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Probing dark energy with braneworld cosmology in the light of recent cosmological data

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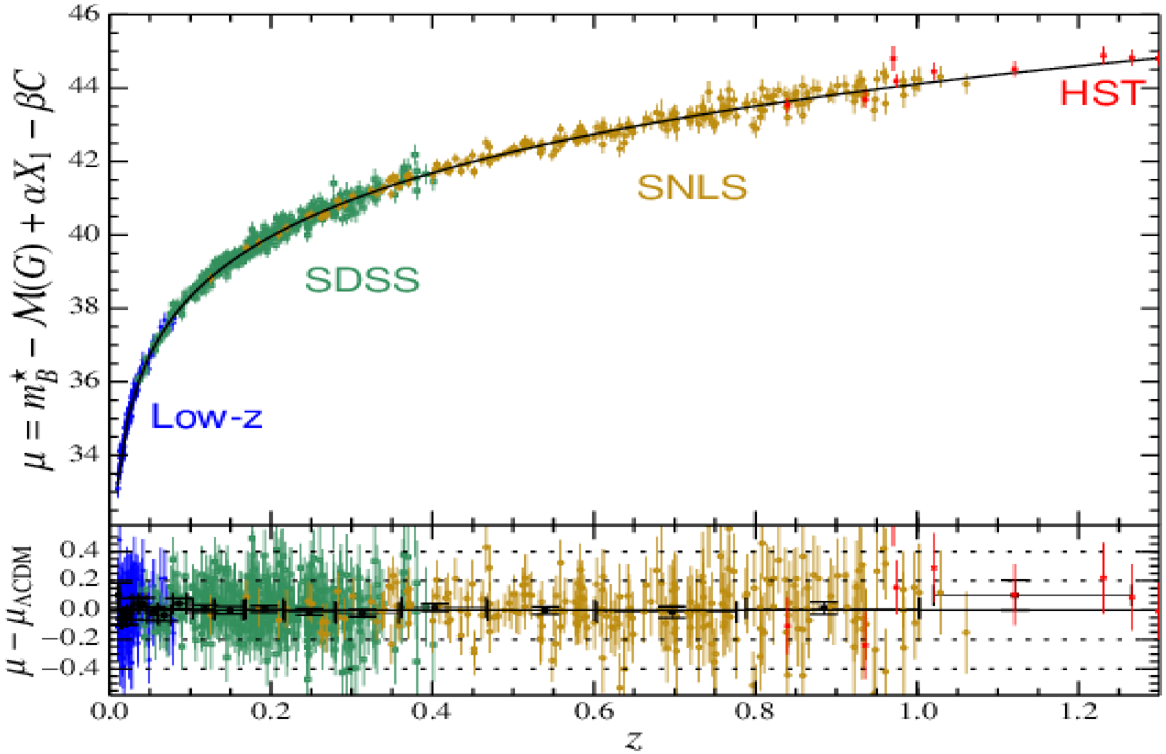
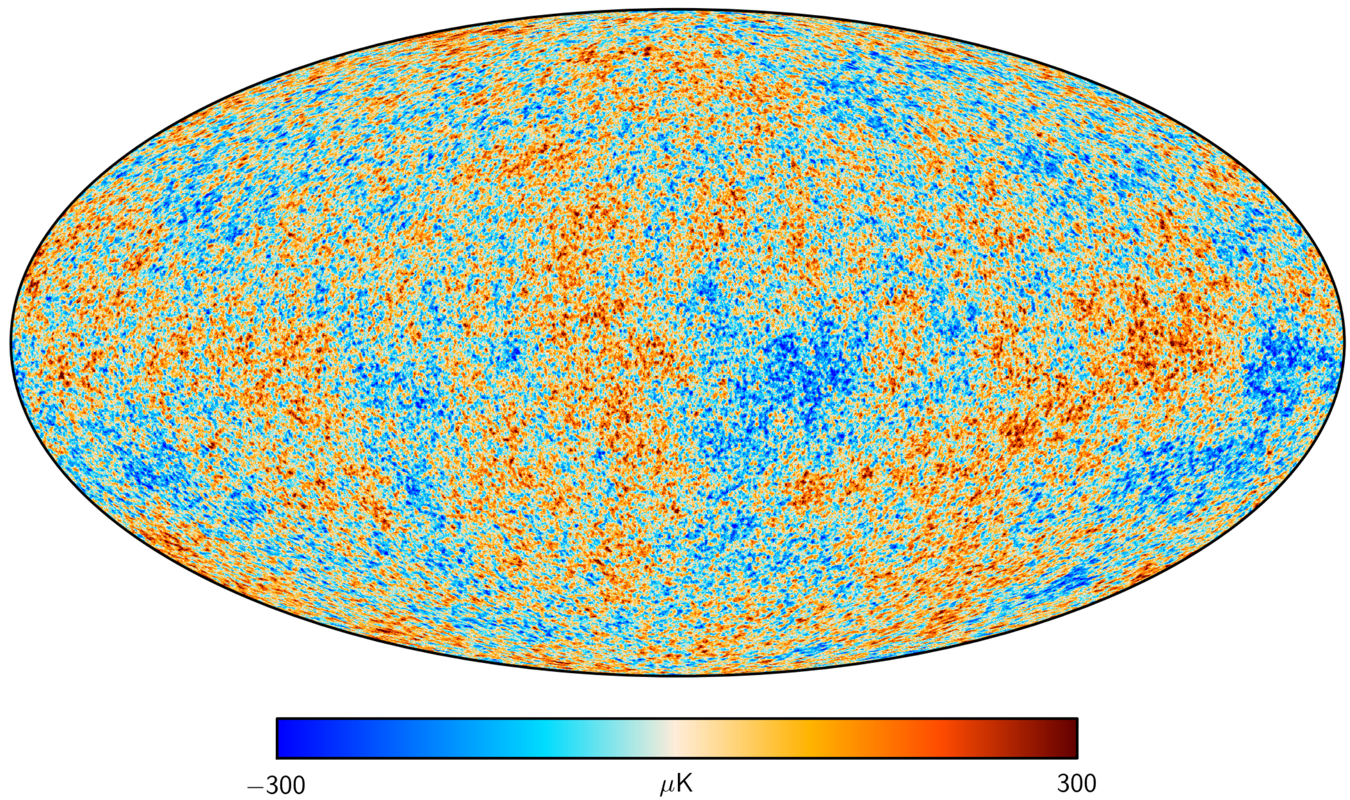
Sexto Encuentro CosmoConce,
Concepción, Chile.
30 November-1December 2017

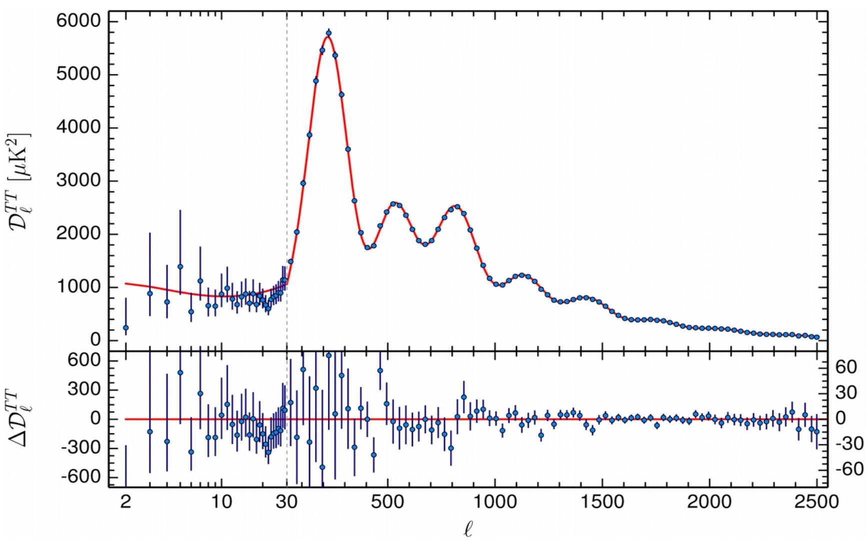


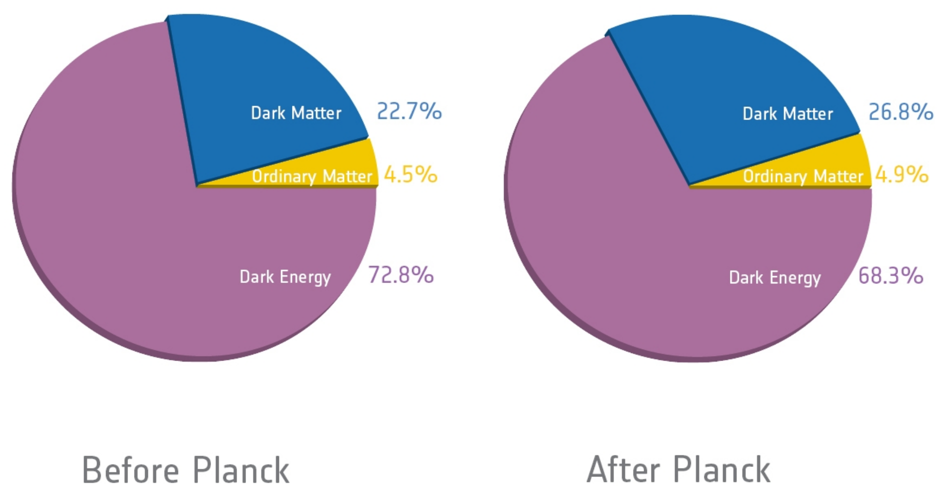
The Joint light-curve analysis (JLA) which consists in 740 data points (Betoule et al A&A, 568, A22,2014)

DARK ENERGY

MODIFIED GRAVITY


−300
μK
300


6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
600
300
0
-300
-600
$\Delta\mathcal{D}_\ell^{TT}$
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ


Dark Matter
22.7%
Ordinary Matter
4.5%
Dark Energy
72.8%
Dark Matter
26.8%
Ordinary Matter
4.9%
Dark Energy
68.3%
Before Planck
After Planck

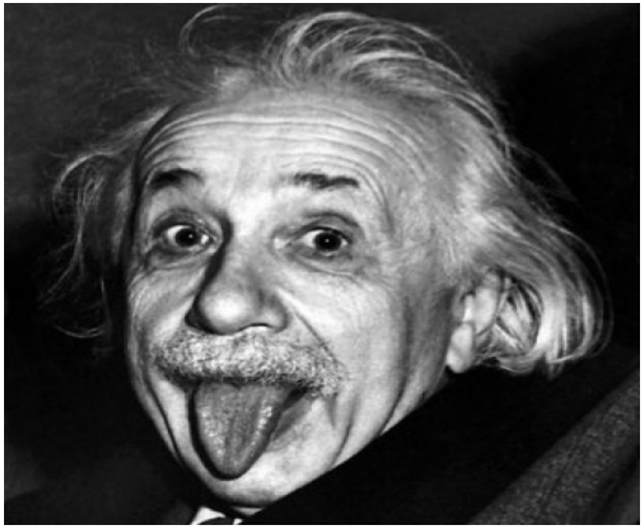
What is the nature of the dark energy/ source of the late cosmic acceleration?

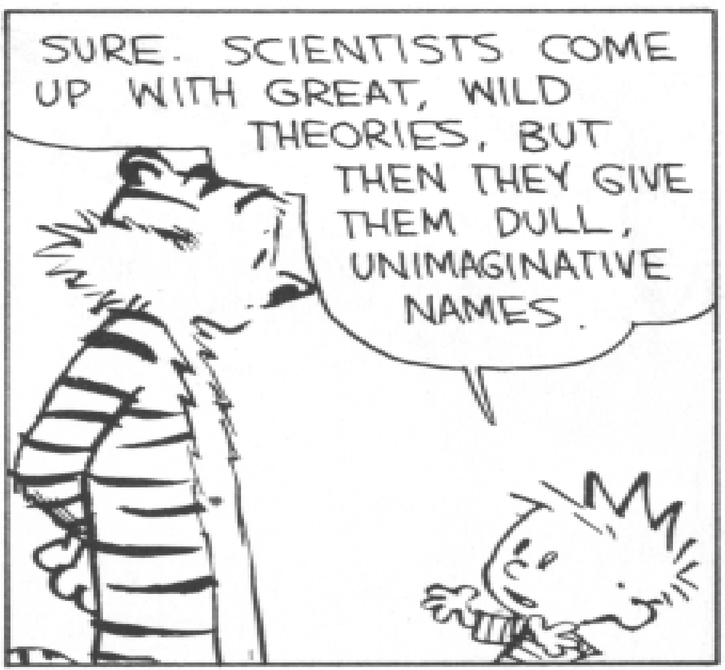
Cosmologists, astronomers, astrophysicists,

particle physicist, etc.

CosmoConce, we have a big challenge ...

Cosmological constant





$$R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu} + \Lambda \, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\frac{\dot{a}^2 + kc^2}{a^2} = \frac{8\pi G\rho + \Lambda c^2}{3}$$

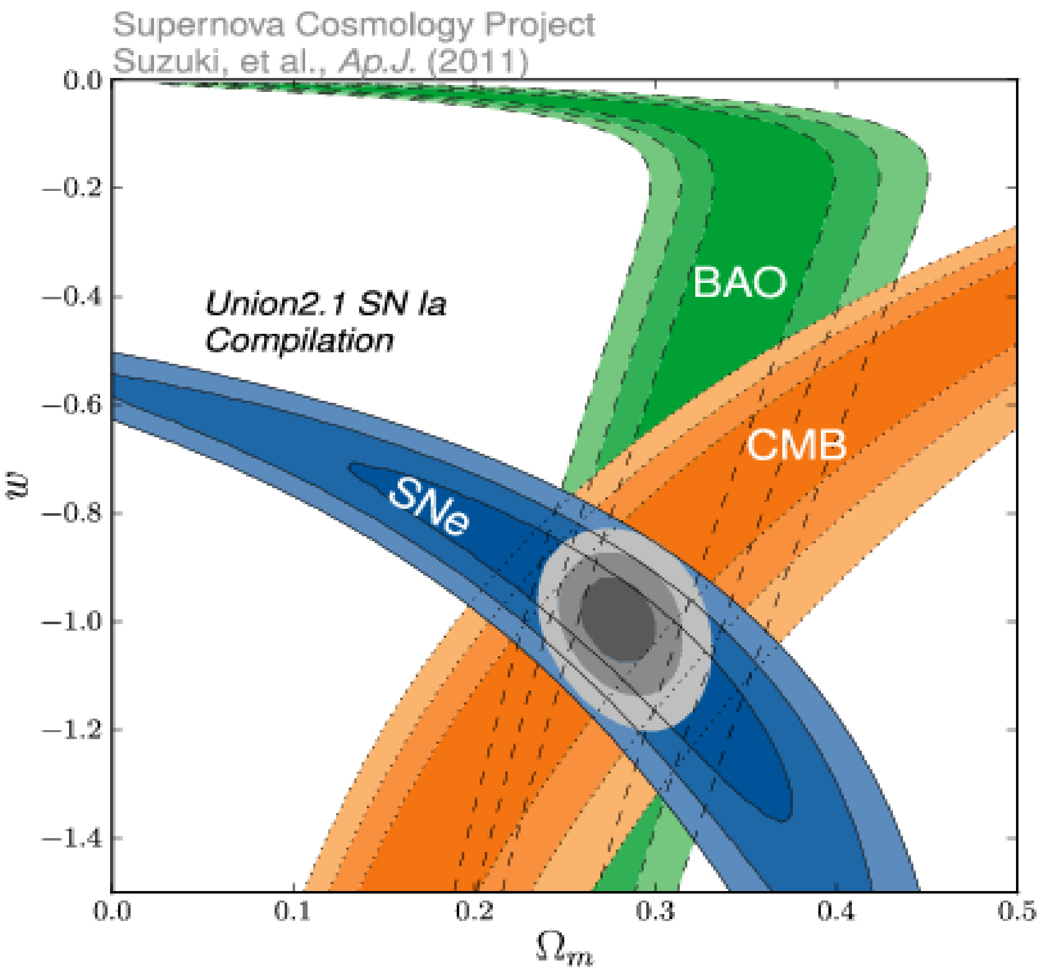
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

$$q(z) = -\frac{\ddot{a}(z)a(z)}{\dot{a}^2(z)}$$

- It was introduced by Einstein to model a static universe !
- Related to the vacuum energy density

The equation of state of DE

The ratio between the pressure and the energy density $w=P/\rho$. If $w<-1/3$ the Universe expansion is accelerated. The equation of state (EoS) for Λ is $w=-1$



The problems of Λ

Although the cosmological constant it the favored candidate by the cosmological observations, it has some fundamental theoretical problems:

- The coincidence problem or why the dark energy energy density is similar to the dark matter energy density today?

- The fine tunning refers to the difference of 120 orders of magnitude in the values predicted by QFT and the observations

Several alternatives have been proposed to solve the problems of Λ

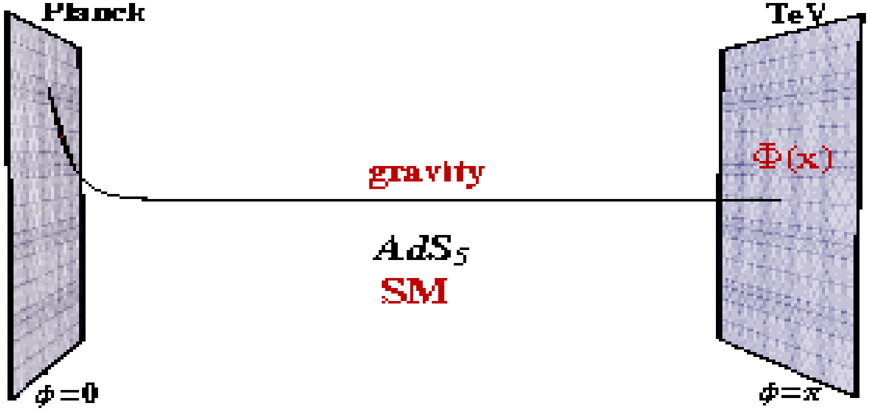
Braneworld

Revision of Brane theory (RS I)

* In this case we will focus our attention to RS models. (Many brane models: DGP, Phantom-brane, etc…)

Randall-Sundrum I model: The main idea is to give a possible solution to the problem of hierarchy.

Brane Cartoon

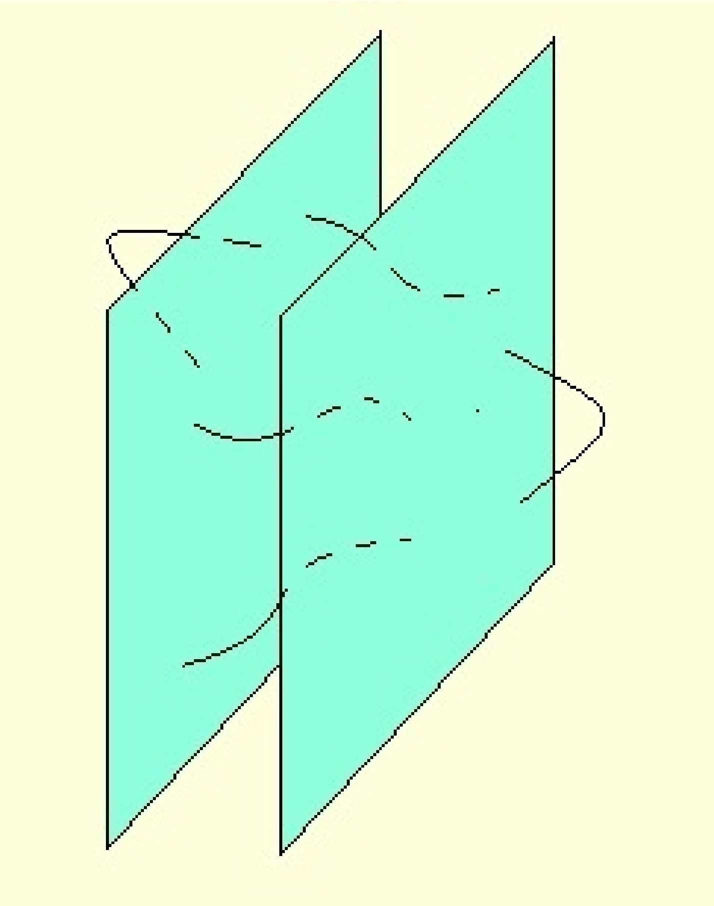


$$R_{AB}-\frac{1}{2}g_{AB}R_{(5)}=-\kappa_*^2\Lambda g_{AB}+\tau\kappa_*^2\sqrt{\frac{-g_h}{g_{(5)}}}\delta_A^\mu\delta_B^\nu g_{\mu\nu}\delta(y)-\tau\kappa_*^2\sqrt{\frac{-g_v}{g_{(5)}}}\delta_A^\mu\delta_B^\nu g_{\mu\nu}\delta(y-\pi r)$$

L. Randall and R. Sundrum, A large mass hierarchy from a small extra dimension, Phys. Rev. Lett. 83 (1999) 3370–3373, [hep-ph/9905221].

Randall-Sundrum II

1. A more economical model with a single brane.
2. It is not necessary for the fifth dimension to be compactified.



$r \to \infty$

*** RS I (With compactification)**

***RS II (Without compactification)**

L. Randall and R. Sundrum, An Alternative to compactification, Phys. Rev. Lett. 83 (1999) 4690–4693, [hep-th/9906064].

Field equations for the brane theory

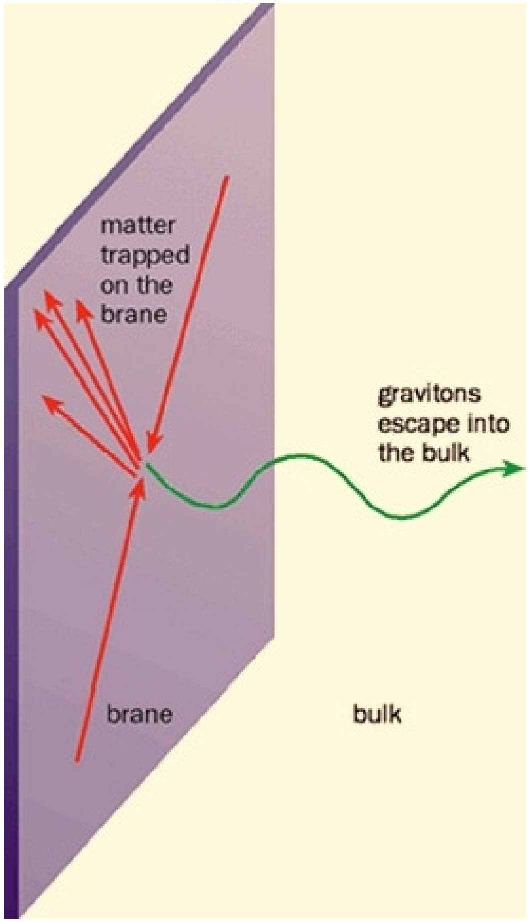
$$G_{\mu\nu} + \xi_{\mu\nu} = \kappa^2_{(4)} T_{\mu\nu} + \kappa^4_{(5)} \Pi_{\mu\nu} + \kappa^2_{(5)} F_{\mu\nu}$$

$$\kappa^2_{(4)} = 8\pi G_N = \frac{\kappa^4_{(5)}}{6}\lambda$$

$$\Pi_{\mu\nu} = -\frac{1}{4} T_{\mu\alpha} T^{\alpha}_{\nu} + \frac{T T_{\mu\nu}}{12} + \frac{g_{\mu\nu}}{24}(3T_{\alpha\beta}T^{\alpha\beta} - T^2)$$

$$F_{\mu\nu} = \frac{2T_{AB} g^A_\mu g^B_\nu}{3} + \frac{2g_{\mu\nu}}{3}\left(T_{AB} n^A n^B - \frac{^{(5)}T}{4}\right)$$

$$\xi_{\mu\nu} = ^{(5)} C^E_{AFB} n_E n^F g^A_\mu g^B_\nu$$



T. Shiromizu, K. Maeda and M. Sasaki, The einstein equations on the 3-brane world, Phys. Rev. D 62 (Jun, 2000) 024012.

Brane background cosmology

Our goal is to study a DE field in a braneworld

$$ds^2 = -dt^2 + a(t)^2(dr^2 + r^2(d\theta^2 + \sin^2\theta d\varphi^2)),$$ **FLRW cosmology.**

$$H^2 = \kappa^2 \rho_{eff},$$

$$\rho_{eff} = \sum_i \rho_i \left(1 + \frac{\rho_i}{2\lambda}\right),$$

No Weyl terms i.e. No Schwarzschild bulk.

Corrective terms with the brane tension terms.

Densities:
Baryonic matter, dark matter, radiation, dark energy.

$$H_{high}^2 = \kappa^2 \sum_i \frac{\rho_i^2}{2\lambda},$$

At high energies.

Modified Friedmann equation

$$H^2 = \kappa^2 \left[\frac{\rho_{0m}}{a^3} \left(1 + \frac{\rho_{0m}}{2\lambda a^3} \right) + \frac{\rho_{0r}}{a^4} \left(1 + \frac{\rho_{0r}}{2\lambda a^4} \right) + \frac{\rho_{0de}}{a^{3(1+\omega_{de})}} \left(1 + \frac{\rho_{0de}}{2\lambda a^{3(1+\omega_{de})}} \right) \right].$$

$$\omega_{de} < -\frac{1}{3} \left[\frac{1 + 2\rho_{de}/\lambda}{1 + \rho_{de}/\lambda} \right],$$ Dark energy constraint

In terms of the density parameter and redshift.

$$E(z)^2 \equiv \frac{H(z)^2}{H_0^2} = \Omega_{0m}(1+z)^3 + \Omega_{0r}(1+z)^4 + \Omega_{0de}(1+z)^{3(1+\omega_{de})} + \mathcal{M} \left[\Omega_{0m}^2 (1+z)^6 + \Omega_{0r}^2 (1+z)^8 + \Omega_{0de}^2 (1+z)^{6(1+\omega_{de})} \right],$$

Where:

$$\mathcal{M} \equiv \frac{H_0^2}{2\kappa^2 \lambda} = \frac{\rho_{crit}}{2\lambda},$$

For Dark Energy we have:

$$\omega_{de} < -\frac{1}{3}\left[\frac{1+4\mathcal{M}\Omega_{0de}(1+z)^{3(1+\omega_{de})}}{1+2\mathcal{M}\Omega_{0de}(1+z)^{3(1+\omega_{de})}}\right],$$

Deceleration parameter:

$$q(z) = \frac{q_I(z) + \mathcal{M}\, q_{II}(z)}{E(z)^2},$$

$$q_I(z) = \frac{\Omega_{0m}}{2}(1+z)^3 + \Omega_{0r}(1+z)^4 + \frac{\Omega_{0de}}{2}(1+3\omega_{de})(1+z)^{3(1+\omega_{de})},$$

$$q_{II}(z) = 2\Omega_{0m}^2(1+z)^6 + 3\Omega_{0r}^2(1+z)^8 + \Omega_{0de}^2(2+3\omega_{de})(1+z)^{6(1+\omega_{de})}.$$

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The data

- **H(z) data:** The measurements of the expansion rate of the Universe as a function of redshift. We use 34 data points which span the redshift range $0.07 < z < 2.3$.

$$\chi^2_H = \sum_{i=1}^{34} \frac{\left[H_{th}(z_i) - H_{obs}(z_i)\right]^2}{\sigma^2_{H_i}},$$

- **SNIa data:** We use the Lick Observatory Supernova Search (LOSS) sample containing 586 points in the range $0.01<z<1.4$ (Ganeshalingam et al. 2013).

$$d_L(z) = (1+z)\int_0^z \frac{dz'}{E(z')}. \quad \rightarrow \quad \mu(z) = 5\log_{10}[d_L(z)/\mathrm{Mpc}] + \mu_0,$$

$$\chi^2_{\mathrm{SNIa}} = A - B^2/C \quad \rightarrow$$

$$A = \sum_{i=1}^{586} \frac{[\mu(z_i) - \mu_{\mathrm{obs}}]^2}{\sigma^2_{\mu_i}},$$

$$B = \sum_{i=1}^{586} \frac{\mu(z_i) - \mu_{\mathrm{obs}}}{\sigma^2_{\mu_i}},$$

$$C = \sum_{i=1}^{586} \frac{1}{\sigma^2_{\mu_i}}.$$

- **BAO data:** Baryon acoustic oscillations are the signature of the interactions of baryons and photons in a hot plasma on the matter power spectrum in the pre-recombination epoch.

Quantity	z	BAO measurement	Survey
$d_z \equiv \frac{r_s(z_d)}{D_V(z)}$	0.106	0.336 ± 0.015	6dFGS[32]
d_z	0.44	0.0870 ± 0.0042	WiggleZ[33,34]
d_z	0.6	0.0672 ± 0.0031	WiggleZ[33,34]
d_z	0.73	0.0593 ± 0.0020	WiggleZ[33,34]
d_z	0.15	0.2239 ± 0.0084	SDSS DR7[35]
d_z	0.32	0.1181 ± 0.0022	SDSS-III BOSS DR11[36]
d_z	0.57	0.0726 ± 0.0007	SDSS-III BOSS DR11[36]
$\frac{D_H(z)}{r_s(z_d)}$	2.34	9.18 ± 0.28	SDSS-III BOSS DR11[37]
$\frac{D_H(z)}{r_s(z_d)}$	2.36	9.00 ± 0.3	SDSS-III BOSS DR11[38]

$$\chi^2_{6dFGS} = \left(\frac{d_z(0.106) - 0.336}{0.015}\right)^2,$$

$$\chi^2_{WiggleZ} = \left(\frac{d_z(0.44) - 0.0870}{0.0042}\right)^2 + \left(\frac{d_z(0.6) - 0.0672}{0.0031}\right)^2 + \left(\frac{d_z(0.73) - 0.0593}{0.0020}\right)^2,$$

$$\chi^2_{DR7} = \left(\frac{d_z(0.15) - 0.2239}{0.0084}\right)^2,$$

$$\chi^2_{DR11A} = \left(\frac{d_z(0.32) - 0.1181}{0.0023}\right)^2 + \left(\frac{d_z(0.57) - 0.0726}{0.0007}\right)^2,$$

$$\chi^2_{DR11B} = \left(\frac{\frac{D_H(2.34)}{r_s(z_d)} - 9.18}{0.28}\right)^2 + \left(\frac{\frac{D_H(2.36)}{r_s(z_d)} - 9.00}{0.3}\right)^2.$$

Distance scale

$$D_V(z) = \frac{1}{H_0}\left[(1+z)^2 d_A(z)^2 \frac{z}{E(z)}\right]^{1/3},$$

Angular diameter distance

$$d_A(z) = d_L(z)/(1+z)^2$$

Sound horizon → $r_s(z) = \int_z^\infty \frac{c_s(z')}{H(z')}dz',$

$$\chi^2_{BAO} = \chi^2_{6dFGS} + \chi^2_{WiggleZ} + \chi^2_{DR7} + \chi^2_{DR11A} + \chi^2_{DR11B},$$

- **CMB data:** A useful method to obtain cosmological constraints, without performing a complete perturbative analysis, is to reduce the full likelihood information to a few parameters: the acoustic scale, lA, the shift parameter, R, and the decoupling redshift, z*

$$R = \sqrt{\Omega_m H_0^2}\, r(z_*), \qquad l_A = \frac{\pi r(z_*)}{r_s(z_*)},$$

$$z_* = 1048[1 + 0.00124(\Omega_b h^2)^{-0.738}][1 + g_1(\Omega_m h^2)^{g_2}],$$

$$g_1 = \frac{0.0783(\Omega_b h^2)^{-0.238}}{1 + 39.5(\Omega_b h^2)^{0.763}}, \qquad g_2 = \frac{0.560}{1 + 21.1(\Omega_b h^2)^{1.81}}.$$

$$X = \begin{pmatrix} l_A^{th} - l_A \\ R^{th} - R \\ z_*^{th} - z_* \end{pmatrix},$$

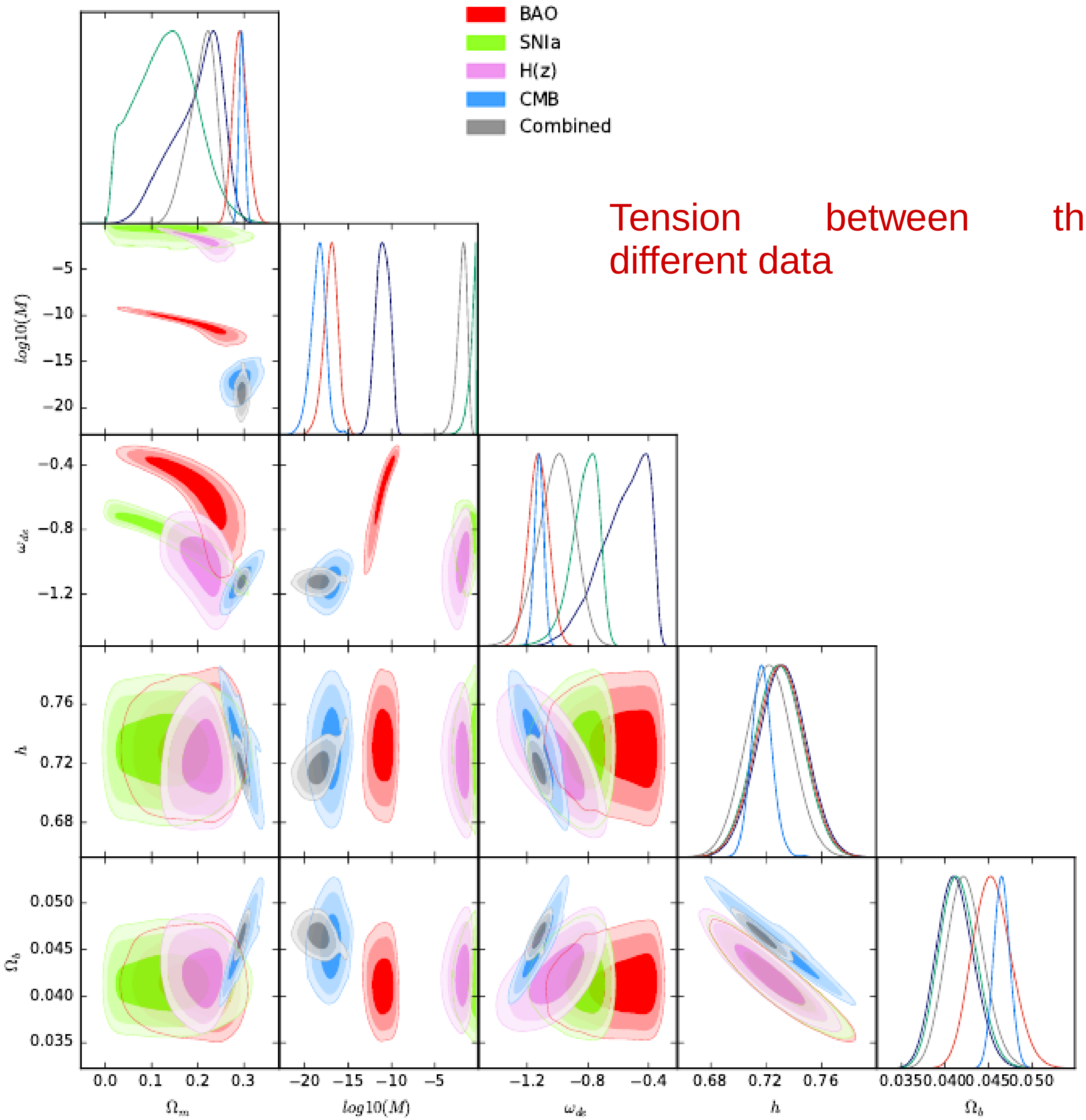
R=1.7492 ±0.0049, lA=301.787±0.089, z*=1089.99±0.29

$$\chi^2_{Pl} = X^T \, \mathrm{Cov}_{Pl}^{-1} \, X,$$

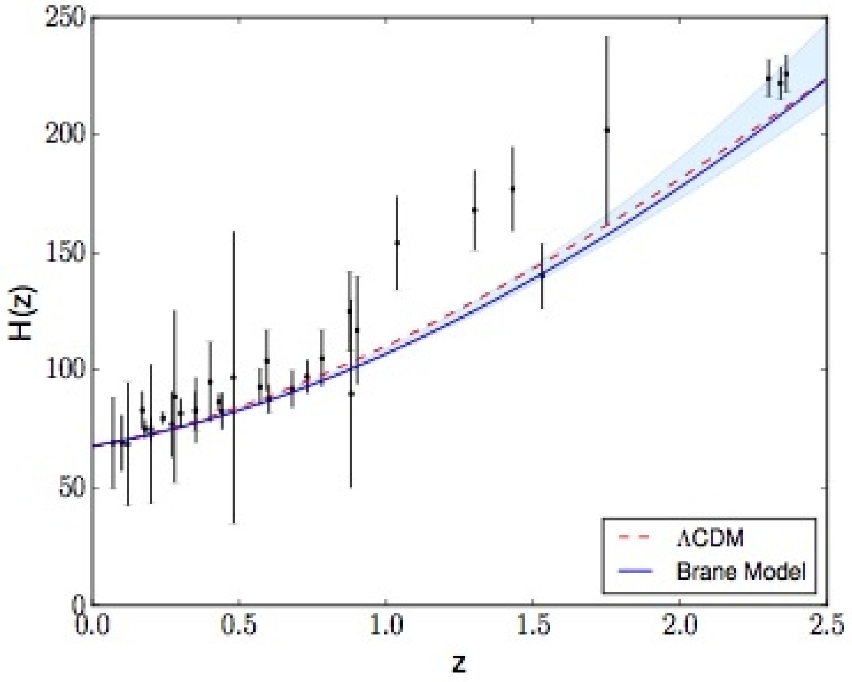
$$\mathrm{Cov}_{Pl}^{-1} = \begin{pmatrix} 162.48 & -1529.4 & 2.0688 \\ -1529.4 & 207232 & -2866.8 \\ 2.0688 & -2866.8 & 53.572 \end{pmatrix}.$$

Results

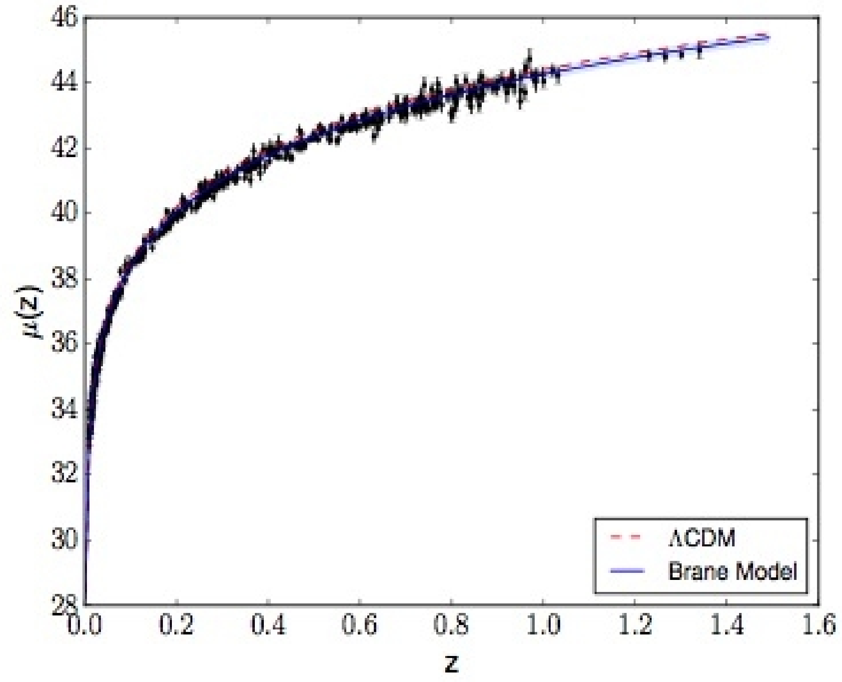
Model	χ^2	h	Ω_m	w_{de}	$\log(\mathcal{M})$	$\lambda(h^2\mathrm{eV}^4)$
			$H(z)$			
Brane	18.19	$0.72^{+0.01}_{-0.01}$	$0.21^{+0.02}_{-0.03}$	$-1.00^{+0.11}_{-0.12}$	< -0.88	$> 3.07 \times 10^{-10}$
ΛCDM	17.15	$0.71^{+0.01}_{-0.01}$	$0.24^{+0.01}_{-0.01}$	-1.0	———	———
			SNIa			
Brane	574.73	$0.72^{+0.01}_{-0.01}$	$0.13^{+0.06}_{-0.07}$	$-0.81^{+0.07}_{-0.10}$	< -0.31	$> 8.27 \times 10^{-11}$
ΛCDM	576.12	$0.72^{+0.01}_{-0.01}$	$0.24^{+0.01}_{-0.01}$	-1.0	———	———
			BAO			
Brane	5.46	$0.73^{+0.01}_{-0.01}$	$0.20^{+0.04}_{-0.07}$	$-0.53^{+0.13}_{-0.19}$	< -9.52	> 0.13
ΛCDM	13.95	$0.66^{+0.01}_{-0.01}$	$0.29^{+0.02}_{-0.02}$	-1.0	———	———
			CMB distance constraints			
Brane	10.87	$0.73^{+0.01}_{-0.01}$	$0.29^{+0.01}_{-0.01}$	$-1.12^{+0.06}_{-0.06}$	< -15.0	$> 4.05 \times 10^{4}$
ΛCDM	0.94	$0.68^{+0.005}_{-0.005}$	$0.31^{+0.008}_{-0.008}$	-1.0	———	———
			Joint analysis			
Brane	636.70	$0.71^{+0.01}_{-0.01}$	$0.30^{+0.01}_{-0.01}$	$-1.12^{+0.03}_{-0.03}$	< -16.2	$> 6.42 \times 10^{5}$
ΛCDM	640.79	$0.68^{+0.004}_{-0.004}$	$0.30^{+0.005}_{-0.005}$	-1.0	———	



Tension between the different data



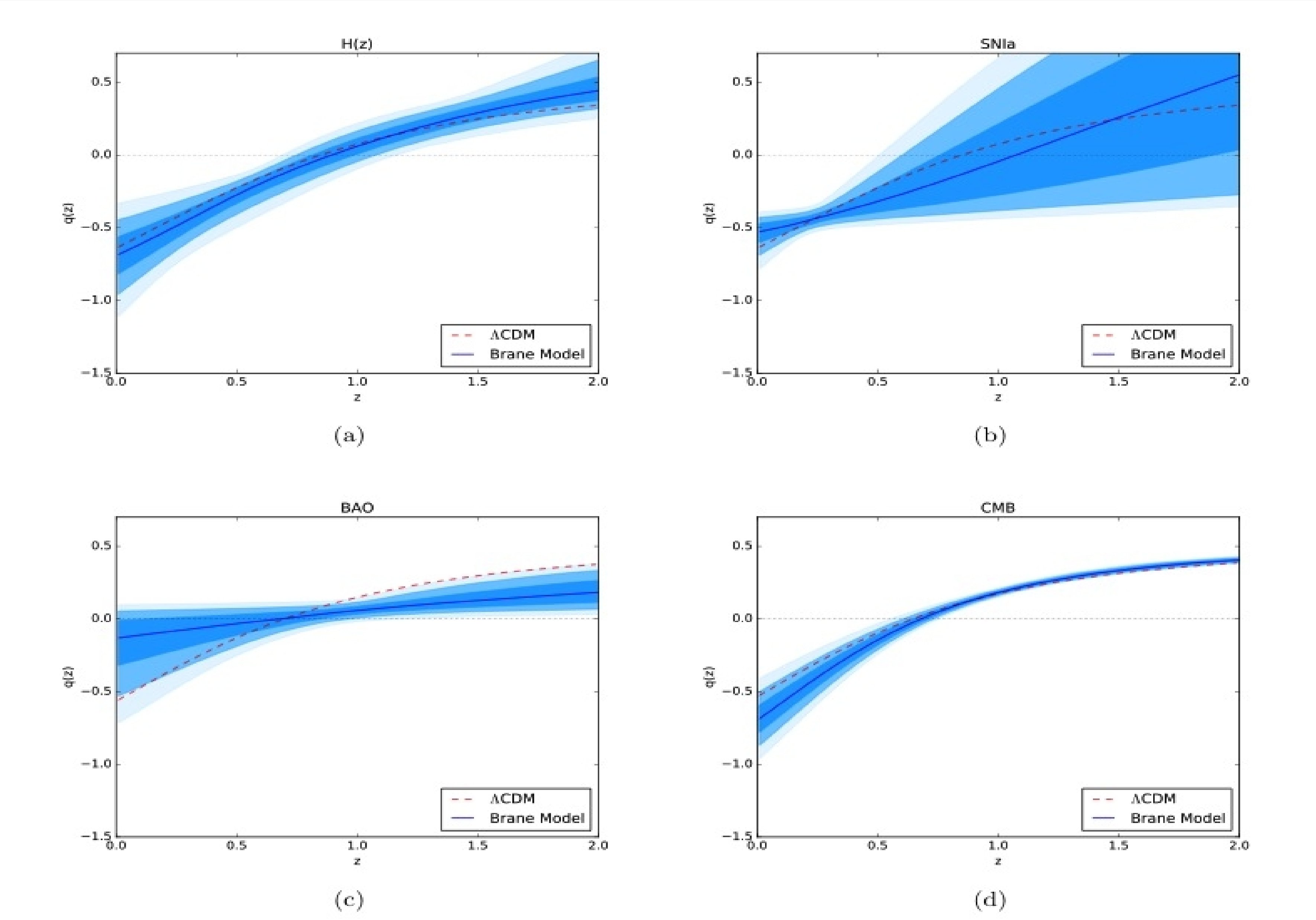
(a)



(b)

Experiment/Observation	Cut-off (eV^4)
Table-Top	138.59×10^{48}, [49]
Astrophysical	5×10^{32}, [45–48]
BBN	10^{24}, [51]
Joint analysis	$6.42h^2 \times 10^5$

Deceleration parameter



Summary

- We investigated a RSII-like braneworld model with a DE field.
- We put constraints on the brane tension and the DE EoS using latest cosmological data
- We found an important tension between the different constraints.
- We can accelerate the Universe but with a dark energy field.

Thanks

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