Gamma-Ray Burst as distance indicators in Cosmology

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Work in collaboration with José Ignacio Cabrera and Juan Carlos Hidalgo

Mon.Not.Roy.Astron.Soc. 501 (2021) 3, 3515-3526

Cosmology from Home 2022

Outline

- The dark energy problem: state of art
- GRBs as cosmological probe —properties—
- Calibration of GRBs
- Impact of GRBs on Dark Energy constraints
- To take home

The dark energy problem: state of art

The standard cosmological model

1. We live in an expanding universe.

2. Einstein equations.

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

3. Our physical universe can be described by the RW metric.

$$ds^2 = -c^2 dt^2 + a^2(t) \left[\frac{dr^2}{1 - Kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2 \right]$$

$K = 0$

$K < 0$

$K > 0$

4. Friedmann Equations

$$H^2 = \left(\frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \rho$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3} (\rho + 3p)$$

Dark Energy

$\ddot{a} > 0 \Rightarrow p < -\frac{\rho}{3}$

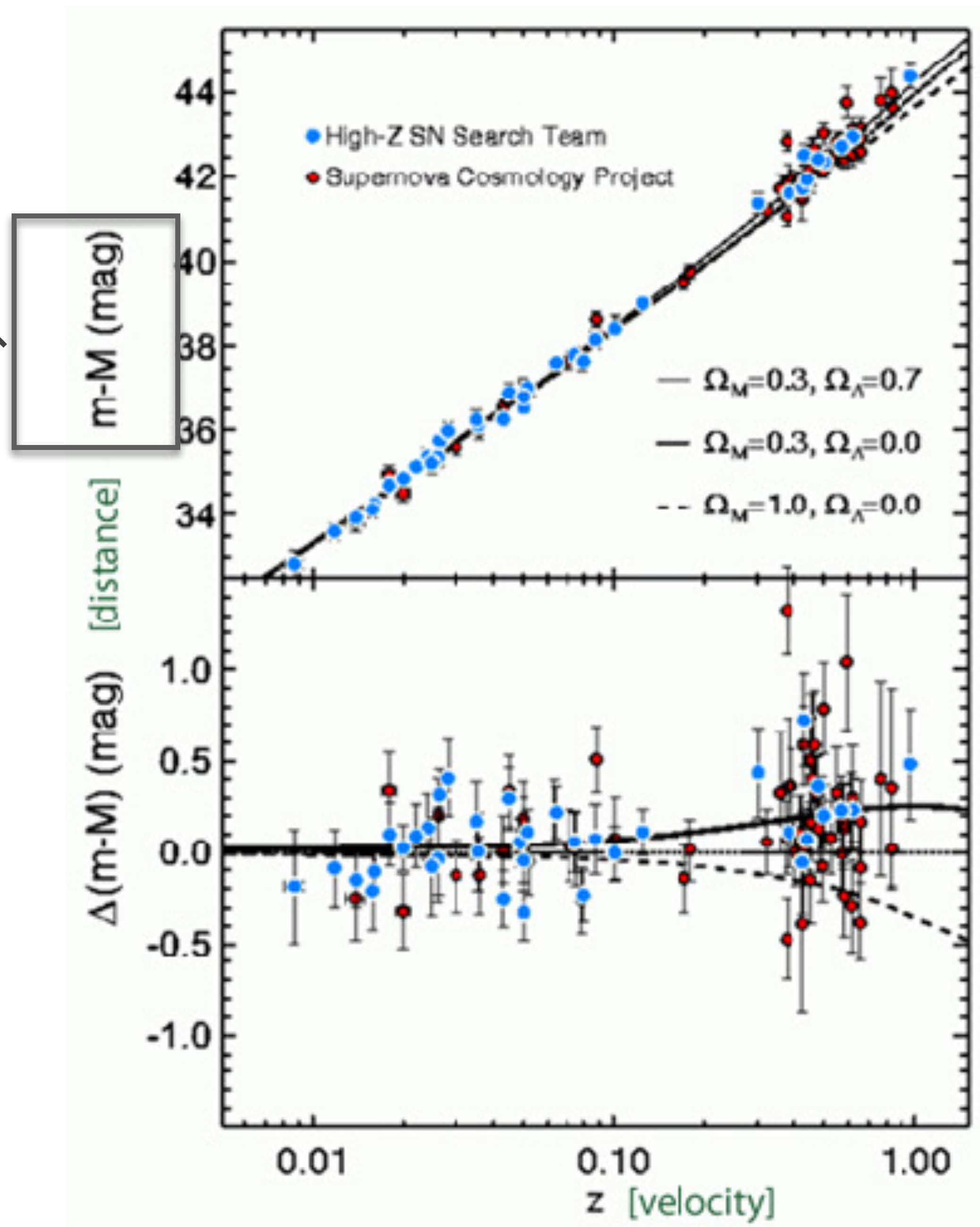
$$w = p/\rho < -\frac{1}{3}$$

5. Continuity

$$\dot{\rho} + 3H(\rho + p) = 0$$

Observational evidence for cosmic acceleration

$$m - M \equiv 2.5 \log \left(\frac{F_{\rm int}}{F} \right) = 5 \log \left[\frac{d_L(z)}{\rm Mpc} \right] + 25$$



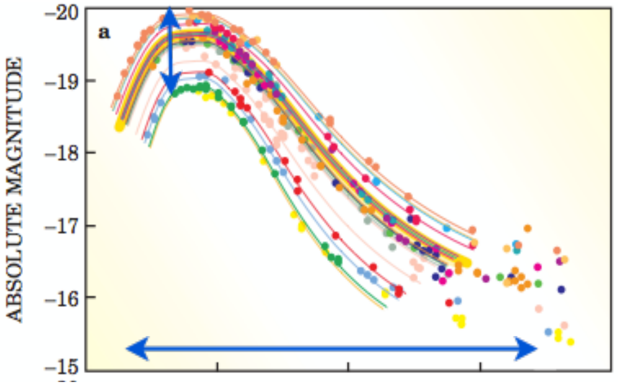
Adam G. Riess, Rev. Mod. Phys., Vol. 84, No. 3, July–September 2012

$$1 + z = \frac{\lambda_{obs}}{\lambda_e} = \frac{a_0}{a(t)}$$

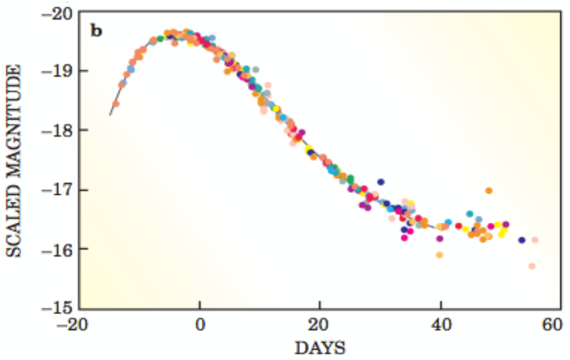
Supernovae are *quasi*-standard candles

Two main sources of variability

1) **Stretch:** intrinsic variability
2) **Color:** dust extinction



Perlmutter (2003)



The usual way to do things…

Multiple Theoretical Models of Dark Energy

↓

Development of statistical methods to extract maximum information from observations

↓

Constraints on theoretical models

What do we need to know?

Luminosity distance

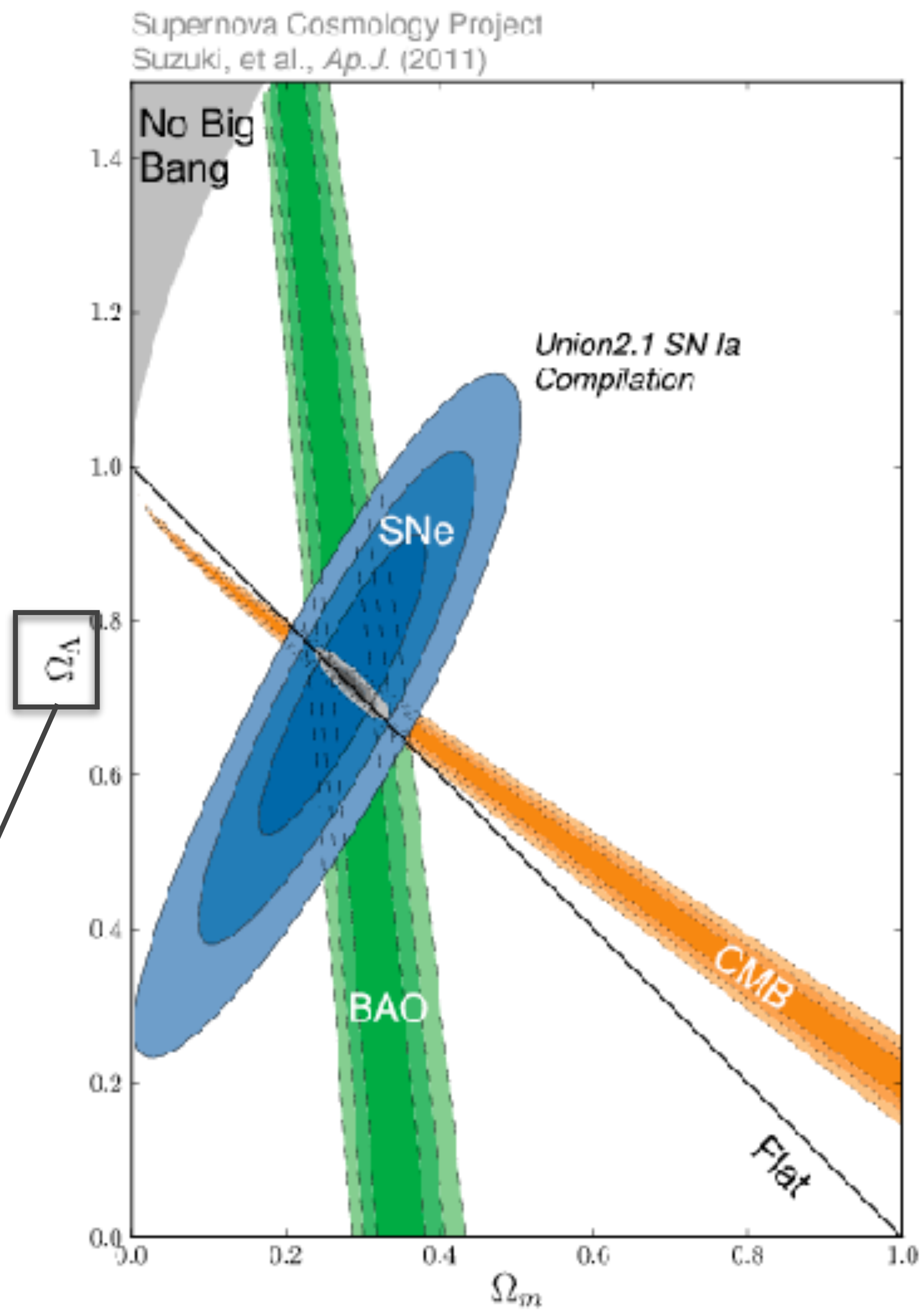
$$\left[\frac{d_L(z)}{10\ \mathrm{pc}}\right]^2 = \frac{F_{\mathrm{int}}}{F}$$

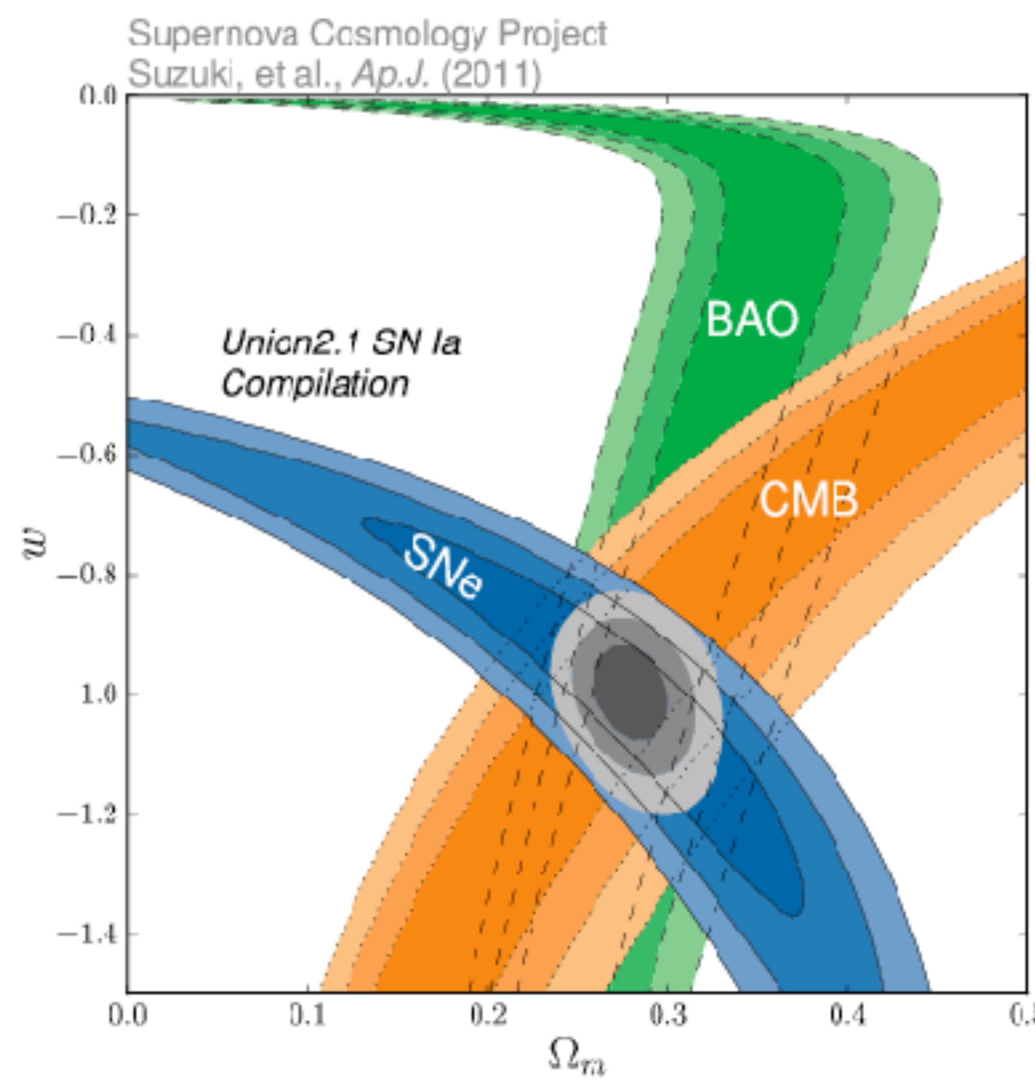
Redshift

$$1 + z = \frac{a_0}{a(t)}$$

$$m - M \equiv 2.5\log\left(\frac{F_{\mathrm{int}}}{F}\right) = 5\log\left[\frac{d_L(z)}{\mathrm{Mpc}}\right] + 25$$

SNe Ia data





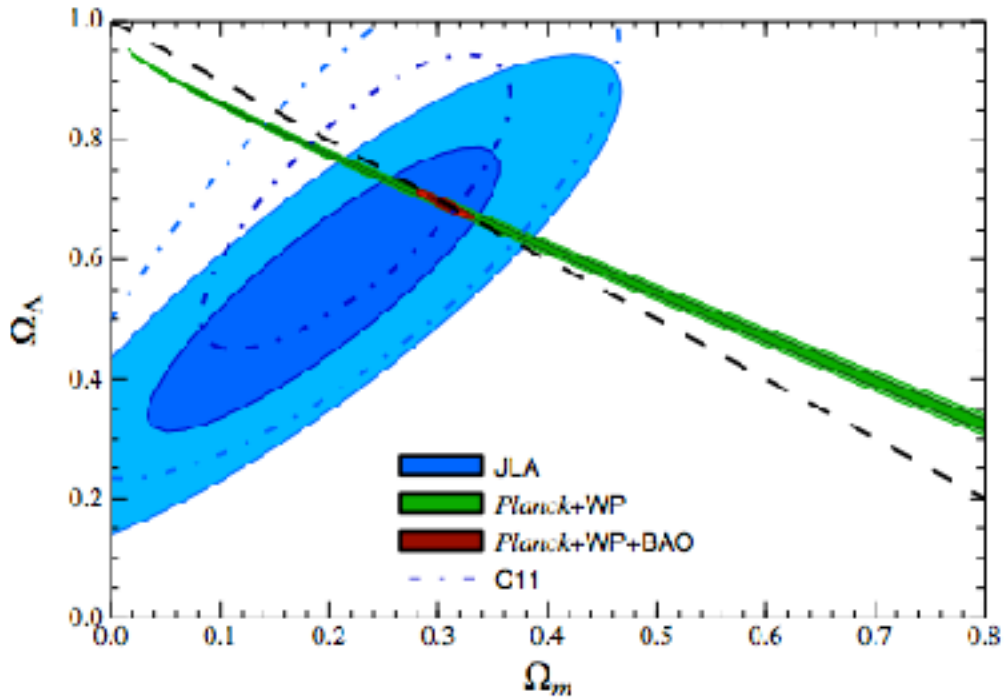
$$p_{\rm DE} = \omega \rho_{\rm DE}$$

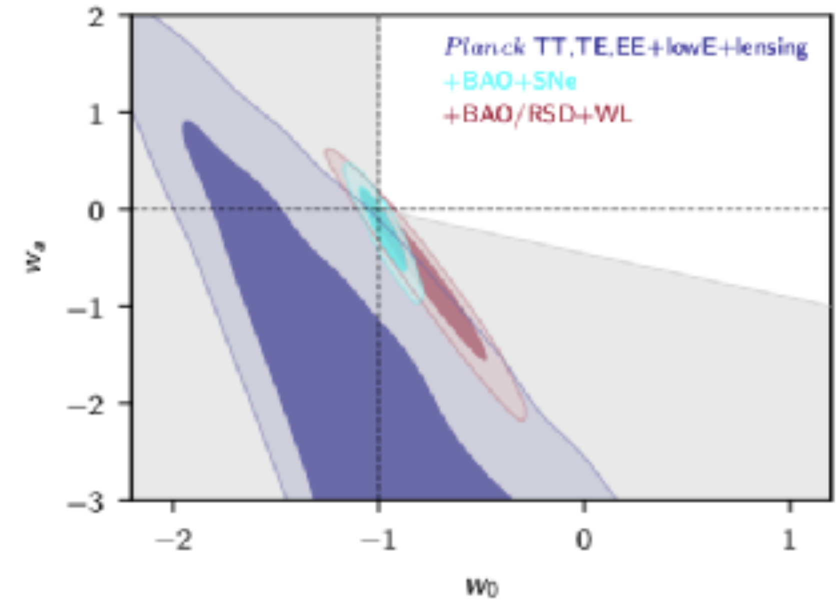
Dark energy equation of state

$\omega = -1 \rightarrow$ **Cosmological constant is the simplest candidate for DE**

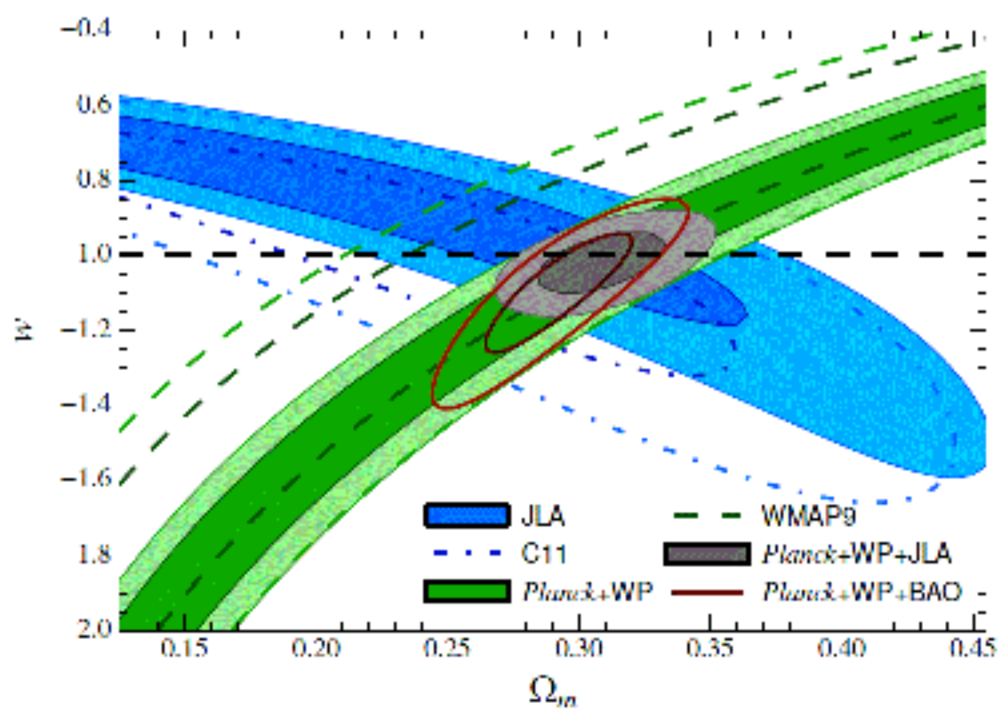
$$\Omega_i = \frac{\rho_i(t_0)}{\rho_c^0} \qquad \rho_c^0 = \frac{3H_0^2}{8\pi G}$$

Huge progress from 1998

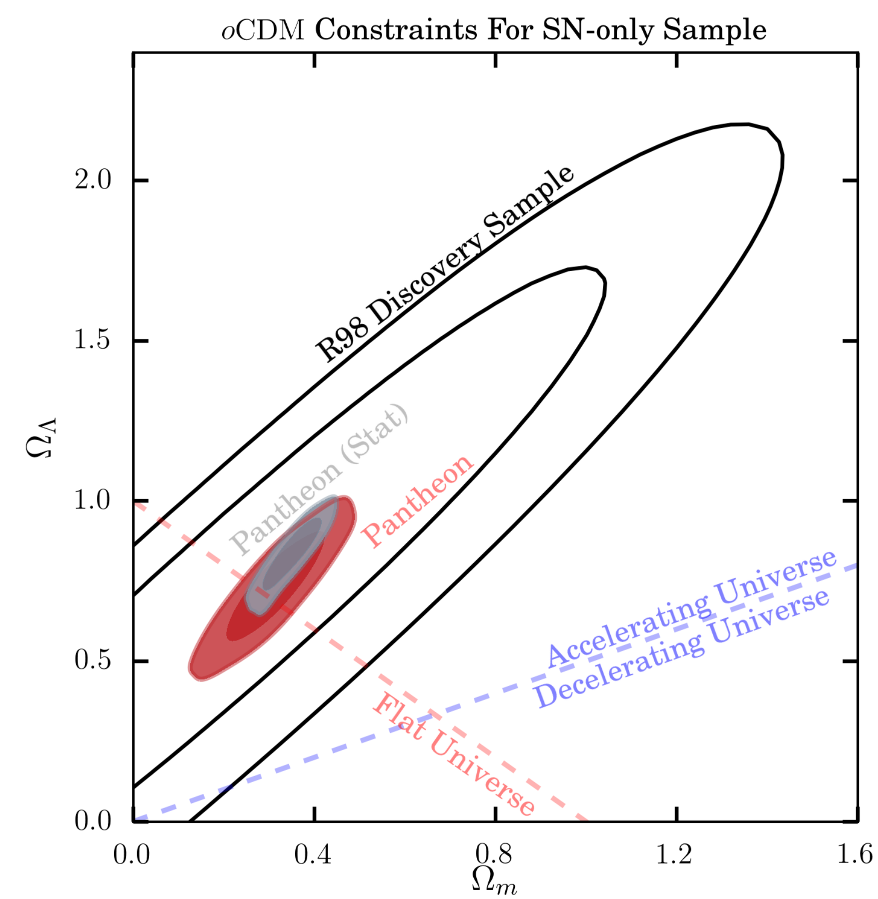




Planck 2018 results. VI. Cosmological parameters
Astron.Astrophys. 641 (2020) A6



SDSS Collaboration (M. Betoule et al.). Astron.Astrophys. 568 (2014) A22



D.M. Scolnic, et al., Astrophys.J. 859 (2018) no.2, 101

Why do we want more cosmological probes?

- Each cosmological probe is characterized by possible systematics.

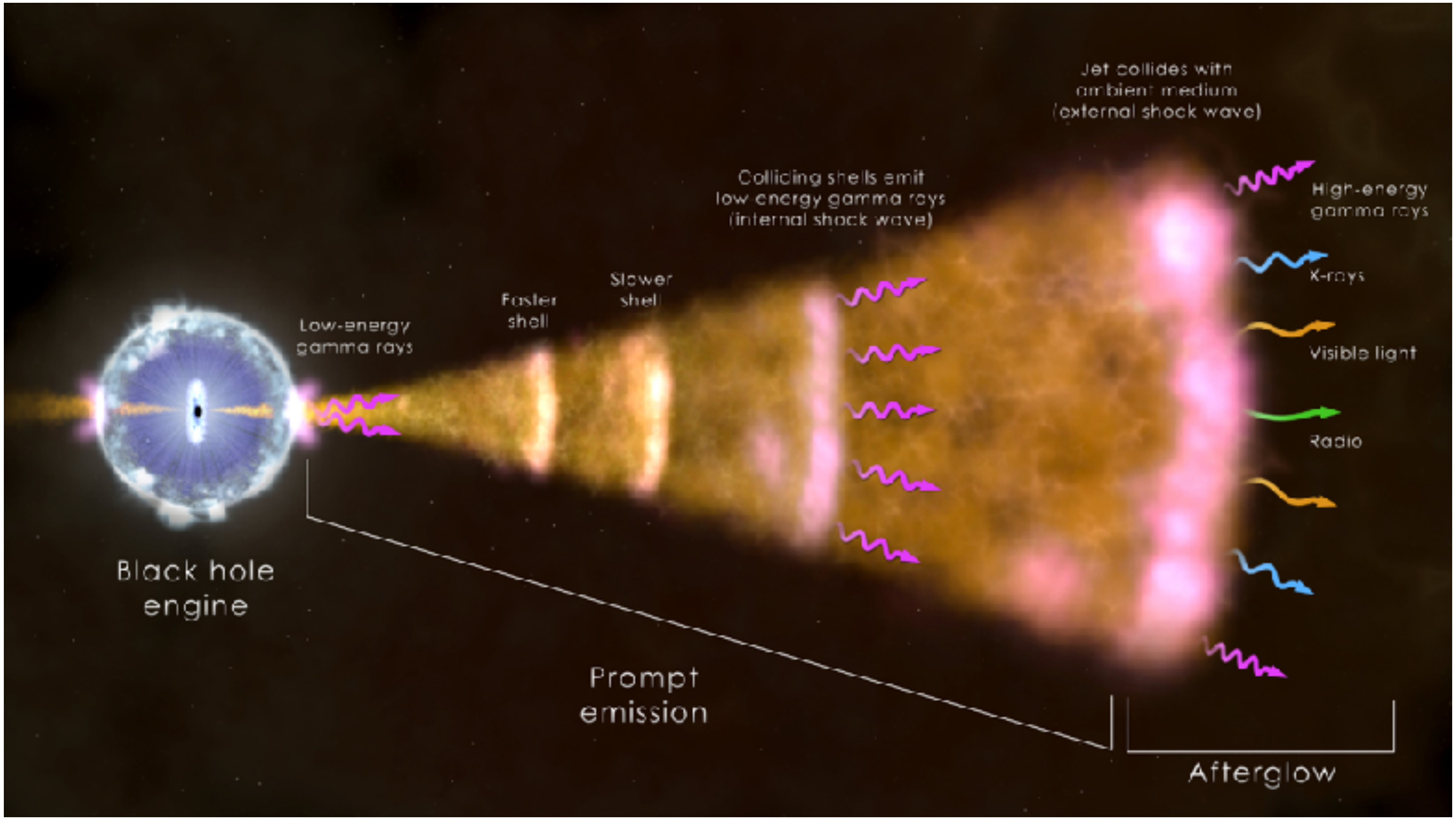
- A contribution from alternative distance indicators covering a wide range of redshifts is key to improve cosmological distance determinations:

Different distribution in the z ➡ Different sensitivity constraining cosmological parameters

GRBs as cosmological probe
— properties —

Gamma-ray Bursts

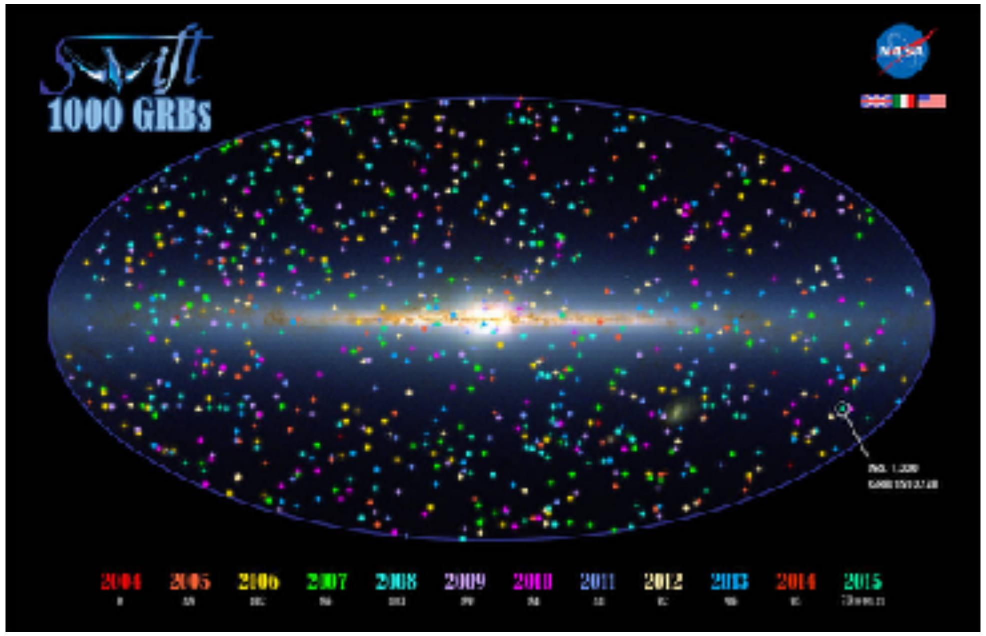
GRBs are the most powerful high-energy events known in the Universe.



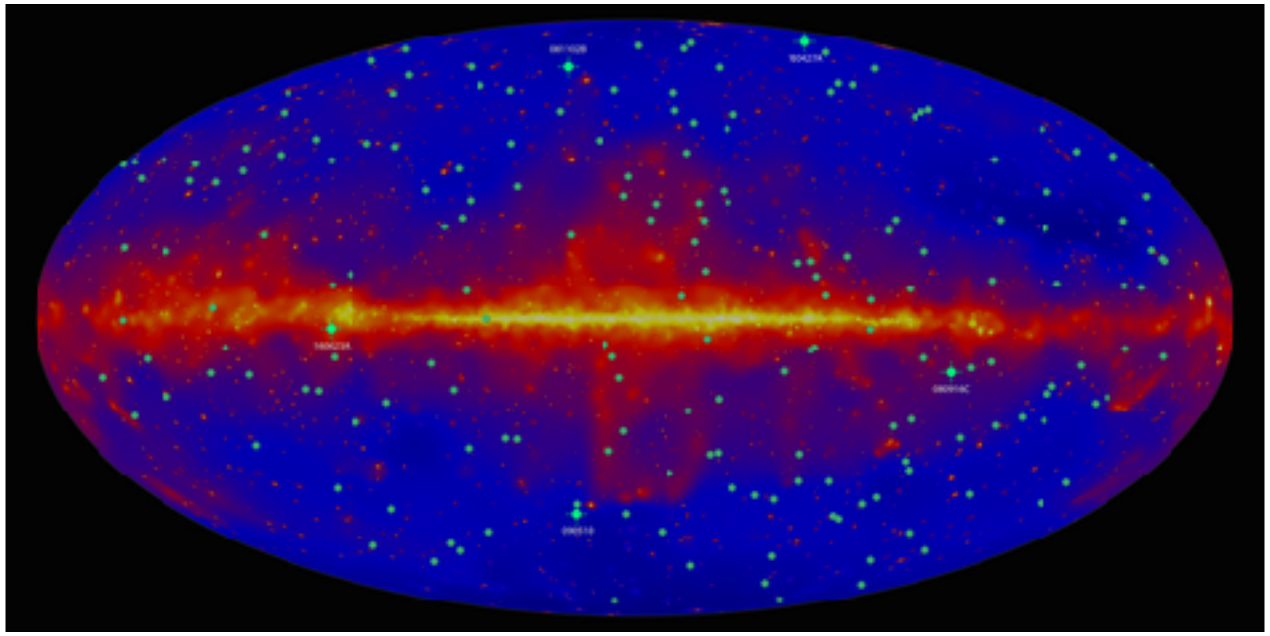
Credit: NASA

Gamma-ray Bursts as cosmological probe

The highest redshifts recorded lie at **z = 8.2** (GRB090423) (Salvaterra et al. 2009; Tanvir et al. 2009) and **z = 9.4** (GRB090429) (Cucchiara et al. 2011).



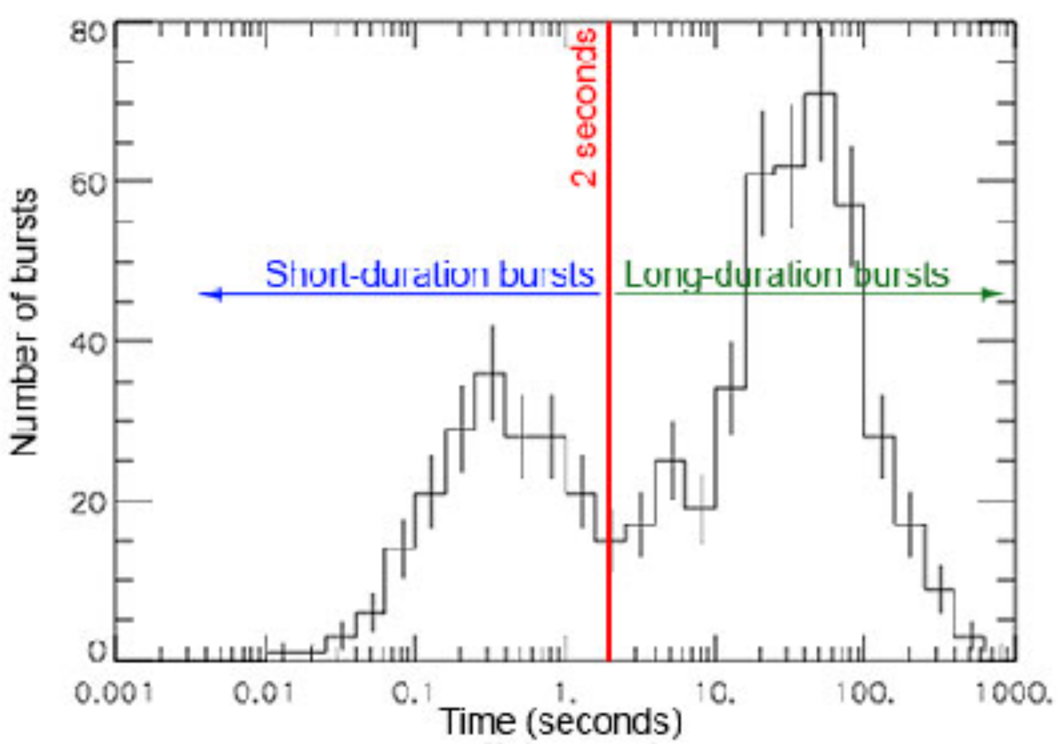
Credits: NASA's Goddard Space Flight Center and 2MASS/J. Carpenter, T. H. Jarrett, and R. Hurt



Credits: NASA/DOE/Fermi LAT Collaboration

Gamma-ray Bursts properties

We define a gamma-ray burst based on its observational properties: an intense flash of gamma rays, lasting from a fraction of a second to up to a few minutes.



https://imagine.gsfc.nasa.gov/science/objects/bursts1.html

Two types:
Short GRBs (t<2s)
Long GRBs (t>2s)

Model:
NS-NS mergers: SGRBs
Massive star collapse: LGRBs

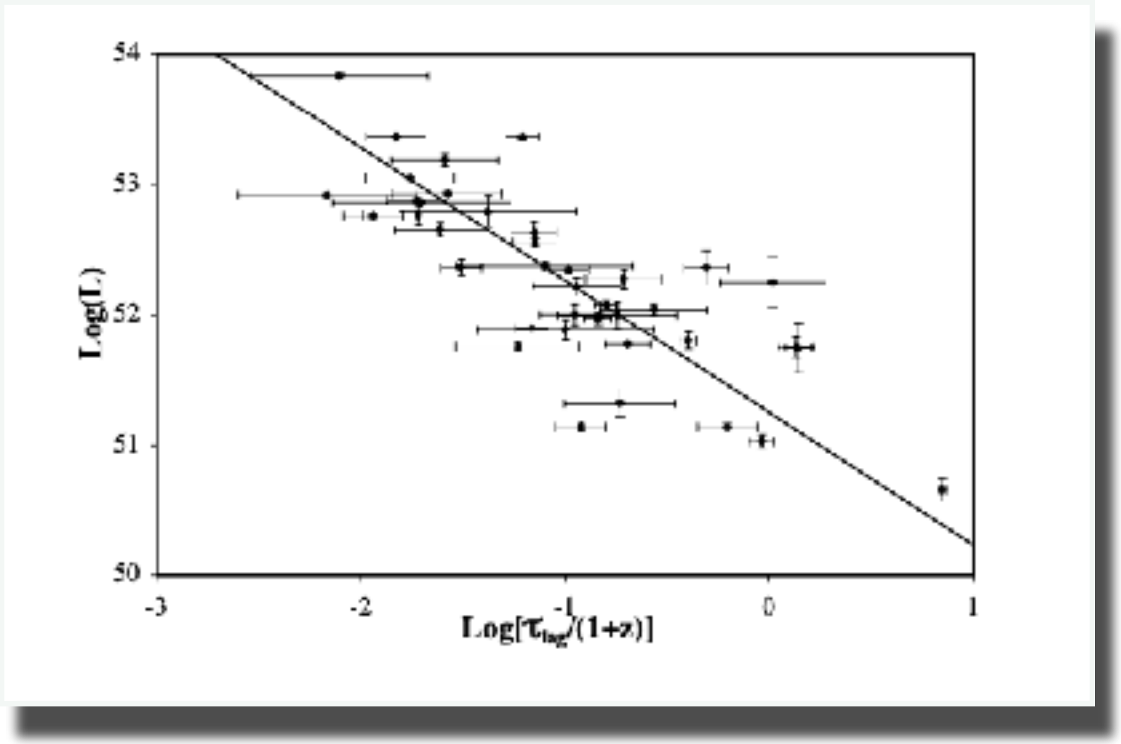
Gamma-ray Bursts as distance indicators

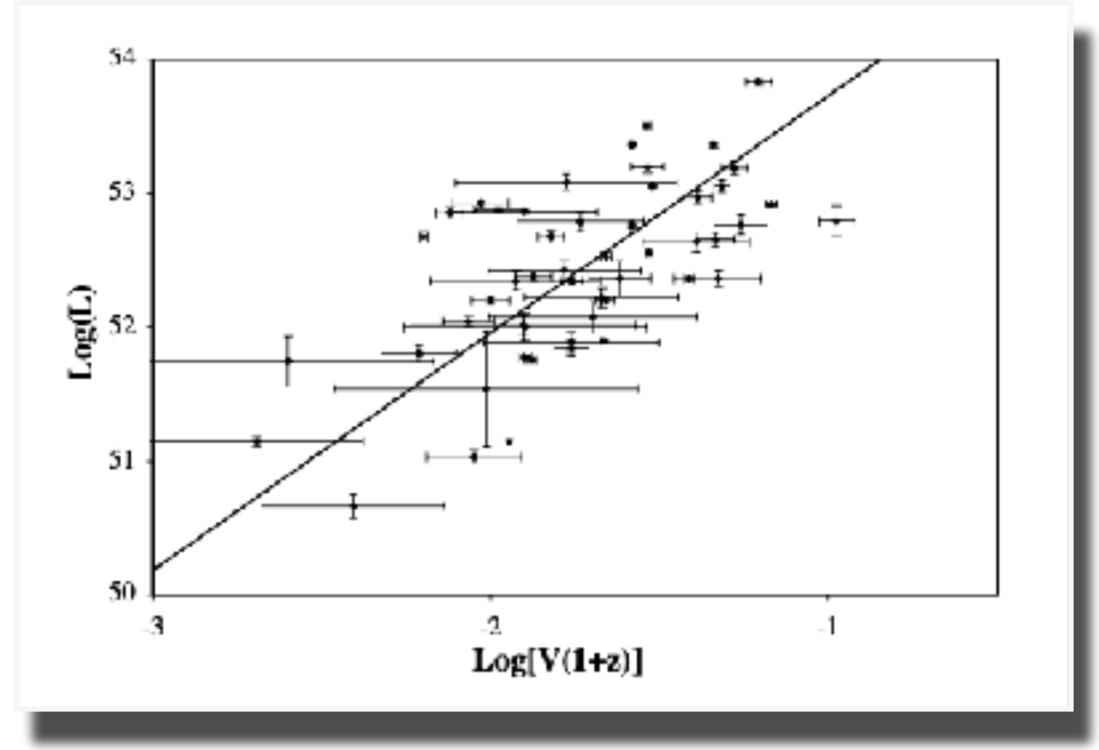
The **main advantage** of GRBs over SNe Ia is that they span a much greater redshift range.

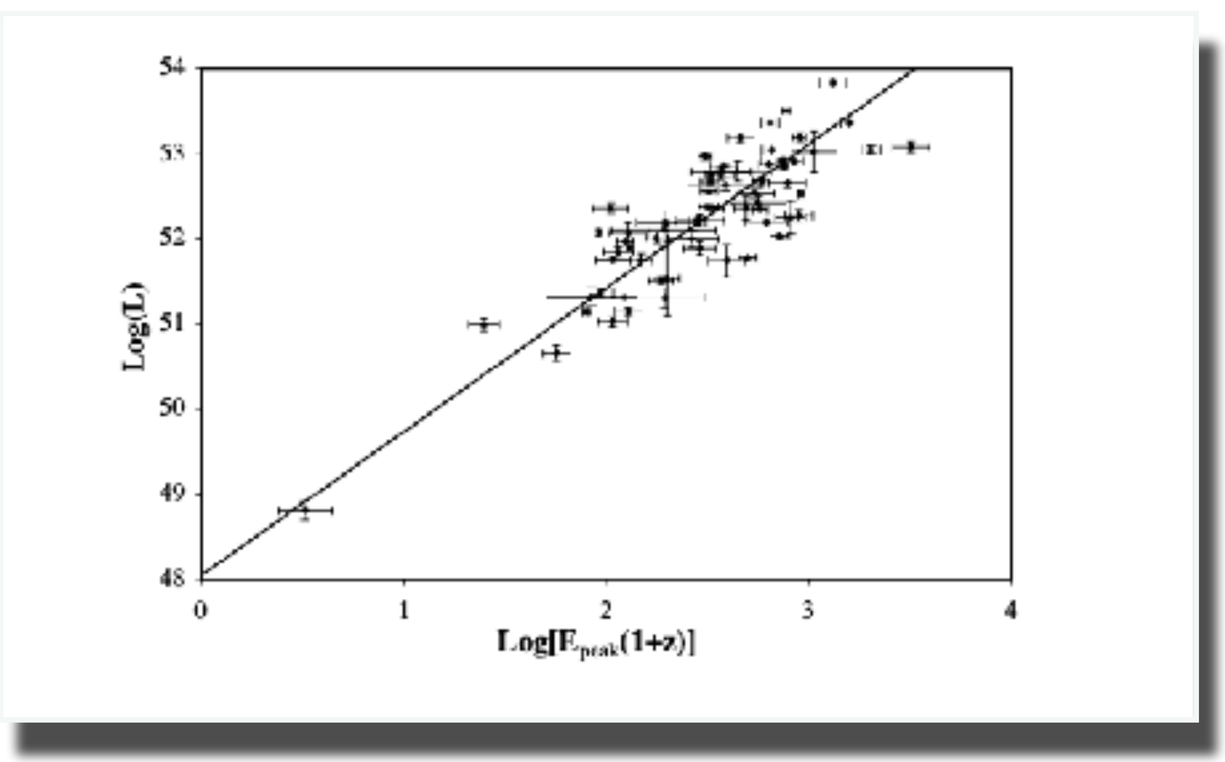
The **main disadvantage** is that the calibration of GRBs depends of a cosmological model a priori.

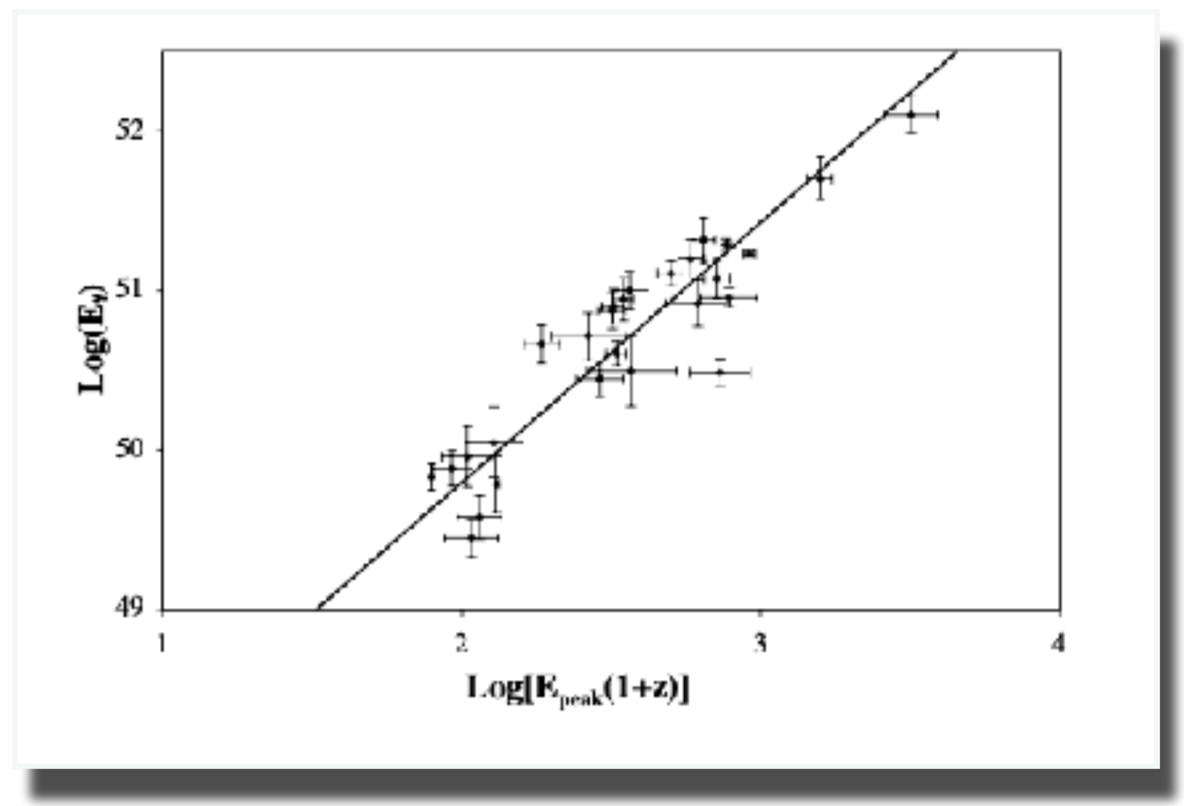
Long duration gamma-ray bursts (LGRBs) have **luminosity relations** which are connections between observable properties of the γ-ray emission with the luminosity or energy (see e.g., Schaefer and Collazi 2007).

Gamma-ray Bursts luminosity relations



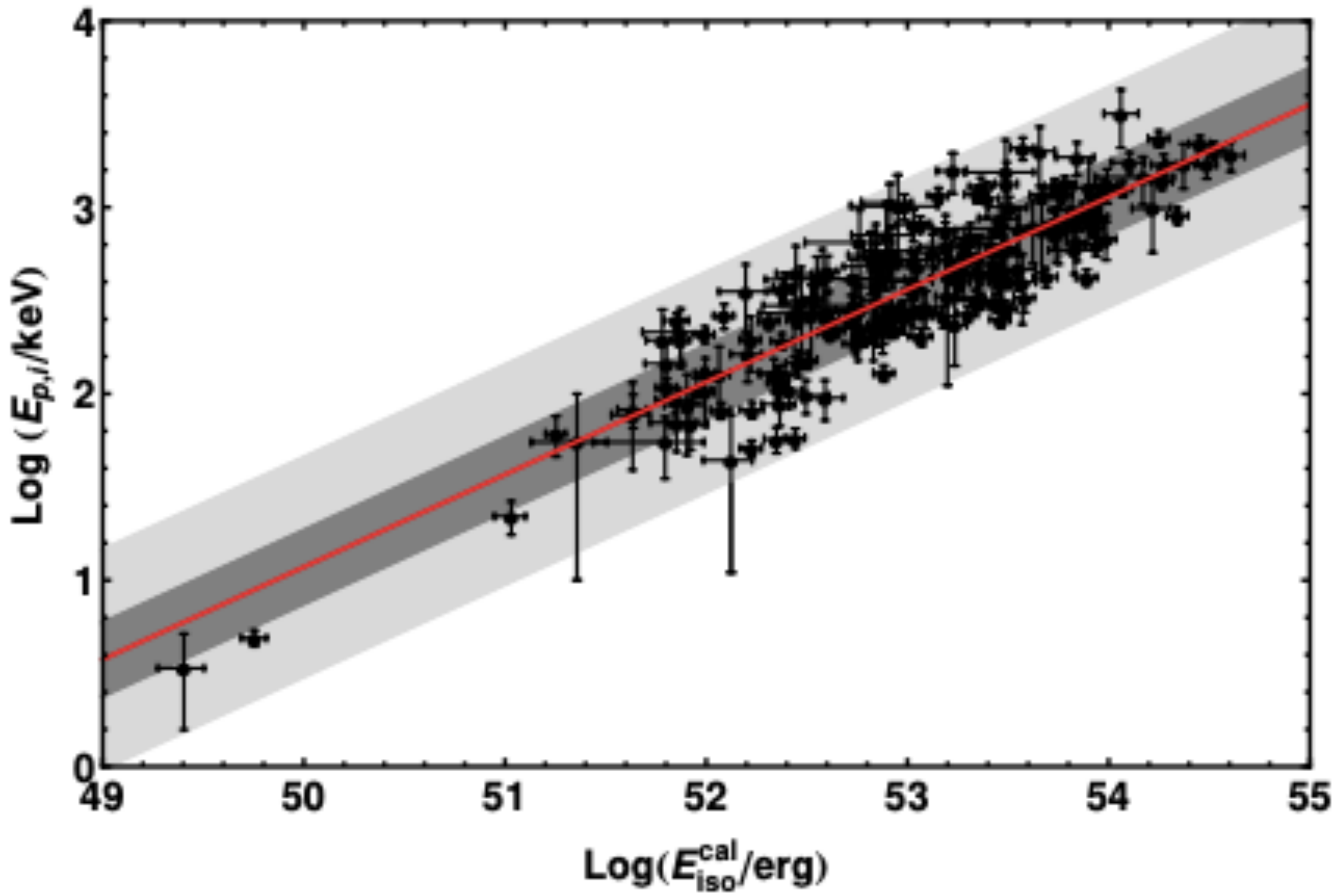






Bradley E. Schaefer, Astrophys.J. 660 (2007) 16-46

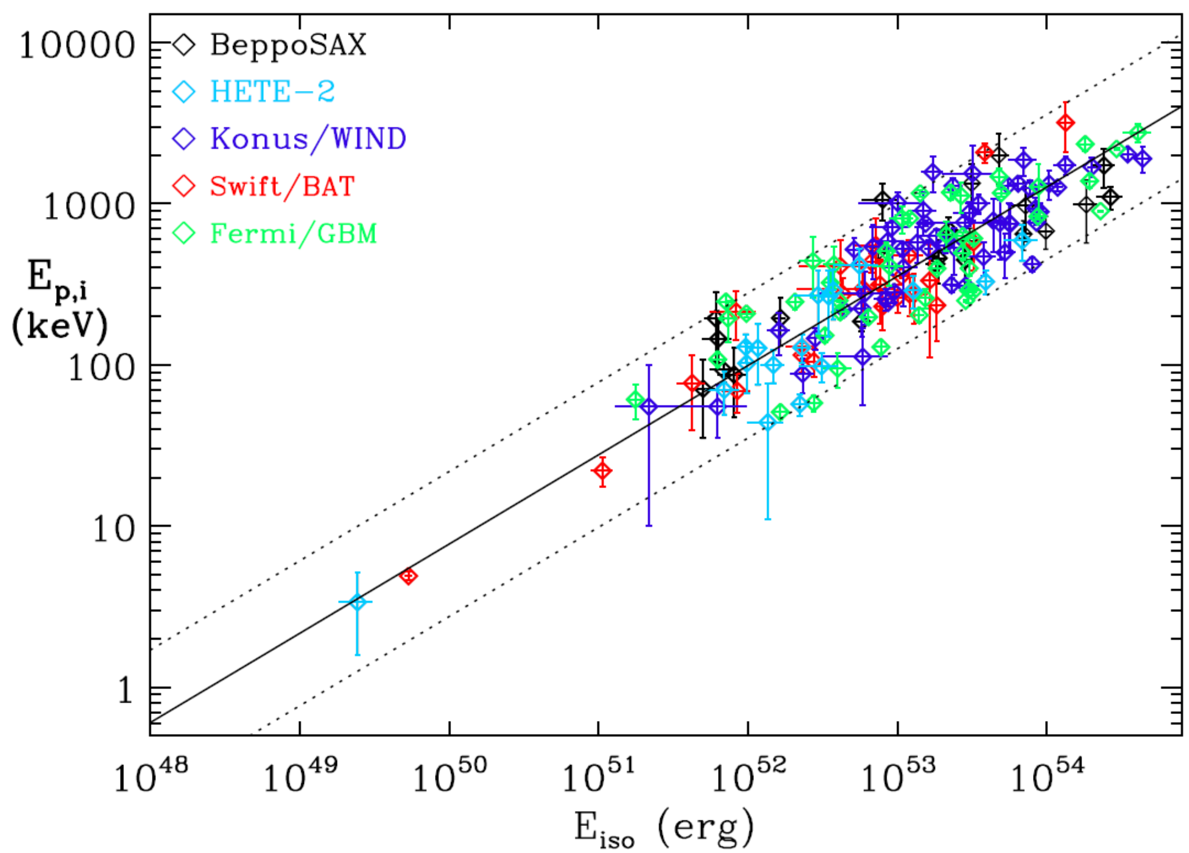
Amati relation



Lorenzo Amati et al. Mon.Not.Roy.Astron.Soc. 486 (2019) 1, L46-L51

Amati relation

$E_p - E_{iso}$ correlation for GRBs with known redshift has been confirmed and extended by measurements of several GRB detectors with spectral capabilities:



Amati & Della Valle,Int.J.Mod.Phys. D22 (2013)

E_p : peak energy of the spectrum

E_{iso} : isotropic energy

Our contribution

➡ Present a **new and independent dataset of GRBs calibrated in a cosmological independent way.**

➡ Because different GRBs detectors are characterized by different detection and spectroscopy sensitivity as a function of GRB intensity and spectrum, we consider **data exclusively from a single catalogue** (the Fermi-GBM), which **prevents selection biasses and other instrument-associated systematics.**

➡ Moreover, **to avoid extra bias**, we select only GRBs with **redshift determined through spectroscopic methods.**

The sample: 74 GRBs

The GRBs spectrum is mainly, but not exclusively, described in terms of an empirical spectral function, the Band function

$$f(E) = \begin{cases} N_0 \left(\frac{E}{100\mathrm{keV}}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right) & E \leq E_b \\ N_0 \left(\frac{E_b}{100\mathrm{keV}}\right)^{(\alpha-\beta)} \exp(\beta-\alpha) \left(\frac{E}{100\mathrm{keV}}\right)^{\beta} & E > E_b \end{cases}$$

The BAT instrument of **Swift** satellite is limited to energies up to 150 keV: **is not possible to obtain directly the flux and luminosity of many GRBs.**

FERMI allows for the determination of all the spectral parameters in the Band function.

We limit our sample to those GRBs with **redshift determined through spectroscopic methods** either from the afterglow or from the host galaxy.

Our sample of 74 GRBs cover the redshift range $0.117 \leq z \leq 5.283$.

Calibration of GRBs

Calibration independent of the cosmological model

Amati relation

$$\log\left(\frac{E_{\rm iso}^{\rm cal}}{\rm erg}\right) = A\log\left(\frac{E_p}{\rm keV}\right) + B$$

STEPS

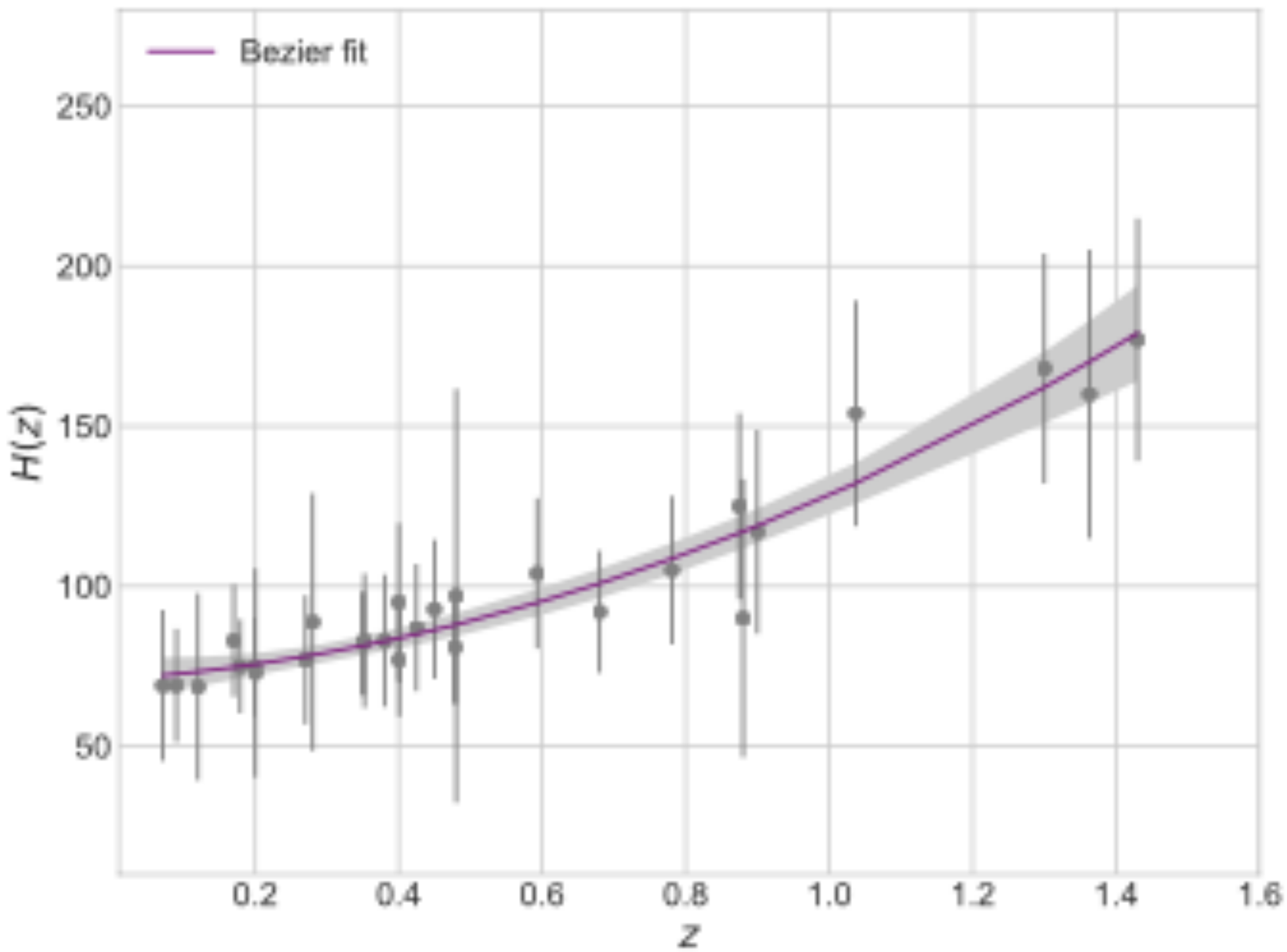
1. The isotropic energy E_{iso}: $E_{\rm iso}(z) = 4\pi d_L^2 S_{\rm bolo}(1+z)^{-1}$

   1.1 We need the luminosity distance $d_L(z) = c(1+z)\int_0^z \frac{dz'}{H(z')}$

   1.2 We employed a Bézier parametric curve of degree 2:

$$H_n(z) = \sum_{d=0}^{n} \beta_d h_n^d(z), \quad h_n^d \equiv \frac{n!(z/z_m)^d}{d!(n-d)!}\left(1-\frac{z}{z_m}\right)^{n-d}$$

1.3 We use Hubble parameter data reported by *Capozziello et al. (2018)*, which comes from the Cosmic Chronometers approach to build a Bézier curve of degree n=2: $H_2(z) = \beta_0 h_2^0(z) + \beta_1 h_2^1(z) + \beta_2 h_2^2$

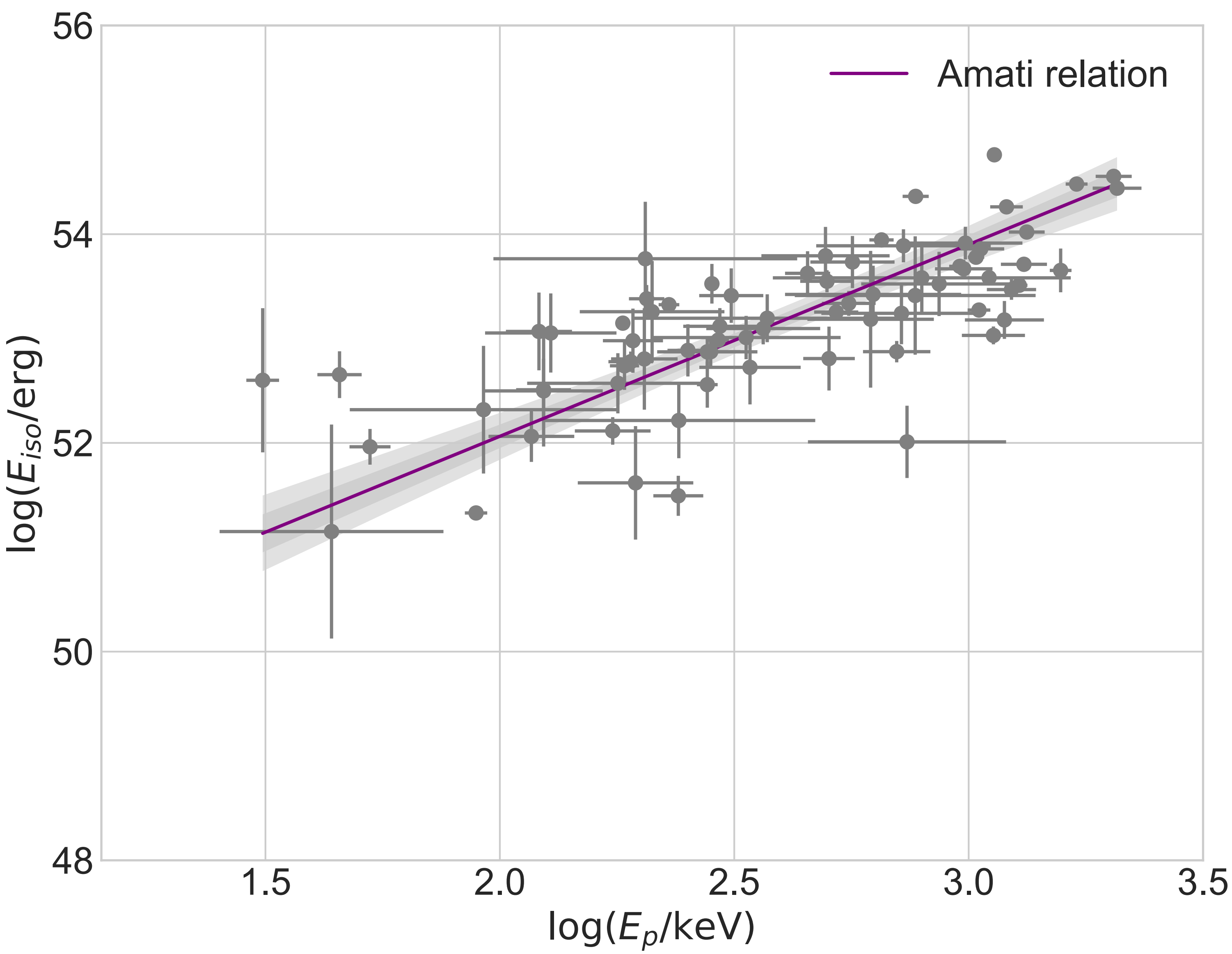


$\beta's$ parameters obtained by adding to the measurement error of the Hubble parameter data, the maximum bias reported in Moresco et al. (2020).

2 Insert the calibrated luminosity distance $d_L^{cal}(z) = c(1+z)\int_0^z \frac{dz'}{H_2(z')}$ into the E_{iso}^{cal}:

$$E_{iso}(z) = 4\pi d_L^2 S_{bolo}(1+z)^{-1}$$

3 Fit the Amati relation

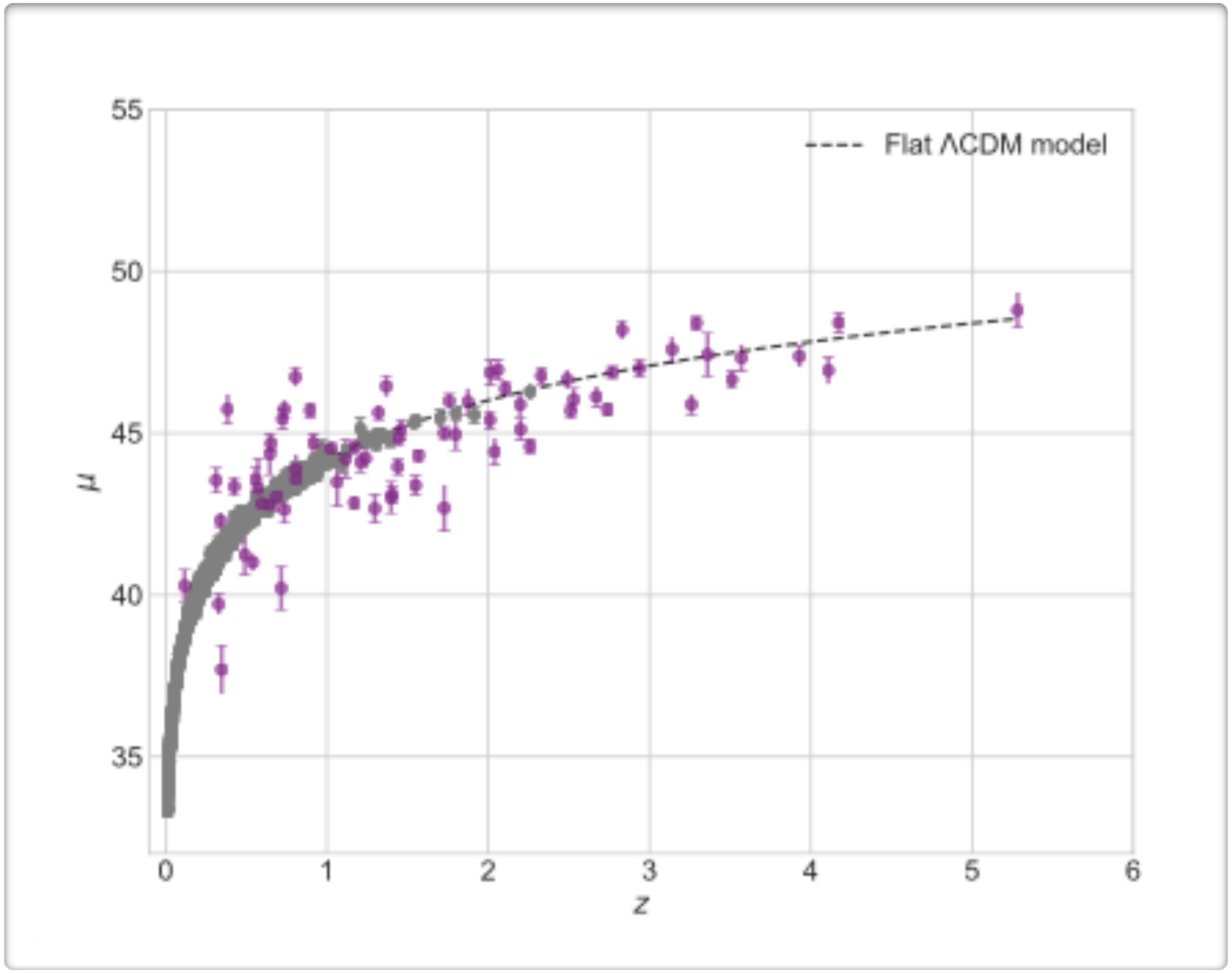


$$\log\left(\frac{E_{iso}^{cal}}{\text{erg}}\right) = A\log\left(\frac{E_p}{\text{keV}}\right) + B$$

$$A = 1.8355 \pm 0.2403$$
$$B = 48.3934 \pm 0.6551$$

4. Calculate the distance modulus for each GRBs and perform the corresponding error propagation:

$$\mu_{\rm GRB} = 5\log(d_L^{\rm cal}/{\rm Mpc}) + 25$$



Impact of GRBs on Dark Energy constraints

Impact of GRBs on Dark Energy constraints

$$H^2(z) = H_0^2[\Omega_m(1+z)^3 + \Omega_X X(z)]$$

Where the dark energy density function X(z) is defined as $X(z) \equiv \frac{\rho_X(z)}{\rho(0)}$

With

$$\rho_X(z) = \exp\left(\int_0^z dz' \frac{3[1+w(z')]}{1+z'}\right)$$

In this work we studied

1. ΛCDM: $\omega = -1$

3. wCDM: $\omega = const$

5. CPL parametrization: $\omega = \omega_0 + \omega_a \frac{z}{1+z}$

Data and methods

CLASS I: Overview, by J. Lesgourgues, arXiv:1104.2932 [astro-ph.IM], http://class-code.net

+

Monte Python

The Monte Carlo code for CLASS in Python

Thejs Brinckmann, Julien Lesgourgues, arXiv:1804.07261
http://baudren.github.io/montepython.html

Observational data

Type Ia Supernovae (SNe Ia) Scolnic et al. (2018)

Baryon Acoustic Oscillations (BAO) Alam et al. (2017) Beutler et al. (2011); Ross et al. (2015)

Cosmic Microwave Background (CMB) Chen et al. (2019)

+

Gamma-Ray Bursts (GRBs) Amati et al. (2019) *or* our calibrated sample

Dark Energy Models

Dark energy models we are studying here

1. ΛCDM:

3. wCDM:

5. CPL parametrization: $$\omega = \omega_0 + \omega_a \frac{z}{1+z}$$

Results

1.ΛCDM model

	SNIa+BAO+CMB		SNIa+BAO+CMB + GRBs(1)		ALL + GRBs(2-no sys)		ALL + GRBs(2-sys)	
	best-fit	mean±σ	best-fit	mean±σ	best-fit	mean±σ	best-fit	mean±σ
Ω_m	0.3179	$0.3179^{+0.00057}_{-0.00058}$	0.3180	$0.3180^{+0.00057}_{-0.00057}$	0.3180	$0.3180^{+0.00057}_{-0.00057}$	0.3180	$0.3180^{+0.00057}_{-0.00057}$

Our results, either including GRBs(1), GRBs(2- no sys) or GRBs(2-sys), are consistent with the ones reported by Amati et al. (2019) only at 2σ.

A. Montiel, José Ignacio Cabrera, Juan Carlos Hidalgo, *Mon.Not.Roy.Astron.Soc.* 501 (2021) 3, 3515-3526

Results

2. wCDM model

	SNe Ia + BAO + CMB		SNe Ia + BAO + CMB + GRBs(1)		ALL + GRBs (2- no sys)		ALL + GRBs (2- sys)	
	best-fit	mean±σ	best-fit	mean±σ	best-fit	mean±σ	best-fit	mean±σ
ω_0	-0.9776	$-0.9782^{+0.01}_{-0.0096}$	-0.9755	$-0.9757^{+0.0099}_{-0.0096}$	-0.9783	$-0.9785^{+0.01}_{-0.0097}$	-0.9779	$-0.9786^{+0.01}_{-0.0098}$
Ω_m	0.3141	$0.3142^{+0.0018}_{-0.0018}$	0.3138	$0.3138^{+0.0018}_{-0.0018}$	0.3143	$0.3143^{+0.0018}_{-0.0018}$	0.3142	$0.3144^{+0.0018}_{-0.0018}$

Results of Amati et al. (2019):

Table 2. 95% confidence level results of the MCMC analysis for the SN+GRB data. The AIC and DIC differences are intended with respect to the ΛCDM model.

Model	w	Ω_m	M	Δ_M	α	β	ΔAIC	ΔDIC
ΛCDM	-1	$0.397^{+0.040}_{-0.039}$	$-19.090^{+0.037}_{-0.037}$	$-0.055^{+0.043}_{-0.043}$	$0.126^{+0.011}_{-0.012}$	$2.61^{+0.13}_{-0.13}$	0	0
wCDM	$-0.86^{+0.36}_{-0.38}$	$0.34^{+0.13}_{-0.15}$	$-19.079^{+0.046}_{-0.046}$	$-0.055^{+0.042}_{-0.042}$	$0.126^{+0.011}_{-0.012}$	$2.61^{+0.13}_{-0.13}$	1.44	1.24

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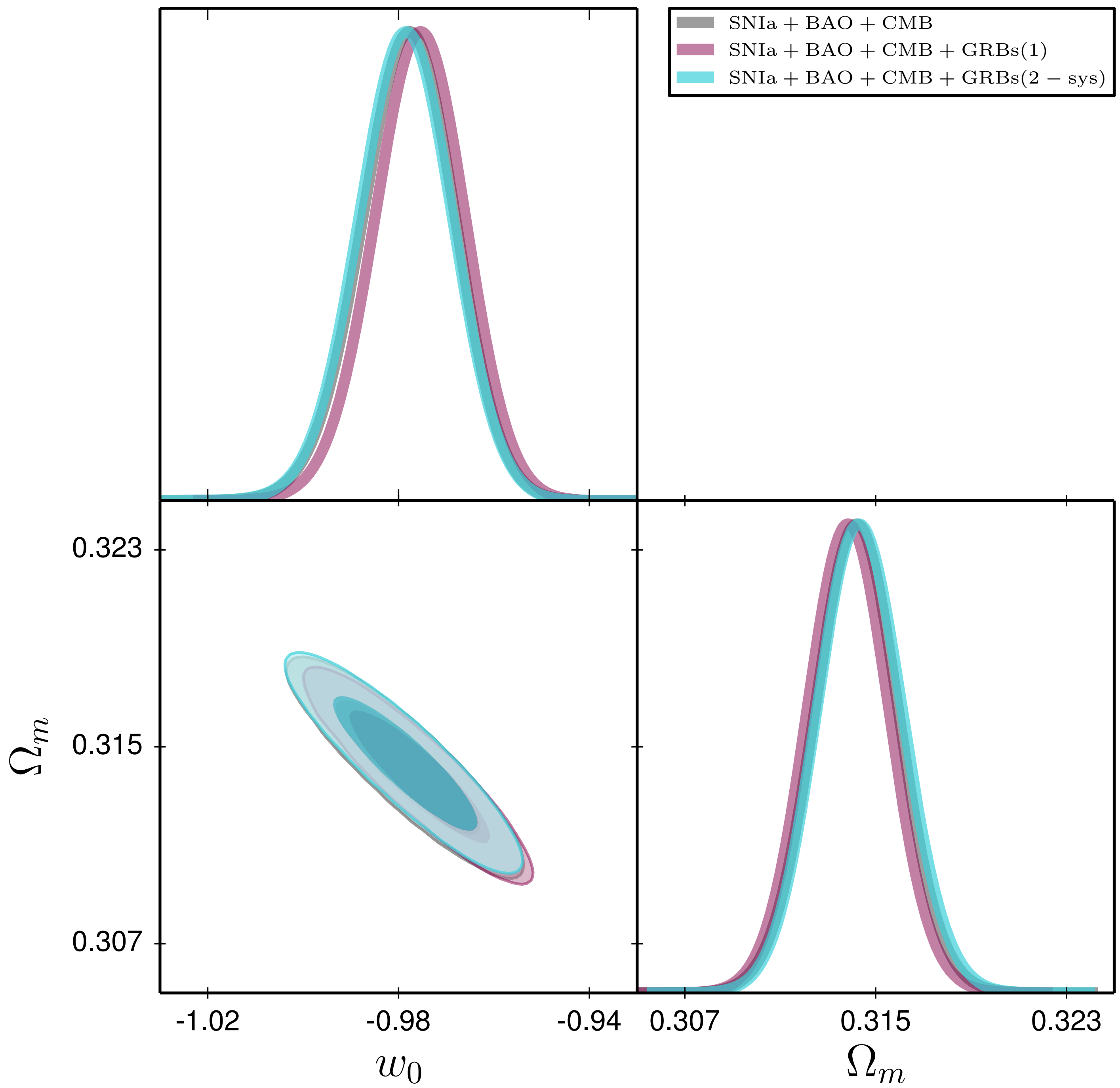
2. wCDM model



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Results

3.CPL model

	SNe Ia + BAO + CMB		SNe Ia + BAO + CMB + GRBs(1)		ALL + GRBs(2-no sys)		ALL + GRBs(2- sys)	
	best-fit	mean$\pm\sigma$	best-fit	mean$\pm\sigma$	best-fit	mean$\pm\sigma$	best-fit	mean$\pm\sigma$
ω_0	-0.9631	$-0.9515^{+0.074}_{-0.078}$	-0.8628	$-0.8548^{+0.073}_{-0.075}$	-1.002	$-0.9933^{+0.066}_{-0.069}$	-1.009	$-0.9982^{+0.064}_{-0.068}$
ω_a	-0.05507	$-0.1079^{+0.3}_{-0.27}$	-0.4361	$-0.4782^{+0.31}_{-0.28}$	0.09276	$0.05013^{+0.27}_{-0.23}$	0.1135	$0.06781^{+0.26}_{-0.22}$
Ω_m	0.3142	$0.3144^{+0.0018}_{-0.0019}$	0.3144	$0.3147^{+0.0018}_{-0.0019}$	0.3139	$0.3142^{+0.0018}_{-0.0019}$	0.3141	$0.3143^{+0.0018}_{-0.0019}$

The parameter values fitting the new sample of GRBs favours the ΛCDM model more than the other two cases.

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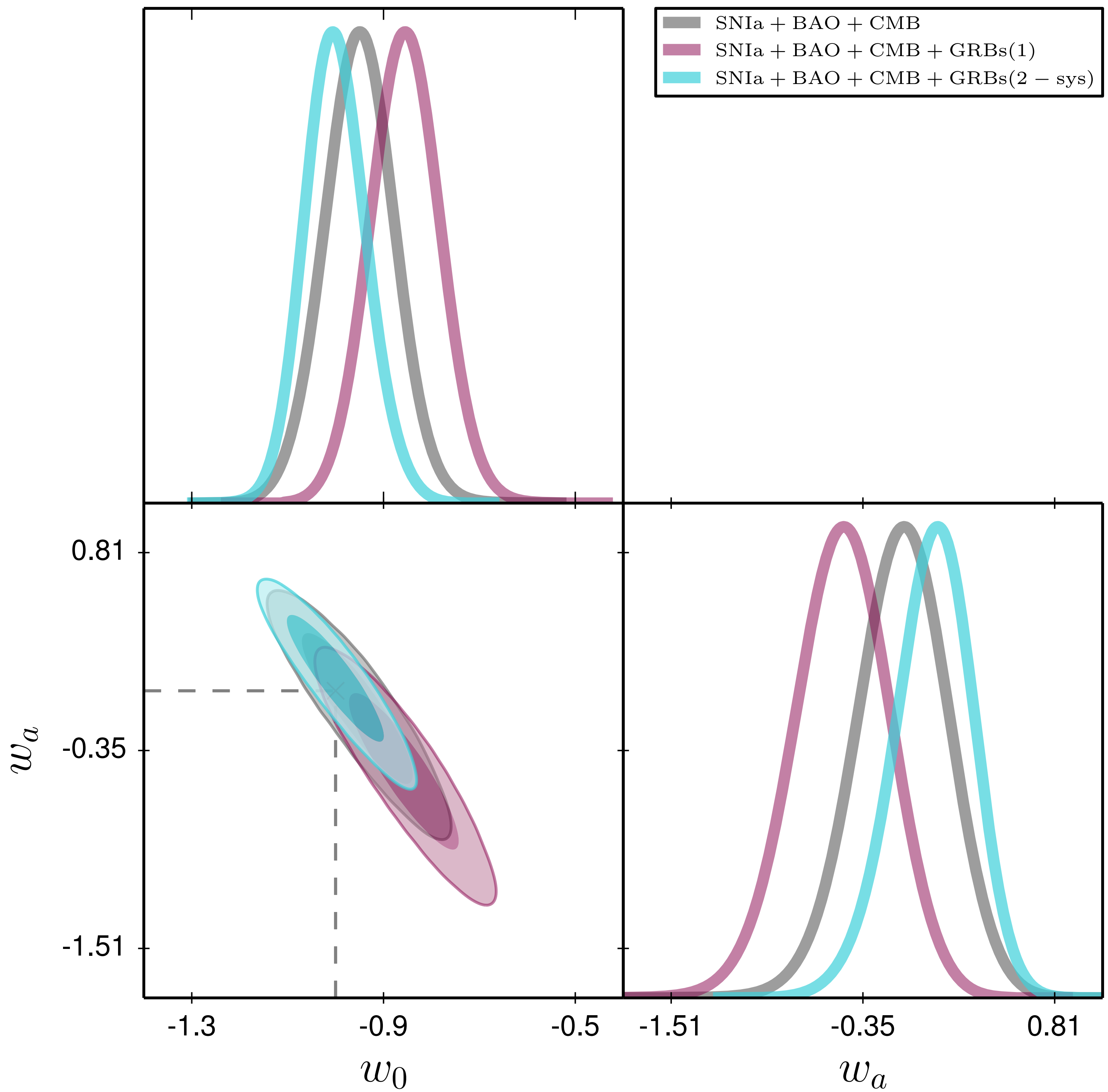
3.CPL model



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To take home…

What did we find?

We have carefully selected a sample of 74 GRBs as tracers of the luminosity distance.

We find consistency with previous works for ΛCDM and ωCDM models at 1σ in the posterior contours of the relevant parameters, with the bonus of a much tighter confidence region for the parameters.

GRBs can be used as standard candes. We argue in favour of our analysis when considering GRBs and other luminosity distance probes.

Thank you for your attention!

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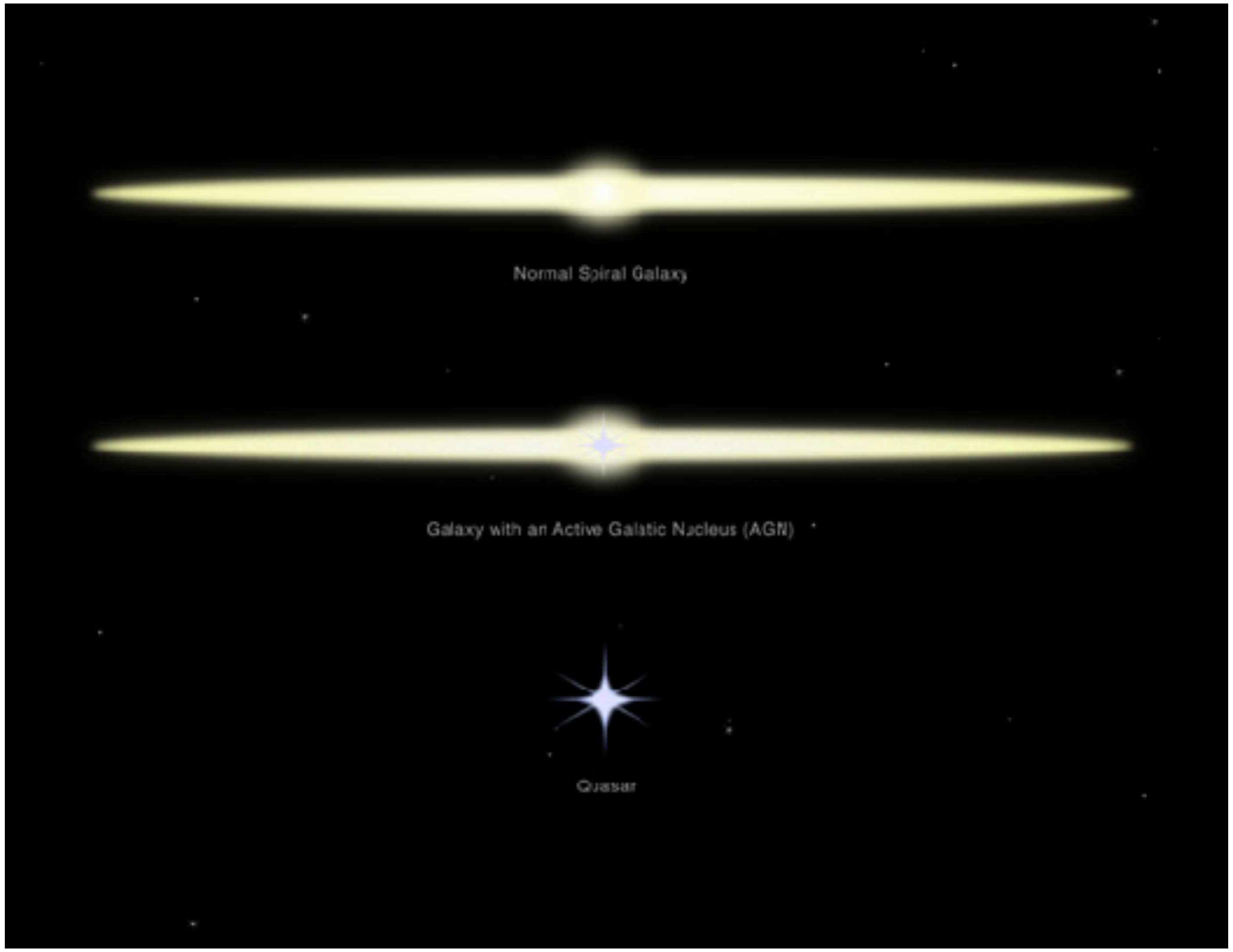
What's next?

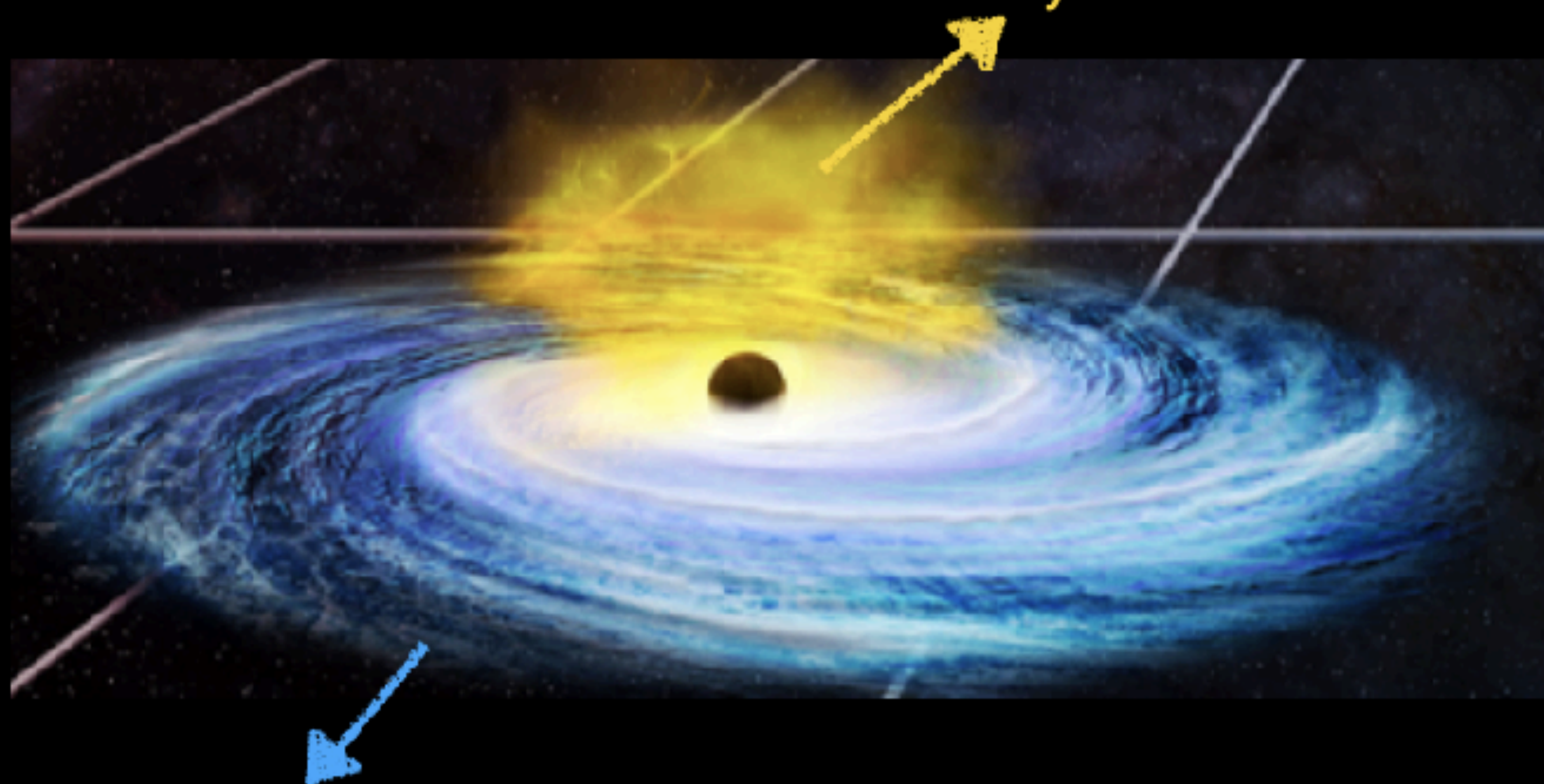
Because the ΛCDM model is still poorly tested in the redshift interval between the farthest observed type Ia supernovae and the CMB, we are interested in extend the previous approach to **quasars (QUASi-stellAR objects)**.

Quasars are the most luminous persistent sources in the Universe, observed up to redshifts of $z \approx 7.5$ (E. Bañados et al. *Nature* 553, 473–476 (2018)).



QUASARS AS STANDARD CANDLES

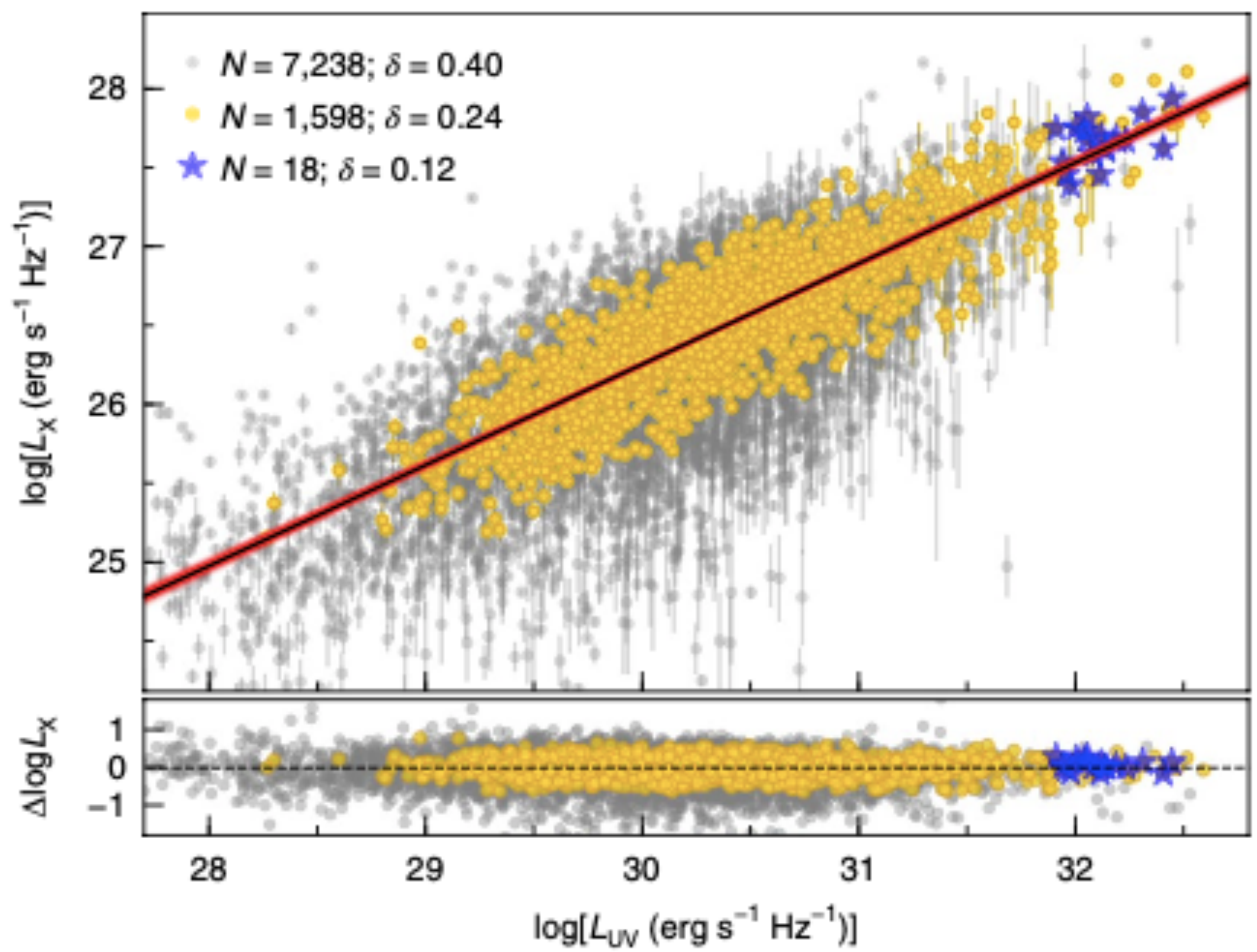
X-rays from the *corona*



Optical/Ultraviolet light from the accretion disc

By using just *two colours* we can build a Hubble Diagram of quasars, for the first time, up to redshift ~5

Risaliti & Lusso (2015), Lusso & Risaliti (2016)



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

Guido Risaliti, Elisabeta Lusso, Nature Astron. 3 (2019) 3, 272-277

The problem is that they obtained the luminosities assuming the standard ΛCDM cosmological model with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$

➡ We are interested in calibrated them in a *cosmological independent way* *(Work in collaboration with Sofía del Pilar Samario, José Ignacio Cabrera and Juan Carlos Hidalgo)*

From the nonlinear relation between L_X and L_{UV} and because $L = 4\pi D_L^2 F$:

$$\log(F_X) = \Phi(F_{UV}, D_L)$$
$$= \beta' + \gamma \log(F_{UV}) + 2(\gamma - 1)\log(D_L),$$

$\beta' = \beta + (\gamma - 1)\log(4\pi)$. F_X and F_{UV} are measured at fixed rest-frame wavelengths.

STEPS OF CALIBRATION

1. By employing the Bézier parametric curve of degree 2:

$$H_n(z) = \sum_{d=0}^{n} \beta_d h_n^d(z), \qquad h_n^d \equiv \frac{n!(z/z_m)^d}{d!(n-d)!}\left(1 - \frac{z}{z_m}\right)^{n-d}$$

We obtained the luminosity distance for quasars $d_L(z) = c(1+z)\int_0^z \frac{dz'}{H(z')}$

... CALIBRATION

2. We fit the nonlinear relation between L_X and L_{UV} in order to obtain β, γ:

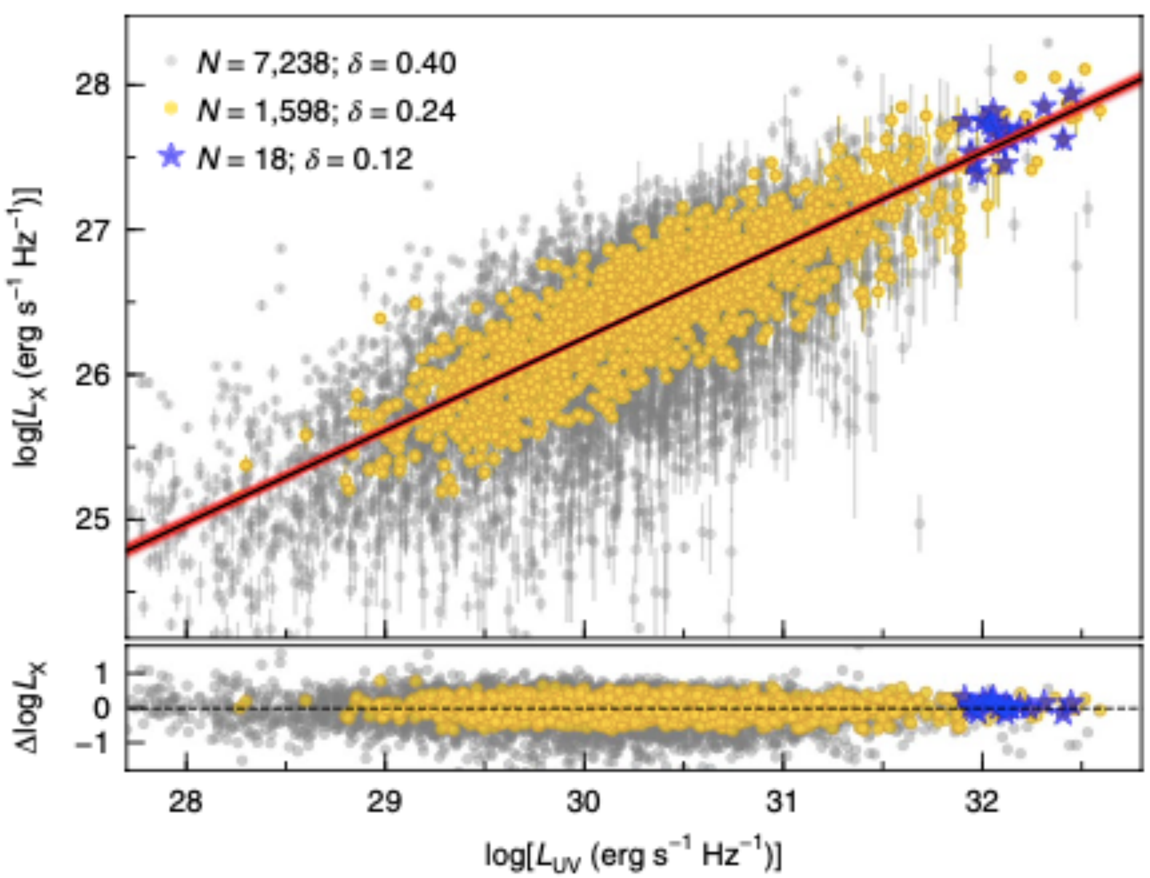
$$\log(L_X) = \gamma \log(L_{UV}) + \beta$$

3. We estimate a distance modulus for each quasar on the sample

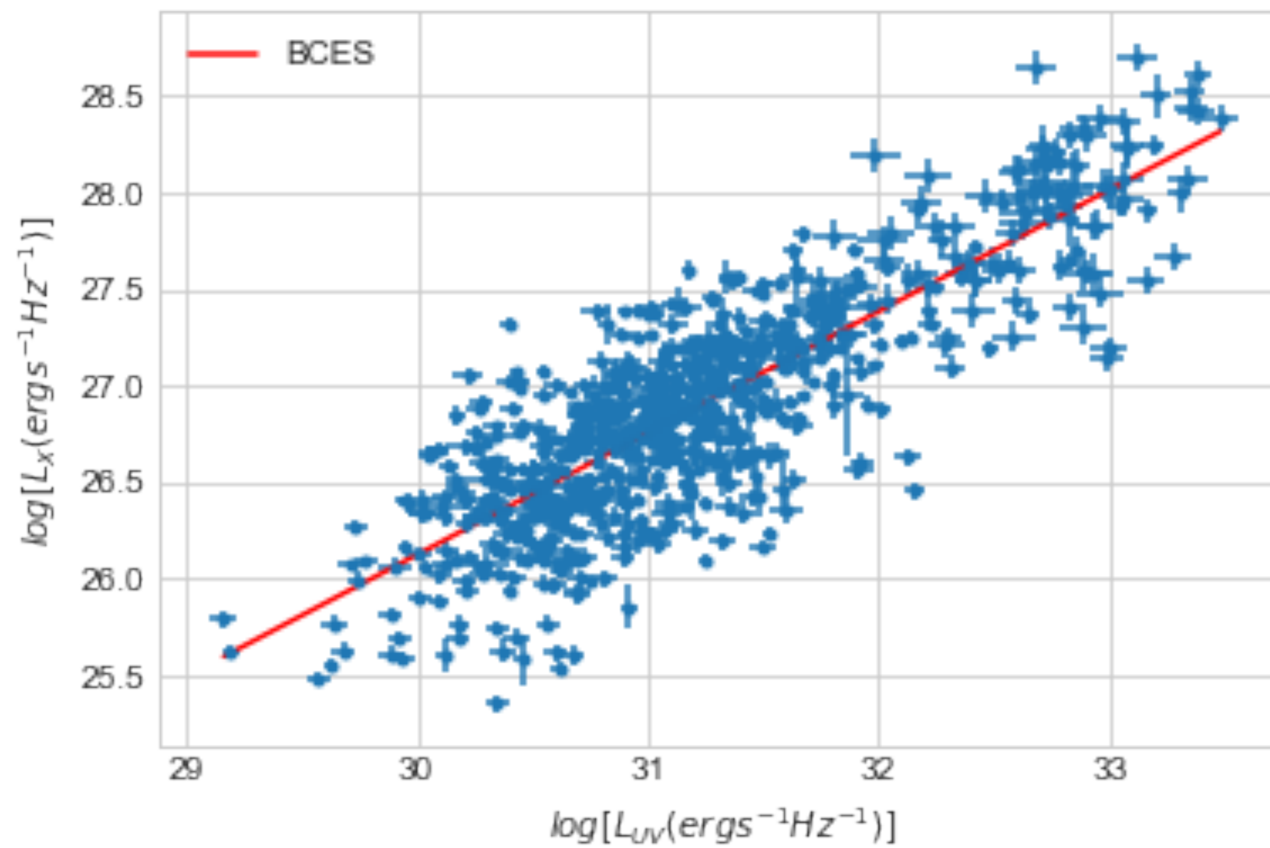
$$\mathrm{DM} = \frac{5}{2(\gamma - 1)}\left[\log(F_{\mathrm{X}}) - \gamma \log(F_{\mathrm{UV}}) - \beta'\right].$$

4. Quasars can be use for cosmological purposes.

Preliminary results



Guido Risaliti, Elisabeta Lusso, Nature Astron. 3 (2019) 3, 272-277



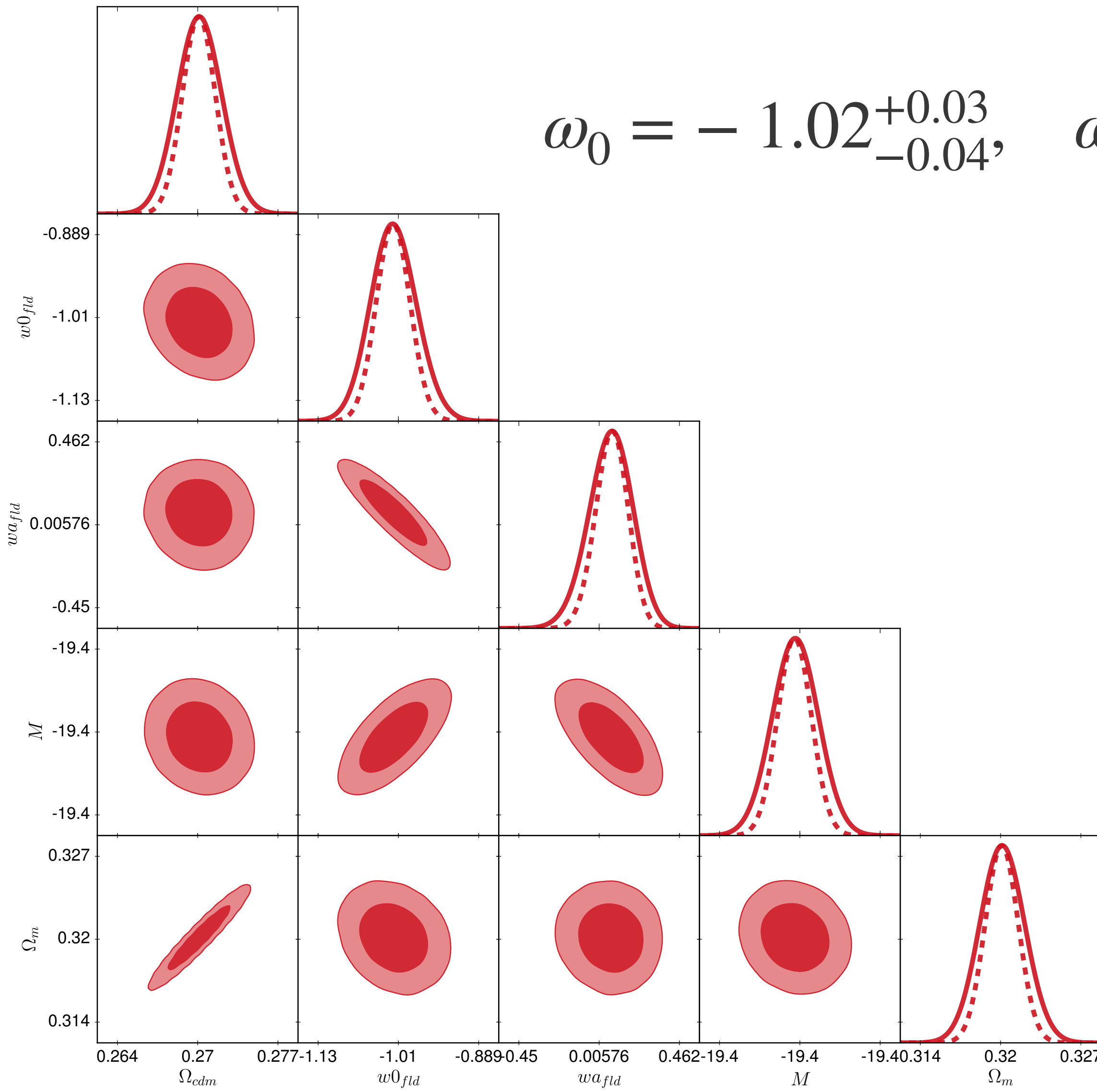
Sofía Samario, Juan Carlos Hidalgo, Ignacio Cabrera and **A. Montiel** (2022)

$\gamma = 0.633 \pm 0.002$

$\gamma = 0.630 \pm 0.016$

Preliminary!

$$\omega_0 = -1.02^{+0.03}_{-0.04}, \quad \omega_a = 0.07^{+0.13}_{-0.12}$$



Sofía Samario, Juan Carlos Hidalgo, Ignacio Cabrera and **A. Montiel** (2022)

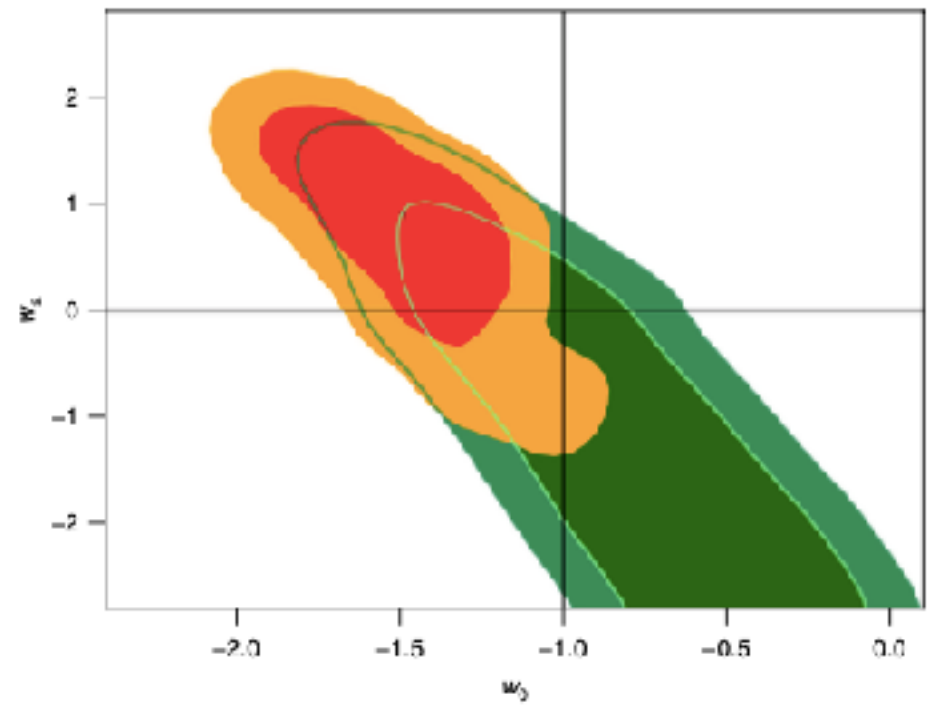


Fig. 4 | Error contours for an evolving dark energy model. Green lines and regions are w_0-w_a error contours (2σ and 3σ for green and dark green, respectively) in a w_0w_aCDM model from Planck – weak lensing data[1]; red/orange regions are the same, with the addition of the constraints from the Hubble diagram of supernovae and quasars. The two black lines show the values corresponding to the ΛCDM model.

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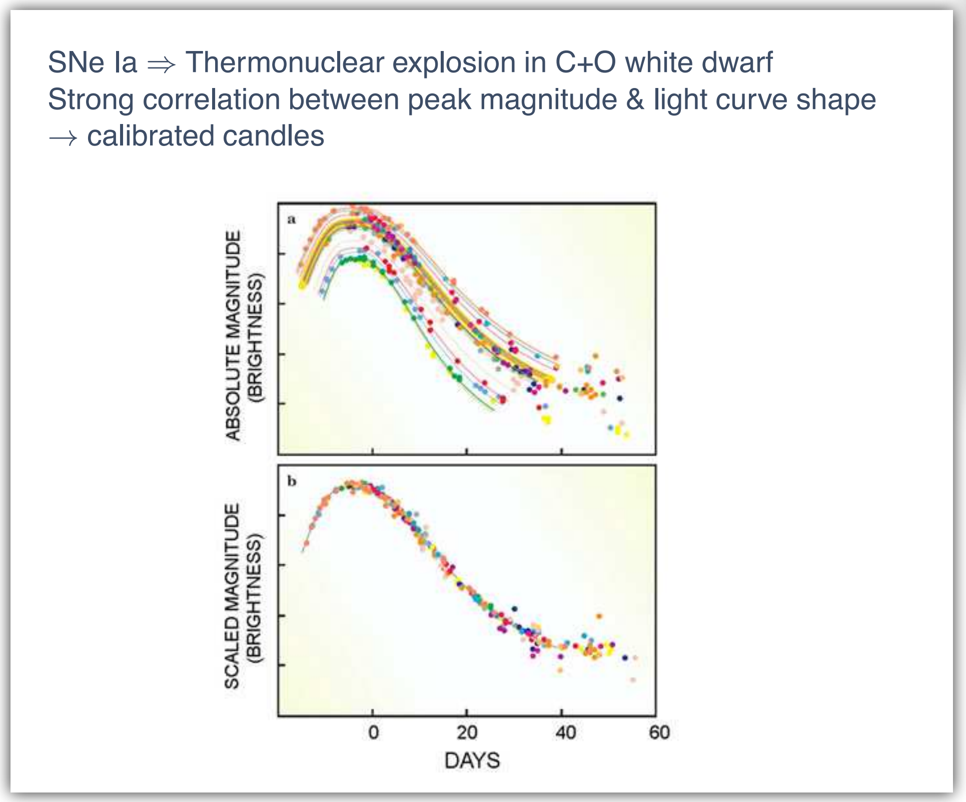
Low redshift cosmological probes

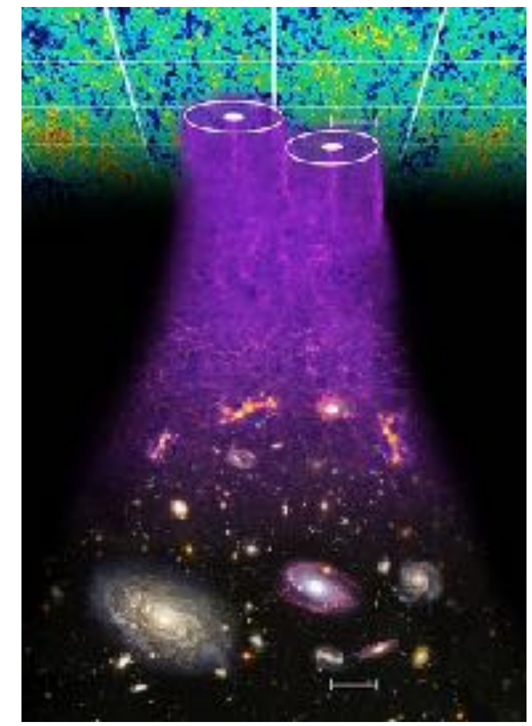
Supernovae data set



$$\chi^2_{SN} = \Delta\mu \cdot \mathrm{C}^{-1} \cdot \Delta\mu$$

$$\Delta\mu = \mu_{\text{theo}} - \mu_{\text{obs}}$$

Baryon Acoustic oscillations



Imprints a scale - standard ruler

$$\chi^2_{BAO} = \Delta\boldsymbol{\mathcal{F}}^{BAO} \cdot \mathbf{C}^{-1}_{BAO} \cdot \Delta\boldsymbol{\mathcal{F}}^{BAO}$$

$$\Delta\boldsymbol{\mathcal{F}}^{BAO} = \mathcal{F}_{theo} - \mathcal{F}_{obs}$$

D.M. Scolnic, *et al.*, Astrophys.J. 859 (2018) no.2, 101
Shadab Alam *et al.*, Mon. Not. Roy. Astron. Soc., 470(3):2617–2652, 2017.

High redshift cosmological probes

CMB (Planck 2018 compressed)

ΛCDM	*Planck* TT, TE, EE + lowE	R	l_A	$\Omega_b h^2$	n_s
R	1.7502 ± 0.0046	1.0	0.46	−0.66	−0.74
l_A	$301.471^{+0.089}_{-0.090}$	0.46	1.0	−0.33	−0.35
$\Omega_b h^2$	0.02236 ± 0.00015	−0.66	−0.33	1.0	0.46
n_s	0.9649 ± 0.0043	−0.74	−0.35	0.46	1.0
wCDM	*Planck* TT, TE, EE + lowE	R	l_A	$\Omega_b h^2$	n_s
R	$1.7493^{+0.0046}_{-0.0047}$	1.0	0.47	−0.66	−0.71
l_A	$301.462^{+0.089}_{-0.090}$	0.47	1.0	−0.34	−0.36
$\Omega_b h^2$	0.02239 ± 0.00015	−0.66	−0.34	1.0	0.44
n_s	$0.9653^{+0.0043}_{-0.0044}$	−0.72	−0.36	0.44	1.0
ΛCDM+Ω_k	*Planck* TT, TE, EE + lowE	R	l_A	$\Omega_b h^2$	n_s
R	1.7429 ± 0.0051	1.0	0.54	−0.75	−0.79
l_A	301.409 ± 0.091	0.54	1.0	−0.42	−0.43
$\Omega_b h^2$	0.02260 ± 0.00017	−0.75	−0.42	1.0	0.59
n_s	$0.9706^{+0.0047}_{-0.0050}$	−0.79	−0.43	0.59	1.0
ΛCDM+A_L	*Planck* TT, TE, EE + lowE	R	l_A	$\Omega_b h^2$	n_s
R	1.7428 ± 0.0053	1.0	0.52	−0.72	−0.80
l_A	$301.406^{+0.090}_{-0.089}$	0.52	1.0	−0.41	−0.43
$\Omega_b h^2$	0.02259 ± 0.00017	−0.72	−0.41	1.0	0.58
n_s	0.9707 ± 0.0048	−0.80	−0.43	0.58	1.0

$$l_A = (1 + z_*) \frac{\pi D_A(z_*)}{r_s(z_*)} ,$$

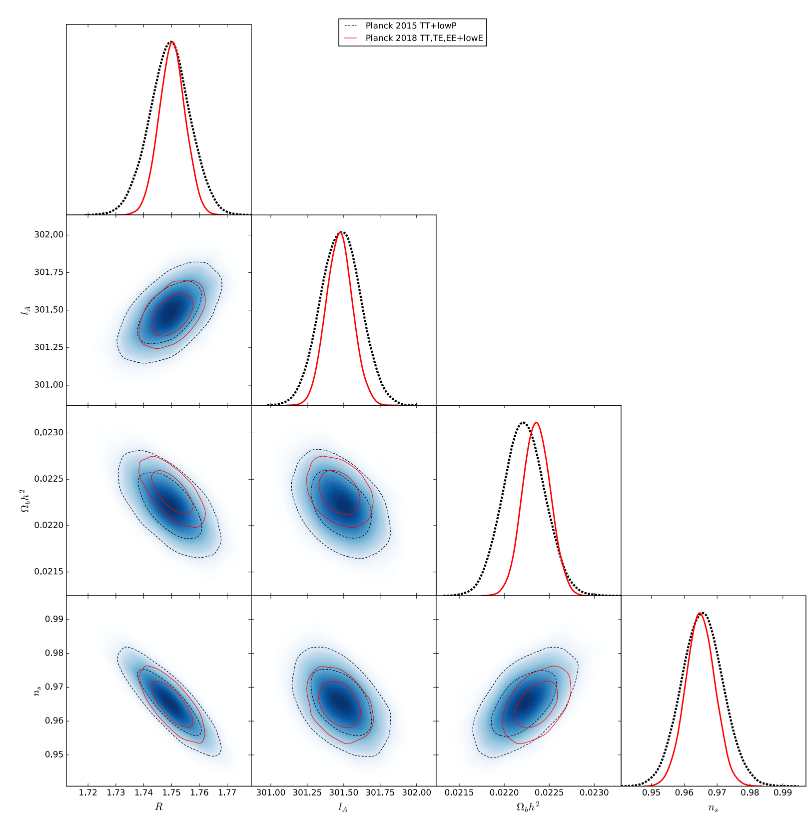
The angular scale of the sound horizon at recombination

$$R(z_*) \equiv \frac{(1 + z_*) D_A(z_*) \sqrt{\Omega_m H_0^2}}{c} ,$$

The scaled distance to recombination

$$\{R, l_A, \Omega_b h^2, n_s\}$$

$$\chi^2_{\text{distance priors}} = \sum (x_i - d_i)(C^{-1})_{ij}(x_j - d_j)$$



Lu Chen, Qing-Guo Huang and Ke Wang, JCAP02 (2019) 028