Understanding Acoustic Scale Observations

The One Sided Fight Against Λ

Ewan Chamberlain
Supervisor: Antony Lewis

University of Sussex

Monday 07 April 2025

Lewis & Chamberlain, arxiv:2412.13894

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Now with DESI DR2!

Outline

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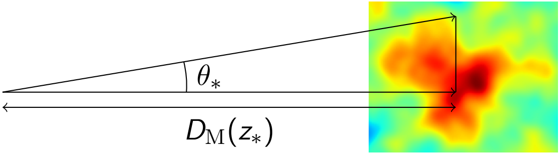
CMB and BAO

- Cosmic Microwave Background (CMB) and Baryon Acoustic Oscillations (BAO) define "standard rulers".



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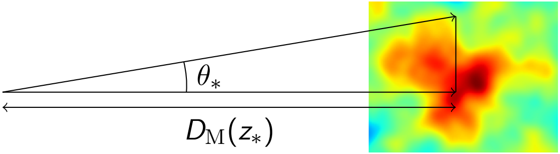

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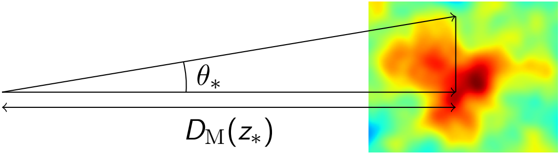

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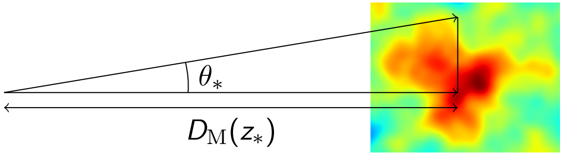
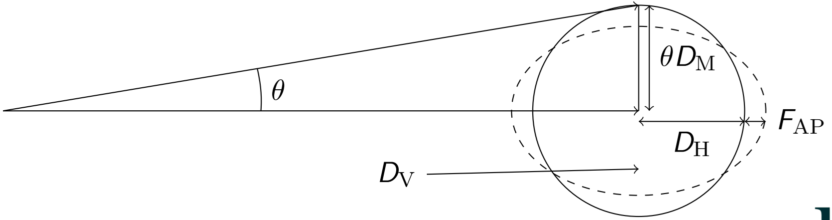
- CMB constrains the angular size of the sound horizon θ_*.
- Measured to within 0.03% by *Planck*.
- BAO measurements detect lower redshift imprints on galaxies.



BAO Measurements

- Line-of-sight: Hubble distance $D_{\mathrm{H}}(z) = c/H(z)$.
- Transverse: angular diameter distance $D_{\mathrm{M}}(z) = c\int_0^z \mathrm{d}z'/H(z')$.
- Angle-averaged BAO scale: $D_{\mathrm{V}}(z) = \left[zD_{\mathrm{M}}^2(z)D_{\mathrm{H}}(z)\right]^{1/3}$.
- Alcock-Paczynski parameter: $F_{\mathrm{AP}}(z) = D_{\mathrm{M}}(z)/D_{\mathrm{H}}(z)$.



Dark Energy

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$$w(a) = p(a)/\rho(a) = w_0 + w_a(1 - a).$$

- $w_0 w_a$CDM not necessarily consistent with the Null Energy Condition (NEC).

Null Energy Condition

- $\forall k : g_{\mu\nu} k^\mu k^\nu = 0, T_{\mu\nu} k^\mu k^\nu \geq 0$ (arXiv:1401.4024)

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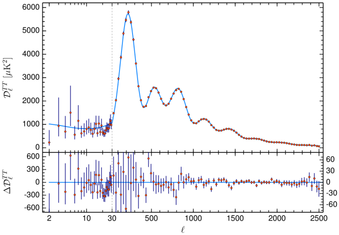
Question

Do DESI measurements imply NEC violation, or is it just an artefact of the model?

Constraints

From *Planck*:

- θ_* is fixed $\implies$ $D_{\rm M}(z_*)$ is fixed.
- $\Omega_{\rm b}h^2$ and $\Omega_{\rm c}h^2$ fixed



Planck 2018 arXiv:1807.06209

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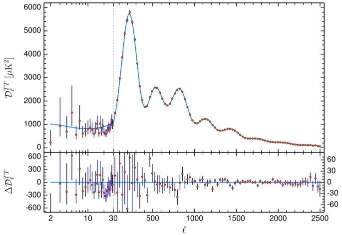

Planck 2018 arXiv:1807.06209

Consider:

- Null energy condition (NEC) requires that for all fluids $\rho + p = \rho(1+w) \geq 0 \implies \mathrm{d}\rho/\mathrm{d}z \geq 0$.

Inequalities

Inequality	Redshift
$D_{\rm H}(0) \geq D^{\Lambda}_{\rm H}(0)$	At $z = 0$
$D_{\rm H}(z) \geq D^{\Lambda}_{\rm H}(z)$	For $0 \leq z \leq z_c$
$D_{\rm H}(z) \leq D^{\Lambda}_{\rm H}(z)$	For $z_c \leq z \leq z_*$
$D_{\rm M}(z) \geq D^{\Lambda}_{\rm M}(z)$	For all z
$\frac{D_{\rm H}}{D^{\Lambda}_{\rm H}} \leq \frac{D_{\rm M}}{D^{\Lambda}_{\rm M}}$	For all z
$F_{\rm AP} \geq F^{\Lambda}_{\rm AP}$	For all z
$D_{\rm V} \geq D^{\Lambda}_{\rm V}$	For $0 \leq z \leq z_c$
$\frac{D_{\rm V}}{D^{\Lambda}_{\rm V}} \geq \left(\frac{F_{\rm AP}}{F^{\Lambda}_{\rm AP}}\right)^{-1/3}$	For $z > z_c$

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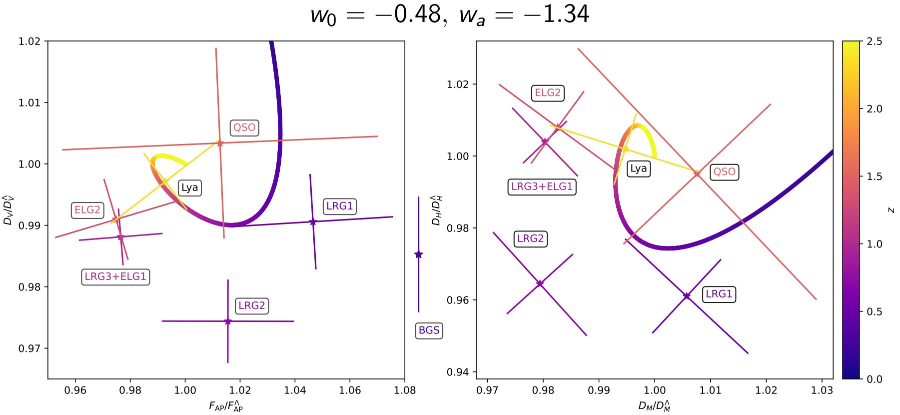
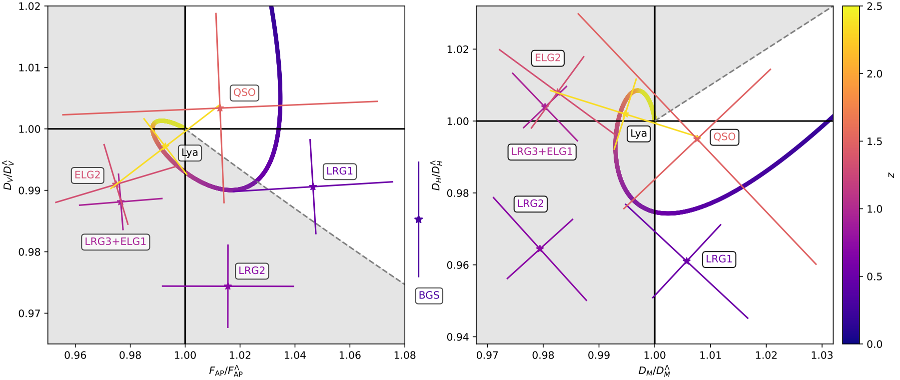
DESI BAO DR2 Measurements



DESI BAO DR2 Measurements

$$w_0 = -0.48,\ w_a = -1.34$$



Conclusions

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Website: ewanchamberlain.github.io
Paper: arXiv:1807.06209

- NEC imposes strict conditions on BAO observables relative to ΛCDM.
- These constraints rule out substantial regions of parameter space.
- DESI+CMB measurements exibit small tensions with ΛCDM that cannot be explained by any NEC-consistent DE model.
- Current acoustic data favour ΛCDM over other NEC-consistent models up to statistical fluctuations.

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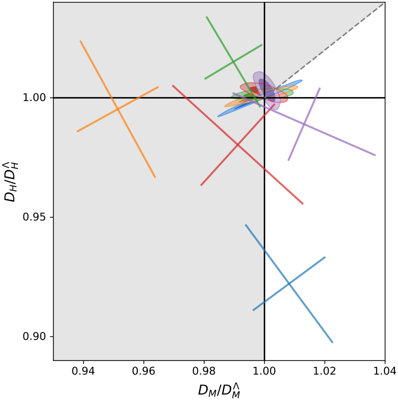
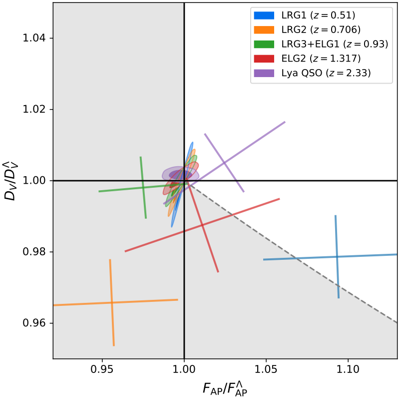
DESI ΛCDM

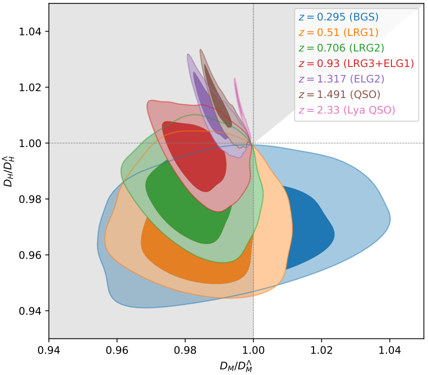


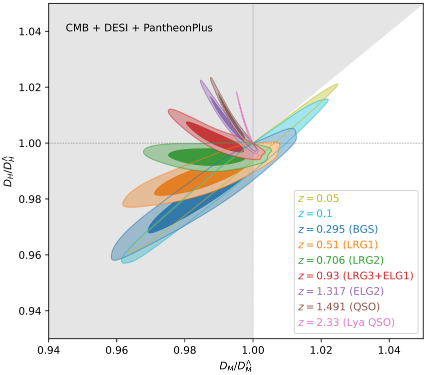
1.00
0.95
0.90
0.94
0.96
0.98
1.00
1.02
1.04
D_M/D_M^Λ
D_H/D_H^Λ



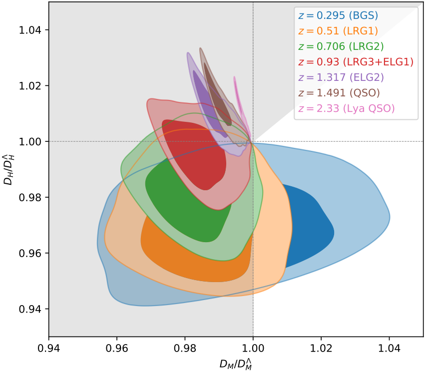
LRG1 ($z = 0.51$)
LRG2 ($z = 0.706$)
LRG3+ELG1 ($z = 0.93$)
ELG2 ($z = 1.317$)
Lya QSO ($z = 2.33$)
1.04
1.02
1.00
0.98
0.96
0.95
1.00
1.05
1.10
F_{AP}/F_{AP}^Λ
D_V/D_V^Λ

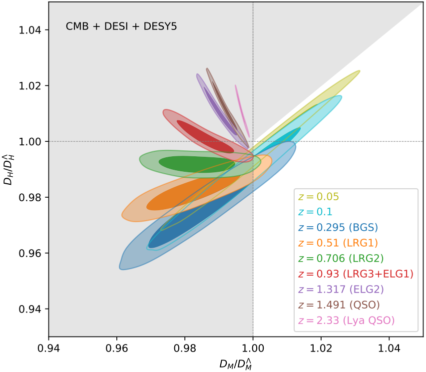
DESI DR1 BAO Measurements + SNe





DESI DR1+DESY5





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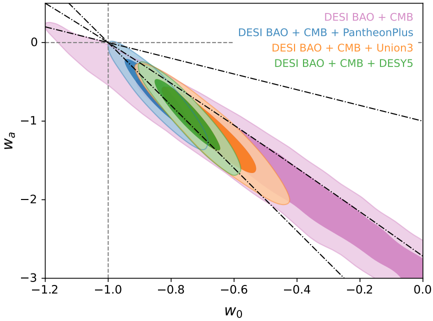
$w_0 w_a$CDM DESI DR1

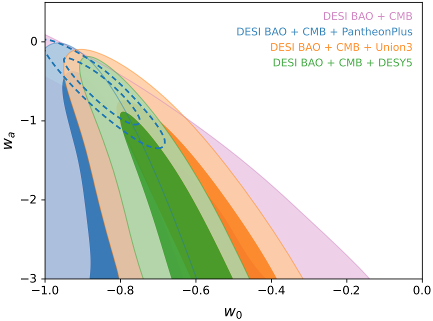
$w_0 w_a$CDM

$$w(a) = w_0 + w_a(1 - a)$$



Max-$w_0 w_a$CDM

$$w(a) = \max\left(w_0 + w_a(1 - a), -1\right)$$



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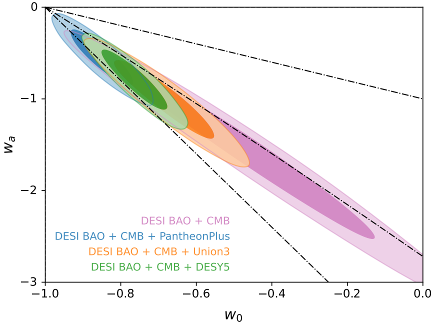

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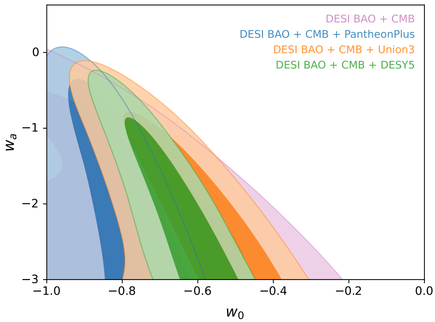
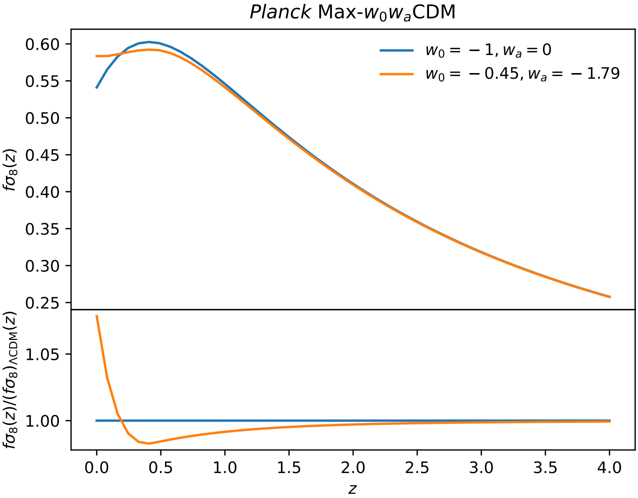


Growth of Structure



Hubble Distance

$$
\begin{aligned}
D_{\mathrm{H}}(z) &\propto \frac{1}{\sqrt{\rho_{\mathrm{m}}(z)+\rho_{\mathrm{de}}(z)}},\\
\frac{\mathrm{d}\rho_{\mathrm{de}}}{\mathrm{d}z} &\geq 0,\\
\rho_{\mathrm{de}}(0) &< \rho_{\Lambda}.
\end{aligned}
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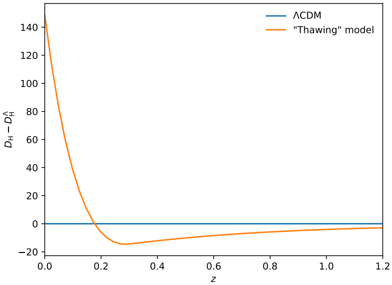

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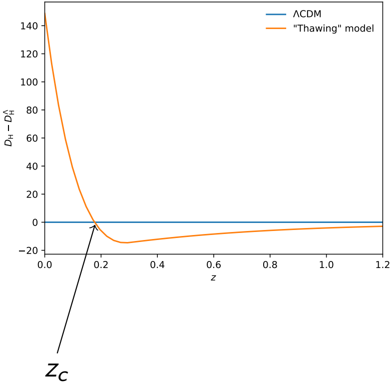
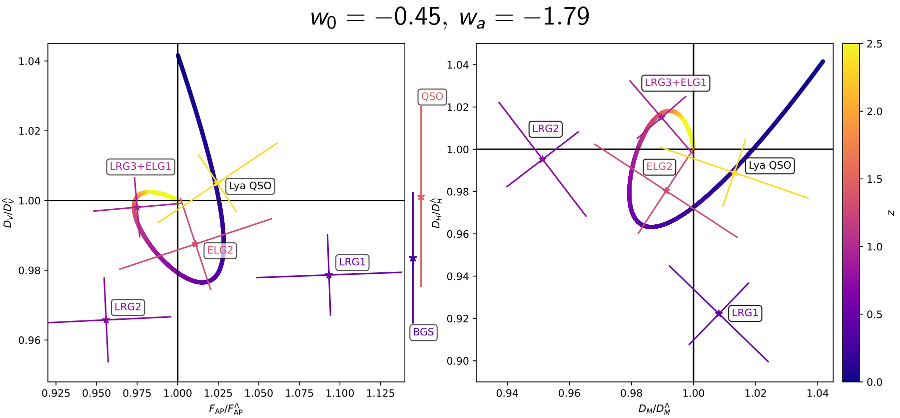
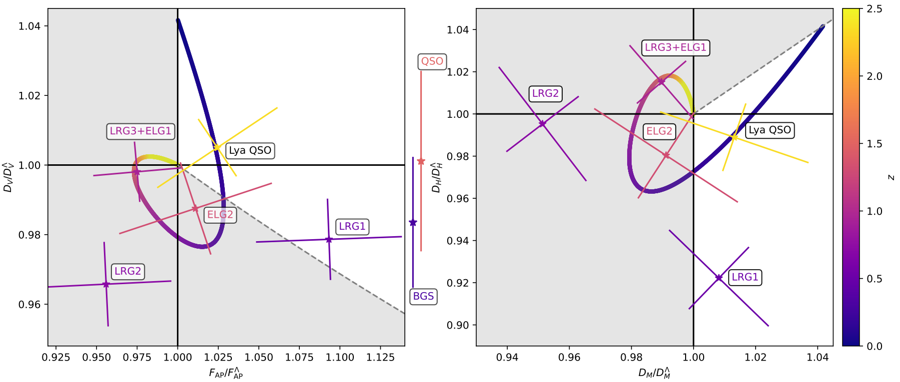


DESI BAO Measurements

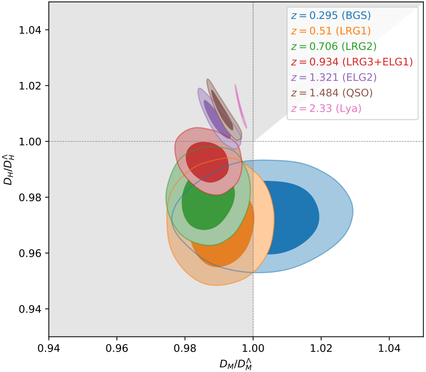


DESI BAO Measurements

$w_0 = -0.45,\ w_a = -1.79$



DESI BAO Measurements + SNe



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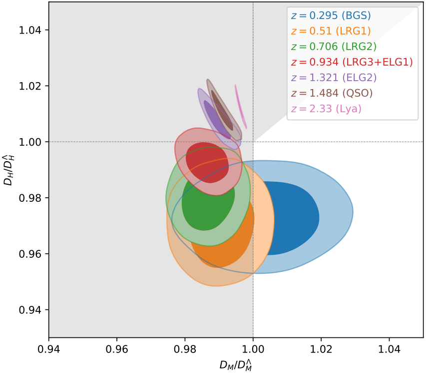
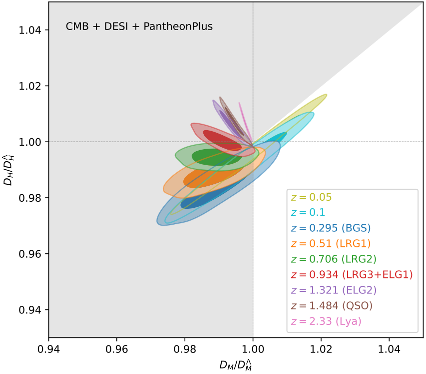
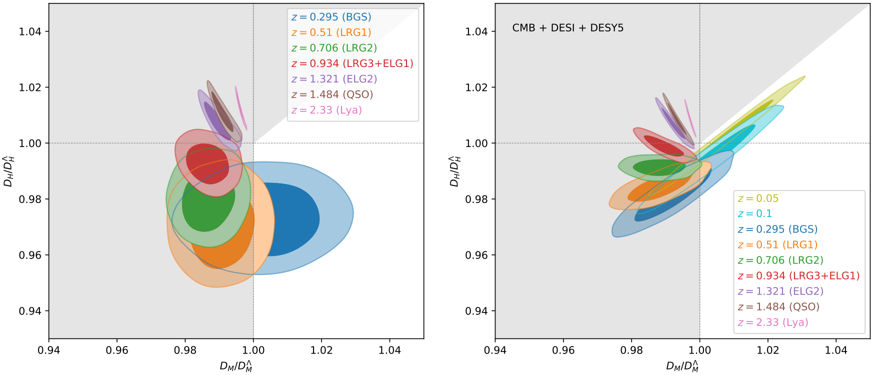




DESI+DESY5



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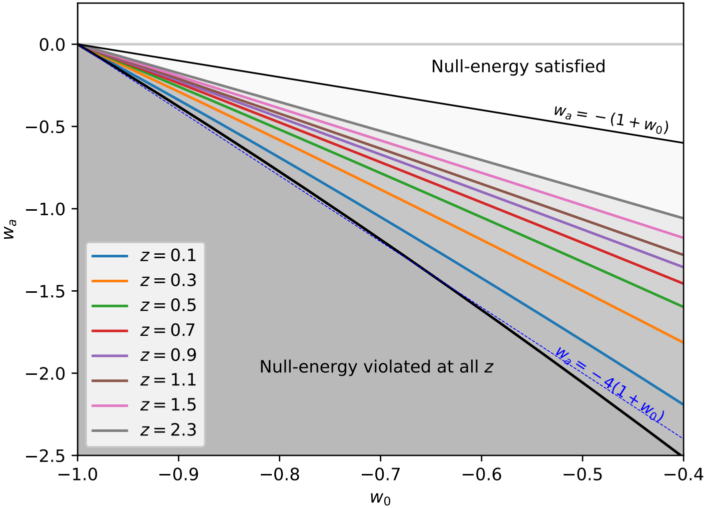
Redshift Bounds



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