

Axions

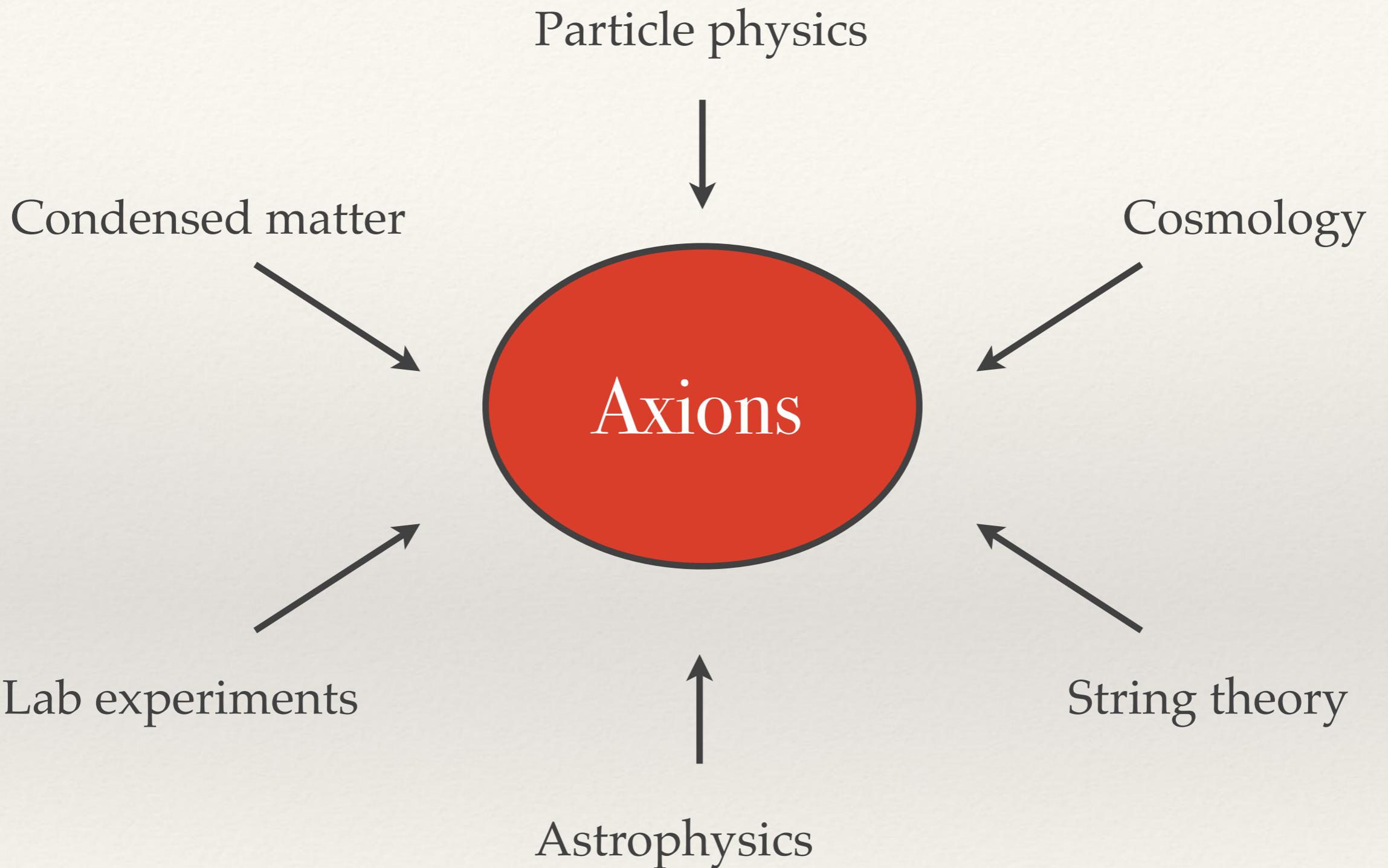


M.C. David Marsh

Department of Applied Mathematics and Theoretical Physics
University of Cambridge



IPA 2016 conference, Orsay



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- Theoretically well-motivated.
- Versatile!
- Interesting hints already exist.
- Developing field: ongoing observational, experimental and theoretical efforts.

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- Astrophysics may guide to fundamental physics discoveries.

Outline:

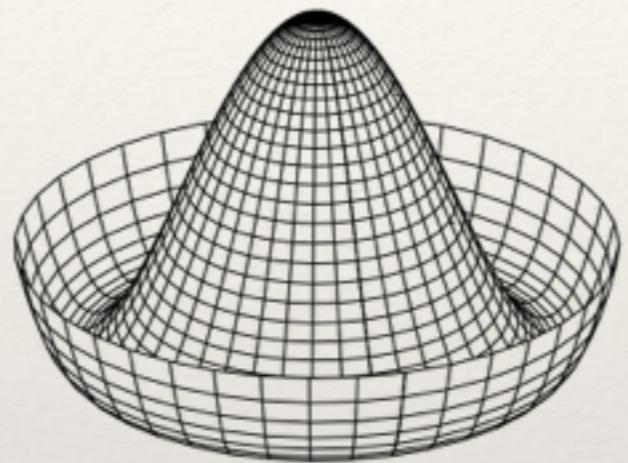
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2. Galaxy clusters are ALP converters
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What is an axion?

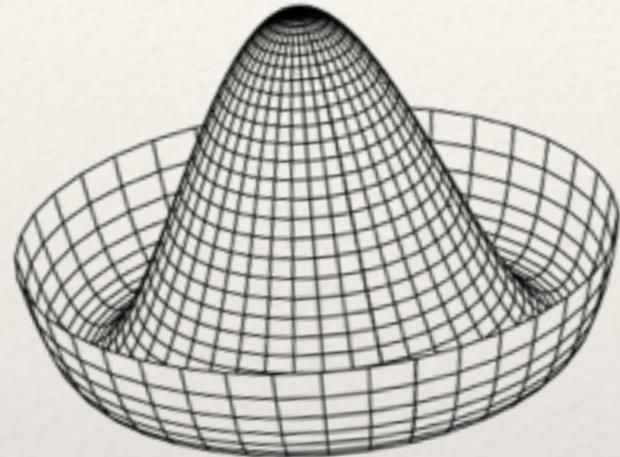
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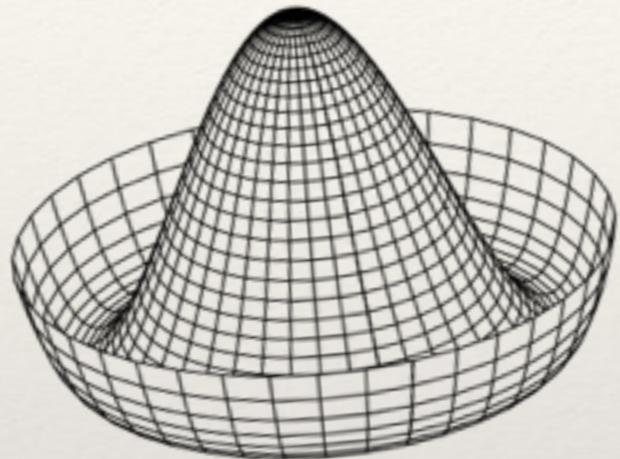
Spontaneously broken ***approximate* global symmetries** give rises to ***approximately massless*** particles: “pseudo Nambu-Goldstone bosons”.



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Peccei-Quinn mechanism:

Axion = pNGB of spontaneously broken, approximate $U(1)_{\text{PQ}}$.

<p><i>CP</i> Conservation in the Presence of Pseudoparticles*</p> <p>R. D. Peccei and Helen R. Quinn <i>Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305</i> (Received 31 March 1977)</p> <p>We give an explanation of the <i>CP</i> conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.</p> <p>experimentally obvious that we live in a here <i>P</i> and <i>CP</i> are good symmetries at grangian. If all fermions which couple to the non-Abelian modynamics" (QCD) is that it offers an explana-</p>	<p>PHYSICAL REVIEW LETTERS 23 JANUARY 1978</p> <p>A New Light Boson?</p> <p>Steven Weinberg <i>Department of Physics, Harvard University, Cambridge, Massachusetts 02138</i> (Received 6 December 1977)</p> <p>that a global $U(1)$ symmetry, that has been introduced in order to predict time-reversal invariance of strong interactions despite the effects would lead to a neutral pseudoscalar boson, the “axion,” with mass roughly 1 MeV. Experimental implications are discussed.</p>	<p>10, NUMBER 5 PHYSICAL REVIEW LETTERS 30 JANUARY 1978</p> <p>Problem of Strong <i>P</i> and <i>T</i> Invariance in the Presence of Instantons</p> <p>F. Wilczek^(a) <i>Columbia University, New York, New York 10027, and The Institute for Advanced Studies, Princeton, New Jersey 08540^(b)</i> (Received 29 November 1977)</p> <p>The requirement that <i>P</i> and <i>T</i> be approximately conserved in the color gauge theory of strong interactions without arbitrary adjustment of parameters is analyzed. Several possibilities are identified, including one which would give a remarkable new kind of very light, long-lived pseudoscalar boson.</p> <p>one of the main advantages of the color gauge a certain class of theories^{4a,b} the para-</p>
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Motivation: Strong CP-problem

$$\mathcal{L}_{\text{eff}} = -\frac{1}{4} \text{tr} (\mathcal{G}_{\mu\nu} \mathcal{G}^{\mu\nu}) + \frac{\bar{\theta}}{64\pi^2} \text{tr} (\epsilon^{\mu\nu\lambda\rho} \mathcal{G}_{\mu\nu} \mathcal{G}_{\lambda\rho}) .$$

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Invariant θ :

$$\bar{\theta} = \theta + \arg [\det(M)] .$$

QCD vacuum:

$$|\text{vac}, \theta\rangle = \sum_k e^{ik\theta} |k\rangle .$$



From quark
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Theory expectation:

$$\bar{\theta} \sim \mathcal{O}(1) ,$$

'Strong CP-problem'

n EDM experiments:

$$\bar{\theta} < 10^{-10} .$$

The QCD axion

“Promote invariant θ to a pNGB”:

Classical symmetry: $a \rightarrow a + \text{const.}$

$$\mathcal{L} = -\frac{1}{2}\partial^\mu a\partial_\mu a + \left(c\frac{a}{f_a} + \bar{\theta}\right) \frac{1}{64\pi^2} \text{tr}(\epsilon^{\mu\nu\lambda\rho} G_{\mu\nu} G_{\lambda\rho}) \quad \text{minimised for CP-conservation}$$

“axion decay constant”

$$+ \mathcal{L}_{\text{int}}(\partial_\mu a/f_a) + c_\gamma \frac{a}{f_a} \frac{1}{64\pi^2} (\epsilon^{\mu\nu\lambda\rho} F_{\mu\nu} F_{\lambda\rho}) .$$

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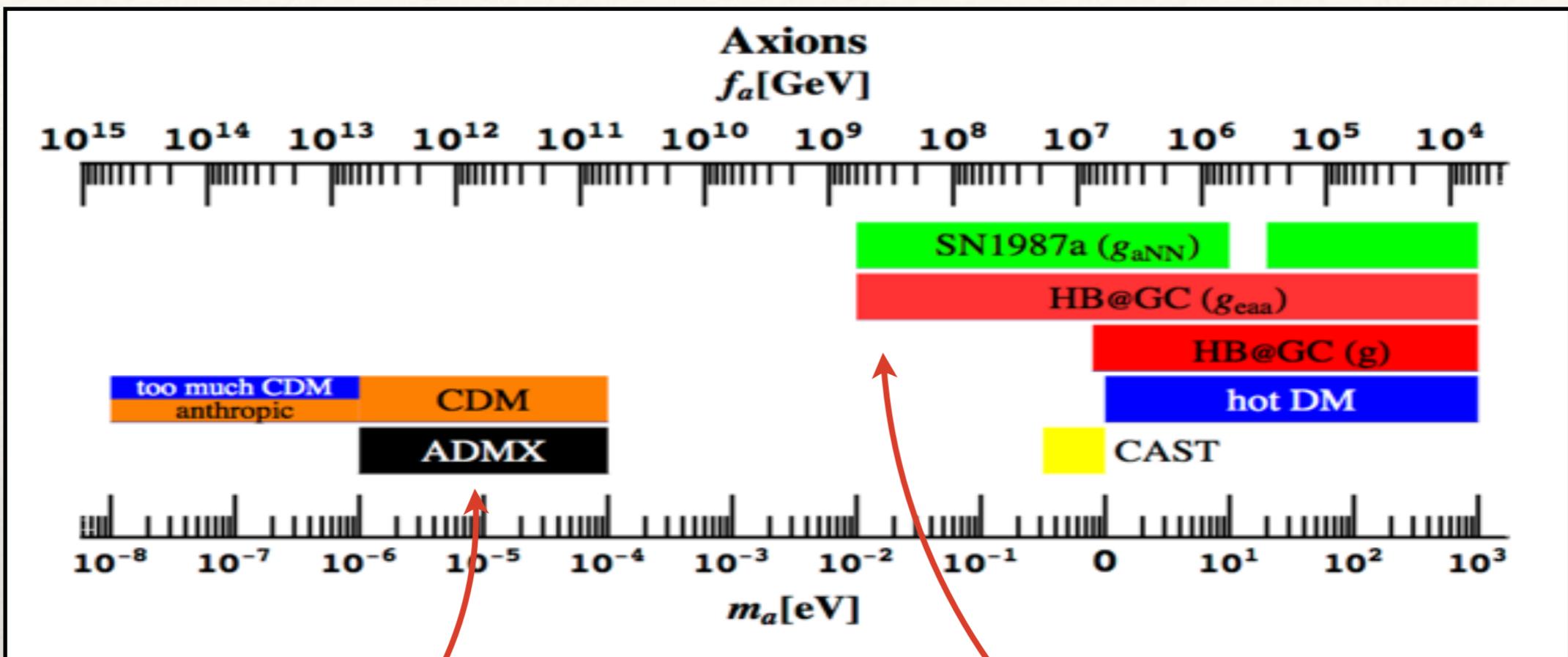
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At low energies (schematically):

$$V(a) = m_a^2 f_a^2 \left(1 - \cos\left(\frac{a}{f_a}\right)\right) . \quad m_a \simeq 6 \text{ eV} \left(\frac{10^6 \text{ GeV}}{f_a}\right) .$$

Parameter constraints



Dark matter
specific bounds

Additional energy loss
in nuclear environments

Jaeckel, Ringwald, arXiv:1002.0329

Axion-like particles (ALPs)

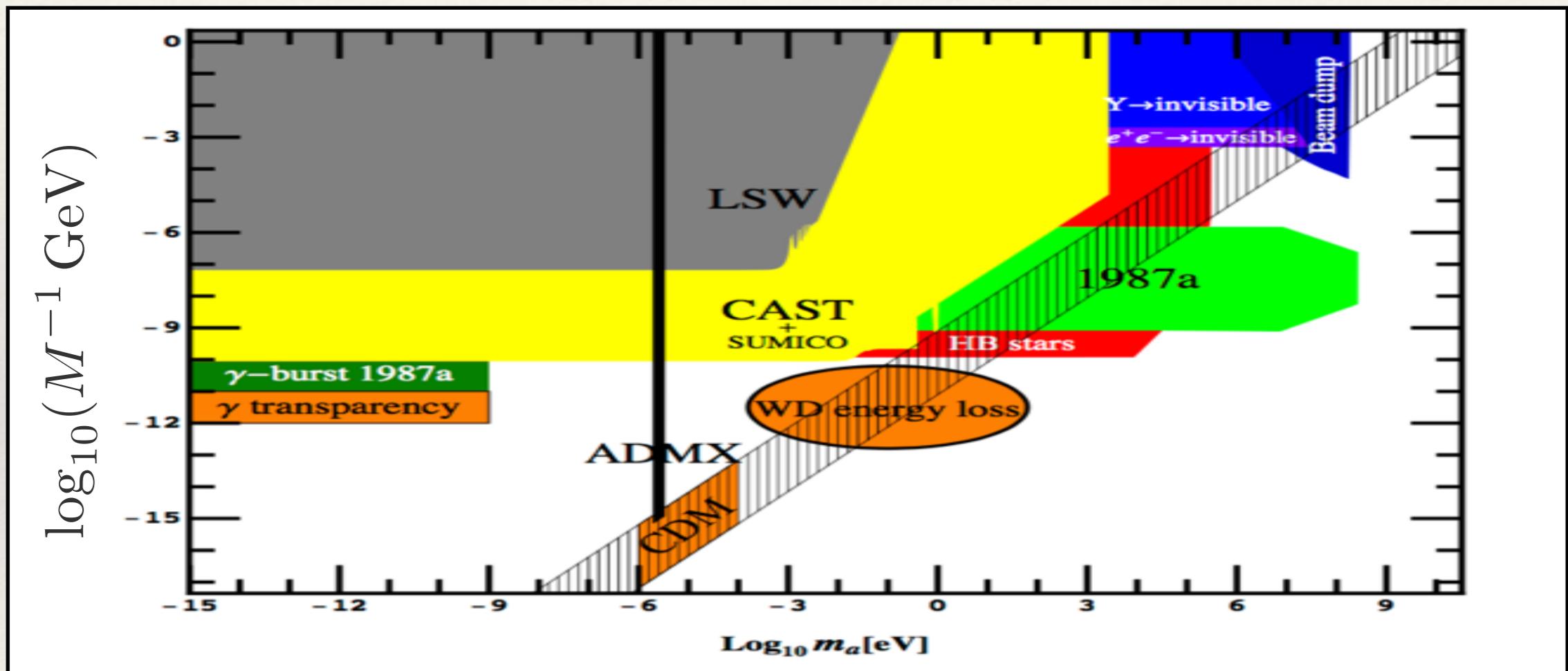
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$$\mathcal{L} = \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} \cancel{m_a^2} a^2 - \frac{a}{4M} F_{\mu\nu} \tilde{F}^{\mu\nu} + c_{af} \frac{\partial_\mu a}{2M} \bar{\psi}_f \gamma^5 \gamma^\mu \psi_f .$$

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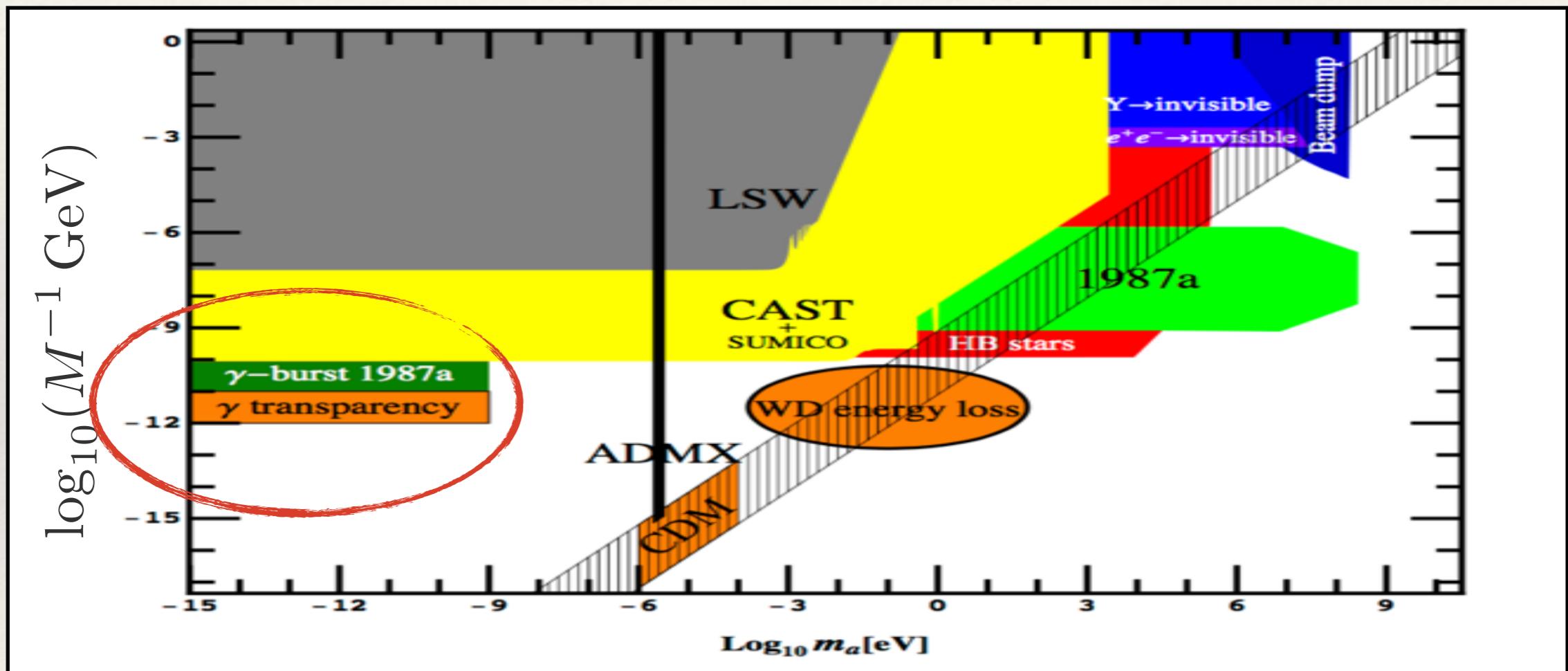


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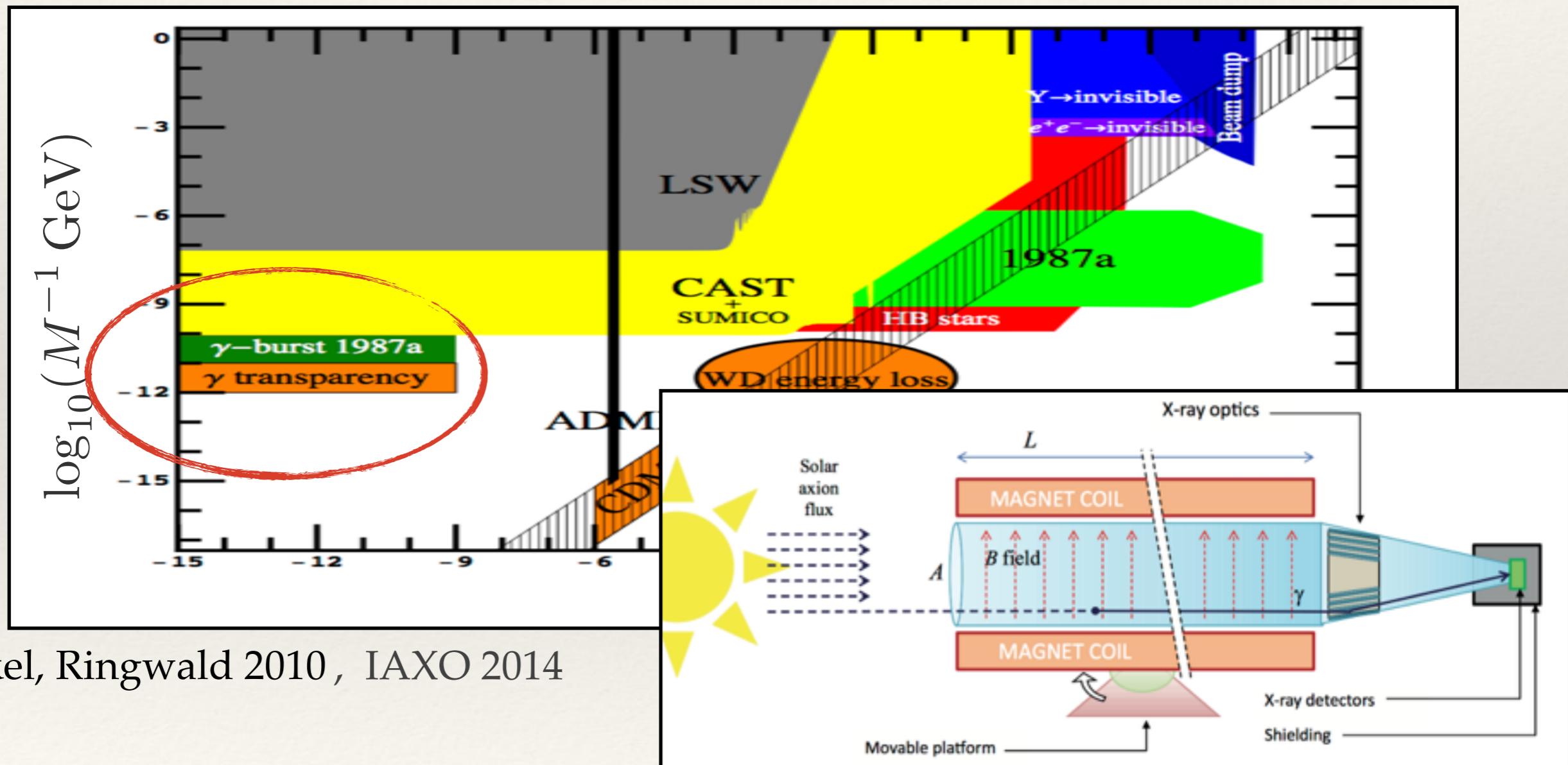


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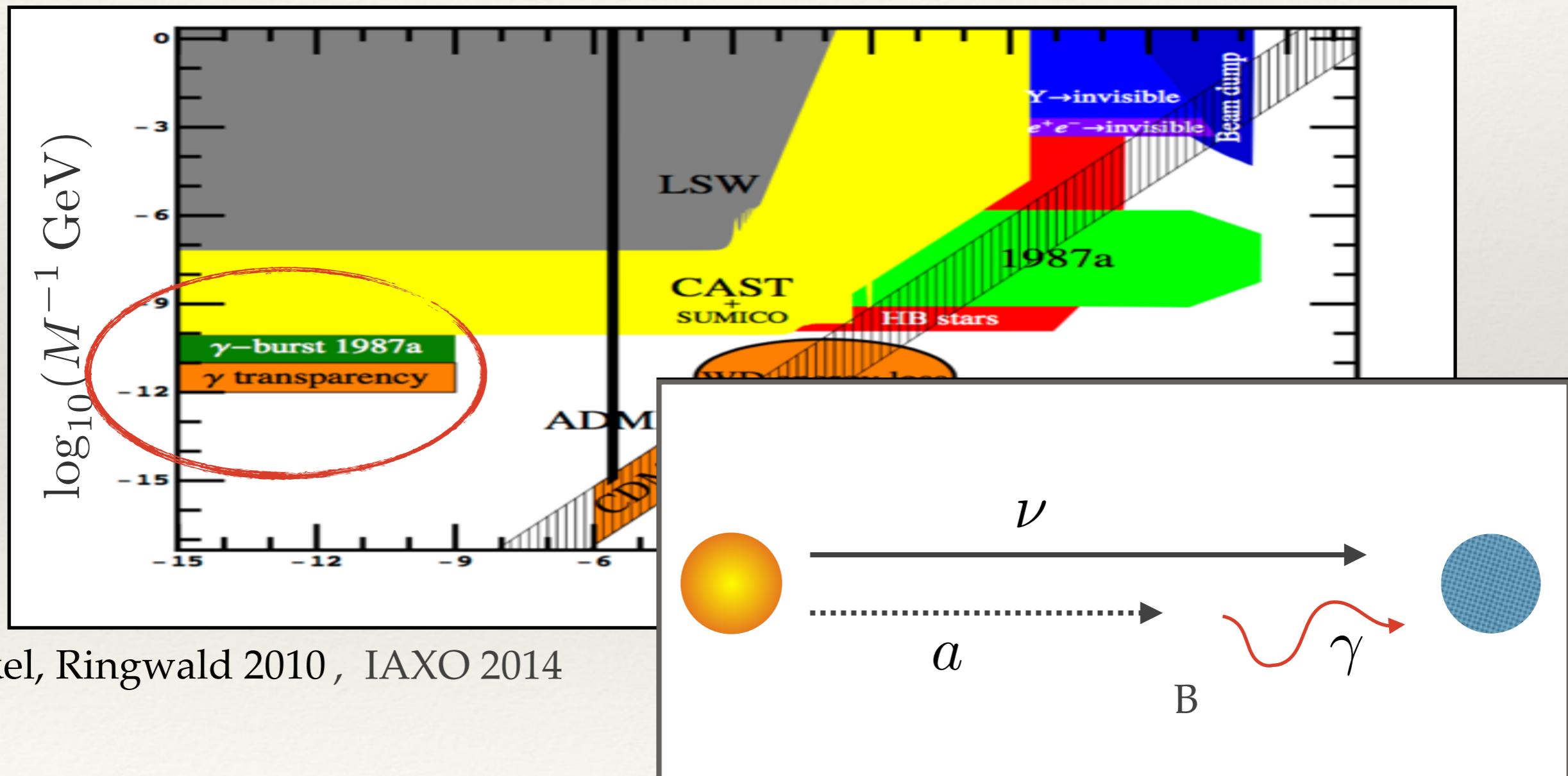


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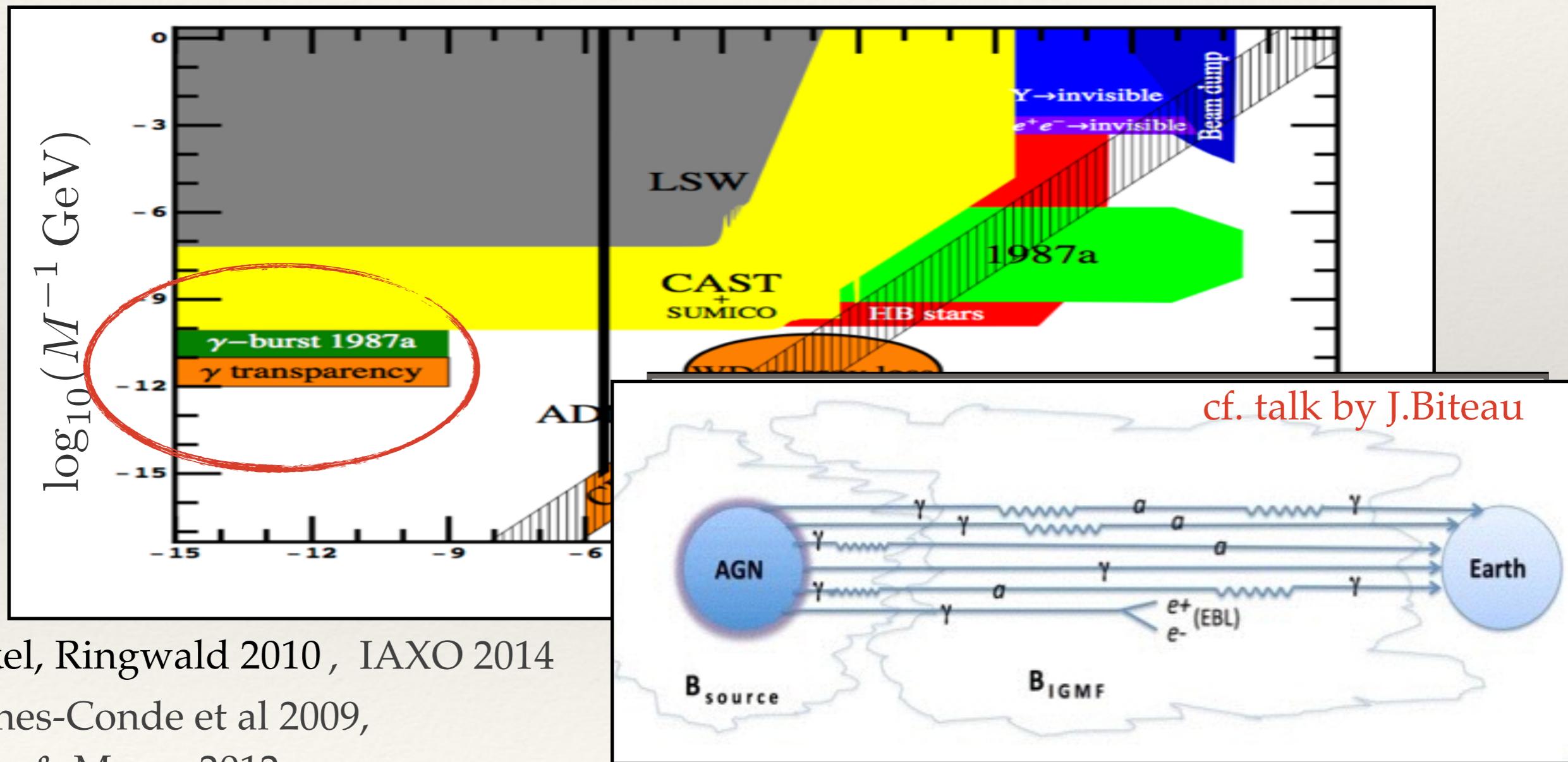
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Sanches-Conde et al 2009,

Horns & Meyer 2012.

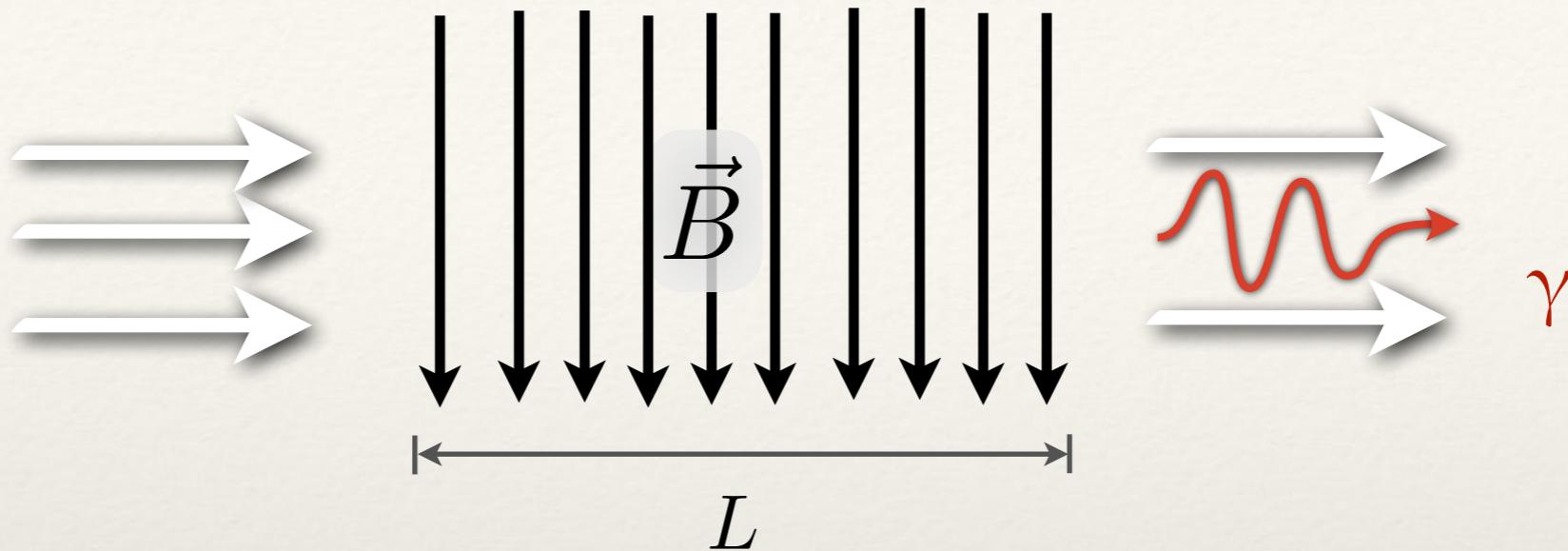
ALP-photon conversion

$$\frac{a}{M} F_{\mu\nu} \tilde{F}^{\mu\nu} = \frac{a}{M} \vec{E} \cdot \vec{B} .$$

Sikivie '83

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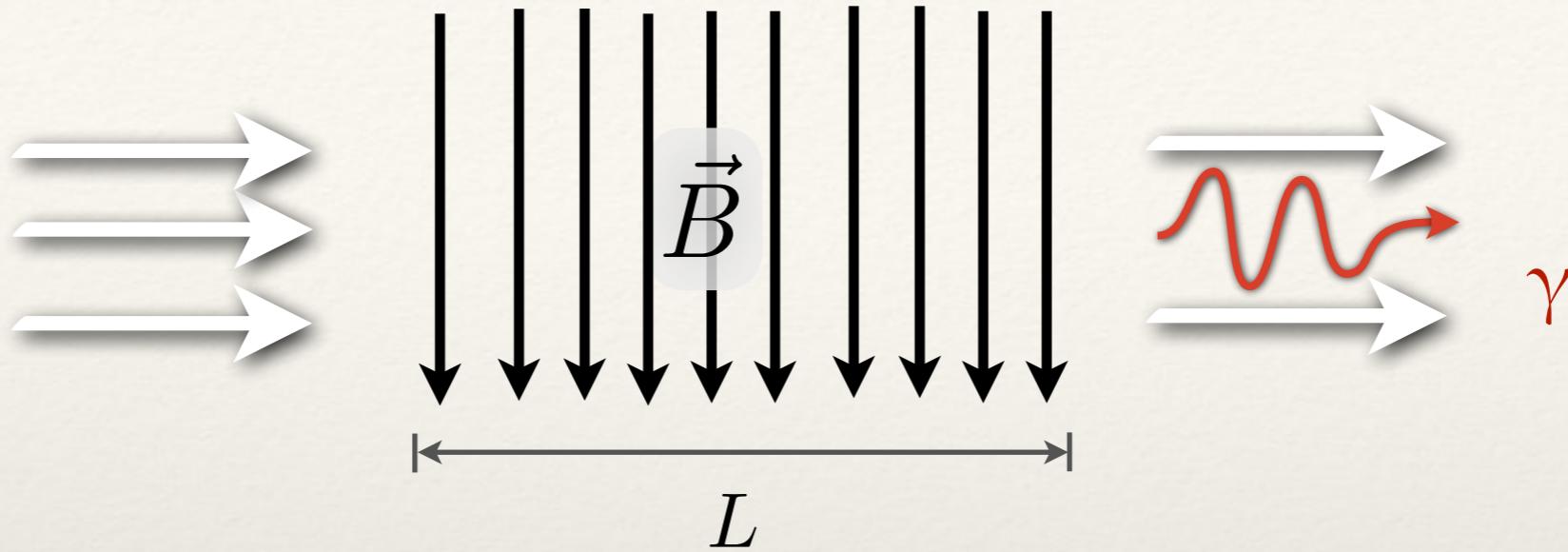
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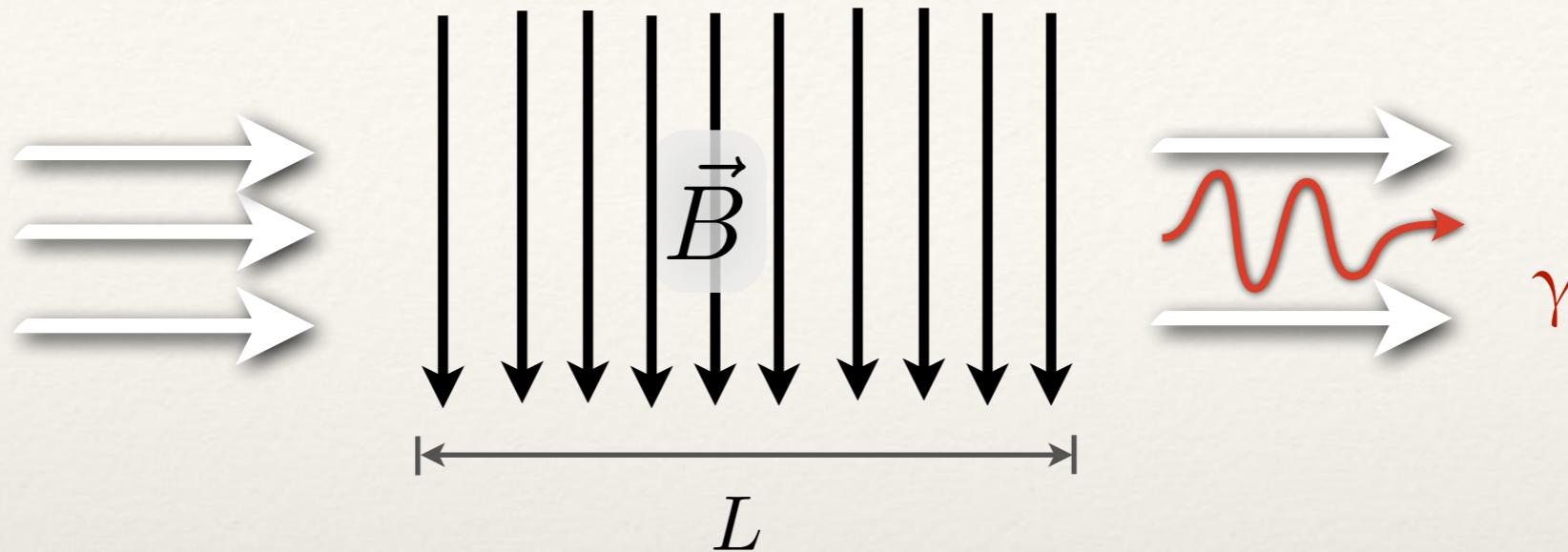


$$\square a = m_a^2 a - \frac{1}{4M} \vec{E} \cdot \vec{B} , \quad \nabla_\nu F^{\mu\nu} = J^\mu + \frac{1}{2M} \epsilon^{\mu\nu\lambda\rho} \nabla_\nu (a F_{\lambda\rho}) .$$

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Linearised, in background magnetic field:

$$\left(\omega + \begin{pmatrix} \Delta_\gamma & \Delta_F & \Delta_{\gamma ax} \\ \Delta_F & \Delta_\gamma & \Delta_{\gamma ay} \\ \Delta_{\gamma ax} & \Delta_{\gamma ay} & \Delta_a \end{pmatrix} - i\partial_z \right) \begin{pmatrix} \gamma_x \\ \gamma_y \\ a \end{pmatrix} = 0 .$$

Here, $\Delta_\gamma = -\frac{\omega_{pl}^2}{2\omega}$, $\Delta_{\gamma ai} = B_i/2M$, $\Delta_a = -m_a^2/\omega$.

Sikivie '83

Conversion probability

Single domain with coherent magnetic field:

$$P(a \rightarrow \gamma) = \sin^2(2\theta) \sin^2 \left(\frac{\Delta}{\cos(2\theta)} \right) \rightarrow \frac{1}{4} \left(\frac{B_\perp L}{M} \right)^2, \quad \text{"Small angle approximation"}$$

$$\text{with } \theta \approx \frac{B_\perp \omega}{M(m_a^2 - \omega_{pl}^2)} \quad \text{and} \quad \Delta = \frac{(m_a^2 - \omega_{pl}^2)L}{4\omega}.$$

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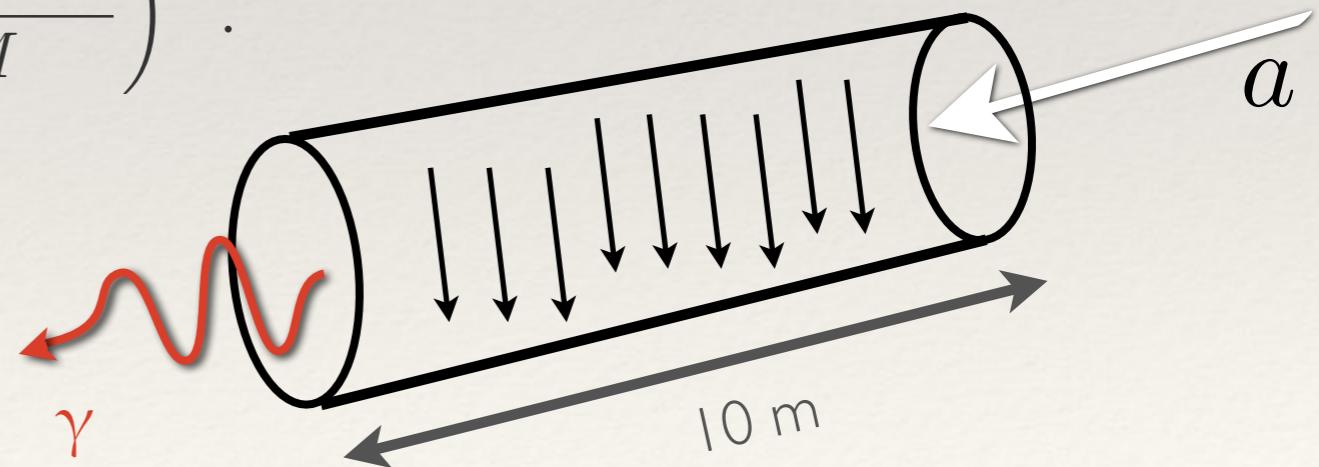
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Look for **strong** magnetic fields ($P \sim B^2$) coherent over **large** distances ($P \sim L^2$).

Example: For CAST-like experiment:

$$P(a \rightarrow \gamma) \approx 2 \cdot 10^{-19} \cdot \left(\frac{B_\perp}{10 \text{ T}} \frac{L}{10 \text{ m}} \frac{10^{11} \text{ GeV}}{M} \right)^2.$$



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Galaxy clusters

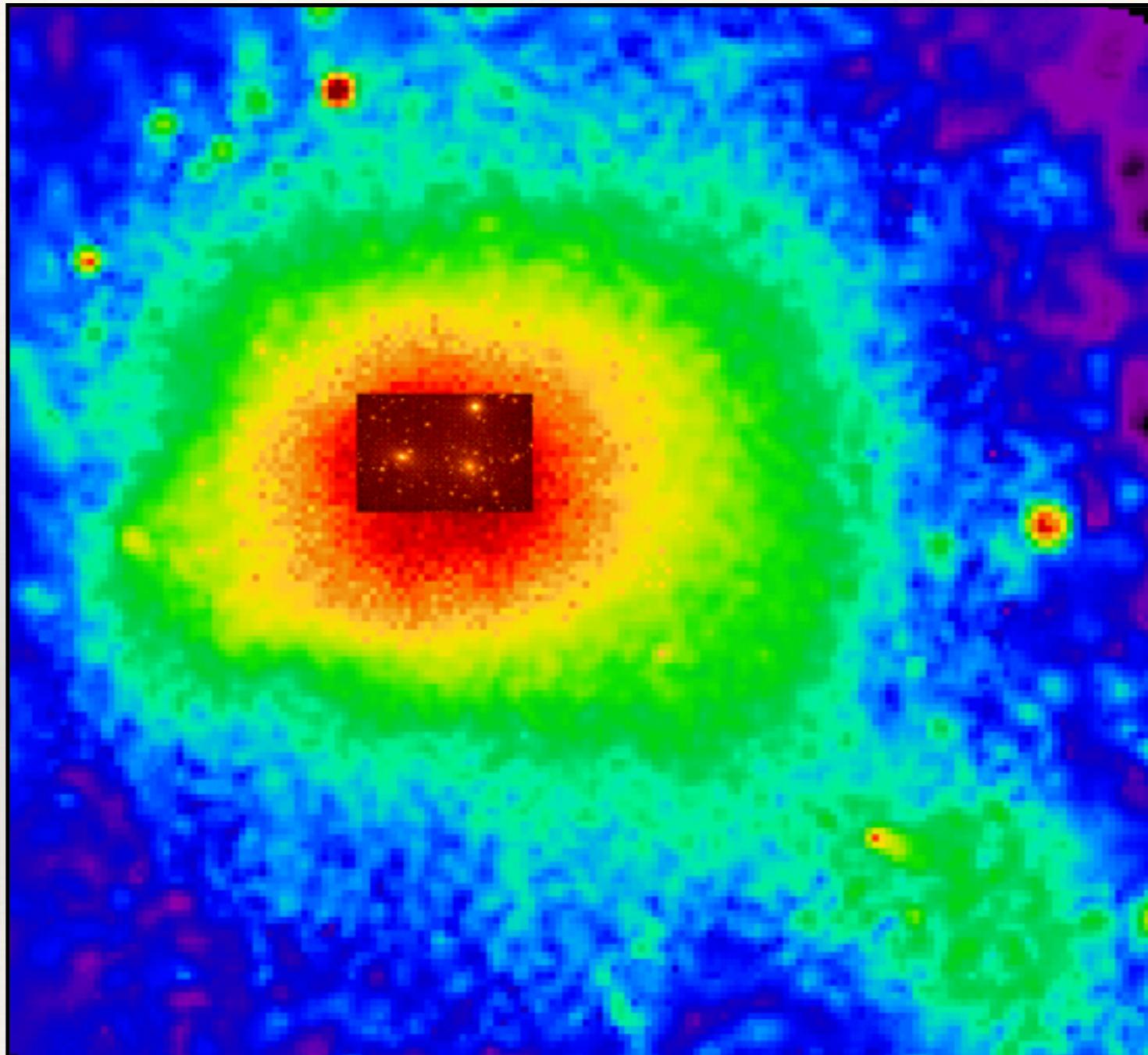
Galaxy clusters are the largest gravitationally bound structures of the universe ($1 \leq R \leq 10$ Mpc, $10^{12} \leq M \leq 10^{15}$ M_{\odot}), and consists of several tens or hundreds of galaxies.



The Coma cluster, as seen by HST.

Galaxy clusters

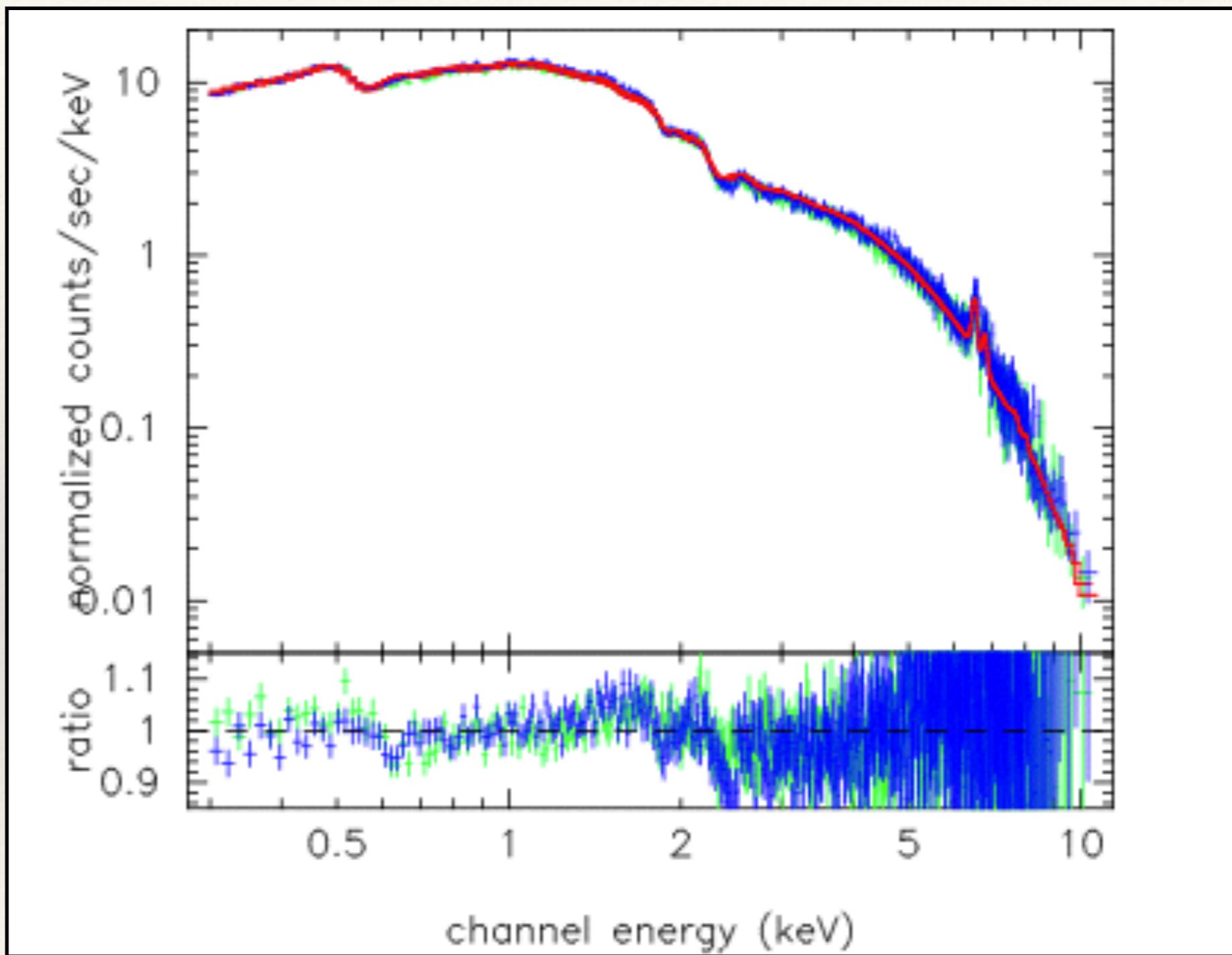
Galaxy clusters are dark matter dominated (90% in mass), and is permeated by hot gas with keV temperatures (9% in mass).



The Coma cluster, as seen by ROSAT.

Galaxy cluster X-rays

X-ray spectra \sim thermal bremsstrahlung + ion lines.

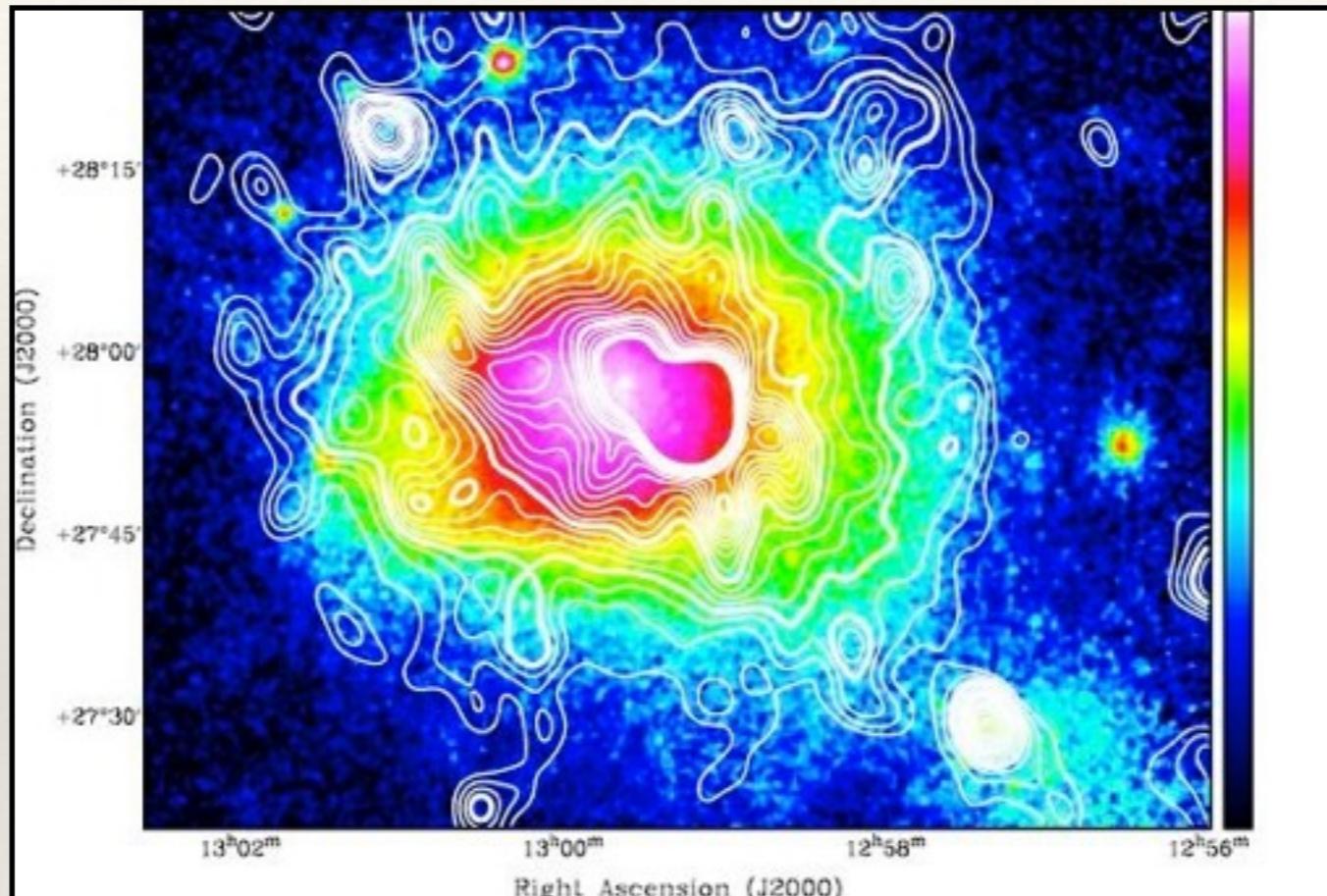


XMM-Newton spectrum for central region of Coma from Arnaud et al., 2001.

Magnetic fields in galaxy clusters

Clusters support magnetic fields with $\langle |B| \rangle = 1-10 \mu\text{G}$.

Radio halos arise from synchrotron radiation of a population of relativistic electrons.



Coma radio halo.

For the Coma cluster, the level of synchrotron emission from the radio halo (and non-observation of IC-CMB hard X-rays), gives $\langle |B| \rangle > 0.2 \mu\text{G}$.

Cluster magnetic fields from Faraday rotation

The birefringence of the magnetised plasma gives rise to Faraday rotation of polarised photons:

$$\Delta\theta \propto \lambda^2 \int n_e(l) \vec{B} \cdot d\vec{l}.$$

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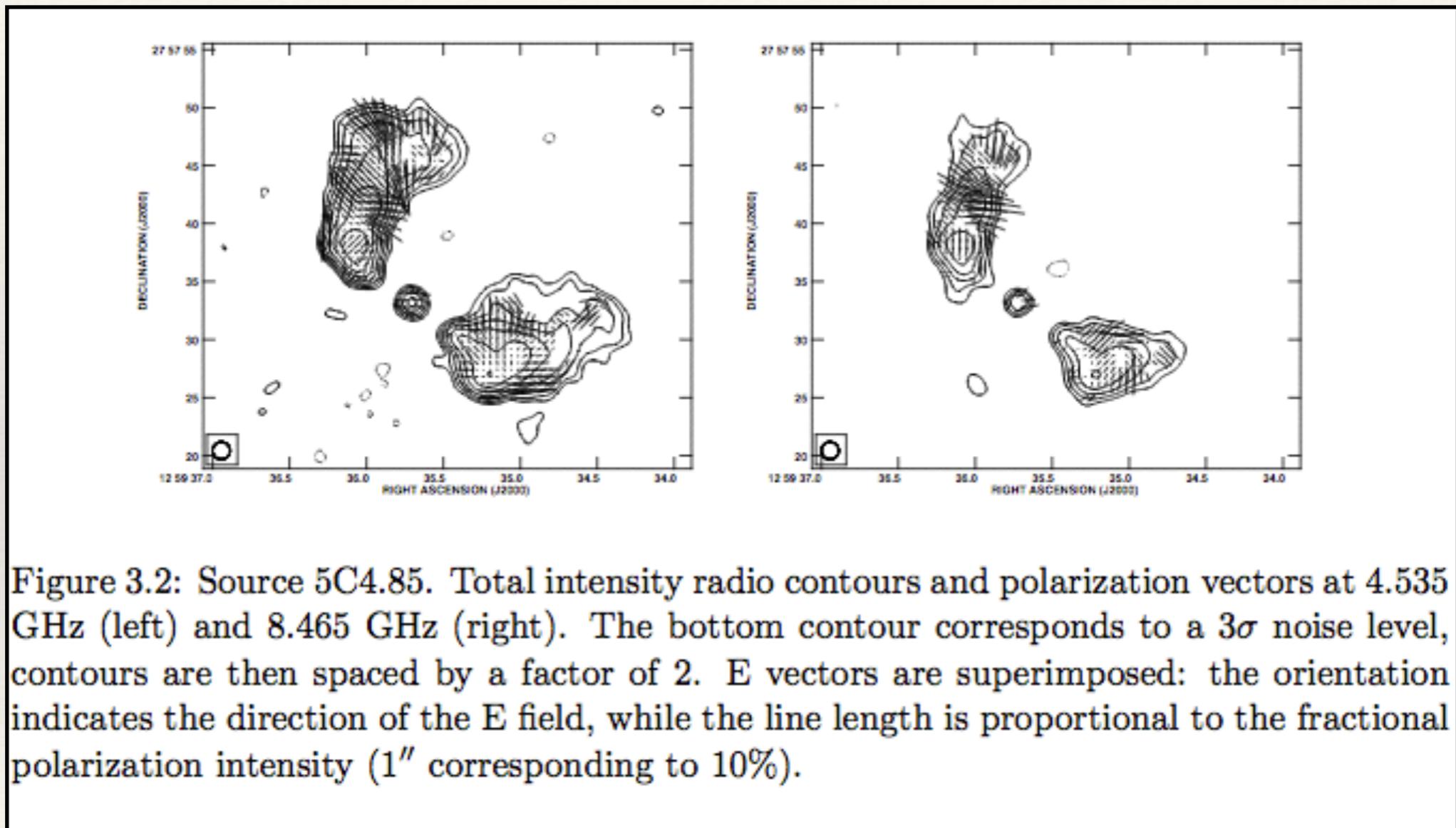
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Rotation measure

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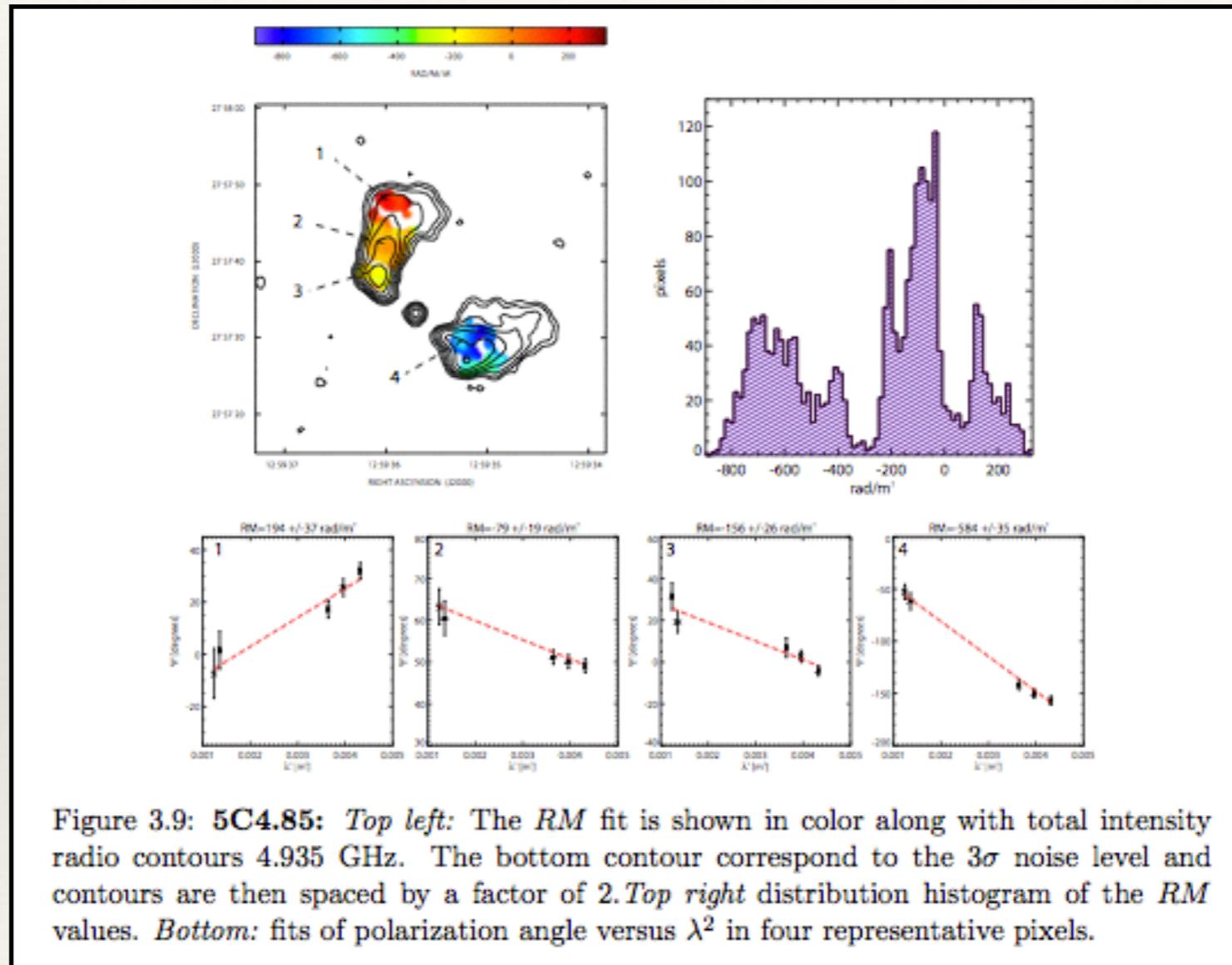


Radio image of a source in Coma, taken from Bonafede's thesis.

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Modelling cluster magnetic fields

Magnetic field model for Coma:

$$1. \quad \langle |\tilde{A}_k|^2 \rangle \sim k^{-n}, \quad k_{\min} \leq k \leq k_{\max}.$$

$$2. \quad \vec{\tilde{B}}_{\text{gen.}} := i\vec{k} \times \vec{\tilde{A}}(k).$$

$$\vec{B}_{\text{tot.}} := \mathcal{C}B_0 \left(\frac{n_e(r)}{n_e(0)} \right)^\eta \vec{B}_{\text{gen.}}.$$

The parameters n , k_{\min} , k_{\max} , η , and B_0 may then be constrained by comparing the observed distribution of RMs from a set of radio sources to simulated mock RMs.

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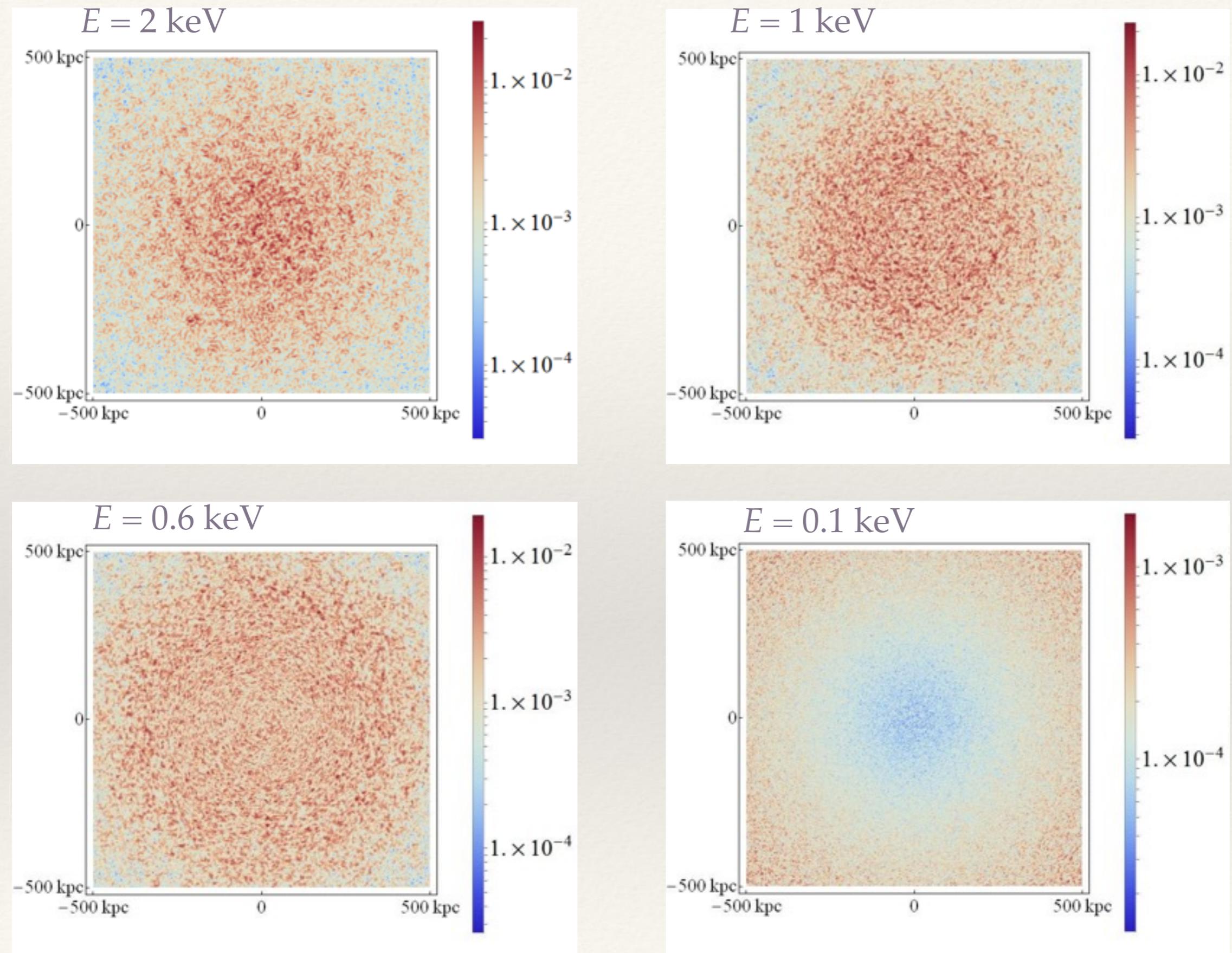
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Baseline: $n=17/3$, $k_{\min}=2\pi/(34 \text{ kpc})$, $k_{\max}=2\pi/(3 \text{ kpc})$, $\eta=0.4-0.7$, and $B_0=3.9-5.4 \mu\text{G}$.

Alternate model: $n=4$, $k_{\min}=2\pi/(100 \text{ kpc})$, $k_{\max}=2\pi/(2 \text{ kpc})$, $\eta=0.7$, and $B_0=5.4 \mu\text{G}$.

Bonafede et al., 2010.

Here $m_a=0$ and $M=7\times 10^{12}$ GeV. Angus, Conlon, D.M., Powell, Witkowski, '13.



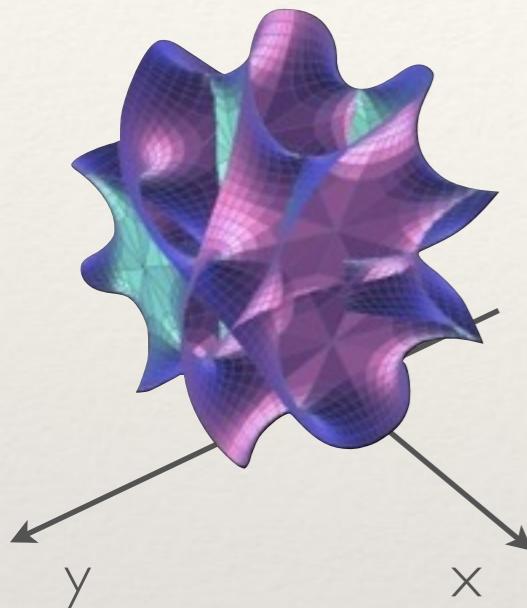
If light ALPs at keV energies are produced
by any mechanism,
galaxy clusters are ideal targets to search for them.

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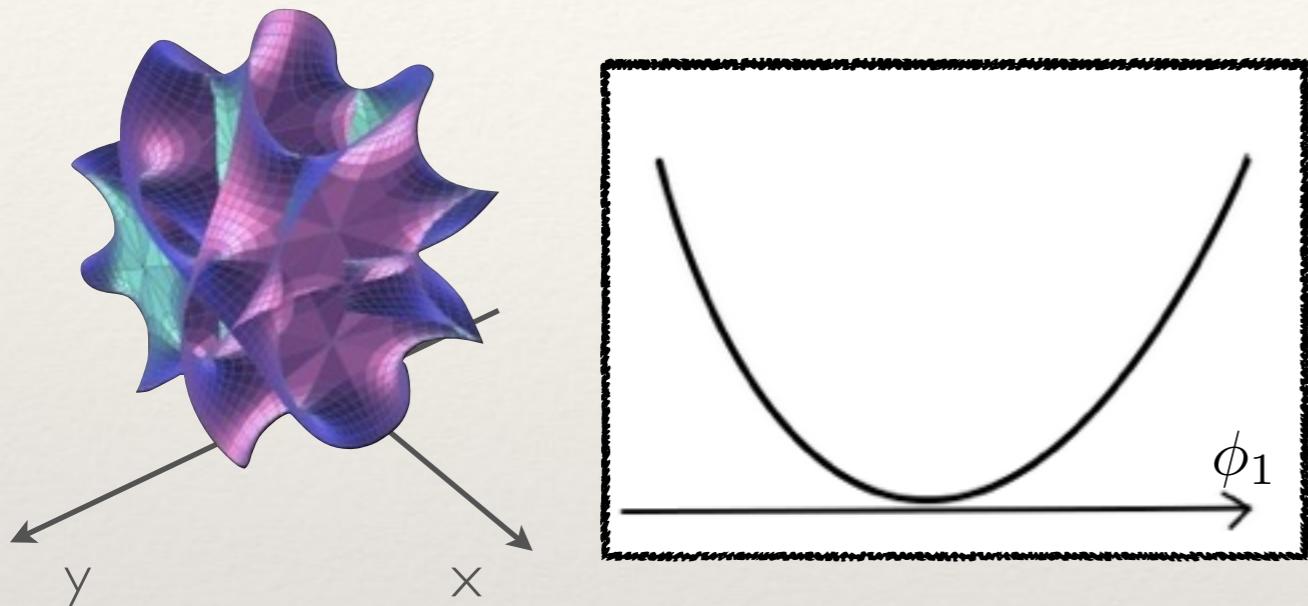
Moduli decay into ALPs

The low-energy spectrum of stabilised compactifications of string theory include massive scalar fields that couple with Planck mass suppressed couplings (moduli).



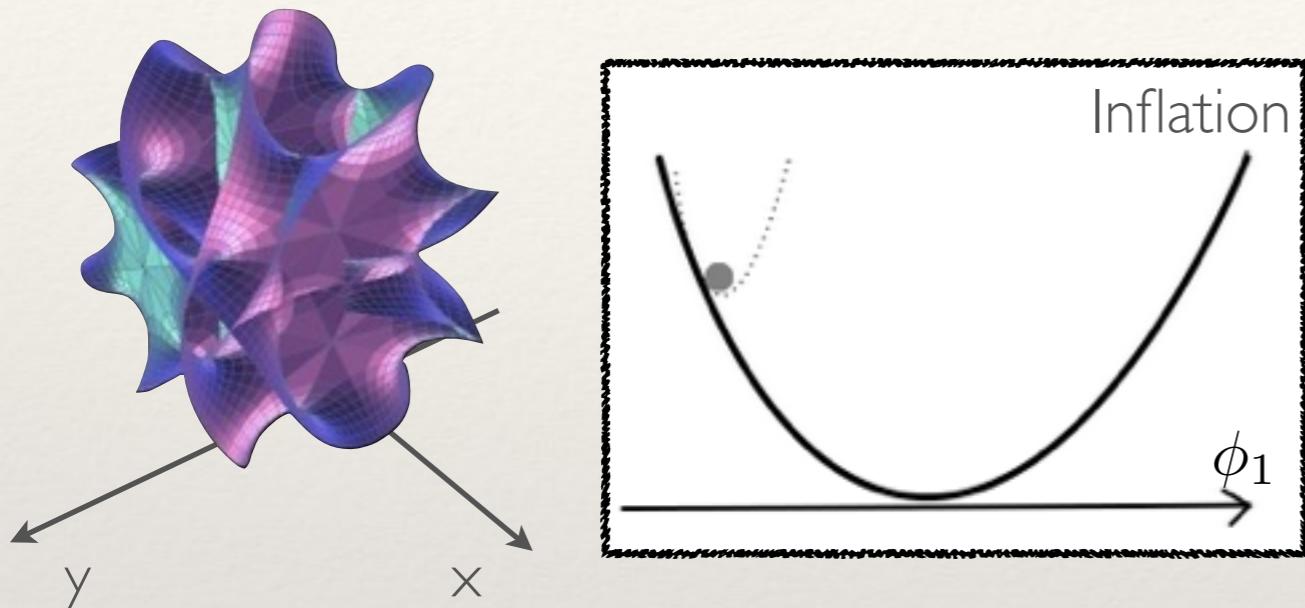
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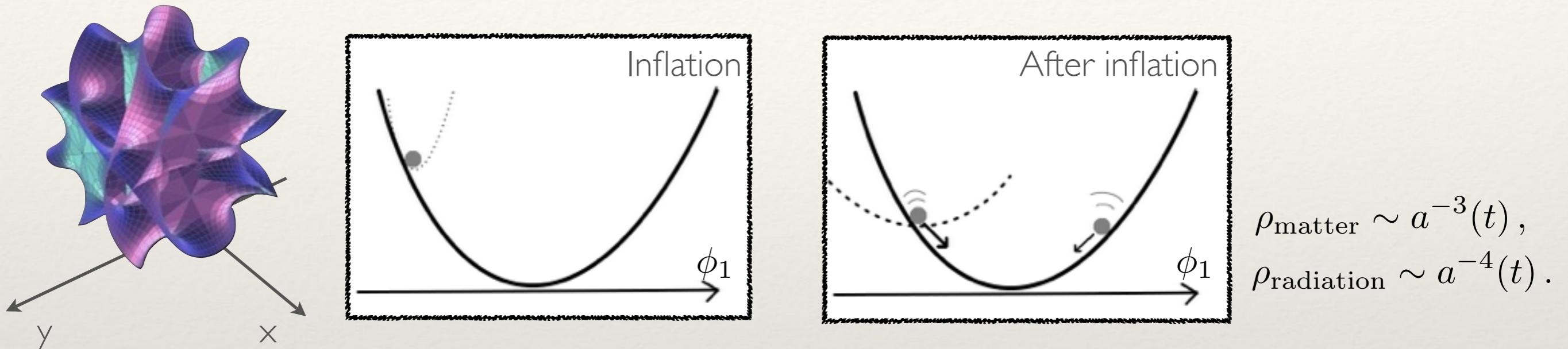
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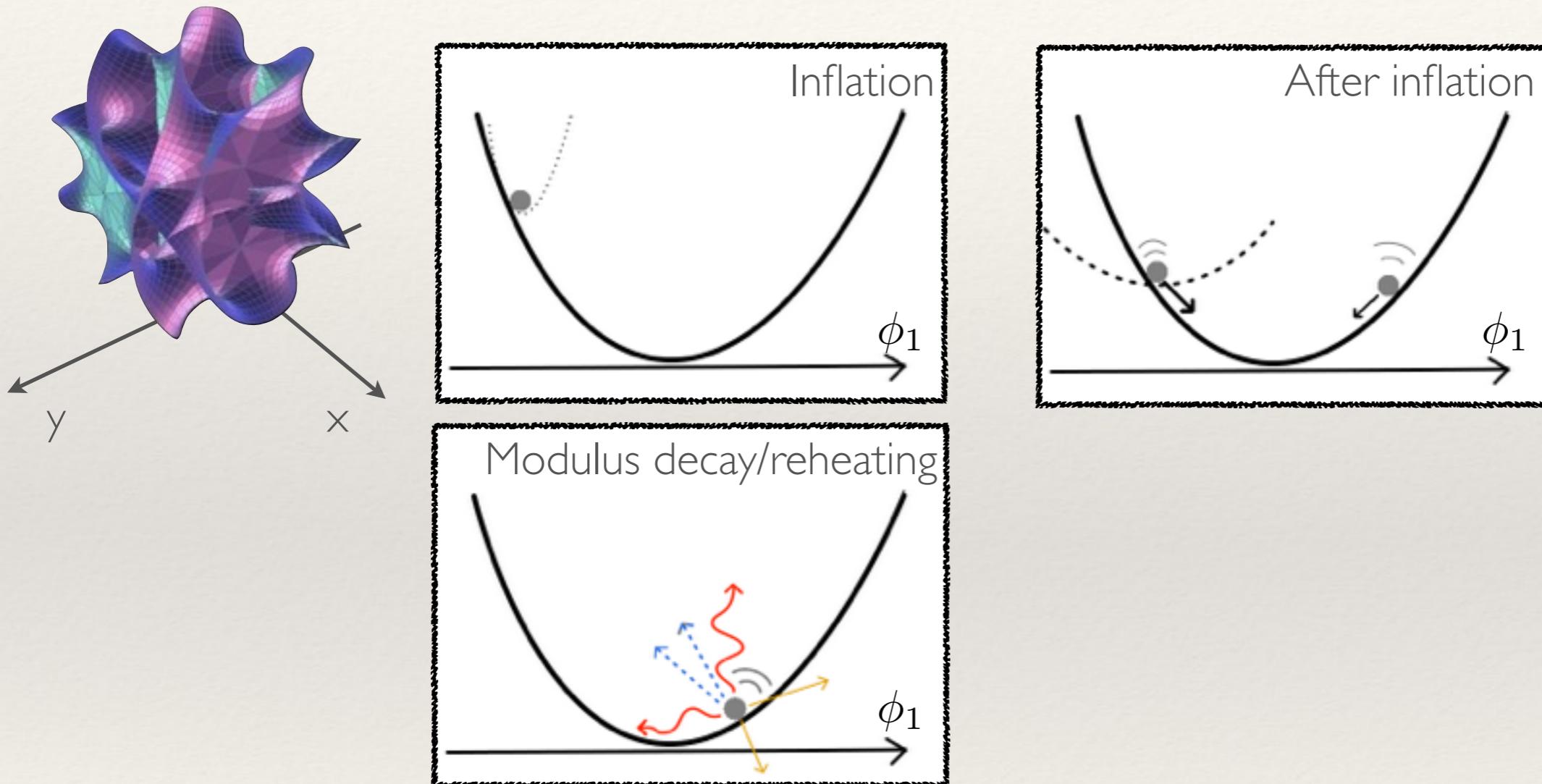
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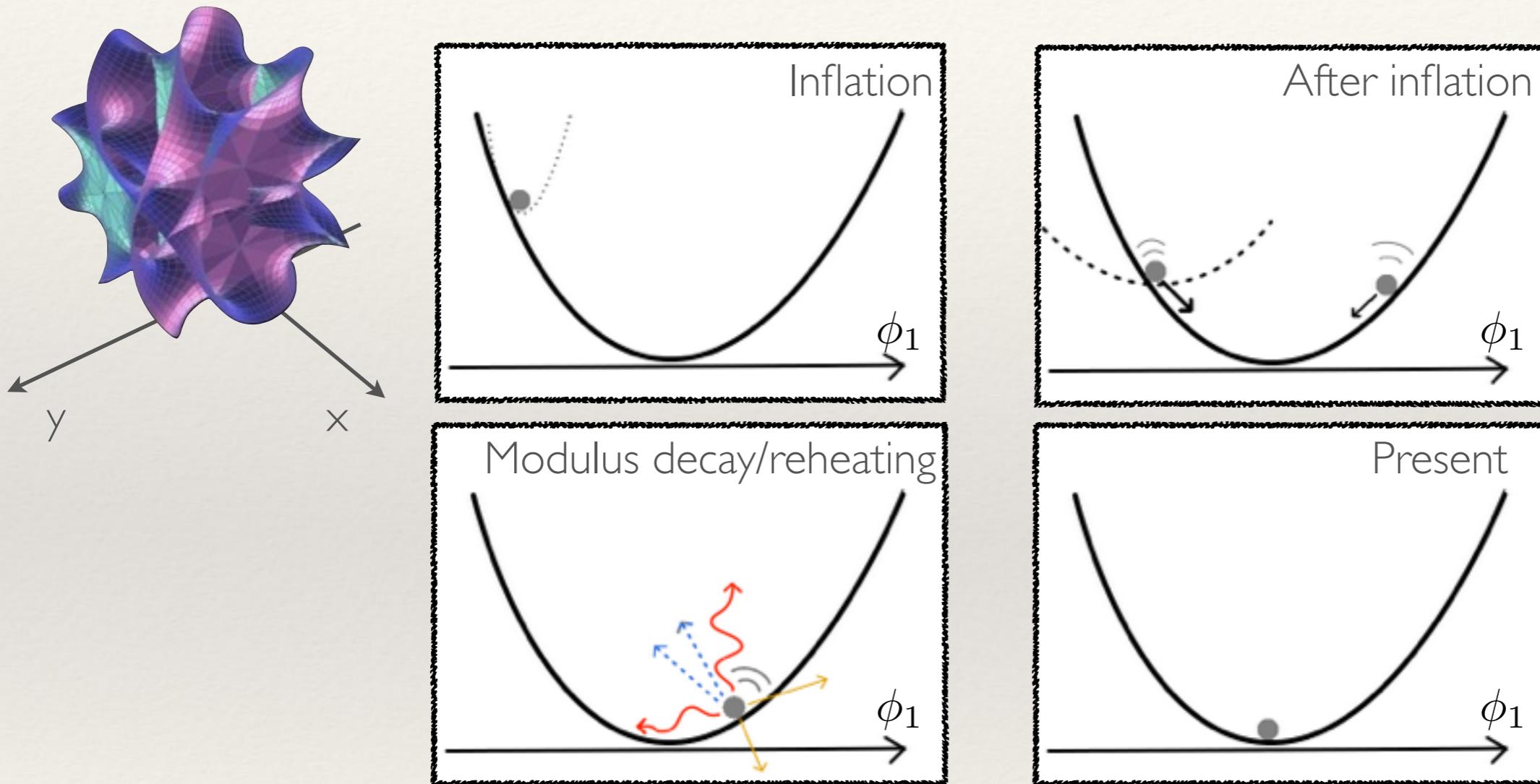
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Moduli and reheating

The decay of the lightest modulus drives reheating, but very weakly coupled fields never thermalise.

Thermal bath:

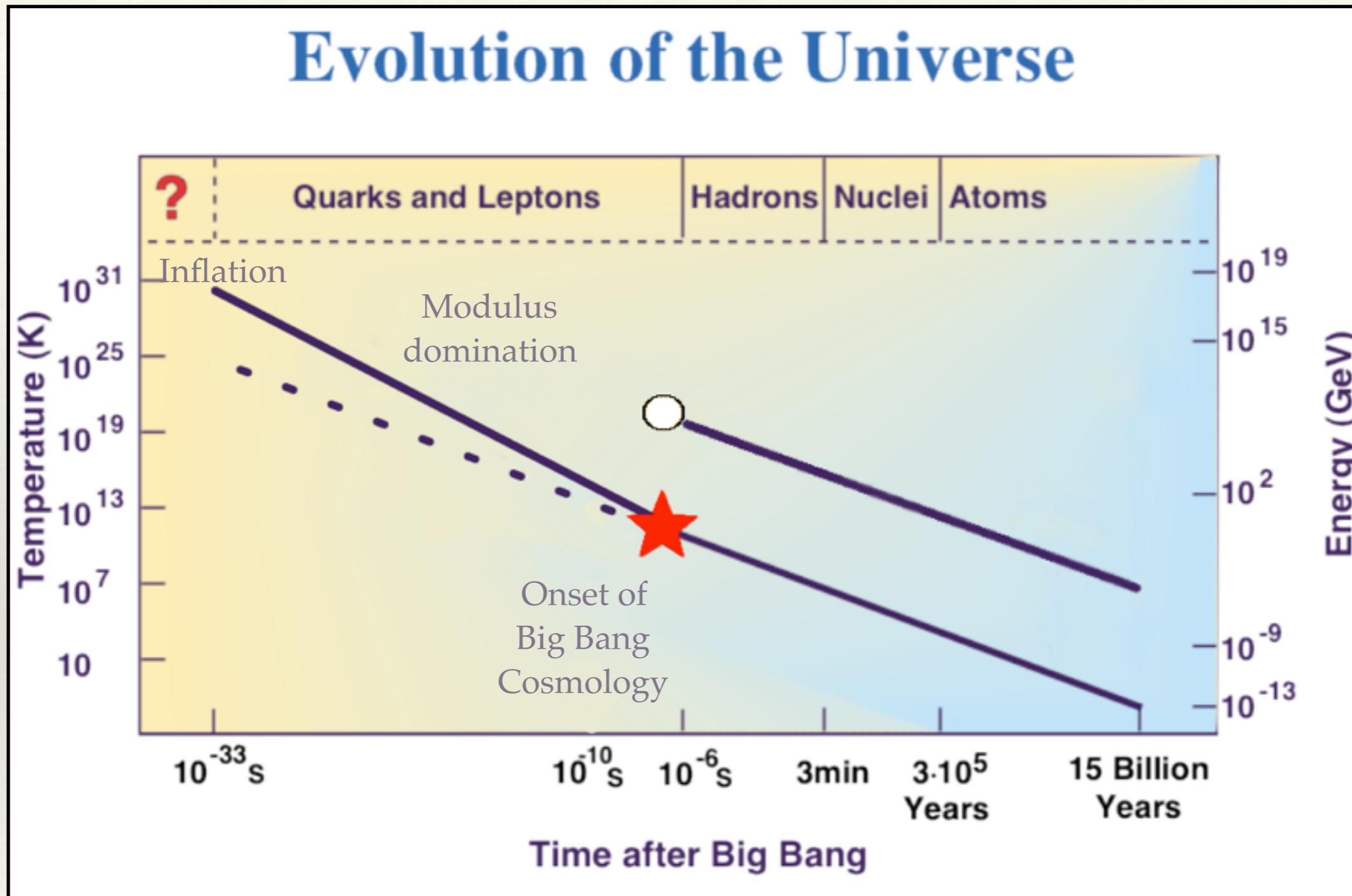
$$T_{rh} \sim (3H_{decay}^2 M_{Pl}^2)^{1/4} \sim (3M_{Pl}^2 / \tau_\phi^2)^{1/4} \sim \frac{m_\phi^{3/2}}{M_{Pl}^{1/2}}$$
$$\sim 0.6 \text{ GeV} \left(\frac{m_\phi}{10^6 \text{ GeV}} \right)^{3/2},$$

Weakly coupled particles (ALPs, hidden photons):

$$E_a^{(0)} = m_{\phi_1}/2 \gg T_{rh},$$

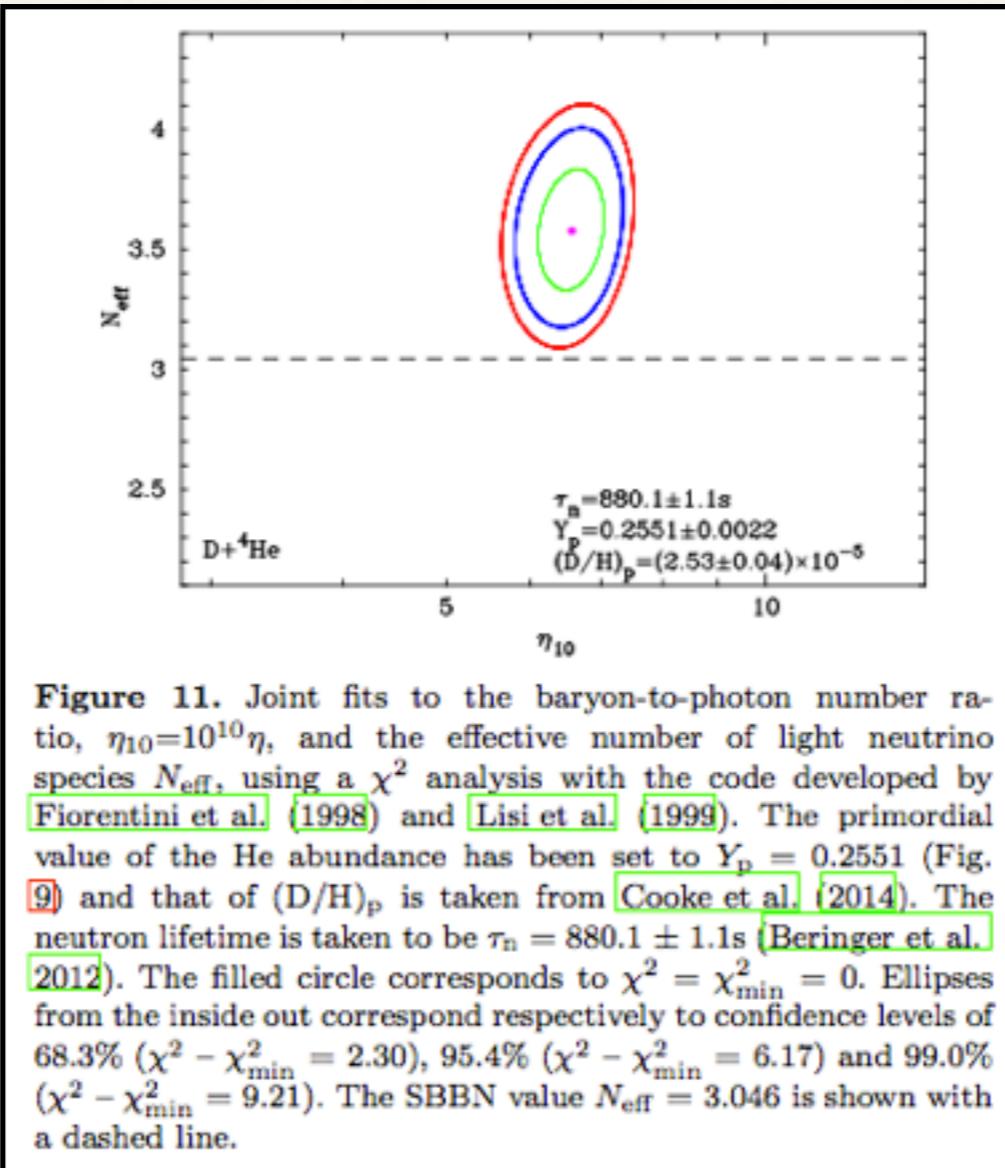
Moduli decay into light, weakly coupled hidden sector fields (e.g. *axion-like particles*, hidden photons) produce *dark radiation* with present energies $E \sim O(0.1\text{-}1 \text{ keV})$.

A Cosmic Axion Background



Constraints on dark radiation

1. **BBN:** $\Delta N_{\text{eff}} > 0$ increases expansion rate at BBN and increase the primordial abundance of ${}^4\text{He}$.
2. **CMB:** $\Delta N_{\text{eff}} > 0$ effectively enhances the Silk damping of high-l multipoles.



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Planck:

$$\text{Planck+WMAP-pol+ high-}l\text{-BAO:} \quad \Delta N_{\text{eff}} = 0.26 \pm 0.27,$$

$$\text{Planck+WMAP-pol+ high-}l\text{-BAO +}H_0: \quad \Delta N_{\text{eff}} = 0.48 \pm 0.25,$$

Planck collab. '15

Constraints on dark radiation

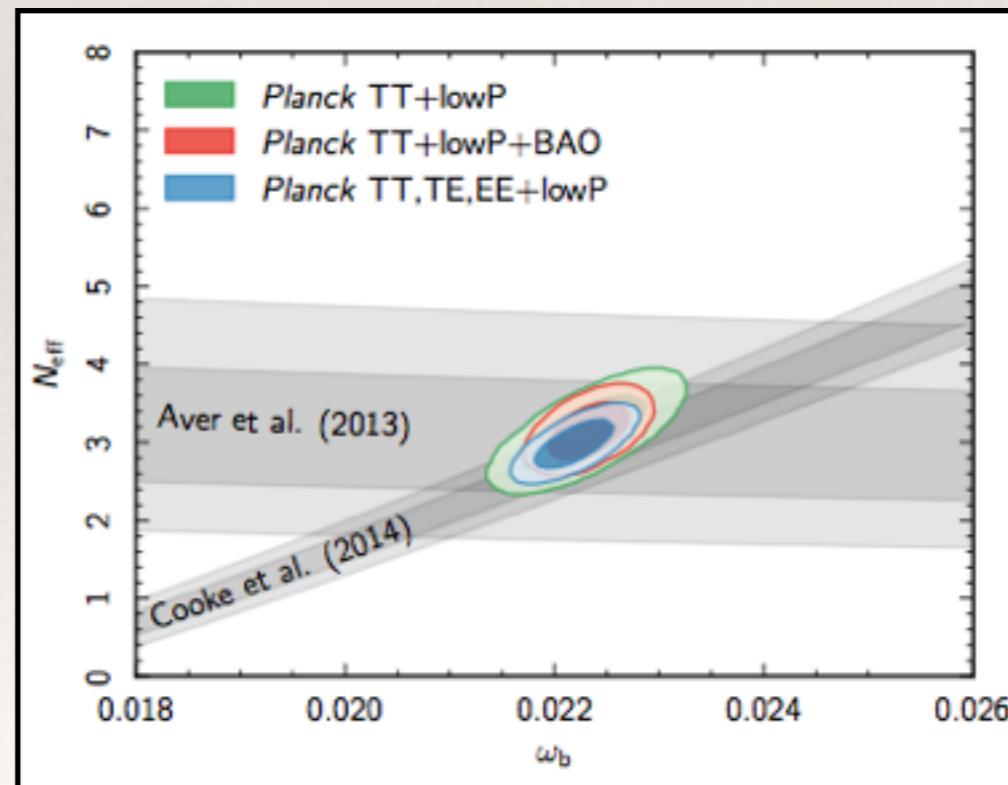
1. **BBN:** $\Delta N_{\text{eff}} > 0$ increases expansion rate at BBN and increase the primordial abundance of ${}^4\text{He}$.
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Planck:

$$\Delta N_{\text{eff}}$$

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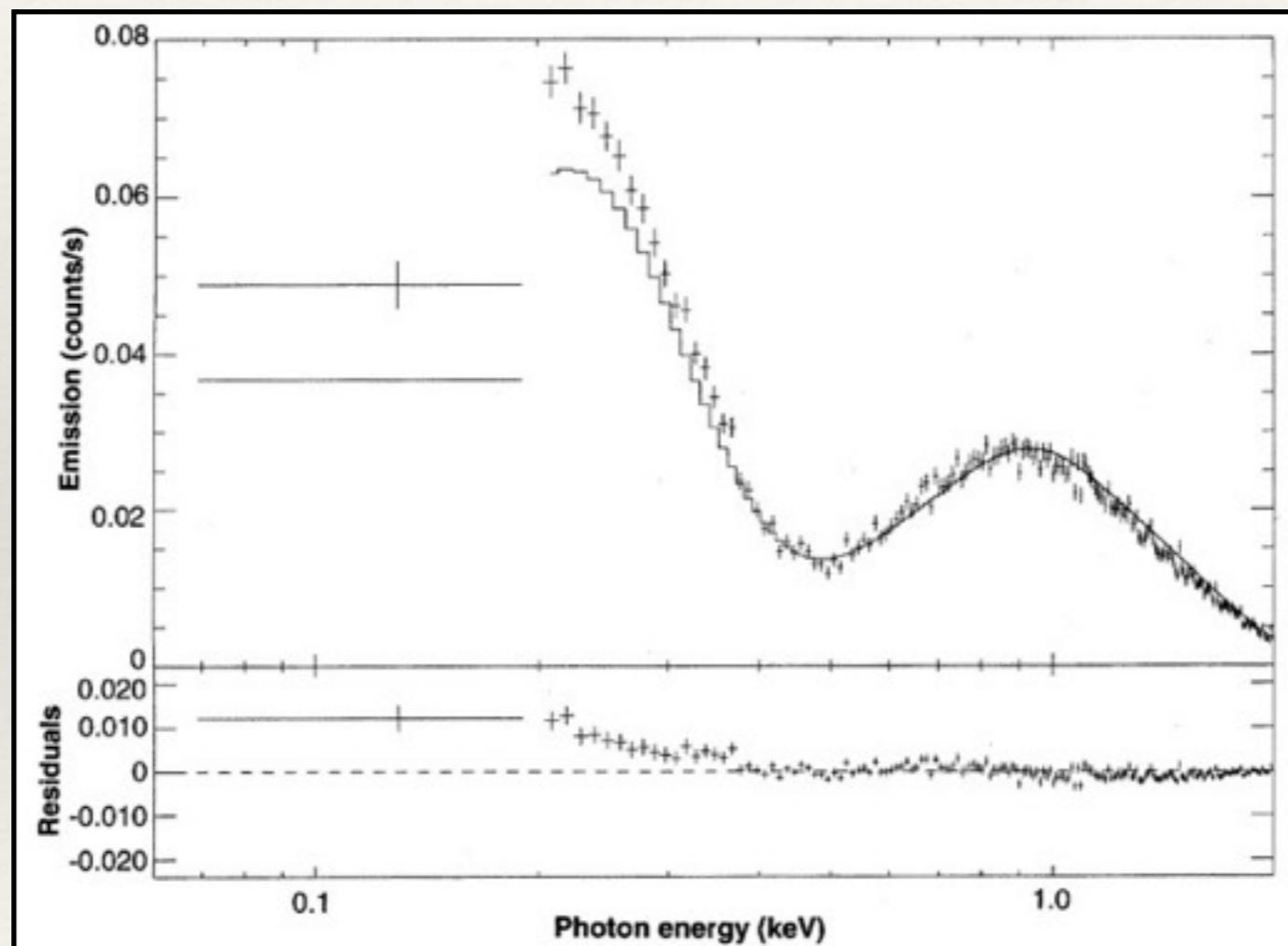


Planck collab. '15

A Cosmic Axion Background and the cluster soft X-ray excess

A CAB could be visible through ALP-photon conversion in clusters, and would result in an additional source of soft X-rays.

Intriguingly, an *excess of soft X-rays* from galaxy clusters have been reported in a large number of clusters since 1996.



EUVE on Virgo from Liu et al. '96.

See also Bonamente et al. '02.

Proposed astrophysical explanations of the cluster soft X-ray excess

Thermal model: Default suggestion at time of detection, currently disfavoured as main explanation (gas would cool too rapidly).



Same for
hot & warm gas

$$\underline{pV} = \underline{nRT}$$

Larger for
warm gas

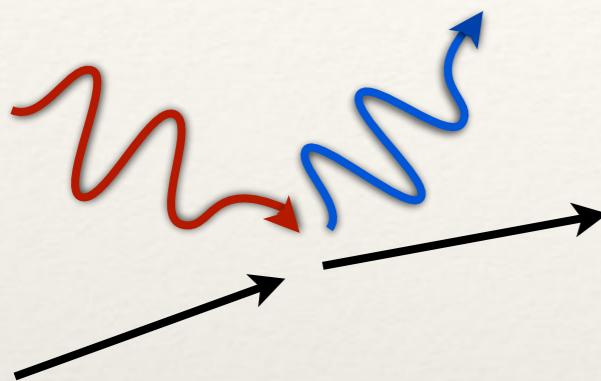
Smaller for
warm gas

$$t_{\text{cooling}}^{(\text{warm})} \sim n_{(\text{warm})}^{-2} \approx 10^{-4} n_{(\text{hot})}^{-2} \sim 10^8 \text{ yrs} \ll \tau^{(\text{cluster dyn.})}.$$

In addition, a warm gas would give rise to unobserved emission lines. Still, possible explanation of excess at large radii.

Proposed astrophysical explanations of the cluster soft X-ray excess

Non-thermal model: Inverse Compton Scattering of CMB photons off non-thermal gas: $E_{\text{scattered}} \sim \gamma^2 E_{\text{CMB}}$.

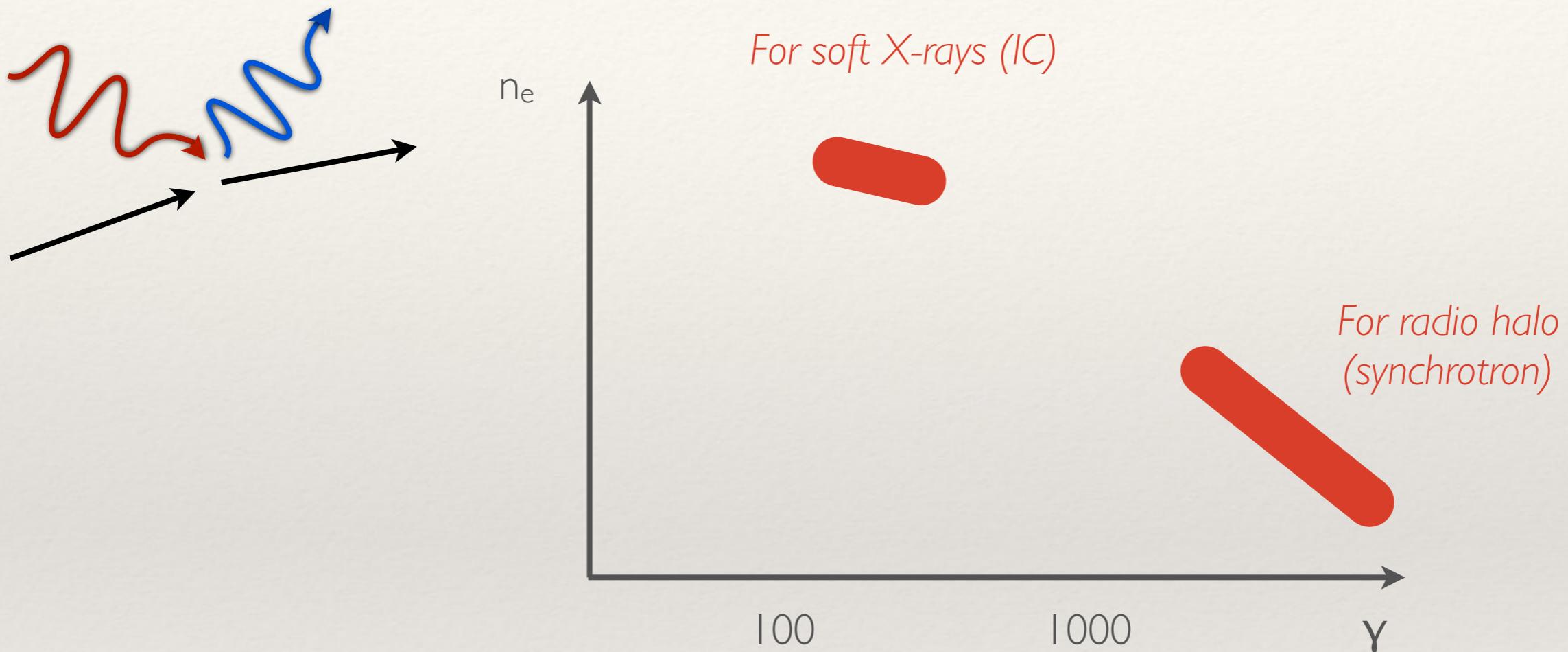


$$\gamma \sim 500$$

Hwang '97, Bowyer et al. '04, Sarazin '99, Atoyan et al '99.

Proposed astrophysical explanations of the cluster soft X-ray excess

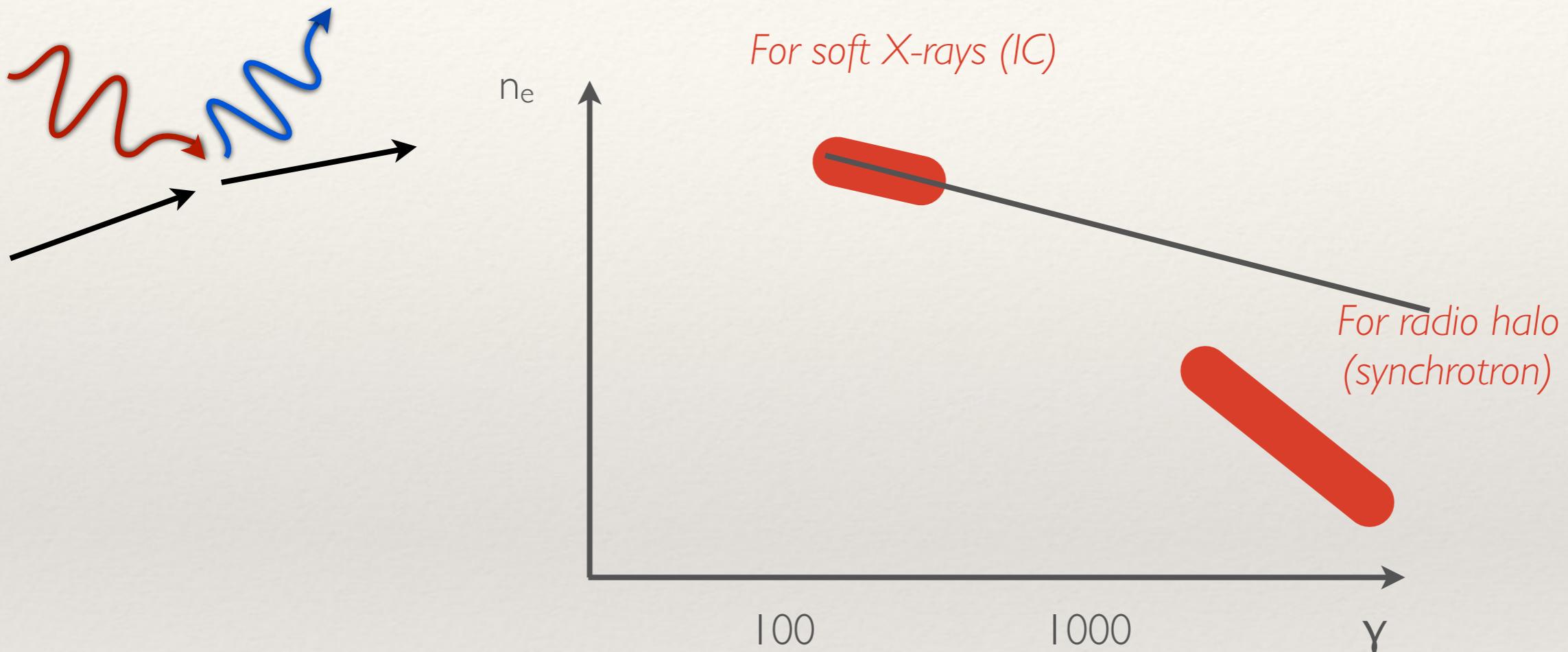
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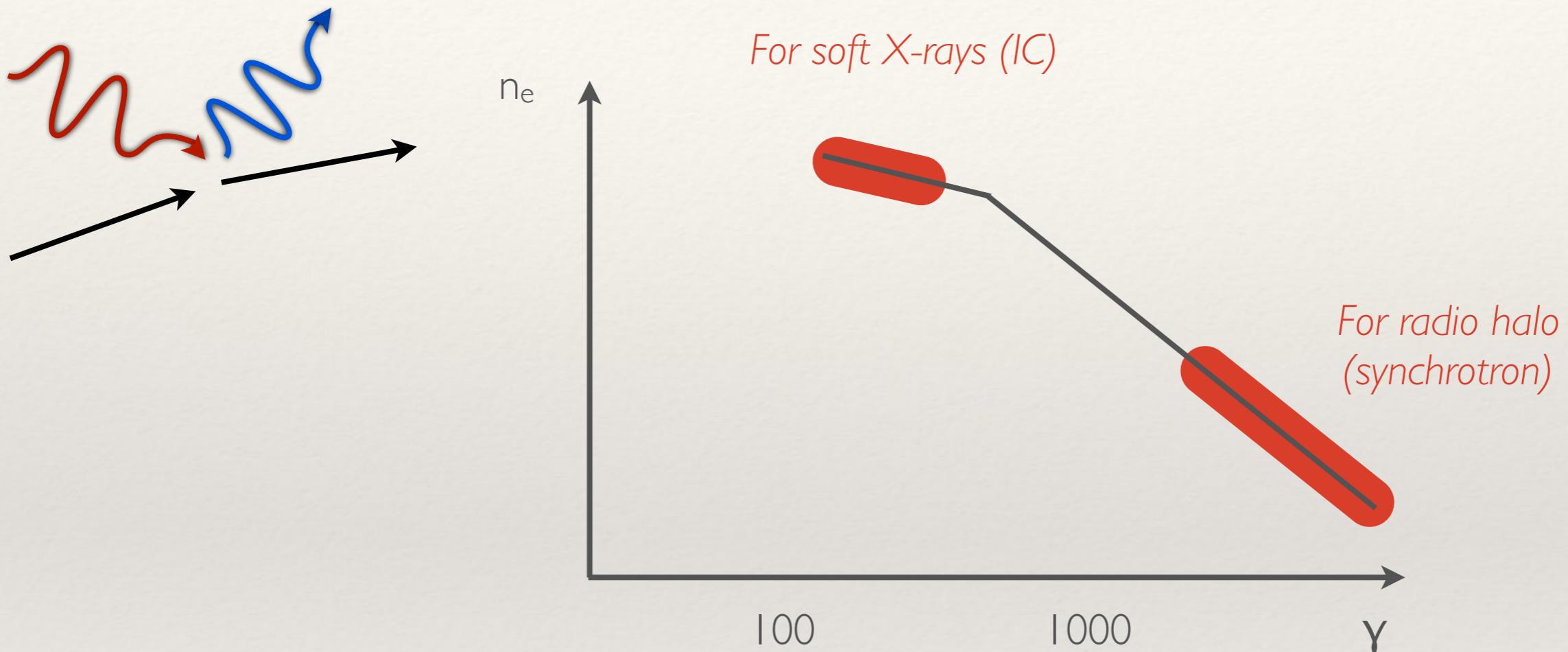
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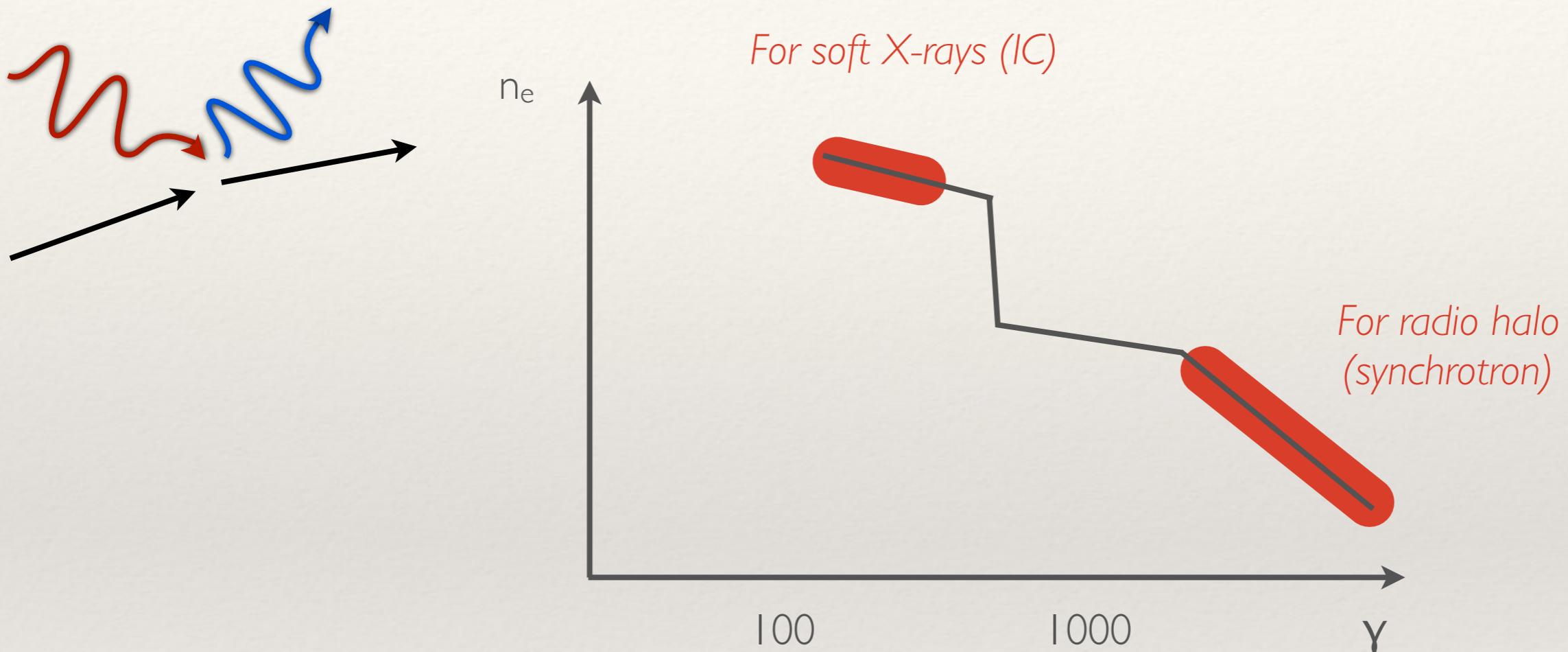
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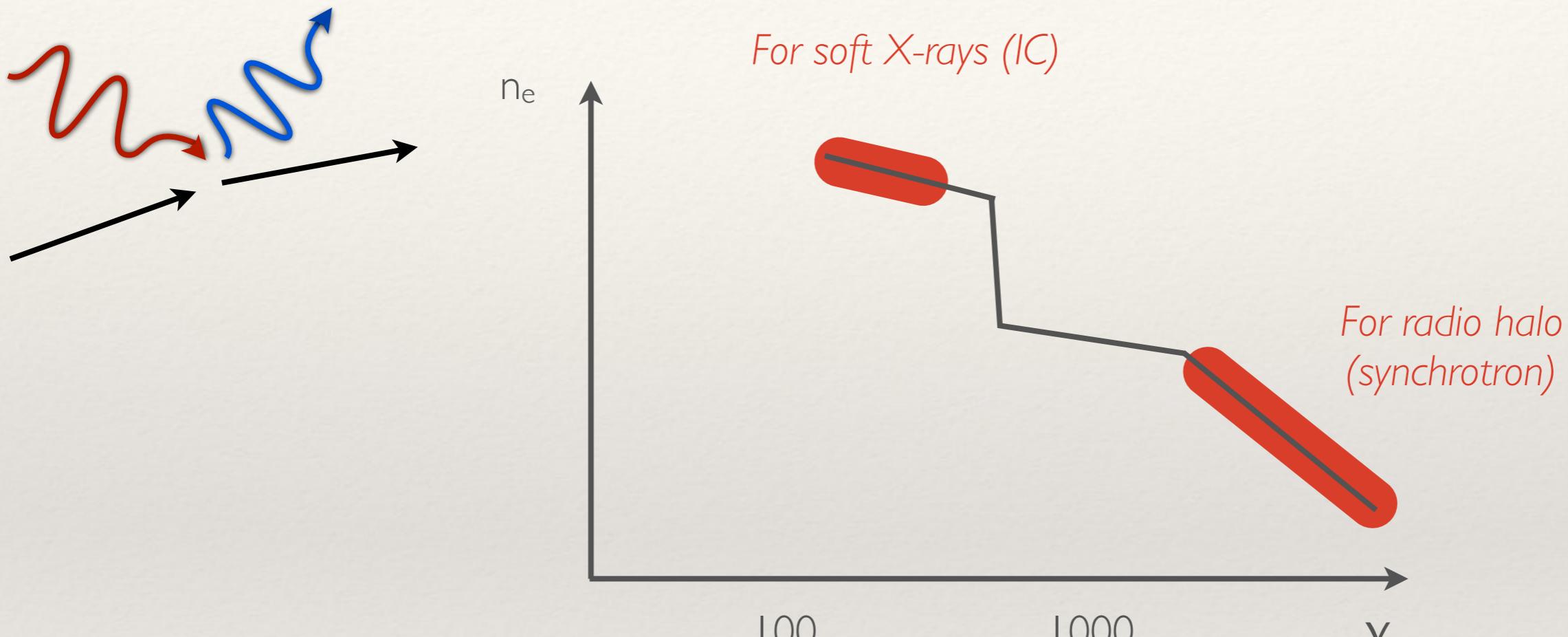


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Fine-tuned IC:

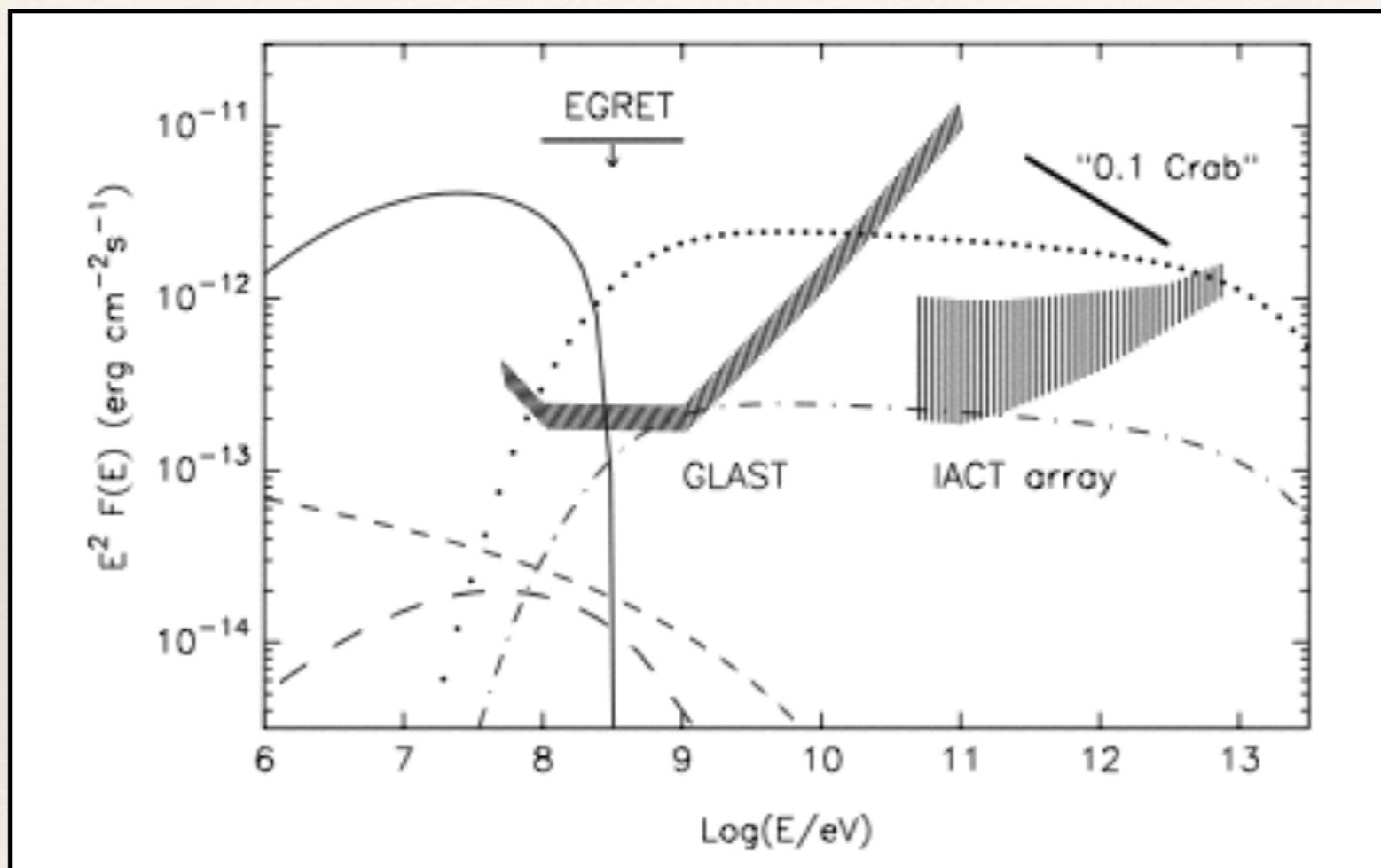
For Coma: $t_{\text{injection}} \sim 1.0-1.4 * 10^9$ yrs. In addition: small injection even in recent past to produce CR's for radio halo.

Hwang '97, Bowyer et al. '04, Sarazin '99, Atoyan et al '99.

Proposed astrophysical explanations of the cluster soft X-ray excess

Non-thermal model: associated bremsstrahlung.

Coma: predicted gamma-ray flux of $\sim 2 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$.



Atoyan, Vollmer 2000,
Sarazin 1999.

Proposed astrophysical explanations of the cluster soft X-ray excess

Non-thermal model: associated bremsstrahlung.

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Zandanel & Ando upper limit: $< 0.6\text{-}2.9 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$.

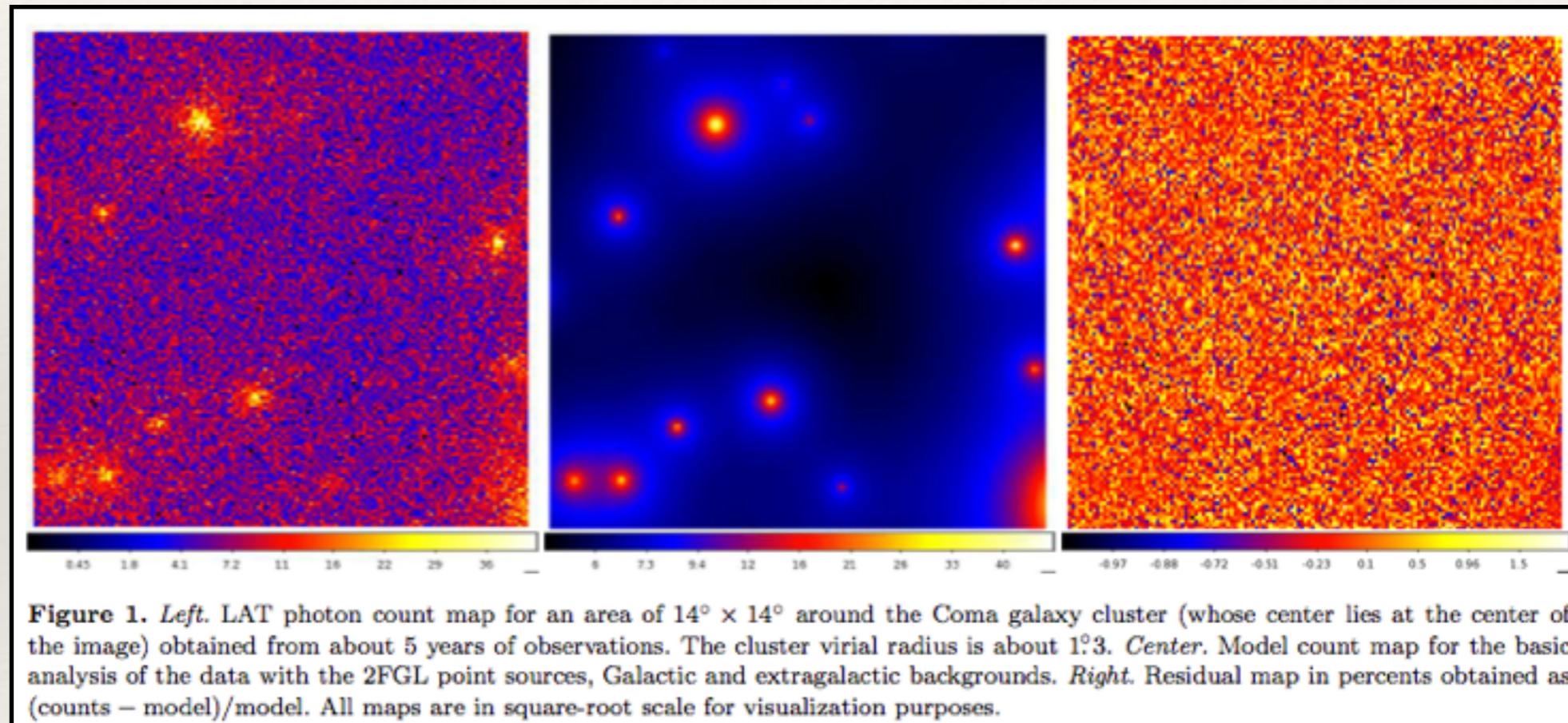


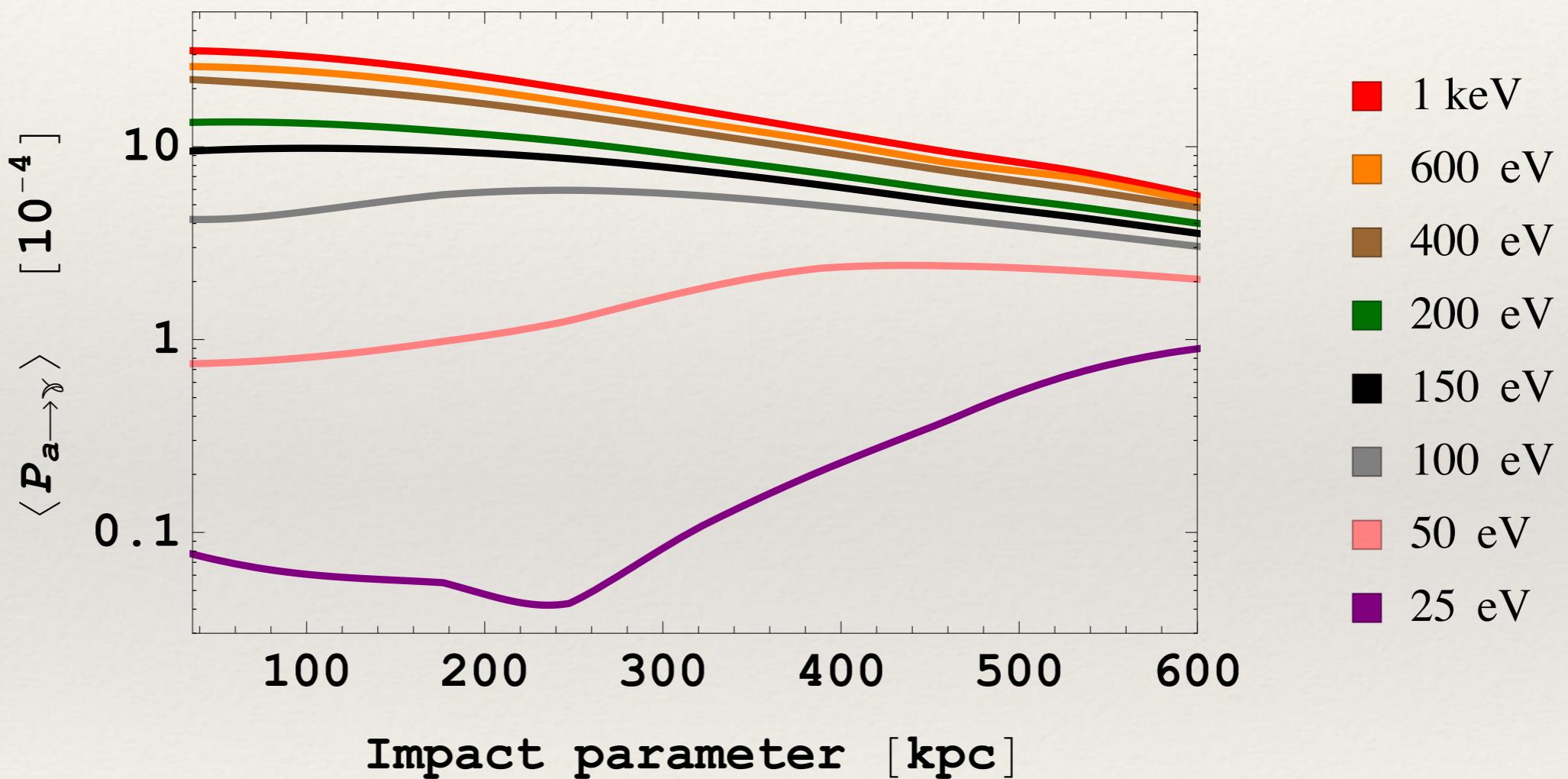
Figure 1. *Left.* LAT photon count map for an area of $14^\circ \times 14^\circ$ around the Coma galaxy cluster (whose center lies at the center of the image) obtained from about 5 years of observations. The cluster virial radius is about $1^\circ.3$. *Center.* Model count map for the basic analysis of the data with the 2FGL point sources, Galactic and extragalactic backgrounds. *Right.* Residual map in percents obtained as (counts - model)/model. All maps are in square-root scale for visualization purposes.

Atoyan, Vollker 2000,
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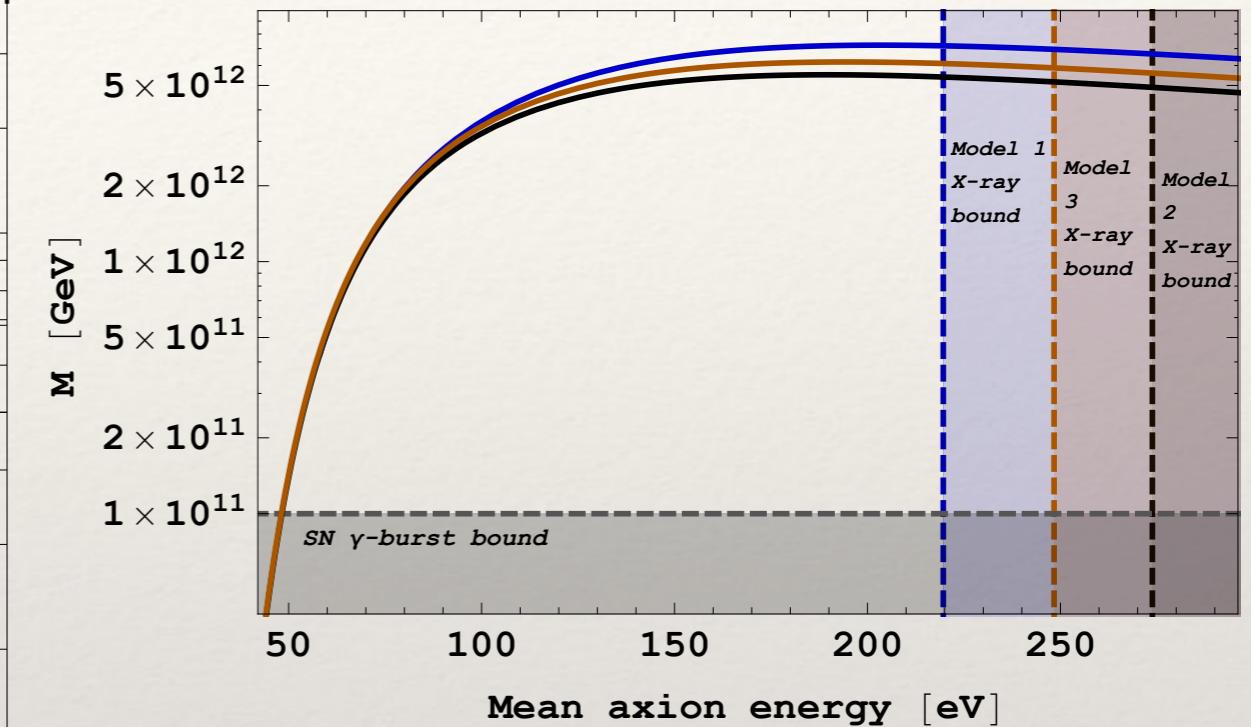
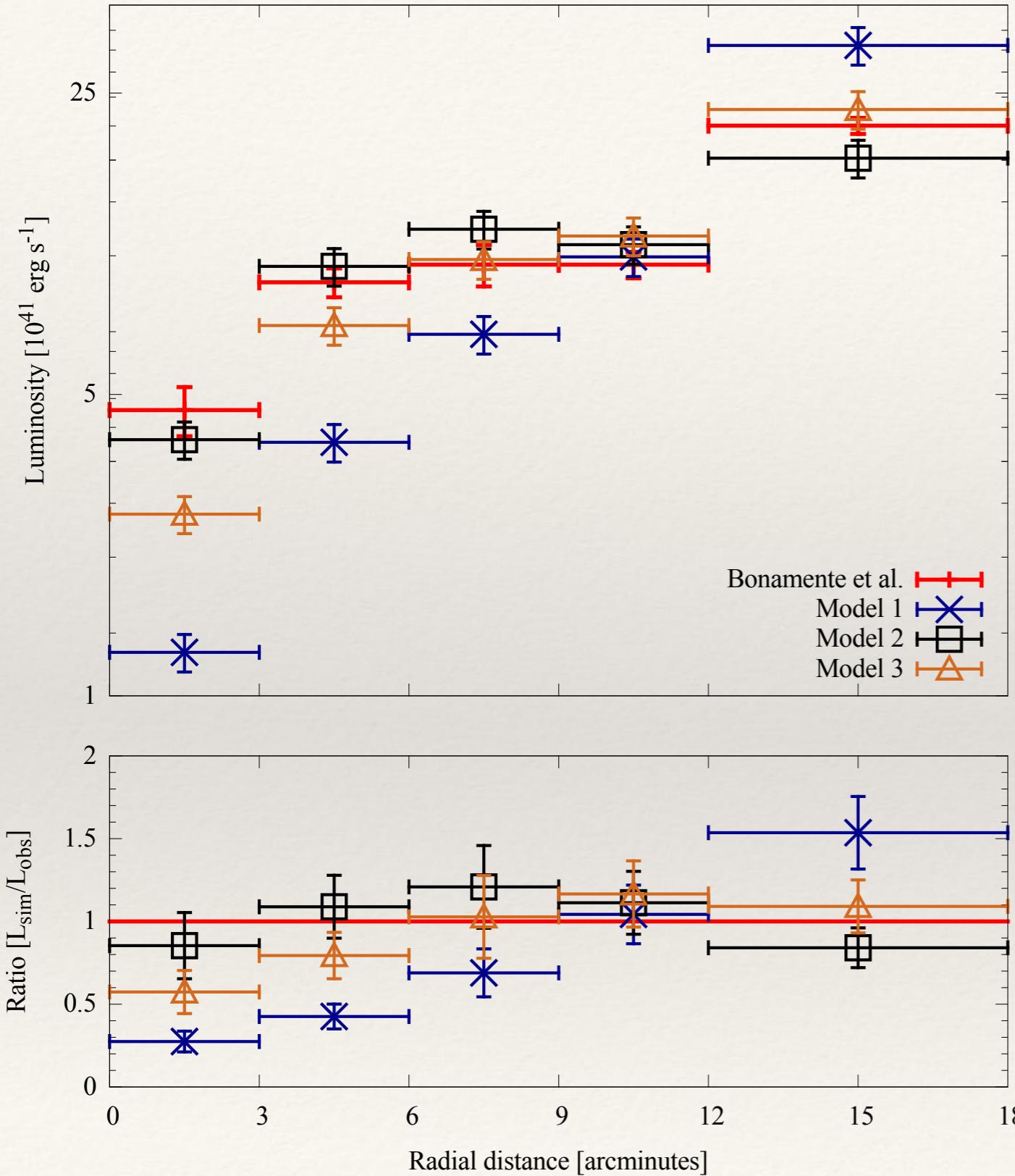
Zandanel, Ando, 2013.

Properties of cluster soft X-rays from a CAB

A CAB explanation of the soft X-ray excess gives distinct predictions for the morphology of the soft X-ray excess, if the electron density and magnetic field is known. *Test with the models for the Coma clusters.*



A Cosmic Axion Background and the Coma soft X-ray excess



A CAB and the cluster soft X-ray excess

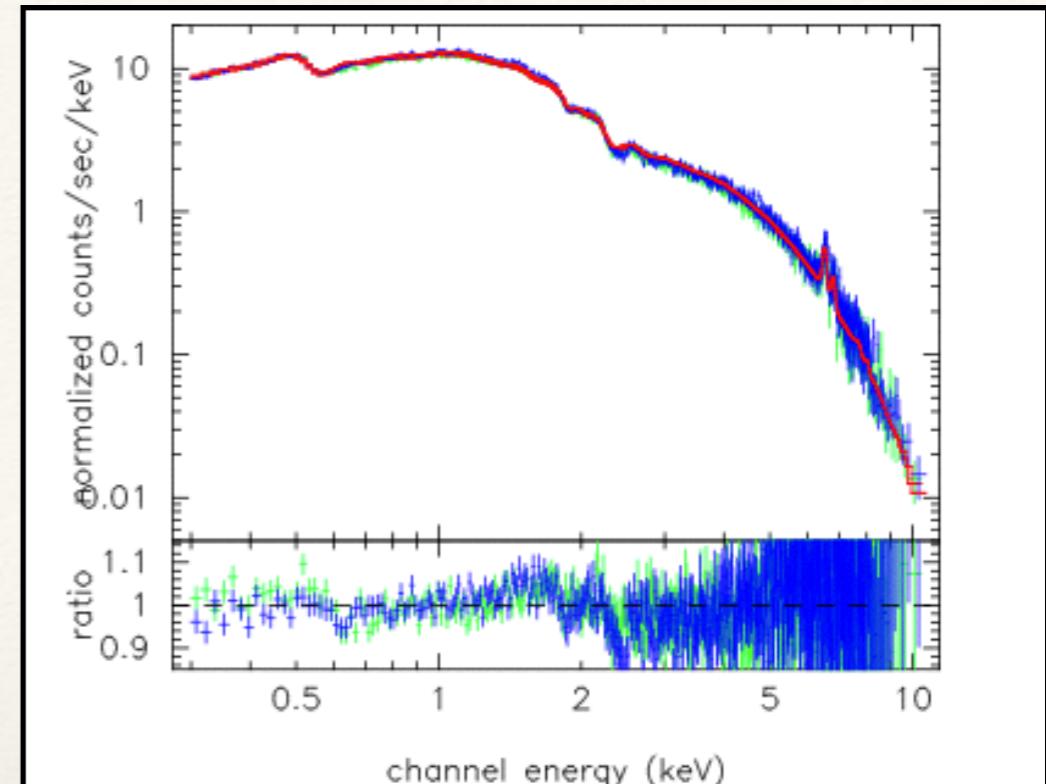
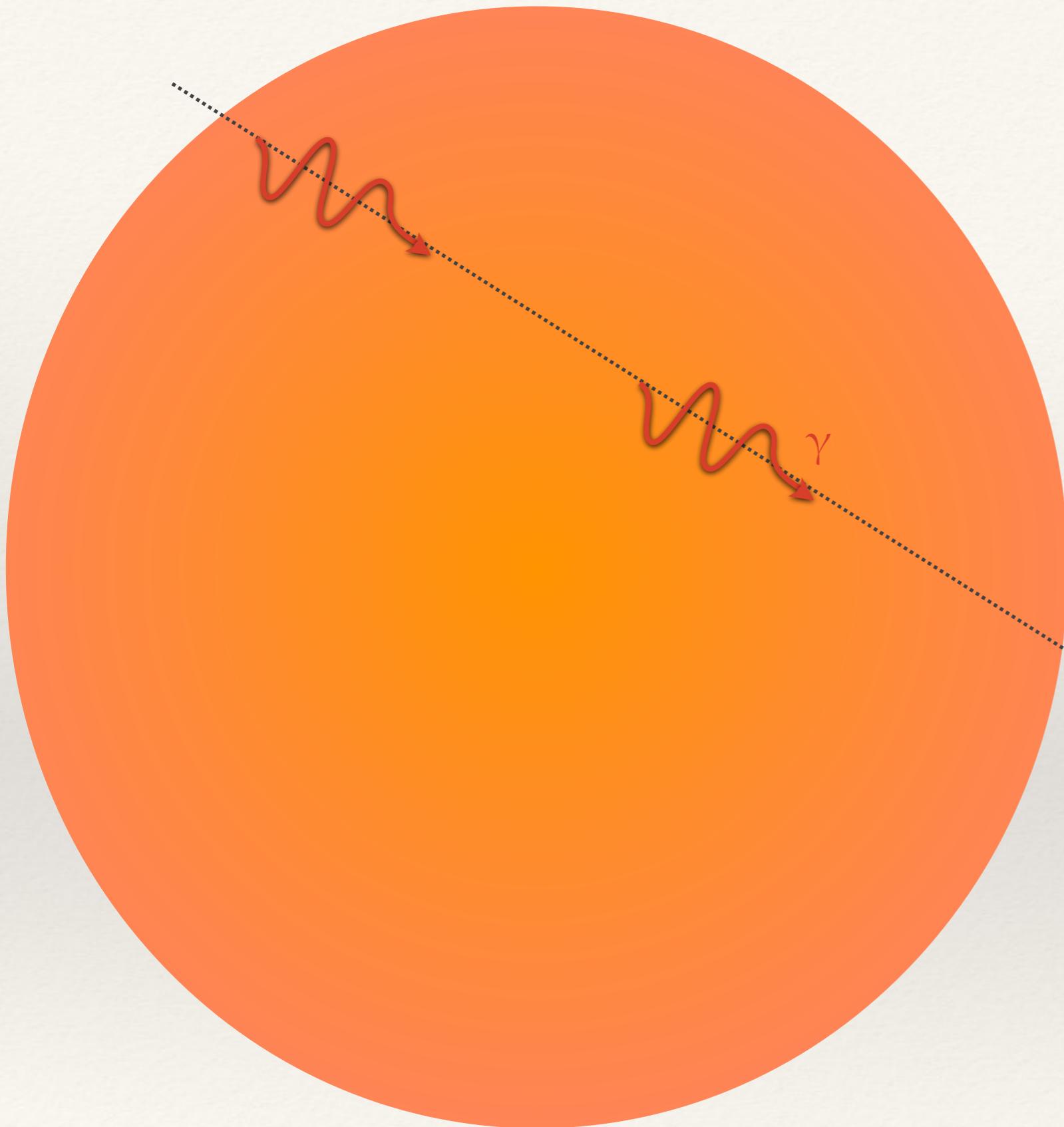
- Soft X-ray excess observed in many clusters. Large FOV needed for reliable background subtraction: ROSAT was ideal.
- Proposed astrophysical explanations not completely satisfactory.
- A CAB explanation works well for clusters where it can be tested, such as Coma.
- Inferred ALP parameters very similar to those from “anomalous transparency hint”.
- ALPs would contribute to re-ionisation, change optical depth to recombination: if observed would give strong constraint on cosmological magnetic field:

$$B \lesssim 10^{-15} \text{ G} \left(\frac{M}{10^{12} \text{ GeV}} \right).$$

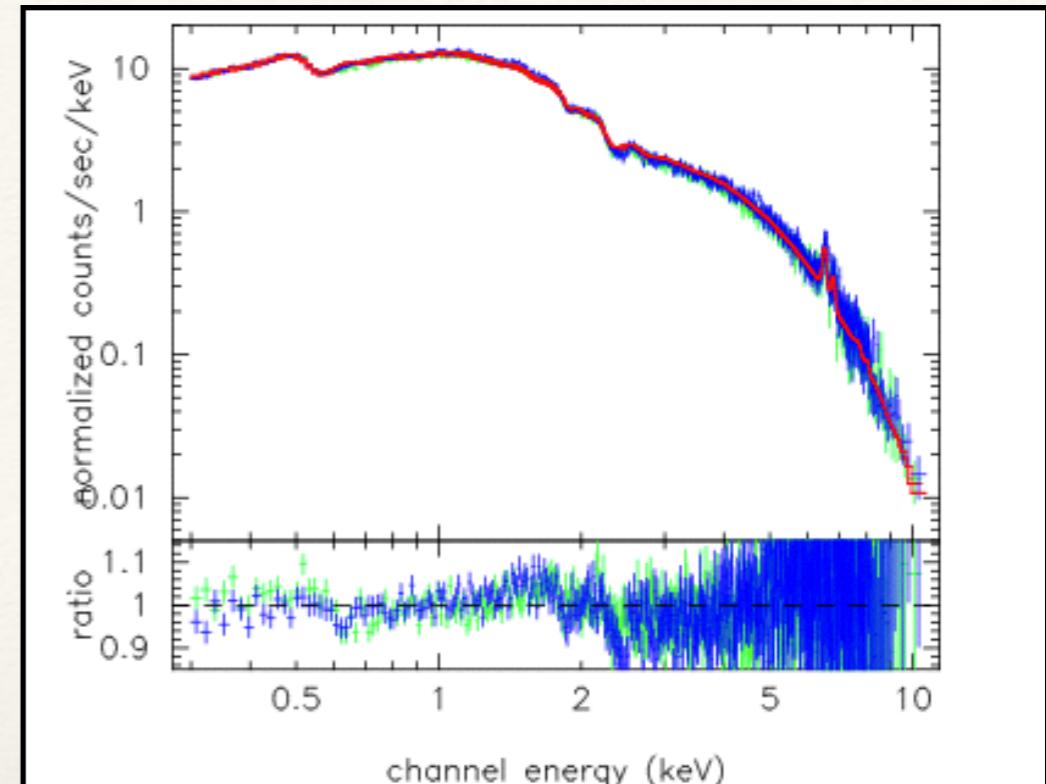
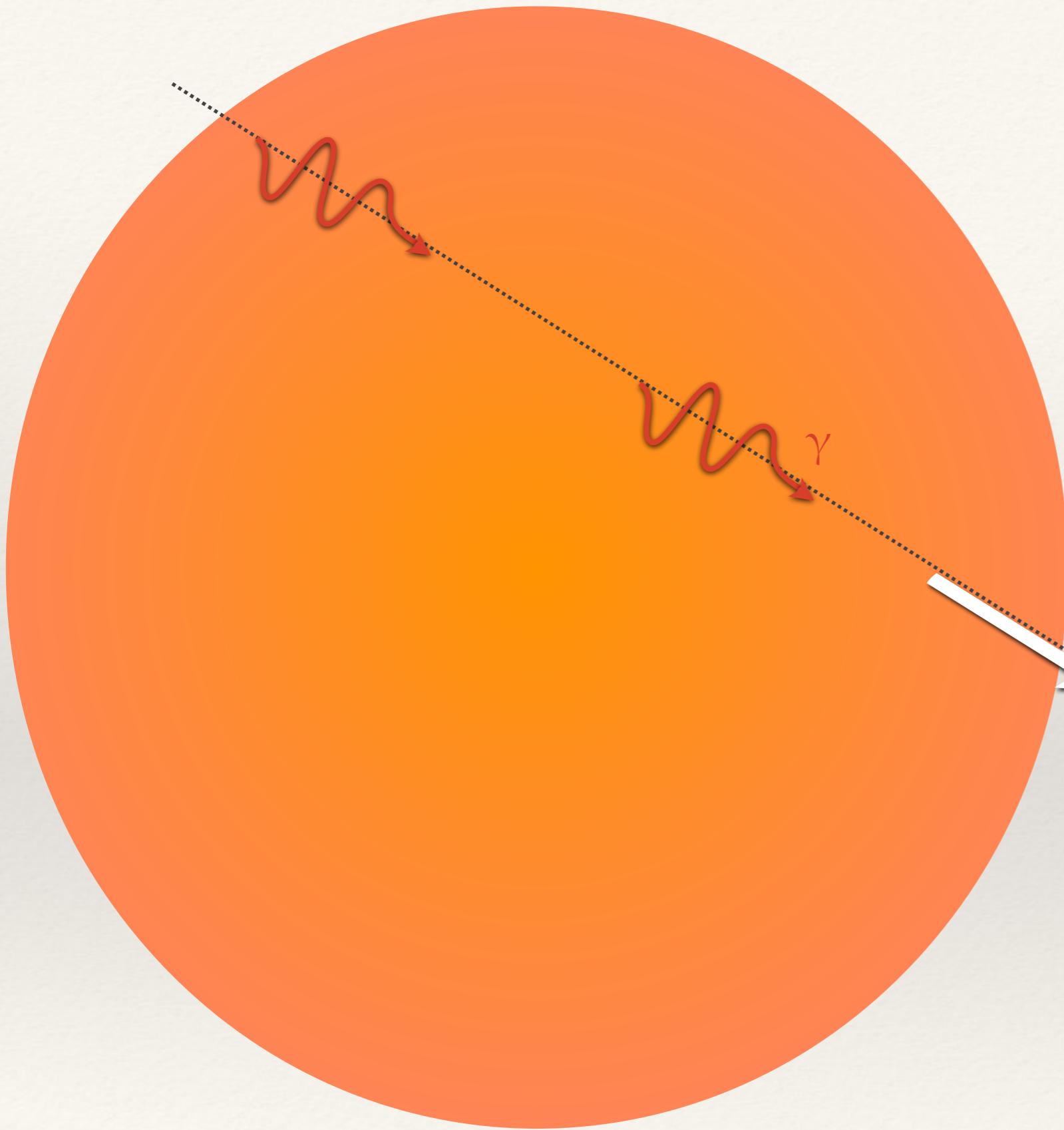
Outline:

1. Axions and axion-like particles (ALPs)
2. Galaxy clusters are ALP converters
3. ALPs from Big bang and the cluster soft X-ray excess
4. ALPs distort the ICM spectrum

Photons convert to ALPs



Photons convert to ALPs



Photons convert to ALPs

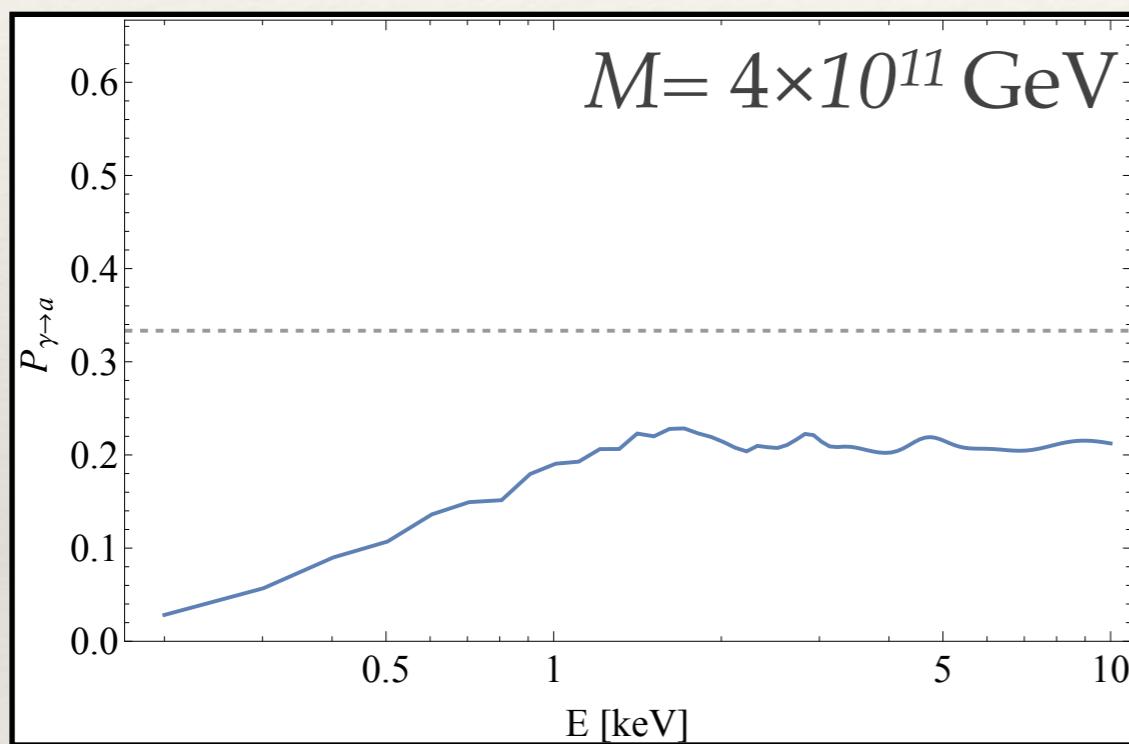
ICM X-ray photons can have unsuppressed conversion probability to light ALPs. Conversion is efficient roughly at energies,

$$E_\gamma \gtrsim 0.54 \text{ keV} \left| \frac{n_e}{10^{-3} \text{ cm}^{-3}} - \frac{m_a^2}{(1.2 * 10^{-12} \text{ eV})^2} \right| \left(\frac{L}{10 \text{ kpc}} \right).$$

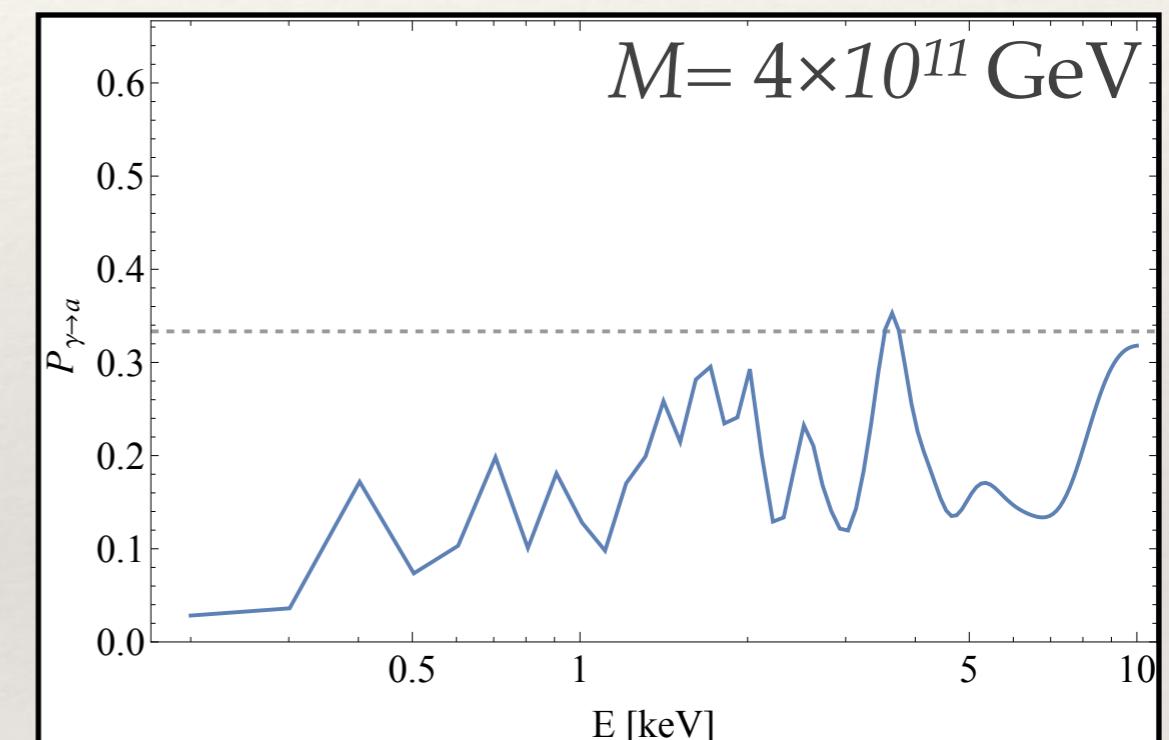
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100 kpc FoV (Coma)

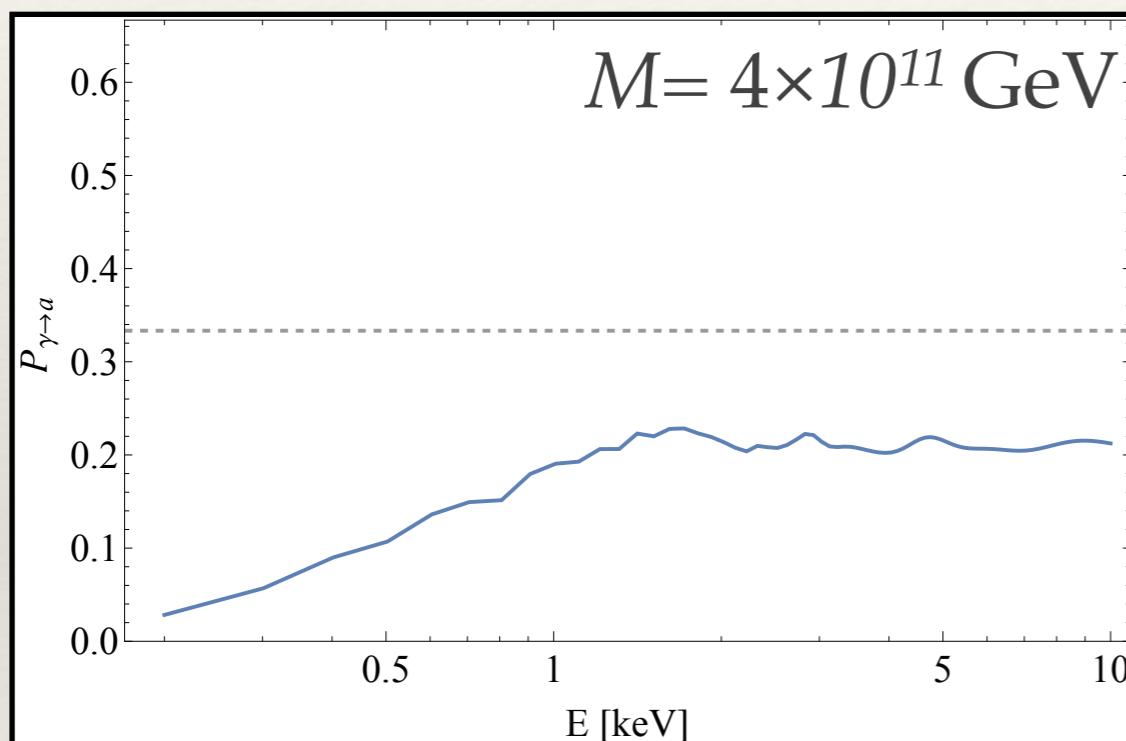


5 kpc FoV (Coma)

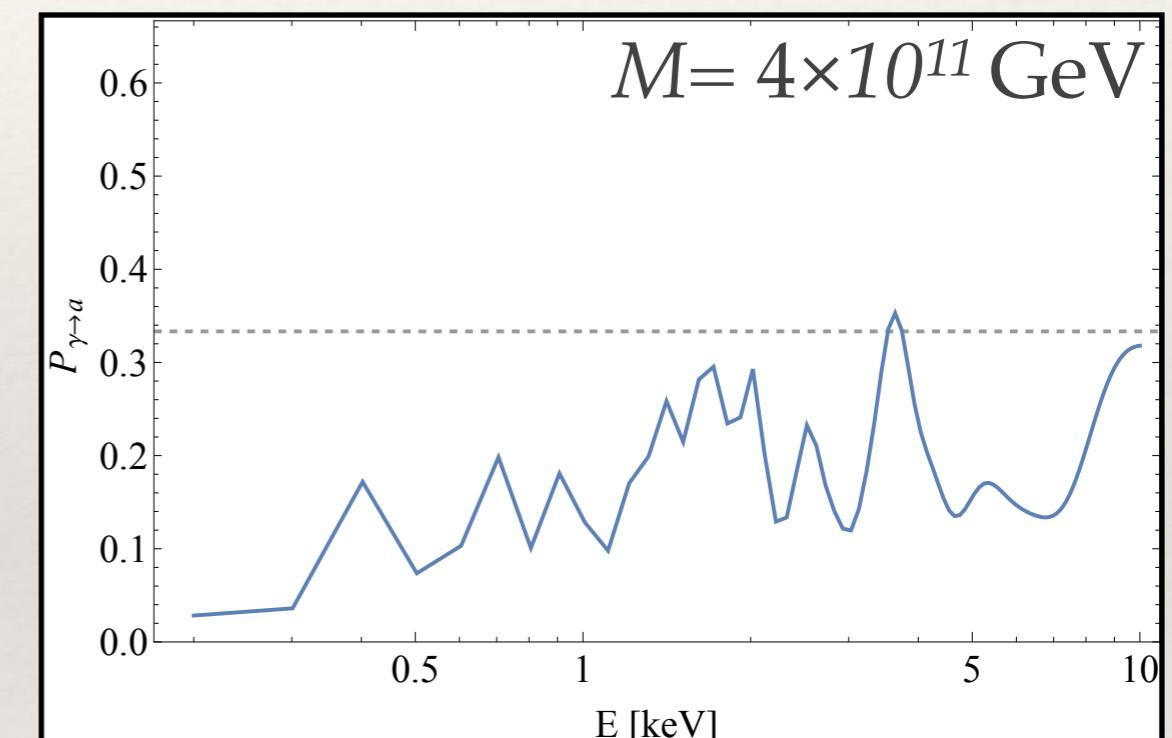
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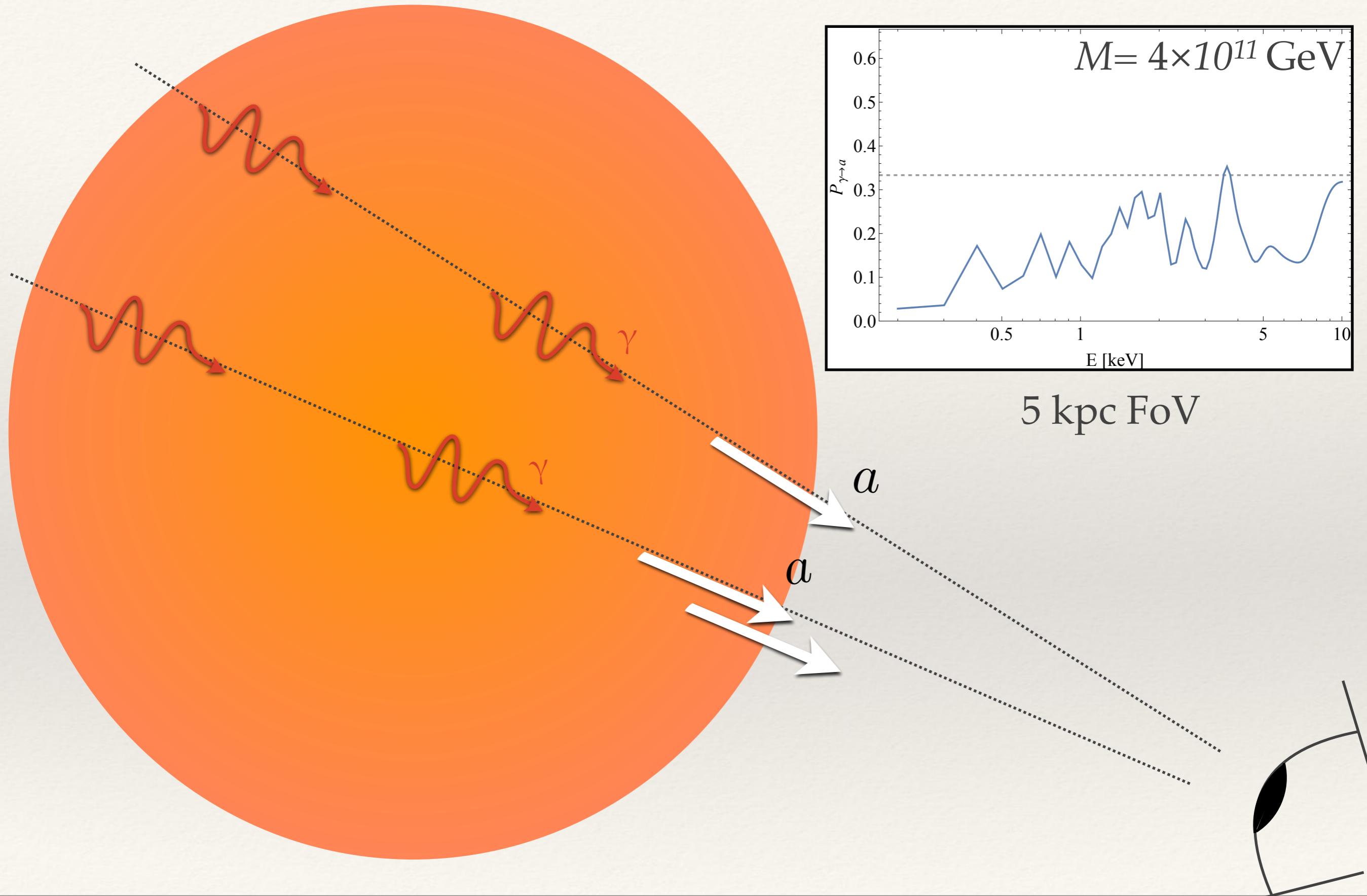
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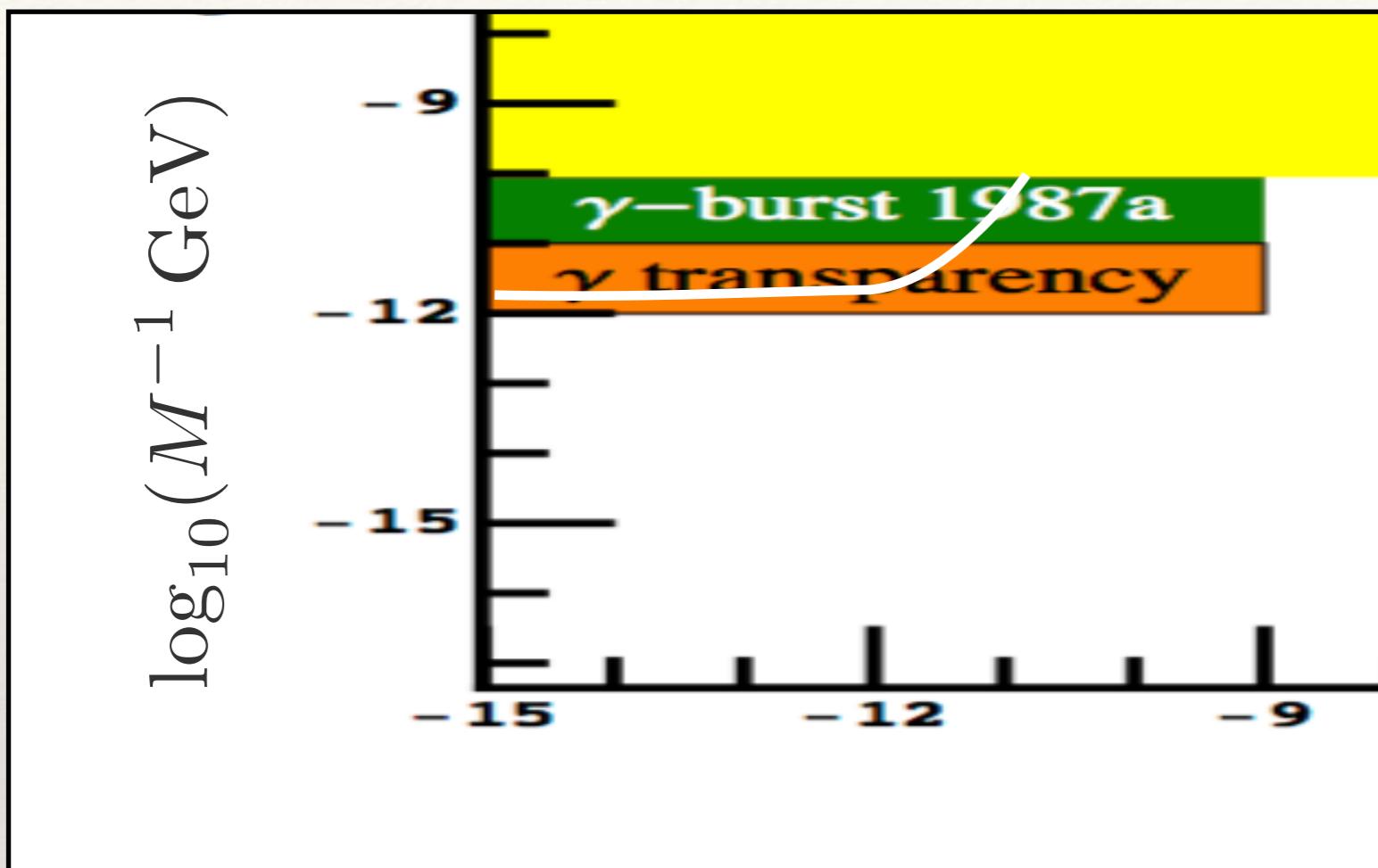
5 kpc FoV (Coma)

Conversions would distort the thermal ICM spectrum.

Small-scale variability in ICM intensity and spectrum



Photons convert to ALPs

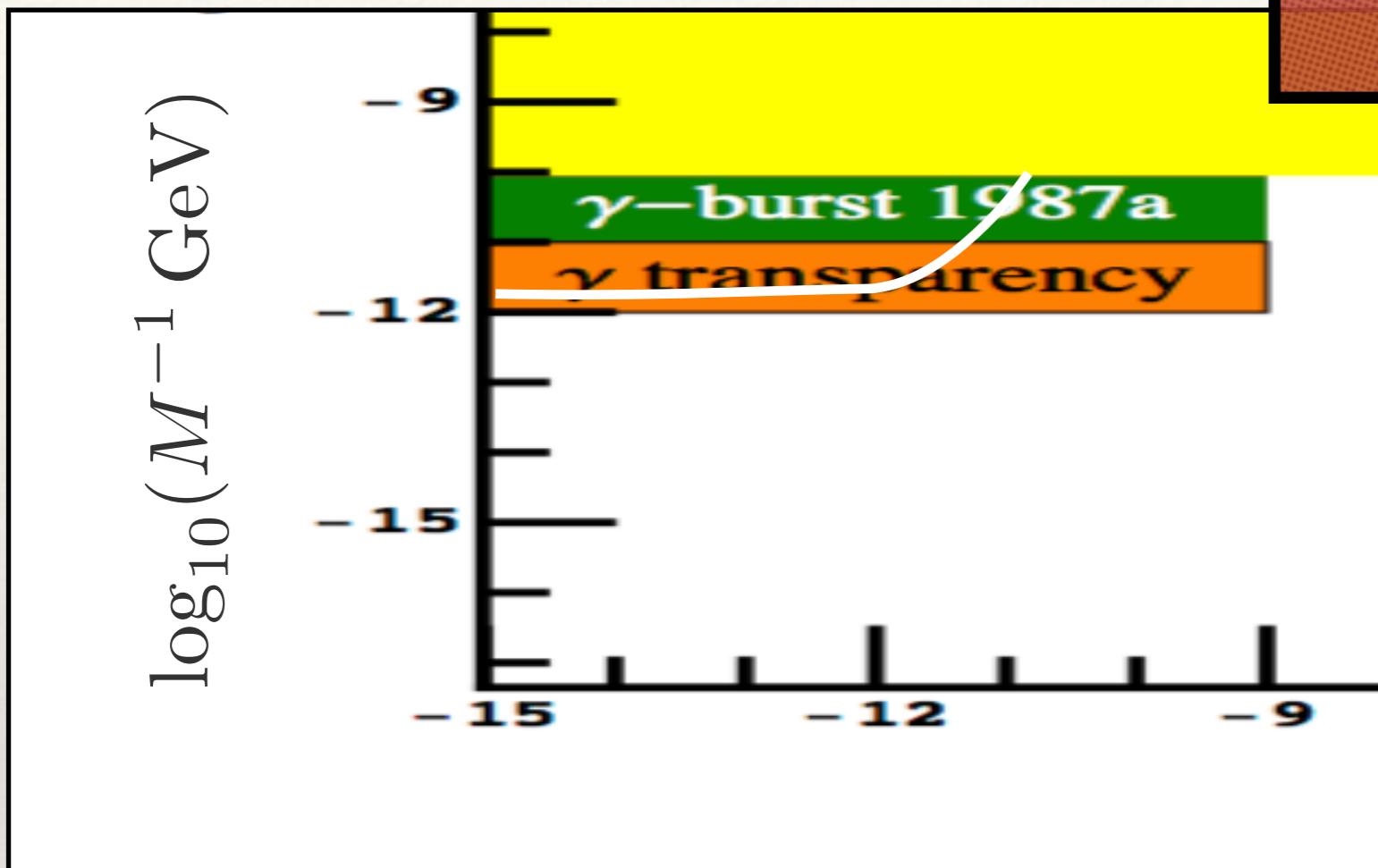


Can strengthen bounds on light ALPs by factor of ~7.

Signal in polarisation and small-scale fluctuations.

Photons convert to ALPs

More detailed study for specific clusters underway

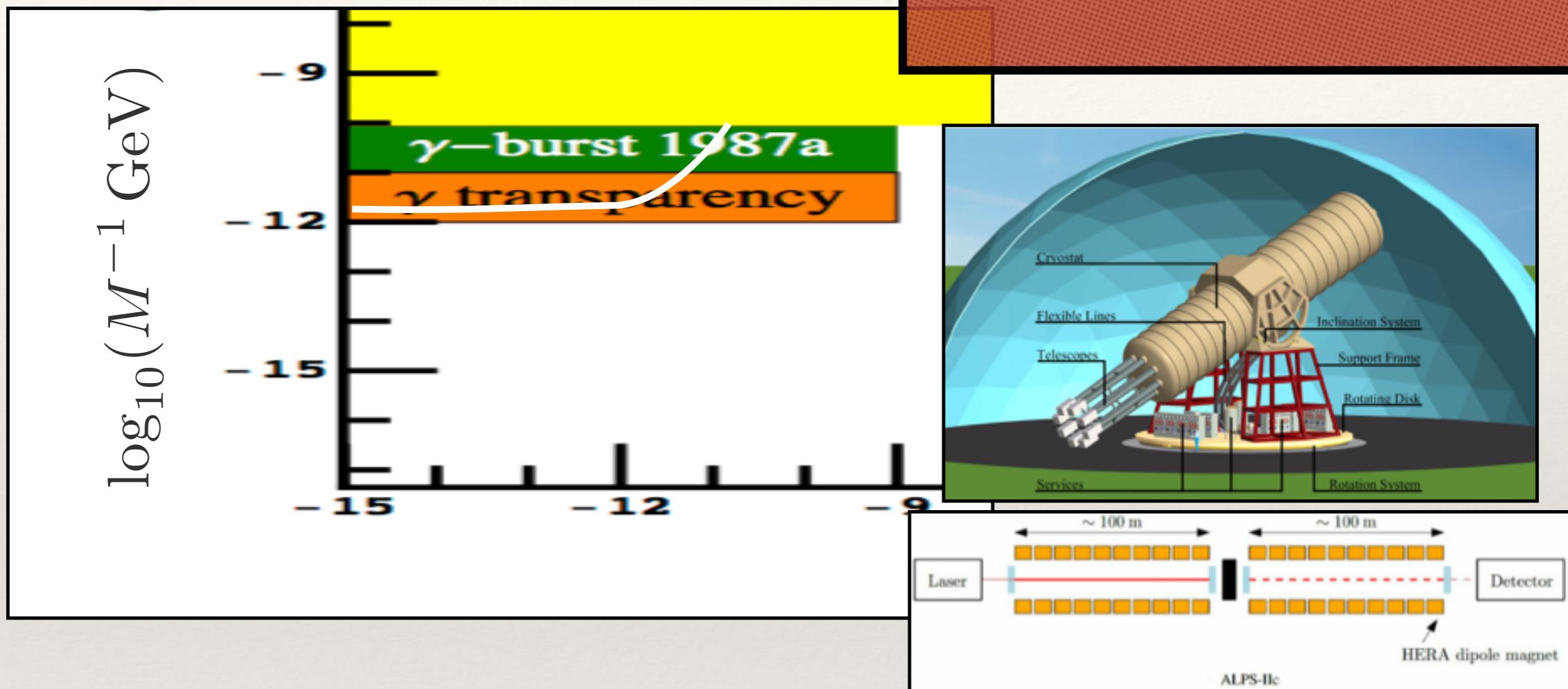


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Conclusions

- Axion physics is *rich* and have *promising* observational and experimental prospects.
- Galaxy clusters are highly *efficient converters* of very light axion-like particles, with $O(1)$ conversion probabilities for $M = 10^{11}$ GeV. Opportunity to use astrophysics to learn about particle physics.
- Large classes of string theory compactifications suggest the existence of a *cosmic ALP background*, which may explain the *cluster soft X-ray excess*.
- Light ALPs distort the *thermal ICM* — possible to detect correlated signatures or derive very strong bounds.

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Thanks!