Can Early-Dark Energy Solve the Arc Statistics Problem?

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Abstract

Since several years the statistics of gravitational arcs in a standard ΛCDM cosmology cannot be reconciled with the observational situation. While this might be due to the scarcity of observational data, such discrepancy asks for some alternative theoretical explanation. We show that a **standard model with recent WMAP normalization is at odds with observations** when a realistic number counts function for background sources is considered. On the other hand, under the same assumptions models with an **early quintessence contribution accommodate very well the existing data**.

Semi-Analytic Strong Lensing Efficiency

Optical Depth of the Cluster Population

The cross section σ_d for gravitational arcs with length-to-width ratio larger than d of individual galaxy clusters is computed using a **fast, semi-analytic algorithm** previously developed. It takes into account finite source size and ellipticity, and nicely reproduces results from fully numerical ray-tracing simulations.

Optical depth of the whole cluster population for sources at redshift z_s:

$$\tau_d(z_s) = \int_0^{z_s}\int_0^{+\infty} N(M,z)\sigma_d(M,z)\frac{dMdz}{4\pi D_A^2(z_s)},$$

where $N(M,z)$ is the abundance of structures with mass M at redshift z, while D_A is the angular diameter distance. The average optical depth $\bar{\tau}_d$ is the integral over z_s of $\tau_d(z_s)$, weighed by the source redshift distribution.

Important Contributions

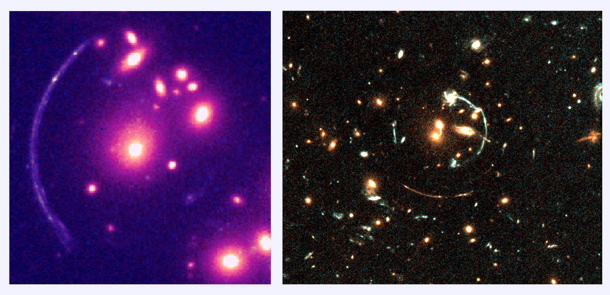
Several factors like baryonic physics and dark matter halos of individual galaxies have been shown to contribute little to the arc statistics of galaxy clusters and are therefore neglected at first order.
A few contributions that **cannot** be ignored:

- Cluster **asymmetries** are included by modeling dark matter halos with elliptical NFW density profiles.
- **Substructures and mergers** are included by constructing semi-analytic merger trees for a synthetic representation of the cluster population.
- The **source redshift distribution** is adapted to observational studies.
- The number counts of background faint galaxies are taken from observations of the Hubble Deep Field and suitably distorted by the lensing magnification bias.

Realistic Number of Arcs

The total number of observed arcs in a given cosmological model is given by $N_d = n_s\bar{\tau}_d$, where n_s is the total number of sources visible below some suitable limiting magnitude.

Observational studies extrapolate ~ 2000 giant arcs (i.e. arcs with length-to-width ratio larger than 10 and $R-$band magnitude ≤ 21.5) in the whole sky.



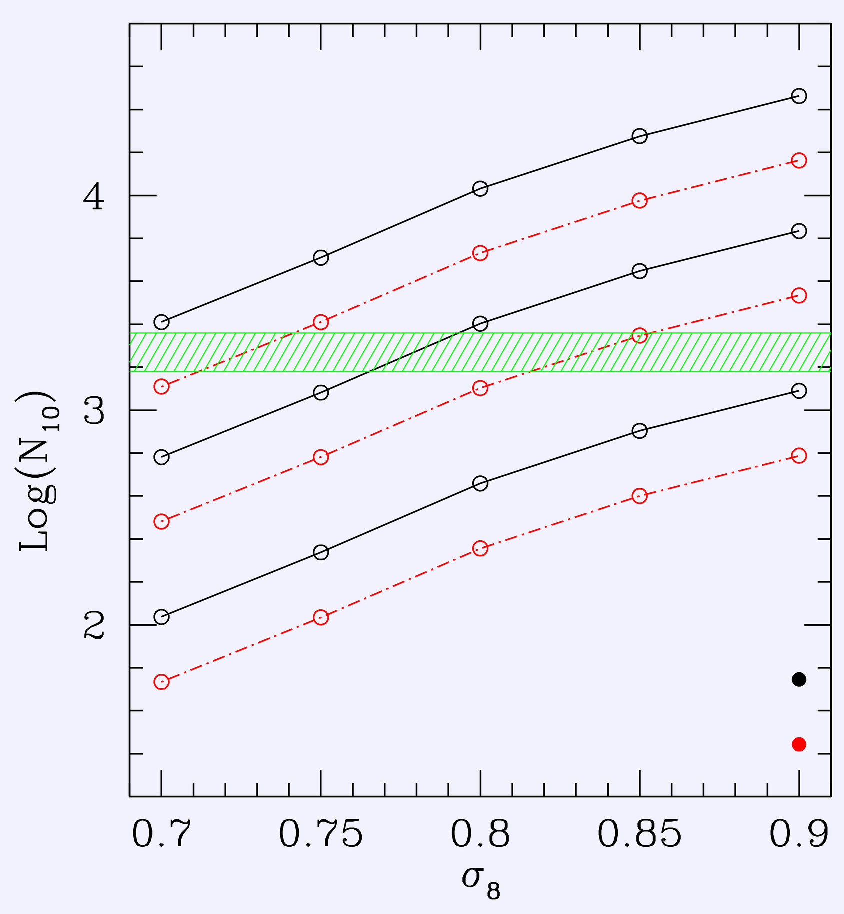
Counts in two different bands are computed here, namely I and R band, where the conversion from one to another is performed by using templates of real spiral galaxies.

Comparison With Observations

ΛCDM With Varying Normalisation

The number of arcs with $d > 10$ and $R \leq 21.5$ (bottom red line) predicted to be observed in a ΛCDM model with different values of σ_8 is compared here to observational data (green shaded area).

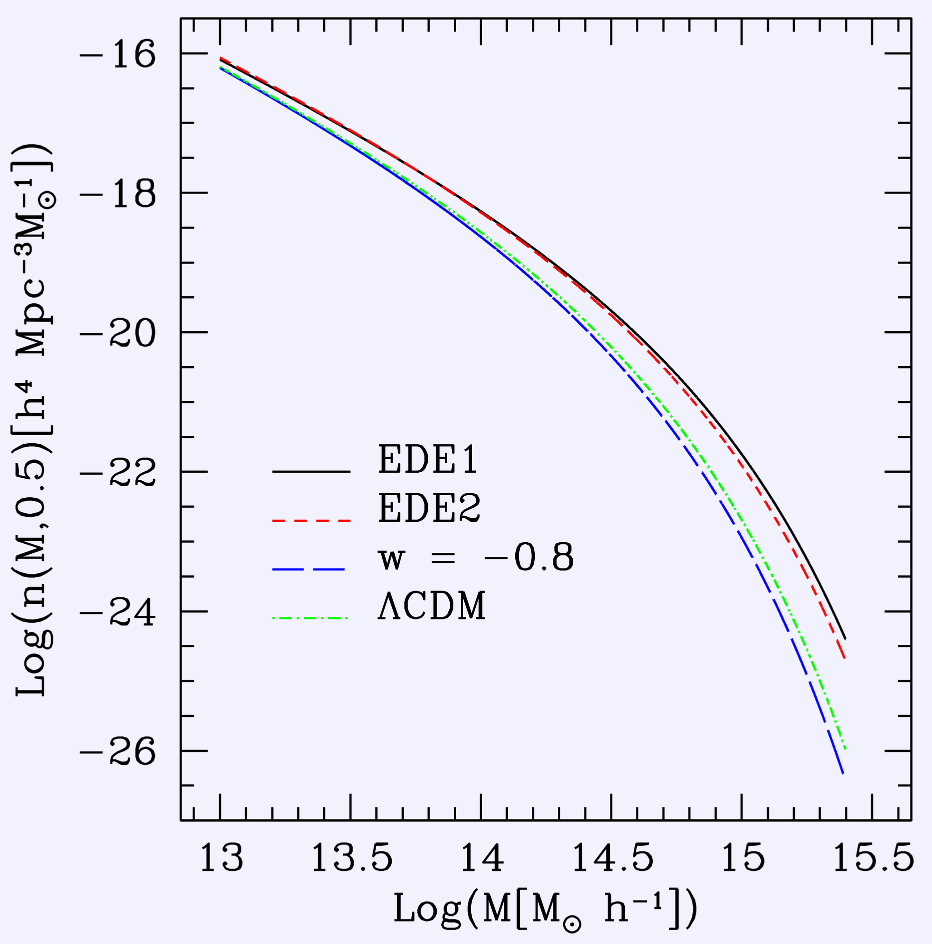
The **predictions fall always short with respect to observations**. While the mild discrepancy at $\sigma_8 = 0.9$ can be accommodated, for instance by baryonic physics, for low$-\sigma_8$ models the discrepancy is of a factor > 6, which cannot be solved by known contributions.



Expected Effect of Early-Dark Energy

Due to the larger Hubble drag, in early quintessence models the entire structure formation process is slower and shifted to higher redshift with respect to the ΛCDM case. As a consequence, individual dark matter halos are more compact and concentrated.

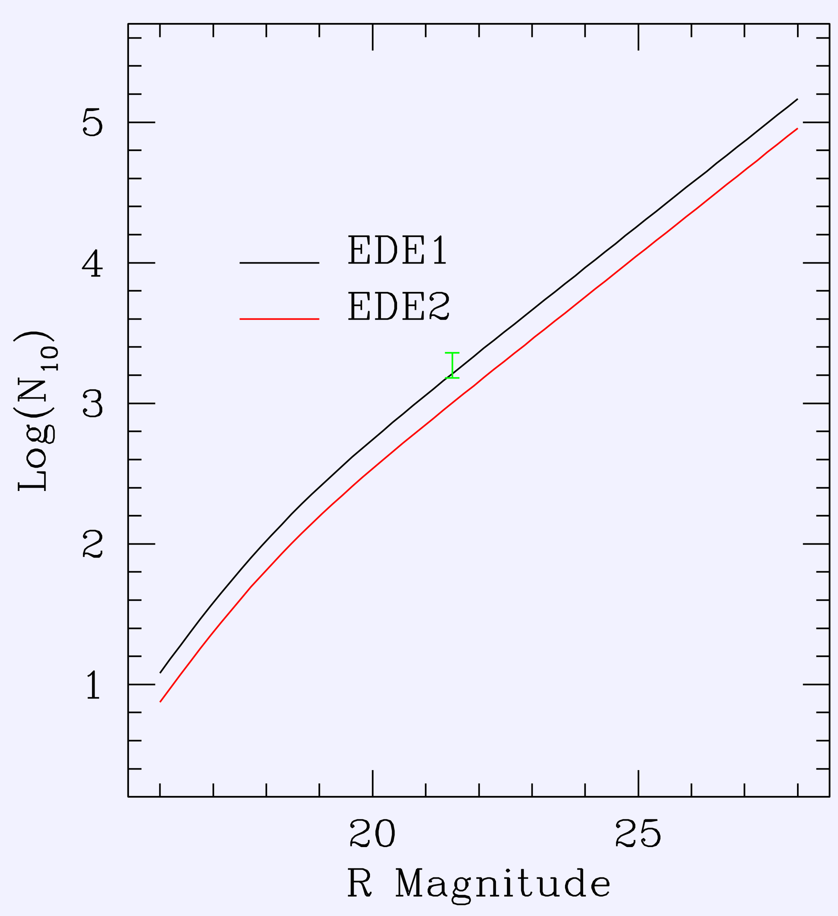
Massive cluster abundance is expected to be significantly increased compared to more standard cosmological models (Figure). Differences in the merger rate are expected as well.



Arc Statistics in Early-Dark Energy Models

In models with early-dark energy one expects to have **more massive clusters**, and individual clusters to be more concentrated, hence to be more efficient lenses.

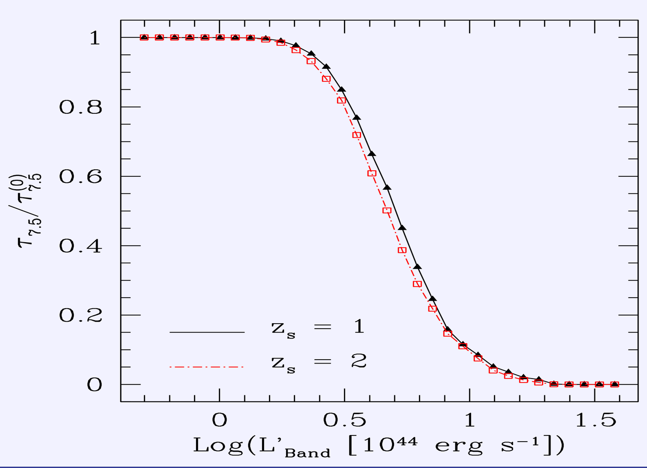
In this Figure we show the number of arcs with length-to-width ratio larger than 10 as a function of the limiting R magnitude for two early-dark energy models with $\sigma_8 \sim 0.8$. The two models have slight differences in the other parameters. The predicted number of arcs perfectly agrees with observations for giant arcs (green bar).



Further Remarks

Improvements

- The observational data suffer of limited statistics. Further studies on large and complete samples of optically or X-ray selected galaxy clusters are necessary before definitive conclusions can be reached.
- **Selection effects** on the samples of selected clusters are to be properly taken into account.



Conclusions

- Using a semi-analytic model that incorporates all the relevant contributions to lensing efficiency, we show that predictions on the abundance of giant arcs in a standard ΛCDM model can be brought in agreement with observations only for a **high value of the power spectrum normalisation**, $\sigma_8 \sim 0.9$.
- While a ΛCDM cosmology with WMAP-3 or WMAP-5 normalisation is in stark disagreement with observations, we show that **models with an early-dark energy contribution nicely fulfill observational constraints** also with a low value for σ_8.
- Better observational studies and a more precise characterization of selection effects, for instance in large cosmological simulations are needed before a firm conclusion can be drawn in this sense.

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