DOE Research Report 2007

Stephen D.H. Hsu

ITS, University of Oregon

January 31, 2007 ITS/UOCHEP

Recent Collaborators

Roman Buniy (UO postdoc), Brian Murray (UO PhD student)

Anthony Zee (UCSB/KITP)

Mark B. Wise (Caltech), Michael Graesser (Caltech → Rutgers), Alejandro Jenkins (Caltech → MIT)

Xavier Calmet (Service de Physique Theorique, Brussels, Belgium)

Francesco Sannino (Niels Bohr Institute, Copenhagen, DK)

Deog-Ki Hong (Pusan National University, Korea)

Publications (2006)

[89] **Precision cosmology: independent evidence for dark energy**, with G. Bothun and B. Murray, astro-ph/0612106.

[88] **Does string theory predict an open universe?**, with R. Buniy and A. Zee, hep-th/0610231.

[87] **Spacetime topology change and black hole information**, hep-th/0608175, to appear in Physics Letters B.

[86] **On the volatility of volatility** (mathematical finance and economics) with B. Murray, Social Science Research Network, SSRN abstract 926379.

Publications (2006) continued

[85] **Physical limits on information processing**, Phys. Lett. B **641**, 99 (2006), hep-th/0607082.

[84] **The null energy condition and instability**, with R. Buniy and B. Murray, Phys. Rev. D **74**, 063518 (2006), hep-th/0606091.

[83] **Discreteness and the origin of probability in quantum mechanics**, with R. Buniy and A. Zee, Phys. Lett. B **640**, 219 (2006), hep-th/0606062.

[82] **Thermal gravity, black holes and cosmological entropy**, with B. Murray, Phys. Rev. D **73**, 044017 (2006), hep-th/0512033.

Dark Energy

Observations, including of Type Ia supernovae (SNe Ia) and Cosmic Microwave Background (CMB) anisotropy, imply that the expansion rate is increasing: $\ddot{R} > 0$.

The Einstein equations can be rewritten

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3} \sum_i (\rho_i + 3p_i).$$

In order for $\ddot{R} > 0$, the dominant component must have $p_{\rm de} < -\frac{1}{3}\rho_{\rm de}$ or *equation of state*

$$w_{\rm de} \equiv p_{\rm de}/\rho_{\rm de} < -1/3.$$

Any such component is called *dark energy* (including Λ, for which $w_\Lambda = -1$).

Fate of the Universe

$$\text{energy conservation:} \quad \dot{\rho}/\rho = -3(1+w)\dot{R}/R$$

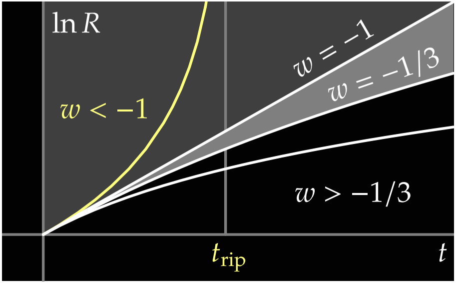
$$\text{solution:} \quad \rho \sim R^{-3(1+w)}$$

$$\text{for } k=0\text{:} \quad R \sim t^{2/[3(1+w)]}, \quad t \to \infty \quad (w > -1)$$

dominant component	w	R
radiation	$1/3$	$\sim t^{1/2}$
dust	0	$\sim t^{2/3}$
cosmological constant	-1	$\sim \exp\left[(\Lambda/3)^{1/2} t\right]$

At present, both Ω_Λ and Ω_{M}, later — only Ω_Λ.

The Big Rip



For $w < -1/3$, the Universe accelerates, $\ddot{R} > 0$.

The observational data favor $w \approx -1$.

$w < -1$: after a finite cosmological time, the Universe hits a Big Rip singularity, with infinite acceleration at each point in space.

Stability and the null energy condition

[84] **The null energy condition and instability**, with R. Buniy and B. Murray, Phys. Rev. D **74**, 063518 (2006), hep-th/0606091.

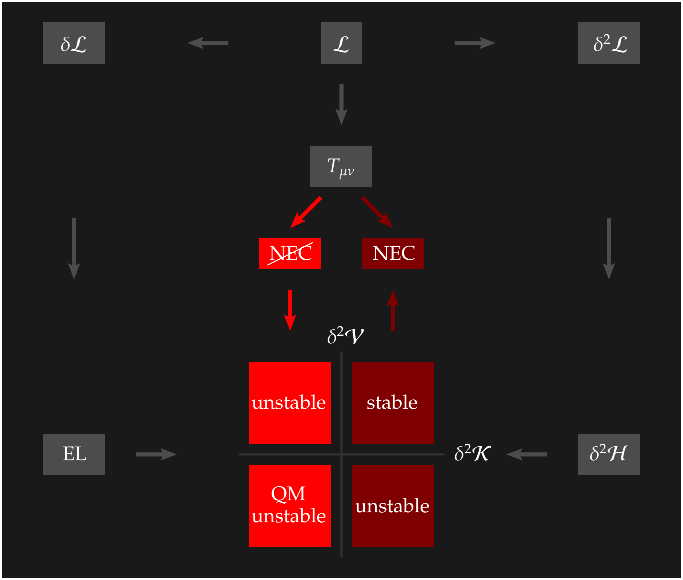
$w < -1$ violates the null energy condition: $T_{\mu\nu}n^\mu n^\nu \geq 0$.

Theorem: For the theory given by the action

$$S = \int d^d x \, |g|^{\frac{1}{2}} \left[\mathcal{L}(\phi_a, D_\mu \phi_a, F_{a\mu\nu}) + \tfrac{1}{2} f(\phi_a) R \right],$$

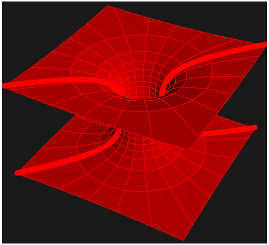
only solutions satisfying the null energy condition can be stable.

Strategy



$\delta\mathcal{L}$
$\mathcal{L}$
$\delta^2\mathcal{L}$
$T_{\mu\nu}$
NEC
NEC
$\delta^2\mathcal{V}$
unstable
stable
EL
$\delta^2\mathcal{K}$
$\delta^2\mathcal{H}$
QM unstable
unstable

Wormholes and time machines



Geodesics:
first converging, then diverging

Expansion of a hypersurface orthogonal null congruence (Landau-Raychaudhuri):

$$\frac{d\theta}{d\lambda} = \underbrace{-\tfrac{1}{2}\theta^2 - \sigma_{\mu\nu}\sigma^{\mu\nu}}_{<0} \underbrace{-R_{\mu\nu}n^\mu n^\nu}_{\gtreqless 0}$$

$R_{\mu\nu}n^\mu n^\nu = T_{\mu\nu}n^\mu n^\nu$, hence $\frac{d\theta}{d\lambda} > 0 \quad \Rightarrow \quad T_{\mu\nu}n^\mu n^\nu < 0$
Exotic matter on the throat stabilizes the wormhole.

To construct traversable wormholes one needs to violate the NEC.

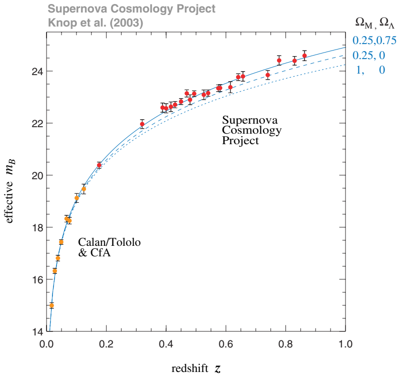
Observations: Type Ia Supernovae

SNe Ia are standardizable candles.

By measuring the spectra and light curves of a large number of SNe Ia, one can determine $R(t)$ and infer information about Ω_M and Ω_Λ.

($\Omega_i \equiv \rho_i/\rho_c$, where $\rho_c = 3H^2/8\pi G$ $\sim 10^{-5}\,\mathrm{GeV\,cm^{-3}}$ is the critical density.)

Conclusion: dark energy causes distant SNe Ia to be dimmer than they would be if there were only matter and radiation.



Independent evidence for dark energy

Is there observational evidence for dark energy which is independent of the supernova surveys, and therefore not subject to systematic effects from dust, evolution or exotic particle physics (such as photon to axion decay)?

Independent evidence for dark energy

[89] **Precision cosmology: independent evidence for dark energy**, with G. Bothun and B. Murray, astro-ph/0612106.

Abstract: We examine whether observations independent of type Ia supernova surveys are sufficient to imply the existence of dark energy. We find that best measurements of the age of the universe t_0, the Hubble parameter H_0 and the matter fraction Ω_m strongly favor the existence of a repulsive, acceleration-causing ($w < -1/3$) component of energy if the universe is nearly flat.

Independent evidence for dark energy

Age of the universe given by

$$t_0 = \int_0^{R(t_0)} \frac{dR}{\dot{R}} \tag{1}$$

which yields

$$t_0 H_0 = \int_0^1 \frac{dx}{(\Omega_m x^{-1} + \Omega_{de} x^{-1-3w})^{1/2}} \,, \tag{2}$$

for w constant in time, assumed flatness: $\Omega_{de} = 1 - \Omega_m$. Define integral as $I(\Omega_m, w)$. t_0, H_0 and Ω_m then determine w.

Time-varying DE equation of state $w(t)$: second term in the denominator becomes

$$\Omega_{de} \exp\left[\int_x^1 \frac{dx'}{x'}(1 + 3w(x'))\right] . \tag{3}$$

Independent evidence for dark energy

Some useful bounds:

If the dark energy *never* exhibits a repulsive equation of state, so $w(t) > -1/3$ at all times, the integral is bounded above:

$$I(\Omega_m, w > -1/3) \;<\; I(\Omega_m, -1/3)\,. \tag{4}$$

Similarly, we deduce

$$I(\Omega_m, w > w^*) \;<\; I(\Omega_m, w^*)\,. \tag{5}$$

Independent evidence for dark energy

Observational data (insensitive to SNe Ia systematics):

Age of universe: e.g., White dwarf cooling. $t_0 = 13.3 + 1.1 - .9$ Gyr.

Hubble parameter: e.g., HST, gravitational lensing. $H_0 = 74 \pm 5$ km/s/Mpc

Matter fraction: Galaxy clustering. $.15 < \Omega_m < .25$

Taking $t_0 = 12.4$ Gyr and $H_0 = 69$ km/s/Mpc, which are each one standard deviation below the favored (central) values in our assumed error model, we obtain $t_0 H_0 = .9$

Independent evidence for dark energy

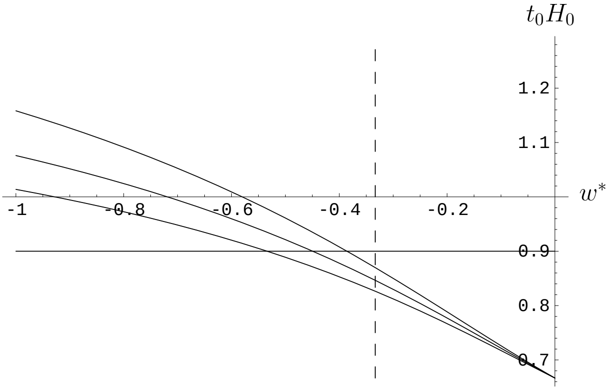


Figure: Allowed region in the $w - t_0 H_0$ plane. The curves correspond to $\Omega_m = .25, .20, .15$, and are *upper* bounds on $t_0 H_0$.

Independent evidence for dark energy

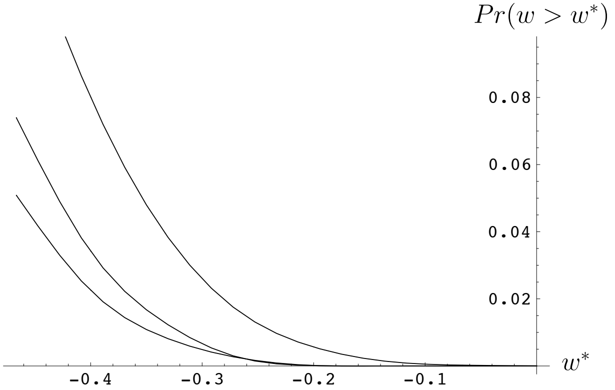


Figure: Probability that w was always greater than w^* for a range of w^* and various cuts on t_0 and Ω_m. See text for details.

Independent evidence for dark energy

Conclusion: Astronomical measurements which are insensitive to potential confounding effects such as dust or exotic particle physics (axions, photon decay) strongly favor the existence of dark energy.