UniverNet – 4th Annual School – Frontiers of Particle Cosmology

Cosmic Equation of State from Strong Gravitational Lensing System

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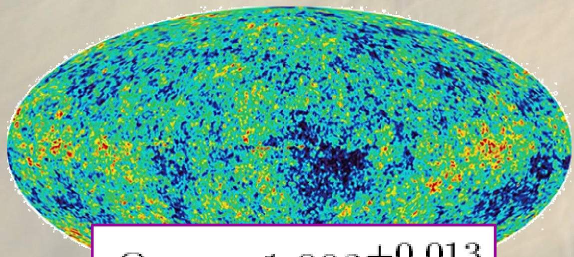
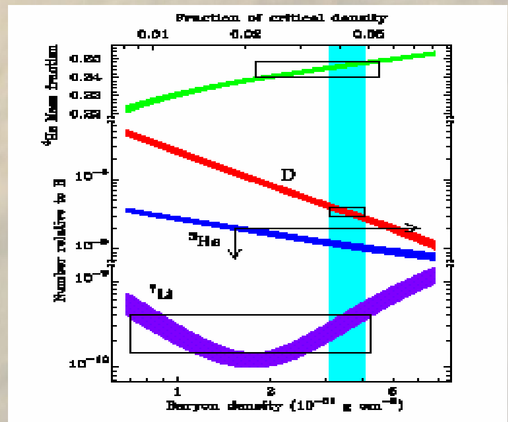
Pilars of Modern Cosmology

CMBR



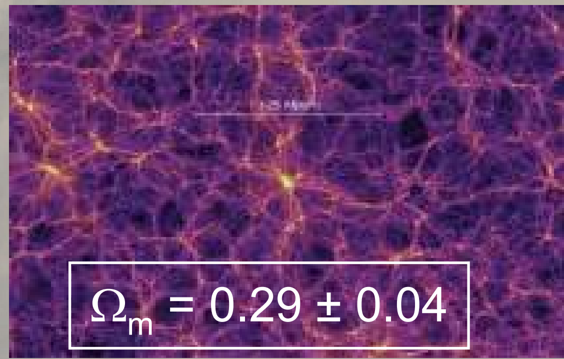
$$\Omega_{\rm tot} = 1.003^{+0.013}_{-0.017}$$

BBN



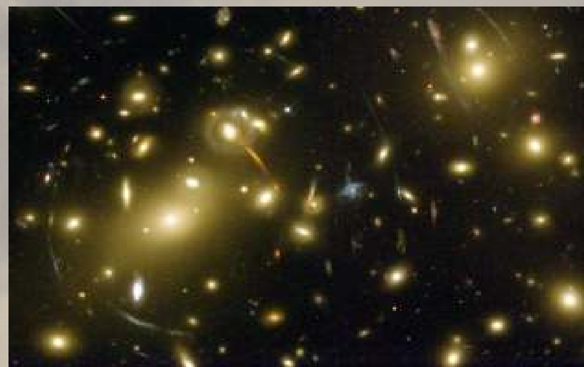
Ω_b = 0.042

LSS



SNIa on high redshifts

Gravitational Lensing



Introduction

- The explanation of he origin of dark energy is far from obvious and broadly speaking involves either invoking an unknown exotic component or modification of gravity at cosmological scales.

- Irrespective of theoretical approach chosen a common point with the observations usually occures at the level of w(z) cofficient in an effective equation of state for dark energy

$$p = w(z)\rho$$

- The power of modern cosmology lies in building up cosistency rather than in single experiment.

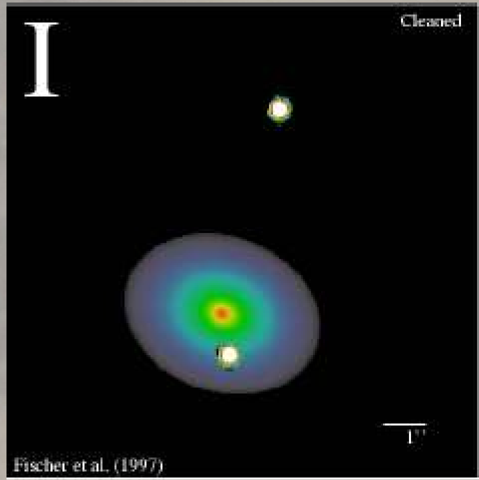
- Every alternative method of restricting cosmological parameters is desired

- We propse to use strongly gravitationally lensed systems in this context

such ida was discussed in *Biesiada M., 2006, Phys. Rev. D 73, 023006*

and in *Grillo et al., 2008, Astron. Astrophys., 477,397*

Gravitational lensing

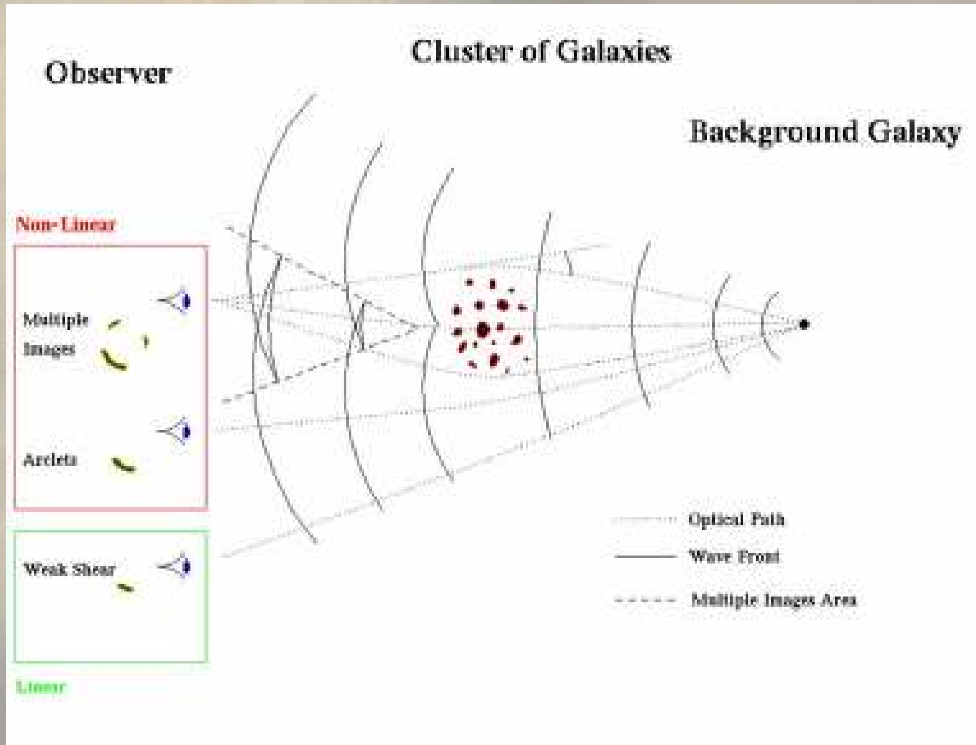


- It is one of the basic consequences of GR (Einstein 1916)
- Deflection of light ray by 1".7 near the limb of the Sun (measured in 1919 !)
- Eddington 1920 - idea of multiple images; Einstein 1935
- Cosmological context :Zwicky 1937 (!)

- New history - Refsdal 1964 - H0 measurement through gravitational lensing
- Walsh, Carswell & Weynmann 1979 - QSO-0957+561A,B
- Paczyński 1986 – microlensing
- Lynds & Petrosian 1986;
  Soucail, Fort, Mellier 1987 - giant arcs in galaxy clusters

Regimes of gravitational lensing

- strong
  - large deflections
  - multiple images
  - microlensing- lensing within lensing fluctuations inside quasar macroimages
- weak
  - tiny distortion of back ground galaxies
  - statistical in nature



Einstein radius - setteld by mass – gives characteristic angular scale of fenomenon

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_L D_S}}$$

for point lens

The Method

- our interest concentrated around:
  - regime:strong & -- lens: galaxy

- the image separations in the system depend on angular diameter distances D_{ls} and $D_{s.}$

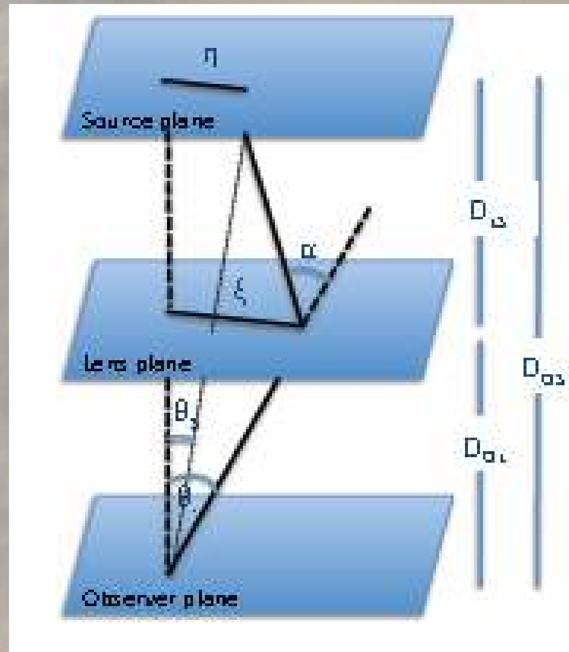
- angular diameter distances determined by background cosmology

$$D(z) = \frac{1}{1+z}\frac{c}{H_0}\int_0^z \frac{dz'}{h(z')}$$

- spatial flatness is assumed (Hinshaw et al. 2009)

$$\Omega_{tot} = 1.0050^{+0.0060}_{-0.0061}$$

- realistic lens model is needed



The Method

- mass density profile approximeted by - SIS -Singular Isothermal Sphere model (SIE –singular isothermal elipsoid)

$$\rho(r) = \frac{\sigma_{SIS}^2}{2\pi G} \frac{1}{r^2} \qquad v_{rot}^2 = const.$$

- Einstein ring reads

$$\theta_E = 4\pi \frac{\sigma_{SIS}^2}{c^2} \frac{D_{ls}}{D_s}$$

$$D(z;p) = \frac{1}{1+z} \frac{c}{H_0} \int_0^z \frac{dz'}{h(z';p)}$$

- σ_{SIS} lens velocity dispersion is well approximated by σ_o - central stellar velocity dispersion (see eg. Grillo et al. 2008)

- Central relation

$$\frac{D_s}{D_{ls}} = \frac{4\pi\sigma_0^2}{c^2\theta_E}$$

$$D^{th}(z_l, z_s, p) \qquad D^{obs}$$

The Method

- cosmological models enter through dsistance ratio

$$D^{th}(z_l, z_s, p) = \frac{D_s(p)}{D_{ls}(p)} = \frac{\int_0^{z_s} [dz'/h(z';p)]}{\int_{z_l}^{z_s} [dz'/h(z';p)]}$$

- for observable counterpart we need realiable assesment of σ_o and θ_E

$$D^{obs} = \frac{4\pi\sigma_0^2}{c^2\theta_E}$$

•advantages of the method:

•independence on H_0

•not affected by dust absorption, source evolutionary effect

- Cosmological parameters were fitted by minimizing

$$\chi^2(p) = \sum_i \frac{(D_i^{obs} - D_i^{th}(p))^2}{\sigma_{D,i}^2}$$

Samples used

Lens ID	z_l	z_s	$\theta_E['']$	$\sigma_0\ [km/s]$
SDSS J0037-0942	0.1955	0.6322	1.47	282 ± 11
SDSS J0216-0813	0.3317	0.5235	1.15	349 ± 24
SDSS J0737+3216	0.3223	0.5812	1.03	326 ± 16
SDSS J0912+0029	0.1642	0.3240	1.61	325 ± 12
SDSS J0956+5100	0.2405	0.4700	1.32	318 ± 17
SDSS J0959+0410	0.1260	0.5349	1.00	229 ± 13
SDSS J1250+0523	0.2318	0.7950	1.15	274 ± 15
SDSS J1330-0148	0.0808	0.7115	0.85	195 ± 10
SDSS J1402+6321	0.2046	0.4814	1.39	290 ± 16
SDSS J1420+6019	0.0629	0.5352	1.04	206 ± 5
SDSS J1627-0053	0.2076	0.5241	1.21	295 ± 13
SDSS J1630+4520	0.2479	0.7933	1.81	279 ± 17
SDSS J2300+0022	0.2285	0.4635	1.25	305 ± 19
SDSS J2303+1422	0.1553	0.5170	1.64	271 ± 16
SDSS J2321-0939	0.0819	0.5324	1.57	245 ± 7
Q0047-2808	0.485	3.595	1.34	229 ± 15
CFRS03.1077	0.938	2.941	1.24	251 ± 19
HST 14176	0.810	3.399	1.41	224 ± 15
HST 15433	0.497	2.092	0.36	116 ± 10
MG 2016	1.004	3.263	1.56	328 ± 32

SLACS

LSD

$$\left\langle \frac{D_{ls}}{D_s} \right\rangle_{SLACS} = 0.58$$

- full sample n=20
- sub-sample n=7
- for comparison
  fit on Union sample – compilation of Kowalski et al. (2008)
  n=307 SNIa

Cosmological models tested

- ΛCDM

$$w = -1$$

$$h(z) = \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda} \qquad \mathbf{p} = \{\Omega_m\}$$

- Quintessence

$$w = const.$$

$$h(z) = \sqrt{\Omega_m (1+z)^3 + \Omega_Q (1+z)^{3(1+w)}}$$

Ω_m fixed $\qquad \mathbf{p} = \{w\}$

- Chevalier-Polarski-Linder

$$w(z) = w_0 + w_a \frac{z}{1+z}$$

$$h(z) = \sqrt{\Omega_m (1+z)^3 + \Omega_Q (1+z)^{3(1+w_0+w_a)} \exp\left(\frac{-3w_a z}{1+z}\right)}$$

Ω_m fixed $\qquad \mathbf{p} = \{w_0, w_a\}$

Results: fits on the full sample n=20

- Lens sample SLACS+LSD (n=15+5)

  prior on Ω_m=0.27

Cosmological model	Best fit parameters (with 1σ)	χ^2/dof
ΛCDM	not possible	
Quintessence	$w = -0.9829 \pm 0.2415$	3.41
Chevalier-Linder-Polarski	$w_0 = 1.2605 \pm 0.8177$	3.05
	$w_a = -9.4443 \pm 4.4193$	

- Union08 SNIa sample (n=307)

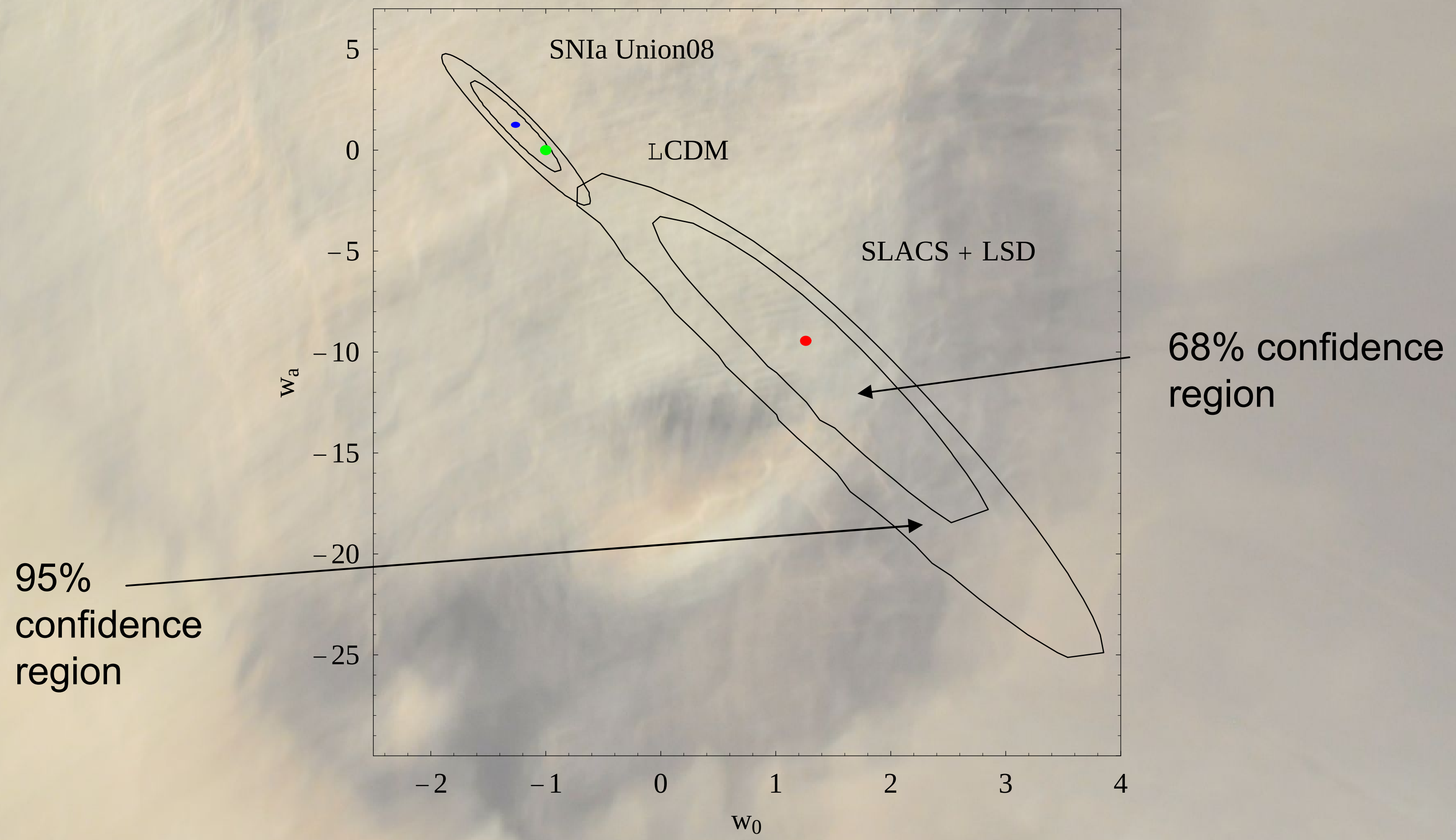
  prior on Ω_m=0.27

Cosmological model	Best fit parameters (with 1σ)	χ^2/dof
ΛCDM	$\Omega_m = 0.287 \pm 0.027$	1.02
Quintessence	$w = -1.061 \pm 0.083$	1.02
Chevalier-Linder-Polarski	$w_0 = -1.263 \pm 0.257$	1.02
	$w_a = 1.254 \pm 1.484$	

•Quintessence : whole 2σ CI from SNIa fits well with 1σ CI from lenses

$\langle -1.23, -0.85 \rangle$ $\langle -1.22, -0.74 \rangle$

Chevalier-Polarski-Linder: bets fits and confidence regions



Results: fits on the restricted sample n=7

- on the restricted sample

  (n=7)

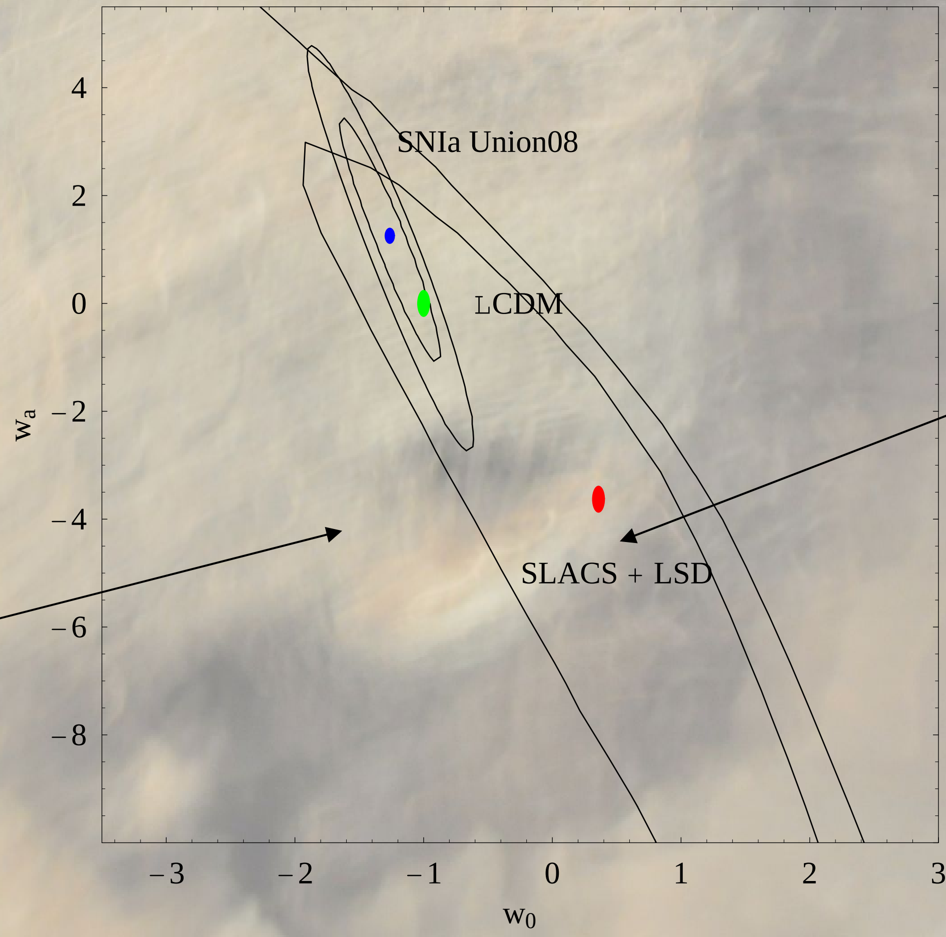
  prior on Ω_m=0.27

Cosmological model	Best fit parameters (with 1σ)	χ^2/dof
ΛCDM	$\Omega_m = 0.2660 \pm 0.2796$	1.76
Quintessence	$w = -0.6320 \pm 0.4461$	3.91
Chevalier-Linder-Polarski	$w_0 = 0.3588 \pm 1.2453$	1.88
	$w_a = -3.6301 \pm 5.3278$	

•ΛCDM fits – agreement with SNIa fits

•Quintessence: 2σ interval for the Union08 falls into 2σ interval for lenses

Chevalier-Polarski-Linder: bets fits and confidence regions



68% confidence region

95% confidence region

Conclusions

- Obtained results demonstrate possibility of practical use of strong gravitational system in constraining cosmological models
- The small number of lenses available (at the time when we start consider this issue - 2009) prevent as from precisely determining parmeters of cosmological, but it still proves the feasibility of the method.
- Over the year the SLACS sample of lenses with realiable data on σ_o and θ_E has grown up to 58 .
- Grillo et al. 2008 demonstrated that sample of 100 or 200 lensing systems would be enough to give competitive constraints (constraints on Ω_Λ) .
- Work on actually available sample is in progress.
- Presented results are also available in the paper:

Biesiada M., Piórkowska A., Malec B., ***MNRAS***, 406,1055-1059 (2010)