Constraining Inverse Curvature Gravity with SuperNovae

José Santiago

Theory Group (FNAL)

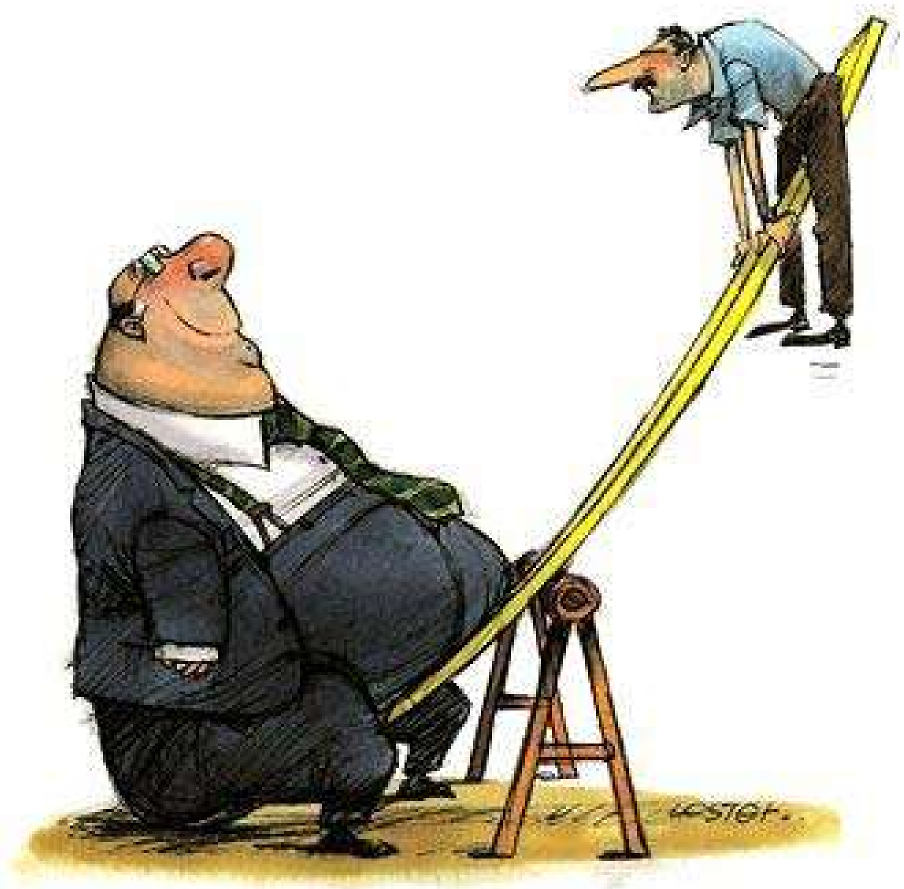
astro-ph/0510453 with O. Mena (FNAL) and J. Weller (UCL)

The Universe in the Large

- SNe allow us to glimpse the Universe at the largest distances with a surprising result ... the Universe is accelerating!
- Standard Explanation (Dark Energy)
  - Simple and consistent with SNe, CMB, LSS, ...
  - CC problem: why $\Lambda \lll (\mathrm{TeV})^4$?
  - Why $\Omega_\Lambda \sim \Omega_m$ now?
- Maybe the Universe is not so dark …

The Universe in the Large

Maybe gravity is standard at short distances ...



The Universe in the Large

... but gets modified at ultra large distances!

A Fresh Look at the Dark Sector

- Could it be a hint of modifications of gravity at ultra large distances (small curvatures)? [Capozziello, Carloni, Troisy ('03), Carroll, Duvvuri, Trodden, Turner ('03), Carroll, De Felice, Duvvuri, Easson, Trodden, Turner ('04)]

$$S = \frac{1}{16\pi G}\int dx\,\sqrt{-g}\left[R - \frac{\mu^6}{aR^2 + bR_{\mu\nu}R^{\mu\nu} + cR_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}}\right]$$

- Corrections negligible in the past (large curvature), kick in for $R \lesssim \mu^2$ (acceleration today for $\mu \sim H_0$?)
- Late time accelerated attractors in vacuum [CDDETT04]
- Simplest example ($\sim 1/R$) ruled out by solar system data [Chiva ('03), Soussa,Woodard ('03),...] but it is OK (plus no ghosts) for $b = -4c \neq 0$ [Navarro, Van Acoleyen ('05)]

Modified Friedmann Equation

- The Standard Friedmann Equation gets modified

$$\frac{H''\mathcal{F}_1(H,H')+\mathcal{F}_2(H,H')}{\mathcal{F}_3(H,H')}\frac{\mu^6}{H^4}+H^2=\frac{8\pi G}{3}\rho$$

- Extremely stiff non-linear second order diff equation
- The source is the standard one without Dark Energy

$$\frac{8\pi G}{3}\rho=\frac{8\pi G}{3}\left[\frac{\rho_{r\,0}}{a^4}+\frac{\rho_{m\,0}}{a^3}\right]\equiv\frac{\omega_r}{a^4}+\frac{\omega_m}{a^3}$$

- Only depends on

$$\alpha\equiv\frac{12a+4b+4c}{12a+3b+2c},\qquad \hat{\mu}\equiv\frac{\mu}{|12a+3b+2c|^{\frac{1}{6}}},\qquad \sigma\equiv\mathrm{sign}(12a+3b+2c)$$

Solving Friedmann Equation

- Numerical codes cannot cope due to stiffness

- Find an approximate analytic solution

$$H_{\text{approx}} = H_E \left(1 - \frac{1}{2}\frac{H_E''\mathcal{F}_1(H_E, H_E') + \mathcal{F}_2(H_E, H_E')}{\mathcal{F}_3(H_E, H_E')}\frac{\mu^6}{H_E^4}\right)$$

Very accurate (better than 0.1%) for $z \gtrsim$ few.
$H_E = \sqrt{8\pi G\rho/3}$ is the standard Einstein solution.

- Match to numerical solution: Use H_{approx} as initial condition for the numerical integrator at $z \sim 5$(approximation very accurate but numerical codes can cope)

Fit to SuperNovae Data

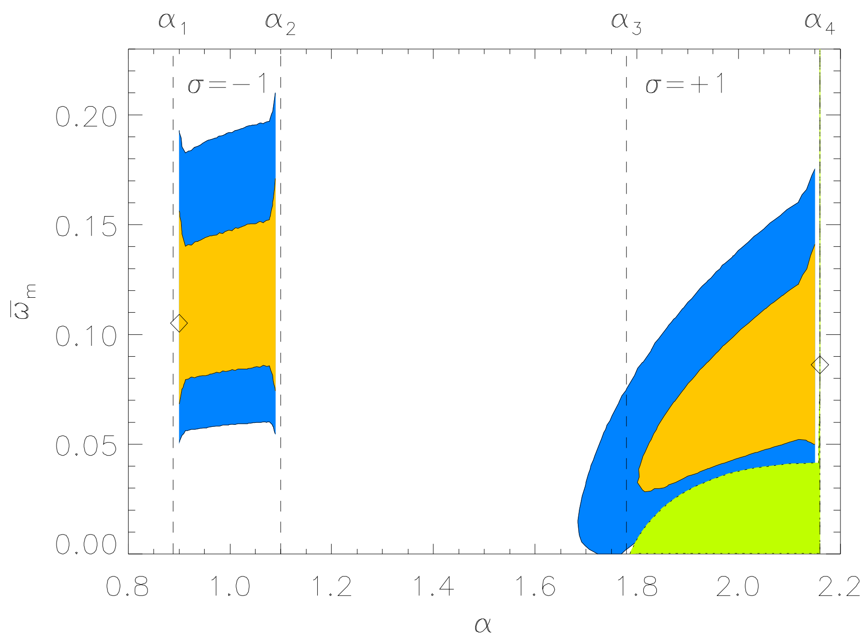
- SNe data is insensitive to the absolute scale of $H(z)$, thus we measure all dimensionful quantities in units of $\hat{\mu}$.
- The relevant parameters for the fit are then α and $\bar{\omega}_m \equiv \omega_m/\hat{\mu}^2$
- The value of σ is fixed by the evolution of the system

$$\sigma = -1, \quad \text{for } 0.89 \lesssim \alpha \lesssim 1.10,$$ (Low)

$$\sigma = +1, \quad \text{for } 1.10 \lesssim \alpha \lesssim 2.16,$$ (High)

Opposite values of σ lead the system to a singularity in the past while other values of α give bad fits to SNe data.

Fit to SuperNovae Data (cont'd)



Low

$$\alpha = 0.9, \quad \bar{\omega}_m = 0.105, \; \chi^2 = 184.9,$$

High

$$\alpha = 2.15, \quad \bar{\omega}_m = 0.085, \; \chi^2 = 185.2,$$

- We fit the Golden data set of HST [Riess et al. ('04)]
- Very good fits, comparable to $\Lambda\text{CDM}\ (\chi^2 = 183.3)$
- The Universe hits a singularity in the past in the green region

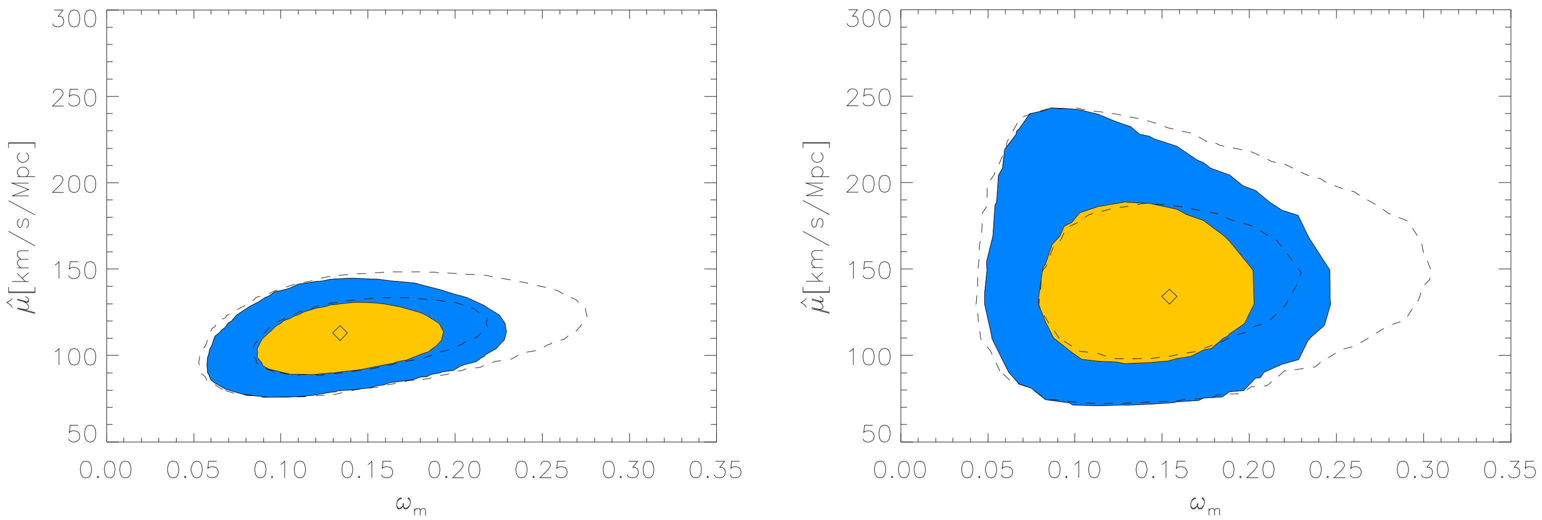
Setting scales: H_0 and the age of the Universe

- To set the scale we impose a prior on H_0 from Hubble Key Project

$$H_0 = 72 \pm 8 \text{ Km s}^{-1} \text{ Mpc}^{-1}$$ [Freedman *et al.* ('01)]

- We also impose a prior on the age of the Universe $t_0 > 11.2$ Gyrs
  [Krauss, Chaboyer ('03)]
- The marginalized result for ω_m is

$$\omega_m = 0.14 \pm 0.03 \text{ (low) } [\pm 0.04 \text{ (high)}] \Rightarrow \omega_m \geq 0.07 \, (95\% c.l.)$$



Conclusions and Future Work

- Inverse curvature modifications of gravity easily pass solar system, ghost freedom and geometrical cosmological tests without the need of Dark Energy
- The study of perturbations will put the model to more stringent tests and maybe will help to tell it apart from Dark Energy (work in progress)
- The class of models we have considered are not really that bright

$$0.07 \leq \omega_m \leq 0.21 \quad (95\% \, c.l.), \quad (\omega_b = 0.0214 \pm 0.0020)$$

maybe other models will allow us to get rid of dark matter?

- This “brighter” look at the Universe might bring interesting surprises so ... stay tuned!