The Expansion History of the Universe: Myths and Facts

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www.dfg.unito.it/ricerca/caustic

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SCIENTIFIC BACKGROUND

- **Observations of SNae:** Interpretation in the ΛCDM model
- **Alternative cosmological models:** Conformal gravity and kinematic conformal gravity
- **GRBs as cosmological probes:** Bayesian approach

BAYESIAN ANALYSIS

- **Parameter forecasts (posterior probability):** Likelihood and priors
- **Bayesian evidence:** Parallel tempering

High-redshift type Ia Supernovae (SNae)

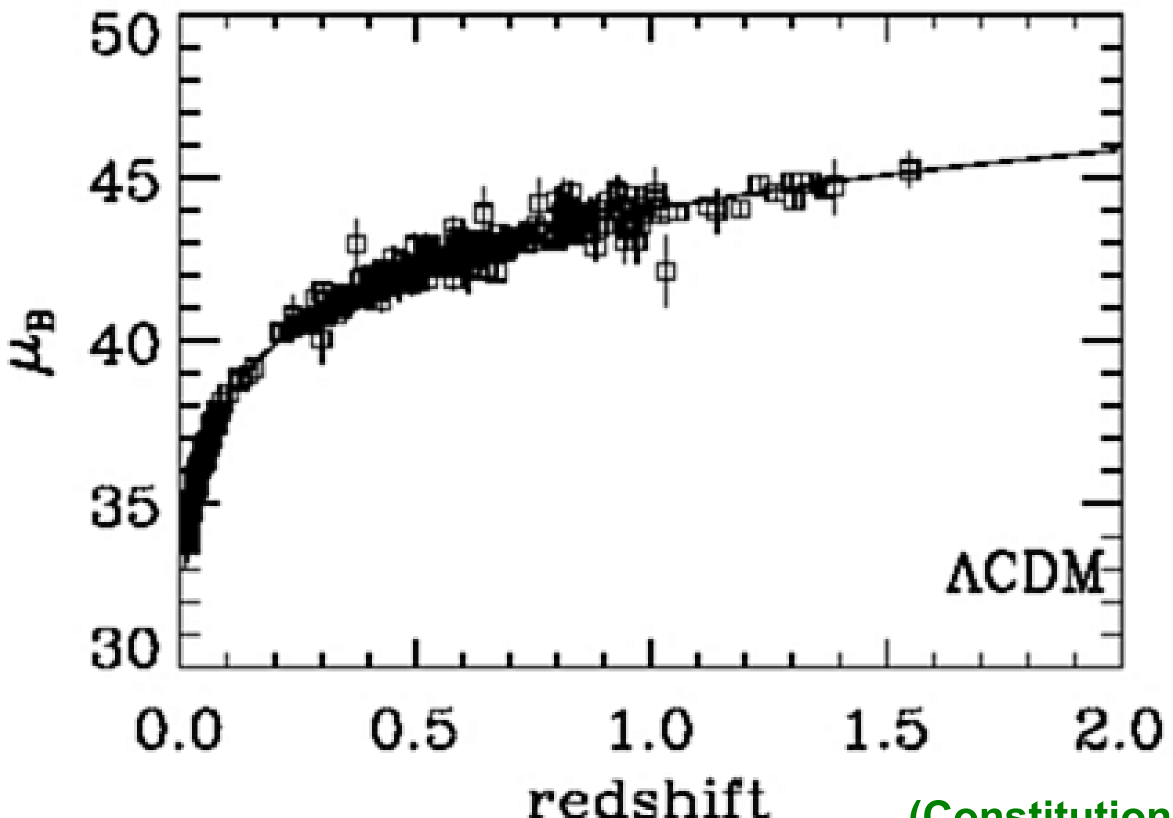
Hubble Diagram of SNae in ΛCDM

Cosmological parameters Ω_0 (and Ω_Λ)

$$\mu_B(\theta, z_i) \approx m_i - M = 5\log_{10} d_L(\theta, z) - 5$$

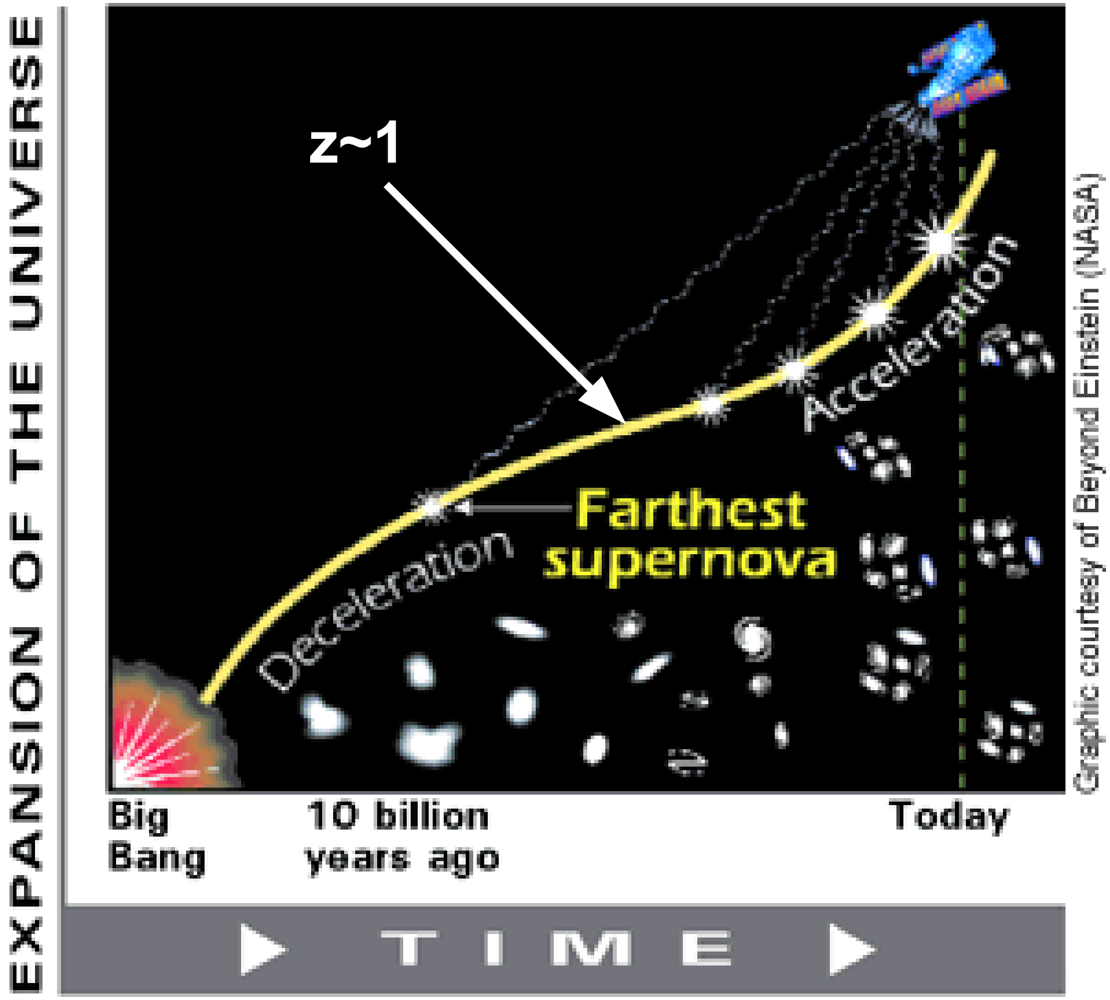
Observables

Intrinsic luminosity



(Constitution set of Hicken et al 2009)

The expansion history of the ΛCDM model



Can we probe the deceleration phase at redshift larger than z≈1?

Conformal gravity: No deceleration phase!

- **Conformal cosmology (CG)** (Mannheim 1990)

- **Kinematic conformal cosmology (KCG)** (Varieschi 2010)

Cosmology in conformal gravity - CG

Action:

$$I_W = -\alpha \int d^4x \sqrt{-g}\, C_{\mu\nu\kappa\lambda} C^{\mu\nu\kappa\lambda} \qquad g_{\mu\nu}(x) \Rightarrow \Omega(x) g_{\mu\nu}(x)$$

“Friedmann” equation:

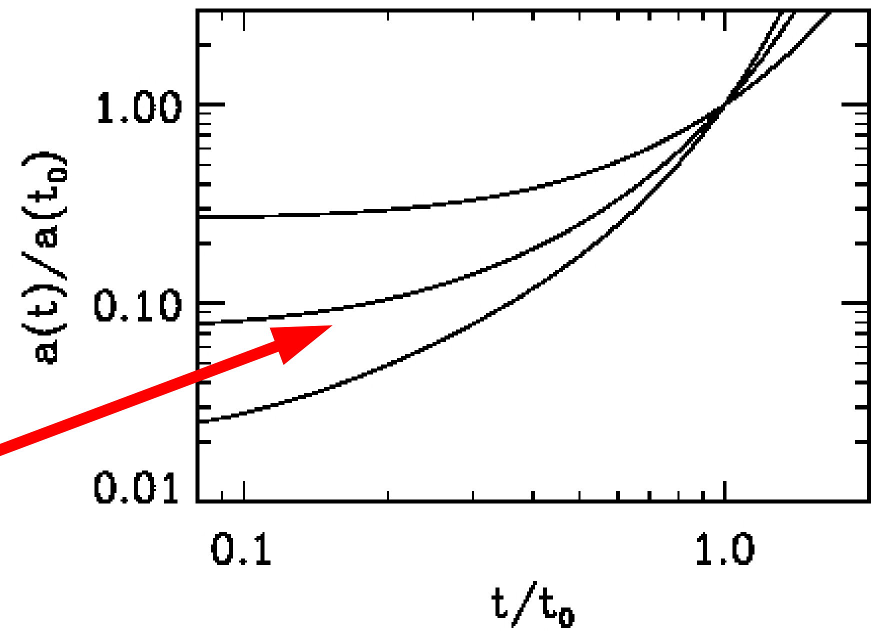
$$\dot{a}^2 a^2 = H_0^2 (\Theta_\Lambda a^4 + \Theta_k a^2 - \Theta_{nr} a - \Theta_r)$$

Deceleration parameter:

$$q = -\frac{\Theta_{nr}}{2} - \Theta_r - \Theta_\Lambda$$

(Same as ΛCDM model with $\Theta_{nr,r} \rightarrow -\Omega_{nr,r}$)

Always accelerated expansion!



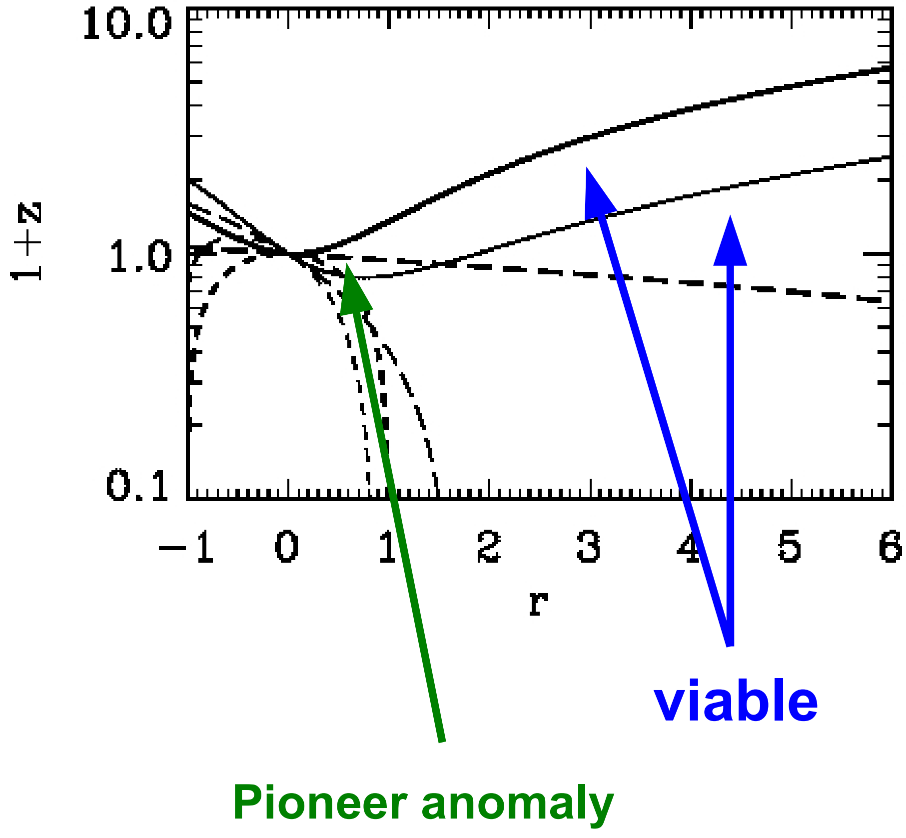
Kinematic conformal cosmology - KCG

Conformal gravity Schwarzschild solution:

$$ds^2 = -B(r)c^2dt^2 + \frac{dr^2}{B(r)} + r^2 d\Omega \quad \textbf{with } B(r) = 1 - \frac{\beta(2-3\beta\gamma)}{r} - 3\beta\gamma + \gamma r - \kappa r^2$$

Redshift

$$1 + z = \frac{a(0)}{a(r)} = \sqrt{1 - kr^2} - r\delta$$



New inverse-square law:

$$F(d_L) = \frac{L_0}{4\pi d_L^2}\left(\frac{d_{rs}}{d_L}\right)^{a_V}$$

Distance modulus

ΛCDM and CG

$$\mu(\theta, z) = 5\log_{10} d_L(\theta, z) - 5$$

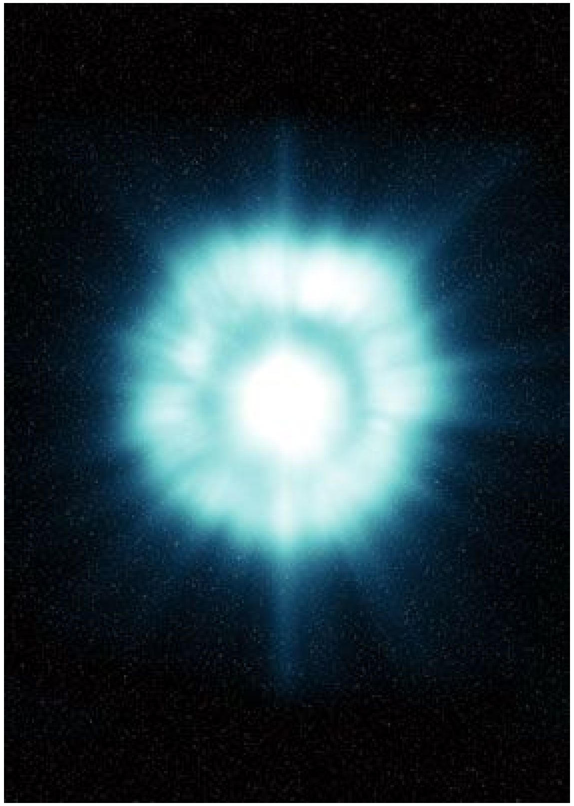
$$\theta = \begin{cases} \Omega_0 & \Lambda CDM \\ q_0 & CG \end{cases}$$

KCG

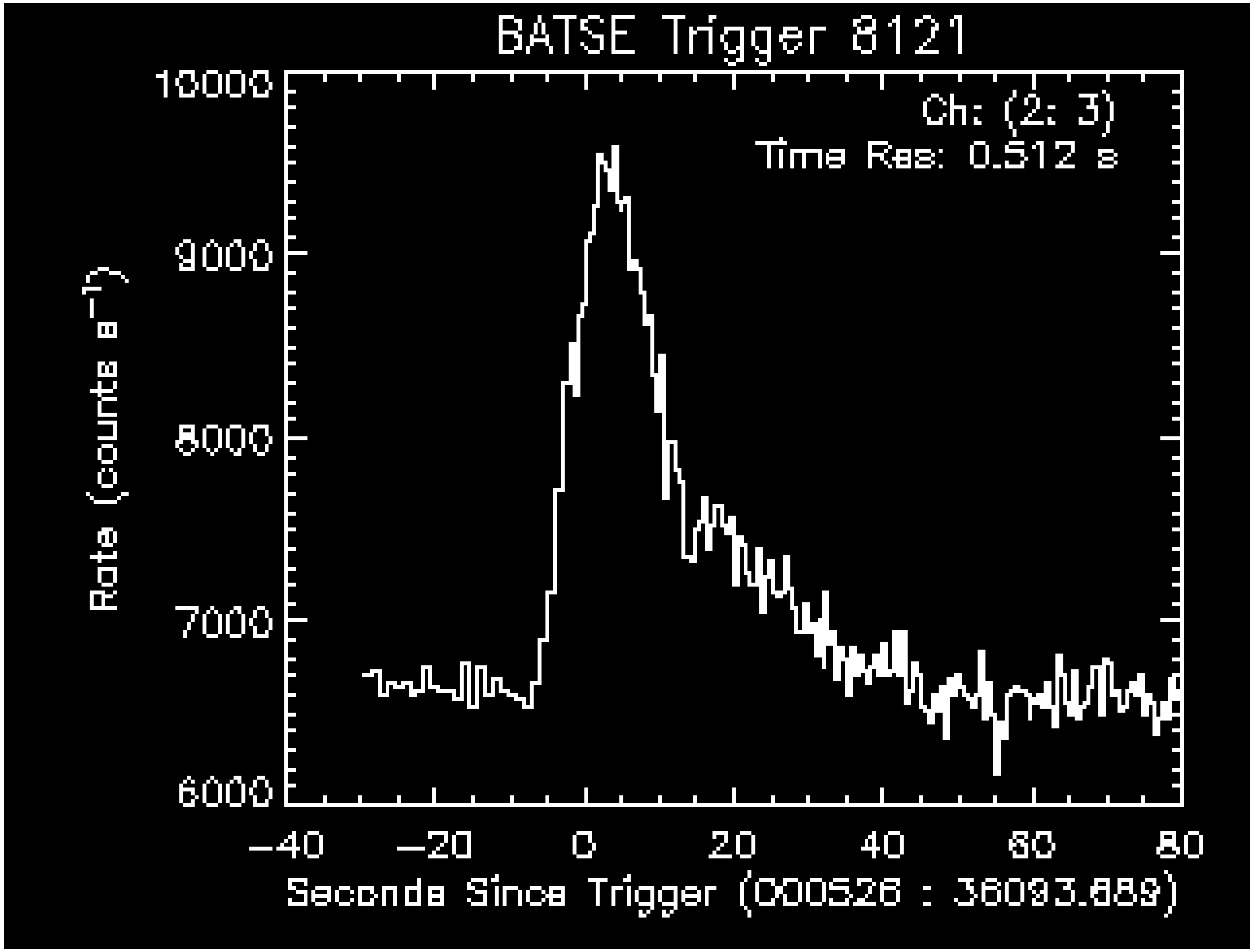
$$\mu(\theta, z) = 2.5(2 + a_V)\log_{10}\left[\frac{\delta_0(1+z) + \sqrt{(1+z)^2 - (1-\delta_0^2)}}{2\delta_0}\right]$$

$$\theta = (a_V, \delta_0)$$

Gamma-ray bursts (GRBs) as cosmological probes



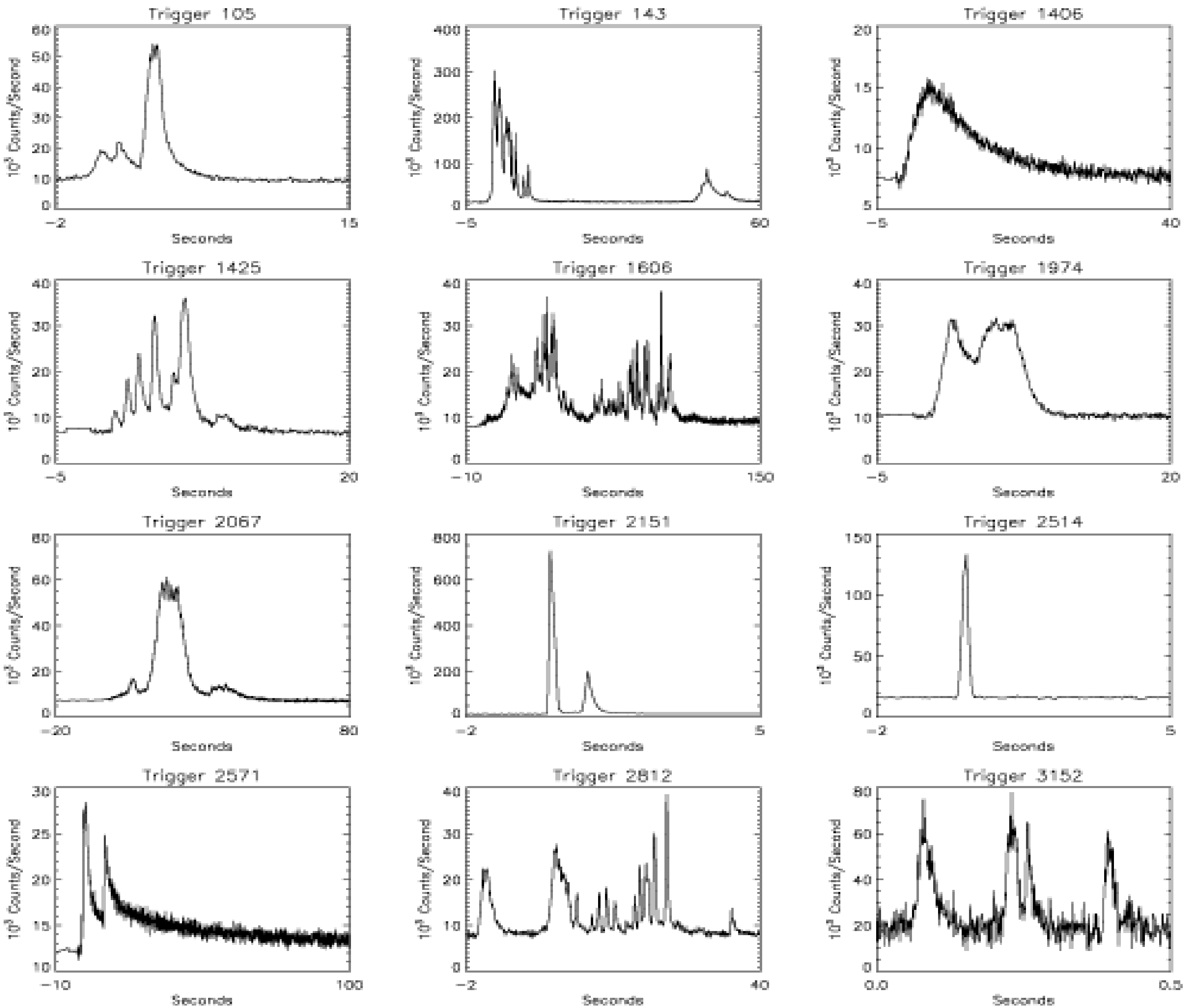
Light curve



GRBs are currently observed up to redshift z~8

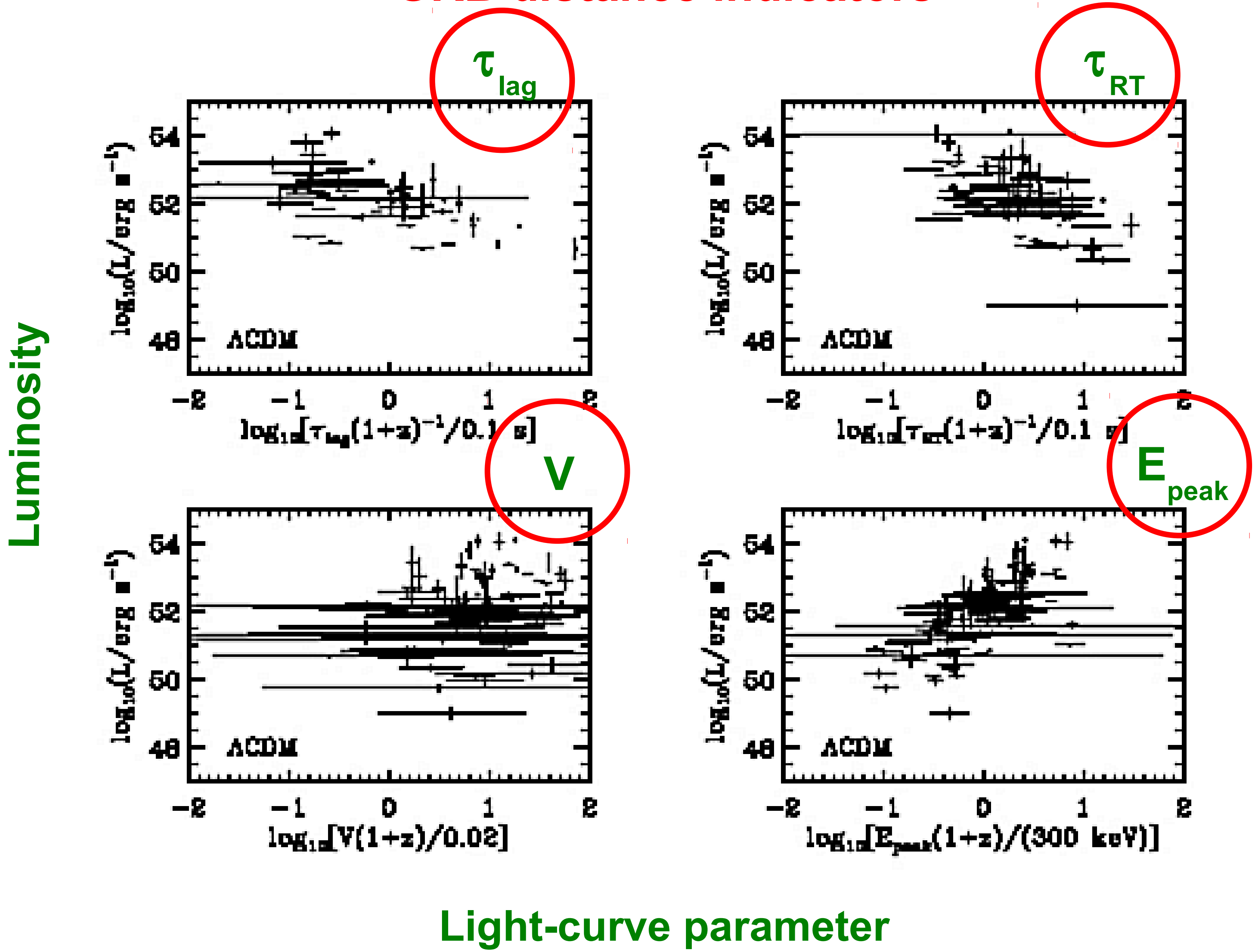
GRB light curves

Counts/second



Time

GRB distance indicators



(GRB sample from Schaefer 2007)

Distance indicator relations

$$\log_{10} P_{bolo} = a + b \log_{10} X - f(\theta, z)$$

X = light-curve parameter

flux

$$f(\theta, z) = \log_{10}[4\pi d_L^2(\theta, z)]$$ (ΛCDM, CG)

$$f(\theta, z) = \log_{10}[4\pi d_L^2(\theta, z)] + a_V \log_{10}\left(\frac{d_L}{d_{rs}}\right)$$ (KCG)

NO NEARBY GRBs → NO CALIBRATION (unlike SNae)

Bayesian parameter estimation

$$p(\theta|D,M)=\frac{p(D|\theta,M)\,p(\theta|M)}{p(D|M)}$$

Likelihood

$$p(D|\theta,M)\sim\exp\left(-\frac{1}{2}\delta Y^T C^{-1}\delta Y\right)$$

δY = measures – expected values(θ)

D = {all the observables, including uncertainties}

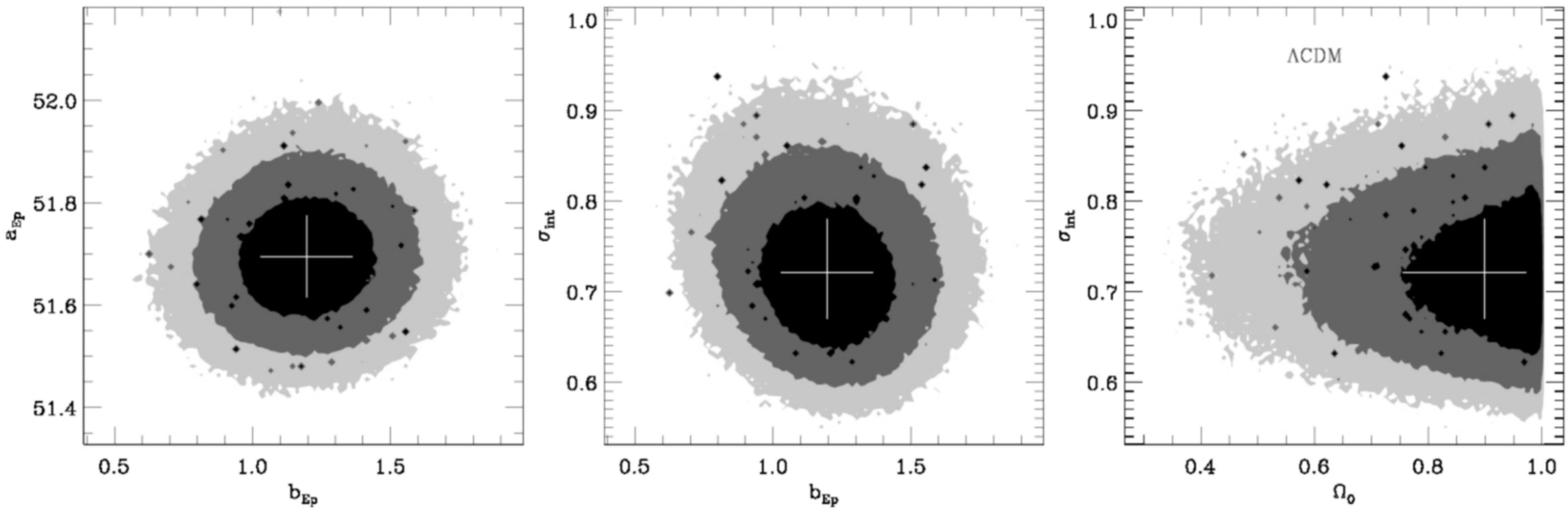
C = covariance matrix

Analysis is performed over the 4 relations at the same time!

Analysis performed with APEMoST (Automated Parameter Estimation and Model Selection Toolkit) by Buchner and Gruberbauer: `apemost.sourceforge.net`

Parameter probability density functions: p(θ | D, M)

a vs b — **σ_{int} vs b** — **σ_{int} vs Ω_0**

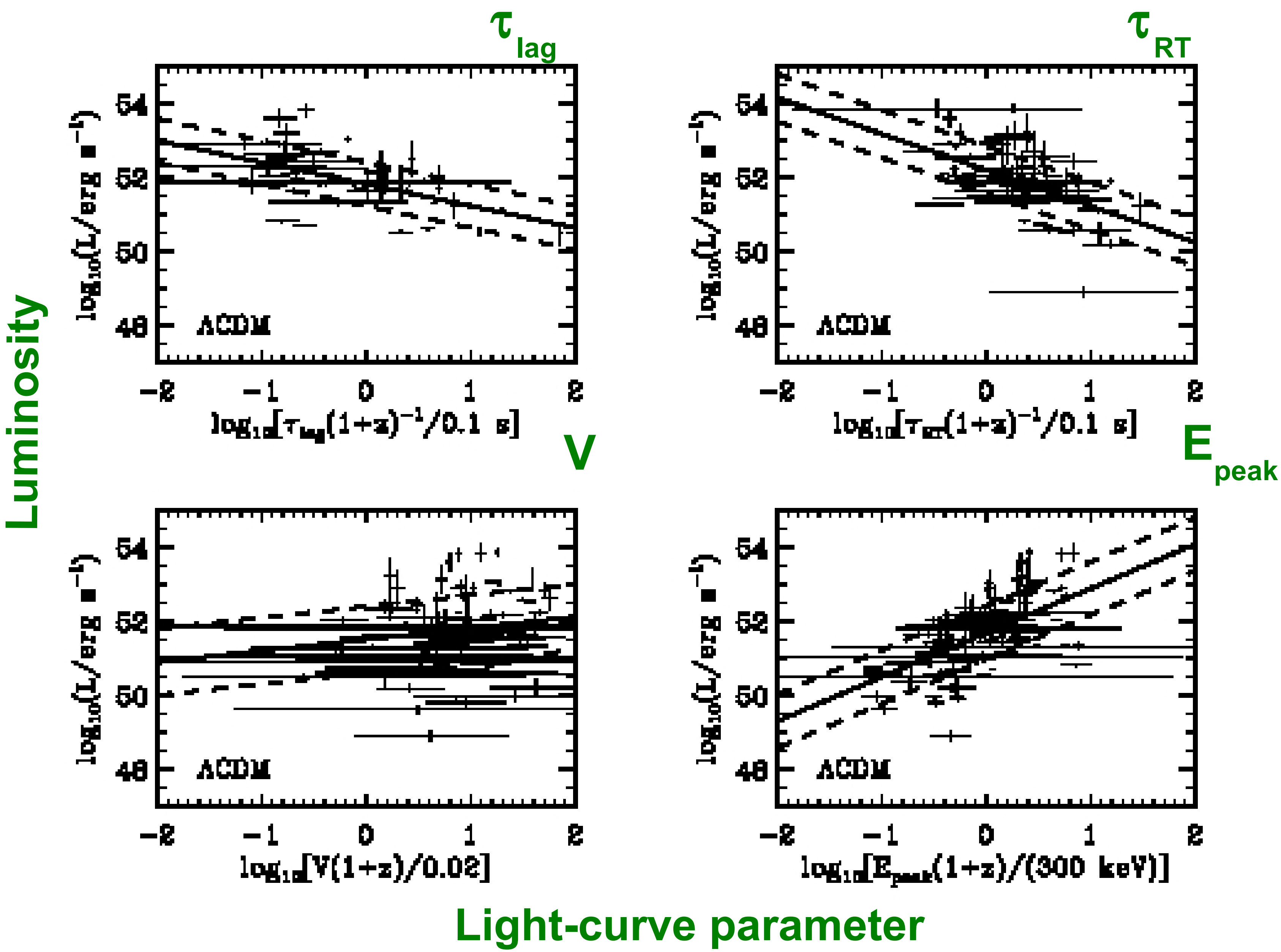


(similar PDFs for the 4 relations)

$$\log_{10} P_{bolo} = a + b \log_{10} X - f(\theta, z)$$

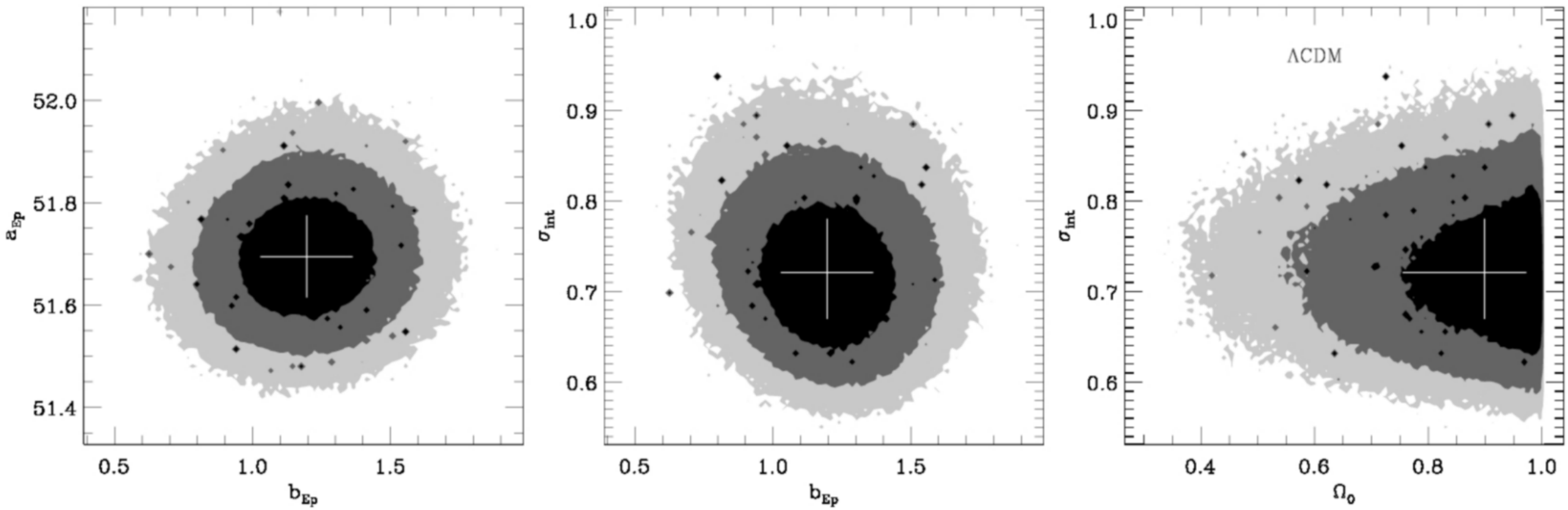
$W_i = a + b \log_{10} X_i - f(\theta, z_i)$ **is the mean of $\log_{10} P_{bolo}^{i}$ with variance σ_{int}^{2}**

GRBs distance indicators



Parameter probability density functions: p(θ | D, M)

a vs b | **σ_{int} vs b** | **σ_{int} vs Ω_0**



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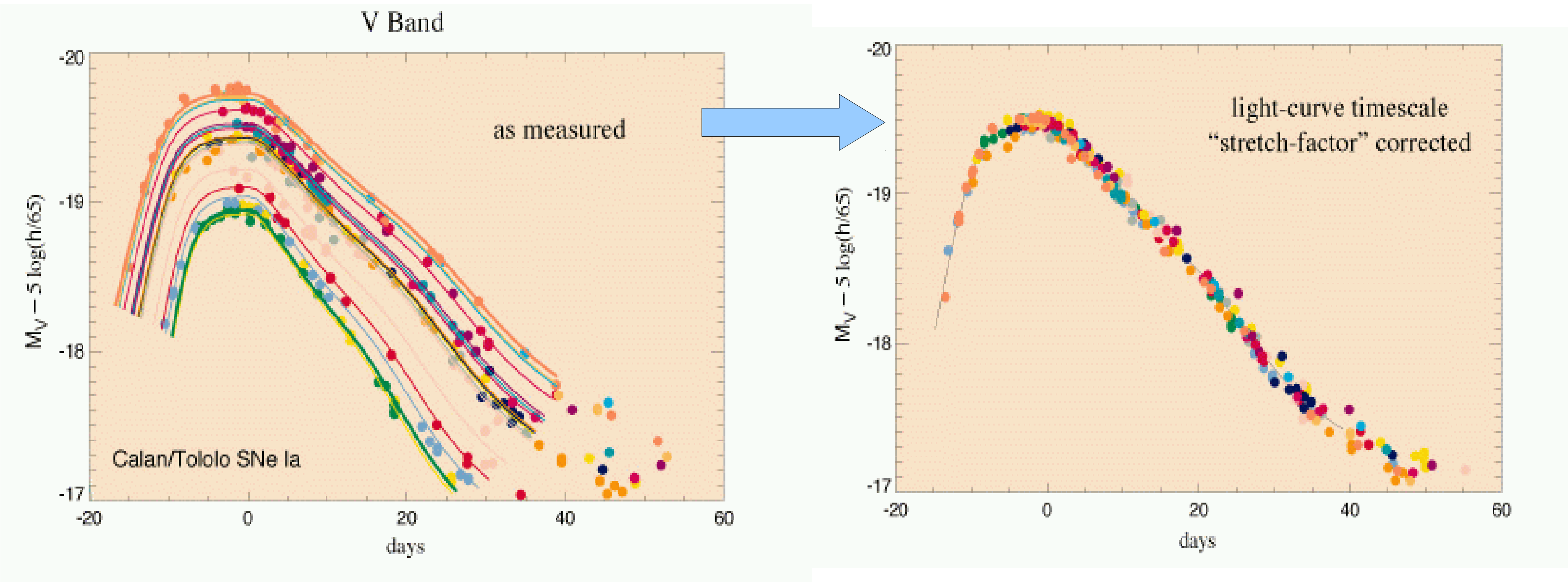
Combining with other probes to obtain tighter constraints?

e.g. SNae

Supernova Light Curves



Shape parameter **Colour parameter**

$$\mu_B(\theta, z_i) = m_i - M + \alpha(s_i - 1) - \beta c_i$$

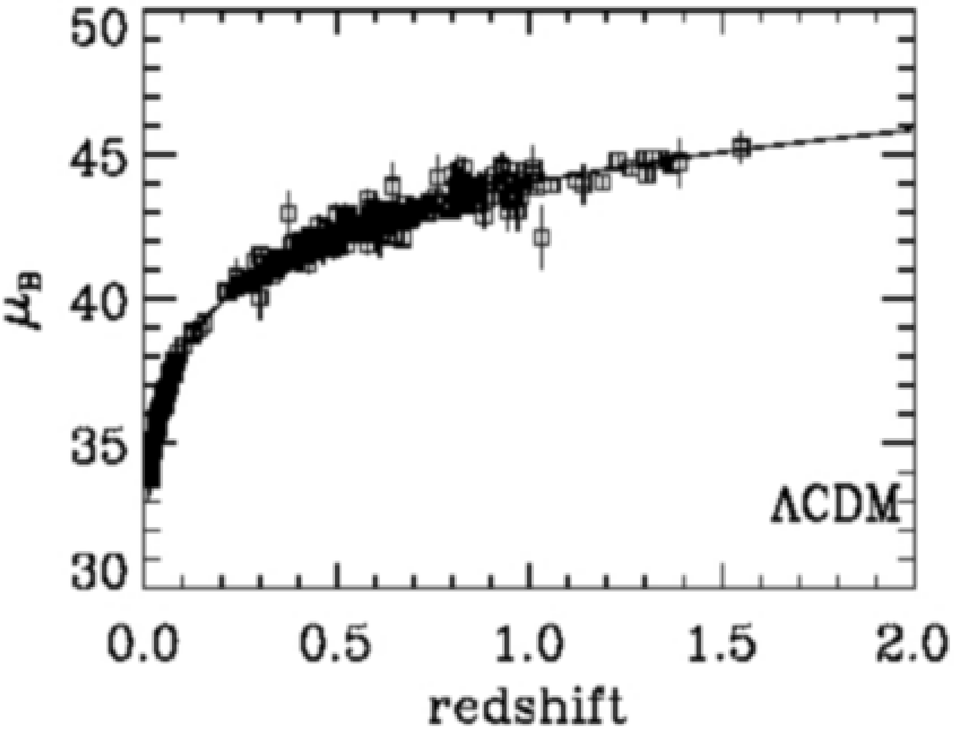
Cosmological parameters **Free parameters**

Observed and derived quantities

$$\mu_B(\theta, z_i) = m_i - M + \alpha(s_i - 1) - \beta c_i$$

Observables

This is NOT a plot of directly observed quantities!

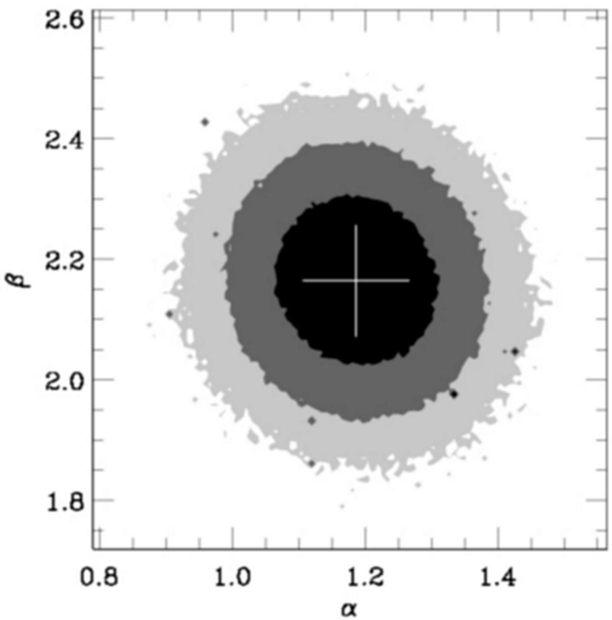


(Constitution set of Hicken et al 2009)

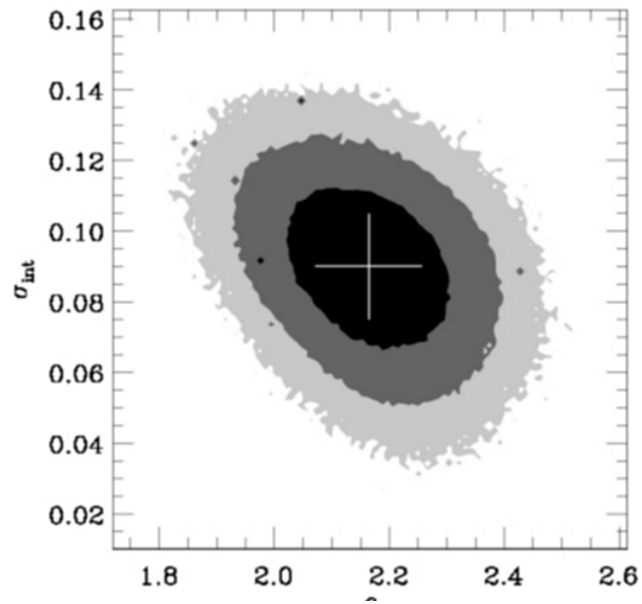
Bayesian parameter estimation again...

Parameter probability density functions: $p(\theta \mid D, M)$
derived for the SNae alone

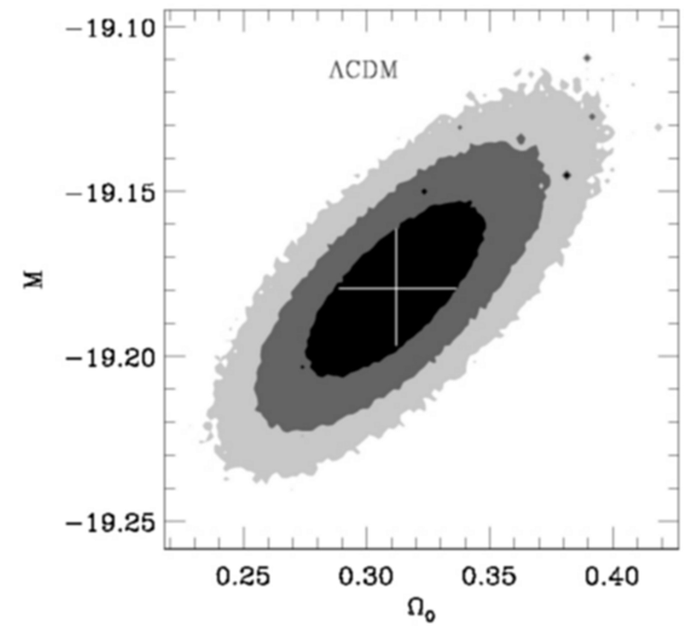
β vs α

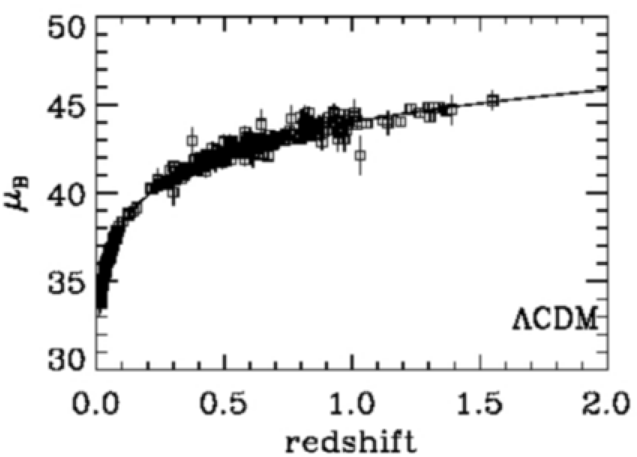


σ_{int} vs β

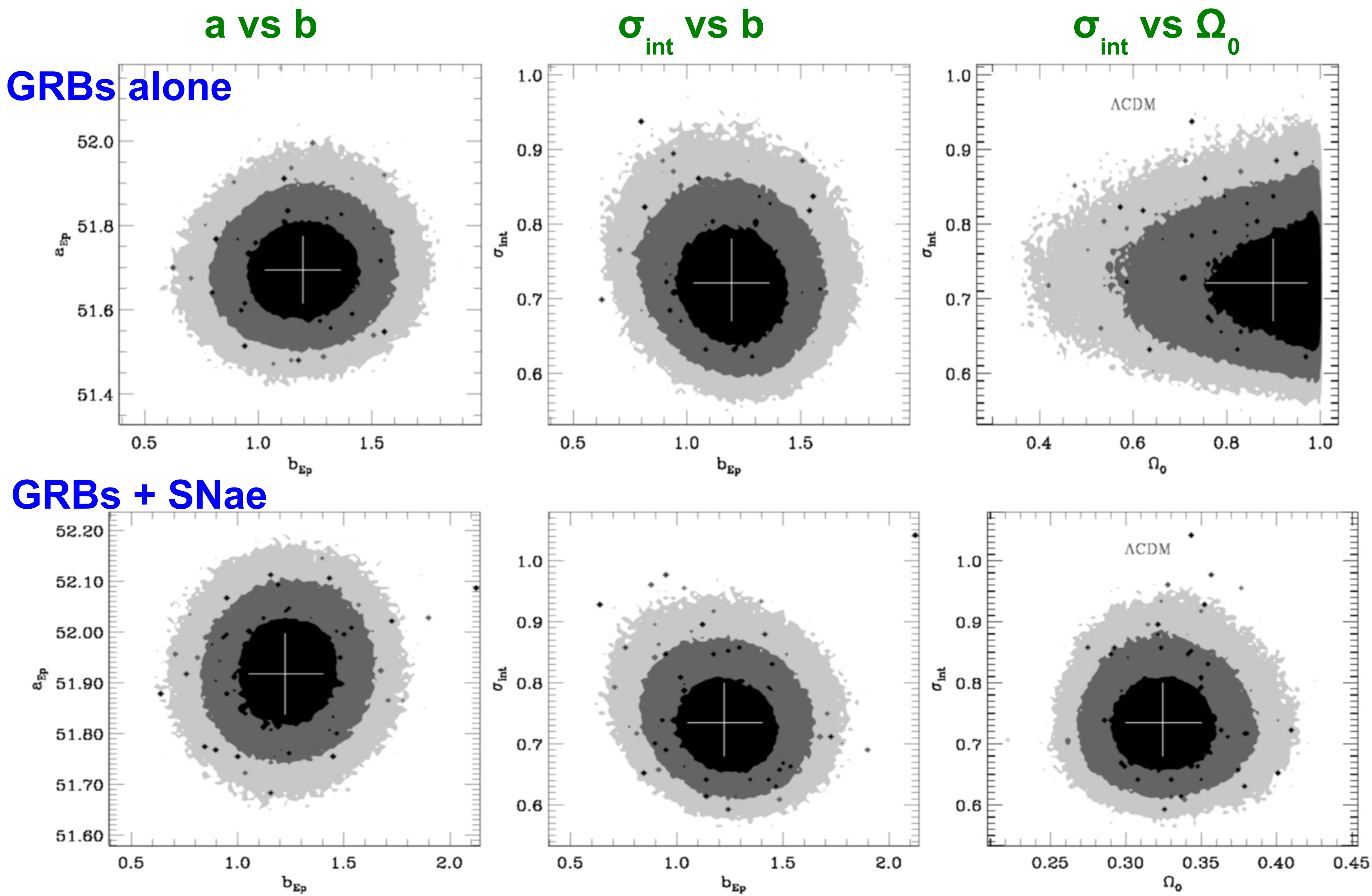


M vs Ω_0





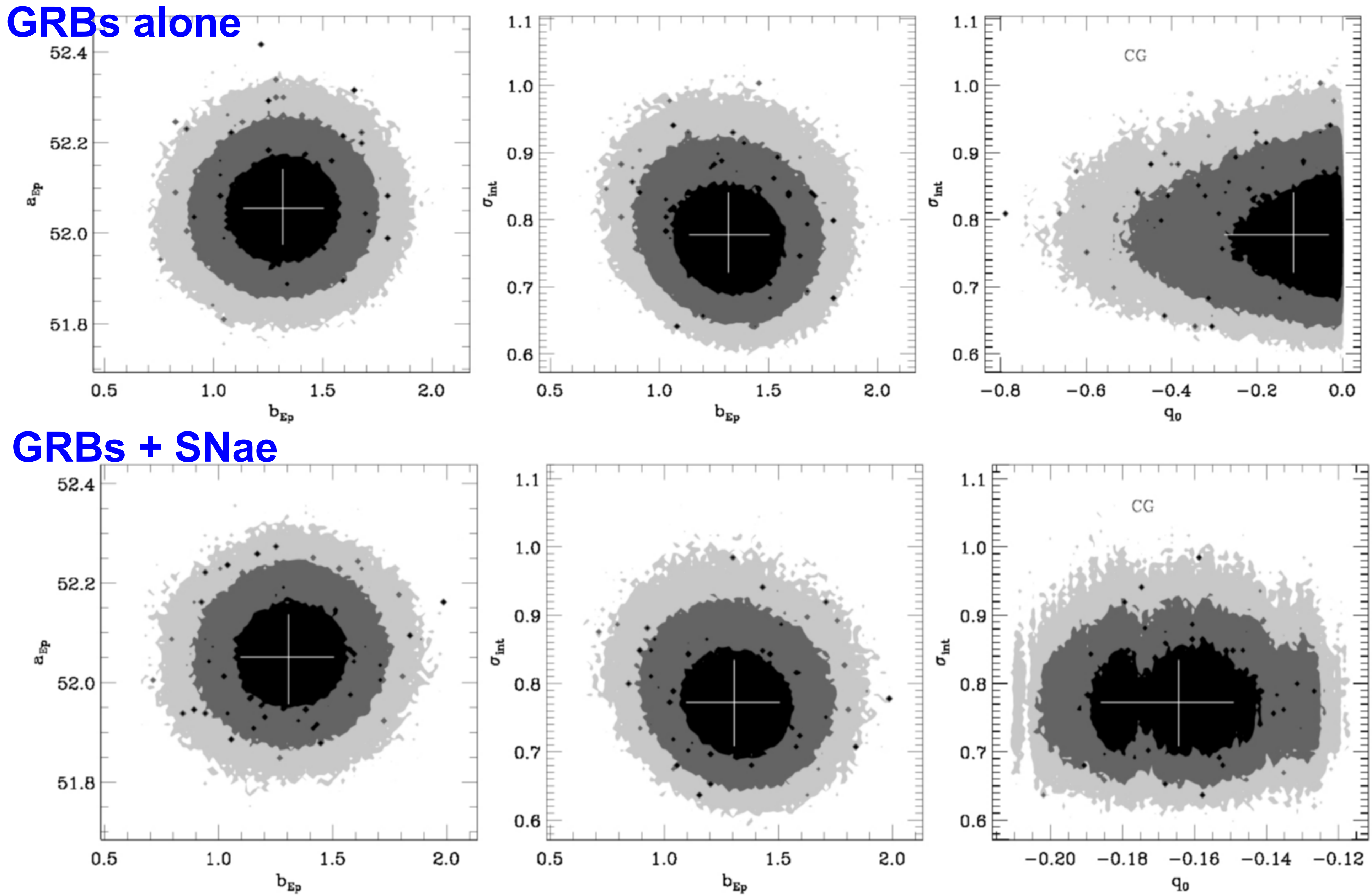
Combining GRBs with SNae



What happens in CG and KCG?

CG

a vs b | σ_{int} vs b | σ_{int} vs q_0

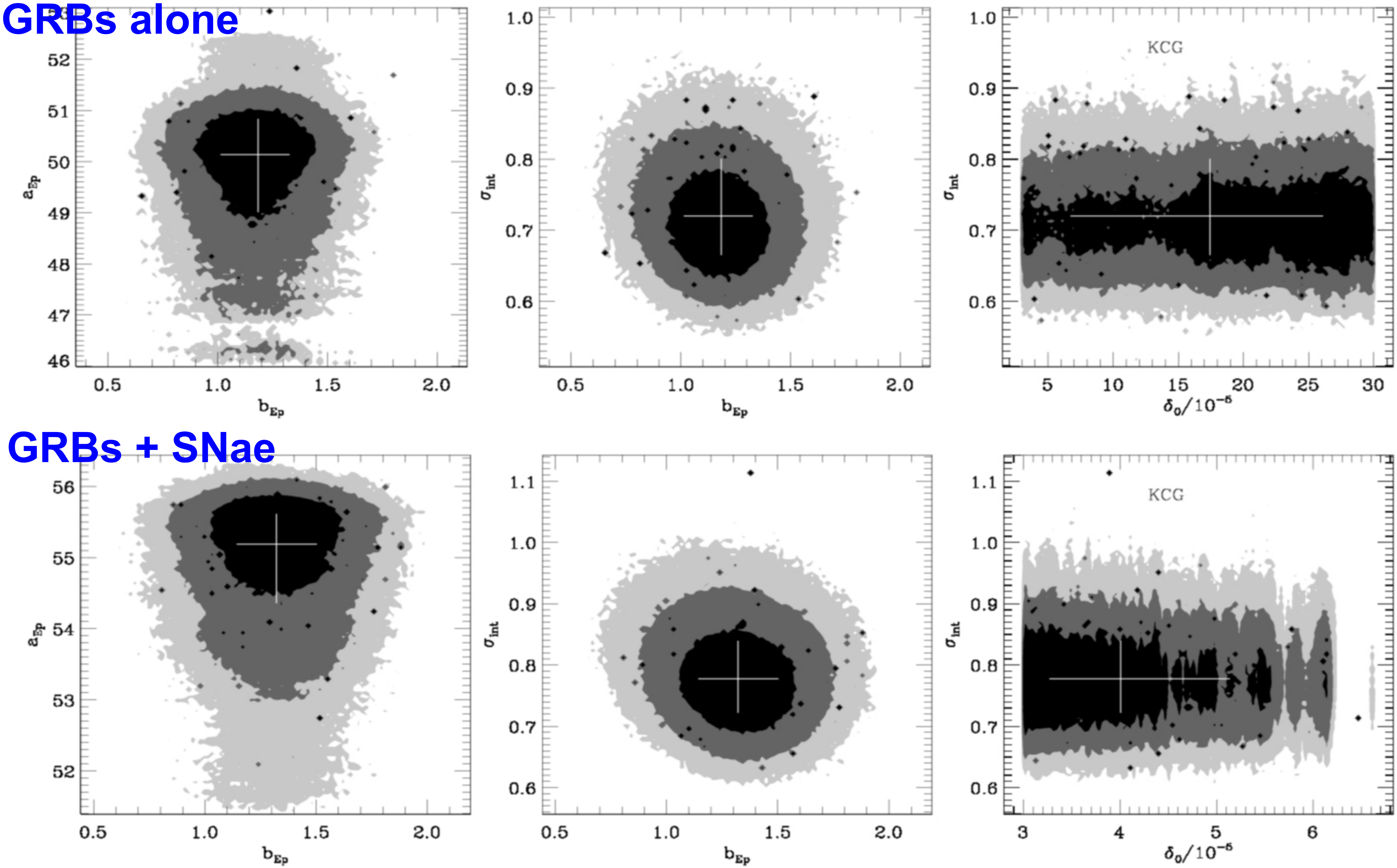


KCG

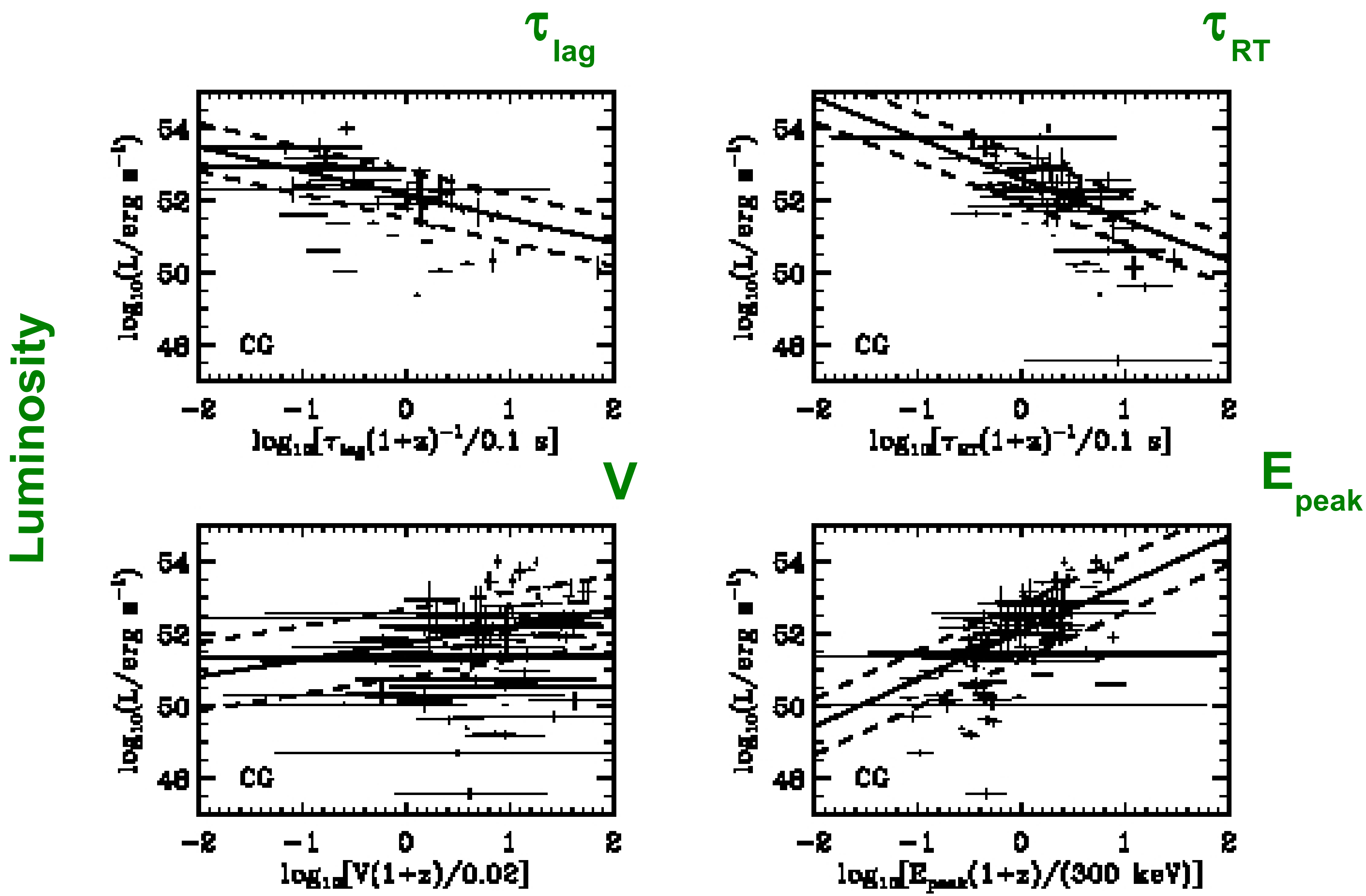
a vs b | **σ_{int} vs b** | **σ_{int} vs δ_0**

GRBs alone

GRBs + SNae

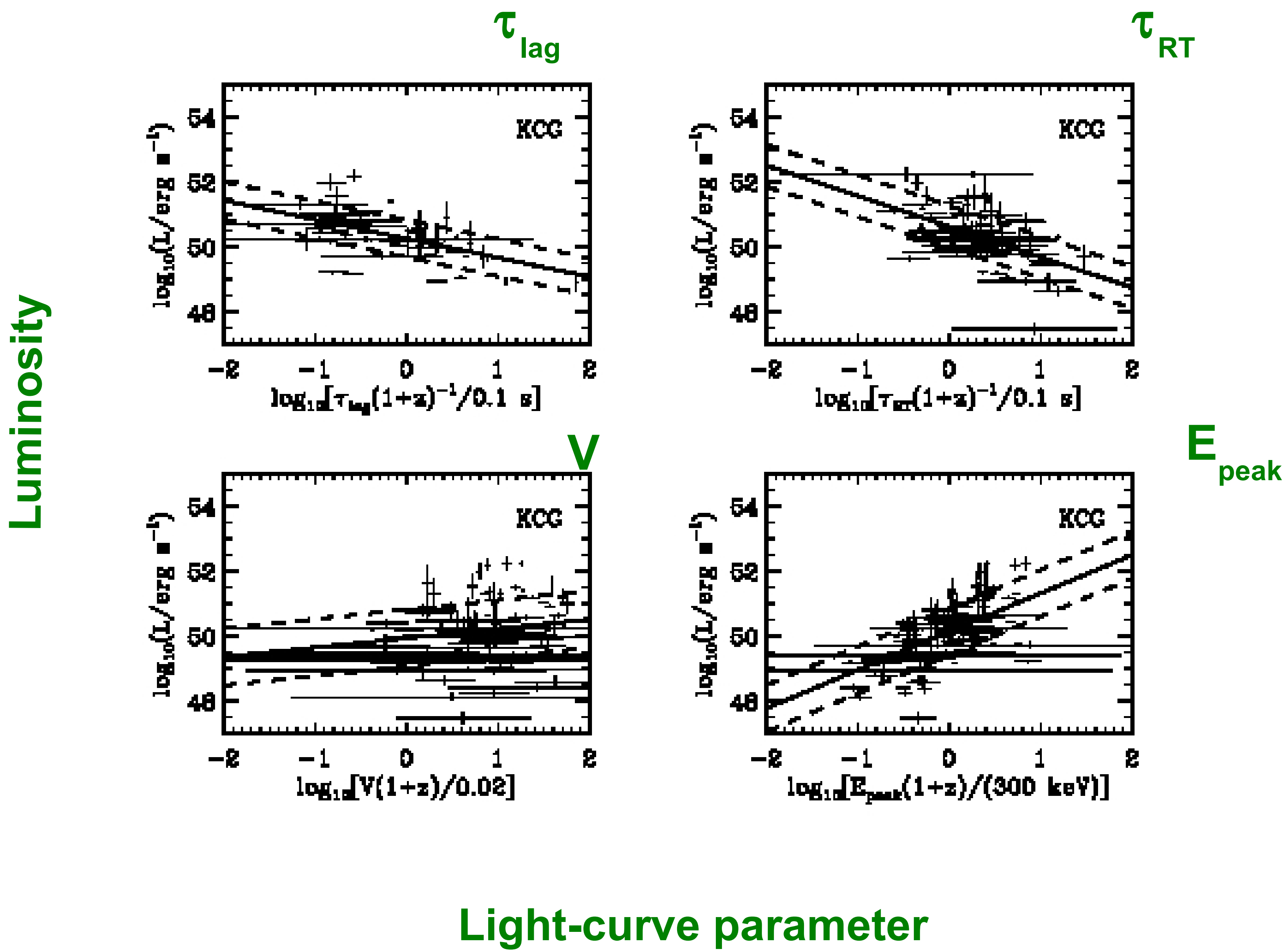


GRBs distance indicators in CG



Light-curve parameter

GRBs distance indicators in KCG



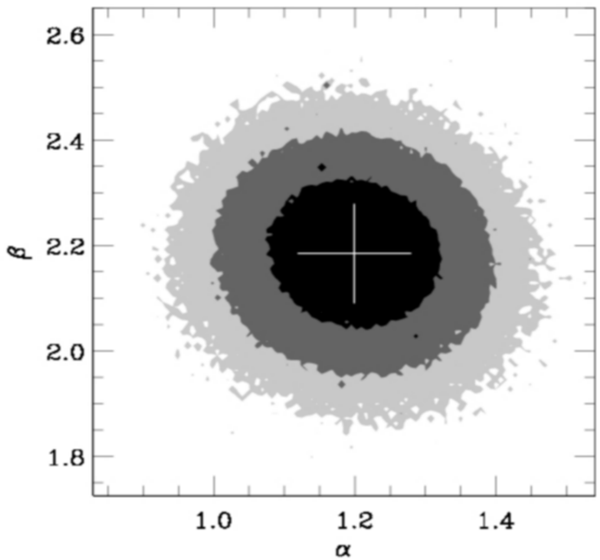
Models without an early decelerated expansion

can clearly describe the GRB data

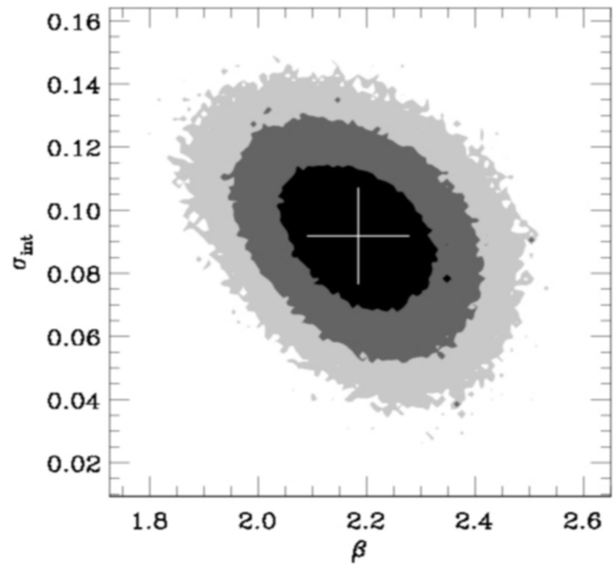
For completeness: SNae in CG and KCG?

PDFs of SNae parameters in CG

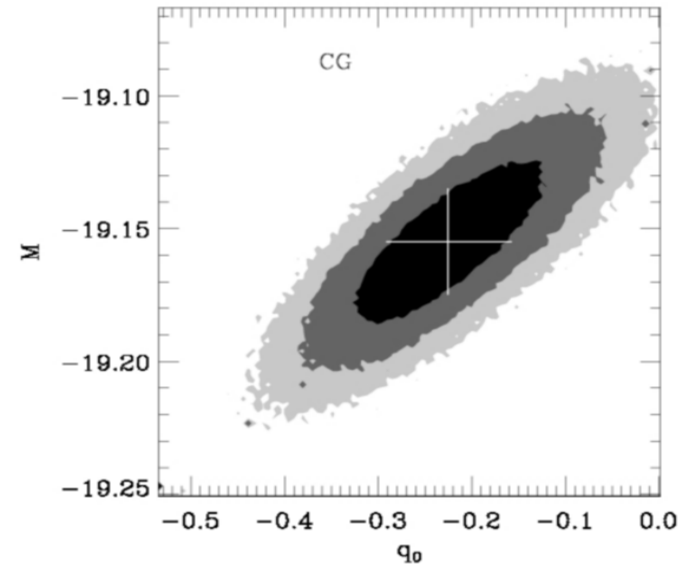
β vs α

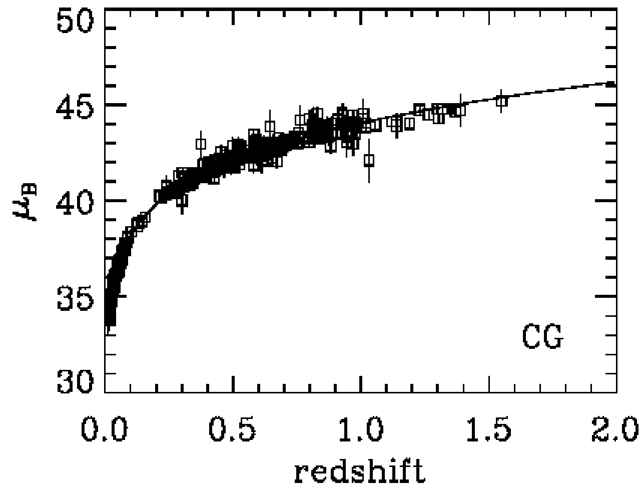


σ_{int} vs β



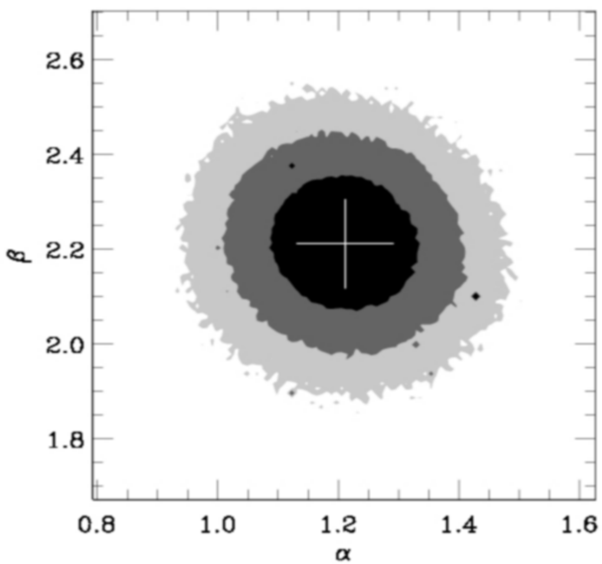
M vs q_0



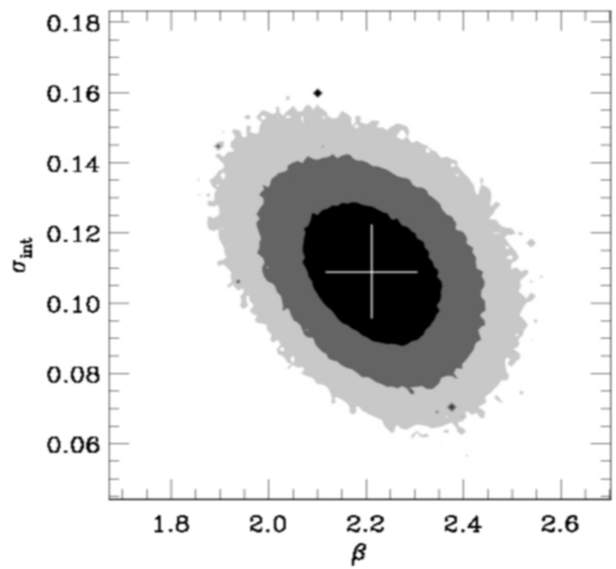


PDFs of SNae parameters in KCG

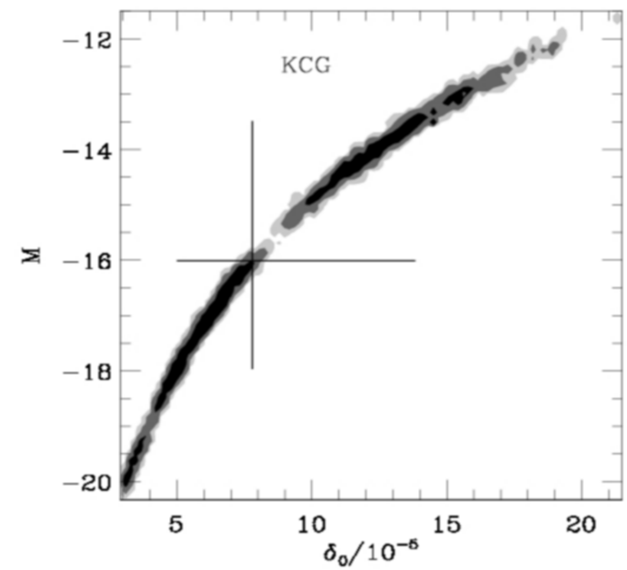
β vs α

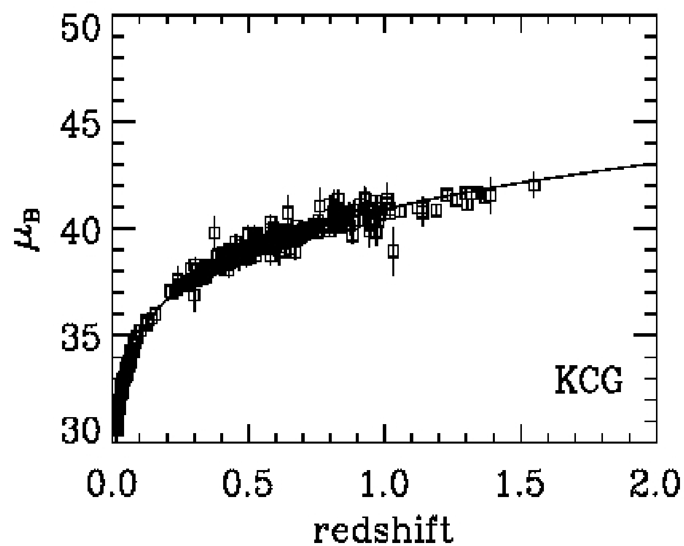


σ_{int} vs β



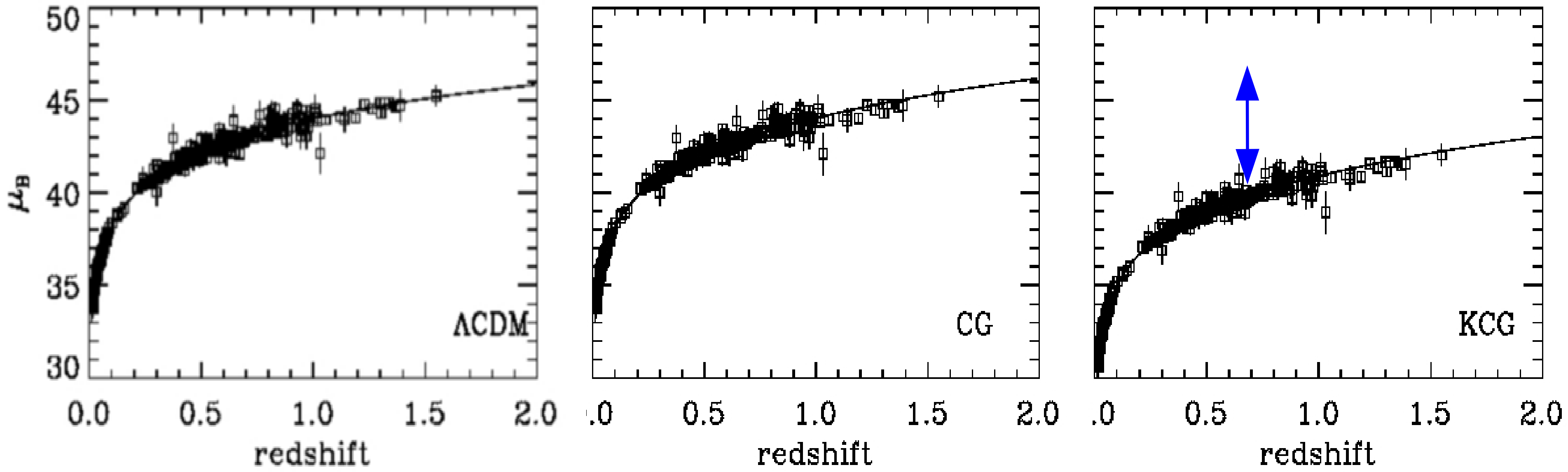
M vs δ_0





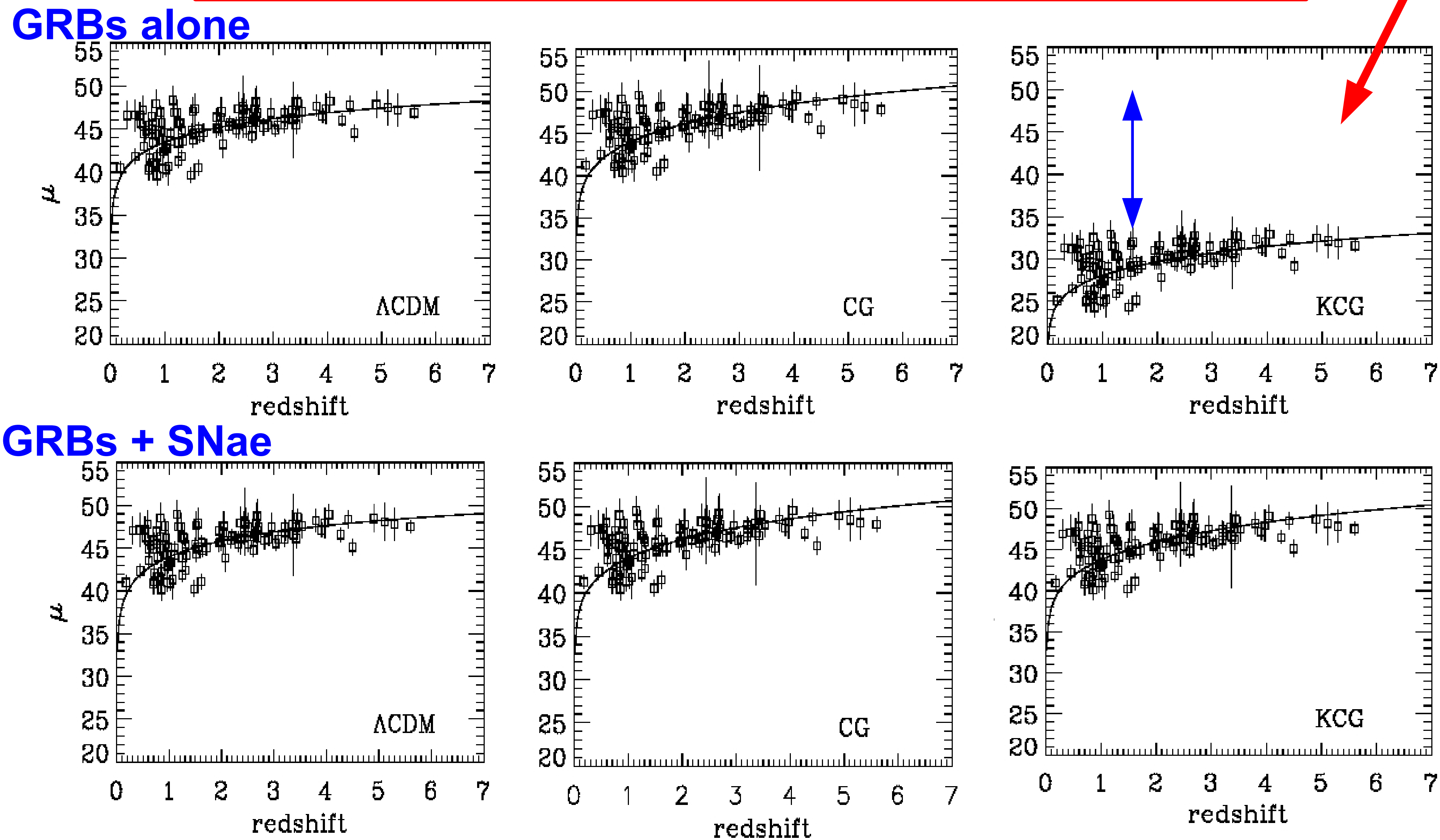
Hubble diagram of SNae in the three models

the distance modulus μ
is indeed a model-dependent quantity



Hubble diagram of GRBs in the three models

the distance modulus μ
is indeed a model-dependent quantity



Two issues:

- find the parameters that can describe the data ➡ done
- compare the models ➡ ?

The Bayesian Evidence

$$p(D|M) = \int p(D|\theta, M)\, p(\theta|M)\, d\theta$$

Model posterior probability

$$p(M|D) = \frac{p(D|M)\, p(M)}{p(D)}$$

Comparing two models:

$$\frac{p(M_1|D)}{p(M_2|D)} = \frac{p(D|M_1)}{p(D|M_2)} \frac{p(M_1)}{p(M_2)}$$

B_{12} = Bayes factor

Estimate performed with APEMoST (Automated Parameter Estimation and Model Selection Toolkit) by Buchner and Gruberbauer: apemost.sourceforge.net

Parallel tempering algorithm

$$p_\beta(\theta|D, M) = \frac{[p(D|\theta, M)]^\beta p(\theta|M)}{p_\beta(D|M)}$$

$$\frac{\partial \ln p_\beta(D|M)}{\partial \beta} = \langle \ln p(D|\theta, M) \rangle_\beta$$

$$\ln p(D|M) = \int_0^1 \langle p(D|\theta, M) \rangle_\beta d\beta$$

$$20\ chains\,(values\ of\ \beta \in [0,1])$$

Values of ln B_{12}

sample \ M_1/M_2	ΛCDM/CG	ΛCDM/KCG
GRBs	37.9	12.0
SNae	6.6	7.2
GRBs + SNae	1.5	24.3

$B_{12} > 1$ ⇒ M_1 favoured over M_2

Conclusions

- ΛCDM, CG, and KCG can describe the observational data

- The Bayes factor favours ΛCDM over CG and KCG

But ΛCDM has dark matter, dark energy...