Alternatives to the Dark Matter Paradigm

David F. Mota

INSTITUTE FOR THEORETICAL PHYSICS,
UNIVERSITY OF HEIDELBERG

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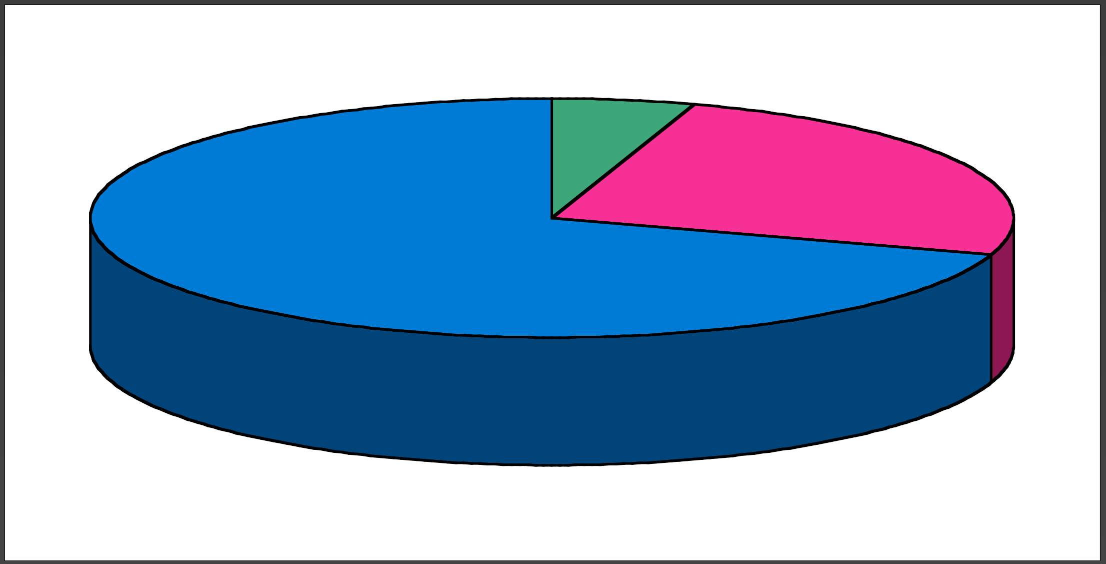
The Standard Cosmology:
Basic Ingredients



- 5% Ordinary Matter
- 25% Dark Matter
- 70% Dark Energy
- Gravity described by Einstein’s General Relativity

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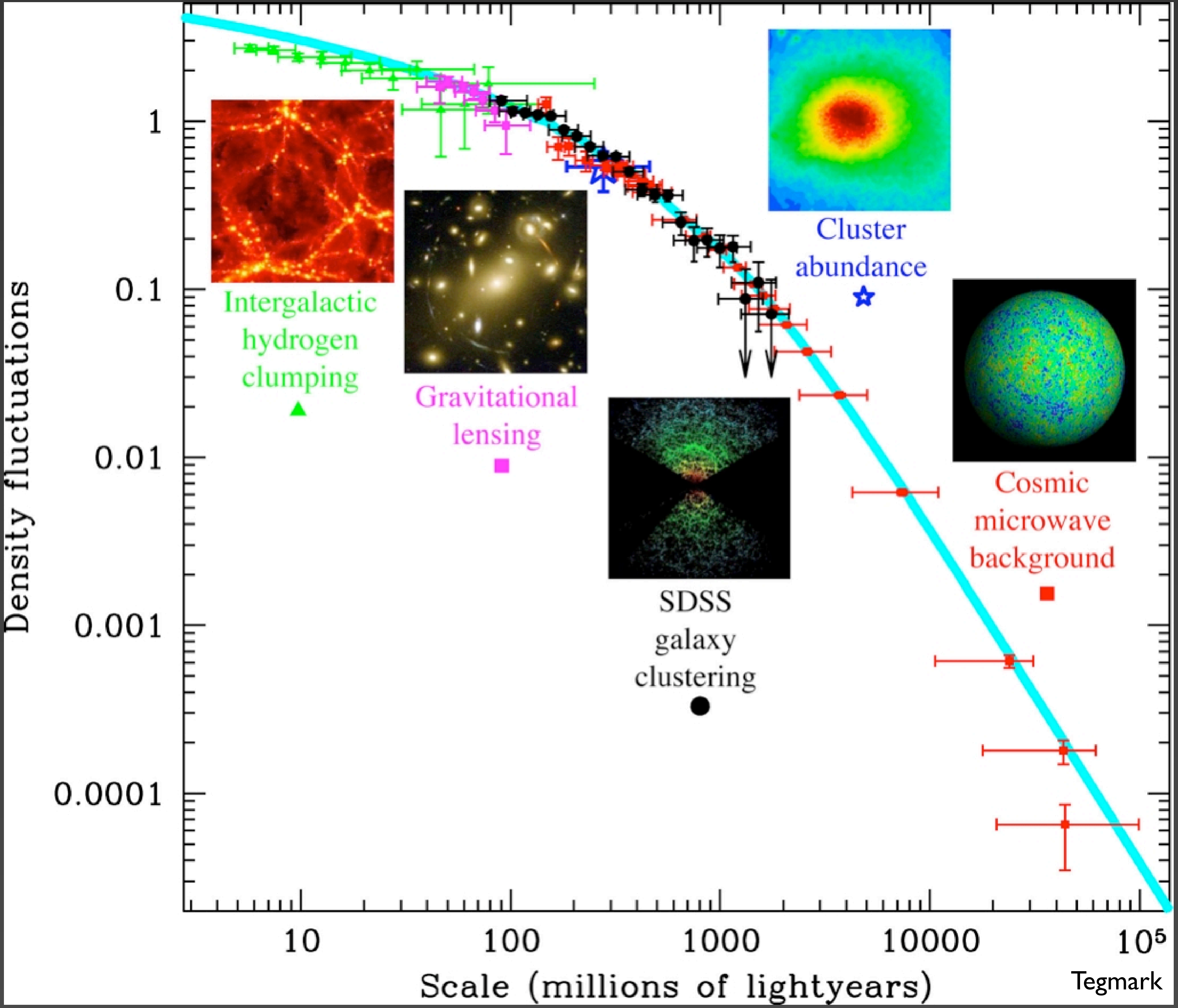

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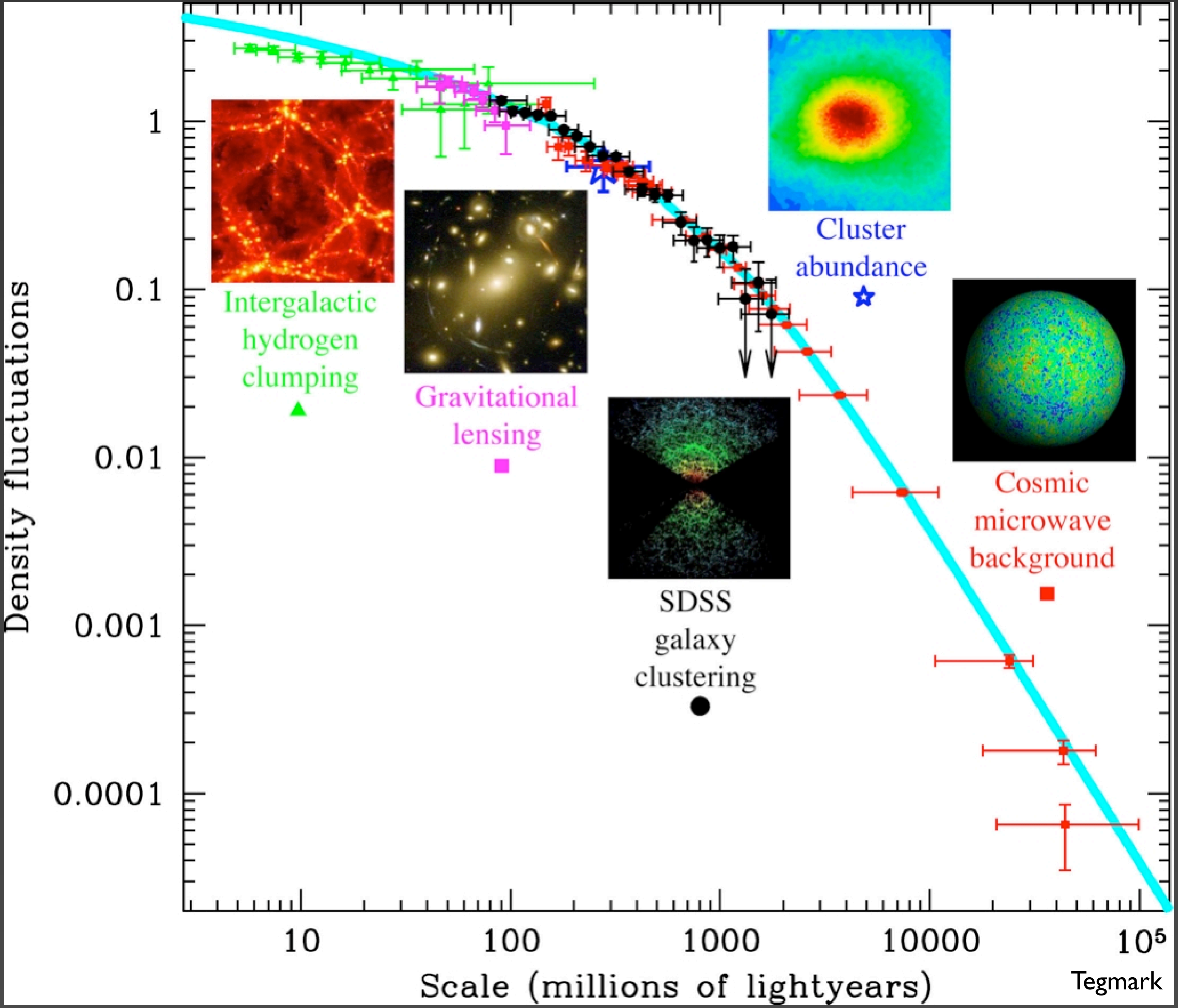

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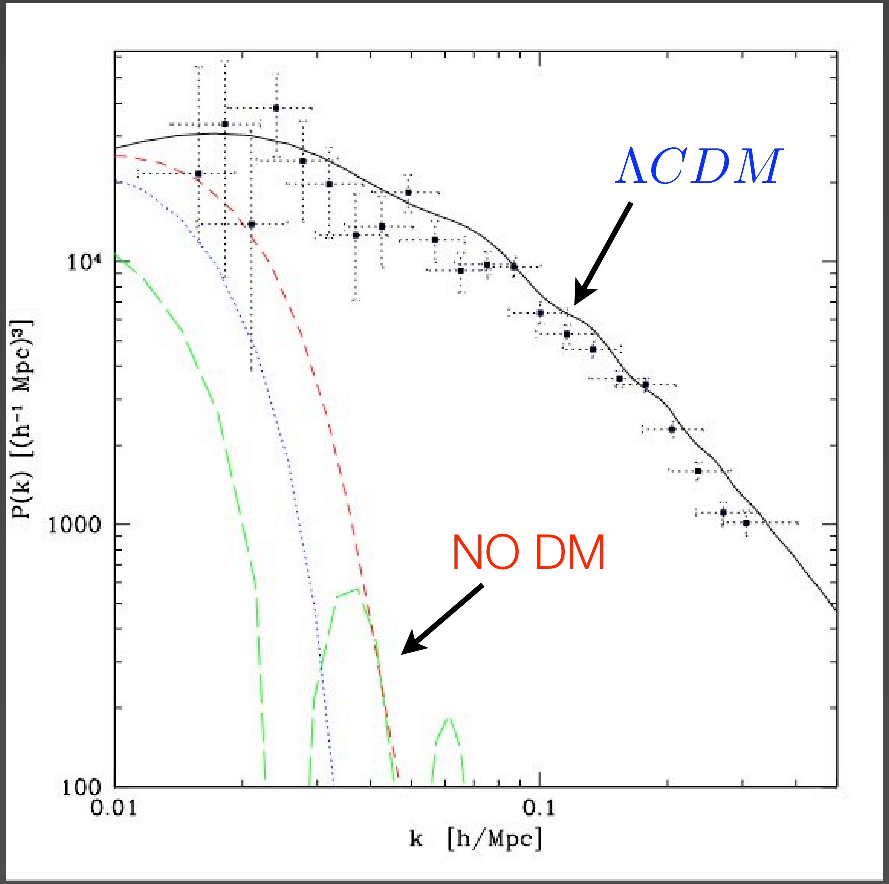

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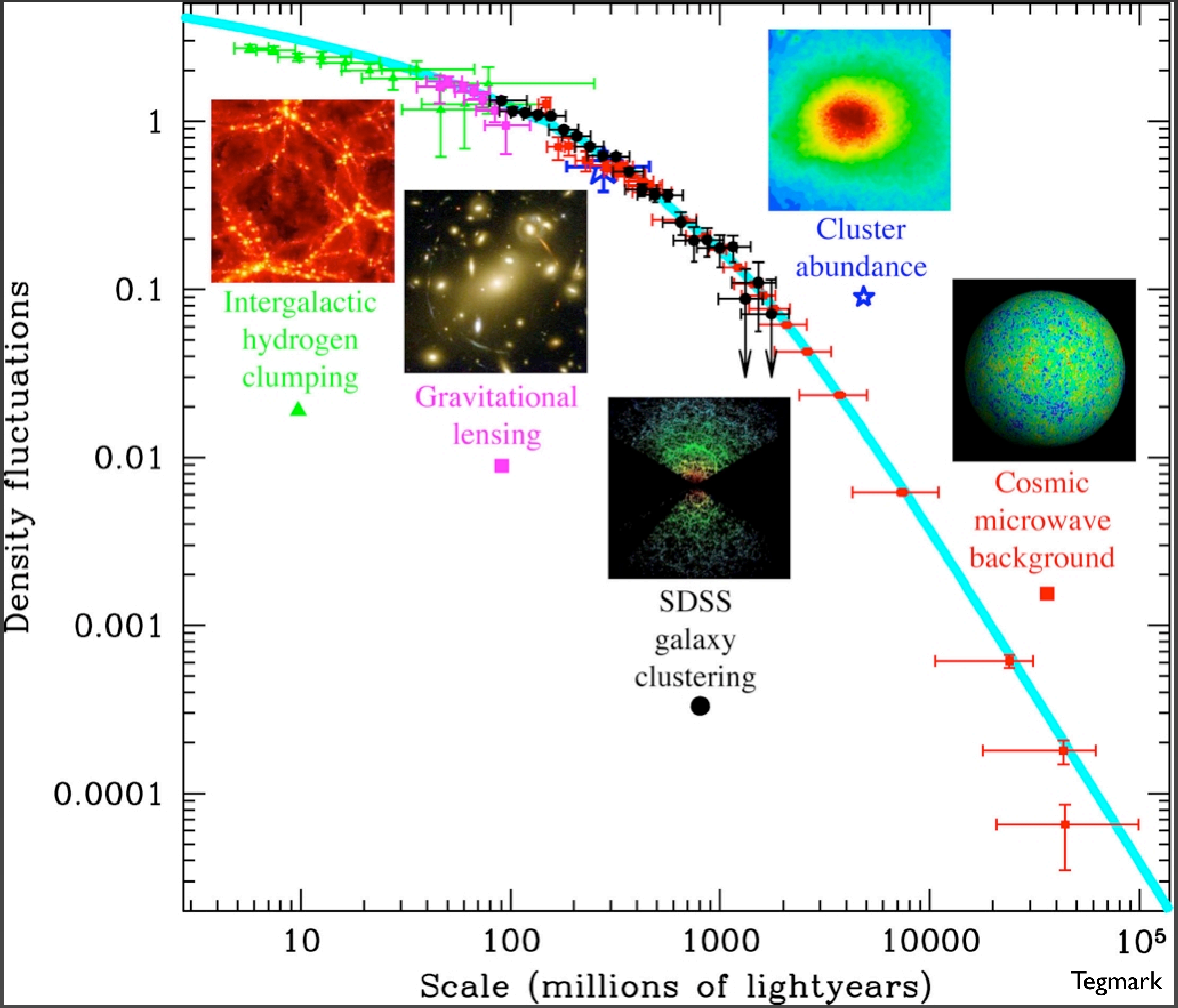

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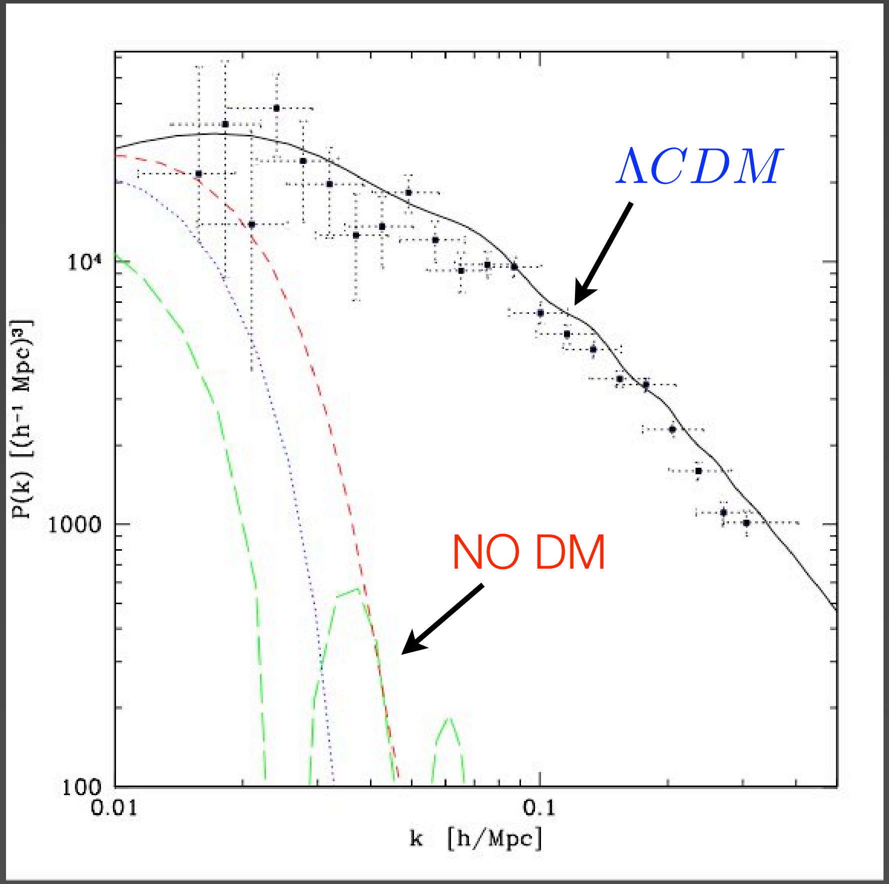

The need of dark matter is ***overwhelming!***

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    - *What if the mass is fine but not the gravity law?*

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- **Moreover dark matter has its own problems!**

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- Milgrom(1984) noticed Dark Mater is only needed to explain galaxy rotation curves once Newtonian accelerations due to gravity are very small

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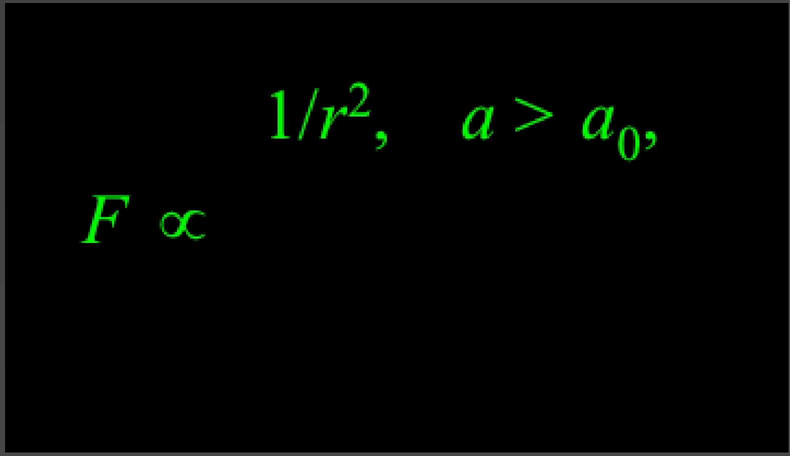

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Does MOND works?

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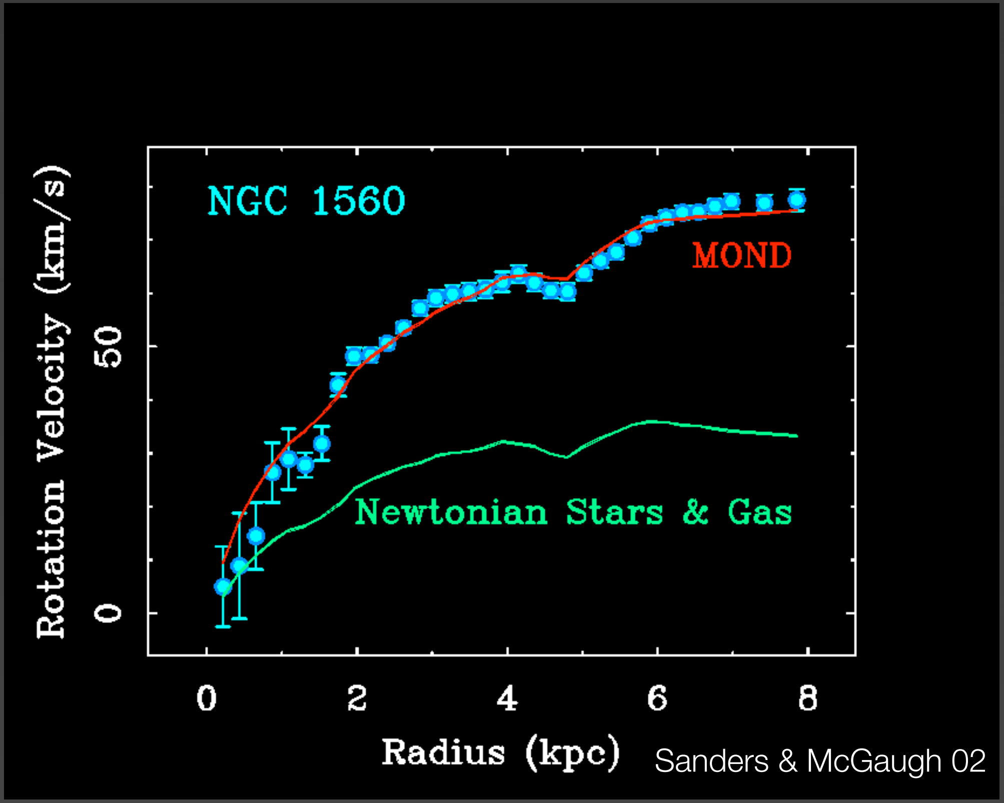
- Fits to rotation curves are generally very good
- Mass-Luminosity (Tully-Fisher) relation is automatic, unlike CDM
- No problem with cusps
- Even works well for low surface brightness galaxies (purportedly with lots of CDM)



Sanders & McGaugh 02

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  - *Gravitational waves:* Binary Pulsar
  - *Expansion history:* Friedmann equation, BBN
  - *Cosmological Structure:* CMB, LSS
  - *Gravitational lensing:* Cluster mass consistency

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Einstein Gravity: $\tilde{g}_{\mu\nu} = g_{\mu\nu}$

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Conformal transformations preserve angles

(Does not work: Not enough gravitational lensing!)

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Both gravitational lensing and galaxy observations are well explained!

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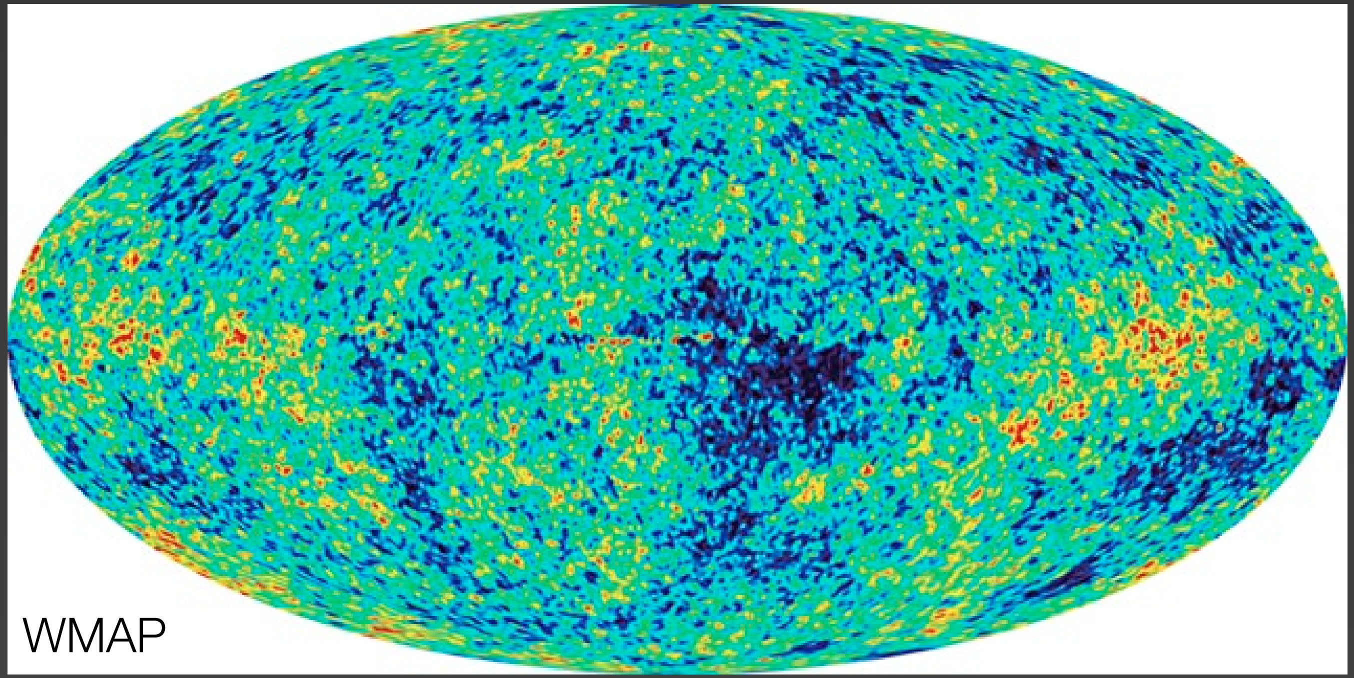
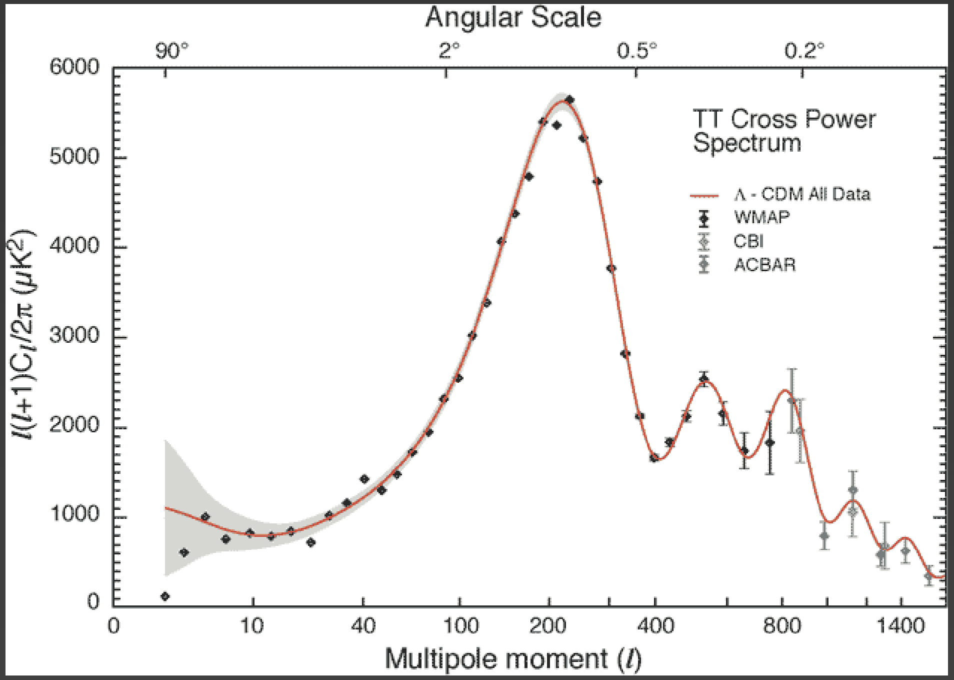
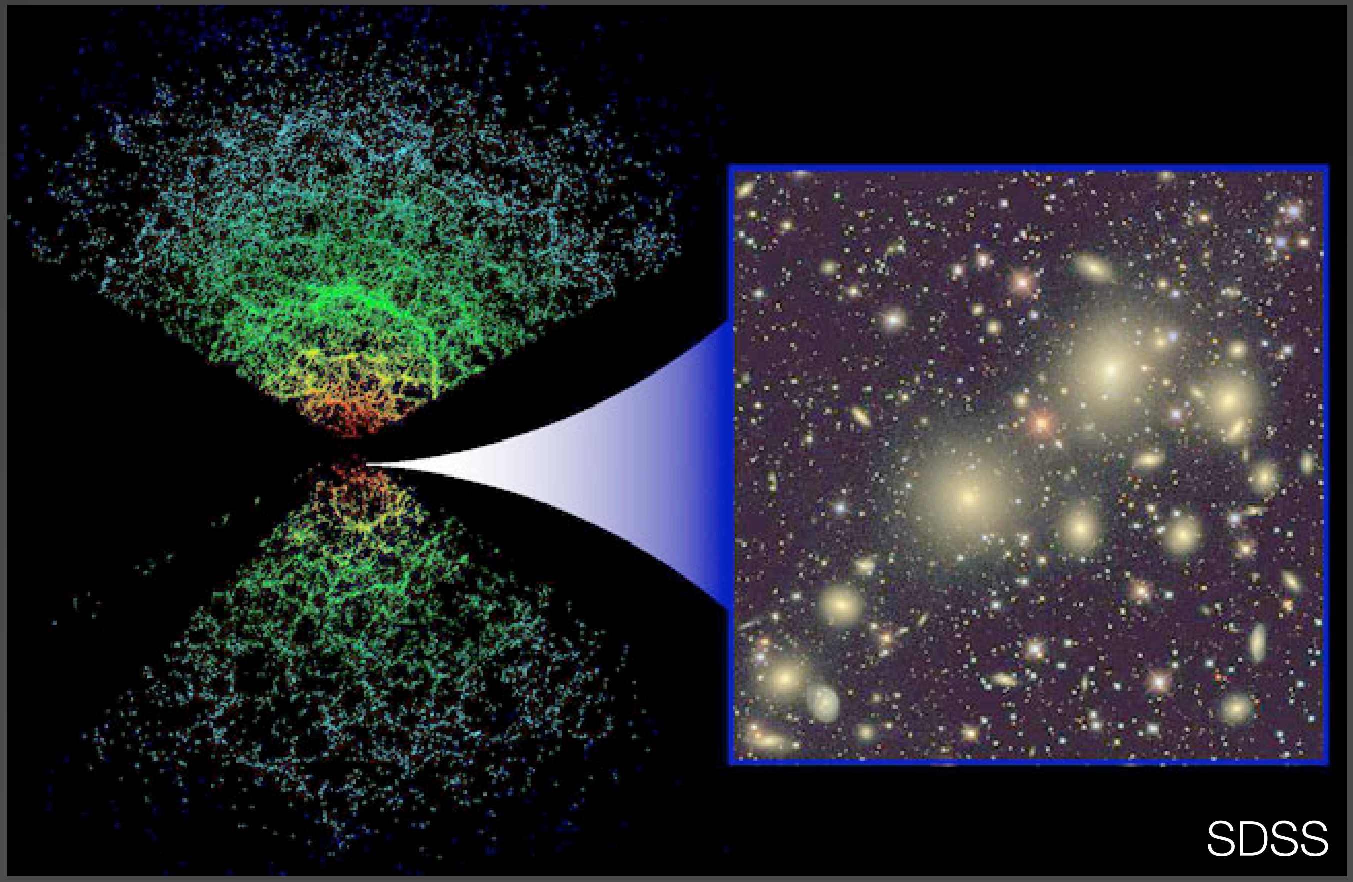
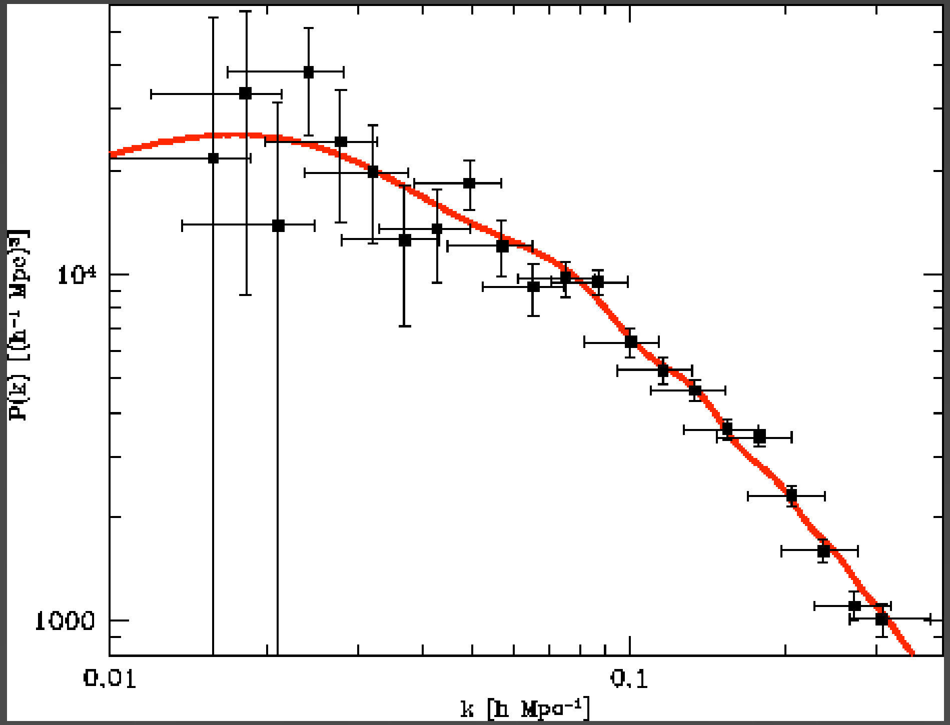
Cosmology

Could TeVeS explain present days cosmological observations?!









TeVeS Background Evolution

- Friedmann equation is basically unaltered

$$H^2 = 8\pi G(\rho_\phi + \rho_b)/3$$

  - save for a small time dependence for $G = G_0 e^{-2\phi}$
  - The vector field does not contribute to the background expansion
- ϕ presents tracking behaviour. Since it must be small during BBN, it will be nowadays
- So, expansion basically 'normal'!

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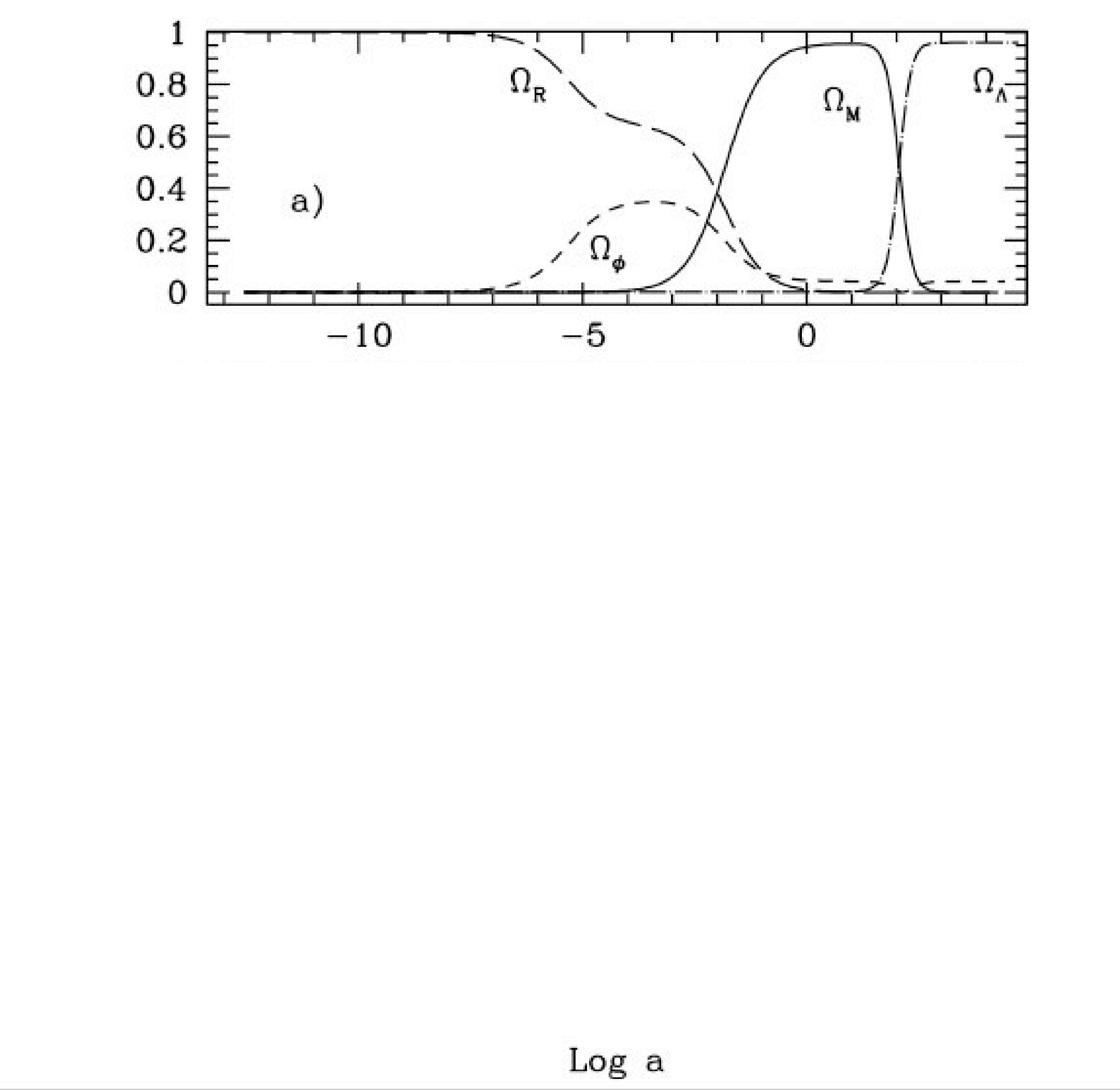
$$c_2 \neq 0$$

Bourliot,Ferreira,Mota&Skordis 06



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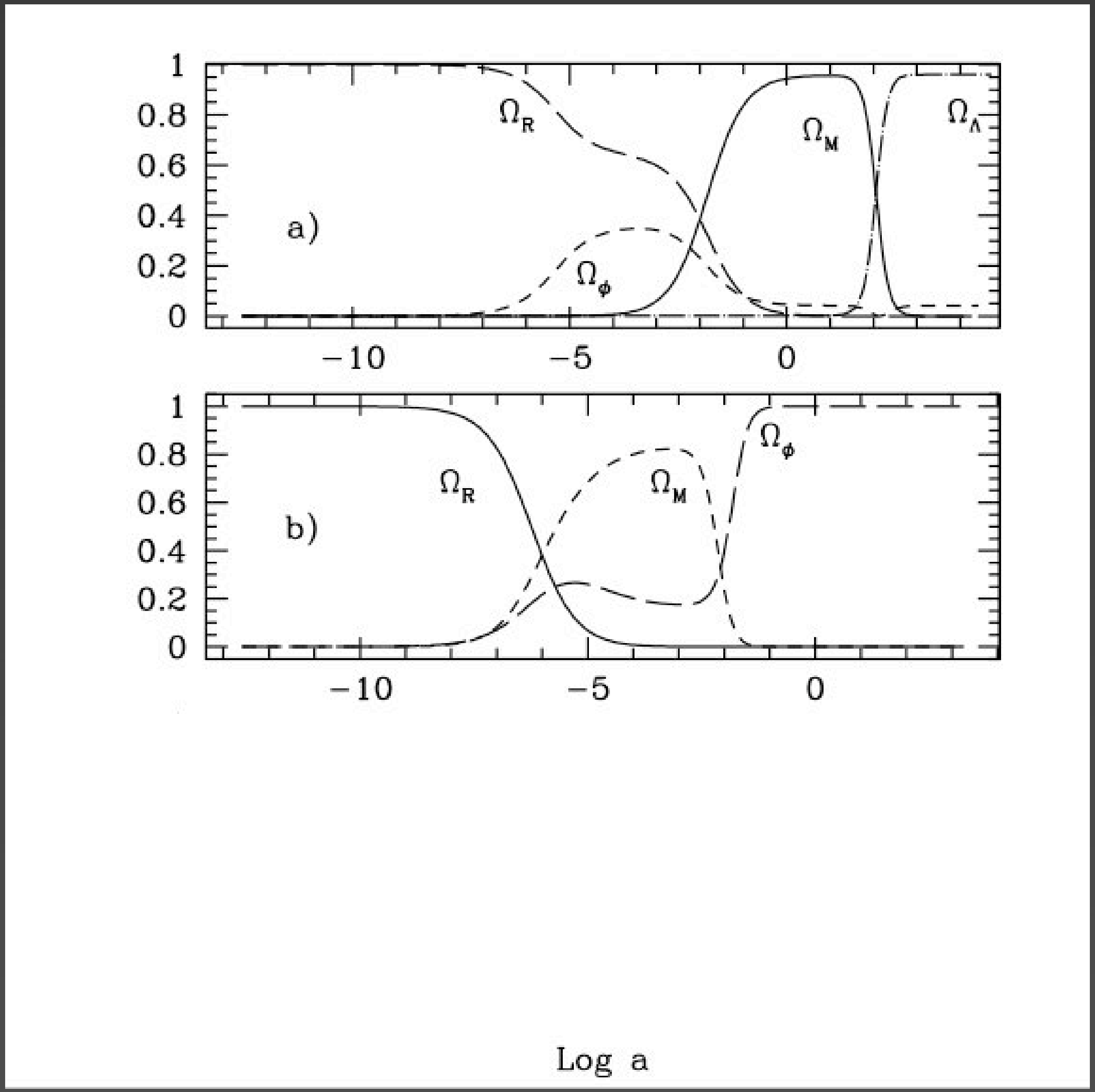

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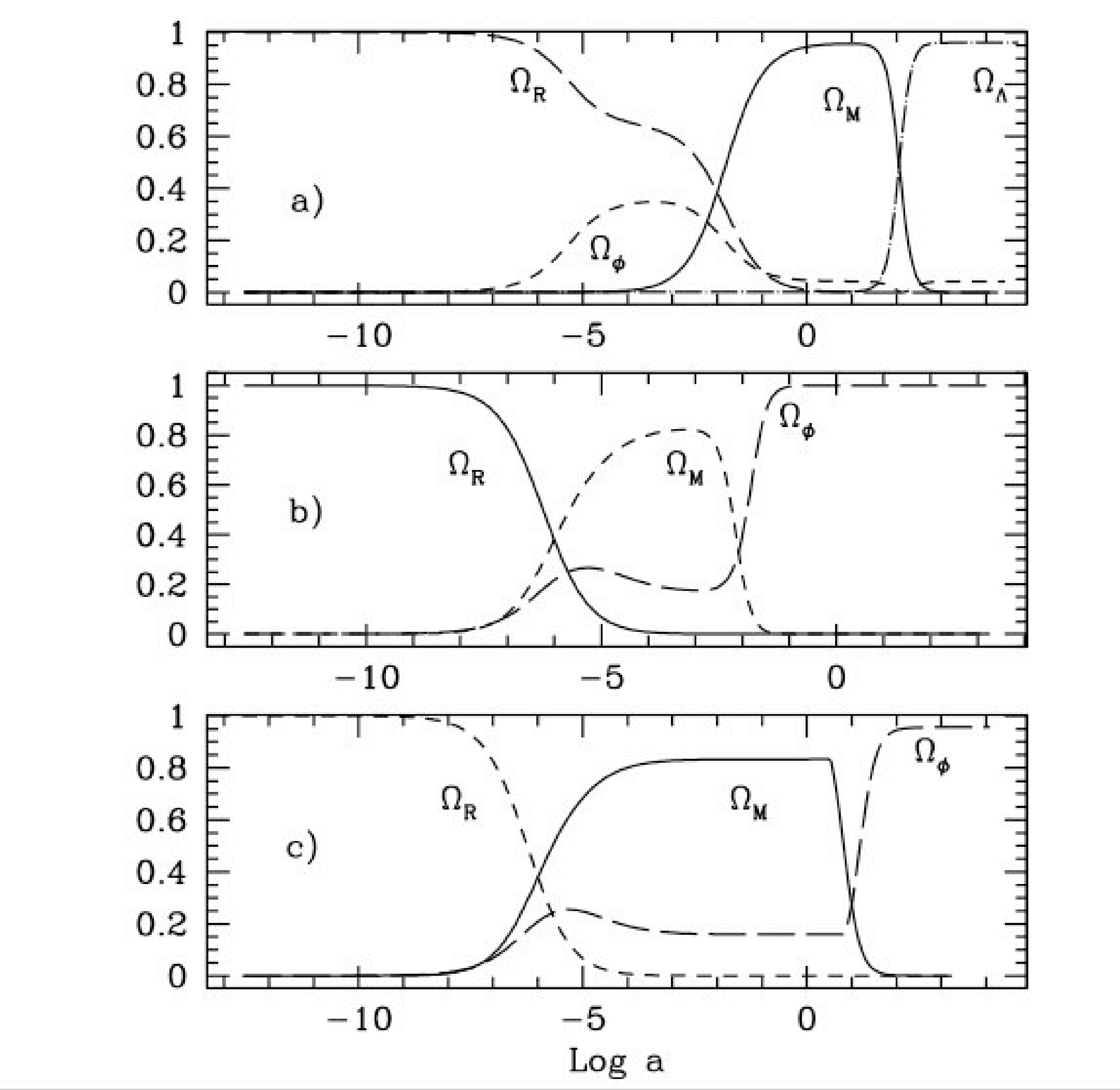

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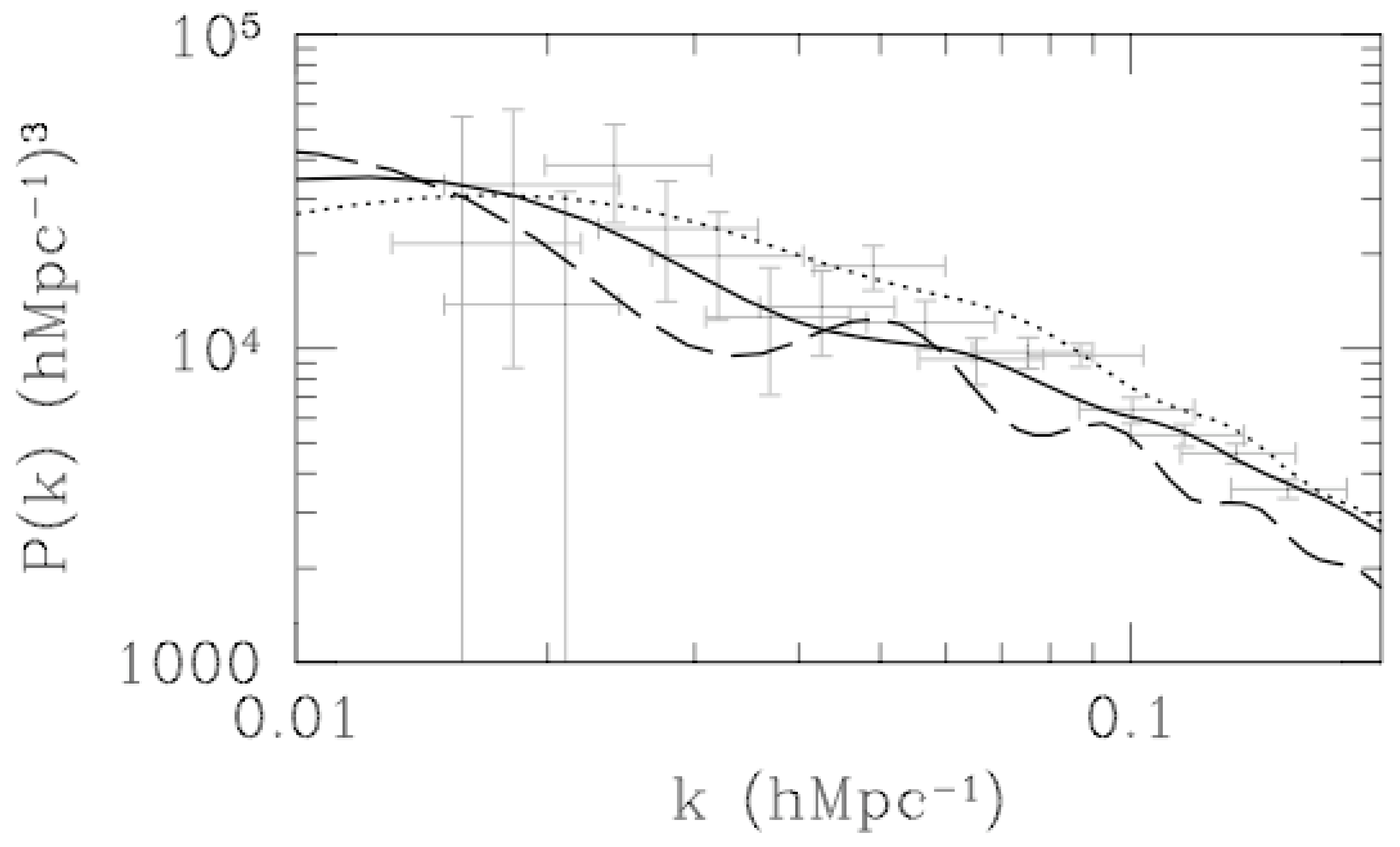

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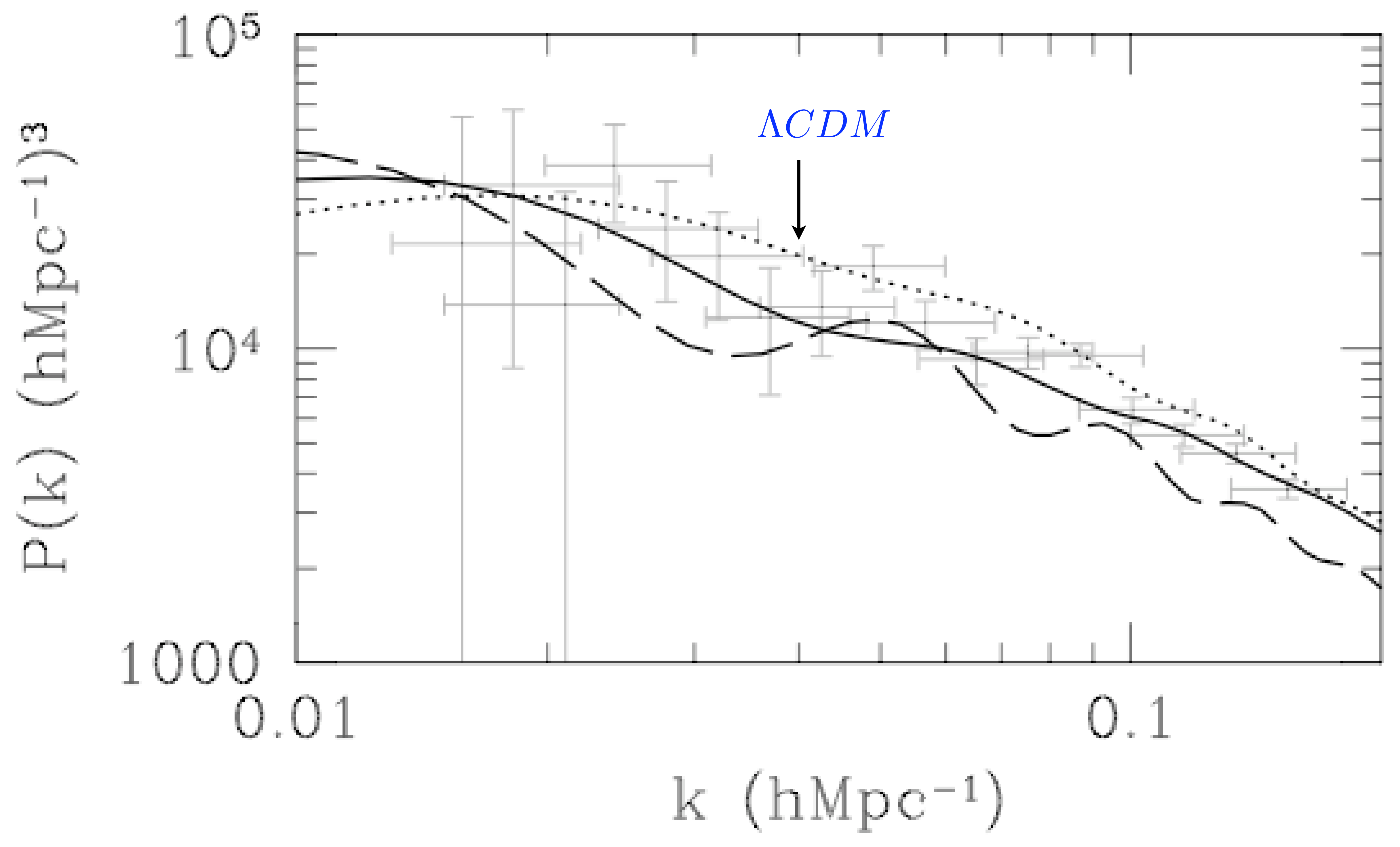

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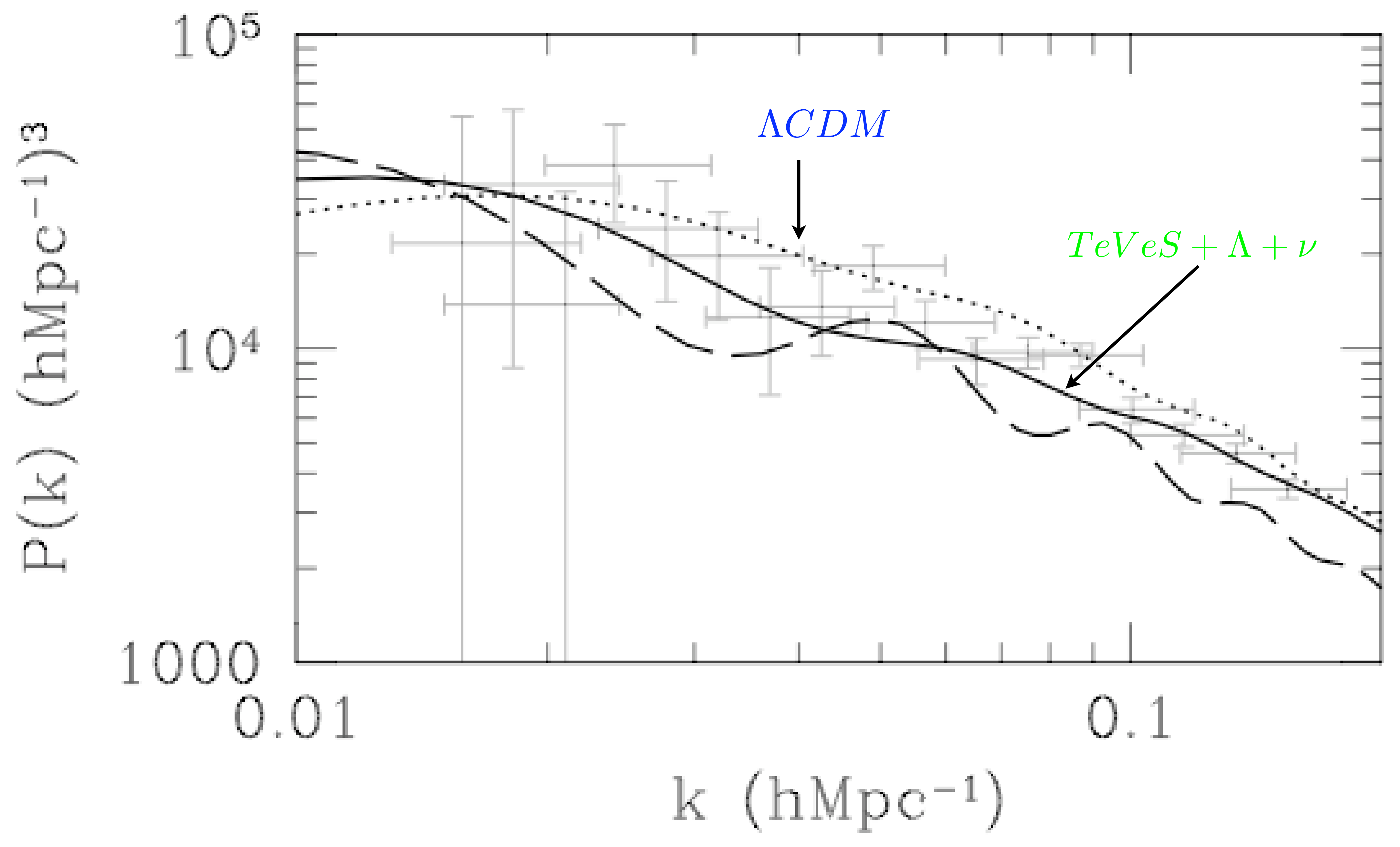

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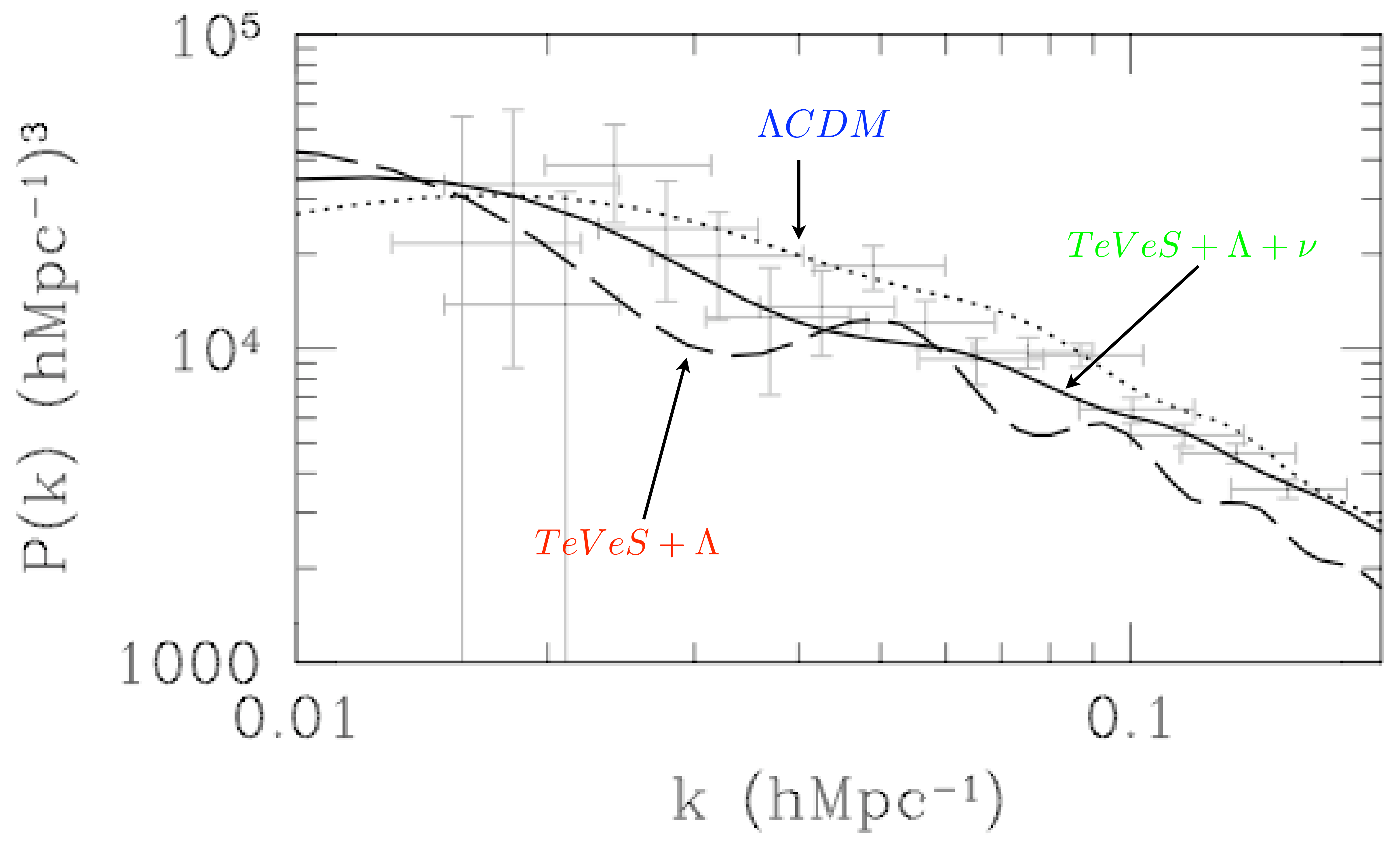

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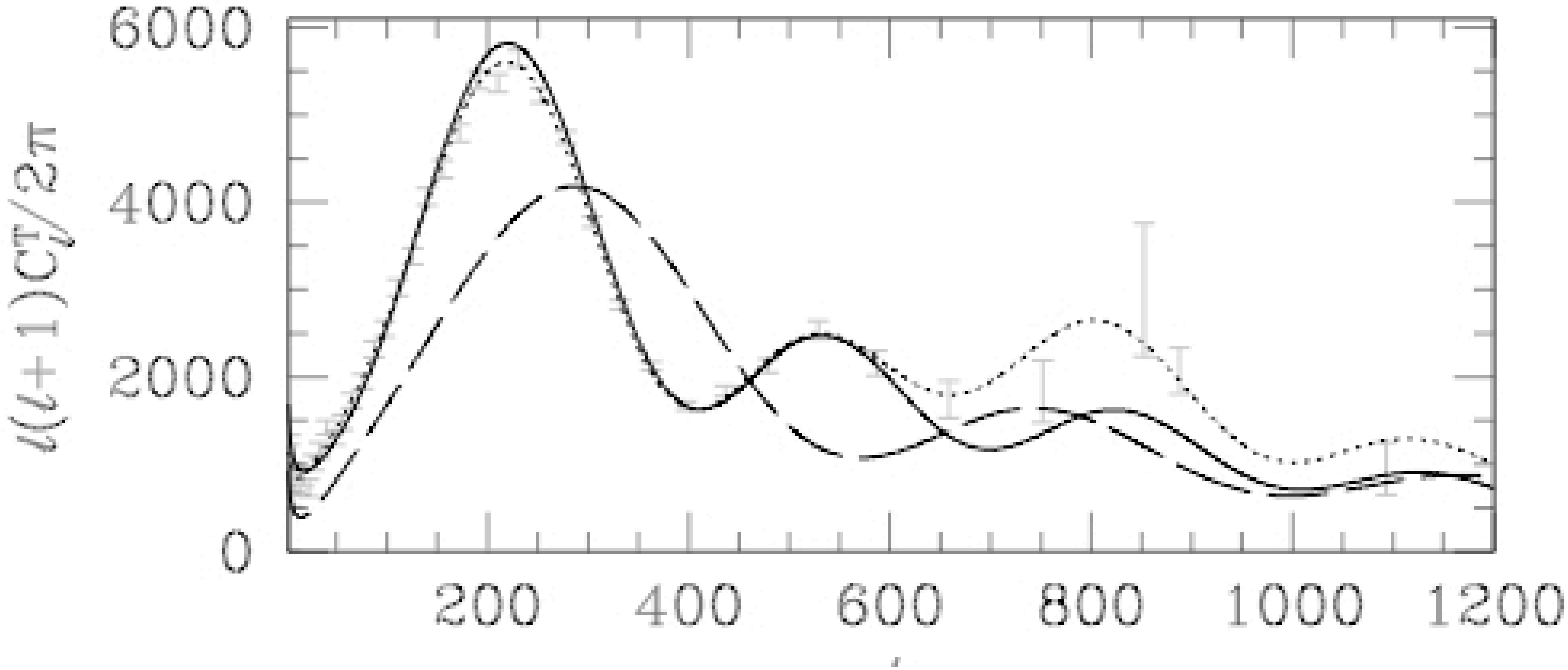

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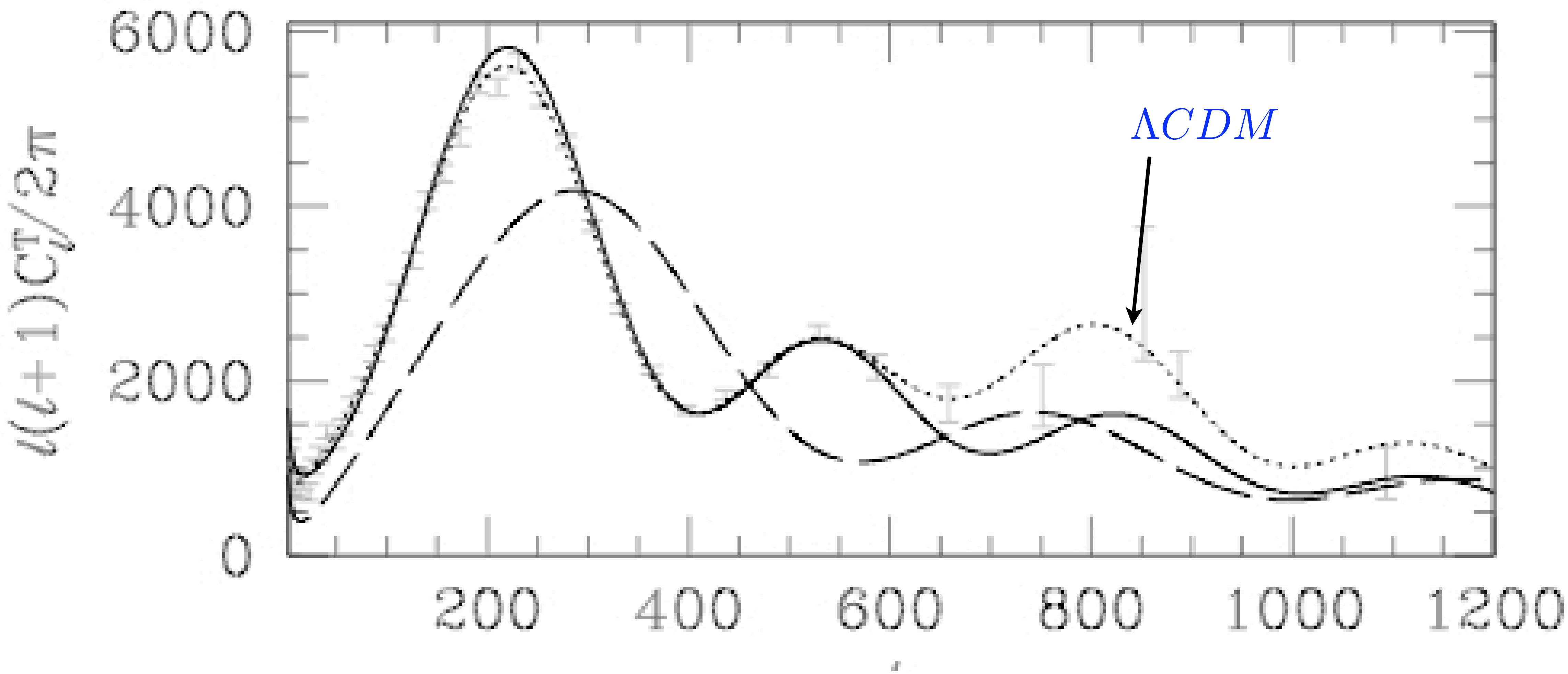

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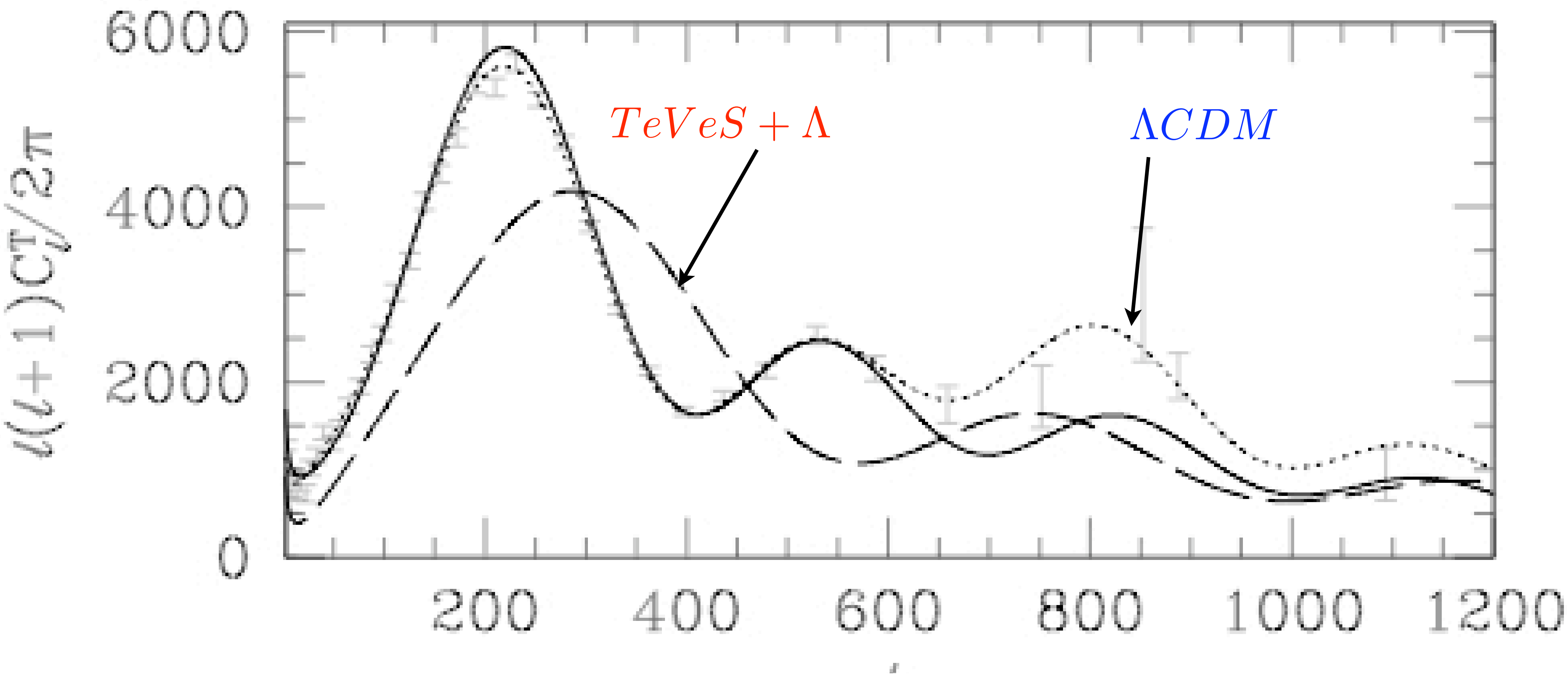

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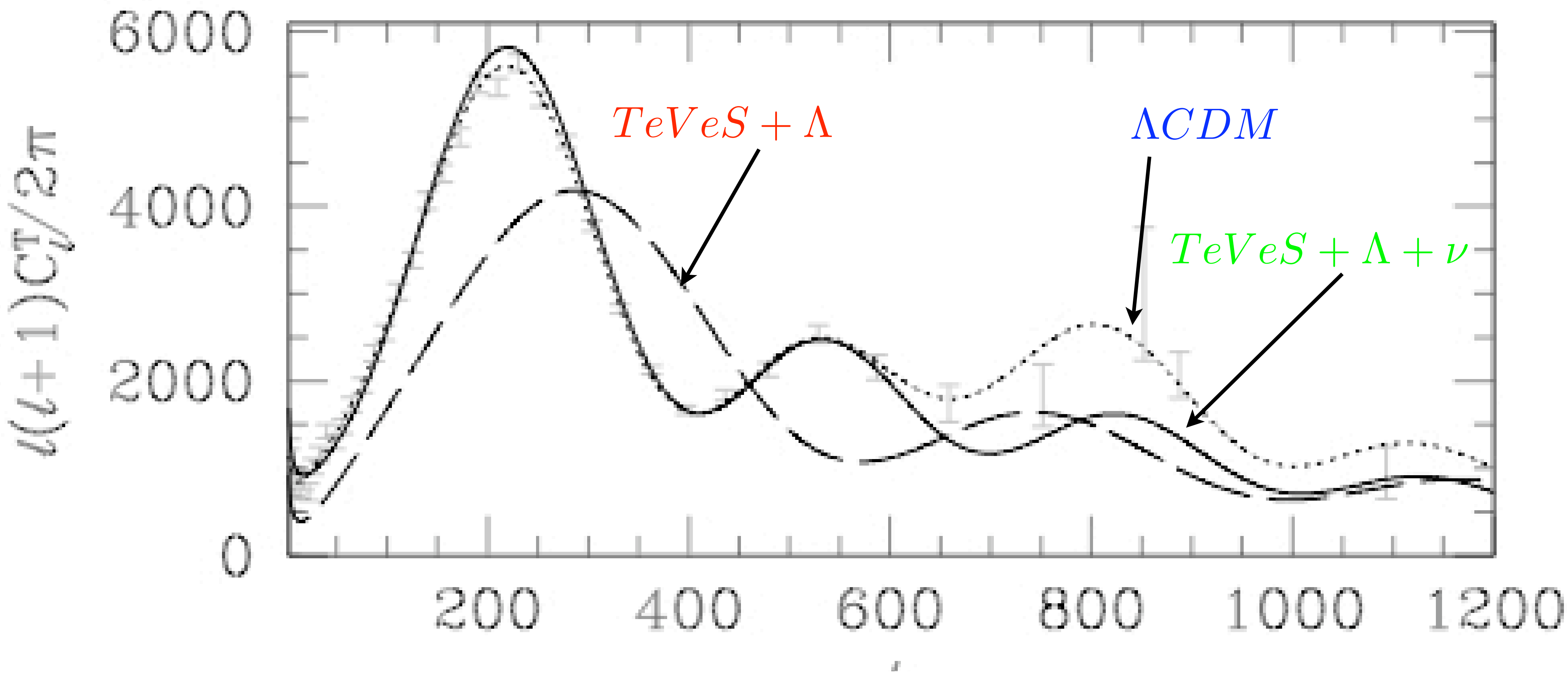

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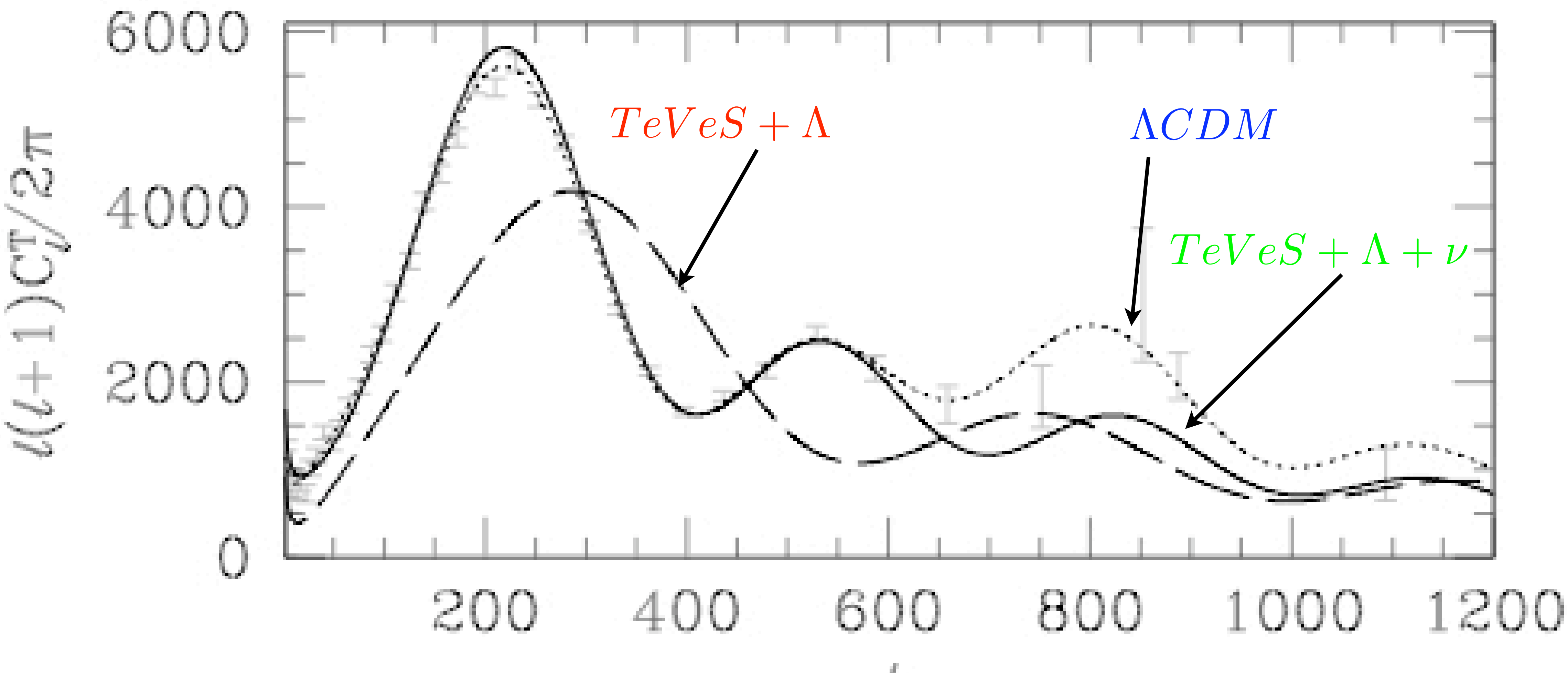

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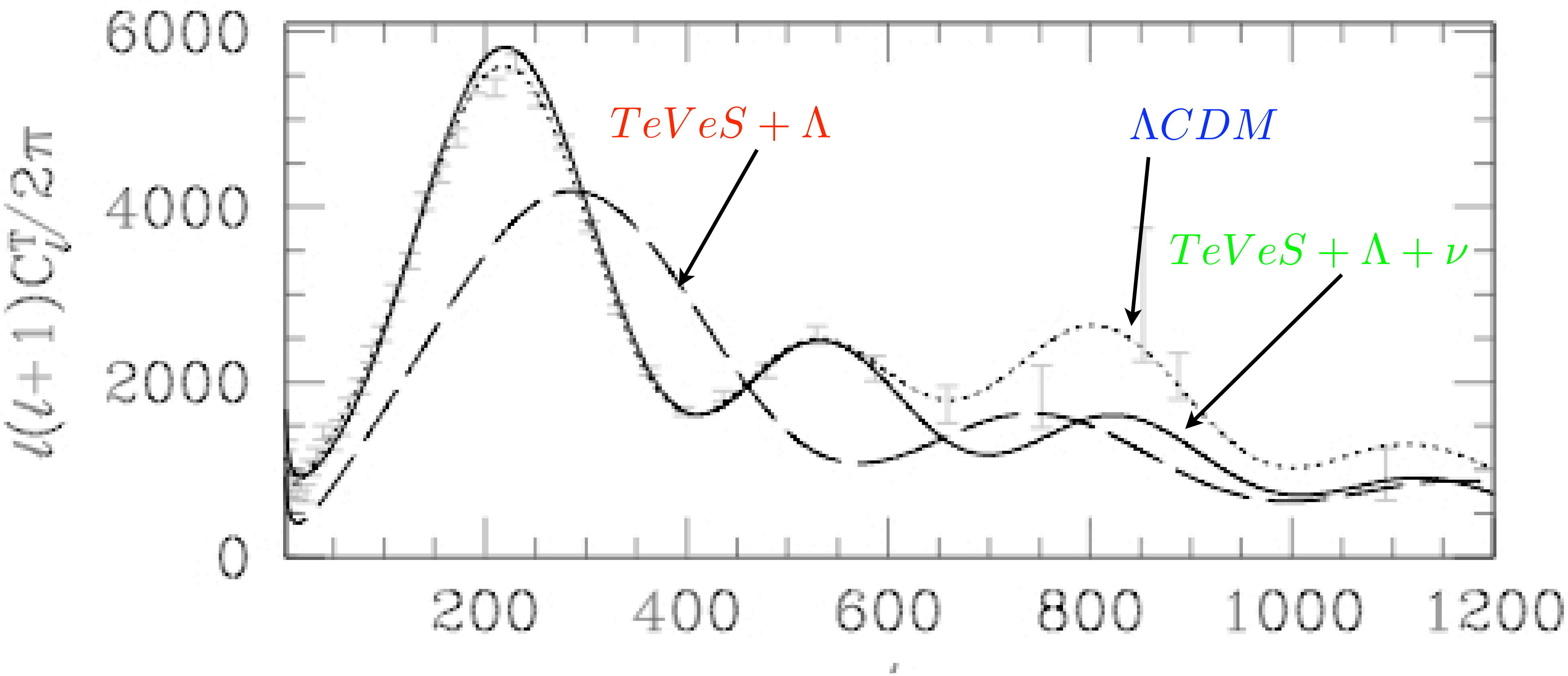

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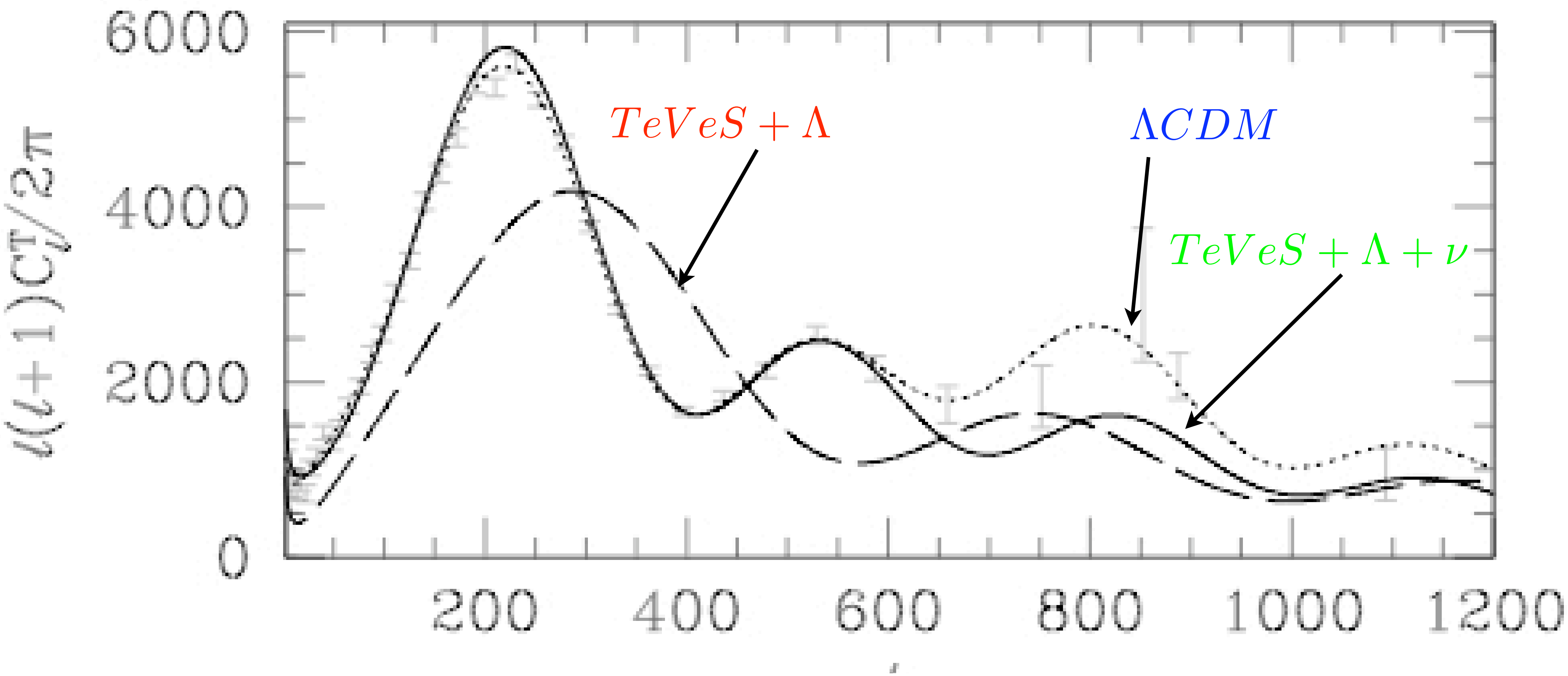

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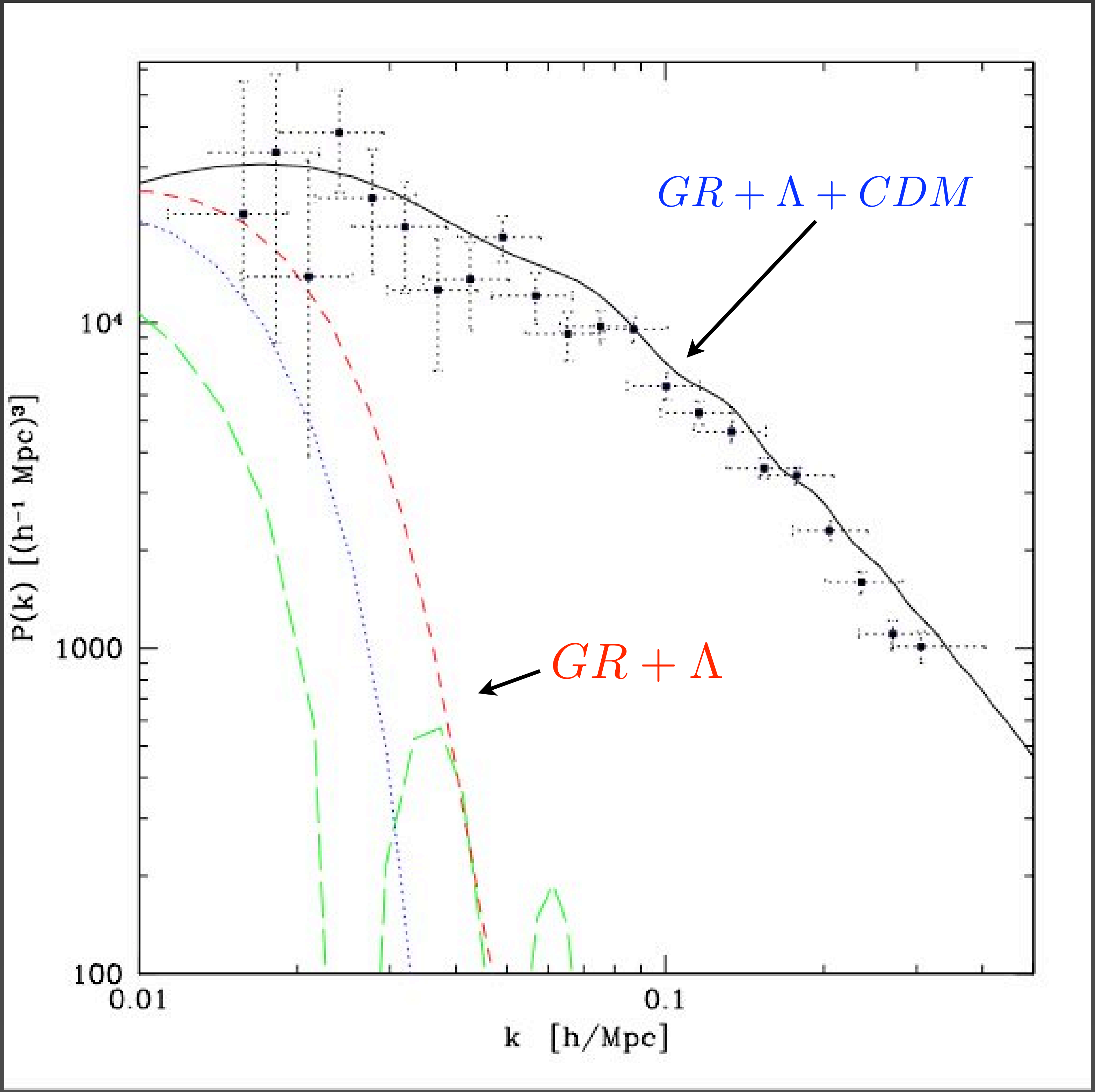
(3rd peak is very low: problems with WMAP 3)

But why don’t we see small scale damping?



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Dodelson&Ligouri 06

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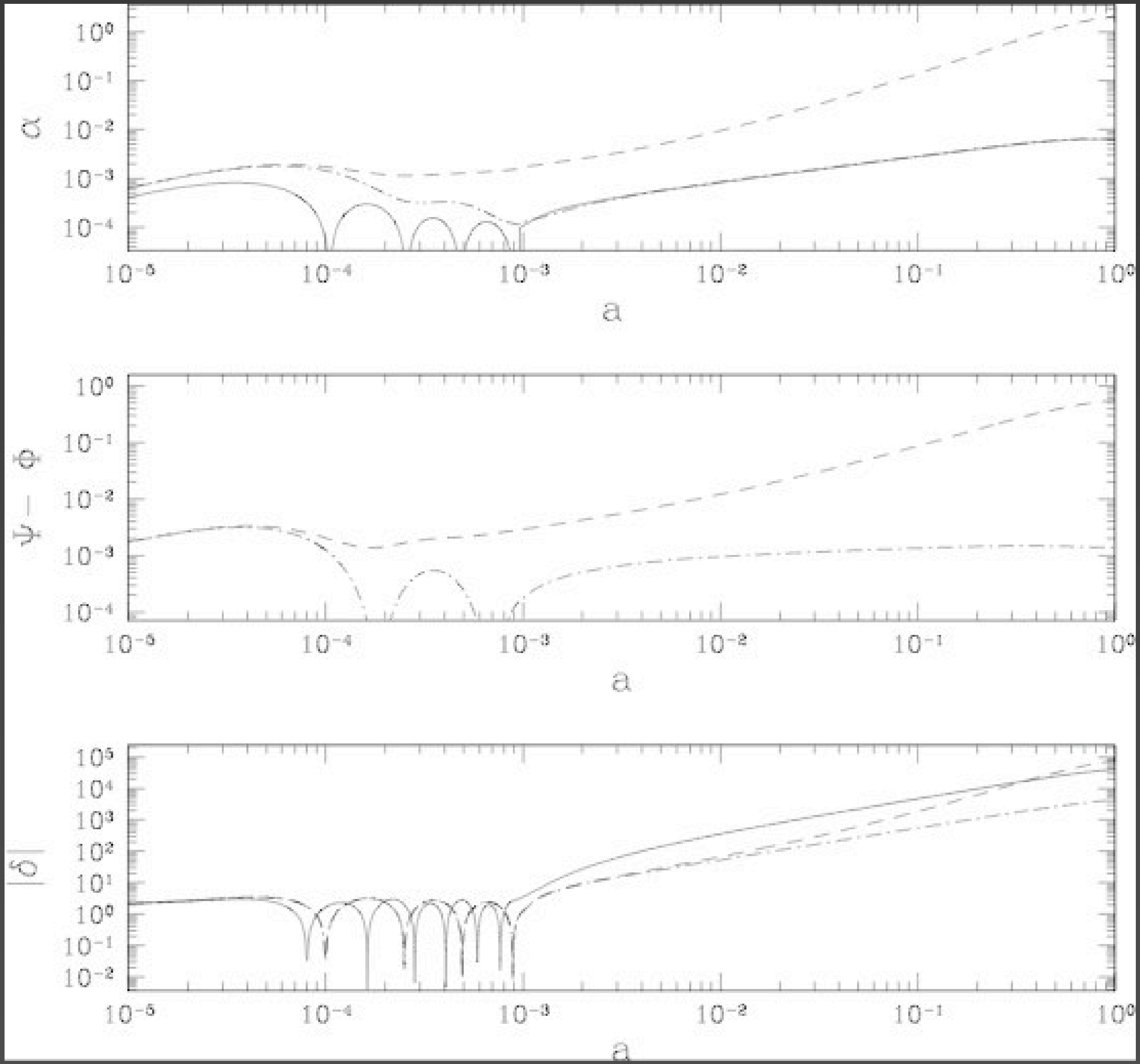
- *Perturbations in vector field, support gravitational potential through recombination!*

Depending on the parameters, vector perturbations can grow sourcing gravitational potentials

Dodelson&Ligouri astro-ph/0608602



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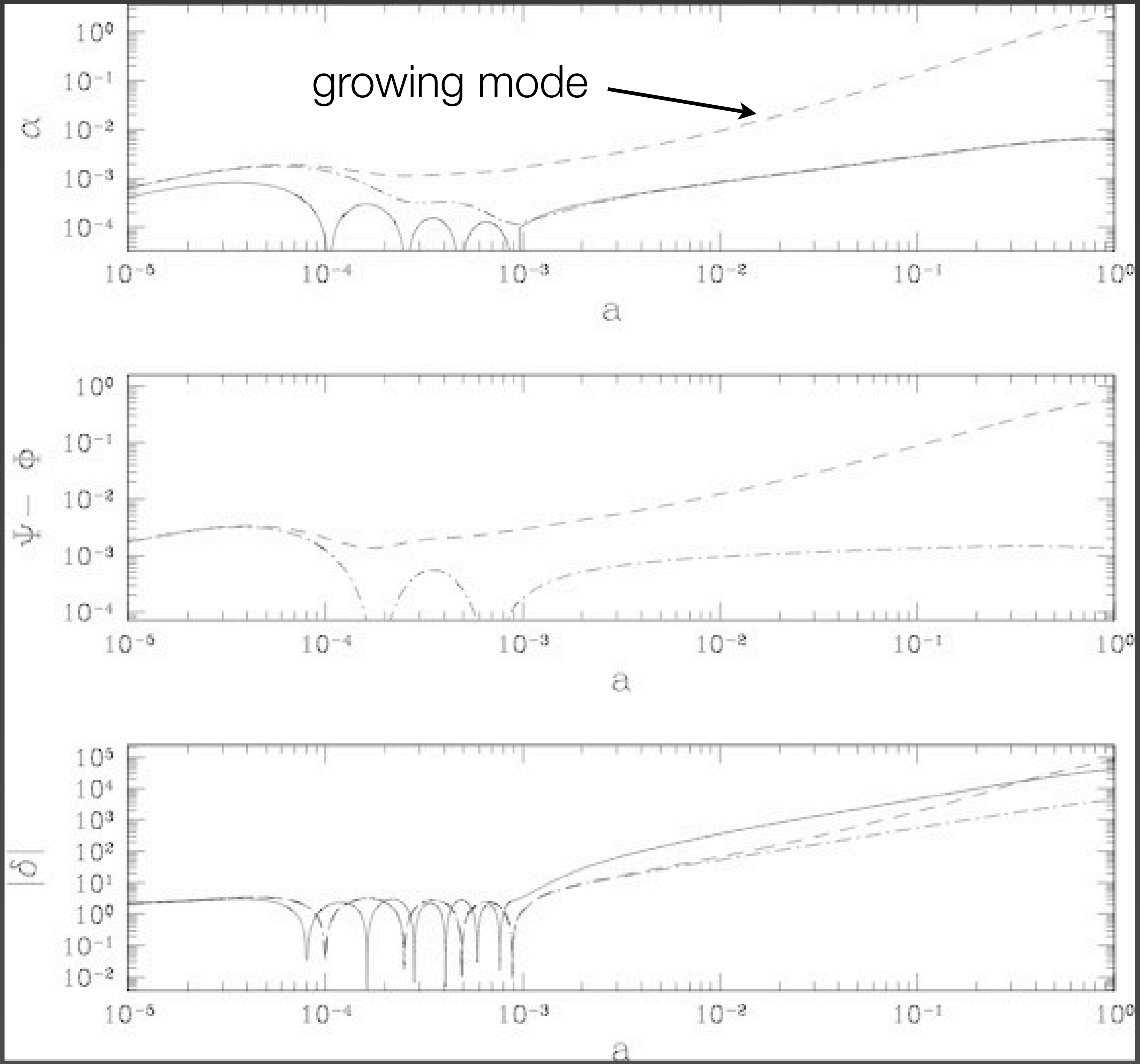

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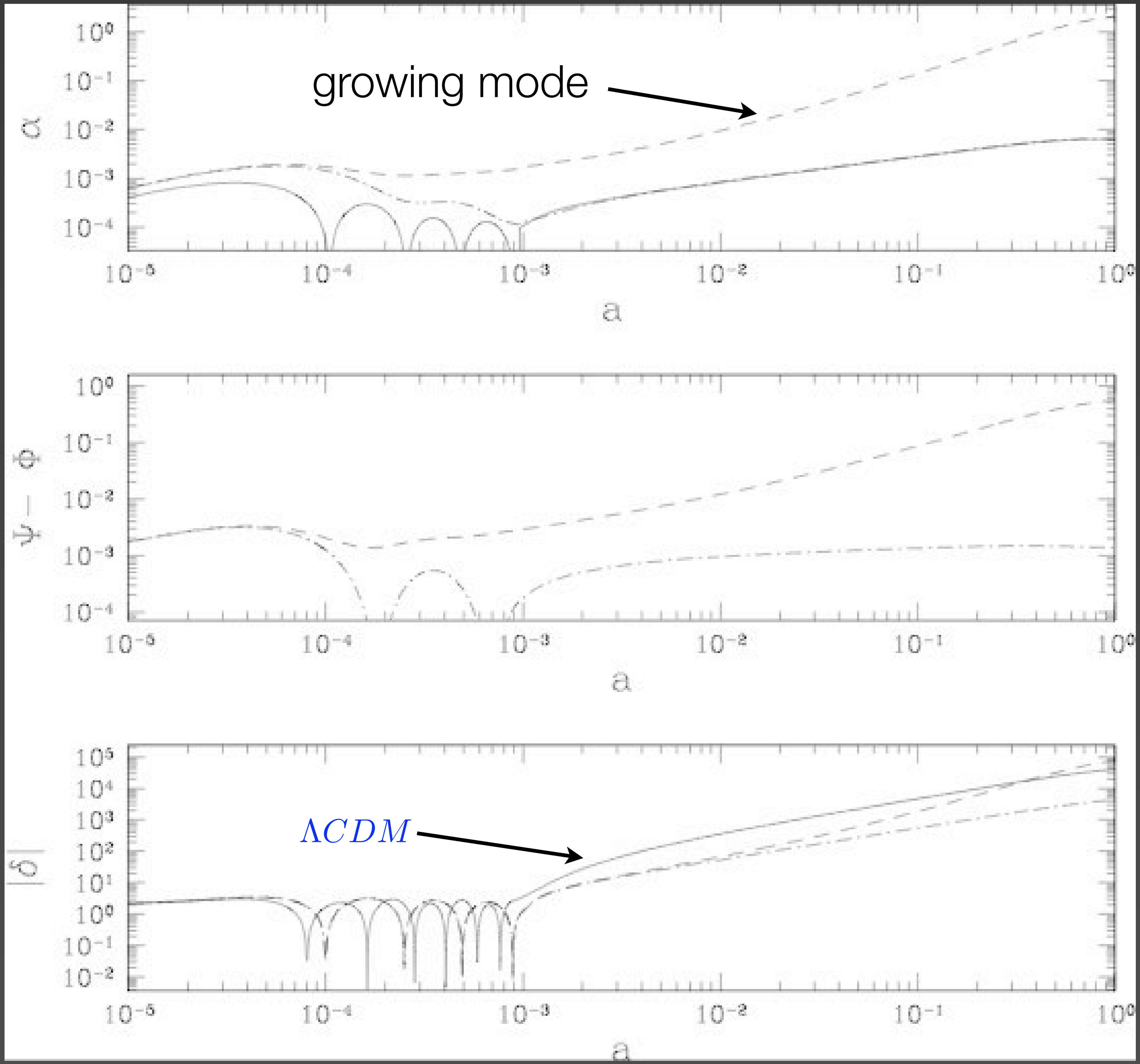

growing mode

ΛCDM

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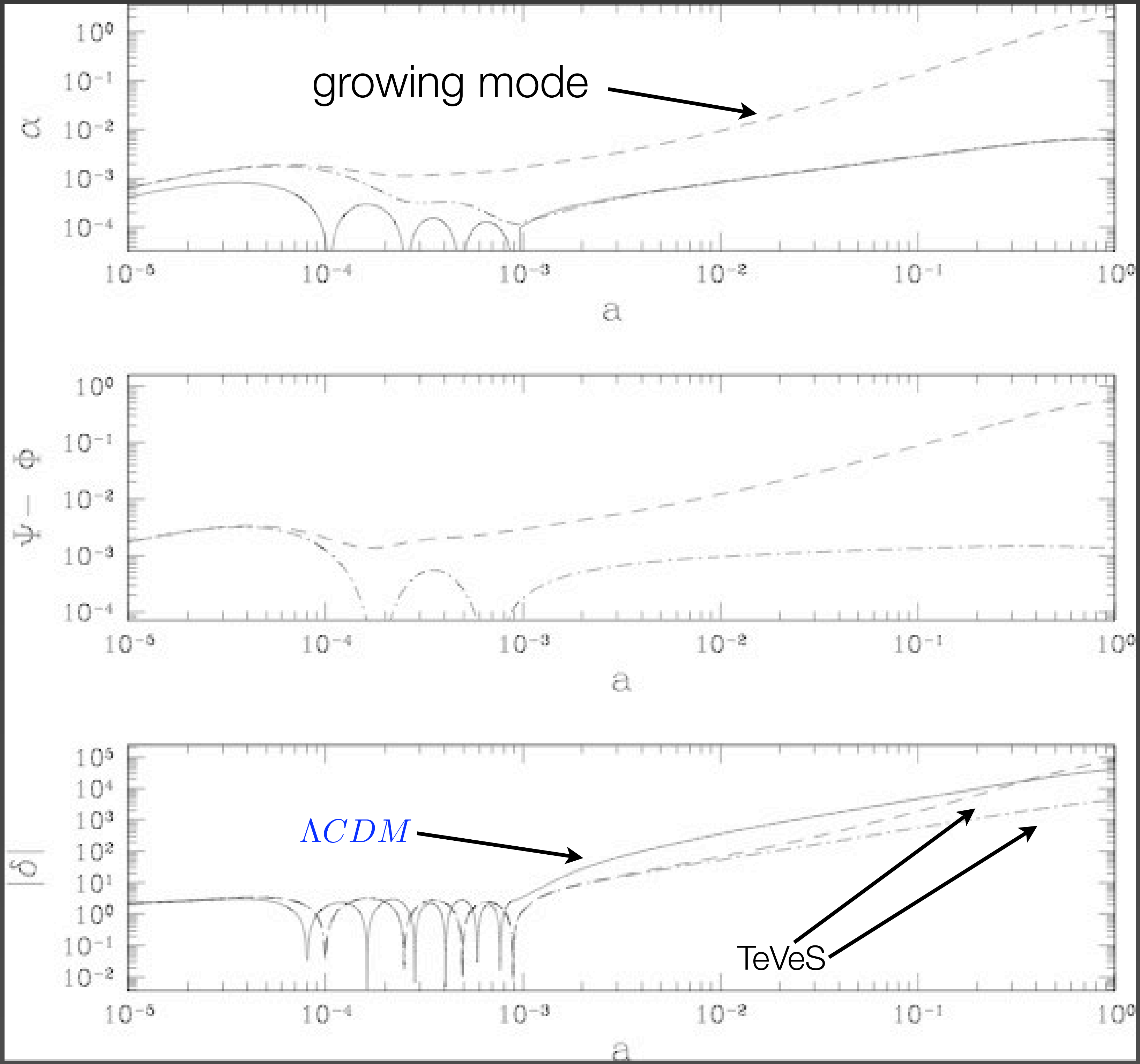

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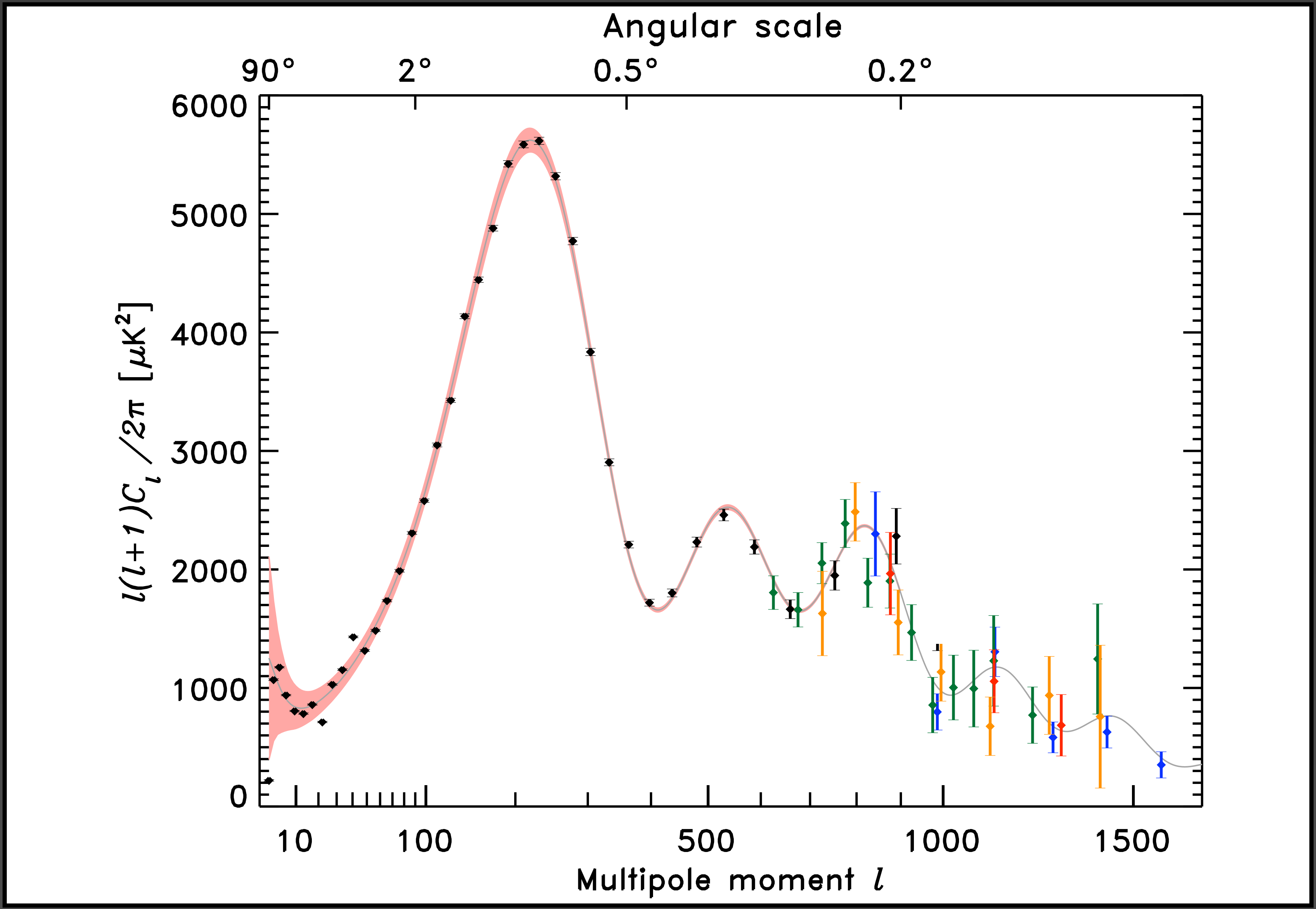

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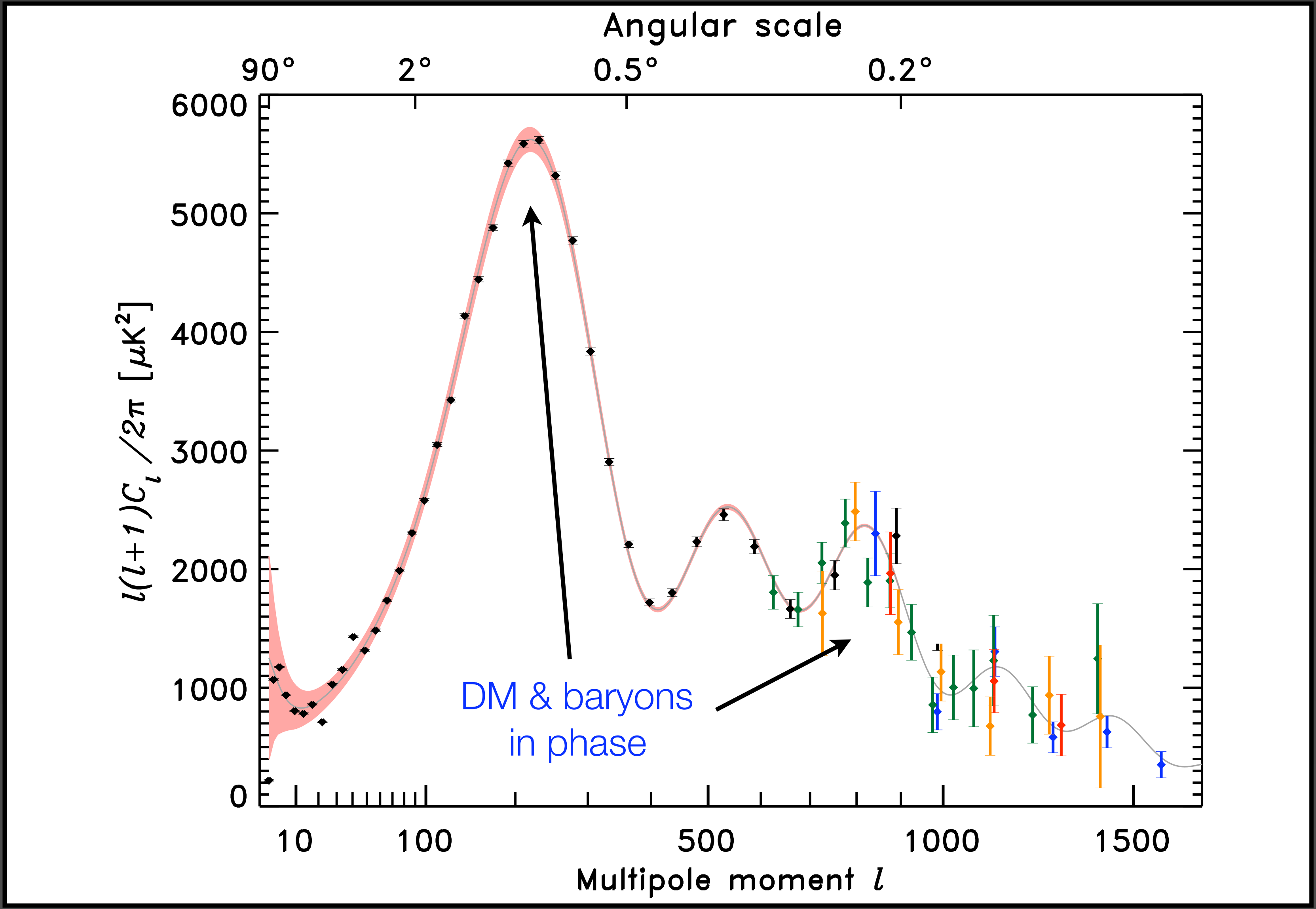

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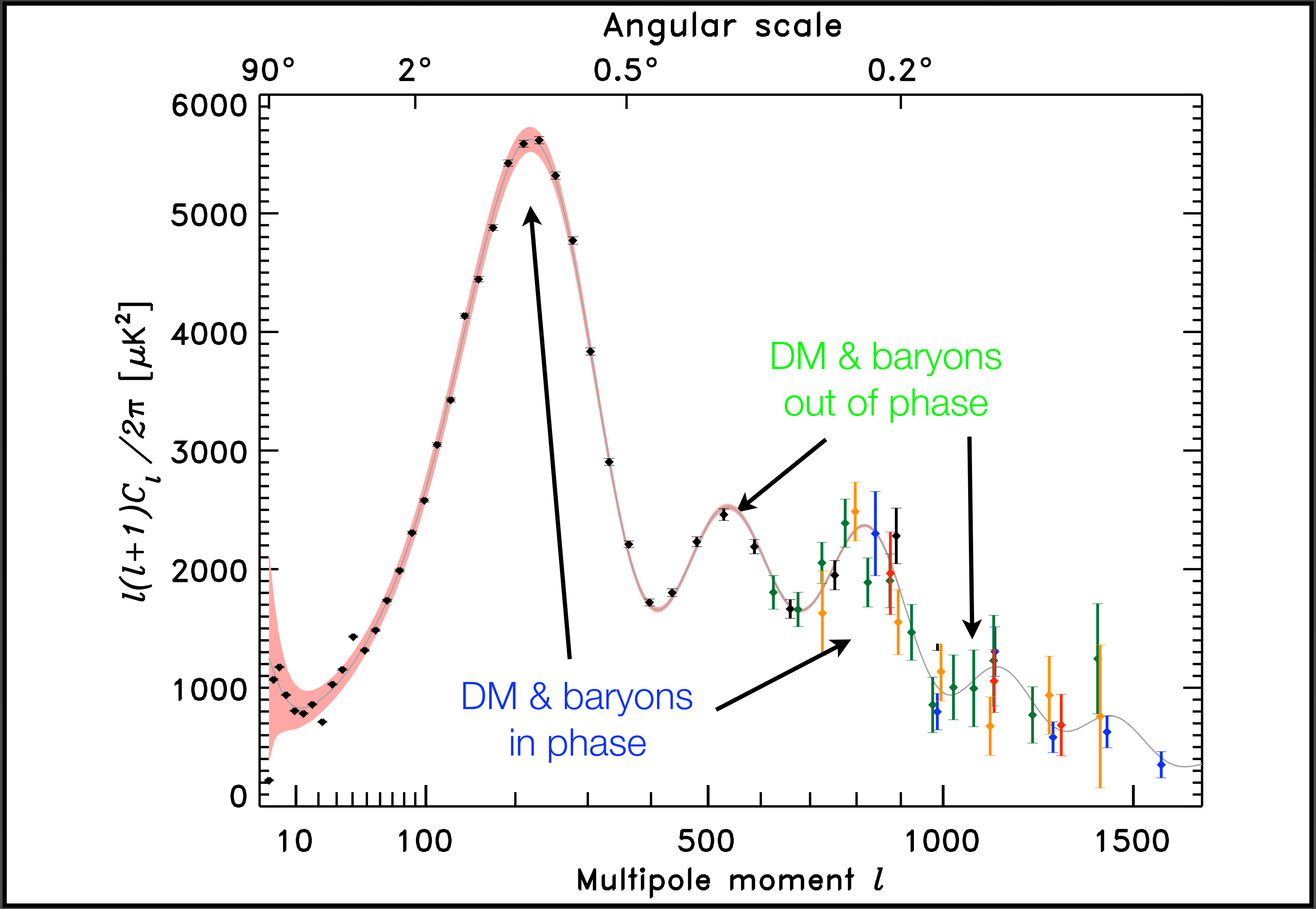

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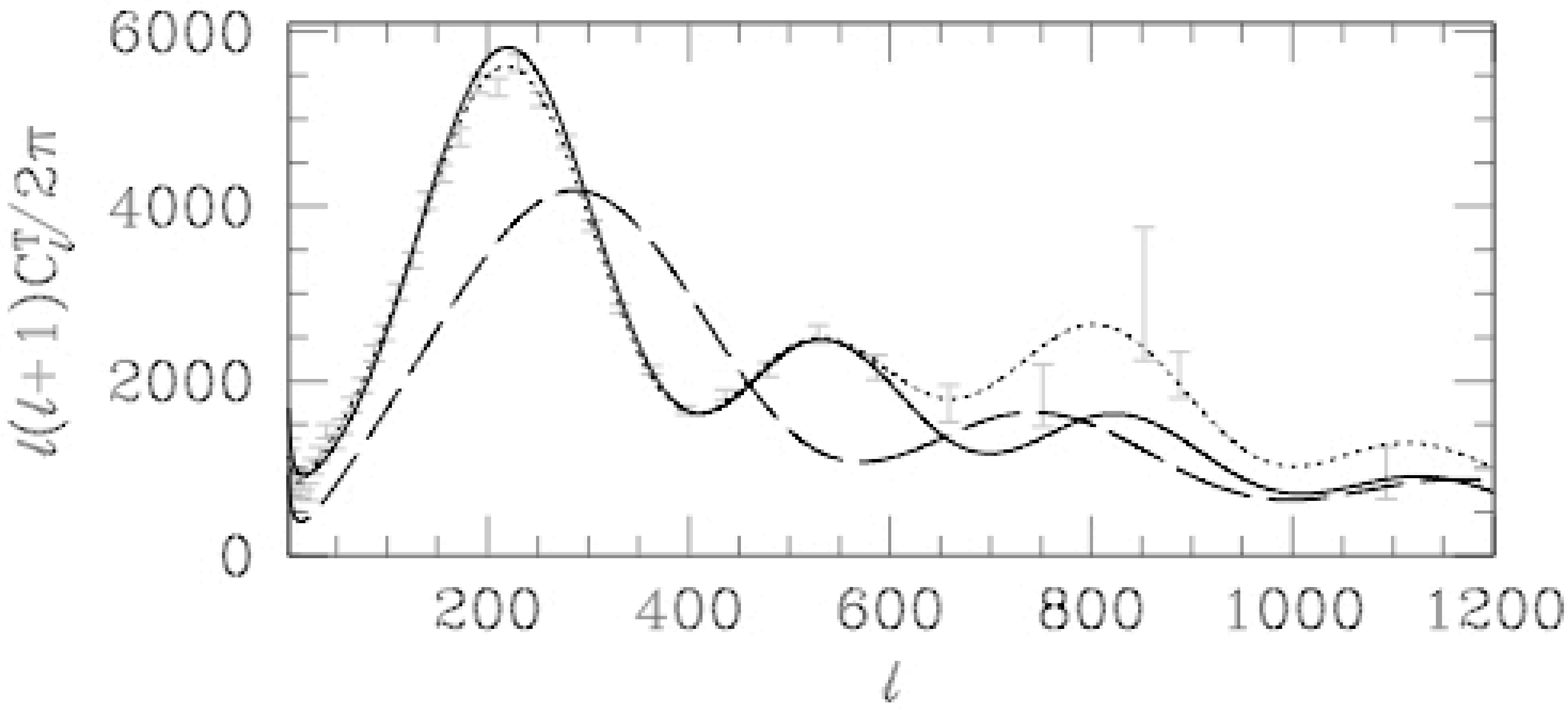

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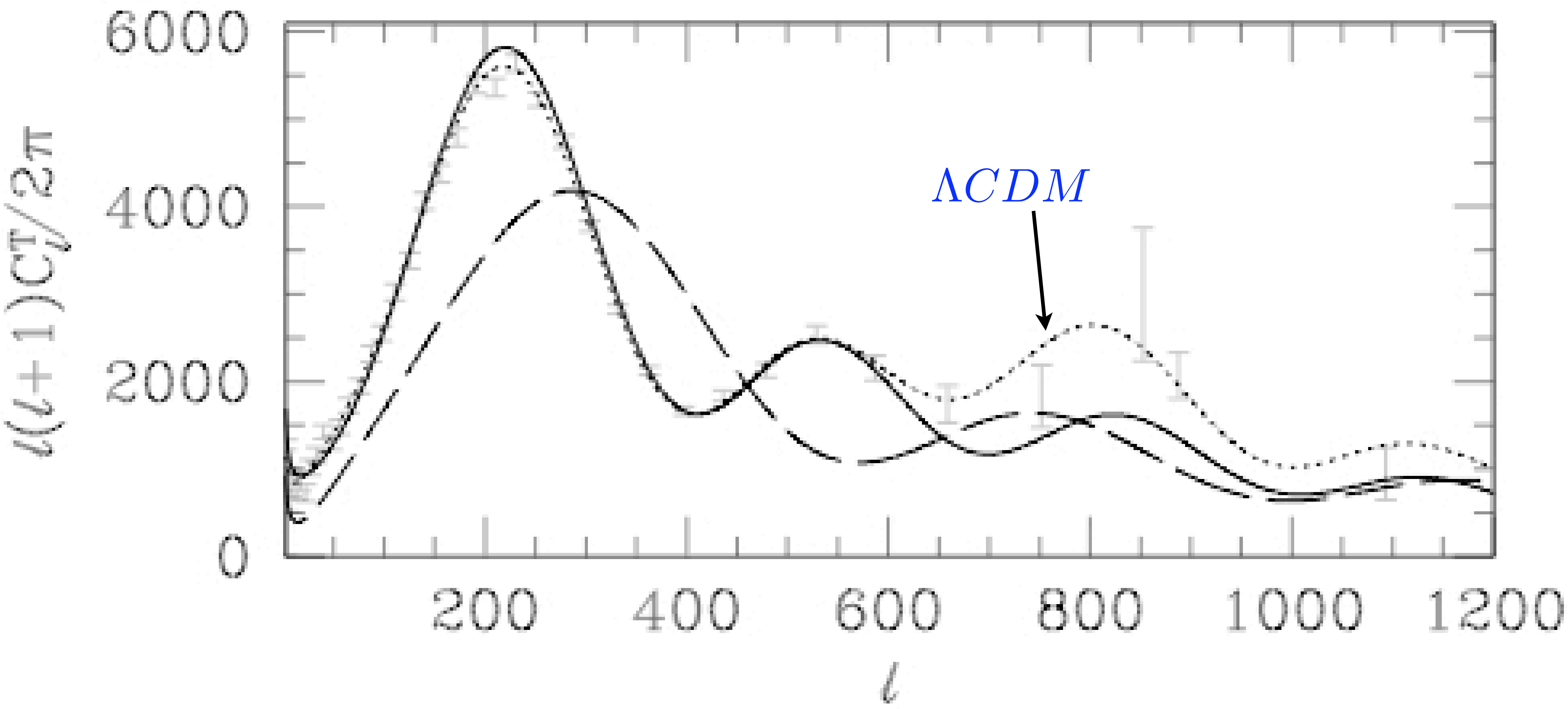

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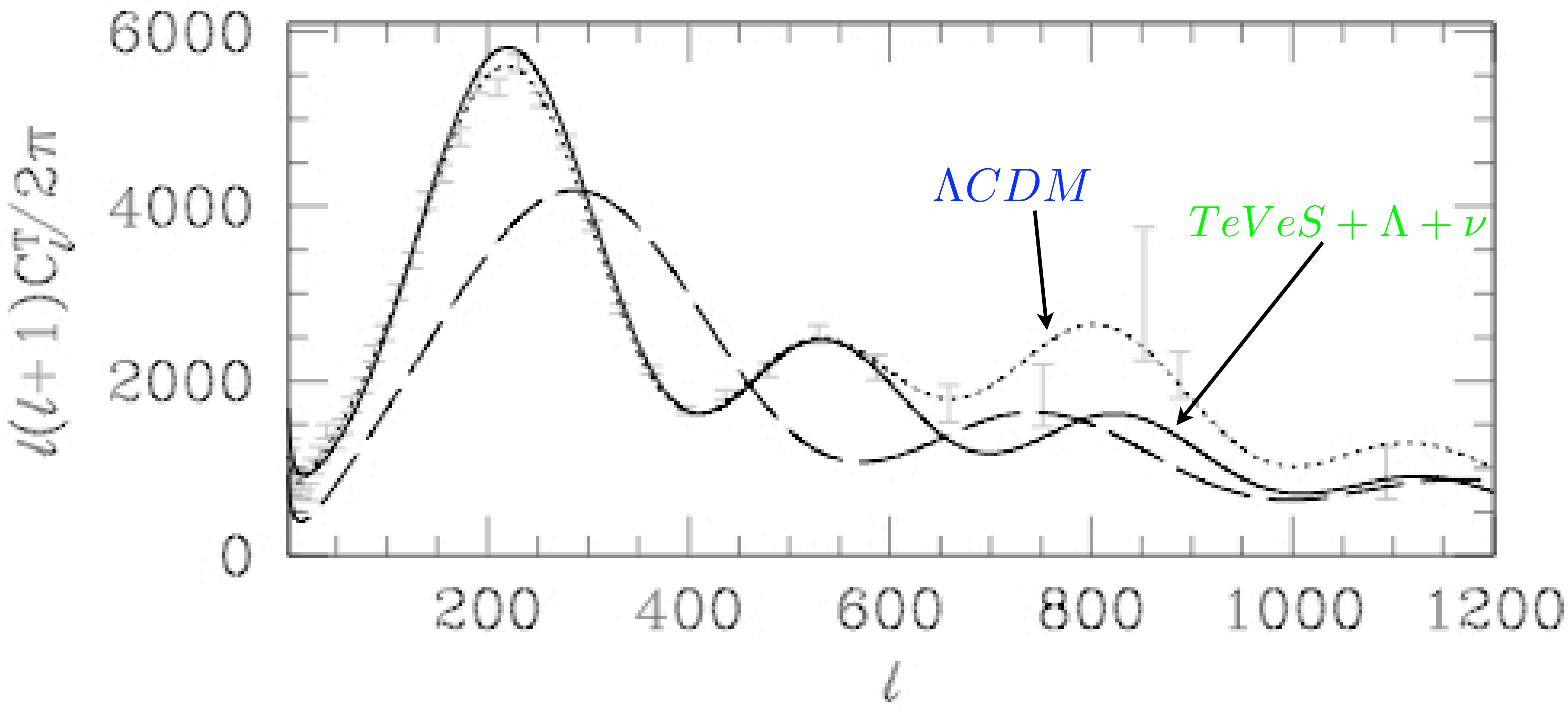

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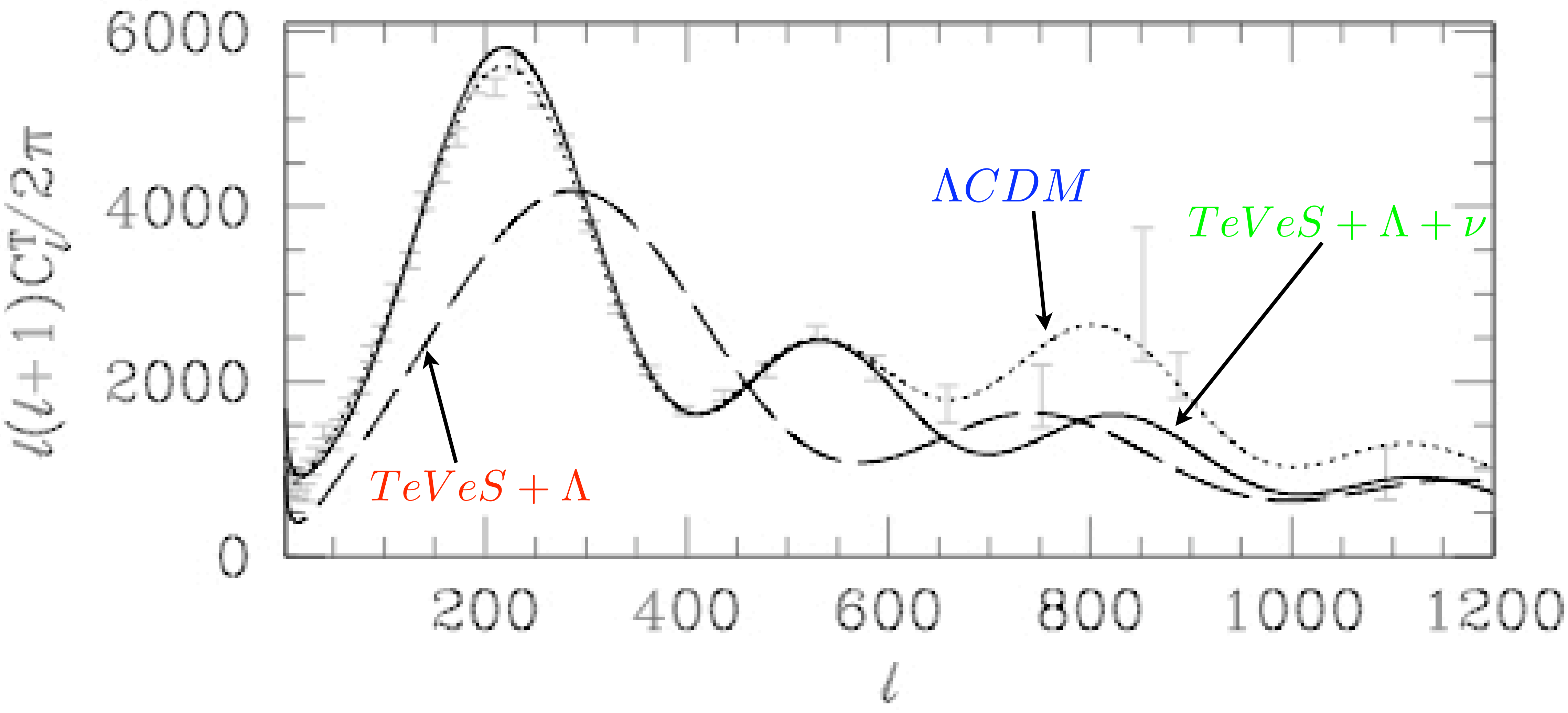

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Work in progress

Mota,Ferreira,Skordis&Zhao

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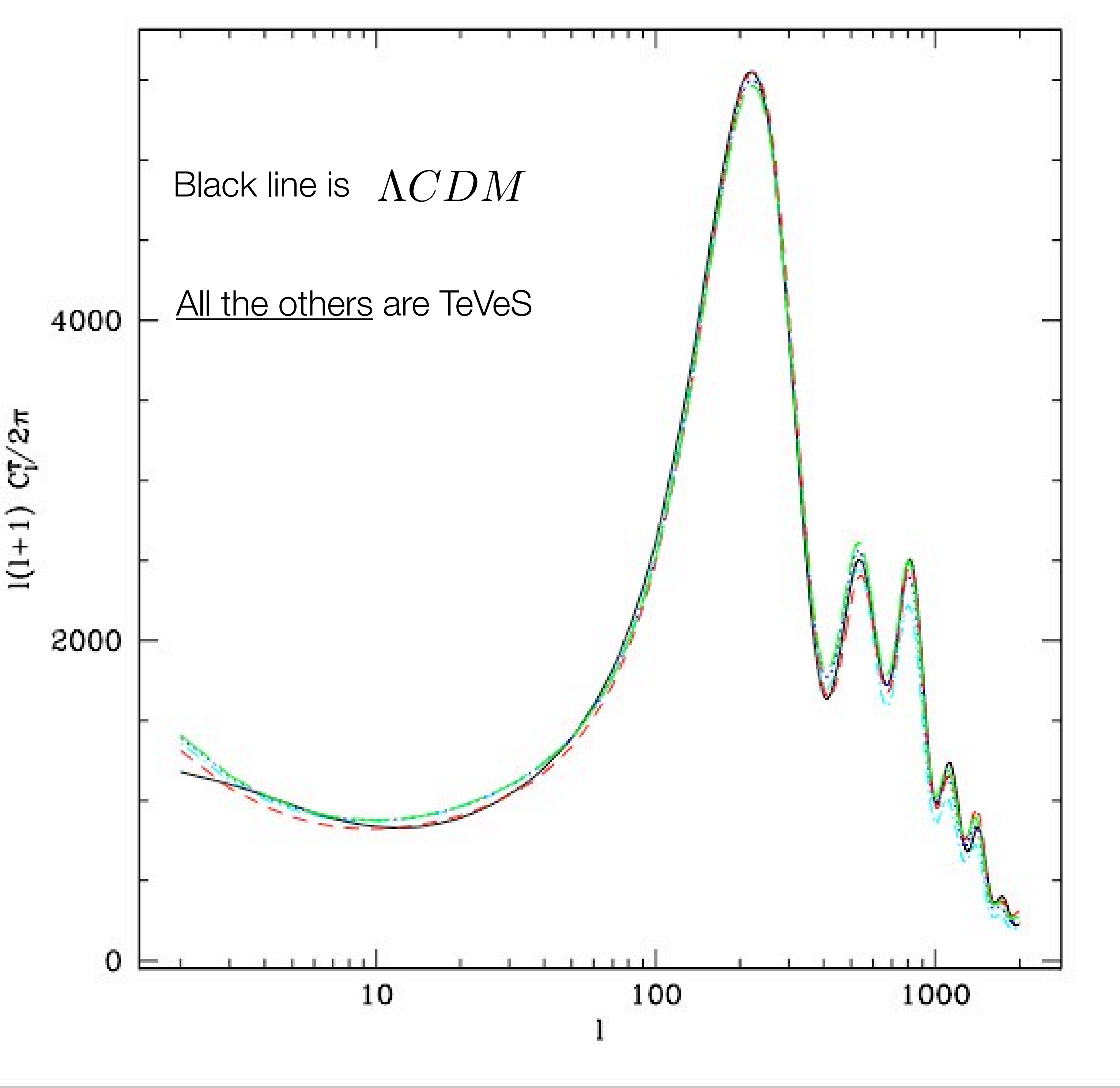

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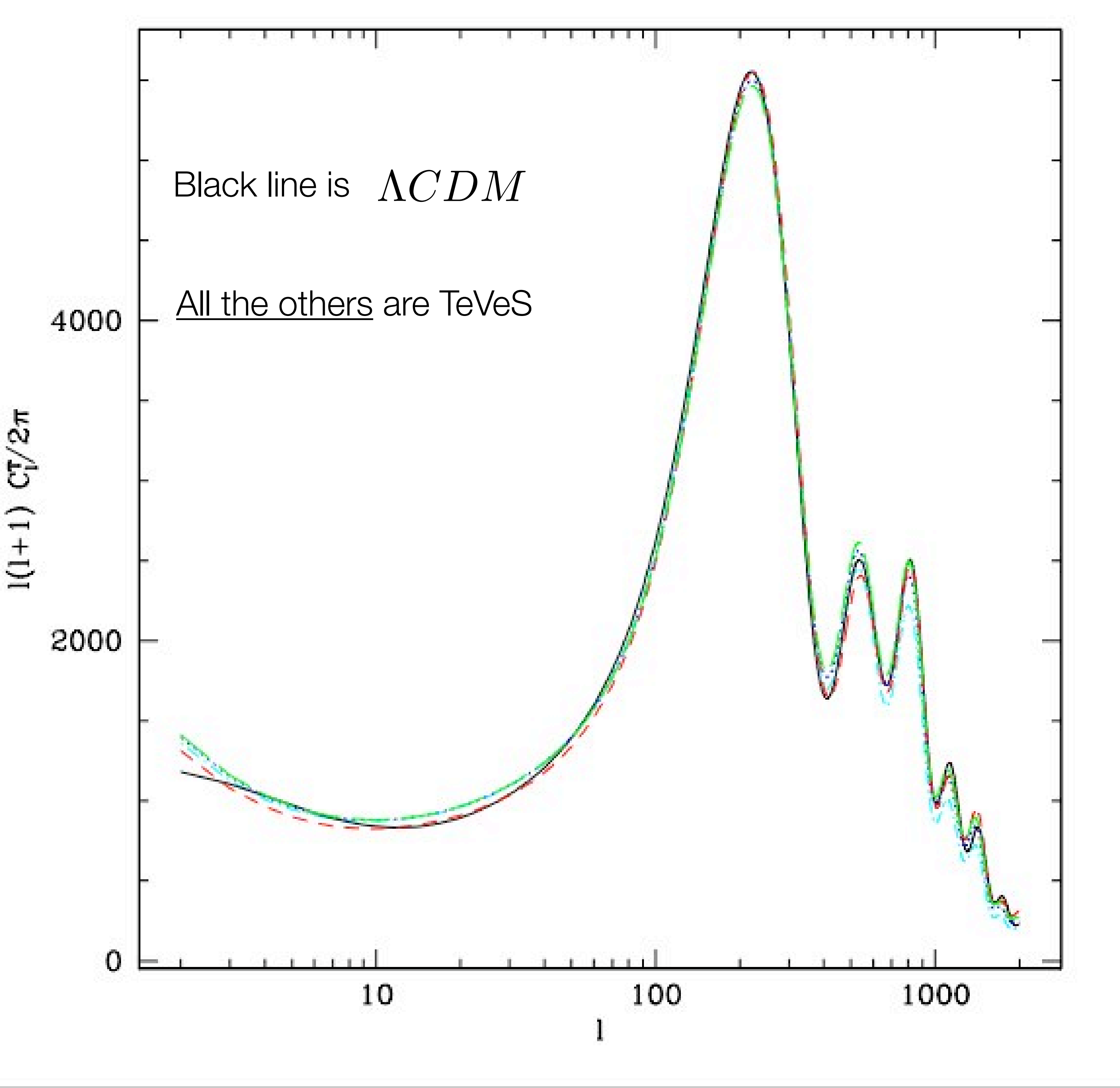
Massive Neutrinos

<u>Isocurvature perturbations</u>



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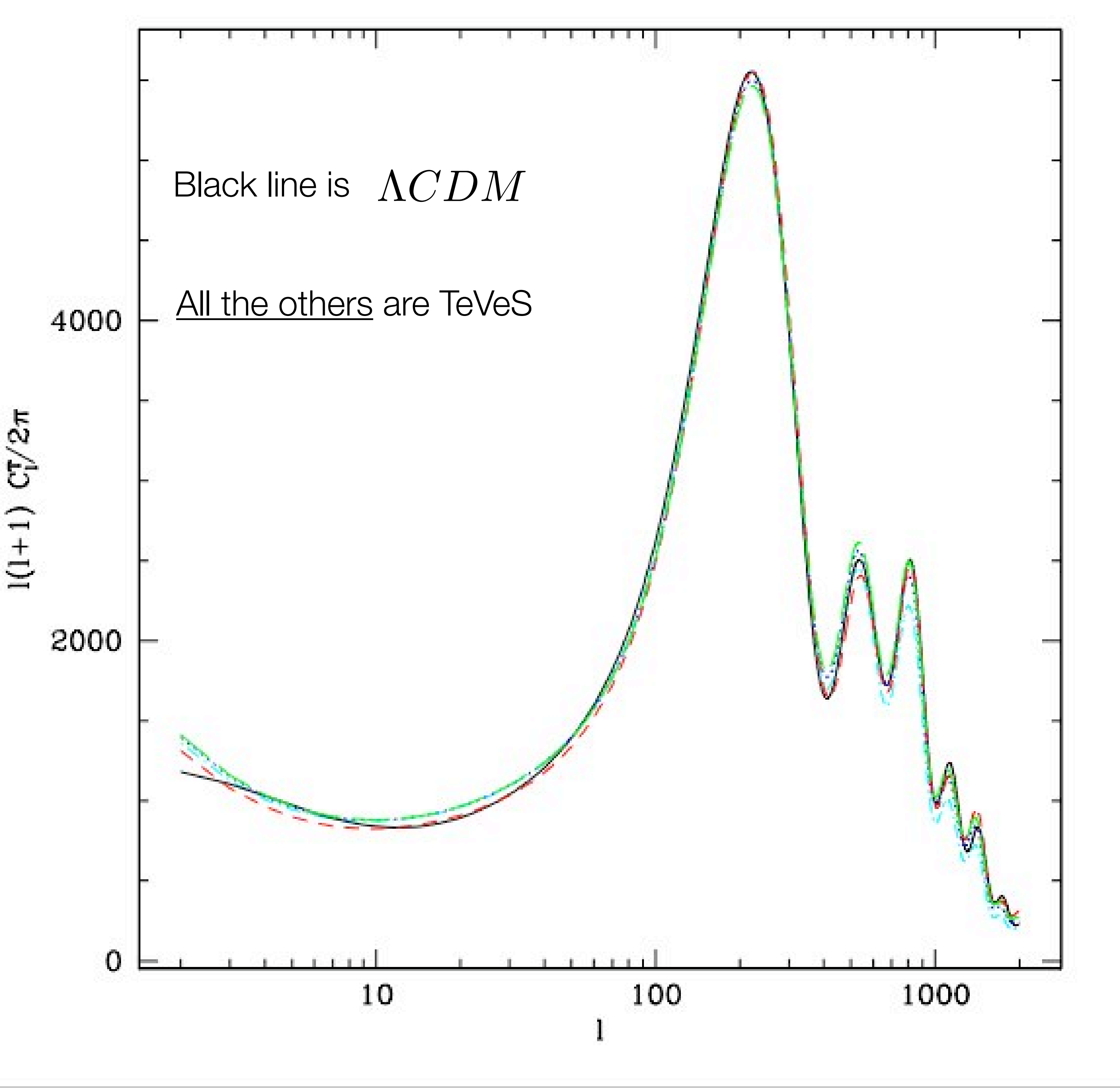
BUT:
No good Ho
No good P(k)



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Lensing convergence map in Bullet cluster

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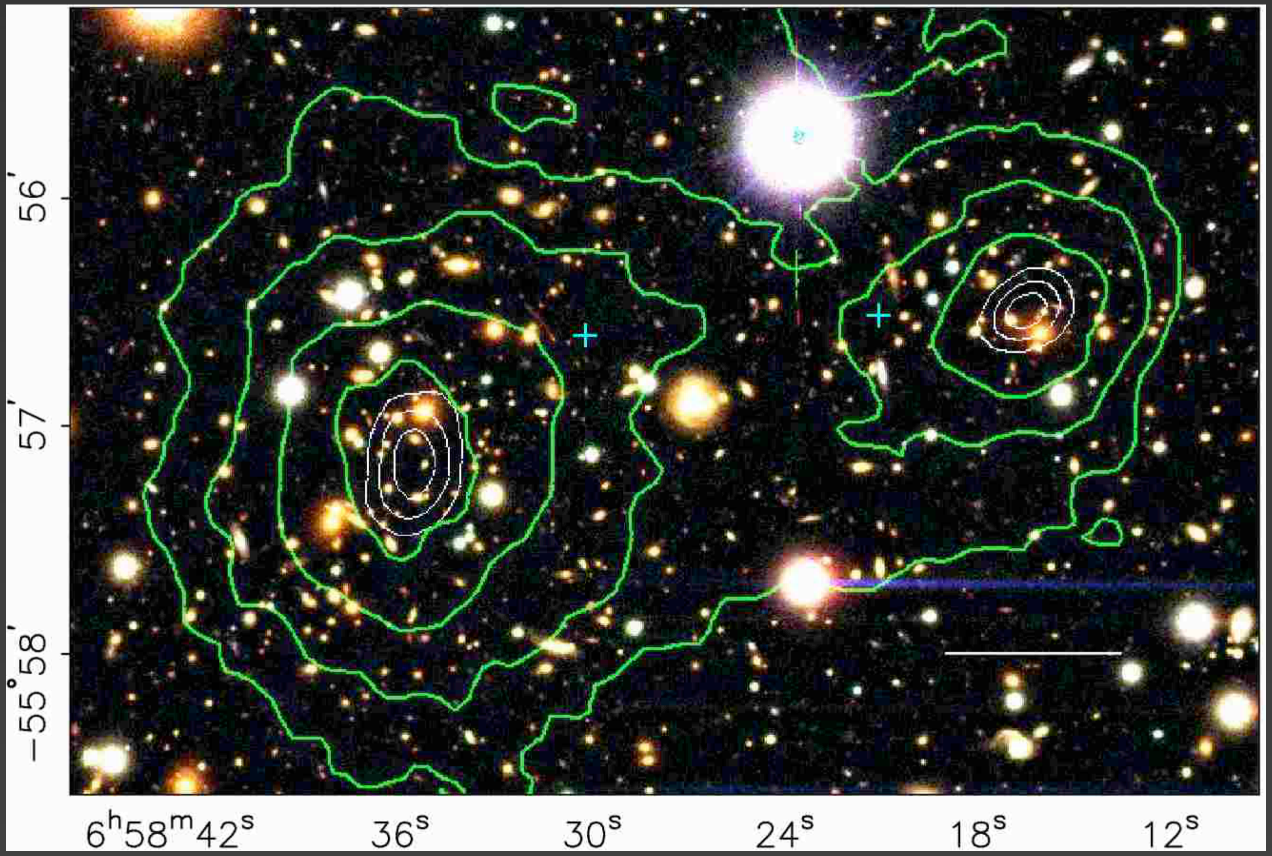

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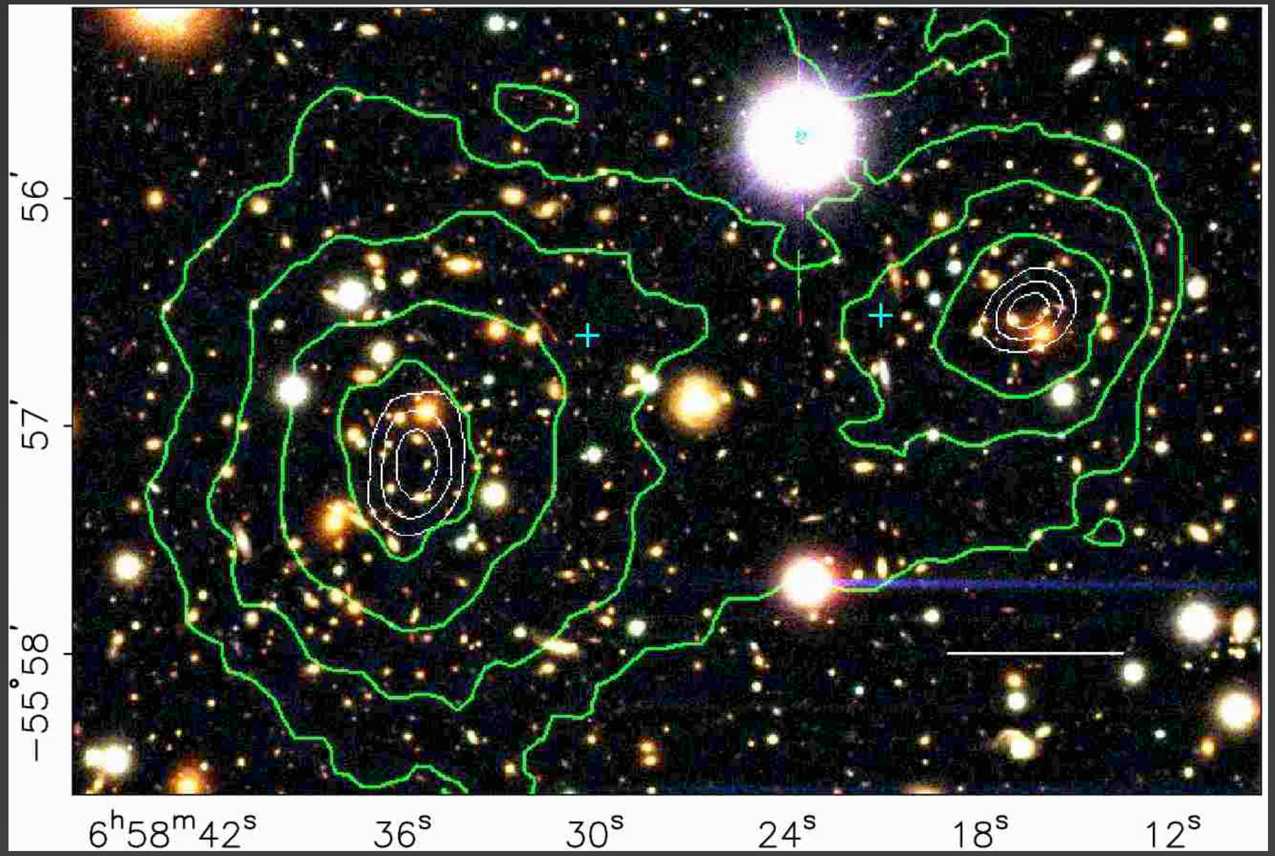

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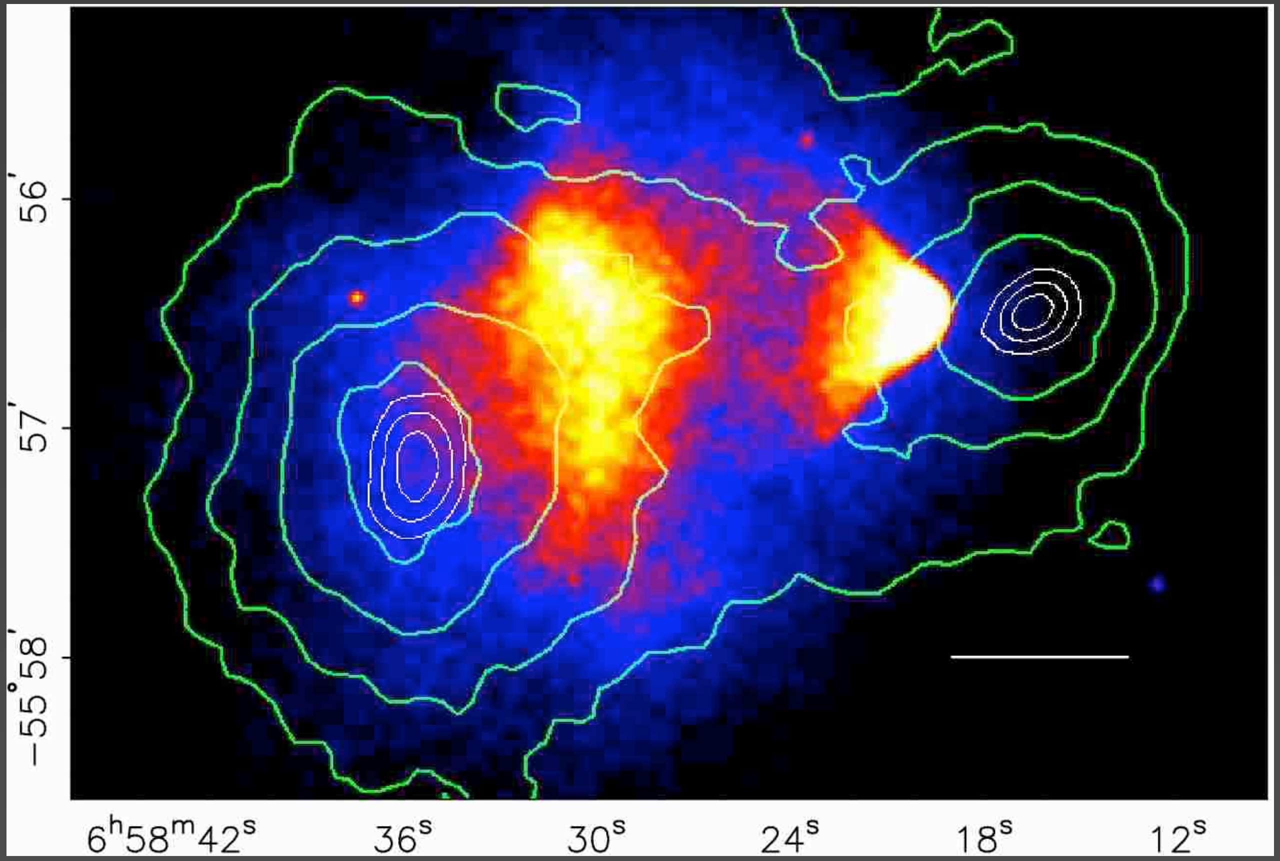

x-ray plasma offset from gravitational field peaks

Newtonian gravity:
k proportional to mass density
=> Most Mass in Galaxies
(Dark Matter!)

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Gravitational potential peaks do <u>not</u> necessarily coincide with matter location! Depend on $\mu(x)$ especially if this is rapidly varying with position inside the system

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$$\nabla.(\mu(|\nabla\Phi|/a_0)\nabla\Phi) = 4\pi G\rho \qquad \frac{GM(r)}{r^2} = \int \frac{\sin(\theta)d\theta d\psi}{4\pi}\frac{\partial\Phi(r,\theta,\psi)}{\partial_r}\mu(x)$$

(Angus,Famaey&Zhao 06)

$$\mu(x) = 1 - [\frac{1+\alpha x}{2} + \sqrt{(\frac{1-\alpha x}{2})^2 + x}]^{-1}, \qquad x = \frac{|\nabla\Phi|}{a_0}$$

Gravitational potential peaks do not necessarily coincide with matter location! Depend on $\mu(x)$ especially if this is rapidly varying with position inside the system

MOND: What you see (in terms of lensing convergence/gravitational potential) is not what you get (in terms of density)

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- Modified Gravity models are young, complex and are not fully explored