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Theory of Relativity Seminar
Wydział Fizyki UW and DBP NCBJ

5 May 2023

Measuring the speed of light on extragalactic objects

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Introduction

1. First measurements of c ever:
Ole Rømer (moons of Jupiter) 1676
James Bradley (aberration of light) 1728

2. VSL theories Moffat 1992; Magueijo + Albrecht 1999
(+Barrow, Smolin...)

3. Sobering remarks: only dimensionless constants are a legitimate subject of physical enquiry;

4. Constancy of c underlies Relativity; Maxwell equations

$$c_{\mathrm{EM}}^2 \equiv \frac{1}{\varepsilon_0 \mu_0}$$

5. Modern revival Salzano, Dąbrowski, Lazkoz 2015

Measuring the speed of light using extragalactic objects

First proposal

homogeneous, isotropic
FLRW models

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right)$$

Salzano, Dąbrowski, Lazkoz (2015)
PRL, 114:101304
to be tested with future BAO data

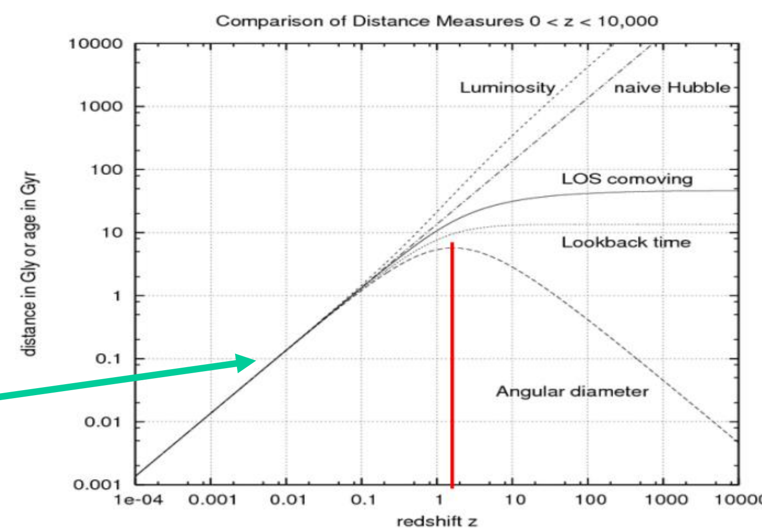
Outline of their method

Three distances in cosmology:

Comoving distance $D(z) = \int_0^z \frac{c\,dz'}{H(z')}$

Luminosity distance $D_L(z) = (1+z)D(z)$

Angular diameter distance $D_A(z) = \frac{1}{(1+z)}D(z)$



z_{max}

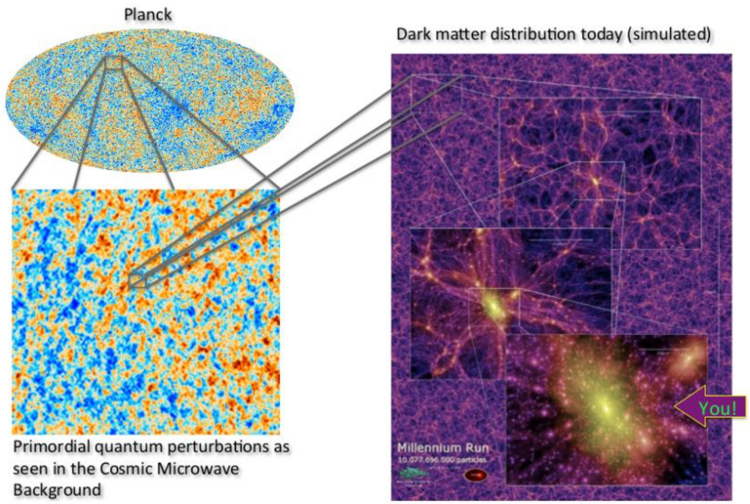
$$D_A(z_{max}) = \frac{c}{H(z_{max})}$$

$$\frac{\partial D_A(z_{max})}{\partial z} = 0$$

One expects
$c = c_0$

Standard speed of light

Baryon Acoustic Oscillations



Credit: F. Leclercq, A. Pisani , B.D. Wandeldt arXiv:1403.1260v1

Observations

Credit: PNtelis

Primordial Observations

"Initial" Conditions
Temperature, T
In the far past, z~1100

$$\delta_T(t;r) = \frac{T(t;r) - \bar{T}(t)}{\bar{T}(t)}$$

Temperature Surveys

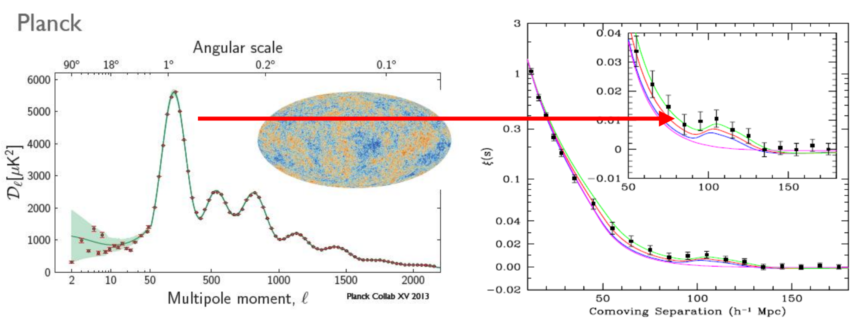
Late time Observations

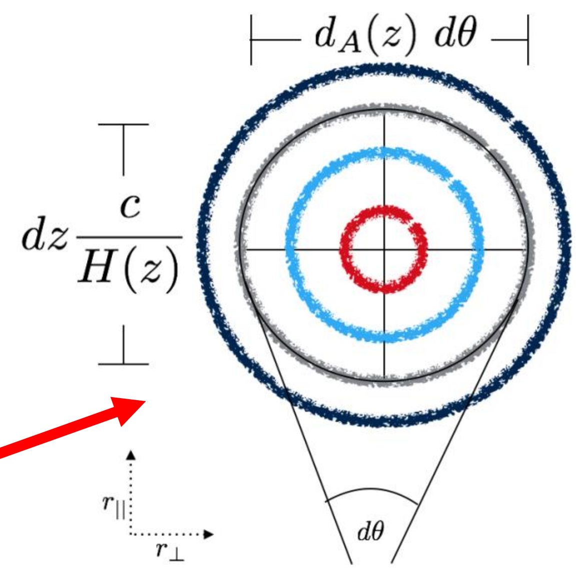
"Final" Conditions
Galaxy density, n
In the near past, z ~ [0.5,6]

$$\delta(t;r) = \frac{n(t;r) - \bar{n}(t)}{\bar{n}(t)}$$

Redshift Surveys

Combined to Constrain Perturbed Cosmology !!





Alcock-Paczyński test

Credit: Pierros Ntelis
https://hal.archives-ouvertes.fr/tel-01674537/document

Salzano, Dąbrowski, Lazkoz (2015)
PRL, 114:101304
to be tested with future BAO data

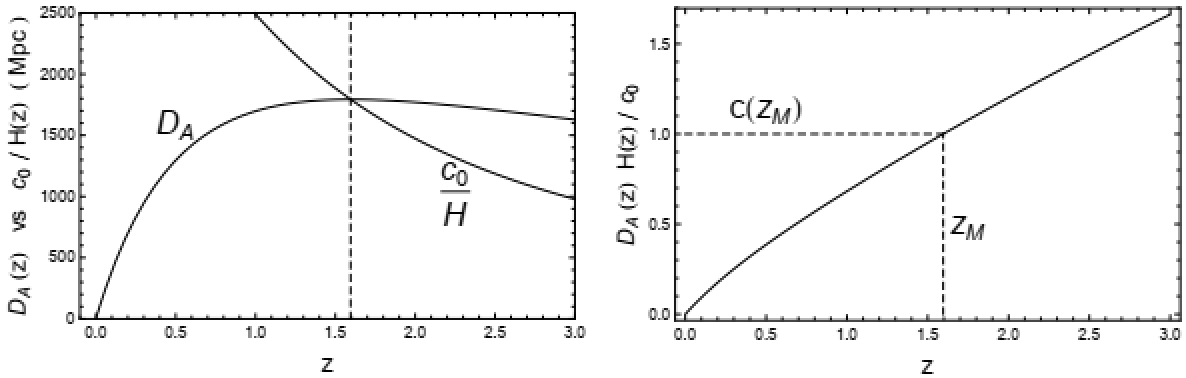


Figure 1. Method implementation: maximum redshift detection *left panel*; speed of light measurement *right panel*.

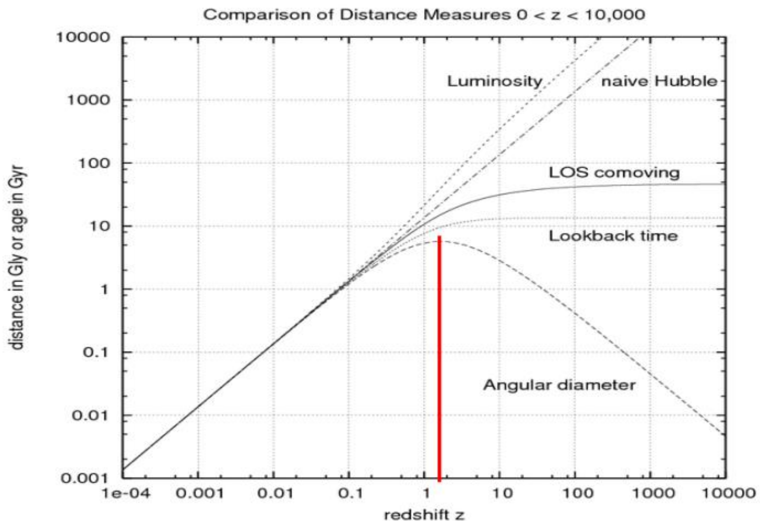
Implementation left for the future –
when radial and tangential BAO modes will be
accurately measured

Measuring the speed of light
using extragalactic objects

first measurement on extragalactic sources:

Cao, Biesiada, Jackson, Zheng, Zhu (2017) JCAP 02, 012

$$D_A(z_{max})H(z_{max}) = c$$



H(z) from passive evolving galaxies;

$D_A(z)$ from intermediate L compact radio QSOs (standard rulers)

z_{max}

Cosmic Chronometers

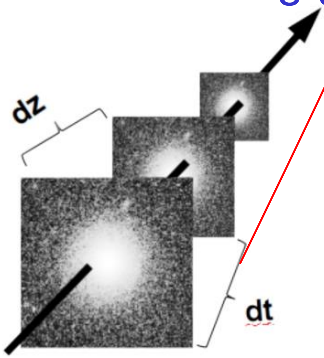
Moresco (2015) MNRAS 450, L16

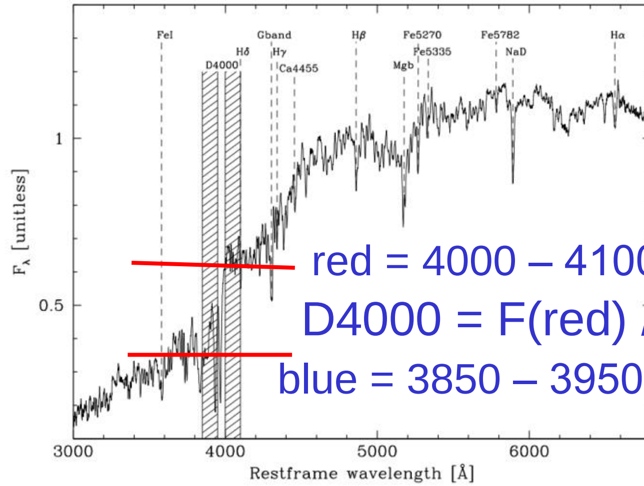
Cosmology model independent

$$\boxed{H(z) = \frac{\dot{a}}{a} = -\frac{1}{1+z}\frac{dz}{dt}}$$

Jimenez & Loeb (2002)

Passive evolving galaxies





red = 4000 – 4100 Å

D4000 = F(red) / F(blue)

blue = 3850 – 3950 Å

D4000 break – onset of series of metal absorption features

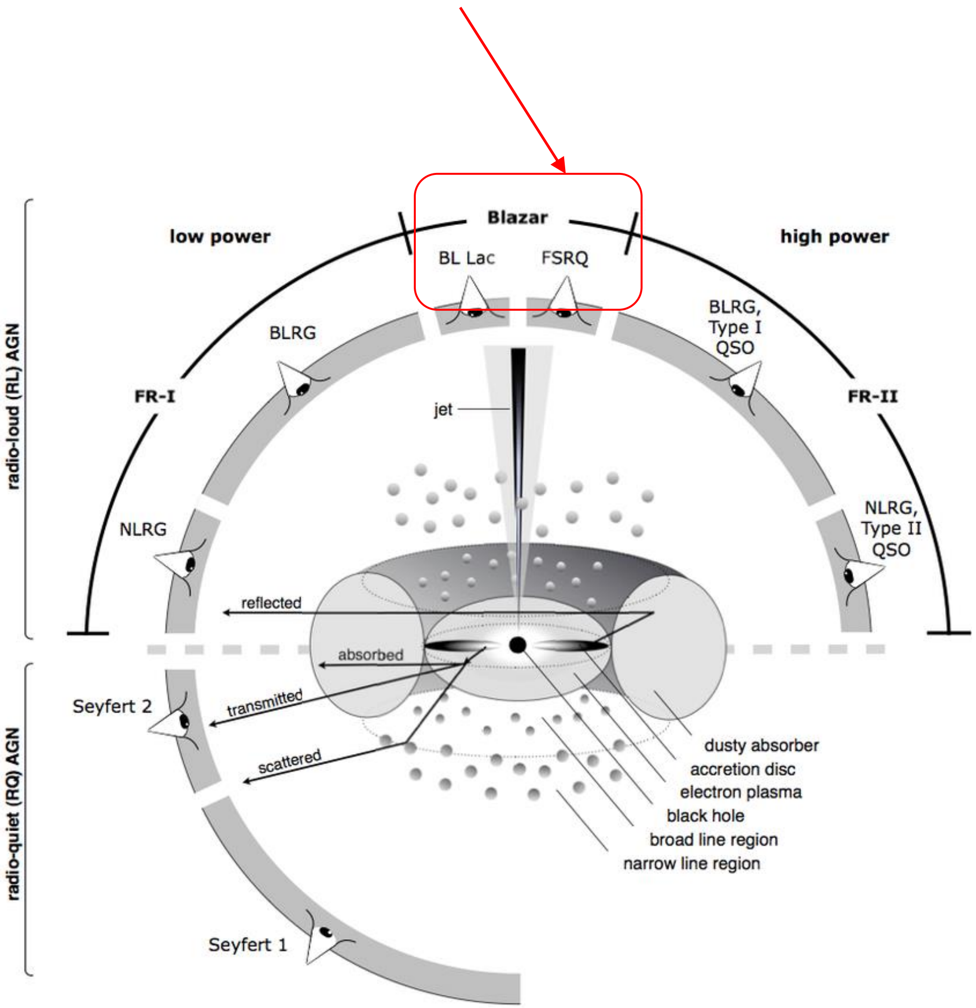
Credit: M. Moresco,
16 Marcel Grossmann Meeting
2021

$$H(z) = -\frac{1}{1+z} A(Z,SFH) \frac{dz}{dD4000_n}$$

estimated from data

calibrated on different SPS models

Compact radio sources



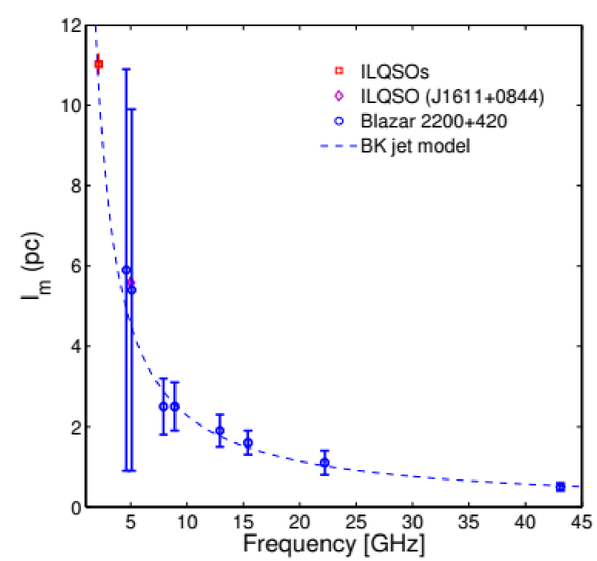
Unified model of AGNs, QSOs and radio-sources

Jet orientation w.r.t. line of sight responsible for morphological differences

compact radio sources – we look along the jet
angular size = size of the base of the jet

base of the jet – unit optical depth
– Blandford – Koenigl (1979) model

$$l_m \sim \nu^{-1}$$



THE ASTROPHYSICAL JOURNAL, 806:66 (7pp), 2015 June 10 doi:10.1088/0004-637X/806/1/66
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EXPLORING THE PROPERTIES OF MILLIARCSECOND RADIO SOURCES

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Preston et al. 1985 survey at 2 GHz
1398 radio sources – including 917 compact

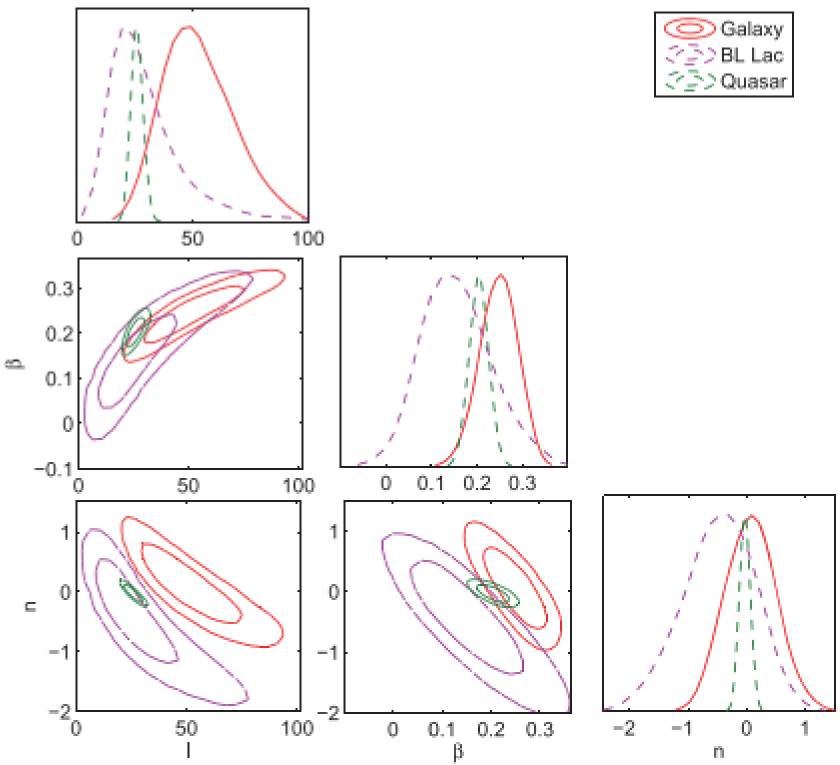

Figure 3. Constraints on compact source parameters obtained from three subsamples with different optical counterparts.

$$\boxed{\theta(z) = \frac{l_m}{D_A(z)}}$$

$$l_m = l\left(\frac{L}{L_0}\right)^{\beta}(1+z)^n$$

Conclusion:

only radio-quasars are promising for further calibration

A&A 606, A15 (2017)
DOI: 10.1051/0004-6361/201730551
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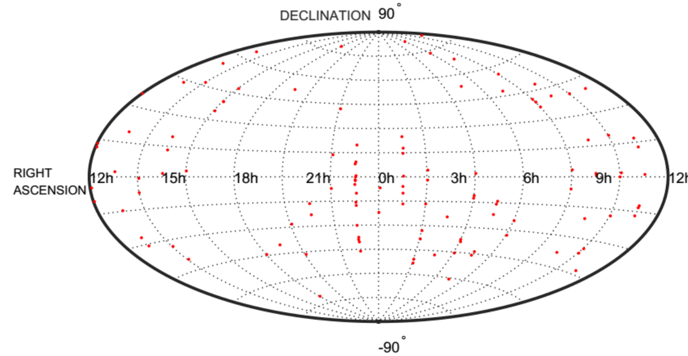
Astronomy & Astrophysics

Ultra-compact structure in intermediate-luminosity radio quasars: building a sample of standard cosmological rulers and improving the dark energy constraints up to $z \sim 3$

Shuo Cao[1], Xiaogang Zheng[1,2], Marek Biesiada[1,2], Jingzhao Qi[1], Yun Chen[3], and Zong-Hong Zhu[1]



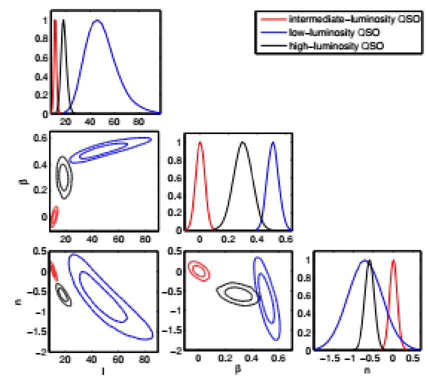
120 compact radio sources (QSOs) at 2 GHz

Steps:

1. expansion rate reconstruction from H(z) data (cosmic chronometers)

2. robust selection of luminosity sample

3. calibration of standard rulers – intermediate luminosity QSO (ILQSO) $10^{27} < L\ [\mathrm{W/Hz}] < 10^{28}$



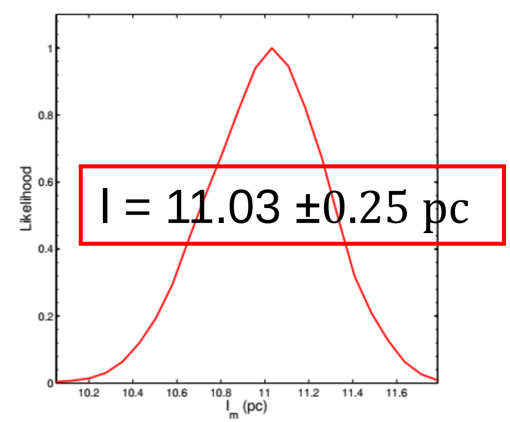
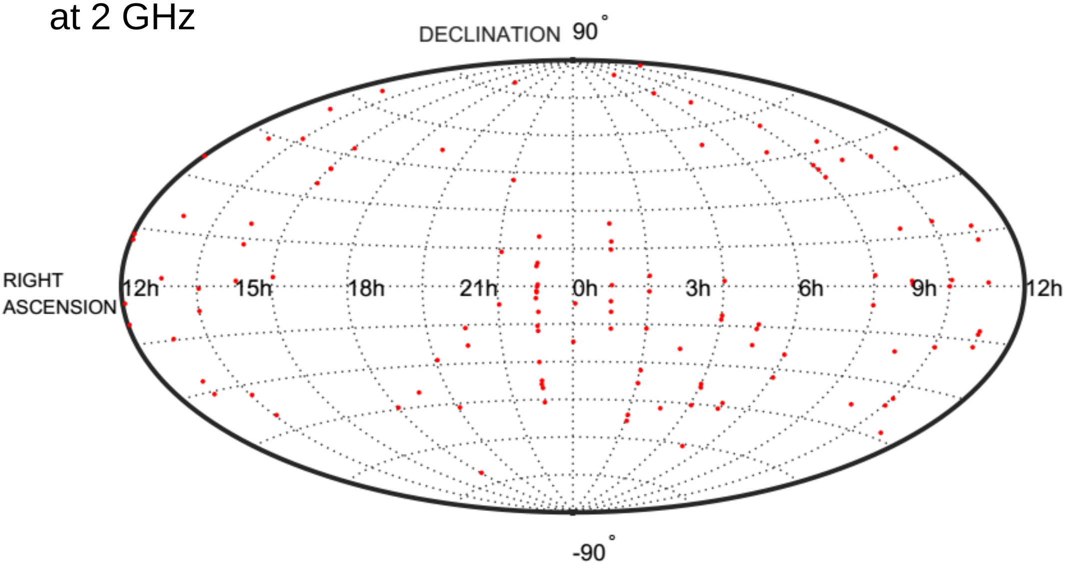


Fig. 4. Corrected linear size of compact quasars derived in a cosmological model independent way, using the observational $H(z)$ data.

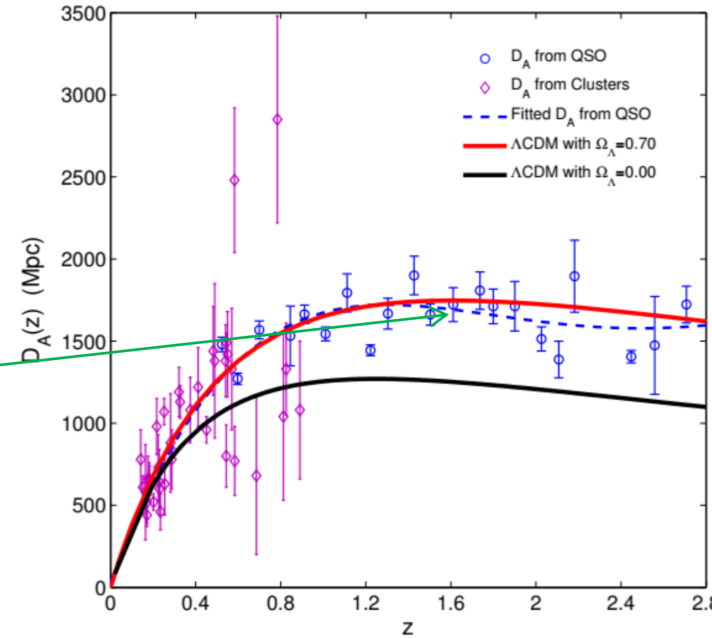
120 compact radio sources (QSOs)
at 2 GHz



l = 11.03 ±0.25 pc

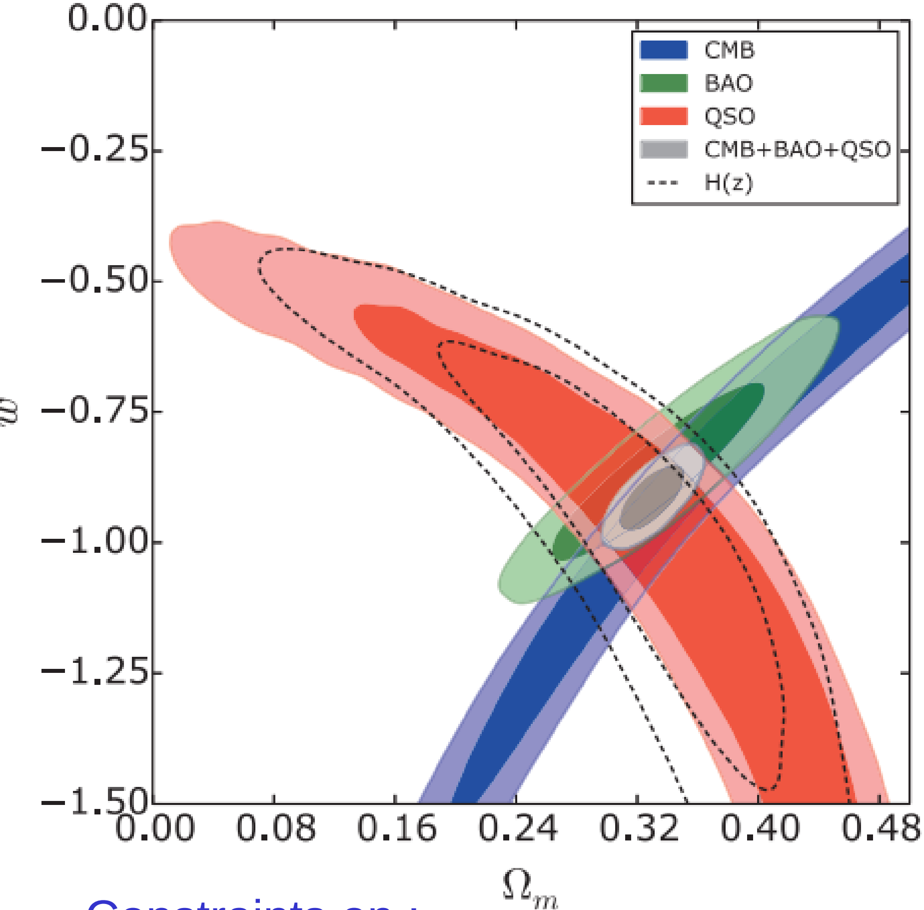
Steps:

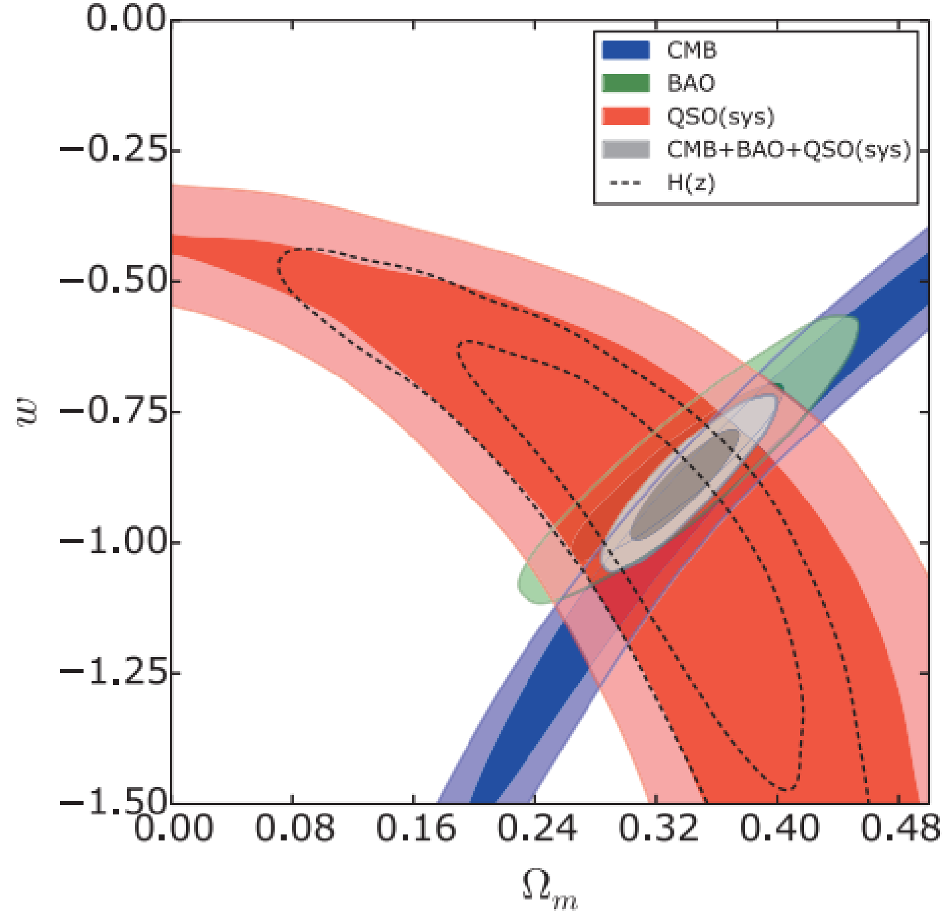
4. D_A (z) reconstruction (GP) from binned ILQSO data



5. Use calibrated ILQSO to test cosmological models

Some constraints on the parameters of ΛCDM (and beyond)





Constraints on :

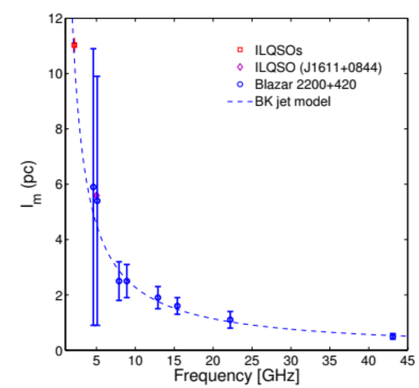
Modified gravity f(T) theories

Qi Z-H., Cao S., M.B., Zheng X., Zhu Z.-H., Eur J Phys C (2017) 77:502

Interacting DE/DM Zheng X., M.B., et al. JCAP (2017)030

Verification of this method at different frequencies

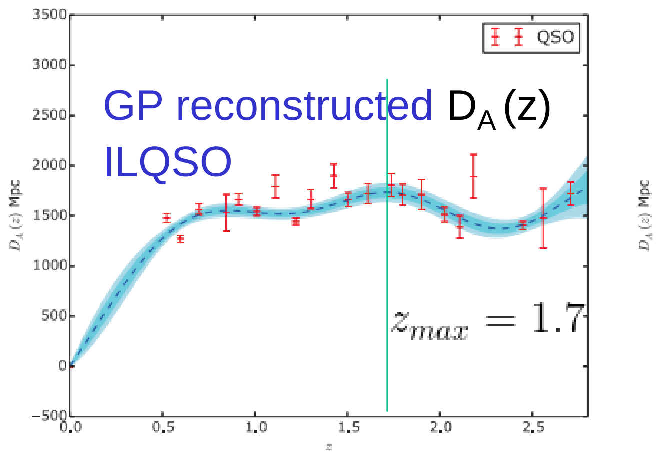
Cao S., M.B., et al., Eur J Phys C (2018) 78:749

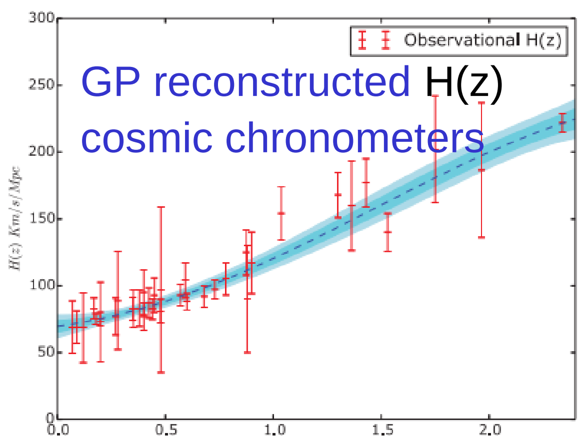


Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

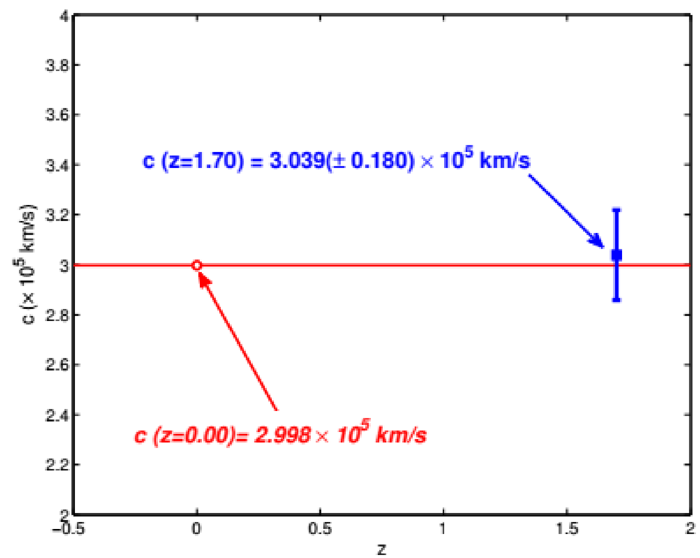
Measuring the speed of light with ultra-compact radio quasars

Shuo Cao,[a] Marek Biesiada,[a,b] John Jackson,[a] Xiaogang Zheng,[a] Yuhang Zhao[a] and Zong-Hong Zhu[a]





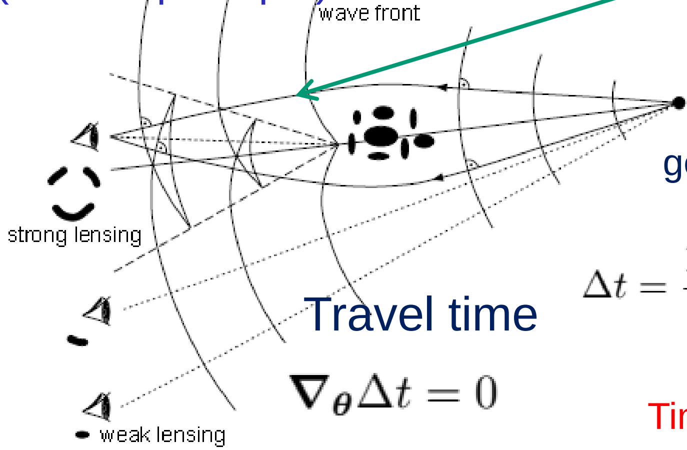
$$D_A(z_{max})H(z_{max}) = c$$



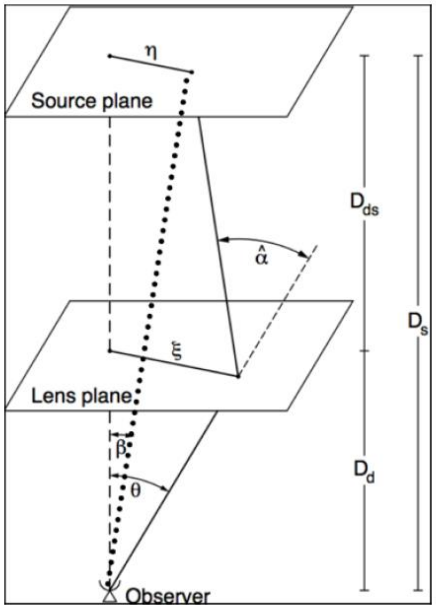
Measuring the speed of light using extragalactic objects - strong gravitational lensing

caustics

Wavefront formalism
(Fermat principle)



Light rays formalism



$$\phi(\boldsymbol{\theta}) = \frac{D_{ls}}{D_l D_s}\frac{2}{c^2}\int \Phi(D_l\boldsymbol{\theta}, z)dz$$

geometrical term

Newtonian potential at lens plane

$$\Delta t = \frac{1+z_l}{c}\frac{D_{\rm ol}D_{\rm os}}{D_{\rm ls}}\left[\frac{(\boldsymbol{\theta}-\boldsymbol{\beta})^2}{2} - \phi(\boldsymbol{\theta})\right]$$

Travel time

$$\nabla_{\boldsymbol{\theta}}\Delta t = 0$$

Time delay distance

Fermat potential

Lens equation

$$\hat{\boldsymbol{\alpha}}(\boldsymbol{\theta})D_{ls} + \boldsymbol{\beta}D_s = \boldsymbol{\theta}D_s$$

$$\boxed{\boldsymbol{\theta} - \boldsymbol{\beta} - \nabla_{\boldsymbol{\theta}}\phi = 0}$$

$$\boxed{\theta_{\rm E} = 4\pi\frac{\sigma_{\rm ap}^2}{c^2}\frac{D_{\rm ls}}{D_{\rm s}}\left(\frac{\theta_{\rm E}}{\theta_{\rm ap}}\right)^{2-\gamma} f(\gamma)}$$

Einstein radius

$$A(\boldsymbol{\theta}) = \frac{\partial\boldsymbol{\beta}}{\partial\boldsymbol{\theta}} \qquad \mu(\boldsymbol{\theta}) = \frac{1}{\det A(\boldsymbol{\theta})}.$$

$$\boldsymbol{\alpha} = \nabla_{\boldsymbol{\theta}}\phi$$

magnification

Observables:
* image positions and shape distortions
* time delay between images
* flux ratios magnification ratios

Measuring the speed of light using extragalactic objects - strong gravitational lensing Version 1

Time delay distance

$$D_{\Delta t} = \frac{D_l^A D_s^A}{D_{ls}^A} \qquad D_{ls}^A = \frac{1}{1+z_s} D_{ls}$$

$$\Delta t_{ij} = \frac{D_{\Delta t}(1+z_l)}{c} \Delta \psi_{ij}$$

Time delays

Fermat potential difference

Distance sum rule

$$D_{ls} = \sqrt{1+\Omega_k D_l^2} D_s - \sqrt{1+\Omega_k D_s^2} D_l$$

Flat universe $D_{ls} = D_s - D_l$

$$\boxed{c = \frac{D_l^A(1+z_l)D_s^A(1+z_s)}{(1+z_s)D_s^A - (1+z_l)D_l^A} \frac{1}{\Delta t_{ij}} \Delta \psi_{ij}}$$

The Astrophysical Journal, 867:50 (6pp), 2018 November 1
https://doi.org/10.3847/1538-4357/aae5f7
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Testing the Speed of Light over Cosmological Distances: The Combination of Strongly Lensed and Unlensed Type Ia Supernovae

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Received 2018 August 4; revised 2018 September 23; accepted 2018 October 1; published 2018 October 30

from lensed images of host galaxy

$$c = \frac{D_l^A(1+z_l)D_s^A(1+z_s)}{(1+z_s)D_s^A - (1+z_l)D_l^A}\frac{1}{\Delta t_{ij}}\Delta\psi_{ij}$$

from redshift matched unlensed SNIa

from lensed SNIa

Relative Uncertainties of Factors Contributing to the Accuracy of c Measurement

	$\delta\Delta t$	$\delta\Delta\psi$	δ LOS	
Lensed SNe Ia	1%	3%	1%	
	σ_{meas} (mag)	σ_{int} (mag)	σ_{lens} (mag)	σ_{sys} (mag)
Unlensed SNe Ia	0.08	0.09	$0.07 \times z$	0.01 $(1+z)/1.8$

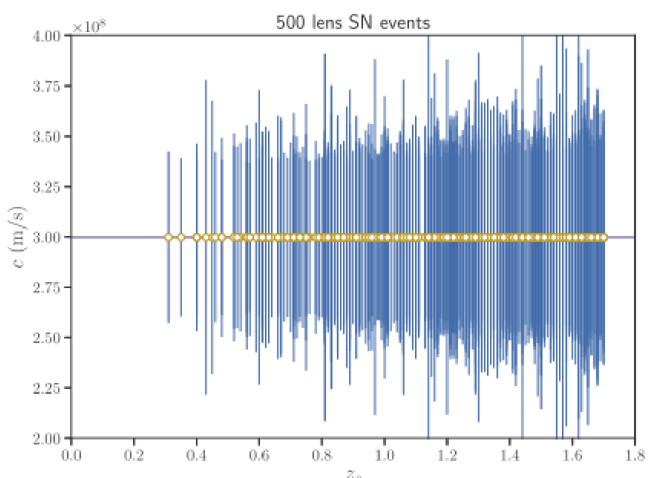

Figure 1. Individual measurements of the speed of light from the forthcoming LSST survey.

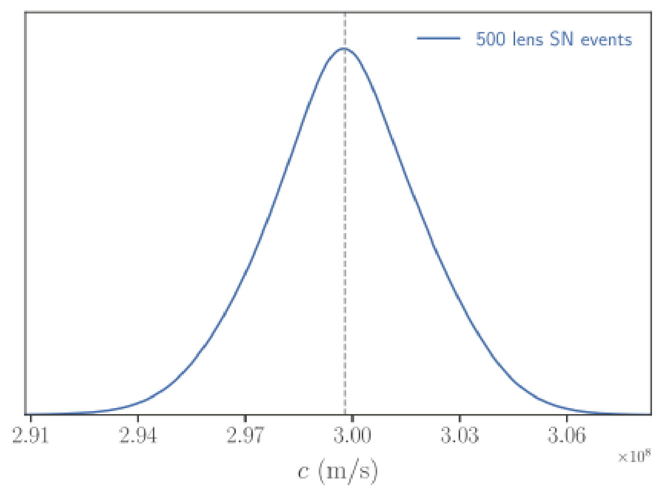

Figure 2. Probability distribution of the speed of light c possible to obtain from the forthcoming LSST survey.

$$\frac{\Delta c}{c} = 0.005$$

Measuring the speed of light using extragalactic objects - strong gravitational lensing Version 2

Spherically symmetric power-law mass density profile

$$\rho \propto r^{-\gamma}$$

Strong lensing: mass inside the Einstein radius

$$M_{\rm lens} = \frac{c^2}{4G}\frac{D_{\rm s}D_{\rm l}}{D_{\rm ls}}\theta_{\rm E}^2$$

$$\theta_{\rm E} = 4\pi\frac{\sigma_{\rm ap}^2}{c^2}\frac{D_{\rm ls}}{D_{\rm s}}\left(\frac{\theta_{\rm E}}{\theta_{\rm ap}}\right)^{2-\gamma} f(\gamma)$$

stellar dynamics (spherically symmetric Jeans equation): mass projected inside aperture radius scaled to the Einstein radius

$$M_{\rm dyn} = \frac{\pi}{G}\sigma_{\rm ap}^2 R_{\rm E}\left(\frac{R_{\rm E}}{R_{\rm ap}}\right)^{2-\gamma} f(\gamma)$$

$$= \frac{\pi}{G}\sigma_{\rm ap}^2 D_{\rm l}\theta_{\rm E}\left(\frac{\theta_{\rm E}}{\theta_{\rm ap}}\right)^{2-\gamma} f(\gamma)$$

$$\boxed{c = \sigma_{ap}\sqrt{\frac{4\pi}{\theta_E}\left(1 - \frac{1+z_l}{1+z_s}\frac{D_l^A}{D_s^A}\right)\left(\frac{\theta_E}{\theta_{ap}}\right)^{2-\gamma} f(\gamma)}}$$

Speed of light

The Astrophysical Journal Letters, 888:L25 (6pp), 2020 January 10 https://doi.org/10.3847/2041-8213/ab63d6
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Precise Measurements of the Speed of Light with High-redshift Quasars: Ultra-compact Radio Structure and Strong Gravitational Lensing

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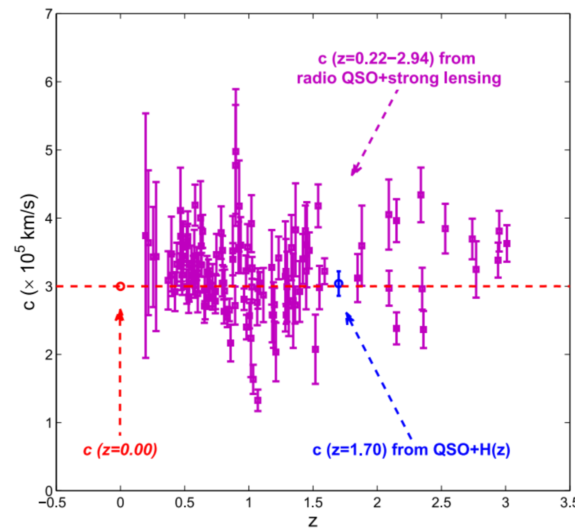
Received 2019 November 7; revised 2019 December 18; accepted 2019 December 18; published 2020 January 16

We used a catalog of 118 lensing systems from SLACS, BELLS, LSD and SL2S (Cao, MB, et al. 2015, ApJ 806:185)

observable / measureable

$$c = \sigma_{ap}\sqrt{\frac{4\pi}{\theta_E}\left(1-\frac{1+z_l}{1+z_s}\frac{D_l^A}{D_s^A}\right)\left(\frac{\theta_E}{\theta_{ap}}\right)^{2-\gamma} f(\gamma)}$$

obtainable from (redshift matched) ultra-compact radio QSOs



$$\boxed{c = 3.005(\pm 0.060)\times 10^5\ km\ s^{-1}}$$

summary

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 506, 2181–2188 (2021) https://doi.org/10.1093/mnras/stab1868
Advance Access publication 2021 July 6

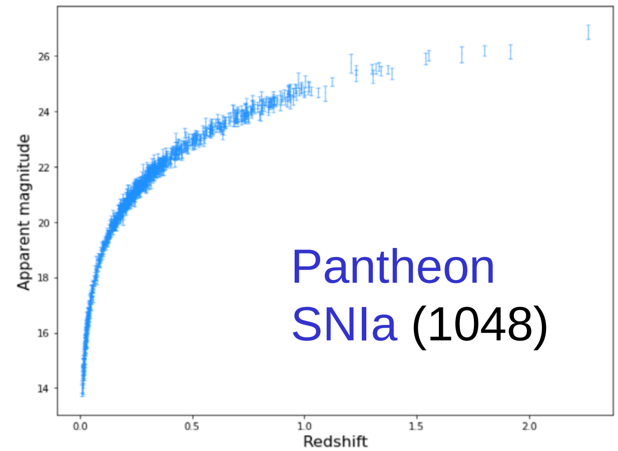
Consistency testing for invariance of the speed of light at different redshifts: the newest results from strong lensing and Type Ia supernovae observations

Tonghua Liu,[1,2] Shuo Cao,[2,3★] Marek Biesiada,[2,4★] Yuting Liu,[2] Yujie Lian[2] and Yilong Zhang[2]

$$T_{zs} = \frac{c(z_s, z_l)}{c_0}$$

distances from redshift matched SNIa (standard candles)

$$T_{zs} = \frac{\sigma_{ap}}{c_0}\sqrt{\frac{4\pi}{\theta_E}\left(1 - \frac{1+z_l}{1+z_s}\frac{D_l^A}{D_s^A}\right)\left(\frac{\theta_E}{\theta_{ap}}\right)^{2-\gamma} f(\gamma)}.$$



$$m_{B,corr} = m_B + \alpha^* \cdot X_1 - \beta \cdot \mathcal{C} + \Delta M$$

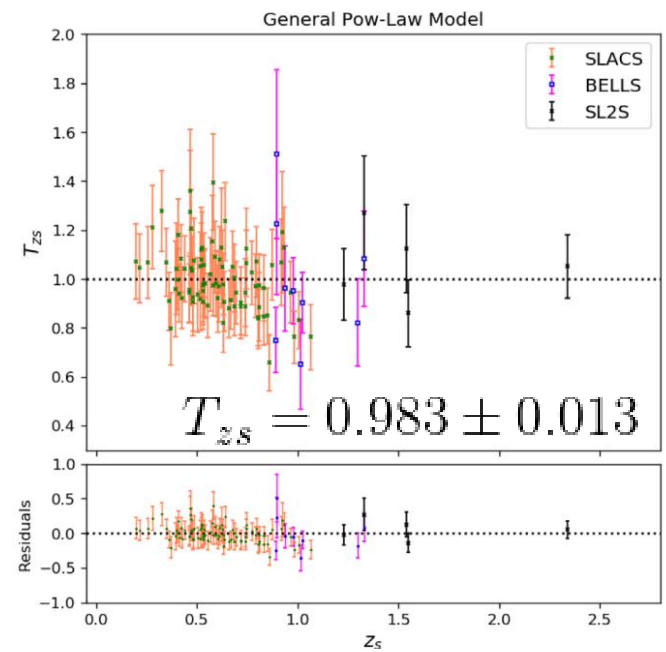
We used a catalog of 161 lensing systems from SLACS, BELLS, LSD and SL2S
(Chen Y., et al. 2019, MNRAS 488, 3745)

Absolute magnitude M_B cancels !

$$T_{zs} = \frac{\sigma_{ap}}{c_0}\sqrt{\frac{4\pi}{\theta_E}\left(1 - \frac{1+z_s}{1+z_l}10^{0.2\Delta m_{B,corr}}\right) f(\gamma)\left(\frac{\theta_E}{\theta_{ap}}\right)^{2-\gamma}}$$

$$\Delta m_{B,\,corr} = m_{B,\,corr}(z_l) - m_{B,\,corr}(z_s)$$

$$c = 2.950(\pm 0.04)\ km\ s^{-1}$$



Measuring the speed of light using extragalactic objects

reconstructed distances $D_L(z)$ + expansion rate $H(z)$

Liu Y., Cao S., MB et al. 2023, ApJ accepeted

Idea

Luminosity distance

$$D_L(z) = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

Its derivative

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

$$\boxed{c = \frac{D'_L(z)H(z)}{1+z} - \frac{D_L(z)H(z)}{(1+z)^2}}$$

One needs:

e.g. $D_L(z) = \ln(10)\frac{c_0}{H_0}(x + ax^2 + bx^3)$, $x = \log(1+z)$

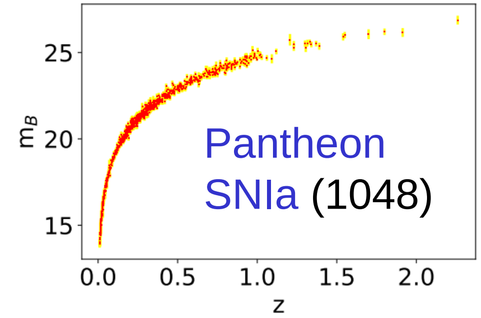
Functional form of $D_L(z)$ – reconstructed from

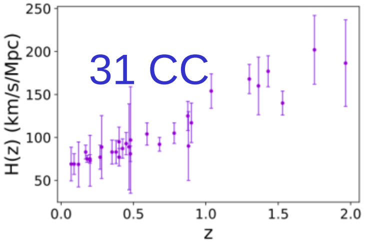
- Standard candles – SNIa
- QSO[UV-X] standard candles

Functional form of H(z) – reconstructed from

* cosmic chronometers

*GW observed by DECIGO





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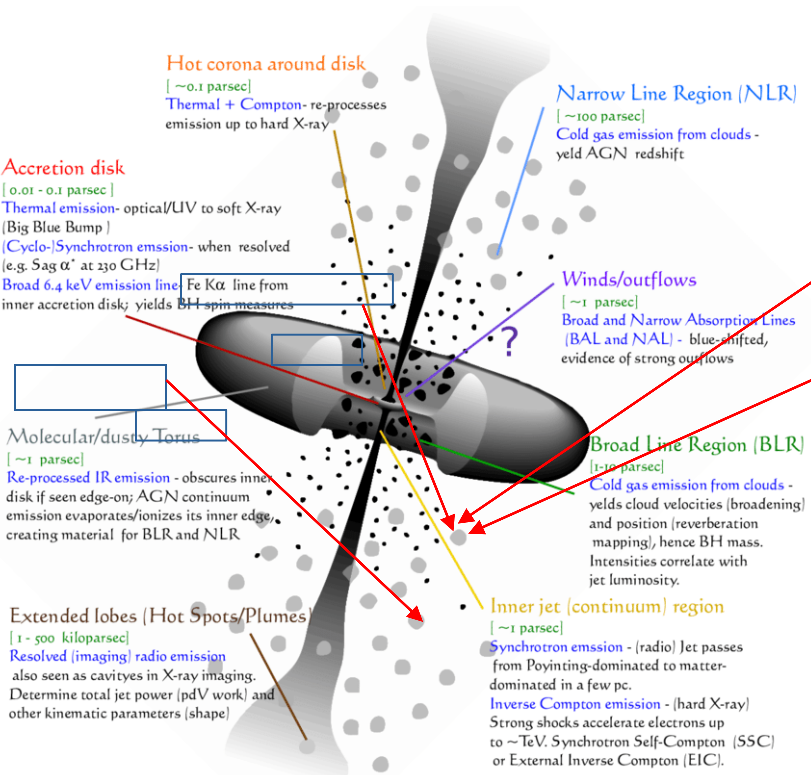
MNRAS **507,** 919–926 (2021)
Advance Access publication 2021 July 31
https://doi.org/10.1093/mnras/stab2154

QSO as standard candles

Hubble diagram at higher redshifts: model independent calibration of quasars

Xiaolei Li,[1★] Ryan E. Keeley,[2★] Arman Shafieloo ,[2,3★] Xiaogang Zheng,[4] Shuo Cao,[5] Marek Biesiada[5,6] and Zong-Hong Zhu[5]



$$\log(L_{\rm X}) = \gamma \log(L_{\rm UV}) + \beta_1$$

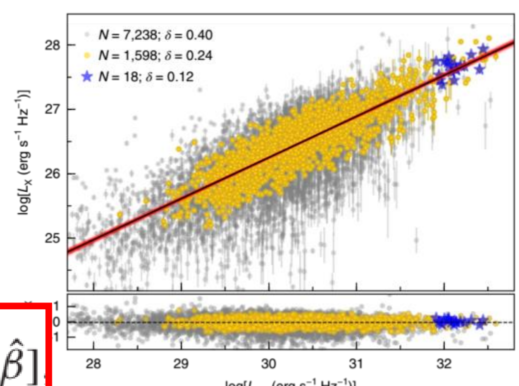
γ from fluxes in redshift bins

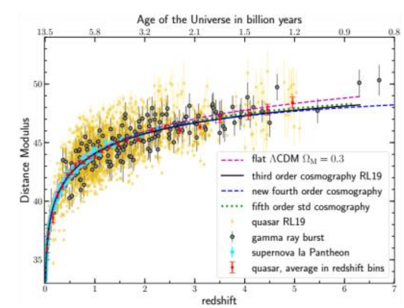
$$\log(F_{\rm X}) = \gamma \log(F_{\rm UV}) + (2\gamma - 2)\log(D_{\rm L}) + \beta_2$$

$$\beta_2 = \gamma \log(4\pi) - \log(4\pi) + \beta_1,$$

Risaliti & Lusso 2019
Nature Astronomy

Lusso et al. 2019
A&A Lett. - tension with LCDM





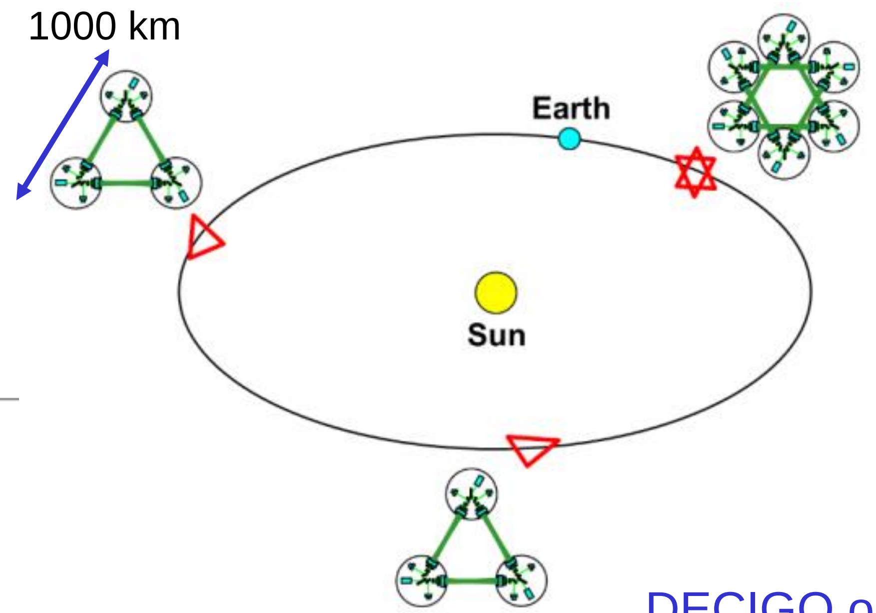
$$\boxed{\log(D_L) = \frac{1}{2 - 2\hat{\gamma}} \times [\hat{\gamma}\log(F_{\rm UV}) - \log(F_{\rm X}) + \hat{\beta}]}$$

Credit: https://www.researchgate.net/publication/344342737_Numerical_Models_of_AGN_Feedback/figures?lo=1

The future –
widen the frequency band of ground based detectors

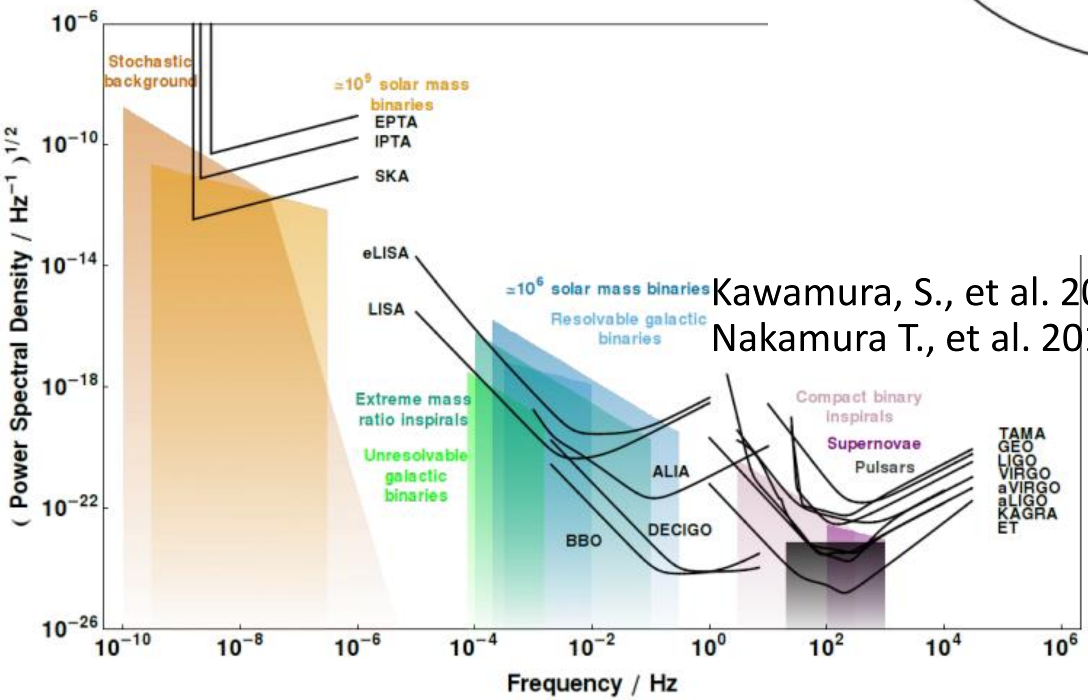
LISA – 0.1 mHz – 100 mHz

DECIGO – 1 mHz – 100 Hz

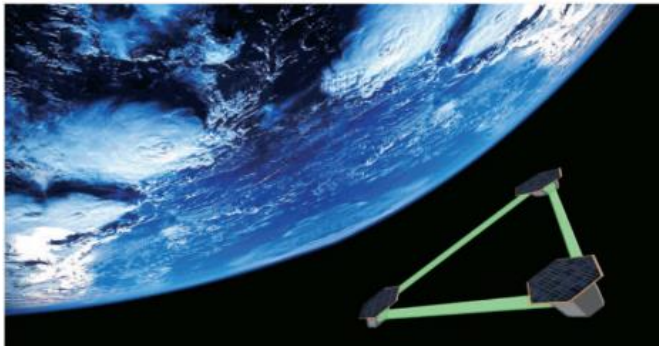


DECIGO orbit

Kawamura, S., et al. 2019, IJMPD, 28, 1845001
Nakamura T., et al. 2016, Prog. Theor. Exp. Phys. 093E01



Detector noise power spectrum density of different ground and space detectors



B-DECIGO smaller scale detector

DECIGO

DECIGO sensitivity

ET: r_0 = 1917 Mpc
DECIGO r_0 = 6709 Mpc
B-DECIGO r_0 = 535 Mpc

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Possibility of Direct Measurement of the Acceleration of the Universe Using 0.1 Hz Band Laser Interferometer Gravitational Wave Antenna in Space

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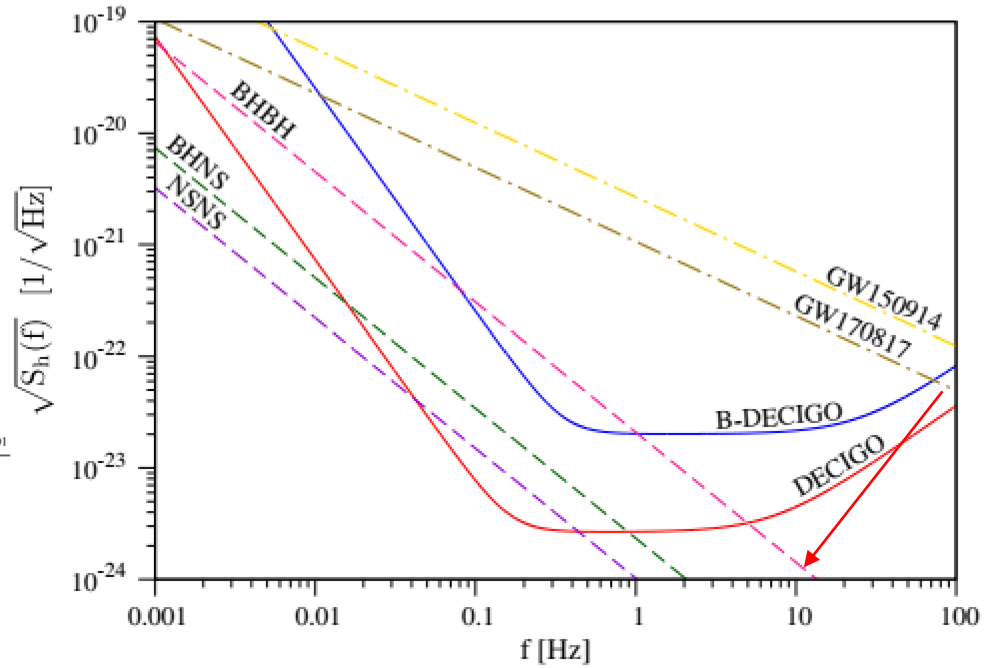
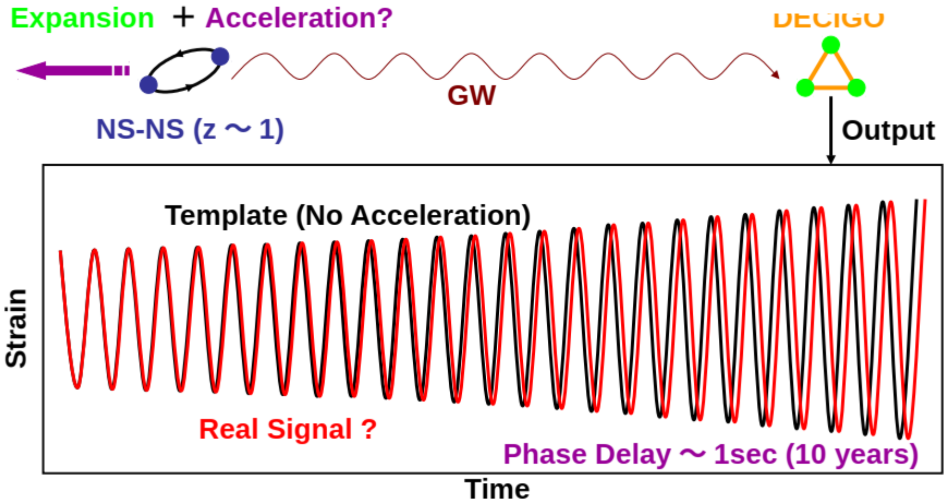
(Received 4 June 2001; published 9 November 2001)

It may be possible to construct a laser interferometer gravitational wave antenna in space with $h_{rms} \sim 10^{-27}$ at $f \sim 0.1$ Hz in this century. Using this antenna, (1) typically 10^5 chirp signals of coalescing binary neutron stars per year may be detected with $S/N \sim 10^4$; (2) we can directly measure the acceleration of the universe by a 10 yr observation of binary neutron stars; and (3) the stochastic gravitational waves of $\Omega_{GW} \gtrsim 10^{-20}$ predicted by the inflation may be detected by correlation analysis. Our formula for phase shift due to accelerating motion might be applied for binary sources of LISA.



GW150914
GW170817
could have been detected by DECIGO and visible for 10 days
7yrs
prior to coalescence;
10^5
10^7 cycles

$$\widetilde{h}(f) = e^{i\Psi_{acc}(f)}\widetilde{h}(f)|_{noaccel}$$



$$\Psi_{acc}(f) \equiv -2\pi f X(z_c)\Delta T(f)^2$$
$$= -\Psi_N(f)\frac{25}{768}X(z_c)M_z(\pi M_z f)^{-8/3}$$

$$\boxed{X(z) = \frac{1}{2(1+z)}\left[H_0(1+z) - H(z)\right]}$$

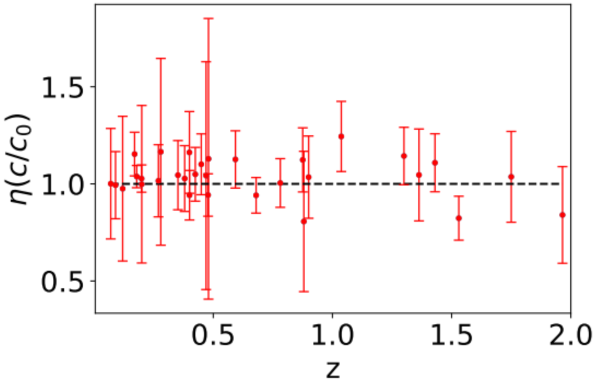
Acceleration parameter X(z)

Results

$$\eta = \frac{c}{c_0}$$

Table 1. The weighted mean and median values of η parameter measuring the invariance of the speed of light from the $QSO + H(z)$ and $Pantheon + H(z)$ samples. The associated dispersion measures are: weighted standard deviation and median absolute deviation.

	Mean(η)	Median(η)
$Pantheon + H(z)$	1.03 ± 0.03	1.04 ± 0.05
$QSO + H(z)$	1.19 ± 0.07	$1.22^{+0.05}_{-0.13}$



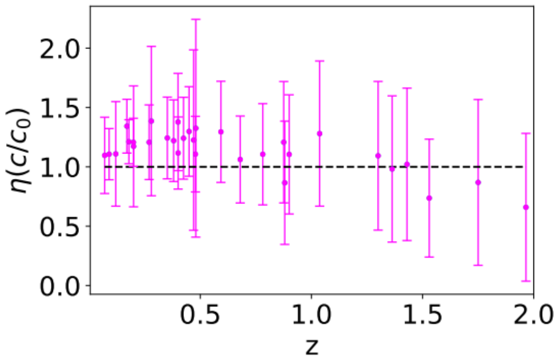


Table 2. η parameter measuring the invariance of the speed of light from the $QSO + X(z)$ and $Pantheon + X(z)$ samples and its precision.

	η	$\Delta\eta$
$Pantheon + X(z)$	1.002 ± 0.001	10^{-3}
$QSO + X(z)$	1.016 ± 0.002	10^{-3}

Conclusions

- Uncharted territory of measuring c using extragalactic sources is being conquered
- Other fundamental constants – fine structure constant $\alpha = \frac{e^2}{\hbar c}$
  John Webb, Victor Flambaum et al. – many multiplets method

$$\frac{\Delta\alpha}{\alpha} = -1.09 \pm 0.36 \times 10^{-5} \qquad (0.6 < z < 1.6)$$

- Empirical support that the laws of physics are the same on Earth now as they were in a distant universe across its history
- Perhaps will lead to the unexpected?
- Could be used as a cross-check of cosmological probes.

Thank you !