Exploring the consequences of parameter values in cosmological models with CosmoEJS, an interactive package of cosmology Java simulations

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Introduction

It is not only important to constrain the parameters of cosmological models with the most recent and precise observations, but it is also crucial to understand the physical consequences of those parameters for the different, but complimentary observations involved. **CosmoEJS** is an interactive **Java** package of simulations that allow the user to explore the ramifications of choosing various values for the cosmological parameters of a particular model [1]. These simulations now include observations of the growth of structures of galaxies, as well as, the expansion history of the universe. Users can visually inspect the plotted theoretical values of their model, compare numerical fitting using χ^2 values, calculate derived cosmological values, and finally plot the expansion trajectory of their models as they evolve in time. The current list of more than 30 built-in observations includes several recent supernovae Type Ia surveys (SNe), baryon acoustic oscillations (BAO), the cosmic microwave background (CMB) radiation, gamma-ray bursts (GRB), measurements of the Hubble parameter, $H(z)$, the Alcock-Paczynski (AP) test, and the growth parameter, $f(z)$ and $\sigma_8 f(z)$. The simulations allow for many different classes of models, including dark energy, the cosmological constant and modified gravity.

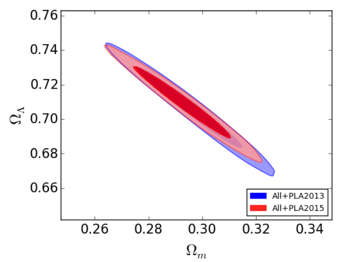

Figure 1. 2D contour plots showing 68% and 95% confidence constraints on {Ω_m, Ω_Λ}, from combining all data sets in the introduction with CMB measurements from Planck (PLA) [4].

Cosmological Background

The cosmic acceleration can be explained by a cosmological constant, or some other form of repulsive dark energy, *i.e.* a negative pressure and a negative equation of state, or by an extension or modification to gravity at cosmological scales of distances. In the context of general relativity (GR), to account for this dark energy effect, the addition of a Λ term to Einstein's Field Equations (EFE) can be used to derive equations of motion with a cosmological constant of the desired value consistent with the dynamics of Friedmann-Lemaitre-Robertson-Walker (FLRW) universe. We provide a means of testing these commonly accepted models of the Universe and others with large scale observations of the expansion of the universe, thereby deriving the parameters for the standard model in cosmology. We can better understand how constraints on parameters of a particular model determine its fit to different data sets and evolutionary dynamics by exploring these models using **CosmoEJS**.

Acknowledgments

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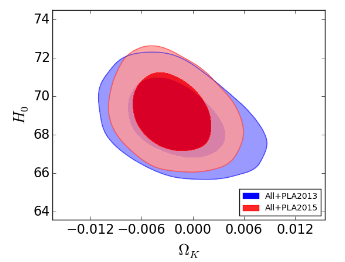

Figure 2. 2D contour plots showing 68% and 95% confidence constraints on {H_0, Ω_K}, from combining all data sets in the introduction with CMB measurements from Planck (PLA) [4].

The Model and Parameters to Fit

As an example, we begin with the general model [2] that allows for varying dark energy and spatial curvature, but can reduce ($w_0 = -1.0$, $w_a = 0.0$, $\Omega_k = 0.0$) to the simple Λ Cold Dark Matter model for constraining matter (Ω_m) and dark energy (Ω_Λ).

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda\left[(1+z)^{3(1+w_0+w_a)}\exp\left(\frac{-3w_a z}{1+z}\right)\right] + \Omega_k(1+z)^2}. \quad (1)$$

Eq. (1) contains the dynamical parameters (all dimensionless except H0) that are allowed to change in the programs. Briefly, these parameters are:

- **$H_0 \approx 69.0$ (km/s Mpc^{-1}) : the Hubble Constant parameter;**
- **$\Omega_m \approx 0.30$: the fractional matter density (subject to the constraint: $\Omega_m = \Omega_b + \Omega_c$);**
- **$\Omega_b \approx 0.05$: the fractional baryon density;**
- **$\Omega_c \approx 0.25$: the fractional cold dark matter density;**
- **$\Omega_\Lambda \approx 0.70$: the fractional dark energy density;**
- **$\Omega_k \approx 0.0$: the fractional curvature density;**
- **$\Omega_0 \approx 1.0$: the sum total energy density (subject to the constraint: $\Omega_0 = \Omega_m + \Omega_\Lambda + \Omega_k$);**
- **$w_0 \approx -1.0$: the equation of state of dark energy ;**
- **$w_a \approx 0.0$: the derivative of w_0;**

As the values of these parameters change, Eq. (1) describes different types of evolutions for the universe. These parameter constraints, see Fig. 1 and Fig. 2, are obtained using **CosmoMC** [3], but **CosmoEJS** can be used to numerically and visually confirm parameter values that match the data sets (and others), then simulate the evolutionary dynamics of the models, see Fig. 3.

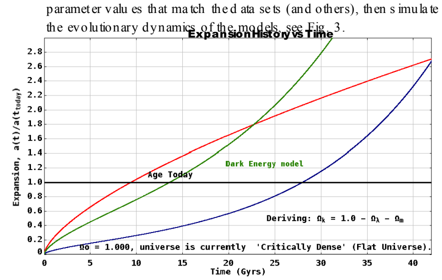

Figure 3. Expansion, $a(t)/a(t_{today})$ versus time (Gyrs = 10^9 years). **CosmoEJS** output showing three different models (curves) of the expansion of the universe, $a(t)/a(t_{today})$ (scale factor), versus time. The three models differ *only* in their fractional matter and dark energy densities, {Ω_m, Ω_Λ} = {1.0, 0.0}, {0.30, 0.70}, {0.01, 0.99} correspond to top (red), middle (green), and bottom (blue), respectively below the solid "Age Today" (black) line. (Note: Labels are draggable in CosmoEJS.)

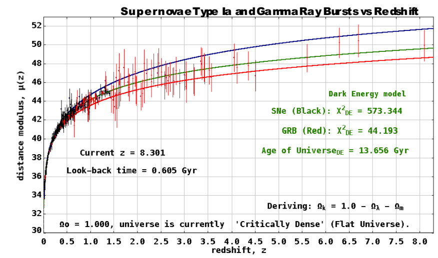

Figure 4. Supernovae Type Ia (SNe) and Gamma Ray Bursts (GRB) versus redshift. **CosmoEJS** output showing three different models (curves) and two different experimental data sets, SNe (black) and GRB (red). The three models differ *only* in their fractional matter and dark energy densities, {Ω_m, Ω_Λ} = {0.01, 0.99}, {0.30, 0.70}, {1.0, 0.0} correspond to top (blue), middle (green), and bottom (red), respectively. (Note: Labels are draggable in CosmoEJS.)

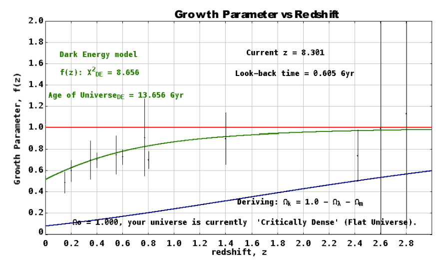

Figure 6. Growth parameter, $f(z)$ versus redshift. **CosmoEJS** output showing three different models (curves) compared to data sets of the growth parameter, $f(z)$ of structure formation of galaxies at different redshift. The three models differ *only* in their fractional matter and dark energy densities, {Ω_m, Ω_Λ} = {1.0, 0.0}, {0.30, 0.70}, {0.01, 0.99} correspond to top (red), middle (green), and bottom (blue), respectively. (Note: Labels are draggable in **CosmoEJS**.) The user can toggle back and forth between $f(z)$ and $\sigma_8 f(z)$ data comparisons as is appropriate for some classes of models.

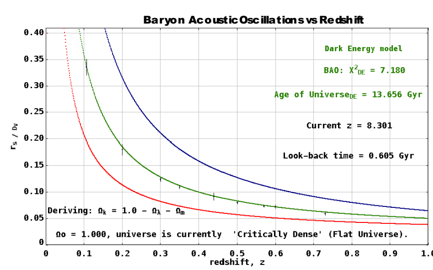

Figure 5. Baryon Acoustic Oscillations (BAO) versus redshift. **CosmoEJS** output showing three different models (curves) compared to data sets of the BAO ratio, the size of the sound horizon, r_s, to its effective distance, D_v in the galaxies. The three models differ *only* in their fractional matter and dark energy densities, {Ω_m, Ω_Λ} = {0.01, 0.99}, {0.30, 0.70}, {1.0, 0.0} correspond to top (blue), middle (green), and bottom (red), respectively. (Note: Labels are draggable in CosmoEJS.)

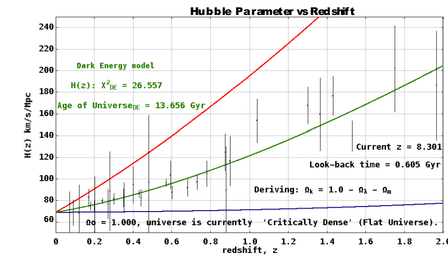

Figure 7. Hubble Parameter, $H(z)$ versus redshift. **CosmoEJS** output showing three different models (curves) compared to data sets of the expansion rates $H(z)$ of galaxies at different redshift. The three models differ *only* in their fractional matter and dark energy densities, {Ω_m, Ω_Λ} = {1.0, 0.0}, {0.30, 0.70}, {0.01, 0.99} correspond to top (red), middle (green), and bottom (blue), respectively. (Note: Labels are draggable in CosmoEJS.)

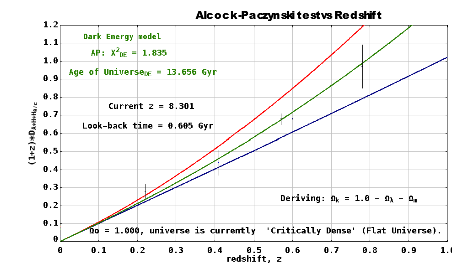

Figure 8. Alcock-Paczynski test versus redshift. **CosmoEJS** output showing three different models (curves) compared to data sets of the Alcock-Paczynski test. The three models differ *only* in their fractional matter and dark energy densities, {Ω_m, Ω_Λ} = {1.0, 0.0}, {0.30, 0.70}, {0.01, 0.99} correspond to top (red), middle (green), and bottom (blue), respectively. (Note: Labels are draggable in **CosmoEJS**.)

Results and Discussion

At present **CosmoEJS** is designed as a research and educational tool. The programs are precise enough to perform research grade calculations for testing most classes of cosmological models. They also allow the user to select inputs for parameters that are perhaps not scientifically accepted. This allows the user to discover how parameters influence the shape of the curve for a particular theoretical model, thereby understanding the physical interpretation of a model's fit to the data. Variations of the programs have been used for science outreach and for classroom illustration. Future versions of the programs (in-progress) will involve an optimization method for the fitting of the cosmological models to the data sets to provide best-fit cosmological parameters. We will also provide the user with a field to enter their own function for integration as the theoretical model (in-progress). This will allow for exotic models of cosmic acceleration including several types of modified gravity models. The programs will continue to receive updates and modifications for new more precise data sets as these become publicly available.

References

[1] J. Moldenhauer, L. Engelhardt, K. Stone, E. Shuler, *Modern Cosmology: Interactive Computer Simulations that use Recent Observational Surveys*, 20 May 2013, American Journal of Physics (Vol.81, Issue 6), [arXiv:1212.4661].

[2] M. Chevallier and D. Polarski, *Accelerating Universes with Scaling Dark Matter*, Int. J. Mod. Phys. D10, (2000) [gr-qc/0009008].

[3] CosmoMC, http://cosmologist.info/cosmomc/.

[4] Based on observations obtained with Planck (http://www.esa.int/Planck), an ESA science mission with instruments and contributions directly funded by ESA Member States, NASA, and Canada.

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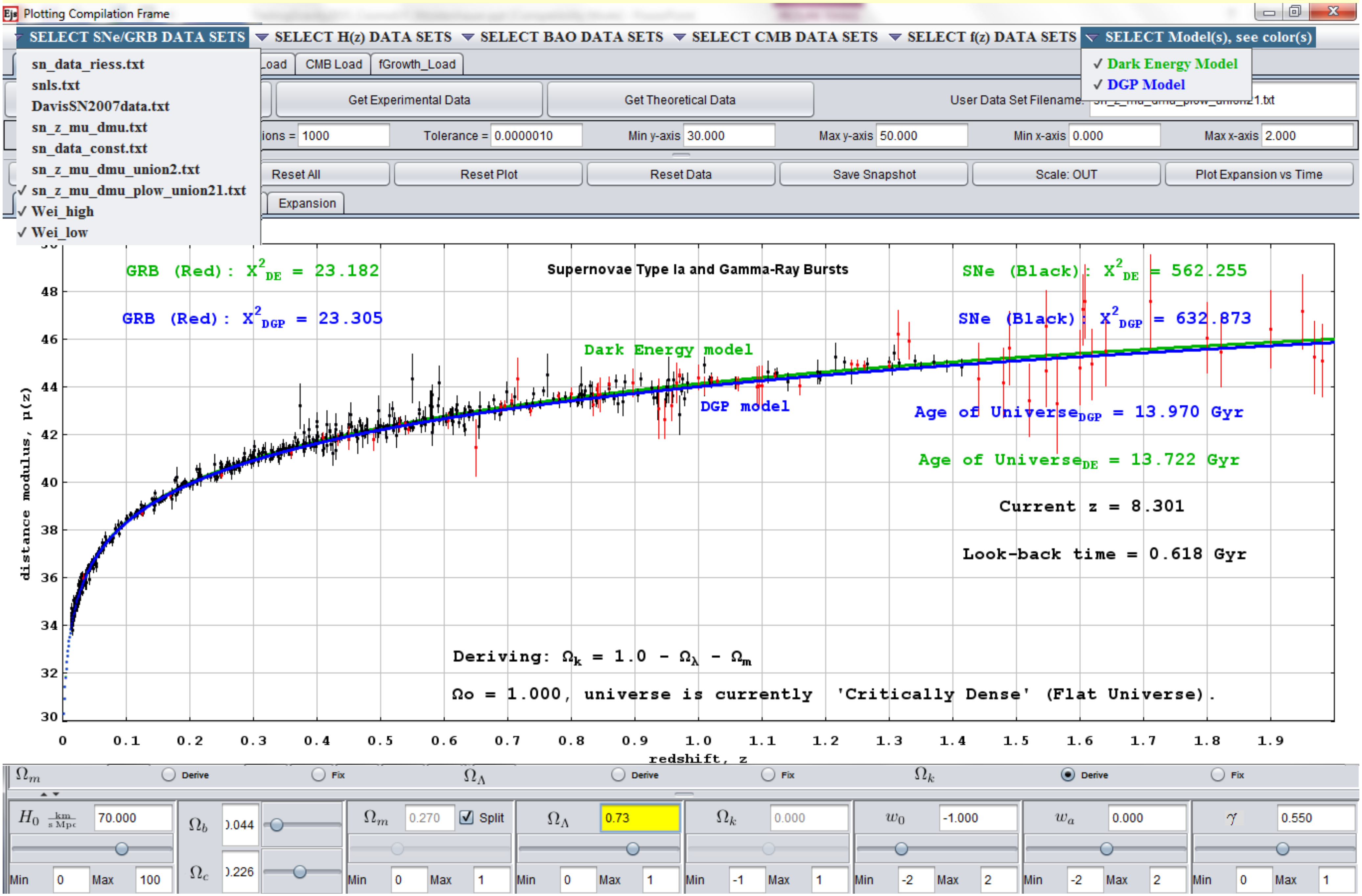

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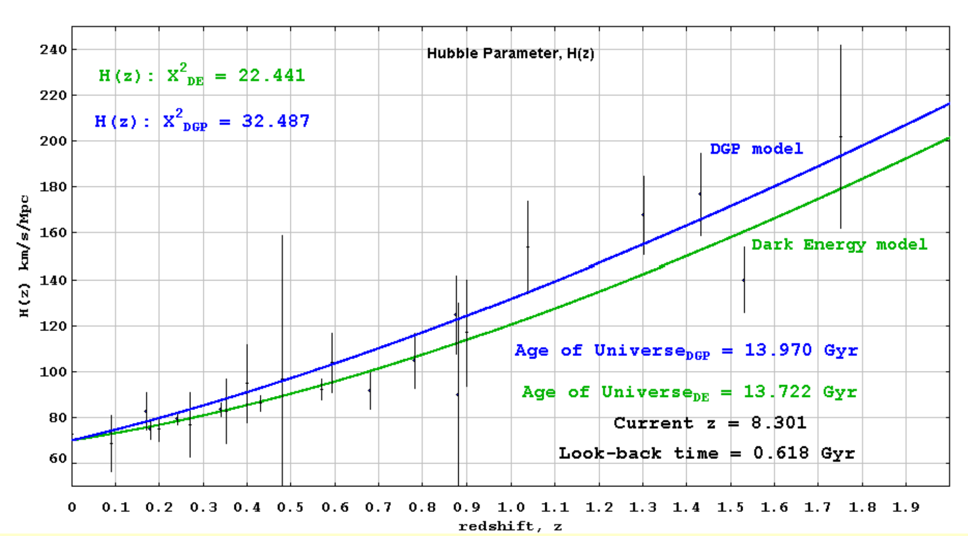

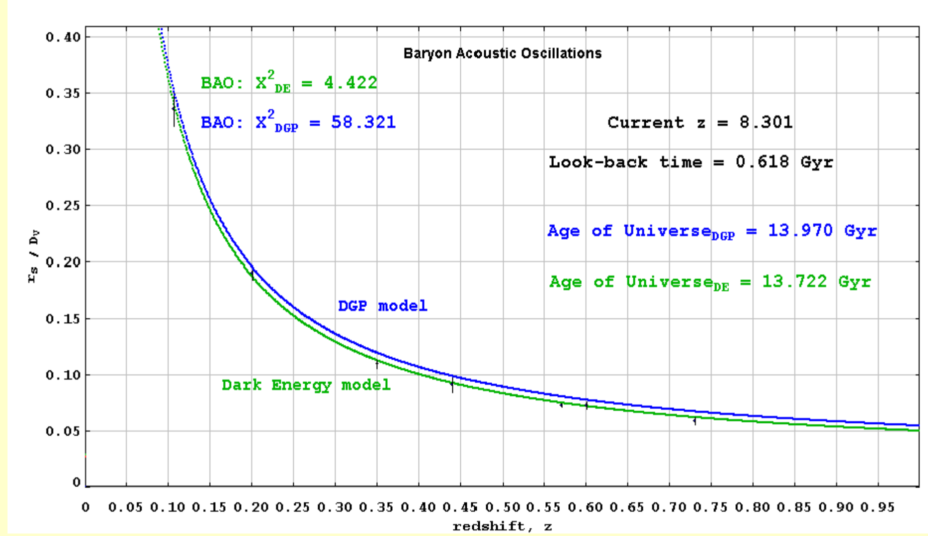

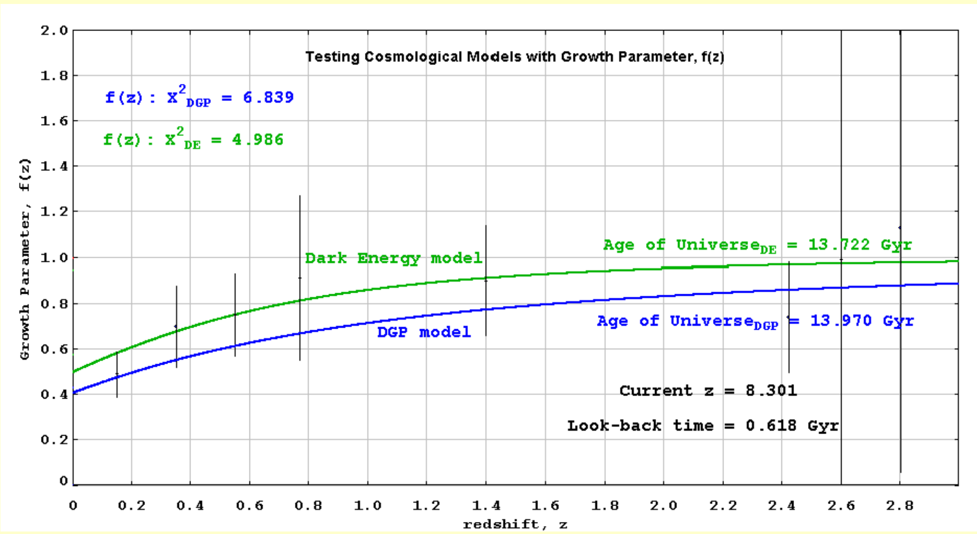

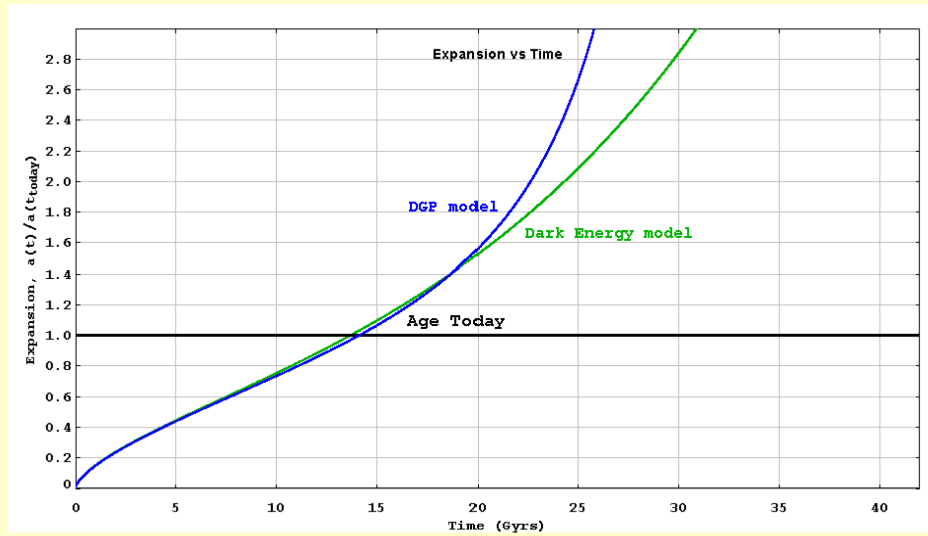

JM, L. Engelhardt, K. Stone, E. Shuler, Am. Jour. Phys., Vol. 81, Issue 6, 2013. arXiv:1212.4661

- Come see the poster for more models or **CosmoEJS** is publicly available at http://www.compadre.org/osp/items/detail.cfm?ID=12406

Thank you to the Donald A. Cowan Physics Institute