DISCOVERY OF A 4σ DEVIATION FROM ΛCDM USING THE HUBBLE DIAGRAM OF QUASARS

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AGN13: Beauty and the Beast
Milano, 9-12 October 2018
The (tight) X-ray/UV non-linear relation


Log $L_X \sim 0.6 \log L_{UV} + 7$
$\sigma = 0.24$ dex!
Cosmology with quasars

The distance modulus

\[ D_L(z, \Omega_M, \Omega_\Lambda) \]


\[ \log(L_X) = \beta + \gamma \log(L_{UV}) \]


Standardise the quasar emission

\[ \log(F_X) = \Phi(F_{UV}, D_L) \]

\[ = \beta' + \gamma \log(F_{UV}) + 2(\gamma - 1)\log(D_L) \]

\[ D_L(z, \Omega_M, \Omega_\Lambda) \]

The \( L_X-L_{UV} \) non-linear relation as a way to measure quasar distances

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AGN13, Oct 9-12, 2018
Cosmology with quasars
The Quasars Hubble Diagram


~800 quasars

Supernovae Cosmology Project (Sullivan+11, Suzuki+12)
Cosmology with quasars

The Quasars Hubble Diagram


~800 quasars

Excellent agreement with SNe @ z=0.3-1.4

Supernovae Cosmology Project (Sullivan+11, Suzuki+12)
Cosmology with quasars
The Quasars Hubble Diagram


Test cosmological models in a poorly explored redshift range

Supernovae Cosmology Project (Sullivan+11, Suzuki+12)
Cosmology with quasars
The new! Quasars Hubble Diagram

~1600 quasars: SDSS+3XMM+XMM LP+archive/literature

Risaliti & Lusso submitted
The XMM-Newton program on z~3 quasars

~1Ms AO-16 (co-I, PI: Risaliti): 30 non-jetted SDSS quasars @z=3-3.3 observed for 25-35 ks
Cosmology with quasars

The new! Quasars Hubble Diagram: sample

~1600 quasars: SDSS+3XMM+XMM LP+archive/literature

\[
\begin{align*}
\text{E(B-V)<0.1} & \quad (N=5,377) \\
\Gamma>1.7 & \quad (N=4,026) \\
F_{\text{EXP}}<F_{\text{MIN}}+2\delta & \quad (N=3,409) \\
\text{TOTAL} & \quad N=7,075
\end{align*}
\]
Cosmology with quasars

The new! Quasars Hubble Diagram: $L_X$-$L_{UV}$

Risaliti & Lusso submitted

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Cosmology with quasars
The new! Quasars Hubble Diagram: redshift dependence

\[
\log D_L = \frac{1}{2-2\gamma} (\gamma \log F_{UV} - \log F_X) + \beta.
\]

Risaliti & Lusso submitted
Dispersion in the Hubble diagram

Risaliti & Lusso 2015
(800 QSOs)

Risaliti & Lusso, subm
(1,600 QSOs)

\( \Delta (\log D_L) \)

\( z \sim 3 \) QSOs

SN1a

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Cosmology with quasars
The new! Quasars Hubble Diagram

~1600 quasars: SDSS+3XMM+XMM LP+archive/literature

deviation from the $\Lambda$CDM model emerges at higher redshift, with a statistical significance of $\sim 4\sigma$!
Cosmology with quasars
The new! Quasars Hubble Diagram

Risaliti & Lusso submitted

Cosmographic approach

\[ P[\log(1+z)] = D_L = k \Sigma_i a_i [\log(1+z)]^i \]
\[ k = \ln(10)c/H_0 \]
\[ a_2(\Omega_M), a_3(\Omega_M) \]

Intersections magenta lines and black curve are the points with \( w = 1 \) (left) and \( w = -1 \) (right), values of \( w \) decrease from left to right.

Data suggest: **dark energy density increasing with time**.

Within the \( w \)CDM model: \( \Omega_M > 0.3 \) and \( w < -1.3 \).
Cosmology with quasars

The new! Quasars Hubble Diagram

$w_0 - w_a$ plane where $w(z) = w_0 + w_a z / (1 + z)$, $w = -1$ no evolution data suggest: dark energy density increasing with time.

Within the $\Lambda$CDM model: $\Omega_M > 0.3$ and $w < -1.3$

Risaliti & Lusso (2017)

Risaliti & Lusso submitted
Cosmology with quasars

The new! Quasars Hubble Diagram

\( w_0-w_a \) plane where \( w(z)=w_0+w_a z/(1+z) \), \( w=-1 \) no evolution

Data suggest: **dark energy density increasing with time**.

Within the \( \Lambda \)CDM model: \( \Omega_M>0.3 \) and \( w<-1.3 \)
Do we need an extension to the $\Lambda$CDM? Yes, we do!

Shanks et al. 2018 ArXiv1810.02595
Riess et al. 2018 ArXiv1810.03526
To summarise

New branch of Observational Cosmology using Quasars are standard candles
Measure the Dark Matter & Energy content in the Cosmos
Deviation from the $\Lambda$CDM model at high redshift, with a statistical significance of $\sim 4\sigma$

Risaliti & Lusso (2017, AN, 201713351)