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

David Marsh

Rudolph Peierls Centre for Theoretical Physics,
University of Oxford

String Phenomenology 2014, ICTP, Trieste, Italy

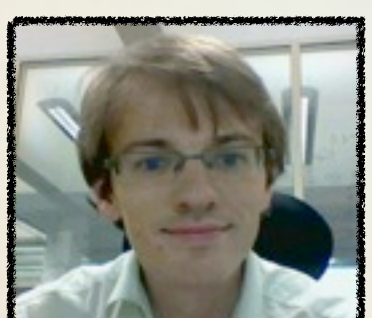
Mostly based on:

J. Conlon & *D.M.*: arXiv:1304.1804 [hep- ph], (JHEP).

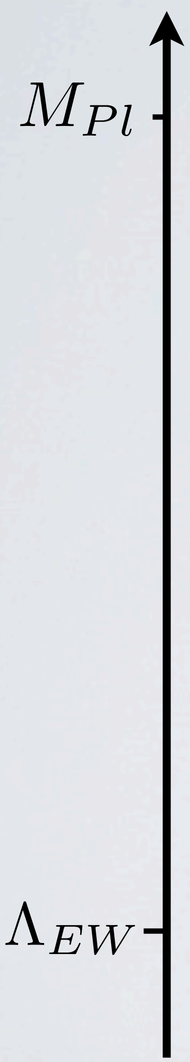
J. Conlon & *D.M.*: arXiv:1305.3603 [astro-ph:CO], (PRL).

S. Angus, J. Conlon, *D.M.*, A. Powell, L. Witkowski:
arXiv:1312.3947 [astro-ph:HE].

J. Conlon, D. Kraljic, M. Rummel, arXiv:1406.5188 [hep-ph].

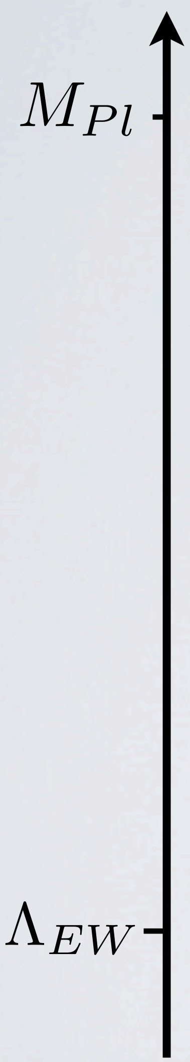
String pheno = String theory as a fundamental theory



String pheno = String theory as a fundamental theory

Challenge for any proposed quantum gravity:

$$\Lambda_{\rm EW} \ll M_{Pl}\,.$$



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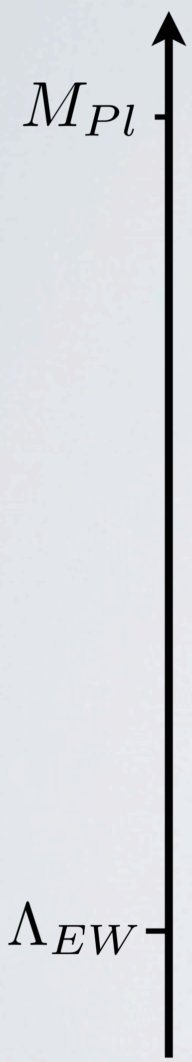

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Challenge for string theory:

Many apparent solutions with different cosmologies and low-energy predictions.

Obtaining explicit solutions are computationally costly.

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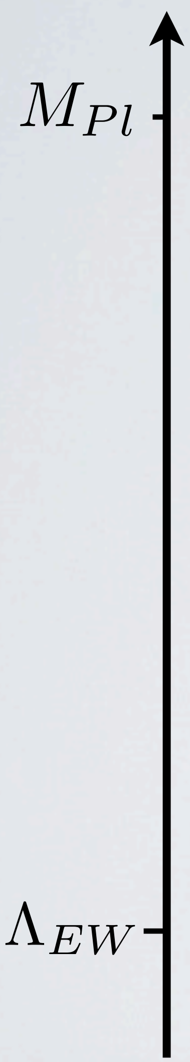


Challenge for any proposed quantum gravity:

$$\Lambda_{\rm EW} \ll M_{Pl}\,.$$

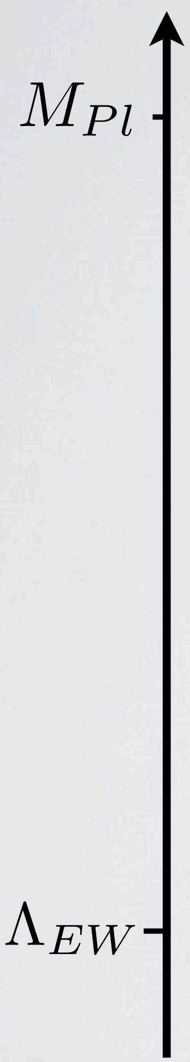
Challenge for string theory:

Many apparent solutions with different cosmologies and low-energy predictions.

Obtaining explicit solutions are computationally costly.

Testing solutions experimentally one-by-one is not feasible.

String pheno = String theory as a fundamental theory



(Obviously incomplete list of) possible resolutions:

- Identify *consistency conditions* for the EFT's.

- Study particularly *UV-sensitive phenomena* in string theory.

- Construct *scenarios* with some common properties. Statistically study *large ensembles* of vacua. Identify fruitful and barren corners of the 'landscape' of vacua.

- Determine the *most generic properties* of the EFT's and the corresponding cosmologies.

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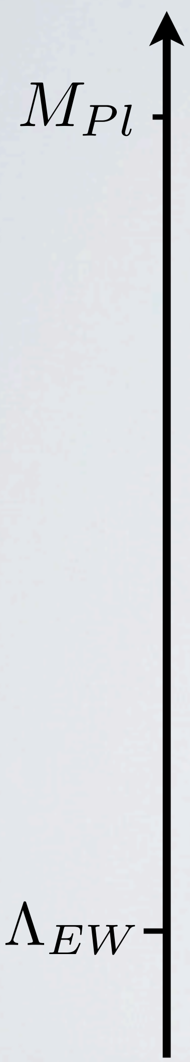

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- Determine the *most generic properties* of the EFT's and the corresponding cosmologies.

C.f. talks by: Palti, Colinucci, Cvetic, Shafer-Nameki, Grimm, Lukas, Vaudrevange, Nilles, Westphal, Finelli, Dutta, Takahashi, Burgess, Hebecker, Sagnotti, Conlon, goodsell, Maharana, Antoniadis, Ovrut, Uranga, Marchesano, Jockers, Kumar, Krippendorf, Rizos, Ratz, Weigand, Shiu, Kaloper, Zavala, Lüst, Garcia Etxebarria, Mayrhofer, Triendl, Anderson, Martucci, Ibanez, Rummel, Shukla, Pedro, Witkowski, Staessen, Savelli, Ruehle, Pugh, Zoccarato, Till, Andriot, Heidenreich, Larfors, Terrero Escalante, Pongkitivanichkul, Retolaza, torabian, Valenzuela, Gray, Mehta, Ramos-Sanchez, Montero Munoz,, Groot Nibbelink, Fazzi, Junghans, Martin-Contreras, Wan-Zhe, Ye, Gwyn, Sumitomo, Sousa, Braun, Mayorga Pena, Hayashi, Lin, Plauschinn, Biaszczyk, Oehlman.

String pheno = String theory as a fundamental theory

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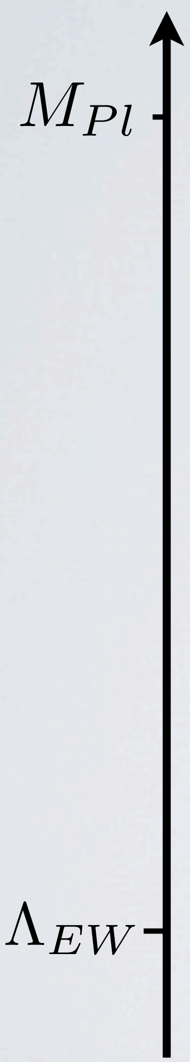

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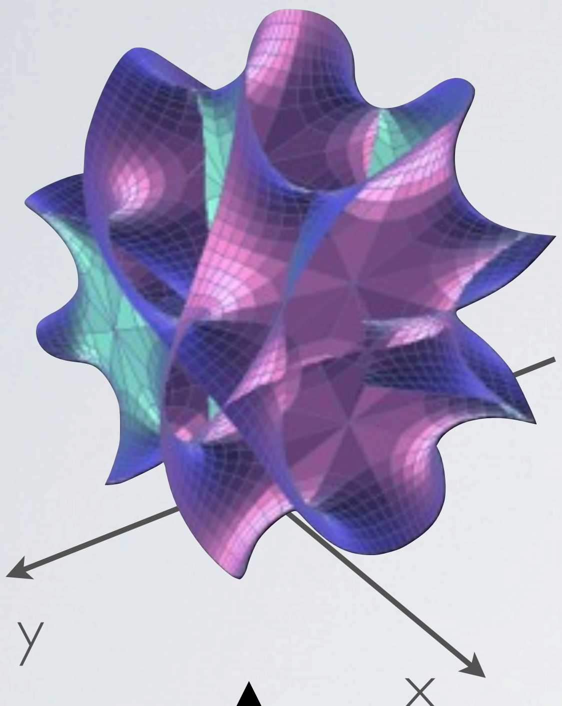
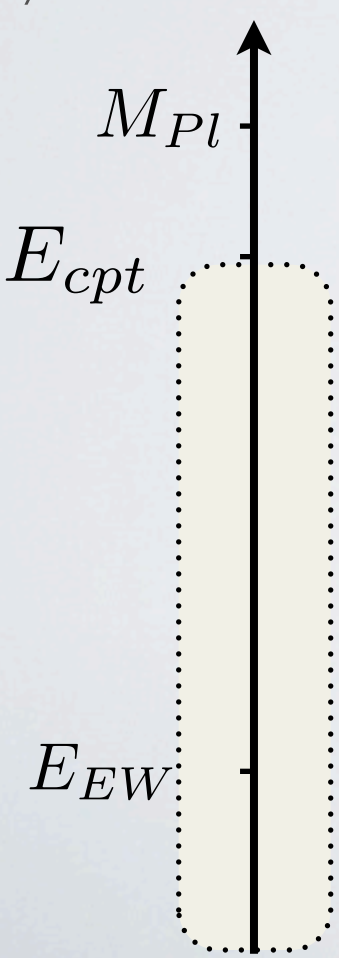
- Construct *scenarios* with some common properties. Statistically study *large ensembles* of vacua. Identify fruitful and barren corners of the 'landscape' of vacua.
- Determine the *most generic properties* of the EFT's and the corresponding cosmologies.

In this talk, I will discuss some *generic cosmological consequences* of a broad class of string theory models, and then consider how some of these models may provide the solution to a longstanding astrophysical puzzle.

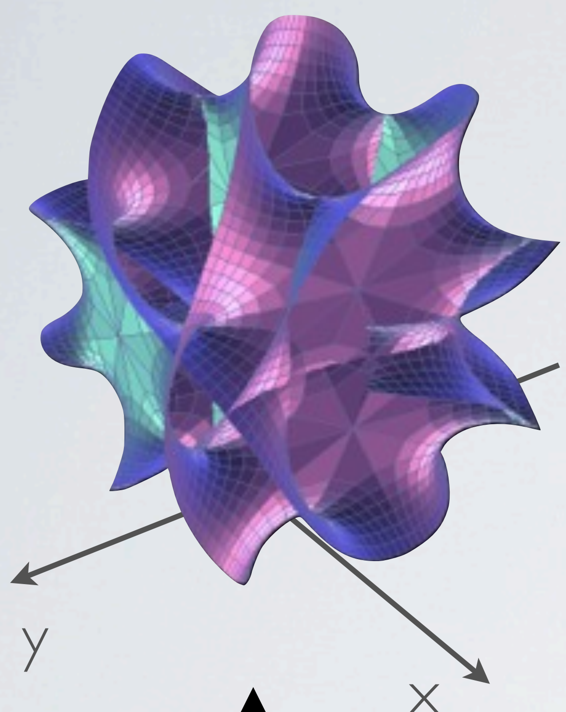
Moduli and cosmology

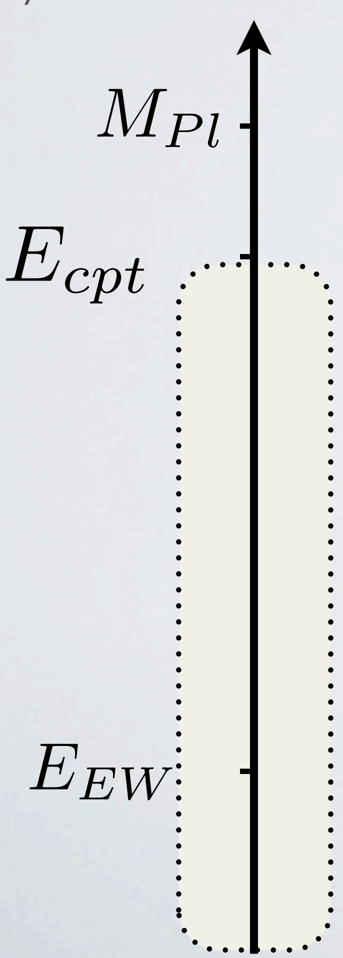




Genericity assertions:

Moduli and cosmology

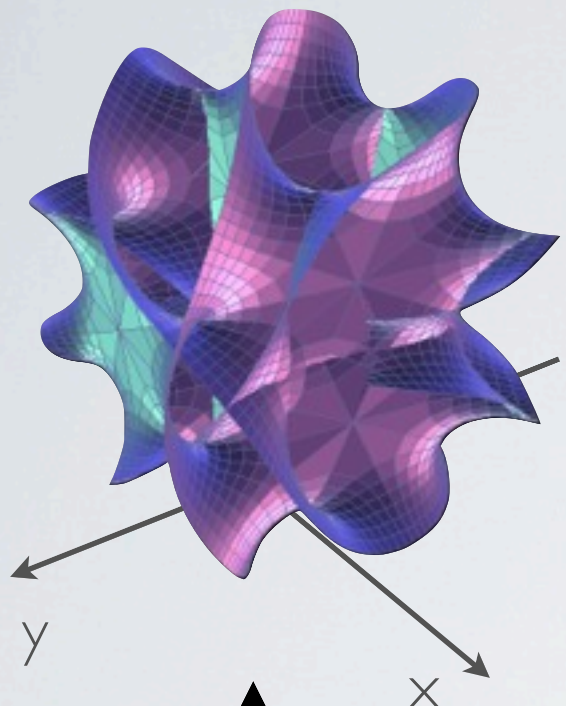


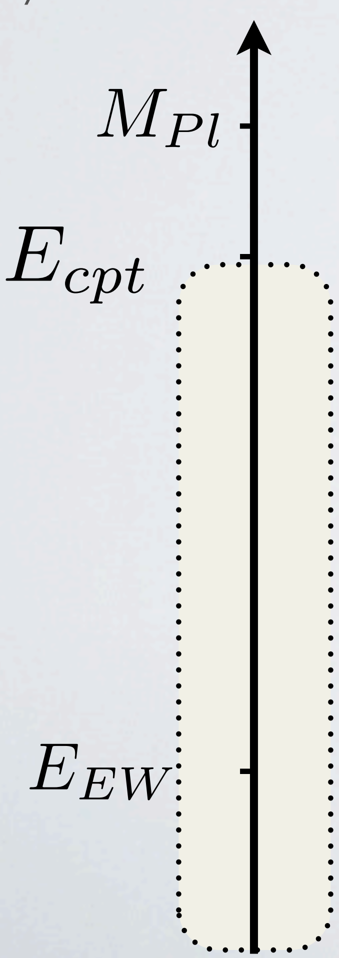


Genericity assertions:

1. String compactifications come with moduli.

Moduli and cosmology





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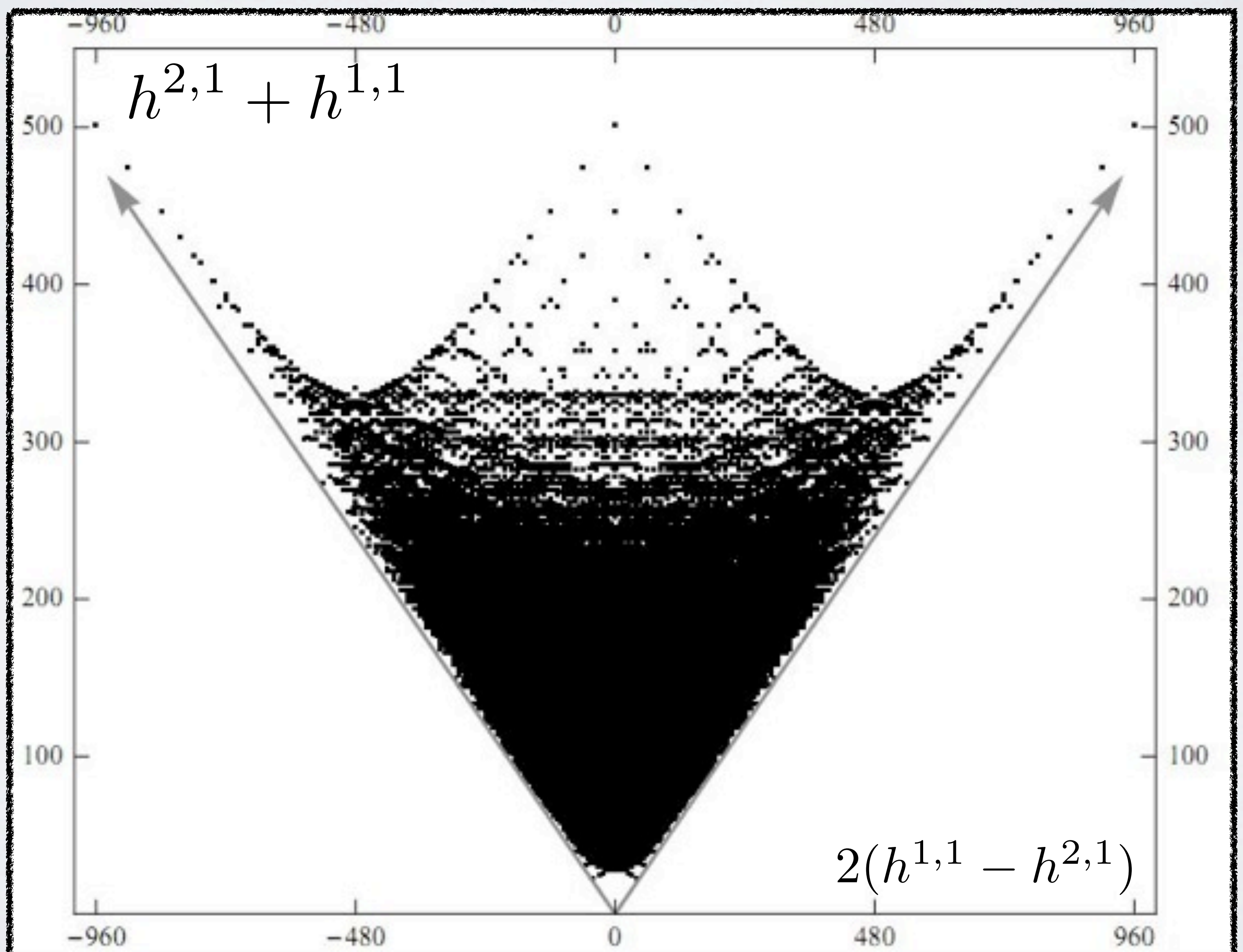
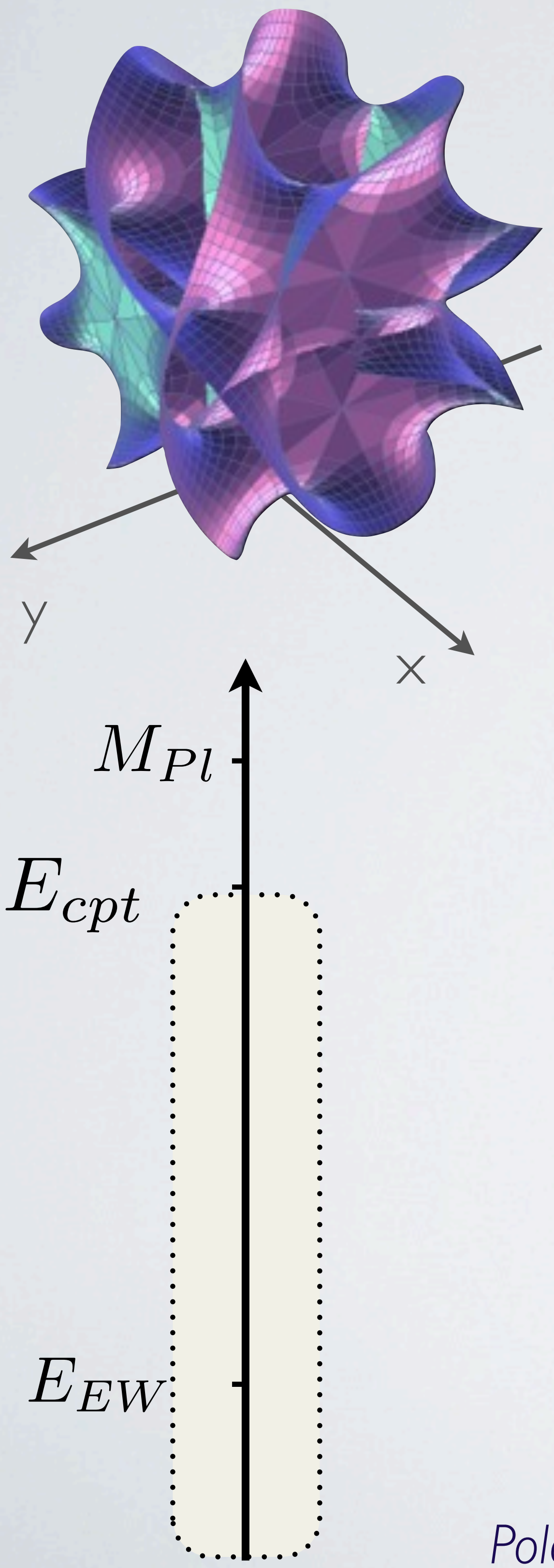


Kreuzer, Skarke '02, figure from Candelas,. Constantin, Skarke, '12.

Moduli and cosmology

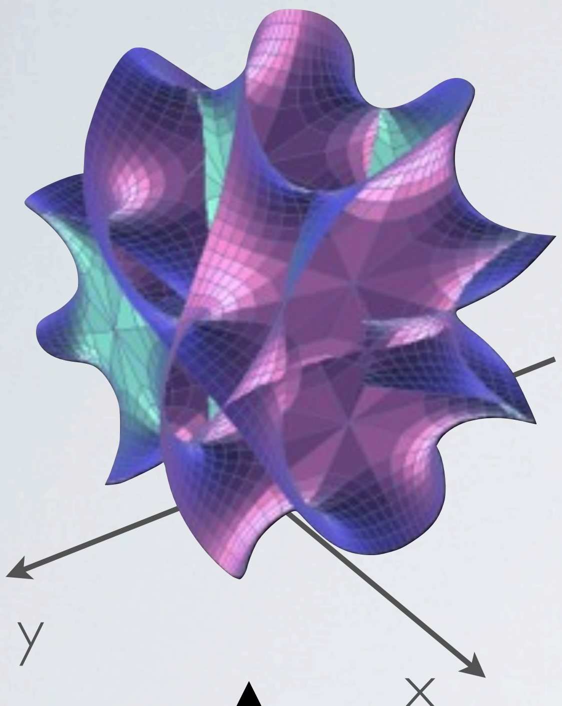


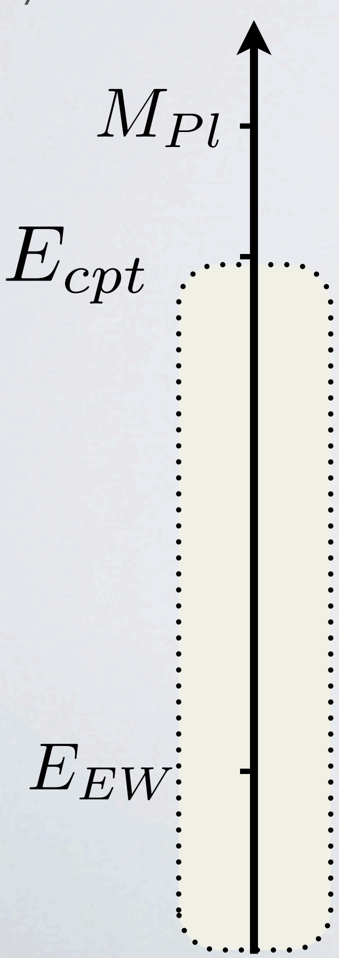
Genericity assertions:

2. Moduli can cause cosmological problems:

Polonyi '81, Coughlan & Ross '83, Banks, Kaplan, Nelson '93, de Carlos, Casas, Quevedo, Roulet '93.

Moduli and cosmology



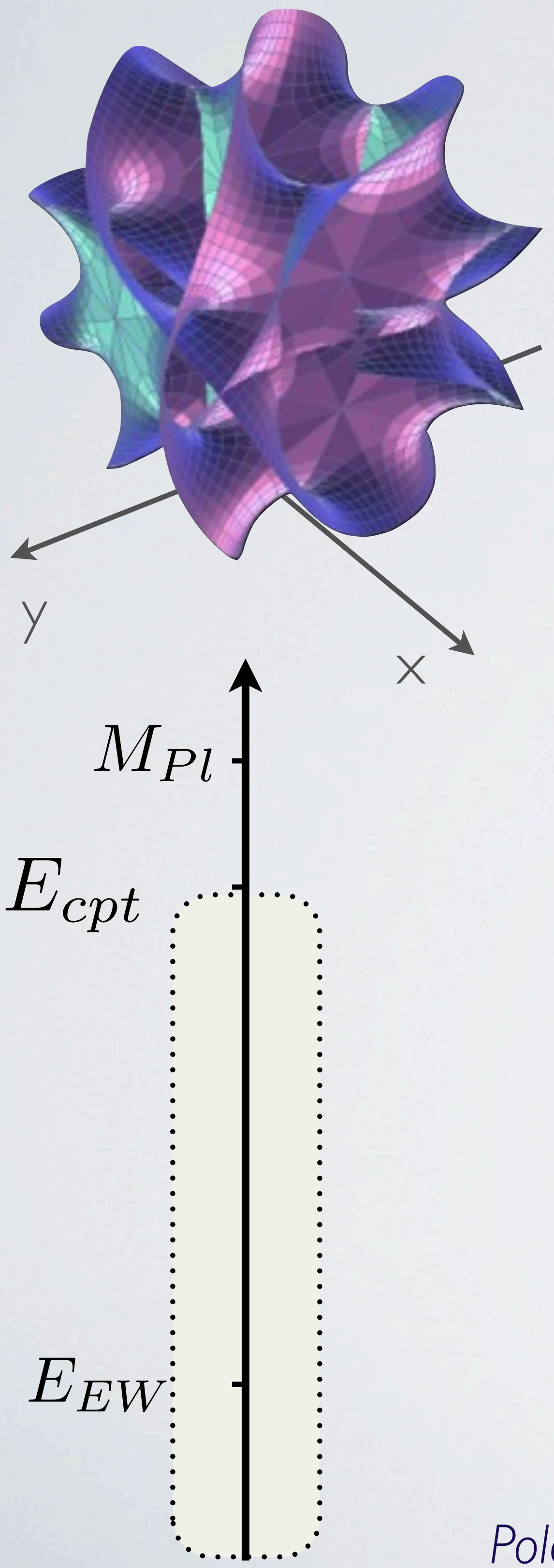


Genericity assertions:

2. *Moduli can cause cosmological problems: constraints from 'fifth forces' and from variation of the fine-structure constant for light scalars are very strong,*

Polonyi '81, Coughlan & Ross '83, Banks, Kaplan, Nelson '93, de Carlos, Casas, Quevedo, Roulet '93.

Moduli and cosmology



Genericity assertions:

2. *Moduli can cause cosmological problems: so moduli should be massive. But massive moduli can also cause problems:*

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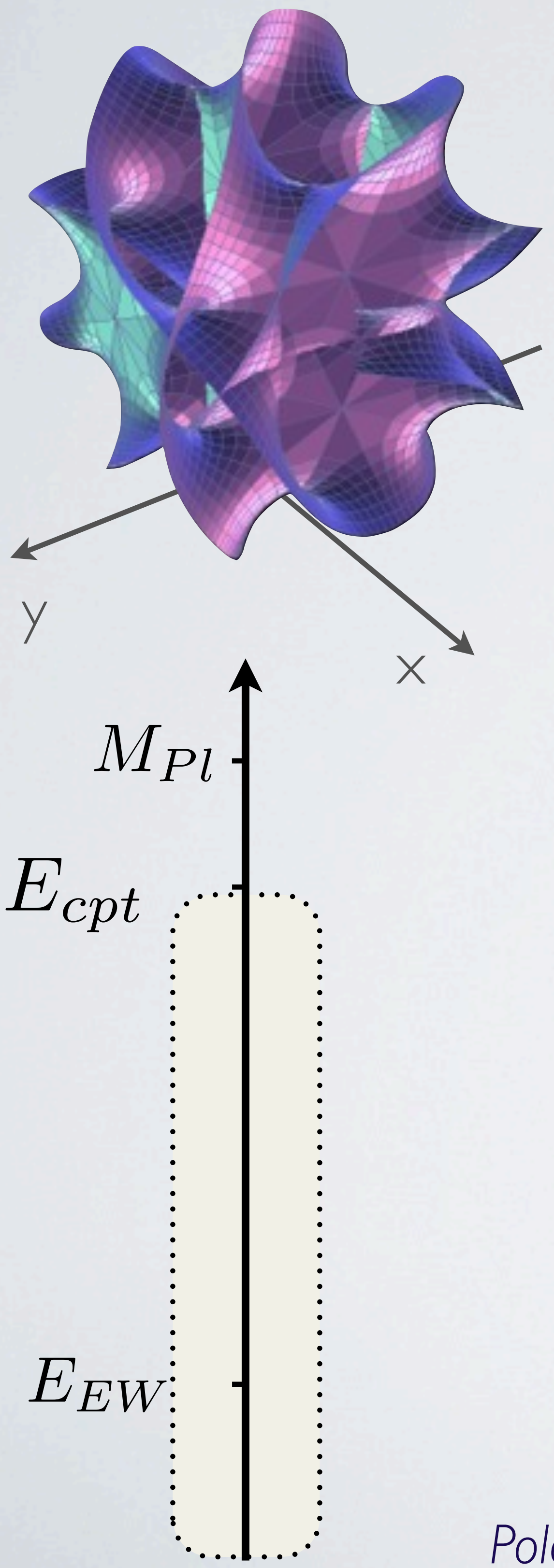
Moduli and cosmology



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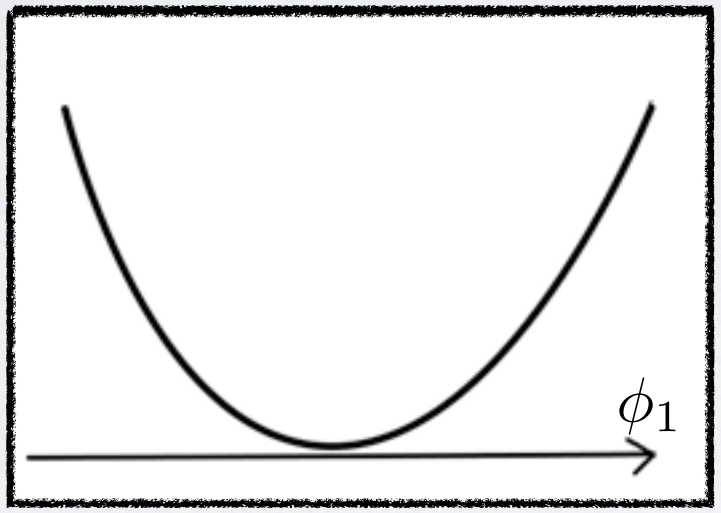

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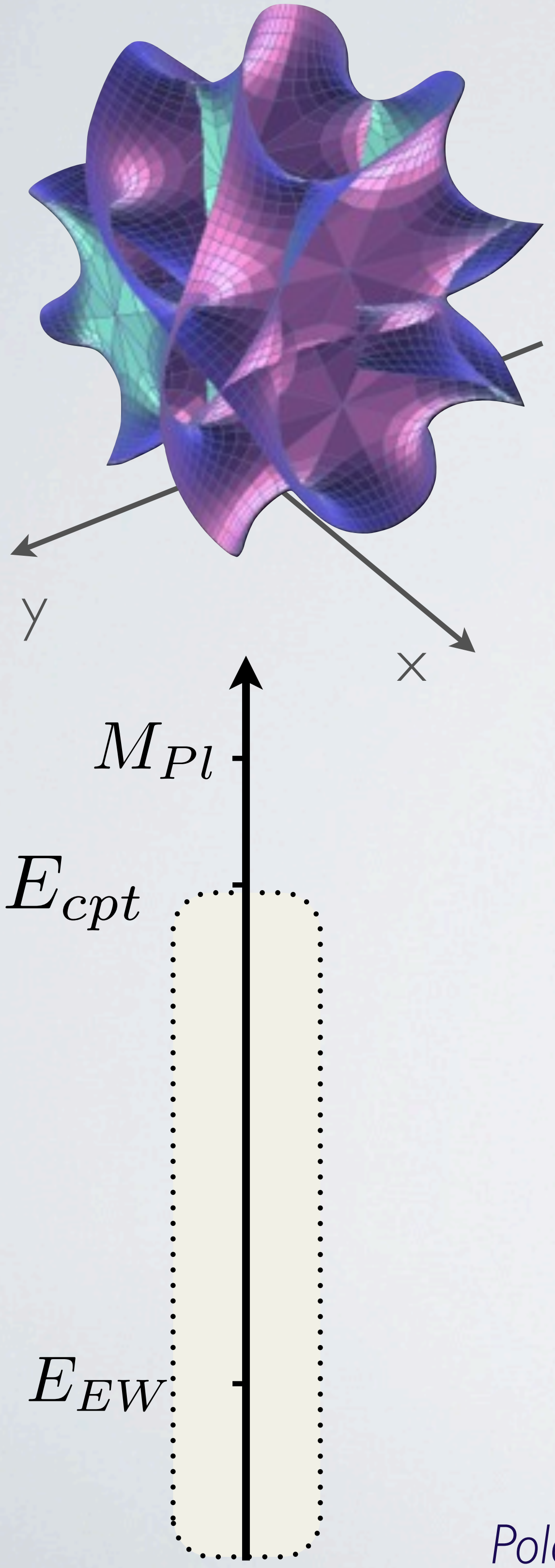
Moduli and cosmology



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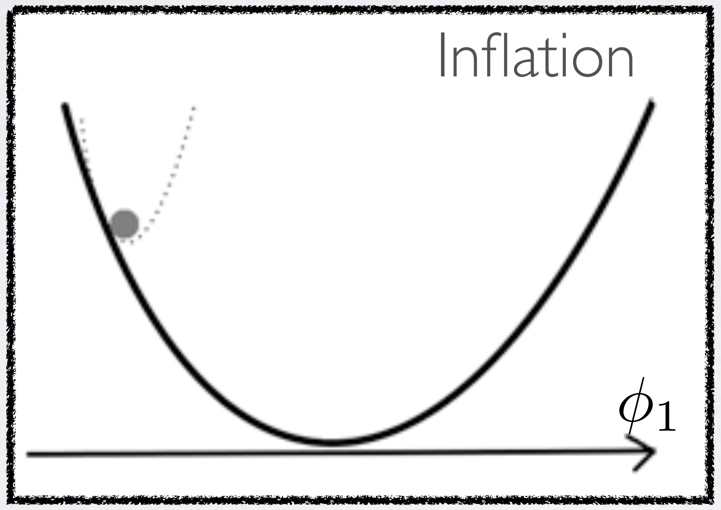

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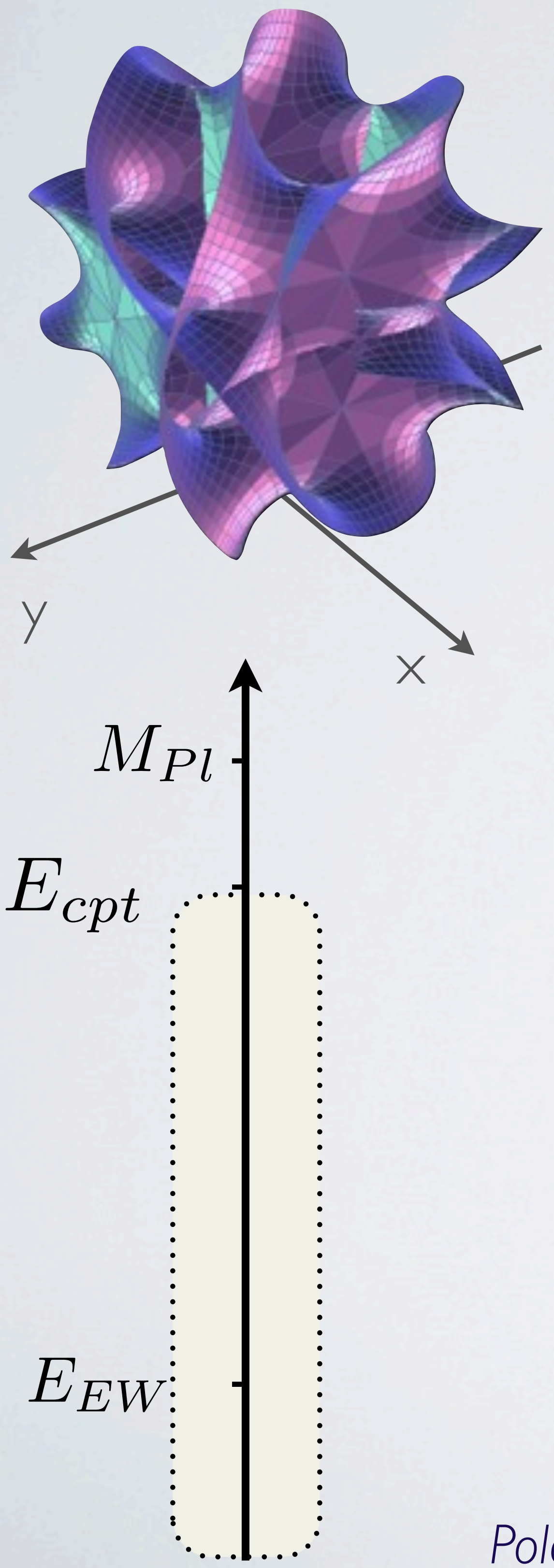
Moduli and cosmology



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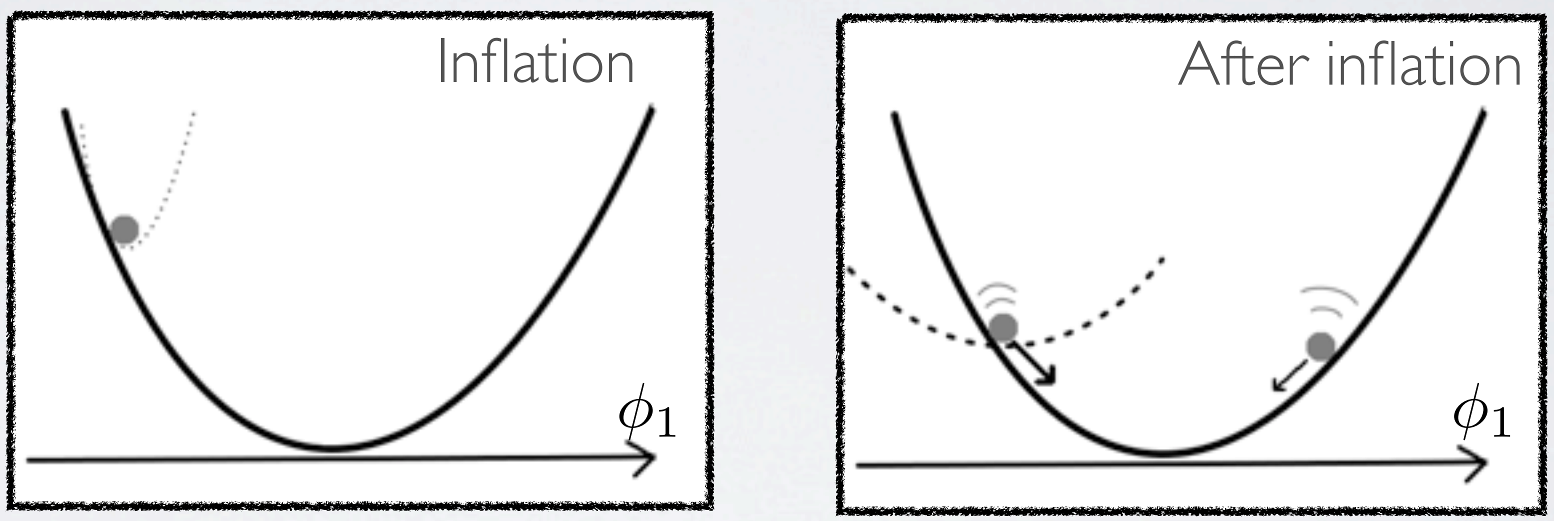
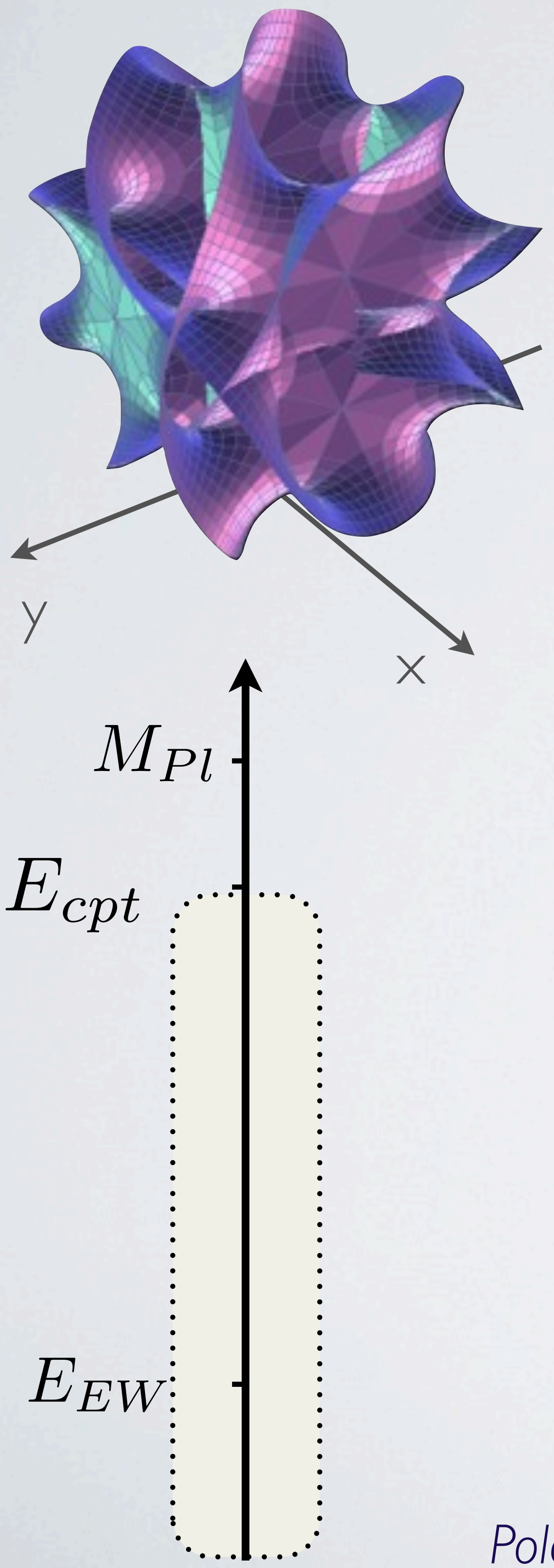


$$\rho_{\rm matter} \sim a^{-3}(t) \, ,$$
$$\rho_{\rm radiation} \sim a^{-4}(t) \, .$$

Polonyi '81, Coughlan & Ross '83, Banks, Kaplan, Nelson '93, de Carlos, Casas, Quevedo, Roulet '93.

Moduli and cosmology



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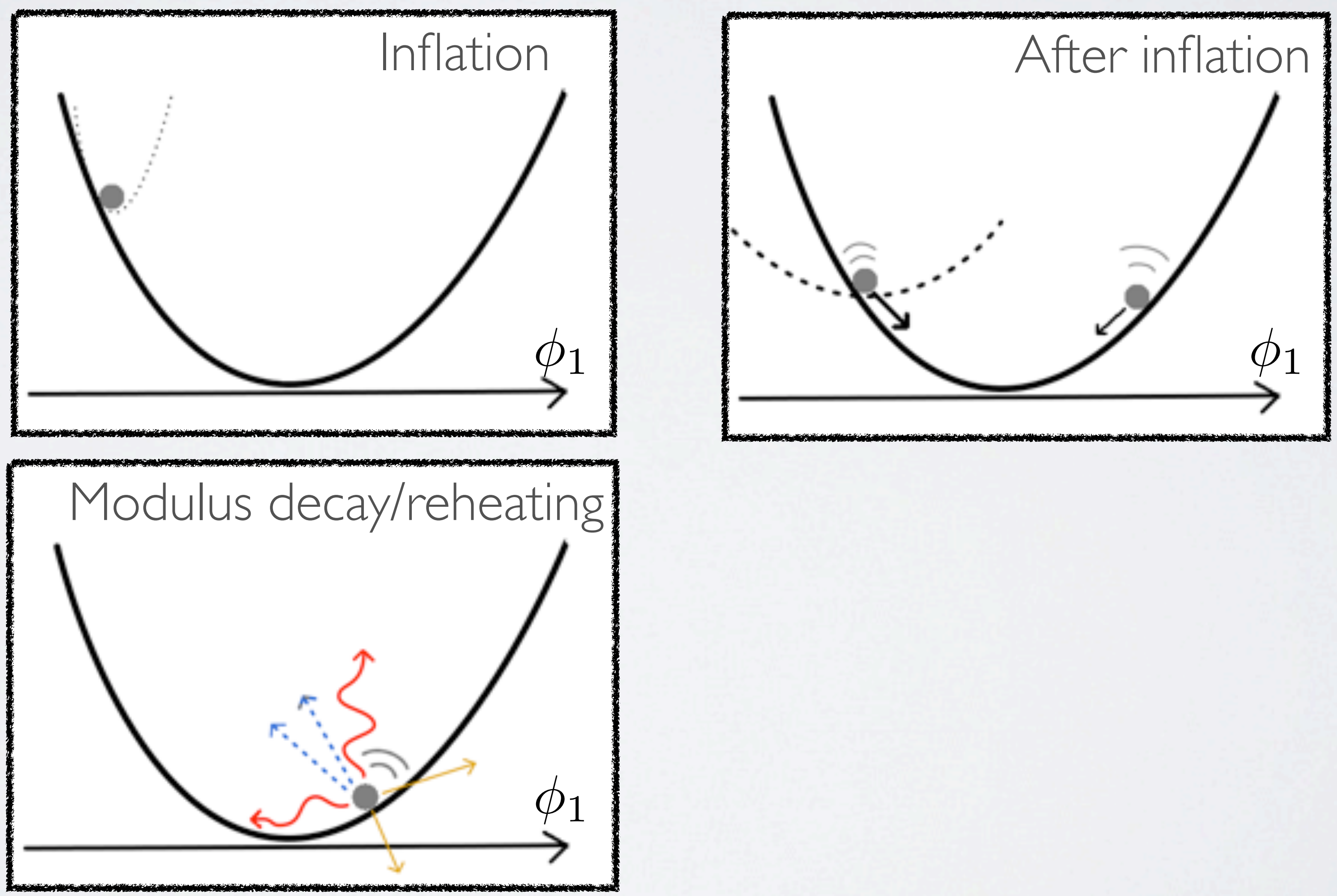

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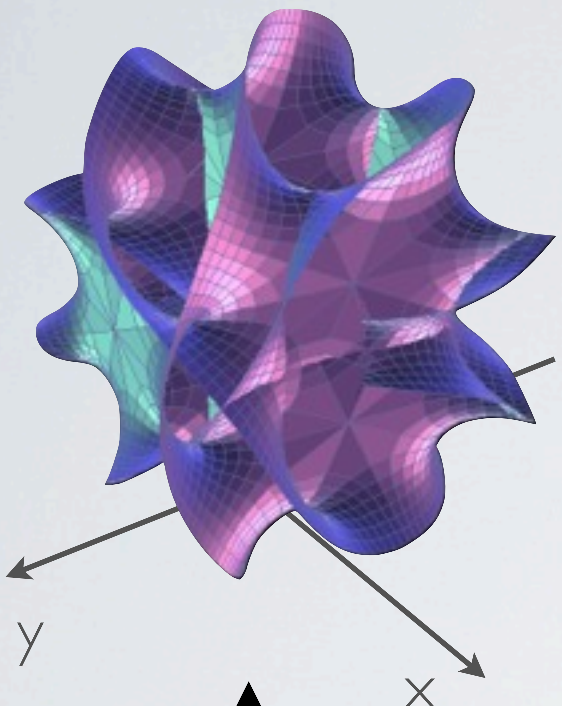

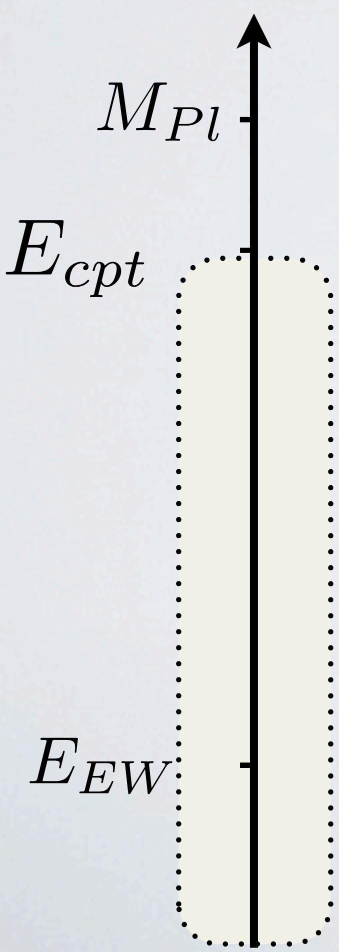

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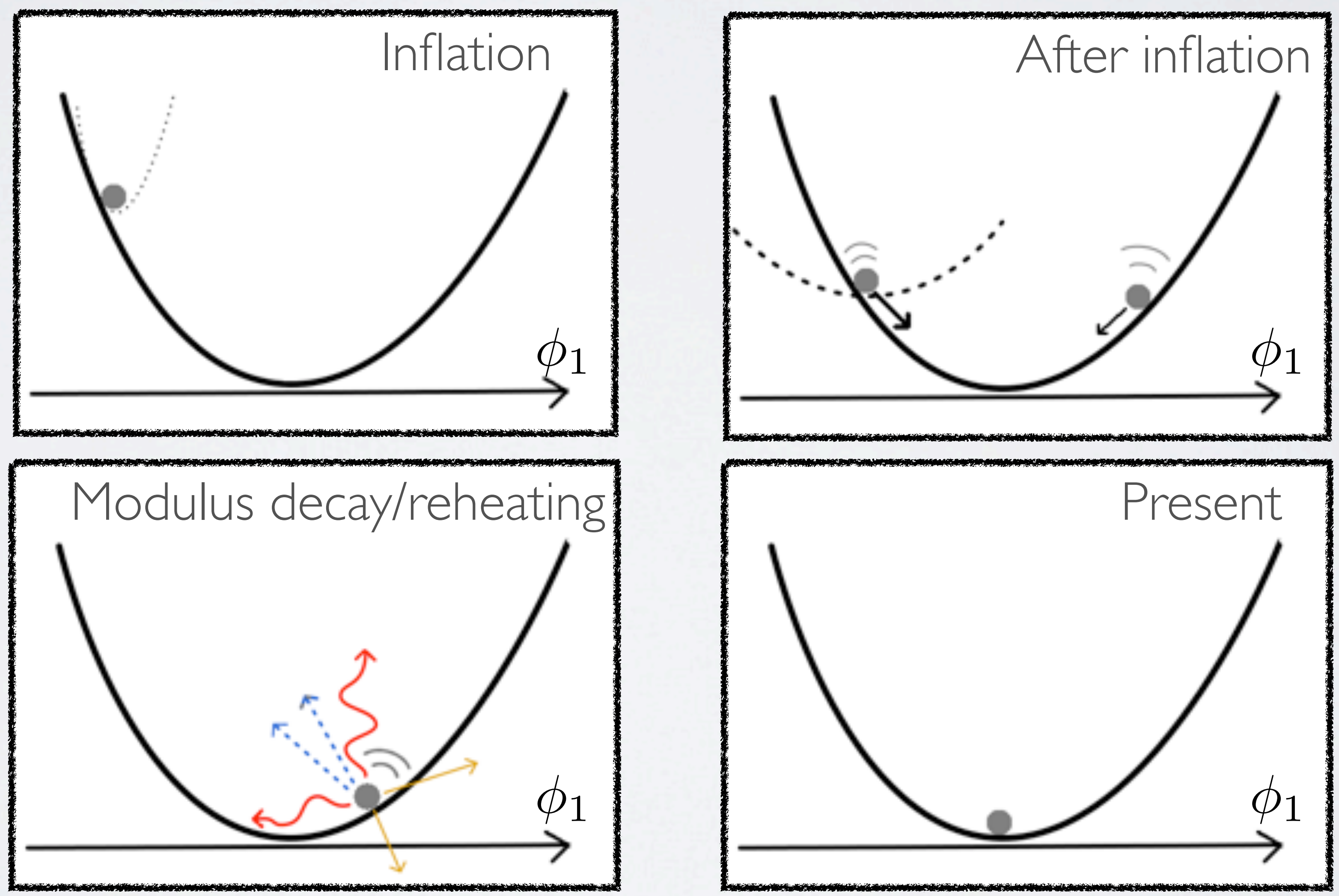

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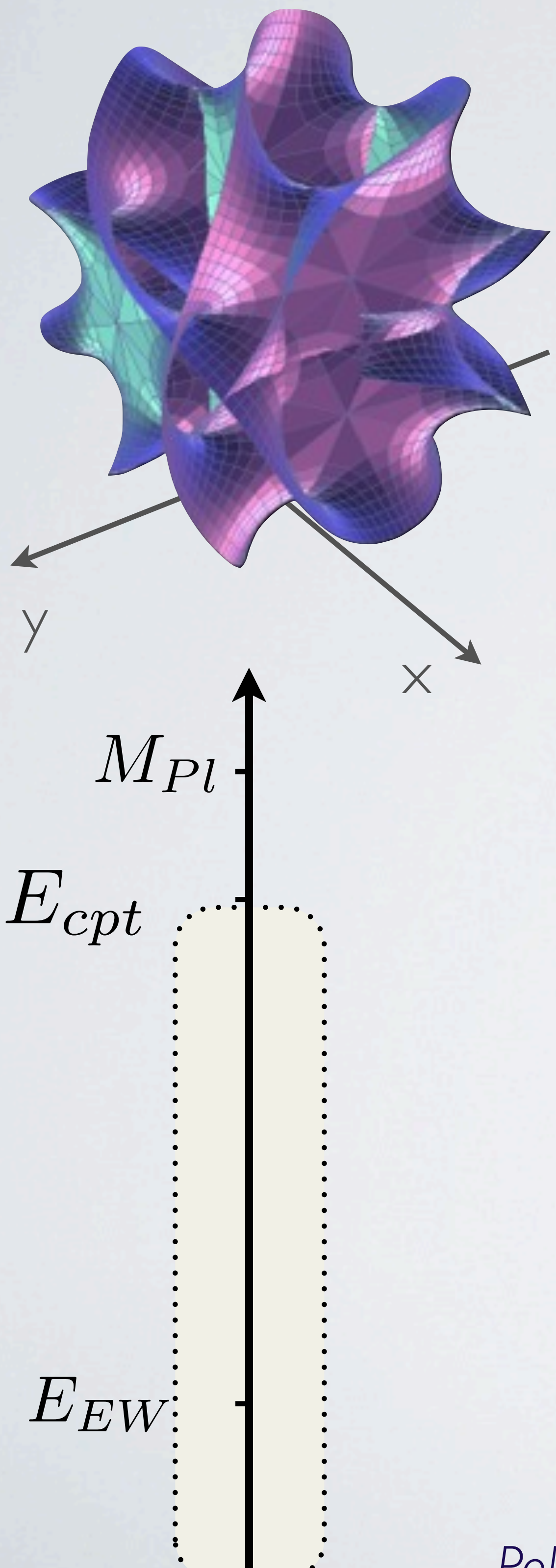

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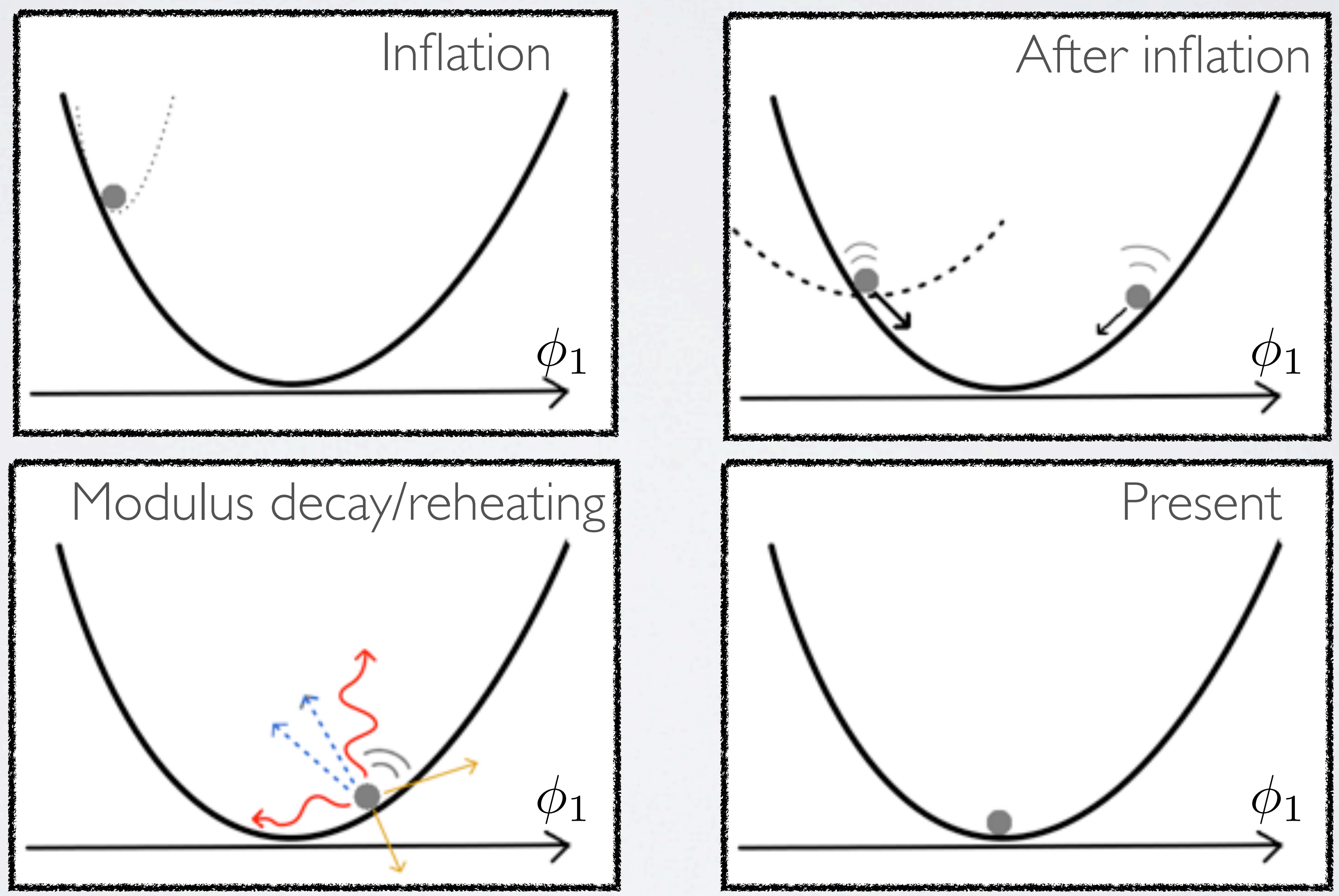
2. Moduli can cause cosmological problems: the most long-lived moduli start the Big Bang.



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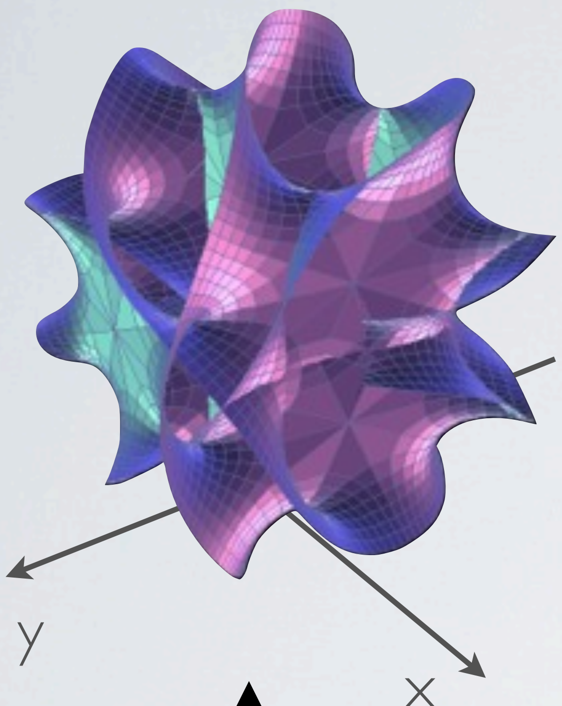
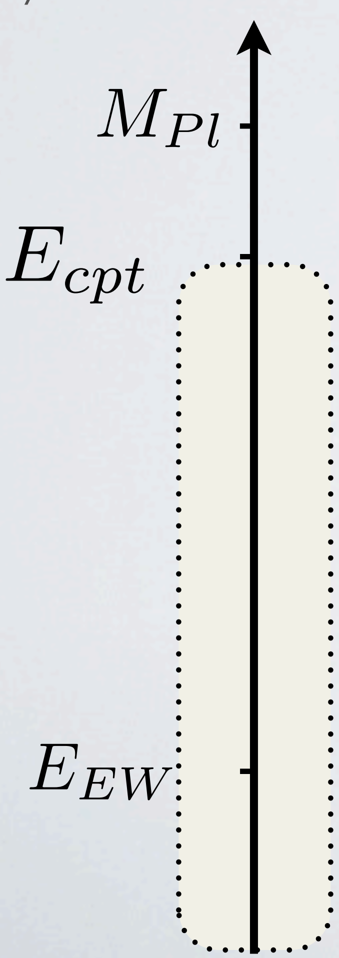
Moduli and cosmology





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The typical decay rate of gravitationally coupled scalars is:

$$\Gamma_\phi \sim \frac{1}{8\pi}\frac{m_\phi^3}{M_{\rm Pl}^2}\,.$$

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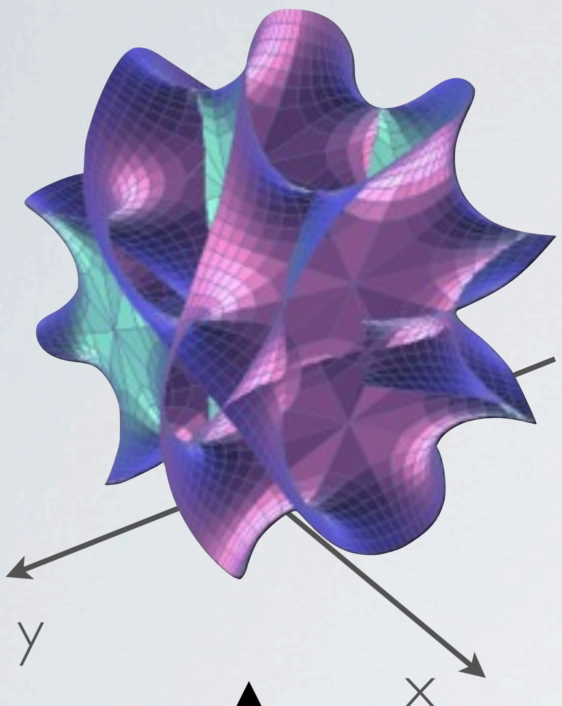
Moduli and cosmology



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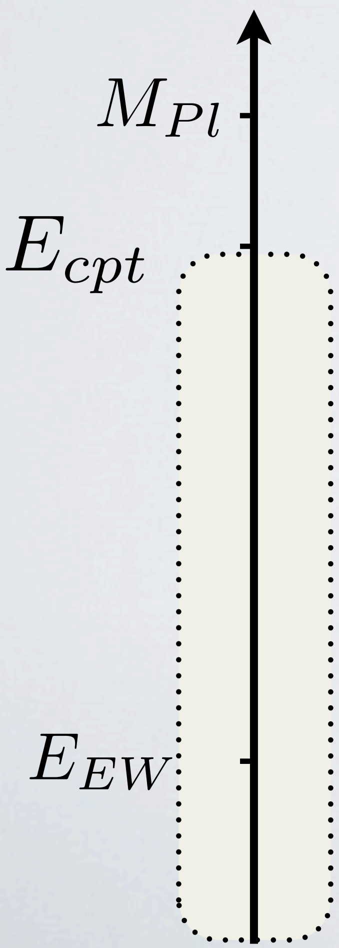

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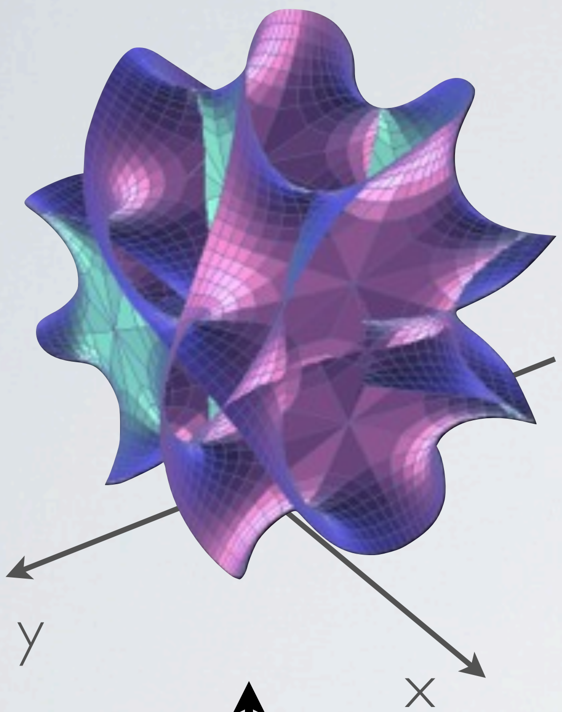

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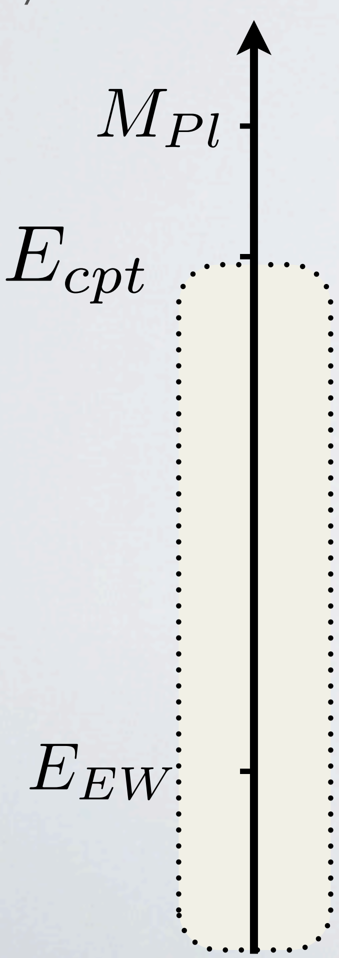
BBN requires T > O(1 MeV), so $m_\phi \gtrsim 3 \cdot 10^4~{\rm GeV}\,.$



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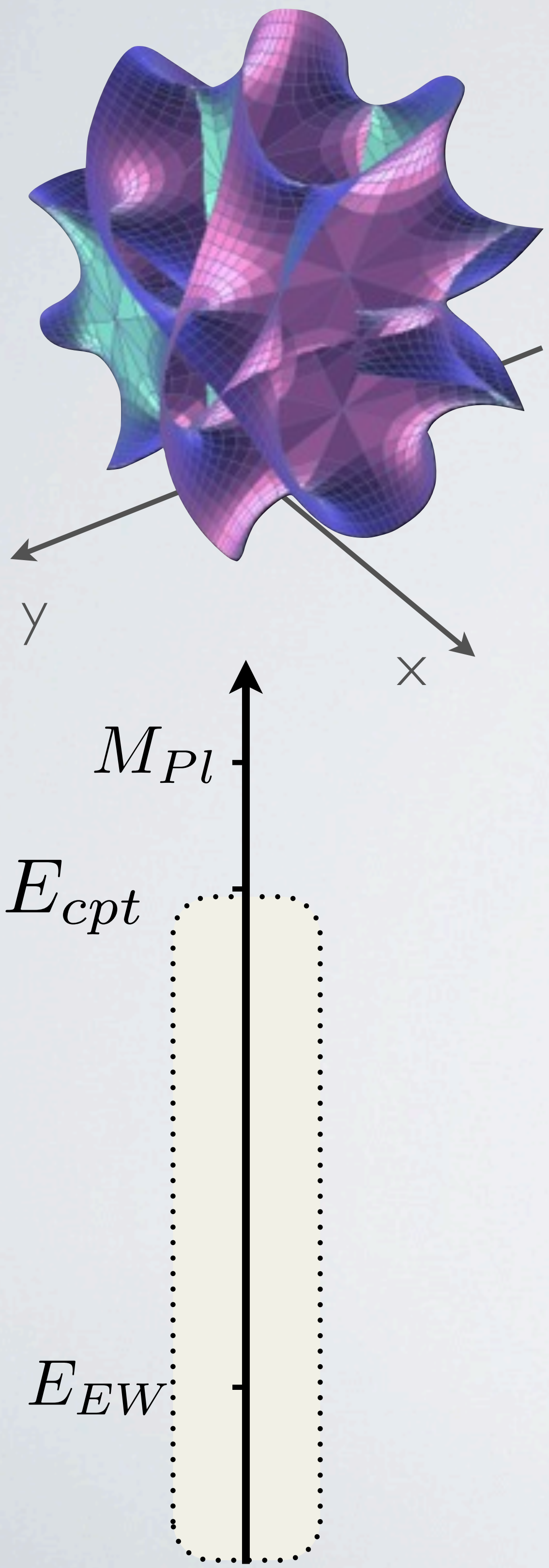
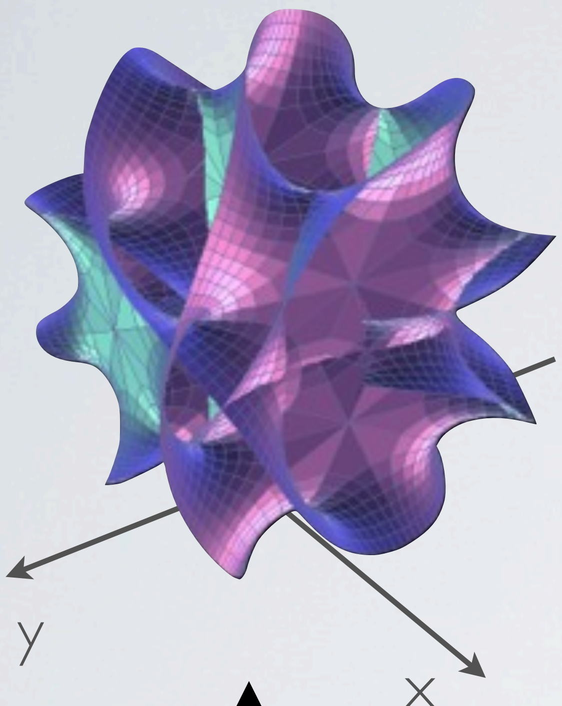
Moduli and cosmology

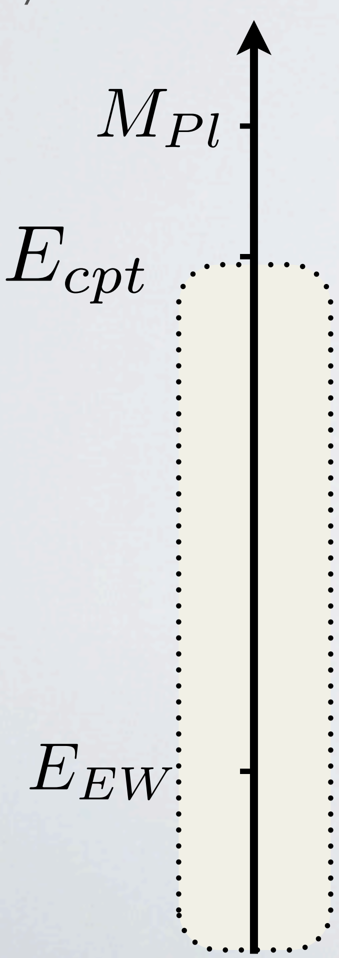


Genericity assertions:

3. String compactifications come with light hidden sectors.

Moduli and cosmology





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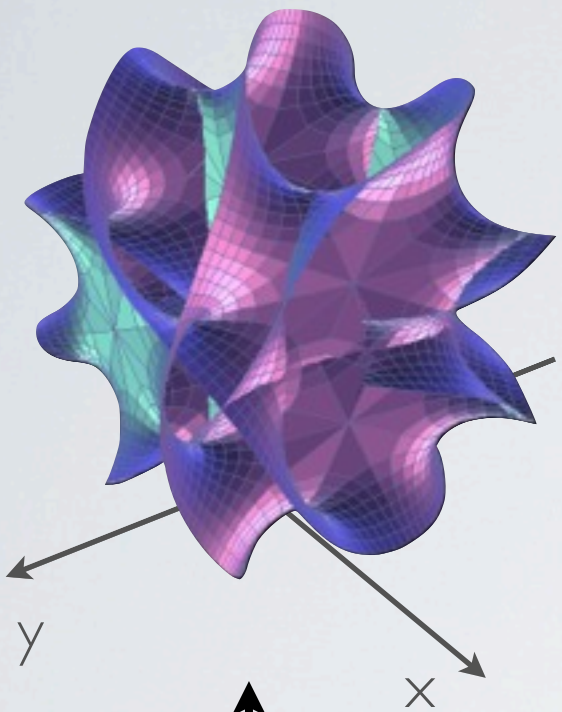

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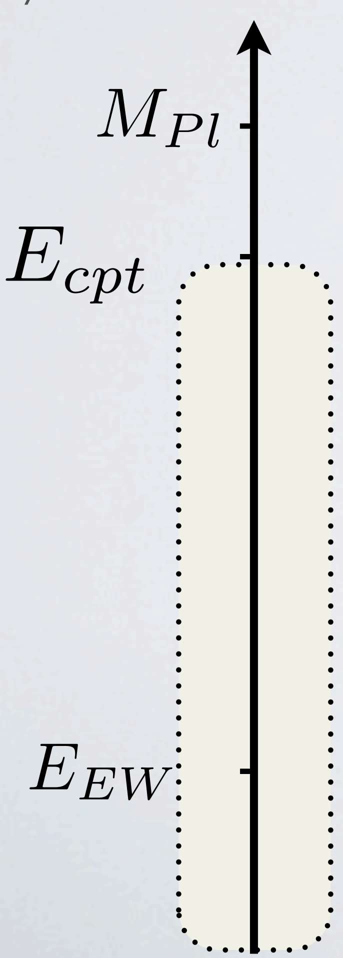
Examples:

Closed string *U(1)'s, (open string) hidden gauge groups,*

axion-like particles, ...



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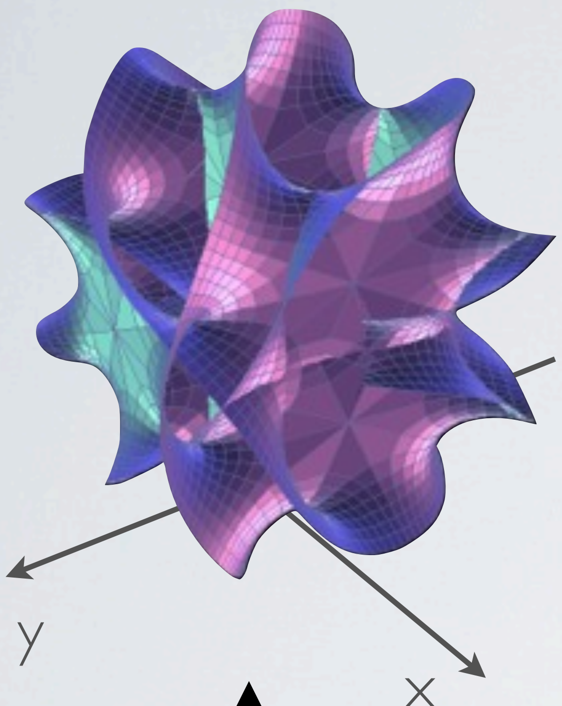

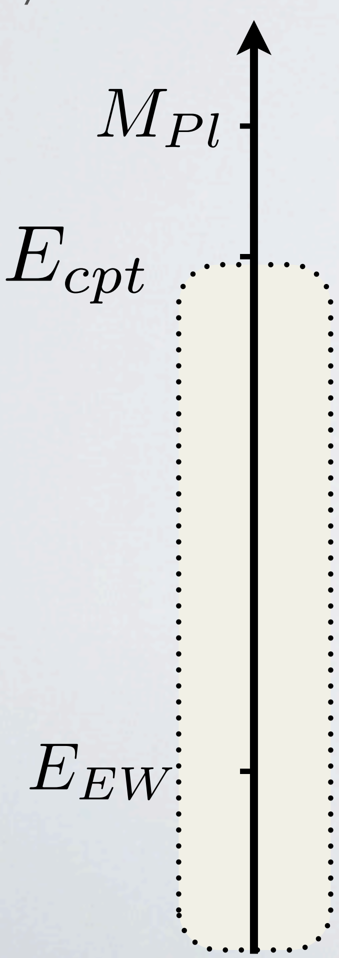

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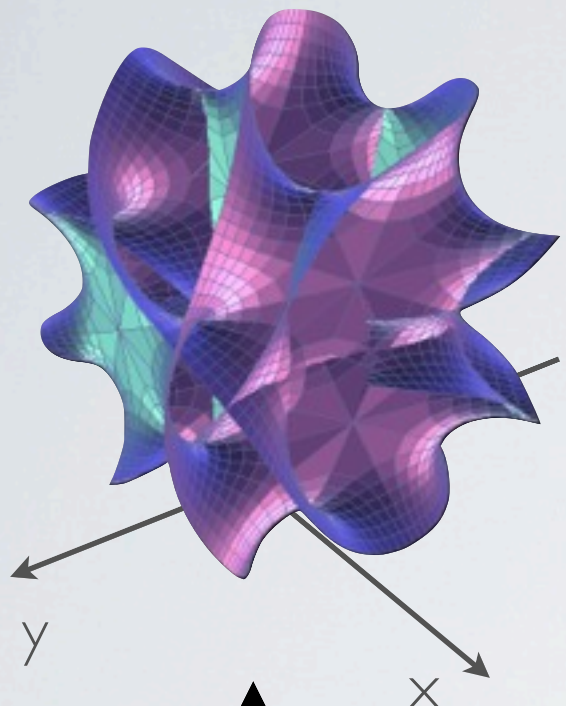
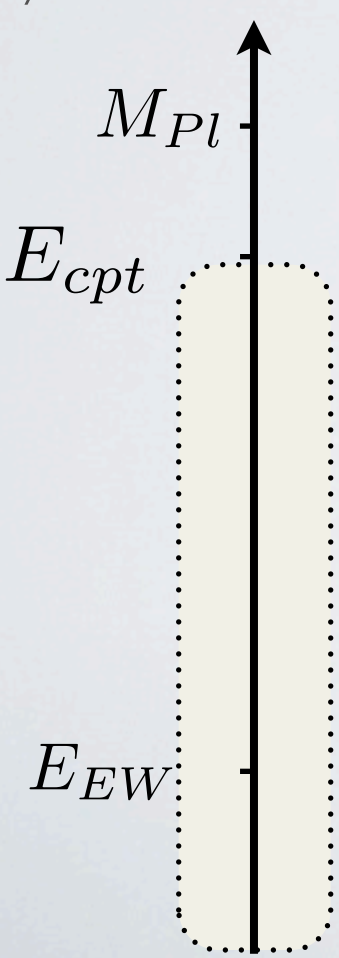
low-energy axion-like particles
=
axions in tree-level Calabi-Yau compactification
-# non-perturbative effects in the superpotential
-# projected out from orientifold planes
-# anomalous U(1)'s .

Moduli and cosmology

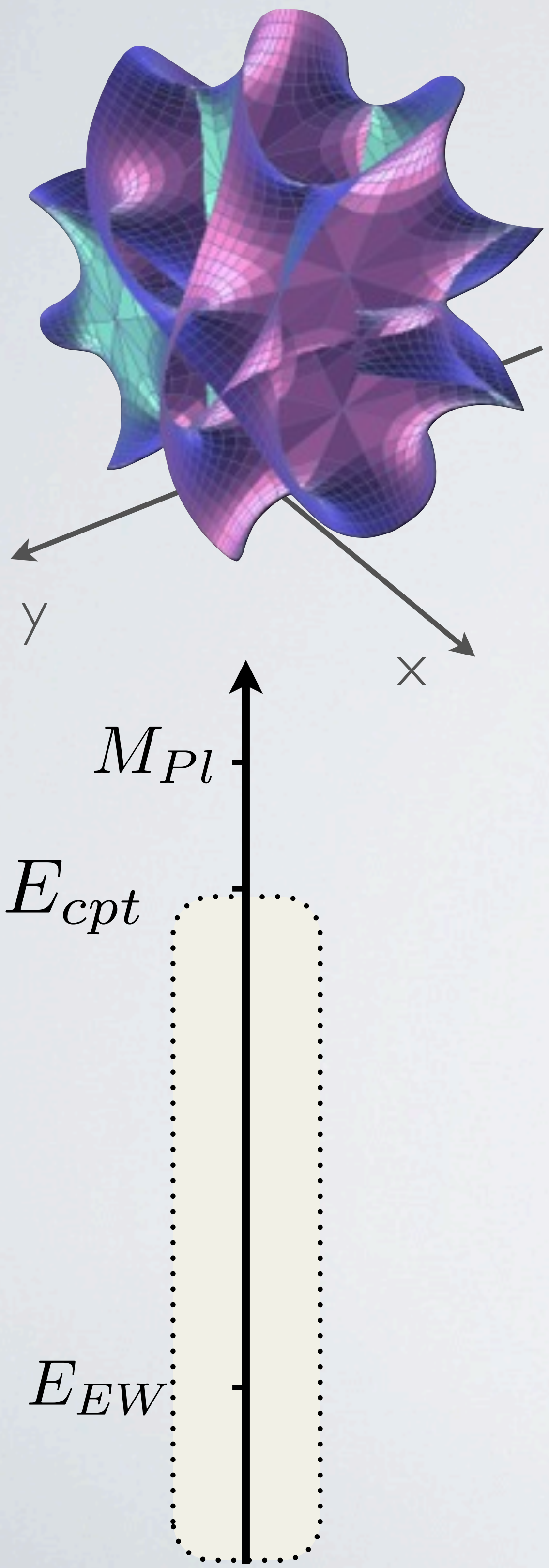




Genericity assertions:

4. *Decay rates into light hidden sectors are not automatically suppressed.*

Moduli and cosmology



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Example:

A modulus: $T = \tau_b + i a_b\,,$

A no-scale Kähler potential: $K = -3\ln\left(T + \bar{T}\right)\,,$

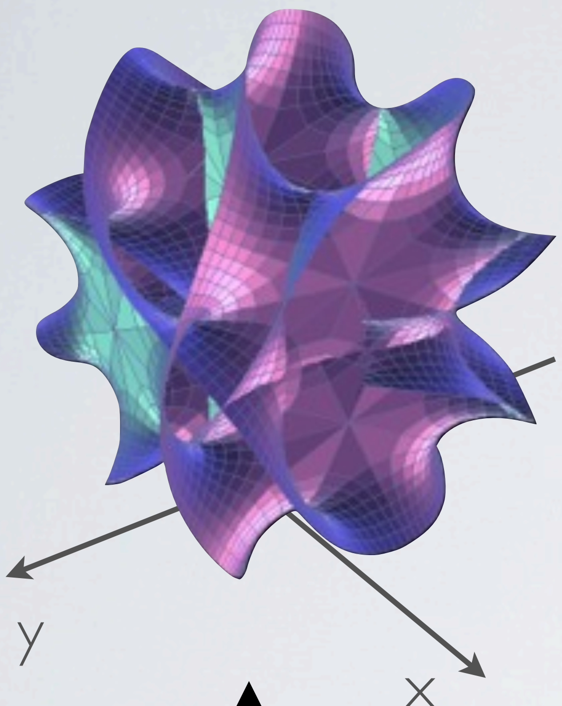
Kinetic terms: $\mathcal{L} = \dfrac{3}{4\tau_b^2}\left(\partial_\mu \tau_b \partial^\mu \tau_b + \partial_\mu a \partial^\mu a\right)\,,$

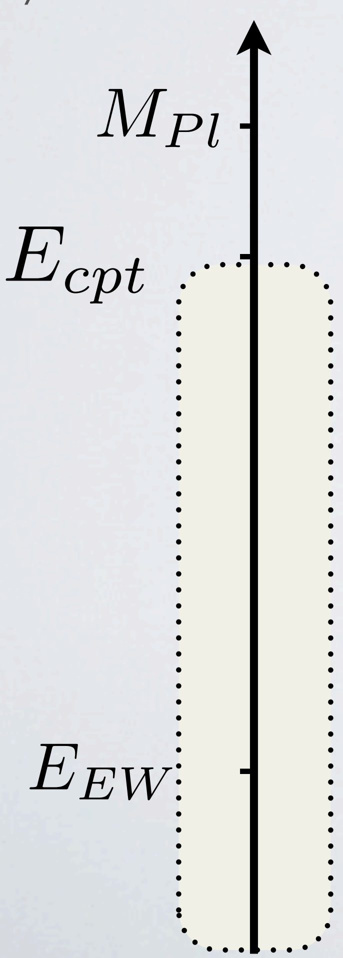
Canonical normalisation:

$$\mathcal{L} = \frac{1}{2}\partial_\mu(\delta\tilde{\tau}_b)\partial^\mu(\delta\tilde{\tau}_b) + \frac{1}{2}e^{-2\sqrt{\frac{2}{3}}\delta\tilde{\tau}_b}\partial_\mu \tilde{a}\partial^\mu \tilde{a}\,.$$

(in LVS): Cicoli, Conlon Quevedo '12, Higaki, Takahasi, '12.

Moduli and cosmology





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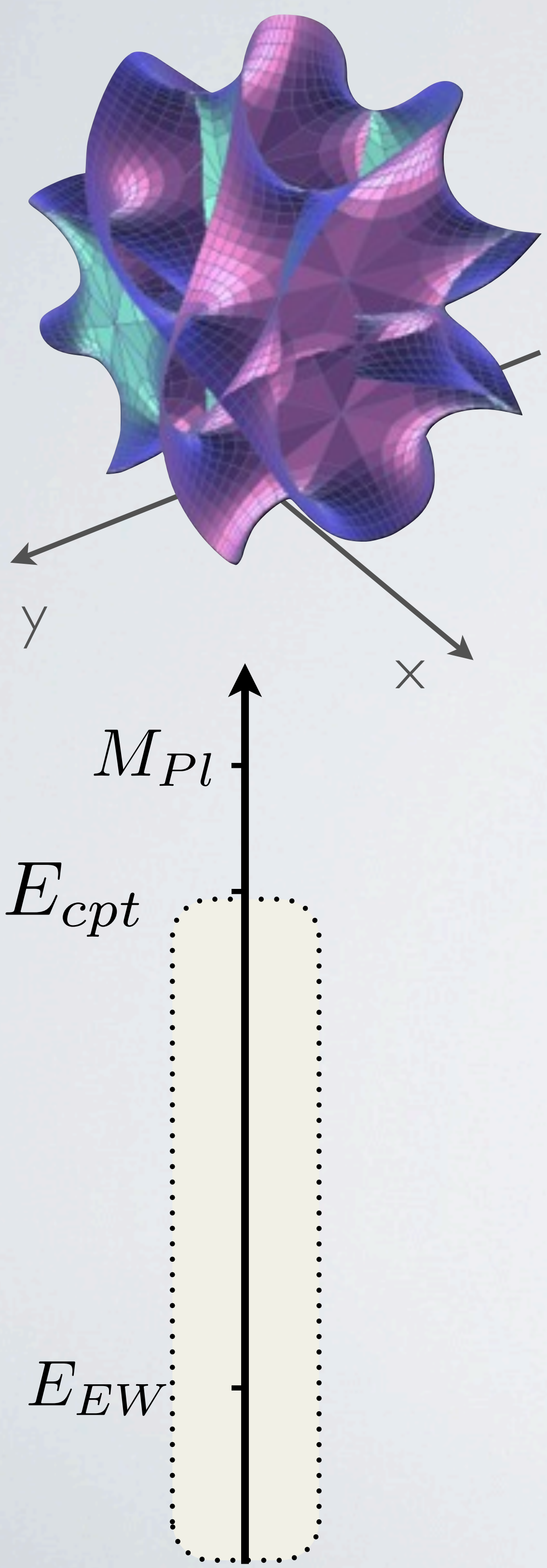
Decay rate for $m_{a_b} \ll m_{\tau_b}$: $\Gamma_{\tau_b \to a_b a_b} = \frac{1}{48\pi}\frac{m_{\tau_b}^3}{M_{\rm Pl}^2}$.

(in LVS): Cicoli, Conlon Quevedo '12, Higaki, Takahasi, '12.

Moduli and cosmology



Genericity assertions:

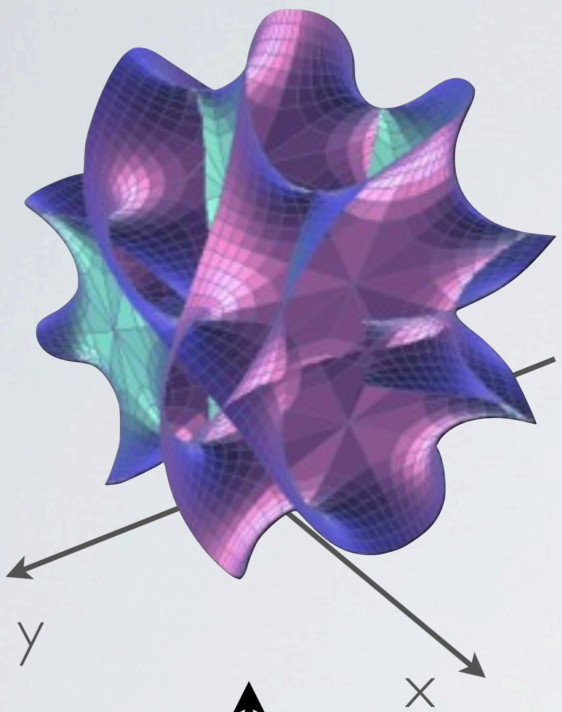
1. String compactifications come with moduli.

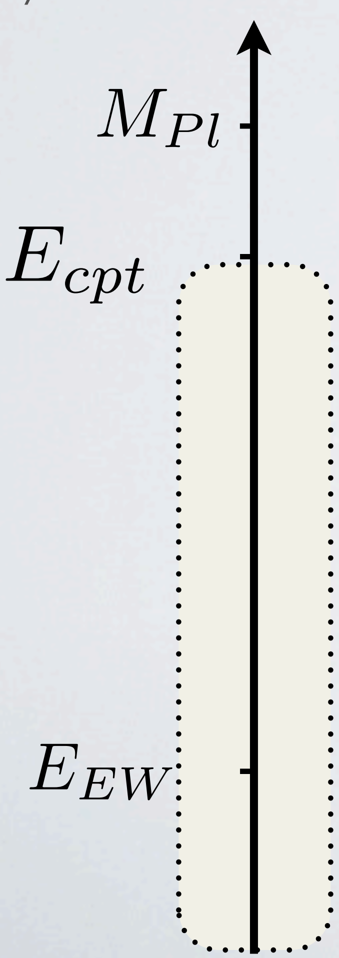
2. Moduli can cause cosmological problems: the lightest moduli start the Big Bang.

3. String compactifications come with light hidden sectors.

4. Decay rates into light hidden sectors are not automatically suppressed.

Moduli and cosmology





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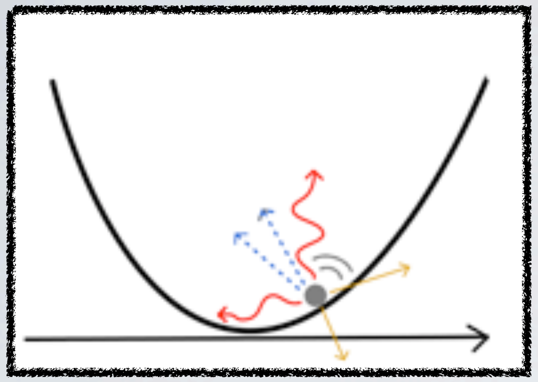
Consequence:

String cosmology includes some amount of dark radiation.

Dark radiation



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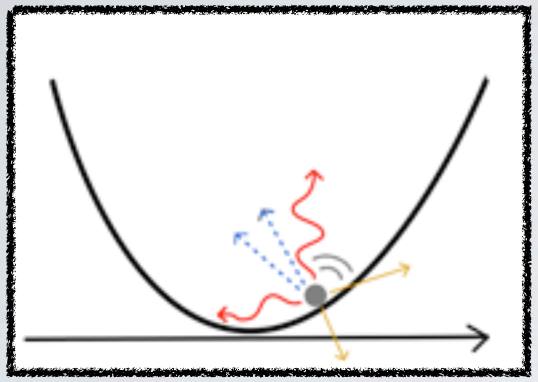


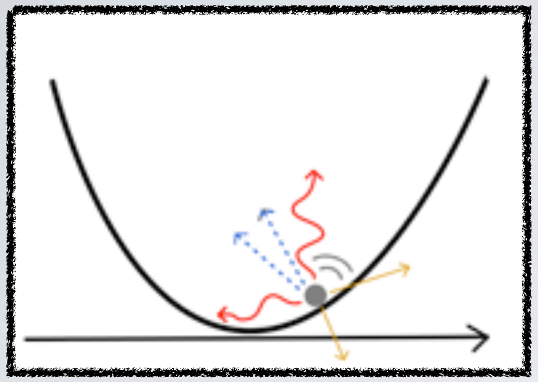
String cosmology includes some amount of dark radiation.

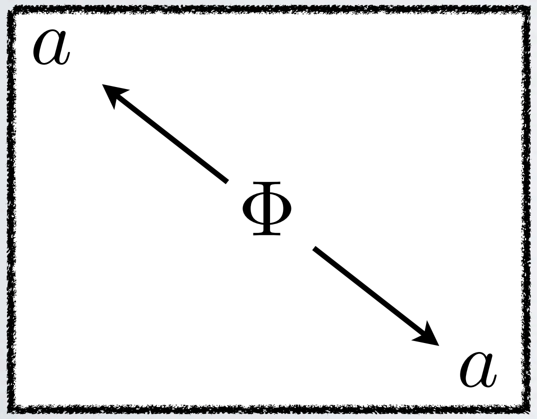
Visible sector: populated through $\phi \to \gamma\gamma\,,\; HH\,...$ and thermalize at,

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

$$\sim 0.6\ \text{GeV}\left(\frac{m_\phi}{10^6\ \text{GeV}}\right)^{3/2}\,,$$

Dark radiation





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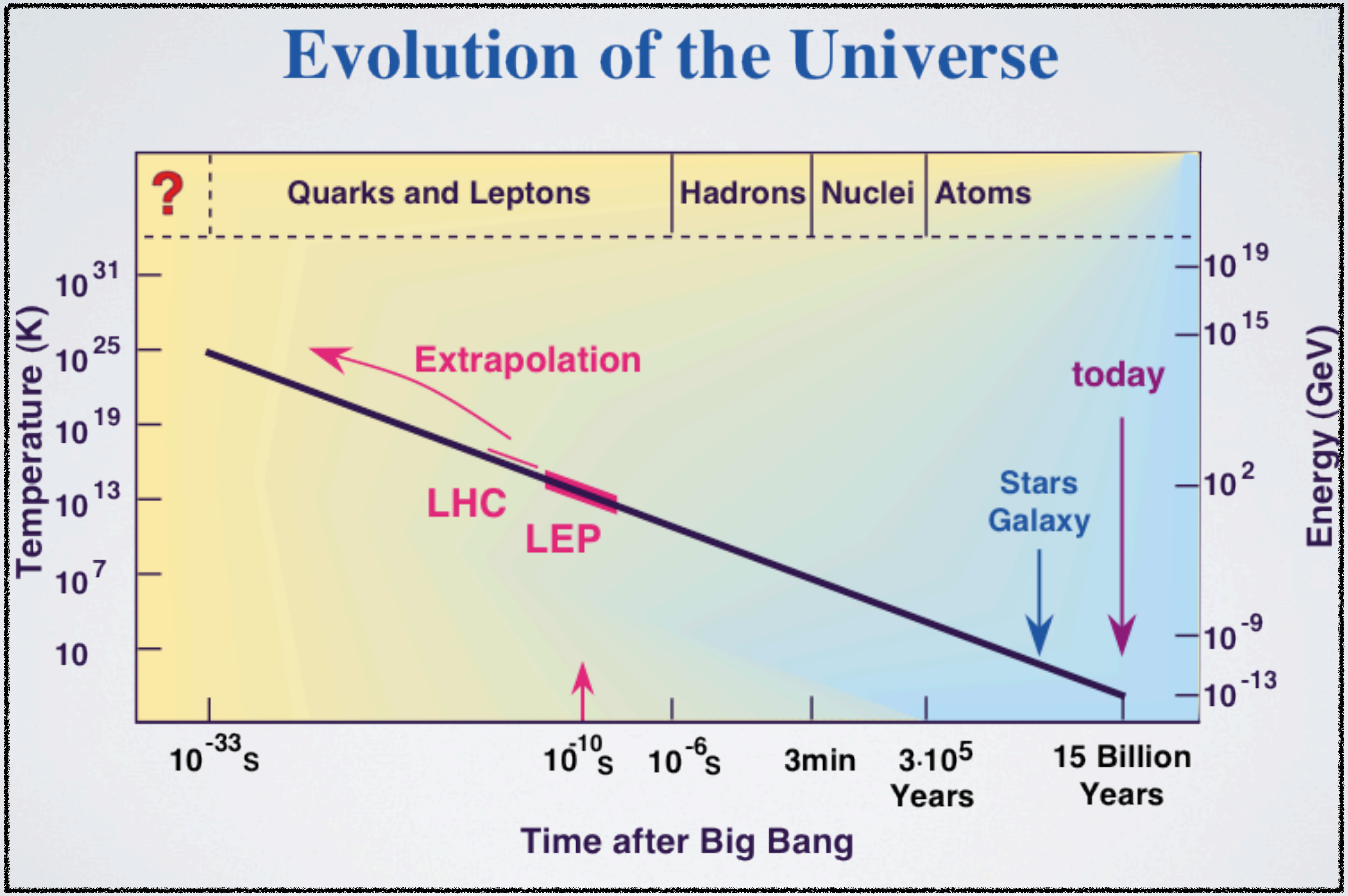
$$\sim 0.6\ \mathrm{GeV}\left(\frac{m_\phi}{10^6\ \mathrm{GeV}}\right)^{3/2}\,,$$

Dark radiation: populated through e.g. $\phi \to aa$ with an initial energy of,

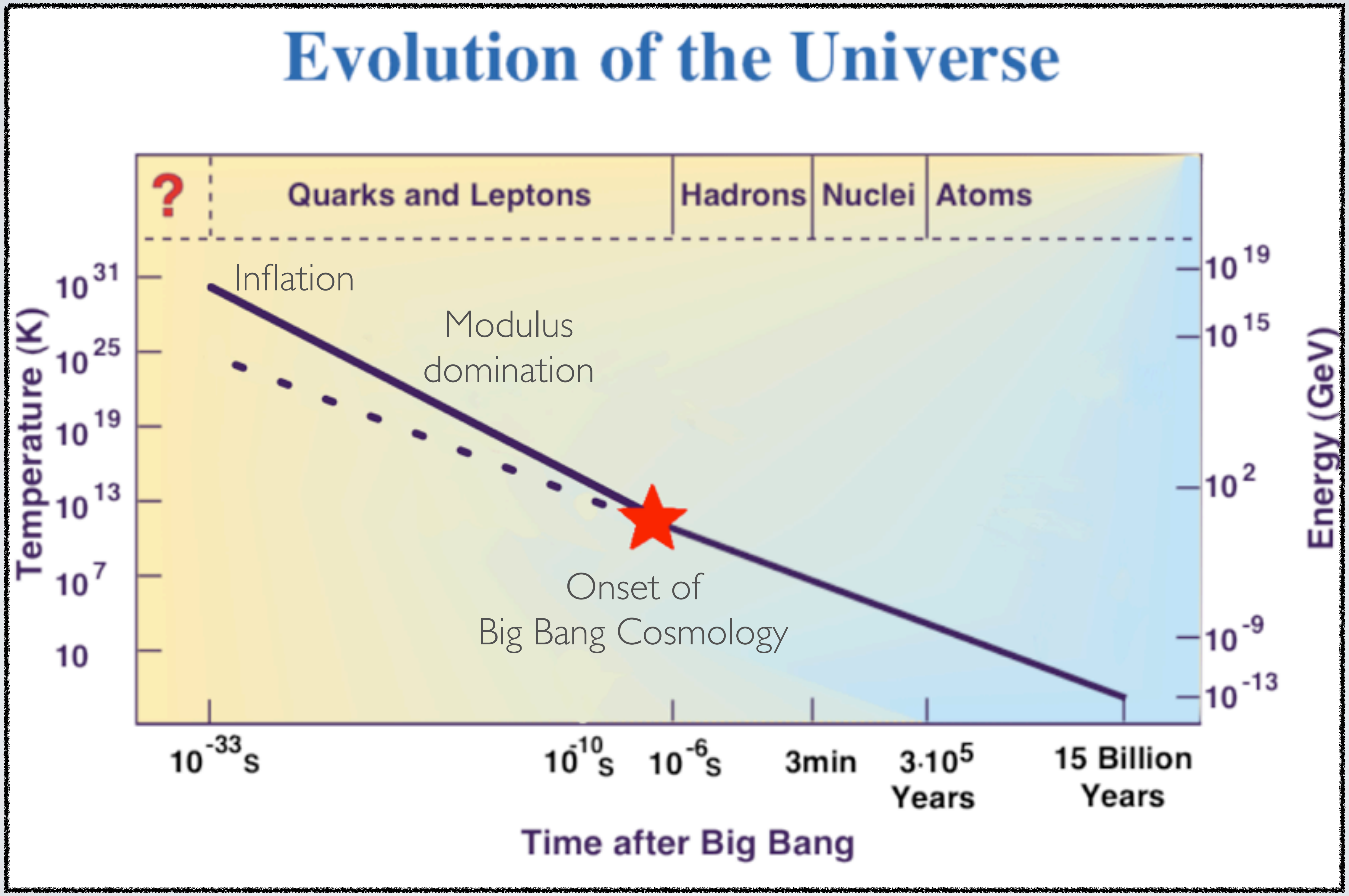
$$\boxed{E_a^{(0)} = m_{\phi_1}/2 \gg T_{rh}\,,}$$

and are too weakly coupled to ever thermalise.

Dark radiation



Dark radiation



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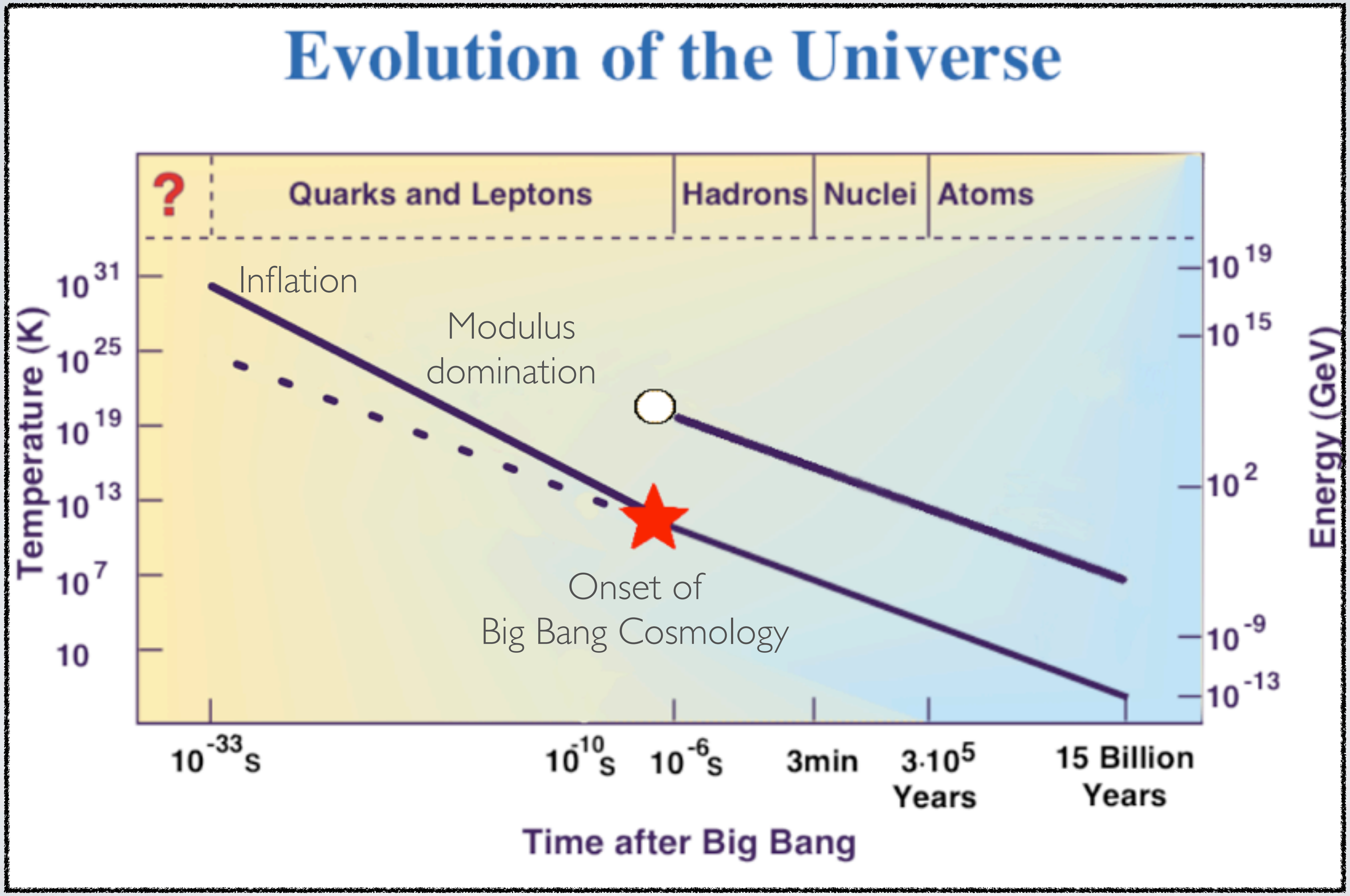

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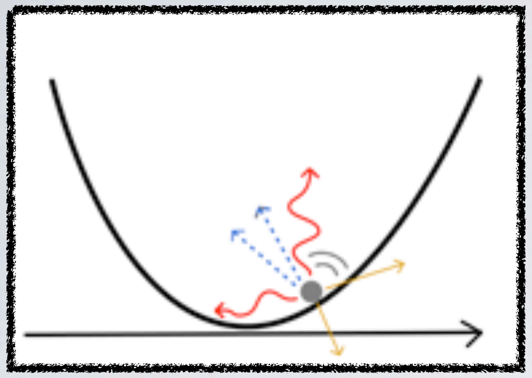
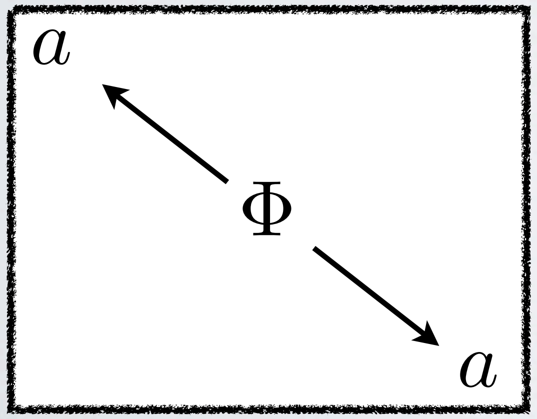
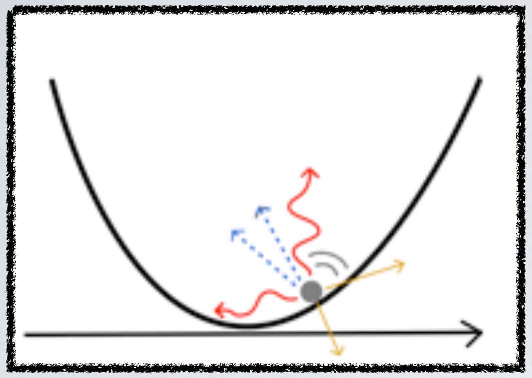


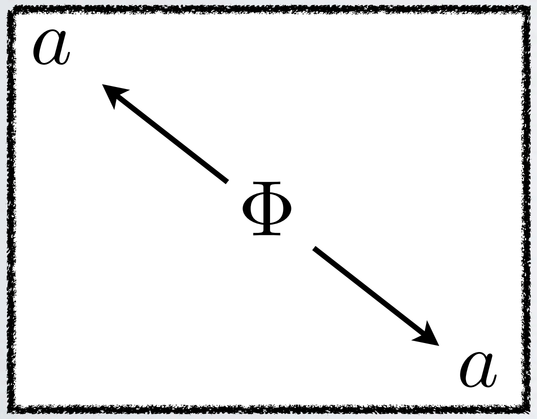


String cosmology includes some amount of dark radiation.

But how much?

Dark radiation





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Energy density: $\rho_{\rm d.r.} = \rho^{\rm tot}_{\rm rad.} - \rho_\gamma - \rho_\nu \, ,$

Conventional parametrisation: $\Delta N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_{\rm d.r.}}{\rho_\gamma} \, .$

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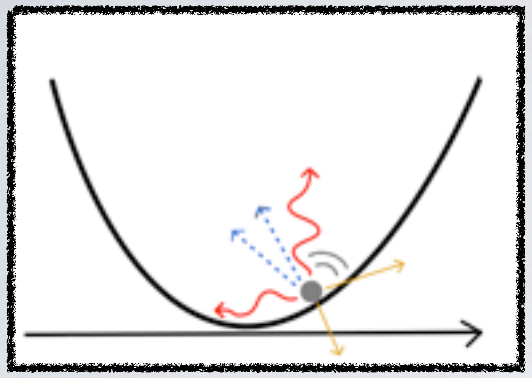

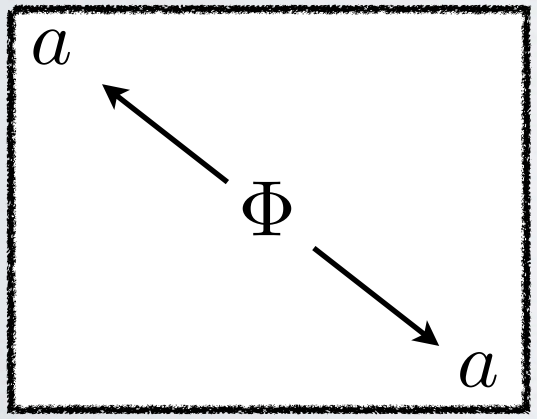

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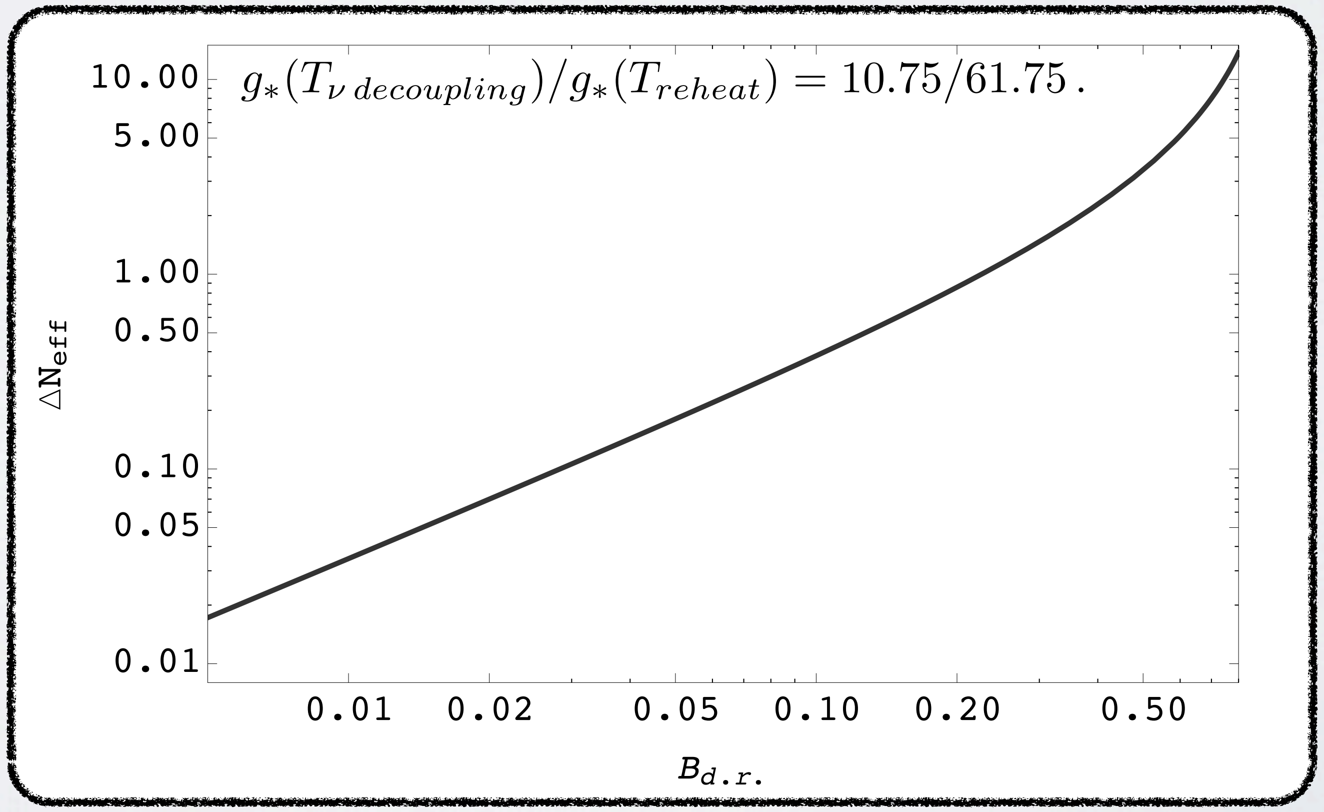
From modulus decay: $\Delta N_{\text{eff}} = \frac{43}{7}\left(\frac{g_\star(T_\nu)}{g_\star(T_{rh})}\right)^{1/3} \frac{\Gamma_{\Phi\to\text{d.r.}}}{\Gamma_{\Phi\to\text{vis.}}} \,.$



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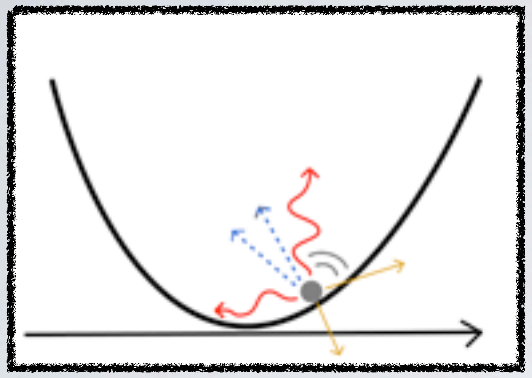
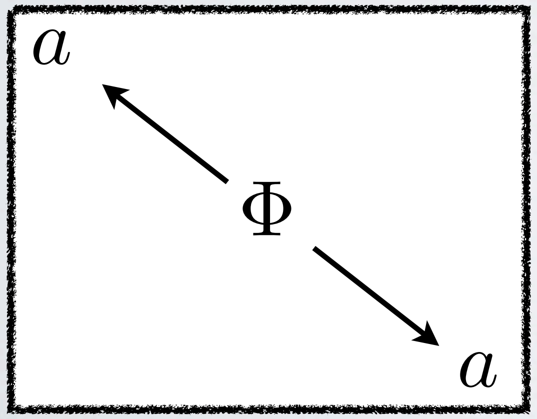


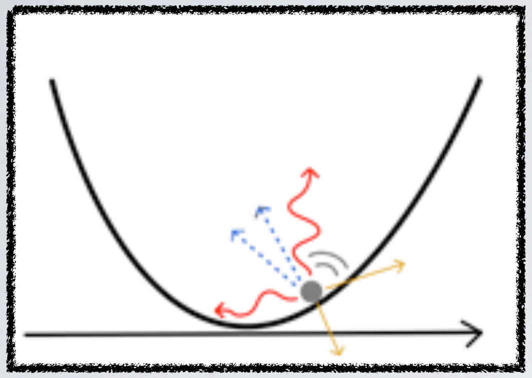


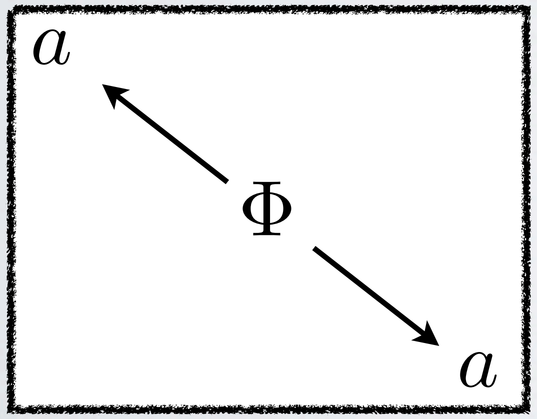
Example: the (sequestered) type IIB Large Volume Scenario

Lightest modulus: $\tau_b\,,\ m_{\tau_B} \sim 10^6\ \mathrm{GeV}\ \text{ for } m_{\rm soft} \approx \mathrm{TeV}\,.$

Cicoli, Conlon Quevedo '12, Higaki, Takahasi, '12.

Dark radiation





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Visible sector decay modes: Γ:

Dominant hidden sector decay mode:

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Dark radiation

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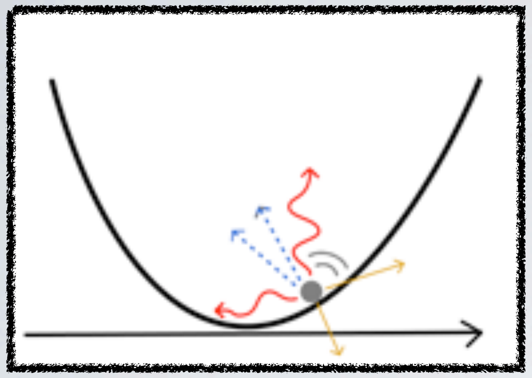

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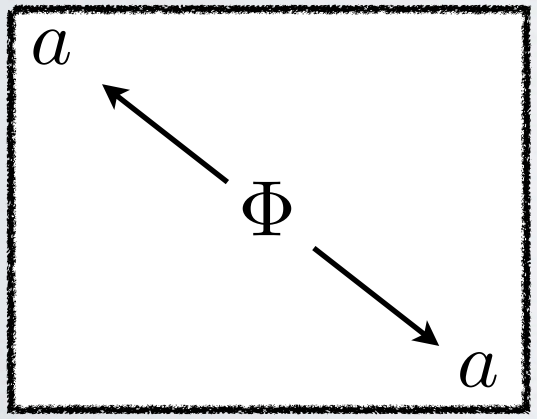
Gauge bosons: loop suppressed: $\sim \left(\frac{\alpha_{\mathrm{SM}}}{4\pi}\right)^2 \frac{m_{\tau_b}^3}{M_{\mathrm{Pl}}^2}\,.$

Fermions: chirality suppressed: $\sim \frac{m_f^2 m_{\tau_b}}{M_{\mathrm{Pl}}^2}\,.$

Scalars: soft-mass suppressed... : $\sim \frac{m_0^2 m_{\tau_b}}{M_{\mathrm{Pl}}^2}\,.$

...but Giudice-Masiero term

$K \supset Z \frac{H_u H_d}{T_b + \bar{T}_b} + \mathrm{c.c.}$ gives: $\frac{Z^2}{24\pi}\frac{m_{\tau_b}^3}{M_{\mathrm{Pl}}^2}\,.$



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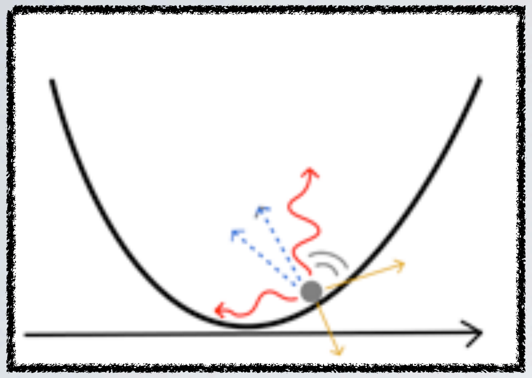

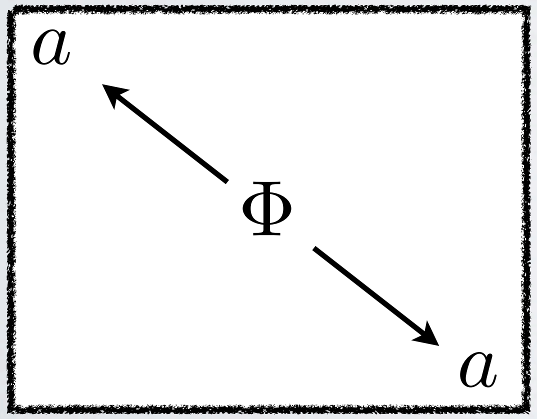

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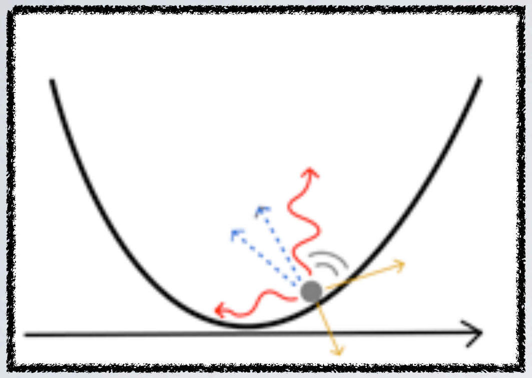
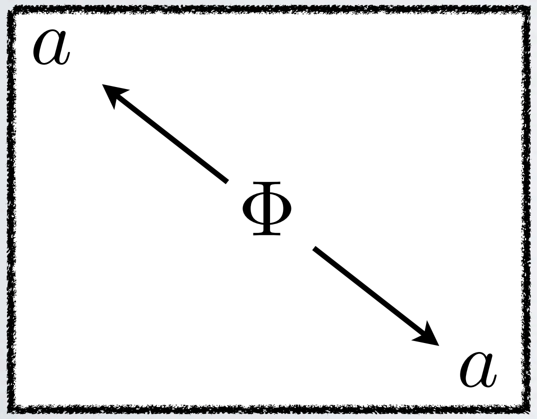
Dominant hidden sector decay mode:

Volume axion: $\frac{1}{48\pi}\frac{m_{\tau_b}^3}{M_{\mathrm{Pl}}^2}\,.$

Cicoli, Conlon Quevedo '12, Higaki, Takahasi, '12.

Dark radiation





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Lightest modulus: $\tau_b\,,\ m_{\tau_B} \sim 10^6\ \mathrm{GeV}\ \ \mathrm{for}\ m_{\mathrm{soft}} \approx \mathrm{TeV}\,.$

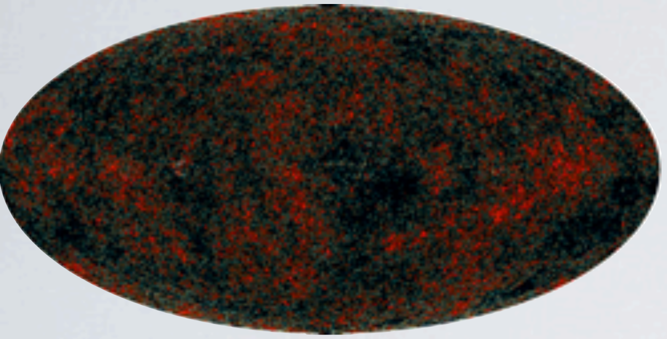
Result:
$$\Delta N_{\mathrm{eff}} = \frac{43}{7}\left(\frac{g_\star(T_\nu)}{g_\star(T_{rh})}\right)^{1/3}\frac{1}{2Z^2} \approx \frac{1.75}{Z^2}\,.$$

"Moduli induced axion problem"

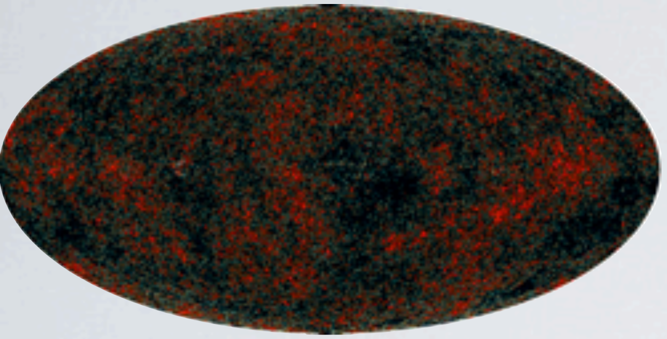
See also talk by Angus.

Cicoli, Conlon Quevedo '12, Higaki, Takahasi, '12, Higaki, Nakayama, Takahashi '13, see also Hebecker et al '14.

Dark radiation



Dark radiation

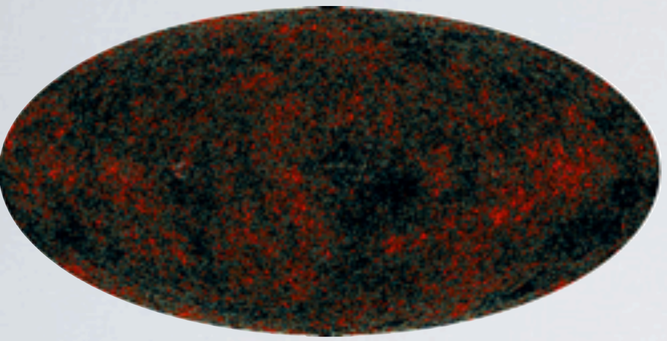


Constraints:

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

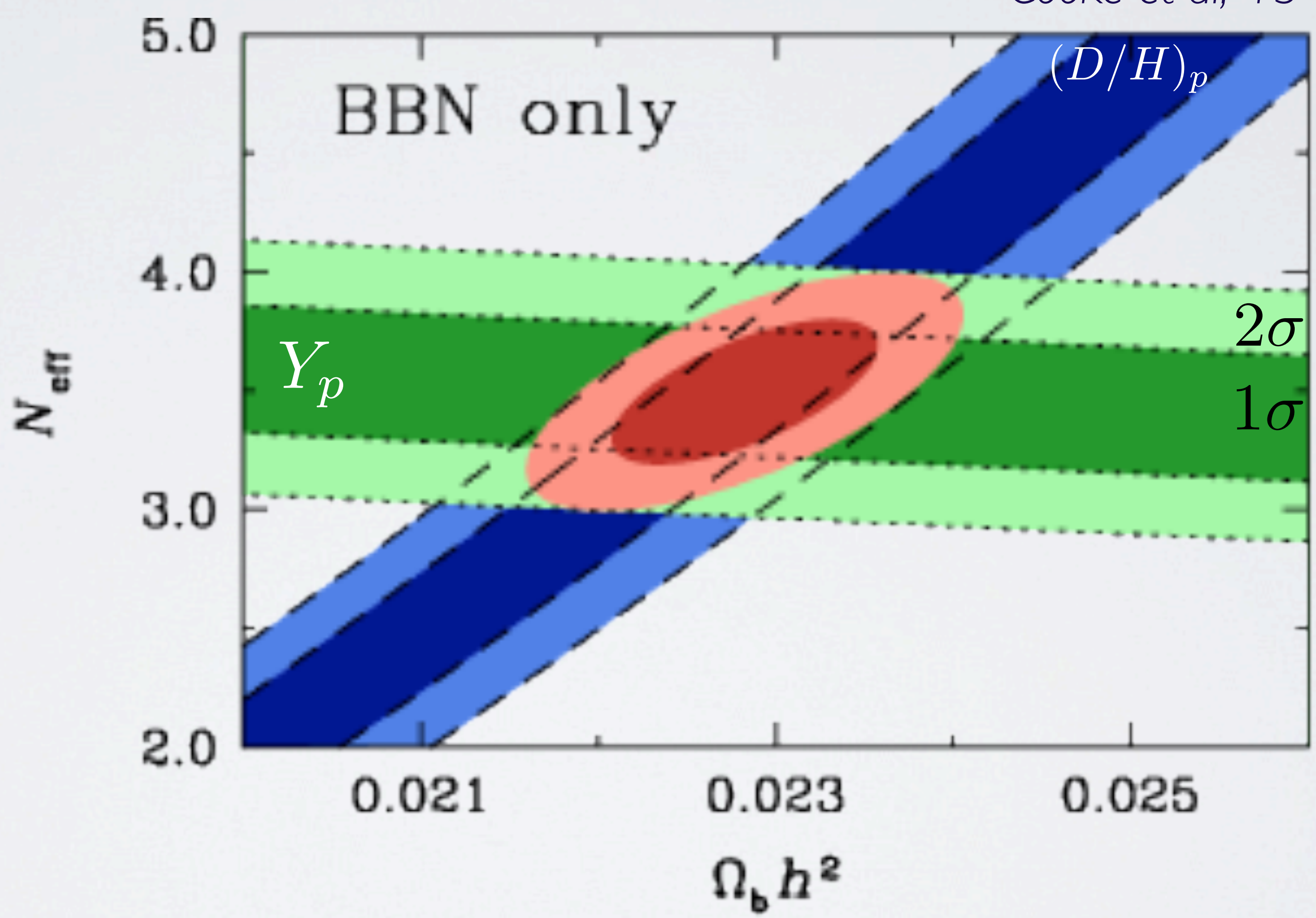
2. CMB: $\Delta N_{\rm eff} > 0$ effectively enhances the Silk damping of high-l multipoles.

Dark radiation



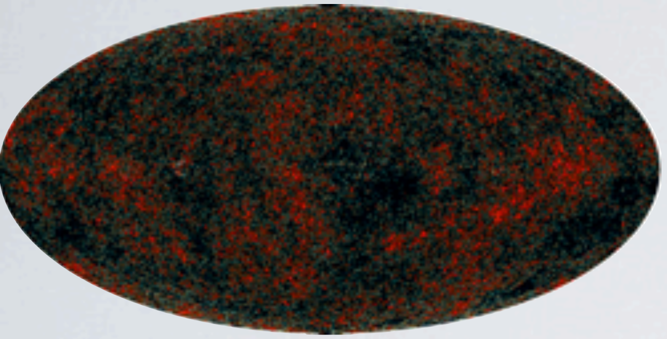
1. BBN analysis suggests $\Delta N_{eff} \approx 0.5$.

Cooke et al, '13



Best fit: $\Delta N_{\rm eff} = 0.46 \pm 0.20\,.$

Dark radiation

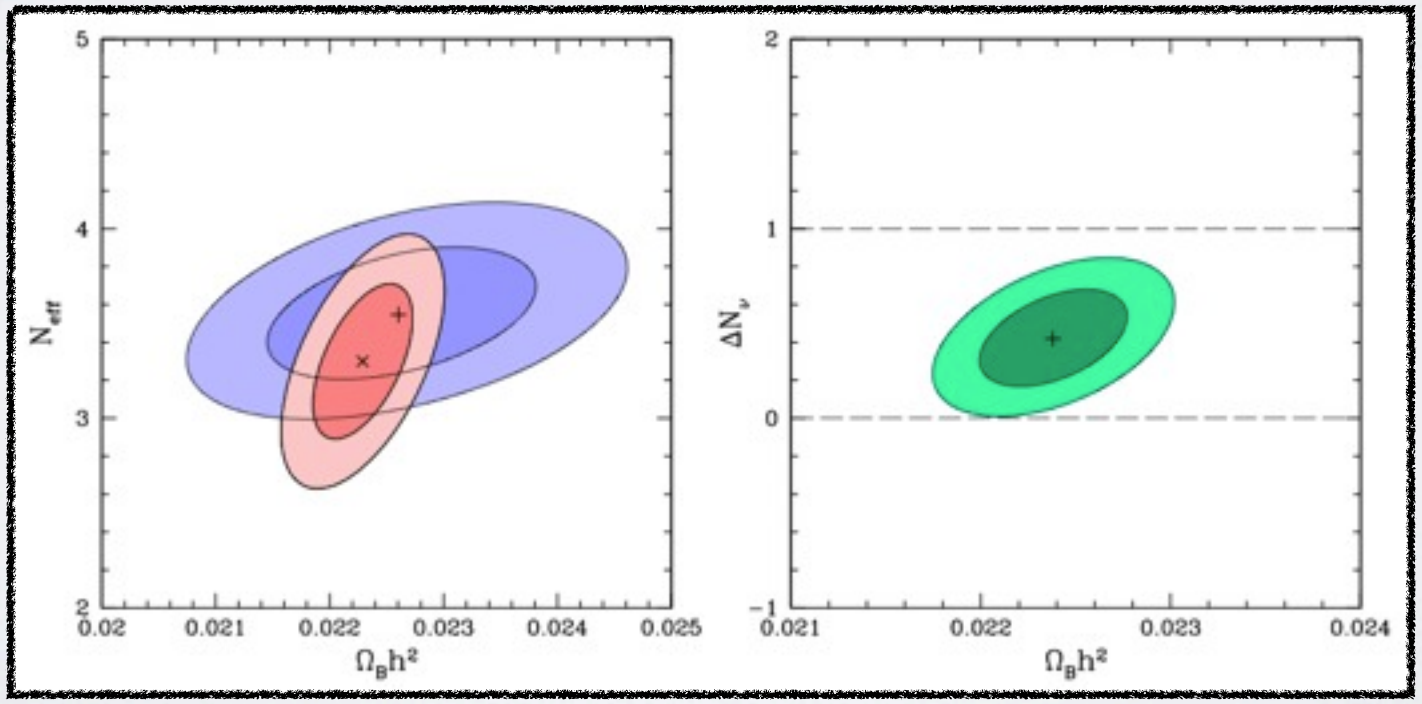


2. CMB data mildly suggests $\Delta N_{\rm eff}>0$.

Planck:

	$\Delta N_{\rm eff}$
Planck+WMAP-pol+ high-l+*BAO*:	0.26 ± 0.27 ,
Planck+WMAP-pol+ high-l+*BAO* +H_0:	0.48 ± 0.25 .

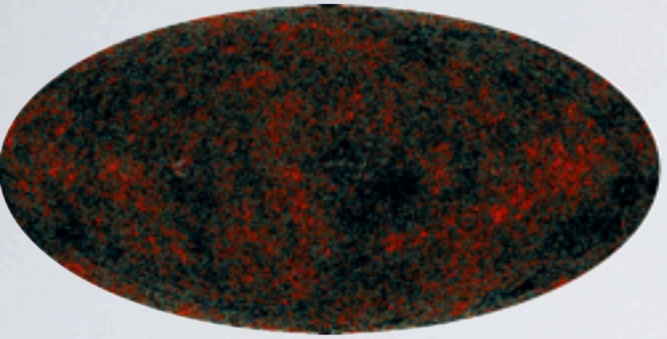
Planck+BBN:



0.40 ± 0.16 .

Planck collaboration '13, Nollet, Steigman '13.

Dark radiation



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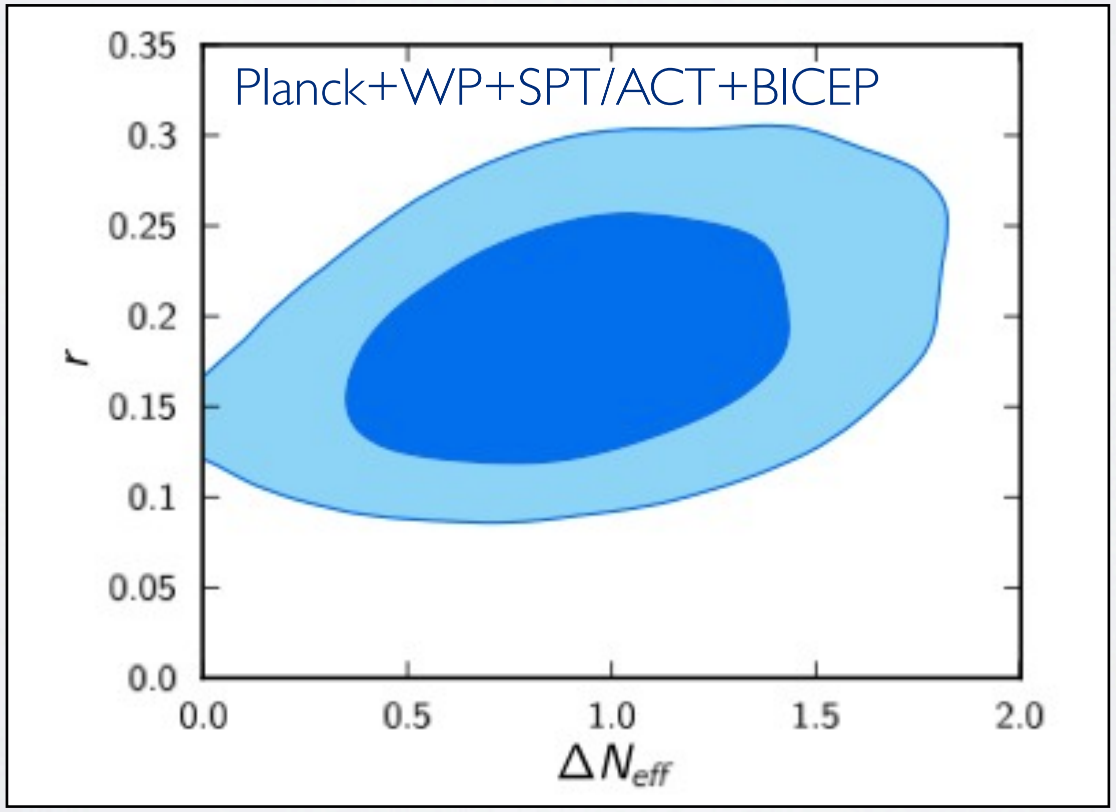
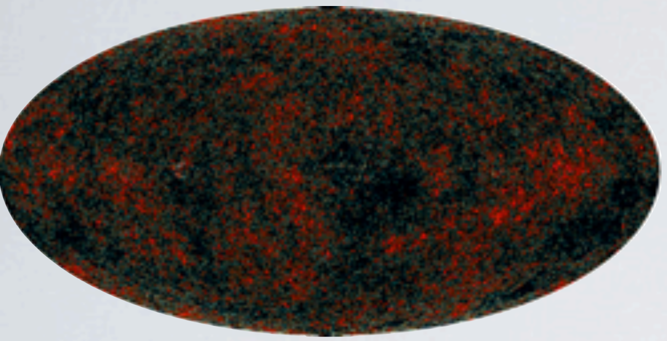
Planck+BICEP:



$0.81 \pm 0.25\,.$

Dvorkin, Wyman, Rudd, Hu '14.

Dark radiation



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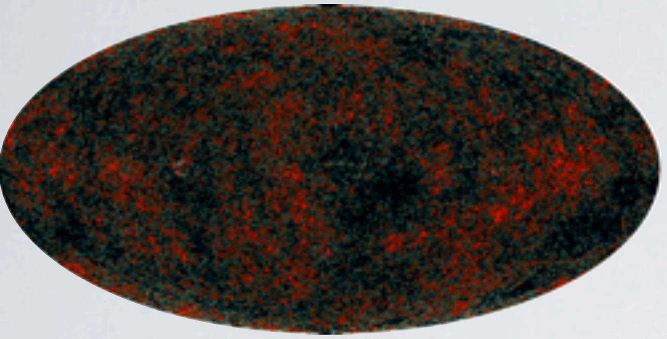
Projected sensitivities:

Planck-pol:	$\pm 0.20\,,$
'Next generation':	$\pm 0.044\,.$

Galli et al '10.

Axionic dark radiation



For the rest of this talk, I will entertain the theoretically and observationally well-motivated assumption that there is some *axionic dark radiation* in our universe.

What do we know about it?

Characteristic energy:

$$T_{CMB} < E_a^{\text{today}} \lesssim 2 \text{ keV} .$$

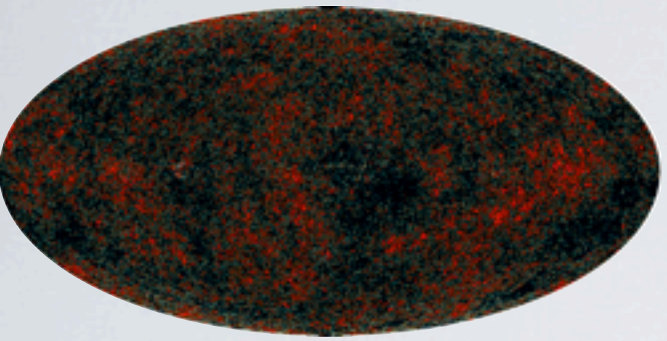
$$E_a^{(\text{today})} \sim \left(\frac{10^6 \text{ GeV}}{m_\phi}\right)^{1/2} 200 \text{ eV} ,$$

Flux:

$$\Phi_a\Big|_{E_a=200 \text{ eV}} \sim \left(\frac{\Delta N_{eff}}{0.50}\right) 10^6 \text{ cm}^{-2}\text{s}^{-1} .$$

Conlon, DM '13.

Axionic dark radiation



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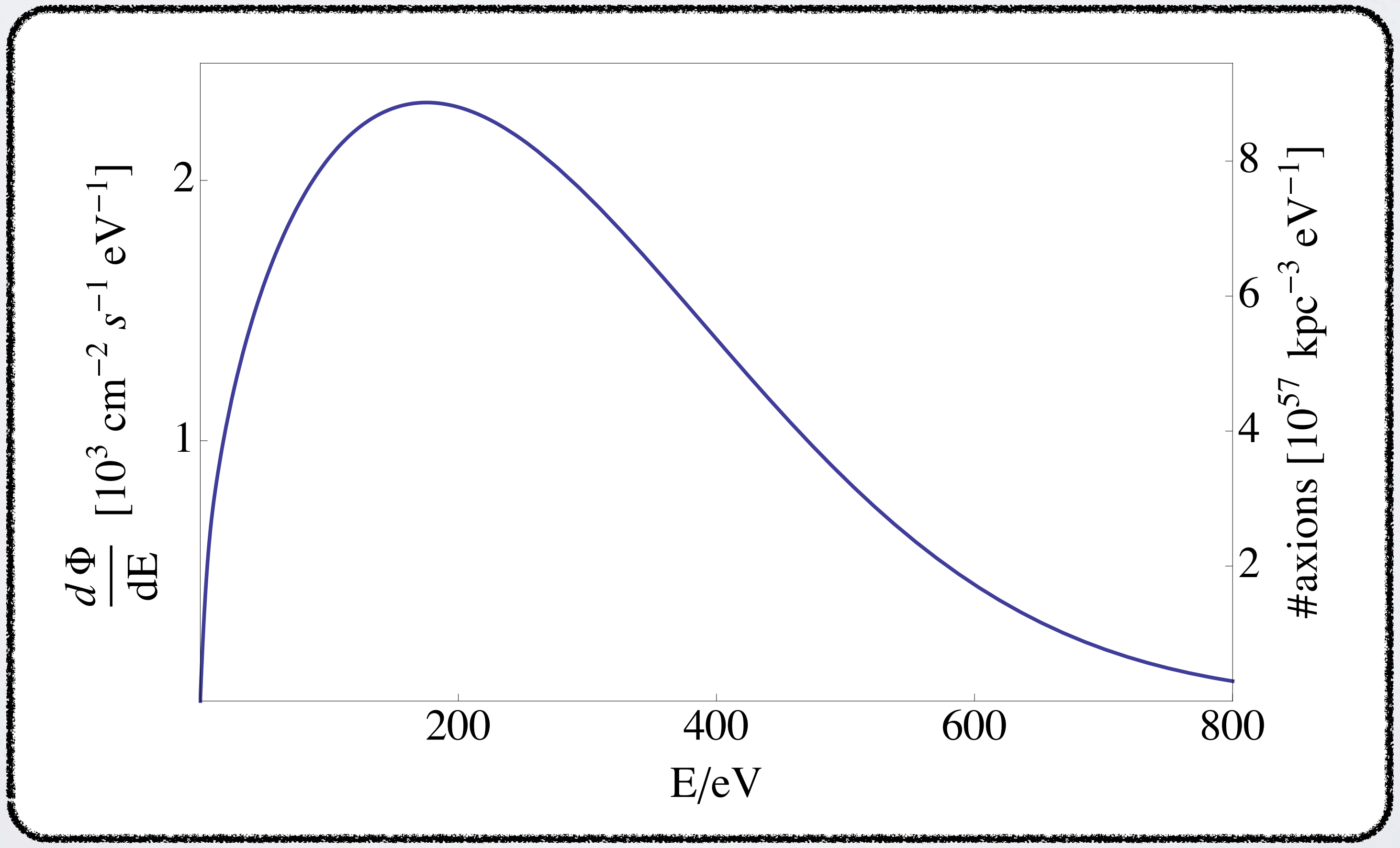
Spectrum: *Cosmic Axion Background (CAB):*



Conlon, DM '13.

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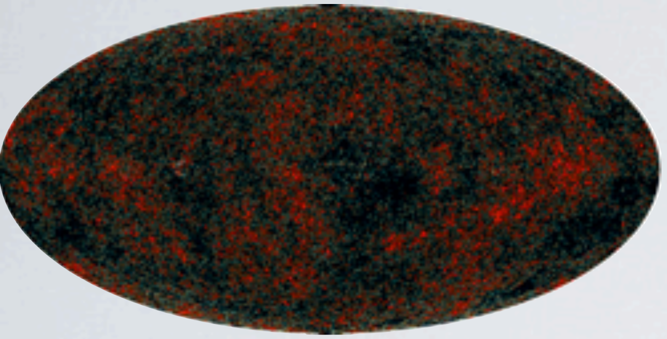

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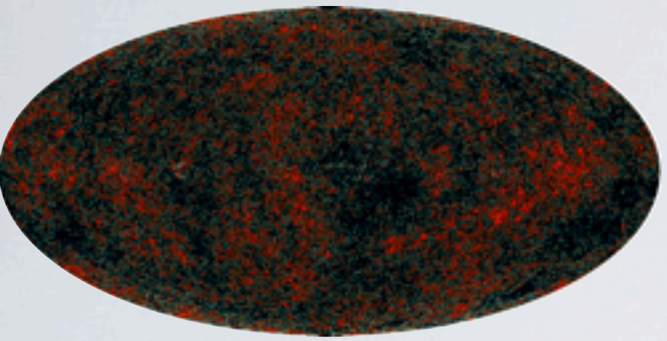
Model dependent couplings:

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

Axionic dark radiation



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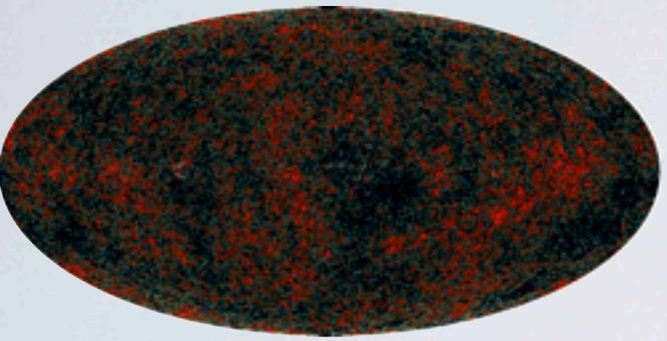

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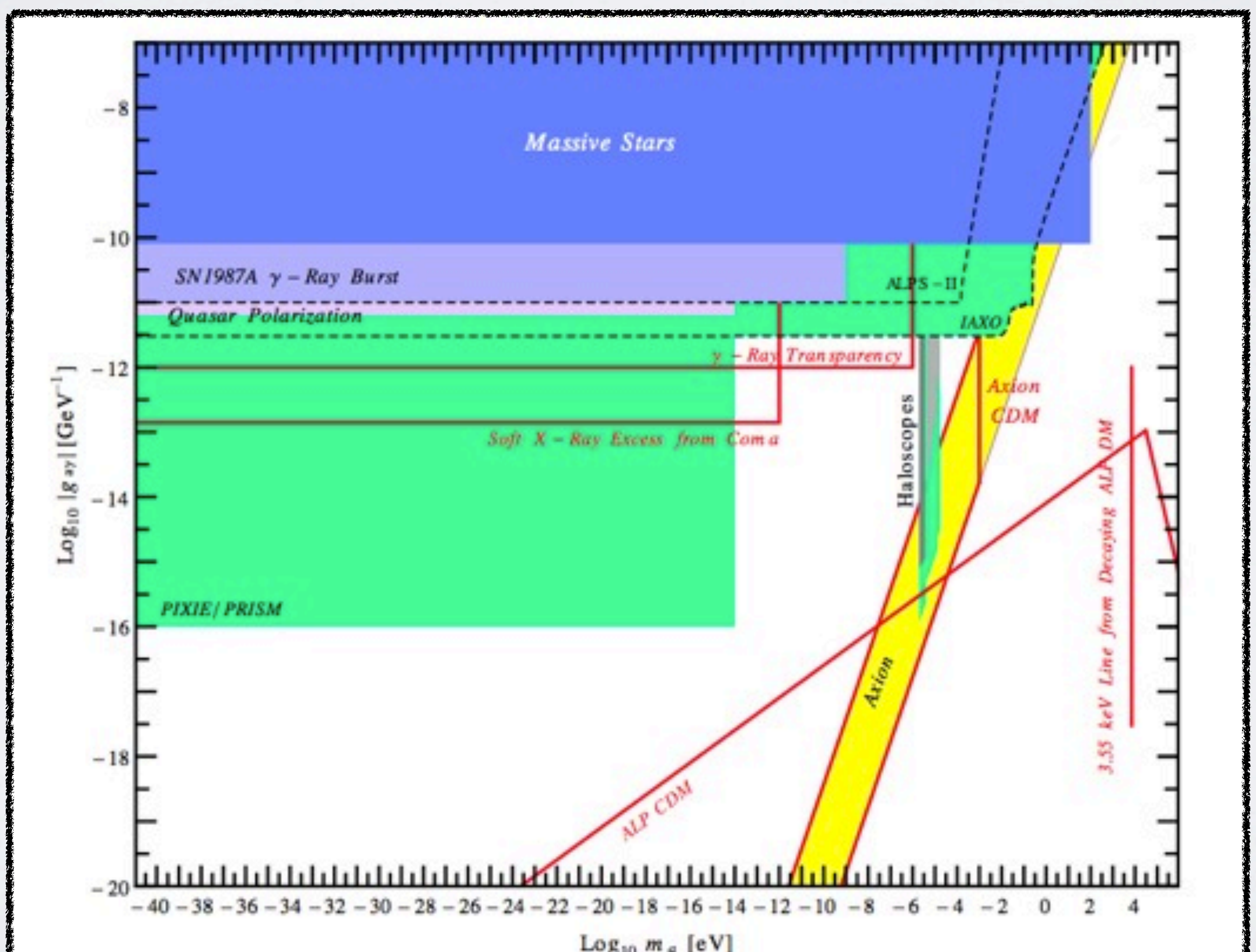
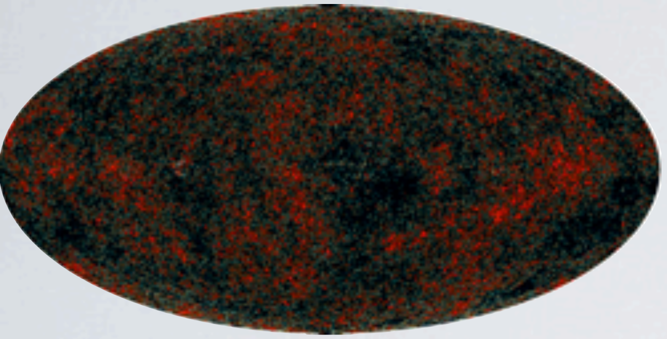
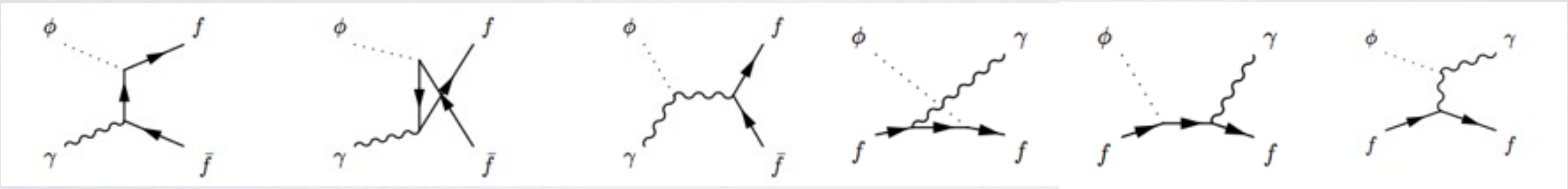


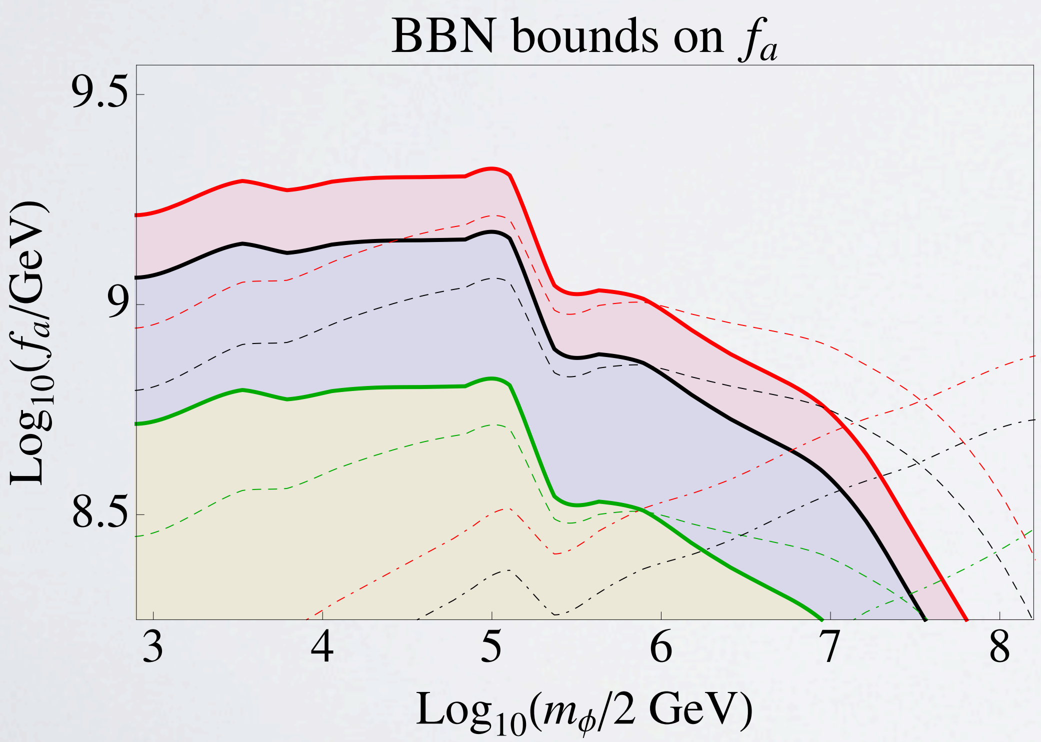
From: Dias, Machado, Nishi, Ringwald, Vaudrevange '14.

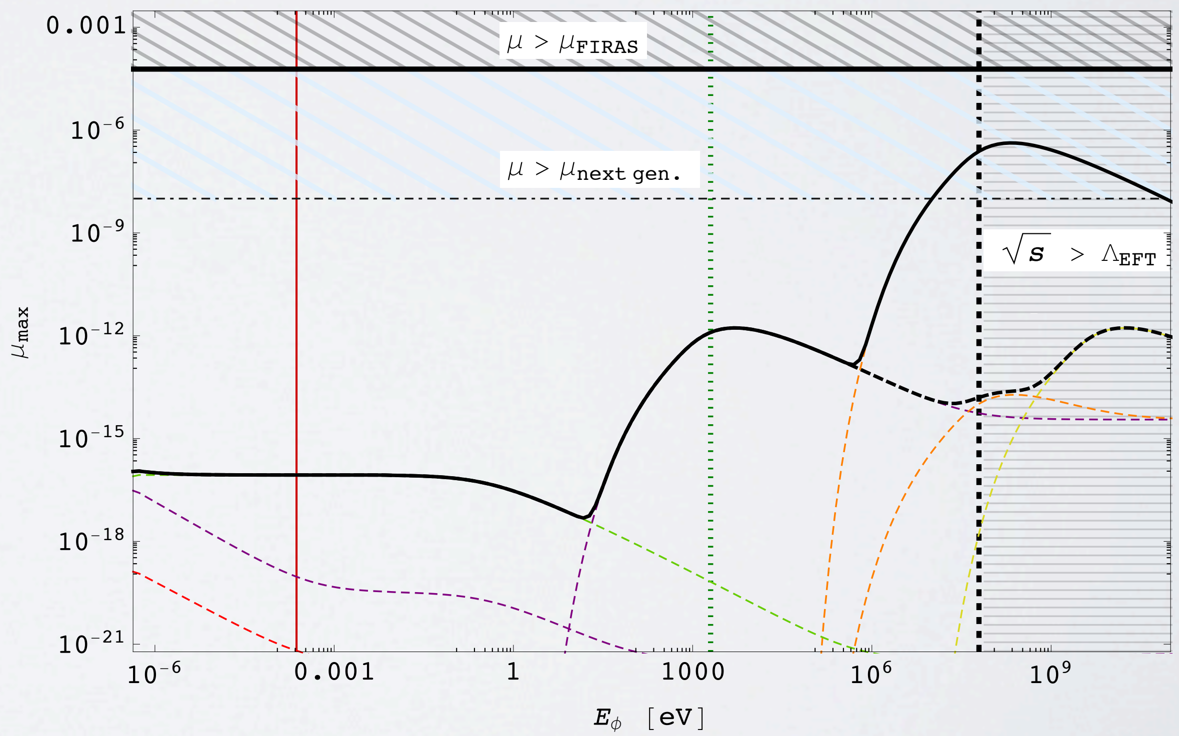
Detecting a CAB



The CAB may access high-energy processes which otherwise would be kinematically inaccessible.







Conlon, DM '13, DM '14, see also Higaki, Nakayama, Takahashi, '13.

Detecting a CAB

ALP-photon conversion:

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

Sikivie '83

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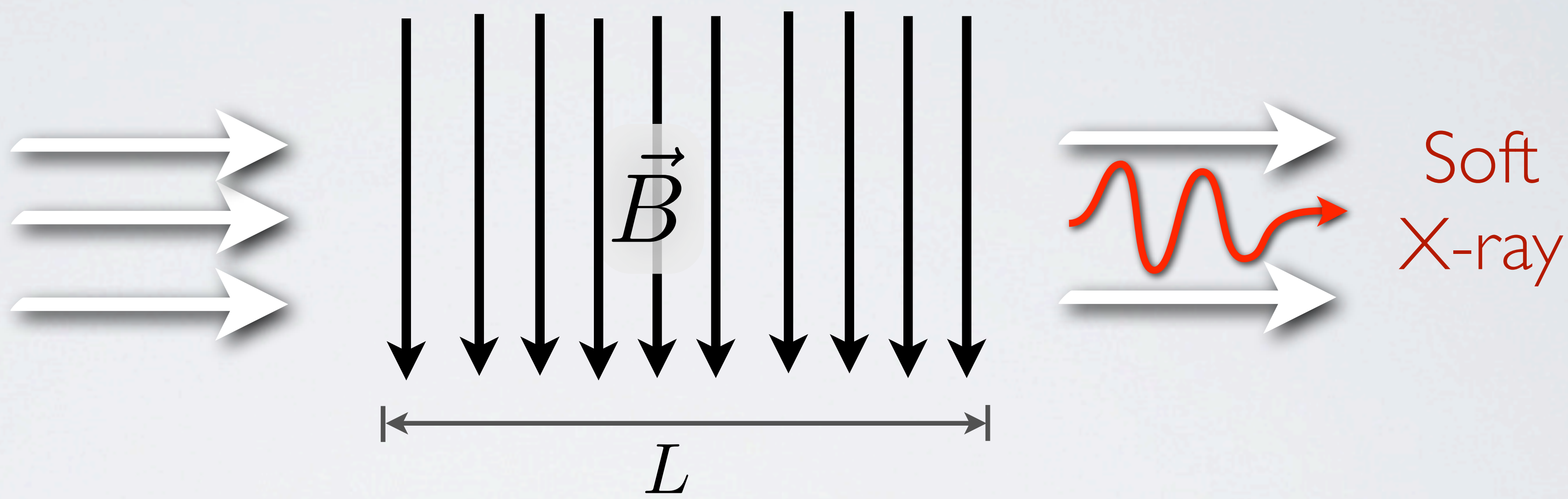

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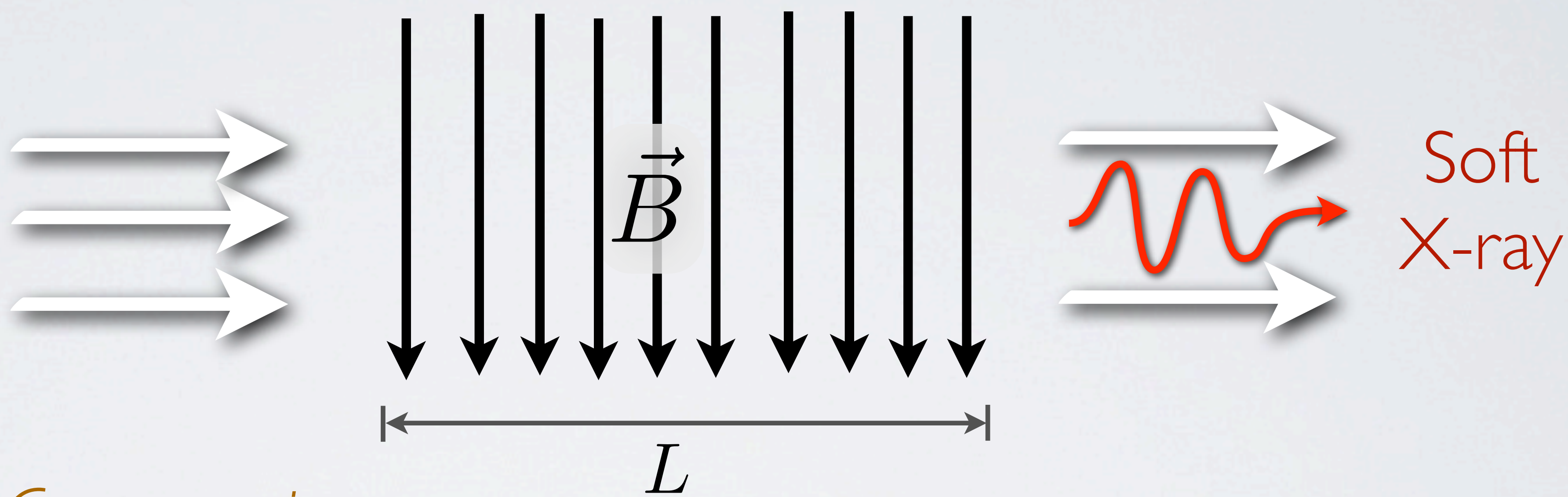


Computation:

At the linearised level the three-level system is governed by a Schrödinger-like equation:

$$\left(\omega + \begin{pmatrix} \Delta_\gamma & \Delta_\mathrm{F} & \Delta_{\gamma a x} \\ \Delta_\mathrm{F} & \Delta_\gamma & \Delta_{\gamma a y} \\ \Delta_{\gamma a x} & \Delta_{\gamma a y} & \Delta_a \end{pmatrix} - i\partial_z\right)\begin{pmatrix} \gamma_x \\ \gamma_y \\ a \end{pmatrix} = 0\,.$$

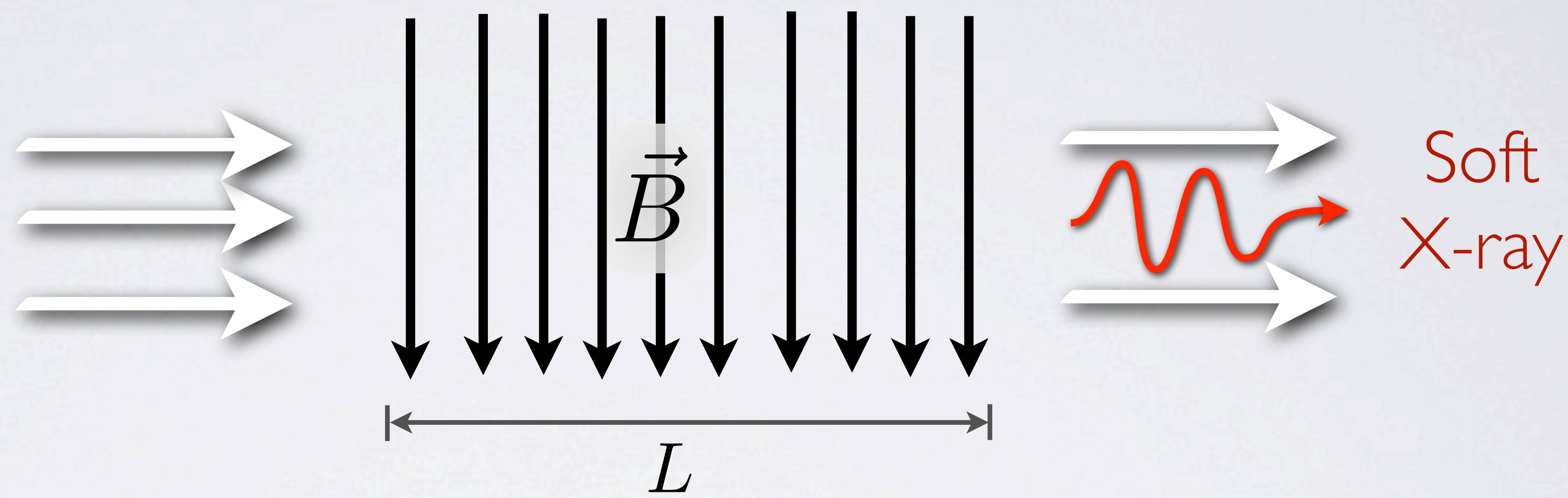
Here, $\Delta_\gamma = -\frac{\omega_{pl}^2}{2\omega}\,,\ \Delta_{\gamma a i} = B_i/2M\,, \Delta_a = -m_a^2/\omega.$

Sikivie '83

Detecting a CAB

Q: Can a CAB be detected?

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



Result:

$$P(a\to\gamma) = \sin^2(2\theta)\sin^2\left(\frac{\Delta}{\cos(2\theta)}\right) \to \frac{1}{4}\left(\frac{B_\perp L}{M}\right)^2\,,$$

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

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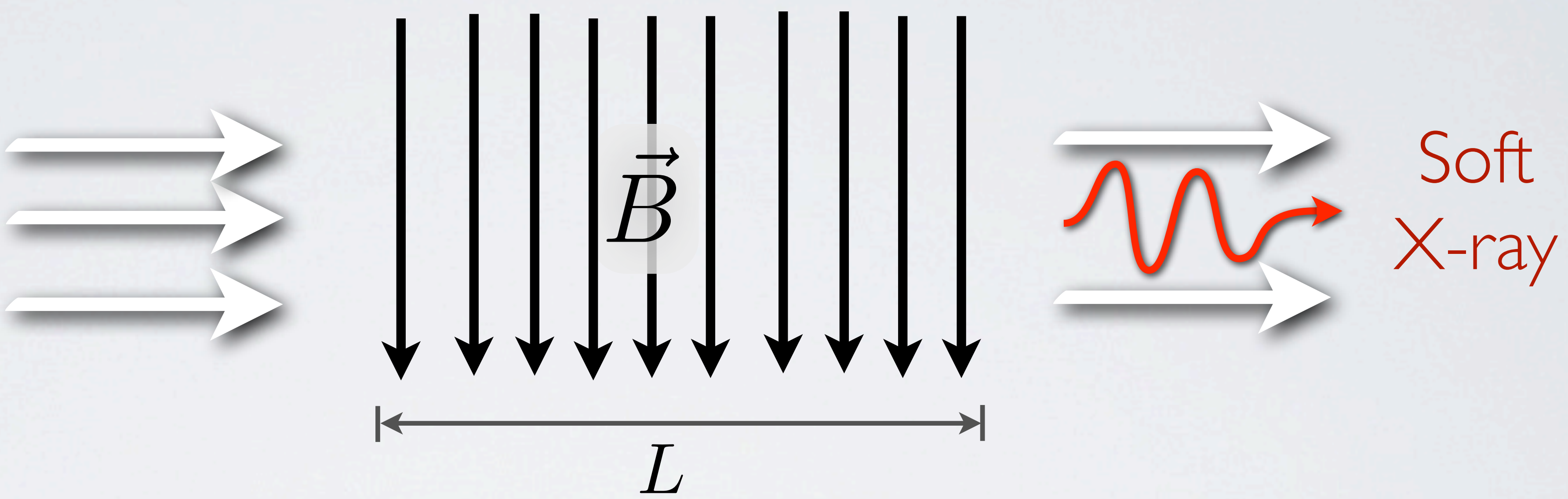

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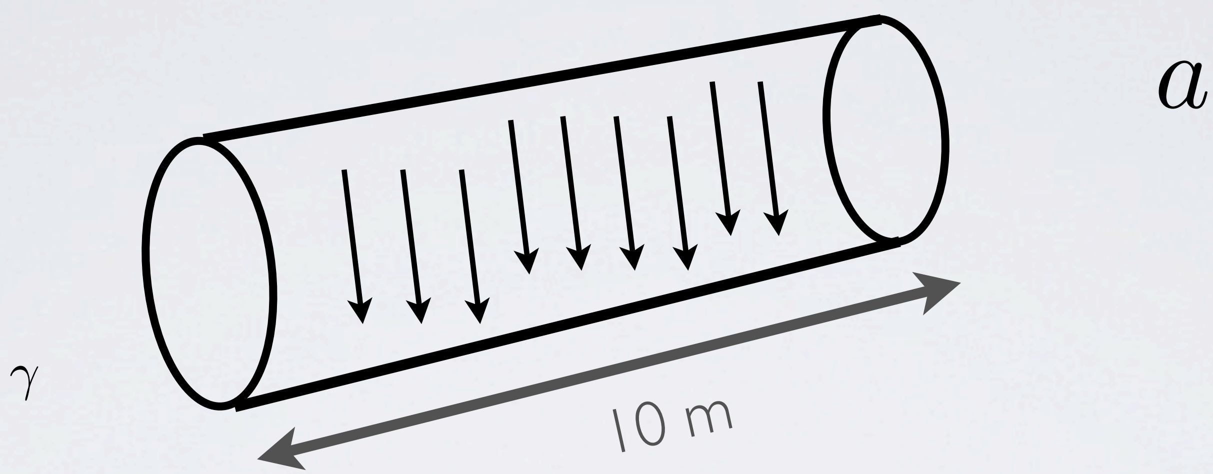
A: Look for strong magnetic fields coherent over large distances.

Detecting a CAB

In the lab:

Quick example: For CAST-like experiment:



For an aperture of 1 m^2 and a baseline of 10 m with 10T magnets, the expected event rate from CAB conversion is,

$$R(a \to \gamma) \sim \Phi_a \cdot P(a \to \gamma) \approx 10^8 \ \mathrm{s}^{-1} \cdot 10^{-18} \approx 10^{-10} \ \mathrm{s}^{-1} \,,$$

for $M = 10^{11}$ GeV.

One expected event per ~300 years.

Detecting a CAB

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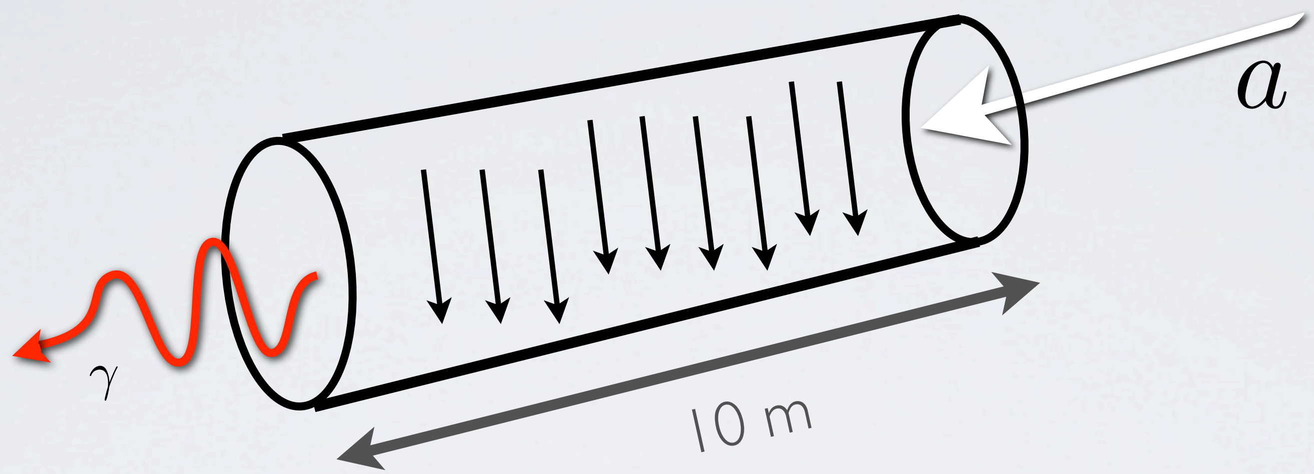

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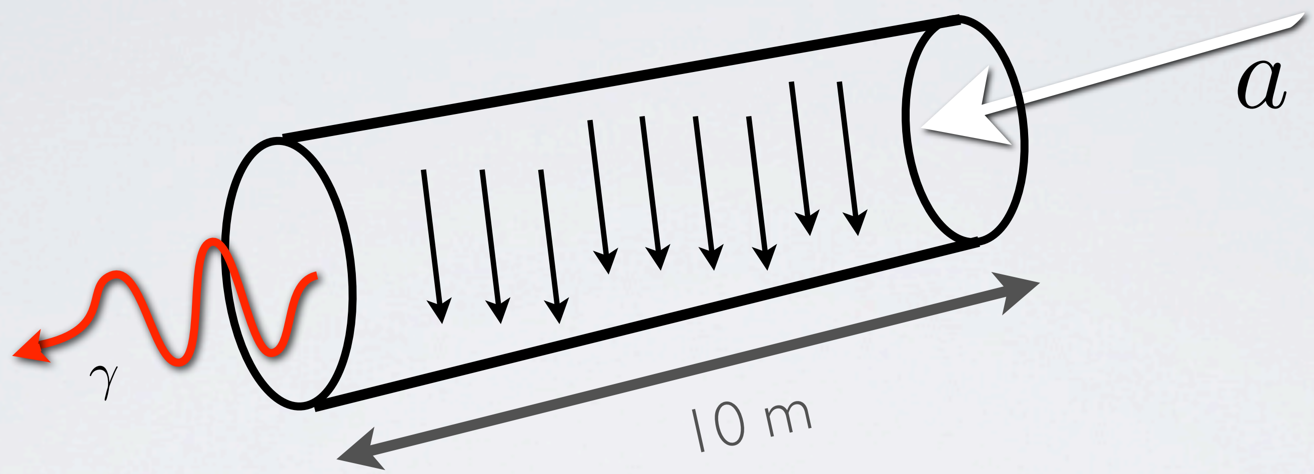

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A Cosmic Axion Background is very dark

One expected event per ~300 years.

Detecting a CAB

In space:

Detecting a CAB

In space:

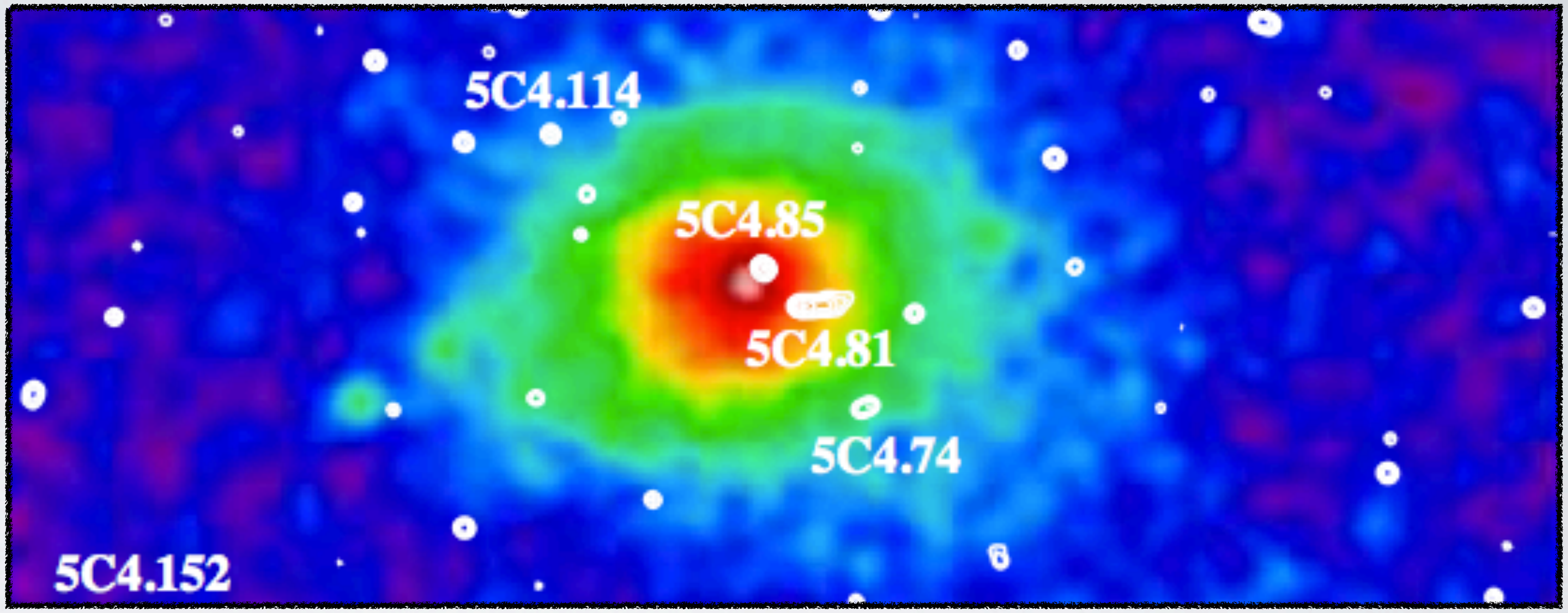
Galaxy clusters are the largest gravitationally bound objects in the universe, and typically contain magnetic fields of μG strength which are coherent over kiloparsec scales.*

Clusters, such as Coma, then provide an interesting laboratory to search for a Cosmic Axion Background.

* 1 kpc = $3*10^{19}$ m.

Detecting a CAB

In space:



Towards the lower end of the X-ray spectrum, clusters are visible through the thermal Bremsstrahlung emission from the hot intracluster medium (ICM) with T~8 keV.

Detecting a CAB

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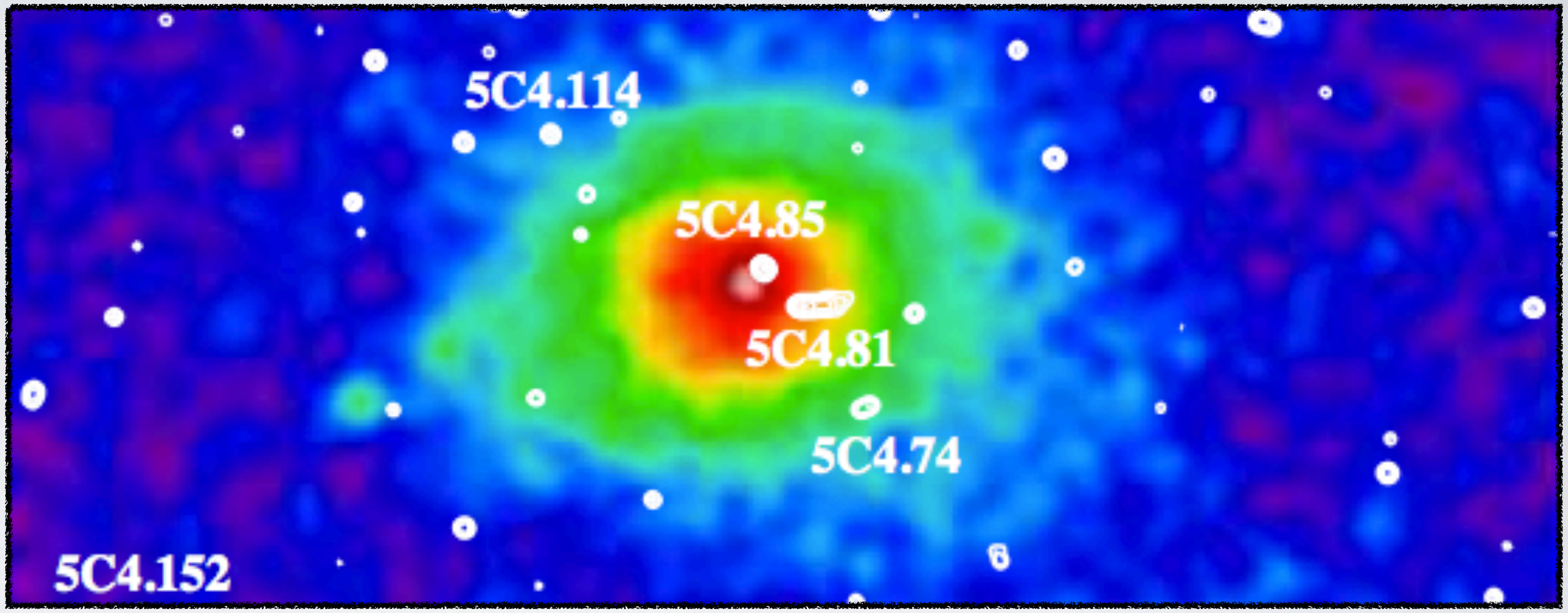


Towards the lower end of the X-ray spectrum, clusters are visible through the thermal Bremsstrahlung emission from the hot intracluster medium (ICM) with T~8 keV.

Excess emission above the thermal background has been observed by a number of experiments in a large number of galaxy clusters since 1996.

The cluster soft X-ray excess

In space:

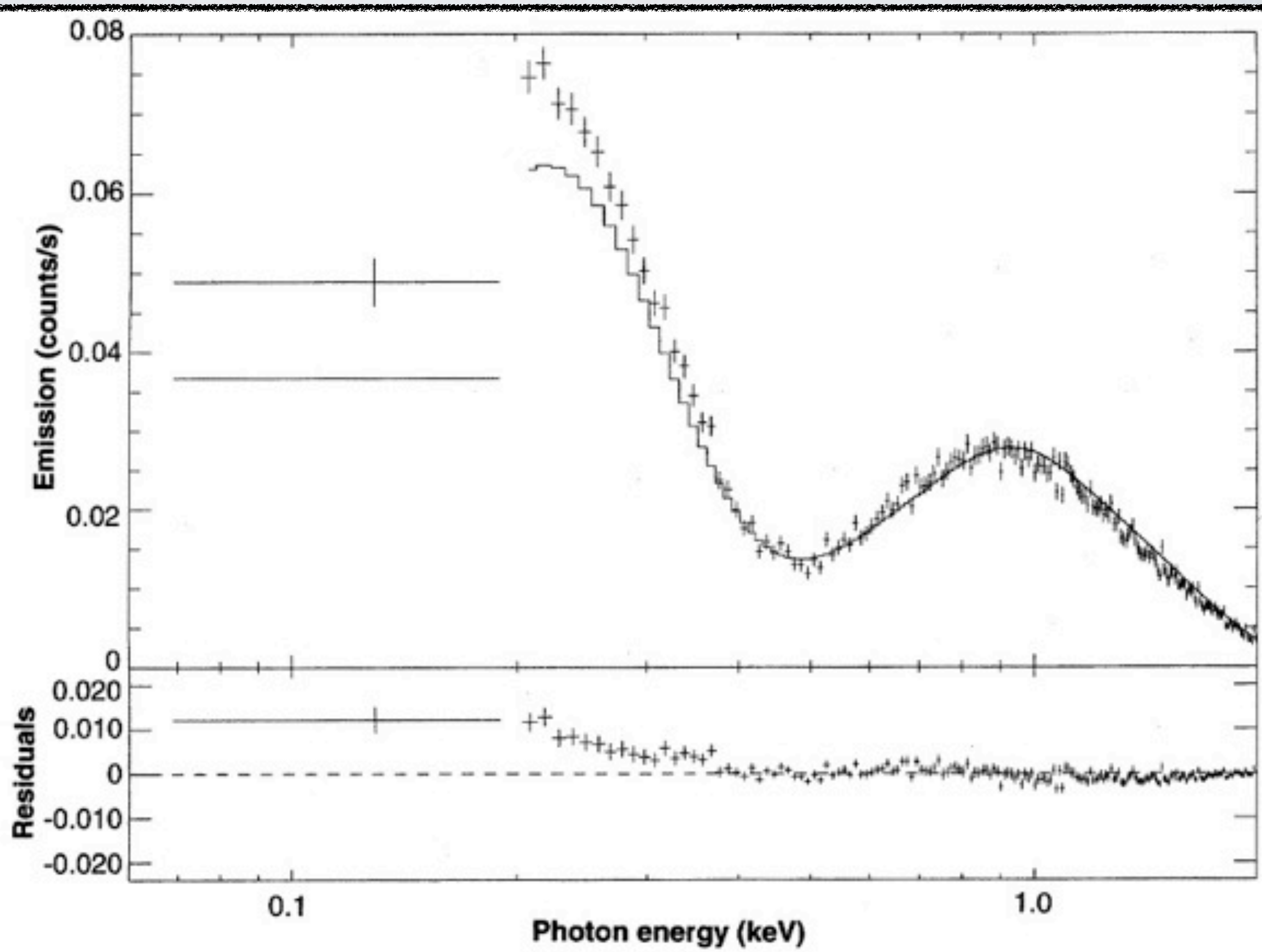
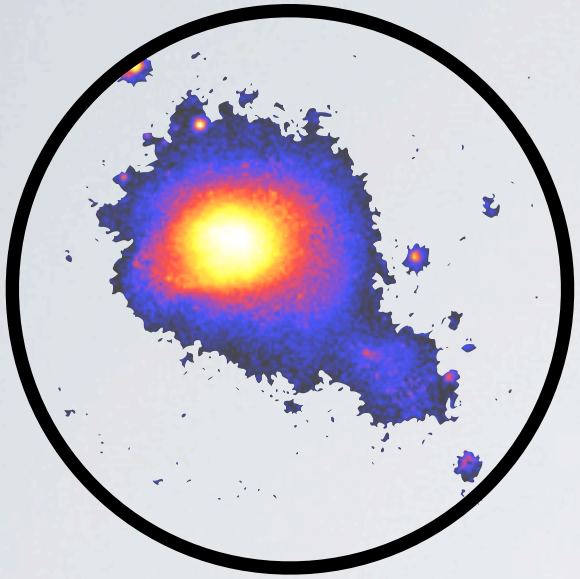


Fig. 2. Performance of the best fit MEKA single-temperature model (solid line) in a simultaneous fit to the EUVE DS and ROSAT PSPC data (the former is the first data point). The count rates correspond to those of the detected emission, and the residual is the difference between measured and model count rates.

Liu *et al*, 1996.

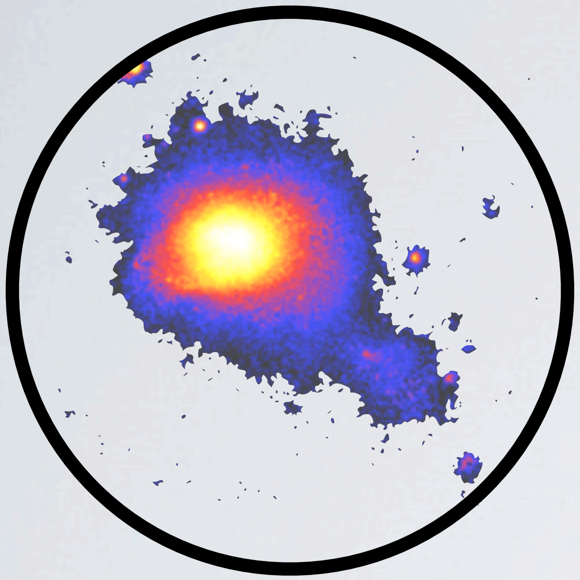
The cluster soft X-ray excess

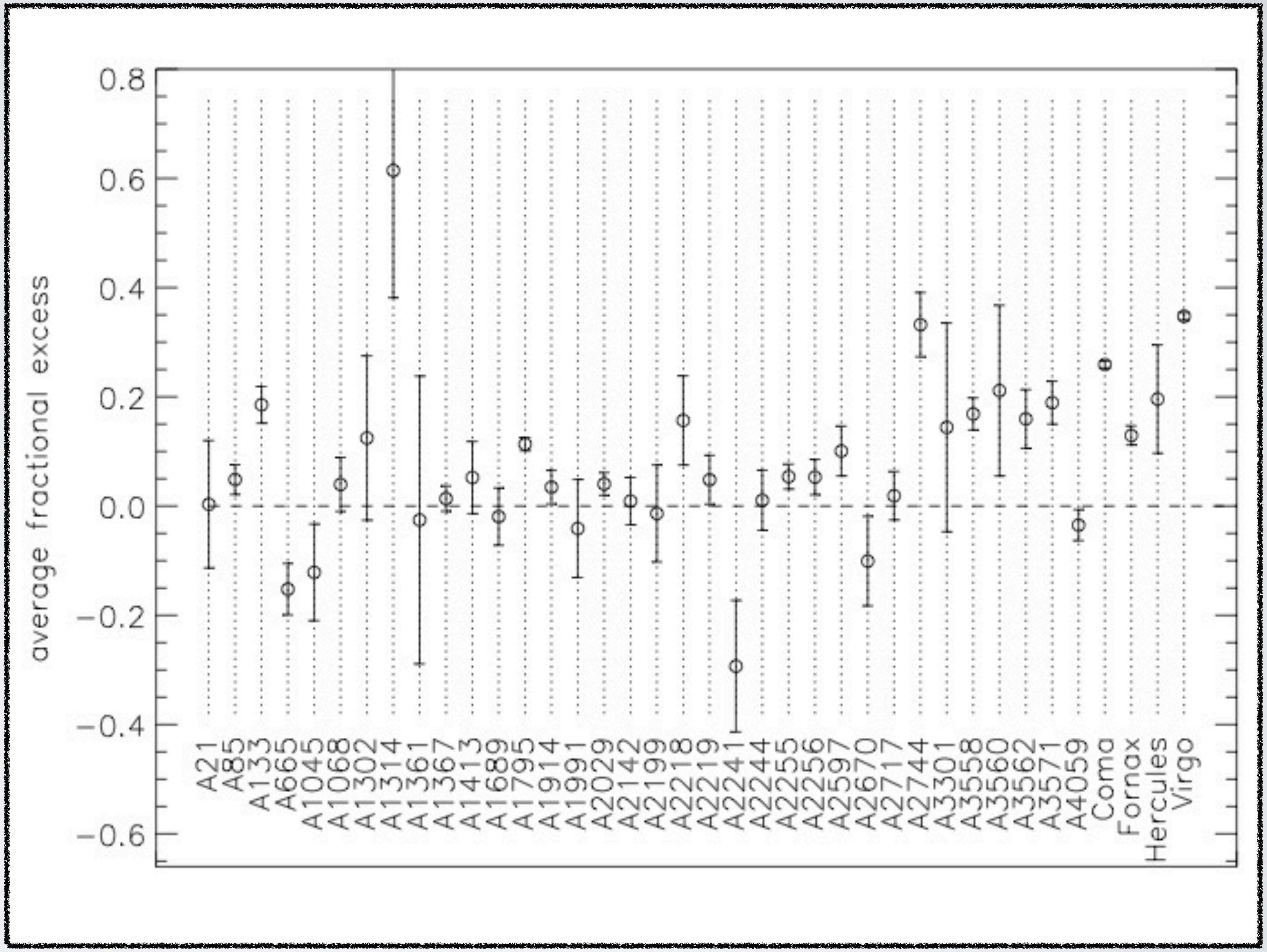


Brief history of the cluster soft X-ray excess:

- The cluster soft excess was first discovered in Coma and Virgo using EUVE data, and was soon after claimed also in other clusters.
- Challenges in background subtraction (and obtaining the correct H column densities) led to an initial controversy regarding the excess in some clusters.
- The ROSAT satellite provided a large (2°) field-of-view and a good sensitivity to soft X-rays, and is to-date the best instrument for soft excess studies.
- ROSAT consolidated the discovery, and established a significant excess in dozens of additional clusters.

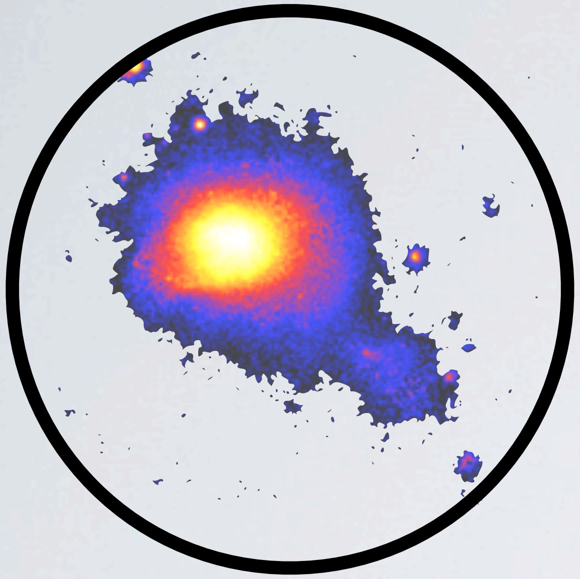
The cluster soft X-ray excess





Bonamente et al, '02.

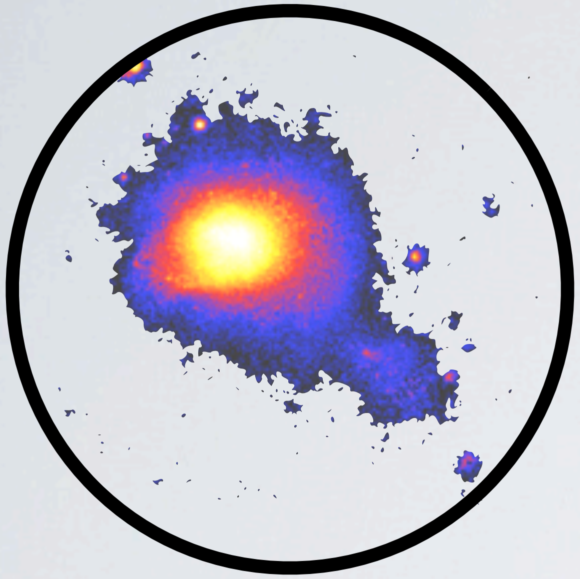
The cluster soft X-ray excess



Properties of the cluster soft X-ray excess:

- It is *soft*. No excess is detected above ~400 eV.
- It is *diffuse* and cannot be associated with local sources.
- It is *extended* and can be found out to large radii (at least 5 Mpc for Coma).
- As a *general morphological trend* based on a study of 38 clusters, the excess tends to become more significant away from the cluster centre.

The cluster soft X-ray excess



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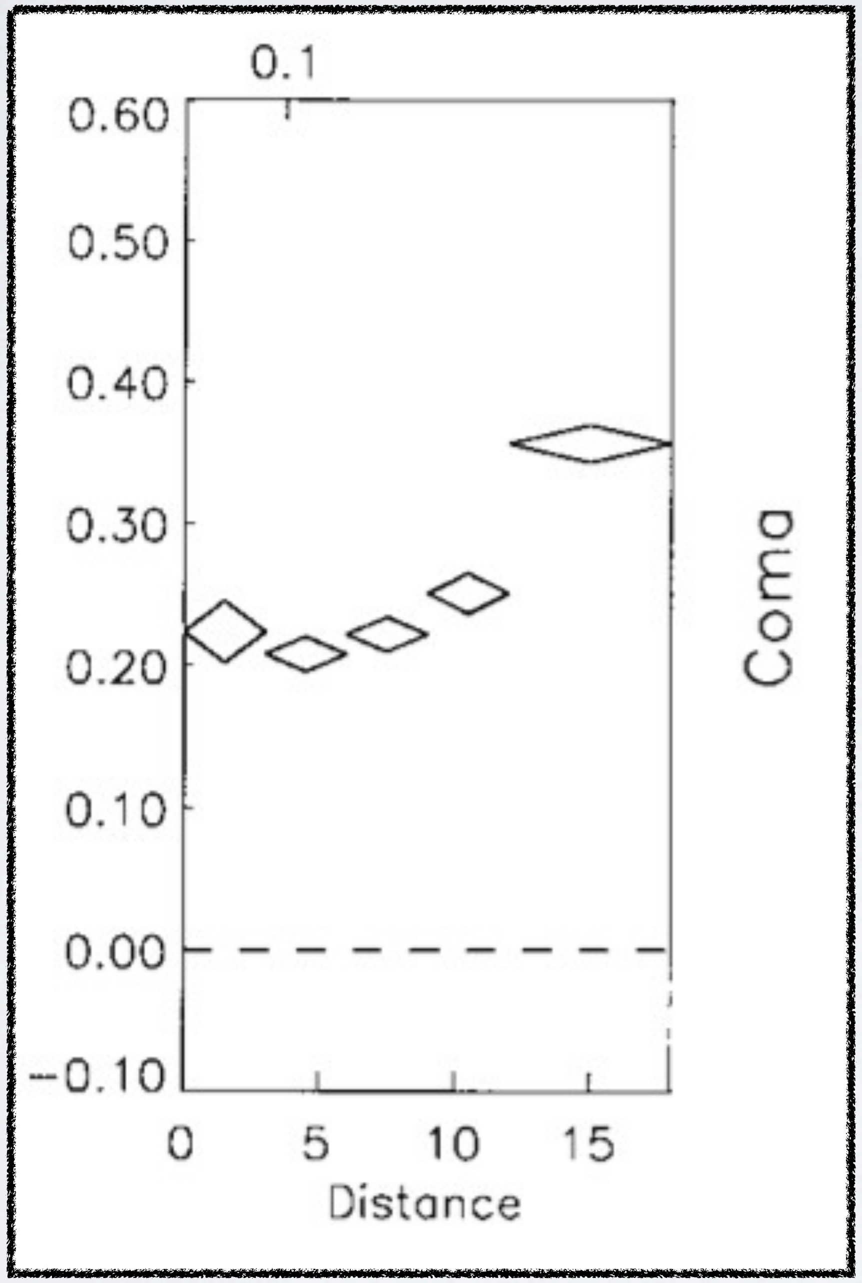

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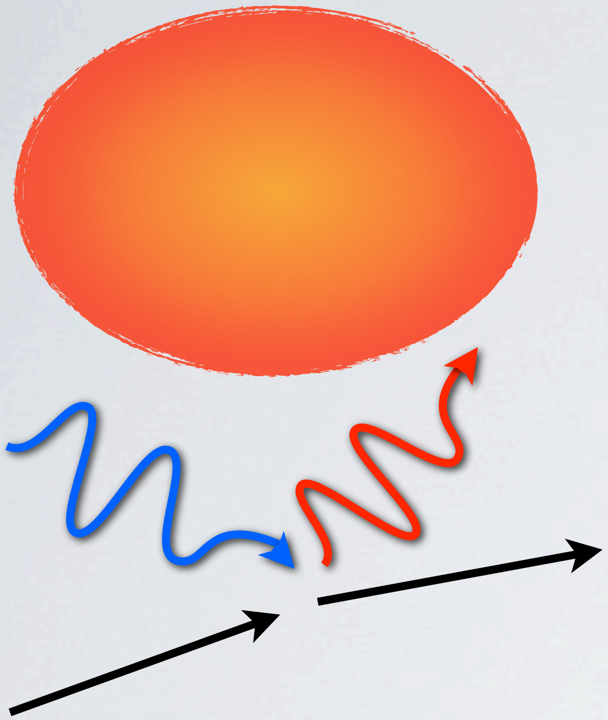
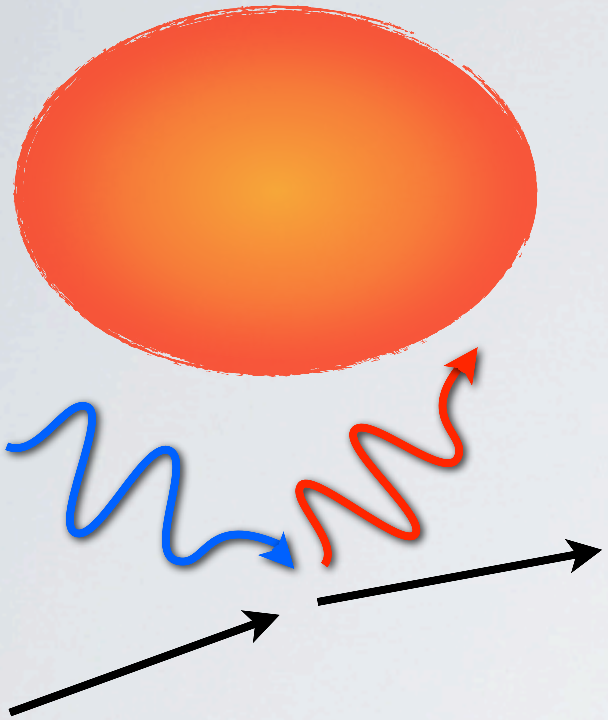


Proposed astrophysical explanations:

- It is *bremmstrahlung* from a warm (T~200 eV) gas.
- It is *inverse-Compton* of the CMB off relativistic cosmic ray electrons.

The cluster soft X-ray excess



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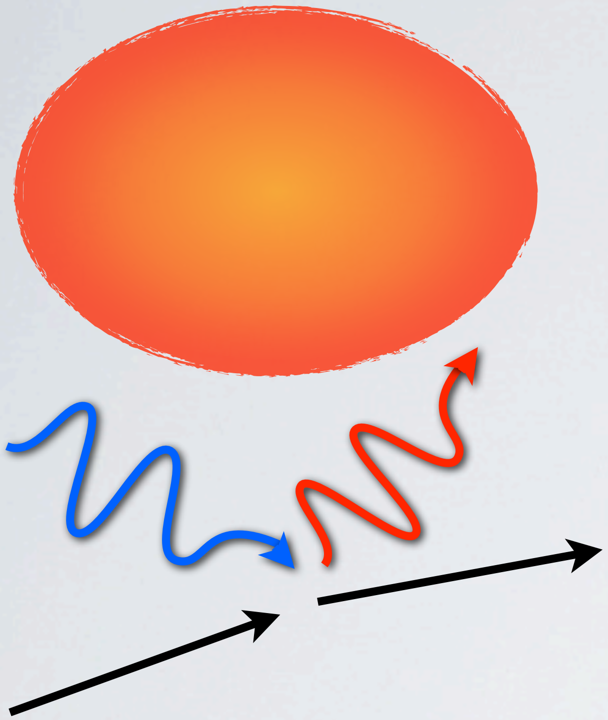

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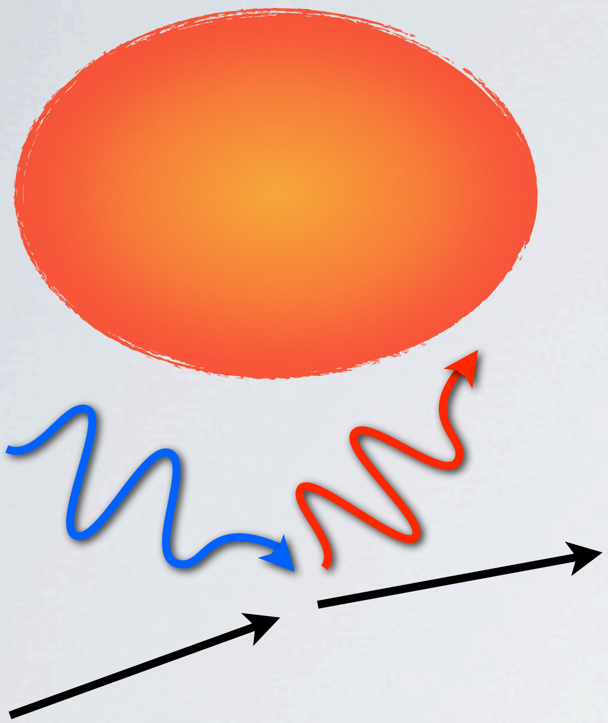

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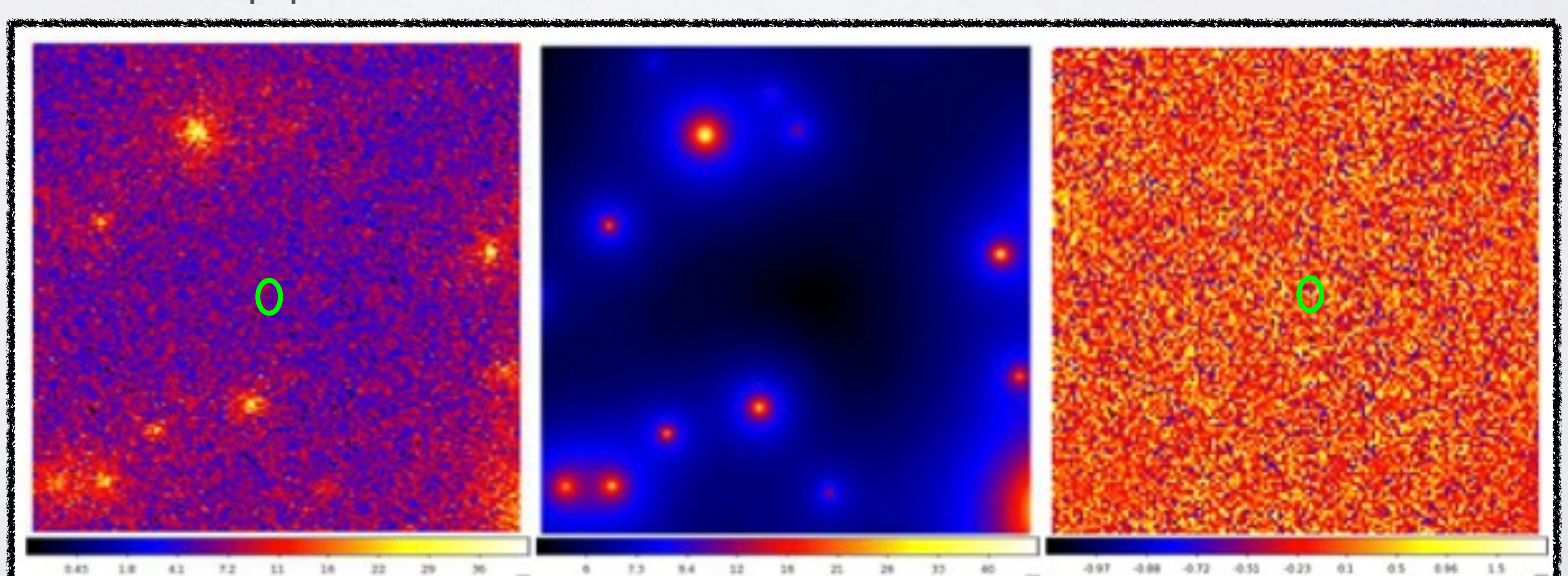
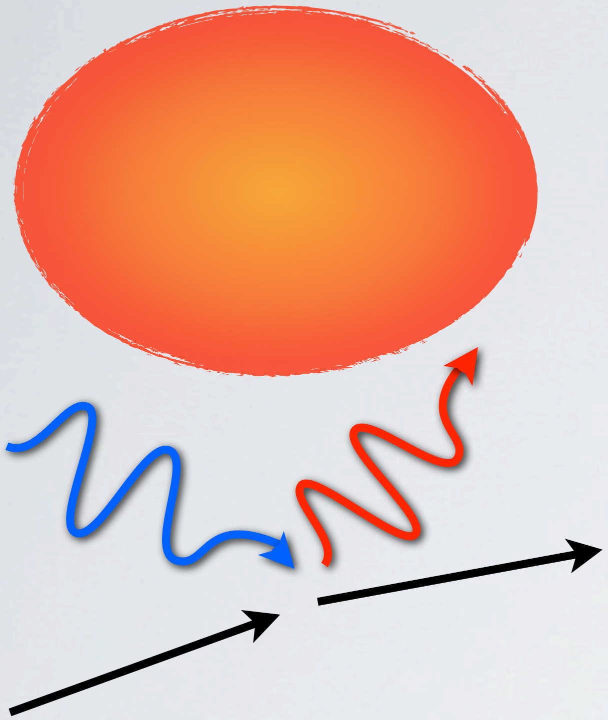
Coma: predicted gamma-ray flux of ~ $2*10^{-8}$ cm^{-2} s^{-1}, but Fermi upper limit: < $0.6\text{-}2.9*10^{-9}$ cm^{-2} s^{-1}.



Atoyan, Vollker '00, Sarazin '99, Zandanel, Ando, '13.

The cluster soft X-ray excess



Proposed astrophysical explanations:

In sum, neither proposed astrophysical explanation is completely compelling.

Conlon, DM '13, Angus, Conlon, DM, Powell, Witkowski, '13.

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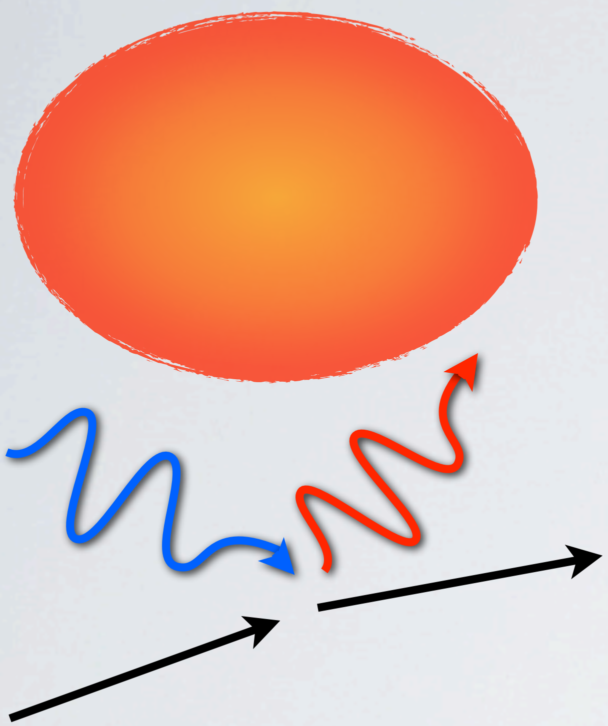

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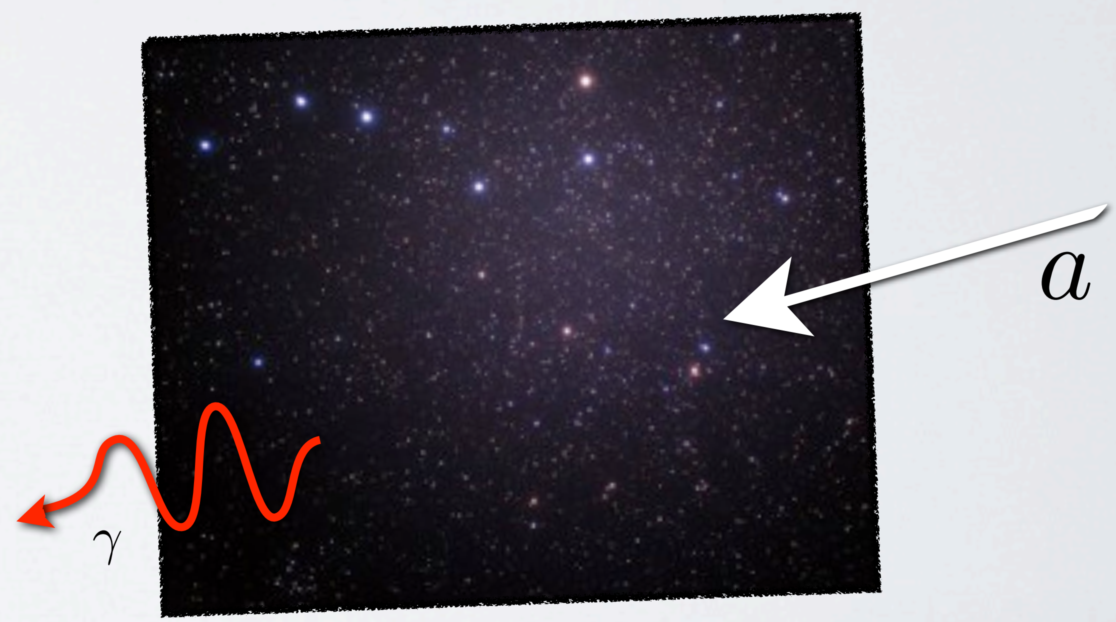
How about axion-photon conversion of the CAB?



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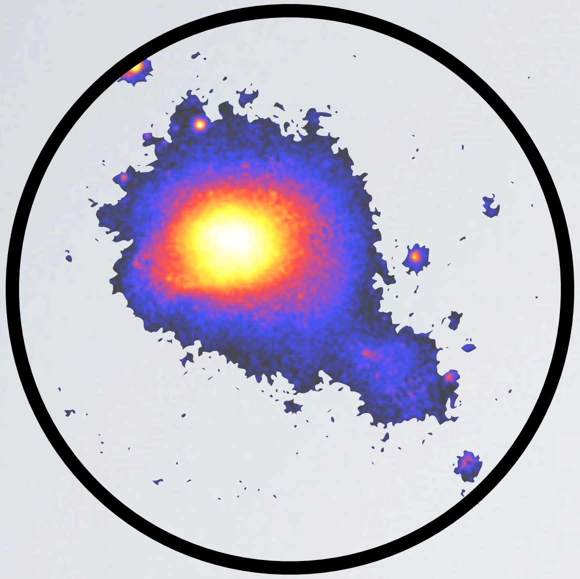
The CAB and the cluster soft X-ray excess

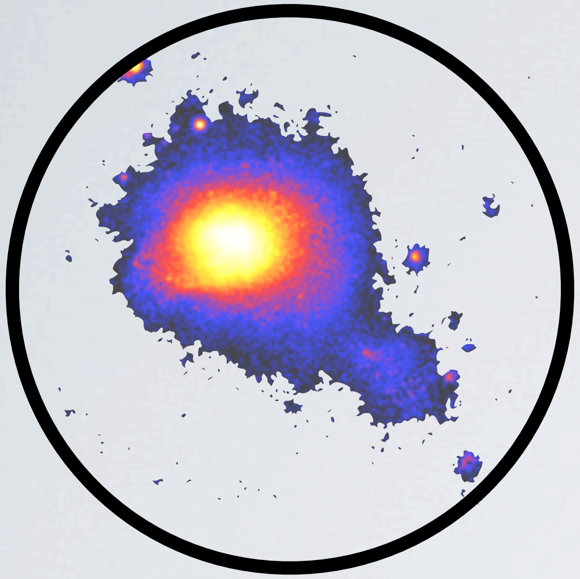


*

Axion-photon conversion in clusters:

- Clusters can be rather efficient converters of axions into photons.
- The conversion probability depends on the magnitude and coherence length of the magnetic field, the energy of the axion and plasma frequency of the plasma.

The CAB and the cluster soft X-ray excess



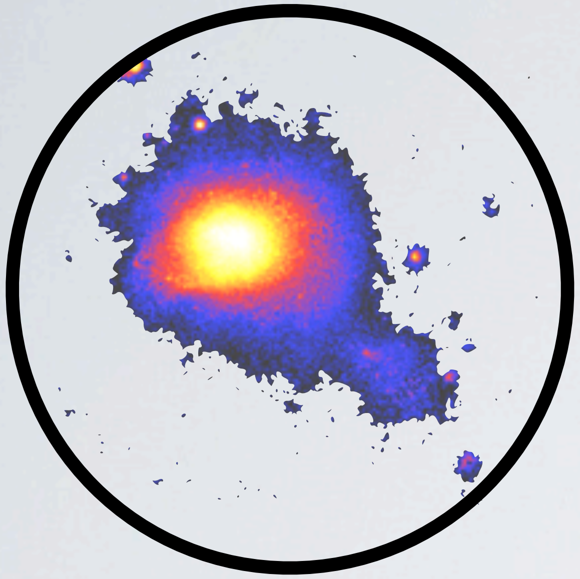
*

Magnetic fields in clusters:

Faraday rotation: the magnetised ICM induces different phase velocities for left- and right-handed photons, giving rise to a rotation of the plane of polarisation proportional to

$$\Delta\theta \propto \lambda^2 \int n_e B_{||} dl \,.$$

The CAB and the cluster soft X-ray excess



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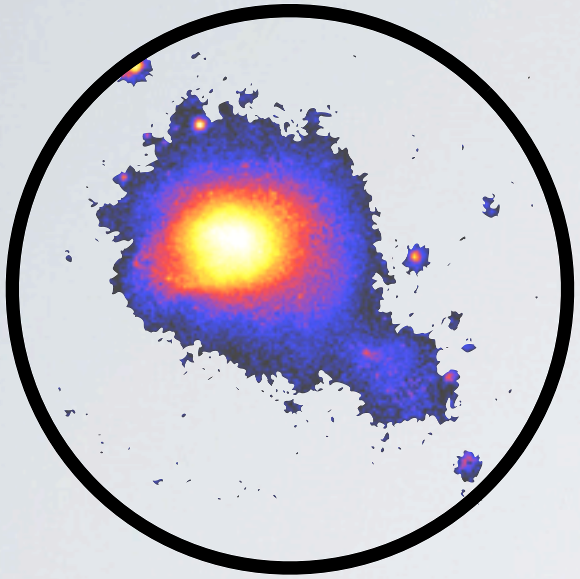
Rotation Measure (RM)

The CAB and the cluster soft X-ray excess



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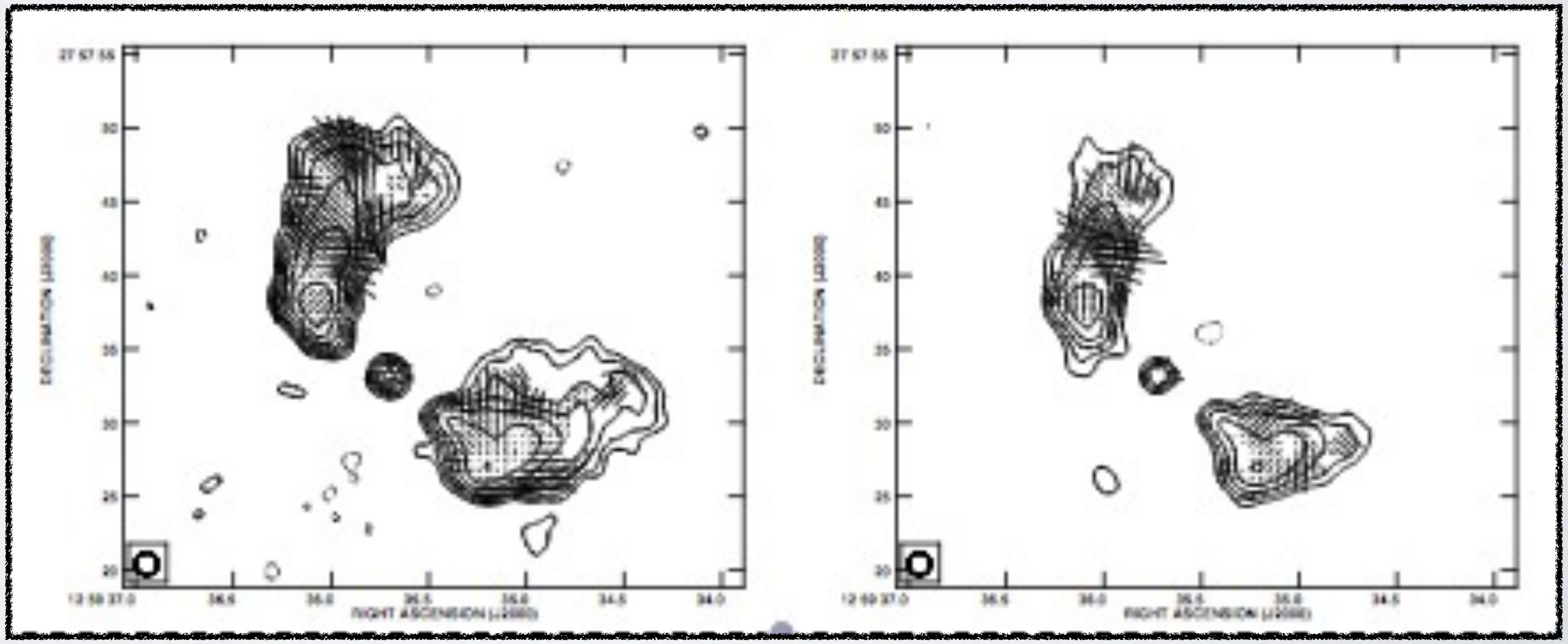
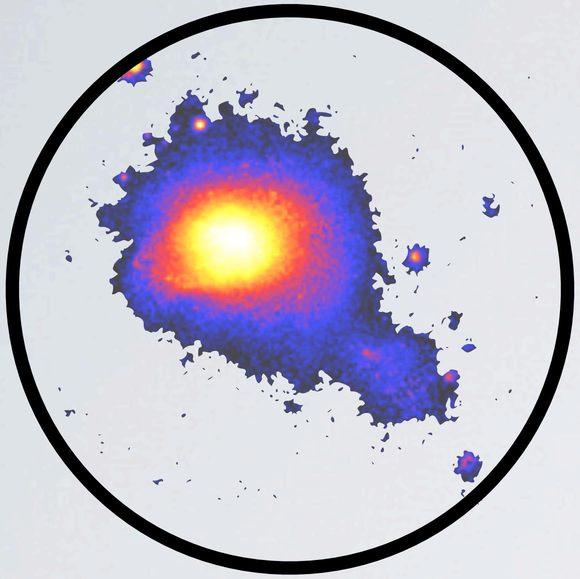


Bonafede thesis, 2010.

The CAB and the cluster soft X-ray excess



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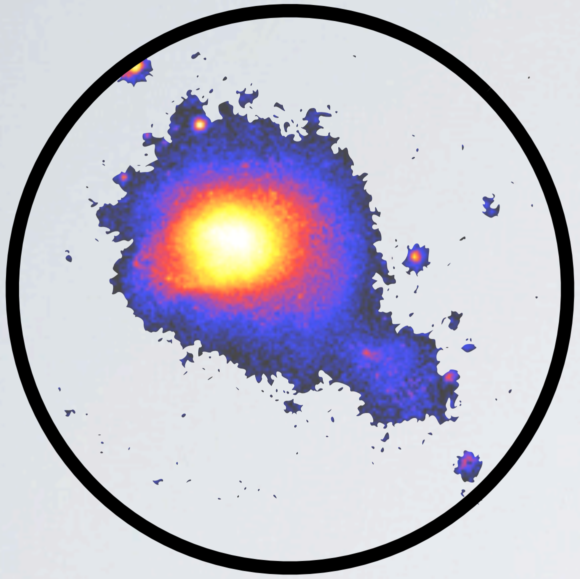
$$\vec{B}^{(\mathrm{tot})} = B_0 \vec{\mathfrak{b}} \left(\frac{n_e(r)}{n_e(0)} \right)^{\eta} \, .$$

Bonafede *et al* 2010.

The CAB and the cluster soft X-ray excess



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Bonafede *et al* 2010.

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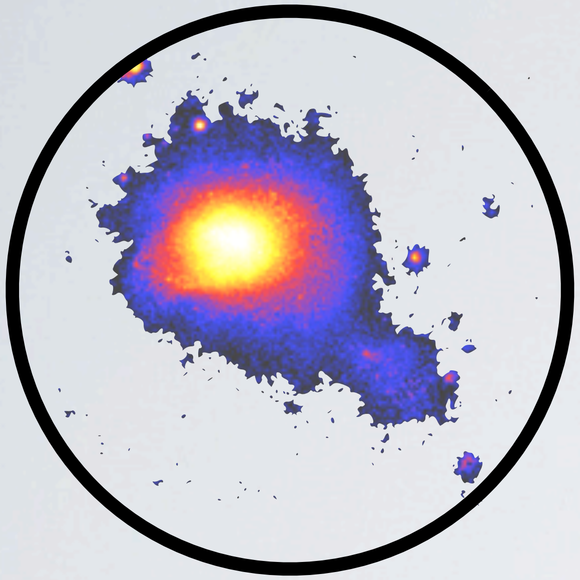

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Bonafede *et al* 2010.

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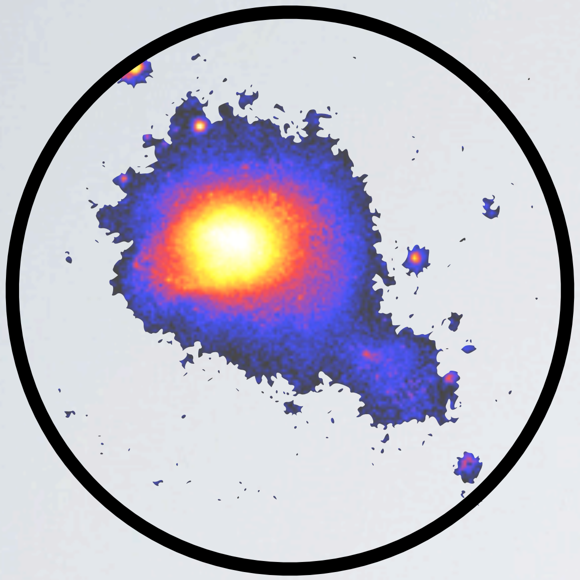

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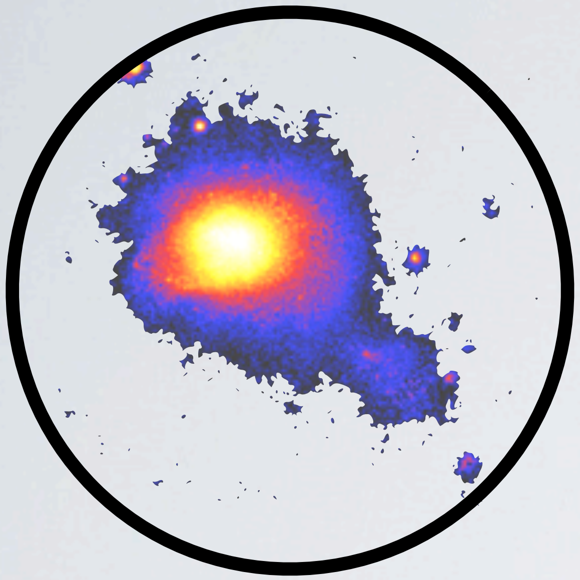
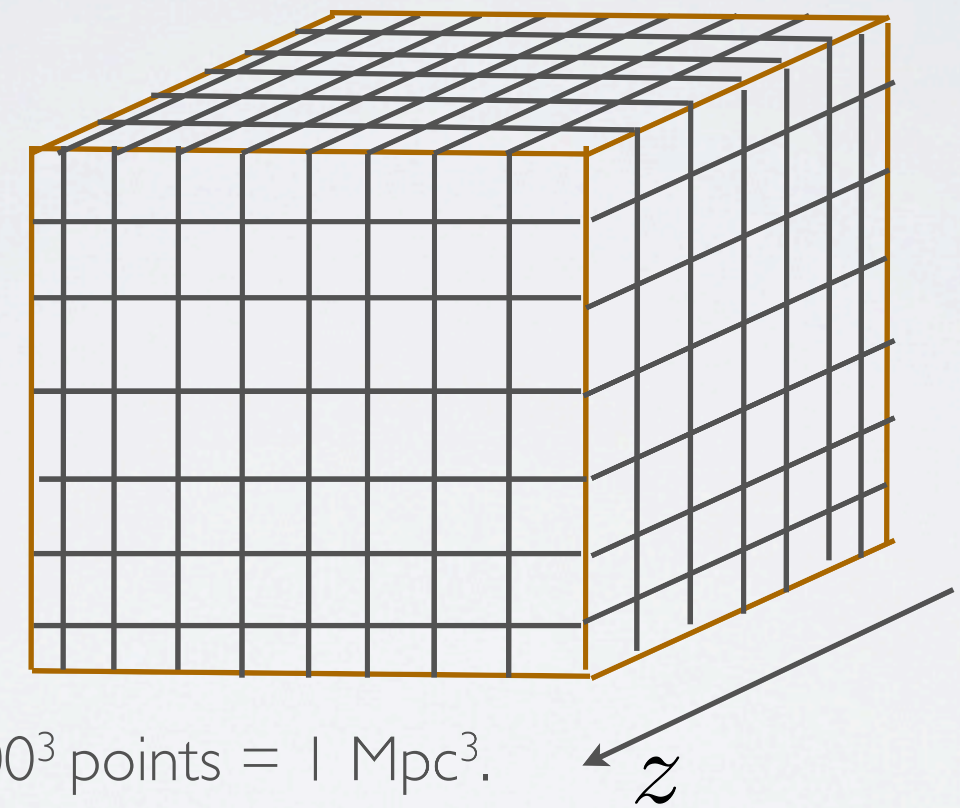
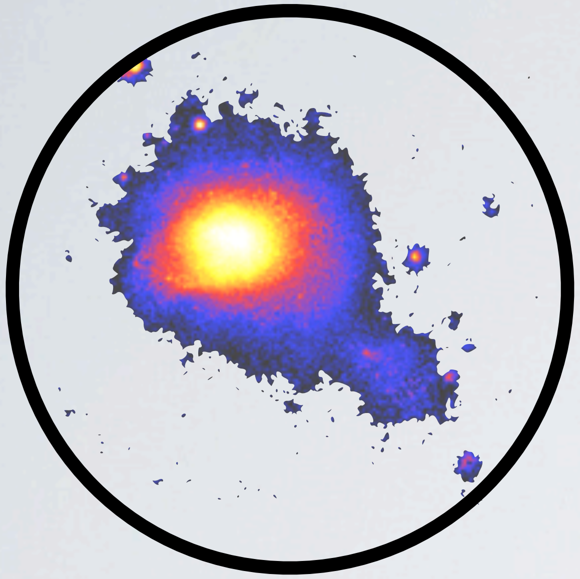


Simulation:



Size: 2000^3 points = 1 Mpc^3.

The CAB and the cluster soft X-ray excess



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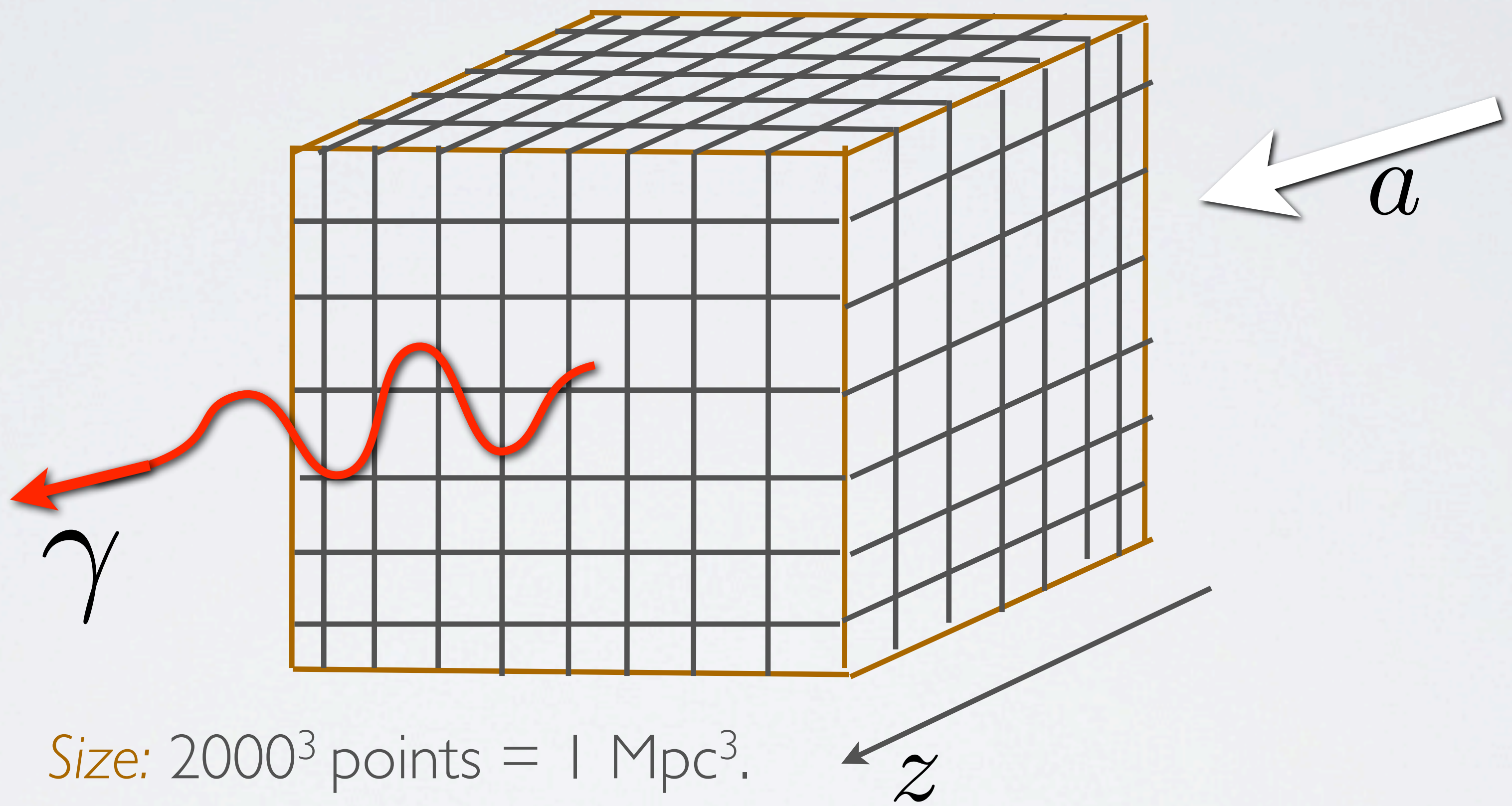

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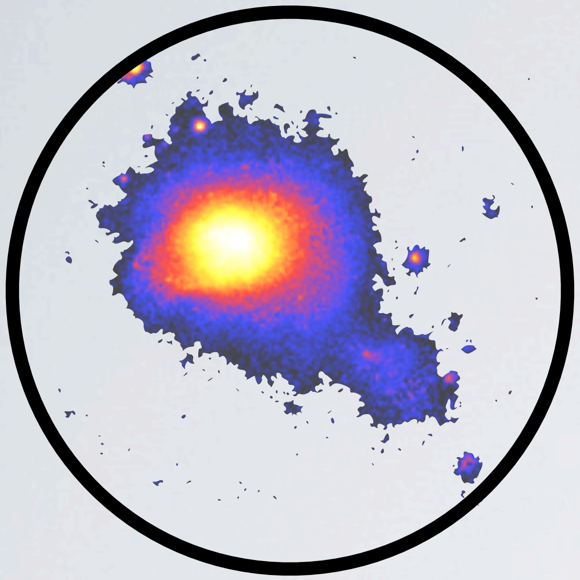
$$\left(\omega + \begin{pmatrix} \Delta_\gamma & \Delta_{\mathrm{F}} & \Delta_{\gamma a x} \\ \Delta_{\mathrm{F}} & \Delta_\gamma & \Delta_{\gamma a y} \\ \Delta_{\gamma a x} & \Delta_{\gamma a y} & \Delta_a \end{pmatrix} - i\partial_z\right)\begin{pmatrix} \gamma_x \\ \gamma_y \\ a \end{pmatrix} = 0\,.$$

The CAB and the cluster soft X-ray excess



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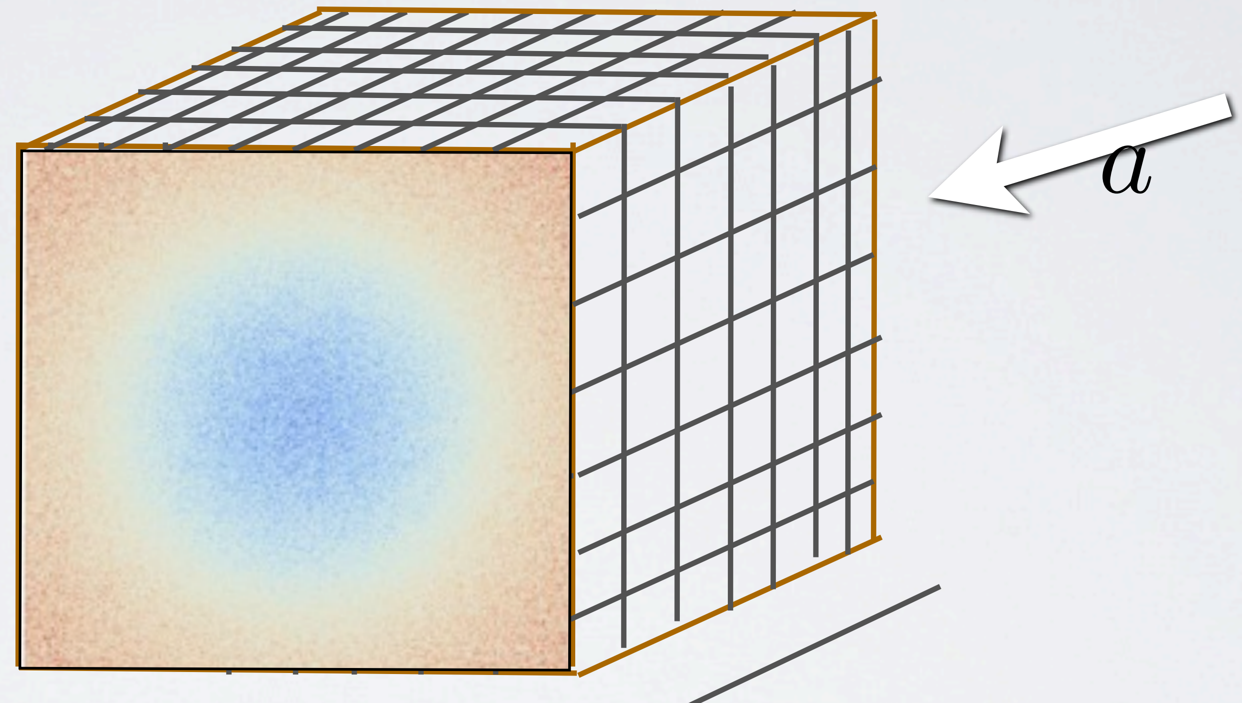

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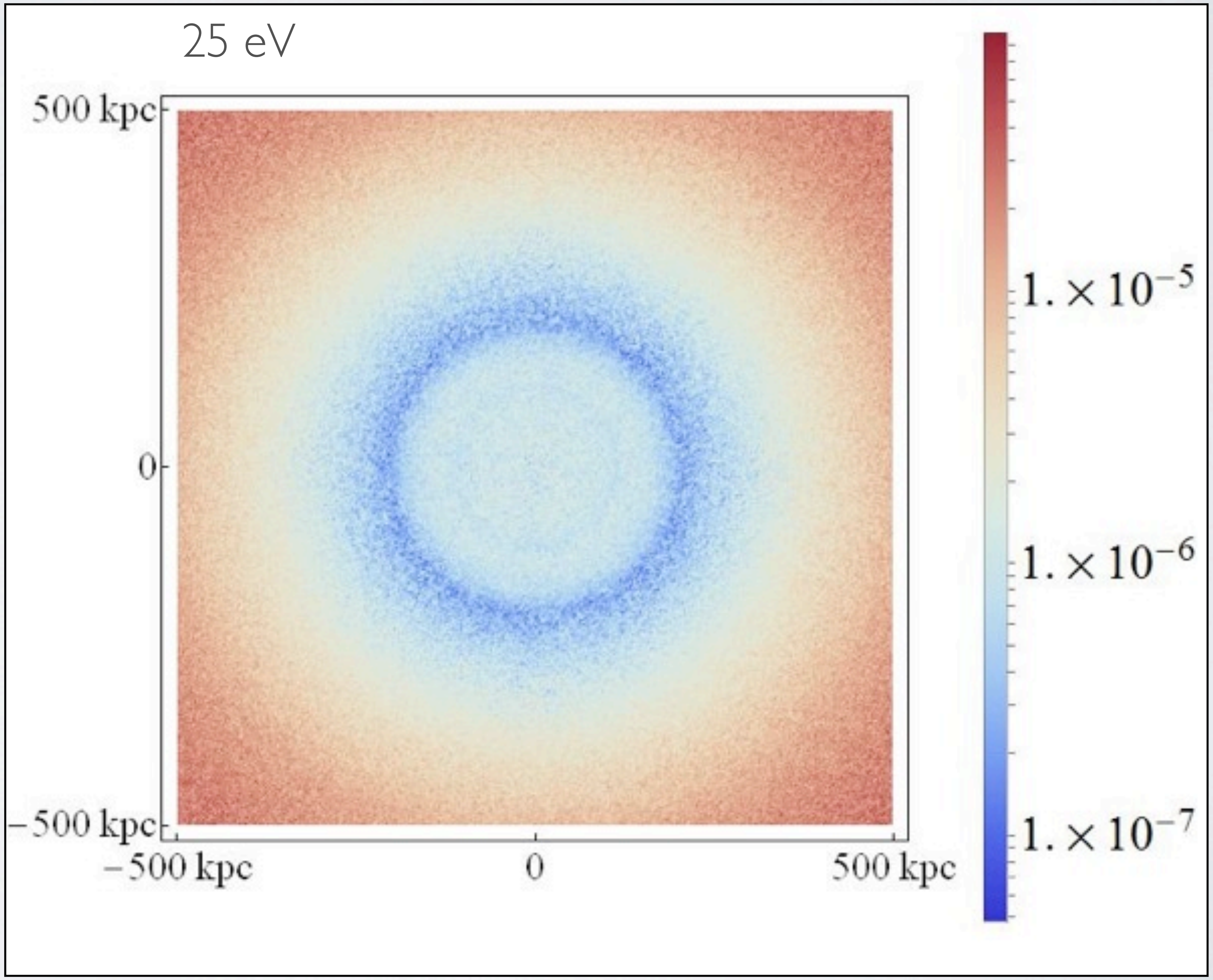
The CAB and the cluster soft X-ray excess

Coma conversion probabilities:



Angus, Conlon, DM, Powell, Witkowski, '13.

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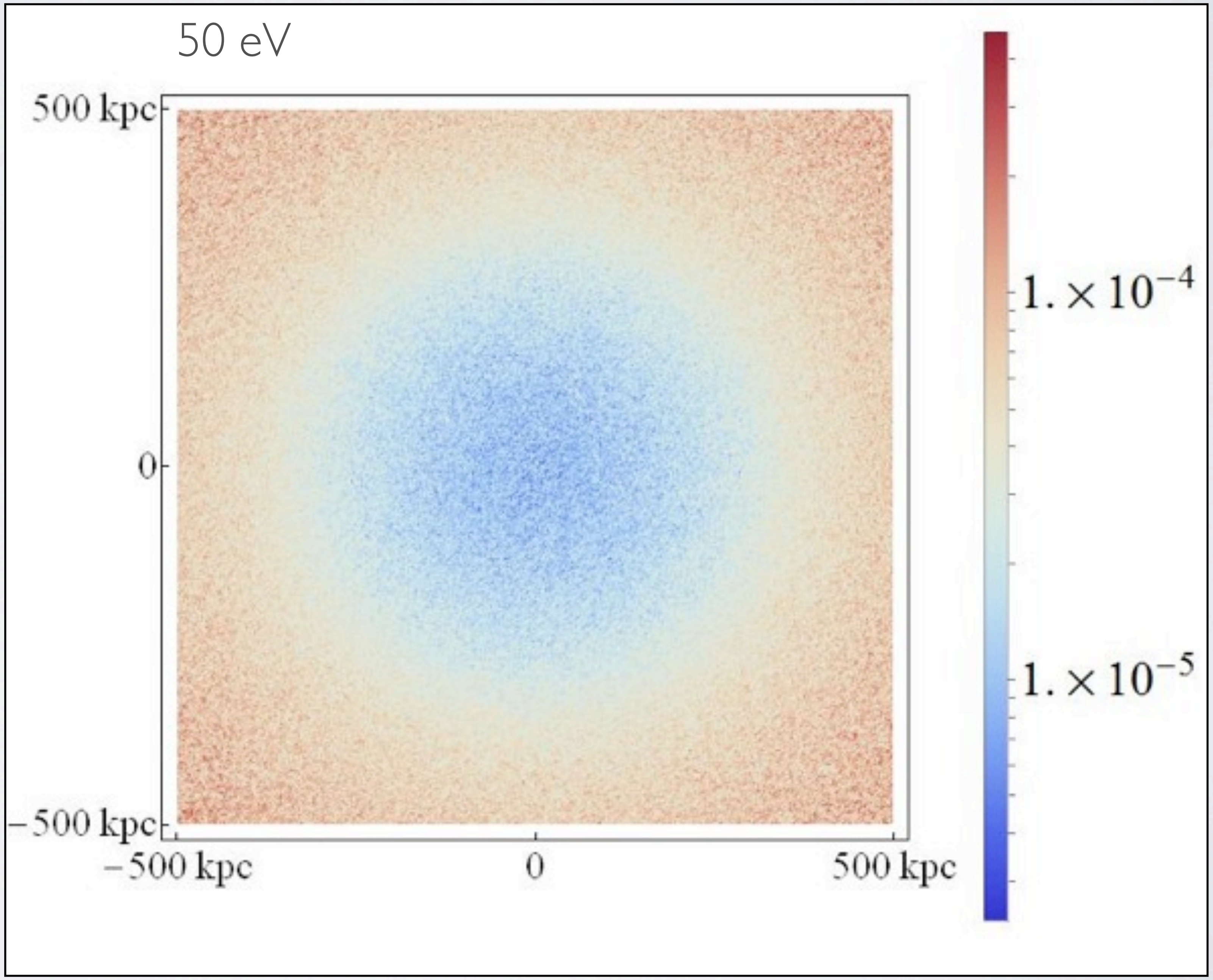

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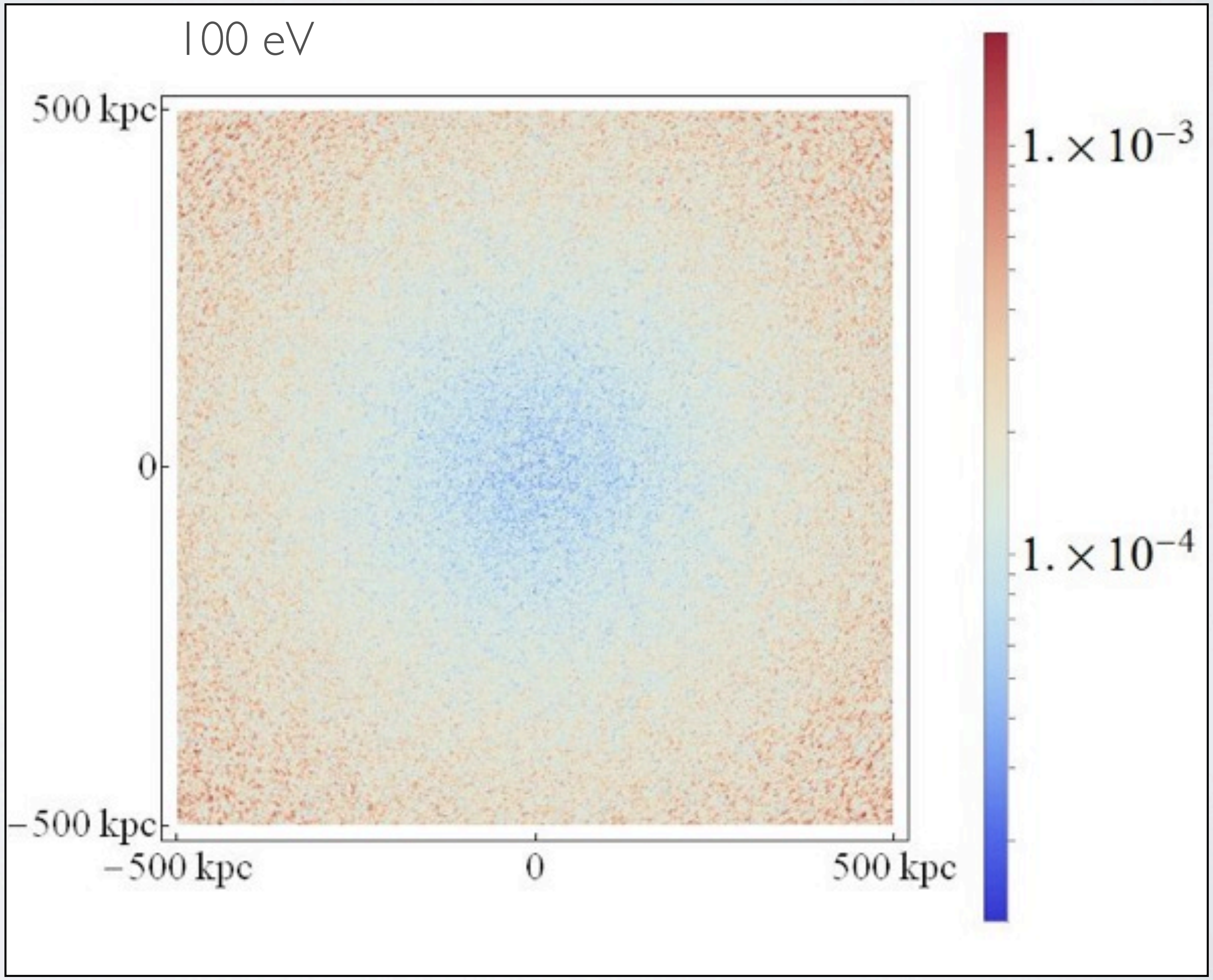

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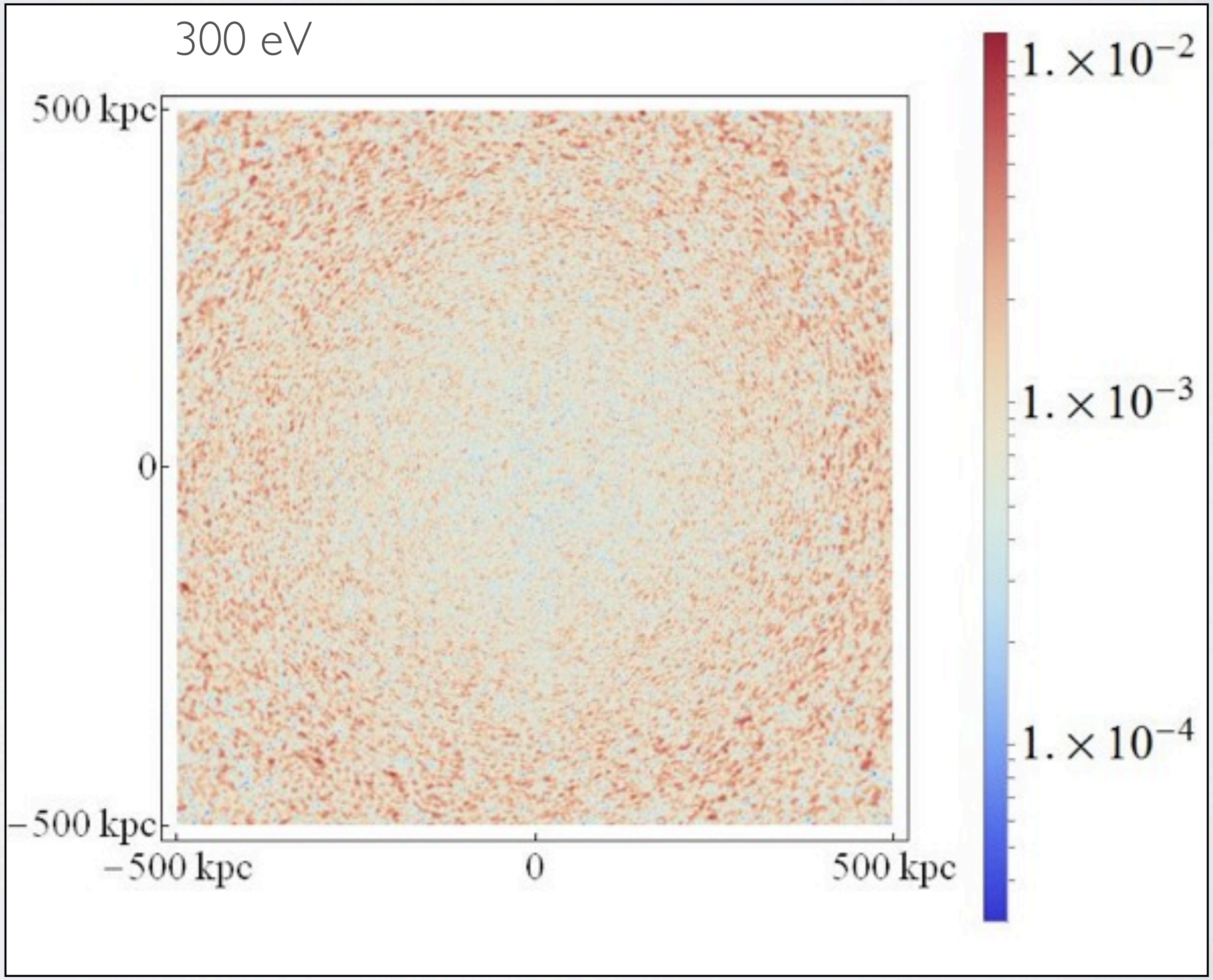

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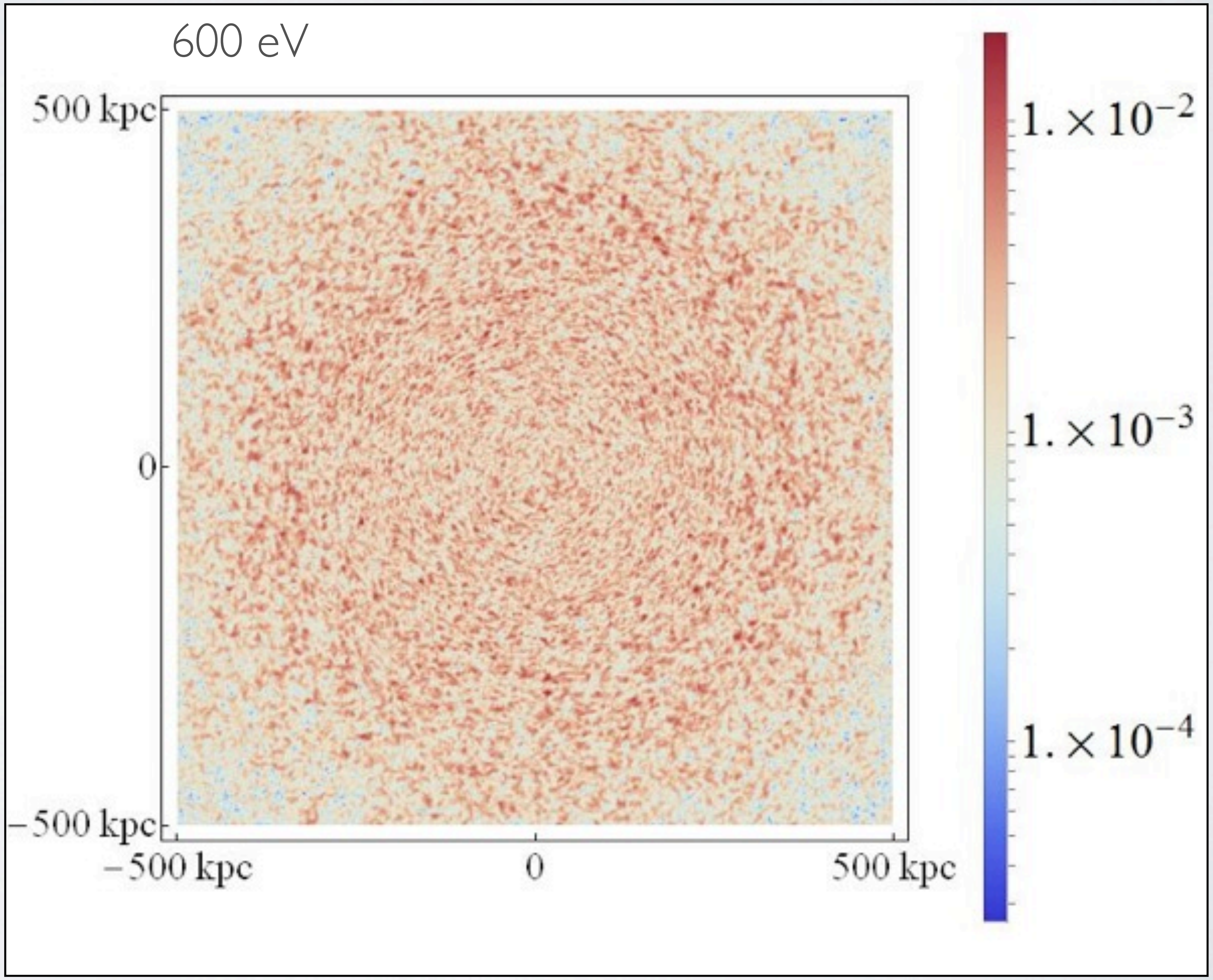

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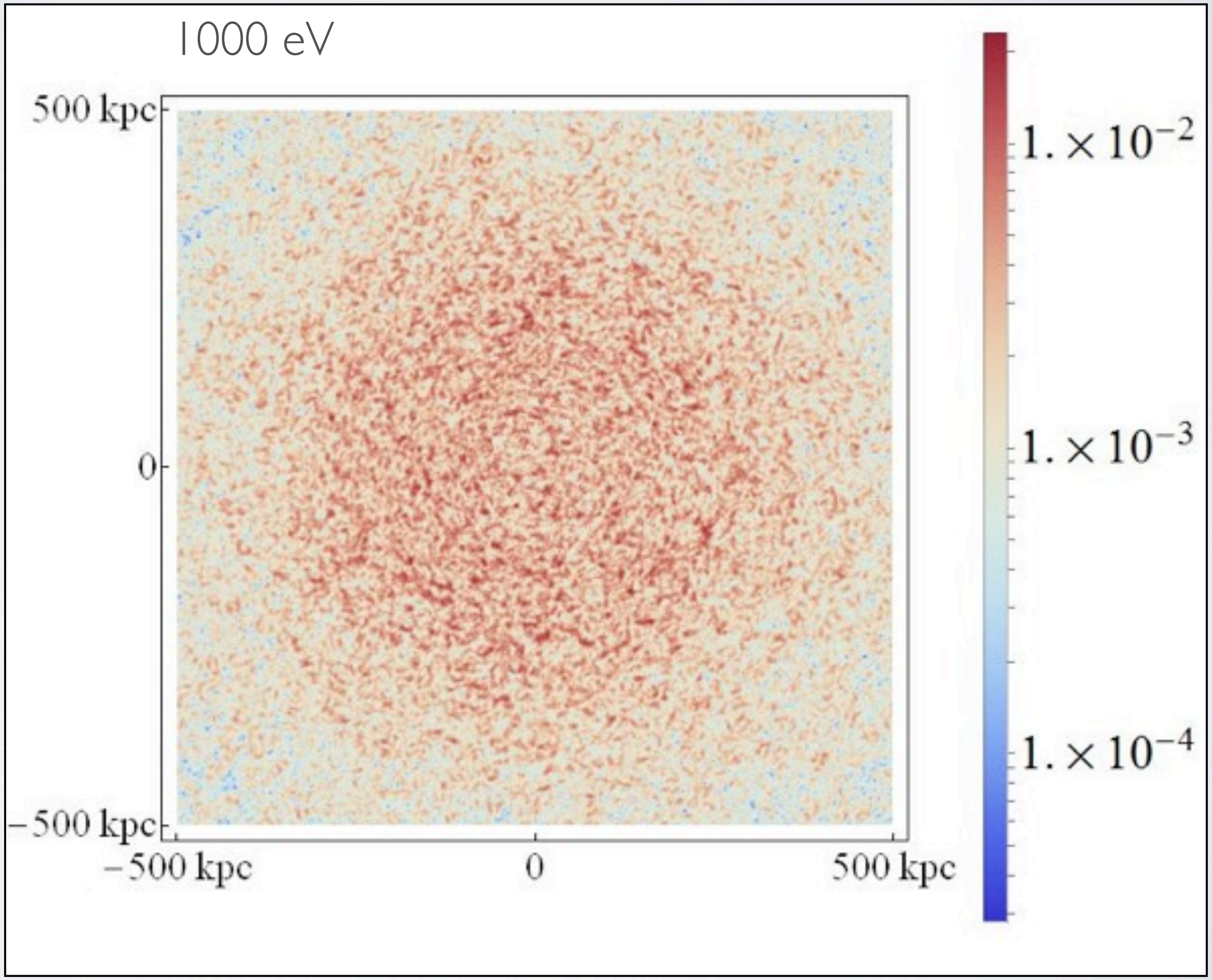

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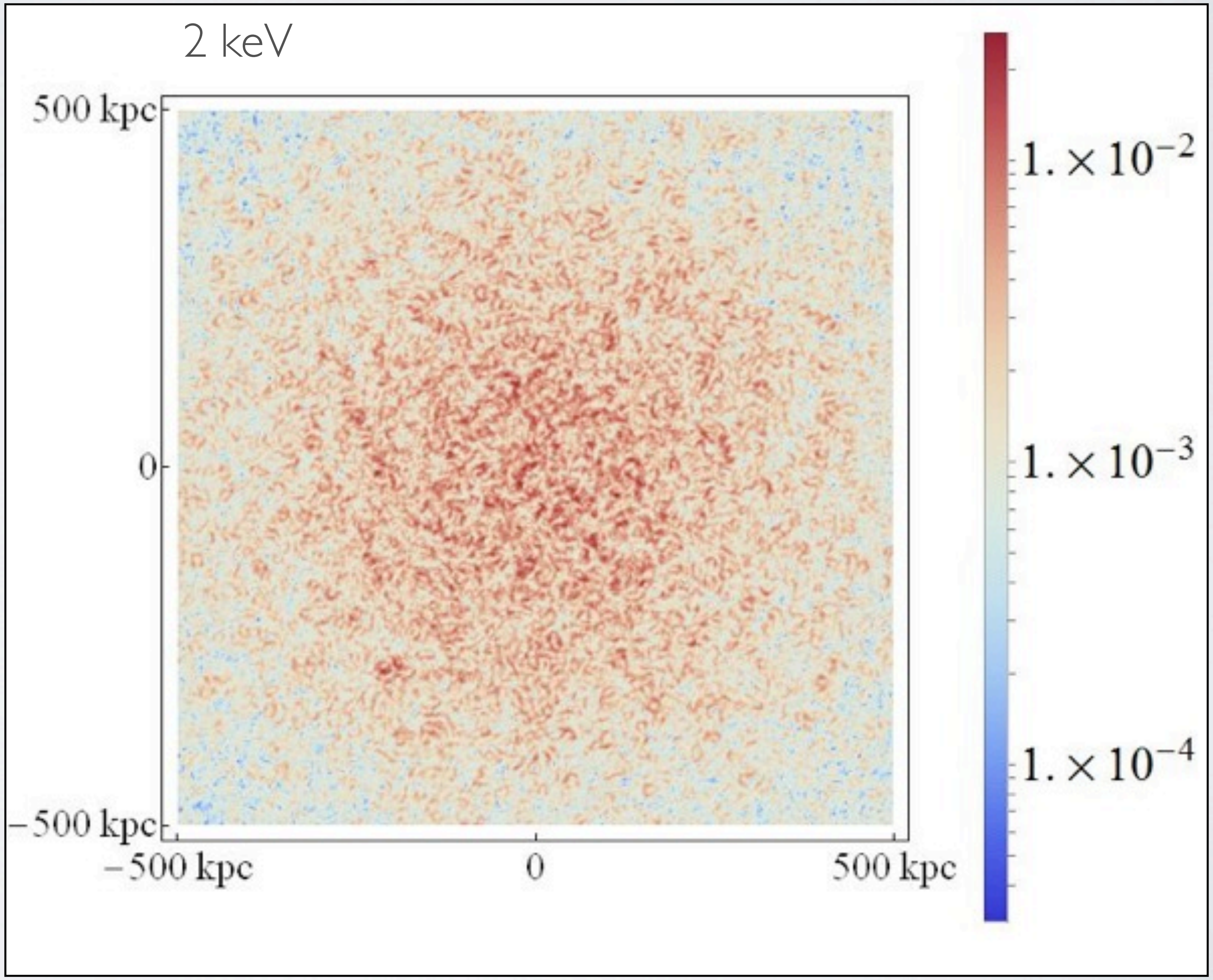
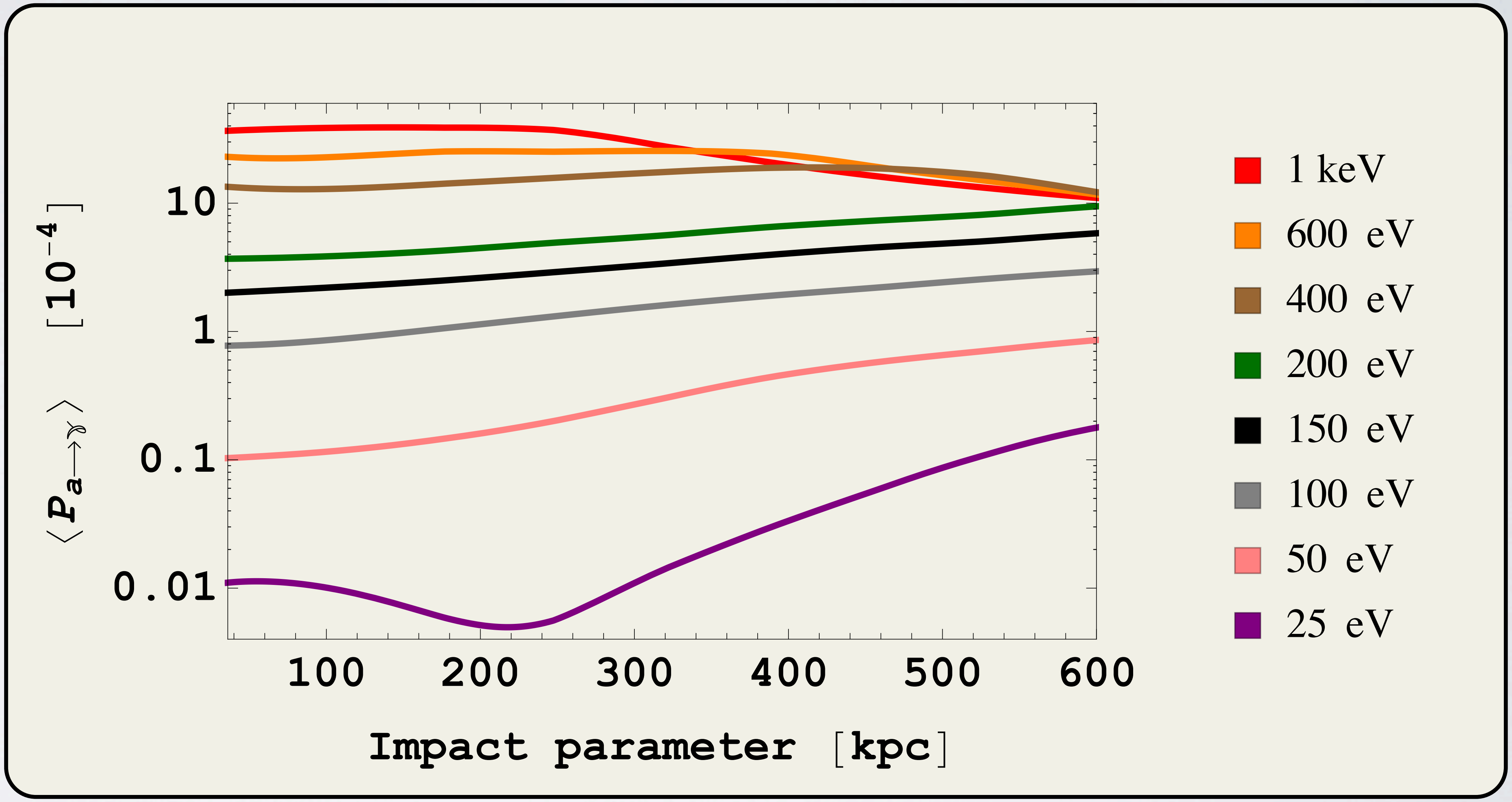


Angus, Conlon, DM, Powell, Witkowski, '13.

The CAB and the cluster soft X-ray excess

The conversion probabilities "fall out of" the small angle approximation as the impact parameter is decreased.



Model 1:
Λ ~ 2-34 kpc ~O(15 kpc).

Angus, Conlon, DM, Powell, Witkowski, '13.

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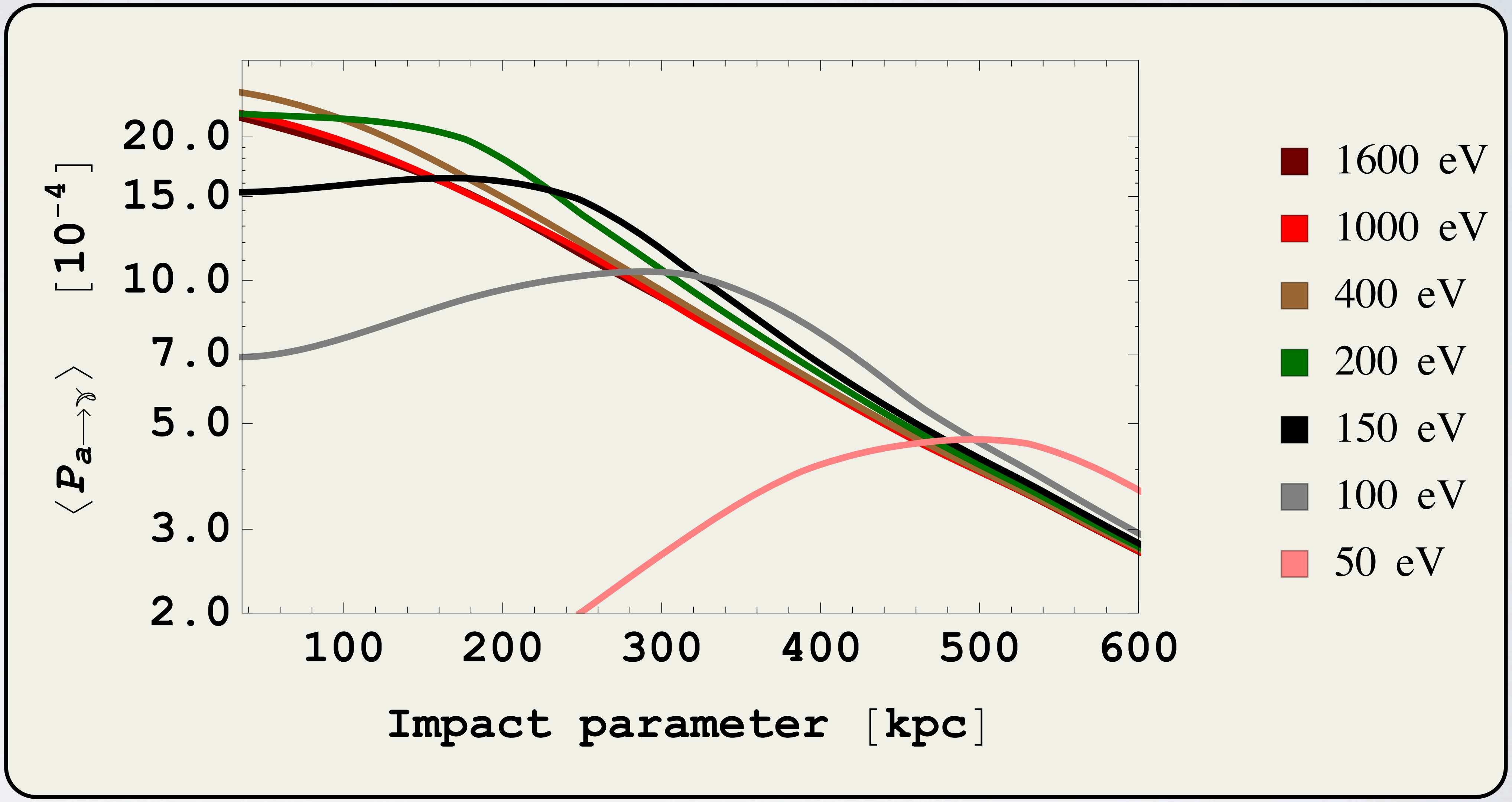
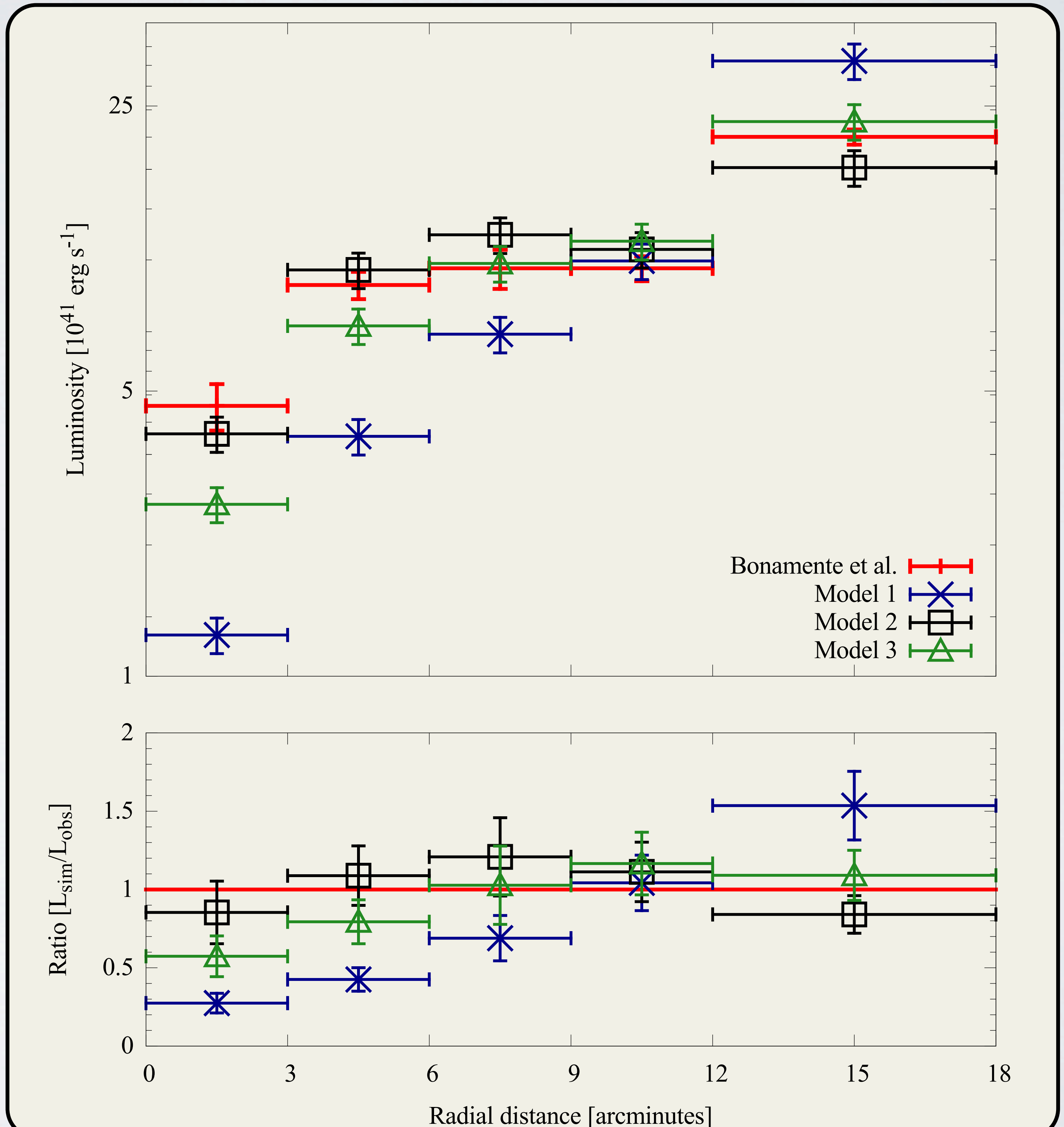


Model 2:
Λ ~ 2-4 kpc ~O(4 kpc)

Angus, Conlon, DM, Powell, Witkowski, '13.

The CAB and the cluster soft X-ray excess

Comparison with observations:

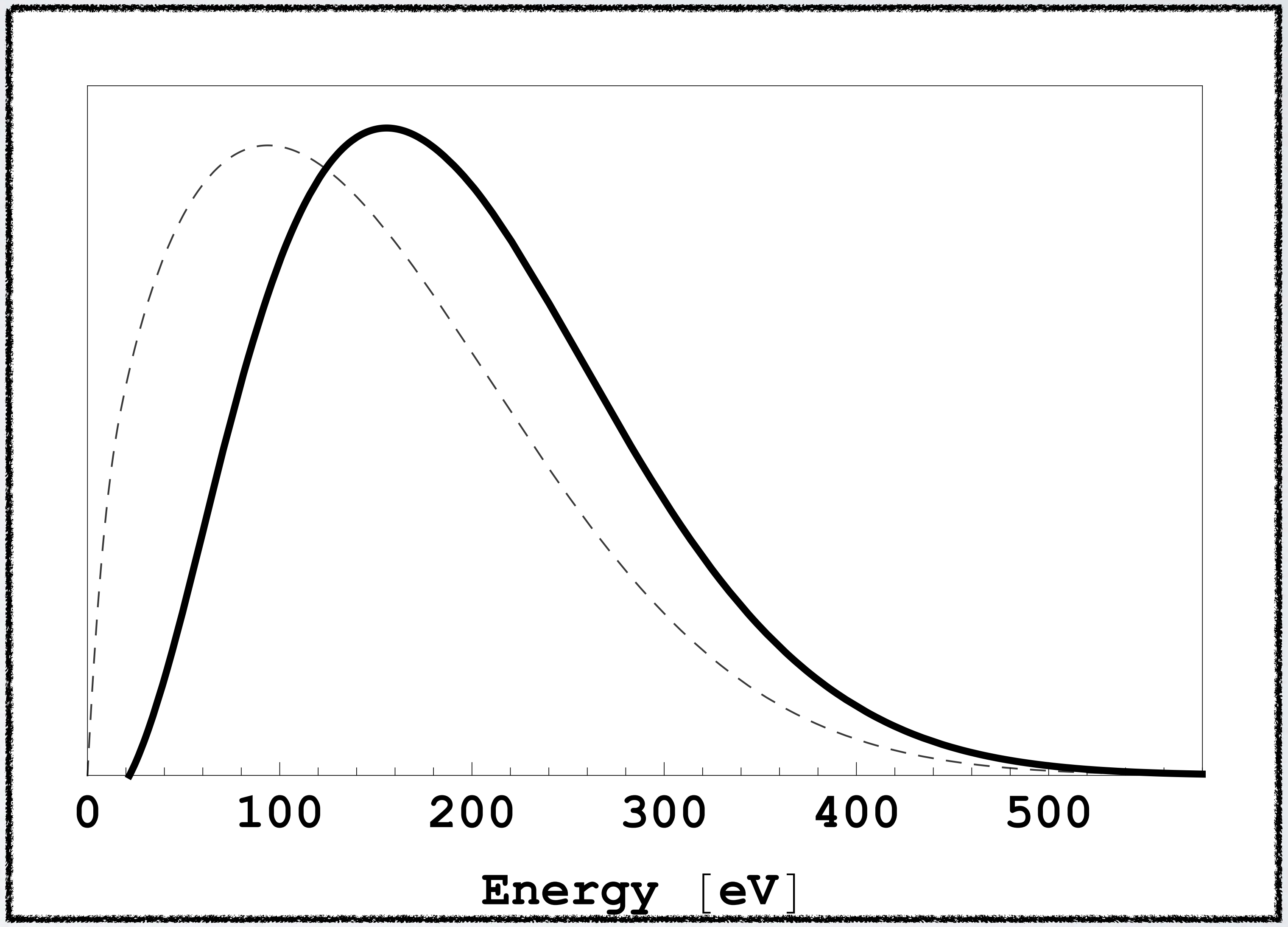


Model 1:
Λ ~ 2-34 kpc.
Model 2:
Λ ~ 2-4 kpc.
Model 3:
Λ ~2-100 kpc

Angus, Conlon, DM, Powell, Witkowski, '13.

The CAB and the cluster soft X-ray excess

Further features:



Angus, Conlon, DM, Powell, Witkowski, '13.

The CAB and the cluster soft X-ray excess

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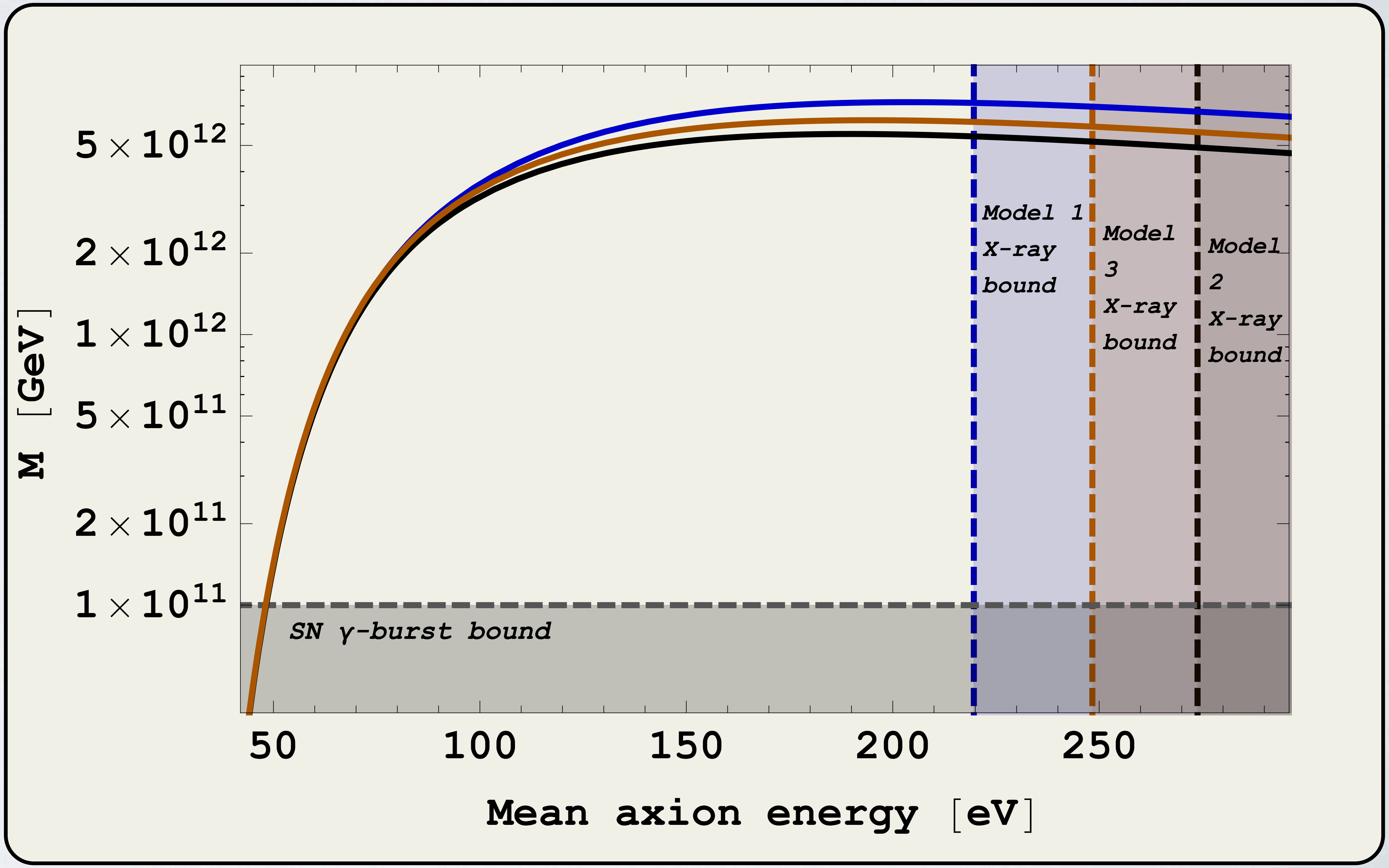
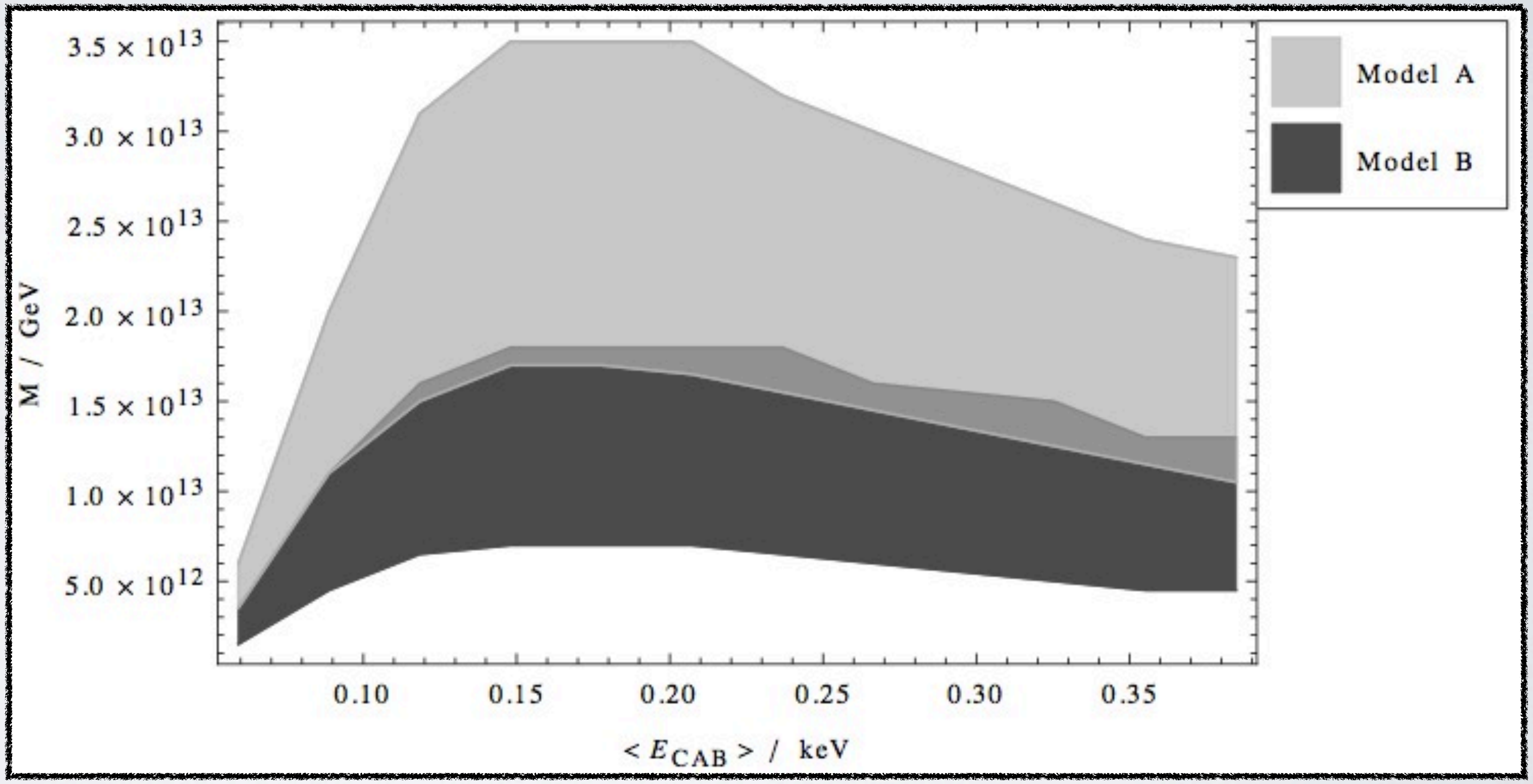


Angus, Conlon, DM, Powell, Witkowski, '13.

The CAB and the cluster soft X-ray excess

Outskirts of Coma:
Soft X-ray excess found out to 5 Mpc from centre.



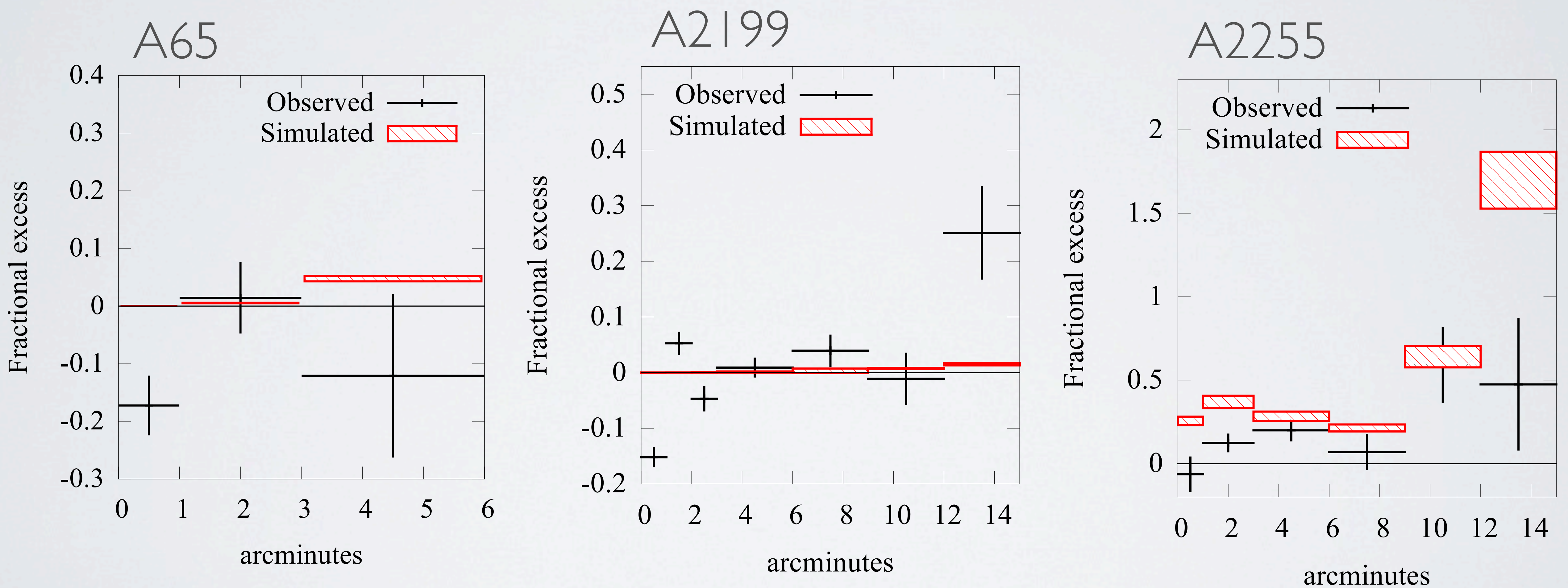
Conlon, Kraljic, Rummel, '14.

The CAB and the cluster soft X-ray excess

Other clusters:

Soft X-ray excess found in other clusters.

Preliminary



Powell, (to appear).

The CAB and the cluster soft X-ray excess

Does it work?

- Yes. Axion-photon conversion of the CAB may explain the soft excess in Coma.
- However, the results are sensitive to the magnetic field structure beyond what is currently constrained by observations.
- Further studies of other clusters (in detail and statistically), and a better understanding of the cluster magnetic field will help clarifying if the CAB explanation is viable.
- Other consequences of the existence of a CAB, such as axion-photon conversion in the Milky Way* may provide complimentary constraints/signals.

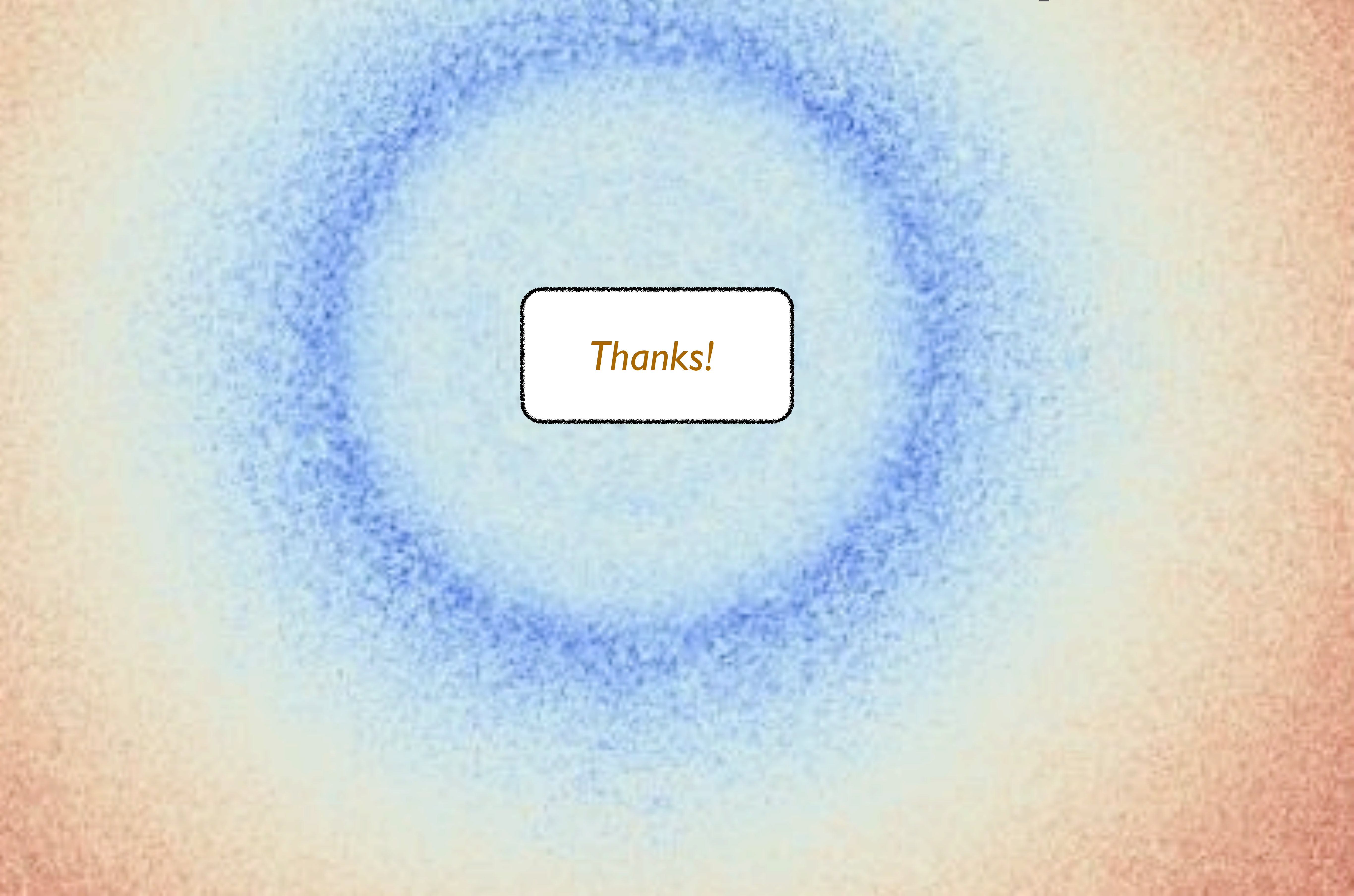
* Fairbairn '13, Conlon, Day, '14.

The CAB and the cluster soft X-ray excess

Conclusion

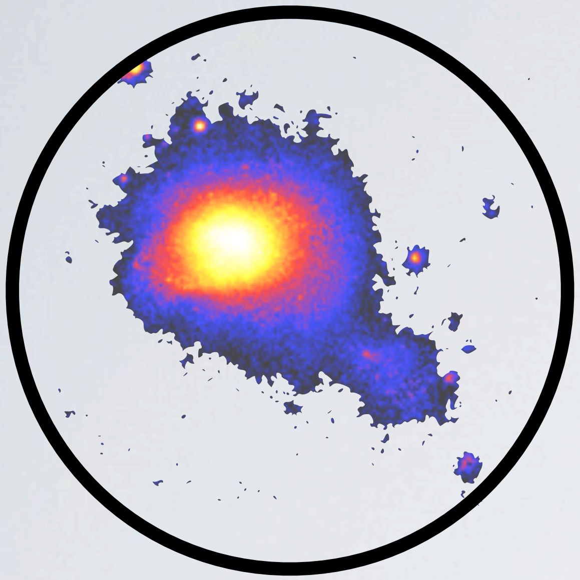
- Some amount of dark radiation should be expected for generic string compactifications. Bounds on the amount of dark radiation constrain explicit models.
- Axionic dark radiation is hard to detect, but ALP-photon conversion in the μG magnetic fields of galaxy clusters provide possibly the most powerful setting to search for such particles.
- For the Coma cluster, ALP-photon conversion can explain the longstanding soft X-ray excess.

The CAB and the cluster soft X-ray excess



Thanks!

Extra slides



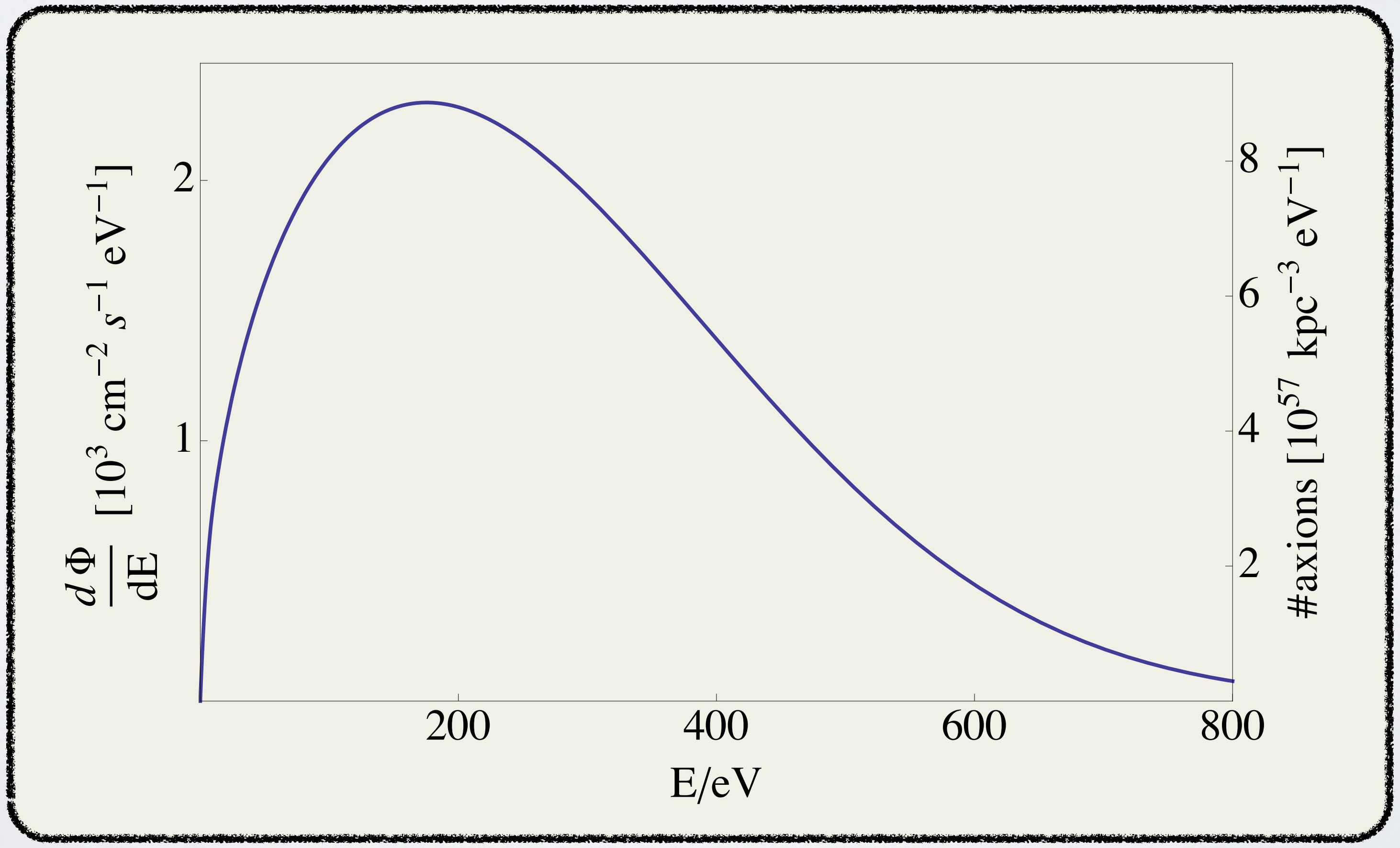
The Cosmic Axion Background

If a CAB was detected with a non-thermal spectrum, then one would be able to infer the existence of a particle species with mass,

$$m_{\phi_1} > \left(\frac{E_a/T_{CMB}}{10^6}\right) 4 \text{ TeV} \,,$$

interacting by operators suppressed by the scale,

$$\Lambda \gtrsim \left(\frac{E_a/T_{CMB}}{10^6}\right)^{3/2} 7 \cdot 10^{16} \text{ GeV} \,.$$



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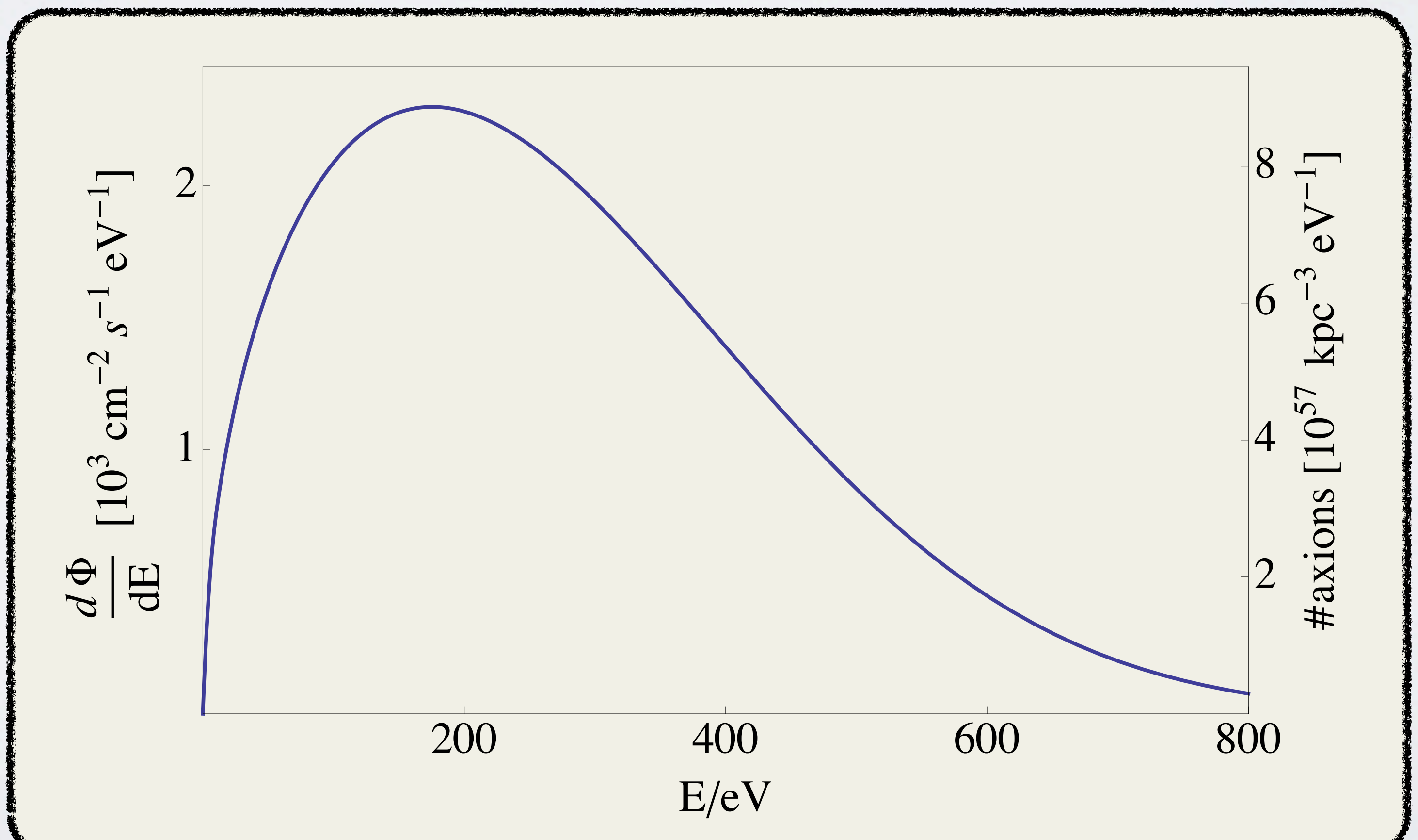
Moduli



Proposed astrophysical explanations of the cluster soft X-ray excess

Thermal model:
Default suggestion at time of detection, currently disfavoured as main explanation.

Problems:

- The gas would *cool too rapidly*:

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- It would give rise to *unobserved emission lines*.

Still, suggested to be possible explanation of excess at large radii.

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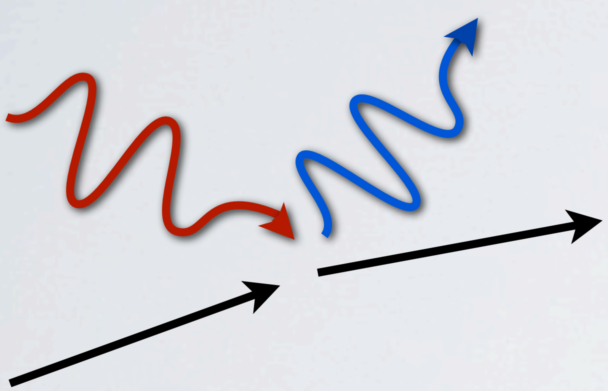
Non-thermal model:

Inverse Compton Scattering of CMB photons off non-thermal gas:

$$E_{\text{scattered}} \sim \gamma^2 E_{\text{CMB}} \,.$$



Hwang 1997,
Bowyer *et al* 2004,
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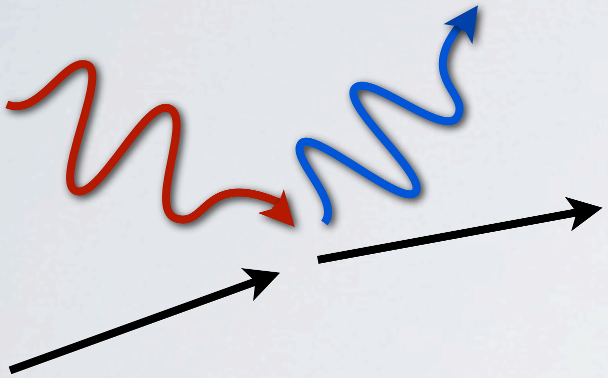

$$\underbrace{E_{\rm scattered}}_{\sim 200\ \text{eV}} \sim \gamma^2 E_{\rm CMB}\,.$$

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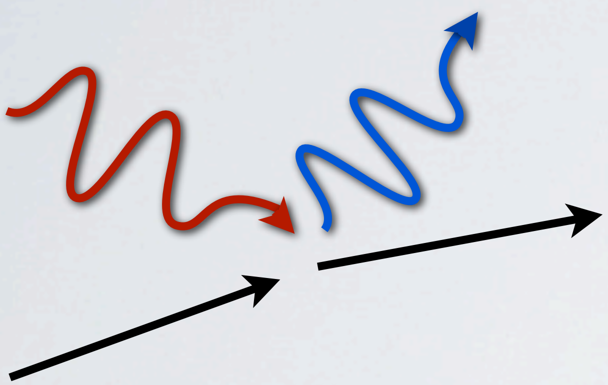

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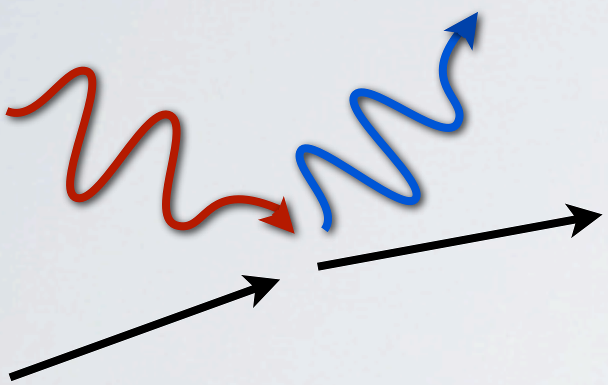

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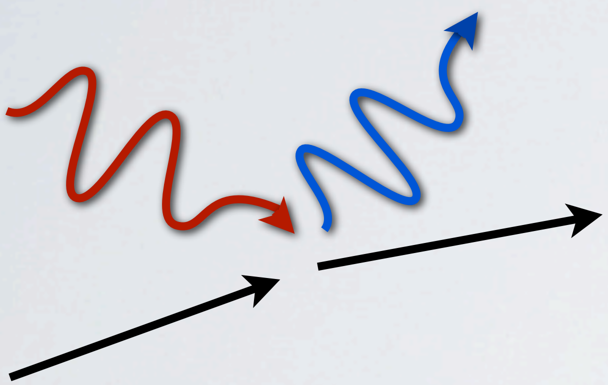

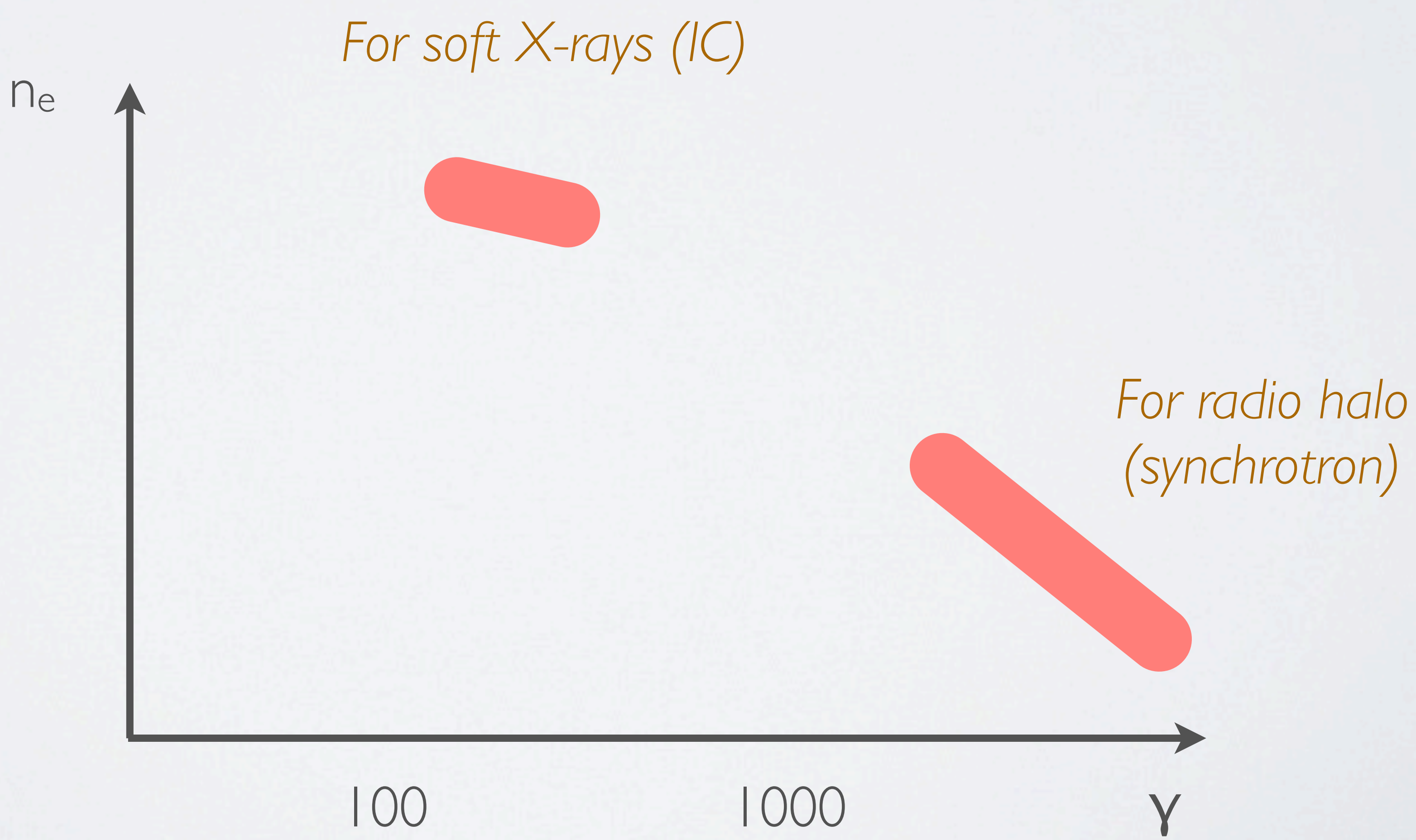

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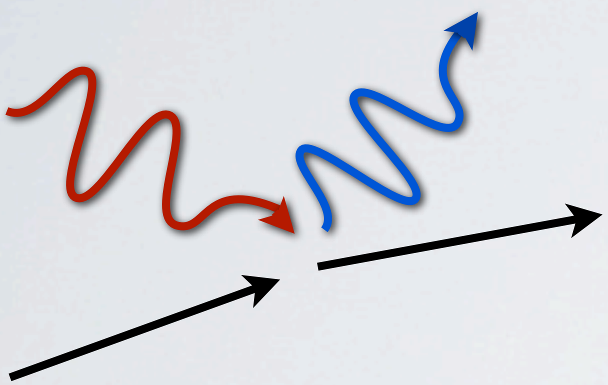

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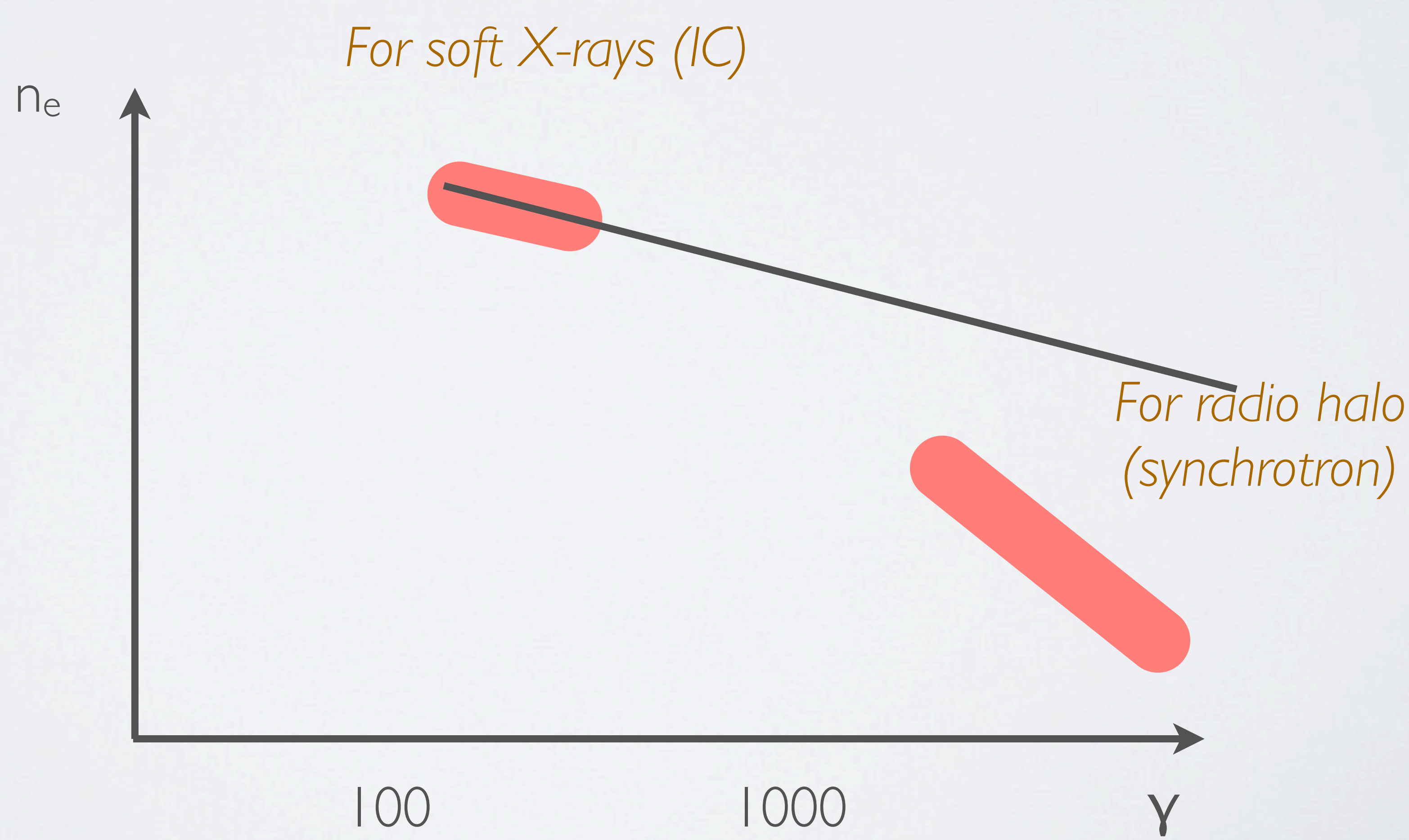

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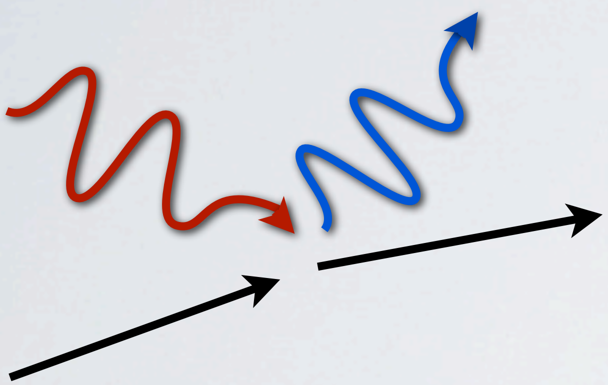

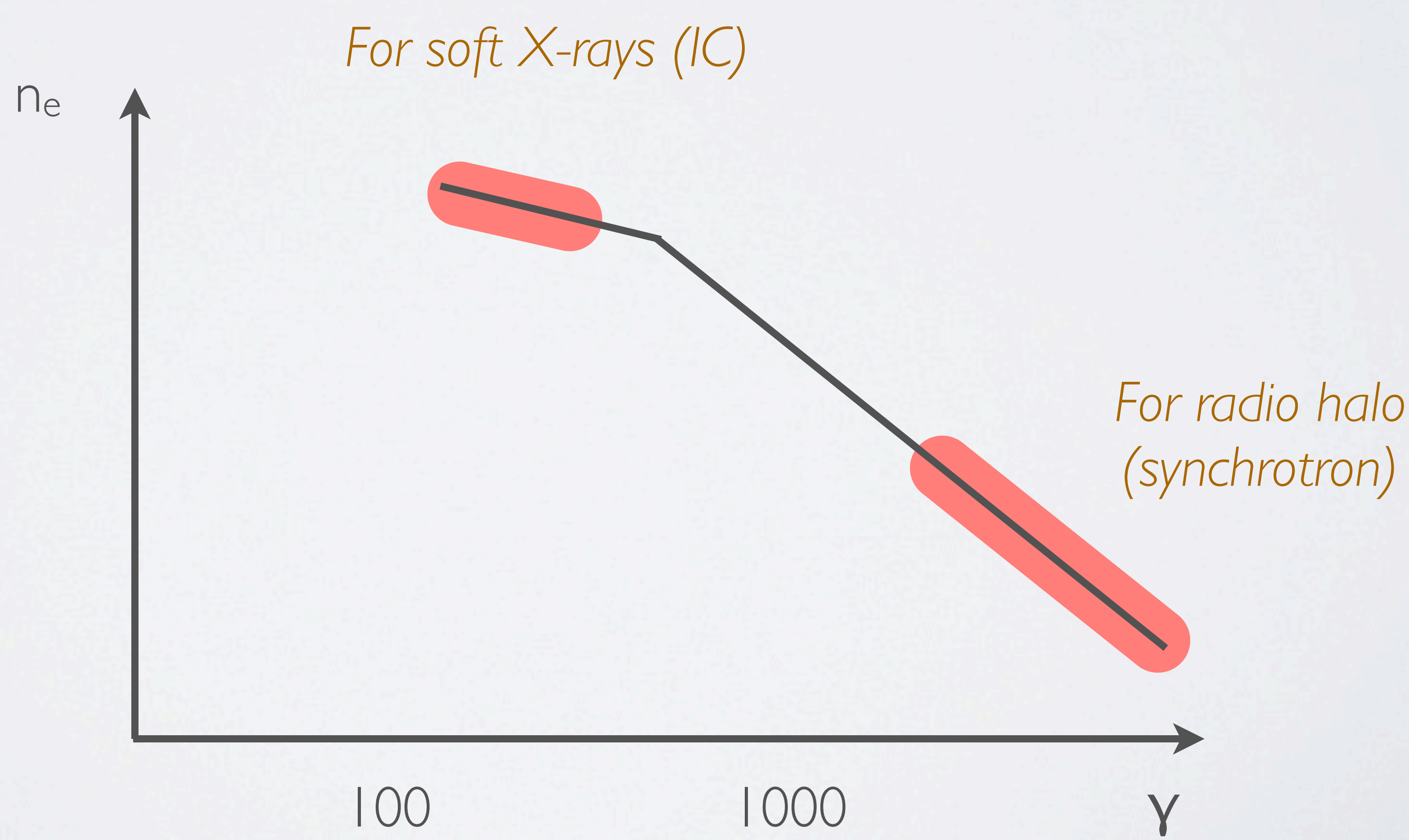

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~200 eV

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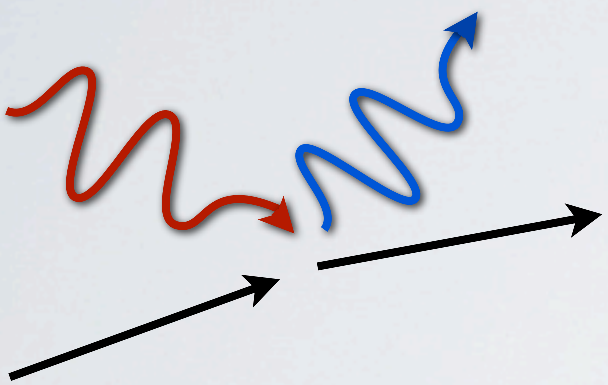

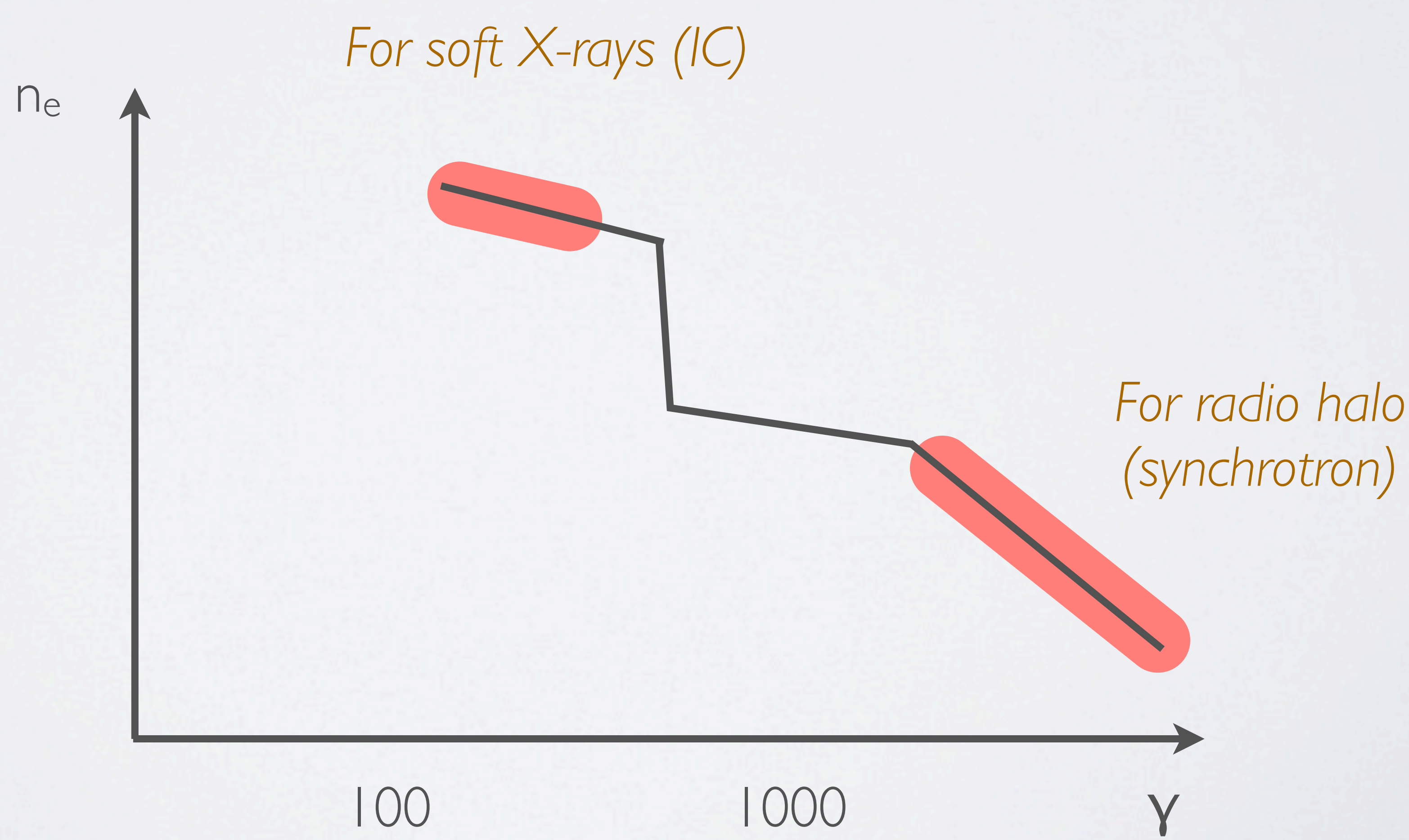

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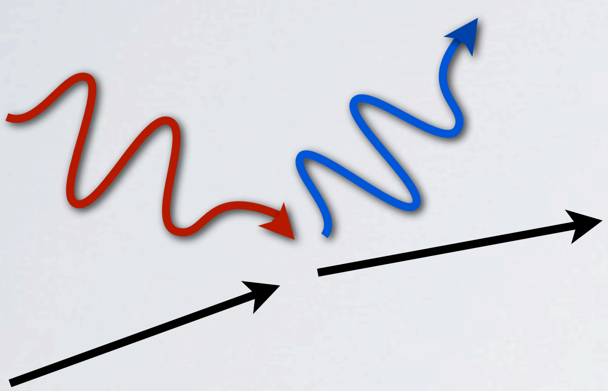

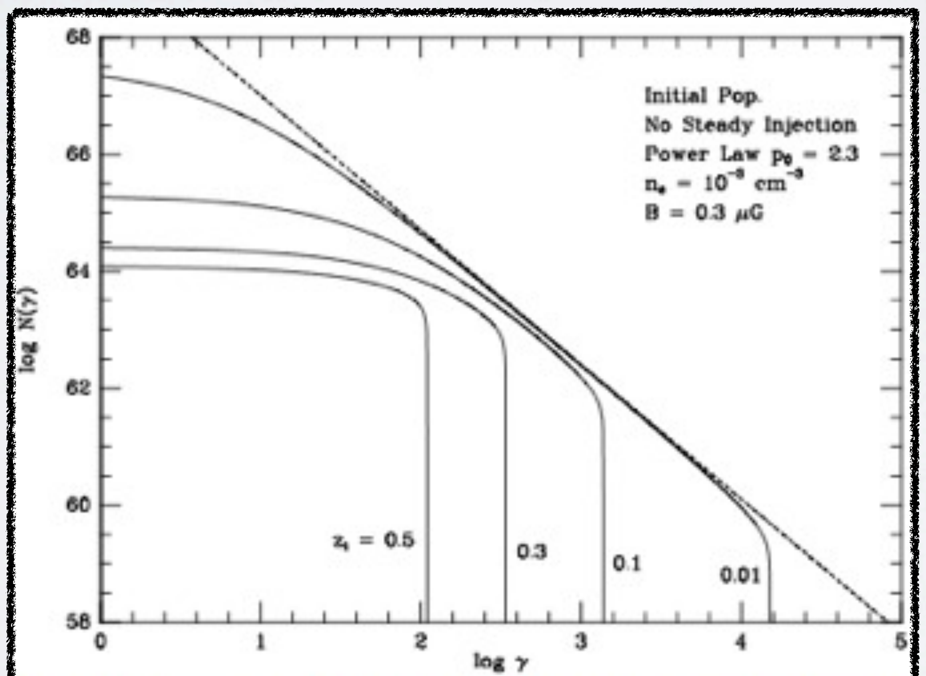

Fig. 3. The present day relativistic electron populations in models with no current particle acceleration (e.g., no subcluster merger at present). An initial population of electrons, which is shown as a dashed line, was introduced into the cluster at a redshift of $z_i = 0.01, 0.1, 0.3$, and 0.5.

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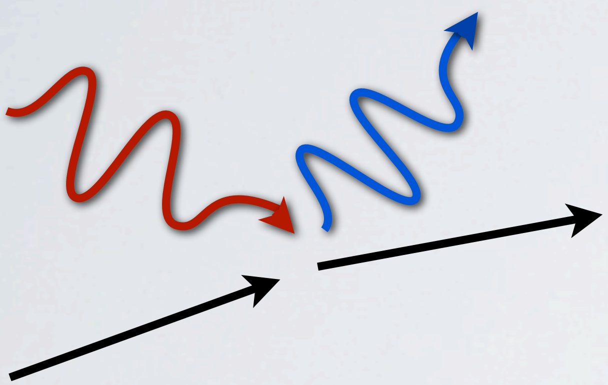

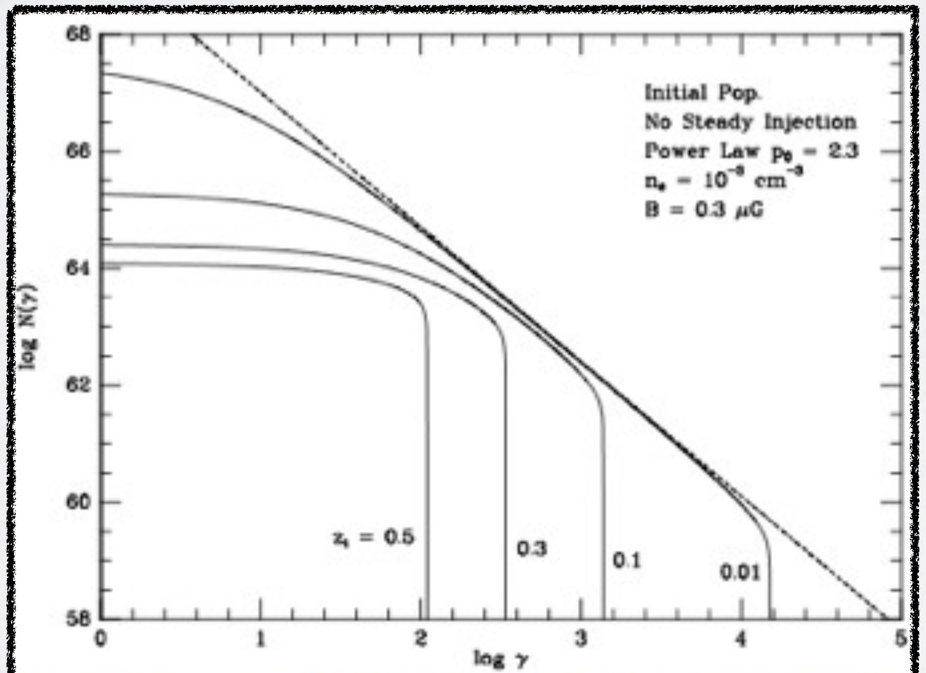

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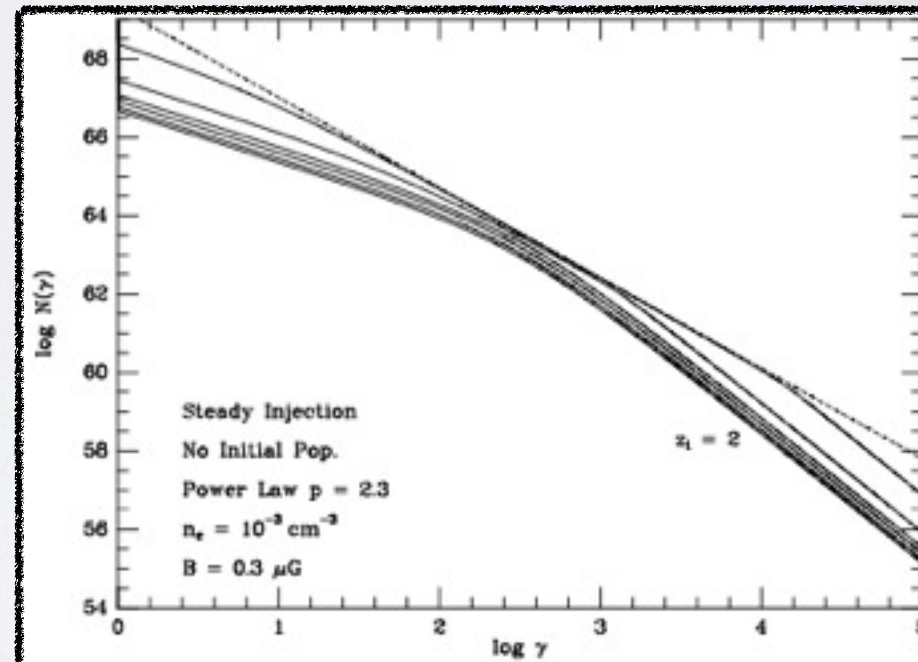

Fig. 4. The present day relativistic electron populations in a series of models with ongoing particle acceleration, perhaps due to a cluster merger shock. he solid curves show models for clusters which started at redshifts of $z_i =$ 2, 1, 0.5, 0.3, 0.1, and 0.01 (bottom to top). The short-dashed curve gives the total power-law spectrum of all of the injected particle over the cluster lifetime.

Hwang 1997,
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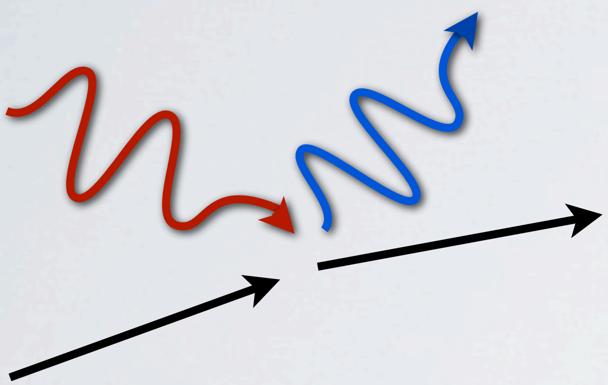
Proposed astrophysical explanations of the cluster soft X-ray excess



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Fine-tuned IC:

For Coma: $t_{injection} \sim 1.0\text{-}1.4 * 10^9$ yrs.

In addition: small injection even in recent past to produce CR's for radio halo.

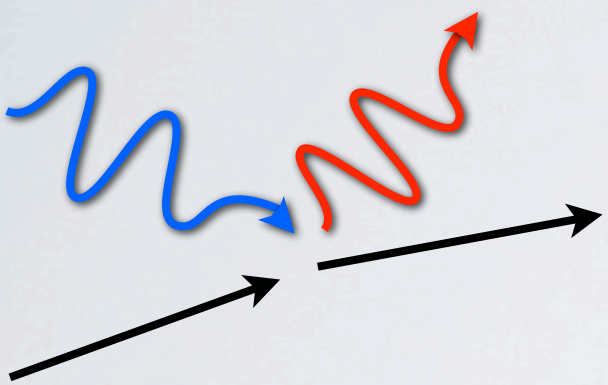
Tsay *et al* 2002.

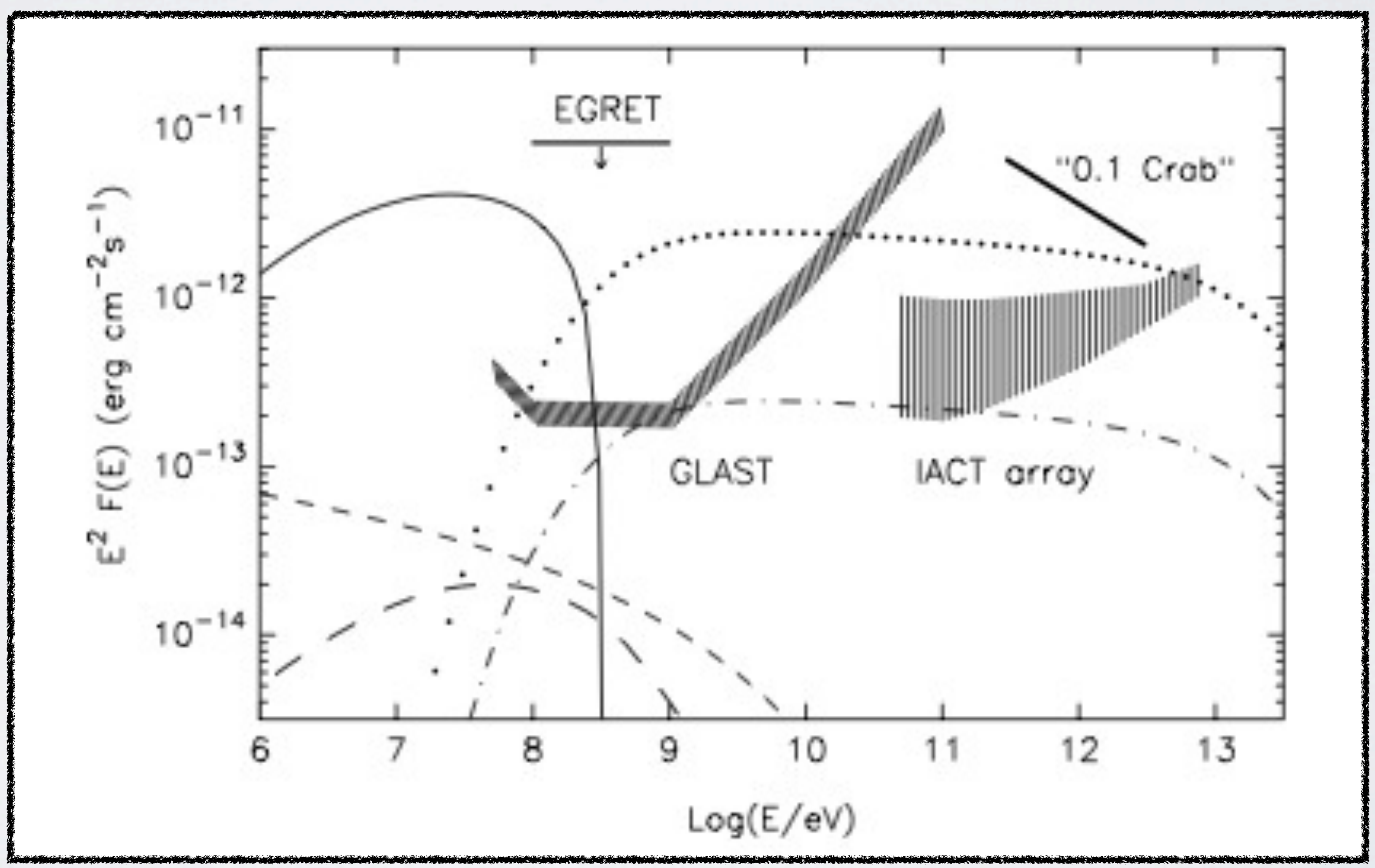
Proposed astrophysical explanations of the cluster soft X-ray excess

Non-thermal model:

Additional constraint: associated bremsstrahlung:

Coma: predicted gamma-ray flux of ~ $2*10^{-8}$ cm^{-2} s^{-1}.





Atoyan, Vollker 2000, Sarazin 1999.

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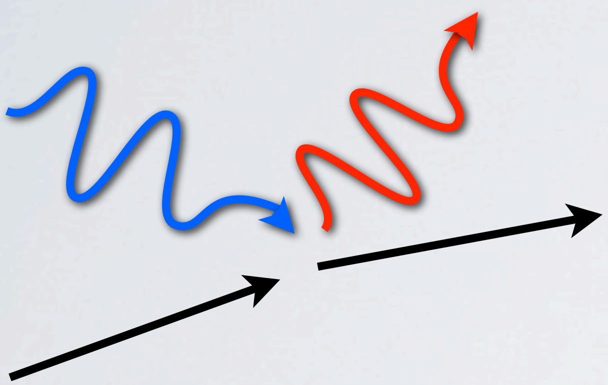

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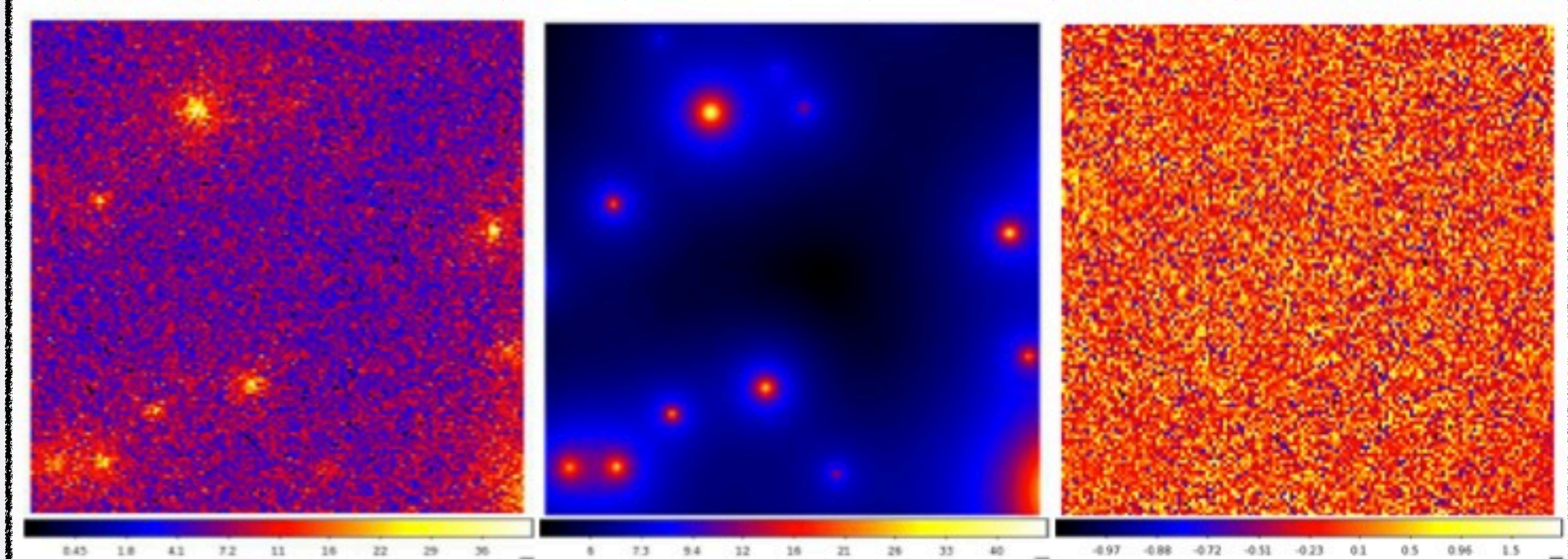

Figure 1. *Left.* LAT photon count map for an area of 14° × 14° around the Coma galaxy cluster (whose center lies at the center of the image) obtained from about 5 years of observations. The cluster virial radius is about 1°.3. *Center.* Model count map for the basic analysis of the data with the 2FGL 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, Sarazin 1999.

Zandanel, Ando, 2013.

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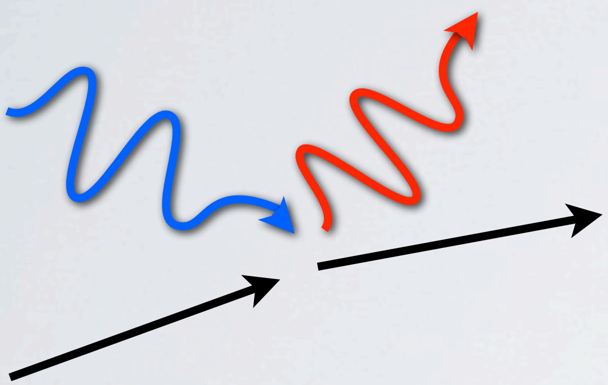

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Coma: predicted gamma-ray flux of ~ $2*10^{-8}$ cm^{-2} s^{-1}.

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

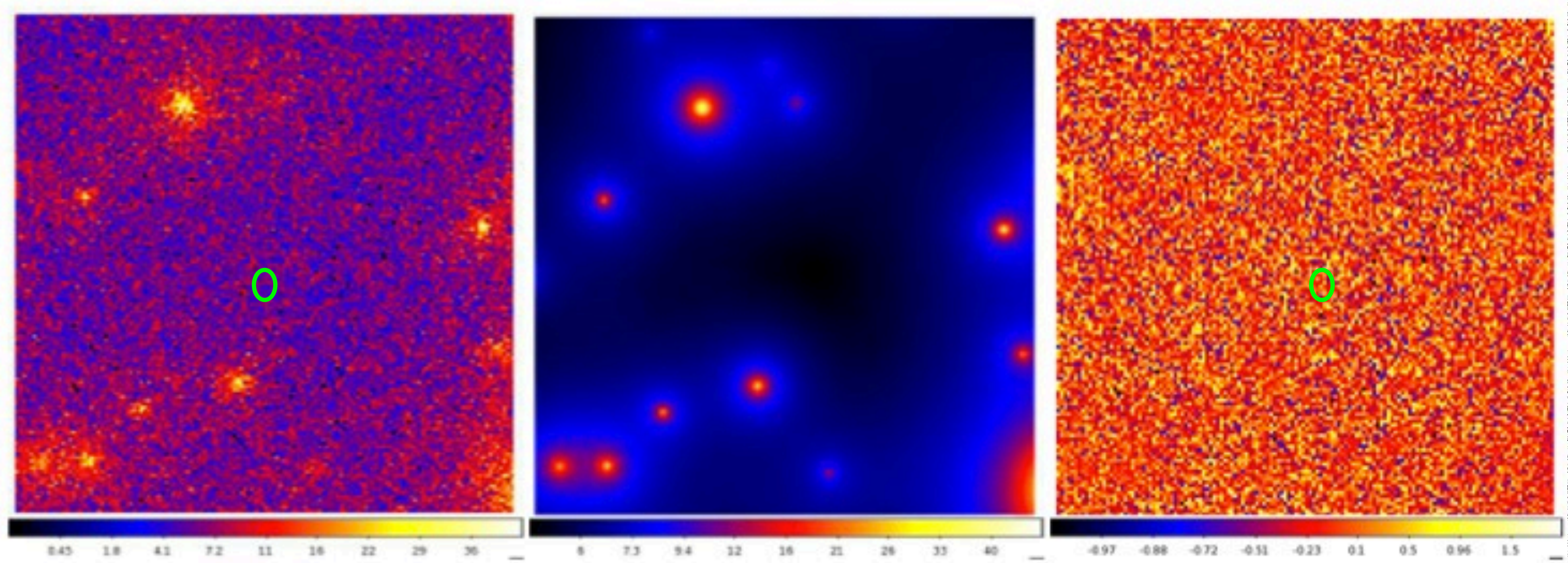

Figure 1. *Left.* LAT photon count map for an area of 14° × 14° around the Coma galaxy cluster (whose center lies at the center of the image) obtained from about 5 years of observations. The cluster virial radius is about 1.°3. *Center.* Model count map for the basic analysis of the data with the 2FGL 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, Sarazin 1999.

Zandanel, Ando, 2013.