}$ at 95% C.L.

Planck Coll. Results XIII (2015)

- Energy of CAB spectrum set by parent modulus mass.

A Cosmic ALP Background

- **Proposition:** cluster soft excess generated by conversion of a cosmic ALP background into X-ray photons in the cluster's magnetic field.

Conlon, Marsh 1305.3603

- Given the magnetic field in a particular cluster, this gives a testable prediction for soft X-ray flux.

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ALP-photon Conversion in Clusters

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Conversion in Clusters

- Magnetic fields in clusters turbulent, typically $\mathcal{O}(1 - 10\ \mu\mathrm{G})$ in magnitude, coherent over 1-100 kpc.

e.g. Govoni & Feretti astro-ph/0410182

- Probabilities (in a certain approximation) with magnetic field domain sizes L and cluster size D, is $P \propto \frac{D}{L}\left(\frac{BL}{M}\right)^2$ so

$$P(a \to \gamma) = 0.9 \cdot 10^{-3} \left(\frac{D}{1\ \mathrm{Mpc}} \frac{L}{10\ \mathrm{kpc}}\right) \left(\frac{B}{2\ \mu\mathrm{G}} \frac{10^{13}\ \mathrm{GeV}}{M}\right)^2$$

- Thus clusters are very efficient at ALP-photon conversion (~3 orders of magnitude higher than the Milky Way).

Conversion in Clusters

- Typical Luminosity for a CAB of energy $\sim 200\ \mathrm{eV}$ converting to photons in a cluster $\mathcal{L} \sim 10^{42}\ \mathrm{erg\ s^{-1}}$ for $M \sim 10^{13}\ \mathrm{GeV}$.
- Comparable magnitude to observed soft excesses.

- Magnetic field varies from cluster to cluster.
- Need to check CAB predictions for soft excess in individual clusters against data.
- Two CAB parameters **M** and **CAB mean energy** can be fit and compared across clusters.

Simulations

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The Magnetic Field

- Assume the magnetic field in galaxy clusters can be modelled as stochastic, Gaussian fields with power-law power spectrum.
- The magnitude of the field falls as a power of the gas density of the intra-cluster medium.

  Bonafede Talk Tomorrow
- The resulting 5-parameter model has been constrained for the four clusters of interest to us previously:

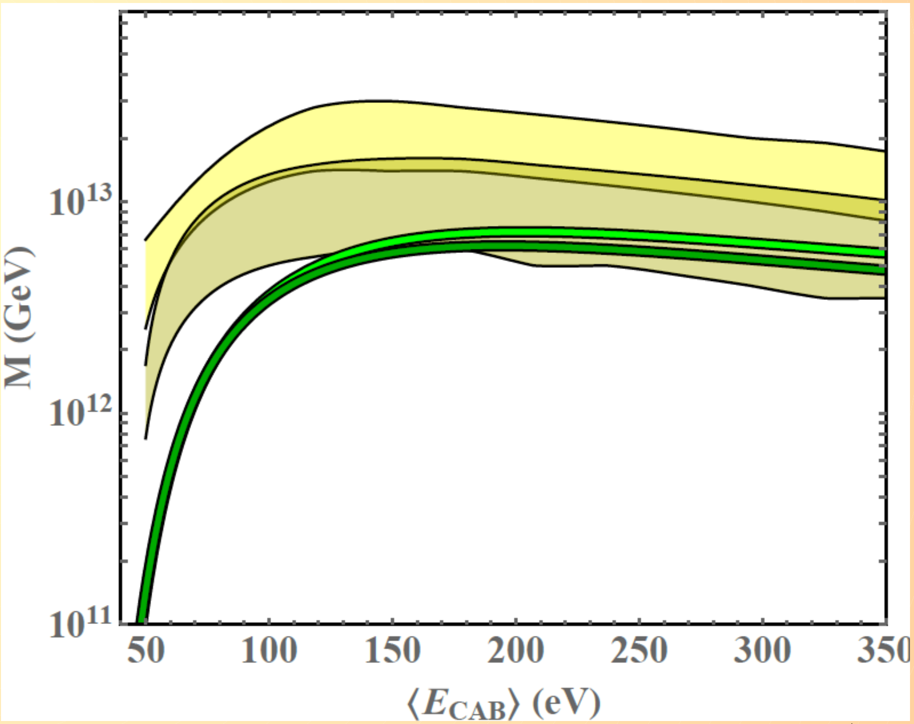
  Murgia et al. (2004), Govoni et al. (2006)
  Bonafede et al. (2010), Vacca et al.(2010)
  Vacca et al. (2012)
- Numerically calculate conversion probabilities by solving EoM for discrete simulated magnetic fields. .

Coma

- Well established soft excess, very high statistical significance.
- Constrain CAB parameters by fitting magnitude in Coma centre (green).
- Outer parts of cluster (up to 5 Mpc) agrees with centre (yellow).

Kraljič, Rummel, Conlon 1406.5188

Angus, Conlon, Marsh, AP, Witkowski 1312.3947



- Morphology of simulations of Coma fit excess data well (given magnetic field model uncertainties).

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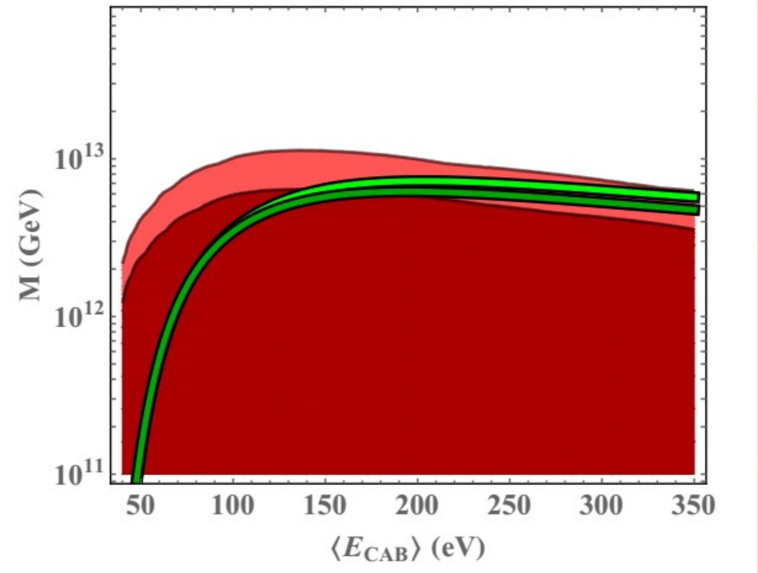
A665

- A665 shows **no evidence** for a soft excess.
- The green lines are from Coma, red is the region which produces a soft excess in A665.
- Constrain parameters by stipulating CAB should not produce observable excess.
- There is slight disagreement, but still large magnetic field model uncertainty.

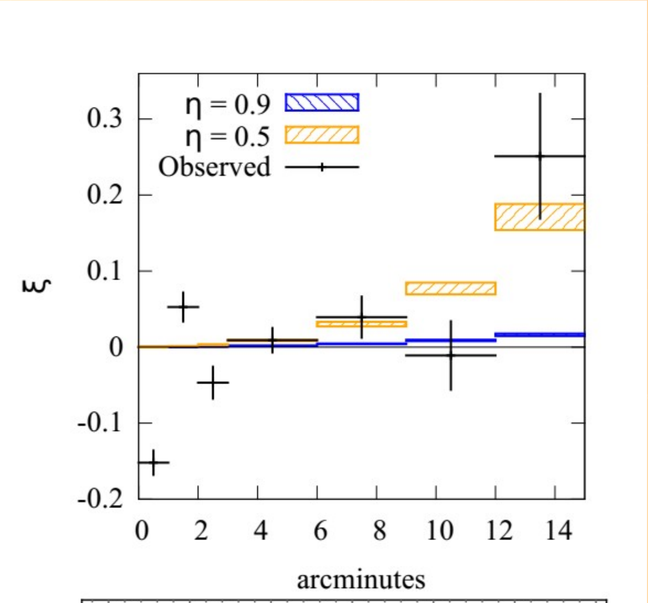


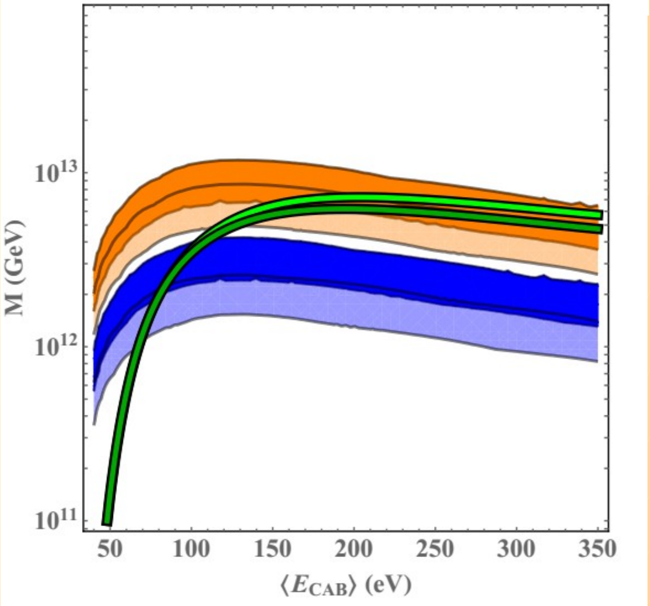
AP 1411.4172

A2199

- Soft excess observed with low sig.
- Uncertainty on steepness of radial decline of field.
- Can easily reproduce magnitude of excess for Coma parameters.
- Morphology prefers a less steep field decline.   .

AP 1411.4172





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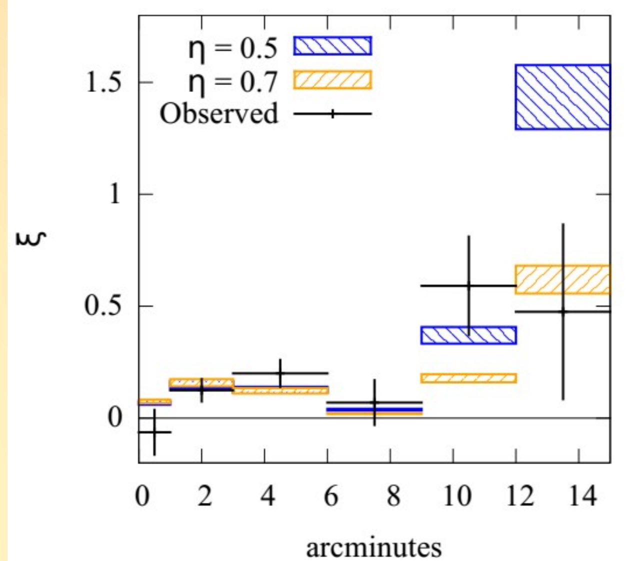
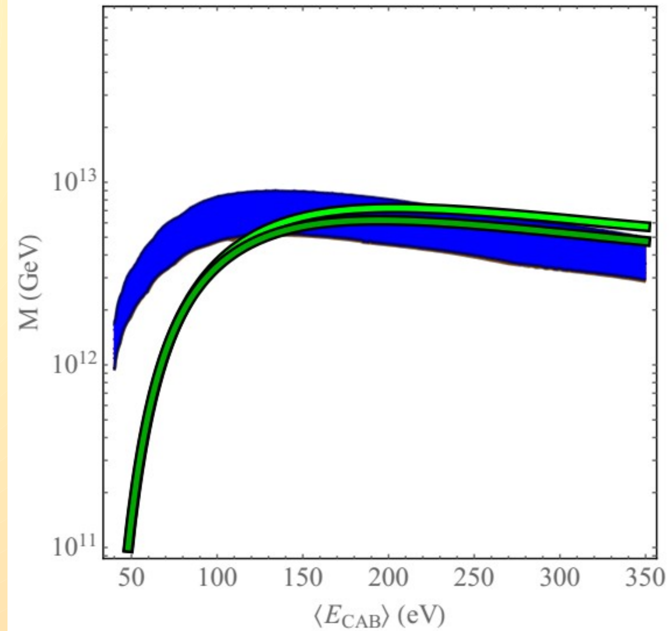
A2255

- Significant excess observed, low sig.
- Morphology fit very well.
- Outer two points have poor signal.
- Inner 9 arcminutes fit well for Coma parameters.
- Approximation of field with 2 different power spectra for inner and outer regions.





AP 1411.4172

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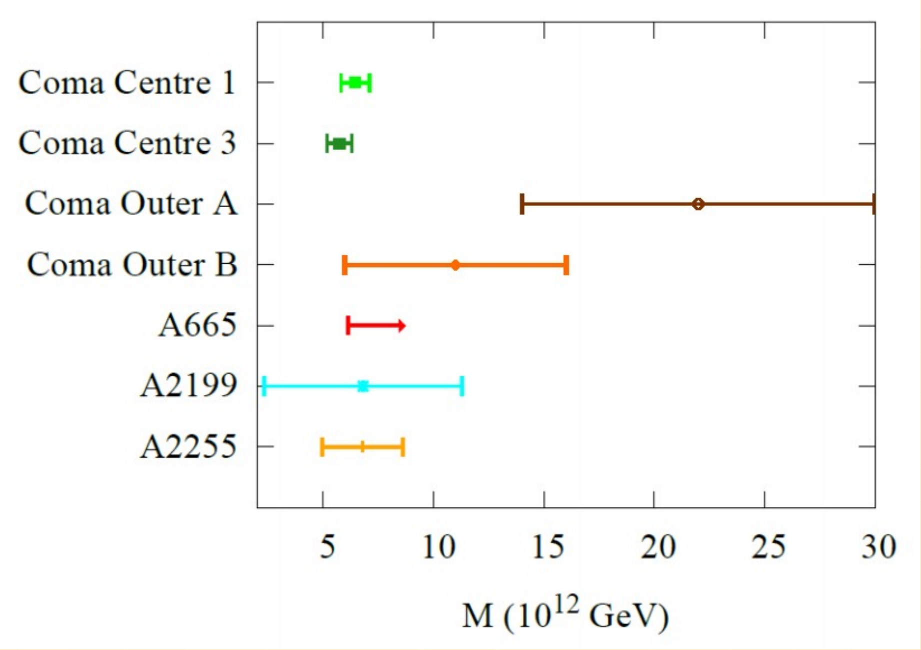
Results

- Best fit CAB parameters regions from the Coma, A665, A2199 and A2255 clusters agree well with each other.
- Morphology a good fit in each cluster where the excess is observed.
- Magnetic field uncertainties are large.

Angus, Conlon, Marsh, AP, Witkowski 1312.3947
Kraljič, Rummel, Conlon 1406.5188
AP 1411.4172



Supernovae

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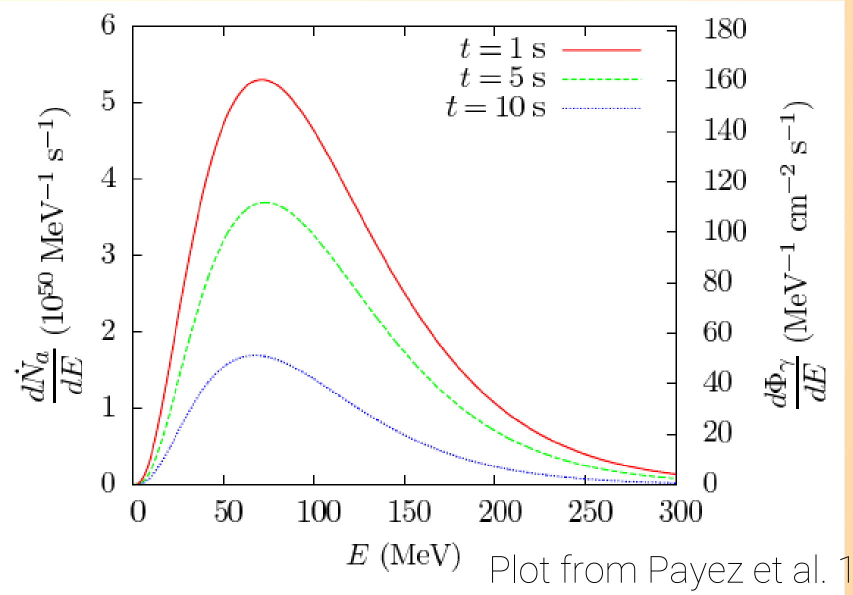
SN1987a

- Core-collapse supernovae produce a **large amount of ALPs** through the Primakoff process.
- Scattering of gamma ray photons off electric fields of protons produces gamma ray energy ALPs.
- Back-conversion of ALPs in **astrophysical magnetic fields** produces gamma ray burst coincident with neutrino burst.
- Lack of observation of burst from SN1987a can be used to bound ALP-photon coupling: $M > 1.9 \times 10^{11}$ GeV



Plot from Payez et al. 1410.3747

Brockway et al. Astro-ph/9605197, Grifols et al. astro-ph/9606028
Payez et al. 1410.3747, also Mirizzi talk Thursday

Supernovae in Clusters

- SN1987a located in LMC, ALPs back-convert to photons in Milky Way field.
- Bound from lack of observation with old GRS satellite.
- Modern gamma ray satellites (**Fermi-LAT**) much more sensitive, but chances of supernovae close by very small!
- Galaxy clusters have much larger conversion probabilities than Milky Way.
- If supernova in **galaxy cluster**, back-conversion will take place very efficiently.
- Clusters contain many galaxies → **several supernovae per year**!
- Gamma ray burst from Virgo cluster observable with Fermi-LAT for

$$M \lesssim 1 - 3 \times 10^{11}\ \mathrm{GeV}$$

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Summary

- A **soft X-ray excess** has been observed in many galaxy clusters.
- Conversion of a **cosmic ALP background**, forming a component dark radiation, into photons could explain excess.
- Simulations of Coma, A665, A2199 and A2255 give a consistent picture of CAB parameter space, and correct morphology.
- Still large amount of uncertainty in magnetic field model.

- **Galaxy clusters** are great places to look for astrophysical imprints of ALPs. See **David Marsh**'s talk Thurs for more.

Extra Slides

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Alternative Explanations

- **Warm ICM Component:** Soft excess is the thermal emission of a second, colder component to the intra-cluster gas

  Problem: 1) higher electron densities in cool gas => larger cooling rates
  2) no lines detected in excess

- **WHIM:** Warm gas at outskirts of cluster
  Simulations predict most of baryons in filamentary warm-hot intergalactic Medium
  => thermal emission produces soft excess
  Filaments aligned along line of sight?

- **Inverse Compton Scattering:** Relativistic electrons off CMB
  Rel. electrons known to exist due to radio synchrotron emission in magnetic fields from clusters

  Problem: 1) can't explain both with same electrons, B fields too large
  2) lack of associated gamma emission from relativistic protons etc

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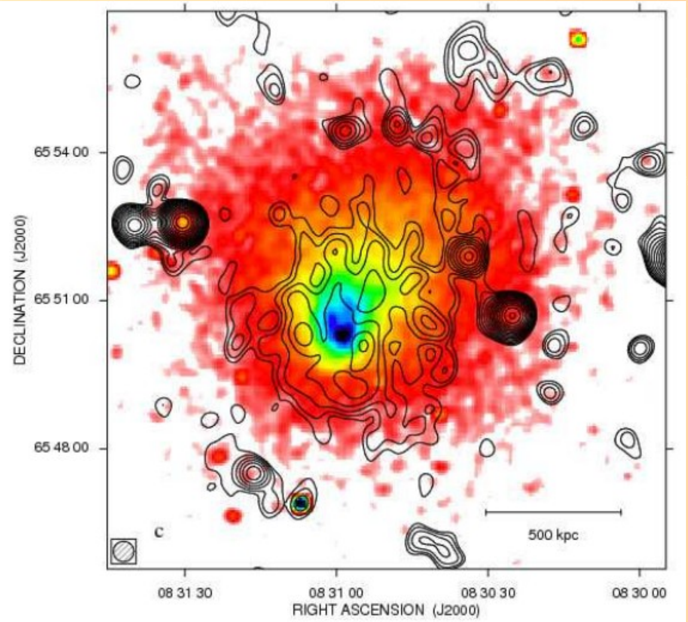
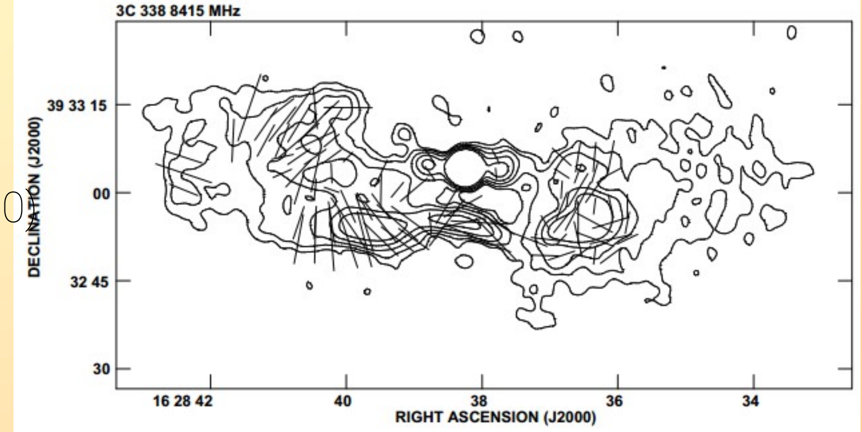
Cluster Magnetic Fields

- Field observations
  - synchrotron radio emission
  - Faraday rotation

- Constrain magnetic field by making various model assumptions
  => equipartition
  => faraday rot. with fixed magnetic field cells
  => gaussian random field

Murgia et al. (2004)
Govoni et al. (2006)
Bonafede et al. (2010)
Vacca et al.(2010)
Vacca et al. (2012)





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Model

- Simulate stochastic, multi-scale, gaussian random field, with power spectrum

$$|B_k|^2 \sim k^{-n+2}$$

- Limit modes to $\frac{2\pi}{\Lambda_{max}} \leq k \leq \frac{2\pi}{\Lambda_{min}}$
- Modulate field such that $B(r) = B_0 \left(\frac{n_e(r)}{n_0} \right)^{\eta}$
- Parameters have been constrained by fitting to Faraday rot. maps or radio halo images.
- Field produced on large 2000^3 grid, ALP-photon wavefunction numerically 'propagated' from one grid point to next.