STRING THEORY ON THE SKY

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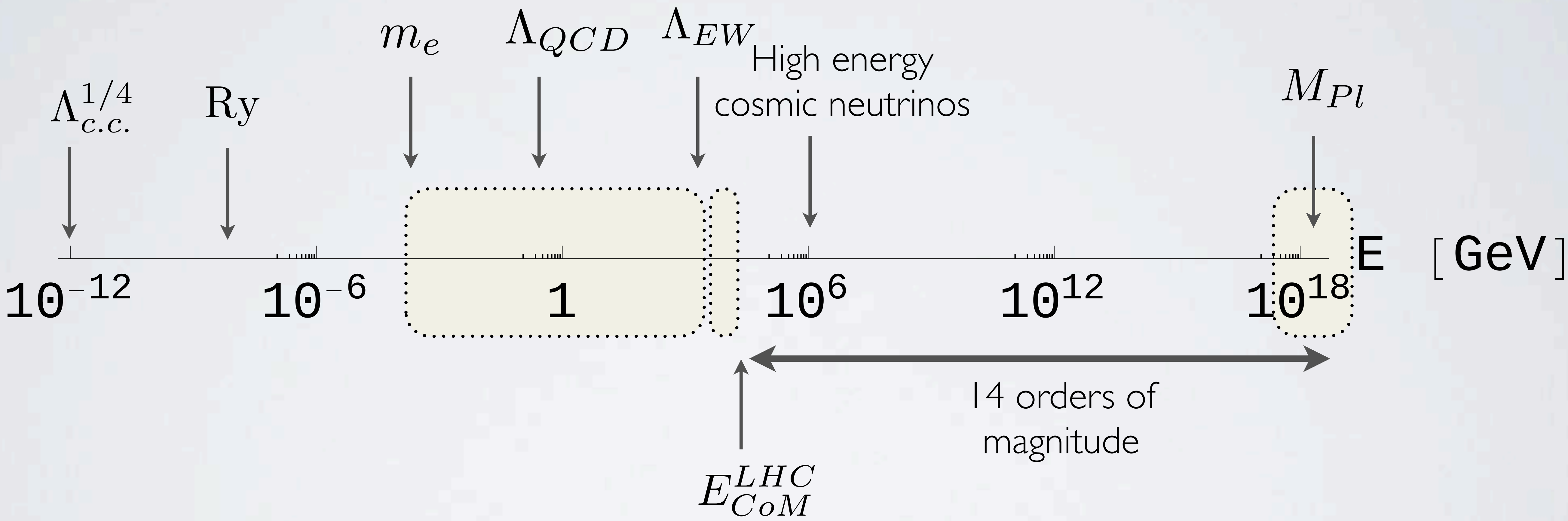
Saturday Morning Theoretical Physics, 25/01, 2014

The challenge of quantum gravity

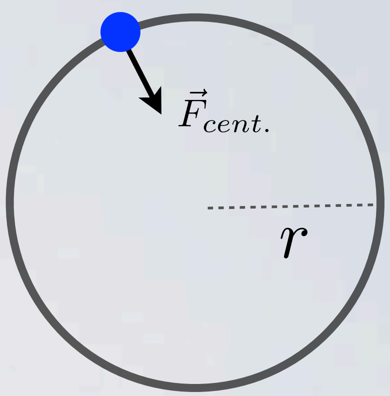
The scales of nature:



The challenge of quantum gravity

Probing quantum gravity with LHC technology:

How big an accelerator would be needed to probe the Planck scale physics directly?



The LHC magnets provide the centripetal force:

$$F_{cent.} = qvB = \frac{mv^2}{r}\,,$$

giving, $$r = \frac{p}{qB}\,.$$

With the same type of magnets,

$$r_{Pl} = \frac{p_{Pl}}{p_{LHC}} r_{LHC}\,.$$

The challenge of quantum gravity

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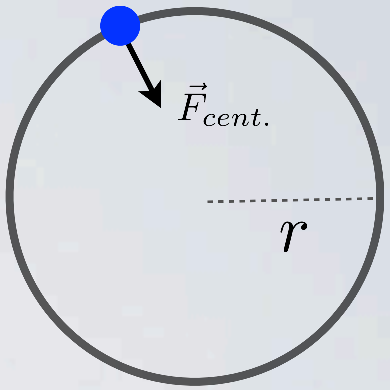
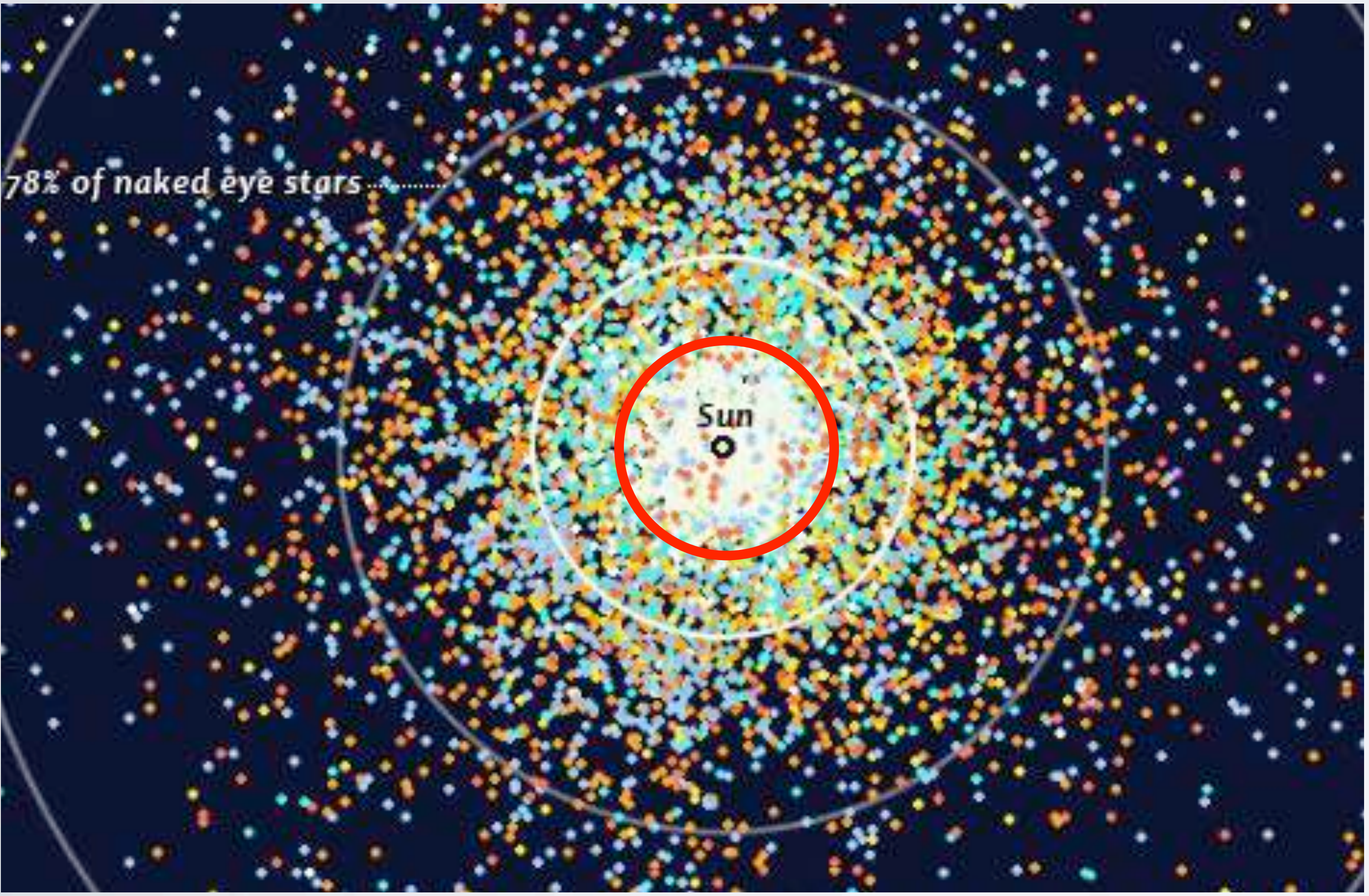




Giving,

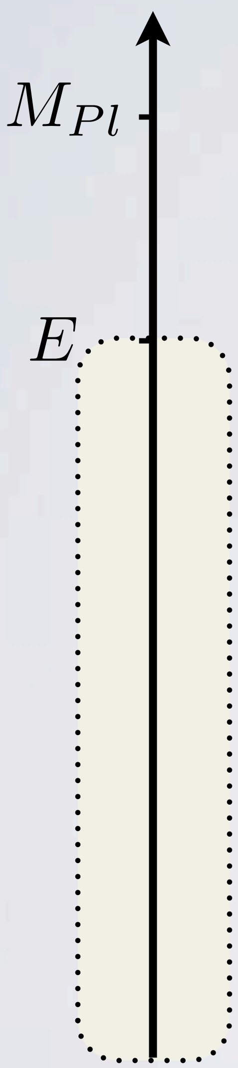
$$r_{Pl} = \frac{2.4 \cdot 10^{18}\ \text{GeV}}{7 \cdot 10^{3}\ \text{GeV}} \frac{27}{2\pi}\ \text{km}$$

$$= 1.5 \cdot 10^{15}\ \text{km} = 160\ \text{l.y.}$$

While accelerator experiments are not suitable to *directly* probe quantum theories of gravity, Planck scale physics can still be important for cosmology and particle physics.

The challenge of quantum gravity

Effective field theories:



At energies $E \ll M_{Pl}$, information about the theory of quantum gravity is encoded the *low-energy effective field theory (EFT):*

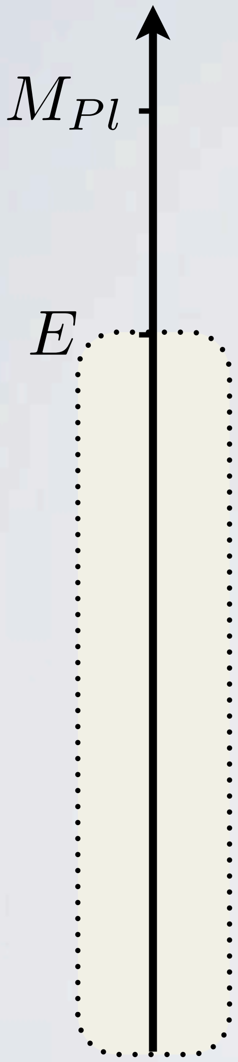
$$\mathcal{L} = \partial_\mu \phi \partial^\mu \phi - V_{EFT}(\phi)\,,$$

with $V_{EFT} = V_0 + \frac{1}{2} m^2 \phi^2 + \frac{\lambda}{4} \phi^4 + \sum_{n=5}^{\infty} c_n \frac{\phi^n}{M_{Pl}^{n-4}}\,.$

Interestingly, several proposed physical phenomena such as *cosmic inflation, baryogenesis* and *supersymmetry breaking* rely on very particular properties of the Wilson coefficients c_n, which then can be used to constrain proposed theories of quantum gravity.

The challenge of quantum gravity

Testing quantum gravities:



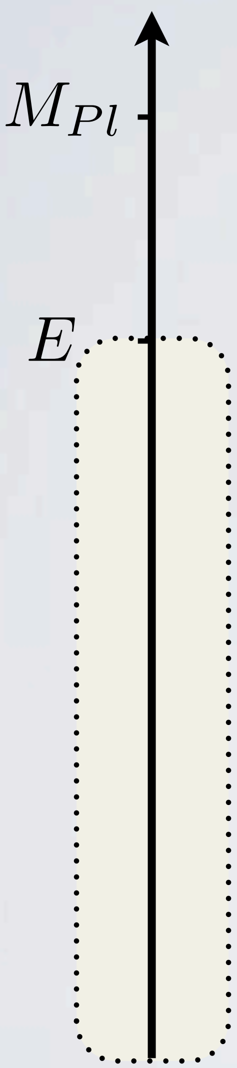
1. Propose a consistent theory at energies $\approx M_{Pl}$.
2. Compute the relevant EFT (c_n), and derive predictions.
3. Compare predictions with cosmological and particle physics data.

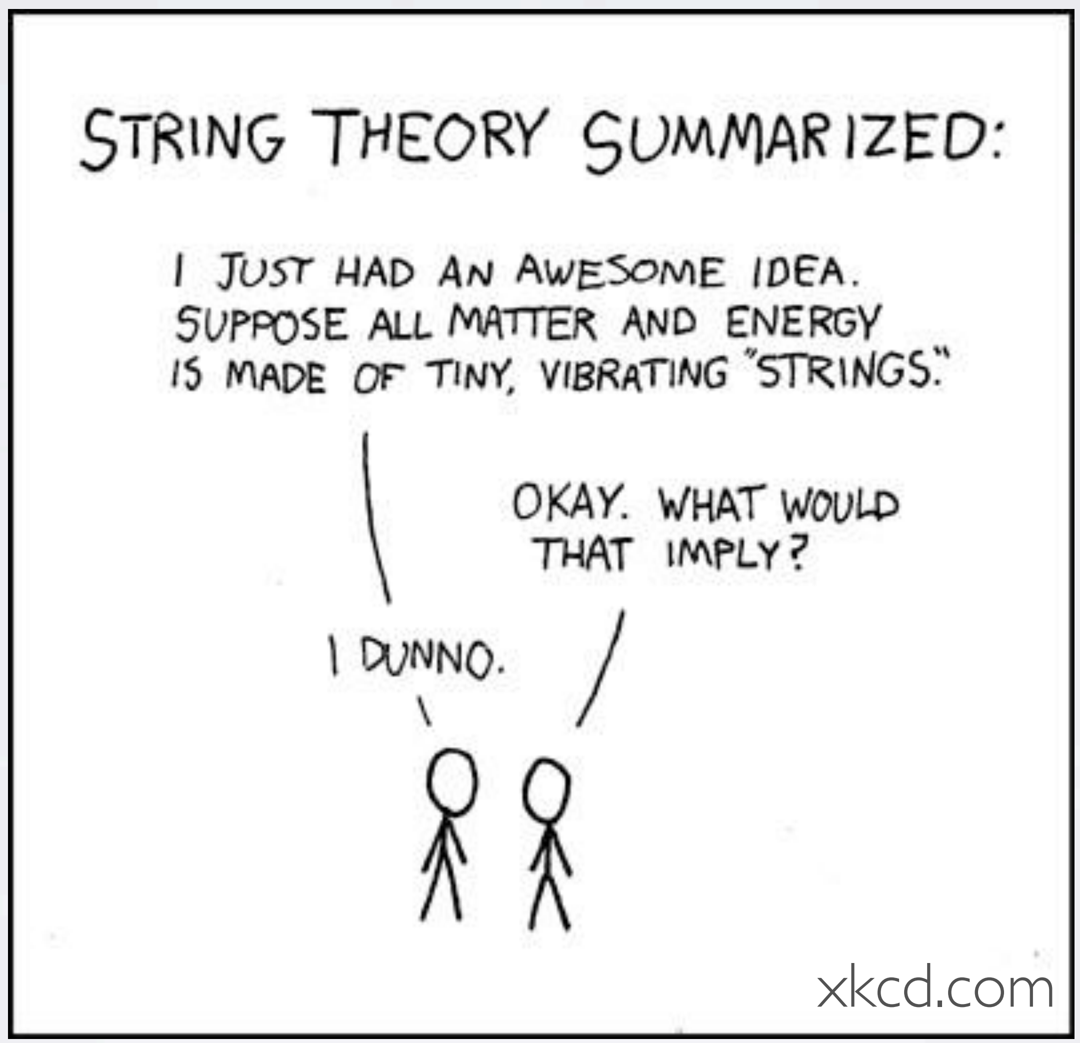
In practice, this is extremely challenging. There is only one candidate theory of quantum gravity which is well-developed enough to allow such computations – string theory – and even this theory has proven complicated.

The challenge of quantum gravity

Testing quantum gravities:

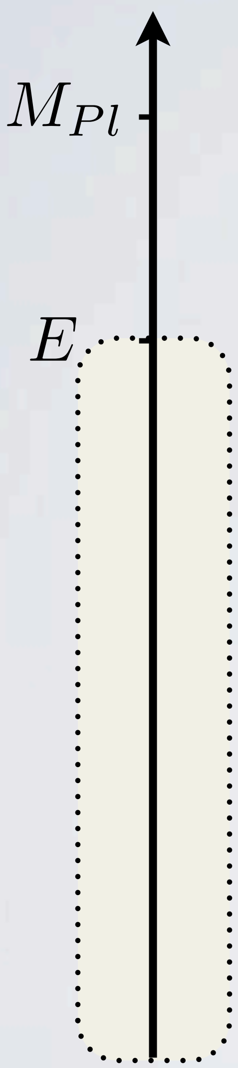
In popular culture:





The challenge of quantum gravity

Testing quantum gravities:



In reality:
Much of the initial excitement in string theory was spurred by a number of remarkable properties of the theory:

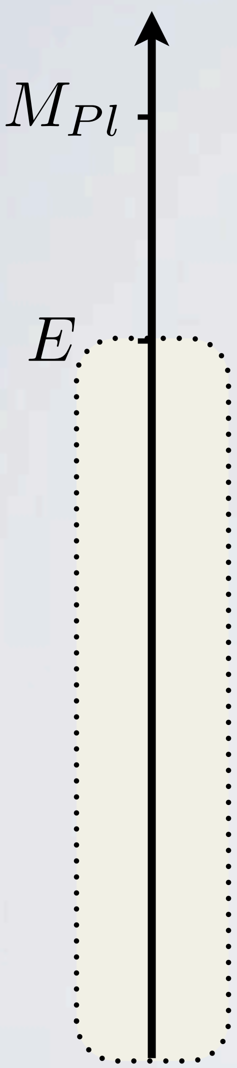
- the highly non-trivial consistency requirements the theory satisfied *(c.f. Green and Schwarz, 1984)*,
- it's apparent lack of tunable parameters,
- the automatic inclusion of gravity,
- the dualities connecting various formulations of the theory,
- the insight into the micro-physics of black holes.

However, this is not enough to go from point 1 to 2.

Issue: String theory has *many* solutions (vacua) with different coefficients c_n and completely different cosmologies.

The challenge of quantum gravity

Testing string theory models:



Modified scheme:

1. Propose a consistent theory at energies $\approx M_{Pl}$ (string theory).
2. Find a vacuum (model).
3. Compute the relevant EFT (c_n), and derive predictions.
4. Compare predictions with cosmological and particle physics data.

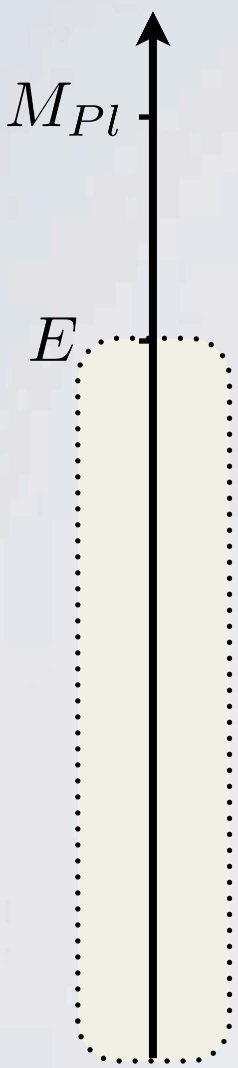
For any given model, deriving its predictions is still very hard, but explicit models can been constructed and ruled out this way.

But there are *many* models.* Can we learn something which goes beyond *"this one isn't us"* from this analysis?

* For type IIB flux vacua, the number of models has been estimated to $\sim 10^{500}$.

The challenge of quantum gravity

Testing string theory models:



A more efficient approach can be obtained by:

- Identify consistency conditions for the EFT's.
- Statistically study ensembles of vacua.
- Construct large classes of models with some common properties. Determine generic properties of the EFT's and the corresponding cosmologies.

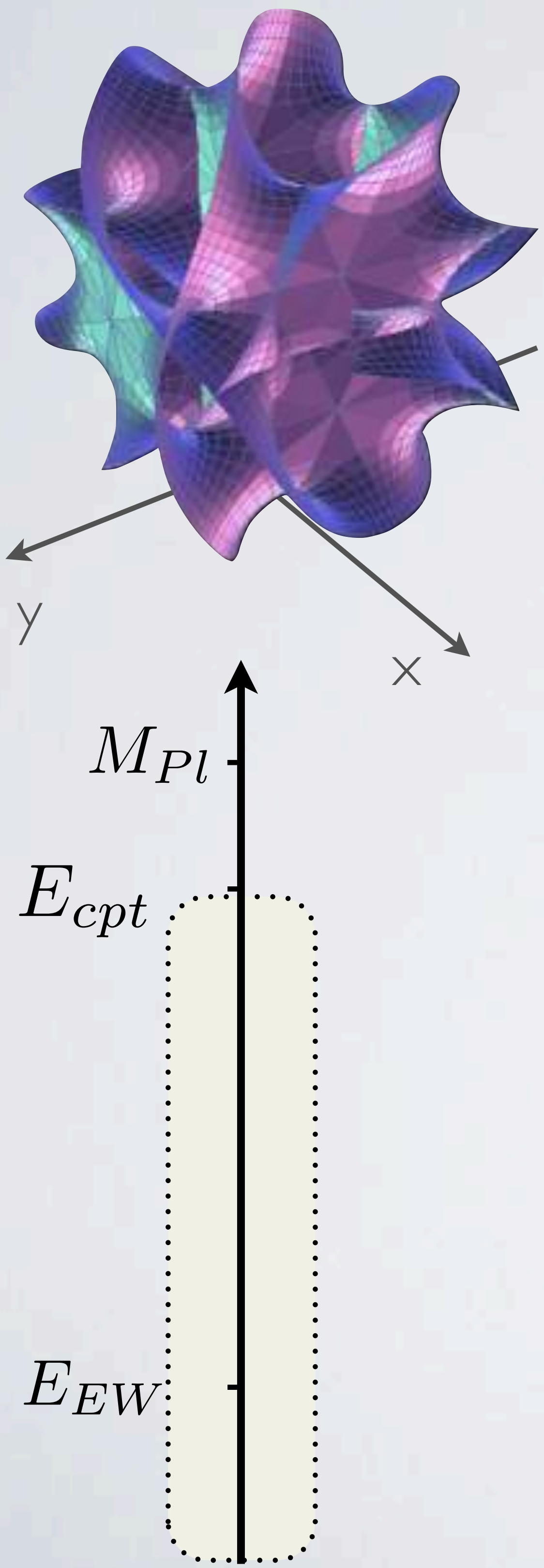
In this talk, I will discuss a new, generic prediction motivated by a broad class of string theory models, and how this prediction may give rise to observational signals.

Finally, I will mention how these signals may already have been observed and discuss our work in figuring out if this is the case.

Outline

1. How to construct string vacua.
2. Cosmology of stabilized string vacua.
3. Axionic dark radiation, the *Cosmic Axion Background* and the cluster soft X-ray excess.

How to construct string vacua



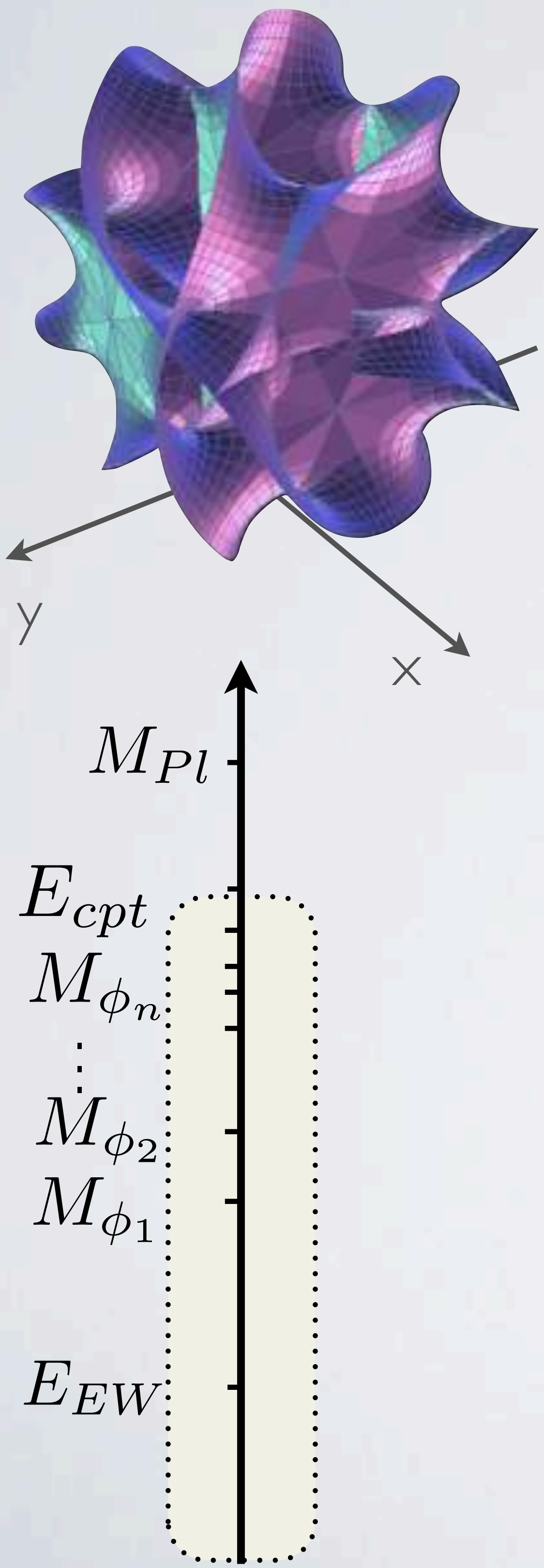
Famously, string theories require six additional space-time dimensions* for consistency. We don't observe these extra dimensions, which is consistent with them being compact and small with $E_{cpt} = 1/R_{cpt} \gg E_{EW}$.

By perturbing the metric tensor around a known compactification, $g_{mn} = g^0_{mn} + \delta g_{mn}$, one finds massless fields (particles), called *moduli.* These fields parametrize the size and shape of the compactification manifold.

Before the values of the moduli fields are fixed, the Wilson coefficients c_n of the 4-dimensional low-energy EFT cannot be determined. Consequently, few predictions can be made.

*More precisely, anomaly cancellation in the string world-sheet CFT requires additional field content with central charge $c=9$.

How to construct string vacua



Over the past decade, much progress have been made in understanding how potentials (and masses) for the moduli can be generated.*

In sum, while different compactifications give rise to different detailed predictions for the Wilson coefficients c_n, several properties commonly occur in large classes of solutions. Two of these properties which will be important in this talk are:

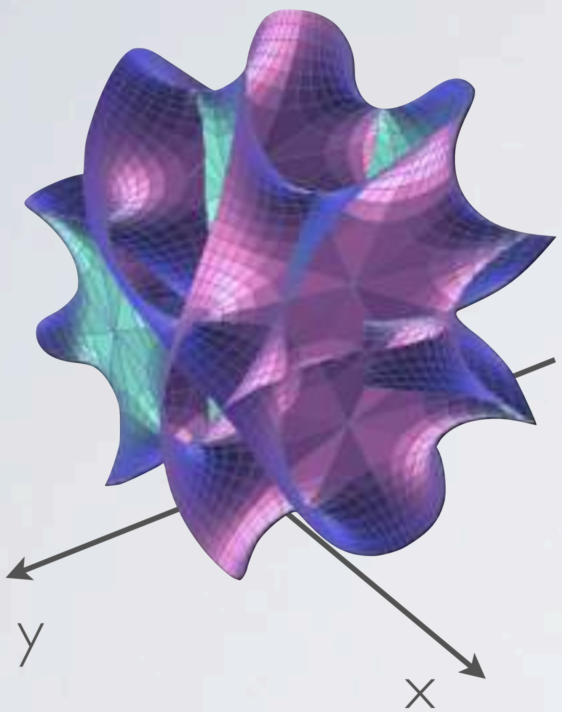
- The lightest modulus has a mass of $M_{\phi_1} \sim 10^6$ GeV.**
- Additional light fields called *axions* are typically present and can be much lighter than the 'stabilized' moduli.***

* Utilizing e.g. a generalized form of quantized electromagnetic flux.

** In several schemes with superpartner masses of ≈TeV.

*** In some cases, these axions may contribute to the dark matter.

How to construct string vacua



Axions were first suggested as a solution to the *strong CP-problem*,* and it was later realized that string compactifications gives rise to particles with very similar properties.**

Salient properties relevant for this talk:

- Axions are light (pseudo-)scalar particles with feeble interactions suppressed by some mass scale *M*.
- Axions may interact with gauge fields (e.g. photons) as,

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

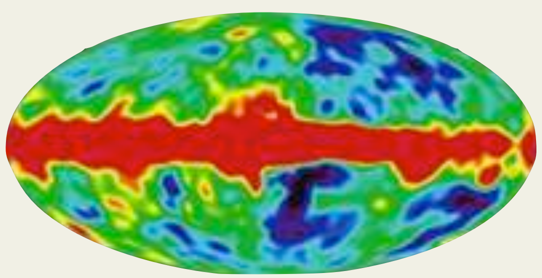
* The *strong CP-problem* refers to the surprising smallness of the neutron EDM.

** The number of axions in the low-energy theory depends on the details of moduli stabilization, and many can be unrelated to the strong force.

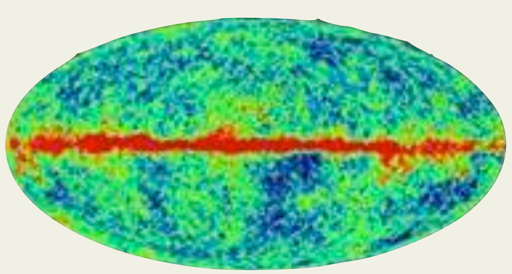
Cosmology of stabilized string vacua

The CMB

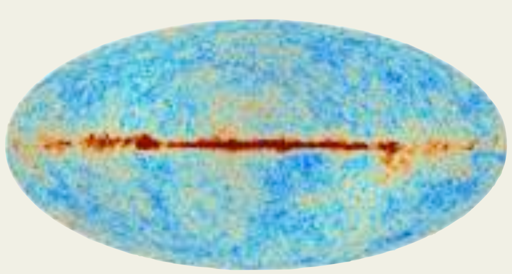
Penzlas and Wilson, 1965.



COBE, 1992.



WMAP 2003



Planck 2013

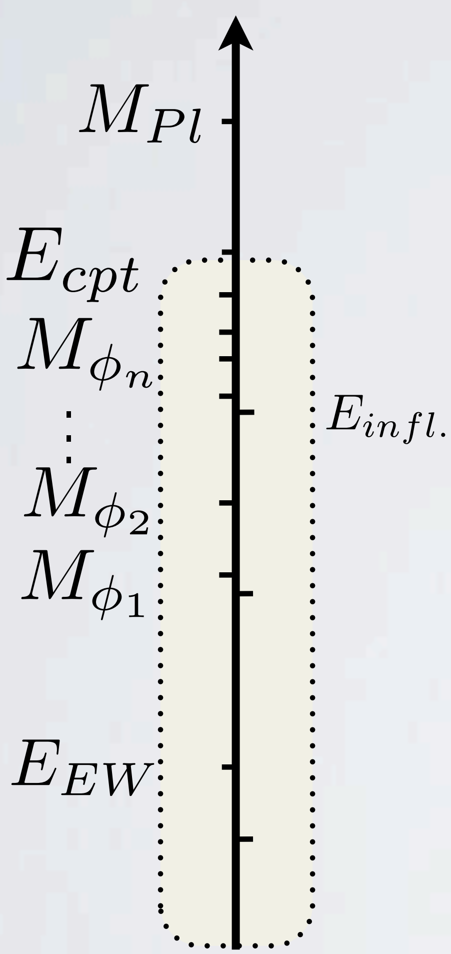
Observational cosmology has made remarkable progress over the past few decades. Studies of the Cosmic Microwave Background (CMB) have given evidence for a period of inflation – or something very similar – in the early universe.

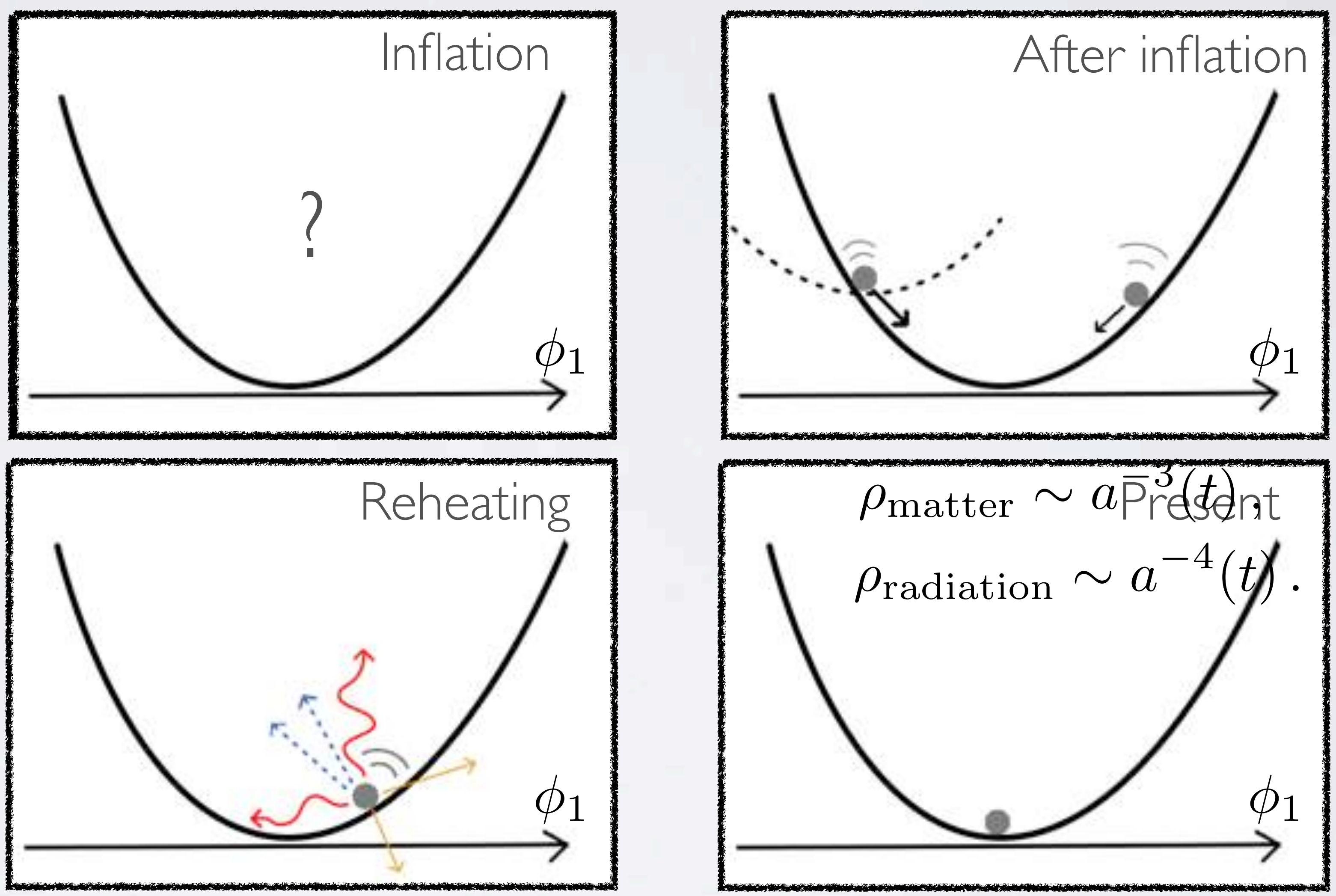
Inflation can be accommodated in stabilized string models, and studies of detailed string models of inflation have shown that *moduli generically become displaced* during inflation.

This fact has far-reaching consequences for cosmology.

Cosmology of stabilized string vacua

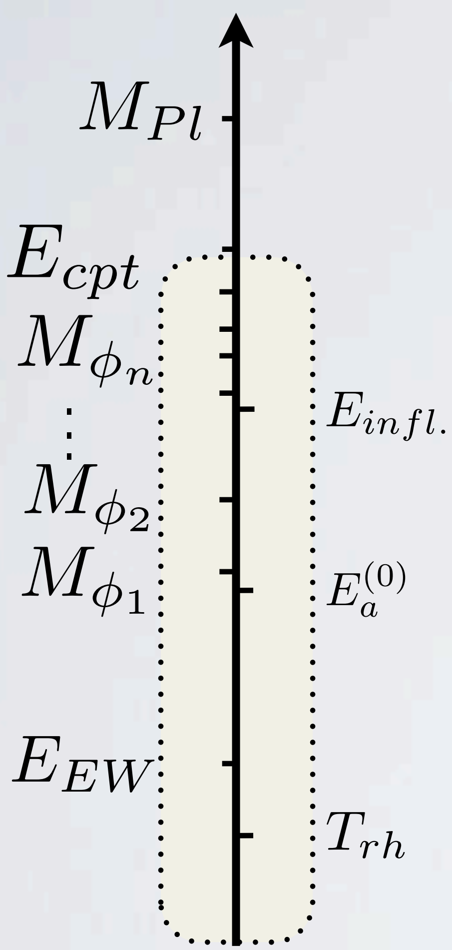
A brief review of a microsecond:





$$\tau_{\phi_i} \sim 8\pi \frac{M_{Pl}^2}{m_{\phi_i}^3} \sim 10^{-6}\ \mathrm{s}\ \left(\frac{10^6\ \mathrm{GeV}}{m_{\phi_i}}\right)^3$$

Cosmology of stabilized string vacua



At (the final stage of) reheating, the lightest modulus may decay into ordinary matter and radiation, $\phi_1 \to \gamma\gamma\,,\; HH\ldots$ as well as any additional light particles, e.g. axions,

$$\phi_1 \to aa\,.$$

The remainder of this talk will focus solely on the consequences of this decay channel.

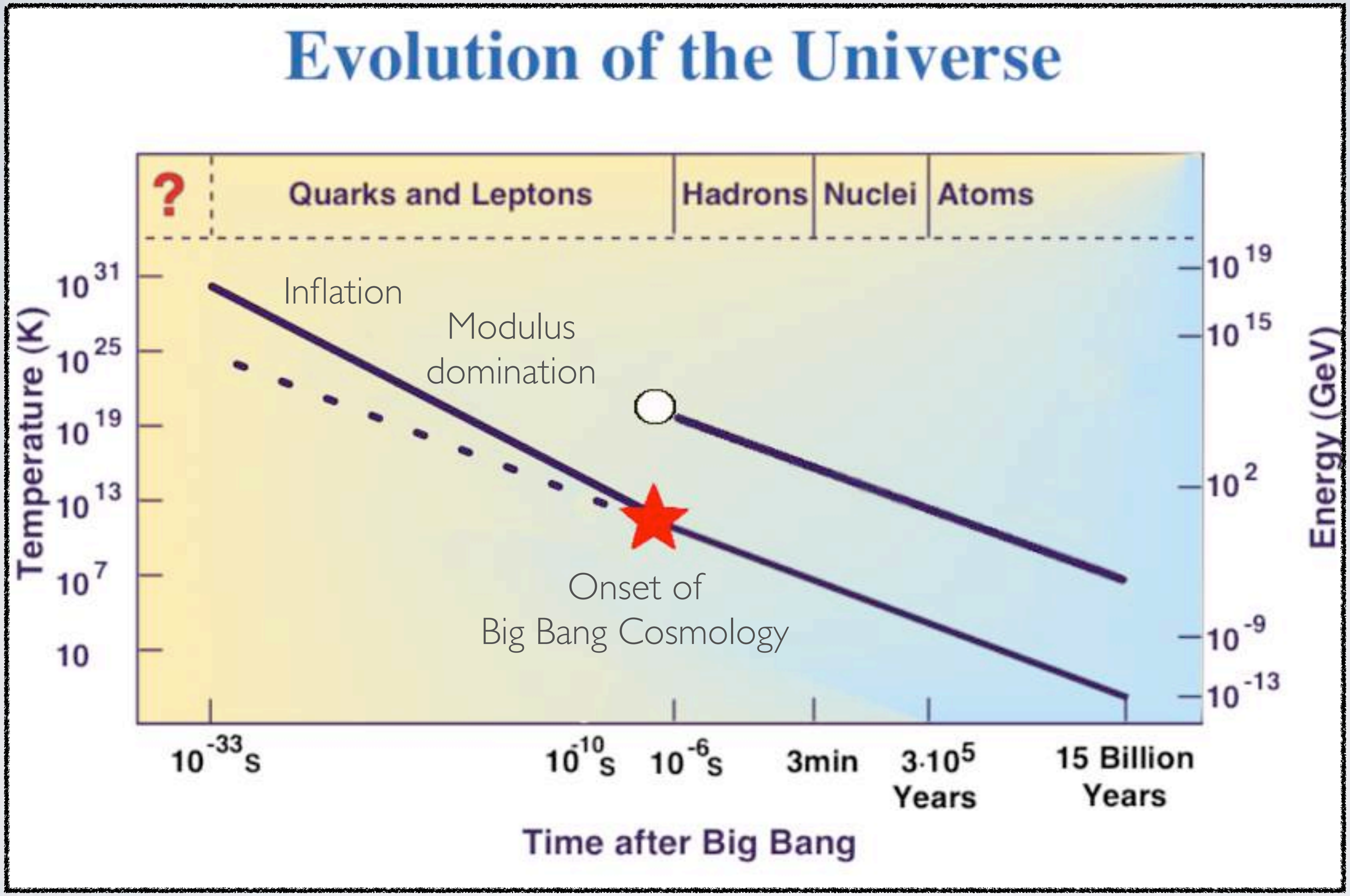
While ordinary particles thermalize at,

$$T_{rh} \sim \frac{m_{\phi_1}^{3/2}}{M_{Pl}^{1/2}} \sim 0.6\ \text{GeV}\left(\frac{m_{\phi_1}}{10^6\ \text{GeV}}\right)^{3/2}\,,$$

axions have an initial energy of,

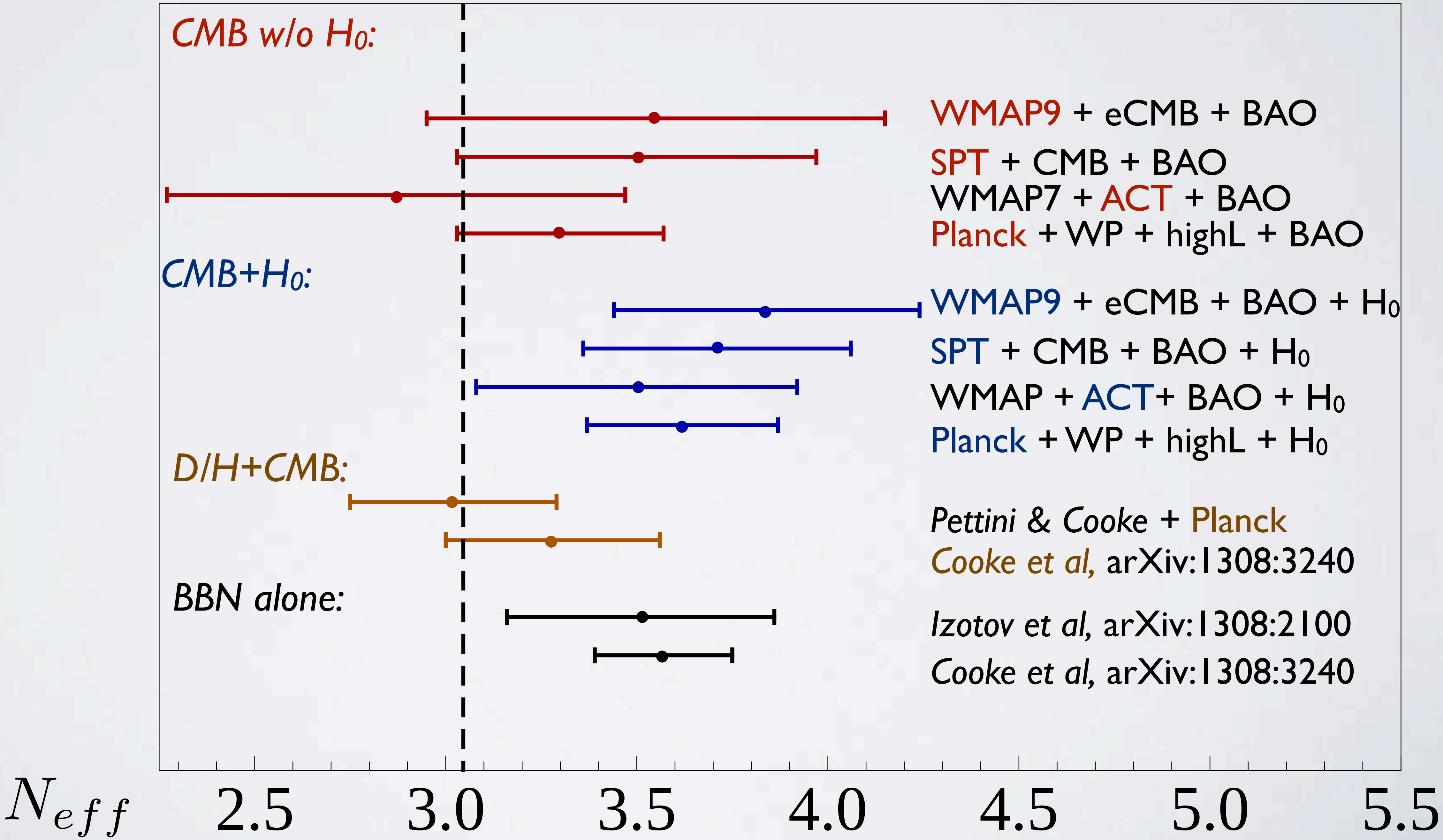
$$E_a^{(0)} = m_{\phi_1}/2 \gg T_{rh}\,.$$

Cosmology of stabilized string vacua



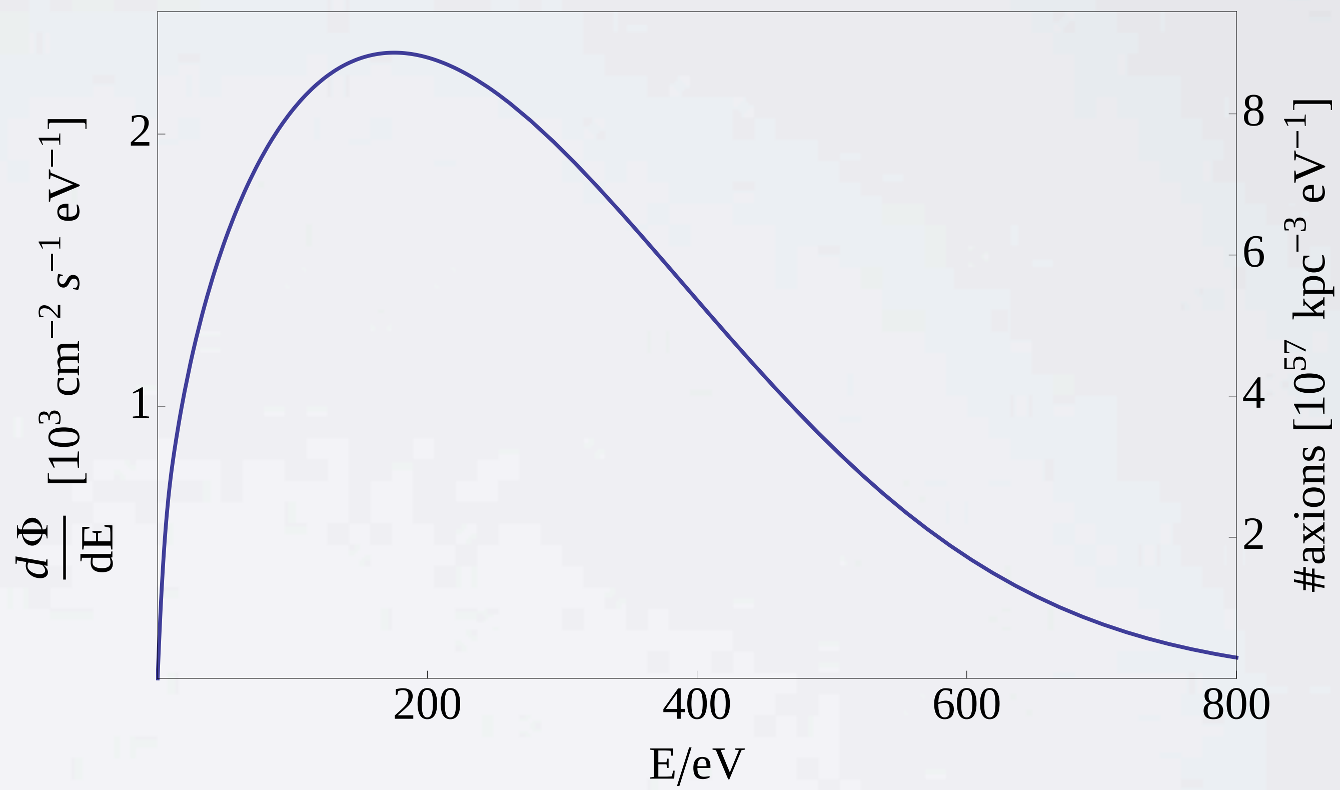
Axionic Dark Radiation

Relativistic axions produced this way would contribute to the *'dark radiation'* of the universe for which there are 1-2.5 σ observational hints (but no firm evidence).



The Cosmic Axion Background

This axionic dark radiation would still be present today, but with energies red-shifted to $E_a^{(\mathrm{today})} \sim 200\ \mathrm{eV}$, and a flux of $\sim 10^6\ \mathrm{s^{-1} cm^{-2}}$.

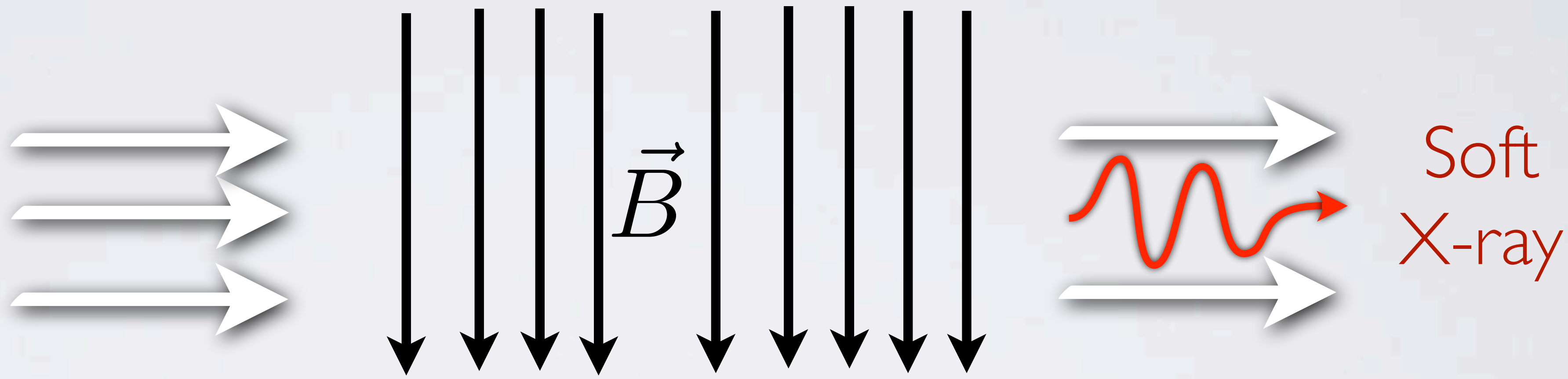


In analogy with the CMB, we call this a *Cosmic Axion Background (CAB)*.

The Cosmic Axion Background

Can a CAB be detected?

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



Computation of oscillation probability is essentially a Schrödinger equation:

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

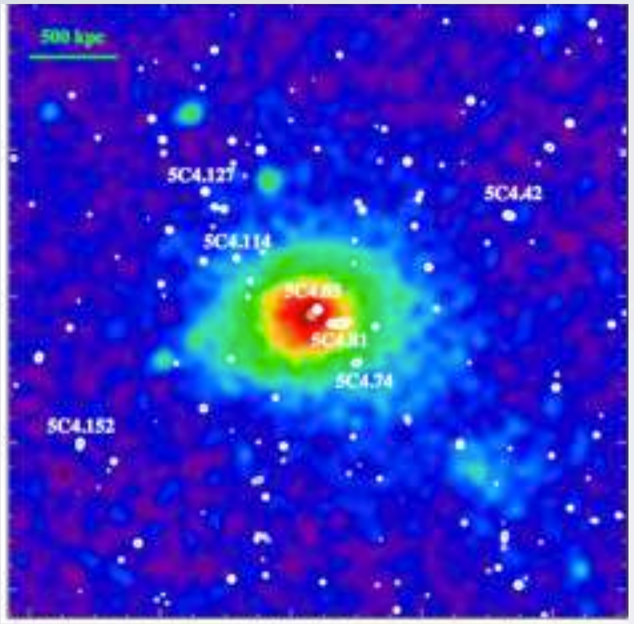
For a homogeneous magnetic domain of length L (in the small mixing approximation):

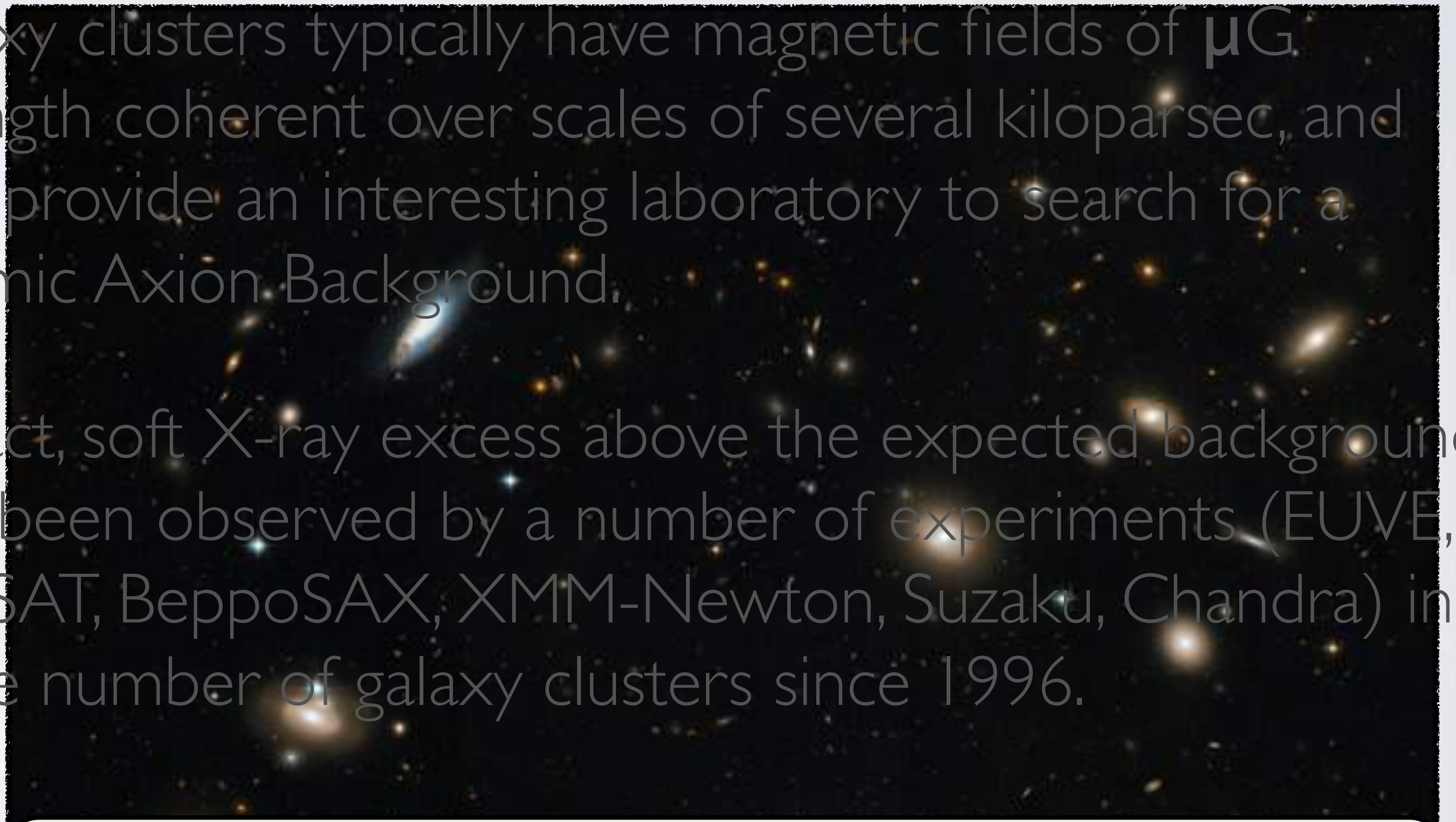
$$P(a \to \gamma) = \frac{1}{4} \left(\frac{BL}{M} \right)^2 .$$

The Cosmic Axion Background

Can a CAB be detected?

Look for strong magnetic fields coherent over large distances.





Galaxy clusters typically have magnetic fields of μG strength coherent over scales of several kiloparsec, and thus provide an interesting laboratory to search for a Cosmic Axion Background.

In fact, soft X-ray excess above the expected background has been observed by a number of experiments (EUVE, ROSAT, BeppoSAX, XMM-Newton, Suzaku, Chandra) in a large number of galaxy clusters since 1996.

Has signs of a CAB been detected but gone unnoticed for 18 years?

The CAB and the cluster soft X-ray excess

Using a stochastic model for the Coma cluster magnetic field consistent with Faraday rotation measurements,* the conversion probabilities can be summarized as:

* The magnetized intracluster medium induces different phase velocities for left- and right-handed photons, thus giving rise to a rotation of the plane of polarization. The rotation phase is proportional to

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

and is therefore sensitive to the cluster magnetic field.

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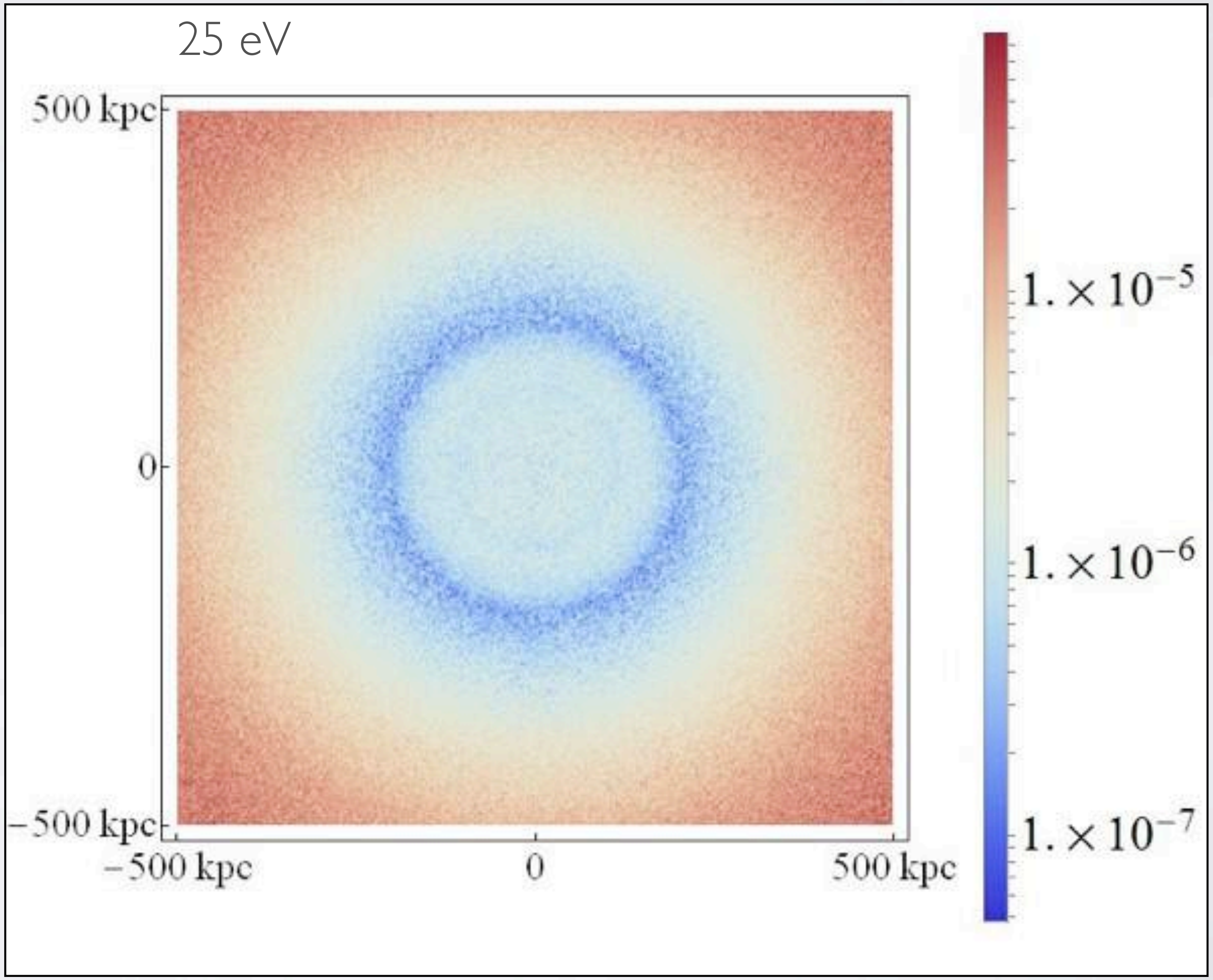

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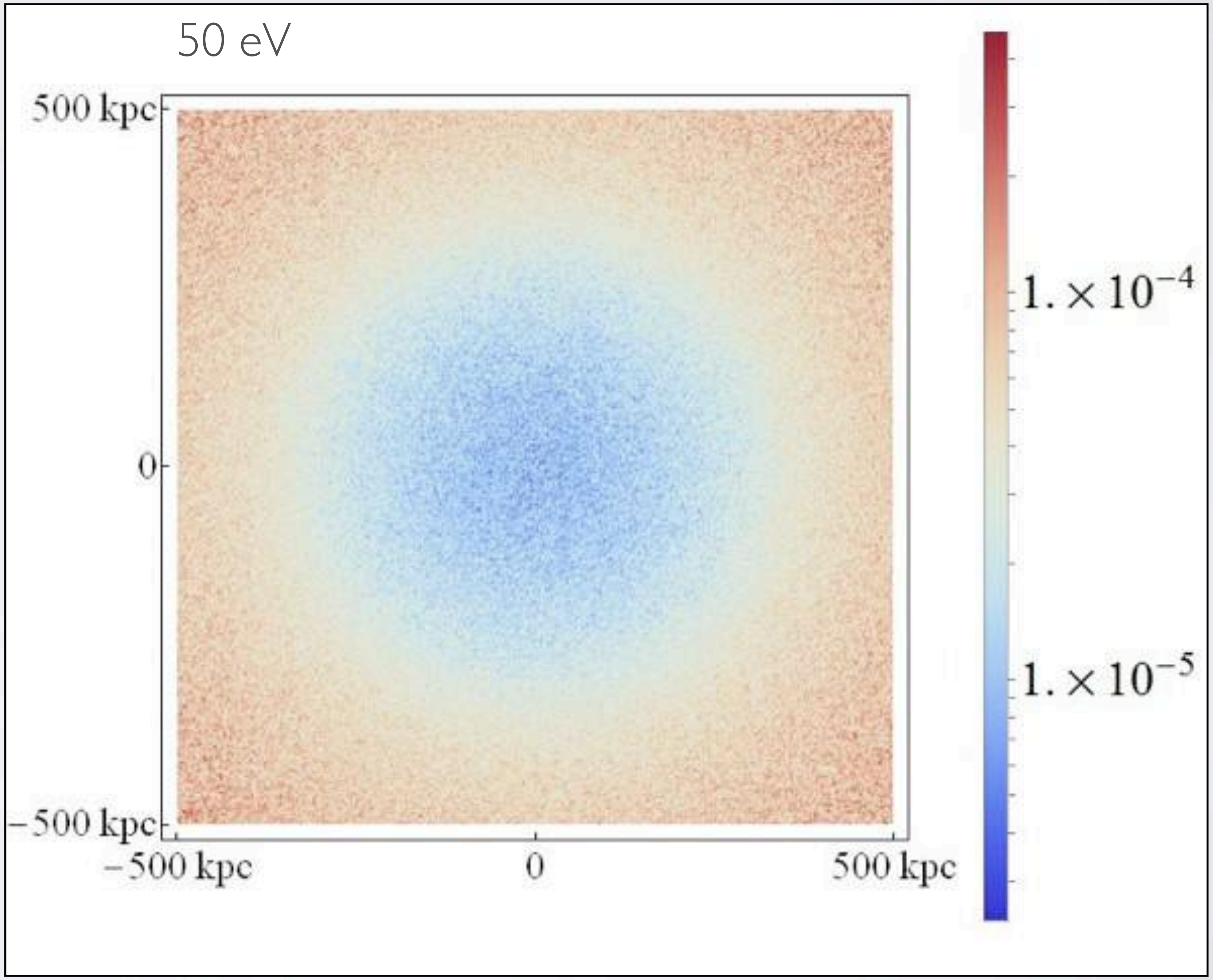

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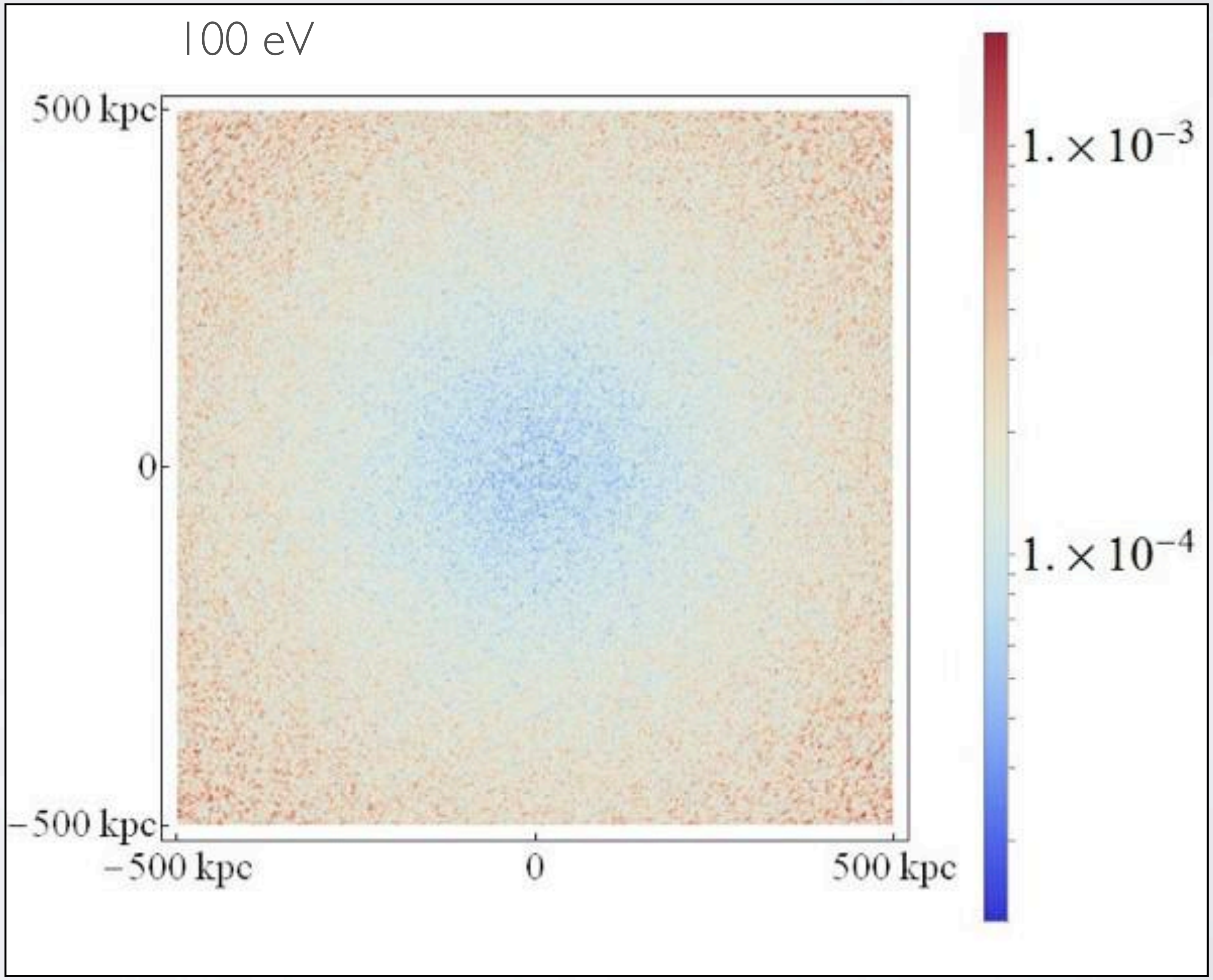

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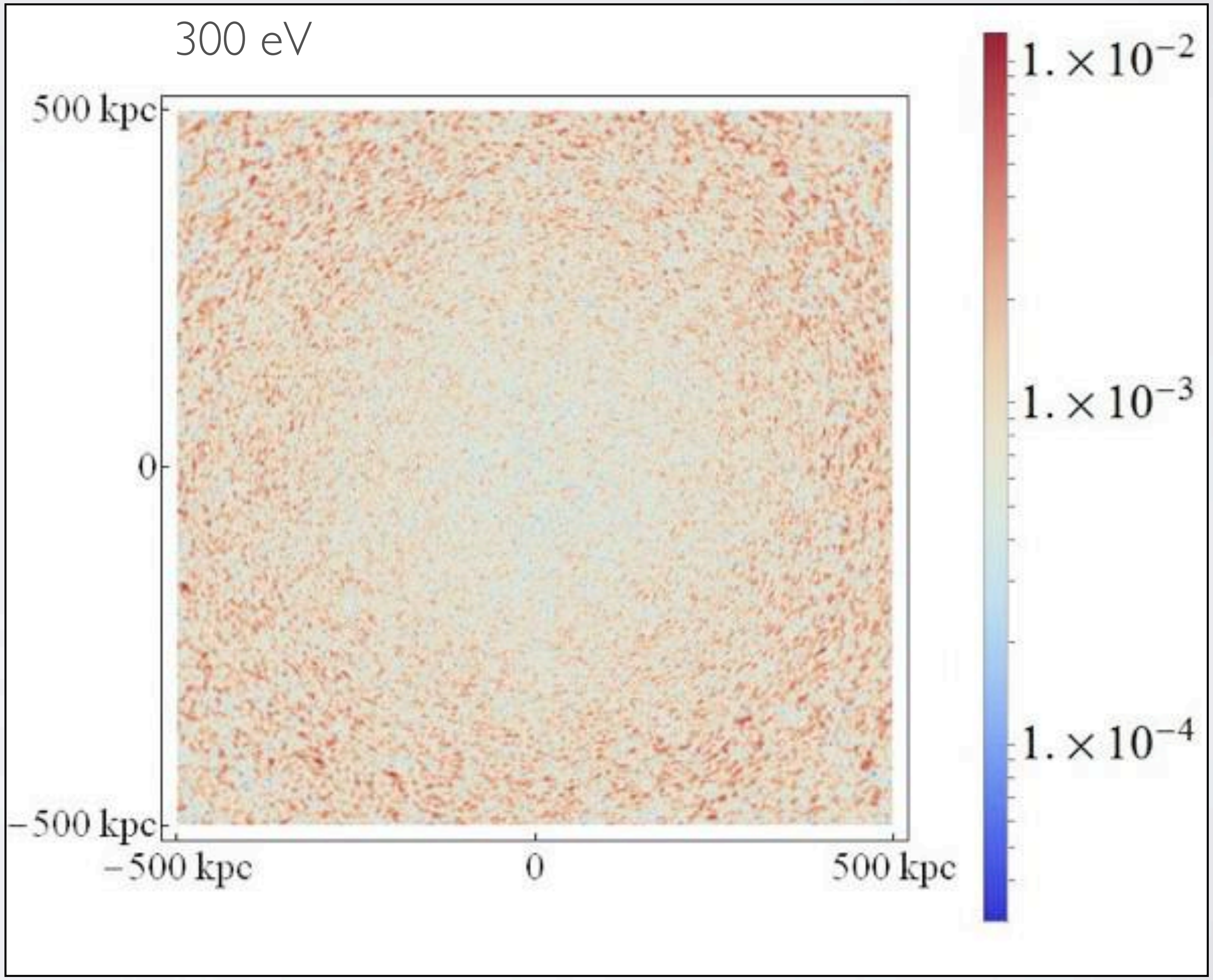

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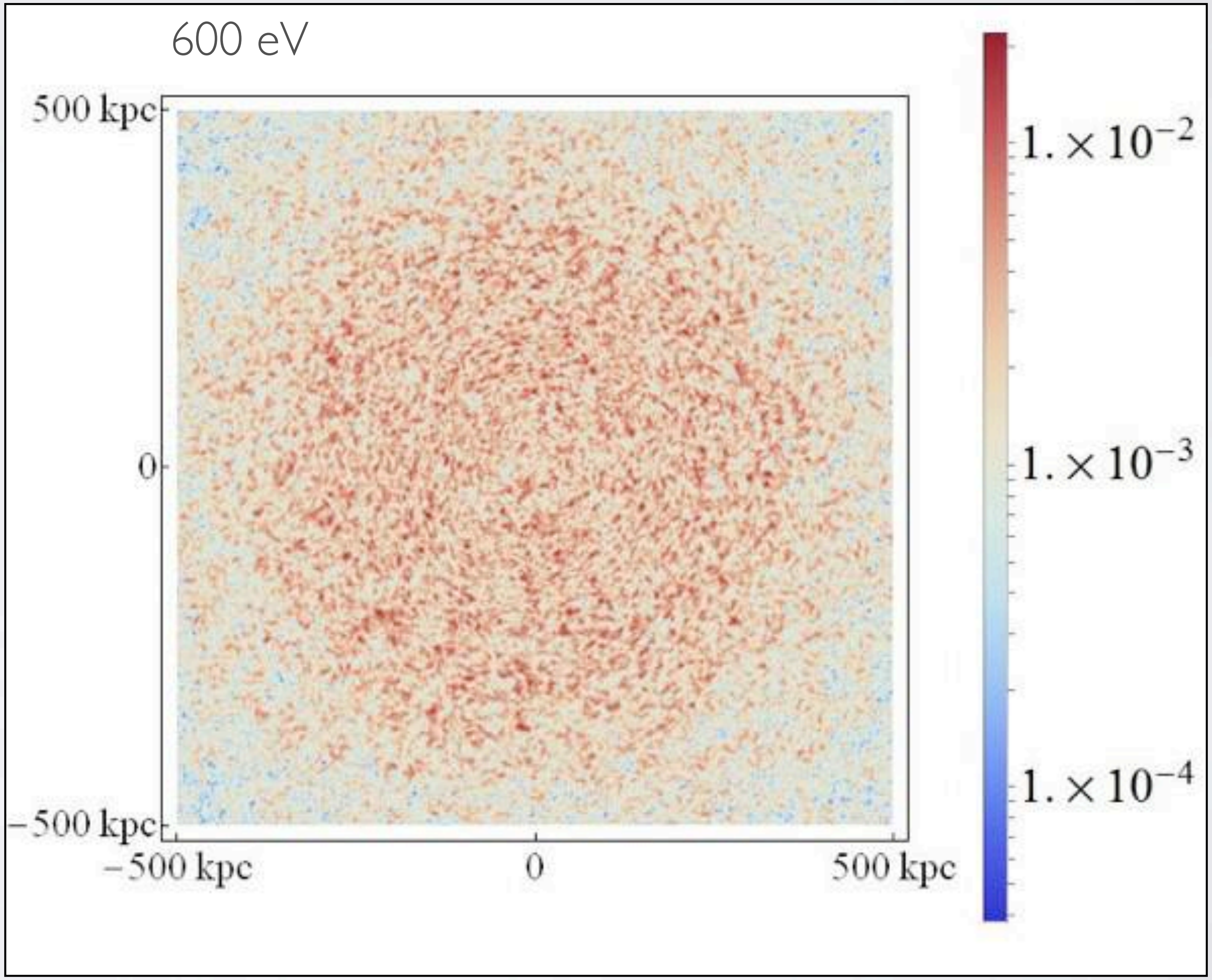

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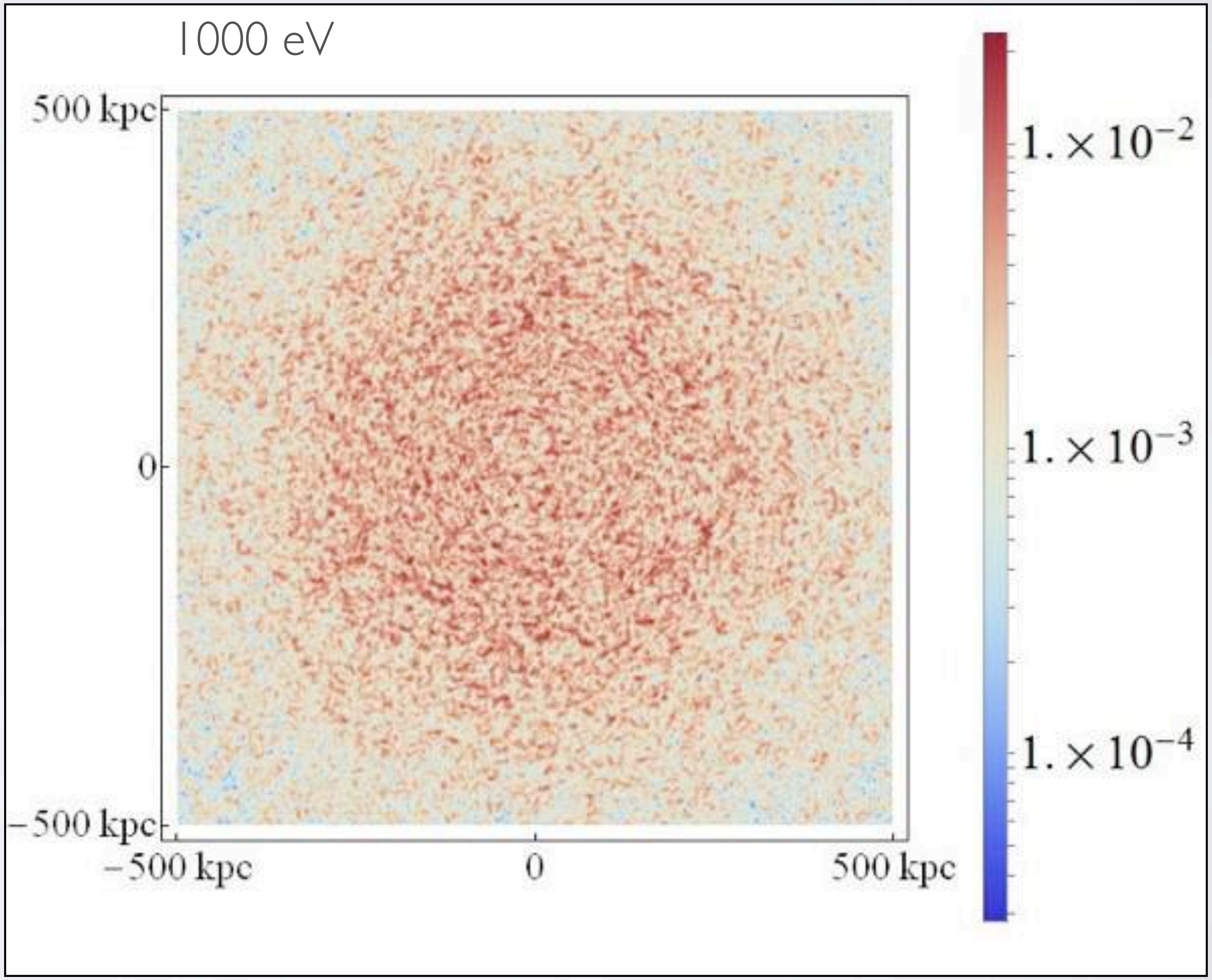

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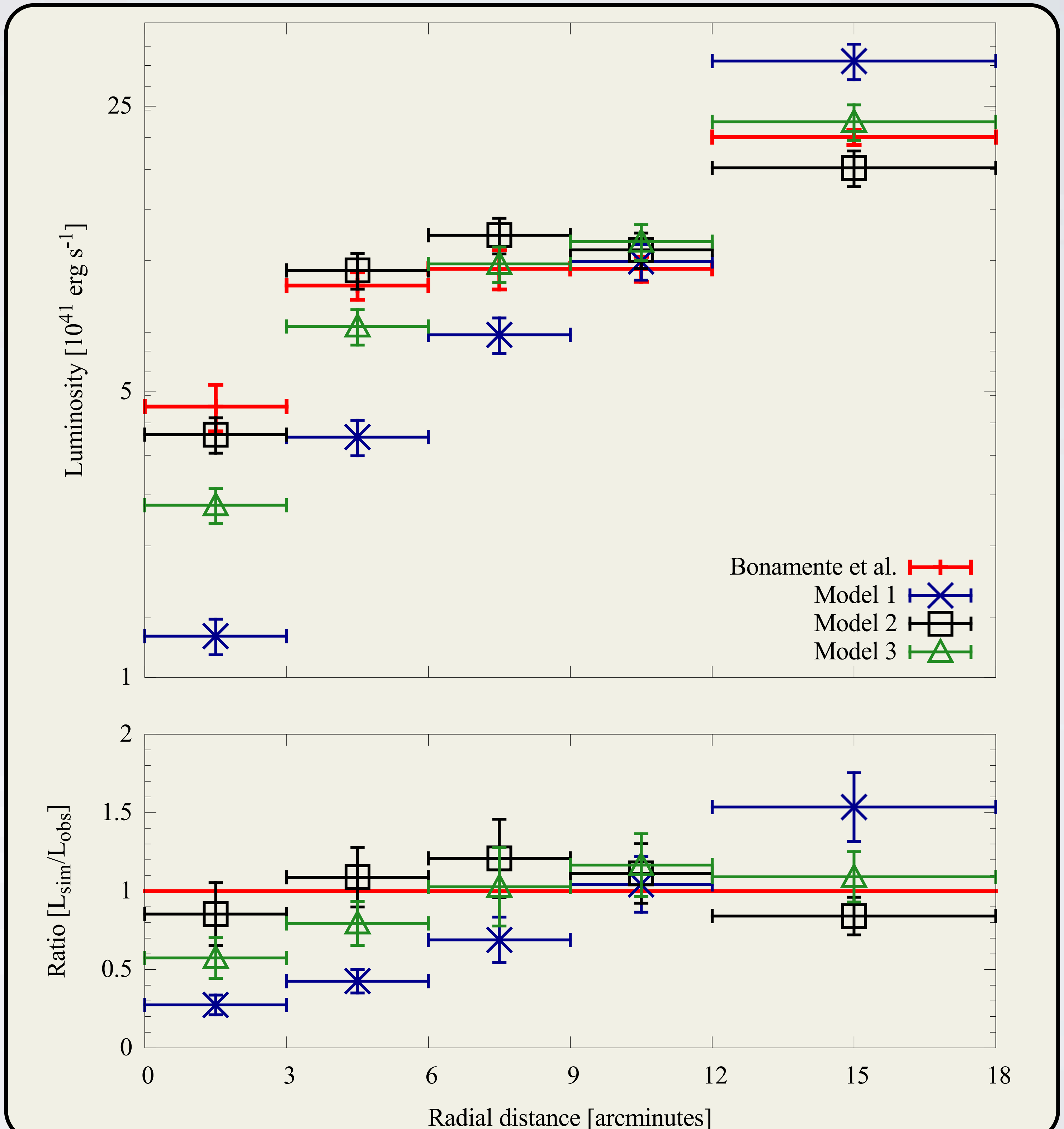
The CAB and the cluster soft X-ray excess

Comparison with observations of the soft excess give:



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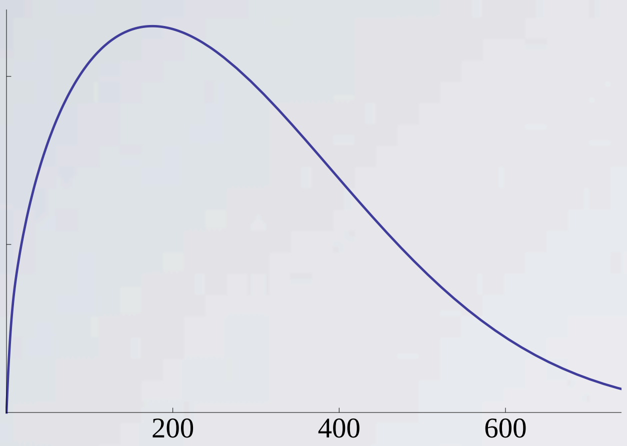

If a CAB is discovered, then what does that imply?

By measuring the CAB mean energy: $r = \frac{E_a^{(\text{today})}}{T_{CMB}} \approx \frac{E_a^{(0)}}{T_{rh}}$.

By establishing a non-thermal CAB spectrum:

$$T_{rh} \sim \frac{m_{\phi_1}^{3/2} M_{Pl}^{1/2}}{\Lambda} .$$

Successful BBN requires T_{rh}>4 *MeV*, implying the constraints,

$$m_{\phi_1} > 4r \text{ MeV} ,$$

$$\Lambda \sim r\sqrt{m_{\phi_1} M_{Pl}} > 2r^{3/2}\sqrt{1\text{MeV } M_{Pl}} .$$

For $r \approx 10^6$, this implies:

$$m_{\phi_1} > \left(\frac{r}{10^6}\right) 4 \text{ TeV} ,$$

$$\Lambda \gtrsim \left(\frac{r}{10^6}\right)^{3/2} \cdot 10^{17} \text{ GeV} .$$

Conclusions

In sum,

- It's hard to derive *general* predictions valid for all string vacua, but falsifiable predictions can be made from *large classes* of vacua.
- Axionic dark radiation is an example of this. Precise measurements of the radiation content of the universe provide direct constraints on large classes of string models.
- More model dependently, axionic dark radiation can be detected from axion-photon conversion in magnetic fields. The cluster soft X-ray excess may be the first signal of a string theory Cosmic Axion Background.
- The detection of a CAB would strongly suggest the existence of moduli, one of the few generic string theory predictions.

Conclusions

Thanks for your attention!

Extra slides

Proposed astrophysical explanations of the cluster soft X-ray excess

Thermal model:
Postulates the existence of an additional Bremsstrahlung emitting warm gas with ($T \sim 200$ eV).
Problems: But such a gas would cool too rapidly, and furthermore give rise to unobserved emission lines.

Non-thermal model:
Inverse Compton Scattering of CMB photons off non-thermal gas [c.f. Hwang 1997, Bowyer et al, 2004, ...].

Problems: Most such models are now ruled out based on overproduction of radio waves from synchrotron emission. Independently, Fermi has not observed galaxy clusters, yet most these models predict correlated gamma-ray emission [Atoyan, Voelk, 1999].

The QCD-axion

The QCD vacuum posses a non-trivial structure which allows for CP-violation through a combination of terms like,

$$\theta \int d^4x F_{\mu\nu} \tilde{F}^{\mu\nu}$$

and the phases of the quark mass matrix, as parametrized by $\bar{\theta} = \theta + \mathrm{Arg}\,(\det M)$. Bound on CP-violation from observed neutron EDM requires $\bar{\theta} < 10^{-9}$.

The Peccei-Quinn solution of the strong CP-problem proposes an additional chiral global *U(1)* symmetry, which is spontaneously broken. The QCD-axion is the Nambu-Goldstone boson of this broken symmetry, which can be viewed as taking $\bar{\theta}$ to be a dynamical field with a potential induced by non-perturbative effects. The minimisation of this potential gives $\bar{\theta} = 0$.

The cosmological constant and the string theory landscape